Snowmass2021 - Letter of Interest

Physical Effects of Nonlocally Coherent Quantum Gravity

Thematic Areas: (check all that apply ☐/■)
☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) *Theory Frontier, TF01: String theory, quantum gravity, black holes; TF05: Lattice gauge theory; TF09: Astro-particle physics & cosmology*

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Abstract: If quantum states of geometry, like those of particles, are nonlocally coherent on light cones of any size, they could produce detectable fluctuations in laboratory experiments, leave detectable signatures in cosmic microwave background anisotropy and large scale structure, and account for the absolute value of the cosmological constant. Opportunities exist to explore all of these possibilities.

I. QUANTUM COHERENCE OF GEOMETRY

Consider the simplest version of quantum gravity: the active gravity of quantum pointlike particles. Because of gravity, a superposition of delocalized particle states also leads to a delocalized, Schrödinger-cat-like macroscopic superposition of space-times. As usual in quantum mechanics, there should be no paradox if the preparation of entangled states is causal.

The effect of coherence can be estimated by extrapolation of classical relativity and quantum mechnics. Consider the gravity of a particle of mass m that decays into two photons. The initial spherically-symmetric Schwarzschild metric of the point mass acquires directional distortions, since the mass-energy is no longer in a point, but a line. The gravitational effect can be measured by a set of clocks distributed on a spherical surface, which are compared by viewing from the center (Fig. 1).

Over a time $\tau \sim R/c$, the distortion of dimensionless gravitational potential Δ makes the clocks vary coherently with position on the causal diamond surface over large angular separations, by about

$$\delta\tau \sim \tau\Delta \sim \tau(Gm/Rc^2) \sim (c\tau/R)Gm/c^3. \tag{1}$$

Note that the magnitude $\delta\tau$ of the distortion is independent of distance; it only depends on the particle mass.

The wave function of the space-time includes a superposition of different orientations of gravitational distortions, each aligned with the direction of the particles. Each element in the superposition is a coherent macroscopic causal diamond. A measurement of a particle axis will always occur with a causal diamond distortion consistent with the outcome. This purely-geometrical behavior is apparent only in a nonlocal, spacelike comparison of clocks in different directions on timescale τ.

If there are many particles in the causal diamond, the coherent amplitudes add, and the variance of distortion adds in quadrature, so the correlation of two clocks B and C separated by a large angle is about

$$\langle \delta\tau_B \delta\tau_C \rangle \sim N(Gm/c^3)^2. \tag{2}$$

This estimate is valid until the number N of EPR pairs (or virtual pairs) in a causal diamond is large enough that the gravity of the particles affects the mean curvature, so their number must not exceed $N \sim c^3\tau/Gm$. The coherent large-angle variation on a black hole or cosmological horizon is then about

$$\langle \delta\tau^2 \rangle \sim (c^3\tau/Gm)(Gm/c^3)^2 \sim Gm\tau/c^3. \tag{3}$$

Planck's constant $\hbar$ does not appear in Eq. (3); although this is a quantum correlation, it is a property of geometry, not of mass-energy. Unlike particle position uncertainty, it increases with m.

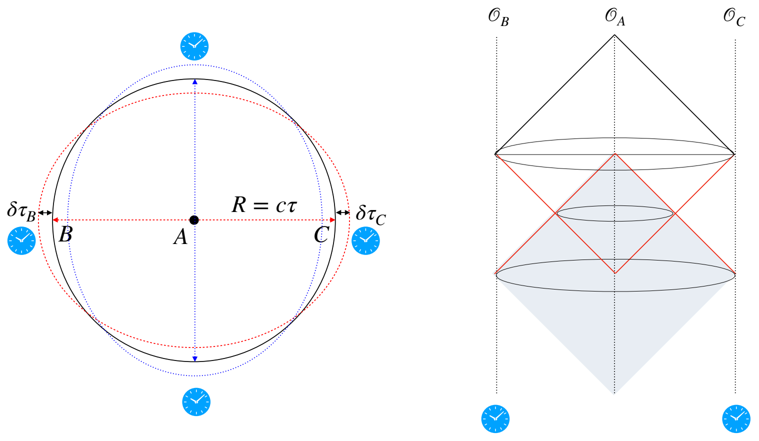

FIG. 1. Coherent active gravitational effect of an EPR particle pair on clocks. A point mass on world line A decays into oppositely directed null particles along an indeterminate axis. A time τ later, the gravitational field of the particles creates a coherent gravitational time dilation, or curvature, on the boundary of a causal diamond of radius $R = c\tau$, as shown at the right. The particle state creates a coherent superposition of curvature states: comparison of clocks B and C on the surface of the causal diamond shows a directional variation $\delta\tau$ aligned with the particle state. Two causal diamonds are necessary to perform the measurement: one to prepare a coherent state for the clocks, and another for the particle decay, gravitational shock wave, and return light cone for a comparison of clocks in different directions.

This simple model can be used to estimate measurable directional perturbations or fluctuations from coherent quantum gravity itself, in the absence of matter, say near a black hole. If we set $m = m_P \equiv \sqrt{\hbar c/G}$, the Planck mass, Eq. (3) gives

$$\langle \delta\tau^2 \rangle \sim \tau t_P, \tag{4}$$

where $t_P \equiv \sqrt{\hbar G/c^5}$ denotes the Planck time. The directionally-coherent, large-angle fluctuation in scalar curvature on a horizon or causal diamond surface then has a variance or uncertainty

$$\langle \Delta^2 \rangle \sim \langle \delta\tau^2 \rangle / \tau^2 = t_P/\tau. \tag{5}$$

This extrapolation of the coherent nonlocal effect of quantum gravity on scale τ, from standard gravity and quantum superposition principles, is much larger than a calculation from linearized gravity and local effective field theory, which yields $\langle \Delta^2 \rangle \sim (t_P/\tau)^2$. It is not known which estimate, if either, is correct.

II. PHYSICAL EFFECTS

Although coherent, holographic gravity is in some sense well understood on the gravitational side from thermodynamic derivations of the Einstein equations[1], the example above highlights the fact that nobody knows how quantum gravity works, or how emergent locality can be reconciled with effective field theory. On the quantum side, macroscopic geometrical coherence is well controlled in special systems, such as anti-de Sitter space[2, 3], but not in any realistic physical context. The coherence of time remains a deep problem in quantum measurement theory[4], and a rigorous account of macroscopically-coherent quantum geometry is still needed to reconcile information flow in black holes with quantum unitarity[5, 6]. In spite of advances in mathematical understanding of abstract systems, the interpretation and phenomenology of macroscopic gravitational quantum coherence in the real world is not well understood. Theory would be greatly advanced with meaningful input from experiments.

It is clear that coherence of quantum gravity can profoundly affect the gravitational coupling and fluctuations of the particle vacuum. An effect as large as Eq. (5) would fundamentally change the quantum correlations of cosmic perturbations from inflation, and the physical interpretation of cosmic acceleration. This note draws attention to some nonlocal effects of coherent quantum gravity that could be measurable, and in some cases may perhaps already have been measured:

Laboratory Experiments. Interferometers can now achieve sub-Planck-time sensitivity in strain power spectral density[7, 8], so they can measure nonlocal spacelike correlations of the magnitude in Eq. (5). A systematic experimental program could significantly constrain models of quantum-gravitational coherence [9–11]. The technologies required have considerable overlap with those developed to detected coherent dark matter in the laboratory[12], as well as gravitational waves.

Inflation. Holographic gravity significantly modifies quantum degrees of freedom during inflation [13]. If the amplitude in Eq. (5) is correct, coherent quantum gravity is the main source of cosmic perturburations[14, 15]. In that case, holographic quantum correlations produce distinctive nonlocal directional correlations in the cosmic microwave background, which may already have been measured[16]. In principle, the large angle correlations in a holographic theory may be exactly predictable with no cosmic variance, unlike the standard theory. Precision tests can be improved with better CMB maps, including better reconstruction of the pattern of primordial curvature using polarization data. Exotic relic 3D correlations of galaxies or HI gas survive in the linear regime, and could be measured in proposed cosmological surveys. This program requires a large number of precisely measured mode amplitudes and phases, similar requirements to tests of primordial nongaussianity.

The cosmological constant. Effective field theory leads to a famously wrong, enormous value of the cosmological constant Λ [17]. Coherent quantum gravity would change the gravitational effect of virtual states of the particle vacuum[18], and could explain why Λ nearly vanishes, from cancellations due to causal symmetry. The actual (measured, nonzero) physical value of Λ could be due to the tiny gravitational drag of virtual states of the QCD vacuum[19], in which case it might be exactly calculable using new kinds of averages on a lattice, from a semiclassical calculation of gravitational drag by nonlocally correlated virtual energy-momentum flows. In this scenario, the emphasis of the cosmic dark energy program would change from a differential measurement of the equation of state (that is, better measurements of $w = -1$) to an absolute measurement of the value of Λ itself. Like other constants of nature, its value would be connected via theory to other measured microscopic properties of the standard model, such as the pion mass or Λ_{QCD}.

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