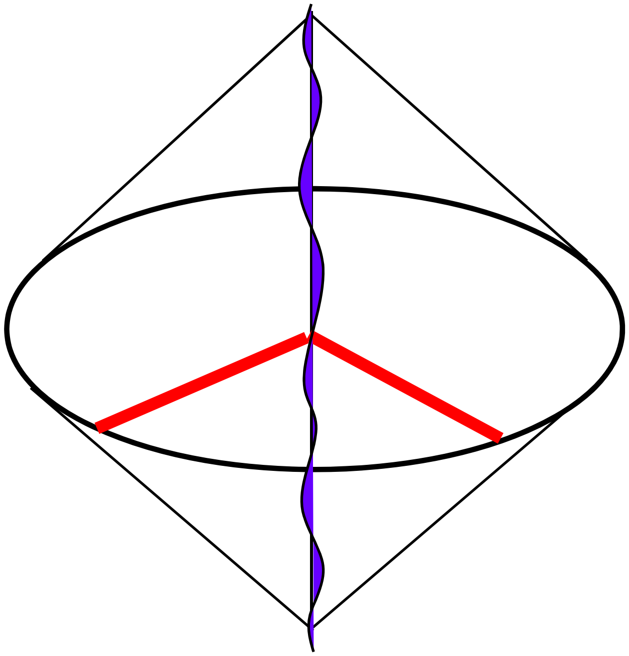
Planck Scale Physics in the Laboratory



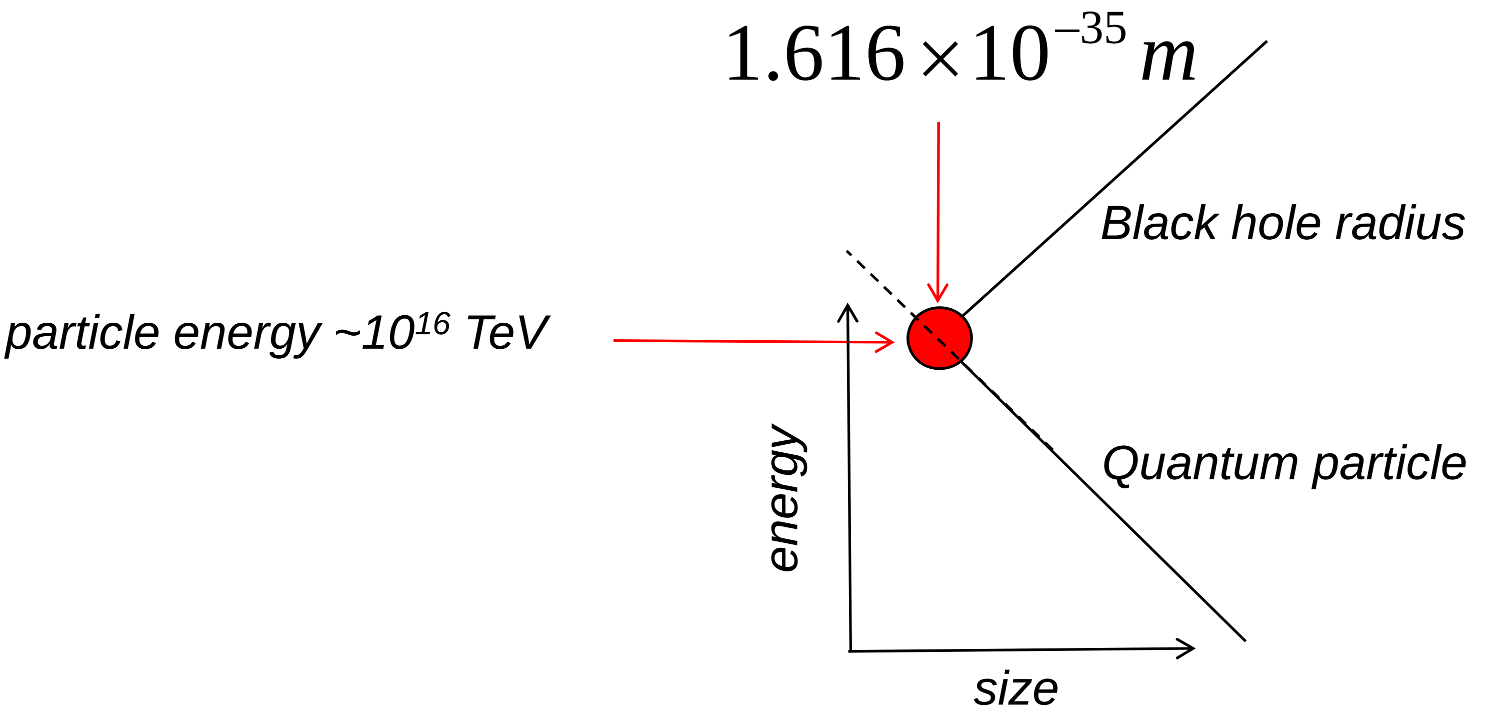
Craig Hogan

University of Chicago and Fermilab

Planck scale

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

The physics of this "minimum time" is unknown



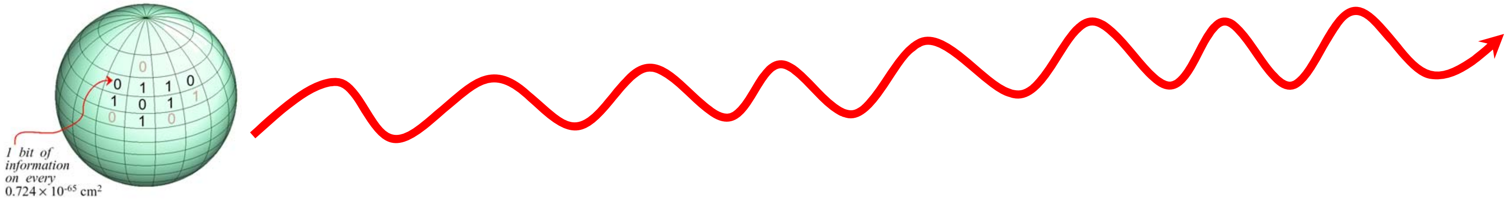
Particle confined to Planck volume makes its own black hole

Black Hole Evaporation: a clue to unification

Hawking (1975): black holes slowly radiate particles, lose energy

convert “pure spacetime” into normal particles like light

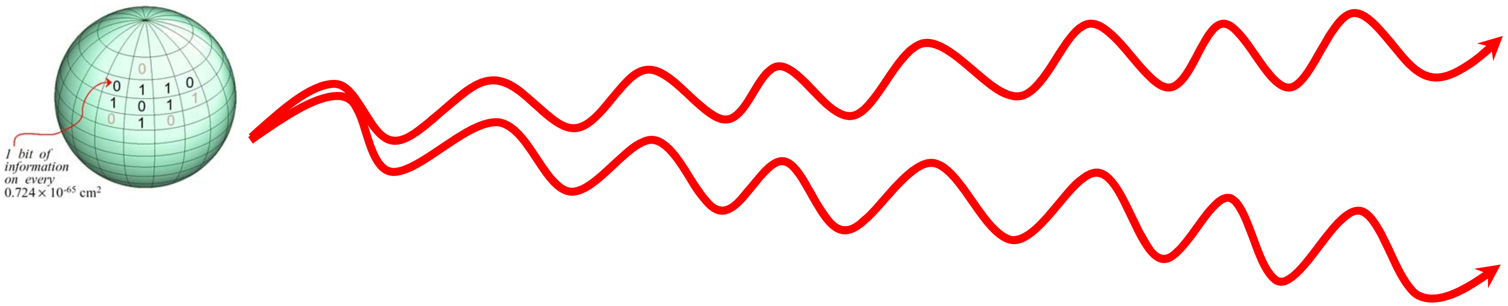
number of particles ~ entropy ~ area of the surface in Planck units



Initial state: black hole

Final state: particles

Number of initial and final states must match

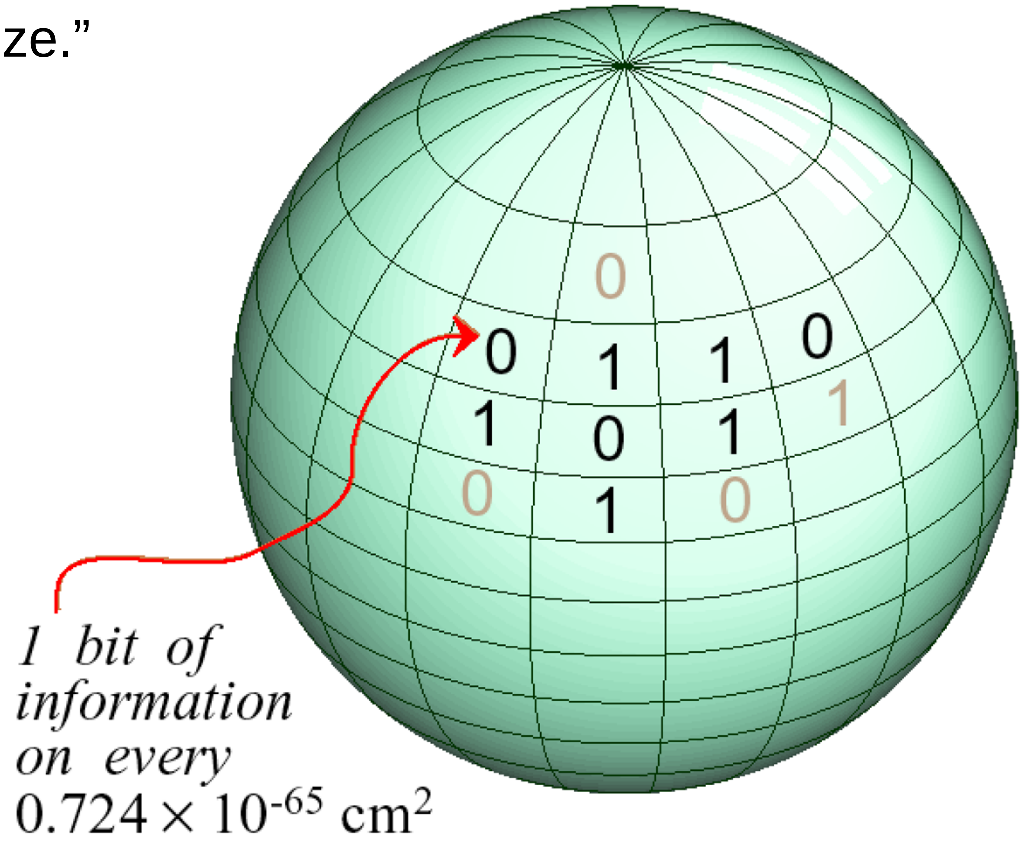


calibrates the number of quantum degrees of freedom of spacetime : no parameters

One way to implement a minimum length: holography

"This is what we found out about 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



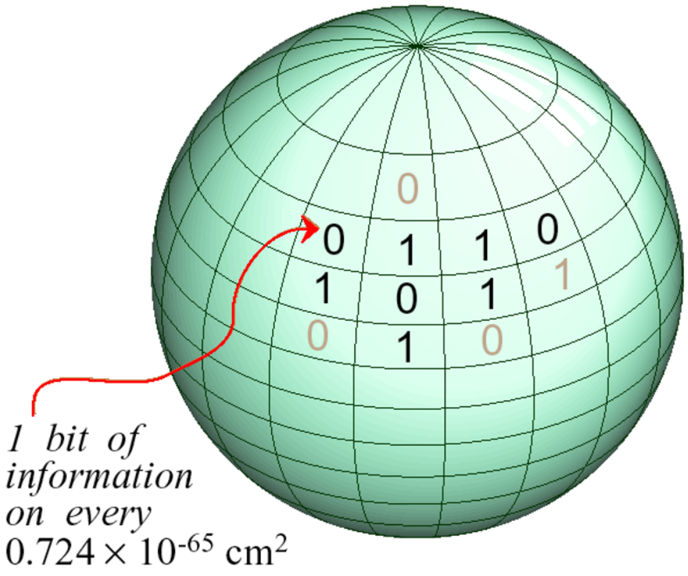
Holographic Principle

Black hole evaporation

covariant entropy bound

AdS/CFT dualities in string theory

Matrix theory



1 bit of information on every 0.724 × 10^{-65} cm^2

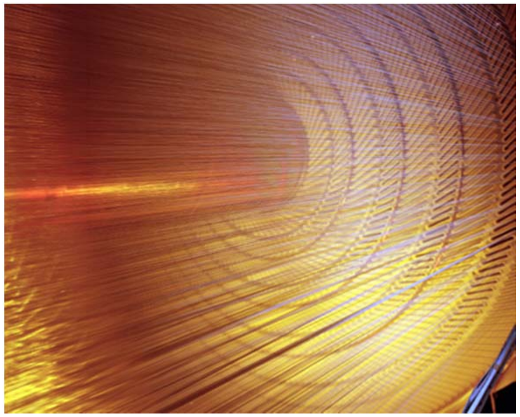
All suggest theory on 2+1 D null surfaces with Planck scale bound

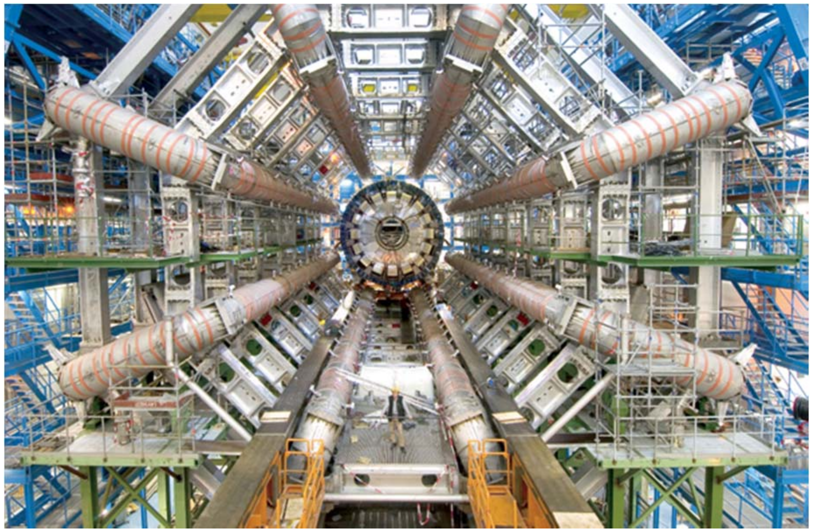
But there is no agreement on what it means for experiments

Bekenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Banks, Fischler, Shenker, Unruh

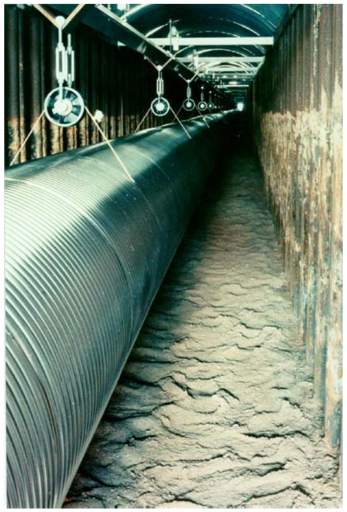
Two ways to study small scales

CERN and Fermilab particle colliders rip particles into tiny pieces—tiny, but not small enough





Interferometers measure collective phase of coherent light; sense jitter in position



Interferometers might probe Planck scale physics

One interpretation of the Planck limit predicts a detectable effect:

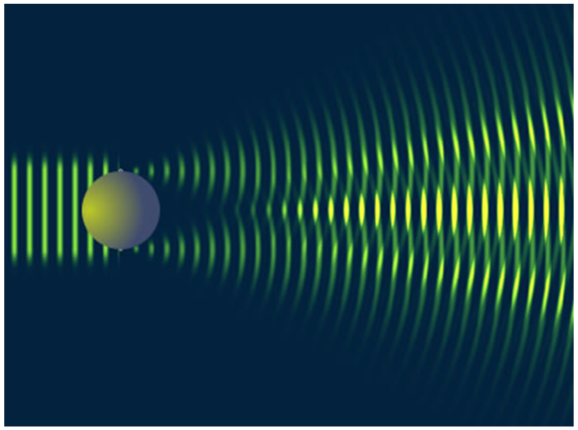
"holographic noise"

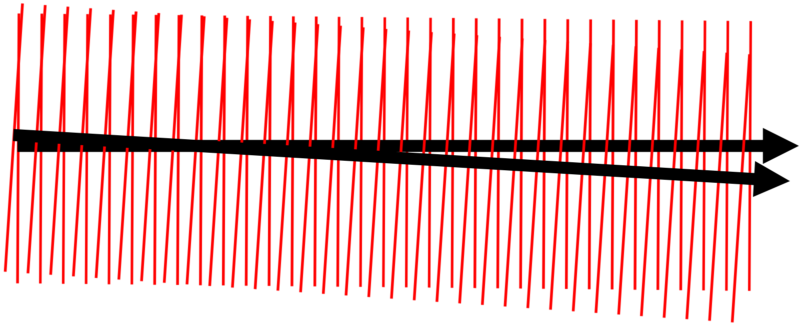
Different from gravitational waves or quantum field fluctuations

Planck-amplitude noise spectrum with no parameters

We are developing an experiment to test this hypothesis

A new uncertainty of spacetime?





Posit Planck maximum frequency in any direction

Then transverse positions may be fundamentally uncertain by Planck diffraction limit >> Planck length

Classical direction ~ ray approximation of a Planck wave

Holographic interpretation of noncommutative geometry

Matter, radiation, metric all remain classical

But position operators obey Planckian quantum conditions

Positions in different directions drift apart like a Planck random walk

Matter position measured with radiation

Positions measured in different directions do not commute; decohere by about a Planck time per Planck time

Nearby waves in the same direction agree, but decohere with separation

“Holographic” interpretation of noncommutative geometry:

$$[\hat{x}_i, \hat{x}_j] = i(Cct_P)^2\theta_{ij}$$

CJH: arXiv:1002.4880

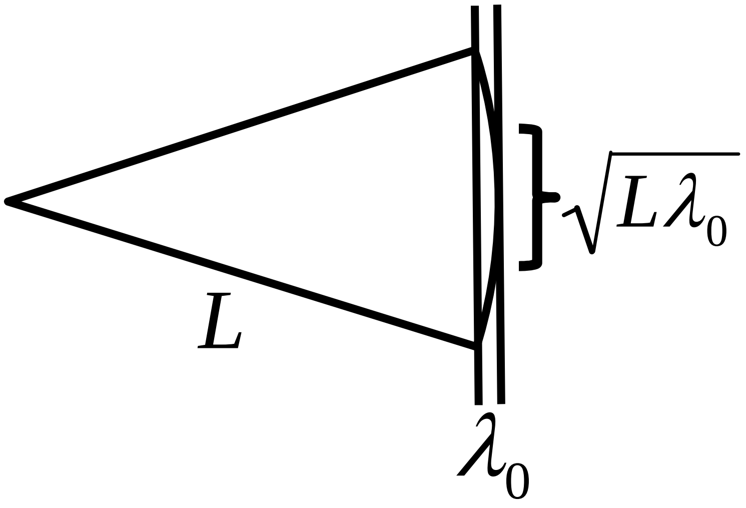
Quantum limits on measuring event positions

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 transverse dimension: small phase difference of events over large transverse patch

Bandwidth interpretation of holographic bound

Hypothesis: observable correlations between light sheets are limited by the information capacity of a Planck frequency carrier: Planck bandwidth limit,

$\approx 10^{44}$ bits per second

Predicts position uncertainty at “Planck diffraction scale”

Allows calculation of experimental consequences

Matter jitters about classical geodesics defined by massless fields

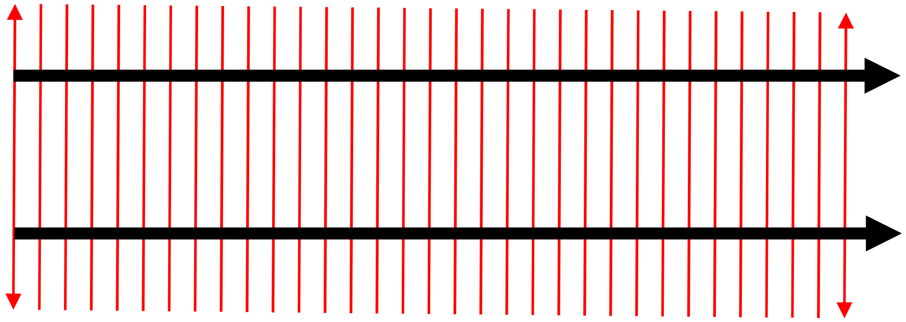
~ Planck length per Planck time

Only in the transverse (in-wavefront) directions

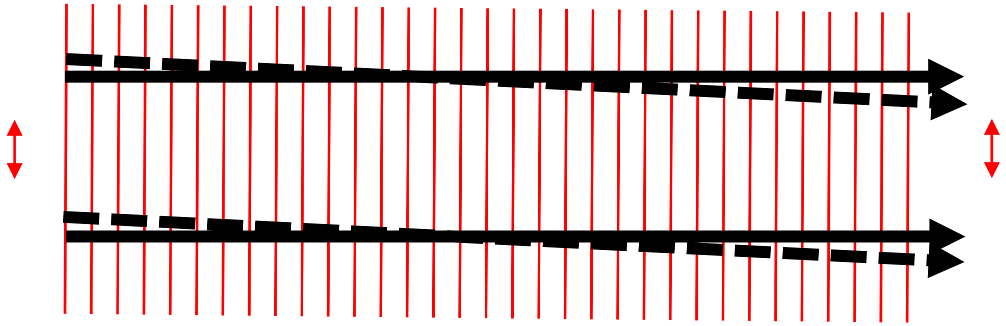
Quantum effect: state depends on measurement

Coherent phase gives coherent transverse jitter on scale L

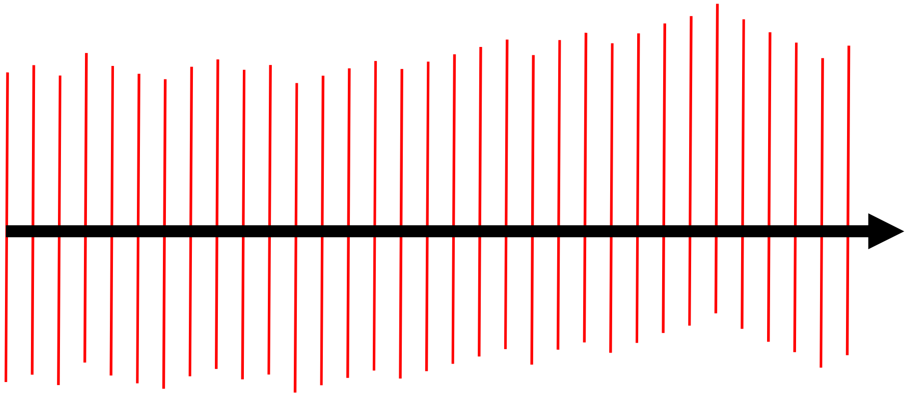
Rays in direction normal to Planck wavefronts



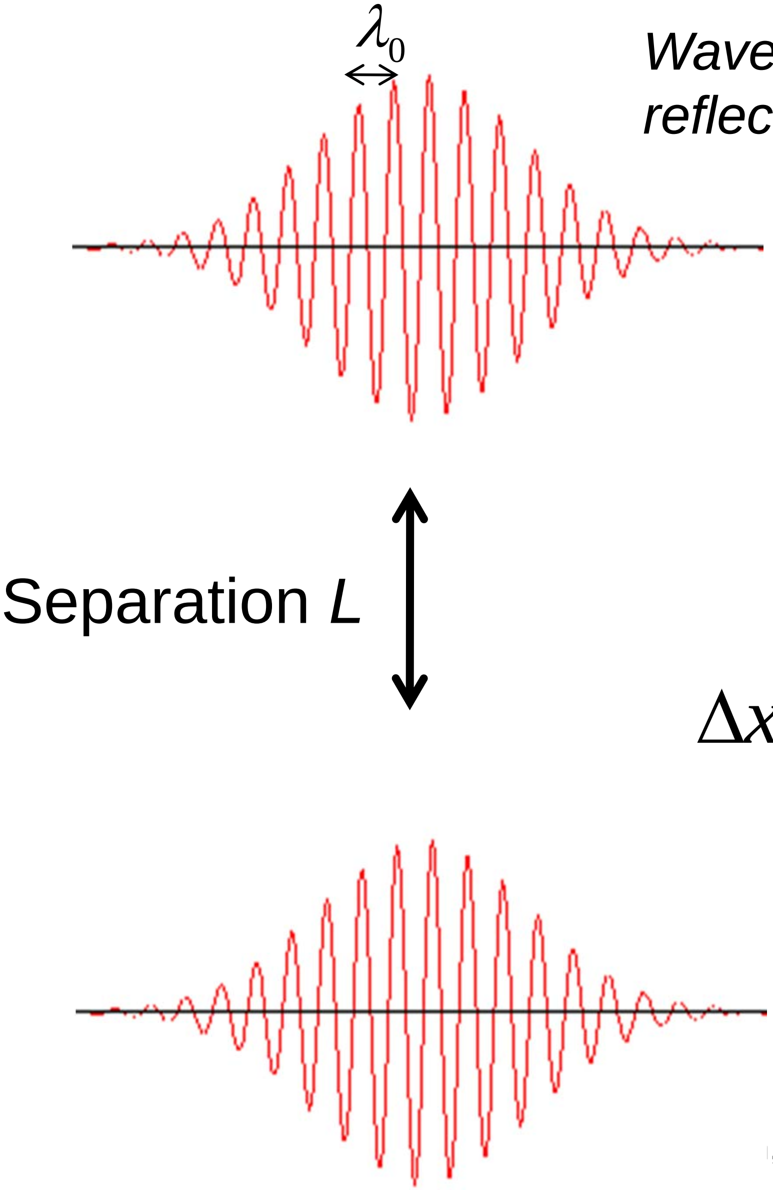
Localize in wavefront: transverse momentum uncertainty



jitter of position transverse to wavefront: about a Planck length per Planck time



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



Separation *L*

Wavefunction of 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

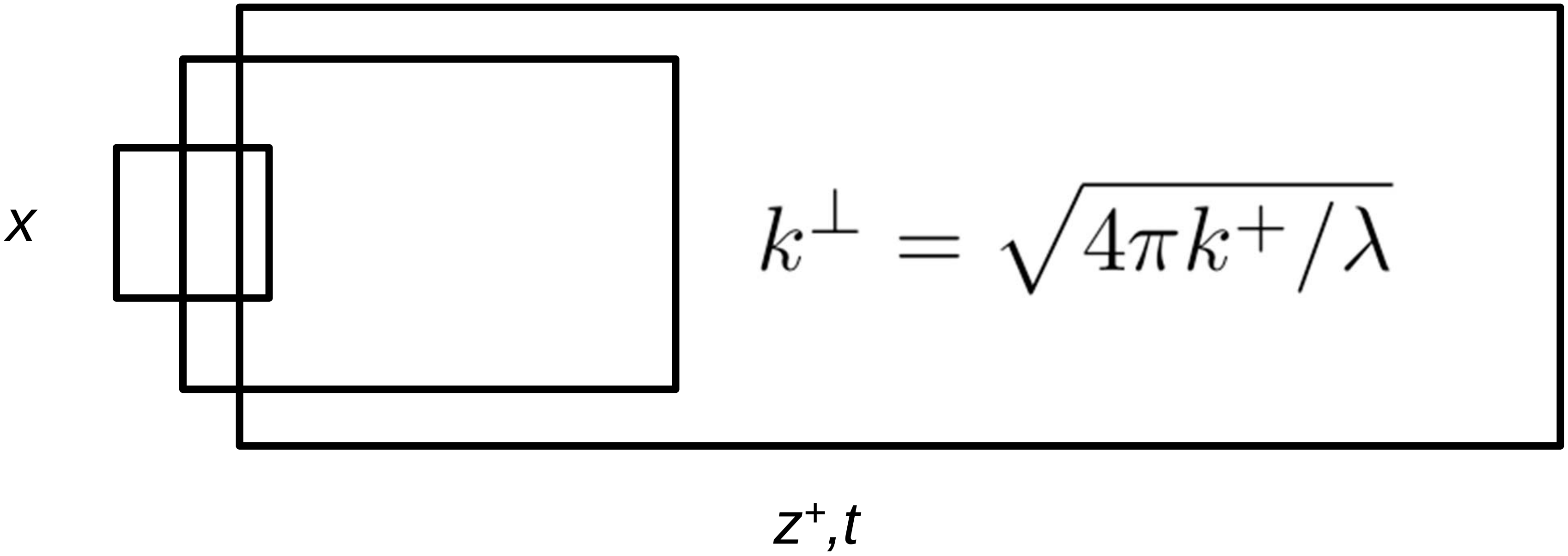
Wave modes mix longitudinal and transverse dimensions

Wavepacket spreading ~ slow transverse diffusion or diffraction

Transverse coherence over macroscopic longitudinal timescale

more ray-like on large scales

not the same as field theory limit



$$k^{\perp} = \sqrt{4\pi k^{+}/\lambda}$$

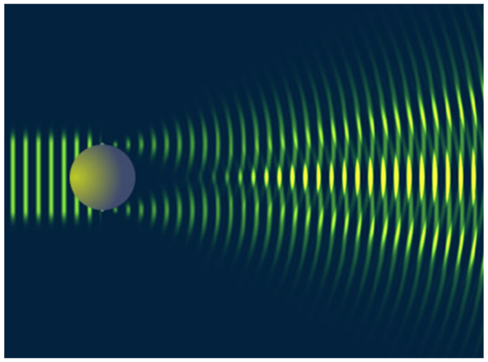
Approach to the classical limit

Angles become **less uncertain** (more ray-like) at larger separations:

$$\Delta\theta^2 > l_P / L$$

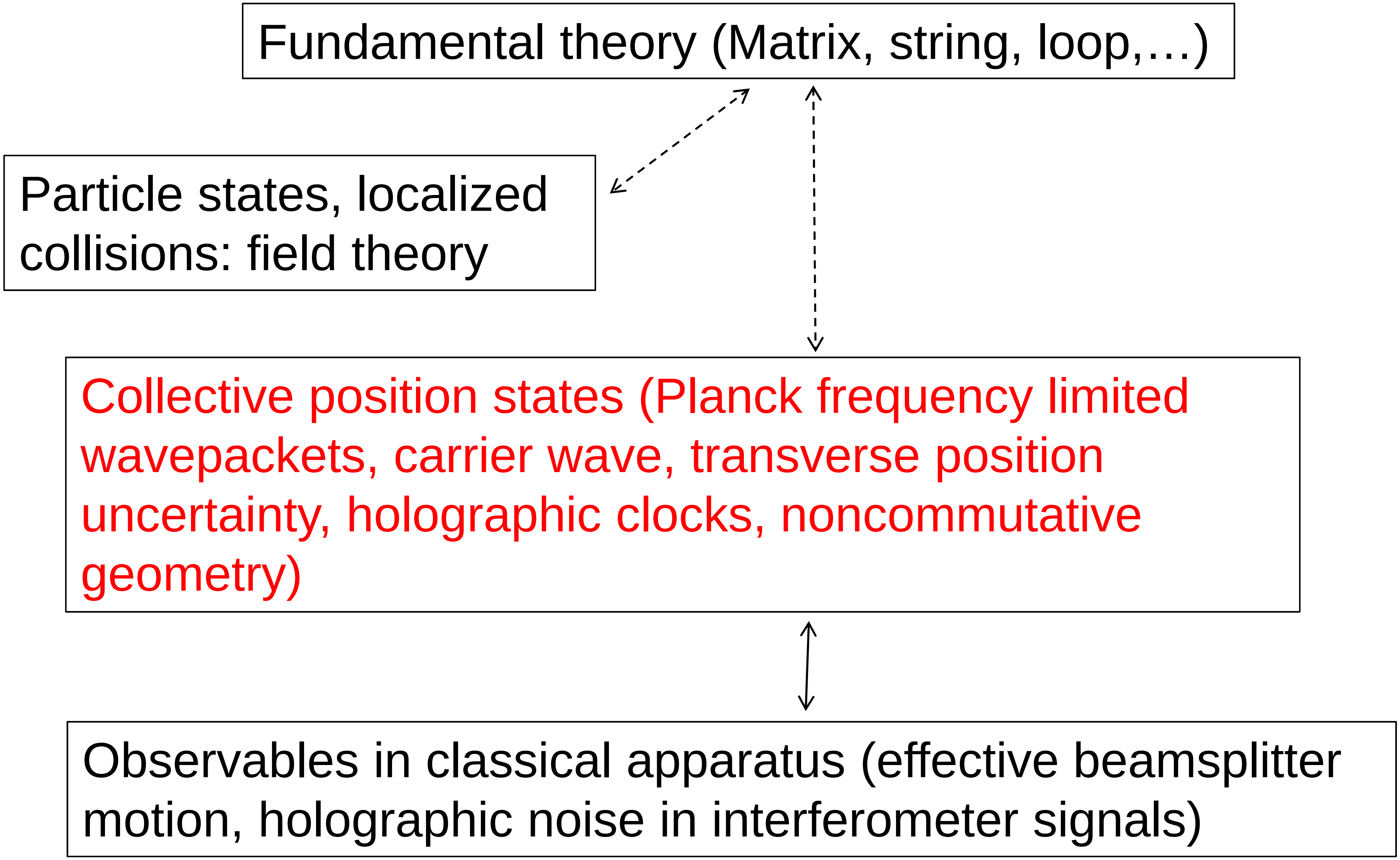
Transverse positions become **more uncertain** at larger separations:

$$\Delta x^2 > l_P L$$



- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

A candidate phenomenon of unified theory



Fundamental theory (Matrix, string, loop,…)

Particle states, localized collisions: field theory

Collective position states (Planck frequency limited wavepackets, carrier wave, transverse position uncertainty, holographic clocks, noncommutative geometry)

Observables in classical apparatus (effective beamsplitter motion, holographic noise in interferometer signals)

Survey of phenomenological theory: **arXiv:0905.4803**

Arguments for new indeterminacy

- Wavepackets with maximum frequency
- Holographic information bounds
- Black hole evaporation
- Matrix theory
- Non-commuting position operators **(arXiv:1002.4880**)
- Noncommutative geometry (Moyal algebra)

Ways to calculate the noise

- Wave optics solutions with Planck carrier
- Planck wavelength interferometer limit
- Precise calibration from black hole entropy

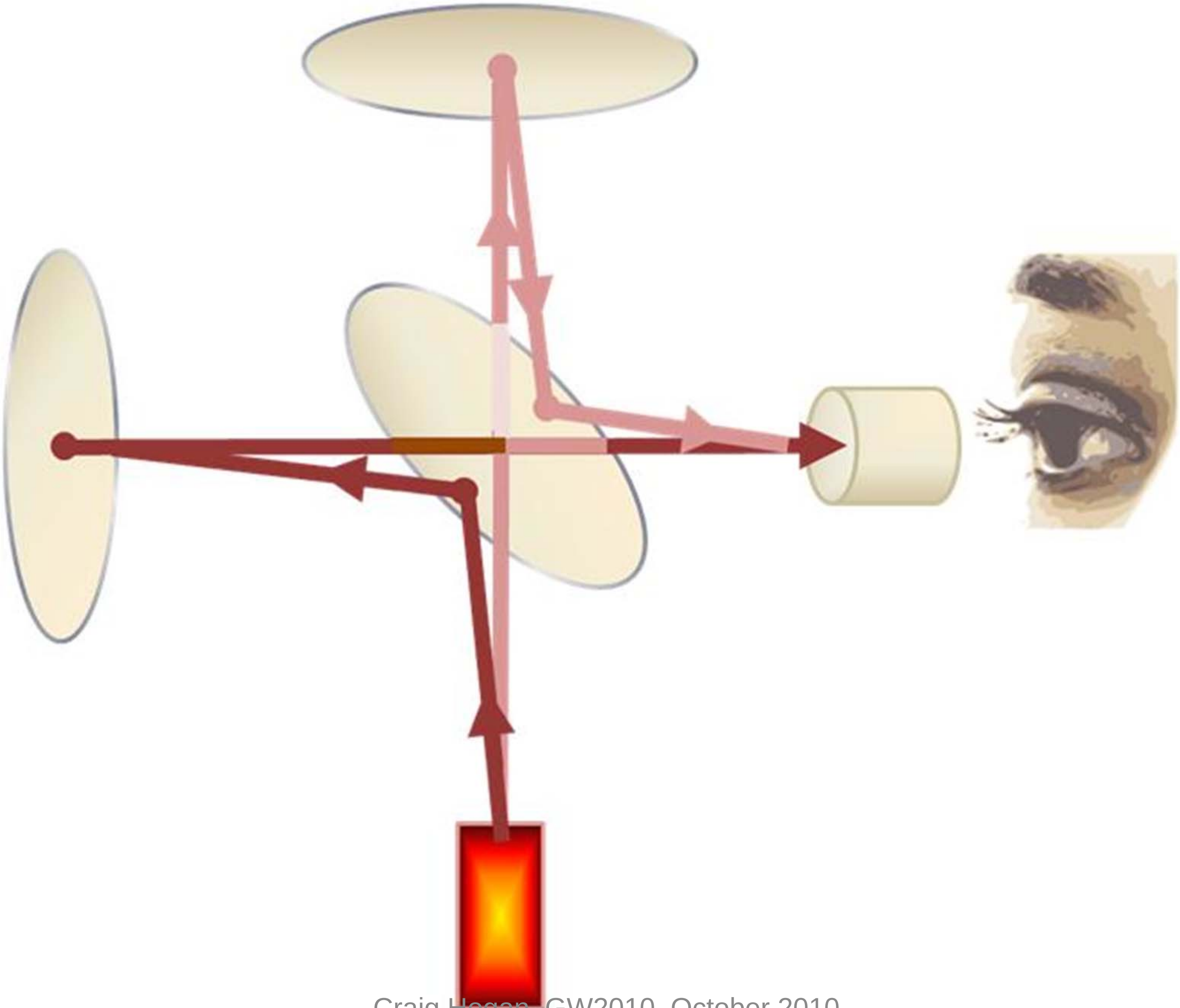
No argument is conclusive: motivates an experiment!

Michelson Interferometers

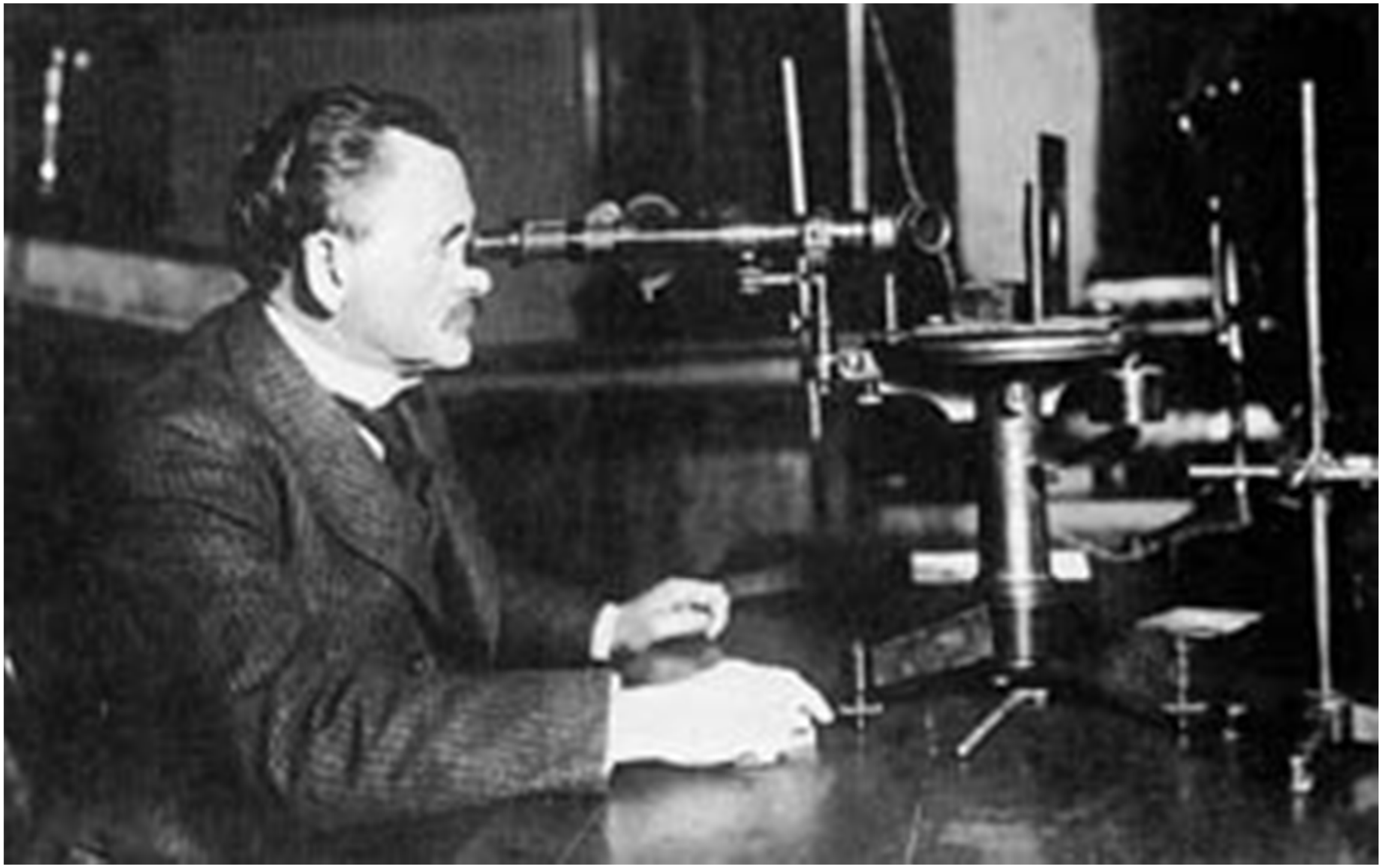
Devices long used for studying spacetime: interferometers

Albert Michelson

Michelson interferometer

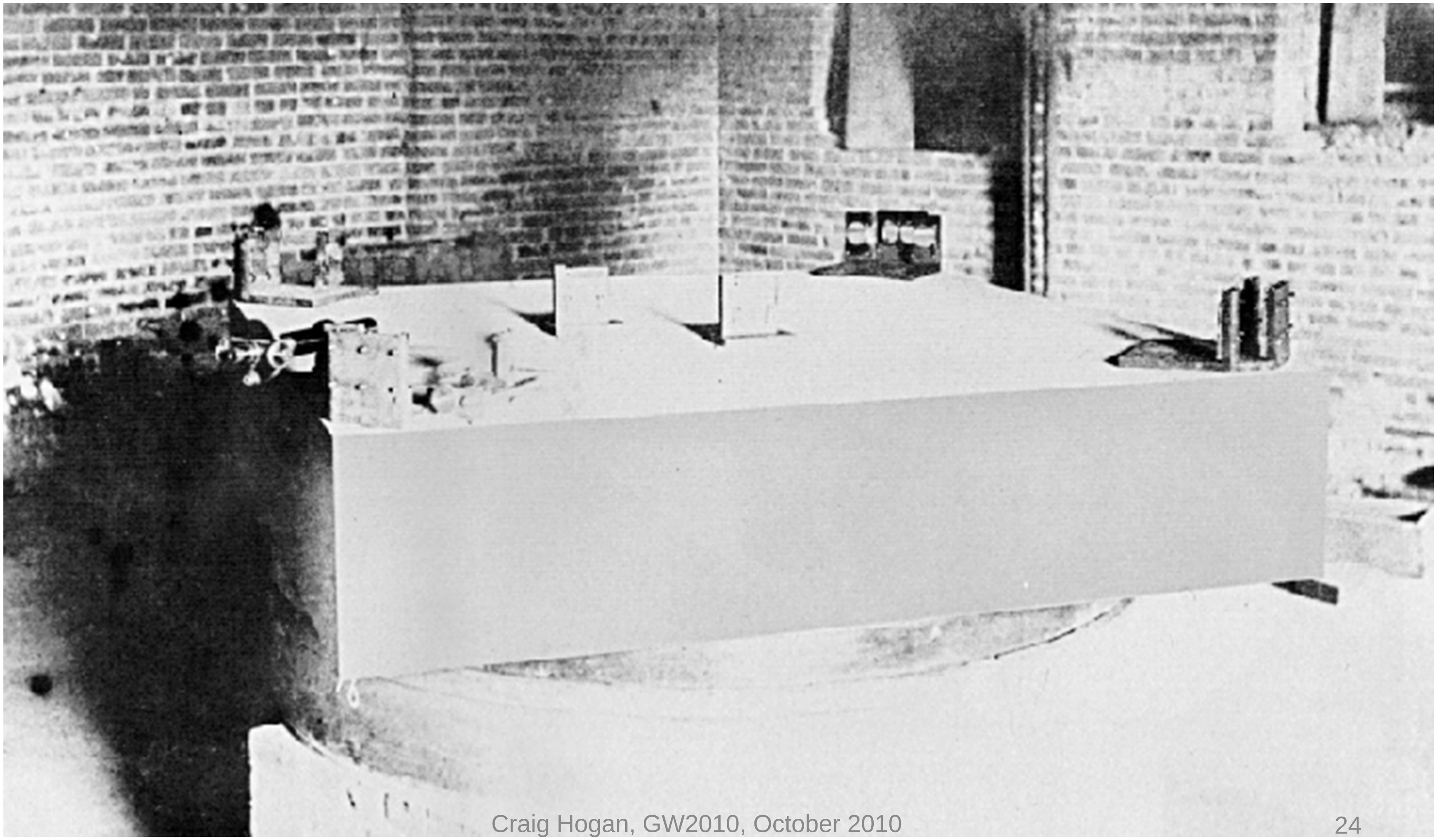


Albert Michelson reading interference fringes



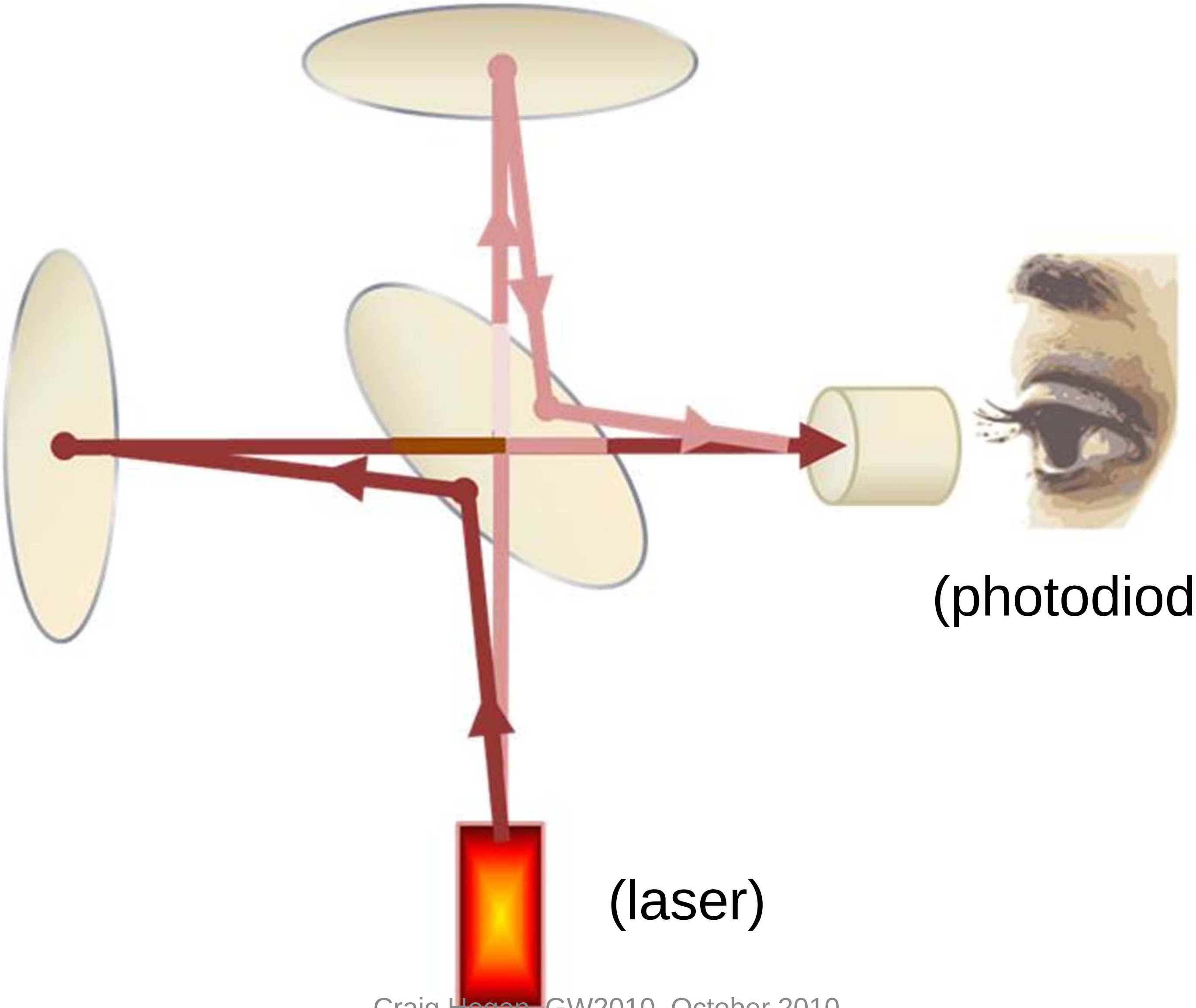
First and still finest probe of space and time

Original apparatus used by Michelson and Morley, 1887



Michelson and team in suburban Chicago, winter 1924, with partial-vacuum pipes of 1000 by 2000 foot interferometer, measuring the rotation of the earth

Michelson interferometers today

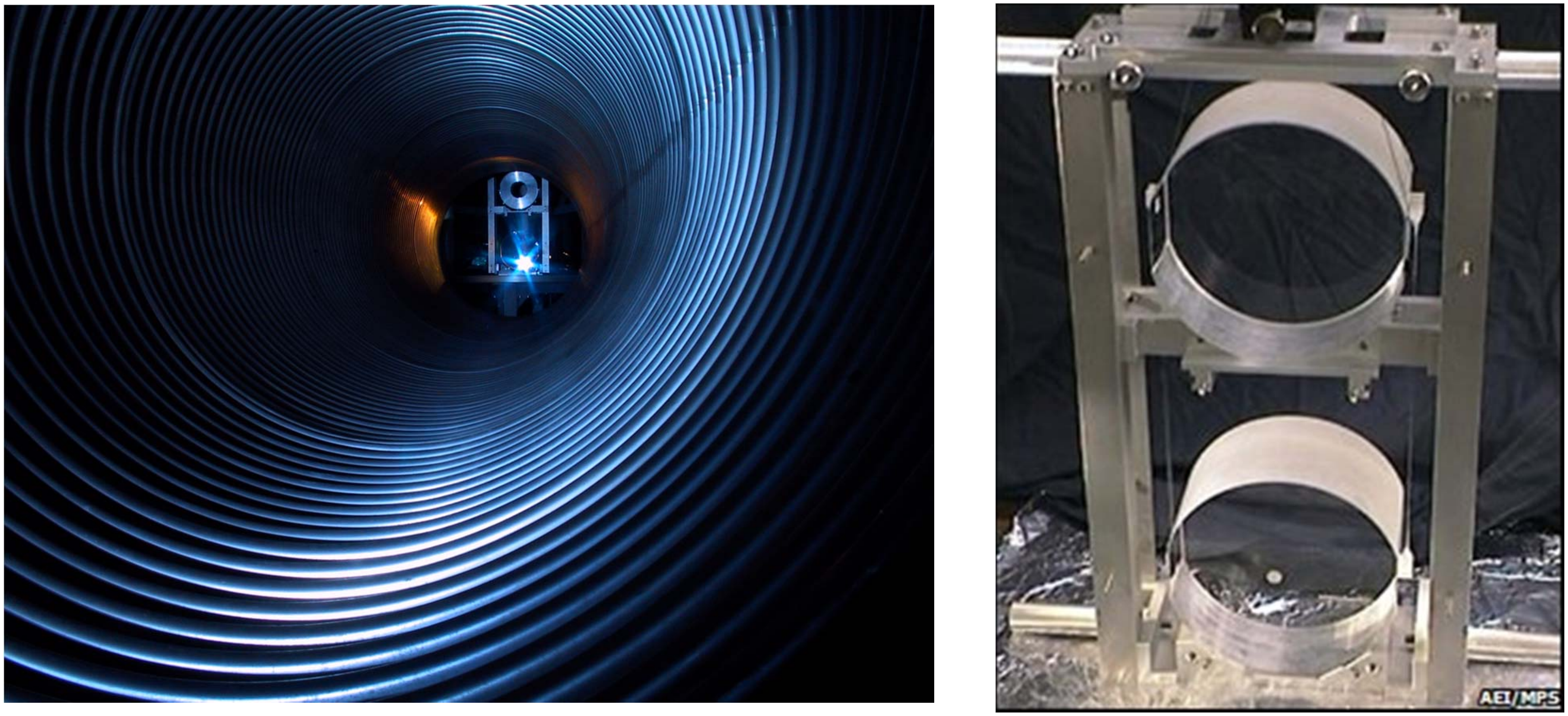


(photodiode)

(laser)

Attometer Interferometry

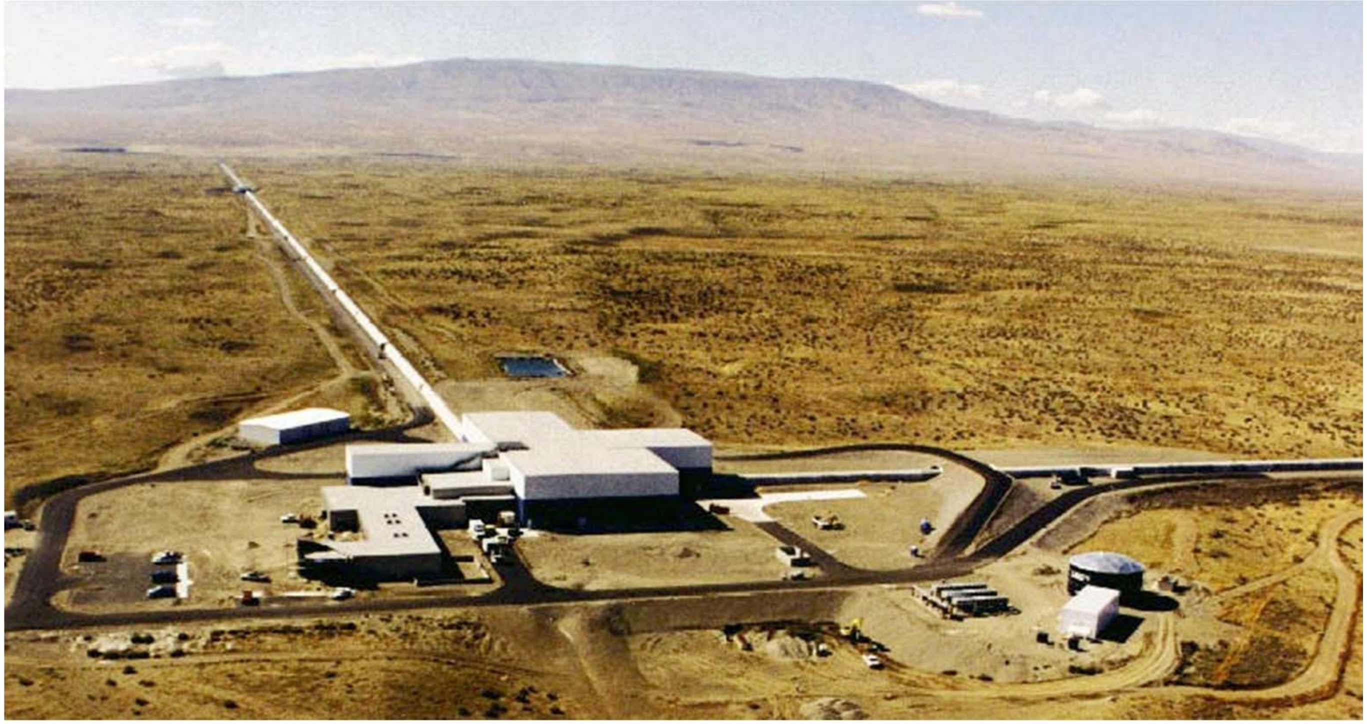
Interferometers now measure transverse positions of massive bodies to $\sim 10^{-18}\, m/\sqrt{Hz}$ *over separations ~*10^3 *m*



GEO600 beam tube and beamsplitter

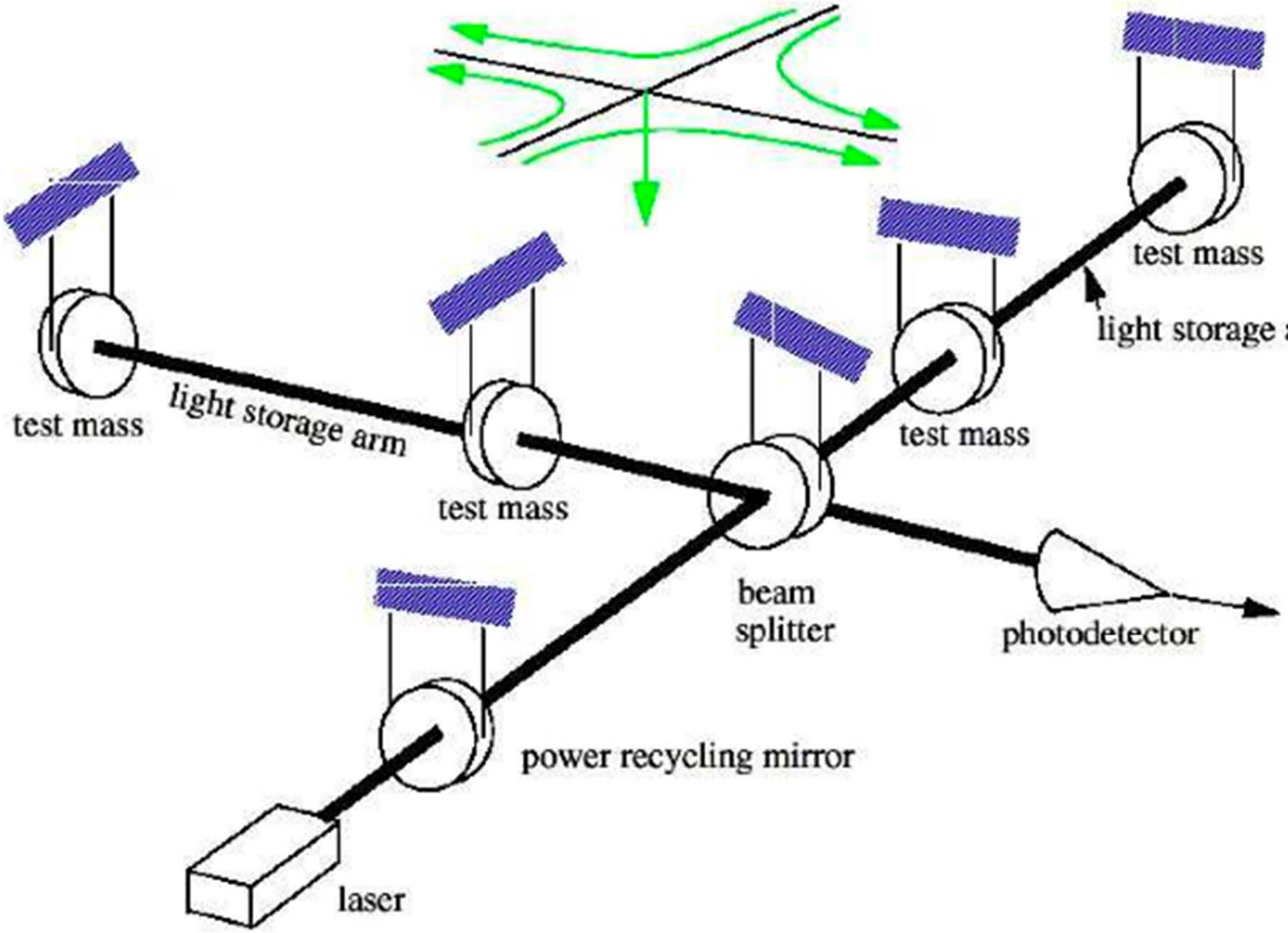
GEO-600 (Hannover)

LIGO: Hanford, WA and Livingston, LA

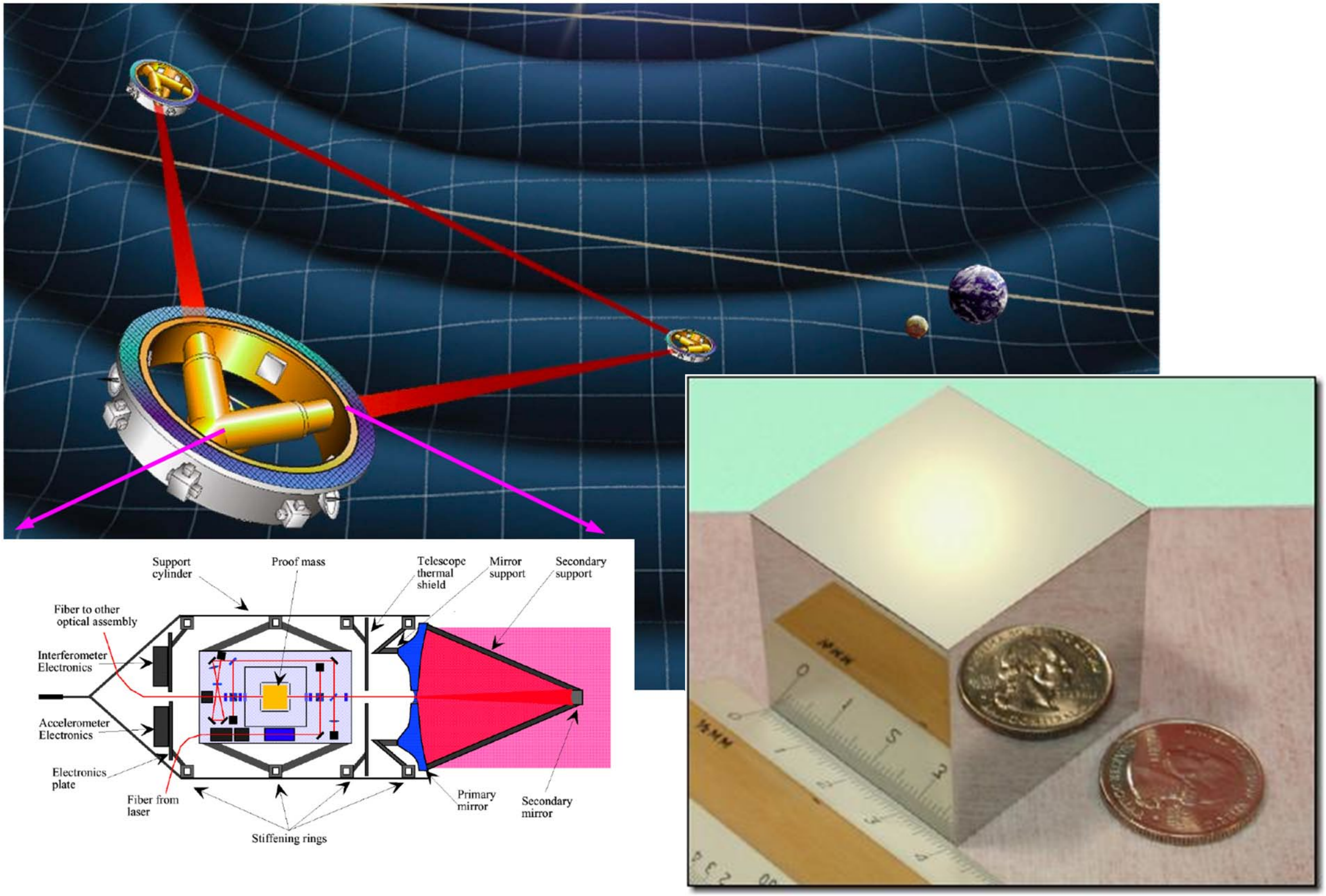


Designed for gravitational waves at audio frequencies (50 to 1000 Hz)

LIGO interferometer layout



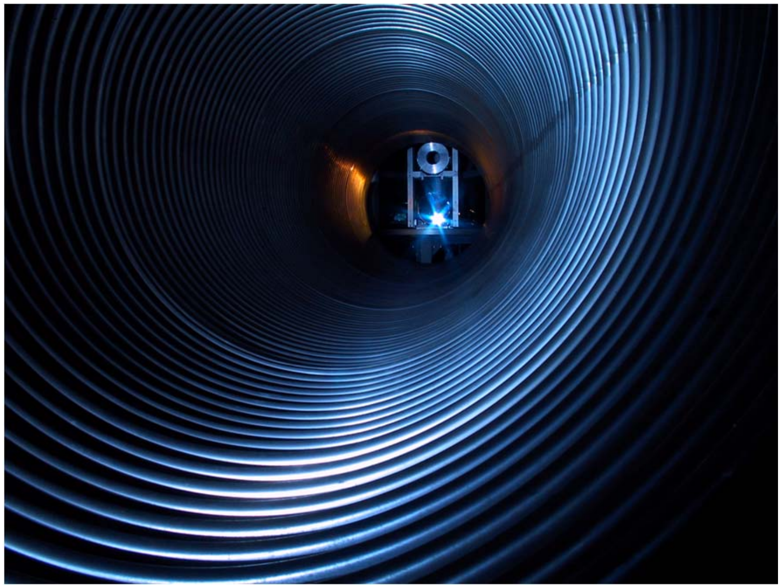
Future LISA mission: 5 million kilometers, ~ 0.1 to 100 milliHertz



Holographic Noise in Interferometers

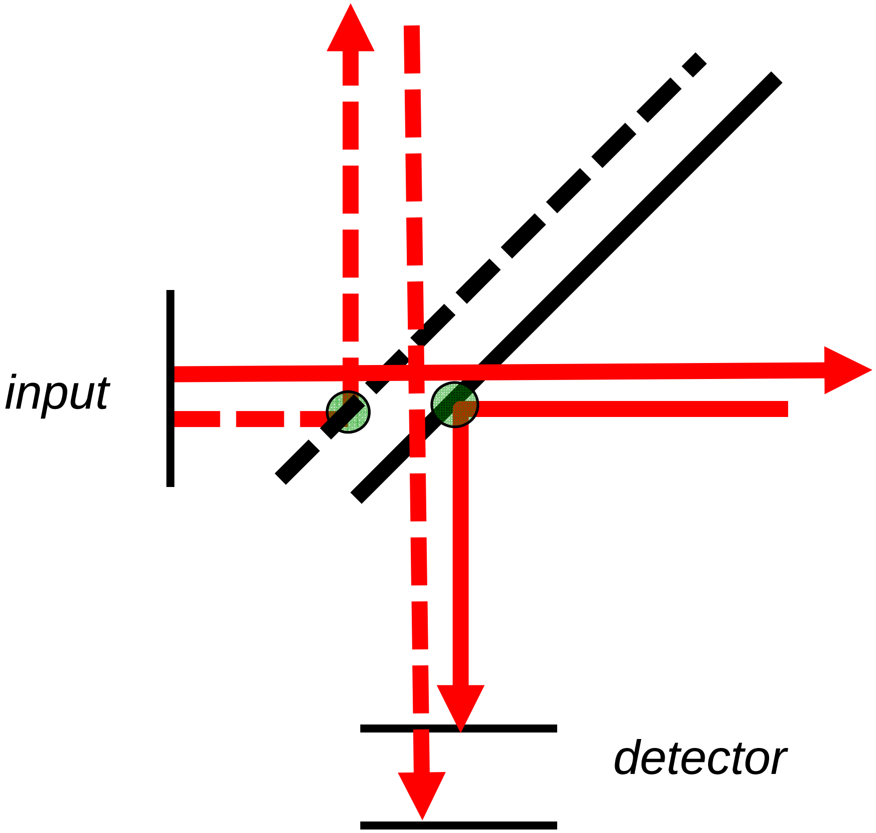
tiny position differences caused by spacetime jitter

holographic noise in signal: “Movement without Motion”



Holographic noise in a Michelson interferometer

Jitter in beamsplitter position leads to fluctuations in measured phase



Range of jitter depends on arm length:

$$\Delta x^2 = \lambda_P L$$

this is a new effect predicted with no parameters

Universal Holographic Noise

Spectral density of equivalent strain noise independent of frequency:

$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22} \mathrm{Hz}^{-1/2}$$

Detected noise spectrum can be calculated for a given apparatus

CJH: arXiv:0712.3419 Phys Rev D.77.104031 (2008)
CJH: arXiv:0806.0665 Phys Rev D.78.087501 (2008)
CJH & M. Jackson: arXiv:0812.1285 Phys Rev D.79.12400 (2009)
CJH: arXiv:0905.4803
CJH: arXiv:1002.4880

Interferometers as holographic clocks

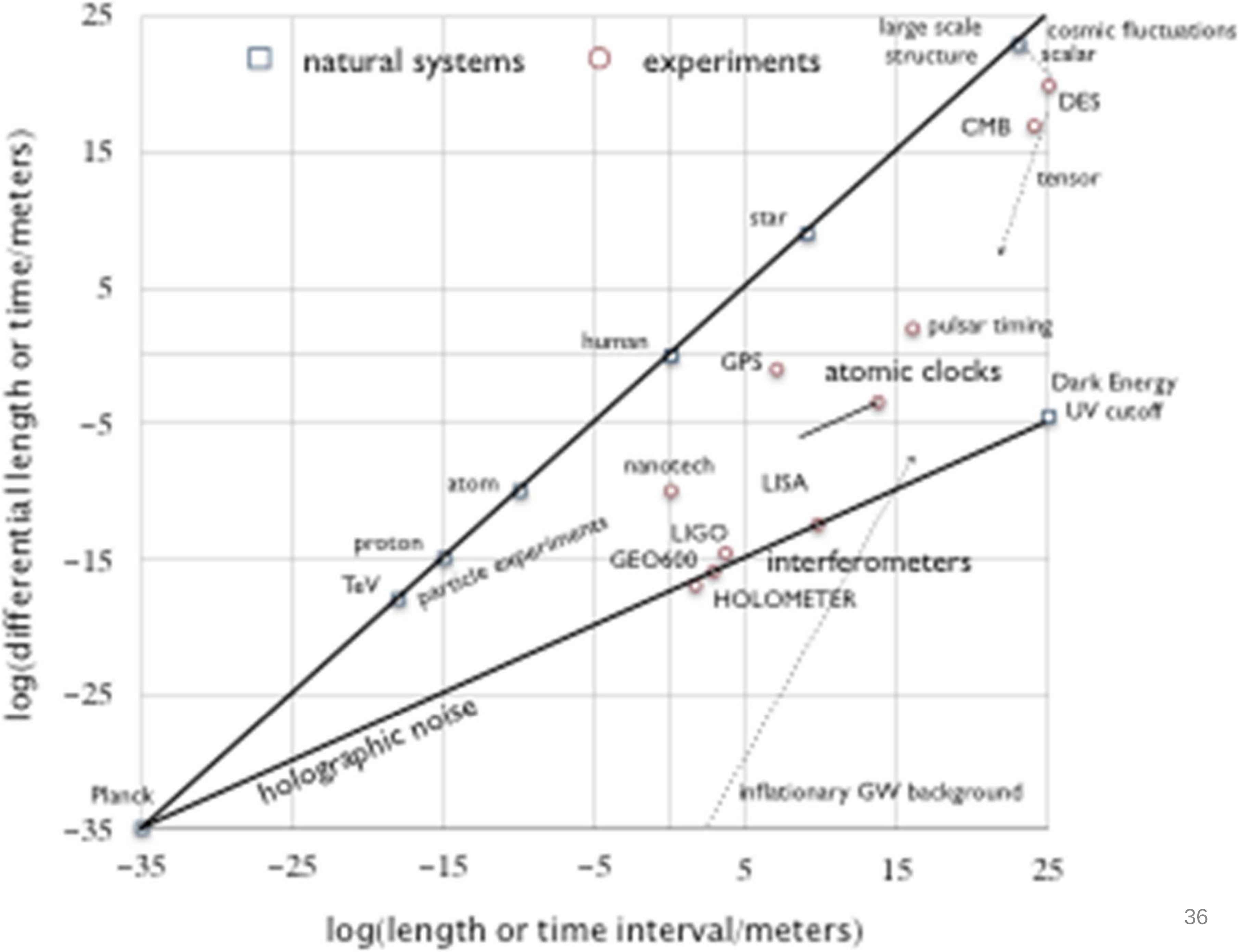
Over short (~ size of apparatus ~ microsecond) time intervals, interferometers can reach Planck precision (~ attometer jitter)

Predicted noise in *differential* frequency between two directions:

$$\frac{\Delta\nu(\tau)}{\nu} = \Delta t(\tau)/\tau = \sqrt{\frac{5.39\times 10^{-44}\mathrm{sec}}{2\pi\tau}} = 9.26\times 10^{-23}/\sqrt{\tau/\mathrm{sec}}$$

Compare to best atomic clocks (over longer times):

$$\frac{\Delta\nu(\tau)}{\nu} = 2.8\times 10^{-15}/\sqrt{\tau/\mathrm{sec}}$$


□ natural systems
○ experiments
large scale structure
cosmic fluctuations
scalar
DES
CMB
tensor
star
pulsar timing
human
GPS
atomic clocks
Dark Energy UV cutoff
nanotech
LISA
atom
LIGO
proton
particle experiments
GEO600
interferometers
TeV
HOLOMETER
holographic noise
Planck
inflationary GW background
25
15
5
−5
−15
−25
−35
−35
−25
−15
−5
5
15
25
log(differential length or time/meters)
log(length or time interval/meters)

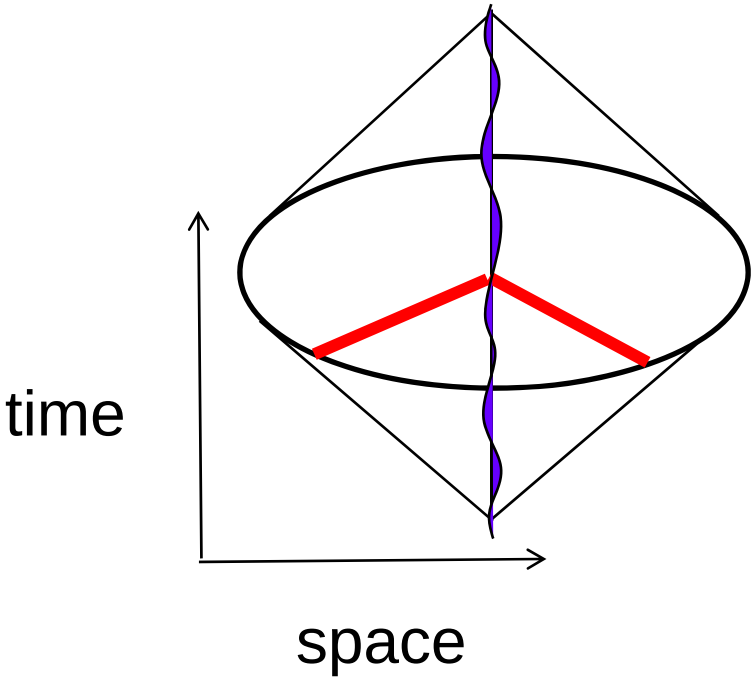
Current experiments: summary

- Interferometers are the best technology for detecting the effect
- Most sensitive device, GEO600, operating close to Planck sensitivity
- GEO600 “mystery noise”: inconclusive
- A definitive sub-Planck limit or detection is difficult with GEO600: evidence is based on noise model
- LIGO: wrong configuration to study this effect
- No experiment has been designed to look for holographic noise
- More convincing evidence: new apparatus, designed to eliminate systematics of noise estimation

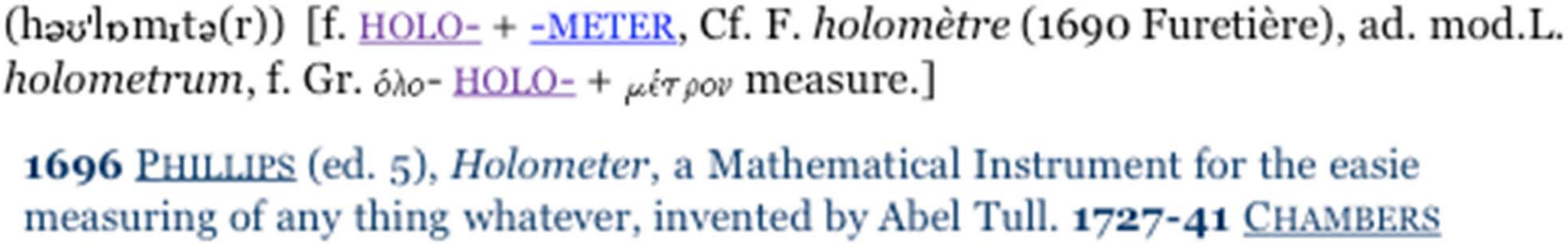
The Fermilab Holometer

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)

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

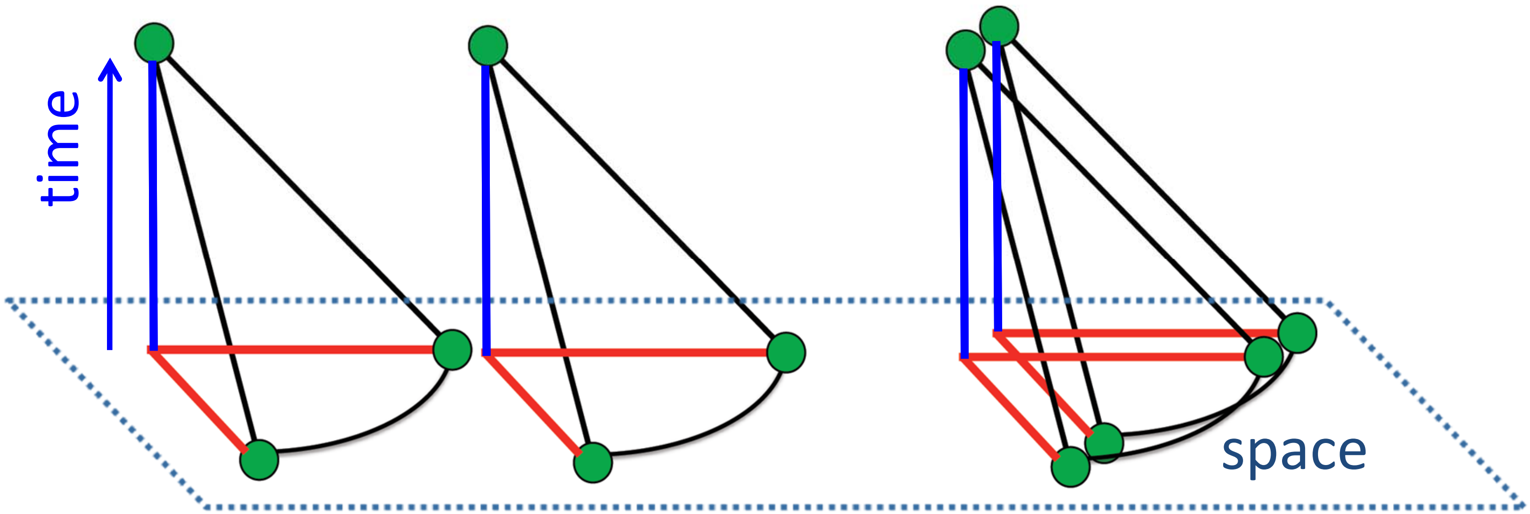
use the broad band nature of the noise to measure at high frequencies (MHz) where other correlated noise is expected to be small

Conceptual Design of the Fermilab Holometer

Correlate two Michelson interferometers at high (MHz) frequency

noncommutative geometry: **wave phases in different directions random-walk by a Planck length per Planck time**

World lines of beamsplitters

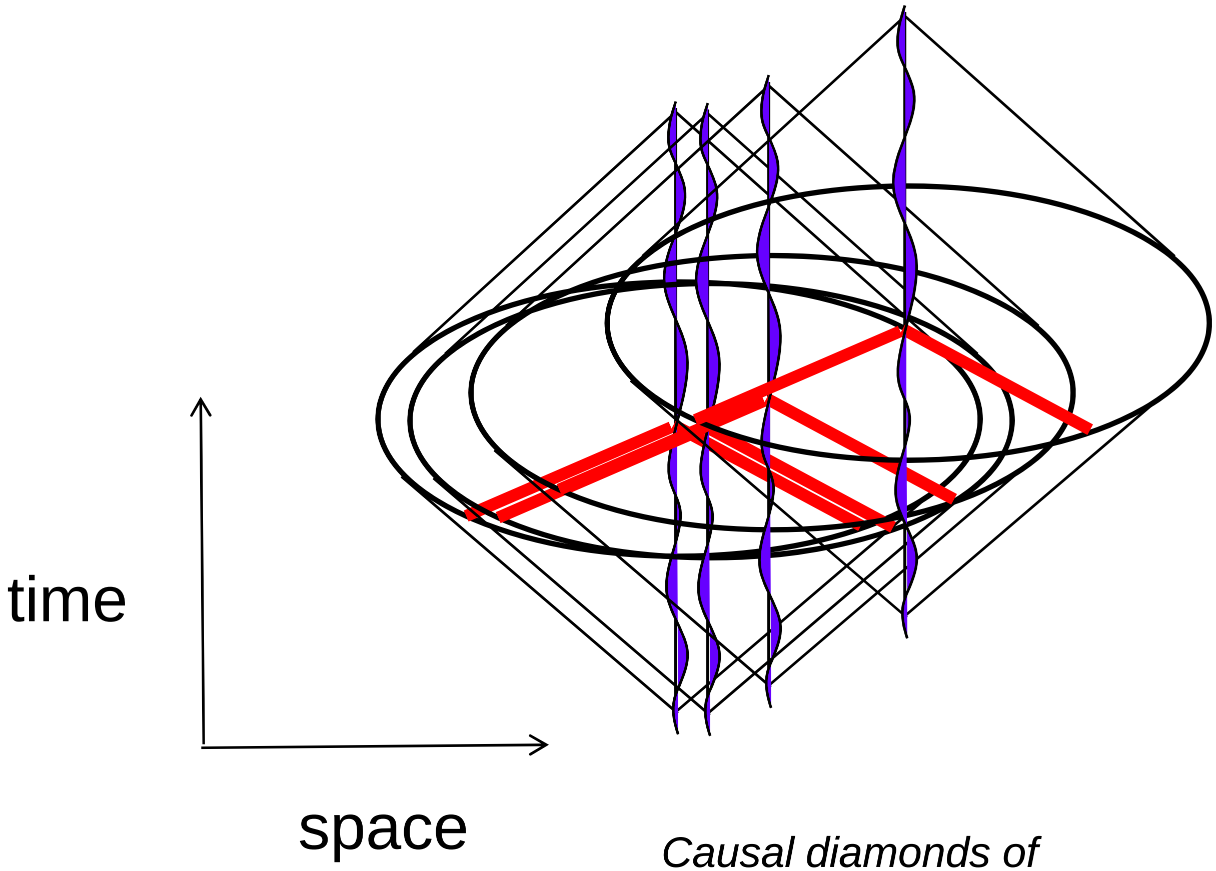


Separate spacetime volumes:
No correlation

Overlapping spacetime volumes:
Correlated holographic noise

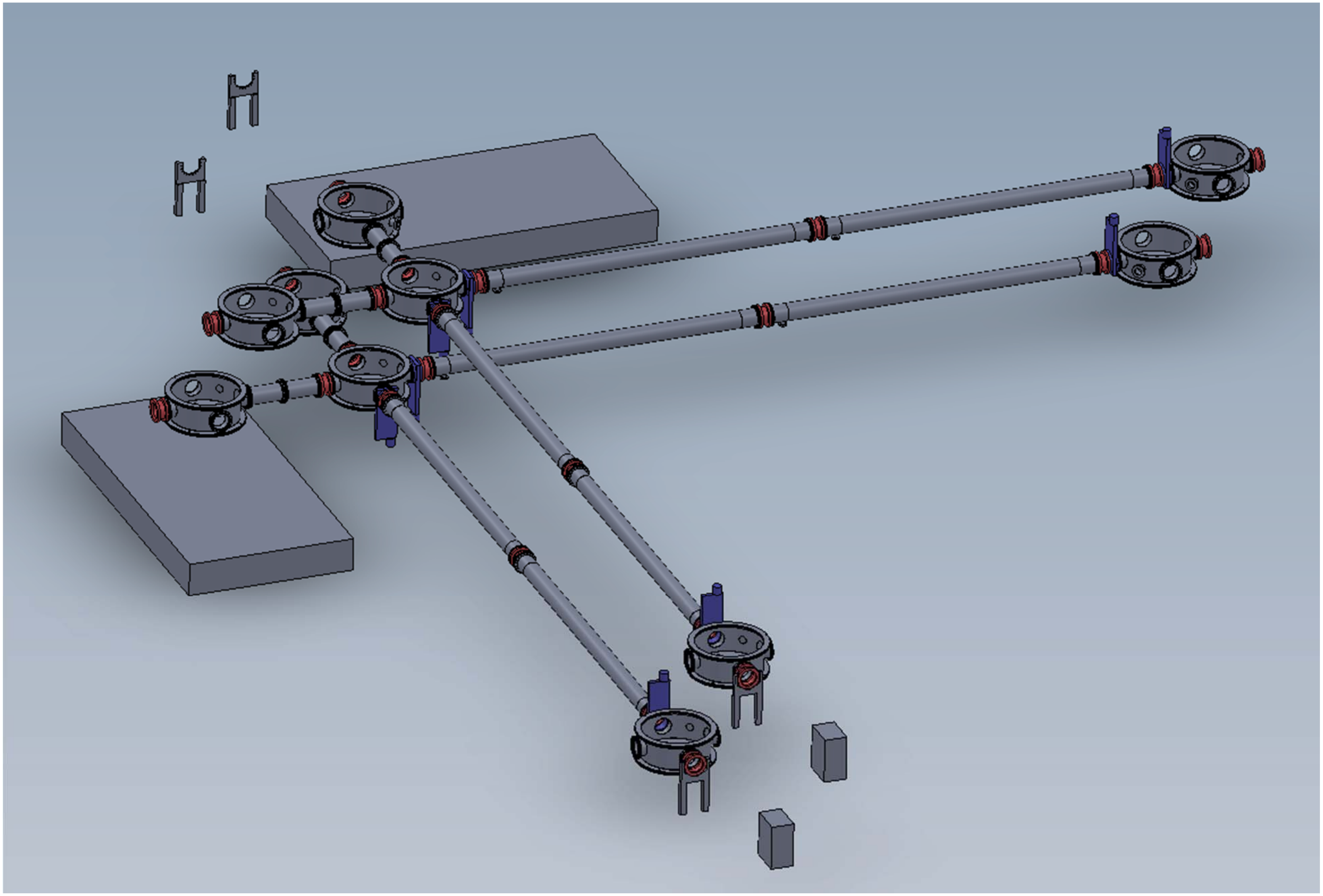
Fermilab holometer: a stereo search for holographic noise

Compare signals of two 40-meter Michelson interferometers at different separations and orientations



Causal diamonds of beamsplitter signals

Holometer layout (shown with 20 foot arms in “close” configuration)



Broadband system noise is uncorrelated

Coherently build up holographic signal by cross correlation

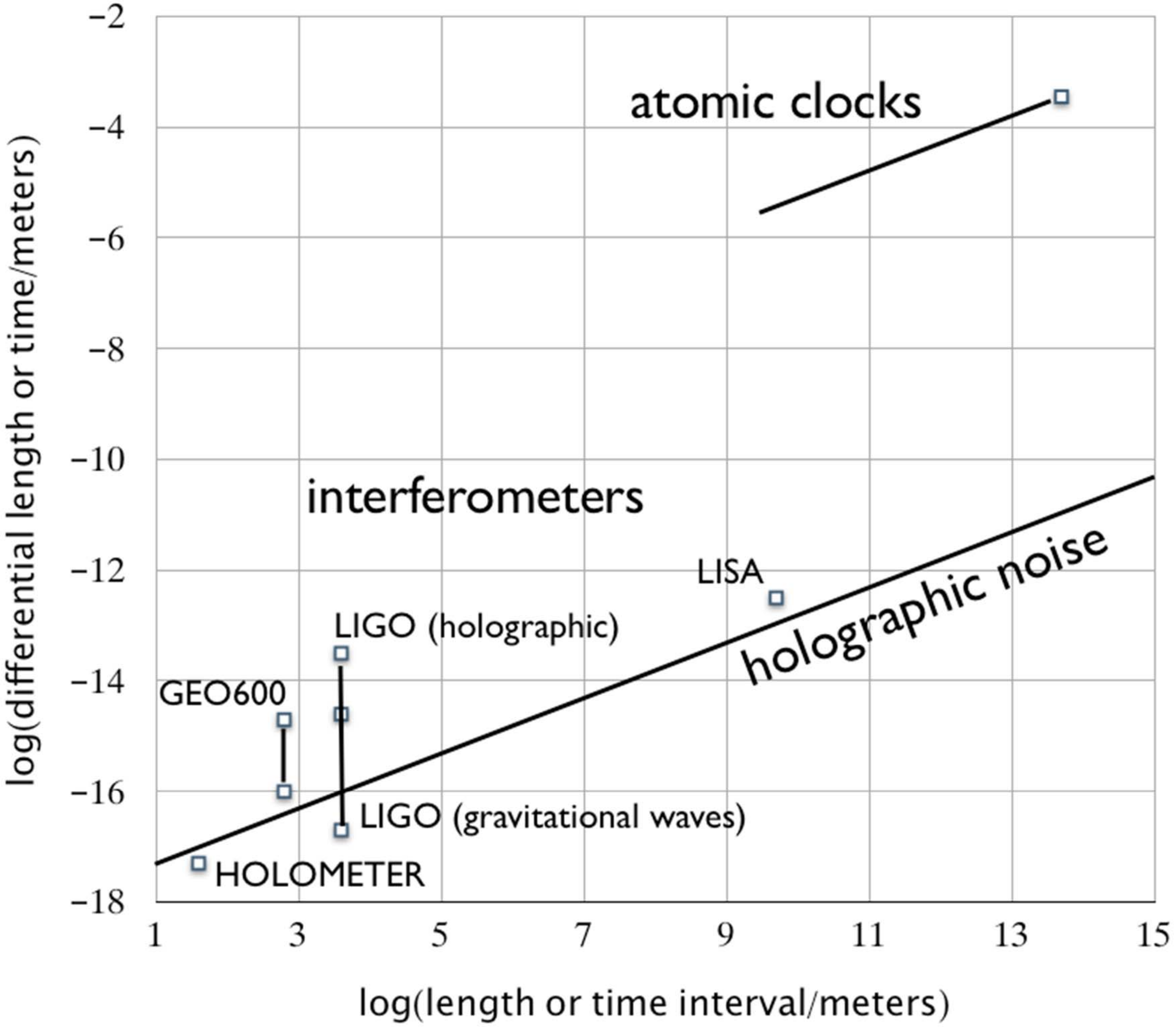
holographic signal = photon shot noise after

$$t_{\mathrm{obs}} > \left(\frac{h}{P_{\mathrm{BS}}}\right)^2 \left(\frac{\lambda_{\mathrm{opt}}}{\lambda_{\mathrm{Pl}}}\right)^2 \left(\frac{c^3}{32\pi^4 L^3}\right)$$

For beamsplitter power P_{BS}=2 kW, arm length L=40m, time for three sigma measurement is about an hour

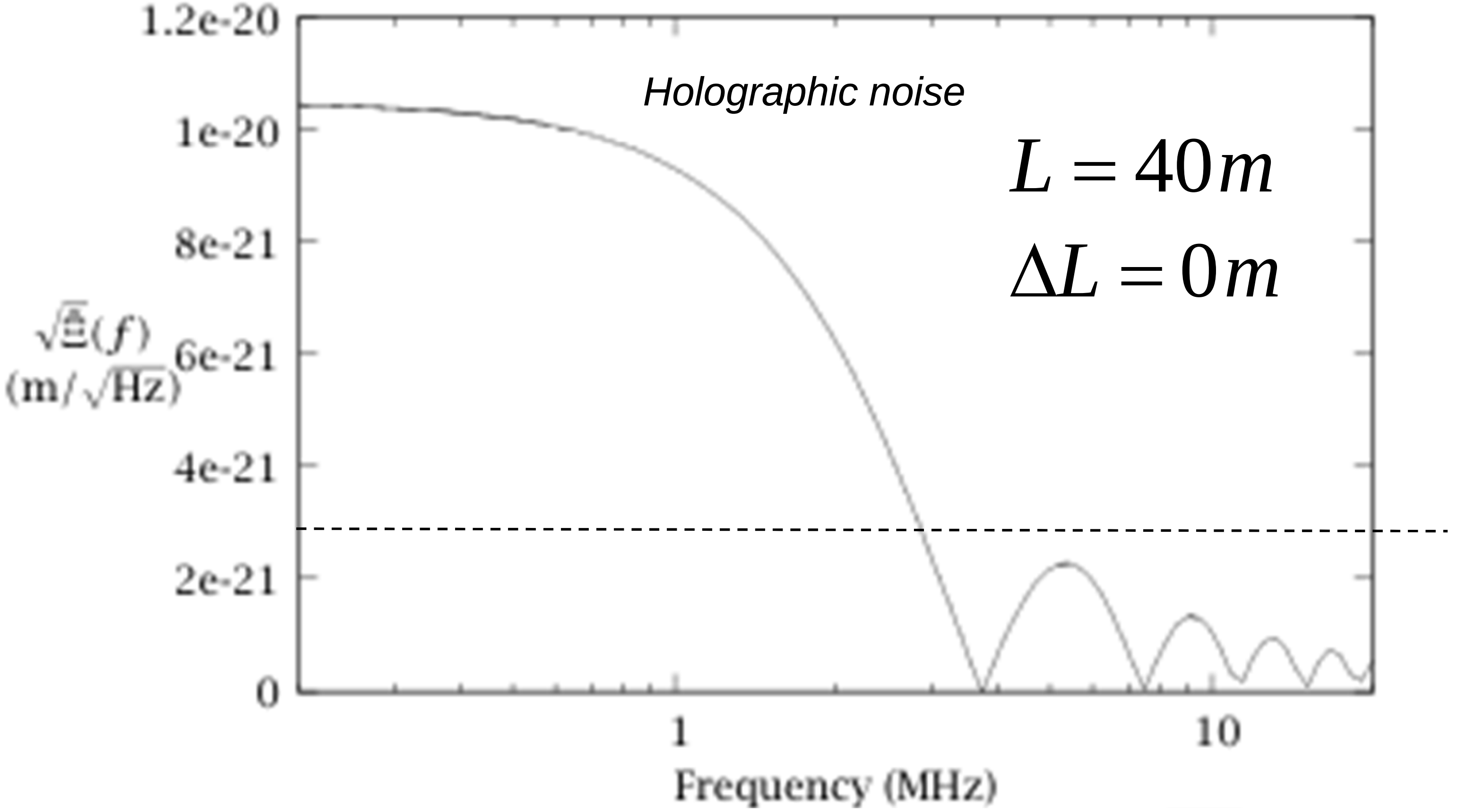
Thermal lensing limit on beamsplitter power drives design

Reject spurious correlations in the frequency domain


atomic clocks
interferometers
holographic noise
LISA
LIGO (holographic)
GEO600
LIGO (gravitational waves)
HOLOMETER
log(differential length or time/meters)
log(length or time interval/meters)
−2
−4
−6
−8
−10
−12
−14
−16
−18
1
3
5
7
9
11
13
15

Predicted Planck-amplitude frequency spectrum

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



Holographic noise

$L = 40m$

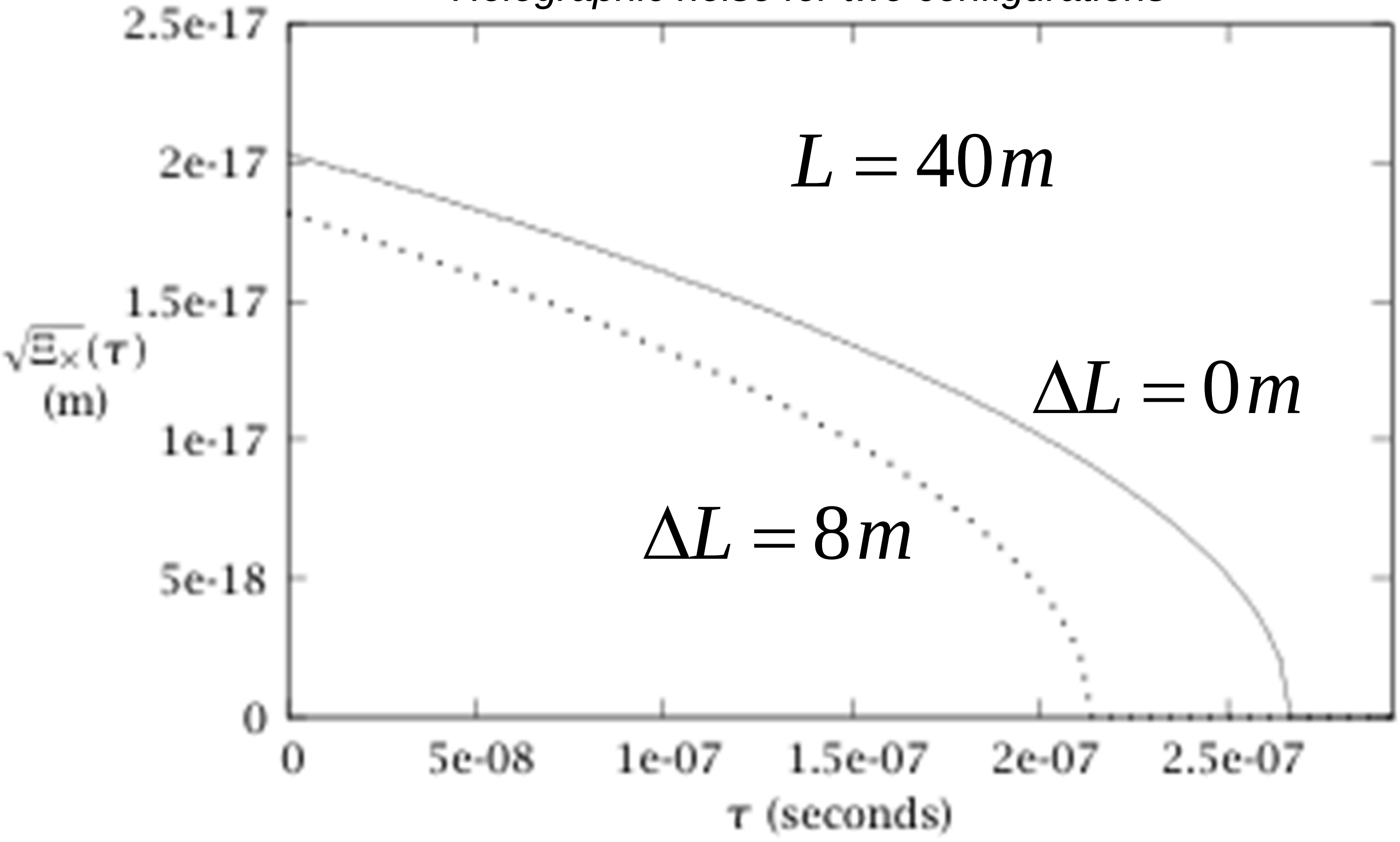
$\Delta L = 0m$

Correlated shot noise after ~10 hour run

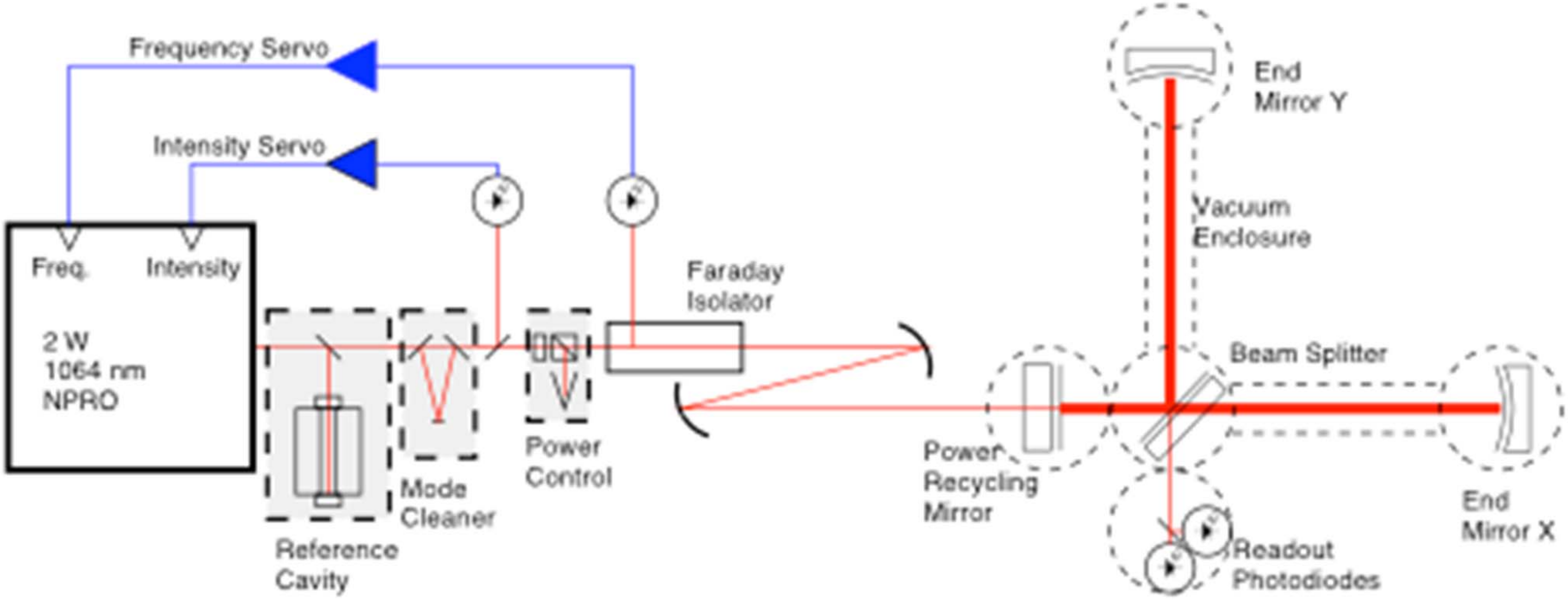
Predicted time-domain correlation, decorrelation

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

Holographic noise for two configurations

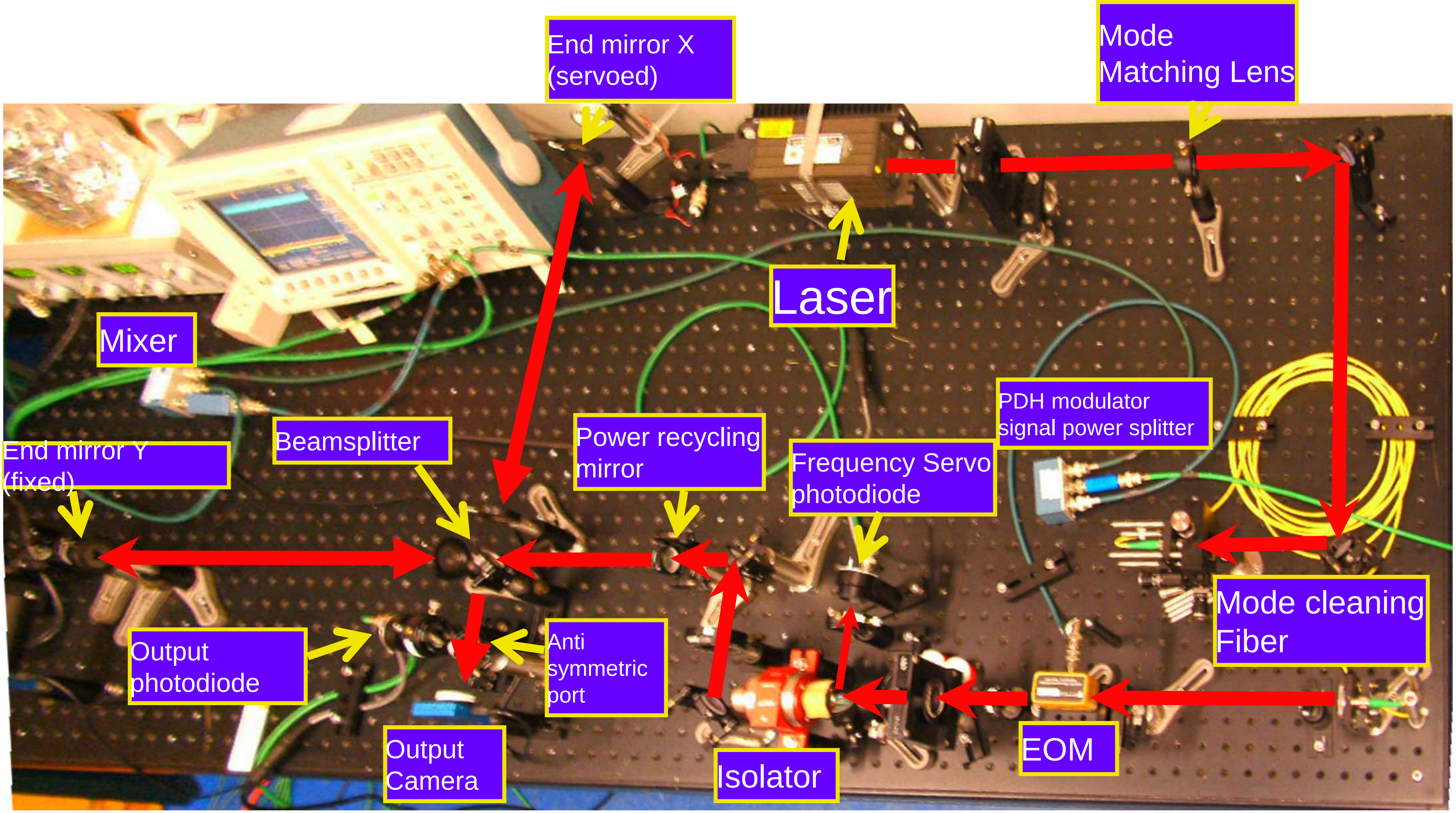


Optical layout: standard power-recycled Michelson



S. Waldman, MIT

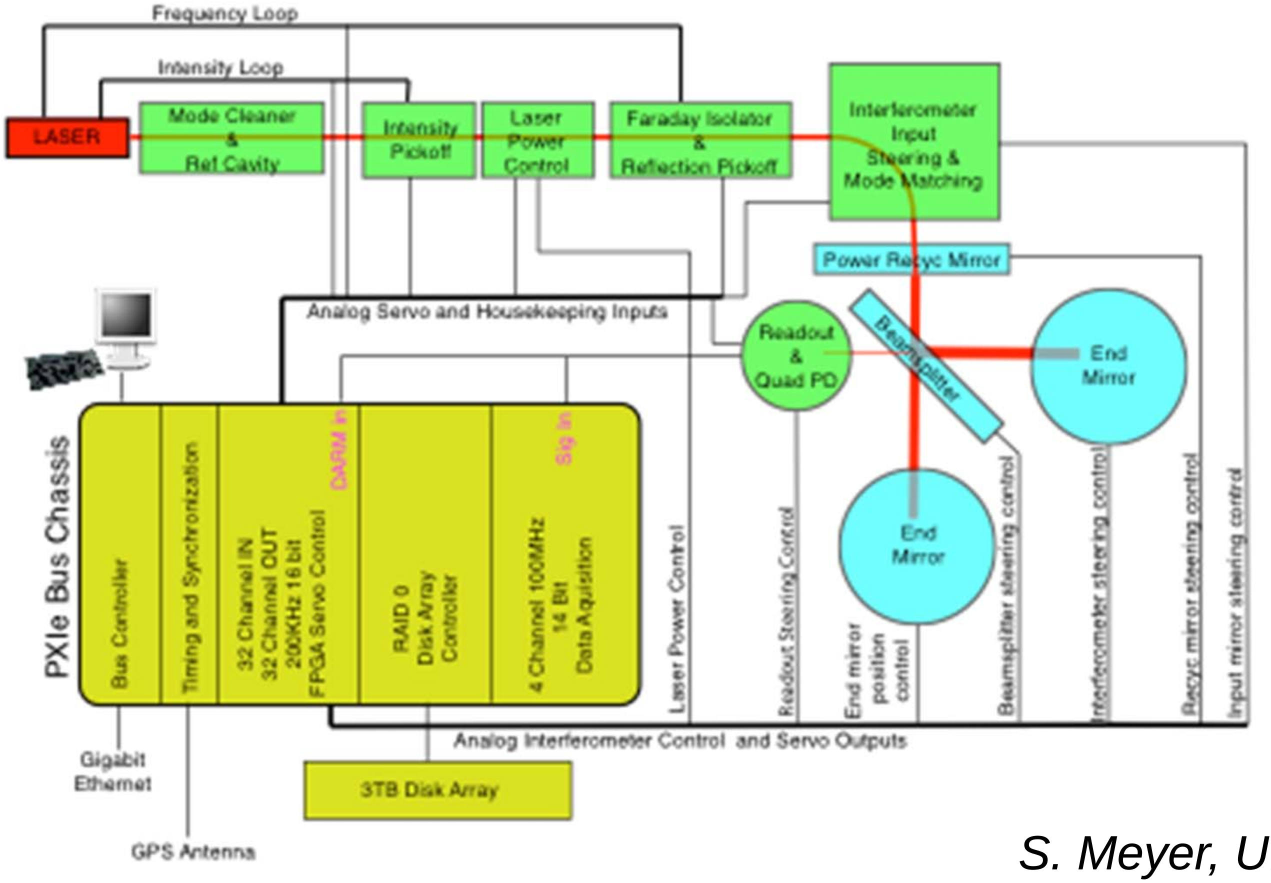
Table-top prototype power-recycled Michelson interferometer in the Fermilab Linac lab



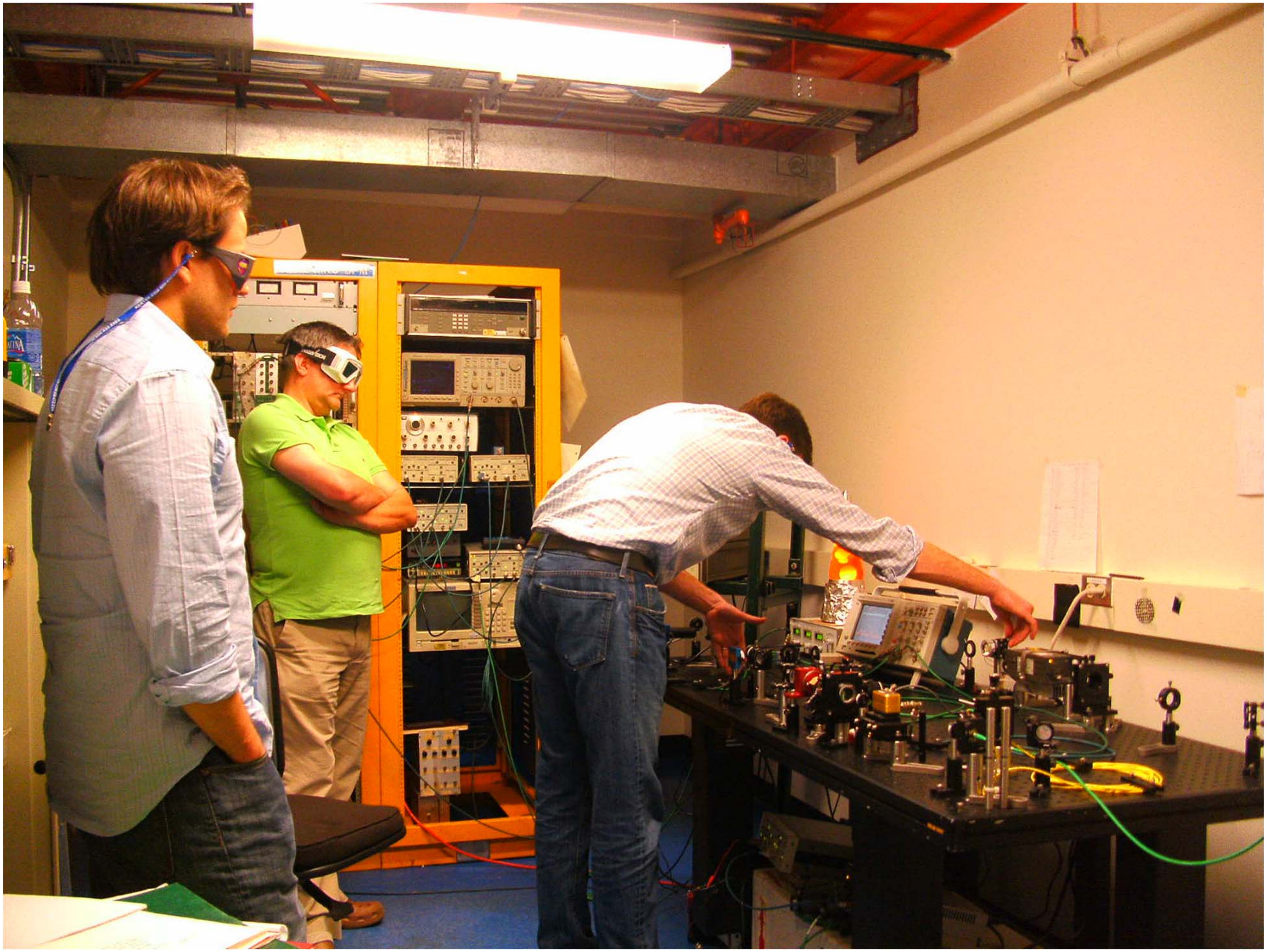
Control & data system

Off-the-shelf components and control software

Designed to control RF noise



S. Meyer, U. Chicago




LCWR

Status of the Fermilab Holometer

Team:

- Fermilab (A. Chou, H. Glass, G. Gutierrez, CJH, J. Steffen, C. Stoughton, R. Tomlin, J. Volk, W. Wester)
- MIT (R.Weiss, S.Waldman)
- Caltech (S. Whitcomb)
- University of Chicago (S. Meyer + students)
- University of Michigan (R. Gustafson)
- includes LIGO experts

Operating tabletop prototypes at Fermilab, U. Chicago

- Successful edge-locked interferometer, power recycled cavity
- Correlation, noise tests with blackbody radiation

Developing 40m prototype cavity at Fermilab

Developing & testing detectors, electronics, control systems

Deploy full experiment in the next year

Physics Outcomes

If noise is not there,

Constrain interpretations of holography: Planckian frequency bound or noncommutative geometry do not affect position measurement

If it is detected, experiment probes Planck scale unification

Study holographic relationships among matter, energy, space, time

Shape interpretation of fundamental theory