What precisely can we learn from “quantum gravity experiments”?

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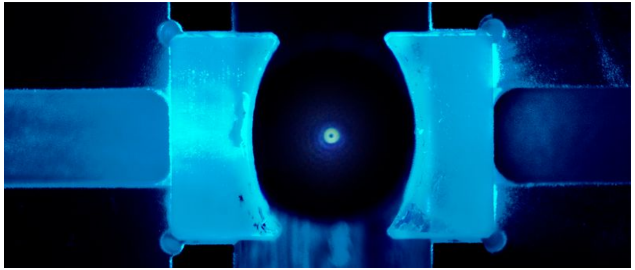
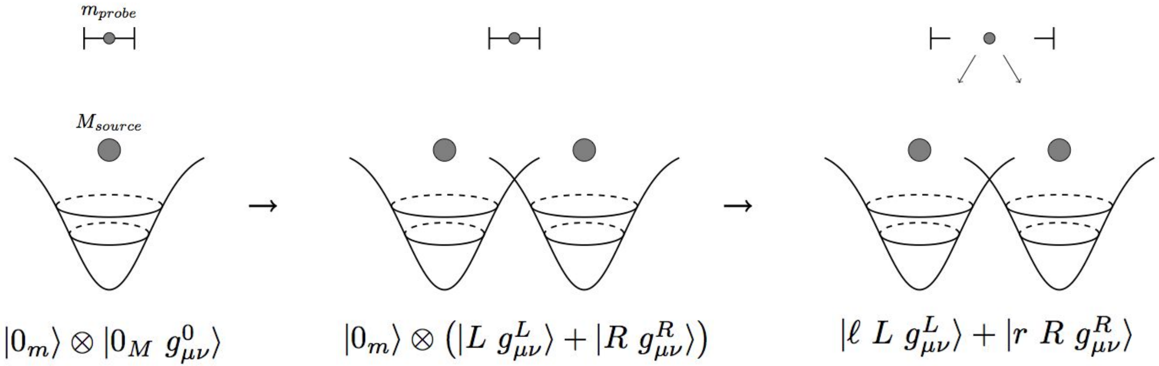
The basic line of questioning

"Is gravity quantum?"

- Can the gravitational field be put into quantum superposition?
- Can we measure this?
- What would it mean if we do?



From Markus Aspelmeyer



Review: Carney, Stamp, Taylor 1807.11494

Q&A

1. Do we have a theory of quantum gravity that works?
2. What if gravity isn't quantum?
3. Can we detect gravitons (in practice)? If so, does it matter?
4. Can we detect entanglement generation by the Newton interaction (in practice)? If so, does it matter?
5. Do you expect large quantum gravity fluctuations in interferometers?

1. Do we have a theory of quantum gravity that works?

$$S = \frac{1}{8\pi G_N}\int d^4x\sqrt{-g}\left[R + \mathcal{L}_{\text{matter}} + \frac{c_1}{m_{\text{Pl}}^2}R^2 + \cdots\right] \qquad \hat{g}_{\mu\nu} = \eta_{\mu\nu} + \hat{h}_{\mu\nu}$$

Effective field theory: Quantize metric fluctuations → gravitons, same as EM field → photons.

Valid energy at densities where $R/m_{pl}^2 \ll 1$ (i.e., almost anywhere other than near singularities).

Inevitable under simple assumptions. Any **alternative hypothesis** must violate one of:

- Unitary scattering
- Lorentz invariance
- Cluster decomposition (“spacetime locality”)

For example, string theory reduces to this model at low energies.

Nice recent review: Donoghue 2211.09902

FAQ

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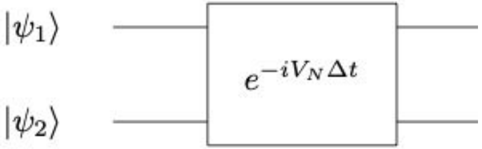
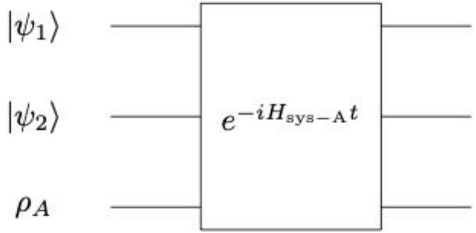
2. What if gravity "isn't quantum"?



$$id\,|\psi\rangle = -\sum_{i\neq j} \frac{G_N m_i m_j}{|\hat{\mathbf{x}}_i - \hat{\mathbf{x}}_j|} dt\,|\psi\rangle$$

"Standard quantum gravity"

Basic prediction from virtual graviton exchange



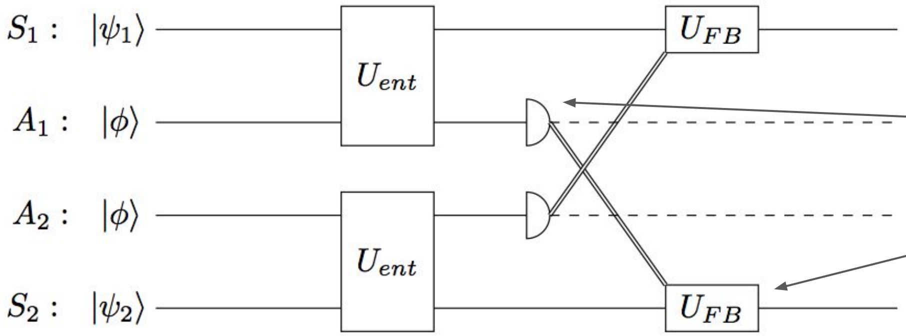
$$id\,|\psi\rangle = \left[-\sum_{i\neq j} \frac{G_N m_i m_j}{|\hat{\mathbf{x}}_i - \langle\hat{\mathbf{x}}_j\rangle\,|} dt + dW\right] |\psi\rangle$$

No entanglement ("classical gravity")

Not coherent—has intrinsic noise

Kafri, Milburn, Taylor 1404.3214
+ many others

2. What if gravity “isn’t quantum”?



S_1,S_2 = two masses in the lab

Measure position of mass (accuracy **σ**)

Feedback = apply potential (strength v)

$$\frac{d\langle \hat{\mathbf{p}}_i \rangle}{dt} \approx -\sum_{j \neq i} \eta_{ij}\gamma_j \int d^3\mathbf{x} \, \langle \nabla\phi(\mathbf{x} - \hat{\mathbf{x}}_i) \rangle \, p_j(\mathbf{x})$$

ϕ = 1/r $\quad \gamma_i = v^2 m_i, \quad \eta_{ij} = G_N m_i / v^2,$

Reproduces average EOM of Newtonian gravity. No entanglement can be generated. Two free parameters: v, **σ**

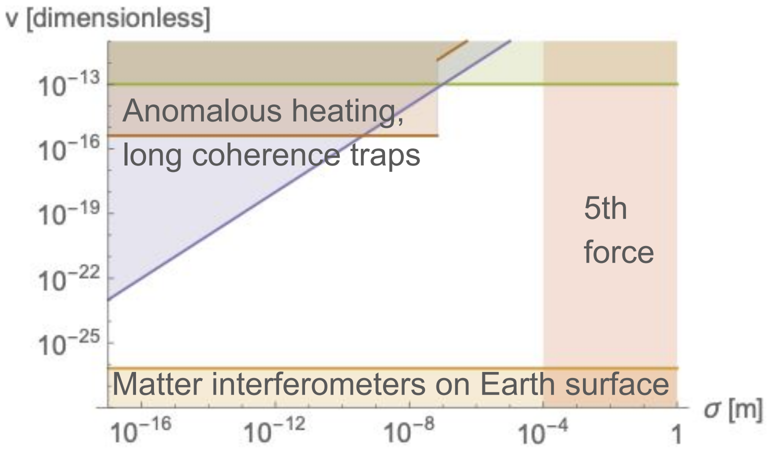
Kafri, Milburn, Taylor 1404.3214
Carney, Taylor 2301.08378

2. What if gravity “isn’t quantum”?

Violation of unitarity → anomalous heating, decoherence etc

$$\left\langle \frac{dE}{dt} \right\rangle_{\mathrm{BA}} \approx \frac{v^2}{\sigma^2}$$

$$\left\langle \frac{dE}{dt} \right\rangle_{\mathrm{shot}} \approx \frac{G_N^2 m_a \rho_0}{v^2 d}$$



How to rule out unconstrained parameter space?

- Test if gravity can entangle
- Test if gravity generates anomalous noise

See questions 4,5.

Carney, Taylor 2301.08378

2. What if gravity “isn’t quantum”?

$$\hat{H}_{\mathrm{Q}} = \hat{H}_{\mathrm{det}} + \hat{H}_h + \int d^3\mathbf{x}\,\hat{h}_{\mu\nu}\hat{T}^{\mu\nu}$$

Quantized metric fluctuations → h = operator

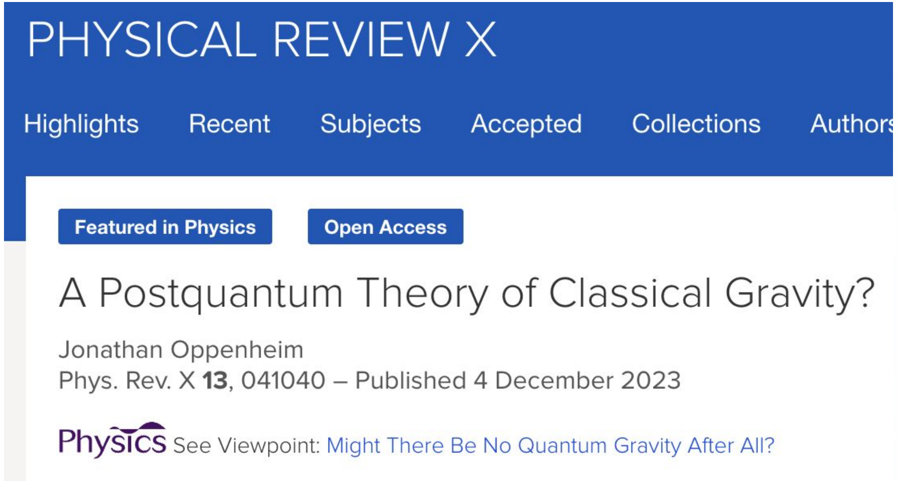
$$\hat{H}_{\mathrm{SC}} = \hat{H}_{\mathrm{det}} + H_h + \int d^3\mathbf{x}\,h_{\mu\nu}\hat{T}^{\mu\nu}$$

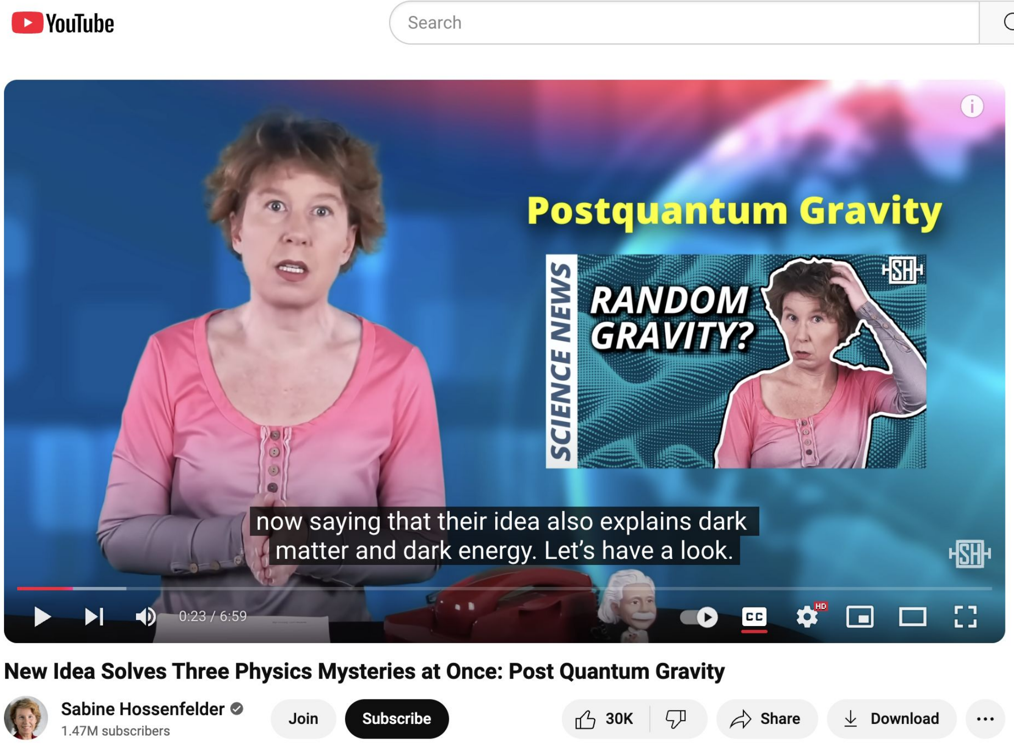
“Classical” gravity: h = classical random variable, drawn from probability distribution P(h)

To make self-consistent, need to add additional noise terms as just discussed

Possible way to get all of this together: recent Oppenheim et al work (feel free to ask about this)

2. What if gravity “isn’t quantum”?





2. What if gravity “isn’t quantum”?

- Interesting attempt to make a relativistic version of the classical gravity models we just discussed
- Same basic idea: add classical stochasticity
- Detailed construction seems to predict things that don’t work, e.g., scattering and orbits are wrong

$$
\begin{aligned}
\frac{d\sigma}{d^3\mathbf{p}_1' d^3\mathbf{p}_2'} = & \frac{(2\pi)^2}{u}\frac{\lambda^4}{m^4} \\
& \times \left\{ \delta^4(p_1' + p_2' - p_1 - p_2) \left[\left(\frac{1}{(\mathbf{p}_1' - \mathbf{p}_1)^2 + m_\phi^2} \right)^2 + \left(\frac{D_2}{[(\mathbf{p}_1' - \mathbf{p}_1) + m_\phi^2]^2} + D_0 \right)^2 \right] \right. \\
& + \delta^4(p_1' - p_1 - (p_2' - p_2)) \left(\frac{D_2}{[(\mathbf{p}_1' - \mathbf{p}_1) + m_\phi^2]^2} + D_0 \right)^2 \\
& \left. + \frac{VT}{(2\pi)^4} \left(\frac{D_2}{[(\mathbf{p}_1' - \mathbf{p}_1) + m_\phi^2]^2} + D_0 \right) \left(\frac{D_2}{[(\mathbf{p}_2' - \mathbf{p}_2) + m_\phi^2]^2} + D_0 \right) \right\}.
\end{aligned}
$$

Carney, Matsumura, in prep
Hertzberg, Loeb 2404.13037

FAQ

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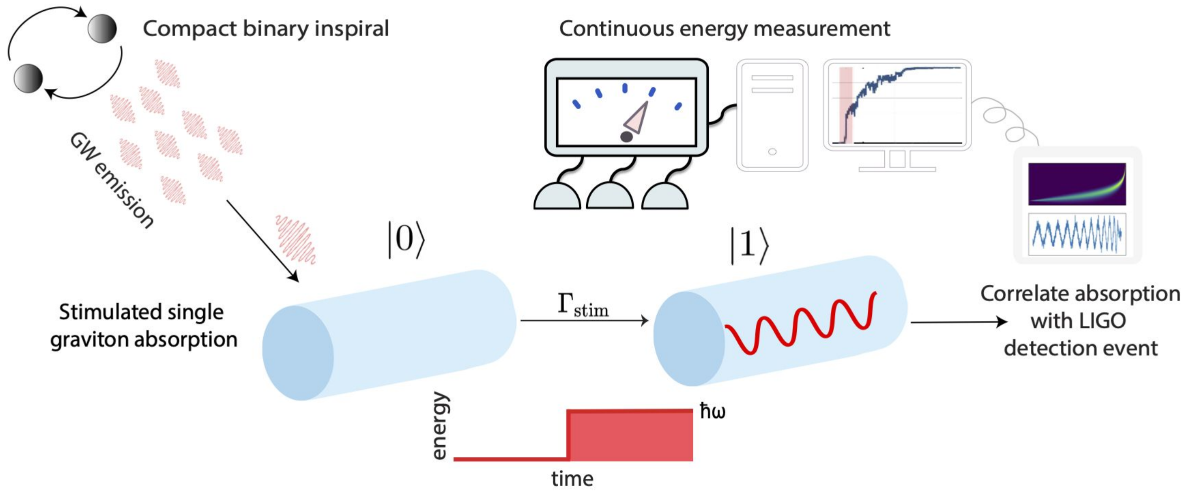
2. What if gravity isn't quantum?
3. **Can we detect gravitons (in practice)? If so, does it matter?**
4. Can we detect entanglement generation by the Newton interaction (in practice)? If so, does it matter?
5. Do you expect large quantum gravity fluctuations in interferometers?

3. Can we count gravitons?



Weber bar:
gravitational wave → vibration → voltage

Fancy quantum Weber bar:
gravitational wave (“graviton”) → phonon → voltage

Tobar, Manikandan, Beitel, Pikovski 2308.15440

Other known options:

Graviton → photon conversion in B field [Dyson 2012]

Graviton → sideband photon conversion in optical interferometer [GQuEST @ Caltech]

3. Can we count gravitons?

So, the answer is apparently yes.

Next question: can such a measurement distinguish these models?

$$\hat{H}_{\mathrm{Q}} = \hat{H}_{\mathrm{det}} + \hat{H}_h + \int d^3\mathbf{x}\,\hat{h}_{\mu\nu}\hat{T}^{\mu\nu}$$

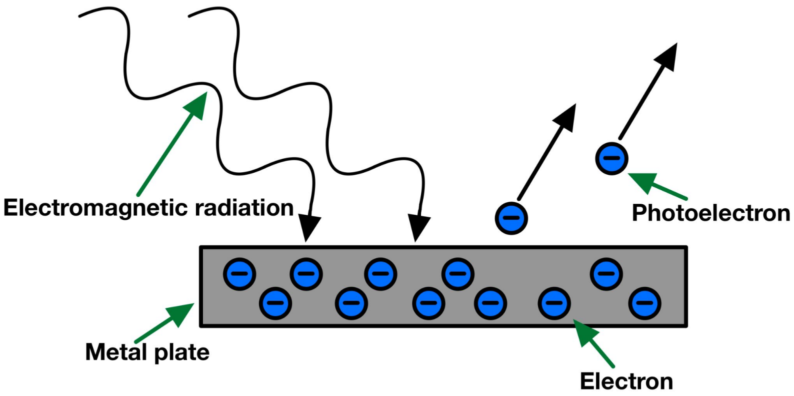
Quantized metric fluctuations → h = operator

$$\hat{H}_{\mathrm{SC}} = \hat{H}_{\mathrm{det}} + H_h + \int d^3\mathbf{x}\,h_{\mu\nu}\hat{T}^{\mu\nu}$$

“Classical” gravity: h = classical random variable, drawn from probability distribution P(h)

Carney, Domcke, Rodd arXiv:2308.12988
Carney 2408.00094

3. Can we count gravitons?



Consider either quantum or classical EM fields:

$$\hat{H}_{\mathrm{Q}} = \hat{H}_{\mathrm{det}} + \hat{H}_A + \frac{e}{m}\hat{\mathbf{p}} \cdot \hat{\mathbf{A}}$$

$$\hat{H}_{\mathrm{SC}} = \hat{H}_{\mathrm{det}} + H_A + \frac{e}{m}\hat{\mathbf{p}} \cdot \mathbf{A}$$

Classical, random $P_{cl}(A)$

Textbook perturbation theory leads to identical predictions for excited electron events:

$$\frac{dP(g \to c)}{dt} \approx \eta I(t)\Theta(\omega - \Delta)$$

→ **Observation of discrete photoelectrons does not require quantization of the EM field**

Analogous statement is true in gravity!

Glauber 1963
Mandel and Wolf, *Quantum Optics and Coherence*

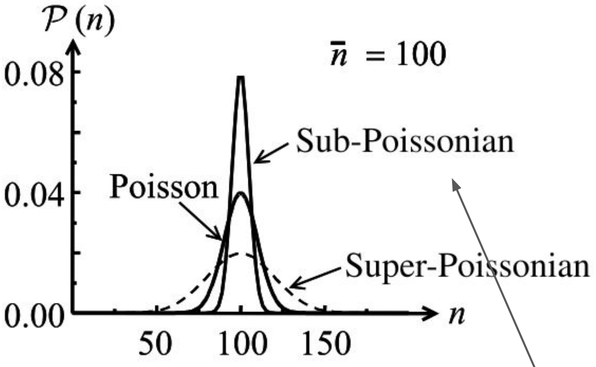
3. Can we count gravitons?

How to distinguish classical/quantum models?

Consider a single-mode state expressed in the coherent state basis:

$$\rho = \int d\beta P(\beta) |\beta\rangle \langle\beta| , \quad \int d\beta P(\beta) = 1$$

- If P(β) ≥ 0 everywhere → classical ensemble exists
- If P(β) < 0 somewhere → can find observable w/ no classical explanation



Produced by e.g. squeezed state.

Inconsistent with semiclassical model.

$$\langle \Delta N^2 \rangle - \langle N \rangle = \eta^2 \Delta t^2 \int d\beta P(\beta) \Delta I_\beta^2$$

Observed in optics in 1980’s

3. Can we count gravitons?

Detecting sub-Poisson statistics requires detector efficiency ~O(1)

$$\langle \Delta N^2 \rangle - \langle N \rangle = \eta^2 \Delta t^2 \int d\beta P(\beta) \Delta I_\beta^2$$

In Weber bar: $\boldsymbol{\eta} \sim 10^{-20}$

→ Impossibly difficult to detect this.

Carney, Domcke, Rodd arXiv:2308.12988

FAQ

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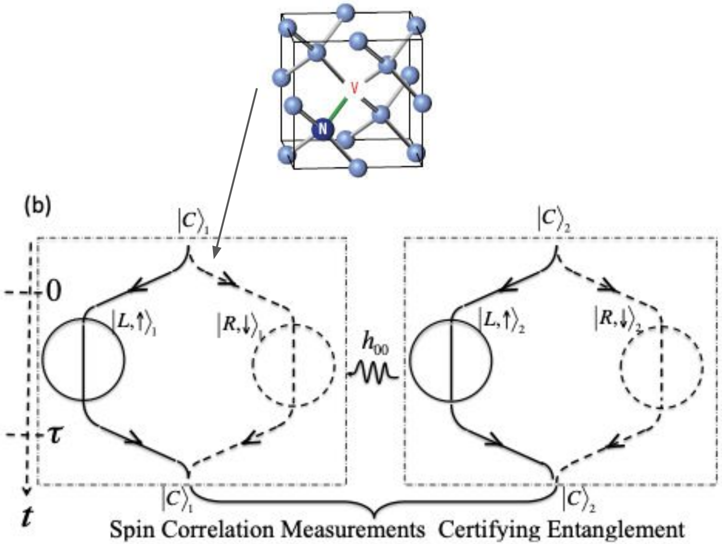
4. Can we detect gravitational entanglement?

$$|LL\rangle \to |LL\rangle + |LR\rangle + e^{i\Delta\phi}|RL\rangle + |RR\rangle$$

$$\Delta\phi = \frac{G_N m^2 \Delta x \Delta t}{\hbar d^2} \approx 60 \times \left(\frac{m}{1\,\mathrm{ng}}\right)^2 \left(\frac{\Delta x}{1\,\mu\mathrm{m}}\right)\left(\frac{\Delta t}{1\,\mathrm{s}}\right)\left(\frac{1\,\mathrm{mm}}{d}\right)^2$$



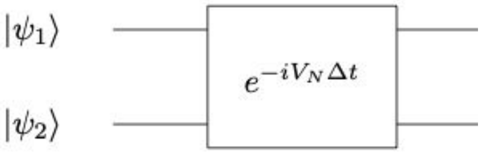
All of these parameters are extremely challenging to achieve, especially B field gradient, coherence time.

Example: gas collisions cause Γ_{deco} ~ nAv ~ 10^8 Hz for XHV (P ~ 10^{-14} torr), T ~ 4 K He gas

Probably need more practical version, but I think some version of this is going to get done in my lifetime

Bose et al 1707.06050

4. Can we detect gravitational entanglement?



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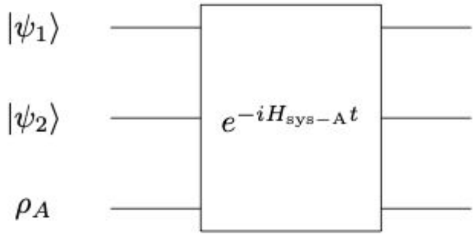
"Standard quantum gravity"



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No entanglement ("classical gravity")

Not coherent—has intrinsic noise

Kafri, Milburn, Taylor 1404.3214
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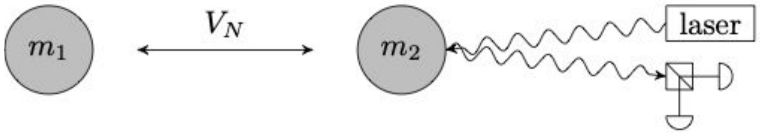
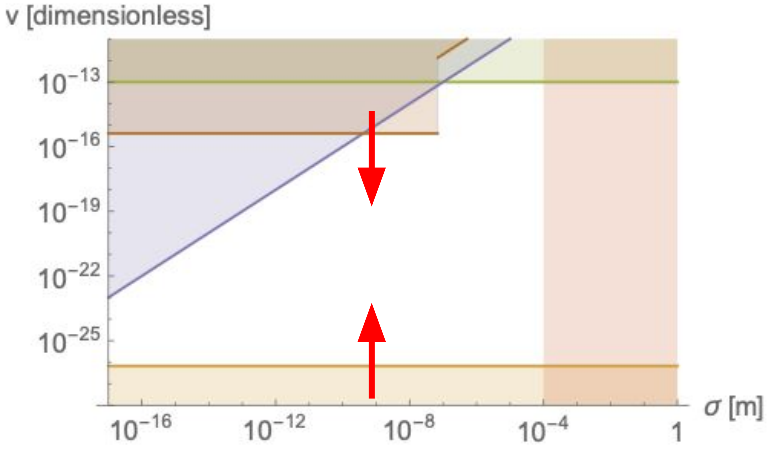
4. Can we detect gravitational entanglement?



Idea: ask a simpler question: is the gravitational interaction reversible/coherent?

Quantitative bound from any given experiment.



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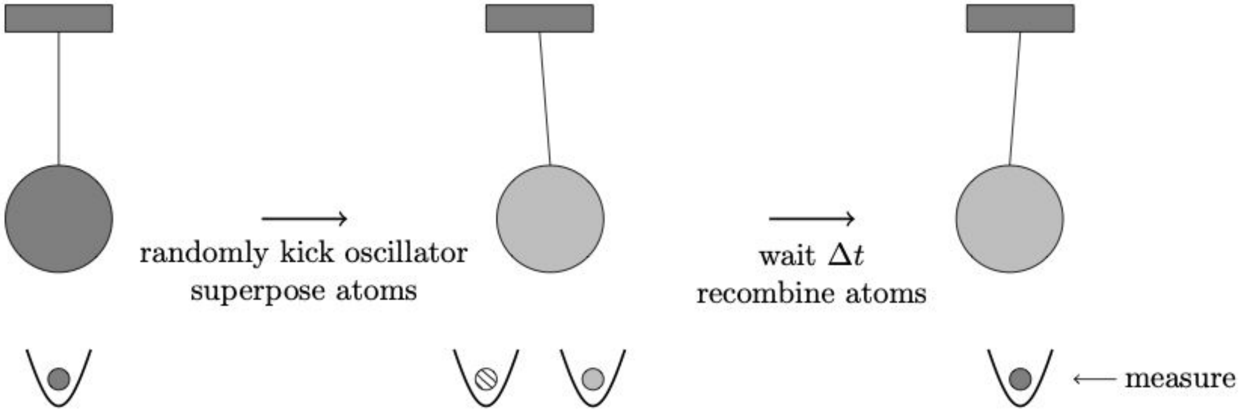
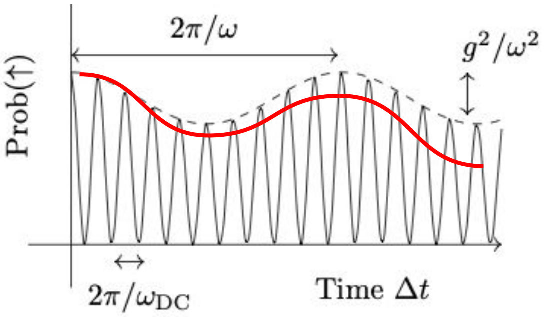


Example: use high-Q mechanical oscillator as low-noise "source" for grav field. Constrain presence of noise, e.g.:

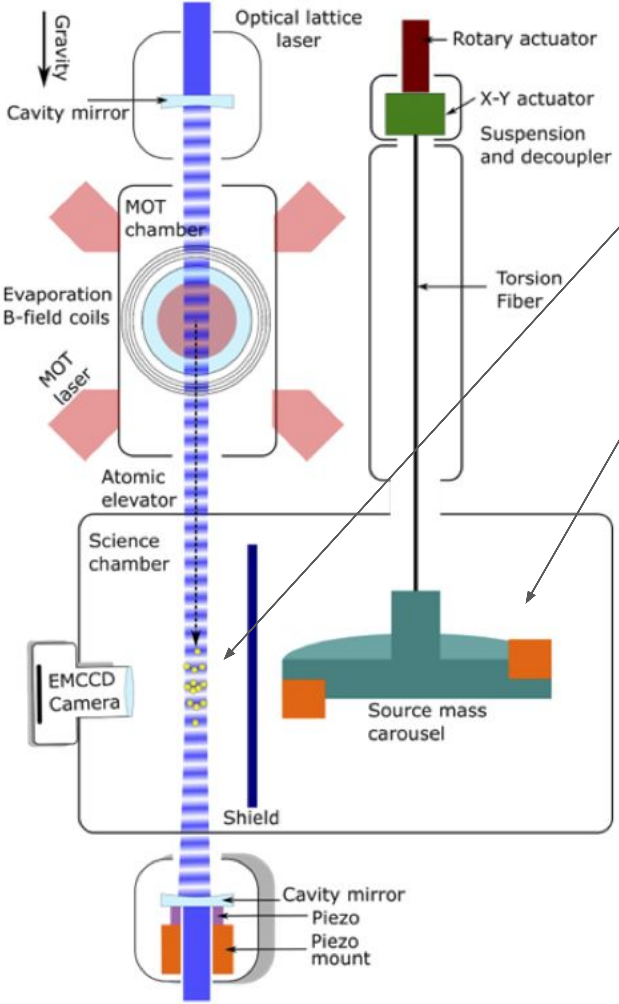
$$\langle \sigma_-(t) \rangle_{\text{incoh}} = e^{-2i\varphi(t)} e^{-\Gamma_{\text{incoh}} t}, \quad \Gamma_{\text{incoh}} = \frac{G_N^2 M m^2 \ell^2 \sigma^2}{d^6 v^2}$$



Null hypothesis (gravitons): no noise.

Non-entangling models: $\Gamma > 0$

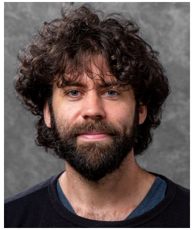
Carney, Muller, Taylor 2101.11629
Streltsov, Pedernales, Plenio 2111.04570
Ma et al 2111.00936



Lattice atom interferometer (t_{coh} ~ 60 s)

High-Q torsion pendulum “source mass” (m ~ 1 g)

~5 years → rule out ~2 orders of ν,σ parameter space



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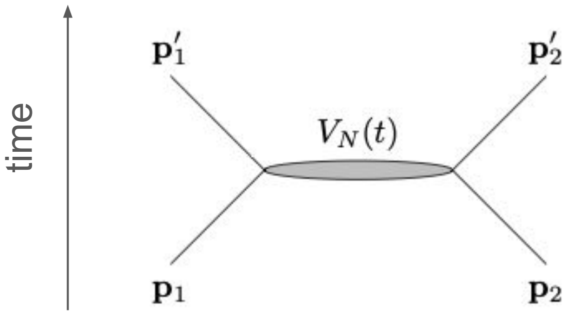
4. Can we detect gravitational entanglement?

Here is a theorem: any model in which scattering is

- unitary,
- Lorentz invariant, and
- has coherent, entangling $V_N = G\, m_1 m_2 / r$ interaction

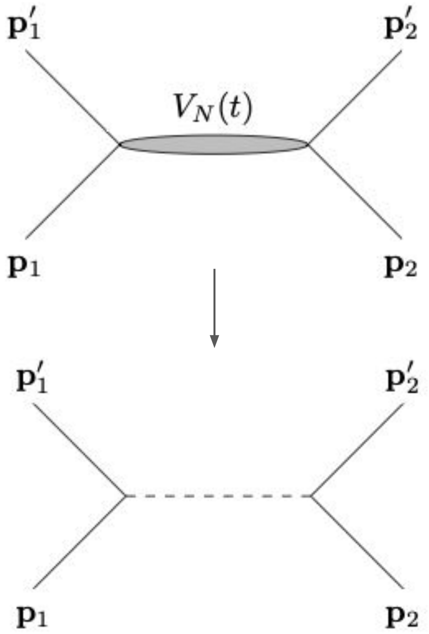
Necessarily has quantized gravitational radiation.
(simple consequence of optical theorem)

→ Testing these assumptions = testing if graviton exists



Belenchia et al 1807.07015
Carney 2108.06320
Danielson, Satishchandran, Wald 2112.10798

4. Can we detect gravitational entanglement?



Central idea: require non-relativistic scattering amplitudes to be non-relativistic limit of a Lorentz-invariant amplitude

Example: consider 2 → 2 Newtonian scattering

$$\mathcal{M}_{\mathbf{p}_1\mathbf{p}_2\to\mathbf{p}_1'\mathbf{p}_2'} = \langle \mathbf{p}_1'\mathbf{p}_2'|V|\mathbf{p}_1\mathbf{p}_2\rangle = \frac{G_N m^2}{(\mathbf{p}_1'-\mathbf{p}_1)^2+\mu^2} \longrightarrow \frac{G_N m^2}{(p_1'-p_1)^2+\mu^2}$$

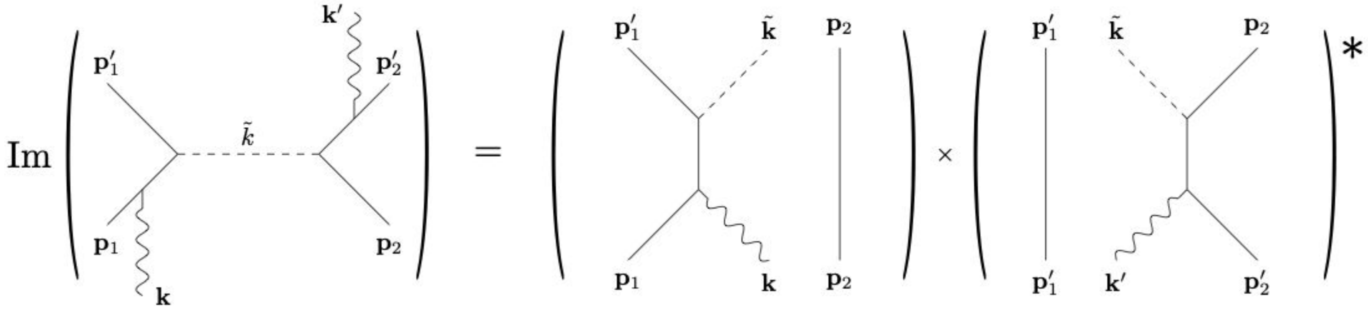
3-vector

4-vector

Here $\mu \to 0$ is a regulator. Unique Lorentz-invariant extension to this order

(Can multiply and add functions which are trivial near the pole $\Delta p^2 = -\mu^2$)

4. Can we detect gravitational entanglement?



$$1 = S^\dagger S \iff \mathrm{Im}\,\mathcal{M}_{\alpha\to\beta} = \sum_X \mathcal{M}(\alpha \to X)\mathcal{M}^*(\beta \to X)$$

Unitarity + Lorentz invariance requires final-state, quantized gravitational radiation (dashed lines). Argument fixes coupling ~ $G_N^{1/2}$ m, but not spin.

→ If you can experimentally determine that the gravitational interaction is unitary and entangling, you prove that the gravitational radiation field is quantized.

Carney 2108.06320

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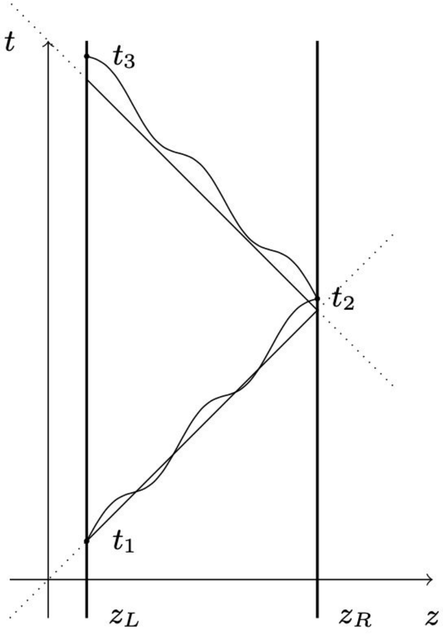
5. “Holographic noise”?



Measure the length variations in an interferometer with baseline L. Two predictions:

$$\langle \Delta L^2 \rangle = \pi L_{\rm pl}^2 \left[\frac{12}{9} \log(L\Lambda) + \text{const.} + \mathcal{O}((L\Lambda)^{-1}) \right]$$

Graviton fluctuations

$$\langle \Delta L^2 \rangle = c L_{\rm pl} L, \quad c = \mathcal{O}(1)$$

“Holographic noise”

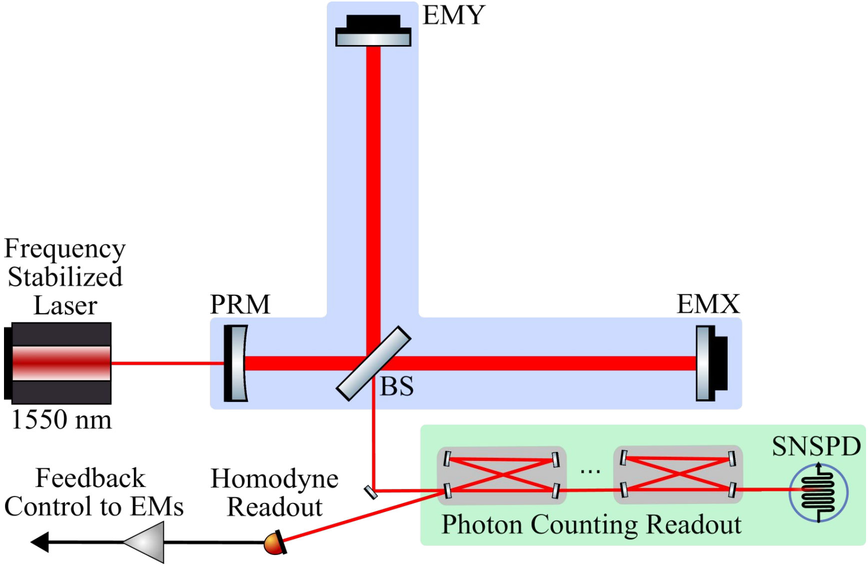
With L ~ km ~ 10^{38} * L_{pl}, the latter might be observable. The former is definitely not.

(If c=1, this gives a position uncertainty Δx ~ 10^{-16} m, but unclear frequency dependence…)

Violates EFT locality

Hogan 0706.1999
Chou et al 1512.01216
Verlinde, Zurek 1902.08207
Carney, Karydas, Sivaramakrishnan 2409.03894

5. “Holographic noise”?



Holometer experiment @ Fermilab

~MHz-band GW detector, basically small LIGO

New GQuEST experiment @ Caltech + Fermilab

~MHz-band GW detector, small LIGO + sideband photon counting readout

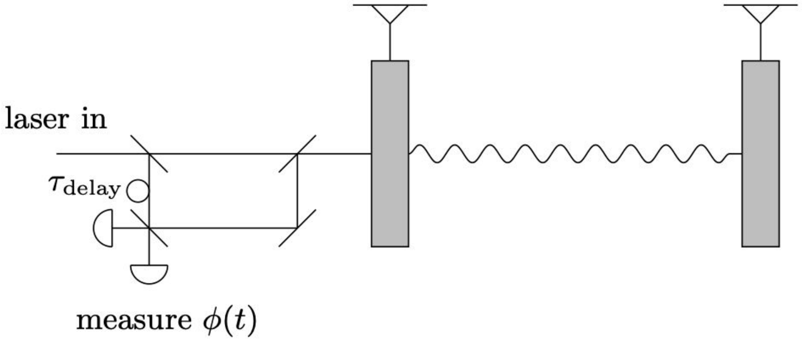
5. “Holographic noise”?

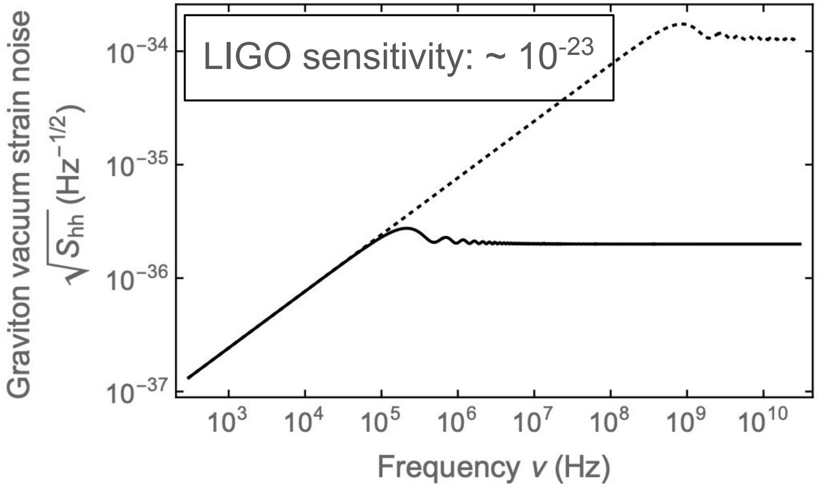
In perturbation theory, string theory (and therefore AdS/CFT) should reduce to graviton physics at this energy, so the naive expectation is the EFT prediction

Graviton calculation gives a **finite** answer once you include an actual model for a detector. But maybe holographic effects in non-perturbative calculation?

$$\begin{aligned}
\dot{X} &= -\frac{\kappa}{2}X + \sqrt{\kappa}X_{\rm in} \\
\dot{Y} &= -\frac{\kappa}{2}Y + \sqrt{\kappa}Y_{\rm in} + F_h + gx \\
\dot{x} &= \frac{p}{m} \\
\dot{p} &= -m\omega_m^2 x - \gamma p + F_{\rm m,in} + gX.
\end{aligned}$$

$$F_h = \frac{\sqrt{2\bar{n}}\omega_\ell \ell_{\rm Pl}}{V}\int \frac{d^3\mathbf{k}}{\sqrt{(2\pi)^3 2E_{\mathbf{k}}}}\sum_s [W_s(\mathbf{k})b_{\mathbf{k},s} + h.c.]$$





Jaekel, Reynaud 1994
Carney, Karydas, Sivaramakrishnan 2409.03894

FAQ

1. Do we have a theory of quantum gravity that works?
   a. **Yes, ordinary graviton physics**
2. What if gravity isn't quantum?
   a. **Pretty weird! Some "classical gravity model" examples, are there better ones…?**
3. Can we detect gravitons (in practice)? If so, does it matter?
   a. **Yes, but does not distinguish between quantum and classical gravity**
4. Can we detect entanglement generation by the Newton interaction (in practice)? If so, does it matter?
   a. **Probably eventually, and does distinguish between quantum/classical gravity**
5. Do you expect large quantum gravity fluctuations in interferometers?
   a. **Maybe! But would be large violation of basic graviton prediction…**