Beyond the Cosmic Frontier

Exploring quantum emergence of geometry and matter

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2011 Nobel Prize in Physics for discovery of cosmic acceleration

Trifecta. Saul Perlmutter (*left*), Brian Schmidt (*center*), and Adam Riess shared the 2011 Nobel Prize in physics.

would win a Nobel Prize had come to be matched by a growing certainty about who the individual winners might be. The Shaw Prize, awarded in 2006, had already singled them out: Brian Schmidt and Adam Riess from the High-z Supernova Search Team—which Garnavich was a part of—and Saul Perlmutter, leader of the competing Supernova Cosmology Project (SCP). Yet, when his wife named the winners, all he could say was, "Shit." The disappointment of being left out was far more intense than Garnavich had imagined.

A Week in Stockholm

For the rival teams whose discovery of dark energy had transforme scientists' picture of the universe, the 2011 Nobel festivities were flurry of jubilation, disappointment, and one-upmanship

EARLY MORNING ON 4 OCTOBER 2011, THE DAY THE PHYSICS Nobel was announced, astrophysicist Peter Garnavich was woken up by a phone call that came not from Stockholm but from his wife,

lic Radio th that I was d sachusetts, Harvard University astrophysicist Robert Kirshner—who

ROYA

d f

Cosmic Expansion Accelerates

What is the new physics revealed by cosmic acceleration?

Is it a new property of *gravity*, a new form of *energy*, or both?

What is the relationship between *mass* and *space-time* on large scales and at low densities?

How is *cosmic structure* affected by *cosmic acceleration*?

Probe with measurements of the evolution of the expansion, the motion and structure of mass, and the curvature of space-time

New Energy or New Gravity?

Essence of general relativity (gravity):

"Mass tells space-time how to curve, and space-time tells mass how to move"

--J. A. Wheeler

Probe physics of dark energy astronomically by measuring:

Motion from galaxy velocities

Mass from galaxy clustering

Potential (curvature) from deflection of light

This is the DOE Dark Energy Program

New physics beyond energy and gravity

Maybe cosmic acceleration is a signature of a new and fundamental unification of space-time with matter

Maybe matter and space-time are different low-energy behaviors of a single quantum system (“emergence”)

Maybe new experiments can measure other signatures of this system

- Macroscopic quantum properties of geometry
- Violations of locality and Lorentz invariance
- Entanglement of matter and space-time states

Requires physics beyond quantum fields and classical relativity

Architecture of Physics

Classical Geometry

- Dynamical but not quantum
- Responds to particles and fields

Quantum particles and fields

- Inhabit classical geometry

(classical "stage" assumed in quantum field theory)

Explains almost everything, but cannot be the whole story

Cannot explain cosmic acceleration

Beyond Quantum Fields

Quantum states do not obey locality

- Proven by EPR-type experiments
- Nothing happens a definite time or place
- Yet locality is the basis of relativity, assumed by field theory

Classical space-time is emergent

- At the Planck scale, dynamical space-time is indeterminate
- Quantum properties of macroscopic geometry are unknown

Gravity is thermodynamics

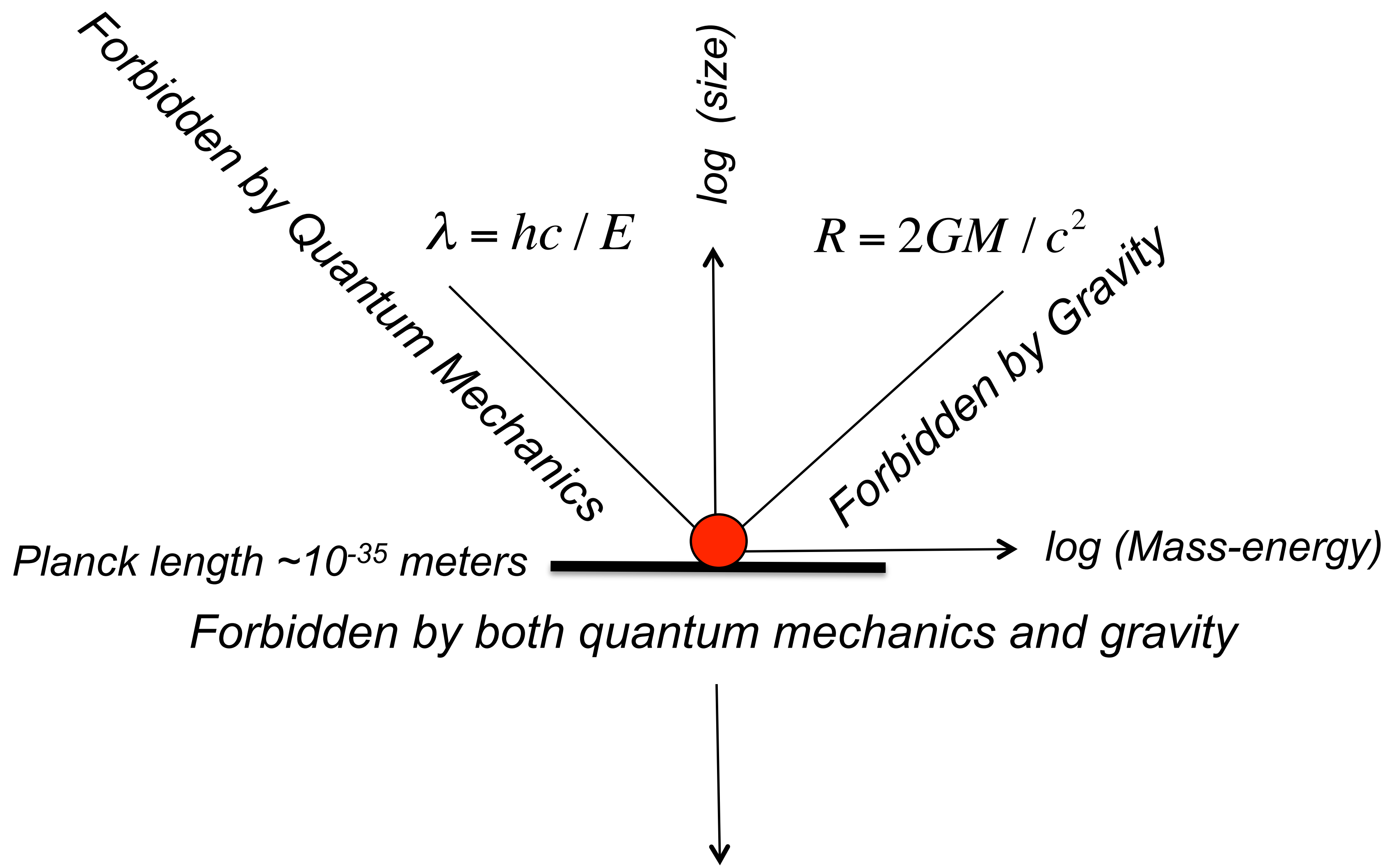
- Theory suggests a statistical “entropic” origin
- Metric does not describe fundamental degrees of freedom

States are holographic

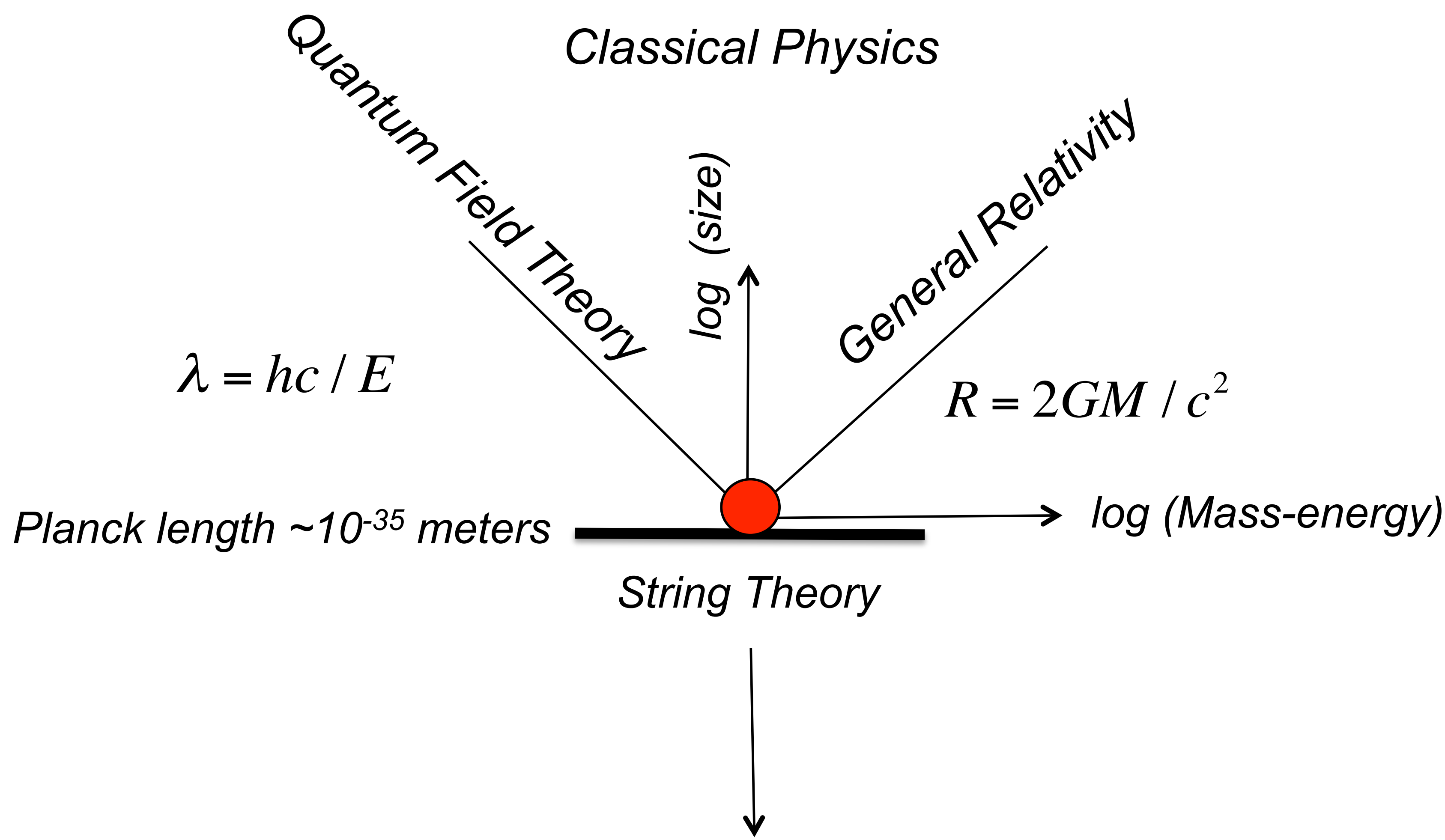
- Information encoded with Planck density on 2D bounding surfaces
- States must have new forms of entanglement

These properties are not described by the standard approximations of quantum field theory

Problem at the Planck Scale

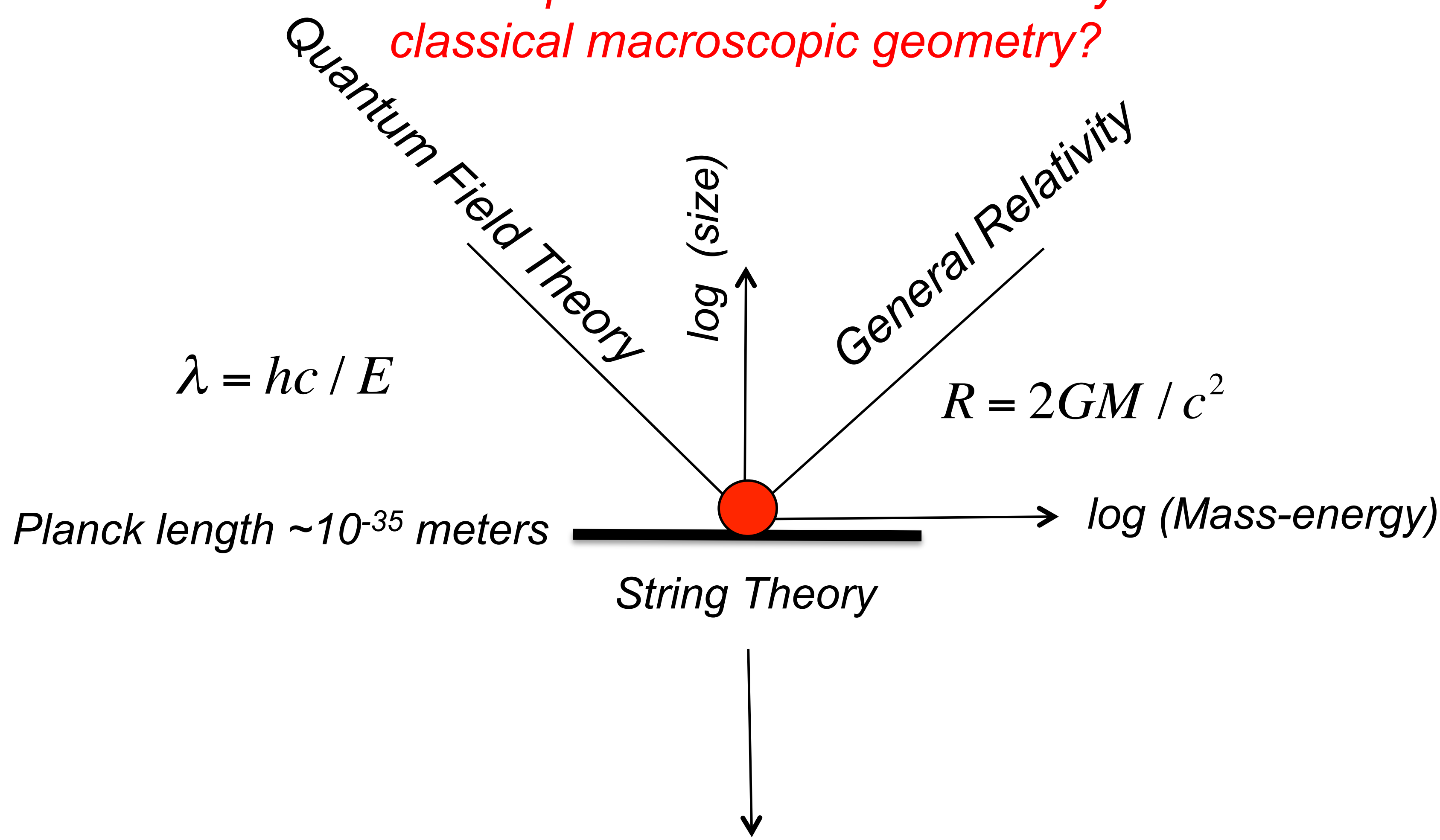


Domains of Theories



Classical geometry is an approximation to a quantum system

Is there quantum behavior of nearly-classical macroscopic geometry?



Quantum geometry may have macroscopic effects

Noncommutative geometry: In the rest frame, Planck scale commutator for position operators in 3D at one time:

$$[x_i, x_j] = x_k \epsilon_{ijk} i \ell_P$$

(~ angular momentum algebra, with x in place of J)

Leads to uncertainty in transverse position on scale *L*:

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

uncertainty increases with separation

tiny quantum departure from classical geometry

purely transverse to separation

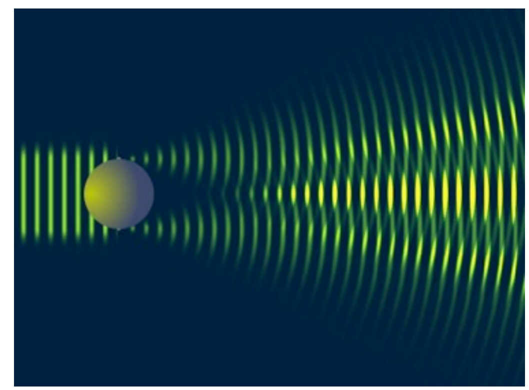
Approach to the classical limit

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” diffraction-like uncertainty

Quantum Geometry via interferometry

The Fermilab Holometer will probe Planck-scale quantum geometry via position measurement with Planck spectral density

Nonlocal, bidirectional position measurement probes noncommutative geometry

Dual, correlated 40-meter Michelson interterferometers now under construction

First science results expected next year

Designed for Planck precision

Quantum-geometrical noise in Michelson interferometer

Signal measures difference of beamsplitter position in two noncommuting directions

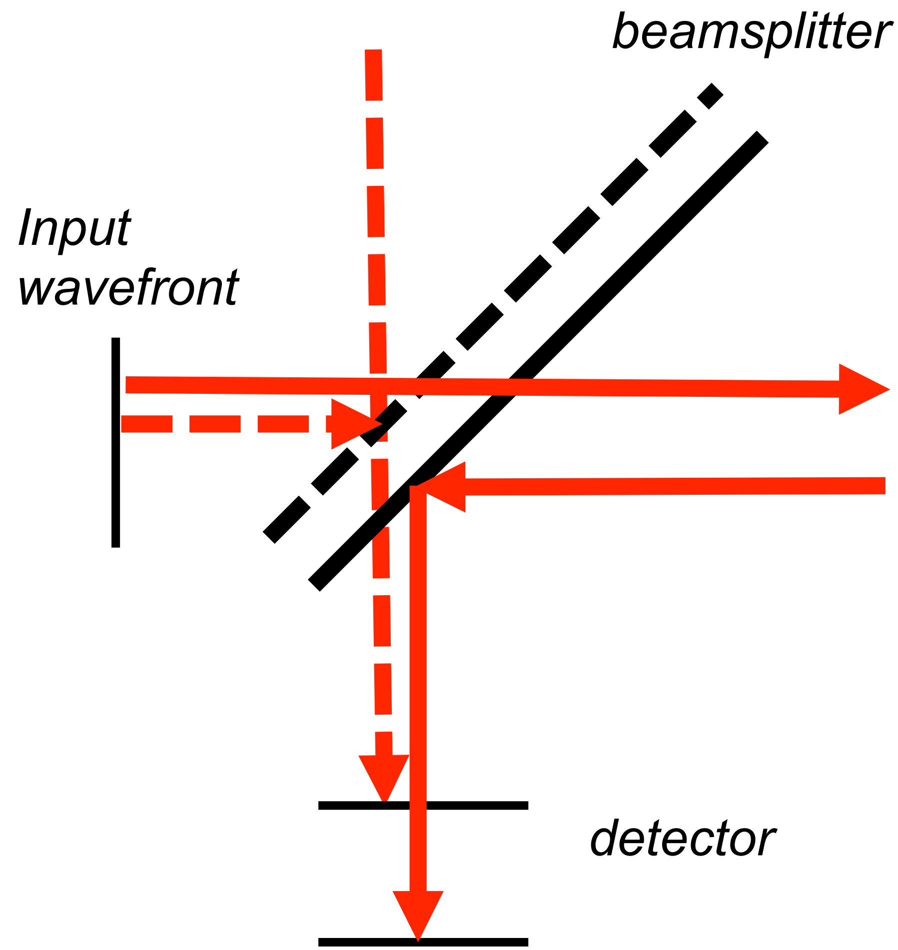
Causal diamond duration is twice the arm length

Geometrical uncertainty leads to fluctuations

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

For durations

$$\tau \approx L/c$$



Coherence of Quantum-Geometrical Fluctuations

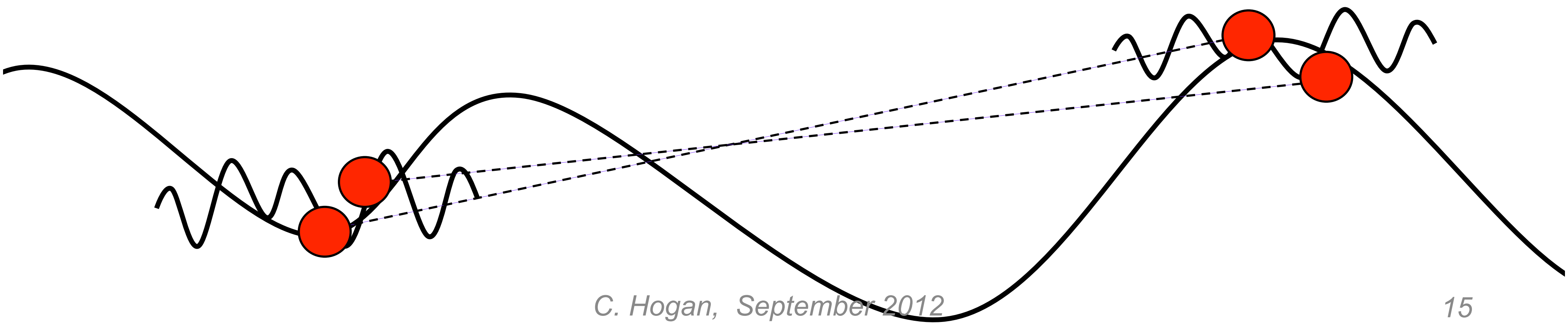
Larger scale modes dominate total displacement

No local measurements depend on choice of distant observer

Displacements of nearby bodies are not independent

Geometrical position states of neighboring bodies are entangled merely by proximity: central to Holometer experiment concept

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

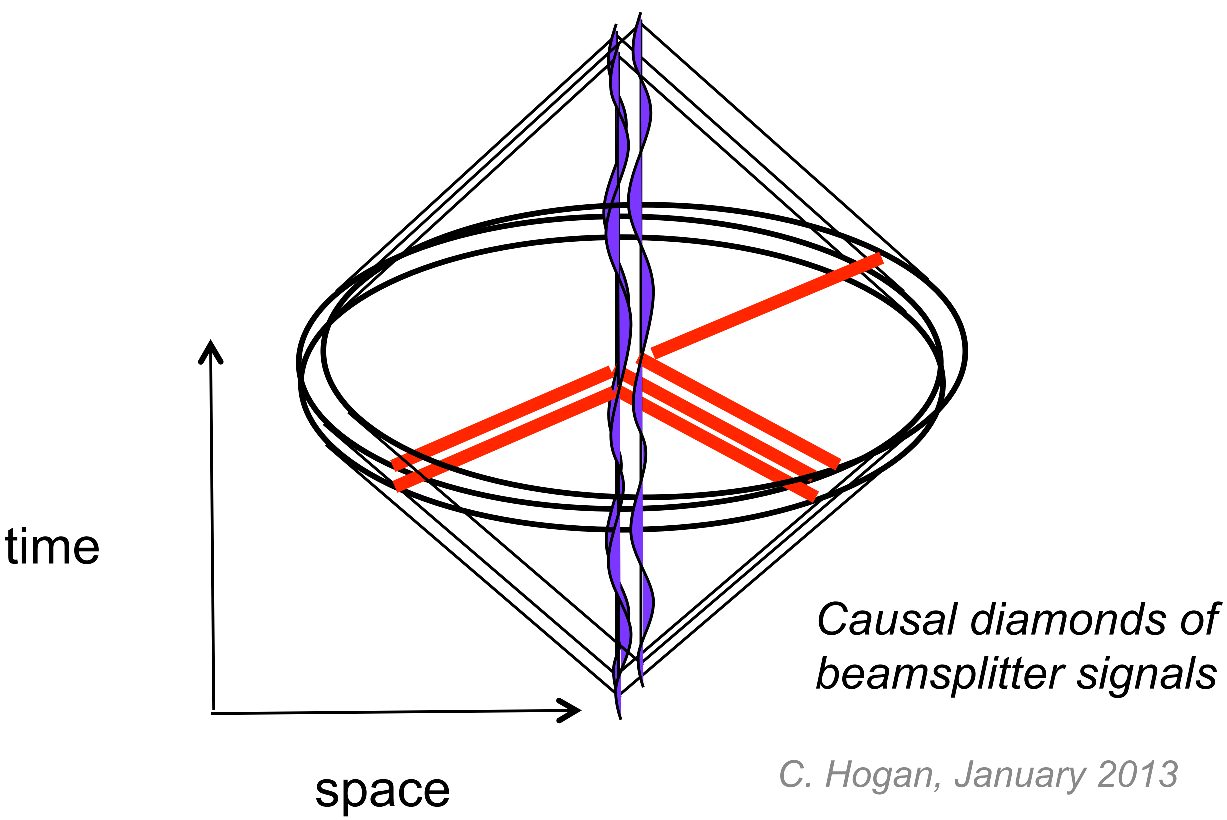


Causal diamonds of two interferometers

Correlate signals of nearly co-located 40-meter Michelson interferometers

Overlapping spacetime volumes collapse into the same state

Non-overlapping configurations are uncorrelated



Holometer Design Principles

Direct test for quantum-geometrical noise

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

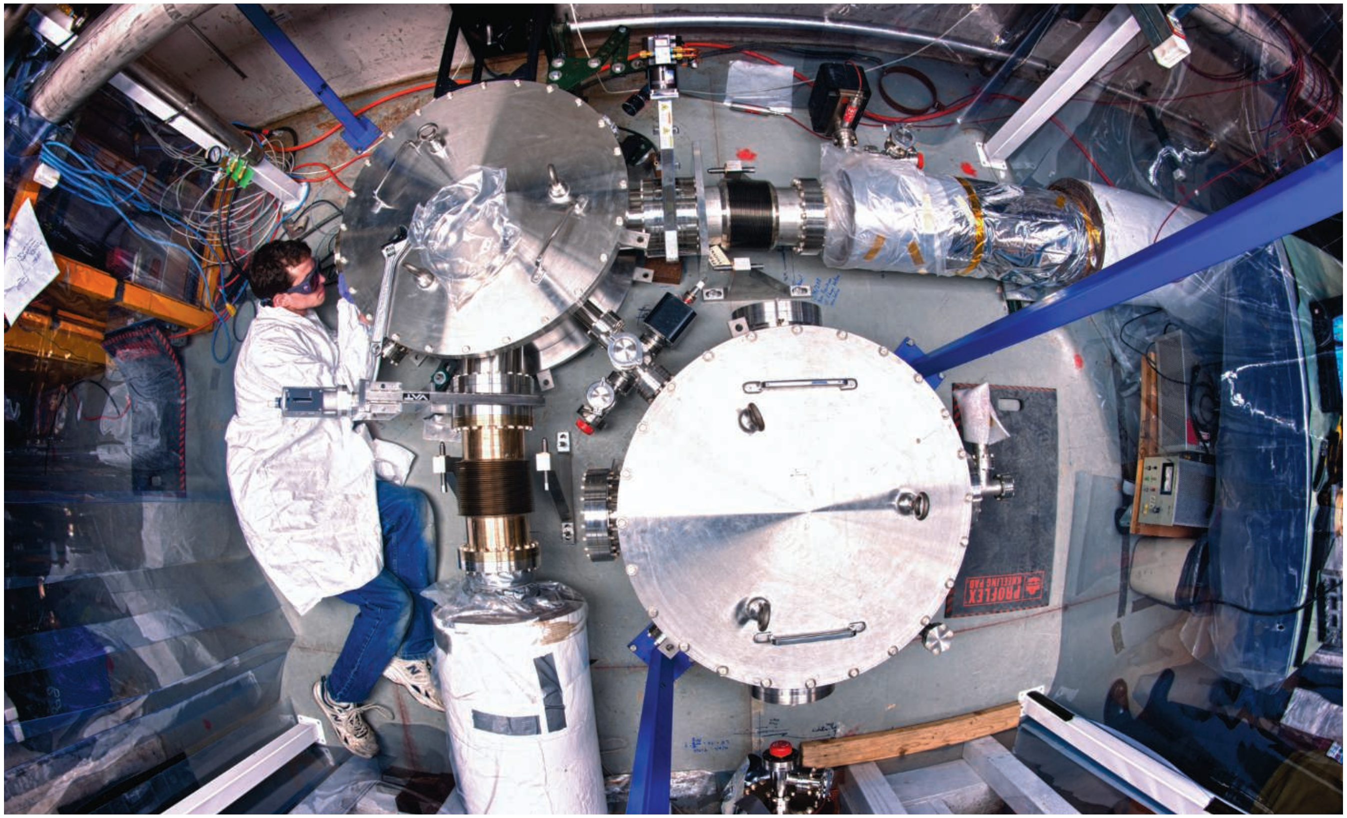
Sufficient sensitivity

- 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

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

in a room increases with the room's volume, not the area of its walls. If the holographic

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

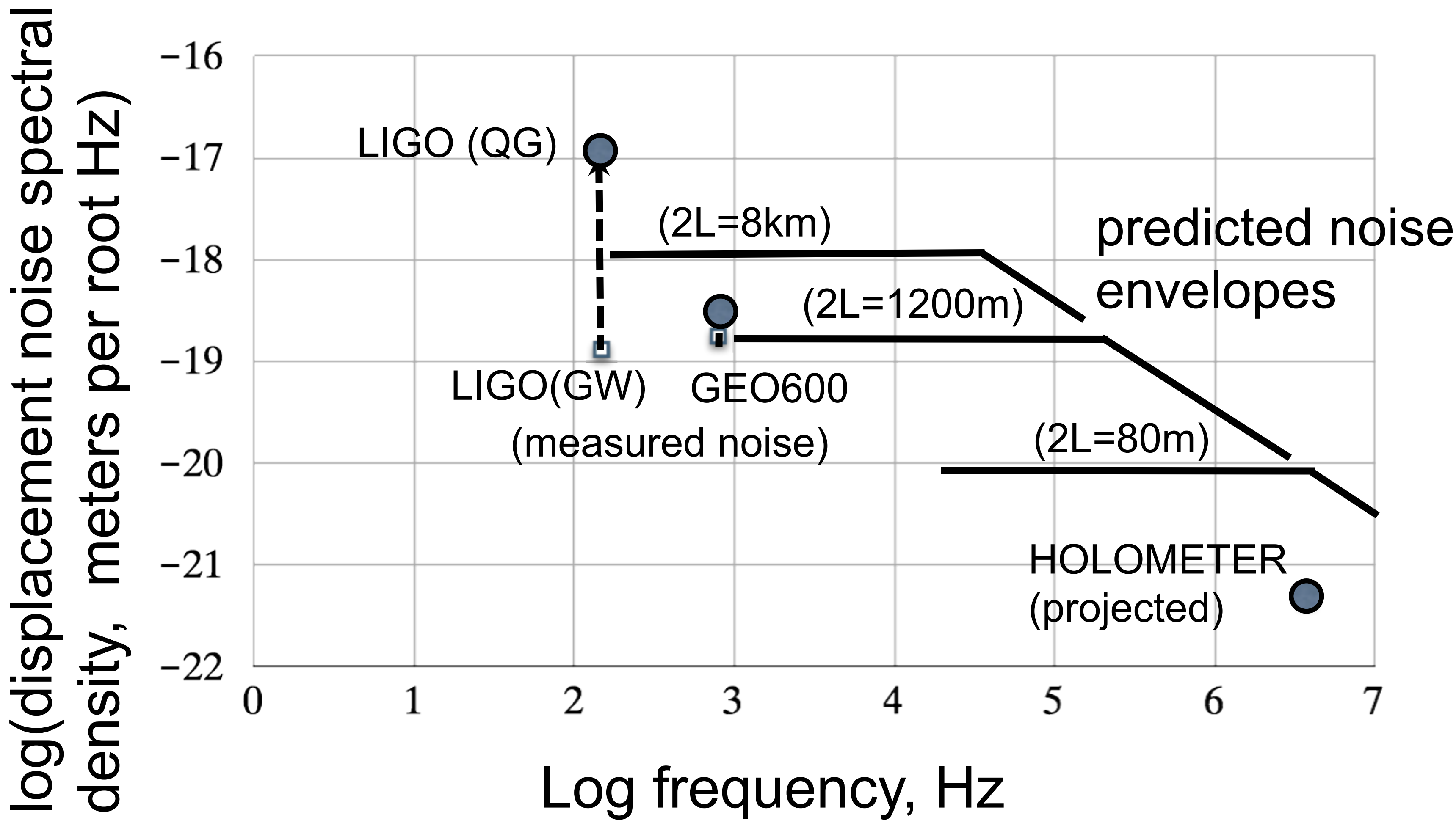
To understand the holographic principle, it helps to view spacetime the way it's portrayed in Einstein's special theory of relativity. Imagine a particle coasting through space, and draw its "world line" on a graph with time on the vertical axis and position plotted horizontally (see top figure, p. 148). 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

Quantum-Geometrical noise in real interferometers

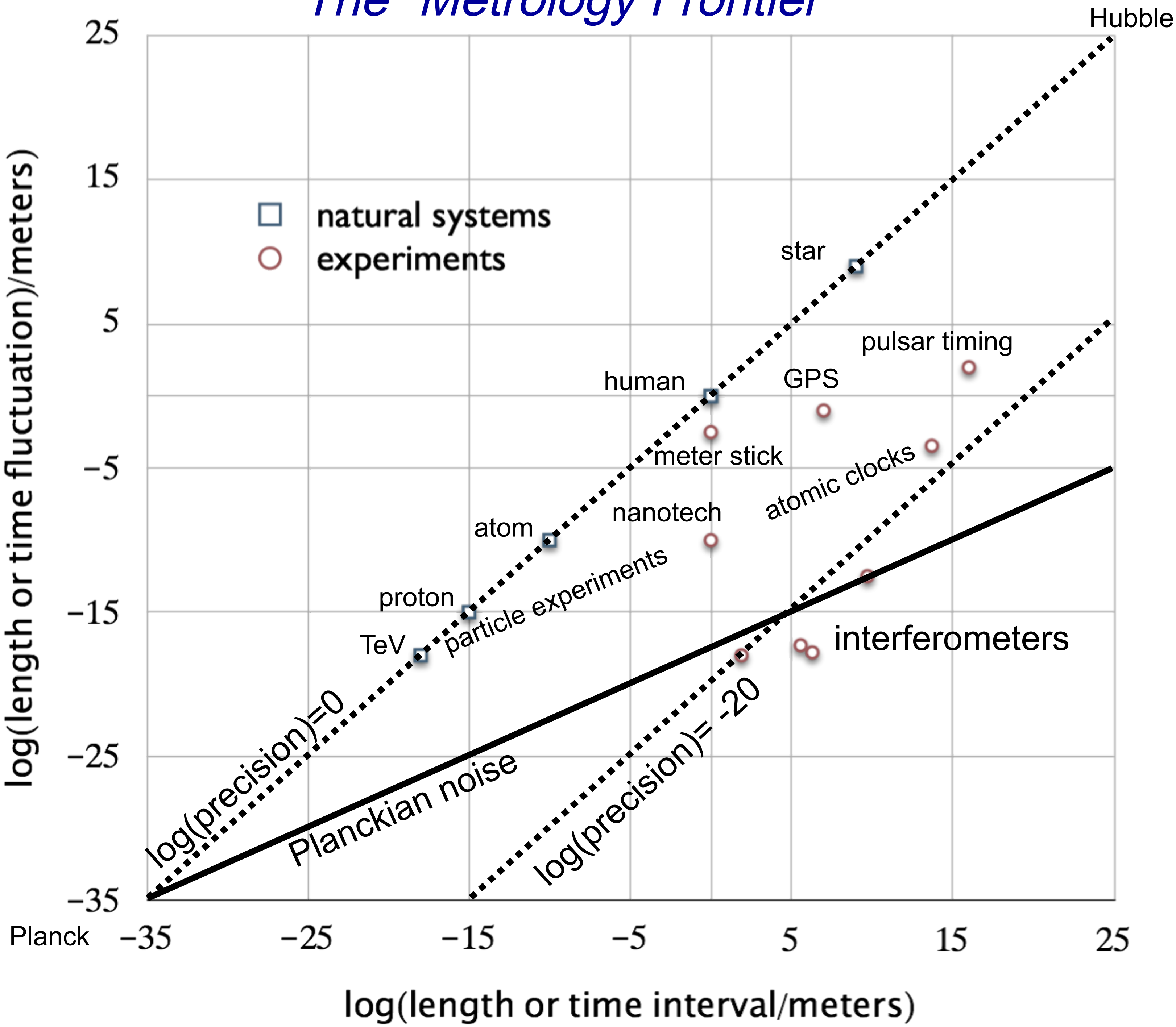
LIGO (2L=8km) design is better for gravitational waves, not for quantum geometry

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

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



The "Metrology Frontier"



Geometrically entangled field modes

Quantum field theory: each plane wave is an independent, quantized degree of freedom

If directions are "fuzzy" due to quantum geometry, modes are entangled

Number of independent states is smaller

Energy density of vacuum is smaller

Maybe new cosmic acceleration physics can be studied in the laboratory, by probing the crossover from matter to geometry at a quantum level

Number of degrees of freedom

Independent degrees of freedom n in causal diamond of duration t:

Field theory: $n \sim (tE)^3$ at energy E

Standard theory; problem with cosmic energy density

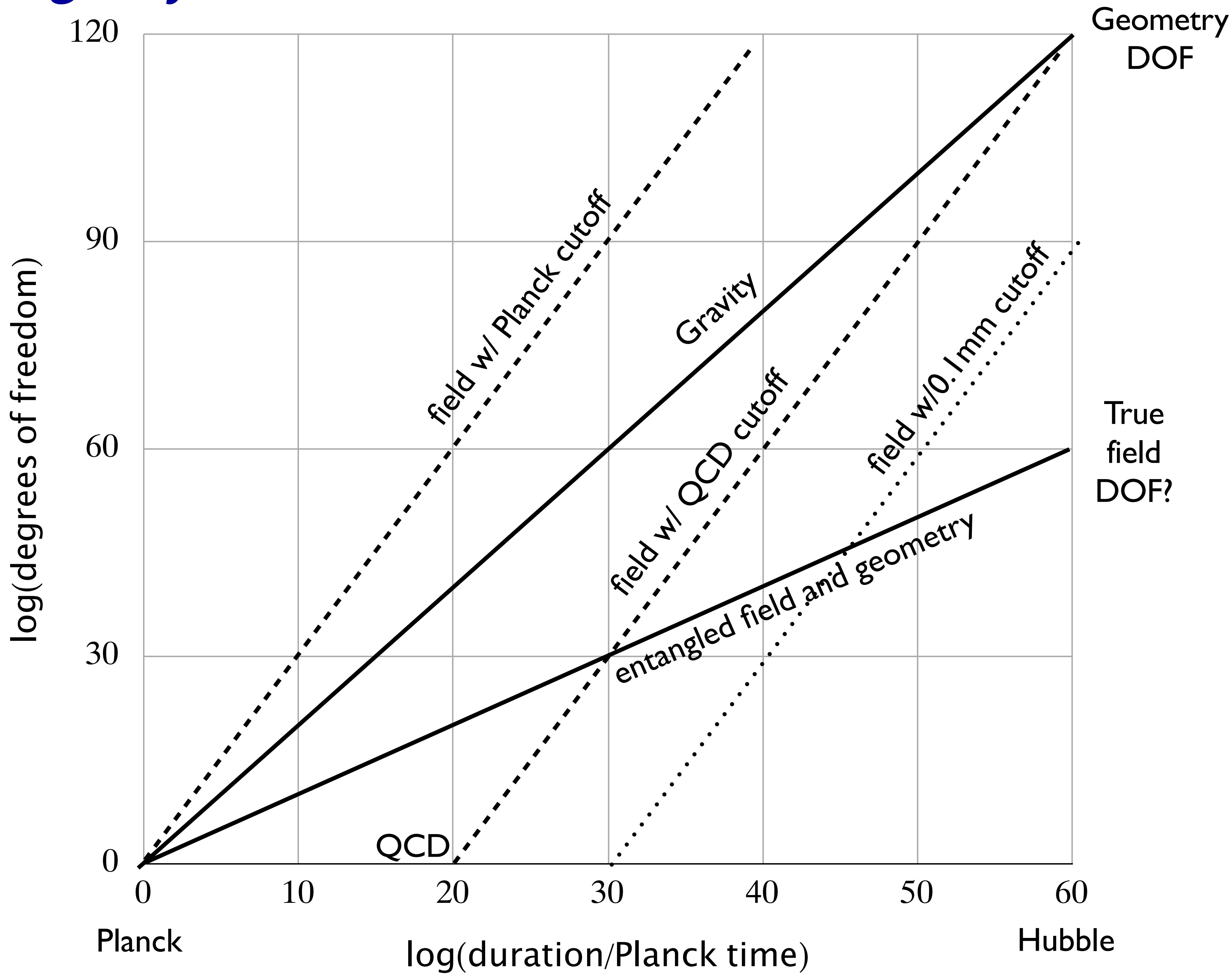
Holographic geometry/gravity: $n \sim (tE_{Planck})^2$

From black hole entropy

Field modes directionally entangled with geometry:
$n \sim (tE_{Planck})$

Sum of vacuum fluctuations ~cosmic density for $H_0 \sim 1/t$

Geometrical entanglement limits are important only for large systems



Experimental probes of emergent unification

Holometer probes quantum-geometrical entanglement of position

- A positive detection of Planckian noise will hint at a path to understanding cosmic acceleration via emergence

Other experiments may probe directional entanglement of particle/field states with geometrical states

- Directly relevant to the dark energy problem
- Requires very high precision
- Nobody is trying this yet
- Is it even possible?

Interferometry in OHEP program

- Interferometry has powerful applications on the "Precision Frontier" and "Metrology Frontier"
  - Precision unmatched by any other measurement technique
  - Metrology matters for fundamental physics
  - Also useful for Axion-like particle searches
  - Applicable to geometrically entangled fields?
- Interferometric experiments are well adapted to capabilities and interests of HEP community
  - Should HEP interest expand to include other projects with fundamental physics impact, such as LISA?
  - Extends to atom interferometry