Search for Space-Time Correlations from the Planck Scale with the Fermilab Holometer

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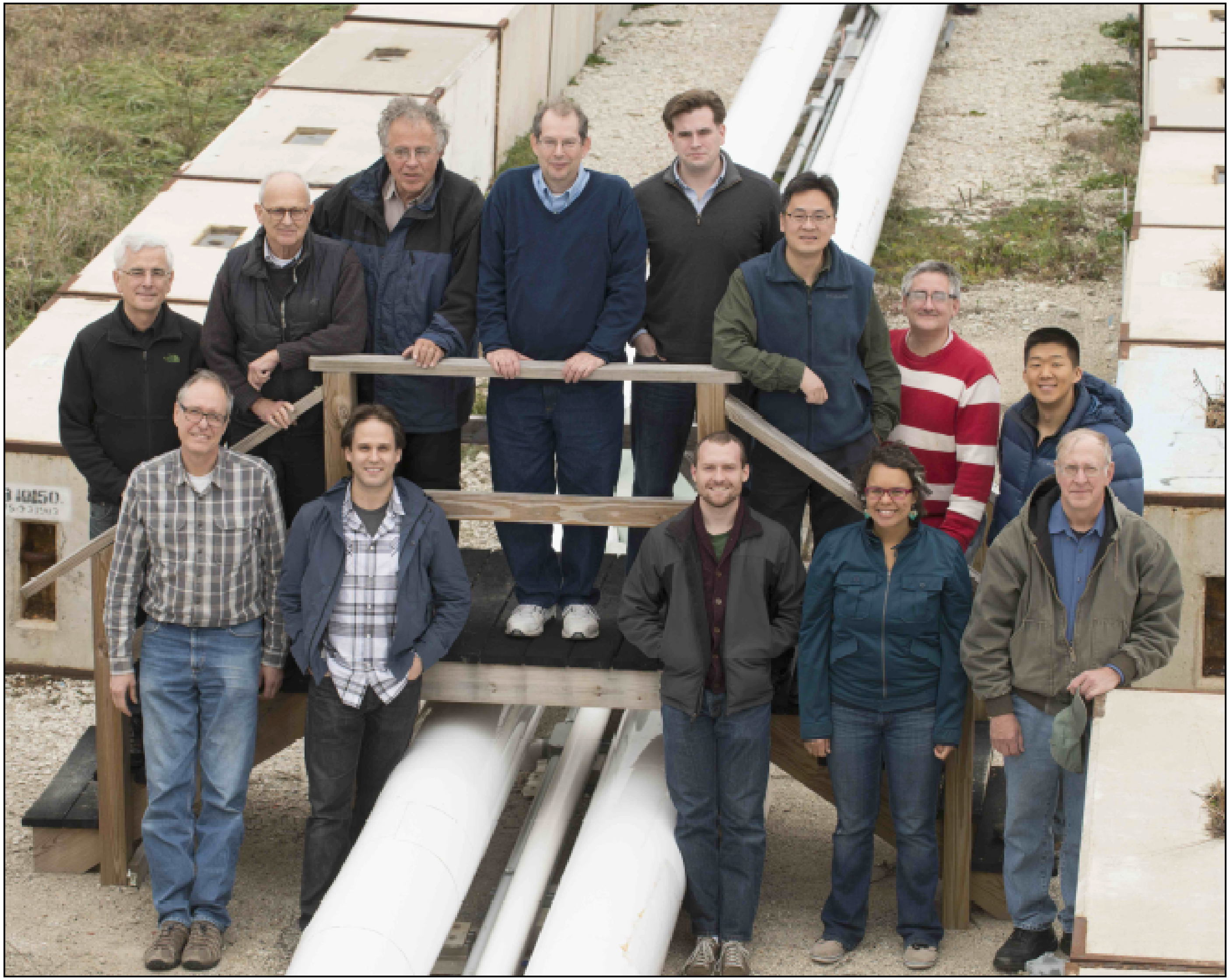
University of Chicago

July 12, 2016

The Holometer Collaboration



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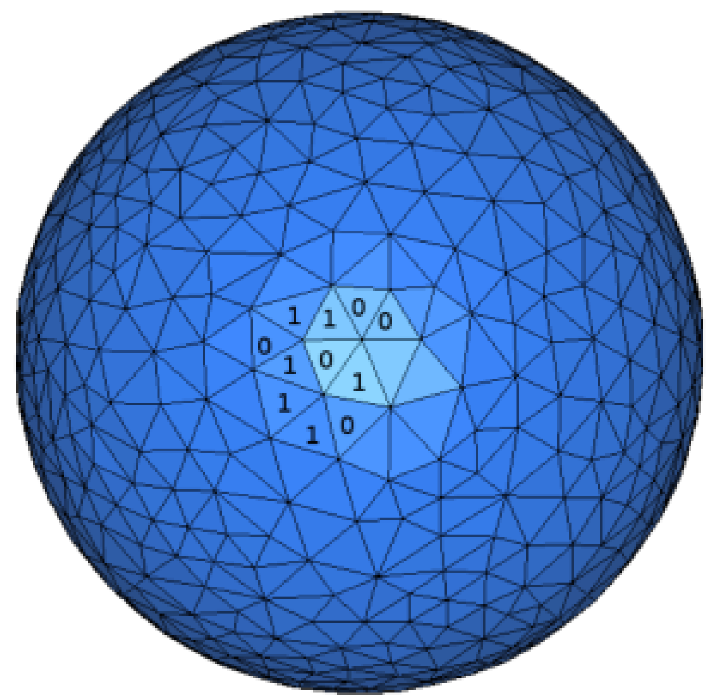
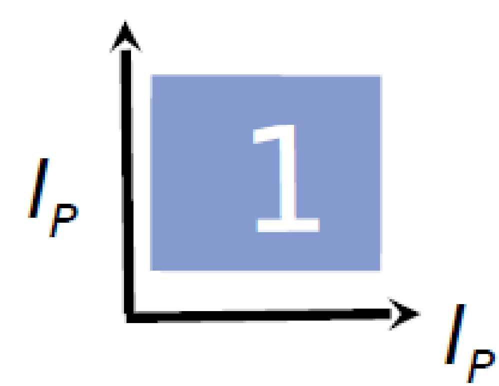
Quantum Space-Time

Quantum principles widely accepted to govern all physical systems

If space-time composed of Planck-scale quantum elements, classical space-time must "emerge" on larger scales as the statistical average of many elements





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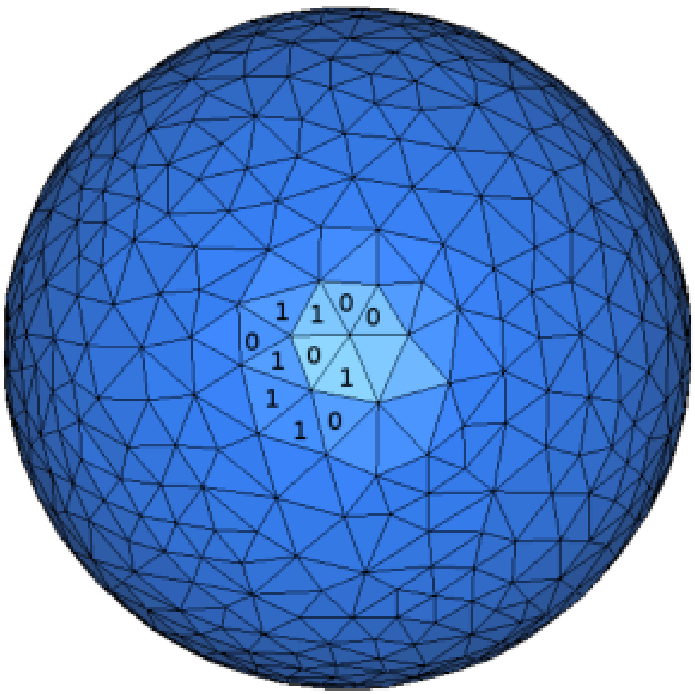
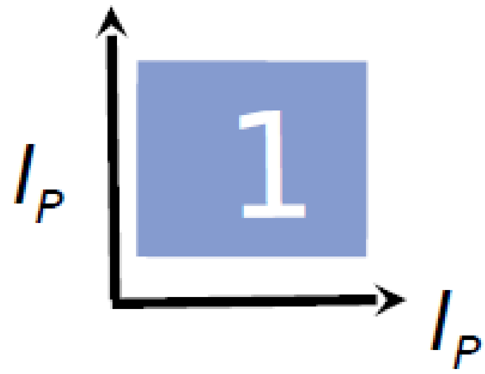
Is this emergence truly perfect?





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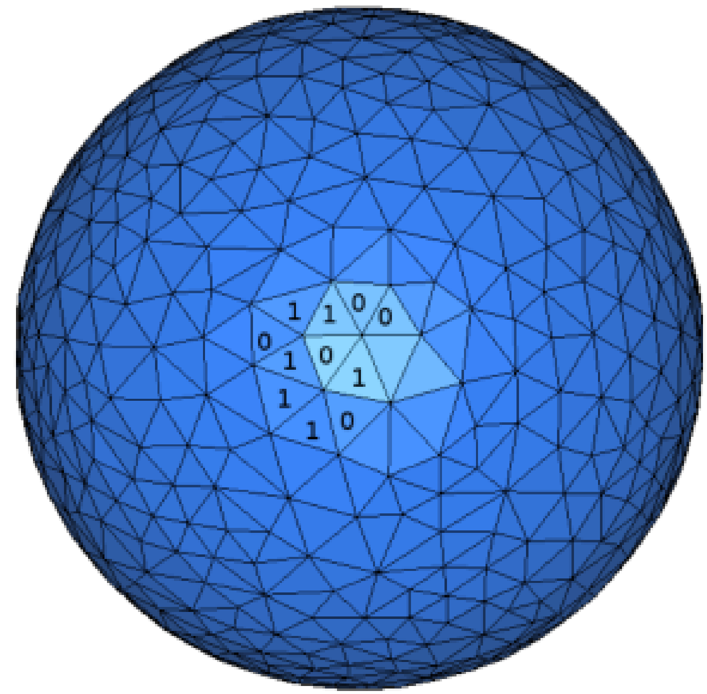
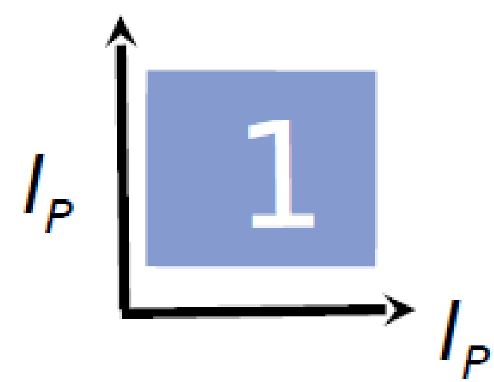


Is this emergence truly perfect?

Are the quantum effects truly confined to the Planck scale?



Quantum Space-Time

Quantum geometric information bounds might exist

- Entanglement of neighboring Planck-scale elements
- Can lead to quantum behavior <u>not</u> confined to the Planck scale
- A “symmetry breaking” in the emergence of classical space-time

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The Holometer program is a systematic search for first evidence of such spatial symmetry breaking

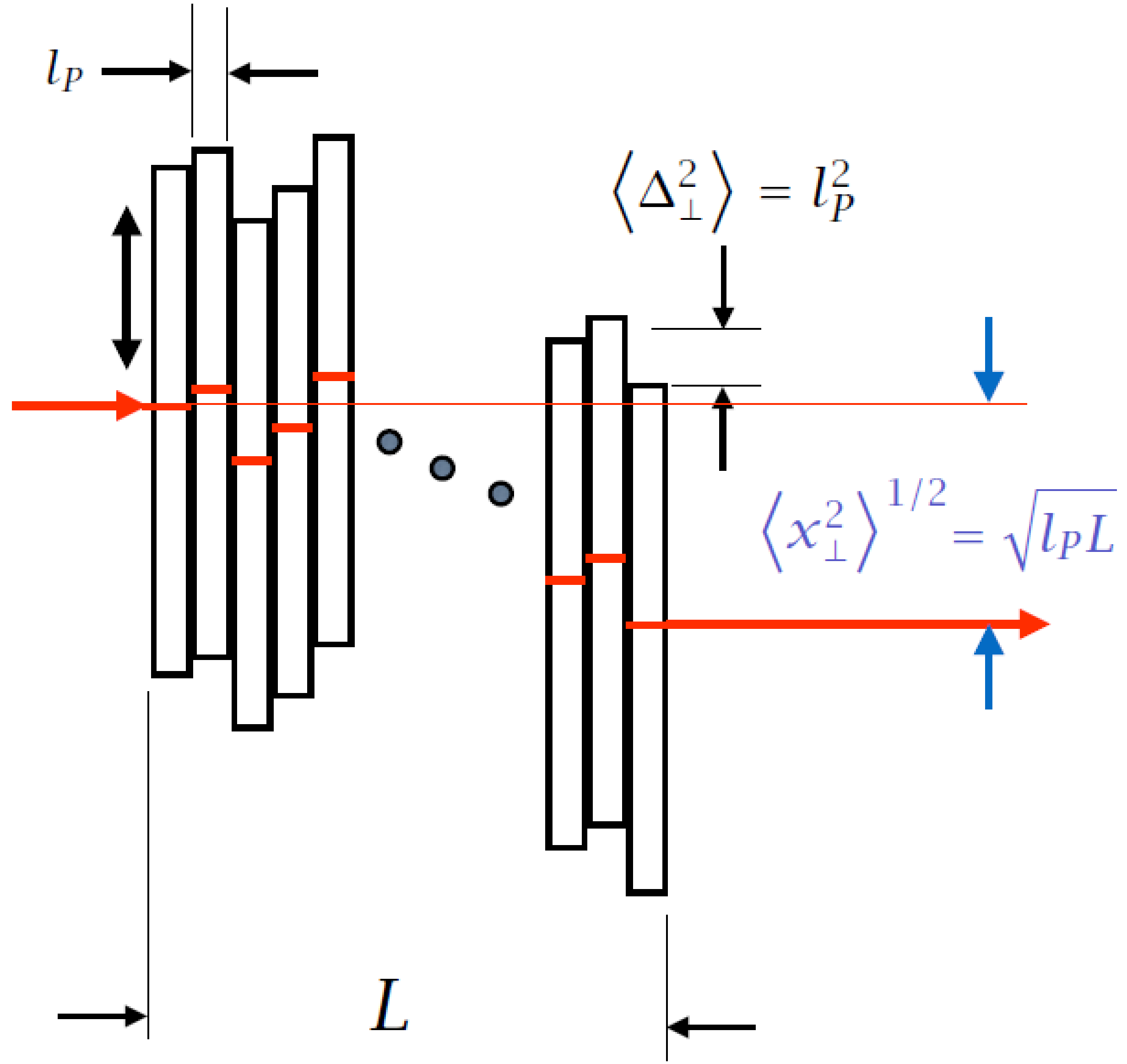
Would manifest as an exotic spatial quantization noise, detectable via optical interferometry

Random-Walk Models of Spatial Quantization Noise

Space-time composed of randomly fluctuating Planck-width layers

No fixed absolute background

Quantum geometrical position uncertainty accumulates as the square-root of the baseline *L*



Stephan Meyer

Random-Walk Models of Spatial Quantization Noise

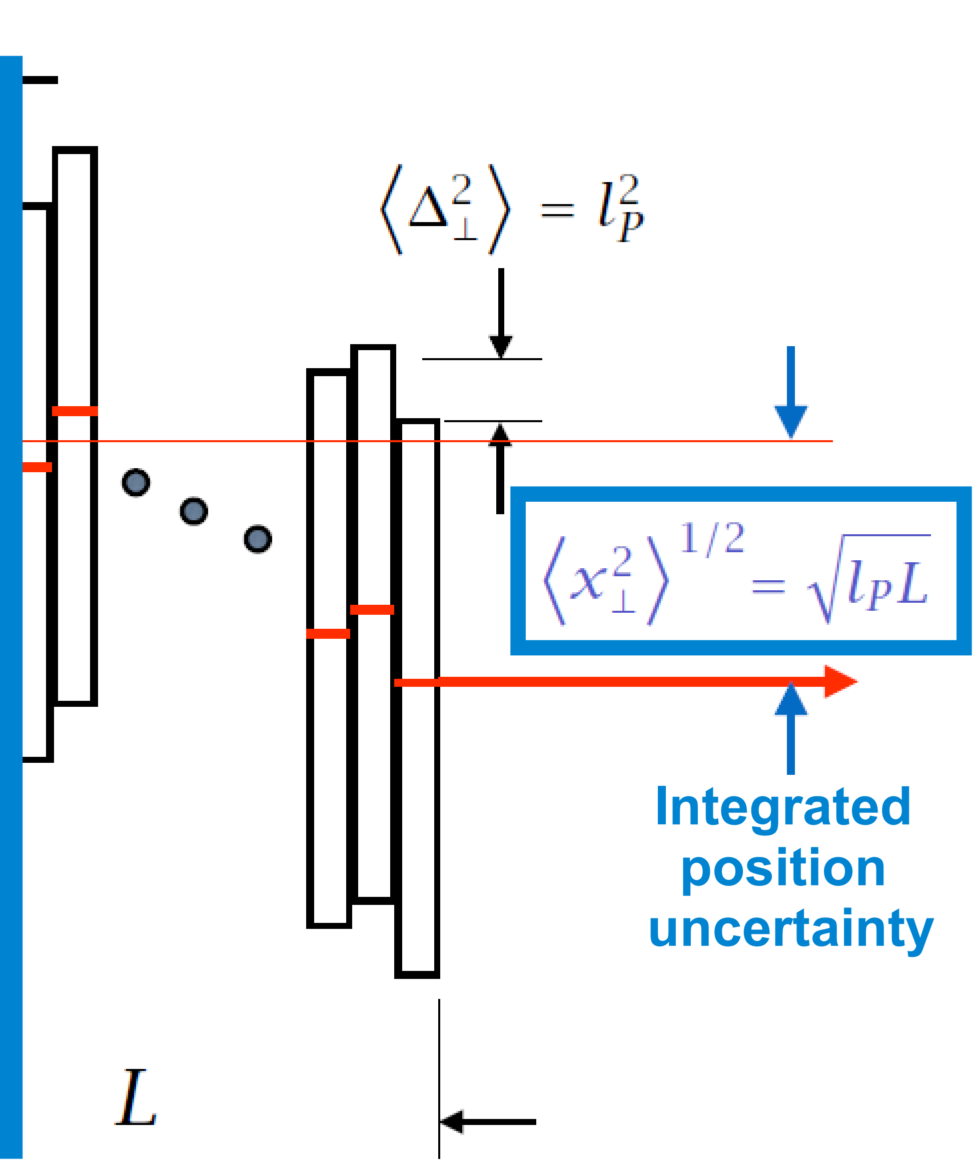
<u>Still a very small effect</u>

For a baseline

L = Hubble radius ,

the integrated position uncertainty is **46 microns**.

But, this faint effect is detectable in optical interferometers.



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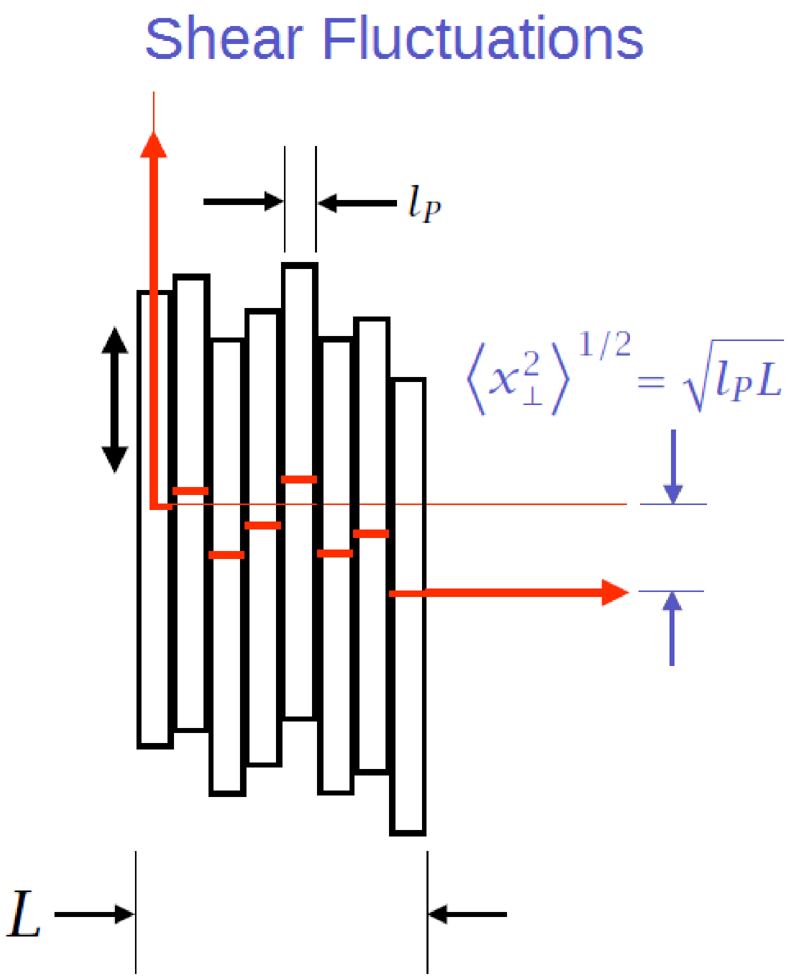
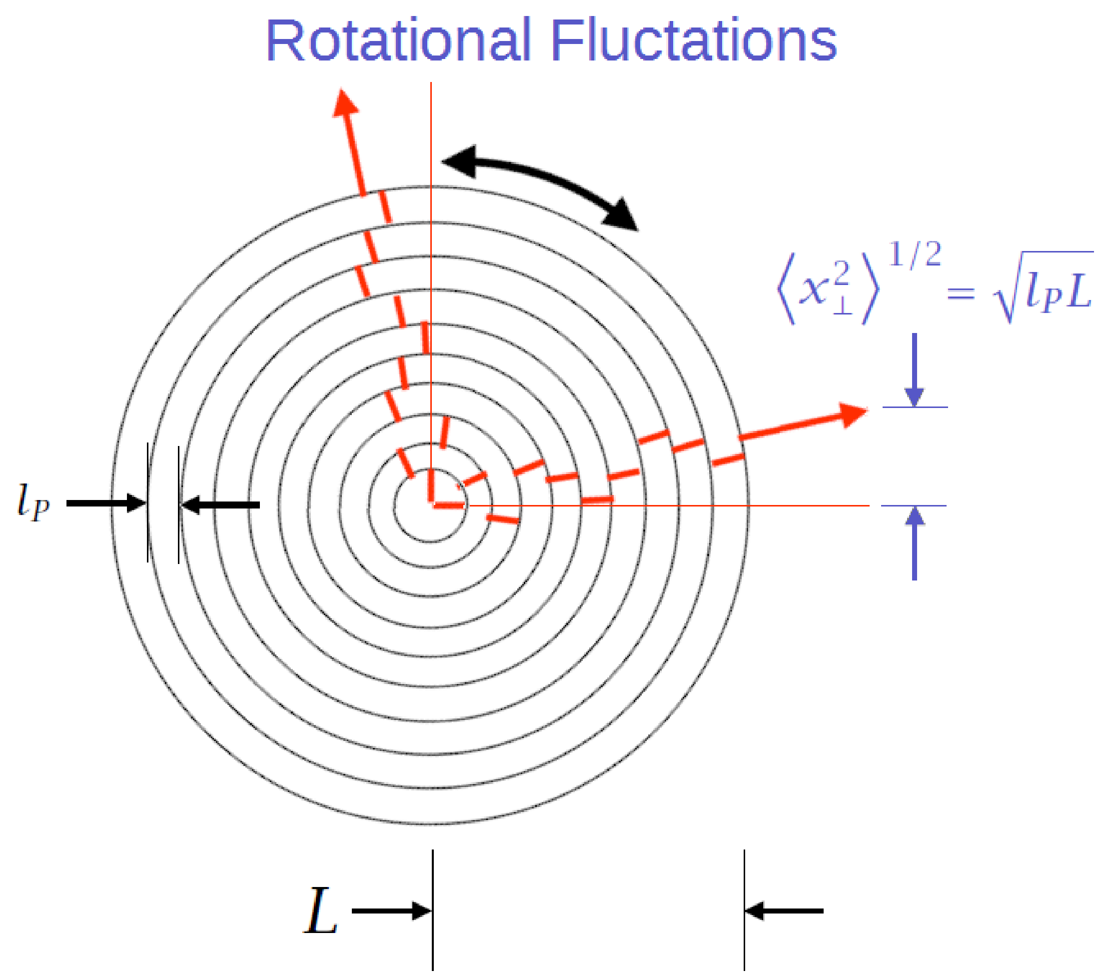
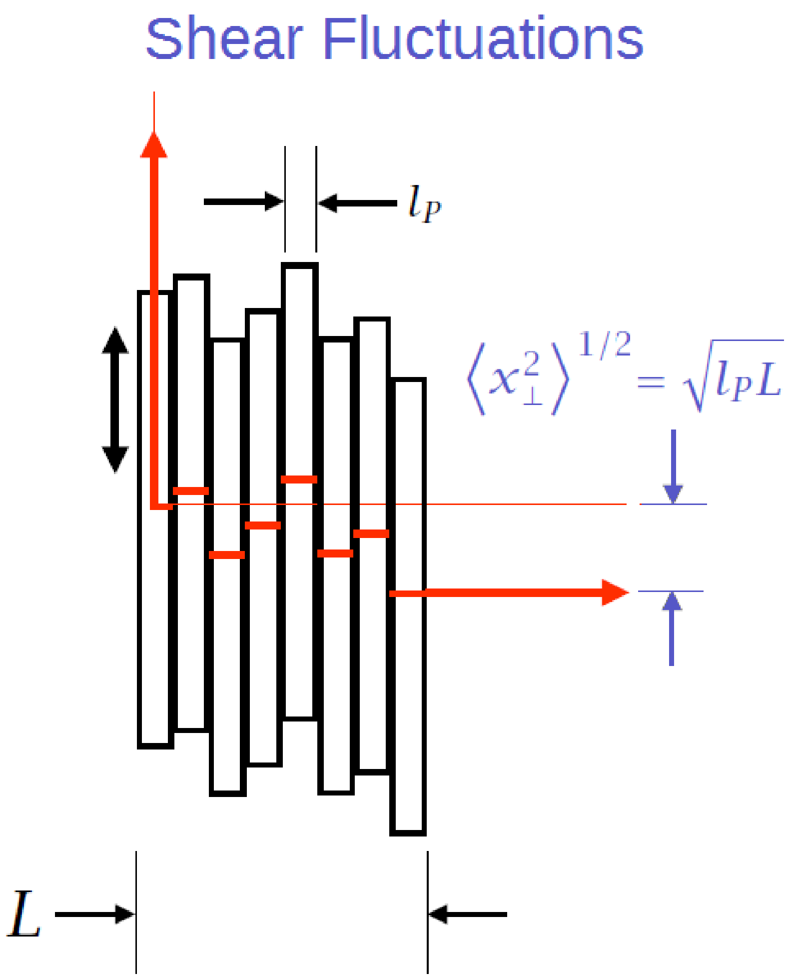
Planck-scale layering not uniquely constrained





Motivates multiple experimental searches



Holometer Phase I Search

July 2015–Feb. 2016

Experimental Design

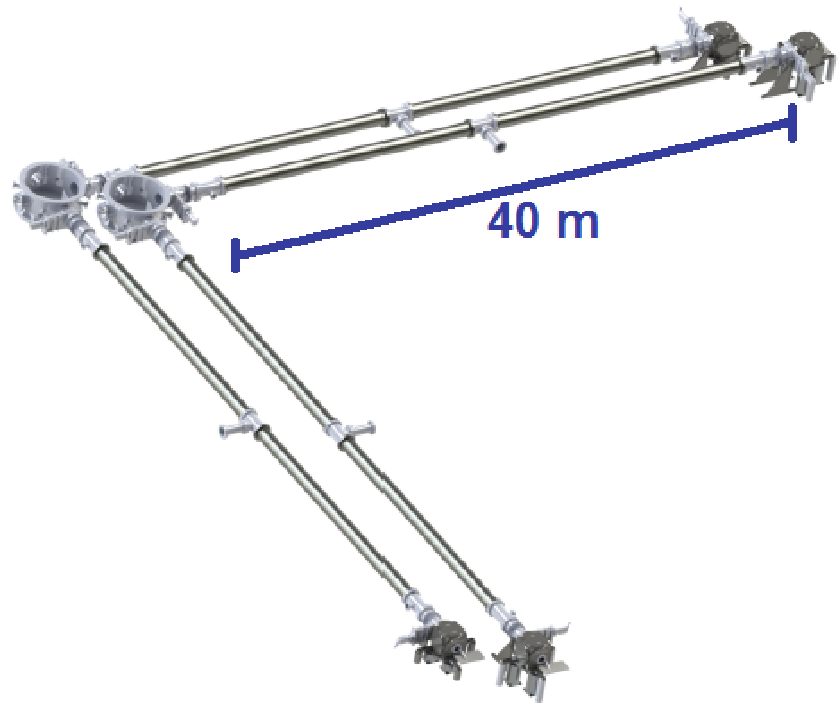
Two independent, co-located power-recycled Michelson interferometers

- 40-m arm length
- 2 kW of storage power

Separate, electrically-isolated:

- Optical systems
- Vacuum systems
- Control systems
- MHz detector readouts

Measure the correlated optical phase fluctuations in a pair of isolated but co-located interferometers



Experimental Design

Situated in an old meson tunnel of the Tevatron at Fermi National Accelerator Laboratory

Google Maps

Correlated Noise Model

We use two interferometers which have uncorrelated shot noise, thermal noise and laser noise. In the Fourier domain:

$$\hat{D}_1(f) = \hat{S}_{\mathrm{H}} + \hat{N}_1 \qquad \text{Interferometer 1}$$

$$\hat{D}_2(f) = \hat{S}_{\mathrm{H}} + \hat{N}_2 \qquad \text{Interferometer 2}$$

and the auto power spectral density of these is:

$$\mathrm{PSD}_1 \equiv \langle \hat{D}_1 \hat{D}_1^* \rangle = |\hat{S}_{\mathrm{H}}|^2 + |\hat{N}_1|^2$$

$$\mathrm{PSD}_2 \equiv \langle \hat{D}_2 \hat{D}_2^* \rangle = |\hat{S}_{\mathrm{H}}|^2 + |\hat{N}_2|^2$$

Correlated Noise Model

The cross spectrum of the two interferometers is

$$\mathrm{CSD} \equiv \left\langle \hat{D}_1 \hat{D}_2^* \right\rangle = |\hat{S}_{\mathrm{H}}|^2$$

and the variance is

$$\mathrm{Var}\left[\mathrm{CSD}\right] = \frac{|N_1|^2 |N_2|^2}{\mathrm{BW} \cdot T_{\mathrm{int}}}$$

where the bandwidth is ~5 MHz and the integration time is 700 hours

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The number of measurements $N = 1.2 \times 10^{13}$

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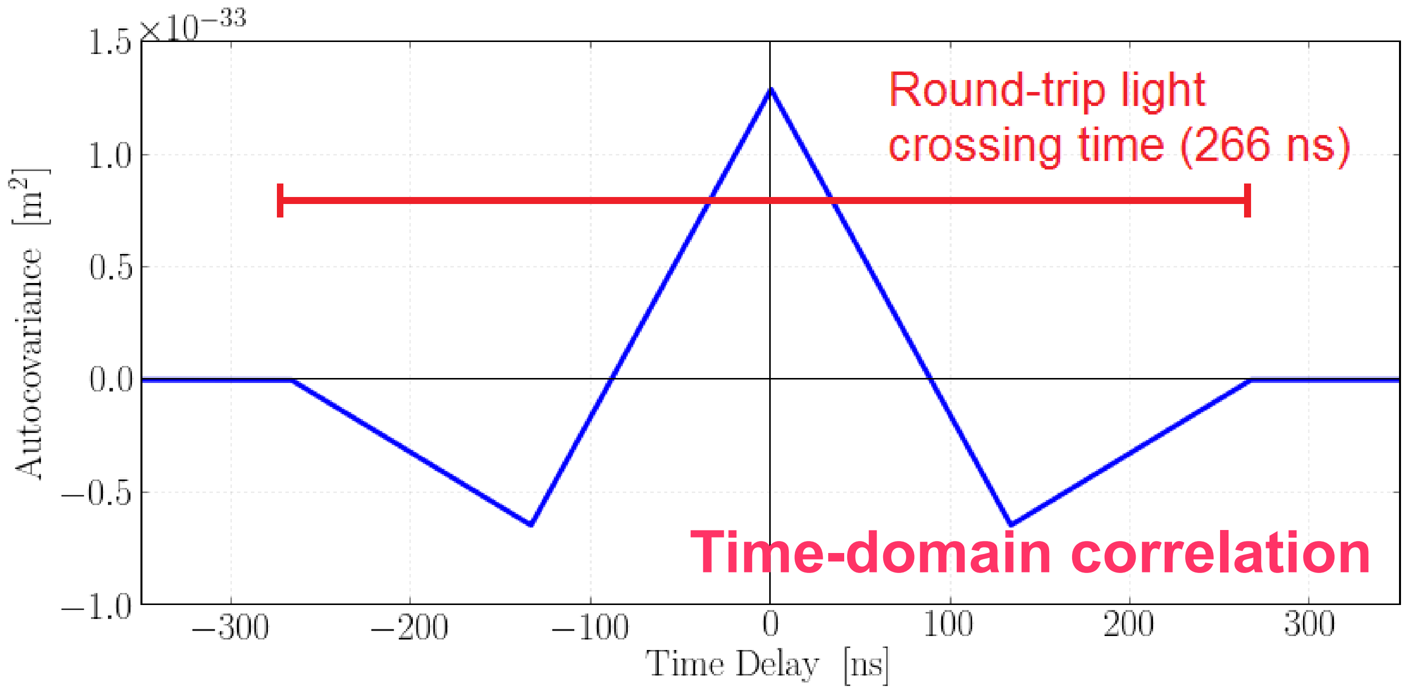
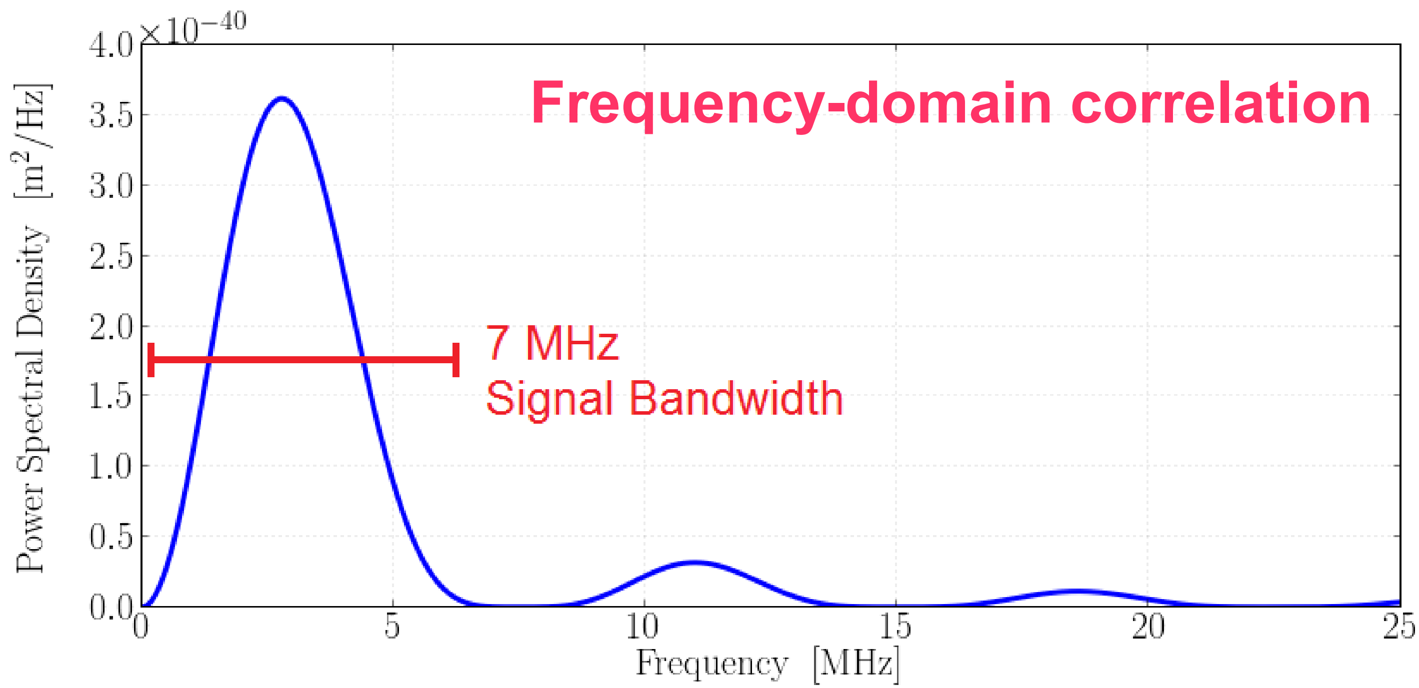
One more advantage of the cross spectrum - we know the phase (it is zero) so we use only the real part of the CSD (homodyne detection).

Predicted Cross-Interferometer Correlation

Manifests as an excess, *correlated* spectral noise in the two optical readout signals

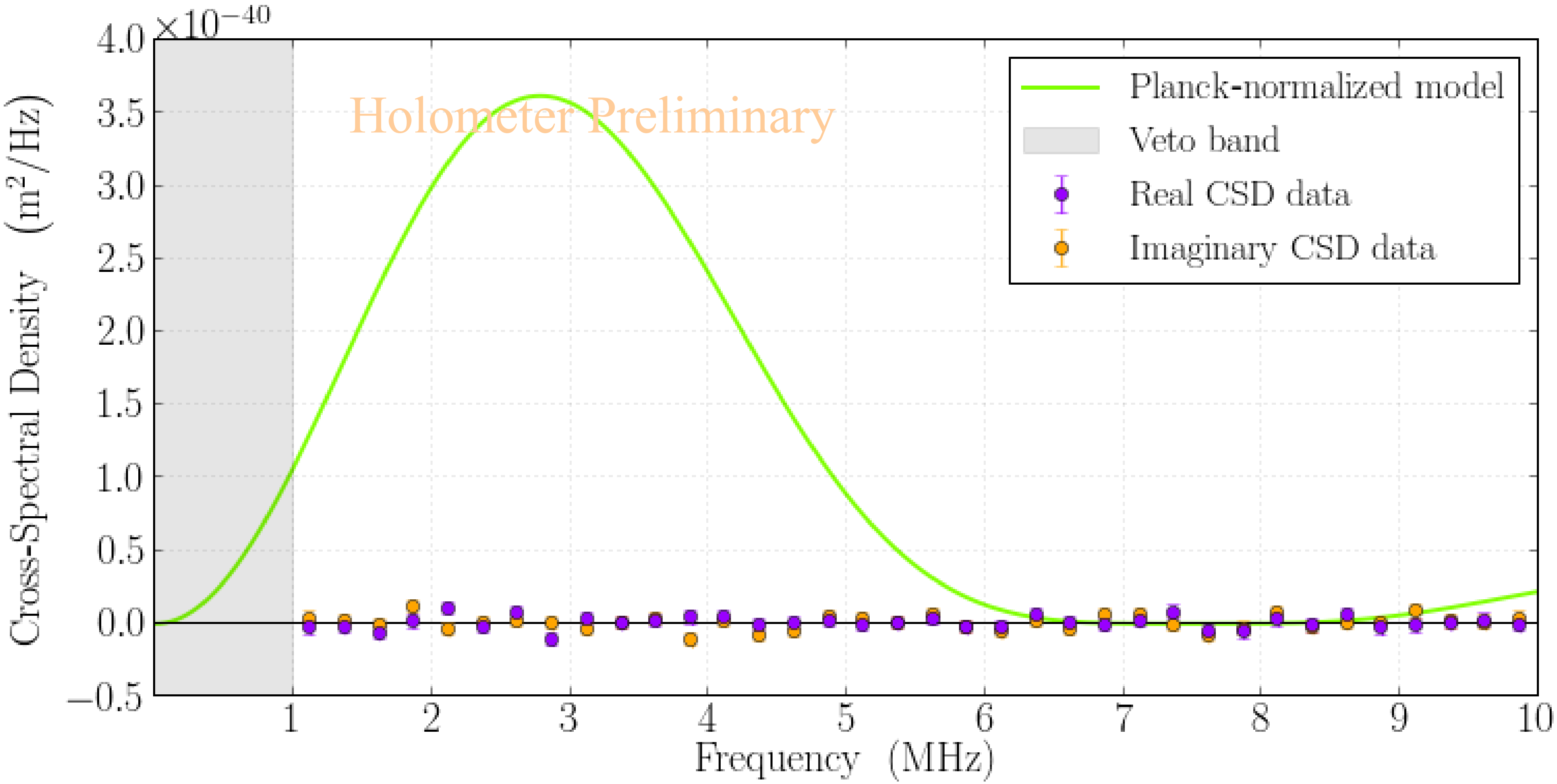




Cross-Interferometer Spectral Density

Integration time = 704 hours

Frequency resolution = 250 kHz



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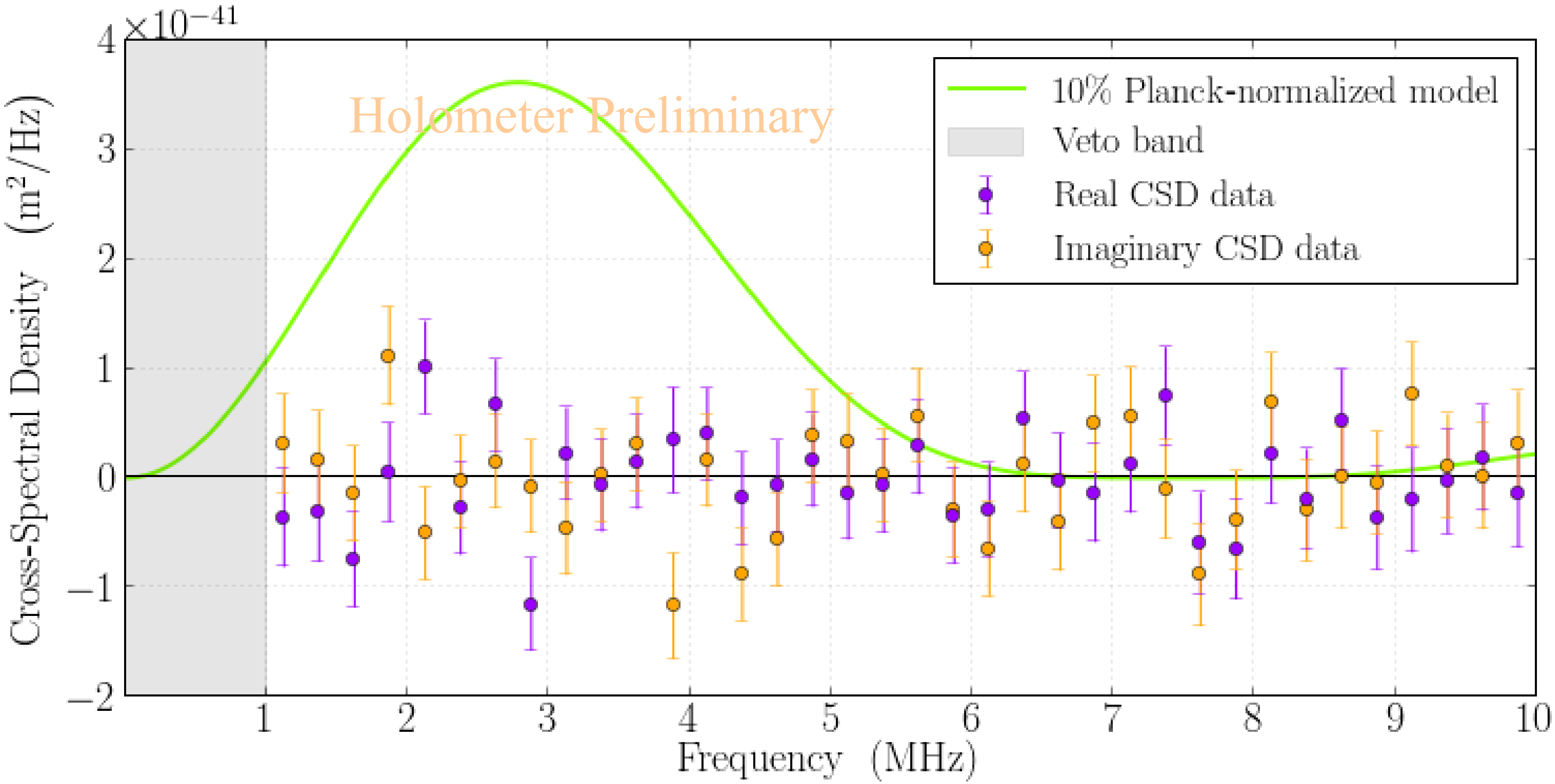
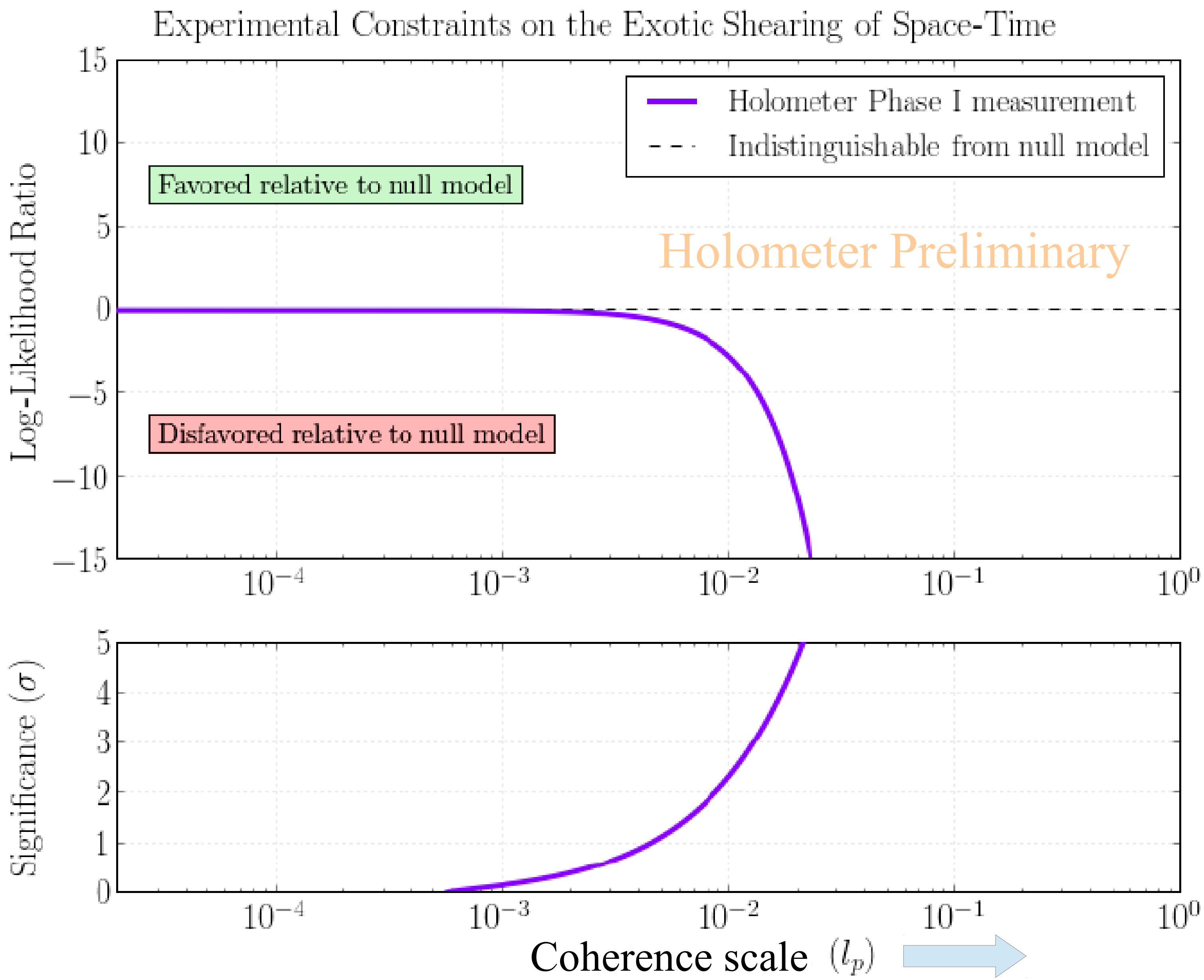


Upper Limits on Exotic Spatial Shear

Spatial shear excluded to a coherence scale 1% of a Planck length



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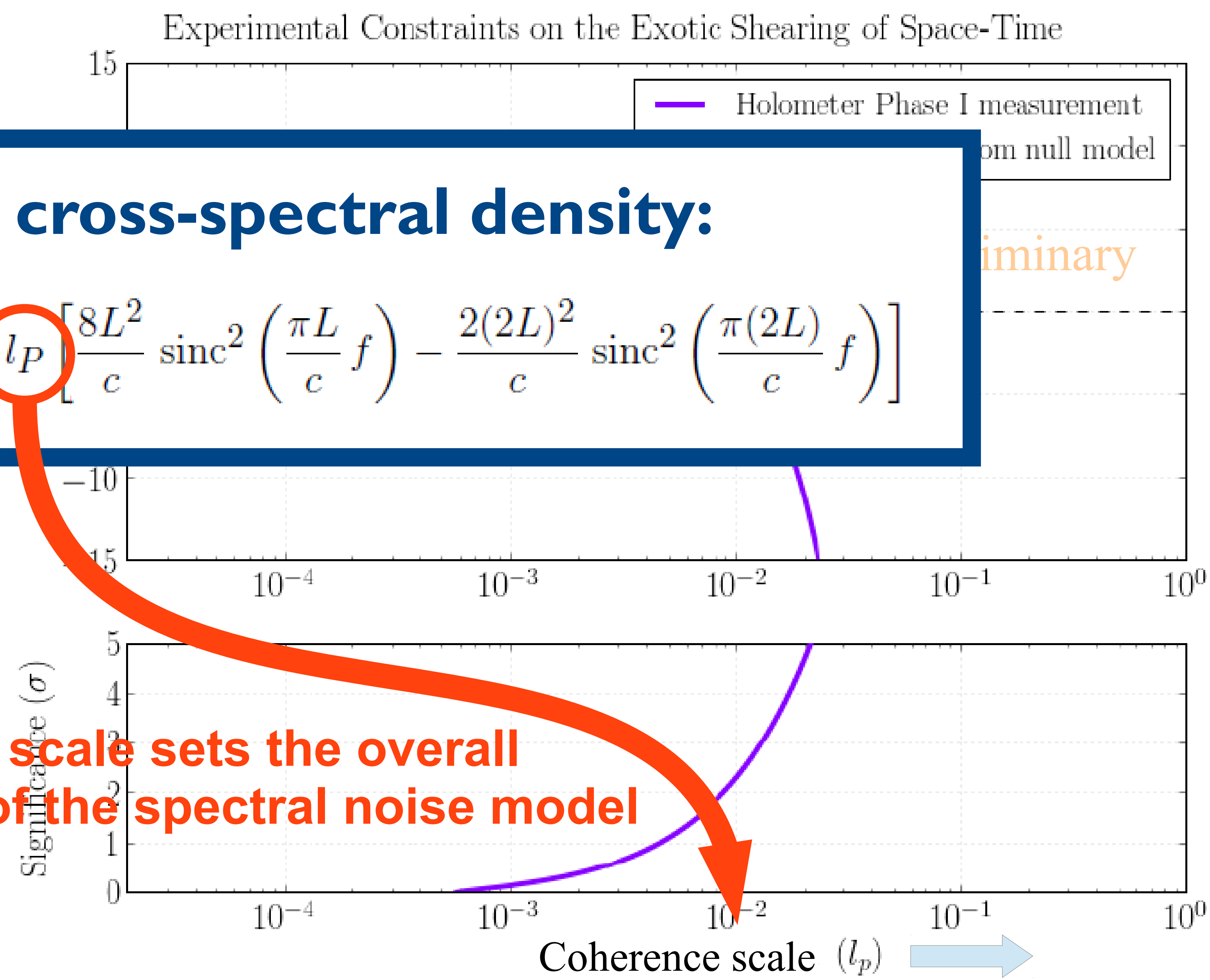
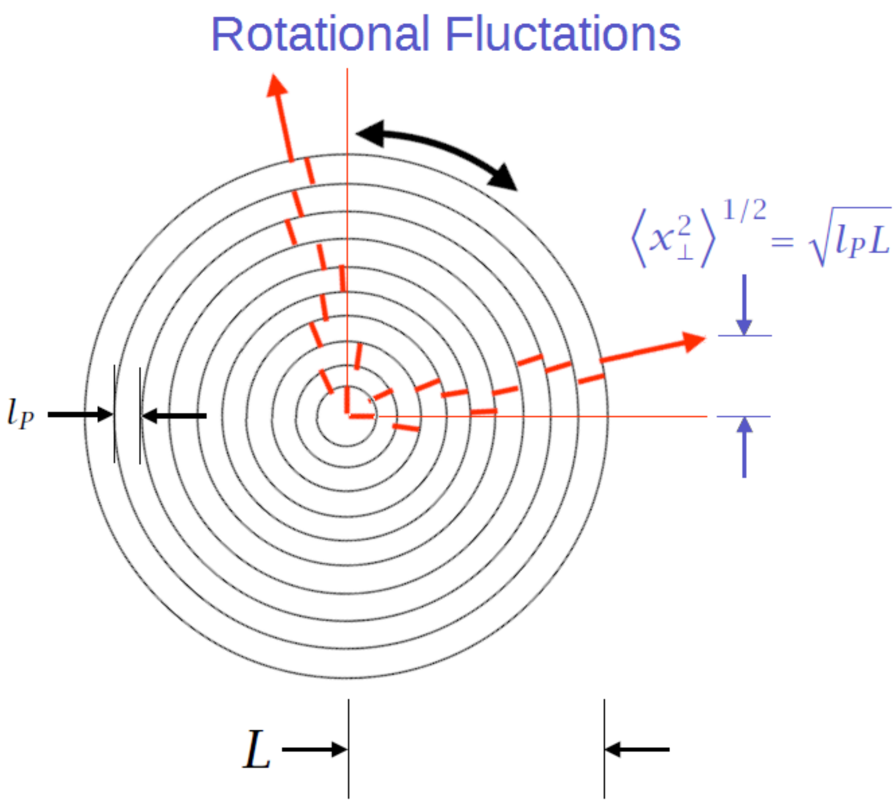


length

Predicted cross-spectral density:

$$\widetilde{C_{SS}}(f\,|\,l_P) = l_P\left[\frac{8L^2}{c}\,\mathrm{sinc}^2\left(\frac{\pi L}{c}f\right) - \frac{2(2L)^2}{c}\,\mathrm{sinc}^2\left(\frac{\pi(2L)}{c}f\right)\right]$$

The coherence scale sets the overall normalization of the spectral noise model



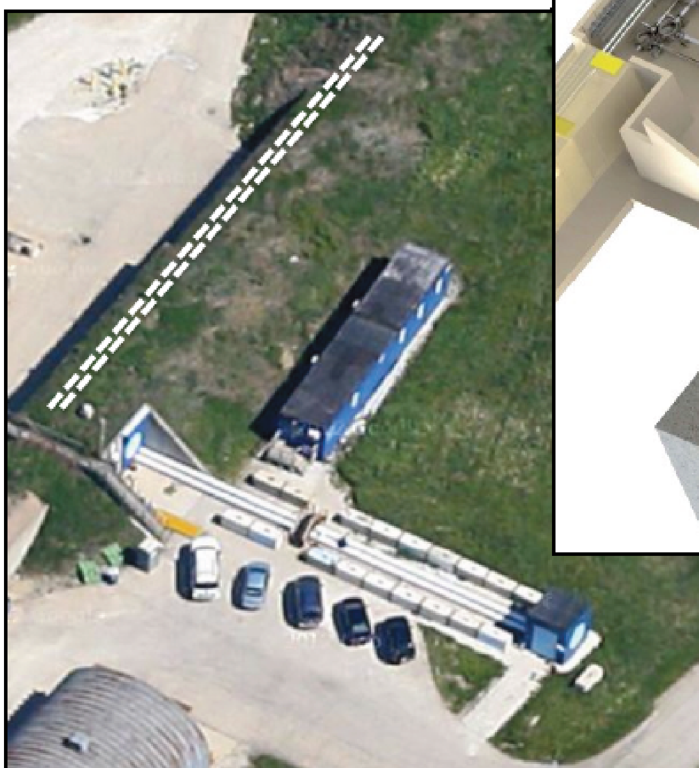
Holometer Phase II Search

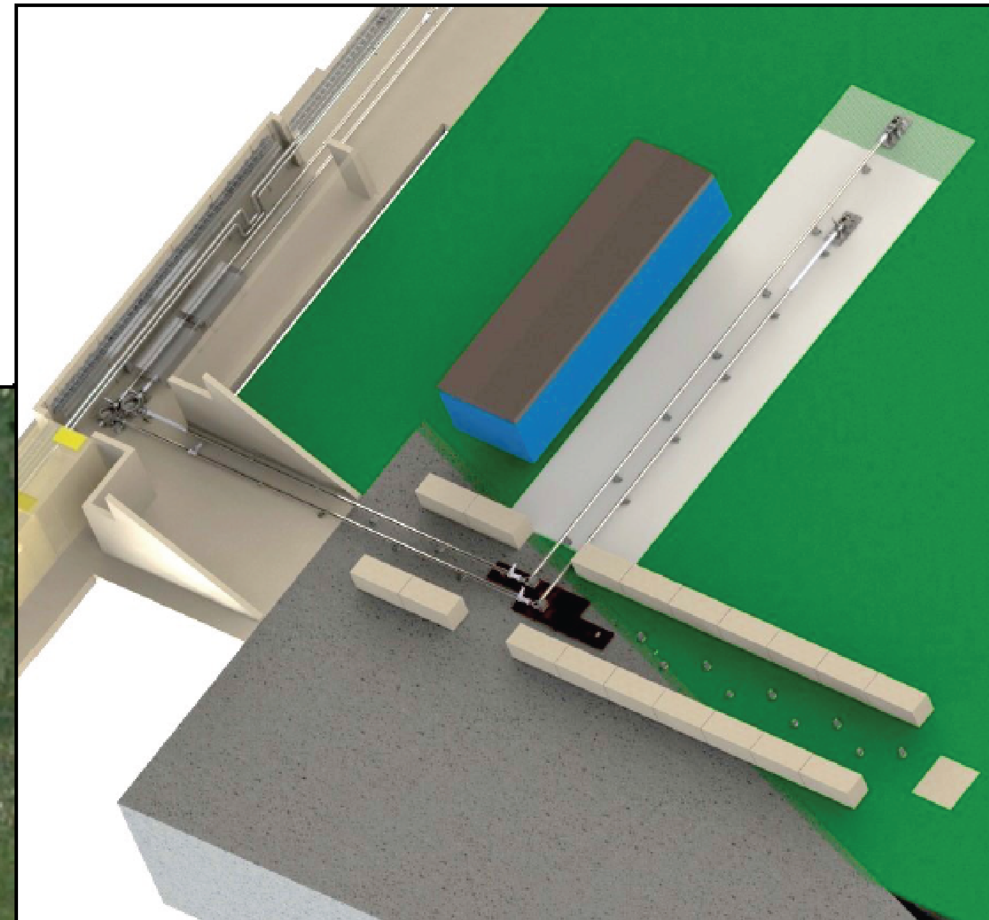
Under construction now

Phase II Experimental Design

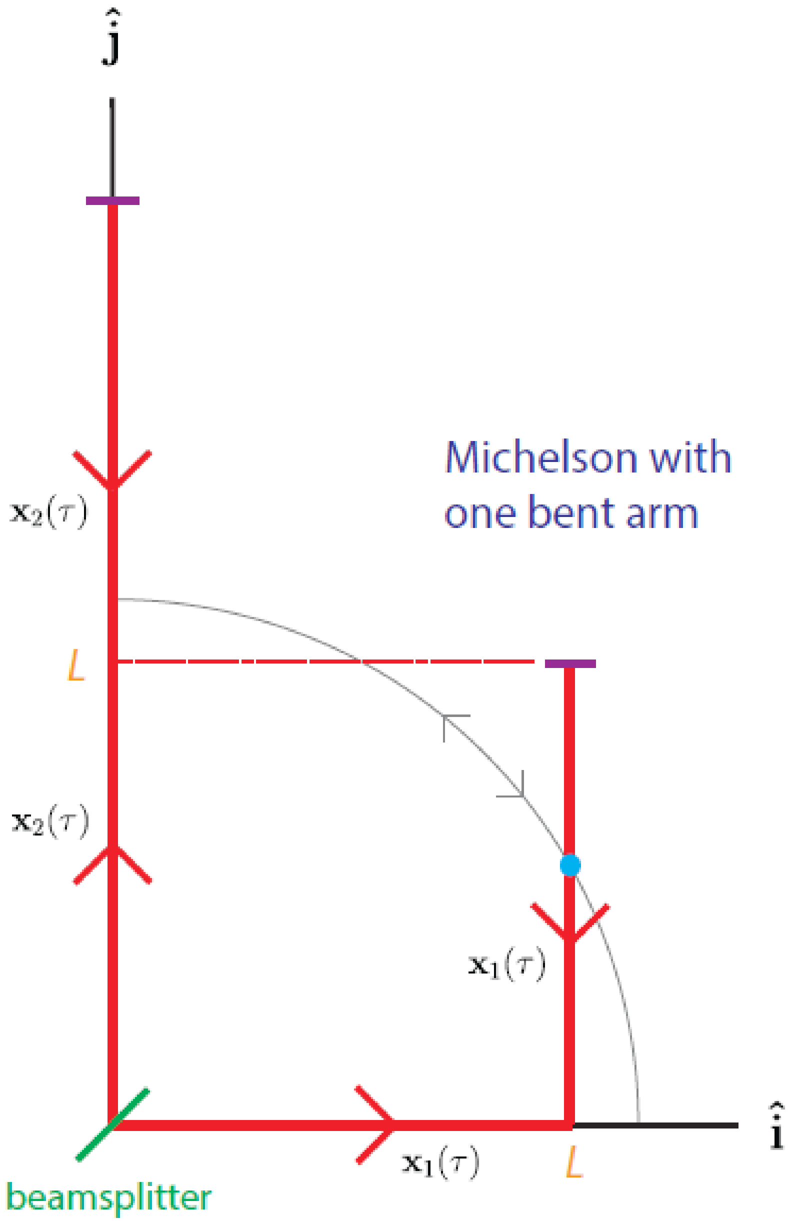
Bends the east arms 90 degrees at their midpoint

Light no longer propagates purely radially inward/outward from beamsplitter



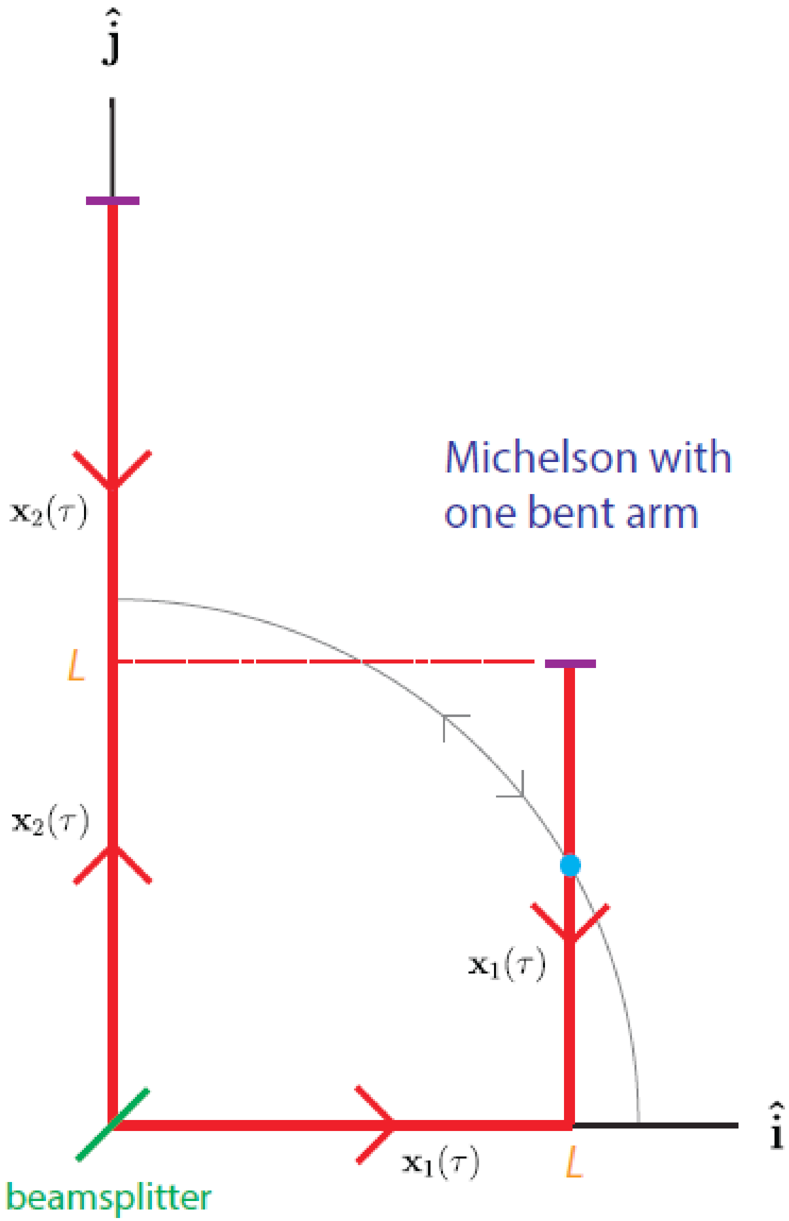


Phase II Experimental Design



Light in the bent arm segment propagates *angularly* relative to the beamsplitter

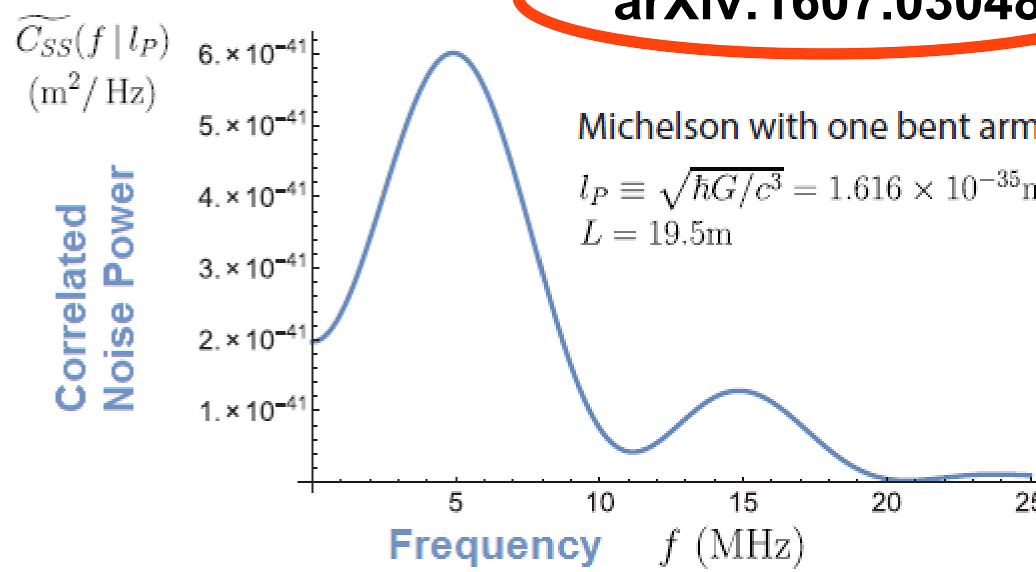
Phase II Experimental Design



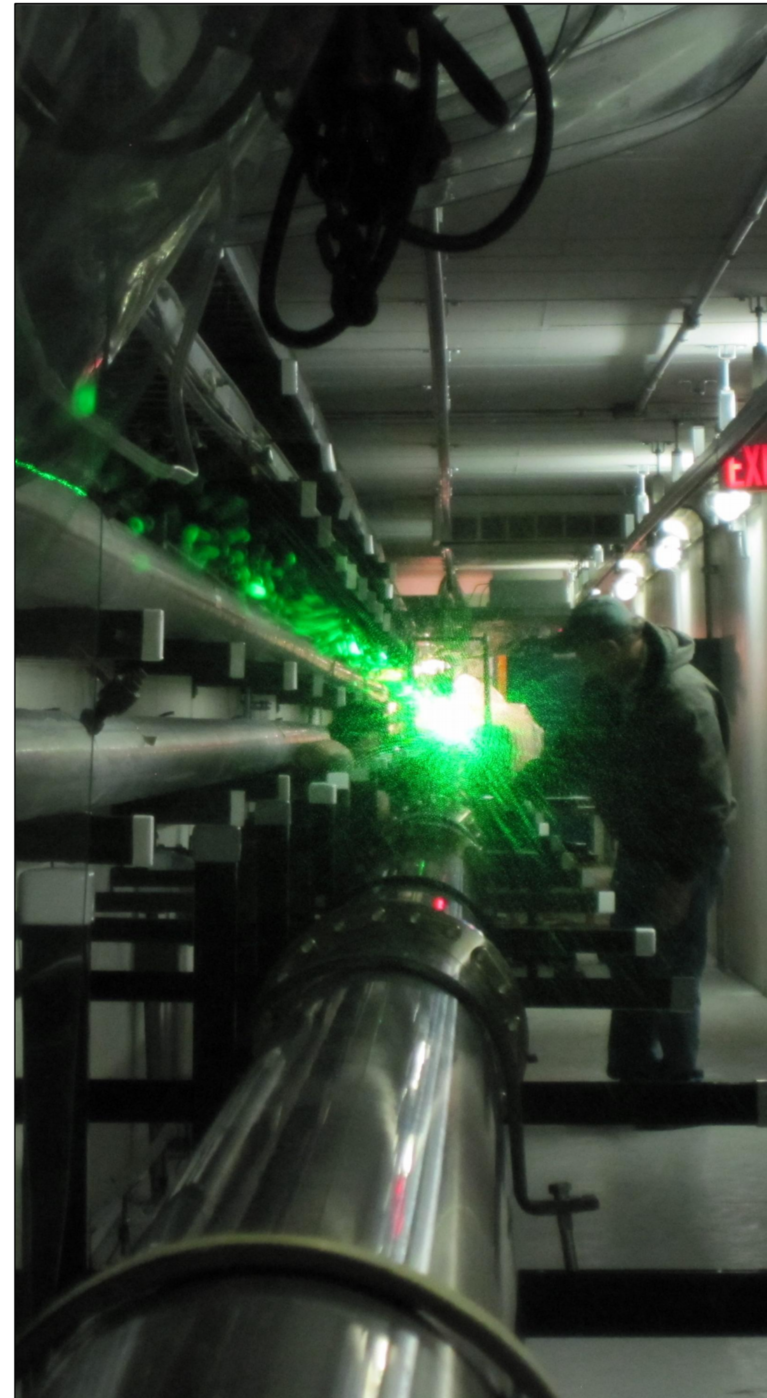
Light in the bent arm segment propagates *angularly* relative to the beamsplitter

Sensitive to quantum "twists"

arXiv:1607.03048



Conclusions



Phase I data exhibit no statistical excess of correlated noise power (null model χ^2/d.o.f. = 0.96)

Geometry of this system is purely sensitive to shear fluctuations

Provides a null/control case for the Phase II rotational search

Hope to begin Phase II operations in fall 2016