Quantum Geometry and the Fermilab Holometer

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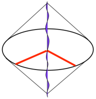
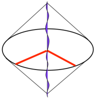


Thank You!

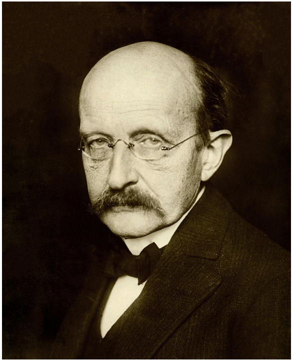


Main Points

- Hypothesis: $[X_i, X_j] = i\ell'_P \epsilon_{ijk} X_k$
- $\langle x_\perp^2 \rangle = L\ell'_P$
- We are building interferometers to search for macroscopic effects

- `http://holometer.fnal.gov` especially scientific bibliography
- Craig Hogan's papers on arXiv re quantum geometry and interferometers

Abstract: Vacuum Vessels for Interferometers

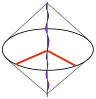


Max Planck: from three physical constants, $c, \hbar, G$, derive:

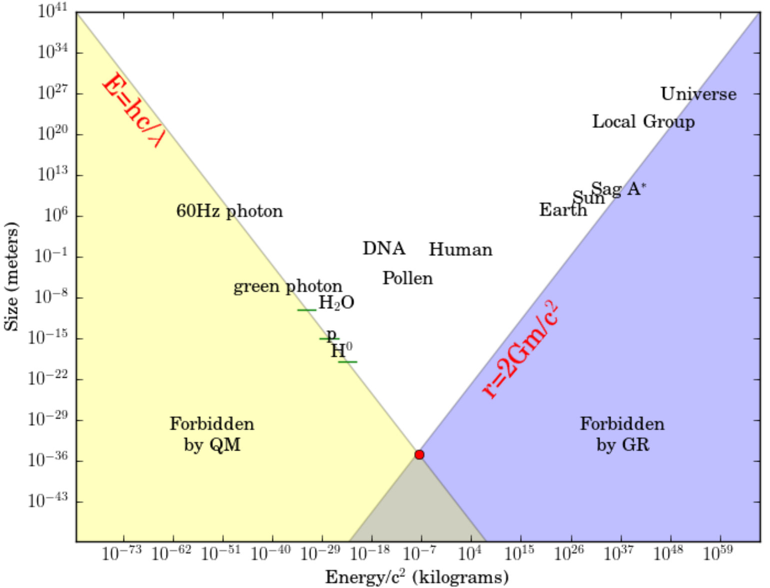
Length: $\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35}\text{m}$

Time: $t_P = \sqrt{\frac{\hbar G}{c^5}} = 5.4 \times 10^{-44}\text{s}$

Mass: $m_P = \sqrt{\frac{\hbar c}{G}} = 2.2 \times 10^{-8}\text{kg}$



Motivation: Size and Energy



Motivation: Theoretical Developments

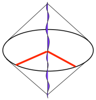
Thermodynamics

- $S_{BH} = 4\pi(R/2\ell_P)^2$
- Formulations of GR from thermodynamics

Holographic Principle

- "Nature's book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size." - Gerard 't Hooft
- Verlinde[1] calculates the number of states in a sphere: $N_G(R) = 4\pi(R/\ell_P)^2$.

Treat space-time as a statistical behavior of a quantum system.
States have new forms of spatially nonlocal entanglement.



[1] JHEP **1104**, 029 (2011)

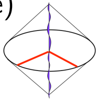
Motivation: Geometry

Paradox

- Classical geometry is based on the primitive notion of spatial points; locality is presumed
- Quantum Physics does not ascribe events to definite points
- How does geometry work for quantum measurements?

Standard Architecture of Physics

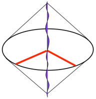
- Dynamic space-time responds to particles and fields but is not quantum
- Quantum particles and fields defined on the "stage" of classical geometry
- This accomodation explains all quantum mechanics (particle) experiments
- Space-time is dynamical: strong gravitational lensing, and pulsar spin-down.



Hypothesis: a new commutator

$$[x_\mu, x_\nu] = i x^\kappa U^\lambda \epsilon_{\mu\nu\kappa\lambda} \ell'_P$$

- x are Hermitian operators on bodies
- eigenvalues of x are locations of bodies
- U is 4-velocity: $\partial x / c \partial t$
- $\epsilon_{\mu\nu\kappa\lambda}$ is antisymmetric 4-Tensor
- the form is covariant
- describes quantum relationship between two timelike trajectories

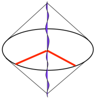


Hypothesis: Macroscopic Uncertainty

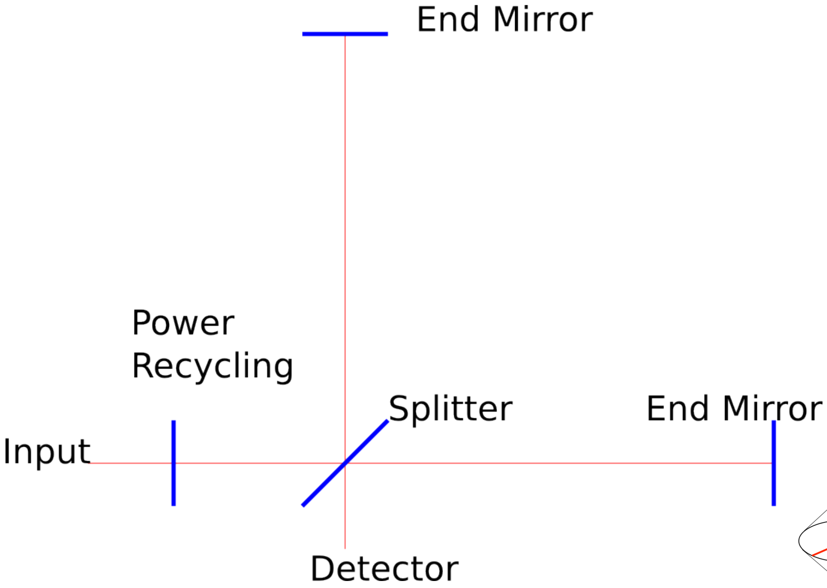
$$[x_i, x_j] = i x_k \epsilon_{ijk} \ell'_P$$

In the Rest Frame

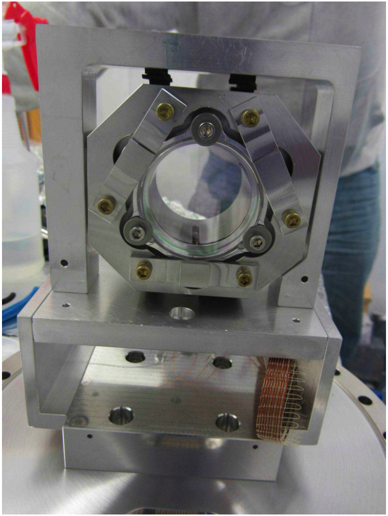
- In the rest frame, turns into Planck scale quantum algebra for position operators in 3D at one time
- Similar to angular mometum algebra, with x in place of J: $N_H(R) = \sum_{l=0}^{R/\ell'_P} 2l + 1 = l_{MAX}(l_{MAX} + 1) \rightarrow (R/\ell'_P)^2$ for $R \gg \ell'_P$.
- Leads to uncertainty in transverse position after propagating distance z: $\langle x_\perp^2 \rangle = z\ell_P/\sqrt{2}\pi$
- Compare to standard quantum limit: $\langle x^2 \rangle > 2\hbar\tau/m$
- Uncertainty increases with separation z.
- This is a "new" quantum departure from classical geometry
- Purely transverse to propagation direction



Experiment: Michelson Interferometer (power recycling)



Experiment: Control two degrees of freedom

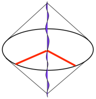


λ_{laser}

- Change λ_{laser} to minimize reflection of input light from the power recycling mirror

ΔL

- End mirrors actuated by three spring-loaded piezo crystals
- 2 kHz resonant frequency
- 14 micron range
- Drive north and east arms differentially to control ΔL



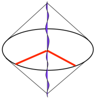
Experiment: $\Delta L(t)$ in an Interferometer

Reference Design for One Interferometer

- Arm Length L $=$ 40 meters
- Optical Wavelength $\lambda = 1.064$ microns
- Power on beam splitter $P_{BS} = 1$ kWatt
- Free Spectral Range $f_c \equiv c/2L = 3.75$ MHz
- Round Trip Time $\tau_c \equiv 2L/c = 267$ nanoseconds

Length Spectral Density

- Holographic Signal for $f < f_c$:
  $\sqrt{\widetilde{\Xi}_H(f)} = 2L\sqrt{\ell_P/c\sqrt{\pi}} = 1.39 \times 10^{-20}\text{meters}/\sqrt{Hz}$
- Poisson (shot) Noise:
  $\sqrt{\widetilde{\Xi}_{shot}(f)} = \sqrt{hc\lambda/4\pi^2 P_{BS}} = 1.64 \times 10^{-18}$ meters$/\sqrt{Hz}$



Signal/Noise is $< 1\%$

Experiment: Increase S; Decrease L

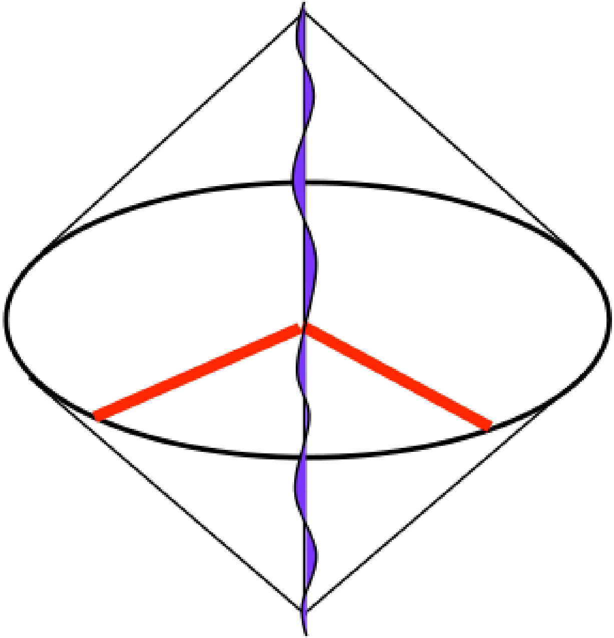
Signal increases with L. Large interferometer for gravitational wave detectors have $L \sim 4kM$.

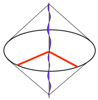
Noise decreases with Power. Even with special glass, loss in beam splitter deforms glass due to thermal heating at $P \sim 3kW$.

Pushing to this extreme, Signal/Noise ~ 1.

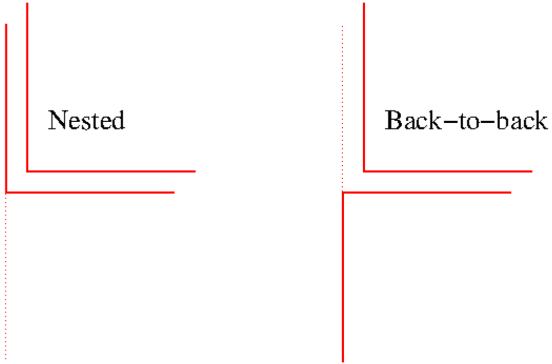
We asked LIGO very politely if we could borrow (and reconfigure) an interferometer but they are using it to look for gravitational waves.

Back to Hypothesis: Coherence





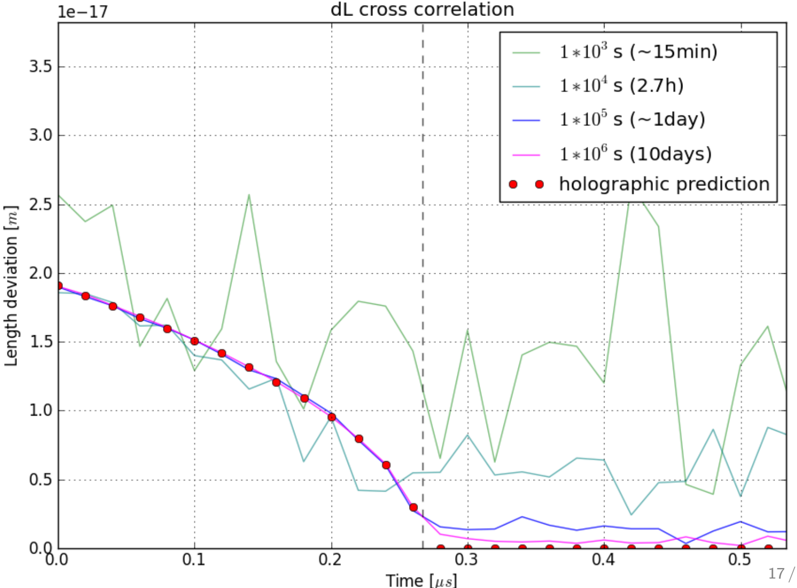
Experiment: Holometer Observing Strategy



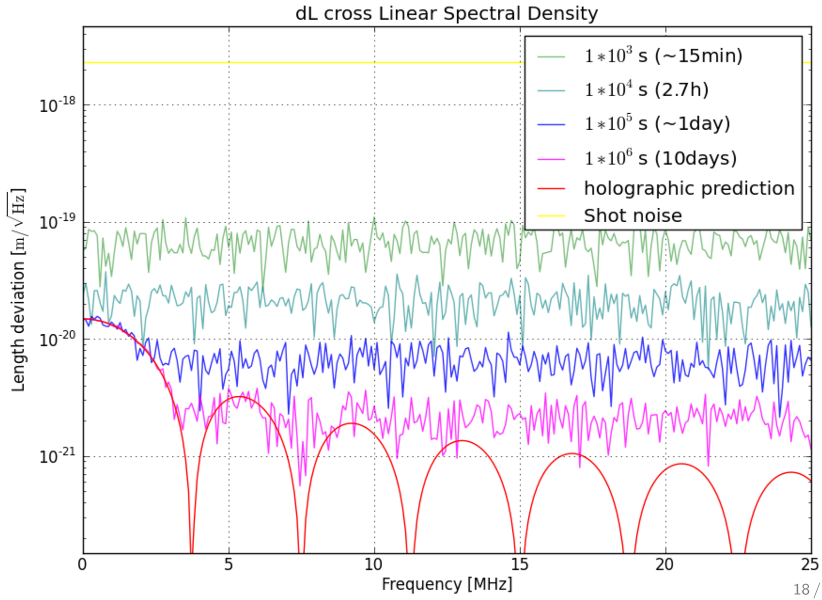
$t_{int} > \tau_{sample} \left(\frac{\pi}{2} \left(\frac{\ell_{shot}}{\ell_H} \right)^2 \right)^2 \sim$ minutes to reach S/N=1

Note: non-gaussian noise in optics and electronics will (probably) dominate exposure time.

Exp: Cross Correlation $\sqrt{\widetilde{\Xi}(\tau)} = \sqrt{\langle L_0(t) L_1(t+\tau) \rangle}$

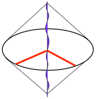


Experiment: Shape in Frequency Space

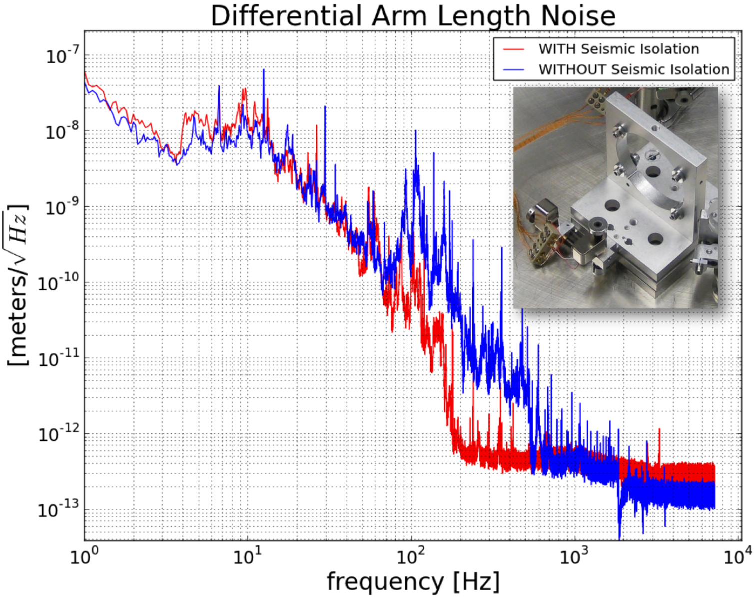


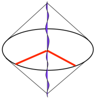
Experiment: Parts List

- 2W (continuous) Nd:YAG infrared laser
- Beam splitter substrate: polished flat to lose < 50 ppm to scattering; Suprasil 3001 (loss < 1 ppm)
- End mirrors: 78m radius; Ion Beam Sputtering (loss < 10 ppm)
- Vacuum System: 304L stainless steel $+$ conflats; free of Hydrocarbon contamination
- Control System: Digital filtering w/FPGA (NI PXIe-7852R) to control end mirrors (ΔL and alignment)
- Cross Correlation: 4 channels @ 100 MHz (NI PXIe-5122) and 32-core computer



Experiment: Status

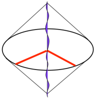




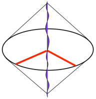
Experiment: Vacuum Vessels for End Mirror

History: Michelson-Gale-Pearson Sagnac effect

2010 x 1113 ft rectangular interferometer in Clearing, IL (1925)
12-inch steel water pipes, evacuated to 13 Torr. Mirrors adjusted by mechanical feedthroughs, coordinated via telephone.



- The Fermilab Holometer tests the hypothesis that space-time is described by non-commuting operators.
- The planck length scale is “magnified” to produce macroscopic effects
- Two interferometers have been constructed. We will characterize non-gaussian noise sources this summer.



Homework

Calculate the magnitude of the coherence of the Holographic Signal between two interferometers. Each interferometer has an arm length of 40 meters. The beam splitters are separated in $(x, y, z) = (25, 25, 10)$ inches.

Calculate for two configurations:

– nested

– back-to-back

Please email answers to `stoughto@fnal.gov` and let me know whether you want your answer included in the conference paper, anonymously or with your name.