The Holometer: Measurements of Spacelike Coherent Fluctuations of Space-Time

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on behalf of the Holometer Collaboration

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The holographic bound — *infrared* catastrophes in a definite background space-time

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!*

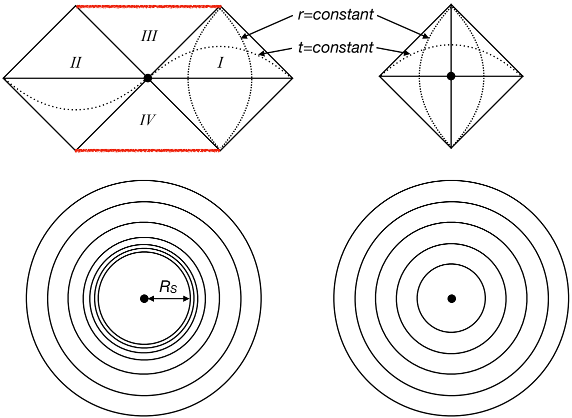
$$S_{BH} = \frac{kA}{4\ell_P^2}$$

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 — a third of empty Baikal!

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]

The cosmological constant as the energy of vacuum

G. Lemaître — PNAS **20**, 12 (1934)

12 *ASTRONOMY: G. LEMAITRE* PROC. N. A. S

EVOLUTION OF THE EXPANDING UNIVERSE

BY G. LEMAITRE

UNIVERSITY OF LOUVAIN

Read before the Academy, Monday, November 20, 1933

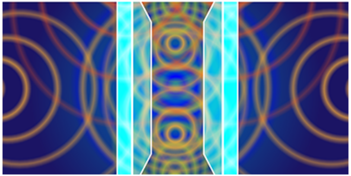
The problem of the universe is essentially an application of the law of gravitation to a region of extremely low density. The mean density of matter up to a distance of some ten millions of light years from us is of the order of 10^{-30} gr./cm.^{3}; if all the atoms of the stars were equally distributed 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

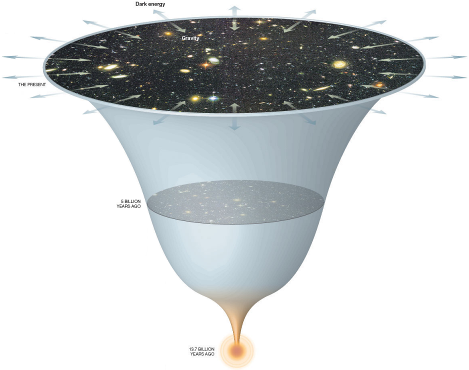
$$\rho_0 = \frac{\lambda c^2}{4\pi G} \cong 10^{-27} \text{ gr./cm.}^3 \qquad (1)$$

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]

Correlations in the space-time vacuum

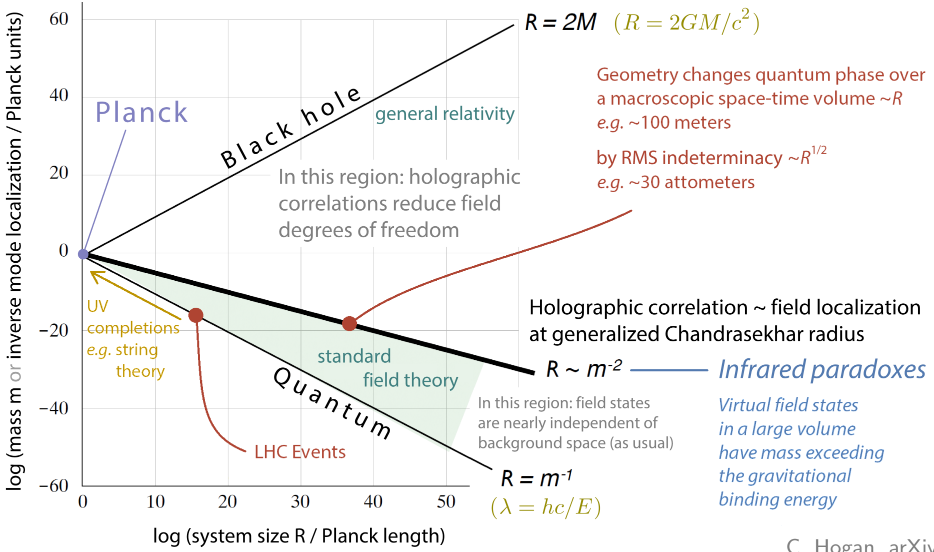
- **Claim**: *Even the low-energy, ground-state limit of quantum gravity cannot be described by perturbative graviton fields on a background metric.*
- **Scaling of information needs nonlocal correlations of space-time at large separations!**

Can EFT 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

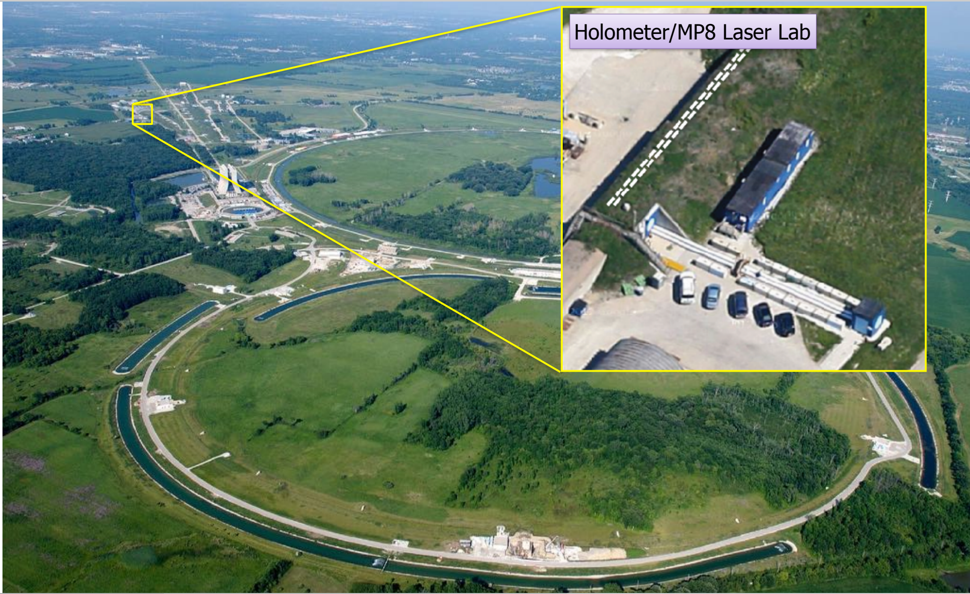
- *"Spukhafte"* correlations (in the EPR sense) should exist in flat space-time with no dynamics.
  Thermodynamic behavior of BH horizons applies to Unruh horizon entropy in accelerated frames.
- Can we understand correlations in a space-time without a built-in boundary like AdS space?

A new phenomenological regime



C. Hogan, arXiv:1412.1807

The Fermilab Holometer



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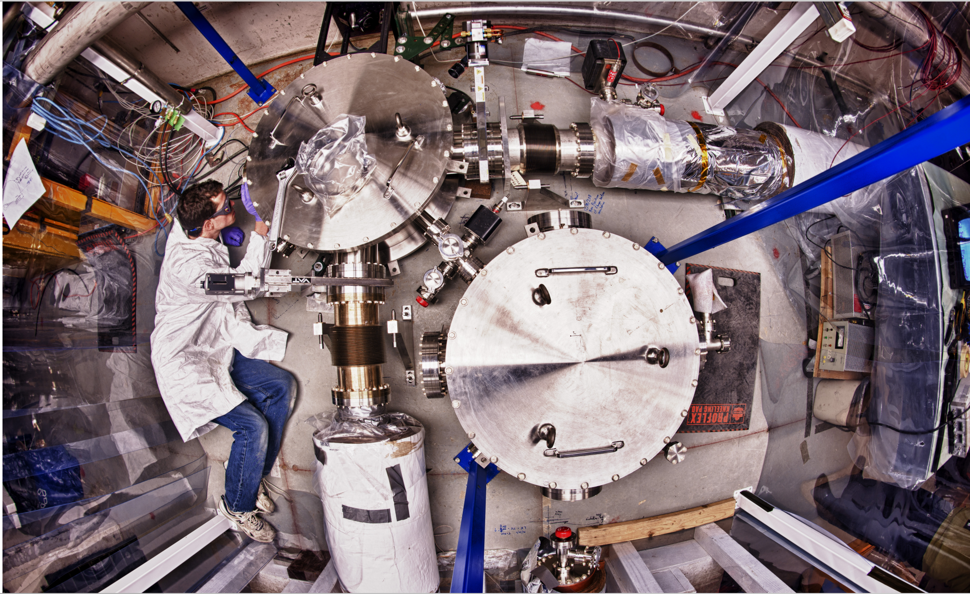
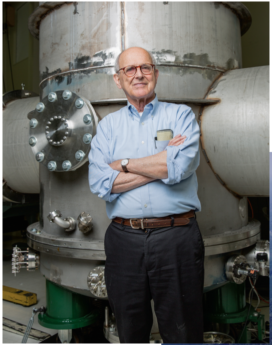


Extending LIGO technology to nonlocal correlations



LIGO ⟶ Holometer

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

Laser interferometers: the most precise in differential position measurements.

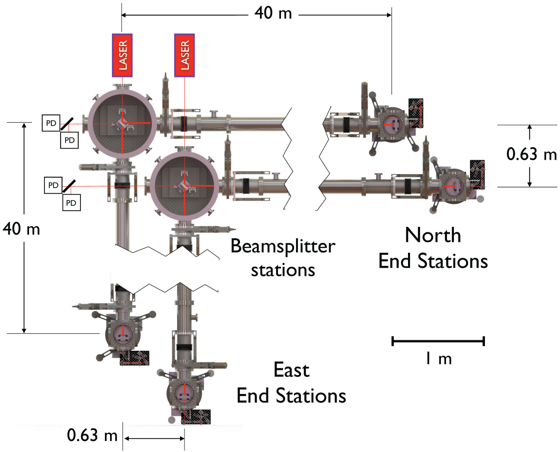
In dimensionless strain units $h \equiv \delta L/L$, the power spectral density reaches

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

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 timelike and spacelike* correlations across the system.

First-generation Holometer (2011-2016)



Cross-spectral density with two interferometers:

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

Spacelike coherence: e.g. one Planck scale jitter per Planck time, each generating a flat response over system scale L/c due to its delocalized nature.

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

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

$\text{PSD} \equiv \tilde{h}^2(f) \cdot L^2$ is **shot noise** limited and reaches:

$$\boldsymbol{\tilde{h}^2(f) \approx t_P} \approx 10^{-44}\,\mathrm{s}$$

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.

INPUT SIDE

Lasers & Active Optics

- Correlated optical intensity noise
- Correlated optical phase noise

Continuously measured during data acquisition

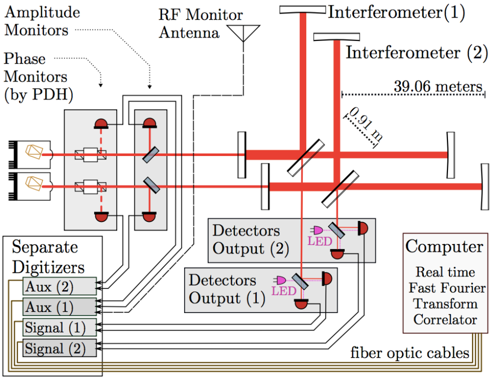
OUTPUT SIDE

Detectors & Readout Electronics

- Correlated electronics noise
- Cross-channel signal leakage

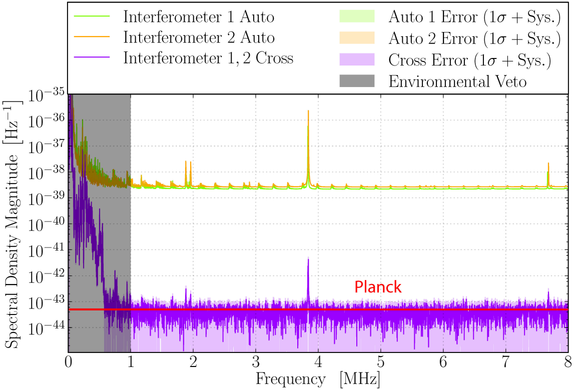
Measured offline using optical sources of independent white noise (incandescent light bulbs)

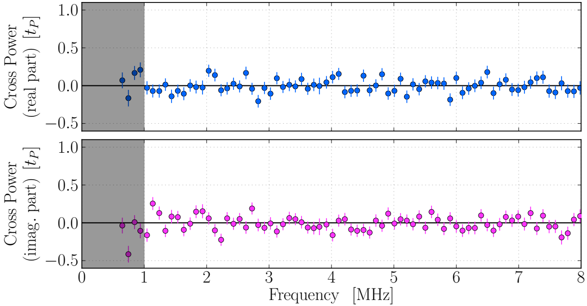
Realtime Monitoring of Laser Noise and Radio-Frequency (RF) Environment



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

1st-gen Holometer: a verified symmetry at 0.25 Planck scale



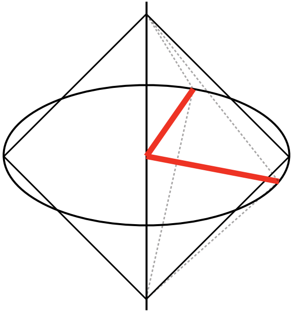


- 145 hour data — PRL **117**, 111102 (2016)
- 704 hour data — CQG **34**, 165005 (2017)
- Instrumentation — CQG **34**, 065005 (2017)
- *Clean null test for exploring general geometries.*

- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, **Planck** units.
- At 100 kHz, uncorrelated noise is averaged down over 2.5×10^{11} independent measurements.
- Cross-power spectral density in $\delta L/L$, normalized to $L = 39\,\mathrm{m}$, reaches an upper limit below $\mathbf{0.25}\, t_P$.

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.

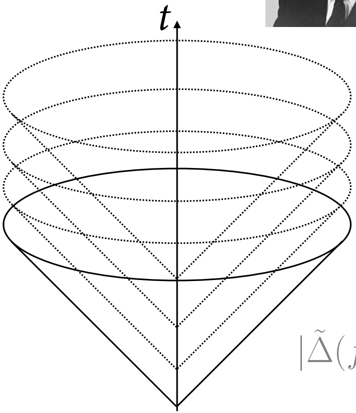


Lorentz symmetry •	Poincaré symmetry
- Lorentz boosts - Rotations	- Translations

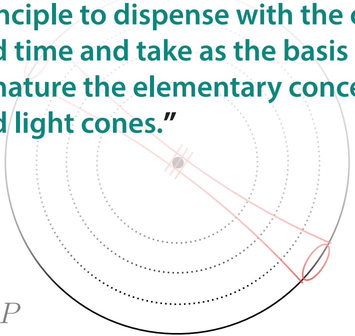
2nd-gen Holometer: Models on covariant structures — CQG **34**, 135006 & **35**, 204001

- 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 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."**



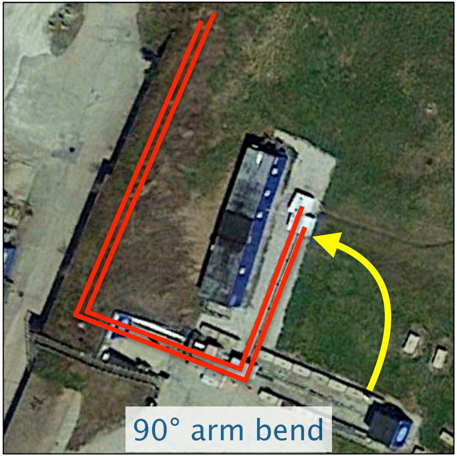
— J. A. Wheeler

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

American Philosophical Society

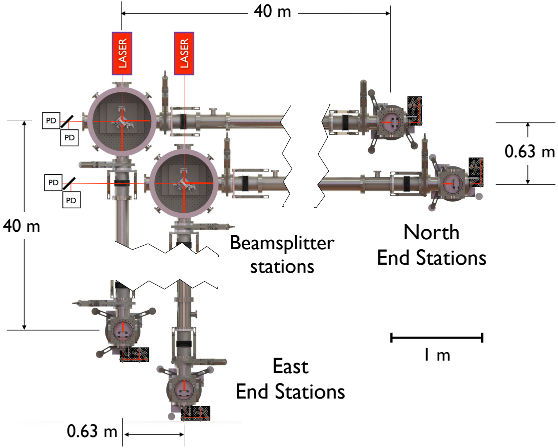
First-generation Holometer (2011-2016)

Second-generation Holometer (2017-2020)

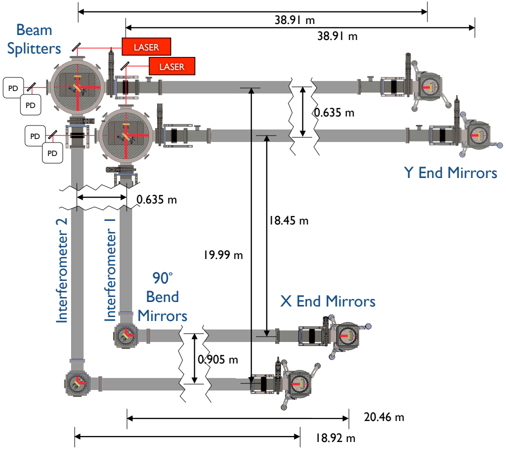


Bend mirror added. Unmodified: optics, electronics, control system, and data acquisition chain.

First-generation Holometer (2011-2016)



Second-generation Holometer (2017-2020)

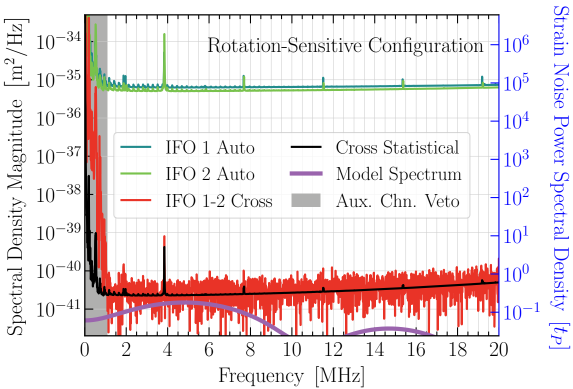


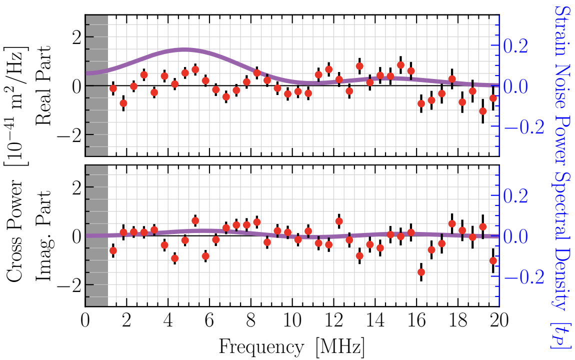
Bend mirror added. Unmodified: optics, electronics, control system, and data acquisition chain.

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.

2nd-gen Holometer: 1-axis rotational fluctuations constrained at 0.25 Planck scale

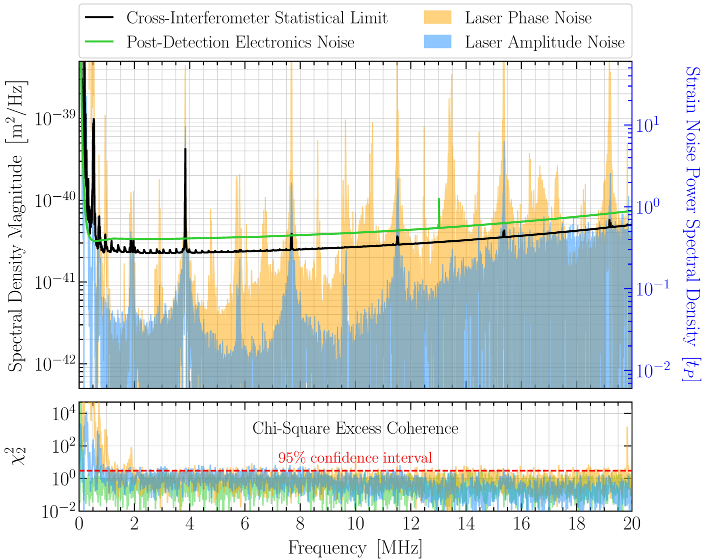




- 1098 hour data — PRL **126**, 241301 (2021)
- For a nominal model of rotational fluctuations with spacelike coherence on light cones, the data sets a $\mathbf{0.25}\, t_P$ upper bound on the normalization.

- **Left:** Independent bins at 9.92 kHz resolution.
- **Right:** Rebinned to 496 kHz, real & imaginary.
- At 496 kHz, uncorrelated noise is averaged down over 1.96×10^{12} independent measurements.

Cross-interferometer limits on environmental noise correlations



All causal horizons are universal boundaries of coherent quantum information, where the decoherence of space-time happens for the observer.

- **G. 't Hooft**'s models of black hole information — arXiv:1605.05119, Found. Phys. 46:1185, 48:1134, arXiv:1804.05744, 1809.05367, 1902.10469
  - Because of gravitational frame dragging / backreaction, entire horizon is a coherent quantum object, with antipodes entangled. Horizon is a quantum-classical boundary for information.
- **E. Verlinde & K. Zurek**, arXiv:1902.08207, JHEP 2020:209 / **K. Zurek**, arXiv:2012.05870
  - Reproduces the same angular correlations as the 't Hooft BH models for causal diamonds in flat space (conformal Killing horizons), and the random walk scaling of Planckian fluctuations as probed by the Holometer, using topological BH mapping and tools from AdS/CFT.
- **T. Banks & K. Zurek**, arXiv:**2108.04806** — Conformal description of near-horizon vacuum states
- **T. Banks & W. Fischler**, arXiv:1109.2435, 1810.01671, IJMPD 27:1846005, Front. Phys. 8:111
  - Holographic Space-Time — Localization of information: Causal diamonds are Hilbert spaces, intersecting / nested ones are tensor products / subspaces. "Fast scrambling" at the boundaries.
- Causal order superpositions, Nat. Commun. 10:3772 • Wigner's friend paradox, arXiv:1902.09028

Standard quantum limit for mass m, duration τ

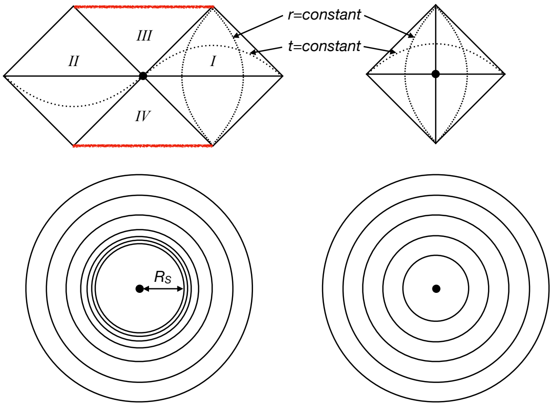
$$\left\langle \Delta x^2 \right\rangle \gtrsim \hbar\tau/m$$

Coherent quadrupolar distortions needed for a BH horizon of radius $R = c\tau$ to radiate at the standard Hawking flux, one graviton of $\lambda \sim c\tau$ per time τ

$$\left\langle (\delta R/R)^2 \right\rangle \sim t_P/\tau$$

Fluctuations of this scale exist on causal diamonds in flat space (conformal Killing horizons) of radius $R = c\tau$ and duration τ.

Thermodynamic behavior of BH horizons applies to Unruh horizon entropy in accelerated frames.



The coherence on all null surfaces gives rise to an estimate larger than conventional EFT by $\sim \tau/t_P$.

In frequency space, corresponds to strain power spectral density t_P over bandwidth $1/\tau$.

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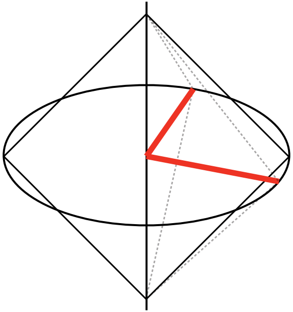

Lorentz symmetry • Poincaré symmetry

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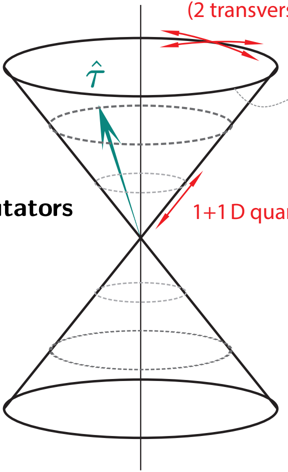
Light cones as coherent quantum objects

- 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 commutators

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

Toy model: "directional" eigenstates of proper time

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

Model of correlations on inflationary horizon:

C. Hogan, PRD **99**, 063531 and CQG **37**, 095005

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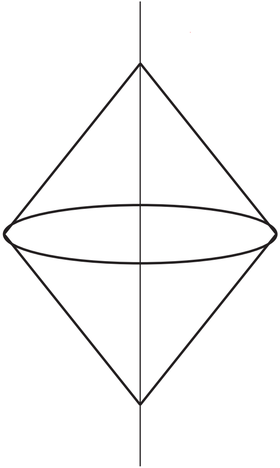

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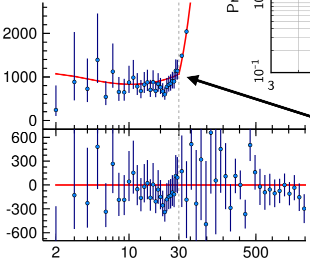
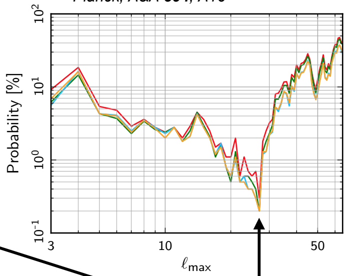
Cosmic structure is an image of primordial quantum states —
the fluctuations "froze in" at the inflationary horizon!



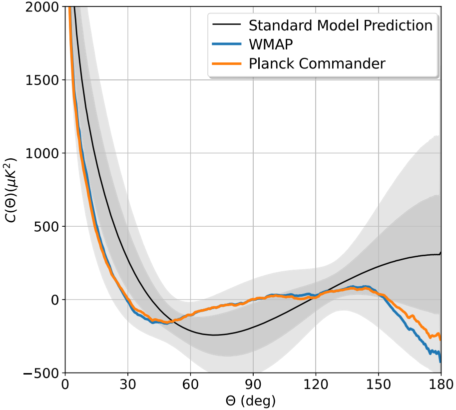
Planck, A&A **594**, A16



Odd multipoles dominate up to

$\ell \approx 28$

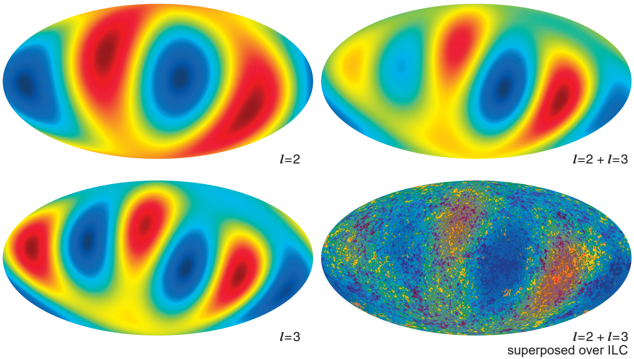
*Hagimoto, Hogan, Lewin, and Meyer, ApJL **888**, L29*



Cosmic microwave background anomalies may contain concordant signatures!

Cosmic structure is an image of primordial quantum states —
the fluctuations "froze in" at the inflationary horizon!

WMAP, ApJS ***192****, 17*

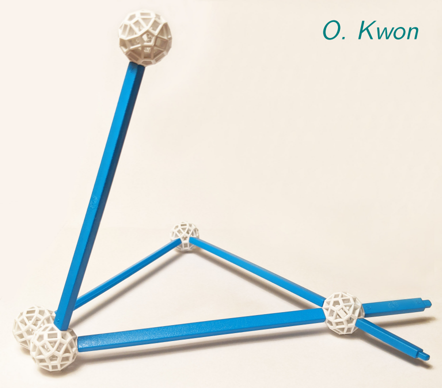


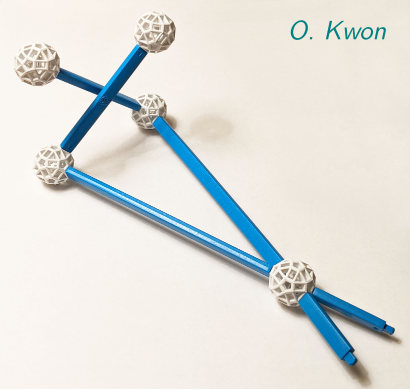
CQG ***33****, 184001*

feature	p-value	data
in angular space		
low variance ($N_{\rm side} = 16$)	$\lesssim 0.5\%$	Planck 15
2-pt correlation $\chi^2(\theta > 60^\circ)$	$\lesssim 3.2\%$	Planck 15
2-pt correlation $S_{1/2}$	$\lesssim 0.5\%$	Planck 15
2-pt correlation $S_{1/2}$	$\lesssim 0.3\%$	Planck 13 & WMAP 9yr
2-pt correlation $S_{1/2}$ (larger masks)	$\lesssim 0.1\%$	Planck13
	$\lesssim 0.1\%$	WMAP 9yr
hemispherical variance asymmetry	$\lesssim 0.1\%$	Planck 15
cold spot	$\lesssim 1.0\%$	Planck 15
in harmonic space		
quadrupole-octopole alignment	$\lesssim 0.5\%$	Planck 13
$\ell = 1, 2, 3$ alignment	$\lesssim 0.2\%$	Planck 13
odd parity preference $\ell_{\rm max} = 28$	$< 0.3\%$	Planck 15
odd parity preference $\ell_{\rm max} < 50$ (LEE)	$< 2\%$	Planck 15
dipolar modulation for $\ell = 2 - 67$	$\lesssim 1\%$	Planck 15

We are finally ready to probe a general 3D geometry!

*The class of theories motivated by recent lessons requires entangling all three dimensions — e.g. measuring **two** orthogonal rotational axes corresponding to incompatible observables.*





UK QTFP ST/T006331/1 at Cardiff University: CQG **38**, 085008 • Theory manuscript forthcoming!

Thanks to...

Fermilab

Fermi Research Alliance LLC

U.S. DEPARTMENT OF ENERGY | Office of Science

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Kavli Institute
for Cosmological Physics
at The University of Chicago

NASA

NSF

FORD FOUNDATION

NRF National Research Foundation of Korea

JOHN TEMPLETON FOUNDATION

We are building a team to commission the next design. Collaborate with us!

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Lee McCuller,[3,7] Stephan S. Meyer,[3] Jonathan Richardson,[3,5] Chris Stoughton,[1] Raymond Tomlin,[1] Samuel Waldman,[8] and Rainer Weiss[7]

[1]*Fermi National Accelerator Laboratory* [2]*University of Michigan* [3]*University of Chicago* [4]*Vanderbilt University*
[5]*California Institute of Technology* [6]*KAIST* [7]*Massachusetts Institute of Technology* [8]*SpaceX*