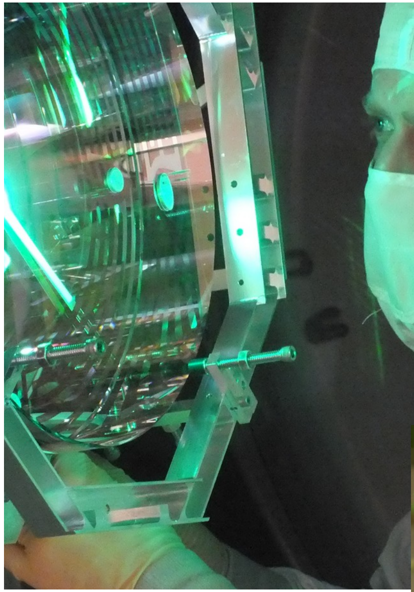
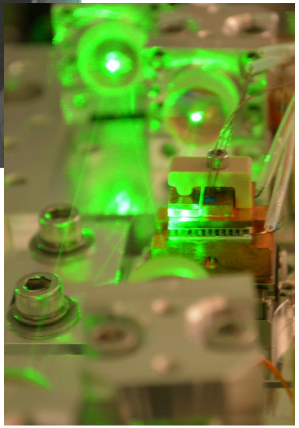
Quantum Control Platforms for Gravitational Physics in GQuEST



How strongly can we probe mirror displacement for gravitational physics?

Is squeezed light the best we can do?

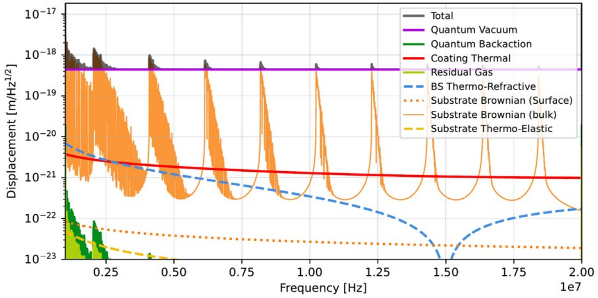


Lee McCuller

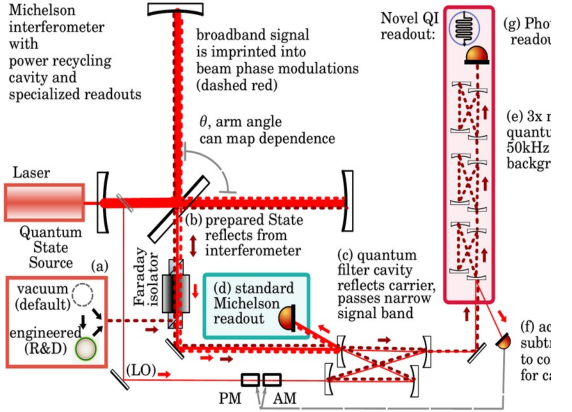
Caltech

FNAL QICK workshop

12 Jan. 2023



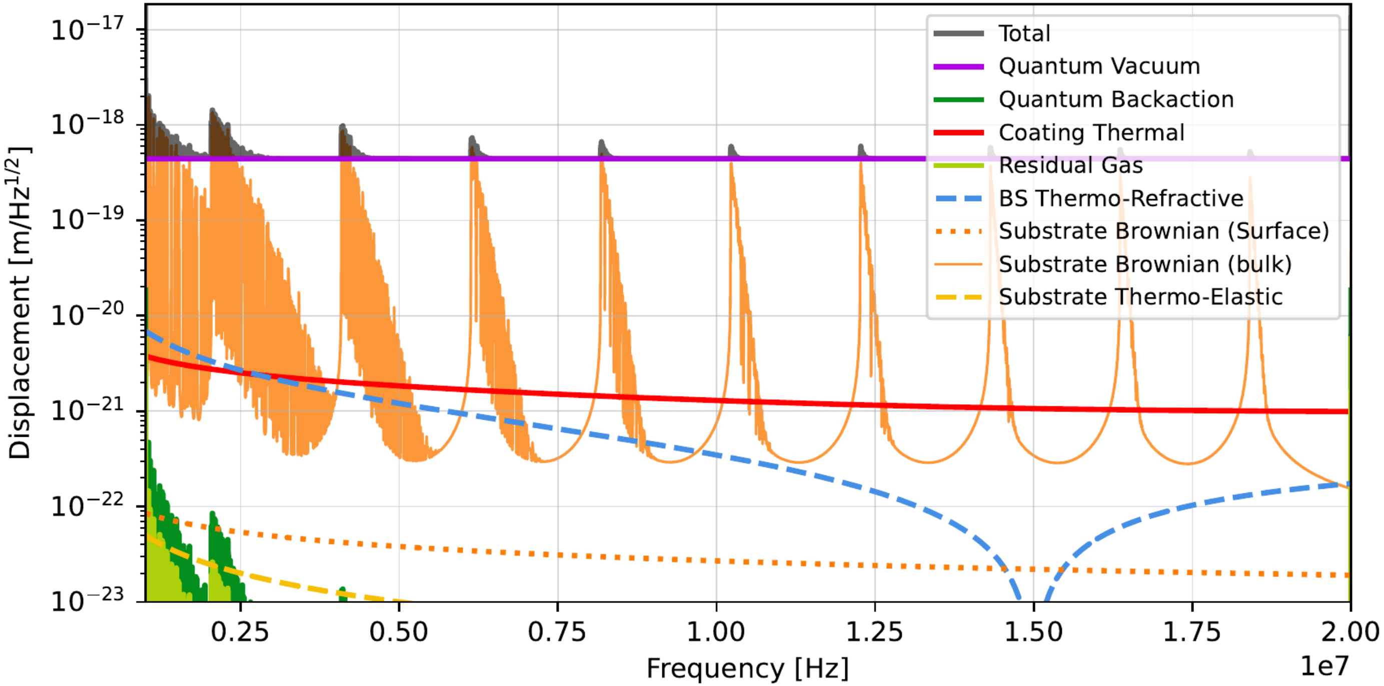
How small can we make classical noise?



Shouldn’t we always be rewarded for making a better instrument?

GQuEST experiment:

Gravity from Quantum Entanglement of Space-Time



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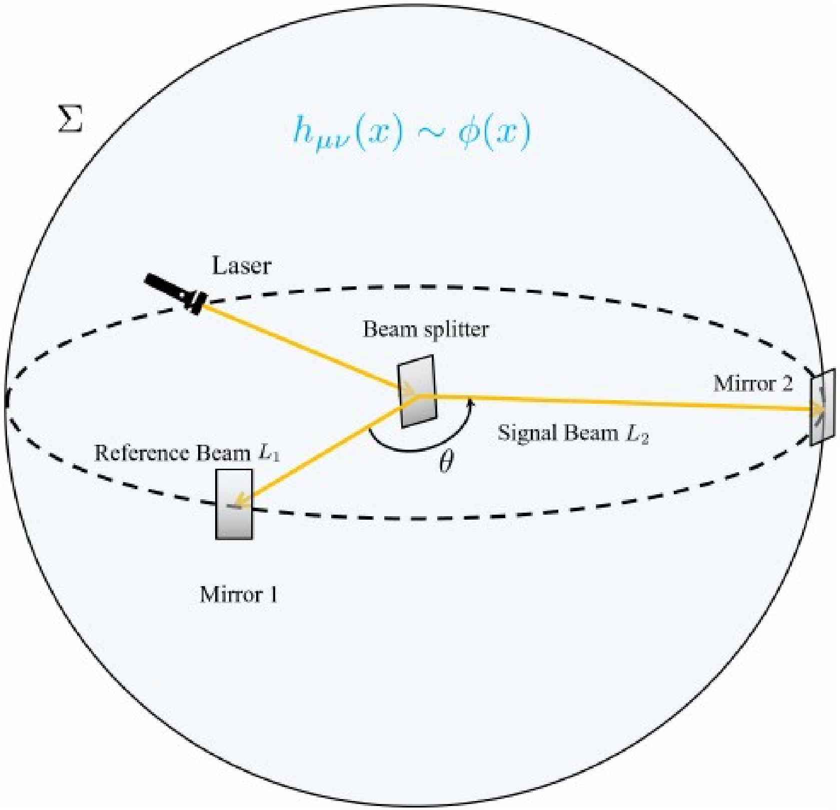
University-Scale Experimentation

- Achieving quantum-noise limited sensitivity is tough
  - Acoustic isolation takes a lot of engineering
- High Frequency signals are ideal when the physics supports them
  - Many efforts are center on low-mass dark matter
- The best experiments test a model, a theory.
  - Ideally, either test result is significant
- New theory predicting observable signatures of quantum gravity checks these boxes:

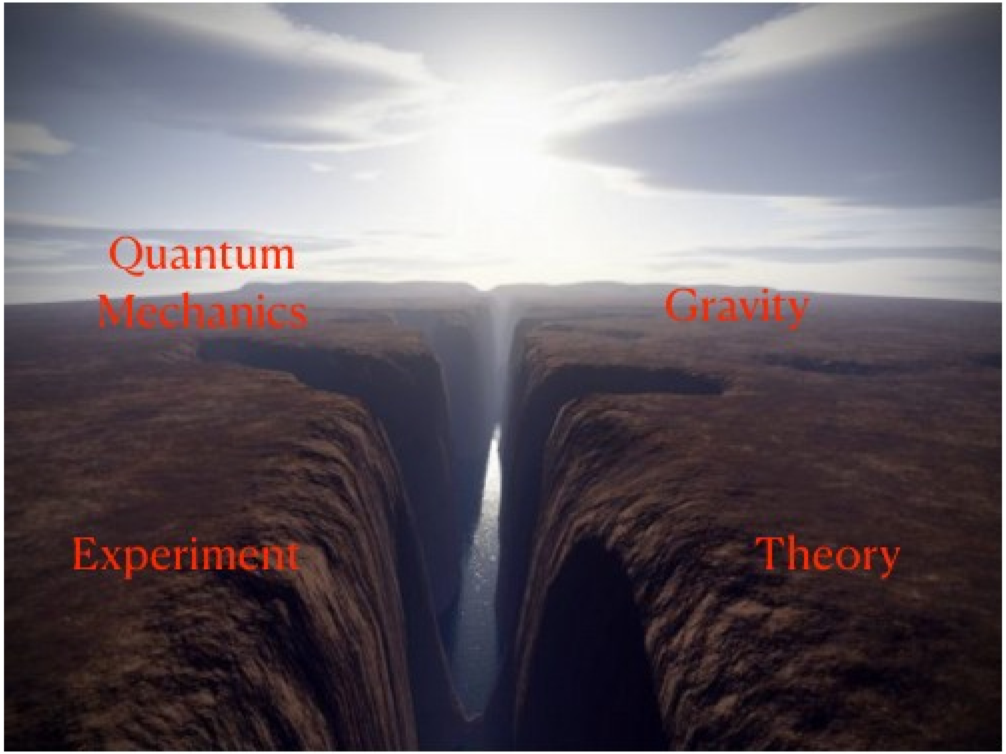


Li et al, arXiv:2209.07543 [gr-qc]

Extreme Physics in “mundane” space

- Kathryn Zurek @**Caltech**
- Systematically bridging the divide, theory side

“ Quantum Gravity entails spacetime fluctuations from entanglement entropy ”

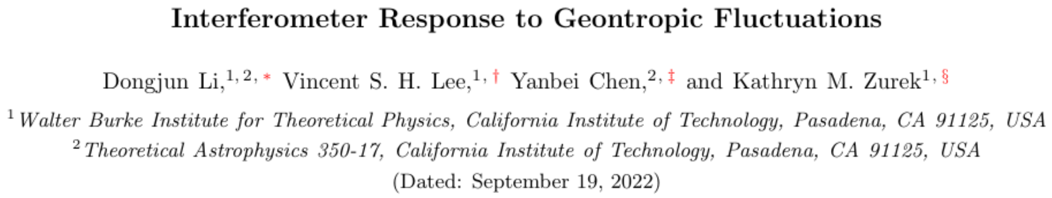


Banks, KZ 2108.04806

E. Verlinde, KZ 1902.08207
E. Verlinde, KZ 1911.02018

Prediction of interferometer response

- Fluctuations of Newtonian potential on micro/local scales
- Looks like a field that causes isotropic dilations of the metric
- Thermal population
- Behaves much like a <u>stochastic background</u>



Interferometer Response to Geontropic Fluctuations

Dongjun Li,[1, 2, *] Vincent S. H. Lee,[1, †] Yanbei Chen,[2, ‡] and Kathryn M. Zurek[1, §]

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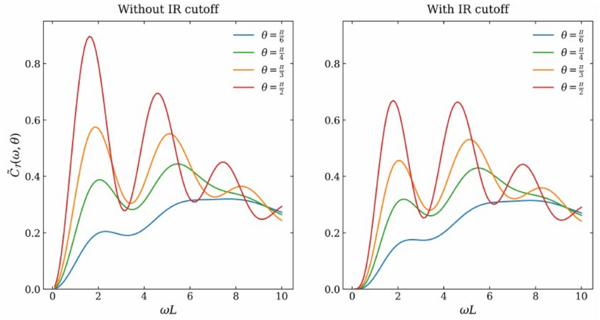
[2] *Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, CA 91125, USA*

(Dated: September 19, 2022)



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

$$\phi(x) = l_p \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{\sqrt{2\omega(\mathbf{p})}} \left(a_{\mathbf{p}} e^{ip\cdot x} + a^\dagger_{\mathbf{p}} e^{-ip\cdot x}\right)\,,$$

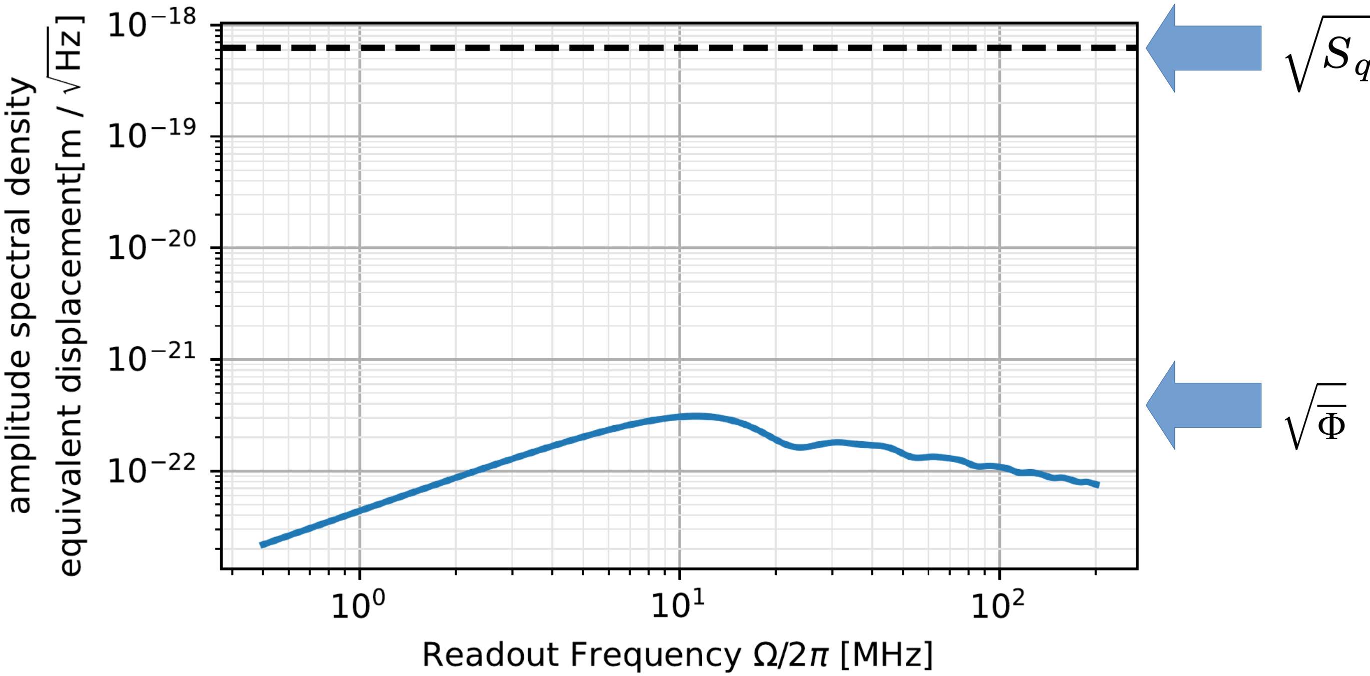
$$\mathrm{Tr}\left(\rho_{\mathrm{pix}} a^\dagger_{\mathbf{p}_1} a_{\mathbf{p}_2}\right) = (2\pi)^3 \sigma_{\mathrm{pix}}(\mathbf{p}_1) \delta^{(3)}(\mathbf{p}_1 - \mathbf{p}_2)$$

$$\sigma_{\mathrm{pix}}(\mathbf{p}) = \frac{a}{l_p \omega(\mathbf{p})}\,,$$

(Minimal set of equations
to build the phenomenology)

A Tabletop Stochastic Search

- Michelson Interferometer
- 10kW+
- 1550nm
- Broadband signal
- Will need cryogenic Si



$$S_\phi \equiv \alpha\Phi(\Omega)$$

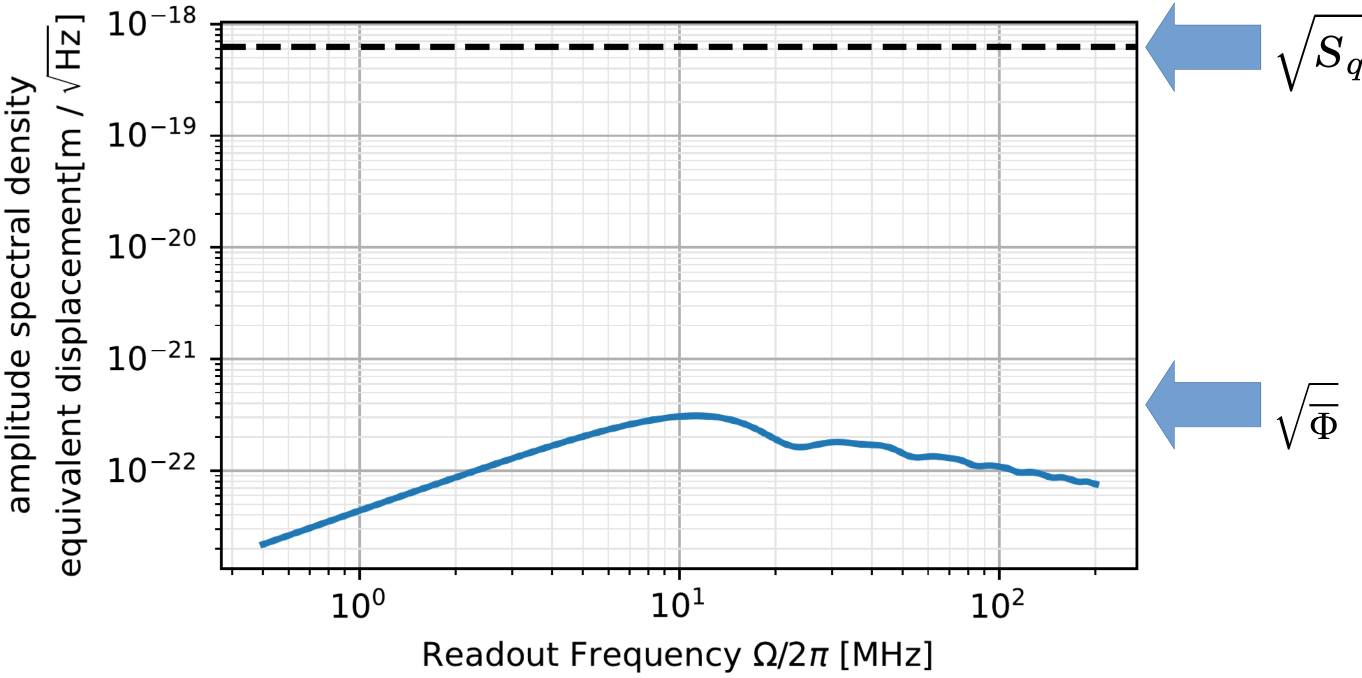
$$\overline{\Phi} \equiv \max_{\Omega<\infty} \Phi(\Omega)$$

$$\overline{\Phi} \approx \left(3\cdot 10^{-22}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2 \left(\frac{L}{5\mathrm{m}}\right)^2 \qquad S_q \approx \left(5\cdot 10^{-19}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2 \left(\frac{10\mathrm{kW}}{P_{\mathrm{bs}}}\right) \qquad N = \Delta T \Delta F = \frac{S_q^2}{\alpha^2\overline{\Phi}^2} \approx 10^{13}$$

A Tabletop Stochastic Search

$$N = \Delta T \Delta F = \frac{S_q^2}{a^2\overline{\Phi}^2} \approx 10^{13}$$

$$\Delta T_{1\sigma} \approx 185\mathrm{Hr}$$



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Blame the time-series

Here is where it gets interesting:

The background noise-power is from observing *vacuum fluctuations* of the optical light

- Michelson interferometers observe the vacuum due to their *Fringe light*. Which makes them measure the optical signal field vs. time
- Is this necessary? If there is no *signal power* then **why can I not test observing *something* vs. observing *nothing***
- Instead, measure the *optical signal power* *(vs. time)*

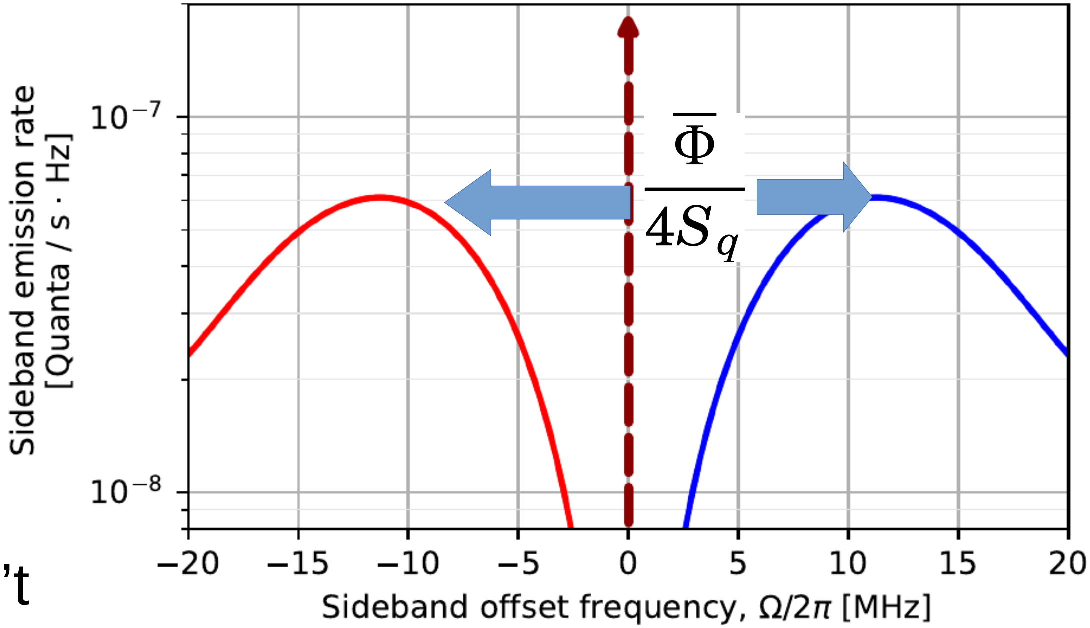
different observable, different statistics

LM: arXiv:2211.04016

A Tabletop Particle Search

So… lets view this
as a particle detector

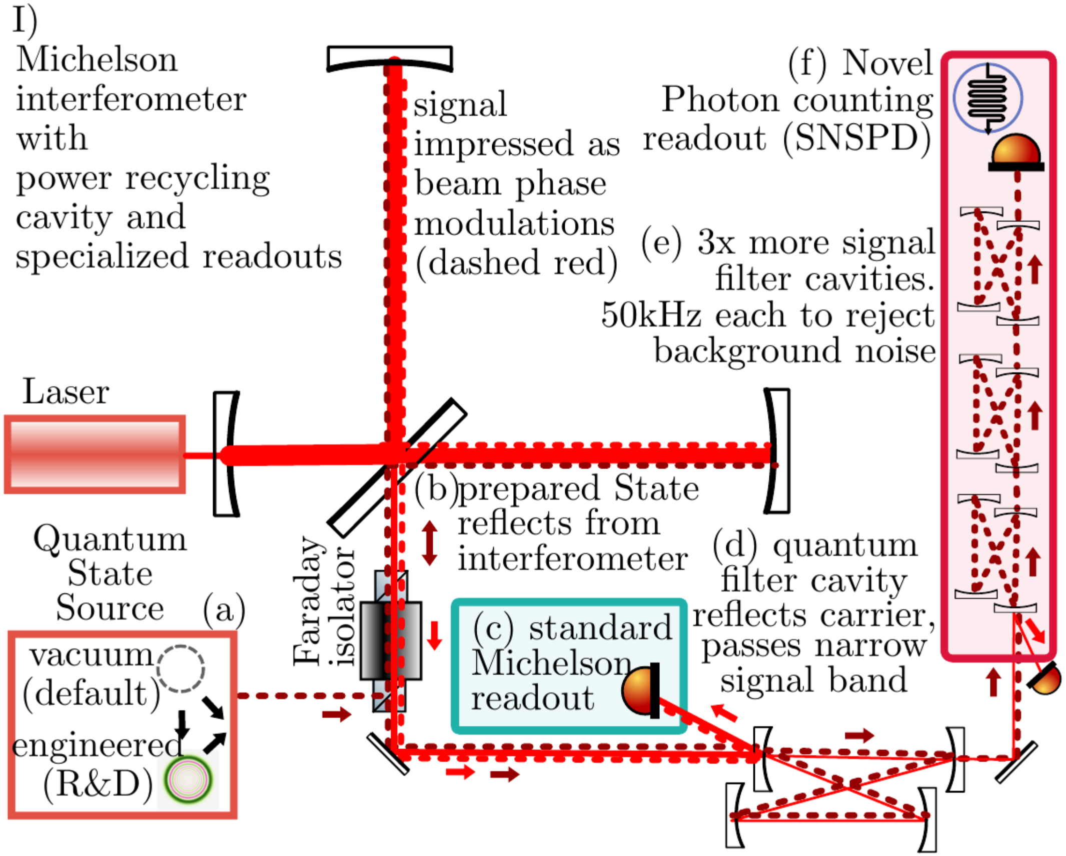
- 1e-7 photons/(s Hz) emitted (spectral flux-density)
- over 10MHz (1e7 Hz) signal bandwidth
- Should take 1second for 1σ by Poisson statistics
  - Shot noise quantum limit isn't so fundamental for this search



arXiv:2211.04016

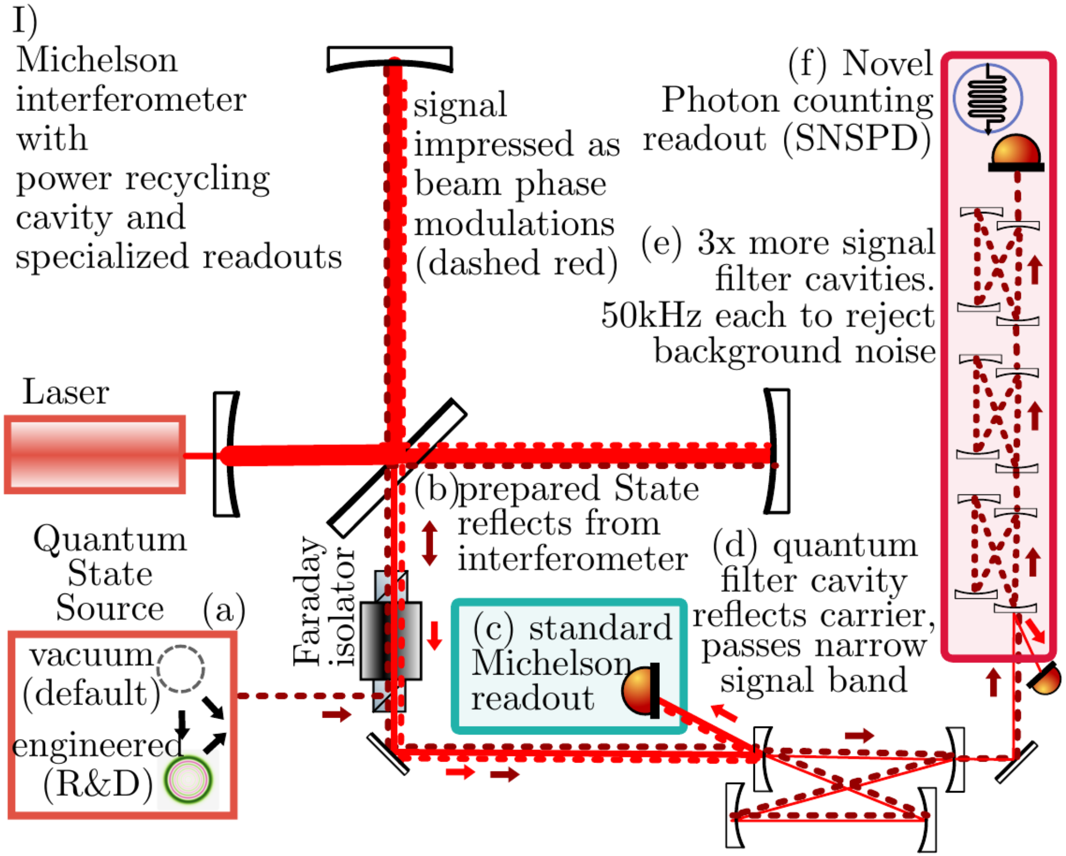
The GQuEST Realization

- Metric fluctuation signal modulates Stokes, anti-Stokes photon side-bands
- Use a series of optical filters to select photon sidebands
- Requires extreme sideband/carrier contrast ~240db
- New interferometer for Raman/Brillouin spectroscopy of <u>spacetime</u>



arXiv:2211.04016

50kHz Photopower Integration



I) Michelson interferometer with power recycling cavity and specialized readouts

signal impressed as beam phase modulations (dashed red)

(f) Novel Photon counting readout (SNSPD)

(e) 3x more signal filter cavities. 50kHz each to reject background noise

Laser

(b)prepared State reflects from interferometer

Quantum State Source (a)

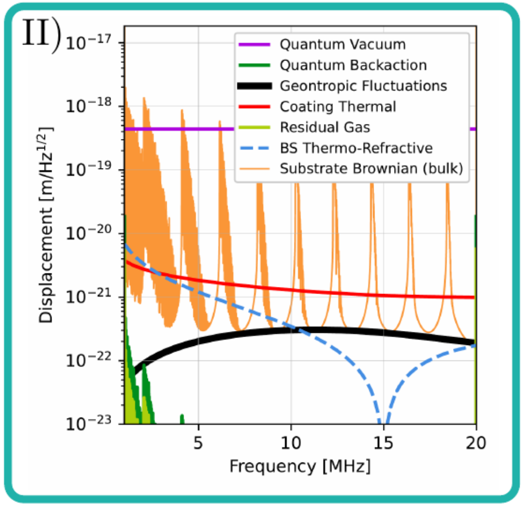
vacuum (default)

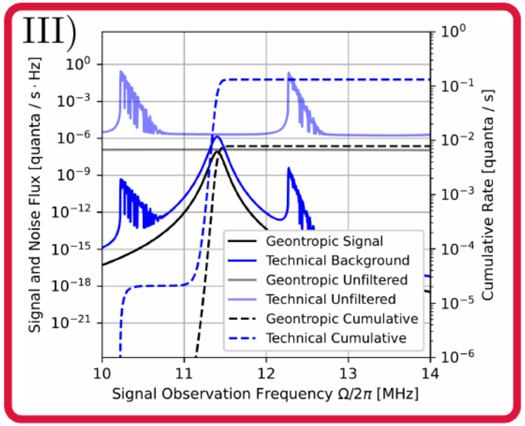
engineered (R&D)

Faraday isolator

(c) standard Michelson readout

(d) quantum filter cavity reflects carrier, passes narrow signal band

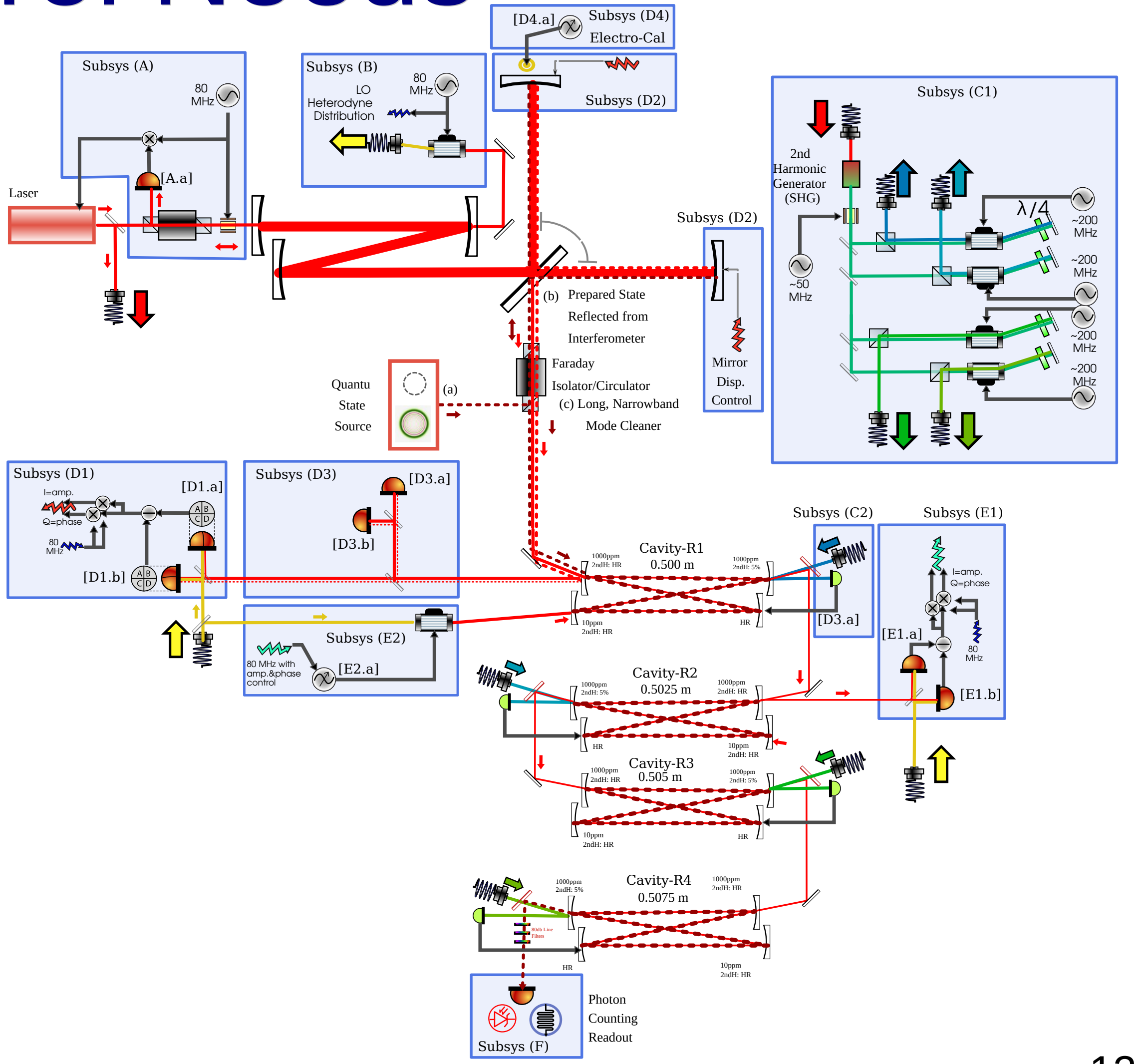




arXiv:2211.04016

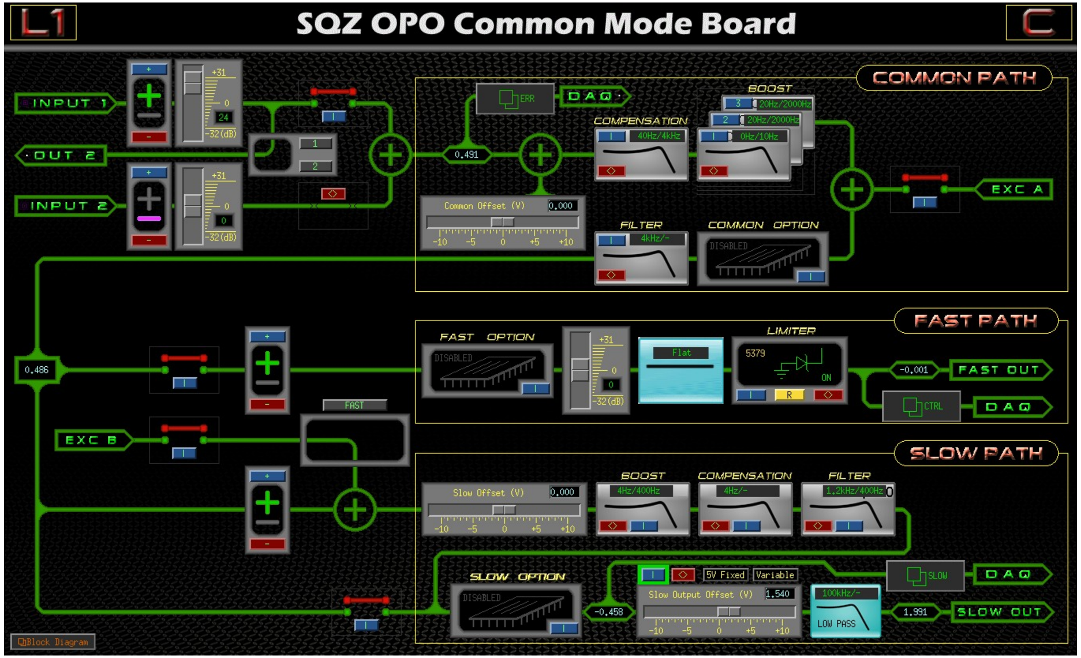
Sensing and Control Needs

- Good active and tons of passive isolation of laser noise
- Feedback control of interferometer and cavities
- Many VCO sources and demodulators



High Speed Servo Board

- The LIGO “Common Mode” board is a generic 2-channel in, 2-channel out servo in analog
- Implements 8 custom, toggle-able Sallen-Key filters
  - equiv, digital biquad filter (i.e. SoS)
  - Much more aggressive loop shapes than PID. Are conditionally stable!
- Offsets added at appropriate points
- Along with testpoint/excitation for loop measurements
- Demodulation, mixing done externally with low noise demod boards.
- Requires ~40 binary controls and many analog readbacks ($$, annoying for univ. labs)

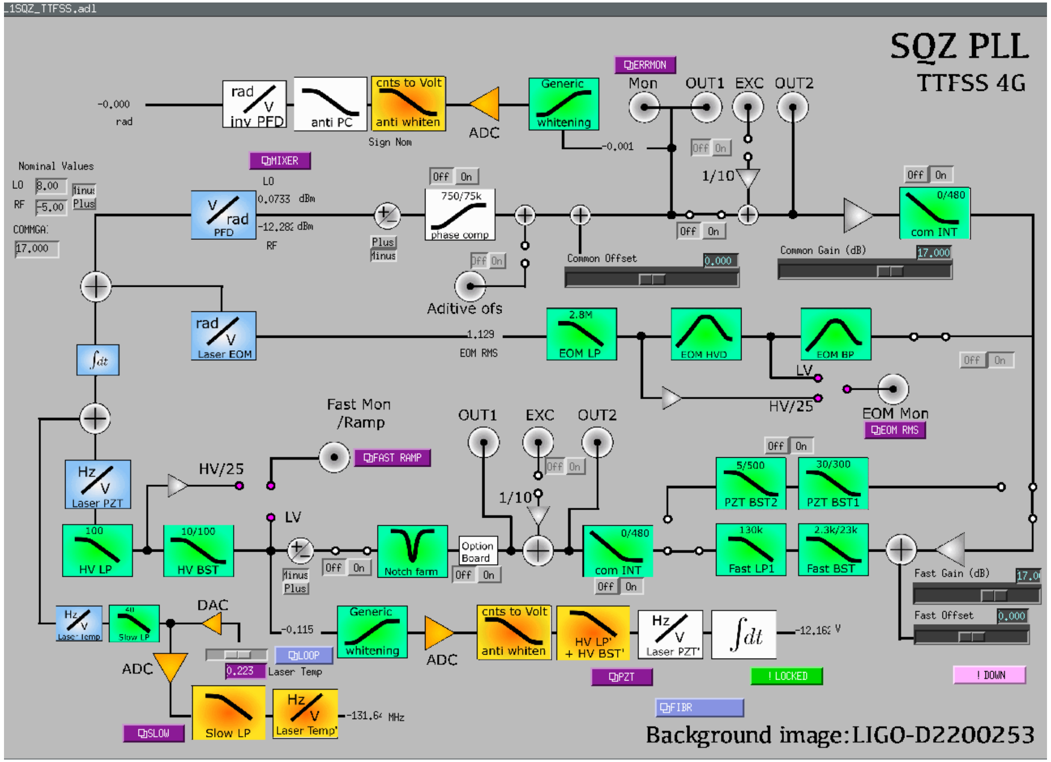


The schematics and design are public - on generation 7: https://dcc.ligo.org/LIGO-D040180

Generally, we need the full dynamic range Of op-amps (~1e-10/rtHz), which means a 16 bit ADC at 4GHz with “whitened” front-end noise shaping

“TTFSS”

- Table-top frequency stabilization servo.
  - Actuates with laser temp, laser PZT, EOM.
  - EOM path is in a short 10ns round-trip for highest bandwidth.
  - Locks two lasers to shot noise of the beatnote to 100kHz or so.
    - Ends up limited by fiber or acoustic pickup between the lasers.
  - Basically makes a secondary laser equivalent to a primary
  - The VCO on the secondary allows one to then modulate the secondary substantially faster than an AOM for single-sideband modulation
  - This is a principle of operation for the LIGO in-vacuum squeezed light source and its coherent control system.

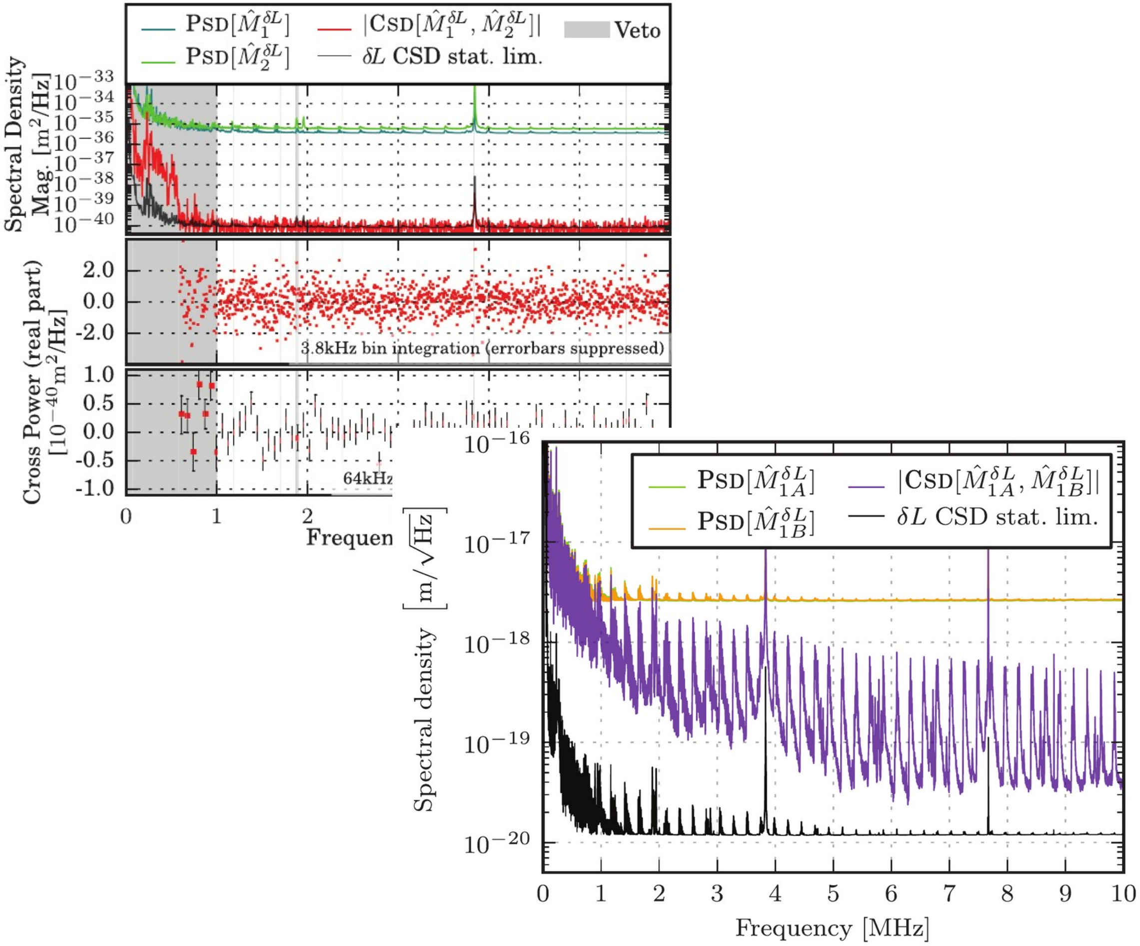


Background image:LIGO-D2200253

The schematics and design are public - on generation 4: https://dcc.ligo.org/D1700077

Cross Correlating Spectrum Analyzer

- Also equipped with a “standard Michelson” readout.
- Like Holometer, needs multi channel ~100MHz time-averaged cross correlations to dig in to noise
  - Gives Resolution that photon counting doesn’t

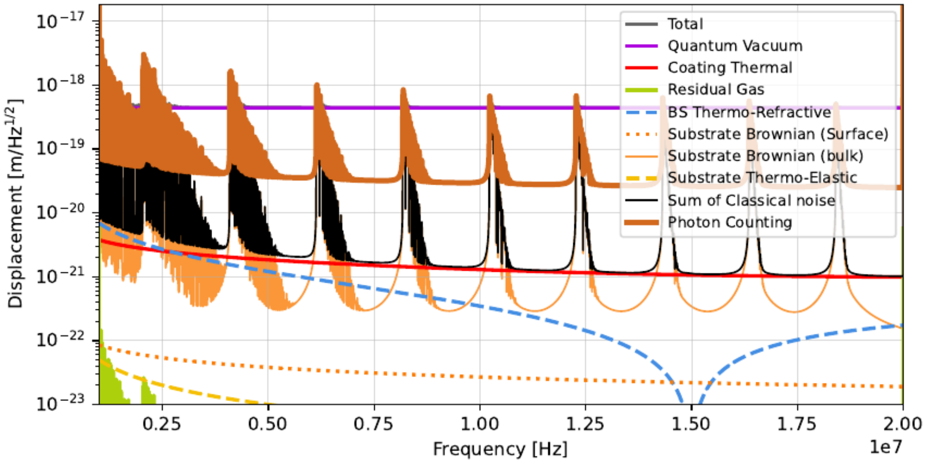


Class. Quantum Grav. 34 (2017) 065005

GQuEST experiment:

Gravity from Quantum Entanglement of Space-Time

- Intends to test quantum gravity fluctuation signals
- Intends to demonstrate the utility of photon counting for interferometers
  - This makes them much more like other HEP rare-process detectors
- I do anticipate counting to be useful in the future of GW astronomy
- Squeezing doesn't improve quantum performance
  - new platform to explore non-Gaussian quantum improvements



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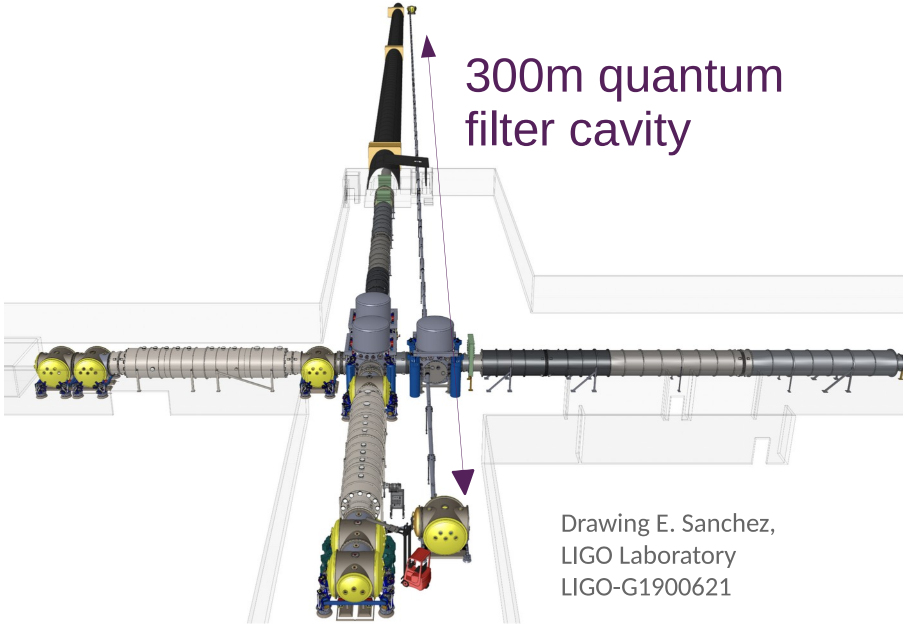
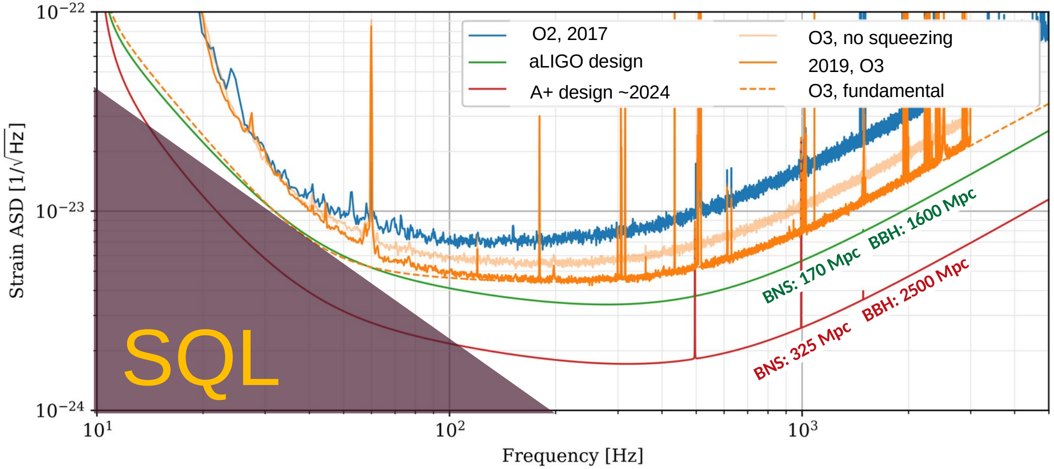
The A+ Upgrade

- 6db of frequency-dependent squeezing
  - Early install, aiming at 4.5db in Run 4
  - Sub-SQL during observations!
- 2x improved coating thermal noise
  - Still researching, but good leads
- Active wavefront control
  - Lowers squeezing loss
- Balanced homodyne readout
  - Multiple benefits
- Bigger Beamsplitter



300m quantum filter cavity

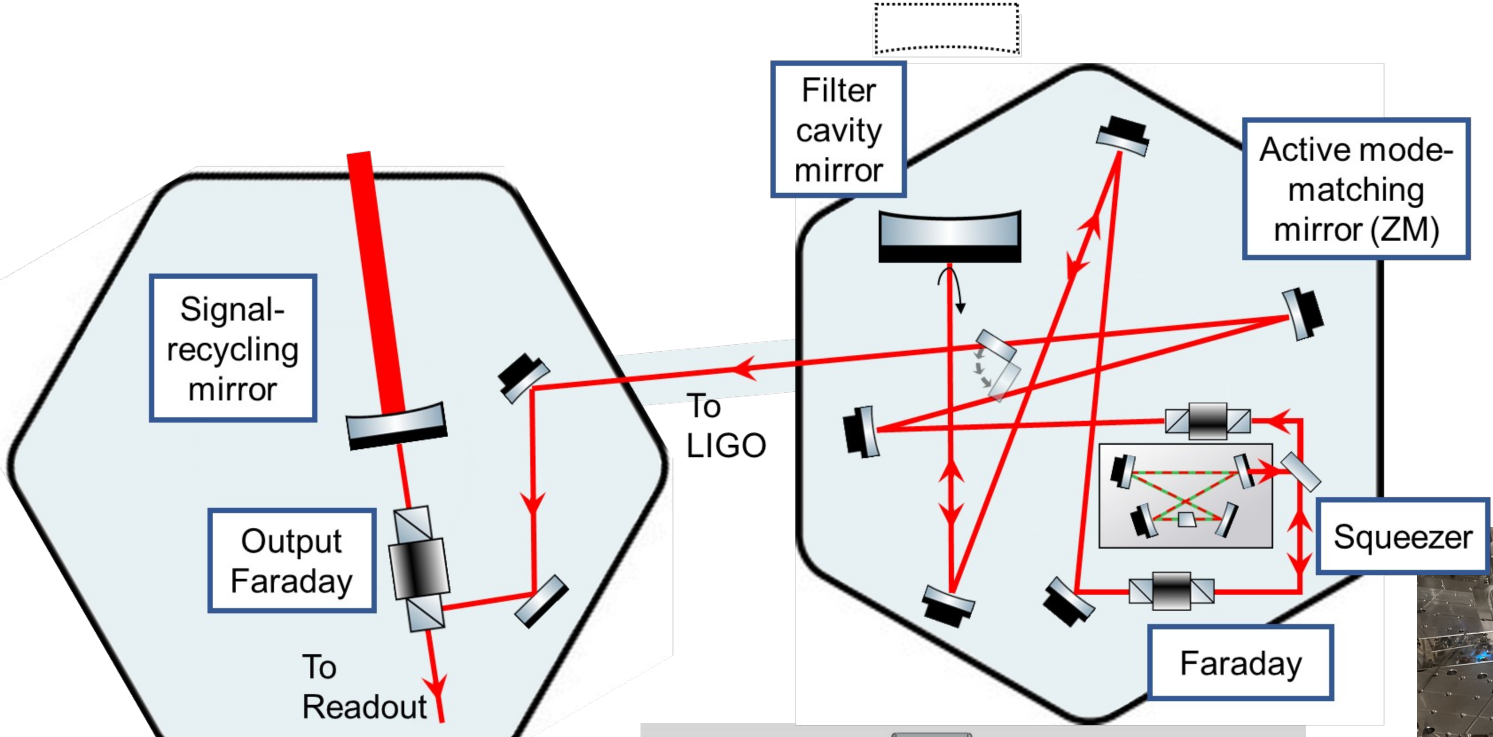
Drawing E. Sanchez, LIGO Laboratory LIGO-G1900621

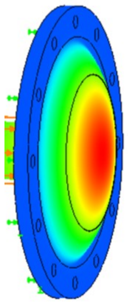


Reference Curves LIGO T1800042-v5

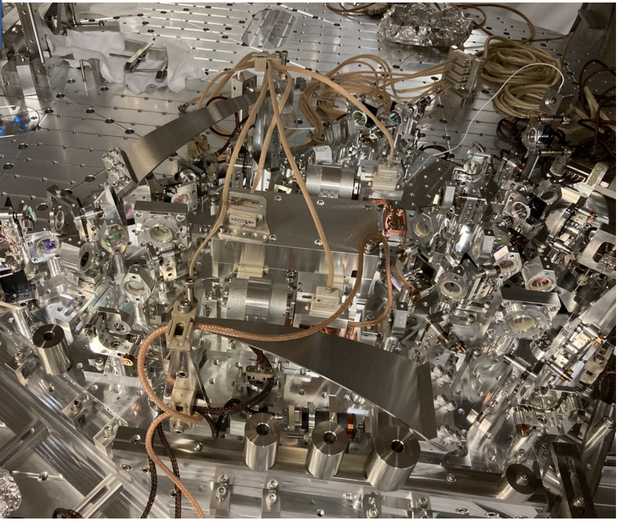
Filter Cavity Hardware

Drawings: Wenxuan Jia and Dhruva Ganapathy

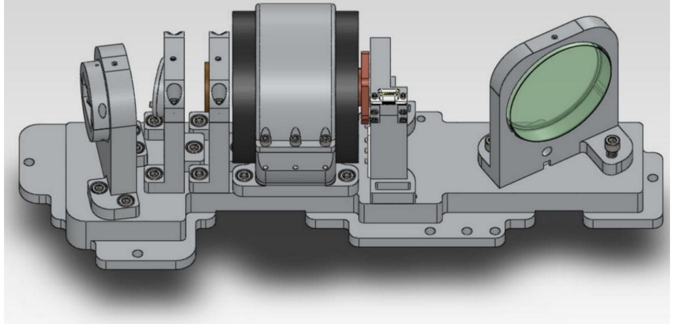




V. Srivastava, et al., Opt. Express 30, 10491-10501 (2022)



Ultralow-loss Faraday isolators (UF/Montclair)



Filter Cavity Installation