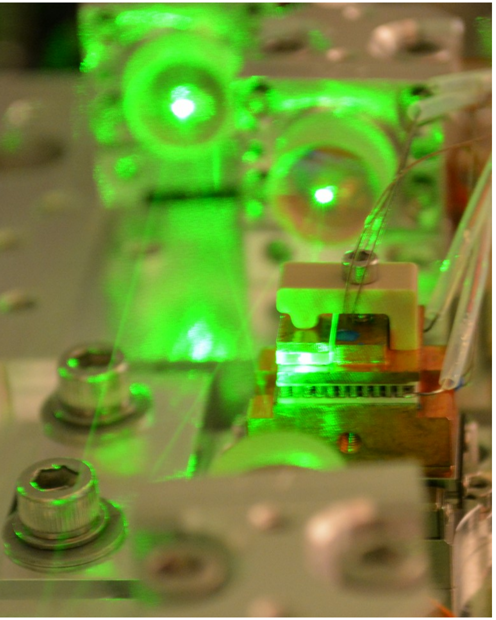
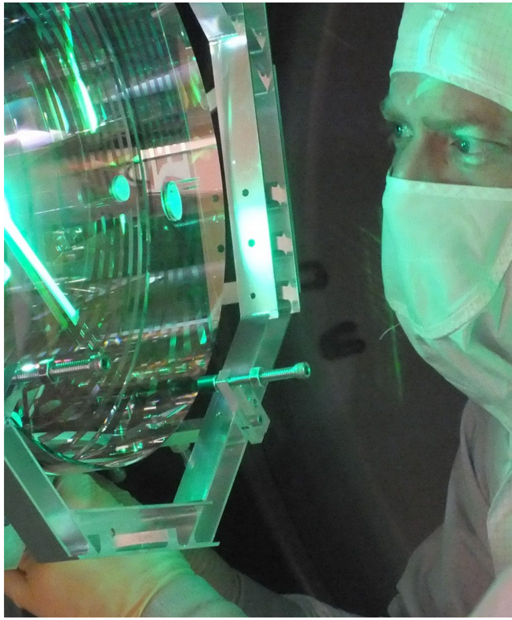
Wielding the Quantum Correlations in advanced LIGO



LIGO's optical
Parametric amplifier

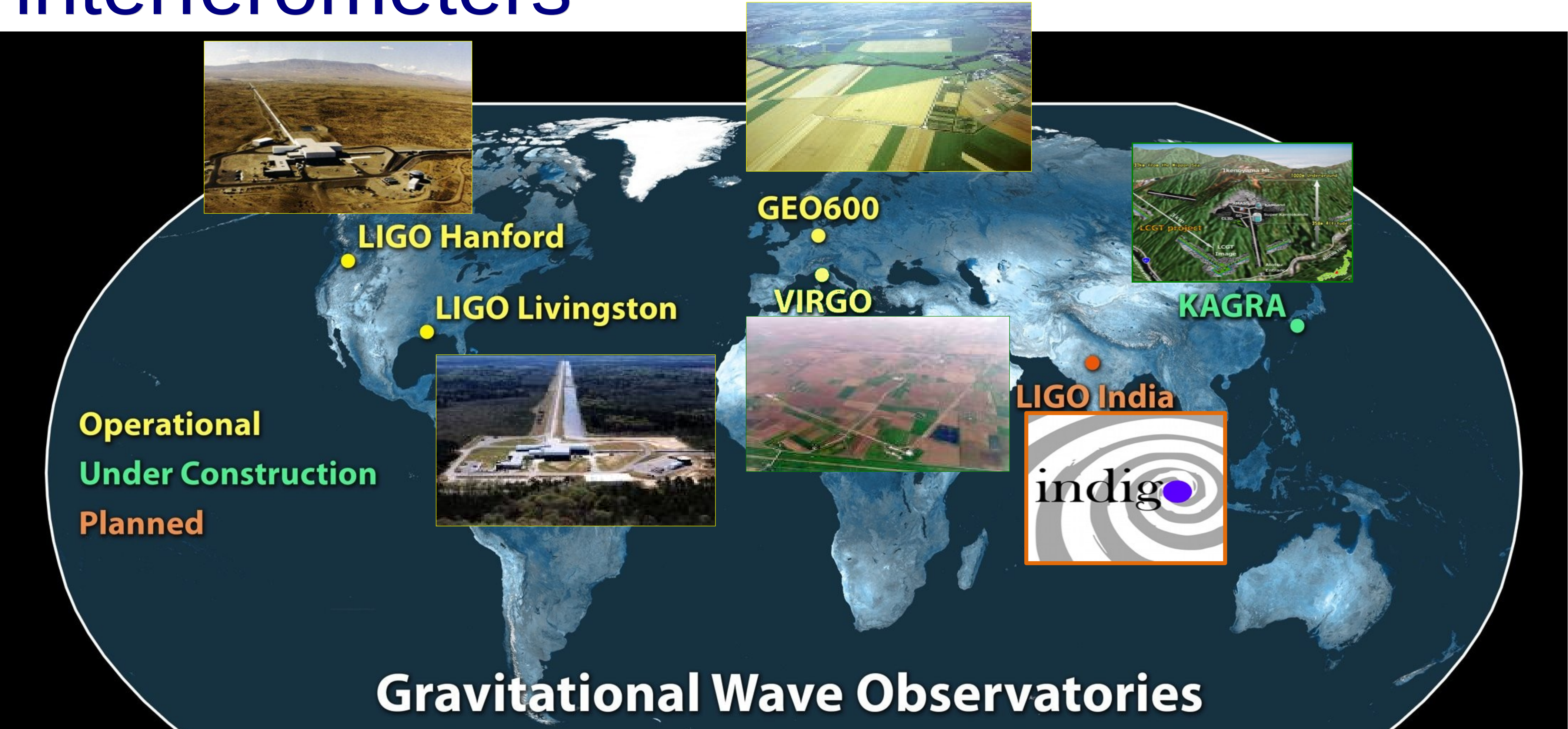
Lee McCuller, MIT
for the SQZ team
(LIGO Laboratory, in collaboration with ANU)

Optomechanics for DM
9 Apr. 2021

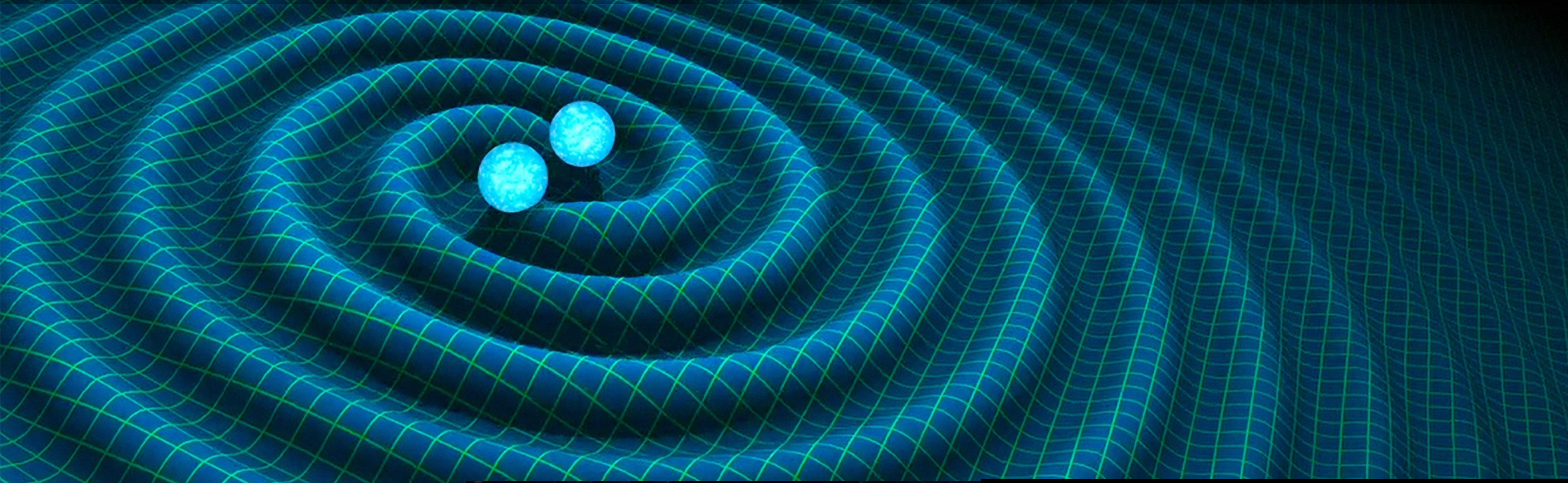


How strongly can we
probe the LIGO mirrors?

Observatory Network of km-scale interferometers



Gravitational Waves from the Cosmic Collider



Binary black holes

Image: NASA's Goddard Space Flight Center.

Gravitational transients in space-time

Image: MIT, CC BY-NC-ND 3.0

Neutron Star "atom smashing"

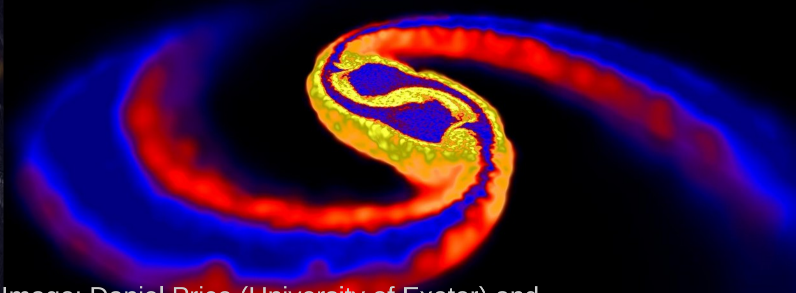
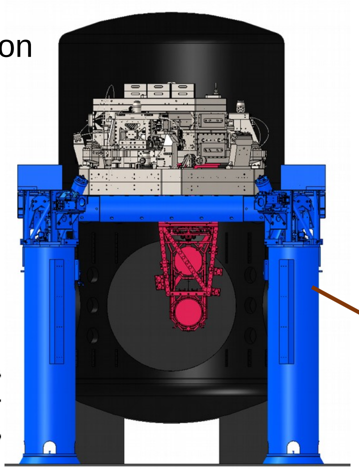


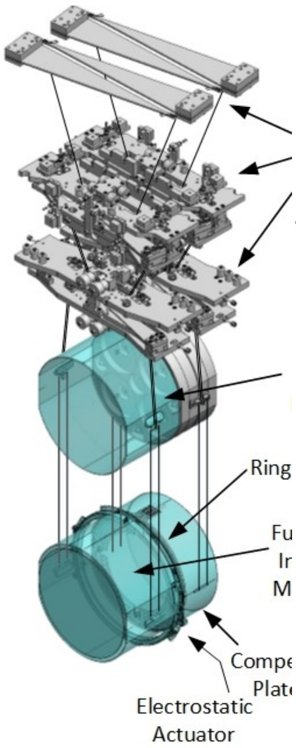
Image: Daniel Price (University of Exeter) and
Stephan Rosswog (International University Bremen), Science 2006

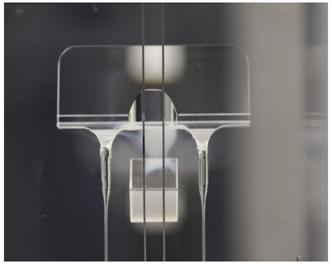
advanced LIGO's noise sources

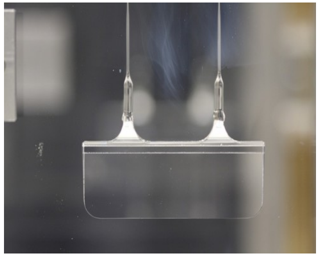
Active inertial isolation



Passive quadruple Suspension

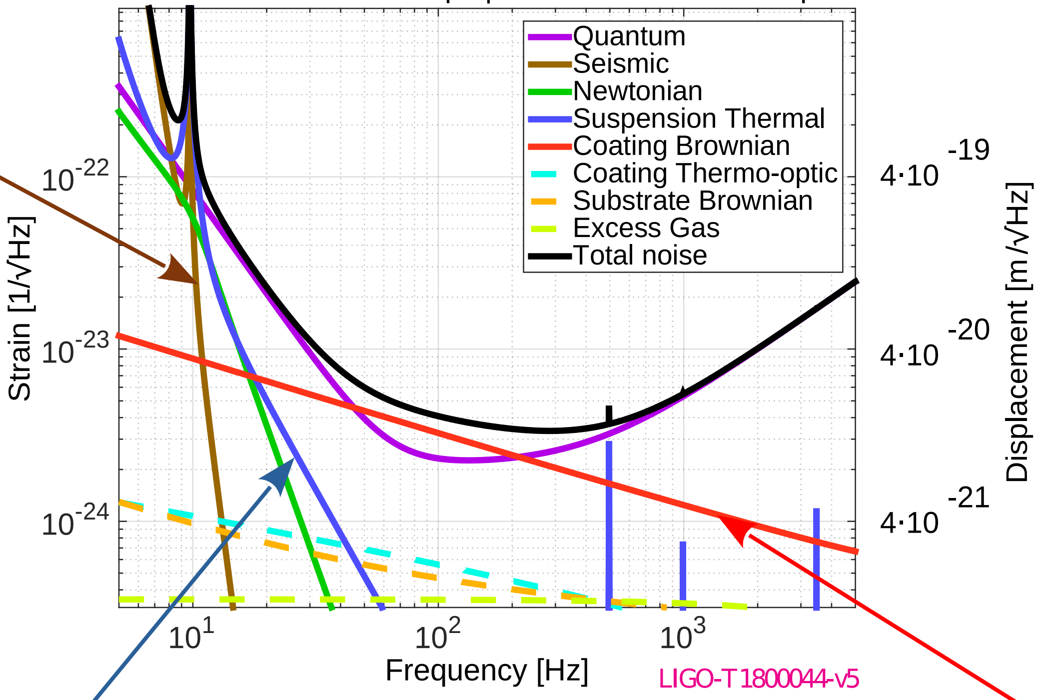






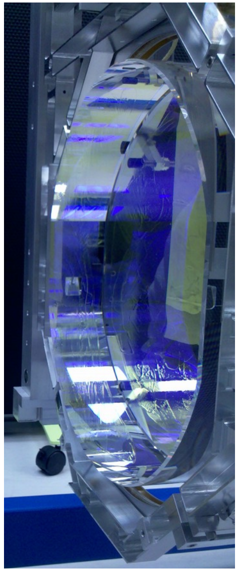
aLIGO Design Curve

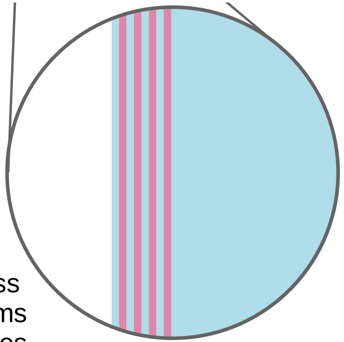
1.4:1.4M. NSNS-173 Mpc | 30:30M. BHBH-1600Mpc



Fused Silica Suspension
Q~1 billion, 2 week ringdown

0.2nm smooth core optics,
~40ppm loss on 6cm beam

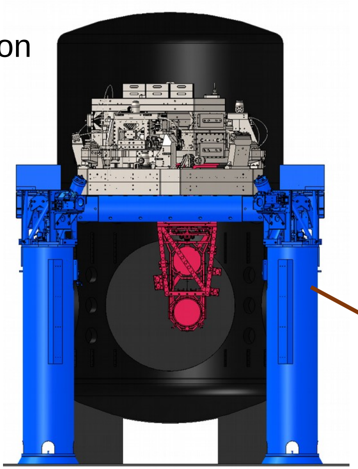




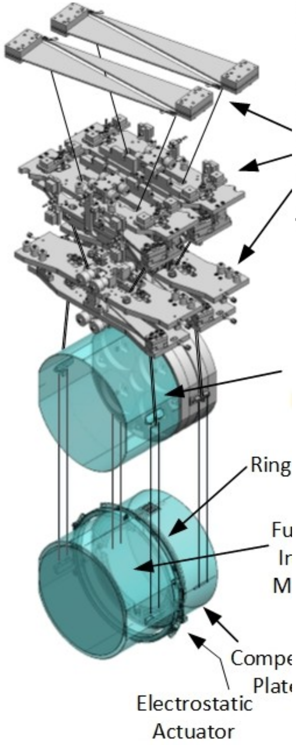
Coating materials minimize structural loss
from frustrated two-level systems
fluctuating into thermal noises

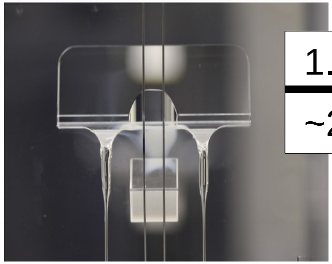
advanced LIGO's noise sources

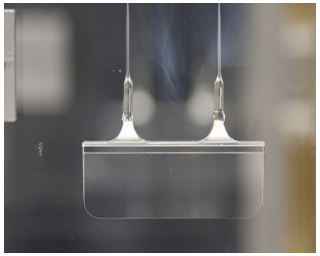
Active inertial isolation

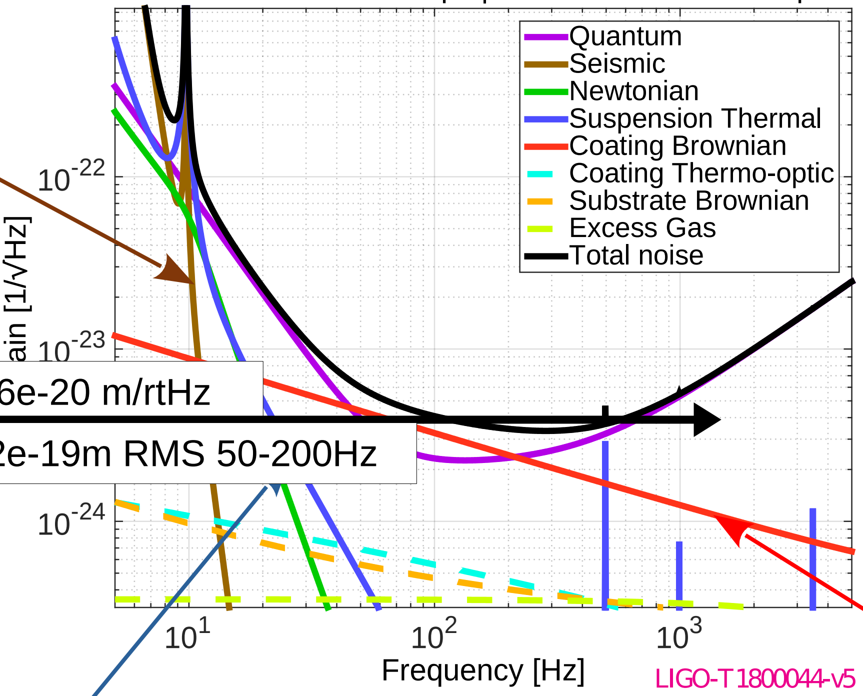


Passive quadruple Suspension









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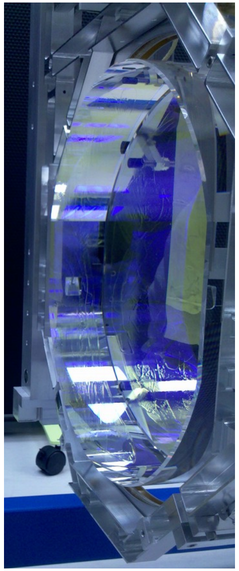

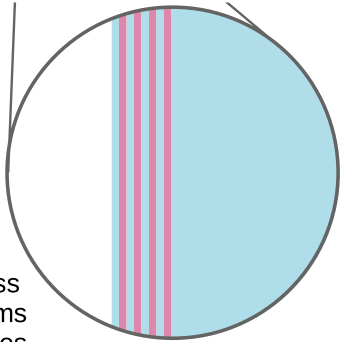

Coating materials minimize structural loss
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fluctuating into thermal noises

Continuous Precision Measurements

This argument by *Braginsky*

Measurement 1 $\hat{x}(t)$

Measurement 2 $\hat{x}(t+\Delta t)$

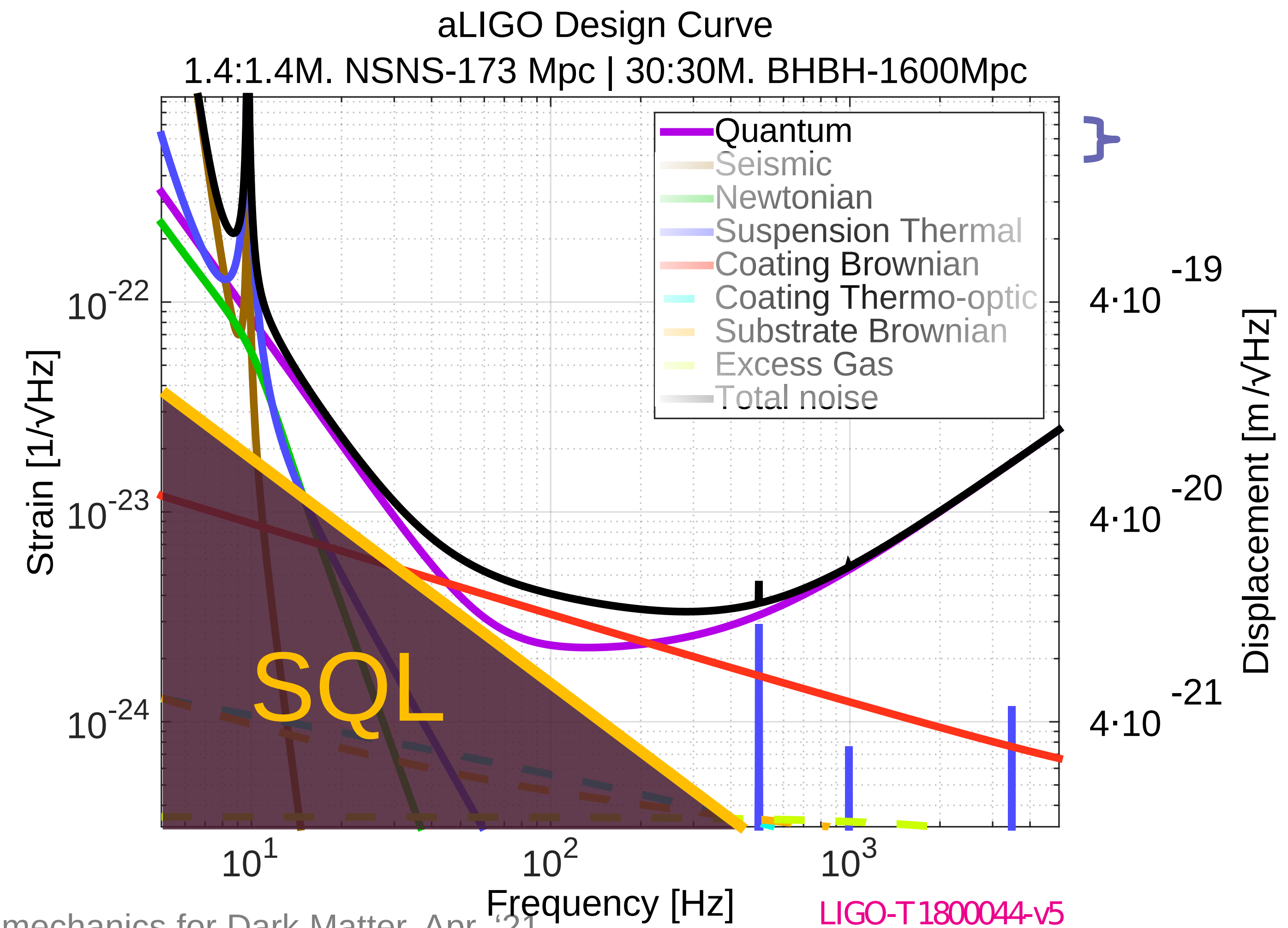
Measurement 2b $\dot{x}(t) \propto \hat{p}$

$$\Delta\hat{x}\Delta\hat{p} \geq \frac{\hbar}{2} \quad \Rightarrow \quad \Delta x_{\mathrm{sys}} = \underbrace{\frac{\hbar}{2\Delta x_{\mathrm{probe}}}}_{\Delta p} \frac{\Delta t}{M}$$

Add system and probe uncertainty, convert to frequency domain

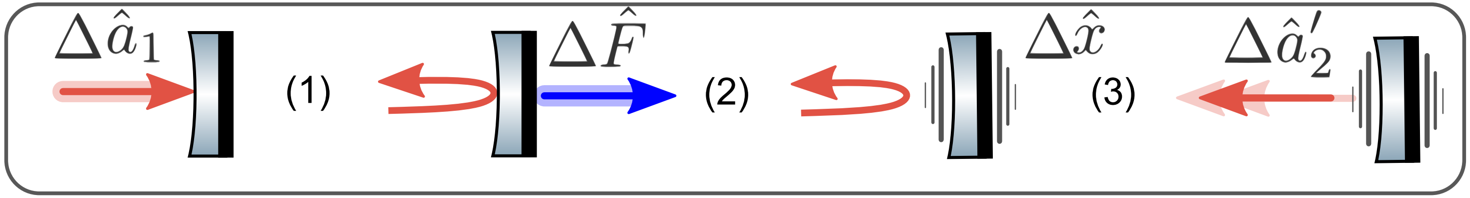
$$\Delta x^2_{\mathrm{meas}}(\Omega) \geq \Delta x^2_{\mathrm{probe}}(\Omega) + \Delta x^2_{\mathrm{sys}}(\Omega) \geq \frac{2\hbar}{M\Omega^2}$$

The Standard Quantum Limit on 10kg



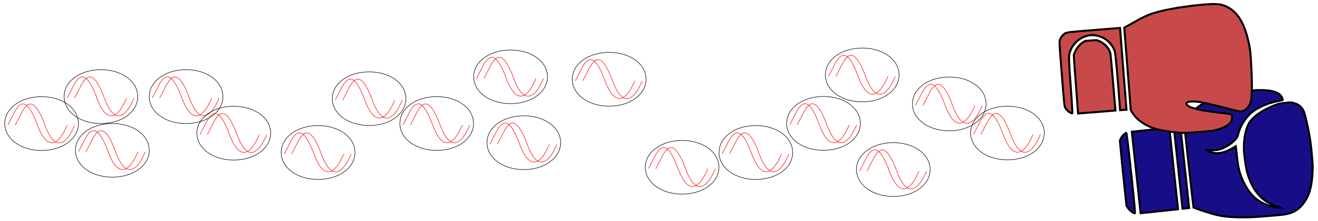
Cartoon: Particle Picture

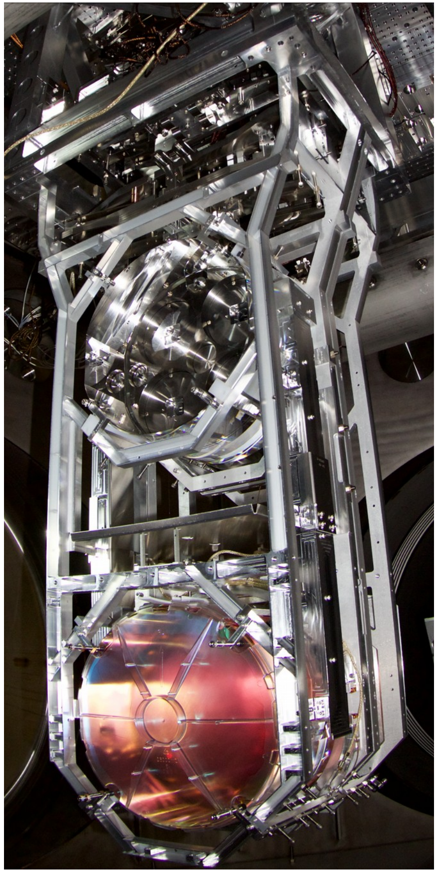
Amplitude → Force → Displacement → Phase:



LIGO Mirrors are suspended 40kg glass cylinders

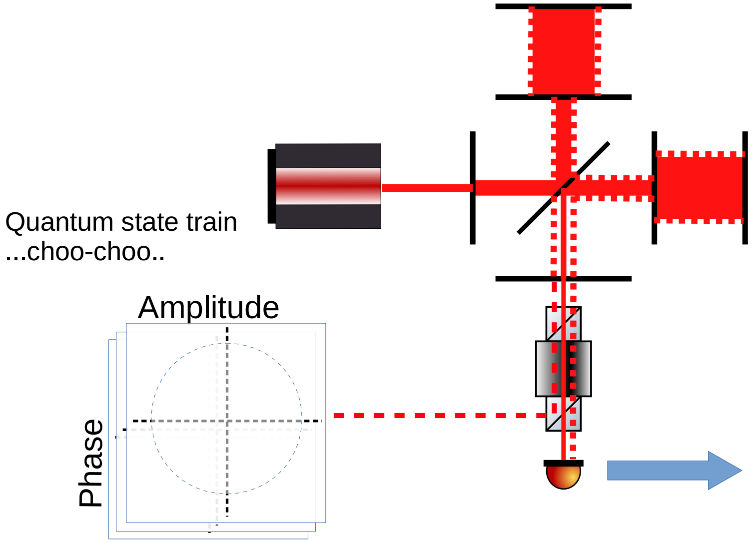
photon shot noise causes
***momentum transfer* → femto-N punches**

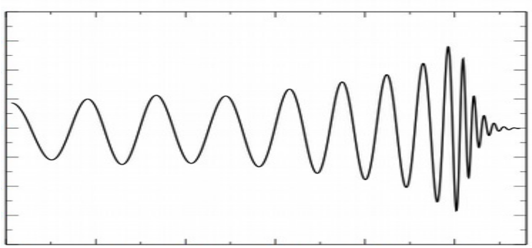


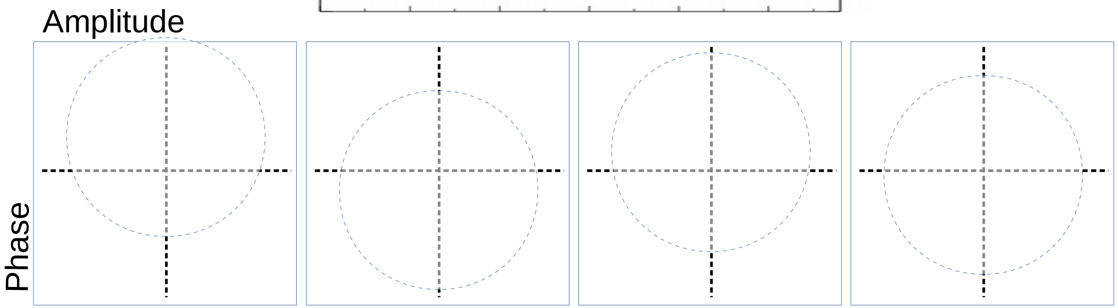


The Measurement Process

- Caves' "Quantum-mechanical Noise in an interferometer," PRD 1981 makes the leap that **the *quantum state* responsible *for noise* is from the *unused port***
- A more modern interpretation is that the interferometer simply applies a displacement operation to its signal state
  - The "default" signal state is vacuum







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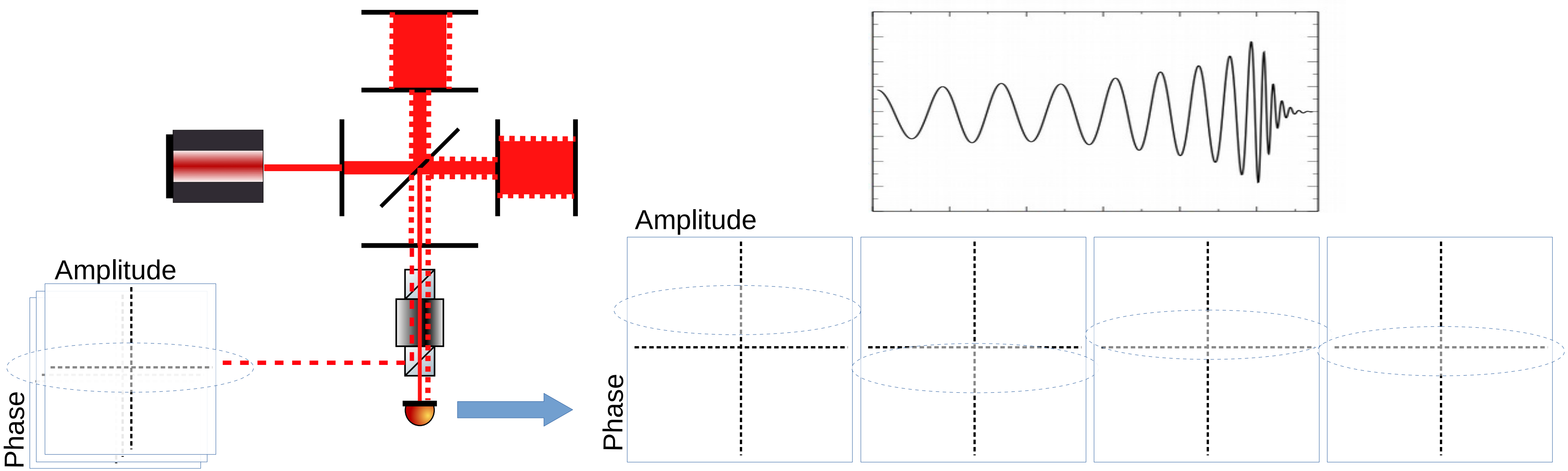
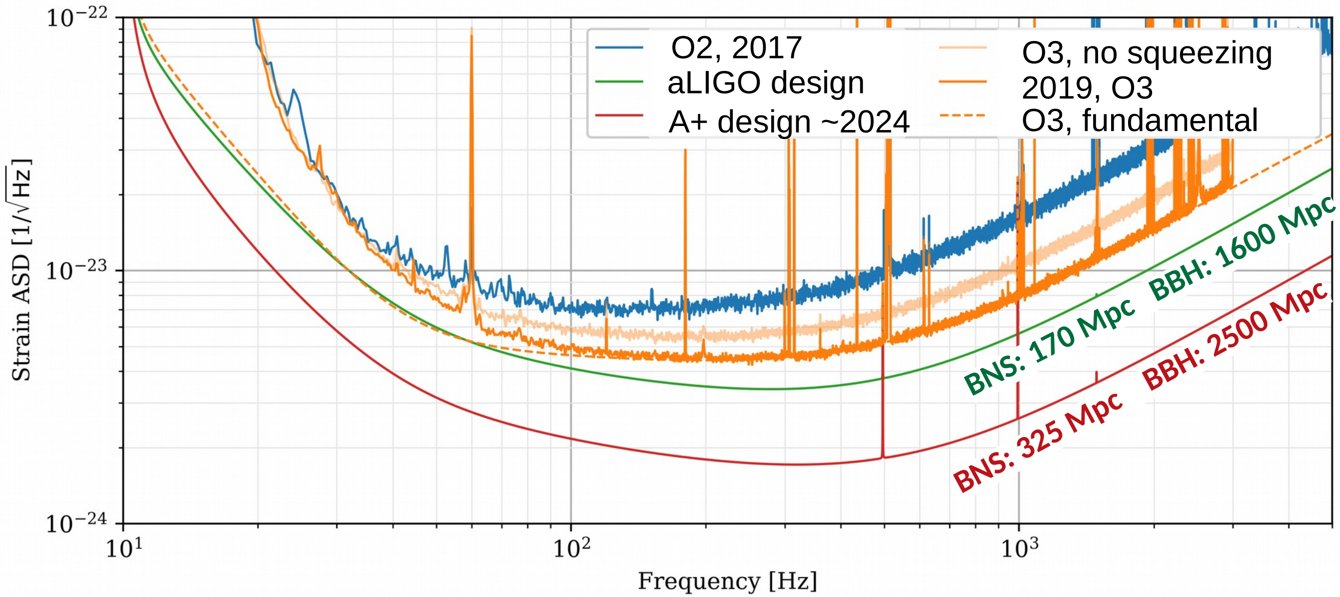


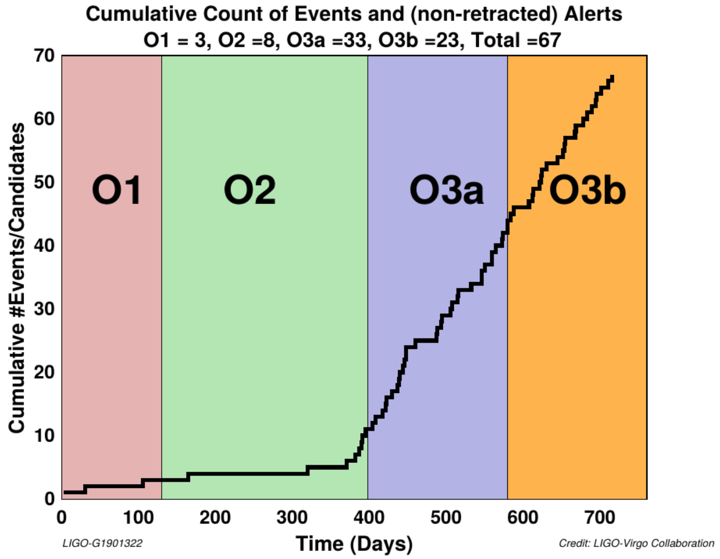
Squeezing in Observing Run 3

- O3 saw *many improvements:*
  Power level, scatter, duty cycle, *grounding*, laser noises, angular and auxiliary control, glitch and data analysis
- The detectors have become *impressively* quantum limited: 120Mpc
- Enter Squeezing, 3db @ ~30% losses 120→ 140MPc

  → 50% rate increase on top of everything else

Buikema, A. et al.
Sensitivity and performance of the Advanced LIGO detectors in the third observing run.
Phys. Rev. D 102, 062003 (2020).

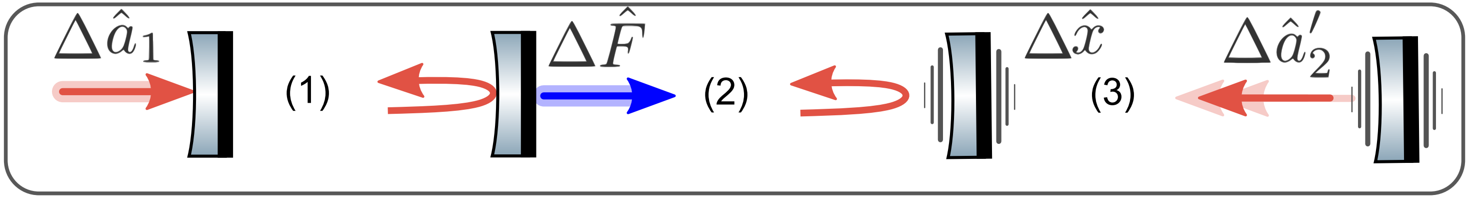




 Reference Curves LIGO T1800042-v5 Rates: LIGO-VIRGO Collab. G1901322

Cartoon: “Wave” Picture

Amplitude → Force → Displacement → Phase:

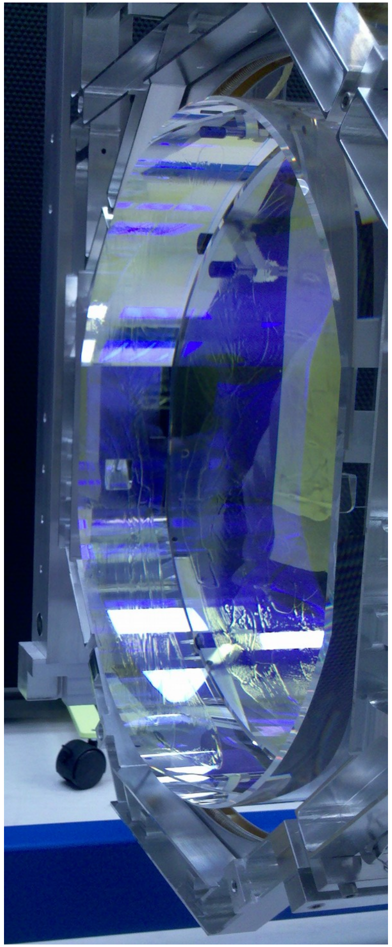


Mechanics cause a shear action on the optical phase-space

Due to radiation pressure & mechanical susceptibility

$$\begin{bmatrix} \Delta\hat{a}_1' \\ \Delta\hat{a}_2' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\mathcal{K}(F) & 1 \end{bmatrix} \begin{bmatrix} \Delta\hat{a}_1 \\ \Delta\hat{a}_2 \end{bmatrix}$$

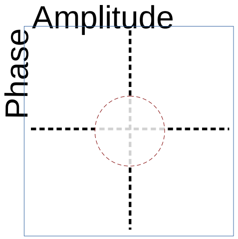
Shear = rotation * squeezing * rotation



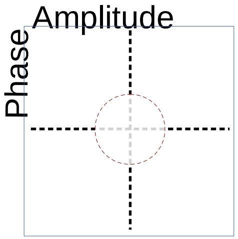
H. J. Kimble, Yuri Levin, Andrey B. Matsko, Kip S. Thorne, and Sergey P. Vyatchanin
Phys. Rev. D 65, 022002

Standard Quantum Limit, optics picture

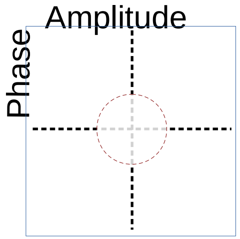
$F \ll 60\text{Hz}^*$



$F = 60\text{Hz}^*$

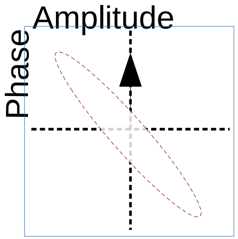


$F \gg 60\text{Hz}^*$

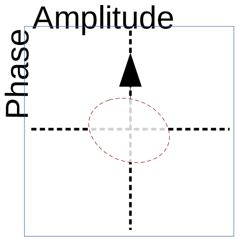


Amplitude → Force → Displacement → Phase:
Phase-space Shear

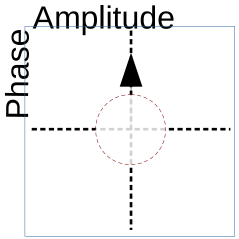
$$\begin{bmatrix}\Delta\hat{a}_1' \\ \Delta\hat{a}_2'\end{bmatrix} = \begin{bmatrix}1 & 0 \\ -\mathcal{K}(F) & 1\end{bmatrix}\begin{bmatrix}\Delta\hat{a}_1 \\ \Delta\hat{a}_2\end{bmatrix}$$



$\mathcal{K} \gg 1$



$\mathcal{K} \approx 1$

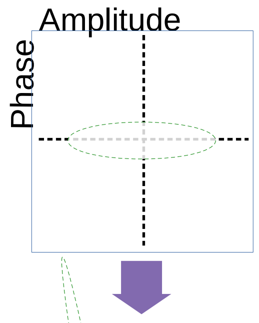


$\mathcal{K} \ll 1$

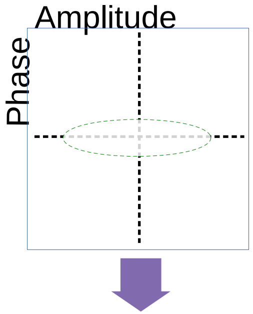
* ~60Hz is approximate crossover only in aLIGO full power design

Squeezing Probes Harder

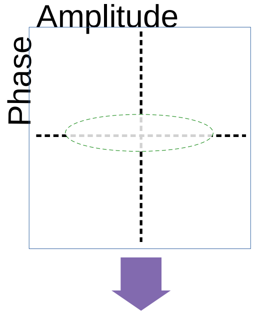
$F \ll 60\text{Hz}^*$



$F = 60\text{Hz}^*$

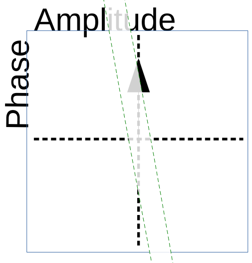


$F \gg 60\text{Hz}^*$

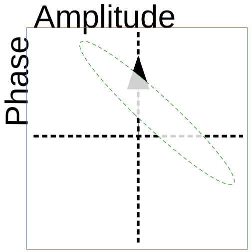


Amplitude → Force → Displacement → Phase:
Phase-space Shear

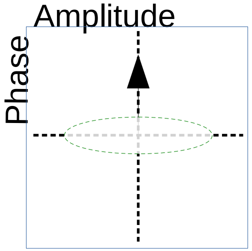
$$\begin{bmatrix}\Delta\hat{a}_1' \\ \Delta\hat{a}_2'\end{bmatrix} = \begin{bmatrix}1 & 0 \\ -\mathcal{K}(F) & 1\end{bmatrix}\begin{bmatrix}\Delta\hat{a}_1 \\ \Delta\hat{a}_2\end{bmatrix}$$



$\mathcal{K} \gg 1$



$\mathcal{K} \approx 1$

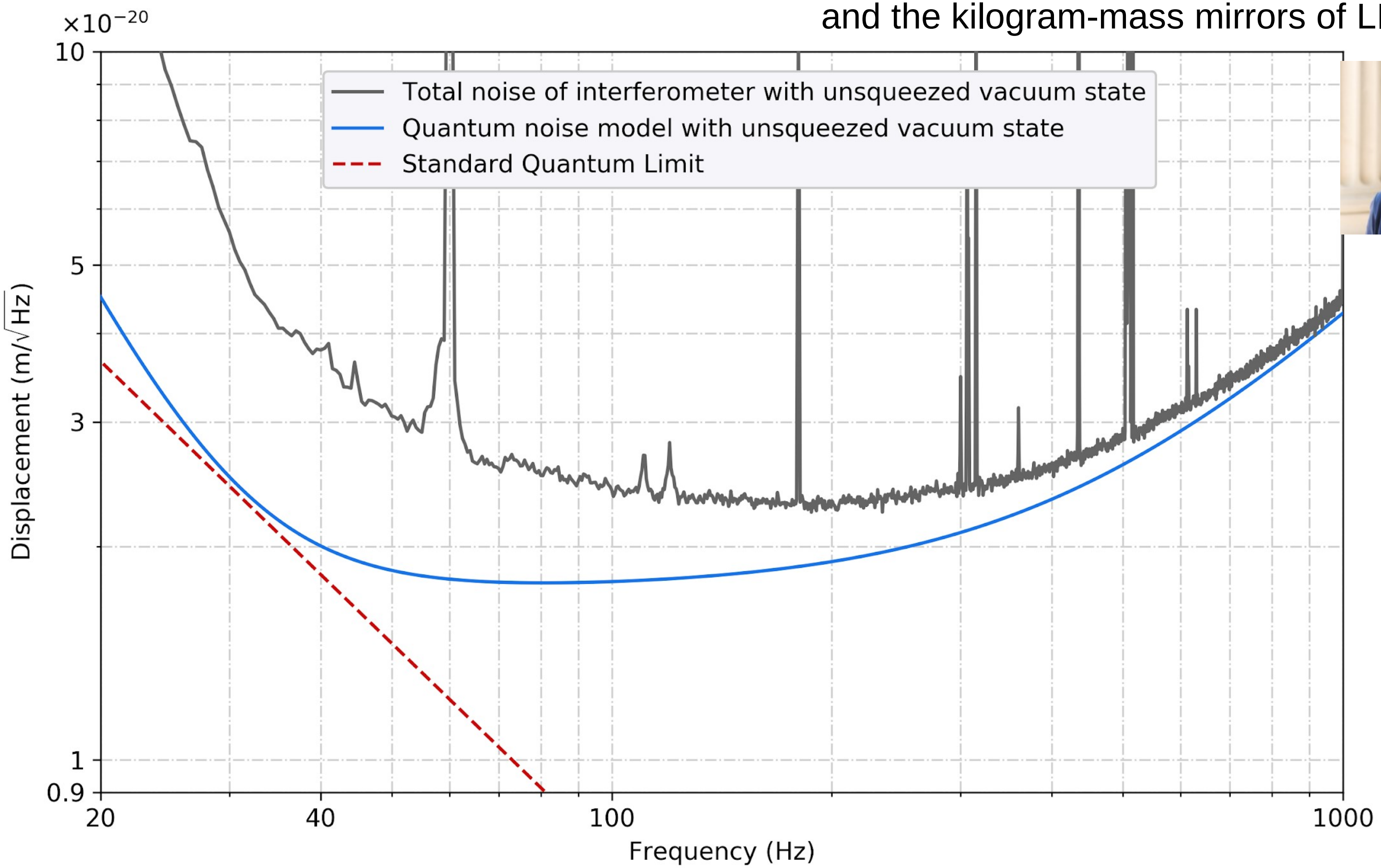


$\mathcal{K} \ll 1$

* ~60Hz is approximate crossover only in aLIGO full power design

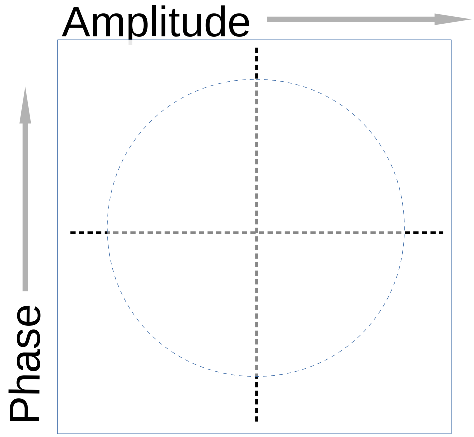
Testing the SQL

Haocun Yu. **McCuller, L.** et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).



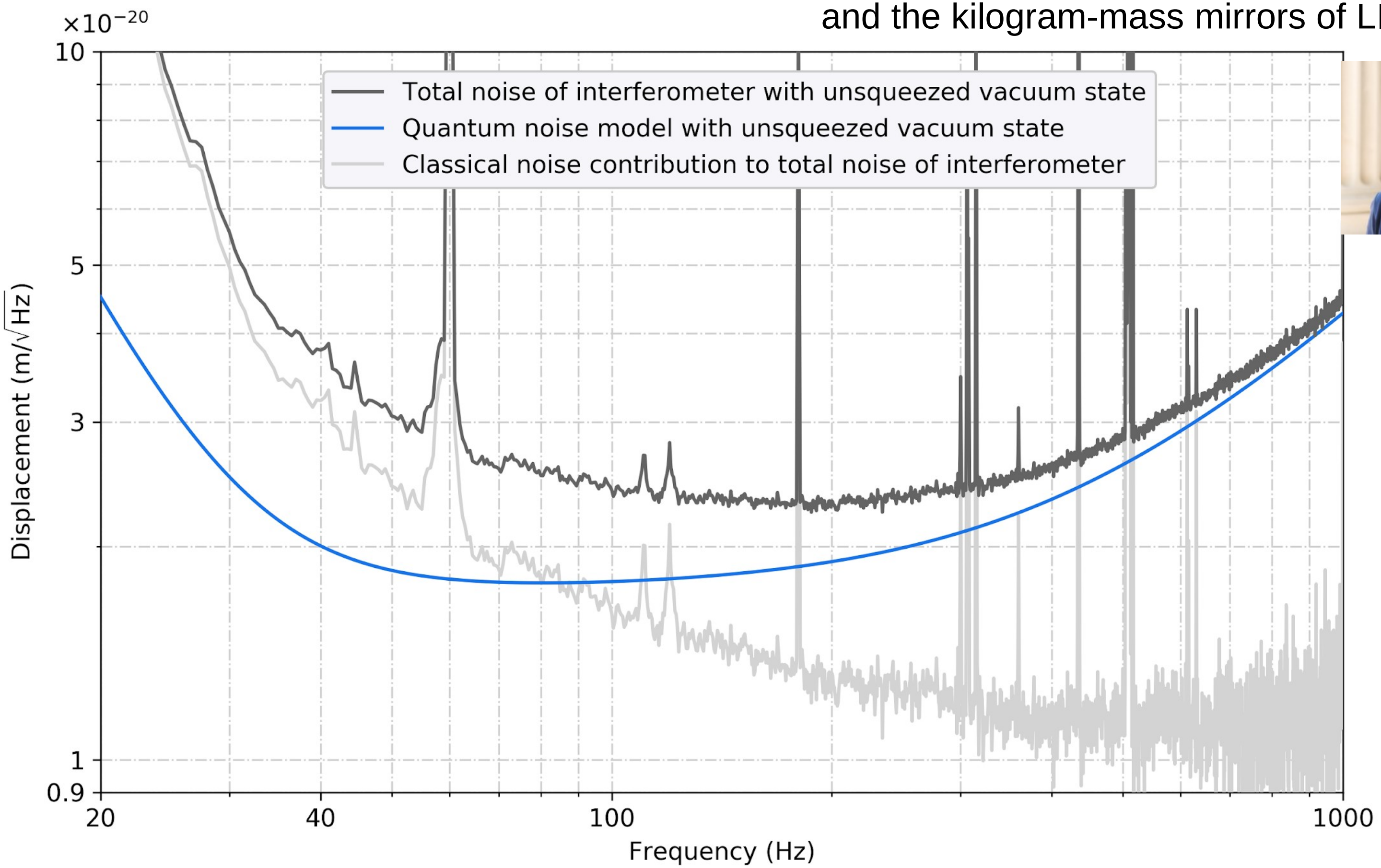
Left: measurements performed by Haocun Yu

No injected squeezing



Determine Instrument Noise

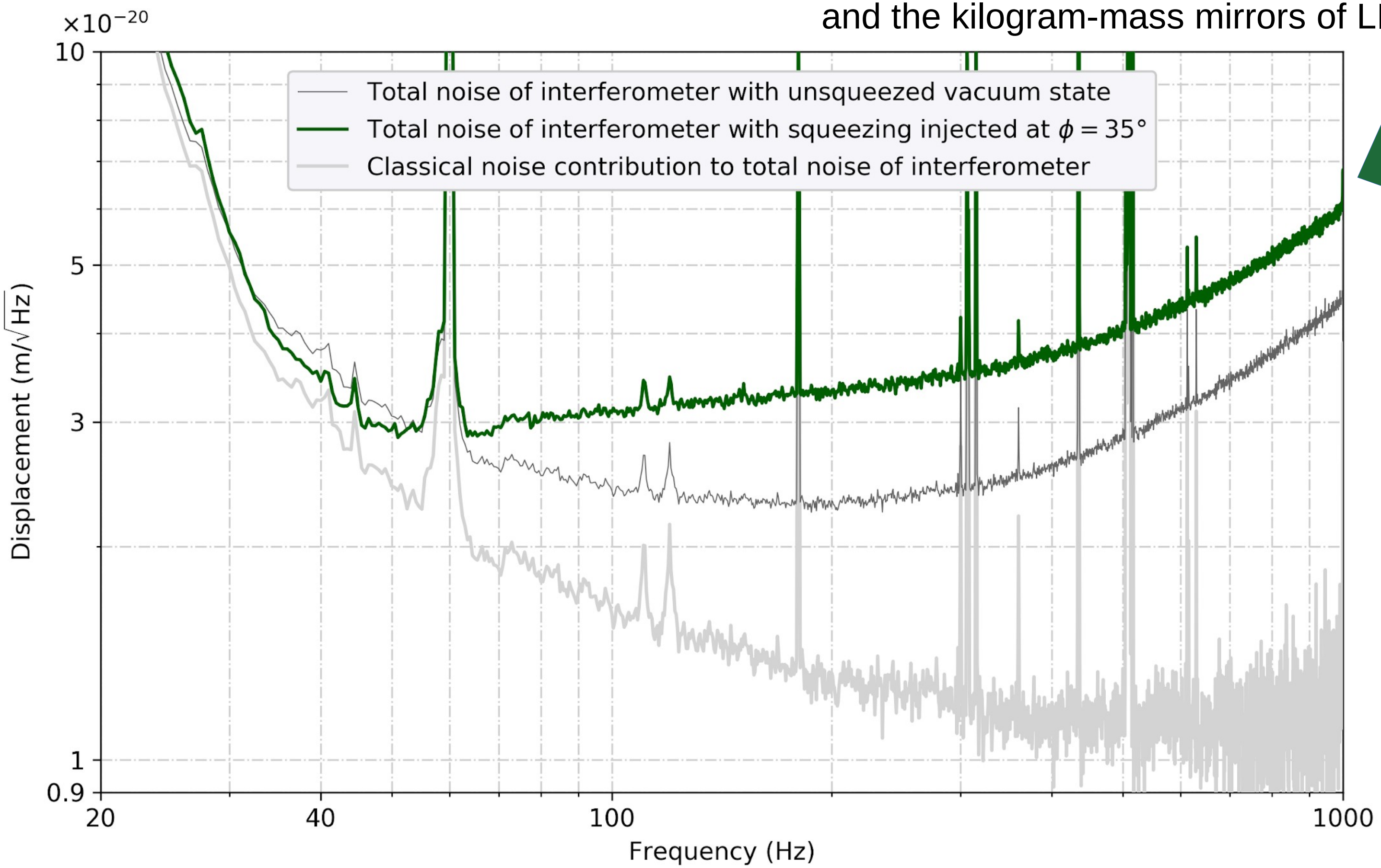
Haocun Yu. **McCuller, L.** et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).

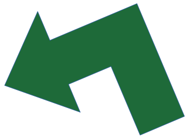


Left: measurements performed by Haocun Yu

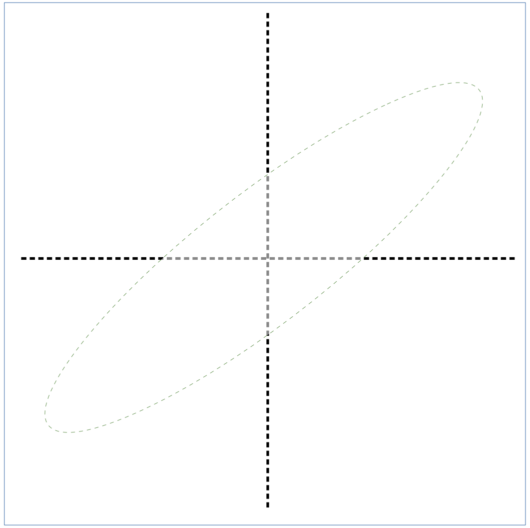
Inject Squeezing at an Angle

Haocun Yu. **McCuller, L.** et al. Quantum correlations between light and the kilogram-mass mirrors of LIGO. Nature 583, 43–47 (2020).

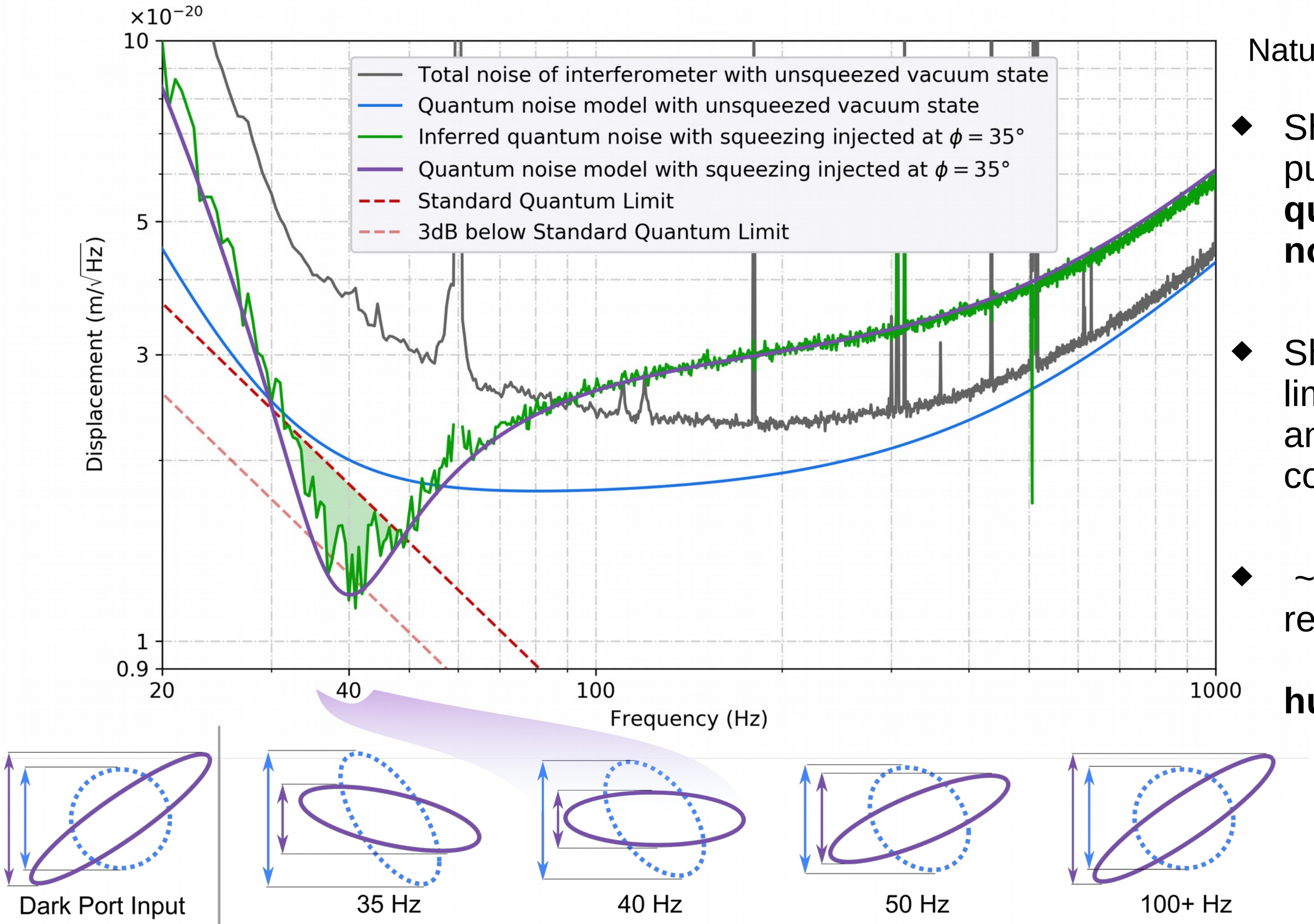




Squeezing
at 35deg injected



Sub-SQL Quantum Noise in 40kg



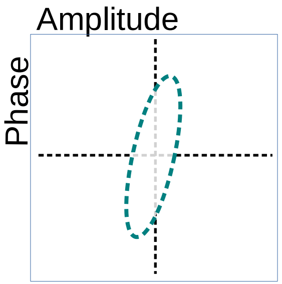
Nature 583, 43–47 (2020).

- Shows that the vacuum indeed pushes the mirrors: **quantum radiation pressure noise**
- Shows that the SQL is not a limit → mirror motion creates and maintains quantum correlations
- ~billion-times heavier than recent sub-SQL measurements,

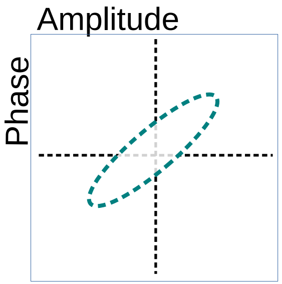
human scale! Room temp!

But I want more Squeezing *and* more Astrophysics

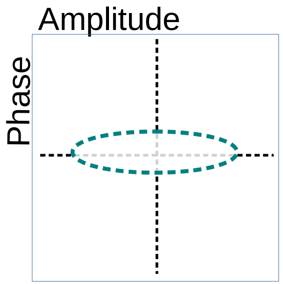
$F \ll 60\text{Hz}^*$



$F = 60\text{Hz}^*$

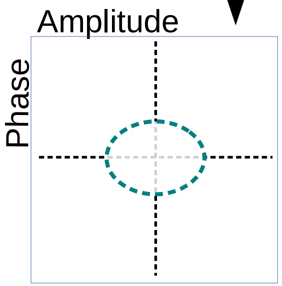


$F \gg 60\text{Hz}^*$

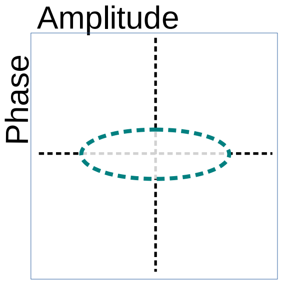


merely unsqueezes

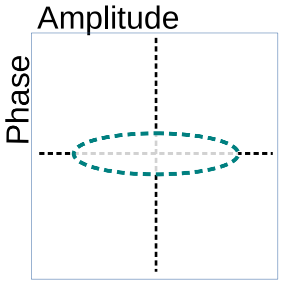
Frequency Dependent Squeezing



$\mathcal{K} \gg 1$



$\mathcal{K} \approx 1$



$\mathcal{K} \ll 1$

W. G. Unruh
Phys. Rev. D 19, 2888

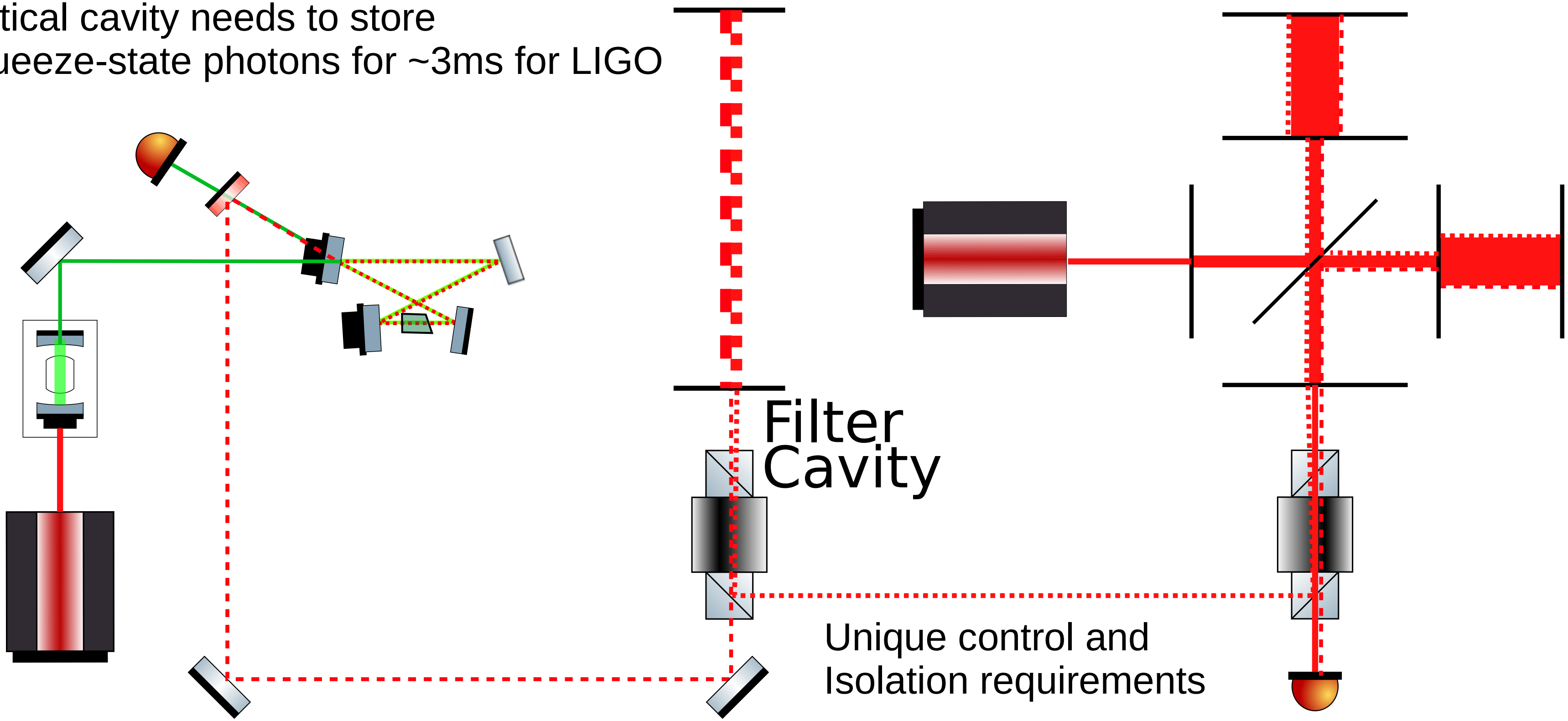
H. J. Kimble, Yuri Levin, Andrey B. Matsko, Kip S. Thorne, and Sergey P. Vyatchanin
Phys. Rev. D 65, 022002

Quantum Filter Cavity

McCuller, L. et al.
Frequency-Dependent Squeezing for Advanced LIGO.
Phys. Rev. Lett. 124, 171102 (2020).

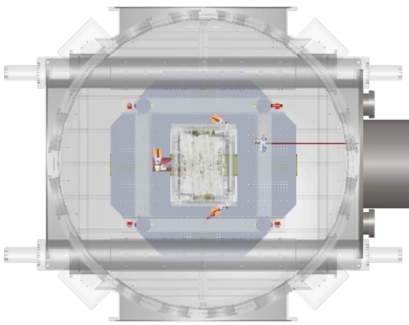
Zhao, Y. et al. Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors. Phys. Rev. Lett. 124, 171101 (2020).

Optical cavity needs to store squeeze-state photons for ~3ms for LIGO

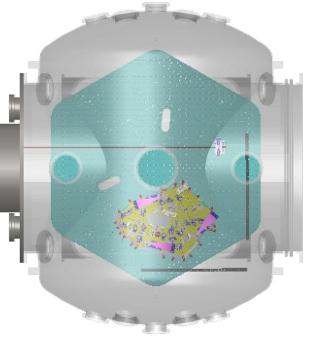


Unique control and Isolation requirements

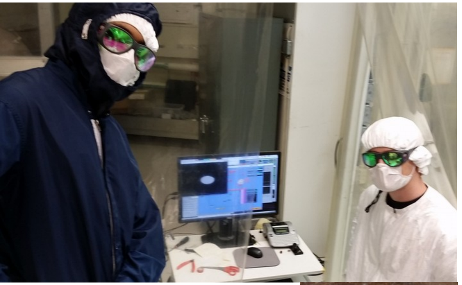
MIT 16m Filter Cavity



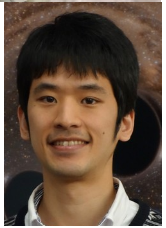
Finesse 80,000 → ~100Hz linewidth → photons travel ~1000km

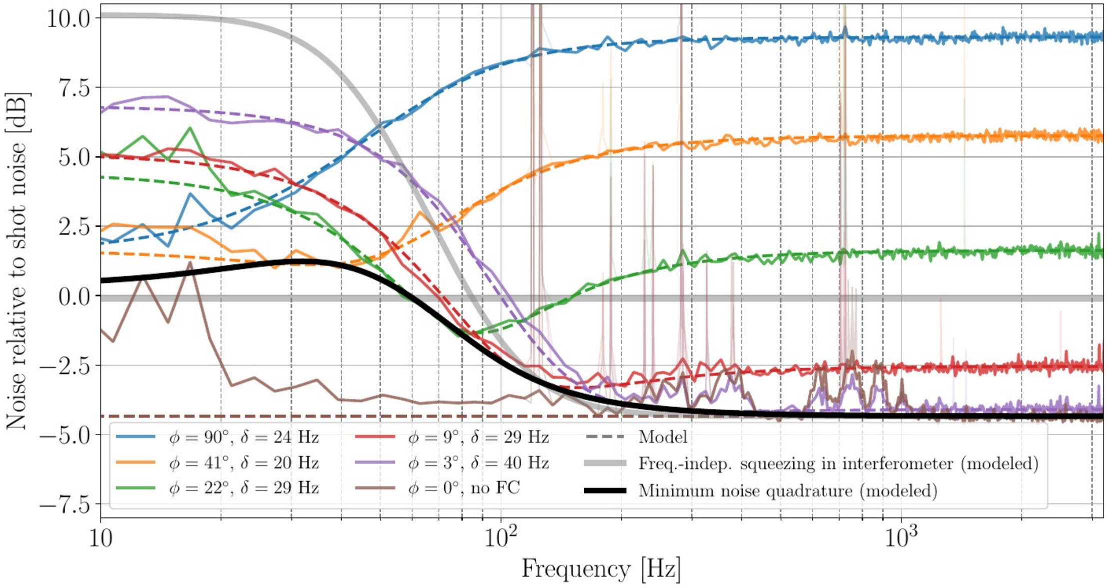


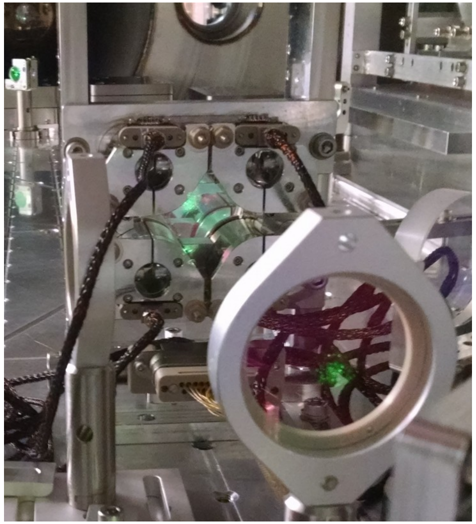
McCuller, L. et al. Frequency-Dependent Squeezing for Advanced LIGO. Phys. Rev. Lett. 124, 171102 (2020).



Chris Whittle,
Dhruva Ganapathy
and
Kentaro Komori

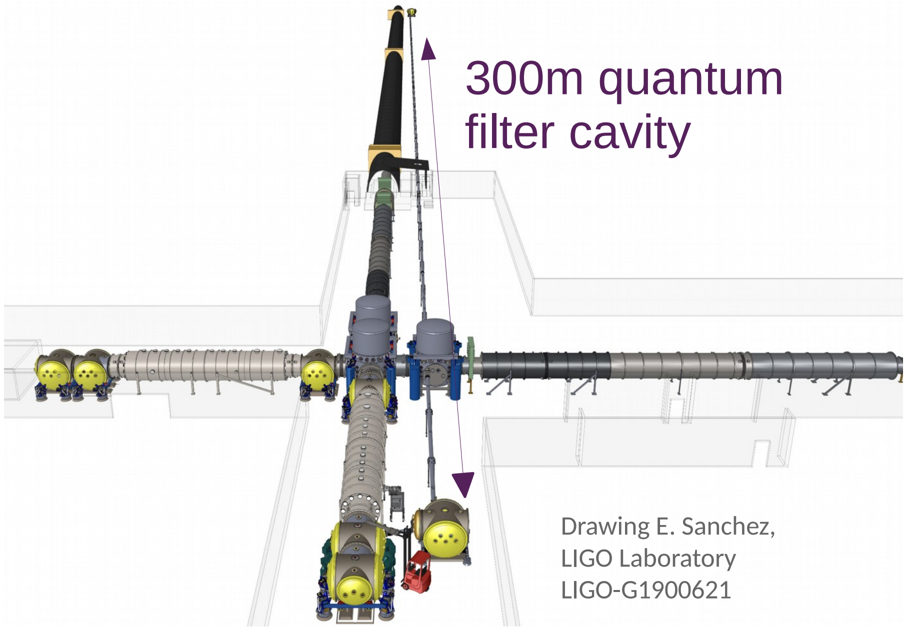




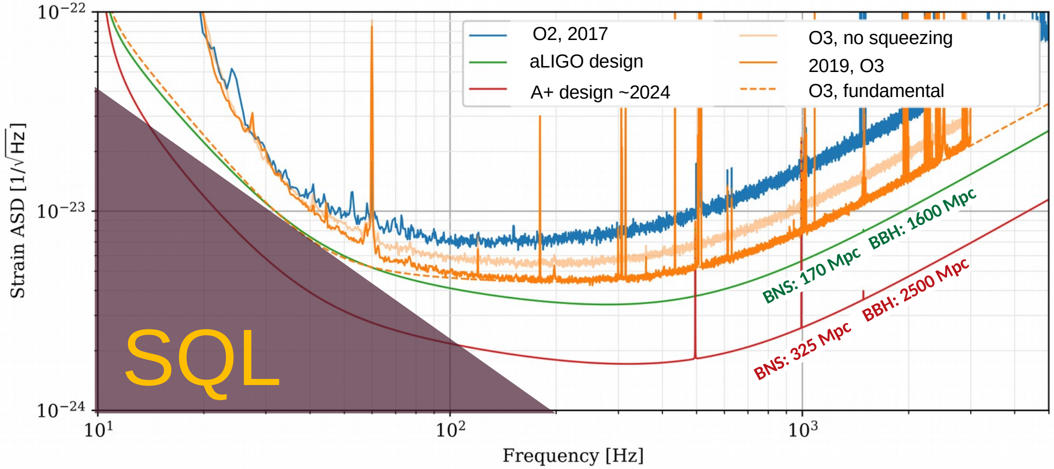


The A+ Upgrade

- 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



Drawing E. Sanchez, LIGO Laboratory LIGO-G1900621



Reference Curves LIGO T1800042-v5