Interferometry and Quantum Geometry

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Quantum Geometry

Classical geometry: points (events), lines, surfaces

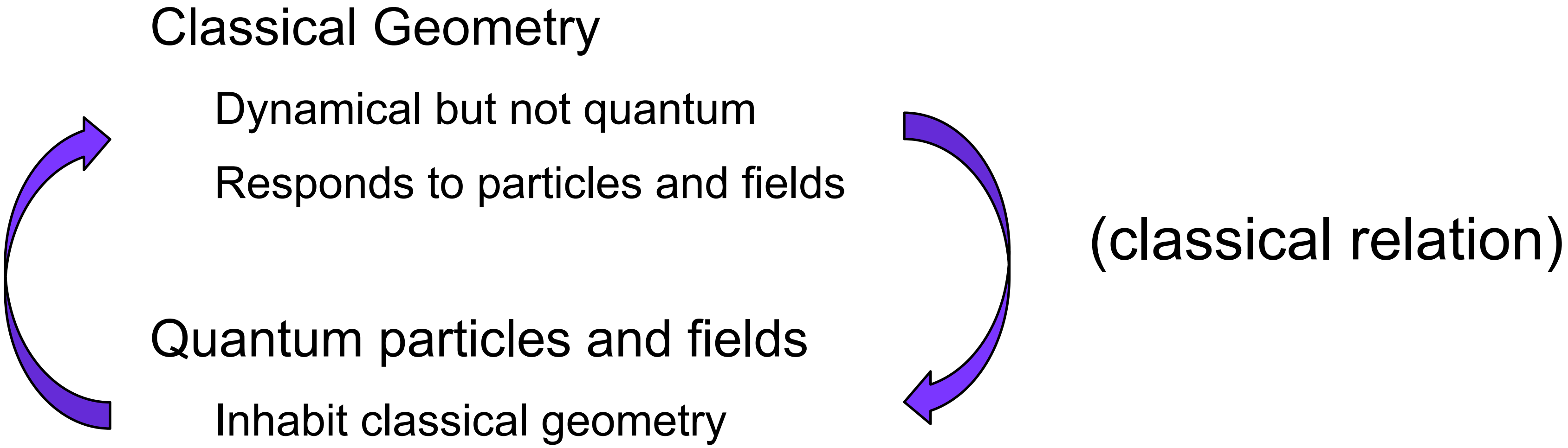
Quantum physics: nothing happens at a definite time or place

Geometry exists only to the extent it can be measured

All measurements are quantum

How does quantum geometry work?

Architecture of Physics



Classical Geometry

- Dynamical but not quantum
- Responds to particles and fields

(classical relation)

Quantum particles and fields

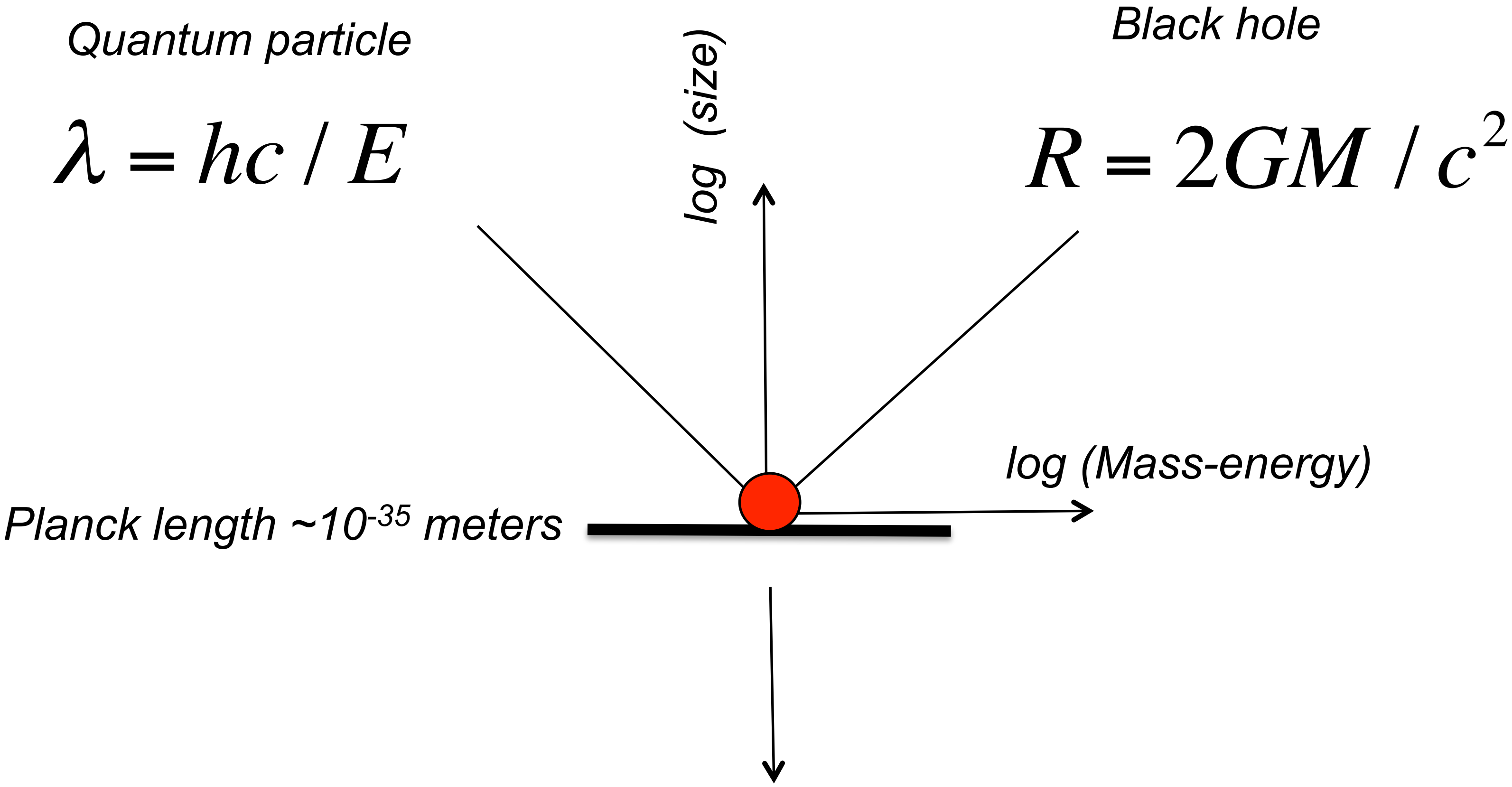
- Inhabit classical geometry

Explains almost everything, but cannot be the whole story

- Cosmic acceleration
- Thermodynamic, holographic behavior of gravity
- Nonlocality of quantum physics
- Incompatible foundations: classical and quantum definitions of position
- Dynamical classical geometry inconsistent beyond the Planck scale

Planckian Quantum Geometry

Dynamical geometry must be quantum beyond the Planck scale



Quantum particle

$$\lambda = hc / E$$

Black hole

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

Planck length ~10^{-35} meters

New Planck scale 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 observable effects on larger scales

Emergent Space-time

Perhaps classical space-time is an approximate behavior of a quantum system over long durations

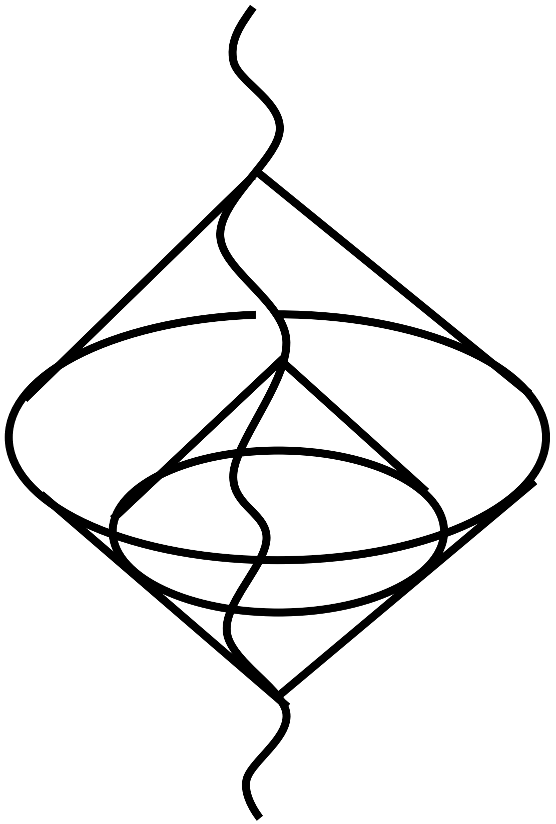
Locality, direction, separation of scales may only acquire meaning after many Planck times

Quantum matter entangles with geometrical degrees of freedom

Some quantum-geometrical degrees of freedom may not be describable using quantum fields or metric fluctuations

New Planckian effects may not be confined to Planck scale

Quantum Geometry of Emergent Space-time



Space-time is defined as a quantum system relative to a world line

States are nonlocal and holographic, encoded on 2D surfaces of causal diamonds

Hilbert space represented by *NxN* matrix, where *N* is the duration in Planck units (ticks of a Planckian clock)

Causal structure and Lorentz covariance are built in; gravity is statistical

“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

transform like classical positions on large scales

Form dictated by covariance

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

(Commutator depends on world-line of coordinates)

Interpret as a quantum relationship in emergent space-time between two timelike trajectories

Quantum-Geometrical Uncertainty of position

In the rest frame, commutator in 3D at one time:

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

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

geometrical wave function describes positional relationship between any 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: quantum geometry

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 commutator

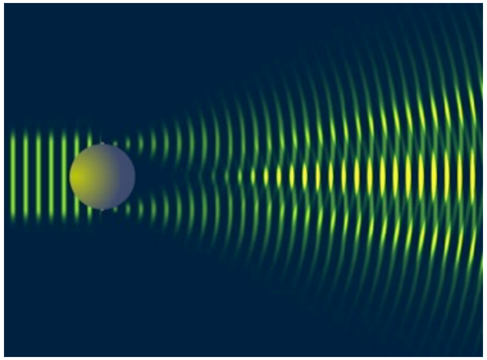
Approach to the classical limit

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

Far fewer degrees of freedom

Directions have intrinsic “wavelike” uncertainty

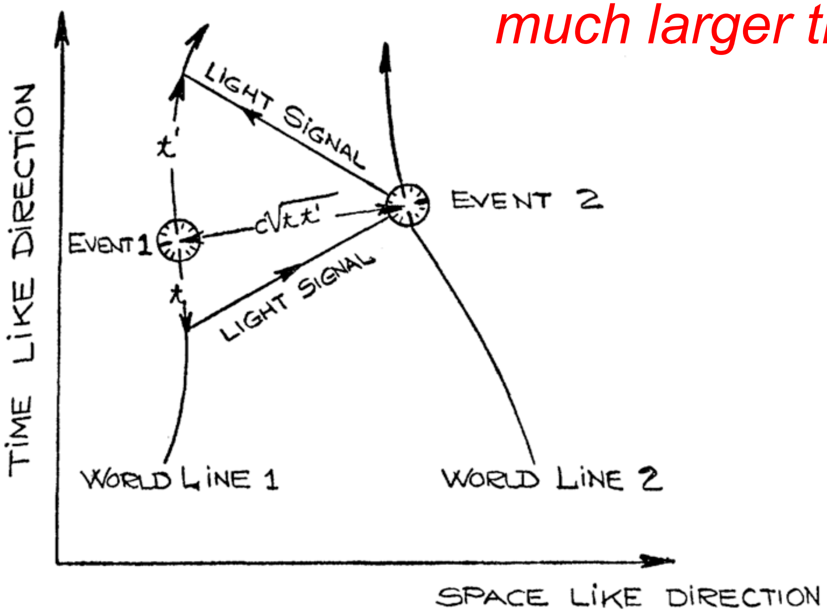
Wave interpretation

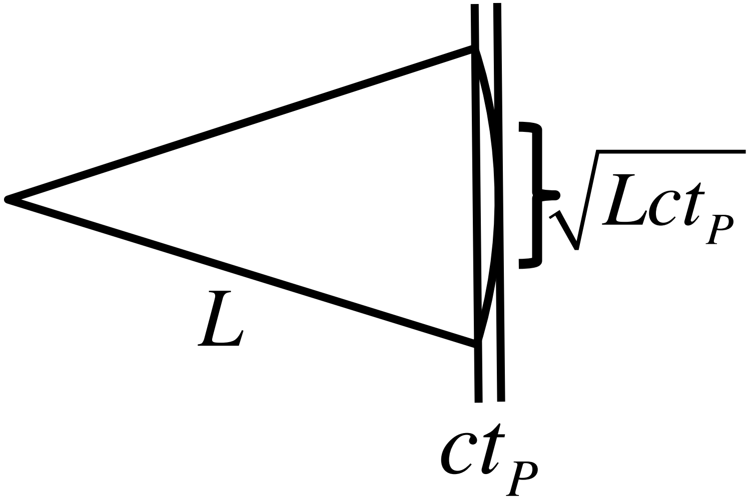
Spacelike-separated event intervals are defined with clocks and light

But transverse positions defined by Planckian waves are uncertain by the diffraction limit,

$$\sqrt{Lct_P}$$

much larger than the Planck length

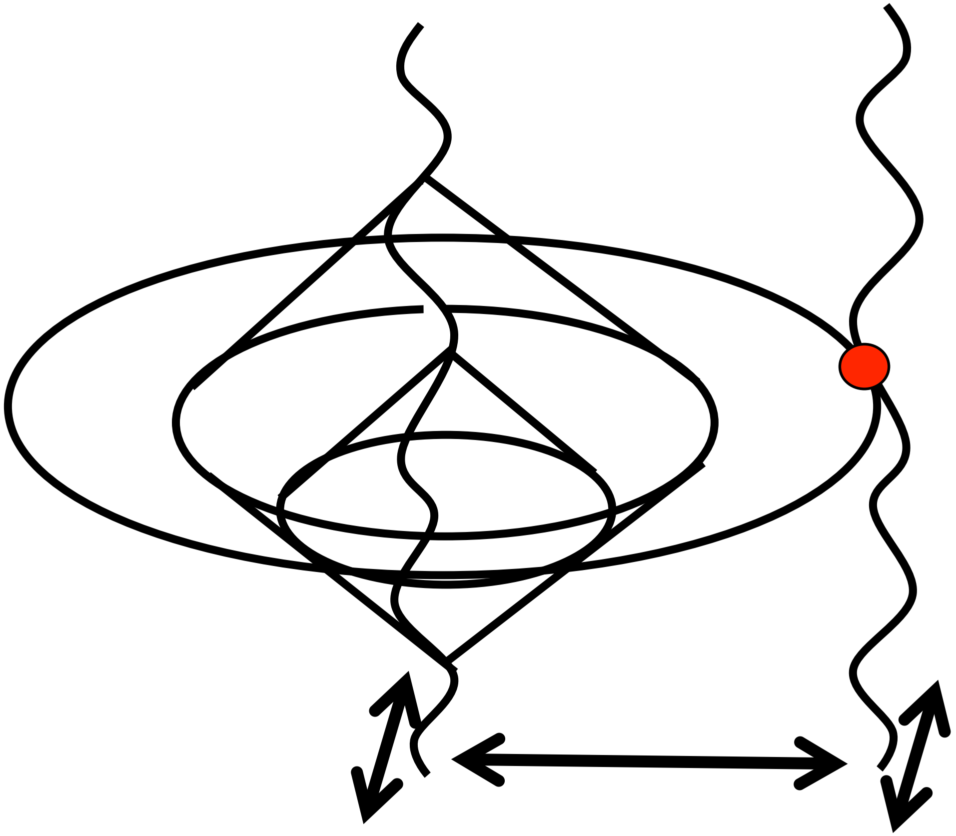




Wigner (1957): quantum limits with one spacelike dimension and physically-realizable clocks

Add transverse dimension and Planck frequency limit: new position uncertainty

Quantum-geometrical uncertainty and fluctuations



$$\Delta x \sim \sqrt{ct_P L}$$

Transverse uncertainty >> Planck length for large L

→fluctuations in nonlocal transverse position

Coherence of Quantum-Geometrical Fluctuations

Larger scale modes dominate total displacement

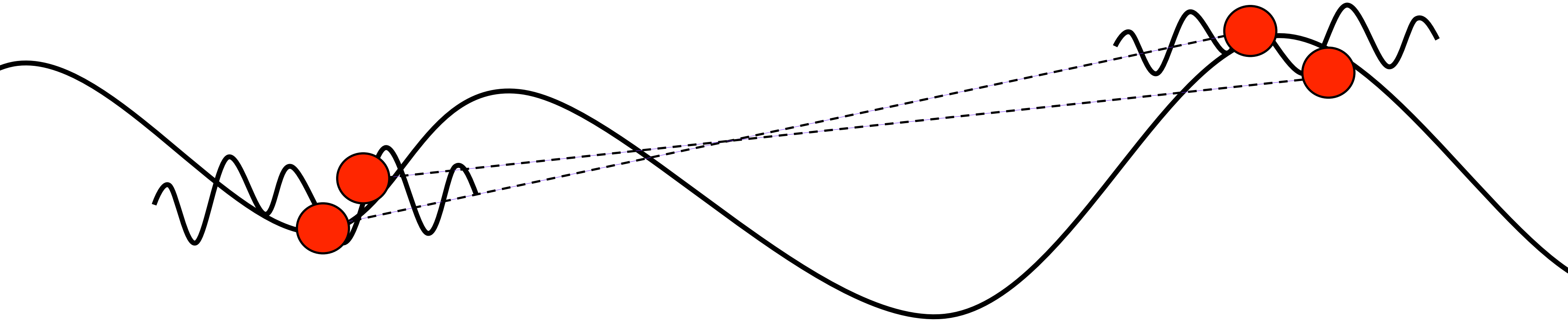
Displacement of nearby bodies is not independent

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

Depends only on position and no other property of a body

Geometrical position states of neighboring bodies are entangled

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



Quantum Geometry is only important for large masses

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

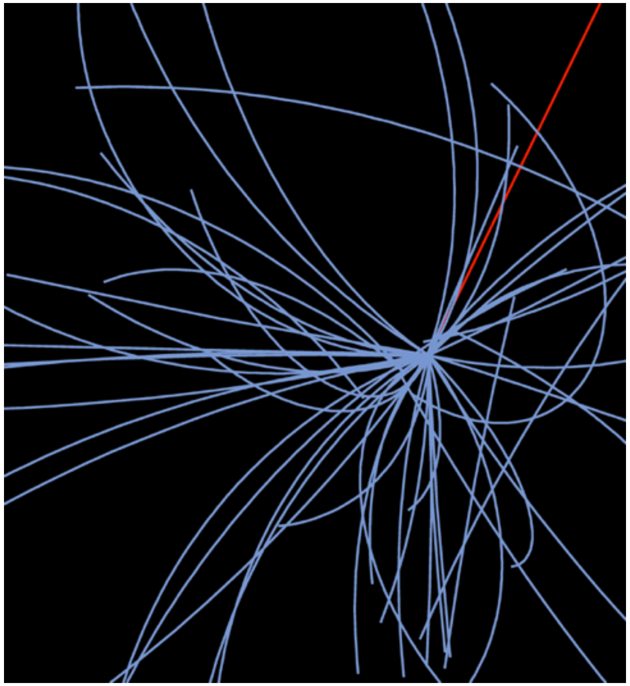
$$\Delta x^2 \equiv \langle (x(t) - x(t+\tau))^2 \rangle \geq 2\hbar\tau/m$$

(standard interferometer limit)

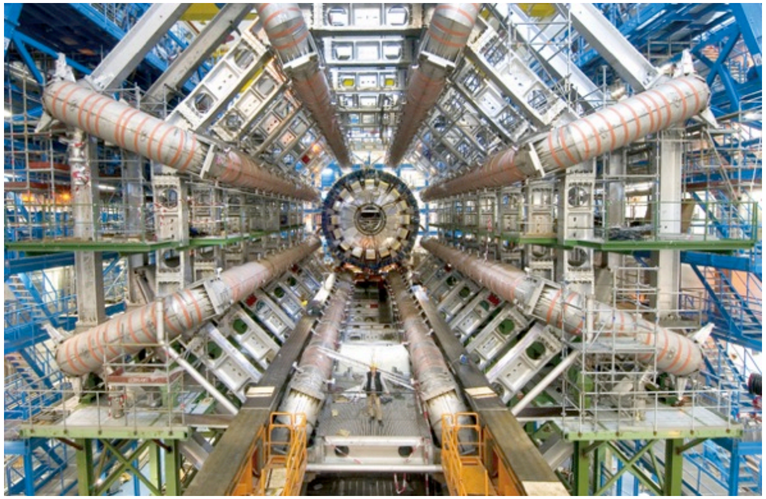
This dominates geometrical uncertainty unless mass is greater than the Planck mass

Field theory works great for elementary particle experiments (localized, but much larger than Planckian)

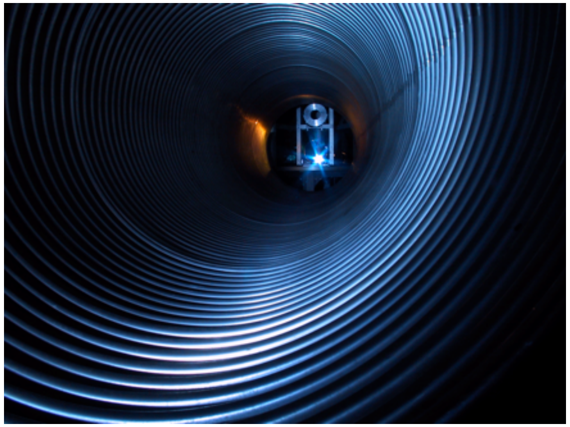
Two ways to study small scales



particle colliders measure microscopic products of localized events



Interferometers compare macroscopic positions of massive bodies: better to probe emergent Planckian quantum geometry



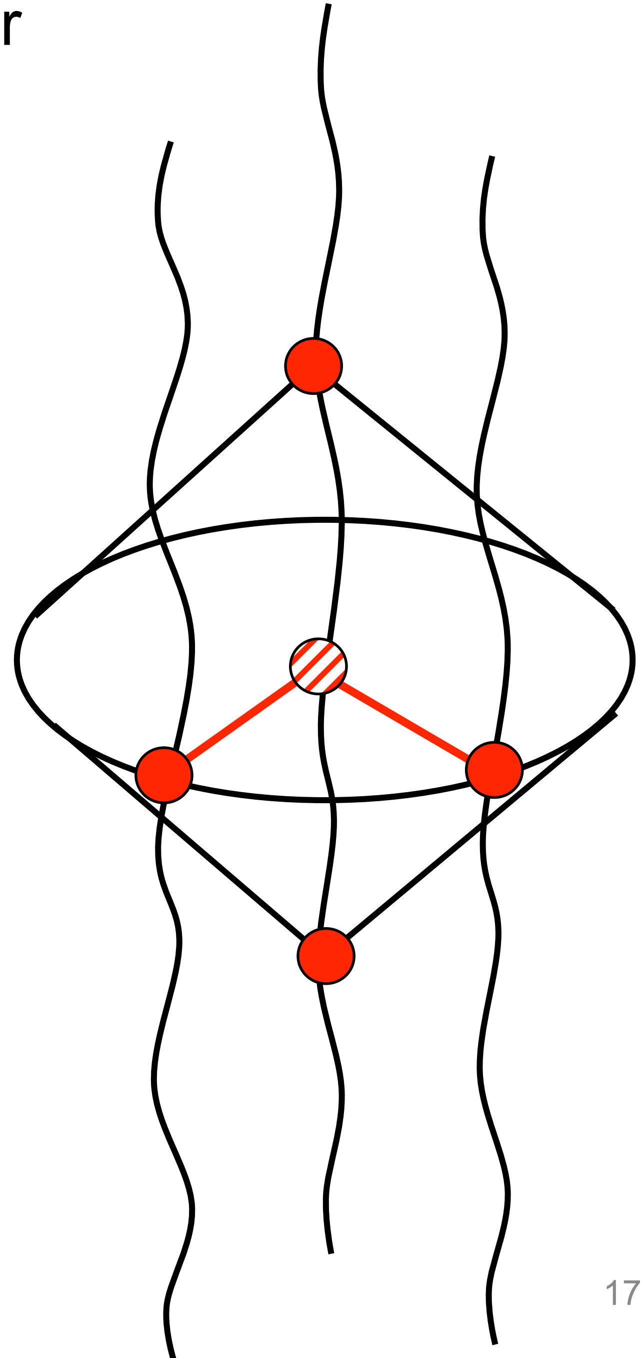
Space-time of Michelson interferometer

3 world lines: beamsplitter and two end mirrors

3 overlapping, entangled world cylinders

4 events contribute to interferometer signal at one time ●

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



Quantum-geometrical noise in Michelson interferometer

Signal measures difference of beamsplitter position in two noncommuting directions

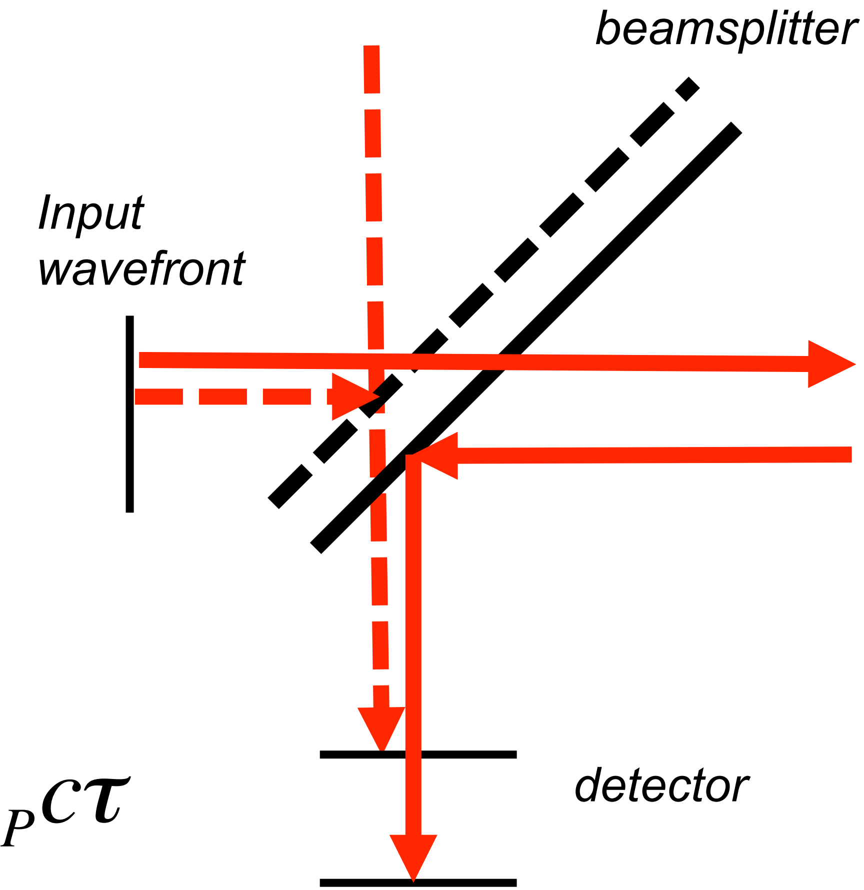
Causal diamond duration is twice the arm length

Geometrical uncertainty leads to fluctuations

$$\Delta x_{12}^2 \approx 2\Delta x_1 \Delta x_2 \approx l_P c\tau$$

For durations

$$c\tau < 2L$$



Interferometers can reach Planckian sensitivity

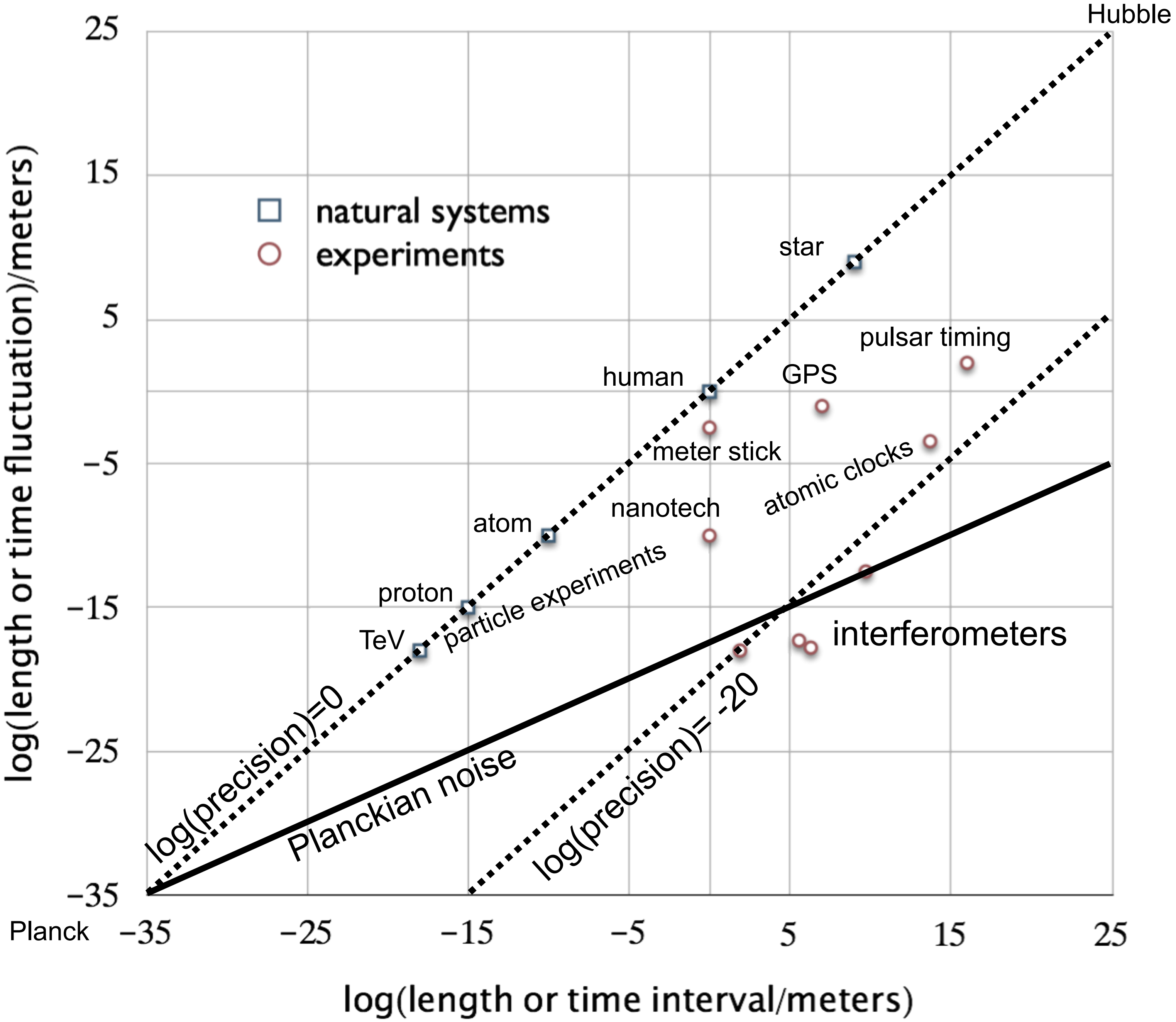
Over short (~ size of apparatus ~ microsecond) time intervals, interferometers can reach Planck precision (~ attometer jitter)

Fractional random variation in differential frequency or position between two directions over time interval $\boldsymbol{\tau}$

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

Compare to best atomic clocks (over longer times):

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


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

Response of simple Michelson interferometer

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

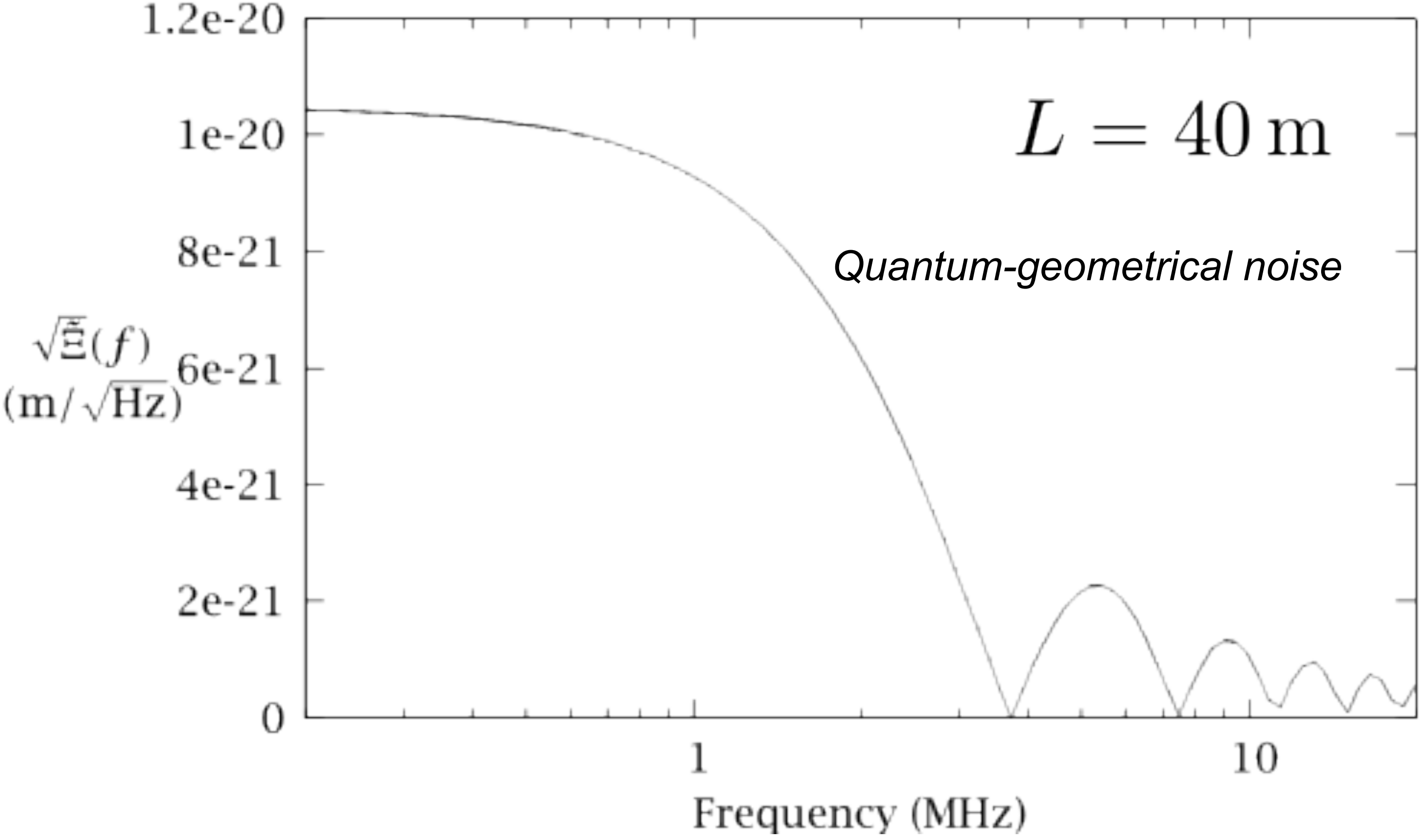
$$\tilde{\Xi}(f) = \frac{4c^2 t_P}{\pi(2\pi f)^2}[1 - \cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$

Depends only on Planck scale and L

Measured noise is not sensitive to modes longer than 2L

Interferometer position noise spectrum, including transfer function

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

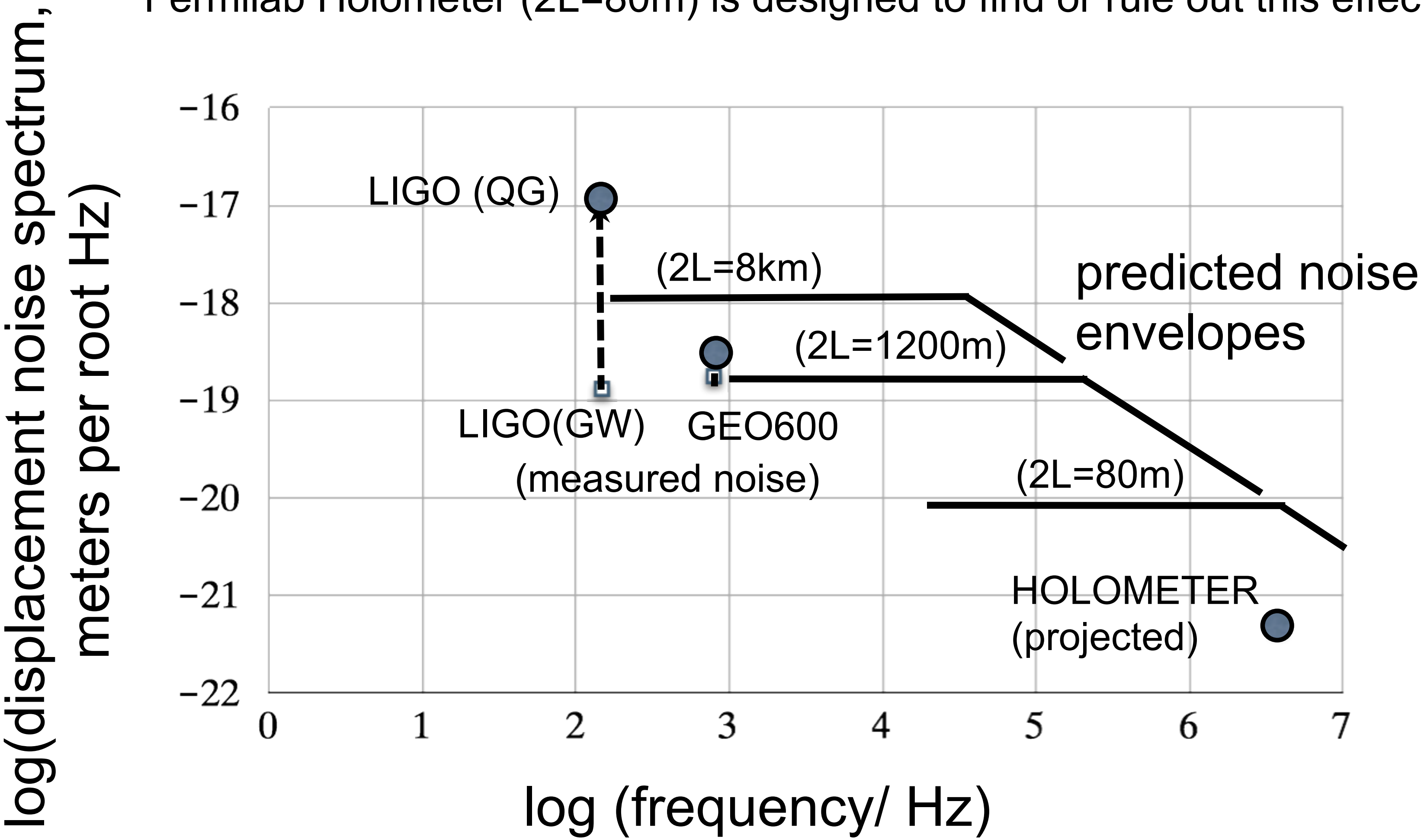


Quantum-Geometrical noise in interferometers

LIGO (2L=8km) design is better for gravitational waves, not for quantum geometry

GEO600 (2L=1200m) is already close to quantum geometry prediction

Fermilab Holometer (2L=80m) is designed to find or rule out this effect



“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!

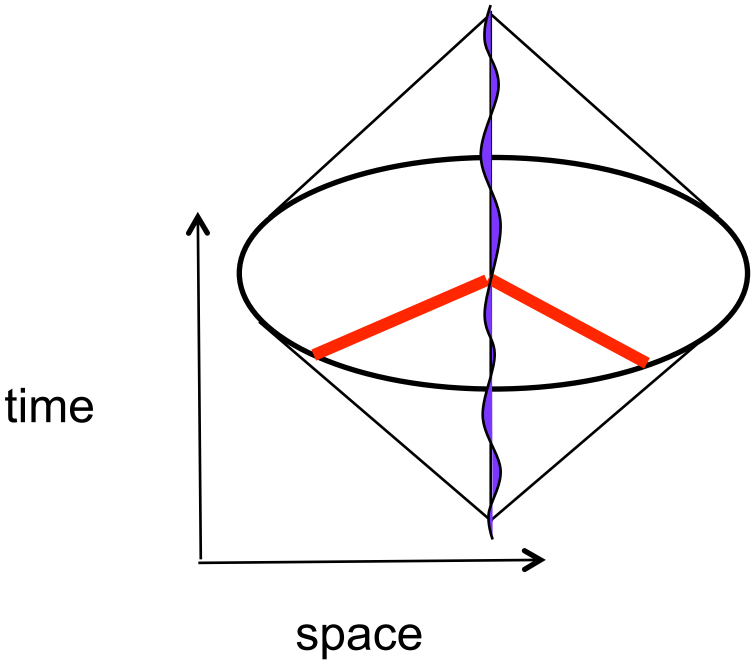
> *“Physics is an experimental science”*
>
> *--I. I. Rabi*

The Fermilab Holometer

We are developing a machine specifically to probe Planckian position fluctuations:

"Holographic Interferometer"

More detail: talk by J. Steffen



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 quantum-geometrical 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 quantum-geometrical noise

- Frequency spectrum
- Time-domain correlation function

Experiment Concept

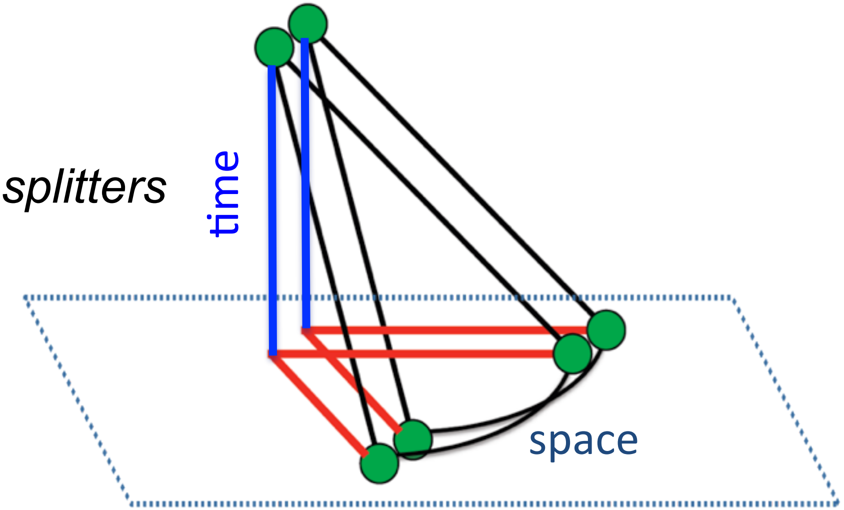
Measurement of the correlated optical phase fluctuations in a pair of isolated but collocated power recycled Michelson interferometers

exploit the spatial coherence of quantum-geometrical noise

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

Overlapping spacetime volumes -> correlated fluctuations

World lines of beamsplitters



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

Under construction at Fermilab

- Funded mostly by A. Chou Early Career Award

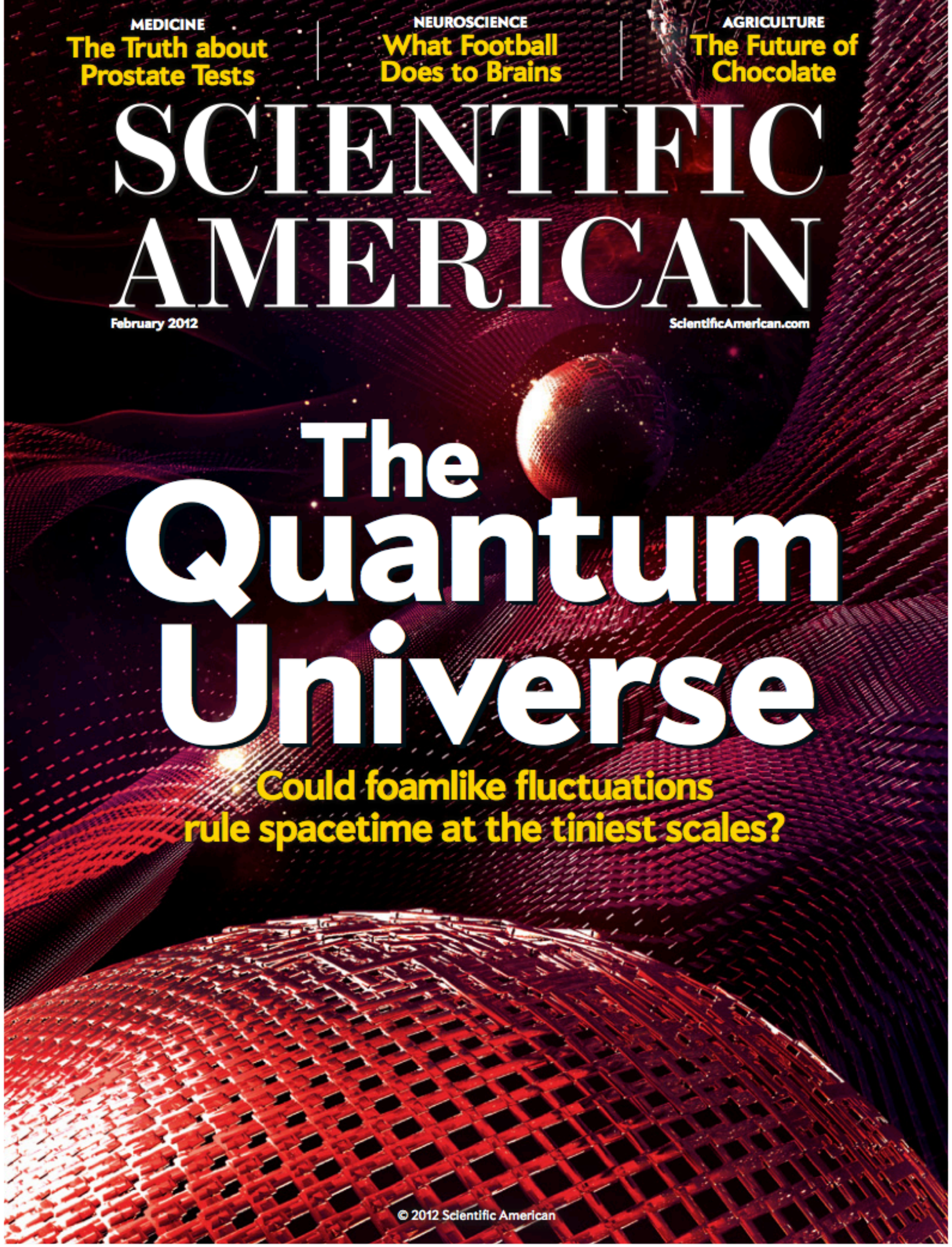
Power-recycled 40m interferometer operated with finesse ~100

Developing & testing detectors, electronics, control systems

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

Not foamlike!

Not at the edge of the universe!



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February 2012

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The Quantum Universe

Could foamlike fluctuations rule spacetime at the tiniest scales?

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

NEWS**FOCUS**

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-

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

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-

Physics Outcomes

If noise is not there,

Set a sub-Planckian upper limit on commutator, in a certain interpretation of emergent space-time

Information density of macroscopic positions > holographic bound

If it is detected,

experiment probes Planckian quantum geometry

Information density of macroscopic positions ~ holographic bound