Probing Quantum Correlations in Space-Time at the Fermilab Holometer

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Quantum
Space-Time
Phenomenology

Quantum

Space-Time

Phenomenology

$$F = m\,a$$

A law of nature?

$$F(t) = m\,a(t)$$

Galileo: Physical motion can be described as a function of time.

Oscillations of a pendulum "take equal time," measured with a pulse.

Soon thereafter, pulses are measured with pendulums.

Modern clocks are also based on oscillators!

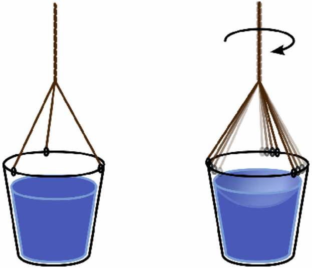
$$F(t) = m\,a(t)$$

Newton: There is an unobservable time, "***absolute*** *and equal to itself*."

You can only measure things evolving through time, and not time itself.

Time becomes an *untestable* mathematical axiom.

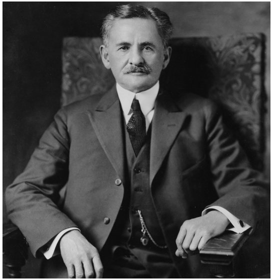
Absolute space?

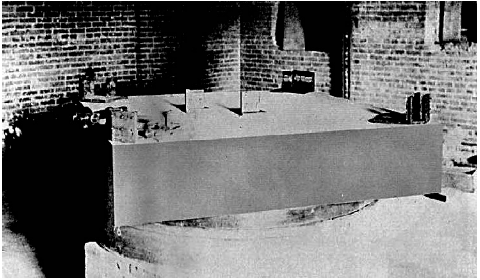


Newton: Local rotation agrees with measurements against distant stars.

There must be a universal global inertial frame of reference.

Even today, inflationary cosmology has a “preferred” frame of reference.





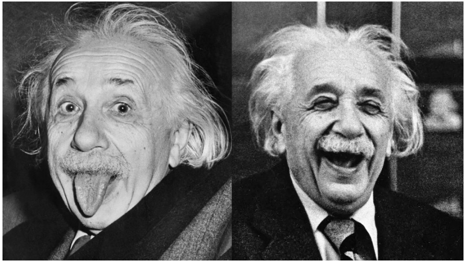
Michelson: The speed of light is independent of any observer frame in space-time.

There can be no background against which to measure it.

No "aether": no universal medium, no global refrence frame.

Einstein insists on a ***principle of invariance***:

- A consistent underlying physics, independent of an arbitrary choice of coordinate frame or measurements relative to a specific observer.



General Relativity:

- The gravitational field is *space-time itself*. It must have a physical reality and dynamics *independent* from the "background space-time" coordinates on which we construct all other theories of physics.
  - GR is soon beautifully confirmed by experiments.

The Beginning of the World from the Point of View of Quantum Theory.

SIR ARTHUR EDDINGTON [1] states that, philosophically, the notion of a beginning of the present order of Nature is repugnant to him. I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature. Thermodynamical principles from the point of view of quantum theory may be stated as follows: (1) Energy of constant total amount is distributed in discrete quanta. (2) The number of distinct quanta is ever increasing. If we go back in the course of time we must find fewer and fewer quanta, until we find all the energy of the universe packed in a few or even in a unique quantum.

Now, in atomic processes, the notions of space and time are no more than statistical notions; they fade out when applied to individual phenomena involving but a small number of quanta. If the world has begun with a single quantum, the notions of space and time would altogether fail to have any meaning at the beginning; they would only begin to have a sensible meaning when the original quantum had been divided into a sufficient number of quanta. If this suggestion is correct, the beginning of the world happened a little before the beginning of space and time. I think that such a beginning of the world is far enough from the present order of Nature to be not at all repugnant.

It may be difficult to follow up the idea in detail as we are not yet able to count the quantum packets in every case. For example, it may be that an atomic nucleus must be counted as a unique quantum, the atomic number acting as a kind of quantum number. If the future development of quantum theory happens to turn in that direction, we could conceive the beginning of the universe in the form of a unique atom, the atomic weight of which is the total mass of the universe. This highly unstable atom would divide in smaller and smaller atoms by a kind of super-radioactive process. Some remnant of this process might, according to Sir James Jeans's idea, foster the heat of the stars until our low atomic number atoms allowed life to be possible.

Clearly the initial quantum could not conceal in itself the whole course of evolution; but, according to the principle of indeterminacy, that is not necessary. Our world is now understood to be a world where something really happens; the whole story of the world need not have been written down in the first quantum like a song on the disc of a phonograph. The whole matter of the world must have been present at the beginning, but the story it has to tell may be written step by step.

G. LEMAÎTRE.

40 rue de Namur,
Louvain.

[1] NATURE, Mar. 21, p. 447.

Lemaître:

- GR describes an expanding universe.
- Space-time itself had a "beginning."

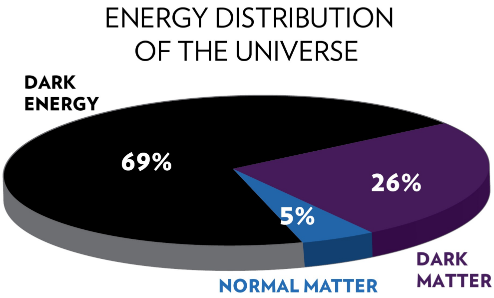
Einstein adds a constant to "fix" GR.

Hubble's data confirms the expansion.

Einstein abandons the constant,
calling it his "greatest blunder."

Lemaître identifies this "cosmological constant" as a real physical entity: the **energy of vacuum in quantum theory!**

- It must be positive for the age of the universe to be consistent with data, meaning, *the expansion is accelerating*.
  - Experimentally confirmed 67 years later (High-Z Supernova Search).

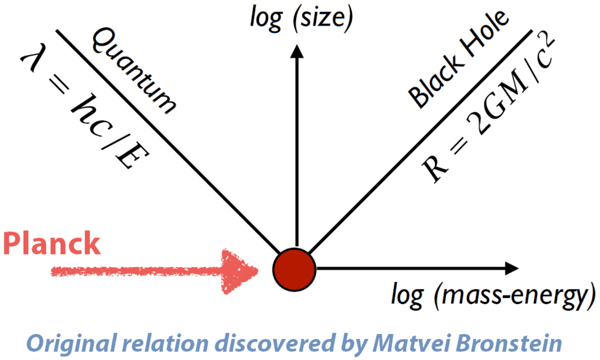


$67 \sim 74\,\%$ is "dark energy" of vacuum!

"No point is more central than this, that space is not empty, it is the seat of the most violent physics."

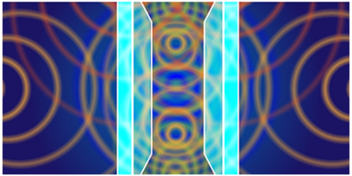
— J. A. Wheeler

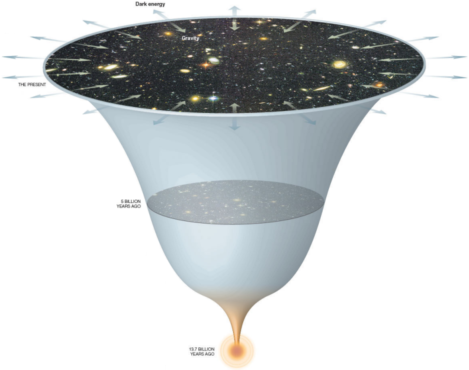
- Quantum theory: all states are probabilistic.
- Vacuum: a state with an infinite number of virtual fields constantly popping in and out of existence.
- Space-time not well-defined at the smallest scales.



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

- The energy of vacuum measured in a lab matches our theories!
- If we scale this theory to the universe, prediction is 122 orders of magnitude larger than the actual energy density.





- A fine-tuned constant is 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!*

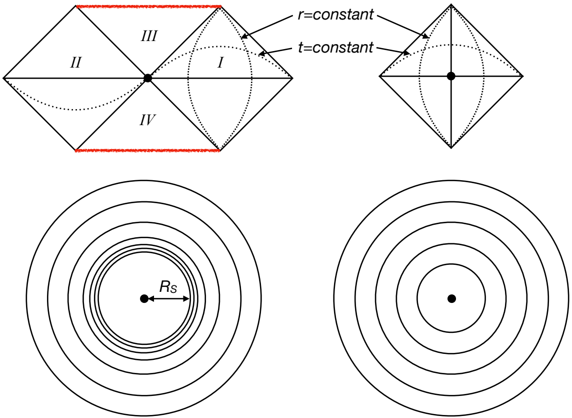
$$S_{BH} = \frac{kA}{4\ell_P^2}$$

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 Switzerland!

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]

A phenomenology connecting QM and GR

- **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 should exist even in special relativistic space-time with no dynamics.
  Thermodynamic behavior of BH horizons applies to Unruh horizon entropy in accelerated frames.
- Can we understand correlations in flat space-time, without a built-in boundary like AdS space?

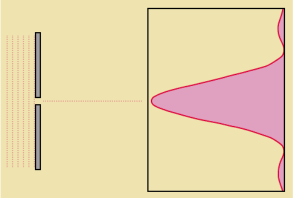
Quantum

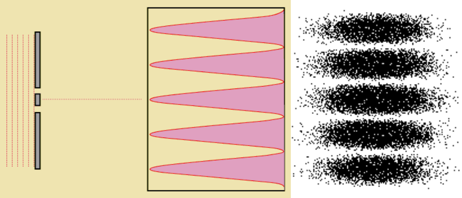
Space-Time

Phenomenology

Heisenberg's uncertainty principle for particles: $\Delta x \, \Delta p \geq \hbar / 2$

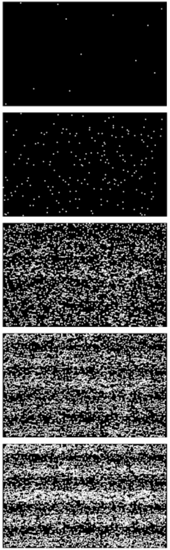
- One fewer dimension of information, or independent degree of freedom.





Each particle acts like it takes a superposition of paths.

But the probabilistic paths "collapse" if we try to detect them individually!



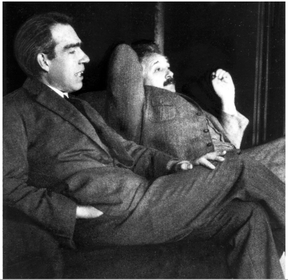
Epistemic

uncertainty

- The laws of physics are deterministic.
- There is an absolute underlying reality.
- We just do not know or observe the hidden information.

"I, at any rate, am convinced that [God] does not throw dice."

— Albert Einstein



Ontic

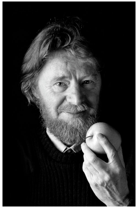
indeterminacy

- Nature "has not decided on" a definite outcome "before it is observed."
- The probabilities of quantum mechanics, and the lack of definite information, are fundamental realities.

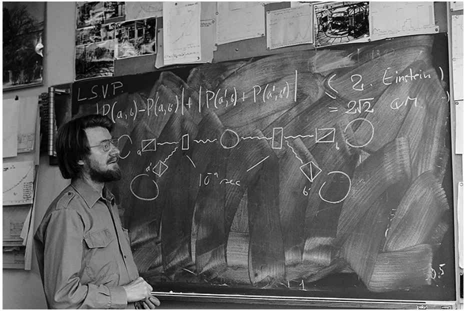
"Einstein, stop telling God what to do!"

"Everything we call real is made of things that cannot be regarded as real."

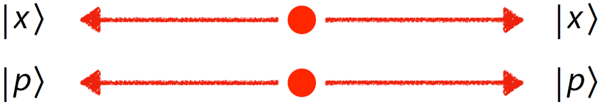
— Niels Bohr



Bell's inequality



The Einstein-Podolsky-Rosen "paradox"



- If quantum indeterminacies are fundamental, both particles are part of a *single system* extended across the separation, sharing a smaller total info content.
- **Entanglement**: The state of one particle is *not a degree of freedom independent* from the other one.
- *"Spukhafte Fernwirkung"*: One measurement instantly determines the uncertainty in the other— faster than light, faster than information can travel.
  - A violation of causality?

"I would not call [entanglement] *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought."

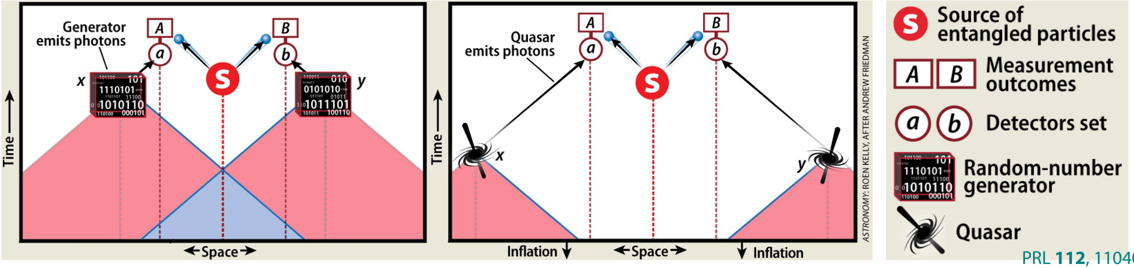
— Erwin Schrödinger

- A quantum theory only predicts correlations among observables.
- *Quantum system includes the observer, the measurement device... and the background space-time.*

A remaining loophole: nonlocalities in the quantum system of background space-time

Over decades, countless Bell tests have confirmed entanglement. Is it fundamental?

- Can experimenters "randomly" and "freely" choose which observable to measure each time?
  - "Free Will Theorem": This is connected to whether the laws of nature are deterministic!
- Random-number generators? Both could be "determined" by common events in the past.
- Cosmic Bell tests: "Choices" set by signals from "causally disconnected" cosmic phenomena.
- Holographic space-time: Are these causal structures and symmetries exact and absolute?



PRL **112**, 110405

Studying *"spukhafte Fernwirkung"* in quantum gravity

- Proposals in AMO physics: Can we reach the scales and precision levels to study gravity?
- Large coherent states are really difficult. What if we sample faster than decoherence?
- Entanglement may show up even in flat space-time, the non-excited vacuum state with no GR dynamics and curvature.

PRL **119,** 240402 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

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(Received 6 September 2017; published 13 December 2017)

All existing quantum-gravity proposals are extremely hard to test in practice. Quantum effects in the gravitational field are exceptionally small, unlike those in the electromagnetic field. The fundamental reason is that the gravitational coupling constant is about 43 orders of magnitude smaller than the fine structure constant, which governs light-matter interactions. For example, detecting gravitons—the hypothetical quanta of the gravitational field predicted by certain quantum-gravity proposals—is deemed to be practically impossible. Here we adopt a radically different, quantum-information-theoretic approach to testing quantum gravity. We propose witnessing quantumlike features in the gravitational field, by probing it with two masses each in a superposition of two locations. First, we prove that any system (e.g., a field) mediating entanglement between two quantum systems must be quantum. This argument is general and does not rely on any specific dynamics. Then, we propose an experiment to detect the entanglement generated between two masses via gravitational interaction. By our argument, the degree of entanglement between the masses is a witness of the field quantization. This experiment does not require any quantum control over gravity. It is also closer to realization than detecting gravitons or detecting quantum gravitational vacuum fluctuations.

DOI: 10.1103/PhysRevLett.119.240402

PRL **119,** 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

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(Received 6 September 2017; revised manuscript received 6 November 2017; published 13 December 2017)

Understanding gravity in the framework of quantum mechanics is one of the great challenges in modern physics. However, the lack of empirical evidence has lead to a debate on whether gravity is a quantum entity. Despite varied proposed probes for quantum gravity, it is fair to say that there are no feasible ideas yet to test its quantum coherent behavior directly in a laboratory experiment. Here, we introduce an idea for

Quantum

Space-Time

Phenomenology

What are the symmetries and degrees of freedom?

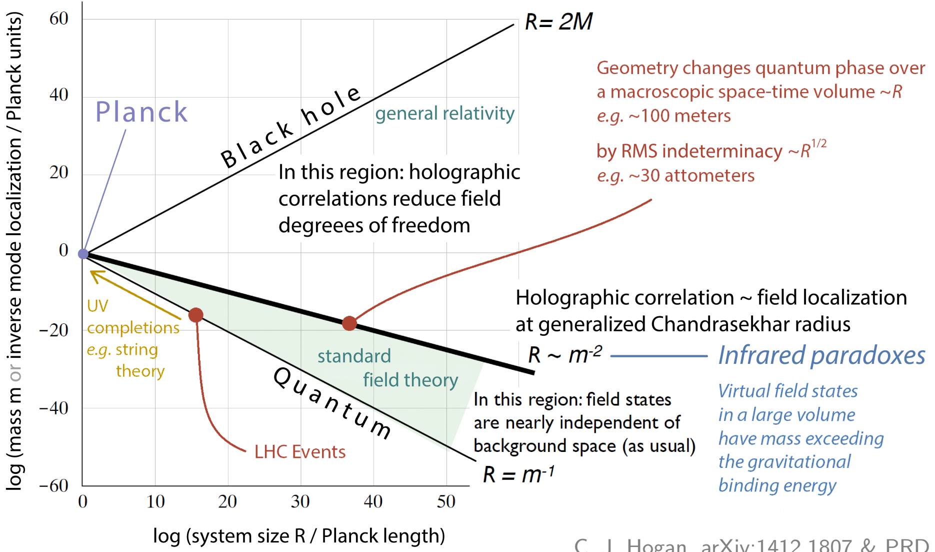
- Space-time is an **emergent** behavior of a quantum system with many degrees of freedom — must be holographic and less independent than local fields (especially at macroscopic scales).
- Space-time constructed **relationally**. An *a priori* definite background is a global conspiracy!
- 4-positions and inertial frames are defined operationally, with a measurement by an observer.

Lorentz Symmetry	•	Poincaré Symmetry
- Lorentz boosts - Rotations		- Translations

- Lorentz invariance well-tested in 1-D. We can try measuring space-time correlations in 2-D?

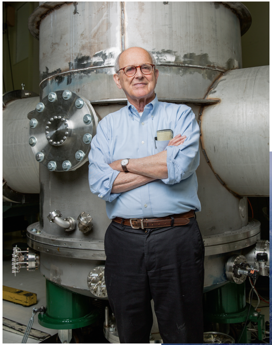
CQG **33**, 105004 and **34**, 075006. Also see Verlinde and Zurek, arXiv:1902.08207

A new phenomenological regime of interest



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

Can LIGO technology be adapted to nonlocal correlations?



LIGO $\longrightarrow$ Holometer

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

Laser interferometers: the most precise in differential position measurements.

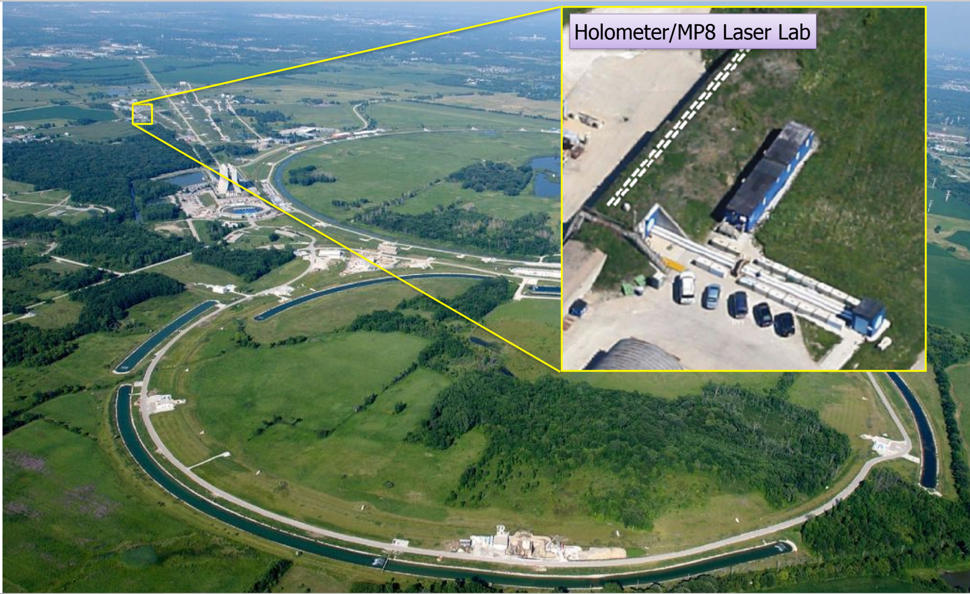
In dimensionless strain units $h \equiv \delta L/L$, the power spectral density reaches

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

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.

The Fermilab Holometer



First-generation Holometer (2011-2016)

Cross-spectral density with two interferometers:

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

Naive model: delocalized Planckian fluctuations, each with a flat response over timescale L/c

(*variance scales like a random walk over* $L = 39\,\mathrm{m}$)

$$\tilde{h}^2(f) \approx \boldsymbol{t_P} \, \mathrm{sinc}^2(\pi f L/c)$$

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

For straightforward interpretation via properties of space-time, all light propagation is *in vacuo*, with no cavity within the arms.

Noise spectrum is flat and dominated by shot noise.

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

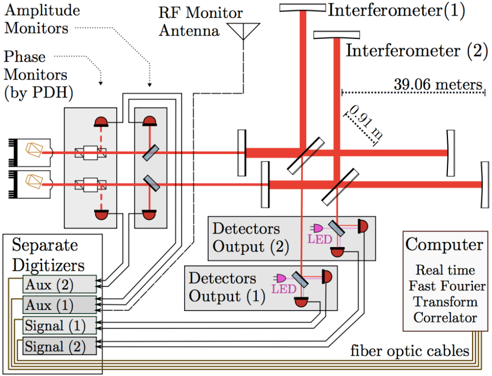
OUTPUT SIDE

Detectors & Readout Electronics

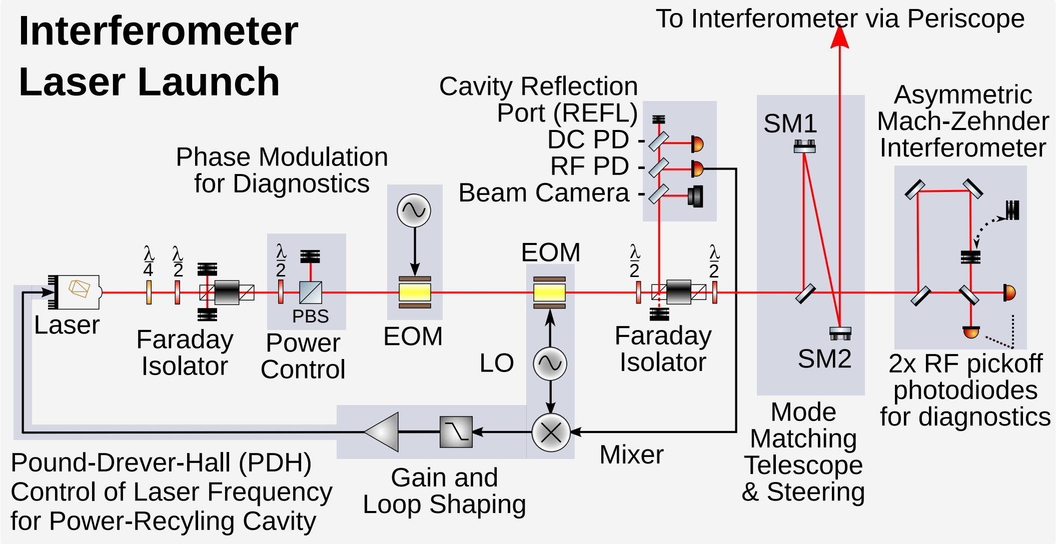
- Correlated electronics noise
- Cross-channel signal leakage

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

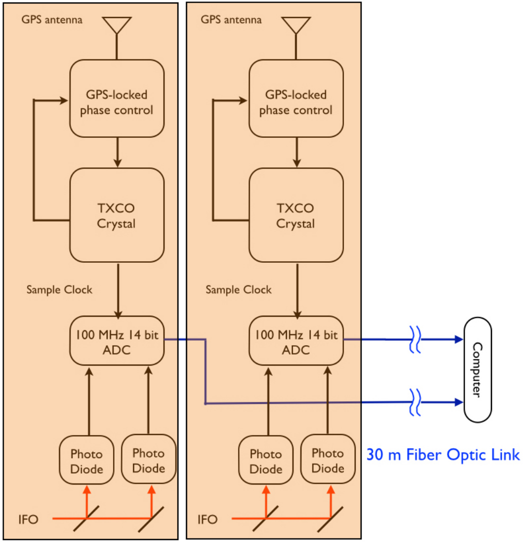
Realtime Monitoring of Laser Noise and Radio-Frequency (RF) Environment



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


Interferometer
Laser Launch
To Interferometer via Periscope
Cavity Reflection
Port (REFL)
DC PD -
RF PD -
Beam Camera -
Phase Modulation
for Diagnostics
SM1
SM2
Asymmetric
Mach-Zehnder
Interferometer
λ/4
λ/2
λ/2
PBS
EOM
EOM
λ/2
λ/2
Laser
Faraday
Isolator
Power
Control
LO
Faraday
Isolator
2x RF pickoff
photodiodes
for diagnostics
Mode
Matching
Telescope
& Steering
Mixer
Pound-Drever-Hall (PDH)
Control of Laser Frequency
for Power-Recyling Cavity
Gain and
Loop Shaping

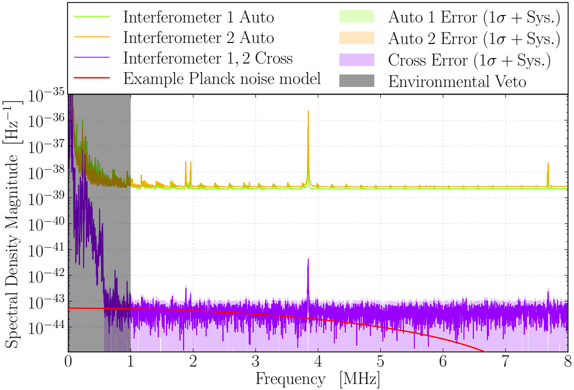
Isolated high-speed data acquisition systems and sampling clocks

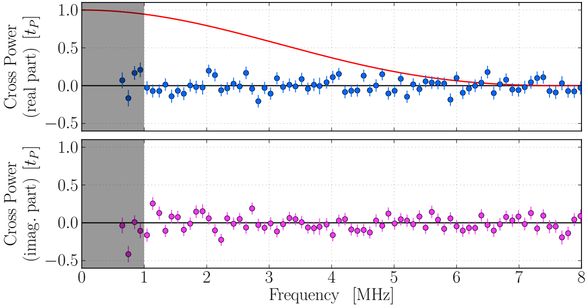


Each ADC (analog-to-digital converter) unit individually synchronized to a GPS-provided clocking signal.

Relative drift of sampling clocks follow a normal distribution of width $\sim 10\,\text{ns}$, limiting inter-channel decorrelation to less than 10%.

Cross-spectral density (CSD) calculated from real-time Fast Fourier Transform (FFT)





- 145 hour data — PRL **117**, 111102 (2016)
- 704 hour data — CQG **34**, 165005 (2017)
- Instrumentation — CQG **34**, 065005 (2017)
- ***Null control for the 2nd-gen Holometer!***

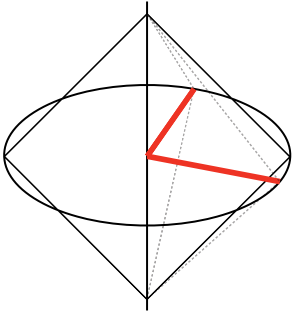
- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, Planck units.
- Example spectrum of $t_P \,\mathrm{sinc}^2(\pi f L/c)$, the auto-correlation of a flat "boxcar" response at scale L.
- *Light probes radial null (lightlike) paths to and from the beamsplitter measurements, in 2-D.*

Translational correlations ruled out. How about rotational correlations?

First-generation Holometer:

- 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.

  On these light cones, radial distances (in multiple dimensions) are identified with proper time durations on the observer's world line.



Null result indicates an underlying exact symmetry — a structure with no quantum indeterminacy. What might this be?

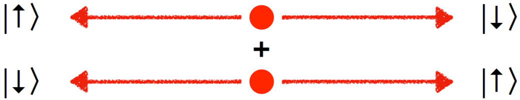
Second-generation Holometer: a Lorentz invariant model

- Correlations respect exact causal structure (in radial directions from the observer's world line)
- Correlations are purely transverse (along these causal surfaces), with rotational symmetry

Second-generation Holometer: conceptual motivations

Newton's measurement of local inertial frames with a spinning bucket of water

- The agreement between local and global frames in flat space-time fails at the Planck scale.
- A single quantum carries enough mass-energy and indeterminacy of angular momentum to cause significant gravitational frame dragging of the inertial frame (or Lense-Thirring effect).
- A Planckian subsystem has no well-defined inertial frame. The statistical emergence of local frames should show rotational fluctuations.



Apache Point Observatory lunar laser ranging *Gravity Probe- B*

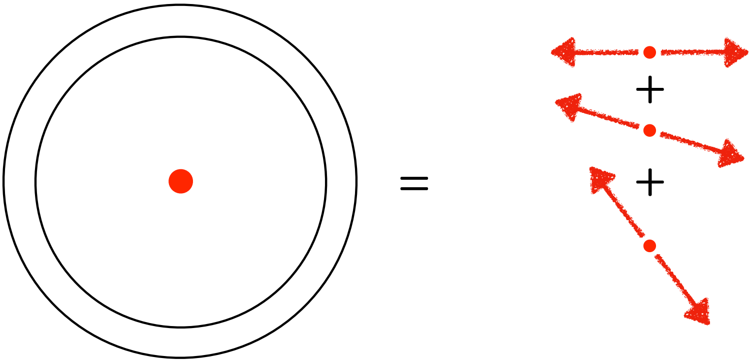
"Spukhafte Fernwirkung"

- Einstein-Podolsky-Rosen is not a violation of causality.
- In fact, it captures a nonlocal invariant relationship between events defined by the universal speed of light, and a natural reduction of the total degrees of freedom.

EPR pairs in PET spatial imaging: directionally entangled around causal structures

- Atom in the ground S state emits an isotropic wave function, a superposition of all directions.
- Directions of detection events are correlated from entanglement (spatial imaging method).
- EPR pairs are part of a single nonlocal system, structured on light cones. Exact causality.

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



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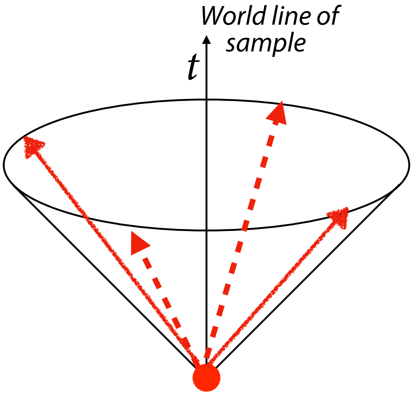
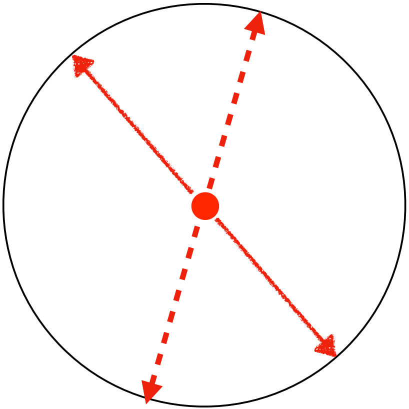
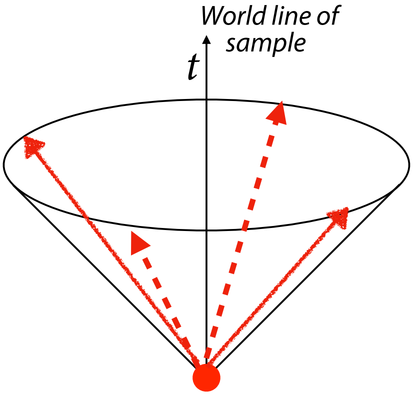
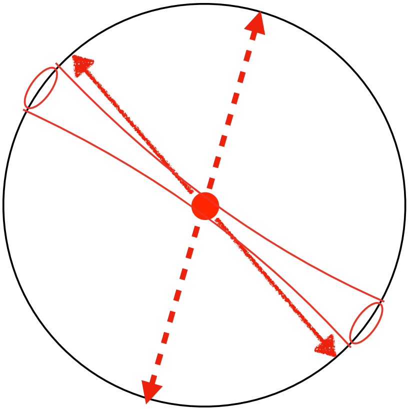
- EPR pairs are part of a single nonlocal system, structured on light cones. Exact causality.





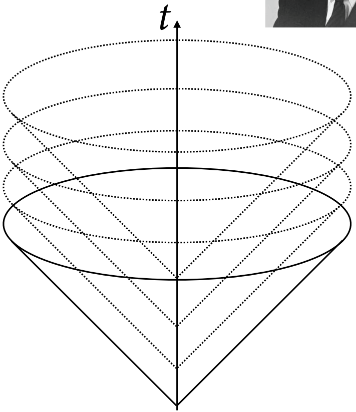
- *Nonlocal spacelike correlations extend indefinitely on light cones, following causal structure.*
- Standard quantum limit: spatial uncertainty in PET scales with separation (diffractive modes)
- Transverse momenta of detected photons are **anticorrelated in the atom's frame**.



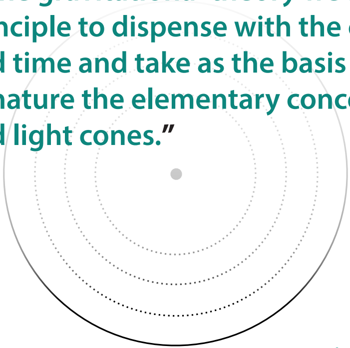


$$\left\langle \Delta x_\perp^2 \right\rangle_\gamma = \lambda_\gamma L$$

$$\left\langle \Delta \theta^2 \right\rangle_\gamma = \lambda_\gamma / L$$



"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.**"

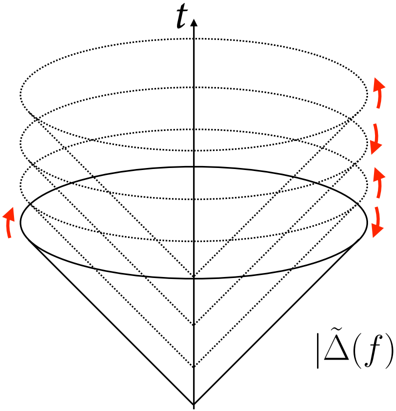


— J. A. Wheeler

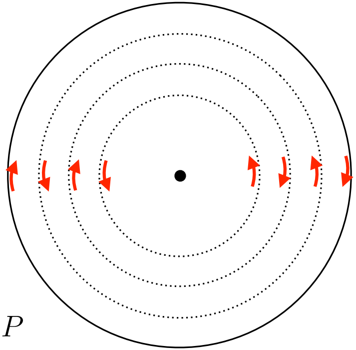
American Philosophical Society

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.
- Directional uncertainty scales down with separation, showing emergence of classicality.



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



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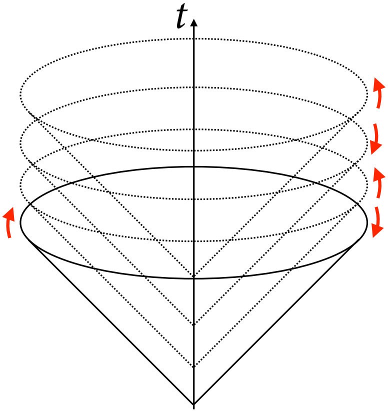
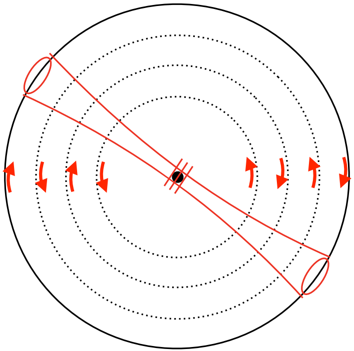




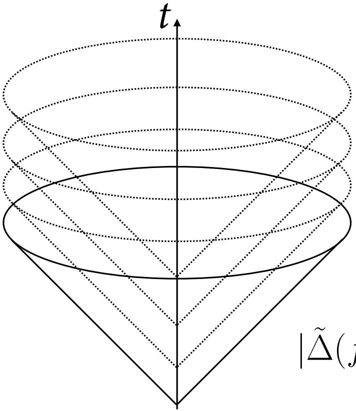
For duration

$$L = c\tau$$

$$\left\langle \Delta x_\perp^2 \right\rangle_P = \lambda_P L$$

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

- For each enclosed causal diamond, light cones foliate space-time with Planckian bandwidth.
- Light cone boundary (spacelike 2-sphere) has correlations for two independent rotational axes.
- Invariant structure identifies radial distance with proper time duration on observer's world line.



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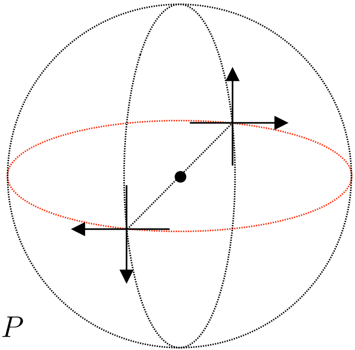
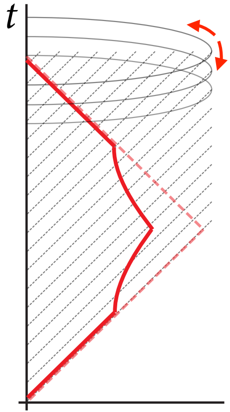
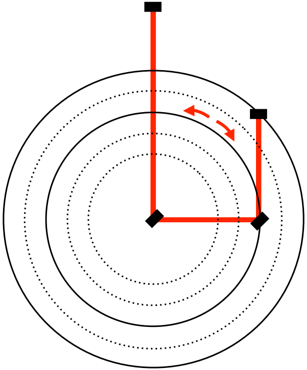


CQG 34, 135006

- *Sub-Planckian* strain spectral density, *broadband & faster than light crossing time* (nonlocal).
- No large coherent state needed: superluminal sampling is *faster than the rate of decoherence*.
- Mean rotation vanishes, but *mean square* fluctuation accumulates across the time correlation.





$$\langle \Delta x_\perp^2 \rangle_P = \ell_P L$$

$$= \text{PSD } t_P L^2$$

$$\times \text{ Bandwidth } c/L$$

where $\text{PSD} = \tilde{h}^2(f) \cdot L^2$

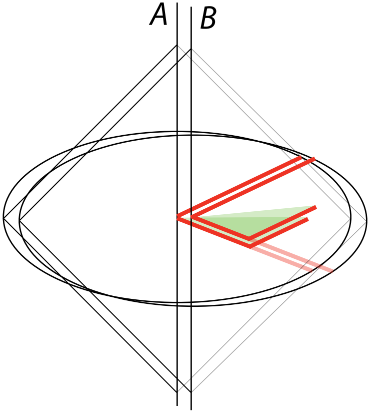
$$h \equiv \delta L / L$$

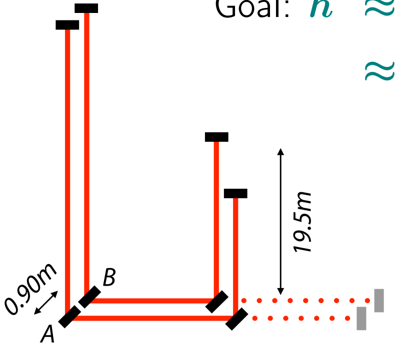
$$\tilde{h}^2(f) \approx t_P$$

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

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.





Goal: $\tilde{h}^2 \approx t_P \equiv \sqrt{\hbar G / c^5}$
$\approx (Nf)^{-1} \approx 10^{-44}\,\mathrm{s}$

Use $f \approx 10^{15}$ Hz photons.

Need to integrate over $N \approx 10^{29}$ photons.

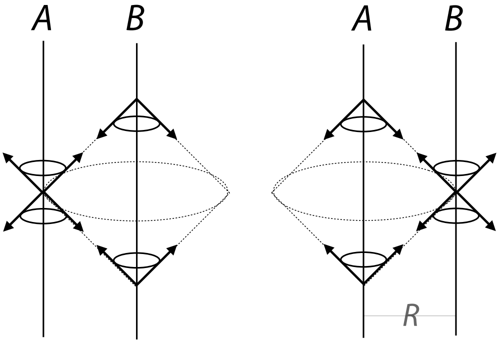
A unique signature of relational emergent space-time

- 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!

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



- 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).

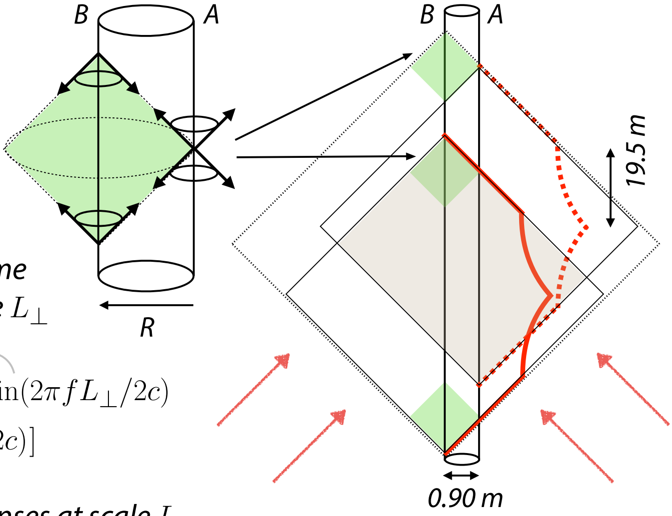
Toy model of cross-spectrum for one transverse segment of length $L_\perp$

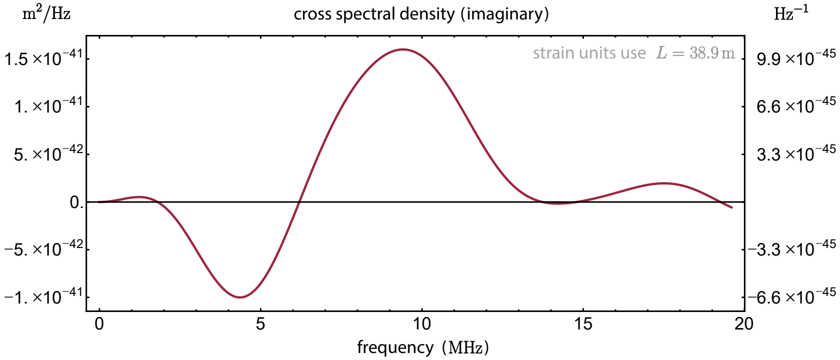
antisymmetry across spatial separation, at scale R

antisymmetry in time correlation, at scale $L_\perp$

$$\tilde{S}_{BA}(f) \approx i\, t_P \, \sin(2\pi f R/c) \;\; \mathrm{sgn}(f) \, \sin(2\pi f L_\perp/2c) \times [2(L_\perp/c)^2 \, \mathrm{sinc}^2(\pi f L_\perp/2c)]$$

correlation of flat “boxcar” responses at scale $L_\perp$





CQG 35: 204001

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.*

$$\tilde{S}_{BA}(f) = \sum_n 2\beta_n \left[2\,(L_n/c)^2\,\mathrm{sinc}^2(\pi f L_n/2c)\right]\; i\,t_P\,\sin(2\pi f R/c)\;\sin(\pi f L_n/c)\;\mathrm{sgn}(f)$$

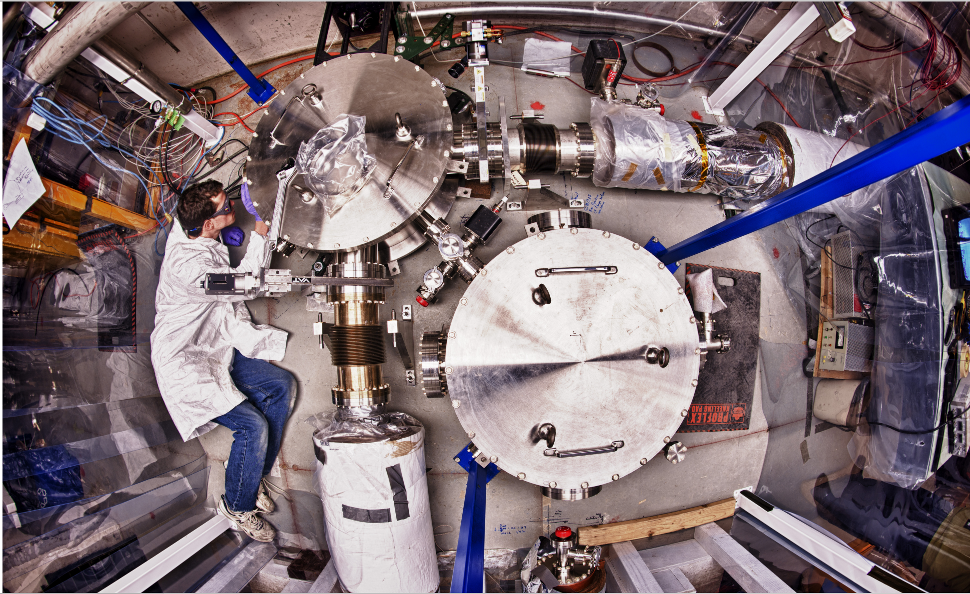
$$\approx \sum_{n=1}^{4} 0.291\, i\, t_P\, \beta_n \left[\frac{38.9\mathrm{m}}{c}\right]^2 \frac{|f|}{15.4\mathrm{MHz}}\,\frac{R}{0.90\mathrm{m}}\left(\frac{L_n}{19.5\mathrm{m}}\right)^2 \mathrm{sinc}^2\left[\pi\frac{f}{15.4\mathrm{MHz}}\frac{L_n/2}{19.5\mathrm{m}}\right]\;\sin\left[\pi\frac{f}{15.4\mathrm{MHz}}\frac{L_n}{19.5\mathrm{m}}\right]$$

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

Can we really measure rotation at this level of sensitivity?

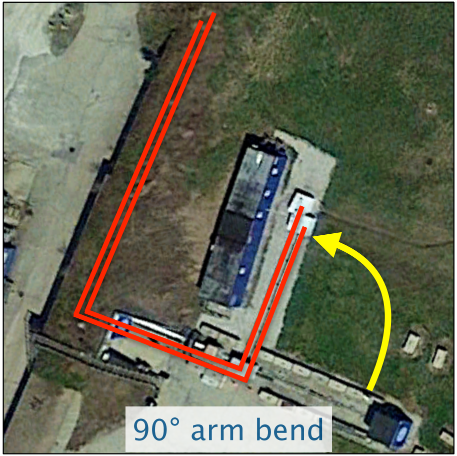
Measuring the rotation of the Earth with light traveling in two directions around a loop.
Albert Michelson, winter 1924, suburban Chicago.

Can we really measure rotation at this level of sensitivity?



First-generation Holometer (2011-2016)

Second-generation Holometer (2017-present)



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

Preview of Preliminary Data and Systematics

Future
Research Program
in Cosmology

The cosmological constant

Holographic correlations may reformulate the SM field vacuum, determine its emergent gravity!

- We used Planck bandwidth world lines. They cannot be perfect "lines" of arbitrarily fine resolution.
- Relationships between them at separation $c\tau$ are a fraction t_P/τ of the available information, and their mutual entanglement must be consistent with the total bandwidth for each world line.
- In a volume of radius $c\tau_0$, world lines "emerge" from holographic quantum system with localization:

$$ct_P\,(\tau_0/t_P)^{1/3}$$

- In a system of size $10^{61}\ell_P$ (cosmic horizon), world lines localized at the $10^{20}\ell_P$ 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}!

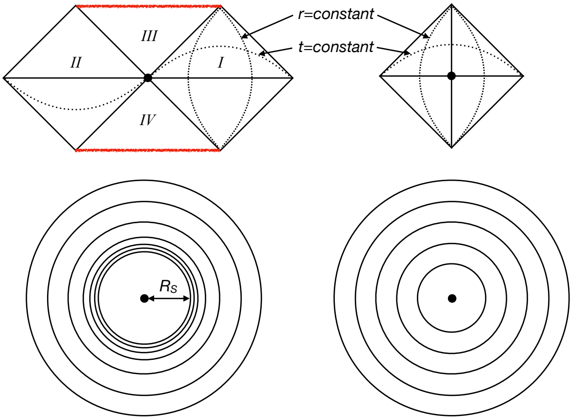
PRD **95**, 104050 • CQG **35**, 204001 • arXiv:1804.00070

Information delocalized across **the whole horizon — a single quantum object!**

Antipodes antisymmetrically identified with each other, with a reversal of time.

Their field states: Entangled radial components due to gravitational backreaction / dragging (e.g. incoming p with outgoing u). Spherical harmonics expansion has ***odd values of ℓ only***.

Matched null cone foliations between this BH and distant asymptotically flat space in our model: Same time antisymmetry associated with oppositely directed null trajectories!

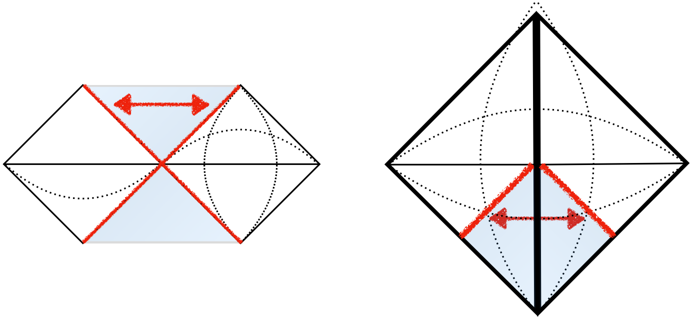


If the vacuum of space-time has virtual black holes, its structure may be very different from AdS/CFT.

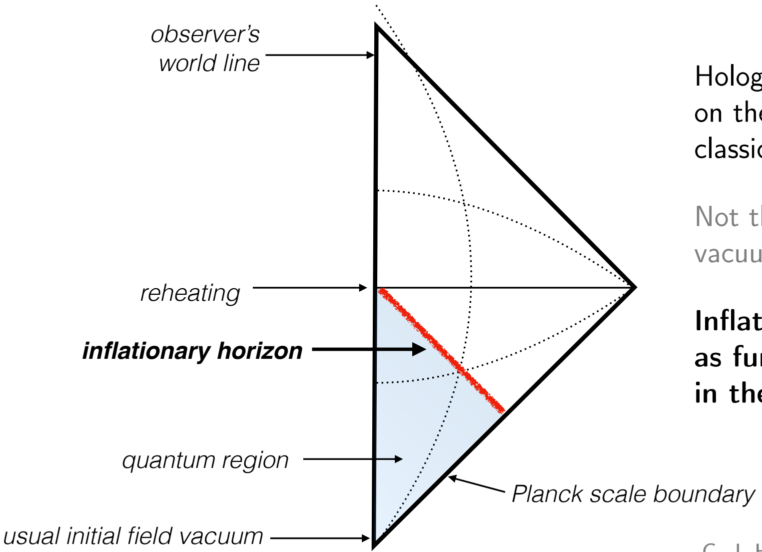
G. 't Hooft, Found. Phys. 46: 1185, arXiv:1605.05119, Found. Phys. 48: 1134, arXiv:1804.05744, arXiv:1809.05367

Perhaps inflation works the same way!

- Black hole and cosmological "singularities" lie behind the horizon.
- For an observer on the outside, the entire BH horizon or **inflationary horizon is a single quantum object**. Antipodes are antisymmetrically identified.
- As Wheeler prefigured, geometrical states live on null surfaces. *"Spukhafte"* correlations of space-time everywhere on the horizon — organized via causal diamonds, not 3+1 D points on a background.



New quantum-classical boundary on the inflationary horizon



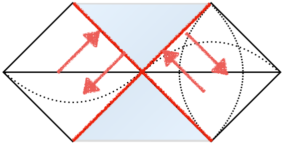
Holographic correlations freeze out on the inflationary horizon, into the classical "background."

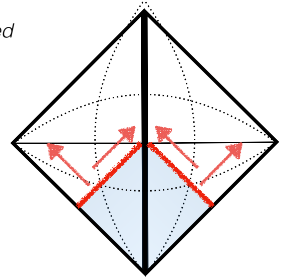
Not the standard quantum field vacuum fluctuations.

Inflationary perturbations arise as fundamental quantum noise in the emergence of locality.

C. J. Hogan, arXiv:1811.03283 (PRD, in print)

Everything inside the horizon is entangled as viewed from everywhere outside

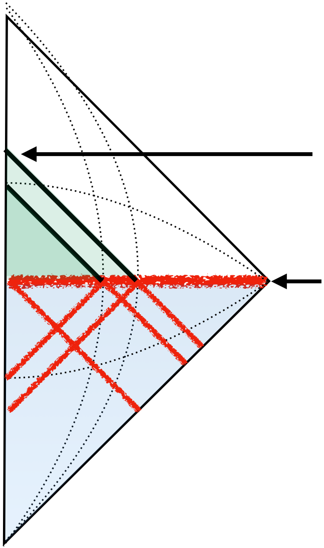




black hole emits omnidirectional particle/wave states	horizon emits omnidirectional curvature-perturbation states
horizon entangles particle states at different times and directions	horizon entangles perturbations at different times and directions
incoming, outgoing states interfere nonlocally, antipodally	incoming, outgoing states interfere nonlocally, antipodally
reacts back on black hole metric antisymmetrically	forms classical perturbations antisymmetrically

Cosmology slides
adapted from C. J. Hogan

Emergence of a whole system during inflation



Distant states become determinate relative to each observer as its classical horizon grows

Inflationary horizon of every observer ends at reheating

More distant universe is still in a superposition until it re-enters the horizon

Superposition includes different cosmic backgrounds and frames

C. J. Hogan, arXiv:1811.03283 (PRD, in print)

- How large are the quantum fluctuations in this emergence?
- Scalar curvature perturbation $\sim$ Fractional variance in clock rate on horizon
- Assume standard quantum uncertainty with Planck bandwidth. Emergent dimensionless curvature perturbations at horizon radius c/H are:

$$\langle \Delta\tau^2 \rangle = \tau t_P \qquad \langle \Delta^2 \rangle \equiv \langle \Delta\tau^2 \rangle / \tau^2 = t_P/\tau \approx H t_P$$

- Limited information content leads to larger perturbations. Dominant over standard perturbations in slow roll inflation, where the usual scaling is $\Delta^2_{S,\delta\phi} = \frac{1}{8\pi^2} H(\phi_0)^2 t_P^2 \epsilon^{-1}$
- This is still entirely consistent with current data for an effective potential of $V \propto \phi^4$. Inflation is quite overfitted!

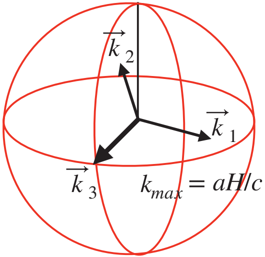
A general directional antisymmetry

- A statistically isotropic scalar distribution of zero mean is odd under reflections!

$$\Delta(\vec{x}) = -\Delta(-\vec{x}) \quad \text{and} \quad \tilde{\Delta}(\vec{k}) = -\tilde{\Delta}(-\vec{k})$$

(real odd pattern in x, imaginary odd spectrum in k)

- For *any* observer in its cosmic rest frame, primordial curvature perturbation is antisymmetric and vanishes at the origin.
- General to the emergence of locality in a background-independent *relational* space-time!
    - Classicality is organized by all observers agreeing on differential measurements in causal diamonds.
- A set of vectors that spans three dimensions has a unique invariant scalar product that is antisymmetric.



Covariant scalar from emergent wave vectors: $\mathscr{E}_{4D} \propto \epsilon_{\kappa\lambda\mu\nu} k_1^\kappa k_2^\lambda k_3^\mu u_\phi^\nu$

Use a projection onto observer's "inflaton frame," $u_\phi^\nu \propto (1,0,0,0)$

Prediction: a scale-invariant antisymmetric bispectrum should show a large correlation of different directions.

$$\mathscr{B} = \langle \mathscr{E}(\overrightarrow{k}_1, \overrightarrow{k}_2, \overrightarrow{k}_3)\ \tilde{\Delta}(\overrightarrow{k}_1)\tilde{\Delta}(\overrightarrow{k}_2)\tilde{\Delta}(\overrightarrow{k}_3)\rangle$$

$$\langle \mathscr{B}(\mathscr{E})^2 \rangle \approx \langle \tilde{\Delta}^2 \rangle^3 \ \text{ at } |\mathscr{E}| = \mathcal{O}(1)$$

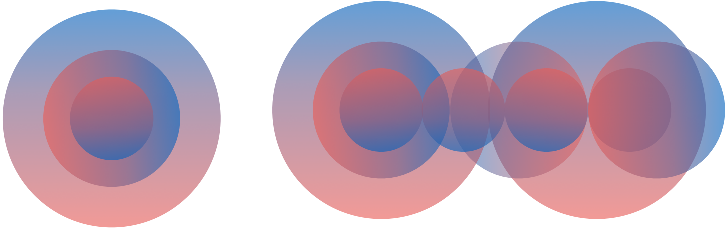
In standard inflation, local momentum conservation of field mode interactions allow correlation only among coplanar triplets, so this bispectrum is zero (even for nongaussian theories)!

C. J. Hogan, arXiv:1811.03283 (PRD, in print)

A picture of "*spukhafte*" dipole modes

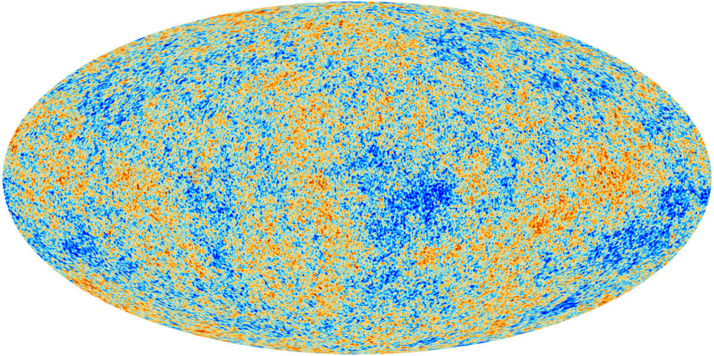
Different scales freeze out with different orientations

whole distribution is statistically isotropic and scale invariant



Maybe we have been staring at a *"spukhafte"* pattern all along!

Cosmic structure is a relic of quantum fluctuations during inflation

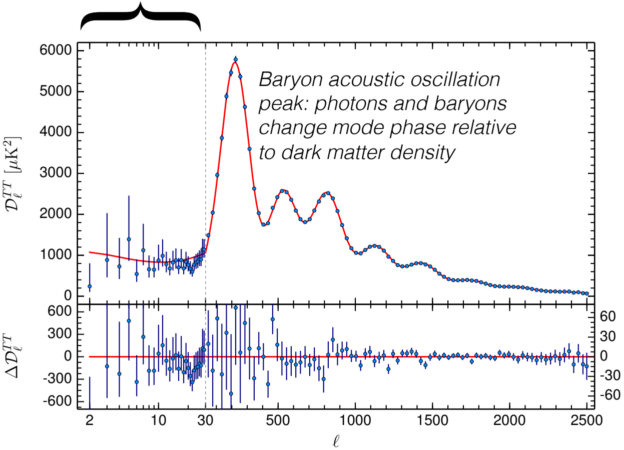


The specific pattern is an intact image of a primordial quantum state

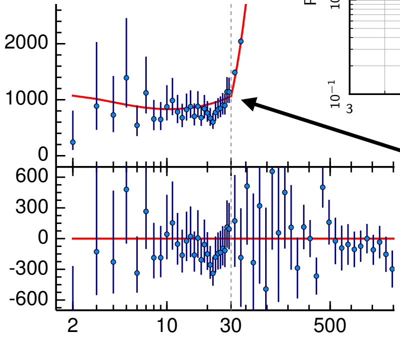
Its correlations contain information about the quantum state

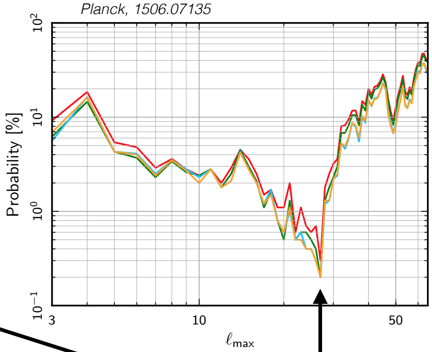
CMB temperature maps primordial potential in all directions
Antisymmetry should be nearly intact in TT spectrum at largest scales

Planck TT band power



This data is always processed in power units. Very few people have ever seen the phase information!





Odd multipoles dominate up to

$$\ell \approx 28$$

Maybe the quadrupole is actually zero!

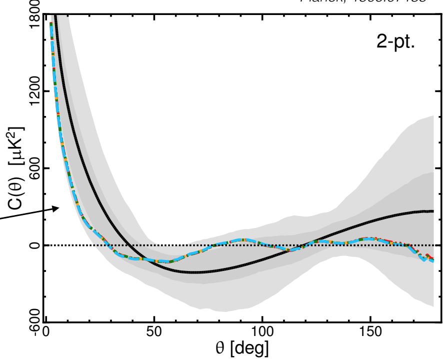
Primordial dipole is predicted to be anomalously large, but cannot be observed because of the kinematic dipole

Primordial quadrupole is predicted to be negligible
Largest scale anisotropy should be close to octupolar

This is consistent with data, unexpected in standard model

Planck, 1506.07135

Explains a longstanding puzzle: anomalously small two-point temperature correlation function at large angular separation



A bizarre coincidence in alignment?

How small could the primordial quadrupole be?
Measured quadrupole is very closely aligned with the octupole!
Could it be dominated by leakage from the octupole?

WMAP (Bennett et al. 2011)

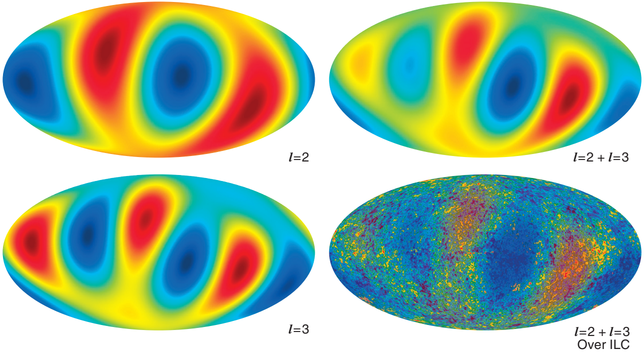


Figure 14. $l = 2$ quadrupole and $l = 3$ octupole maps are added. The combined map is then shown superposed on the ILC map from Figure 2. Note that the quadrupole and octupole components arrange themselves to match the cool fingers and the warm regions in between. The fingers and the alignment of the $l = 2$ and $l = 3$ multipoles are intimately connected.

Many small anomalies. Perhaps there is a common explanation!

How many $2.5 \sim 3\,\sigma$ anomalies do we need before we decide we are missing something?

p-values of various anomalies, from 1506.07929

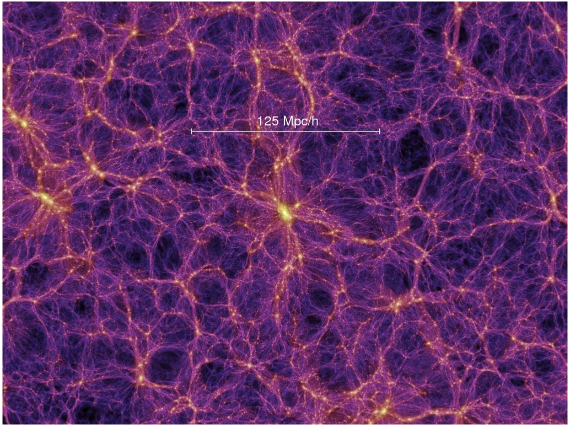
feature	p-value	data
in angular space		
low variance ($N_{\text{side}} = 16$)	$\leq 0.5\%$	Planck 15
2-pt correlation $\chi^2(\theta > 60^\circ)$	$\leq 3.2\%$	Planck 15
2-pt correlation $S_{1/2}$	$\leq 0.5\%$	Planck 15
2-pt correlation $S_{1/2}$	$\leq 0.3\%$	Planck 13 & WMAP 9yr
2-pt correlation $S_{1/2}$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

Primordial correlations in gravitational potential remain mostly intact until a structure goes nonlinear

Potential can be probed by galaxy density in the linear regime, on scales << CMB

Orbital motion mixes away primordial antisymmetry on scales smaller than the cosmic web

$$L_* \approx 40\text{Mpc}$$



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

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