Interferometry and Quantum Geometry

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Architecture of Physics

Classical Geometry

- Dynamical but not quantum
- Responds to particles and fields

Quantum particles and fields

- Inhabit classical geometry

Explains almost everything

Classical and Quantum Geometry

Classical positions are *coordinates of points* (“events”)

Quantum mechanical positions are *operators*

- Observables are properties of interactions, not events
- Events do not interact
- Interactions do not have determinate positions
- Measurements are not localized

These cannot possibly be the same thing

Dynamical geometry-> strong curvature from a Planck quantum

Geometry must be quantum at that scale

Nobody knows how it works

Planckian Quantum Geometry

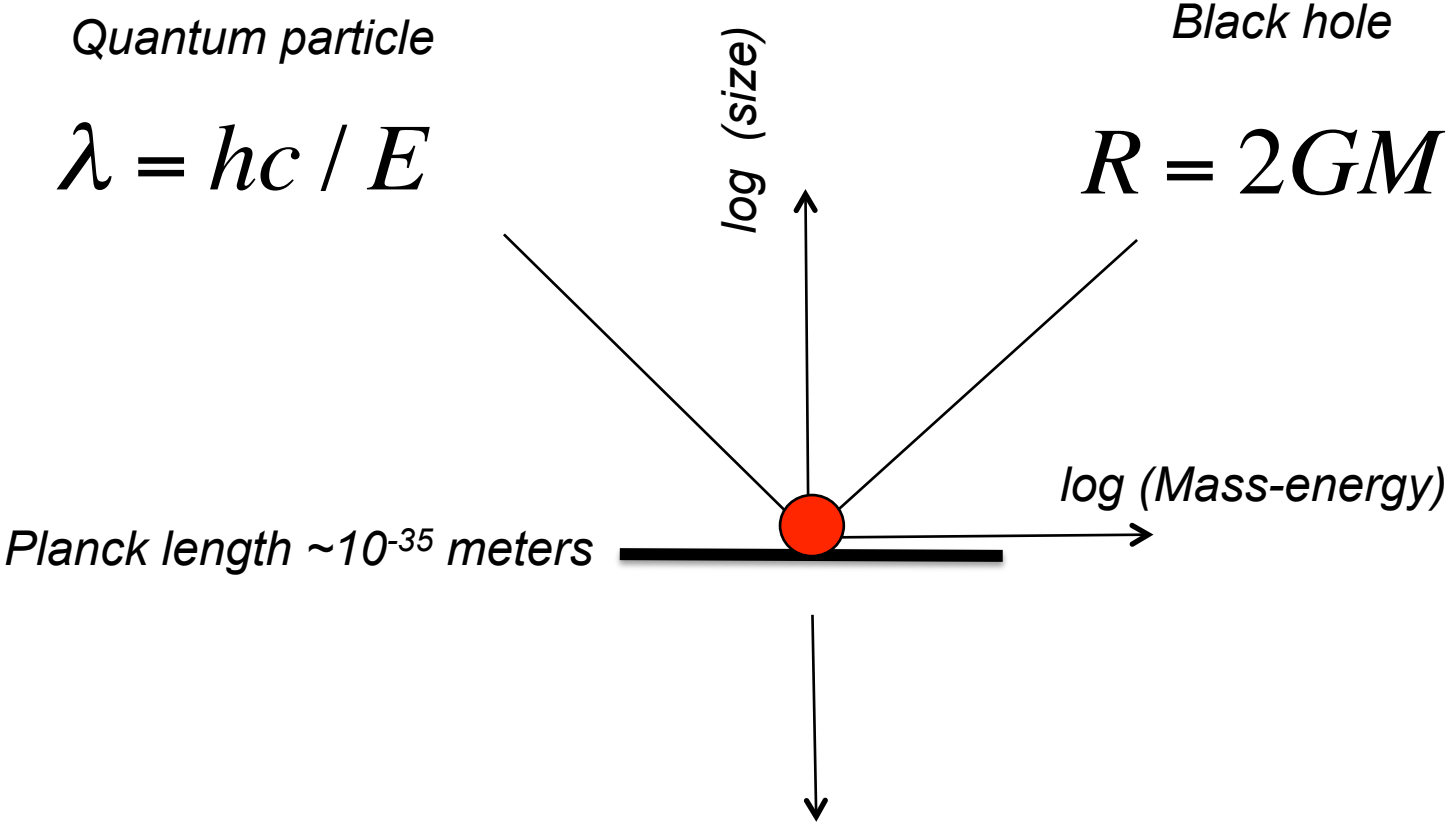
Physics of space and time beyond the Planck scale is unknown

Quantum particle

$$\lambda = hc / E$$

Black hole

$$R = 2GM / c^2$$



Can we measure quantum behavior of geometry?

Can interferometers probe Planckian physics?

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

The physics of quantum geometry originates at this tiny scale

But it may lead to effects on larger scales

Emergent Space-time

Perhaps classical space-time is not fundamental, but is an approximate macroscopic behavior of a quantum system

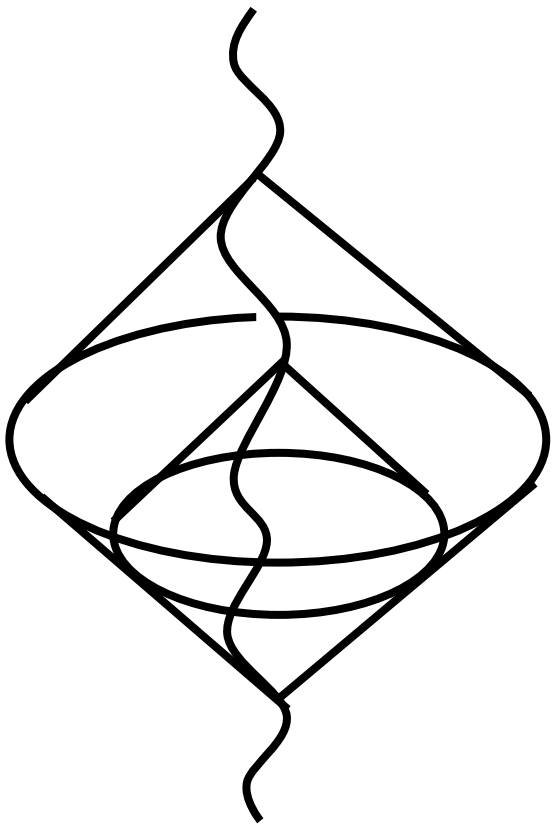
Locality, direction, etc. may only acquire meaning in a macroscopic limit

True degrees of freedom may not correspond to quantized classical modes

Planckian physics may not be confined to Planck scale

Maybe there are experiments we can do

Emergent Space-time



"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."

T. Banks

Covariant noncommutative geometry

$$[x_\mu, x_\nu] = \bar{x}^\kappa \bar{U}^\lambda \epsilon_{\mu\nu\kappa\lambda} i\ell_P$$

Positions are operators, not 4-vectors

Behave like classical position on large scales

Form dictated by covariance

Departure from classical behavior: *covariant* but not *invariant*

(Depends on origin and velocity of coordinates)

Interpret as a quantum relationship between two timelike trajectories: the origin, and x

Quantum-Geometrical Uncertainty of position

In the rest frame (*U*=1,0,0,0), commutator in 3D at one time becomes

$$[x_i, x_j] = \bar{x}^k \epsilon_{ijk} i \ell_P$$

Leads to uncertainty in (time-invariant) wave function

$$\Delta x_i \Delta x_j \geq |\bar{x}^k \epsilon_{ijk}| \ell_P / 2$$

Uncertainty increases with separation

Interpret as a property of the wave function that describes positional relationship between two trajectories

Quantum departure from emergent classical geometry

Planckian effect not confined to Planck scale

Purely transverse to separation

Macroscopic limit is classical geometry

$$\Delta\theta_1 \Delta\theta_2 \geq \ell_P / 2 |\bar{x}_3|$$

Angles indeterminate at the Planck scale

Approximately classical on large scales

Information content in sphere of radius *R*:

$$(R/\ell_P)(R^2/\Delta x_i \Delta x_j) \approx (R/\ell_P)^2$$

Agrees with covariant/ holographic entropy bound from gravity

Motivates choice of Planckian normalization

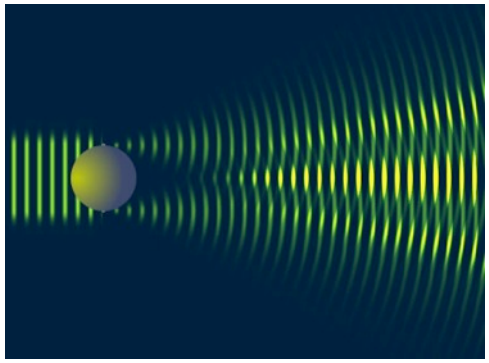
Approach to the classical limit

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

$$\Delta\theta_1 \Delta\theta_2 > l_P / L$$

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

$$\Delta x_1 \Delta x_2 > l_P L$$



Not the classical limit of field theory

Directions have intrinsic “wavelike” uncertainty

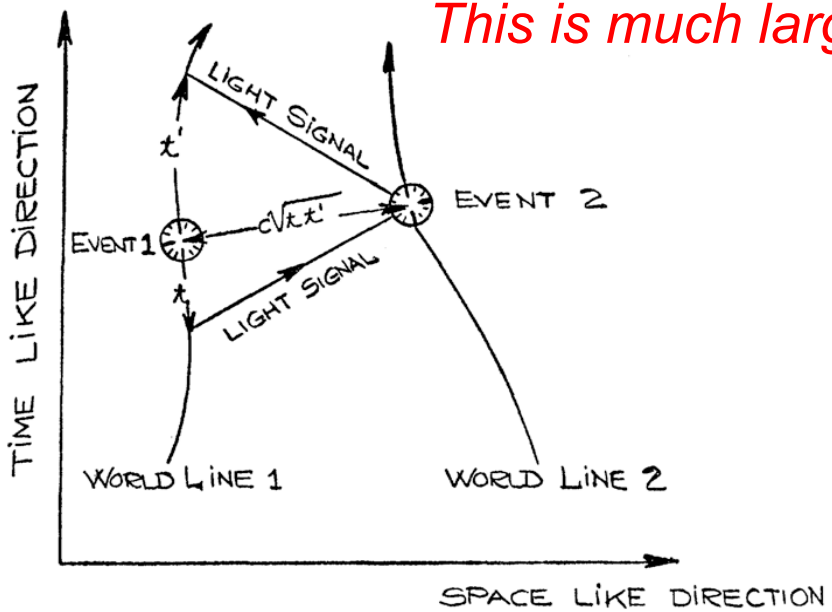
Wave interpretation

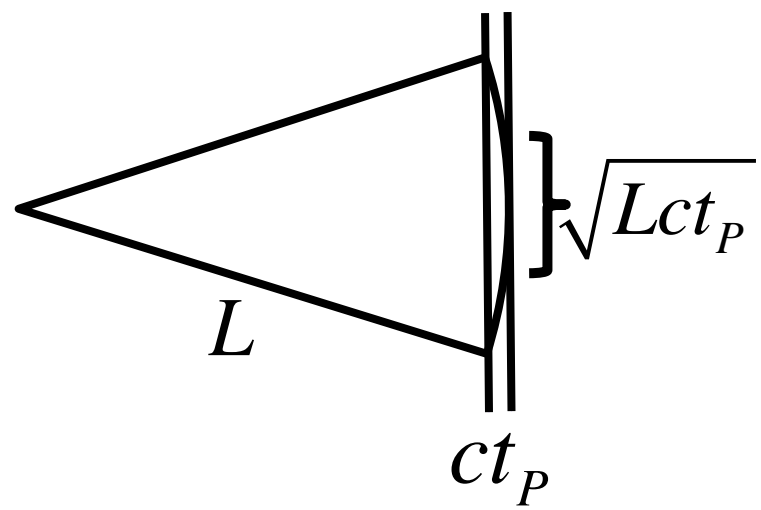
Spacelike-separated event intervals are defined with clocks and light

But transverse positions of Planckian wavefunctions are uncertain by the diffraction limit,

$$\sqrt{Lct_P}$$

This is much larger than the wavelength

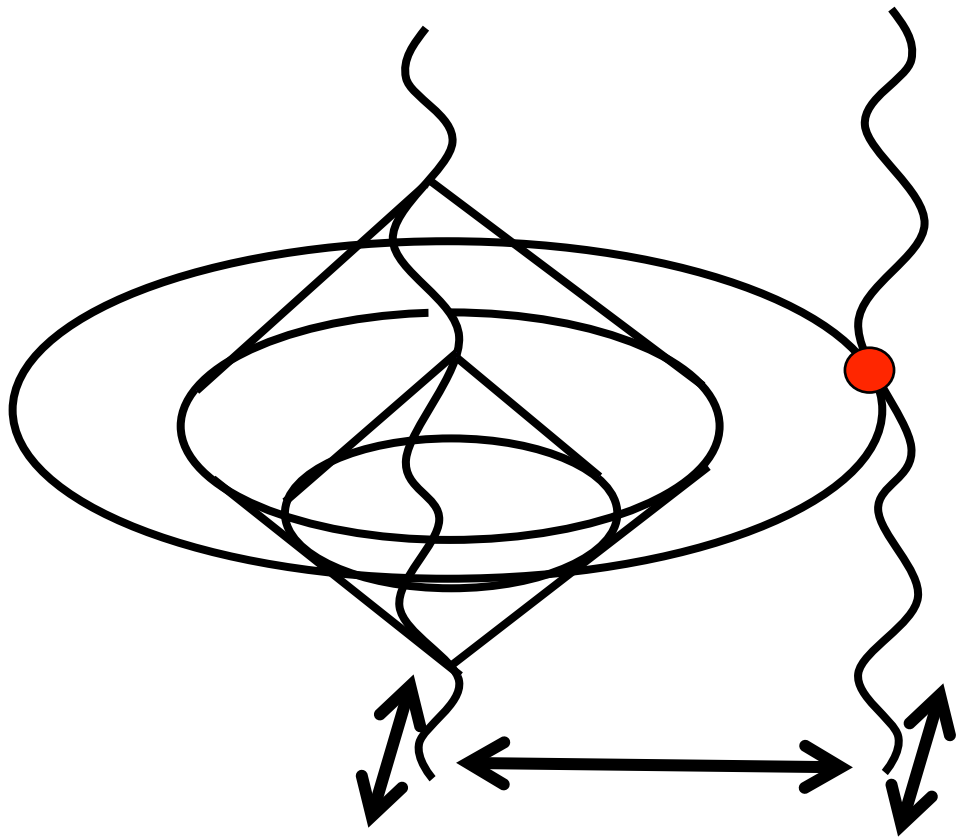




Wigner (1957): quantum limits with one spacelike dimension and physically-realizable clocks

Add transverse dimension and Planck frequency limit: new position uncertainty

Transverse position uncertainty and fluctuations



$$\Delta x \sim \sqrt{c t_P L}$$

Transverse uncertainty >> Planck length for large L

→fluctuations in nonlocal transverse position measurements

Coherence of Quantum-Geometrical Fluctuations

Larger scale modes dominate total displacement

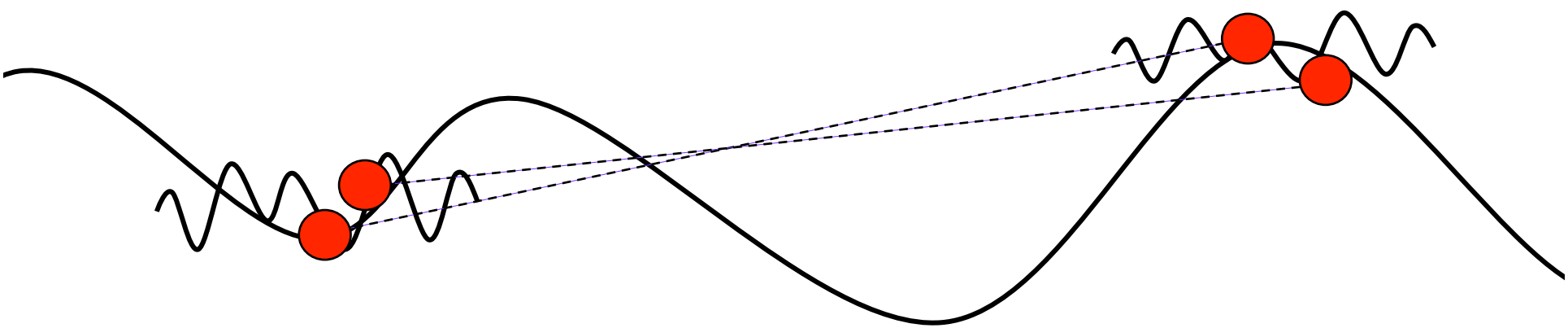
Displacement of nearby objects is not independent for each body

Causal diamonds: local effects do not depend on choice of distant observer

Depends only on position and no other property of a body

Geometrical states are "entangled"

Massive bodies share almost the same displacement if they are in almost the same place, compared with separation



Quantum Geometry only important for large masses

Standard Heisenberg uncertainty between two measurements of mean position at different times

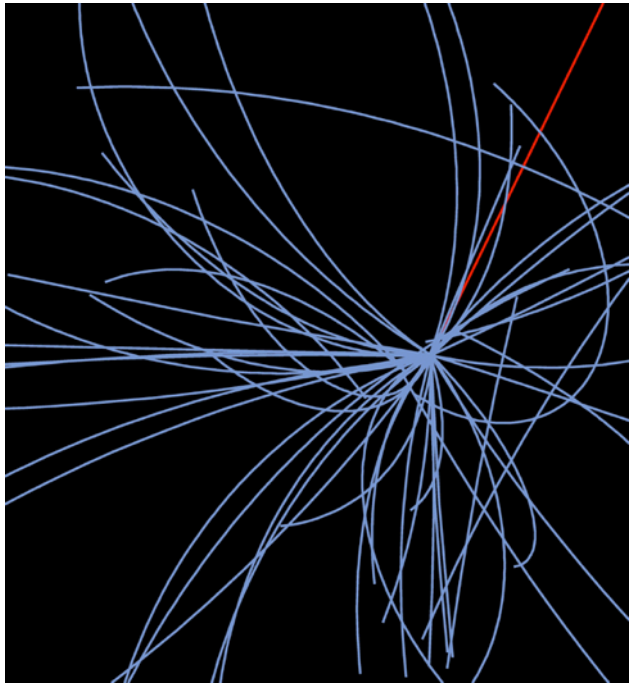
$$\Delta x^2 \equiv \langle (x(t) - x(t+\tau))^2 \rangle \geq 2\hbar\tau/m$$

(standard interferometer limit)

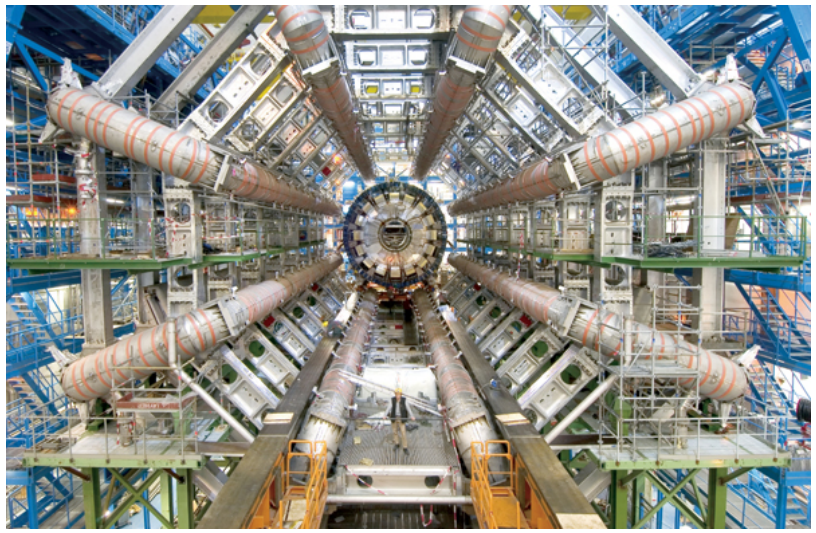
This dominates geometrical uncertainty unless mass is greater than the Planck mass

Field theory works great for elementary particles

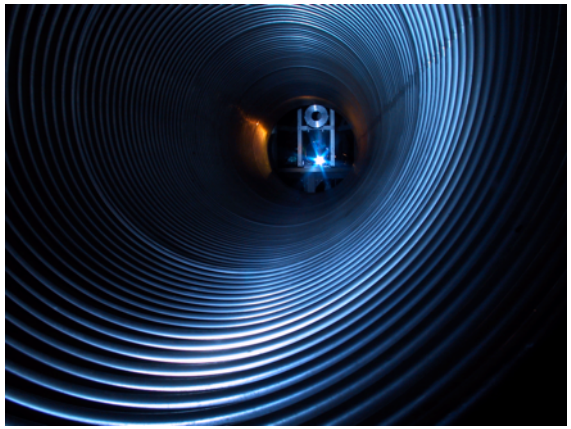
Two ways to study attometer scale physics



particle colliders measure microscopic products of localized events



Interferometers compare macroscopic positions of massive bodies

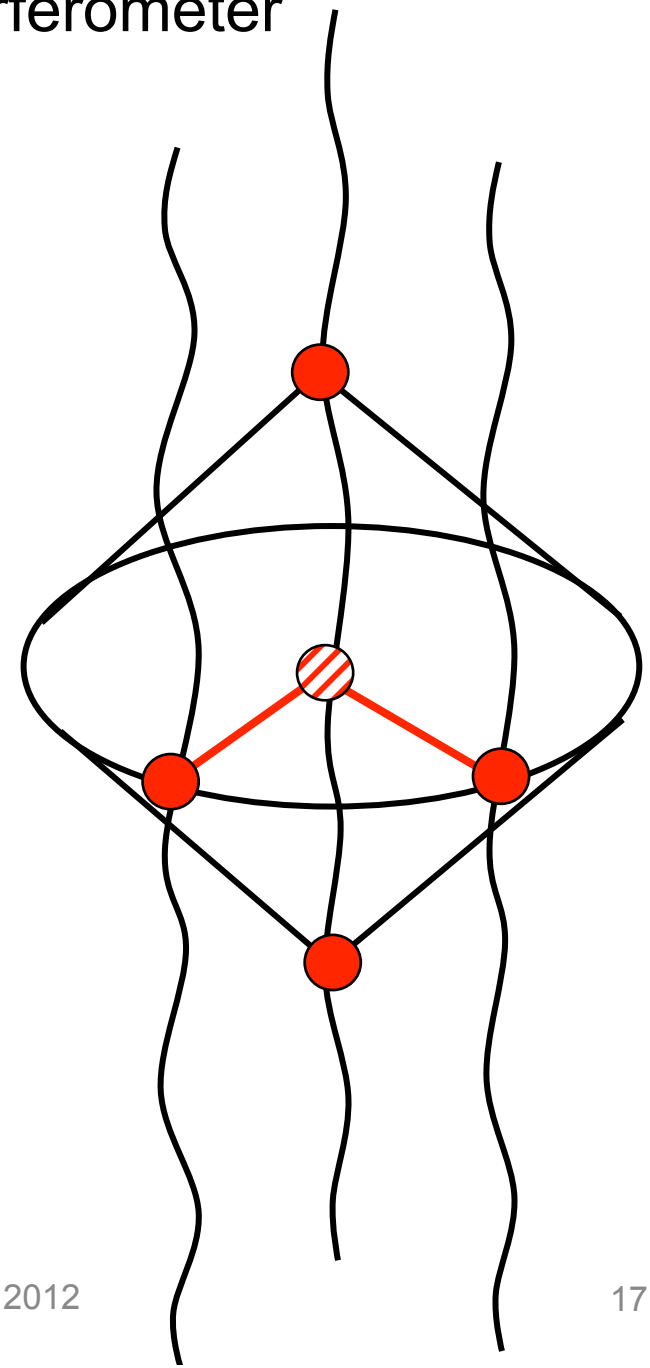


Spacetime diagram of Michelson interferometer

World lines of beamsplitter and two end mirrors

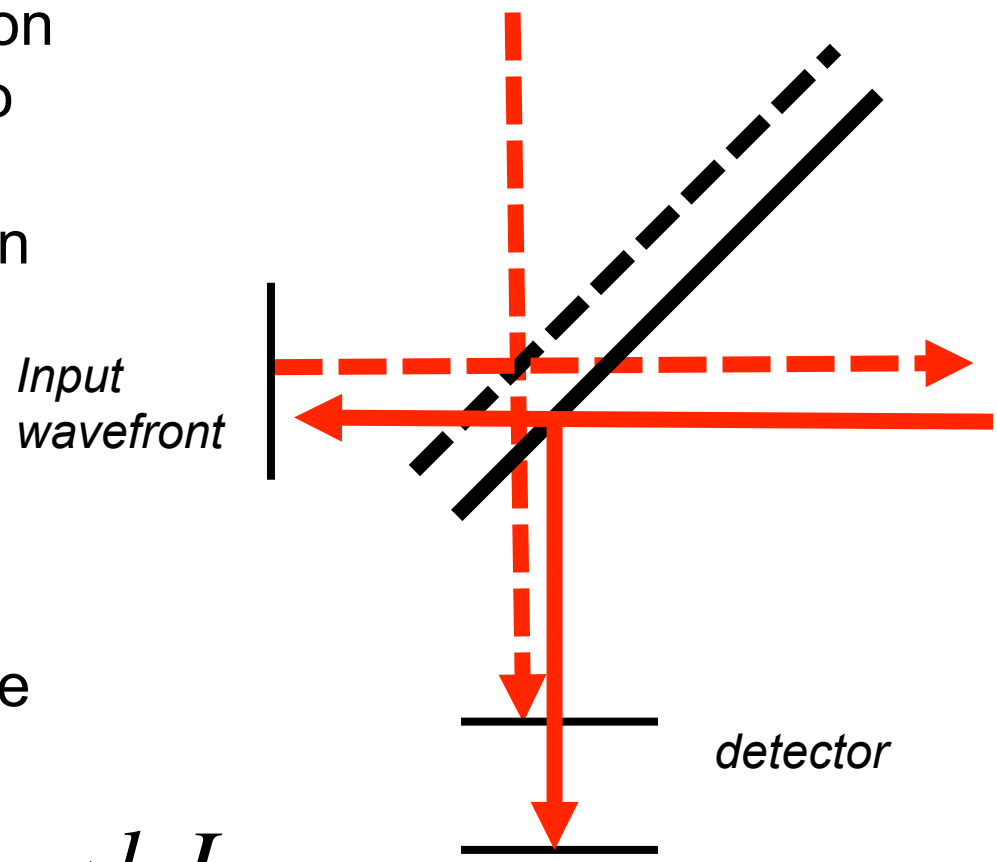
Events contributing to interferometer signal at one time

Measurement is coherent, nonlocal in space and time, includes position in two directions



Quantum-geometrical noise in a Michelson interferometer

"jitter" in beamsplitter position between reflections leads to fluctuations in measured phase between reflections in different directions



Range of jitter and timescale depends on arm length:

$$\Delta x_1 \Delta x_2 \approx l_P L$$

this is a new effect predicted with no parameters

Response of simple Michelson interferometer

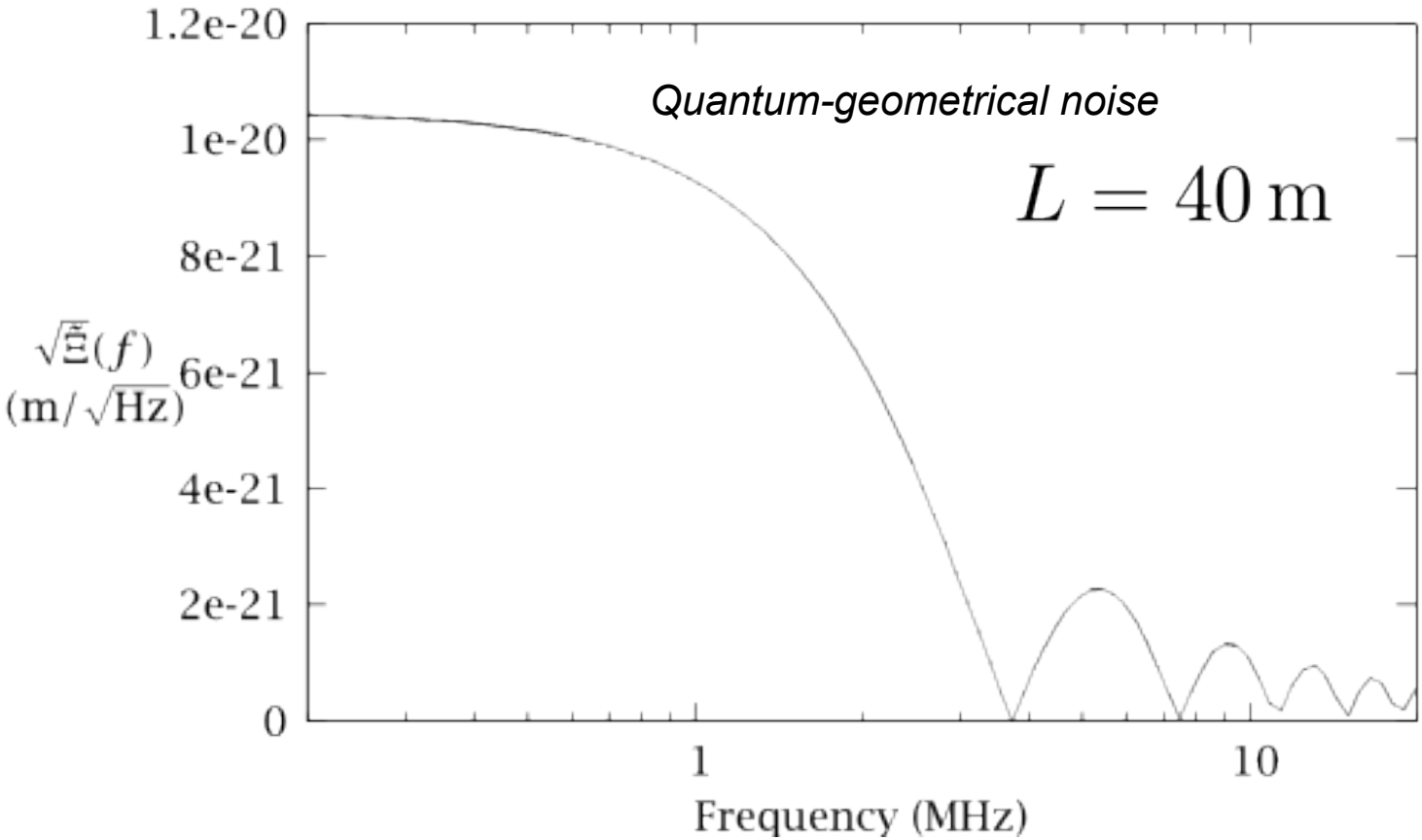
spectral density of noise in position at frequency f, in apparatus of size L:

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

Depends only on Planck scale and L

Measured noise is not sensitive to modes longer than 2L

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



Interferometer noise, including transfer function

Interferometers can reach Planckian sensitivity

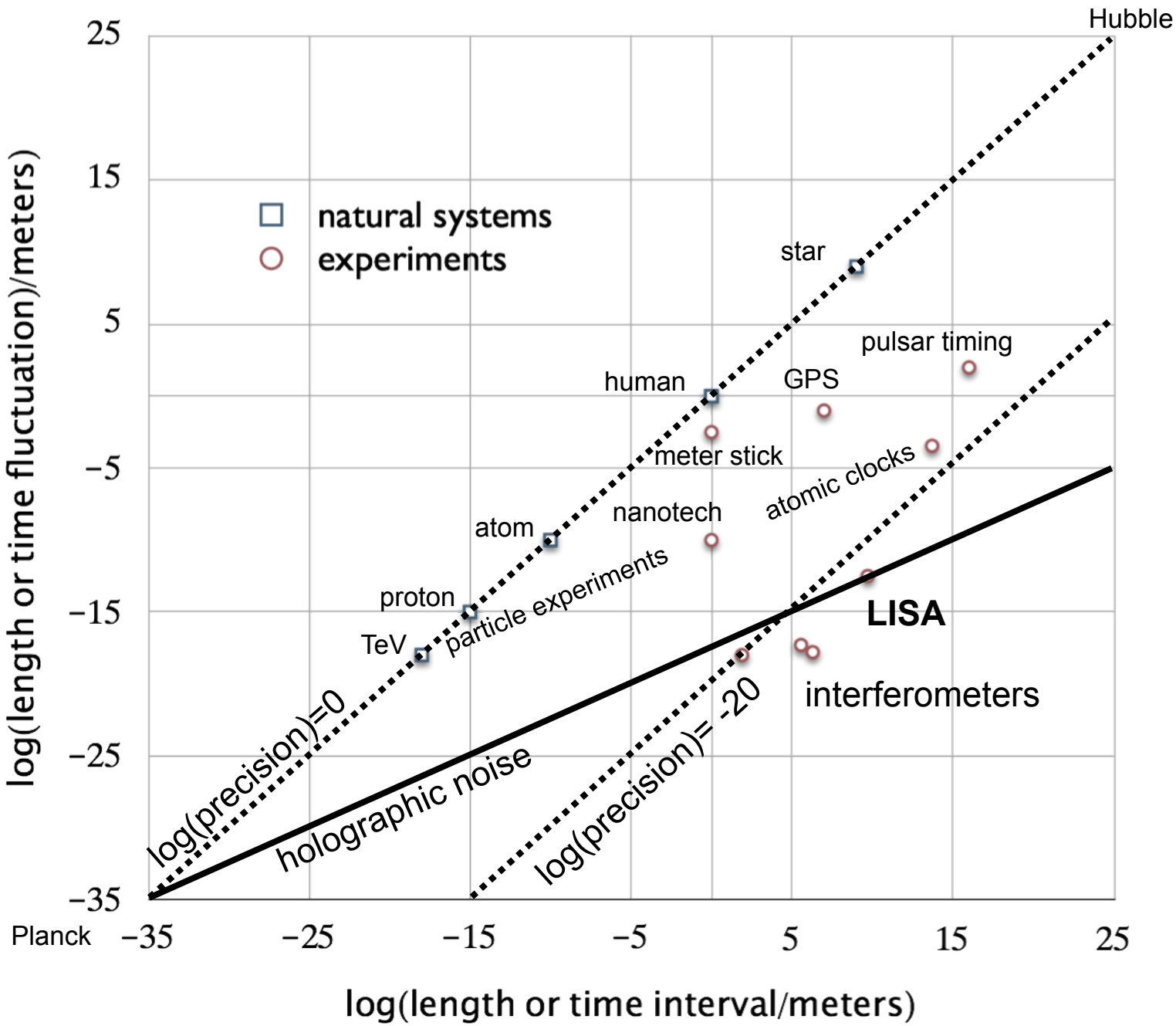
Over short (~ size of apparatus ~ microsecond) time intervals, interferometers can reach Planck precision (~ attometer jitter)

Predicted random variation in differential frequency between two directions over time interval τ

$$\frac{\Delta\nu(\tau)}{\nu} \approx \Delta t(\tau)/\tau = \sqrt{\frac{2 \times 5.39 \times 10^{-44}\mathrm{sec}}{\pi\tau}} = 1.8 \times 10^{-22}/\sqrt{\tau/\mathrm{sec}}$$

Compare to best atomic clocks (over longer times):

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

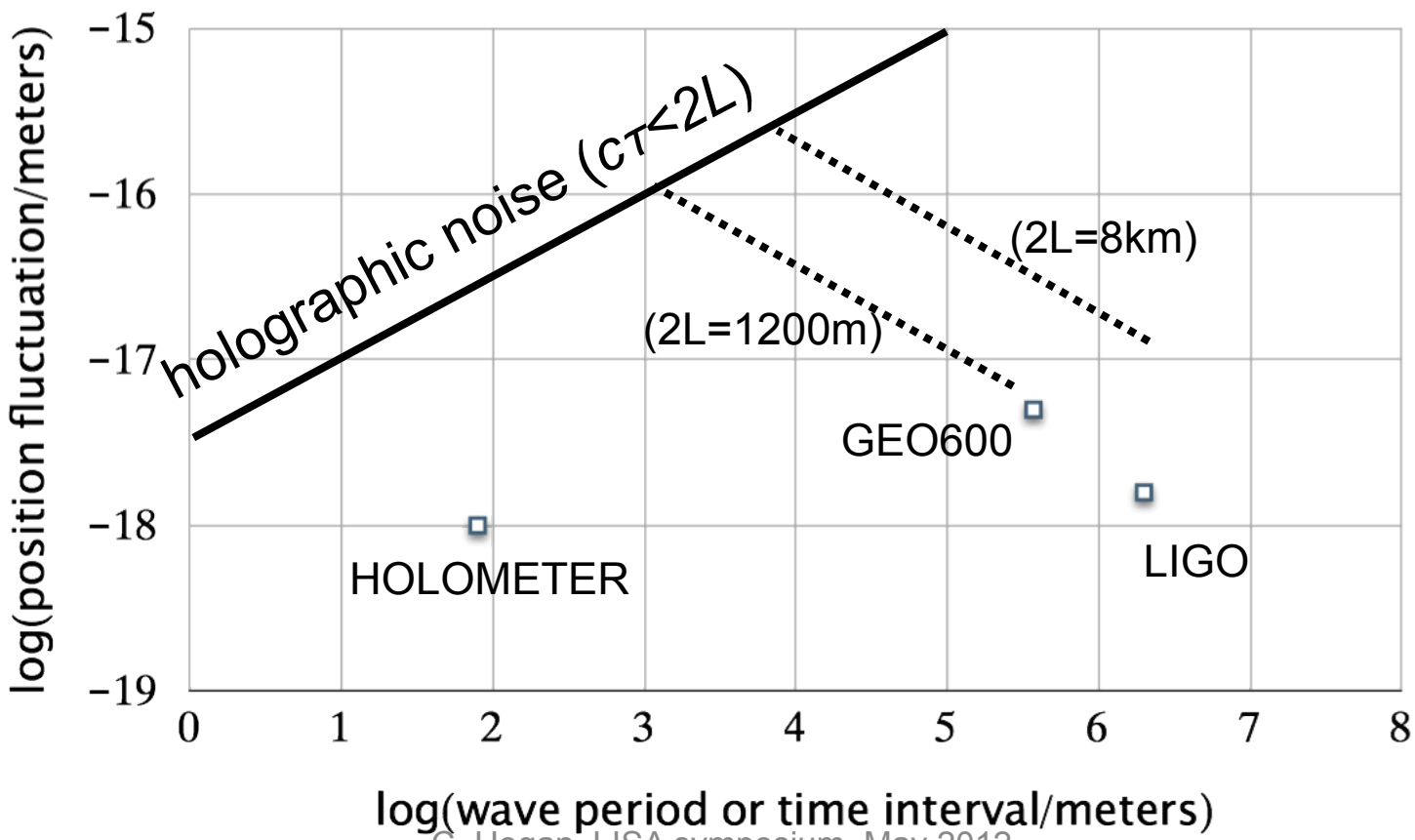

Hubble
25
15
5
−5
−15
−25
−35
Planck
−35
−25
−15
−5
5
15
25
log(length or time fluctuation)/meters)
log(length or time interval/meters)
natural systems
experiments
star
pulsar timing
human
GPS
meter stick
atomic clocks
atom
nanotech
proton
particle experiments
TeV
LISA
interferometers
log(precision)=0
holographic noise
log(precision)= -20

Quantum-Geometrical fluctuations in interferometers

Almost an important noise source for GEO 600

No fluctuation in 1D: Quantum geometry sensitivity < GW sensitivity

Fabry-Perot arm cavities of LIGO (x100), folded GEO600 arms (x2)



"Interferometers as Probes of Planckian Quantum Geometry"

CJH, Phys Rev D 85, 064007 (2012)

"Covariant Macroscopic Quantum Geometry"

CJH, arXiv:1204.5948

Phenomenon lies beyond current predictive scope of well tested theory

There is reason to suspect new physics at the Planck scale

Motivates an experiment!

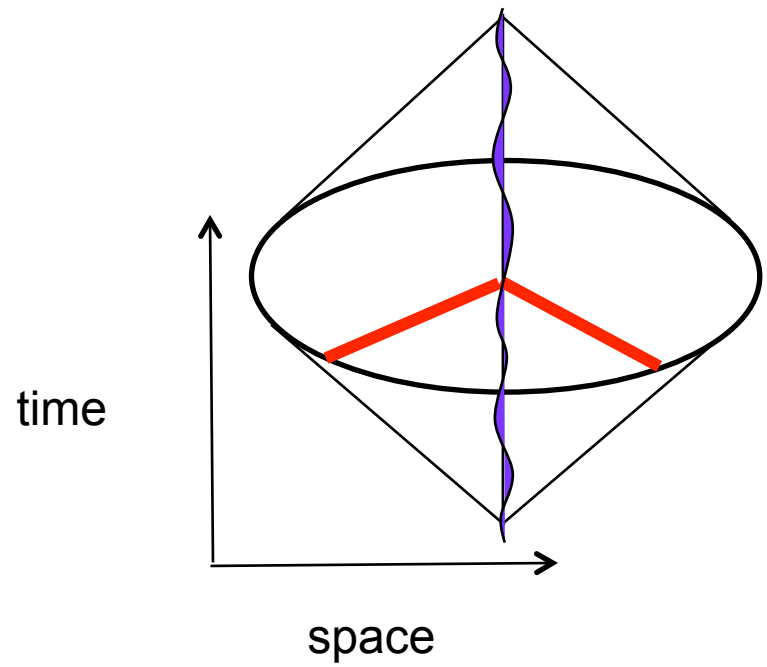
"Physics is an experimental science"

--I. I. Rabi

The Fermilab Holometer

We are developing a machine specifically to probe Planckian jitter in position:

"Holographic Interferometer"



Spacetime diagram of an interferometer

In the Oxford English Dictionary

holometer, *n*.

Pronunciation: /həʊˈlɒmɪtə(r)/

Etymology: < HOLO- *comb. form* + -METER *comb. form*[2], Compare French *holomètre* (1690 Furetière), < modern Latin *holometrum* , < Greek *ὁλο-* HOLO- *comb. form* + -METER *comb. form*[2].

A mathematical instrument for making all kinds of measurements; a pantometer.

1696 E. PHILLIPS *New World of Words* (ed. 5) , *Holometer*, a Mathematical Instrument for the easie measuring of any thing whatever, invented by Abel Tull.

1728 E. CHAMBERS *Cycl.* (at cited word), The Holometer is the same with Pantometer.

1830 *Mechanics' Mag.* **14** 42 To determine how far the holometer be entitled to supersede the sector in point of expense, accuracy or expedition.

Holometer Design Principles

Direct test for the quantum-geometrical “holographic” noise

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

Sufficient sensitivity

- Achieve sub-Planckian sensitivity
- Provide margin for prediction
- Probe systematics of perturbing noise

Measure signatures and properties of the holographic noise

- Frequency spectrum
- Time-domain correlation function

Correlated holographic noise in nearby interferometers

Matter “moves” coherently

- Nearby measurements with same orientation almost agree

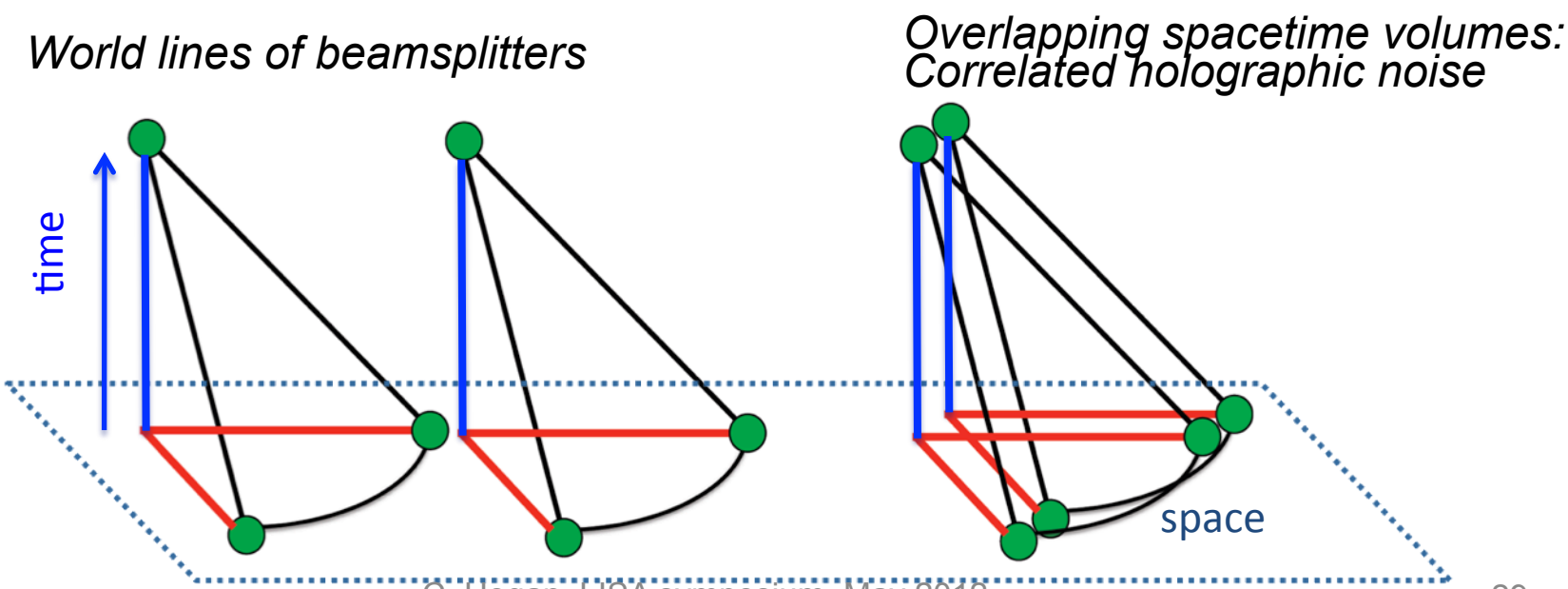
Spacelike separations within causal diamond collapse into the same state

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

measure at high frequencies (MHz) where other correlated noise is small



Dominant photon shot 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

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)
- University of Chicago (S. Meyer, CJH + students R. Lanza, L. McCuller, B. Brubaker, E. Hall, J. Zelenty, B. Kamai)
- University of Michigan (R. Gustafson)
- includes LIGO experts

Under construction at Fermilab

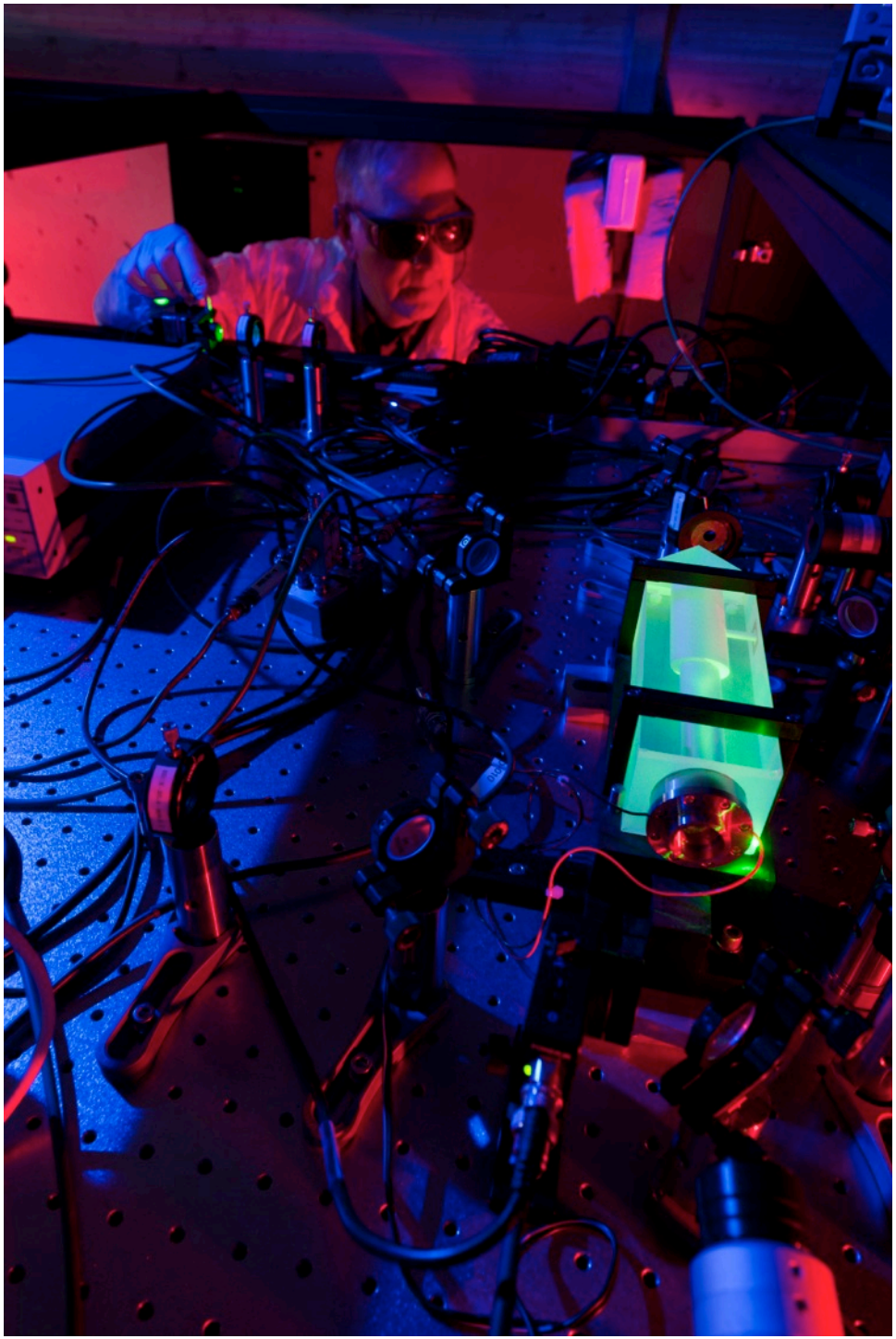
- Correlation, noise tests with blackbody radiation
- Funded mostly by A. Chou Early Career Award

Power-recycled 40m operated with finesse ~100

Developing & testing detectors, electronics, control systems

- Vacuum systems of both interferometers are complete
- Results expected in a year or two


PROFLEX

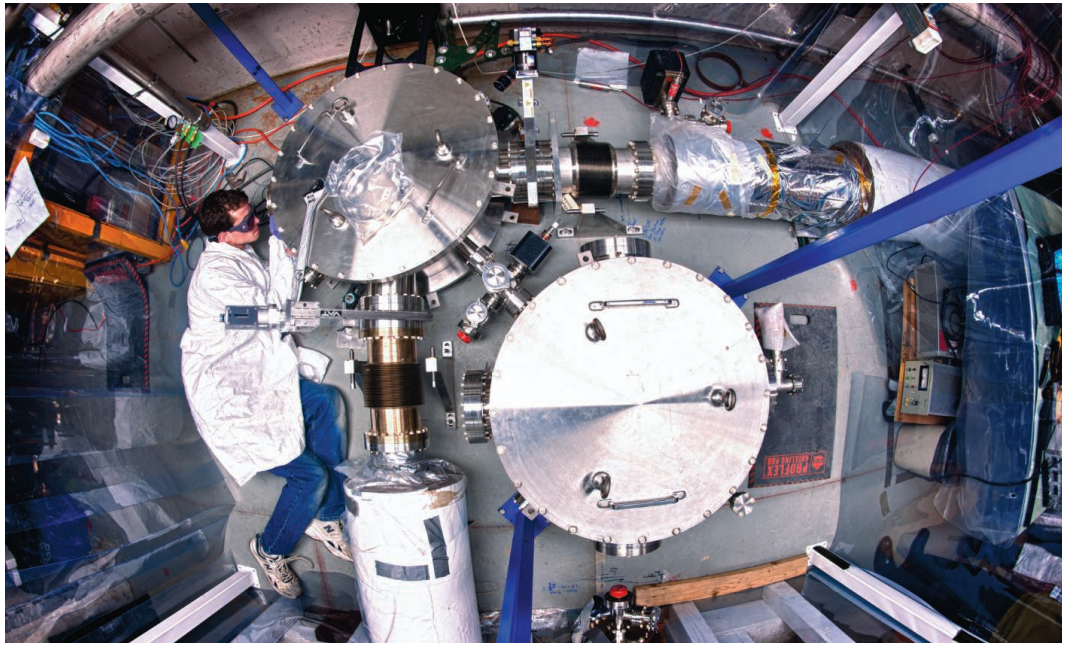


EXIT


B 10150

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

Not a test of the holographic principle!
Drives theorists nuts!



Hands-on. Student Benjamin Brubaker tinkers with the Fermilab holometer.

PHYSICS

Sparks Fly Over Shoestring Test Of 'Holographic Principle'

A team of physicists says it can use lasers to see whether the universe stores information like a hologram. But some key theorists think the test won't fly

BATAVIA, ILLINOIS—The experiment looks like a do-it-yourself project, the scientific equivalent of rebuilding a 1983 Corvette in your garage. In a dimly lit, disused tunnel here at Fermi National Accelerator Laboratory (Fermilab), a small team of physicists is constructing an optical instrument that looks like water pipes bolted to the floor.

in a room increases with the room's volume, not the area of its walls. If the holographic principle holds, then the universe is a bit like a hologram, a two-dimensional structure that only appears to be three-dimensional. Proving that would be a big step toward formulating a quantum theory of spacetime and gravity—perhaps the single biggest chal-

Not everyone cheers the effort, however. In fact, Leonard Susskind, a theorist at Stanford University in Palo Alto, California, and co-inventor of the holographic principle, says the experiment has nothing to do with his brainchild. "The idea that this tests anything of interest is silly," he says, before refusing to elaborate and abruptly hanging up the phone. Others say they worry that the experiment will give quantum-gravity research a bad name.

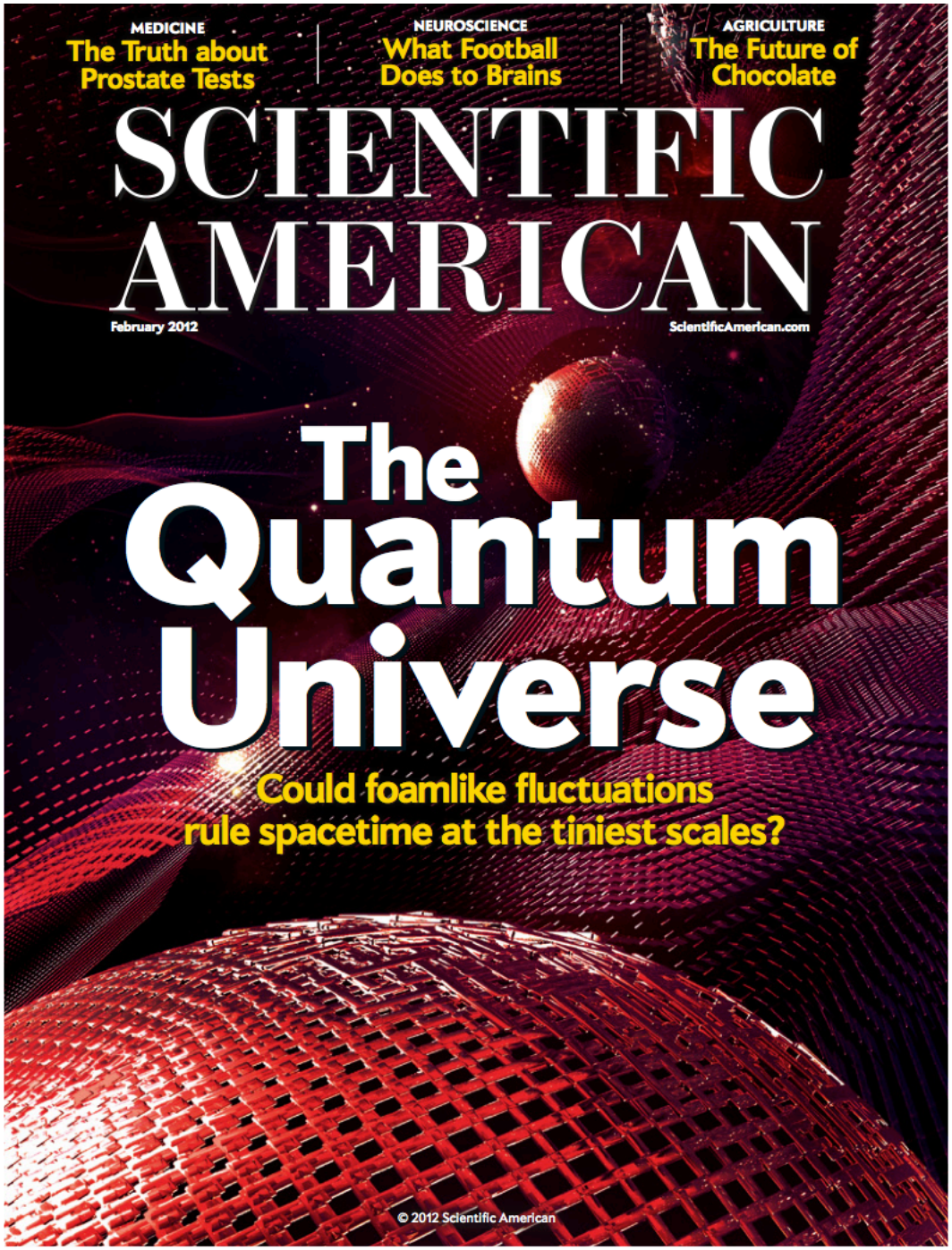
Black holes and causal diamonds

To understand the holographic principle, it helps to view spacetime the way it's portrayed in Einstein's special theory of relativity. Imagine a particle coasting through space, and draw its "world line" on a graph with time on the vertical axis and position plotted horizontally (see top figure, p. 148). From the particle's viewpoint, it is always right "here," so the line is vertical. Now mark two points or events on the line. From the earlier one, imagine that light rays go out in all directions to form a cone on the graph. Nothing travels faster than light, so the interior of the "light cone" contains all of spacetime that the first event can affect.

Similarly, imagine all the light rays that can converge on the later event. They define another cone that contains all the spacetime that can influence the second event. The cones fence in a three-dimensional, diamond-

Not foamlike!

Not at the edge of the universe!



Physics Outcomes

If noise is not there,

- Set a Planckian upper limit on commutator in a certain interpretation of noncommutative geometry
- Information density of macroscopic positions > holographic bound

If it is detected,

- experiment probes Planck scale unification
- Study emergence of classical spacetime from quantum system
- Shape interpretation of fundamental theory