

*On the notion of the large-scale structure  
of the Universe*

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# Abstract

Cosmology is a young science, and there are only a few works on the epistemology of cosmology. One of the four pillars of this science is the large-scale structure of the Universe. The story of related discoveries begins in the late 1960s and continues to the present day, as this field of research becomes increasingly active. This history is intrinsically linked to the histories of the notions of time, space, space-time, and astrophysics in general. We present a summary of these histories, from which it is possible to make a history of representations of the large-scale structure of the Universe. A quick overview of the uses of the term structure in different fields finishes to provide the context for an epistemological study. For this study, we choose a sociological approach by conducting ten interviews with various researchers in astrophysics and cosmology, and these interviews show how thinking about the notion of large-scale structure and its representations is expressed today, and is representative of the history that preceded it. In particular, we study the link between the structure and its substructures, the images used to talk and think about them, and the status of this structure in the discourse of scientists and in the history of cosmology. This study shows that structure is understood as a holistic entity and that the discourses reflect epistemological structuralist viewpoints.

# Acknowledgements

I write these lines at the beginning of the Summer of 2024.

First of all, I would like to thank my thesis supervisor, Matthias Dörries, who believed in my project from the very beginning and allowed me to work at my own pace, providing me with methodological and historical epistemology tools I didn't have, and without which I wouldn't have been able to deliver such a structured and organised work. I probably wanted to cover too many topics, and you knew how to guide me in refining my focus without causing frustration.

I would also like to thank Catherine Allamel-Raffin and Jonathan Freundlich, who, along with Mr. Dörries, readily and enthusiastically agreed to be part of my jury. Each of you is interested in this work for different reasons, and I hope you are all satisfied with it. Our first meeting to discuss my thesis topic was with the three of you, and I'm glad to be concluding this work with the same people.

Naturally, I owe a lot to everyone else who proofread, corrected, and suggested improvements: my parents Anne-Françoise and Eric Jego (sorry about the accent), my sister Emmanuelle Jego, Jonathan Freundlich, Marie Leroy, Simon Landrieux, and Coralie Thomas. There's a bit of your work and time in this thesis. Thanks also to everyone with whom I discussed my topic or parts of my thesis, and who, through some particularly memorable conversations, influenced my writing and the subjects covered: Matthieu Béthermin, Katarina Kraljic, Pedro Ferreira, Félix Vivant, Jonas Mézière, Selyo Boutruche, and Tessa Blot. I'll add a shout-out to the SHIELD team for that, as I know you'll be reading this.

A huge thank you to the researchers who participated in the interviews: Katarina Kraljic, Françoise Combes, David Alonso, John Peacock, Rebecca Smethurst, Aniruddh Herle, Simon White, Roland Lehoucq, Jim Peebles, and Benjamin L'Huillier. Regardless of status and undoubtedly busy schedules, I perceived great kindness and spontaneity in all the discussions I had with these people. I must admit, being able to talk about philosophy and history so easily with a Nobel laureate who had never heard of me before reassures me about the

scientific community's willingness to engage with epistemological questions. Thank you all for giving me your time and playing along—it was a pleasure, and I hope the final result of this work interests you. I couldn't have done it without your contributions.

Extra thanks go to Matthieu and Katarina, who will now accompany me during my PhD. Alongside this thesis, I had to create a PhD project with you, apply for ENS funding grants, and—most importantly—wait (sometimes with a bit of stress) for the results. In the end, we got the funding, and I couldn't be happier to start this doctoral journey after finishing this thesis. Special thanks again to David (whom I'll probably have to include in all the acknowledgements I'll ever write) because without you and my 2022 research internship under your supervision at Oxford, I wouldn't be here. And honestly, all parallel realities seem less fun than this one, where you're responsible for my start in cosmology.

As this thesis concludes my four years of studies at ENS, I want to thank the professors who have influenced my academic journey, from the PTSI/PT preparatory classes at Lycée Chevrollier to this M2 in Epistemology in Strasbourg—especially Simon Moulin, Christine Magee Banchereau, Guillaume Nibaudeau, Jean-Paul Fortin-Ripoche, Jean-Marie Reynaud, Jean-Sébastien Lauret, Jérémy Neveu, and Dominique Aubert. Detailing what each has contributed to my studies would take too long, so I'll simply say a general thank you.

Finally, I want to thank my family, who followed my thesis writing process and supported me throughout my studies, all the way to my upcoming PhD. You've always made everything easier for me—my parents, for giving me the freedom to make my own choices while still advising me and taking an interest in what I do and what I want to do; my sisters, for always setting an example and fighting for me when things got tough; and my grandparents, who have always been proud of me and made sure to tell me so, which has been a great source of motivation.

Coralie, I hope you're not tired of hearing about the large-scale structure of the Universe every day because it's not going to stop here.

To Dada



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# Introduction

« À la fin du XIX<sup>e</sup> siècle, l'extension de l'univers, du moins de l'univers matériel, se réduisait à celle de notre galaxie. Ayant répertorié et compté les étoiles, les astronomes ont découvert qu'elles se répartissent dans une vaste concentration qui en rassemble une centaine de milliards : notre galaxie aussi nommée la Voie lactée. Durant le XIX<sup>e</sup> siècle, ils se sont employés à en mesurer la forme et les dimensions, à déterminer la position (centrale ou non) qu'y occupe notre système solaire. Les observations étaient difficiles, et d'âpres discussions se sont déroulées à propos de ces questions. »<sup>1</sup>

"At the end of the 19th century, the extension of the universe, or at least of the material universe, was limited to that of our galaxy. Having cataloged and counted the stars, astronomers discovered that they are distributed in a vast concentration that gathers about a hundred billion of them: our galaxy, also called the Milky Way. During the 19th century, they endeavored to measure its shape and dimensions, to determine the (central or not) position of our solar system within it. Observations were difficult, and fierce debates ensued regarding these questions."

In this excerpt from his article "Scientific Cosmology" in the *Revue de Métaphysique et de Morale* n°3 of 2004, astrophysicist Marc Lachièze-Rey describes a time when the structure of the Universe could only be the subject of metaphysical discussions because it had not yet been observed, and when astronomers gradually understood the place of the solar system in a galaxy that had only recently been identified as such. He mentions a "material universe" which is the object of astronomers' observations—everything that can be seen as far as the available technology allows. Here, we already detect a subtlety in the use of the term "material." There would be at least one Universe and a material Universe, and certainly, therefore, an immaterial or more-than-material Universe. This plurality of aspects of the word "Universe" is also reflected in modern definitions of the cosmos. The cosmos, from the Greek *kosmos* (good order, order of the Universe, world<sup>2</sup>), is, according to standard French dictionaries, "The Universe considered as a well-ordered system."<sup>3</sup> in contrast to chaos, or "The Universe and its laws, or, more generally, any Universe, real or stemming from a

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<sup>1</sup> Lachièze-Rey, M., *Cosmologie scientifique, Revue de Métaphysique et de Morale*, n° 3, 2004, pp. 399-411.

<sup>2</sup> Dictionnaire de l'Académie Française, I. Cosmos, nom masculin

<sup>3</sup> Dictionnaire Le Robert, cosmos, nom masculin

scientific or fantastical conception."<sup>4</sup>, as well as outer or interstellar space. These definitions are given a posteriori to a complex history of discoveries and interpretations, both visual, semantic, and scientific, of the world around us, and they are still subject to evolution.

If, at first glance, these notions of Universe, cosmos, and world are familiar and integrated into common vocabulary, it is remarkable that such classic definitions immediately raise major questions, both in philosophy and physical sciences. For example, the notion of the existence of what the Universe contains sparks physical and metaphysical debates about dark matter and dark energy, for which astronomical observations provide only indirect evidence. In particular, from the independent works of the American school represented by Jim Peebles at Princeton, the Russian school led by Yakov Zel'Dovich in Moscow, and the emerging one in Cambridge with Martin Rees in the late 1970s, the large-scale structure of the Universe has become one of the main subjects of modern astrophysics and cosmology (the academic reference on this subject remains Jim Peebles' manual<sup>5</sup>). A quick search on NASA's ADS database<sup>6</sup> indicates that the phrase "large-scale structure of the Universe" appears in more than twelve thousand scientific articles since the 1980s. This notion of structure, and thus of organization and arrangement of the constitutive parts of the Universe, is understood starting from the scale of galaxy clusters, *i.e.*, beyond the megaparsec (Mpc). One Mpc is about three million light-years, meaning a distance that light takes approximately three million years to travel.

Of course, this work does not aim to exhaustively study the history of cosmology or to definitively answer, within a limited number of pages, all the questions that arise when mentioning the large-scale structure of the Universe. In this introduction, and starting from these brief main definitions, the terms concerned with the large-scale structure of the Universe will be stated and defined, particularly cosmology, and, because its history demands it, first as metaphysics and then as physical science. Several epistemological questions related to this structure, which will be detailed, form the subject of the study conducted in this thesis, whose organization is detailed in Section 0.4, following the problematization (Section 0.1), a detailed account of my personal formation (Section 0.2), as well as a review of the literature on the subject and the presentation of the method used (Section 0.3).

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<sup>4</sup> Dictionnaire Larousse, cosmos, nom masculin

<sup>5</sup> Peebles, P. J. E., *The Large-Scale Structure of the Universe*. Princeton University Press, 1980, 423p.

<sup>6</sup> <https://ui.adsabs.harvard.edu/search/>

## 0.1 Why an epistemology of the large-scale structure of the Universe?

The etymology of the word "cosmology" evokes a discourse about the world. As a human conception of the cosmos, it necessarily exists as long as humans have conceived of a world around them. However, the first written traces of cosmological and astronomical considerations, including representations of constellations, date back to the Mesopotamian civilization, around 6,000 years ago<sup>7</sup>. Furthermore, as the science of the physical laws governing the Universe, its formation, and its evolution, cosmology is a branch of astrophysics, itself young and primarily based on the observation of celestial bodies, i.e., astronomy. Thus, cosmology as a physical science of the Universe is even younger than astrophysics. It is possible to trace its appearance in modern science back to the late 1920s, with the discovery of the Hubble-Lemaître parameter<sup>89</sup>  $H$  by Edwin Hubble at the Mount Wilson Observatory near Pasadena, California, following the work of the Belgian priest and astronomer Georges Lemaître, whose contributions were little known in the scientific community at the time. This parameter characterizes the proportionality, observed today, between the apparent recession speed of observable galaxies and the distance between these galaxies and the observer.

Since this theorization and modeling of the apparent expansion of the local observable Universe, this science, though young, has experienced significant and spectacular developments during its hundred years of existence. In particular, since it emerged after the developments in chemistry and photography, and within a tradition of algebraic geometrization of physical laws, spectroscopy and the geometry of space-time are at the core of cosmology. Regarding the first point, spectroscopy initially allowed the composition of the closest stars and galaxies to Earth to be determined by identifying absorption lines, following technological advancements that made it possible to observe, record, and analyze the light coming from them. The range of the observed and studied electromagnetic spectrum then widened, and the construction of radio telescopes in the 1960s enabled the observation, by

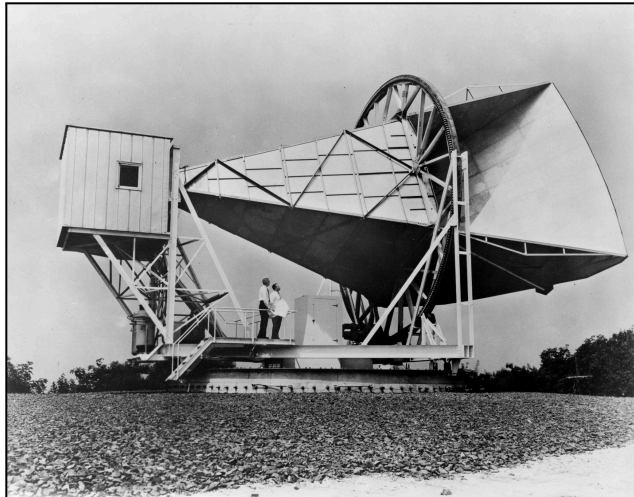
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<sup>7</sup> Swerdlow, N. M., (dir.), *Ancient Astronomy and Celestial Divination*, Cambridge, 1999, 388p.

<sup>8</sup> The Hubble-Lemaître parameter was long attributed solely to Edwin Hubble. A vote made the name used here official in 2018. : « IAU members vote to recommend renaming the Hubble law as the Hubble–Lemaître law », IAU, 29 Octobre 2018.

<sup>9</sup> Hubble, E., A relation between distance and radial velocity among extra-galactic nebulae. *Proceedings of the National Academy of Sciences*, 1929, 15, pp. 168–173.

Arno Penzias and Robert Wilson<sup>10</sup> at the Bell Labs Holmdel Complex in New Jersey using a horn antenna (Figure 1), of a radiation present everywhere in the Universe and predicted by Ralph Alpher (Johns Hopkins University, Baltimore), Robert Herman (University of Texas, Austin), and George Gamow (George Washington University, Washington D.C.) in the 1940s, and later independently by Yakov Zel'Dovich in Moscow and the group formed by Dicke, Peebles, Roll, and Wilkinson<sup>11</sup> at Princeton: the cosmic



**Figure 1** : Penzias and Wilson under the horn antenna that enabled the discovery of the cosmic microwave background. The signal is concentrated by the horn and directed toward the cabin on the left, where it is recorded by instruments. Image from the public domain.

microwave background radiation. This microwave radiation, also called fossil radiation, consists of photons among the first to move freely in the Universe, emitted when light and matter decoupled. The very slight inhomogeneities in this fossil radiation are an indicator of fluctuations in the distribution of matter in the primordial Universe, which, according to the dominant interpretation, are the cause of the inhomogeneous distribution of galaxies in the Universe over its evolution and today. This distribution of galaxies, and more generally of matter on scales of billions of light-years, is what is referred to as the large-scale structure of the Universe.

Until the 1970s, it was commonly believed, both due to the philosophical legacy left by Hubble and the lack of evidence to the contrary, that the distribution of galaxies was homogeneous. The first observations discerning a non-homogeneous organization and estimating the characteristics of this structure were made by the Americans Laird Thompson and Stephen Gregory in 1978<sup>12</sup>. Following this, various works were published, including those by Margaret Geller and John Huchra, who worked at the Harvard-Smithsonian Center for Astrophysics in Cambridge, in 1989<sup>13</sup>: in their article "Mapping the Universe," they represented a filament of galaxies more than 500 million light-years long and 300 million

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<sup>10</sup> Penzias, A. A., Wilson, R. W., A Measurement of Excess Antenna Temperature at 4080 Mc/s, *The Astrophysical Journal*, 1965.

<sup>11</sup> Dicke, R. H., Peebles, P. J. E., Roll, P. G., Wilkinson, D. T., *Cosmic Black-Body Radiation*. in *The Astrophysical Journal*, 1965

<sup>12</sup> Gregory, S. A., Thompson, L. A., The Coma/A1367 supercluster and its environs, *Astrophysical Journal*, Vol. 222, 1978, pp. 784-799. DOI : 10.1086/156198

<sup>13</sup> Geller, M. J., Huchra, J. P., Mapping the Universe, *Science*, 1989.

light-years wide, named the "Great Wall." Since this discovery, astronomical surveys on increasingly larger scales have been conducted, revealing more distant structures like the Sloan Great Wall, with ever greater precision. Today, especially with the help of the "Zel'Dovich approximation"<sup>14</sup> on structure formation, structures are generally classified into four categories: nodes, filaments, walls (or pancakes), and voids. A node has a typical size of about one megaparsec, filaments and walls around ten megaparsecs, and voids about one hundred megaparsecs. For comparison, our galaxy is about thirty kiloparsecs long, which is thirty times smaller than a megaparsec. All these structures form what is commonly referred to as the cosmic web, which is a component of the large-scale structure of the Universe. What the cosmological community refers to as the large-scale structure of the Universe also includes the specificities of the patterns and arrangements of galaxies, as well as gas and dark matter.

As for dark matter, it is a type of matter that interacts only through gravity (its lack of electromagnetic interactions making it unable to absorb or emit electromagnetic radiation, meaning it would be more appropriate to speak of invisible rather than dark matter) and helps explain various phenomena at galactic scales and beyond:

(1) Galaxy rotation curves: The stars and gas inside galaxies orbit around the galactic center. However, observations show that the rotation speed of stars remains high even at the edges of galaxies, where visible matter is very scarce. The presence of dark matter is invoked to explain this velocity distribution.

(2) Collisions of galaxy clusters: When two galaxy clusters collide, gravitational lensing effects are observed, where light from galaxies behind the clusters is bent. Observations show that the amount of visible matter in the clusters is not enough to explain the magnitude of the light deflection, suggesting the presence of dark matter.

(3) Fluctuations in cosmic radiation and their links to large-scale structure: These can be explained by assuming that dark matter provided the gravitational potential necessary to form the structures we observe today.

(4) Formation and evolution of galaxies: Numerical simulations of galaxy formation and evolution show that dark matter plays a crucial role in the gravitational attraction necessary to form galaxies and galaxy clusters on large scales.

(5) Gravitational lenses: Gravitational lensing effects, where light from distant objects is bent by the gravity of massive objects between them and the observer, can also be used to

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<sup>14</sup> Zel'dovich, Y., An approximate theory for large density perturbations, *A&A*, 5, 84, 1970.

infer the presence of dark matter and cannot be explained by considering only classical matter.

In general, according to current models, it is the distribution of dark matter that creates the gravitational potential necessary for the structuring of classical matter, known as baryonic matter and mainly composed of protons, neutrons, and electrons, into galaxies. Many works have already been published on this intriguing element, whether in astrophysics, the philosophy of science, or the history of science. This dark matter remains elusive, and many studies focus on its nature. Despite the absence of direct evidence for the existence of dark matter particles, astrophysicists are trying to uncover its nature through experiments, such as those conducted at large particle accelerators like the Large Hadron Collider (LHC) at CERN.

Dark matter is an integral part of the dominant model in cosmology, often called the standard model of cosmology, the  $\Lambda$ CDM model. CDM stands for Cold Dark Matter, which is the dominant model for dark matter that assumes dark matter is cold, meaning it has only low, non-relativistic speeds (much lower than the speed of light in a vacuum) and thus lacks significant thermal agitation. Lambda ( $\Lambda$ ) refers to the cosmological constant or, equivalently though physically different, dark energy (the term "dark" is also misleading here, as is the term "energy"), which is thought to be responsible for the acceleration of the expansion of the Universe. In many ways, the  $\Lambda$ CDM model can be considered the current paradigm, or at least the dominant theory in astrophysics and cosmology since the late 20th century. It is a set of equations based on Albert Einstein's general relativity and physical laws, i.e., models, that explain most observed phenomena on a cosmological scale and, with more difficulty, on a galactic scale. Regarding the notion of a paradigm, one can, of course, refer to Thomas Kuhn's work in *The Structure of Scientific Revolutions*<sup>15</sup>. However, studying a paradigm is not the primary focus of this thesis. The  $\Lambda$ CDM model (referred to as just " $\Lambda$ CDM" in the rest of this work, omitting the term "model," i.e., "in  $\Lambda$ CDM" for "in the  $\Lambda$ CDM model") is the dominant model today, and this can be explained by its ability to accurately reproduce, through simulations, the large-scale structure of the Universe and its statistical properties and to explain most observed phenomena with a very limited number of physically motivated parameters that have a clear physical meaning. This model is incomplete and contains elements that are still active subjects of study today, such as its two main components,  $\Lambda$  and CDM. Dark energy is still entirely undetectable, and if it is an energy of the vacuum, as it is

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<sup>15</sup> Kuhn, T., (1962, éd. augm. 1970), *The Structure of Scientific Revolutions*, University of Chicago Press ; trad. fr. par Laure Meyer : *La Structure des révolutions scientifiques*, préface de Jean-Pierre Luminet, Paris, Flammarion (Champs), 2018.

often associated with, the calculations possible for such a quantity in quantum mechanics give a value entirely different from what one would expect based on cosmological observations. Moreover, dark matter remains very mysterious, and the absence of particle detection despite ongoing experiments on Earth, such as particle collisions at the LHC<sup>16</sup> or ionization in XENON1T<sup>17</sup>, pushes the astrophysics and particle physics community to search for alternative models of dark matter. Research on dark matter is very active in cosmology concerning the large-scale structure of the Universe. Questions arise around the Hubble-Lemaître constant, whose exact value is debated, as well as, for instance,  $\sigma_8$  which represents the amplitude of density fluctuations of matter on a scale of 8 megaparsecs, and thus measures how densely or sparsely populated regions of the Universe are at this distance scale.

As we can see, cosmology is a young science that raises various epistemological questions. Moreover, it is primarily an observational science where experiments must rely on simulations. Indeed, theories of the Big Bang, inflation, or, more generally, large-scale physical objects are not theories and objects that can be studied in a laboratory on Earth. Furthermore, like any science, there exist competing ideas to the main paradigm that develop and sometimes flourish, attempting to provide explanations for phenomena that the models of the paradigm do not explain or explain incompletely or ad hoc, such as dark matter or dark energy. This is the case for the main theory competing with dark matter, MOND (for Modified Newtonian Dynamics), which, without completely replacing the paradigm, modifies certain laws, or modified gravity theories that seek to account for the effects of large quantities of mass on space-time without resorting to general relativity, or by modifying it.

Few people have ever been interested in epistemological questions regarding cosmology outside the very attractive terms like dark matter and black holes, for example. A recent book, *Philosophy of Astrophysics: Stars, Simulations, and the Struggle to Determine What is Out There*<sup>18</sup>, compiles and completes the major works that have been conducted in the philosophy of astrophysics, and the annotated bibliography of this book reveals that fewer

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<sup>16</sup> Giudice, G. F., *A Zeptospace Odyssey: A Journey into the Physics of the LHC*. Oxford et New York : Oxford University Press, 2010.

<sup>17</sup> XENON Collaboration. Dark matter search results from a one ton-year exposure of xenon1t, *Phys. Rev. Lett.*, 2018. DOI : 10.1103/PhysRevLett.121:111302

<sup>18</sup> Boyd, N. M., De Baerdemaeker, S., Heng, K., Matarese, V. (ed.), *Philosophy of Astrophysics : Stars, Simulations, and the Struggle to Determine What is Out There*, Springer, Synthese Library, vol. 472, 2023, 332 p.

than a hundred articles have been selected by the authors<sup>19</sup>. Thus, concerning the large-scale structure of the Universe, an epistemological study that would include a history of major concepts as well as a discussion with cosmologists about these concepts and a philosophical positioning of the community has not yet been done. Although limited in the number of pages, it is such a study that this Master's thesis proposes. In particular, we will seek to analyze what cosmologists do and think when they address the large-scale structure of the Universe. This notion emerged at the end of the 20th century with the first large galaxy surveys, and the history that concerns us is that of this notion since 1980, although it is essential to study the term structure in other scientific and historical contexts in order to grasp its meaning well. From a history of the notion of the large-scale structure of the Universe, several questions can be raised. What is the role of visual representation when it comes to observing the Universe at a large scale? And since it involves the visual, what images of the large-scale structure of the Universe exist and have existed, by what means are they created, and what do we see in them? Is there a philosophy of the Universe outside its representations, both among cosmologists and a less specialized public? These questions will underpin the reflection presented here and will drive the analytical argumentation regarding what cosmologists say about their discipline and their object of study. By keeping visual, semantic, and mental representations of the large-scale structure of the Universe as a common thread, we will conduct a historical epistemology of this notion and examine the philosophy of cosmologists regarding their object of study.

## 0.2 Personal background

Before outlining the method that will be used in this thesis and the form it will take, it is customary in STS<sup>20</sup> to reflect on one's own background and perspective on the studied subject. While it would be illusory to claim that such a perspective can be purely objective, the goal here is to clarify its origin as neutrally as possible, informing readers about who is writing and the potential biases that may arise. This is particularly important in my case.

I have completed scientific higher education, initially in a preparatory class for grandes écoles, which led me to the École Normale Supérieure (ENS) Paris Saclay, where I

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<sup>19</sup> One can read in the commented bibliography: « Especially given the relatively small size and recent vintage of this field (there are only 87 entries in this bibliography, 66 of which are from 2010 onwards, and 32 since 2020) the articles in this volume constitute a significant and timely addition ».

<sup>20</sup> *Science and technology Studies* (Études des Sciences et Technologies).



affirmed and developed my interest in astrophysics within the Department of Teaching and Research in Physics. Alongside my third-year undergraduate studies and my first year of Master's, I took optional STS courses offered by the ENS, notably in the philosophy and sociology of science. Additionally, I completed a third-year undergraduate year in mathematics alongside my first year of Master's, which allowed me to also obtain a diploma in fundamental mathematics. These studies reflect a passion for both abstraction and reflexivity concerning the fundamental sciences I study.

In the scientific studies I have undertaken at the ENS, modern 20th-century physics is taught, comprising quantum mechanics, relativity, modern astrophysics, as well as classical areas of physics that have withstood the test of time, such as statistical physics or Lagrangian mechanics. The historical aspects of these sciences are mentioned but occupy a minor role in the education of students, and the philosophy or sociology of physics is rarely taught or studied unless one follows optional courses. This absence has certainly guided me toward courses that explicitly deal with these subjects.

During two research internships—one at the Department of Cosmology at the University of Oxford and the other at the Max Planck Institute for Astrophysics in Garching bei München—I encountered a community of which I am now a part, as well as the effective use of cosmological models and dark matter. Thus, I have access not only to a concrete insight into the activities of cosmologists in the laboratory but also to a number of tacit knowledge elements that will need to be articulated, as well as a significant understanding of the paradigm represented by the  $\Lambda$ CDM model and its place within the community of researchers in cosmology. I confirmed my desire to pursue this path by undertaking a specialized Master's degree in astrophysics at the University of Strasbourg, within the astronomical observatory, and by preparing a doctoral thesis on the large-scale structure of the Universe.

Before embarking on this doctoral thesis and taking advantage of my final year of studies at the ENS, I had the opportunity to enroll in a Master's program in the epistemology and history of science and technology at the Faculty of Historical Sciences in Strasbourg. It was within this framework that this thesis was written. My intention in doing so was to focus on how science is conducted, nurtured, and forms a system of knowledge, particularly in the domain that is originally mine: cosmology. This is what I am realizing in these pages. This Master's program allows me to acquire a foundational knowledge base in history, philosophy, and sociology of science, complementing the initial elements I was taught in previous years. This enables me to enrich the intuitive and concrete approach I have to cosmology through

my scientific studies and research internship experiences with a historical approach, as well as an abstract one through philosophy and an anthropological one through sociology. While I do not entirely share Auguste Comte's statement that “*one does not fully understand a science until one knows its history*”<sup>21</sup> (I simply think that one never fully understands a science), I willingly acknowledge that an epistemological study of cosmology is quite relevant for attempting to gain a comprehensive view of it and enriching our conception of its object: the Universe. Therefore, it is with the aim of conducting such a study that I seek to apply the knowledge acquired in this Master's program in addition to what I already knew about cosmology.

In hindsight, I admit to having learned a great deal through writing this thesis, particularly regarding the controversies and details that punctuate the history of the large-scale structure of the Universe. My preconceived notion that this history was relatively smooth and that I already knew its main actors has had to be revised to allow for a narrative that initially appeared less intuitive but ultimately proves to be more accurate and complete.

## **0.3 Method and literature**

### **0.3.1 Method of historical epistemology**

As this is an epistemological work, this thesis aims to present elements of history, sociology, and philosophy of science. These various disciplines, when correctly coordinated, allow for the study of a science and its object, proposing an analysis that clarifies and makes understandable the rules of a knowledge production system. The notion of the large-scale structure of the Universe is not and has not been fixed over time. On the contrary, the imaginations of cosmologists, as well as the representations and vocabulary used to describe this structure, have evolved since the first observations of an organization and the initial theoretical models aiming to explain it, and they are still not the same among all cosmologists today. In this context, a historical approach, or historical epistemology, seems appropriate and aims to show how we arrive at a dominant theory that is discussed in various ways.

Historical epistemology is a branch of philosophy and the history of science that examines the development of knowledge and the ways in which it has been constructed,

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<sup>21</sup> Comte, A., *Cours de philosophie positive, Tome premier contenant les préliminaires généraux et la philosophie mathématique*, Paris : Rouen Frères, 1830, p.80.

validated, and justified over time. Essentially, it studies the historical contexts, cultural influences, and conceptual frameworks that have shaped knowledge production in different periods and civilizations through the evolution of knowledge systems, how different cultures and societies have approached questions of knowledge, and how various forms of inquiry have shaped our understanding of the world. There is no single version of it, and for our study, we will focus on the works of Ian Hacking, specifically his publications *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science*<sup>22</sup> for the fundamental elements of his philosophy and for the question of visual, semantic, and mental representation of the large-scale structure of the Universe, as well as *The Emergence of Probability*<sup>23</sup> to provide an example of the emergence and evolution of a complex notion in the fundamental sciences. Hacking's approach is a reference in epistemology. He emphasizes the historical evolution of concepts and the central role of experimental practices. This approach invites us to understand science not as a timeless quest for truth but as a dynamic and contextual process of knowledge construction. This is how we will proceed to develop the histories of the major physical concepts we will discuss.

To conduct this historical epistemology study, it will first be necessary to establish a history of techniques, ideas, institutions, locations, and scientists, as well as a history of successful or unsuccessful attempts to establish or explain a scientific fact. A priori, it is a very complex task to propose all these elements, regardless of the scientific object of history, precisely because the history of each object is itself complex and contains a wide diversity of actors, both human and non-human. Regarding the large-scale structure of the Universe, this history is relatively short. However, it is situated within the history of cosmology, of the Universe, and of space-time as scientific objects, and it is obviously not possible to account for all the elements that have influenced its current state in a single work. We will focus here on the essential points of the history of human thought regarding the Universe and space-time, which involves going back to some thinkers from Antiquity and mentioning the main thinkers and scholars of this history up to the present, then on the history of modern cosmology and the ideas that have shaped what we think today about the large-scale structure of the Universe. One way to learn about the history of a scientific notion is to discuss it with researchers directly involved in research or communication around this object. Organizing interviews with members of the scientific community to question them about what they do

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<sup>22</sup> Hacking, I., *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science*, Cambridge University Press, 1983, 304 p. ISBN : 978-0521282468

<sup>23</sup> Hacking, I., *The Emergence of Probability*, Cambridge University Press, 2<sup>e</sup> éd., 2006, 246 p. ISBN : 978-0521685573

and think and to analyze what they say falls within the realm of laboratory anthropology. This approach was popularized mainly by Bruno Latour and Steve Woolgar in *Laboratory Life: The Construction of Scientific Facts*<sup>24</sup> and is complemented by an understanding of the scientists' work environment through observation in their laboratories. The habits and biases of the observer must be set aside to avoid personal biases as much as possible. This is a mental effort that is difficult to fully achieve, especially when one already has knowledge and familiarity with the observatories and offices of cosmologists, but it is important to keep this in mind during interviews. This requires recordings, note-taking, and analyzing the textual transcriptions of the recordings. It is important, when one wishes to study what a cosmologist says, to provide a transcription that is as faithful as possible to what was said during the interview. This is not only a question of good sociological practice but also of ethics and respect for those who agreed to an interview. Note-taking is subject to errors, misunderstandings, strong personal biases, omissions, and transformations that render it unreliable, although it remains useful for organizing thoughts and marking important points.

Ten interviews were conducted between February and March 2024. We will analyze how representations of the large-scale structure of the Universe come into play in these discussions, which terms dominate, and we will compare these terms with those used in the past.

Ultimately, based on a historical study and a set of sociological and anthropological surveys, Ian Hacking's philosophy provides both a pre-existing framework in which it is possible to position and study the ways of thinking and acting of scientists regarding the large-scale structure of the Universe, and sometimes cosmology in general. From its various aspects, we will retain from the philosophy of science a critical reasoning method, primarily regarding the semantics, methods, and implications of cosmology. We will also rely on what it brings to metaphysical reflections, which are essential when studying the Universe as a whole or on a large scale, particularly because it helps determine what pertains to cosmology and what lies beyond the reach of purely scientific reasoning. Finally, to develop elements of the philosophy of science concerning the large-scale structure of the Universe, it will be appropriate to distance ourselves from religious discourses on the subject, or at least to clearly state what can be designated as scientific, which, as we will see, is particularly subtle at first glance in cosmology but becomes quite clear when addressing cosmologists.

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<sup>24</sup> Latour, B., Woolgar, S., *La vie de laboratoire: la production des faits scientifiques*, Paris : La Découverte, 2013.

It is important to remember, regarding the philosophy, sociology, or history of science, that it is never possible to draw a detailed and absolutely complete panorama of all the elements necessary for the epistemology of the large-scale structure of the Universe. However, an effort is made in this work to address the most important points and to allow for a detailed discussion of the studied points.

### **0.3.2 Literature and interviews**

The literature concerning the large-scale structure of the Universe primarily consists of scientific articles, mostly available for free in non-final versions prior to publication in peer-reviewed journals on the internet archive *arXiv*<sup>25</sup>. These articles are often incomprehensible, both in mathematical terms and in physical jargon, for anyone who wishes to read them without being well-informed or without having taken cosmology courses and spent time in research work. In cosmology, it is common for experts in a particular field, such as strong gravitational lensing, to feel uncomfortable reading an article on another specialization, like, for example, a simulation of the cosmic reionization epoch. The same difficulty arises for a reader of an academic textbook in cosmology, no matter how well-written it may be. Some important or relevant scientific articles to discuss the history or philosophy of cosmology will be cited in this work, but it is obviously not necessary to be able to read them to understand the development of this thesis. It is also the rule applied when it comes to equations or physical explanations: it would be unfortunate and illogical to disregard them, as they are central to the models, but an effort is made to present and integrate them into the development without requiring a deep understanding of the terms and symbols used to follow the narrative.

This work, while primarily aimed at an academic audience, is designed to be readable by anyone who wishes to engage with it, without prerequisites in physical science or philosophy. Historically, articles by cosmologists, astrophysicists, and astronomers or major collaborations like Planck are foundational to what has been and is the imagination surrounding the large-scale structure of the Universe. Some of these articles will serve as the basis for the history of this notion, its representations, and descriptions. In the academic milieu, the informative and comprehensive course taught by Françoise Combes at the Collège de France in 2018-2019, titled "Galaxy Clusters and Large Structures of the Universe," which

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<sup>25</sup> Pour les articles récents de cosmologie sur *arXiv* : <https://arxiv.org/list/astro-ph.CO/recent>

is available online<sup>26</sup>, will also be utilized, along with all the courses and seminars from the Collège de France. Interesting essays produced by Jim Peebles<sup>27</sup> and Simon White<sup>28</sup>, which are also available on *arXiv*, will serve to support our arguments regarding the philosophy specific to cosmologists.

Furthermore, while some objects of astrophysics, such as dark matter, stars, compact objects like black holes, or exoplanets are particularly appealing to the general public and therefore sources of numerous popular science books, it is rare to find books that offer discussions about the cosmic web. If they exist, these discussions generally comprise one or a few chapters dealing with the Big Bang theories and the expansion of the Universe and are found in fairly general books, sometimes lacking seriousness, about the Universe, which may poorly address a wide range of issues, such as Einstein's theories and the place of life on Earth. We will deliberately avoid the very popular yet sometimes questionable interventions of figures like Neil deGrasse Tyson, Étienne Klein, or Lawrence Krauss. On the contrary, we will reference communicators and mediators who strive to tackle subjects in detail and in an understandable way, citing their sources, such as David Louapre, notably his YouTube video "*Les plus GRANDES structures de l'Univers*"<sup>29</sup>, Rebecca Smethurst (Dr. Becky) on YouTube, who is an astrophysicist<sup>30</sup>, or the YouTube channel "History of the Universe"<sup>31</sup>. These videos and channels provide historical elements and present, with artistic visuals or those from scientific publications, interesting results in cosmology concerning the large-scale structure of the Universe. While these works are not explicitly mentioned, they inspire the manner in which the history of astrophysics and cosmology is narrated here. Works that straddle the line between popular science and philosophy or semantics, such as *Les idées noires de la physique (The dark/black ideas of physics)* by Vincent Bontems, Roland Lehoucq, and Scott Pennor, are also of interest and offer avenues for reflection, not strictly on the subject of this work but on semantic questions related to astrophysical and cosmological objects like black bodies, black holes, dark matter, or dark energy. However, this type of original work remains relatively rare.

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<sup>26</sup> Combes, F., *Amas de galaxies et grandes structures de l'Univers*, Cours du Collège de France, 2018 - 2019. <https://www.college-de-france.fr/fr/agenda/cours/amas-de-galaxies-et-grandes-structures-de-univers>

<sup>27</sup> Peebles, P. J. E., The physicists philosophy of physics, *arXiv*, 2024. DOI : 2401.16506

<sup>28</sup> White, S., Reconstructing the Universe in a computer: physical understanding in the digital age, *arXiv*, 2018. DOI : 1806.06348

<sup>29</sup> Louapre, D., *Les plus GRANDES structures de l'Univers*, ScienceEtonnante, YouTube, 2023.

[https://www.youtube.com/watch?v=l\\_mYUOhIOMg&t=1s&ab\\_channel=ScienceEtonnante](https://www.youtube.com/watch?v=l_mYUOhIOMg&t=1s&ab_channel=ScienceEtonnante)

<sup>30</sup> Smethurst, R., *How do cosmic supervoids prove that dark energy exists? | Space is Weird - Boötes Void*, DR. Becky, YouTube, 2019. [https://www.youtube.com/watch?v=\\_ZopKQC4-gY&ab\\_channel=Dr.Becky](https://www.youtube.com/watch?v=_ZopKQC4-gY&ab_channel=Dr.Becky)

<sup>31</sup> Farrow, J., Kelly, D., *Why Does The Universe Look Like This?*, History of the Universe, YouTube, 2022. [https://www.youtube.com/watch?v=iDqQ9qgTWmg&t=1188s&ab\\_channel=HistoryoftheUniverse](https://www.youtube.com/watch?v=iDqQ9qgTWmg&t=1188s&ab_channel=HistoryoftheUniverse)

Regarding publications on philosophy specifically, and as we seek to study the links between philosophy and cosmology, the choice is made here to include, among others, philosophical works proposed by individuals trained in physics. This is also the case regarding space-time, and on this point, the works of Albert Einstein, such as *Relativity: The Special and General Theory, Relativity and the Problem of Space*<sup>32</sup>, accompanied by a history of the notions of space and time, come from a decidedly reliable source. Major articles are drawn from the digital archive of the philosophy of science, PhilSci<sup>33</sup>, which allows for sorting publications by subjects, as well as the very dense Stanford Encyclopedia of Philosophy<sup>34</sup>. However, explicitly relevant articles for our study are (very) rare on these platforms, so this cannot constitute a complete bibliographic reference set. Therefore, it is also essential to pay attention to more general philosophy works, and the writings of Nelson Goodman, Hilary Putnam, Catherine Elgin, Israel Scheffler, Richard Rorty, and David Lewis compiled in the book *Starmaking*<sup>35</sup> will be used here: according to Goodman<sup>36</sup>, different versions of the world exist, and thus here by extension, different versions of the large-scale structure of the Universe have emerged over the years and continue to exist among different cosmologists, and these same cosmologists have opinions on the reality of this structure. As we will see in analyzing interviews, since this structure is composed of more or less tangible elements (the intergalactic gas does not have the same status as dark matter, for example), it is sometimes thought of and described as an artifact of the human mind. It should be noted that caution is generally warranted regarding cosmology and epistemology related to the science of the Universe, as this subject is a source of intense religious and metaphysical debates. In connection with the general philosophy of physics, we will also draw reflections on semantics from Ian Hacking in *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science*, and reflections on models, instruments, and meanings of ideas in physical sciences from Pierre Duhem, and once again from Ian Hacking, as previously mentioned. These philosophies are generally informative about physics and thus its specializations, of which cosmology is a part, despite its particular status. Pierre Duhem's works are foundational in the philosophy of physics, and reference will be made to his book

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<sup>32</sup> Einstein, A., *La relativité: théorie de la relativité restreinte et générale, la relativité et le problème de l'espace*, Paris : Payot & Rivages, 2016, 224 p. ISBN : 978-2-228-91618-9

<sup>33</sup> <https://philsci-archive.pitt.edu/>

<sup>34</sup> <https://plato.stanford.edu/>

<sup>35</sup> McCormick, P. J. (ed.), *Starmaking*, Cambridge : The MIT Press, 1996, 240 p. ISBN : 9780262529143

<sup>36</sup> Alors que certains auteurs, comme Elgin et Rorty, adoptent une perspective proche de Goodman, d'autres, comme Putnam et Scheffler, apportent des critiques qui soulignent l'importance de maintenir une forme de réalisme modéré.

*The Physical Theory: Its Object, Its Structure*<sup>37</sup> when we analyze the models and theories that have contributed to creating the notion of large-scale structure of the Universe, with the third chapter of the same book regarding physicists' opinions on physical theories serving as a tool to analyze our interviews. Concerning visual representations, which are particularly relevant when discussing the cosmic web, recent works by Catherine Allamel-Raffin on the production of images specifically in astrophysics, as well as the socio-political narrative of the development of the Hubble Space Telescope (HST) by Robert Smith in *The Space Telescope: A Study of NASA, Science, Technology, and Politics*<sup>38</sup>, will support the historical context in which the evolution of modern astrophysics takes place.

Given the scarcity of sources outside of cosmology research that deal specifically with the large-scale structure of the Universe, the most pertinent choice seems to be to conduct interviews, in line with the tradition initiated by Bruno Latour, to gather the opinions and thoughts of cosmologists. Ten interviews were conducted, lasting approximately thirty minutes to an hour, with mostly experienced researchers in cosmology, whether in the field of large-scale structure of the Universe, in mediation and popularization, or both. Only one doctoral student was solicited and accepted to participate. Here is the list of those who agreed to participate in an interview, in no particular order (notably, only one person, David Louapre, declined the interview for very good reasons related to a lack of time. I thank him for still taking the time to respond to my request with enthusiasm): Katarina Kraljic, Françoise Combes, David Alonso, John Peacock, Rebecca Smethurst, Aniruddh Herle, Simon White, Roland Lehoucq, Jim Peebles, and Benjamin L'Huillier. These interviews, along with the questions used, will be detailed in Chapter 2. We will also present the participants in more detail to account for the relevance of their contributions<sup>39</sup>. In the future, these interviews may be supplemented by recorded interventions available on the American Institute of Physics (AIP) website<sup>40</sup> as well as on various radio stations or podcast platforms<sup>41</sup>.

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<sup>37</sup> Duhem, P., *La théorie physique. Son objet, sa structure*, Lyon : ENS Éditions, 2014 [paru 1906], 206 p. ISBN : 978-2-84788-834-8 et 2-84788-834-9

<sup>38</sup> Smith, R. W., Hanle, P. A., Kargon, R. H., Tatarewicz, J. N., *The Space Telescope. A study of NASA, science, technology, and politics*, Cambridge : Cambridge University Press, 1993, 496 p. ISBN : 978-0521266345

<sup>39</sup> L'ensemble des entretiens est retranscrit en annexe. Ce document annexe est disponible pour le jury du mémoire ainsi que pour les personnes concernées par sa rédaction. Des parties de ce dernier peuvent être disponibles sur demande auprès de l'auteur et après accord avec la personne concernée par l'entretien souhaité.

<sup>40</sup> <https://ww2.aip.org/>

<sup>41</sup> On trouve beaucoup d'interventions de personnalités comme Jim Peebles, Hubert Reeves ou David Elbaz sur différentes plateformes comme YouTube, des sites universitaires ou RadioFrance.



## **0.4 Work plan**

This thesis is divided into three parts, progressing from the more general to the more specific. Firstly, Chapter 1 presents the history of the notion of large-scale structure of the Universe. This history begins around 1980 and is intrinsically linked to the history of modern cosmology, even though the beginnings of cosmological ideas precede the 20th century and will be mentioned, as well as the history of ideas of space, time, Universe, and structure in the physical sciences. Chapter 2 focuses on the interviews that were conducted with cosmologists. It precisely outlines the questions posed during the interviews, presents the individuals involved, and provides a preliminary analysis of their activities and thoughts based on their statements. Chapter 3 develops a philosophy of the notion of large-scale structure of the Universe, its representations, and the ideas associated with it, particularly from the interviews in Chapter 2 and the publications of Ian Hacking and Pierre Duhem. Finally, a synthesis of the development undertaken throughout this thesis is presented in the conclusion. A bibliography in alphabetical order is provided at the end of the document. An appendix of about one hundred pages complements this document and contains the written transcriptions of the interviews. However, this appendix is not public but is intended for the jury of the thesis. Any other person interested in additional elements contained in this appendix can contact the author of the thesis via email.

# Chapter 1 : History of the notion of large-scale structure of the Universe

To conduct a sociological and philosophical study of the visual and mental representations of the large-scale structure of the Universe, it is necessary first to establish its history. As with any scientific notion, this history is complex and has the particularity of still being ongoing, unlike other theoretical physics objects like the ether or the hypothetical planet Vulcan, which can reasonably be considered obsolete. The history of the large-scale structure of the Universe is deeply intertwined with the evolution of the notions of time, space, and space-time, as well as with the creation and interpretation of images and data in cosmology.

The convergence between cosmology and the philosophy of space-time dates back to the early speculations of ancient thinkers and intensified with the major advances of modern physics. In Antiquity, conceptions of the cosmos were embedded in mythological and religious frameworks where time, space, and the Universe were envisioned in an anthropocentric manner. However, the advent of classical physics, particularly the works of Isaac Newton on universal gravitation, opened the door to a tradition of mathematization of the physical sciences, formalizing the notions of space and time, and establishing an absolute, independent framework of space and time that served as a conceptual foundation for what is now termed Newtonian physics.

At the beginning of the 20th century, Albert Einstein's theory of special relativity radically disrupted these classical views by proposing that time and space are intrinsically linked and interdependent, forming the indivisible continuum known as space-time. This was followed by general relativity, which extends (and thus generalizes) this idea by integrating gravitation into the very structure of space-time and theorizing a direct relationship between matter and energy and the geometry of the Universe. This perspective laid the groundwork for modern cosmology and is within this framework that the notion of large-scale structure of the Universe exists. In this chapter, we will first delve into the histories of the notions of space, time, and space-time, as well as the emergence of modern cosmology, then onto the histories of the Universe, both its own history and the discoveries that led to the models of the Big Bang, cosmic inflation, galaxy evolution, the expansion of the Universe, and dark matter, along with the history of the notion of the Universe, and then of its structure and

representations. On this last point, it is crucial to present the history of recent techniques that have led to large-scale observations in order to explain the images created and interpreted by cosmologists. A philosophical analysis of these elements will be proposed in Chapter 3.

## 1.1 Space, time, and astrophysics

The large-scale structure of the Universe is a structure of space-time, and since these objects fall within the domains of cosmology and theoretical physics, we first revisit the histories of the concepts of space, time, and space-time, followed by the emergence of scientific cosmology.

The histories we aim to present here are a mix of the history of physical and mathematical ideas, and occasionally of the history of metrological and instrumental techniques, although the latter aspect is less prominent in this work. Particularly for concepts as fundamental as space and time, many more or less successful attempts at physical definitions emerged before Einstein's general relativity, which, moreover, does not address all the questions that arise, especially at the Planck scale. These concepts are fundamental because humans constantly experience time and space subjectively: time as a psychological experience of flow from past to future, and space as a physical, perceptual experience of the body's position in relation to other objects.

### 1.1.1 Space, time, and space-time

#### Space :

The tradition of geometrization of space in the West, upon which Einstein's theory of general relativity and the status of space-time used today in cosmology rest, begins concretely with Isaac Newton but draws its sources from Arab Antiquity and, in the West, from the writings of Aristotle and Plato, which we will revisit when discussing time. We will also return to the thinkers of Antiquity when we discuss the modeling of the motion of celestial bodies.

Let us begin here with a state of ideas in the West in 1850, before the publication of the works of the German mathematician Bernhard Riemann: until the mid-19th century, the space of physicists was the absolute space defined by Isaac Newton in the famous *Philosiae Naturalis Principia Mathematica*<sup>42</sup> in 1687. This space is affine, Euclidean, and independent of the objects it contains. The affine character is defined by two mathematical properties posed here and then explained:

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<sup>42</sup> Newton, I., *Philosophiae naturalis principia mathematica*, Londres, 1687, 2<sup>e</sup> éd. 1713, 3<sup>e</sup> éd. 1726.

Definition of an affine space :

Given a vector space  $V$ , an affine space with direction  $V$  is a non-empty set  $E$  equipped with a function  $\phi$  that, for each pair of points  $(A, B)$  in  $E^2$ , associates a vector in  $V$ , denoted by  $\overrightarrow{AB}$ , satisfying the following conditions :

$$1 : \forall (A, B, C) \in E^3, \overrightarrow{AB} + \overrightarrow{BC} = \overrightarrow{AC},$$

$$2 : \forall A \in E, \forall \vec{v} \in V, \exists ! B \in E, \overrightarrow{AB} = \vec{v}.$$

First, a mathematical vector, noted with an arrow " $\rightarrow$ ," is an oriented line segment on which one can perform operations, such as multiplication or addition, and corresponds here quite simply to directed distances with a starting point "A" and an endpoint "B." The logical symbols " $\forall$ " and " $\exists$ " are read respectively as "for all" and "there exists," the "!" denotes uniqueness, and " $\in$ " is read as "belongs to." In practice, an affine space is thus a space in which vectors exist that can be added together, and the result of the addition does not take into account the intermediate steps (the result is directly the vector between the starting point and the endpoint), and, given a starting point, a vector admits only one unique endpoint such that the vector corresponds to the path from departure to arrival. An affine space thus allows for the definition of vectors, and an affine space that is also Euclidean admits the measurement of distances and angles thanks to the existence of a scalar product (which it is unnecessary to define precisely here); it is said to be equipped with a metric space structure. It should be noted that a Euclidean space is only so if it is of finite dimension, which is the case for the space of classical Newtonian physics, namely a three-dimensional space. The notions of rest and motion in this space have an absolute character: a physical object is at rest if its position in space does not change over time; otherwise, it is in motion. However, it was already clear that only the movements of physical objects relative to others or to reference frames could be observed. A reference frame is a set of points fixed with respect to one another, such as the walls of a house, the surface of the planet Earth, or the hold of a ship. In particular, no physical experiment allows one to distinguish a fixed reference frame, stationary in absolute space, from a reference frame in uniform translation, known as inertial or Galilean, in absolute space; this will be referred to as the principle of relativity.

In 1863, while working at the University of Graz, the Austrian physicist Ernst Mach challenged the idea of absolute space in *Die Mechanik: Ein historischer und kritischer Entwurf ihrer Entwicklung*<sup>43</sup>: according to Mach, the acceleration or rotation of a body has no meaning with respect to absolute space but only with respect to distant masses. His

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<sup>43</sup> Mach, E., *La mécanique : exposé historique et critique de son développement*, ouvrage traduit, sur la 4e édition allemande, par Émile Bertrand,; avec une introduction de Émile Picard, 1904, 510 p.

conjecture, which he shares with Moritz Schlick, known as Mach's principle and which would later inspire Einstein, states that inertia, i.e., the conservation of an initial velocity of a material body, is induced by "the totality of other masses present in the Universe"; however, the reason for this action of the masses in the Universe is not detailed by the physicist. In practice, classical mechanics choose an approximately inertial reference frame and study the movements of physical objects relative to this reference frame considered fixed.

Since Newton, physical space has been a mathematically defined space, and until the discovery of non-Euclidean geometries, little distinction was made between physical space and mathematical space. More than two thousand years elapsed between Euclid's *Elements* (*Στοιχεία*)<sup>44</sup> during Greek Antiquity and the consequences of the debates regarding Euclid's fifth axiom. This axiom states that, given a line  $D$ , only one line  $D'$  can pass through a given point that is parallel to  $D$ . Concerned with the implications of this axiom, the French mathematician Adrien-Marie Legendre published in 1774 his *Éléments de géométrie*<sup>45</sup> in which he substituted the following axiom: the sum of the angles of a triangle is less than or equal to one hundred eighty degrees, and if equality holds, this is equivalent to Euclid's fifth axiom. Here we see the beginnings of non-Euclidean spaces, and a space in which the sum of the angles of a triangle is strictly less than one hundred eighty degrees is, in fact, hyperbolic (see Figure 2). Later, around 1823, the mathematicians János Bolyai and Nikolai Ivanovich Lobachevsky, respectively Hungarian and Russian, developed hyperbolic geometries, which inspired the work of many other scientists such as Eugenio Beltrami, Felix Klein, and Henri Poincaré until the end of the 19th century. It is in the same movement that studies are conducted on spherical geometry (see Figure 2). From these discoveries, advances in the rigor of axiomatization and the scope of geometry will notably be made by David Hilbert and Jean-Victor Poncelet.

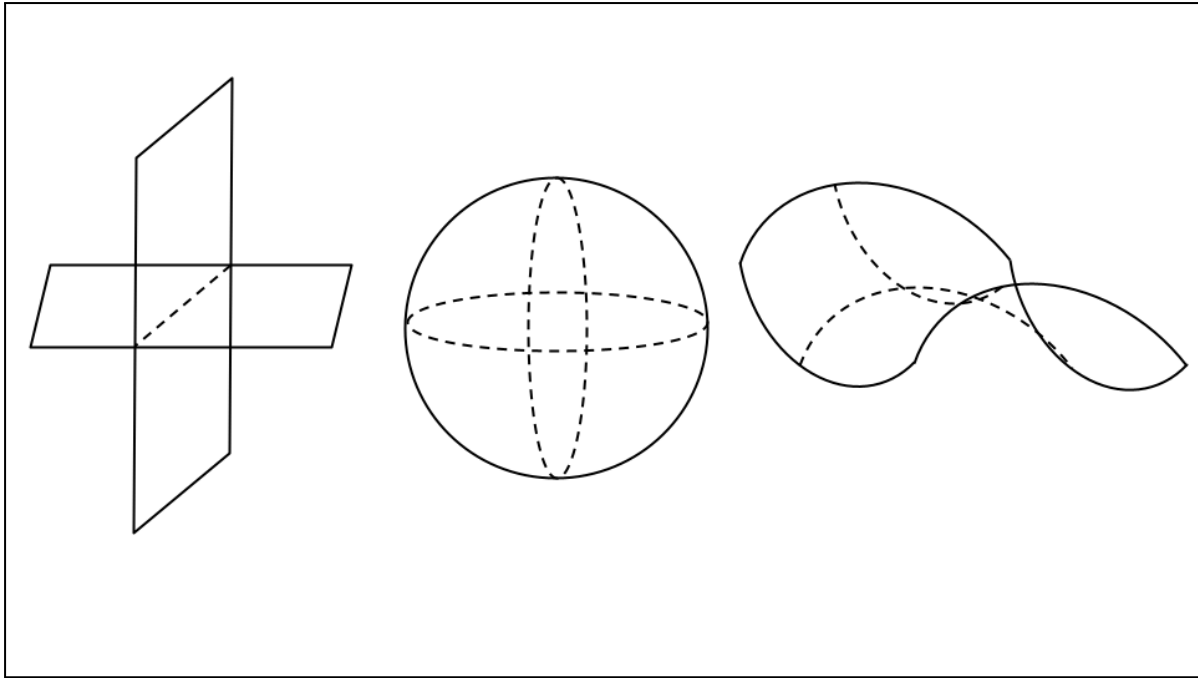
It was in 1854 that the conception of the notion of space changed radically, with the oral presentation of his thesis "*Die Hypothesen, welche der Geometrie zu Grunde liegen*"<sup>46</sup> by Bernhard Riemann, published a year after his death, during the admission examinations to the

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<sup>44</sup> Heiberg, J. L. (éd.), Menge, H. (éd.), *Euclidis Opera omnia*, Leipzig, Teubner, 1883-1916, huit volumes. Cet ouvrage fait référence pour les traductions des *Éléments* d'Euclide.

<sup>45</sup> Legendre, A.-M., *Éléments de géométrie*, Paris, Firmin Didot, 1794 (rééd. Blanchet, 1823), 334 p.

<sup>46</sup> Riemann, B., Sur les hypothèses qui servent de fondement à la Géométrie. *Annali di Matematica* 3, pp. 309–326, 1869. DOI : 10.1007/BF02422984



**Figure 2:** Schematic representation of three-dimensional spaces: Euclidean (left), spherical (middle), and hyperbolic (right, shown as a hyperbolic paraboloid). Euclidean space is flat, with zero curvature at every point. Spherical space has positive curvature at every point, and hyperbolic space has negative curvature at every point.

philosophical faculty of Göttingen, preceded by an inaugural dissertation (thesis) in 1851 titled *Theorie der allgemeinen Funktionen einer veränderlichen komplexen Größe*<sup>47</sup>. Riemann left behind an extremely dense mathematical legacy that is part of the continuity and influence of the works of Carl Friedrich Gauss, who was his doctoral advisor, and Augustin-Louis Cauchy. In his 1851 text, he introduced what are now called Riemann surfaces, of which the sphere and hyperbolic paraboloid are part, and he made an abstract generalization to more than two dimensions under the name of varieties. While the mathematics required to define these notions correctly is far too complex to be exposed in an epistemology thesis, it is worth noting that the generalization of the notion of distance in these non-Euclidean spaces will prove to be an indispensable and major tool for the establishment of the theory of special relativity half a century later, and Riemann thus positions himself as the father of modern topology<sup>48</sup>. The greatest conceptual revolution regarding space that Riemann proposes in his work is surely that whereas his predecessors based geometry on a list of axioms to be accepted, he argues that one must start from the infinitesimal properties of space to determine its global properties. The metric properties of a

<sup>47</sup> Riemann, B., *Théorie générale des fonctions d'une grandeur variable complexe*, Göttingue, 1851.

<sup>48</sup> This is not the only field where Bernhard Riemann was foundational; his work in analysis is also significant, with a famous and widely studied function, as well as a theory of integral calculus, bearing his name.

space can now be determined by defining a Riemannian structure: the distance  $m$  between a point  $x$  and an infinitely nearby point  $x + dx$  is given by the square root of what is called a quadratic form (a polynomial in which all terms are of degree two):

$$m = \sqrt{ds^2} = \sqrt{\sum_{i,j} g_{ij}(x^1, \dots, x^n) dx^i dx^j}. \text{ The quantities } g_{ij} \text{ are coefficients that depend on}$$

the point  $x$  considered,  $n$  is the dimension of the variety considered, and the terms  $dx^1, \dots, dx^n$  are the components of  $dx$  in  $n$  dimensions. In mathematical terms, the symbol

$\sum_{i,j}$  means that we sum by repeating the subsequent terms while varying the indices  $i$  and  $j$ .

Additionally, at each point, Riemann introduces invariant quantities that are today called sectional curvatures. In cases where the curvature is constant at each point in space, if the curvature is zero, we recover Euclidean geometry; if the curvature is negative, we find the hyperbolic geometries of Bolyai and Lobachevsky; and if the curvature is positive, we obtain spherical geometry. More generally, Riemann's innovative approach allows for the consideration of more general spaces, not necessarily homogeneous and isotropic, which would inspire Einstein in founding general relativity.

Finally, Riemann also proposes new physical ideas: at a small scale, it is the physical properties of matter that determine geometry, which cannot be entirely described by the mathematical model he has just developed. In fifty years, and with the efforts of other scientists such as Bruno Christoffel, Gregorio Ricci-Curbastro, or Tullio Levi-Civita (whose names appear in various mathematical elements of Einstein's theories), differential geometry has developed, along with tensor calculus, absolute differential calculus, the notion of parallel transport, and geodesics. All these elements of advanced mathematics are the foundations upon which the mathematics of general relativity were built. However, apart from this theory, the implications of Riemann's ideas on physical space remained little known for nearly a century.

The direct influence of Riemann's work can be found in that of the German mathematician and theoretical physicist Hermann Weyl, and in that of the French mathematician Élie Cartan, the former having simplified Riemann's developments and the latter generalizing Weyl's work, a task that would be completed by another French mathematician, Charles Ehresmann, in the 1950s.

Moreover, since the developments of quantum physics, there exists in physical space a length scale called the Planck length, approximately  $l_p = 1.616244 * 10^{-35}$  m. This length, determined from fundamental constants of modern physics, corresponds to the length scale below which one must take into account quantum mechanics in order to account for the effects of gravity. The theory that would successfully explain the quantum characteristics of gravity does not exist, and it is uncertain whether it can exist, but it would be such a theory that theoretical physicists would need to describe the phenomena of this fundamental force at very small scales.

Finally, another major property of mathematically defined physical space is the set of its symmetries. Since Antiquity, the basic symmetries of Euclidean space, for example, of a triangle, have been the subject of theorems. It is in the more modern theory of groups, primarily attributed to the French mathematician Évariste Galois in the 1830s, that the systematic theorization of the symmetries of space was born. It is possible to consider transformations of space, in the form of rotations, translations, deformations, or others, and a symmetry is invariant under certain types of transformations. For example, an axial symmetry is characterized by the absence of change in space after any rotation around the given axis. If this kind of geometric study is attributed to group theory, it is because the mathematical object studied is not so much space itself, but rather the group of possible transformations, for which we seek the invariants once a space is chosen. Once again, Felix Klein played a major role in the development of this field, as did the Norwegian mathematician Sophus Lie, who worked notably at the universities of Leipzig and Oslo during the second half of the 19th century and whose work from 1873-1874 on transformations concerning the continuous symmetries of space strongly influenced the mathematics of quantum physics.

The pinnacle of the influence of the mathematical notion of symmetry in physics is certainly Noether's theorem, named after the German mathematician Emmy Noether, who stated it in the early 20th century. This theorem is formulated as follows: To every infinitesimal transformation that leaves the action integral invariant corresponds a conserved quantity. In practical terms, this means that given a space, if that space does not change after a certain transformation, then there exists a physical quantity that is conserved. For example, in a homogeneous space (which has the same properties everywhere), invariance under translation in space corresponds to the conservation of momentum, this being the product of mass and the velocity of a physical body. In an isotropic space (which has the same properties in all directions), invariance under rotation in space corresponds to the conservation of



angular momentum, which, with some approximations, quantifies why a person spinning on ice gains rotational speed by pulling in their arms.

### **Time:**

We are discussing physical time here, as a dimension made up of a succession of instants (the continuity of which is up for discussion). In the same way as the coordinate of a point on a line, an instant can be defined by a single unique number: a date, for example. This time flows locally at a regular rate, unlike psychological time, which can seem longer when one is bored, and seems to stop or be shortened when one sleeps and is distorted when one dreams. Moreover, in physical sciences, time is usually not defined; it is posited *a priori* and exists without the need for a pre-existing entity. It can be defined in certain modern theories of loop quantum gravity, one of the founders of which is the Italian Carlo Rovelli, who studies the contingency of physical time in his popular science book *Et si le temps n'existait pas ?*<sup>49</sup>. In this theory, there is neither time nor reference space; these objects are formed above a physical substrate that mathematically precedes them.

The beginnings of classical mechanics can be found in the works of Aristotle and Plato during Antiquity. These views are more philosophical than physical, but it is still relevant to outline their main aspects since they left a strong imprint on Western thought until the emergence of classical physics. In Plato's work, the becoming of things is distinguished from the entirety of visible appearances in their movements and is an abstract object of the world of ideas. He thus distinguishes between the movement and evolutions of the world of appearances and the becoming that moves in the world of ideas. He mythologizes the movements of the heavens by attributing them to the wills of the gods, who arrange them according to a cyclical order. The idea of cyclical time, which loops, can also be found in other cultures in Antiquity and afterward, notably in East Asia. Aristotle develops Plato's idea but proposes a conception that is not quite identical: the order to which movements obey is not confined to a world of essences, which would be the world of ideas, but corresponds more to a motor for appearances; these are physical causes and not just abstract mathematical structures<sup>50</sup>. The general theory of causes that Aristotle proposes implies that the movement of the stars is itself the consequence of a cause. In this type of reasoning, comparable to the

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<sup>49</sup> Rovelli, C., *Et si le temps n'existait pas ?*, Dunod, 2023, 192p.

<sup>50</sup> Aristote, *Physique*, , Livre 2, Chapitre 2, § « Physique et mathématique », 193b-194a, pp. 122-123 Paris : Flammarion, 2010. ISBN : 978-2-08-070887-8

Münchhausen trilemma<sup>51,52</sup> (or Agrippa's trilemma), to escape an infinite regression of causes, Aristotle chooses to invent a first divine cause and thus opts for the outcome of dogmatic arrest. What Plato and Aristotle attempt to accomplish here is to show that the becoming of things is explicable, and above all rationalizable.

Subsequently, during the Middle Ages, time transitioned from quality to quantity, particularly with the development of clockmaking and thus the practice of measuring durations and quantifying instants. Time as a physical parameter was born with the writings of Galileo Galilei, who first studied, around 1573 (when he was nineteen), the isochronism of pendulums in Pisa and what would later be called Galilean mechanics: the fall of bodies. He deduced, notably by choosing time as a fundamental parameter, that the velocity of a freely falling body is proportional to the duration of its fall. Then Newton formalized this idea and used the parameter  $t$  in his equations, and it became a degree of freedom, a dimension, allowing for the tracking of interactions of matter in space. This dimension is then represented by a line, a mathematical object also analogous to a dimension, and this line is oriented; it is the arrow of time that goes from the past to the future. Similarly, the points on the line represent instants, and their proximity between neighbors is infinite. This mathematization is not trivial; it transforms each instant, whether past, present, or future, into an abstract entity, and the flow of time is reconstructed using initial conditions and a differential equation on  $t$  (*i.e.*, one that expresses variations over time) known as Newton's second law or the fundamental principle of dynamics:

<p><u>Fundamental principle of dynamics in translation :</u>          In a Galilean reference frame, the acceleration of the center of mass of a physical body with constant mass <math>m</math> is proportional to the resultant of the forces acting on it and inversely proportional to its mass :</p> $\vec{a} = \frac{\sum_i \vec{F}_i}{m}.$
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where  $a$  is the acceleration, thus the variation in time of the velocity of the body, here in vector form (therefore directed and with a sense), and the forces are everything that acts on the physical body in question and are denoted  $F_i$ , also in vector form in the equation. Furthermore, in a manner analogous to symmetries through transformations in space, Noether's theorem also applies with the time dimension: the equations of physics, such as the fundamental principle of dynamics, are symmetric with respect to a translation in time (the physical laws are expressed in the same way regardless of the instant), and this symmetry

<sup>51</sup> Empiricus, S., *Les Esquisses pyrrhoniennes*, I, 15

<sup>52</sup> Empiricus, S., (traduit du grec ancien par Pellegrin, P.), *Esquisses pyrrhoniennes*, Paris, Seuil, 1997, 570 p. ISBN : 2-02-026298-3)

also implies the conservation of a quantity, which is the energy involved in the interaction between the objects at play.

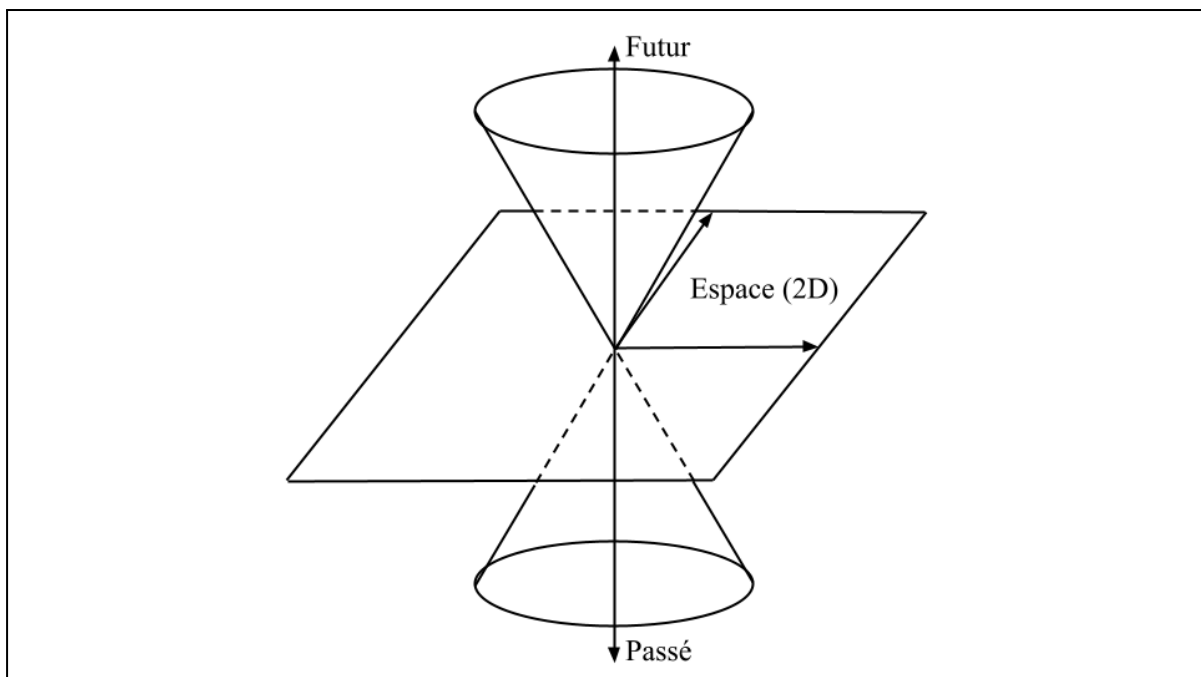
Let us return to the notions of cause and circularity of time: there exists in physics a principle, thus a statement that has not yet been disproven. This is the principle of causality, which actually contains two statements: 1) a cause always precedes its effects, and 2) an effect cannot retroact on its cause (this particular point makes time travel to the past of already existing phenomena difficult to conceive). This principle is a constraint imposed on any mathematical theory for it to be realistic and physically admissible, and it was clearly stated by the French scholar and encyclopedist Jean Le Rond d'Alembert and the Swiss mathematician Leonhard Euler in the 18th century. Among other things, the principle of causality implies a non-cyclic time: on a circle, no point occupies a particular position, and no instant positioned on a circle or even on any closed curve, more generally, would be positioned before or after all other instants. Therefore, in this type of temporal structure, consequences could precede their causes. Here we also find a notion of the arrow of time, a notion first introduced by the British astrophysicist Arthur Eddington in 1928<sup>53</sup>, which assigns a direction to the line representing the time dimension composed of instants. However, the equations of physics indicate that it seems that no phenomenon at the microscopic scale can occur except in one direction; they are reversible. To find a reason for the arrow of time, one must look into the nature of irreversible phenomena. In practice, at the macroscopic scale, it seems customary that certain phenomena occur only in one direction: a broken glass does not spontaneously reform, and without external action, heat exchanges between two bodies always occur from the hotter body to the colder body. It is the Austrian physicist and philosopher Ludwig Boltzmann who first attempted to explain the arrow of time using thermodynamics and statistical physics, which he greatly developed, particularly in his treatise *On the Relationship between the Second Principle of the Mechanical Theory of Heat and the Theory of Probabilities in Relation to the Laws of Thermal Equilibrium*<sup>54</sup>. Boltzmann's idea is relatively simple to explain, but the associated mathematical aspects involve numerous physical notions and intermediate equations: the arrow of time as understood in thermodynamics is given by the evolution of a physical quantity called entropy, which characterizes the degree of disorder of a physical system. This term was first used by the Prussian physicist Rudolf Clausius in 1865 and is the subject of the second principle of

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<sup>53</sup> Eddington, A., *The Nature of the Physical World*, Cambridge, Cambridge University Press, 1928, pp. 95-96.

<sup>54</sup> Boltzmann, L., Über die Beziehung dem zweiten Hauptstädte der mechanischen Wärmetheorie und der Wahrscheinlichkeitsrechnung respektive den Sätzen über das Wärmegleichgewicht, *Wiener Berichte*, Vol. 76, 1877, p. 373-435.

thermodynamics, also called Carnot's principle: the entropy of a closed system (without interaction with the outside) can only increase or remain constant if the system is in thermodynamic equilibrium (it does not undergo any evolution at the macroscopic scale). Statistics comes into play in characterizing what disorder is for each possible state of the system: a glass into which hot and cold water is introduced can evolve into a vast number of different states, for example, a glass where hot and cold water are separated, or a glass where the temperature has homogenized after mixing and thermal exchanges. This latter state is far more probable than the former, and its entropy is higher because there is no particular organization of the water molecules. However, at thermodynamic equilibrium, the entropy reaches a maximum, and in this case, time loses its arrow. The question arises regarding the Universe: if it is a closed system, then the second principle of thermodynamics should apply to it; however, other ideas compete with this, such as the idea of a Universe evolving toward a maximum of structural complexity through the effects of gravitation, rather than disorder. These aspects are difficult to verify and are still very speculative. There is another common



**Figure 3:** Schematic representation of a light cone, or Minkowski cone, for radiation propagating on a flat surface (two dimensions of space). The third dimension represented by a vertical line is time. For a source located at the origin, the radiation points outward, causing the circle to expand from the present into the future. Similarly, one can represent the set of points from which light can reach the source at the origin, and then the circle shrinks from the past to the present.

possibility for explaining an arrow of time in physics: the propagation of radiation, which only occurs outward from the source that emits it. This is commonly represented by a light

cone, named after the work of the theoretical physicist Hermann Minkowski in 1905, where the lower part represents the light that arrives from the past, and the upper part extends into space into the future, as in the case of radiation in two dimensions of space (it would be difficult to represent three-dimensional radiation propagating in time, thus in four dimensions). An example of a light cone is given in Figure 3. Furthermore, this radiative arrow highlights that any unpowered source is doomed to extinguish: the radiation disperses outward and is accompanied by a loss of energy corresponding to the energy of the emitted photons; the energy of a lone source can only be depleted as it disperses in the form of radiation. Let us note that all the processes defining a direction for time (the principle of causality, the second principle of thermodynamics, gravitation, or radiation) are not understood as causes of the arrow of time but rather as explanations: there exists an arrow of time, and one can attempt to define it and demonstrate its existence, but the reason for this existence remains mysterious to this day. When it is possible to base this existence on another physical object, as in Carlo Rovelli's theory, the question then arises of explaining the existence of this initial object, which leads to relatively equivalent metaphysical considerations.

If the equations of physics are invariant under translation in time, they are not necessarily invariant under time reversal (the transformation of the parameter  $t$  into  $-t$ ). This symmetry, known as T symmetry, is not always verified, for example, in particle physics. The consensus is rather that CPT symmetry is the rule, being a combination of T symmetry with C and P symmetries. C stands for electric charge, meaning that a positive charge becomes negative and vice versa, while a neutral particle remains neutral. P stands for parity, so the spatial vector  $(x, y, z)$  becomes  $(-x, -y, -z)$ . In 1954, the German and Austrian physicists Gerhart Lüders and Wolfgang Pauli established a proof of the CPT theorem, which first appeared in the works of Julian Schwinger in 1951, stating that a "local Lorentz-invariant quantum field theory with a Hermitian Hamiltonian must possess CPT symmetry"<sup>55</sup>. We will not delve into each point of this theory precisely, but what it indicates in practice is that a convincing quantum physics theory must consist of laws respecting CPT symmetry, meaning that they are invariant when time, parity, and electric charge are reversed. Time thus plays one of the central roles concerning the validity of physical laws, also at the quantum level.

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<sup>55</sup>It is, of course, unfeasible to elaborate on the terms stated in this theorem in a work of epistemology, as that is not its main subject. However, one can refer to the book by David Griffiths, which serves as an introduction to particle physics and particularly discusses CPT symmetry: Griffiths, D., *Introduction to Elementary Particles*, New York/Chichester/Brisbane etc., Wiley & Sons, 1987, 392 p. ISBN : 0-471-60386-4

Finally, in addition to the Planck length, there exists a Planck time, approximately  $t_p = 5,391 * 10^{-44}$  s. This is the theoretical time it would take for a photon to traverse the Planck length in a vacuum. In this context, it represents the shortest duration for which current scientific theories make sense, and the question of the continuity or discreteness of time cannot be physically studied below a duration equal to the Planck time.

### **Space-time:**

Let us note that we will not study the notion of space-time in quantum physics and in theories aimed at unifying general relativity and quantum physics, as these considerations are still too recent and very incomplete. In order to address space-time, let us first complete the previous exposition on space with a major element in the history of modern physics that we have deliberately omitted until now: the ether. This term has historically designated different notions that generally correspond to the material substance acting as a medium for the transmission of effects between two bodies, such as the transmission of gravitational force, electromagnetic radiation, or the diffusion of gases, for example. This notion is more descriptive than explanatory, and its history is complex and encompasses numerous physical ideas, sometimes contradictory or detached from one another. Here, we provide only a panoramic view that allows us to situate the context of the development of Einstein's theory of special relativity, and for a more complete discussion of this notion, one can read *Einstein 1905: de l'éther aux quanta* by the physicist and historian Françoise Balibar, which serves as a reference here<sup>56</sup>, or more directly the account and discussions by Einstein himself in *La relativité: théorie de la relativité restreinte et générale, la relativité et le problème de l'espace*.

Let us begin in Antiquity: as studied and analyzed by his successors, Aristotle (who is not the only one nor the first to use this notion, but certainly the most prominent and retained) indicated in his treatise *On the Heavens*<sup>57</sup> that there exists a fifth element in addition to water, earth, fire, and air, corresponding to ether, which is present only in the celestial sphere. This ether is the element of celestial bodies that has the nature of moving in circular paths, and it is nobler the farther it is from the Earth. According to various authors, ether can be composed of several substances (there are three ethers in Pythagorean thought, which are different from the three ethers of Plato) and may approach one or more of the four elements of Aristotle's

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<sup>56</sup> Balibar, F., *Einstein 1905: de l'éther aux quanta*. Paris : PUF, 1992, 125 p. ISBN : 978-2-13-044298-1

<sup>57</sup> Du ciel, dans *Aristote, Œuvres complètes* (trad. Catherine Dalimier & Pierre Pellegrin), Éditions Flammarion, 2014, 2923 p. ISBN : 978-2081273160

world. In the Middle Ages, the advent of alchemy fueled ambitions to use the ether mentioned in Greek writings to, for example, transform lead into gold: it then became a divine essence (its divine nature was already present among the Greeks in Antiquity, Ether being the primordial god personifying pure air, that which the gods breathe, the sky and its brilliance) or quintessence, and it also became the object of esotericists and no longer just of scholars. The scientific revolution that is the emergence of classical physics changes the status given to ether, and now there are actually two ethers in question: gravitational ether and luminiferous ether.

First of all, the gravitational ether finds its origin in the writings on his theory of vortices by René Descartes<sup>58</sup>: he rejects the idea of a vacuum in which planets could move and instead prefers a space composed of transparent globules forming large vortices that carry with them and hold the planets in place. However, the Earth is stationary with respect to its own vortex, allowing Descartes to follow Copernican ideas (the heliocentric model) without opposing the Church; however, this is not a predictive theory: Descartes' vortices intervene to justify the movement of planets a posteriori but do not allow for their calculation. The vast majority of Descartes' ideas have, in fact, turned out to be false, but they fueled the debate between philosophy and physics and inspired Newton with new ideas. Newton opposed the vortex theory and was also against the idea of interaction between physical bodies through a vacuum, but in light of the effectiveness of his theory of universal gravitation, he too appealed to an ether that this time allows the transmission of gravitational force and is neither predictive nor explanatory, but *ad hoc* to eliminate the notion of a vacuum as a medium for propagation and interaction. It should be noted that this ether is the medium for the gravitational force but does not experience it; it does not feel the influence of physical laws and does not intervene in calculations<sup>59</sup>.

Following Newton's publications, the Dutch physicist Christiaan Huygens changed his mind and abandoned his Cartesian ideas. In his *Discourse on the Cause of Gravity*, he states:

*"I had not extended the action of gravity to such great distances, like from the Sun to the planets, or from the Earth to the Moon, because the vortices of Mr. Descartes, which once seemed very plausible to me, and which I still had in mind, got in the way."*<sup>60</sup>

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<sup>58</sup> It is indeed a physical theory, but that does not appear in *Le Monde* mais plutôt dans *Les principes de la philosophie* : Descartes, R., *Les principes de la philosophie*, (Traduction française de l'abbé Picot), 1647 ; texte de l'édition Alquié.

<sup>59</sup> One finds a description of Newton's mechanical ether in *Scholium général* du livre III de *Philosophiae naturalis principia mathematica*.

<sup>60</sup> Huygens, C., *Discours de la cause de la pesanteur*, dans *Œuvres complètes*, tome XXI, pp. 451-488, 1691.

Concerning the luminiferous ether, Descartes' ether also plays the role of a medium for the propagation of light in the form of pressure, and Newton's ether is also the one that allows the propagation of light in the form of particles, and its oscillations are responsible for colors. For Huygens, light also propagates within it, but this time in the form of a wave, and a balance is struck after the numerous and intense debates and advancements related to electricity, magnetism, and the nature of light in the 19th century by the father of electromagnetism, James Clerk Maxwell, in these words:

*"Ethers were invented to make the planets swim, to constitute electric atmospheres and magnetic emanations, to transmit sensations from one part of our body to another, and so on, until all space had been filled three or four times with ethers... The only ether that has survived is the one invented by Huygens to explain the propagation of light."*<sup>61</sup>

After the development of the theory of electromagnetism by Maxwell and the formulation of Maxwell's equations, physicists were still in search of evidence for the existence of an ether, and although the descriptions provided are varied, it must be solid (rigid) and elastic, which makes its structure difficult to conceive. This ether is mostly at rest, thus constituting a preferred reference frame to refer to. This history takes a major turn in 1887 when the American physicists Albert Abraham Michelson and Edward Morley publish the results of an experiment, now known as the Michelson-Morley experiment, which aims to demonstrate the motion of the Earth through the ether<sup>62</sup>. This is an optical experiment of exceptional precision, which earned them the Nobel Prize in Physics in 1907, and it remains in history as one of the most significant negative-result experiments ever conducted. Indeed, the results of this experiment show, among other things, that the existence of the ether and its motion must at least be called into question, and it was Mach who first arrived at the conclusion of the non-existence of the ether. Another conclusion implied by this publication is the absolute nature of the speed of light in a vacuum, deduced by the Dutch theoretical physicist Hendrick Lorentz, who continued to support the ether thesis by seeking alternative forms. However, this hypothesis sparked debate within the scientific community at the beginning of the 20th century, and as Poincaré had already anticipated<sup>63</sup>, it would be abandoned following Einstein's work.

The first work of Einstein that concerns us here is the formulation of the theory of special relativity, which occurs in a context of unity of electromagnetism, primarily thanks to

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<sup>61</sup> Maxwell, J., *Ether*, dans *Encyclopedia britannica*, 9<sup>e</sup> éd, VIII, 1878, pp. 568-572.

<sup>62</sup> Michelson, A. A., Morley, E. W., On the relative motion of the Earth and the luminiferous ether, *American Journal of Science*, vol. s3-34, no 203, 1<sup>er</sup> novembre 1887, pp. 333-345. DOI : 10.2475/ajs.s3-34.203.333.

<sup>63</sup> Poincaré, H., *La Science et l'Hypothèse*, Chapitre 12, Flammarion, 1917, pp. 245-259.



Maxwell, and which indicates that the speed of light depends only on the properties of the medium, thus among other things, the constancy of the speed of light in a vacuum regardless of the reference frame, and a gradual abandonment of the ether. The main idea behind special relativity is to propose a theory that allows one to move from physical laws expressed in one inertial frame to the same laws expressed in another inertial frame while keeping the speed of light in a vacuum constant and independent of the observer's reference frame. Moreover, physicists and mathematicians such as the German Woldemar Voigt, Poincaré, and Lorentz had already worked, before 1905, on the formulas allowing the transition from one reference frame to another within the framework defined by Galilean relativity, which is what we now know as Lorentz transformations:

Lorentz Transformations :  
 Let  $(t, x, y, z)$  and  $(t', x', y', z')$  be the coordinates of an event in two inertial reference frames with relative velocity  $v$  along the  $x$ -axis, and  $c$  the speed of light in a vacuum. The relations between the coordinates are given by :

$$\begin{cases} t' = \gamma \left( t - \frac{vx}{c^2} \right) \\ x' = \gamma (x - vt) \\ y' = y \\ z' = z \end{cases}$$

where  $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ .

The respective roles of these scientists in the work attributed to Einstein were indeed the subject of heated controversies in the 2000s. Nonetheless, in 1905, Einstein published from Bern the very famous article "*Zur Elektrodynamik bewegter Körper*" (On the Electrodynamics of Moving Bodies)<sup>64</sup> in which he presents special relativity. The postulates grouped in this theory are: 1) the laws of physics verify the principle of relativity, 2) the speed of light in a vacuum is constant in all inertial reference frames and does not depend on the motion of the source or that of the observer, and 3) the ether is an arbitrary notion that does not intervene in relativity. With this theory and the Lorentz equations, it appears that space (three coordinates) and time (one coordinate) play inseparable roles, and it is no longer a matter of space and time, but rather a space-time continuum, which will later be studied as such and thus in four dimensions by Minkowski in the case where space is flat, hence the term Minkowski space in this case. Another consequence of special relativity is that space-time is homogeneous and isotropic, thus possessing the same properties concerning the laws of physics at every point and in all directions: this is the cosmological principle. Even more spectacular and decidedly less intuitive: when moving from one reference frame to

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<sup>64</sup> Einstein, A., *Zur Elektrodynamik bewegter Körper*, *Annalen der Physik*, vol. 17, 1905, pp. 891-921. DOI : 10.1002/andp.19053221004

another, not only can the observed lengths be shortened or dilated, but so too can the durations: the duration between two events measured in any inertial reference frame will always be greater than that measured in the reference frame in which these two events occupy the same spatial position (the term event is used in its sense in special relativity, namely as a point in space-time), so the absolute time proposed by Newton completely disappears. This property arises from the nature of the Lorentz factor  $\gamma$ , which is always greater than one.

Following special relativity, Einstein developed the theory of general relativity, which, as its name suggests, generalizes relativity to gravitation. He submitted his paper in 1915 to the Royal Academy of Sciences of Prussia<sup>65</sup>, and it was republished in March 1916 in the journal *Annalen der Physik* No. 49. Einstein imagined several thought experiments within the framework of special relativity and determined that by equating gravitational mass (the one that causes a body to fall under gravity) with inertial mass (the one that relates force and acceleration), one must conclude that there is a local equivalence between accelerated motion and free fall. This strict equality of the two types of masses has been verified to this day. Moreover, in seeking to keep the physical laws—namely, the laws of dynamics, gravitation, and electromagnetism—unchanged regardless of the reference frame (thus not only in inertial frames), the mathematics necessary to express these laws is that of tensor calculus. He also noted that the presence of masses and energy in the Universe implies phenomena that are impossible in a perfectly flat space at every point: space-time is thus non-Euclidean. It follows that the presence of mass-energy (a term encompassing both mass and energy, which share the same role in Einstein's theory, as can be seen in the expression  $E = mc^2$  for a resting mass  $m$ , which is equivalent to an energy  $E$  up to a factor of  $c^2$ ) locally curves space-time, and the notion of distance and the expression of physical laws must be reconsidered in terms of tensor calculus. Without delving into the details of the mathematics developed by a number of 19th and 20th-century mathematicians who influenced or directly worked with Einstein, including Hilbert, Minkowski, Levi-Civita, Ricci-Curbastro, Christoffel, and Mileva Einstein (who was Albert's wife and whose potentially unacknowledged contribution to the theory attributed to her husband is a source of controversy), we can nonetheless discuss Einstein's equation here:

Einstein's equation :

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

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<sup>65</sup> Einstein, A., On the General Theory of Relativity, *Sitzungsber. Preuss. Akad. Wiss*, Berlin, 1915, pp. 778-786.

The terms with indices  $\mu$  and  $\nu$  are tensors, here mathematical objects in four dimensions, and the indices  $\mu$  and  $\nu$  vary between 1 and 4 (for the three spatial dimensions and for the time dimension). This equation is, therefore, actually a set of 16 differential equations. The left side represents the curvature of space-time, and the tensor  $g_{\mu\nu}$  is called the metric tensor, containing the information necessary to determine the distances between events in space-time. In fact, solving Einstein's equation amounts to determining a metric, thereby allowing one to know the geometry of space-time. The right side corresponds to the amount of mass-energy, and  $T_{\mu\nu}$  is called the energy-momentum tensor. One can make a note about the term containing  $\Lambda$ : this parameter is called the cosmological constant. It was initially introduced by Einstein for ideological reasons (he wanted to ensure a static universe, neither expanding nor contracting) and was later abandoned in the face of observations of the expansion of the Universe. The cosmological constant was reintroduced by Peebles in 1980 to explain the acceleration of this expansion. This theory of general relativity has undergone numerous and spectacular observational verifications, such as the prediction of the precession of Mercury's perihelion, the effects of gravitational lensing, and the existence of black holes following the discovery of the Schwarzschild metric<sup>66</sup> in 1916 by the German astronomer Karl Schwarzschild, which is a solution to Einstein's equations in the case of an observer external to a non-rotating isolated spherical body (which can generally apply to stars, planets, or compact objects like black holes or neutron stars). It allows, notably, if contrary to Einstein's initial intuition, one admits a non-stationary Universe, to obtain the FLRW metric (for Friedmann-Lemaître-Robertson-Walker, resulting from the work of all these theorists) which shows that three homogeneous and isotropic models of the Universe are possible: flat on average, with positive curvature (the Universe is then closed, of finite volume), or with negative curvature (the Universe is then open, of infinite volume), and one can draw an analogy with two-dimensional surfaces as presented in Figure 2. Furthermore, the theory of general relativity, coupled with the subsequent astronomical observations, brings cosmology into the realm of sciences with mathematical models, the  $\Lambda$ CDM model being based on general relativity.

### 1.1.2 Modern astrophysics and the birth of cosmology

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<sup>66</sup> Schwarzschild, K., Die erste bekannte exakte Lösung der Einstein'schen Feldgleichungen, *Sitzungsber. Preuss. Akad. Wiss*, Berlin, 1916, pp. 189–196.

We will now revisit the main stages in the construction of cosmology from modern astrophysics through attempts to describe the structures and organizations of celestial bodies, more extensive astrophysical objects, and the Universe itself. This is a particularly timely approach, as we will see that this science is primarily paved with discoveries of increasingly larger and, above all, increasingly distant objects. However, this paragraph makes little mention of the evolution of instruments and industrial techniques related to astronomy; this choice allows us to focus on the different celestial structures and their natures to arrive at the notion of the large-scale structure of the Universe. A discussion regarding observation instruments will be provided in part 3.1.2. Furthermore, we will not go into detail about each type of observable object in the Universe, as their richness is vast, and their physical properties can vary greatly even within the same group of objects (for instance, one only needs to look at the diversity of planets found simply within our solar system to realize this).

First of all, during Antiquity, the Babylonians, Egyptians, and Greeks were already observing celestial bodies moving faster than other celestial objects and determined that these were planets, a term whose etymology in Ancient Greek means "wandering star." In Eastern astronomy, the reference was the *Almagest* of the Alexandrian Claudius Ptolemy<sup>67</sup>, written around the year 150, which constituted a collection of the most advanced knowledge in astronomy at the end of Antiquity. For more than a millennium, only other stars, the planets of the solar system, and occasional asteroids were known. Nebulae were also sometimes mentioned, in the *Almagest*, for example, whose etymology means "cloud" (from *nebula*) to designate objects with diffuse luminosity, the nature of which could not be precisely determined by the observational techniques of the time. This changed in the early 20th century thanks to the work of Hubble in Pasadena: firstly, in 1924, he showed that there are other systems composed of many stars like our own, and therefore, that there are other galaxies besides the Milky Way (still referred to as nebulae at the time, a term that carries a very different meaning in astrophysics today), notably the Milky Way's nearest neighbor, Andromeda<sup>68</sup>, which is the only object visible to the naked eye in the sky outside of the Milky Way. More precisely, Andromeda was not the first to be referred to as a galaxy; that title belonged to NGC 6822 in 1925. However, over time, Hubble cataloged several hundred galaxies, and others were discovered from his method by other astronomers. He also developed a method for classifying galaxies based on their morphologies: the Hubble

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<sup>67</sup> Hamilton, N. T., Swerdlow, N.M., Toomer, G. J., *The Canobic Inscription: Ptolemy's Earliest Work*, dans Berggren J. L., Goldstein, B. R. (éd.), *From Ancient Omens to Statistical Mechanics*, 1987.

<sup>68</sup> Hubble, E., A spiral nebula as a stellar system, Messier 31, *The Astrophysical Journal*, vol. 69, 1929, pp. 103-158.

sequence, later modified and expanded by Gérard de Vaucouleurs, which is still used today despite the difficulty of fitting all observed galaxies into a limited number of categories. This reflects the diversity of shapes, sizes, and colors that galaxies can take, and thus raises the question of the role and reason for these different structures. Subsequently, in addition to the previously unknown work of Abbé Lemaître, in his 1929 article, Hubble observed that these galaxies are receding from the Milky Way and that their rate of recession seems proportional to their distance from the Milky Way. This resulted in the Hubble-Lemaître law, which allows one to determine, from spectroscopic observations, with some precision the depth of the observed objects, and the idea that the Universe is expanding: galaxies do not necessarily have a proper velocity that moves them away from us, but space-time itself is evolving, and the Universe is expanding, carrying galaxies along in its expansion like raisins in a rising loaf of bread (this common analogy is limited to a three-dimensional space). In the 1960s, astronomers discovered by observing the sky in radio wavelengths that some celestial bodies are both extremely distant and extremely luminous. These celestial bodies are called quasars, short for quasi-stellar objects, because they were initially associated with stars. In particular, the object 3C 48 was the subject of numerous publications between 1960 and 1963<sup>69</sup>, and it wasn't until the work of astrophysicist Donald Lynden-Bell in 1969 that they were clearly identified as galaxies containing a supermassive black hole at their center, which is the source of the radio emissions<sup>70</sup>. He was also the first to suggest that most galaxies possess a supermassive black hole at their center. In the meantime, the accumulation of observations of individual galaxies has shown that certain regions of space are very dense in galaxies, while others are more empty. These dense regions, when the galaxies are gravitationally bound to one another, form either groups or clusters of galaxies. In practice, a group is a collection of around ten to a hundred galaxies that are gravitationally linked, while clusters are much larger, potentially containing thousands of galaxies that are also gravitationally bound and can extend over several megaparsecs. Clusters were first cataloged in 1958 by the American astronomer George Abell, who was then working in Los Angeles<sup>71</sup>, and here too there are as many types of clusters as there are clusters, each having its own geometry and structure, certainly influenced by its environment and history. When clusters themselves are gravitationally bound, the notion of superclusters appears, the first of which, the one in which

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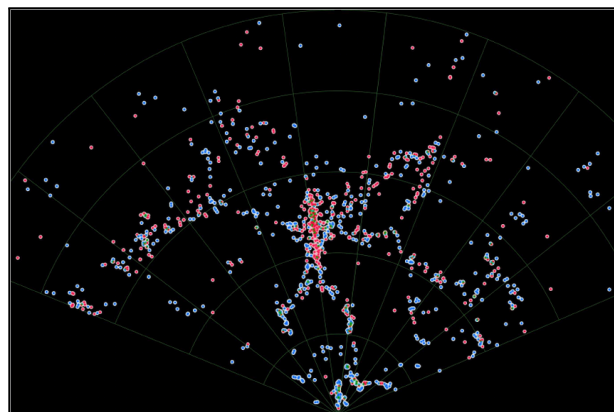
<sup>69</sup> Schmidt, M., The Discovery of Quasars, *Proceedings of the American Philosophical Society*, vol. 155, No. 2, 2011, pp. 142-146.

<sup>70</sup> Lynden-Bell, D., Galactic Nuclei as Collapsed Old Quasars, *Nature*, vol. 223, 1969, p. 690. DOI : 10.1038/223690a0

<sup>71</sup> Abell, G. O., The distribution of Rich Clusters of Galaxies, *Astrophysical Journal Supplement*, vol. 3, p.211, 1958. DOI : 10.1086/190036

our galaxy evolves, was studied in the 1950s by Gérard de Vaucouleurs, culminating in a publication in 1958<sup>72</sup>, although the term remained vague for a long time: the boundaries of this supercluster were only clearly defined since 2014, when a group consisting of R. Brent Tully, Hélène Courtois, Yehuda Hoffman, and Daniel Pomarède published in *Nature* the map of cosmic flows (the movements of galaxies), allowing for the contours of a complex overall shape for this supercluster now named Laniakea<sup>73</sup>. Observations reveal that the larger the structures observed, the lower their density relative to the average density of the Universe. Galaxies contain, within a few kiloparsecs, a density one hundred million times greater than that of the Universe on average; for large and rich clusters, it is a thousand times more within a few megaparsecs, and for a supercluster, this density is only ten times greater than the average density of the Universe. This leads to the notion that there are no identifiable structures larger than this, a super-supercluster. While such structures have indeed not been observed, and at even larger scales, the Universe becomes very homogeneous and isotropic, spatial observations from the late 20th century and early 21st century have nevertheless shown the existence of filamentary structures linking clusters together. The first observation of this type was made public in the article by Gregory and Thompson in 1973, followed by various works, including the major paper by Geller and Huchra, "Mapping the Universe" in 1989, in which a filament of galaxies extending over hundreds of megaparsecs, the "Great Wall," or "Great Wall Cfa2," visible in Figure 4, is described as the largest thin sheet-like structure detected at the time of publication. These structures are surrounded by vast cosmic voids, even more immense regions where the average density is lower than the average density of the Universe, and where the filaments, walls, and clusters define the boundaries.

These observations of increasingly vast and deeper regions are increasingly the observational tools of cosmology: at this scale, cosmologists study the organization of these clusters, filaments, and walls, which

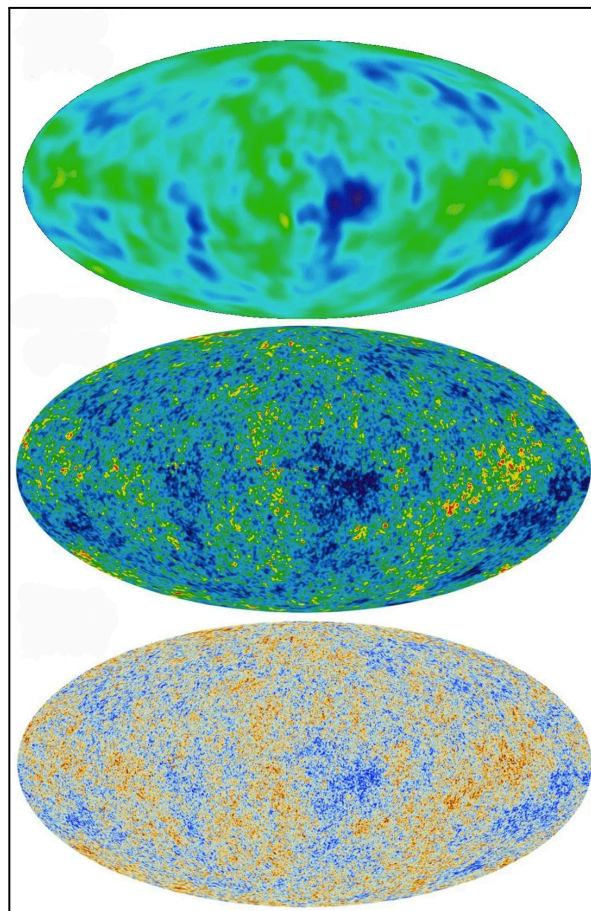


**Figure 4:** Projected view of a slice of the Universe according to the CFA Redshift Survey. The Earth observer is located at the base of the cone. The red dots represent young galaxies, while the blue dots are old galaxies. The center corresponds to the Coma cluster, and the Great Wall crosses it horizontally. Taken from Lapparent, Geller, and Huchra (1986).

<sup>72</sup> Vaucouleurs de, G., Further evidence for a local super-cluster of galaxies: rotation and expansion, *The Astronomical Journal*, Vol. 63, no 7, 1958, pp. 253-265. DOI : 10.1086/107742

<sup>73</sup> Tully, R., Courtois, H., Hoffman, Y., Pomarède, D., The Laniakea supercluster of galaxies. *Nature* 513, 2014. DOI : 10.1038/nature13674

constitutes the study of the large-scale structure of the Universe. Currently, the Sloan Digital Sky Survey (SDSS) is one of the most important and comprehensive astronomical surveys ever conducted, with a sixteenth data release expected in 2024<sup>74</sup>. These studies take place in space, examining the three-dimensional distribution of galaxies as well as the rest of the matter (gas, dark matter, dust), and also in time: this structuring must be the result of physical interactions, possibly over cosmic timescales. In this regard, cosmologists are turning to observations revealing the past of the Universe, such as those of the cosmic microwave background, first highlighted by Penzias and Wilson after various predictions by different physicists (Alpher, Herman, Gamow, Zel'Dovich, Dicke, Peebles, Roll, and Wilkinson) in the 1960s, and then observed in more detail successively by the COBE satellite launched in 1989, WMAP launched in 2001, and Planck launched in 2009, with increasingly finer resolutions. The maps of the anisotropies of the cosmic microwave background observed by these three satellites are shown in Figure 5. In practice, the cosmic microwave background corresponds to the photons emitted at the time of the Universe when light could first propagate freely, without being in constant interaction with matter, and which are still present everywhere in the Universe. The very slightly inhomogeneous distribution of matter at that moment implies that certain regions of the Universe are slightly richer in photons than others and thus contain more energy. It is these fluctuations in energy in the cosmic microwave background that the satellites are tasked with observing, which inform cosmologists about the content and state of the Universe at that moment.



**Figure 5:** Maps of the anisotropies of the cosmic microwave background taken across the entire sky by COBE (top), WMAP (middle), and Planck (bottom). The initial maps do not include the central part, which is hidden by the Milky Way, and this area is constructed statistically (by inpainting). The red points represent higher-energy regions, while the blue points indicate lower-energy regions. In practice, these maps are presented in Kelvins, units of temperature, with a difference of 200  $\mu\text{K}$  between the coldest and hottest points. Credit: NASA/WMAP Science Team; ESA and the Planck Collaboration.

<sup>74</sup> Les informations concernant le SDSS sont disponibles sur le site internet du relevé : <https://www.sdss.org/>

Notably, if the spatial distribution of matter is known at that moment thanks to the cosmic microwave background and today through the positioning of galaxies, it then becomes feasible to propose a theory of the formation and evolution of the large-scale structure of the Universe over time.

## **1.2 The Univers and its structure**

Our epistemological study began with elements of the history of the notions of time and space in physics, which led to the emergence of scientific cosmology, built upon a dominant model,  $\Lambda$ CDM, based on Einstein's general relativity and astronomical observations at galactic and extragalactic scales.

To study the large-scale structure of the Universe and its representations, we will first discuss the notion of structure in general within the physical sciences. The majority of physical theories in which this term appears actually emerged before modern cosmology. We will also briefly address other fields, such as linguistics or biology, to provide a more comprehensive idea of what the term structure can encompass. From these ideas, it will be possible to more precisely outline the elements of a historical epistemology of the large-scale structure of the Universe.

### **1.2.1 The notion of structure**

Let us consider here the meanings of the word structure in the sciences. When and why is this term used, and what illustrations can accompany it? First of all, it is possible to examine this notion in the context of sciences other than astrophysics, for example, in materials science (at subatomic, atomic, molecular, and crystalline solid scales) and in other sciences (life sciences and Earth sciences), as well as in linguistics. The following paragraphs serve as examples, clarifications, and show the possibilities for the evolution of representations of different structures over time.

#### **Atomic and Molecular Structure:**

Research on molecular structures has been profoundly influenced by major advances, notably spectroscopy, X-ray diffraction (in the early 20th century), and nuclear magnetic resonance in the 1940s. Among the scientists whose work has most influenced the field are the American chemist Linus Pauling, who received the Nobel Prize in Chemistry for his work on chemical bonds between atoms; American biochemist Robert Corey, whose work primarily focused on



the structure of proteins; and Dorothy Crowfoot Hodgkin, a pioneer in using X-rays to probe the structure of matter. Molecular structure, by definition, encompasses the spatial arrangement of atoms within a molecule, including both interatomic connectivity and the geometric orientation of the bonds. The same set of atoms can be linked and arranged in different ways, notably by the arrangement of electrons in the molecule, thereby constituting different molecular structures; this is referred to as resonance forms or mesomers. This structure is a decisive factor dictating the chemical reactivity and physical characteristics of a molecule. This conceptualization finds tangible representation through three-dimensional representations of molecules, where atomic bonds and the spatial arrangement of atoms are delineated. The use of color distinctions facilitates the identification of individual atoms and functional groups. Two-dimensional representations analogous to these three-dimensional models exist and are commonly used. Among them are Lewis structures, which allow visualization of the chaining of atoms, and Cram representations, which provide a more advanced idea of the geometry of molecules. The latter are a way to bring forth the structure of molecules on a two-dimensional and thus limited medium.

### **Internal Structure of Elementary Particles:**

In particle physics, the examination of the internal architecture of elementary particles, such as quarks, leptons, and bosons, serves to understand the fundamental forces and interactions that govern the Universe at the microscopic scale. Pioneering discoveries, such as the identification of the neutron by James Chadwick in 1932 and the postulation of quarks by Murray Gell-Mann and George Zweig in the 1960s, have significantly contributed to unveiling the internal constitution of matter. The advent of particle accelerators, notably the LHC, has facilitated the exploration of the elementary constituents of matter: through high-energy collisions, it is possible to break particles apart and detect their constituents. Similarly to atomic and molecular physics, the use of the term structure is based on the subatomic arrangement of particles. Feynman diagrams, emblematic of particle interactions, alongside schematic representations delineating the internal architecture of protons, neutrons, and other hadrons, serve as commonly used visual aids to represent and formulate the dynamics of particles and subatomic organization. However, it should be noted that Feynman diagrams represent interactions in space-time, not just in space, as seen with light cones. Thus, a structure can also encompass temporal notions, because it evolves or emerges over time. Furthermore, in quantum physics, which is essential at this scale of matter, Bloch

spheres are a means of geometrically representing, "structurally," a quantum system with two levels, which is therefore the quantum superposition of two states.

### **Material Structure, Crystalline Structure:**

In the field of materials mechanics, the characterization of a material's structure pertains to the internal arrangement of its constituent elements, such as grains within polycrystalline substances or fibers within composite materials. This organization also influences the mechanical attributes of materials, notably strength, hardness, and elasticity. The trajectory of research on the structure of materials has been considerably shaped by major contributions, including the studies of scientist Robert Hooke on elasticity dating back to 1660 and the work of English engineer Alan Arnold Griffith on the fracture mechanisms of materials in the 1920s, alongside decisive advances in electron microscopy in the 1930s. The use of the term structure emphasizes the hierarchical nature of the internal arrangement of a material: which elements are larger than others and what are their relative importance in the material's characteristics? Even for amorphous materials like glass or plastics, the local organization of atoms plays a major role in the properties of the matter. Similarly, in fluid mechanics, laminar flows arise from a structural organization of fluid layers, while turbulent flows can be explained by the presence of vortical structures and local fluid layers. Additionally, by extension from mechanics, architecture contains a notion of structure that refers to all elements that support and hold buildings. Regarding visual representations in these domains, one will mainly find images obtained with electron microscopes showing the microscopic arrangement of the constituents of matter, as well as schematic diagrams illustrating the spatial arrangement of grains or fibers, along with different layers of materials, at various scales.

In the field of crystallography, which is close to both materials physics and atomic physics, the crystalline structure of a material refers to the systematic and regular arrangement of atoms or ions within a crystal lattice, exerting a considerable influence on its characteristics, including conductivity, transparency, mechanical resilience, and the macroscopic shape of the crystal. The study of how these characteristics vary according to the structural organization—and thus the study of phase transitions—of matter is a field of research in its own right, and the study of such structures in condensed matter physics and nanoscience enables the creation of metamaterials or metasurfaces that exhibit physical properties not yet observed in nature. The studies of German physicist Max von Laue on the diffraction of X-rays through crystals in 1912 marked a crucial milestone in the quest to

observe crystalline structures and earned him the Nobel Prize in 1914. Subsequently, the formulation of Bragg's law in 1913 by Australians William Henry Bragg and William Lawrence Bragg (father and son, respectively) established a practical theory for using X-ray observations to understand the arrangement of atoms and ions in a crystal characterized by symmetries and periodicity of recurring atomic patterns. From these observations emerges the "structure factor," which formally characterizes the Fourier transform of the atomic structure of a unit cell of the crystal and is a directly measurable quantity during the diffraction of a beam of light by a crystal. Other relevant visual representations in crystallography include crystal lattice diagrams and one-dimensional, two-dimensional, or three-dimensional representations of atomic arrangements, often using color distinctions to highlight specific atomic configurations.

### **Structure in Earth Sciences: Geology, Meteorology, and Ecology:**

In the field of geology, geological structure encapsulates the spatial arrangement and configuration of rocks, faults, and folds within the Earth's crust, serving as a fundamental framework for understanding the genesis of landforms and geological phenomena. Knowledge of this structure has been primarily advanced through field observations and the continuous evolution of geophysical methods. Pioneers in the field, such as Scottish geologist James Hutton in the 18th century (a period marking the emergence of geology as a science), laid the groundwork for early theories explaining the evolution of rock layers, and subsequent advancements in disciplines like seismology and mapping have contributed to a deeper understanding of the geological organization of the Earth. Among the relevant visual aids to geological structure are geological maps delineating the distribution of rock formations across terrestrial landscapes, as well as cross-sectional diagrams representing the stratigraphic layers encountered within the Earth's crust. These illustrations have continuously evolved alongside advances in geology.

In meteorology, the vertical structure of the atmosphere delineates how atmospheric attributes, notably temperature, pressure, and humidity, change with altitude. Understanding the vertical structure of the atmosphere is based on the analysis of meteorological data and the application of advanced numerical modeling techniques. Among others, British mathematician Lewis Fry Richardson first envisioned, between 1916 and 1917, using physical models that take this structure into account to predict weather changes. The vertical structure of the atmosphere is defined as the spatial distribution of atmospheric properties in relation to altitude, exerting a discernible influence on the manifestation of meteorological

phenomena. Relevant visual representations of the vertical structure of the atmosphere include vertical temperature profiles, atmospheric stability diagrams, and maps of atmospheric pressure.

In the field of ecology, the structure of the ecosystem refers to the arrangement and distribution of living species as well as their interactions. Pioneers of ecological thought, notably Charles Darwin in the 19th century, initially studied the complex relationships between species and their environment, so the structure of ecosystems was first conceived as a network of interactions. Subsequent advancements in ecological modeling and population ecology have introduced mathematical frameworks and scientific models to study this structure. This term thus encompasses both the geographical properties of biotic entities and their interrelationships, as well as their relationships with abiotic entities. Relevant visual representations of ecosystem structure include representations of trophic networks illustrating interactions between species, maps delineating population distributions, and diagrams showing energy flows within ecosystems.

### **Cellular Biological Structure:**

In the field of cell biology, cellular structure pertains to the arrangement of the components of a cell and their relationships that define cellular functions and interactions within all biological organisms. The earliest traces of the notion of biological cells date back to Robert Hooke, who published his work *Micrographia*<sup>75</sup> in 1665 to report his observations, which were later identified as dead cells emptied of their contents. In the early 19th century, while observing plants, German botanist Matthias Schleiden emphasized the importance of the cell nucleus in plant growth, inspiring physiologist Theodor Schwann, who formulated cell theory in his foundational work, the title of which even includes the word structure: *Mikroskopische Untersuchungen über die Uebereinstimmung in der Struktur und dem Wachsthum der Thiere und Pflanzen* (Microscopic Investigations on the Correspondence Between the Structure and Growth of Animals and Plants)<sup>76</sup>. Subsequently, the advent of advanced microscopy techniques, notably the scientific and industrial development of the electron microscope in the 1930s, allowed researchers to probe biological cells at increasingly fine resolutions and to create increasingly precise images. From this type of observation, the visual representations accompanying this cellular structure include electron micrographs showing cellular

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<sup>75</sup> Hooke, R., *Micrographia : or, Some physiological descriptions of minute bodies made by magnifying glasses*, Londres, J. Martyn and J. Allestry, 1665, 331 p.

<sup>76</sup> Schwann, T., *Mikroskopische Untersuchungen über die Uebereinstimmung in der Struktur und dem Wachsthum der Thiere und Pflanzen*. Sander, Berlin 1839.

organelles in two dimensions, as well as three-dimensional models illustrating the overall architectural configuration of a cell.

### **Syntactic Structure:**

In the field of linguistics, syntactic structure concerns the sequential arrangement and organization of words and parts within a sentence. The work of Swiss linguist Ferdinand de Saussure, published posthumously, on structural linguistics, conducted during the 20th century, laid the fundamental groundwork for the examination of syntactic structures across languages. Saussure is one of the fathers of structuralism, which aims to study each system of objects as a set of relationships rather than as elementary units. Researchers such as Noam Chomsky have since significantly advanced this field from the 1950s, notably through the development of the theory of generative grammar, according to which each language forms a unique structure resulting from a system of universal and innate language construction. Although linguistic representations are intrinsically abstract, graphic aids such as syntax trees provide a means to represent the hierarchical structure of sentences. Syntax trees visually illustrate the syntactic relationships between words and phrases within a sentence, with the branches representing the connections between various linguistic elements.

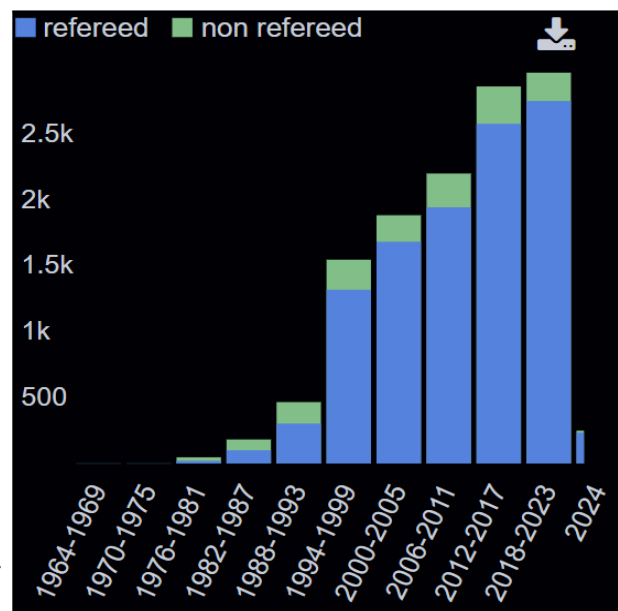
Finally, if we take stock of the previous paragraphs, we notice that the terms *arrangement* and *organization* often recur, but structure does not stop at a mere spatial disposition of elements. It also encompasses the *relationships between these elements, as well as the patterns that allow for the description of the studied system*. The representations are diverse, but they share the commonality of either fixing observations, as with microscopes or X-rays, schematizing spatial arrangements and relationships between elements as in three-dimensional models or syntax trees, or serving as intermediaries between elements and equations, as in Feynman diagrams. Moreover, there is a field of research in the physical sciences that studies systems a priori without structure, known as nonlinear physics. Such systems exhibit chaotic behaviors, and this chaos itself gives rise to structures in the form of geometric configurations, such as fractals, particularly in phase space (the space composed of both positions and velocities/momenta), with the Lorenz attractor being perhaps the best-known representative of nonlinear systems. Ultimately, and especially in the physical sciences, structure is a ubiquitous notion: the search for organizations, interactions, geometric relationships, or temporal relations corresponds to the search for structures.

## 1.2.2 Application to the Univers

Our brief introduction to modern cosmology has focused on observations of the cosmic microwave background. Let us return to this story and continue it, now concentrating on the discovery of the large-scale structure of the Universe, the ideas and publications associated with it, and its graphical and mathematical representations. First, based on the NASA ADS database, which catalogs publications appearing in peer-reviewed scientific journals or not, if we search for occurrences in full articles of the phrase "large-scale structure of the Universe" (since the vast majority of scientific articles in cosmology are written in English), we count an ever-increasing number since the 1970s (see Figure 6 for the evolution of the number of publications).

Hubble's success in characterizing galaxies and the expansion of the Universe in 1929 at Mount Wilson using the Hooker telescope, building on the discovery of the redshift of spectral lines by Vesto Slipher in 1912<sup>77</sup>, along with the little-publicized publication by Georges Lemaître in 1927, established his vision of a homogeneous Universe as predominant and placed cosmology into a paradigm that did not admit any particular large-scale structuring of galaxies. This view was notably challenged by Hubble's rival, Harlow Shapley. From 1914 to 1921, Shapley worked at Mount Wilson, being there at the same time as

Hubble approaching 1920. In 1932, Shapley and astronomer Adelaide Ames published a catalog of the brightest galaxies (and thus generally the closest) in the complete sky. This Shapley-Ames catalog is essentially a reissue and update of the works of William and Caroline Herschel, dating back to the 18th century, based on new astronomical knowledge, particularly the understanding of galaxies outside the Milky Way and the relationship found by Henrietta Leavitt in 1908 between the brightness of certain variable stars (the Cepheids)

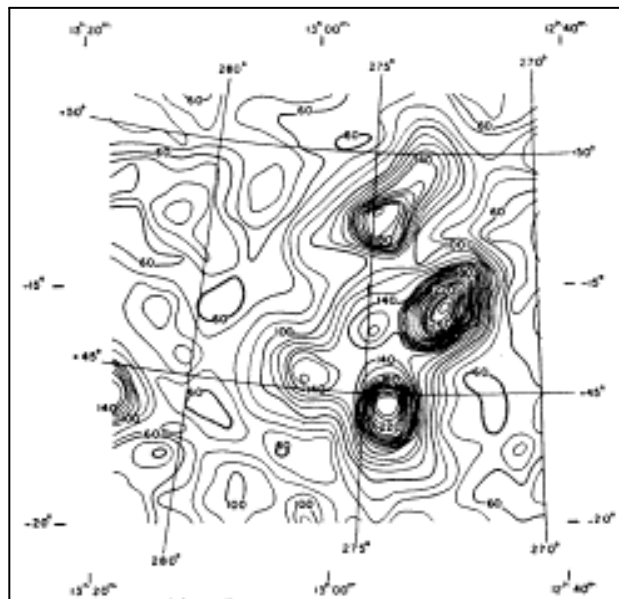


**Figure 6:** Screenshot, taken in early 2024, showing statistics from research on NASA's ADS database website. The articles counted in blue are those published in peer-reviewed journals, while those in green are from articles either rejected or not submitted to such journals.

<sup>77</sup> Slipher, V., *The radial velocity of the Andromeda Nebula*, Lowell Observatory, Bulletin n°58, 1912.

and their pulsations, which allowed for the measurement of the distance of these stars from Earth<sup>78</sup>. In interpreting this catalog, Shapley noted that the spatial distribution of these galaxies, projected onto a two-dimensional sky map, is highly inhomogeneous. Despite Shapley's desire to share his viewpoint, his interventions with figures such as Sir Arthur Eddington or Lemaître left only a weak imprint on the common imagination of cosmologists in the early 20th century. If Hubble did not notice this, it is because he was observing small regions of the sky at long distances, unlike Shapley and Ames, who covered the entire sky at shorter distances. The projection effect on Hubble's observations led him to conclude that the Universe contained a fairly constant number of galaxies in all directions, and thus was homogeneous on the observed scales. In light of modern cosmology, this is a misinterpretation, and it is not the only one Hubble would make: he would refuse to associate his observations of the accelerated recession of galaxies with an expanding Universe and would defend a static Universe model, as Einstein had done.

Around 1950, a major transition would occur with the development of studies on the distribution of galaxies. Until then, it was recognized that clusters, or galaxy groups, could exist, but the question of higher-order clusters, superclusters, or superclusters, was still controversial. In 1948, American astronomers Charles Shane and Carl Wirtanen worked at the Lick Observatory at the University of California, east of San José (Shane was the director there from 1945 to 1958). They published maps of the distribution of galaxies over a region corresponding to 70% of the sky, which corresponds to the portion of the sky visible from Lick Observatory, notably topographic maps (see Figure 7) analogous to geological or meteorological maps. These results, revised in 1954<sup>79</sup>, showed peaks in galaxy density (clusters) but also broader areas visibly containing a high number of galaxies, exceeding the average. This was an initial



**Figure 7:** Reproduction of Figure 13 from the article by Shane and Wirtanen: *The distribution of extragalactic nebulae* (1954). Galaxy clusters are identifiable as density peaks and thus tomographic maxima, and their extended nature hints at the existence of larger structures, known as superclusters.

<sup>78</sup> Leavitt, H., Pickering, E., Harvard College Observatory Circular, volume 173, 1908, pp. 1-3.

<sup>79</sup> Shane, C. D., Wirtanen, C. A., *The distribution of extragalactic nebulae*, *Astrophysical Journal*, vol. 59, 1954.

attempt to visualize galaxies as a whole, a broader structure, and also a first representation of this structuring through graphical means distinct from a mere set of points. Shane and Wirtanen's study was conducted on 800,000 galaxies, which was massive for the time. However, the regions of the most extensive overdensities were not yet well defined by their maps, so the extensions of these results mainly concerned clusters. In particular, in collaboration with Jerzy Neyman and Elizabeth Scott, both professors of mathematics at Berkeley, they proposed a three-parameter model for the distribution of galaxies based on the hypothesis that each galaxy belongs to a group or cluster. By adjusting their parameters to the observations of Shane and Wirtanen, they managed to account for the distribution of galaxies across the entire sky, and by reversing the process, they created a simulation of the sky from the values of these three parameters, which qualitatively corresponded to real observations. This is remarkable, especially in the absence of cosmic voids in this simulation. The Lick galaxy catalog would be used for a long time, and in 1970, Shane indicated that this catalog showed the presence of structures broader than clusters and perhaps even the absence of a uniform background of galaxies<sup>80</sup>. Completely independently, D. Nelson Limber published in 1953<sup>81</sup> a statistical method to study the distribution of galaxies based on a tool developed by his advisor at the Yerkes Observatory, Subrahmanyan Chandrasekhar, with the assistance of his colleague Guido Munch. This tool is the correlation function. In practice, it allows one to measure the probability of finding another galaxy at a certain distance from a known galaxy. If this operation is repeated for a sufficiently large sample of galaxies, or for all the galaxies in a survey, the average correlation function provides the spatial statistical characteristics of the survey. However, this is a tool used on two-dimensional sky maps, and this method is therefore not sensitive to depth but only to two spatial dimensions. Around the same time, and unbeknownst to her, Vera Rubin was in competition with Limber. She completed her thesis at Georgetown University in 1954 under the supervision of Gamow, and while applying the correlation function to Shapley's surveys, her article was rejected by Chandrasekhar, then editor of the *Astrophysical Journal*. She then published her results in the *Proceedings of the National Academy of Sciences*. This method is still widely used in cosmology and especially in the study of the large-scale structure of the Universe and is described in detail in Peebles' handbook published in 1980<sup>82</sup>.

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<sup>80</sup> Shane, C., Distribution of Galaxies, dans *Galaxies and the Universe*, A. Sandage, M. Sandage, & J. Kristian (ed.), Chicago, University of Chicago Press, 1970, pp.647–63.

<sup>81</sup> Limber, D. N., The Analysis of Counts of the Extragalactic Nebulae in Terms of a Fluctuating Density Field, *Astrophysical Journal*, vol. 117, 1953.

<sup>82</sup> Peebles, P. J. E., *The Large-Scale Structure of the Universe*. Princeton University Press, 1980, pp. 172-175.



The discovery of galaxy superclusters came slightly later. In 1958, Abell published his major results, the Abell catalog, in which he recorded thousands of galaxy clusters observed during his thesis at Caltech as part of his participation in the National Geographic Palomar Observatory Sky Survey, which produced excellent quality images with unprecedented depth due to particularly long exposure times. In addition to cataloging them, Abell assigned a size to the clusters based on the brightness of the tenth brightest galaxy within each cluster. From this size, he was thus able to estimate more accurately the number of galaxies belonging to each cluster. Following the initial indications left by Shane and Wirtanen, Abell sought to identify groups of clusters, which he then called second-order clusters and are now known as superclusters. He thus proposed the first concrete statistical and quantitative study of the characteristics of these superclusters. After his premature death at the age of 56 in 1983, his work was continued by Harold G. Corwin Jr. and Ronald Olowin. During the 1960s and 1970s, some researchers, such as the Swiss Fritz Zwicky, attempted to challenge the existence of superclusters. In Zwicky's case, who remains a controversial figure in astrophysics today, the absence of a systematic method and the use of "eyeballed" sketches of the distribution of clusters and their spatial boundaries<sup>83</sup> tended to discredit the arguments in favor of a nearly homogeneous Universe at these scales. Peebles also defended the traditional view of a homogeneous Universe, or at least one devoid of second-order clusters, until the late 1970s. Indeed, before the arrival of larger and, above all, deeper galaxy surveys, doubts lingered about the artificial nature of superclusters, which the human eye might create without them being physically present. In 1969, Peebles and his student Jer-Tsang Yu published a new analysis of the Abell catalog and concluded that the presence of superclusters was not yet proven, and that the distribution of galaxies at this scale could also be explained by chance<sup>84</sup>.

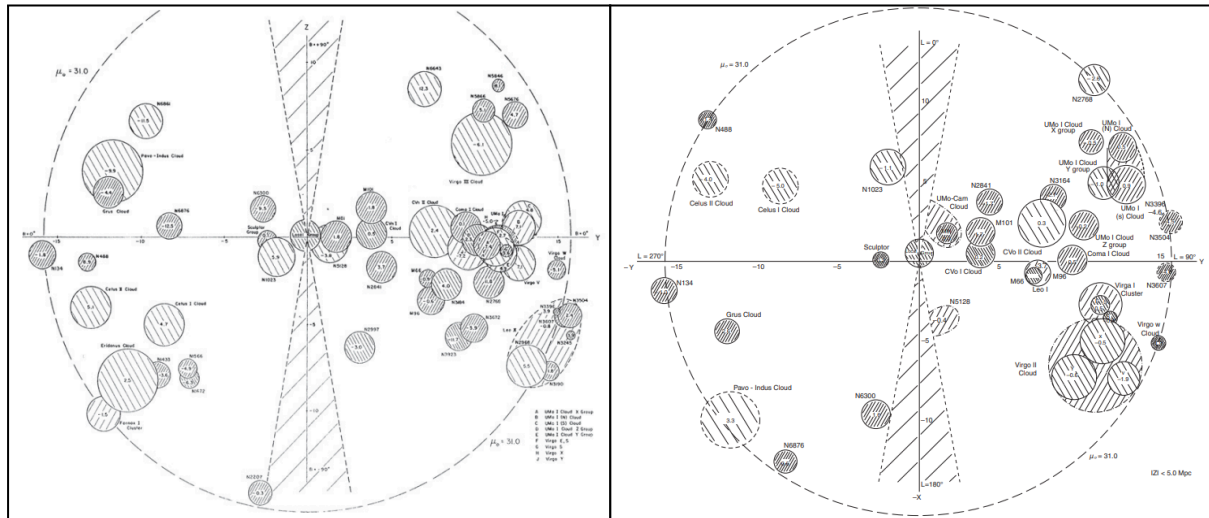
To begin the study of superclusters, the French couple Gerard and Antoinette de Vaucouleurs focused on the one that includes the Milky Way: the local supercluster, or the Poisson-Baleine supercluster, named after the constellations one must aim for in the sky to observe it. This supercluster had been interpreted by Herschel as a local homogeneity of the Universe and by Shapley as a collection of galaxies surrounding the local cluster, or the Virgo cluster. In 1953 and 1956, Gérard de Vaucouleurs published three-dimensional views of the local supercluster, thus external to it. He called it the supergalaxy, a term no longer used

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<sup>83</sup> Zwicky, F., Kowal, C. T., *Catalogue of galaxies and of clusters of galaxies*, ESO, Pasadena, California Institute of Technology, vol. 6, 1968.

<sup>84</sup> Yu, J.T., P.J.E. Peebles, *Superclusters of galaxies*, *Astrophysical Journal*, vol. 158, 1969, pp. 103-113. DOI :10.1086/150175

today, which should not be confused with a galaxy. A reproduction of de Vaucouleurs' work is shown in Figure 8.



**Figure 8:** First maps representing the local supercluster in three dimensions based on the observations and knowledge available in the 1950s and 1960s. The left panel shows the distribution of galaxy clusters in the plane perpendicular to the plane of the local supercluster. The right panel shows the distribution of galaxy clusters in the plane that coincides with the plane of the local supercluster. The local group is at the center. Each hatched circle represents a galaxy cluster. The striped area is the region of the sky obscured by the Milky Way in which we are located. Credit: G. de Vaucouleurs, in *Galaxies and the Universe*, A. Sandage, M. Sandage, & J. Kristian (ed.), Chicago, University of Chicago Press, 1970, pp. 557–600.

De Vaucouleurs did not have the tools required to observe correctly beyond the local supercluster, but he nonetheless postulated that the inhomogeneities, and thus the size of structures at these scales, continue to increase with the depth of observations. These ideas remained marginal and were not developed beyond the 1970s.

At this point in our story, it is important to pause on the notion of observation depth. When astronomers observe the sky with the naked eye, the image that appears is merely a projection on the celestial sphere of the light emitted by the stars in galaxies. In other wavelengths, different electromagnetic signals reach us, such as X-rays, gamma rays, ultraviolet, or infrared light, which emerge from various astrophysical phenomena. When they are very distant, access to the third dimension, to the depth of the observed objects, is achieved by measuring their redshift. According to Hubble's interpretation based on his 1929 work, which prevails today, redshift is the shift to the red of the spectrum of a galaxy moving away from the observer. The more distant a galaxy is, the greater its speed of recession due to the accelerated expansion of the Universe, and the greater its redshift. In practice, redshift is a

physical quantity calculated from the wavelength of a photon emitted by a galaxy and the wavelength of that same photon when observed on Earth.

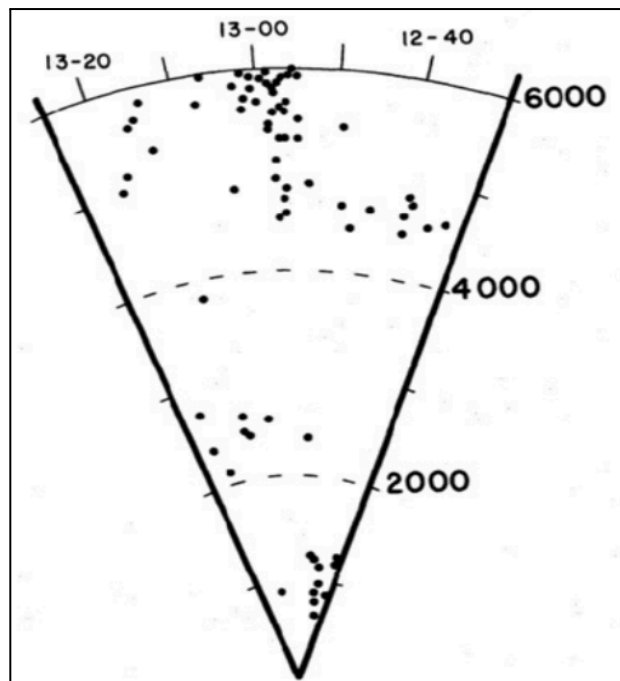
Redshift :  
 Let  $\lambda_0$  be the wavelength of a photon emitted by a galaxy and  $\lambda_{obs}$  the wavelength of the same photon observed on Earth. The *redshift*  $z$  of the galaxy is given by :

$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0}$$

For very small distances between emission and observation,  $\lambda_0 \approx \lambda_{obs}$  and thus  $z \approx 1$ . Since more distant galaxies are receding faster,  $\lambda_{obs}$  increases with distance, and consequently, so does  $z$ .

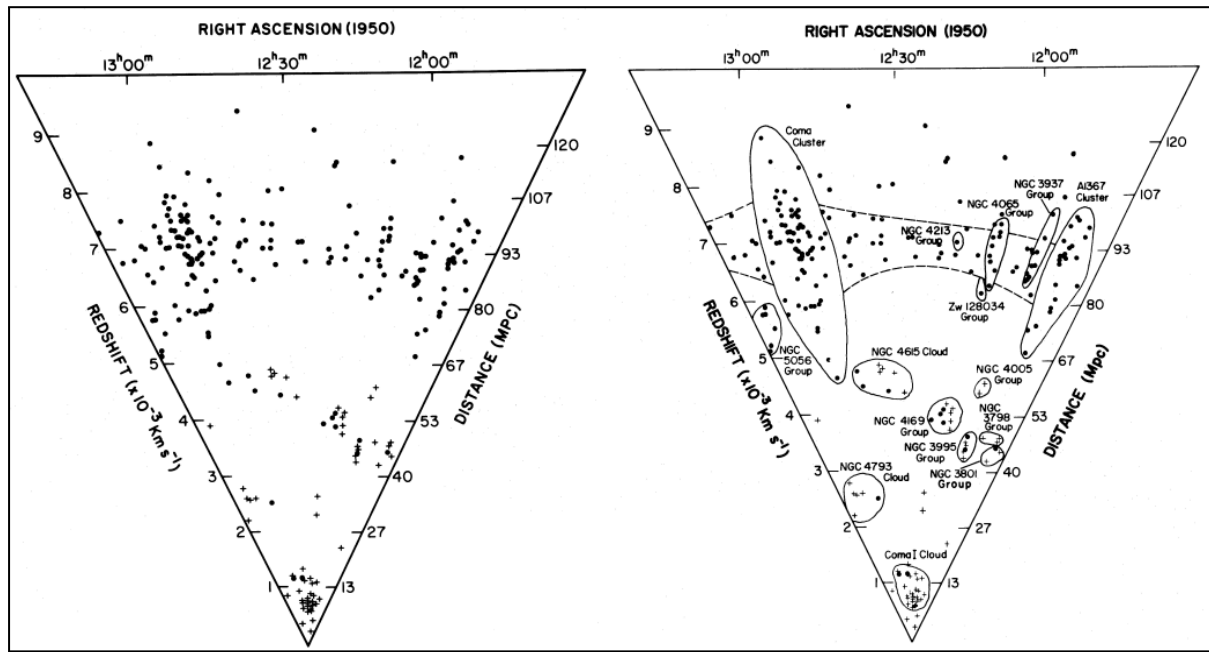
The measurement of redshift thus involves spectroscopic measurements: one identifies known absorption or emission lines in the light spectra of galaxies and compares their position in wavelength to the same line measured in the laboratory on Earth. To determine the redshift of a galaxy, astronomers cannot simply observe visible light; they must also decompose this light and light in wavelengths invisible to the eye (such as infrared) to determine its spectrum. In astronomy, spectral analysis was initially used by William Hyde Wollaston and then by Joseph Fraunhofer between the late 18th and early 19th centuries to determine part of the composition of the Sun. Its use for galaxy observations became more widespread with significant investments, especially in the United States, from the late 1960s onwards. As the years progressed, measurement technologies allowed for observations at higher redshifts.

At the dawn of the 1970s, significant investments were made at the astronomy department of the University of Arizona, then directed by American-Dutch Bart Jan Bok. New telescopes were installed at the Kitt Peak National Observatory (KPNO), including a brand-new spectrograph. In this context, astronomers such as William Tift, Herbert Rood, Guido Chincarini, Laird Thompson, and Stephen Gregory worked on galaxy redshift surveys during the 1970s using various instruments at KPNO. Among their objectives was the ambition to better understand the three-dimensional structuring



**Figure 9:** Reproduction of Figure 1 from the article by Tift and Gregory (1976). The Coma cluster is identifiable at the 4500 mark on the y-axis. The y-axis represents recession velocities, which correspond to redshift, while the x-axis is in degrees and represents right ascension (angle corresponding to terrestrial longitude).

of distant galaxies and thus the large-scale structure of the Universe. These studies enabled Gregory and Tifft to publish, in 1976, an article using the modern representation of the sky in a cone<sup>85</sup> (see Figure 9). In this article titled "Direct observations of the large-scale distribution of galaxies," the authors study the Coma cluster and conclude that almost no galaxy is isolated; on the contrary, they are all part of a cluster or group, and there are visibly structures of matter overdensities that extend beyond the cluster. This observation is still too limited to clearly reveal these structures and the voids around them.



**Figure 10:** Left panel: The Coma cluster is on the left, and cluster A1367 is on the right. Between the two, the points form a bridge-like structure. A large cosmic void is particularly visible around  $z=5$ . Each point represents a galaxy. Right panel: The authors' interpretation of the shapes of the structures formed by the galaxies. Notably, the groups and clusters appear in elongated forms. Credit: Gregory, S. A., Thompson, L. A., "The Coma/A1367 supercluster and its environs," *Astrophysical Journal*, Vol. 222, 1978, pp. 784-799.

It was in 1978 that Thompson and Gregory published the first observation of these cosmic voids in the article "The Coma/A1367 supercluster and its environs." In this article, the authors also used topographic maps, but rather than a cone, they chose to represent their observations in a triangle, as shown in Figure 10. In any case, the projection effects caused by the gravitational attraction of galaxies towards the center of the cluster create a distortion along the redshift axis. The observed shapes of the clusters are elongated along this axis, which reveals cigar-shaped forms highlighted on the right side of Figure 10. These shapes have been nicknamed "fingers of God," and the more massive they are, the longer the clusters appear. From this historical point, representations of structures visible in the sky generally

<sup>85</sup> Tifft, W., Gregory, S., Direct observations of the large-scale distribution of galaxies, *Astrophysical Journal*, vol. 205, 1976, pp. 696-708.

have this distortion corrected. Figure 10 also highlights a group of galaxies between the Coma cluster and the A1367 cluster, which resembles a bridge. Subsequent studies following this article, such as the CfA and CfA2 missions,

In 1978, Thompson and Gregory published the first observation of these cosmic voids in the article "The Coma/A1367 supercluster and its environs." In this article, the authors also used topographic maps, but rather than a cone, they chose to represent their observations in a triangle, as shown in Figure 10. In any case, the projection effects caused by the gravitational attraction of galaxies towards the center of the cluster create a distortion along the redshift axis. The observed shapes of the clusters are elongated along this axis, revealing cigar-shaped forms highlighted on the right side of Figure 10. These shapes have been nicknamed "fingers of God," and the more massive they are, the longer the clusters appear. From this historical point, representations of structures visible in the sky generally have this distortion corrected. Figure 10 also highlights a group of galaxies between the Coma cluster and the A1367 cluster, which resembles a bridge. Subsequent studies following this article, such as the CfA and CfA2 missions, will show that this ensemble is actually part of an immense filamentary structure that will be nicknamed the Great Wall. It is important to understand here that these galaxies do not form a wall in the literal sense that would block passage, but rather that this region of space contains more than other regions on average. The distances between galaxies are still several orders of magnitude beyond the size of an individual galaxy, and they move over extremely long times across such distances.

At the same time, Rood and Chincarini produced rectangular figures, with redshift on the vertical axis and distance to the center of the cluster on the horizontal axis. This type of image does not reveal the three-dimensional geometric structure, nor even the two-dimensional structure, of the clusters: two galaxies at equal distances from the center but located on opposite sides and at the same redshift will be traced at the same position on the image, even though they are physically separated by a great distance. Nevertheless, from this point on, the concept of void or cosmic hole became common, and this usage became increasingly frequent over time, despite Thompson and Gregory's difficulties in asserting their results<sup>86</sup>. Similarly, the term "bridge" emerged, notably in the title of a 1981 article<sup>87</sup>, and it was then referred to as a filamentary structure, making the term "filament" more

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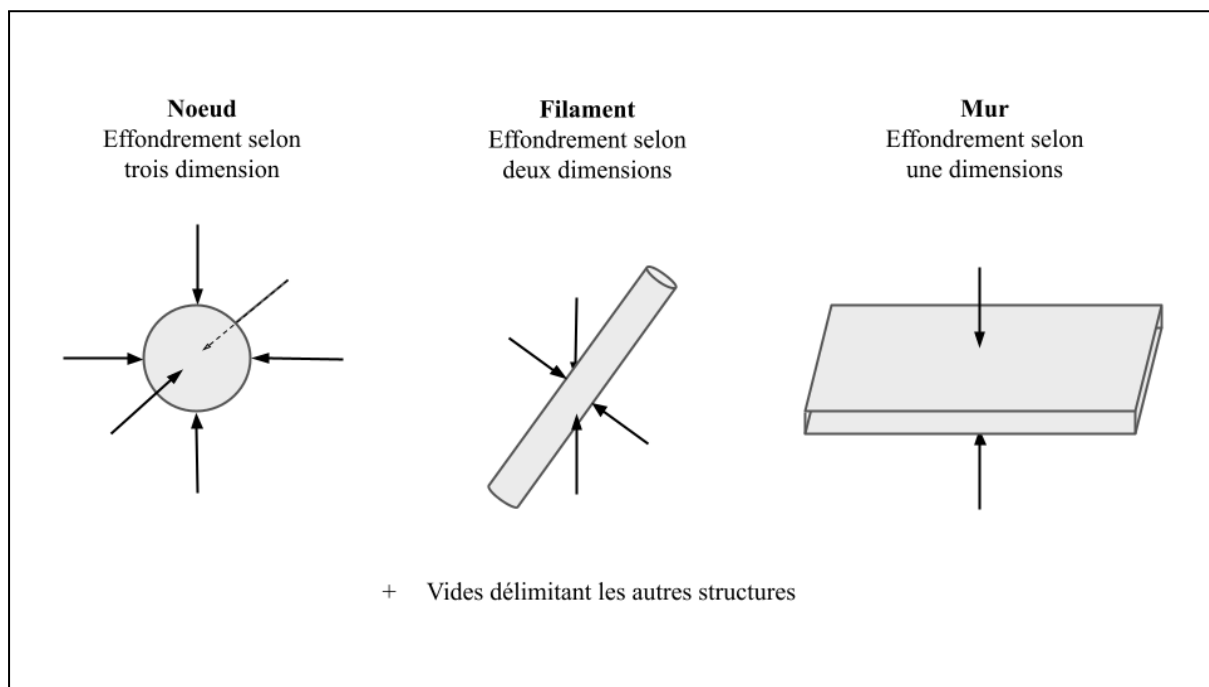
<sup>86</sup> The controversies surrounding the discovery of cosmic voids are recounted from L. Thompson's perspective in his book *The Discovery of Cosmic Voids*. In particular, he criticizes the cosmological community for having more or less deliberately ignored his joint work with Gregory.

Thompson, L., *The Discovery of Cosmic Voids*, Cambridge, Cambridge University Press, 2010, 291 p.

<sup>87</sup> Chincarini, G., Thompson, L. A., Rood, H. J., Supercluster bridge between groups of galaxy clusters, *Astrophysical Journal*, vol. 249, 1981. DOI : 10.1086/183656

common. A more extreme example of a cosmic void, which through communication and media became more famous than the one discovered by Gregory and Thompson, is the Boötes void, described in a publication by Kirshner, Oemler, Shechter, and Shectman in 1981<sup>88</sup>. For the first time, a cosmic void was sufficiently large to test cosmological models: a model embedded in a simulation must be able to reproduce such voids.

It was also at this time that various models of galaxy formation emerged, both in the United States and in the USSR, in Moscow. Peebles favored a bottom-up formation, which involves a succession of accretion of spherical masses that become larger masses, eventually forming galaxies and even groups or clusters of galaxies. Zel'dovich preferred a top-down version, where large structures of overdensities gravitationally collapse to give rise to smaller structures. This latter theory took shape under the name of Zel'dovich approximation. In particular, these models have sometimes been respectively referred to as meatballs and pancakes: the meatballs merge to form increasingly larger ones, and the pancakes (walls)



**Figure 11:** Schematic representation, with an arbitrary scale, of the constituent structures of the cosmic web, along with the axes along which gravitational collapse occurred according to Zel'Dovich's approximation. The voids, although challenging to represent, are sometimes referred to as structures and serve to separate and define the boundaries of filaments, walls, and halos.

collapse along the least dense axis to form filaments that themselves form halos. These two models are not merely mental representations of the large-scale structuring of the Universe;

<sup>88</sup> Kirshner, R. P., Oemler, A. Jr., Schechter, P. L., Shectman, S. A., A million cubic megaparsec void in Boötes ?, *Astrophysical Journal*, vol. 248 1981. DOI : 10.1086/183623

they also imply fundamentally different predominant physical processes: either the large-scale structure arrived before the galaxies that formed within it, or the galaxies form first and subsequently define this large-scale structure. The structures referred to in the Zel'dovich approximation are represented in Figure 11. Because of the Cold War, and especially the impossibilities for Zel'dovich to geographically distance himself from the USSR, the ideas from the East took several years to propagate, while Peebles was already referenced in the West, notably due to his involvement in the discovery and analysis of the cosmic background radiation<sup>89</sup>. In the absence of sufficient data to distinguish between them, these competing ideas coexisted for a large part of the decade. The interlocutor who could bring together and confront these schools of thought was the British Martin Rees, who served as president of the Royal Society from 2005 to 2010. Under his direction, the American Richard Gott<sup>90</sup> developed another theory. He met Zel'dovich in Estonia (then still part of the USSR), a stronghold for discussions in cosmology at that time, in 1977 during a seminar in Tallinn, and took the opportunity to propose a topology of the Universe that placed itself between the two major visions: a sponge or a honeycomb to stay within the culinary metaphors. In this model, the overdensities (clusters, superclusters, filaments, walls) and underdensities (voids) are complementary and can be exchanged without the large-scale structure of the Universe changing its global characteristics. But the proposed metaphors have not always been attached to models. In *Discovery of the Cosmic Voids*, Thompson explains that during a seminar, Abell imagined the city lights once night fell to visually represent this structure:

*“[Abell] described the large-scale distribution of galaxies as being somewhat similar to a view of the Los Angeles city lights at night from his home on Mulholland Drive. The grid of street lights resembled the ridges of galaxies in filamentary superclusters, and cosmic voids were the dark areas in between. It was a fitting comparison.”*<sup>91</sup>

Still during the 1970s-1980s, Estonians Jaan Einasto and Mihkel Jõeveer, who were then working at the Tartu Observatory, particularly focused on the notion of superclusters and spoke of a cell-like structure of the Universe. This vision would be undermined by the lack of data at the time regarding superclusters but remained an attempt at description that was

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<sup>89</sup> This story is told in a romanced and accessible way in the video of the YouTube channel History of the Universe :

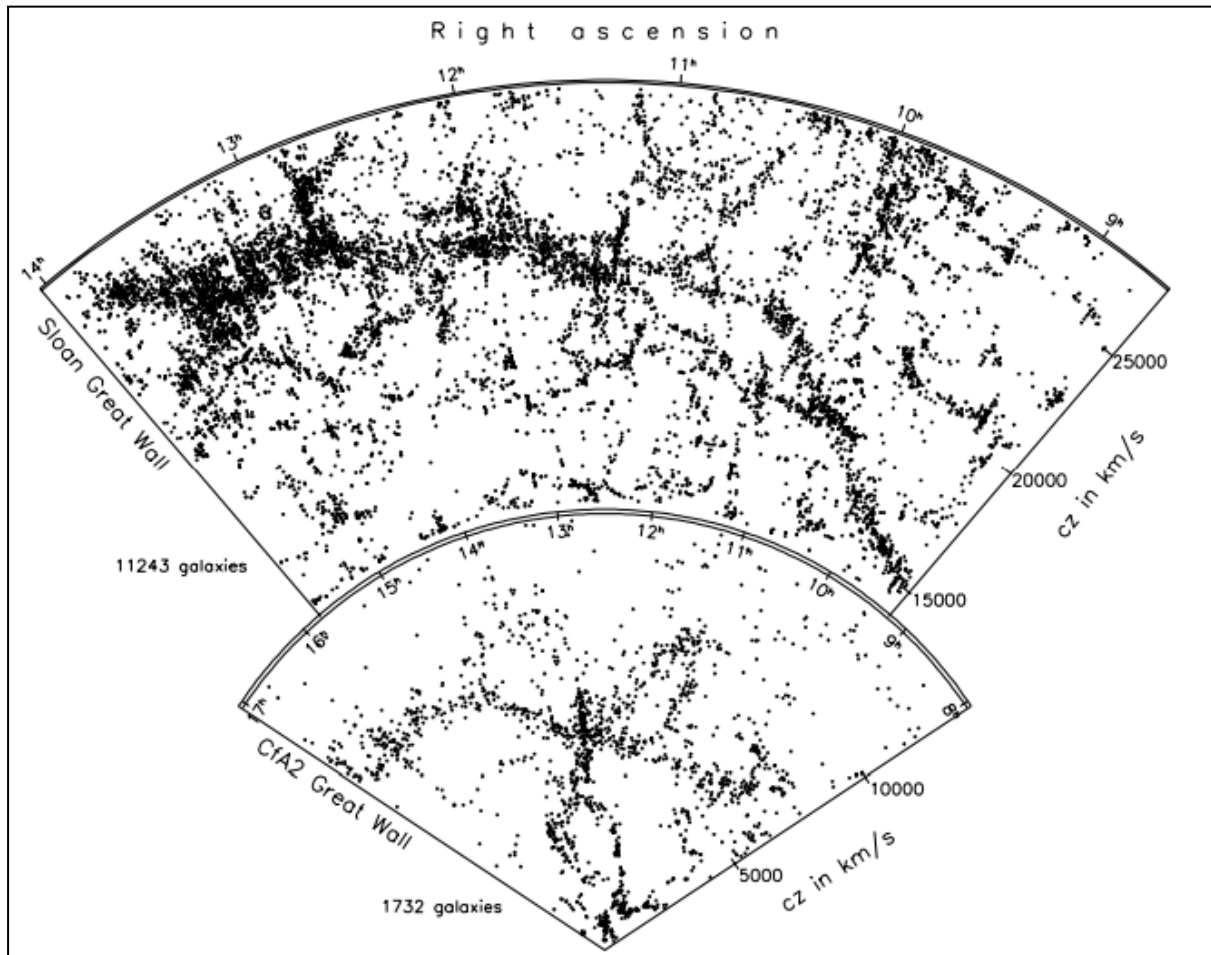
Farrow, J., Kelly, D., *Why Does The Universe Look Like This?*, History of the Universe, YouTube, 2022.  
[https://www.youtube.com/watch?v=iDqQ9qgTWmg&t=1188s&ab\\_channel=HistoryoftheUniverse](https://www.youtube.com/watch?v=iDqQ9qgTWmg&t=1188s&ab_channel=HistoryoftheUniverse)

<sup>90</sup> Gott displays in an informal way his career and works in his book edited in 2016:

Gott, J. R., *The Cosmic Web*, Princeton, Princeton University Press, 2016, 272 p.

<sup>91</sup> *Discovery of the cosmic voids*, p.110.

discussed during the 1977 seminar. Moreover, the proposed models were not always related to metaphors, as was the case for the alternative theory of cosmic turbulence proposed by the Russian theoretical physicist Leonid Ozernoi<sup>92</sup> during the same period. He applied principles of fluid mechanics to the Universe to explain the turbulent nature of structure formation, both on small and large scales.



**Figure 12:** Comparison between the distance scales of the CfA2 observations (bottom) and the SDSS (top). The CfA2 Great Wall and the Sloan Great Wall are annotated on the left side. Once again, each point represents a galaxy, and the axes are redshift and right ascension. Credit: Gott, J. R., et al., "A Map of the Universe," *Astrophysical Journal*, vol. 624, 2005.

To conclude, we can also mention the Dutchman Vincent Icke, who in 1973 also proposed a model resembling, in some respects, the Zel'dovich approximation (they were unaware of each other, as there was no communication between the two researchers) while working at the

<sup>92</sup> One can refer to this article from 1973 :  
 Jones, B. T., Cosmic Turbulence and the Origin of Galaxies, *Astrophysical Journal*, vol. 181, 1973. DOI :  
 10.1086/152048



Leiden Observatory<sup>93</sup>. It was surveys such as the 2dF Galaxy Redshift Survey or the SDSS<sup>94</sup>, launched in 2000, that finally helped resolve the differences between these various models through observations of large regions of the sky (25% of the sky in the case of the SDSS) cataloging an enormous number of astrophysical objects (over 100,000,000 for the SDSS) at sometimes very high redshifts. Figure 12, taken from a 2005 article by Gott, accounts for the differences in scales between the SDSS and CfA2 surveys, notably depicting an immense filamentary structure, larger than the CfA2 Great Wall, known as the Sloan Great Wall. Since light travels at a finite speed in the Universe, objects observed at high redshifts appear to us as they were long ago, billions of years in the case of the most distant ones. Thus, modern observations reveal the large-scale structure of the Universe not merely as a structure of local space, but rather as a structure of spacetime. Among all the images used to describe this structure, the sponge seems to be the least far from reality: it is composed of several sub-structures such as clusters, filamentary or flattened assemblies like walls, but forms a whole in the shape of connected regions of overdensities surrounded by or surrounding underdensities. These surveys also show that at scales greater than billions of light-years, the Universe finally becomes homogeneous, and the structure disappears into details that are small compared to the scales of observation.

In the meantime,  $\Lambda$ CDM has established itself as the standard model of cosmology. It was formally adopted during the 1990s<sup>95</sup>. This reminder provides an opportunity to introduce dark matter into our story and explain the role that cosmologists attribute to it in the structuring of visible matter<sup>96</sup>. Zwicky was the first to postulate the presence of unobserved matter to explain the velocities of galaxies in the Coma cluster in the 1930s. It was not until 1970 that the concept of dark matter, possibly composed of still unknown particles, became formalized and taken more seriously, particularly thanks to Rubin's observations on the rotation speed of stars around the galactic center of Andromeda<sup>97</sup>. In both cases, the observations indicate that the measured gravitational effects cannot be explained by visible matter alone, and that an invisible source of gravitational attraction must exist. Observations

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<sup>93</sup> Icke, V., Formation of Galaxies Inside Clusters, *Astronomy and Astrophysics*, vol. 27, 1973.

<sup>94</sup> A comparison between the observations from CfA2 and from SDSS is given in Figure 12, tirée de Gott, J. R., et al, A Map of the Universe, *Astrophysical Journal*, vol. 624, 2005.

<sup>95</sup> One of the main articles about the development of  $\Lambda$ CDM is from Peebles in 1988 :

Peebles, P. J. E., Ratra, B., Cosmology With A Time Variable Cosmological 'Constant', *Astrophysical Journal*, vol. 325, 1988.

<sup>96</sup> An accessible discussion about dark matter and visible matter is given in the book *Les idées noires de la physique* by Bontems and Lehoucq, illustrated by Pennor's.

<sup>97</sup> Rubin, V., Ford, W. K. Jr., Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions, *Astrophysical Journal*, vol. 159, 1970. DOI : 10.1086/150317

such as the power spectrum of the cosmic microwave background or gravitational lensing further reinforce the need for invisible matter to explain astrophysical phenomena. Today, observations indicate that dark matter would make up about 85% of the total matter, leaving only 15% of visible matter. In 1978, White and Rees worked at Cambridge on a new ingredient to introduce into galaxy formation models<sup>98</sup>. Their idea, now widely accepted, is that galaxies form within invisible halos composed of matter that interacts only through gravitational force, thus without collisions and without emitting light. Once a dark matter halo is in place, baryonic (classical) matter is attracted by the gravitational potential created and forms galaxies. This theory introduces the CDM (cold dark matter) component, which complements the cosmological constant or dark energy  $\Lambda$  of  $\Lambda$ CDM. A few years later, starting in 1982, discussions about the nature of the particles making up this dark matter began. These discussions are still ongoing and are accompanied by competing models to CDM, whether they are models of dark matter of a different nature or models of modified gravity. In particular, the early 1980s marks the period when numerical simulations of galaxy formation began to take this dark matter into account. Attempts to numerically reproduce cosmic voids and superclusters as well as the filamentary structure of the distribution of galaxies emerged in the East with American Adrian Melott and Russians Sergei Shandarin and Anatoli Klypin, as well as contributions from Einasto's group in Tartu<sup>99</sup>. These first attempts notably allowed for comparisons of dark matter models, and the large-scale structure of the Universe then took on the status of a verification tool, rather than merely being an observable. In the West, a team composed of White, American Marc Davis, and Mexico-British Carlos Frenk used another, finer, and more detailed computational method to reproduce the filamentary structure of large-scale galaxy clusters. In practice, once the simulation was performed, it was the correlation functions of the real and simulated galaxies that were compared to estimate the validity of the simulation. After completing his thesis at Oxford, British George Efstathiou was invited to join the trio to form a group of four researchers, nicknamed the "Gang of Four," whose goal was to understand and model the large-scale structure of the Universe with simulations<sup>100</sup>. This group published major results starting in 1985, initially on relatively small volumes, using a CDM model and a Euclidean

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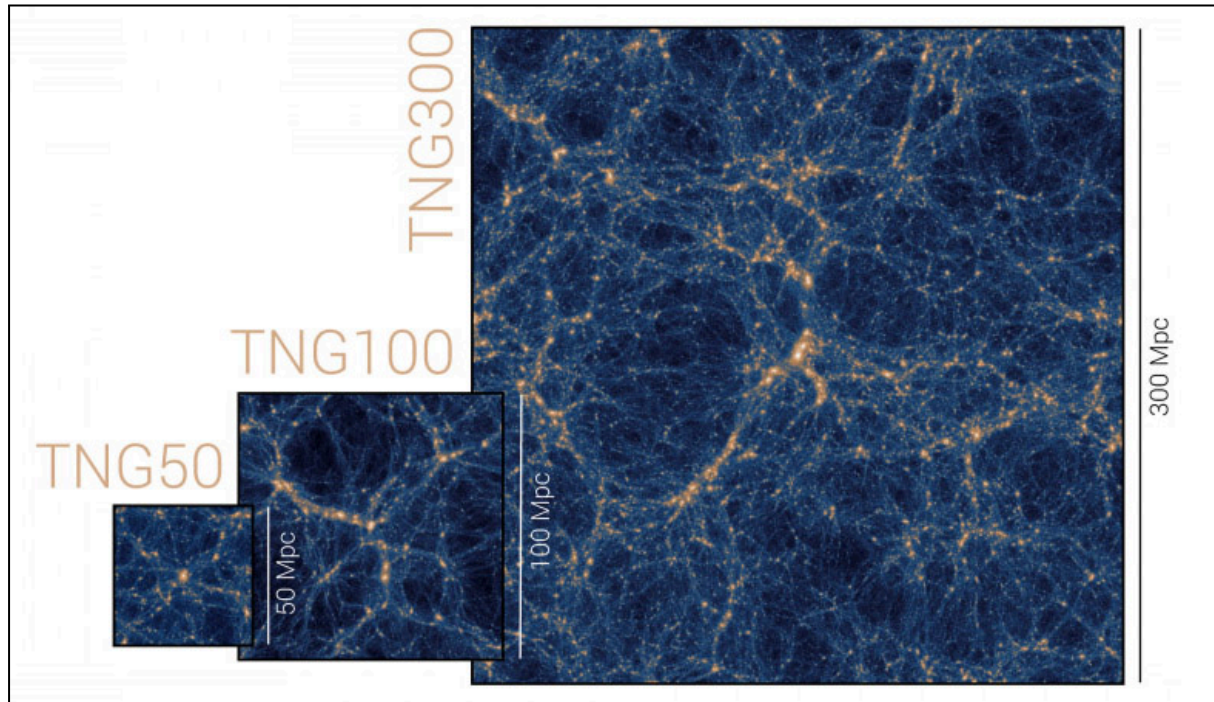
<sup>98</sup> White, S. D. M., Rees, M. J., Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering, *Monthly Notices of the Royal Astronomical Society*, vol. 183, 1978. DOI : 10.1093/mnras/183.3.341

<sup>99</sup> Melott, A. L., Einasto, J., Saar, E., Suisalu, I., Klypin, A. A., Shandarin, S. F., Cluster analysis of the nonlinear evolution of large-scale structure in an axion/gravitino/photino-dominated universe, *Physical Review Letters*, vol. 51, 1983.

<sup>100</sup> One of their main works has more than 5000 citations today:

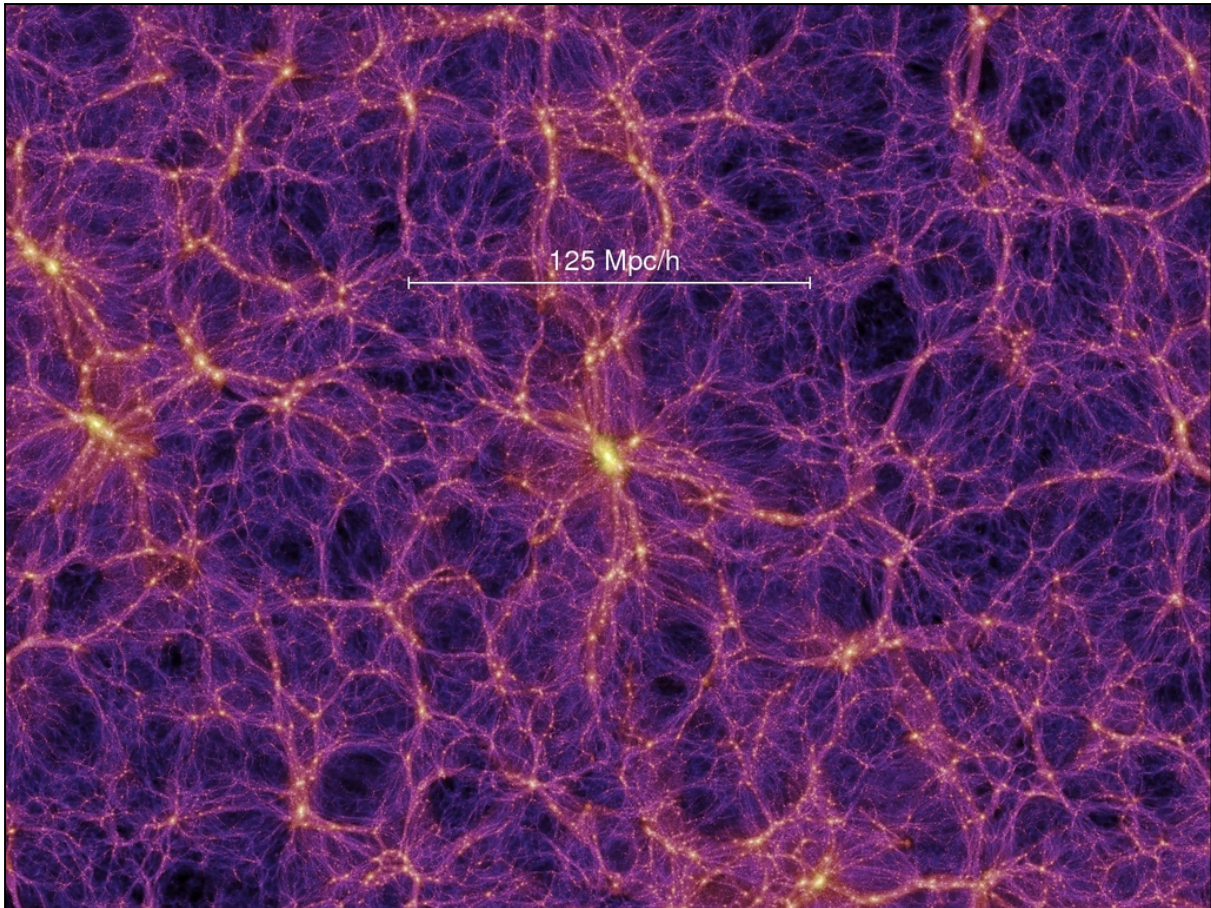
Davis, M., Efstathiou, G., Frenk, C. S., White, S. D. M., The evolution of large-scale structure in a universe dominated by cold dark matter, *Astrophysical Journal*, vol. 292, 1985. DOI : 10.1086/163168

spacetime geometry. They particularly showed that the introduction of a galactic bias (galaxies form more in the most massive halos) greatly improves the fit between simulations



**Figure 13:** Représentation en projection bidimensionnelle de la structure à grande échelle de l'Univers dans trois *runs* de la simulation IllustrisTNG. Les points les plus sombres correspondent à des sousdensités (vides) et les points clairs sont des surdensités (superamas, amas, filaments) dans lesquels se forment des galaxies. Crédit : IllustrisTNG.

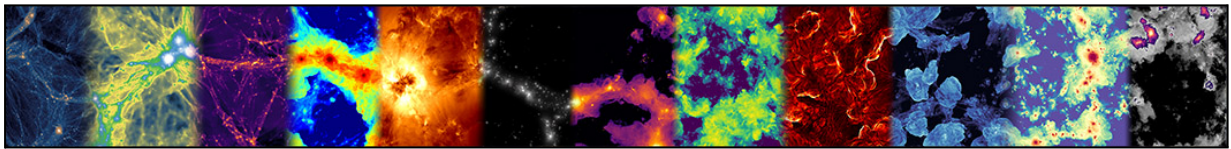
and observations. It was from this point that the last reservations about accepting the existence of superclusters, filaments, and walls of matter on a cosmic scale disappeared, ten years after the evidence of the first cosmic void and filament. Many large-scale simulations of the Universe can be considered descendants of these works from the 1980s. In particular, notable simulations include IllustrisTNG, the Millennium simulation, Uchuu, or Horizon-AGN. All these simulations, and others, emerged in the 21st century and are still in use today. Numerous images are associated with them. For example, projections of what IllustrisTNG provides (Figure 13) and Millennium (Figure 14) are presented here. These images are colored for visualization purposes and greatly depend on what one seeks to show. The visible structures vary depending on whether one is looking at the temperature of the matter, its density, gas, or dark matter, shock surfaces, or mathematically defined topological boundaries. With such simulations, each parameter can lead to a specific type of picture. The representations of the large-scale structure are many and vary, and depend of the age or the simulated Universe. This is illustrated in Figure 15.



**Figure 14:** Two-dimensional projection representation of the large-scale structure of the Universe in the Millennium simulation. The color code is similar to that of the IllustrisTNG simulation (Figure 13). This simulation required a month of computing time on the supercomputer of the Max Planck Institute in Garching bei München. Credit: The Millennium Simulation Project.

Once the major observational discoveries were made, one of the great questions facing cosmologists was why the large-scale structure of the Universe exists. This structure is composed of dark matter forming a shell and baryonic matter forming galaxies, akin to a visible skeleton within this shell. But why, if the Universe is homogeneous at the largest observed scales, is matter distributed so inhomogeneously? We will not delve into the specific elements of the answers that are the cosmic microwave background (which we have briefly discussed) and the theory of cosmic inflation, but we can outline the main points here. As previously discussed, starting in the 1960s and particularly after the first observation of the cosmic microwave background by Penzias and Wilson, measurements became increasingly refined until the temperature fluctuations were detailed with the Planck satellite. These temperature fluctuations are an imprint of the initial inhomogeneities in the spatial distribution of matter shortly after the Big Bang. The dominant theory, for which

cosmologists are currently seeking experimental evidence, is the theory of cosmic inflation, which implies that in an extremely short time, the Universe underwent a rapid expansion that would have smoothed these initial inhomogeneities to give rise to those we know today, allowing dark matter to form the envelope in which galaxies form. This theory has been accounted for in models of Universe evolution since 1985 and the works of the Gang of Four, and has so far been successful in reproducing, from the cosmic microwave background, the large-scale structure observed today. Furthermore, inflation is also an effective way to explain the flatness of the Universe: any initial global curvature is flattened during this extreme process. The first proposals for an inflationary Universe came from American Alan Guth (MIT, 1980)<sup>101</sup> and were independently reworked by Russian Andreï Linde<sup>102</sup> and Russian Alexei Starobinsky in 1982<sup>103</sup>, and then became widely known.



**Figure 15:** Bottom panel of Figure 1 from the article "The Laniakea supercluster of galaxies." The velocity lines are in black, what was previously called the local supercluster is in green, colored points are individual galaxies, and the blue surface represents the boundary of the velocity flows represented. Sub-structures are annotated at their location within Laniakea. Credit: Tully, Courtois, Hoffman & Pomarède (2014).

To conclude this chapter, in 2014, a team from the University of Lyon composed of R. Brent Tully, H el ene Courtois, Yehuda Hoffman, and Daniel Pomar ede was able to propose an advanced representation of the supercluster in which the Milky Way is located (observing the structure in which our own galaxy resides is a significant challenge: it is easier to observe the surrounding houses from home than to visualize the outside of one's own house if one does not know it or see it). This supercluster was named Laniakea ("immeasurable paradise" or "celestial horizon" in Hawaiian) and the discovery was published in *Nature*<sup>104</sup>. With maps of the velocities of the galaxies composing Laniakea, the authors of this article proposed a three-dimensional reconstruction of the shape of the supercluster accompanied by velocity flow lines. This image is reproduced in Figure 16.

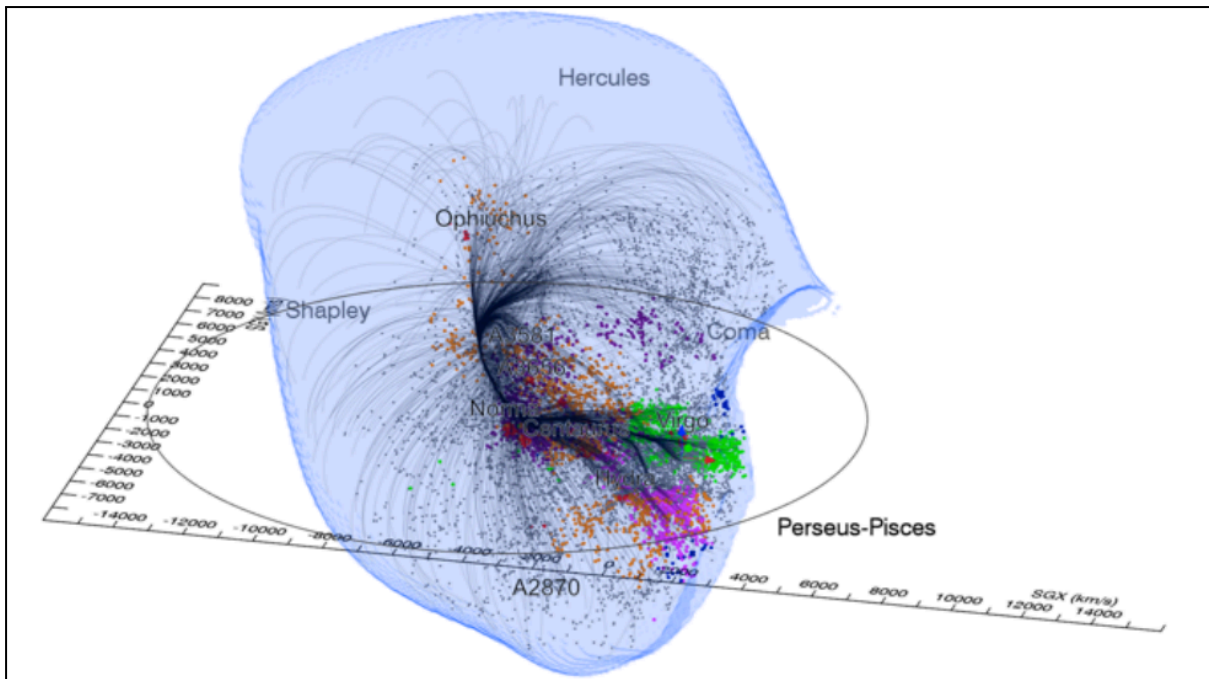
<sup>101</sup> One can read Guth's book for questions about the history of the theory of inflation:

Guth, A. H., *The inflationary universe : the quest for a new theory of cosmic origins*, New-York, Basic Books, 1997, 328 p. ISBN : 978-0-201-32840-0

<sup>102</sup> Linde, A. D., A new inflationary universe scenario: a possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems, *Physics Letters B*, vol. 108, 1982.

<sup>103</sup> Starobinsky, A. A., Dynamics of phase transition in the new inflationary universe scenario and generation of perturbations *Physics Letters B*, vol. 117, 1982.

<sup>104</sup> Tully, R. B., Courtois, H., Hoffman, Y., Pomar ede, D., The Laniakea supercluster of galaxies, *Nature*, vol. 513, 2014. DOI : 10.1038/nature13674



**Figure 15:** Bottom panel of Figure 1 from the article "The Laniakea Supercluster of Galaxies." The velocity streamlines are shown in black, the previously named Local Supercluster is highlighted in green, colored points represent individual galaxies, and the blue surface marks the boundary of the represented velocity flows. Substructures are annotated at their respective locations within *Laniakea*. Cr dit : Tully, Courtois, Hoffman & Pomar de (2014).

## Chapter 2: Interviews with researchers

In the survey conducted in *La vie de laboratoire*, Bruno Latour demonstrates that laboratory science, of which cosmology is a part despite its limited and indirect experimental nature, can be subjected to the analysis of human sciences such as sociology and history, as well as philosophy. By critiquing the preceding sociological tradition, Latour shows how science is not isolated and independent of its context. Anthropology, in particular, allows for an in-depth exploration of a given scientific field, making it an object of study. While the concept of a network developed by Latour proves to be too general and less relevant for the analysis we wish to conduct here regarding cosmologists' attitudes towards the large-scale structure of the Universe and its representations<sup>105</sup>, the interview-based inquiry is quite appropriate.

To conduct these interviews, initial contact via email was necessary. Each request received a response, and only one was negative due to a lack of time, despite an expressed interest from the individual involved. This illustrates the willingness of cosmologists to discuss their discipline in accessible terms and to take a historical and philosophical step back from the objects they study. Once the interview was arranged, each participant received a list of questions a few days in advance. The goal of providing this list was to allow for the formulation of initial ideas that would be further developed during the discussion while attempting not to influence each person's opinions before the interview. It is noteworthy that in several cases, during preliminary discussions, cosmologists questioned their legitimacy to respond to epistemological questions, while subsequently providing relevant and well-developed answers. Without wanting to make the interviews too formal, the use of "vous" (formal address) was systematically employed when the discussion was in French. Each interview was conducted according to the same rules, allowing as much space as possible for improvisations and incomplete thought processes from the cosmologists. Furthermore, since the discussion was between two individuals familiar with the language specific to astrophysics, the responses were formed naturally without particular efforts towards syntax and explanations of the subject, making them more complete and clear. Efforts to explain will be made during the analysis if the historical elements presented in

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<sup>105</sup>In fact, this is not an ethnological study of how cosmologists work or the tacit knowledge involved, as these elements are clearly understood here. Rather, the interviews are part of an investigative effort to gather various explicit viewpoints on the large-scale structure of the Universe and to give a voice to individuals who are both interested in and directly engaged with the subject.

Chapter 1 are not sufficient. Here, we first present the questions asked and (briefly) the individuals participating in the interviews, followed by a preliminary analysis of the responses collected.

## 2.1 Questions and interviews

The aim of the questionnaires used was to address concepts related to the large-scale structure of the Universe while also discussing general cosmological questions, such as those concerning research policies, the models used and their underlying reasons, as well as the past and future of cosmology. This general discussion not only enhances the philosophies of cosmologists regarding the large-scale structure of the Universe with broader contextual elements but also highlights the range of interests of these individuals concerning their own research. This approach allows interviewees to express their philosophies more fully.

Each interview was planned to last approximately thirty minutes to an hour, which was the case almost every time. Here are all the questions sent a few days before each interview, adapted for each case depending on the direction the discussion took<sup>106</sup>:

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- 1) For how long have you been working and why do you work in astrophysics/cosmology?
  - 2) Why are you interested in this field?
  - 3) Do you think different cosmological models (of dark matter, gravitation, space-time) should be treated equally (funding, outreach, judgment of the community)?
    - If so, why is it not the case?
    - If not, what makes a model a dominant one?
  - 4) Do you think LCDM, the halo model, and current cosmology are objective?
  - 5) Would you say large-scale « structure » or « structures »? Is there a difference with the cosmic web?
  - 6) What does the general public know about the large-scale structure of the Universe? What does it imply for the common imagery?
  - 7) How do you picture the future of cosmology? How does it compare to the past?
  - 8) Do you think the cosmological tensions are announcing a paradigm shift?

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<sup>106</sup> If the questions are written in english here, they were in French for half of the interviews. The translation between both languages is as literal as possible, there is therefore little point in rewriting the questions in French here. The French version is then provided in the appendix.



- 9) What epistemological questions are you interested in regarding cosmology and the large-scale structure of the Universe? What would be your answers?
- 

The last question, in particular, allows interviewees to elaborate on one or more subjects that particularly interest them, which may have emerged during the discussion or from reading the questionnaire beforehand. As we will see, each response was different, and a range of interesting questions was raised. While the questionnaire was adapted each time, particularly concerning the order of questions to facilitate the discussion, each interview provided answers to each of the questions presented. The ten interviews took place between February 8 and March 21, 2024, half in French and the other half in English, with half conducted online and the other half in person, either at an institute or observatory, or at a researcher's home. Along with the questionnaire, participants were instructed to speak as much as they wanted on the questions that inspired them the most. Here is a brief<sup>107</sup> presentation of each participant, in chronological order of the interviews<sup>108</sup>:

08/02/2024 - Benjamin L'Huillier: French assistant professor at Sejong University in South Korea, he uses the most advanced cosmological data to test the validity of  $\Lambda$ CDM and its underlying hypotheses. He studies several large-scale cosmological probes, such as Type Ia supernovae, baryon acoustic oscillations, and redshift space distortions. He is particularly interested in dark energy and dark matter, and the possibility of a paradigm shift in cosmology if  $\Lambda$ CDM is falsified, or if current tensions persist and are not observational or measurement errors. The interview was conducted online, with cameras, after a brief in-person meeting during one of his visits for a conference at the Strasbourg Astronomical Observatory. B. L'Huillier was in Seoul during our call.

14/02/2024 - Roland Lehoucq: French researcher at the Commissariat for Atomic Energy (CEA), teacher, author of books and works in media and science fiction that have earned him several distinctions. He focuses his research on cosmic topology, i.e., the shape, curvature, and geometry of the Universe and spacetime on large scales. The interview was conducted online, with cameras.

20/02/2024 - Jim Peebles: Canadian national and currently Emeritus Professor at Princeton University, he received the Shaw Prize in Astronomy in 2004 and the Nobel Prize

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<sup>107</sup> We try to provide the essential elements justifying the interest of an interview with each participant. These descriptions, of course, cannot be exhaustive and will omit certain elements such as academic background or any potential distinctions and awards.

<sup>108</sup> Note that the presentations correspond to the situation of each researcher at the time of the interview. Some careers are still young and will continue to evolve beyond what is presented here, albeit briefly.

in Physics in 2019 for his major contributions to dark energy, dark matter, the Big Bang, primordial nucleosynthesis, the large-scale structure of the Universe, and the prediction of the cosmic microwave background. J. Peebles was at his home in Princeton during the interview, which was conducted online with cameras.

27/02/2024 - Simon White: One of the four directors of the Max Planck Institute for Astrophysics in Garching bei München and a British national. He has notably worked on galaxy formation, large-scale structure formation, and  $\Lambda$ CDM, and collaborated with Martin Rees on the influence of dark matter halos, for which he proposed a universal structure with Julio Navarro and Carlos Frenk regarding the properties of galaxies. He is involved in numerous numerical simulation projects, including the Millennium Simulation, which follows the formation of over two million galaxies. We met at the Max Planck Institute in Garching bei München in 2022, and the interview was conducted online with cameras.

01/03/2024 - Katarina Kraljic: Researcher at the Strasbourg Astronomical Observatory, she specifically studies the distribution of galaxies in the large-scale structure of the Universe from astronomical observations, as well as the role of their position on their properties, particularly their morphology and activity. We met at the Strasbourg Astronomical Observatory in 2023, and the interview took place in her office at the observatory.

05/03/2024 - Françoise Combes: French astrophysicist and holder of the "*Galaxies and Cosmology*" chair at the Collège de France, with a course on the large-scale structure of the Universe in 2018-2019. She received the CNRS gold medal in 2020 for her work on galactic physics in a cosmological context. She studies different models of dark matter and alternative gravity theories. She is also the author of numerous works on science communication and popularization in physics, astronomy, and astrophysics. The interview we conducted was online and recorded, with F. Combes in Paris.

11/03/2024 - David Alonso: Of Spanish and British nationality, he is a professor at the University of Oxford. He is interested in the history of the Universe and its large-scale structure. He is a member of the Legacy Survey of Space and Time, which aims to study dark energy, and of the Simons Observatory, which seeks to determine the impact of potential primordial gravitational waves on the cosmic microwave background. We have known each other personally since 2022, and we talked in his office at Oxford.

12/03/2024 - Rebecca Smethurst: Known as Dr. Becky on YouTube and in her science communication career, this observational astrophysicist works as a junior researcher at the University of Oxford on the role of supermassive black holes in the star activity of galaxies. Her scientific career and her work in science communication have earned her several awards.

We had met in 2022, and the interview took place online between the Institute of Cosmology at the University of Oxford and her home.

15/03/2024 - John Peacock: British professor at the Institute for Astronomy at the University of Edinburgh, where he has served as director. He has received the Shaw Prize in Astrophysics in 2014 and the Royal Astronomical Society Gold Medal in 2023. He is interested in the large-scale structure of the Universe and the structure of galaxies. He was responsible for the 2dF Galaxy Redshift Survey, which contributed to the discovery of the large-scale structure of the Universe. We interviewed at his home in Edinburgh.

21/03/2024 - Aniruddh Herle: An Indian national PhD student at the Leiden Observatory in the Netherlands. He initially focused on strong gravitational lensing and the nature of dark matter at the Max Planck Institute for Astrophysics in Garching bei München, then currently studies weak gravitational lensing and the intrinsic alignment of galaxies within the cosmic web. We have known each other personally since 2022, and we conducted the interview online while he was in Leiden, being filmed.

As these presentations indicate, the ten interviews represent diverse backgrounds and universities. Moreover, various research fields are represented, and when the connection to the specific subject of the large-scale structure of the Universe is weaker, the individual concerned provides a youthful perspective in the case of Aniruddh Herle, or serves as a mediator in the cases of Roland Lehoucq or Rebecca Smethurst, for example. These interviews are therefore representative of different generations, schools of thought, and daily working methods. These elements are part of the selection criteria for the interviews, but it should also be noted that some individuals were easy to contact directly or through an intermediary, which was convenient for both meeting the most relevant individuals possible and for doing so early in the process of constructing this thesis. When no direct or nearly direct contact was possible, researchers always responded quickly to emails with a very kind attitude and showed interest in the subject. Furthermore, once the ten interviews were completed, it would have been too time-consuming and unproductive to conduct more, even though other individuals were recommended. In the case of these individuals, the main selection criterion was their legitimacy to speak on the large-scale structure of the Universe, the history of cosmology, or the public and scientific imagination regarding the Universe. In practice, the list of participants evolved as the interviews were conducted. The first interviewees were those who were available the quickest after responding positively to the contact email, regardless of their geographical location (online calls greatly simplified the entire process). There is necessarily a large element of randomness in the order of the

interviews, and those conducted in Oxford or Edinburgh had to be done within a single week during a trip to these cities. However, chance plays only a small role in the choice of these individuals: the majority were designated by members of the astrophysics community in Strasbourg or Oxford as legitimate and interesting, and while there is a strong element of subjectivity in human relationships, even within the scientific community, the previous presentations support this attempt at objectivity.

Ultimately, it seems that this panel of interviews is necessarily subjective, but an effort has been made to represent the scientific community and to conduct the interviews in equivalent situations, despite the differences between interactions in an office, in a residence, and online. During the interviews, three recording interruptions occurred. These interruptions, caused by external interventions or recording software problems, never completely disrupted the discussion or its continuity. From each interview, there remains at least one audio recording that is not available and a transcription of this recording in writing, in the original language and reviewed before analysis by the individual concerned. Some anonymizations or redactions of terms, phrases, or sections occurred, but nothing that could affect the substance of the discourse. To avoid any loss or addition of information, the quotes translated from French to English here are given in French in the original and official thesis manuscript. However, the analysis will be conducted in English in this version.

## **2.2 Analysis**

In a Latourian logic, the analysis of these interviews follows the principle of symmetry: nature and society are not separate objects, and science cannot be dissociated from the sociopolitical context in which it occurs. No actor in the network associated with the large-scale structure of the Universe occupies a privileged position, and all collected statements must be treated coherently: they are all equally important. We will strive to show what researchers do with their research object as much as the influence that object has on scientific research and how it appears to us.

First, the interviews allow for a study of the images and metaphors that accompany the large-scale structure of the Universe. When images or ideas related to graphical representations are mentioned in discussions, it is essential to understand where they come from and who produced them when they were put down on paper for analysis. We will then need to focus on the question of images in cosmology in more detail, particularly how a simulation or astronomical observations allow for the creation of images, the part of

interpretation that comes into play, and also the selection criteria that make some images prevail. These two elements are discussed by Catherine Allamel-Raffin in two particularly relevant articles titled “The Complexity of Scientific Images: What the Semiotics of Images Teaches Us About Scientific Objectivity”<sup>109</sup> and “What Images Do Physicists Insert in Their Publications? Selection Criteria Adopted in Materials Physics and Astrophysics,”<sup>110</sup> and we can refer to these works to conduct our analysis.

Next, we can analyze what other representations are mentioned, including more abstract and sometimes more mathematical representations of the large-scale structure of the Universe. What objects, words, and concepts are invoked to talk about, describe, explain, and interpret it? In particular, the interviews reveal a diversity in interpretations and possible vocabulary choices for discussing the Universe. This can be studied through the notion of “versions” developed in the book *Starmaking*, allowing us to address the question of realism in cosmology. In this book, Goodman and Elgin argue that we never access the world directly but always through constructed versions of it. A version is thus a representation, an interpretation, or a description of reality. Each version is a specific way of organizing and understanding the world, influenced by our languages, cultures, theories, and practices, but not all versions are equal; there are scientific criteria for coherence and testability, as well as artistic criteria for originality and expressiveness. We will subject the interviews to a reasoned critique through this approach.

These interviews also allow for an examination of the question of structural holism based on the differences between structure (in the singular) and structures (in the plural). This notion also exists in other fields of physical sciences beyond cosmology, primarily in quantum physics and field theory, and we will be able to draw links and distinctions between these areas. We will explore the connections made in the interviews between different types of structures and investigate the question of the place of cosmic voids within the large-scale structure of the Universe. This part of the next chapter relates to the philosophical theory of structuralism, which has two main forms: epistemological structuralism, where structures are primarily tools for organizing knowledge and representations of the world, and ontic structuralism, where structures and relationships between and within structures are the

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<sup>109</sup> Allamel-Raffin, C., La complexité des images scientifiques. Ce que la sémiotique de l'image nous apprend sur l'objectivité scientifique, *Communication & Langages*, vol. 149, 2006, pp. 97-111. DOI : <https://doi.org/10.3406/colan.2006.4620>

<sup>110</sup> Allamel-Raffin, C., Quelles images les physiciens insèrent-ils dans leurs publications ? Les critères de sélection adoptés en physique des matériaux et en astrophysique, *Visible*, vol. 10, 2013. DOI : <https://doi.org/10.25965/visible.507>

fundamental substance of reality. We will examine what these two approaches contribute to the interpretation of the interviews.

Finally, we can analyze the doors this notion opens in cosmology. The large-scale structure of the Universe is, among other things, an example of modern cosmography, *i.e.*, a way to graphically represent the world. This can be compared with the cosmographies preceding the major discoveries and astronomical observations of the past half-century and opens the discussion on the future of cosmology. We will also see what connections the interviewees make between this object of cosmology and other scientific fields, as well as the epistemological questions that these researchers pose based on reflections about their field of research. These exchanges raise questions about the nature of reality and how the observed structures influence our understanding of physics, particularly what a model is and what constitutes a “good” model. These elements lie on the edge of the subject of this thesis, but we can nevertheless outline the main points.

It should be noted that from all the interviews, it was necessary to select quotes to illustrate certain thoughts and develop the points of interest in Chapter 3. Of course, an interview lasting several dozen minutes cannot be summarized or accurately represented by a limited number of quotes. Furthermore, some ideas are shared by several interviewees, but it would be unreasonable to present all quotes supporting a particular idea. In this context, it is important to remember that the statements developed later use the words of the participating cosmologists as faithfully and reasonably as possible but do not engage their responsibility. This thesis engages only the responsibility of its author.

# Chapitre 3 : Elements of philosophy on the Universe

In his essay “The Physicists' Philosophy of Physics,” Peebles revisits the hypotheses that scientists consciously or unconsciously utilize in their research activities. He recalls, concluding the chapter corresponding to the introduction of these hypotheses, that as the American physicist and author Steven Weinberg stated in the chapter "Against Philosophy" in his book *Dreams of a Final Theory*,

*“Physicists do of course carry around with them a working philosophy. For most of us, it is a rough-and-ready realism [but] we should not expect [philosophy] to provide today’s scientists with any useful guidance about how to go about their work or what they are likely to find.”*<sup>111</sup>

According to Weinberg, scientific activity occurs within a philosophical context but does not require or seek the opinion of philosophy about the world. While communications between scientists and philosophers were significant until the early 20th century, it is true that this tradition has largely faded today, and the prevailing stereotype is that science makes little use of philosophy. In this Chapter 3, we aim to demonstrate that, at least in the context of research on the large-scale structure of the Universe, this is not entirely true, and may even be mostly false. The interviews presented in Chapter 2 will be analyzed here according to the organization announced in 2.2, and will serve to illustrate how science and epistemology communicate and mutually serve one another, whether unconsciously or consciously, in the minds, discourses, and activities of cosmologists. In this sense, this work shares Peebles' ambition and, it is to be hoped, can showcase a more exciting use of epistemological concepts in the natural sciences.

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<sup>111</sup> Weinberg, S., *Dreams of a Final Theory: The Scientist's Search for the Ultimate Laws of Nature*, New York, Knopf Doubleday Publishing Group, 1992, 352 p.

### 3.1 Representations of the large-scale structure of the Universe

This section and the next implicitly use the discussions surrounding the notion of "version" compiled in *Starmaking*. We do not discuss all the alternatives to Goodman's philosophical proposals but focus instead on his work and the nuances brought by other authors present in the book. Goodman introduces the notion of "version." Each personal experience of the world leads to the creation of representations, which are human-specific objects, and these versions create worlds. In this sense, Goodman defends the thesis that physical objects are human creations, and this is also true for the large-scale structure of the Universe, and more generally for the world as a whole: "*we make versions, and right versions make worlds.*" When we mention representations here, they should be understood as versions according to Goodman, with additions from Elgin and Rorty. We set aside the moderate realism defended by Putnam, Lewis, and Scheffler because, as we will show later, it corresponds very little to what is expressed in the interviews. According to Elgin, versions are not only human constructions but also cognitive tools. She emphasizes that these versions help us better understand and interact with the world, showing that different versions can be evaluated not in terms of objective truth but in terms of their utility, internal coherence, and explanatory power. Rorty provides a very pragmatic view of the notion of version. Indeed, according to him, the value of a version is not its objectivity as Goodman proposes, but its practicality. These cognitive and practical aspects of representations are essential for understanding how scientists think.

First, let us focus on the public imagination when talking about the Universe. On this point, the cosmologists interviewed are unanimous: very few of the discoveries and astronomical observations are understood outside the academic sphere. Several remarked that the general public is poorly defined, and we find in practice three main categories: people who have no scientific training and are not interested in it, people who have a school education in natural sciences, and people who, regardless of their training, are interested in these subjects through lectures, popular science, videos, and other media. In particular, the research fields of dark matter and dark energy, which are essential for the large-scale structure of the Universe, are poorly understood even though they generate significant interest, primarily because they appear mysterious and cosmologists themselves readily



acknowledge that they do not exactly know what lies beneath these terms, which are also criticized as poorly chosen:

*“It is an unfortunate naming. It sounds a bit scary if you don't know what it is. But there is some rationale behind those words, as it falls in this realm of the unknown.” - A. Herle*

*“People usually get really, really confused with dark energy, dark matter, and the Big Bang, for example. It's very easy to conflate the expansion of the universe with the existence of dark energy. [...] The nomenclature itself trips people up quite a lot. [...] Very often people think of [dark matter and dark energy] as being the same thing.” - D. Alonso*

Moreover, the scales to which different astrophysical objects refer are also poorly understood:

*“The one thing that I come across a lot is that the general public do not understand the distinction between the scales of the Universe. So, for example, galaxy versus universe often gets used interchangeably by the public and people are not aware of the scales beyond that.” - R. Smethurst.*

*“In astrophysics, there are scales that are both gigantic and microscopic. So, by definition, and because science in general has been built against appearances, we are already a bit in another world. We think against the appearances of the world and against what we are used to seeing in the everyday world. It's difficult for the general public and for actors in astrophysics and science in general to think against themselves and against the appearances of the world.” - R. Lehoucq*

Consequently, the common imagination is not as rich as the history presented in Chapter 1 might suggest. We will return to this point in the conclusion, but it is worth noting that the interviewees, particularly R. Lehoucq, B. L'Huillier, and A. Herle, insist that to create a coherent and as scientifically correct as possible imagination in the general public, efforts must be made by cosmologists to explain that, indeed, there are still unresolved questions, but that we know much more today than we did a century ago about the Universe and, among other things, about its largest structures and their evolution.

Let us now turn our attention to the images invoked by cosmologists in their discussions. This focus on images is motivated by the same reasons expressed by Allamel-Raffin: *“Scientific work is often reduced either to simple observation, or to pure formalization, or conversely, to the status of language or discourse that is more or less comparable to others. All these options underestimate the particular contribution of images in science: they are neither raw data from experience nor mere fictions; they allow for a*

*particular type of mediation with the real.*"<sup>112</sup> In cosmology, the most obvious of these images is surely the most famous one, namely the cosmic web. It is not so much an image as it is a term used to simply designate what we perceive in the images of the large-scale structure of the Universe. Regarding this subject, two main trends emerge from the interviews. The first, quite direct, is that the cosmic web is not more, or not much more, than a practical term for describing the form of the distribution of galaxies at large scales:

*"I think cosmic web is a colloquial term for the large scale structure."* - R. Smethurst

*"The cosmic web is the entirety of the filaments. That's why we talk about a spider web; it gives the impression of filaments crossing each other. It resembles neurons; it resembles many things, and indeed, they are filaments, [...] it is the large structure."* -

F. Combes

*"The structure or the structuring of the Universe is a general question we can ask, and as we currently understand it, this structure or this structuring takes the form of a cosmic web."* - B. L'Huillier

The second trend found, although more nuanced, does not contradict the previous statements. It states that the cosmic web is not only a practical or useful image but that naming what we observe in this way carries a deeper meaning. For Peebles, this description can bias the way the mind processes the information obtained through observations, and White emphasizes that the visual interpretation of an image of the large-scale structure depends, in fact, on what is emphasized in the graphical representation. Ultimately, Peacock adds to this discussion the origin of this way of thinking about graphical representations, indicating that it is actually more rooted in theory than in observations: numerical simulations reveal, through the Zel'dovich approximation, filamentary structures that converge into nodes, which, according to the usual ways of presenting the results of these simulations, leads to an image similar to a spider web (or a fishing net for Peebles) that divides space into different substructures and dominates the gravitational field that actually gave rise to it. In this modern cosmology, simulations are thus a more significant source than observations for representing the Universe at large scales.

*"It is true that the name provides a connotation which can bias your thinking. The cosmic web is very evocative of a web, and especially as in a fisherman's web. It is a good description of the observations of how the galaxies are distributed: there are these fine filamentary-like structures."* - J. Peebles

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<sup>112</sup> Allamel-Raffin, C., La complexité des images scientifiques, p. 97.

*“So you then see pictures [...] of the galaxy distribution [...] that look kind of vaguely like a neural network. And this is what people think of when they think about the cosmic web. [...] But it is very much dependent on the visual representation that you have. You can make visual representations which emphasize the densest structures and where the low-density connections between them are less evident, and then it looks much less web-like.” - S. White*

*“The cosmic web is often used as a term for a subdivision of space into interiors of different topological characters. So typically one would talk about voids, sheets, filaments, and nodes, and those represent places where the gravitational potential field has different properties. And those distinctions are useful, first of all because they match what you see visually. Obviously, you can create mathematical tools out of thin air, but the useful tools are the ones that you feel are capturing something of the impression that you gain when you inspect the data yourself. [...] The cosmic web is an interesting thing actually. Did it come from observations in the real Universe or did it come in theory? I think the honest answer is it came more from the theory, from making simulations of non-linear gravitational collapse.” - J. Peacock*

Furthermore, Alonso distinguishes between the images of the cosmic web and the images of filaments and voids. According to him, the cosmic web is a morphological skeleton, thus a visual representation that highlights the shape of observable structures but does not show what creates them. What creates these structures, and is not represented by the cosmic web, would be rather a map of the inhomogeneities in the distribution of matter, such as the maps of the cosmic microwave background in Figure 5:

*“So I think for me large-scale structure is anything that studies large-scale inhomogeneities. The cosmic web is kind of a morphological skeleton for this structure, that's a more narrow statement than what tells you something about the non-Gaussianity in the distribution of matter, which is what actually gives rise to filaments and huge voids.” - D. Alonso*

Regarding the cosmic microwave background map made by Planck, Lehoucq recalls that this type of observation of the complete sky is modified to address the lack of information in the direction of the Milky Way, which then obscures the backgrounds.

*“On the complete Planck map, they completely cut the Milky Way, and then they do inpainting to complete the bits they removed because it's impossible to see the cosmic microwave background through the plane of the Milky Way. [If the image] was shown*

*real, there would be a huge hole in the plane of the Milky Way, and we only observe what is around.” - R. Lehoucq*

Other geometric aspects of the Universe are mentioned and are more subtle to transcribe on graphics. Lehoucq references cosmic topology, which, although it is a different domain from the study of the large-scale structure of the Universe, proposes figures that allow for two-dimensional representations of examples of shapes that a finite universe without edges could take. L’Huillier, who works on comparisons of different cosmological models, speaks among other things about the curvature of the Universe, which, although it appears null today, could be slightly non-null and thus imply a non-flat Universe. Peebles discusses the theory of cosmic strings, which could explain the structuring of matter at large scales based on lines of energy and mass. These ideas are typically represented respectively by probability distributions over the basic cosmological parameters or diagrams describing the interactions between particles or between strings. While these images are not directly representations of the structure of the Universe, they still convey some information about it. In practice, these images are part of studies that seek, among other things, to understand this structure.

*“Literally, we assume a flat universe, but in fact, it's very easy to also include curvature. [...] We often see it as contours: the stronger the observational constraints on curvature, the smaller these contours will be.” - B. L’Huillier*

*“There was a notion back in the last century, in the 1990s, perhaps even earlier, of cosmic strings, lines of energy that in some versions of fundamental theory of particle physics are predicted. Cosmic strings are lines of mass produced by a field. It's an elegant theory. For a time, people were arguing this might be the way the Universe is built. As it's going, by the way we saw it, it didn't work. But the idea of a cosmic string is still very relevant, and what effect it would have is in running across the Universe; it would produce concentrations of matter and maybe even close to flat sheets.” - J. Peebles*

If images are part of the tools of scientific research, they also complicate it: *“The very fact that they are mixed further alters the nature of the difficulties faced by scientists when producing these images. Indeed, when a problem arises, the scientist does not know a priori whether it is related to the symbolic aspect of the image (that is, to the software programs) or to the indexical aspect of the image (to the functioning of the telescope, the CCD camera, atmospheric disturbances), or even to the choices the scientist has made during the image*

*production process. Here again, the human factor has not been eliminated, far from it!*"<sup>113</sup> as indicated by Allamel-Raffin. Introducing images into science implies incorporating images into scientific choices and adds a layer of determination to these choices.

The different statements presented previously show a certain attachment to the fundamental aspects of cosmology among the interviewees. Generally, discussions regarding the cosmic web or how to view and represent large-scale structure lead to reflections on what creates this structure and on the Universe that contains it. White adds to this:

*"It is clear that the structure is not like a soap foam, for example, where there are very clear bubbles made of air, separated by walls made of soapy water. That is not a good description of the structure in the universe. And so whether things look separated or not is very, very dependent on how you define them."* - S. White

Thus, if images are usable to discuss the Universe and its structure, others also serve as examples of what this structure does not resemble, and of a distribution of matter that does not correspond to what is observed. This method of proceeding by elimination is relevant in the physical sciences and has notably been used to differentiate the main ideas of galaxy formation at the end of the 20th century. The physical sciences tend to function more by eliminating false ideas than by affirming true ones, as the notion of truth is extremely subtle, and nothing ensures that models can exactly correspond to nature. More easily found are metaphors and statements centered on images that can be used to speak about structure outside the usual terms of cosmology. Allowing oneself to use vocabulary from other scientific fields permits speaking in analogies, and thus leads to more liberated and illustrative statements. For instance, Herle uses the notion of architectural structure to detail his thoughts. Similarly, paleontology, particularly the reconstruction of a complete system from a skeleton, is utilized twice by Lehoucq and Peebles.

*"The building has a structure. If the building is being built and they have just put iron pillars, they put the structure up. The structure upon which to build the building. So if you zoom way out, then it's the large-scale structure. But there are structures within this thing. So if you ask what a halo is, it is a structure, and there are lots of halos within the large-scale structure."* - A. Herle

*"In paleontology, they have a piece of bone, and with that, they reconstruct an entire dinosaur because they have models, representations of living beings, comparisons of*

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<sup>113</sup> Allamel-Raffin, C., *La complexité des images scientifiques*, p. 110.

*bones from all sorts of beings. They reconstruct the complete being, including its skin and its gait.” - R. Lehoucq*

*“This is an epoch of time when people are gathering data in great abundance and learning from it what happened. People look at fossils and deduce the presence of unlikely objects like these massive dinosaurs. Astronomers now are examining, in as much detail as they can master, the way galaxies are distributed and the way the galaxies are.” - J. Peebles*

The analogy between galaxies and dinosaurs is interesting. Indeed, as we have seen, the depth at which galaxies are located is known through redshift. Since light travels through spacetime at a finite speed, the farther an object is, the older the light that reaches us has been emitted, and therefore the image obtained is of the galaxy as it was long ago. In practice, astronomical surveys thus observe remnants from bygone cosmic eras, and sky maps are constructed from already aged light. Lehoucq even speaks of reconstructing the gait and skin of dinosaurs from fossils. For the Universe, we reconstruct its evolution and its content from an observed distribution today of light emitted by concentrations of mass. These analogies also show that the notion of large-scale structure of the Universe contains more than just images. These images, as we have shown, are of different types. Allamel-Raffin provides a classification in astrophysics: there are source images made up of raw data, processed images, simulation and modeling images (synthetic) aimed at studying the processed product<sup>114</sup>. In practice, and as seen here, processed and simulation images create a basis for the scientists' imagination and for discourses that seek to be objective and measured. Synthetic images are more illustrative, and it is these that give rise to metaphorical and freer discourses, better suited for individual interpretation. Although they are created in an institute or a laboratory and produced from a combination of instruments and treatments, images are not confined there. They evolve and become broader thoughts that in turn influence what scientists perceive when they observe a graphical representation. The nature of these images is not unique, and this is also what Allamel-Raffin emphasizes regarding the CfA images: a precise and exhaustive classification is unfeasible, and each type of image is of a mixed nature<sup>115</sup>. Moreover, some elements are fixed, such as the image on paper or on the screen, but the interpretation is always subject to change.

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<sup>114</sup> Allamel-Raffin, C., *La complexité des images scientifiques*, p. 101.

<sup>115</sup> Allamel-Raffin, C., *La complexité des images scientifiques*, p. 102-104.

## 3.2 What the notion of large-scale structure of the Universe encompasses

In the article “What Images Do Physicists Insert into Their Publications? The Selection Criteria Adopted in Materials Physics and Astrophysics,” Allamel-Raffin highlights four major criteria influencing the selection of images to include in scientific publications: the informative and innovative characteristics, the clarity and conciseness of the image, and its relevance as a support for scientific discourse. Indeed, we have seen that these elements appear both in the history of representations of the large-scale structure of the Universe and in what the interviewed individuals say about these images. Additionally, images do not exist in isolation and are intrinsically linked to equations and scientific concepts. Representations of the large-scale structure of the Universe are graphic, mental, but also mathematical, conceptual, and philosophical. First, the mathematical equations of physics, particularly in cosmology, are seen both as a means of describing and predicting the distribution of galaxies. Peacock emphasizes their importance since the quantities expressed in equations specify the object being studied, and objects defined from the fundamental quantity of density, represented by the density field, are less physically significant:

*“If you talk about structures it's like botany. The way I look at it as a physicist is you say: what's the quantitative thing that you're dealing with? And that is the position-dependent density field, a density which is a function of space and time. End of the story. You can analyze that in very quantitative ways by definitions of what you mean by a void, filaments, superclusters, and so on. But these are human-made definitions.”* - J. Peacock

However, he does not consider such equations to be part of the notion of large-scale structure. Here, there is a contradiction between his statements and those of Kraljic, for example, who believes that this notion encompasses a whole set of mathematical and geometric concepts.

*“- So would the large-scale structure of the Universe also include some materials, or some terms and mathematical equations?”*

*- No, it's broadly the matter. It's whatever fields are necessary to describe everything that's going on. So there are fluctuations in spacetime curvature, fluctuations in the density of matter, there are fluctuations in the phase space distribution of photons, you know, but all these things are specified by a certain number, a limited number of*

*functions of the position. So there's a complete description at the classical level, at least, of everything in the Universe in terms of the number of fields.” - J. Peacock*

*“In ‘large-scale structure of the Universe,’ you not only have the anisotropic distribution of matter itself, but the whole notion, for example, of the two-point function, the power spectrum, the spacetime itself and its properties, its topology, its curvature, etc.” - K. Kraljic*

In particular, the two-point function and the power spectrum are statistical mathematical tools for describing observations. The first allows counting galaxies and analyzing their distribution statistically from a formula, and the second is a way of physically quantifying this statistical distribution. Moreover, not only equations or formulas are mentioned, but also more general mathematical terms, such as the geometric terms used by Kraljic above, and also the term parameter as used by L’Huillier:

*“We manage to explain everything in a bunch of observations from the CMB, the distribution of galaxies, large structures in the universe, etc., just with these six parameters [of  $\Lambda$ CDM].” - B. L’Huillier*

When discussing simulations, Herle indicates that to identify elements within the large-scale structure, one must first ask how to define these elements computationally. In this case, the tools used, such as a detection algorithm called the halo finder, influence the structure observed and the structures that compose it. Thus, these mathematical tools are included in what is called, as a result of such analyses, the large-scale structure.

*“If you are working with simulations, this is a very important question to ask. What is a structure? What is an object? And then your results vary drastically because this depends on your halo finder and all this stuff, but this has nothing to do with the real world. This is a simulated structure formation question. And then when you're an observer, you want to say that you studied this object, but it needs to be reasonably self-contained in order to say that this is one entity. But it's interesting because from perturbation theory you come up with the relation that this thing has to be a certain value into the mean density contrast for it to sort of separate out from the expansion of the rest of the material.” - A. Herle*

We note in these statements that the mathematical question also arises in the case of observations. An astrophysical object is considered a standalone entity if it stands out from the surrounding matter; Herle speaks of autonomy or independence from this environment. For this, a branch of mathematics called perturbation theory allows defining thresholds from which a quantity is a standalone entity. Thus, within this entity is embedded a mathematical



notion. As we gradually see, there are intermediaries in the definition, observation, and mental representation of what a structure can be for cosmologists. The interviews allow us to identify three main intermediaries. The first, as L’Huillier reminds us, is an observational intermediary: the cosmic scale.

*“We have what we call the cosmic scale. We measure distances to known objects at a certain distance, and then we use those distances to measure things further away, etc.” - B. L’Huillier*

This cosmic scale is constructed using standard candles, a term used to refer to objects like Cepheids studied by Leavitt to determine distances. A well-defined type of object allows for the construction of a rung in the cosmic scale, from which other objects, like supernovae, are calibrated to create further rungs. The observation and positioning of galaxies tracing the structure of the Universe relies on the use of these standard candles, and the representations of this structure therefore implicitly contain this information. A second conceptual intermediary between observations and representations is recalled by Lehoucq:

*“We try to reconstruct the volume of the cone from its surface, which is not in two spatial dimensions and one of time, but three spatial dimensions and one of time.” - R. Lehoucq*

Indeed, astronomical observations occur on a sky onto which the light reaching us is projected. Observing a portion of the sky is observing a projection on a sensor of the light contained within the cone defined by the angular opening of the portion of the sky in question. The observed structure can also be projected, then in two dimensions, or represented with a dimension of redshift allowing the cone to be shown, but one must still sacrifice a dimension of space to project this cone onto paper for writing an article. Finally, Peacock mentions a third intermediary that is fundamental and is found, among other things, in simulations. This intermediary consists of the physical phenomena that, over time, separate different regions of space into different structures.

*“So you look at how the structures emerge in simulations. You find yourself thinking about the tidal aspects of the gravitational force, the properties of the gravitational potential, and see how space was split up in certain areas and have different visual impressions.” - J. Peacock*

If this intermediary is particularly mentioned for simulations, it is because it is in this context that phenomena occurring over cosmic timescales can be observed in fast motion. Thus, as Peacock’s statement suggests, thinking about the large-scale structure of the Universe involves considering various phenomena. We see here that these phenomena can be

observational, numerical, or purely physical. The mental representations of this structure call upon mental maps, and these maps contain more than just the spatial distribution of matter. One of the major concepts associated, at least mentally, with this large-scale structure is that of infinity or, more limitedly, large spaces. Combes emphasizes this point: the human brain struggles to represent very large spaces compared to those it experiences daily.

*“I think that in the questions that need to be explained in general, there is the infinite, the large, the vast spaces. We do not realize these vast spaces.” - F. Combes*

To intuitively represent the Universe and the large scales, various means exist, and Peebles mentions, for example, the method of an inflated balloon that mimics the expanding Universe by drawing an analogy between the surface of the balloon and four-dimensional spacetime:

*“The great Dutch astronomer Willem de Sitter introduced a very handy model of a balloon in which we live on a surface. You blow up the balloon, we move apart, and yet every observer sees the galaxies around moving away.” - J. Peebles*

However, he also insists that we only have access to a part of the Universe, the observable Universe. On this point, Lehoucq agrees and thus justifies the general questions about the topology of the complete Universe, particularly the question of the existence of boundaries or edges:

*“You could say large-scale structure or you could say large-scale structure of the Universe. Which has an interesting implication: we don't know what the world is, what the Universe is like. We know what we see, which could be a tiny patch of an immense, larger Universe. And maybe what we're seeing is some local aberration; who knows, we can only speak of what we can see.” - J. Peebles*

*“The implicit idea we have in cosmology is that the Universe is infinite because if it is not infinite, the alternative is that there are edges. Now, a Universe with edges obviously poses philosophical problems. [...] Finite Universes without edges do not fit within an acceptable cosmological model. [...] A finite Universe with edges,] would be a sophisticated version of periodic boundary conditions. The Universe would be smaller than the observable Universe, smaller or of a neighboring size, and that would change a lot about our position and how we interpret observations.” - R. Lehoucq*

Representing the large-scale structure of the Universe, whether graphically, conceptually, mathematically, or mentally, involves facing limits and physical questions about the meaning of the word scale. How large is this structure in practice, and can we really imagine it based on observations and equations? Moreover, speaking of large-scale structure means discussing

the large-scale structure of the visible Universe. As Peebles clarifies, we can only talk about and interpret what we see.

### **3.3 Structuralist holism : epistemological and ontological structuralisms**

The notion of structure itself, constituted by elements related through physical laws that change over time, raises the question of structuralist holism. To give short and standard definitions of these two terms, we can begin with holism. There are several definitions of this term depending on the context in which it is used. In our case, it refers to ontological holism, which posits that the properties of each part can only be understood in their entirety. According to this line of thought, a being is determined by the whole to which it belongs, and knowing this whole is necessary to understand its properties that cannot be reduced to those of its elements. Following this approach, structuralism is a holistic line of thought that applies to structure (the definition of which is not unique, especially when considering the various scientific fields to which it can belong). We can distinguish two main structuralisms: first, ontological structuralism, which argues that the very nature of the real world is fundamentally composed of structures; and second, epistemological structuralism, or simply structuralism, which holds that our knowledge of the world and the way humans understand and grasp the world is structural: we use conceptual structures to represent and comprehend the world. Structuralism has been applied to various fields, such as sociology or the philosophy of science, notably and especially in quantum physics. A key reference in this field is the British philosopher Steven French and his book *The Structure of the World: Metaphysics and Representation*<sup>116</sup>. In cosmology, although structuralism has not yet been explored, the ontological perspective would imply that large-scale structures, such as galaxy filaments and cosmic voids, are more fundamental than the galaxies themselves. The properties of galaxies and galaxy clusters would then be derived from the underlying structures of the cosmic network, which would provide direct access to the real and fundamental characteristics of the Universe. The epistemological perspective could imply that our models of the universe, such as  $\Lambda$ CDM, are not direct descriptions of reality but mathematical structures that organize our observations and knowledge. The cosmological parameters, such as the density of dark matter

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<sup>116</sup> French, S., *The Structure of the World: Metaphysics and Representation*, Oxford, Oxford University Press, 2016, 414 p. ISBN : 9780198776666

or dark energy, and even objects like galaxies or galaxy clusters, would then be seen as elements related within the theoretical structure rather than as autonomous physical entities. Before delving into the discussion between ontological structuralism and epistemological structuralism, let's first examine the cosmologists' thoughts on structure and the observable structures in the Universe. Structures are the physical objects that shape the large-scale structure of the Universe. Notably, this term applies to all scales; Smethurst associates it with a wide variety of objects:

*“If you said structures, I would think about everything from gas filaments in the Milky Way to entire galaxies to clusters. [...] And I think it comes from the context of what you're reading.”* - R. Smethurst

However, as illustrated by the statements of L'Huillier, White, and Kraljic, the general trend in our interviews is that, when in the plural, the word structures refers to a set of objects at least at the galactic scale, such as galaxies or clusters:

*“I would tend to say the structures, the large structures of the Universe, to refer to everything that is superclusters, etc. And I would rather say the large-scale structuring of the Universe, so the way the universe is structured, which is a form of cosmic web indeed. So the large structures would be individual structures, pieces of the cosmic web.”* - B. L'Huillier

*“If I wanted to emphasize galaxies, galaxy clusters, and galaxy superclusters, I would talk about structures.”* - S. White

*“[Large-scale structures] are all the large-scale structures or grandes. It depends on the definition, but typically beyond galaxy groups. Beyond, let's say, a megaparsec or ten megaparsecs.”* - K. Kraljic

The large-scale structure of the Universe, strictly speaking, is a more subtle notion than that. For example, Herle and Kraljic agree that it is a very broad term. Herle specifies that the term is, in his view, so vague that one cannot ascribe it real physical meaning without further information:

*“Large-scale structure of the Universe, in the singular, I think is a very broad formulation. It means one thing, in my opinion, very general.”* - K. Kraljic

*“I think large-scale structure is a nice name. It is spectacularly vague. There is nothing you can get from that apart from: it is a structure at large scale.”* - A. Herle

In practice, the meaning attributed to the term large-scale structure is found in the reason why this field of research exists. Alonso thus relates the issue of local inhomogeneities in the Universe to the question of its structure, and this vision is echoed in L'Huillier's explanation regarding cosmic voids:

*“Right now, we kind of have that idea that the large-scale structure is inhomogeneities in the distribution of non-relativistic matter, which by definition is the cosmic web, because we know that that matter does distribute itself according to filaments, sheets, voids, and clusters. However, it has very often been understood as the fact that there are anisotropies in the universe.”* - D. Alonso

*“For me, I would consider [cosmic voids] as a structure because it is part of the structuring of the Universe which consists of under-densities and over-densities. So for me, if an over-density is a structure of the universe, an under-density is too.”* - B. L'Huillier

The general trend that emerges is that the structure of the Universe does not merely correspond to the substructures that may be filaments, walls, and clusters. Other terms are also found, such as notions of inhomogeneities, structuring (and thus evolution over time), density fields, and gravitational fields, for example. The structuralist holism resides here in the idea that the large-scale structure of the Universe cannot be reduced to a collection of individual objects. However, an exception to this view can be found in the statements of Combes, who believes it is merely a matter of vocabulary:

*“When it is in the singular: the large-scale structure, the large-scale structuring; or the large structures. It's a bit the same thing. But it's a bit of a convention that comes up in both English and French. So I think it's really vocabulary and that it's the same thing.”* - F. Combes

However, as White points out, vocabulary is not trivial. The definitions attributed to words and how data are represented justify or invalidate the physical meaning of a discourse, particularly here regarding the density of certain regions of the Universe and cosmic voids:

*“You can meaningfully talk about high and low density regions, and then the low density regions are clearly spatially connected. And then whether you think of them as space-filling low density regions or as a set of separate low-density regions, as voids... It very much depends on how you represent the data.”* - S. White

As we see here, the notion of structure is important because it encompasses many things, whether physical entities, relationships between these entities, or significant definitions to clarify the physical object being studied. In particular, these examples show that the

definition of large-scale structure is not unique, and that different people from different nationalities and working in different institutions may express slightly varying views. Now, assuming that the large-scale structure of the Universe is a central theme to which researchers in cosmology can attach various notions and concepts, let's see if the thoughts expressed in the interviews about it fall more under ontological structuralism or epistemological structuralism. Is structure a tool for representing the world, or is it a fundamental reality? As one might expect from cosmologists, the epistemological point of view is predominant. This is, with one nuance, the only perspective explicitly discussed in the interviews. In particular, Peebles and Peacock explicitly acknowledge that cosmological models, such as  $\Lambda$ CDM or the notion of gravitational fields and other fields, are approximations of reality, and that scientific research aims to improve this approximation to better align models with observations. Peebles even questions the reality that science claims to approximate:

*"I avoid belief. I think there is a very strong case that the  $\Lambda$ CDM theory is a good approximation to reality. Even that is rather a controversial statement. What is reality? We don't know. We feel we have an approximation to reality because the theories fit so many tests. We don't know that that means that the theory is a good approximation to reality. But the case seems persuasive. [...] And I have often wondered why do we think the Universe operates in a rational way, when we are subject to apparently irrational aspects of the Universe all the time? Why is the fundamental nature of reality logically arranged to obey physical laws that are written down in mathematical terms? Why do we assume that? Well, because it works. But someone had to assume it before we knew it worked. And of course, the planets were a good lesson."* - J. Peebles

*"There's a complete description at the classical level, at least, of everything in the Universe in terms of the number of fields. Except even that is an approximation. [...] I think there's implicitly some loss of information, some averaging that hides these very fine scale details, but that's a good approximation."* - J. Peacock

The mathematizability of physical phenomena is a tradition that has continued to strengthen since Newton, and as French indicates, *"Perhaps then we simply have to accept that the distinction between the mathematical and the physical has, at the very least, become blurred or that it cannot be drawn at all."*<sup>117</sup> The mathematical models can merge with physical phenomena. Additionally, Lehoucq emphasizes his questioning of the nature of the Universe,

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<sup>117</sup> French, S., *The Structure of the World: Metaphysics and Representation*, p. 230.

and the approximation that simulated models of Universes constitute, in which it is possible to recreate the large-scale distribution of galaxies. White, a specialist in cosmological simulations, explains that the large-scale structure is one of the three major aspects of a complete model of the Universe that allows for a comparison with direct observations of the world as we perceive it:

*“What would the observable Universe be? And are there other variants of Universes? There are model Universes, for example, those that come from large structure simulations where we model the evolution [of the Universe] over billions of years with all the structures that form and with multi-scale systems so sophisticated that we can almost see individual galaxies within absolutely gigantic meshes.”* - R. Lehoucq

*“I'd say there are three aspects of the Universe. The geometry of the Universe, the contents of the Universe, the structure in the Universe, which you can think of as somehow setting initial conditions at some time, plus a set of physical laws to determine its evolution. If all those aspects are defined, then, in principle, past the time when quantum uncertainties are significant, it is a deterministic problem, and then you can evolve forwards in time and ask whether the results are consistent with what we see at different epochs.”* - S. White

Lehoucq shares this epistemological approach rather than ontological regarding dark matter:

*“This question of dark matter, here's how it might appear: like a ghost, literally a ghost to explain the real. We are in a situation that has already occurred in the history of science where we 'invoke' ghosts to explain a phenomenon that manifests itself before our eyes.”* - R. Lehoucq

Another nuance to this epistemological view is provided by Alonso. Indeed, in his remarks, the link between the notion of large-scale structure and the reality of the world is slightly stronger because studying structure leads to fundamental questions about the nature of the Universe. This approach results in grouping under the notion of structure observations that help answer these fundamental questions, such as the cosmic microwave background (CMB):

*“Why are there anisotropies in the universe? That's a fundamental question which connects with inflation. And the initial conditions that give you small fluctuations in the density of the universe, where do they come from? Why are they there? So depending on who you talk to, the CMB would be part of the structure in the sense that it allows you to understand where all these structures are coming from.”* - D. Alonso

The nuance to these remarks is that scientists can still admit there is an objective reality of the objects they discuss and study. Peacock thus proposes an ontological view of cosmological objects, at least at the scale of particles and the Universe as a whole:

*“This is the core philosophical question. Is there actually a truth about the Universe? You can say there's no such thing as objective truth. It's just a set of explanations, of models that approach more closely to the matching with what we see observationally. And I think personally that's too abstract of a point of view. In the space between us now, there are thousands of neutrinos left from the early stages of the Big Bang, no doubt that these particles have an objective existence. So it's not just a sociologically determined way of looking at the Universe.” - J. Peacock*

All these remarks are interesting because they contrast with what many philosophers say about objects in science. For example, French and other major figures of structuralism, like James Ladyman, advocate for an ontological structuralism, while thinkers whose primary activity is scientific research, like David Bohm, Basil Hiley, or Henri Poincaré, lean more towards an epistemological interpretation. Additionally, the epistemological status of cosmic voids also informs us about what cosmologists consider real or not, and what can be designated as structure. Opinions on this topic vary. For example, Herle considers voids to be defined rather as the absence of structure, while Alonso and Peacock oppose this view and readily accept attributing the status of structure to voids, which thus become an integral part of the larger large-scale structure of the Universe:

*“I think it is by definition the absence of structure. It is an absence of density, an under-density, it is a negative convergence.” - A. Herle*

*“Yes, it is a structure in the sense that, by definition, a void is something that is surrounded by objects that have a higher density. So in that sense, it is a structure, it implies the existence of structures around it.” - D. Alonso*

*“They are a visually striking phenomenon. You can make catalogs of regions of space according to a certain definition of voids, although it is not a unique definition. So you have some predilection there, but the regions of space with underdensities have objective properties. So they are as real structures as anything.” - J. Peacock*

In practice, these three viewpoints are not in philosophical disagreement regarding what a cosmic void is. While opinions differ, it is mainly because the definitions used to discuss them are different. This is also what Peacock emphasizes: there are several definitions of cosmic voids. It is worth noting that responses might follow a completely different trend if one were to address researchers in another field of physical sciences. Ultimately, and



following this development on cosmic voids, one of the elements that stands out most when cosmologists are asked about the large-scale structure of the Universe and its epistemological status is that this notion is not well defined enough, or at least not perfectly defined. According to White, it is precisely because it is a structure, and that the number of components and relationships that a cluster encompasses is quite small, unlike, for example, a galaxy of stars:

*“On the whole, galaxies are very different objects from stars, and you can think about them separately. Large-scale structures are less well defined because even the biggest clusters only have a thousand galaxies, that is not a very large number. And typically when people look at large-scale structures, they are defined by relatively small numbers of galaxies, and what people would call a filament have a few tens or fifty galaxies. So it is a rather noisy definition that depends on how you link things together, exactly where you would even put the filament or what you think is a filament.”* - S. White

Thus, before properly defining and agreeing within the community on the status of the large-scale structure of the Universe, it would be necessary to define precisely and exclusively objects like filaments. In this regard, Peebles spoke cautiously about filaments in the 1980s, and this caution is still evident in the interview conducted forty years later:

*“You need to be careful about this because the human eye is very good at finding patterns, even in noise. It's far better to see the occasional leopard that's not there than to miss a leopard that is there. It's very important to see patterns that are just barely, barely, barely detectable and may, of course, be false. [...] There's a web-like structure. And it's seen both in observations and in simulations. Because it's seen in simulations with standard  $\Lambda$ CDM, it is not a challenge to the theory, whether it is a distraction from more interesting aspects of large-scale structure.”* - J. Peebles

Finally, Kraljic adds that astrophysical objects in general are quite abstract. In his opinion, it would be good to revisit the definitions and meanings of the terms used by cosmologists as the basis of the theories. According to Peacock, the foundation of all these studies is the density field, and this is well defined. Thus, it is from this field that it would be necessary to clearly establish what constitutes structures:

*“Every day we deal with quite abstract objects of which we know nothing. And perhaps it would be good to try to revisit the questions of the theory based on these principles that we have established from the beginning. Could we not come back to*

*them? I think that would be quite an interesting loop that always brings us back to the knowledge of our unknowledge.” - K. Kraljic*

*“You can change how you classify things and the classifications change, but the density field is the fundamental thing that underlies all of this and is not subject to hidden definitions.” - J. Peacock*

Ultimately, as cosmology has been built upon principles and observations whose quality and resolution continue to increase, the definitions of abstract terms like structures or even the large-scale structure of the Universe are changing. In this case, the status of these objects also changes. Since structure is here a tool for representation rather than a fundamental reality of the Universe, it evolves with its representations and the concepts it encompasses. Fifty years ago, voids and superclusters were not known. Today, the most modern observations can probe very ancient epochs of the Universe, and the definitions improve. However, they are still constructed on previous work, and an introspection of cosmology, as Kraljic indicates, could lead to a clarification of what the large-scale structure of the Universe is, both ontologically and epistemologically. Such introspections have occurred and continue to occur in quantum physics, for example, where the status of photons and elementary particles has evolved significantly and moved away from what was accepted as correct over a century ago.

### **3.4 The place of the large-scale structure of the Universe in cosmology**

To conclude this chapter, let's explore the openings that the large-scale structure of the Universe evokes for the cosmologists interviewed. This analysis primarily serves to situate this research domain within a broader network and to understand the importance of this field more directly from the words of researchers. This positioning can first be done in time. In particular, the difference between cosmology in the last century and what is being done today is significant, especially in terms of workforce and financial investments:

*“We have gone from an individual enterprise to Big Science, collaborations with thousands of people.” - B. L’Huillier*

*“I personally find [the future of cosmology] quite depressing. The results that we get from the modern experiments are very precise, but achieved at great financial and human cost. So in the absence of really, really clever new ideas, what the field is*

*doing is basically taking the things that succeeded in the past and scaling them up.” -*

J. Peacock

The term Big Science used by L’Huillier is quite relevant in cosmology. In this regard, one can refer to the account of the creation and use of the iconic Hubble telescope by Smith: *The Space Telescope. A study of NASA, science, technology, and politics*. After the initial Big Science projects (mainly initiated by the construction of weapons of mass destruction during World War II), early ideas for scientific telescopes in orbit above the Earth’s atmosphere emerged in the 1950s. This telescope was envisioned in the 1970s but was not launched until the 1990s, and corrections were necessary after its launch. The scale of this endeavor was unprecedented. Before 1970, the study of the Universe was conducted by teams of a few dozen or even hundreds of individuals who sometimes gathered during seminars. Today, most astrophysical collaborations, especially those aimed at studying the cosmic web, are significant political and administrative subjects. In light of this observation, and the ever-increasing acquisition of images and data, Peebles, Kraljic, and Alonso are more optimistic. The former highlights the open questions in cosmology that should inspire growing research efforts. The latter two express some concern about how cosmologists will achieve this progress, as it seems that adaptation and changes in operation will be necessary to avoid what Peacock fears: merely repeating the same analyses but with more data. The mentioned solutions include artificial intelligence, which would bring a new approach to studying the large-scale structure of the Universe, particularly by analyzing it without direct human visual input, as well as the rapprochement between cosmology and astrophysics:

*“In the years around 2000, experimental programs in progress became clear, complete enough to tell us a story that seemed to be convincing. A dramatic advance like that happens rarely. And I don’t know whether we will have another such advance in cosmology. There are many open questions in cosmology. We’ve mentioned only a few. The properties of galaxies are pretty well accounted for within the standard  $\Lambda$ CDM, but not totally. But of course, that is in part because galaxies are complicated. We were able to make good progress in cosmology so far because we focused on the simplest of all problems in which the predictions are pretty easy to compute and compare to measurements that are going to be done very precisely. The properties of galaxies surely tell us something about the nature of physical reality and in particular about the nature of dark matter, which is, the evidence says, distributed around the outskirts of the galaxy. As I said, I can’t believe the present model for dark*

*matter is complete. I'm looking for advances that will teach us, maybe, it can be made more complete.” - J. Peebles*

*“We will find the tools and now it will be a lot of artificial intelligence to help work with and analyze all this data. In the past, the window was much more open to different models because there were no observational constraints. Now, we have so much data and so many constraints [...] that the window of all these possibilities is somewhat more restricted than in the past.” - K. Kraljic*

*“I think I am excited about cosmology, but maybe not for the same reason that we were excited about cosmology in the past. In the past, you were excited about cosmology because you were accessing the origins of scales, or time scales that would allow you to uncover new potential areas of the standard physics model. You knew for sure you would probably be able to detect something new there. I don't see where it is going now. We know that the uncertainties with which we know certain core parameters are going to improve over the next decade, but they're not going to improve by orders of magnitude, so I don't think there will be massive new surprises that come from that. However, in order to get those improvements, we're going to need to understand the signals that we are detecting a lot better than we do right now. We are going to get outstanding maps of the large-scale structure over most of the sky, going all the way to redshift three or four. We are going to have maps of the universe on many different wavelengths, on many different scales. In order for us to extract the most information from that, we need to understand what we are seeing and so far there has been this huge divide between cosmology and galaxy evolution and astrophysics.” - D. Alonso*

One of the main subjects addressed in the interviews is  $\Lambda$ CDM, which underpins the theory of the large-scale structure of the Universe. The validity or invalidity of  $\Lambda$ CDM is a very important topic for cosmologists, given the attachment that each has had in developing their thoughts and opinions during our discussion. It seems that  $\Lambda$ CDM raises many philosophical questions, for example, for L'Huillier and Kraljic, the question of Occam's razor and the number of parameters necessary and sufficient to adequately approximate the structure of the Universe:

*“[With competing models,] we're going to have extra parameters and in physics, in science, we have Occam's razor, so the idea is that if we have two models to describe the same thing, we tend to prefer the simplest one. As long as we don't have a real reason to reject  $\Lambda$ CDM, we will keep it as the main model. [...] Right now, we have*

*‘Stage IV,’ so the fourth generation of cosmological surveys with DESI, with Euclid in the European Union, with LSST... If the results do not indicate a deviation from  $\Lambda$ CDM or the concordance model, will it be possible to go further? Where is the limit on these parameters?’ - B. L’Huillier*

*“ $\Lambda$ CDM is a six-parameter model. There are certain regimes, certain scales where the model does not sufficiently explain the data. So I wouldn’t say it’s the simplest because if you take a model with twenty parameters, it fits much better. And in that case, one might say we have a perfect model that explains the data. [...] But we don’t learn more by adding more. It’s just that it becomes more phenomenological if you have more and more parameters.” - K. Kraljic*

Peebles emphasizes the robustness of  $\Lambda$ CDM and the fact that it has survived many tests since its inception, which is not only impressive for a physical theory but also the best one could expect: such a model will never be perfect, as a perfect description of the entire Universe is certainly unattainable. According to him, having this model is particularly encouraging for future cosmological research.

*“First, you will have seen, I assume, the statistical measures of the angular distribution of the thermal radiation in which theory and measurements follow the same oscillations to remarkable precision. You may also be aware that in the galaxy distribution, there is statistically the same pattern of oscillations in the power spectrum. The same theory with the same parameters fits both. It is, to me, deeply moving because these are two statistics that in the distribution of matter, in the distribution of radiation that are based on measurements that are very different. They’re looking at the Universe in a very different way. [...]  $\Lambda$ CDM is really pretty good, but it’s not perfect. How could we be surprised at that? Well, we are taking a stab at the nature of the Universe on the immense scales of cosmology. That we got close is, to me, wonderfully encouraging. In fact, surprising that we could do so well.”*

- J. Peebles

These remarks should be contextualized: Peebles has witnessed most of the developments in modern cosmology. He has been part of the research efforts in foundational areas of current theories, and his career has been rich in success to the point that he has received a significant number of awards and recognitions, including the Nobel Prize. This optimism and enthusiasm come from someone who has essentially completed his career. These comments are not self-serving, and there are good reasons to think he is sincere. This contrasts with the concerns expressed by cosmologists in the interviews. Indeed, the most worried are those

whose careers are still far from over. And when studying the Universe as a whole, it is reasonable to be concerned about the scientific community's ability to advance towards a better understanding of the observed phenomena. However, prospects exist, and if, as Kraljic indicates, certain windows are more restricted than in the past, the solidity of the work done so far and the myriad of open questions seem to provide at least fertile ground for scientific research, which increasingly accompanies epistemological questioning. The question of model choice in physics is dense, and it is not appropriate to elaborate extensively on this topic here. Nonetheless, we can see that in these discussions,  $\Lambda$ CDM corresponds to what Duhem writes in *La théorie physique. Son objet, sa structure*: its object, its structure: the physical theory is convenient ( $\Lambda$ CDM is very adaptable), aesthetic ( $\Lambda$ CDM is simple and aims to model the Universe), and economical ( $\Lambda$ CDM has only six fundamental parameters)<sup>118</sup>. It allows for classification and composition of laws expressed mathematically. It is coherent that this model is the one of cosmology and that it serves to model the large-scale structure of the Universe. Although the interviews show that all scientists are aware of the subjective element involved in the choice of dominant models, they also indicate that the confidence in  $\Lambda$ CDM and the desire to test it further are justified. Moreover, Duhem also proposes a philosophical explanation of what constitutes a scientific experiment, and this explanation particularly applies to observations at the largest scales: a physical experiment consists of two parts. The first is the observation, during which the eye is the main tool. The second is the interpretation of this observation, and this is where one must be a physicist, as the justification of an interpretation and a mental representation can only come from a good knowledge and application of physical theories.<sup>119</sup> Cosmology has a special status, as Lehoucq reminded us during the interview: there are no possible experiments in the laboratory when dealing with the Universe. There is no Big Bang or expansion of the Universe on the laboratory bench. At best, cosmological experiments are analogies between a model system and the entire Universe<sup>120</sup>. Discussions on this topic can be found in the book *Philosophy of Astrophysics*, but we can also see here, through the words of the interviewees, that cosmologists willingly speak of their field as a science like all others, with models and observations to compare to the predictions of these models, and that cosmology is ultimately

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<sup>118</sup> Duhem, P., *La théorie physique. Son objet, sa structure*, item 30.

<sup>119</sup> Duhem, P., *La théorie physique. Son objet, sa structure*, item 221.

<sup>120</sup> In this regard, Karl Popper does not believe that cosmology can have the status of a science. This viewpoint has been revisited many times, and it is now generally accepted that observations and simulations provide a scientific basis similar to that of experimental data.

the scientific field that requires the most knowledge of physics. This position is particularly well summarized by Alonso:

*“Essentially, because the system you're trying to understand is so vast, you need to cover all these different areas. It gives you a good understanding, or it requires for you to have a good understanding of lots of different areas of physics.”* - D. Alonso

Lachièze-Rey speaks of observational science, in lieu of experimental science<sup>121</sup>. To conclude, let us add two elements: the large-scale structure of the Universe is not the only element whose epistemological status needs to be clarified, and Combes and White respectively mention gravitation and complex systems. According to Combes, it would also be good to gather the knowledge gained since the formulation of the theory of general relativity by Einstein, namely the observation of extreme objects like black holes, attempts to formulate alternative theories, the detection of gravitational waves, or observations of gravitational lenses, and study what these phenomena teach us about the nature of gravitation and whether its status has evolved since:

*“We could highlight the fact that the Universe helps us understand not only how galaxies are formed, the origin of structures, but also the fundamental equations of physics. Because I think we have learned a lot recently, not least with gravitational waves, black holes, [...] but what is gravity?”* - F. Combes

Regarding complex systems, and as he develops in the essay *Reconstructing the Universe in a computer: physical understanding in the digital age*, White questions how it is possible to extract knowledge from studies on objects like galaxies, which are composed of a vast number of elements and are influenced by very diverse physical phenomena like supernova explosions, matter accretion by black holes, or the gravitational force exerted by baryonic and dark matter. According to him, the large-scale structure of the Universe is not a complex or chaotic system, and it is important to distinguish between these two possible regimes, highlighting that the spatial scale being studied is not correlated with the complexity of the system.

*“I'm very interested in the issue of what we mean by knowledge in complex systems. And I'm not sure that the large-scale structure of the Universe is actually one of the most complex ones, because in the end, it is not very far from a gas in a random field. It has been known to be amplified, but not so far from the initial Gaussian features that it has lost all memory of the initial conditions. People analysing the large-scale*

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<sup>121</sup> Marc Lachièze-Rey, *Historicité de la cosmologie*, *Cahiers François Viète*, vol. 9/10, 2005, pp. 139-149.

*structure have schemes which allow them to reconstruct the initial conditions from the current large scale structure.” - S. White*



# Conclusion

This thesis studies the concept of large-scale structure of the Universe from a historical and epistemological approach. The main question we asked was: what are the graphic and mental representations of the large-scale structure of the Universe, and how have they evolved? This question opens our study to what cosmologists think about notions related to large-scale structure. Thus, after providing a contextualized history of discoveries and images related to this structure, we examined, through ten interviews with cosmologists and astrophysicists, the epistemological status of the structure, the substructures that may compose it, and the relationships between these substructures. We also discussed the place of this notion in the history of cosmology and the perspectives that the current state of knowledge opens for the future of this still-young science.

The history presented in Chapter 1 begins with a contextualization of the concept of spacetime, as cosmology studies the Universe and the evolution as well as the content of this spacetime. From this contextualization, we drew the broad outlines of modern astrophysics, before delving into the history of the concept of large-scale structure of the Universe.

Chapter 2 presents the interviews conducted to study the relationships between the thoughts of the scientific community and this history. The various main themes that emerge from these interviews are thus introduced. We examine images as well as the mental and mathematical representations addressed, along with the question of structuralist holism and the place of the large-scale structure of the Universe in the larger network formed by cosmology, and by extension astrophysics.

It is in Chapter 3 that these four main points are studied in more detail, using a significant number of quotes directly extracted from the interviews. These quotes allow us to present the statements of each interviewee without filtering or altering their thoughts too much, and to propose an epistemological analysis of the large-scale structure of the Universe.

Our analysis shows that the history proposed in Chapter 1 has a strong influence on, for example, the concept of structure today. Major discoveries were made over four or five decades, between 1965 and the 2000s, and in stages corresponding to the main advances in observational and modeling technologies. This today implies differing views on cosmic voids, the definitions of structures, and structure in general. In particular, discussions concerning numerical simulations contain more definitive opinions on what is scientifically

relevant to discuss and on the definitions of filaments, cosmic voids, or the skeleton of large-scale structure. Furthermore, while observations of the sky prior to 1990 primarily focused on galaxies and their distribution across the celestial sphere and along the redshift axis, the term that is now central to cosmology is increasingly the density field and its inhomogeneities. This density field is situated at a higher level of abstraction than galaxies, but it also implies that for scientists, it is more fundamental. Thus, the discussion surrounding the large-scale structure of the Universe has shifted from observational discussions to discussions about the fundamental characteristics of the Universe.

Moreover, cosmologists adopt an epistemological structuralist viewpoint: structure is a system of entities, phenomena, and relationships that allows for the representation of the Universe without necessarily presupposing that this structure exists at a fundamental level. It is not necessarily a reality, but it practically represents the Universe that humans observe at large scales. However, a nuance must still be made: today, it seems that this notion still struggles to leave the scientific community. The observation is that the general public, whether educated in the physical sciences or not, has a very limited knowledge of the organization of the content of the Universe. This thesis proposes a bridge to transfer this notion into another realm, that of epistemology.

Let us recall that, as with any historical study, choices have been made to propose a standard history to refer to. Some scientific contributions have undoubtedly been forgotten, and certain elements have been intentionally set aside to clarify the most important aspects for our study. There are few references in the philosophy of cosmology, so it has not been possible to refer to a text that would be considered authoritative. In this context, we have sought to go further than the works of popularization or mediation in the history of cosmology, and this within a limited space and time.

To conclude this thesis, let us make one last remark. The final question of each interview was very open-ended. It invited the interviewees to freely discuss one or more subjects in the epistemology of cosmology that particularly interested them. The responses to this question are difficult to use in the body of this thesis, and only one quote is extracted. However, it is remarkable that each response was very different from the others, indicating that the diversity of topics discussed is as important as the number of participants. Among these topics, we find the meaning of the word Universe, the usefulness of all these cosmological studies, the reasons that lead to believe that mathematical equations are a good way to represent phenomena, the philosophical beauty of cosmological theories that, with very few parameters, can explain a vast quantity of observations, and more. These responses

are indicative of the interest that astrophysicists have, consciously or not, in epistemological questions. Each of these topics is certainly worthy of interest and of studies similar to what this thesis proposes. This enthusiasm and curiosity are, on one hand, reassuring, as they prove that scientists are not blind to the philosophical and sociological debates surrounding their disciplines, and on the other hand, encouraging for future studies in the epistemology of cosmology, which is still a young and largely unexplored research field. We hope that this thesis can serve as a source of motivation or information for future works.

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# Appendix

About a hundred pages of interview transcriptions complete this thesis. However, this appendix is neither public nor intended for dissemination but is meant for the thesis jury. Anyone else interested in additional elements that would be in this appendix can contact the author of the thesis via email: baptiste.jego@etu.unistra.fr; jegobapt@gmail.com.

The interviews transcribed in Part I of the appendix are presented in the format ‘Q: Question’ for Baptiste Jego, and ‘R: Response’ for the person being interviewed, whose name is included along with the date of the interview before the transcription. They are presented in chronological order. Each transcription has been validated, sometimes after anonymization and censorship by the concerned individual, and is provided with their consent. The anonymized sections are available after all the transcriptions, in Part II, and are not replaced by brackets ‘[...]’ in the original text to avoid identifying the individual behind an anonymous statement. The censored sections are, of course, not available and have been removed without any specific indications in the texts. It should be noted that these transcriptions are faithful to the spoken language used during the interviews, which explains the sometimes incorrect syntax, but they remain comprehensible.

Part III is informative and provides the French version of the questionnaire used when the interview was conducted in French. The correspondence between the French questionnaire and the English questionnaire is intended to be literal.

## **I - Interview transcriptions**

## **II - Anonymised parts**

See the annex document for parts I and II.

## **III - Questions in French**

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- 1) Depuis combien de temps travaillez-vous en astrophysique/cosmologie ?
  - 2) Pourquoi avoir choisi ce milieu ?

- 3) Pensez-vous que les différents modèles (de matière noire, de gravitation, d'espace-temps) devraient être traités de manière égale (financements, vulgarisation/médiation, jugement de la communauté) ?
    - Si oui, pourquoi cela n'est visiblement pas le cas ?
    - Si non, qu'est-ce qui fait les modèles dominants ?
  - 4) Pensez-vous que  $\Lambda$ CDM, le modèle de halo, et la cosmologie actuelle sont objectifs ?
  - 5) Diriez-vous « structure » ou « structures » à grande échelle ? Et quelle serait la différence avec la toile cosmique ?
  - 6) Qu'est-ce qui parvient de notre connaissance de la structure de l'Univers au grand public ? Quel effet cela a sur l'imaginaire commun ?
  - 7) Comment envisagez-vous le futur de la cosmologie, et quelles différences faire avec son passé ?
  - 8) Les tensions cosmologiques et les points d'ombres actuels annoncent-ils un changement de paradigme ?
  - 9) Quelles questions d'épistémologie vous intéressent concernant la cosmologie et la structure à grande échelle de l'Univers ? Quelles réponses y donneriez-vous ?
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