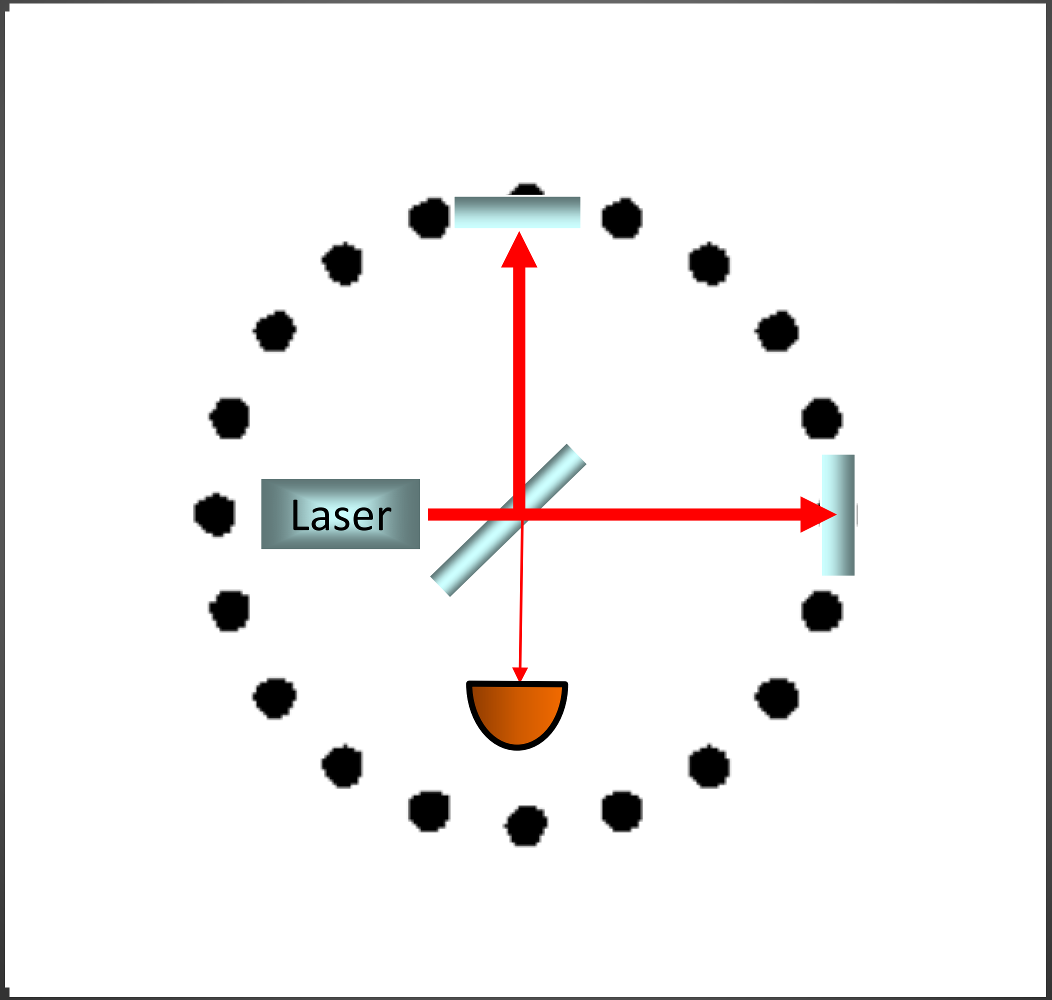
# Listening to the universe: detecting gravitational waves with laser interferometry

Sheila Dwyer for the
LIGO Scientific Collaboration

# Direct detection of gravitational waves



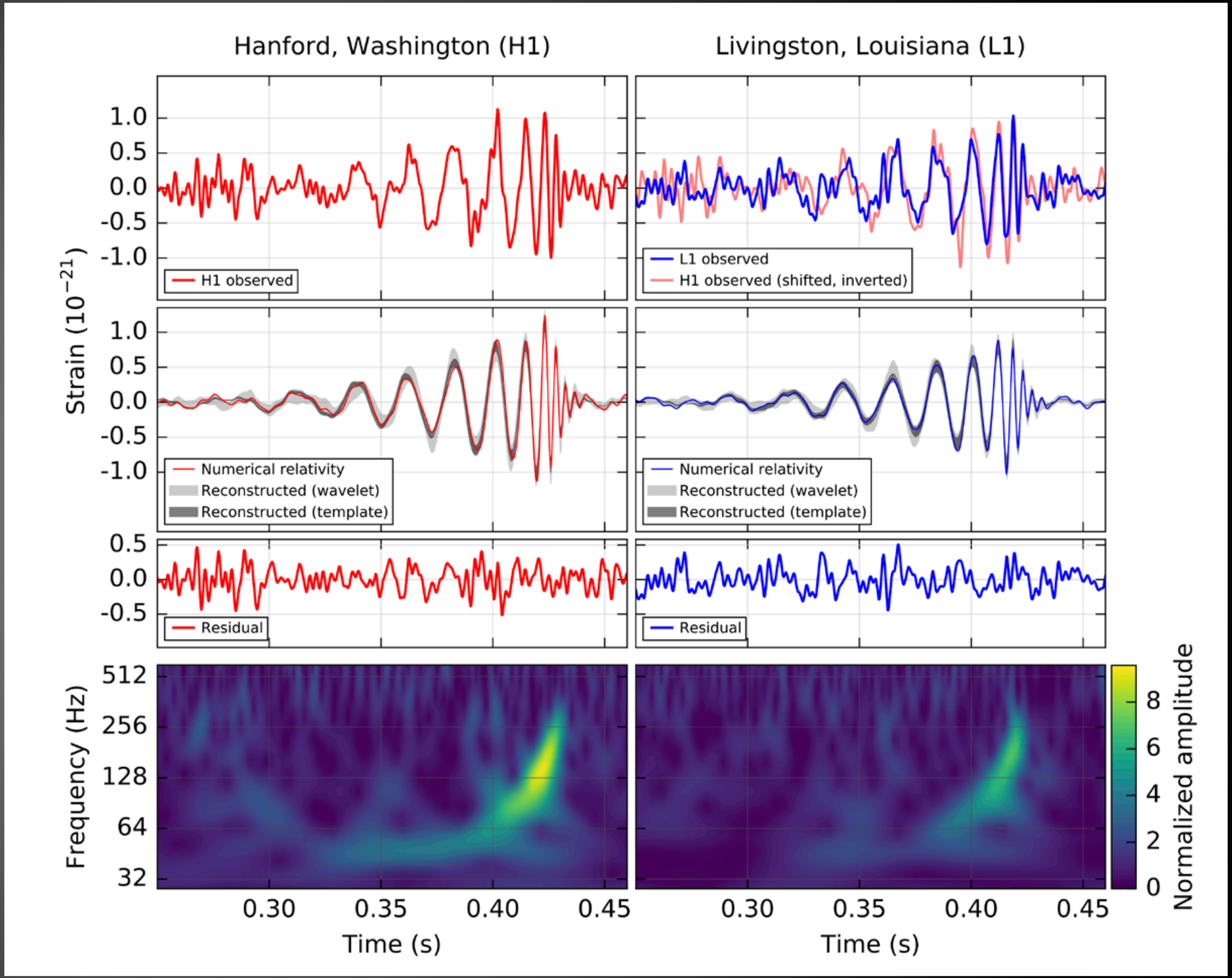

Wikimedia commons

*GW150914:*

$h = {}^{\Delta L}/_{L} = 10^{-21}$

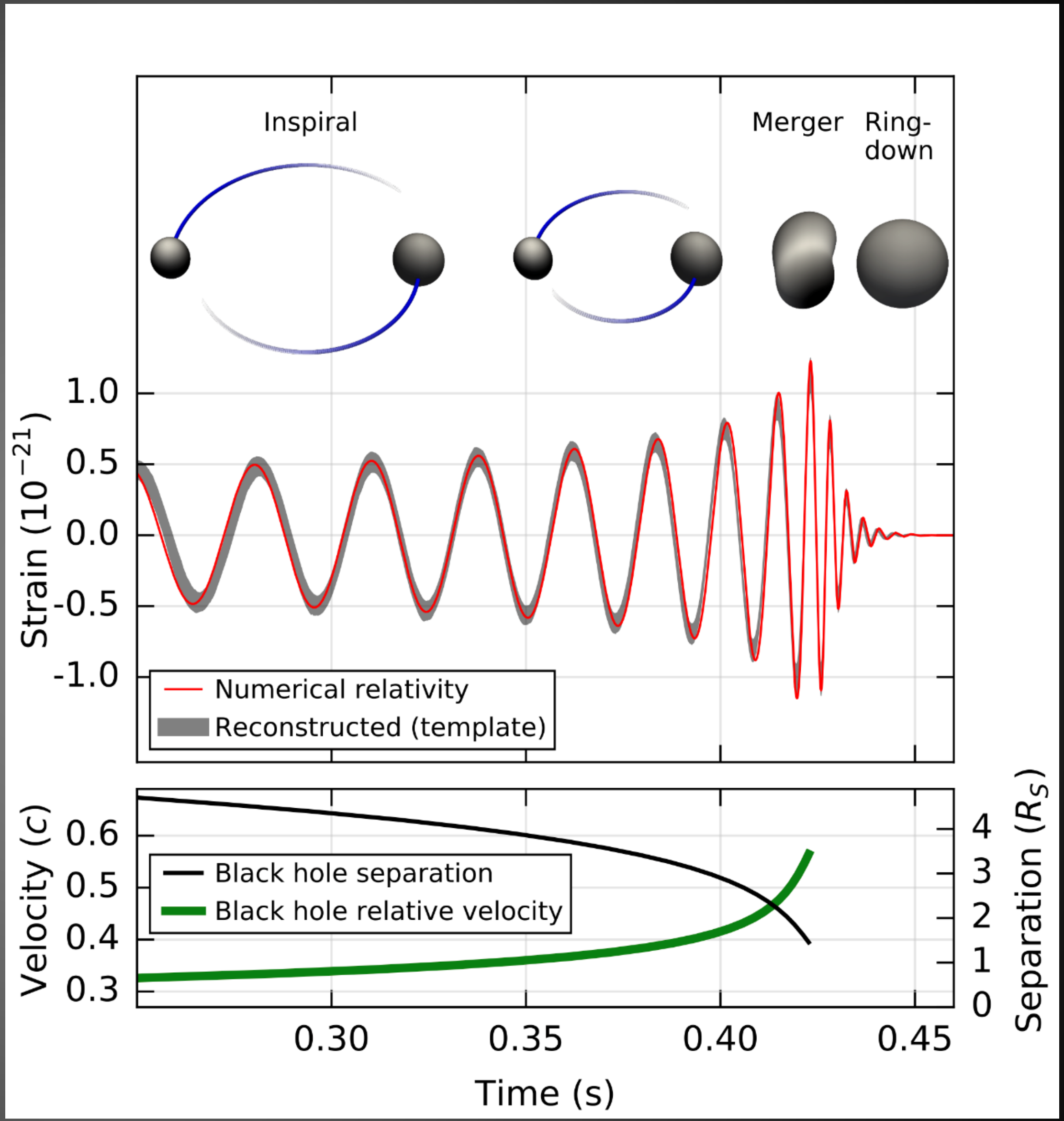
# We got one!

September 14$^{th}$ at 2:50 am



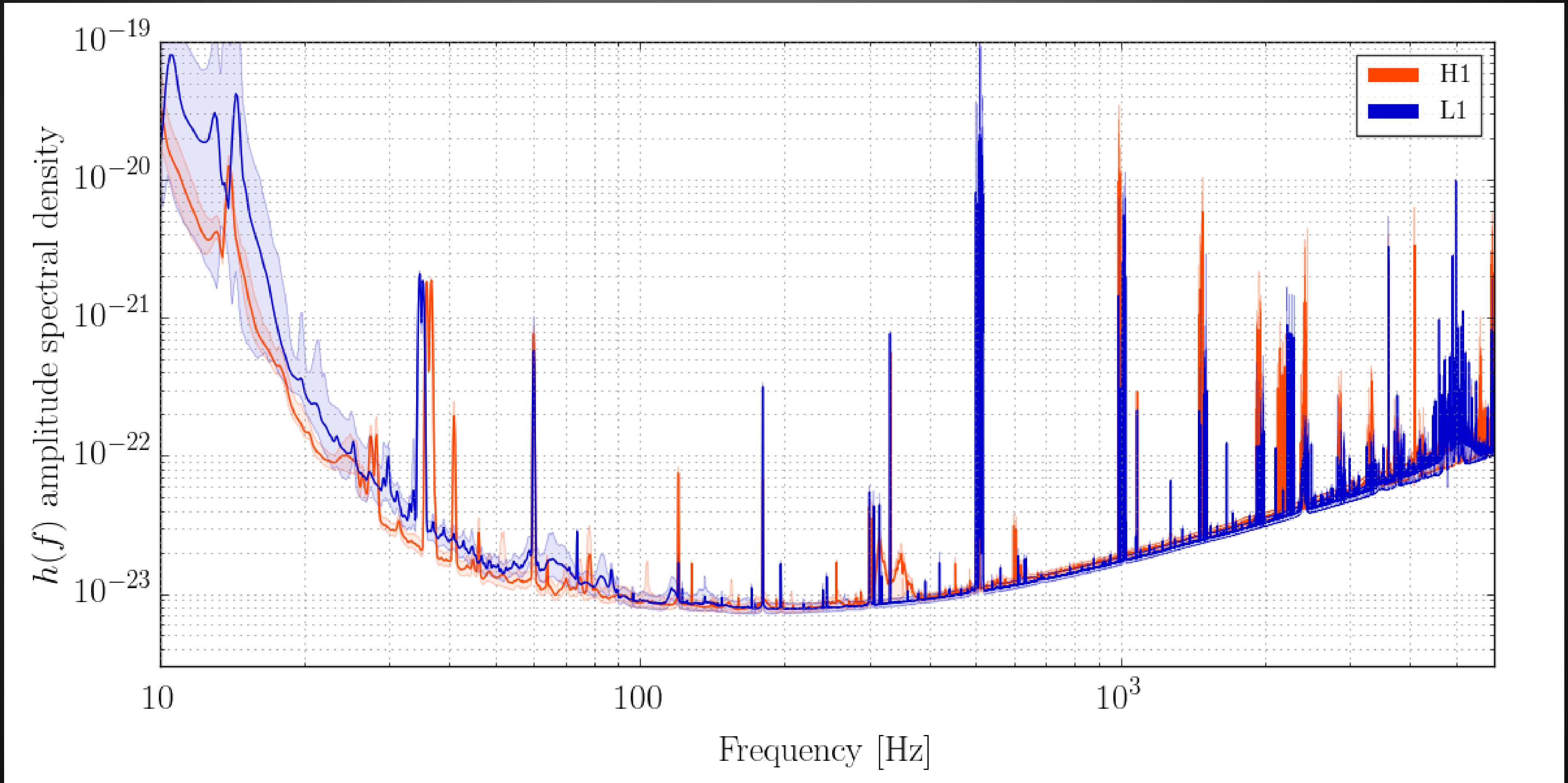

LIGO scientific collaboration, PRL **116** 061102
http://dx.doi.org/10.1103/PhysRevLett.116.061102

- First direct detection of gravitational waves
- First observation of binary black holes
- First observation of stellar black holes larger than 10 solar masses
- First observation of a merger of 2 black holes
- First test of general relativity in strong field, dynamic regime




PRL **116** 061102
http://dx.doi.org/10.1103/PhysRevLett.116.061102

# Strain sensitivity



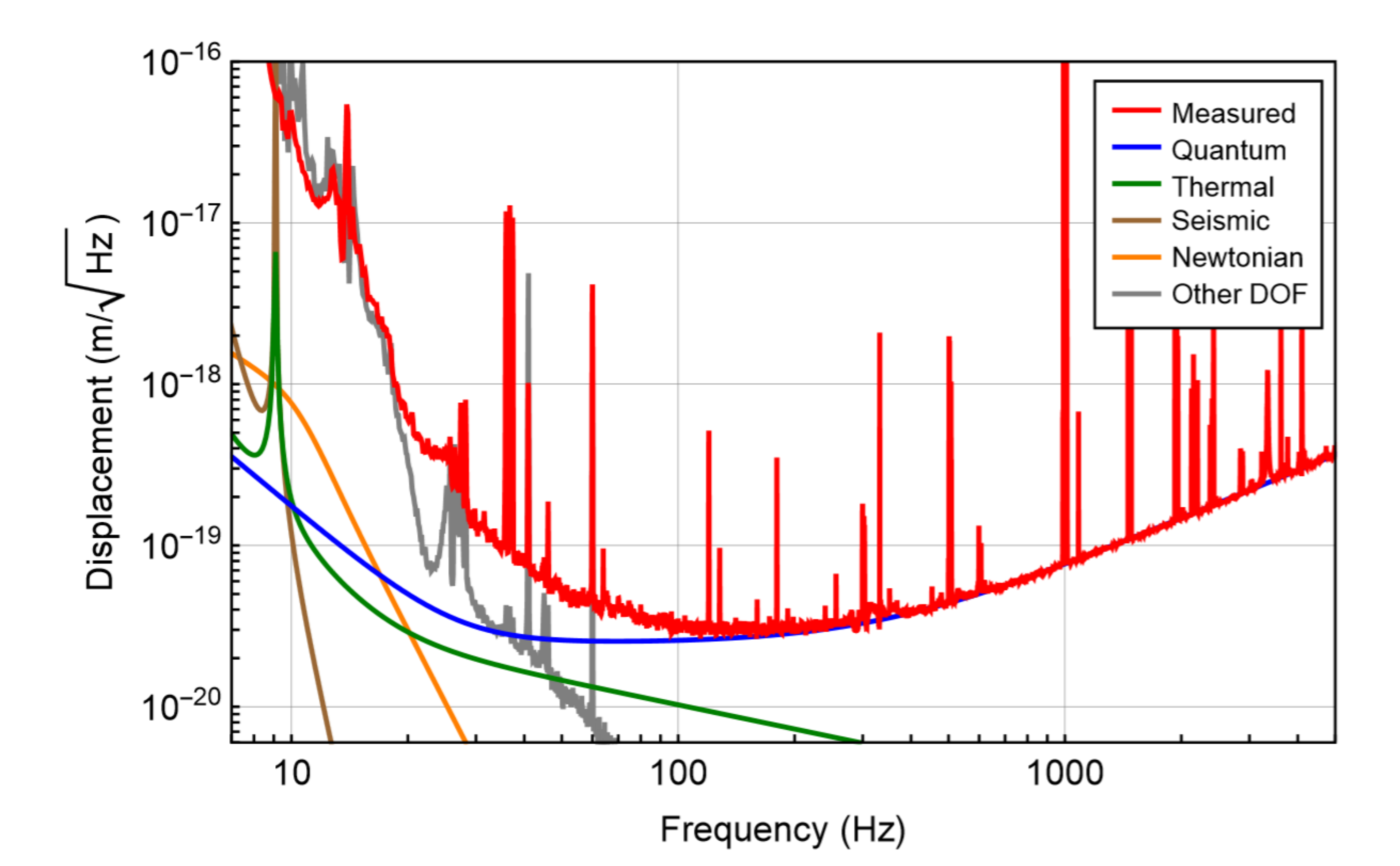
# How can we achieve this kind of strain sensitivity? First, separate the test masses as much as possible

4km arm length, displacement sensitivity requirement is $10^{-20}$ meters

Photo: G Moreno

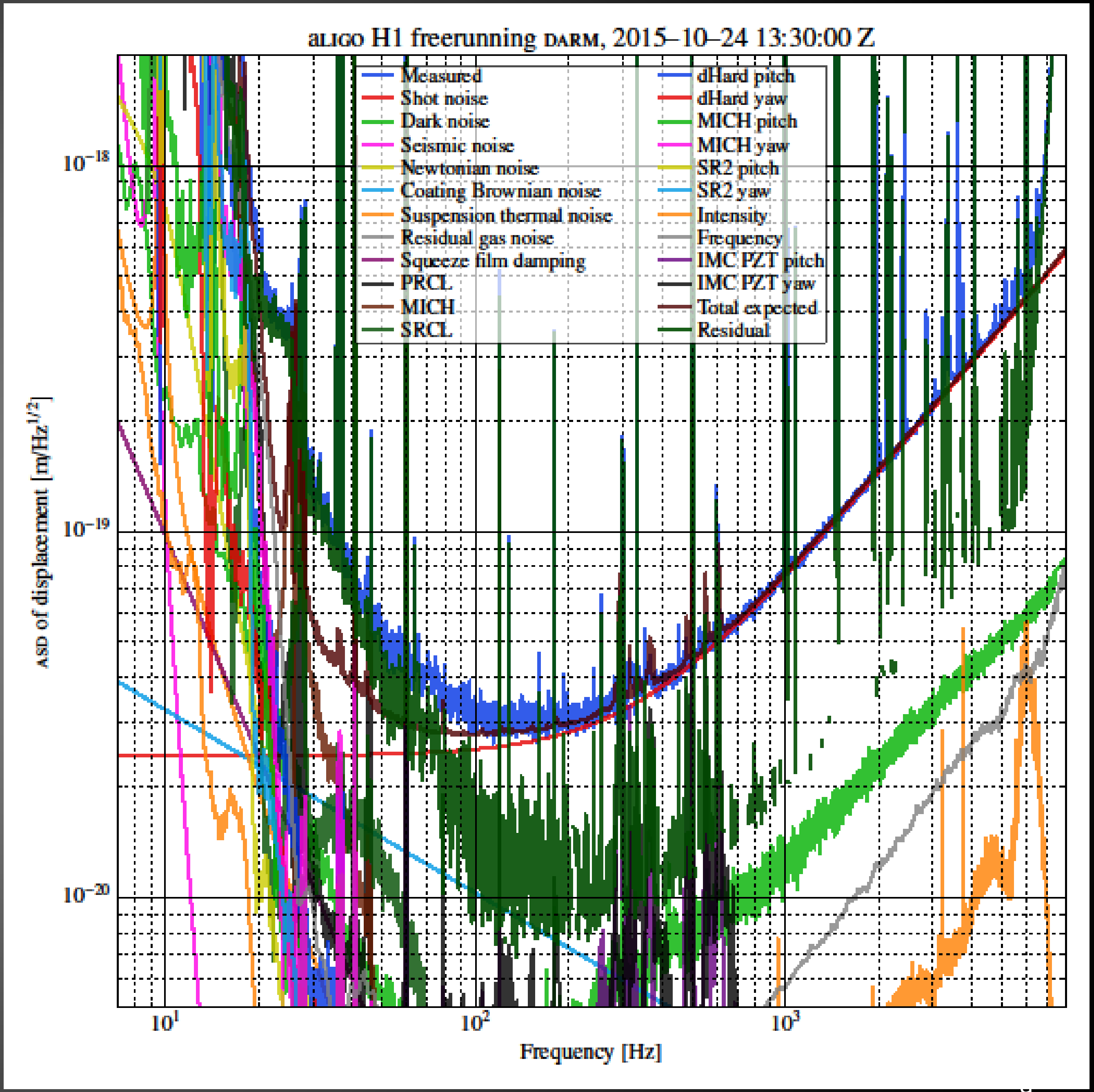
Photo: R Ward S Ballmer

# Displacement sensitivity



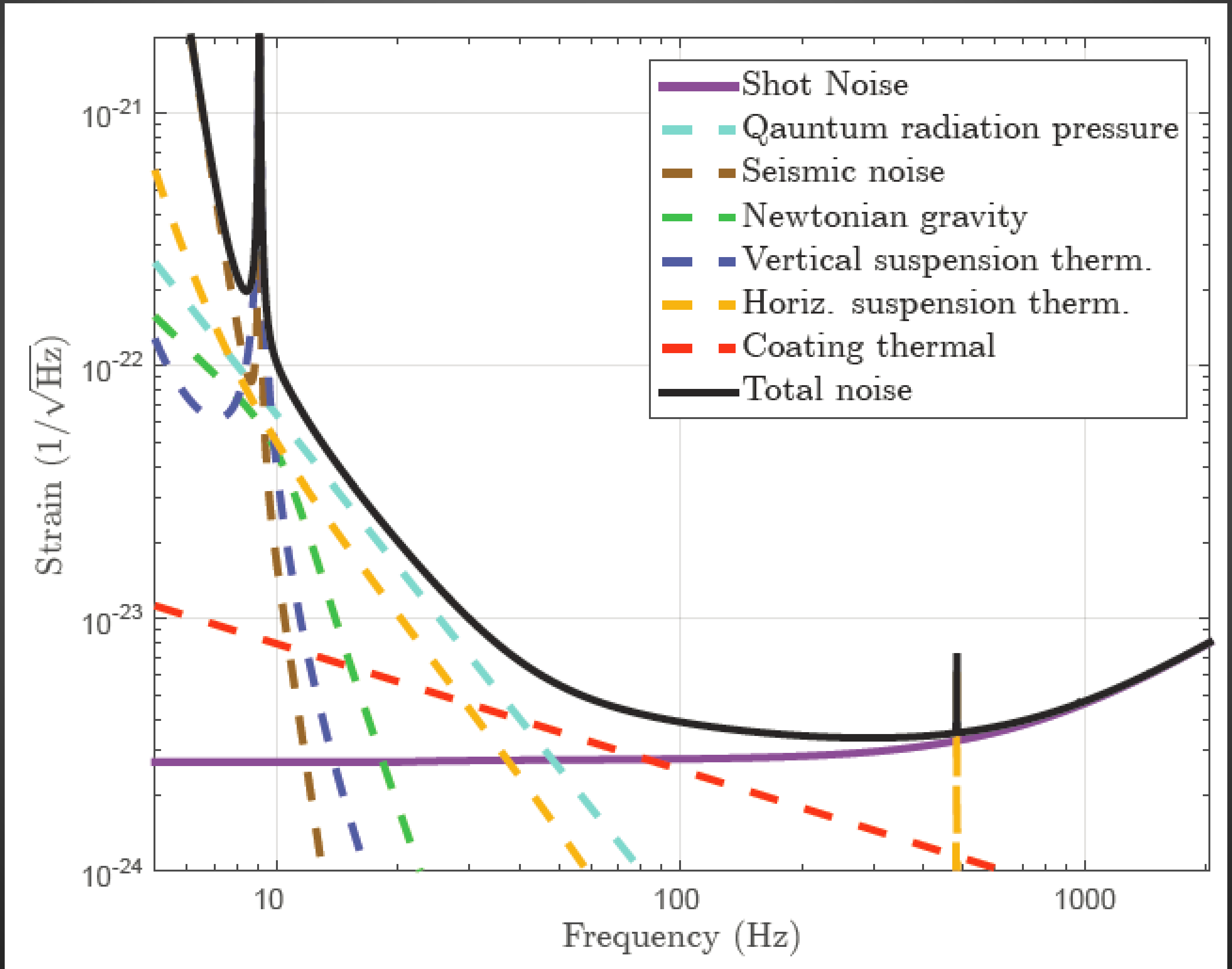

http://arxiv.org/abs/1602.03838

# Current displacement sensitivity:
# Limited by many types of technical noise

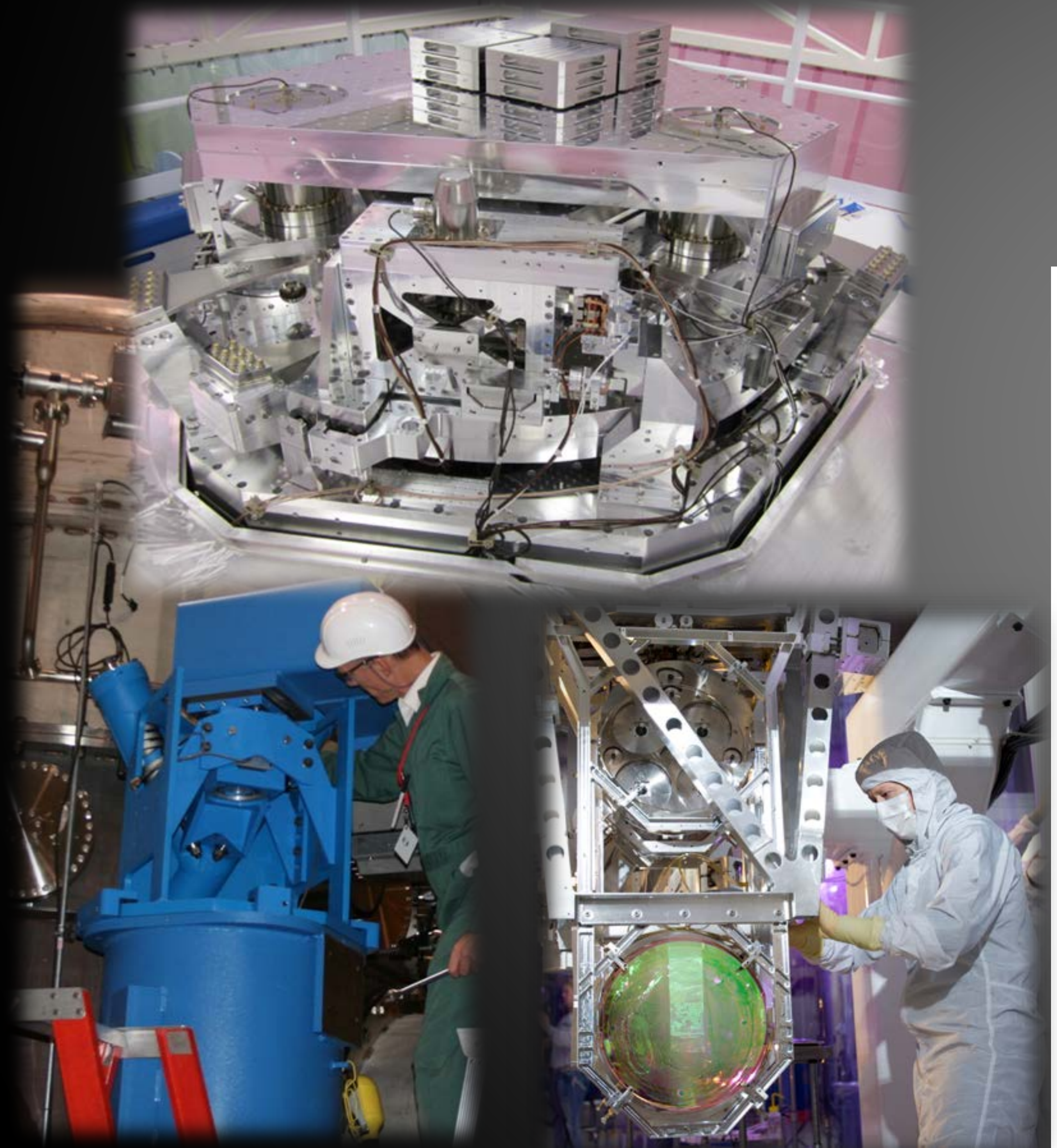



Noise budget courtesy of Evan Hall, Caltech

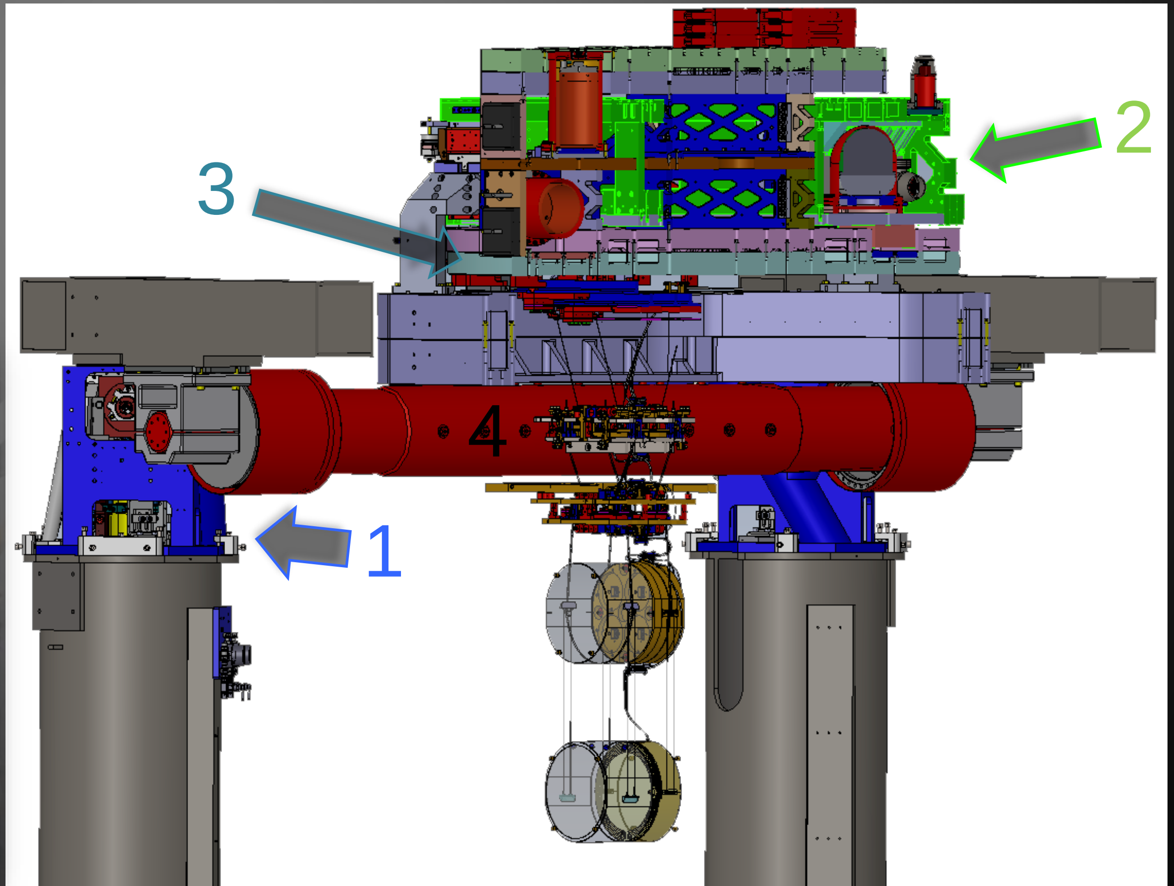
# Advanced LIGO fundamental noises



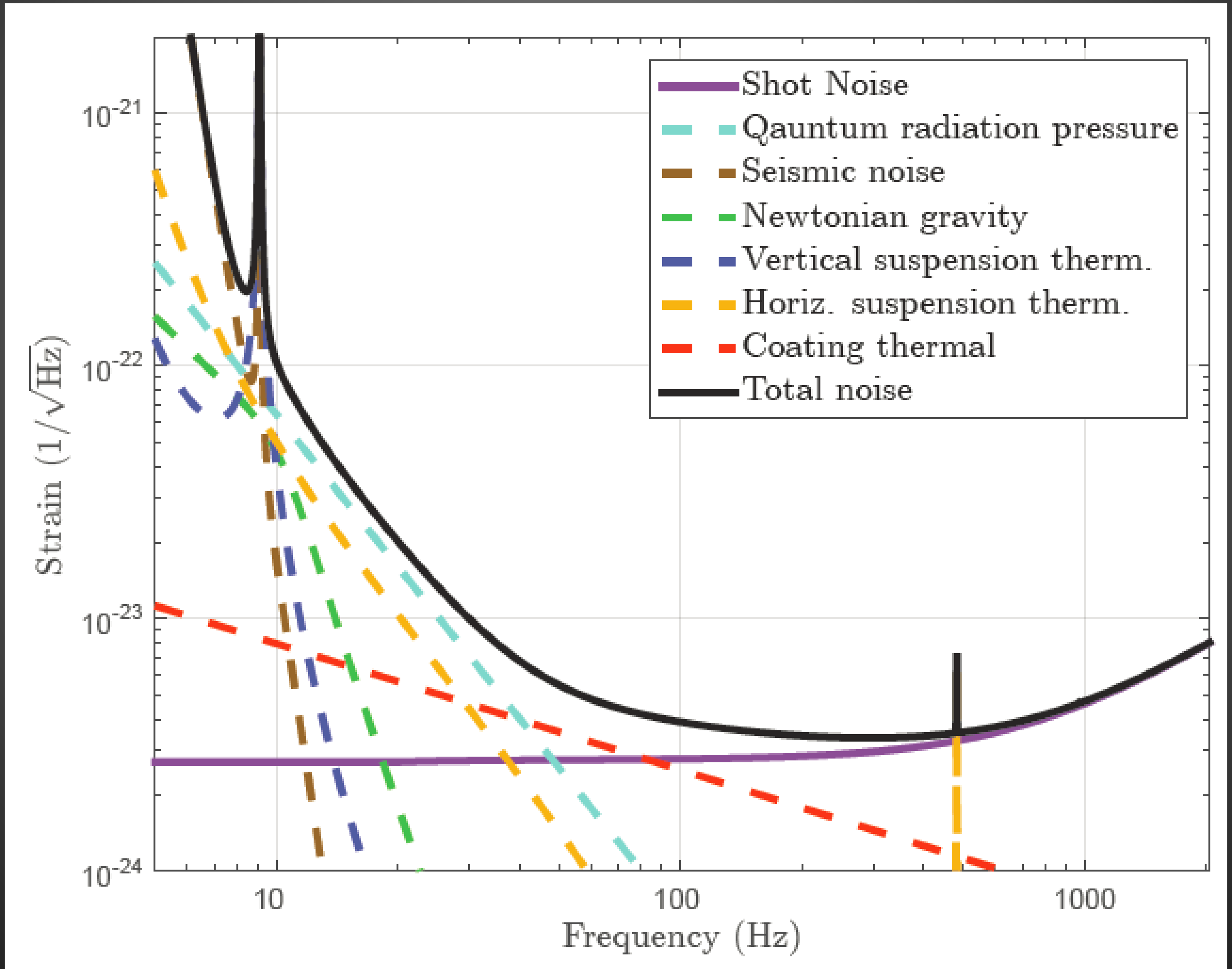
# Isolating test masses from the environment



Test mass motion should be < $10^{-19}$ [m/rtHz] at 10 Hz
Ground Motion at 10 Hz ~ $10^{-9}$ [m/rtHz]
10 orders of magnitude of isolation needed for test masses!

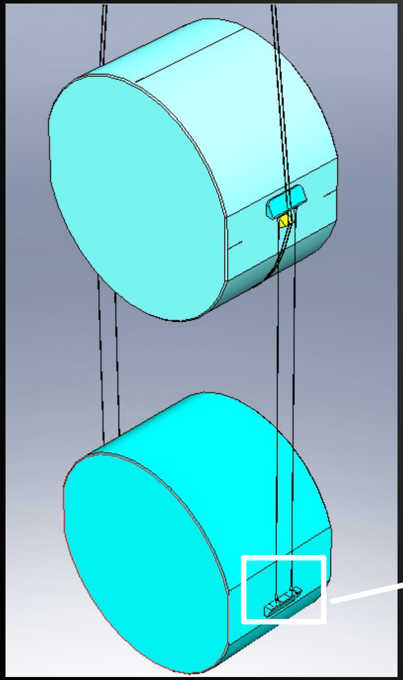


# Advanced LIGO fundamental noises



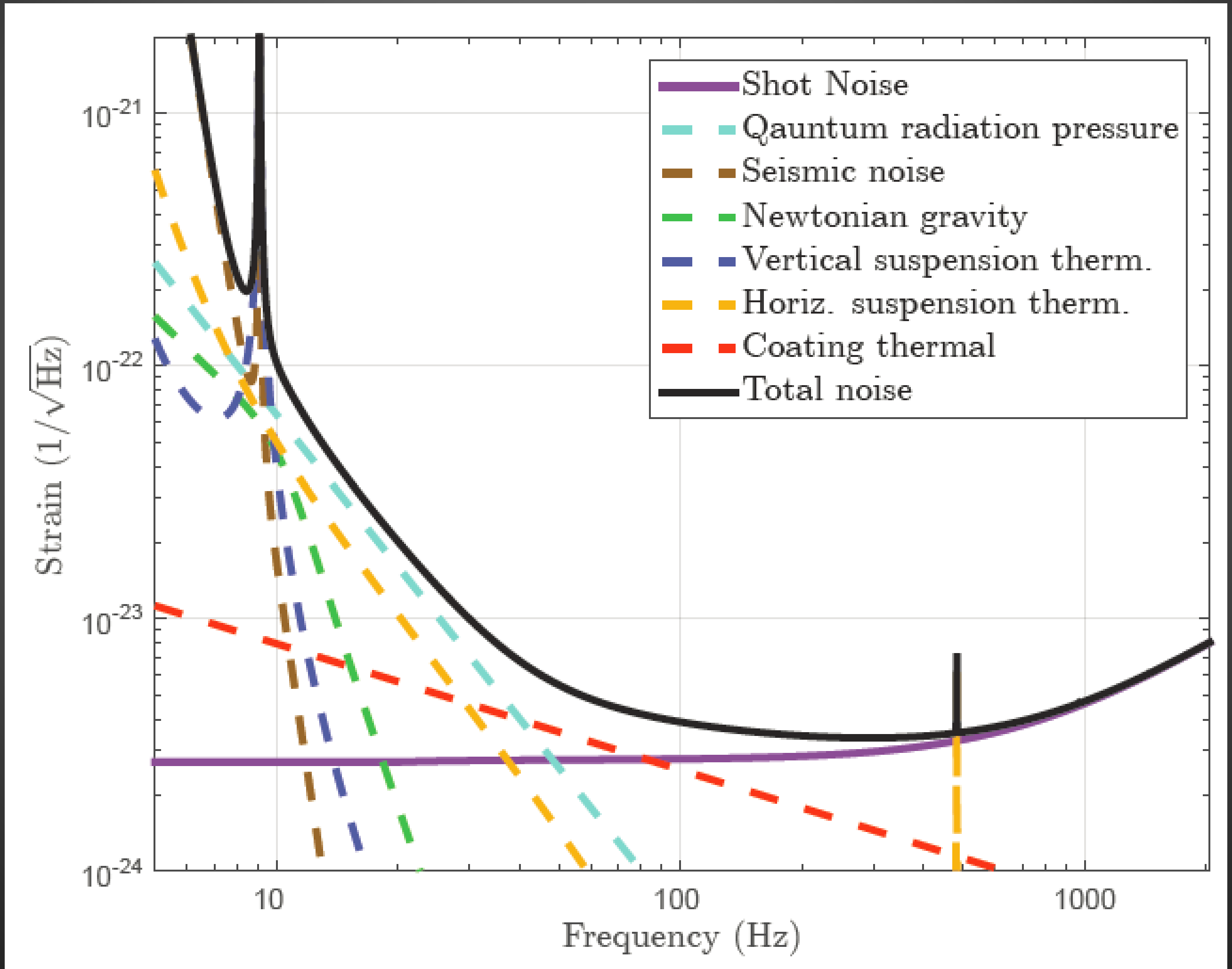
# Suspension thermal noise

- Equipartion theorem sets total thermal energy in a oscillator ($kx^2 = k_BT/2$)
- Away from the resonance frequency, level of noise is set by quality factor of the oscillator
- Reducing mechanical dissipation reduces thermal fluctuations



Photos: LIGO Lab

# Advanced LIGO fundamental noises



# Coating thermal noise

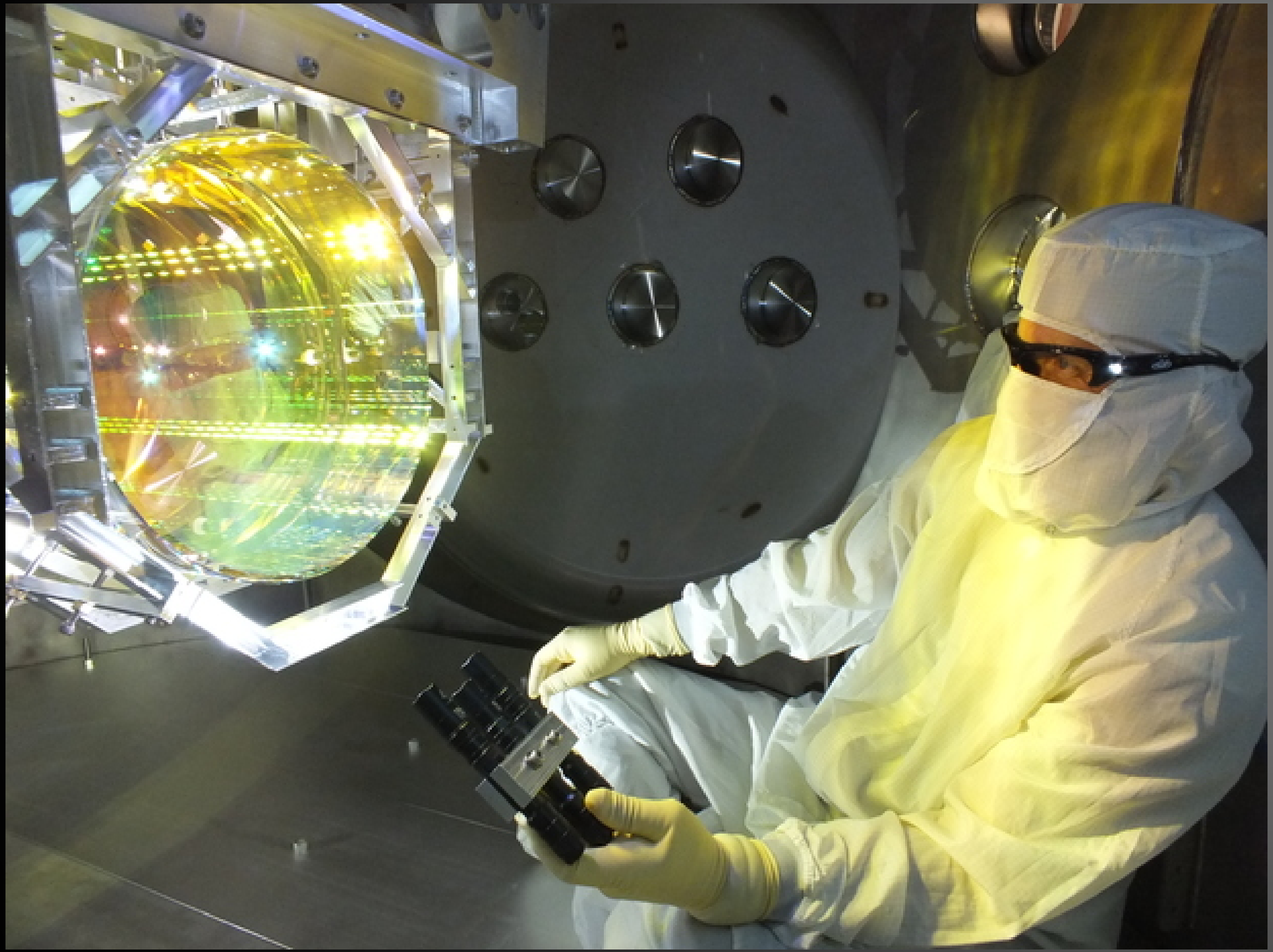
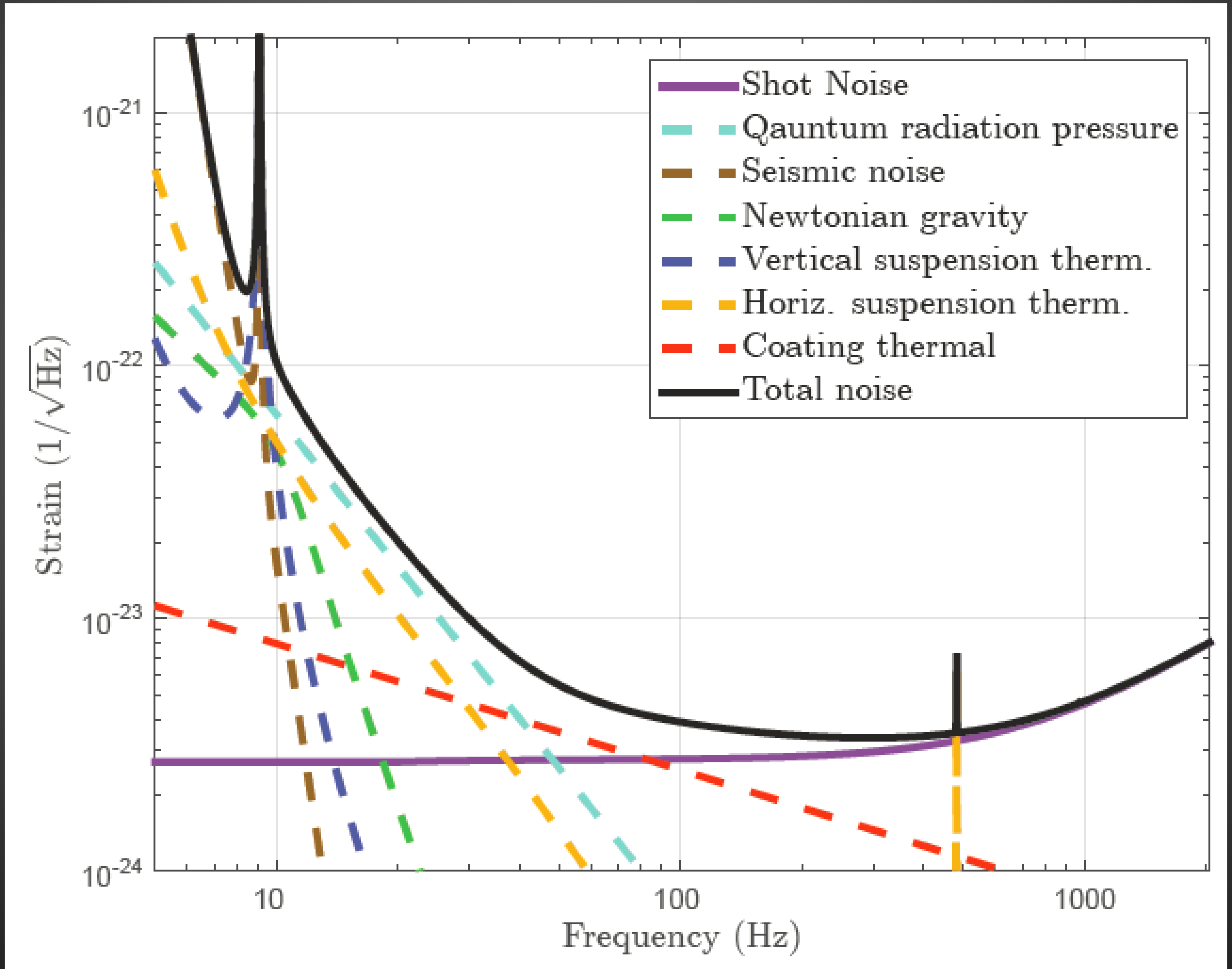


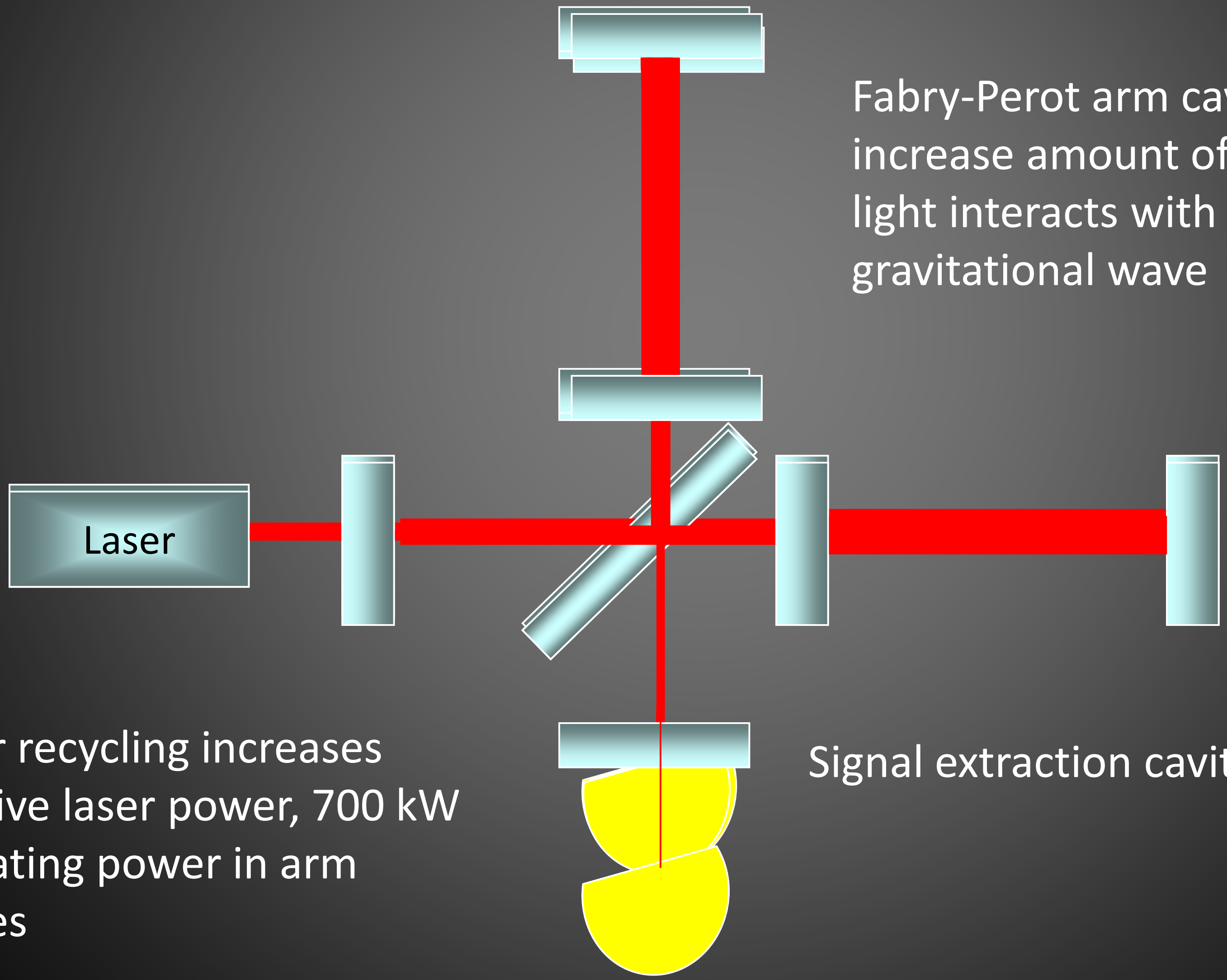
Photo: M Heitze LIGO Lab

- Dielectric coatings used in mirror coatings have high mechanical losses compared to substrate (Fused Silica)
- Brownian motion changes thickness of the coating

# Quantum Noise: shot noise and radiation pressure noise



# Current approach to quantum noise




Fabry-Perot arm cavities increase amount of time that light interacts with a gravitational wave

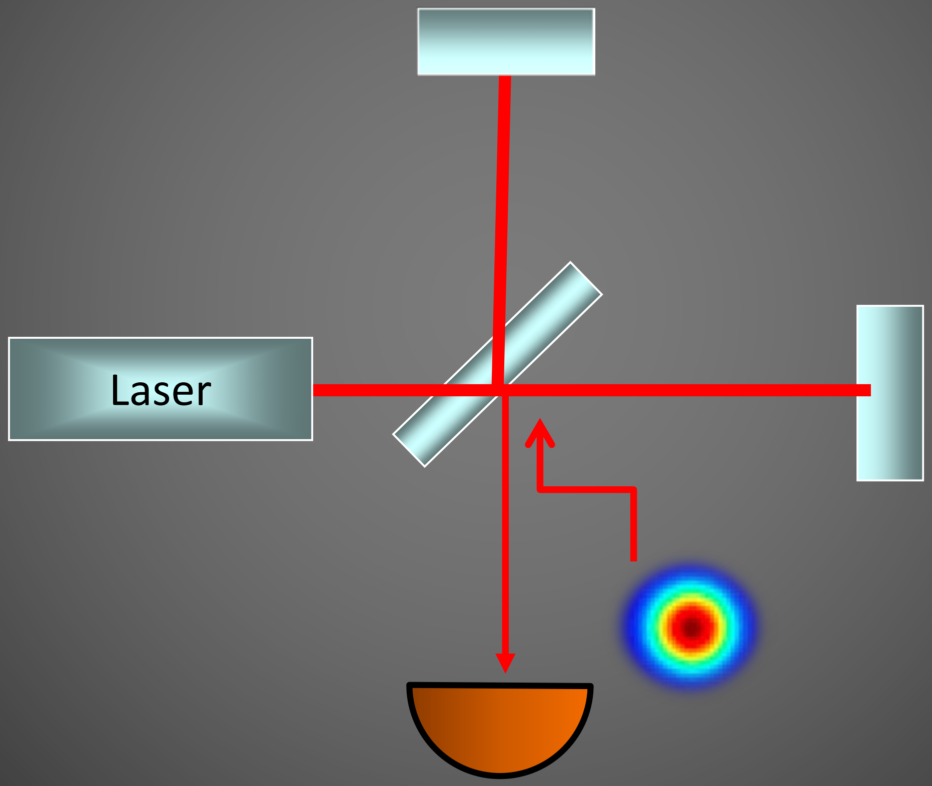
40 kg test masses to avoid radiation pressure noise

Signal extraction cavity

Power recycling increases effective laser power, 700 kW circulating power in arm cavities

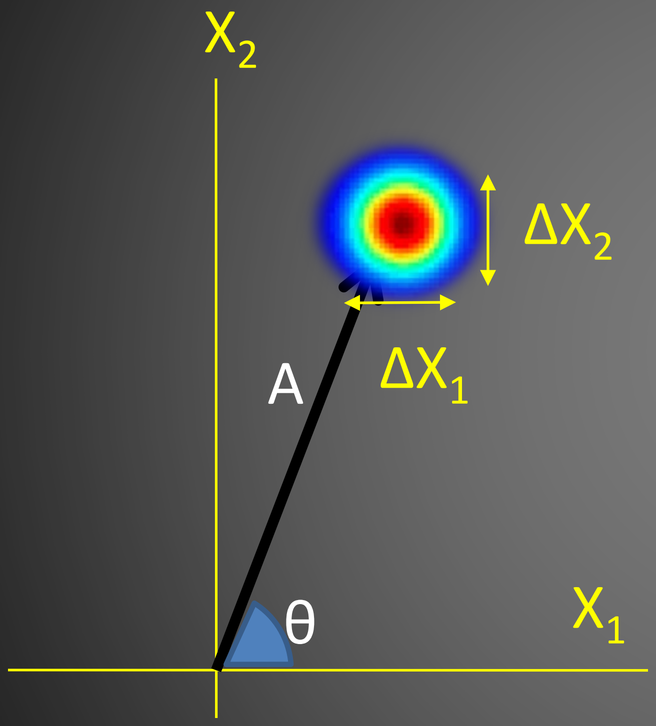
# Quantum noise in interferometers

Vacuum fluctuations (Caves, PRL **45** 75-79, 1980):



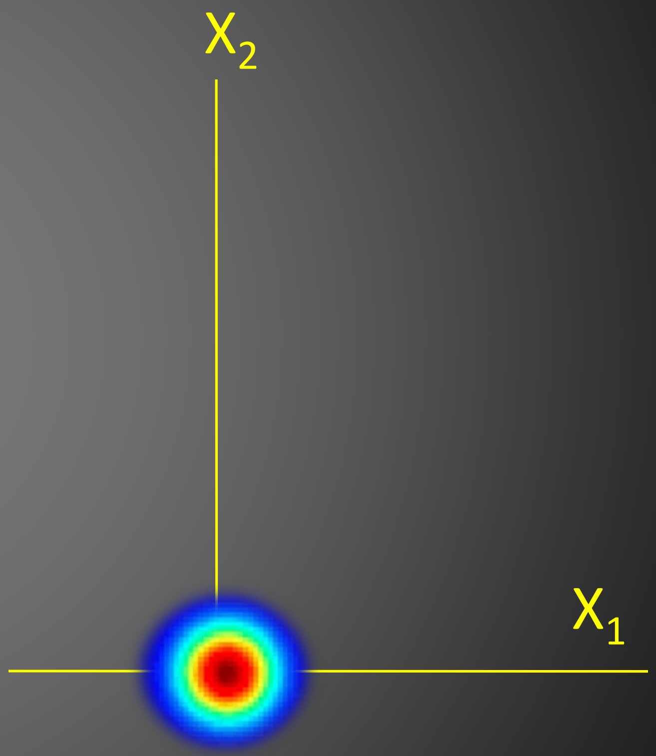

Alternative solution: Squeezing

# Quantum Light



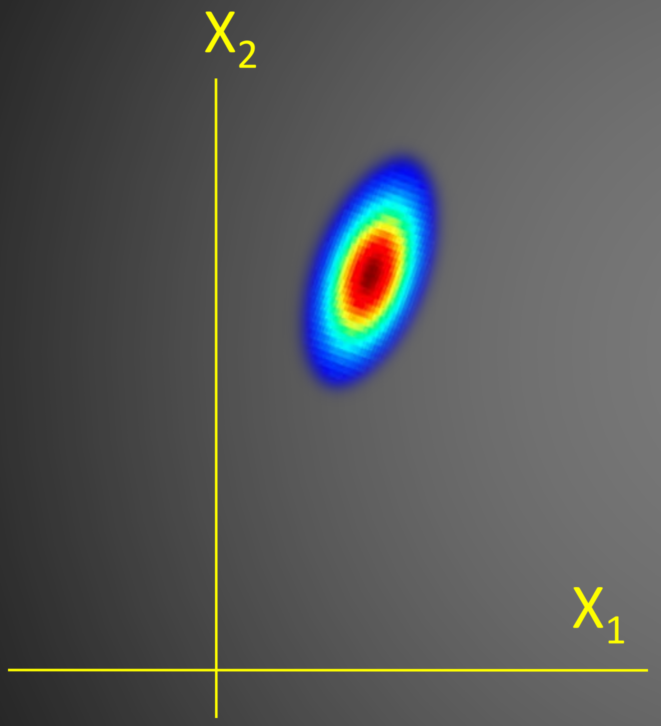

The uncertainty principle

$$\boxed{\Delta X_1 \, \Delta X_2 \geq 1}$$




Vacuum fluctuations

# Squeezed light and squeezed vacuum

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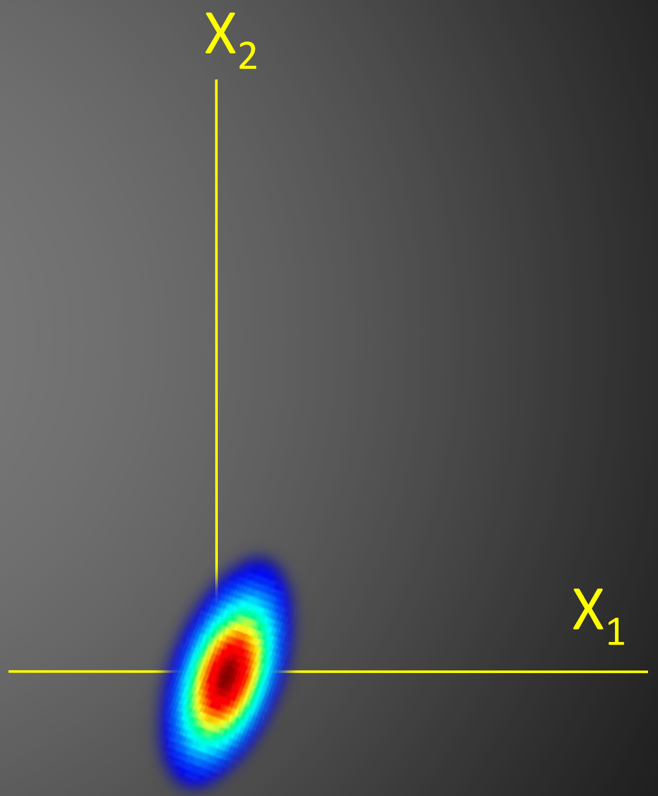
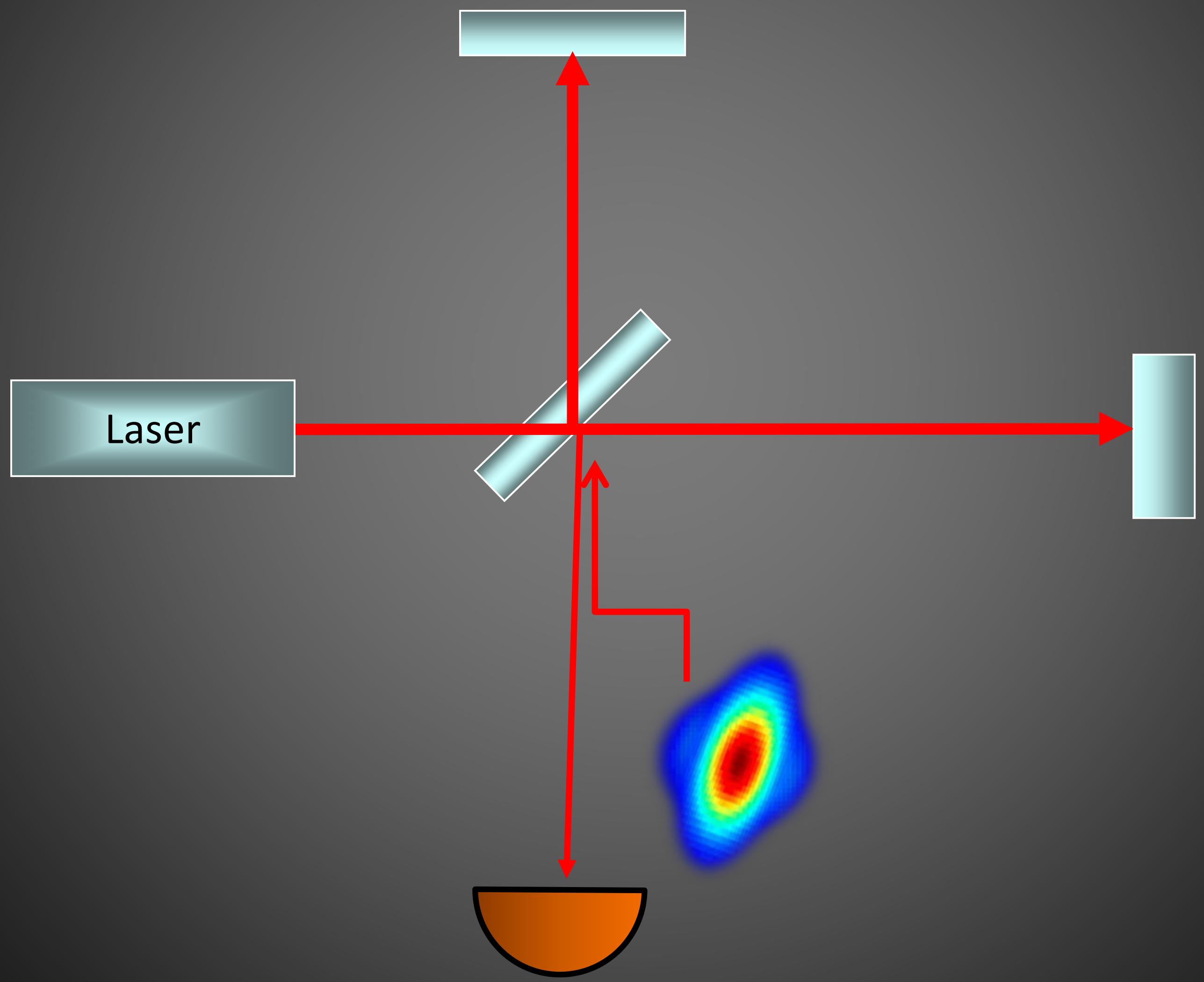
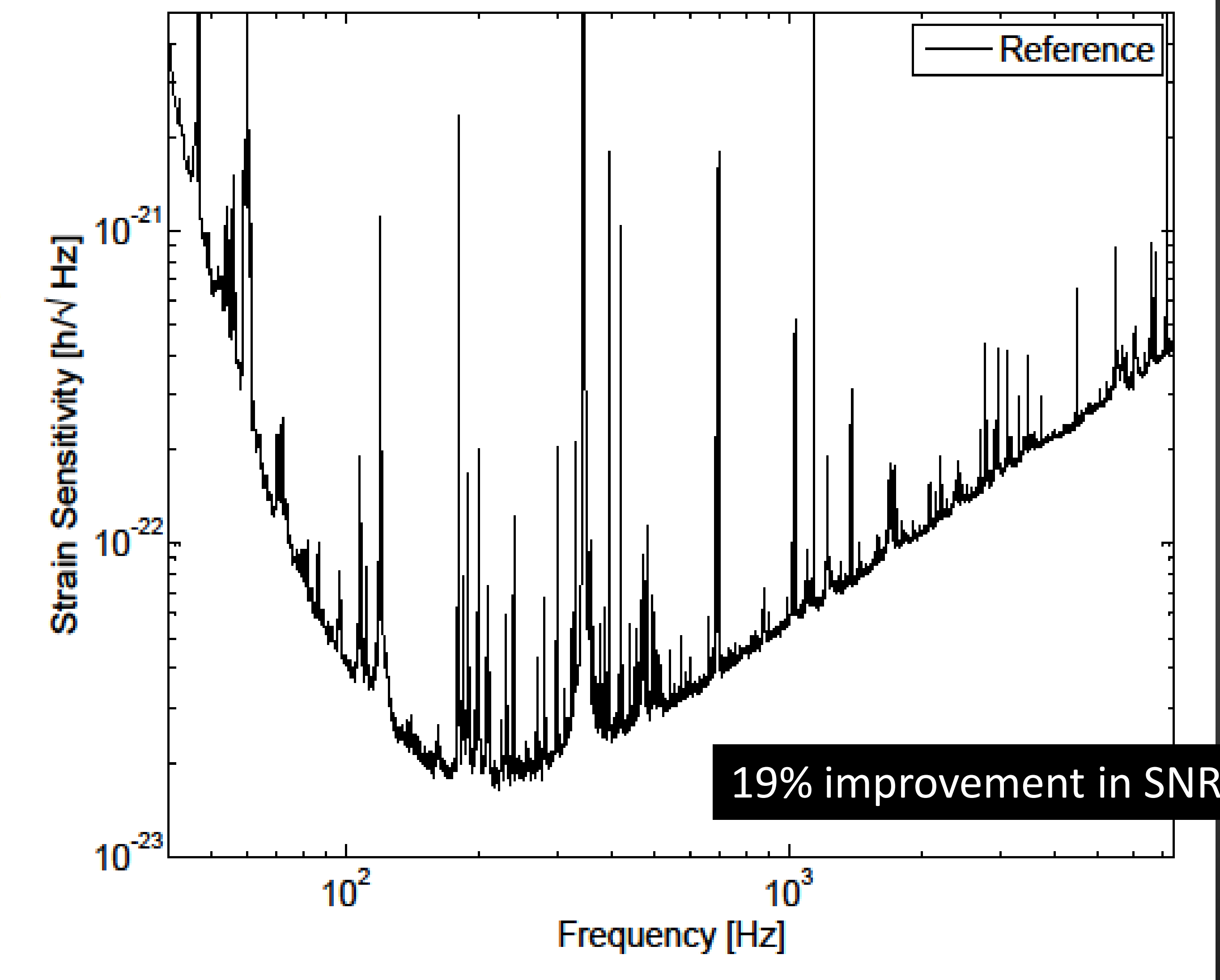



Squeezed vacuum

# Squeezing in an interferometer



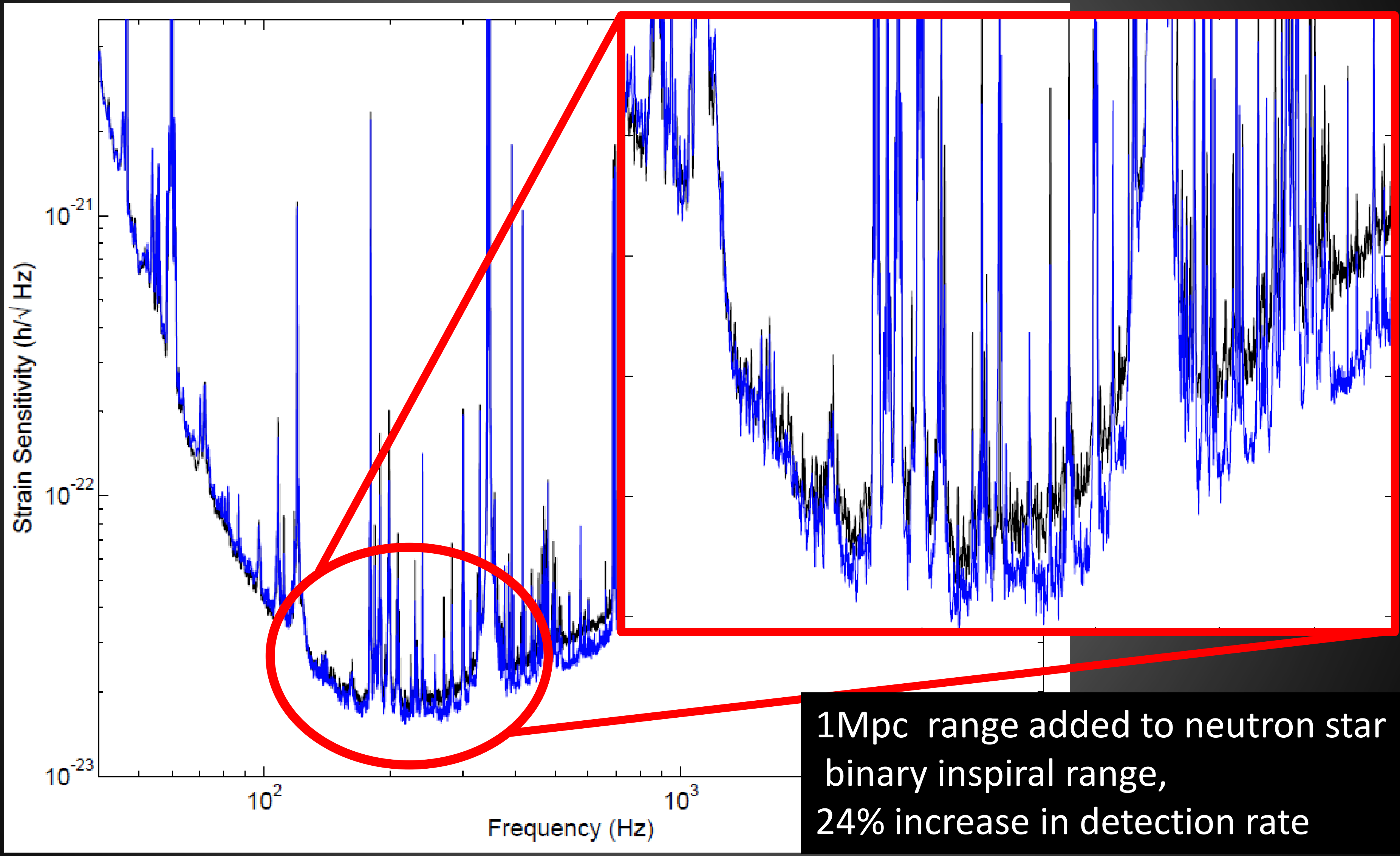
# Squeezing in Enhanced LIGO




19% improvement in SNR for pulsars

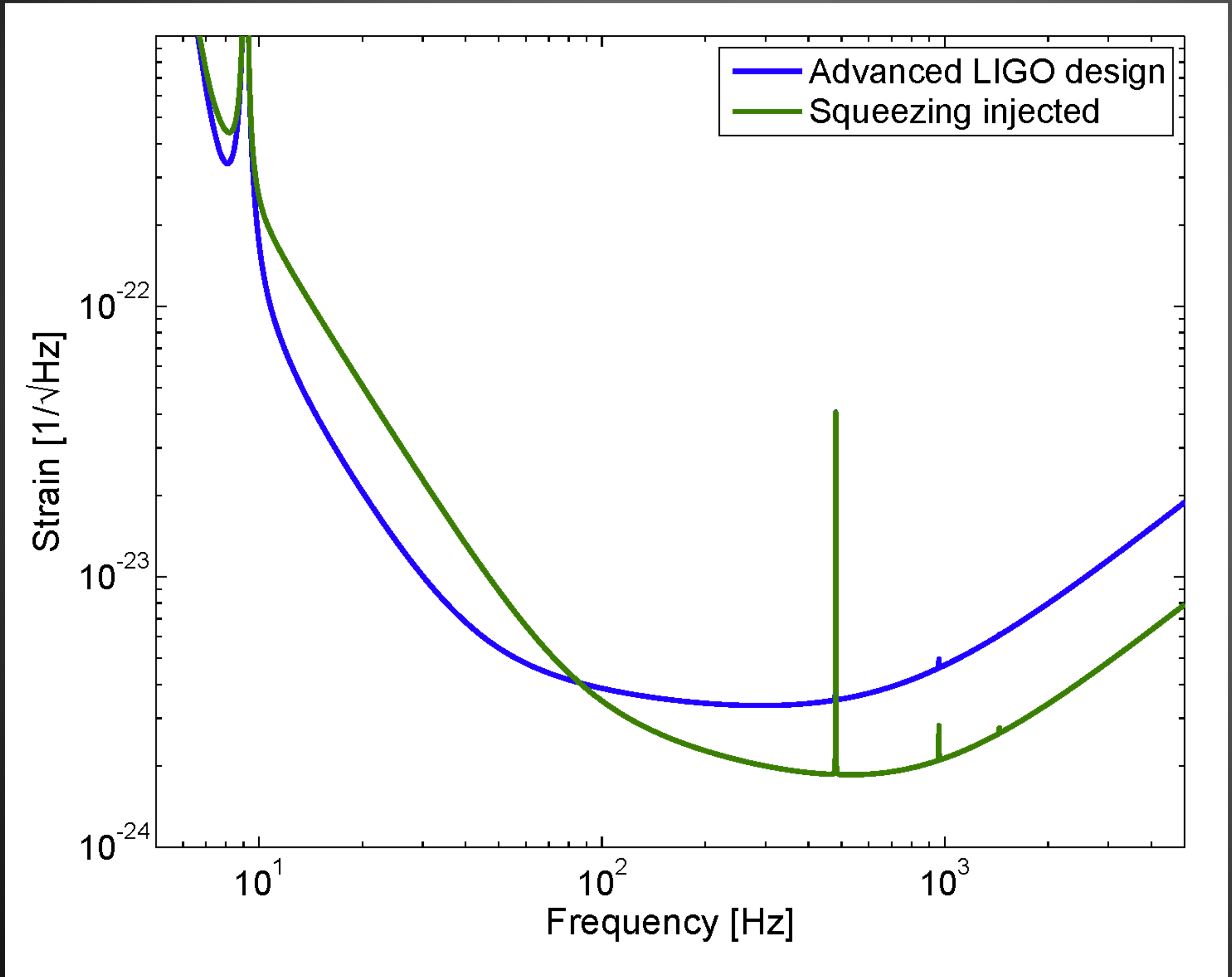
LIGO Scientific Collaboration, Nature Photonics **7** 613-619 (2013)

# No additional noise introduced



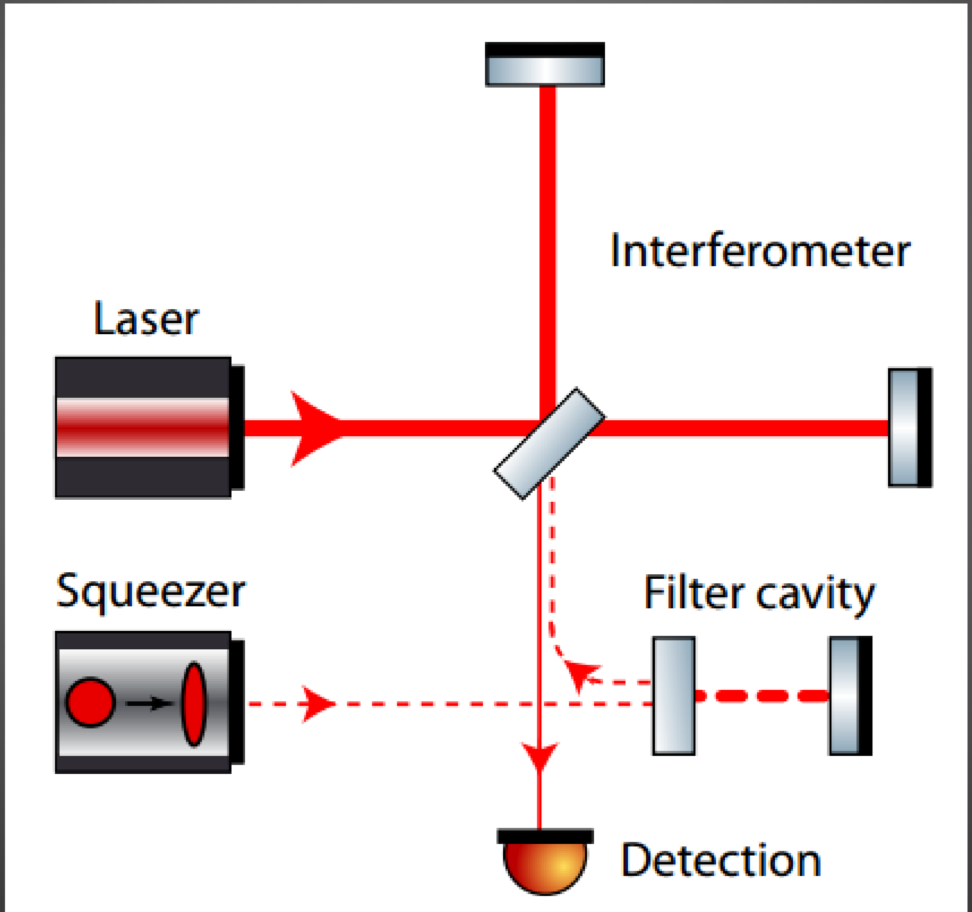

1Mpc range added to neutron star binary inspiral range,
24% increase in detection rate

# Squeezing with a radiation pressure noise limited interferometer



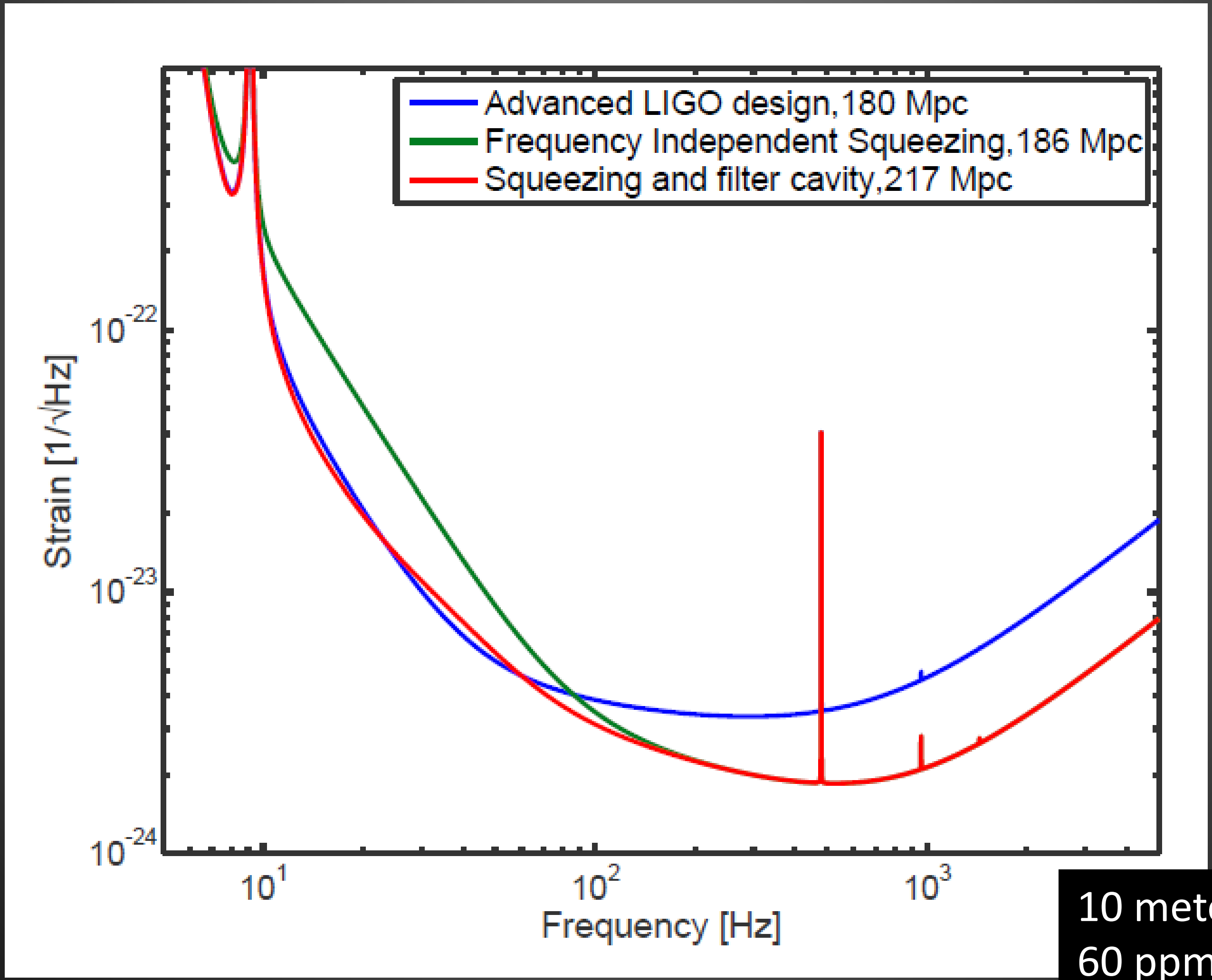

Astrophysical Benefits:
Lynch et al, in prep

# Frequency Dependent Squeezing



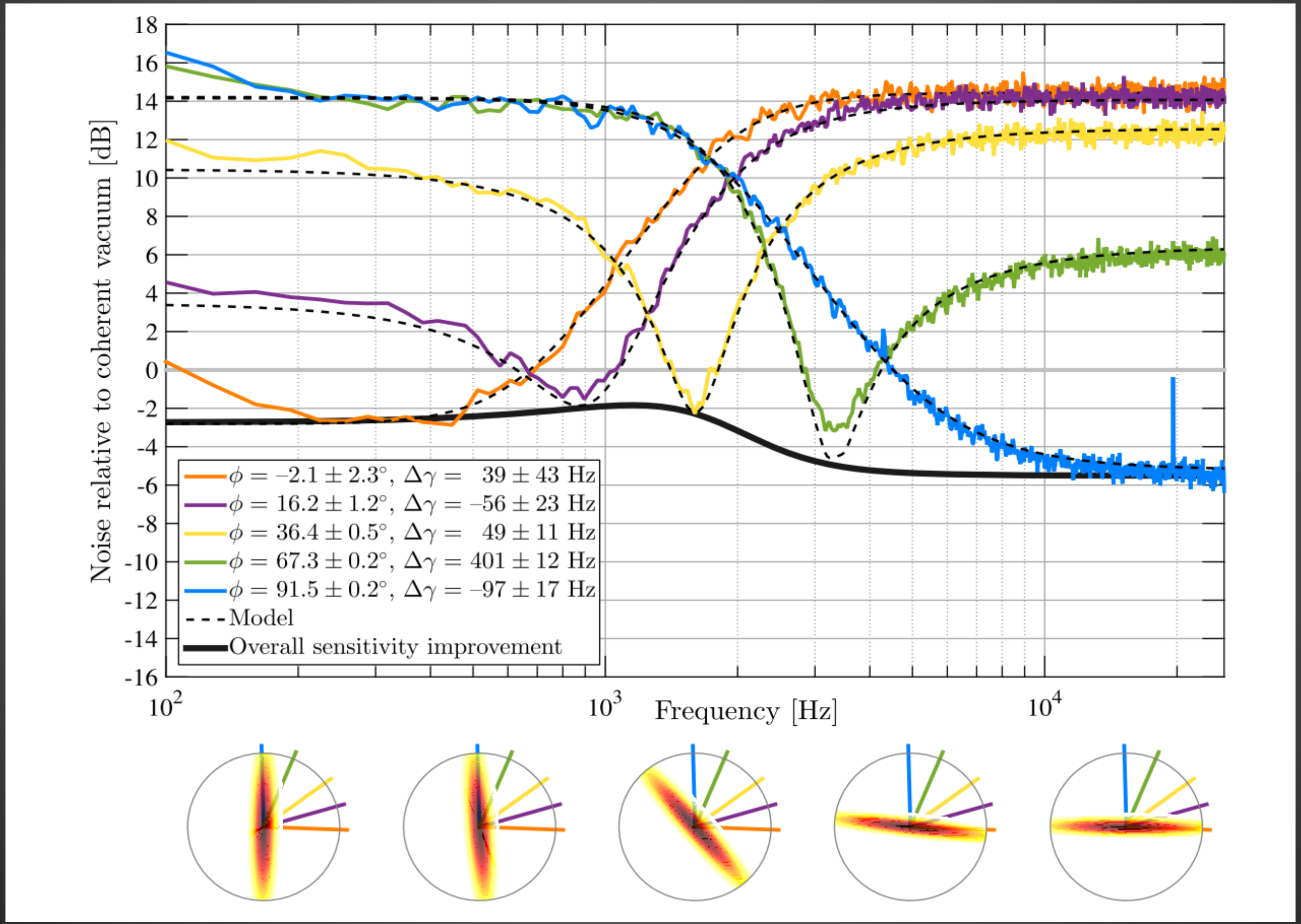

Evans et al, PRD **88** 022002 (2013)

# Frequency Dependent Squeezing




10 meter Filter Cavity
60 ppm round trip losses

# Frequency dependent squeezing recently demonstrated in the audio band




Oekler et al PRL Jan 2016

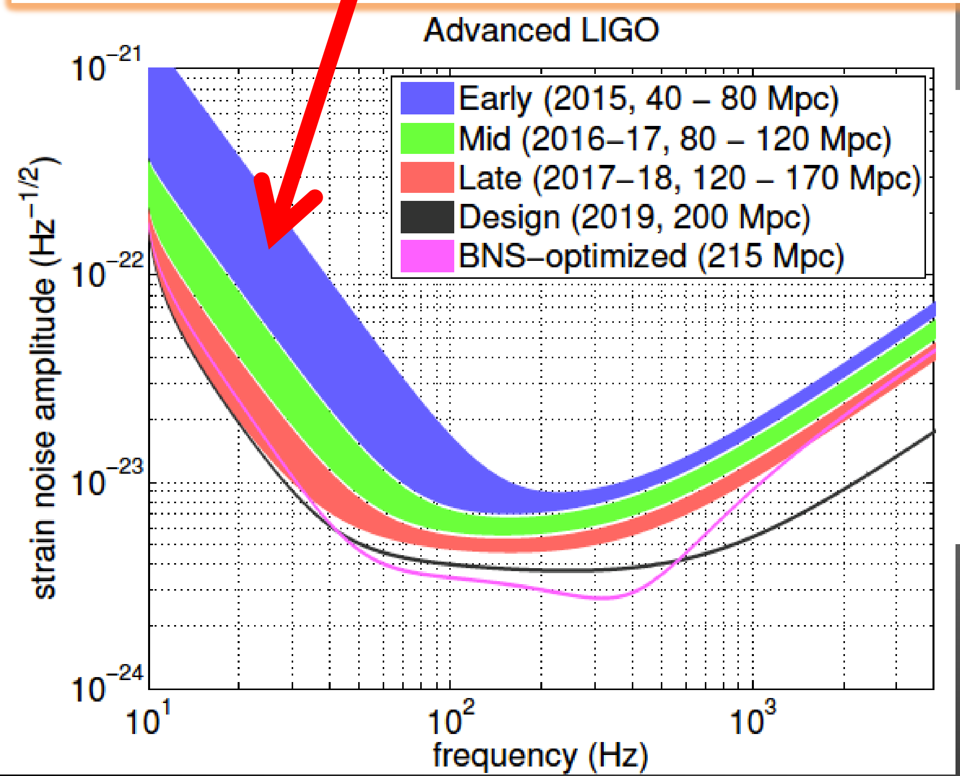
http://dx.doi.org/10.1103/PhysRevLett.116.041102

# Future Plans: Next few months

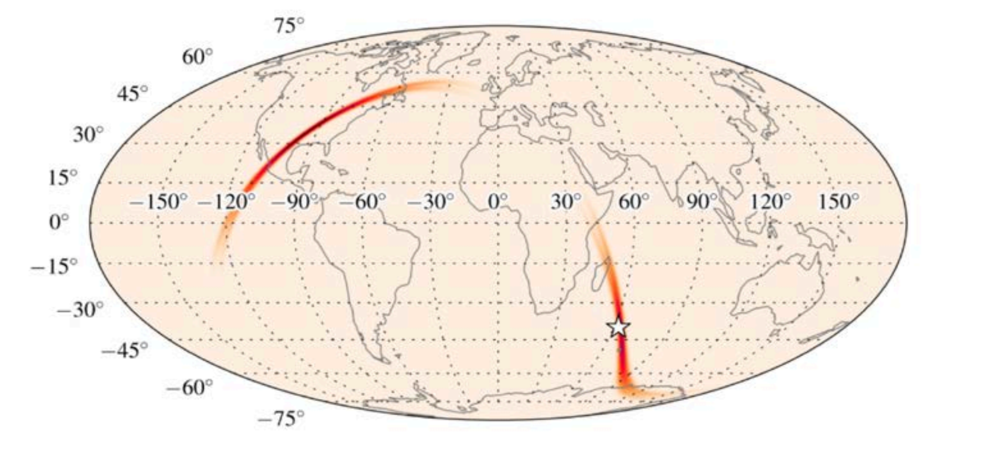
- Increase input power from 20Watts to 50 Watts
  - Increase circulating power from ~100kW to ~250 kW
- Work on reducing low frequency noise
  - Important for sensitivity to binary black holes
- Prepare for next observing run in later part of the year

# Observing Scenario

| Epoch | Estimated Run Duration | $E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO | Virgo | BNS Range (Mpc) LIGO | Virgo | Number of BNS Detections | % BNS Localized within 5 deg$^2$ | 20 deg$^2$ |
|---|---|---|---|---|---|---|---|---|
| 2015 | 3 months | 40 – 60 | – | 40 – 80 | – | 0.0004 – 3 | – | – |
| 2016–17 | 6 months | 60 – 75 | 20 – 40 | 80 – 120 | 20 – 60 | 0.006 – 20 | 2 | 5 – 12 |
| 2017–18 | 9 months | 75 – 90 | 40 – 50 | 120 – 170 | 60 – 85 | 0.04 – 100 | 1 – 2 | 10 – 12 |
| 2019+ | (per year) | 105 | 40 – 80 | 200 | 65 – 130 | 0.2 – 200 | 3 – 8 | 8 – 28 |
| 2022+ (India) | (per year) | 105 | 80 | 200 | 130 | 0.4 – 400 | 17 | 48 |




http://arxiv.org/abs/1304.0670




Localization of source,
Hanford and Livingston LIGO detectors,
First science run at end 2015

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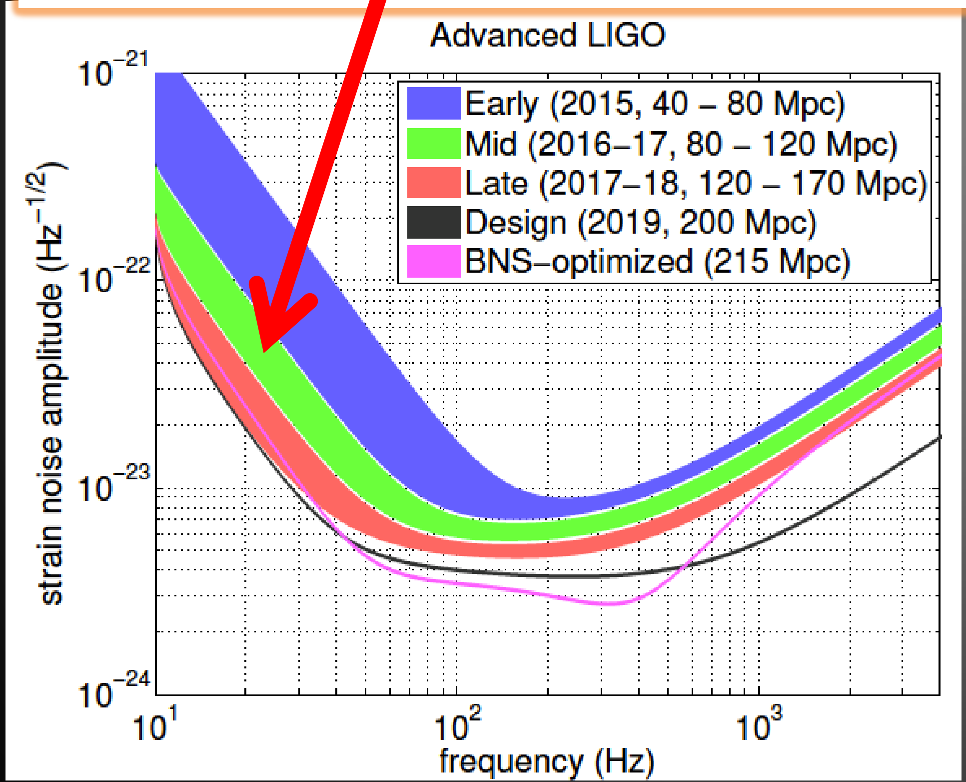


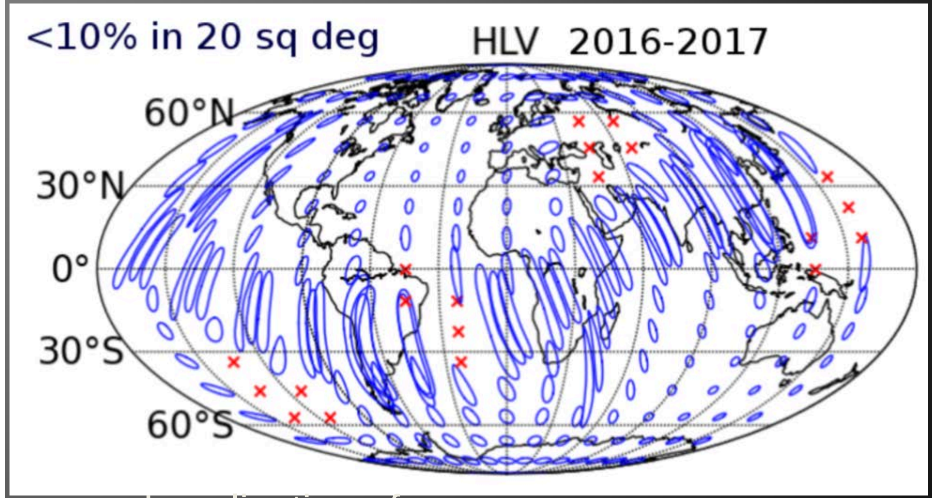


Localization of source,
Hanford, Livingston and Virgo detectors,
Observing 2016-17

| Epoch | Estimated Run Duration | $E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO | Virgo | BNS Range (Mpc) LIGO | Virgo | Number of BNS Detections | % BNS Localized within 5 deg$^2$ | 20 deg$^2$ |
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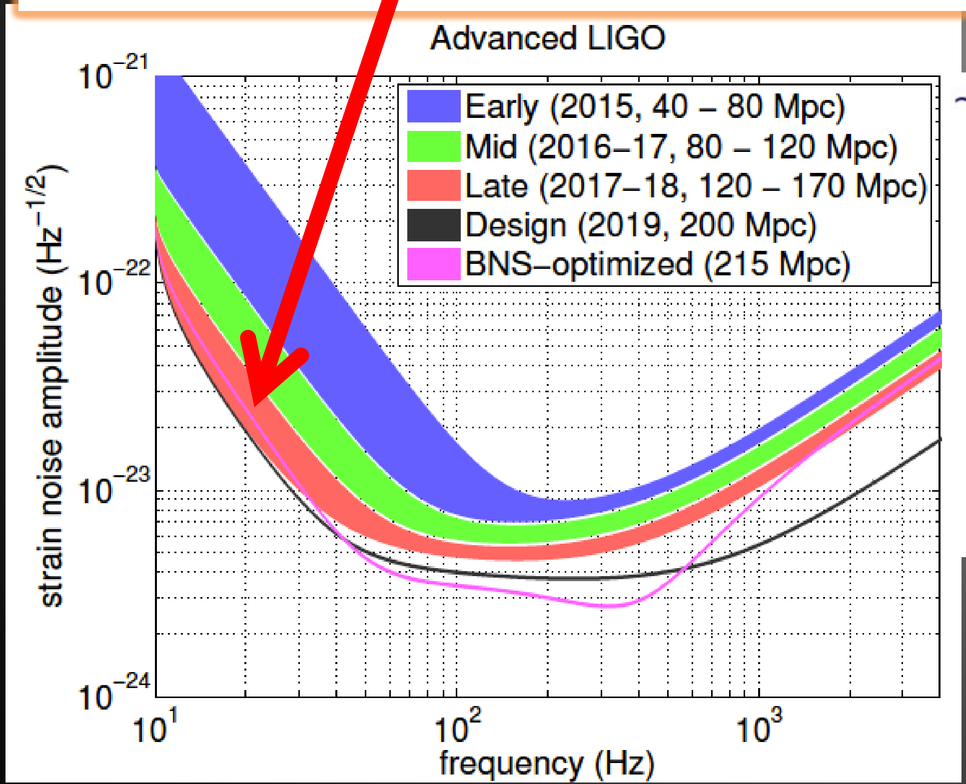


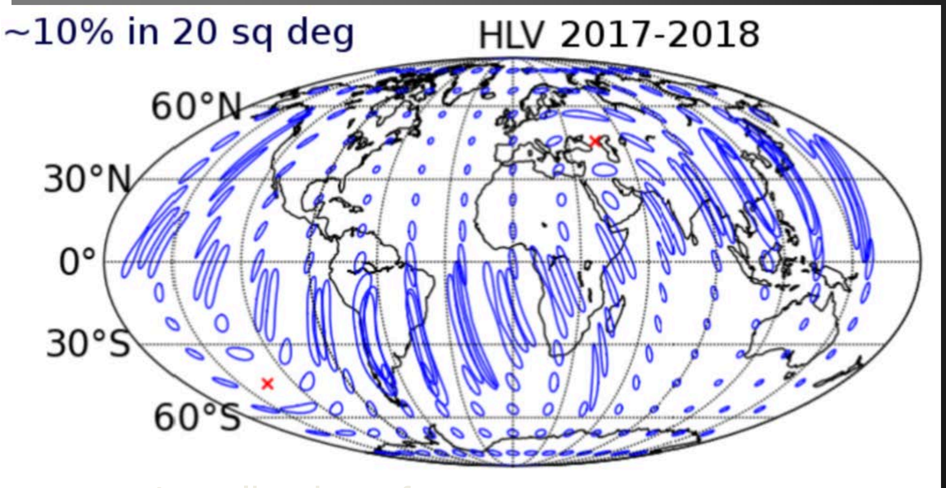


Localization of source,
Hanford, Livingston and Virgo detectors,
Observing 2017-18

| Epoch | Estimated Run Duration | $E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO | Virgo | BNS Range (Mpc) LIGO | Virgo | Number of BNS Detections | % BNS Localized within 5 $\mathrm{deg}^2$ | 20 $\mathrm{deg}^2$ |
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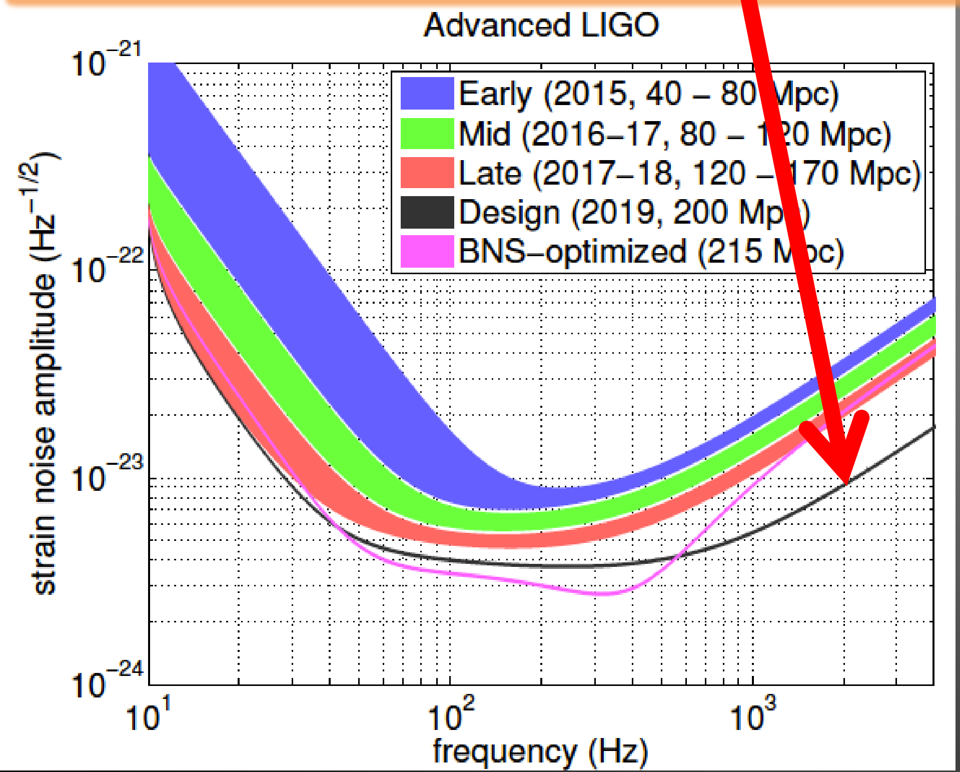


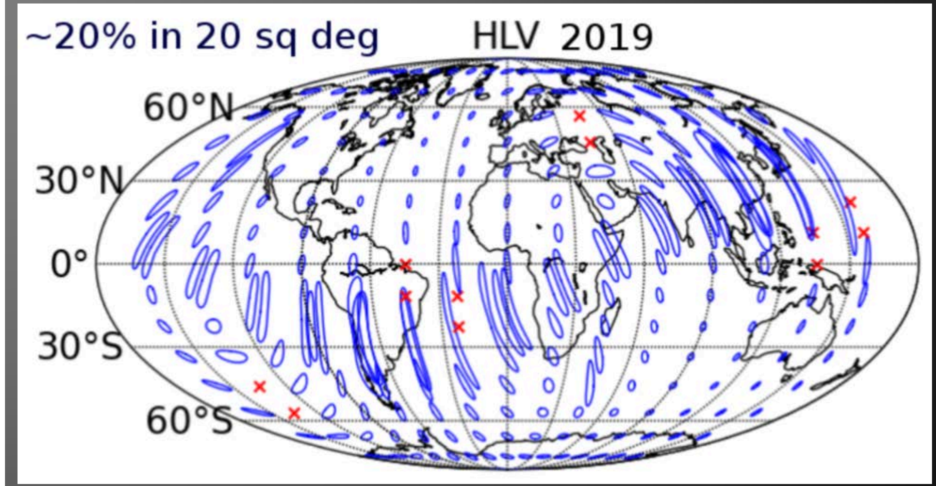


Localization of source,
Hanford, Livingston and Virgo detectors,
Observing 2019

| Epoch | Estimated Run Duration | $E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO | Virgo | BNS Range (Mpc) LIGO | Virgo | Number of BNS Detections | % BNS Localized within 5 deg$^2$ | 20 deg$^2$ |
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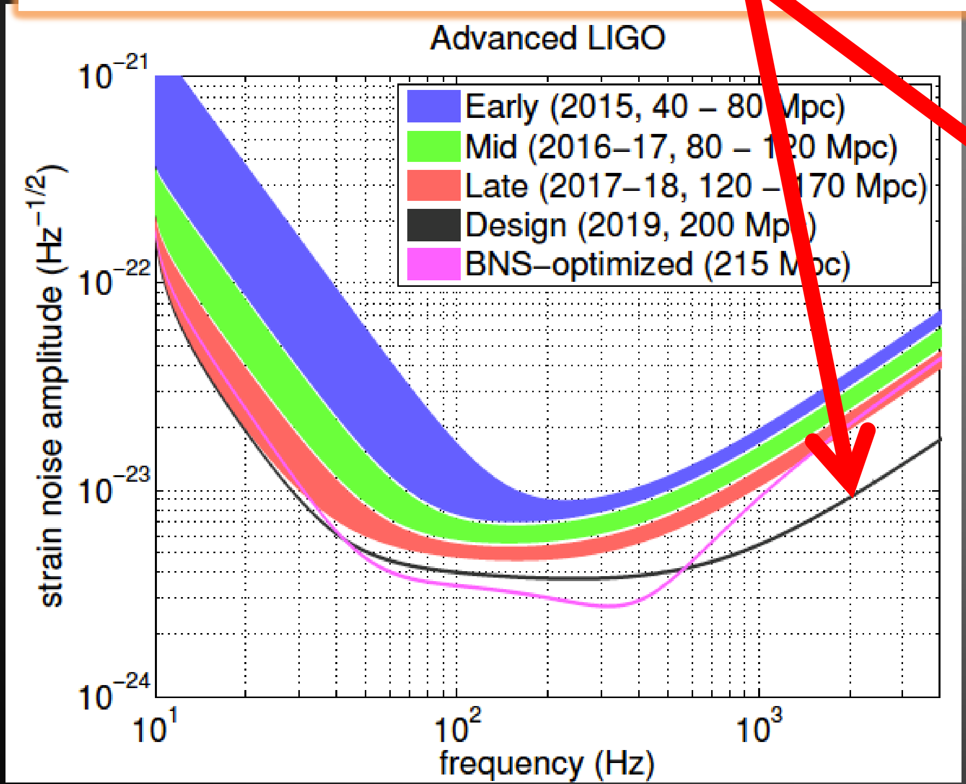
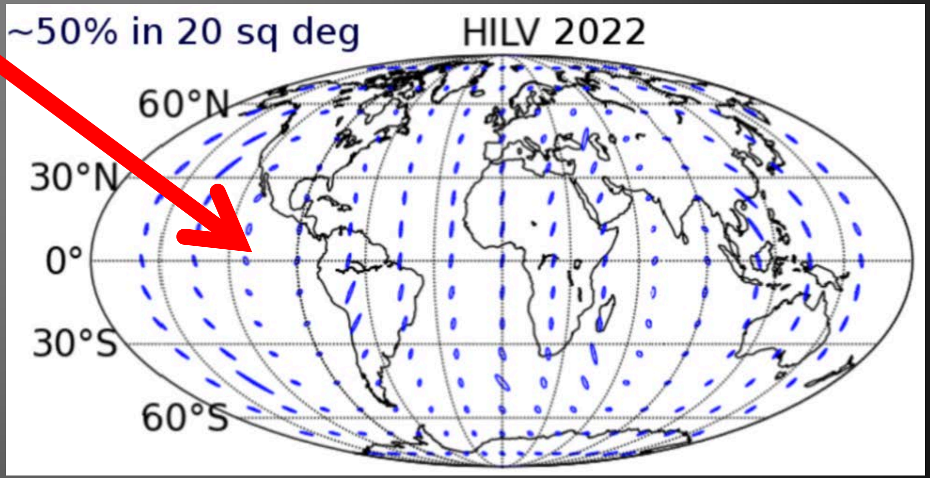
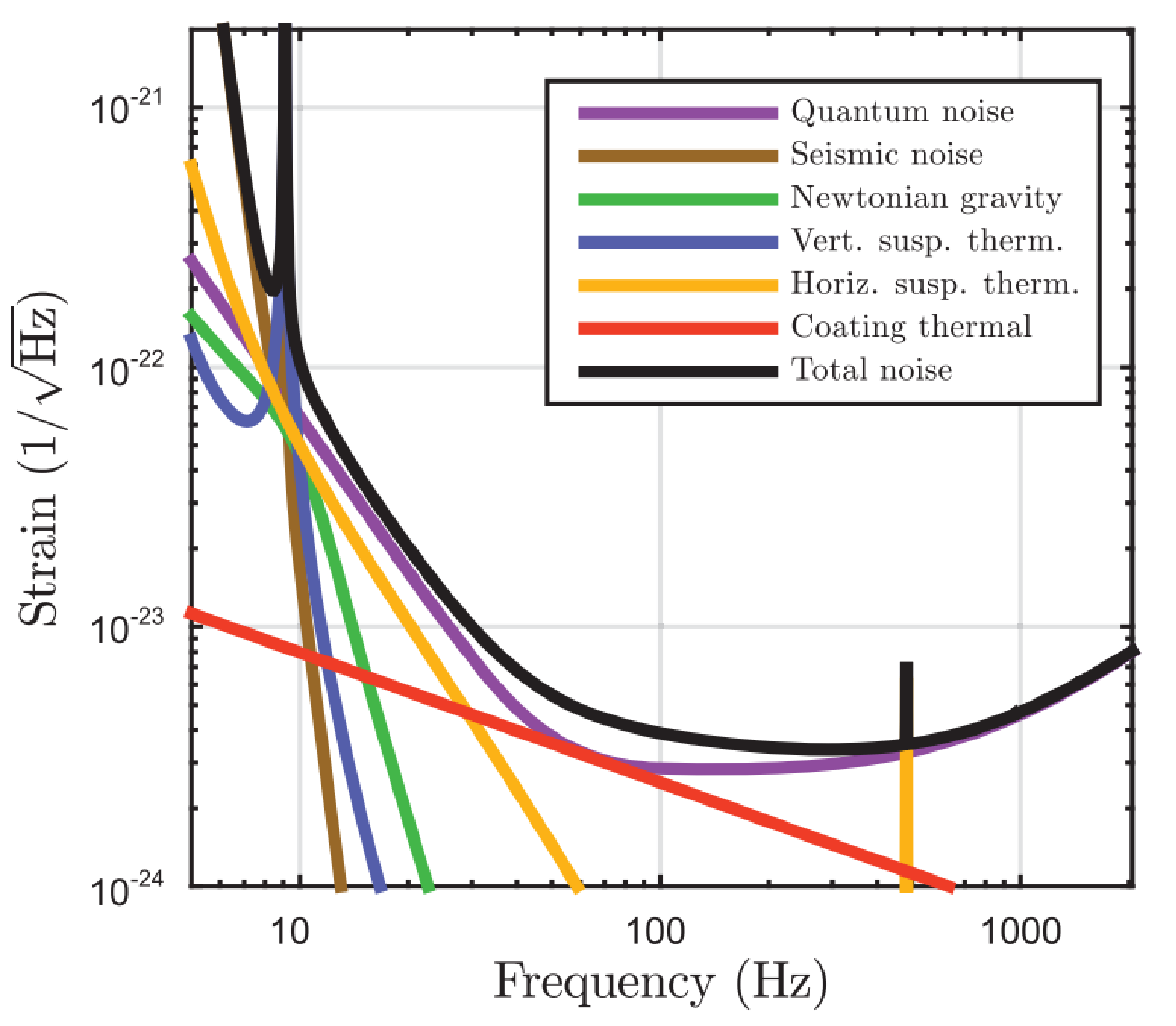
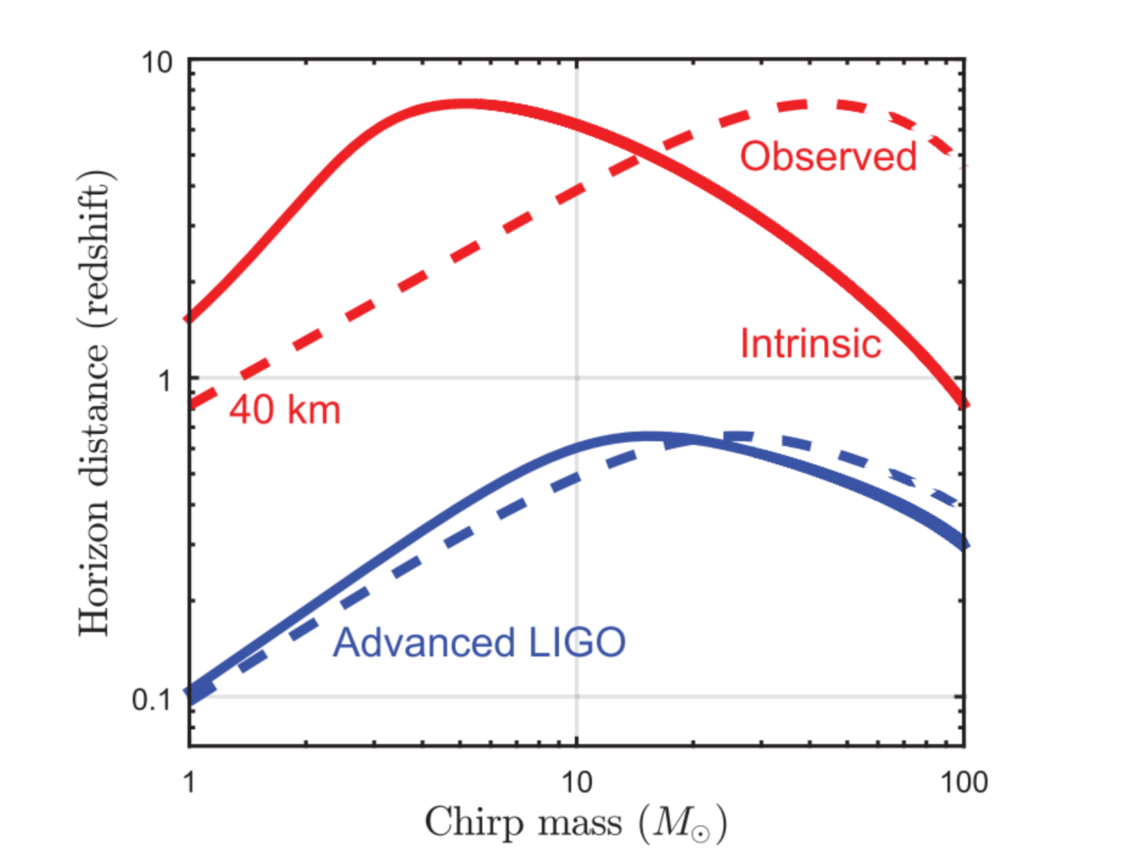



Localization of source,
Hanford, Livingston, Virgo, India detectors,
Observing 2022

# Extending our reach to cosmological distances



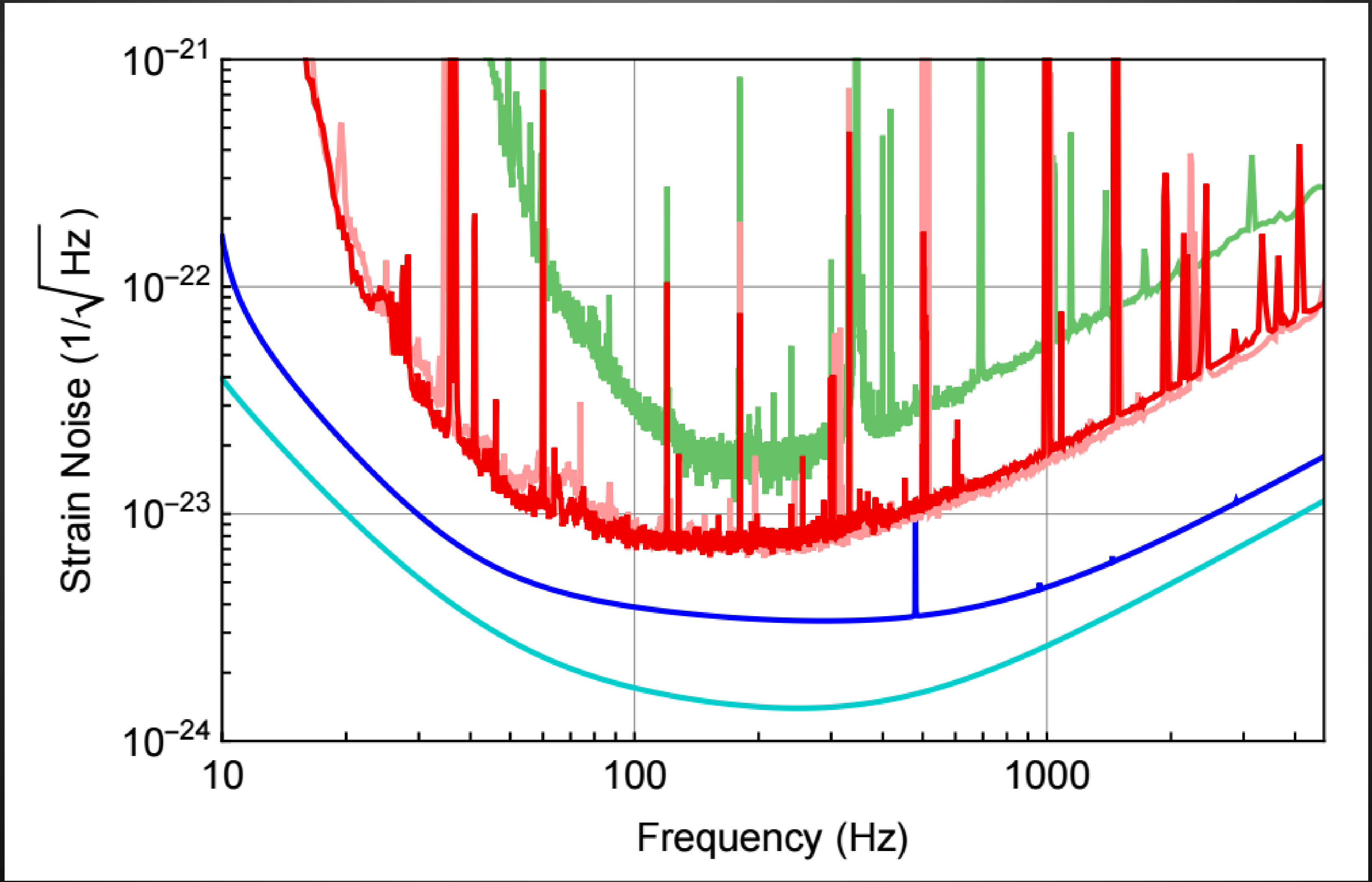

Dwyer et al
http://dx.doi.org/10.1103/PhysRevD.91.082001

# Thanks for your attention!

- LIGO has detected gravitational waves from a binary black hole merger
- This required making the most precise displacement measurements ever made
- Several techniques, including squeezing, are available to improve the sensitivity further

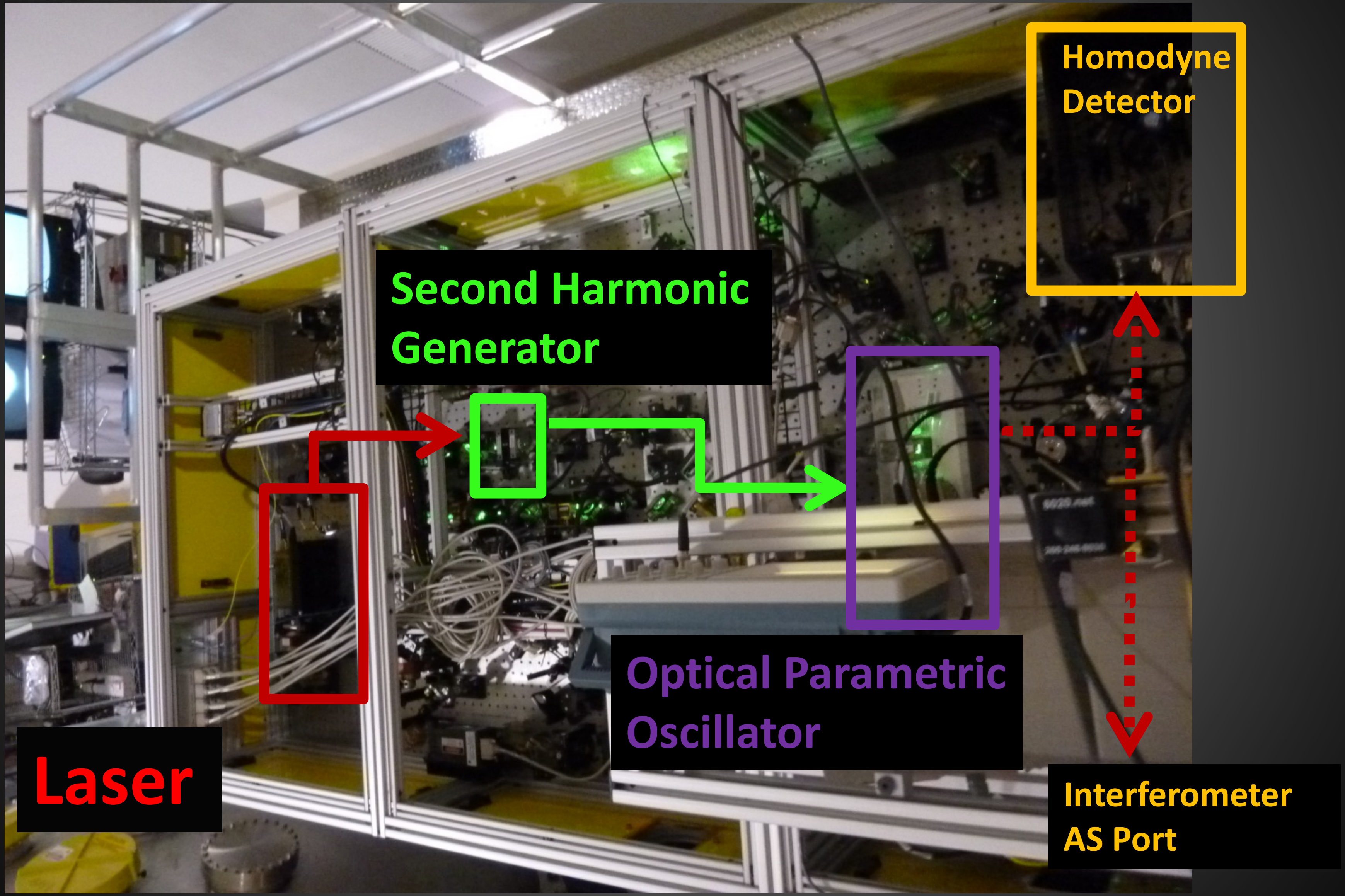

Jorge Cham @ PhD comics

# Extra Slides

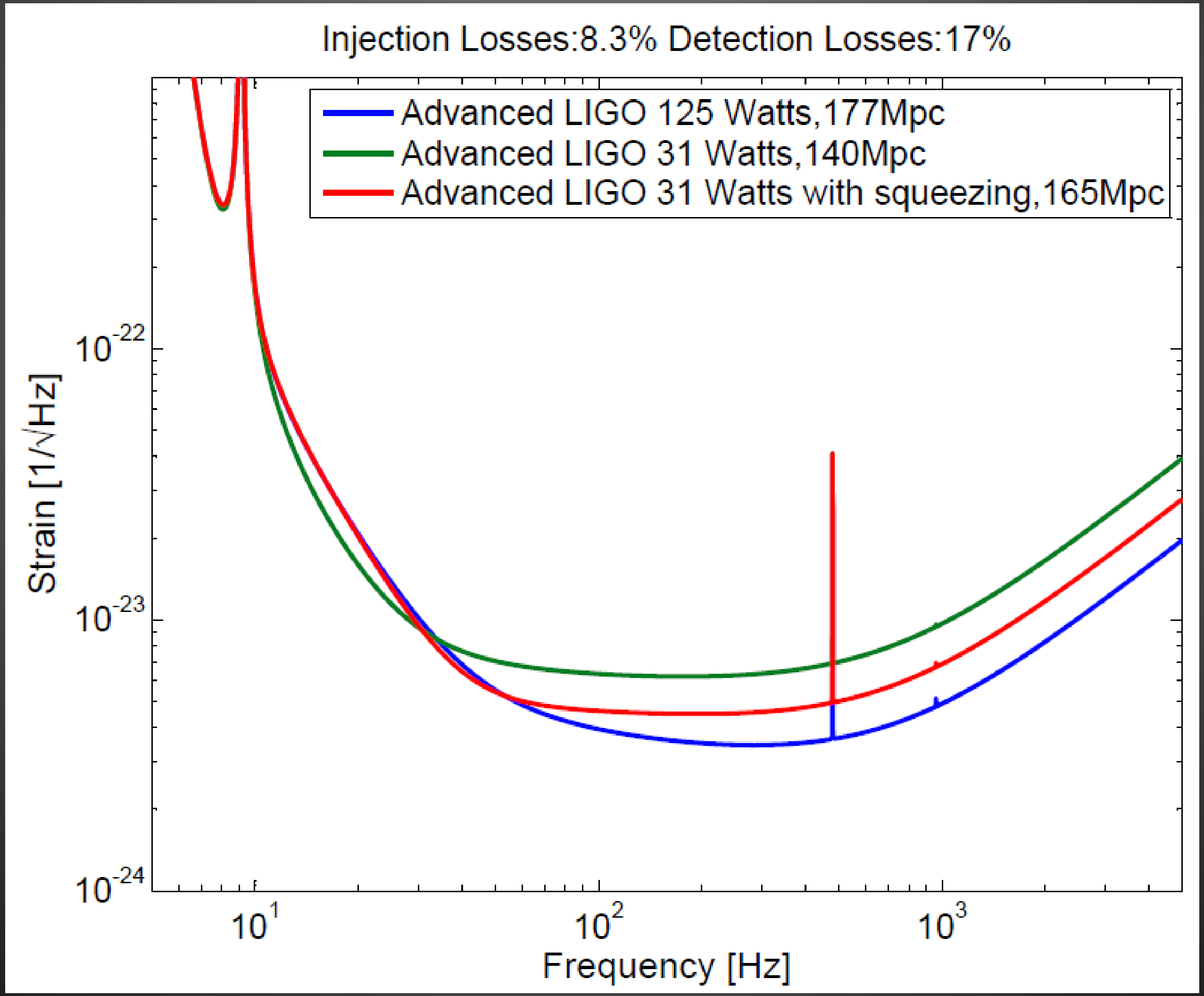


Strain Noise (1/√Hz)
10^−21
10^−22
10^−23
10^−24
10
100
1000
Frequency (Hz)

# A squeezer table

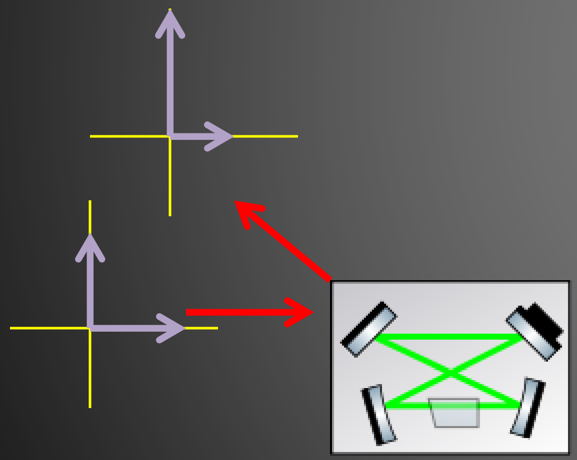


# An alternative to high power operation in Advanced LIGO



# Squeezer: Optical parametric oscillator

Classical OPO:
Phase sensitive amplifier



Quantum OPO:
Turns a vacuum state into
 squeezed vacuum