Probing spacetime fluctuations

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Based on work with **L. Freidel**

Upcoming work with **N. Afshordi, G. von Gersdorff, L. Freidel**

Theory Canada 18

Motivation for phenomenology

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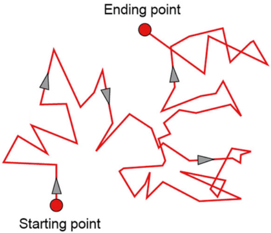
Phenomenology

Focus on phenomena as they appear to us as well as how the theories make them appear

How do microscopic fluctuations become observable?

Microscopic fluctuations $\longrightarrow$ Macroscopic signature?

Quantum gravity	**Brownian motion**
$\ell_P \sim 10^{-35}\,\mathrm{m}$	unresolved microscopic fluctuations
local fluctuations are tiny	visible diffusion



Does this happen for spacetime fluctuations?

[Wheeler, Amelino-Camelia, Hogan, Verlinde, Zurek]

How to measure spacetime fluctuations?

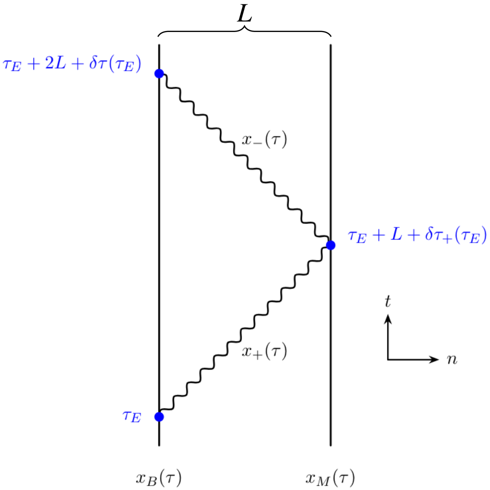
Geometry fluctuates

$\Downarrow$

Light pulse return time fluctuates

$$\tau \to \tau + \delta\tau$$

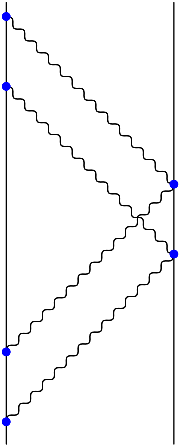
A light pulse samples spacetime geometry



From time delay to timing noise - **Interferometer**

Repeat the experiment

$$\delta\tau_1,\ \delta\tau_2,\ \delta\tau_3, \ldots$$



Noise power spectral density

Correlations of arrival-time fluctuations

$$S(\omega) = \int \frac{d^4p}{(2\pi)^3} \underbrace{\delta(\omega - p^0)}_{\substack{\text{interferometer}\\ \text{frequency}}} \underbrace{|R(p)|^2}_{\substack{\text{interferometer}\\ \text{response}}} \times \underbrace{\Sigma_n^{ab}\Sigma_n^{cd} \left\langle \tilde{h}_{ab}\tilde{h}_{cd} \right\rangle_\rho (p)}_{\substack{\text{metric noise kernel}\\ \text{in the state } \rho}}$$

Model-independent framework

Dynamics of h_{ab} + State ρ $\longrightarrow$ timing-noise spectrum

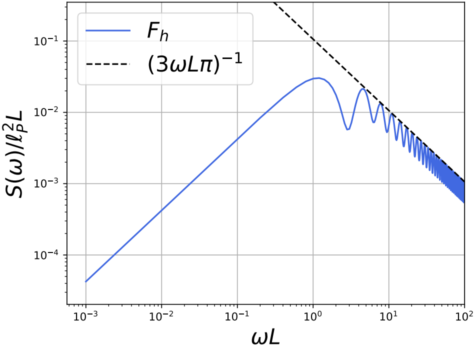
Vacuum gravitons [D. Carney et al., '24]

Gravitons: quantized gravitational radiation

Question: does this show Brownian accumulation?

$$S_{\text{vac}}(\omega) \sim \ell_P^2 L F_h(\omega L) \sim \left(1.6 \cdot 10^{-39} \frac{\text{m}}{\sqrt{\text{Hz}}}\right)^2$$

$$S_{\text{LIGO}} \sim \left(10^{-19} \frac{\text{m}}{\sqrt{\text{Hz}}}\right)^2$$



The vacuum noise kernel suppresses the low-frequency random walk

Standard vacuum gravitons give a small baseline

Cosmological graviton states

Thermal bath Bose-Einstein factor:

$$n_\beta(\omega) = \frac{1}{e^{\beta\omega} - 1}$$

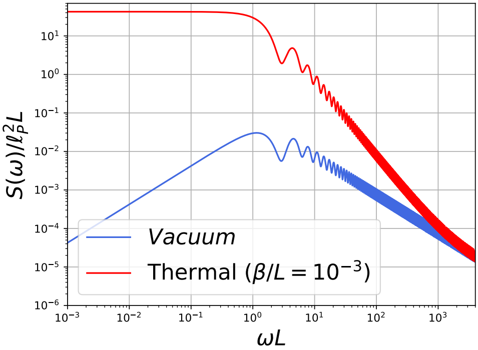
Thermal noise spectrum at $\omega = 0$:

$$S_\beta(0) \sim \ell_P^2 L^2 k_B T$$

$$\sim \left(3.3 \cdot 10^{-12} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2$$

$$\times \left(\frac{L}{10^{26}\mathrm{m}}\right)^2 \left(\frac{T}{3\mathrm{K}}\right)$$

This shows **Brownian accumulation**



Inflationary squeezed states

Occupation number:

$$n_{\mathrm{sq}}(\omega) = \sinh^2 r(\omega) \sim e^{2r(\omega)}$$

Enhanced due to cosmic expansion

Cosmological graviton states amplify the noise

Matter vacuum: stress-tensor fluctuations

Ordinary quantum fields fluctuate and source the geometry.

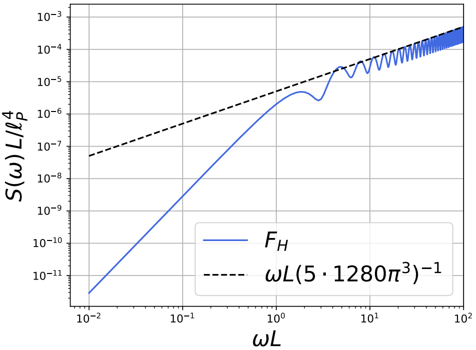
$$\langle : T_{ab} :: T_{cd} : \rangle \longrightarrow \langle h_{ab} h_{cd} \rangle$$

Standard vacuum subtraction/renormalization leaves stress-tensor correlations

$$S_{\text{matter}}(\omega) \sim \frac{\ell_P^4}{L} F_H(\omega L)$$

How vacuum-energy fluctuations should enter is tied to the **cosmological-constant problem**

Wightman vs Feynman prescription: small or infinite?



Backreaction exposes a renormalization question

Conclusions

- We are designing models of **spacetime fluctuations**.
- We tested controlled sectors: vacuum **gravitons**, thermal and squeezed gravitons, **stress-energy fluctuations**.
- The timing-noise observable is **well-defined** to study spacetime fluctuations.
- Graviton noise can show signatures of **Brownian accumulation** – relevant for cosmology.
- Matter backreaction is small in the Wightman prescription, but it exposes a sharper question: how should stress-tensor noise be renormalized for a vacuum noise observable?

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Thank you!