A Multimodal Probe for General Holographic Coherence of Quantum Space-Time States on Causal Horizons

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Nathaniel Selub (UC Berkeley) **Robert H Hadfield** (Univ. of Glasgow) **Karim P Y Thébault** (Univ. of Bristol)

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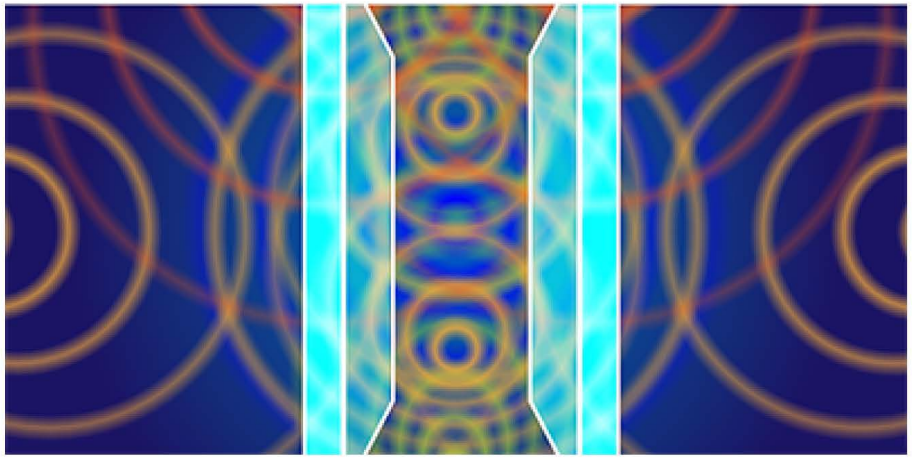
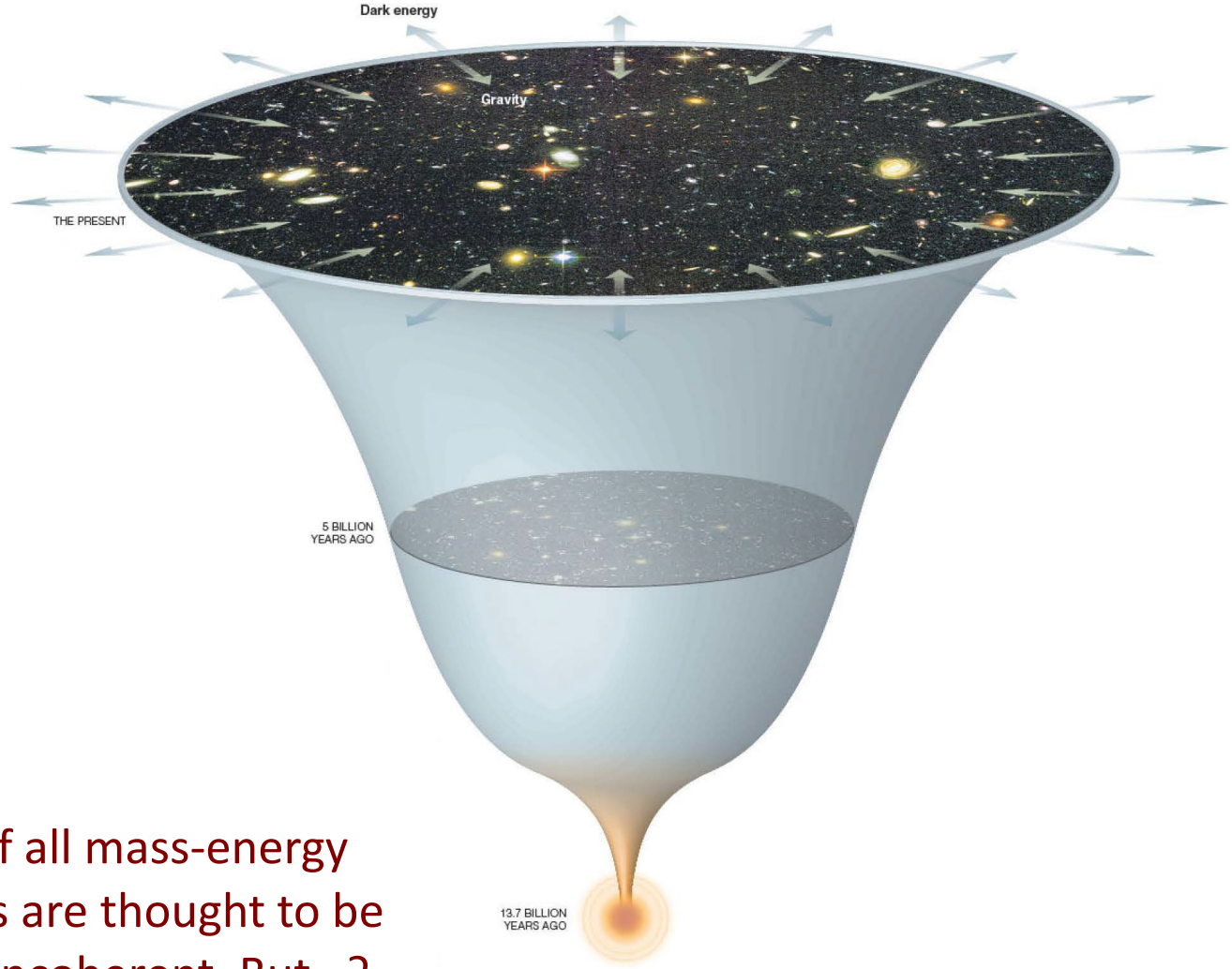
PRIFYSGOL CAERDYDD

Vacuum energy is huge in standard theory

- 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.



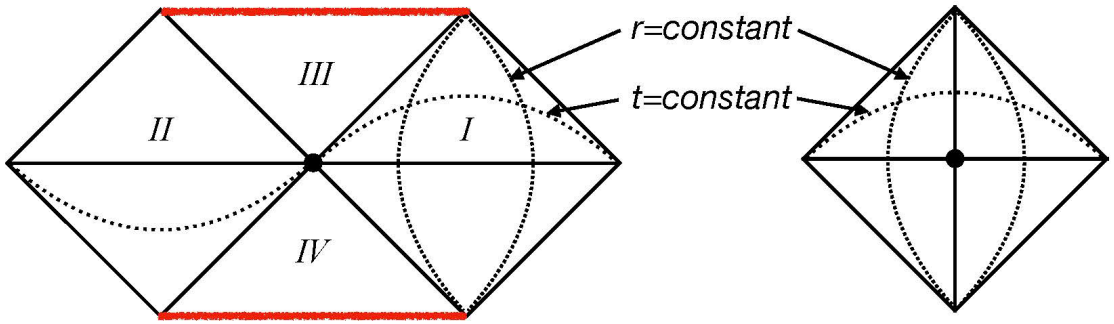


Even the “small” value of “dark energy” is 70% of all mass-energy in the universe. Effects from vacuum fluctuations are thought to be undetectable only because they are completely incoherent. But…?

Holographic entropy in flat space-time: IR problem from information of background

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!*

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

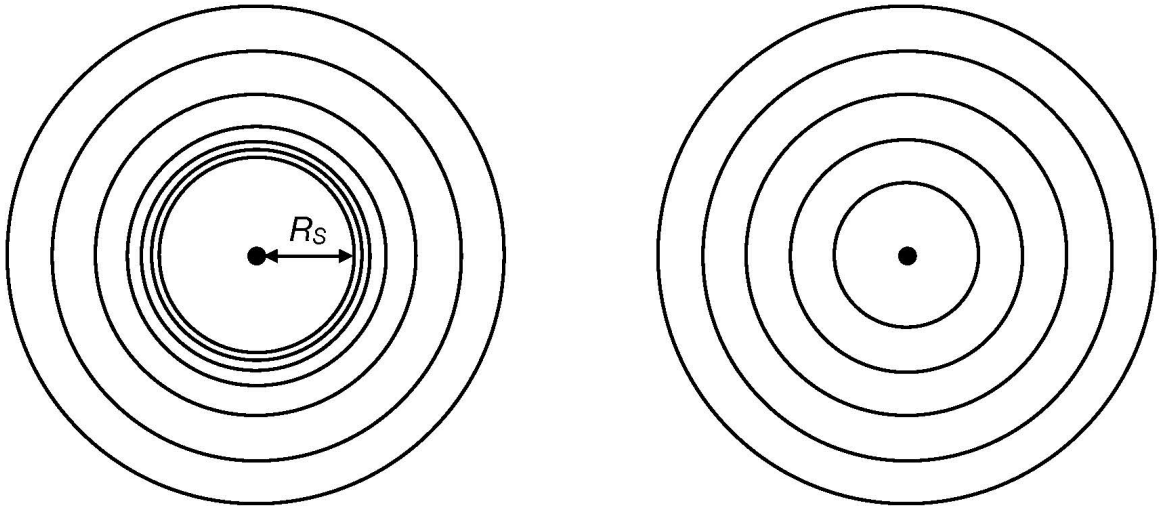


In local QFT with a definite background, a system of scale R and cutoff m has total modes

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

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

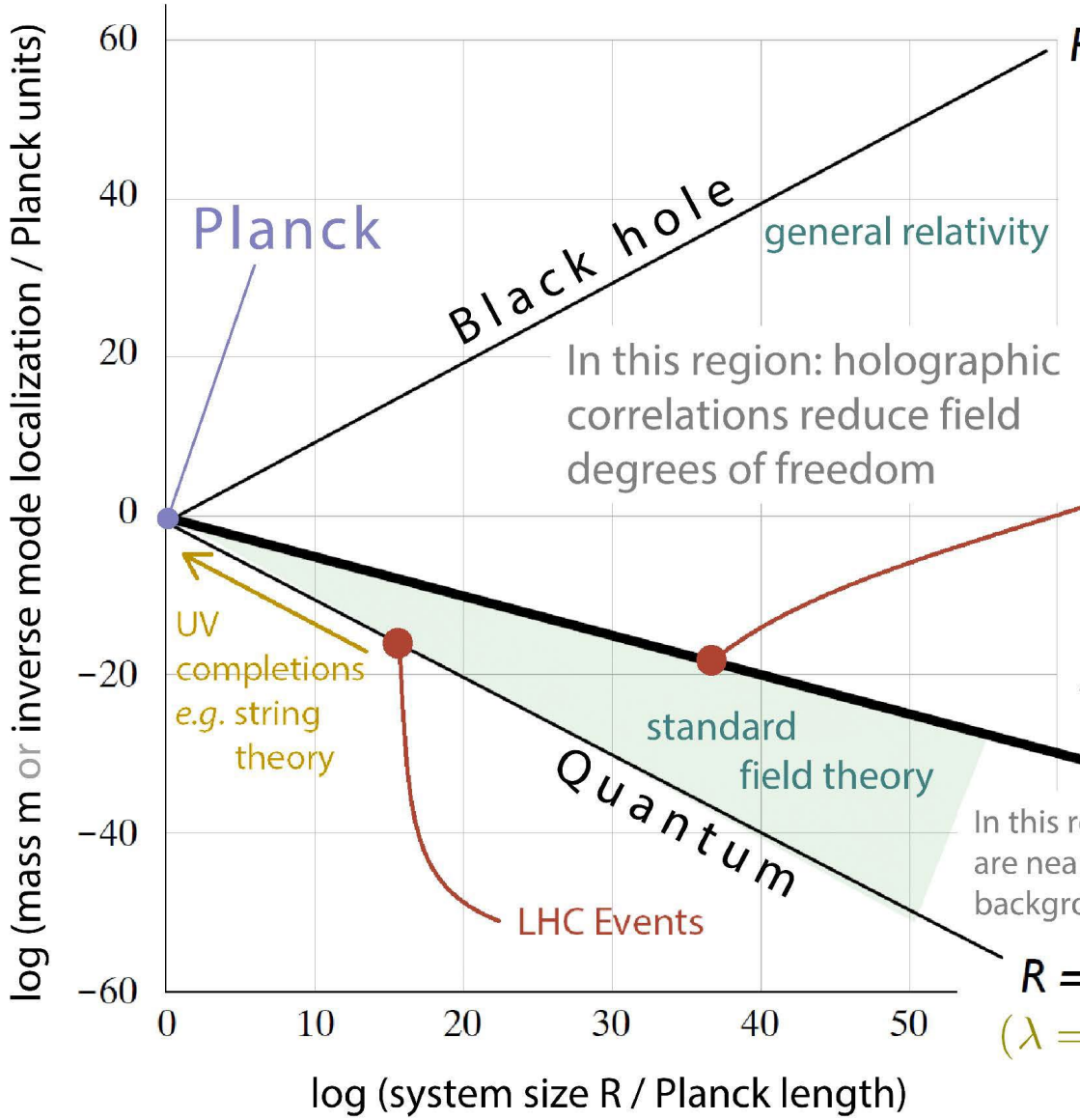
CKN, PRL **82**, 4971



Cosmological constant = IR boundary condition on total degrees of freedom!

Banks & Fischler, 1811.00130

The background needs quantum correlations at the regime of IR bound set by CKN



$R = 2M \quad (R = 2GM/c^2)$

Geometry changes quantum phase over a macroscopic space-time volume ~R
e.g. ~100 meters

by RMS indeterminacy ~$R^{1/2}$
e.g. ~30 attometers

In this region: holographic correlations reduce field degrees of freedom

Total number of states ~$R^{3/2} \ll R^2$

Holographic correlation ~ field localization at generalized Chandrasekhar radius

$R \sim m^{-2}$ ——— *Infrared paradoxes*

In this region: field states are nearly independent of background space (as usual)

Virtual field states in a large volume have mass exceeding the gravitational binding energy

$R = m^{-1}$
$(\lambda = hc/E)$

C. Hogan, arXiv:1412.1807

Causal structure of background “holistically” coupled to all quantum states via gravity

> “[because of] the holistic nature of renormalization theory...
> an individual mode will have no way of knowing whether its own subtraction is correct unless it ‘knows’ how the subtractions are being done for all other modes.”

Hollands and Wald, Gen. Rel. Grav. **36**, 2595

Quantum Field Theory Is Not Merely Quantum Mechanics Applied to Low Energy Effective Degrees of Freedom

QFT insists that vacuum energy must be subtracted in local and covariant manner, but renormalization assumes a globally Minkowskian background, which cannot be correct.

Holography for all causal boundaries: Large correlations in space-time superpositions

Even a flat space-time background has a massive amount of information.

Superpositions of causal structure from the holographic information or energy of the vacuum lead to **uncertainties in space-time that are not Planck scale but rather Planck random walk scale ("holographic noise")**.

Hypothesis:

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

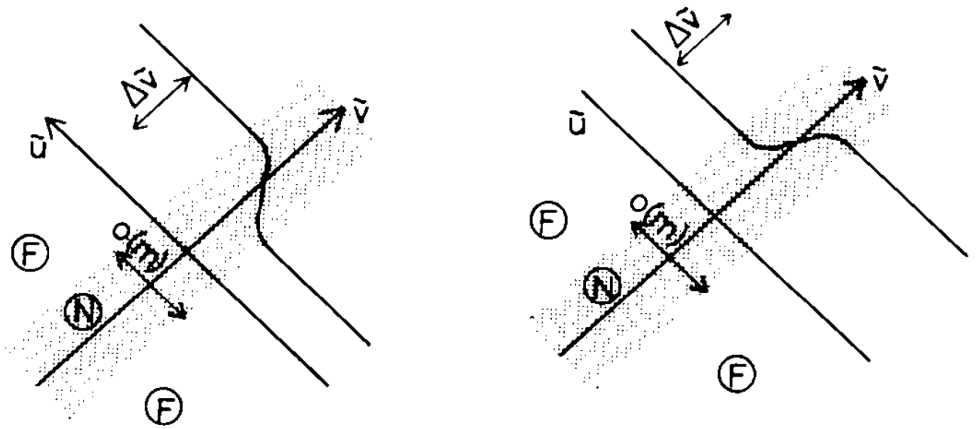


Fig. 2. The path of a null geodesic in the $(\hat{u}, \hat{v})$ plane as described by eq. (2) for $m \ll 1$, $\rho_0 \gg m$, and (a) $\rho_0 < 1$, (b) $\rho_0 > 1$. The near region N and the far region F, as well as the shift $\Delta\hat{v}$, are indicated.

Dray & 't Hooft, Nucl. Phys. B **253**, 173

To get correct scale of correlations, all causal horizons have coherent quantum states

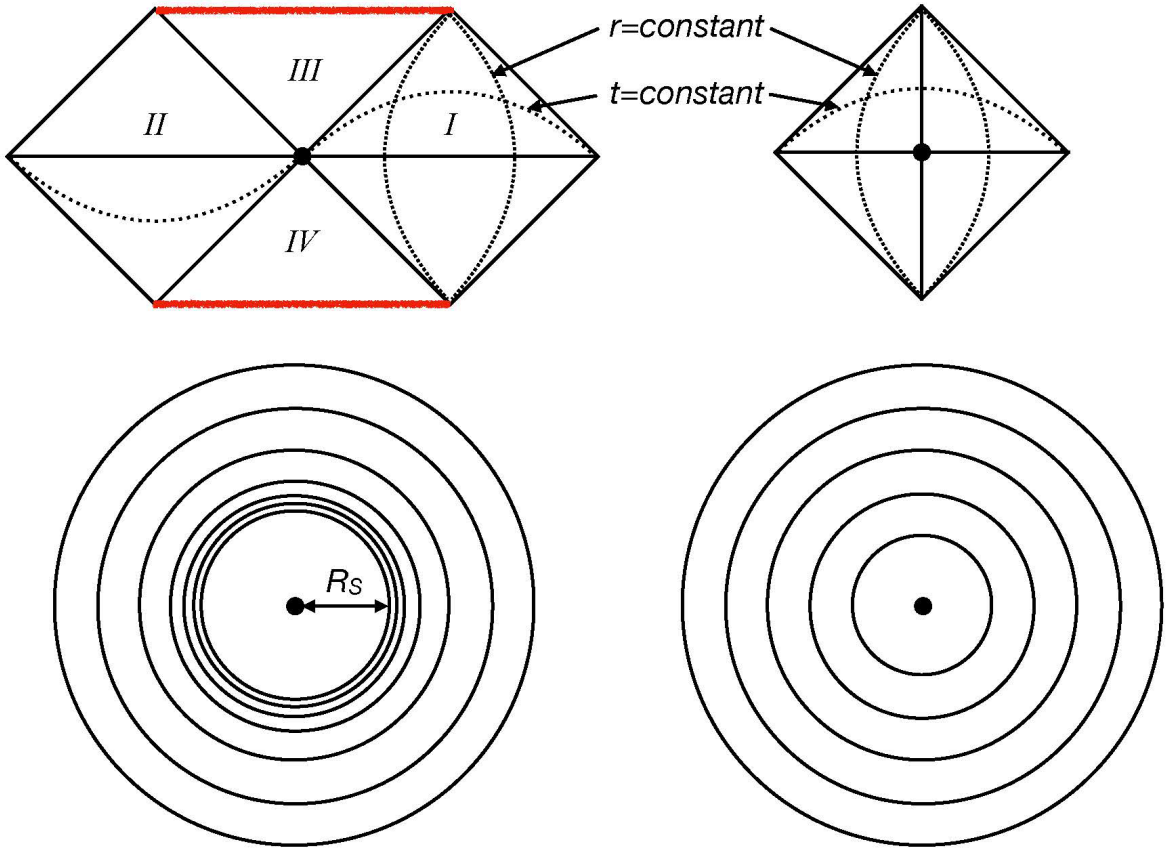
Standard quantum limit for mass m, duration τ

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

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.



This is a random walk with Planck steps!

Hogan, 2007-2023 / Hogan & Kwon, 2014-2023

also see Marolf, Springer Proc. Phys. **98**, 99 (hep-th/0312059)

A new law of holography, universal to all general horizons?

First law of entanglement entropy

$$\delta S = \delta\langle K\rangle \quad \text{where} \quad \rho = \frac{e^{-K}}{\mathrm{Tr}(e^{-K})}$$

Banks-Zurek finds a new universal conjecture

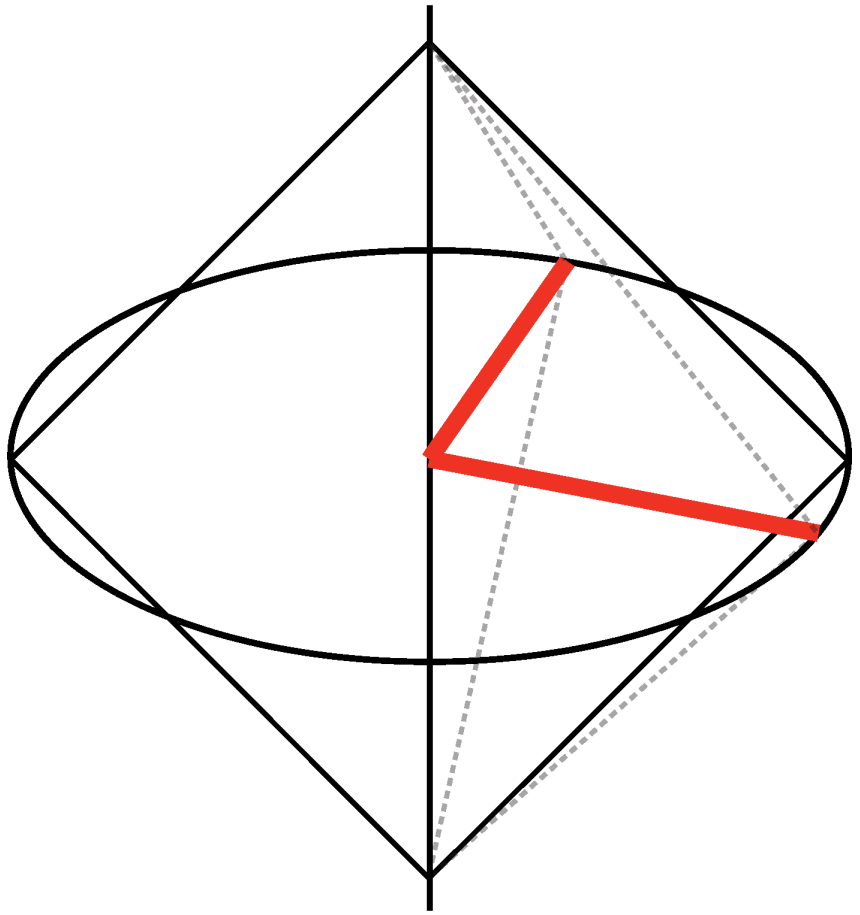
$$\langle \Delta K^2\rangle = \langle K\rangle = S = \frac{A}{4G}$$

PRD **104**, 126026 (2021)

Holographic dimensional reduction requires large scale correlations!

In AdS/CFT, the AdS scale controls the nonlocality, the information density, and the UV-IR relation.

This universality replaces the AdS scale with the size of a causal diamond in flat space-time.



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A roadmap:

Cohen, **Kaplan**, and **Nelson**, PRL **82**, 4971 (1999)
Effective Field Theory, Black Holes, and the Cosmological Constant

Carlip, PRL **82**, 2828 (1999)
Black hole entropy from conformal field theory in any dimension

Solodukhin, Phys Lett B **454**, 213 (1999)
Conformal description of horizon's states

Casini, **Huerta**, and **Myers**, JHEP **2011**, 036 (2011)
Towards a derivation of holographic entanglement entropy

Jacobson and **Visser**, SciPost Physics 7, 079 (2019)
Gravitational thermodynamics of causal diamonds in (A)dS

Banks and **Zurek**, PRD **104**, 126026 (2021)
Conformal description of near-horizon vacuum states

Future speculations: Banks, 2306.07038
Fun accessible bonus paper: Banks, 2309.07203

Why is this infrared thermodynamic effect not captured by effective field theory?

"Can I just say something about all these [graviton] effective field theory arguments? I think they are technically incorrect. **Okay, so you want to use unitarity. That means you have to use a non-Lorentz invariant gauge**....

.... **The only gauge invariant things you calculate in gravity are scattering amplitudes at infinity. This, by definition, is a finite-time, finite-space observable.** We don't know how to define that in standard [gravitational EFT]. **And the gauge you would think of using ... is a gauge where the time slices stay within a causal boundary, within a causal diamond. That gauge is not translation invariant.**

So even if you could think about some way to do the calculation in gravitational EFT, you'd have to be doing it in a non-translation invariant, non-Lorentz invariant gauge which was unitary. I don't think anybody's ever set that calculation up...."

***Tom Banks**, post-talk discussion, KITP program on Origin of the Vacuum Energy (July 31, 2019)*

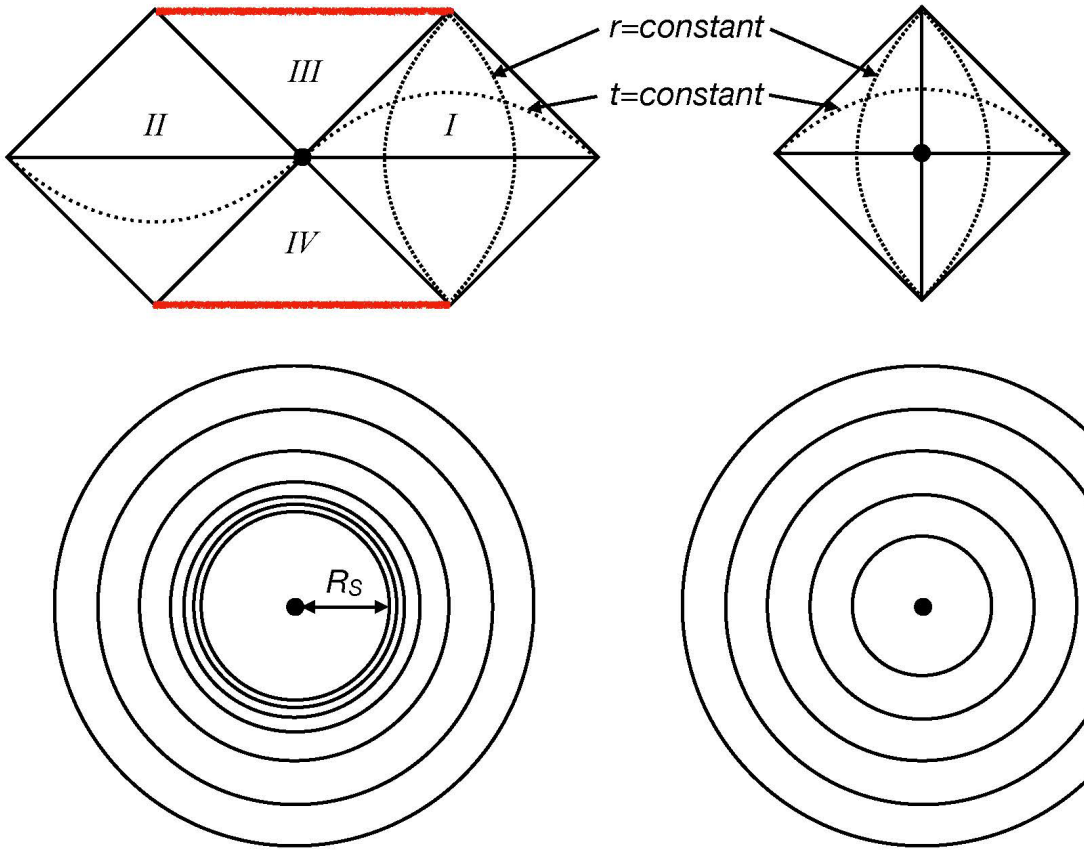
’t Hooft’s algebra for black hole information

Coherent states on the BH horizon due to gravitational back reaction / frame dragging

$$[u^{\pm}_{lm},\, p^{\mp}_{l'm'}] = i\delta_{\ell\ell'}\delta_{mm'} \qquad [u^{\pm}_{lm},\, p^{\pm}_{l'm'}] = 0$$

$$u^{-}_{\rm out} = \frac{8\pi G}{l^2+l+1}p^{-}_{\rm in} \qquad u^{+}_{\rm in} = -\frac{8\pi G}{l^2+l+1}p^{+}_{\rm out}$$

$$[u^{+}_{lm},\, u^{-}_{l'm'}] = i\frac{8\pi G}{l^2+l+1}\delta_{ll'}\delta_{mm'}$$



Angular correlation of fluctuations of holographic boundaries

’t Hooft: Coherent states on BH horizon from gravitational back reaction / frame dragging

$$[u^{\pm}_{lm},\, p^{\mp}_{l'm'}] = i\delta_{\ell\ell'}\delta_{mm'} \qquad [u^{\pm}_{lm},\, p^{\pm}_{l'm'}] = 0$$

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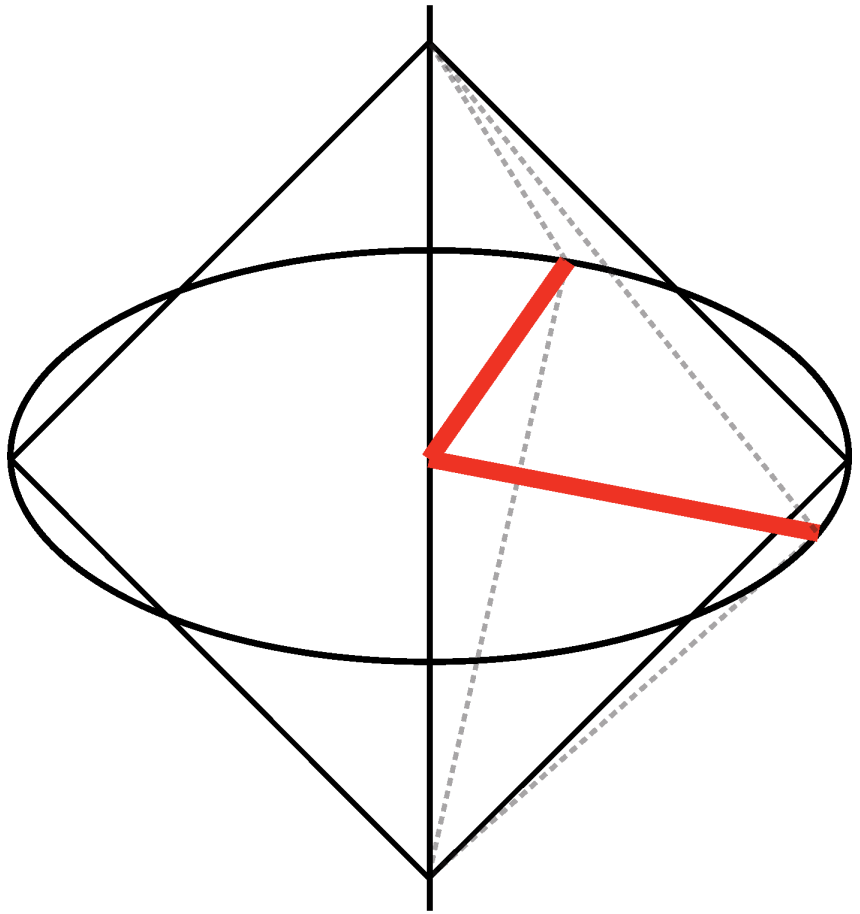


Verlinde-Zurek model maps these spherical harmonic modes onto causal diamonds in flat space-time via topological BH coordinates

$$\left\langle \delta u^{-}(\mathbf{r}_1)\,\delta u^{+}(\mathbf{r}_2)\right\rangle = \frac{1}{\sqrt{2\pi}}\,\ell_P L\cdot \mathbf{G}(\mathbf{r}_1,\,\mathbf{r}_2) \qquad \mathbf{G}(\mathbf{r}_1,\,\mathbf{r}_2) = \sum_{l,m}\frac{Y_{l,m}(\mathbf{r}_1)\,Y^{*}_{l,m}(\mathbf{r}_2)}{l^2+l+1}$$

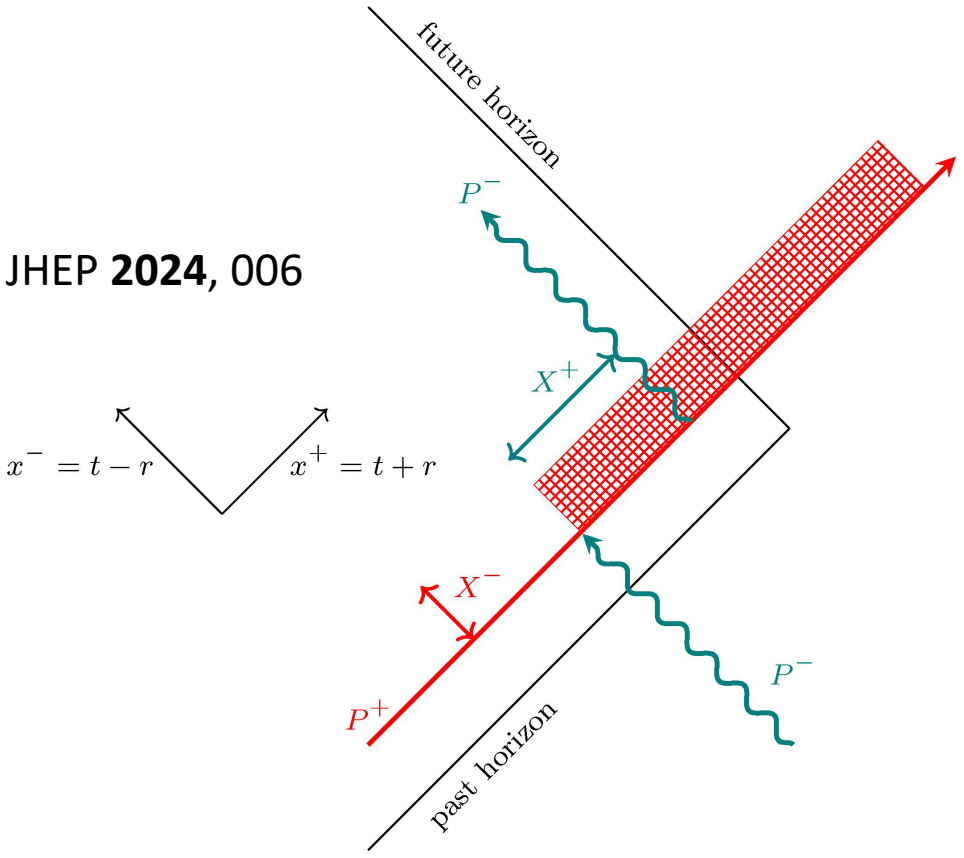
VZ, PLB **822**, 136663

CFT & entanglement entropy (Banks & Zurek, PRD **104**, 126026) / **Shock waves from vacuum states** (VZ, PRD **106**, 106011)
Fluid-gravity correspondence (JHEP **2024**, 331) / **Iyer-Wald (Noether) charges** (PRL **134**, 121501) / also see: 2311.18049

The measurement problem in quantum space-time

- This is a commutator between ***operators***.
- For an observational signature, modeling the quantum ***state reduction*** from the ***measurement*** is necessary to derive the detector response.
- The only experimental predictions from Zurek so far use effective field theory to map these onto classical metric fluctuations — these 1D heuristic models do NOT test all other versions of the theory!
- Any effective theory that is indistinguishable from a classical stochastic fluctuation, isotropic with a finite coherence scale, by construction cannot be holographic.

JHEP **2024**, 006



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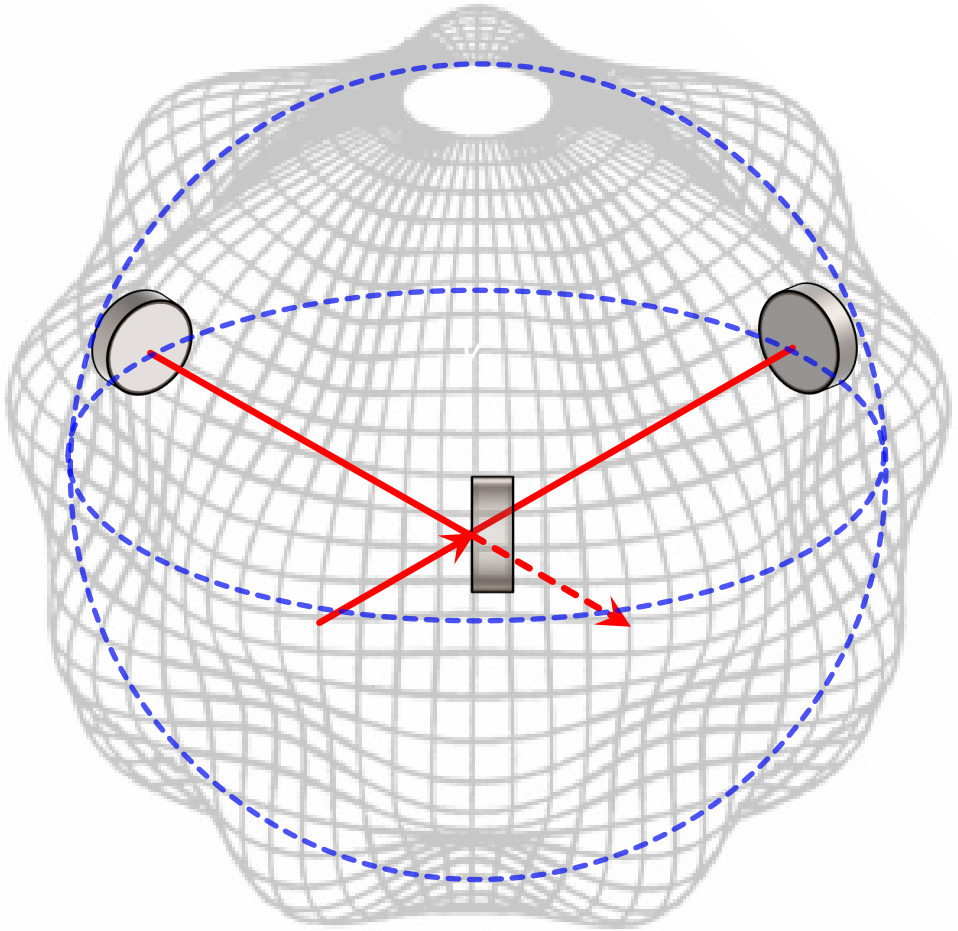
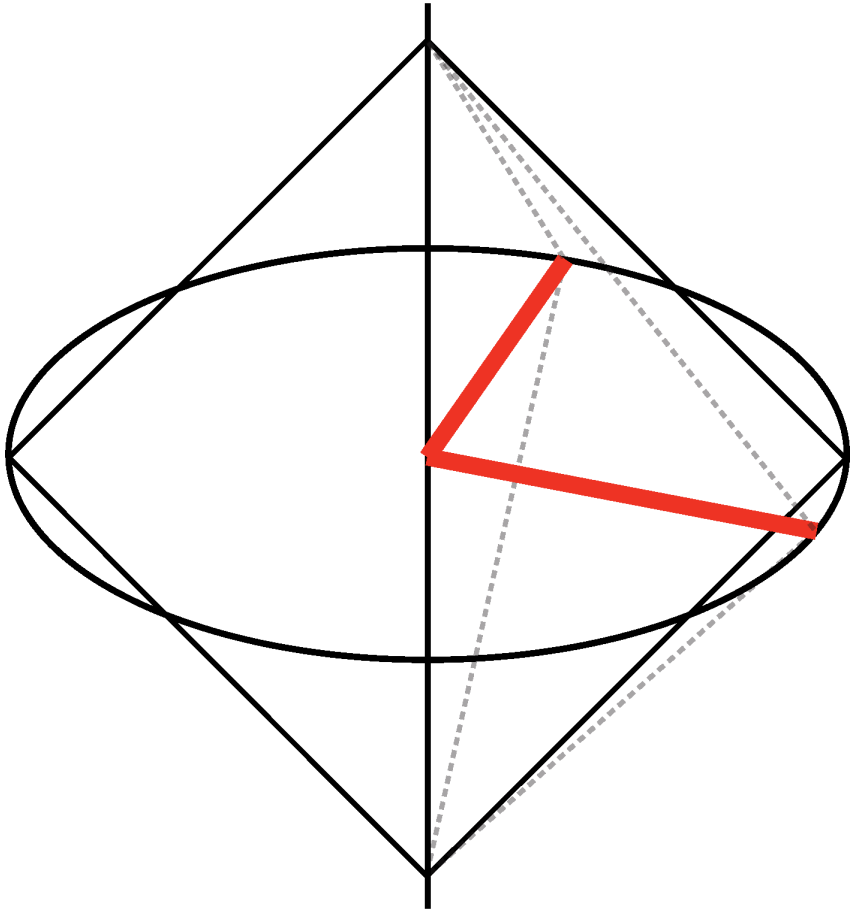
A causal diamond has coherent states like a hydrogen atom





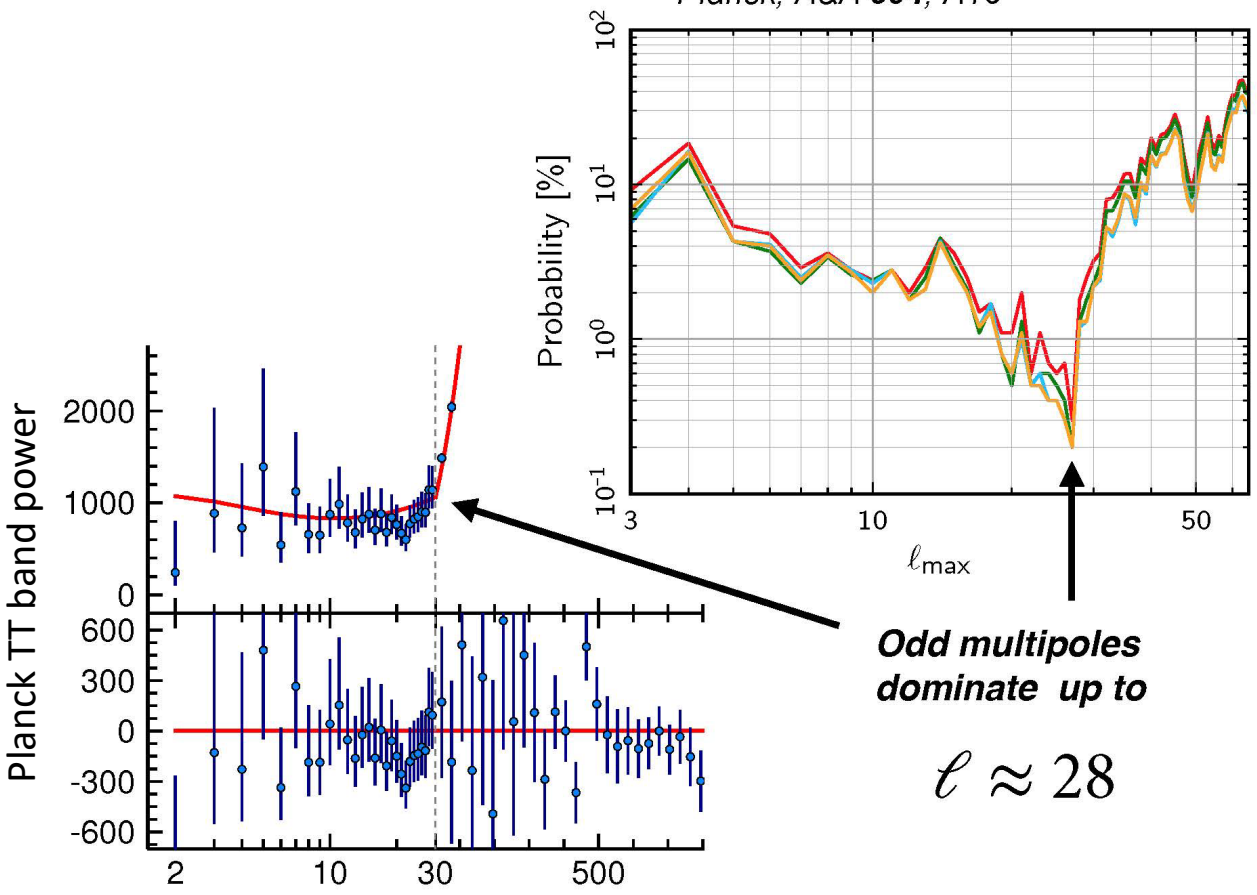
’t Hooft: odd modes only

VZ: includes all modes

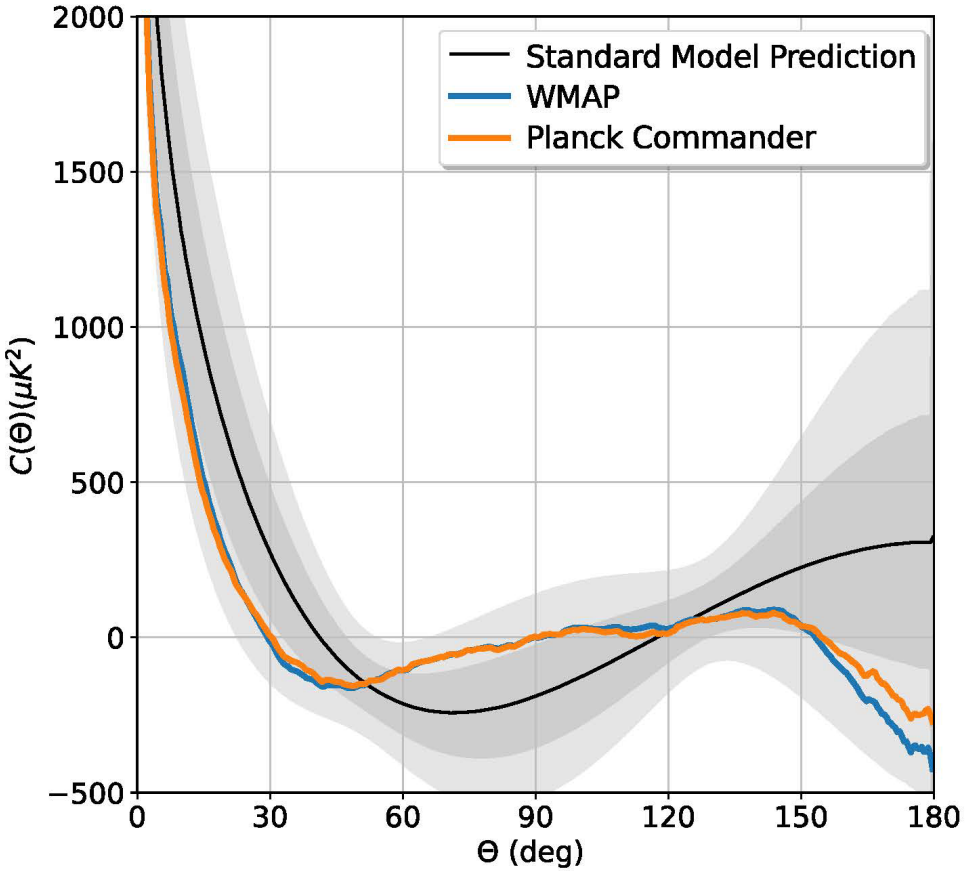
CMB anomalies: holographic symmetries on the inflationary horizon?

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

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



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



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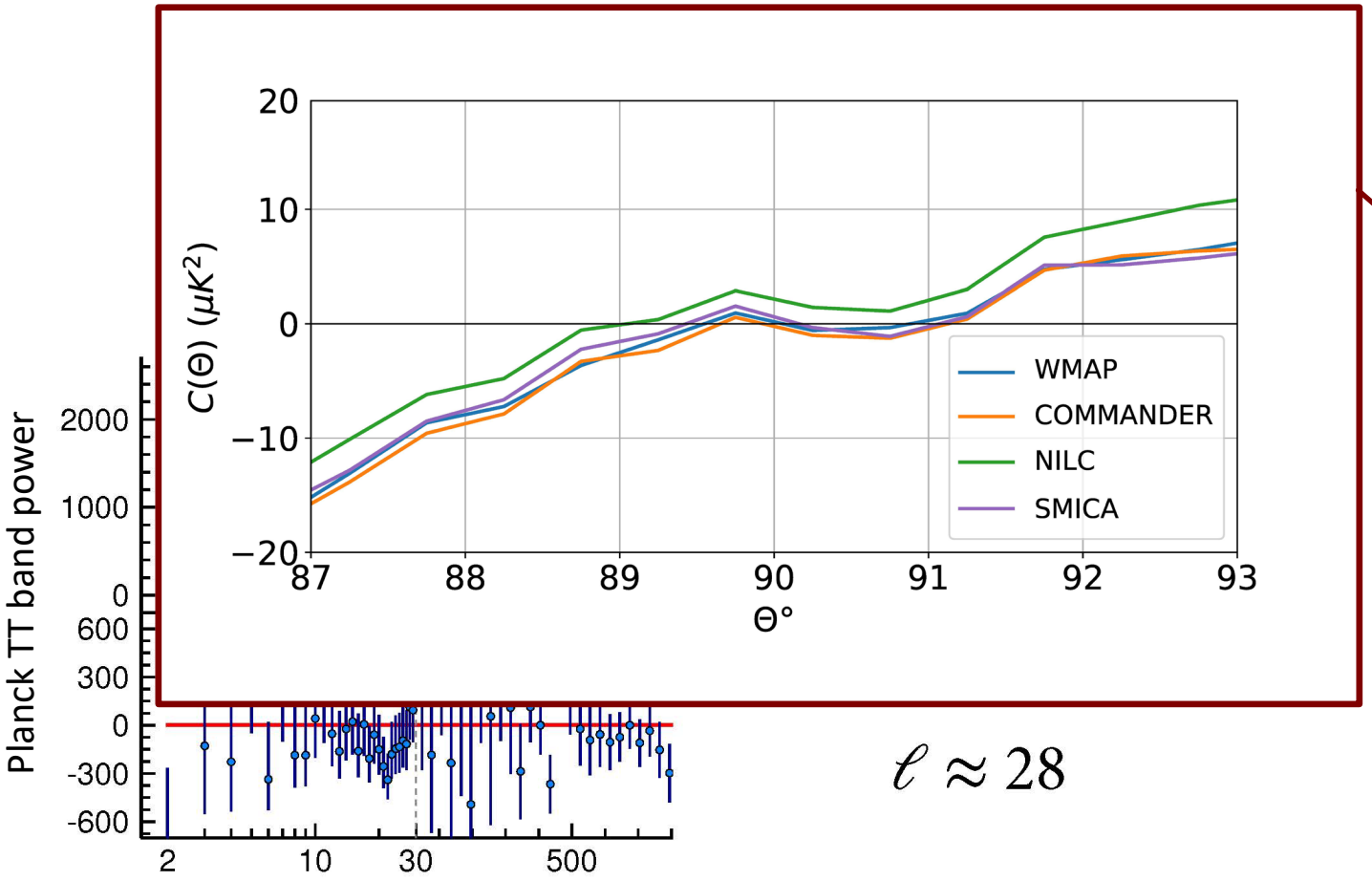
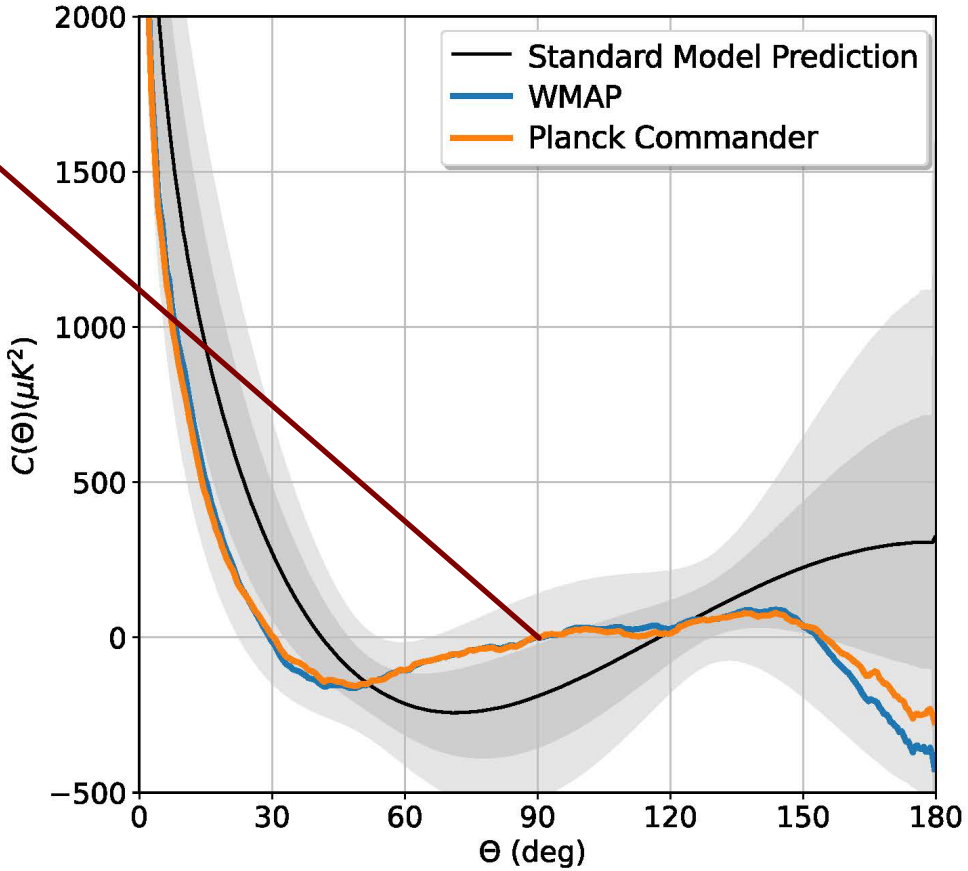


$\ell \approx 28$

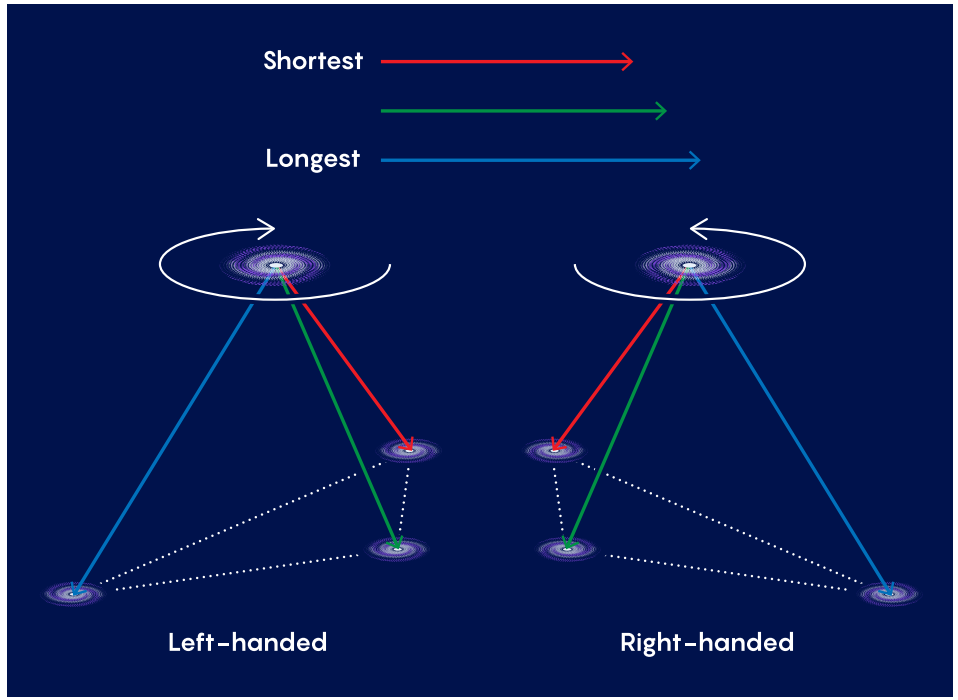
Hagimoto, Hogan, Lewin, and Meyer, ApJL **888**, L29



Parity violation in large-scale structure?

7.1σ — Hou, Slepian, and Cahn, MRNAS **522**, 5701

2.9σ — Philcox, PRD **106**, 063501 & PRL **131**, 181001



Quantum space-time modes must follow causal boundaries

Penrose diagram of standard quantum inflation:
initial coherent mode states extend (acausally) to spacelike infinity

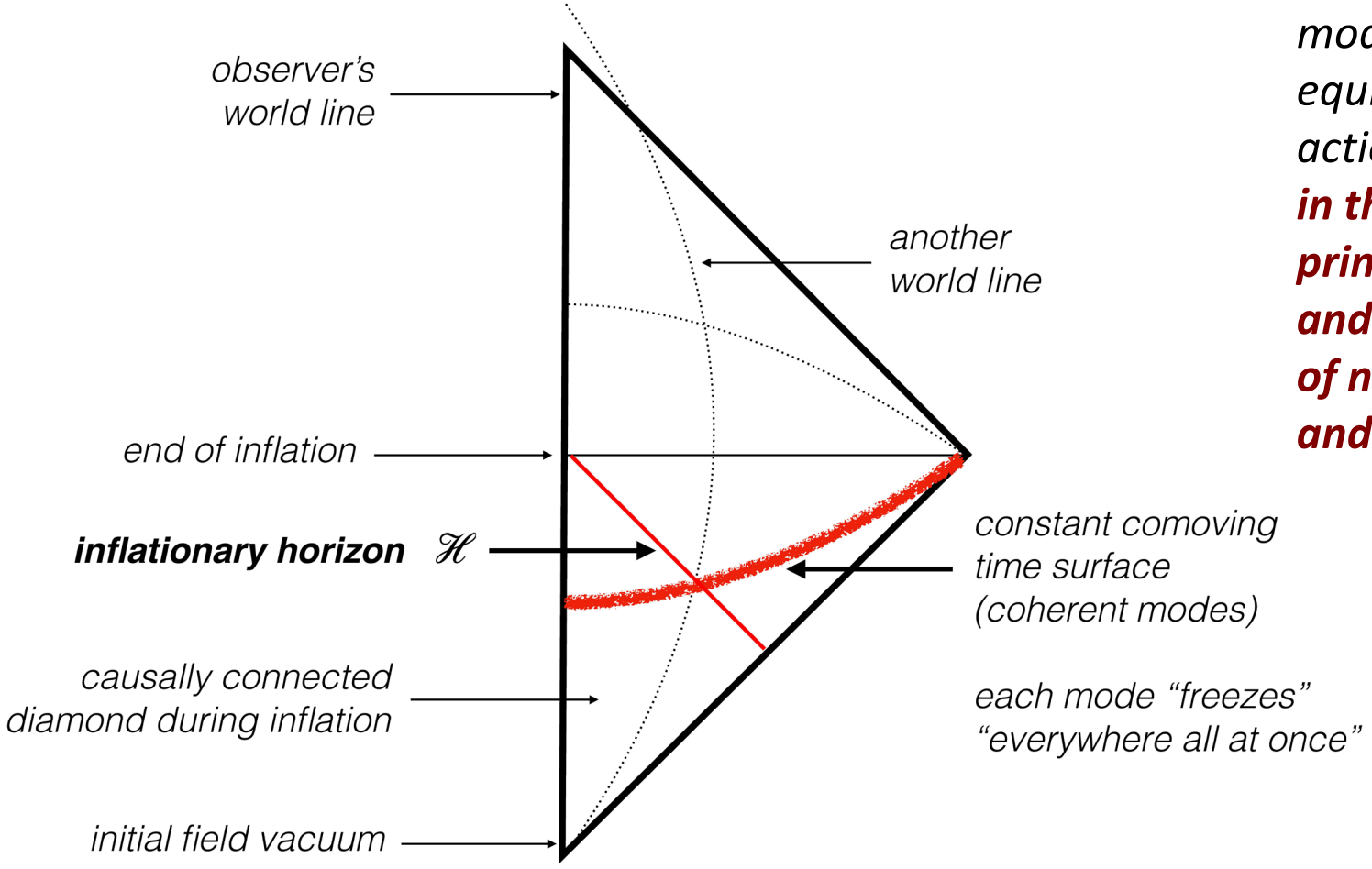


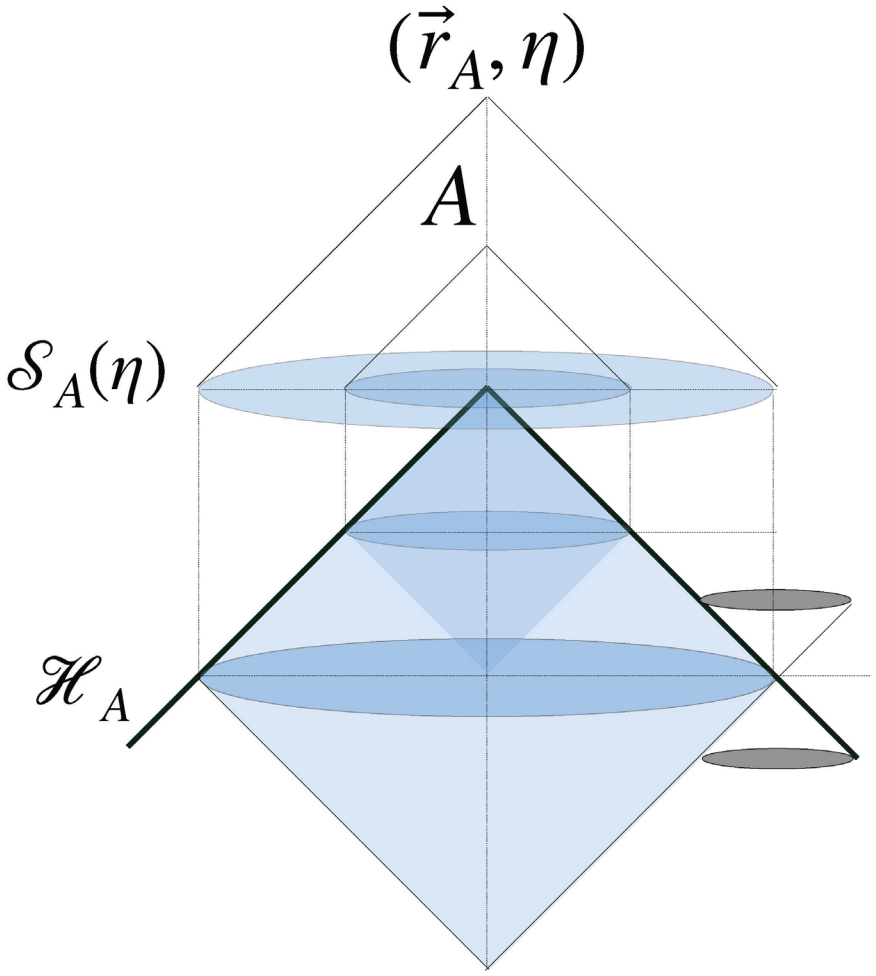
Figure by Craig Hogan

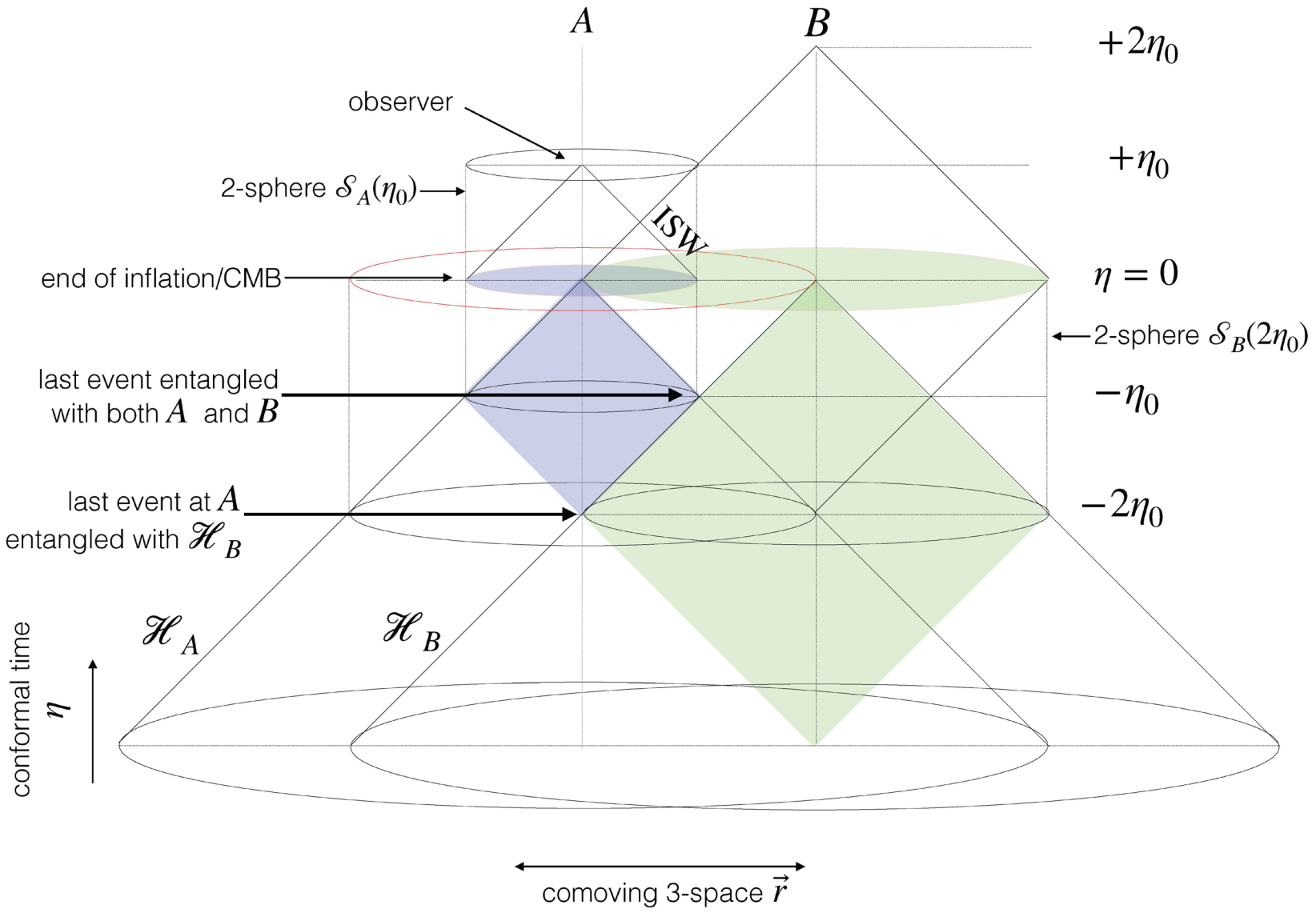
"Just as the proper recognition of this atomicity requires in the electromagnetic theory a modification in the use of the field concept equivalent to the introduction of the concept of action at a distance, so it would appear that ***in the gravitational theory we should be able in principle to dispense 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

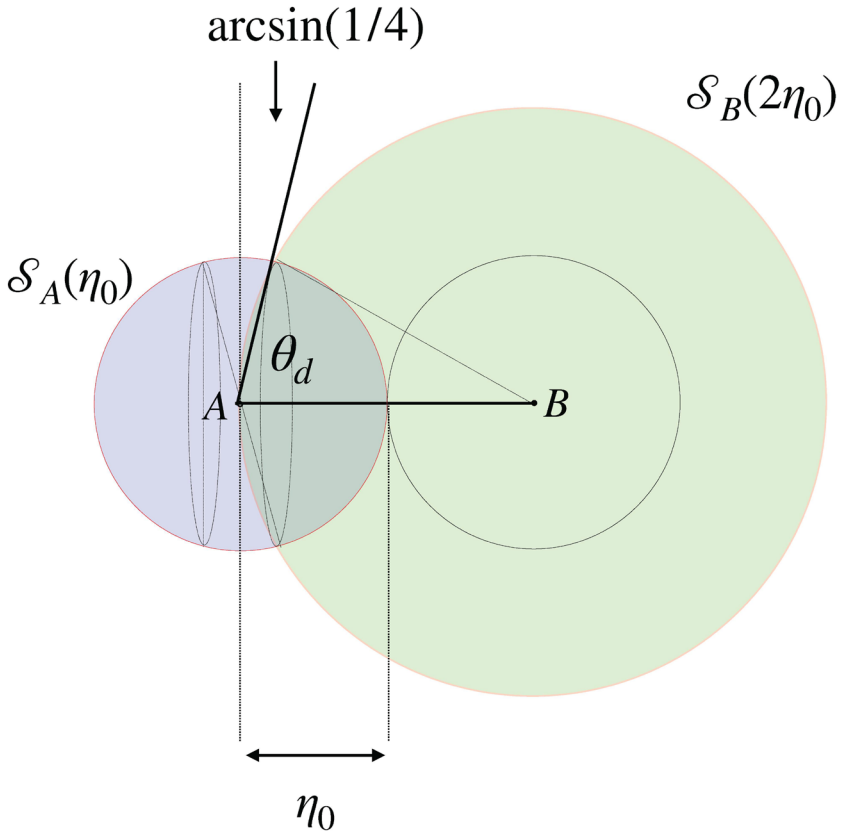
Primordial quantum geometric correlations: Inflation with two-way causal bounds

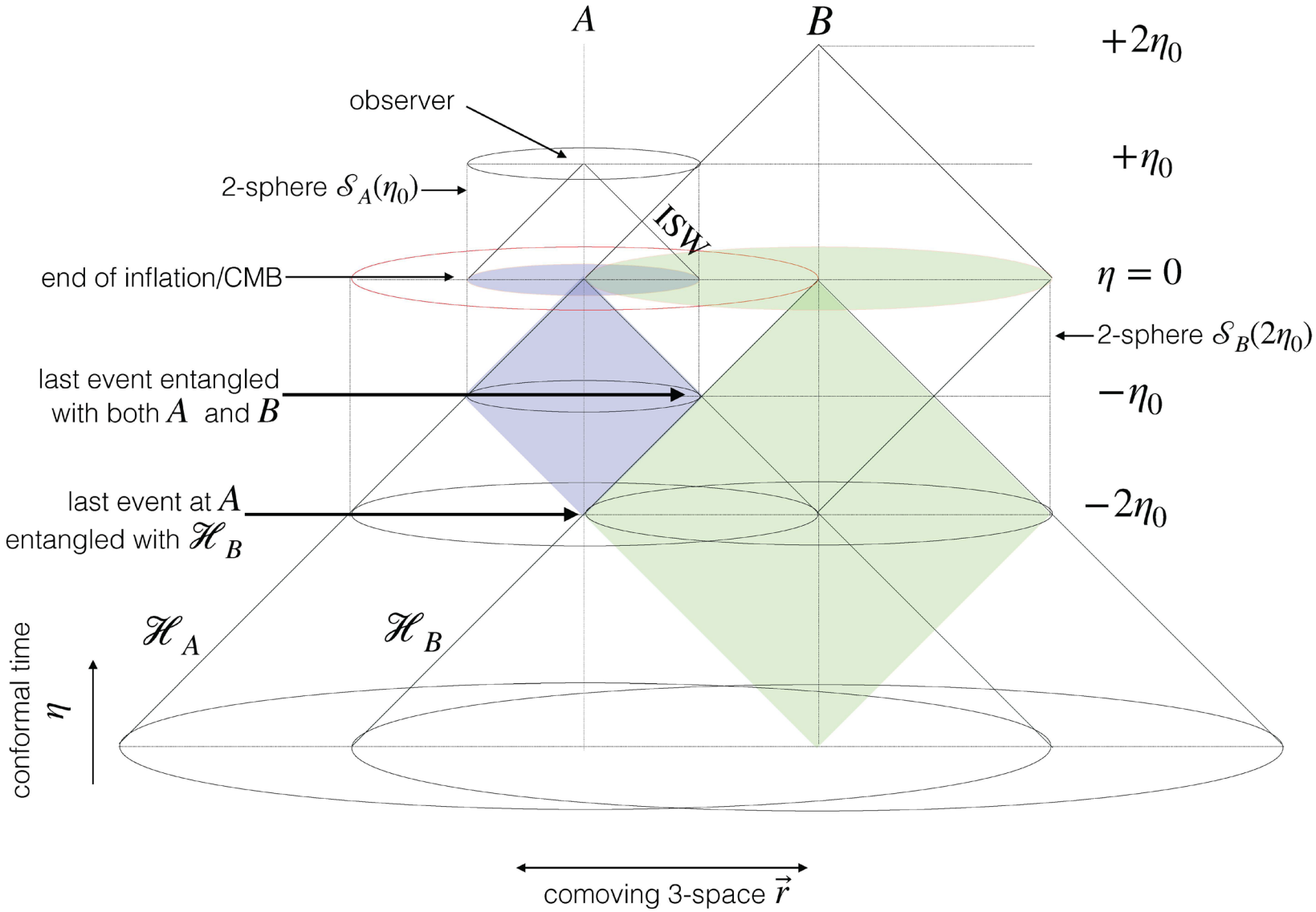




arXiv:2312.16147

Inflation with two-way causal bounds: “Causal shadows” in the CMB





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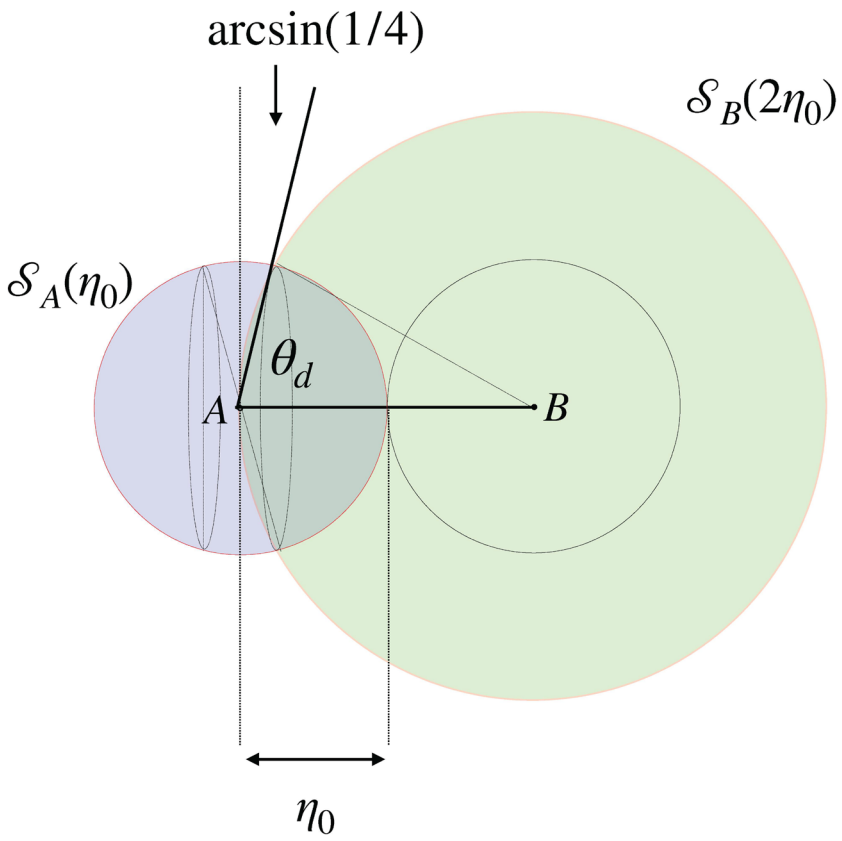
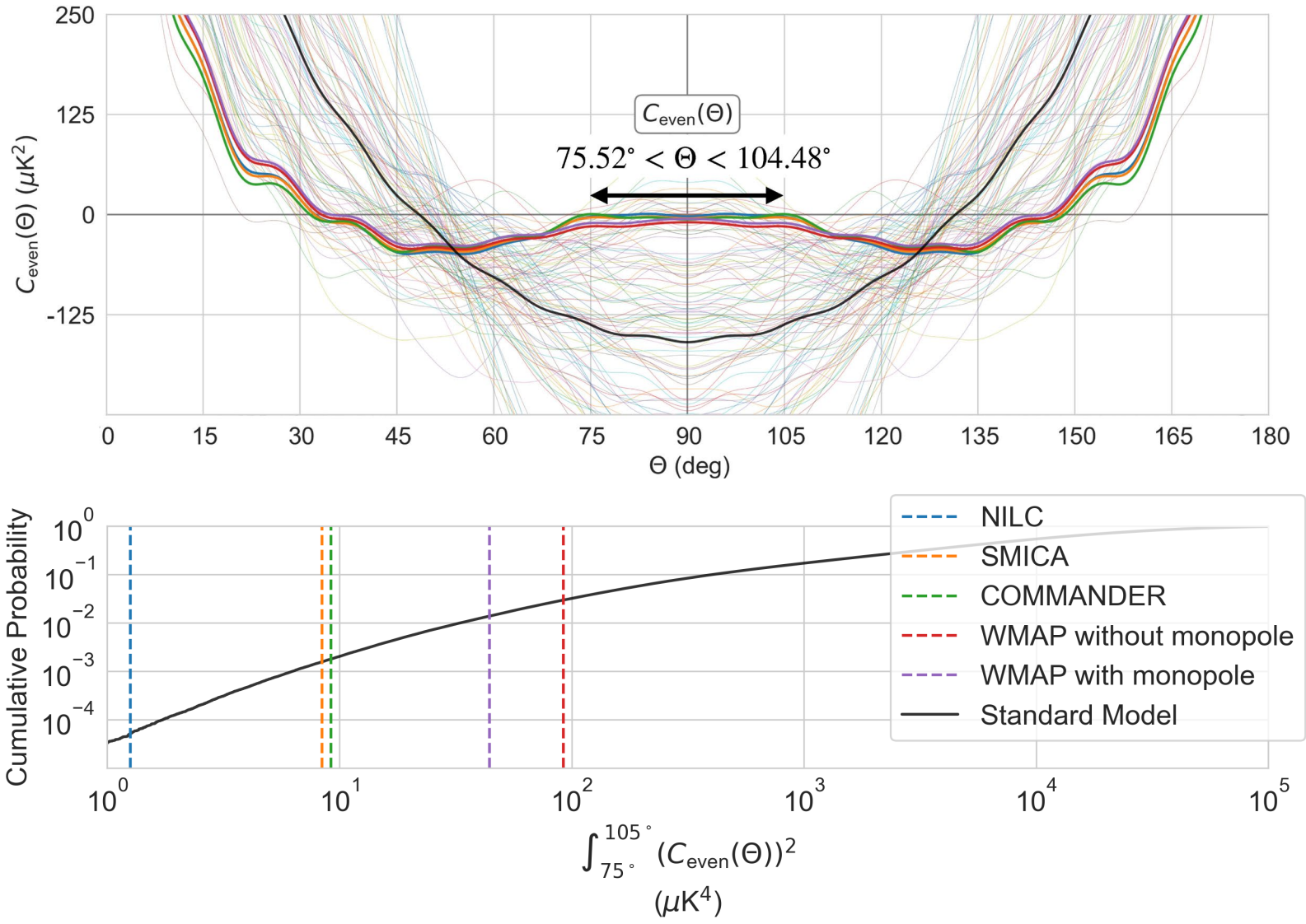
“Causal shadows” in the CMB: Planck maps unlikely in standard model ($10^{-2.8}$–$10^{-4.3}$)





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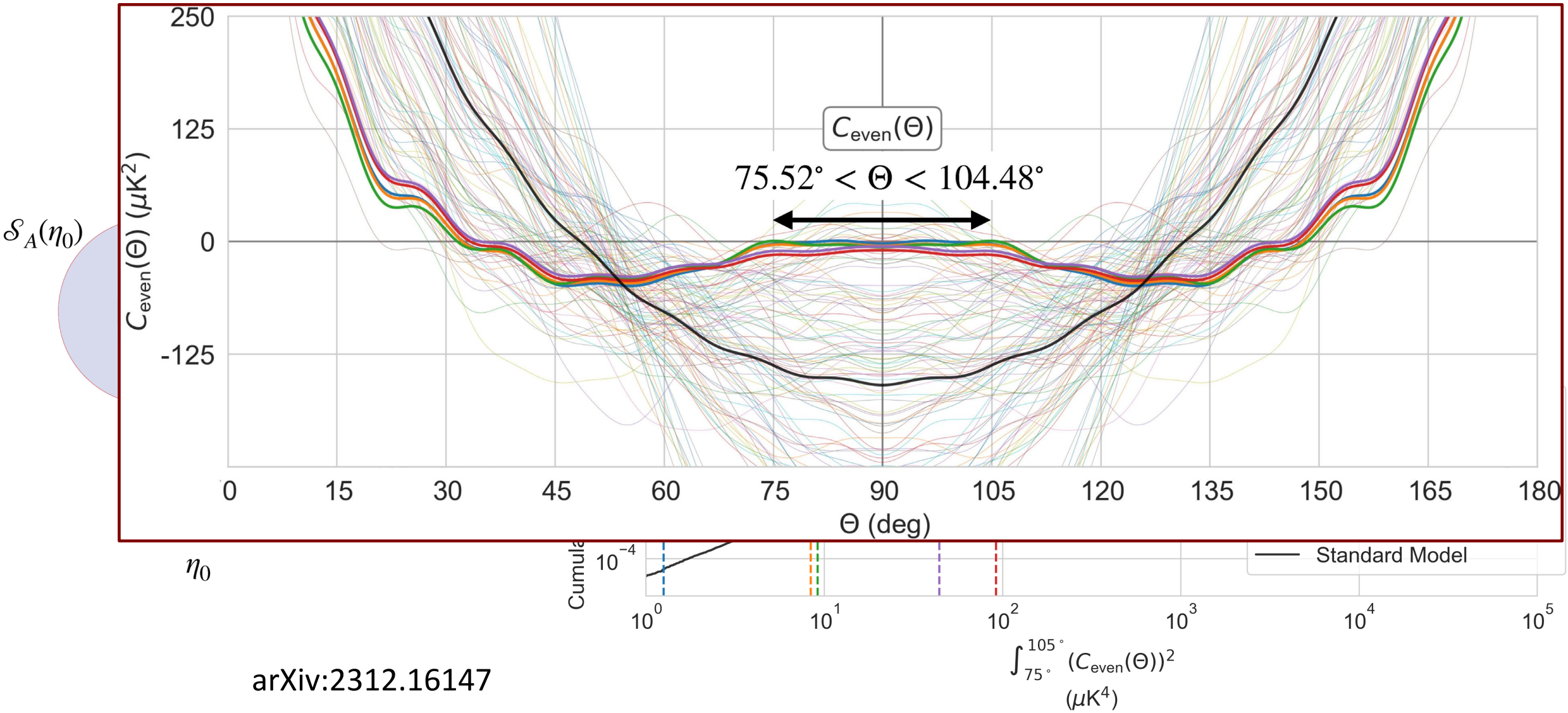
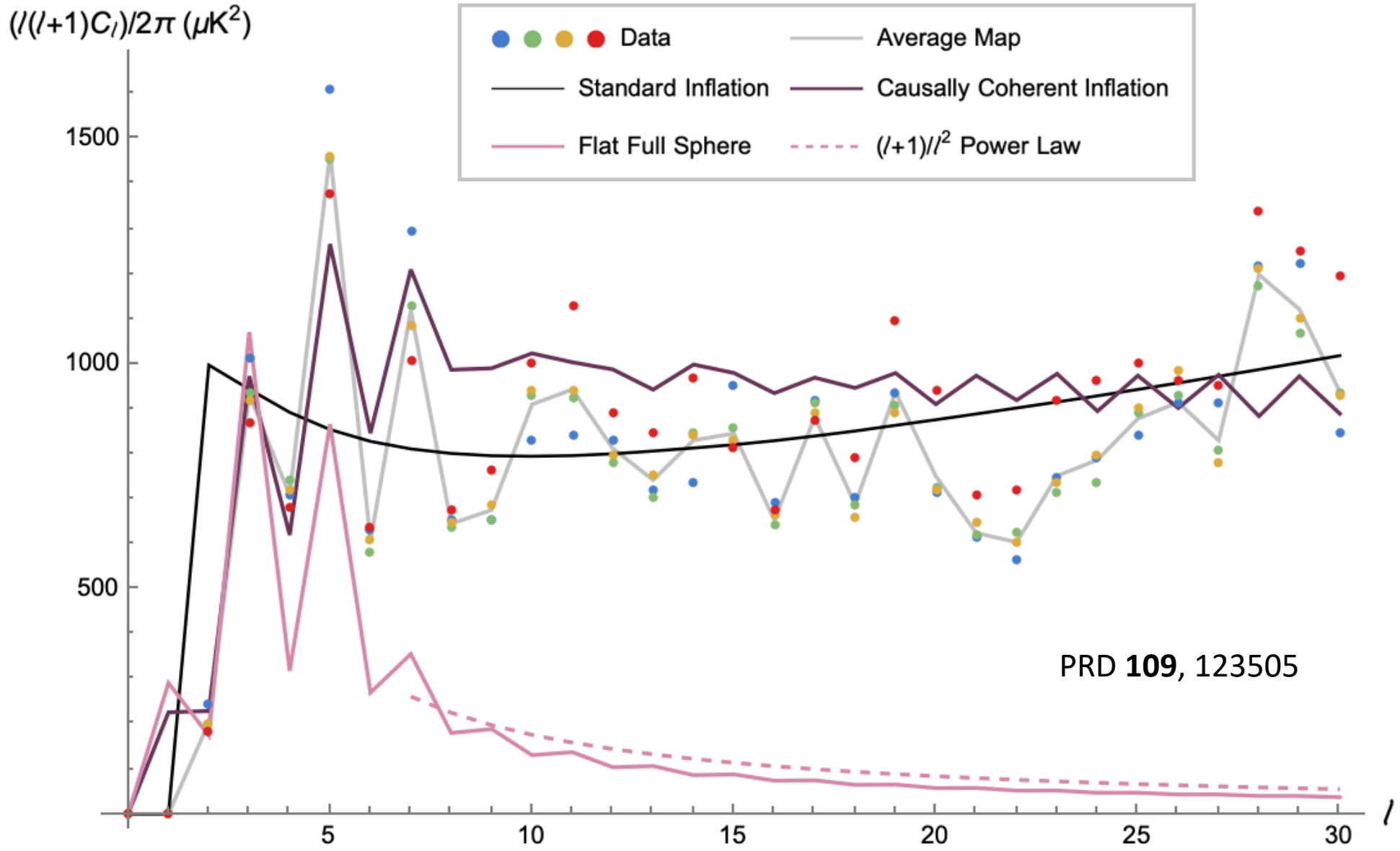


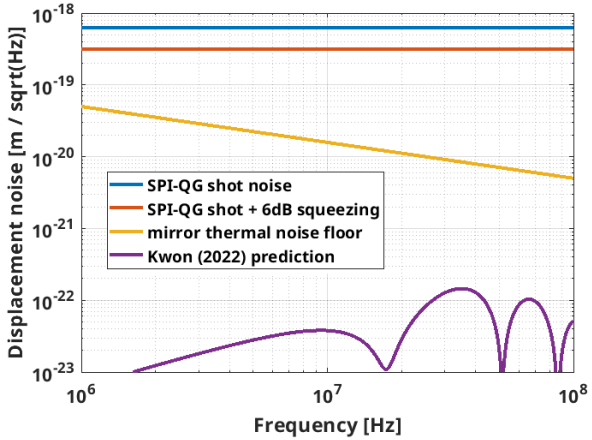
arXiv:2312.16147

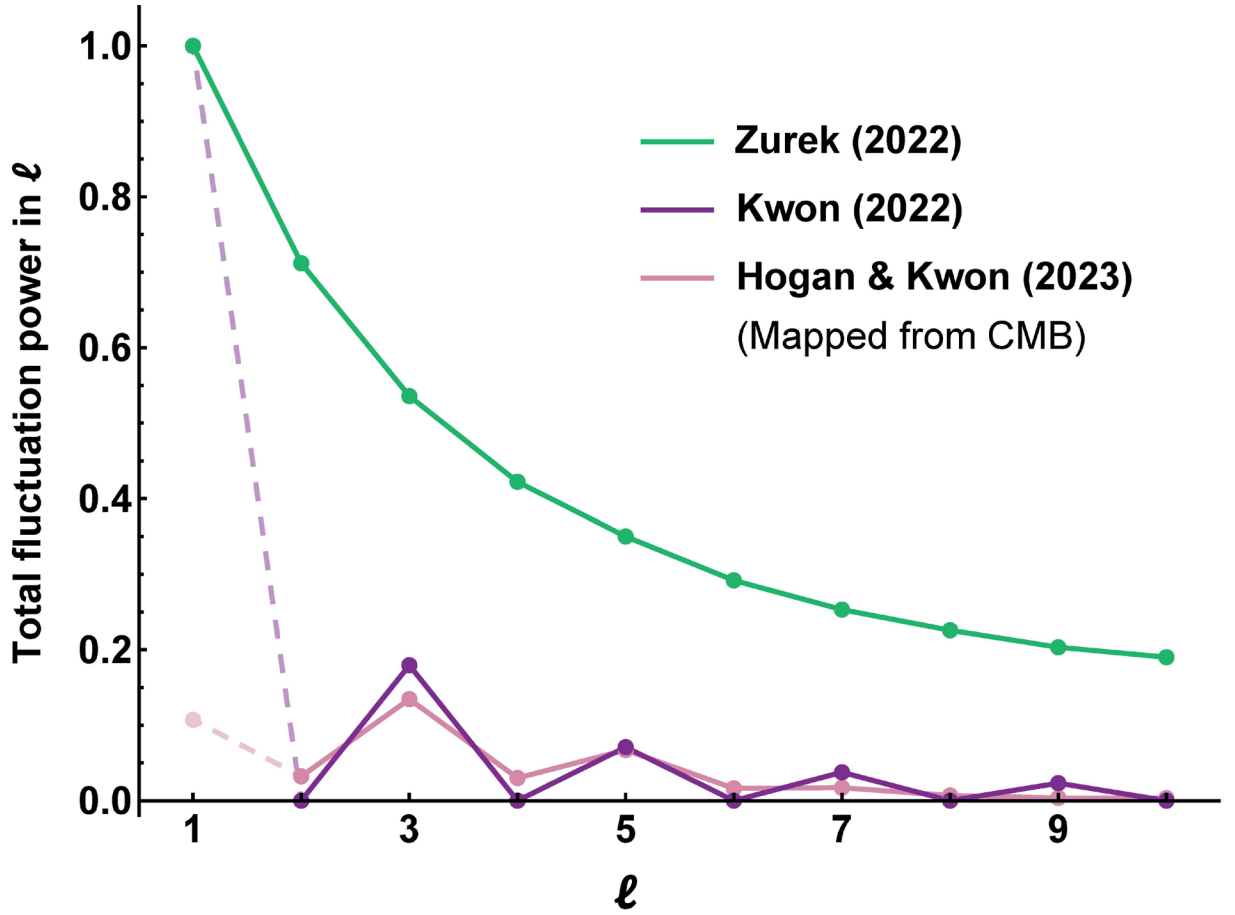
Concordant mapping between CMB signatures and flat space-time correlations

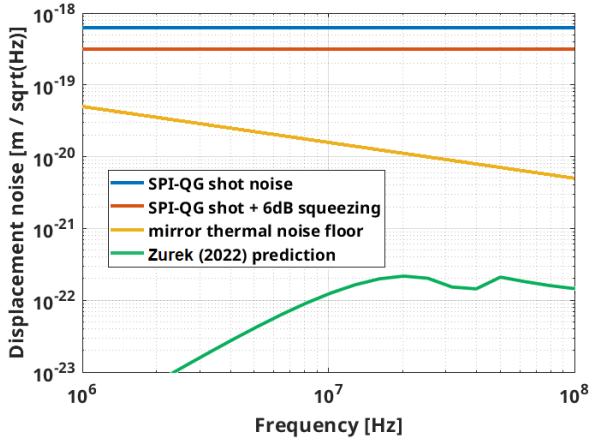


PRD **109**, 123505

Next-generation **interferometric** searches: Quantum coherence on causal horizons



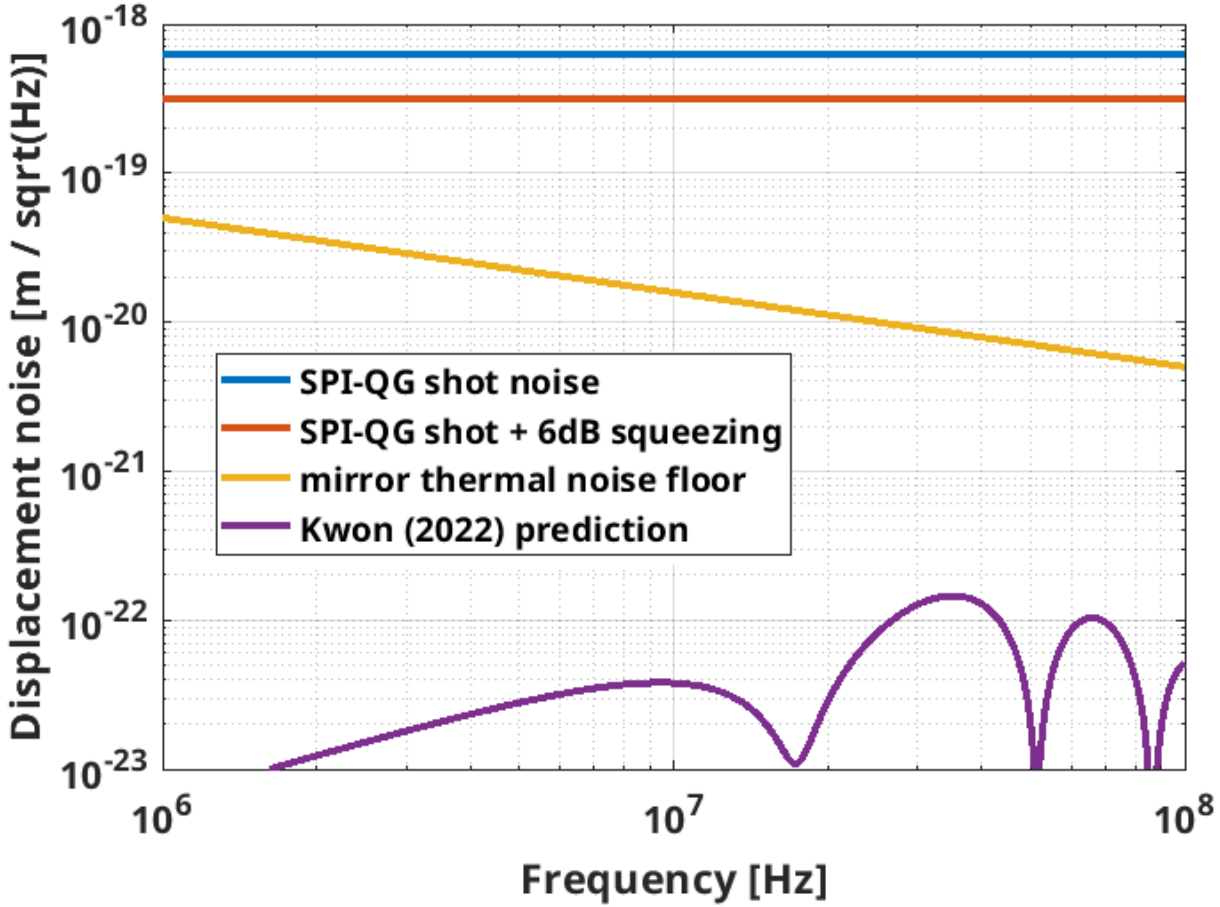




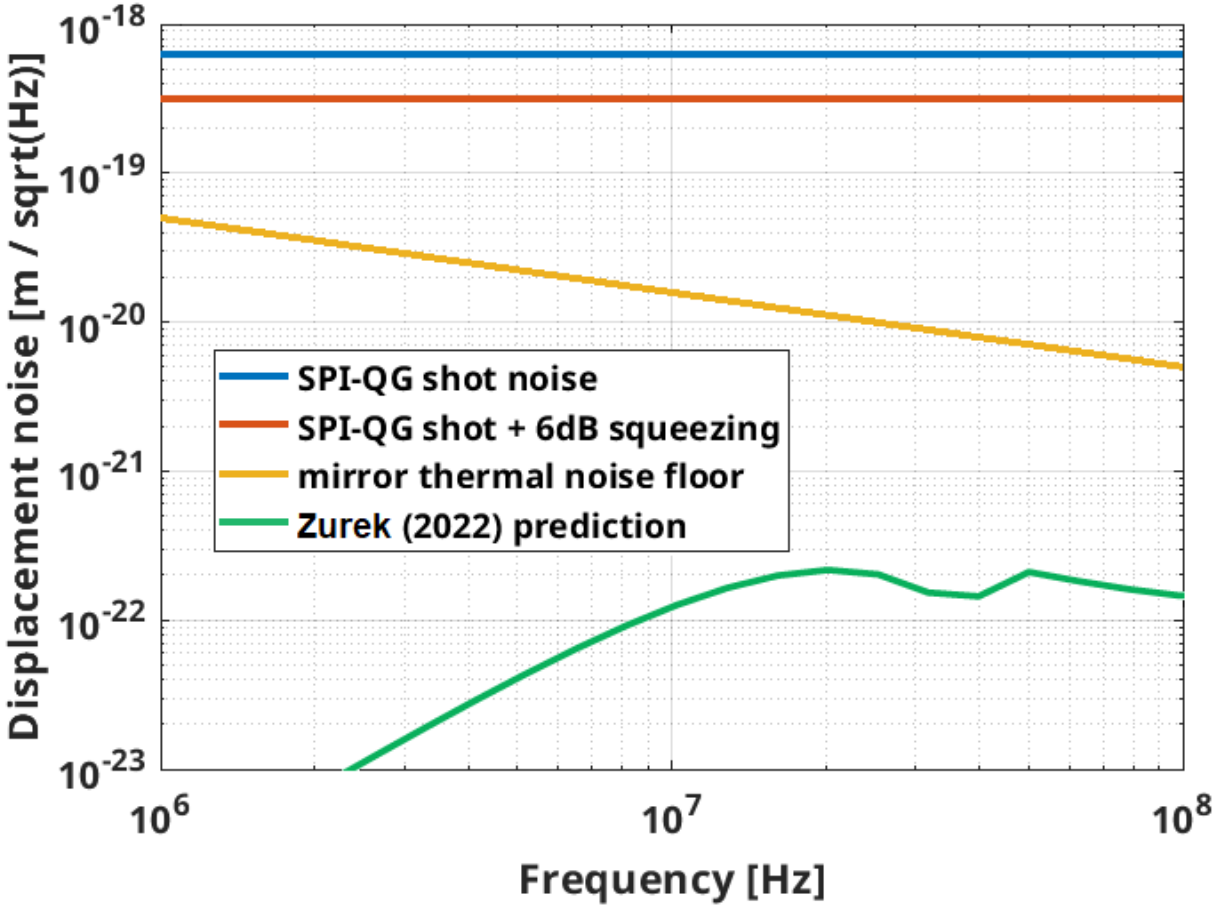
PRD **109**, 123505 — Spectrum derived from scaling invariance and symmetries consistent with CMB “anomalies.”

We think Zurek spectrum has excessive corrugation of null boundaries/wavefronts and causes ***defocusing*** of astrophysical images.
(This is different from the previously tested *blurring* effects from quantum foam!)

Next-generation interferometric searches (6 x 6m optical table)



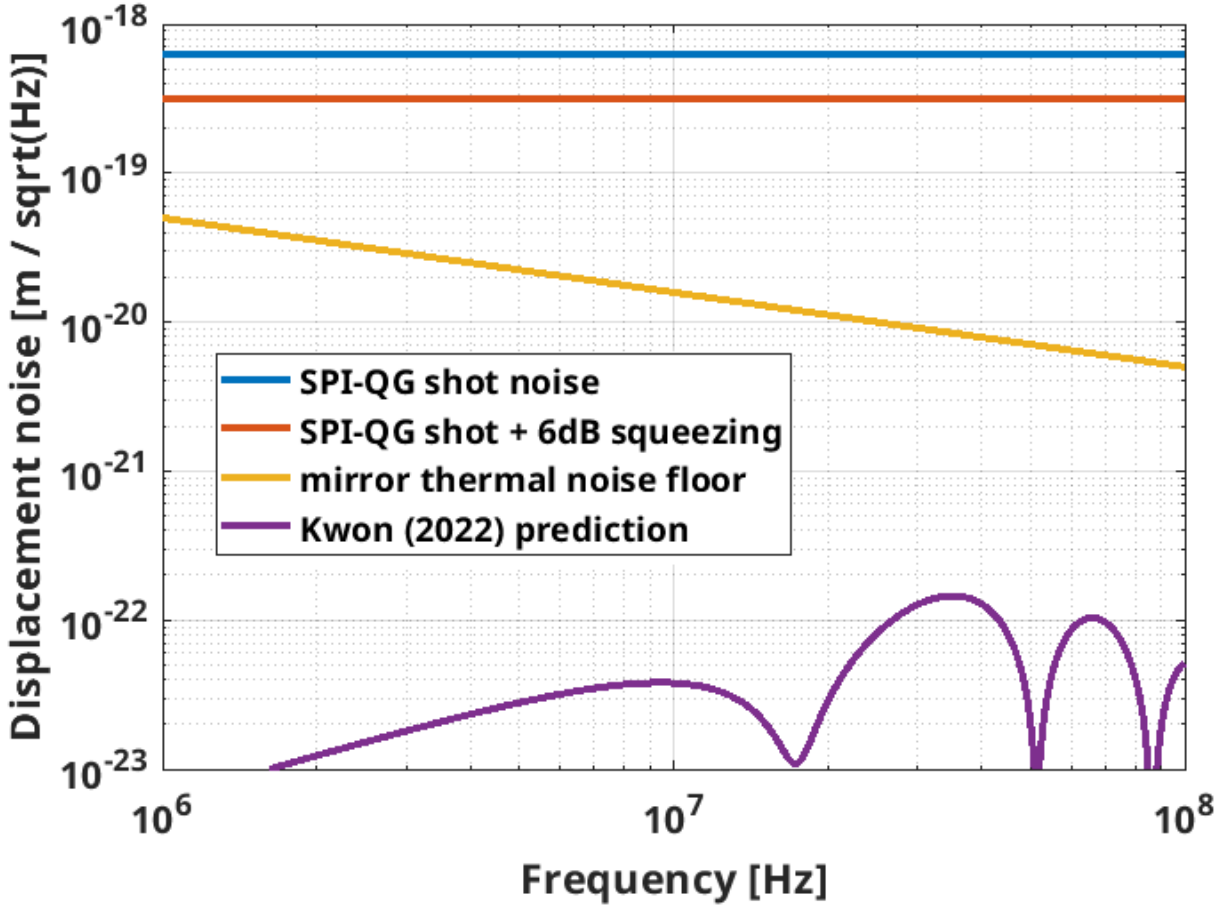
Kwon, Found. Phys. **55**, 19

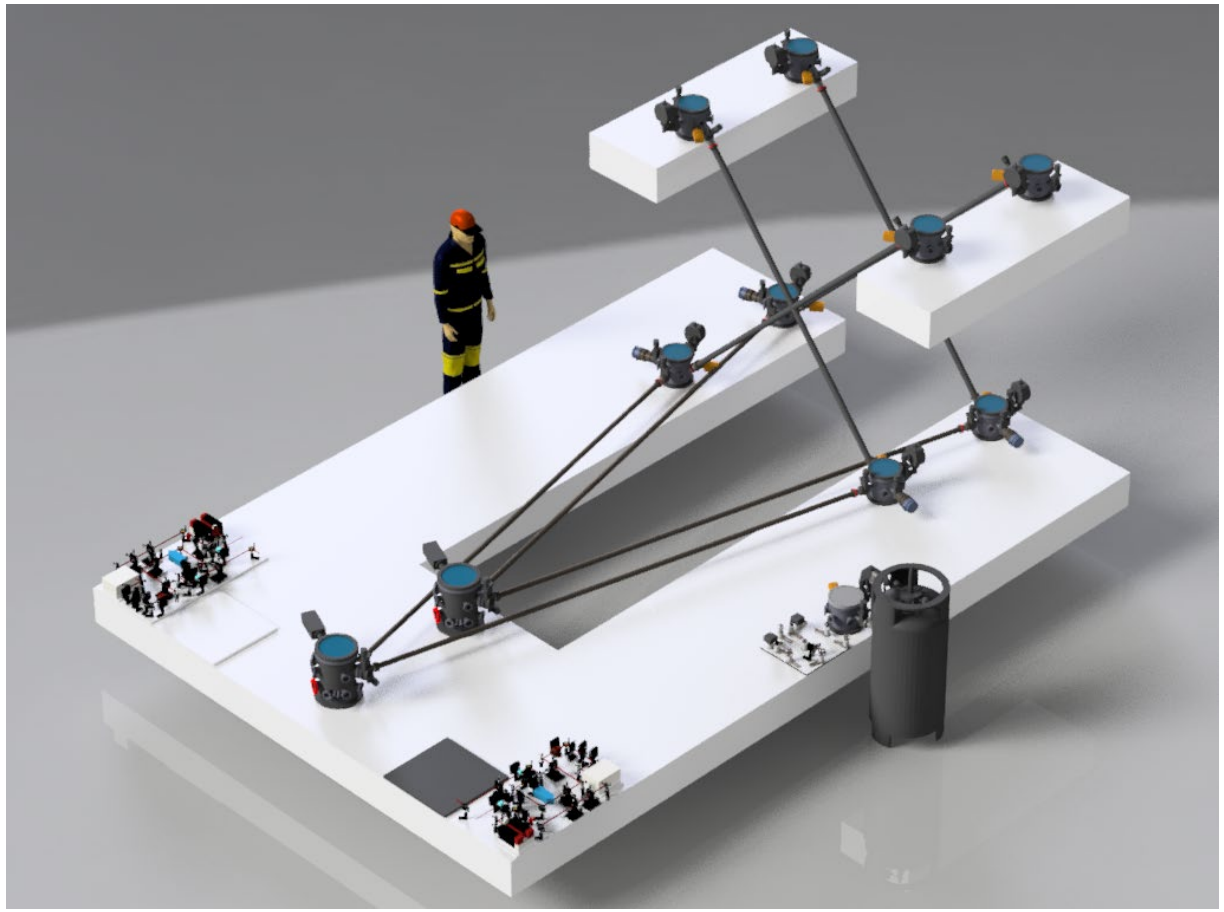


Li, Lee, Chen, and Zurek, PRD **107**, 024002

Simple 2D Michelson configuration

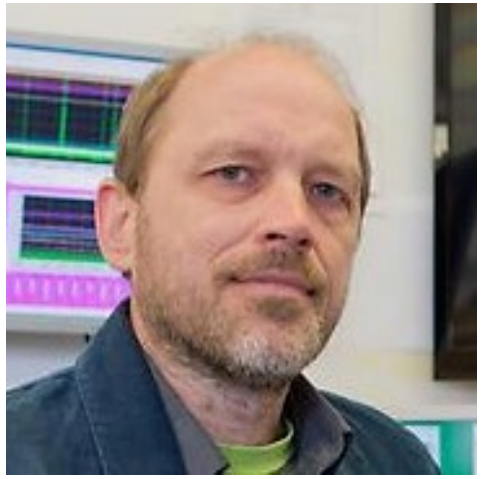
Next-generation interferometric searches (6 x 6m optical table)

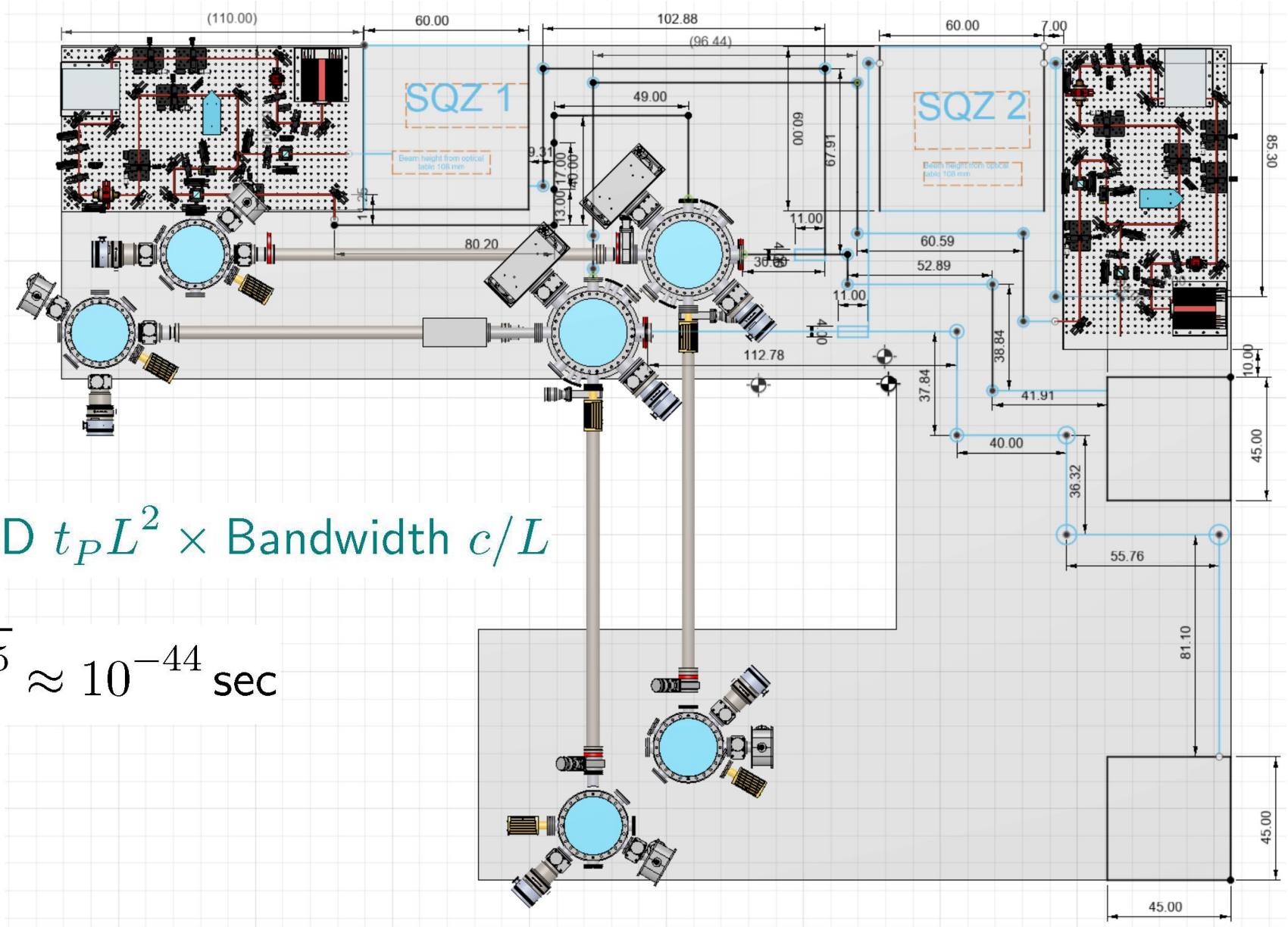




Kwon, Found. Phys. **55**, 19

The QUEST experiment at Cardiff – 1.8m prototype, 500MHz sampling

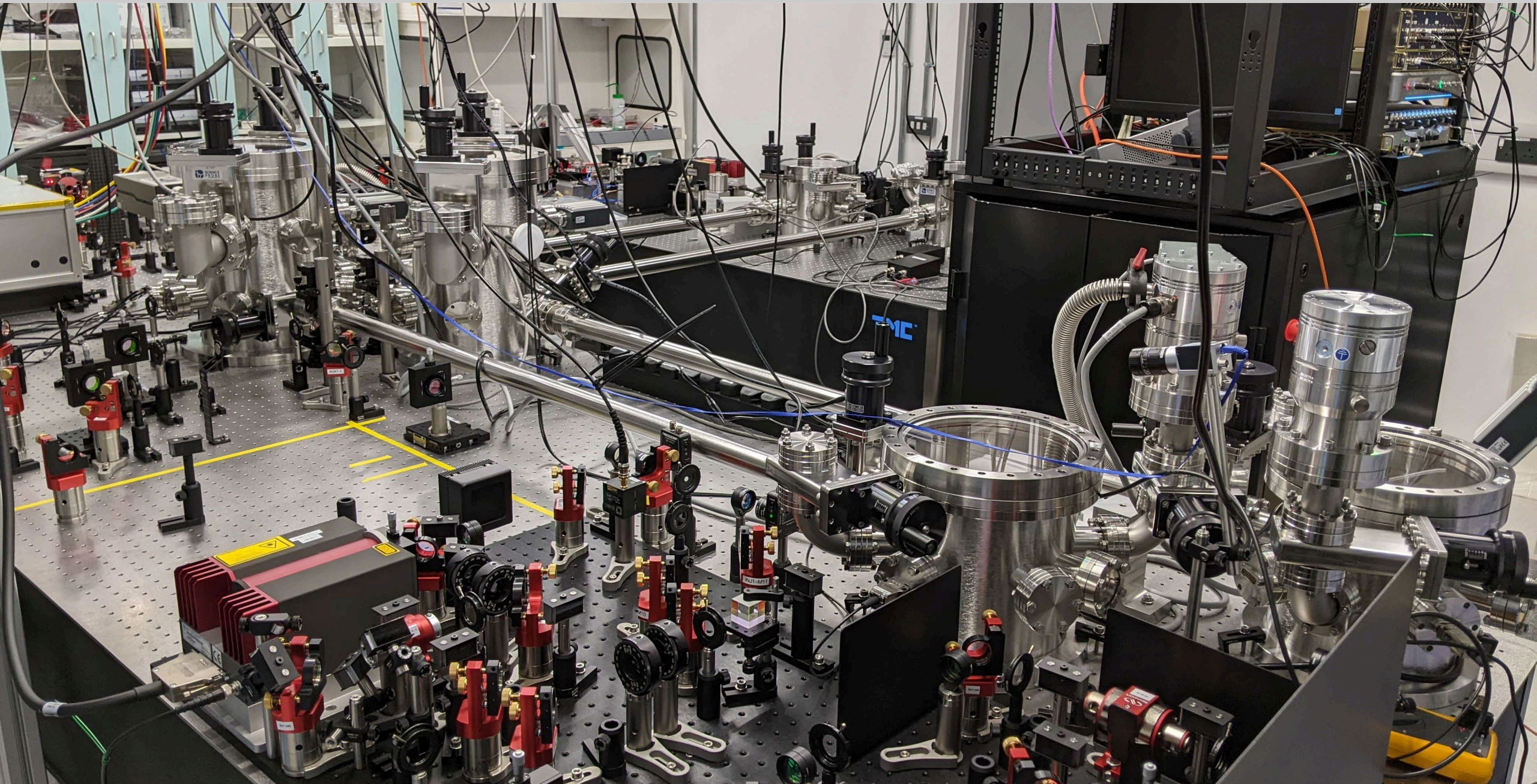




$$\langle \Delta x^2 \rangle_P \approx \ell_P L \approx \text{PSD } t_P L^2 \times \text{Bandwidth } c/L$$

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

The QUEST experiment at Cardiff – 1.8m prototype, 10kW design power



Next-generation interferometric searches (6 x 6m optical table, new clean room)

A non-exhaustive list of works predicting quantum gravity signals in interferometers

Holography:

Bub, He, Mitra, Zhang, and Zurek, PRL **134**, 121501 (2025)
— Iyer-Wald (Noether) charges

Kwon, Foundations of Physics **55**, 19 (2025)

Bak, Keeler, Zhang, and Zurek, JHEP **2024**, 331 (2024)
— Fluid-gravity correspondence

Banks and Fischler, 2311.18049

Gukov, Lee, and Zurek, PRD **107**, 016004 (2023)
— Jackiw-Teitelboim gravity

Verlinde and Zurek, PRD **106**, 106011 (2022)
— Gravitational shockwaves from vacuum states

Banks and Zurek, PRD **104**, 126026 (2021)
— CFT and entanglement entropy

Verlinde and Zurek. Phys Lett B **822**, 136663 (2021)

A bunch of old papers from Hogan and Kwon, 2007-2023

Graviton noise:

Maulik Parikh and Francesco Setti, PRD **111**, 046004 (2025)
Quantum-gravitational noise correlation in nearby detectors

Hing-Tong Cho and Bei-Lok Hu, PRD **105**, 086004 (2022)
Quantum noise of gravitons and stochastic force on geodesic separation

Sugumi Kanno, Jiro Soda, and Junsei Tokuda

- PRD **104**, 083516 (2021)
  Indirect detection of gravitons through quantum entanglement
- PRD **103**, 044017 (2021)
  Noise and decoherence induced by gravitons

Maulik Parikh, Frank Wilczek, and George Zahariade

- PRD **104**, 046021 (2021)
  Signatures of the quantization of gravity at gravitational wave detectors
- PRL **127**, 081602 (2021)
  Quantum mechanics of gravitational waves
- Int J Mod Phys D **29**, 2042001 (2020)
  The noise of gravitons

Holography for causal diamonds: Coherent accumulation of gravitational shockwaves

The background space-time is correlated on holographic causal diamonds.

Quantum fluctuations of causal structure from vacuum energy accumulate coherently with gravitational memory, leading to **uncertainties that are not Planck scale but rather Planck random walk scale ("holographic noise")**.

Hypothesis:

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

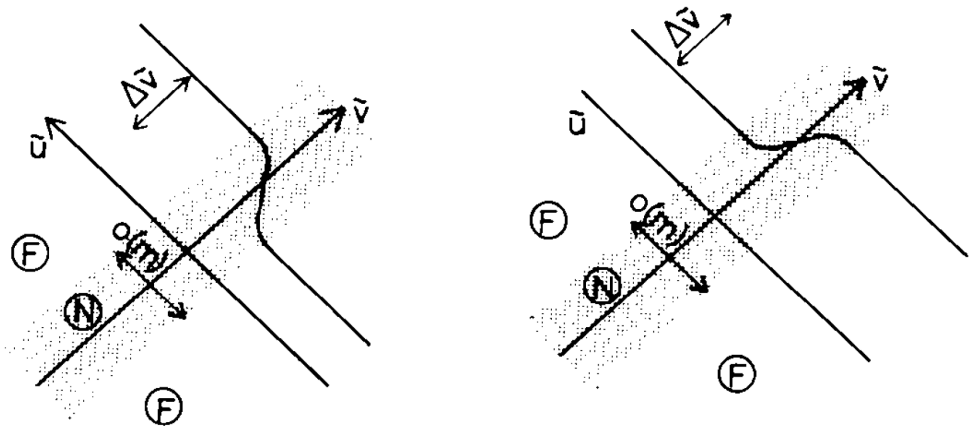
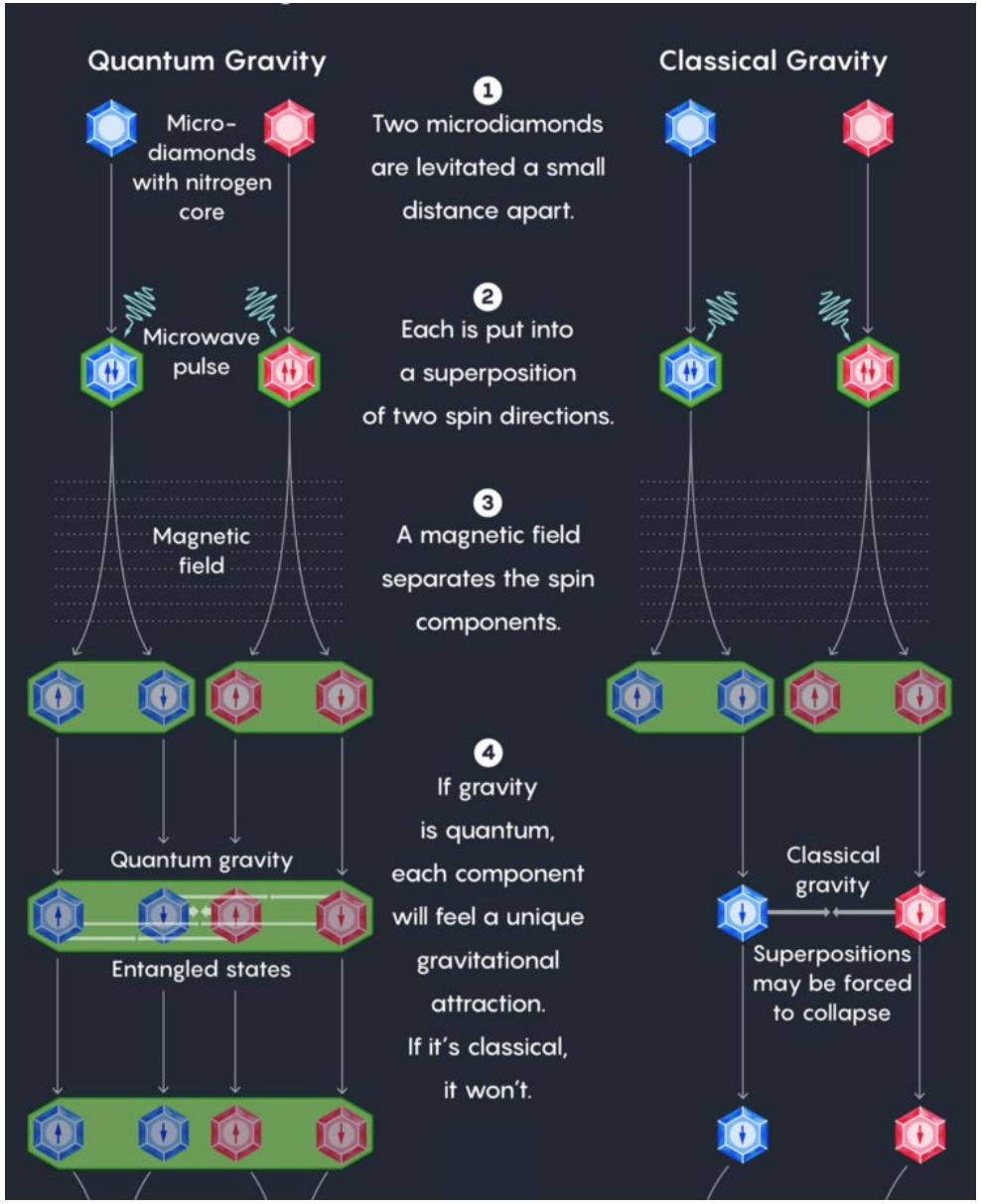
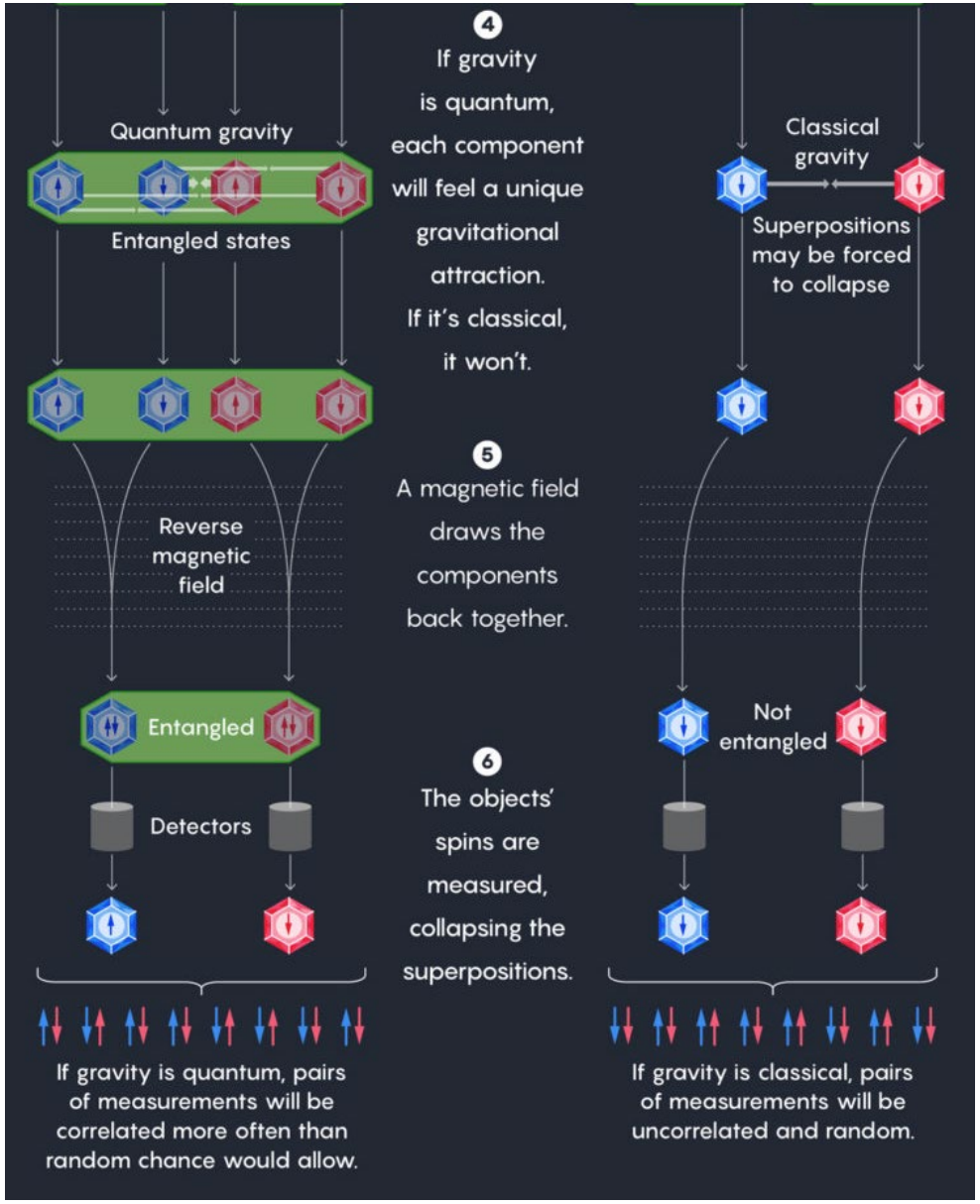


Fig. 2. The path of a null geodesic in the $(\hat{u}, \hat{v})$ plane as described by eq. (2) for $m \ll 1$, $\rho_0 \gg m$, and (a) $\rho_0 < 1$, (b) $\rho_0 > 1$. The near region N and the far region F, as well as the shift $\Delta\hat{v}$, are indicated.

Dray & 't Hooft, Nucl. Phys. B **253**, 173

In context of gravitationally induced entanglement, as superpositions of geometry





In context of gravitationally induced entanglement, as superpositions of geometry

Gravitationally induced entanglement

- **Large coherent states of matter** in spatial superposition states, interacting via gravity
- **Superpositions of geometry** created by the active gravity of such states

Holographic noise

- **Macroscopic causal volumes of quantum space-time** whose holographic microstates are **coherent** at scales set by the size of the causal boundaries — requires specific theory
- **Superpositions of geometry** created by gravitational shockwaves from vacuum states, which accumulate because of the coherence and gravitational memory

Work in progress

In context of gravitationally induced entanglement, as superpositions of geometry

Gravitationally induced entanglement

- **Large coherent states of matter** in spatial superposition states, interacting via gravity
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- **Bell's inequality violation** between the spins of such states of matter
- Probes (low-energy) **excited states of quantum gravity**

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Gravitationally induced entanglement

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- **Superpositions of geometry** created by the active gravity of such states
- **Bell's inequality violation** between the spins of such states of matter
- Probes (low-energy) **excited states of quantum gravity**
- Extremely challenging to test experimentally
- Provides one number as the result

Holographic noise

- **Macroscopic causal volumes of quantum space-time** whose holographic microstates are **coherent** at scales set by the size of the causal boundaries — **requires specific theory**
- **Superpositions of geometry** created by gravitational shockwaves from vacuum states, which accumulate because of the coherence and gravitational memory
- **Irreducible excess correlation** in space-time fluctuations
- Probes the **ground state of quantum gravity** with no real mass-energy present
- **Testable with state-of-the-art interferometry**
- **Measures a spectrum that can be modulated**

Work in progress

Acknowledgments

Thank you!

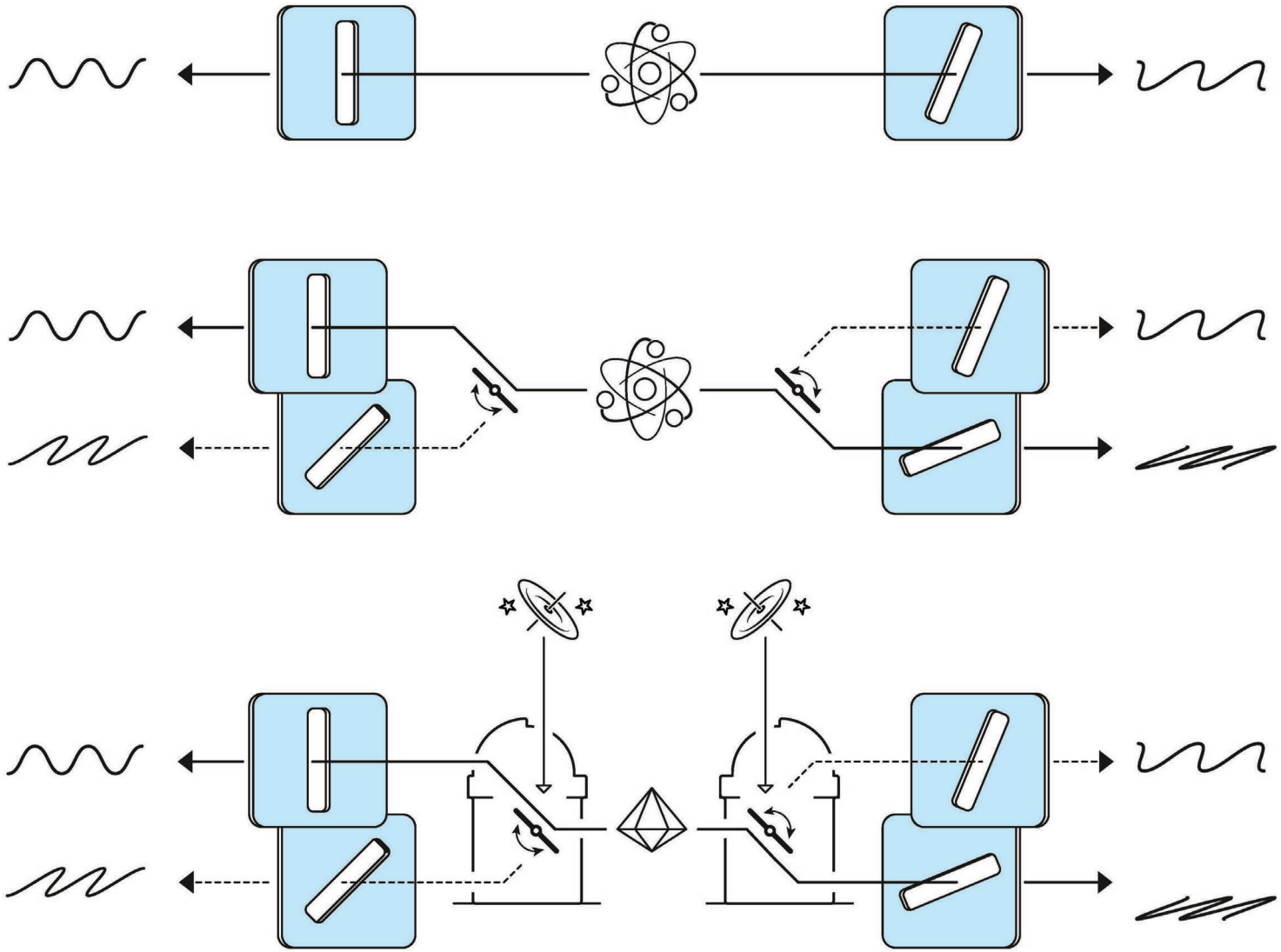
O. Kwon, arXiv:2204.12080, Foundations of Physics 55, 19 (2025)

C. Hogan, **OK**, et al., arXiv:2303.06563, PRD 109, 123505 (2024)

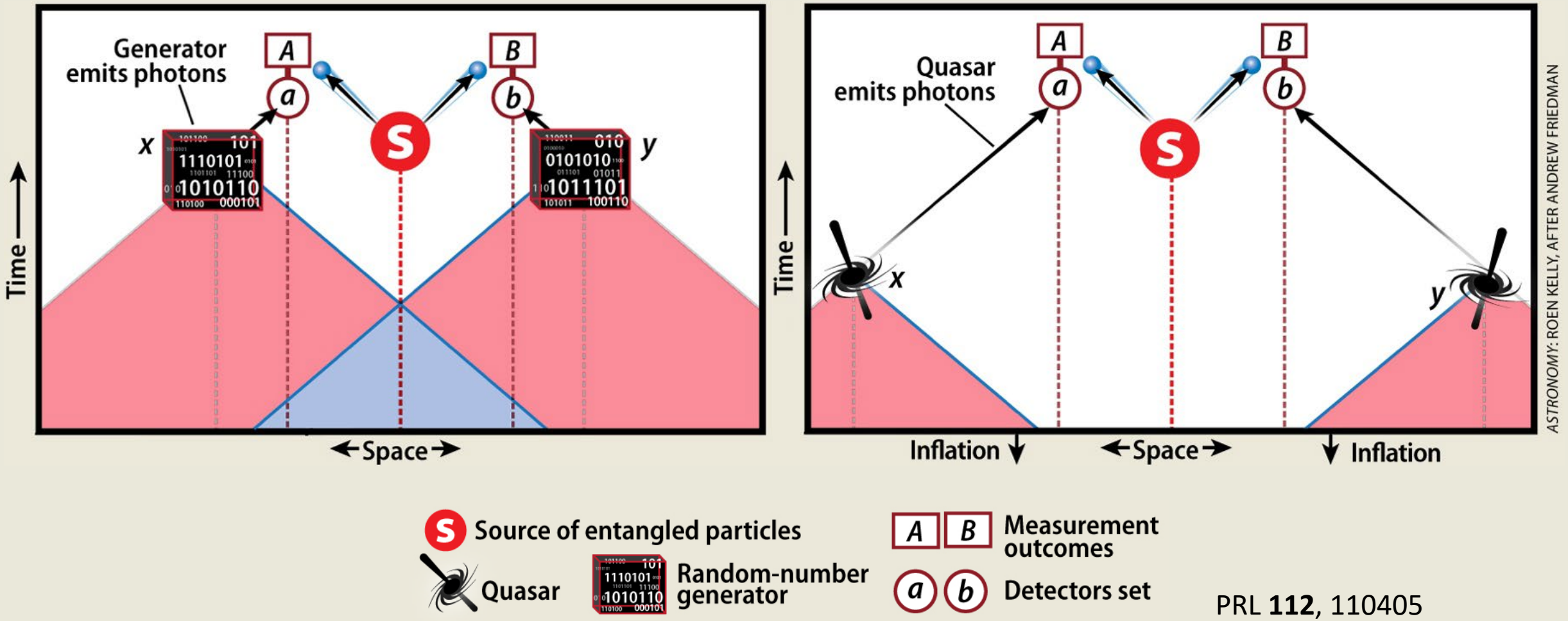
C. Hogan, **OK**, et al., arXiv:2312.16147

A. Patra, ... , **OK**, ... , and H. Grote, arXiv:2410.09175, PRL *in press*

Bell tests!

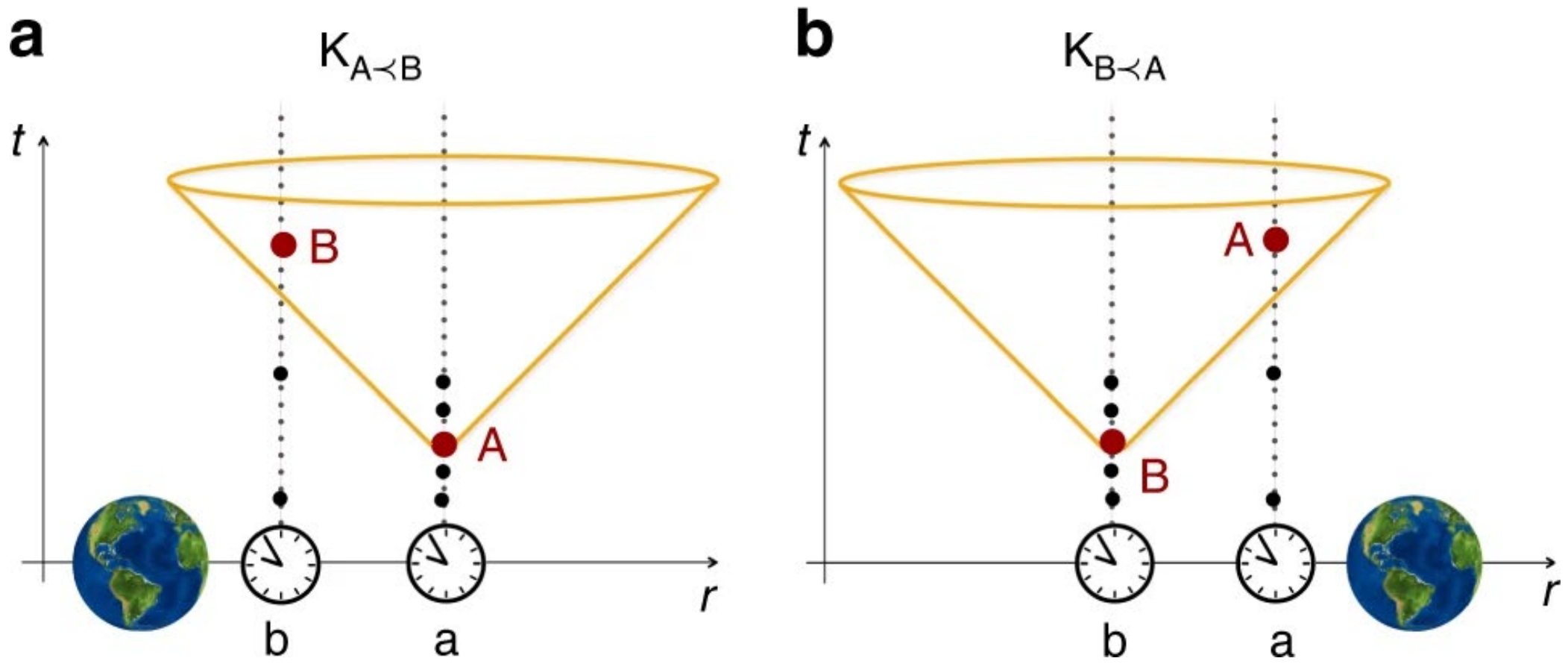


“Loophole-free” Bell tests?



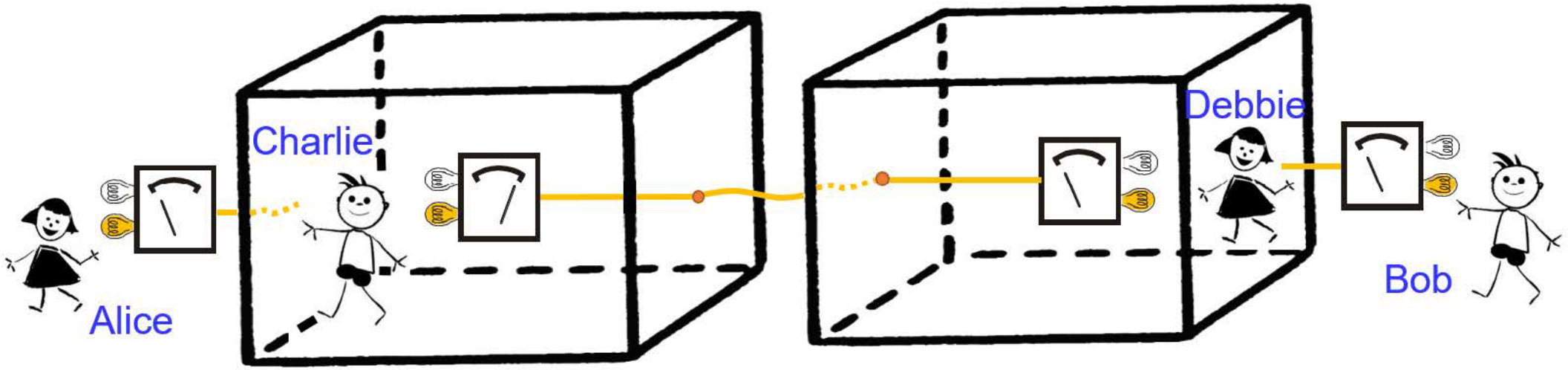
PRL **112**, 110405

Causal structure coupled to quantum superpositions of mass-energy



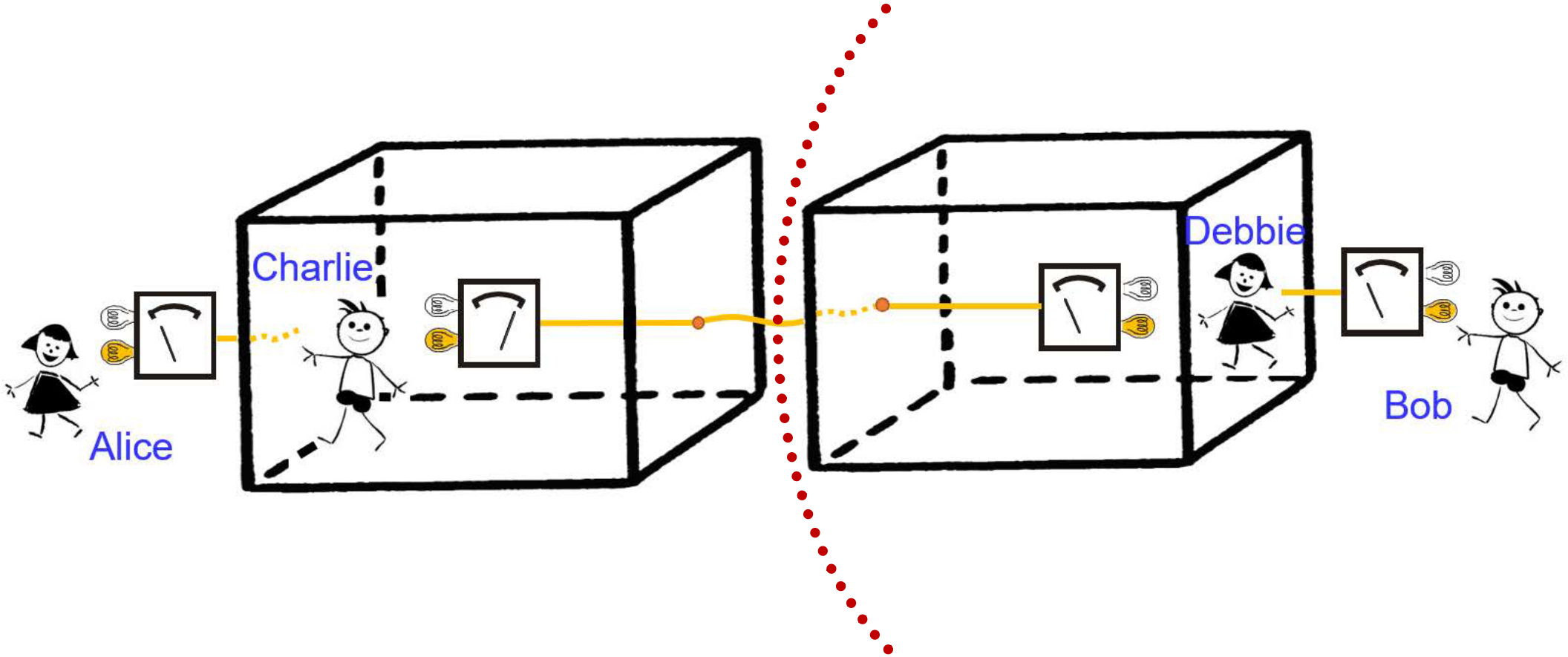
Zych et al., Nat. Comm. **10**, 3772

Wigner-Bell test: a no-go theorem for observer-independent facts?



Entropy 20, 350 / Nat. Comm. 9, 3711

Perhaps equivalent to solving issue of quantum information with (Rindler) horizons!



Durham, Observer-independence in the presence of a horizon, arXiv:1902.09028

Further developed and formalized into a more robust correspondence:

Hausmann and Renner, The firewall paradox is Wigner's friend paradox, arXiv:2504.03835