Photon Counting Interferometry to Detect Geotropic Space-time Fluctuations with GQuEST

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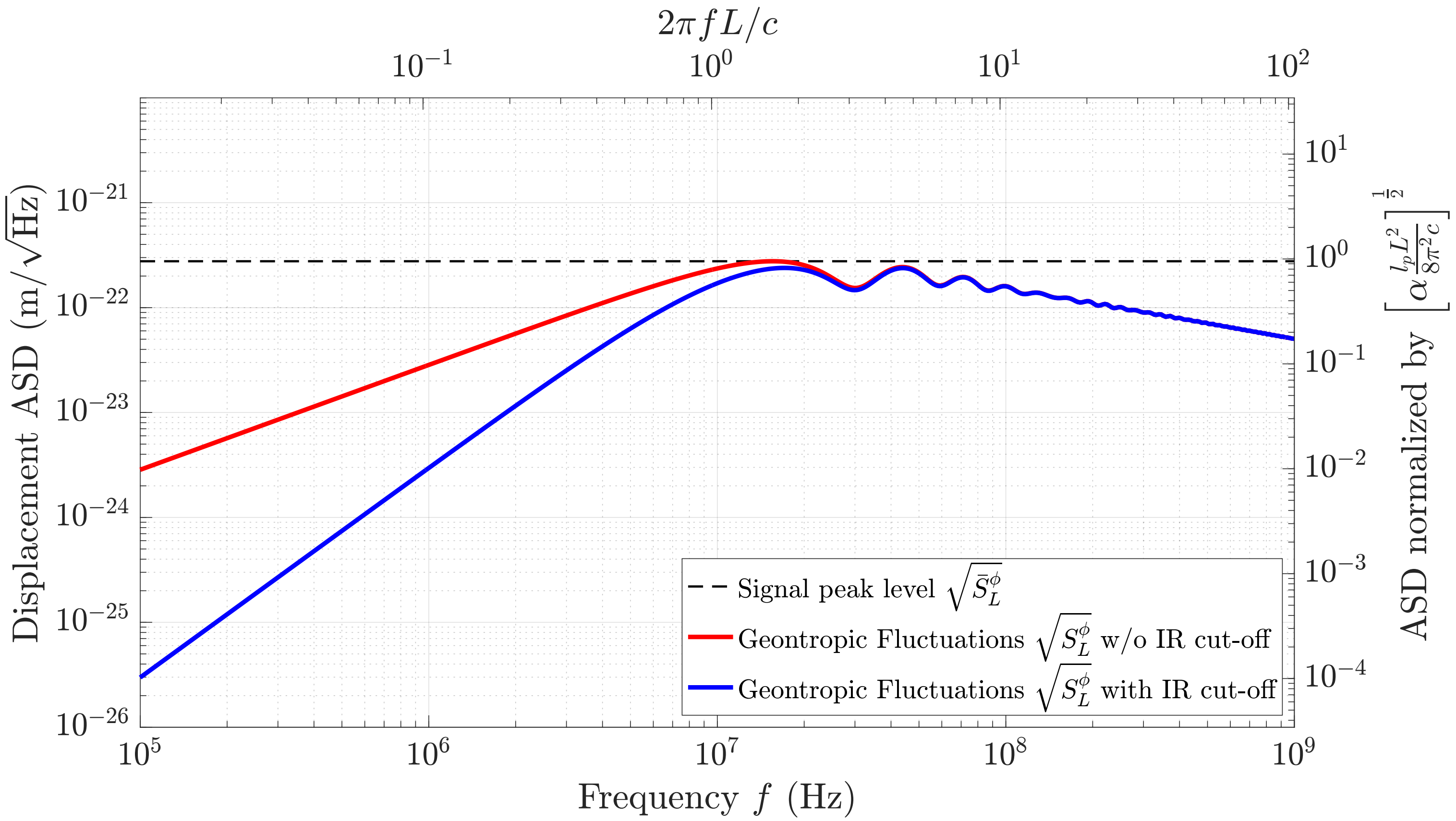
Quantum Mechanics and General Relativity

- Quantum Mechanics and General Relativity make very accurate predictions in their own realms
- These two theories are incompatible
- Many theories exist, like String Theory, LQG, etc, but either don’t make testable predictions or their predictions have not been supported by experiment
- Holographic quantum gravity theories point to detectable spacetime fluctuations

The Proposed Signal

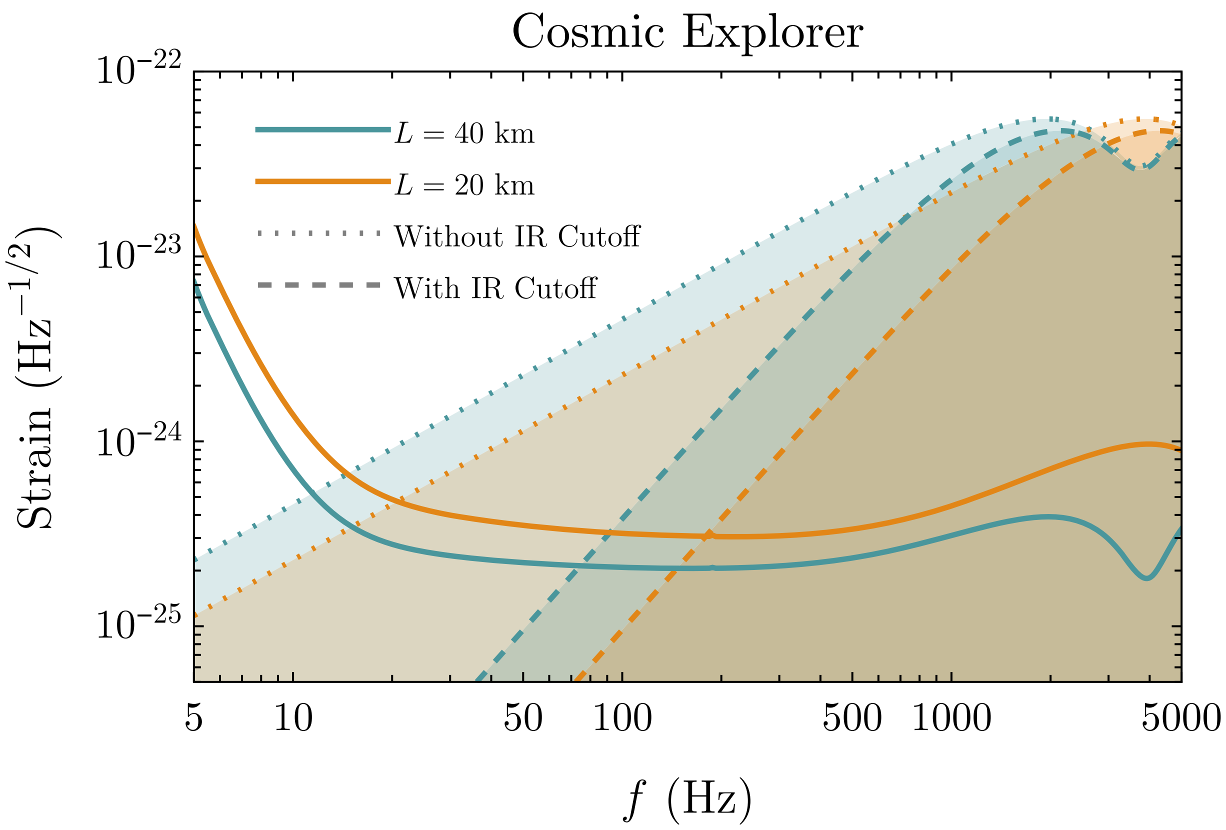
Spacetime Metric modified with a scalar field

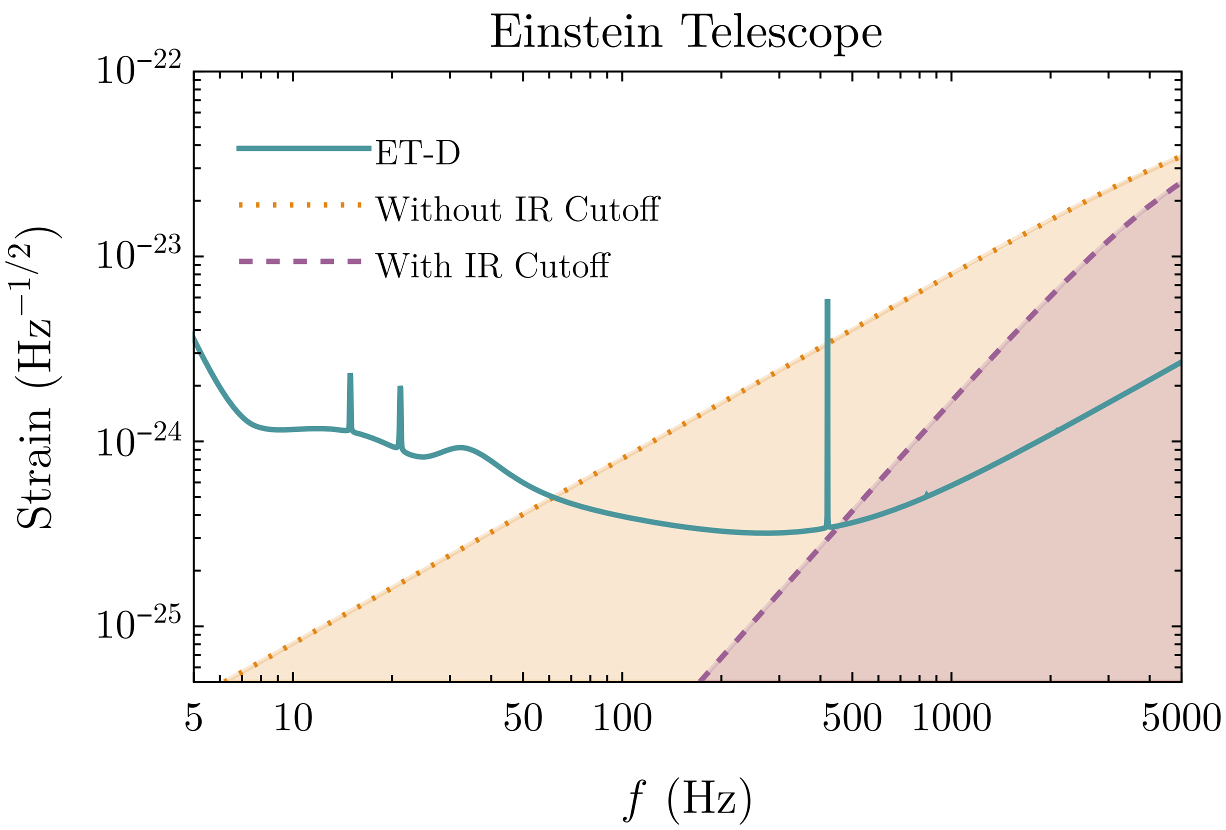
$$ds^2 = -dt^2 + (1-\phi)(dr^2 + r^2 d\Omega^2)$$



Important Features: low amplitude, high frequency, stochastic, and has medium-range spatial correlations

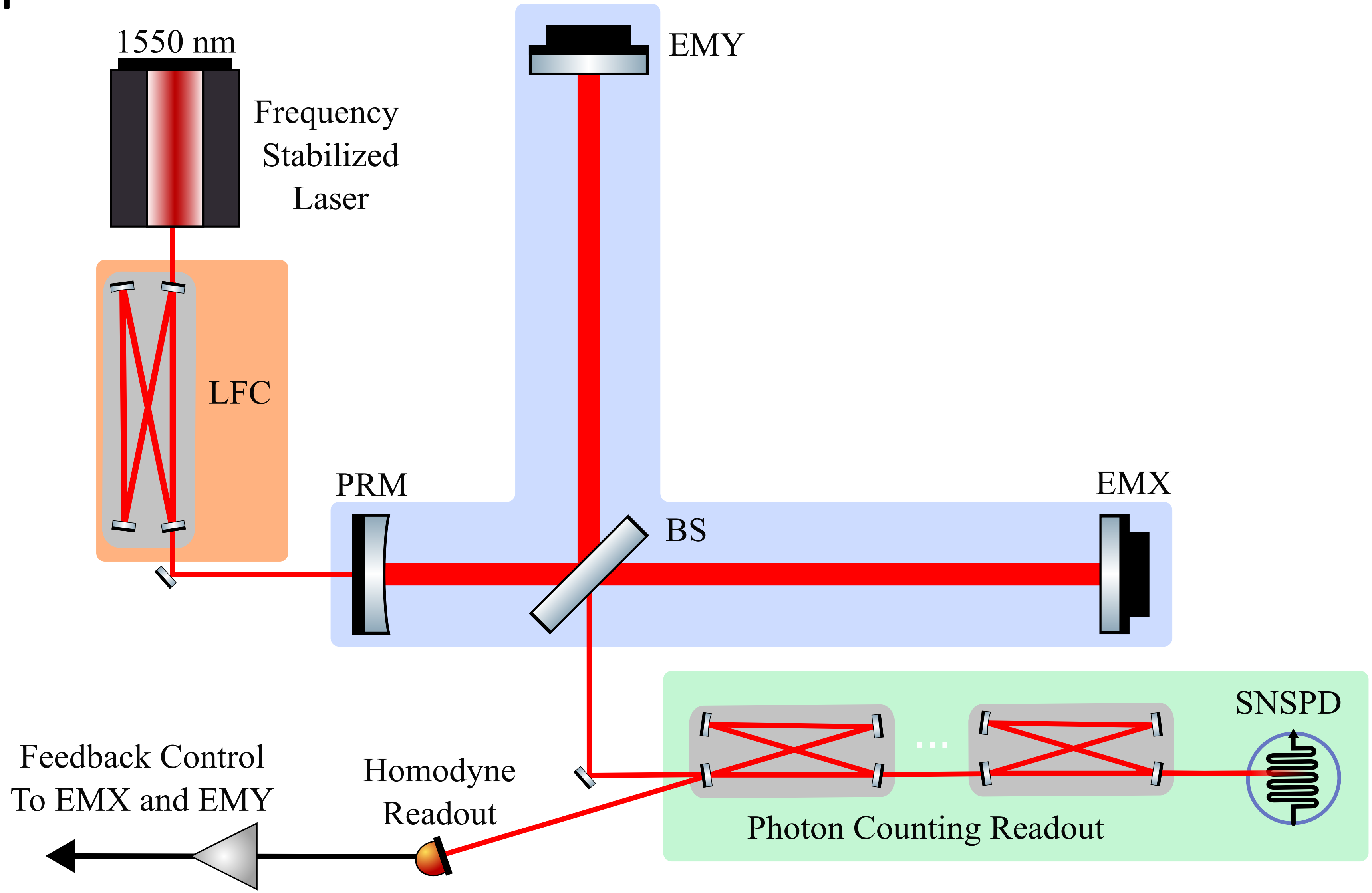
Problematic for 3rd Generation GW Detectors



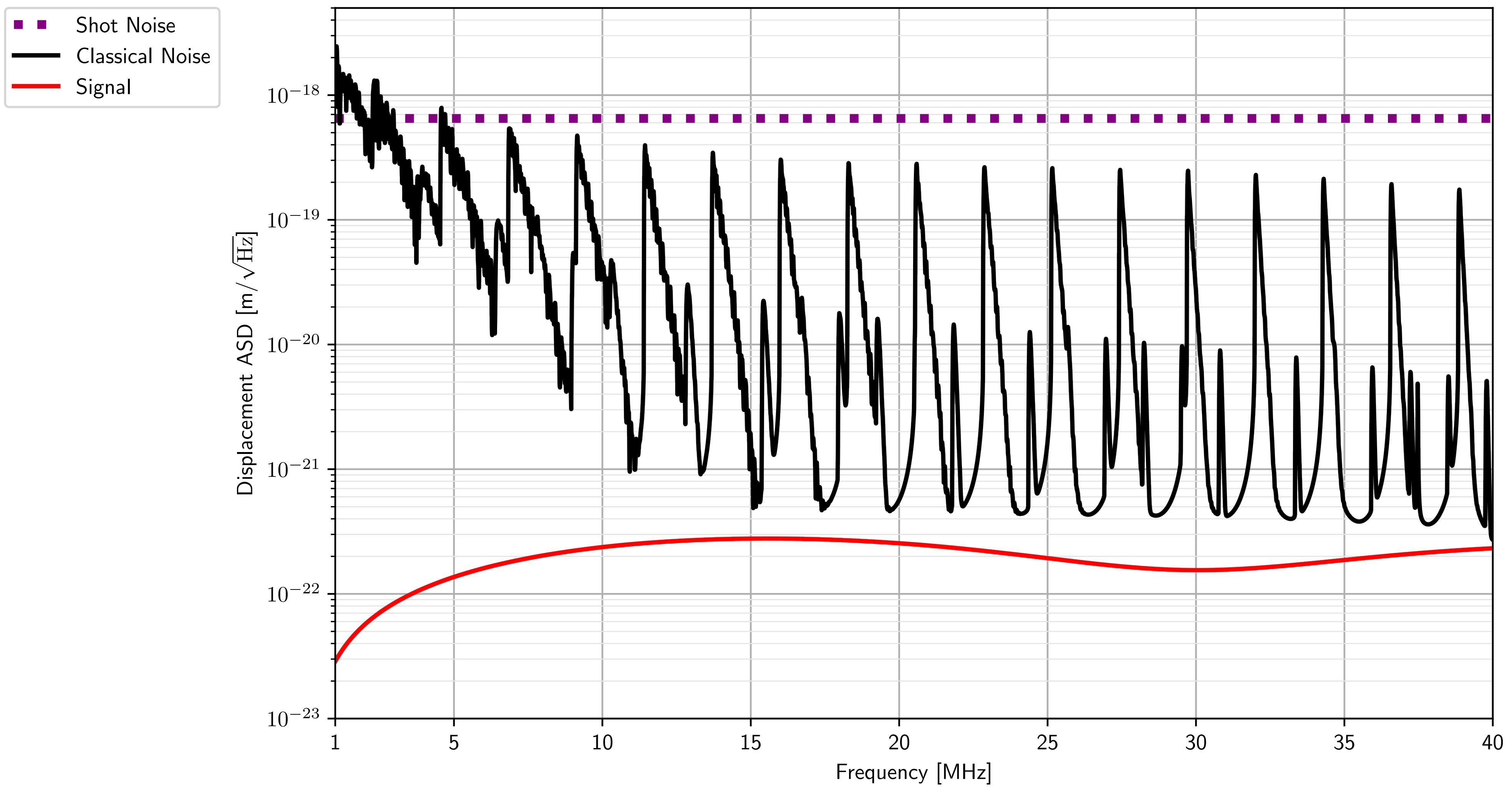


Bub et al., 2023

The Detector

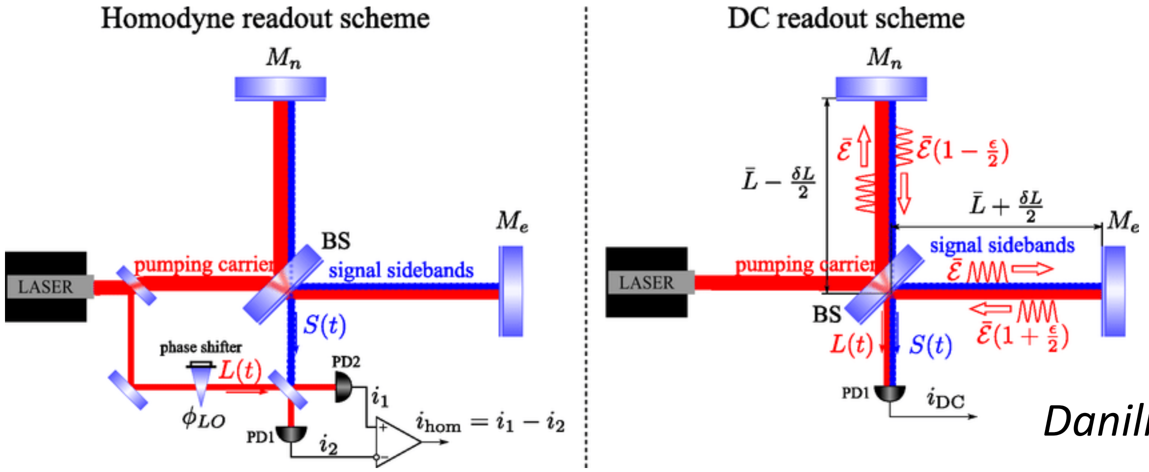


What if we could build a detector limited by classical noise instead of shot noise?



Problems with Homodyne

- Homodyne is used in LVK detectors to sense amplitude and phase
- However, for excess power measurements, Homodyne is no longer optimal
- Homodyne readout's sensitivity is limited by the shot noise
- What is a better readout scheme for excess power measurements?



Danilishin & Khalili, 2012

Photon Counting

- Consider an interferometer with no classical noise operated perfectly at the dark port
- All photons are signal photons!
- Much shorter integration time

$$\mathrm{SNR}^2_{\mathrm{fringe}} = T\Delta f \left(\frac{\overline{S}^{\phi}_{L}}{\overline{S}^{q}_{L}} \right)^2$$

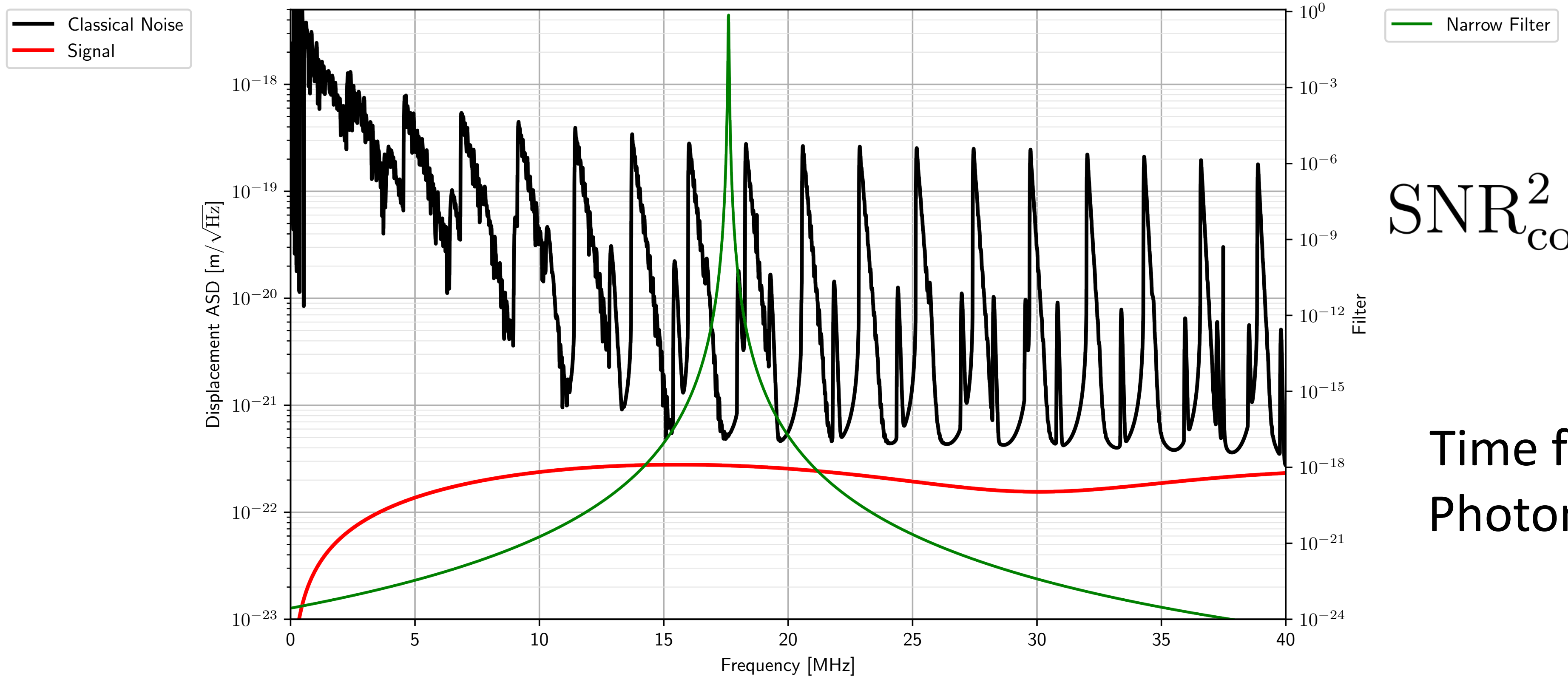
Time for SNR of 1 with Fringe Readout: $5.7 \cdot 10^5$ s = 1 week

$$\mathrm{SNR}^2_{\mathrm{count}} = T\Delta f \frac{\overline{S}^{\phi}_{L}}{2\overline{S}^{q}_{L}}$$

Time for SNR of 1 with Photon Counting: 0.25 s

But there *is* carrier light and classical noise

- An interferometer can't be operated at the dark fringe
- Conditions of a perfect interferometer can be mimicked with a series of narrow optical band pass filters

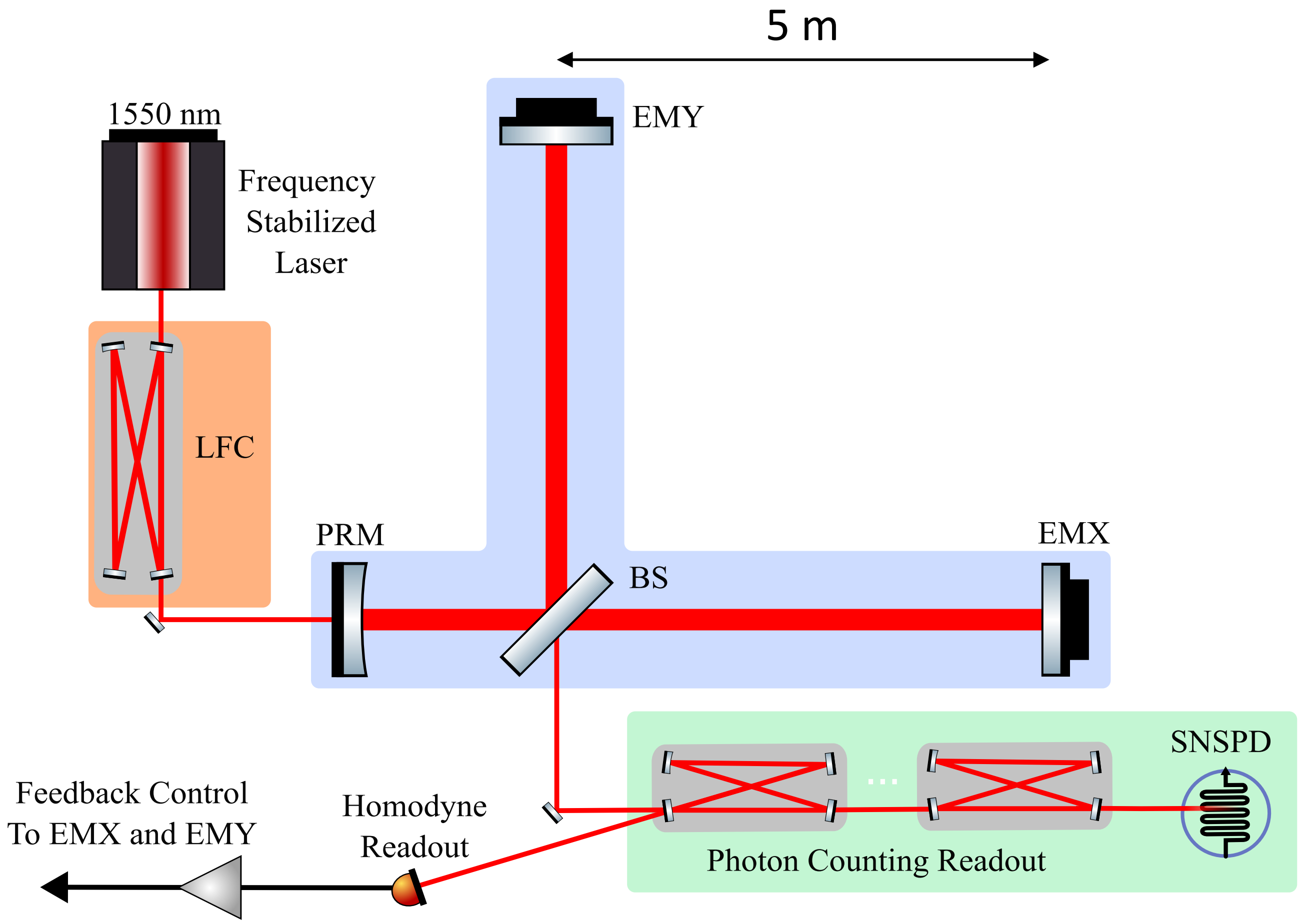


$$\mathrm{SNR}^2_{\mathrm{count}} = \frac{T\Delta\epsilon}{4}\frac{\left(\overline{S}^{\phi}_{L}\right)^2}{\overline{S}^{q}_{L}\overline{S}^{c}_{L}}$$

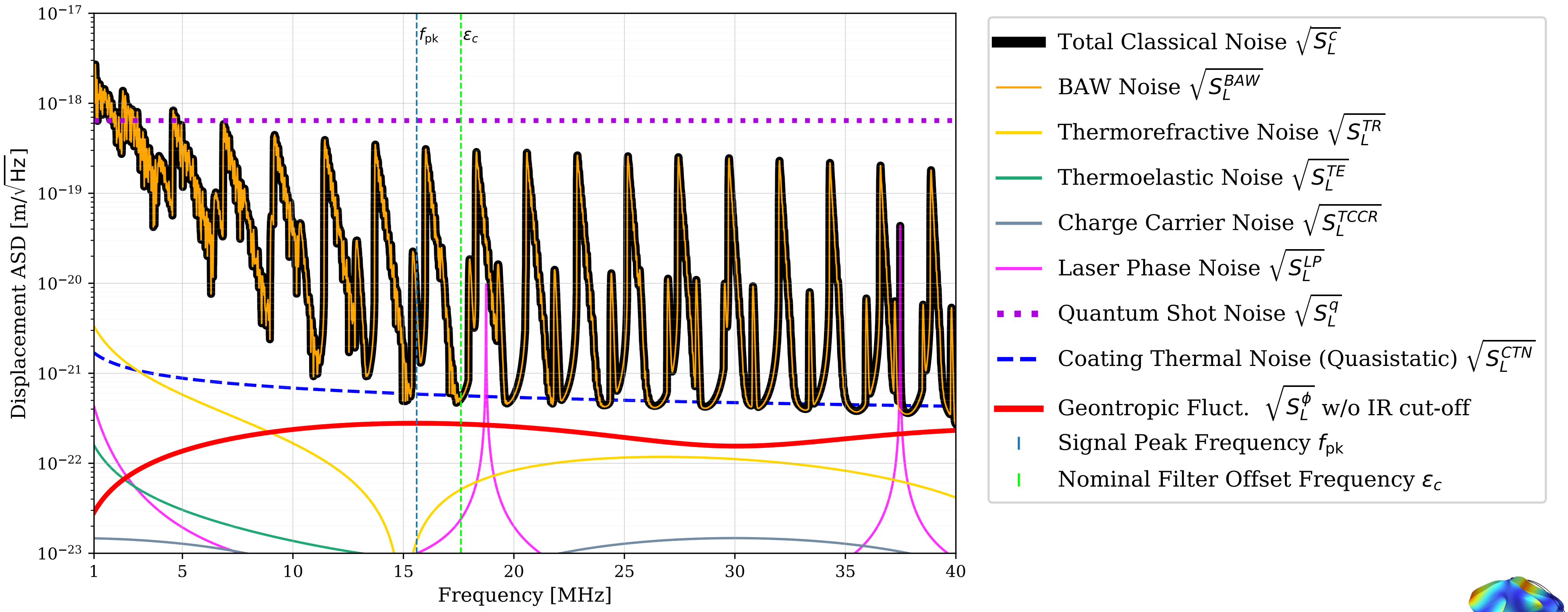
Time for SNR of 1 with Filtered Photon Counting: $8.6 \cdot 10^3$ s = 2.4 hours

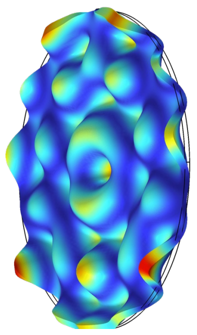
GQuEST Configuration

- Using a power-recycled Michelson interferometer
- Photon counting readout scheme
- Can still collect data with homodyne readout and use it for feedback control
- 10 W input, 10 kW circulating power, 100 mW output power
- 1550 nm light for use with Silicon Optics



Noise Budget





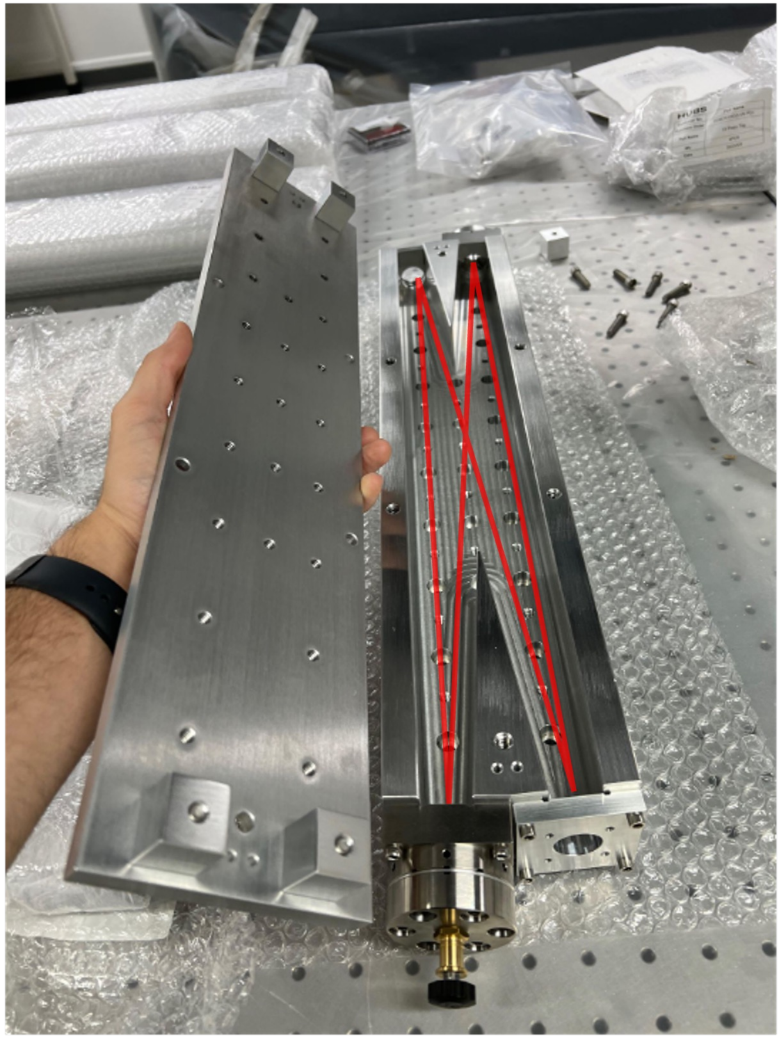
- Dominated by thermal noise from the optics: coating and bulk
- To reduce bulk noise, use thin, stiff, and high Q optics
- High thermal conductivity desirable to limit thermal lensing
- Silicon: stiff, high Q, high thermal conductivity

4 Requirements for Photon Counting

1. Carrier suppression → 4 Optical Bandpass Filters with 22 orders of magnitude suppression in power
2. Low Dark Count Rate Detector → Single Photon Detector (SNSPD)
3. Low Classical Noise → Detector R&D
4. Small Contrast Defect → Excellent Controls and additional R&D

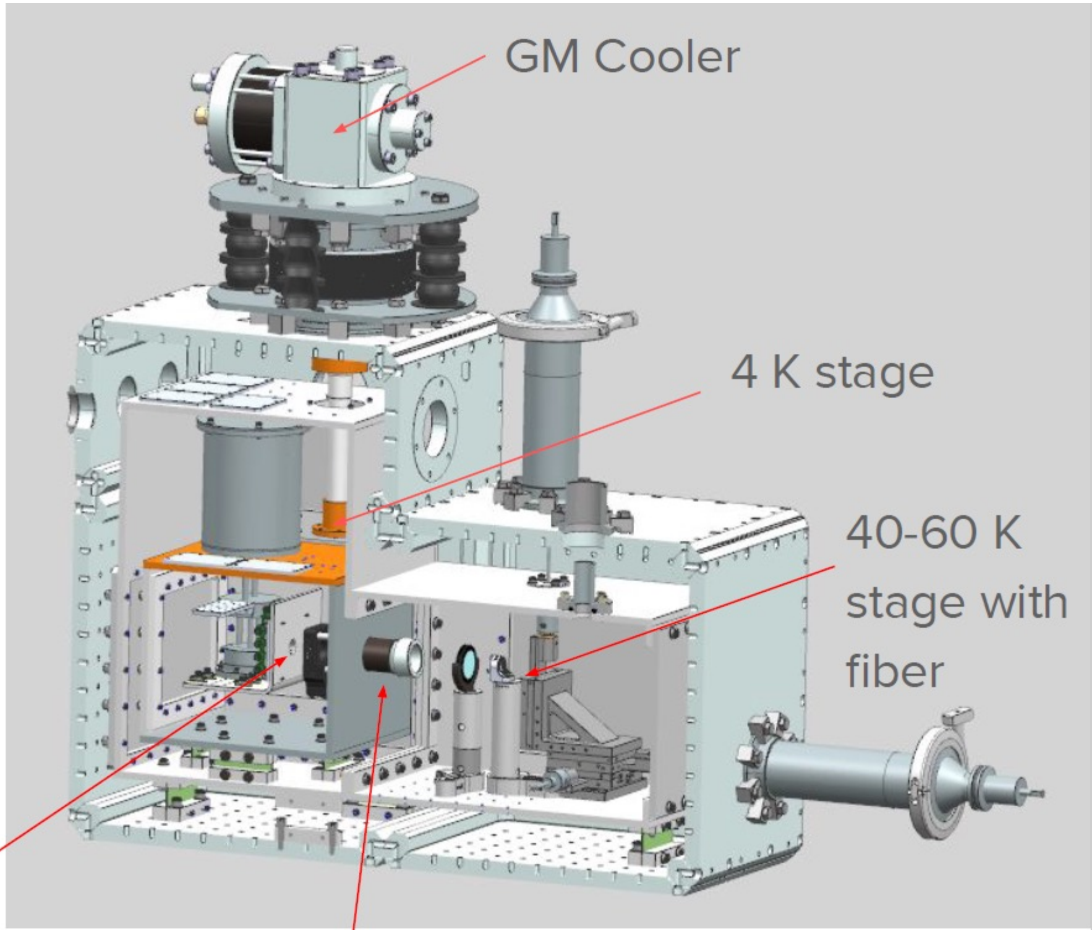
Optical Bandpass Filters

- 6 orders of magnitude of carrier suppression each
- Bowtie Cavity Configuration
- 4 cavities in total to suppress carrier
- Multiple cavities also prevent higher-order spatial modes and frequency modes from leaking through
- 25 kHz integrated bandwidth
- Locked using 775 nm light



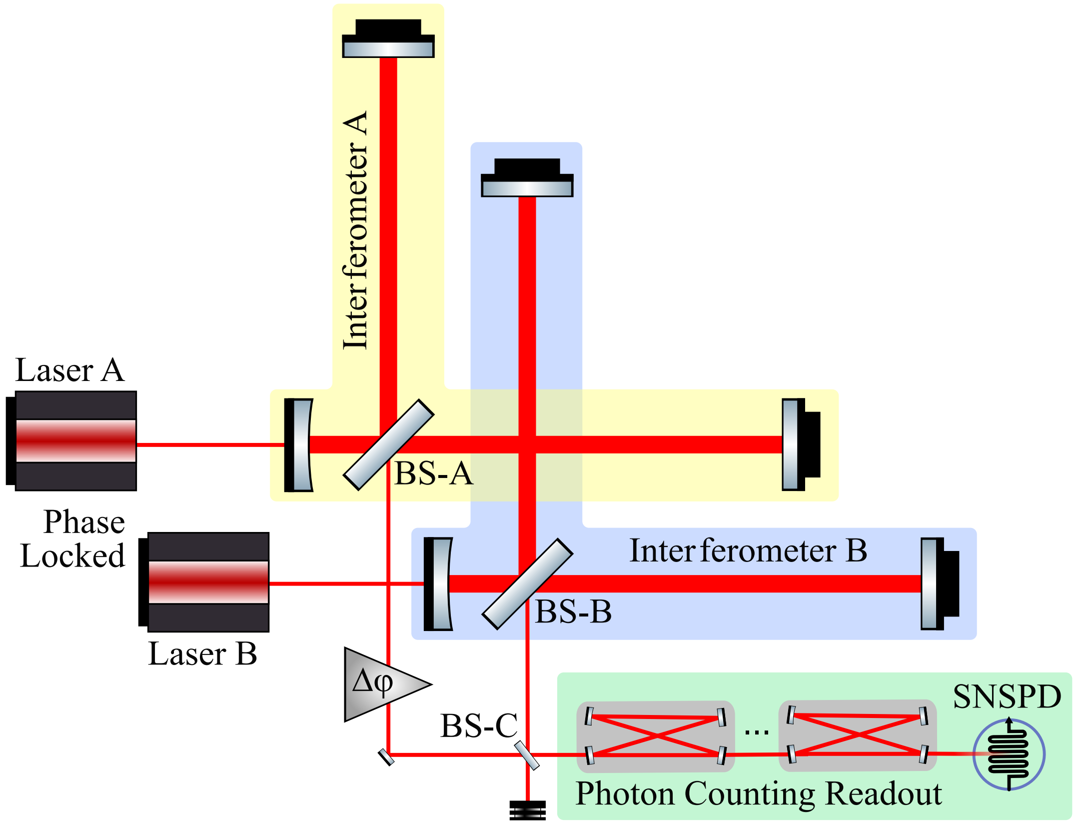
SNSPD: Superconducting Nanowire Single Photon Detector

- Used at the end of the Photon Counting Readout
- Aiming for a Dark Count Rate an order of magnitude below the signal level (which would be 10^{-4} Hz)
- Requires temperatures as low as 0.8 K



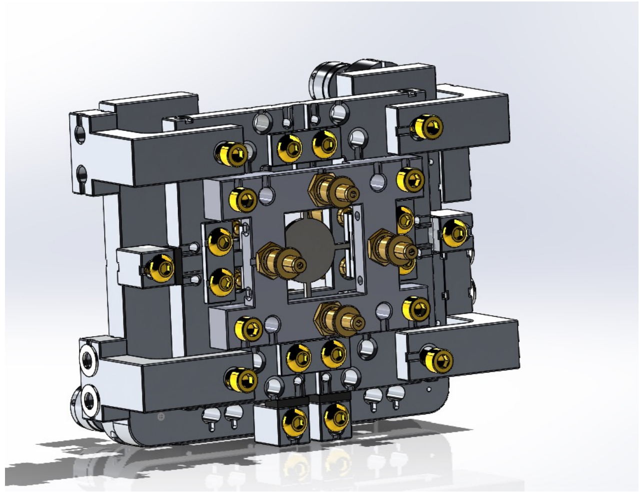
Full GQuEST Configuration

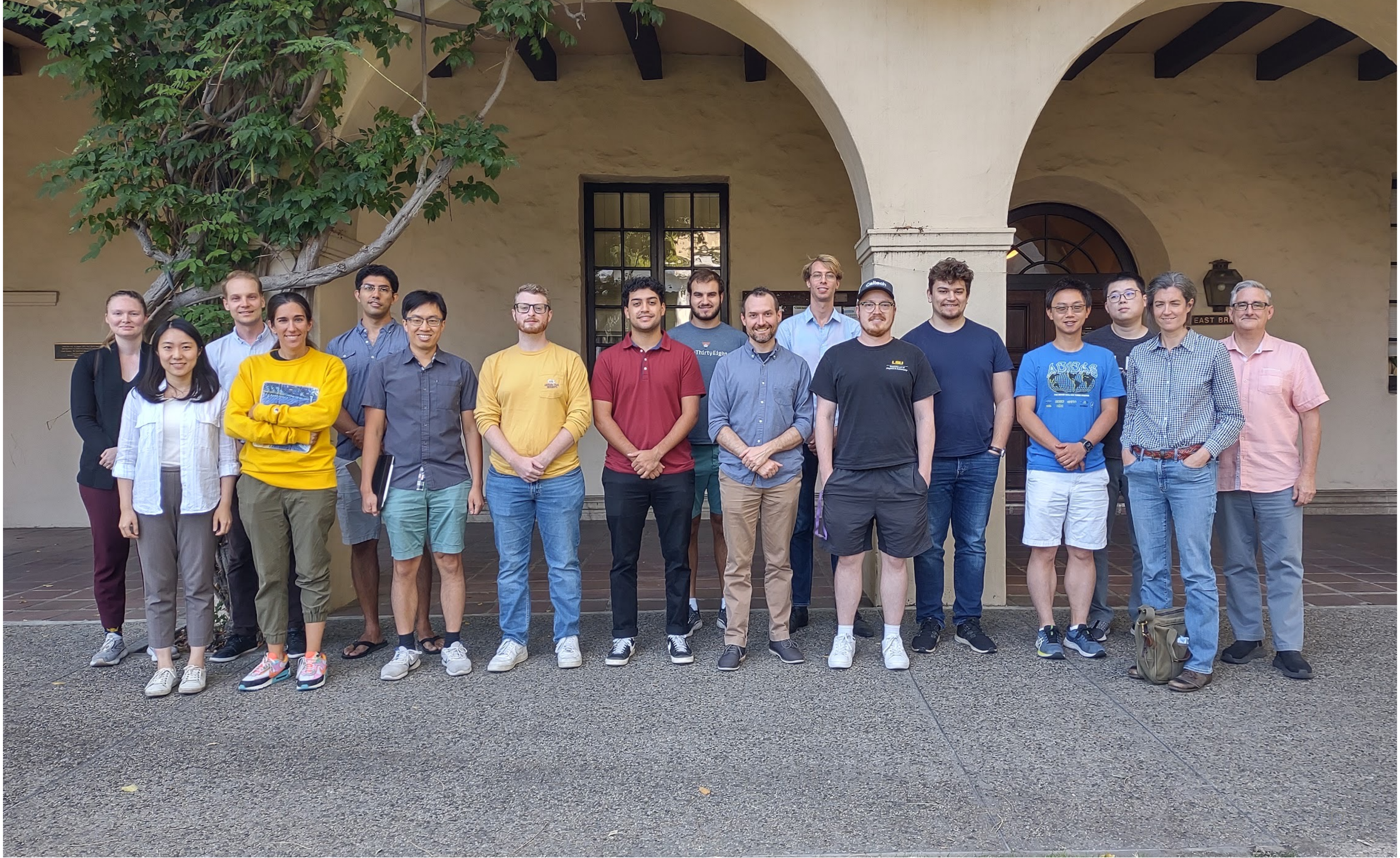
- Classical Noise still above Signal
- Two phase-locked, co-located Power Recycled Interferometers to cross-correlate
- Assuming stationarity of signal and noise, only need one photon counting readout
- Can switch whether the output has just noise or signal + noise
- Potentially limited by noise at BS-C



Highlight of other topics

- Custom Mirror Mount to hold optics and mode match by correcting for astigmatism
- Laser Filter Cavity to reduce laser phase noise and act as a reference for other cavities
- Very beginning of work to make bandpass filters with atomic transitions

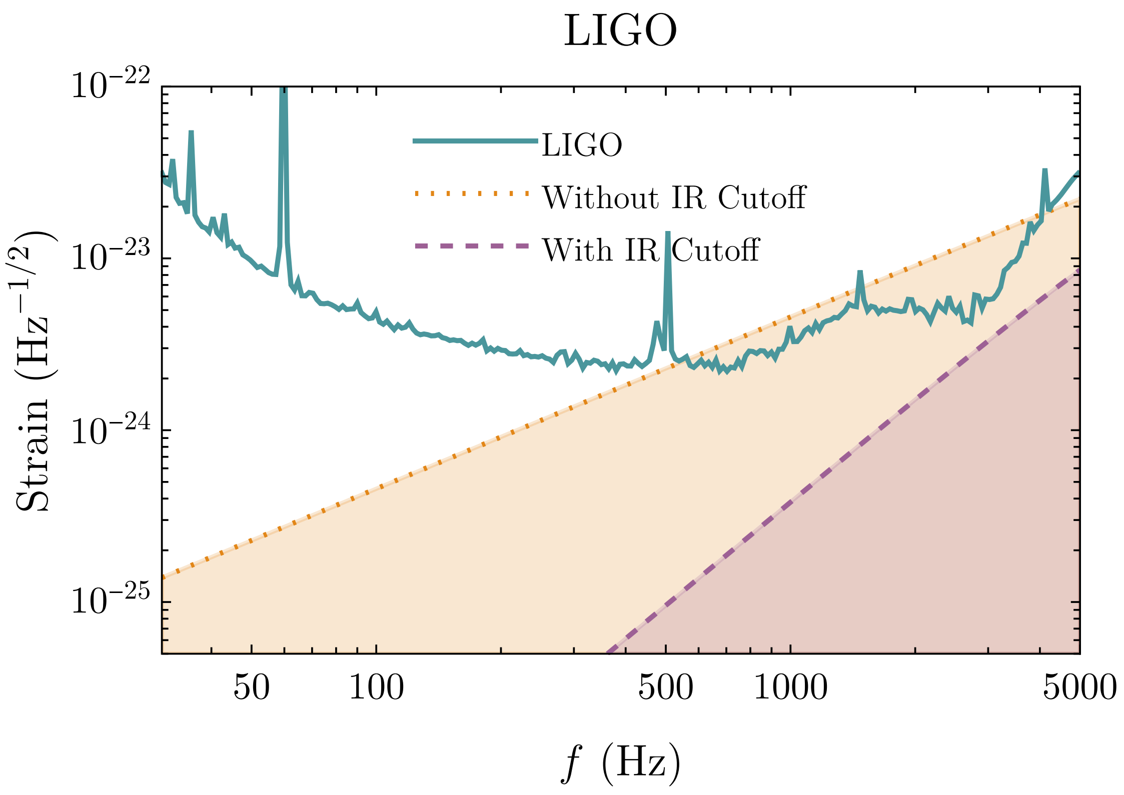



Caltech
LSU

Thank you!

Extra Slides

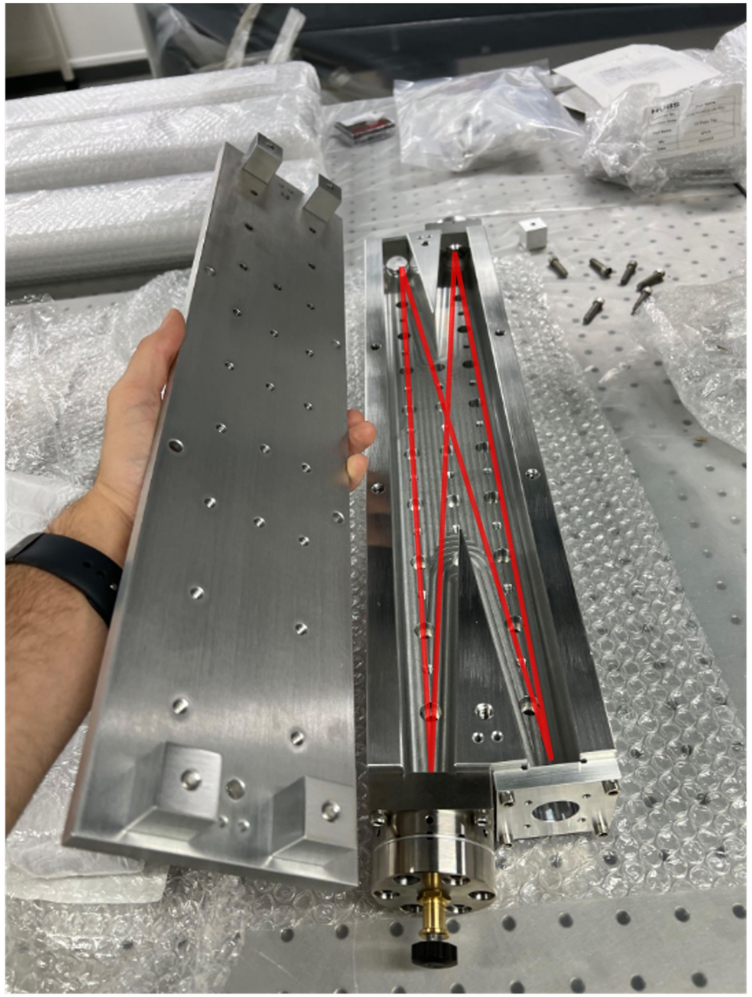
Spacetime Fluctuations in LIGO



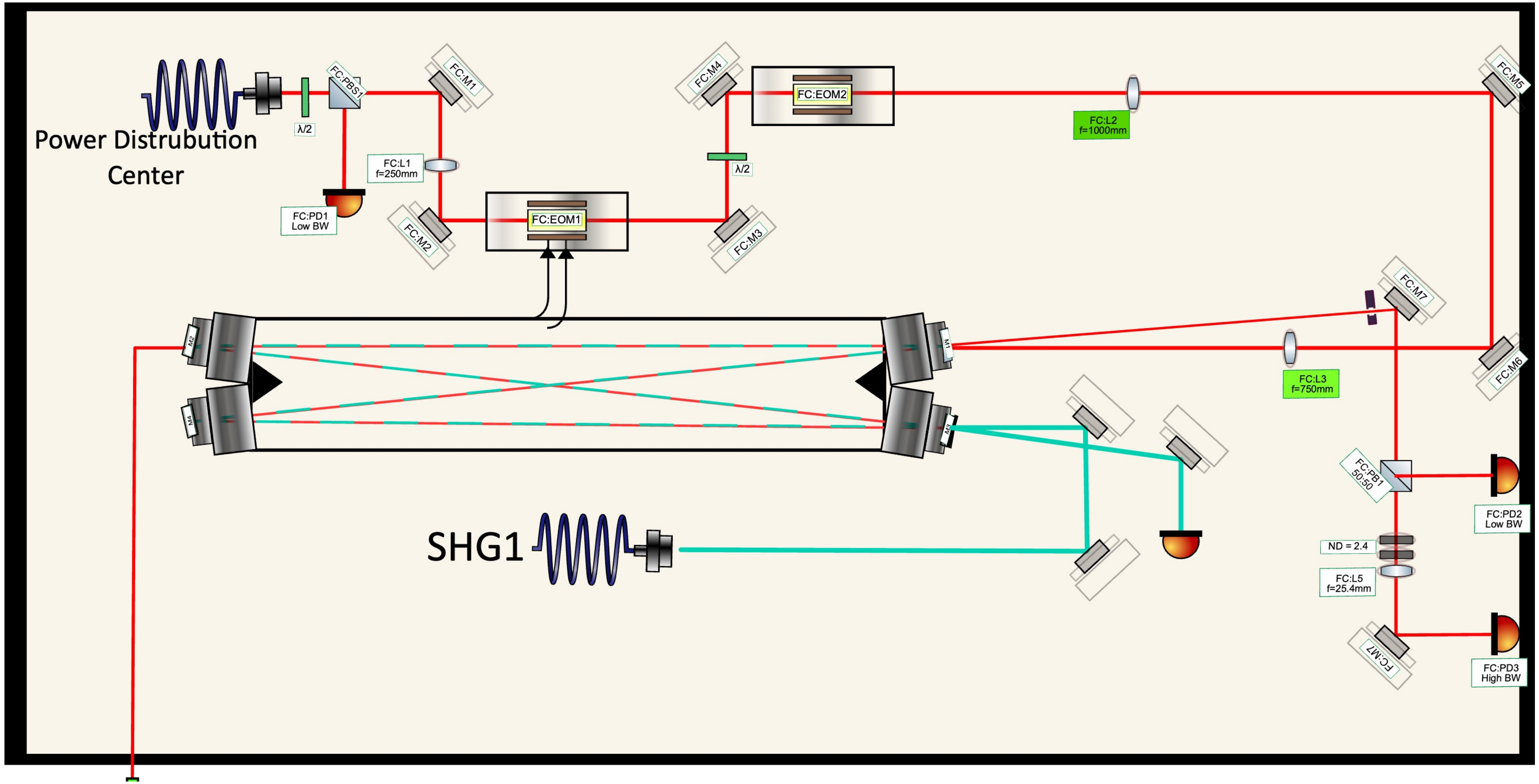
Bub et al., 2023

More on Optical Bandpass Filters

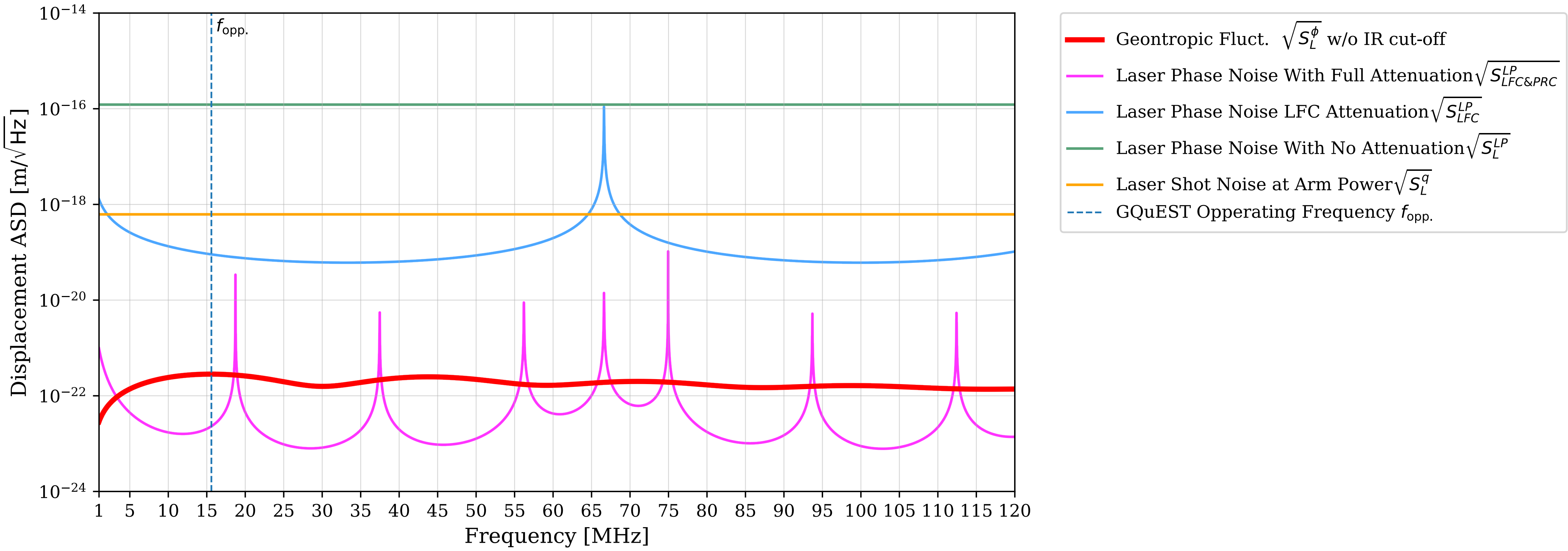
- Finesse of 3000
- FSR of 125 MHz (2.4 m long)
- 42 kHz individual bandwidth
- Round Trip Guoy phase of $2\pi/3$
- 10 ppm loss per mirror: 98% signal transmission
- Allow for an effective signal band between 8 MHz and 40 MHz



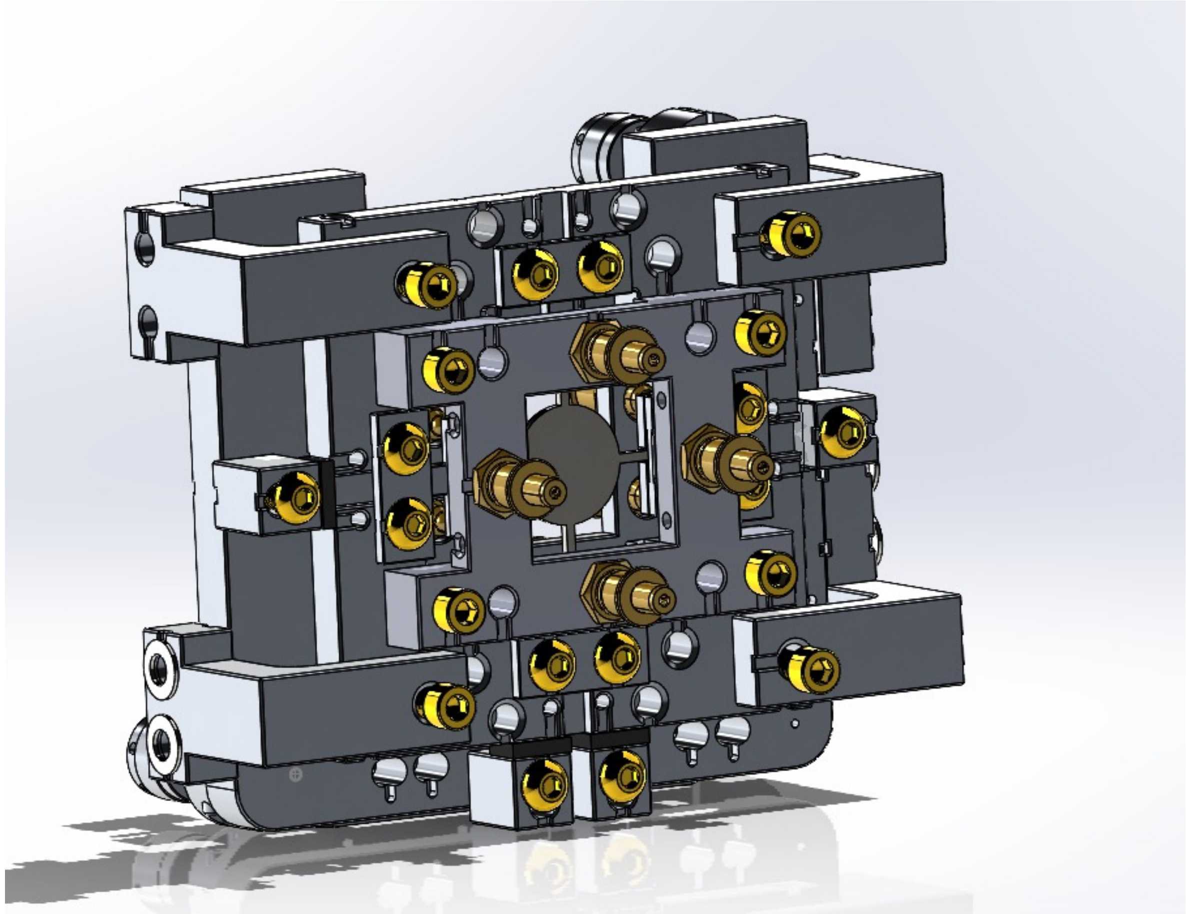
Bowtie Cavity Laser Design

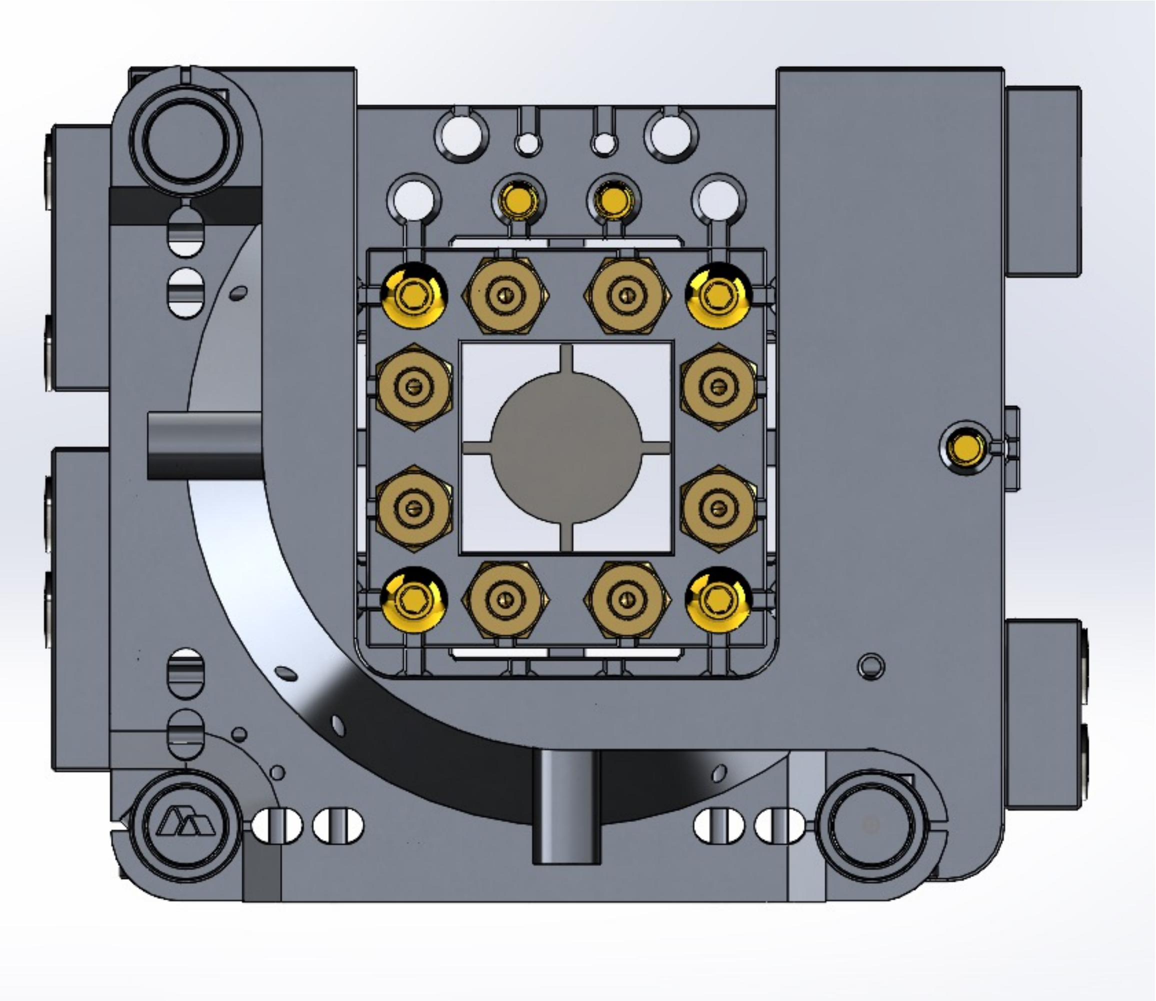


Laser Filter Cavity Justification

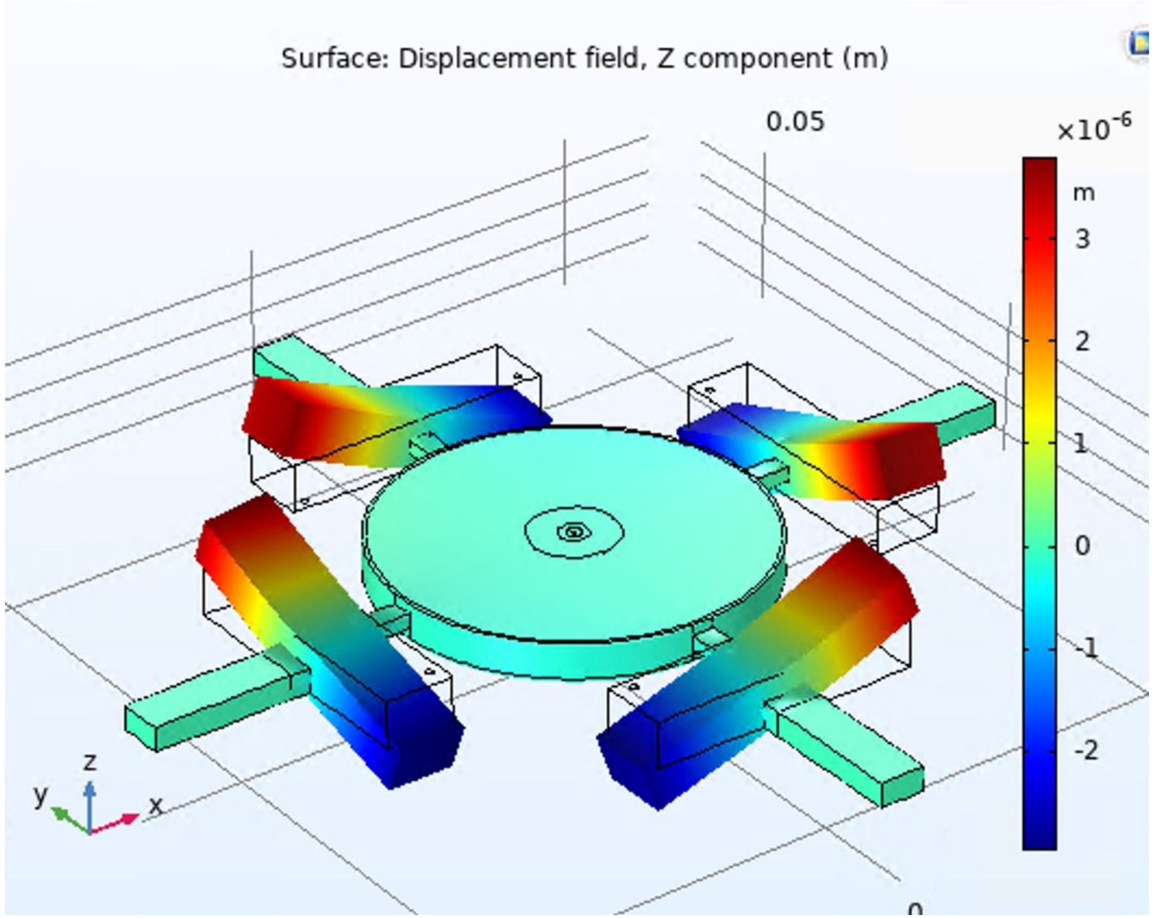


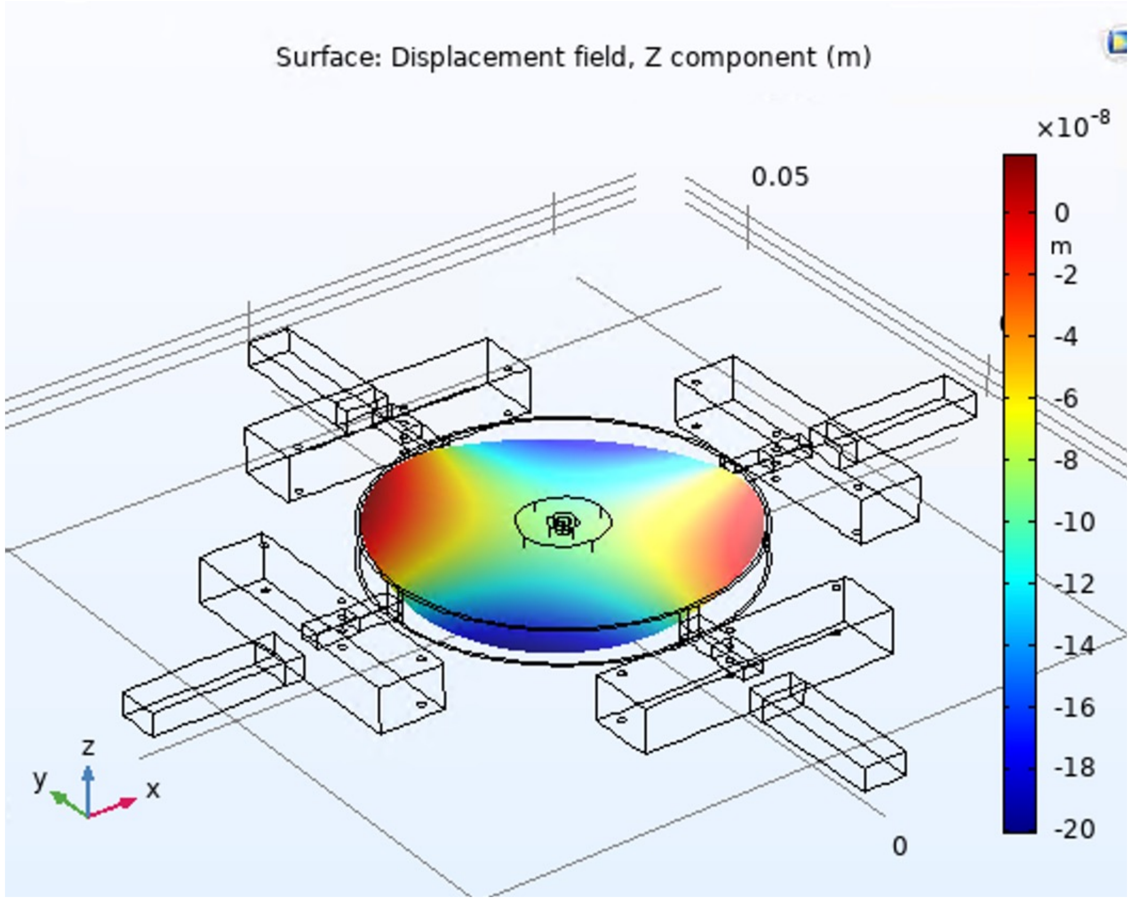
Custom Mirror Mount Design





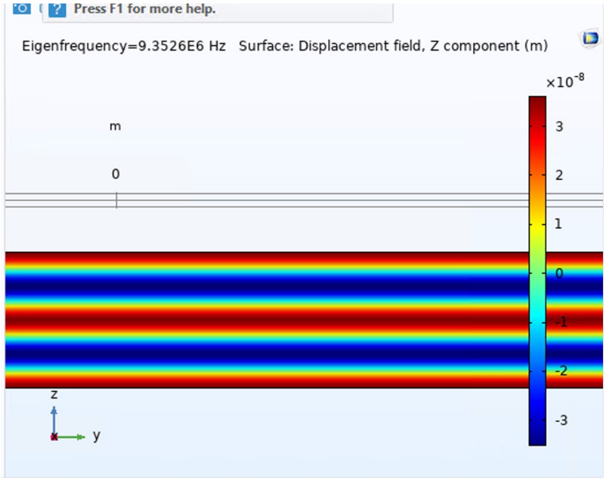
Custom Mirror Mount Simulation

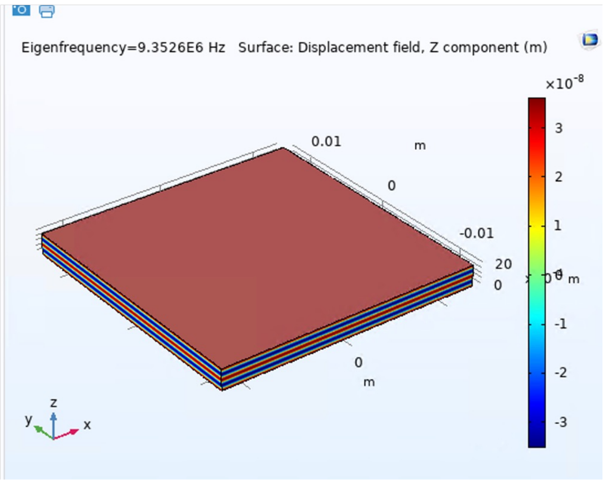


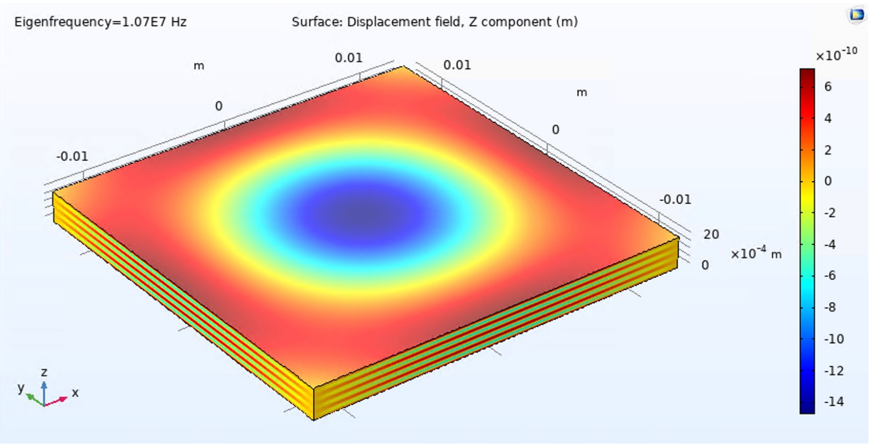


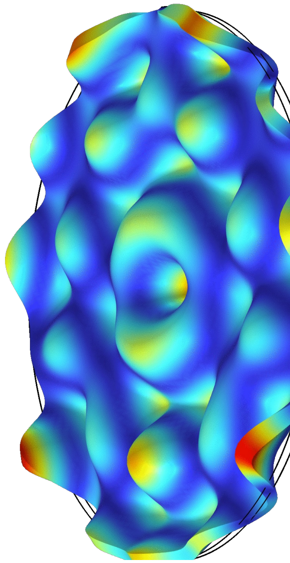
Eigenmode Decomposition Theory

- The mirror has (many) eigenmodes
- Each eigenmode displaces the mirror surface, which affects the phase of the light and looks like signal
- The strength of the noise from each eigenmodes is proportional to the overlap integral of the beam and the eigenmode

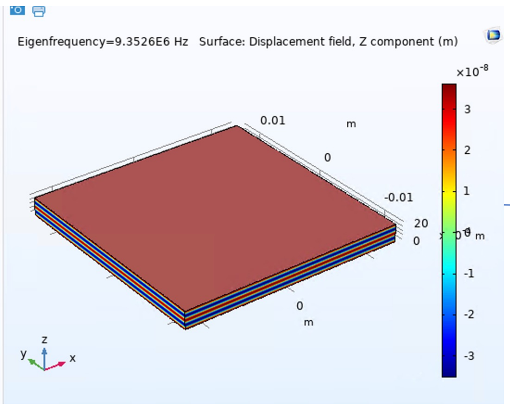




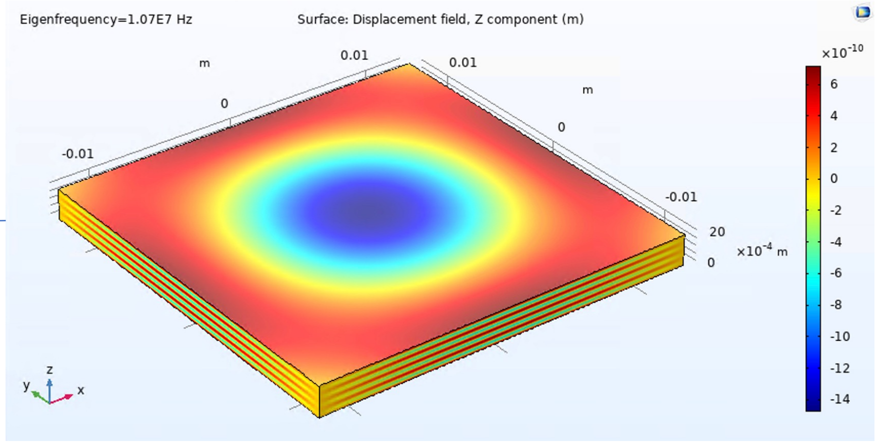




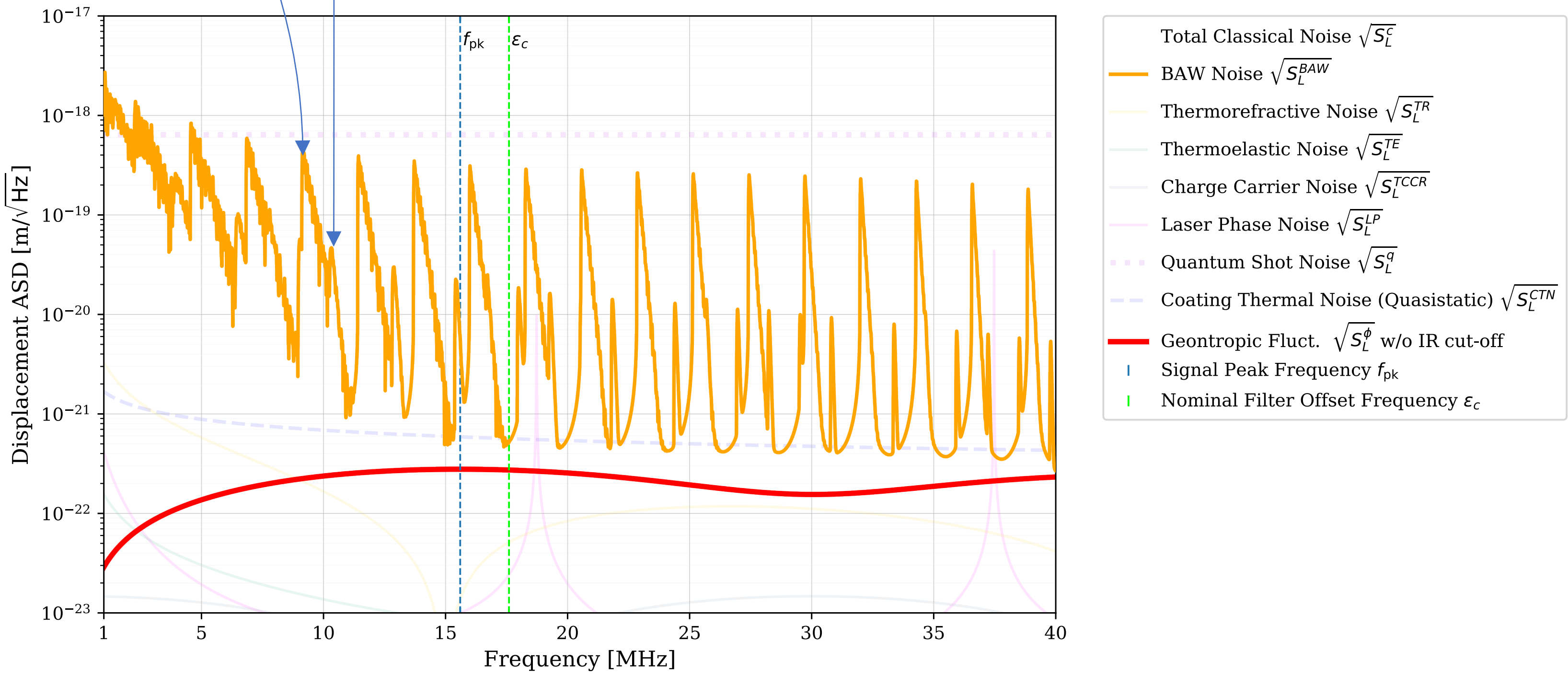
What are these modes?



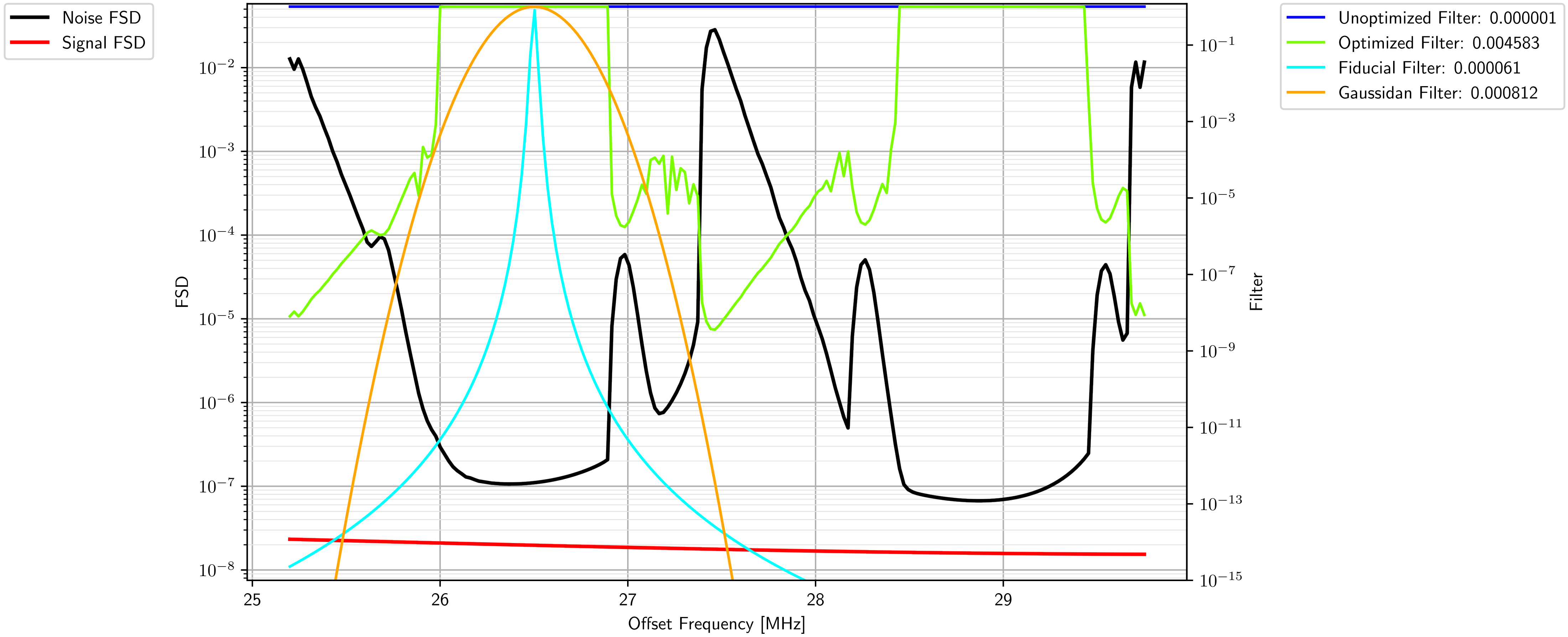
Longitudinal



Transverse



Better Filter Justification



“Quantum Gravity” measurement limit

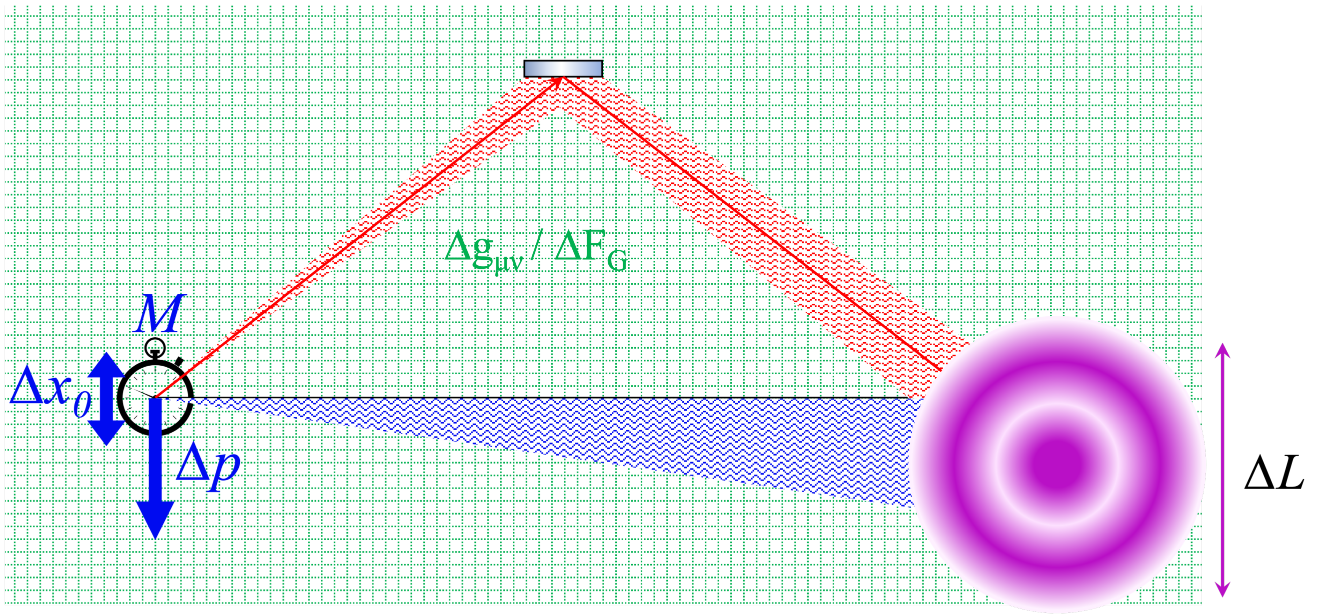
$$\left.\begin{array}{l} \Delta L > r_s = \dfrac{GM}{c^2} \quad \Rightarrow \quad M < \dfrac{\Delta L\, c^2}{G} \quad \text{(‘Schwarzschild limit’)} \\[2em] \Delta L \geq \sqrt{\dfrac{\hbar L}{cM}} \qquad \text{(Standard Quantum Limit)} \end{array}\right\} \Rightarrow \quad \Delta L \geq \sqrt{\frac{\hbar L G}{c^3 \Delta L}}$$

$$\boxed{\Delta L \geq (l_{\mathrm{P}})^{\frac{2}{3}} (L)^{\frac{1}{3}}}$$

Jack Ng & Van Dam (1994)

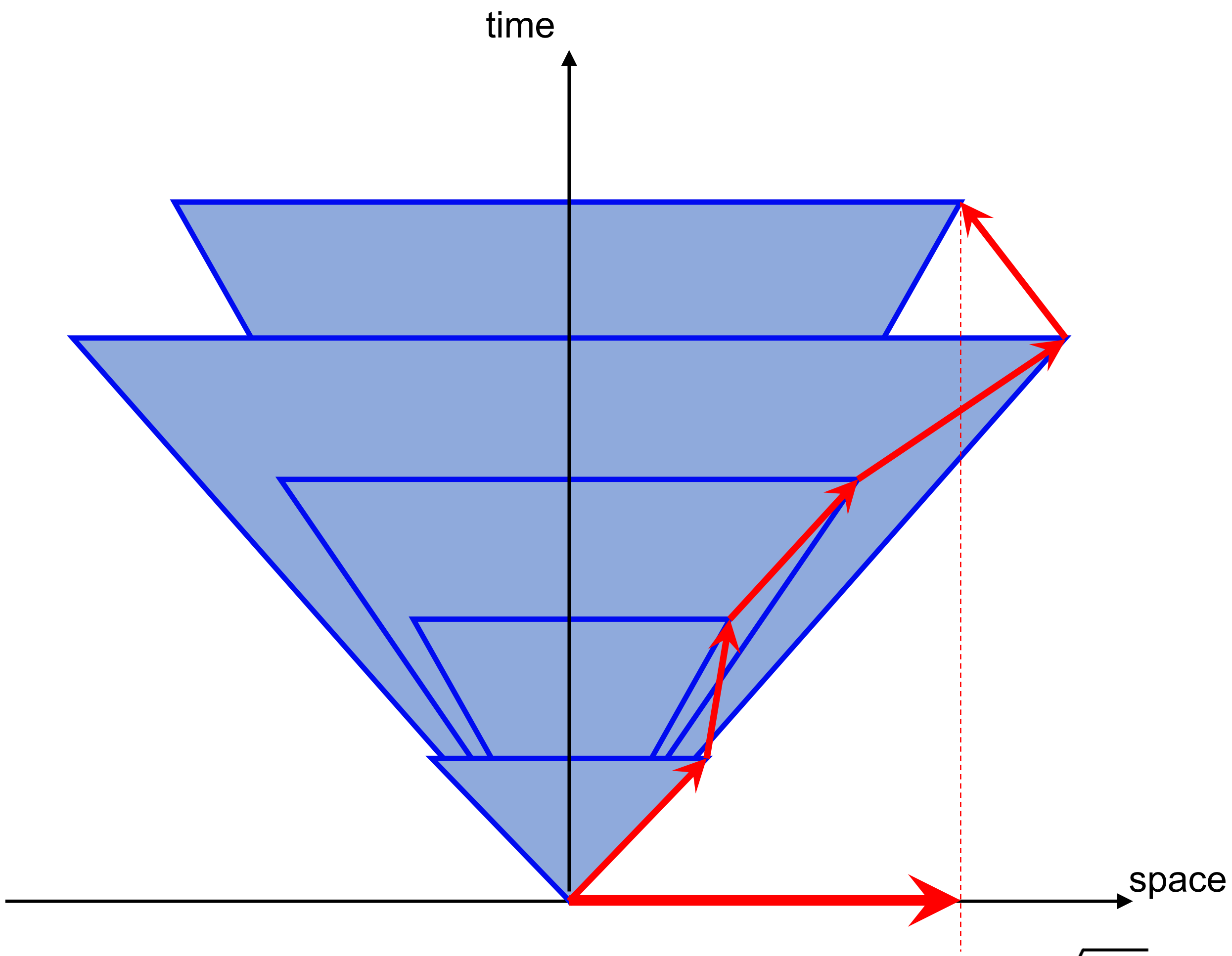
Limits on distance measurements from Quantum Gravity

$$\boxed{\Delta L \propto (l_{\mathrm{P}})^{\alpha}(L)^{1-\alpha}}$$



- $\alpha = 1$ EFT/String Theory/ LQG
- $\alpha = \frac{2}{3}$ Hoop Conjecture/ ‘Old’ holography (Y. Jack Ng & Van Dam)
- $\alpha = \frac{1}{2}$ Random walk, ‘New’ holography (Zurek & Verlinde, Hogan & Kwon)

Light cone fluctuations accumulate like a random walk



- Step size:

$$\delta l \sim l_{\mathrm{P}}$$

- Number of steps

$$N \sim \frac{L}{l_{\mathrm{P}}}$$

Total length: $L \pm \sqrt{N}\delta L \;\sim L \pm \sqrt{L\, l_P}$

Can we detect displacements $\sim \sqrt{l_P\, L} \approx 10^{-18}\sqrt{L}$ **m ?**

Verlinde & Zurek (2019)
Hogan (2012)