GQuEST
Introduction and Overview

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GQuEST collaboration at Caltech September 2023

A Brief History of GQuEST
Gravity from the Quantum Entanglement of Space-Time

Kathryn et al. describe quantum gravity observables in interferometers. Rana and Lee's experience at LIGO and the Holometer motivate the design.

Fermilab has Holometer equipment, experience with: cryogenics, optics, digital signal processing and projects.

The GQuEST collaboration has funding from

- Department of Energy: Office of Science
- Heising-Simons Foundation

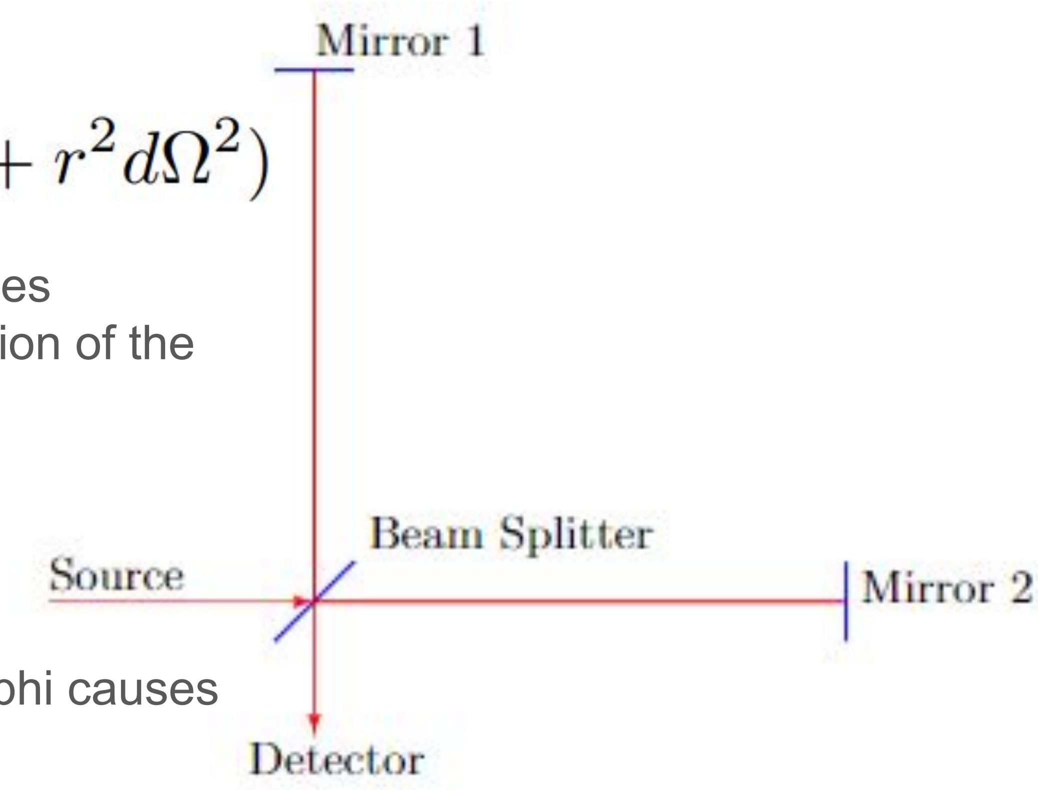
to design, build, and operate the experiment. We received one year of funding from DOE with more expected.

Current focus is to build a TECHNOLOGY DEMONSTRATOR

5 year time frame

“Elevator Speech”

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



IFOs are operated by setting the distances to the two mirrors such that a small fraction of the source power reaches the detector.

Changing the phase difference changes the power on the detector

In this version of the metric, a non-zero phi causes phase change that we detect.

This detection is at the input light’s reference frequency c/λ and also in sidebands.

We focus on the sidebands!

Fiducial GQuEST Design

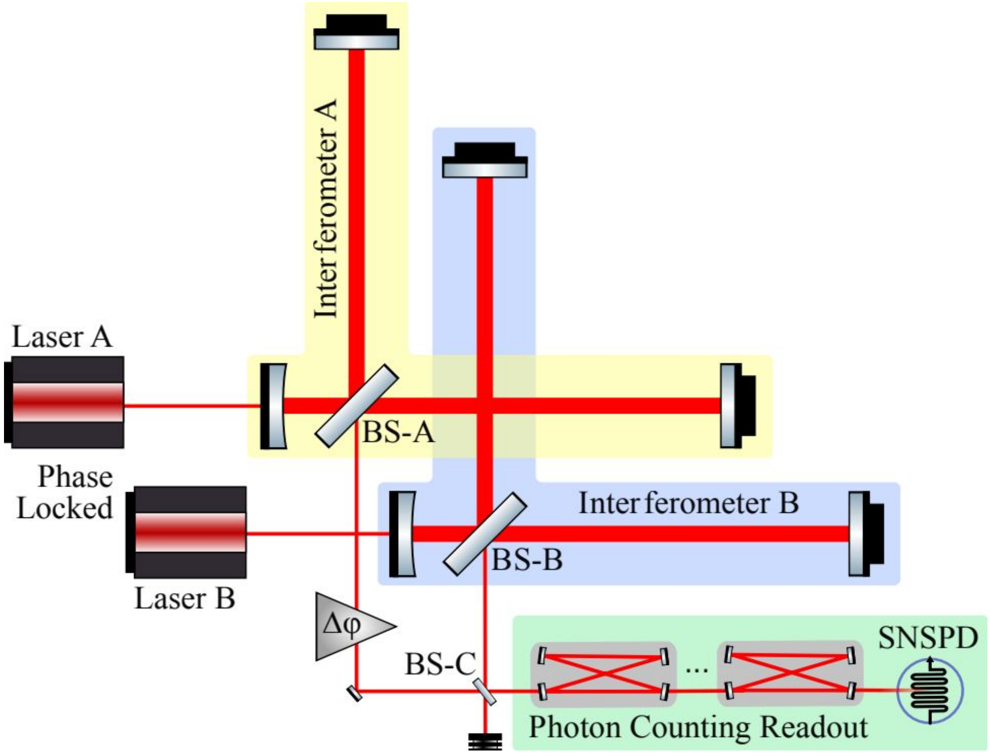
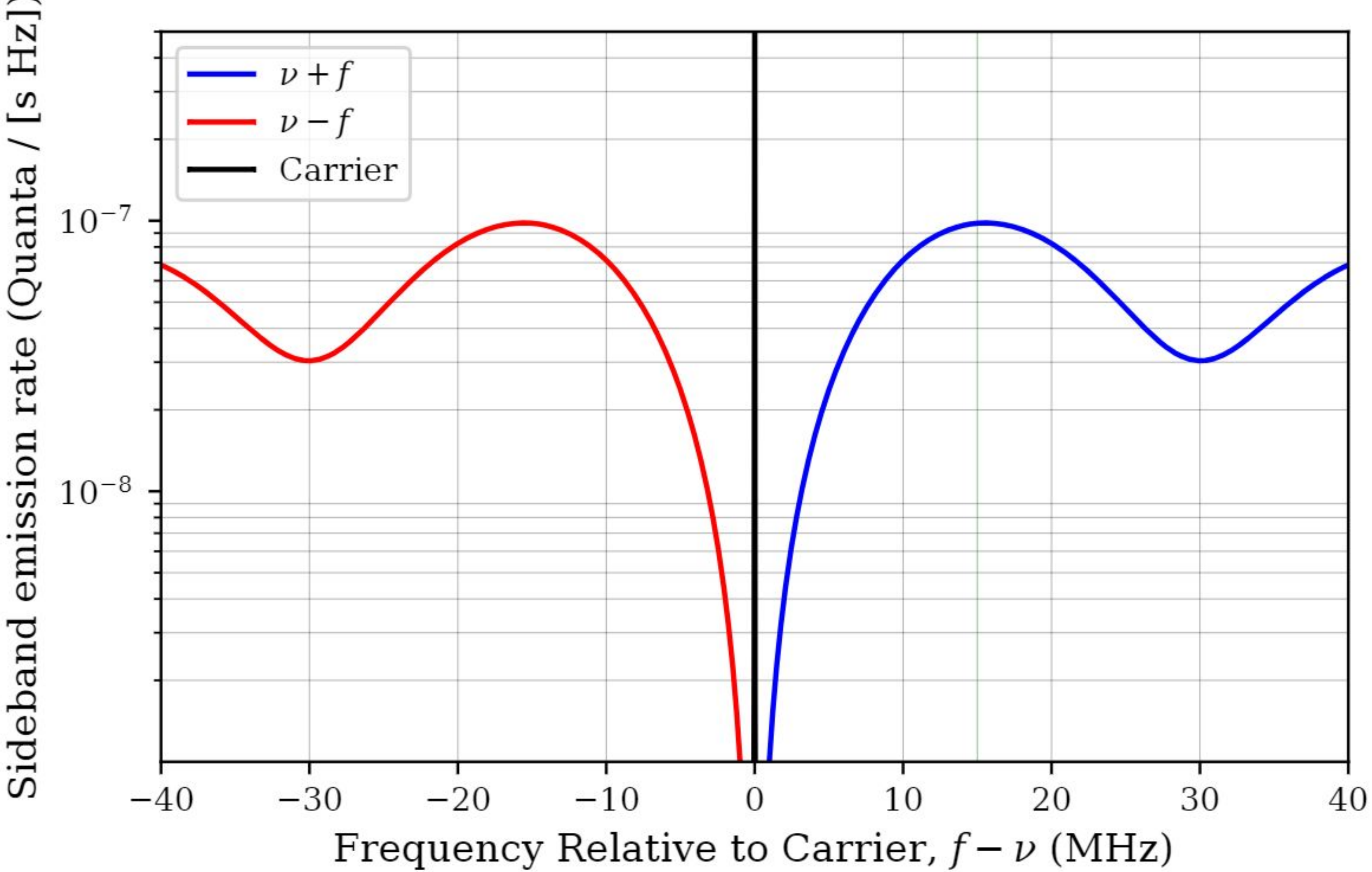


TABLE I. Parameters of the fiducial GQuEST design. The noise spectral densities are evaluated at 17.6 MHz.

parameter	symbol	value
Geontropic fluct. scale parameter	α	$\mathcal{O}(1)$
IFO arm length	L	5 m
Power on beamsplitter	P_{BS}	10 kW
Laser wavelength	λ	1550 nm
Laser frequency	ν	193.4 THz
Nominal filter offset frequency	ϵ_c	17.6 MHz
Filter bandwidth (FWHM)	$\Delta\epsilon$	25 kHz
Twin IFO separation	L_s	1.5 m
IFO inter-arm angle	Θ	90°
Signal Spectral Density (peak)	$\overline{S}_L^{\phi}$	$\left(3\cdot10^{-22}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$
Thermal Noise Spectral Density	$\overline{S}_L^{c}$	$\left(10^{-21}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$
Shot Noise Spectral Density	$\overline{S}_L^{q}$	$\left(6\cdot10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$
Filtered signal photon flux	$\dot{N}^{\phi}_{\mathrm{pass}}$	$1.4\cdot10^{-3}$ Hz
Filtered classical noise photon flux	$\dot{N}^{c}_{\mathrm{pass}}$	$1.6\cdot10^{-2}$ Hz
Photon Detector Dark Count Rate	$\dot{N}^{d}$	$< 10^{-3}$ Hz
Observation time for 5σ test for $\alpha = 1$	T	$\mathcal{O}(10^5)$ s



$\nu + f$
$\nu - f$
Carrier
Sideband emission rate (Quanta / [s Hz])
10^{-7}
10^{-8}
−40
−30
−20
−10
0
10
20
30
40
Frequency Relative to Carrier, $f - \nu$ (MHz)

Experimental Considerations: Physical Stability

- On paper the length difference (and hence phase difference) is constant.
- In practice, everything moves! Mechanical vibration, laser frequency, effects in mirror surface and substrate, ….
- We keep the differential arm length (aka DARM) constant with feedback systems to keep the output power at a constant level.

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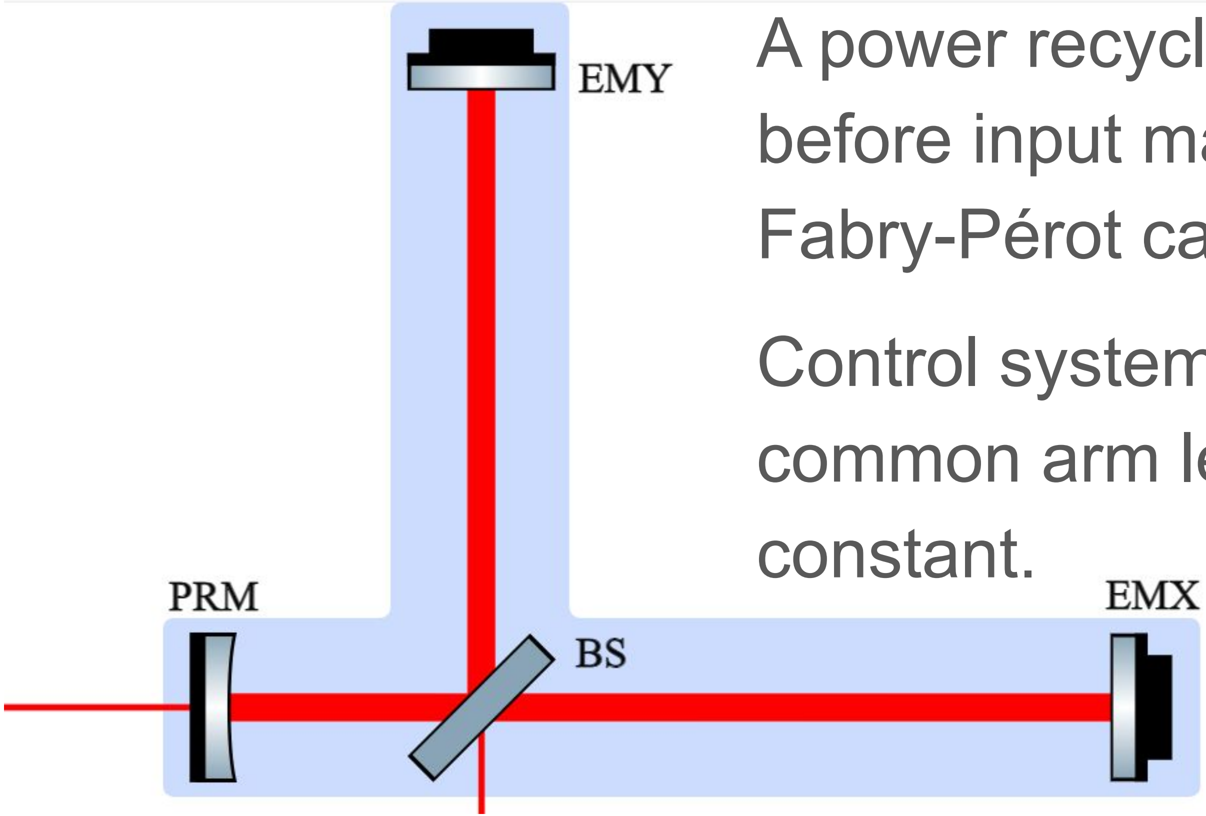
Experimental Considerations: More photons on target



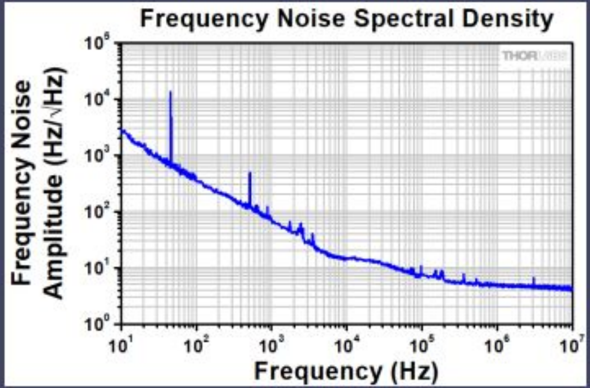
A power recycling mirror (PRM) before input makes the IFO a Fabry-Pérot cavity.

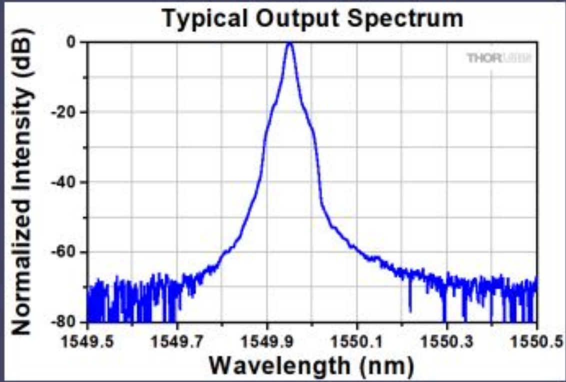
Control system keeps the common arm length (CARM) constant.

Experimental Considerations: laser phase noise → sidebands

- Input laser phase noise (White): 10^{-7} rad/$\sqrt{\text{Hz}}$
- Laser Power: 10 W
- Shot noise with cavity power: $6.2 \cdot 10^{-19}$ m/$\sqrt{\text{Hz}}$

Δ is 0.1 nm ~ 12 MHz





See Ian MacMillan's talk on Laser Noise

Experimental Considerations: homodyne readout

The "standard quantum limit" arises from poisson noise on the number of photons/second on the beam splitter.

Expressed as (effective) length changes:

$$\overline{S}_L^q = \frac{\hbar c}{2kP_{\mathrm{BS}}} \approx \left(6.2 \cdot 10^{-19}\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2 \left(\frac{10\ \mathrm{kW}}{P_{\mathrm{BS}}}\right)\left(\frac{\lambda}{1550\ \mathrm{nm}}\right)$$

The expected signal (3 10^{-22} m/rtHz) is << this noise.

See Sander Vermeulen's talk on Interferometery

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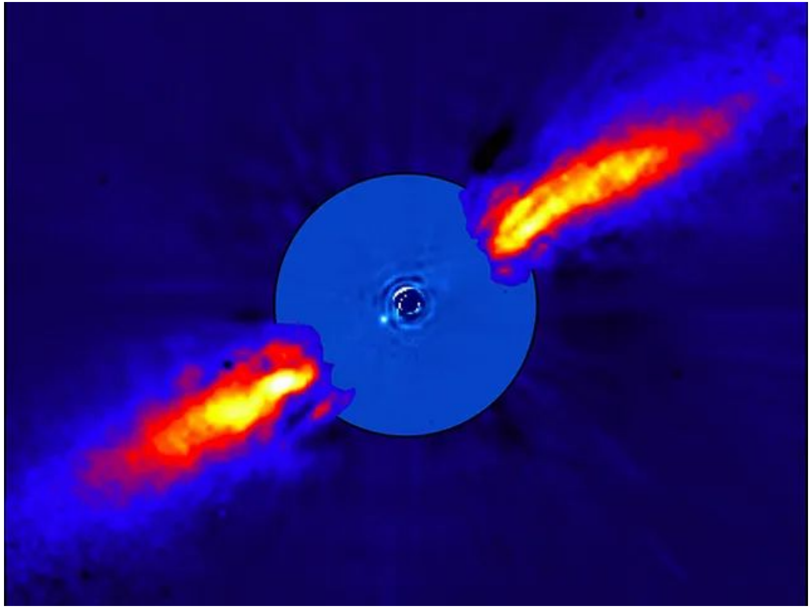
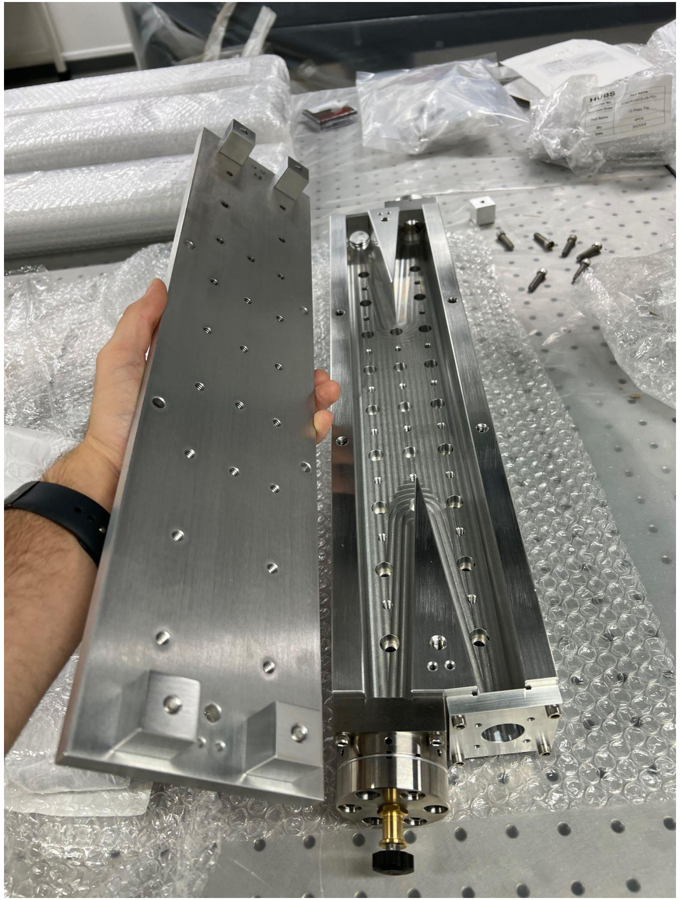
Experimental Considerations

S/N in the SIDEBAND scales more favorably, but the ratio of power (near λ)/(sidebands) is very large.

An analogy in the spatial domain is coronagraph imaging of exoplanetary systems.



Experimental Considerations: Output Filters



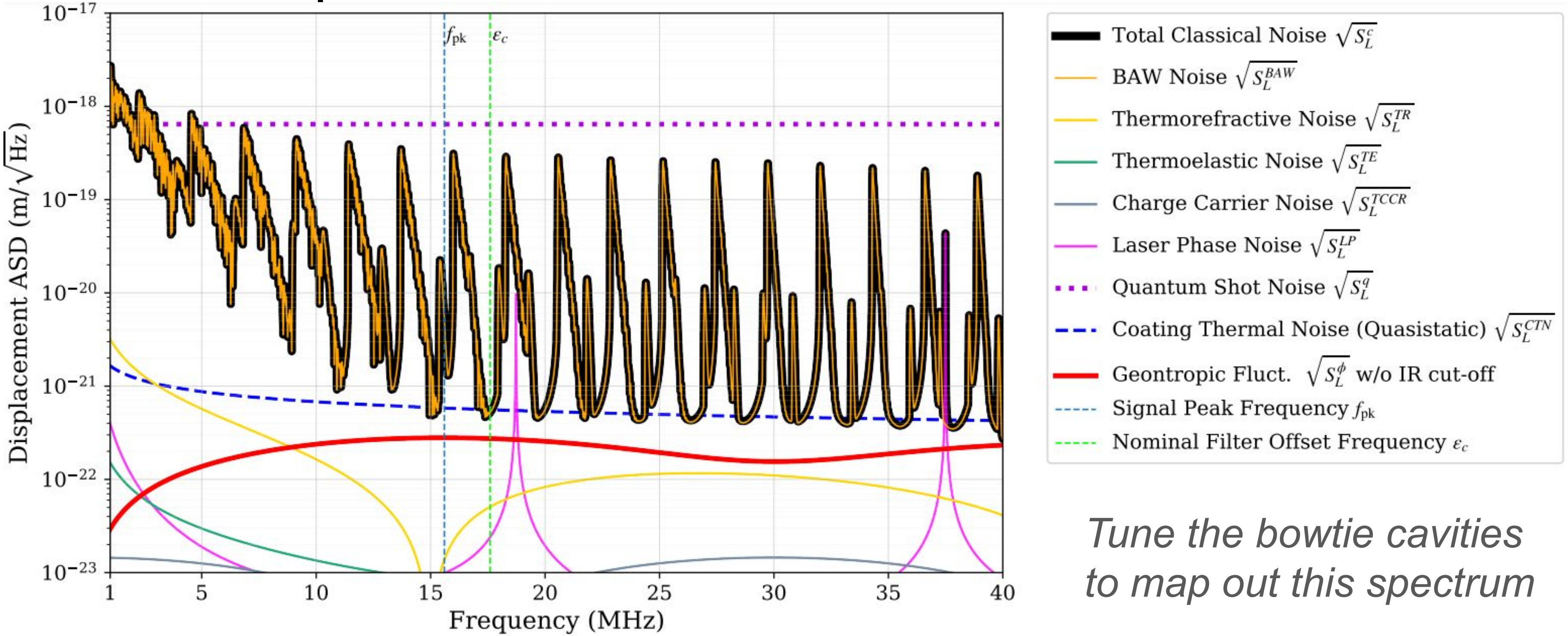
Non-signal light suppressed by ~60 dB (factor of 10^6) in the frequency domain

The “bowtie cavities” resonance frequency can be actively tuned to be from 8 to 40 MHz

Four cavities in series yield 240 dB (factor of 10^{24}) suppression

See Torrey Cullen’s talk on Technology Demonstrator

Experimental Considerations: All the Noise!



Tune the bowtie cavities to map out this spectrum

Mirrors are not perfect: the substrate is a drum; coatings have thermal noise

See Daniel Grass' talk on Thermal Noise

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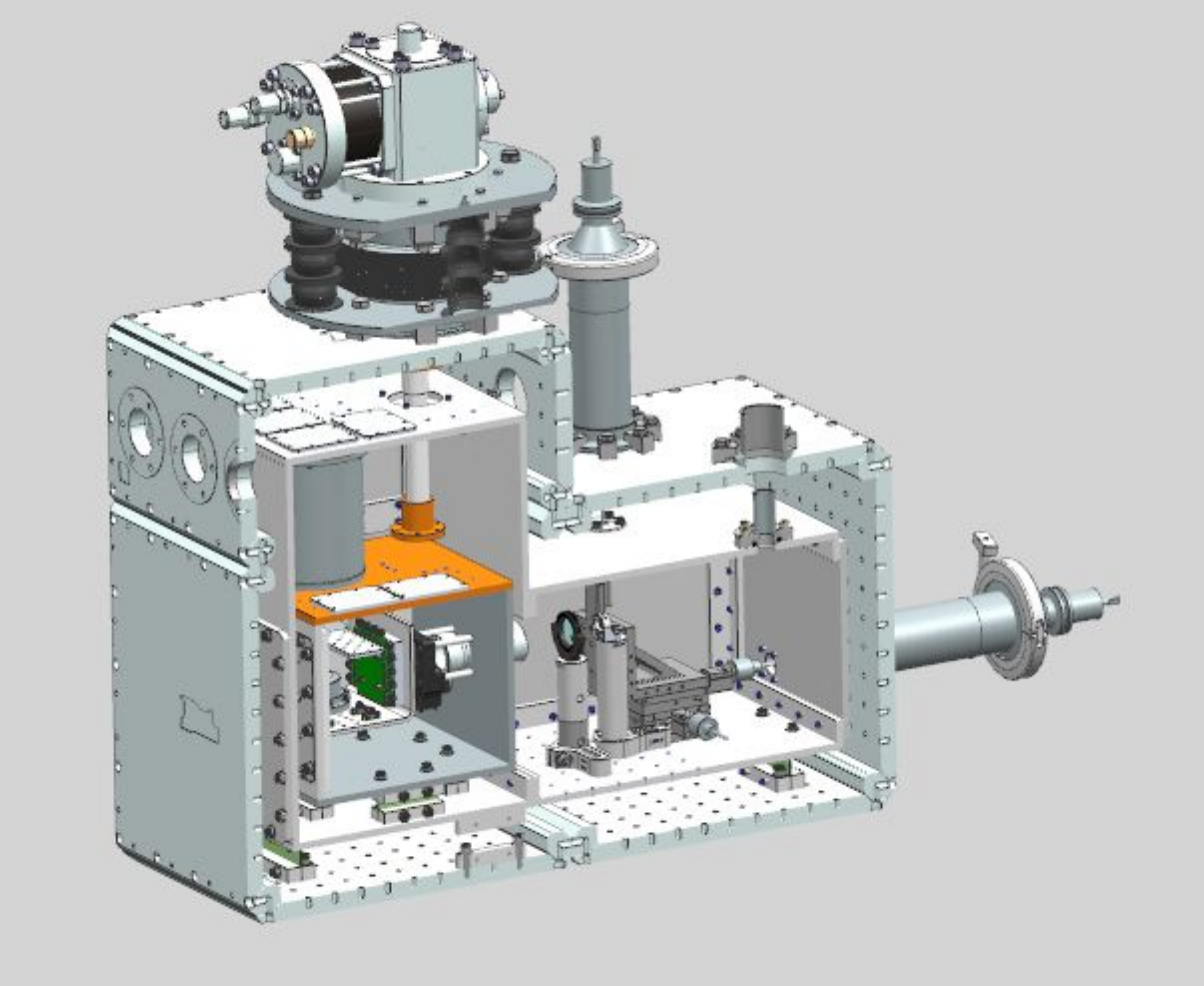
Experimental Considerations: Photon Counter

- JPL is providing SNSPD counters: Superconducting Nanowire Single Photon Detector.
- Thermal Radiation photons would overwhelm the rate. Sources are:
  - Near the detector (so place in cold dewar)
  - Shining from IFO optics (so couple with fiber and optical filters)

See Alex Ramirez’s talk on Photon Counting



Dewar under construction at Fermilab to hold:

- SNSPD detector,
- optical filters
- thermal shields
- alignment

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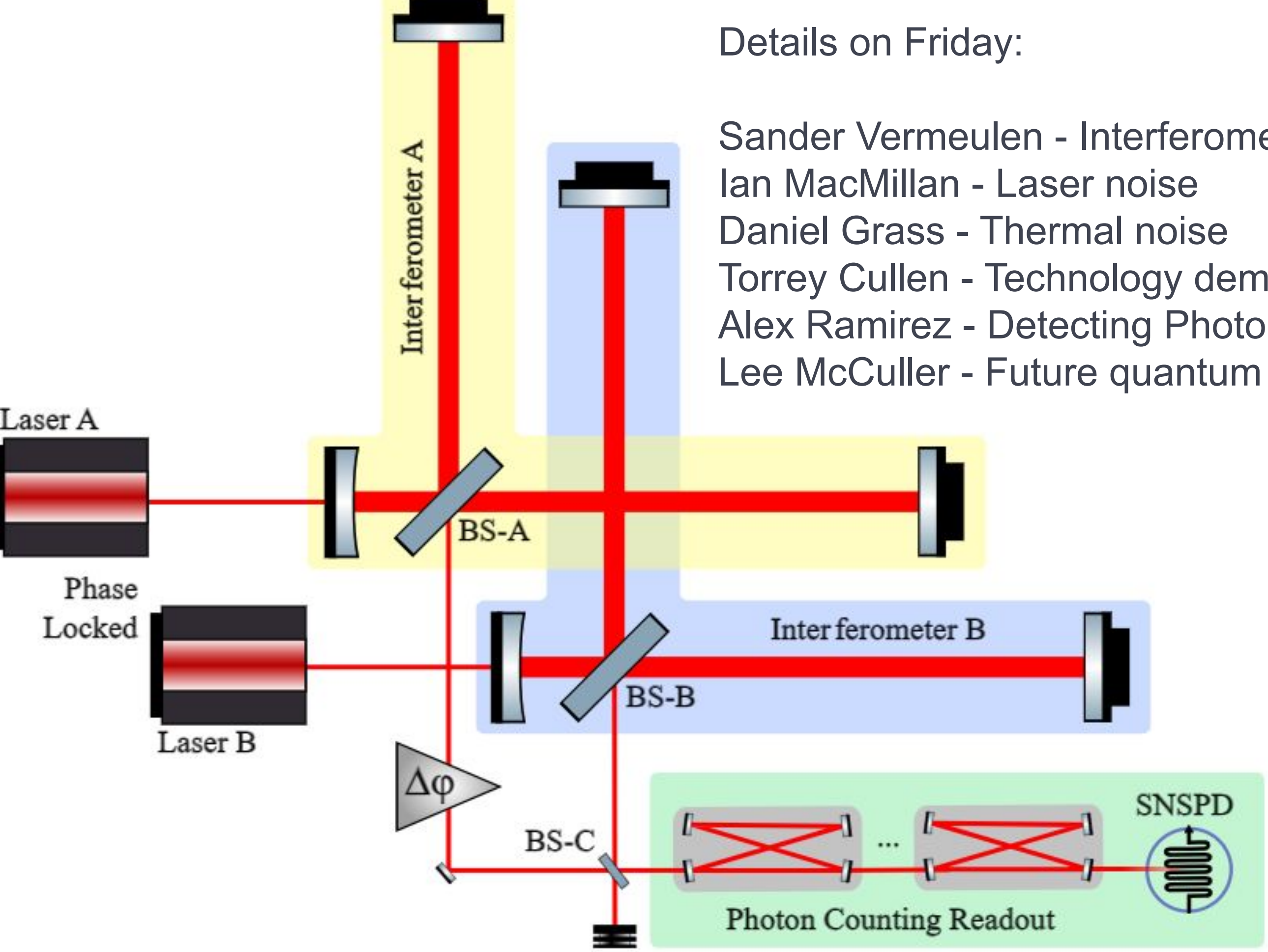
Science Operations

Map out spectrum by repeating these steps:

- Choose a frequency
- Count photons for ~ 1 hour to 24 hours.

Characterize the EXCESS:

- Modulate signal by changing $\Delta\varphi$
  - This modulation can be time-dependent, blinded
- Change L
  - Technology Demonstrator will have a small L



Details on Friday:

Sander Vermeulen - Interferometry Basics and current limits
Ian MacMillan - Laser noise
Daniel Grass - Thermal noise
Torrey Cullen - Technology demonstrator and filter cavities
Alex Ramirez - Detecting Photons One At A Time
Lee McCuller - Future quantum experiment possibilities