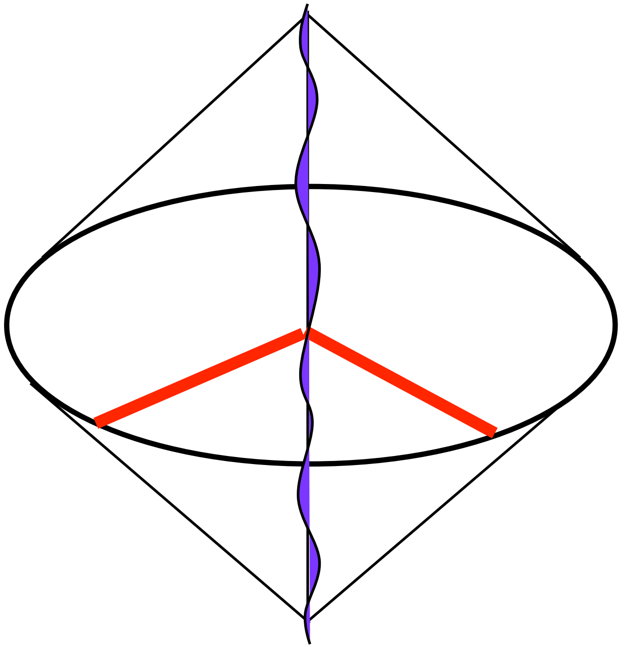
# Holographic Noise in Interferometers

*A new experimental probe of Planck scale unification*



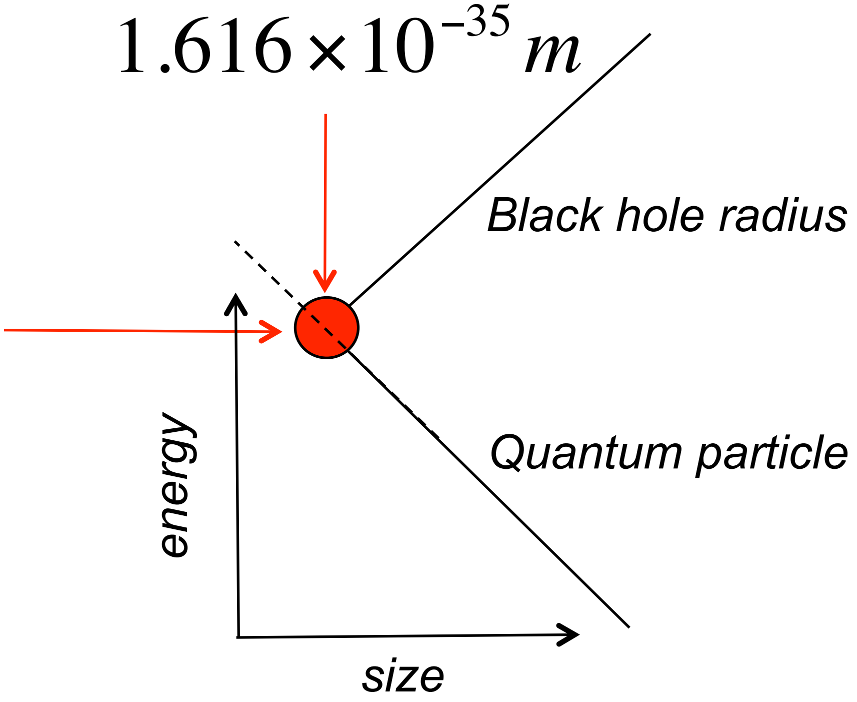
# Planck scale

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \text{ seconds}$$

*The physics of this "minimum time" is unknown*

$$1.616 \times 10^{-35}\, m$$

*particle energy ~$10^{16}$ TeV*



*Particle confined to Planck volume makes its own black hole*

# Interferometers might probe Planck scale physics

One interpretation of the Planck frequency/bandwidth limit predicts a new kind of uncertainty leading to a new detectable effect:

*"holographic noise"*

Different from gravitational waves or quantum field fluctuations

Predicts  Planck-amplitude noise spectrum with no parameters

*We are developing an experiment to test this hypothesis*

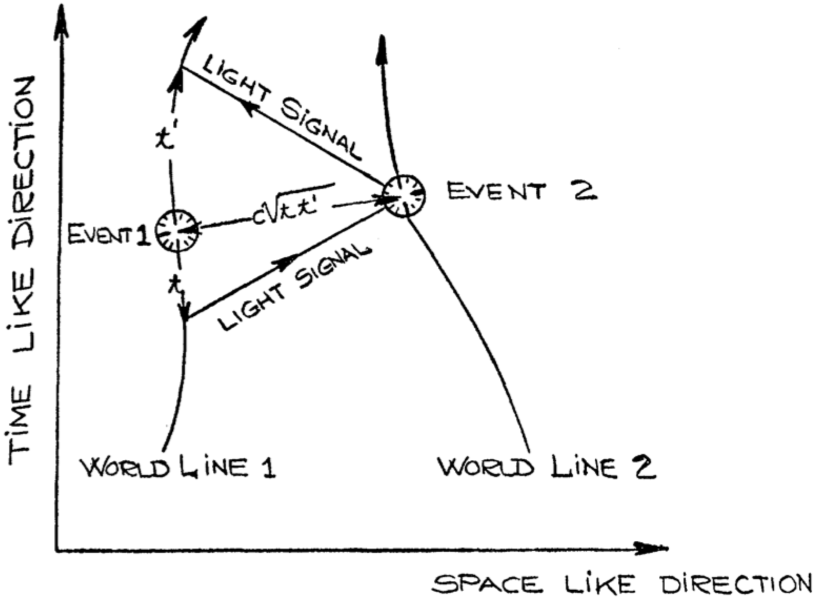
# Quantum limits on measuring event positions

Spacelike-separated event intervals can be defined with clocks and light

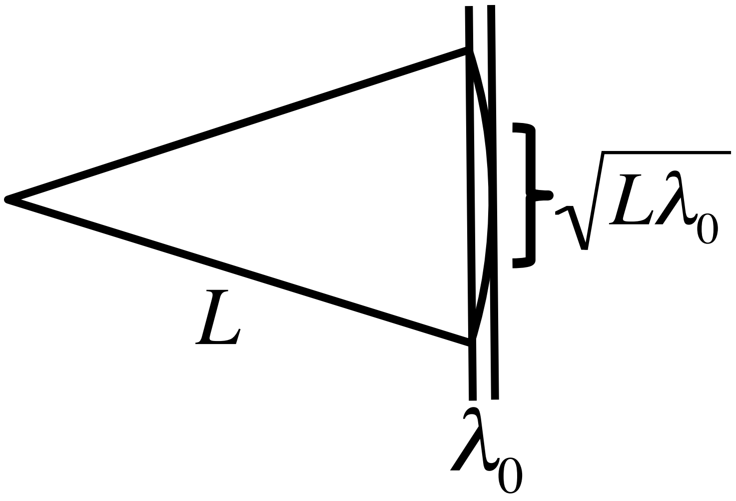
But transverse position measured with frequency-bounded waves is uncertain by the diffraction limit,

$$\sqrt{L\lambda_0}$$

*This is much larger than the wavelength*

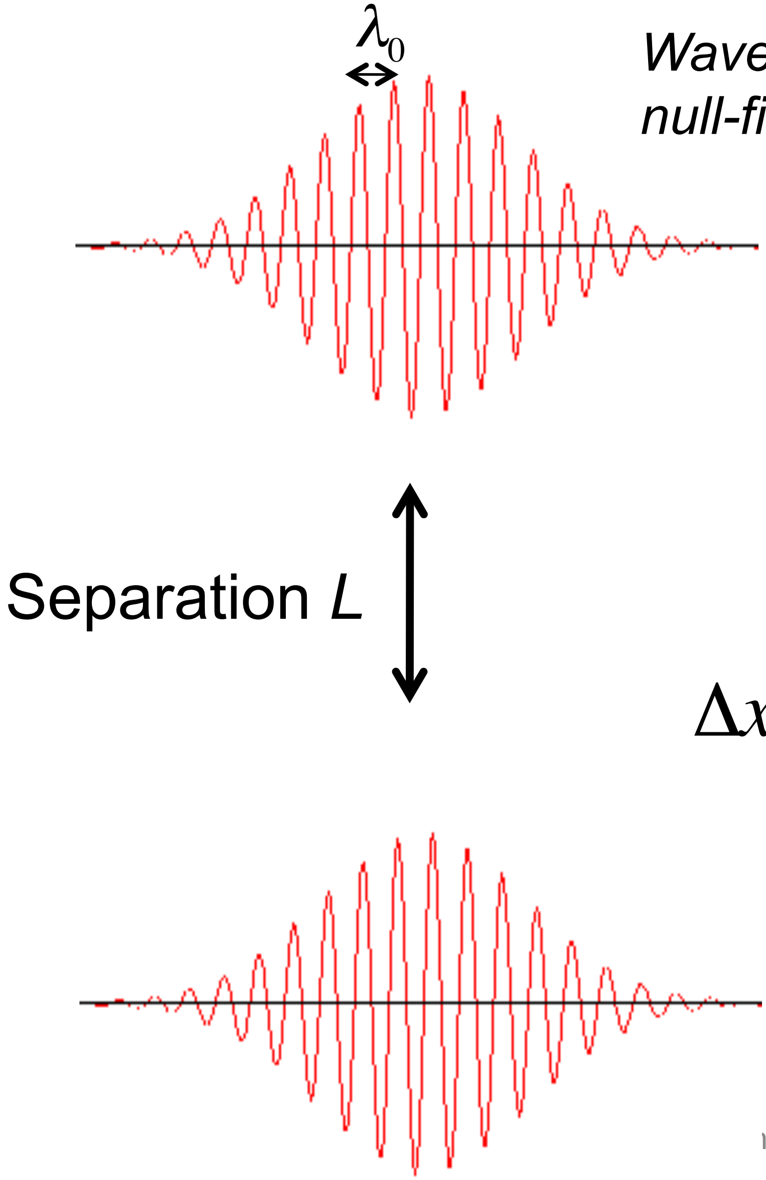


*Wigner (1957): quantum limits with one spacelike dimension*



*Add second dimension: small phase difference of events over large transverse patch*

# Nonlocal comparison of event positions: phases of frequency-bounded wavepackets



*Wavepacket of phase: relative positions of null-field reflections off massive bodies*

$$\Delta f = c / 2\pi\Delta x$$

$$\Delta x_L = L(\Delta f / f_0) = \sqrt{cL / 2\pi f_0}$$

Uncertainty depends only on $L, f_0$

# Physics Outcomes

If noise is not there,

Constrain interpretations of holography: no Planckian frequency bound or noncommutative geometry affects wavepackets of position

If it is detected, experiment probes Planck scale unification

Study holographic relationships among matter, energy, space, time

Shape interpretation of fundamental theory

*Main weakness of the program: there is no standard theory of Planck scale unification that can be cleanly tested with this (or any other) experiment*

# Survey of theoretical background: **arXiv:0905.4803**

Arguments for new indeterminacy

- Wavepackets with maximum frequency
- Holographic information bounds
- Black hole evaporation
- Matrix theory
- Noncommutative geometry (Moyal algebra)

Ways to calculate the noise

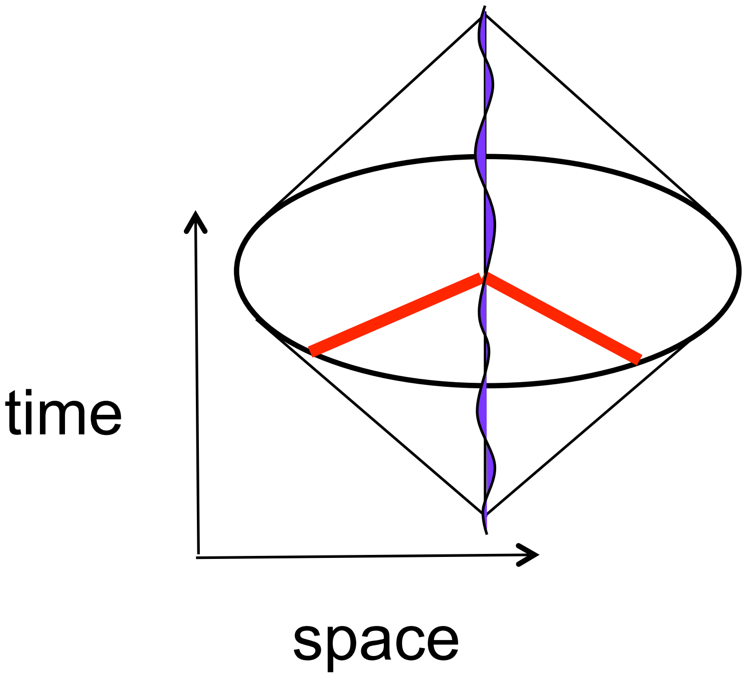
- Wave optics solutions
- Planck wavelength interferometer limit
- Precise calibration from black hole entropy
- Non-commuting clock operators (arXiv:1002.4880)

*No argument is conclusive: motivates an experiment!*

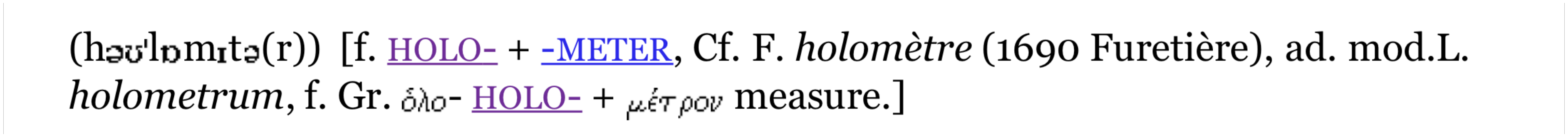
# The Fermilab Holometer

*We are developing a machine specifically to probe the Planck scale:*

*“Holographic Interferometer”*



*Spacetime diagram of an interferometer*



(həʊˈlɒmɪtə(r)) [f. HOLO- + -METER, Cf. F. *holomètre* (1690 Furetière), ad. mod.L. *holometrum*, f. Gr. ὁλο- HOLO- + μέτρον measure.]

**1696** PHILLIPS (ed. 5), *Holometer*, a Mathematical Instrument for the easie measuring of any thing whatever, invented by Abel Tull. **1727-41** CHAMBERS

# Strategy for Our Experiment

## Direct test for the holographic noise

- Positive signal if it exists
- Null configuration to distinguish from other noise

## Sufficient sensitivity

- Provide margin for prediction
- Probe systematics of perturbing noise

## Measure properties of the holographic noise

- Frequency spectrum
- Spatial correlation function

# Correlated holographic noise in nearby interferometers

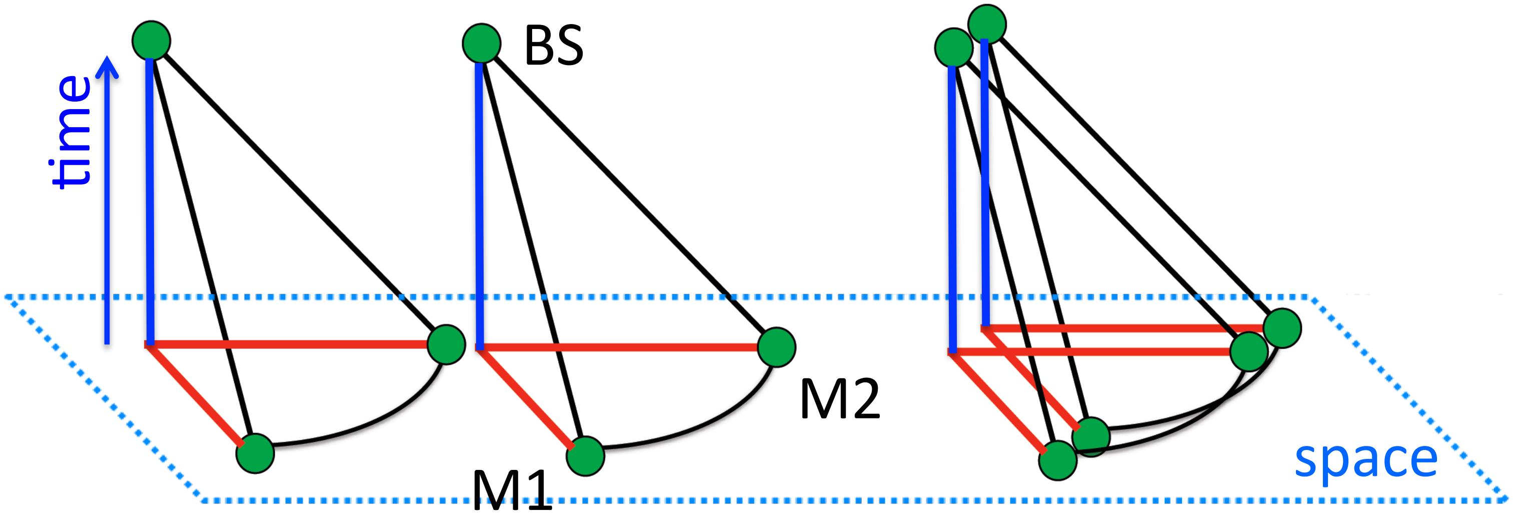
Matter on a given null wavefront "moves" together

- no locally observable jitter should depend on remote measurements
- phase uncertainty accumulates over ~*L*
- Nearby clocks with same orientation agree

Spacelike separations within causal diamond must collapse into the same state (i.e., clock differences must agree)

*Nonoverlapping spacetime volumes, uncorrelated noise*

*overlapping spacetime volumes, correlated holographic noise*



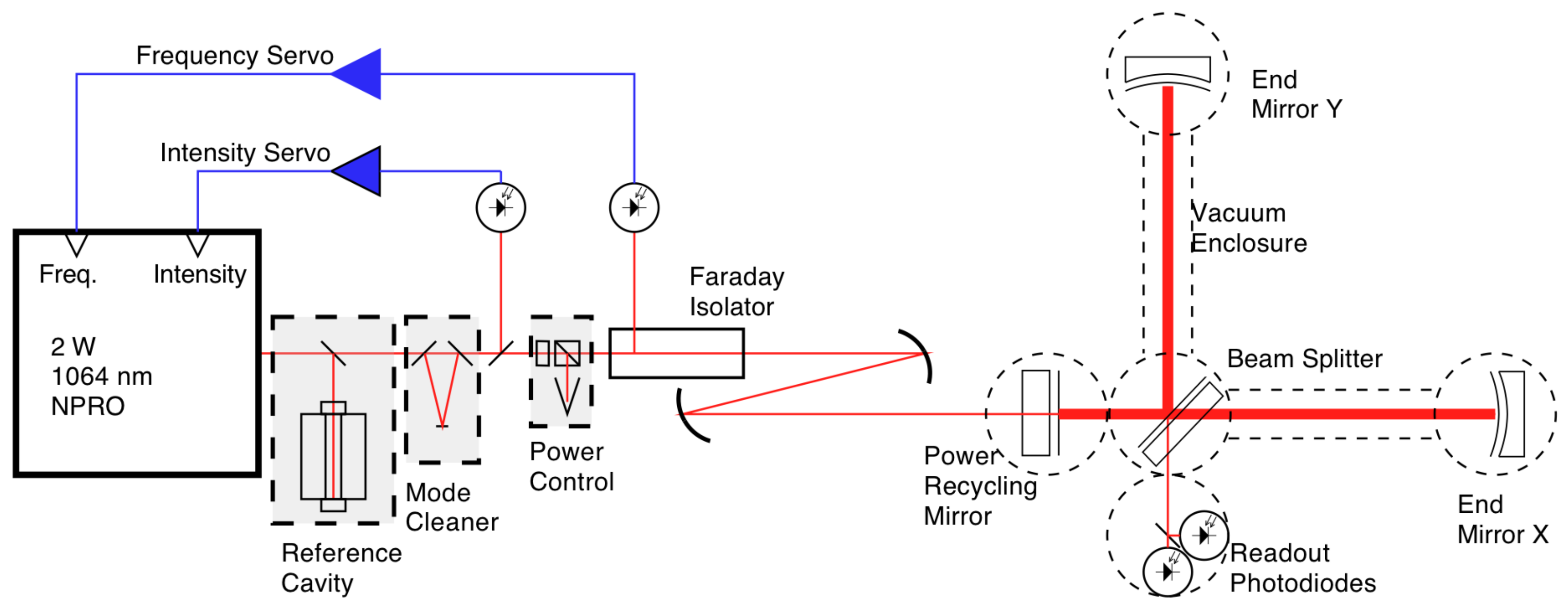
# Experiment Concept

Measurement of the correlated optical phase fluctuations in a pair of isolated but collocated power recycled Michelson interferometers

exploit the spatial correlation of the holographic noise

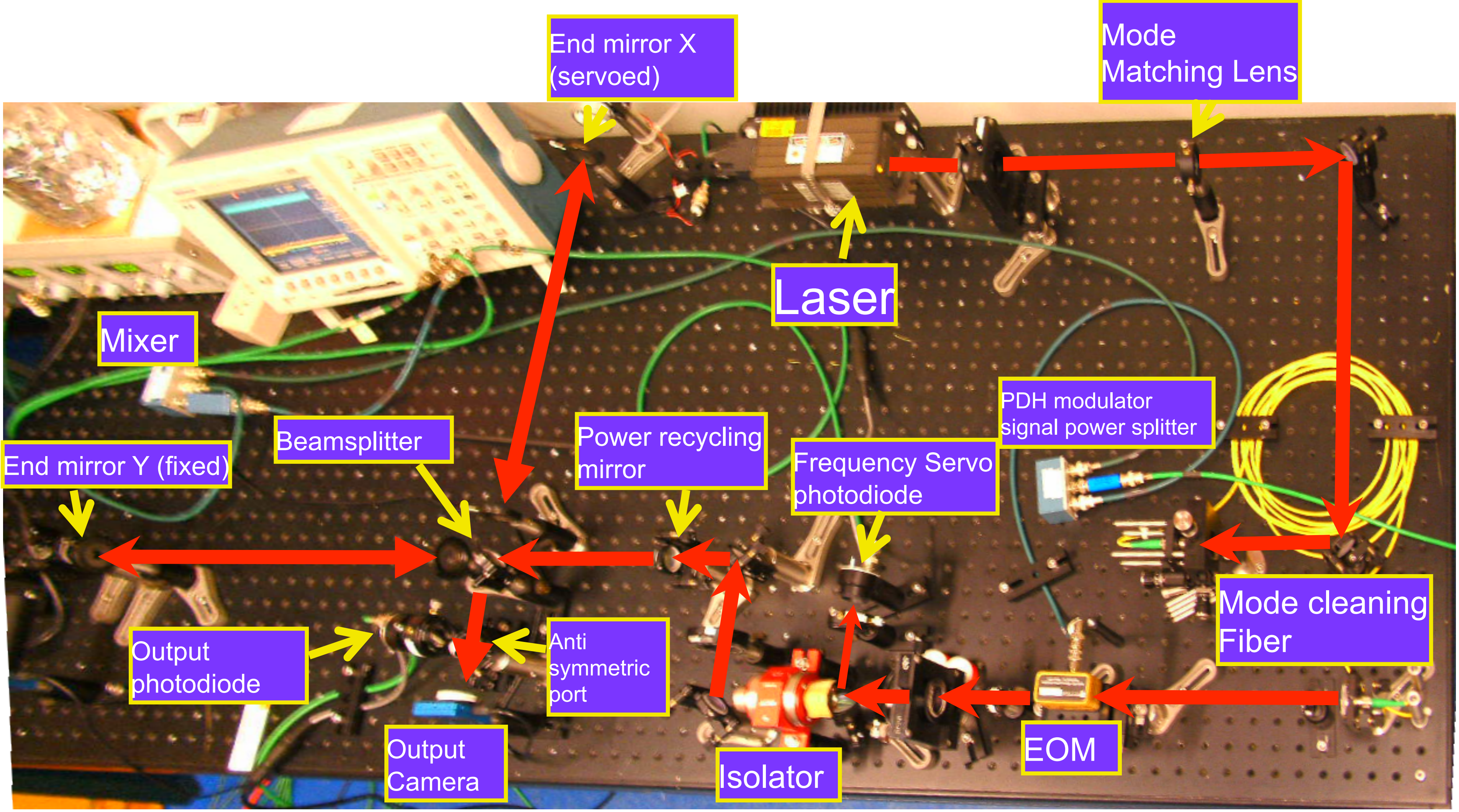
use the broad band nature of the noise to measure at high frequencies (MHz) where other correlated noise is expected to be small

# Optical layout of each interferometer: standard power-recycled Michelson



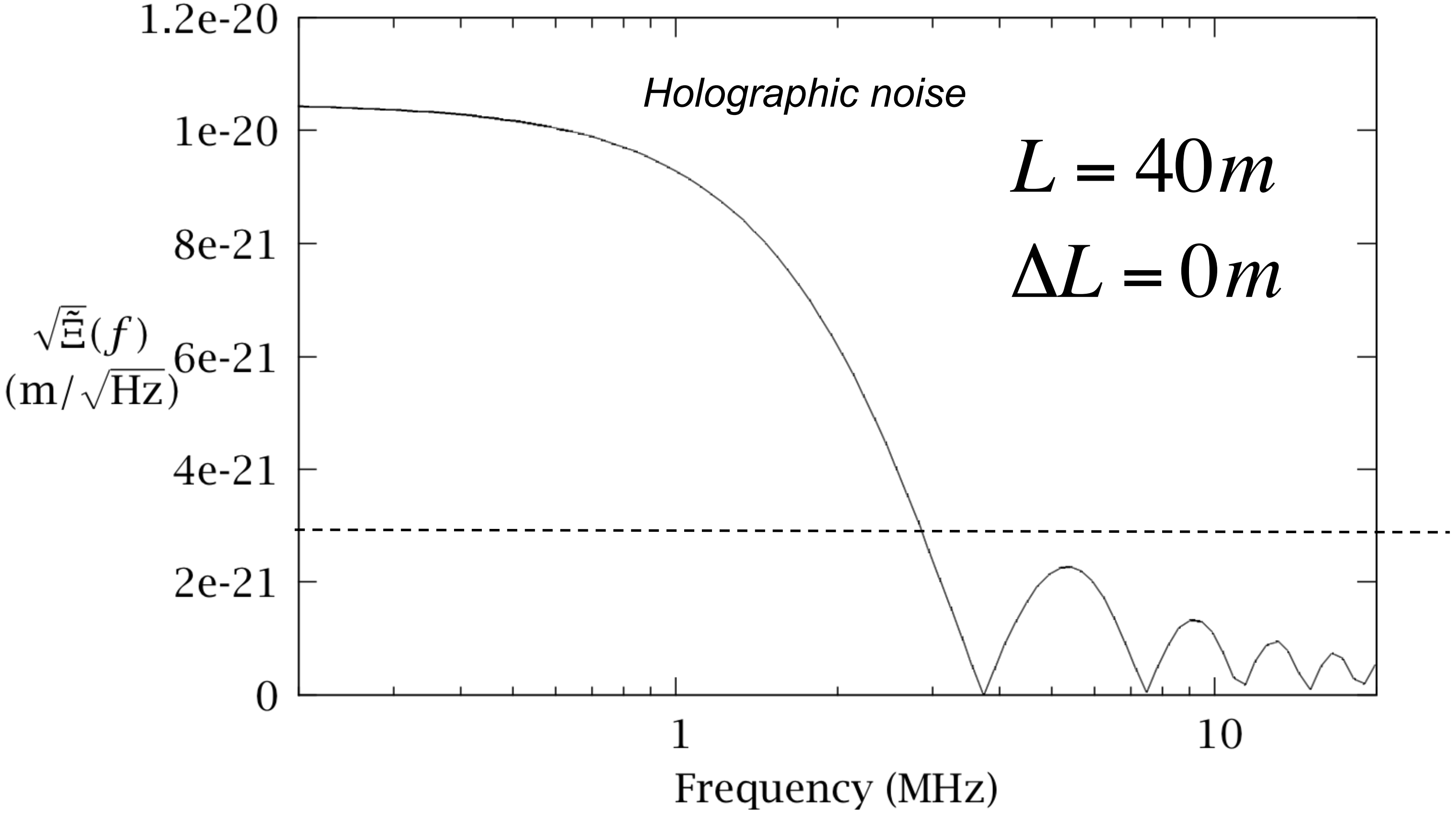
*S. Waldman, MIT*

# Table-top prototype power-recycled Michelson interferometer in the Fermilab Linac lab



# Predicted Planck-amplitude frequency spectrum

$$\tilde{\Xi}(f) = \frac{c^2 2t_P}{\pi(2\pi f)^2}[1 - \cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$

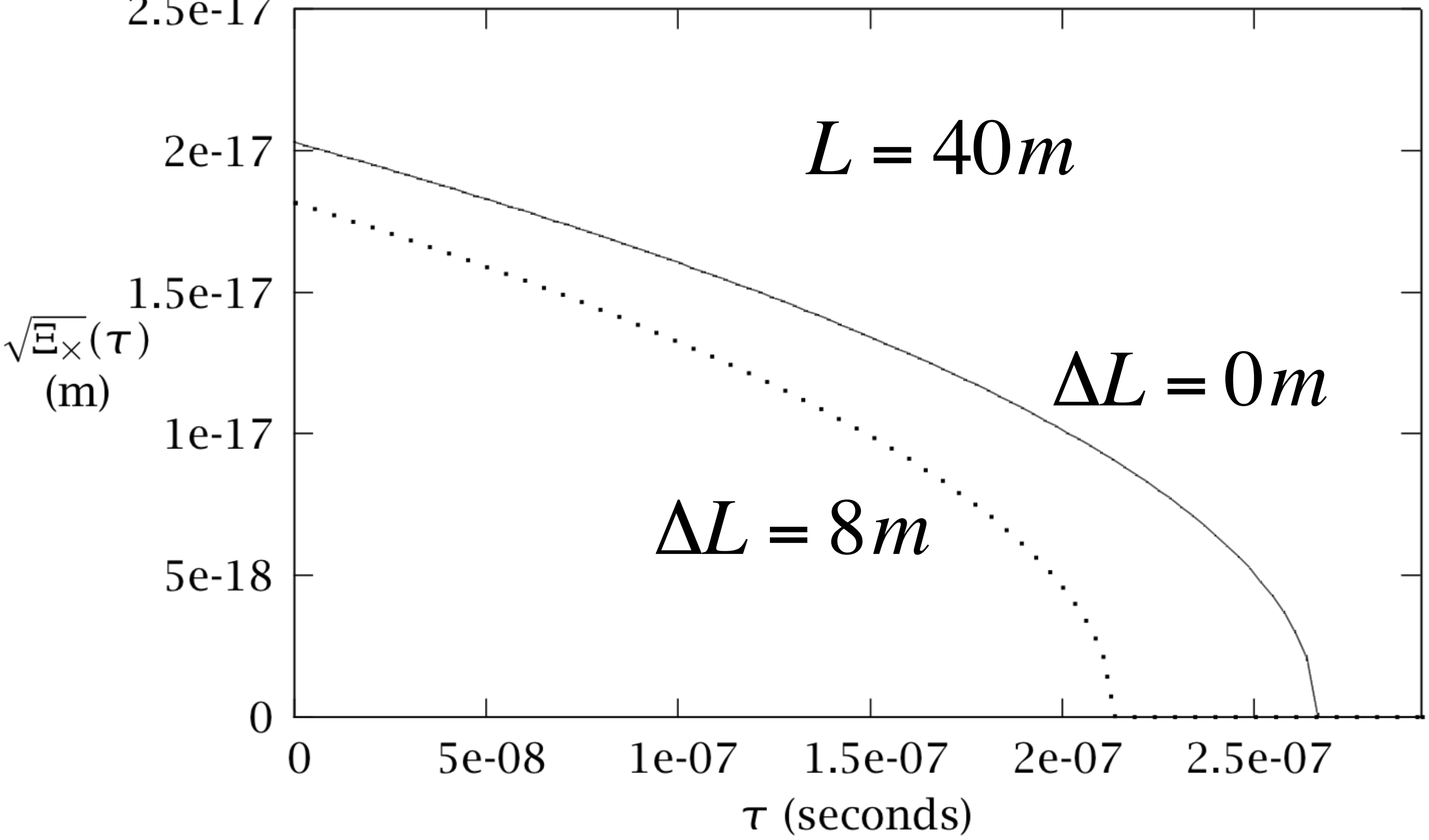


*Correlated shot noise after ~10 hour run*

# Predicted time-domain correlation, decorrelation

$$
\begin{aligned}
\Xi_\times(\tau) &\approx (\lambda_P/\pi)(2L - 2\Delta L - c\tau), \qquad 0 < c\tau < 2L - 2\Delta L \\
&= 0, \qquad c\tau > 2L - 2\Delta L.
\end{aligned}
$$

*Holographic noise for two configurations*



# P-990 History

- May, 2009:  Meeting at Hannover (Geo600)
- Conceptual design at presented at June 2009 PAC meeting
- Summer 2009: tabletop optics, electronics systems developed; funding from FRA
- November, 2009 FNAL PAC proposal:  $1.55M construction + $1.53M 3-year operations in rented warehouse, starting June, 2010.  PAC recommends that lab ”proceed expeditiously”  after theory review
- March, 2010:  ”plan B”begins – full-scale cavity R&D on site
- Short-term Goal:  operational 1d 40 meter prototype cavity complete by September 1, 2010.
- Longer term: all components of final machine tested on site

# Goals for Holometer R&D

- Build experience, validate approach, verify performance and quality of vacuum, optics, detectors, electronics
- In stages:
  1. One 40-m moderate finesse cavity
  2. Upgrade optics and (possibly) mechanical mounts for higher finesse
  3. 1 bent interferometer inside
  4. 2 bent interferometers inside
  5. Extend in 2D, ”out the roll up door” of MP

# Short-term schedule for Holometer R&D

- Mid May:  MP tunnel, south of MP8, cleaned, interlocked for laser safety
- Mid June: Vacuum parts arrive; all other components for moderate finesse 1D cavity available for integration.
- Study completed by September 1.
- Ongoing:  evaluation of performance; use resources to implement following phases if possible.

# Leading the Field

- Only GEO600 has the sensitivity to see this effect, but can not modulate it.
- LIGO has power recycling in each arm (to enhance sensitivity to gravitational waves) so it approx 200 times less sensitive.
- A brief run of nearly colocated interferomers at LIGO (H1,H2) is under analysis, but also does not have competitive sensitivity
- Our design yields good s/n in hours; modulate with same apparatus to confirm.

# FNAL involvement/future

- Theory: Craig building international collaboration
- Technical: site and infrastructure for R&D; vacuum expertise; laser operations experience (GammeV, etc.)
- Management: funding, project management, safety.
- We will either set the first experimental limit at the Planck scale, or open a new field of research.

# Community/Why FNAL?

world class collaborators:

Rai Weiss (COBE and LIGO), Sam Waldman (LIGO) from MIT;
Stephan Meyer (co-PI; CMB) U Chicago/KICP;
Stan Whitcomb (LIGO) CalTech;
Dick Gustafson (LIGO, GammeV) U Mich.

Although this is a "small" project at FNAL, it is too large for a single university group.
The infrastructure of a national laboratory is essential.

# Backup slides

# Report from the Fermilab Physics Advisory Committee November 2009

"The Committee reviewed the updated proposal —"The Fermilab Holometer: A Program to Measure Planck Scale Indeterminacy" — to perform an experiment to detect holographic noise. A pair of laser interferometers would be used to search for the predicted spatial fluctuations and disentangle them from other noise sources. Specifically, holographic noise must be correlated in a pair of co-located interferometers, and would vanish when the interferometers are spatially separated by more than their size. To the best of our knowledge, the type of noise the holometer is sensitive to has not been excluded by other experiments. The Committee reasserts that the Planck scale physics addressed by this proposal fits squarely in the intellectual mission of the Laboratory. If the experiment were successful in detecting holographic noise, it would be a ground-breaking discovery. In addition, the transfer of optical cavity expertise to Fermilab may be important for other Laboratory experiments (e.g., for a future axion experiment). Therefore the proposed experiment would be a coherent addition to the Fermilab particle-astrophysics and particle-physics programs. The experiment has no known comparable dual-interferometer competitor at this time. The sensitivity of the single interferometer, GEO600, is close to the appropriate level of sensitivity, and it may be possible for it to rule out holographic noise at the predicted level. The Fermilab experiment is challenging, but the Fermilab Holometer Collaboration is experienced–with members also drawn from LIGO and GEO600. The Fermilab role in the proposed holometer is unique, important, and significant."

# Report from the Fermilab Physics Advisory Committee (continued)

“The Committee re-asserts that it is important that members of the external theory community be given an opportunity to comment on the theoretical basis for the proposed measurement. The concept of the inferred holographic fluctuations of the relative position of macroscopic objects is based on plausible arguments about information limits in the quantum definition of space. However, the concept unfortunately is not grounded in a fundamental theory. No agreement has yet emerged in the theory community about the soundness of the hypothesis under test. In addition, there is no active engagement of scientists outside the proposing group in refining the theoretical framework. Accordingly, the Committee recommends that a critical review of the theory underpinning this proposal be undertaken by the external theory community. If this review were to be positive, the Committee recommends that the Laboratory proceed expeditiously with the proposed Fermilab Holometer.”