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A Classical Resolution of the Cosmological Constant Problem

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Abstract

The "Cosmological Constant Problem" is generally regarded as one of the outstanding unsolved problems in science. By analyzing the actual physics behind the mathematics we show that a natural and simple resolution is provided by the fact that general relativity, the very theory used to model cosmology, is a fundamentally *classical* theory of actual objective, invariant classical events both constituting and defining spacetime itself.

1 Introduction

In 1917, Einstein (who else?) made the first application of general relativity to cosmology [1]. The universe was then thought to be synonymous with our galaxy, the Milky Way - other galaxies confirmed only in 1924. Therefore, Einstein sought a relativistic solution to the universe that was static, unchanging (on average at least), had existed infinitely in the past, and would exist infinitely into the future.

However, Einstein's original general relativistic equations of 1915 did not admit such a static solution. In Newtonian terms, a non-changing universe is unstable due to the universal attraction of gravity, and will collapse by its own accord in a finite time - and the same remains true in general relativity.

Therefore, Einstein introduced an extra "balancing" term, which can be made to act as a repulsive force (in Newtonian terms). If chosen correctly, such a term makes a static solution possible.

The simplest way, which Einstein adopted[1], is to add an extra term, Λg_{ab}, to the left-hand (geometrical) side of the equations of general relativity. This is allowed as the covariant derivative of the metric $g^{ab}_{;b} \equiv 0$, so local energy-momentum conservation $T^{ab}_{;b} = 0$ is still fulfilled. Here Λ is a free scalar constant parameter, “unbekannten universellen Konstante” [1]. In principle, one is free to add arbitrarily many correction terms to Einstein’s Equations, but in the spirit of simplicity (“Ockham’s Razor”) one should try to keep them to a minimum while still fulfilling the observational facts, giving

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

So, now Einstein mathematically had concocted a static, general relativistic solution to the universe - which everybody at the time “knew” and agreed was static and unchanging. However, shortly after, it was shown that the solution was static but *unstable* (like a needle balancing on its tip) - the slightest perturbation, which in a physical universe is inevitable, would make the universe either collapse or expand anyway[2].

And in 1929, Hubble observed that the universe actually is expanding, making Einstein’s introduction of the extra cosmological term seem completely unnecessary. In fact, if Einstein had not introduced the Cosmological Constant he could have *predicted* that the universe must be expanding (or contracting) more than a decade before it was actually observed, and he considered the introduction of Λ the biggest blunder of his career. This shows that it can be very hard to break from the scientific prejudices of one’s own time, even for a true genius of Einstein’s caliber.

However, when the genie is out of the bottle it is very hard to put back in. In 1998, two independent research collaborations [3], [4], observed that the expansion of the present universe seems to be *accelerating*. This is impossible using Einstein’s original equations from 1915, but becomes perfectly possible if the Cosmological Constant Λ is reintroduced, but in a different context: not to give a static universe, but a universe that is speeding up. Because of its structure Λg_{ab} is completely negligible when the universe, cosmologically speaking, is “small”, but automatically becomes dominant when the universe expands beyond a certain size. Early on, the energy density in a “hot big bang” universe is completely dominated by radiation, a little later by matter, but as both of these *decrease* due to the expansion, the Cosmological Constant term will, sooner or later, come to dominate. When this happens, the universe

[1]Wir können nämlich auf der linken Seite der Feldgleichung den mit einer vorläufig unbekannten universellen Konstante $-\lambda$ multiplizierten Fundamentaltensor $g_{\mu\nu}$ hinzufügen, ohne daß dadurch die allgemeine Kovarianz zerstört wird [1].

[2]Einstein: “if there is no quasi-static world after all, then away with the cosmological term” [2]

goes from the (expected) decelerating phase of radiation/matter into the (unexpected, before 1998) seemingly accelerating phase of the present universe. The magnitude of Λ tells us when that happens. However, this invisible "dark energy" often associated with Λ has never been independently observed. It is *only* indicated, indirectly, through cosmological observations filtered through the present standard model of cosmology (observational data make no sense until interpreted through a model). So, presently Λ is analogous to the ancient "explanation" of why the planets go around the Sun: There were supposedly invisible angels behind them beating their wings, pushing the planets around an orbit [5].

By placing the new term on the left-hand (geometrical) side of Einstein's Equations, as in Eq. (1), it can be viewed as an extra, intrinsic, contribution to the spacetime curvature. By placing it on the right-hand (physical) side, it can be seen as representing the energy-momentum of the vacuum itself. However, the classical vacuum is truly empty, $T_{ab} = 0$, and general relativity is fundamentally a classical theory that has nothing to do with quantum physics ($\hbar$ nowhere to be found). However, if we disregard that obvious, but usually completely neglected, fact and try to calculate Λ as arising from the contribution of quantum fluctuations in a vacuum, the result comes out (at least) 10^{120} times larger than the one seemingly needed to explain cosmological observations

$$\frac{\Lambda_{\text{``}theory\text{''}}}{\Lambda_{\text{``}obs\text{''}}} \geq 10^{120}, \tag{2}$$

which in turn would mean that no gravitational structures could ever have formed.

This extreme discrepancy between theory and the real world is "the Cosmological Constant Problem" [6], generally regarded as one of the outstanding unsolved problems of fundamental physics (and an example of what happens when one tries to mix general relativity with quantum physics, despite the fact that no theory of quantum gravity exists). Without a high-energy cutoff, the zero-point energy of the infinite number of normal quantum field theory modes actually makes $\Lambda_{\text{``}theory\text{''}} \to \infty$. However, the "high-energy" cutoff needed to reproduce the "observed" Λ turns out to be of the order of 1 *milli*-eV, *i.e.* just a tiny fraction of the energy of visible light. The problem is therefore not really of unexplored high-energy/short length-scale origin, but should be understandable *now*. A physical explanation of this hypothetical "dark (= invisible) energy" is, so far at least, much more problematic than the very problem it is intended to solve.

2 General relativity is a *classical* theory

Einstein's classical equations of general relativity are a system of ten coupled, nonlinear partial differential equations that have to be solved simultaneously. To achieve analytical cosmological solutions to a physically realistic universe is out of the question. Therefore, early researchers made drastic simplifications to make way forward. "The Cosmological Principle" was decided upon as a reasonable assumption and workable approximation: at any epoch the (model) universe is postulated to be exactly homogeneous and isotropic[3].

Under the assumption of "the Cosmological Principle", and its many associated simplifying symmetries, Friedmann, Robertson, Walker (and Lemaître) deduced the resulting unique FRW-solution to Einstein's Equations

$$ds^2 = c^2dt^2 - a^2(t)[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)] \tag{3}$$

With this extreme simplifying assumption[4], implying that the universe is filled with an idealized absolutely homogeneous and isotropic perfect fluid of scalar density ρ and scalar pressure p, with the simple energy-momentum tensor

$$T_{ab} = (\rho + p/c^2)u_a u_b - pg_{ab}, \tag{4}$$

where u is the velocity 4-vector, Einstein's coupled system of ten partial differential equations reduces to an extremely simplified system of only two coupled ordinary differential equations that *do* allow analytical solutions [9], [10], [11]: "Friedmann's Equations" (with Einstein's extra cosmological "correction" added in parenthesis)

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - kc^2(+\frac{\Lambda c^2}{3}a^2) \tag{5}$$

$$\dot{\rho} + \frac{3\dot{a}}{a}(\rho + p/c^2) = 0 \tag{6}$$

where the "dot" is shorthand for time derivative, $\dot{a} = da/dt$, $\dot{\rho} = d\rho/dt$.

This results in that the only dynamical degree of freedom remaining in *the model* is the cosmic scale-factor, $a(t)$, which describes the general, universal, homogeneous, smooth expansion of space at any given time, t. Also, the evolution of this model universe is adiabatic and reversible, conserving entropy.

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[3] "It is a completely arbitrary hypothesis, as far as I understand it... Yet we must not accept such a hypothesis without recognizing it for what it is." [7]

[4] "This rawest of all possible approximations may be considered as an attempt to set up an ideal structural background on which are to be superposed the local irregularities due to the actual distribution of matter and energy in the actual world." [8]

The parameter k encodes the *universal*[5] spatial geometry of this crude model, and, as one is free to recalibrate coordinates at will (general covariance), it is only the sign of k that matters: $k = +1$ describes a universe with positive spatial curvature (in this case $a(t)$ is directly related to the physical radius of the model universe); $k = -1$ describes a universe with negative spatial curvature; with $k = 0$ being the (unlikely, probability zero) borderline case which describes a flat universe with Euclidean spatial geometry everywhere. The cosmic scale-factor of the model is connected to the observable Hubble parameter, $H(t)$, through $H = \dot{a}/a$.

In this very idealized *model* there is a "critical density", $\rho_{crit} \equiv 3H^2/8\pi G$, which gives the flat $k = 0$ case[6]. The dimensionless parameter $\Omega = \rho_{obs}/\rho_{crit}$ is commonly used to distinguish the three different cases, where ρ_{obs} is the observed physical density (assumed exactly homogeneous): $\Omega > 1 \leftrightarrow k = +1$; $\Omega < 1 \leftrightarrow k = -1$; $\Omega \equiv 1 \leftrightarrow k = 0$.

What not normally is emphasized nearly enough is that the whole *concept* of the cosmic scalefactor a, Hubble's parameter $H = \dot{a}/a$, the Hubble constant $H_0 = H(t = now)$, k, the critical density $\rho_{crit} = 3H^2/8\pi G$, and the dimensionless density parameter $\Omega = \rho/\rho_{crit}$, etc., *all* crucially depend on the perfect, and eternal, homogeneity and isotropy of the idealized and highly simplified Friedmann-Robertson-Walker *model* universe $\neq$ the *real* universe, together with the assumption of an idealized perfect fluid for the energy-momentum tensor T_{ab} - neither of which are obeyed by the real, physical universe.

Through the assumptions of absolute homogeneity and isotropy, t is a universal "cosmic time", the same everywhere throughout space in the model. (Which is *not* the case in the real universe, due to both special and general relativistic effects.)

For a FRW-model universe without any gravitation at all H would be *constant* and the age of such a universe would simply be $age = H^{-1}$. For a non-empty universe, gravitation decelerates the expansion, but as a fair approximation for a model universe with $\Omega \sim 1$, $age \simeq H_0^{-1} = H^{-1}(t_{now})$.

If extrapolated backwards in time, the temperature increases (hence the designation "hot" big bang) and at $t = 0$ reaches a singular origin, where the density, temperature and spacetime curvature all become infinite and the

[5]Which simply is not true, as there then would be no gravitation anywhere apart from its effect on the homogeneous scale-factor, a, of the universal expansion, precluding the known structure in the universe. The Riemann curvature tensor, R_{abcd}, which is the complete description of the curvature - and hence gravity - for a given spacetime, for the FRW model universe gives the coordinate-invariant $R_{abcd}R^{abcd}$ as just a function of $(k, a, \dot{a}, \ddot{a})$, and hence the *same* everywhere at any given "cosmic time", t.

[6]Contrary to popular belief, it is almost infinitely easier (by a factor $\sim 10^{10^{100}}$) to generate a smooth flat early universe *without* inflation than with inflation [12], which is just as well, as inflation involves (very) *hypothetical* particle physics at energies *way* beyond the experimental reach of terrestrial accelerators, making it empirically untestable.

model fails[7].

The FRW-model universe itself is thus *forced by hand* to be exactly isotropic and homogeneous, *i.e.*, to obey "the Cosmological Principle". In the real universe this *may* have been a fair approximation when the cosmic microwave background radiation (CMB), according to the model, was released (cosmological redshift $z \sim a_{now}/a_{decoupling} \sim 1,100$), but today is a very poor approximation. Already in 1970, de Vaucouleurs [13] demonstrated that actual observations instead support a "hierarchical", *inhomogeneous* cosmology in which the scale-factor a, insofar it can be used at all, becomes scale-dependent. Since then, huge inhomogeneous regions of cosmic "voids" and "filaments" have been discovered [14], [15], quite unexpected by theoretical ideas at the time. The largest known structure so far is $\sim 10^{10}$ lightyears [16], already comparable to the entire observable universe, and current evidence implies that even larger structures are expected as soon as deeper redshift surveys will be completed [17].

The standard model of cosmology tries to treat the generation and evolution of structures, assumed generated solely by gravity[8], as small perturbations superposed on the idealized state = the smooth background Friedmann-Robertson-Walker spacetime geometry, but this breaks down when inhomogeneities become significant and nonlinear effects overwhelm the linear ones. Furthermore, to work at all this process must be "doped" by huge amounts of (still hypothetical) dark matter in order to reproduce, statistically, the observed structure in the "mere" 14 billion years available since the big bang in the model. Also, due to the highly nonlinear nature of general relativity, in a

[7]The Riemann curvature invariant $R_{abcd}R^{abcd} \to \infty$ as $t \to 0$ for the Friedmann-Robertson-Walker metric.

[8]Recently, the importance of magnetic fields have been emphasized [18], [19], presaged already in the 1940s by Hannes Alfvén [20]. Turbulence in the universe was also noted as another crucial aspect by George Gamow, one of the originators of the "hot big bang model", already in 1952 [21] - it would automatically give self-similar, roughly scale-invariant seeds for subsequent structure formation without the need for any "exotic" (unknown/unknowable) physics at all. Neither of these are implemented in the standard model of cosmology, even though both the kinetic and magnetic Reynold's numbers in the early universe would be enormous ($\sim O(10^{16})$ and $\sim O(10^{24})$ respectively [22]), way above where turbulent flows are to be expected, $Re_{critical} \simeq 100$, invalidating any global "Hubble flow" and making a universal H meaningless. For the *real* universe, structure formation is thus *not* properly modeled by just the simple gravitational Jeans instability assuming linearized acoustic inviscid Euler equation with newtonian gravity (*linear* in the gravitational potential ϕ) and density equation without diffusion, all on a *smooth* passive background FRW-metric assumed independent from structure formation. Many other non-gravitational (non-geodesic) effects from known (but neglected) physics, *and* incorporation of general relativity - *nonlinear* in the gravitational potentials g_{ab} - can be crucial to understand both structure formation in, and the global dynamics of, the *real* physical universe, and may well make all "exotic" (hypothetical) absurdly finely tuned ingredients (*e.g.* dark matter and dark energy) needed in the naïve FRW-standard model entirely superfluous.

hierarchical (= real) universe, first averaging and then deducing the dynamics is *not* the same as first deducing the dynamics and then averaging. (But large N-body simulations have so far used only Newtonian gravitation, linear in the gravitational potential, which fail to reproduce the observed power-law behavior of the large-scale structure of the real universe [17].)

Extrapolating data from high-z (early universe) observations, like CMB, to low-z (late universe) observations, like supernovae, is quite sensitive to which dynamical model of the universe (*e.g.* FRW or "realistic") is used. This is clearly seen in the "Hubble Constant Tension" [23] where [high-z + FRW-extrapolation] $\Rightarrow H_0 = 67$ km/s/Mpc, and [low-z] $\Rightarrow H_0 = 74$ km/s/Mpc. In a real inhomogeneous and anisotropic universe the value "H_0" furthermore, at best, is just an average mean, *not* a fundamental universal constant as in the naïve FRW-model.

The observed redshift, z, however, is well-defined through

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}, \tag{7}$$

where λ is the wavelength, regardless of whether a global scale-factor a is well-defined/relevant or not.

Even so, the standard model of cosmology requires eleven (with *additional* simplifying assumptions, reducing to seven) [24], *a priori* free parameters, painstakingly adjusted to fit cosmological observational data. In this connection there is reason to recall John von Neumann's famous remark: "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk", *i.e.*, one should not be overly impressed when a model with many free parameters fits the data set well - with enough parameters, you can fit *any* data[9].

[9] A case in point: it has been mathematically proven that with enough Ptolemaic epicycles one can reproduce, *i.e.* fit, *any* motion whatsoever to arbitrary accuracy. This is what the standard ΛCDM "concordance cosmology" is starting to resemble - an unfalsifiable [25] complicated dogma, where every new observational result not compatible with it entails the introduction of new arcane *ad hoc* ingredients with accompanying free parameters, just waiting to be replaced by something simpler and physically more natural. When there are as many, or more, free adjustable parameters as observational information channels, it is never a good sign. The standard model of *particle physics*, relevant to the early epochs of a big bang-model, has around two *dozen* free parameters, and is thus in even worse shape. Together, the two "standard models" provide an embarrassing plethora of free parameters relevant to the FRW model-universe. (In theories "beyond the standard model" parameters typically rank in the hundreds, or more.) The Ptolemaic theory also had a wealth of adjustable parameters, Newton's theory that superseded it has - *none*.

2.1 No quantum vacuum contribution to T_{ab}

Even though it of course is mathematically allowed to move Λg_{ab} (geometrically an intrinsic curvature of classical empty spacetime if on the left-hand side) to the right-hand side of Einstein's equations

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

physically it is *not* permissible to then interpret Λg_{ab} as the *vacuum* energy-momentum tensor, as it *per definition* must be identically zero for the purely classical theory of general relativity

$$T_{ab}(vacuum) \equiv 0 \neq 0 + \langle \rho \rangle g_{ab} \tag{9}$$

where[10] $\langle \rho \rangle = \frac{c^4}{8\pi G}\Lambda$ is supposed to be the, formally infinite, energy density of the quantum "vacuum", teeming with infinitely many "virtual particles" - at least in the approximate description using perturbative and merely Lorentz-covariant (*special* relativistic) Feynman diagrams. In curved spacetime quantum field theory particle-states are generally not even well-defined [26] and the same is true for nonperturbatively interacting special relativistic quantum field theory as there then are no asymptotic (=particle) states [27]. However, $\langle \rho \rangle \sim \hbar c \int_0^{k_{cutoff}} k^3\, dk$, so classically ($\hbar \to 0$), appropriate for cosmology based on general relativity, $\langle \rho \rangle$ becomes zero.

If the cutoff is taken to be $k_{cutoff} = 2\pi / l_{Planck}$, and $\hbar$ retained (which would necessitate a theory of *quantum* gravity - which does not exist), we get the previously quoted disastrous 10^{120} discrepancy between "observation" and "theory". However, relativistic fluid dynamics is but an *approximation* of the motion of a many-body system. A true description of a fluid would, in principle, need to account for the motion of each individual particle. Only provided that the desired level of accuracy is much lower than the continuum approximation is it acceptable to consider a system as a fluid, *making Λ as a classical fluid incompatible with its proposed origin from "quantum fluctuations"* as only the expectation value would be constant (averaged over all space) whereas *its local magnitude would fluctuate wildly* (actually divergently, without any cutoff) both in space and time resulting in a very *inhomogeneous*, locally *non*-constant, "Cosmological Constant" and making the expectation value $\langle \rho \rangle$ ill-defined. Even if we conveniently try to "forget" that general relativity is a classical theory, this in itself would invalidate the FRW-metric for "vacuum energy".

Luckily, in the more exact treatment of the Casimir effect [28] by Lifshitz [29], which underlies its modern understanding and theoretical extensions, fields have no zero-point energy. They are classical but coupled to the

[10]For any $T_{ab} \propto g_{ab}$, $\rho = -p/c^2$, Eq. (6) giving $\rho = const$.

material, so the Casimir effect is today understood to have nothing at all to do with "quantum fluctuations" of the vacuum itself, rather it is explained by quite normal interactions of materials with their own nearby electromagnetic modes, *i.e.* by generalized van der Waals forces between charged particles. This is clearly evidenced empirically by the fact that the *real*, measured, Casimir effect is both material- and temperature-dependent. To date, there is *no*[11] laboratory experimental evidence for *any* quantum zero-point energy of the vacuum[12].

3 *Quantum* Gravity?

We have already emphasized that general relativity is a *classical* theory, having nothing at all to do with quantum physics. In it, the static, globally flat, simple Minkowski-metric of *special* relativity is replaced by the dynamical general spacetime metric g_{ab} as a direct result of the *Equivalence Principle* - the universality of free-fall.

However, as nature at its most fundamental level (today) is described by quantum physics, many expect that general relativity should be the macroscopic limit of some (unknown) theory for quantized gravity, that is, *"Quantum Gravity"*.

This goal has not been accomplished, despite almost a century of attempts.

The main problems are that:

i) In quantum mechanics there are no trajectories for objects, hence accelerations for them cannot be defined. So, the Equivalence Principle - *the whole physical basis of general relativity* - cannot be applied in the quantum domain.

ii) Gravitation cannot be treated like the other three known fundamental forces, in terms of quantum field theory, both because the gravitational "coupling constant" $\propto G$, Newton's constant for universal gravitation, is *not* dimensionless, which in turn means that the resulting quantum field theory is "non-renormalizable" (the normal methods for hiding infinities do not work) giving nonsensical results, and because gravity is a *global* effect, not local like quantum field thory (this is evident as a mere change to free-falling coordinates makes gravity, locally, *vanish*).

iii) Quantum field theories are defined on a spacetime background given by *classical* relativity, so cannot explain gravity - spacetime itself - as a microscopic interaction.

[11] "Still, no known phenomenon, including the Casimir effect, demonstrates that zero-point energies are real" [30].

[12] And it is very unlikely there ever will be, as a physical zero-point energy of the vacuum would preclude ever having a Minkowski-metric, making all the triumphs of particle physics impossible. Along with both classical electromagnetism and $E = mc^2$ to boot.

iv) Worst of all, there are no experiments to guide the construction of a theory. So, "Quantum Gravity" is presently outside of science proper - which always should be based on the "scientific method" of hypothesis, real experimental *test*, *better* hypothesis... and so on in a never ending loop. But for "Quantum Gravity" only the first step of hypothesis is possible - opening up for some extremely wild and speculative (and untestable) "theories".

3.1 Events in relativity = classical observations ≠ quantum

Niels Bohr [31], always emphasized that a classical framework is independently needed[13] to connect purely formal quantum mechanics with observable facts, as observers and their measuring devices by necessity are classically real. The results of measurement must be expressed classically; there must be a classical region of every experiment where physicists can set apparatus, read pointers and so on[14]. The classical world is a necessary additional assumption, "the primary unanalyzable reality of ordinary experience", according to Bohr, and not a concept derivable from quantum mechanics. Both the abstract quantum mechanical formalism and the real classical level, in terms of measuring devices and observers, are independently required. He also said "there is no quantum world", just a quantum mathematical algorithm to connect experiences in our *real* world - the only one. As John Wheeler asserts: "No elementary quantum phenomenon is a phenomenon until it is a registered (observed) phenomenon" [38].

Furthermore, John Bell [39] showed that all measurements eventually can be boiled down to *positions* of things, including the position of instrument pointers, or of ink on a computer output, etc. But positions in space at a given time are *events* which *are* relativity which shows how to, *e.g.*, relate measurements, *i.e.* objective classical events, in different frames of reference.

Wheeler also states "Happily, nature provides its own way to localize a point in spacetime, as Einstein was the first to emphasize. Characterize the point by what happens there! Give a point in spacetime the name *"event"*."

[13] A multitude of alternative "resolutions" of the quantum measurement problem have been proposed over the years, without succeeding.

[14] No amount of linear quantum "decoherence" [32] (quantum phase randomization), neither internal nor environmental, can ever explain the disappearance of coexisting quantum possibilities [33], [34] if everything, including measuring instruments and observers, are quantum entities. This is demonstrated very transparently in *e.g.* [35]. Wigner [36], and also von Neumann [37], argues that the nonlinear collapse, finally allowing definite outcomes to be realized, happens when the consciousness of the observer (somehow) terminates the von Neumann-chain of ever larger linear superpositions. However, where and how does consciousness first enter into the hierarchy of life (human/cat/cockroach/amoeba/.../God)? The problem is then just replaced by an even trickier one.

[40] - events are the invariant fundamental "atoms" of reality, the same for all observers, the point-manifold of which *build up and constitute* the totality of spacetime. Relativity is per definition a classical theory in which objective classical events, and their interconnections given in terms of invariant spacetime intervals, are indispensable. Events are primary, the fundamental concept of observed nature. The geodesics in curved spacetime *are* gravity, and they consist of classical *events*. (In a hypothetical gravitational-free world, or whenever gravity may be neglected for all practical purposes as in particle physics experiments, the geodesics are straight lines $\leftrightarrow$ special relativity.)

Several authors, *e.g.* [41], [42] and many more, have linked gravity to the mechanism that turns the mere subjective quantum mechanical "tendencies for possibilities" into cold, hard, classical facts - events. This is possible as general relativity is a nonlinear theory. The three other known fundamental interactions, Quantum ElectroDynamics, Quantum FlavorDynamics ("the weak force") and Quantum ChromoDynamics, are all purely *quantum* mechanical and, as such, lacking a way to classically *realize* their mere quantum potentialities and hence, by themselves, cannot generate the classical world. For example, a quark quantum field is never detected, instead there are various signals in a detector classically observed. Even though QFD and QCD are nonlinear (non-abelian) in their gauge-fields, quantization[15] linearizes them.

The nonlocality of reality[16] [43], [44], empirically validated [45], has a direct analogue in general relativity as the energy-momentum of the gravitational field is not locally defined - due to the Equivalence Principle it is always possible to choose local free-falling coordinates which makes gravity, locally, evaporate[17]. The generally covariant four-divergence $T^{ab}_{;b} = 0$ is not really a conservation law but describes the exchange of energy and momentum between (local) matter with energy-momentum tensor T^{ab} and (nonlocal) gravitation [46]. Gravity in general relativity is a *global* effect, not a local one, impossible to mimic with local quantum field theory.

Furthermore, the very origin of quantization is *bound states* - discrete bound states in atoms, for example, result in quantized photons. Even in quantum mechanics a *free* particle can have *any* of a continuum of *non*-quantized energies. But in general relativity objects float freely along geodesics as long as

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[15] For example by inserting their "classical" action in the Feynman functional path-integral - "summing", *i.e.* functionally integrating over all field histories - which is just a fancy description of linear quantum superposition of amplitudes.

[16] Bell's theorem is not merely a statement about quantum mechanics but about nature itself, and will survive even if quantum mechanics is superseded by a more fundamental theory in the future. Although Bell used aspects of quantum theory in his original proof, the same results can be obtained without doing so.

[17] This also shows that localized gravity (*e.g.* gravitons), in terms of merely special relativistic Lorentz-covariant local quantum field theory, never can encapsulate all of gravity.

only gravity is at play[18], disqualifying quantization.

All said and done, this leads us to conclude that it is futile to expect that gravity should be quantized[19], as it would rob us of the classical world in terms of events that is absolutely crucial for making sense of quantum mechanics - and crucial for making observations in the first place. Classical events are indispensable for the scientific endeavor, and as general relativity describes this spacetime of events it should not be quantized. Deterministic chaos can, and demonstrably does, exist in classical mechanics as it is a theory of *events* which is nonlinear - the necessary criterion for chaos. Quantum-mechanically, chaos (*e.g.* extreme/exponential sensitivity to initial conditions) *cannot* exist [48], as quantum mechanics is a *linear* theory about quantum amplitudes[20]. Through gravitation we can thus understand both *why* events occur at all, and why the measurement can lead to "randomness" - for all practical, but not fundamental, purposes, unlike the "magical" Born rule of wavefunction "collapse" where perfect randomness is postulated *a priori* without any physical description, precluding any real understanding[21]. Relativity is a theory of actualities, real occurrences, our very perceptions. Quantum mechanics, unless "measured" (giving events), is a theory of abstract possibilities we never have actual contact with. What is often missed is that quantum mechanics is just as *deterministic* as classical mechanics, or even *more* so due to the simple linearity of its equations - which is required for quantum superposition to be possible. *All* the uncertainty, "randomness" and probabilities of "quantum mechanics" actually *only* appears in the (normally ill-defined) "measurement", producing classical events. Quantum mechanics in itself does *not* contain information, *linear* quantum mechanics only contains *potential* information in terms of *potential* outcomes (often infinitely many possibilities for any given situation).

[18] The reason we feel gravity at all is because, for example, the floor hinders the, for gravity, "natural" free-fall through spacetime, destroying geodesic motion through the *non-gravitational* electromagnetic interaction between body and floor.

[19] Freeman Dyson [47] has argued that an individual graviton is *in principle* unobservable and that the quantization of the gravitational field is *not* a logical consequence of the quantum constituents making up the measuring apparatus, and therefore no inconsistency can arise in a world where gravity is classical and the rest of the interactions are quantum, and, as physics is about *observed* phenomena, hence making "Quantum Gravity" physically meaningless.

[20] To obtain N bits of information regarding its future dynamics a chaotic system requires $\sim N$ bits of input information, a linear system only $\sim logN$, validating Bohr's insight that the classical world is independently needed. A mathematical consequence of discrete (quantized) energy levels is that quantum time-evolution contains only *periodic* motions with definite frequencies - quite the opposite of chaos. So there is no chaos in quantum physics, only regularity.

[21] Born's prescription for measurement "collapse", $\Psi = \sum_{n=1}^{\infty} \psi_n \xrightarrow{\text{``meas''}} \psi_k$, where $|\psi_k|^2$ = probability of obtaining k on *measurement*, is of course nonlinear - albeit completely *ad hoc*, and also unable to produce the exponential sensitivity to initial conditions typical of chaos, as the "unmeasured" dynamical quantum evolution of Ψ is unitarily *linear*.

Quantum mechanics is not a theory of what is, but a theory of what eventually could be[22]. Information is only created by "measurement" of events[23] - which are described by truly nonlinear general relativity. "Quantum Gravity" is thus a pseudo-problem, a mirage, "Quantum Spacetime" an oxymoron.

4 *Apparent* "acceleration" of universe due to inhomogeneous structure formation

A. Einstein (1917):
"According to the general theory of relativity the metrical character (curvature) of the four-dimensional space-time continuum is defined at every point by the matter at that point and the state of that matter. Therefore, on account of the lack of uniformity in the distribution of matter, the metrical structure of this continuum must necessarily be extremely complicated." [1]

In an inhomogeneous and evolving universe (like the real one) there is no logical reason at all to introduce a *homogeneous* Cosmological Constant the same everywhere & everywhen.

On the contrary, the dynamics of a non-homogeneous universe without Λ can *mimic* "acceleration" when interpreted through a (falsely assumed) homogeneous model [50]. The natural variation of expansion rate with position in the real universe is then (falsely) interpreted as an additional variation in time, due to the finite speed of information transfer.

A model of the universe smoothed-out on the largest possible scale, like FRW, ignores smaller-scale inhomogeneities, but the effects of those inhomogeneities actually alter the dynamical relations at the larger scale [51]. The averaging scale is not usually explicitly stated but remains hidden. This implicit averaging is however crucial for how the standard FRW-cosmological model tries to deal with matter and structure formation, while, by construction, the spacetime metric being assumed to be exactly uniform.

To make this important point more intuitively obvious, the popular picturesque 2D "inflating balloon"-analogy for the universe can still be used, but with a crucial modification: The usual "coins" (representing gravitationally

[22] "It would not be surprising if it should turn out that the origin and destiny of the energy in the universe cannot be completely understood in isolation from the phenomena of life and consciousness." [49]

[23] Even in a would-be quantum computer the information manifest only by *e.g.* reading, *i.e.* "measuring", the printout. The von Neumann entropy related to "quantum information" is built from representation-invariant *squares* of quantum amplitudes, *i.e.* of already irreversibly "measured" entities. As always, any concept of entropy needs coarse-graining of macroscopically (= *measured*) indistinguishable microscopic states.

bound galaxies/galaxy clusters) glued to the surface must be replaced by "rubber bands" crisscrossing the balloon surface. Regions "in between" (voids) will then expand increasingly fast relative to the "rubber bands" (filaments of the cosmic web), giving an apparent acceleration between gravitationally *unbound* expanding "voids" and the complex gravitationally *bound* "filamentary" structure. Furthermore, in the *real* universe the "rubber bands" get stronger, and the "voids" weaker (the balloon surface ever more pliable), as structure formation proceeds, making the effect ever more pronounced with time. As a result, it is automatically only after appreciable structure ("rubber band") formation has taken place that an (apparent) "acceleration" should be observable, which means that *now*, when interpreted through a homogeneous and isotropic FRW-model, we would deduce (wrongly) that "Ω_Λ" $\sim$ "Ω_{matter}". As always, such graphic "balloon" analogies are not exact, and should not be perceived as such, but *can* be very illuminating and useful for guiding the mind.

Even in FRW, *with* "dark energy", Λ only accounts for the expansion of the universe in its later stages, when matter began to form structures - but in this idealized model it is merely a completely unrelated and unexplained "Cosmic Coincidence", unlike the natural outcome in an inhomogeneous universe without Λ.

Inhomogeneities not only alter the dynamics, but also can significantly affect the observational determination of the parameters of the effective standard model of cosmology [52], as in the *real* universe, cosmological information reaches us via null geodesics in the empty spacetime of voids *between* galaxies. Relations between observed quantities thus depend not only on the cosmological model, but also on the *evolving* structure, giving a cumulative effect with increasing z - at least until z becomes so high that it corresponds to such early epochs of the universe that structure formation was negligible. Recently, actual observations have indicated strong deviations from isotropy all the way out to at least 5 billion lightyears [53].

The case for an *inexplicably tiny* Λ, inferred from the unrealistic exactly homogeneous and isotropic FRW-standard model of cosmology, thus vanish when interpreted through a more realistic model of the universe.

5 Summary and Conclusion

As general relativity is a purely classical theory, cosmologies based on it have no problem with "huge" vacuum energy densities, naïvely expected to arise from "virtual particles" in divergent perturbative local quantum field theory calculations, as classical general relativity is oblivious to them. We may thus without further ado set $\Lambda = 0$ [24]. The extremely *tiny* Λ seemingly needed to explain cosmological observations - when interpreted through the lens of the overly simplified exactly homogeneous and isotropic geometric spacetime background of the standard model of cosmology - is an artifact of the FRW-model universe. When interpreted through the lens of the real physical *inhomogeneous* universe Λ can be put to rest - all according to Einstein's wishes.

To conclude, physical systems generally tend to get more complex with size, and it is hard to see why this should not apply also to the largest system possible - the whole physical universe. Spontaneous self-organization [54] in a complex system requires strong dynamical nonlinearity and nonequilibrium [55], both fulfilled in the present state of the *real* universe (but *not* in the FRW standard model), allowing structure formation in, and the dynamics of, the actual physical universe - without any Λ.

What explanation of cosmological data since 1998 sounds more plausible?:

i) Known physics ($\Lambda = 0$) in a "lumpy" (real) hierarchical universe, the complexity of which capable of giving approximate scale-invariance over a wide range of scales without precise tuning of parameters, where differentiated order of complexity is *unfolded* at simultaneous interweaved processes at a multitude of levels (co-evolution of macro- and micro-structures).

ii) Completely unknown ($\Lambda \neq 0$) and absurdly fine-tuned physics in a "smooth" (unreal) simple universe, the idealized fluid of FRW having *zero* complexity, and where structure is *built up* solely in "bottom-up" fashion due to (hypothetical) cold dark matter put in by hand as perturbations and (hypothetical) dominant dark energy with an inexplicably small Λ.

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