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# Quantum modalities, potential particles and a quantum mechanical kinetic theory of the Special Relativity and the Newtonian gravitation

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**Yannis Delmas-Rigoutsos**

*Université de Poitiers*

*E-mail:* [yannis.delmas@univ-poitiers.fr](mailto:yannis.delmas@univ-poitiers.fr)

**ABSTRACT:** This article suggests a new quantum mechanical framework to investigate the relations between space-time and particles.

First, we introduce a formal framework to deal with possible worlds, we say *potential worlds*, independent of interpretations: the *quantical modal logic*. This framework is compatible but simpler than multiple-world and pilot-wave interpretations and avoids ontological commitments. On this basis, we reformulate virtual particles of QFT as *potential particles* and, adding a few reasonable hypotheses, we show that Lorentz transformation and Special Relativity (SR) emerge as a Quantum Mechanical phenomenon, unlike EINSTEIN's interpretation. This *kinetic theory of SR* relies mainly on a reformulation of SR without “rods and clocks”. We use the same model to derive Newtonian gravitation solely from a gravitational redshift assumption.

This theory drives us to suggest the *trans-world gravitation hypothesis* that the weight might be active between the potential worlds. If this effect is real, we show it to be experimentable with available techniques. Finally, in a speculative part of this article we explore some foreseeable consequences of the trans-world gravitation phenomenon. We suggest that it could contribute explanations for the cosmic inflation, the dark matter and the cosmological constant problem. Moreover, our kinetic theory in an expanding universe might lead to a justification of the MOND theory.

**KEYWORDS:** High energy physics - theory [hep-th], Quantum logic [math.LO], Special relativity [physics.gen-ph], Quantum gravitation [gr-qc], cosmic inflation [astro-ph], dark matter [astro-ph], cosmological constant [gr-qc]

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# 1 Introduction

## 1.1 Raising a question

For nearly a century, there had been attempts at binding together quantum physics and gravitation. “Combining the principles of [the General theory of relativity (GR)] and quantum theory is probably not just a technical problem that could be solved by sufficiently powerful mathematics. It is a more of a conceptual issue and the decades of failure of sophisticated mathematics in delivering quantum gravity indicates that we should try a different approach” [30]. In this article, we will explore a different approach, following an insight from John BELL [5] considering Special relativity (SR) to be phenomenal. This idea will lead us to a framework that could sketch out some aspects of a merged theory of gravitation and QM.

Metaphorically speaking, we know that such a merged theory could certainly not be something like “ $\text{GR} \oplus \text{QM}$ ”, since many phenomena are on the fringe of both application domains, even in our near phenomenal environment. Thus many authors are rather searching for something like “ $\text{GR} \otimes \text{QM}$ ”. This line of research is appealing and somehow general, but it does assume that fundamental phenomena of one theory are not already consequences of the other. On the contrary, we suggest here that the SR should be understood as a quantal<sup>1</sup> phenomenon, provided some reasonable hypotheses.

Our proposed framework, the *potential particle model*, suggests a new QM interpretation, the *potential world modal interpretation*, somewhat in between pilot-wave and many-world interpretations. In a second part of this article, we are more conjectural and explore a hypothesis about how gravitation could behave in this framework. Our *trans-world gravitation hypothesis* is inspired by this interpretation, but is not a matter of metaphysics: it can be tested with existing apparatus. Being more speculative, we explore some possible consequences of this hypothesis and show it could contribute explanations for cosmic inflation [27], dark matter [41, see] and the cosmological constant problem [38, see].

## 1.2 Relying on a methodology

For QM and gravitation, as for any experimental corpus, theories are immensely underdetermined by evidence. In other words, attempts to unify theories are only limited by imagination. Since human creativity is immense, we shall try and compel us to a *parsimony principle*: “We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances”<sup>2</sup>.

The second methodological difficulty we face when we deal with evolution of QM is what we could call the *incomprehension imperative*: the idea that QM cannot be understood with clarity<sup>3</sup>. This imperative may also be satisfaction with abstruse, absurd or nonsensical

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<sup>1</sup>To ease the formulation, this paper uses the adjective “quantal” to mean “quantum mechanical”. We will still use the noun “quantum” for quanta, but as we will emphasize, QM is not only about quanta.

<sup>2</sup>NEWTON’s formulation.

<sup>3</sup>For example, Richard FEYNMAN: “I think I can safely say that nobody understands quantum mechanics.” (*The Character of Physical Law*, 1967, p. 129.). This affirmation circulates mostly in two popular versions: “If people say they understand quantum mechanics, they’re lying,” or “If someone thinks he under-

“explanations”. For example, many courses or popular science present particles in a double-slit YOUNG-type experiment as passing through “both” slits, or “neither”. For some authors, more cautious, this is a “question that cannot be answered”. As a consequence, many would follow Paul DIRAC when he contended: “The only object of theoretical physics is to calculate results that can be compared with experiment [...] it is quite unnecessary that any satisfactory description of the whole course of the phenomena should be given”<sup>4</sup>. But how could one hope to solve conceptual issues this way? Our second methodological principle will be a *clarity principle*: Expression should seek for clarity, comprehension and logical soundness.

Garrett BIRKHOFF and John VON NEUMANN [10] showed, a long time ago, that physics *cannot* be described by Classical Logic (CL) alone and introduced Quantum Logic (QL) to deal with observations. A first consequence of preceding principle will be to put all reasoning in a quantum logical context, instead of classical, whenever necessary<sup>5</sup>. For example, the sentence that “the electron passes through the left slit and the right slit” is false (zero measure). The statement that “the electron passes through the left slit or<sub>CL</sub> the right slit” is also false (zero measure). What is true is that it passes through the left or<sub>QL</sub> the right slit —with a quantum logical “or”, *i.e.* a superposition of states.

### 1.3 An insight from John BELL

In the search for such a QM–GR integration, we immediately encounter a conceptual difficulty, well summed up by David BOHM: “In relativity, movement is continuous, causally determinate and well defined; while in quantum mechanics it is discontinuous, not causally determinate and not well defined”<sup>6</sup>. One could add that QM deals with particles of no dimension, while GR diverges on punctual bodies, dealing rather with densities. So should one seek to express QM in a GR space-time or should one seek to express GR in some sort of a quantal model?

Recently, Alessio BENAOLI, Alessandro FACCHINI and Marco ZAFFALON [9] clearly showed “that QM is a theory of probability —not just that probabilities can be derived from QM”. To be more precise: QM has a second level, atop of logic and beneath mechanics: a quantal statistical and probability theory. Moreover, even though the usual GR interpretation views gravitation as a reciprocal effect between particles and a special object called space-time, this does not completely rule out mechanisms where gravitation would emerge from effects of the curvature of coordinates on quantum phenomena.

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stands quantum mechanics, it’s because he doesn’t.” These formulations follow suit with an old catchword of Niels BOHR: “Those who are not shocked when they first come across quantum mechanics cannot possibly have understood it” (cit. W. HEISENBERG, *Physics and Philosophy*, 1958). Many other thinkers of QM propagate a similar conception, leading to a form of resignation: “All of modern physics is governed by that magnificent and thoroughly confusing discipline called quantum mechanics... It has survived all tests and there is no reason to believe that there is any flaw in it... We all know how to use it and how to apply it to problems; and so we have learned to live with the fact that nobody can understand it” (Murray GELL-MANN, 1977, cit. I. B. COHEN, *The Newtonian Revolution*, 1983).

<sup>4</sup> *The Principles of Quantum Mechanics*, 1930, p. 7.

<sup>5</sup> Quantum Logic becomes classical when propositions commute [16] —see n. 37 and 41.

<sup>6</sup> *Wholeness and the Implicate Order*, 1980, p. xv.

Following discussions at the CERN, John BELL published uncommon views about “How to teach special relativity” [5]. According to him, we should “emphasize the continuity with earlier ideas”, sorry that “usually it is the discontinuity which is stressed, the radical break with more primitive notions of space and time”. He then argues that we could see SR as being phenomenal instead of fundamental. Following this inspiration, in this paper, we will endorse a third principle, a *measure principle*: all that we know about phenomena, is known through experience. Coordinates, momentum and the other physical quantities result from measure operations, and therefore from interactions. So even space-time may be phenomenal.

## 2 Special relativity as a phenomenon

### 2.1 A relativity without “rods and clocks”

The Special Relativity (SR) theory usually relies on an abstract concept of reference frame, with ideal “rods” and “clocks”. This view is incompatible with our measure principle, for which no quantity exists *in abstracto*. Howard ROBERTSON [37] showed that SR can be deduced from some general postulates and three experimental facts. We will use his work, expunged the notion of abstract reference frames, to find a SR formulation compatible with our principles.

ROBERTSON’s first postulate is that “there exists a reference frame —EINSTEIN’s ‘rest-system’— in which light is propagated rectilinearly and isotropically in free space with constant speed  $c$ ”. We reformulate this as the following<sup>7</sup>.

**Fact 1** (reference observer). *An observer  $\mathbf{O}$  exists, for which, in free space, light is propagated rectilinearly and isotropically at a constant velocity  $c$ .*

ROBERTSON, then, postulates “the existence of a reference frame [...] —EINSTEIN’s ‘moving system’— which is moving with any given constant velocity [...] with respect to [first reference frame]”, also supplied with abstract “rods and clocks”. We will disregard this postulate and only suppose that we can observe, in moving systems  $\mathbf{S}$ , relative remoteness and relative duration. Both are measured by means of interactions internal to  $\mathbf{S}$ , but outcomes of these observations can be traced from the outside,  $\mathbf{O}$ <sup>8</sup>. Here, note that the *remoteness* and *duration*, *coordinates*, are space and time distances at the macroscopic and quantum levels for  $\mathbf{S}$ . Their measures result from sub-quantum mechanisms, and therefore may have structures very different from those of sub-quantum contiguity and consecution *intervals*. For speed, we will use the terms *velocity* and *rapidity*, as usual, for the macroscopic and quantum phenomena; at the sub-quantum level, we will speak of *displacement pace* (table 1).<sup>9</sup>

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<sup>7</sup>Isotropy and constancy of light speed is one of the best verified physical facts, up to 17 orders of magnitude [20]. We implicitly incorporate the methodological principle that a reference observer exists (not necessarily unique).

<sup>8</sup>This point may sound quite evident. It is not. Its mathematical demonstration in QM is an essential result of Hugh EVERETT’s work [21]. See appendix 5.1.

<sup>9</sup>We do not view matter as *being in* space-time, but merely as *having* coordinates, as *descriptive* properties (emerging quantities, as we shall see).

macroscopic / quantum	sub-quantum
position in space-time	placement in sub-space and time
remoteness, duration, coordinates	interval (of contiguity and consecution)
velocity, rapidity	displacement pace

**Table 1.** vocabulary for usual quantities

Then, with ROBERTSON, let us suppose **S** is moving at velocity  $c\vec{\beta}$  and use clever axis representation (movement along  $x$  axis, especially); the transformation of coordinates between **O** and **S** has (locally) the following form.<sup>10</sup>

$$\Lambda_\beta = \begin{pmatrix} a_0 & \beta a_1/c & 0 & 0 \\ \beta a_0 c & a_1 & 0 & 0 \\ 0 & 0 & a_2 & 0 \\ 0 & 0 & 0 & a_2 \end{pmatrix} \quad (2.1)$$

The first fact to determine  $\Lambda_\beta$  is the MICHELSON–MORLEY type experiments, in **S**<sup>11</sup>:

**Fact 2** (MICHELSON–MORLEY). *In **S**, “The total time required for light to traverse, in free space, a distance  $l$  and to return is independent of its direction.”*

If we suppose this fact to be general, one can consider a light beam making any angle from the  $x$  axis, and then one finds the Lorentz–Fitzgerald contraction as a consequence:  $a_2 = a_1/\gamma$ —with Lorentz factor  $\gamma = 1/\sqrt{1-\beta^2}$ . Then, ROBERTSON [37] adds KENNEDY and THORNDIKE experimental result as: “The total time required for light to traverse a closed path in [a reference frame] is independent of the velocity [of this frame] relative to [first reference frame]”. The important thing is that we do not need to suppose  $c$  constant in **S**, but simply deduce it from being constant in **O**. We will state this fact as:

**Fact 3** (KENNEDY–THORNDIKE). *“The total time required for light to traverse a closed path”, as experienced from a system **S**, “is independent of the velocity of” **S** “relative to” **O**.*

Following ROBERTSON, again, one finds that  $a_0 = a_1 = \gamma g_\beta$  and  $a_2 = g_\beta$ . Eventually, one may conclude that  $\Lambda_\beta$  is a Lorentz transformation ( $g_\beta = 1$ ), if we add a last fact, the IVES and STILWELL experiments<sup>12</sup>:

**Fact 4** (time dilation). *“The frequency of a moving atomic source is altered by the factor”  $1/\gamma$  relative to the “velocity of the source with respect to the observer.”*

ROBERTSON wanted to show that one can “replace the greater part of EINSTEIN’s postulates with findings drawn inductively from the observations”, but our small reformulation, here, shows a more general fact. In any theory obeying this four experimental facts, local coordinates, measured from systems moving at constant velocity for a reference observer,

<sup>10</sup>We do not reproduce here the full extent of ROBERTSON’s proof, only the relevant differences.

<sup>11</sup>Note the difference with fact 1: this fact is about **S**, not **O**.

<sup>12</sup>This fact makes use of two relatively moving observers, but this can be interpreted coherently with our measure principle.

should be transformed according to a Lorentz transformation, at least for linear approximation<sup>13</sup>.

Can QM provide a frame for some sub-quantum theory from which one could derive these four facts? It would then be coherent with SR and would have locally a Minkowskian metrics (with linear approximation).

## 2.2 The potential particle model

In general, decoherence by the environment make the macroscopic experience diagonalize: all the macroscopic observables commute and the applicable logic and statistics are classical. But it is *not always* the case. For example, ASPECT’s experiments show that macroscopic statistics may not be classical, and violate the BELL’s inequality. More generally, if one considers a quantal binary alternative (a qubal —see appendix 5.3), an observer may measure outcomes that can be intrinsically correlated to other observations.

But what does mean here the word “possible”? In appendix 5.2, we describe what could be a quantal modal logic, a quantal logic for possibility. A possible solution state of a QM model is called *potential*<sup>14</sup>. In pilot-wave interpretations of QM, the wave-function describes the probabilities of the different potential outcomes, one of which only is real. In EVERETT’s relative state interpretation or in the popular many-world interpretation, all potential outcomes are as real, one of which is ours. In this article we will stick to physics and shall not come to interpretative questions. We will consider potential worlds, coherent observation models, but not discuss their reality.

Let us suppose we conduct a qubal experiment, leading to two potential outcomes: left and right. The observed system  $\mathbf{S}$  will evolve in a way such that an observer  $\mathbf{O}_1$  will measure “left” or “right”. Seen from the outside (observer  $\mathbf{O}_2$ ), we have two possible states  $[\text{left}]_{\mathbf{S}\bullet\mathbf{O}_1} = [l]_{\mathbf{S}} \otimes [L]_{\mathbf{O}_1}$  and  $[\text{right}]_{\mathbf{S}\bullet\mathbf{O}_1} = [r]_{\mathbf{S}} \otimes [R]_{\mathbf{O}_1}$ : system and observer have evolved to a pointer state. These states, or more generally Hilbert subspaces, act as impervious “worlds” because they cannot exchange any information [21].

Let us be conjectural now, and combine quantal modal logic with many physicists’ insight of quantum particles as the superposition of “virtual particles”. Quite generally, these “virtual particles” follow FEYNMAN’s paths conceptions [23, 24], as a means of computation or as a heuristic representation for quantum fields theories<sup>15</sup>: these virtual particles are meant to encompass all possibilities within a mathematical model. In our attempt at a theory, let us consider only *potential particles*: particles existing in potential worlds of minimal dimension accessible from some quantal potential world. These potential particles, again, are neither imaginable particles nor virtual particles of a model or another; these are conceived as physical, and hopefully experimentable. Note, however, that their potential worlds may not be quantal potential worlds, but only sub-quantum potential worlds, that might not be accessible to direct experimentation (we will come back to that matter hereun-

<sup>13</sup>Perhaps should we have stated it as an experimental fact, that in general this approximation is possible.

<sup>14</sup>In this article we will restrict the use of the term “potential” to this precise modal meaning, and leave “possible” to general or informal use.

<sup>15</sup>Virtual particles can also be seen as mathematical artifice to represent fields, similarly to HUYGENS–FRESNEL principle, see *e.g.* [23], esp. sec. 7.



der). Potential particles, surely, may have properties very different from those of quantum particles—in the same way as complex ions in solution have very different properties from bare ions. For example, if mass is an emerging property, one can imagine that, having no mass, potential particles propagate at a universal “displacement pace”  $c$ , whereas quantum particles can be measured at various velocity magnitudes. Physics for sub-quantum level has to be theorized; it may be extremely different from quantum and macroscopic ones. At the sub-quantum level of description, there may be nothing like a space-time we are used to, but, perhaps, only contiguity and consecution relations. The SCHROEDINGER’s equation at the quantum level might just be the result, by symmetry, of the superposition of numerous (perhaps infinite) potential interactions of potential particles.<sup>16</sup>

Virtual particles are generally supposed to encompass an infinite number of degrees of freedom: each virtual particle of QFT being a superposition of other virtual particles. This surmise causes severe divergence in the model. We will suppose here that any quantical model has a finite Hilbert dimension, though extremely huge<sup>17</sup>. This supposing, we are able to reason at the lowest dimensional level, dealing only with one potential world at a time. Moreover, we will suppose here that at any pertinent time one can have a Hilbert basis compatible with all potential particles having a displacement pace.

### 2.3 Kinetic theory of Special relativity

Some clues, mainly from contemporary theories, especially due to renormalisability questions, suggest that sub-quantum potential particles should be thought of without inertial mass. This mass would be acquired through a coupling mechanism. Present research favors the BROUT–ENGLERT–HIGGS–HAGEN–GURALNIK–KIBBLE (BEH) mechanism, *i.e.* interaction with BEH bosons, with some recent experimental support [3]. We shall not rely on the BEH theory but, in coherence with it, let us suppose all sub-quantum particles at the lowest dimensional level (potential particles) are massless. Accordingly, all of them have a displacement pace of the same magnitude (in some sort of sub-space-time). Between two interactions, the displacement pace of a potential particle would be uniform and have a specific direction<sup>18</sup>. During such an interval, the potential particles move like ideal non-interacting photons, whereas quantum particles do engage in interactions in different potential worlds, and so correspond to superpositions of potential particles. The less a photon interacts, the closer the “mean” displacement pace of its superposition will be, in magnitude, to the common pace. So, if we suppose that velocity accounts for some sort of “mean” displacement pace (see hereunder), light with minimum interaction will always have the same velocity magnitude,  $c$ , which we can identify with the only displacement pace magnitude of potential particles (to a factor). If the sub-space-time is supposed Euclidean, homogenous and isotropic, this would also account for facts 1 and 2. Note that we

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<sup>16</sup>Other authors proposed similar hypothesis, following hydrodynamical interpretation of QM (Madelung fluid), notably BOHM [11], figuring quantum particles as condensations of a sub-quantum fluid [7, see].

<sup>17</sup>There is no need to suppose that the Hilbert model space itself is finite dimensional; it is sufficient to suppose that the density operators representing states are of finite rank.

<sup>18</sup>We suppose it to be rectilinear, for now, but geometry of sub-space-time may appear to be more complex.

presuppose no sub-quantum notion of relative motion: on the contrary, all displacements occur at same pace magnitude, and all interactions emerge from combination and emission of sub-quantum potential particles in diverse directions<sup>19</sup>. This accounts for fact 3.

For fact 4, we need to be more precise. We will formalize the velocity of a particle as a mean displacement pace of the potential particles it is the superposition of.

First, let us consider a set  $I$  of potential particles (minimum dimensional), in which at least one of the particles exists. Even with entanglement, we can find an eigenbasis,  $[j]\langle j|$ , for all the momentum operators  $(\widehat{p}_{in})_{i \in I, n=1..3}$ , with the convention that for non-existing potential particles at that moment momentum is  $\vec{0}$ <sup>20</sup>. In each eigenstate  $[j]\langle j|$ , which corresponds to a potential world of minimal dimension,  $\vec{p}_{ij}$  is well defined by the triple  $(\langle \widehat{p}_{in} \rangle_j)_{n=1..3}$ . Since all potential particles are supposed massless,

$$\vec{p}_{ij} = \frac{h}{c} \nu_{ij} \vec{\beta}_{ij}, \quad (2.2)$$

where  $\vec{\beta}_{ij}$  is a unit vector —the displacement pace of the potential particle  $i$  in state  $[j]\langle j|$ . If that particle does not exist in this potential world at that time,  $\nu_{ij} = 0$  and  $\vec{\beta}_{ij}$  is arbitrary. Energy content of the particle is also well defined:  $\langle E_i \rangle_j = h \nu_{ij}$ . In SR, for massive particles,  $E = \gamma m c^2$  and  $\vec{p} = \gamma m \vec{v}$ , that is  $\vec{p} = \frac{E}{c} \vec{\beta}$ . This relation is also true for massless particles:  $E = h \nu = p c$ . So, in state  $[j]\langle j|$ , let us define for  $I$ :  $\vec{\beta}_{Ij} := \frac{c \vec{p}_{Ij}}{E_{Ij}}$  the velocity, where  $\vec{p}_{Ij} := \sum_{i \in I} \vec{p}_{ij}$  the momentum, and  $E_{Ij} := \sum_{i \in I} E_{ij}$  the energy content. Since all potential world accessible from observation world only develops particles into potential particles, the existing set  $I$  can vanish in no such potential world:  $E_{Ij} \neq 0$ , and therefore  $\vec{\beta}_{Ij}$  is well defined as a triple of hermitian operators. Above definition reformulates to:

$$\vec{\beta}_{Ij} = \frac{\sum_{i \in I} \nu_{ij} \vec{\beta}_{ij}}{\sum_{i \in I} \nu_{ij}}. \quad (2.3)$$

Now, let  $\rho$  be a state:  $\rho = \sum_{j \in J} \lambda_j [j]\langle j|$ . If we suppose an equal energy content in every potential world  $j$  the superposition of which  $\rho$  is,  $N_{I\rho} = \sum_{i \in I} \nu_{ij}$ .

$$\vec{\beta}_{I\rho} = \frac{\sum_{i \in I} \nu_{ij} \vec{\beta}_{ij}}{N_{I\rho}}. \quad (2.4)$$

But momentum is

$$\langle \vec{p}_I \rangle_\rho = \sum_{j \in J} \lambda_j \vec{p}_{Ij} = \sum_{j \in J} \sum_{i \in I} \lambda_j \vec{p}_{ij}, \quad (2.5)$$

<sup>19</sup>For potential particles, there can probably be no notion of a trajectory: since quantum particles of the same type are indistinguishable, i.e. logically identical, so should be underlying potential particles. A potential particle, in a potential world, only exists between two interactions.

<sup>20</sup>We note  $\widehat{x}$  hermitian operators,  $\langle \widehat{x} \rangle_\rho$  operator expectations,  $[j]$  and  $\langle j|$  normalized DIRAC's kets and bras,  $[j]\langle j|$  associated projector/density operator,  $\vec{x}$  a three-dimensional coordinate/velocity vector (a triple of expectations or a triple of operators).

so, if we define:

$$\vec{\beta}_{I\rho} := \frac{c \langle p_I \rangle_\rho}{\langle E_I \rangle_\rho}, \quad (2.6)$$

and we note that  $E_{Ij} = \sum_{i \in I} h \nu_{ij} = h N_{I\rho}$ , then

$$\vec{\beta}_{I\rho} = \frac{\sum_{i \in I, j \in J} \lambda_j \nu_{ij} \vec{\beta}_{ij}}{N_{I\rho}}. \quad (2.7)$$

Velocity, momentum and energy content can be coherently defined as emerging quantities in a way not unlike the emerging quantities in the kinetic theory of gases.

If the potential particles have a balance between the potential directions (isotropy in pace), emerging velocity is zero. The velocity magnitude rises with a common orientation in some direction of displacement. In the limit, if a vast proportion of displacement paces of potential particles heads in the same direction, the emerging velocity magnitude will be close to  $c$ .

Now, let us imagine two mono-directional streams of potential particles; if they have the same direction, they have no possibility for interaction, since they both are displaced at the same pace magnitude —the greyhound cannot catch the rabbit. At angle  $\pi$ , on the opposite, the probability of interaction is at a maximum. At angle  $\theta$ , we can imagine a relative interaction propensity progressing with  $(1 - \cos \theta)$ , that is  $(1 - \vec{\beta}_{i_1} \cdot \vec{\beta}_{i_2})$ . In this hypothesis, accelerating a quantum particle in a direction amounts to raise the number of potential particles in this direction. Each interaction then tends to replace more frequently a potential particle in the opposite direction by a potential particle with another direction, and so raises the level of directionality.

Now let us come back to fact 4 and consider a system  $S$  in which there are two disjoint parts  $S_1$  and  $S_2$  potentially interacting. Their velocities are  $c\vec{\beta}_S$ ,  $c\vec{\beta}_{S_1}$  and  $c\vec{\beta}_{S_2}$ . If we suppose  $S$  coherent enough (this is generally implied), then  $\vec{\beta}_{S_a} = \vec{\beta}_S + \vec{b}_a$  with  $b_a \ll \beta_S$ .

In our framework, for each potential particles  $i_1$  in  $S_1$  and  $i_2$  in  $S_2$  there is a propensity factor for interaction of  $(1 - \vec{\beta}_{i_1} \cdot \vec{\beta}_{i_2})$ . The overall factor is thus

$$f = \sqrt{\prod_{i_1 \in S_1, i_2 \in S_2} (1 - \vec{\beta}_{i_1} \cdot \vec{\beta}_{i_2})^{\frac{\nu_{i_1}}{N_{S_1}} \frac{\nu_{i_2}}{N_{S_2}}}}. \quad (2.8)$$

Since  $\nu_{i_a} \ll N_{S_a}$ ,

$$f^2 \approx 1 - \sum_{i_1 \in S_1, i_2 \in S_2} \frac{\nu_{i_1}}{N_{S_1}} \frac{\nu_{i_2}}{N_{S_2}} \vec{\beta}_{i_1} \cdot \vec{\beta}_{i_2} \quad (2.9)$$

$$= 1 - \left( \sum_{i_1 \in S_1} \frac{\nu_{i_1}}{N_{S_1}} \vec{\beta}_{i_1} \right) \cdot \left( \sum_{i_2 \in S_2} \frac{\nu_{i_2}}{N_{S_2}} \vec{\beta}_{i_2} \right) \quad (2.10)$$

$$= 1 - \vec{\beta}_{S_1} \cdot \vec{\beta}_{S_2} \quad (2.11)$$

$$= 1 - \beta_S^2 - \vec{\beta}_S \cdot (\vec{b}_1 + \vec{b}_2) - \vec{b}_1 \cdot \vec{b}_2 \quad (2.12)$$

$$\approx 1 - \beta_S^2. \quad (2.13)$$

We find a probability factor of  $\sqrt{1 - \beta_S^2} = \frac{1}{\gamma}$ , therefore a time dilation factor of  $\gamma$ . This accounts for fact 4 and shows that proper time of a quantum particle emerge as a collective property of its component potential particles —without the needs to consider any mass.

This quantical *kinetic theory of Special Relativity* reformulates SR in the context of finite-rank QM, without the needs of a QFT. It makes use of a displacement pace representation for potential particles and make emerge a phenomenal time-dilation factor on the wave function. How could we integrate gravitation in such a framework?

### 3 The potential particle model and gravitation

#### 3.1 An equivalence principle

As early as 1905, Albert EINSTEIN [19] notes that in SR energy content decomposes into kinetic energy ( $K$ ) plus a constant, the energy content at rest. On that basis, if a body symmetrically emits light for energy  $L$ , EINSTEIN notes that  $K_{\text{before}} - K_{\text{after}} = (\gamma - 1)L$ . Since  $K \approx \frac{1}{2}M.v^2$ , he concludes: “If a body gives off the energy  $L$  in the form of radiation, its mass diminishes by  $L/c^2$  [...] radiation conveys inertia between the emitting and absorbing bodies.” Here, EINSTEIN assimilates inertia (*Trägheit*), moving mass, and energy content (*Energieinhalt*). This reasoning is very general in its form, and thus valid also in our sketch framework with emerging kinetic energy. It is also coherent with observations, now numerous. So let us acknowledge this equivalence and consider inertia and (ponderous) energy content as equivalent.

**Fact 5.** *A body of mass  $m > 0$  at rest has got an energy content  $m c^2$ .*

#### 3.2 A fundamental experiment

In our potential particle model, particles of potential worlds of minimal dimension (potential particles) bear some resemblance to photons. They are massless, especially. So, one may anticipate that they behave in gravitation not unlike photons. For these, the main observable phenomenon is their “gravitational redshift” —which is, in fact, a blueshift when going inwards a gravitational well and a redshift when going outwards. In our environment, the reference quantitative facts about this phenomenon are the POUND–REBKA–SNIDER’s experiments [33–35] that confirmed that this frequency shift is quantitatively equivalent to a Doppler–Fizeau effect. Later on, the global navigation satellite systems added an extensive experimental confirmation [2, 49].

**Fact 6** (gravitational frequency shift). *Outside of a ponderous body of Schwarzschild radius  $R_s$ <sup>21</sup>, a photon undergoes a shift in frequency when it moves from distance  $r$  to distance  $r'$ , quantitatively:*

$$\frac{\nu'}{\nu} = \frac{\sqrt{1 - \frac{R_s}{r}}}{\sqrt{1 - \frac{R_s}{r'}}}. \quad (3.1)$$

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<sup>21</sup>We use here the SCHWARZSCHILD approximation: spherical non-rotating body with only massive energy content ( $Mc^2$ ). Then,  $R_s = 2GM/c^2$ .

If the variation in distance is small,  $\delta r \ll r$ ,

$$\frac{\delta \nu}{\nu} \approx -\frac{R_s}{2} \frac{\delta r}{r^2} = -\frac{G M}{c^2} \frac{\delta r}{r^2}. \quad (3.2)$$

### 3.3 Kinetic theory of Newtonian gravitation

Now, let us consider a system  $S$  consisting of potential particles,  $i \in S$ . For each of these potential particles let us note  $\vec{\beta}_i$  the displacement pace. This pace is an hermitian operator, for which we will again reason in an eigenbasis. In such a basis, the potential particles may not have a definite position, but if we consider  $S$  compact enough, compared to  $r$ , we can consider that  $r$  is the same for all  $i \in S$  and that we can define a unique centrifugal unit vector  $\vec{z}$ . Then,

$$\delta r_i = \vec{z} \cdot \vec{\beta}_i \delta t. \quad (3.3)$$

So, if we suppose that fact 6 applies to potential particles,

$$\frac{\delta \nu_i}{\nu_i} = -\frac{r_s}{2r^2} \vec{z} \cdot \vec{\beta}_i \delta t. \quad (3.4)$$

Now, let us evaluate the variation in energy content of  $S$ , with modal velocity (2.4):

$$\frac{\delta E_S}{E_S} = \frac{\sum_{i \in S} -h \nu_i \frac{R_s}{2r^2} \vec{z} \cdot \vec{\beta}_i \delta t}{h N_S} \quad (3.5)$$

$$= -\frac{R_s}{2r^2} \vec{z} \cdot \frac{\sum_{i \in S} \nu_i \vec{\beta}_i}{N_S} \delta t \quad (3.6)$$

$$= -\frac{R_s}{2r^2} \vec{z} \cdot \vec{\beta}_S \delta t \quad (3.7)$$

$$= -\frac{G M}{r^2 c^2} \vec{z} \cdot \vec{\beta}_S \delta t \quad (3.8)$$

When the kinetic energy is small, fact 5 applies, so

$$\delta E = \frac{G M m_S}{r^2} \vec{z} \cdot \vec{\beta}_S \delta t, \quad (3.9)$$

And we can integrate  $\vec{\beta}_S$  along the trajectory:

$$\Delta E = \frac{G M m_S}{r^2} \Delta r. \quad (3.10)$$

Thus, the gravitational “redshift” applied to the minimal potential particles is sufficient to make the Newtonian gravitation emerge.

## 4 Is gravitation acting between alternate worlds?

Can we describe further on the relation between the potential worlds and the gravitation and connect our reasoning to GR?

#### 4.1 The potential particle model and gravitation

GR decomposes gravitation into two components: 1) all forms of energy, modelled by an density field  $\hat{T} = (T_{\mu\nu})$ , produce a curvature of a special object called space-time, 2) everything in the universe when submitted to no influence other than gravitation follows a geodesic of this object<sup>22</sup>. We will not presuppose GR but we shall keep this decomposition. Since there is experimental evidence that gravitation propagates, we will call these two components emission and reception of gravitation, or *emitted* and *received gravitation*.

In our sketch framework, any potential particle is massless and supposedly associated with a frequency  $\nu$  corresponding to an energy in  $h\nu$  and a momentum in  $h\nu/c$ . As a heuristic, one may thus view energy–momentum as some sort of effervescence of potential particles (each one counted with its frequency  $\nu$ ), or some sort of sub-quantum scrum. Emerging as a superposition of sub-quantum potential particles, energy is this scrum’s time flow, and momentum its space flow. More potential particles make more inertia emerge. We emphasize that this is a heuristic view: since potential particles are continuously being absorbed and emitted, from the quantum or above level viewpoint we essentially count the superposition; much in the same way as the HUYGENS–FRESNEL principle represents wave propagation as a continuous re-emission of punctual sources on wave surfaces, one can think of a trajectory as a superposition of numerous creations and annihilations of potential particles, corresponding to minimum dimensional potential worlds. In this picture, from a sub-quantum level viewpoint, the quantum particles merely exist as correlated propagations of interaction. If our framework is correct, the traditional view of gravitation as an interaction between two inertias, *i.e.* two energy contents, holds no more. Two collectives cannot indeed interact *per se*: interaction should also mean something at the sub-quantum level. We will now formulate an experimentable hypothesis on that matter.

Clifford WILL in his review of experimental tests of GR [49] considers that “it is possible to argue convincingly that if EEP [Einstein’s equivalence principle]<sup>23</sup> is valid, then gravitation must be a ‘curved space-time’ phenomenon, in other words, the effects of gravity must be equivalent to the effects of living in a curved space-time. As a consequence of this argument, the only theories of gravity that can fully embody EEP are those that satisfy the postulates of ‘metric theories of gravity’ [...]”. Note that “living in a curved space-time”, in our framework is a matter of measured coordinates and may be an emerging property of space-time, or even of sub-space. So, pushing our investigations further, the question is now: on which level of physical modeling does gravitation play?

We see three main possibilities.

1) We can imagine gravitation as being essentially a quantum level phenomenon. In that case, GR curved metrics may emerge from sub-quantum phenomena in some way similar to what we suggested for SR or Newtonian gravitation.

<sup>22</sup>See appendix 5.4 for a more thorough discussion on that matter.

<sup>23</sup>Following Robert DICKE, *Einstein’s equivalence principle* is the weak equivalence principle (WEP, see app. 5.4) plus *local Lorentz invariance*: “the outcome of any local non-gravitational experiment is independent of the velocity of the freely falling reference frame in which it is performed”, plus *local position invariance*: “the outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed” [49, see].

Otherwise, one can imagine that gravitation plays essentially at the sub-quantum level, with two (compatible) variants:

2.a) Sub-space, *i.e.* the intervals, is not Euclidean but “curved” by energy content, not unlike the case of QFTs in curved space (B. UNRUH, S. HAWKING, R. PENROSE, R. WALD).

2.b) Some sort of “force” is exerted between potential particles.

There has been a lot of research on quantical gravitation, leading for the time being to no generally accepted theory. We will therefore leave the first hypothesis (1) aside, to begin with. The second hypothesis (2.a) is at the very least untimely: it would be too speculative for our roughly sketched theory, since we have no proposal, yet, for the mathematical structure of intervals. So, we will explore the third hypothesis (2.b).

## 4.2 The trans-world gravitational hypothesis

Is gravitation exerted at the quantum particle level? Does it use some sort of vector particles, *i.e.* gravitons? Or does gravitation differ from the “other interactions”? There is another entry point into addressing these questions: is the weight an in-world phenomenon, *i.e.* a phenomenon limited to each potential world, like “other interactions”, or is it exerted across worlds, that is also between worlds otherwise inaccessible?

In our hypothesis, inertia and gravitation are proportional to the energy content of all potential particles in a given location. More precisely, it corresponds to linearity with respect to mass for given and received Newtonian gravitation, to linearity of given Einsteinian gravitation of the stress-momentum-energy tensor, and to linearity of the geodesic movement of received Einsteinian gravitation. If this hypothesis is correct, gravitation given by a body, resulting from its energy content, would apply to all potential particles indifferently, and thus its given gravitation would apply to *all* potential worlds. Considering this phenomenon the other way round, test bodies would receive a gravitation that would be the superposition of gravitation from *all* possible worlds.

Pushing the hypothesis further, if  $|\psi\rangle = b_1|\psi_1\rangle + b_2|\psi_2\rangle$ , with  $|b_1|^2 + |b_2|^2 = 1$ , we could imagine that received gravitation should be something like  $g = |b_1|^2 g_1 + |b_2|^2 g_2$ . Let this be our formal hypothesis, and let us look at experimentable consequences.

**Hypothesis** (*trans-world gravitation*). *Gravitation acts at the sub-quantum level, and produces its effects between worlds according to the coefficients of BORN’s rule.*

A lot of conjectures and suggestions have been made to explain difficulties with gravitation. Our assumption, on the contrary, is a *testable hypothesis*, as we shall see in the following section. Would it be in accordance with the experiment, it would also institute Born coefficients, or propensity probabilities, as a directly observable quantity.

## 4.3 Crucial experiment

The experiment we advocate combines a qubal<sup>24</sup> and a gravitation test. Providing nothing induces unwanted decoherence along the measurement chain, we could use any type of qubal, for example a measure of a randomized qubit, or of a spin in a Bell pair. In this

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<sup>24</sup>See appendix 5.3. The qubal, or quantal simple binary alternative, has an ambition similar to SCHROEDINGER’s cat or WIGNER’s friend, but with a clearly formulated experimental protocol.



experiment, we would have a qubal with results “1” and “2” determining the position of a heavy context body  $M$ , test body being a gravimeter. In branch 1 of the alternative, that is if result “1” appears, body  $M$  will be put in place  $r_1$  at some date  $t$  previously defined. In branch 2, that is if result “2” appears, mass  $M$  will be put in place  $r_2$  at the same date  $t$ . If we except gravitation, any observer in branch 1 can note then that  $M$  is in position  $r_1$ , by view or contact, for example. If the trans-world gravitation hypothesis is valid, it will not be the case with gravity.

Let us suppose this qubal has Born coefficients  $b_1$  and  $b_2$ . Classically, measurable gravity strength given by  $M$  would be  $g_1$  in case 1, and  $g_2$  in case 2. The experimental context body may be, for example, a 1 t quarry stone moved from a distance to a point  $d_1 = 1$  m away from the gravimeter in case 1, and remaining distant in case 2<sup>25</sup>. With a rough evaluation  $g_2 \ll g_1$ , and  $g_1 = G M/d_1^2 \approx 7 \times 10^{-11} \times 10^3/1^2 = 7 \times 10^{-8} \text{ m.s}^{-2} = 7 \text{ } \mu\text{Gal}$ . This value comes in the range of today’s microgravimetry instruments. If our hypothesis is correct, and if effect follows the measurement chain, received gravity strength would be  $g \approx |b_1|^2 g_1$ . In particular, if the qubal branches are equiprobable, then  $g \approx \frac{1}{2} g_1$ .

An experimental success would urge us to revise large-scale gravitational reasoning and take into account the gravitation received from alternate potential worlds. We will shortly explore some possible consequences of such an effect in the following sections. These hypothetical consequences are incentives to experiment our trans-world gravitation hypothesis, since it would then link several topical difficulties. On the contrary, a failure of this experiment would suggest that gravitation is confined to potential worlds and respects EVERETT’s relative state separation, and thus that gravity may be ultimately linear in some wave-function representation, an invitation to elaborate quantical theories of gravitation. In both cases, we would better understand possible articulations of gravitation and quantical physics.

We will now explore some possible consequences of the trans-world gravitation.

#### 4.4 Exploration of consequences

If the trans-world hypothesis is confirmed, our framework anticipates that we could perceive gravitation received from other potential worlds, *i.e.* gravitation originating from no source in our world. Could this “shadow gravitation” explain some aspects of the cosmic inflation, the dark matter and/or the cosmological constant?

##### 4.4.1 Potential worlds and cosmic inflation

The idea of the cosmic inflation was developed in the early 1980s by Alan GUTH [27]. It is generally thought to be a phase transition of the early universe, and is still in want of a generally accepted explanation. In GR it could be linked to a term similar to the cosmological constant in the energy-momentum stress tensor, and/or be an early effect of a scalar field. Cosmic inflation is modeled as a metric expansion of the universe. It is believed to be exponential and to correspond to 26 orders of magnitude, at least —considerably more

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<sup>25</sup>One can also imagine making use of the heavy bodies of the building industry: bridge elements, building parts, or even entire buildings (in Zurich in 2012 a 6 200 t historical building was moved 60 m away).



in some models. Its duration is extremely hypothetical; in some theories, inflation is even perpetual in some parts of the universe. The main justification for this idea is that it solves the horizon and flatness problems<sup>26</sup>. The foremost observational evidence in favor of inflation is the CMB, which is very homogeneous, and whose variations are interpreted as inhomogeneities corresponding to “quantum fluctuations” scaled up by the inflation process. How could we address this question within our framework?

Cosmology suggests that there are two main effects of gravitation —or space-time curvature, whatever the cause: the first one is attractive and directed, the other is (metrically) expansive and isotropic. In a symmetric situation, the balance of forces nullifies the first effect. In an early stage of the universe, before the separation of relative states (or potential worlds), such a situation occurs, leaving only the expansive component of gravitation. Cosmic inflation could be understood as a measure of the universe’s gravitational symmetry. Without our hypothesis, this symmetry is very soon destroyed and inflation is often supposed to last something like  $10^{-33}$  s or  $10^{-32}$  s. If there is trans-world gravitation, the universe perceived by gravitation is much more symmetrical and homogeneous than the same universe seen by electromagnetic radiations: quantal fluctuations produce no gravitational asymmetry and so inflation may last longer. In such a situation, inflation would cease, or become negligible, when trans-world received gravitation (*i.e.* gravitation given by alternate worlds) becomes relatively small, compared to in-world inhomogeneities. Quantitatively, we only know that this situation happens before the decoupling epoch (the CMB wall), at redshift  $z \approx 1000$ . To investigate further, one would have to evaluate the quantitative incidence of the two effects.

#### 4.4.2 The shadow gravitation as dark matter

**The discrepancy between the visible and dynamical matter** As early as 1933, Fritz ZWICKY noticed a discrepancy between the matter visible due to its electromagnetic emissions and the dynamical mass according to observable gravitational effects<sup>27</sup>. This is the origin of the generic term “dark matter”. “[By 1980] Astronomers in general thought in terms of rather conventional dark matter —cold gas, very low-mass stars, failed stars (or super planets), stellar remnants such as cold white dwarfs, neutron stars, or low-mass black holes”. This conventional dark matter is generally called “baryonic dark matter”, since most of its energy content is made of baryons. Part of this dark matter, mainly X-ray emitting gas in galaxy clusters, has now become visible; part is still invisible, but its proportion in the universe’s energy content is quite precisely estimated. The WMAP satellite observations of the CMB fluctuation spectrum are in excellent agreement with a flat universe as it is today ( $\Omega_{\text{total}} = 1.099 \pm 0.1$ ) and with the “concordance model of the Universe”:  $\sim 5\%$  baryonic matter,  $25\%$  cold dark matter,  $70\%$  dark energy. Observations and theoretical models of the early universe have set a constraint for baryonic matter quantity:  $\Omega_b = 4\% \cdots 5\%$ , so

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<sup>26</sup>The horizon problem is that of the relative large-scale homogeneity and isotropy of the universe. The flatness problem is that of the almost critical density of a flat space-time in GR. Observations, especially from the *Planck* satellite, confirm that the space-time curvature is under 0.005 [32].

<sup>27</sup>Quotations and historical facts about dark matter without explicit reference are from [41].

“only one tenth of the baryons are actually shining”<sup>28</sup>. “The remainder of the mass-energy content of the Universe is thought to consist partly of dark matter that is unidentified, and primarily of dark energy of even more uncertain nature. The dark matter fills the Universe, promotes structure formation and accounts for the discrepancy between the visible and dynamical mass of bound astronomical systems such as galaxies and clusters; it is the major constituent of such systems.” In 2009, and still today, “the candidate dark matter particles have not been detected independently of their presumed gravitational effects”. Robert SANDERS [41] concludes that “the existence of dark matter remains hypothetical and is dependent upon the assumed law of gravity or inertia on astronomical scales. So it is not at all outrageous to consider the possibility that our understanding of gravity is incomplete.”

**Shadow gravitation** If there is some trans-world gravitation, we receive gravitation from all worlds, from matter present in our world and from matter existing in alternate potential worlds. In other words, gravitation is the contribution of our world and of some sort of *gravitational shadow of alternate worlds*. This gravitational shadow acts as if it were some sort of matter (*i.e.* energy content) interacting with usual matter by no means other than gravitation. Thus, it does contribute to the “dark matter”.

Now, let us imagine the early fluctuations that initiated the build-up of a galaxy. In the alternate worlds with a long common history (the modally close worlds), the counterparts of this galaxy may have vastly different orientations and positions. In fact, if universe structures are distant descendants of quantum fluctuations, the alternate worlds should reflect that any interaction may correspond to multiple potential outcomes in multiple directions and that any sub-quantum “trajectory” may correspond to multiple moments of interaction. At the galaxy scale, one can imagine that gravitation given by alternate worlds’ counterparts produce something like a halo, interacting purely by means of gravitation. This may account for galactic stability.

Finally, the observation of the “Bullet” galaxy cluster (1E 0657–558,  $z = 0.296$ ) showed that “[any] nonstandard gravitational force that scales with baryonic mass” is insufficient to account for the decoupling between the visible mass (galaxies and X-ray emitting plasma) and the map of gravitational strength (projected along the line-of-sight) by weak gravitational lensing methodology [13]<sup>29</sup>. More precisely, this map suggests that “unobserved matter, whatever it is, behaves like the stars and not like the hot diffuse gas — it is dissipationless” [41]. This is precisely what we could expect if this “matter” is the gravitational shadow of galaxies of alternate potential worlds.

**MOND and kinetic theory of relativity** In 1983, Mordehai MILGROM published an alternative proposal to non-baryonic dark matter: a modification of NEWTON’s second

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<sup>28</sup>Luminous part:  $\Omega_v \approx 3\%$ , X-ray emitting gas of galaxy clusters:  $\Omega_g \approx 2.5\%$ , so shining baryonic matter:  $\Omega_v + \Omega_g \approx 5\%$ . Other components can also be estimated; CMB:  $\Omega_{\text{CMB}} = 5 \times 10^{-5}$ , neutrinos:  $\Omega_\nu \approx 3\% \cdots 10\%$ . See [41] for references.

<sup>29</sup>Douglas CLOWE *et al.* [13] also mention that “other merging clusters, MS 1054–03 (Jee et al., 2005) and A520 (in preparation), exhibit similar offsets between the peaks of the lensing and baryonic mass, although based on lensing reconstructions with lower spatial resolution and less clear-cut cluster geometry.”

law of motion or a modification of NEWTON’s law of gravitation. In this phenomenal theory, Newtonian gravitational strength,  $a = \frac{GM}{R^2}$ , becomes  $\frac{a^2}{a_0} = \frac{GM}{R^2}$  in the case of tiny accelerations:  $a \ll a_0$ . As of today, this Modified Newtonian dynamics (MOND) has no theoretical foundation, but it is greatly resilient to observational evidence. Furthermore, it explains more phenomena than the cold dark matter model. [41, see]

Being tentative, let us put forward an idea which could lead to some theoretical justification of MOND. We saw above that Newtonian gravitation can be deduced, in our kinetic framework, from the gravitational redshift (sec. 3). One could also imagine a similar reasoning with (non-directional) redshift due to the universe expansion,  $\frac{H_0 d}{c}$ . Both effects could compensate for  $\frac{\delta r}{r^2} \frac{2GM}{c^2} \approx \frac{H_0 \delta r}{c}$ , *i.e.*  $\frac{GM}{r^2} \approx \frac{H_0 c}{2}$ . So, one can expect something to happen when gravitational strength goes down to the order of magnitude of  $H_0 c/2 \approx 3 \times 10^{-10} \text{ m.s}^{-2}$ —close to the MOND order of magnitude ( $a_0 \approx 10^{-10} \text{ m.s}^{-2}$ ).

#### 4.4.3 The cosmological constant and trans-world gravitation

**The cosmological constant problem** For each quantum field theory, even a space totally devoid of particles (its idealized zero-point state) still “contains” virtual particles: this is called its *vacuum*. The question is: do these vacua contribute to weight? It is commonly believed they do, in the form of the cosmological constant  $\Lambda$ , but this belief does not come without trouble. In their historical survey, Svend Erik RUGH and Henrik ZINKERNAGEL [38] “distinguish at least three different meanings to the notion of a cosmological constant problem: 1. A ‘physics’ problem: QFT vacuum  $\leftrightarrow \Lambda$  [...] 2. An ‘expected scale’ problem for  $\Lambda$  [...] 3. An ‘astronomical’ problem of observing  $\Lambda$ ”. We will focus here on the second point, named the “vacuum catastrophe” by Ronald J. ADLER *et al.* [1], noting that “numerous papers have been written about it”.

The zero-point energy density is believed to be evaluated by counting the QFT modes and applying a cutoff to elude divergence. This (strong) divergence is not *per se* an extraordinary difficulty—and it is physically somewhat understood; the “vacuum catastrophe” is the fact that even with a reasonable cutoff, the zero-point energy density is evaluated to be way bigger than astronomical observations—and this fact is not at all understood. If we limit ourselves to the electroweak theory and set a 100 GeV cutoff,  $\rho_{\text{vac}}^{\text{EW}} \sim 10^{46} \text{ erg.cm}^{-3} = 10^{45} \text{ J.m}^{-3}$ . “This is already a huge amount of vacuum energy attributed to the QED ground state which exceeds the observational bound on the total vacuum energy density in QFT by  $\sim 55$  orders of magnitude” [38]<sup>30</sup>. If we set the cutoff at the Planck energy level, the same evaluation rises up to  $\sim 120$  orders of magnitude. “This is probably the worst theoretical prediction in the history of physics!”<sup>31</sup> Moreover, this is only for QED; accounts of other quantum field theories are extremely challenging: introducing the BEH mechanism requires a massive choice, so to say, and the overall procedure is very model dependent<sup>32</sup>. Finally, we should add that a huge value for the cosmological constant

<sup>30</sup>Gravitational observations (in the context of a model) constrain  $\rho \lesssim 10^{-9} \text{ J/m}^3$ —see *e.g.* [1, 38].

<sup>31</sup>M. P. HOBSON, G. P. EFSTATHIOU, A. N. LASENBY, *General Relativity: An introduction for physicists*, Cambridge University Press, 2006, p. 187.

<sup>32</sup>Even in the case of QED, far better understood than QCD, the procedure is not sound: the energy density estimation depends on the cutoff—which is based on a belief—and on the regularization of a

is coherent with the inflationary model [27].

The theoretical connection of zero-point energy density and gravitation is, for the time being, highly speculative as, on the one hand, energy in QM, as in classical physics, is defined only to a constant, and, on the other hand, gravitation in GR is given by any form of energy content, with an absolute value. In the future, any expected connection between QFTs and GR will have to deal with this gap [47, see]. At present, we know no experimental result linking gravitation and any QFT, so it is only speculative whether or not we can assimilate (mechanical) energy in the sense of QFTs to energy (content) in the sense of GR. We can broaden the question, taking into account one of the best predictions of physics: gravitation is so faint, compared to the “other forces” that one can compute the magnetic moment of the electron up to eleven exact digits without taking gravitation into account *at all*.

**Trans-world analysis of vacuum** Can our framework shed some light on this situation? It can at least raise some questions. Do the QFT vacua exert their effects in each potential world or are these vacua trans-world phenomena? Is vacuum gravitation “diluted” with time or is it essentially time-independent? If we consider given and received gravitation, it would certainly be a surprise if the QFT vacua gave no gravitation, but what could be the meaning of receiving gravitation for a ground state? Even more fundamentally, are the QFT vacua to be thought of as objects or as mere reification of relations between objects?<sup>33</sup>

In our framework, any quantum particle is a swarm of potential particles, the boundary of which is mostly the choice of a representation. In a way, a vacuum contributes to all quantum particles. The vacua are often presented as fluctuations in time of void space. This representation is not actually coherent: the vacuum state corresponds to the lowest energy eigenspace of the free Hamiltonian of a QFT, so it is not much a fluctuation in time (it does not change), but variations between potential worlds. Thus, vacua should be best viewed as trans-world phenomena, and one can therefore expect that they dilute their gravitational effect with the increasing modal distance between all worlds. If this is the case, 120 orders of magnitude would indeed not be that big, corresponding, roughly, to  $\log_2 10^{120} \approx 400$  symmetrical qubals. Nevertheless, since they are not really objects, QFT vacua do not

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delta-function by a volume —the symmetries of which have a major incidence on the result.

<sup>33</sup>Reflection about the motion started to be questioned rationally, in the Ancient times, by conceiving the empty space. Later, GALILEO used this notion for his relativity principle, and NEWTON considered it a necessary basis for establishing his laws. Some notion of “free space” is also fundamental for relativity: we supposed it, implicitly, when expressing facts 2 and 3, above. Blaise PASCAL, a philosopher and experimenter, made a clear distinction between empty space (*vide*, emptied space, space devoid of matter) and nothingness (*néant*): nothingness has no quality, contrary to empty space. The interpretation of his experimental setups would be different today, but we can still keep the fundamental difference between a space *physically* devoid of matter and an *ideal* space-time with no content. Sticking to experimental facts, we know now that the intergalactic space contains  $\sim 10^{-12} \text{ m}^{-3}$  molecules. Even the extreme empty space between galactic clusters contains at least the cosmic microwave background. Closer to us, extreme laboratory empty space would certainly also contain the cosmic neutrino background estimated  $\sim 5.10^{-5} \text{ m}^{-3}$  at 1.9 K on a theoretical basis [14]). So, everywhere, there is matter — or, to be more exact, a probability of the presence of matter. The vacua do not exist as physical states of a place.

gravitate, *stricto sensu*; the participating particles give and receive gravitation, but not the vacua themselves.

## 5 Appendices

### 5.1 Measure and objectivity in QM

Copenhagen school views on QM did not allow separation between the observed system,  $\mathbf{S}$ , and the observer,  $\mathbf{O}$ . John VON NEUMANN’s *Grundlagen* [45]<sup>34</sup> introduced a first separation showing that quantal probabilities reduce to classical ones in a measurement experiment, along the measurement chain. The analysis of the decoherence phenomenon [50, 51] showed later that the environment,  $\mathbf{E}$ , of an experiment makes its wave-function evolve rapidly, resulting in its diagonalization on a “pointer basis”. This explains the “classical aspect of our world”, but does not exhaust the subject of objectivity, *i.e.* the compatibility of observations by different observers of a same experiment.

This matter was first physically addressed by Hugh EVERETT [21]. EVERETT notes that interactions  $\mathbf{S} \bullet \mathbf{O}_1$ , *i.e.* a first observer ( $\mathbf{O}_1$ ) apparatus, are phenomena for a second observer  $\mathbf{O}_2$ . Thus, one must be able to analyze experimental observations as interactions between a system,  $\mathbf{S}$ , an observer,  $\mathbf{O}_1$ , and, possibly, an environment,  $\mathbf{E}$ . Moreover, a coherent measure theory must account for intersubjectivity: when there are two observers reciprocal observations must be reconcilable ( $\mathbf{O}_2$  from  $\mathbf{O}_1$  and  $\mathbf{O}_1$  from  $\mathbf{O}_2$ ). He discusses  $(\mathbf{E} \bullet \mathbf{S} \bullet \mathbf{O}_1 \bullet \mathbf{O}_2)$  as a fundamental problem and answers it with a relativist rationale: the relativity of states. Let us emphasize that EVERETT resorts to the usual wave function formalism of QM from the viewpoint of a second observer<sup>35</sup>. On this basis, he defines the quantal relative information and the relative state functions, and proves evolution rules from which he can derive usual measure observations in a coherent way: “observers who have separately observed the same quantity will always agree with each other”.

Technically, EVERETT’s fundamental point is that in an interaction a system-observer pair,  $\mathbf{S} \bullet \mathbf{O}_1$ , will eventually evolve up to a point where “the relative system states become approximate eigenstates of the measurement” [21]. If  $|L\rangle$  and  $|R\rangle$  are observer (*i.e.* apparatus) states, if  $|l\rangle$  and  $|r\rangle$  are the corresponding system eigenstates for the measure, and if  $\mathbf{S}$  is before the interaction in the superposition state  $a|l\rangle + b|r\rangle$ , with  $|a|^2 + |b|^2 = 1$ , then  $\mathbf{S} \bullet \mathbf{O}_1$  evolves eventually to the correlated state  $a|l\rangle \otimes |L\rangle + b|r\rangle \otimes |R\rangle$ <sup>36</sup>. From  $|L\rangle$  version of  $\mathbf{O}_1$ , (relative) state of  $\mathbf{S}$  is  $|l\rangle$ , whereas it is  $|r\rangle$  in the  $|R\rangle$  version of  $\mathbf{O}_1$ . Probabilities are  $|a|^2$  and  $|b|^2$  respectively, in agreement with BORN’s rule. For an external observer  $\mathbf{O}_2$ , there is neither something like a “separation” or “split” of  $\mathbf{S} \bullet \mathbf{O}_1$  in two universes, nor a “wave function collapse”:  $\mathbf{S} \bullet \mathbf{O}_1$  merely evolves unitarily, according to its (extraordinarily

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<sup>34</sup>English translation [46].

<sup>35</sup>He emphasizes that he uses only “pure wave mechanics” [21].

<sup>36</sup>Some authors argued that not every situation will evolve this way. This is true; it is not necessary to suppose that such a  $\mathbf{S} \bullet \mathbf{O}$  system *will always* evolve that way —*i.e.* that  $\mathbf{S} \bullet \mathbf{O}$  eigenstates are tensor products of  $\mathbf{S}$  and  $\mathbf{O}$  states. EVERETT, indeed, only considers that it does when the interaction is a measurement. For our purpose here, it is sufficient to consider cases *where*  $\mathbf{S}$  evolves with  $\mathbf{O}$ , according to  $\mathbf{O}$ ’s eigenstates, and accept the experimental fact that *when* it does so, it does so according to Born’s rule.

complex) Schrodinger equation. Nowadays, one may add that this evolution will generally become classical very quickly, due to decoherence by the environment **E**.

## 5.2 Quantum logic and quantal modal logic

In logic, a formalism exists to deal with possibility and necessity: modal logic. Nevertheless, the classical modal logics will be of no use here: many experiments fall within the range of classical logic, but not all. It is well known that we must reason within Quantum logic (QL) [10, 15, 26, 28, 31, 36].

In the (classical) modal logics, one defines the possibilities with (i) a set, the *model*, the elements of which are the “possible worlds” — we will say *potential worlds*, (ii) a relation of *satisfaction* between worlds and propositions (or statements), and (iii) a relation of *accessibility* between worlds which describes what worlds are possible from the point of view of another world [12]. We shall similarly define the Quantal Modal Logic.

**Quantum Logic** One can define a Quantum Logic system within algebra as an orthomodular lattice<sup>37</sup> [10]. One can also follow a syntactic approach using deduction [16, 25, e.g.]. By Piron’s theorem [31], one can conceive Quantum Logic as being the structure of some closed sub-Hilbert spaces of a Hilbert space in the same way as Boolean logic is the structure of subsets of a set<sup>38</sup>. If we stick to physics, a simple proposition is a statement that after a specific experiment a specific observable lies within a specific range of values; for example “detector 1 has measured an electron with a speed less than  $10 \text{ m.s}^{-1}$ ” or “photon spin in the direction  $\vec{n}$  was measured as positive”. Ultimately, simple propositions are always yes-no statements and always about some observation at a specific moment. Technically, one can model a proposition  $L$  = “particle goes through the left slit” either by a sub-Hilbert space  $\mathcal{L}$  or by its corresponding projection operator  $\hat{L}$ . With the one-dimensional simplification frequently used in pedagogic writing  $\hat{L} = |\text{left}\rangle\langle\text{left}|$  and  $\mathcal{L} = \mathbb{C}|\text{left}\rangle$ . Complex propositions combine simple propositions by conjunction (“and”), disjunction (“or<sub>QL</sub>”) and negation. Conjunction is the intersection of spaces:  $\mathcal{A} \wedge \mathcal{B} = \mathcal{A} \cap \mathcal{B}$ . Quantal disjunction is the sum of spaces:  $\mathcal{A} \vee \mathcal{B} = \mathcal{A} + \mathcal{B}$ , *i.e.* all linear combinations of elements in  $\mathcal{A} \cup \mathcal{B}$ . Quantal negation, contrary to the classical one, is not only a false conjunction, but corresponds to an orthogonal subspace,  $\mathcal{L}^\perp$ ; so there are many ways for a state to satisfy neither a proposition nor its negation. For example, in a double-slit experiment, the “left” and “right” propositions are exclusive, meaning  $\mathcal{L} \perp \mathcal{R}$ , so the  $L$  and  $R$  propositions are negation of each other. In English, one can say that “the particle goes either through the left slit, or through the right slit” —with an exclusive “or” but a quantal “or”!

<sup>37</sup>A lattice is a partially ordered ( $\leq$ ) set in which every two elements have a supremum ( $\vee$ ) and an infimum ( $\wedge$ ). It is orthocomplemented if there is a least element (0), a greatest element (1) and an involution reversing order, the orthocomplement ( $\cdot^\perp$ ). It is orthomodular if  $a \leq b$  implies  $a \vee (a^\perp \wedge b) = b$  [10]. One can also define orthomodularity saying  $a \leq b$  implies that  $a$  and  $b$  commute or are compatible ( $a \subset b$ ) [16]. In this formalism, 0 is the falsity, 1 is the truth, the order ( $\leq$ ) is the consequence relation, the supremum ( $\vee$ ) is the disjunction/superposition (“or”), the infimum ( $\wedge$ ) is the conjunction (“and”) and the orthocomplement ( $\cdot^\perp$ ) is the negation.

<sup>38</sup>Constantin PIRON showed that any finite or denumerable Quantum Logic system can be represented in a projective geometry, and thus as subspaces of a Hilbert space [31].



**Potential worlds** Any simple proposition corresponds to an observation, and thus to a moment in time: “the photon has its spin up in the direction  $\vec{n}_1$  at time  $t_1$ ”. Sometimes there is no ambiguity, but it may be necessary to explicit time in some circumstances; note that, in this case, time is merely an index, not a parameter. By definition, a wave function  $\psi$  satisfies a proposition  $P$  concerning a time  $t$ , if  $\hat{P}[\psi(t)] = [\psi(t)]$  or, equivalently, if  $[\psi(t)] \in \mathcal{P}$ ; one writes  $\psi \models P$ . Can one consider all states in  $\mathcal{H}$ , the total reference Hilbert space, as being potential worlds? Probably yes in very simple pedagogic examples where we use only few dimensions and very short histories; probably not in the general case: each observation at least doubles the necessary dimensions of  $\mathcal{H}$ , so any whole timeline may lead to dimensional complexities. Restrictions may need to be applied in the future, but, for a start, we define a *potential world*  $\mathcal{W}$  to be a non-zero measure sub-Hilbert space of  $\mathcal{H}$ . In this article *we will restrict the use of the term “potential” to this precise modal meaning*, and leave “possible” to general or informal use. We say that “ $\mathcal{W}$  satisfies the proposition  $P$ ” or that “ $P$  is true inside  $\mathcal{W}$ ”, and we write  $\mathcal{W} \models P$ , if any  $[\psi] \in \mathcal{W}$  satisfies  $P$ , except perhaps for some zero-measure subspace. As for EVERETT [21], a potential world  $\mathcal{W}$  will generally be expressed as a recorded history: “observation 1 measured value  $a$  for  $A$ ”, “observation 2 measured value  $b$  for  $B$ ”, etc.<sup>39</sup>.

**Accessibility relation** Let us imagine we add a new observation to  $\mathcal{W}$ , for example  $X$  with two values  $+$  and  $-$ . This observation determines two subspaces:  $\mathcal{X}^+ \perp \mathcal{X}^-$ , with  $\mathcal{W} = \mathcal{X}^+ + \mathcal{X}^-$ . In such a case, we say that  $\mathcal{X}^+$  and  $\mathcal{X}^-$ , and more generally any other sub-Hilbert space of non-zero measure and non-zero orthocomplement  $\mathcal{Y}$  is accessible from  $\mathcal{W}$ ; we write  $\mathcal{W} \triangleright \mathcal{Y}$ . The accessibility relation can be thought of as the logical identity of past observable interactions; in [21] it corresponds to shared automatic apparatus memories<sup>40</sup>.

**Modalities** As usual in modal logic, we say that  $P$  is necessary in  $\mathcal{W}$ ,  $\mathcal{W} \models \Box P$ , if any world accessible from  $\mathcal{W}$  satisfies  $P$ :  $\forall \mathcal{X} \triangleleft \mathcal{W}, \mathcal{X} \models P$ . We can, similarly, define that  $P$  is potential (possible) in  $\mathcal{W}$ ,  $\mathcal{W} \models \Diamond P$ , if at least one world accessible from  $\mathcal{W}$  satisfies  $P$ :  $\exists \mathcal{X} \triangleleft \mathcal{W}, \mathcal{X} \models P$ . In our example,  $\mathcal{W} \models \Diamond “X = +”$ ,  $\mathcal{W} \not\models \Box “X = +”$ , and  $\mathcal{W} \models \Box “A = a”$ .

If  $P$  is a QL proposition and  $\mathcal{W}$  a potential world, one always has  $\mathcal{W} \models P \vee P^\perp$ , but, in general, a potential world may satisfy neither  $P$  nor  $P^\perp$ : corresponding observations may not be available for experimentation. So  $\mathcal{W} \not\models P$  does not imply, in general, that  $\mathcal{W} \models P^\perp$ , even when  $\mathcal{W}$  is one-dimensional. In classical modal logics, necessity and potentiality (possibility) are dual. In Quantal modal logic it is true when  $\mathcal{W}$  and  $P$  are compatible ( $\mathcal{W} \subset \mathcal{P}$ )<sup>41</sup>:  $\mathcal{W} \not\models \Box P$  is equivalent to  $\mathcal{W} \models \Diamond P^\perp$ <sup>42</sup>; but this is not true for any world and

<sup>39</sup>We use histories to express potential worlds, not more. This approach, despite similarities, is fundamentally different from the “consistent histories” of Robert GRIFFITHS and Roland OMNÈS or the “decoherent histories” of Murray GELL-MANN and James B. HARTLE: both are essentially attached to Classical Logic. We will not go further on this matter here; it would need more development.

<sup>40</sup>In the PMI, it corresponds to a world “split”, but this is not a technically precise expression.

<sup>41</sup>This compatibility relation is equivalent to the commutation of observables. With [16], let us define  $\mathcal{E} \circ \mathcal{F} = \mathcal{E} \cap (\mathcal{E}^\perp + \mathcal{F})$ , the projection of  $\mathcal{F}$  on  $\mathcal{E}$ , and define  $\mathcal{E}$  and  $\mathcal{F}$  to be compatible,  $\mathcal{E} \subset \mathcal{F}$ , by  $\mathcal{E} \circ \mathcal{F} = \mathcal{F} \circ \mathcal{E}$ , or equivalently  $\mathcal{E} \circ \mathcal{F} = \mathcal{E} \cap \mathcal{F}$ , or also equivalently  $\mathcal{E} \circ \mathcal{F} \subseteq \mathcal{F}$ .

<sup>42</sup>Proof.- If  $\mathcal{W}$  is a potential world, if  $P$  is a proposition and  $\mathcal{P}$  the corresponding subspace, and if  $\mathcal{A} \subset \mathcal{P}$ , then  $\mathcal{W} = \mathcal{W} \circ \mathcal{P} + \mathcal{W} \circ \mathcal{P}^\perp = \mathcal{W} \wedge \mathcal{P} + \mathcal{W} \wedge \mathcal{P}^\perp$ . If we suppose that  $\mathcal{W} \not\models \Box P$ , then  $\mathcal{W} \not\models P$ , so  $\mathcal{W} \wedge \mathcal{P}^\perp$  is

any proposition.

**Causal preorder: the logical “arrow of time”** The Quantical modal logic is only a formalism; it does not rule, in general, what is and what is not a possibility. Neither does the Hilbertian wave function formalism. Only the experimental register can give us a clue about what possibly happens and what cannot happen when there is no observation. Nevertheless, one can use these models to explicit a concept of observer. Following [21], one can define an observer as a record of observation memories. An observer  $\mathbf{O}$  resides in a potential world, but not only one: when  $\mathbf{O}$  resides in  $\mathcal{P}$ , meaning  $\mathcal{P}$  satisfies all his memories-propositions, then  $\mathbf{O}$  resides *identically* in any potential world  $\mathcal{B}$  from which  $\mathcal{P}$  is accessible ( $\mathcal{B} \triangleright \mathcal{P}$ ). There are also different versions of  $\mathbf{O}$  in each potential world  $\mathcal{A}$  accessible from  $\mathcal{P}$  ( $\mathcal{P} \triangleright \mathcal{A}$ ). These  $\mathcal{B}$ -worlds are the only logical past of  $\mathbf{O}$  (“before”) and the  $\mathcal{A}$ -worlds are the various potential futures of  $\mathbf{O}$  (“after”). In each  $\mathcal{A}$ ,  $\mathbf{O}$  sees himself as the only existing version of  $\mathbf{O}$ , except perhaps for imagination and for gravitational perception. Note that an *imaginable* version is not necessarily a *potential* version. Note also that, for  $\mathbf{O}$ ,  $\mathcal{P}$  and all its  $\mathcal{B}$ -worlds are indistinguishable: no physical means can differentiate them.

### 5.3 Quantical simple binary alternative (qubal)

If we want to observe a quantical behavior of gravitation, we need to focus on experimental situations not reducible to any classical interpretation. The first experimental evidence in this direction is the ASPECT’s experiments showing violation of BELL’s inequality. Since then, there had been many experiments showing new evidence of this violation. All can be interpreted in terms of a quantical entanglement. On the theoretical side of this question, a generalization of BELL’s inequality, the quantical Fréchet bounds, have been proven to be violated by entangled states [9]. This proves that no classical logic, or non-quantical statistics, can generally describe entangled states.

Let us consider an experimental setup with such an entanglement, where an observer measure a quantity with two potential values, say “+” and “−”, for example a spin in some direction. This setup’s quantical representation is a potential world  $\mathcal{W}$  with two accessible worlds  $\mathcal{A}^+$  and  $\mathcal{A}^-$ . Note that we supposed that these are *potential* values (and worlds), and not only *imaginable* values: both are effectively measured in some instances of this very experimental setup. Such an entanglement might involve long duration and distance: entanglement may be macroscopic. As a consequence, decoherence phenomena do not systematically make classical all the macroscopic systems<sup>43</sup>.

So, such setups are good candidates for genuine quantical situations that could be used to test gravitation. Note also that any experience can ultimately be reduced to yes–no observations. Therefore, let us define a *quantical simple binary alternative* —a *qubal*— as an experimental setup leading to a binary measure that could be part of a larger setup able to give non-classical statistics: entanglement, BELL’s inequality violation or Fréchet bounds violation. As an example, the measure of the spin of one particle in some direction could

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a non-zero subspace. Since this is a world accessible from  $\mathcal{W}$ , we infer  $\mathcal{W} \models \Diamond P^\perp$ .

<sup>43</sup>Literature gives numerous examples of macroscopic quantical behavior, the most famous being Erwin SCHROEDINGER’s cat mind experiment, but their interpretation is not always unequivocal.



give a qubal. Qubits and quantical encryption devices could also be convenient ways to provide with qubals.

In a situation where we really have a qubal, we have two accessible worlds,  $\mathcal{A}^+$  and  $\mathcal{A}^-$ , each one having a non-zero probability, according to Born’s rule. The question we ask in section 4 is now: if we are in  $\mathcal{A}^+$ , where the experiment is positive, can we know anything of  $\mathcal{A}^-$ , where the experiment is negative? Depending on one’s interpretation of QM,  $\mathcal{A}^-$  is just a mathematical possibility (in PWI) or does really exist (in RSI and PMI); but in any case if we strictly follow EVERETT’s framework the answer is straightforward: we cannot. No information can go from one world to an inaccessible one. Would this be final, we could not settle between PWI and RSI, and the choice would be essentially a matter of personal convenience —one’s metaphysical preference. But EVERETT relied only on “pure Quantum Mechanics”, and QM is not final as a description of nature; notably, we still seek for a framework integrating what we know of the quantical phenomena and what we know of the inertia-gravitation.

#### 5.4 What is gravitation?

**The weak equivalence principle** JOHN Philoponus first introduced a notion of impulse (*impetus*) or of a “power to move” to account for the continuation of movement<sup>44</sup>, a notion later expanded by IBN SĪNĀ, Jean BURIDAN and GALILEO, leading to the laws of conservation of momentum and kinetic energy by Christiaan HUYGENS [29, see]. Isaac NEWTON’s *Principia* define inertia as a “*vis insita* or innate force of matter”, as a “*vis inertiae* or force of inactivity”, or as a “power of resisting by which every body as much as in it lies endeavors to persevere in its present state whether it be of rest or of moving uniformly forward in a right line”; NEWTON adds it is essentially mass. A few lines before, he opens the *Principia* with a paragraph stating that weight is proportional to mass as an experimental fact. Inertia, mass and weight are here proportional or equivalent. EINSTEIN’s equivalence, NEWTON’s equivalence and also GALILEO stating that all weighting objects fall the same way, are nowadays considered to be variations of an *equivalence principle*. This “principle” is often ill-defined as a physical concept since it is generally deeply interwoven with mechanics<sup>45</sup>. Today, one defines *weak equivalence principle* (WEP) to be the equivalence of inertia and gravitation: inertial mass and weighting mass for Newtonian mechanics, inertial energy and ponderous energy nowadays. The experimental register for this equivalence is considerable; it goes back, at least, to Simon STEVIN’s *Principles of statics* (1586) and have reached a precision of  $10^{-14}$  with the MICROSCOPE satellite experimentation [43].

**Received and given gravitation** NEWTON’s gravitation law is a reciprocal force between two massive bodies  $C$  (context) and  $T$  (test) with intensity  $GM_C M_T / d^2$ . For Newtonian gravitation, thanks to WEP, acceleration of a test body,  $GM_C / d^2$ , is independent of the test mass (but it must have a mass). For this reason, one can virtualize test body and

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<sup>44</sup>Before him, movement was not something to model mathematically. For example for ARISTOTLE weight was a *clinamen*, a final tendency to be in a low place, and any motion needed an effective motor to continue its course.

<sup>45</sup>For example, in Newtonian mechanics, NEWTON’s and GALILEO’s equivalences are logically equivalent.

reify potential gravitation as a field—at least for massive test bodies light enough not to disturb the context body,  $0 < M_T \ll M_C$ . Experiments (now numerous) show that gravitation concerns every object, with or without mass. EINSTEIN generalized this consideration and postulated we can decompose the gravitation phenomenon into two parts which we call here the received and given gravitations. The *received gravitation* is theorized by the fact that any movement receiving no other influence than gravitation follows a geodesic of a special object, the space-time. The received gravitation includes the inertia. Experimental evidence supports WEP: the received gravitation is the same for all forms of energy content. The *given gravitation* is theorized by the fact that bodies with a energy content density field  $\hat{T} = (T_{\mu\nu})$  create a curvature of the space-time object such that

$$\left(\Lambda - \frac{1}{2}R\right) g_{\mu\nu} + R_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \quad (5.1)$$

where  $(g_{\mu\nu})$  is the metric of the space-time,  $(R_{\mu\nu})$  is this metric’s Ricci curvature tensor, modeling its propagation,  $G$  is NEWTON’s constant, and  $\Lambda$  is a “cosmological constant”<sup>46</sup>. We only know direct experimentation of the given gravitation for mass energy, but, on the one hand, cosmological evidence suggests that it can account only for a small part of the observed gravitation phenomenon, and, on the other hand, the symmetry with received gravitation suggests that tensor  $\hat{T}$  should enroll any form of energy content. So, in GR, inertia (inertial energy) is now better described by tensor  $\hat{T}$ , a generalization of energy-momentum in the form of energy content density and flux. Nonetheless, the question remains open for QFT vacua: since they allow no energy transfer, and since they are omnipresent and isotropic, whether they should be counted in this energy content, and how.

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<sup>46</sup>There is experimental support for  $G$  being constant, under a  $10^{-12}$  per year [49]. According to usual conventions, Greek letters indices range for space-time coordinates.

## 6 Discussion

### 6.1 Synoptic abstract of kinetic theory

Sub-quantum	Quantum	Macroscopic (in most cases <sup>47</sup> )
Quantum logic		Classical logic
Quantum mechanical densities and expectations		Kolmogorov probabilities and statistics
?	Schrödinger equation	Lagrangian mechanics
position operator in space, function of time		position in space-time
interval (of contiguity and consecution)	remoteness, duration, coordinates	
Euclidean space		Minkowskian space-time
displacement pace		velocity, rapidity
gravitational redshift	Newtonian gravitation of massive bodies, gravitational redshift of photons	

**Table 2.** Correspondence for quantities and phenomena

assertion	status	in this article
potential particles (PP) are massless	experimental fact for photons	hypothesis for PP
PP propagate linearly and isotropically at the same pace	experimental fact (1, 2) for light in void	hypothesis for all massless particles
light closed path duration is independent of observer	experimental fact (3) for light in void	consequence of model
conservation of momentum and energy content	experimental fact for particles (macroscopic)	hypothesis for PP
time dilation of moving systems, Lorentz factor	experimental fact (4)	consequence, if we define velocity as $c\vec{\beta} := \frac{c^2 \langle \vec{p}_S \rangle}{\langle E_S \rangle}$
Minkowsky geometry of space-time	SR, coherent with low-gravity experimental facts	consequence (when sub-space is Euclidean)
a body of mass $m > 0$ have $mc^2$ energy content at rest	experimental fact (5)	consequence (of SR [19])
gravitational “redshift”	experimental fact (6) for light	hypothesis for all massless particles
Newtonian gravitation	experimental fact for $R_s \ll R$	consequence

**Table 3.** Main results and hypotheses of the quantical kinetic theory

### 6.2 Does relativity determine space-time ontology?

**What is relativity?** GALILEO and EINSTEIN both share a relativist approach. However their application of the parsimony principle led them to different interpretative conclusions. GALILEO, in his *Dialogo*<sup>48</sup> traces some sort of relativity principle back to archaic physics.

<sup>47</sup>Most of the macroscopic phenomena, not all —see appendix 5.3.

<sup>48</sup>*Dialogo sopra i due massimi sistemi del mondo*, 1632.

Nicolaus COPERNICUS, for example, cite VIRGIL’s *Aeneid*: “We set out from harbor, and lands and cities recede.”<sup>49</sup>. GALILEO resorts to the example of the ship from Venice to Alep and her speed “like nothing” for passengers [4, see]. Galilean relativity is mostly a use of a perspective rationale, it does not imply the nonexistence of absolute velocities. Hugh EVERETT’s relativity of states for the Quantum mechanics (QM), like GALILEO’s, draws no ontological consequence. Opposite to these weak forms of relativity, EINSTEIN’s Special relativity (SR) and General theory of relativity (GR) follow Ernst MACH’s very restrictive interpretation of the parsimony principle and rules out absolute velocities: only relative velocities do really exist.

**Observation vs. ontology** EINSTEIN strong relativity’s vision of space-time is now deeply assimilated in the mainstream scientific culture—even taught in high school. Nevertheless, there exists alternate visions of relativity, notably BELL’s. John BELL [5] advocated that one could teach SR as a phenomenon. Our kinetic theory of the emergence of SR shows that there is a possibility that absolute Euclidean space-time (intervals) and speed (displacement pace) may exist, underlying, from which a phenomenal MINKOWSKI space-time may emerge. It is not a formal necessity to naturalize it. SR and GR are theories, models of nature, they can well be adopted without assuming EINSTEIN’s interpretation. Let us remind that before the turn of the 20th century, physicists thought that molecules would never be observed. For that reason, some authors, like Ernst MACH or Wilhelm OSTWALD, rejected atomism [14]. This should make us cautious about strong relativity: what is not observable today may become observable tomorrow. This situation is recurring in physics’ history: parsimony principle, also known as OCKHAM’s razor, should not be too quick to “shave away” interpretations, as long as they aim at some experimental validation that may not be straightaway.

**Kinetic interpretation of SR** Astronomy before Johannes KEPLER conceived celestial movements only with circles. For that reason, theoretical astronomers designed the epicycles to understand as circular movement combinations what were actually ellipses. Today, the “natural” movement is conceived as being the inertial movement, so one tends to understand any movement in these terms: Newtonian gravitation is a free fall and Einsteinian gravitation is a pathway along a geodesic. Quintessence, dark matter, dark energy, etc. many of these notions may also be contemporary epicycles. These notions have a great phenomenal validity, but they do put a heavy shroud of complexity over the picture. The trans-world gravitation is only a hypothesis yet, but it shows that there might be simple solutions to today’s astronomy puzzles.

Our potential particle model and kinetic theory are a framework waiting to be completed. The nature of sub-space-time intervals still has to be understood. As far as we know, the sub-quantum space, the sub-space, may be continuous, even Euclidean, as we supposed here, or may be a grid, a network, or merely a relation. The interval relation may have emerged by some sort of geometrization mechanism *à la* PERELMAN<sup>50</sup>. This line

<sup>49</sup>VIRGIL, *Aeneid*, III 72. Nicolaus COPERNICUS, *De revolutionibus orbium coelestium*, 1543, chap. I.8.

<sup>50</sup>Grigori PERELMAN uses Ricci-Hamilton flow to homogenize the metric on manifolds, and proves that any 3-dimensionnal manifold can be geometrized. One can imagine a similar mechanism to make the local

of research can be traced back to Richard S. HAMILTON, who introduced the Ricci flow (1982) and drew a parallel with the heat equation. This parallel may have a more profound physical meaning. An emergence scenario may give us some clues to sub-quantum gravitation.

**Finiteness of the experience** Our model relies heavily on the fact that quantum and macroscopic quantities, such as coordinates or momentum, are observables, results of measures, of interactions. Thus, even considering ideal measures, our experience is intrinsically finite. On the other hand, for more than a century and a half, fields have been a very fruitful concept of physics. GR and QFTs made it a prime concept of today’s physics, pivotal to make wave and corpuscular behaviors converge —fields overtaking classical waves, and corpuscles being quanta of these fields. This approach has led to new understandings and new ways to consider particles, especially with quasi-particles (Cooper pairs, phonons, holes, etc.). But, what are these fields actually? Are they physical objects or merely theoretical reifications of physical relations<sup>51</sup>? Fields represent an infinite number of degrees of freedom —even a *continuous* infinite number ( $2^{\aleph_0}$ ), for example in the form of a Fock space. What could this mean *physically*, that is with respect to possible experience? Our model chooses to make use only of a finite dimensional Hilbert space, or, at least of states density operators with finite rank. Perhaps could the reader attached to fields reason to the limit or consider our model as mere heuristics.<sup>52</sup>

### 6.3 What is real in QM?

**Measurements and observations** Historically, there have been a fundamental methodological distinction between an *observed system*, quantical, an *observer*, considered classical, and a *measuring* process, that may be iterated, based on *observables*, which are mainly classical quantities. For that reason, epistemologically, there have been two clearly distinct processes: “quantical” or “unitary” periods, during which the evolution is described by a Schroedinger equation, and “wave function collapses” or “reductions” or “projections”, that serve as initial conditions for the future and are linked to the past by BORN’s rule, similar to an absolute form of probabilities [46]. This divide has been a major epistemological difficulty and has raised a great deal of debate on the “measurement problem”. In general, a science is the instrumented construction of an abstraction, called theory, of the reality it observes, called its object; this abstraction tends to encompass, eventually, the totality of its object. In the case of physics, the object could be the physical systems considered to be isolated (sufficiently, or ideally), and possibly the whole universe, everything that surrounds us, and, in any case, experimenters. Experimental models have to be surpassed,

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sub-space interval relation build up from an initial poorly structured contiguity relation.

<sup>51</sup>By reification of a relation, we mean constituting as an object what is really relation between objects. For example, in Newtonian mechanics the gravitational potential of a body **M** is a reification of the gravitational force between **M** and test masses (real or virtual).

<sup>52</sup>NEWTON relied on forces for its mechanics but prevented speculation about their nature: “hypotheses non fingo”. In 1936 EINSTEIN [14, cit.] argued, we should establish physics theory on fields. Here we are, now, with a very efficient tools, but again not forging hypotheses about it. Perhaps are we in a time to build other tools.

thanks to theoretical thinking, in order to encompass them. Scientific disciplines, to set up this approach, usually adopt a point of view called “methodological realism”, assuming that there does exist an objective reality accessible by experimentation.

Some authors have objected that in the case of quantum physics, objectivity does not exist, in the sense that any experiment, which is “subjective”, disturbs the reality to be observed<sup>53</sup>. Indeed, this makes it more complex to integrate subjectivities into an objective whole, but there is no fundamental obstacle against it: this is very common in the social sciences, for example. However, one should be cautious. It is not, in general, possible to bestow a truth value to any vulgar proposition, like “the electron passed through the left slit”. But every *experimental* proposition does have a truth value (for example, the proposition  $L$  “an electron was measured to pass through the left slit” has a meaning and a truth value (if no experimental test has taken place, then  $L$  is just false).

Experience in a quantical world correspond to three types of situations. The most common is our everyday life: we see a purely classical world, with classical logic and classical statistics. These situations are now well understood thanks to decoherence mechanism [50, 51]. The second corresponds to quantum physics experimentation: experimenters design apparatus specifically to cascade some microscopic changes up to observable macroscopic pointers along the measurement chain. Among these situations, the intricate situations have two distant macroscopic devices record observations the statistics of which violate the BELL inequalities. This third type supplies with quantical binary simple alternatives, qubals. All three types have abundant observations.

**Mainstream QM interpretations** The main challenge to the methodological realism is the superposition phenomenon: when  $|\chi\rangle$  and  $|\psi\rangle$  are solutions of the Schroedinger equation of a system, any normalized linear combination of them is also a solution. Three main classes of interpretations for the formalism aim at overcoming this difficulty:

- According to the *Copenhagen school interpretations* (CSI, Niels BOHR, Werner HEISENBERG) any measurement operation determines a state of the system, prepares it for future measurements, and defines its wave function for later evolution. Each measurement *actualizes* the *possibilities* of the system-observer inseparable couple.
- In the *pilot-wave interpretations* (PWI, Louis DE BROGLIE, David BOHM, John BELL), the system is described by a “pilot” wave function and by particles or singular waves. Pilot wave describes all the *possibilities* for the system, and an propensity for each outcome of a measurement. In each measurement, particles *reveal* which possible outcome happens to be real.
- Third category interpretations, usually called *many-world interpretations*, following Hugh EVERETT’s ideas, refrain from giving greater importance to one state over another. The first approach is EVERETT’s relative state interpretation (RSI) [21, 22]. Another is what Yoav BEN-DOV [8] calls the “popular many-world interpretation”

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<sup>53</sup>This is especially the case if, instead of an epistemological definition of objectivity, we consider a physical one: being invariant by change of observation conditions.

(PMI) —extremely popular indeed, and generally mistaken for it<sup>54</sup>. In these interpretations, the different solution states, the different *possible* evolutions of the system, *are as real* as one another. The measurement experiment merely provides the observer with partial information relative to his point of view. All versions of the observer, who may be thought of as living in parallel universes, have their own reading of the relative states of the observed system.

**Potential worlds modal interpretation** In these three interpretation classes, there is some notion of possibility and some notion of reality. What is exactly reality is much debated between these classes and among each class. Such a discussion is not the purpose of this article. We focused here on clarifying the possibility structure, using Quantal Modal Logic (appendix 5.2). This drove us to introduce the *potential world modal interpretation* (PWMI). PWMI is some sort of “greatest common interpretation” of pilot-wave and many-world interpretations: it is in agreement with both PWI and RSI regarding possibilities, but says nothing about “reality”.

As of time writing, there is no experimental evidence in favor of one interpretation of QM or another. It is mostly a matter of metaphysics or pedagogy —as it is commonly understood without any significant discussion. If the trans-world gravitation hypothesis is false but QM holds generally, EVERETT’s work shows that no experiment may settle between RSI and PWI: reality remains a matter of personal inclination. On the contrary, if our trans-world gravitation hypothesis receives an experimental confirmation, it would mean that alternate worlds emit gravitation to ours, and so exist in some way. RSI would then be the most adequate representation of alternate worlds, except when gravitation joins the game. On the other hand, for in-world reasoning, the best heuristic support is PWI —again, when gravitation is out of the game.

There have been many attempts to prove BORN’s rule, but they are still controversial, even in RSI context. An experimental confirmation of our hypothesis would change the purport of these attempts. It would also bring some support to Lev VAIDMAN’s terminology for Born’s coefficients: *measure of existence*, for a world in a many-world interpretation [44].

**Superposition of potential worlds** Note that PMI, albeit convenient at the macroscopic level, due to decoherence, is not rigorously coherent with QM at a microscopic level, as noted by Yoav BEN DOV [7, esp. p. 106] and Bernard D’ESPAGNAT [17, 18]. For example, consider an experiment measuring an electron spin in the direction  $\vec{n}_1$ ; this leads to two potential worlds:  $\mathcal{S}_1^+$  and  $\mathcal{S}_1^-$ . Neither of these worlds can be conceived without superposition: in each one, one can add a measure of spin in a new direction,  $\vec{n}_2$ , not parallel to  $\vec{n}_1$ ;  $\mathcal{S}_1^+$  appears then as a superposition of the two accessible worlds  $\mathcal{S}_{12}^{++}$  and  $\mathcal{S}_{12}^{+-}$ . Therefore, in general, the potential worlds cannot be figured as being in Boolean disjunction: they are in quantal disjunction, *i.e.* in superposition. As stated by Jean-

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<sup>54</sup>See [7] for an historical presentation. PMI emerged with Bryce S. DEWITT in the 1970s, putting RSI in the background. At the quantal level, DEWITT formulation is not coherent with QM results, cf. [7] esp. p. 106 and [17] (English translation: [18]). Nevertheless, due to decoherence, DEWITT PMI is, in practice, convenient at the macroscopic level.



Marc LÉVY-LEBLOND: from the point of view of the universe, there is only one world<sup>55</sup>. So one cannot count potential worlds, but, still, if we reason relatively to some global state or density operator, we benefit from conditional probabilities for relative states [21]. This provides us with quantical probabilities, similar to classical (KOLMOGOROV) ones.

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<sup>55</sup>“The “many worlds” idea [PMI] again is a left-over of classical conceptions. The coexisting branches here [...] can only be related to “worlds” described by classical physics [...] To me, the deep meaning of EVERETT’s idea is not the coexistence of many worlds, but, on the contrary, the existence of a single quantum one.” [7, cit.]



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