Open Limitations of Quantum Gravity: a Brief Overview

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Abstract

Despite years of sustained research on multiple avenues, unification of Quantum Field Theory (QFT) and General Relativity (GR) appears to be heading towards a dead end. There are by now dozens of review articles, podcasts, blog entries, conference proceedings and books explaining the challenges of unification and debating the status of this presumptive failure. Yet no consensus exists on what the next steps ought to be and on whether the whole unification effort is to be abandoned. The (modest) goal of this short review is to go over the main conceptual limitations of Quantum Gravity (QG) programs. This tutorial reflects a personal viewpoint, likely to stand at odds with the wide spectrum of opinions of those working in this field.

Key words: Quantum Field Theory, General Relativity, field unification, Quantum Gravity.

1) Poincaré invariance breaks down on any curved spacetime, with the exception of its flat tangent space (Minkowski spacetime). By contrast, standard QFT has no content outside Poincaré invariance. Thus, strictly speaking, QFT and GR *cannot both be* consistent in a curved background.

2) GR is not renormalizable because Newton's constant carries a negative mass dimension.

3) Since QFT is a relativistic framework, its equations can be cast in a generally covariant form. But solving the covariant equations in a curved background does not enable a *unique Fourier decomposition*, which means that two independent observers no longer agree on the particle content of their setups. Thus, the concept of quantum particles becomes *observer dependent*.

4) Quantum matter can be indeed considered as the source of gravitation. But while quantum matter is represented by operators, spacetime is defined by numbers. This discrepancy is circumvented in *semiclassical gravity*, whereby quantum matter enters through the so-called "expectation values",

an approximation allowing equations to have numbers on both sides. Yet semiclassical gravity cannot be acceptable in a true QG theory.

5) Since gravity is an inherent property of spacetime, quantizing gravity ultimately implies quantization of spacetime. But quantum theory only makes sense on a classical spacetime continuum.

6) Quantum theory assumes a *fixed* spacetime background, while GR operates in a spacetime that *changes dynamically* in response to massive objects.

7) Time plays a contrasting role in QFT versus GR. In quantum physics, time acts as an independent variable through which states evolve, with the Hamiltonian operator acting as the generator of infinitesimal time translations. By contrast, in GR time is treated as a dynamical variable organically coupled to matter.

8) GR does not have an underlying Hilbert space and a probabilistic interpretation of the gravitational wave function.

9) *Gravitational decoherence* induces transition to classical behavior. Likewise, the quantum superposition of a pair of massive particles - spatially separated and placed in the gravitational field of a third particle - is prone to transition to chaos and nonintegrable dynamics (the 3-body problem).

10) A prime example of how faulty interpretations arise from ad-hoc mixing of GR and QFT is the *cosmological constant problem* (c.c.p). The root cause of the c. c. p is the quadratic divergence of the zero-point vacuum energy in the presence of gravitation. Standard QFT in Minkowski space-time discards the zero-point vacuum energy using a normal time-ordering procedure. Because vacuum energy gravitates and couples to all other field energies present at the quantum level, cancellation of the zero-point term is no longer possible when gravitation produces measurable effects.

The origin of the c.c.p. can be traced to a couple of erroneous interpretations:

a) First off, the *GR vacuum* describes a setting devoid of any matter and energy content, a far cry from the concept of *quantum vacuum* which contains an infinite superpositions of quantum fluctuations. Strictly speaking, the GR vacuum represents an unphysical abstraction, as real-life measurements are never possible in the absence of matter and energy.

b) The textbook analysis of *energy density of the quantum vacuum* (VED) follows from Pauli's model of 1951, in which quantum vacuum is considered a reservoir of *free harmonic oscillators*. In his lectures, Pauli shows that deriving a nearly vanishing VED is contingent upon fulfilling three corollary conditions called *polynomial-in-mass-constraints.* The analysis of [9] indicates that the Standard Model violates these constraints and the Lorentz invariance of the VED stress-energy tensor. It follows that basing the c.c.p. on Pauli's model clearly points in the *wrong direction*.

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