The Fermilab Holometer

A Probe of Planckian Quantum Geometry

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Γεωμετρία

Geometry: “measure the world”

Space is defined by classical relationships:

points and lines

2300 years ago: Euclid

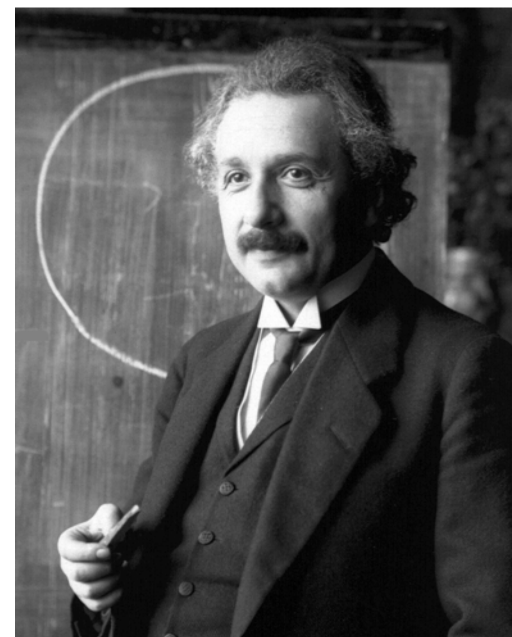
Geometry and physics

Newton: "absolute" space and time

- Matter in continuous motion
- Space is a passive "stage"

Einstein: unified space-time

- General Relativity: *dynamical* geometry
- Geometry participates: exchanges energy and information with matter
- *"Space-time tells matter how to move, and matter tells space-time how to curve" -J. Wheeler*
- Still classical: definite events, continuous paths



Quantum Revolution

Starting in 1900: a new theory of matter

Still not reconciled with dynamical geometry





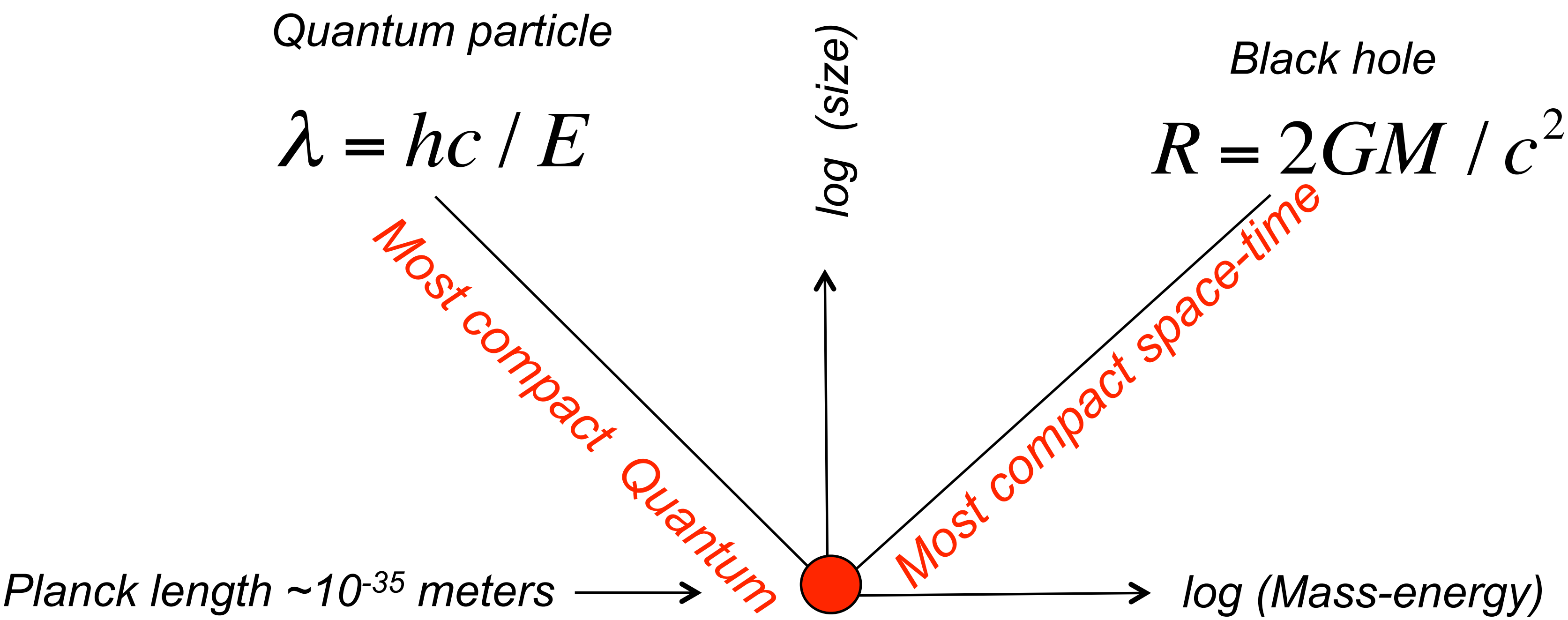
"Planck scale": gravity + quantum

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

equivalent Planck length ~10^{-35} meters

Far too small to observe directly

Dynamical geometry is inconsistent with quantum mechanics at the Planck scale

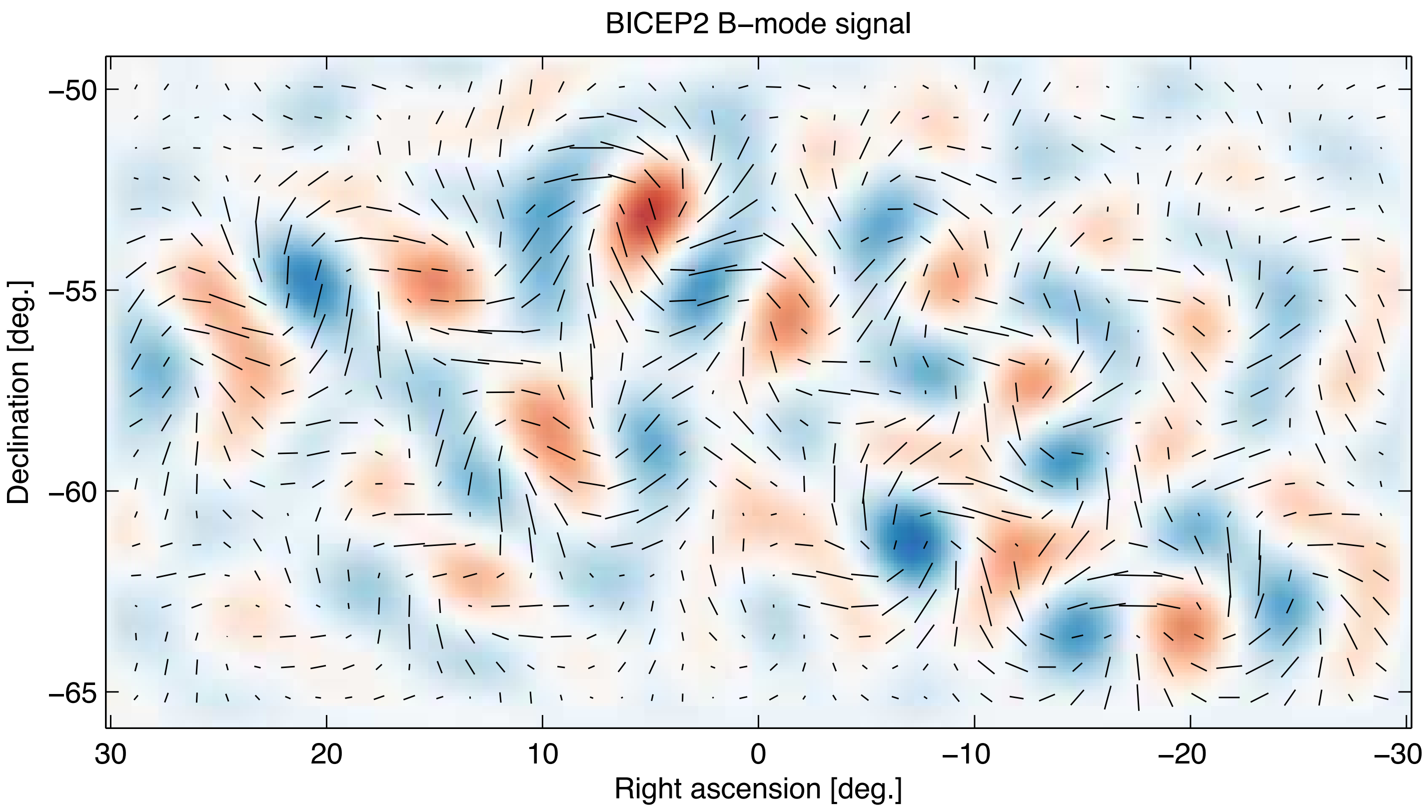


Forbidden by both quantum mechanics and gravity

March 2014: Swirling signature of tensor modes at recombination, seen in CMB polarization

Attributed to primordial graviton-like quanta

Points to Planck scale quantum physics during inflation



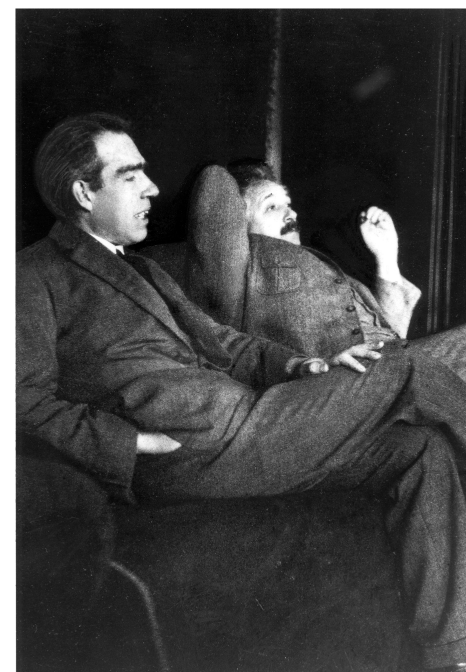
Quantum Physics, Locality, and Geometry

Classical geometry is based on locality

- Everything happens at a definite place and time
- Events are labeled by coordinates, map onto real numbers
- Also true in General Relativity

Quantum physics (and reality) do not respect locality

- Nothing happens at a definite place or time
- Interactions are represented by operators on states
- In a general state, delocalization is macroscopic
- Proven by EPR/Bell-type experiments



A major controversy in the early 20th century

Partially reconciled by *quantum field theory*

Quantum Field Theory

Classical Geometry ("space-time")

- Dynamical but not quantum
- Responds to classical local average of particle/field energy

Quantum particles and fields

- Quantize spatially nonlocal field modes (e.g., plane waves) in a classical geometry
- Local interactions, nonlocal states

Geometry and field mode spatial structure are ***continuous, determinate and classical****: not part of the quantum system*

Explains all experiments with particles

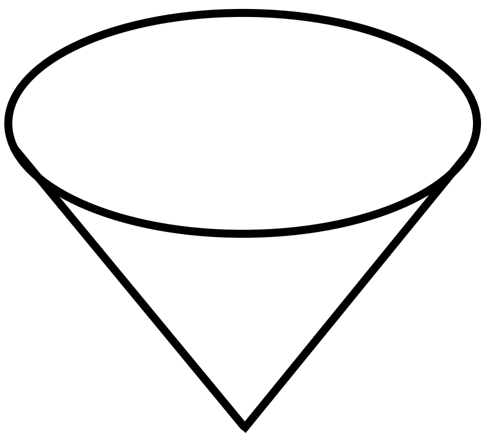
But a dynamical geometry that exchanges energy and information with quantum matter cannot be classical

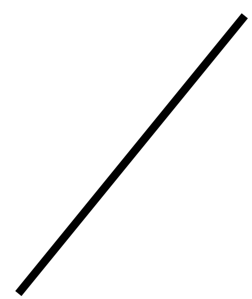
quantum and classical systems can't respond to each other

Dynamical geometry must be quantum on all scales

Consider the gravity of photon state

- Wave function instantaneously and retroactively changes on detection
- No limit to the size
- Geometry that interacts with quantum matter must be a quantum system





Photon path wave function before detection

After detection

Dynamical geometry may be a statistical behavior

Theory suggests a statistical origin of gravity

- Bardeen et al. laws of black hole thermodynamics
- Beckenstein- Hawking black hole evaporation
- Unruh radiation
- Jacobson thermodynamic formulation of GR
- Verlinde entropic formulation of Newtonian gravity and GR

Then, metric does not describe fundamental degrees of freedom

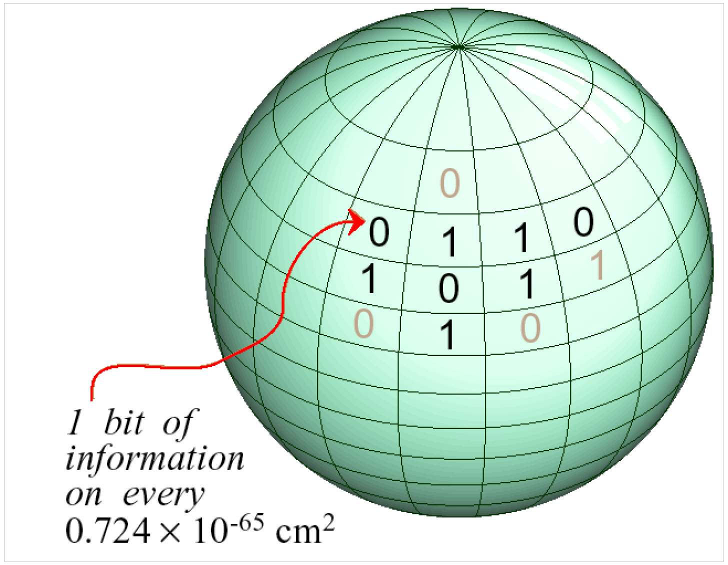
Classical space-time is a statistical approximation of a quantum system

Physical states may be holographic

Information encoded with Planck density on 2D bounding surfaces

- ‘t Hooft, Susskind holographic principle
- Maldacena ADS/CFT dualities in string theory
- Bousso covariant entropy bound: “causal diamonds”
- Banks theory of emergence

Requires new forms of spatially nonlocal entanglement that are not included in field theory



Challenges for Quantum Field Theory

Quantum states do not obey locality

- Yet locality is the basis of relativity
- Field theory assumes classical nonlocal structure of states
- Particle creation entails instant nonlocal occupation of a macroscopic state

Inconsistency at the Planck scale

- At the Planck scale, geometry is indeterminate
- Inflation with now-observed large B modes requires UV completion beyond field theory

Gravitational theory suggests that gravity and geometry are statistical

- GR can be derived and interpreted thermodynamically
- Requires new fundamental degrees of freedom (not the metric)

Physical states appear to be holographic and nonlocal

- Information encoded with Planck density on 2D bounding surfaces
- Much less information than field theory
- States must have new forms of spatially nonlocal entanglement

Physics needs to go beyond the approximations of quantum field theory

Not all of these issues are as yet addressed by string theory

Macroscopic effects of quantum geometry

Quantum field theory assumes classical space-time; predicts that Planck scale effects are highly suppressed at large scales

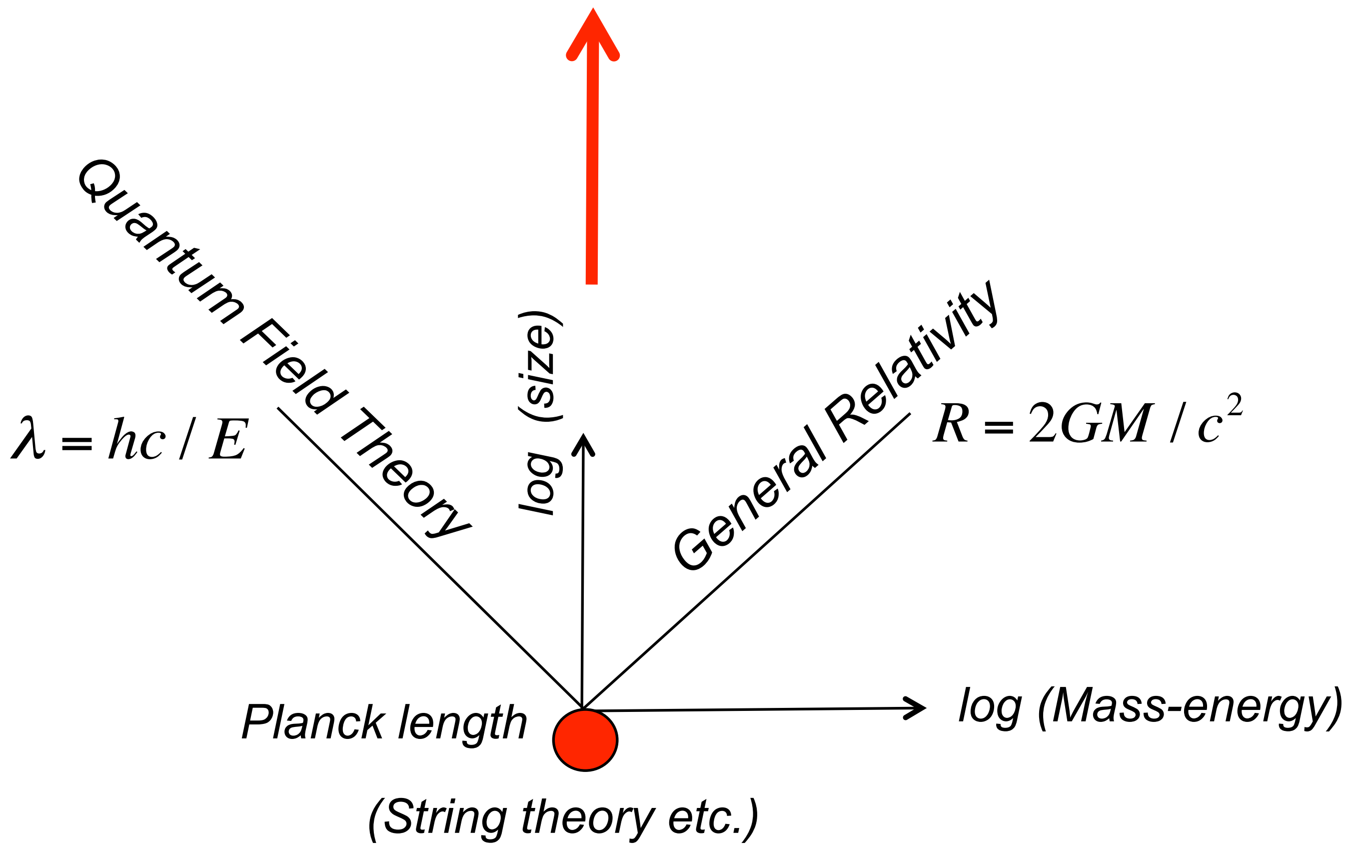
Also true in string theory, using fields for macroscopic limit

But quantum geometry may have new degrees of freedom, different from either field theory or general relativity

Planckian effects may be observable on macroscopic scales

Not confined to Planck scale “quantum foam”

Is there quantum behavior of macroscopic geometry?



Deviations from classical geometry on larges scales must be small enough to agree with experiments, but may be larger than minimal deviations in field theory

Space-time as an information bounded system

Perhaps positions are encoded in a wave function with the information capacity of Planck frequency carrier wave

(a Planckian Shannon channel)

Positional precision is subject to a Planck bandwidth limit,

$$\approx 10^{43}$$ bits per second

Measurement of position is limited to this fidelity

This hypothesis is sufficient to estimate macroscopic geometrical indeterminacy without further knowledge of fundamental theory

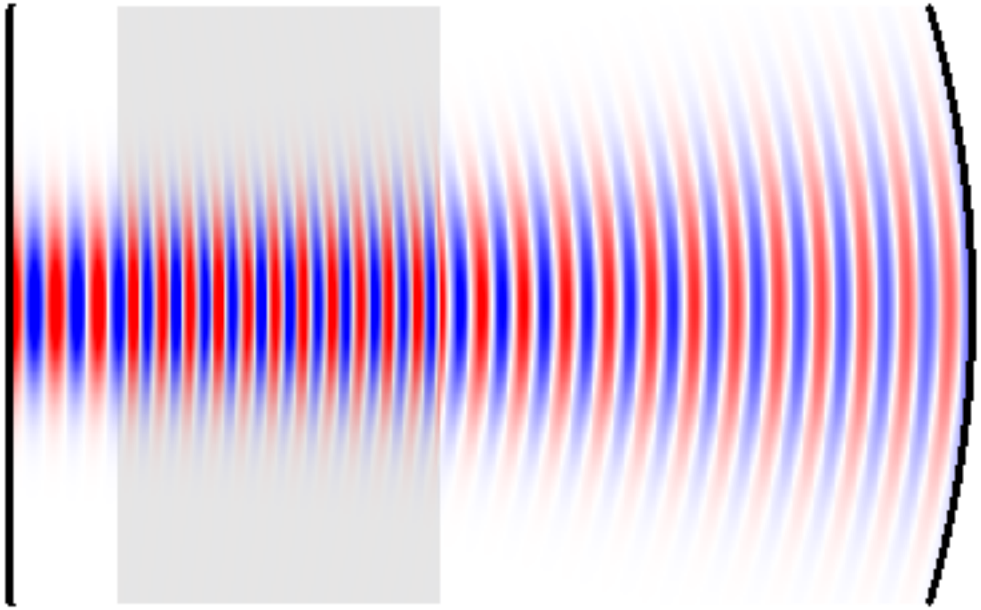
Corresponds to information in holographic gravity

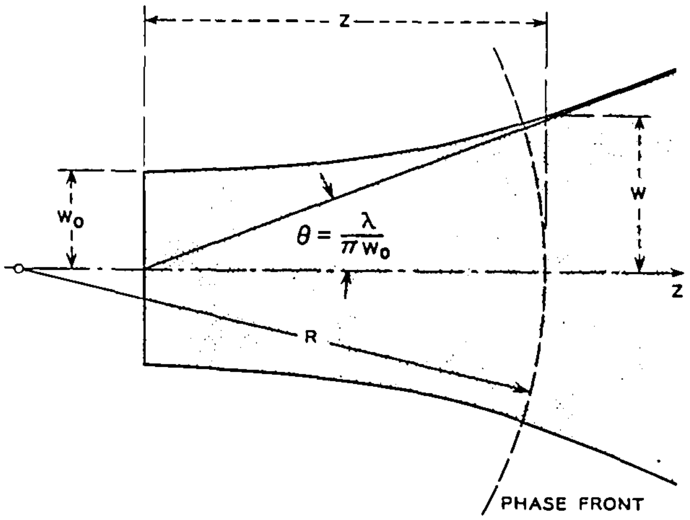
Waves have finite directional resolution

Any particle wave function has a *directional resolution bound*
For a massless field,

$$\langle \Delta\theta^2_{min} \rangle = w^2_{min}/z^2 = \sqrt{2}\lambda/\pi z$$

Planck resolution bound may apply to geometry





Planck diffraction scale of directional resolution

$$\langle \Delta\theta^2 \rangle = ct_P/\sqrt{4\pi}L$$

(Exact normalization comes from gravitational information; best estimate is based on noncommutative position algebra)

Directions indeterminate at the Planck scale

Approximately classical on scales larger than the Planck length

Directional entanglement of quantum geometry and fields

Posit that *states cannot exceed Planck diffraction limit on directional information*

On large scales, standard plane wave field modes violate this bound even far below Planck frequency

Fields are ***directionally entangled*** with Planckian geometry

Reduces information content: **agrees with holographic gravity**

Little effect on particle experiments

- Affects only measurements in large systems and two directions
- Same scale as "IR cutoff" hypothesis of Cohen, Kaplan & Nelson
- (Prevents quantum field states from exceeding black hole mass)
- Eliminates fine tuning of field vacuum energy

Transverse position uncertainty

Planck bound on directional information leads to diffractive indeterminacy of position wave function transverse to separation:

$$\langle x_\perp^2 \rangle = Lct_P/\sqrt{4\pi} = (2.135 \times 10^{-18}\mathrm{m})^2 (L/1\mathrm{m})$$

quantum departure from classical geometry

increases with radial separation L

purely transverse to separation: "directional uncertainty"

Preserves classicality of radial separation, causal structure

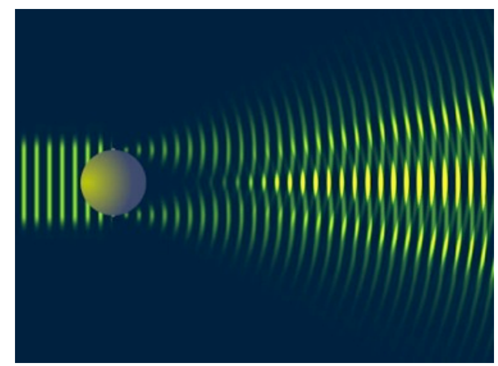
Approach to the classical limit

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

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

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

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



Not the classical limit of field theory

Far less information

Directions have intrinsic "wavelike" uncertainty

Planckian directional uncertainty only dominates normal quantum mechanics for large masses

Standard quantum limit for uncertainty of position over time interval tau:

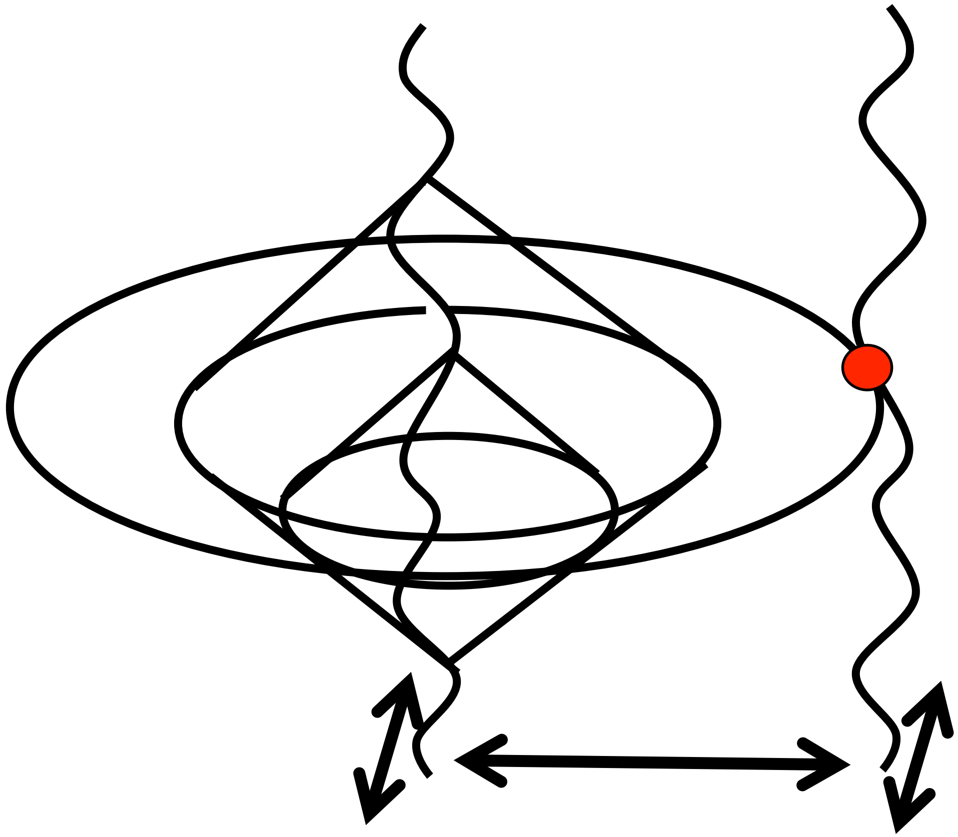
$$\Delta x^2_{SQL} \equiv \langle (x(t) - x(t+\tau))^2 \rangle \geq 2\hbar\tau/m$$

> geometrical uncertainty, for mass < Planck mass

Field theory works great for elementary particles

But positions of large masses may have Planckian quantum-geometrical directional uncertainty larger than standard quantum theory

Quantum-geometrical uncertainty and fluctuations



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

Transverse uncertainty >> Planck length for large L

→fluctuations in transverse position on timescale L/c

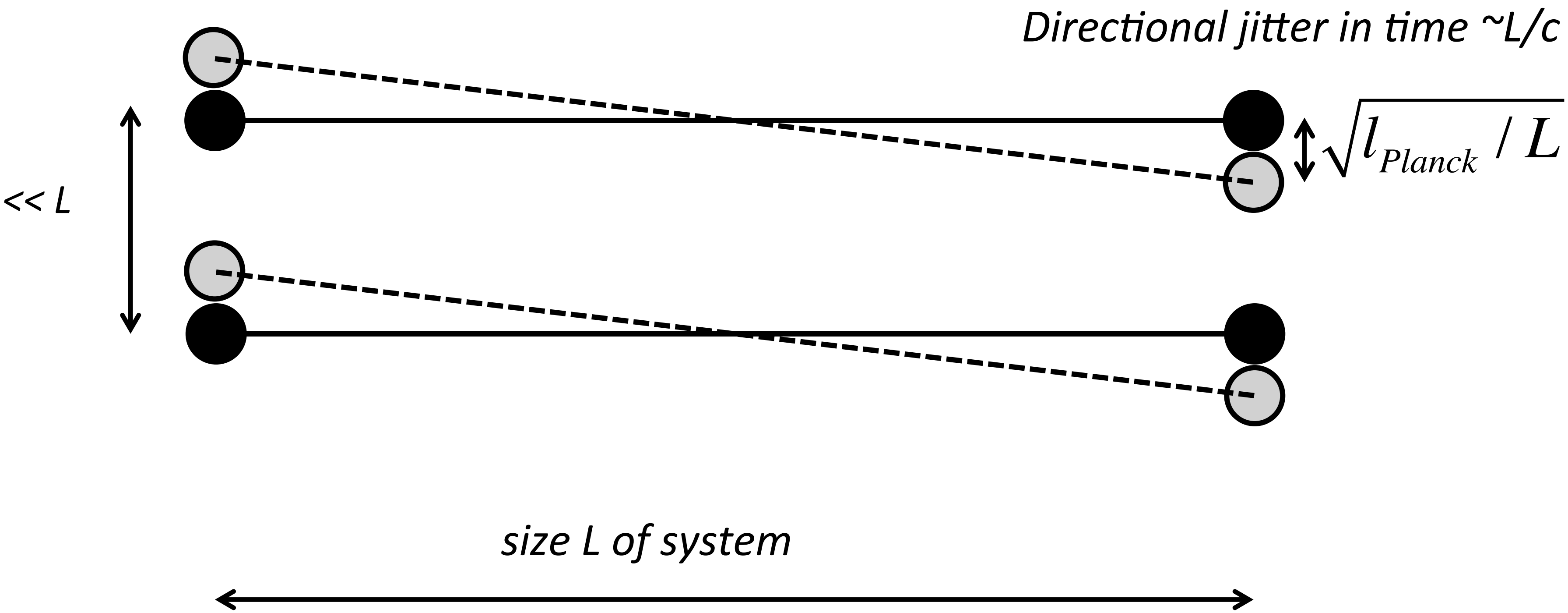
Planckian directional fluctuations

Directional fluctuation ~ diffraction scale of Planck wavelength

Timescale ~ system size

Directions to nearby bodies are entangled

Directional states are entangled (~ same jitter) for separations << L



Coherence of Quantum-Geometrical Fluctuations

Larger scale modes dominate total displacement

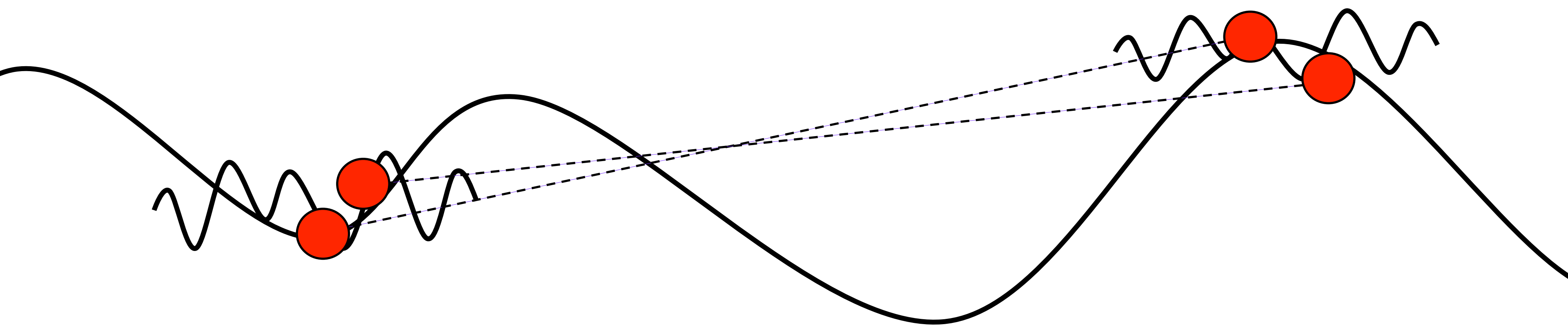
No local measurements depend on choice of distant observer

Displacements of nearby bodies are not independent, but entangled

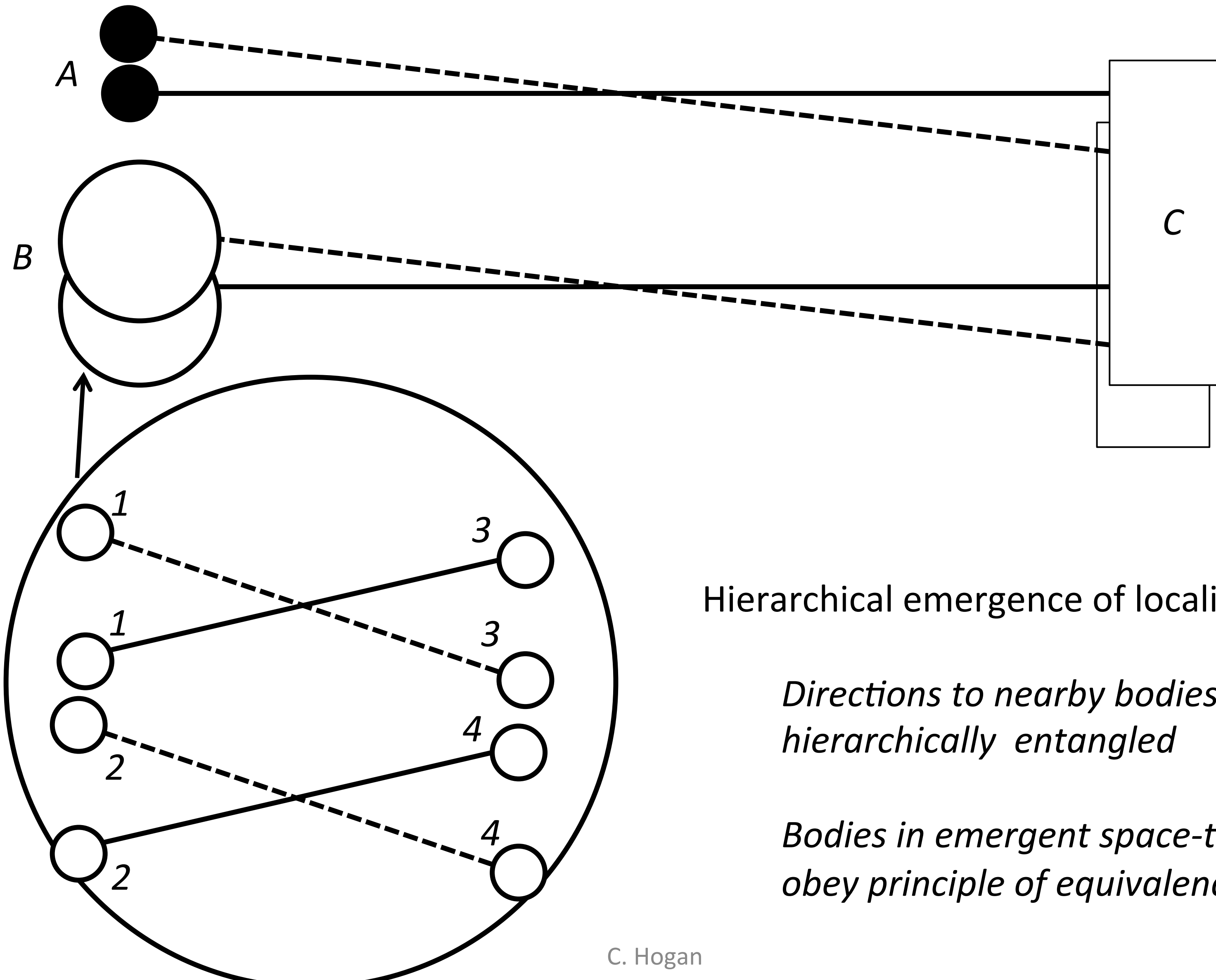
Events on null sheets (defined by distant observer's causal diamond) and nearly the same direction collapse into the same transverse position state

Position states of neighboring bodies are entangled merely by proximity

Bodies "move together": ***this is how classical locality emerges***



Locality from recursive hierarchical entanglement



Hierarchical emergence of locality

Directions to nearby bodies are hierarchically entangled

Bodies in emergent space-time obey principle of equivalence

“Interferometers as Probes of Planckian Quantum Geometry”
CJH, Phys Rev D 85, 064007 (2012)

“A Model of Macroscopic Quantum Geometry”

CJH, arXiv:1204.5948

“Directional Entanglement of Quantum Fields with Quantum Geometry”

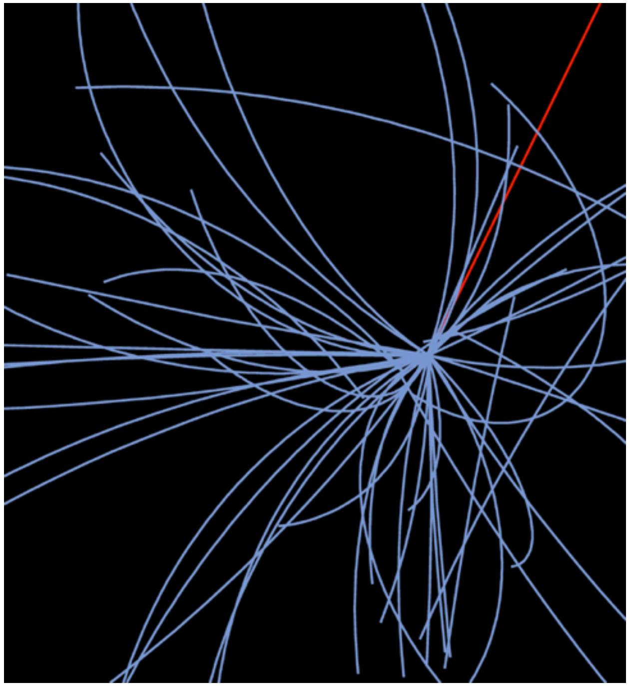
CJH, arXiv:1312.7798

Phenomenon lies beyond scope of well tested theory

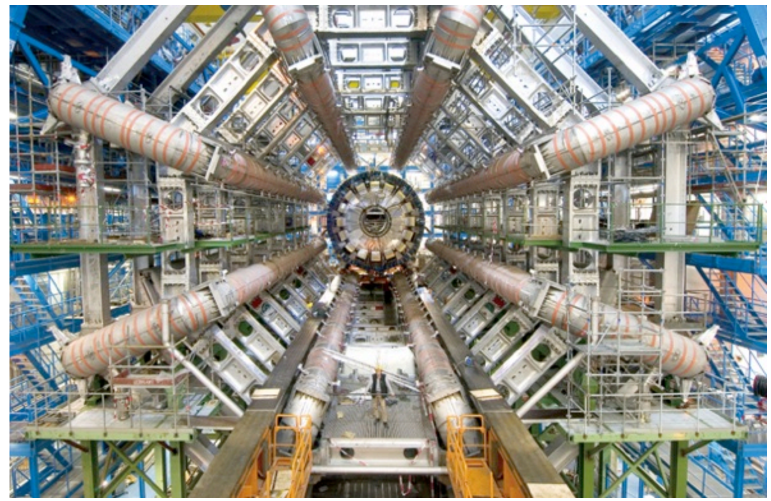
There is reason to suspect new Planckian effects on large scales

Motivates an experiment! But what kind?

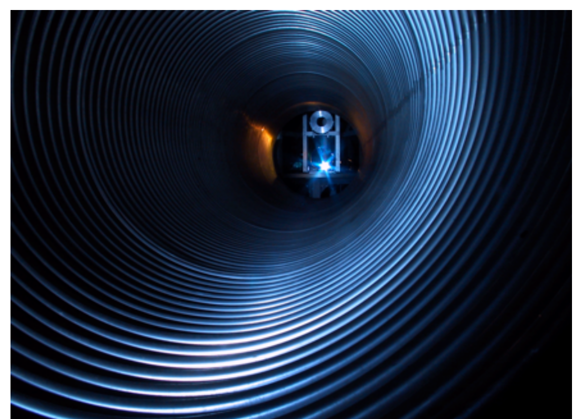
Two ways to study small scales



particle colliders measure microscopic products of localized events

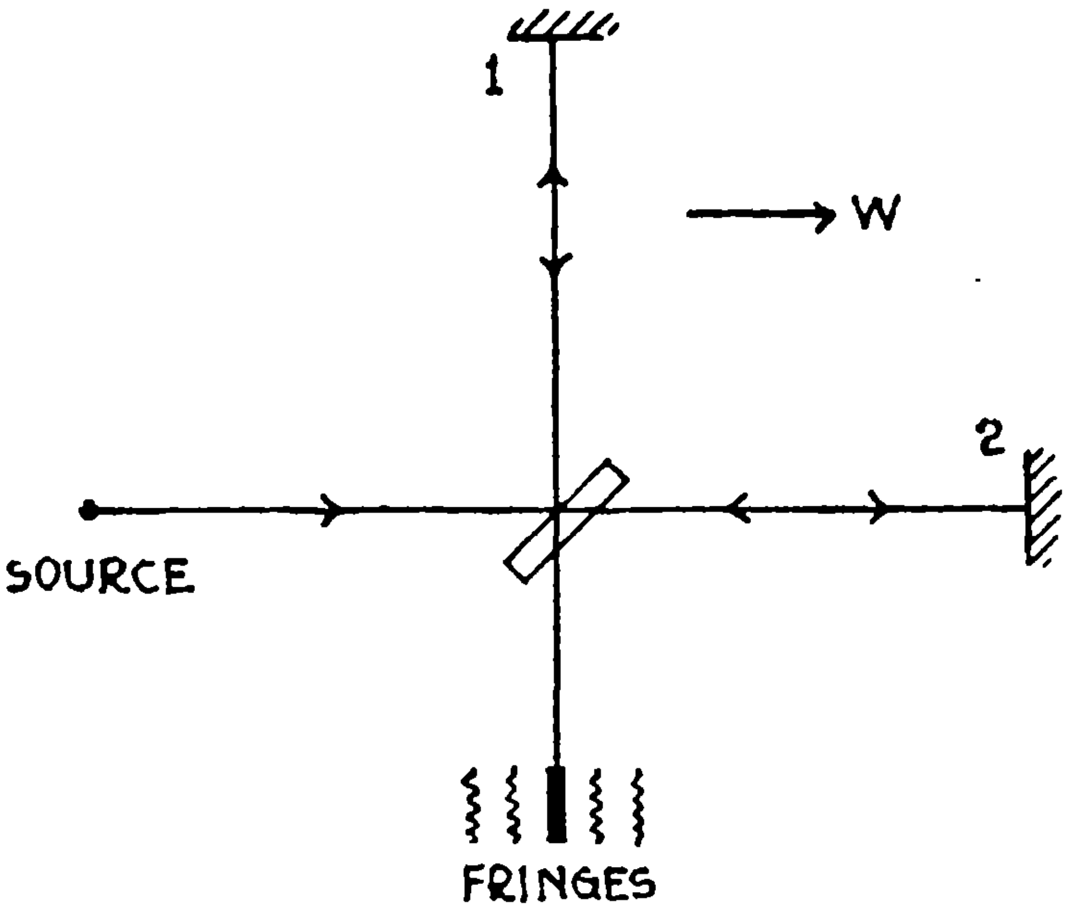


Interferometers compare macroscopic positions of massive bodies: better probe of Planckian quantum geometry

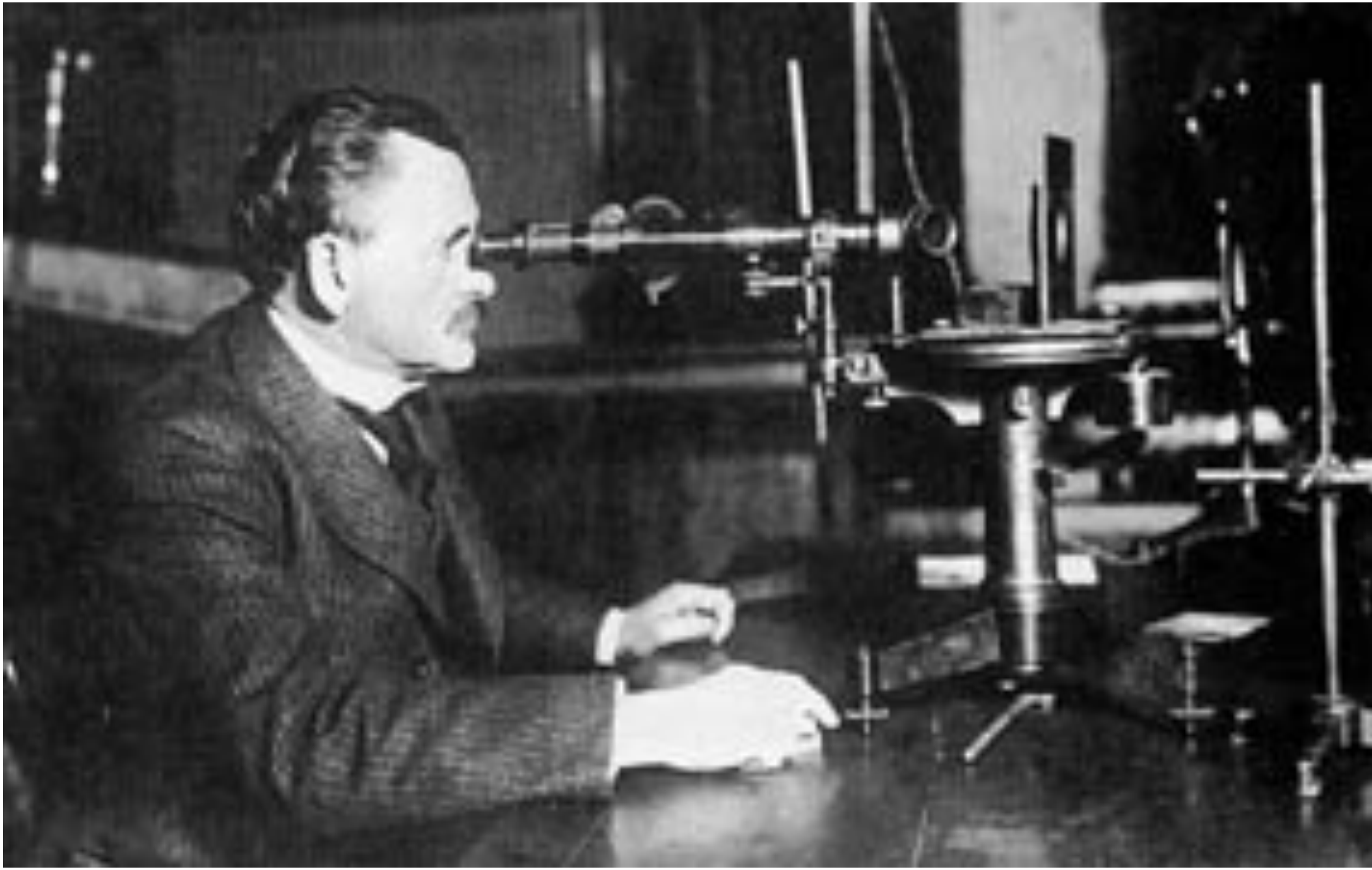


Michelson Interferometer

measures position differences in space and time with extraordinary precision



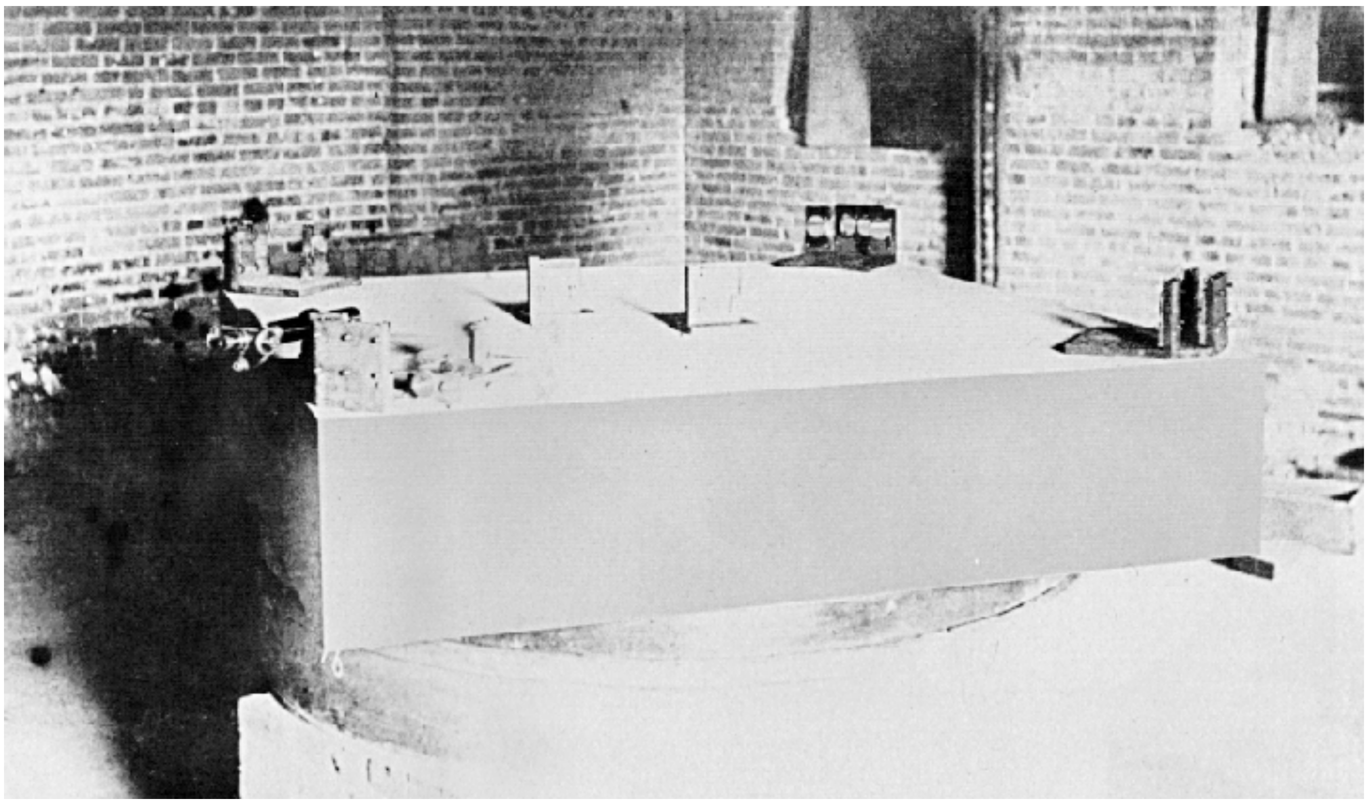
Albert Michelson



Michelson reading interference fringes

Michelson and Morley experiment, 1887

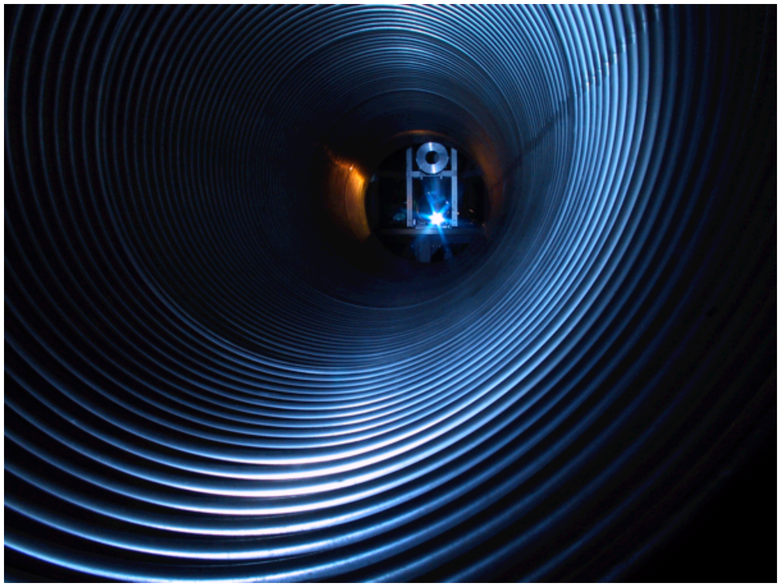
Showed that the measured speed of light is always the same in different directions, independent of motion

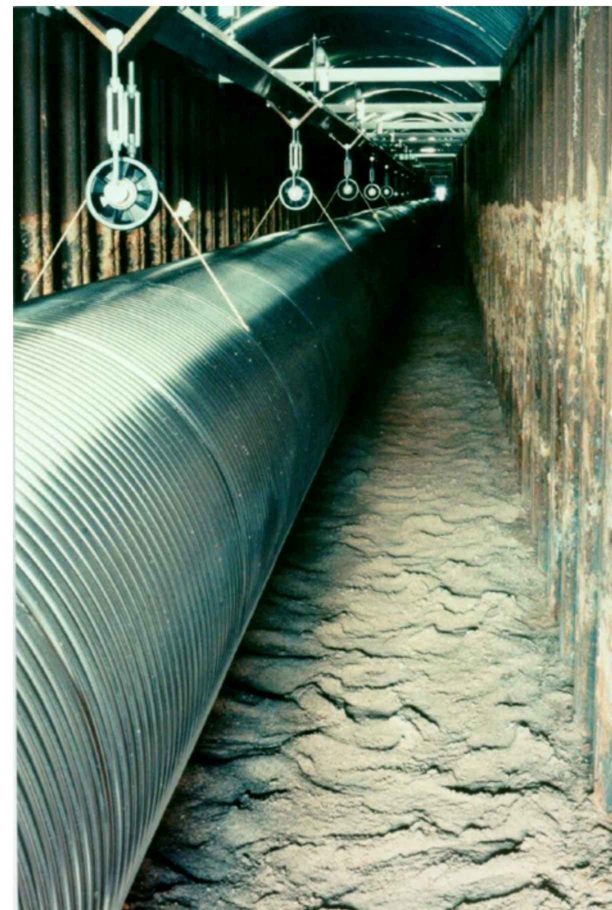


Original apparatus used by Michelson and Morley, 1887

New attometer technology of interferometers

Positions of mirrors measured to ~10^{-18} m, over a distance of ~10^{3} m

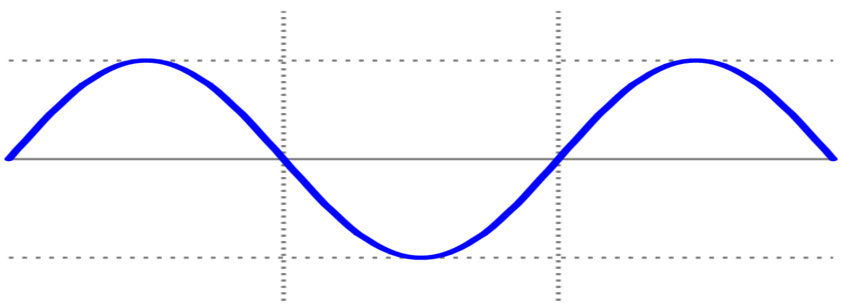




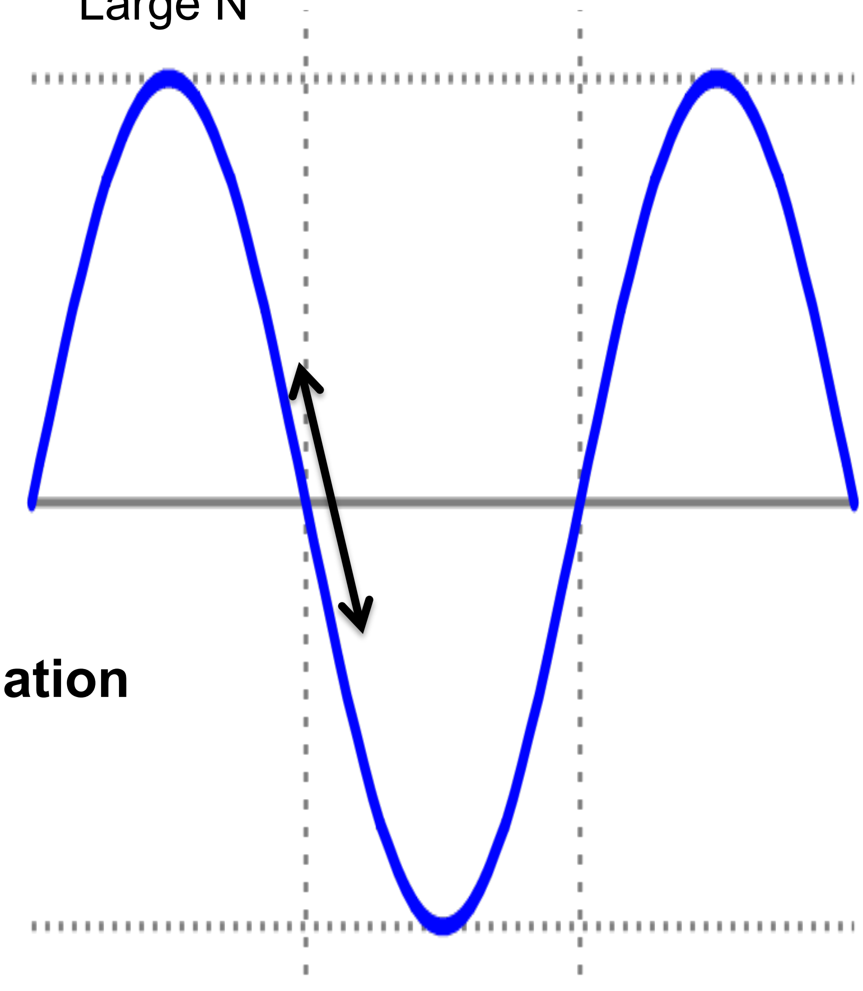
Intense lasers have precise phase resolution and can make precise position measurements

Amplitude^2 = N
Amplitude=sqrt(N)

Small N



Large N



Photon number-phase uncertainty relation
ΔN×Δϕ=1/2

$$\Delta x = \Delta\phi \times \frac{\lambda}{2\pi} = \left(\frac{1}{2\sqrt{N}}\right) \times \frac{\lambda}{2\pi}$$

C. Hogan

Interferometers can reach Planckian sensitivity

Planck fractional random variation in differential frequency or position over time interval $\boldsymbol{\tau}$

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

~ 6 orders of magnitude beyond the best atomic clocks (over short intervals)

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

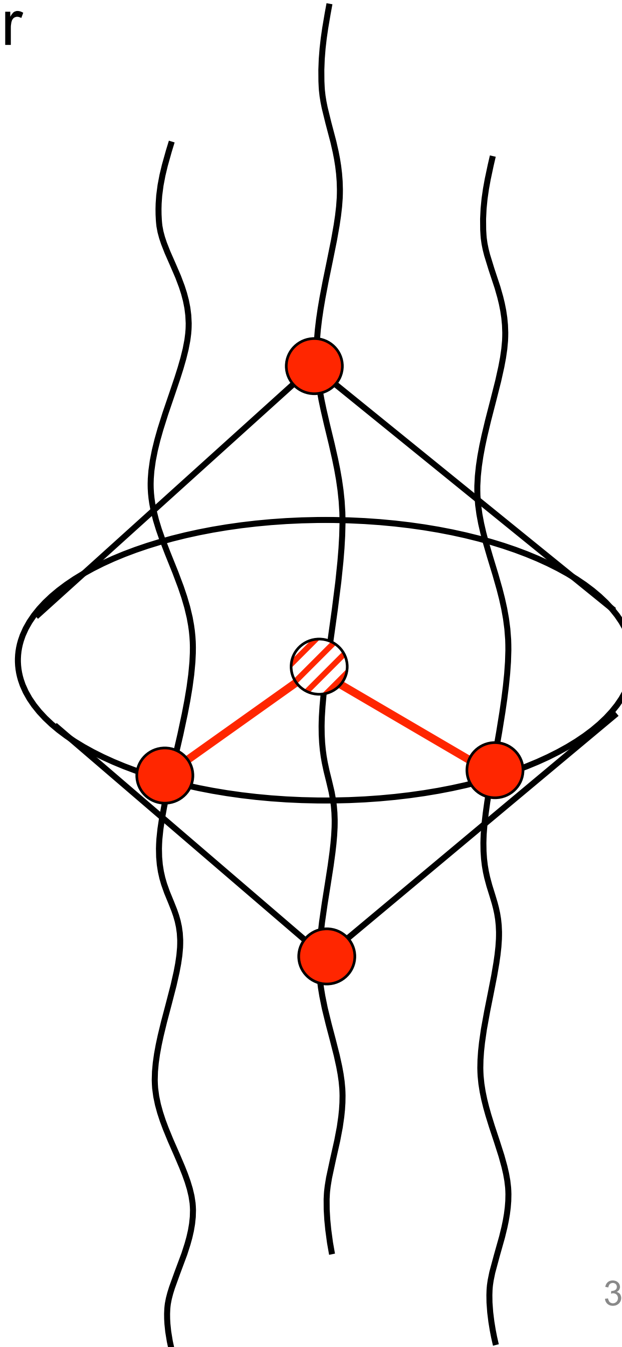
Space-time of Michelson interferometer

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



Planckian directional noise in Michelson interferometer

Signal measures difference of beamsplitter position in two noncommuting directions

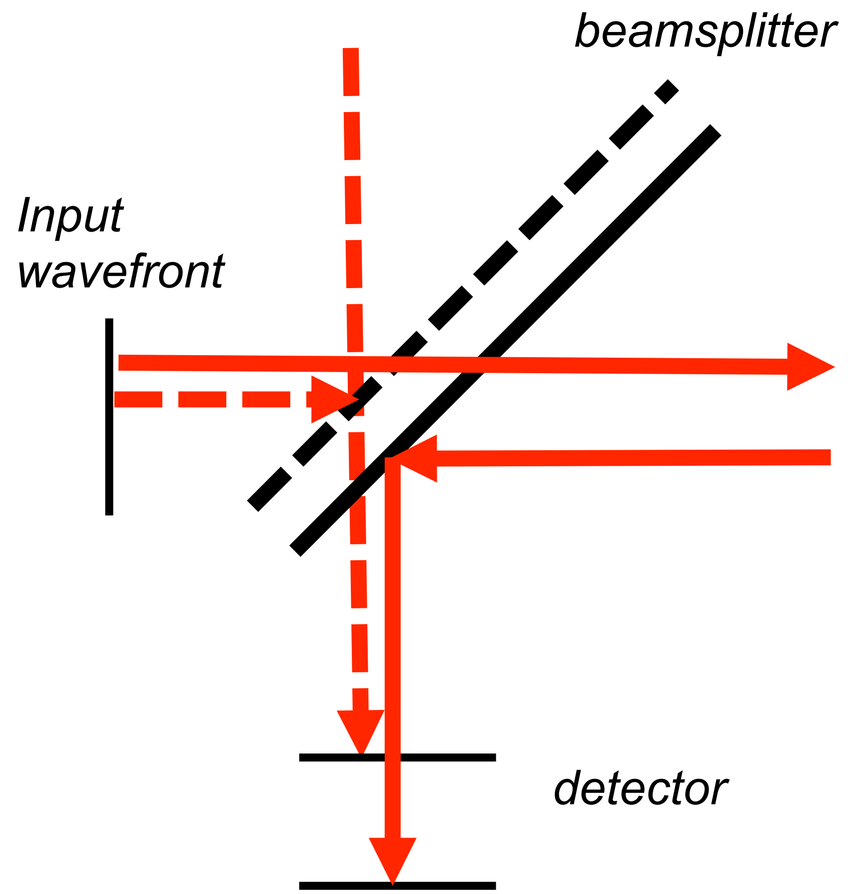
Causal diamond duration is twice the arm length

Geometrical uncertainty leads to fluctuations

$$\langle x_{\perp}^{2} \rangle \approx L \ell_{P}$$

For durations

$$\tau \approx L/c$$



Planck noise spectrum in a simple Michelson interferometer

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

$$= \frac{c^2 t_p}{\sqrt{\pi}(2\pi f)^2}\left[1-\cos(f/f_c)\right], \quad f_c \equiv \frac{c}{4\pi L}$$

Depends only on Planck scale and system geometry

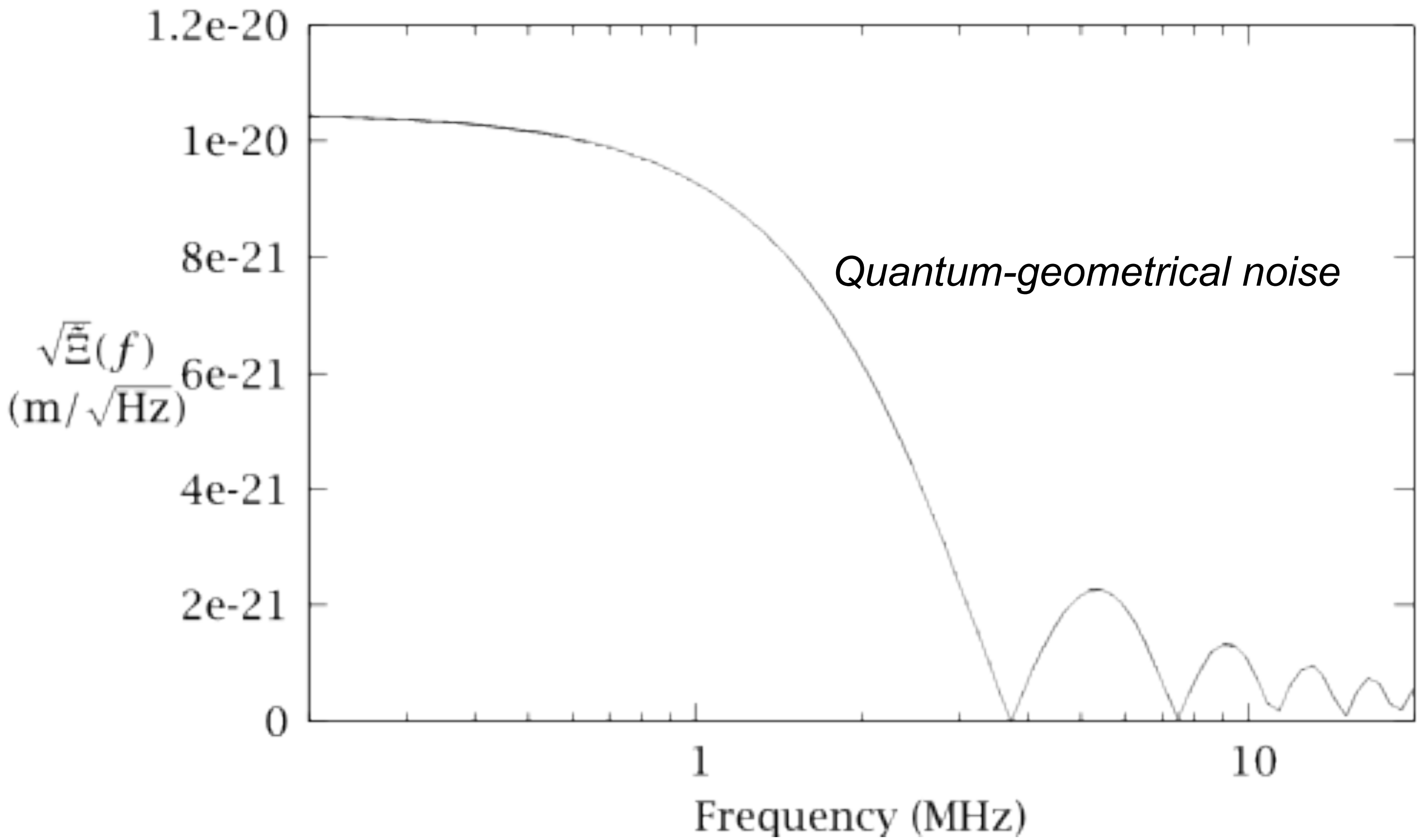
Measured noise is not sensitive to modes longer than 2L

At low frequency, angular noise power spectral density is

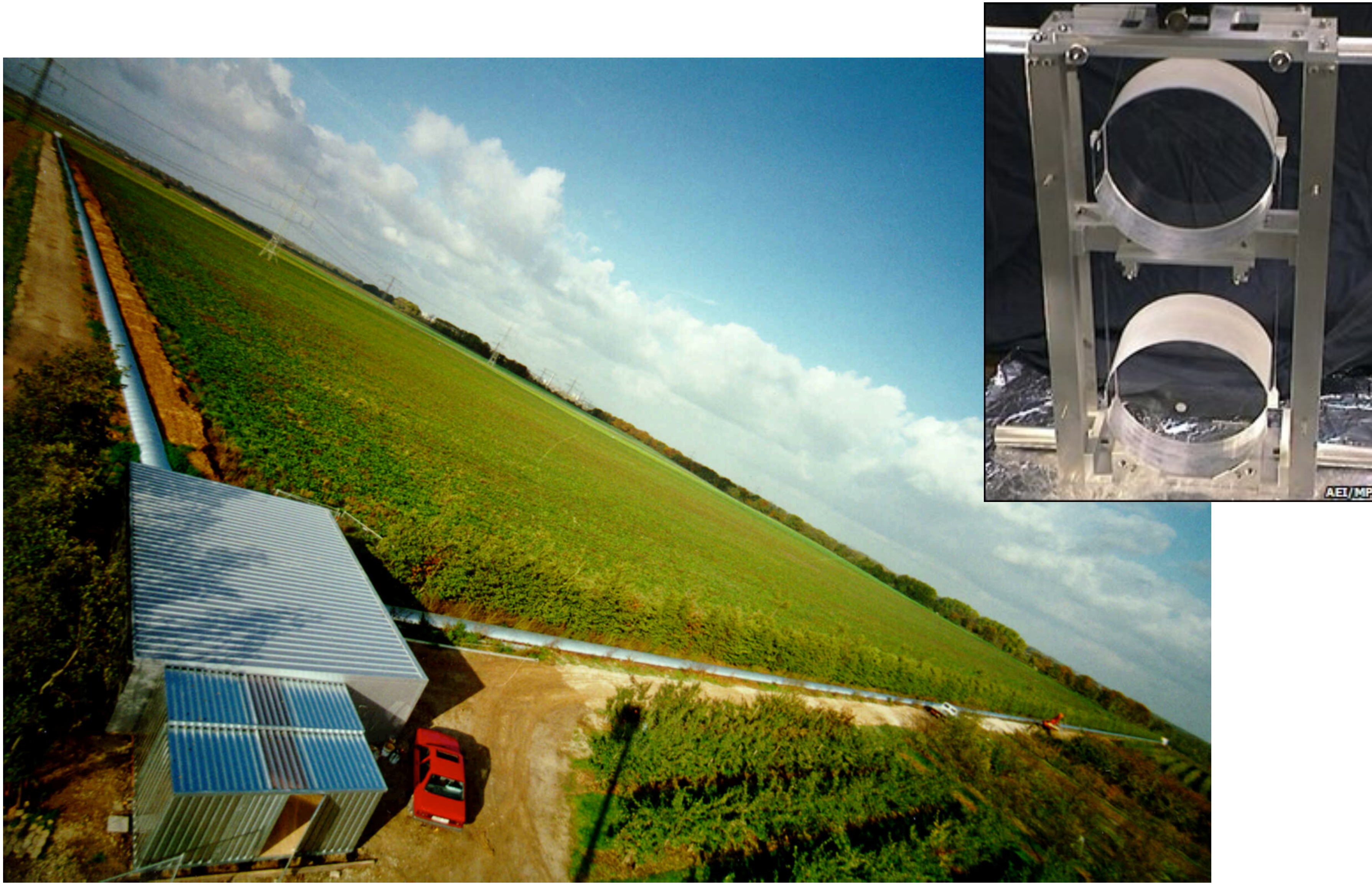
$$h^2 = (\Delta L/L)^2 = t_P/\sqrt{4\pi} = (1.23\times 10^{-22}\mathrm{Hz}^{-1/2})^2$$

Interferometer phase noise spectrum, including transfer function

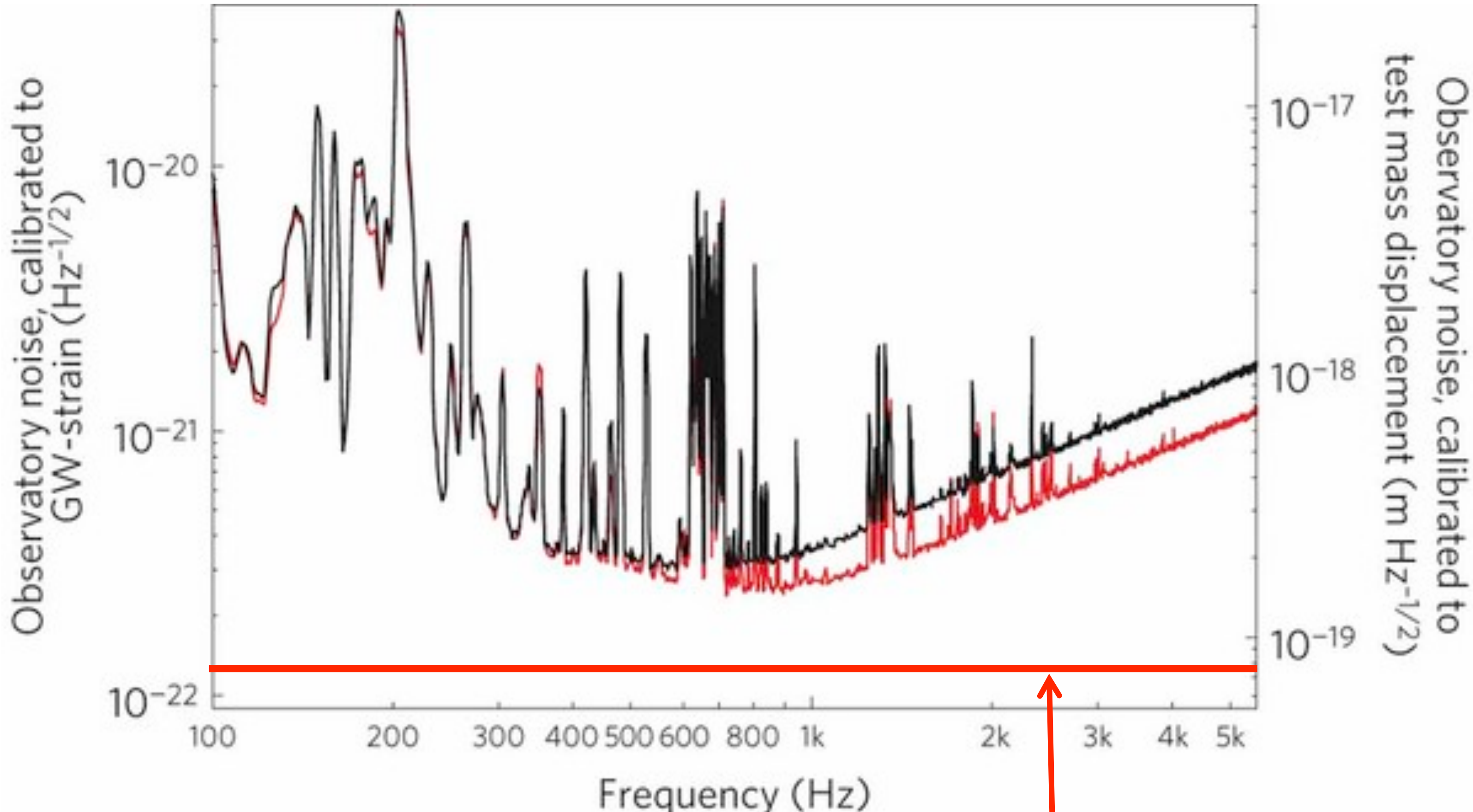
Depends only on the Planck scale and interferometer configuration



GEO-600 (Hannover): best displacement sensitivity today



GEO600 noise (2011) and predicted Planckian noise



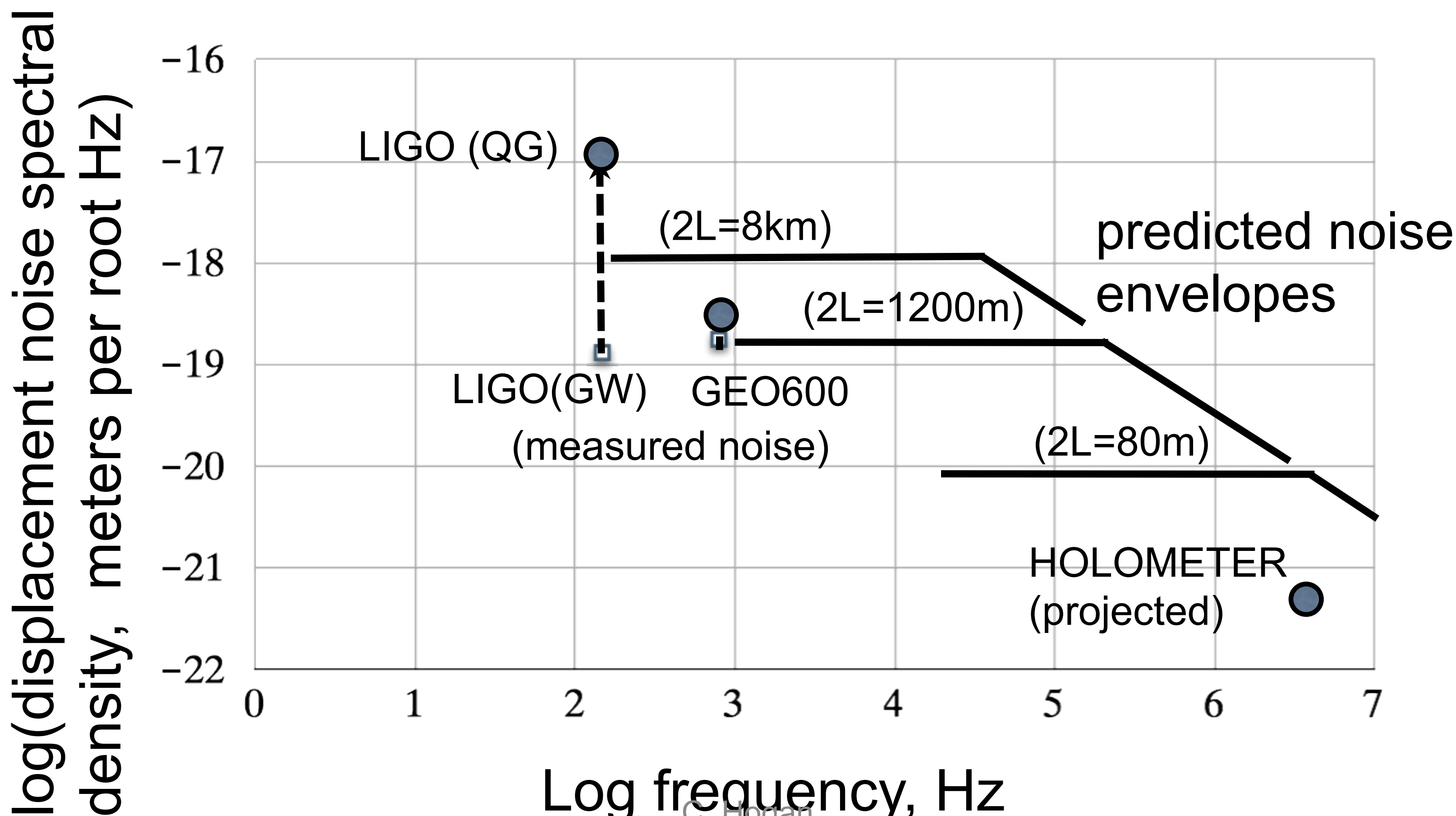
$$h^2 = (\Delta L/L)^2 = t_P/\sqrt{4\pi} = (1.23 \times 10^{-22}\mathrm{Hz}^{-1/2})^2$$

Quantum-Geometrical noise in real interferometers

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

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

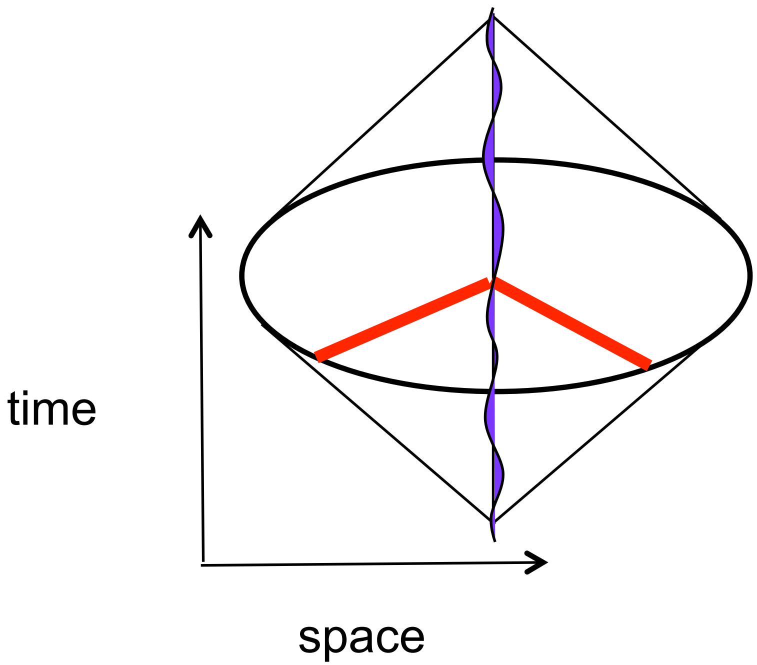
Fermilab Holometer (2L=80m) is designed to find or rule out this effect



The Fermilab Holometer

We are building a machine specifically to probe Planckian fluctuations and their nonlocal correlations in space and time:

"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 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

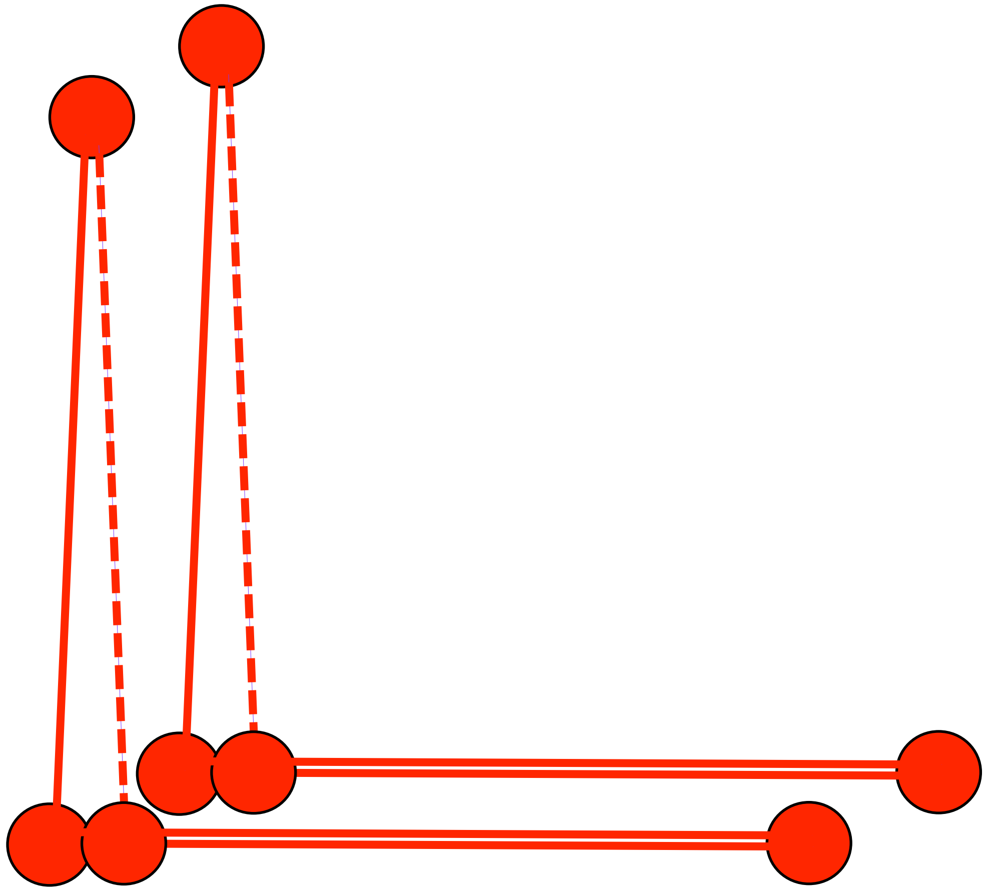
Measure signatures and properties of quantum-geometrical noise

- Frequency spectrum
- Time-domain correlation function
- Spatial correlations, configuration dependence

Correlated signals in adjacent interferometers

Geometrical directional states are entangled

"collapse" into the same state with measurement



Experiment Concept

Measure 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

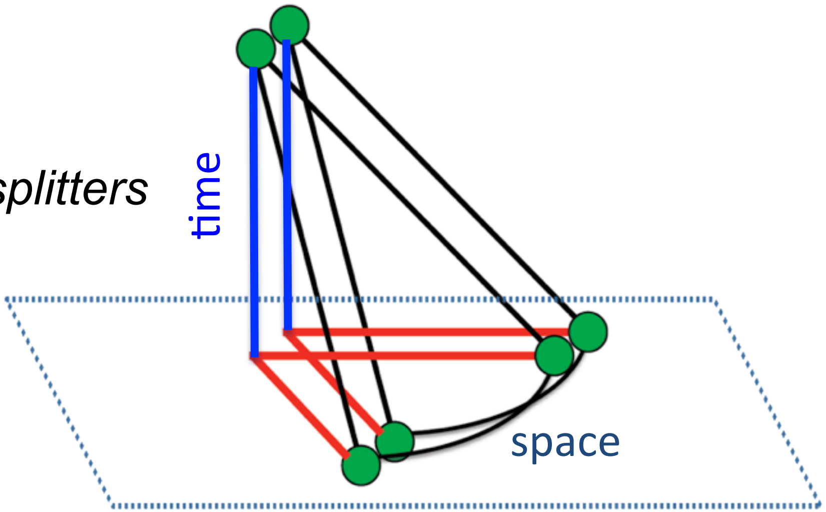
Sensitive to nonlocal entanglement of quantum-geometrical position states

Integrate (~minutes to days) to reduce photon shot noise

Correlated holographic noise contribution accumulates

Overlapping spacetime volumes -> correlated fluctuations

World lines of beamsplitters



Distinguish exotic from conventional noise

Holographic noise has a predicted spectral shape

- Normalization of spectrum scales as arm length L^2
- Interferometer response function cuts off at $f=c/2L$

Conventional RF backgrounds are frequency dependent (narrow lines, ~1/f, etc.)

- Discriminate against conventional backgrounds such as AM radio

Configuration changes

- Orientation of two interferometers
  - Nested for maximum correlation
  - Back-to-back, or in-line to turn off correlation
  - Change arm length to verify scaling with L

Time Domain autocorrelation

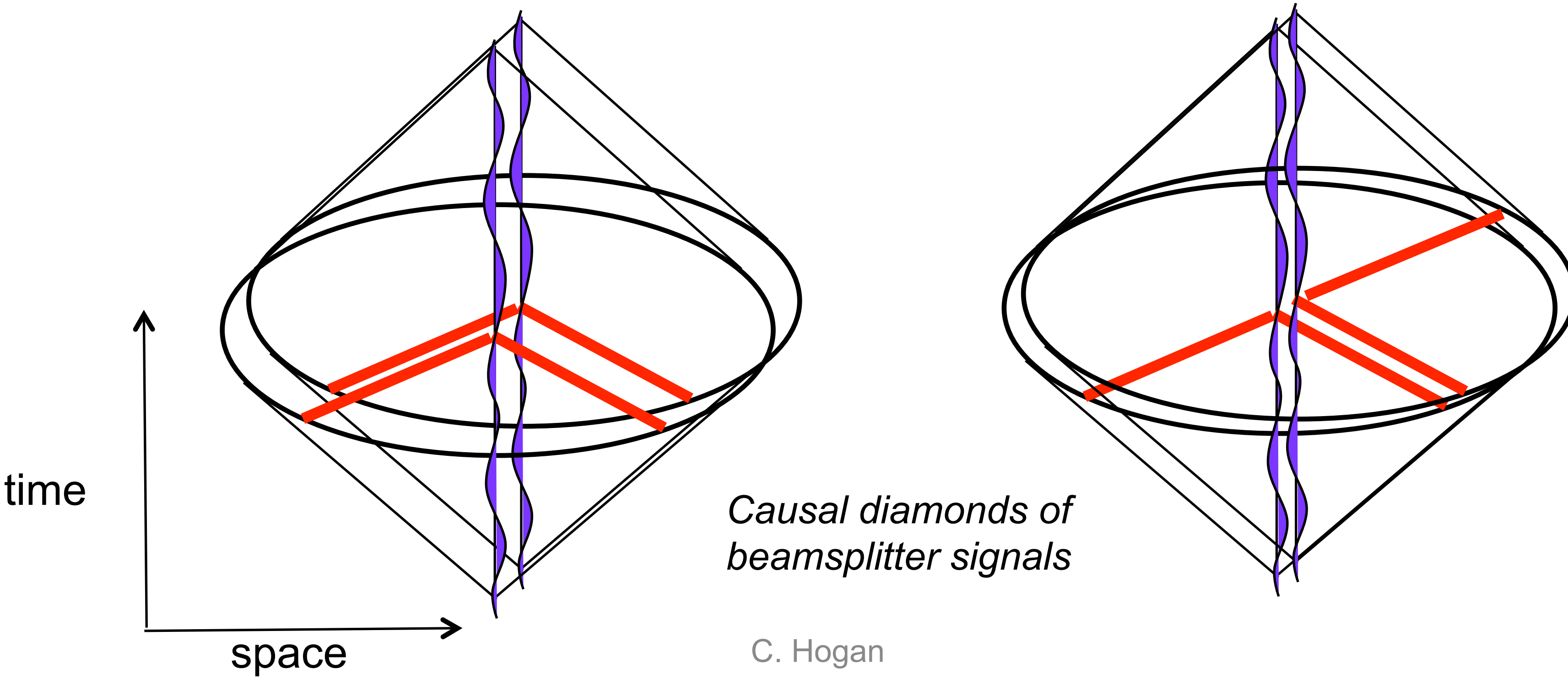
- Reflects causal structure of system layout

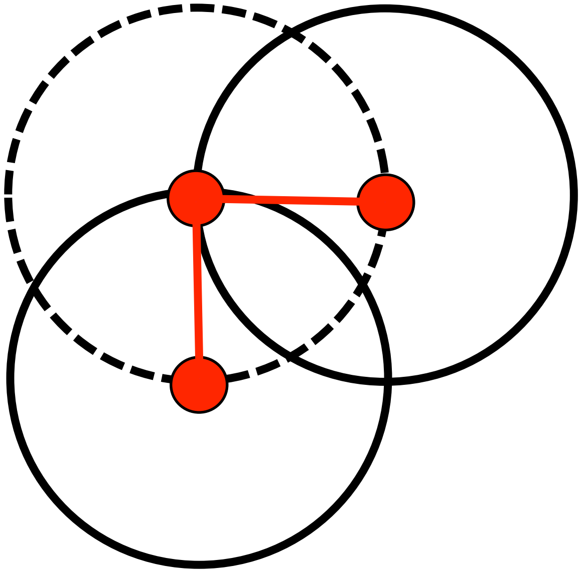
Spacetimes of two interferometers

Overlapping spacetime volumes collapse into the same state

Correlates signals of nearly co-located Michelson interferometers

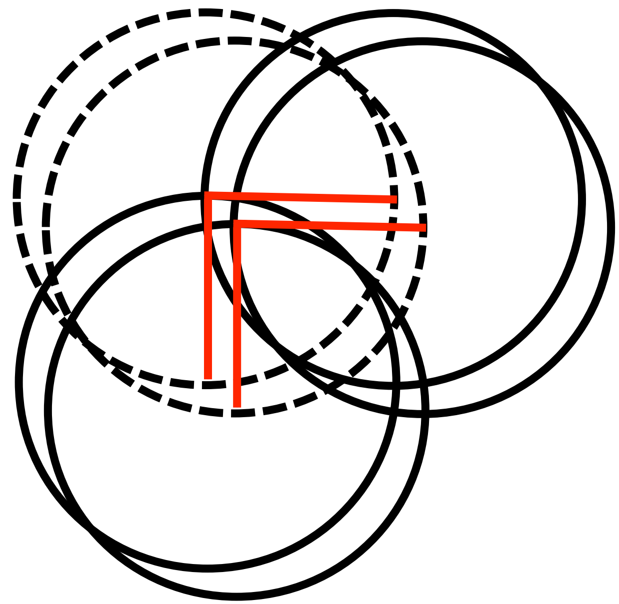
Non-overlapping configurations are uncorrelated

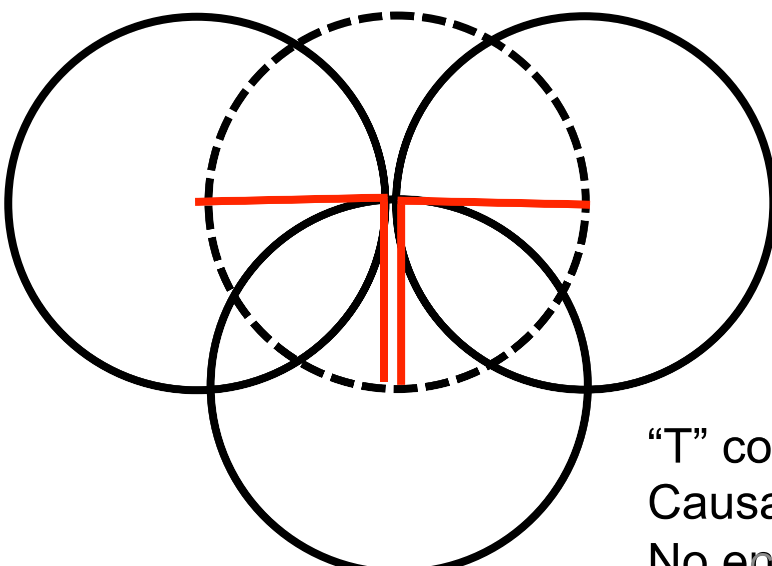




Top view of one interferometer

“L” configuration of 2 interferometers
Highly entangled positions
Highly correlated signals

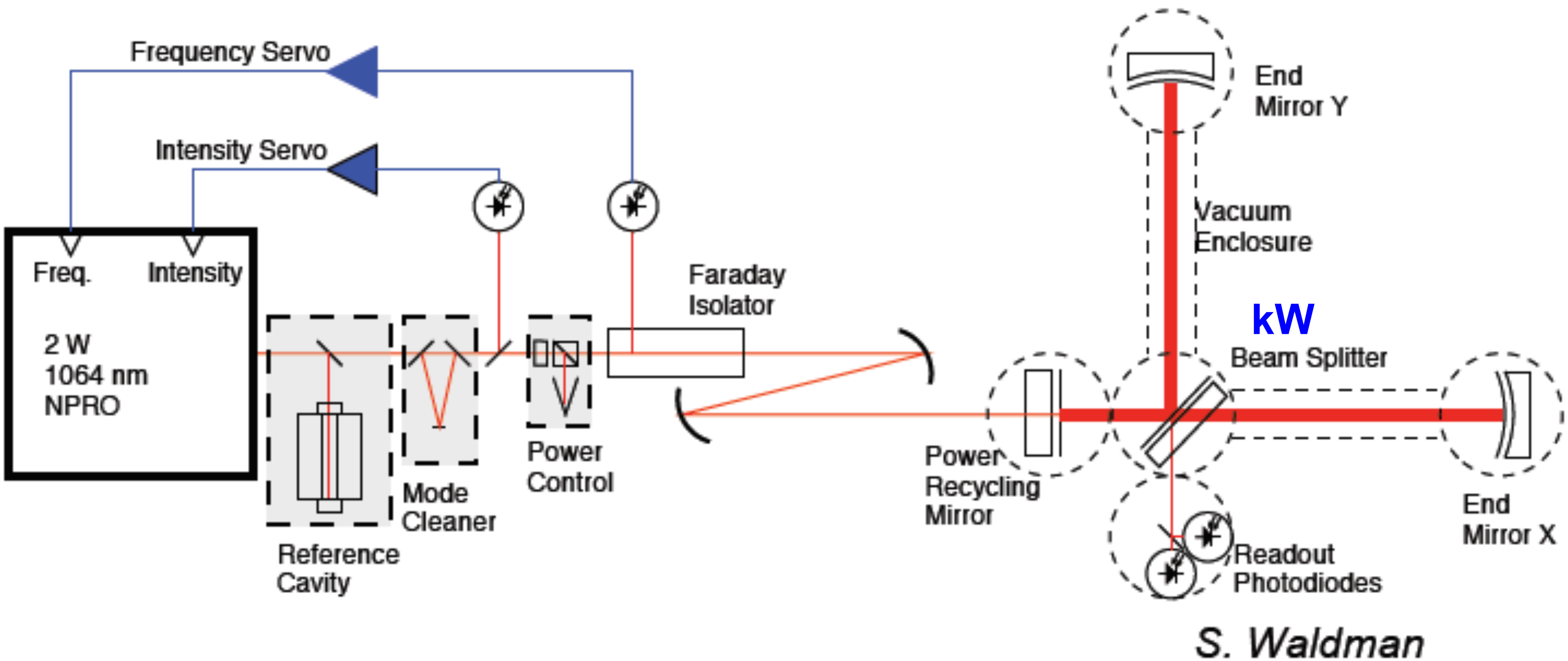




“T” configuration of 2 interferometers
Causal diamonds are independent
No entanglement or signal correlations

Holometer optical configuration

(2 of these)



Power recycling cavity enhances power by factor of 2000 → 2 kW

Many technologies borrowed from LIGO and GEO600

The Holometer is located at MP8, a beamline in the meson area of FNAL


B 10150

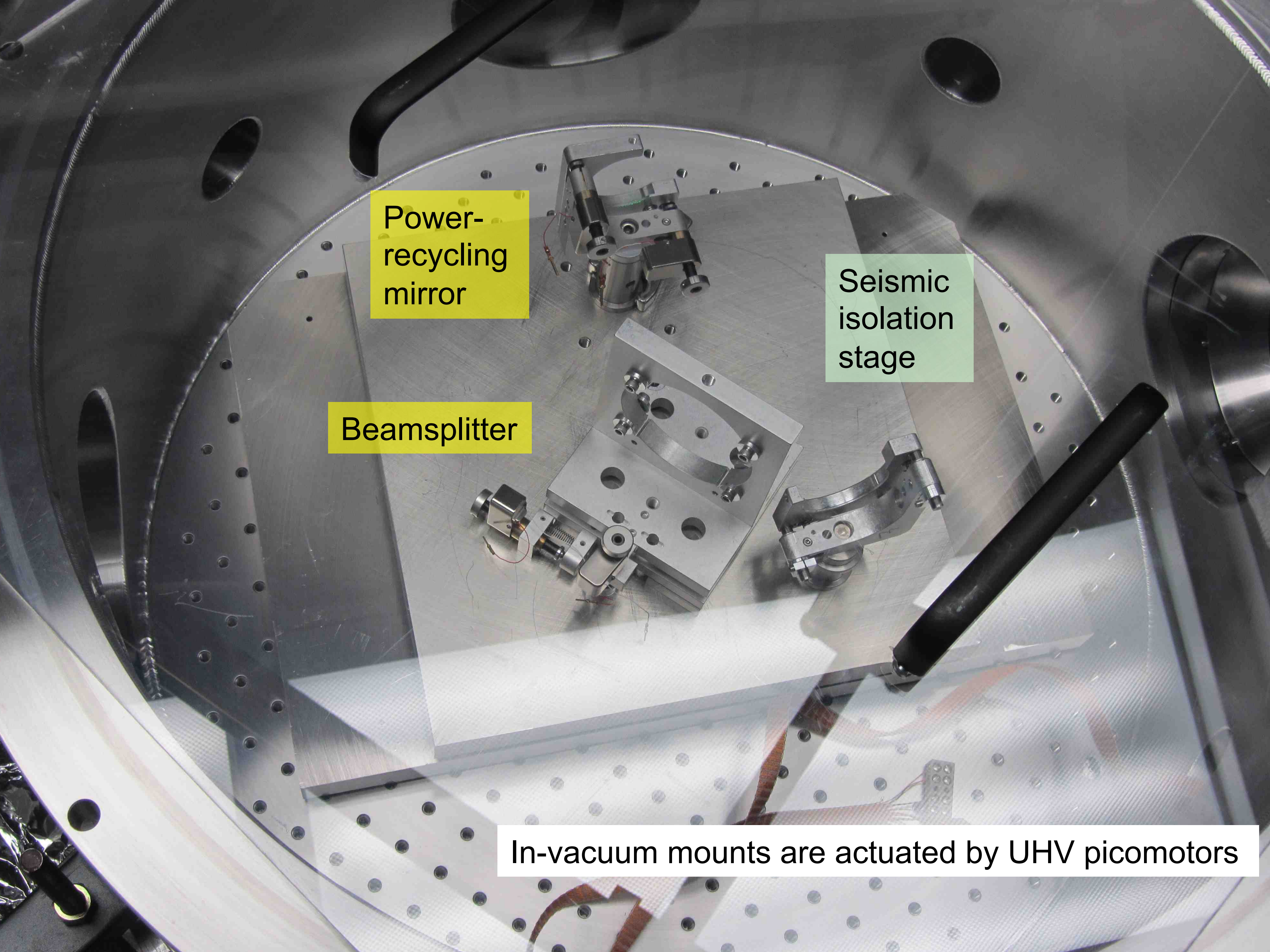
Adjacent systems


East arms


North arms

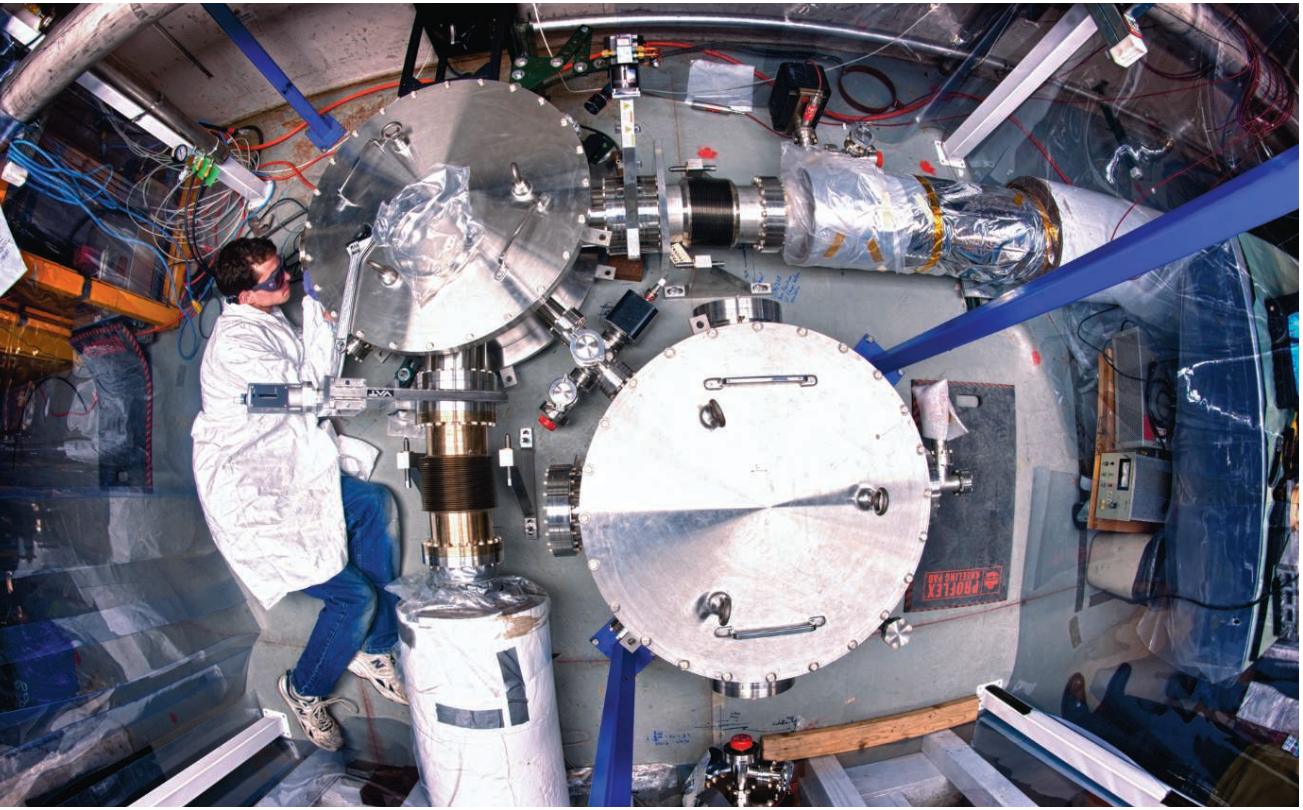
Hut with east end mirrors

East end station


Power-
recycling
mirror
Seismic
isolation
stage
Beamsplitter
In-vacuum mounts are actuated by UHV picomotors

Michelson and team in suburban Chicago, winter 1924, with partial-vacuum pipes of 1000 by 2000 foot interferometer, measuring the rotation of the earth with light traveling in two directions around a loop

Not a test of the holographic principle!



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

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

Skeptical Theorists

“The [holographic] principle, however, does not predict the quantum “jitters” that Hogan’s experiment seeks to detect; it predicts their absence. They would conflict with Einstein’s principle of relativity, which is central to the formulation of the holographic principle (and to our understanding of countless previous experimental results).”

“we believe that Hogan’s experiment does not actually test this principle.”

-R. Bousso and L. Susskind

My response:

-indeed, the experiment does not “test the holographic principle”

-indeed, the proposed effect violates general relativity (a classical theory)

-this is a new effect: quantum fluctuations independent of mass

-but it is consistent with previous experiments

-consistent with holographic information bounds

-and consistent with relativity as a classical limit

Status of the Fermilab Holometer

Currently in commissioning at Fermilab

- Funded mostly by A. Chou DOE Early Career Award
- Also by NASA, NSF, UC, URA, KICP

Power-recycled 40m interferometers operating with high finesse

Measured noise is close to shot-noise-limited design sensitivity

- Main systems of both interferometers are in place
- Cross-correlation measured, cross talk is acceptably low
- Cavity power >1kw, locked for >30 minutes
- Planck sensitivity measurement expected within a year

Physics Outcomes

If noise is not there,

Set a sub-Planckian limit on position information

Rule out some kinds of macroscopic quantum geometry

Information density of macroscopic positions > holographic bound

If it is detected,

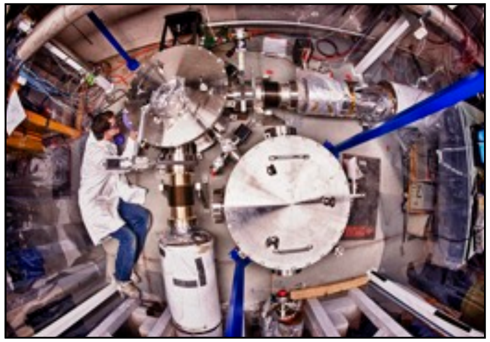
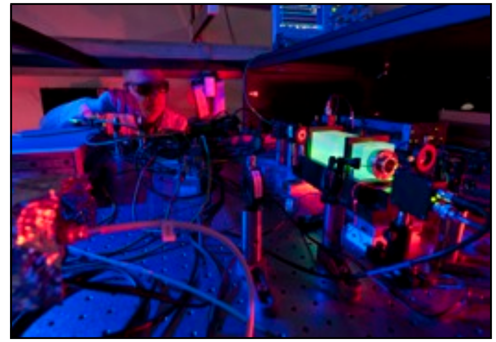
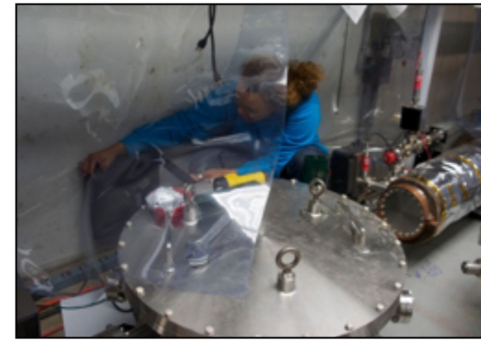
experiment probes Planckian quantum geometry

Information density of macroscopic positions ~ holographic bound

Holometer Team

A. Chou
H. Glass
H. Gustafson
C. Hogan
B. Kamai
R. Lanza
L. McCuller
S. Meyer
J. Richardson
J. Steffen
C. Stoughton
R. Tomlin
S. Waldman
R. Weiss
W. Wester
J. Volk

4 PhD students
numerous UC undergrads + REUs
(including 3 senior theses)
High school students
High school teachers

Visit us at : holometer.fnal.gov