Testing the Foundations of Quantum Space-Time with Interferometers Using Quantum Metrology

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Craig J Hogan (University of Chicago)

Robert H Hadfield (University of Glasgow)

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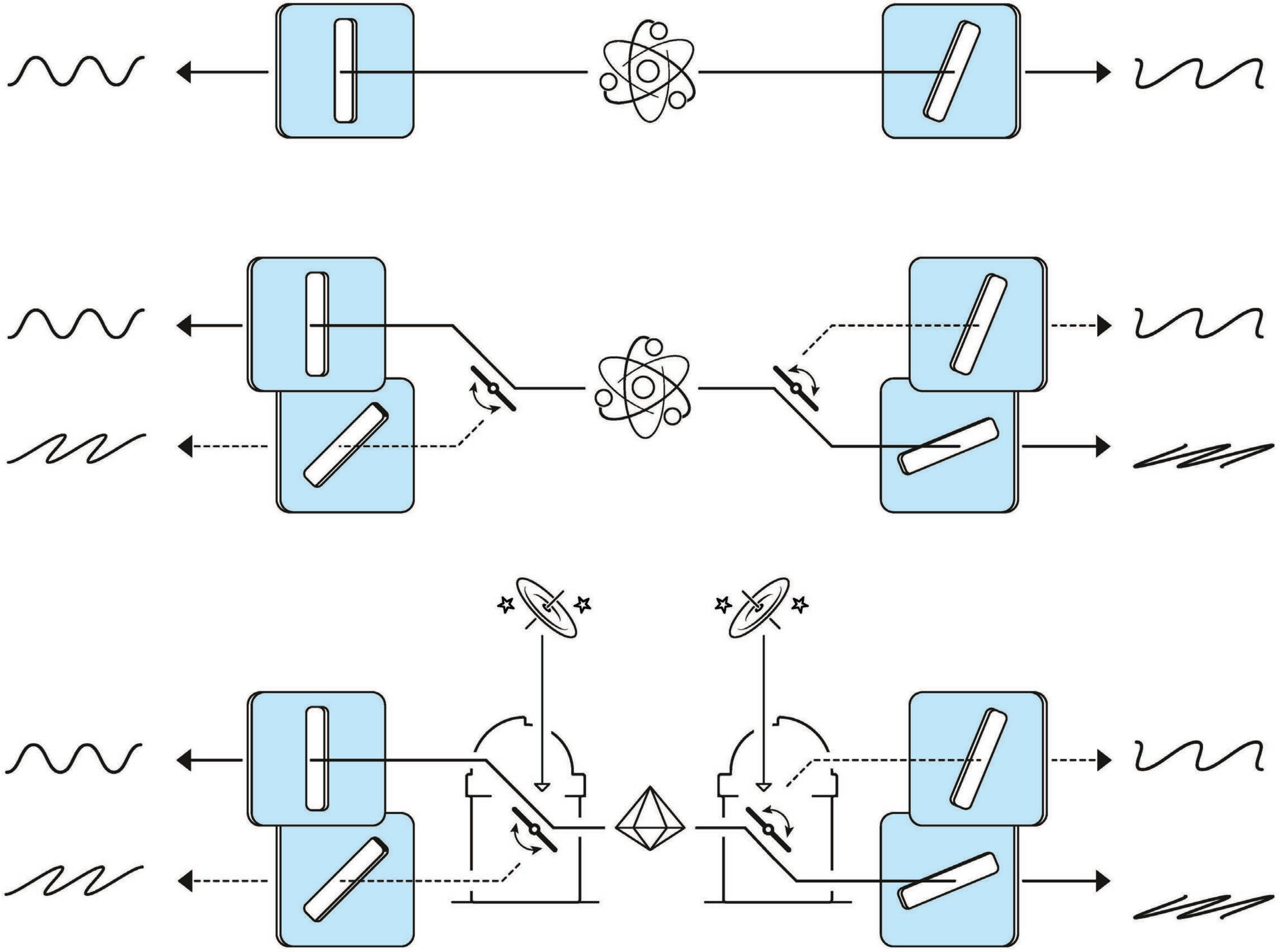
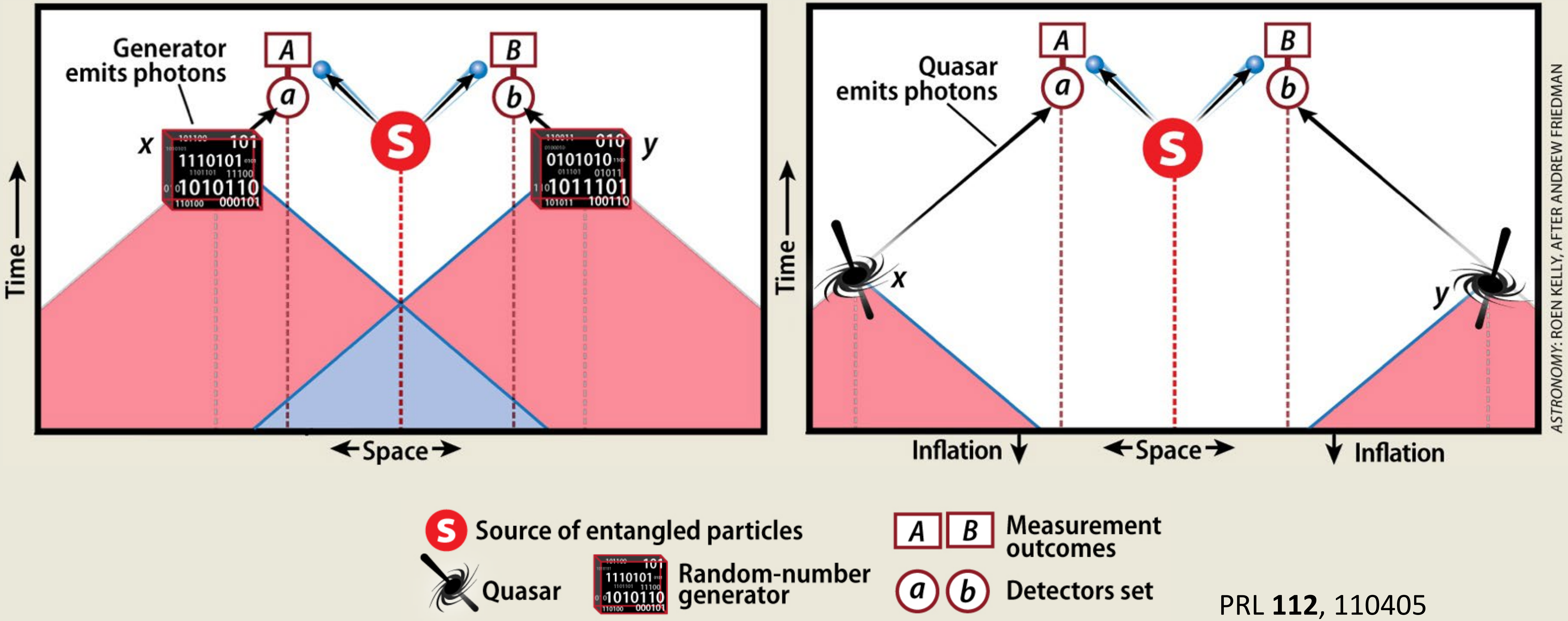
University of Glasgow

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Bell tests!

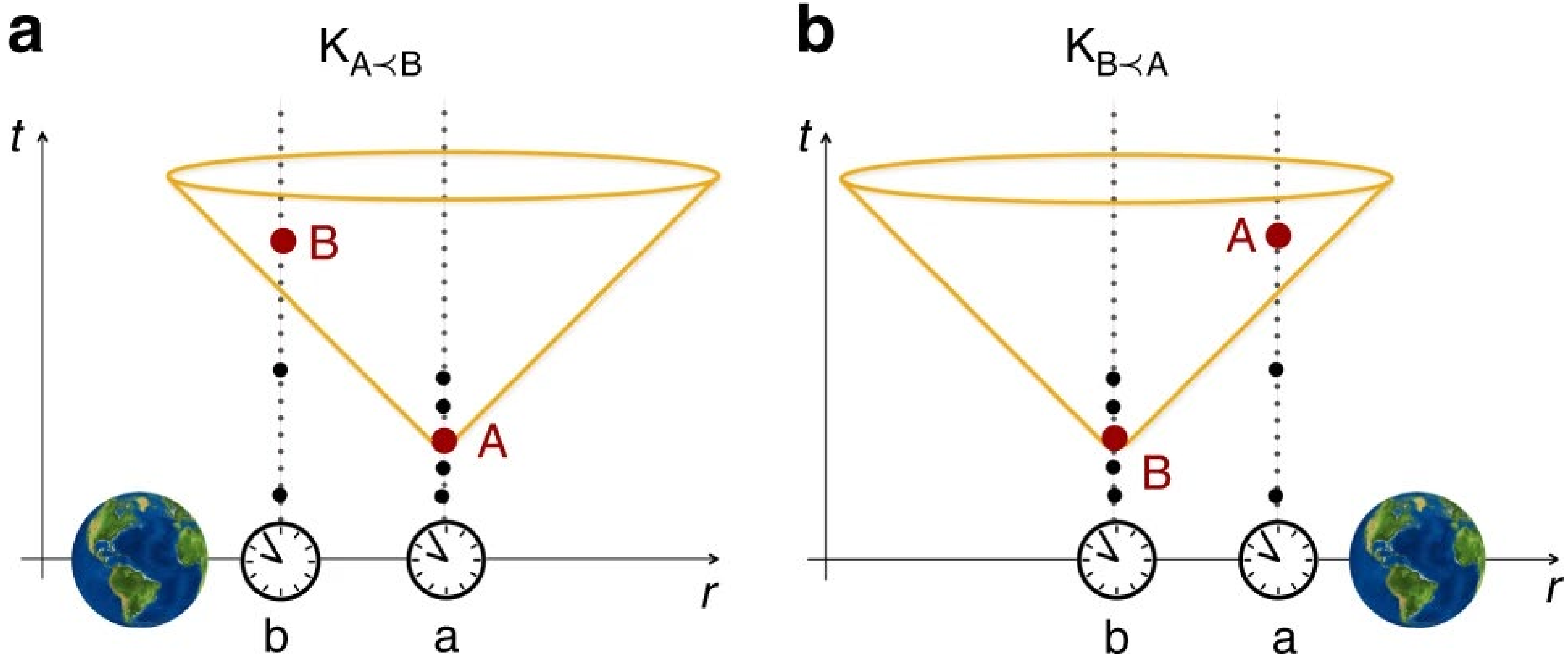


“Loophole-free” Bell tests?



PRL **112**, 110405

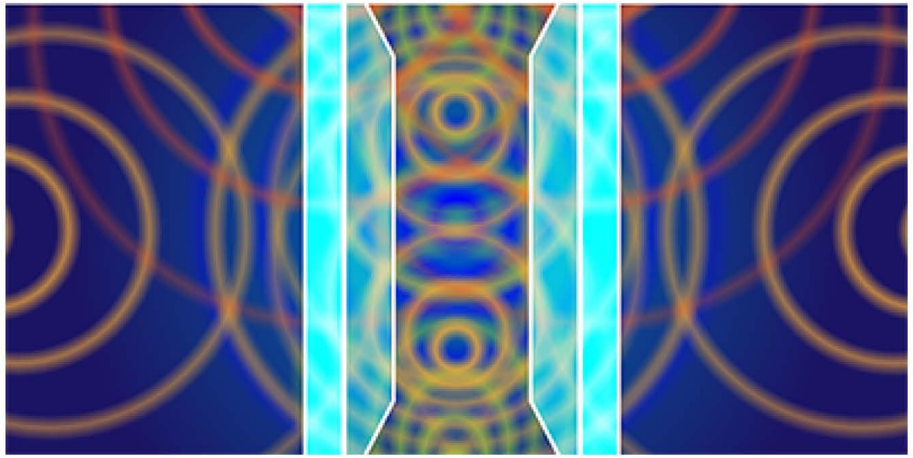
Causal structure coupled to quantum superpositions of mass-energy

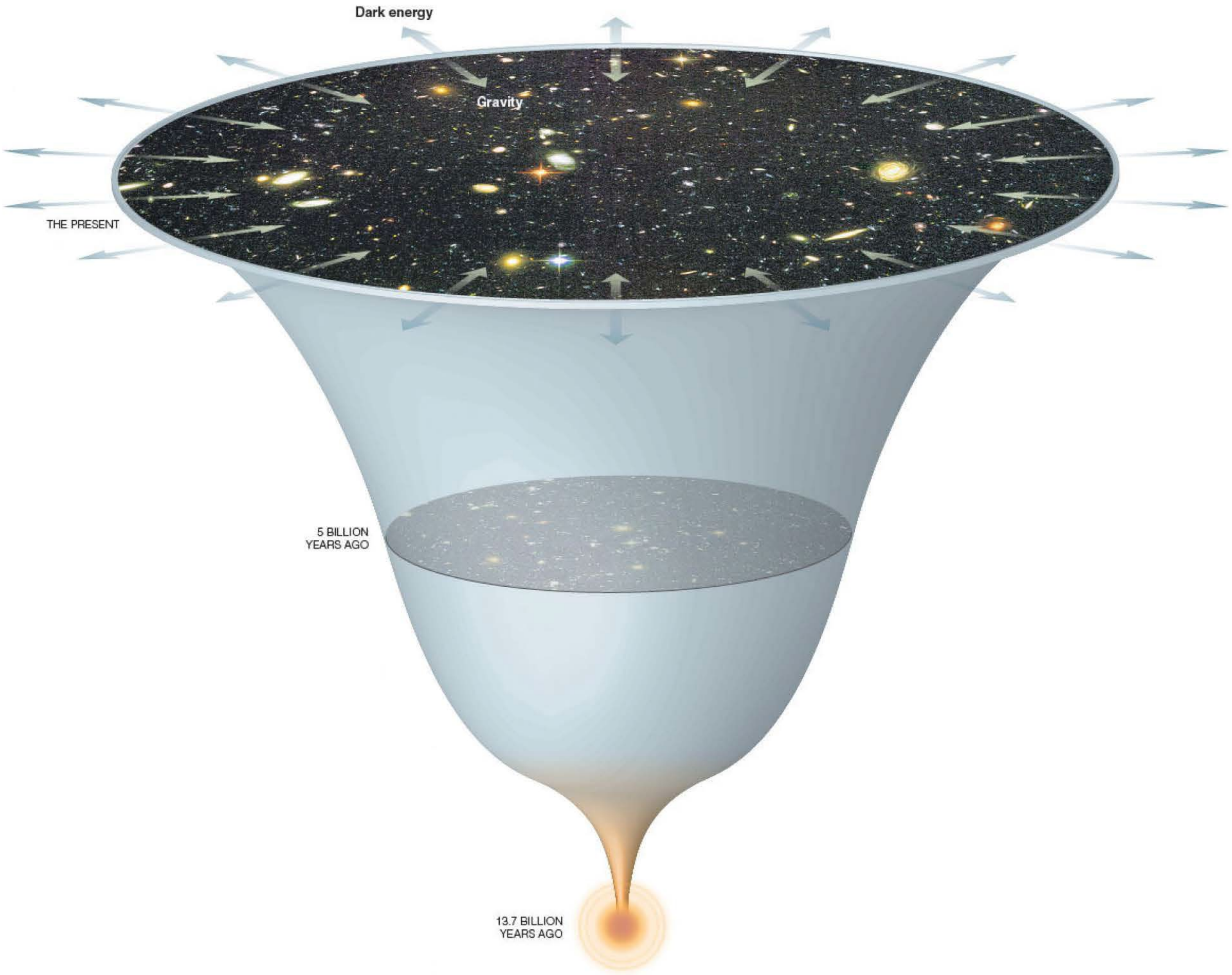


Zych et al., Nat. Comm. **10**, 3772

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.





Holographic entropy in flat 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!*

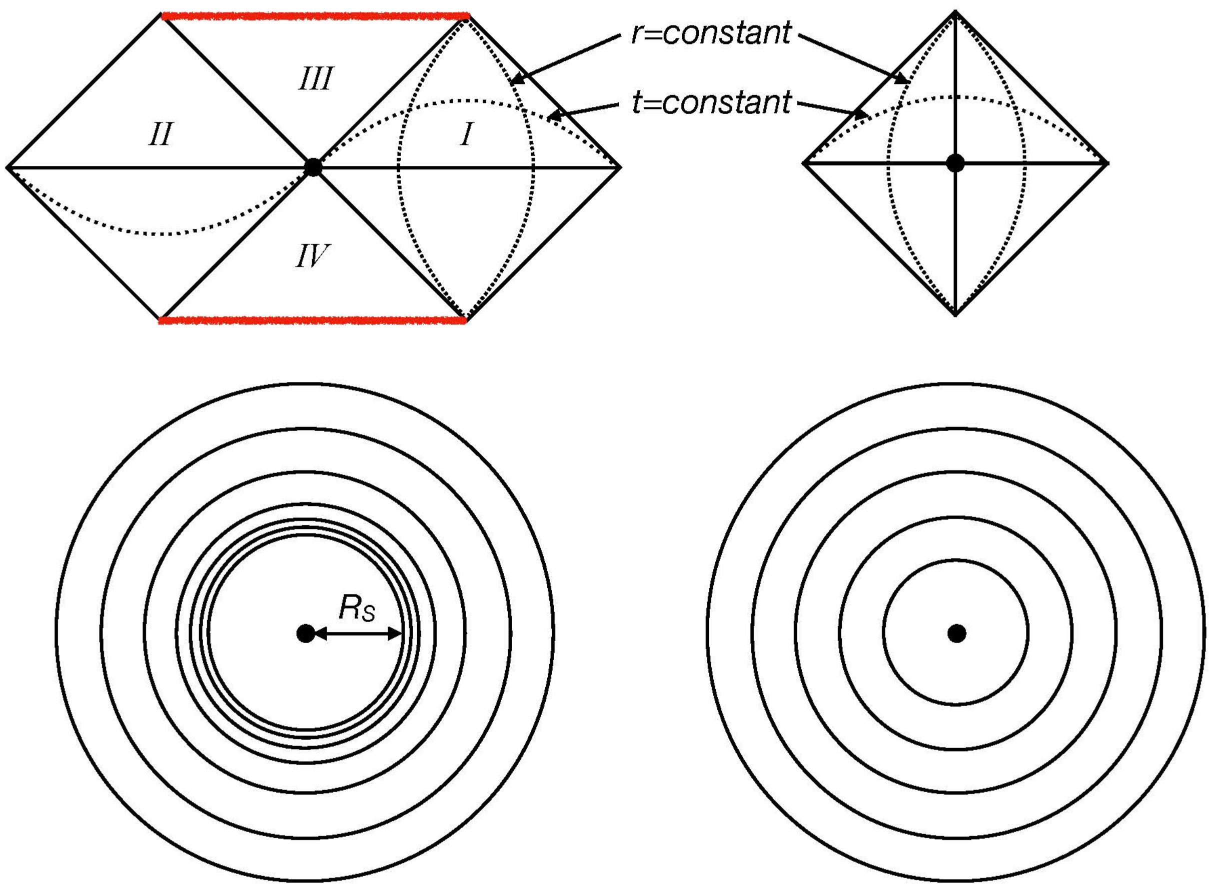
$$S_{BH} = \frac{kA}{4\ell_P^2}$$

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!

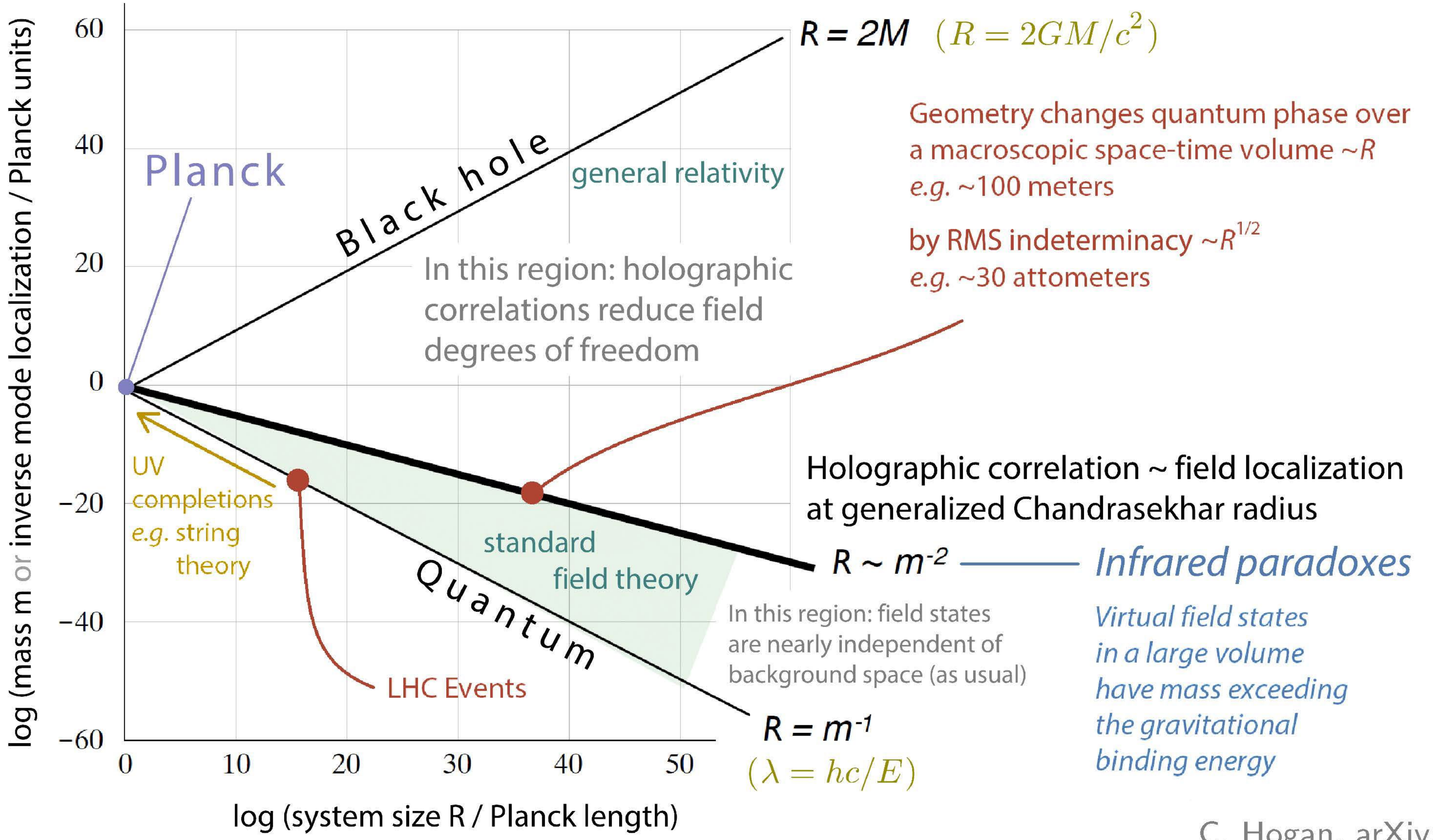
CKN, PRL **82**, 4971



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

Cosmological constant = IR boundary condition on total d.o.f. — Banks & Fischler, 1810.01671 & 1811.00130

IR regime might show signatures from quantum correlations of the background



C. Hogan, arXiv:1412.1807

Causal structure of background inevitably coupled to quantum states via gravity

"[because of] the holistic nature of renormalization theory...

an individual mode will have no way of knowing whether its own

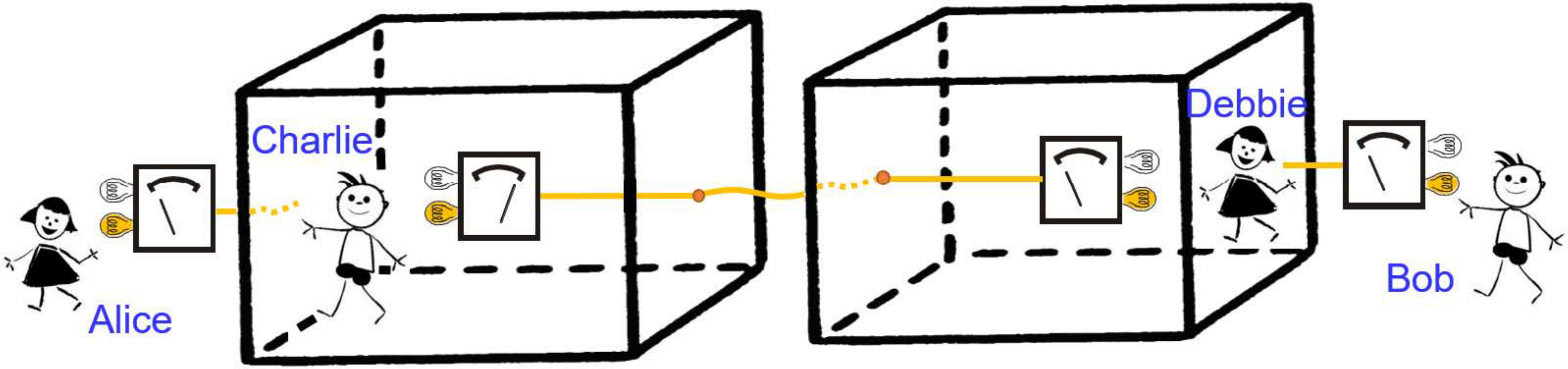
subtraction is correct unless it 'knows' how the subtractions are

being done for all other modes."

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

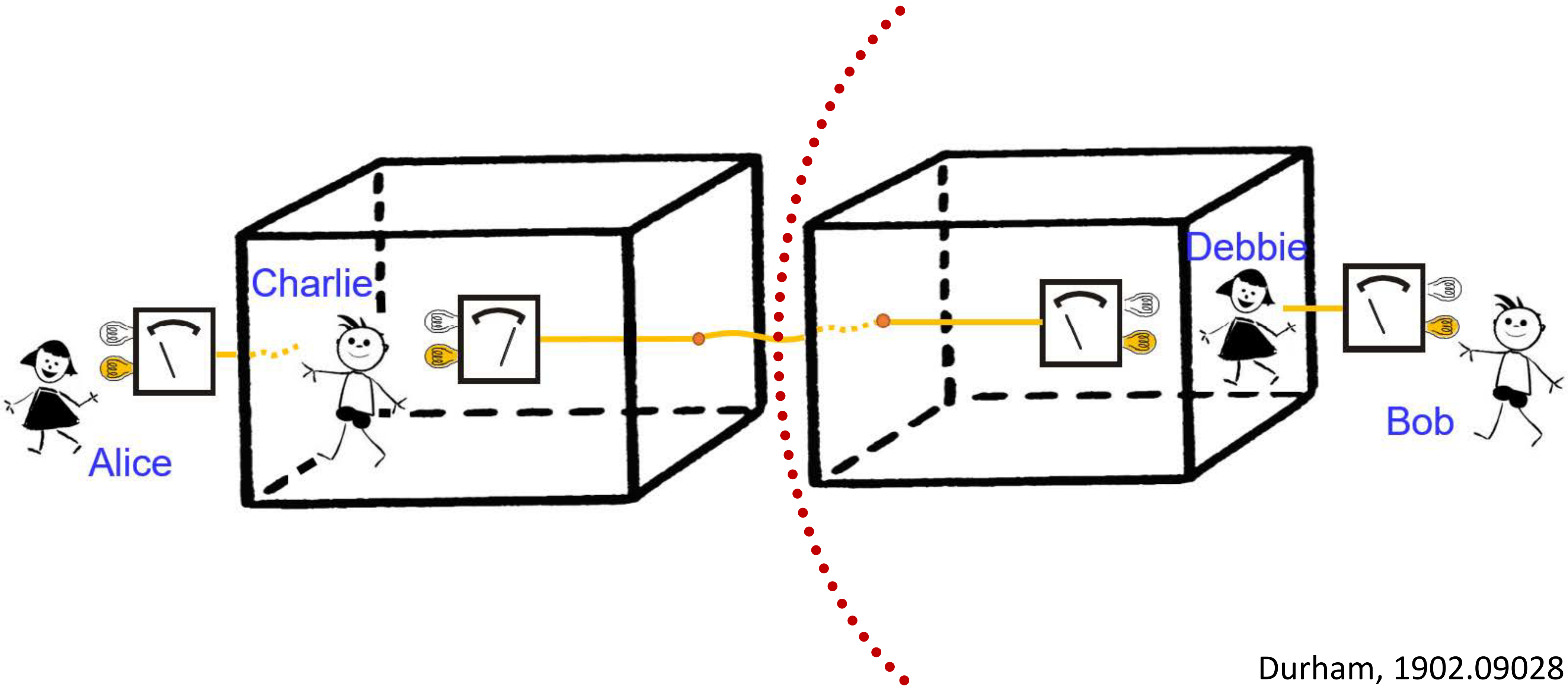
QFT insists that vacuum energy must be subtracted in local and covariant manner, but renormalization assumes a globally Minkowskian background, which cannot be correct.

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



Brukner, Entropy **20**, 350 / Frauchiger & Renner, Nat. Comm. **9**, 3711

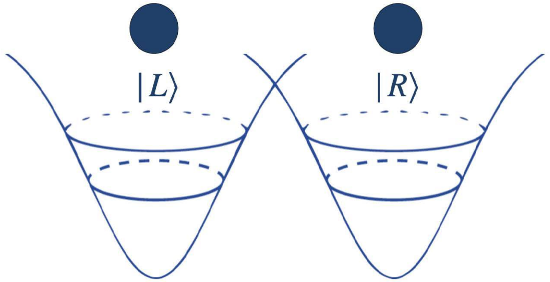
Perhaps resolved when Rindler horizons are considered!



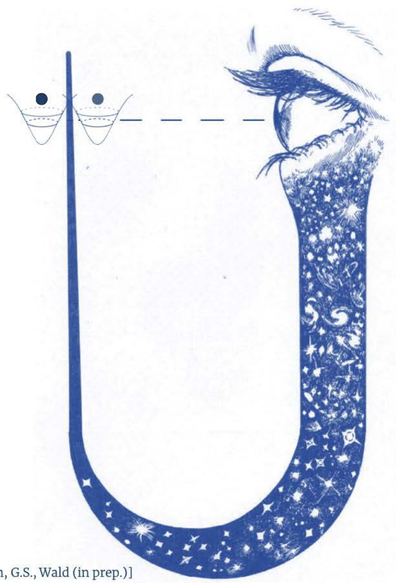
Durham, 1902.09028

Horizons act as quantum-classical boundaries.

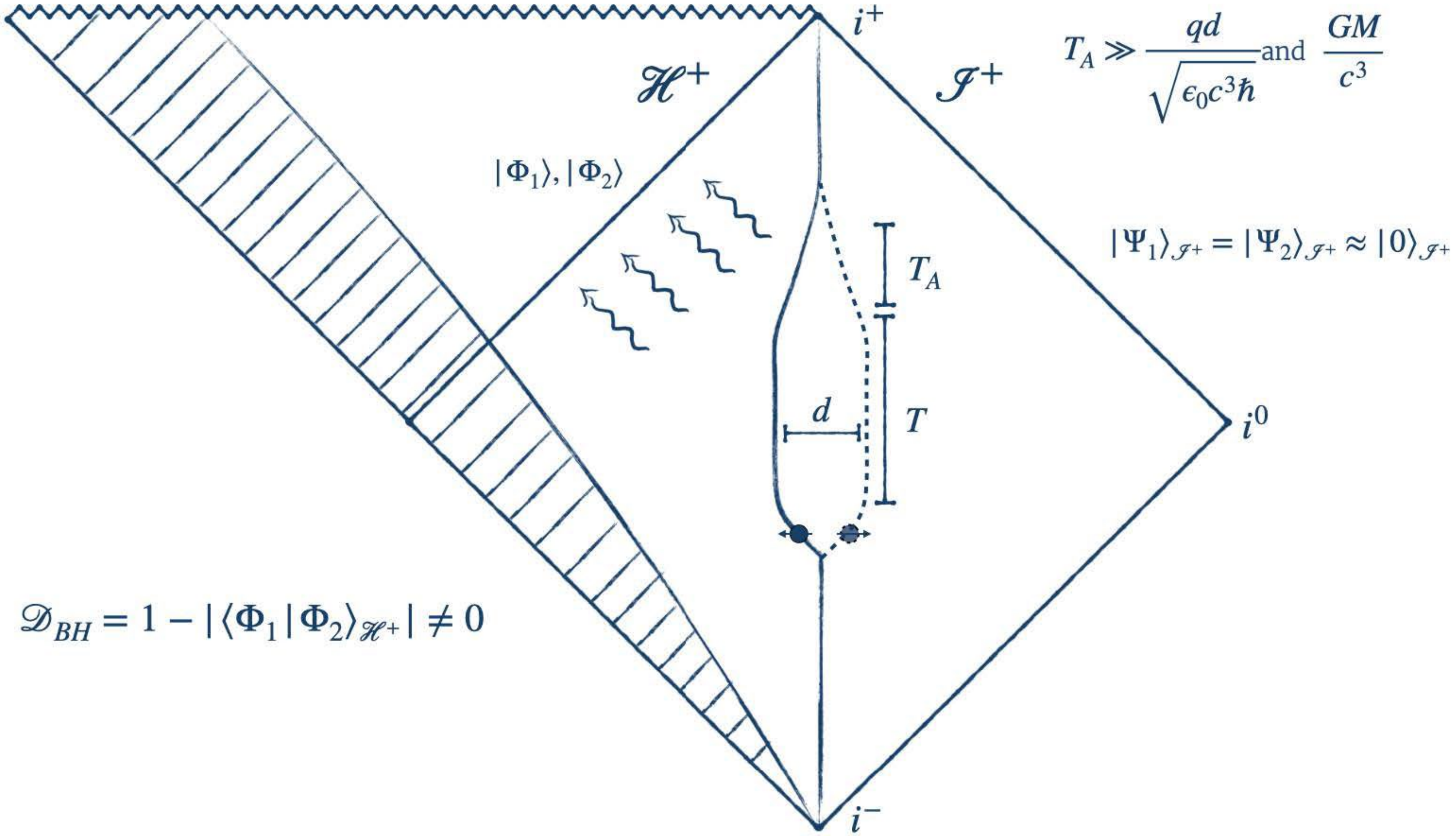
All Killing horizons cause decoherence



[Bose et al. 2017], [Marletto et al. 2017],[Aspelmeyer et al., 2011-now], ...



[Wheeler, Frontiers of Time (1979)], [Danielson, G.S., Wald (in prep.)]



Figures from Gautam Satishchandran

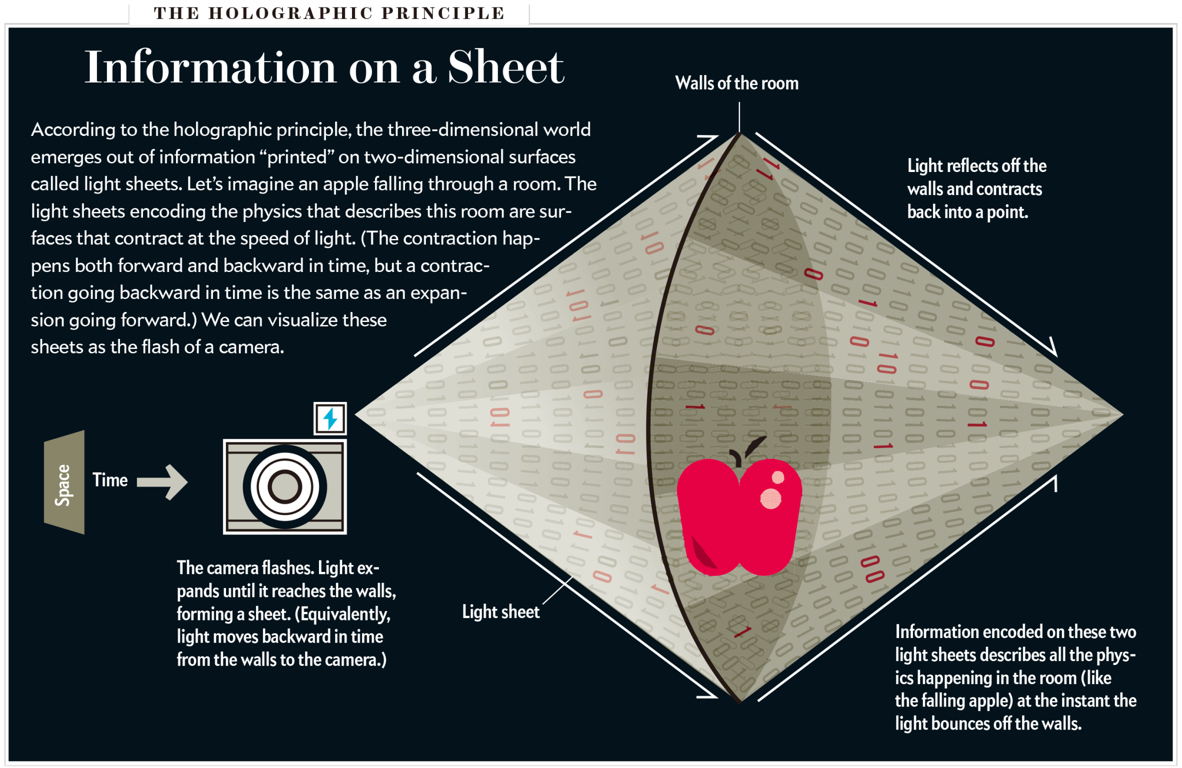
Danielson, Satishchandran, and Wald, IJMPD **31**, 2241003 + 2301.00026

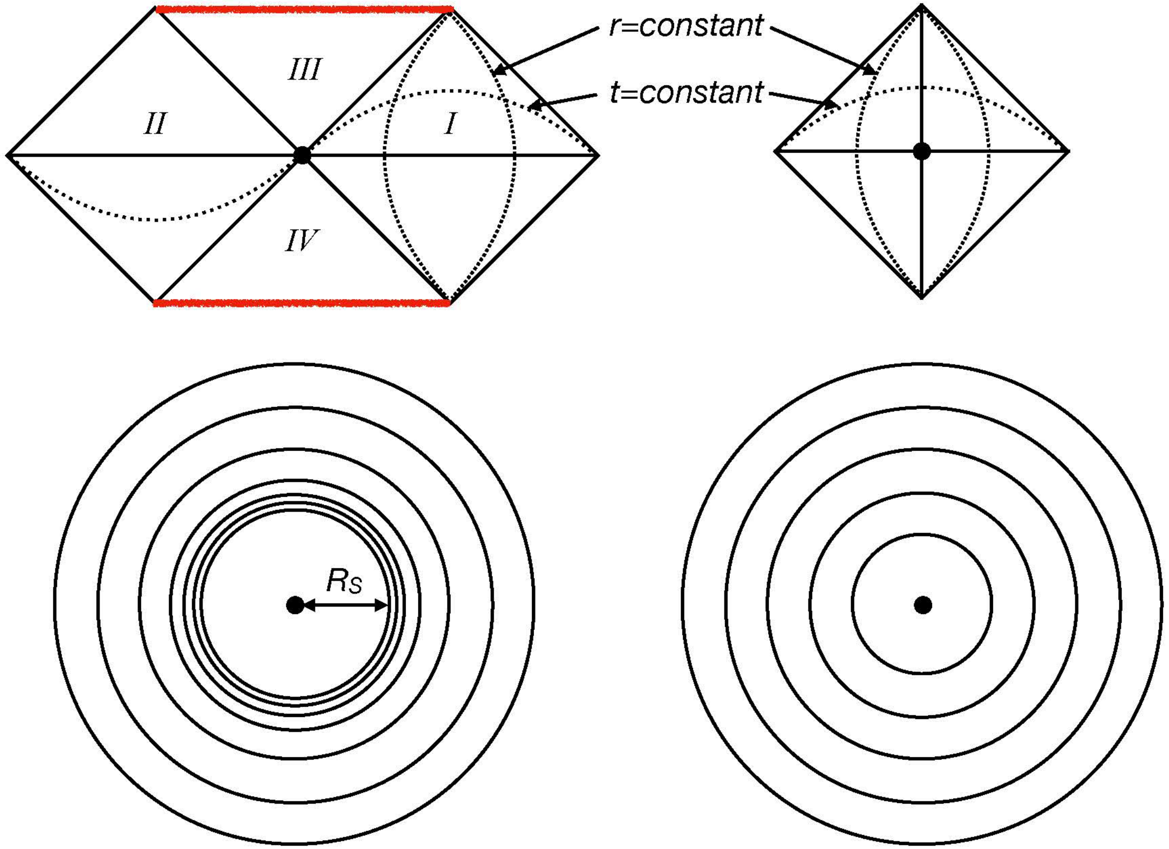
The main thesis of our research program: **“Holographic noise”** in space-time

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.**

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

Causal horizons as universal boundaries of coherent quantum information





Causal horizons have coherent quantum states

Standard quantum limit for mass m, duration τ

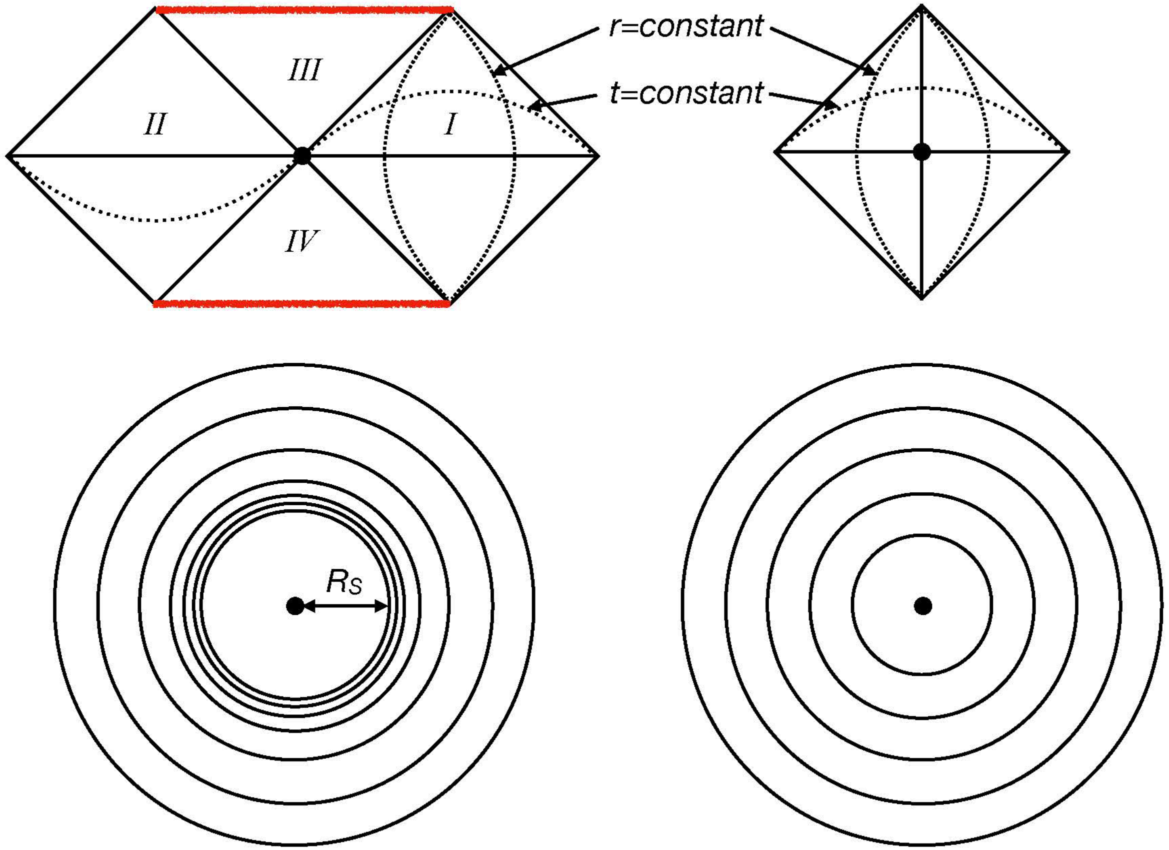
$$\left\langle \Delta x^2 \right\rangle \gtrsim \hbar\tau/m$$

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

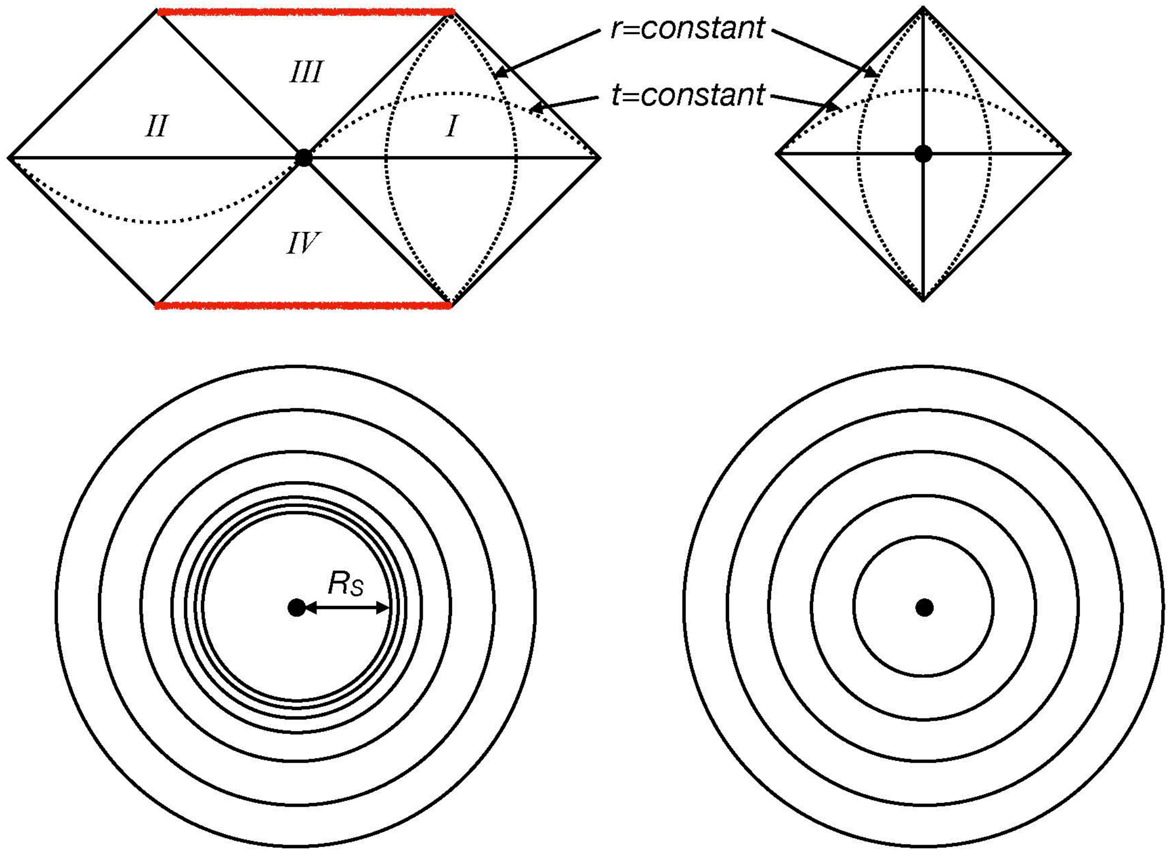
’t Hooft’s algebra for black hole information

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

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

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

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



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)

Angular correlation of fluctuations of holographic boundaries

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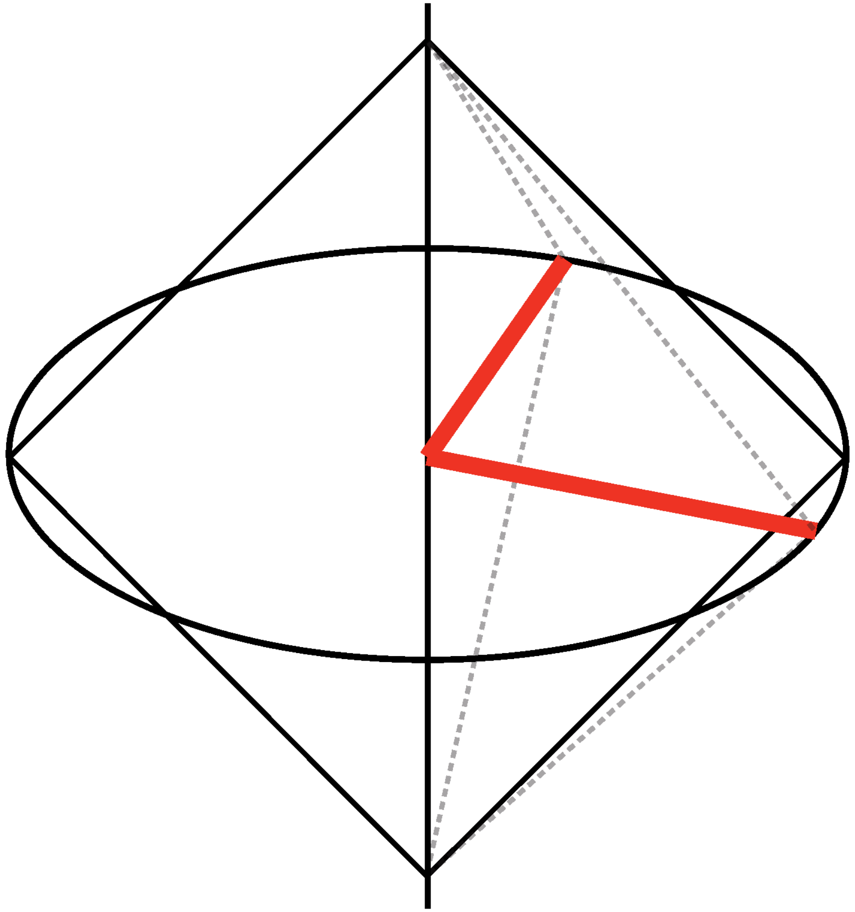

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VZ, PLB **822**, 136663

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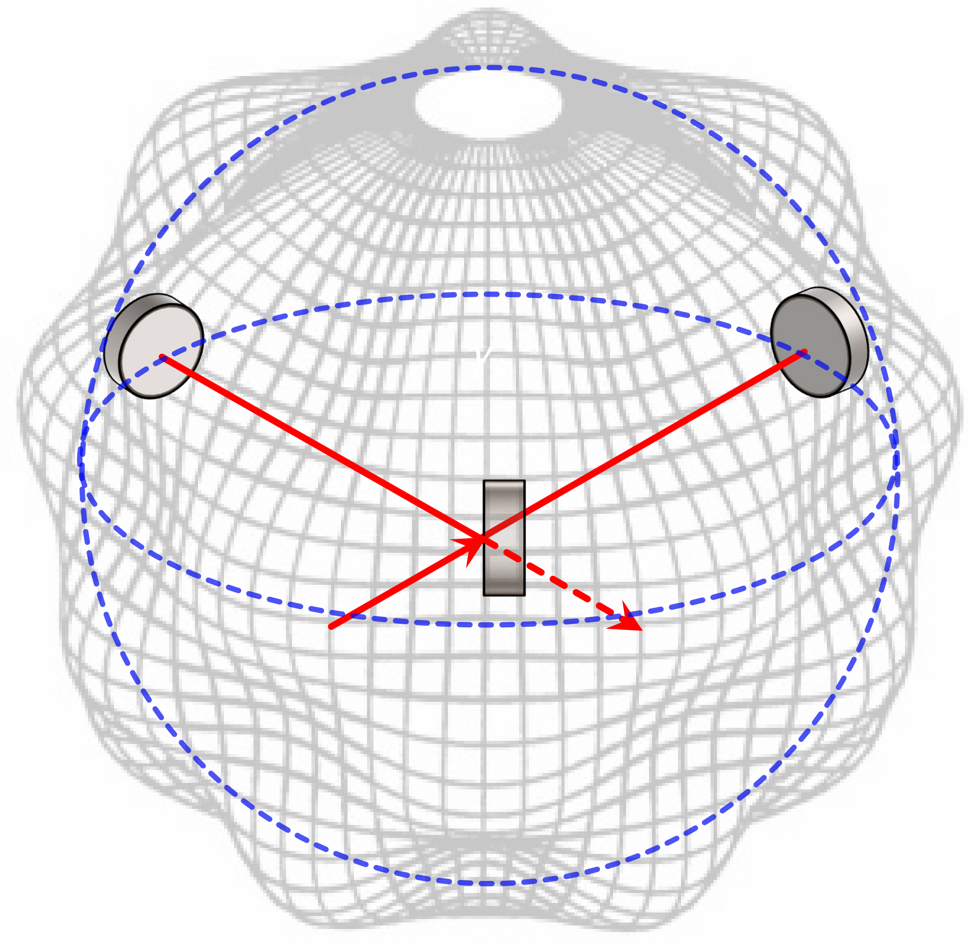
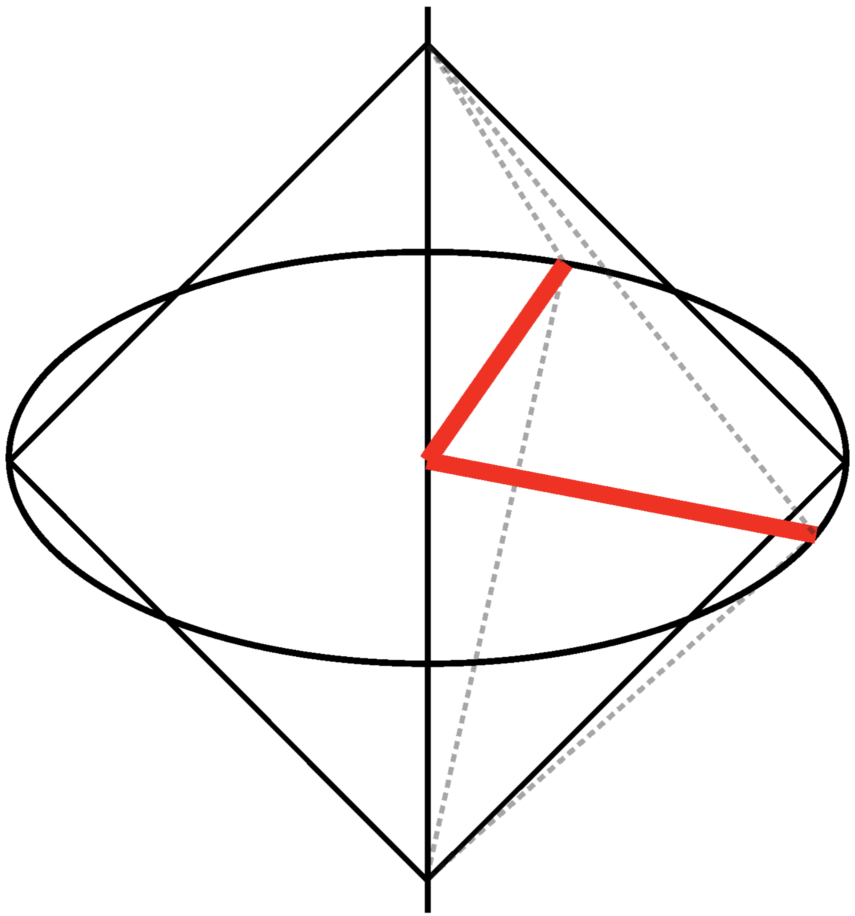
A causal diamond has coherent states like a hydrogen atom



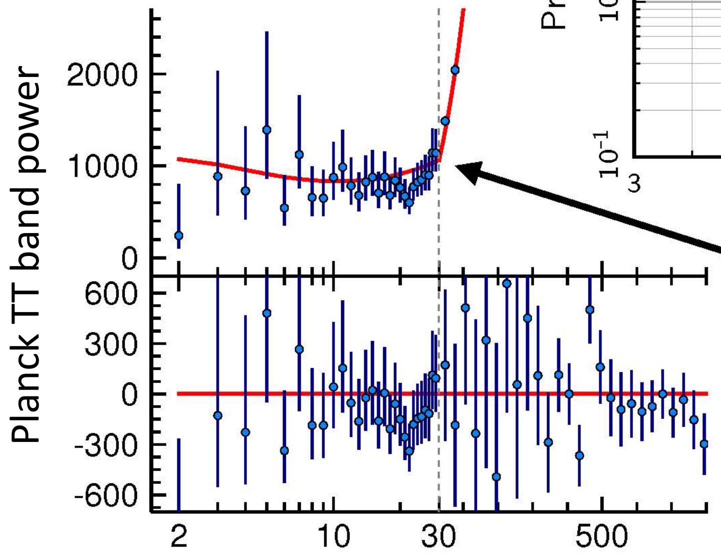


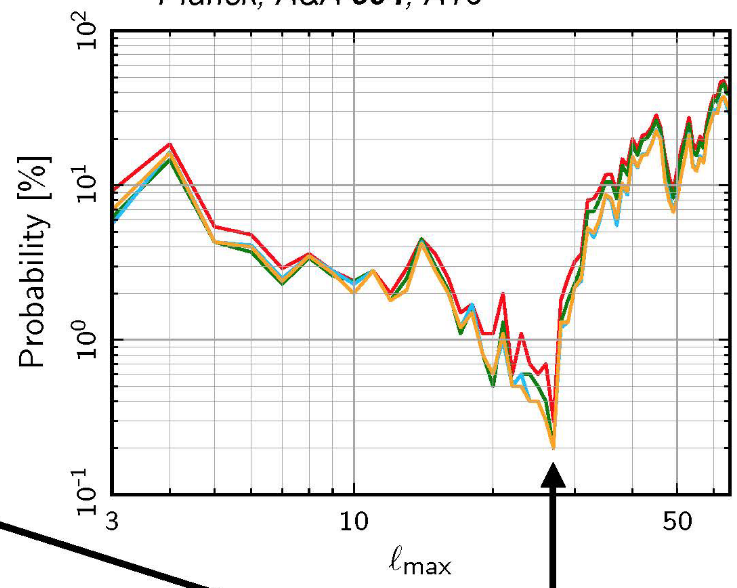
’t Hooft: odd modes only

VZ: includes all modes

CMB anomalies: holographic symmetries on the inflationary horizon?

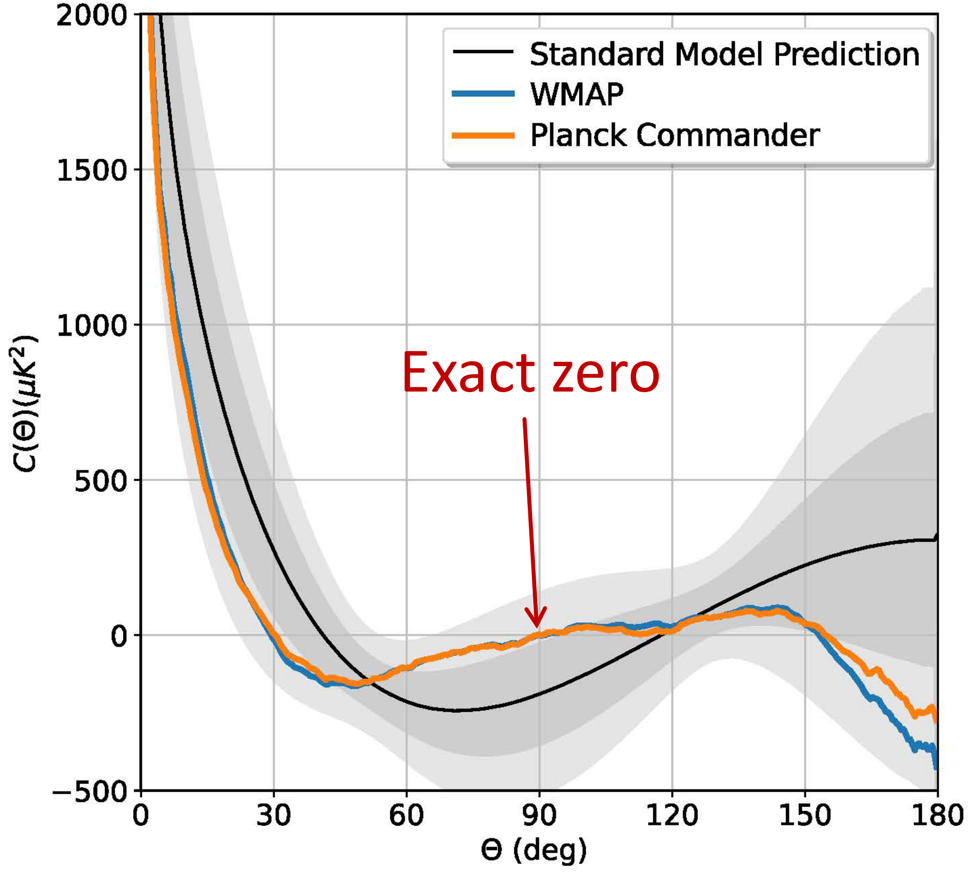
Cosmic structure is an image of primordial quantum states—
the fluctuations "froze in" at the inflationary horizon!





Odd multipoles dominate up to

$\ell \approx 28$



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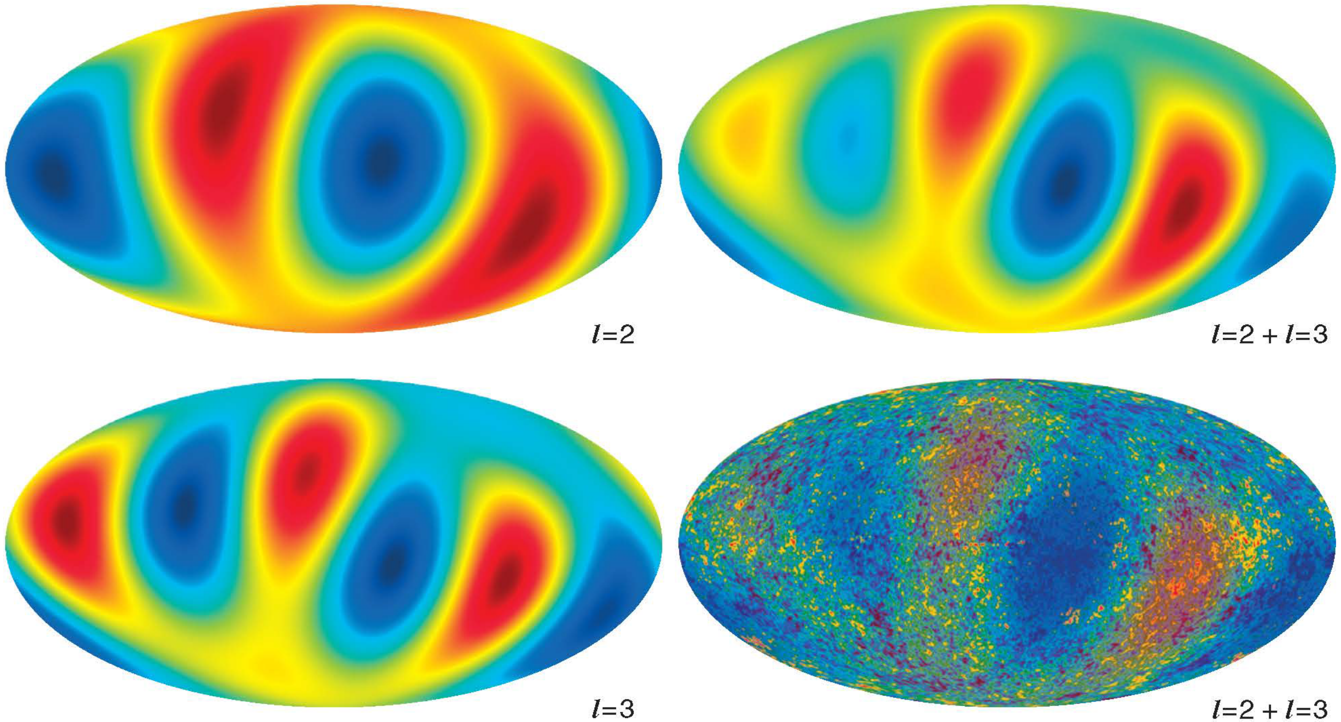
*WMAP, ApJS **192**, 17*



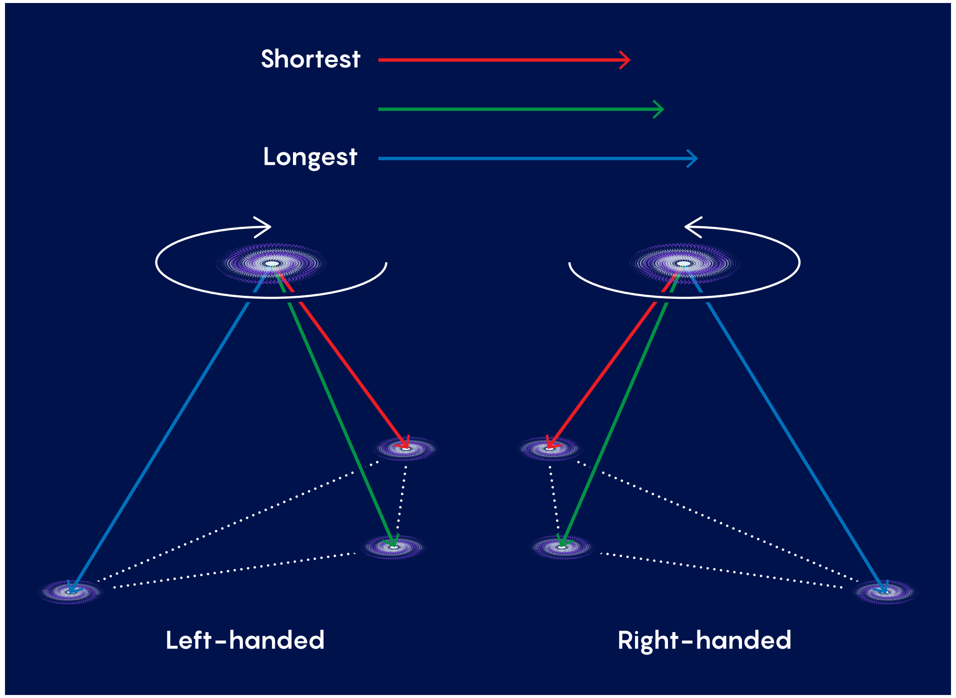
*CQG **33**, 184001*

feature	p-value	data
in angular space		
low variance ($N_{\rm side} = 16$)	$\leq 0.5\%$	Planck 15
2-pt correlation $\chi^2(\theta > 60°)$	$\leq 3.2\%$	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 $\ell_{\rm max} = 28$	$< 0.3\%$	Planck 15
odd parity preference $\ell_{\rm max} < 50$ (LEE)	$< 2\%$	Planck 15
dipolar modulation for $\ell = 2 - 67$	$\leq 1\%$	Planck 15

Parity violation in large-scale structure?

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

2.9σ — Philcox, PRD **106**, 063501 + 2303.12106



Causal horizons as the basis of our standard description of space-time

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

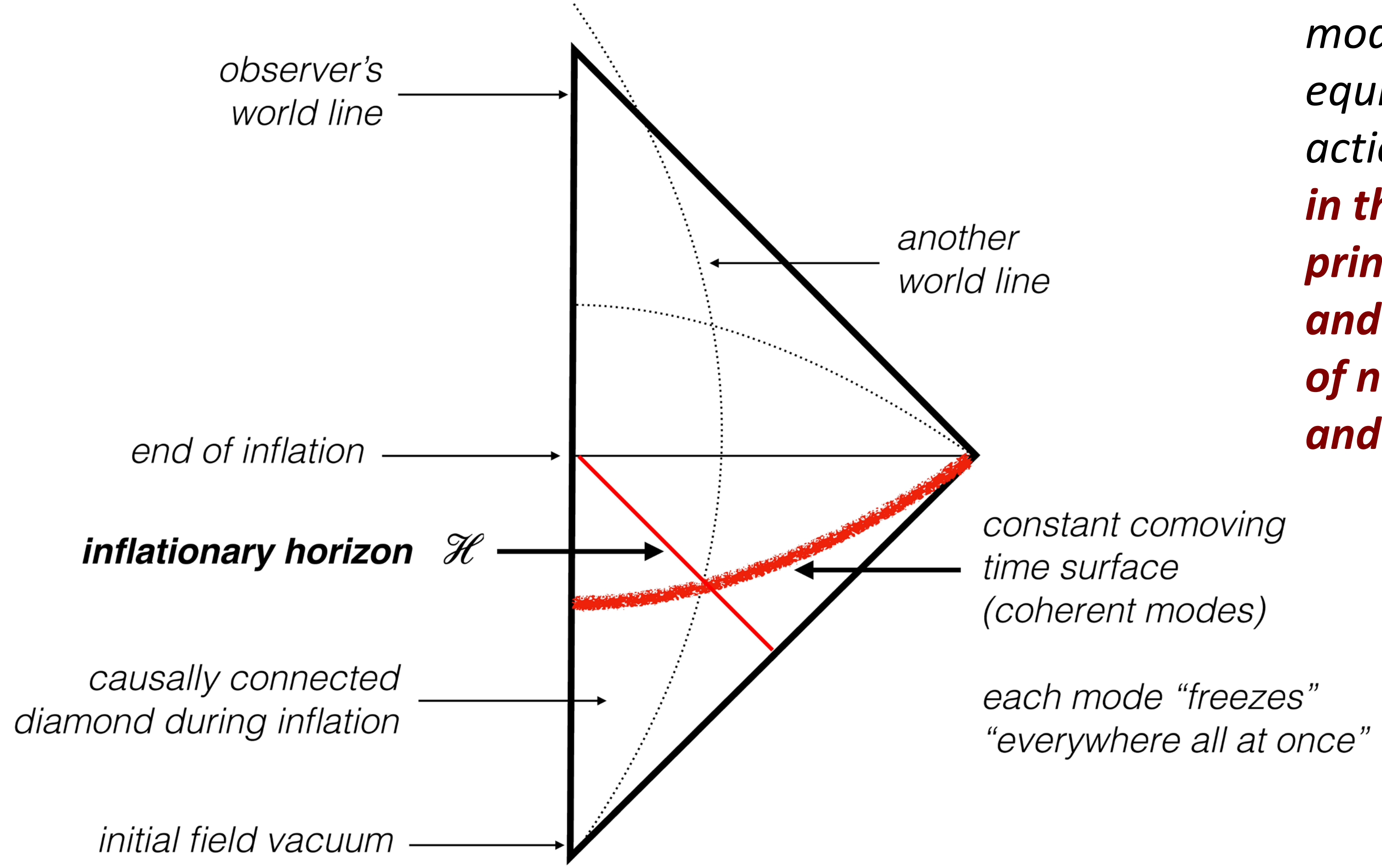


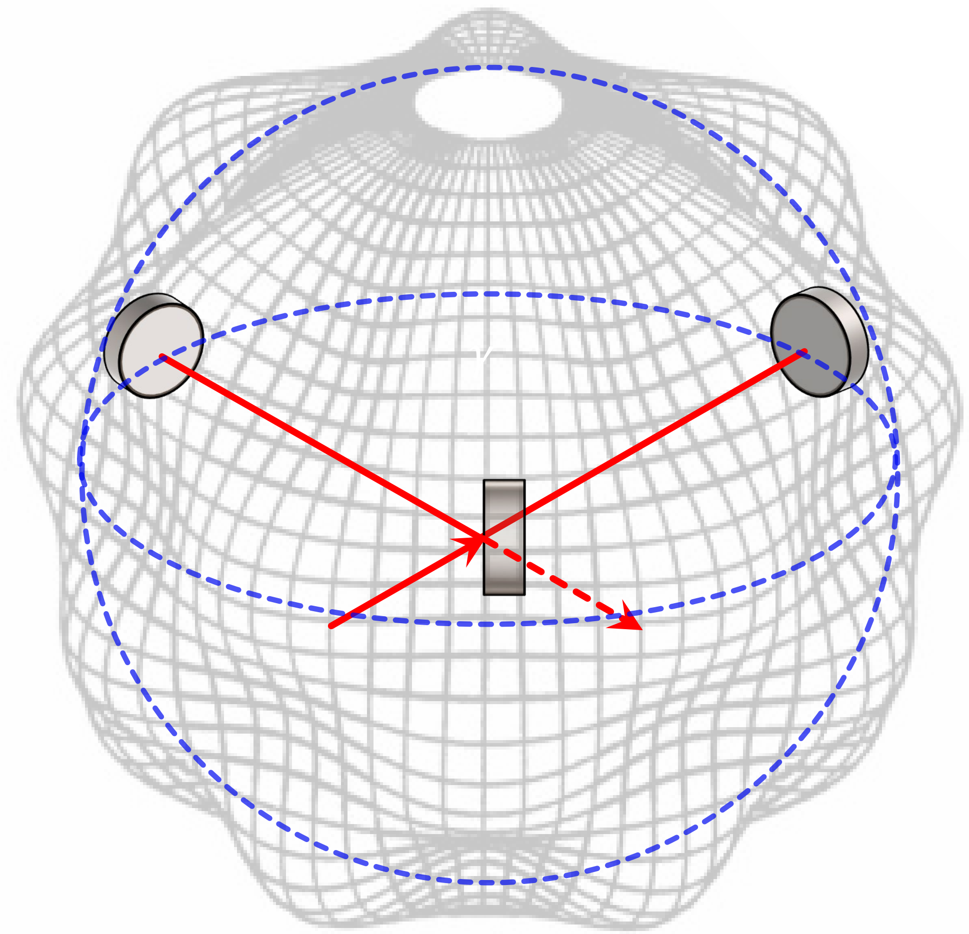
Figure by Craig Hogan

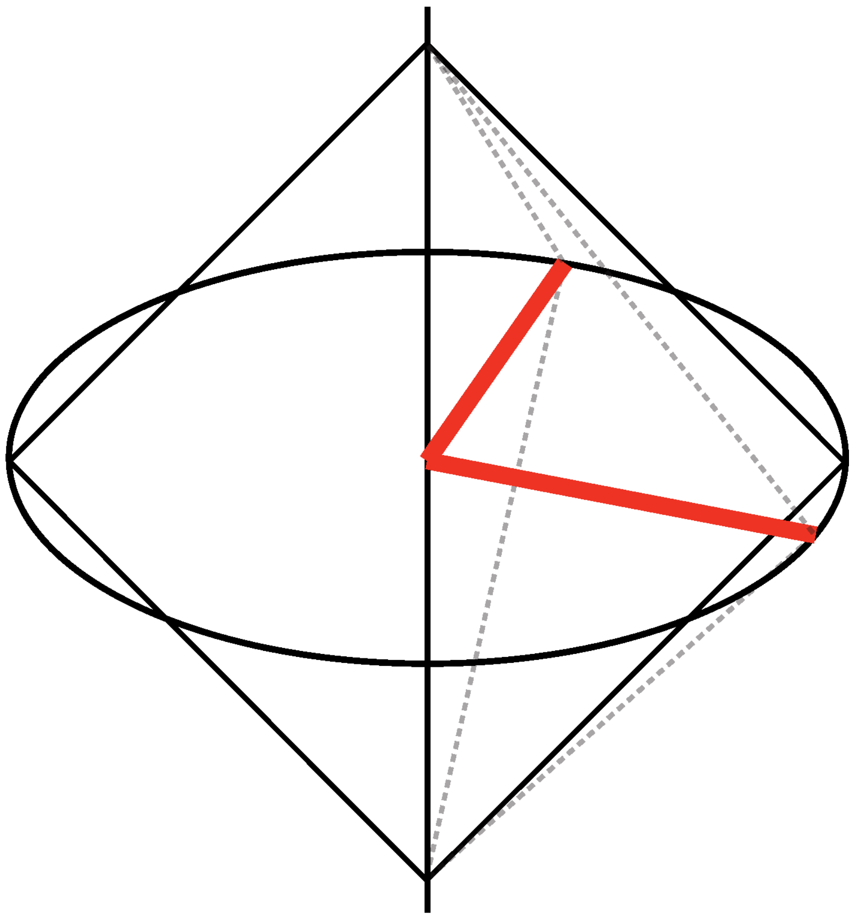
"Just as the proper recognition of this atomicity requires in the electromagnetic theory a modification in the use of the field concept equivalent to the introduction of the concept of action at a distance, so it would appear that ***in the gravitational theory we should be able in principle to dispense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

A causal diamond has coherent states like a hydrogen atom

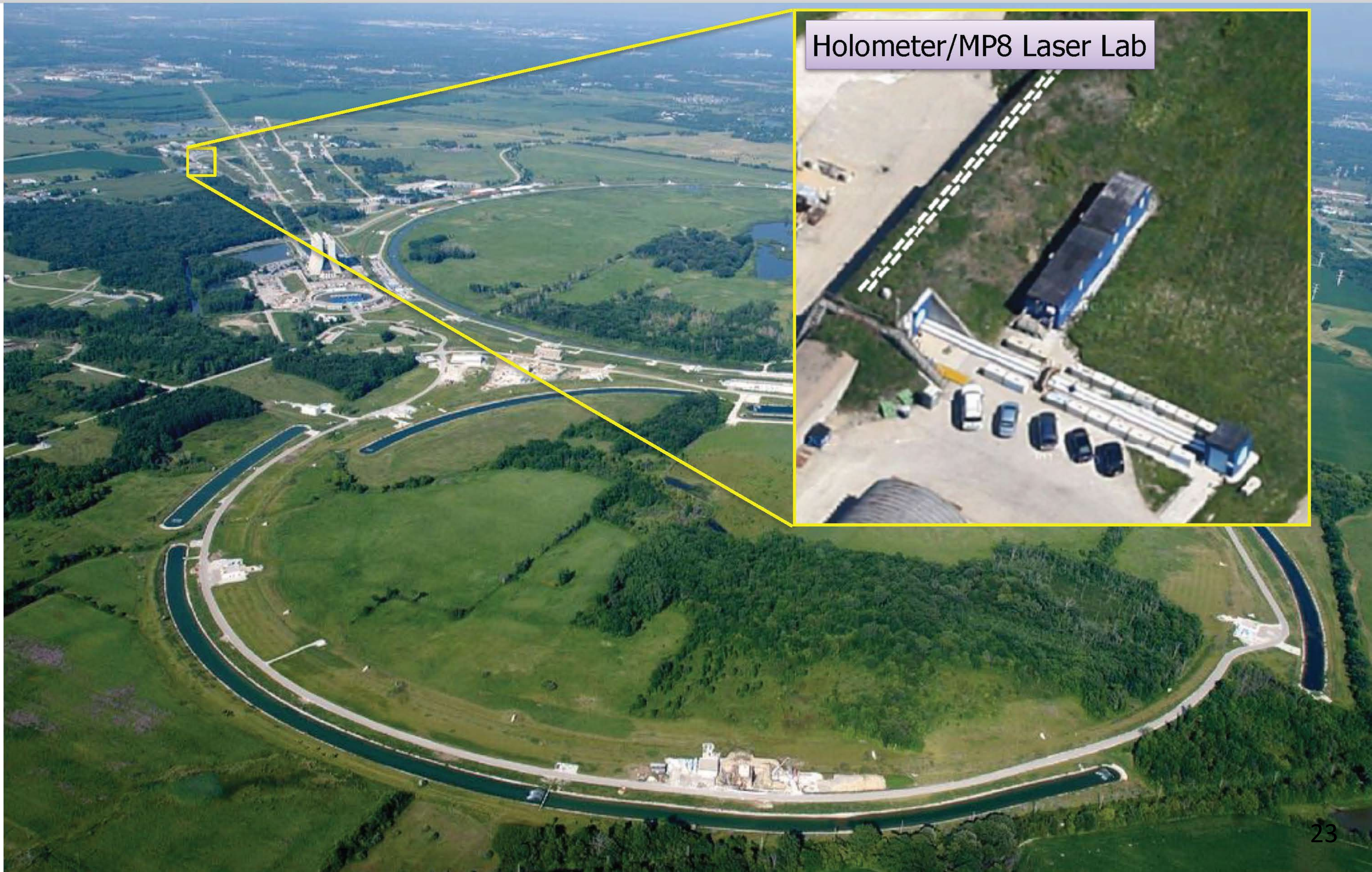




’t Hooft: odd modes only

VZ: includes all modes

The Holometer (2009 – 2020)



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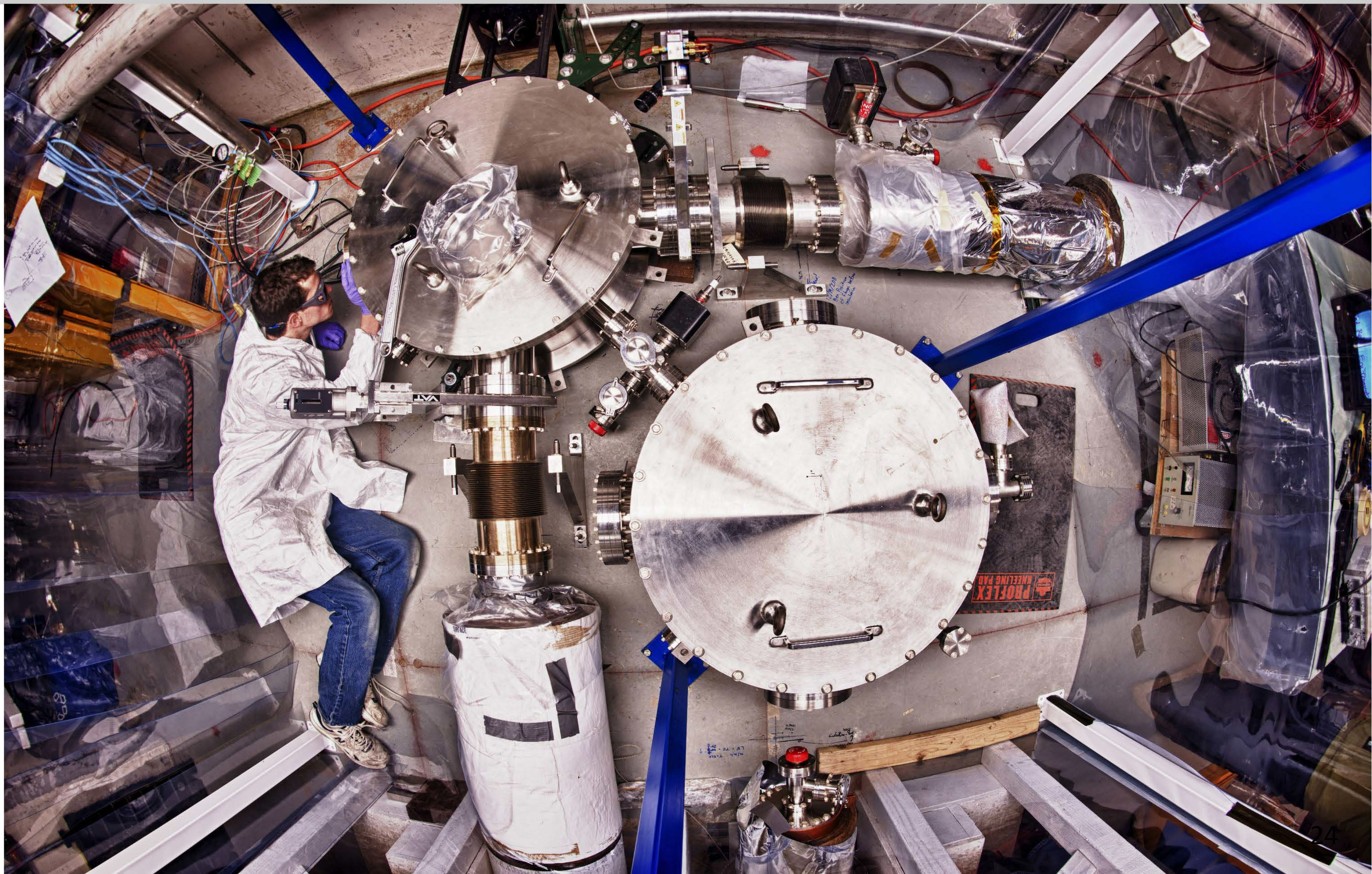


The Holometer (2009 – 2020)

The Holometer: Sub-Planckian strain PSD at superluminal frequencies

Laser interferometers: the most precise in differential position measurements.

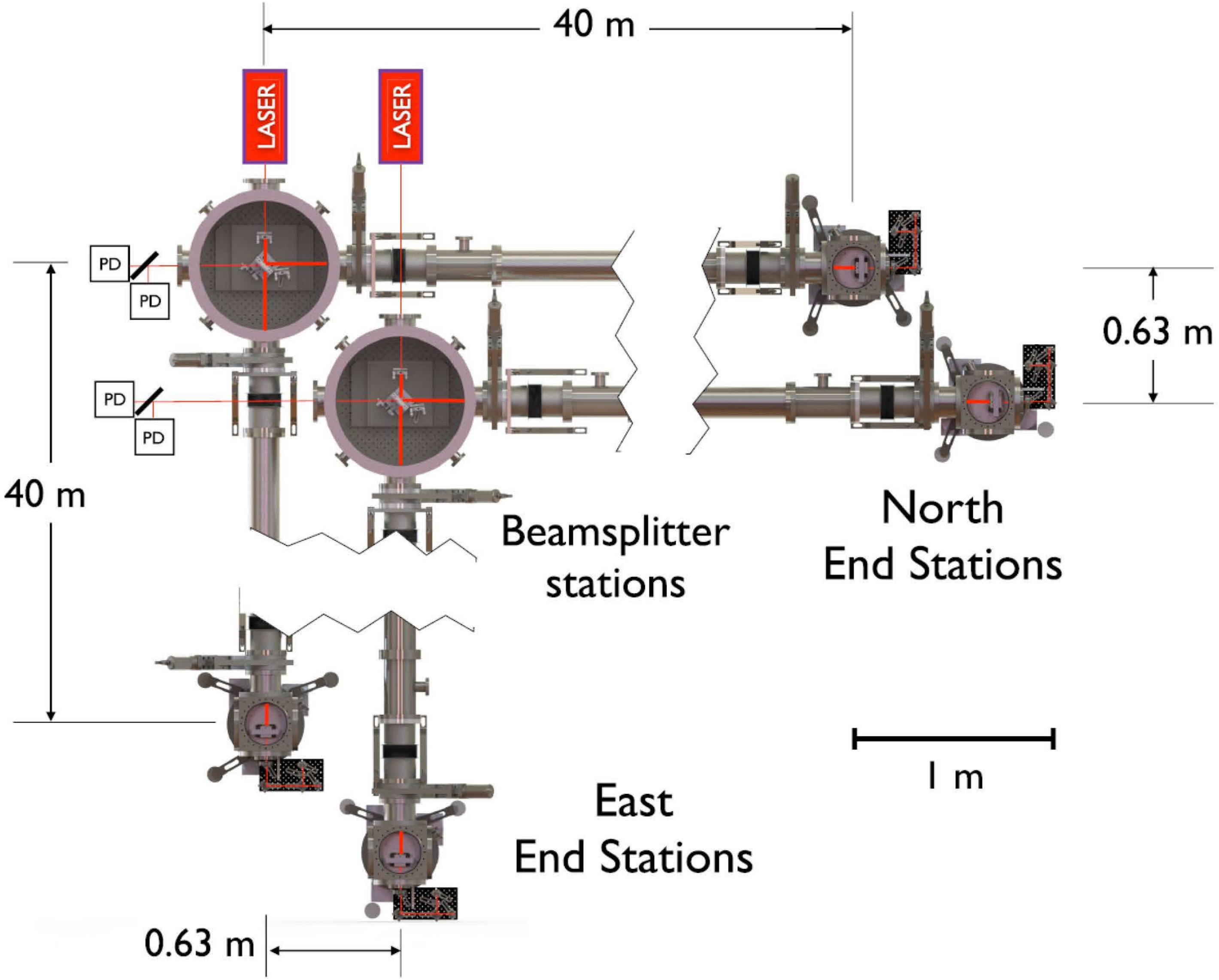
In dimensionless strain units $h \equiv \delta L/L$, the power spectral density reaches

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

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.

The Holometer: Colocated interferometers, carefully isolated



The Holometer: Interferometry far below the quantum limit

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.

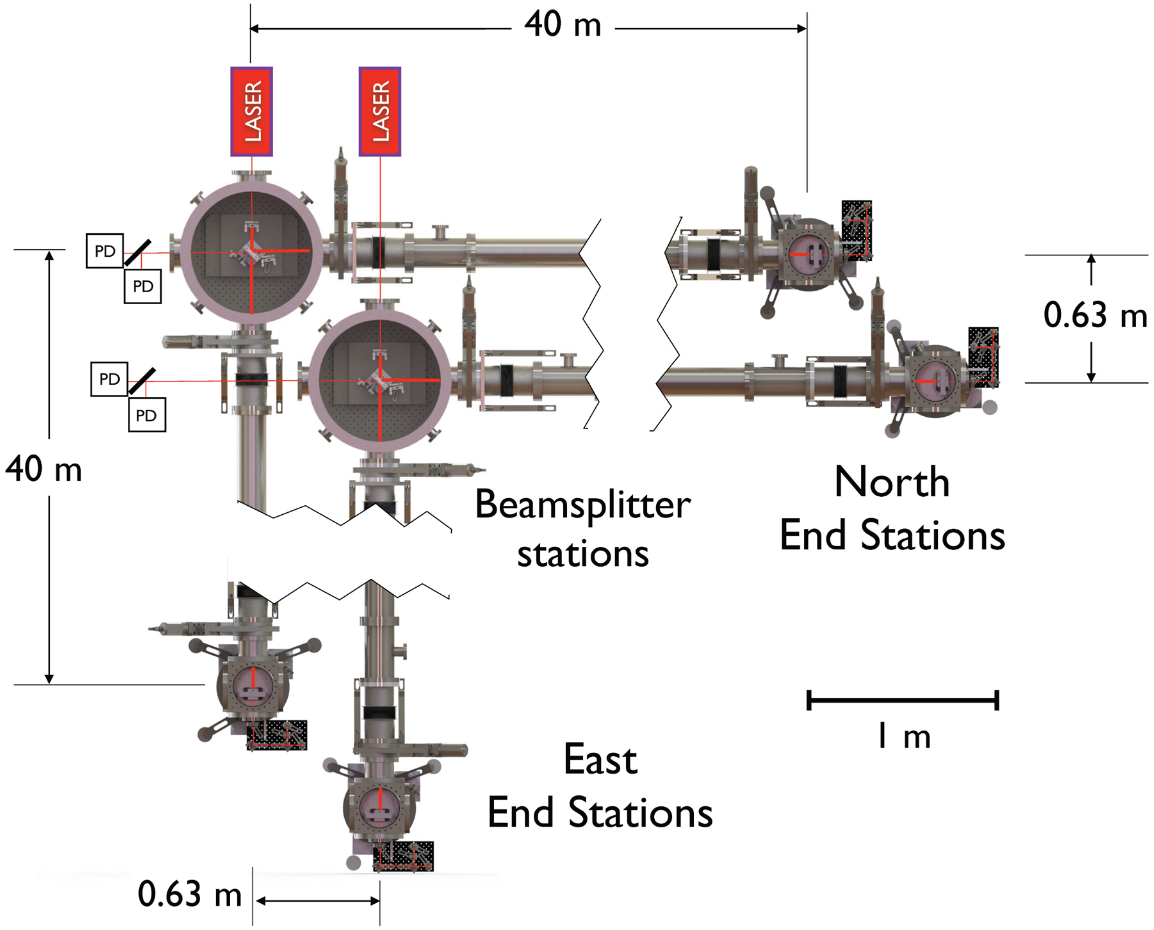
Variance scales like a **random walk** over $L = 39\,\text{m}$:

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

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

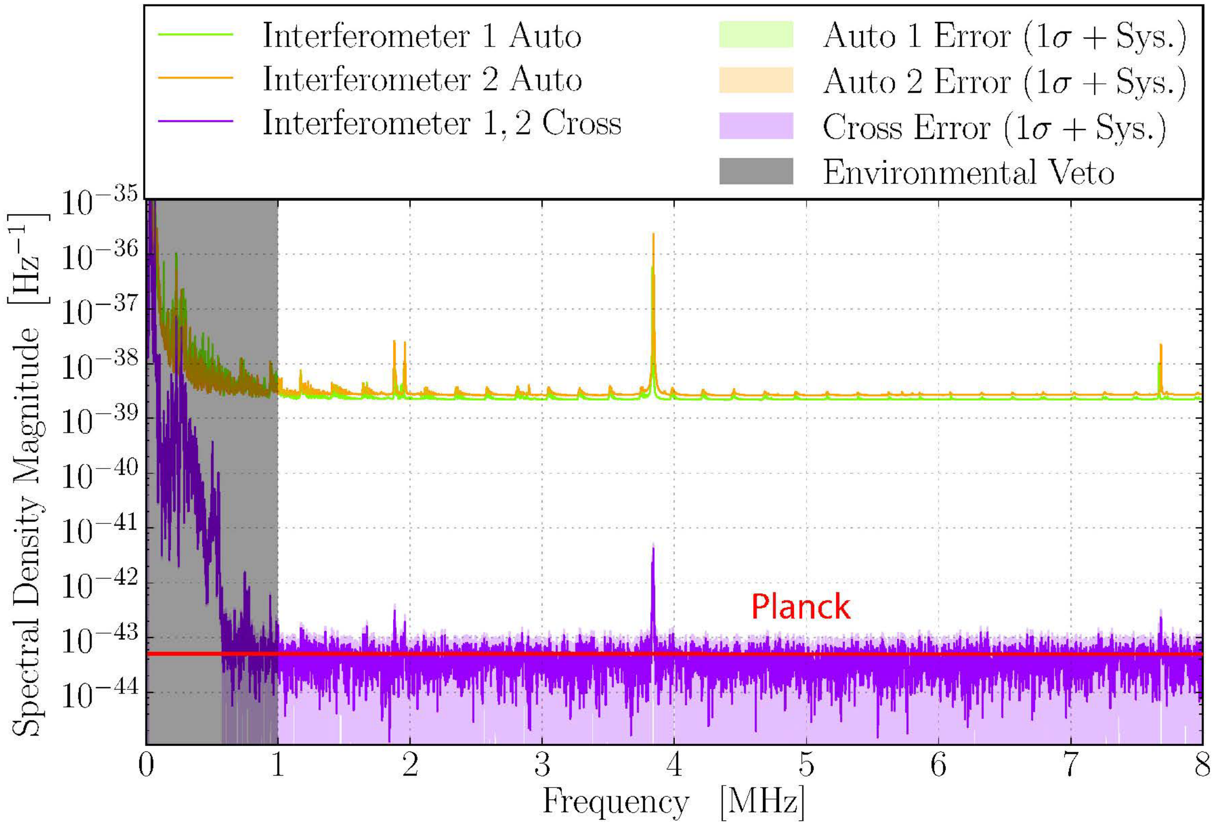
$$\tilde{h}^2(f) \approx t_P \approx 10^{-44}\,\text{s}$$

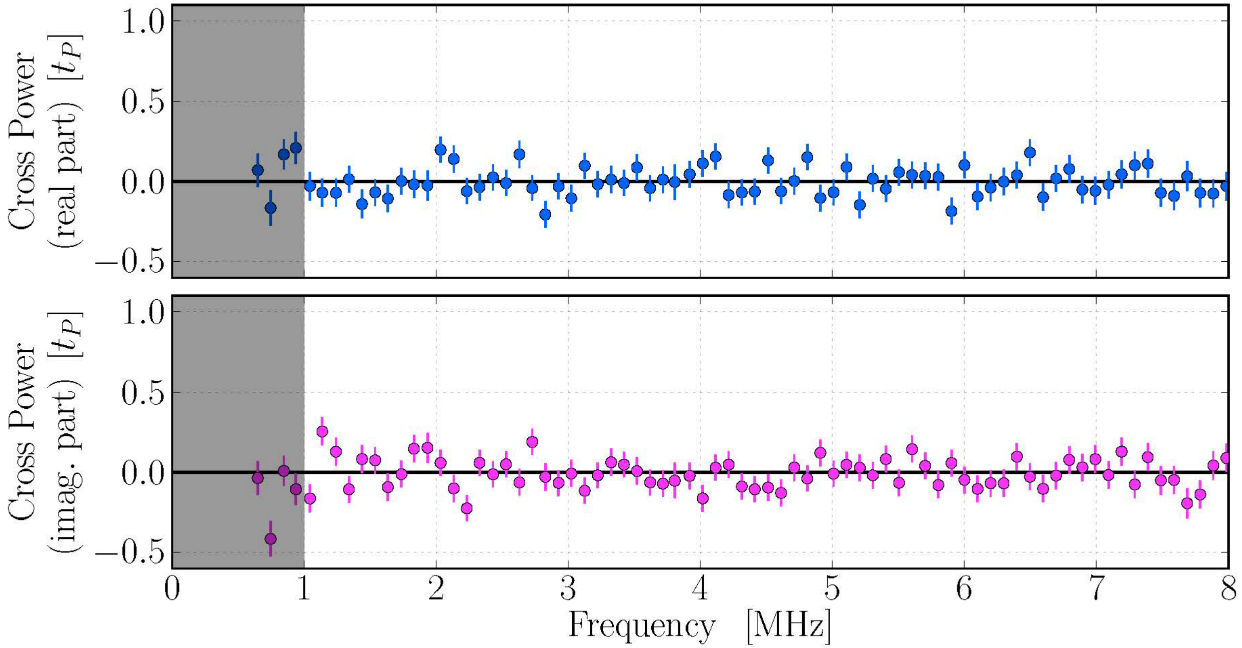
The sampling rate and bandwidth must far exceed the 7.7 MHz **inverse light crossing time**.



Incoherent noise averages down as $1/\sqrt{N}$ for *N* independent measurements (shot / thermal noise).

The Holometer: Upper limit at 0.25 Planck time (2kW, 704 hours)

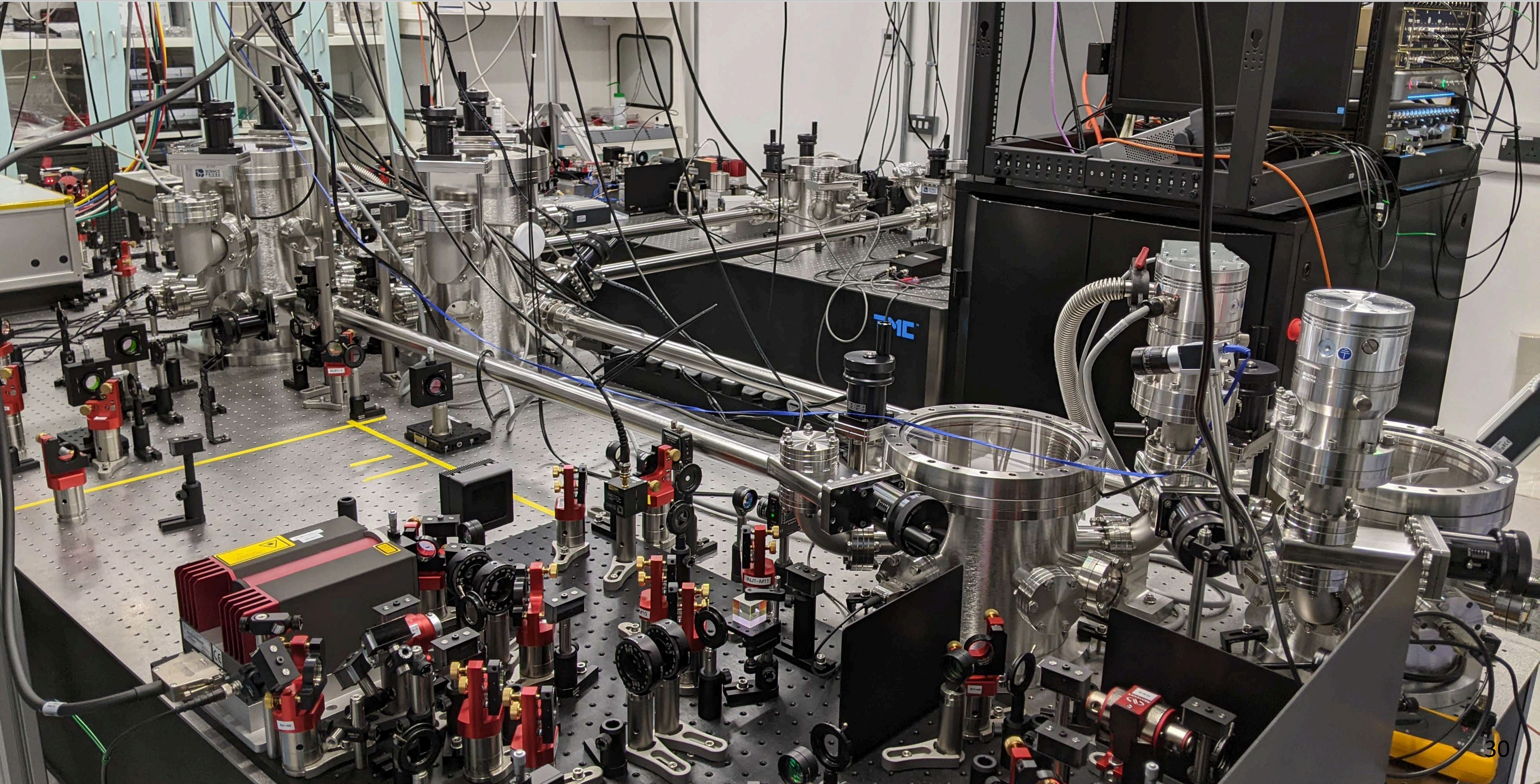




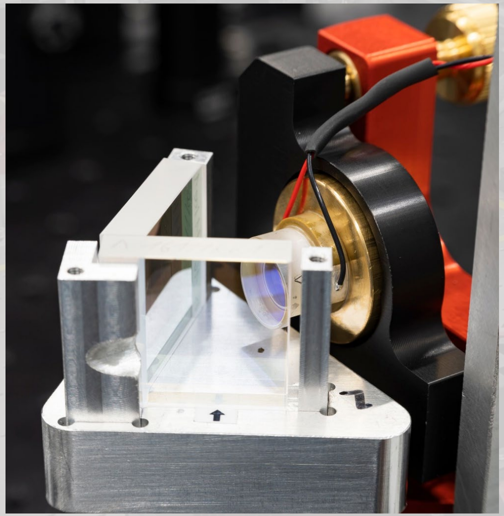
- 145 hour data — PRL **117**, 111102 (2016)
- 704 hour data — CQG **34**, 165005 (2017)
- Instrumentation — CQG **34**, 065005 (2017)
- *Clean null test for exploring general geometries.*

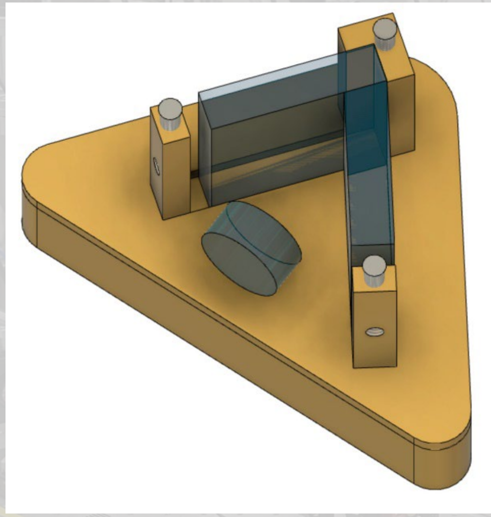
- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, **Planck** units.
- At 100 kHz, uncorrelated noise is averaged down over 2.5×10^{11} independent measurements.
- Cross-power spectral density in $\delta L/L$, normalized to $L = 39$ m, reaches an upper limit below $\mathbf{0.25}\,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

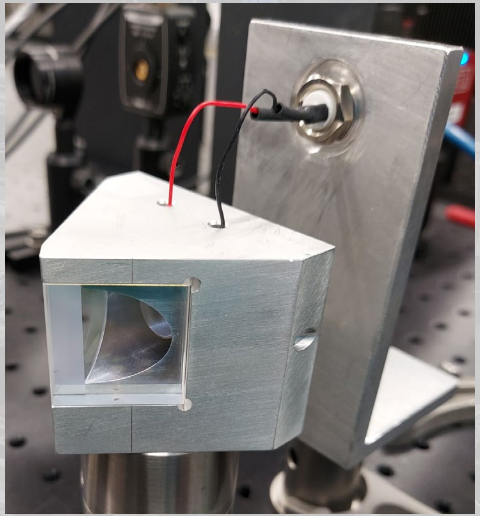
The Cardiff interferometers (1.8m prototype, 10kW design power)

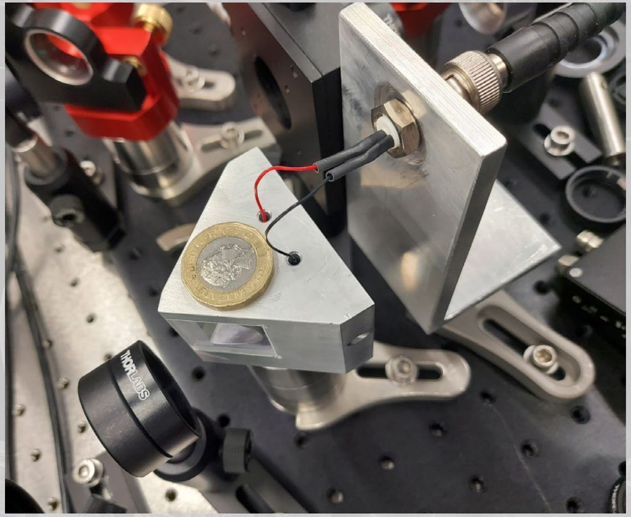


The Cardiff interferometers – Output mode cleaners

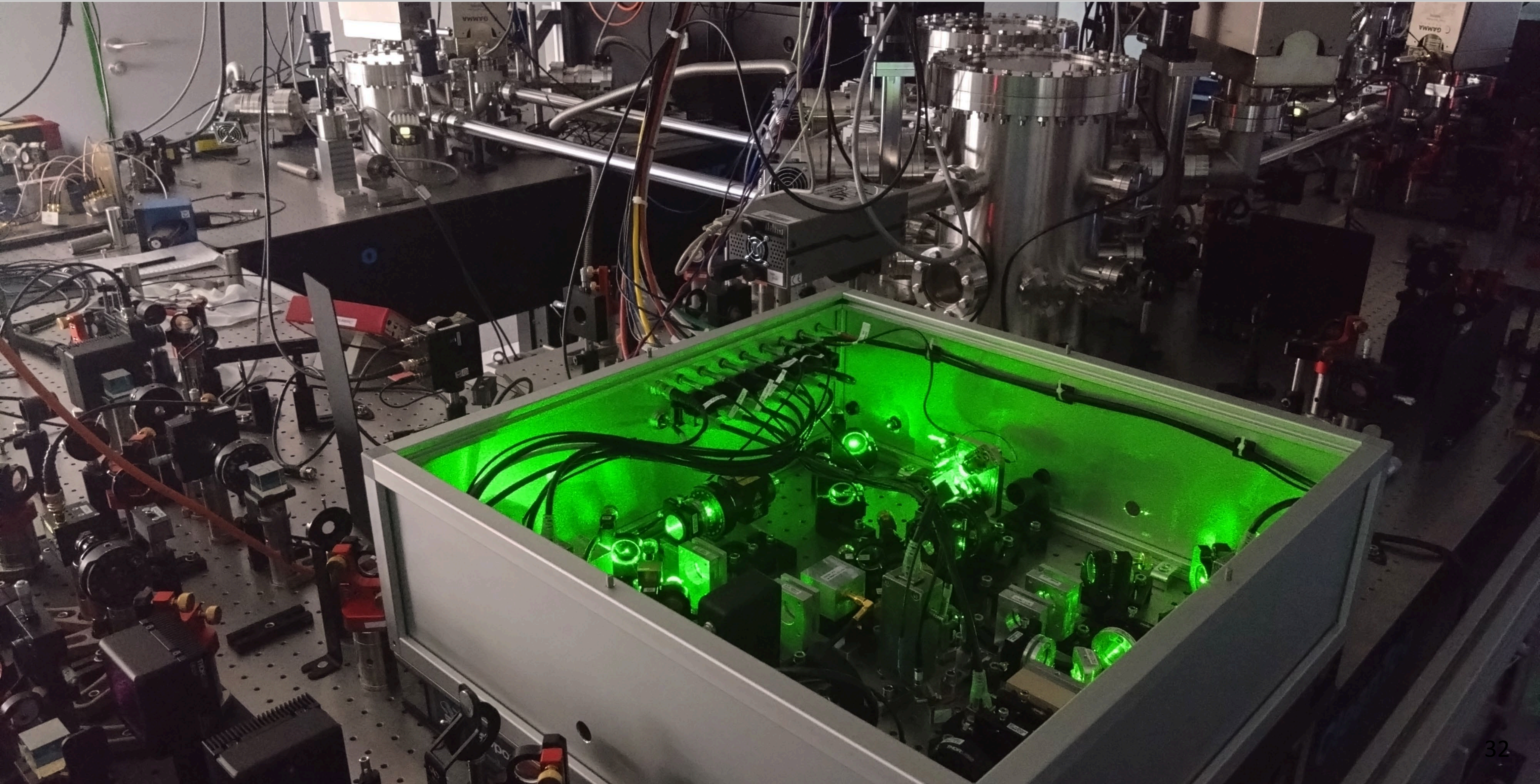








The Cardiff interferometers – Squeezed vacuum injection



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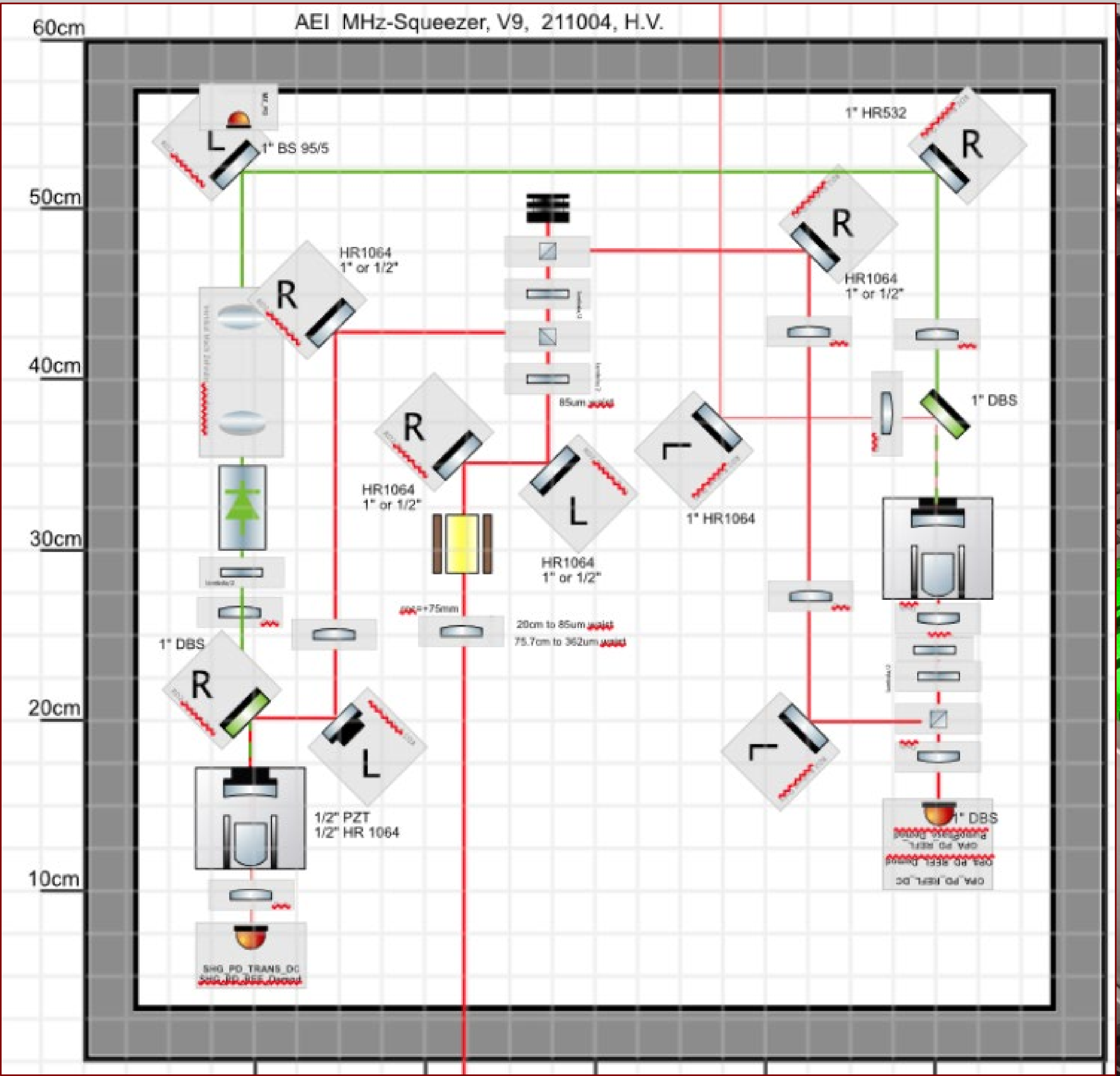
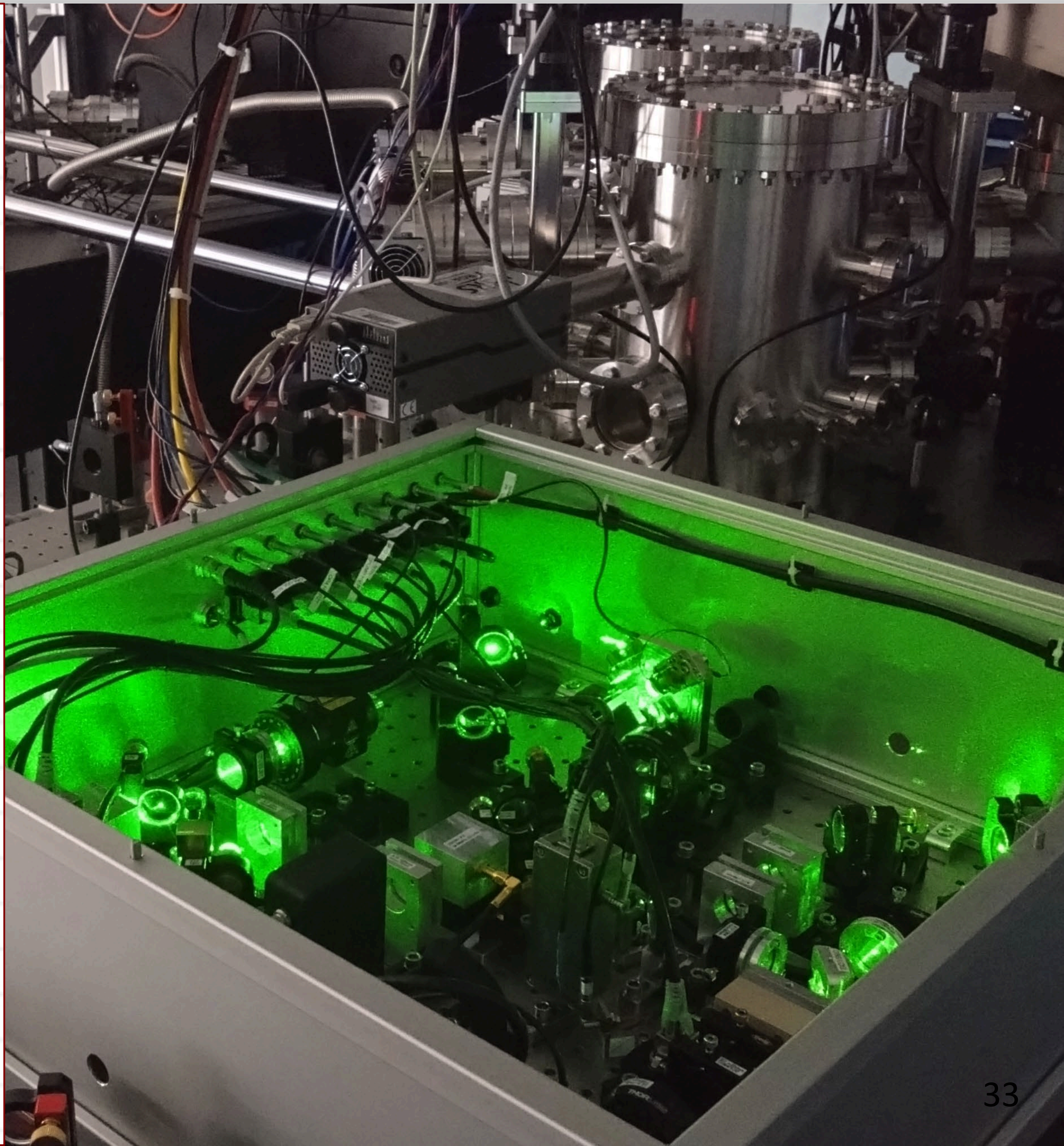
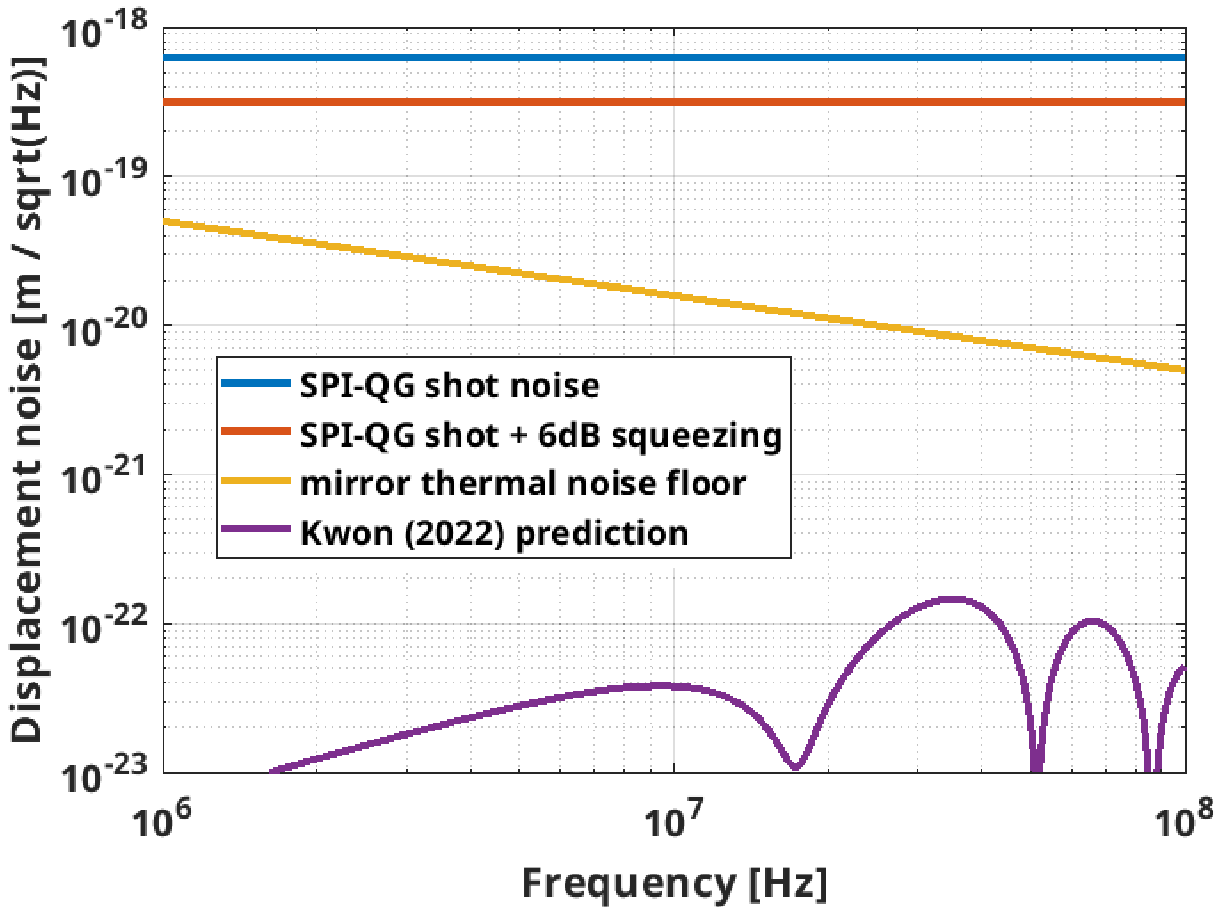
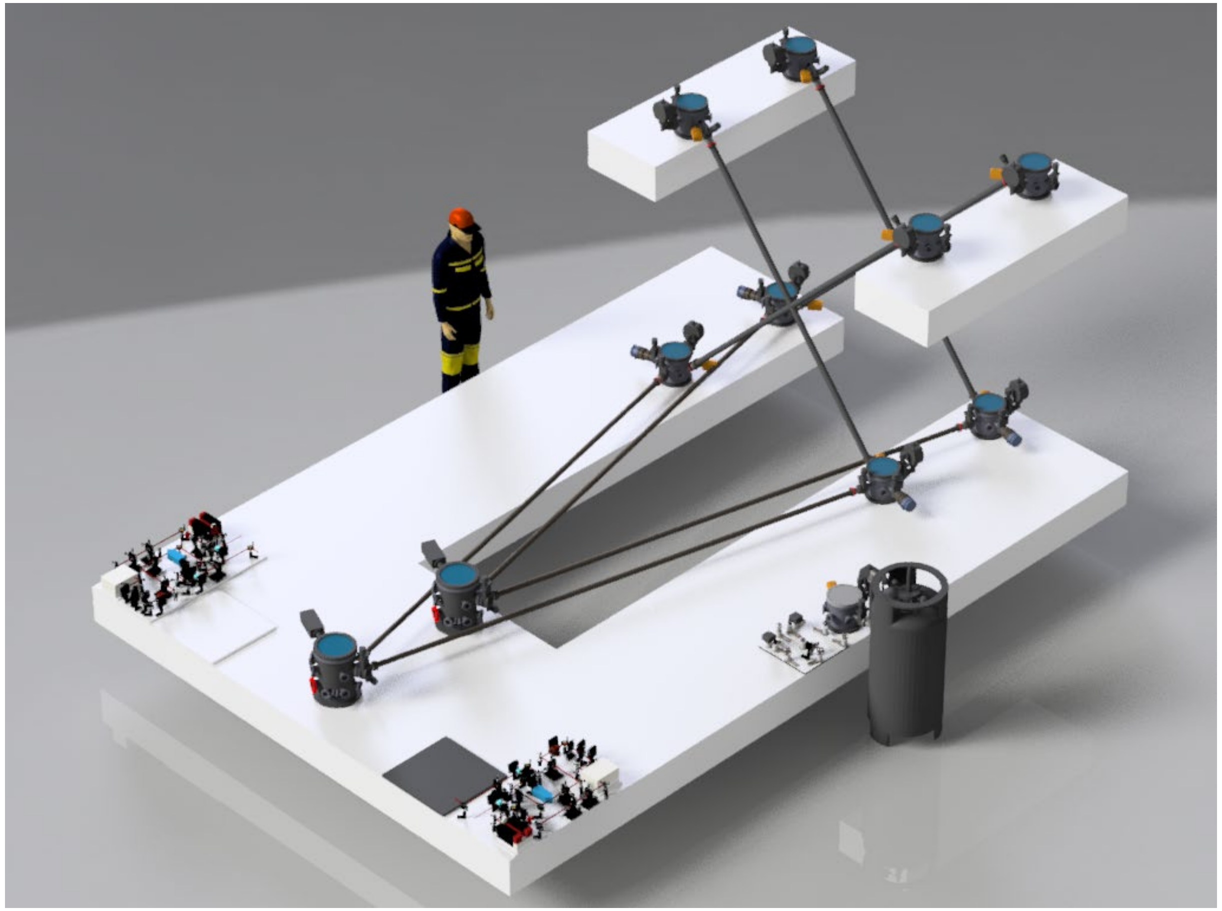




The Cardiff interferometers (new lab with 6 x 6m optical table)

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





Kwon, 2204.12080

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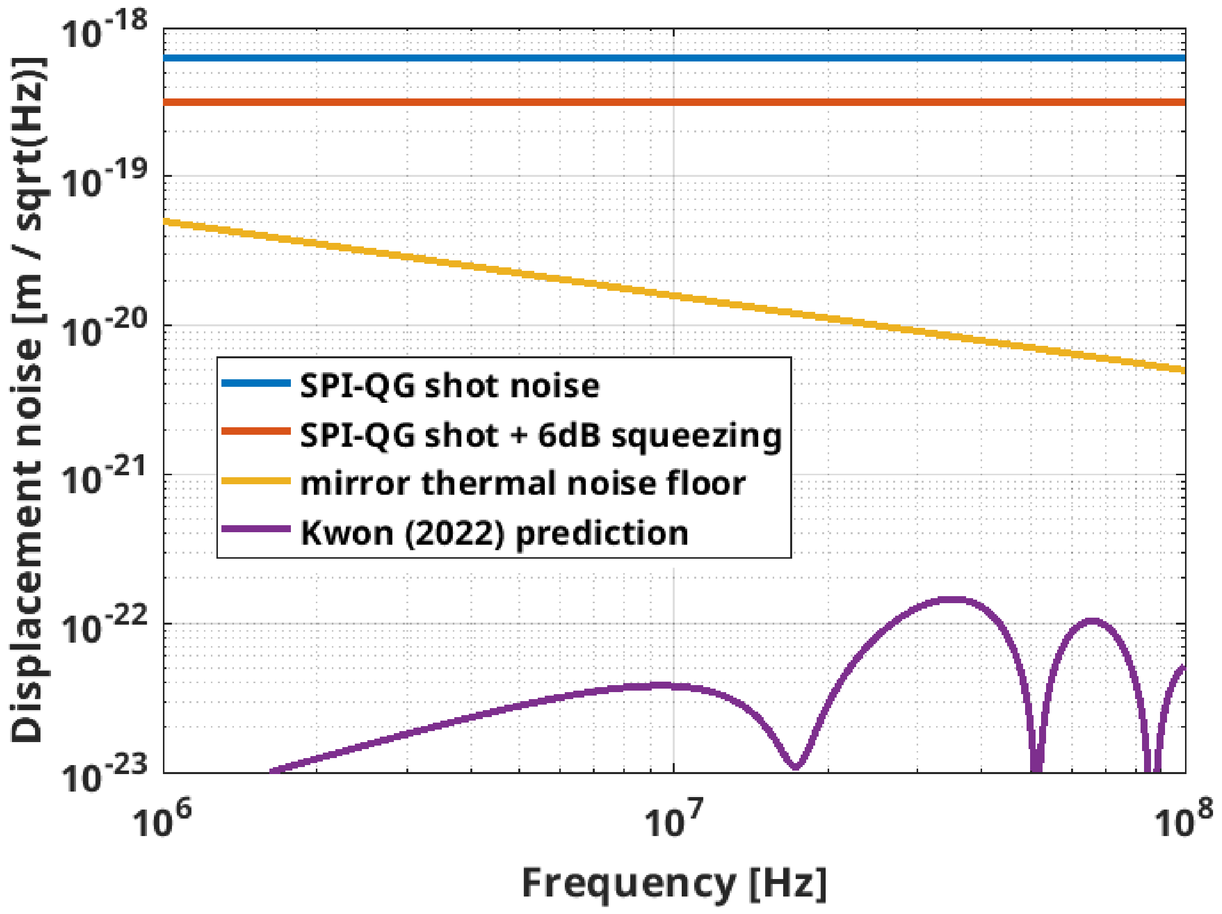
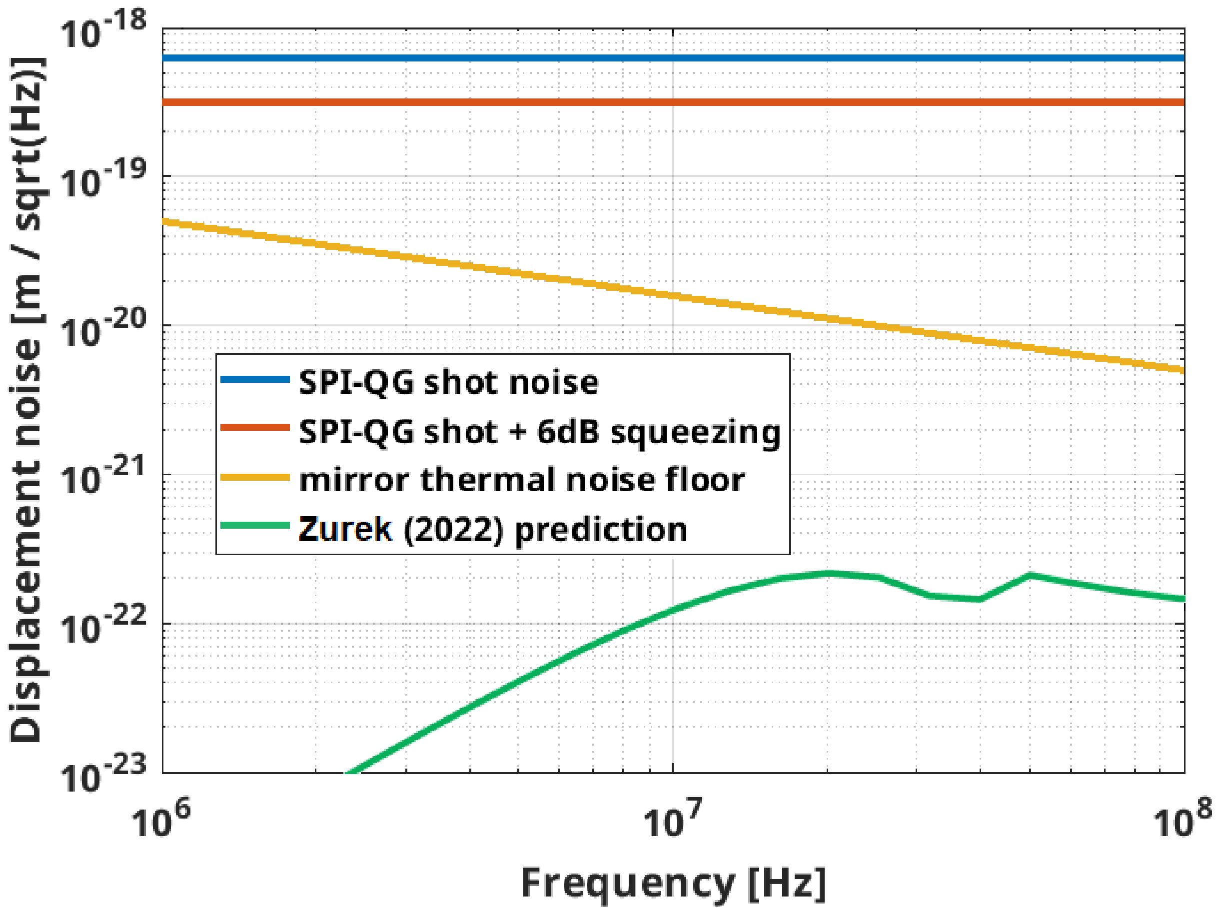


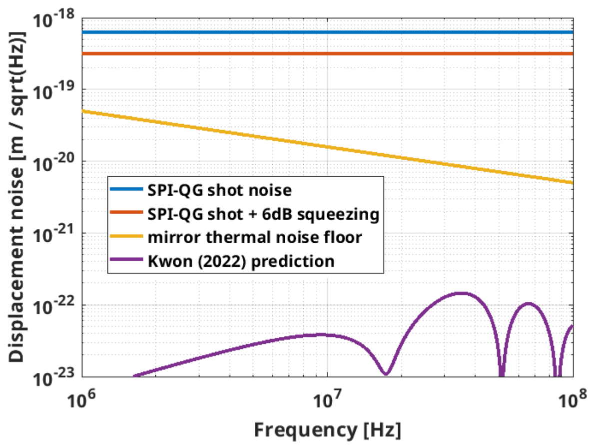
Kwon, 2204.12080

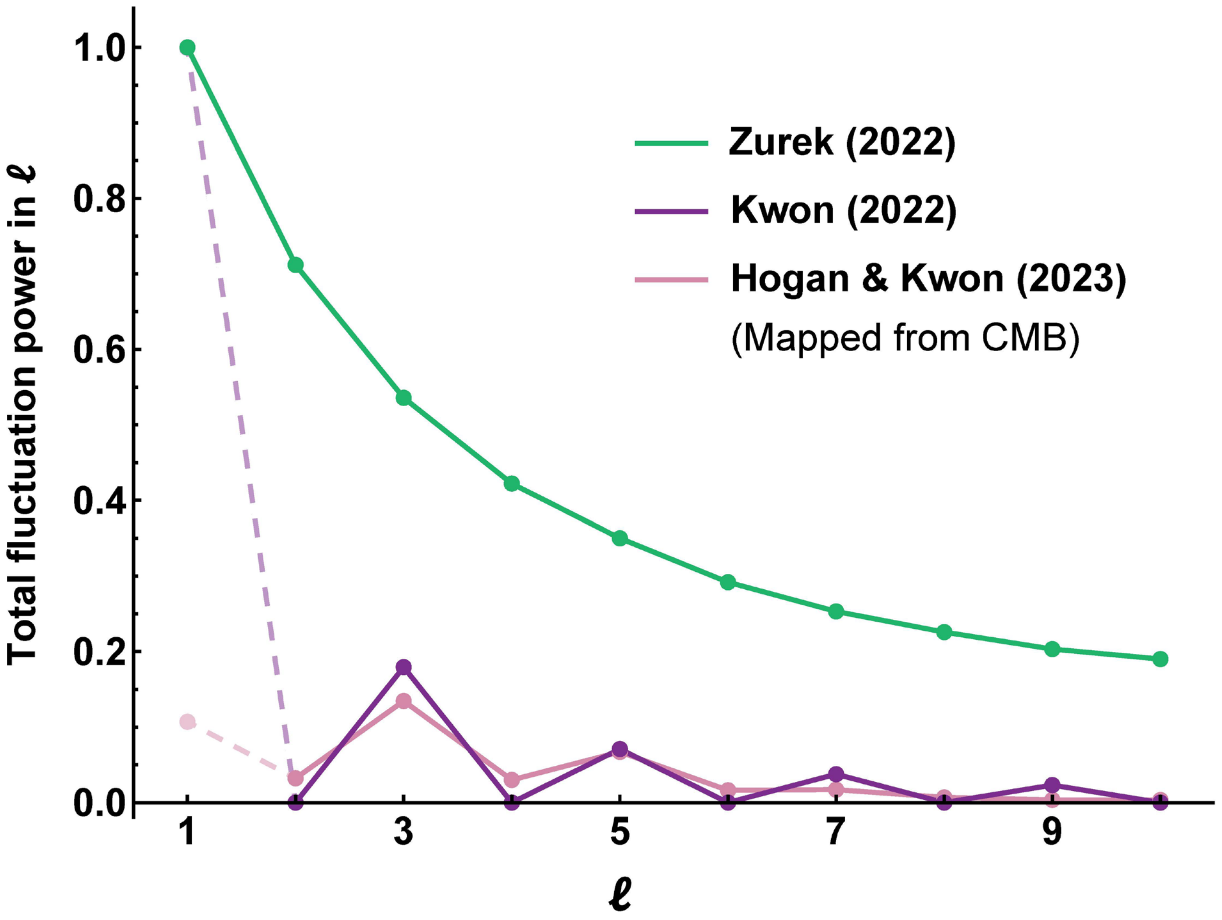


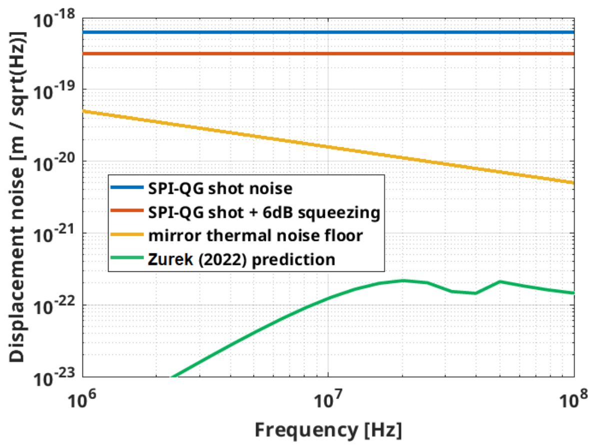
Li, Lee, Chen, and Zurek, PRD **107**, 024002

Simple 2D Michelson configuration

Next-generation searches: Quantum coherence on causal horizons?





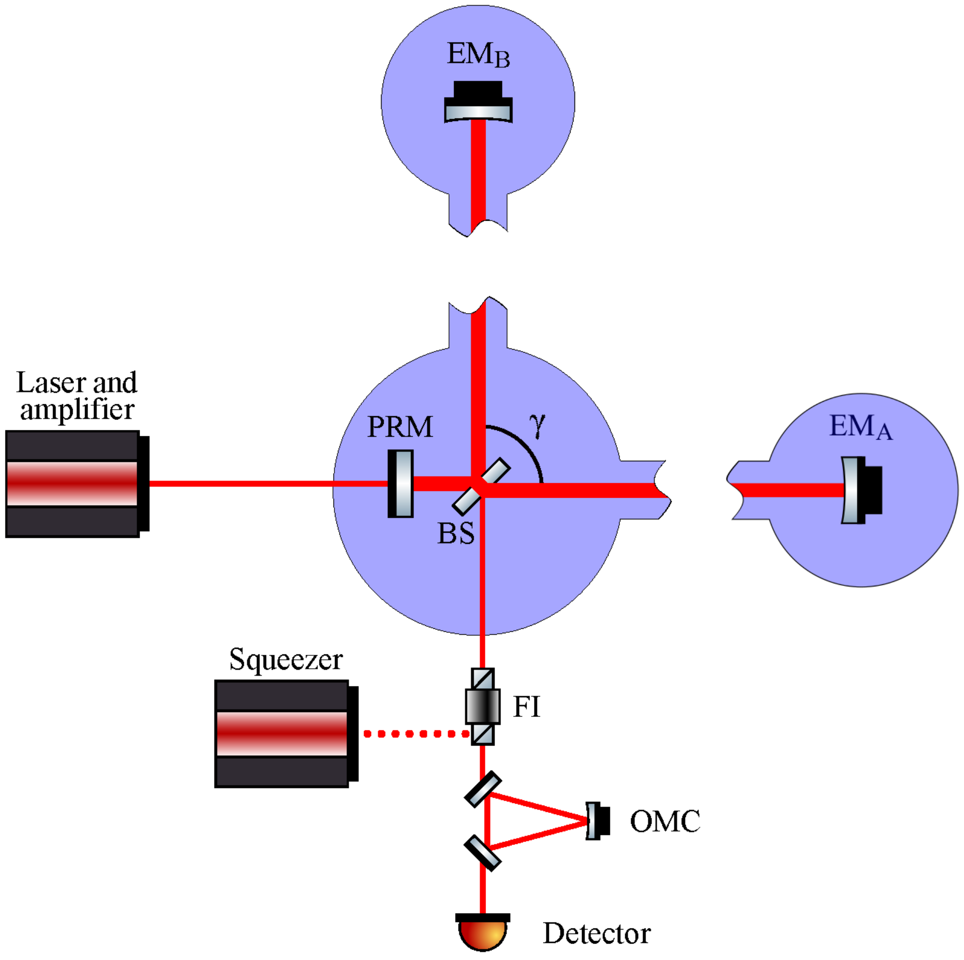


Hogan & Kwon, 2303.06563 — Spectrum derived from scaling invariance and symmetries consistent with CMB “anomalies.”

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!)

Future upgrade: Single photon readout concept



Current design — CQG **38,** 085008

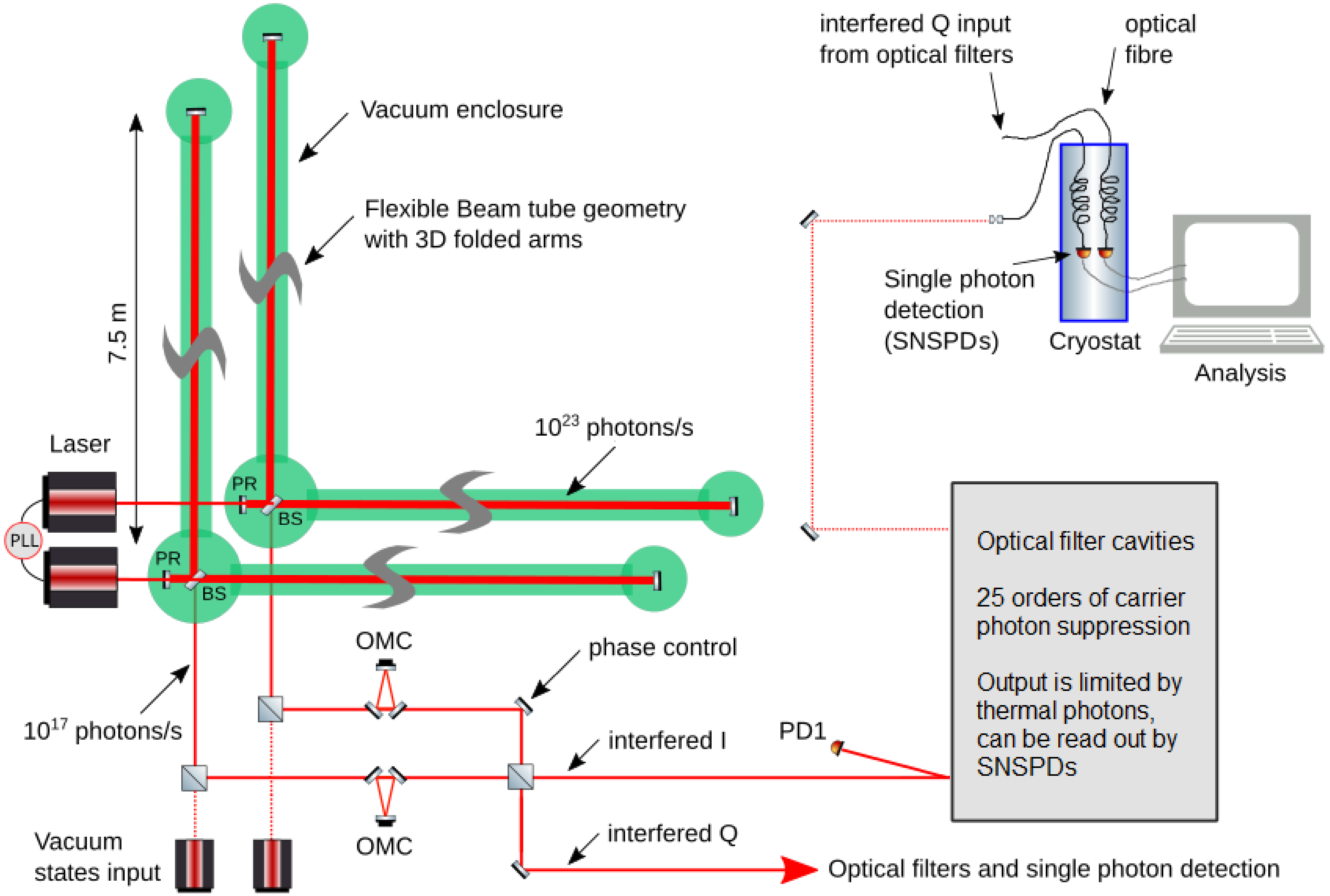
- 10^{23} photons / s circulating power (10kW)
- 10^{17} photons / s output power (10mW)
- Shot noise dominated
- Squeezed quantum states of vacuum injected

Future single photon readout

- 10^{17} photons / s output is passed through a set of **optical cavities that filter out 25 orders of magnitude** of carrier photons
- Limited by thermal photons, nominally 2.5 / s
- 5×10^{-4} / s signal photons pass through in a sideband offset by the signal frequency (35MHz)

Single photon readout concept first conceived by LIGO quantum noise working group, further developed by Lee McCuller (2211.04016)

Future upgrade: Colocated interferometers with interfered / entangled outputs



Schematic from Hartmut Grote, filter cavity design to be published in upcoming work

Future upgrade: Projected sensitivity

Conventional homodyne readout reaches unity signal-to-noise when:

$$S_{sig}(f) = \frac{S_{hom}(f)}{\sqrt{f_{BW,sig} \cdot t_{int}}}$$

Integration time (no squeezing): **200 days**

Signal and shot noise:

$$S_{sig}(f) = (1.4 \times 10^{-22}\,\mathrm{m}/\sqrt{\mathrm{Hz}})^2$$

$$S_{hom}(f) = (5 \times 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}})^2$$

Thermal noise at room temperature:

$$S_{th}(f) = (10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}})^2$$

Bandwidths of signal and optical filter:

$$f_{BW,sig} = 10\,\mathrm{MHz} \qquad f_{BW,fil} = 25\,\mathrm{kHz}$$

Single photon readout at unity SNR when:

$$W_{s,sig} \cdot f_{BW,fil} \cdot t_{int} = 2\sqrt{W_{s,th} \cdot f_{BW,fil} \cdot t_{int}}$$

where the photon emission rates for the signal (*sig*) and the thermal noise (*th*) are:

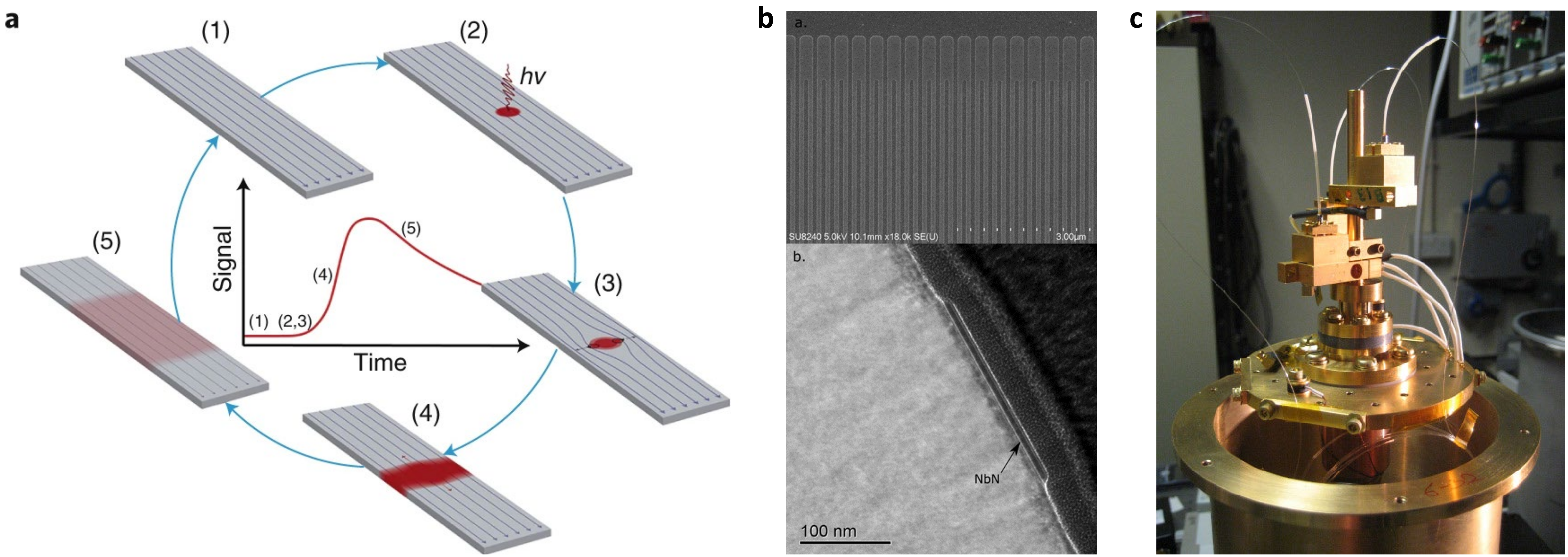
$$W_{s,sig/th}(f) = \frac{S_{sig/th}(f)}{4S_{hom}(f)} \left[\frac{\mathrm{photons}}{\mathrm{s} \cdot \mathrm{Hz}}\right]$$

Integration time at room temp: 600 days

Integration time with 1 order of magnitude reduction in thermal noise: 6 days

If thermal noise reduced by 2 orders, can map out 20 freq bins at 5σ in 1 month!

Latest SNSPD tech: 98% detection efficiency, 10^{-3}/s dark count rate, 10ps timing jitter



Figures provided by Robert Hadfield

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Acknowledgments — Join us!