Interferometric Probes of Planckian Quantum Geometry

Ohkyung Kwon

KAIST

Aug 17, 2015

CTPU Workshop

Topic and Approach

Probing Planck scale effects of quantum spacetime using interferometers.

An empirical approach:

- A phenomenological region consistent with existing experimental bounds but accessible with current technology.
- Interpretation of data to connect specific classes of phenomenology with theoretical principles.
- Effective models are constrained or verified by measurements.

Why do we need to rethink spacetime?

Quantum Gravity: Nonrenormalizable in QFT

Standard approaches within the field theory framework:

- Ultraviolet divergences, correct perturbative theory at higher energies?
- Grand unified theories, supersymmetry/supergravity, Kaluza-Klein compactification and string theory...

Approaching the problem from the gravity side:

- What if the nonrenormalizability is due to the quantization of spacetime, as the Loop Quantum Gravity community believes?
- Spacetime is a dynamical field in general relativity.
- Quantum theory says that all dynamical fields must be quantized, but field theory assumes a coherent and determinate classical background.

Reconciling quantum theory with gravity

Quantum Field Theory

- Completely explains the observed behavior of matter and its interactions at microscopic scales, apart from gravity.
- Quantized particle fields in classical background spacetime, external t.
  - Field eigenmodes are embedded in a geometry with determinate and continuous spatial structures.
  - Measurements or interactions are pointlike events, but cause changes in the state of a nonlocal field system.

General Relativity

- Spacetime the same entity as the gravitational field; dynamic system.
- Diffeomorphism covariance, background-independent action.
- A dynamical geometry couples to classical matter, represented by energy-momentum tensors.

Reason to consider macroscopic scales

Infrared Paradoxes (Cohen Kaplan Nelson 1999)

- A QFT in a volume of size $\mathcal{L}$ and mode frequency cutoff m has total number of modes that scales like $\mathcal{L}^3 m^3$. This leads to a volume-independent energy density in Planck units (with mean occupation $\bar{n}$):

$$\bar{\rho}_f \approx (\bar{n}+1)m^4$$

- A black hole of size $\mathcal{L}$ has a mean density $\mathcal{L}^{-2}$ in Planck units, so this field system is compatible with relativity only in volumes smaller than:

$$\mathcal{L} < \mathcal{L}_{\mathcal{G}}(m) \approx m^{-2}$$

The cosmological constant problem

- QFT fails at cosmic scales, but predicts vacuum energy density in a lab!

The Holographic Principle and thermodynamic gravity

Bekenstein-Hawking black hole entropy:

$$S_{BH} = \frac{kA}{4l_P^2} \qquad \text{where } l_P \equiv ct_P,\ A = \text{area of event horizon}$$

Covariant Entropy Bound (Susskind 1995, Buosso 2002)

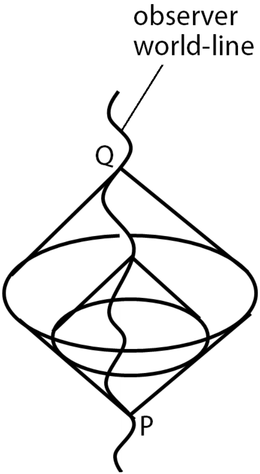
- Area of an arbitrary bounding surface in Planck units must be larger than the entropy contained throughout light sheets enclosed.
- Internal quantum spacetime degrees of freedom can be covariantly projected onto a boundary theory of Planckian information density.

Statistical gravity: (Jacobson 1995, Verlinde 2011)

- Fundamental geometrical objects are 2D null surfaces.
- Positional relationship between bodies equivalent to course-grained information on surfaces between them.

Building a spacetime from causal structures

- We can construct a fabric of spacetime from overlapping causal diamonds (Banks 2009, 2010, 2011):
  - "A time-like trajectory gives rise to a nested sequence of causal diamonds, corresponding to larger and larger intervals along the trajectory."
  - "The holographic principle and causality postulates say that the quantum mechanical counterpart of this sequence is a sequence of Hilbert spaces, each nested in the next as a tensor factor."
- These are our references for information and the duration over which such information is accessible.



Where do we find data on Planckian physics?

Interferometers have now reached Planckian spectral density.

- In gravitational wave detectors, the experimental bound on variance in dimensionless strain per frequency interval is less than Planck time.

$$h^2(f) \equiv \frac{d}{df}\left\langle\left(\frac{\Delta x}{L}\right)^2\right\rangle < t_P \equiv \sqrt{\frac{\hbar G}{c^5}} = 5.391\times10^{-44}\mathrm{sec}$$

- LIGO limit: $h(f) = 3\times10^{-23}\mathrm{Hz}^{-1/2}$ in single interferometer,
  $h(f) = 9.5\times10^{-25}\mathrm{Hz}^{-1/2}$ cross-correlated.
- Includes sensitivity enhancements that assume coherent fluctuations of the metric, implying classical background spacetime.

- There are constraints from observations of cosmic phenomena as well.

Standard local uncertainties

Field theory (Canonically quantized gravity)

- A zero-point estimation shows absence of measurable macroscopic uncertainty from the graviton field. Metric fluctuations average out in any measurement using Gaussian light beam of finite width.

$$h(f) \approx 4\sqrt{\pi^3/c^3}\,(L\lambda/2\pi)^{\frac{1}{4}}\; l_P f \mathrm{e}^{-\frac{\pi L\lambda}{c^2} f^2}$$

Planckian minimum length

- Modified canonical Heisenberg commutator for CM of massive object.
  - Some theories of critical strings (Amati et al. 1997)
  - Certain models of graviton effects (Jaekel and Reynaud 1990, 1994)
  - The quantum-group structure (or Hilbert space rep.) in Kempf et al. (1997)
- Measurable with quantum optics! (Pikovski et al. 2012)

Microscopic uncertainties do not achieve dimensional reduction.

Macroscopically coherent strain noise

- Random Walk Noise ($\langle \Delta x^2 \rangle \approx ctl_P$): Ruled out by LIGO data
  - Standard Heisenberg uncertainty and Schwarzschild limits (Salecker & Wigner 1957, 1958)
  - Dimensionally deformed Poincaré symmetry (Lukierski et al. 1995, Amelino-Camelia 1997)
  - Liouville (non-critical) string theory (Ellis et al. 1992, Amelino-Camelia et al. 1997)
- White Spacetime Noise ($h^2(f) \approx \alpha l_P / c$): LIGO data gives $\alpha < 0.06$
  - Space-time foam as a quantum thermal bath (Garay 1998)
  - Class of theories where the strain spectrum is apparatus independent.
- One-Third Power Noise ($\langle \Delta x^2 \rangle \approx (ctl_P^2)^{\frac{2}{3}}$): Ruled out by TeV γ-ray data from Cherenkov telescopes (Perlman et al. 2015)
  - Modified Salecker-Wigner; time resolution constrained by apparatus size (Karolyhazy 1966, Diosi & Lukacs 1989, Ng & van Dam 1994, Sasakura 1999)
  - *Directionally isotropic application of holographic principle* (Ng and van Dam 2000)

Quantum system of matter and geometry

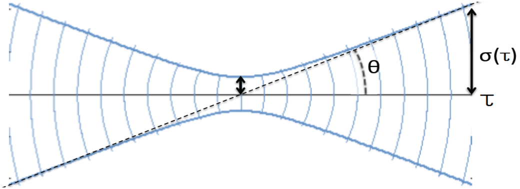
- Matter field states are nonlocal, indeterminate, and macroscopically extended. They cannot unambiguously couple to a classical spacetime. The geometry must display the same entanglement!
- It has been proposed that matter and geometry must be entangled subsystems of a single quantum system (Banks 2009, 2011).
- In such a theory, the metric should not be quantized, because it is itself an emergent entity (Banks 2011, Banks and Kehayias 2011). This is the point of view we take as well.
- In Loop Quantum Gravity, spacetime emerges as spectral properties of quantum operators describing interactions with gravity. Similar in theories of noncommutative geometries (Connes 1994, 2006).

The standard quantum limit

- Standard position wavefunction for mass m at rest, lasting duration τ Nonrelativistic Schrödinger, or nearly-free Wheeler-De Witt:

$$\left(\partial_i \partial^i - 2i\left(\frac{m}{\hbar}\right)\partial_t\right)\psi = 0$$

- "Paraxial" solution: Like Gaussian normal modes in a laser cavity.

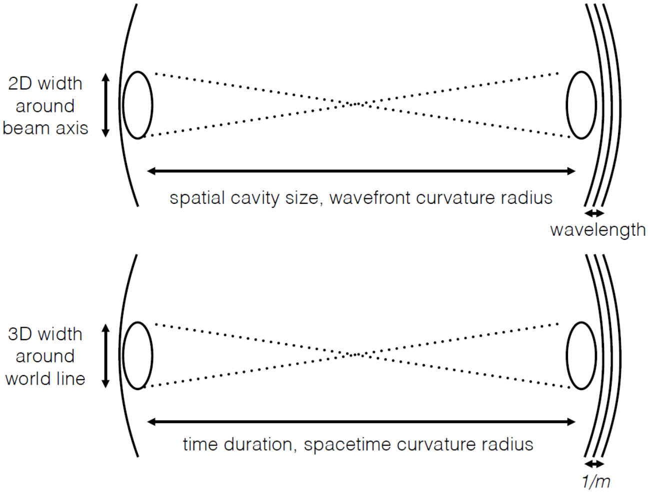


- Standard Heisenberg quantum limit over duration τ for *any* state:

$$\langle (r(t+\tau) - r(t))^2 \rangle = \sigma_0^2(\tau) > \hbar\tau/2m$$

Decoherence of world-lines

- A Planckian bandwidth limit on the system? $m = m_P = \hbar / c^2 t_P$



A Planckian limit on directional resolution

- Paths in a background quantum spacetime of scale $c\tau = \mathcal{L}$ decohere with transverse directional uncertainty (Hogan 2008, 2010, 2012):

$$\langle \Delta x_\perp^2 \rangle \approx \ell_P \mathcal{L} \qquad \langle \Delta \theta_P^2 \rangle \equiv \langle \Delta x_\perp^2 \rangle / \mathcal{L}^2 \approx \ell_P / \mathcal{L}$$

- Behaves like a transverse Planckian random walk, increasing with macroscopic separation.
- Recovers approximate locality:
  - Directional uncertainty decreases with separation.
  - Objects much closer than $\mathcal{L}$ share similar causal diamonds, have entangled spatial states, and show coherent behavior.
- Normalization: Counting number of states using a commutator model.
  - Results in similar spectra as spin network calculations in Loop Quantum Gravity ($\sim \sqrt{l(l+1)}\ell_P$)
  - Matched to number of states in emergent gravity (Verlinde 2011)

$$\ell_P \equiv ct_P/\sqrt{4\pi} \equiv \sqrt{\hbar G/4\pi c^3} = 4.558 \times 10^{-36}\mathrm{m}$$

Piecing the puzzle together

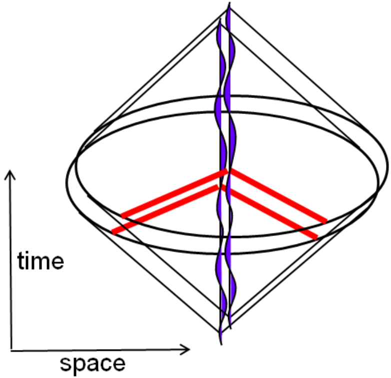
- Solves the CKN infrared paradox:
  - At $\mathcal{L}_{\mathcal{G}}(m) \approx m^{-2}$, smallest angular structure of field states limited by resolution of Planckian geometry; number of states greatly reduced.
  - Same scaling of number of states as the Chandrasekhar limit.
- Holographic scaling of d.o.f.: Above the scale $m = m_P$, geometric uncertainty overrides the standard quantum limit.
- Can preserve covariance; tiny noncommutative Lorentz violation:
  - Over 1 billion light years, accumulates 10µm.
  - In a 100m lab experiment, effective transverse velocity is $\approx 10^{-18.5}c$, or a few mm per year— order of magnitude slower than continental drift.
- Cosmological constant and Λ_{QCD} (Zeldovich 1967, 1968).
  - Curvature entanglement with field vacuum changes most probable macrostate of spacetime (Hogan 2014).
- Black hole information paradox. Uncertainty scales to horizon size over evaporation time.

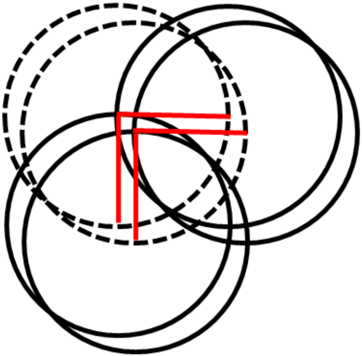
The Fermilab Holometer

An experimental program to probe background spacetime

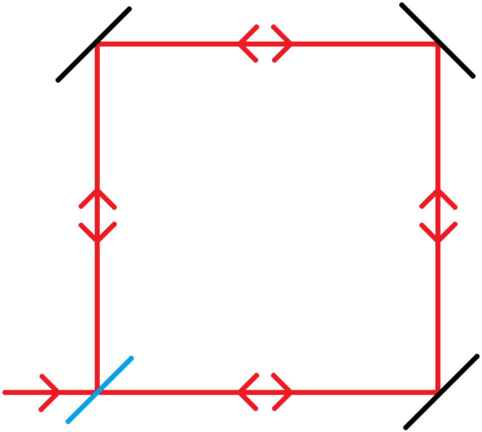
- First measurements of positional cross-correlation between world lines at sub-Planckian spectral precision.
- Measurements on timescales less than apparatus light crossing time.
- Can make delocalized measurements within a causally connected 4-volume of spacetime; sensitive to quantum relationships between macroscopically separated timelike world-lines.
- Can also detect topological defect dark matter or variations in fundamental constants. With improvements in interferometer technology, could be scaled down as an axion detector.

Shear: Nested Michelson configuration (current)

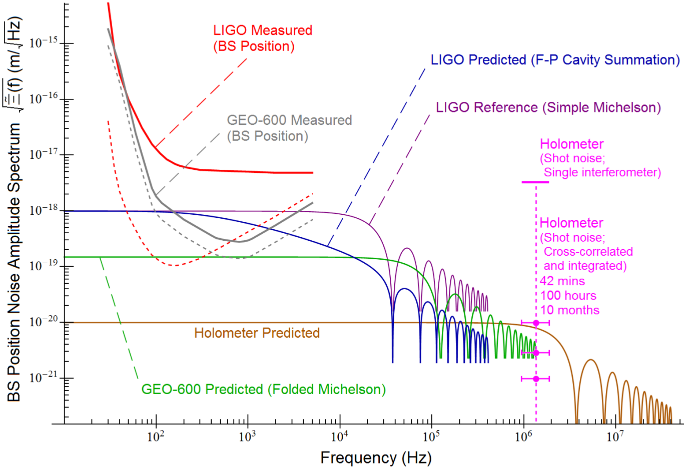




Rotation: Sagnac configuration (planned)

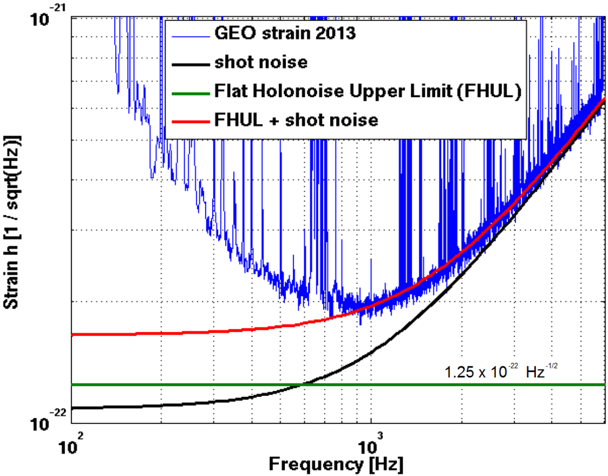


Baseline predictions and detector sensitivities



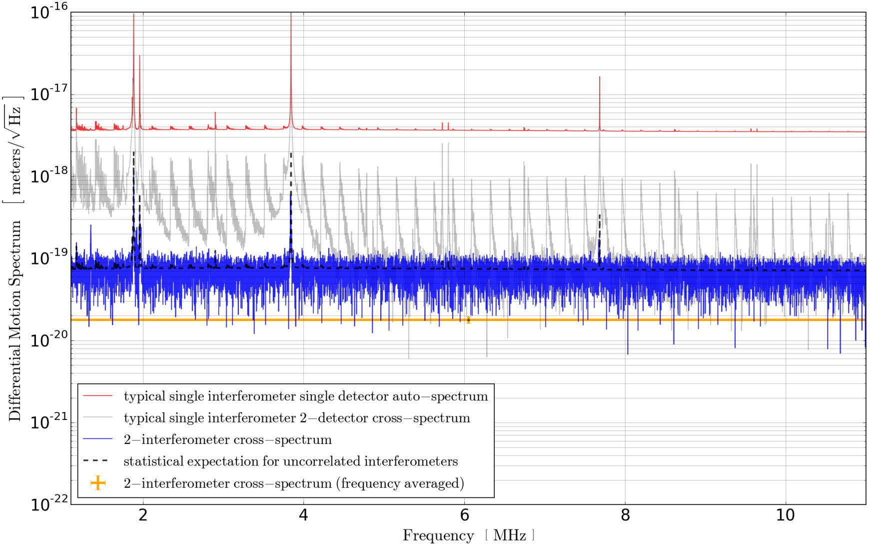
GEO-600 and LIGO measured spectra corrected by GW transfer function. Different interferometer configurations have different causal structures.

Looking for holographic noise in GEO-600

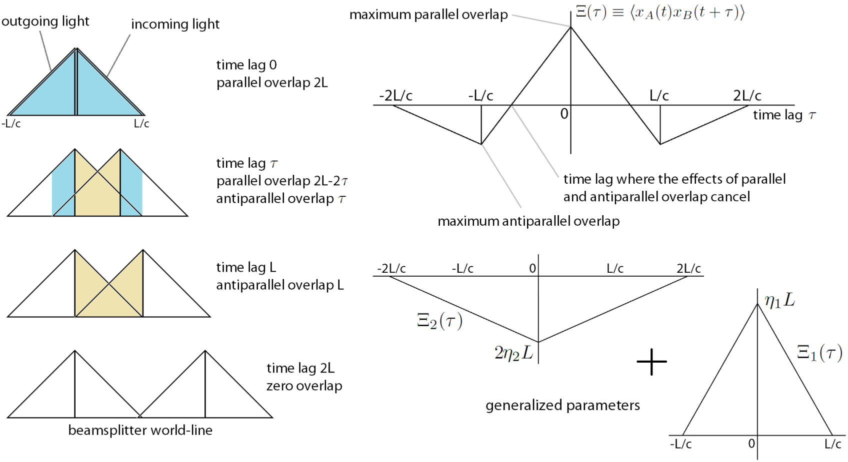


Our baseline prediction: $1.23 \times 10^{-22} Hz^{-1/2}$

Early data for sensitivity projections

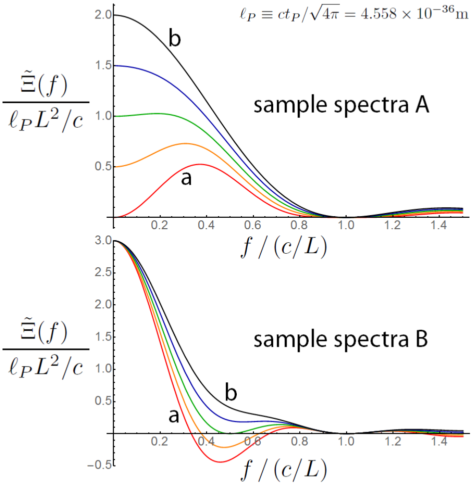


Generalized predictions from causal structures



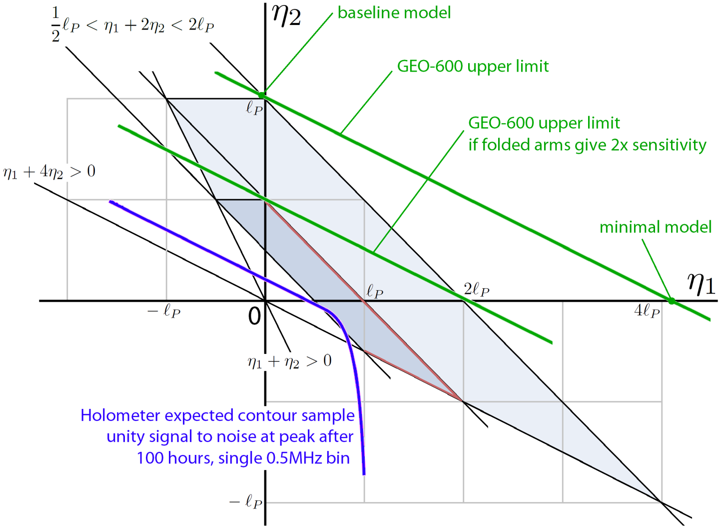
Universal parameters: $c\eta_i \equiv \dot{\Xi}_i(-\frac{L}{c} < \tau < 0) = -\dot{\Xi}_i(0 < \tau < \frac{L}{c})$

Possible ranges of spectra for different parameters



$$\tilde{\Xi}(f) = c\eta_1 \left(\frac{L}{c}\right)^2 \mathrm{sinc}^2\left(\frac{f}{c/\pi L}\right) + c\eta_2 \left(\frac{2L}{c}\right)^2 \mathrm{sinc}^2\left(\frac{f}{c/2\pi L}\right)$$

Sensitivity contours in parameter space



Thank you!