The Fermilab Holometer: Direct Laboratory Probes of Planck Scale Correlations in the Space-Time Vacuum

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Cosmic Controversies Conference

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Cosmological constant as the energy of vacuum

G. Lemaître — PNAS **20**, 12 (1934)

EVOLUTION OF THE EXPANDING UNIVERSE

BY G. LEMAITRE

UNIVERSITY OF LOUVAIN

Read before the Academy, Monday, November 20, 1933

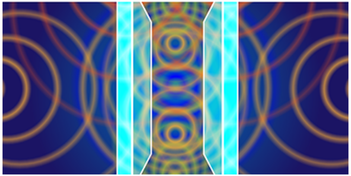
The problem of the universe is essentially an application of the law of gravitation to a region of extremely low density. The mean density of matter up to a distance of some ten millions of light years from us is of the order of 10^{-30} gr./cm.^{3}; if all the atoms of the stars were equally distributed through space there would be about one atom per cubic yard, or the total energy would be that of an equilibrium radiation at the temperature of liquid hydrogen. The theory of relativity points out the possibility of a modification of the law of gravitation under such extreme conditions. It suggests that, when we identify gravitational mass and energy, we have to introduce a constant. Everything happens as though the energy *in vacuo* would be different from zero. In order that absolute motion, i.e., motion relative to vacuum, may not be detected, we must associate a pressure $p = -\rho c^2$ to the density of energy ρc^2 of vacuum. This is essentially the meaning of the cosmical constant λ which corresponds to a negative density of vacuum ρ_0 according to

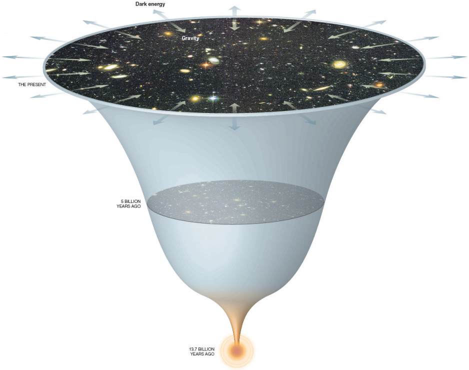
$$\rho_0 = \frac{\lambda c^2}{4\pi G} \cong 10^{-27} \text{ gr./cm.}^3 \qquad (1)$$

Ya. B. Zel'dovich and **A. Krasinski** — Sov. Phys. Usp. **11**, 381 (1968)

The worst failed prediction in fundamental physics — a boundary condition?

- Vacuum energy measured in a lab matches standard QFT.
- If we scale this theory to the universe, prediction is 122 orders of magnitude larger than the actual energy density.





- Is a fine-tuned constant needed for cosmic structure?
- Proposed explanations: multiverses, or a landscape?
- The cosmological constant should be considered an ***infrared*** **boundary condition** for the total degrees of freedom in any fundamental theory of quantum gravity, not a local contribution to the energy density.

[Tom Banks and Willy Fischler, arXiv:1811.00130]

The entropy of a black hole — the amount of information in the system — is proportional to the 2D "surface area" of its horizon. *The information density decreases linearly with scale!*

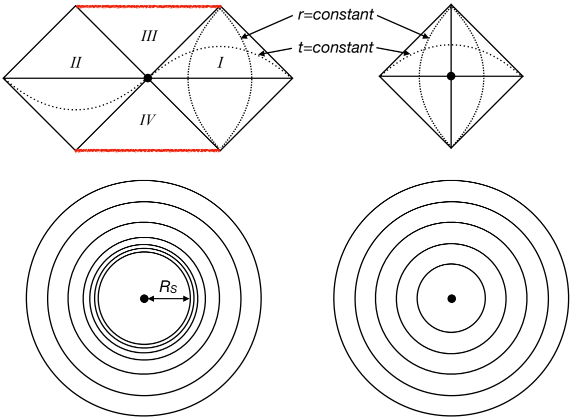
$$S_{BH} = \frac{kA}{4\ell_P^2}$$

In local QFT with a definite background, a system of scale R and cutoff m has total modes

$$\sim R^3 m^3$$

For Λ_{QCD}, gravitational binding energy exceeded at a generalized Chandrasekhar radius of 60 km — half of Lake Michigan!

AdS/CFT omits the degrees of freedom in a Planck resolution background space-time.



[A. Cohen, D. Kaplan, and A. Nelson, PRL **82**, 4971] [T. Banks and W. Fischler, arXiv:1810.01671]

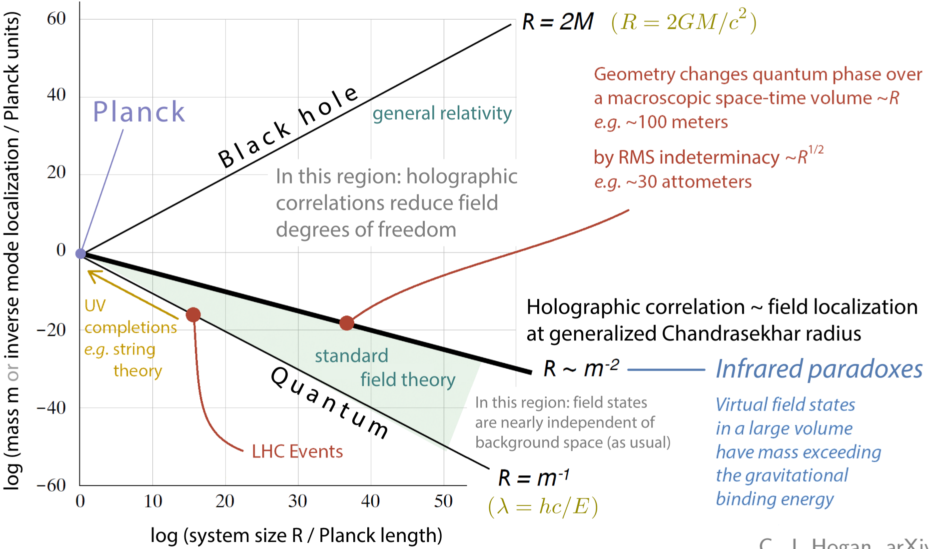
- **Claim**: *Even the low-energy, ground-state limit of quantum gravity cannot be described by perturbative graviton fields on a background metric.*
- **Scaling of information needs nonlocal correlations of space-time at large separations!**

Can QFT accommodate the foundational principles needed in a fundamental theory?

- Quantum Mechanics: No "local realistic" notions of classical geometrical paths and events
- General Relativity: General covariance and background independence

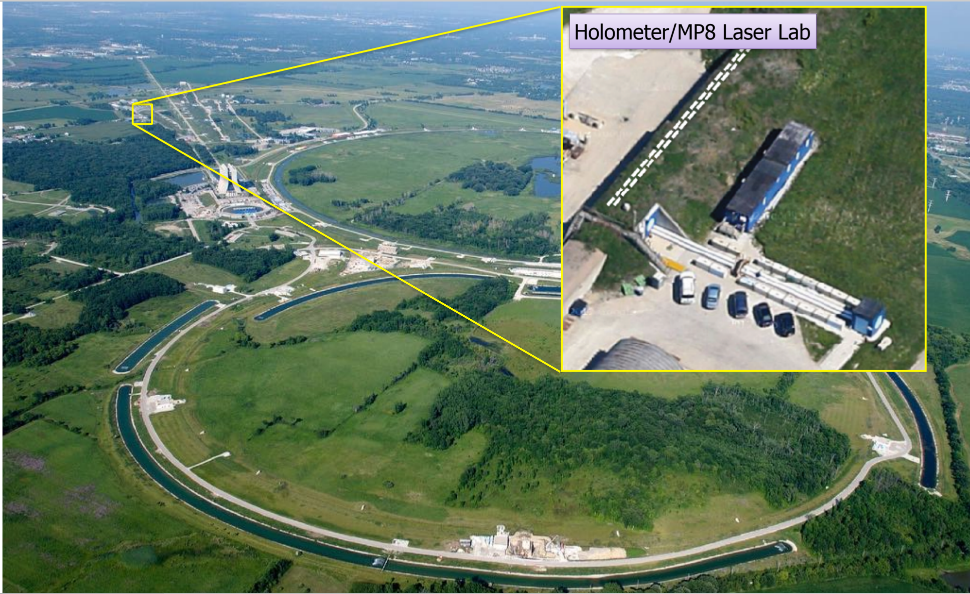
- *"Spukhafte"* correlations (in the EPR sense) should exist in flat space-time with no dynamics.
  Thermodynamic behavior of BH horizons applies to Unruh horizon entropy in accelerated frames.
- Can we understand correlations in a space-time without a built-in boundary like AdS space?

A new phenomenological regime

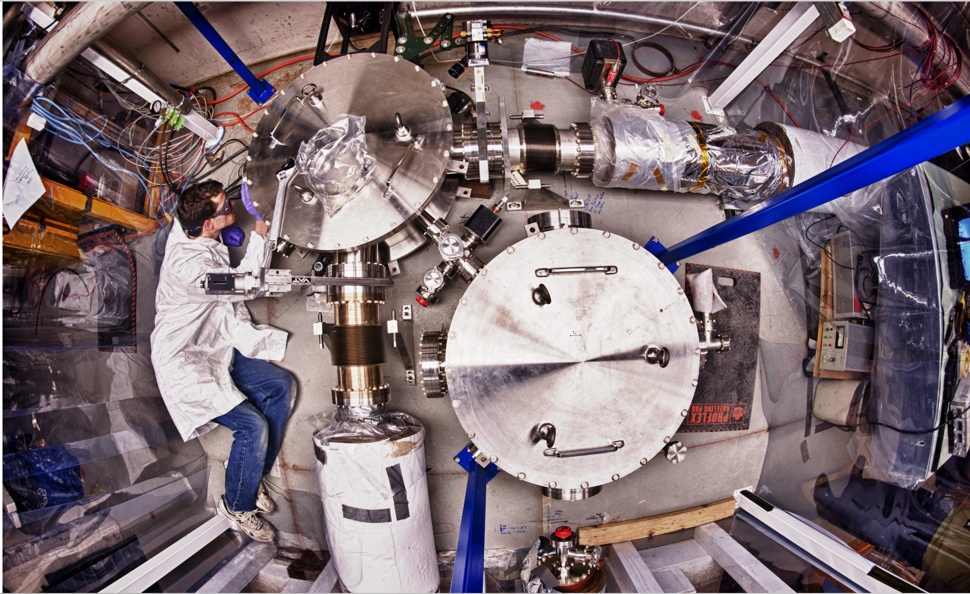


C. J. Hogan, arXiv:1412.1807

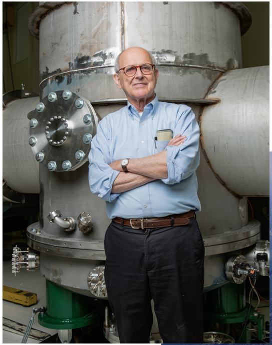
The Fermilab Holometer



The Fermilab Holometer



Extending LIGO technology to nonlocal correlations



LIGO $\longrightarrow$ Holometer

Dick Gustafson (Michigan)
Samuel Waldman (SpaceX)
Rainer Weiss (MIT)

Laser interferometers: the most precise in differential position measurements.

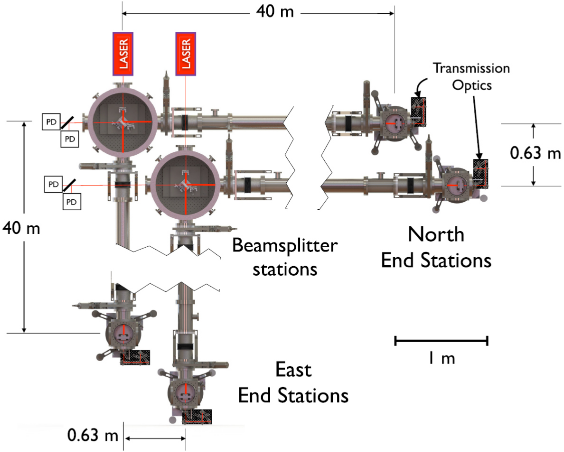
In dimensionless strain units $h \equiv \delta L/L$, the power spectral density reaches

$$\tilde{h}^2(f) \lesssim t_P \equiv \sqrt{\hbar G/c^5} \approx 10^{-44}\,\text{sec}$$

LIGO measures local metric fluctuations and stochastic gravitational waves.

Holometer probes similar stationary noise in space-time position, but at *superluminal* frequencies sensitive to *both spacelike and timelike* correlations across the system.

First-generation Holometer (2011-2016)



Cross-spectral density with two interferometers:

$$\tilde{h}^2(f) \equiv \int_{-\infty}^{\infty} \left\langle \frac{\delta L_A(t)}{L} \frac{\delta L_B(t-\tau)}{L} \right\rangle_t e^{-2\pi i \tau f} \, d\tau$$

Adopt model of delocalized Planckian fluctuations, each with a flat response over timescale L/c.

Variance scales like a **random walk** over $L = 39\,\text{m}$:

$$\langle \Delta x^2 \rangle_P \approx \ell_P L \approx \text{PSD } t_P L^2 \times \text{Bandwidth } c/L$$

For **shot noise** limited PSD $\equiv \tilde{h}^2(f) \cdot L^2$,

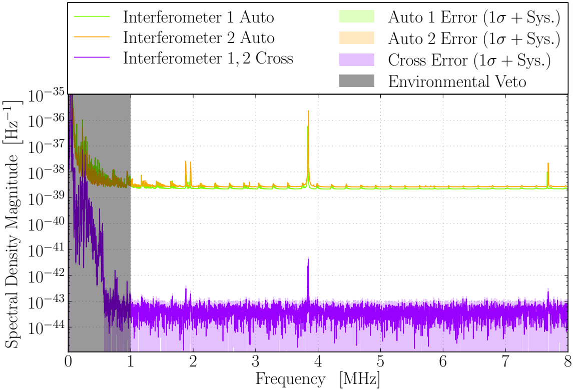
$$\tilde{h}^2(f) \approx t_P \approx (N f)^{-1} \approx 10^{-44}\,\text{s}$$

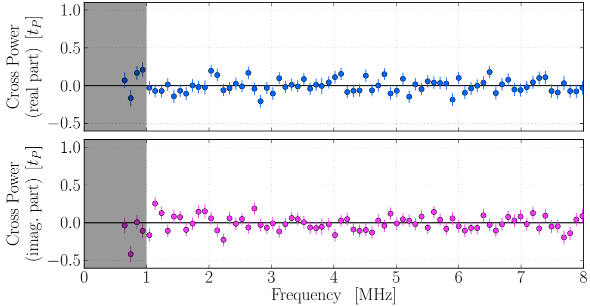
At $f \approx 10^{15}$ Hz, integrate over $N \approx 10^{29}$ photons!

The sampling rate and bandwidth must far exceed the 7.7 MHz **inverse light crossing time**.

Isolated and independent: optics, vacuum systems, electronics, clocks, and data streams.

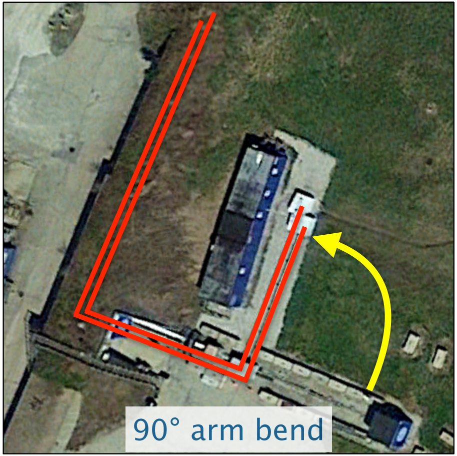
1st-gen Holometer: a verified symmetry at 0.2 Planck scale





- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, Planck units.
- 145 hour data — PRL **117**, 111102 (2016)
- 704 hour data — CQG **34**, 165005 (2017)
- Instrumentation — CQG **34**, 065005 (2017)
- *Serves as null control for 2nd-gen configuration.*
- Cross-power spectral density in $\delta L/L$, normalized to $L = 39$ m, reaches an upper limit below $0.2\, t_P$.
- *Light probes radial null (lightlike) paths to and from the beamsplitter measurements, in 2D.*

First-generation Holometer (2011-2016) **Second-generation** Holometer (2017-present)

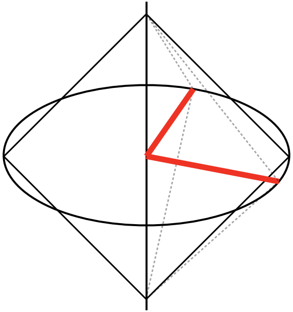


Bend mirror added. Unmodified: optics, electronics, control system, and data acquisition chain.

What are the symmetries and degrees of freedom?

1st-gen Holometer — CQG **33**, 105004 & **34**, 075006 • E. Verlinde & K. Zurek, arXiv:1902.08207

- Radial arms in two orthogonal directions from the beamsplitter.
- All light propagation along null (lightlike) directions from measurements, following the boundary of a causal diamond.



Lorentz symmetry •	Poincaré symmetry
- Lorentz boosts - Rotations	- Translations

2nd-gen Holometer: Lorentz invariant models — CQG **34**, 135006 & **35**, 204001

- Correlations respect exact causal structure (in radial directions from the observer's world line)
- Correlations must be along these surfaces: e.g. transverse ones with rotational symmetry

Light cones as coherent quantum objects

- 1+1D fluctuations: Emergence of proper time
- 2D fluctuations: Emergence of local inertial frame

Decoherence happens on causal diamonds!

Dirac's light cone function for relativistic quantum states

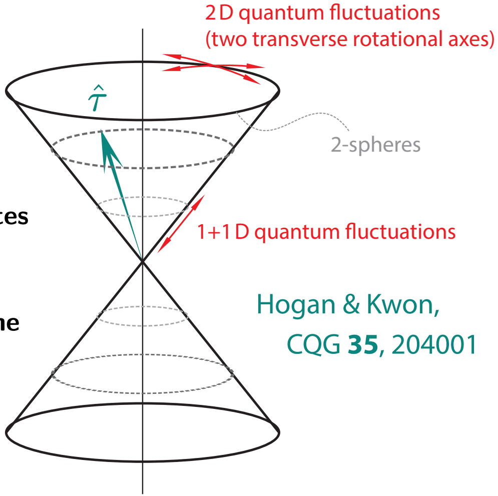
$$\Delta(x) = 2\delta(x^\mu x_\mu)x_0/|x_0| \qquad \tilde{\Delta}(k) = 4\pi^2 i\Delta(k)$$

On light cone — "directional" eigenstates of proper time

$$\left[\,\hat{\tau}_i\,,\ \hat{\tau}_j\,\right] = i\,\epsilon_{ijk}\,\hat{\tau}_k\,t_P$$

Model of cosmological correlations:

Hogan, PRD **99**, 063531 and arXiv:1908.07033

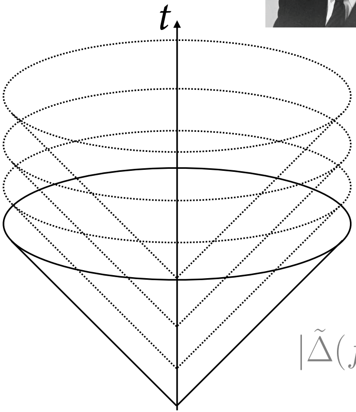


Hogan & Kwon,
CQG **35**, 204001

G. 't Hooft's model of black hole information — similar antipodal antisymmetric entanglement across the horizon

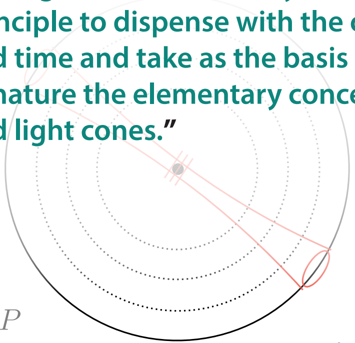
Found. Phys. **46**: 1185, arXiv:1605.05119, Found. Phys. **48**: 1134, arXiv:1804.05744, arXiv:1809.05367

Light cones as the basic quantum elements of space-time



"Just as the proper recognition of this atomicity requires in the electromagnetic theory a modification in the use of the field concept equivalent to the introduction of the concept of action at a distance, so it would appear that **in the gravitational theory we should be able in principle to dispense with the concepts of space and time and take as the basis of our description of nature the elementary concepts of world line and light cones."**

— J. A. Wheeler



$$|\tilde{\Delta}(f)|^2 \approx t_P$$

American Philosophical Society

2nd-gen Holometer: measuring angular rotation (1-axis) at Planck diffraction resolution!

Measuring the rotation of the Earth with light traveling in two directions around a loop.
Albert Michelson, winter 1924, suburban Chicago.

Preliminary

Second-generation Systematics:

Single Interferometer

INPUT SIDE

Lasers & Active Optics

- Correlated optical intensity noise
- Correlated optical phase noise

Continuously measured during data acquisition

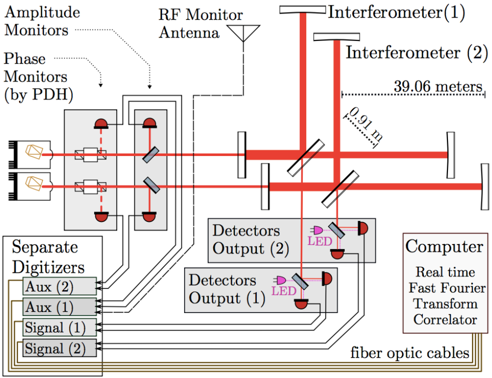
OUTPUT SIDE

Detectors & Readout Electronics

- Correlated electronics noise
- Cross-channel signal leakage

Measured offline using optical sources of independent white noise (incandescent light bulbs)

Realtime Monitoring of Laser Noise and Radio-Frequency (RF) Environment



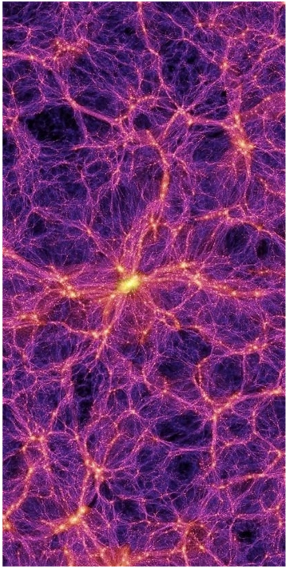
Four RF environmental channels are cross-correlated with the interferometer output channels (8x8 correlation matrix)

Preliminary

Second-generation Systematics:

Cross-interferometer

The cosmological constant (and other cosmic implications — inflationary signatures?)



Holographic correlations may reformulate Standard Model field vacuum and determine its emergent gravity!

- In causal diamonds of radius $c\tau_0$, our posited holographic quantum system would give an "emergent" localization $\sim \boldsymbol{c t_P (\tau_0 / t_P)^{1/3}}$
- In a system of size $\mathbf{10^{61}} \boldsymbol{\ell_P}$ (cosmic horizon), an "emergent" localization at the $\mathbf{10^{20}} \boldsymbol{\ell_P}$ QCD scale — where QCD undergoes a phase change in the vacuum due to chiral symmetry breaking! We posit the kinematic effects of fluctuating inertial frames to become "real" here, as virtual fields acquire mass.
- The emergent "centrifugal" acceleration matches cosmic observations at exactly the 60 km generalized Chandrasekhar radius for Λ_{QCD}!

Follows a numerical connection long-known since Zel'dovich (e.g. Bjorken, PRD **67**, 043508)

Hogan, PRD **95**: 104050 & arXiv:1804.00070 • Hogan & Kwon, CQG **35**: 204001

Observable inflationary signatures: coherent quantum horizons with antipodal antisymmetric entanglement — Hogan, PRD **99**: 063531 & arXiv:1908.07033

Thanks to...

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We hope to design and build a team for the next stage. Collaborate with us!

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