

Search for Signatures of Relational Emergent Space-Time: Nonlocal Cross-Correlations at the Fermilab Holometer

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arXiv:1711.05514 [gr-qc] *with C. J. Hogan*

Common approaches to Quantum Gravity:

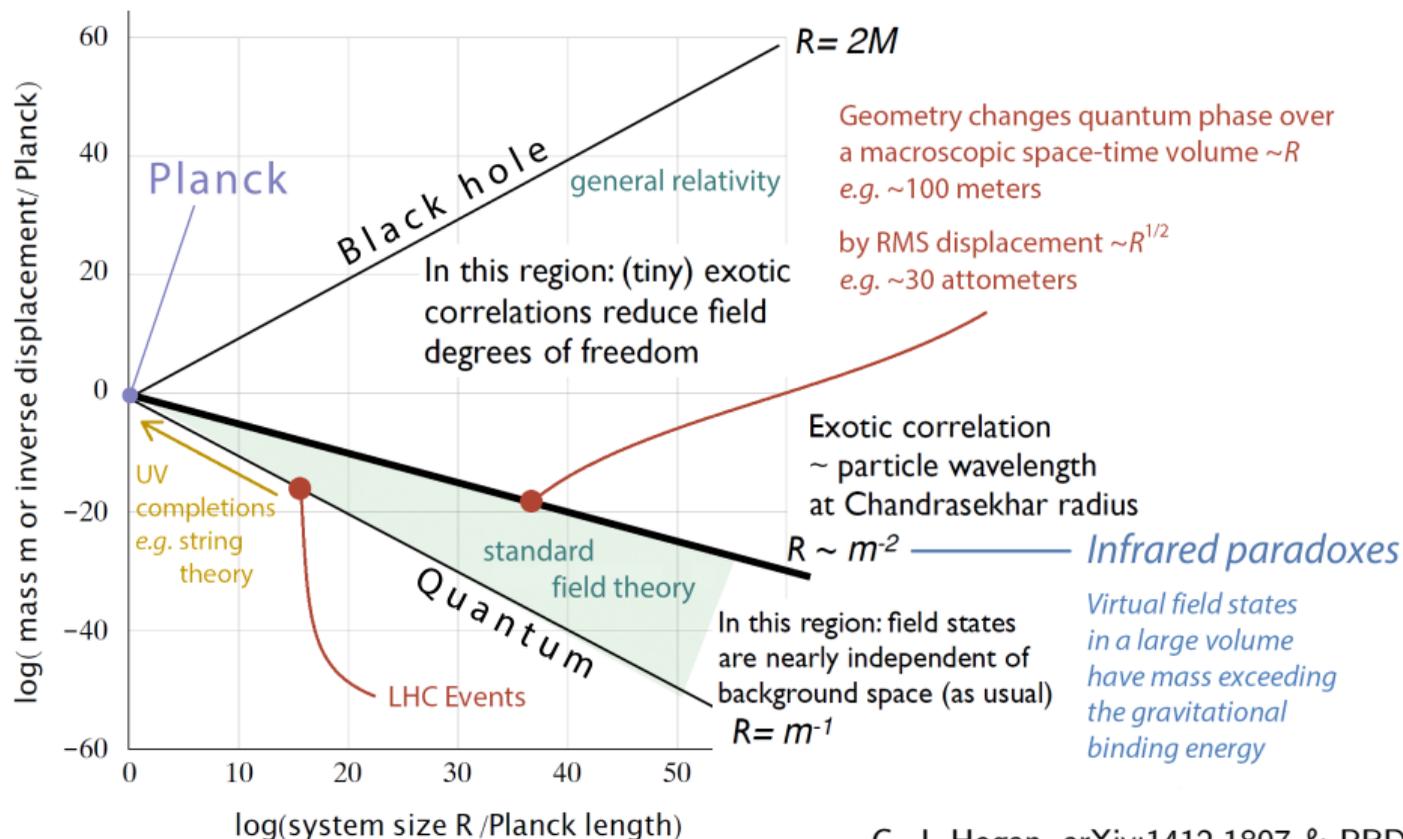
- Ultraviolet completions to Quantum Field Theory:
 - Strings, Noncommutative Geometry (deformations on a background)
- Quantum (field) effects in highly excited states of dynamical space-time:
 - CMB signatures (early universe), Black Holes, Loop Quantum Cosmology

What are the physical principles that a fundamental framework must reconcile?

- Quantum Mechanics: a rejection of local realism
- General Relativity: general covariance and background independence

- **Claim:** *Even the low-energy, ground-state limit of quantum gravity cannot be described by perturbative graviton fields on a background metric.*
- A field theory in a system of scale R and cutoff m has total number of modes $\sim R^3 m^3$.
- Holographic bound from black holes ($S \sim A$). Information density decreases linearly with size!
- **Requires nonlocal spacelike correlations of quantum space-time at large separations!**
- These correlations are typically studied in AdS/CFT dualities, where there are built-in boundaries.
- Or, black hole information “paradoxes” that arise if information is falsely assumed to be localized.
- *But such correlations must be present even in special relativistic space-time with no dynamics.*
- Thermodynamic behavior of BH horizons applies to Unruh horizon entropy in accelerated frames.

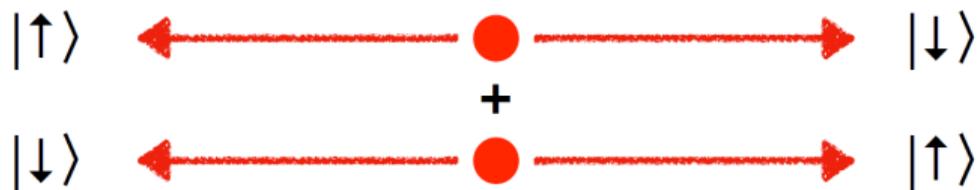
Consistent with Known Experimental Limits • New Phenomenology Outside QFT Regime



C. J. Hogan, arXiv:1412.1807 & PRD 95, 104050

Extending Einstein-Podolsky-Rosen to Space-Time

- *Space-time is an emergent behavior of a quantum system with many degrees of freedom, which are less independent than local fields (especially at macroscopic scales).*
- A Planckian subsystem has no well-defined local inertial frame, due to gravitational frame dragging.
- Space-time is constructed in a “relational” framework. It approaches classicality at large separations, but with residual coherent indeterminacies — manifest as correlations among observables.
- *“Spooky” directional entanglement, in the style of EPR, gives a natural scaling to the “correct” reduction of information in large systems!*

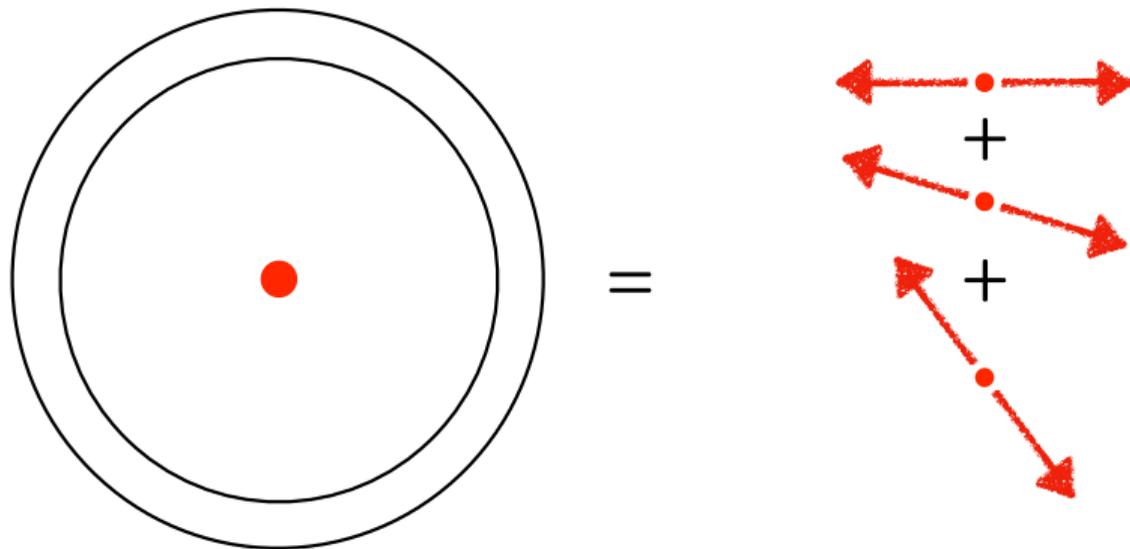


- Correlations demonstrated across hundreds of km, or between photons that have never “coexisted.” No violation of causality! But a classical background and its reference frame are a global conspiracy.

Causal Structure of EPR • Directional Entanglement and PET Spatial Imaging

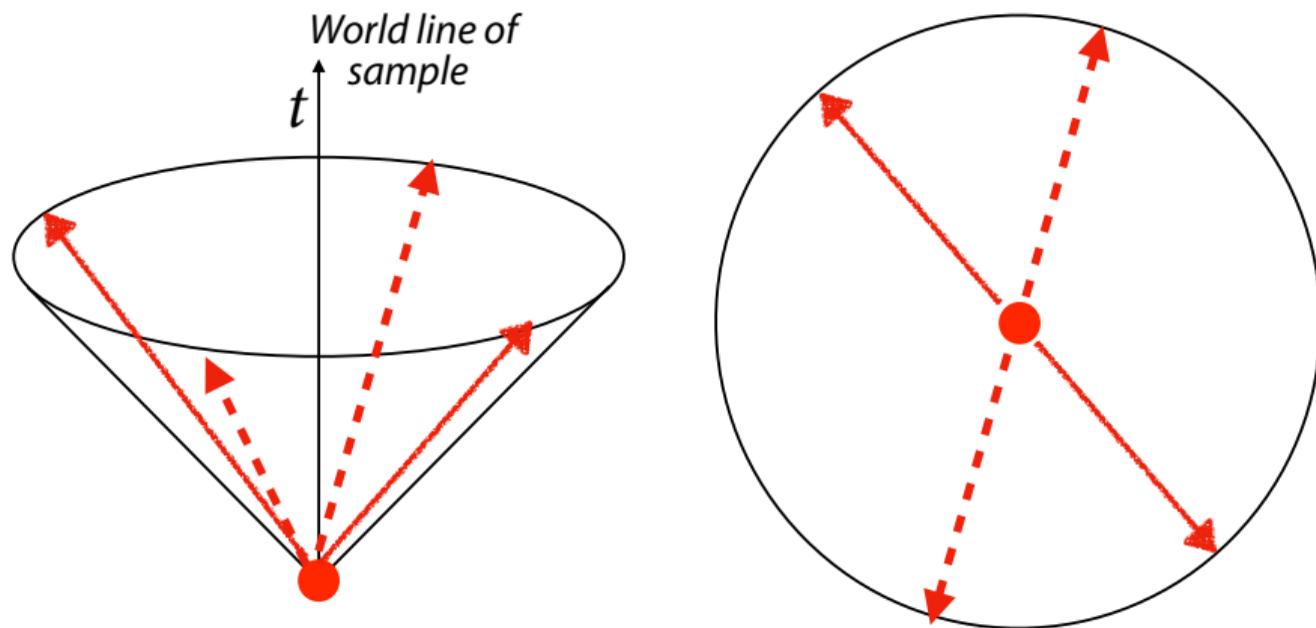
- Atom in the ground S state emits an isotropic wave function, a superposition of all directions.
- The directions of detection events are correlated from entanglement — PET spatial imaging.
- EPR pairs are part of a single nonlocal system, structured on light cones. Causality preserved.

wave function of emitted state = *superposition of directional pairs*



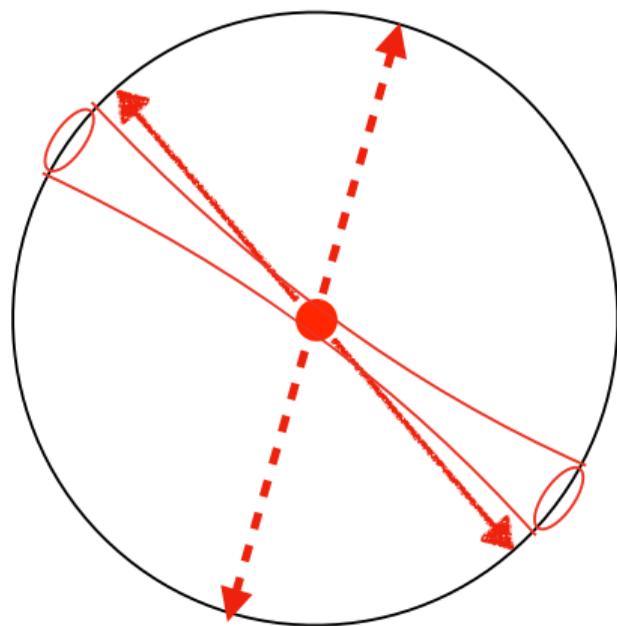
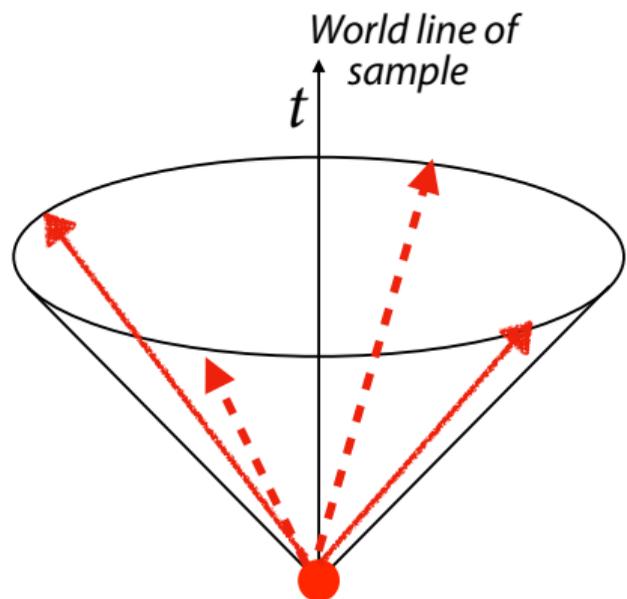
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No Separation of Scales • Nonlocal Signature

- Standard quantum limit: spatial uncertainty in PET scales with separation (diffractive modes)
- Transverse momenta of detected photons are **anticorrelated in the atom's frame**.
- *Nonlocal spacelike correlations extend indefinitely on light cones, following causal structure.*



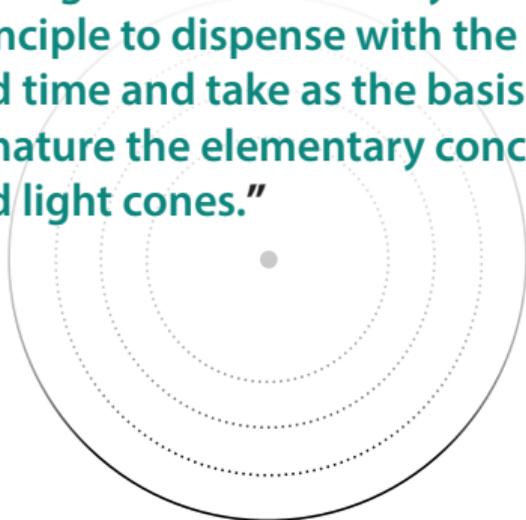
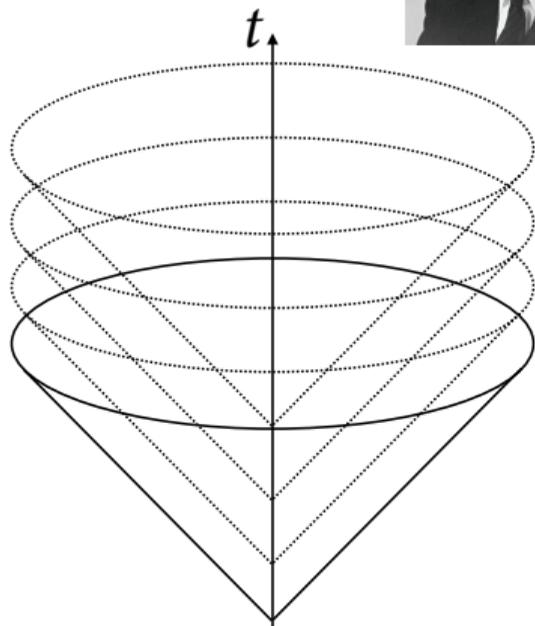
$$\langle \Delta x_{\perp}^2 \rangle_{\gamma} = \lambda_{\gamma} L$$

$$\langle \Delta \theta^2 \rangle_{\gamma} = \lambda_{\gamma} / L$$



“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.**”

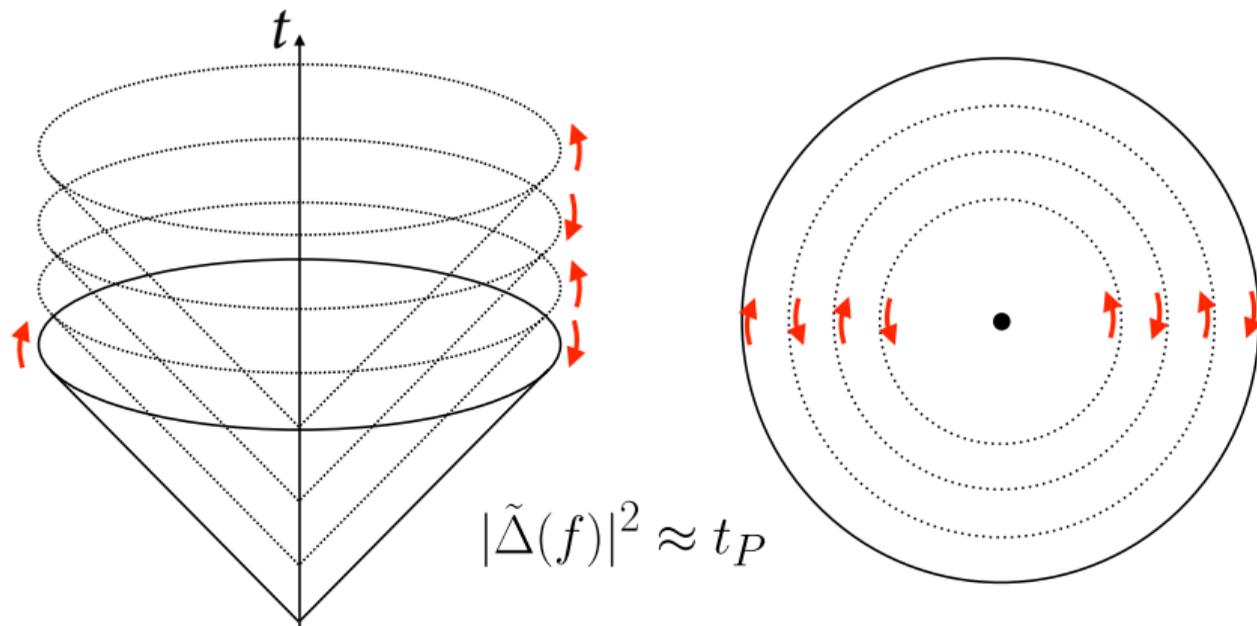
— J. A. Wheeler



American Philosophical Society

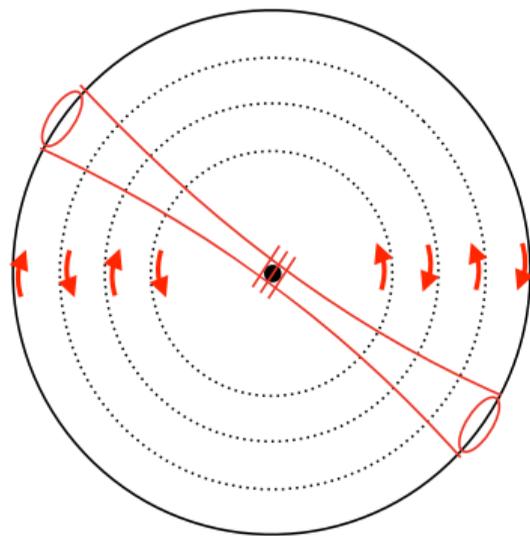
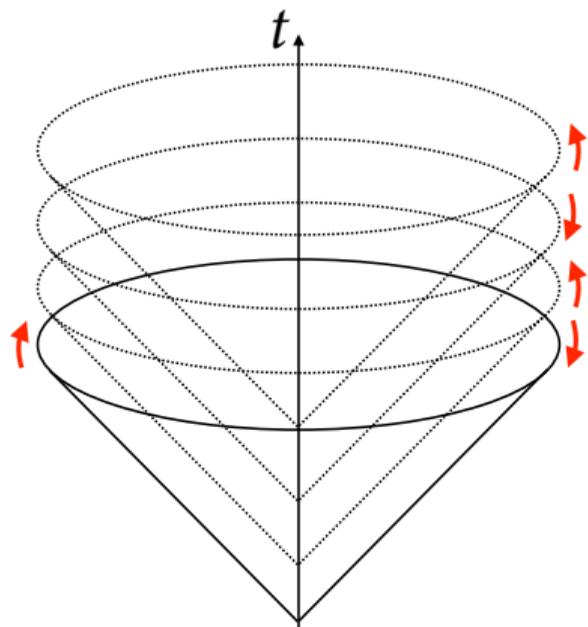
Covariant Emergence of Space-Time Directions and Inertial Frames from Causal Structure

- On an observer's world line, Planck bandwidth (or coherence scale) in *invariant* proper time.
- Planck scale indeterminacy on each foliating null cone — scales as a random walk in lab time.
- Holographic: Each spacelike 2-sphere has correlations for two independent rotational axes.



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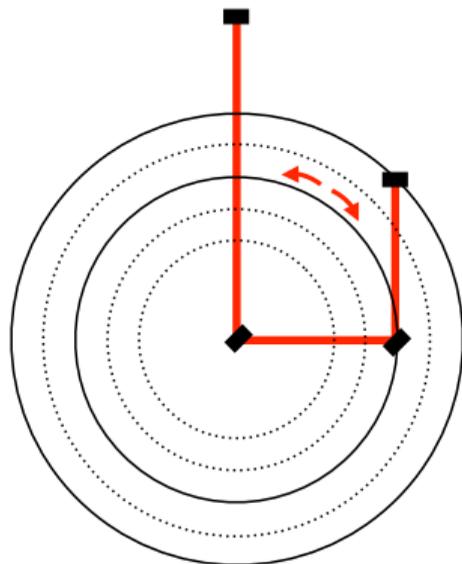
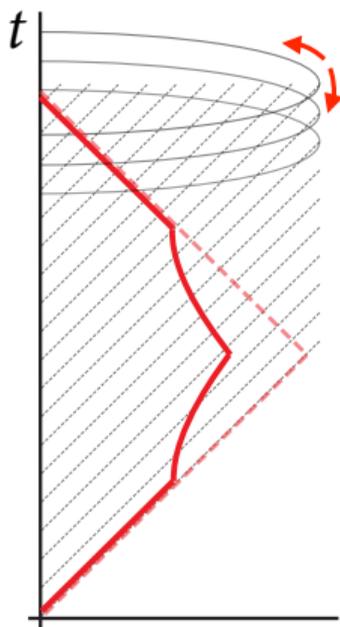
For duration
 $L = c\tau$

$$\langle \Delta x_{\perp}^2 \rangle_P = \lambda_P L$$

$$\langle \Delta \theta^2 \rangle_P = \lambda_P / c\tau$$

Strategy for Detection: Bent Michelson Interferometer

- *Sub-Planckian* strain spectral density, *broadband* & *faster than light crossing time* (nonlocal).
- Unlike AMO, no large coherent state needed. Superluminal sampling *faster than decoherence*.
- Mean rotation vanishes, but *mean square* fluctuation accumulates across the time correlation.



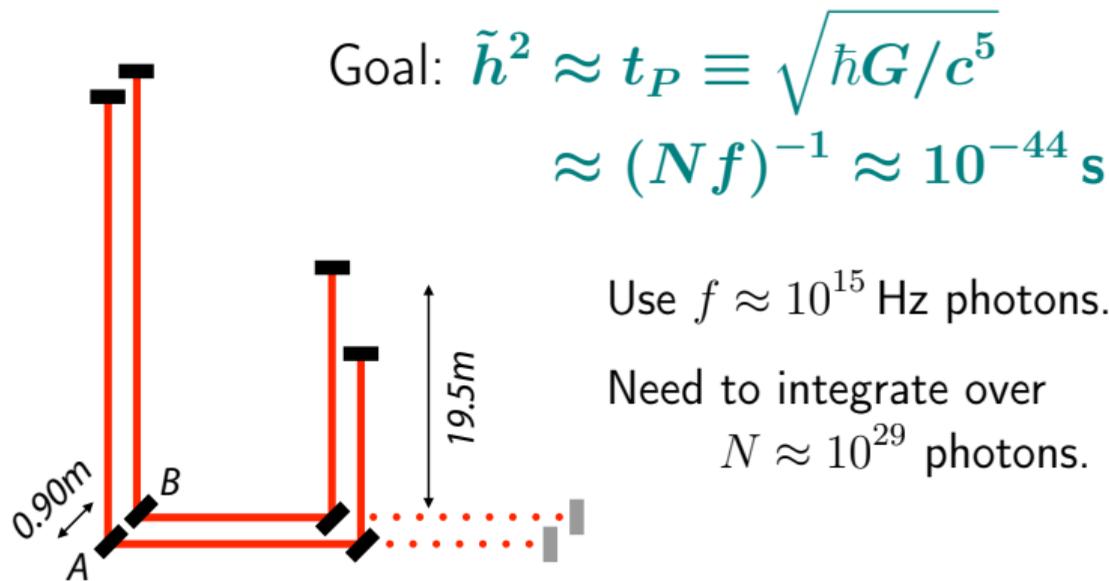
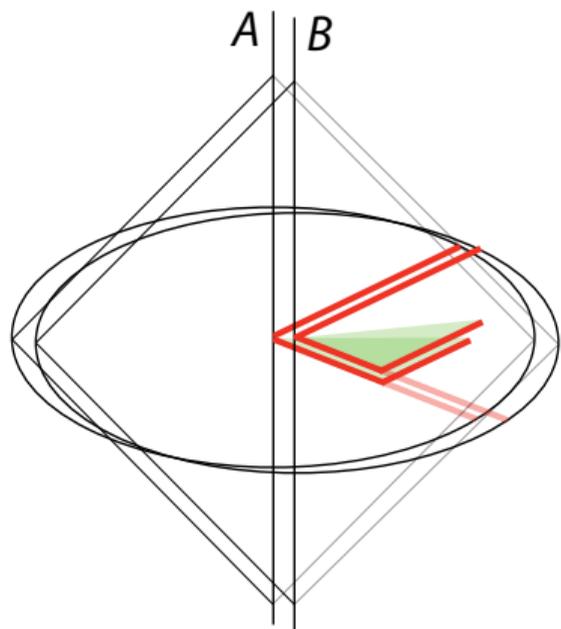
$$\begin{aligned} \langle \Delta x_{\perp}^2 \rangle_P &= \ell_P L \\ &= \text{PSD } t_P L^2 \\ &\quad \times \text{Bandwidth } c/L \end{aligned}$$

$$\begin{aligned} \text{where PSD} &= \tilde{h}^2(f) \cdot L^2 \\ h &\equiv \delta L/L \end{aligned}$$

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

Strategy for Detection: Cross-Correlation & Null Configuration

- Correlated signals: Measurements *share causal 4-volume* of quantum space-time information.
- Signal band limited by standard photon quantum noise. Uncorrelated, can be averaged away.
- Null configuration (radial arms) couples to translational modes, insensitive to transverse ones.

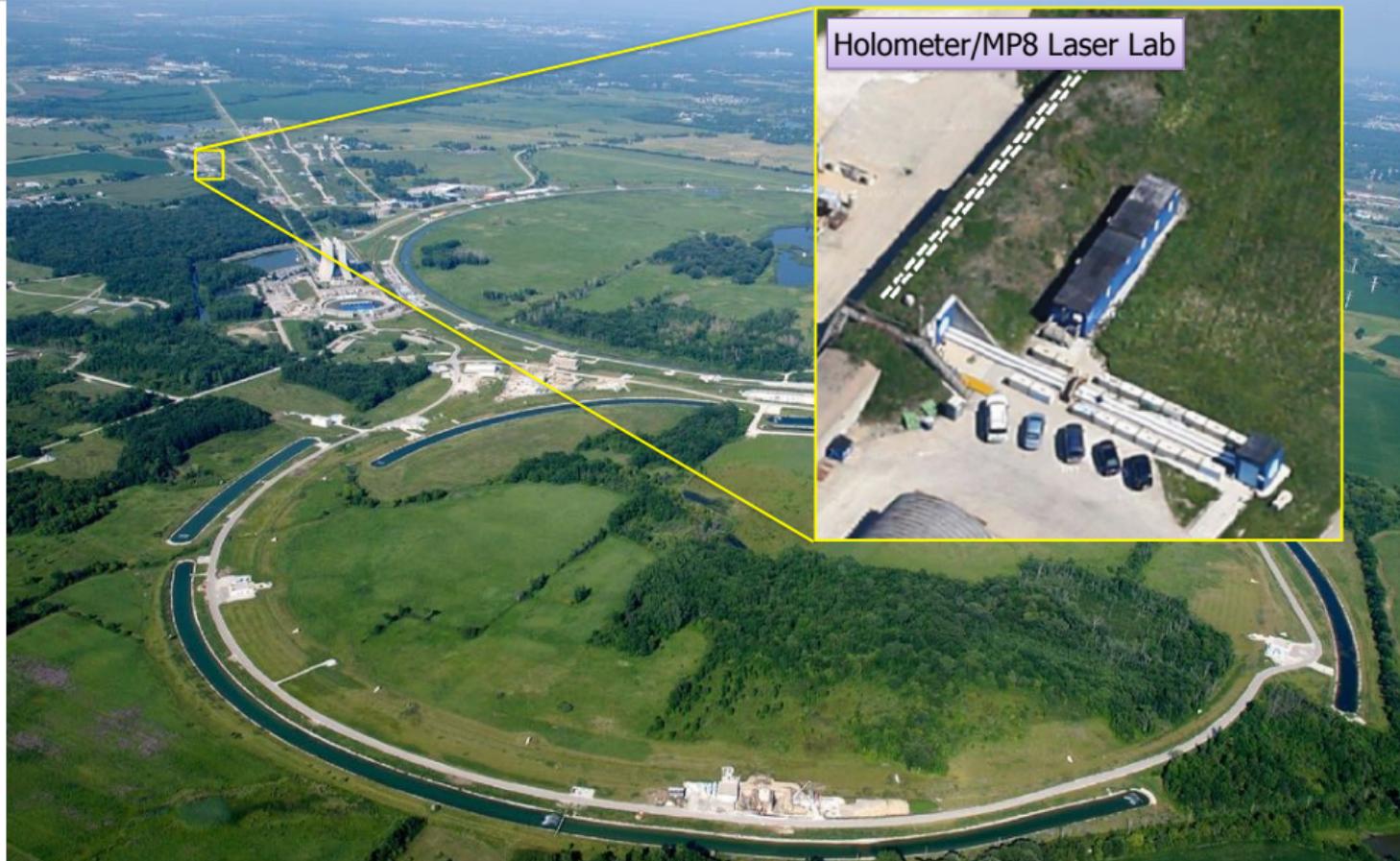


Can we get to this level of sensitivity?

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



Can we get to this level of sensitivity? We did!



First-Generation Holometer (2012–2016)

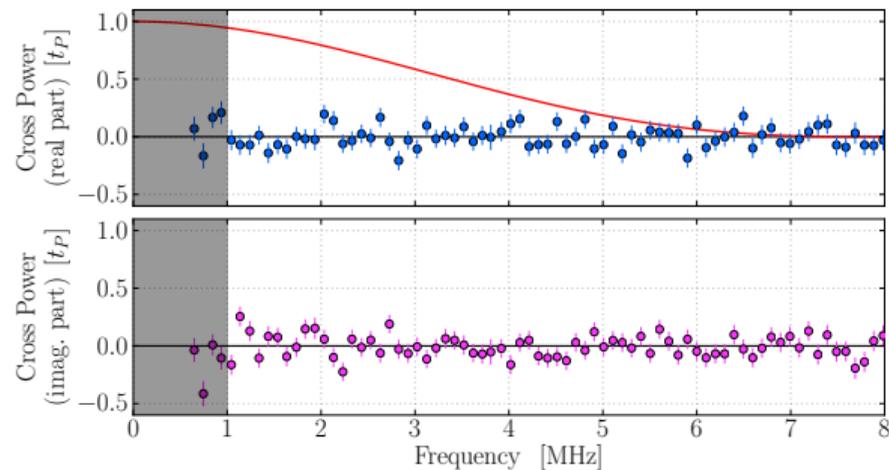
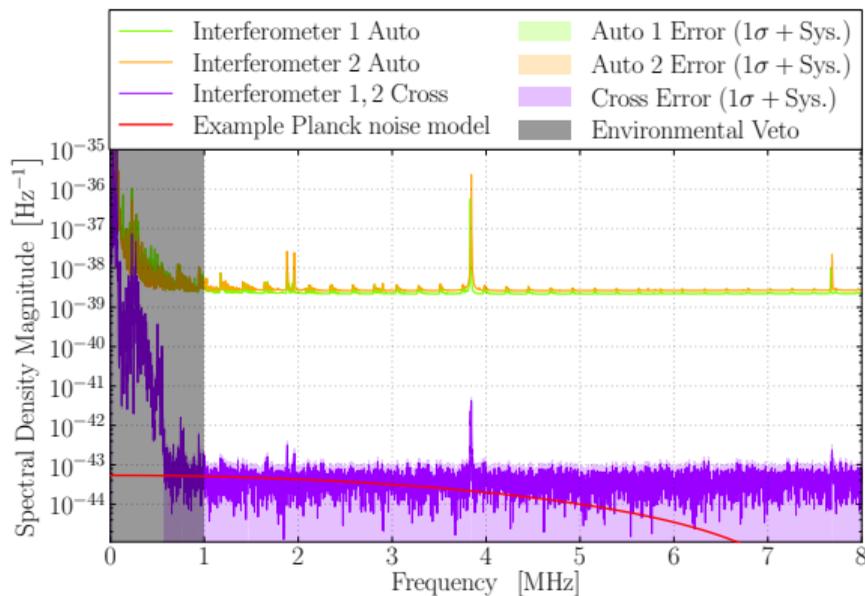


Second-Generation Holometer (2017)



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

First-Generation Holometer: Null Result at 0.1 Planck Scale



- 145 hour data — PRL **117**, 111102 (2016)
- 704 hour data — CQG **34**, 165005 (2017)
- Instrumentation — CQG **34**, 065005 (2017)
- *Dimensionless strain*, normalized to $L = 39$ m.

- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, Planck units.
- Example spectrum of $t_P \text{sinc}^2(\pi f L/c)$, the auto-correlation of a flat “boxcar” response at scale L .
- **Second-Generation Holometer operational, with similar systematics and backgrounds.**

Second-Generation Holometer: A Unique Signature of Relational Emergent Space-Time

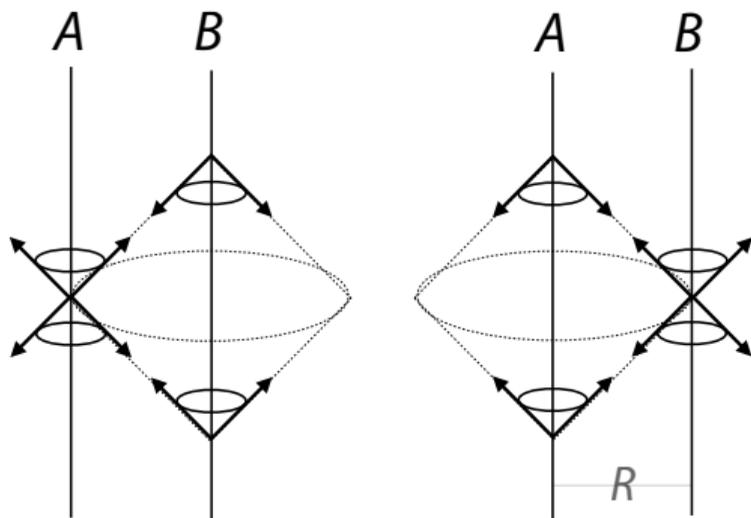
- In the Holometer, there are *two* measurements in *two* observer frames, relatively *non-inertial*.
- World line segments whose causal 4-volumes overlap are entangled via invariant structures:

$$2\Delta_{B|A}(t) = \Delta_A(t + R/c) - \Delta_A(t - R/c)$$

- The antisymmetry leads to a unique signature: a *purely imaginary cross-correlation*!

$$\begin{aligned}\tilde{\Delta}_{B|A} \tilde{\Delta}_{A|B}^* &= i \sin(2\pi f R/c) \tilde{\Delta}_A \tilde{\Delta}_A^* \\ &\approx i \sin(2\pi f R/c) t_P\end{aligned}$$

- Phase info not in **auto**spectrum. “*Pure entanglement information*” of *relational* space-time!
- If confirmed, we have no explanation for the signature in standard physics. Green’s functions apply in a local framework and relate real and imaginary parts by causality (Kramers-Kronig).



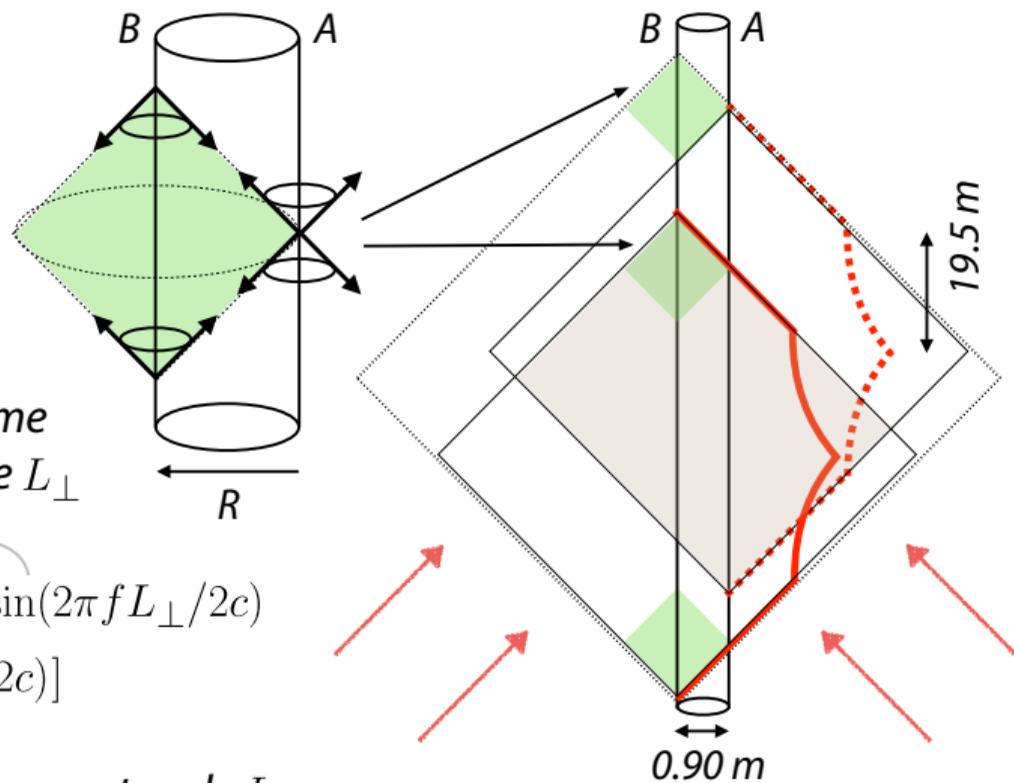
Toy model of cross-spectrum for one transverse segment of length L_{\perp}

antisymmetry across spatial separation, at scale R

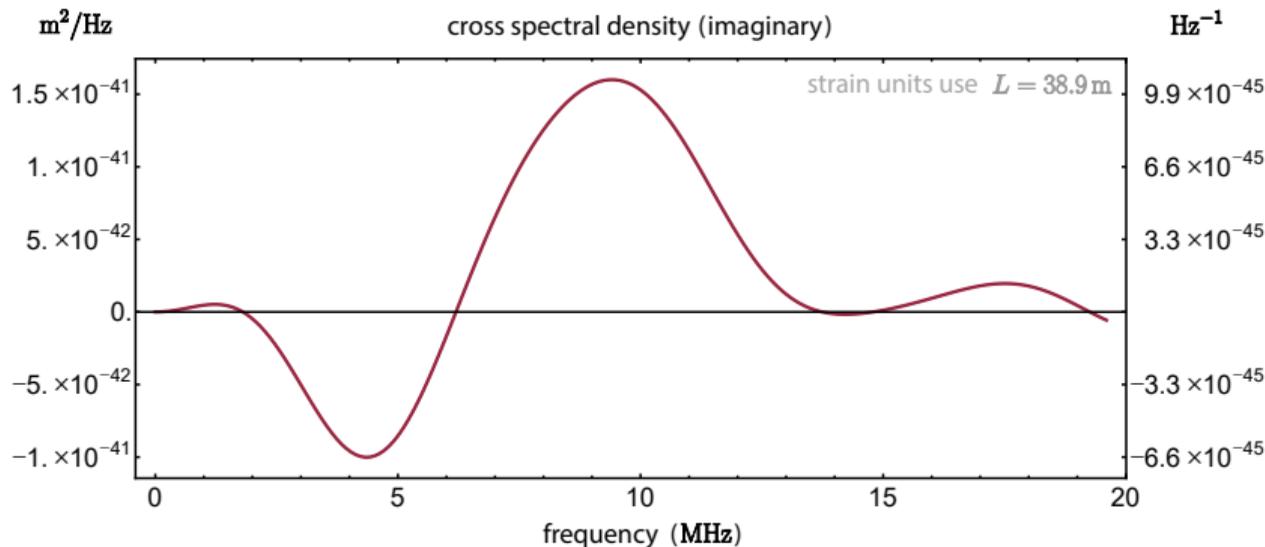
antisymmetry in time correlation, at scale L_{\perp}

$$\tilde{S}_{BA}(f) \approx it_P \sin(2\pi f R/c) \operatorname{sgn}(f) \sin(2\pi f L_{\perp}/2c) \times [2(L_{\perp}/c)^2 \operatorname{sinc}^2(\pi f L_{\perp}/2c)]$$

correlation of flat "boxcar" responses at scale L_{\perp}



Second-Generation Holometer: Modeled Cross-Spectrum (Imaginary)



Data forthcoming!

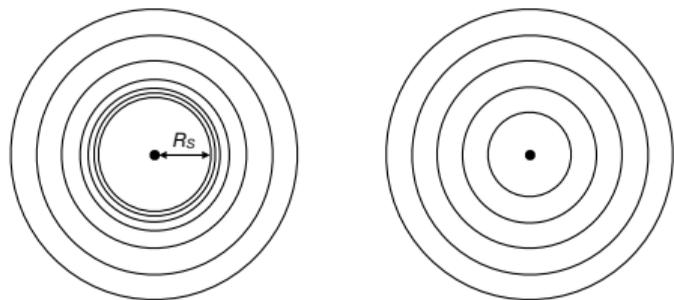
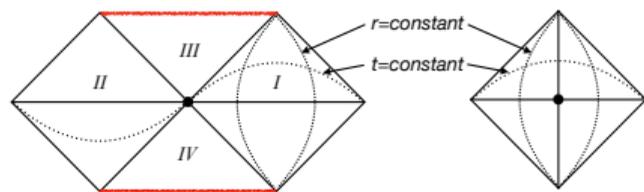
All parameters based on known scales of the apparatus.

Only free parameter is Planck normalization, set as $t_P = t_P \sqrt{4 \ln 2 / \pi}$ by black hole entropy.

$$\begin{aligned} \tilde{S}_{BA}(f) &= \sum_n 2\beta_n [2(L_n/c)^2 \text{sinc}^2(\pi f L_n/2c)] i t_P \sin(2\pi f R/c) \sin(\pi f L_n/c) \text{sgn}(f) \\ &\approx \sum_{n=1}^4 0.291 i t_P \beta_n \left[\frac{38.9\text{m}}{c} \right]^2 \frac{|f|}{15.4\text{MHz}} \frac{R}{0.90\text{m}} \left(\frac{L_n}{19.5\text{m}} \right)^2 \text{sinc}^2 \left[\pi \frac{f}{15.4\text{MHz}} \frac{L_n/2}{19.5\text{m}} \right] \sin \left[\pi \frac{f}{15.4\text{MHz}} \frac{L_n}{19.5\text{m}} \right] \end{aligned}$$

where $L_1 = 11.4\text{m}$ $\beta_1 = 0.84$ $L_2 = 27.5\text{m}$ $\beta_2 = 0.76$ $L_3 = 38.9\text{m}$ $\beta_3 = 2 \times -0.46$ $L_4 = 77.8\text{m}$ $\beta_4 = 0.119$

Connections to Black Hole Physics • Possible Explanation for the Cosmological Constant



Interpreted in terms of concrete observables, these nonlocal correlations have the same physical effect on states of light propagating tangent to a null cone in flat space-time as they do on tangential components of field states near a black hole event horizon.

Black hole model by 't Hooft [arXiv:1605.05119]: antipodes with entangled field states and a reversal of time. Our space-time model posits similarly entangled information and antisymmetry.

Cosmological Constant from Emergent Gravity

- Framework of Planck bandwidth world lines: relations at separation $c\tau$ are a fraction t_P/τ of total available entanglement information, so they “emerge” from the holographic quantum system at a resolution of

$$ct_P (\tau/t_P)^{1/3}$$

- World lines in a system of size $10^{61} \ell_P$ (cosmic horizon) are localized at the $10^{20} \ell_P$ QCD scale!
- Rotational correlations are associated with symmetry breaking of the QCD chiral vacuum, determining its emergent gravity. A heuristic “centrifugal acceleration.”

C. J. Hogan, PRD 95, 104050 & arXiv:1804.00070

We are building a team for the next stage of the Holometer program. Join us!



SCI
FNAL
DOE
KICP

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