Quantum Geometry and Interferometry

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Quantum Physics and Geometry

Classical geometry is made of definite points, based on “locality”

Quantum physics (and reality) do not respect locality

Standard approximation: quantum field theory

Quantum Field Theory

Classical Geometry (“space-time”)

Dynamical but not quantum

Responds to classical average of particle/field energy

Quantum particles and fields

Quantize nonlocalized plane waves extending to infinity, on classical background

Space-time geometry is assumed to be ***classical****: it is not part of the quantum system*

Approximation explains all experiments with particles

But cannot be the whole story about geometry

Challenges for Quantum Field Theory

Quantum states do not obey locality

- Proven by EPR-type experiments
- Yet locality is the basis of relativity, assumed by field theory
- Quantum properties of geometry are assumed away

Inconsistency at the Planck scale

- At the Planck scale, geometry cannot behave classically

Field theory cannot predict the energy of the vacuum

- Yet cosmic expansion accelerates

Gravitational theory suggests that gravity and geometry are statistical behaviors

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

Physical states in black hole systems are 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 (e.g. "Firewalls")

Physics needs to go beyond the approximations of quantum field theory

Not all of these issues are addressed by string theory

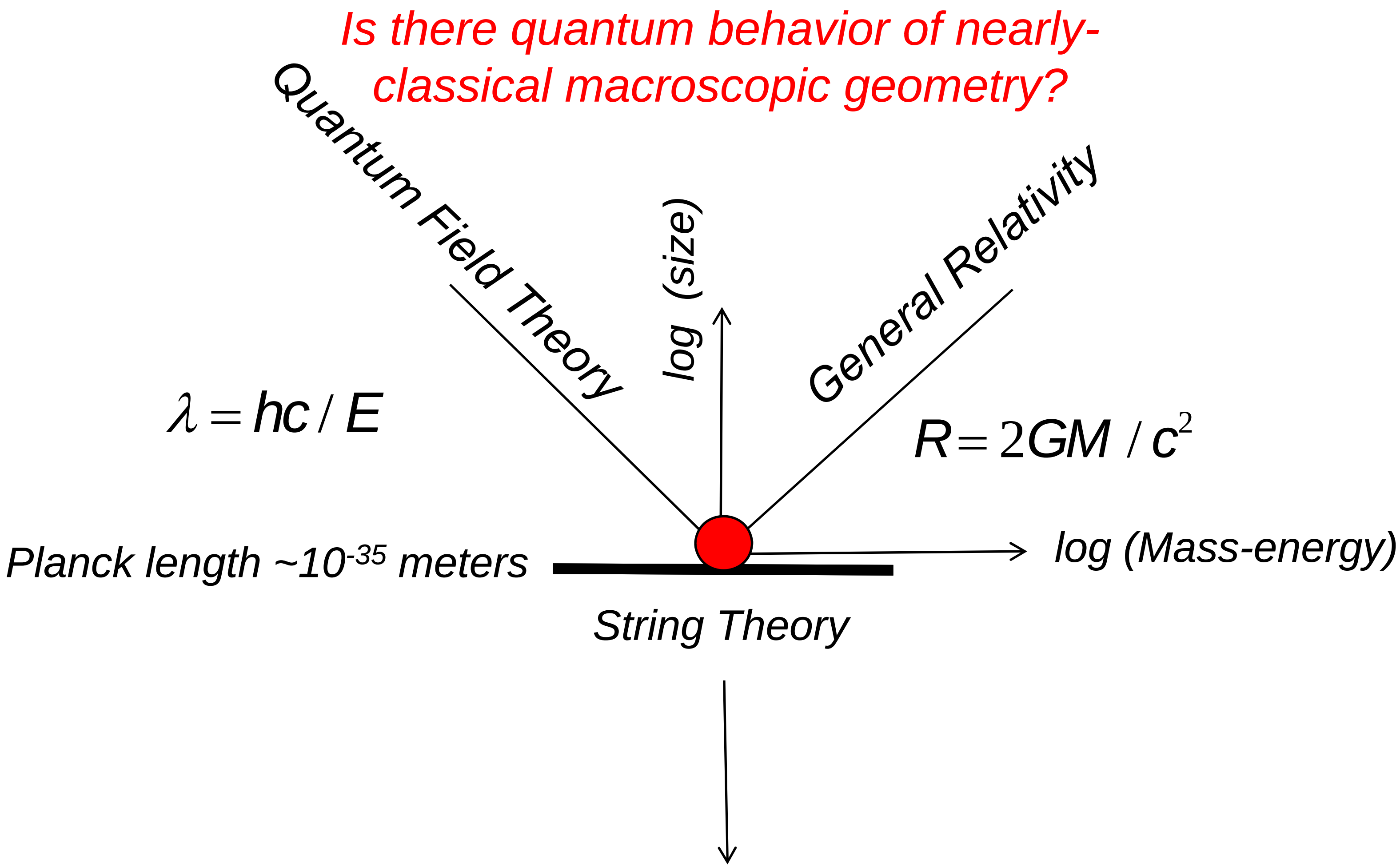
The “Planck scale”: gravity + quantum

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

equivalent Planck length ~10^{-35} meters

Far too small to observe directly

Classical geometry is an approximation to a quantum system



Gravity is thermodynamical

Theory suggests a statistical "entropic" origin of gravity

Bardeen et al. laws of black hole thermodynamics

Beckenstein- Hawking black hole evaporation

Unruh radiation

Jacobson formulation of GR

Verlinde entropic formulation of gravity

Metric does not describe fundamental degrees of freedom

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

Physical states are holographic

Information encoded with Planck density on 2D bounding surfaces

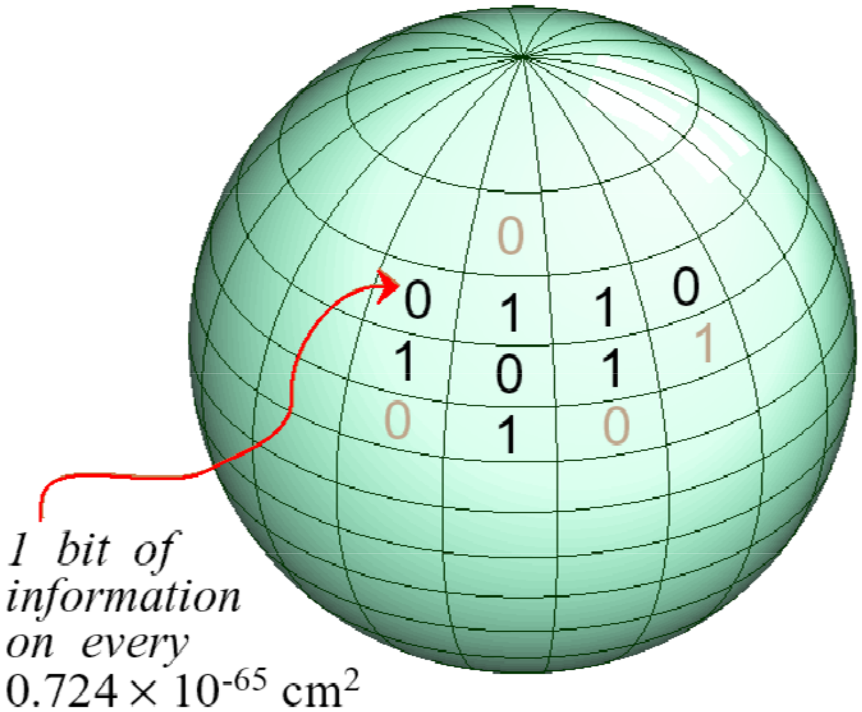
‘t Hooft, Susskind holographic principle

Maldacena ADS/CFT dualities in string theory

Bousso covariant entropy bound: “causal diamonds”

Banks theory of emergence

States must have new forms of spatially nonlocal entanglement



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 and geometry are entangled

Quantum-geometrical degrees of freedom may not be describable using quantum fields or quantized metric

Macroscopic effects of new Planck scale physics

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 real geometry may have quantum effects on larger scales with new degrees of freedom

These might not be describable by quantum field theory

Field theory: classical geometry, quantum matter

New approximation: classical matter, quantum geometry

Requirements for a macroscopic quantum geometry

- Consistent quantum theory
  - e.g. satisfy Jacobi identities
- Consistent with classical geometry
  - must satisfy covariance in macroscopic limit
  - Formulate as a theory of position operators for massive bodies
- Consistent with field theory
  - Unidirectional plane wave modes should propagate along a nearly classical dimension
- Holographic density of states
  - For thermodynamic GR, entropic gravity:

    Number of eigenstates = surface area in Planck units
- Consistent with current experiments

Classical matter in quantum geometry

Posit a quantum algebra for **position operators**:

$$[\hat{x}_i, \hat{x}_j] = \hat{x}_k \epsilon_{ijk} i c t_P / \sqrt{4\pi},$$

Angular momentum algebra, with x in place of J

Describes position of "massive body" in rest frame

Algebra has a covariant formulation

Number of position eigenstates in a 3-sphere agrees with holographic or "entropic gravity":

$$\mathcal{N}_{3S}(R) = 4\pi (R/ct_P)^2$$

Gravity can be a statistical behavior of this system

A new uncertainty in position

Noncommutative geometry: system cannot be an eigenstate of position in more than one direction

Variance of position operators transverse to separation (from angular momentum algebra):

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

quantum departure from classical geometry

increases with distance L

purely transverse to separation direction

Preserves classicality of radial separation, causal structure

Macroscopic limit is classical geometry

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

Angles indeterminate at the Planck scale

Approximately classical and localized on large scales

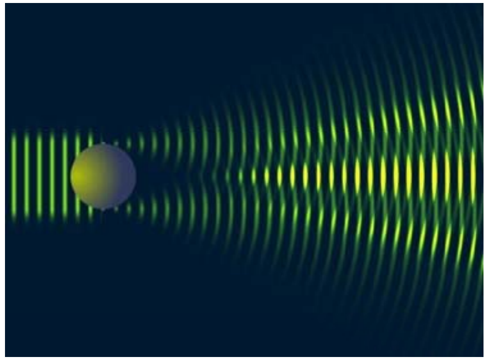
Approach to the classical limit

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 fewer degrees of freedom

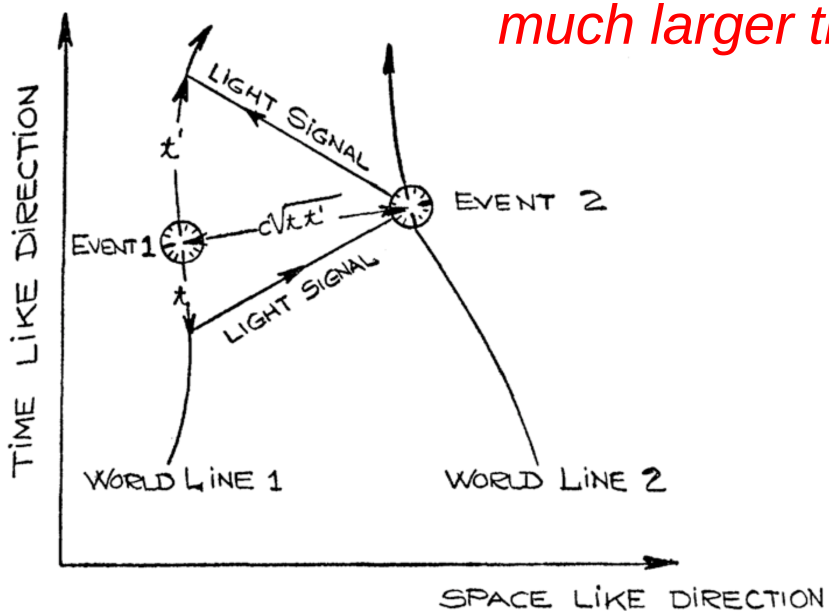
Directions have intrinsic “wavelike” uncertainty

Wave interpretation

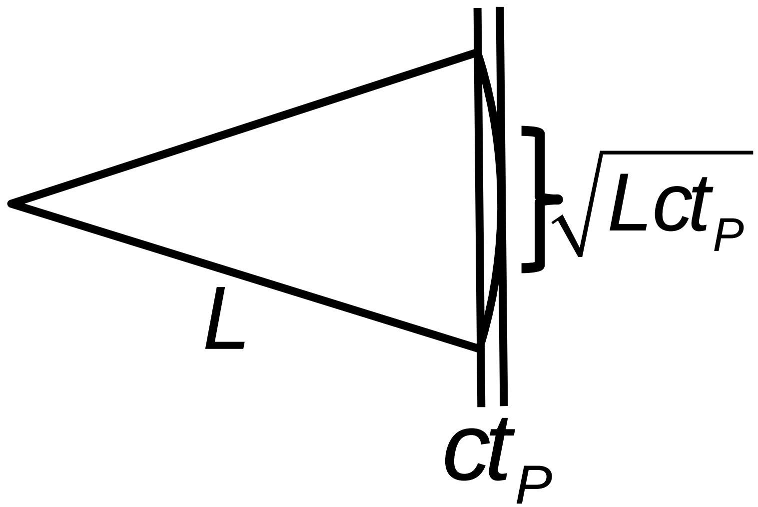
Spacelike-separated event intervals are defined with clocks and light

But transverse positions defined by phases of Planckian waves are uncertain by the diffraction or bandwidth 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: transverse position uncertainty

Space-time as a digital information system

Perhaps spatiotemporal relationships are encoded with the information capacity of Planck frequency carrier wave

(a Planckian Shannon channel)

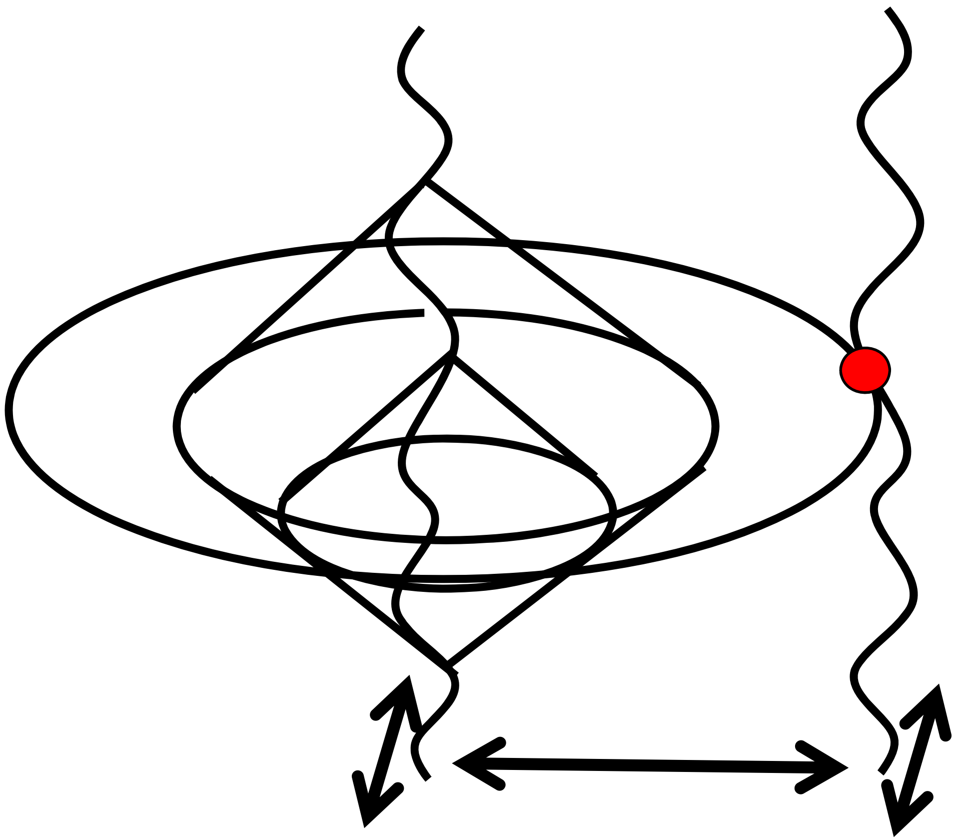
Measurements are subject to a Planck bandwidth limit,

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

“Nature: the Ultimate Internet Service Provider”

Measurement of position is limited to that fidelity

Quantum-geometrical uncertainty and fluctuations



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

Transverse uncertainty >> Planck length for large L

→fluctuations in transverse position

Geometrical uncertainty only dominates 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 measurable Planckian geometrical uncertainty

Coherence of Quantum-Geometrical Fluctuations

Larger scale modes dominate total displacement

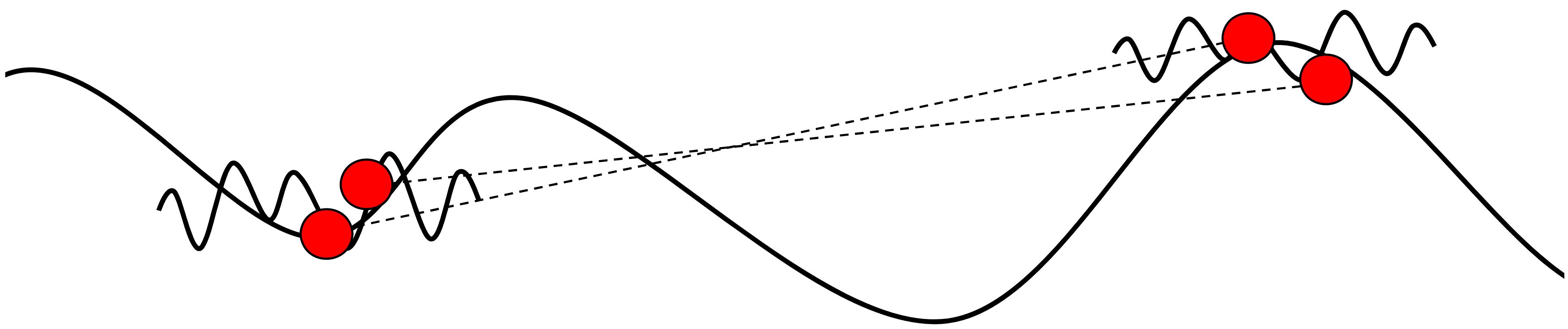
No local measurements depend on choice of distant observer

Displacements of nearby bodies are not independent

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

Geometrical position states of neighboring bodies are entangled merely by proximity

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



“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 scope of well tested theory

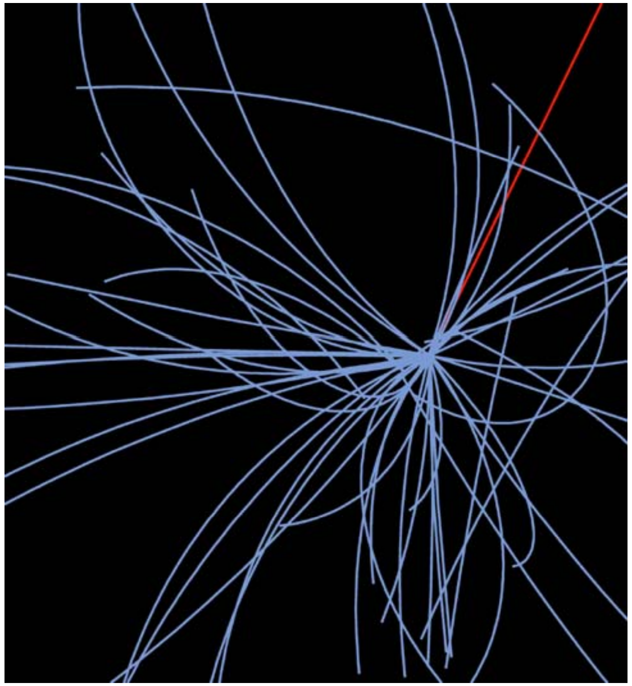
There is reason to suspect new physics at the Planck scale

Motivates an experiment!

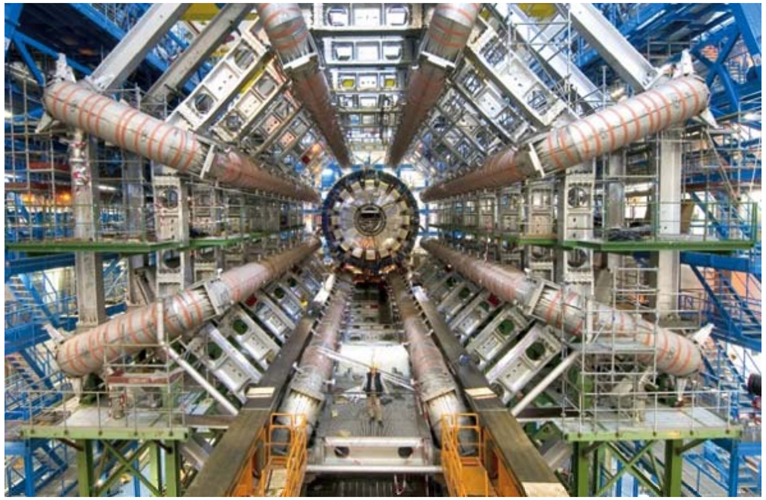
“Physics is an experimental science”

--I. I. Rabi

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

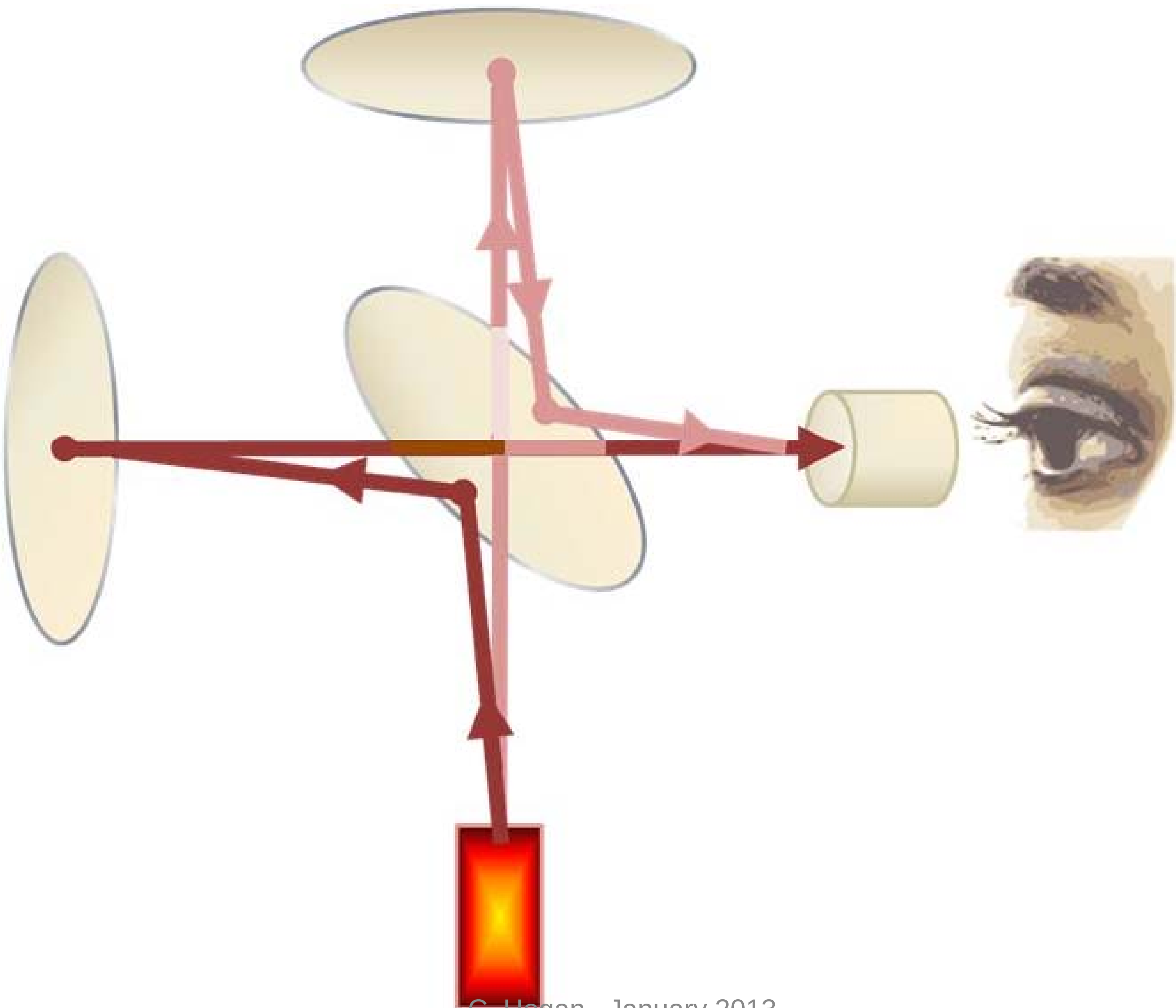
Pioneer of precision experiments

Invented a device to measure position differences in space and time with extraordinary precision:

“Michelson Interferometer”

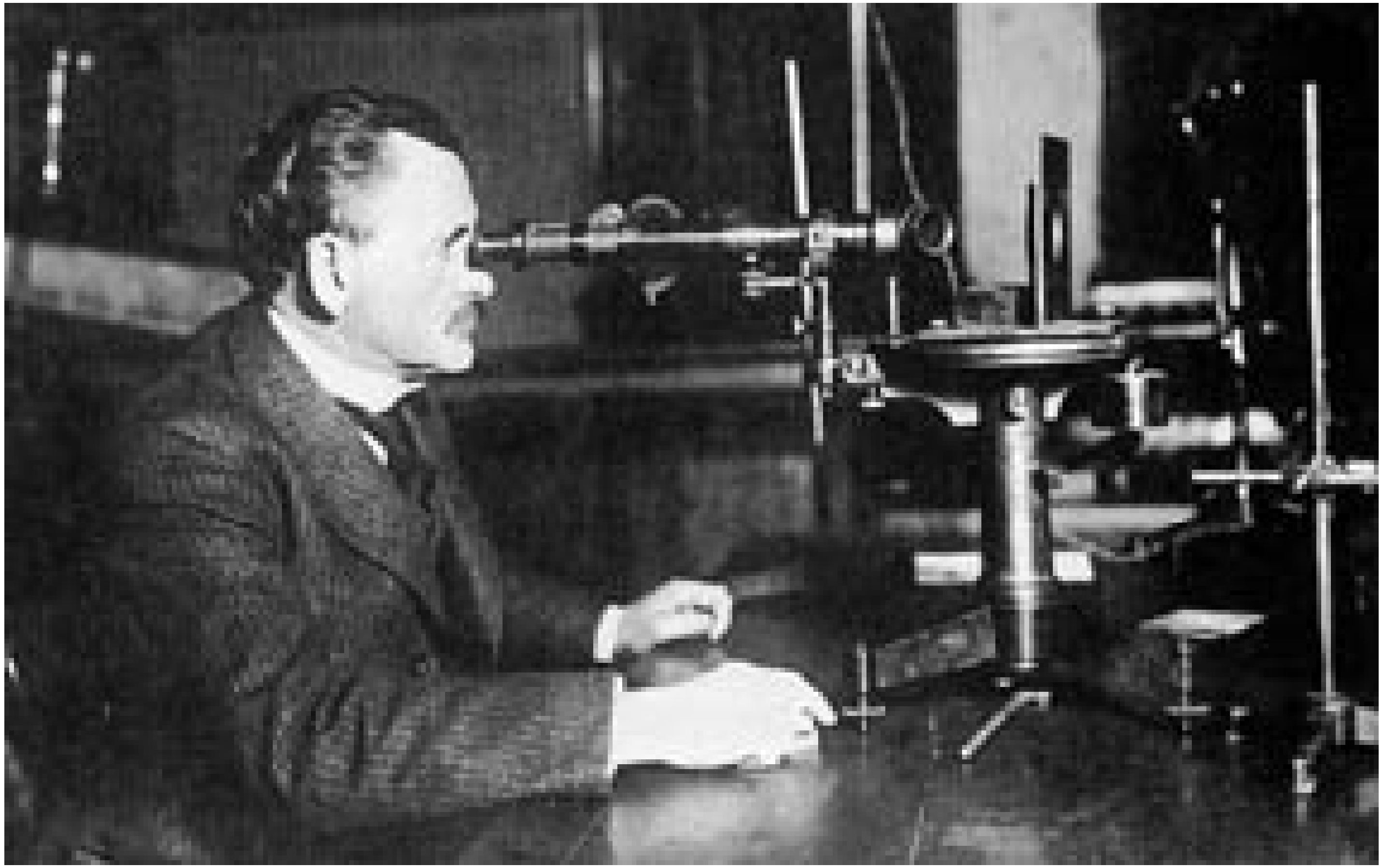
Albert Michelson

Michelson interferometer



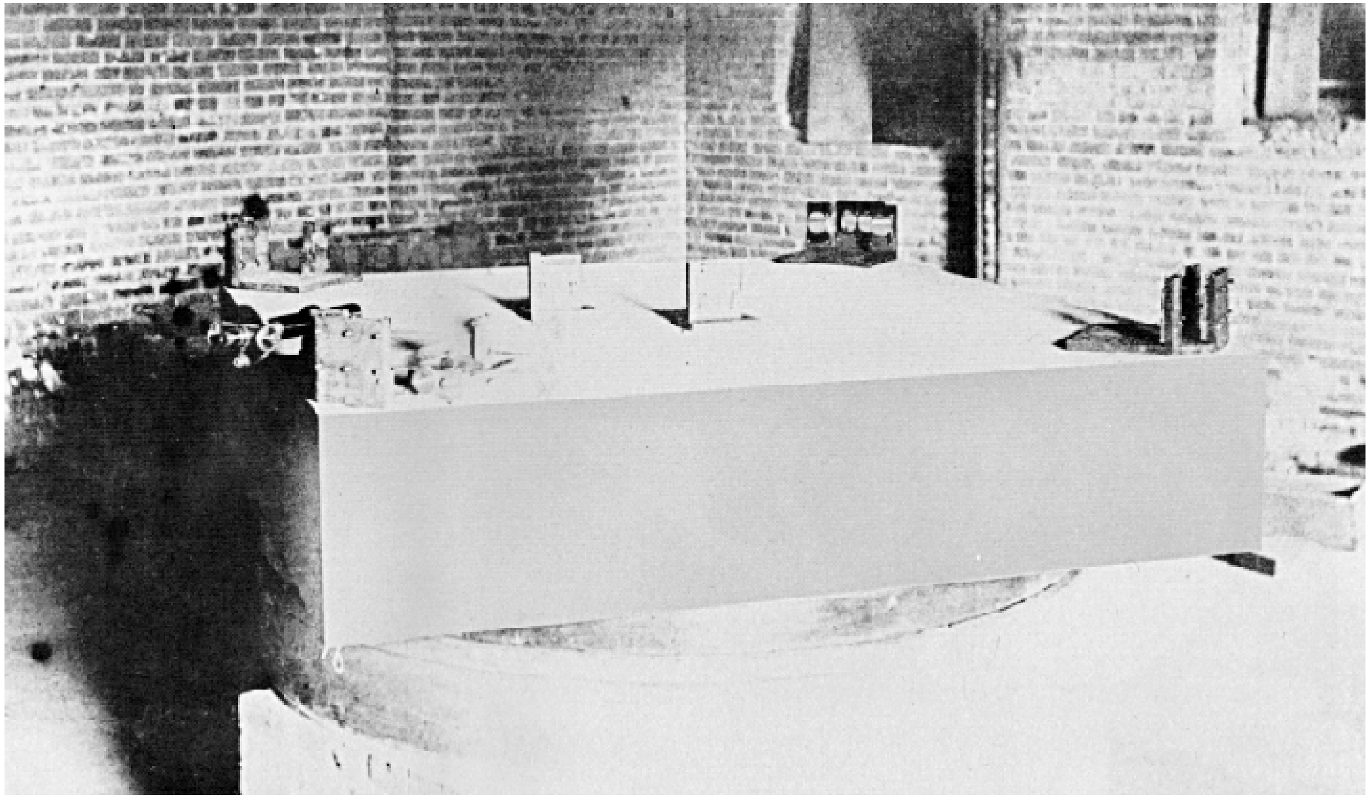
Michelson interferometer

Albert 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 (speed= distance/time)

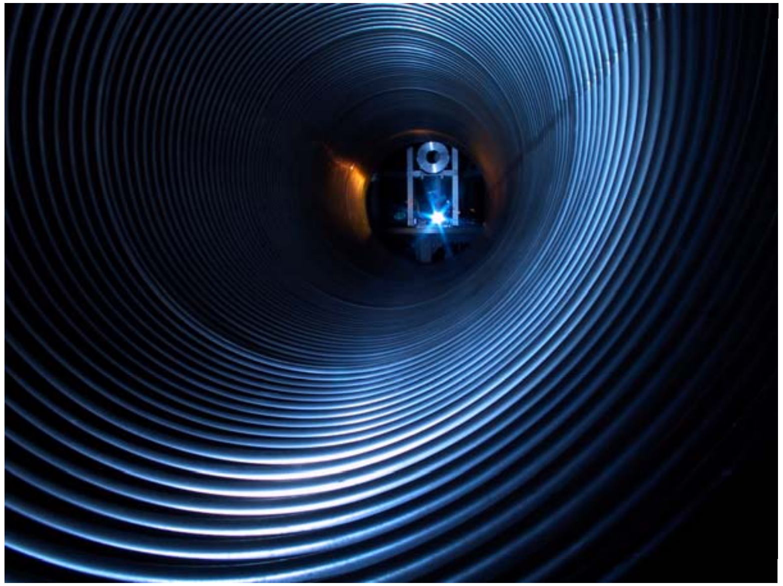


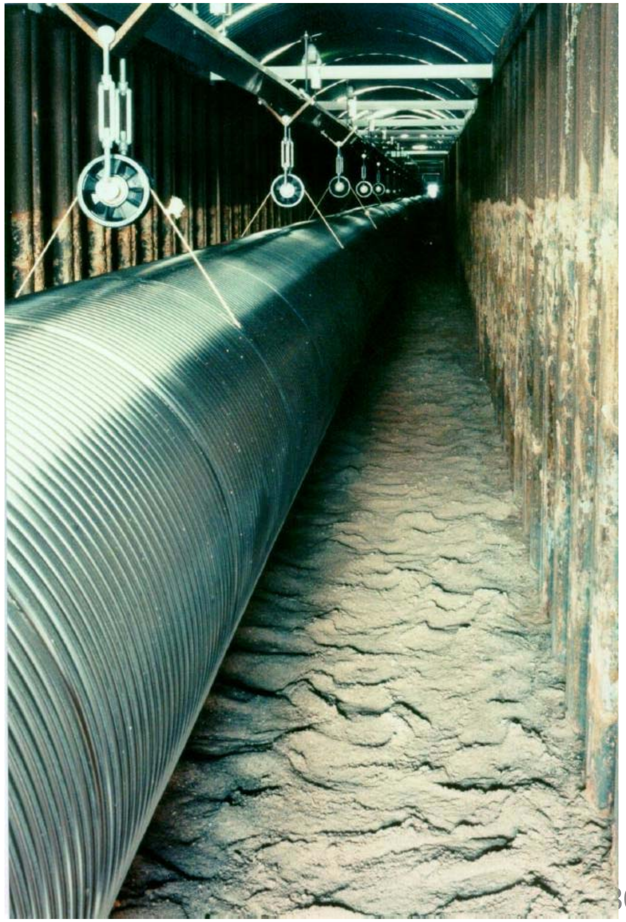
Original apparatus used by Michelson and Morley, 1887

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

New attometer technology of interferometers

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

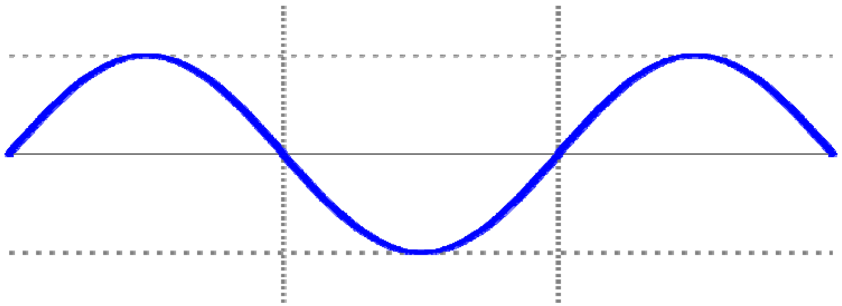




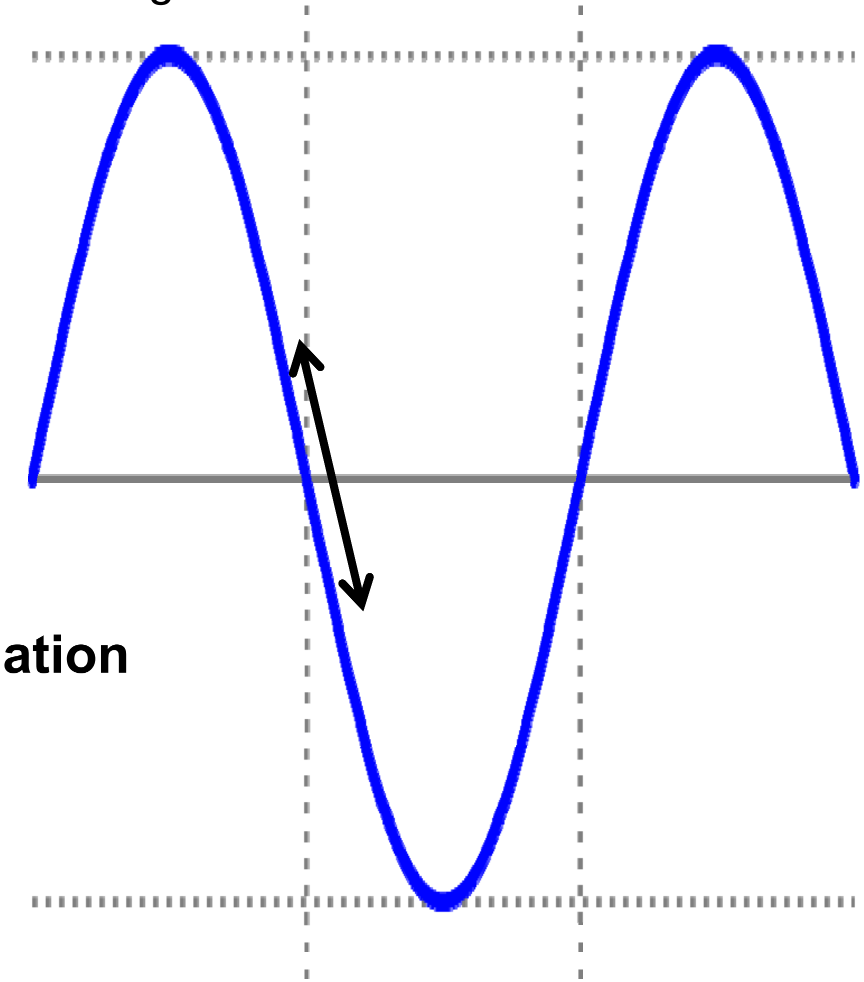
Intense lasers have precise phase resolution and can make precise position measurements

Amplitude^2 = N
Amplitude=sqrt(N)

Small N



Large N



Photon number-phase uncertainty relation
$\Delta N \times \Delta\phi = 1/2$

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

Interferometers can reach Planckian sensitivity

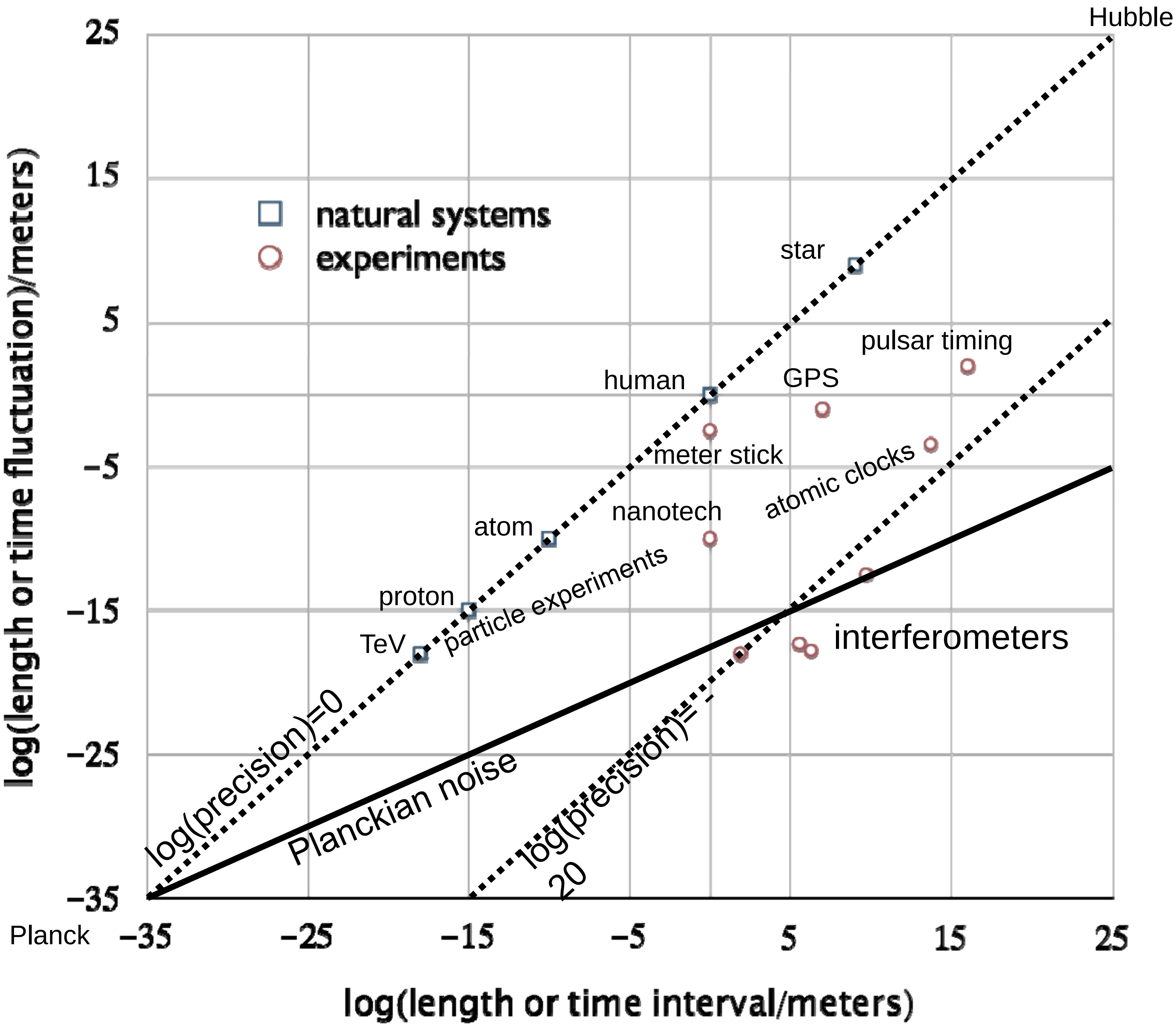
Over short (~ size of apparatus ~ microsecond) time intervals, interferometers can reach Planck precision (~ attometer jitter)

Fractional random variation in differential frequency or position between two directions over time interval 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):

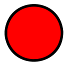
$$\frac{\Delta\nu(\tau)}{\nu} = 2.8 \times 10^{-15}/\sqrt{\tau/\mathrm{sec}}$$


Hubble
natural systems
experiments
star
pulsar timing
human
GPS
meter stick
atomic clocks
nanotech
atom
particle experiments
proton
TeV
interferometers
log(precision)=0
Planckian noise
log(precision)=−20
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

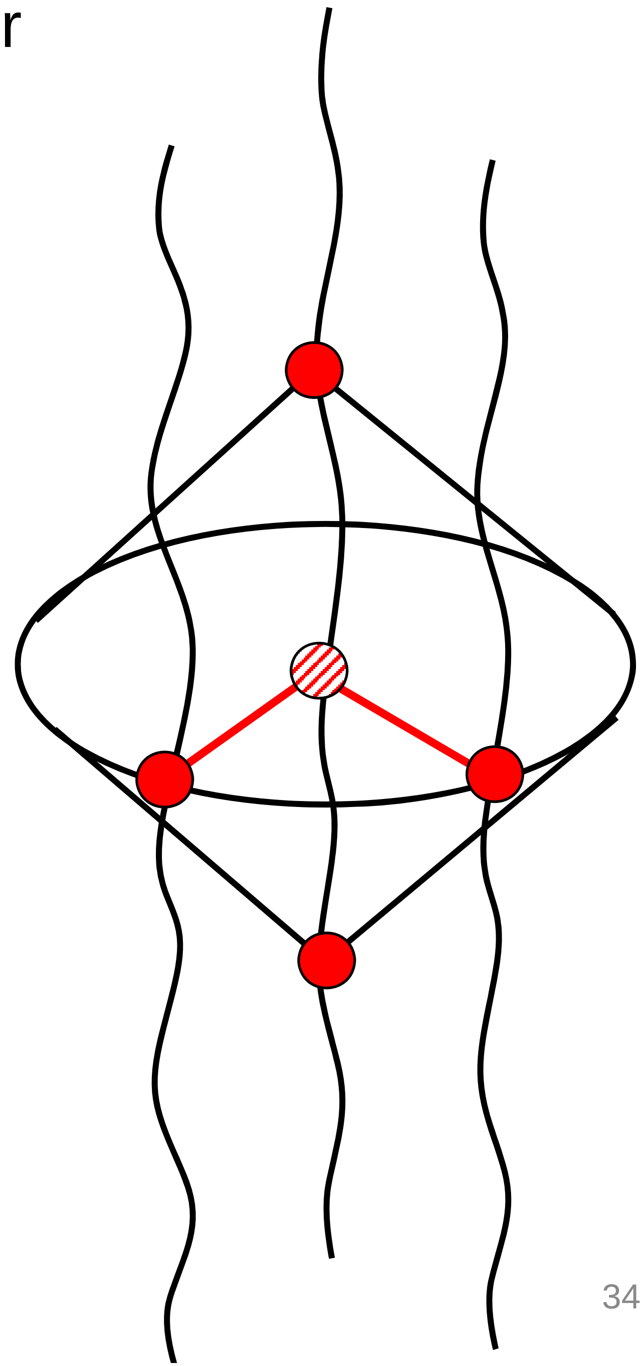
Space-time of Michelson interferometer

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

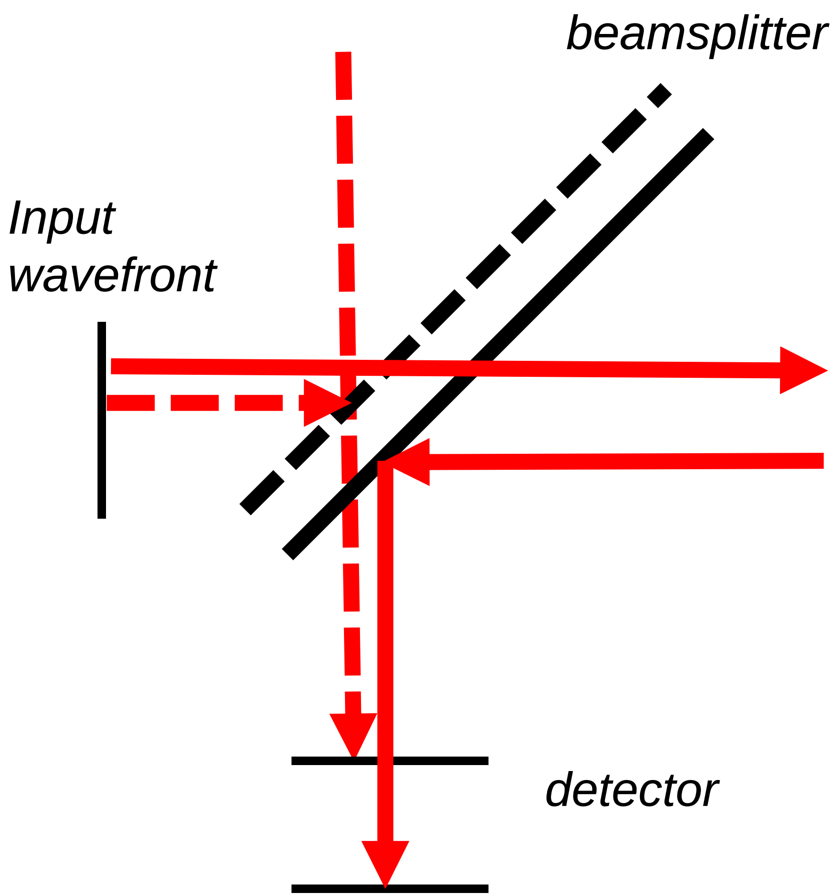
Causal diamond duration is twice the arm length

Geometrical uncertainty leads to fluctuations

$$\langle x_\perp^2 \rangle \approx L\ell_P$$

For durations

$$\tau \approx L/c$$



Response of simple Michelson interferometer

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

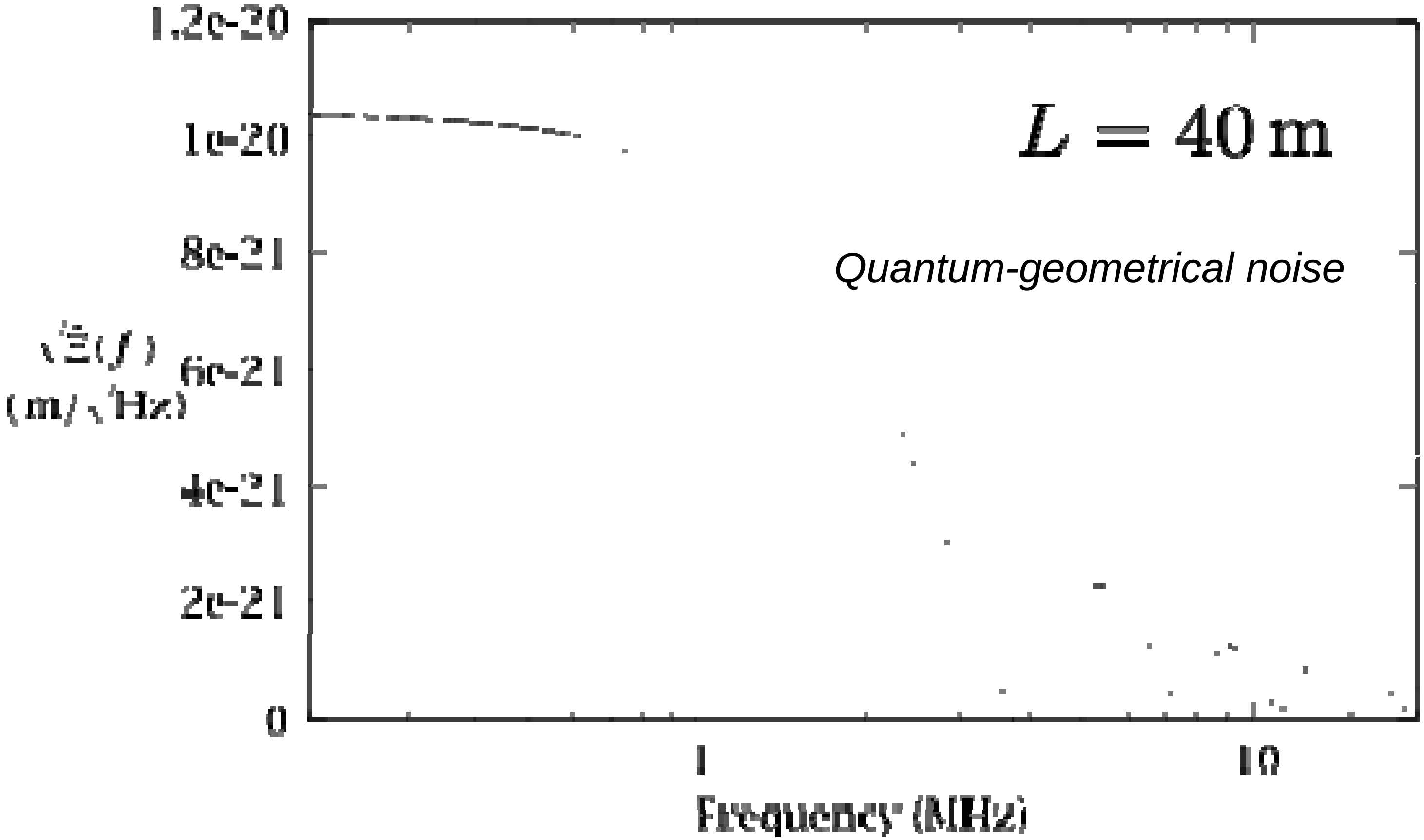
$$\tilde{\Xi}(f) = \frac{4c^2 t_P}{\pi(2\pi f)^2}[1 - \cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$

Depends only on Planck scale and L

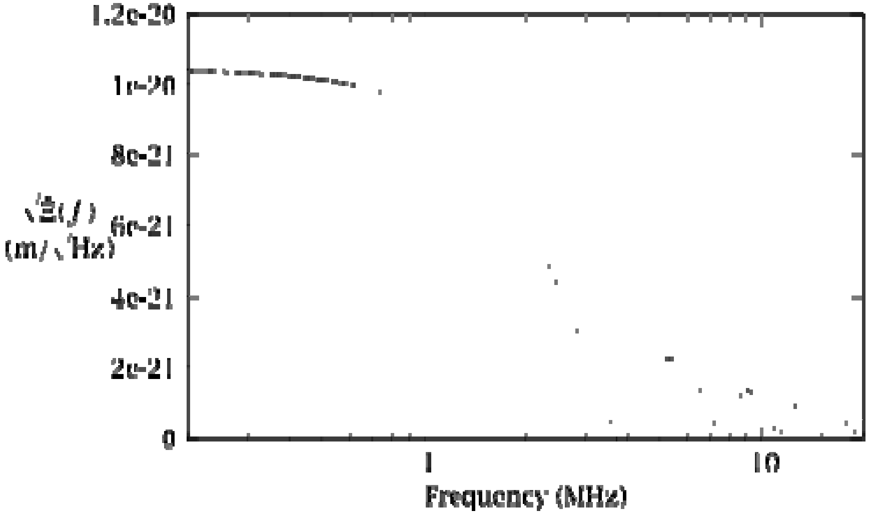
Measured noise is not sensitive to modes longer than 2L

Interferometer position noise spectrum, including transfer function

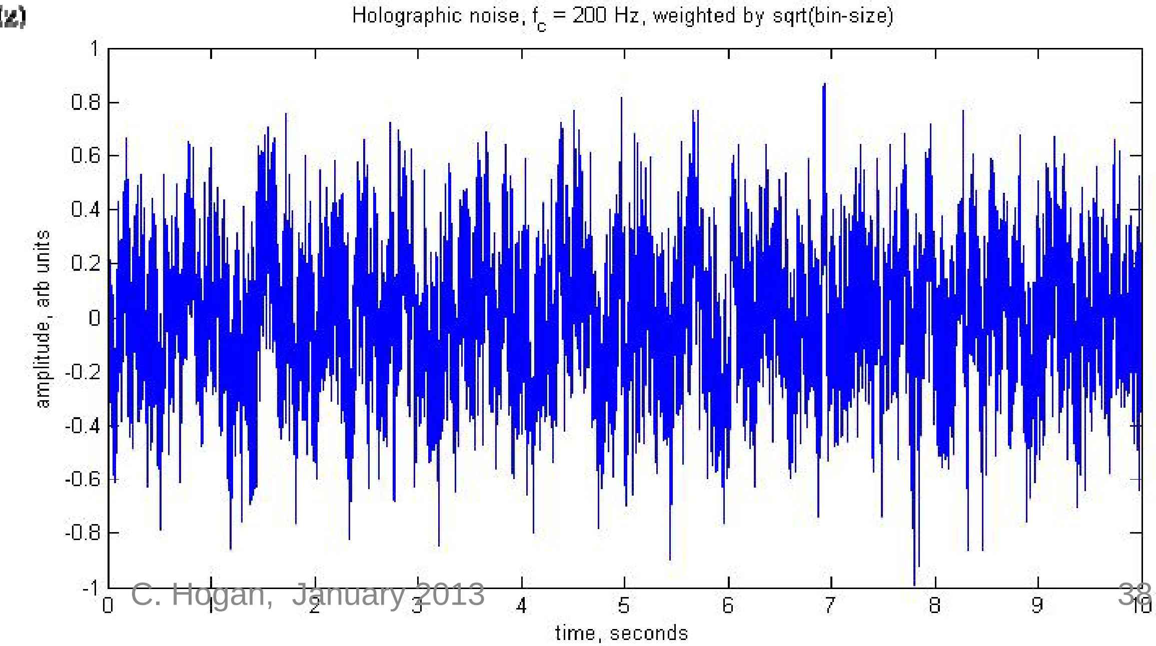
$$\tilde{\Xi}(f) = \frac{4c^2 t_P}{\pi(2\pi f)^2}[1-\cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$



Simulated holographic noise in 40m cavity (slowed by ~10,000 to be audible)



Spectrum and waveform

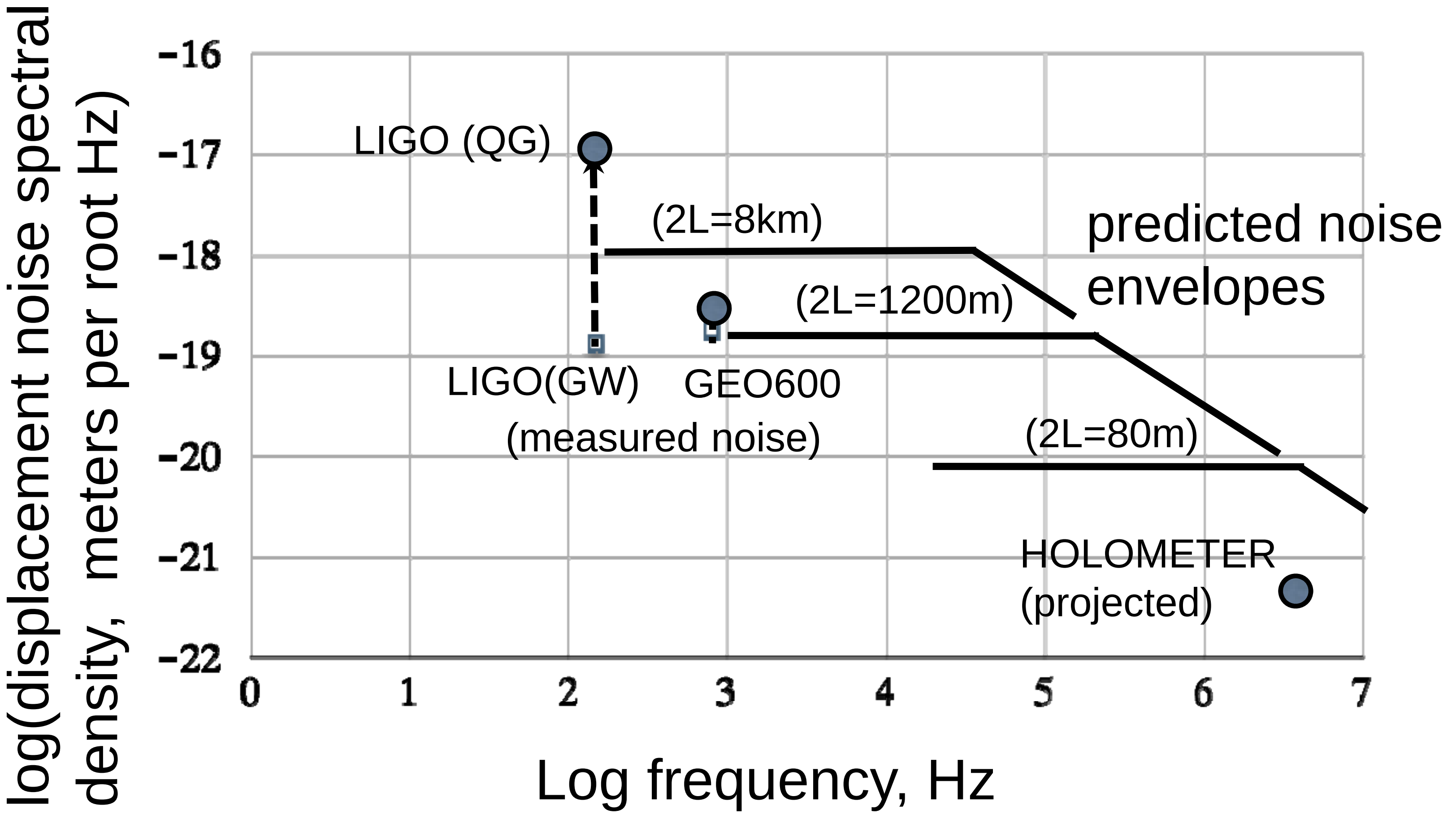


Quantum-Geometrical noise in real interferometers

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

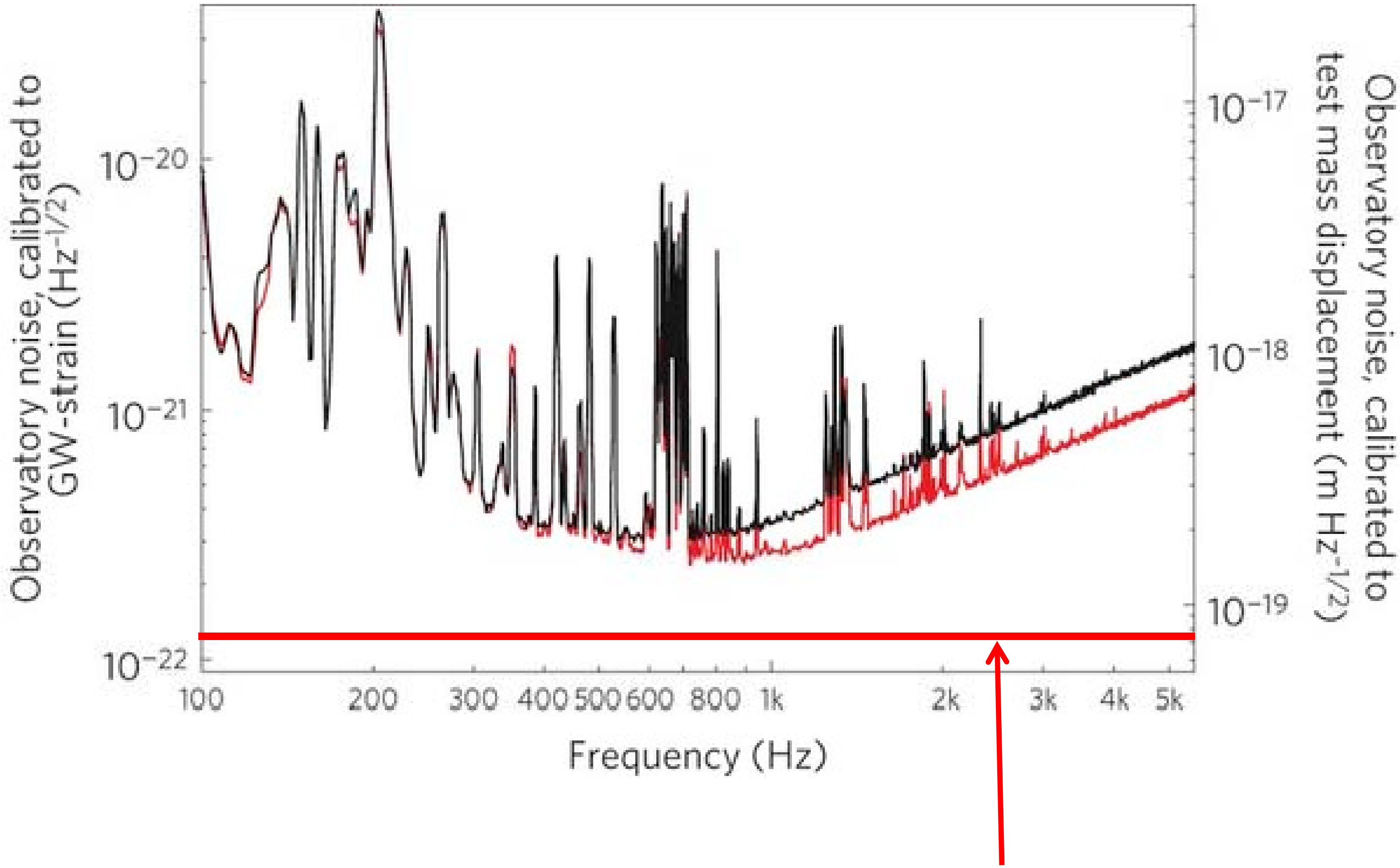
GEO600 (2L=1200m) is already close to quantum geometry prediction

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



GEO-600 (Hannover): best displacement sensitivity

GEO600 noise (2011) and predicted noise

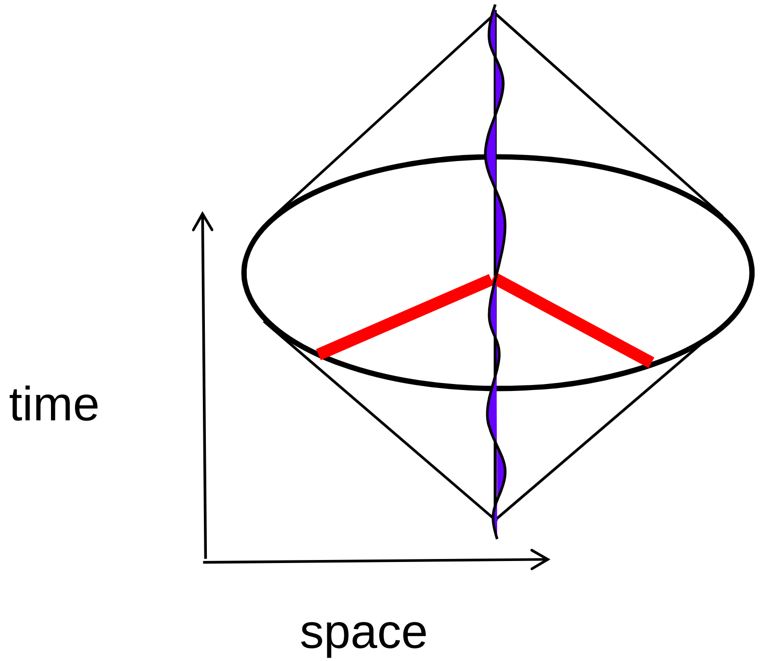


$$h^2 = (\Delta L/L)^2 = t_P/\sqrt{4\pi} = (1.23 \times 10^{-22}\mathrm{Hz}^{-1/2})^2$$

The Fermilab Holometer

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

“Holographic Interferometer”



Spacetime diagram of an interferometer

In the Oxford English Dictionary

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

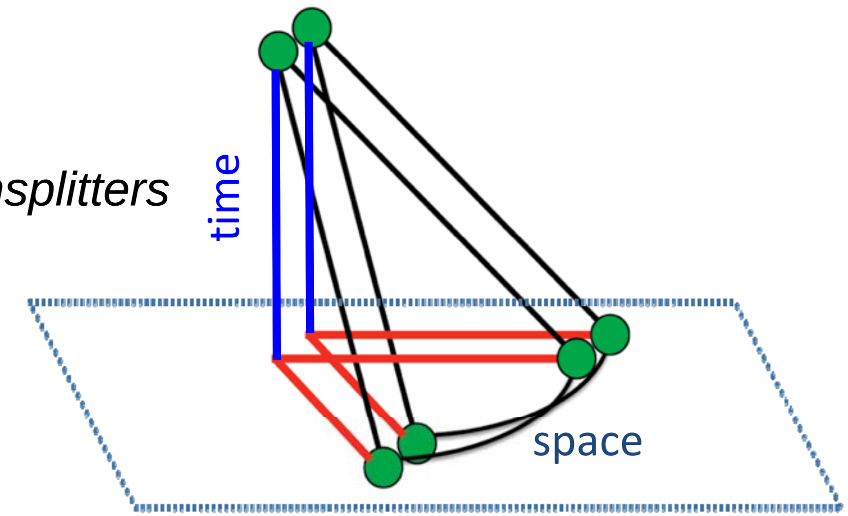
exploit the spatial coherence of quantum-geometrical noise

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

Sensitive to nonlocal entanglement of quantum-geometrical position states

Overlapping spacetime volumes -> correlated fluctuations

World lines of beamsplitters



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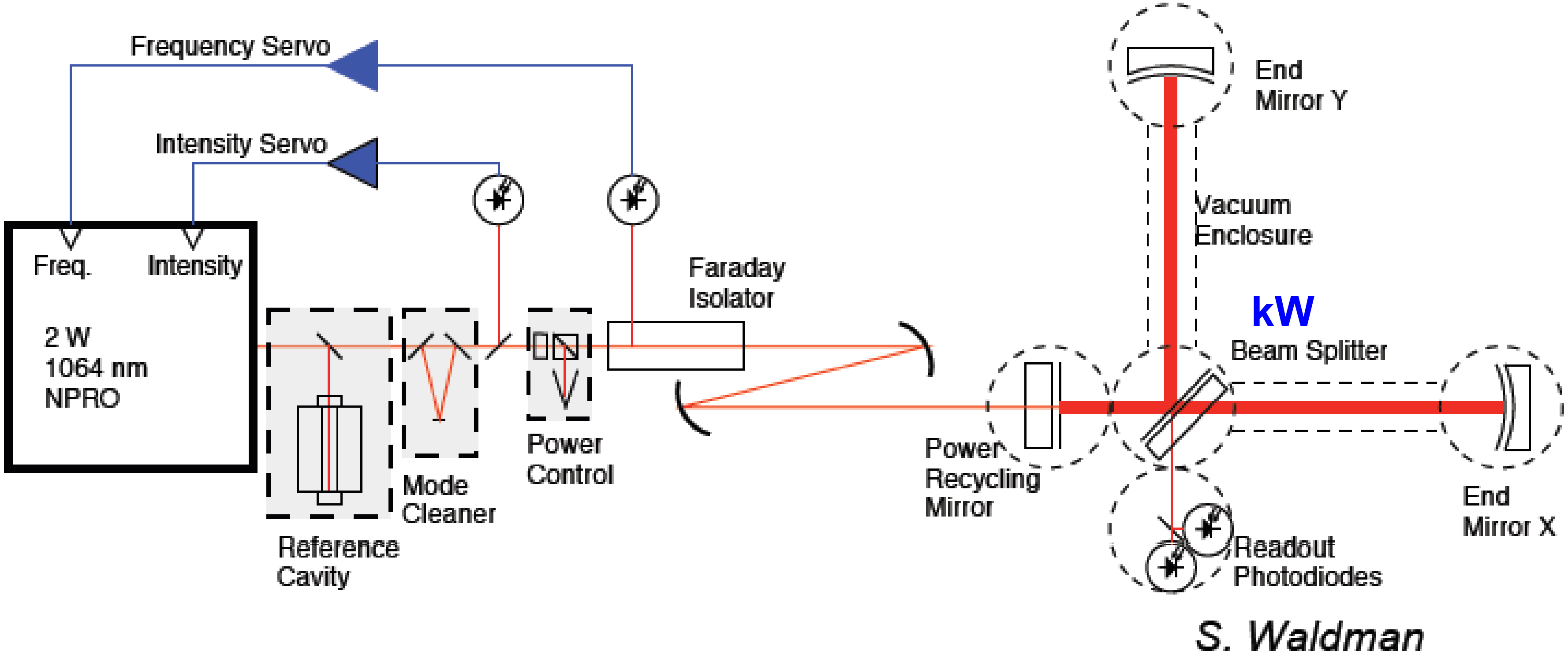
allest scales, the

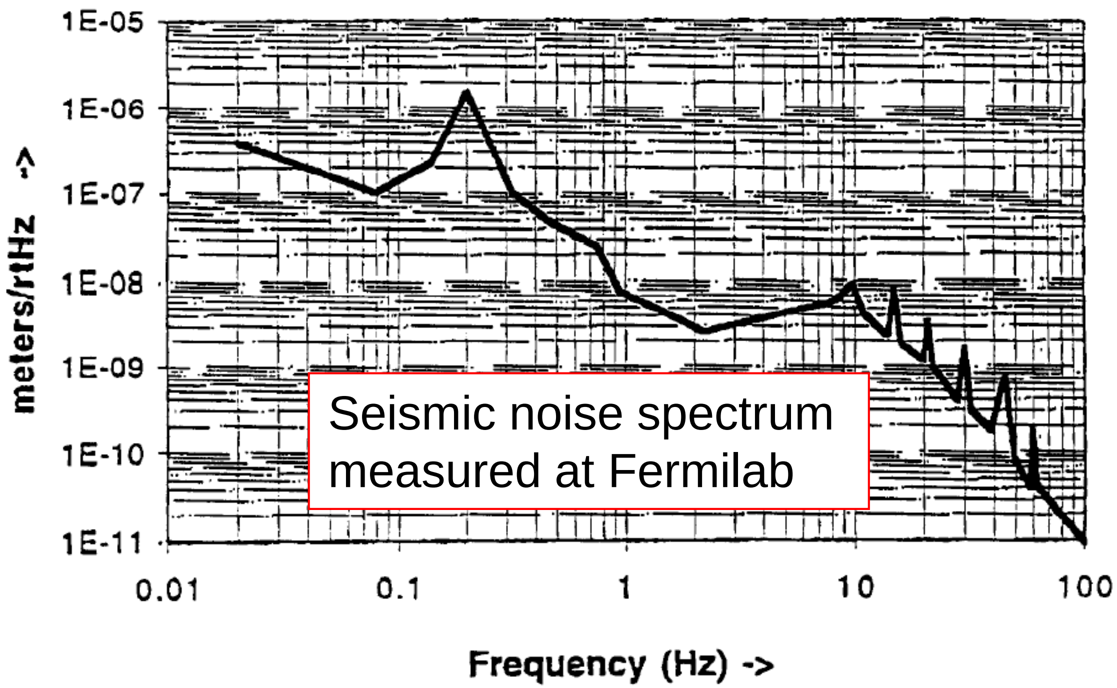
Holometer optical configuration

(We need 2 of these)



Fabry-Perot cavity gives power recycling factor of 3000 → kW beam

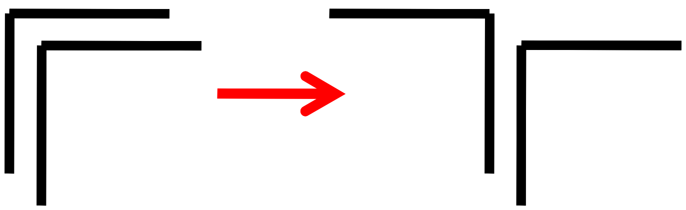
Simplifications relative to GW detectors



- The exotic noise measurement can be made at high frequencies where seismic noise is negligible
  - The holographic noise is predicted to be white for f<c/4L ~ few MHz
  - Most of the noise problems (and corresponding experimental effort) in gravity wave experiments are at lower frequencies
  - Compact vacuum system housing piezo-actuated mirror mounts can be used instead of large vacuum systems holding tall suspension systems
  - At high frequencies, noise is expected to be dominated by photon shot noise

Distinguishing exotic noise from conventional noise

- The 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 usually frequency dependent (narrow lines, ~1/f, etc.)
  – This gives us ways to discriminate against conventional backgrounds such as AM radio stations.
- Experimental knobs:



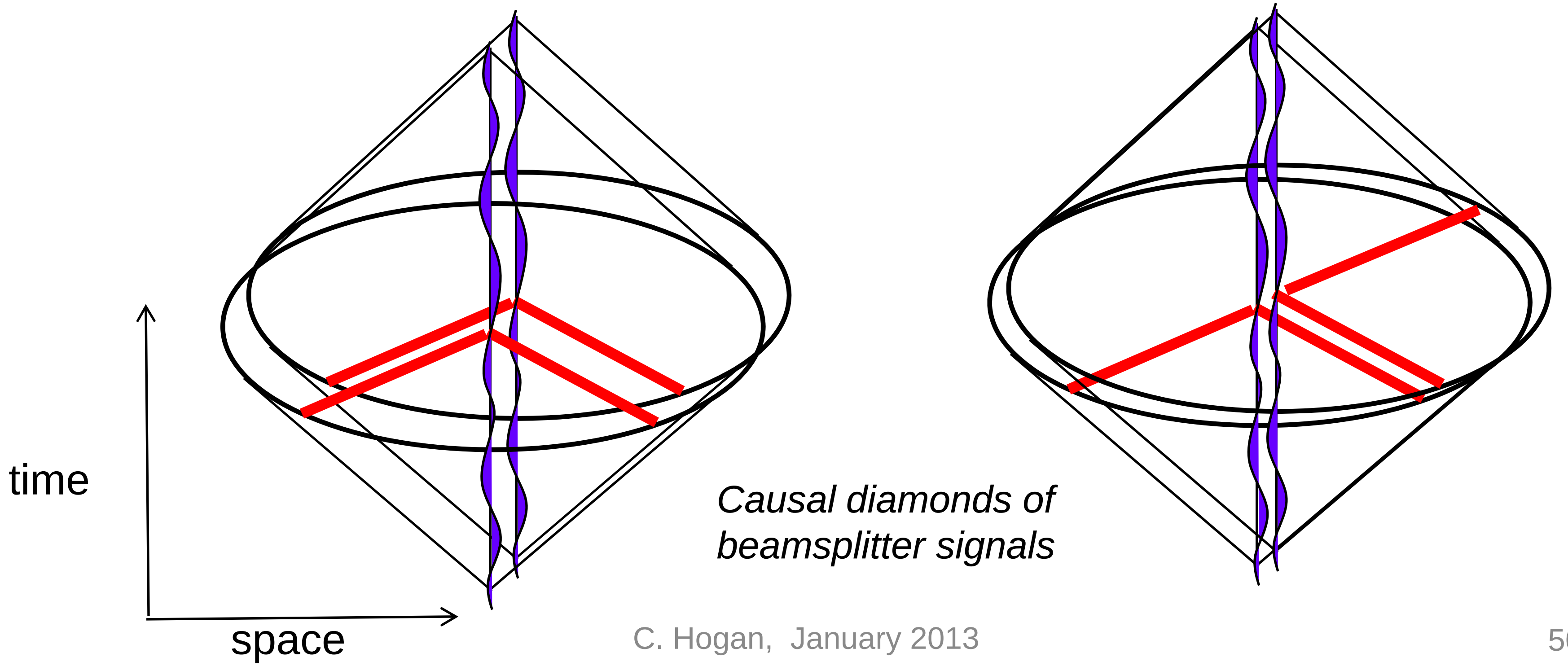
➢Orientation of two interferometers
  ➢ Nested for maximum correlation
  ➢ Back-to-back to turn off correlation
    (information then travels along independent paths)
➢Change arm length to verify scaling with L.

Correlations of two interferometers

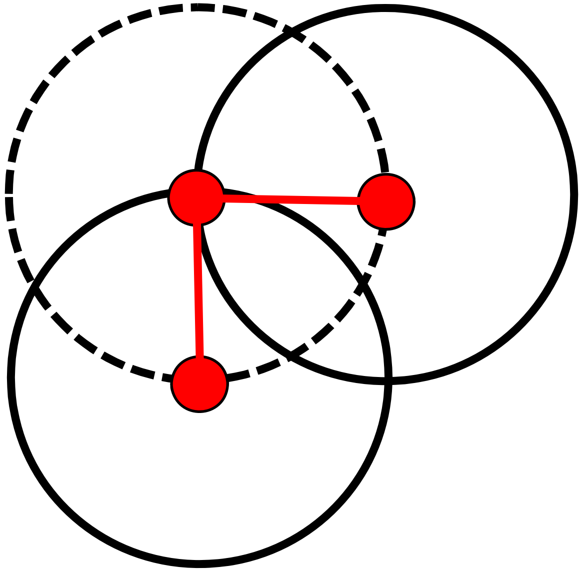
Overlapping spacetime volumes collapse into the same state

Correlates signals of nearly co-located Michelson interferometers

Non-overlapping configurations are uncorrelated

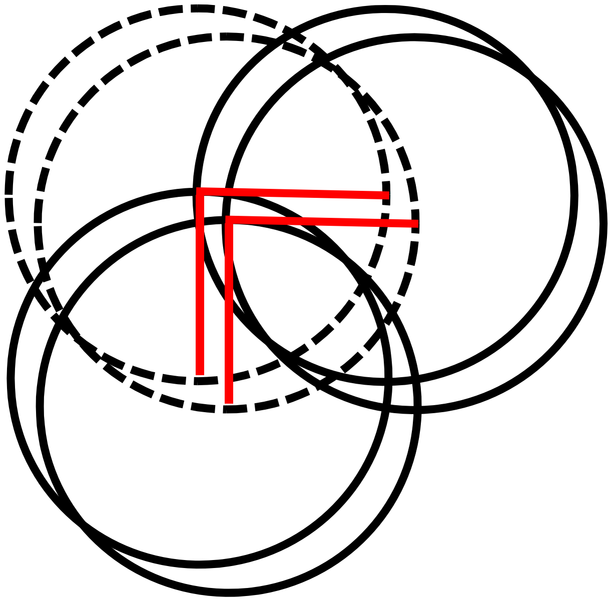


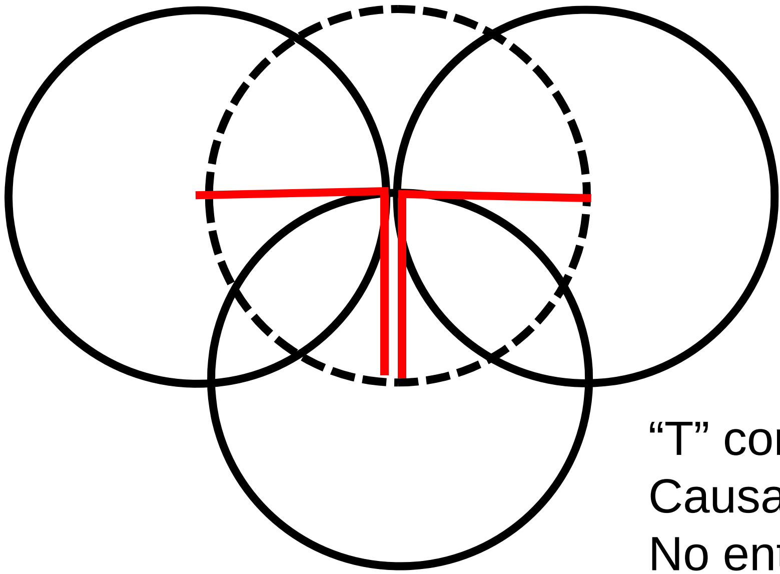
Causal diamonds of beamsplitter signals



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

Ben Brubaker bolting the holometer vacuum system together

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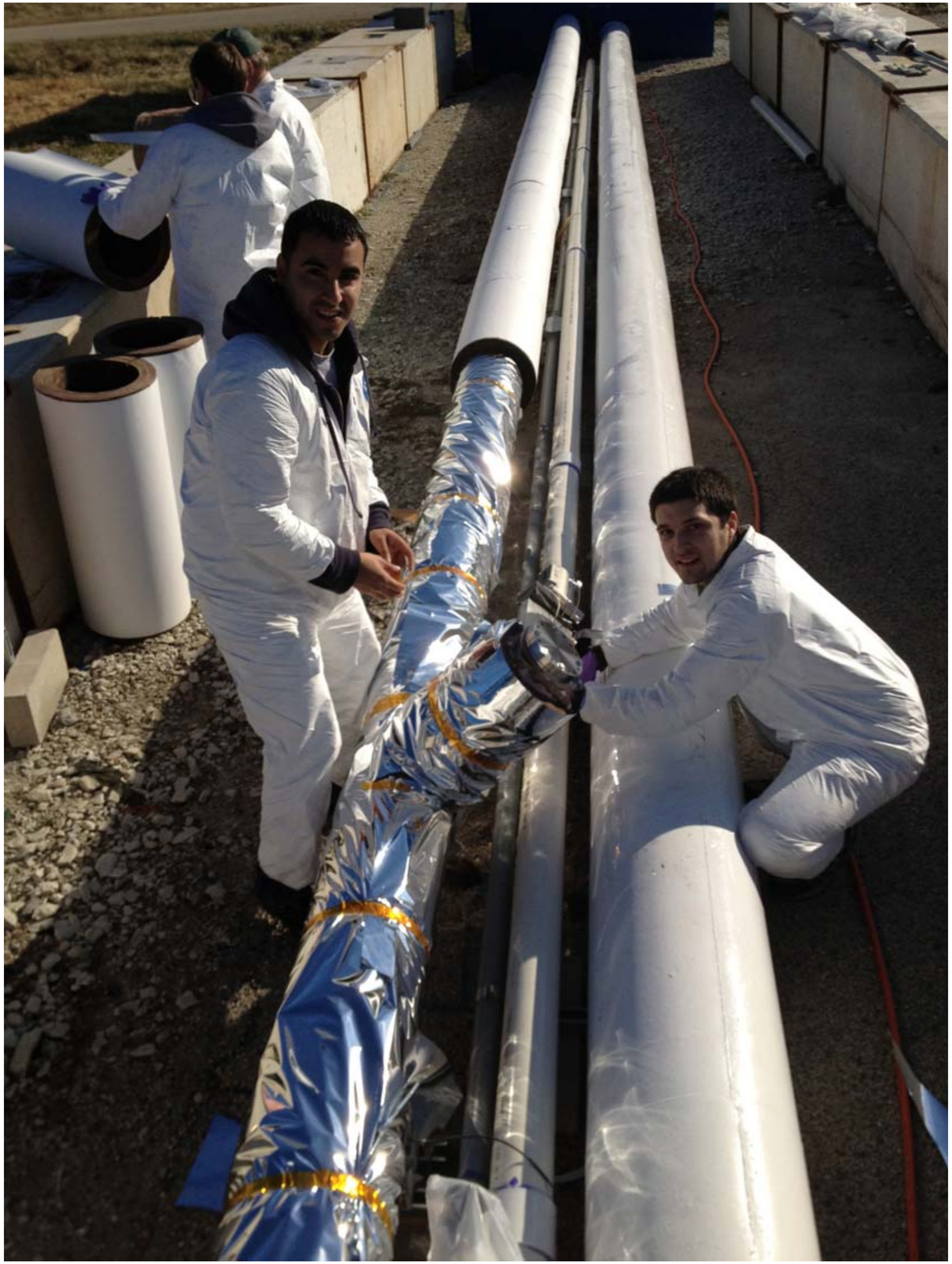
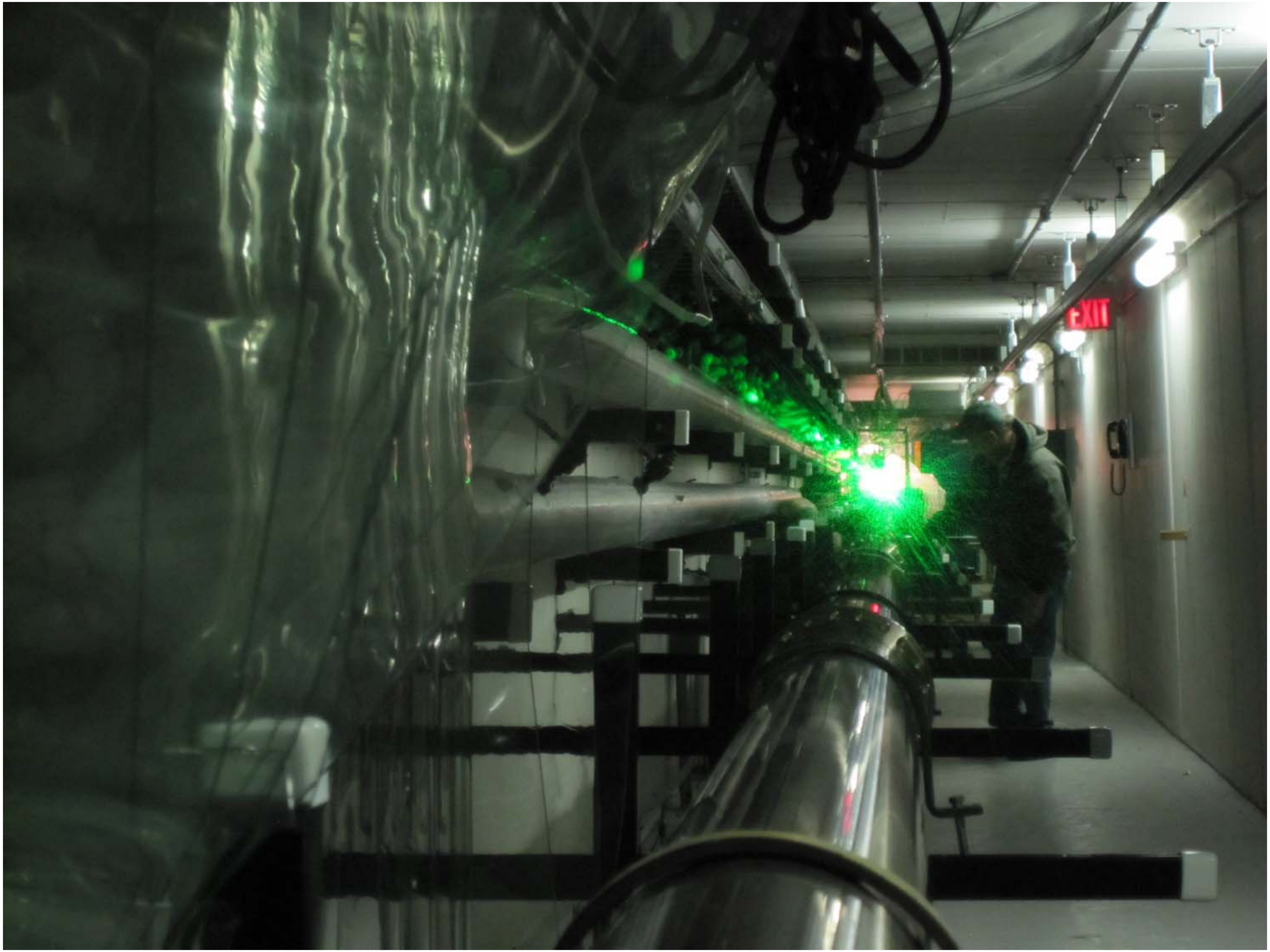



EXIT

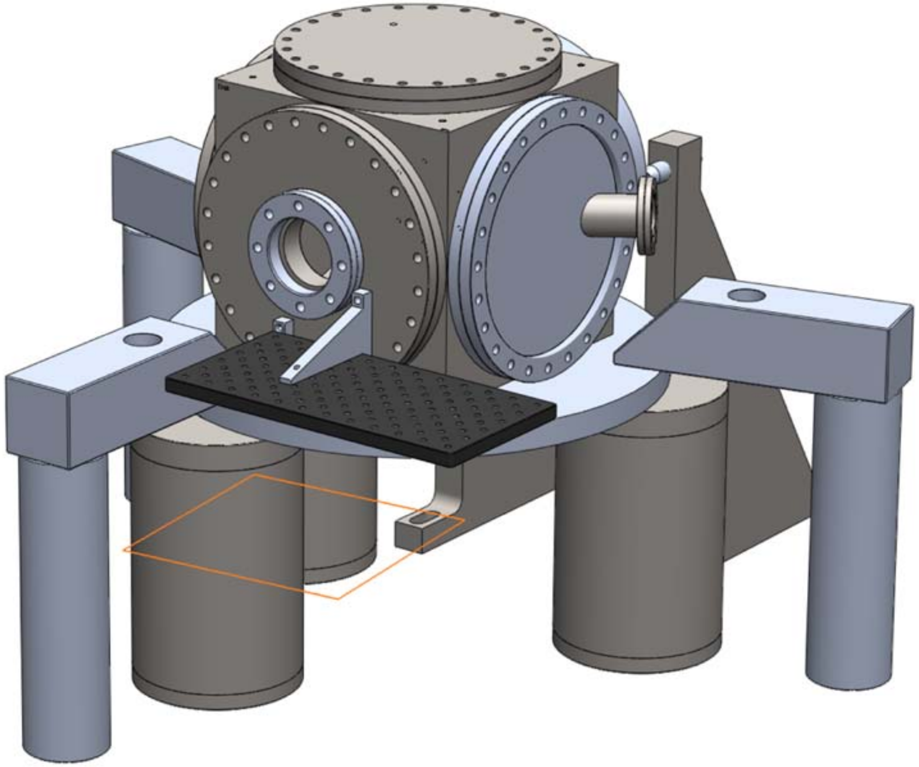
Pipes are insulated with 4” fiberglass + intermediate and exterior radiation shield

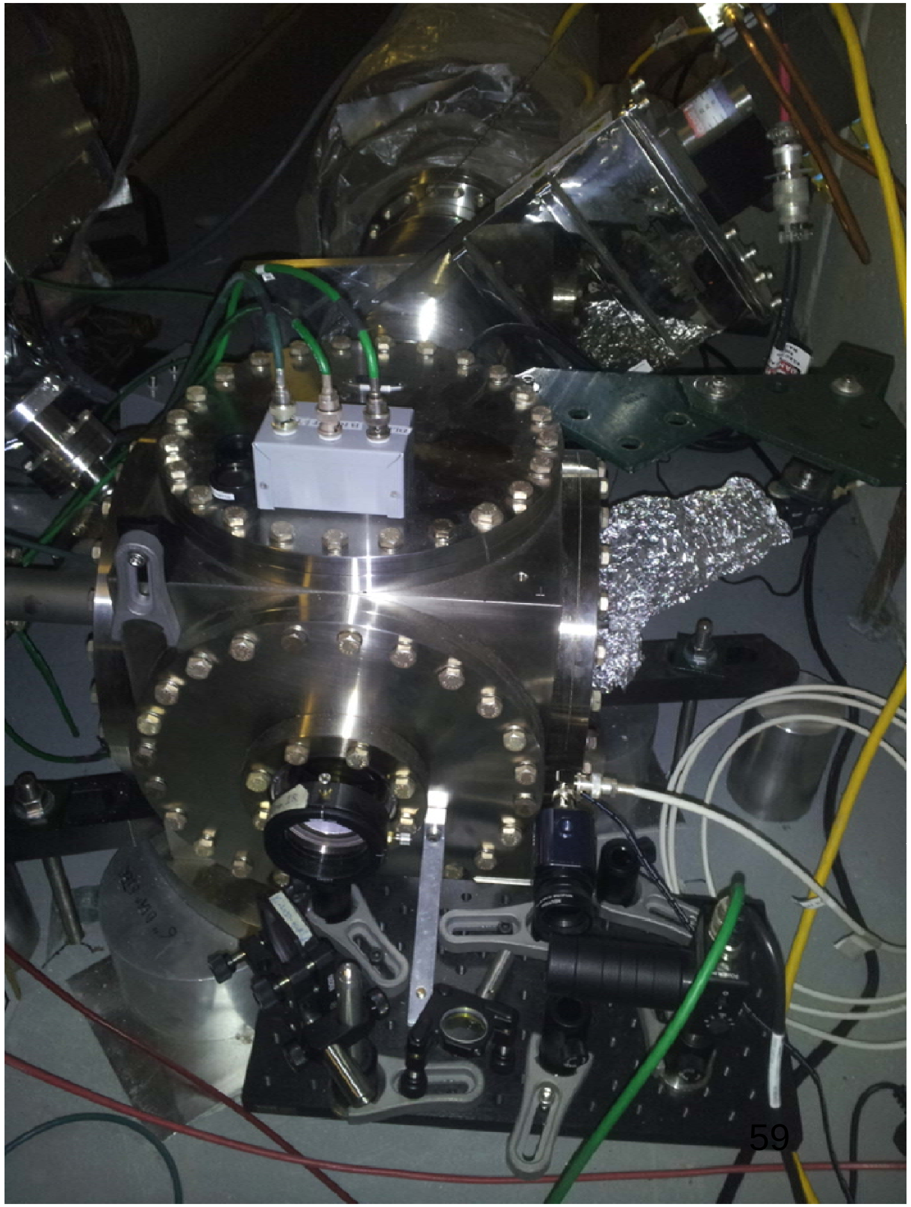
Bake in situ to 200C by flowing 200A current through stainless steel vacuum pipe


East arms


North arms

End mirrors can be adjusted by externally moving the vacuum endstation

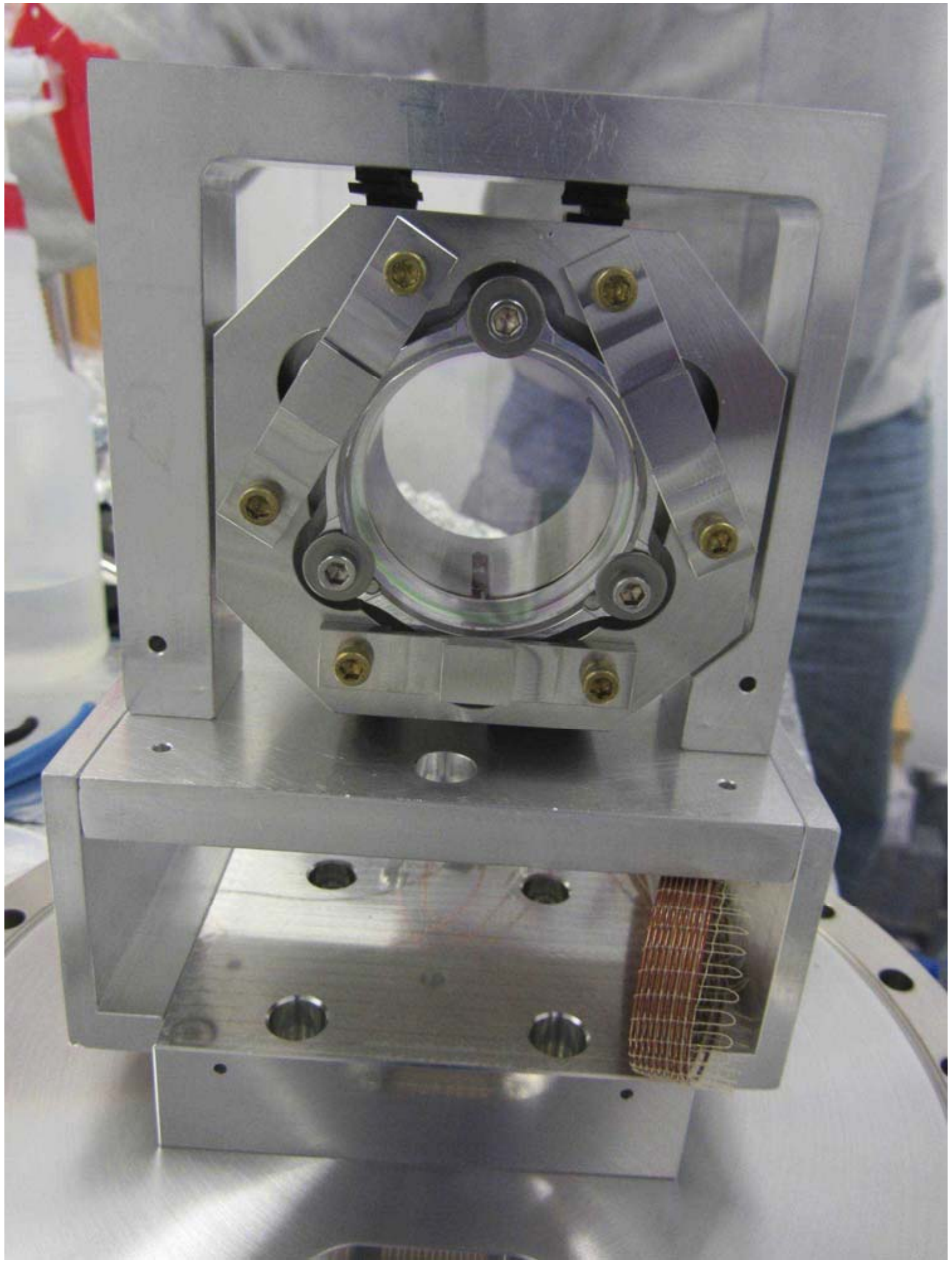




Endstation vacuum mirror mount

- Actuated by 3 spring-loaded PZT stacks.
- 1.4 kHz resonant frequency
- 14 micron PZT stack range allows for ~cm adjustment of beamspot over 40m arm length
- Can compensate for slow thermal expansion of arm length for up to 2 hours.

- North and East end mirrors are driven in antisymmetric motion to compensate for differential arm length motion (DARM) due to seismic noise.

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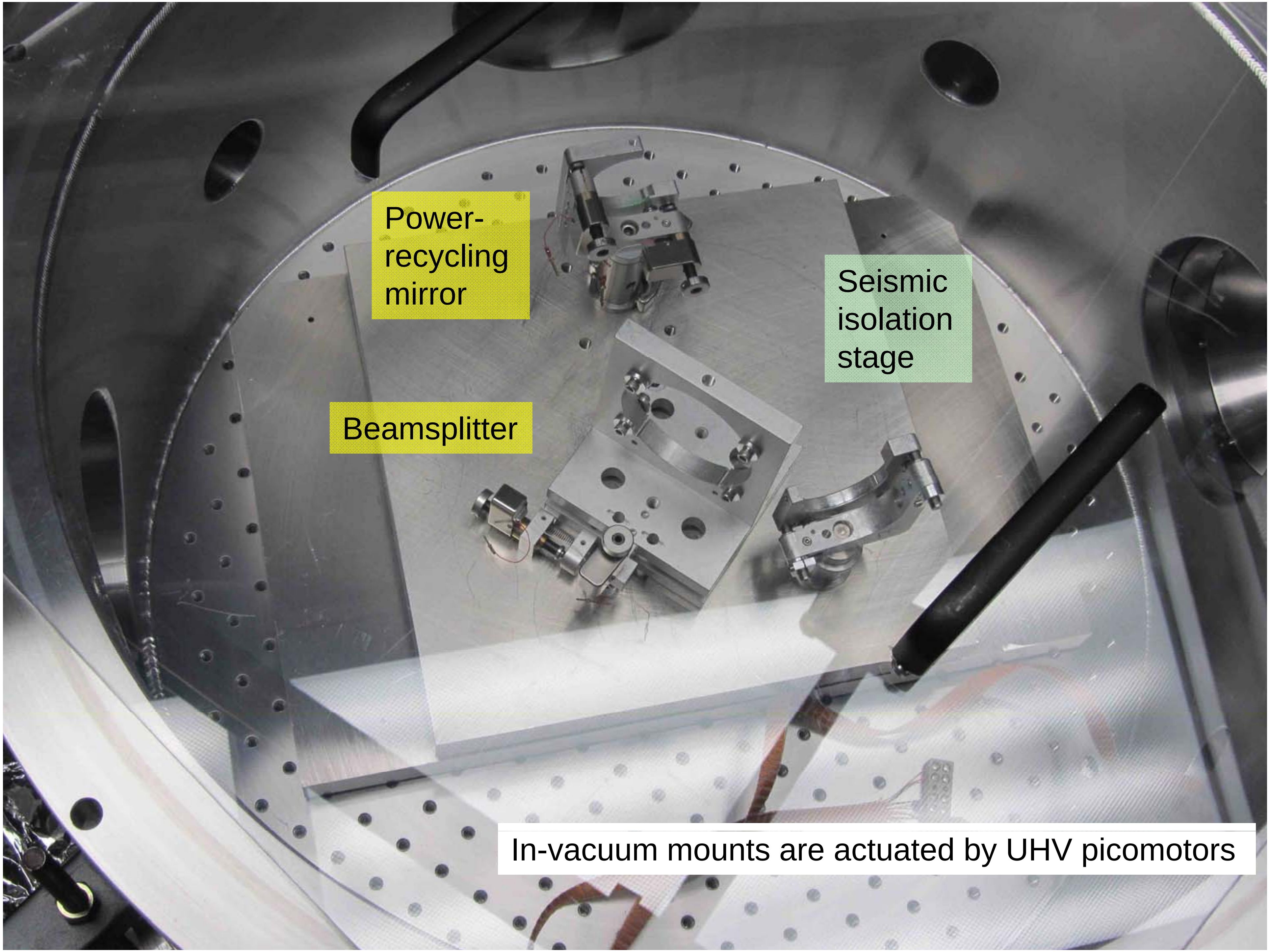
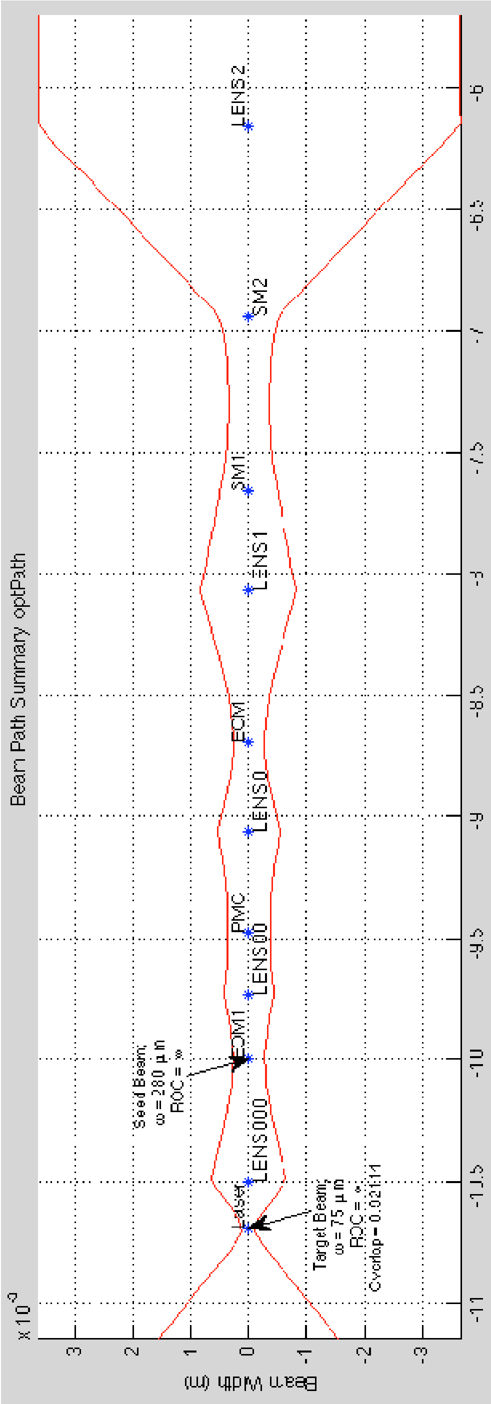
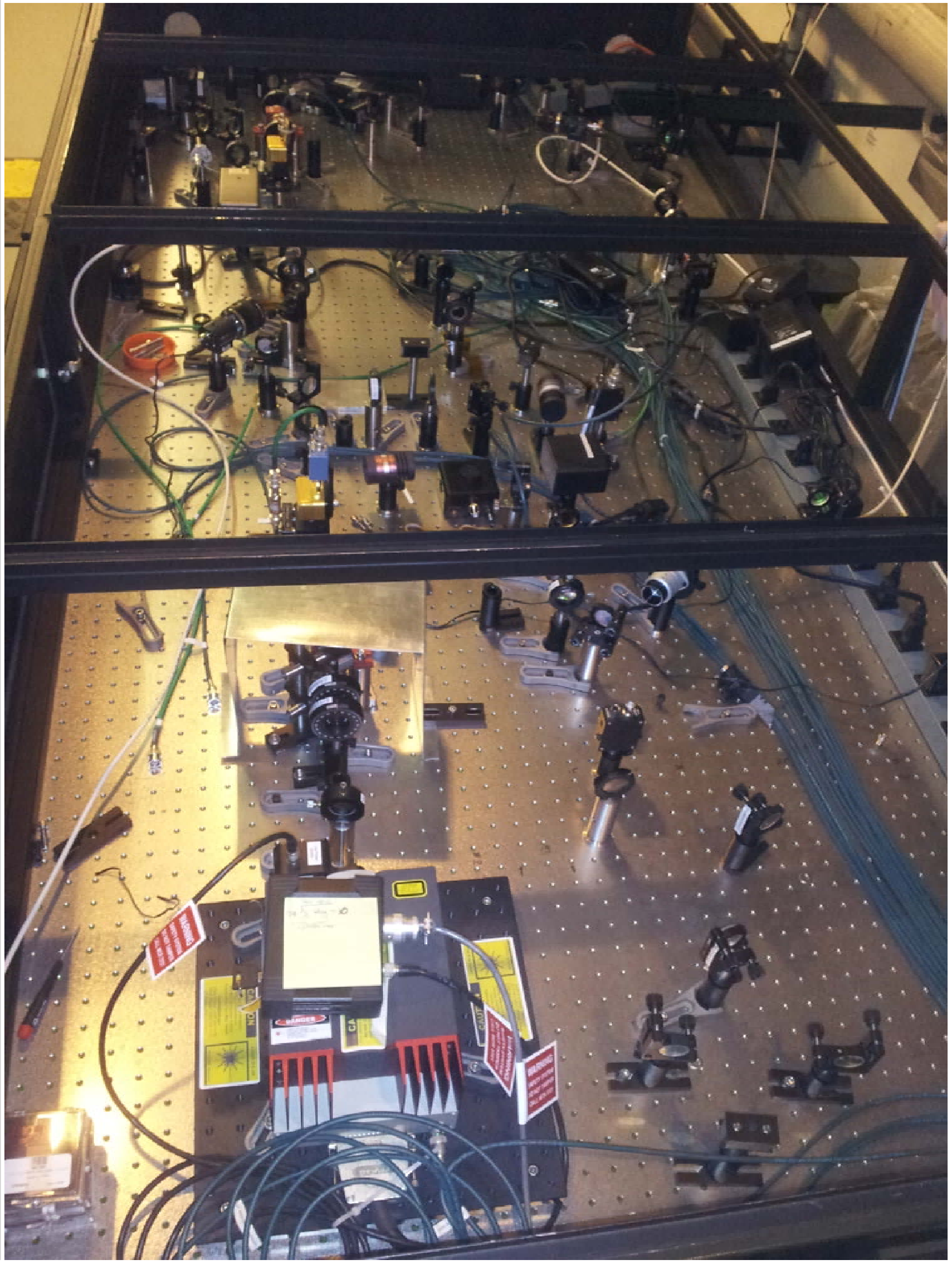

Power-
recycling
mirror
Seismic
isolation
stage
Beamsplitter
In-vacuum mounts are actuated by UHV picomotors

Laser launch





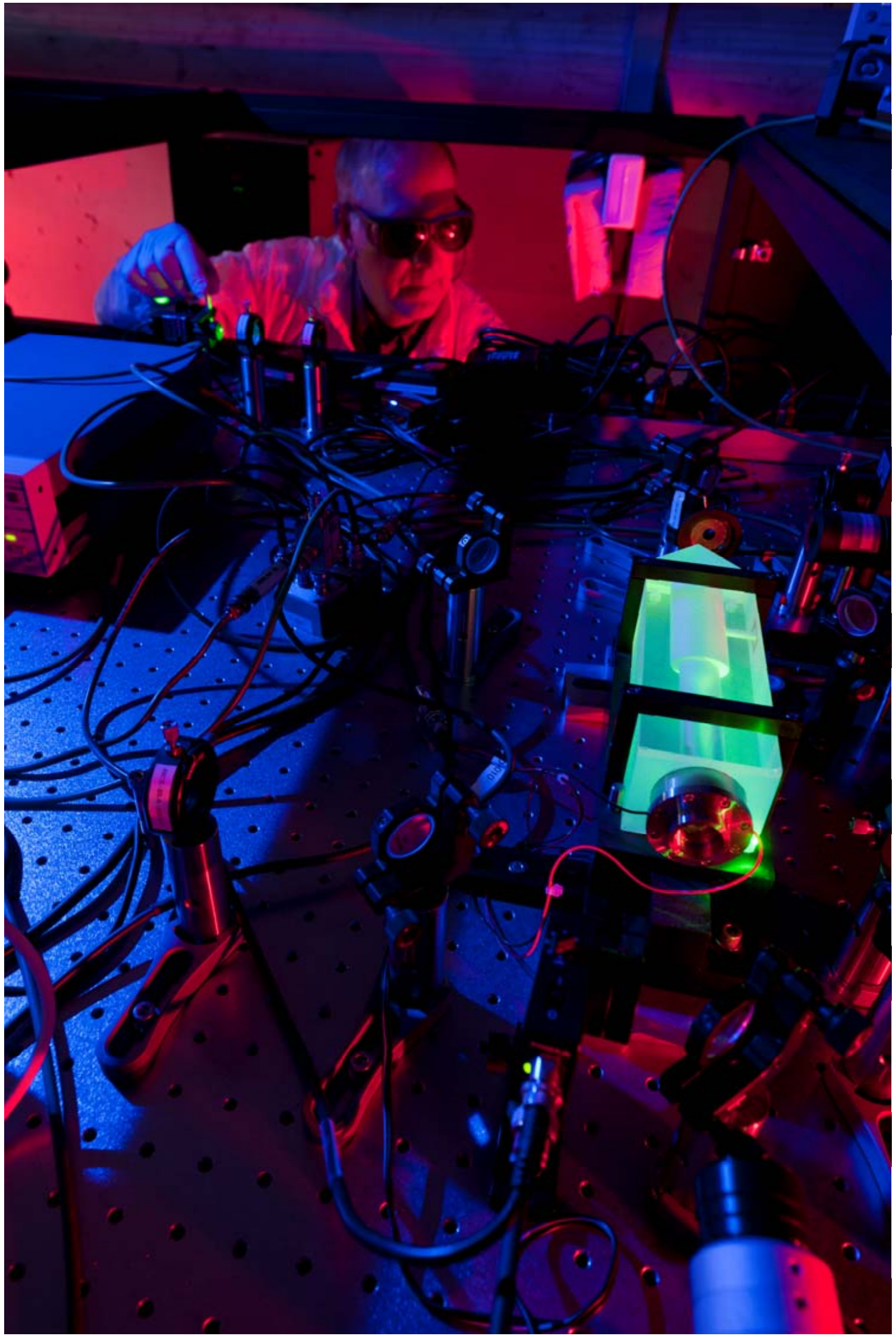
2W, CW
Nd:YAG laser

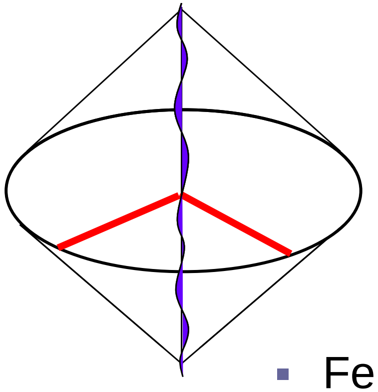
RF optoelectronics to lock the laser to the instantaneous resonance frequency of the interferometer cavity.

Telescope for mode-matching to the 40m cavity.

Active PZT-based steering.

Separate launch for each interferometer





The Fermilab Holometer Team

- Fermilab:
  - A. Chou (co-PI, project manager), C. Hogan, C. Stoughton, R. Tomlin, J. Volk, W. Wester
- MIT LIGO:
  - M. Evans, S. Waldman, R. Weiss
- U.Chicago
  - S. Meyer (co-PI)
- U. Michigan LIGO
  - D. Gustafson
- Northwestern
  - J. Steffen

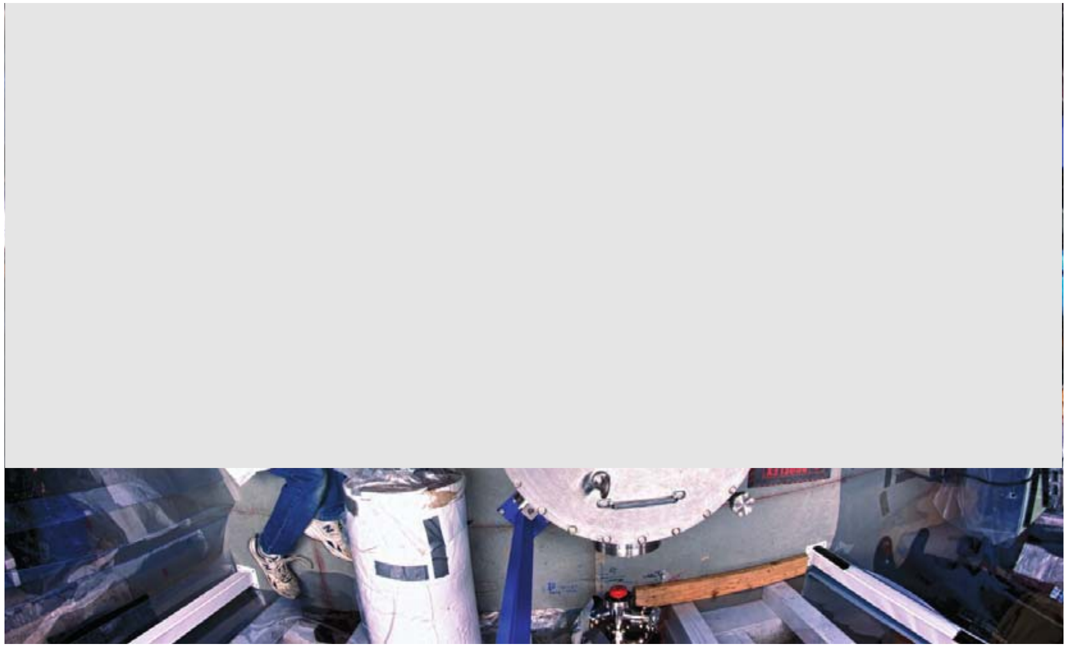
- Training 4 PhD students, and providing research experience to numerous undergrads (including 3 senior theses), and high school students

Status of the Fermilab Holometer

- Currently under commissioning at Fermilab
  - Funded mostly by A. Chou Early Career Award
- Power-recycled 40m interferometers operating with high finesse
- Developing & testing detectors, electronics, control systems
  - Vacuum systems of both interferometers are complete
  - Cross-correlation spectrum has been measured
  - Upgrades to subsystems still pending
  - Planckian sensitivity expected in a year or two

Real experimental physics: noise hunting

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.

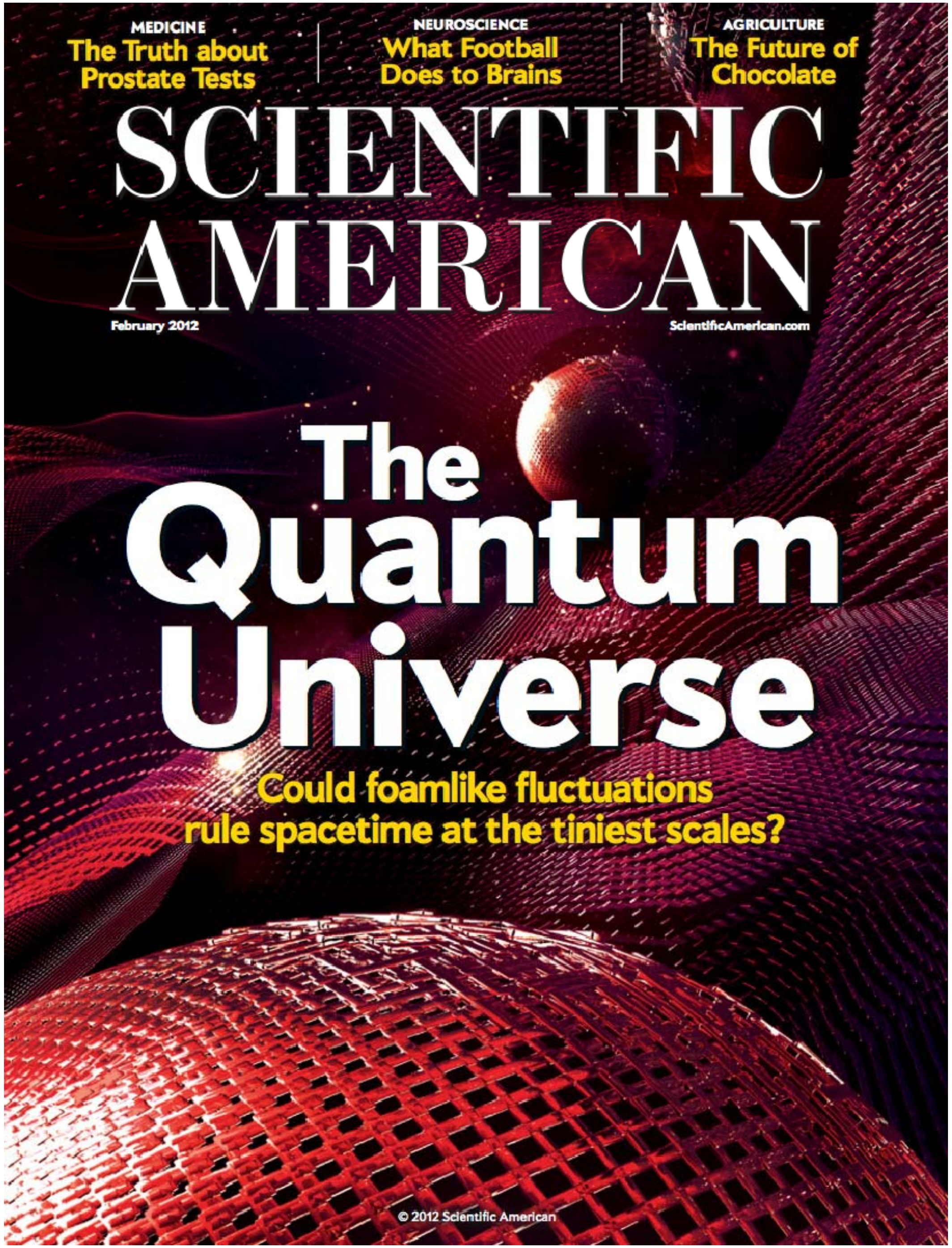
Black holes and causal diamonds

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 sub-Planckian upper limit on noncommutative geometry, in a certain implementation 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