Photon counting interferometry to detect geontropic space-time fluctuations with GQuEST

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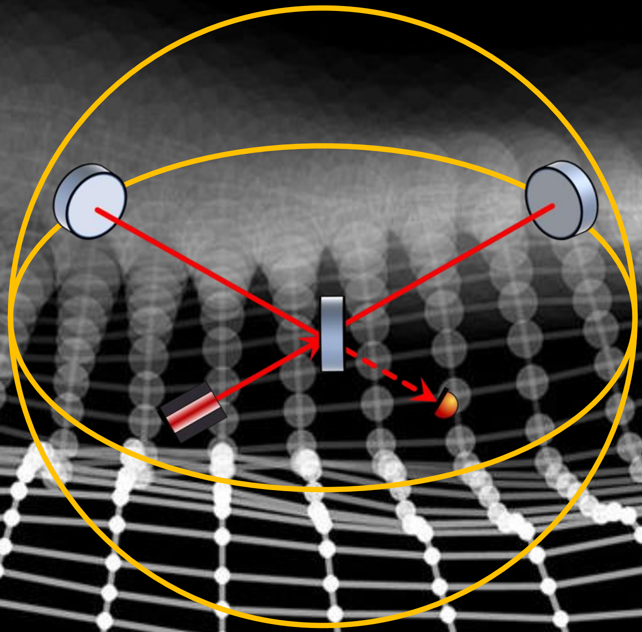


Outline

1. Introduction
2. (Limited) Theoretical Background
3. Laser Interferometry & Homodyne Readout
4. Photon Counting Readout
5. Classical Noise
6. Experimental Implementation

Introduction

- Two 5 m, co-located Michelson laser interferometers

- Search for holographic quantum space-time fluctuations

  i.e. Gravity from the Quantum Entanglement of Space-Time

- Novel ‘*photon counting readout*’ evades quantum shot noise

- Photon Counting Demonstrator is currently under construction

Why use an interferometer to detect quantum gravity?

Gravity is Geometry

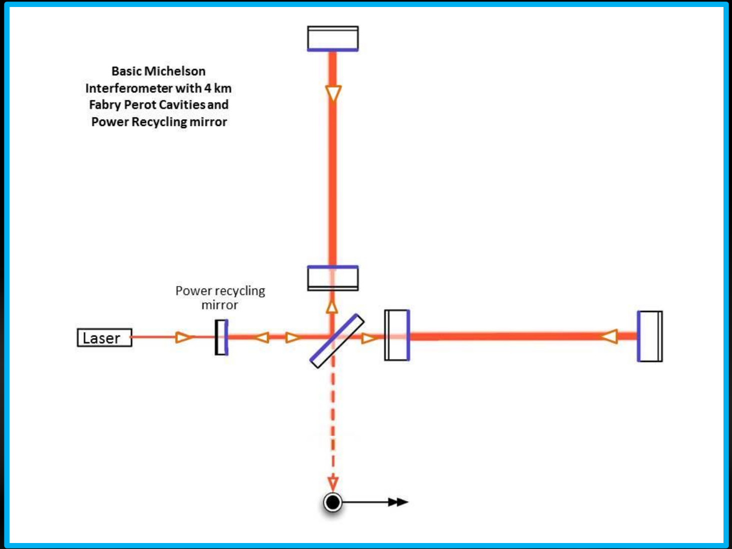
Gravity is Quantum-Mechanical

→ Geometry is Quantum-Mechanical

→ Distance measurements exhibit quantum fluctuations

Why not just use LIGO?

LIGO



Sensitivity to length changes:

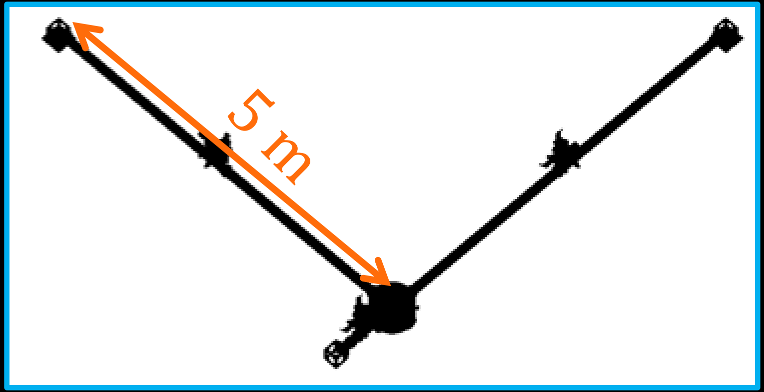
$$\delta L \approx 10^{-20}\ \mathrm{m}$$

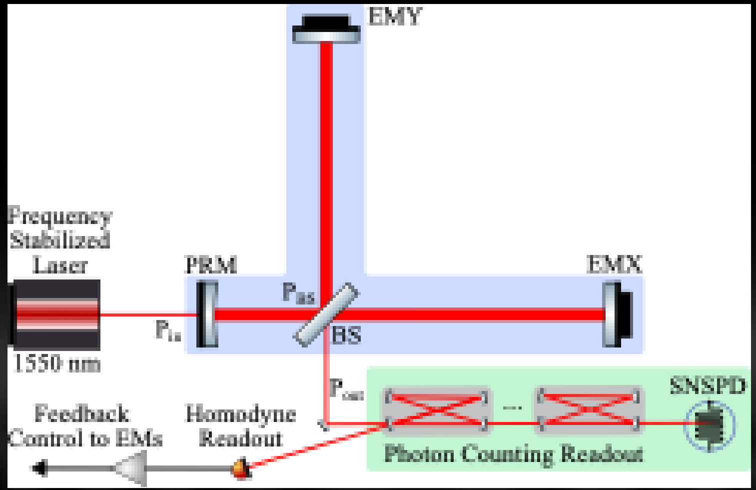
@ 100 Hz

$$\delta L \approx 10^{-21}\ \mathrm{m}$$

@ 18 MHz

GQuEST





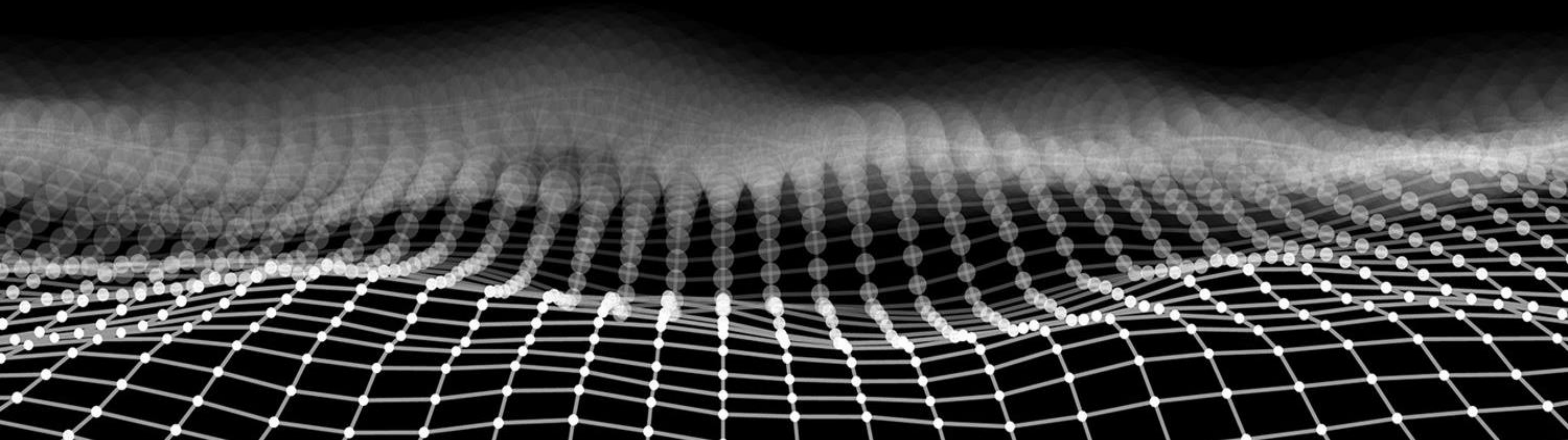
SNR^2 Scaling

$$\propto \left[\frac{S_{\mathrm{Signal}}}{S_{\mathrm{Noise}}}\right]^2$$

$$\propto \frac{S_{\mathrm{Signal}}}{S_{\mathrm{Noise}}}$$

$$\frac{S_{\mathrm{signal}}}{S_{\mathrm{noise}}} \ll 1$$

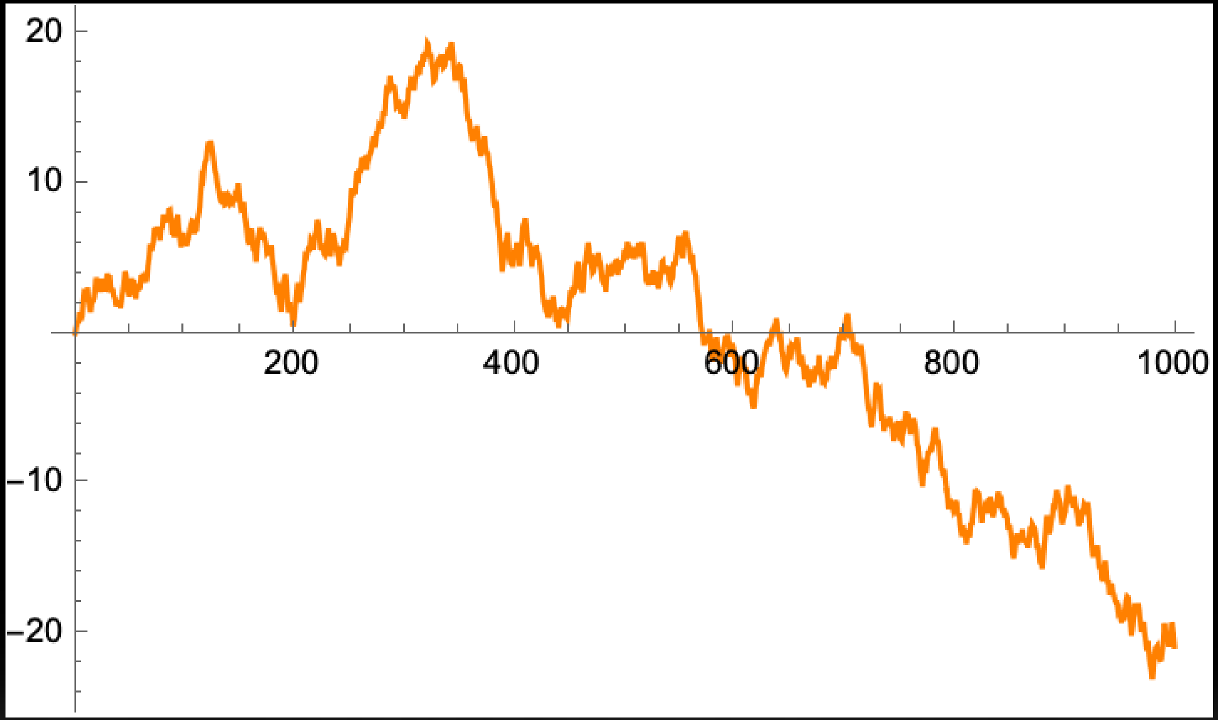
Theoretical Background



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

Planck-scale random walk noise



- Step size:

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

- Number of steps

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

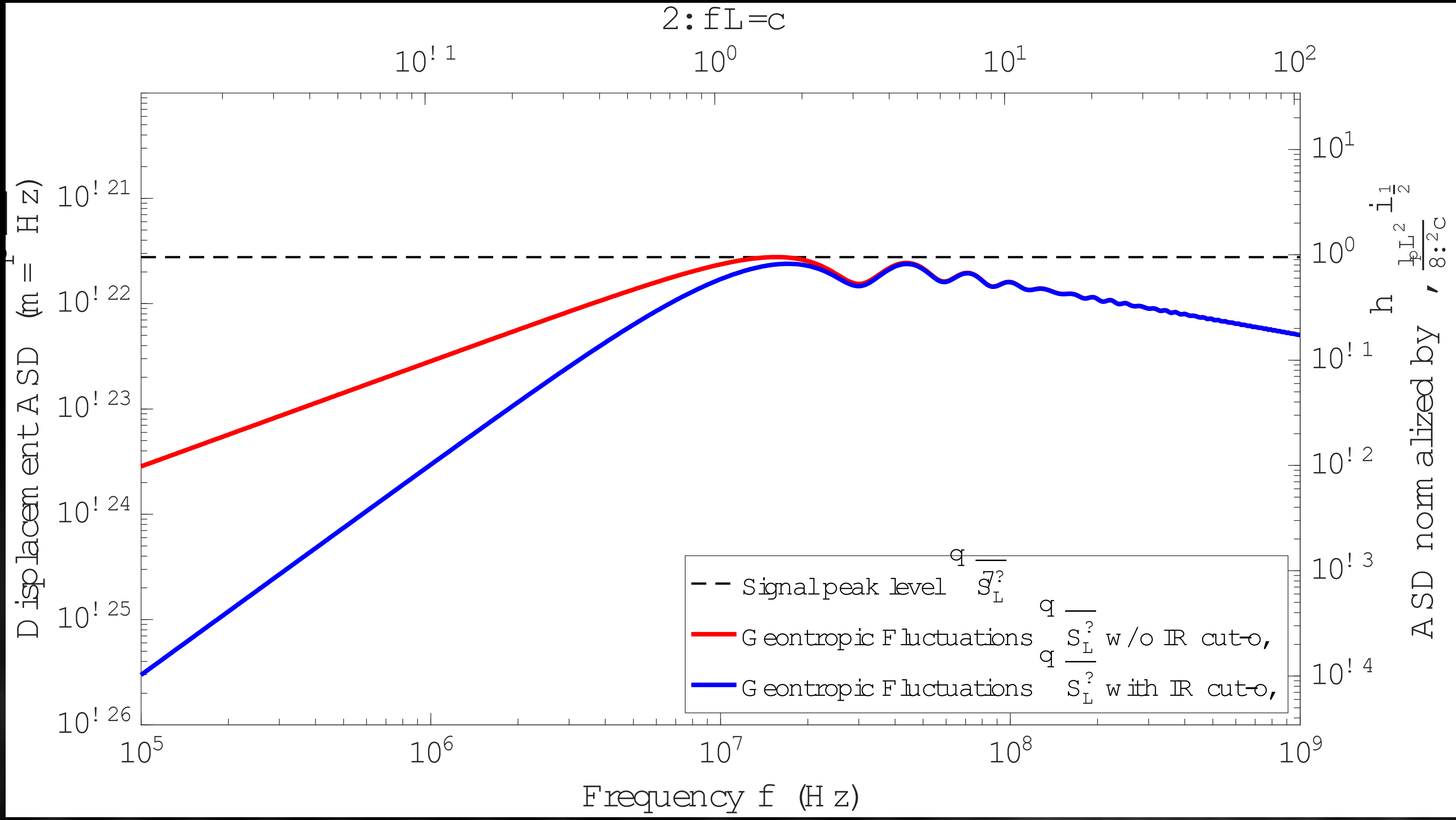
Total length: $L \pm \sqrt{N} \cdot \delta l \; \sim L \pm \sqrt{L\, l_P}$

Proposed Signal from the "Pixellon" Model

- Associate a stochastic scalar field to holographic degrees of freedom: $\phi(\vec{x}, t)$
- The field gravitates, perturbing the metric: $ds^2 = -dt^2 + (1-\phi)\left(dr^2 + r^2 d\Omega^2\right)$

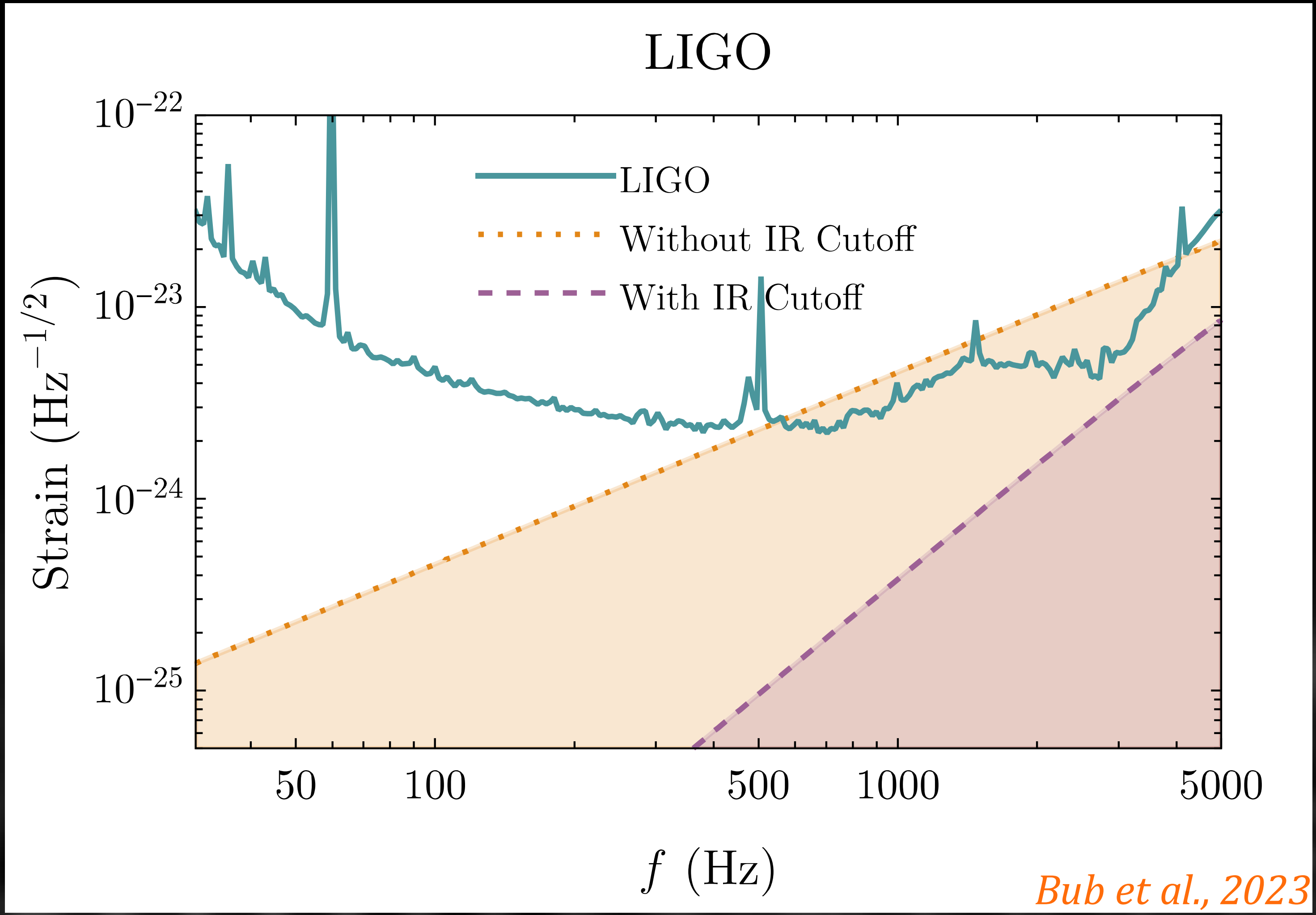
→IFO signal spectrum:

$$\sqrt{S^{\mathrm{sig}}}$$



Spacetime Fluctuations in LIGO

- Looking at frequencies lower than expected signal peak
- Ongoing work to look at peak signal frequency



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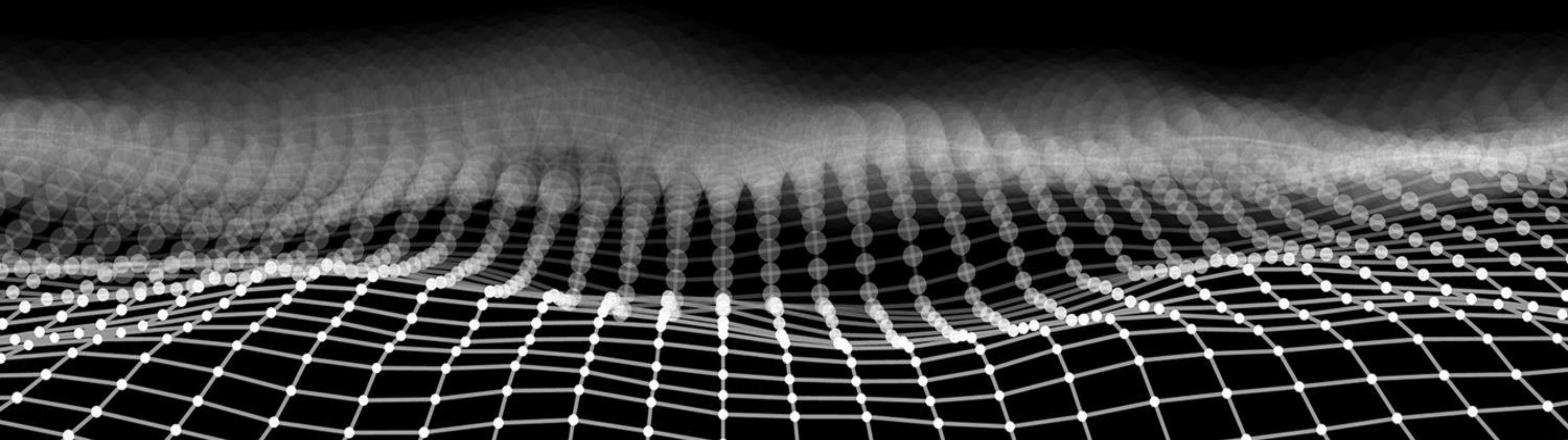
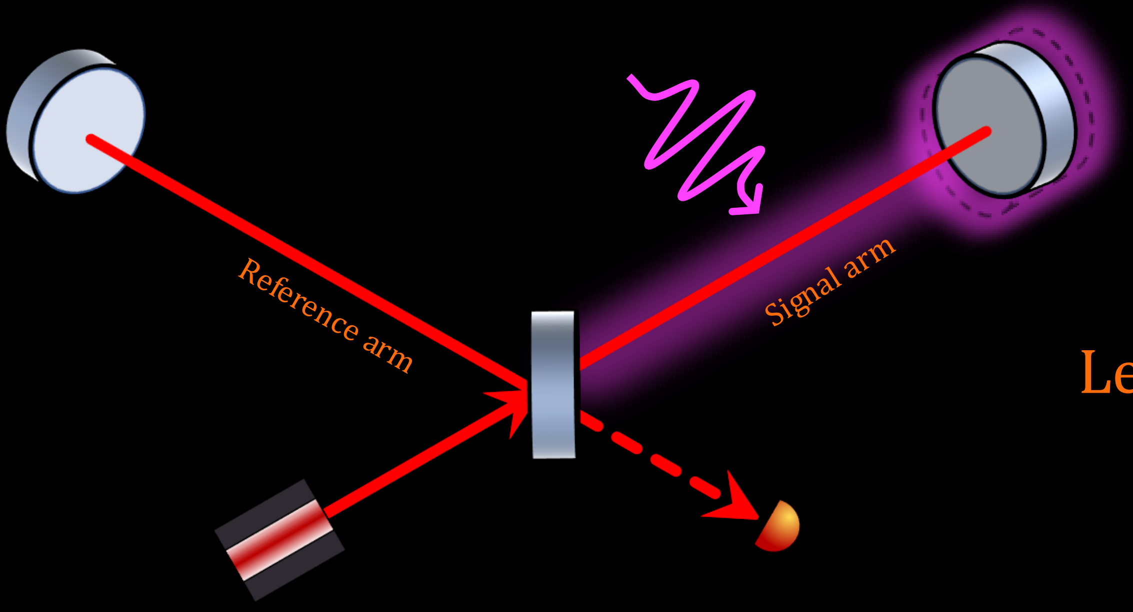
Laser Interferometry & Homodyne Readout



Laser interferometers: differential phase measuring machines



$$\phi = \frac{2\pi n L}{\lambda_0}$$

Length Perturbations in one arm: $\delta L \propto \delta\phi$

Phase modulation of the carrier field:

$$E_{\mathrm{c}}(t) = |E_{\mathrm{c}}|e^{i\omega_{\mathrm{c}}t} \longrightarrow E(t) = \underbrace{|E_{\mathrm{c}}|e^{i(\omega_{\mathrm{c}}t+\boxed{\delta\phi(t)})}}_{\text{Field in signal arm}}$$

Sideband fields

$$E(t) = |E_\mathrm{c}| e^{i(\omega_\mathrm{c} t + \delta\phi(t))}$$

$$\delta\phi(t) \equiv \Phi \sin(\Omega t)$$

Expansion for $\Phi \ll 1$

$$E(t) = |E_\mathrm{c}| e^{i(\omega_\mathrm{c} t + \Phi\sin(\Omega t))} \approx |E_\mathrm{c}| e^{i\omega_\mathrm{c} t}\left(1 + \frac{i}{2}\Phi\left[e^{-i\Omega t} + e^{+i\Omega t}\right]\right)$$

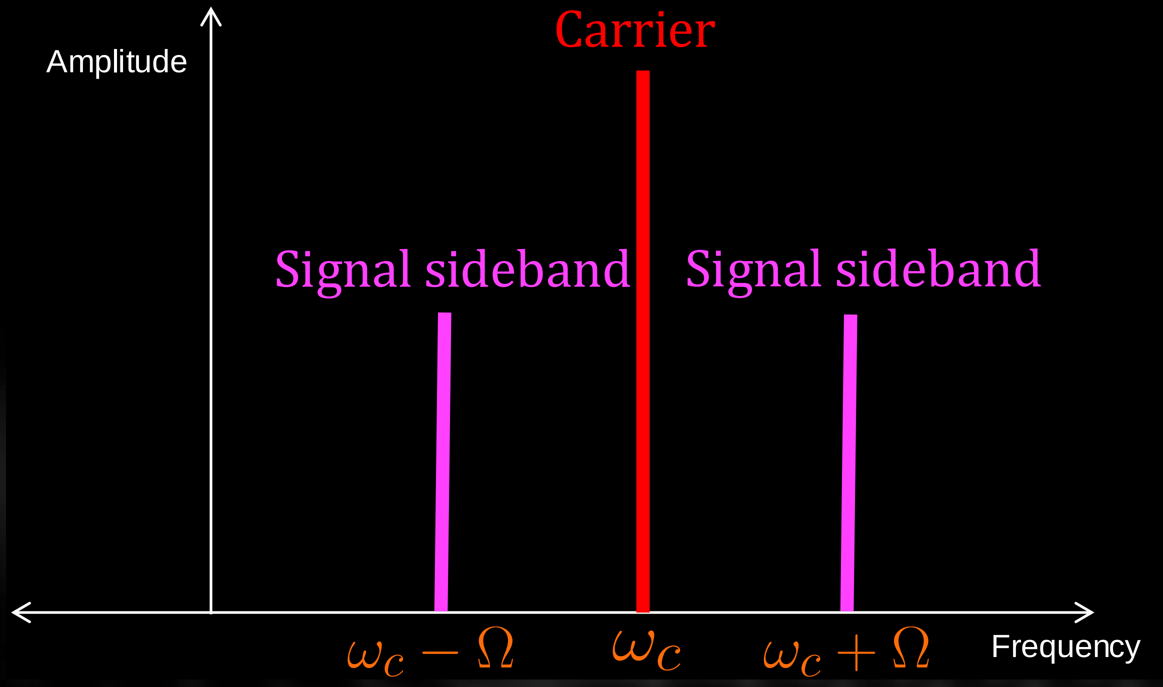
$$\rightarrow E(t) \approx E_\mathrm{c} + E_\mathrm{sig}$$

Carrier field:

$$E_\mathrm{c} = |E_\mathrm{c}| e^{i\omega_\mathrm{c} t}$$

+ Signal sideband fields

$$E_\mathrm{sig} = \frac{i}{2}|E_\mathrm{c}|\Phi\left[e^{i(\omega_\mathrm{c}-\Omega)t} + e^{i(\omega_\mathrm{c}+\Omega)t}\right]$$



Sideband fields (with more complicated $\delta\phi(t)$)

$$E(t) = |E_c|e^{i(\omega_c t + \delta\phi(t))} \qquad \delta\phi(t) \equiv \boxed{A_{\text{sig}}(t)} \sim \mathcal{F}^{-1}\left\{\sqrt{S_\phi^{\text{sig}}(f)}\right\} e^{i\eta_{\text{rand.}}(t)}$$

Expand for $A_{\text{sig}} \ll 1$

$$E(t) = |E_c|e^{i\left(\omega_c t + A_{\text{sig}}(t)\right)}$$
$$\approx |E_c|e^{i\omega_c t}\left[1 + iA_{\text{sig}}(t)\right]$$

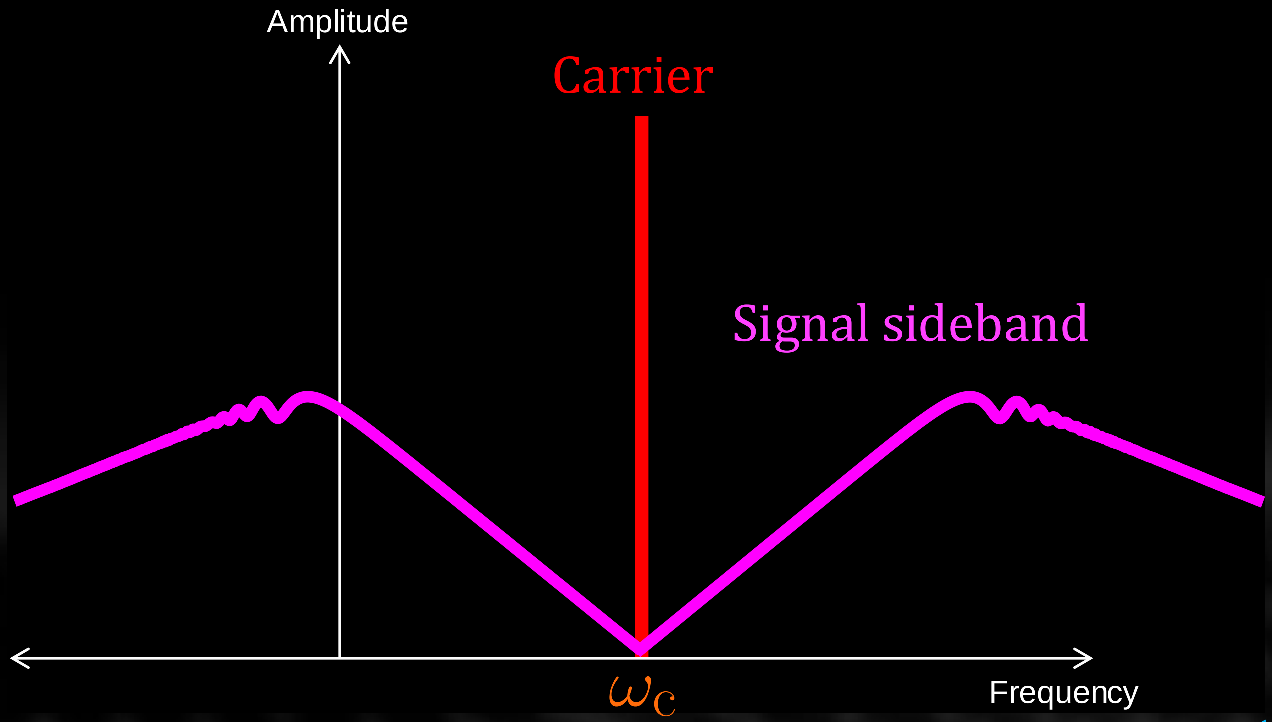
→ $E(t) \approx E_c + E_{\text{sig}}$

Carrier field:

$$E_c = |E_c|e^{i\omega_c t}$$

+ Signal sideband fields

$$E_{\text{sig}} = i|E_c|e^{i\omega_c t}A_{\text{sig}}(t)$$

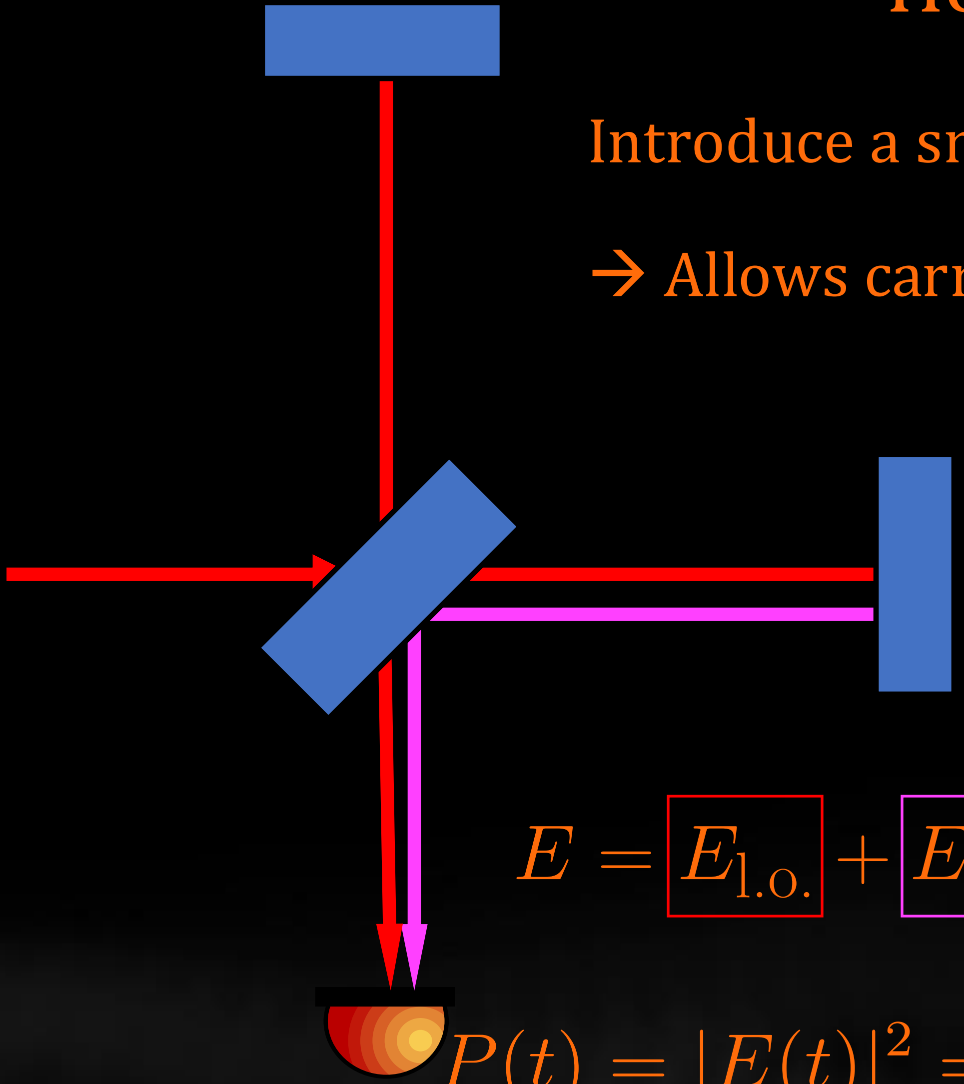


SMV

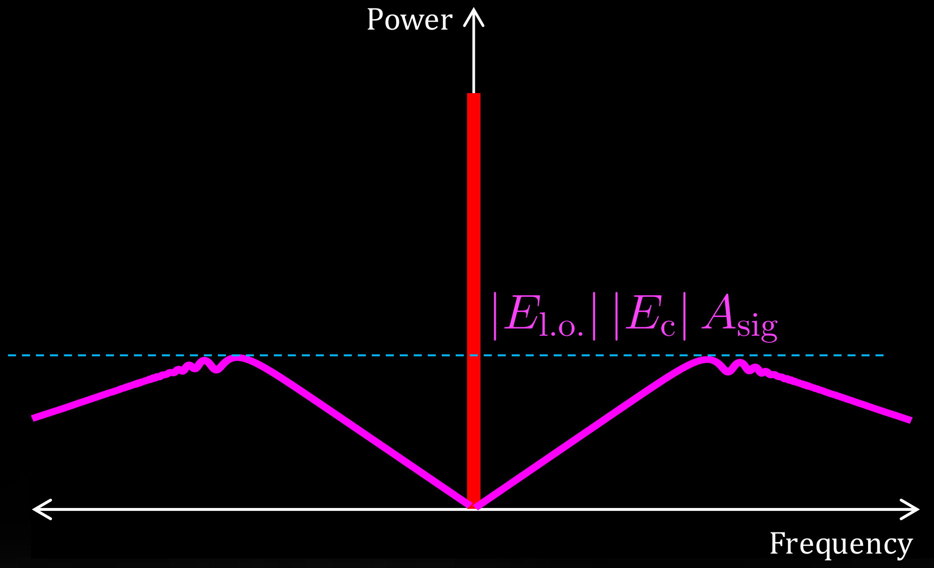
Homodyne Readout

Introduce a small static arm-length difference

→ Allows carrier field to leak into the output: $E_{\text{l.o.}} = |E_{\text{l.o.}}|e^{i\omega_c t}$



$$E = \boxed{E_{\text{l.o.}}} + \boxed{E_{\text{sig}}}$$



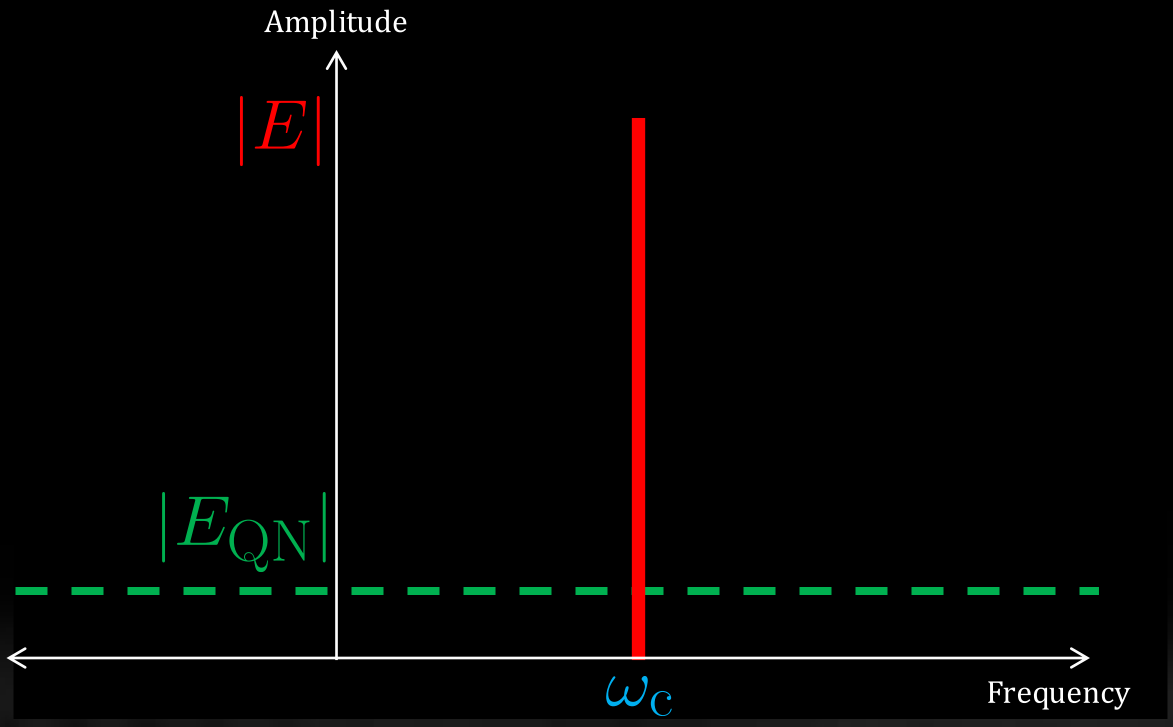
$$P(t) = |E(t)|^2 = \boxed{|E_{\text{l.o.}}|^2} + \underbrace{\boxed{2|E_{\text{l.o.}}||E_{\text{c}}|A_{\text{sig}}}}_{\text{Sidebands beat with ‘local oscillator’}} + \boxed{|E_{\text{c}}|^2\,A_{\text{sig}}^2}$$

Quantum Shot Noise

$$E(t) = |E_{\mathrm{c}}|e^{i\omega_{\mathrm{c}}t} \boxed{+\,\sigma_\phi}$$

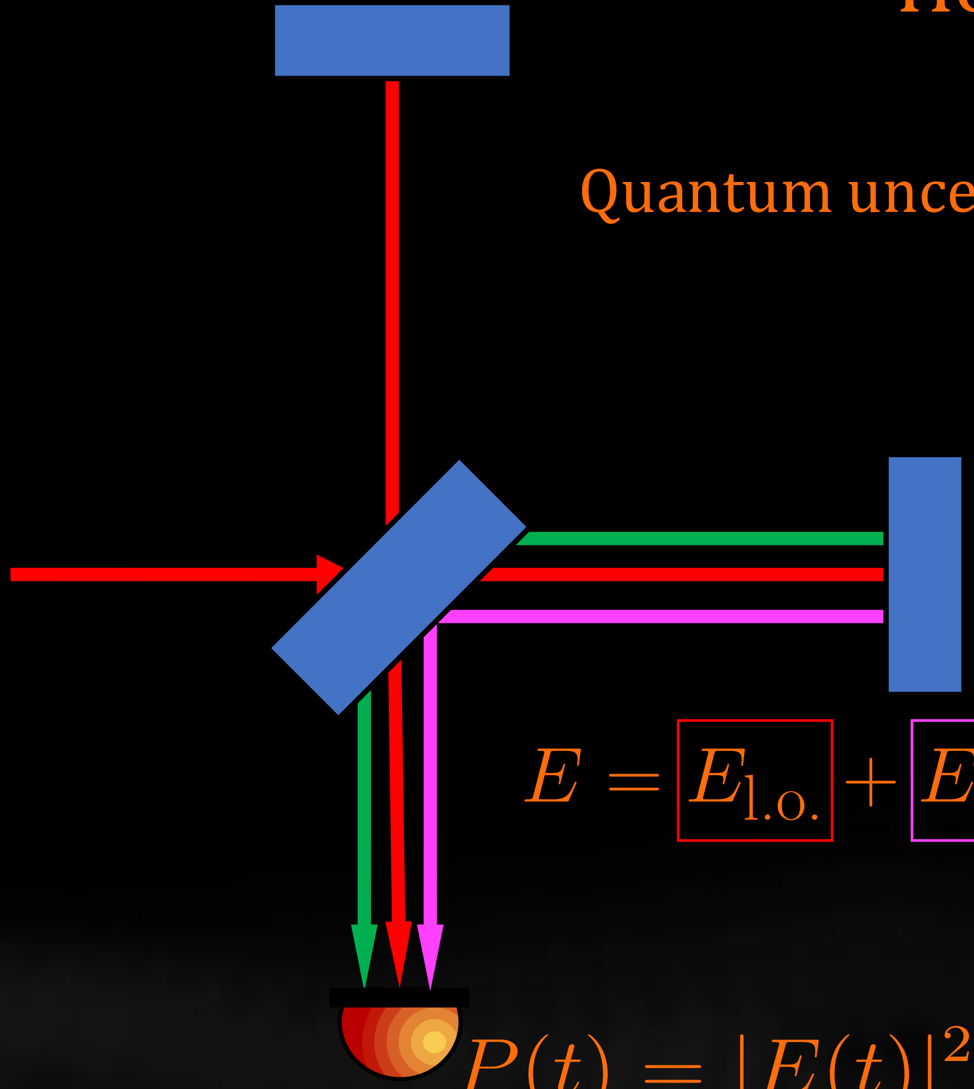
Quantum noise ‘sidebands’:

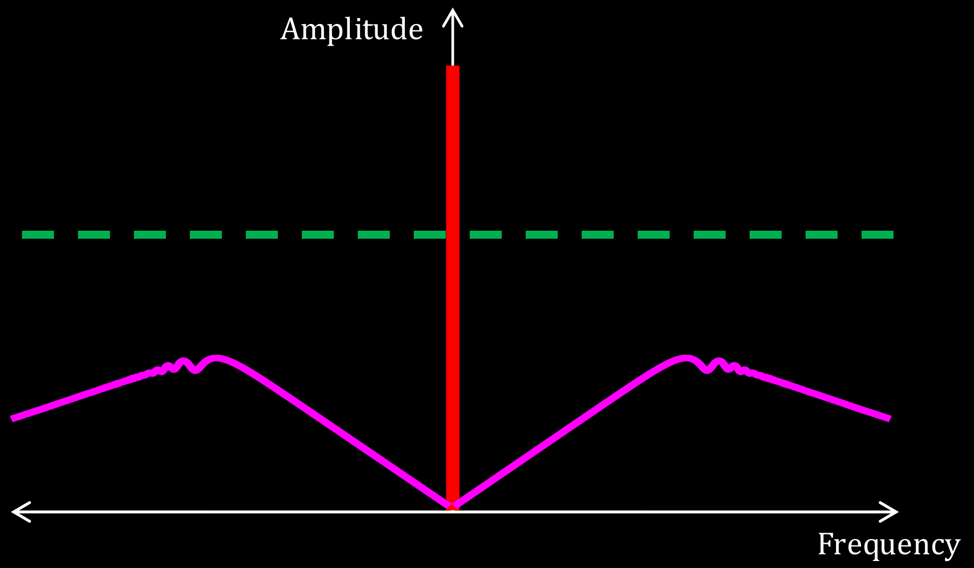
$$\boxed{E_{\mathrm{QN}} = \sqrt{\frac{\hbar\omega_c}{2}} \sum_{\omega=-\infty}^{\infty} \left[\hat{a}^\dagger e^{i(\omega_{\mathrm{c}}+\omega)t} + \hat{a}e^{i(\omega_{\mathrm{c}}-\omega)t}\right]}$$



Homodyne Readout: Shot Noise

Quantum uncertainty produces measured shot noise





$$E = \boxed{E_{\mathrm{l.o.}}} + \boxed{E_{\mathrm{sig}}} + \boxed{E_{\mathrm{QN}}}$$

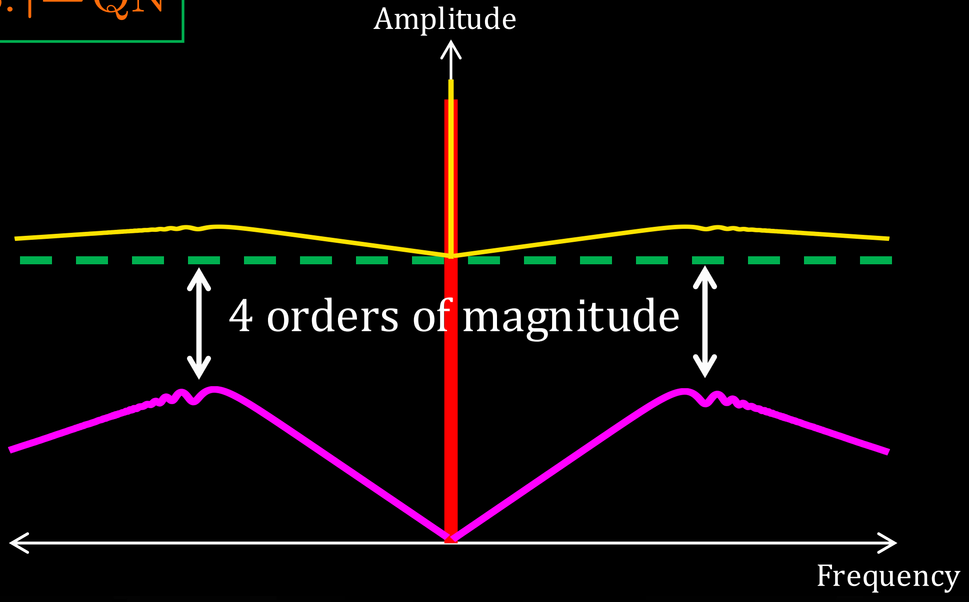
$$P(t) = |E(t)|^2 = \boxed{|E_{\mathrm{l.o.}}|^2} + \boxed{2|E_{\mathrm{l.o.}}||E_c|A_{\mathrm{sig}}} + \boxed{2|E_{\mathrm{l.o.}}|E_{\mathrm{QN}}}$$

$$+ \text{smaller terms}$$

Homodyne Readout: Statistics with Shot Noise

$$P(t) = \boxed{|E(t)|^2} = \boxed{|E_{\mathrm{l.o.}}|^2} + \boxed{2|E_{\mathrm{l.o.}}||E_{\mathrm{c}}|A_{\mathrm{sig}}} + \boxed{2|E_{\mathrm{l.o.}}|E_{\mathrm{QN}}}$$

$$+\,\text{smaller terms}$$



Detection statistic:

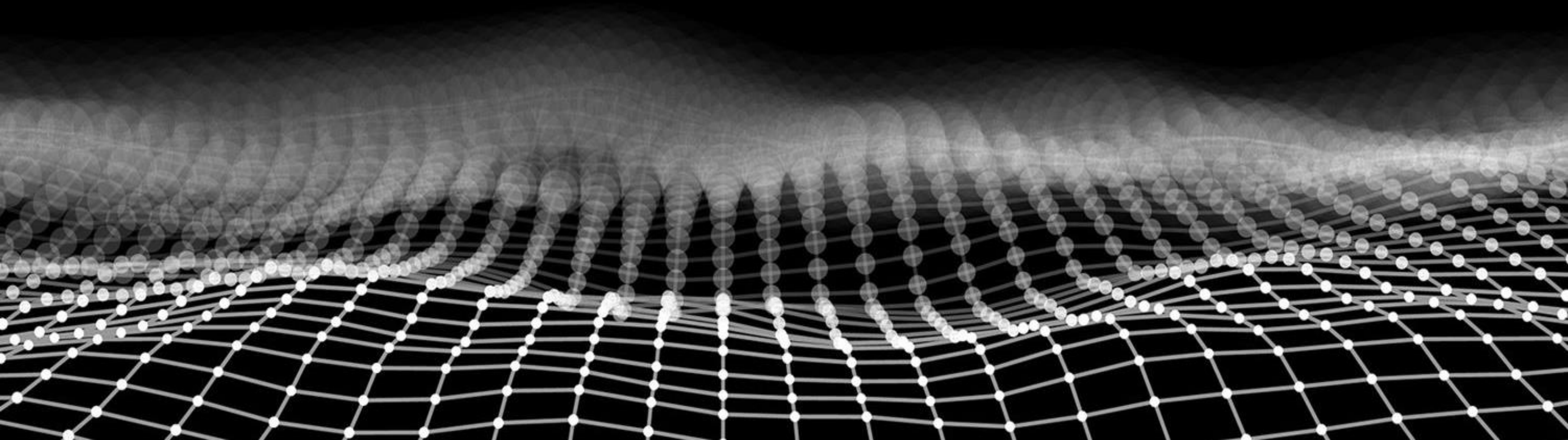
$$\chi^2 = \int \frac{\left(S_{\mathrm{meas}}(f) - S_{\mathrm{noise}}\right)^2}{\mathrm{Var}\left(S_{\mathrm{meas}}\right)} df \propto \left(\frac{S_{\mathrm{signal}}}{S_{\mathrm{noise}}}\right)^2$$

Time for SNR = 1 for a realistic 5 m IFO:
1 week

Can we do better?

→Yes, with photon counting!

Photon Counting



Photon Counting: Intuition

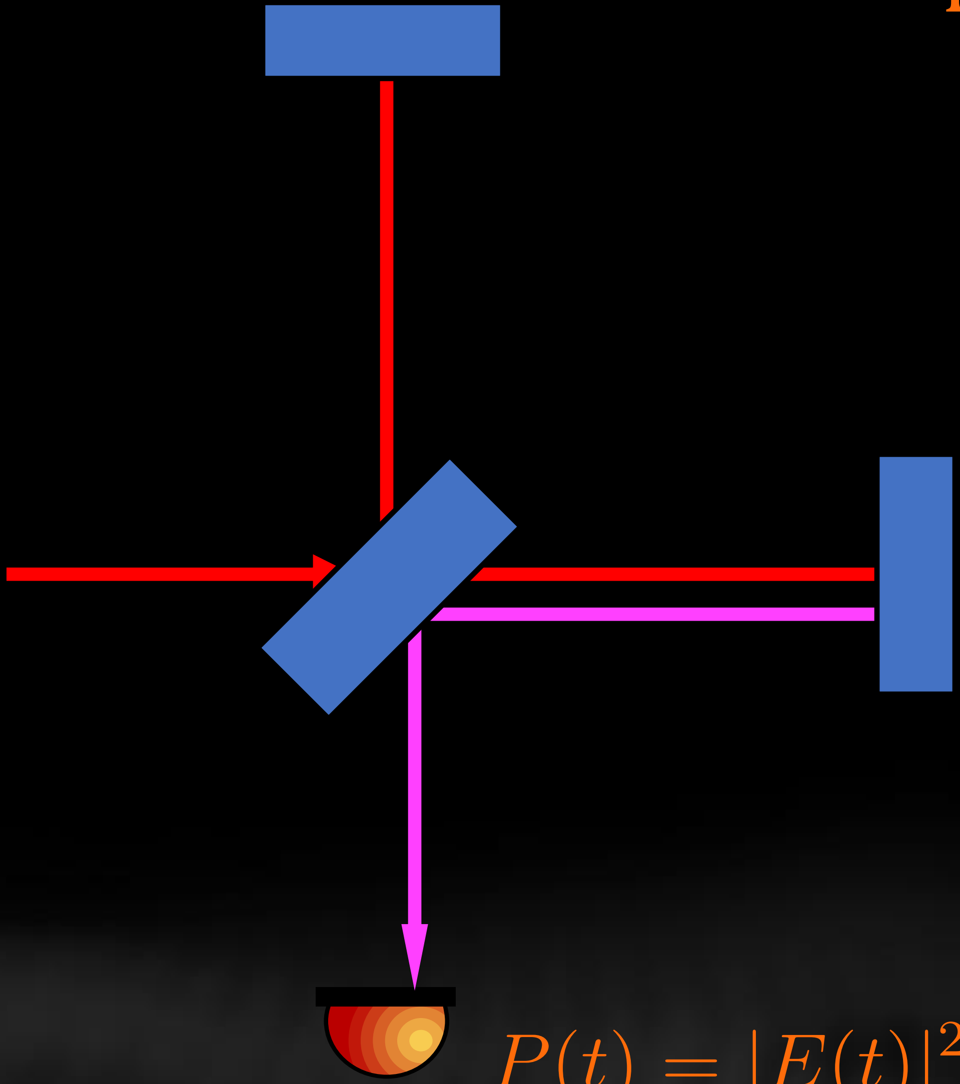
- Homodyne readout measures time-dependence, i.e. phase/frequency of the signal

- The signal model does not specify these properties

→ time-dependence/phase/frequency info is useless for finding a signal that is stationary/stochastic/broadband

→ Devise a quantum measurement that does not provide useless info, in exchange for useful info

Photon Counting



- Consider an interferometer with no local oscillator (and no classical noise)
- All photons measured are signal photons!

$$P(t) = |E(t)|^2 = \boxed{|E_c|^2 A_{\mathrm{sig}}^2}$$

Photon Counting: Statistics

Detection statistic:

$$\left.\begin{aligned} \chi^2 &= \frac{N^2}{\mathrm{Var}\,(N)} = \frac{N^2}{N} = N \\ N &\propto \frac{\left| |E_\mathrm{c}|^2 A_\mathrm{sig}^2 \right|}{\hbar\omega} = \frac{S_\phi^\mathrm{sig}}{2 S_\phi^{QN}} \end{aligned}\right\} \quad \boxed{\chi^2 \propto \frac{S_\mathrm{signal}}{S_\mathrm{noise}}}$$

Recall for Homodyne readout: $\chi^2 \propto \left(\frac{S_\mathrm{signal}}{S_\mathrm{noise}} \right)^2$

Photon Counting vs. Homodyne Comparison

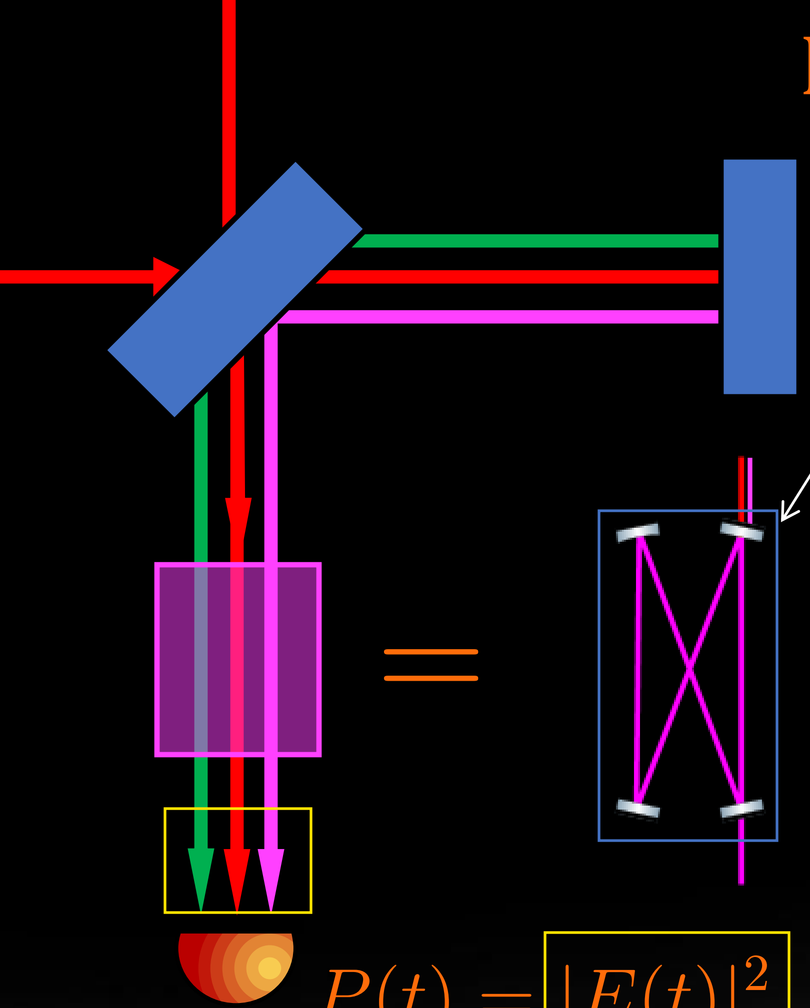
$$\mathrm{SNR}^2_{\text{homodyne}} = T\Delta f \left(\frac{\bar{S}^{\phi}_{L}}{\bar{S}^{q}_{L}} \right)^2$$

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

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

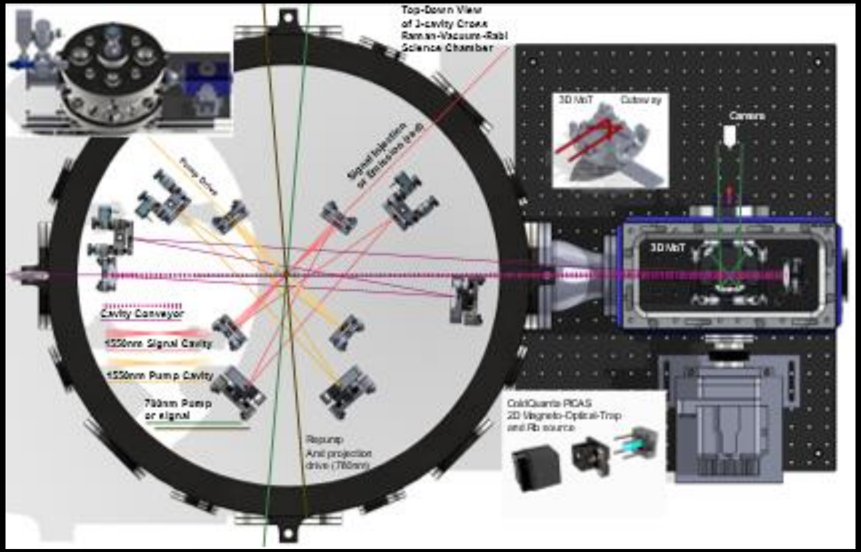
Time for SNR = 1 with Photon Counting:
0.25 s

Photon Counting: Filtering



Narrowband optical filter

or



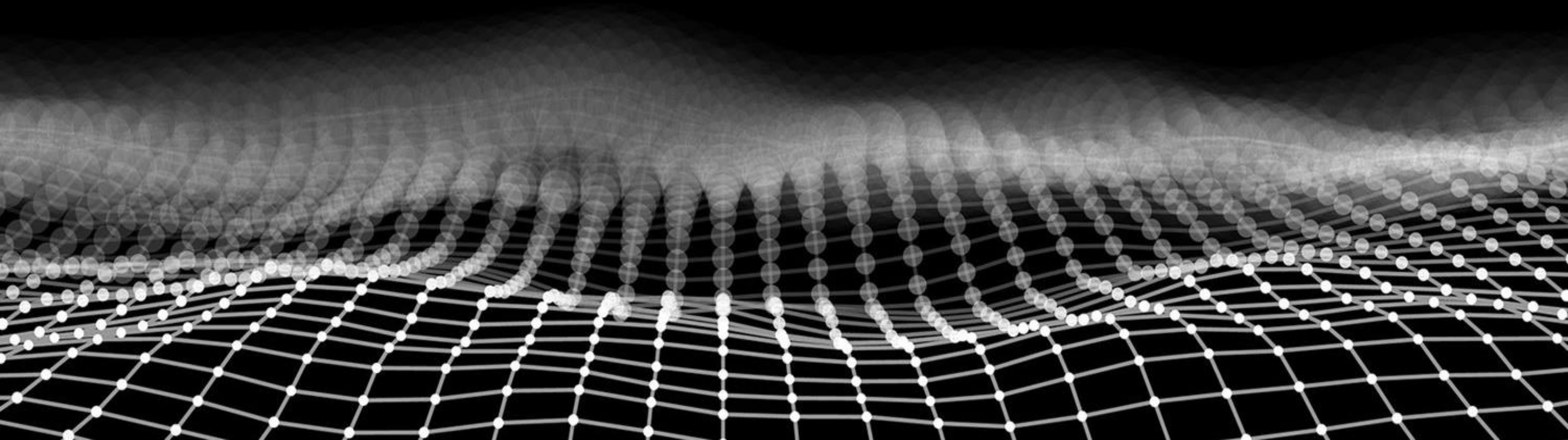
or

?

$$P(t) = \boxed{|E(t)|^2}$$

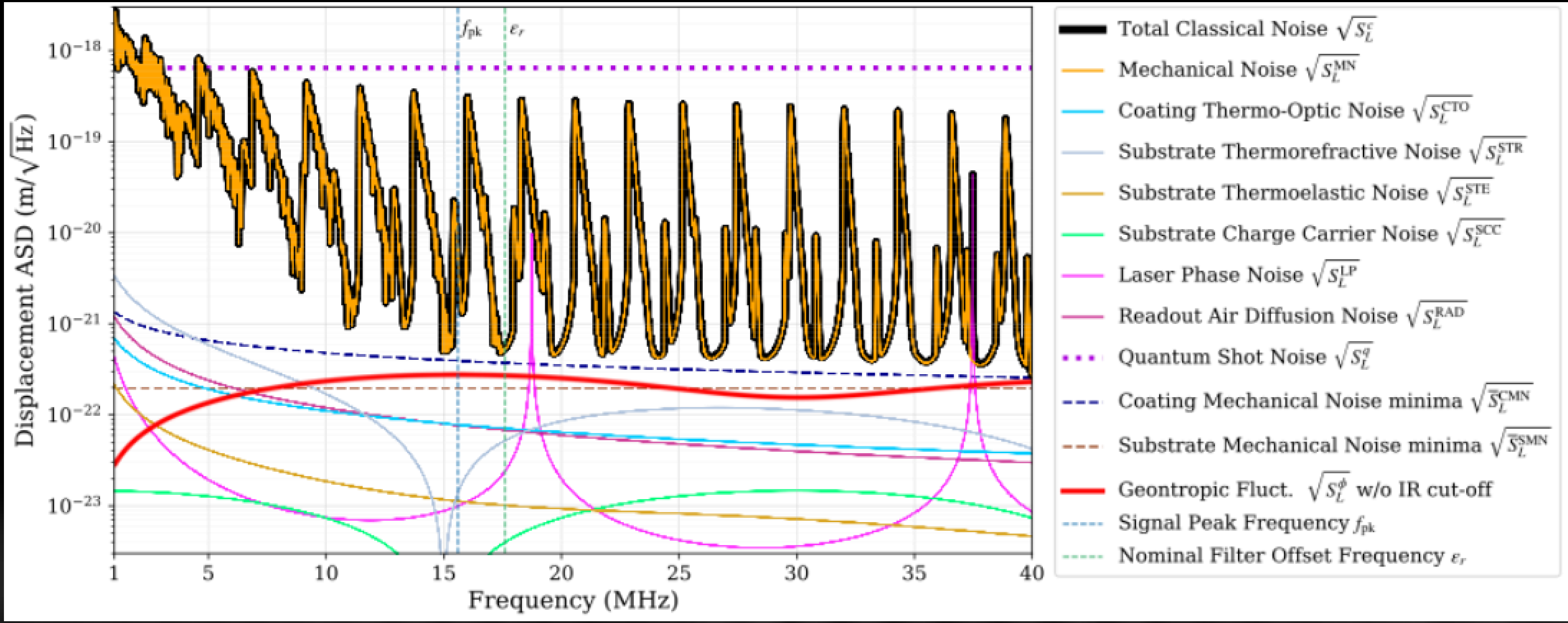
$$= \cancel{\underbrace{|E_{\mathrm{l.o.}}|}_{\to 0}\left(|E_{\mathrm{l.o.}}| + 2|E_{\mathrm{c}}|A_{\mathrm{sig}} + 2E_{\mathrm{QN}}\right) +} \boxed{|E_{\mathrm{c}}|^2 A_{\mathrm{sig}}^2} + \boxed{2|E_{\mathrm{c}}|A_{\mathrm{sig}}E_{\mathrm{QN}} + E_{\mathrm{QN}}^2}$$

Classical Noise



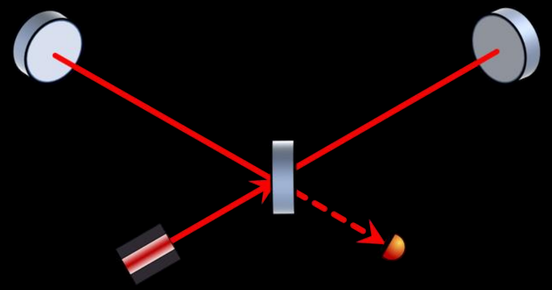
Classical Noise

- Classical noise looks like the stochastic signal



- Recall $\phi = \dfrac{2\pi n L}{\lambda_0}$

Classical Noise: Mirror Thermal Noise



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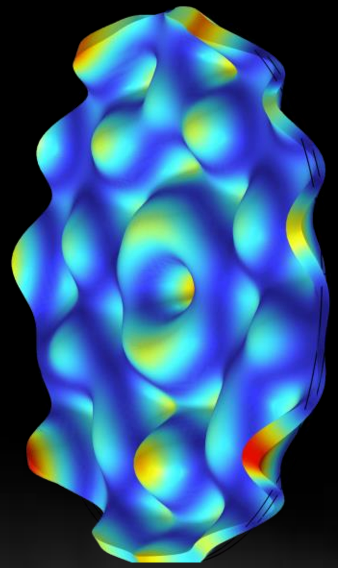
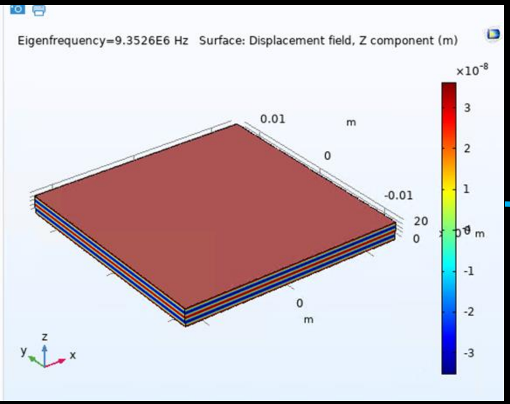
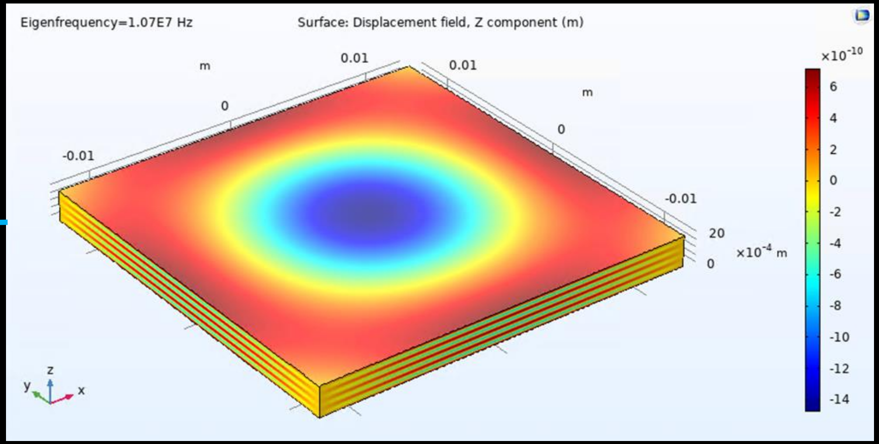


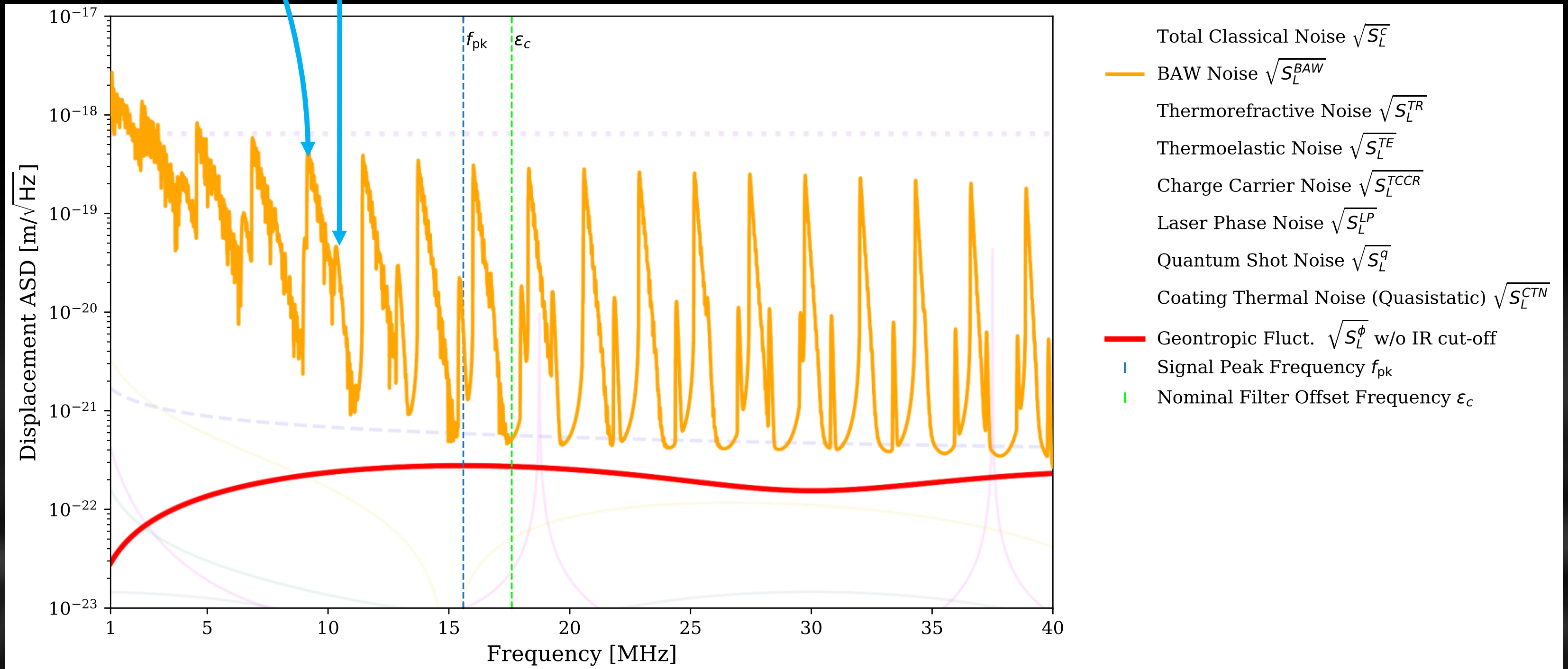
Solid Normal Modes



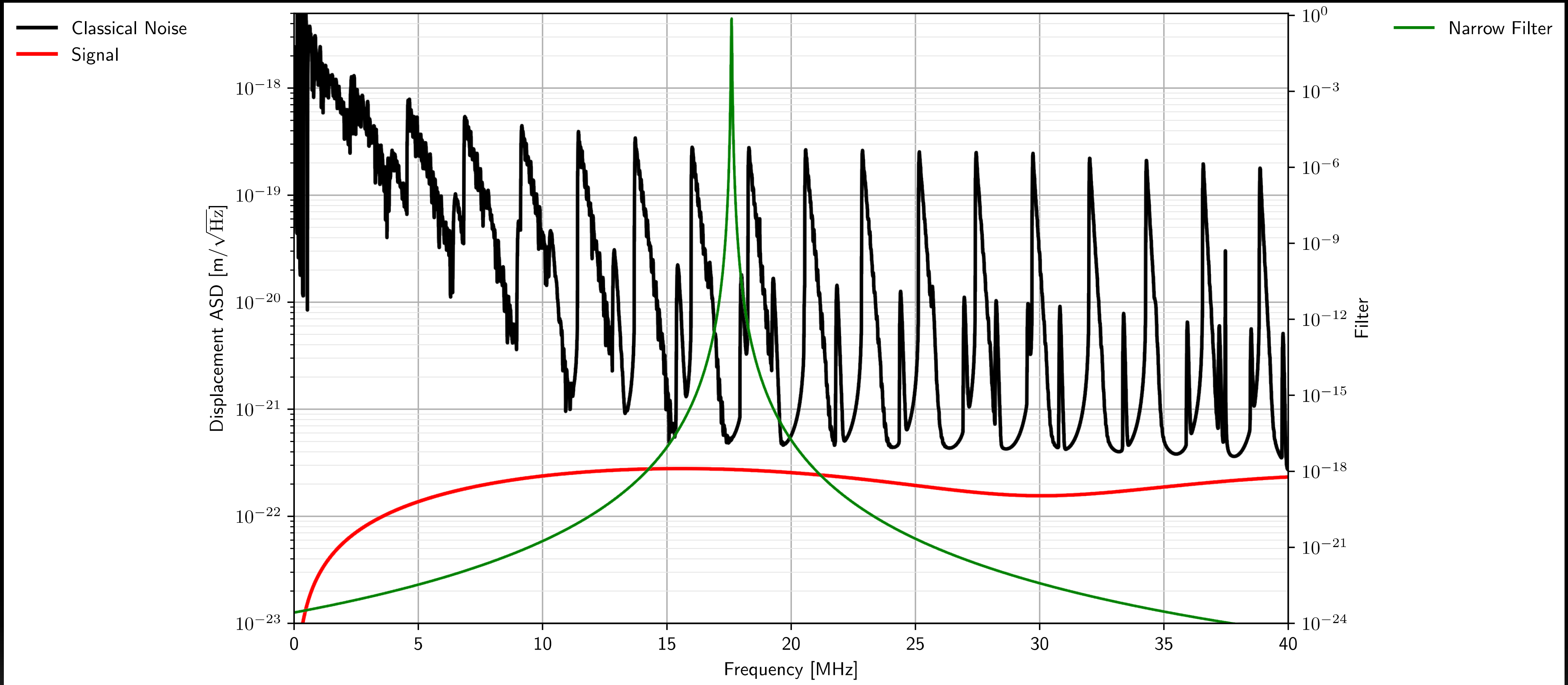
Longitudinal



Transverse



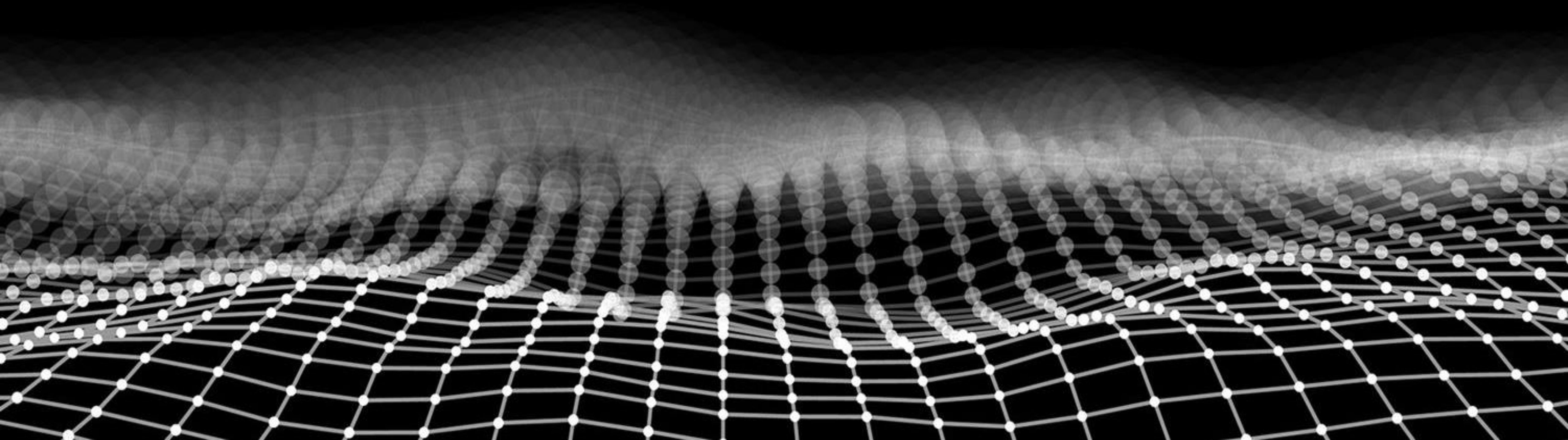
Filter Away Noise Peaks



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

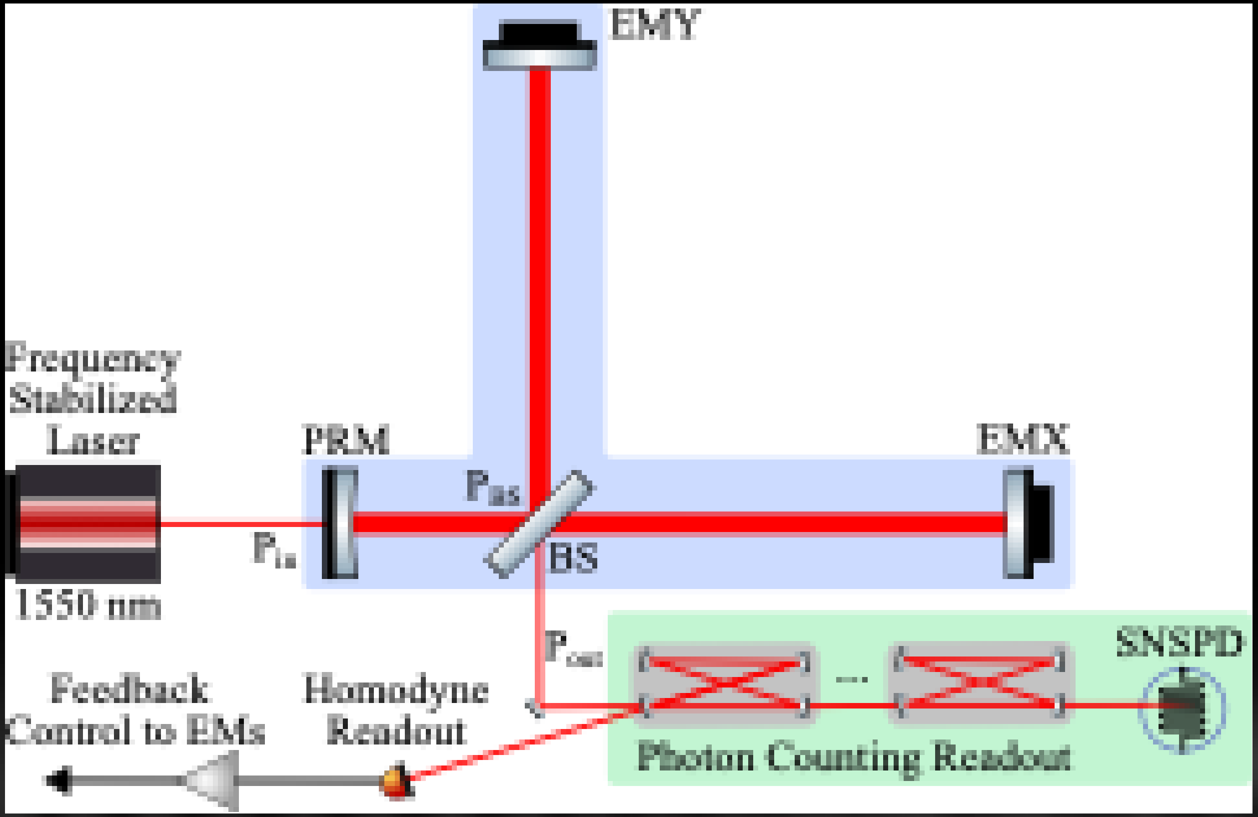
Time for SNR of 1 with Filtered Photon Counting:
$8.6 \cdot 10^3$ s = 2.4 hours

Experimental Implementation



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

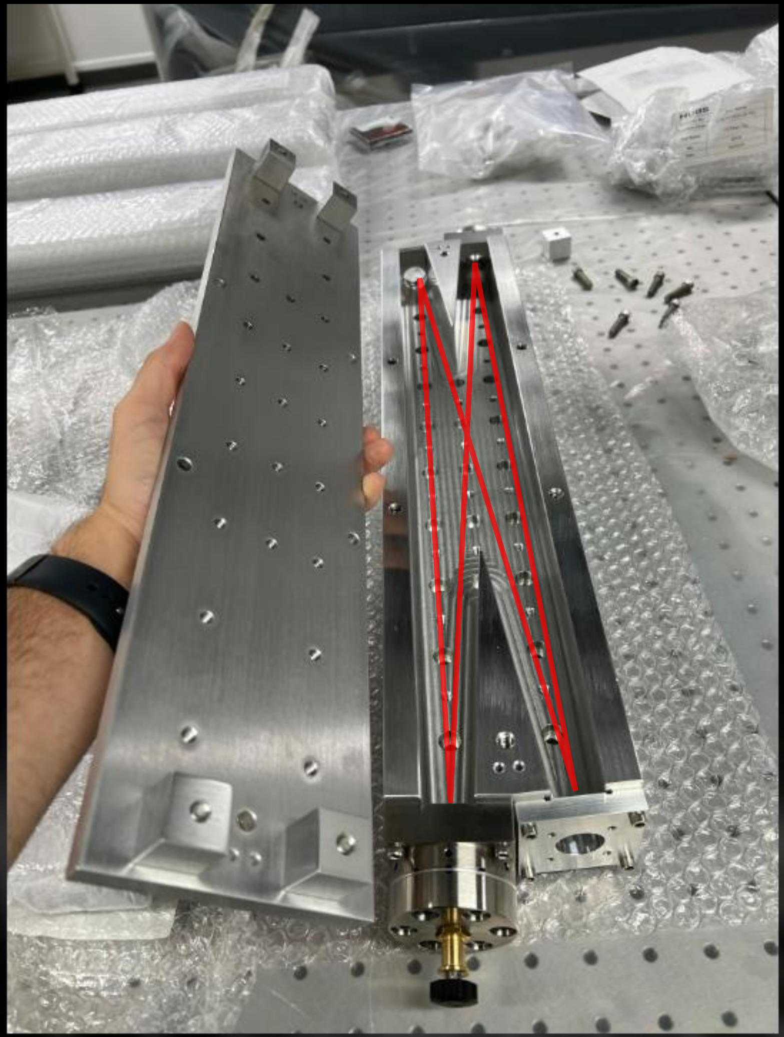


4 Requirements for Photon Counting

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

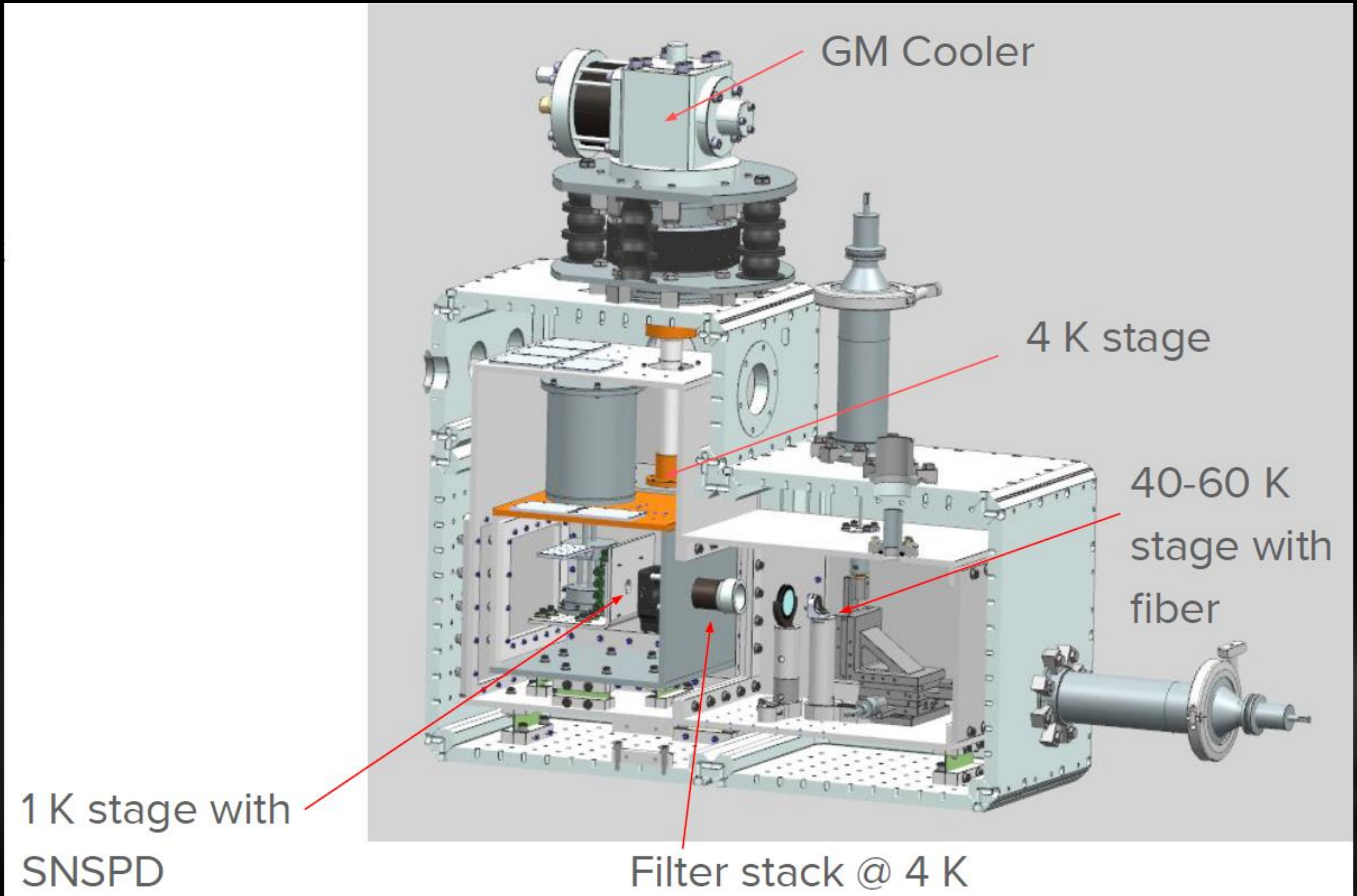
Optical Bandpass Filters

- 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



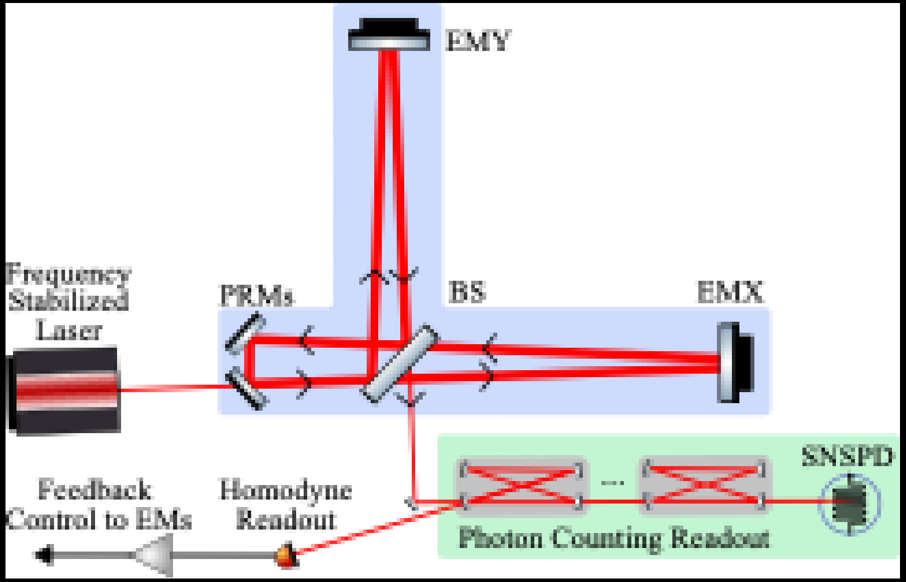
SNSPD: Superconducting Nanowire Single Photon Detector

- 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

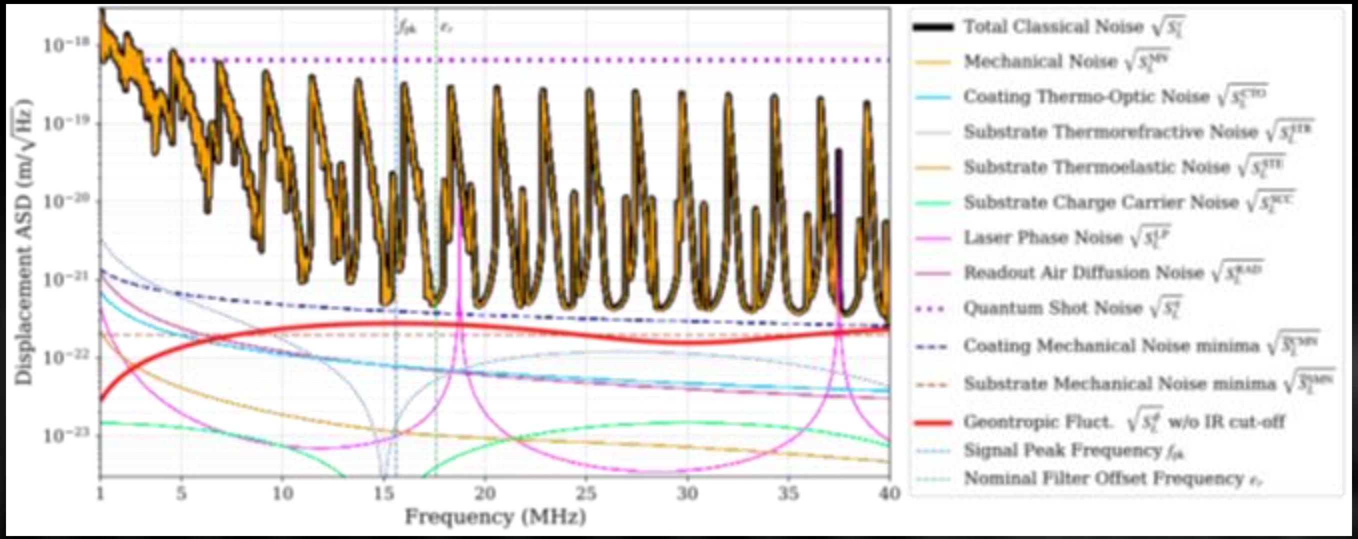


Low Classical Noise

- Substrate Thermorefractive Noise would dominate in a standing wave interferometer
- Necessitates a traveling wave interferometer to avoid this noise

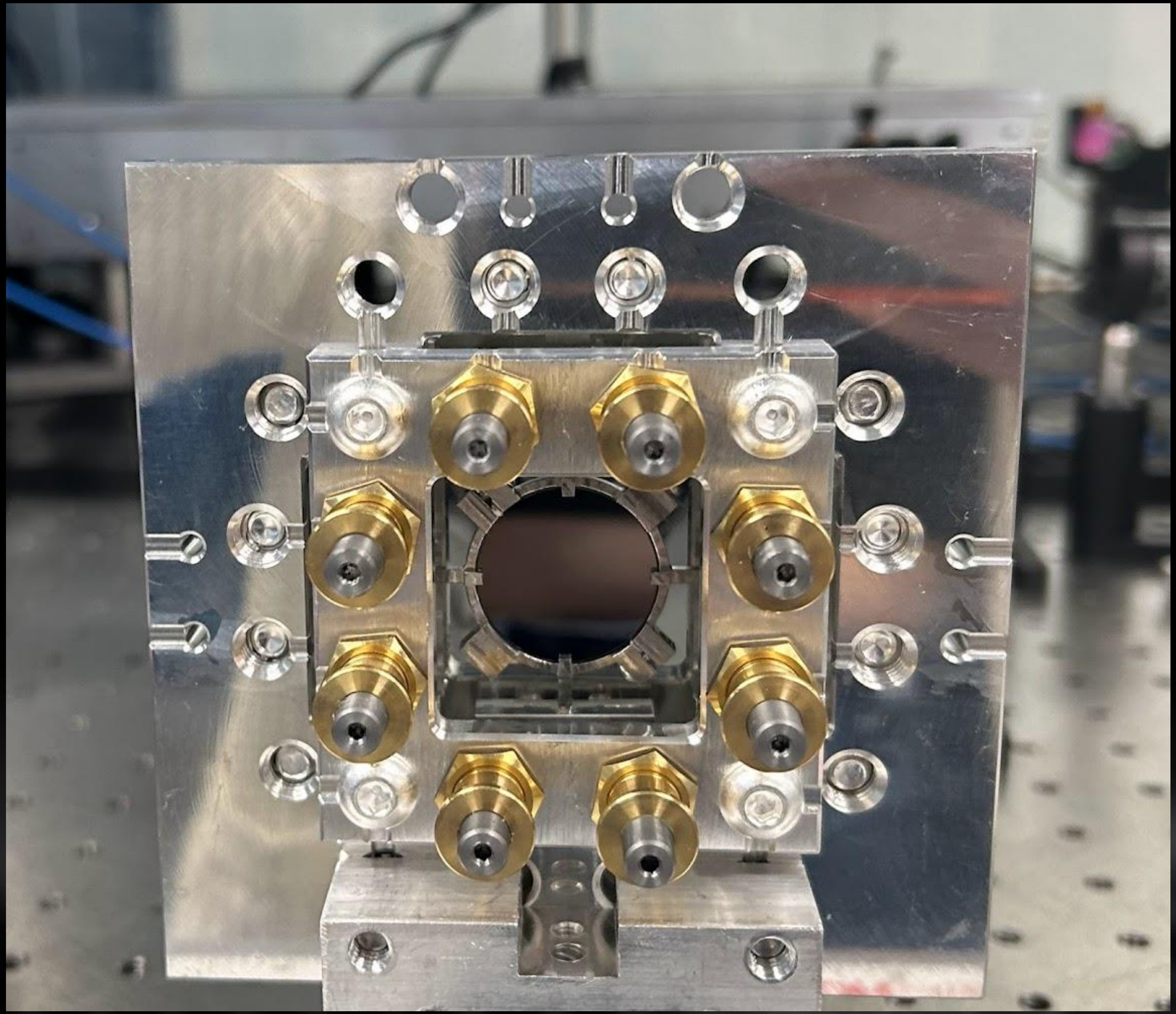


- Need 2 mm thick mirrors to space out noise peaks



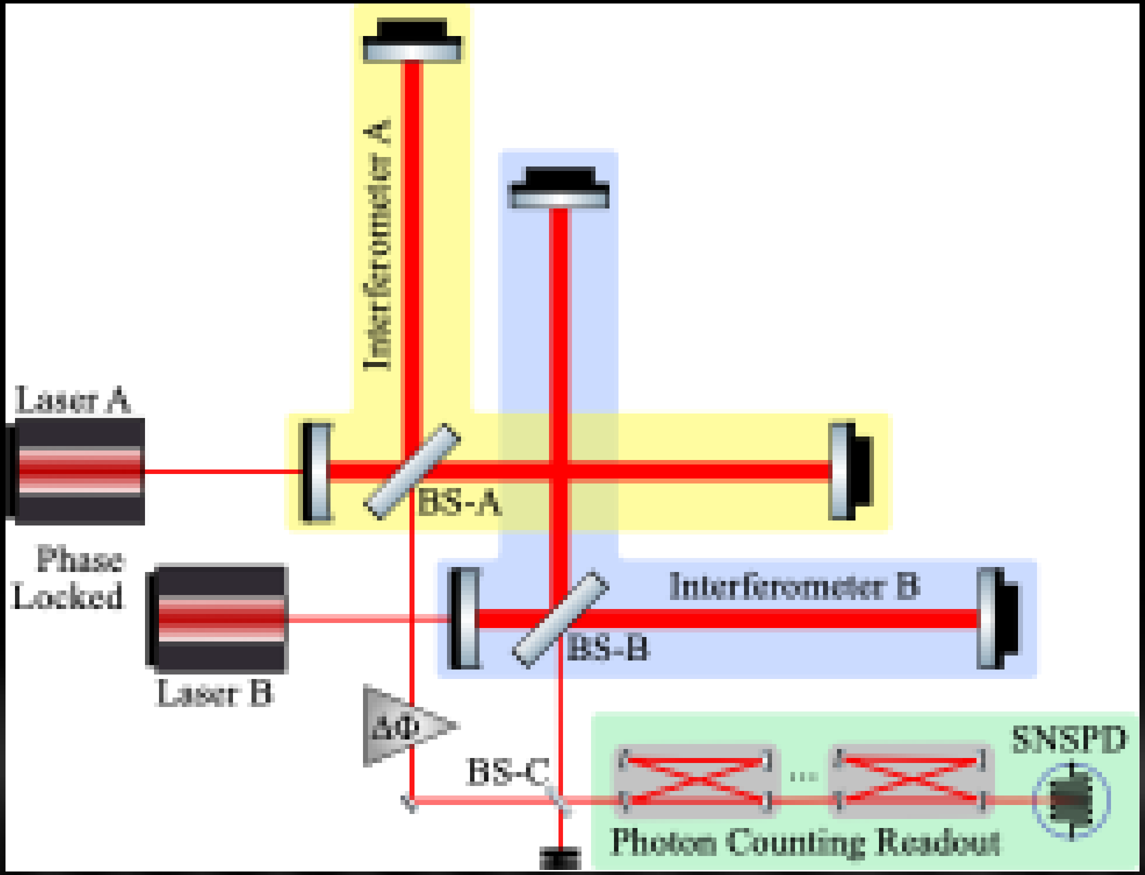
Small Contrast Defect

- Thin Mirrors are susceptible to curvature due to coating stress
- Curved mirrors lens light into higher order modes
- End Mirrors with different surfaces create extra light that might leak through our filters
- This extra, unwanted light is called “contrast defect”
- Designed and tested a Mirror Mount to flatten the mirror

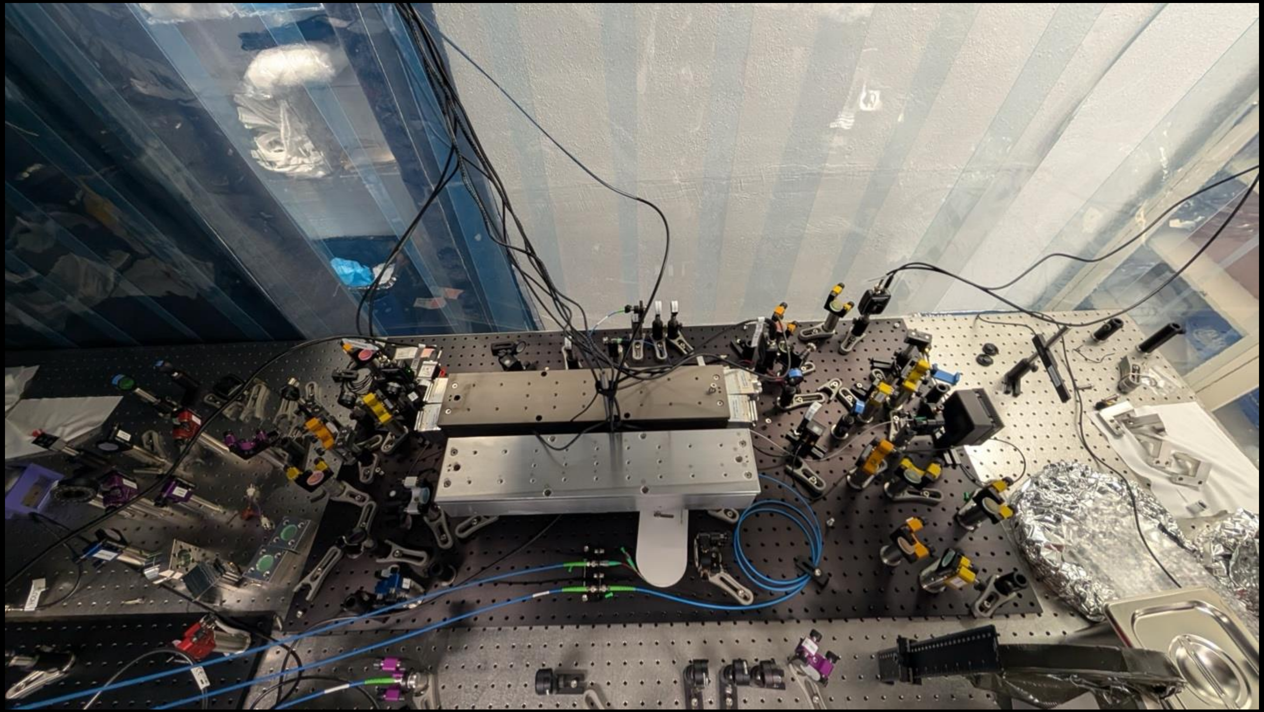


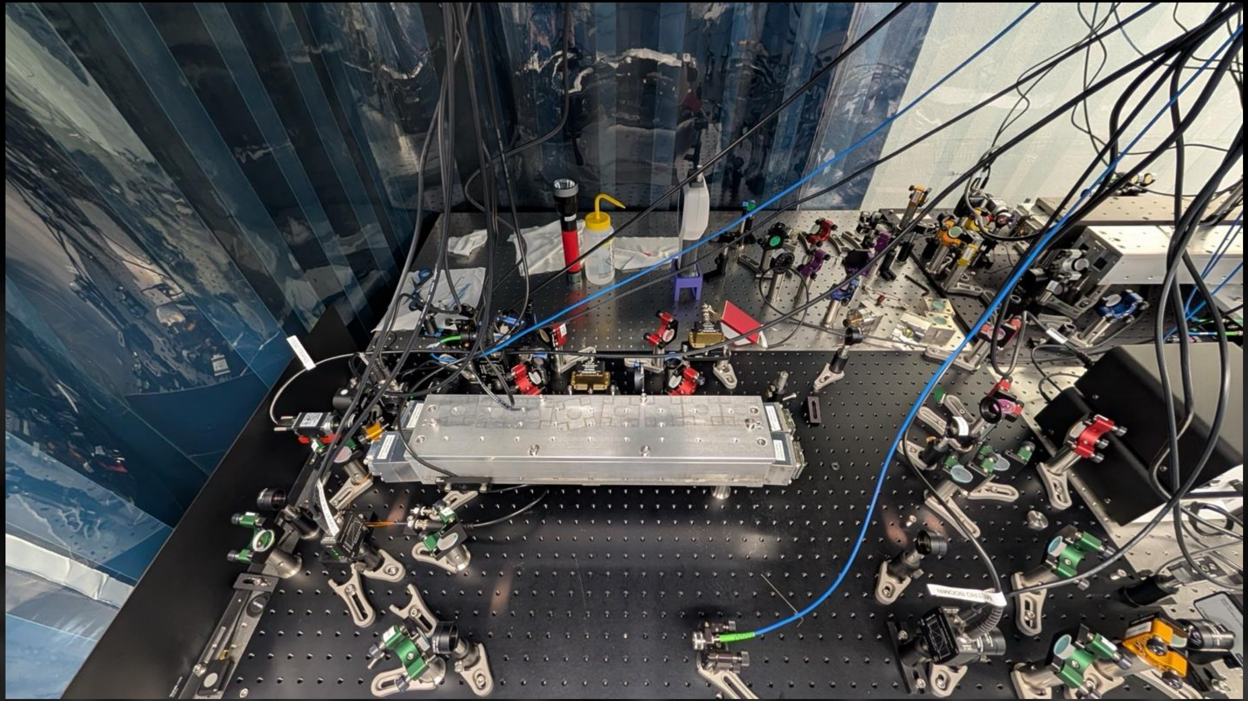
Good Photons vs Bad Photons

- 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 uncorrelated noise or signal + uncorrelated noise
- Correlated noise predicted to be below signal
- Outlook: 5σ test of quantum gravity within a day



Progress Photos





Summary

1. Holographic Quantum Gravity implies (barely) measurable signals

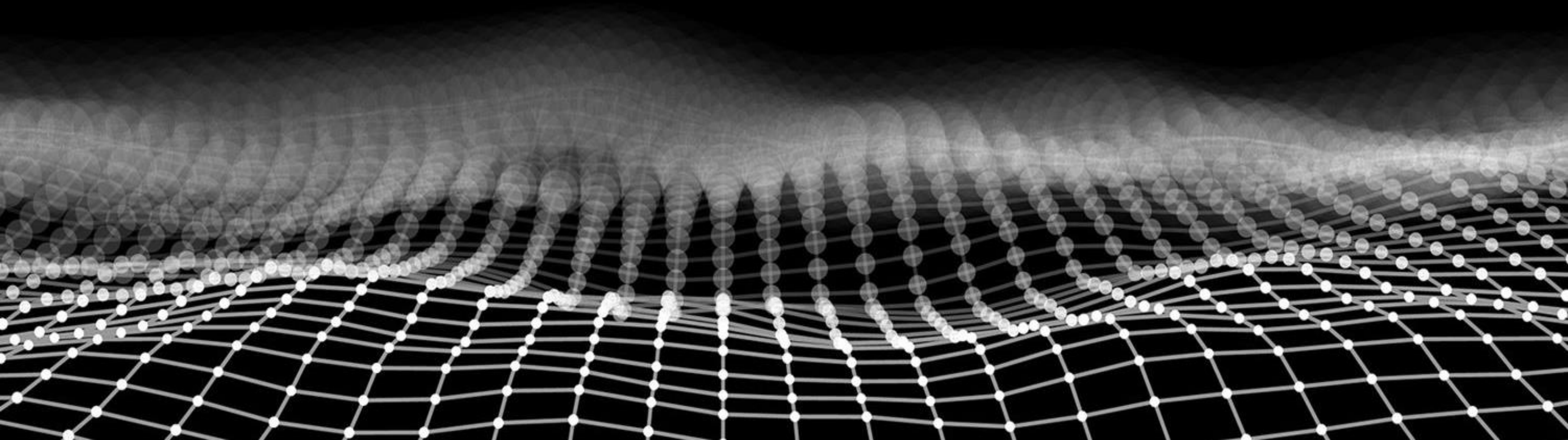
2. Conventional homodyne readout of interferometers is sub-optimal to detect this signal

3. Photon counting readout ignores phase information, which yields a quantum advantage

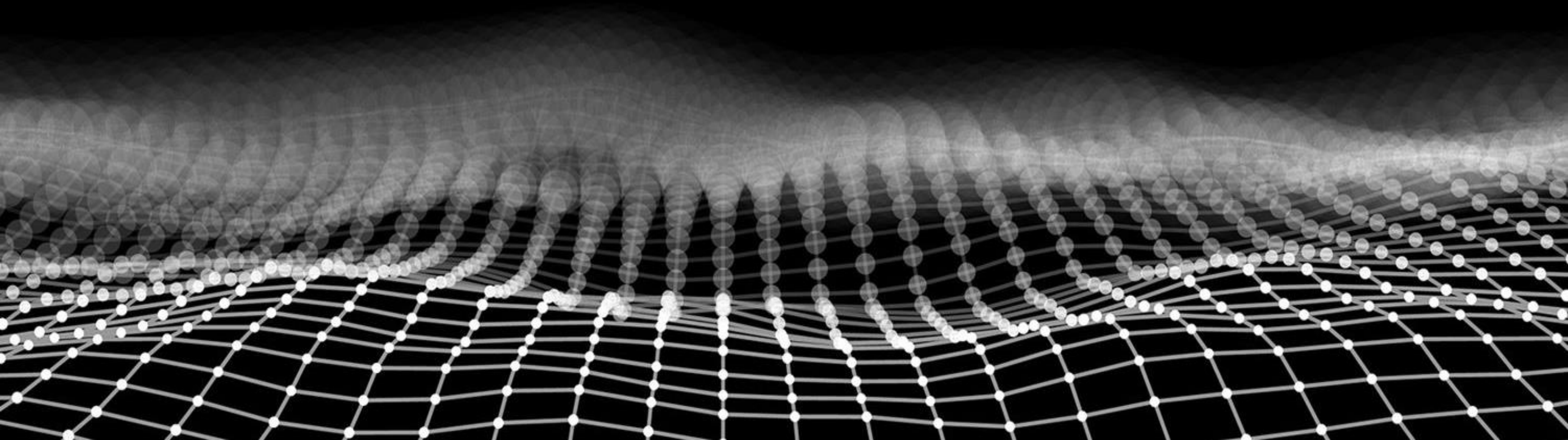
4. If classical noise is mitigated to below the quantum noise, GQuEST can provide a test of quantum gravity within days

Paper QR Code

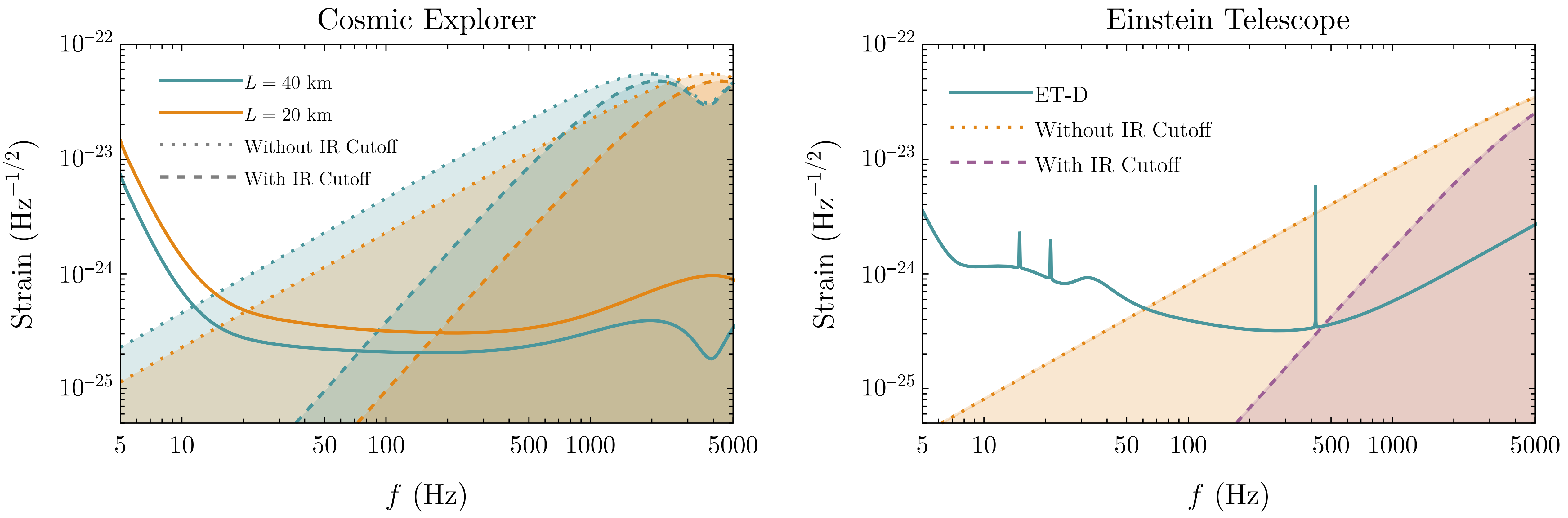
Thank you!



Extra Slides



Signal in 3rd Generation Gravitational Wave Detectors



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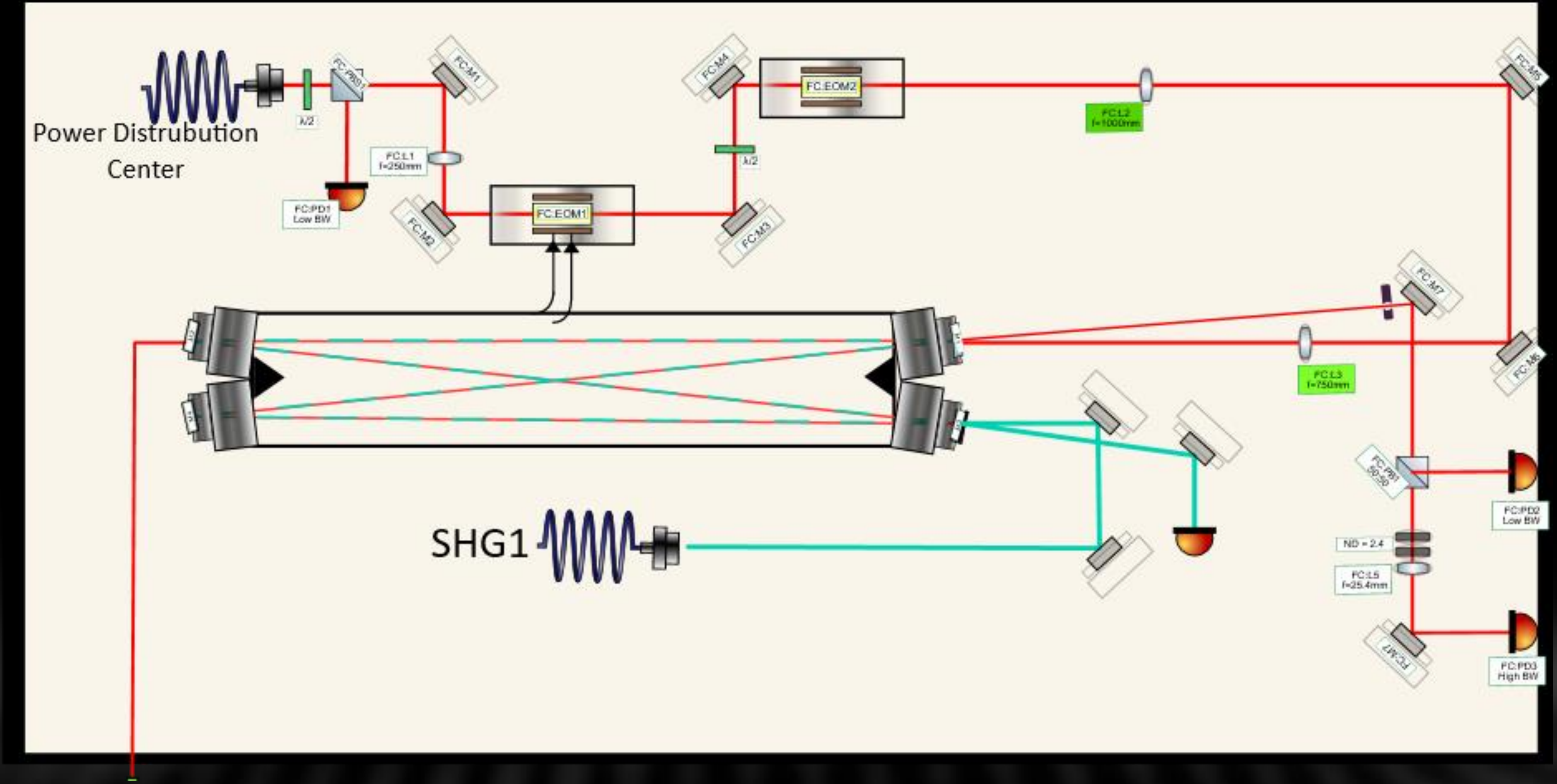
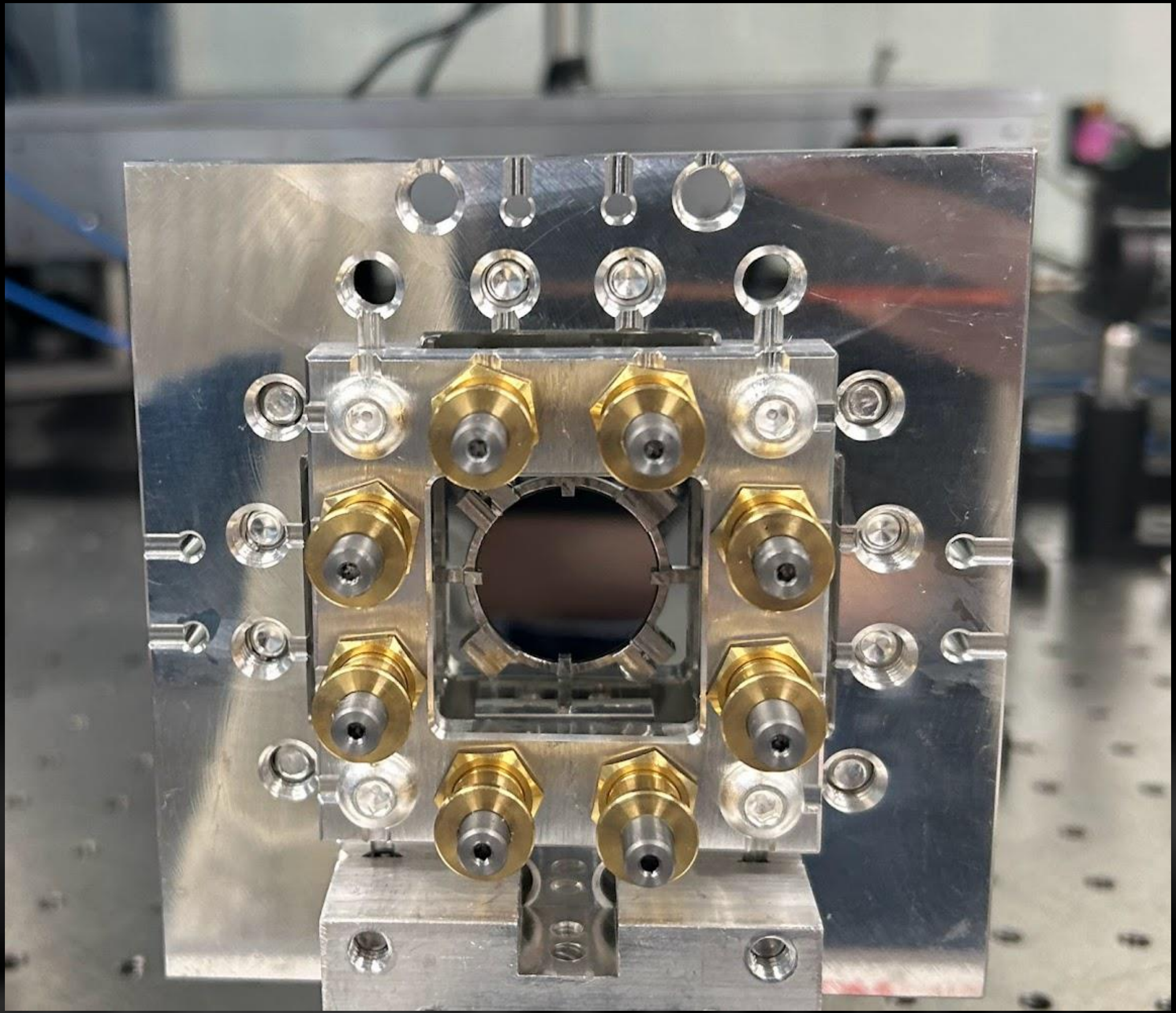
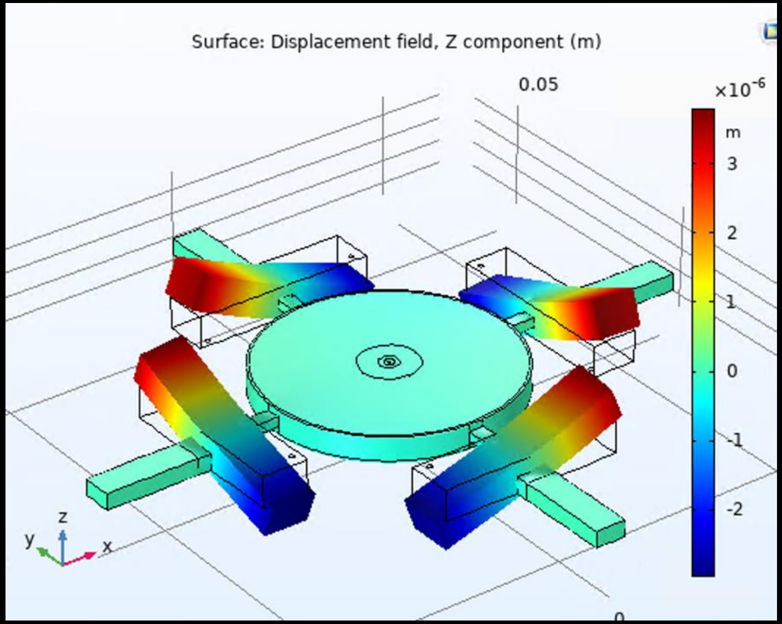
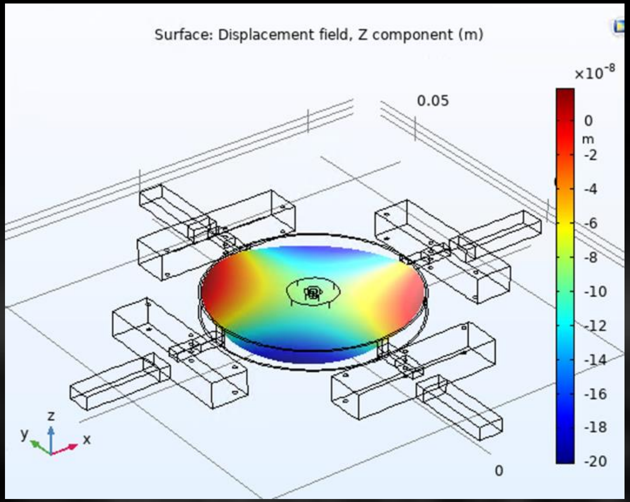
Bowtie Cavity Laser Design



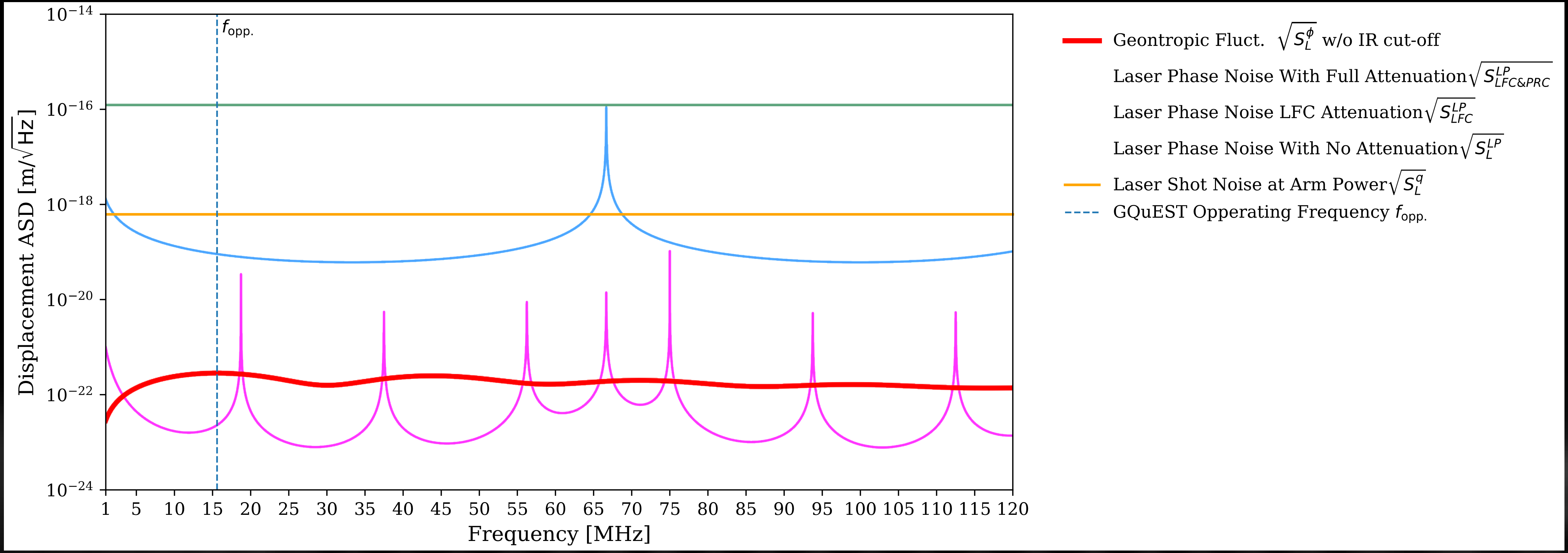
Custom Mirror Mount







Laser Filter Cavity Justification



Better Filter Justification