Quantum Geometry and the Fermilab Holometer

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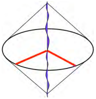
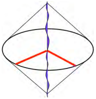


Abstract: The Fermilab Holometer

Main Points

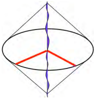
- Hypothesis: $[X_i, X_j] = i\ell'_P \epsilon_{ijk} X_k$
- $\langle x_\perp^2 \rangle = L\ell'_P$
- We are building interferometers to search for macroscopic effects

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



Context: Vacuum Vessels for Interferometers

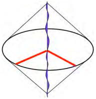
Context: Vacuum Vessels for End Mirror



Context: The Neighborhood

Historical Context: 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.



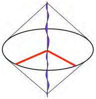
Motivation: Natural Units

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

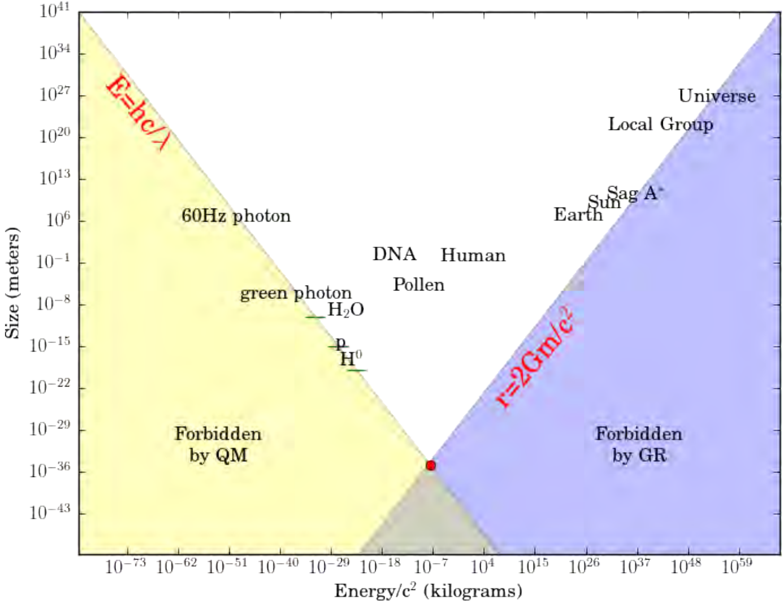
Length: $\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35}\mathrm{m}$

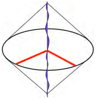
Time: $t_P = \sqrt{\frac{\hbar G}{c^5}} = 5.4 \times 10^{-44}\mathrm{s}$

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



Motivation: Size and Energy





Motivation: Theoretical Developments

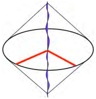
Thermodynamics

- $S_{BH} = 4\pi(R/2\ell_P)^2$
- 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)

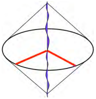
Motivation: Geometry

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 (lensing; pulsar spin-down) but is not quantum
- Quantum particles and fields defined on the "stage" of classical geometry
- This accommodation explains all quantum mechanics (particle) experiments

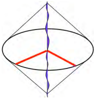


It cannot be the whole story

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

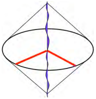


Hypothesis: Macroscopic Uncertainty

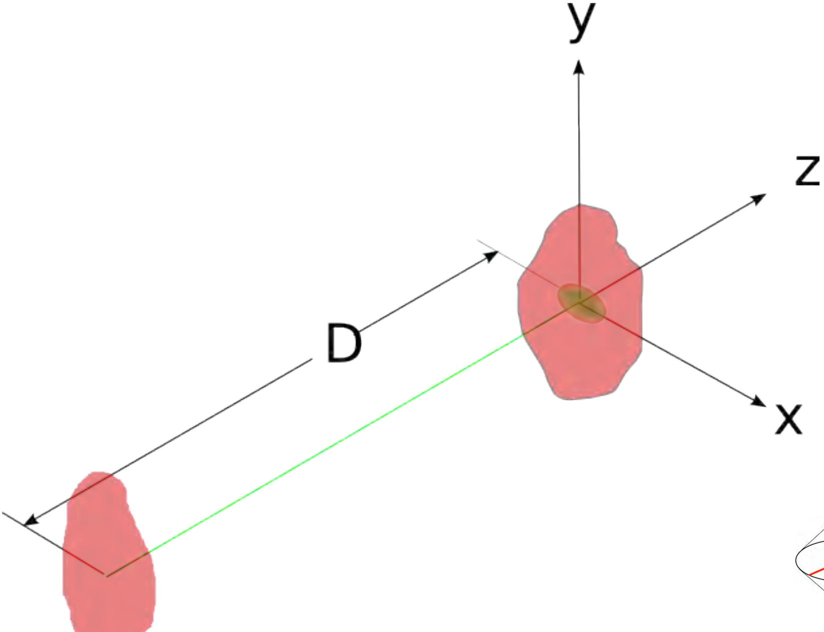
$$[x_i, x_j] = i x_k \epsilon_{ijk} \ell'_P$$

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 momentum algebra, with x in place of J
- Uncertainty in transverse position after propagating D: $\langle x_\perp^2 \rangle = D\ell'_P$
- Uncertainty increases with separation D.
- This is a “new” quantum departure from classical geometry
- Purely transverse to propagation direction



Hypothesis: Transverse Position Uncertainty



Hypothesis: Normalization

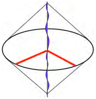
Define the state $|d\rangle$ as two bodies separated by distance $D = d\ell'_P$.

For a given separation D, there are $2d + 1$ states.

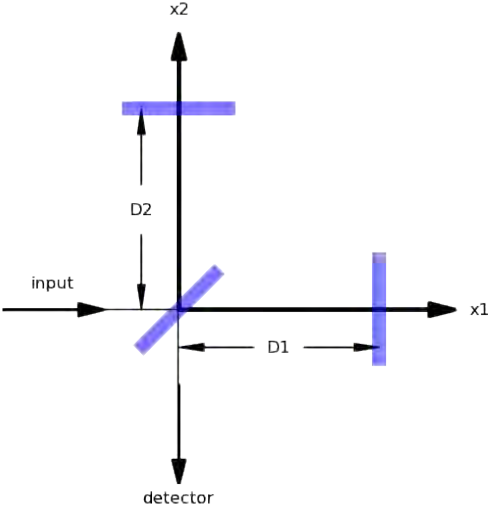
In a sphere, values d are allowed such that $0 \leq d \leq R/\ell'_P$. Each one of these has $2d + 1$ states. So the number of states in a 3-sphere of radius R is

$N_{3S} = \sum_{d=0}^{R/\ell'_P} 2d + 1 = d(d+1) \rightarrow (R/\ell'_P)^2$ for $R \gg \ell'_P$

- Recall that Verlinde calculates $N_G(R) = 4\pi(R/\ell_P)^2$
- $N_{3S}(R) = N_G(R) \rightarrow \ell'_P = \ell_P/2\sqrt{\pi}$
- The normalized transverse position uncertainty is $\langle x_\perp^2 \rangle = D\ell_P/2\sqrt{\pi}$



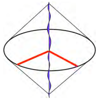
Experiment: Michelson Interferometer



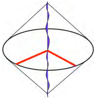
Measure voltage at detector as a function of time.

For a constant number photons per second at the input, this measures

$$\Delta(t) \equiv D2(t) - D1(t)$$



Video demonstration of $\Delta(t)$ at audio frequencies.

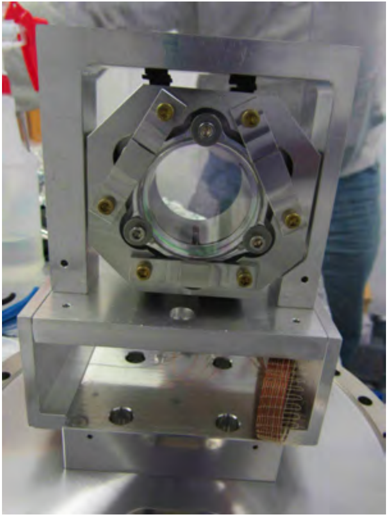


Experiment: $\Delta(t)$ in an Interferometer

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

Experiment: Control two degrees of freedom

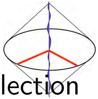


$\Delta \equiv D2 - D1$

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

λ_{laser}

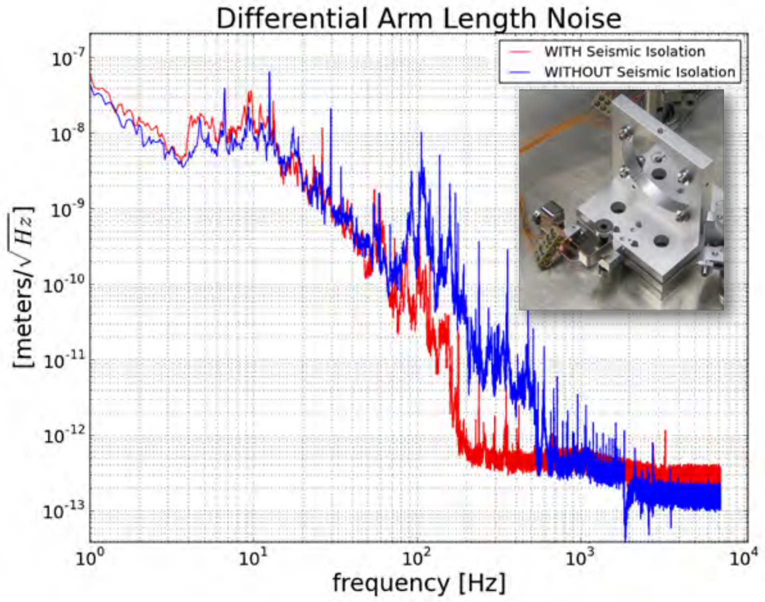
- Power Recycling Mirror (PRM) reflects photons back towards the beam splitter; makes IFO an optical cavity
- Change λ_{laser} to minimize reflection of input light from the PRM

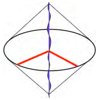


Experiment: Parts List

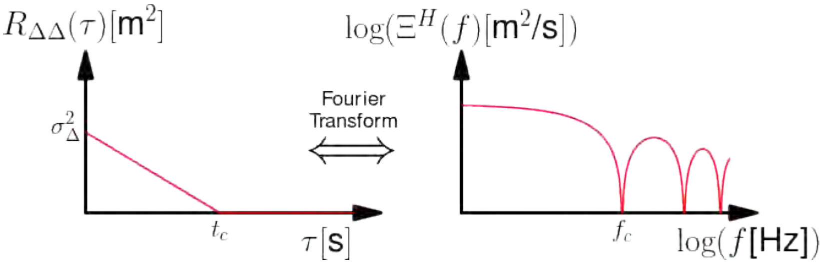
- 2W (continuous) Nd:YAG infrared laser
- Beam splitter substrate: polished flat to lose < 50 ppm to scattering; Suprasil 3001 (loss < 1 ppm)
- End mirrors: 78m radius; Ion Beam Sputtering (loss < 10 ppm)
- Vacuum System: 304L stainless steel + conflats; free of Hydrocarbon contamination
- Control System: 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: Seismic Noise Supression

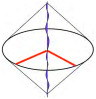




Experiment: Signal Processing



- Autocorrelation function is $R_{\Delta\Delta}(\tau) \equiv E[\Delta(t)\Delta(t+\tau)]$
- At zero time lag, it is the variance: $R_{\Delta\Delta}(0) = \langle x_\perp^2 \rangle$
- Linear extrapolation to zero at t_c
- Predict $\Xi(f)$ from theoretical $R_{\Delta\Delta}$
- Calculate $\Xi(f)$ from measured $\Delta(t)$
- Inverse Fourier Transform yields measured $R_{\Delta\Delta}$



Length Spectral Density

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

Signal/Noise is $< 1\%$

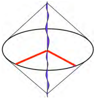
Experiment: Increase Signal; Decrease Noise

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

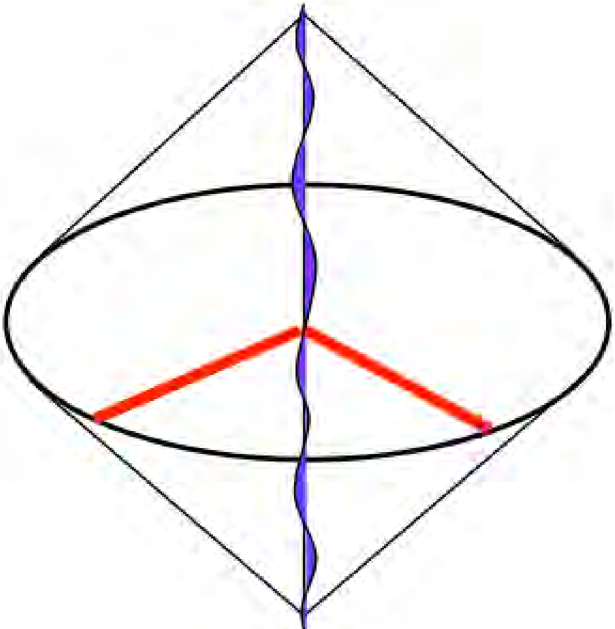
Noise decreases with Power. Even with special glass, loss in beam splitter deforms glass due to thermal heating at $P \sim 3$ kW.

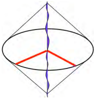
Pushing to this extreme, Signal/Noise ~ 1.

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

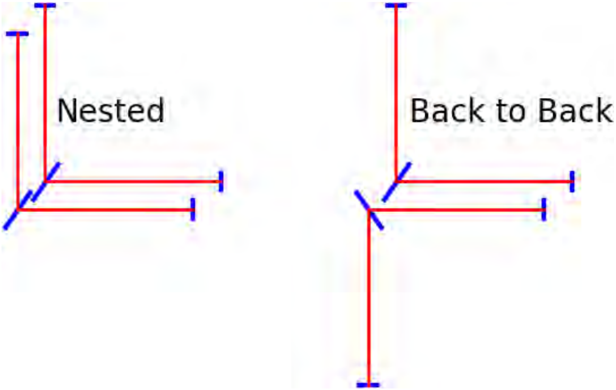


Back to Hypothesis: Coherence



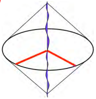


Experiment: Holometer Observing Strategy



$$T_{\mathrm{I}} = \left(\frac{\lambda^2}{P_{\mathrm{BS}}^2 D^3}\right)\left(\frac{1}{\ell_P^2}\right)\left(\frac{h^2 c^3}{8\pi^3}\right) \sim \text{minutes.}$$

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



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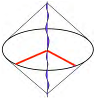

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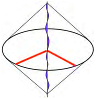

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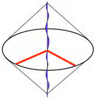
- Holographic noise of two co-located interferometers is correlated and depends on the overlapping spacetime volume.



Conclusion

We have designed, assembled and are currently commissioning the Fermilab Holometer. We will be sensitive to the macroscopic effects of these ideas:

- magnitude of the cross correlation;
- spectral shape of the cross correlation;
- modulation of the cross correlation with the configuration of the interferometers.