Quantum Gravity Phenomenology

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Why do we need quantum gravity?

Because

- We don't know what is the gravitational field of a quantum superposition.
- Black holes seem to destroy information, and we don't know how that is compatible with quantum mechanics.
- General relativity predicts its own breakdown: Singularities.
- It is esthetically unpleasing to have it stand out.
- We hope it will help with other unsolved problems like the cosmological constant or dark matter.

I'll refer as 'quantum gravity' to any attempted solution of these problems.

This does not mean that one necessarily obtains quantum gravity by quantizing gravity.

Why do we need a phenomenology of quantum gravity?

- A naive quantization of gravity does not result in a theory that is fundamentally meaningful.
- There are several 'not-so-naive' approaches to quantize gravity (String Theory, Loop Quantum Gravity, Causal Dynamical Triangulation, Asymptotically Safe Gravity...) but none of them has made contact to experiment.
- The problem has been known since about 80 years now. It seems fair to say that progress has been slow.
- For a long time, research in quantum gravity has focused exclusively on mathematical consistency.
- But without making contact to observation, we can *never* tell which theory describes nature correctly.
- Moreover, experimental input can guide the development of the theory. (In fact, this is historically the norm.)

What is a phenomenological model?

A phenomenological model

- is an extension of a known theory that allows one to compute effects of specific additional features
- bridges the gap between theory and experiment
- it guides the development of the theory by allowing to test general properties.
- is not itself a fundamental theory and therefore not entirely self-contained. It leaves open questions and may work only in some limits

There is no way around phenomenology one way or the other!

Pessimists and Optimists

"We shall have the basic framework of the quantum theory of gravity by 2010, 2015 at the outside."

Lee Smolin,Three Roads to Quantum Gravity (2001), p-211.

"I propose as a hypothesis... that single gravitons may be unobservable by any conceivable apparatus. If this hypothesis were true, it would imply that theories of quantum gravity are untestable and scientifically meaningless. The classical universe and the quantum universe could then live together in peaceful coexistence. No incompatibility between the two pictures could ever be demonstrated. Both pictures of the universe could be true, and the search for a unified theory could turn out to be an illusion."

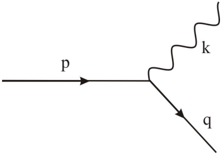
Freeman Dyson, The Edge Annual Question 2012, www.edge.org

What is the relevance of the Planck scale?

- The Planck scale sets the scale at which quantum gravitational effects are expected to become important.
- It should be the only additional dimensionful scale of the model. Dimensionless parameters should be of order one.
- One does not need to directly detect single gravitons to find evidence for quantum gravity. We can instead look for *indirect evidence*, leftover at low energies.
- We should therefore more generally look for ‘Planck scale effects’ that could carry information about the quantum theory without directly probing the regime where quantum effects are strong.

Deviations from Lorentz Invariance

- Violations of Lorentz-invariance: Preferred frame, usually a time-like vector field n_α
- Very general feature of 'emergent gravity' because one needs something to emerge with: a time or temperature for example that constitutes a preferred slicing with fundamental significance
- Lorentz-invariance violation can be constrained by looking for phenomenology of that fundamental timelike vector field n_α, coupled to the Standard Model
- Standard Model extension with higher order operators: Very strongly constrained.



Deformed Special Relativity

- Modified dispersion relation for *free* particles

$$m^2 \approx E^2 - \vec{p}^2 + \alpha \left(\frac{E}{m_{\rm p}} \right) E^2$$

where α should be of order 1 for quantum gravitational effects.

- But no LIV operators (by assumption).
- Consider 2 photons ($m = 0$) with energy E and $E' \ll E$. Difference in arrival time after distance L is

$$\Delta t = t_1 - t_2 = (c(E) - c(E'))\, L \approx (1 + \alpha \frac{E}{m_{\rm p}} - 1)L = \alpha \frac{E}{m_{\rm p}} L$$

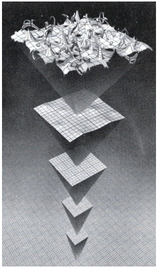
- Insert $L \approx$ Gpc and $E \approx$ GeV, and find

$$\Delta t \approx 1{\rm s}$$

- It's possible to see this in γ-ray bursts. (Nothing has been found.)

Space-time fuzz

- A very general expectation for quantum gravity is that space-time on short distances is not smooth, but fluctuates wildly. It can do anything that isn't explicitly forbidden.
- Big fluctuations may act similar to tiny black holes that immediately decay.
- This can ruin quantum mechanic's unitary evolution and lead to decoherence: pure states may evolve into mixed states by interaction with the space-time fuzz
- Besides this, we have no reason to expect fundamendal Lorentz-invariance, so the CPT theorem does not apply

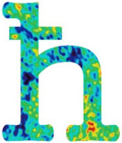


What experiment may be very sensitive to decoherence?

- Decoherence is the loss of phase information (coherence).
- Quantum mechanical oscillation between two eigenvectors of the Hamiltonian is sensitive to loss of coherence
- A system that oscillates between two Hamiltonian eigenvectors and can be easily studied will be useful
- Problem with neutrinos: oscillation length at typical energies very long, also interaction very weak
- Preferably use something more massive: neutral Kaons
- Ellis et al, Nucl. Phys. B **241**, 381 (1984).
- Experiments are now reaching Planck scale sensitivity.

Can the CMB demonstrate that gravity must have been quantized?

- Cosmological perturbation theory: Fluctuations of metric *are* quantized.
- These quantized ‘primordial’ gravitational waves leave traces in the CMB. (Polarization B-modes.)
- Which can be measured if strong enough.
- Can one infer from the CMB data that gravity must have been quantized?
- Answer is unclear but subject of study. See eg arXiv:1309.5343, arXiv:1510.04038, arXiv:1508.01082



Can we just measure the gravitational field of a quantum particle?

- Force measurements are getting more and more precise.
- Sucessful superposition of location states with more and more massive particles (quantum oscillators).
- Can we just measure the gravitation field of a particle in a superposition??
- Current limits: Can measure gravitational force of $\sim$ milligram objects. Can bring $\sim$ nanogram objects into superposition.
- Several groups are pushing these limits.
- (This probes perturbative quantum gravity.)
- See eg arXiv:1602.07539, arXiv: 1512.02083, arXiv:1507.05733, arXiv:1603.04430

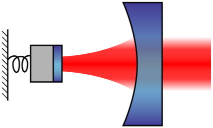


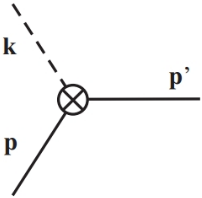
Image: Wikipedia

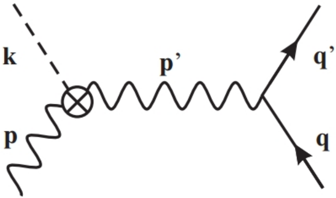
Space-time Defects

- If space-time has a fundamentally non-geometric origin, eg networks, then it approximates today to excellent precision a smooth manifold of dimension four.
- But one expects this approximation to be imperfect: It should have defects.
- Defects will affect the propagation of particles and may have observable consequences.
- Since LIV is ruled out to high accuracy already: Assume Lorentz-invariance.

Space-time defects: Example for Phenomenology

- Space-time defects do not have worldlines.
- They come in two types: Local defects that change a particle's momentum. And non-local effects that dislocate a particle.
- Example for effects on propagation from local defects





- Effects: Photon decay, decoherence, CMB heating
- Constraints: Density smaller than $1/\mathrm{fm}^4$.
- Effects stronger for *smaller* energies and scale with the world-volume → radio range

And there's more

- String Cosmologies, Loop Quantum Cosmology
- Cosmic strings? Moduli?
- Naked singularities?
- Phase transition from non-geometric phase
- Dimensional reduction
- Horizon-scale deviations from GR
- ...

Takeaway

- The phenomenology of quantum gravity is a lively research area at the interface of theoretical and experimental phyiscs
- It brings together many different areas of physics (astro, particle, neutrino, cosmology, etc)
- Various effective models that incorporate quantum gravitational features, some of which make predictions that have been ruled out or will be testable soon.
- More: "Experimental Search for Quantum Gravity," arXiv:1010.3420 [gr-qc], backreaction.blogspot.com
- Next conference: ESQG 2016, Frankfurt, Germany, Sep 19-23.

Parameterizing Induced Decoherence

- To deal with pure and mixed states, talk about density matrix instead of states $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$. Normal time evolution takes the form

$$\frac{d}{dt}\rho = \mathrm{i}[\rho, H] \quad .$$

- With fundamental decoherence change evolution equation to

$$\frac{d}{dt}\rho = \mathrm{i}[\rho, H] + \delta\not{h}\rho \quad .$$

- Where $\delta\not{h}$ parameterizes the non-hermitian part.

$$\delta\not{h} = -2 \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha & \beta \\ 0 & 0 & \beta & \gamma \end{pmatrix}$$

- For quantum gravitational effects, we expect α, β, γ to be approx E^2/m_{p} or m^2/m_{p}
- Are there experiments sensitive to such small terms?

Decoherence in neutral Kaon oscillations

- One can determine the CP-violating parameter ϵ in τ_L limit from

$$\frac{\text{Rate of}(K_L \to \pi^+\pi^-)}{\text{Rate of}(K_S \to \pi^+\pi^-)} = \epsilon^2 \approx 2 \times 10^{-3}$$

- With decoherence (simplified $\beta = 0$)

$$\frac{\text{Rate of}(K_L \to \pi^+\pi^-)}{\text{Rate of}(K_S \to \pi^+\pi^-)} = \epsilon^2 + \frac{\gamma}{|\Gamma_L - \Gamma_S|}$$

  where $|\Gamma_L - \Gamma_S| \approx 10^{-14}\text{GeV}$.

- So one becomes sensitive to γ when $\epsilon^2|\Gamma_L - \Gamma_S| \approx \gamma$ or $\gamma \approx 4 \times 10^{-20}\text{GeV}$.
- Compare to $M^2/m_{\rm p} \approx 3 \times 10^{-20}\text{GeV}$!
- Current constraint: $\gamma \lesssim 5 \times 10^{-21}\text{GeV}$. But constraints on α, β weaker. Experiments running.

$\mathbf{X} = 0.1$