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Dark energy from quantum gravity discreteness

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We argue that discreteness at the Planck scale (naturally expected to arise from quantum gravity) might manifest in the form of minute violations of energy-momentum conservation of the matter degrees of freedom when described in terms of (idealized) smooth fields on a smooth spacetime. In the context of applications to cosmology such 'energy diffusion' from the low energy matter degrees of freedom to the discrete structures underlying spacetime leads to the emergence of an effective dark energy term in Einstein's equations. We estimate this effect using a (relational) hypothesis about the materialization of discreteness in quantum gravity which is motivated by the strict observational constraints supporting the validity of Lorentz invariance at low energies. The predictions coming from simple dimensional analysis yield a cosmological constant of the order of magnitude of the observed value without fine tuning.

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The discovery that the universe is undergoing an accelerated expansion [1, 2] is the source of one of the greatest puzzles of our present understanding of cosmology which goes under the name of the *dark energy* problem. While the assumption of the presence of a cosmological constant Λ remains the most successful phenomenological model, naive theoretical reasoning predicts a value for Λ that is either 120 orders of magnitude to big, or is strictly vanishing when a protective symmetry principle is at play [3]. It would be desirable to have a concrete fundamental calculation leading clearly to $\Lambda_{\rm obs} \approx 1.19\ 10^{-52}\ {\rm m}^{-2}$, the value indicated by observations [4].

A recent work [5] proposed a framework where violations of energy momentum conservation produce a dark energy contribution. The key result of that work was to characterize the effective framework where violations of energy conservation are made compatible with general relativity. As an illustration we applied it to two models, previously considered in the literature, that propose such violations. However, none of these two could be taken as truly realistic. On the one hand, the cosmological time at which the effects would start was not intrinsically defined by the models, and, on the other hand, the strength of the violations of energy conservation were encoded in a phenomenological adjustable parameter with no explicit link to fundamental constants. Therefore, while these examples were illustrative of the idea that small violations can accumulate and contribute non negligibly to Λ, they could not be used to predict its value.

In this paper we bridge this gap by proposing a mechanism to generate Λ and the quantitative estimates based entirely on known fundamental features of the physics involved. The origin of the cosmological term, we suggest, is to be found in the microscopic structure of spacetime and its interaction with matter. We will work under the hypothesis that discreteness of geometry and Lorentz invariance at low energies are fundamental aspects of quantum gravity. Based on these two fundamental features we propose a phenomenological model for quantum-gravity-induced violations of energy conservation depending only on the fundamental constants $G, c, \hbar$ and a few parameters of the standard model (SM). We show that our simple proposal resolves the two limitations of the previous examples and predicts a contribution to the cosmological constant of the correct order of magnitude.

One of the most important constraints on the form of quantum discreteness at Planck scales comes from the observed validity of Lorentz invariance at QFT scales. As shown in [6, 7] this rules out the simple atomistic view of a spacetime foam selecting a preferred 'rest-frame' at the Planck scale. This result, which severely constrains phenomenological ideas, is corroborated by a large collection of empirical evidence [8]. A more subtle theoretical characterization of space-time discreteness at Planck's scale is necessary.

We think that the key for understanding Planckian discreteness lies in the relational nature of physics partly uncovered by Einstein's theory of gravity [9]. In general relativity, geometry can only be probed by the matter degrees of freedom. The metric has a clear physical meaning only when rulers and clocks are introduced [1]. More precisely, the construction of observables (diffeomorphism invariant quantities) requires the use of relational notions involving a mixture of geometric and mat-

[1] For example modified gravity models can be presented in the Jordan or Einstein frames [10]. Thus physics can be described using different notions of geometry, yet at the end 'physical geometry' is identified with the one where 'free particles follow geodesics'. Before the introduction of such test degrees of freedom the identification of physical geometry is meaningless.

ter degrees of freedom. The difficulty of actually defining such quantities is, in fact, one of the most severe technical problems in formal approaches to quantum gravity. In our view such relational perspective is essential for understanding discreteness at the Planck scale [2].

We are thus rejecting the notion of a spacetime foam acting as an empty arena where matter, if there placed, would reveal its preexisting features. Quantum discreteness should arise primarily via the interactions of gravity with those other degrees of freedom, which by their nature, are able to select a preferential rest-frame where the fundamental scale ℓ_p acquires an invariant meaning. In other words, within the relational approach we are advocating, it is clear that, in order to be directly sensitive to the discreteness scale ℓ_p, the probing degrees of freedom must themselves carry their intrinsic scale. Thus massless (scale-invariant) fields are ruled out as leading probes of discreteness simply because they cannot be associated with any local notion of rest frame, and thus, of a fundamental length scale. This argument identifies massive fields as the natural candidates for probes of spacetime discreteness. Such discreteness must be thus thought as becoming relevant, or as 'awaken', by the interactions of gravity with such scale-invariance-breaking fields. The immediate possibility arising from such considerations (and framed in a phenomenological perspective) is that low energy quantum field theoretical excitations of massive fields could interact with the underlying quantum gravity microstructure and exchange 'energy' [3] with it [4].

In order to study the phenomenological implications of these ideas one needs a 'mean field' or macroscopic description of the quantity parametrizing the phenomenon. An obvious choice is the trace of the energy-momentum tensor $\mathbf{T}$—which for a fluid in thermal equilibrium is simply given by $\mathbf{T} = \rho - 3P$—which signals the breaking of conformal invariance, and hence, the presence of massive degrees of freedom. Via Einstein's equations $\mathbf{T}$ is related to the scalar curvature $\mathbf{R} = -8\pi G\mathbf{T}$. Therefore, the presence of massive fields (suitable probes of discreteness according to our rationale) is geometrically captured by a non trivial $\mathbf{R}$.

The effect on the propagation of massive fields must be realized in a deviation from the geodesic motion of free particles due to a 'friction-like' force encoding the noisy interaction with the underlying spacetime granularity. As argued in the previous paragraphs, the force must be proportional to $\mathbf{R}$. In addition, the force should depend on the mass m, the 4-velocity u^μ, the spin s^μ of the classical particle (the only intrinsic features defining a particle), and a time-like unit vector ξ^μ specifying the local frame defined by the matter that curves spacetime. For instance, in cosmology $\xi = \partial_t$ is naturally associated with the time-arrow of the co-moving cosmic fluid. In addition, and according to our preceding arguments, the force should be proportional to the particle's mass, endowing it with a characteristic length scale: the Compton wave-length. Dimensional analysis gives an essentially unique expression which is compatible with the above requirements [5],

$$u^\mu \nabla_\mu u^\nu \;=\; -\alpha \frac{m}{m_p^2}\,\mathrm{sign}(s\cdot\xi)\mathbf{R}\, s^\nu, \tag{1}$$

where $\alpha > 0$ is a dimensionless coupling[6].

The factor $\mathrm{sign}(s\cdot\xi)$ makes the force genuinely friction-like. This is apparent when one considers the change of the mechanical energy of the particle $E \equiv -mu^\nu\xi_\nu$ (defined in the frame defined by ξ^μ) along the particles world-line, namely

$$\begin{aligned}\dot{E} \;&\equiv\; -mu^\mu\nabla_\mu(u^\nu\xi_\nu)\\ &=\; -\alpha\frac{m^2}{m_p^2}|(s\cdot\xi)|\mathbf{R} - mu^\mu u^\nu\nabla_{(\mu}\xi_{\nu)}.\end{aligned} \tag{2}$$

The last term in (2) encodes the standard change of E associated to the non-Killing character of ξ^μ. The first term on the right encodes the friction that damps out any motion with respect to ξ^μ. Energy is lost into the fundamental granularity until $u^\mu = \xi^\mu$ and the particle is at rest with the cosmological fluid, and thus $\dot{E} = 0$.

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[2] A concrete scenario illustrating the idea is the deparametrization of gravity using dust or other suitable (massive) matter degrees of freedom. In these models discreteness of geometry at the Planck scale realizes upon quantization in relational observables involving matter and geometry [11, 12]. Such approach is certainly simplistic because the matter 'rulers' are not properly quantized but illustrates the spirit of our view.

[3] It seems clear that the notion of energy as understood in the context of metric description of spacetime will have to be superseded by a more fundamental notion appropriate to the discrete language in which QG would be framed at the fundamental level.

[4] Some ideas with similar conceptual underpinning have been explored in the context of laboratory searches for quantum gravity phenomenology [13–15]. For a discussion of the implications for the information problem in black hole evaporation see [16, 17].

[5] Higher curvature corrections could be added, but these are highly suppressed by the Planck scale and are thus negligible for the central point of this letter.

[6] There is a remarkable formal similarity of equation (1) with others arising in well understood situations. We have the Mathisson-Papapetrou-Dixon equations [18] describing the dynamics of idealized extended objects in GR,

$$u^\nu\nabla_\nu P_\mu = -\frac{1}{2}\mathbf{R}_{\mu\nu\rho\sigma}u^\nu S^{\rho\sigma},$$

where u^μ represents the 4-velocity of the object, P^μ its 4-momentum, $S^{\rho\sigma}$ its spin and $R_{\mu\nu\rho\sigma}$ is the Riemann tensor. Moreover, we note that the characterization of WKB-trajectories of the Dirac theory on a pseudo-Riemannian geometry [19], to lowest order in $\hbar$, is given by

$$u^\nu\nabla_\nu(mu_\mu) = -\frac{1}{2}\tilde{\mathbf{R}}_{\mu\nu\rho\sigma}u^\nu\langle S^{\rho\sigma}\rangle + \mathscr{O}(\hbar^2).$$

The previous is equivalent to (1) if one considers an effective $\tilde{\mathbf{R}}_{\mu\nu\rho\sigma} \propto m^2/m_p^2\,\mathrm{sign}(s\cdot\xi)\mathbf{R}\epsilon_{\mu\nu\rho\sigma}$ taken to encode a pure torsion-related structure as $\tilde{\mathbf{R}}_{[\mu\nu\rho]\sigma} \neq 0$ (from the first Bianchi identities).

Consistency of (1) and the conservation $s\cdot s$ and the condition $s\cdot p=0$ leads to the following equation for the spin

$$u^\mu\nabla_\mu s^\nu = -\alpha\frac{m}{m_p^2}\,\mathrm{sign}(s\cdot\xi)\mathbf{R}\,(s\cdot s)\,u^\nu. \tag{3}$$

We will not directly use this equation here but it is important due to its potential phenomenological implications.

In this respect, it is also important to point out that the violations of the equivalence principle and Lorentz invariance implied by (1) and (3) can be readily checked not to be in conflict with well known observational bounds by many orders of magnitude [20] for $\alpha\sim O(1)$. A simple indication comes from comparison of the value of $\mathbf{R}$ at the electro weak (EW) transition in cosmology (a regime where our effects will be important) to that associated with, say, the gravitational effect of a piece of lead: this gives $\frac{\mathbf{R}_{lead}}{\mathbf{R}_{EW}}\sim 10^{-24}$.

Coming back to the main argument, the diffusion of energy for a single particle, induced by (1), implies the lack of energy-momentum conservation for a fluid constituted by an ensemble of such particles (we will compute this below). However, violations of energy-momentum conservation are incompatible with general covariance and hence with the standard general relativity description of gravity. Fortunately, there is a simple relaxation of general covariance (originally studied by Einstein) from full coordinate invariance down to spacetime volume preserving coordinate transformations. Such modification—which we only take as an effective low energy description of a (in a suitable sense) general covariant fundamental physics—is called unimodular gravity (UG), and its field equations are just the trace-free part of the standard Einstein's equations

$$\mathbf{R}_{\mu\nu}-\frac{1}{4}\mathbf{R}g_{\mu\nu}=8\pi G\left(\mathbf{T}_{\mu\nu}-\frac{1}{4}\mathbf{T}g_{\mu\nu}\right). \tag{4}$$

Defining $J_\mu\equiv(8\pi G)\nabla^\nu T_{\nu\mu}$, assuming UG integrability $dJ=0$, and using Bianchi identities, one obtains [5]

$$\mathbf{R}_{\mu\nu}-\frac{1}{2}\mathbf{R}g_{\mu\nu}+\underbrace{\left[\Lambda_0+\int_\ell J\right]}_{\Lambda}g_{\mu\nu}=8\pi G\mathbf{T}_{\mu\nu}, \tag{5}$$

where Λ_0 is a constant of integration, and ℓ is a one-dimensional path from some reference event. Thus, the energy-violation current J is the source of a term in Einsteins equations satisfying the dark energy equation of state. Moreover, in UG the vacuum energy does not gravitate [3, 21] resolving the tension previously mentioned between quantum field theory and cosmology [22].

Now we compute $J_\nu\equiv 8\pi G\nabla^\mu T_{\mu\nu}$ as implied by (1). For a particle species i (the interactions between different species are neglected here as their effect lead only to very small corrections) one has $\mathbf{T}^i_{\mu\nu}$ [7]

$$\mathbf{T}^i_{\mu\nu}(x)\equiv\int p_\mu p_\nu\, f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r, \tag{6}$$

where $f^i(x,p,s_r)$ encodes the particle distribution in phase space with s_r denoting the value of the spin of the particle in its rest frame, $\mathrm{D}p=\delta(p^2+m^2)dp^4$, and $\mathrm{D}s_r$ is the standard measure on the sphere of the spin directions. Simple kinetic theory allows to express $\nabla^\mu\mathbf{T}^i{}_{\mu\nu}$ as (see equation 2.113 in [23])

$$\begin{aligned}\frac{\nabla^\mu\mathbf{T}^i_{\mu\nu}}{\mathbf{T}^i} &= -\frac{\int m_i F_\nu f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}{m_i^2\int f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r} \\ &= \alpha\frac{m_i}{m_p^2}\mathbf{R}\frac{\int\left[\frac{s_\nu s_0}{|s_0|}\right]f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}{\int f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}\end{aligned} \tag{7}$$

where 0-components refer to the time direction ξ^μ. Assuming thermal equilibrium at temperature T, and ignoring the negligible additional effects of the force on the distribution, we have $f^i(x,p,s_r)=f^i_T(p)$ where the later is the standard Boltzmann distribution. In the relativistic regime $T\gg m$ one has [8]

$$\begin{aligned}J^\nu &\equiv (8\pi G)\,\nabla^\mu\mathbf{T}_{\mu\nu}=4\pi\alpha\frac{T}{m_p^2}\mathbf{R}\left[8\pi G\sum_i|s_i|\mathbf{T}^i\right]\xi^\nu, \\ &\approx -2\pi\alpha\hbar\frac{T}{m_p^2}\mathbf{R}^2\xi^\nu\end{aligned} \tag{8}$$

where in the last line we write an approximation valid for the case where a single $|s|=\hbar/2$ fermion species dominates. This approximation will be useful in the application of the formula to cosmology.

We now focus on the effects of (8) in the dynamics of the early universe when its macroscopic geometry is well approximated by the flat FLRW metric[9]

$$ds^2=-dt^2+a(t)^2d\vec{x}^2, \tag{9}$$

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[7] There is a subtle point that ought to be noted here: this part of the calculation is carried out by considering a space-time region small enough to be covered by Riemann normal coordinates (i.e. a local inertial frame) in such a way that the standard effects of curvature can be neglected. The region is however large in comparison with the Planck scale so that the energy diffusion effects, the non standard influence of $\mathbf{R}$ in our model, are encoded in the friction force underlying (1).

[8] Isotropy of the equilibrium configuration implies that only the $0-$component of the equations is non trivial. Then the result follows first from the fact that

$$\int|s_0|\mathrm{D}s_r=\frac{2\pi\mathbf{p}|s|}{m}\int|\cos(\theta)|\sin(\theta)d\theta=\frac{2\pi\mathbf{p}|s|}{m},$$

where $\mathbf{p}^2\equiv\vec{p}\cdot\vec{p}$, and the factor $\mathbf{p}/m$ comes from the boost relating the comoving frame to the rest frame of the particle. The next step is

$$\frac{\int\left[\frac{2\pi\mathbf{p}|s|}{m}\right]f_T(p)\mathrm{D}p}{\int f_T(p)\mathrm{D}p}=4\pi|s|\frac{T}{m}\left[1+\mathscr{O}\left(\log\left(\frac{m}{T}\right)\frac{m^2}{T^2}\right)\right].$$

[9] Note that the unimodular condition can be expressed in coordinate free language by the requirement that the volume form ϵ_{abcd} derived from the metric must match a certain predetermined 4-

and where the local frame $\xi = \partial_t$ is identified with co-moving observers. As only massive particles with spin are subjected to the frictional force (1), the diffusion mechanism in cosmology starts when such particles first appeared. According to the standard model—whose validity is assumed from the end of inflation—this corresponds to the electro-weak (EW) transition time. We further assume that a protective symmetry enforces $\Lambda_0 = 0$ (see for instance [24, 25]).

We are now ready to estimate the effective cosmological constant predicted by our model. Using (5), and (8) one gets

$$\Lambda = \frac{2\pi\alpha\hbar}{m_p^2} \int_{t_{\rm ew}}^{t_0} \left[8\pi G(\rho - 3P)\right]^2 T\, dt, \tag{10}$$

with t_0 the present time. It is convenient to change the integration variable in (10) from co-moving time t to temperature T given the essentially direct relation between the two quantities. During the relevant period the matter fields are assumed to be in thermal equilibrium. The density of the universe, during radiation domination[10] is given by, $\rho = \pi^2 g_* T^4/(30\hbar^3)$ where $g_* \approx 100$ is the effective degeneracy factor for the temperatures of interest [26]. Taking into account that temperature scales like a^{-1}, using Friedman equation, and $H(a) = \dot{a}/a$, one gets,

$$\frac{dT}{T} = -\frac{da}{a} = -\underbrace{\sqrt{\frac{8\pi G}{3}\frac{\pi^2 g_* T^4}{30\hbar^3}}}_{H(a)}\, dt. \tag{11}$$

We will now focus just on the leading contributions. In the ultra-relativistic regime standard thermodynamics leads to the expression

$$\rho - 3P \approx \frac{m_t^2 T^2}{2\hbar^3}, \tag{12}$$

where m_t is the top mass. Replacing the leading term in (12) and (11) into (10) one gets

$$\Lambda \;\approx\; 16\alpha\sqrt{\frac{5\pi^3}{g_*}}\;\frac{m_t^4 {T_{\rm ew}}^3}{m_p^5\hbar^2}\;\epsilon(T_{\rm ew}), \tag{13}$$

where

$$\epsilon(T_{\rm ew}) = -\frac{3}{T_c^3}\int_{T_{\rm ew}}^{T_{\rm end}} \left(1 - \frac{T^2}{T_{\rm ew}^2}\right)^2 T^2 dT \tag{14}$$

is a dimensionless correction factor that takes into account the temperature dependence of the quark mass during the EW-transition, namely $m_t^2(T) = m_t^2(1 - T^2/T_{\rm ew}^2)$. The end temperature $T_{\rm end}$ is the one satisfying $2m_t(T_{\rm end}) = T_{\rm end}$ when the top quark's abundance decreases dramatically. The contribution of other fields in the standard model, as well as those tied to simple dark matter models such as WIMPS will not affect the order of magnitude of the estimate [11]. We note that aside from the correction factor, $\epsilon(T) \approx 10^{-3}$—$10^{-4}$ in the range of interest, equation (13) could have been guessed from dimensional analysis. After substitution of the different quantities involved and taking for example $T_{\rm ew} \approx 100$ GeV [27, 28], and adding the gauge boson contributions (not included in (13)) we find

$$\Lambda \approx 4\,\alpha\,\Lambda_{\rm obs} \tag{15}$$

where $\Lambda_{\rm obs}$ is the observed value of the cosmological constant. For other values of $T_{\rm ew}$ see Figure 1 where we plot the value of the dimensionless coupling α needed to fit the observed values as a function of $T_{\rm ew}$. These results are an order of magnitude estimate; a refined calculation would require detailed considerations of the dynamics of the electro-weak transition. However, such details are not expected to modify our result in essential ways.

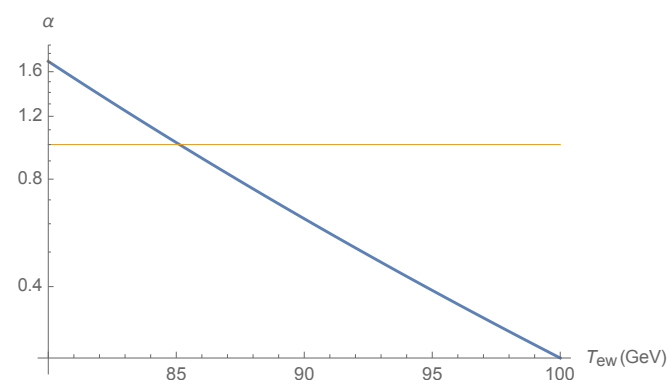

Figure 1: The value of the phenomenological parameter α, see eq. (1), that fits the observed value of Λ_{obs} as a function of the EW transition scale $T_{\rm ew}$ in GeV. The contributions from the massive gauge bosons of the standard model have been included.

We believe that our proposal has important implications of various types. At the theoretical level it provides a novel view that could reconcile Planckian discreteness and Lorentz invariance and gives possibly valuable in-

form e_{abcd}. It is only when one uses coordinates adapted to the latter (which always exist), that the condition can be expressed as the requirement that $\sqrt{-g} = 1$ which is clearly a coordinate dependent expression.

[10] The assumption of radiation domination is appropriate here as the contributions to the effect in question come mainly from the early times close to t_{ew} where $\mathbf{R}$ is the largest.

[11] Massive gauge bosons do not change the order of magnitude estimate, as $m_Z/m_t \approx 1/2$ and $g_{ZW^\pm}/g_{t\bar{t}} = 3/4$. In (13) this leads to a factor $(3/4)^2(1/2)^4$ times 2 as the spin of the bosons is twice that of the fermions, i.e. their contributions is about 7% of that coming from top-quark. From (8) one can work out the precise corrections which are included in Figure 1.

sights guiding the search for a theory of quantum gravity. At the empirical level our analysis opens a new path for searches of new physical manifestations of the gravity/quantum interface.

Concerning the later, we note that one might use (8) to estimate the amount of energy loss in local experiments. Presently (neglecting the cosmic expansion), we find $\dot{\rho} \approx -\alpha(\rho/\rho_{\rm water})^2 10^{-70} g/(cm^3 s)$ where $\rho_{\rm water}$ is the density of sea water. The amount of energy produced is maximal at the EW transition when the density of the universe $\rho(T_{\rm ew}) \approx 10^{25} g/cm^3$, and corresponds to $\dot{\rho}(z_*) + 3\rho H(a) \approx -\alpha\, 10^{-20} g/(cm^3 s)$. Such a minuscule level of energy loss cannot have significant effects on the matter dynamics, and thus would be very hard, but not impossible to detect. Nevertheless, we have seen that such small energy losses can explain the observed late time acceleration of the expansion rate of our universe.

Finally, as the model links ρ and its evolution with the present value of the cosmological constant, and ρ directly enters in the computation of the structure formation leading to galaxies, stars and eventually humans, this framework opens, in principle, a path that might help in addressing the longly debated 'coincidence problem' [26].

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