GWs, Quantum Noise & Squeezed Vacuum States of Light in Terrestrial Interferometers

Steven Saliterman

LIGO (Laser Interferometer Gravitational Wave Observatories) in Livingston, LA & Hanford, WA

Virgo in Santo Stefano a Macerata, Italy

KAGRA in Hida, Japan

Other: GEO600, Hannover, Germany

Future: LIGO-India, Cosmic Explorer (US) & Einstein Telescope (EA)

Space based: LISA

A simulation of an NSBH binary merger consistent with GW200105

Deborah Ferguson (UT Austin), Bhavesh Khamesra (Georgia Tech), and Karan Jani (Vanderbilt University).

Gravitational waves & quantum noise

- Gravitational waves (GW) are space-time deformations created by astrophysical events such as supernovas, and black hole and neutron star mergers. They are emitted by accelerated masses.
- Rai Weiss at MIT in 1972[1] reported on the *various noise sources and counter measures* required to achieve the necessary detection sensitivities using a *Michelson laser interferometers* with *Fabry–Pérot cavities.* Changes of less than 10^{-18} m, or *stain sensitivities,* up to $10^{-23} / \sqrt{Hz}$ were obtainable.
- Sensitivity is primarily limited by (1) shot noise (SN), which depends on *phase* fluctuations of the optical field disturbing the detector at high frequencies, and (2) radiation pressure noise, which depends on *amplitude* fluctuations of the optical field perturbing the position of suspended mirrors at low frequencies.

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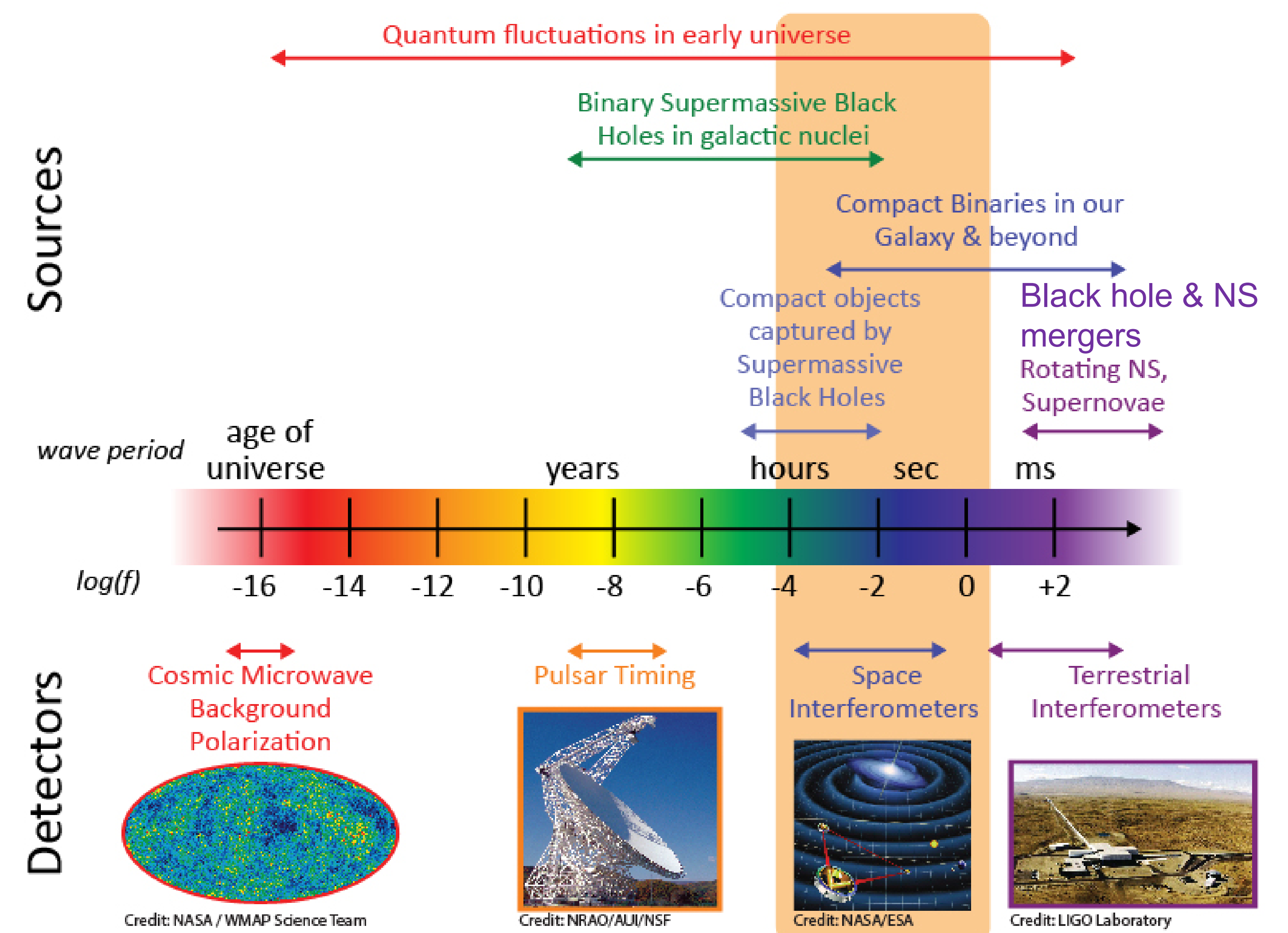
[1] Internal MIT report series , 1972.

Garaventa B, Bawaj M, De Laurentis M, et al. Frequency-dependent squeezing generation with EPR entanglement. 2019:

The Gravitational Wave Spectrum



Frequency Range:

70 GHz to 217 GHz

30 MHz to 300 GHz (10-1 m)

0.1 mHz to .1 Hz

10 Hz to 200 Hz (29-1.5 Mm)

Gravitational waves transport energy as gravitational radiation, a form of radiant energy similar to electromagnetic radiation.

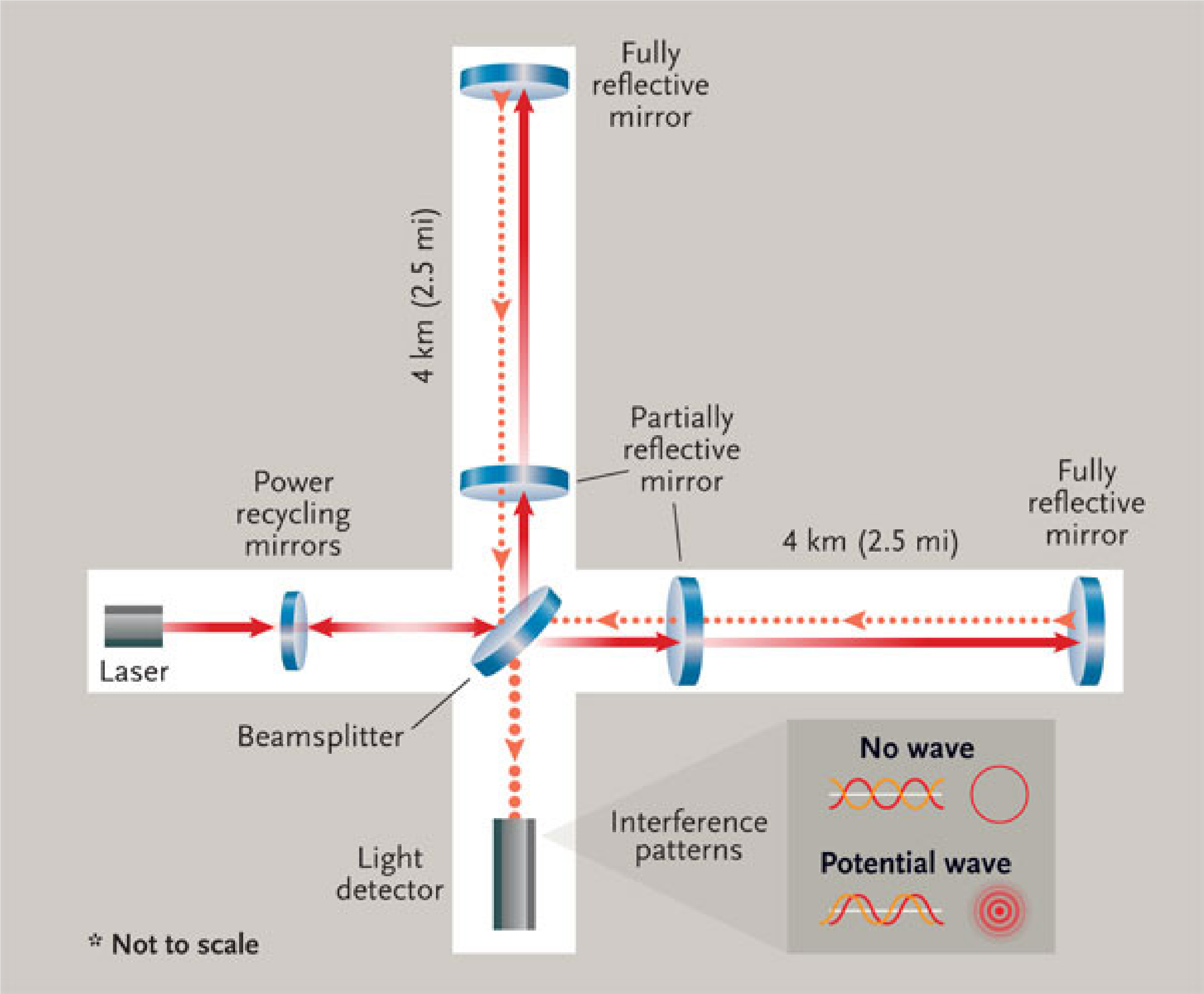
Derived from https://lisa.nasa.gov/

Basic *Michelson Interferometer* with *Fabry–Pérot* Cavities

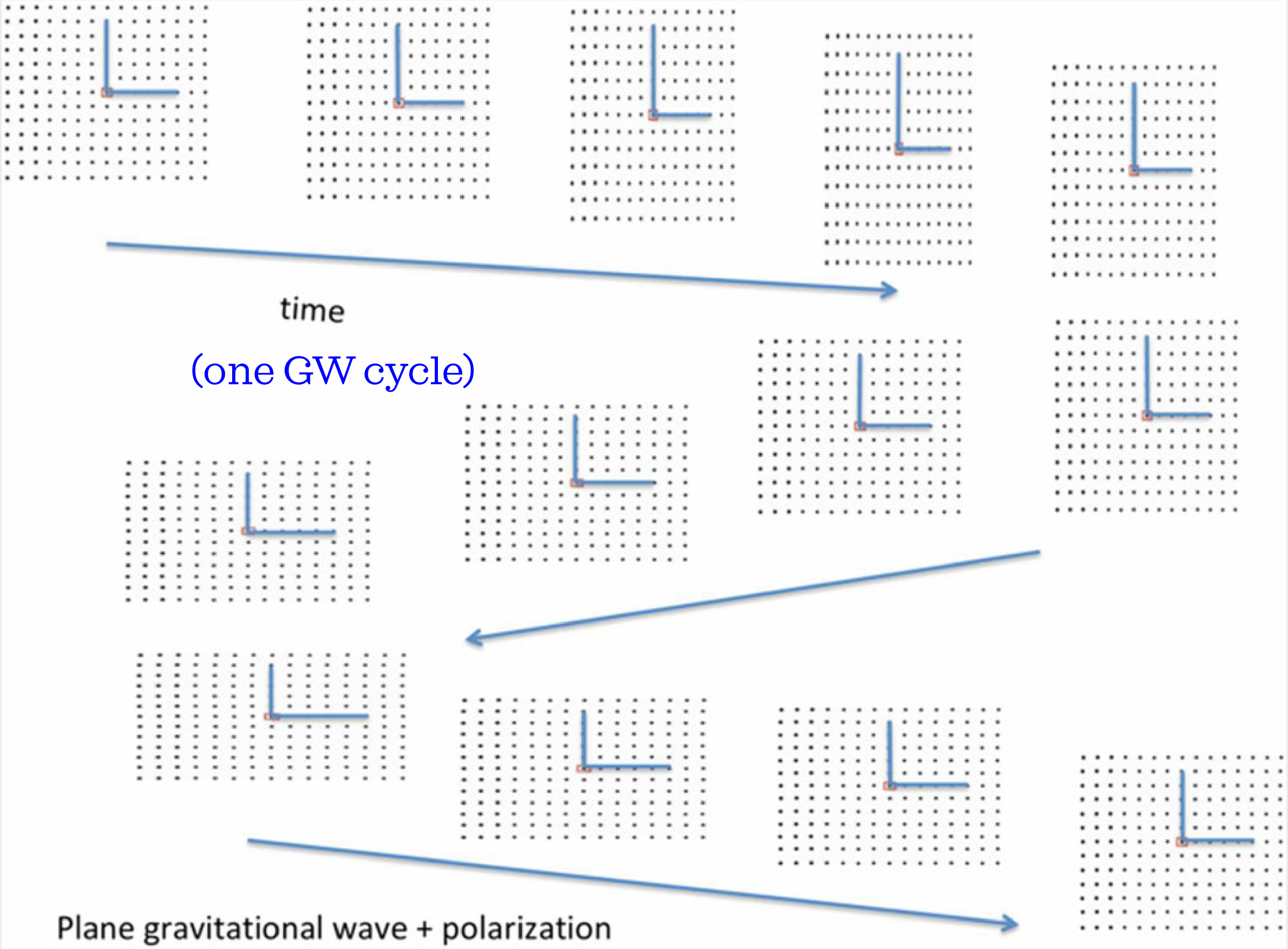
The laser in each arm bounces between its two mirrors about *300 times* before being merged with the beam from the other arm. This gives an effective distance of 1200 km.

The more laser photons merge from each arm the sharper the fringes that are measured by the photodetector.

The power recycling mirror continually reflects the laser light that has traveled through the instrument *back into* the interferometer.



LIGO & https://skyandtelescope.org/astronomy-news/gravitational-wave-detection-heralds-new-era-of-science-0211201644/



Sets of masses are illustrated distributed across space to show simultaneous strain and stretching.

“L” is the interferometer arms. The longer the arms the more the displacement.

A transverse GW will cause stain in space perpendicular to the direction in which they propagate.

Rainer Weiss – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023.
<https://www.nobelprize.org/prizes/physics/2017/weiss/lecture/>

Transduction of gravitational wave to an optical signal

- Gravitational-wave detectors convert the space-time strain caused by a gravitational wave into a change in optical power at their output. The differential displacement ΔL between test masses along the orthogonal interferometer arms is proportional to the gravitational-wave strain amplitude h.

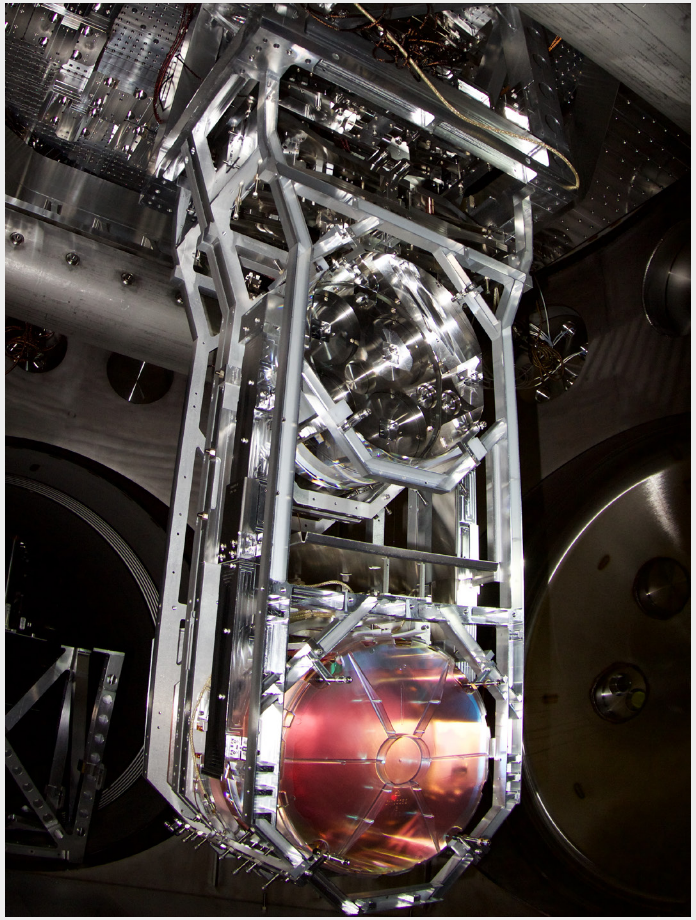
$$h = \frac{\Delta L}{L} = \frac{\delta L_x - \delta L_y}{L} \qquad \text{Lengths } L_x = L + \delta L_x \text{ and } L_y = L + \delta L_y$$

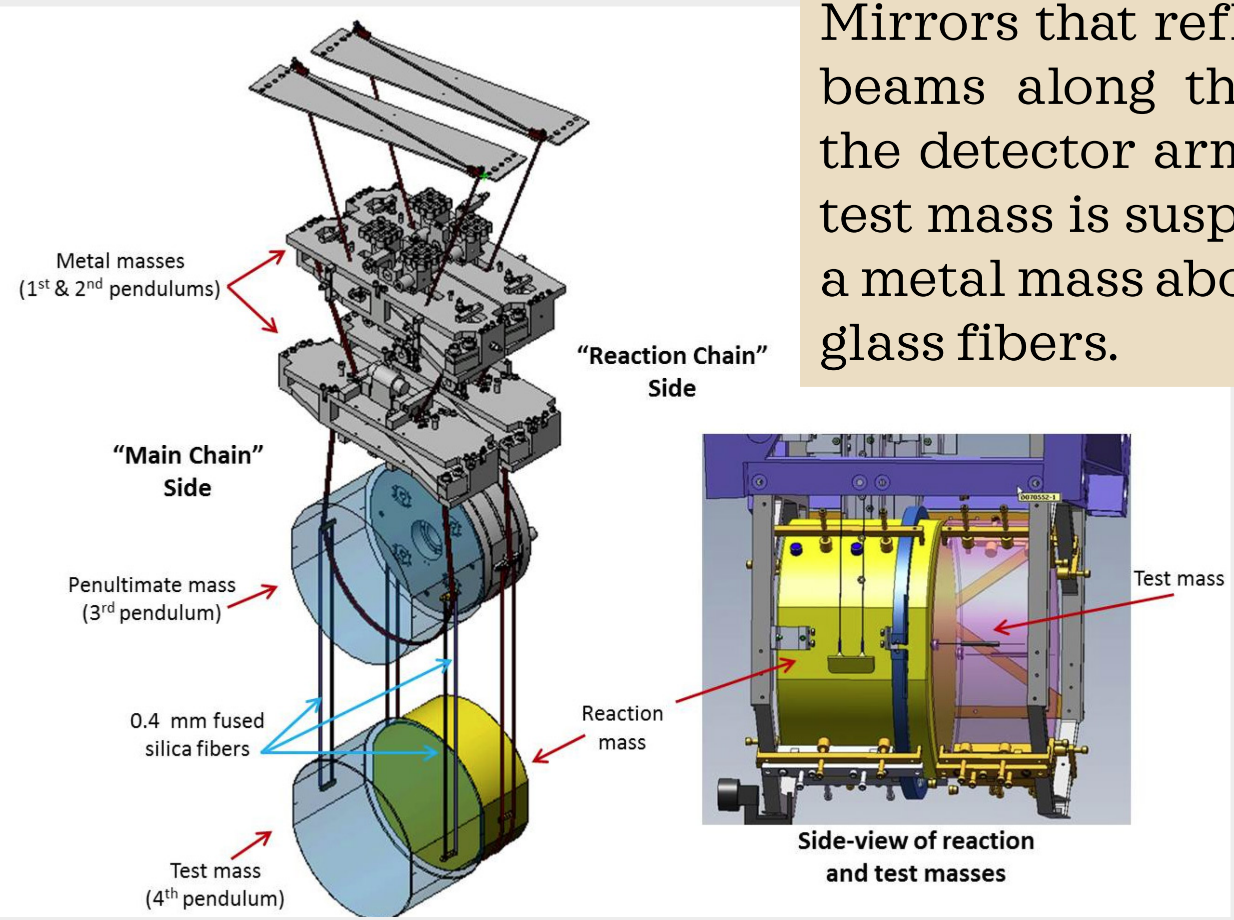
Barsotti L, Harms J, Schnabel R. Squeezed vacuum states of light for gravitational wave detectors. *Reports on Progress in Physics*. Jan 2019;82(1)016905. doi:10.1088/1361-6633/aab906

- These optical power fluctuations are detected by a *photodiode*, and the light's energy can only be absorbed in *discrete quanta* (photons).
- The *random arrival time* of each individual photon results in *photon-counting noise* and causes the output power of a laser interferometer to fluctuate, even in the absence of a passing gravitational wave.
- *Sufficiently small gravitational waves will be hidden by this shot noise*, which thereby limits the detector's sensitivity.

Barsotti L, Harms J, Schnabel R. Squeezed vacuum states of light for gravitational wave detectors. *Reports on Progress in Physics*. Jan 2019;82(1)016905. doi:10.1088/1361-6633/aab906

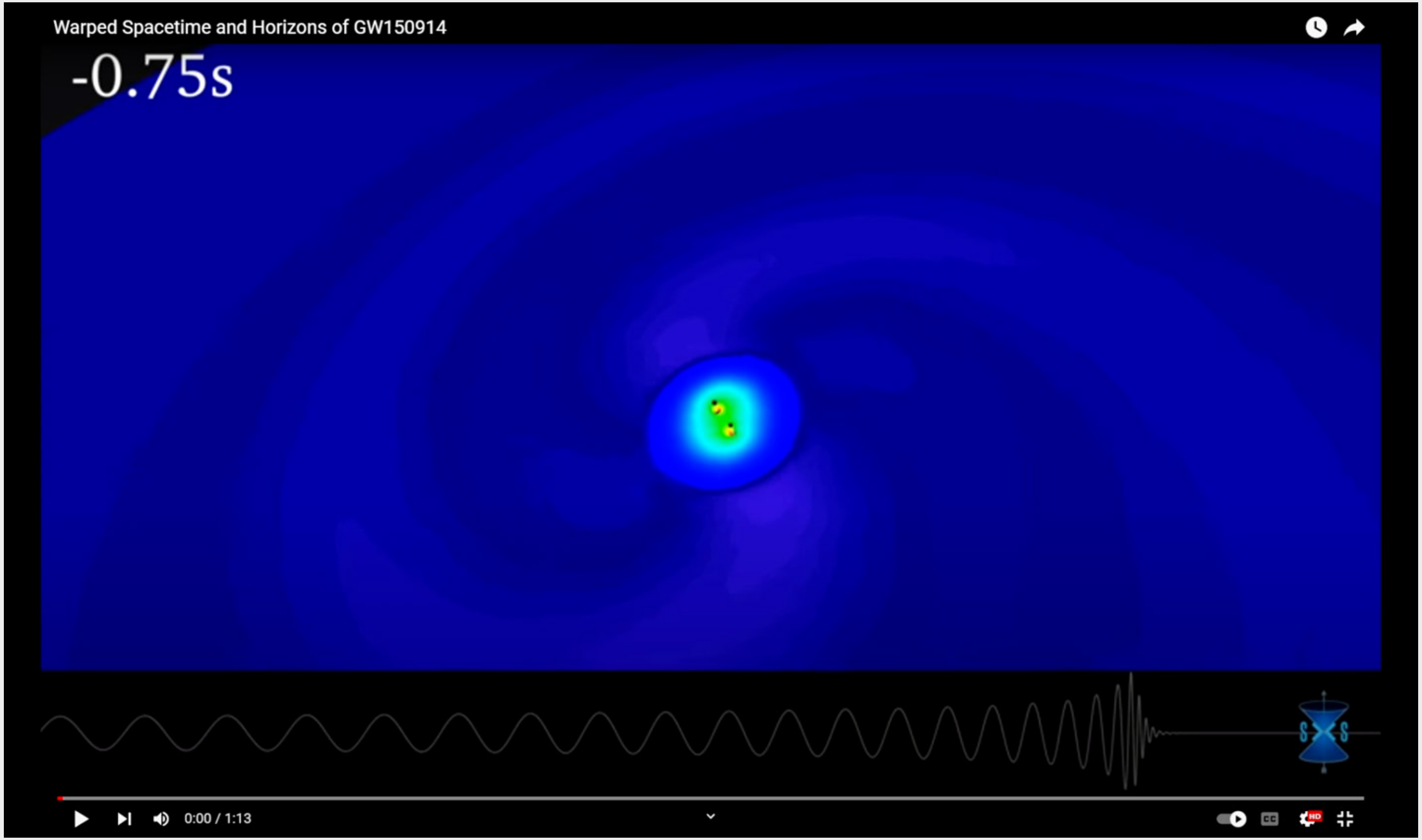
LIGO’s interferometer test masses installed in its quad suspension system.





Mirrors that reflect the laser beams along the lengths of the detector arms. The 40 kg test mass is suspended below a metal mass above by 4 silica glass fibers.

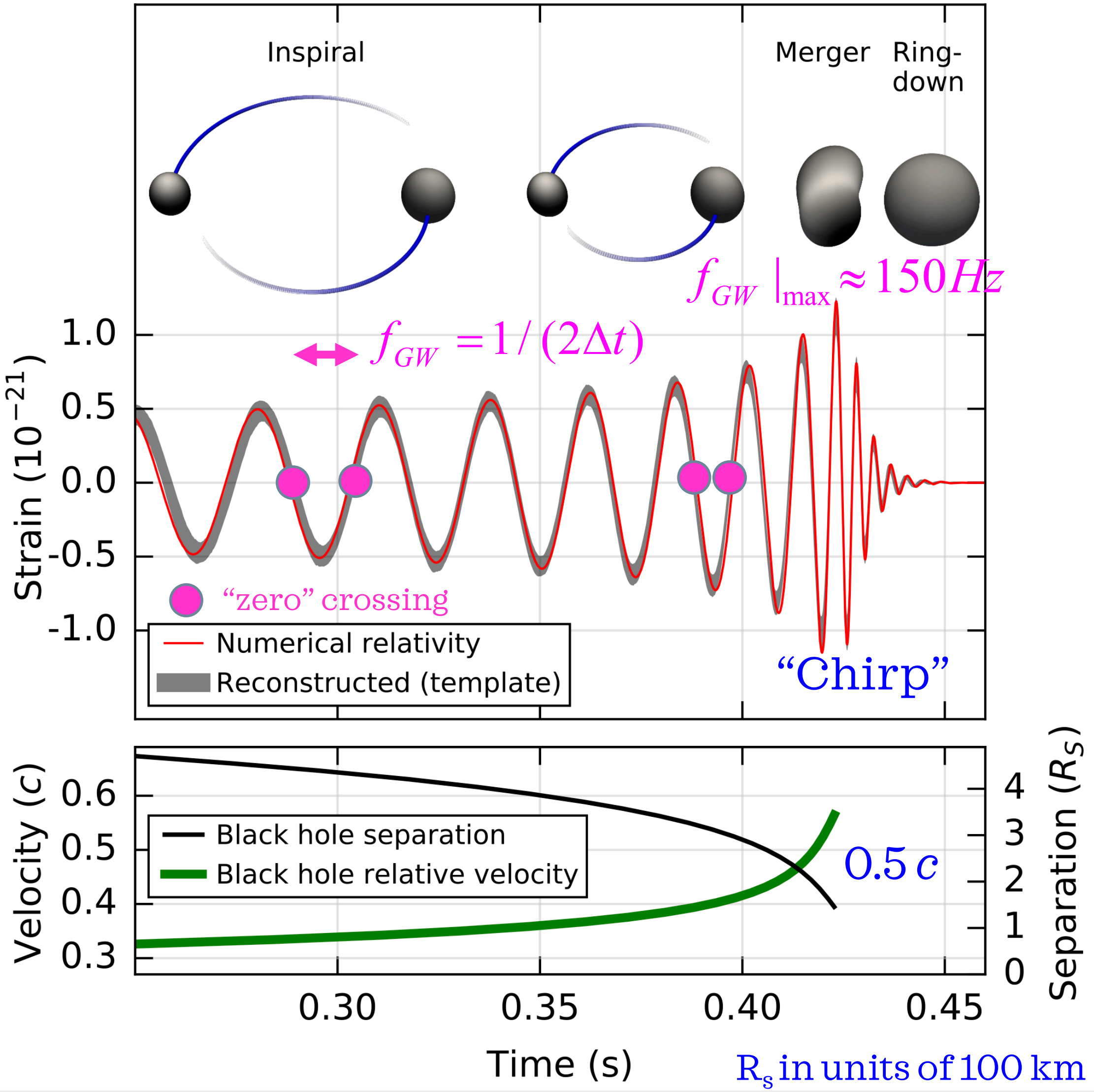
Caltech/MIT/LIGO Lab



Warped Spacetime and Horizons of GW150914

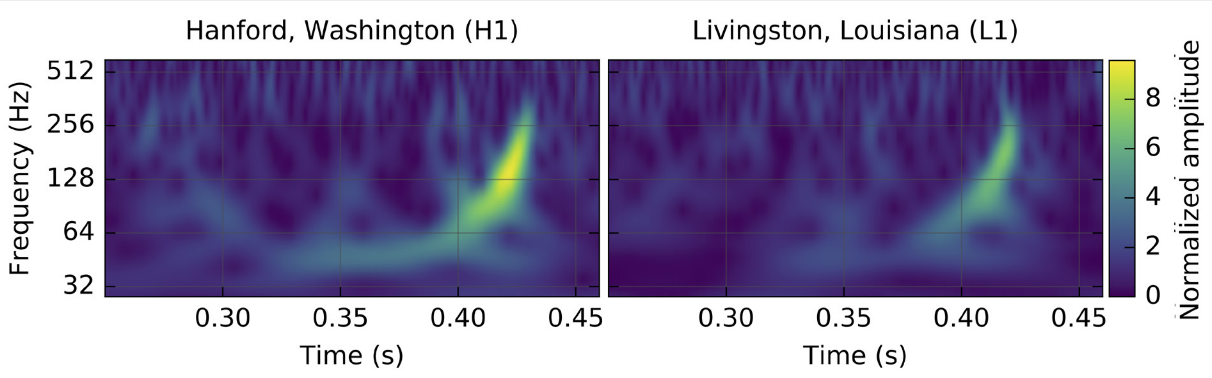
SXS Collaboration https://youtu.be/c-2XIuNFgD0

GW150914 (September 14, 2015)



R_s in units of 100 km

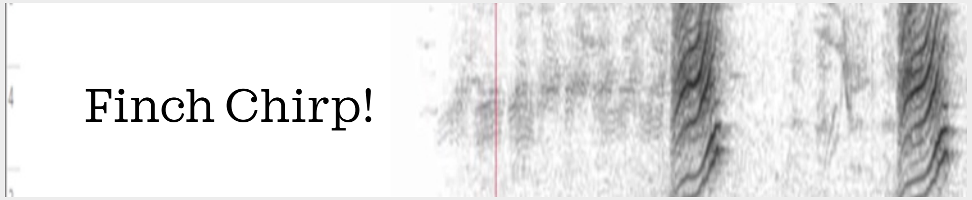
PB filter & instrument noise notch filters



Gravitational wave strain produced by the event as a function of time (s) and frequency (Hz, or number of wave cycles/s). Upward swing 35-150 Hz in 0.2 s.

The waveform describes the merger, coalescence and ringdown, detailing parameters of the merger.

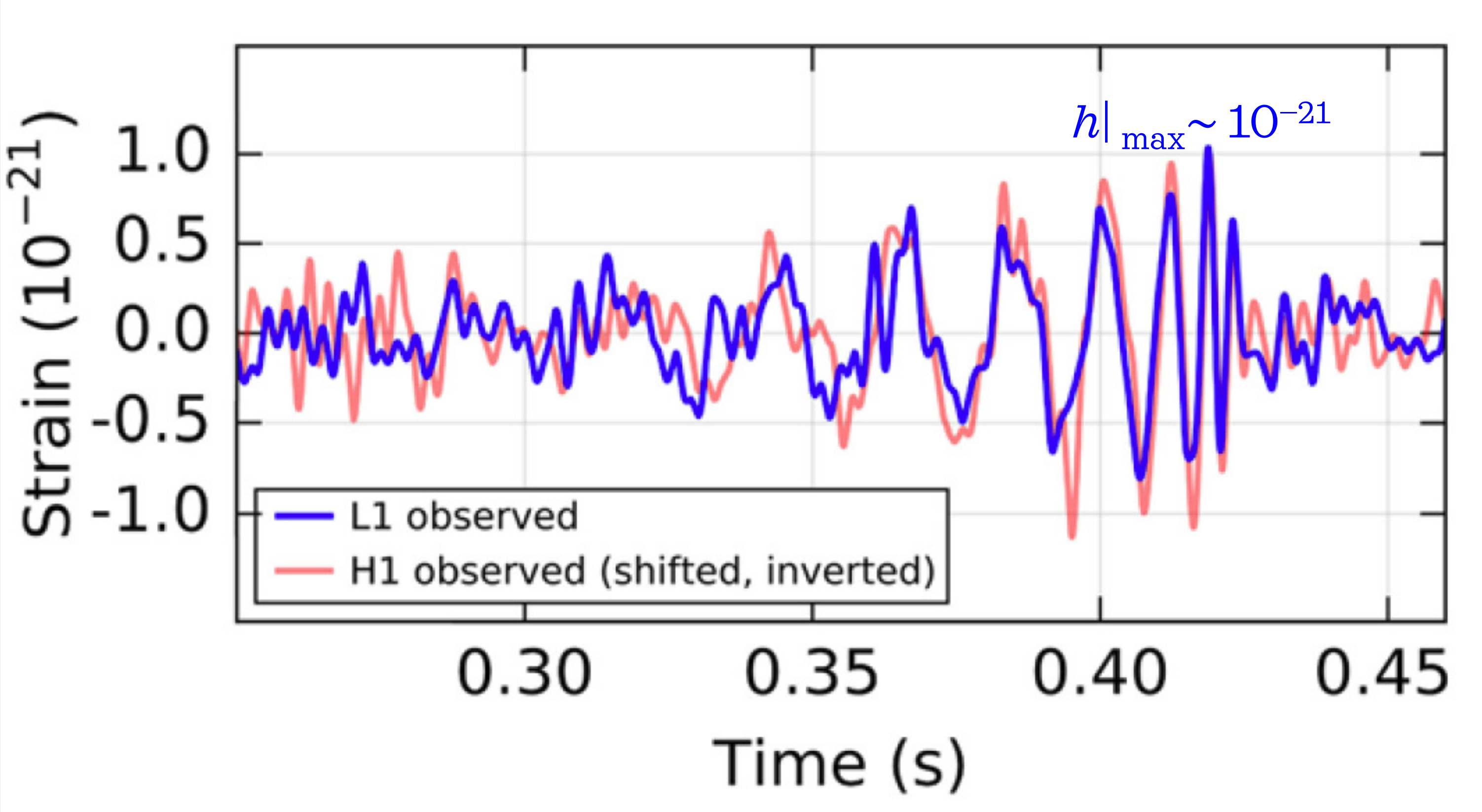
With inspiral the orbital frequency goes up ("chirps"), while by Kepler's Law the orbital separation shrinks.



https://www.ligo.org/science/faq.php#what-are-gw

https://macaulaylibrary.org/asset/244151591

Strain data Livingston vs Hanford detectors



The delay between sites was 6.9 ms, consistent with the time taken for light, or gravitational waves, to travel between the two detectors.

(The Hanford strain here has been shifted back in time by 6.9 ms and inverted.)

Abbott BP, Abbott R, Abbott TD, et al. The basic physics of the binary black hole merger GW150914. *Annalen Der Physik*. Jan 2017;529(1-2)1600209. doi:10.1002/andp.201600209

“Chirp” mass M_C for a two-body system

The orbits decay as the two black holes accelerate around each other and emit energy into gravitational waves determined by the “chirp mass,” as defined below:

1. Chirp mass: $M_C = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$

2. $$M_C = \frac{c^3}{G}\left(\left(\frac{5}{96}\right)^3 \pi^{-8} (f_{GW})^{-11} (\dot{f}_{GW})^3\right)^{1/5}$$

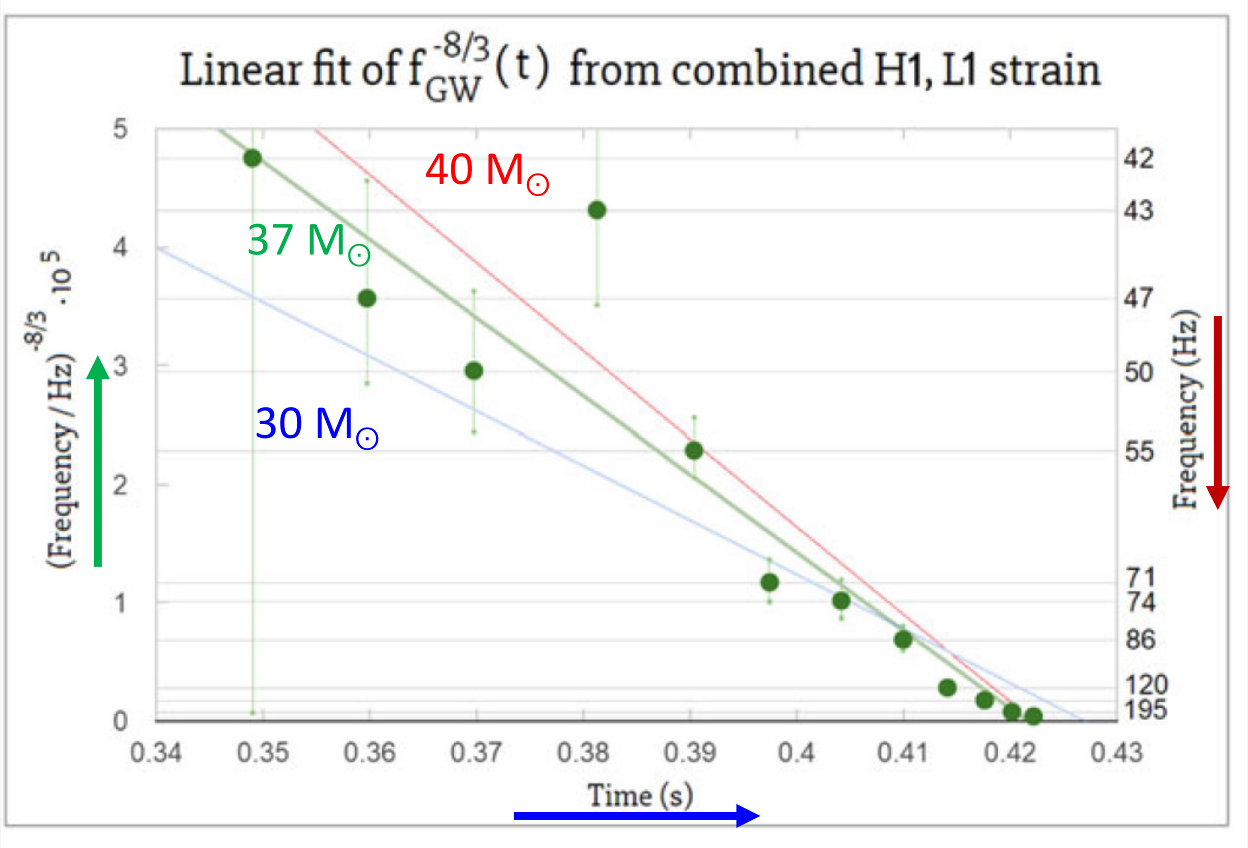
Where $\dot{f}_{GW} = df_{GW} / dt$ is the rate of change of the frequency.

3. Rearrange and integrate with t_C as the time of coalescence:

$$f_{GW}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{GM_C}{c^3}\right)^{5/3} (t_C - t)$$

Chirp mass can be related to Newtons Law of Motion & Universal Law of Gravitation, and Einsteins quadripole formula of GW luminosity, thereby relating the frequency and frequency derivative of an emitted GW to the chirp. *

* See the following for the derivation (appx. A) : Abbott BP, Abbott R, Abbott TD, et al. The basic physics of the binary black hole merger GW150914. *Annalen Der Physik*. Jan 2017;529(1-2)1600209.



M_C can be calculated directly from the time period (zero crossings).

$$f_{GW}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{GM_C}{c^3}\right)^{5/3}(t_C - t)$$

Recall y=mx

The graph shows a linear fit (green line) of $f_{GW}^{-8/3}(t)$. The slope of this fitted line gives an estimate of the chirp mass of ~ 37 M⊙.

The fit shown has residual sum of squares $R^2_{L1-H1} \sim 0.9$; *(authors also found $R^2_{H1} \sim 0.9$ and $R^2_{L1} \sim 0.8$.). (The error-bars have been estimated by repeating the procedure for waves of the same amplitudes and frequencies added to the LIGO strain data just before GW150914. A similar error estimate has been found using the differences between H1 and L1 zero-crossings.)*

Abbott BP, Abbott R, Abbott TD, et al. The basic physics of the binary black hole merger GW150914. *Annalen Der Physik*. Jan 2017;529(1-2)1600209. doi:10.1002/andp.201600209

Distance based on luminosity

GW luminosity from an equal-mass binary inspiral has a peak value which is independent of the mass. Plank Luminosity:

1. $L \sim L_{Plank} = c^5 / G = 3.6x10^{52}\ \mathrm{W}$, Where $L \sim \frac{G}{c^5} M^2 r^4 \omega^6$, $\omega \sim c/r$, $r \sim GM/c^2$ and $M\omega \sim c^3/G$

Omega ω is the orbital angular frequency in radians/sec.

Relating the luminosity of GWs to their strain h at luminosity d_L:

2. Luminosity $L \sim \frac{c^3 d_L^2}{4G} |\dot{h}|^2 \sim \frac{c^5}{4G}\left(\frac{\omega_{GW} d_L h}{c}\right)^2$

3. $\frac{L_{Peak}}{L_{Planck}} \equiv \frac{L_{\max}}{L_{Planck}} \sim 0.2x10^{-3} \sim \left(\frac{\omega_{GW} d_L h_{\max}}{c}\right)^2$

4. Distance $d_L \sim 45\ \mathrm{Gpc}\left(\frac{\mathrm{Hz}}{f_{GW}|_{\max}}\right)\left(\frac{10^{-21}}{h_{\max}}\right) \sim 300\ \mathrm{Mpc}$ (for GW150914, $z \le 0.1$)

L_{peak} in the form of GWs was ~22 orders of magnitude greater than then the output of the sun!

Alternatively, the gravitational wave amplitude h falls off with increasing luminosity distance dL as h ∝ 1/dL.

Abbott BP, Abbott R, Abbott TD, et al. The basic physics of the binary black hole merger GW150914. *Annalen Der Physik*. Jan 2017;529(1-2)1600209. doi:10.1002/andp.201600209

Energy radiated as GW

1. Around the time of peak amplitude the bodies had an orbital separation given by:

$R = \left(\frac{GM}{\omega^2_{\text{Kep|max}}} \right)^{1/3} = 350\text{ km}$ where omega ω is the orbital frequency and $M = m_1 + m_2$

2. Orbital Energy: $E_{\text{orb}} = -\frac{GM\mu}{2r}$ where mu μ is the reduced mass $= m_1 m_2 / M$

3. $E^i_{\text{orb}} \to 0$ for a very large *inital* separation down to r,

and for GW150914, $m_1 \sim m_2 \sim 35M_\odot$ and $r \sim R = 350$ km:

$E_{GW} = E^i_{\text{orb}} - E^f_{\text{orb}} = 0 - \left(-\frac{GM\mu}{2R} \right) \sim 3M_\odot c^2$ (Where i and f refer to intial and final.)

Abbott BP, Abbott R, Abbott TD, et al. The basic physics of the binary black hole merger GW150914. *Annalen Der Physik*. Jan 2017;529(1-2)1600209. doi:10.1002/andp.201600209

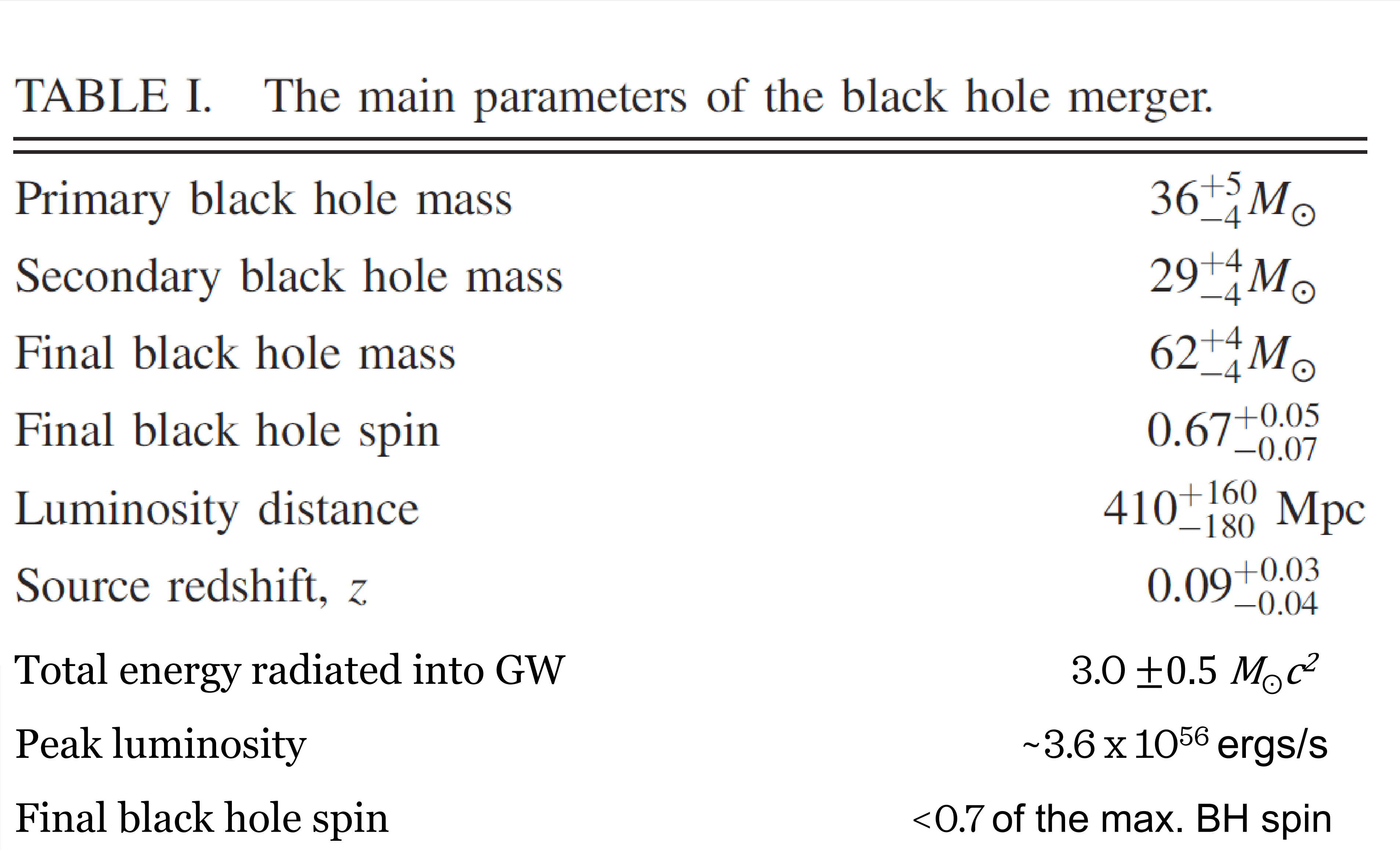
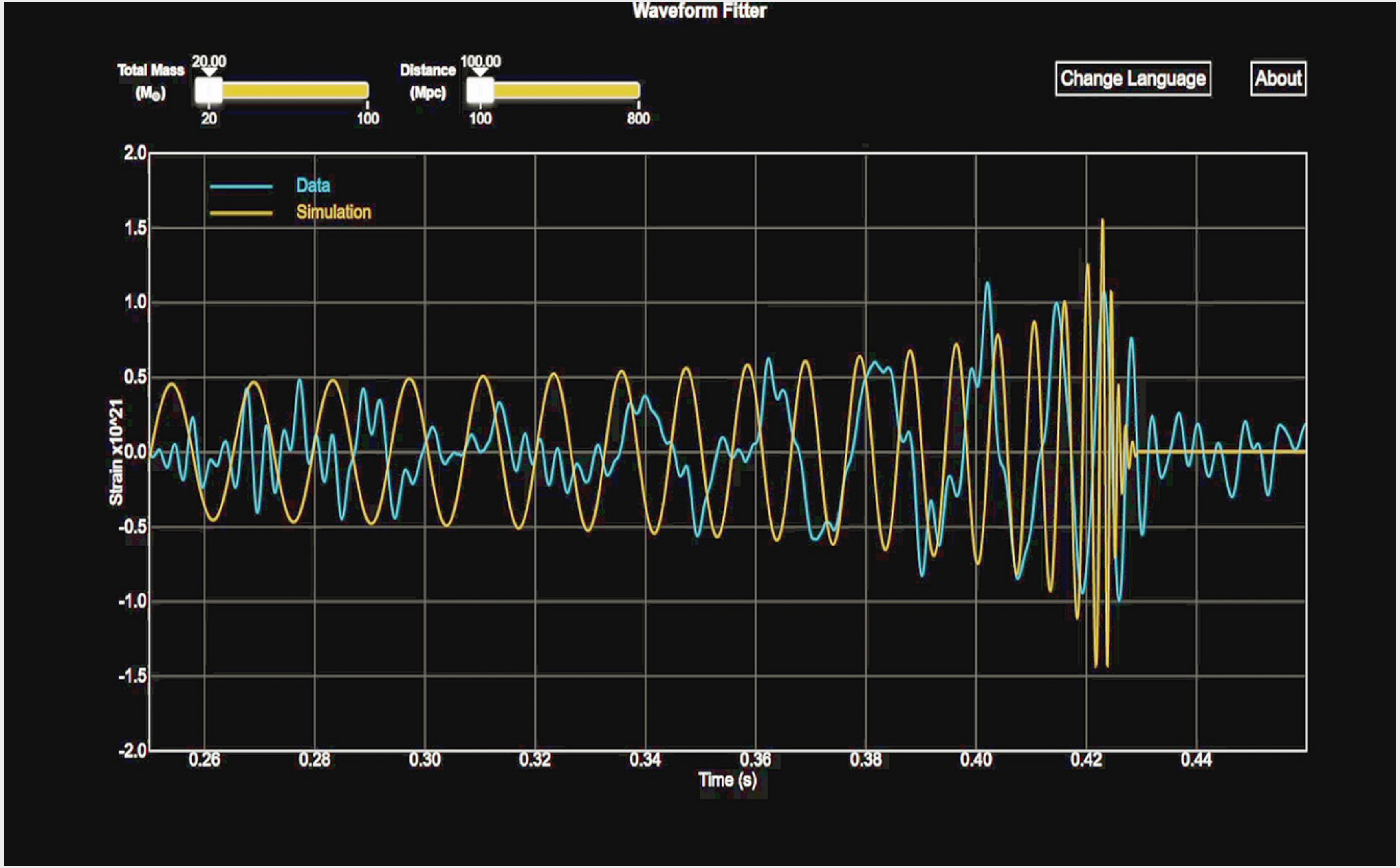


TABLE I. The main parameters of the black hole merger.

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$
Total energy radiated into GW	$3.0 \pm 0.5\ M_\odot c^2$
Peak luminosity	~3.6×10^{56} ergs/s
Final black hole spin	<0.7 of the max. BH spin

Barry C. Barish – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023.
<https://www.nobelprize.org/prizes/physics/2017/barish/lecture/>

Determining Mass & Distance by fitting Simulation to Data

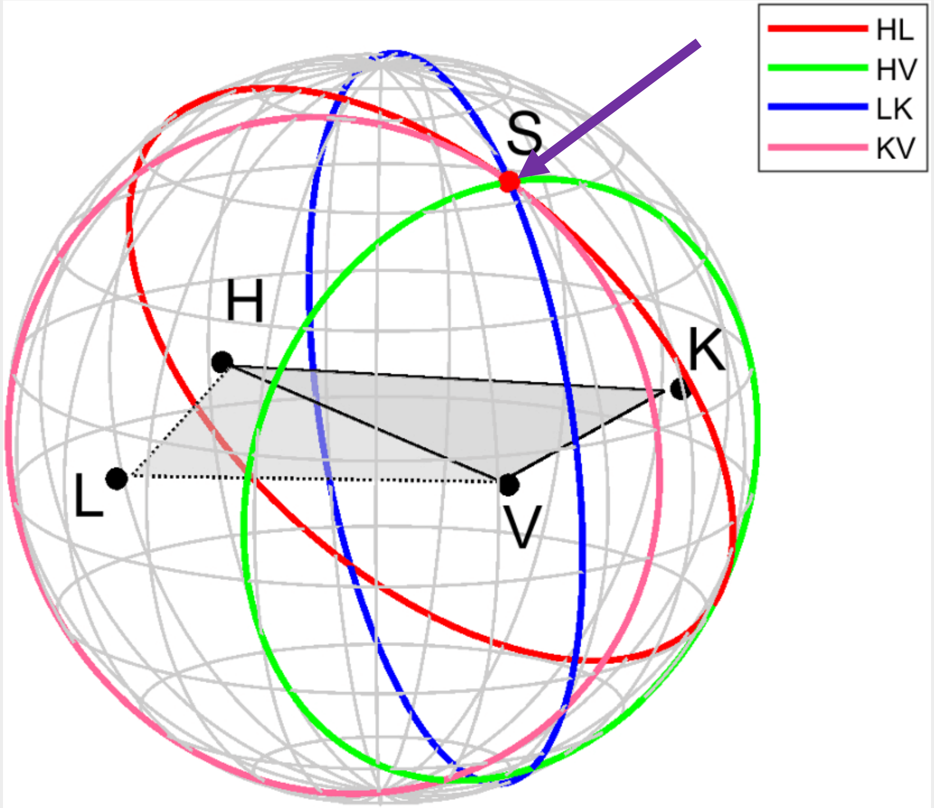


Total Mass ($M_\odot$) 20.00

Distance (Mpc) 100.00

https://data.cardiffgravity.org/waveform-fitter/

Triangulation of a GW



The locations of the four detectors are indicated by black dots, with LIGO Hanford labeled H, LIGO Livingston as L, Virgo as V and KAGRA as K.

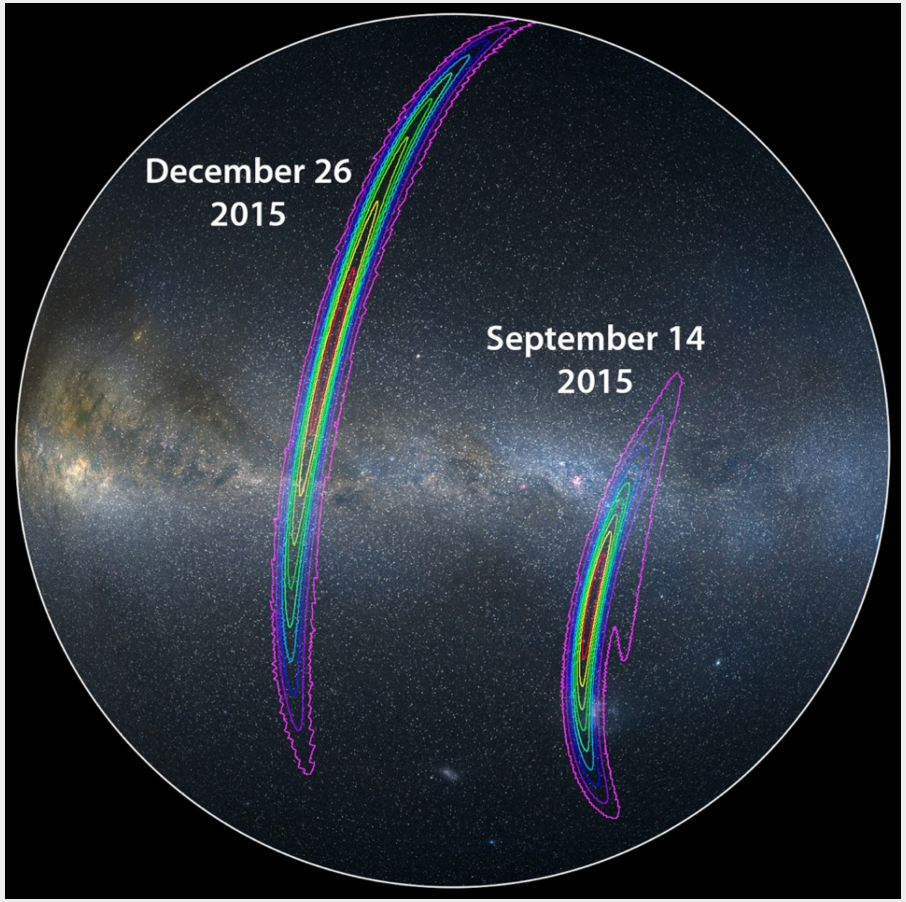
The locus of constant time delay (with associated timing uncertainty) between two detectors forms an annulus on the sky concentric about the baseline between the two sites (e.g. labeled by the two detectors H and V).

For four or more detectors there is a unique intersection region, S.

Image adapted from Chatterji et al. (2006)

Abbott BP, Abbott R, Abbott TD, et al. Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo. *Living Reviews in Relativity*. 2016;19:1-+. doi:10.1007/lrr-2016-1

Localization of GW150914 & GW151226



Localization was to only ~600 & 800 square degrees respectively without benefit of triangulation.

https://www.ligo.org/science/faq.php#what-are-gw

What is "Squeezed States of Light"?

- Also called nonclassical states of light, a subject of quantum optics.
- Any measurement of the complex amplitude of the light field can deliver different values within an uncertainty region.
- Squeezed light is best understood by considering complex phasors for the representation of the state of light in one mode of the optical field. Classically, such a state can be represented by a certain phasor (or its end point in the complex plane).
- There is an uncertainty relation for the quadrature components of the light field, saying that the product of the uncertainties in both components is at least some quantity times Planck's constant *h*.

Dr. Rüdiger Paschotta. https://www.rp-photonics.com/squeezed_states_of_light.html

Squeezed states of light to lessen quantum noise

- A squeezed state with no coherent amplitude is called a *squeezed vacuum state of light*.
- If such a state is overlapped with a coherent laser beam on a semitransparent beam splitter, the two beam-splitter outputs that are generated are *quantum correlated (i.e. a non-separable or entangled state).*
- The squeezed states are injected into the output port of a gravitational-wave detector, producing entangled states in the interferometer arms which are recombined on the beam splitter and leave the interferometer to the output photodiode as squeezed states.

Barsotti L, Harms J, Schnabel R. Squeezed vacuum states of light for gravitational wave detectors. *Reports on Progress in Physics*. Jan 2019;82(1)016905. doi:10.1088/1361-6633/aab906

Benefits of squeezed vacuum states of light

- Replacing regular vacuum states with squeezed vacuum states of light provides a means of improving the *signal-to-noise ratio* of gravitational-wave detectors without increasing the circulating light power or the mirror mass
- With the injection of squeezed states, detectors demonstrated their best broadband sensitivity to gravitational waves.
- Sensitivity enhancements up to 3.2 +/- 0.1 dB beyond shot noise limit.

Barsotti L, Harms J, Schnabel R. Squeezed vacuum states of light for gravitational wave detectors. *Reports on Progress in Physics*. Jan 2019;82(1)016905. doi:10.1088/1361-6633/aab906

Aasi J, Abadie J, Abbott BP, et al. Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light. *Nature Photonics*. Aug 2013;7(8):613-619. doi:10.1038/nphoton.2013.177

Detection

- The dual-recycled *Michelson interferometers with Fabry–Pérot cavities* will pass light through the optical cavity only when they are in resonance with it. [1]
- A gravitational wave of optimal polarization normally incident upon the interferometer plane, will cause one arm to decrease in length, while the other increases. The stretching and squeezing of the spacetime between the mirrors results in more light exiting the interferometer "dark port" to the photodiode. [2]
- Using *squeezed vacuum states of light* improve gravitational wave detection [1]

1. Tse M, Yu HC, Kijbunchoo N, et al. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. *Physical Review Letters*. Dec 2019;123(23)231107. doi:10.1103/PhysRevLett.123.231107
2. Bizouard, MA Gravitational Wave Detection in Encyclopedia of Modern Optics 2nd ed., 2018

History of the utility of squeezed light

- Caves (1980) related the origin of *quantum noise* in an interferometer with *vacuum fluctuations due to the zero-point energy of the electro-magnetic field* , and recognized that *squeezed vacuum states of light* could be used to reduce *quantum noise*.
- Unruh, Yuen and Jaekel (1980-1990) determined that *broadband spectrum of squeezed vacuum states of light can be manipulated* to simultaneously reduce shot noise and radiation pressure noise in a gravitational-wave detector.

Caves C M 1980 Phys. Rev. Lett. 45 75
Caves C M 1981 Phys. Rev. D 23 1693–708
Unruh W G 1983 Quantum noise in the interferometer detector Quantum Optics, Experimental Gravitation, and Measurement Theory ed P Meystre and M O Scully (New York: Plenum) pp 647–60
Yuen H P 1983 Phys. Rev. Lett. 51 719–22
Jaekel M T and Reynaud S 1990 Europhys. Lett. 13 301

First, recall classic electromagnetic optics

- The position, momentum, and number of photons in an EM mode are generally random.
- Consider a plane-wave monochromatic EM mode in a volume *V*, described by the *electric field* Re{E(r, t)}, where :

  1. $\mathbf{E}(r,t) = \left(\frac{2hv}{eV}\right)^{1/2} a\exp(-j\mathbf{k}\bullet\mathbf{r})\exp(j2\pi vt)\hat{\mathbf{e}}$

  Where the complex variable a determines the complex amplitude of the field, such that

  $\frac{1}{2}\varepsilon|A|^2 V = hv|a|^2$, so that $|a|^2$ is energy of the mode expressed in units of photon number.

- $a\exp(j2\pi vt)$ is a rotating phasor whose projection on the real axis determines the sinusoidal field. It also describes the motion of a harmonic oscillator.
- The real and imaginary parts *x* and *rho* $x = \mathrm{Re}(a)$ and $\rho = \mathrm{Im}(a)$ are called the quadrature components of the phasor a because they are a quarter cycle (90°) out of phase with each other. They determine the amplitude and phase of the sine way that represents the temporal variation of the electric field. Also, $\boldsymbol{x}$ ~ to position and ρ ~ to momentum of a harmonic oscillator.

B. E. A. Saleh, Teich M. C. Fundamentals of Photonics, pp. 441, Wiley, 1991.

- Note that a quantum monochromatic electromagnetic mode and a one-dimensional quantum-mechanical harmonic oscillator have identical behavior.
- An EM mode of frequency v is described by a complex waveform *psi*, $\psi(x)$ that governs the uncertainties of the quadrature components of x and *rho*, x and ρ, and the statistics of the number of photons in the mode.
- The probability that $p(n)$ that the mode contains n photons is given by $|c_n|^2$, where the c_n coefficients of the expansion of $\psi(x)$ in terms of the eigenfunction $\psi_n(x)$,

$$2.\ \psi(x) = \sum_n c_n \psi_n(x)$$

- The probability densities of the quadrature components x and ρ are given by the functions psi and phi, $|\psi(x)|^2$ and $|\phi(\rho)|^2$, where $\psi(\cdot)$ and $\phi(\cdot)$ are related by,

$$3.\ \phi(\rho) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \psi(x) \exp(j2\rho x)\ dx$$

- If $\psi(x)$ is known, then $\phi(\rho)$ may be calculated and the probability densities of x and ρ determined. The complex wavefunction psi, $\psi(x)$ therefore determines the uncertainties of the quadrature components of the complex amplitude.

B. E. A. Saleh, Teich M. C. Fundamentals of Photonics, pp. 412-413, Wiley, 1991.

The coherent state

- The Fourier transform relation between psi and phi $\psi(x)$ and $\phi(\rho)$ indicates there is a relation between the power rms widths of the quadrature components given by the uncertainty *sigma* product:

$$4.\ \sigma_x\sigma_\rho \geq 1/4$$

- The uncertainty sigma product $\sigma_x\sigma_\rho$ attains its minimum value of ¼ when the function $\psi(x)$ is Gaussian, and,

$$5.\ \sigma_x = \sigma_\rho = 1/2$$

and the EM is said to be in a coherent state.

B. E. A. Saleh, Teich M. C. Fundamentals of Photonics, pp. 413, Wiley, 1991.

Uncertainties for the coherent & vacuum state

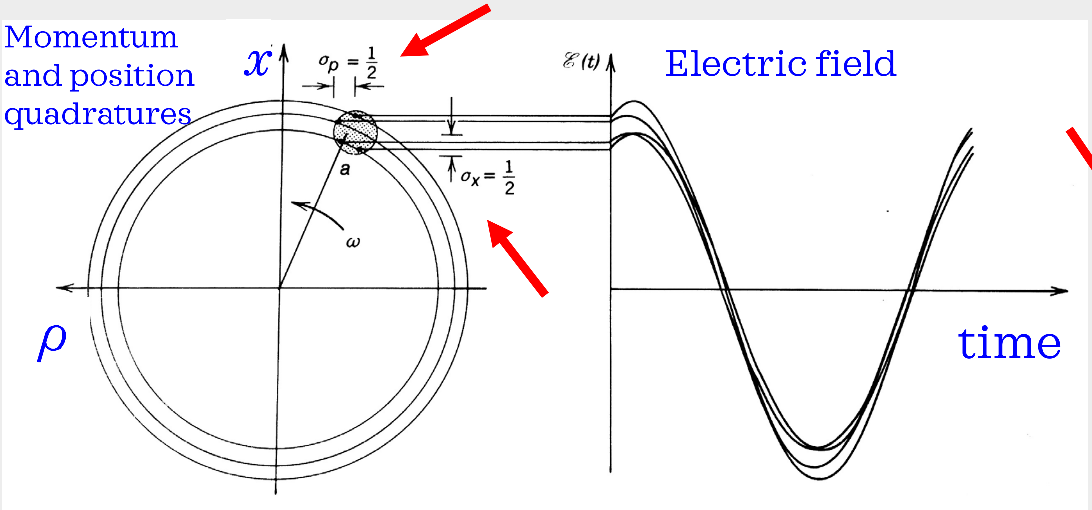
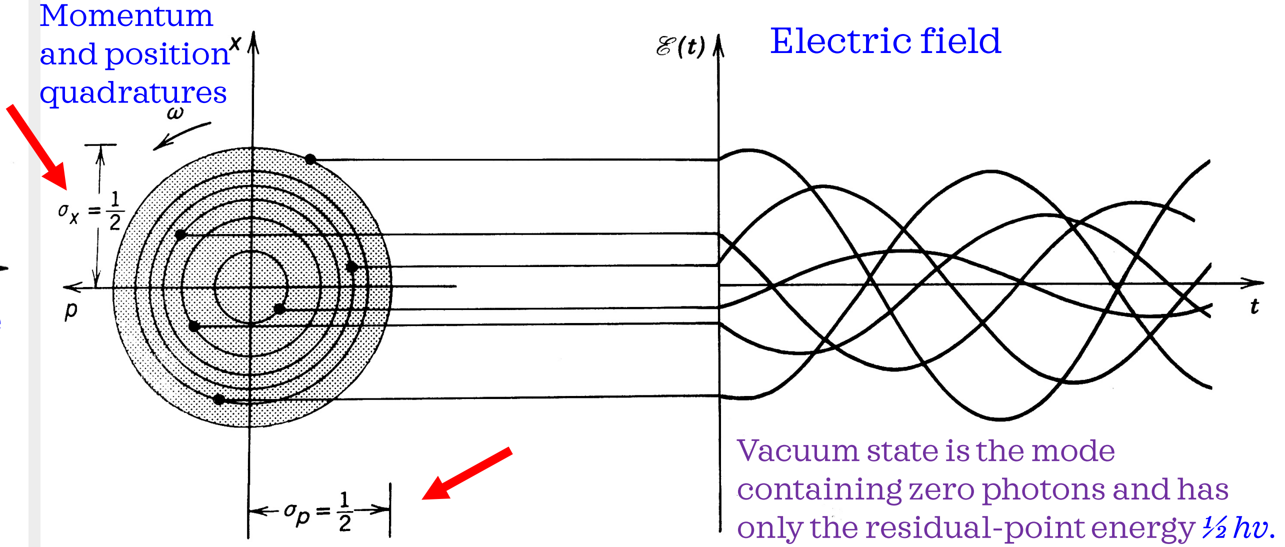


Figure 11.3-2 Uncertainties for the coherent state. Representative values of $\mathscr{E}(t) \propto a \exp(j2\pi\nu t)$ are drawn by choosing arbitrary points within the uncertainty circle. The coefficient of proportionality is chosen to be unity.



Vacuum state is the mode containing zero photons and has only the residual-point energy ½ *hν*.

Figure 11.3-3 Representative uncertainties for the vacuum state.

$\sigma_x = \sigma_\rho = 1/2$ (red arrows)

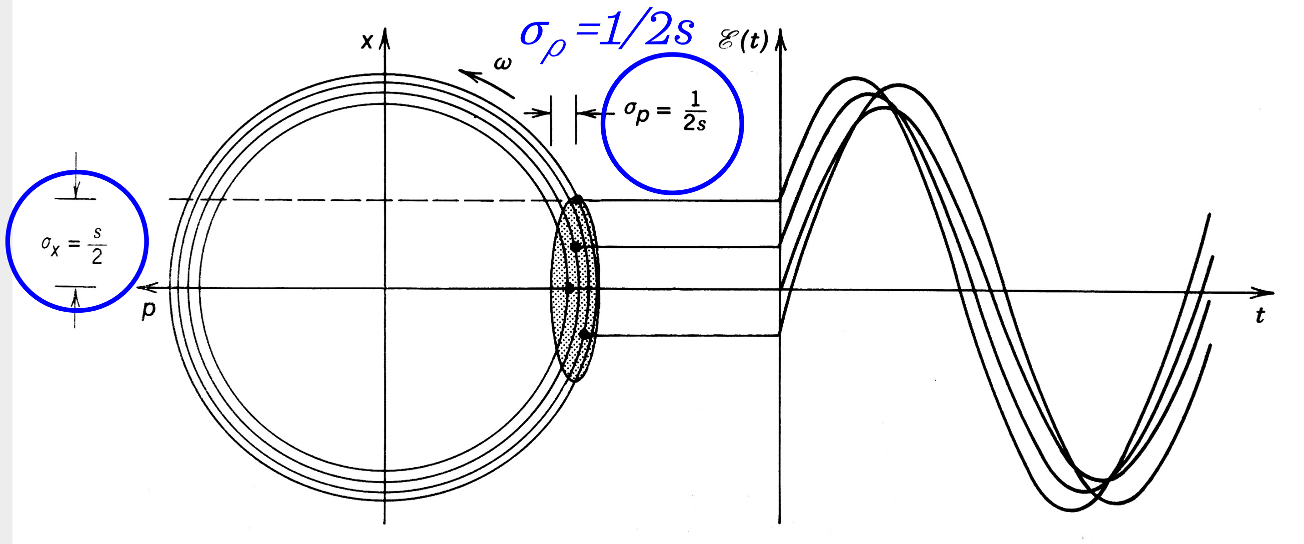
Where x is position and ρ is momentum.
Recall: $x = \mathrm{Re}(a)$ and $\rho = \mathrm{Im}(a)$

Time behavior of the electric field in the limit where $a_x = a_\rho = 0$, where a_x and a_ρ are the mean values for x and ρ.

(The real and imaginary components of the electric field cannot be determined simultaneously with arbitrary precision.)

B. E. A. Saleh, Teich M. C. Fundamentals of Photonics, pp. 414-415, Wiley, 1991.

Uncertainties for the quadrature-squeezed state



σ_ρ =1/2s

σ_x =s/2

Figure 11.3-4 Representative uncertainties for a quadrature-squeezed state.

Although the uncertainty product $\sigma_x\sigma_\rho$ cannot be reduced below its minimum ¼, the uncertainty of one of the quadrature components may be reduced (squeezed) below ½ - but at the expense of an increased uncertainty in the other component!

For example, a state for which is a Gaussian $\psi(x)$ with *stretched width* is σ_x $=s/2$ $(s>1)$, will correspond to a Gaussian $\phi(\rho)$ with a *squeezed width* of σ_ρ $=1/2s$. Note the sum is still ¼.

B. E. A. Saleh, Teich M. C. Fundamentals of Photonics, pp. 415, Wiley, 1991.

- Improved *duty factor* and *distance reach*.
  - *Duty factor* is the fraction of time the detector is recording observational quality data.
  - *Distance reach* is the binary neutron star inspiral range (the distance to which the BNS inspiral* could be detected with SNR of 8, assuming 1.4 solar mass component). This is dependent on the source mass.
- Hartford achieved angle-averaged sensitivity to binary neutron star coalescence to distance of 111 Mpc, and Livingston to 134 Mpc, with duty factors of 74.6% and 77% respectively.
- There is a 5% to 8% increase of the BNS horizon.

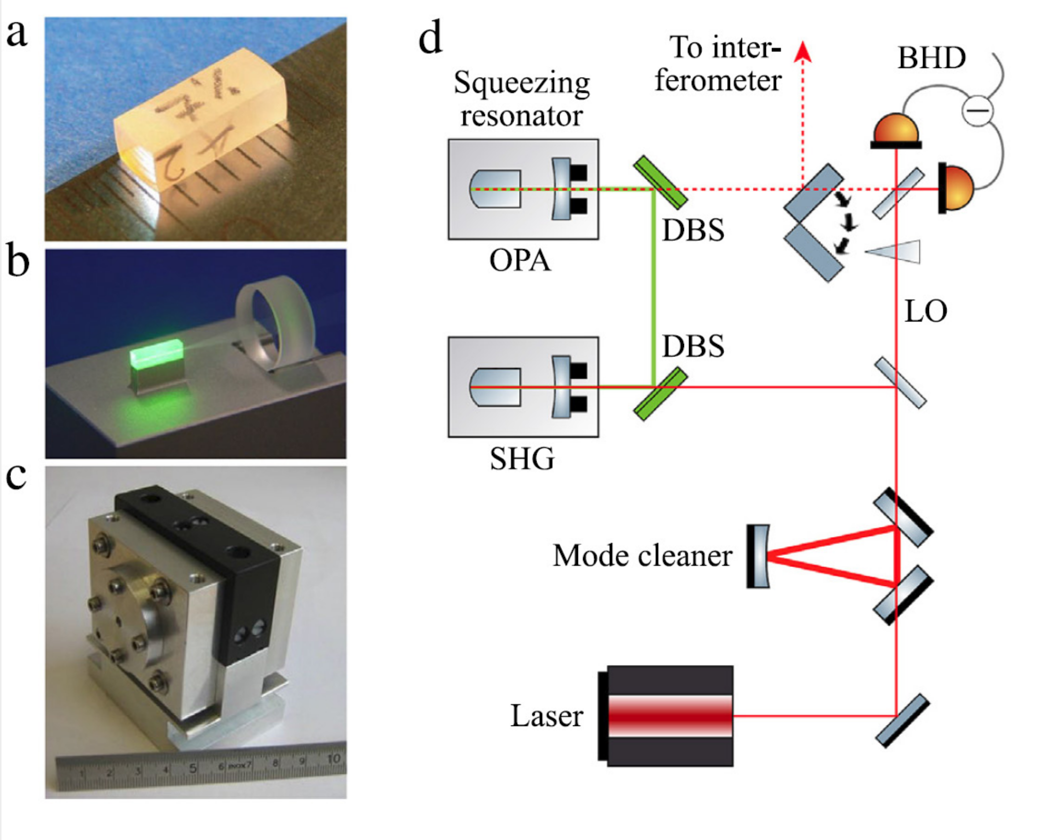
*Paths of a pair of binary stars that are losing energy, and spiralling in towards each other.

Open data from the third observing run of LIGO, Virgo, KAGRA and GEO Draft version February 8, 2023

Acernese F, Agathos M, Aiello L, et al. Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light. *Physical Review Letters*. Dec 2019;123(23)231108. doi:10.1103/PhysRevLett.123.231108

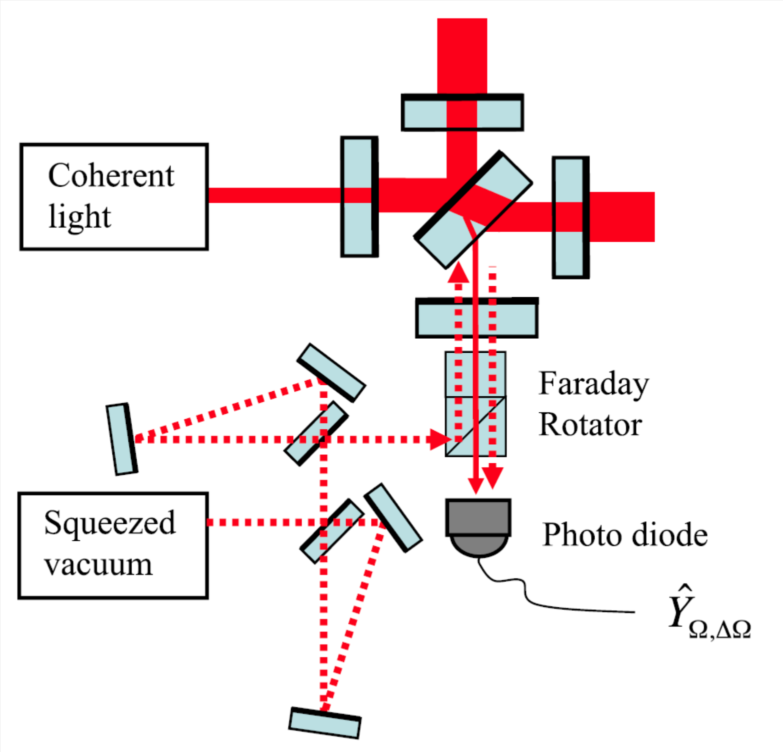
Generation of squeezed light

a) Non-linear crystal ($LiNbO_3$). This is a monolithic squeezing regulator.
b) Half-monolithic (hemilithic) standing-wave squeezing resonator
c) Mechanically stable housing of a standing-wave squeezing resonator.
d) Schematic for the squeezed-light generation.



Schnabel R. Squeezed states of light and their applications in laser interferometers. *Physics Reports-Review Section of Physics Letters*. Apr 2017;684:1-51. doi:10.1016/j.physrep.2017.04.001

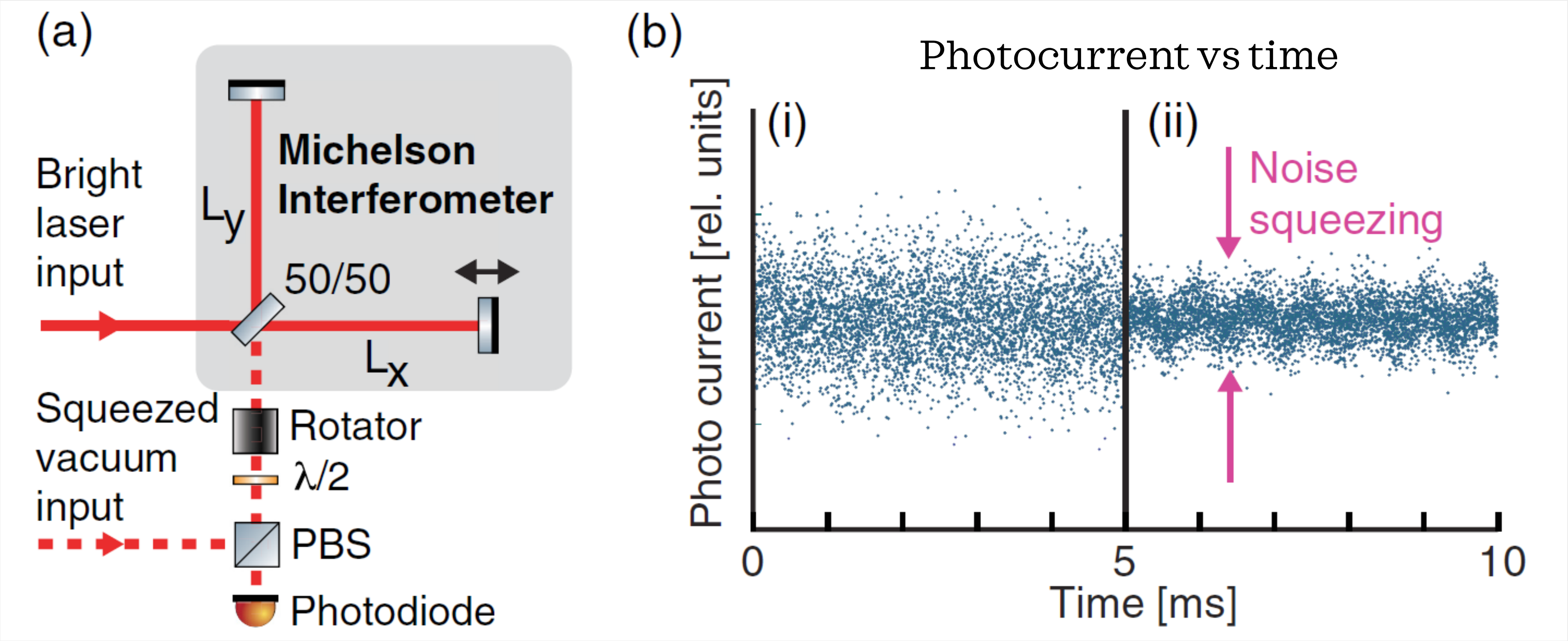
Frequency dependent squeezing injection



A broadband squeezed field with a frequency-dependent squeeze angle that is optimal for gravitational-wave detectors is produced by reflecting off an ordinary broadband squeezed field from two detuned optical filters

Schnabel R. Squeezed states of light and their applications in laser interferometers. *Physics Reports-Review Section of Physics Letters*. Apr 2017;684:1-51. doi:10.1016/j.physrep.2017.04.001

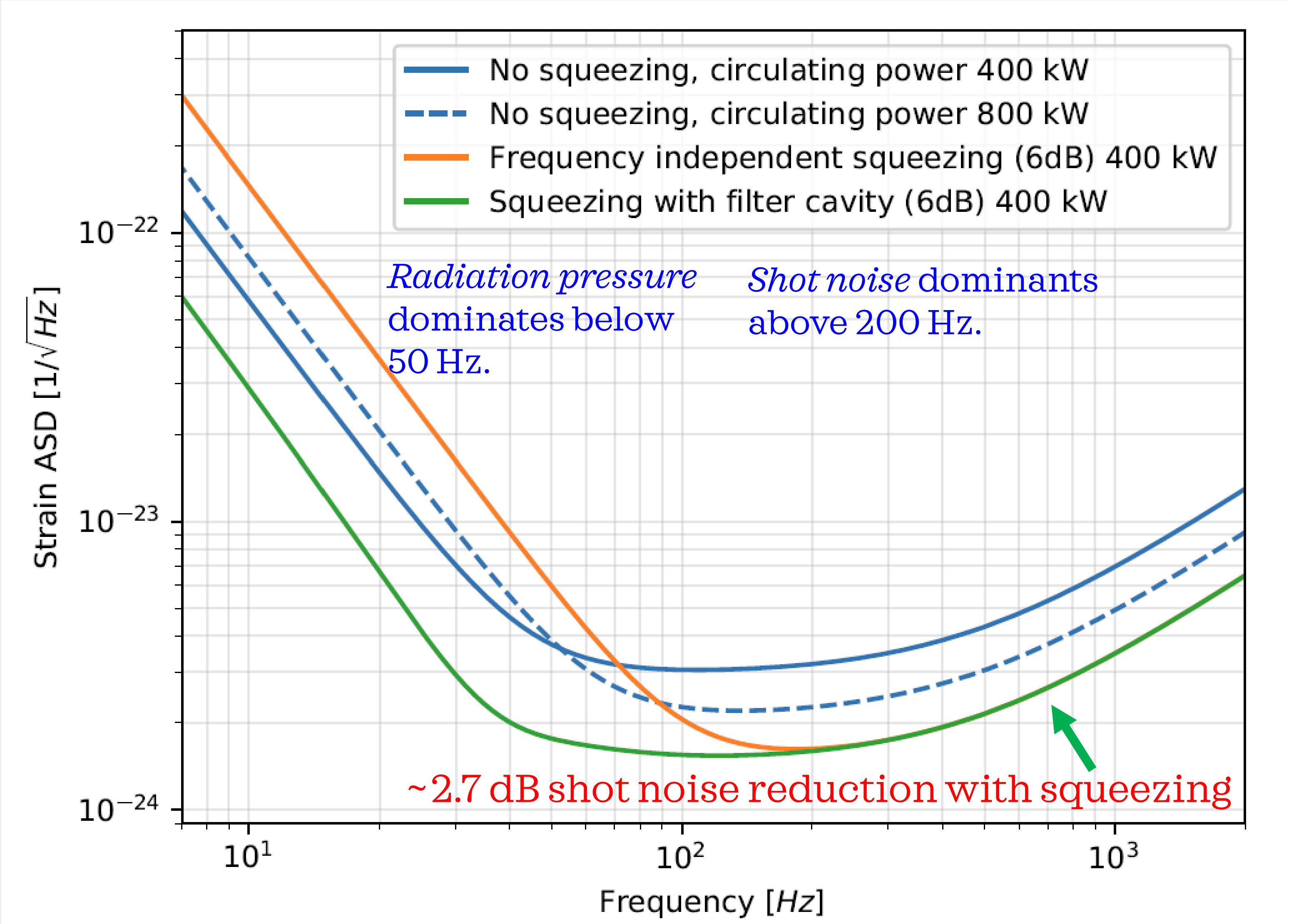
Improved SNR with squeezed light



Sensitivity enhancements up to 3.2 +/- 0.1 dB beyond shot noise limit.

Barsotti L, Harms J, Schnabel R. Squeezed vacuum states of light for gravitational wave detectors. *Reports on Progress in Physics*. Jan 2019;82(1)016905. doi:10.1088/1361-6633/aab906

Improvement



Radiation pressure dominates below 50 Hz.

Shot noise dominants above 200 Hz.

~2.7 dB shot noise reduction with squeezing

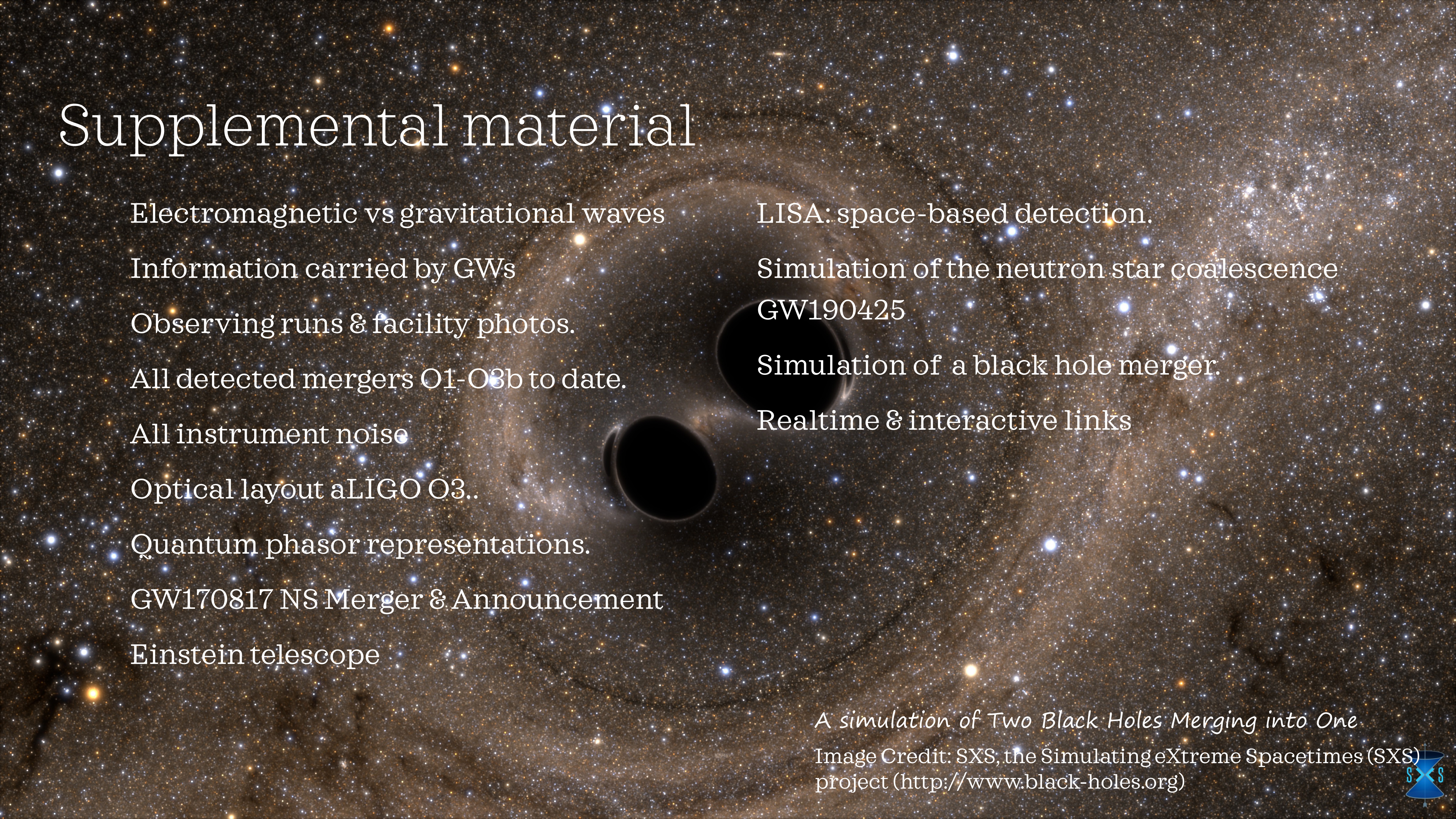
Why use *frequency dependent* squeezing for O4?

The parameters of the injected squeezing, losses, and filter cavity are chosen here so that there is 6 dB of shot noise reduction, and 8 dB of increase in quantum radiation pressure without a filter cavity, and 6 dB improvement in quantum radiation pressure noise with a filter cavity.

Dwyer SE, Mansell GL, McCuller L. Squeezing in Gravitational Wave Detectors. *Galaxies*. Apr 2022;10(2)46. doi:10.3390/galaxies10020046

Supplemental material

- Electromagnetic vs gravitational waves
- Information carried by GWs
- Observing runs & facility photos.
- All detected mergers O1-O3b to date.
- All instrument noise
- Optical layout aLIGO O3..
- Quantum phasor representations.
- GW170817 NS Merger & Announcement
- Einstein telescope
- LISA: space-based detection.
- Simulation of the neutron star coalescence GW190425
- Simulation of a black hole merger.
- Realtime & interactive links



A simulation of Two Black Holes Merging into One

Image Credit: SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

EM vs GW waves – Quote from Kip Thorne

- “Electromagnetic waves (light, radio waves, X-rays, gamma rays, …) are oscillating electric and magnetic fields that propagate through spacetime. Gravitational waves, by contrast, are oscillations of the “fabric” or shape of spacetime itself. The physical character of the waves could not be more different!
- Electromagnetic waves from astrophysical sources are almost always incoherent superpositions of emission produced by individual charged particles, atoms, or molecules. Astrophysical gravitational waves, by contrast, are emitted coherently by the bulk motion of mass or energy. Again, the two could not be more different.
- Astrophysical electromagnetic waves are all too easily absorbed and scattered by matter between their source and Earth. Gravitational waves are never significantly absorbed or scattered by matter, even when emitted in the earliest moments of the Universe’s life.”

Kip S. Thorne – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023. <https://www.nobelprize.org/prizes/physics/2017/thorne/lecture/>

Information carried by GW

"In 1986 Bernard Schutz (one of the leaders of the British-German gravitational-wave effort) identified the *observables* (parameters) that can be extracted from the early inspiral phase of a compact binary's gravitational waves. From the gravitational-wave strain h as a function of time t, $h(t)$, measured at several locations on Earth, one can infer, he deduced [1]:

- The direction to the binary.
- The inclination of its orbit to the line of sight.
- The direction the two objects move around their orbit.
- The *chirp mass*, $M_c = (M_1 M_2)^{3/5} / (M_1 + M_2)^{1/5}$ (where M_1 and M_2 are the individual masses).
- The distance r from Earth to the binary (more precisely, in technical language, the binary's *luminosity distance*)."

[1] B. F. Schutz, "Determining the Hubble Constant from Gravitational Wave Observations", Nature, 323, 310 (1986).

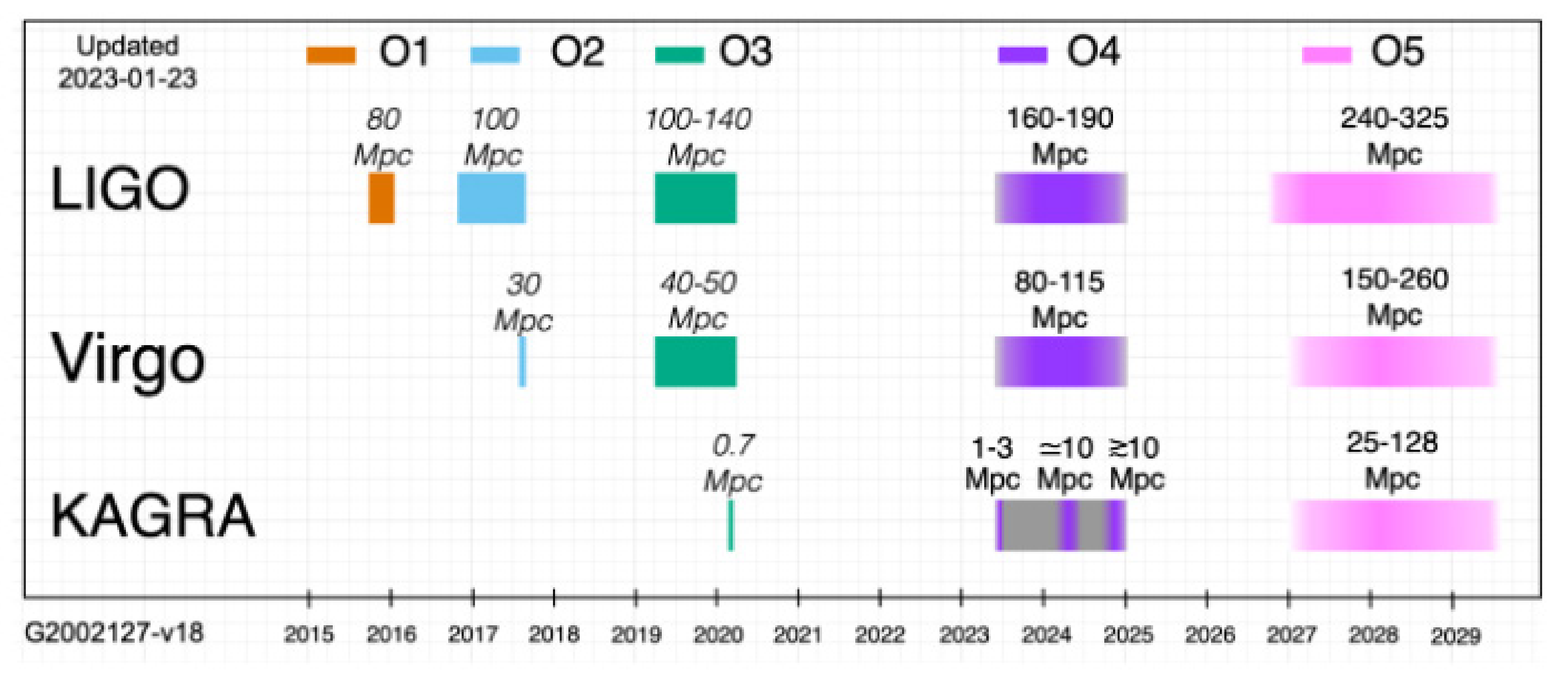
Kip S. Thorne – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023. <https://www.nobelprize.org/prizes/physics/2017/thorne/lecture/>

- “The amplitude of a compact binary’s gravitational-wave strain *h* is proportional to the binary’s mass (if its two objects have roughly the same mass).
- Therefore the distance to which LIGO can see it is also proportional to its mass (so long as the waves are in LIGO’s frequency band, which means for binary masses between a few suns and a few hundred suns, i.e. “stellar-mass” compact binaries).
- Correspondingly, the volume within which LIGO can see such binaries is proportional to the cube of the binary’s mass.
- The masses of then-known stellar-mass black holes were as much as ten times greater than those of neutron stars, so the volume searched would be 1000 times greater than for neutron stars.
- It seemed likely to me that this factor 1000 would outweigh the (very poorly understood) lower number of BBH in the universe than binary neutron stars, BNS.”

Kip S. Thorne – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023. <https://www.nobelprize.org/prizes/physics/2017/thorne/lecture/>

Observing runs

04: May 24 2023 (Tentative)



https://observing.docs.ligo.org/plan/

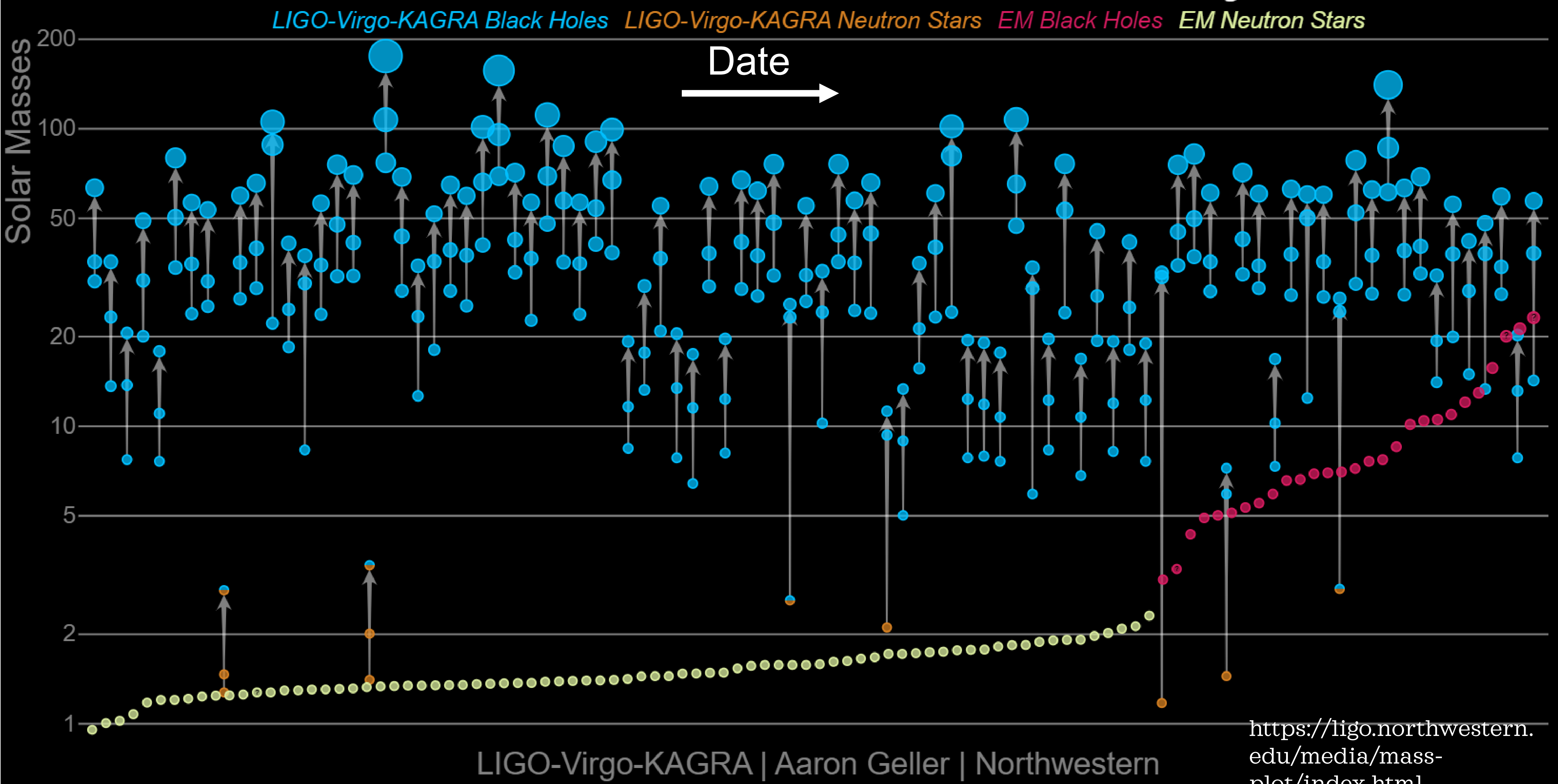
Observing history

- On September 14th, 2015, LIGO (Caltech & MIT) first detected gravitational waves from a binary black hole merger (GW150914).
- During the first observing run (O1), which ran from September 2015 to January 2016, two more binary black hole detections were made.
- The second observing run (O2), which ran from November 2016 to August 2017, detected seven binary black hole mergers, and one binary neutron star merger .
- The third observing run (O3), which ran from April 1 to September 30, 2019 (O3a) and from November 1, 2019 until March 27, 2020 (O3b). Over 80 compact object mergers.*
- The forth observing run (O4) is scheduled to begin this May, and will include aLIGO, Virgo in Italy & KAGRA in Japan.

https://www.ligo.caltech.edu/WA/news/ligo20220123

*See the GWTC-3 catalog for O3b: https://www.ligo.org/detections/O3bcatalog.php

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

https://ligo.northwestern.edu/media/mass-plot/index.html

All instrumental noise that limit sensitivity

A. Quantum noise
B. Thermal noise
C. Seismic noise
D. Newtonian noise
E. Laser frequency noise
F. Laser intensity noise
G. Auxiliary length control noise
H. Actuator noise
I. Alignment control noise
J. Beam jitter noise
K. Scattered light noise
L. Residual gas noise
M. Photodetector dark noise
N. Output mode cleaner length noise
O. Glitches

Buikema A, Cahillane C, Mansell GL, et al. Sensitivity and performance of the Advanced LIGO detectors in the third observing run. *Physical Review D*. Sep 2020;102(6)062003. doi:10.1103/PhysRevD.102.062003

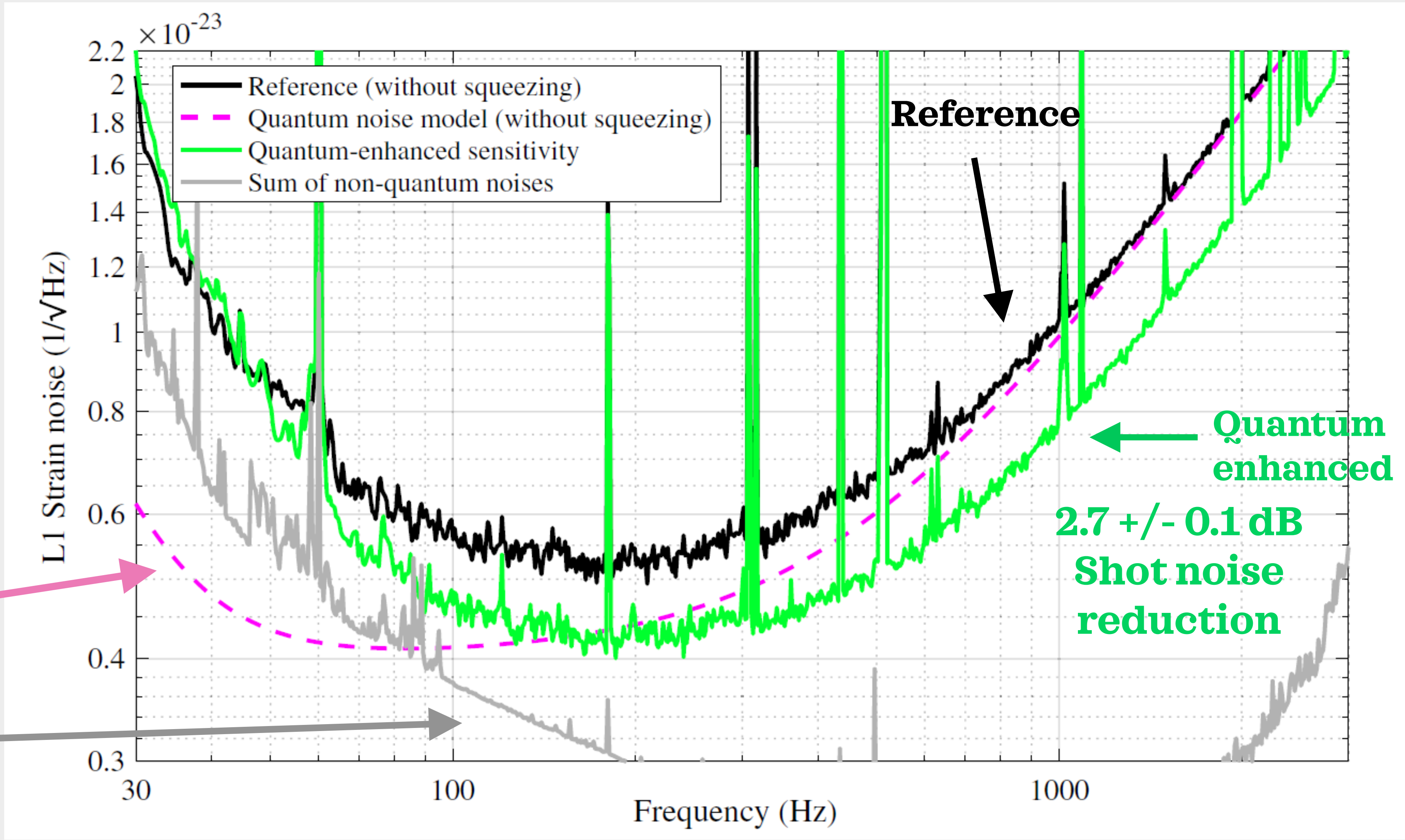
Improved sensitivity of the LIGO Livingston detector during O3.

L1 Strain Noise in $\frac{1}{\sqrt{Hz}}$

vs Frequency (Hz)

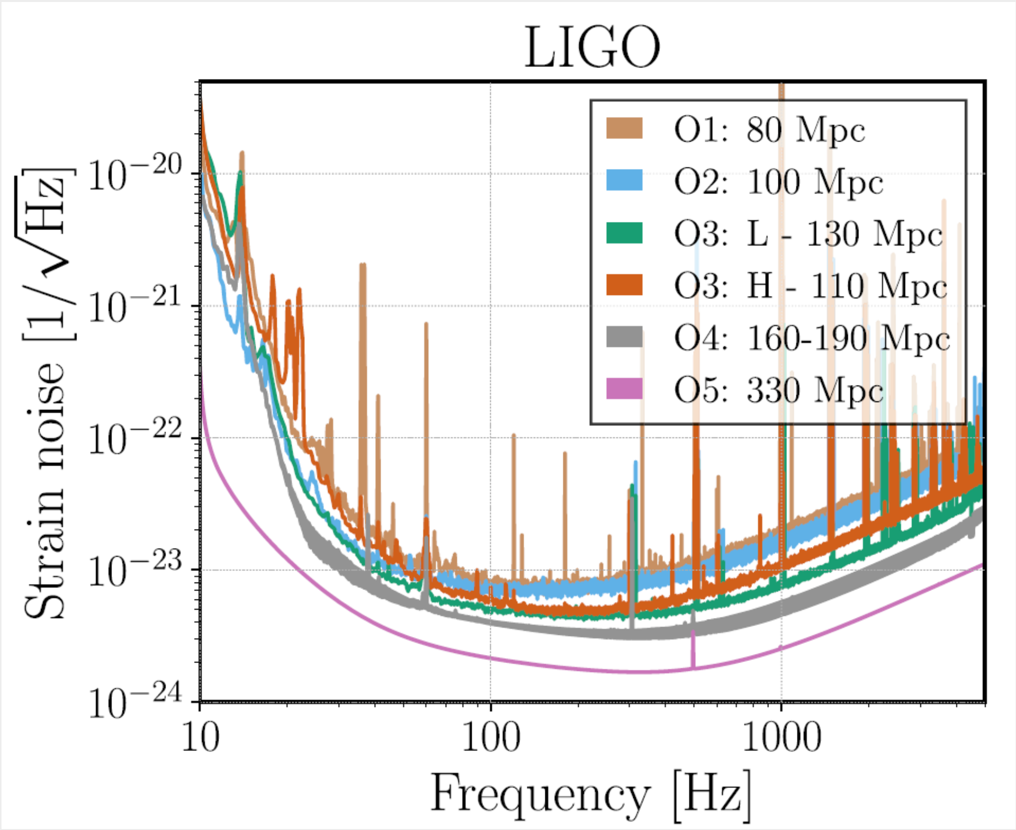
Model of quantum noise in the detector without squeezing injected.

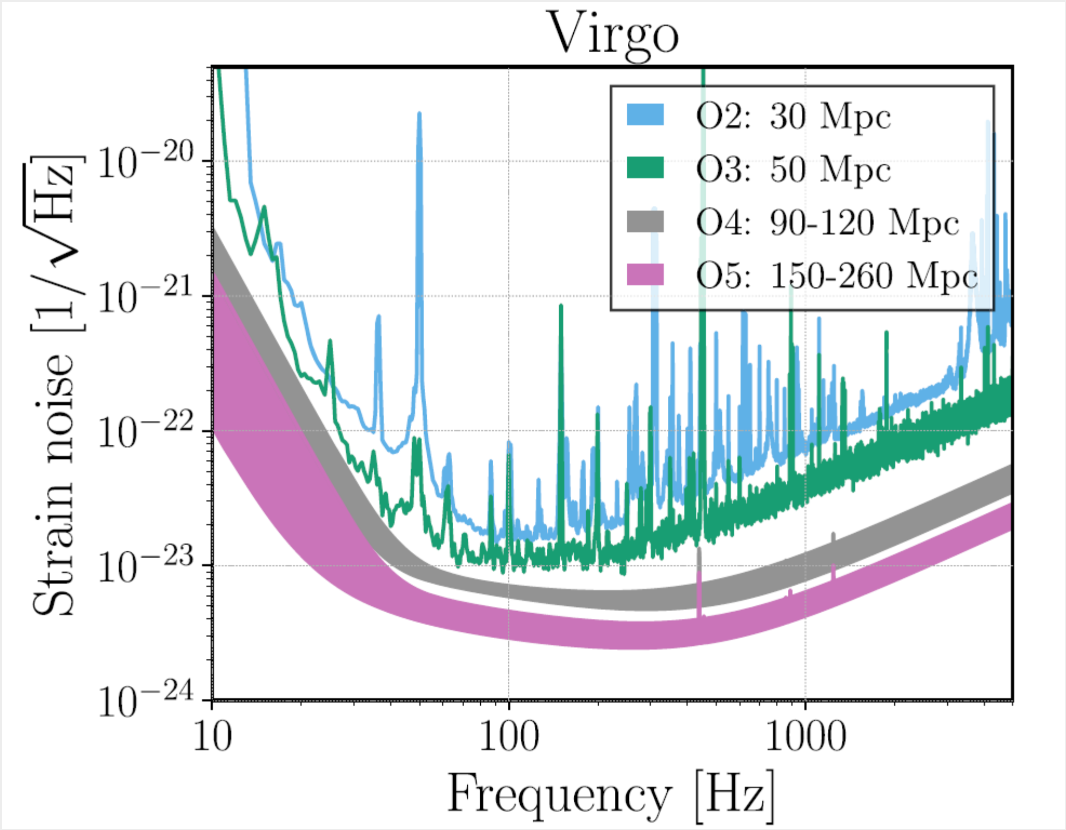
Estimate of the other noises.



Tse M, Yu HC, Kijbunchoo N, et al. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. *Physical Review Letters*. Dec 2019;123(23)231107. doi:10.1103/PhysRevLett.123.231107

Target strain sensitivities (2016)



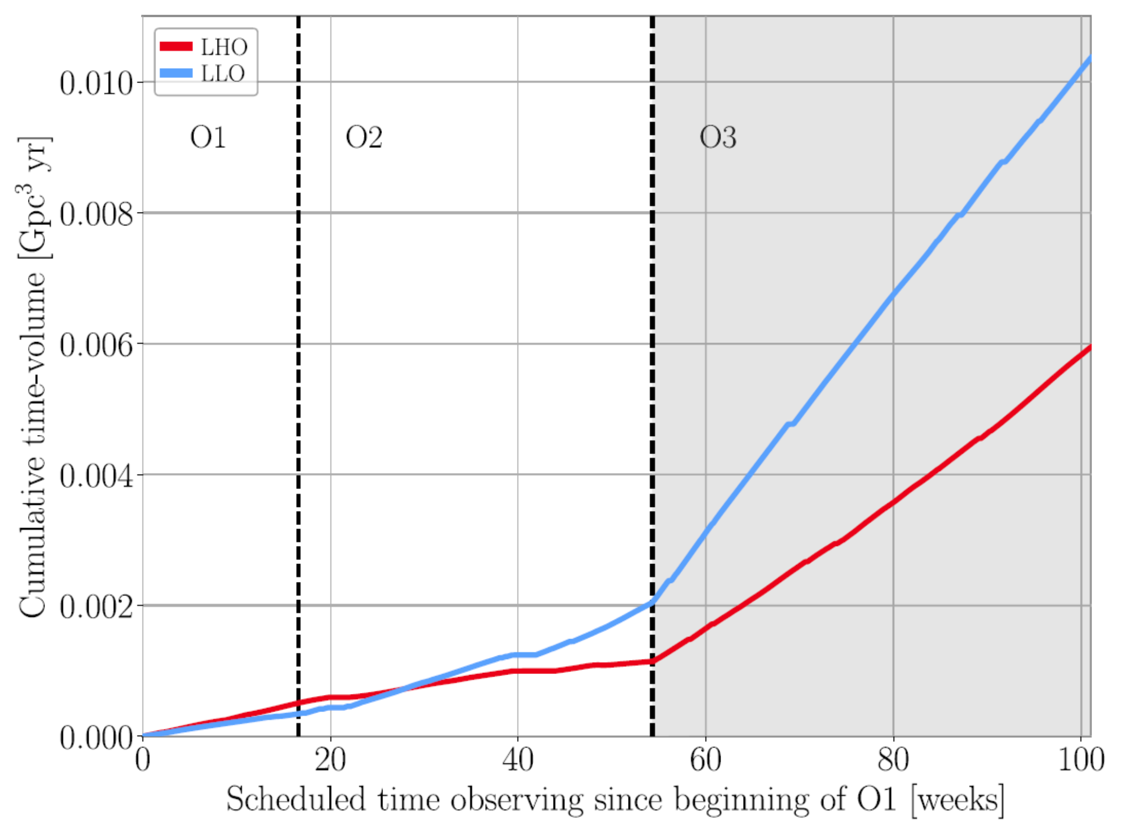


Abbott BP, Abbott R, Abbott TD, et al. Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo. *Living Reviews in Relativity*. 2016;19:1-+. doi:10.1007/lrr-2016-1

Observing volume as proxy for *sensitivity*, calculated as a sphere with radius equal to the binary neutron star inspiral* range.

Comparison of O1, O2 & O3 at LIGO

Cumulative time-volume in Gpc^3 yr. vs time of observation.



*Paths of a pair of binary stars that are losing energy, and spiralling in towards each other.

Buikema A, Cahillane C, Mansell GL, et al. Sensitivity and performance of the Advanced LIGO detectors in the third observing run. *Physical Review D*. Sep 2020;102(6)062003. doi:10.1103/PhysRevD.102.062003

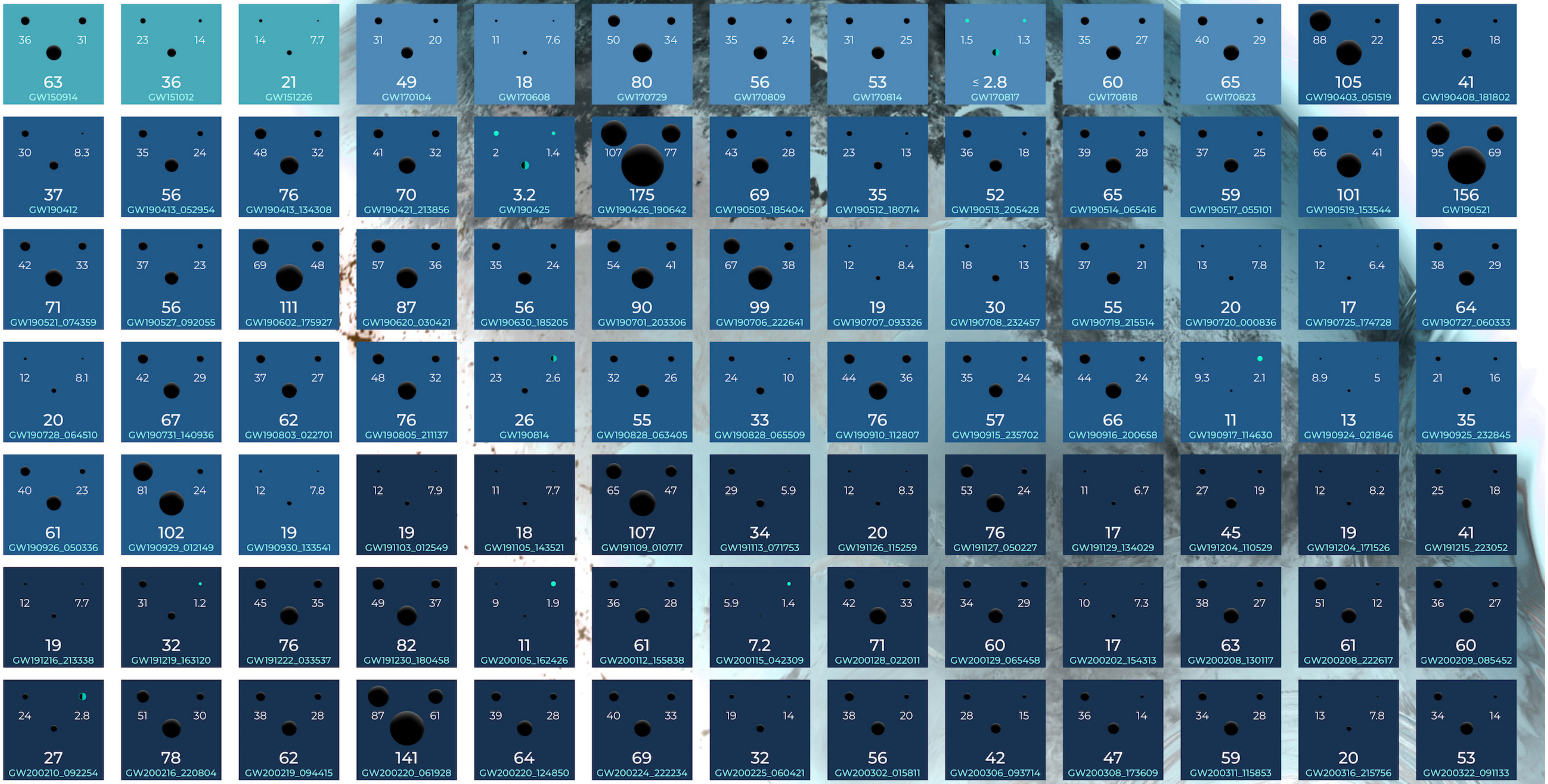
Black Holes (Black), Neutron Stars (Blue) and Uncertain

LIGO/Virgo/KAGRA/C. Knox/H. Middleton

OBSERVING RUN
01
2015 - 2016

02
2016 - 2017

O3a+b
2019 - 2020



GW150914	36	31	63
GW151012	23	14	36
GW151226	14	7.7	21
GW170104	31	20	49
GW170608	11	7.6	18
GW170729	50	34	80
GW170809	35	24	56
GW170814	31	25	53
GW170817	1.5	1.3	≤ 2.8
GW170818	35	27	60
GW170823	40	29	65
GW190403_051519	88	22	105
GW190408_181802	25	18	41
GW190412	30	8.3	37
GW190413_052954	35	24	56
GW190413_134308	48	32	76
GW190421_213856	41	32	70
GW190425	2	1.4	3.2
GW190426_190642	107	77	175
GW190503_185404	43	28	69
GW190512_180714	23	13	35
GW190513_205428	36	18	52
GW190514_065416	39	28	65
GW190517_055101	37	25	59
GW190519_153544	66	41	101
GW190521	95	69	156
GW190521_074359	42	33	71
GW190527_092055	37	23	56
GW190602_175927	69	48	111
GW190620_030421	57	36	87
GW190630_185205	35	24	56
GW190701_203306	54	41	90
GW190706_222641	67	38	99
GW190707_093326	12	8.4	19
GW190708_232457	18	13	30
GW190719_215514	37	21	55
GW190720_000836	13	7.8	20
GW190725_174728	12	6.4	17
GW190727_060333	38	29	64
GW190728_064510	12	8.1	20
GW190731_140936	42	29	67
GW190803_022701	37	27	62
GW190805_211137	48	32	76
GW190814	23	2.6	26
GW190828_063405	32	26	55
GW190828_065509	24	10	33
GW190910_112807	44	36	76
GW190915_235702	35	24	57
GW190916_200658	44	24	66
GW190917_114630	9.3	2.1	11
GW190924_021846	8.9	5	13
GW190925_232845	21	16	35
GW190926_050336	40	23	61
GW190929_012149	81	24	102
GW190930_133541	12	7.8	19
GW191103_012549	12	7.9	19
GW191105_143521	11	7.7	18
GW191109_010717	65	47	107
GW191113_071753	29	5.9	34
GW191126_115259	12	8.3	20
GW191127_050227	53	24	76
GW191129_134029	11	6.7	17
GW191204_110529	27	19	45
GW191204_171526	12	8.2	19
GW191215_223052	25	18	41
GW191216_213338	12	7.7	19
GW191219_163120	31	1.2	32
GW191222_033537	45	35	76
GW191230_180458	49	37	82
GW200105_162426	9	1.9	11
GW200112_155838	36	28	61
GW200115_042309	5.9	1.4	7.2
GW200128_022011	42	33	71
GW200129_065458	34	29	60
GW200202_154313	10	7.3	17
GW200208_130117	38	27	63
GW200208_222617	51	12	61
GW200209_085452	36	27	60
GW200210_092254	24	2.8	27
GW200216_220804	51	30	78
GW200219_094415	38	28	62
GW200220_061928	87	61	141
GW200220_124850	39	28	64
GW200224_222234	40	33	69
GW200225_060421	19	14	32
GW200302_015811	38	20	56
GW200306_093714	28	15	42
GW200308_173609	36	14	47
GW200311_115853	34	28	59
GW200316_215756	13	7.8	20
GW200322_091133	34	14	53

LIGO Observatories in Hanford (LHO), Southeastern Washington State, and in Livingston (LLO), Louisiana (east of Baton Rouge).

The Livingston to Hanford distance is ~ 3000 km.

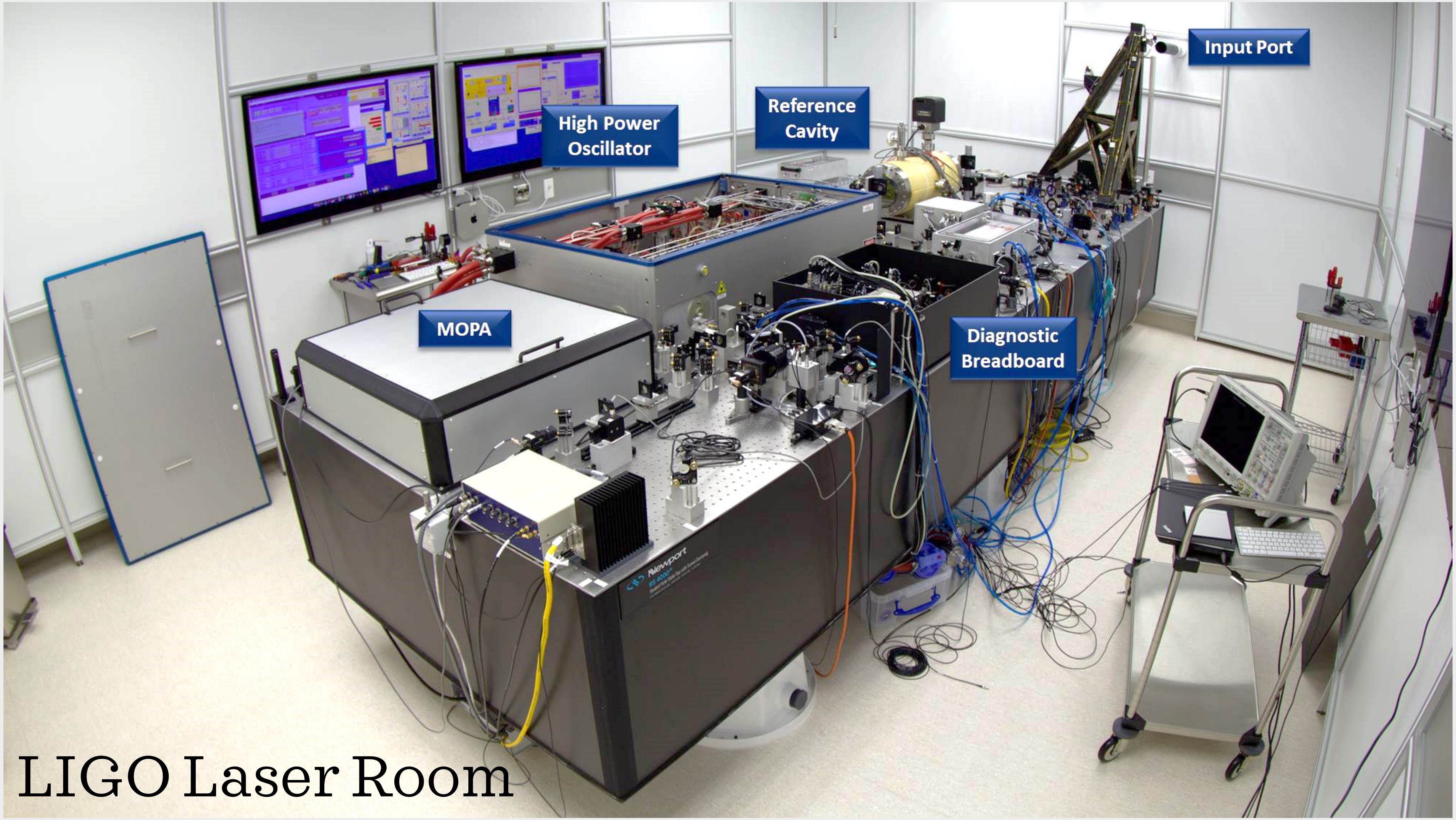
Caltech/MIT/LIGO Lab

Virgo Observatory in Santo Stefano a Macerata, Italy.
KAGRA Gravitational-Wave Detector in Hilda, Japan (in the Kamioka mine & at cryogenic temperatures)
GEO600, Hannover, Germany

Caltech/MIT/LIGO Lab https://www.geo600.org/23386/what-is-geo600

LIGO Hanford Control Room.

Caltech/MIT/LIGO Lab



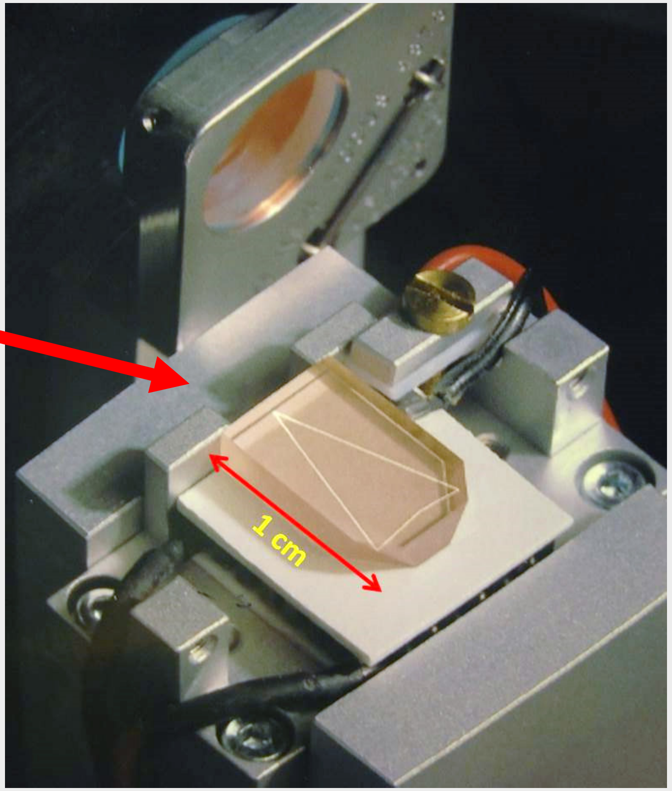
LIGO Laser Room

Caltech/MIT/LIGO Lab

Optics

Light is created by a laser diode at 808 nm (near-infrared) at 4 W

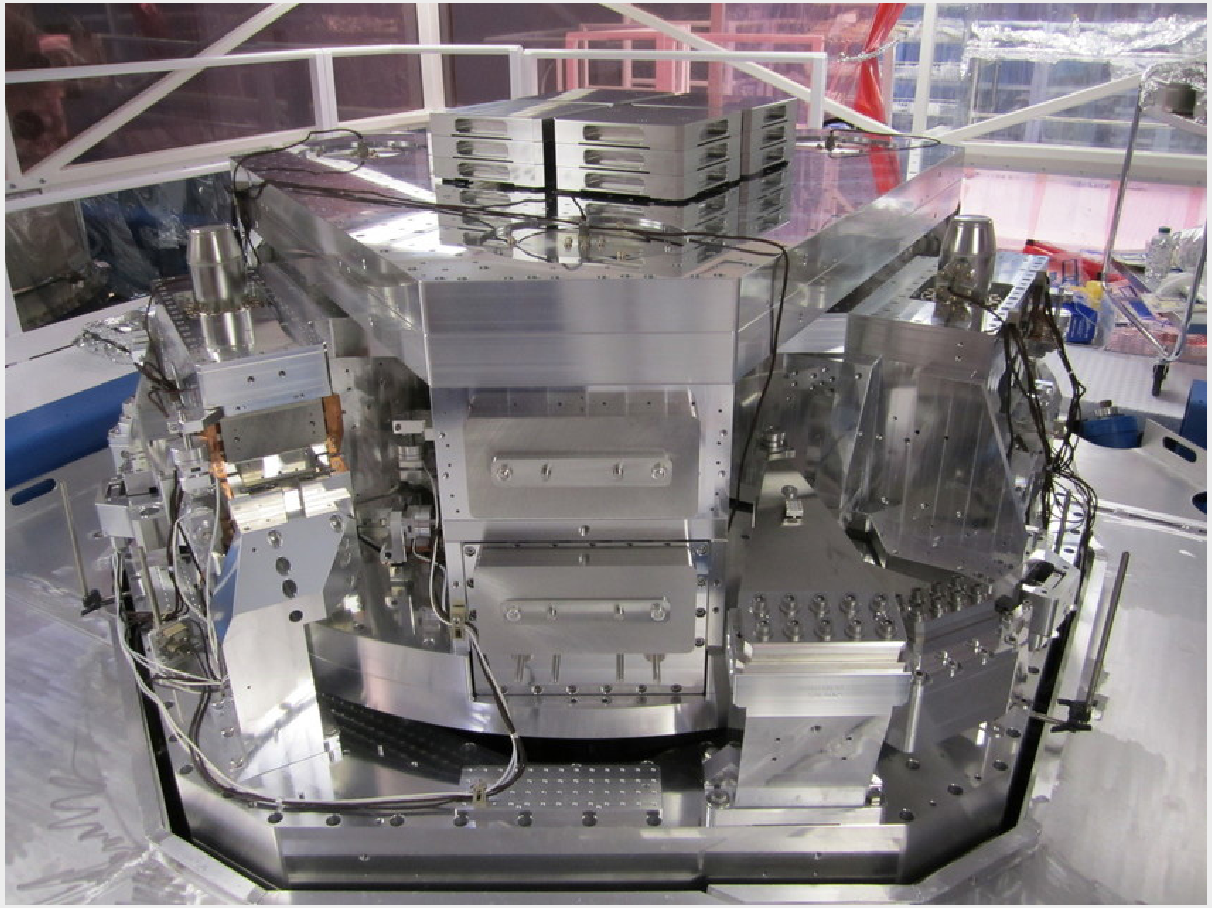
A Non-Planar Ring Oscillator (boat-shaped crystal) generates a 2 W laser beam at 1064 nm that is fed into two laser amplifiers that ultimately boost the beam power to 200 W.

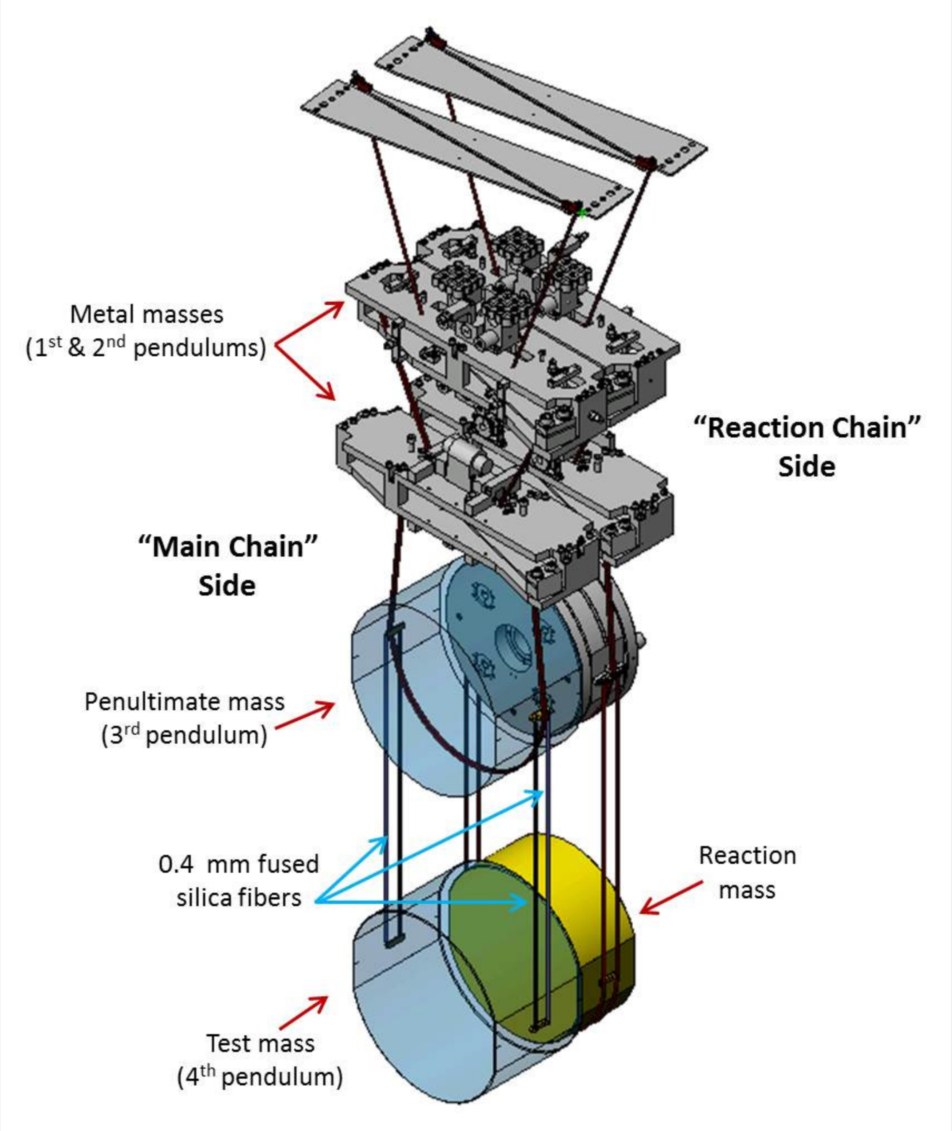


Two of LIGO's pure fused silica mirrors. 40 kg

Caltech/MIT/LIGO Lab

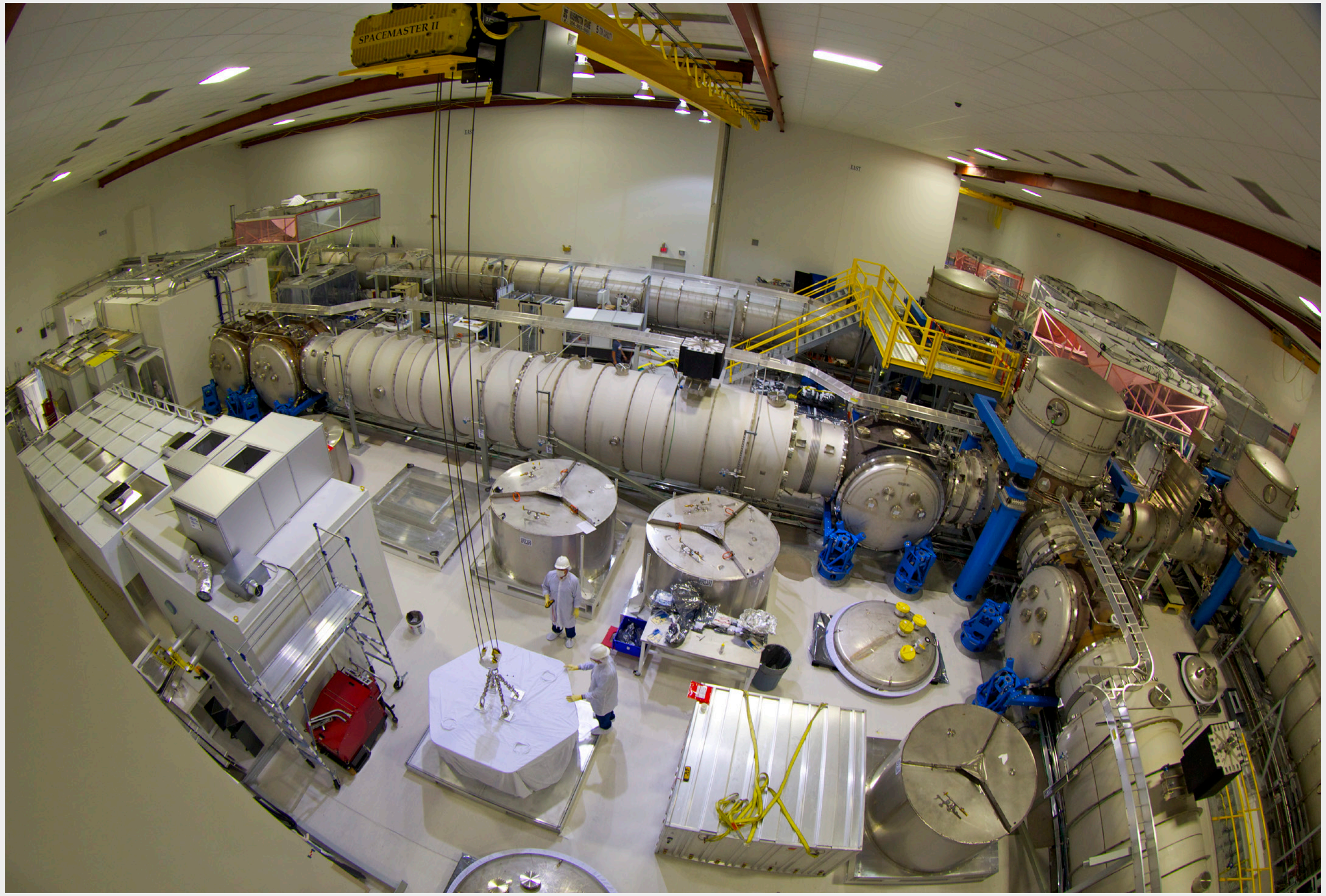
Seismic isolation





Caltech/MIT/LIGO Lab

LIGO Hanford laser and vacuum equipment area

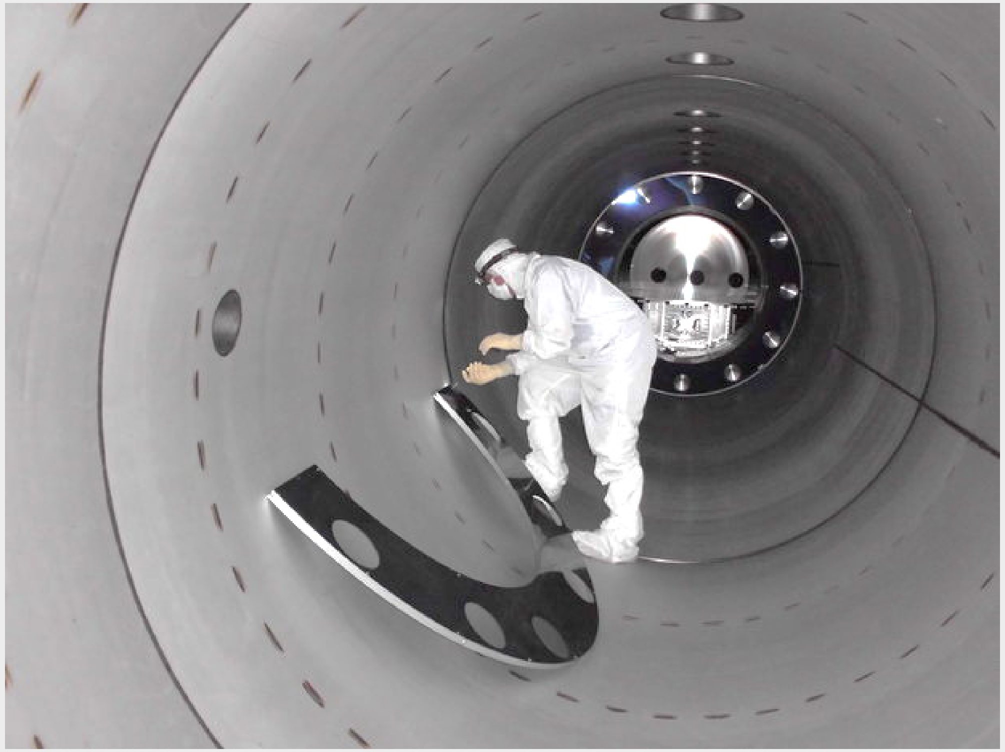


Laser and vacuum equipment area (LVEA) at the corner station of the detector.

LVEA houses pre-stabilized laser, beam splitter, input test masses, and other equipment.

To achieve the one-trillionth atmosphere (pressure of 10^{-9} Torr) required heating, turbo-pumps, then ion pumps.

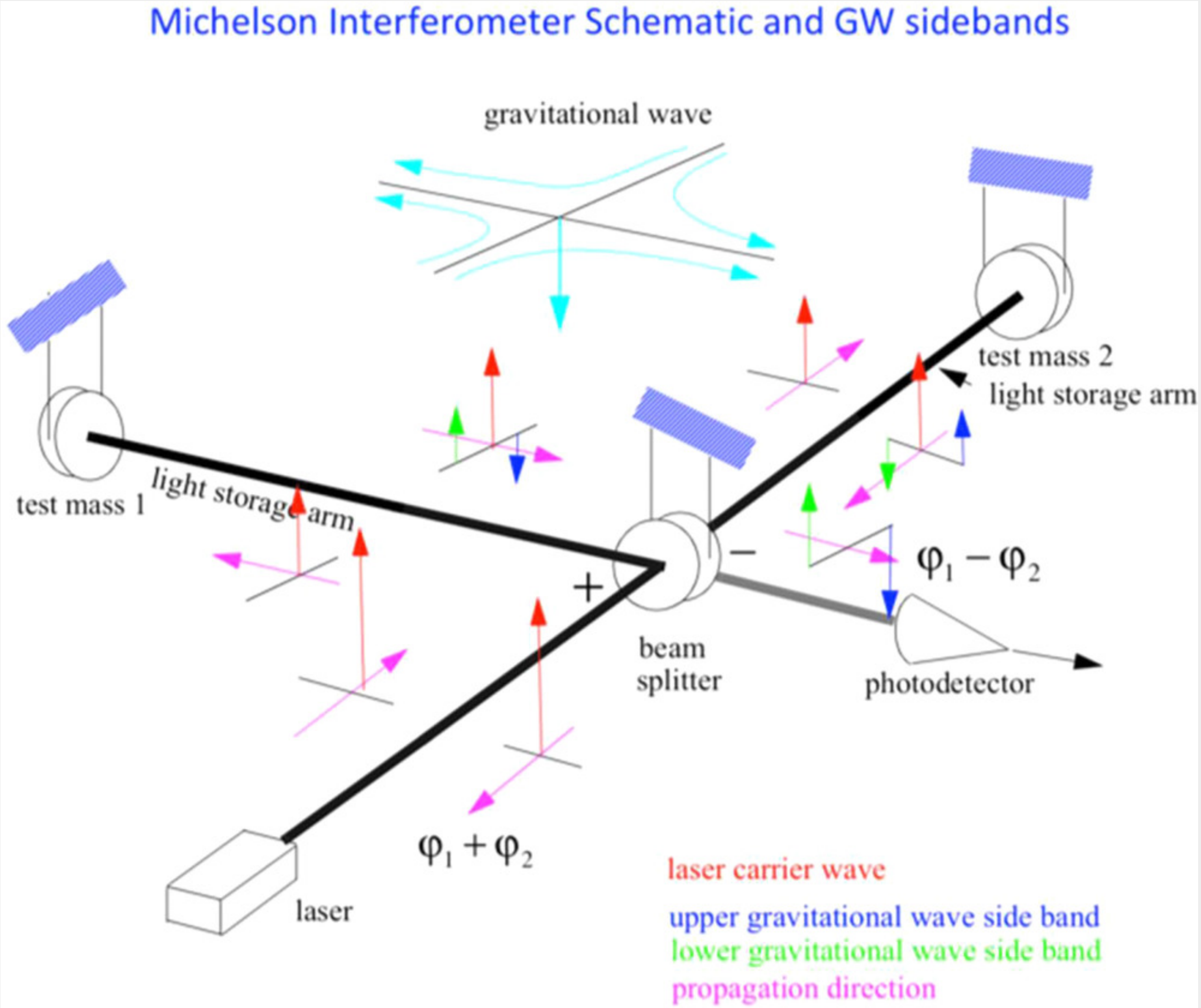
Caltech/MIT/LIGO Lab



Mode cleaner tube baffle installation

Preparing an optical mode cleaner for installation.

Caltech/MIT/LIGO Lab



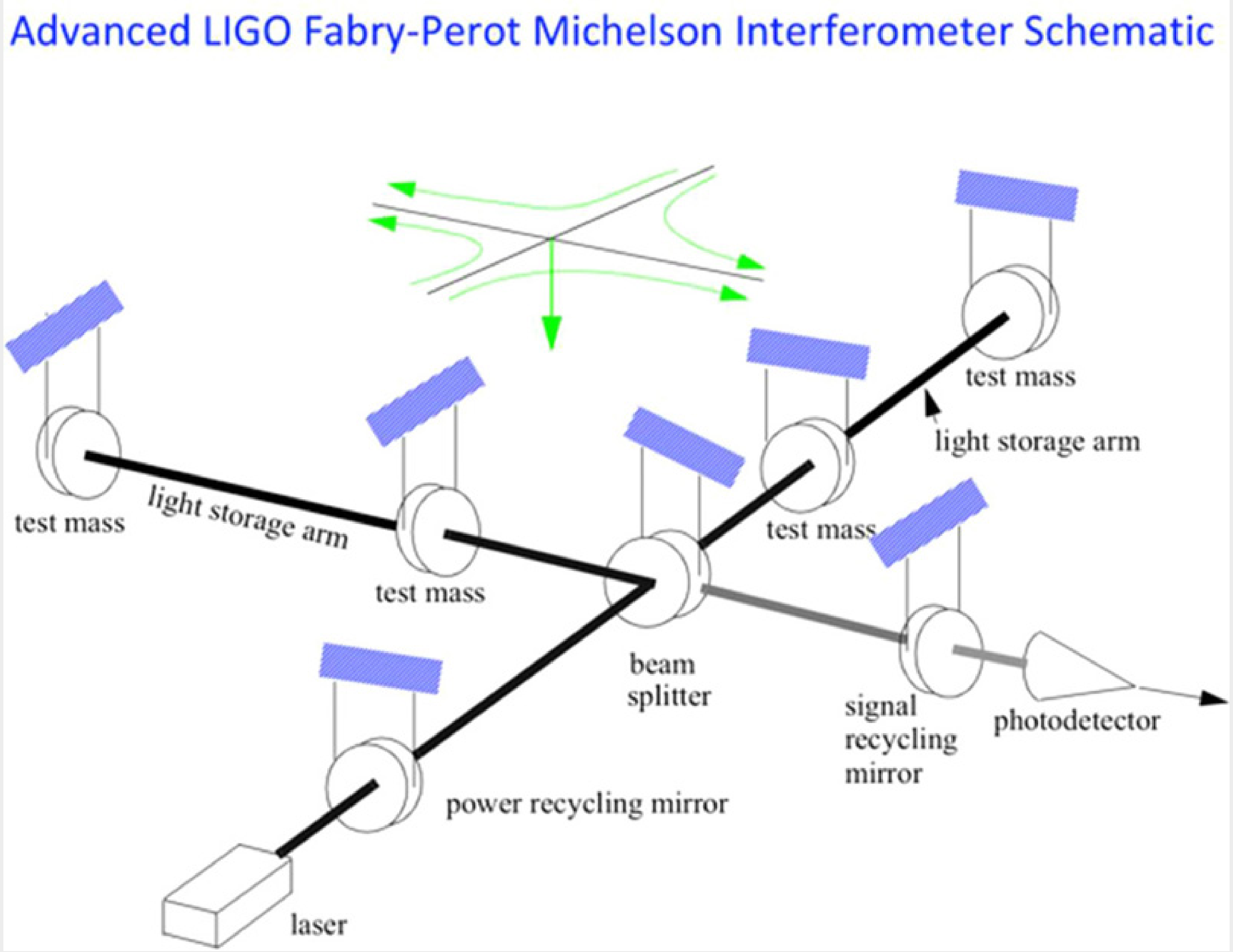
Michelson Interferometer Schematic and GW sidebands

The gravitational wave is compressing space on the test mass 1 side while expanding space on the test mass 2 side.

On reflection from test mass 1, which is moving due to the gravitational wave, the carrier generates two sidebands one at a frequency fg above the carrier (blue) and another fg below (green).

The sidebands carry the information about the gravitational wave both the wave amplitude and the phase. To make the sidebands detectable as a current in the photodetector requires a small amount of carrier to beat against the sidebands.

Rainer Weiss – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023. <https://www.nobelprize.org/prizes/physics/2017/weiss/lecture/>

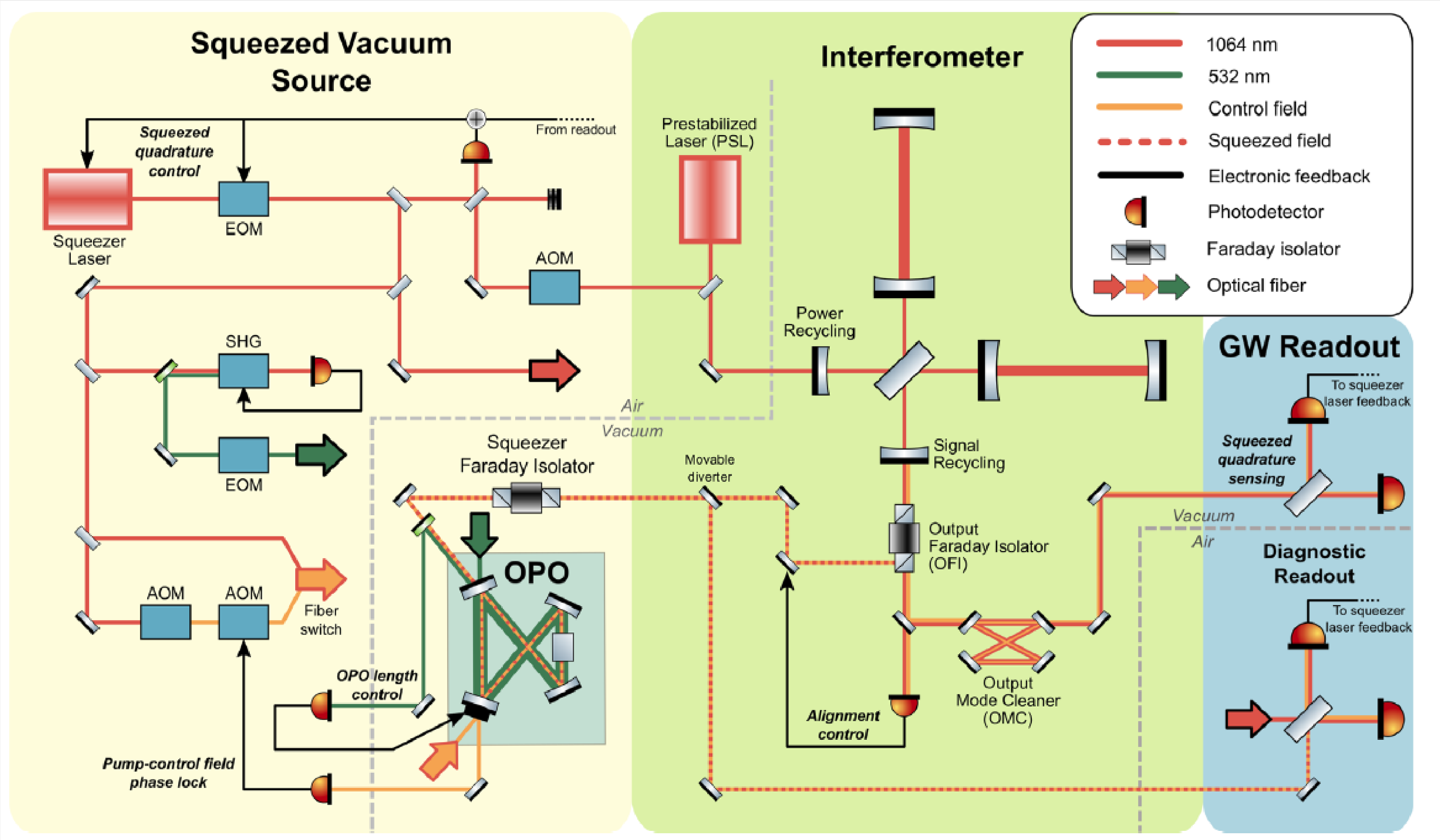


The combination of the *input and end test mass* comprise an *optical resonator* (Fabry-Perot cavities).

A *power recycling mirror* makes another interferometer that cancels the carrier from the laser reflected by the power recycling mirror with the carrier transmitted back by the recycling mirror from the beam splitter.

A *signal recycling mirror* reflects the sidebands back into the interferometer and modifies the spectral response of the entire interferometer to the sidebands, thereby tuning the spectral response of the detector to the gravitational waves being sought.

Rainer Weiss – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023. <https://www.nobelprize.org/prizes/physics/2017/weiss/lecture/>

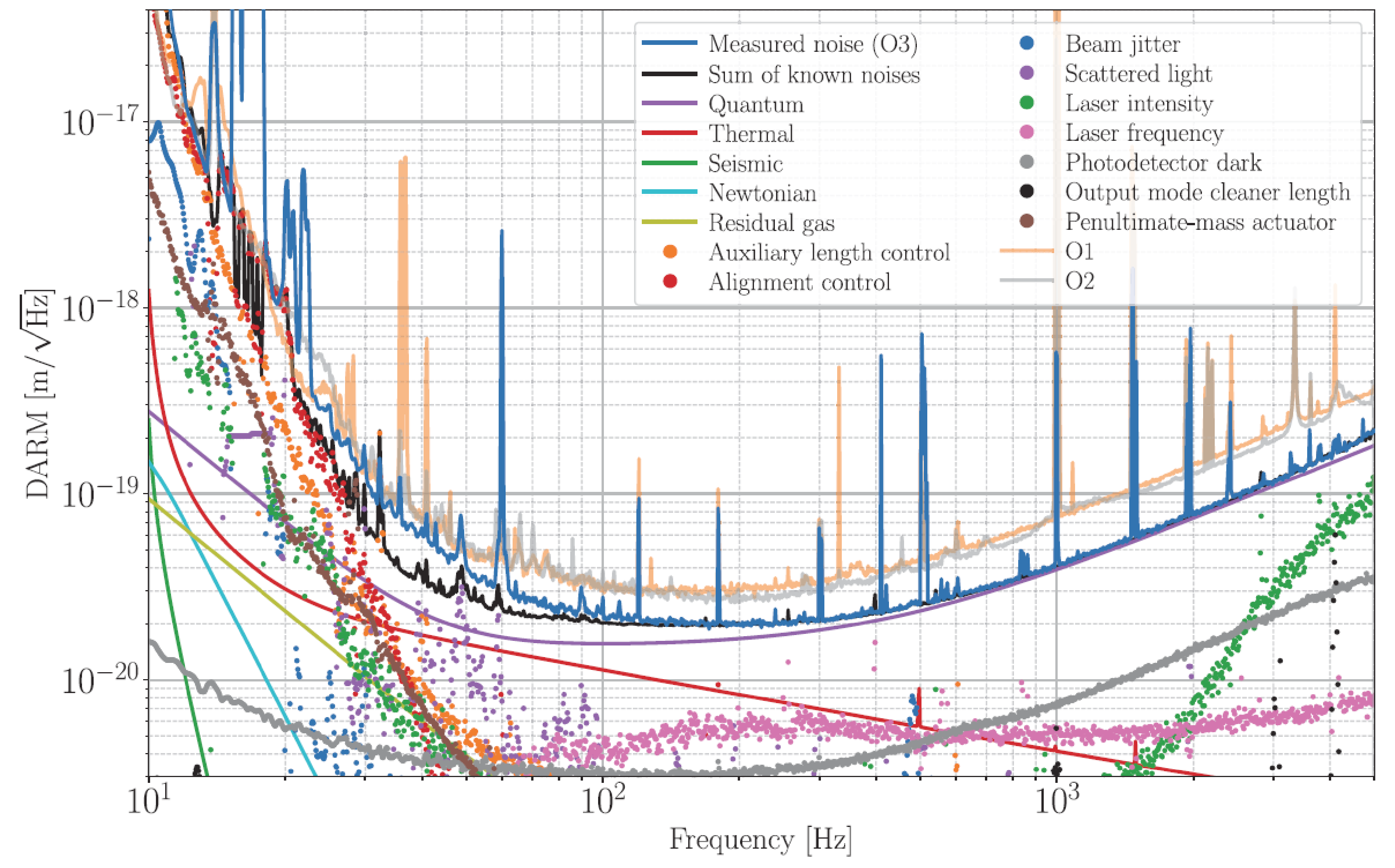


Tse M, Yu HC, Kijbunchoo N, et al. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. *Physical Review Letters*. Dec 2019;123(23)231107. doi:10.1103/PhysRevLett.123.231107

Noise budget at LHO (slight differences at LLO).

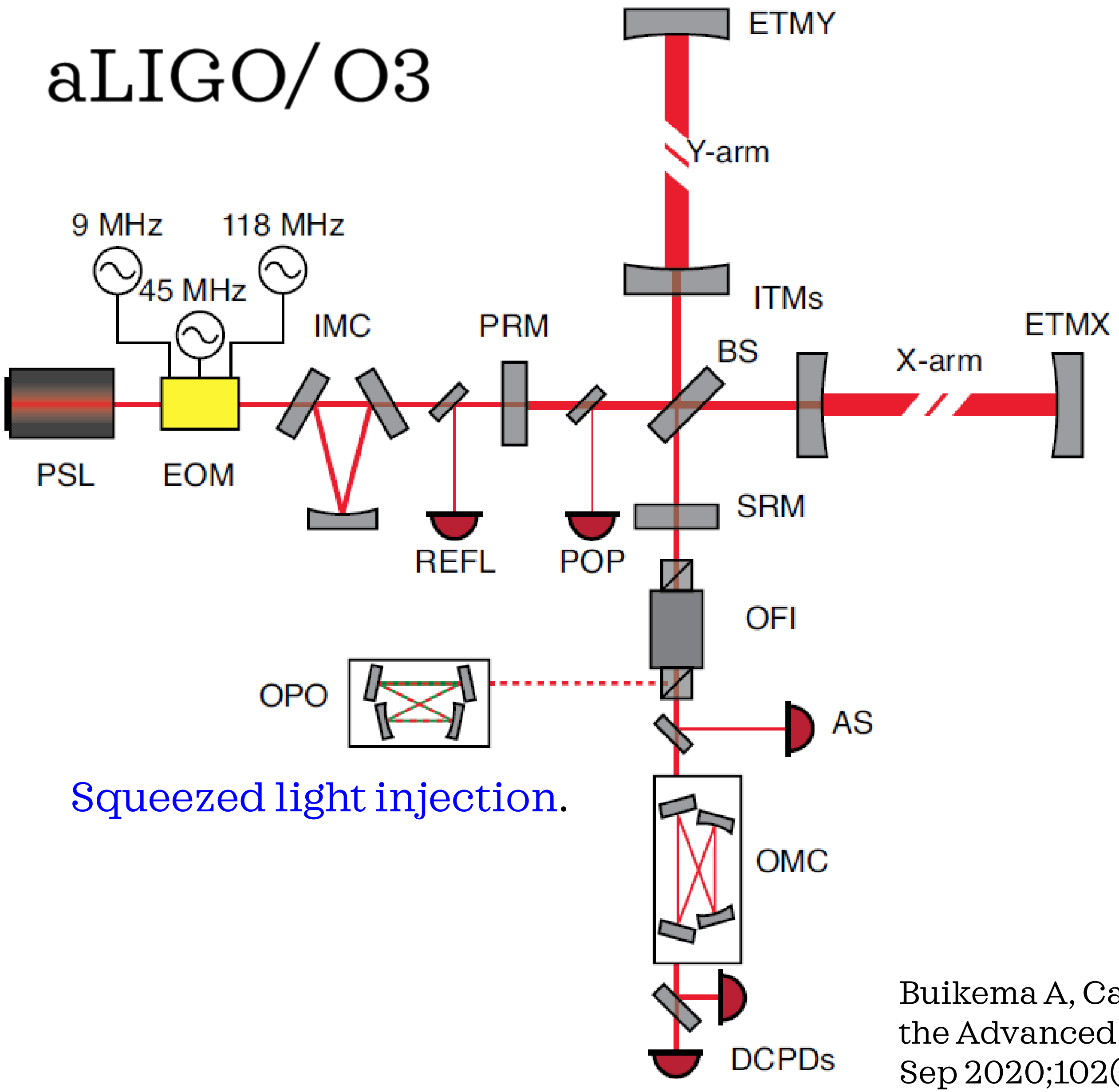
DARM in m/(Hz)$^{1/2}$ vs freq.

(differential arm length)



Buikema A, Cahillane C, Mansell GL, et al. Sensitivity and performance of the Advanced LIGO detectors in the third observing run. *Physical Review D*. Sep 2020;102(6)062003. doi:10.1103/PhysRevD.102.062003

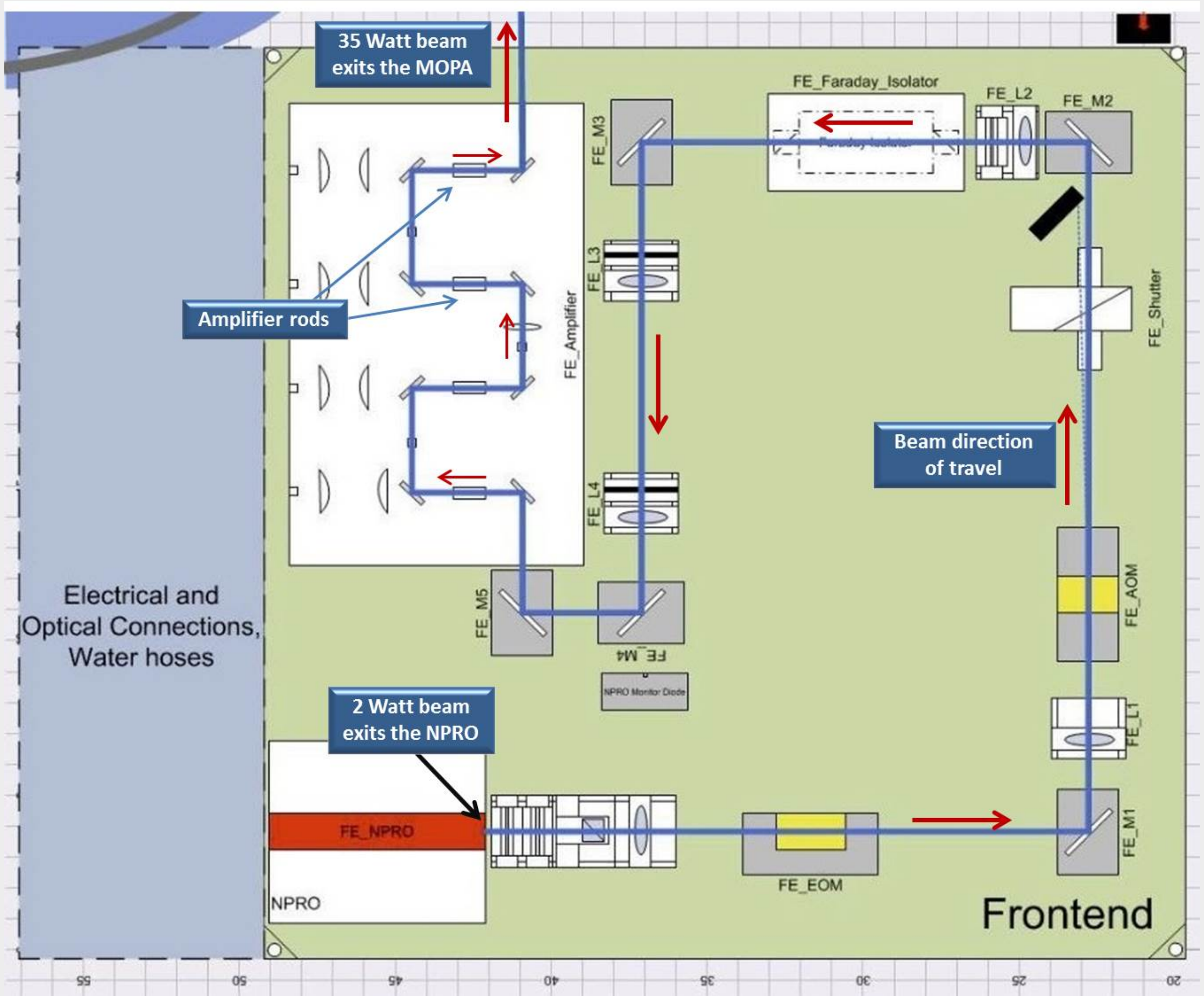
aLIGO/ O3



Squeezed light injection.

PSL – Pre stabilized laser.
EOM – Electro-optic modulator.
IMC – Triangular input mode cleaner.
ITM & ETM - Input and end test masses.
PRM & SRM - Power & signal-recycling mirrors.
BS – Beam splitter.
POP – Power recycling cavity.
REFL – interferometer reflection ports
OFI – Output Faraday isolator
AS – Asymmetric port.
OPO – Optical parametric oscillator
OMC – Output mode cleaner
DCPDs – Output photodiodes
DARM – differential arm length.

Buikema A, Cahillane C, Mansell GL, et al. Sensitivity and performance of the Advanced LIGO detectors in the third observing run. *Physical Review D*. Sep 2020;102(6)062003. doi:10.1103/PhysRevD.102.062003



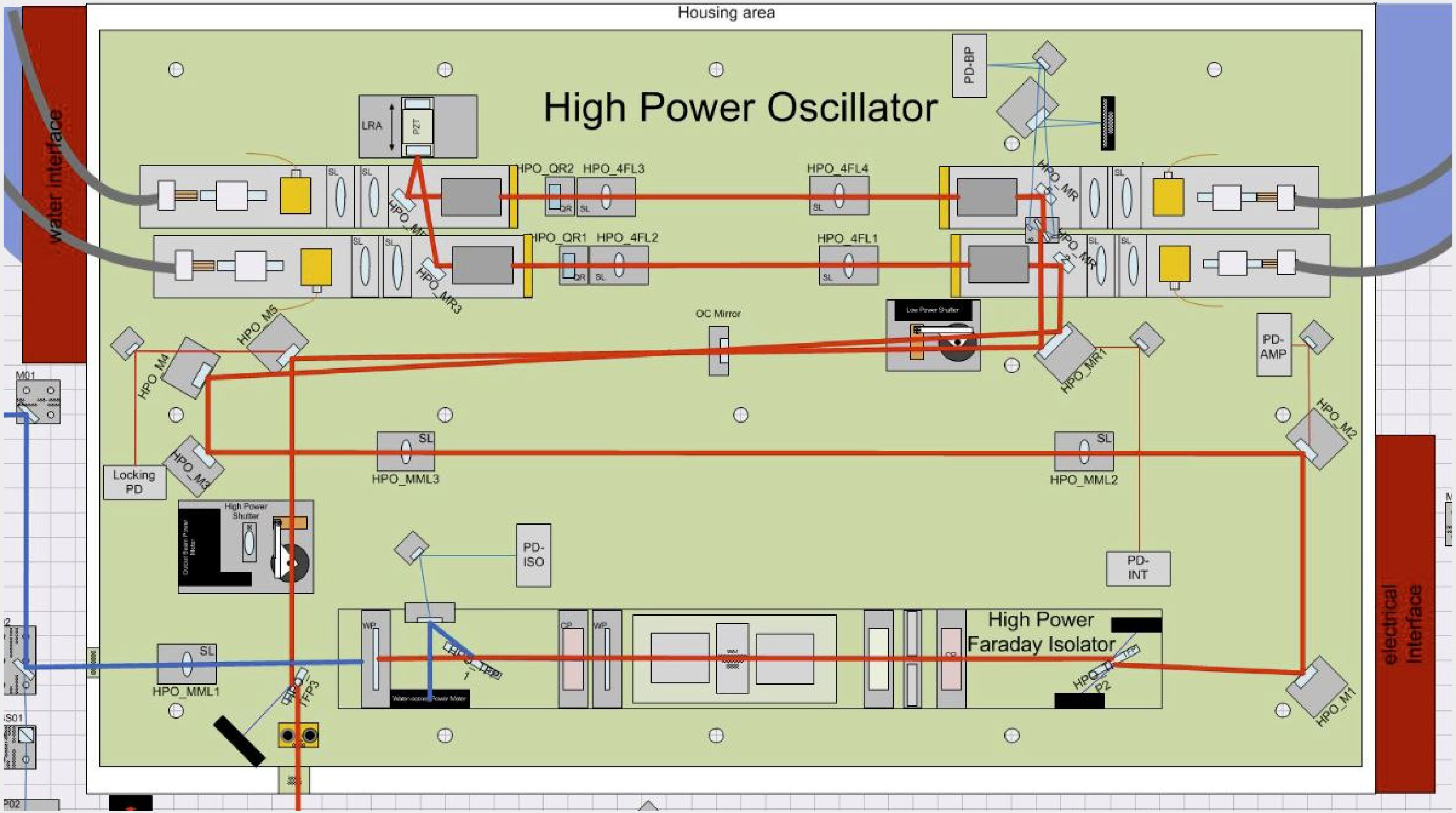
35 Watt beam exits the MOPA

Amplifier rods

Beam direction of travel

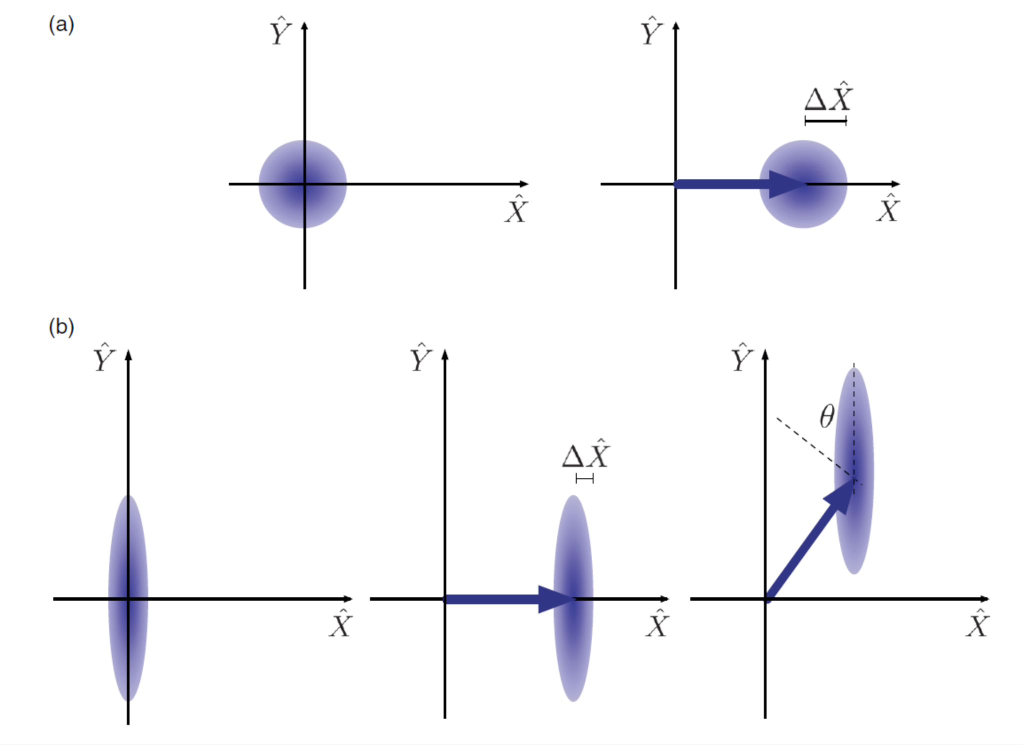
2 Watt beam exits the NPRO

https://www.ligo.caltech.edu/page/laser



https://www.ligo.caltech.edu/page/laser

Quantum phasor representations

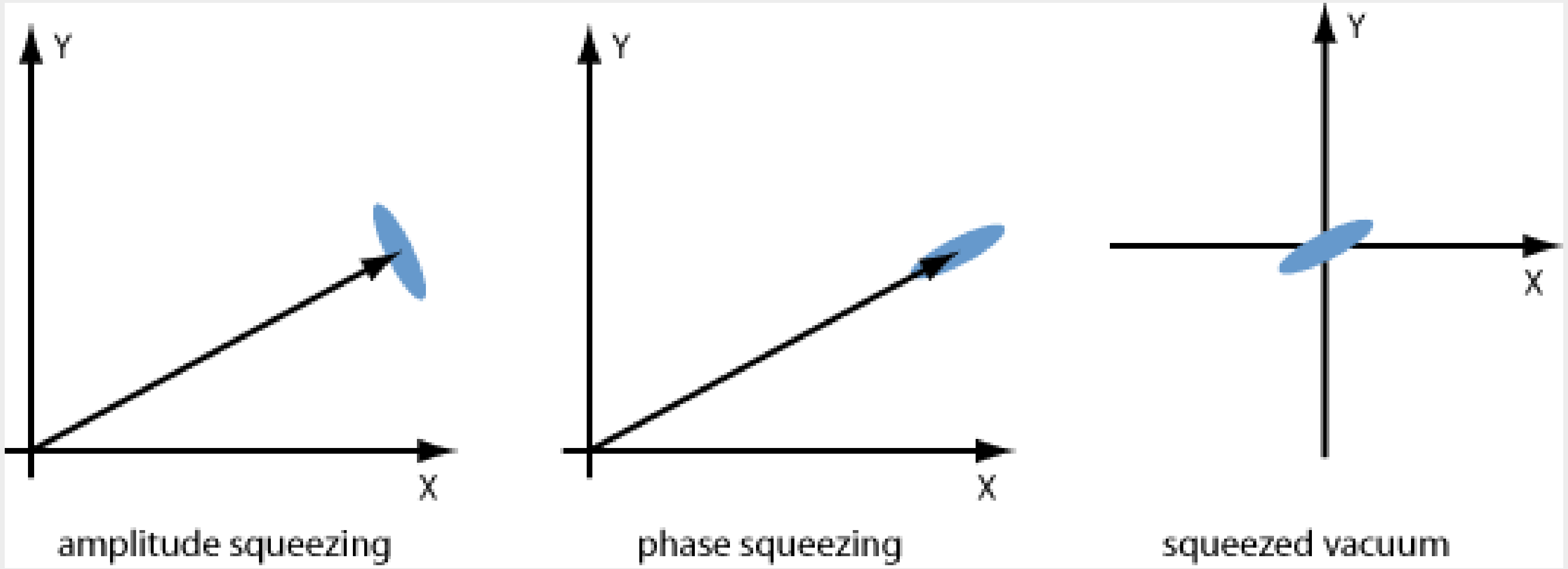


(a) A vacuum state (left) and a displaced vacuum state. The phase space is spanned by the quadrature operators. They are defined for a certain sideband frequency Ω and for a certain bandwidth ΔΩ. The coherent displacement corresponds to a classical modulation at Ω. ΔXˆ visualizes the standard deviation of the uncertainty in the amplitude quadrature amplitude (Xˆ).

b) left to right: A squeezed vacuum state, a displaced amplitude squeezed state, and a squeezed state with squeeze angle θ, defined with respect to the displacement.

Barsotti L, Harms J, Schnabel R. Squeezed vacuum states of light for gravitational wave detectors. *Reports on Progress in Physics*. Jan 2019;82(1)016905. doi:10.1088/1361-6633/aab906

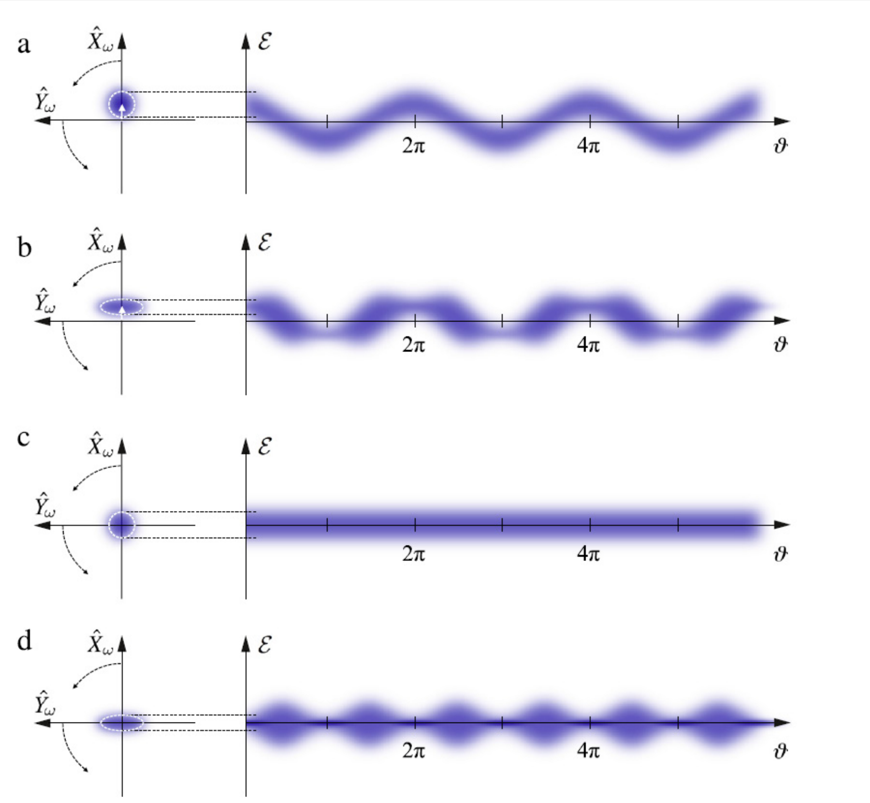
Squeezed *vacuum* states of light



Squeezed vacuum is a “vacuum” only in the sense that the average amplitude (but not the average photon number) is zero. Squeezed light with a non-zero average amplitude is also called bright squeezed light.

https://www.rp-photonics.com/squeezed_states_of_light

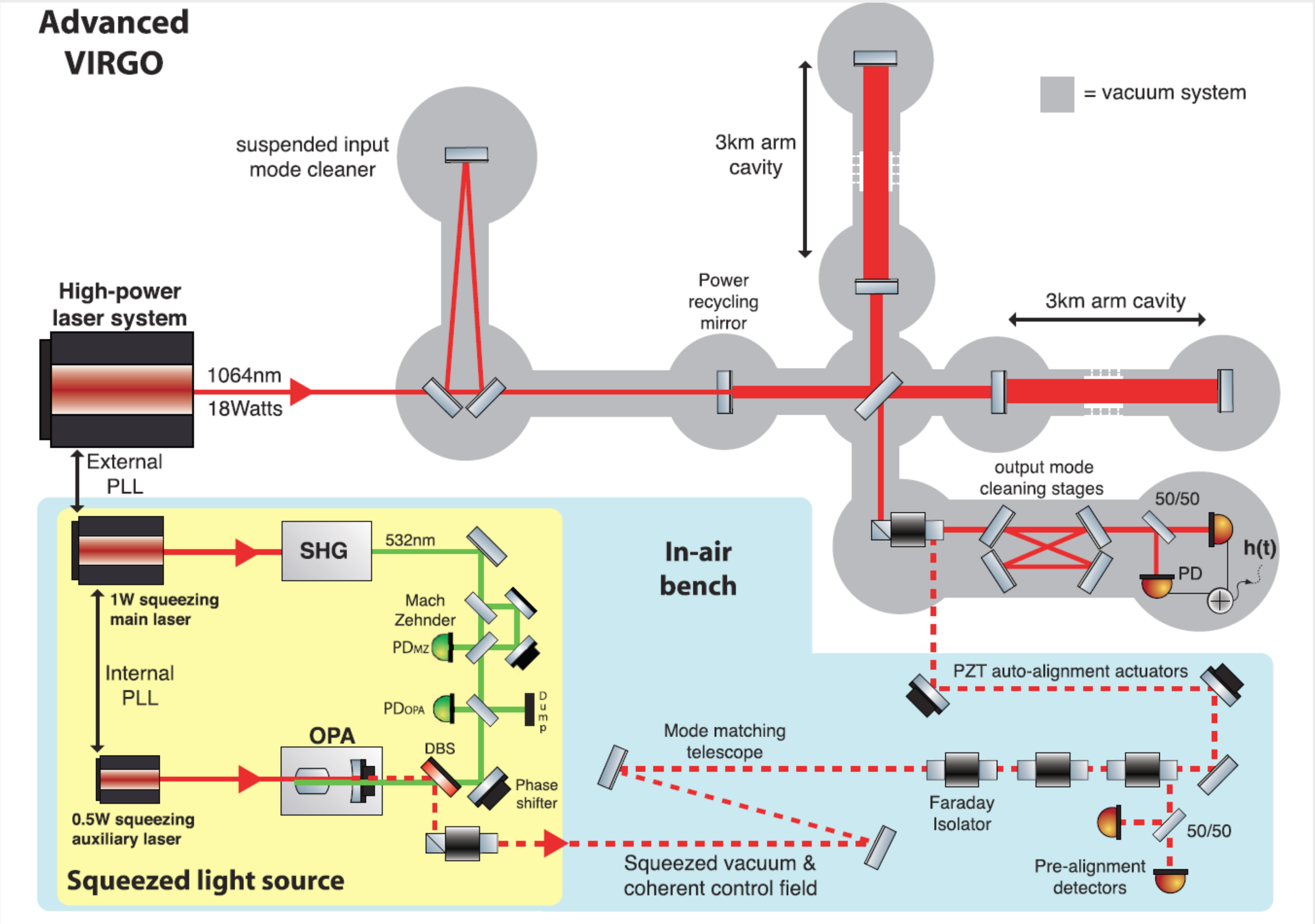
Phase spaces and electric field oscillations of monochromatic light



Monochromatic light in a coherent state is represented by a phasor (white arrow) including its quantum uncertainty (white dashed circle and fuzzy area) located in the phase-space spanned by the quadratures ˆ Xω and ˆ Yω. When the phase space rotates with optical frequency ω/2π, the projection of the quantum phasor onto a fixed (vertical) axis corresponds to the electric field E(t),

a) Weakly displaced coherent state.
b) Corresponding amplitude squeezed state. The electric field uncertainty around the zero average field region is anti-squeezed.
c) Vacuum state at the same optical frequency.
d) Corresponding squeezed vacuum state.

Schnabel R. Squeezed states of light and their applications in laser interferometers. *Physics Reports-Review Section of Physics Letters*. Apr 2017;684:1-51. doi:10.1016/j.physrep.2017.04.001



The dual-recycled *Michelson interferometers with Fabry–Pérot cavities* will pass light through the optical cavity only when they are in resonance with it. [1]

DBS – Dual beam splitter
OPA – Optical parametric oscillator
PD - Photodiode
PLL- Phase lock loop
PZT - Piezoelectric
SHG- Second harmonic generator

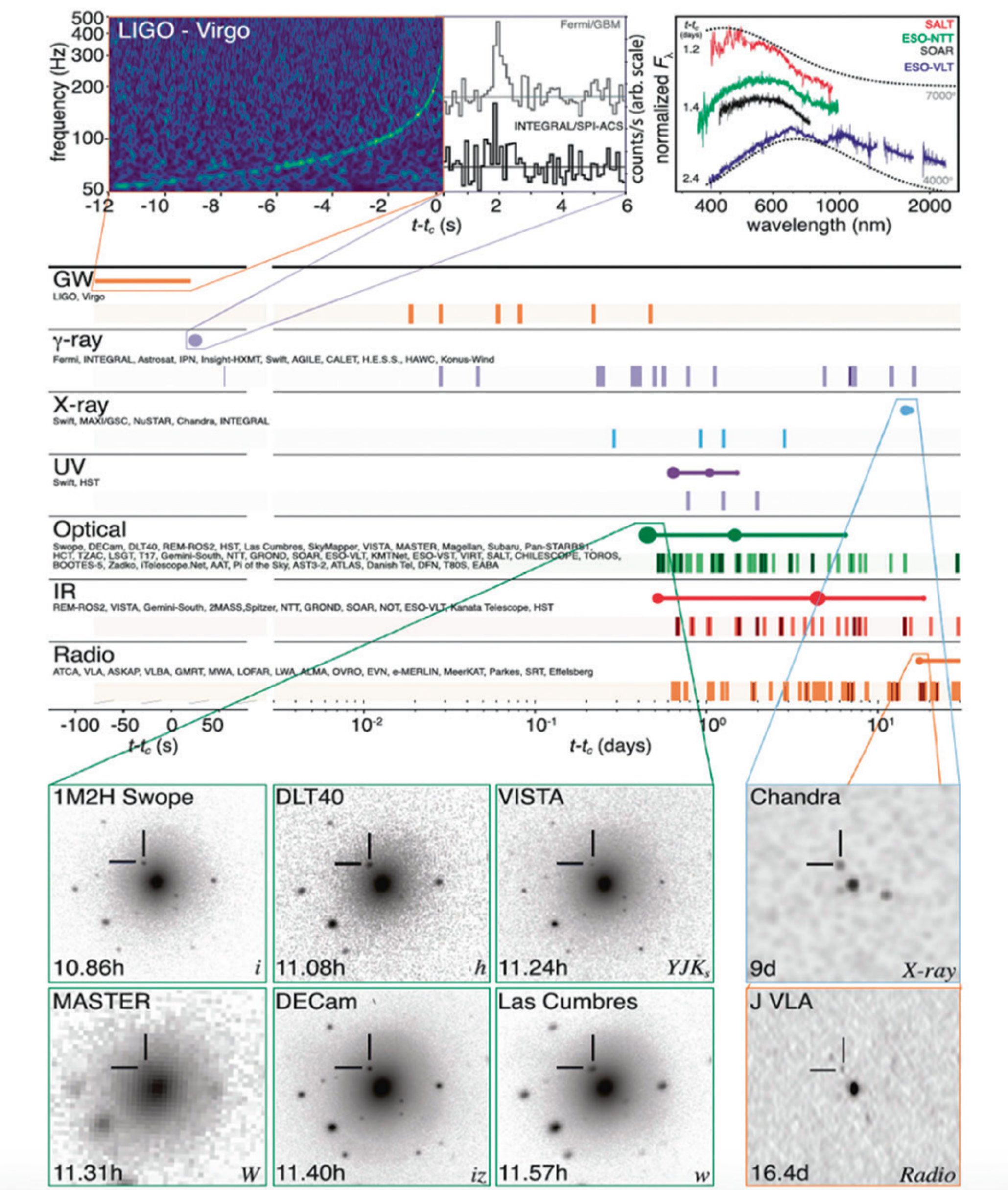
1. Tse M, Yu HC, Kijbunchoo N, et al. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. *Physical Review Letters*. Dec 2019;123(23)231107. doi:10.1103/PhysRevLett.123.231107

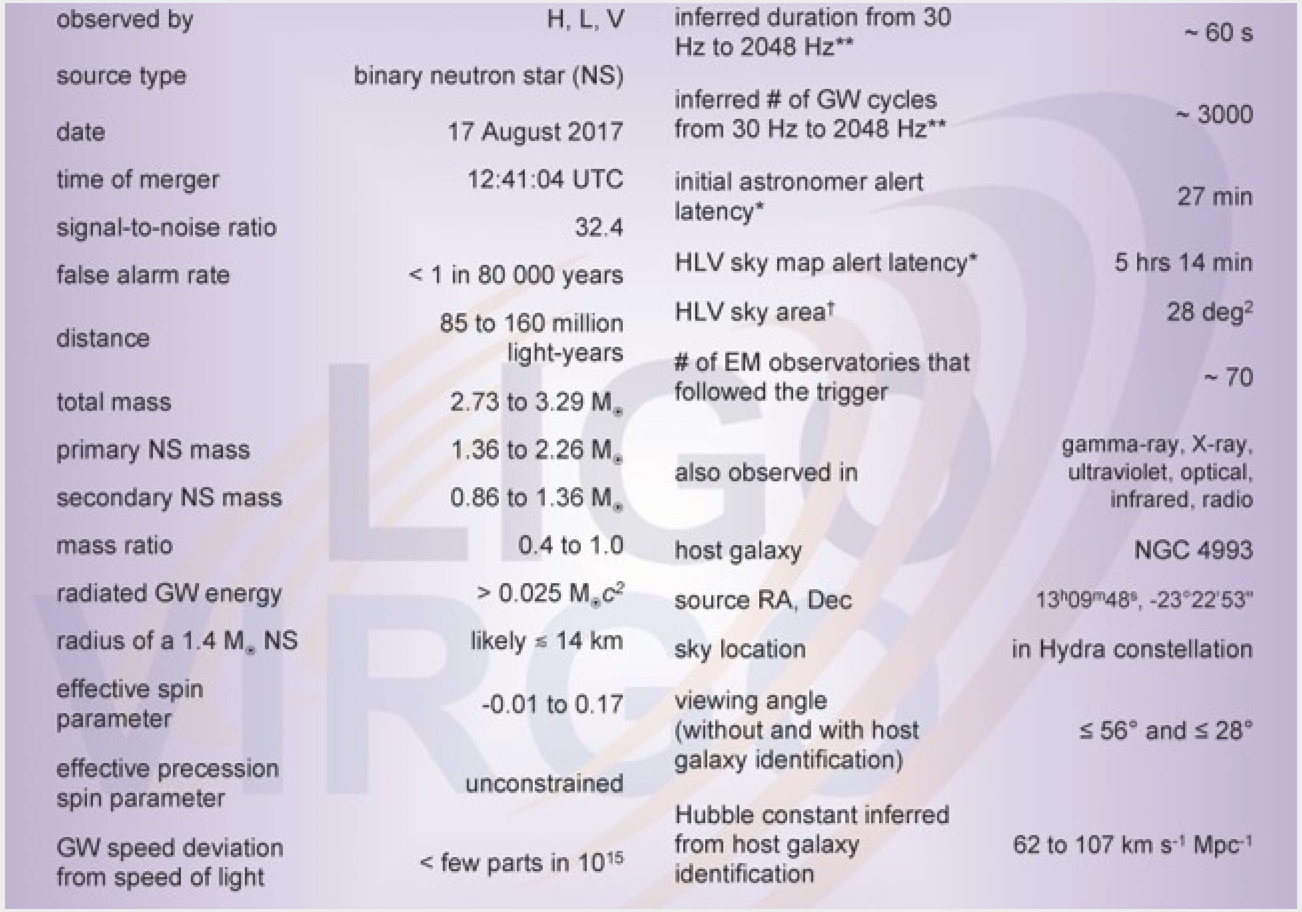
Acernese F, Agathos M, Aiello L, et al. Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light. *Physical Review Letters*. Dec 2019;123(23)231108. doi:10.1103/PhysRevLett.123.231108

GW170817 NS Merger Announcement (3:21:29). A new window should open, or paste link in browser. Takes about 10 s for conference to begin after logo.

https://www.ligo.caltech.edu/page/press-release-gw170817 https://www.youtube.com/watch?v=mtLPKYl4AHs

The electromagnetic counterparts to GW170817





observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≤ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, $-23°22'53''$
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}

https://www.ligo.caltech.edu/page/press-release-gw170817

Barry C. Barish – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2023. Sat. 8 Apr 2023. <https://www.nobelprize.org/prizes/physics/2017/barish/lecture/>

Einstein telescope – site to be determined

- Study of BH properties, their origin (stellar vs. primordial), evolution, demography.
- Neutron Star properties - interior structure (QCD at ultra-high densities, exotic states of matter), and demography.
- Multi-band and multi-messenger astronomy, for instance by increasing joint GW/EM observations.
- New astrophysical sources, such as core-collapse supernovae or isolated neutron stars.
- Investigations on dark energy equation of state, modified GW propagation, Stochastic backgrounds of cosmological origin

Chiummo, A. The Einstein Telescope: status of the project. EPJ Web of Conferences 280, 03003 (2023) 10.1051/epjconf/202328003003

3G design…

- LF & HF dual interferometers (1-10 Hz) with 10 km arms.
- More uniform sky coverage, multi-detectors with different orientations for sky coverage and polarization disentanglement, high duty cycle.
- Silicon or sapphire rather than fused silica test masses at cryogenic temperatures.
- Very high power laser.

Chiummo, A. The Einstein Telescope: status of the project. EPJ Web of Conferences 280, 03003 (2023) 10.1051/epjconf/202328003003

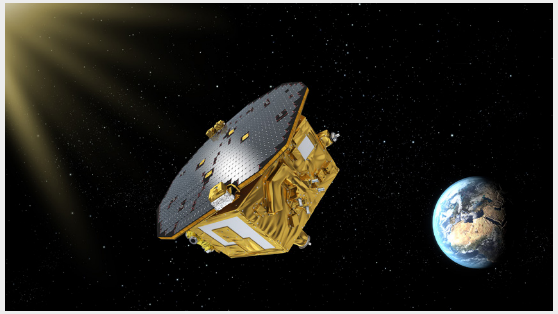
Coupling of EM Fields and Gravity

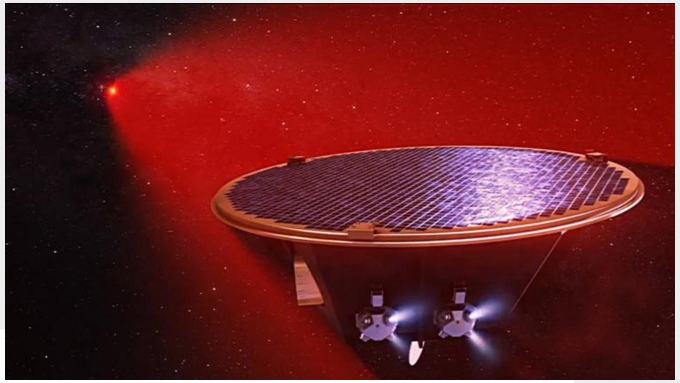
- Generation of electromagnetic waves due to gravitational radiation.
- In principle GWs might be measured not through test masses but rather by transduction of the GWs directly to electromagnetic information.
- The full Einstein-Maxwell's equations take into account curved spacetime within Maxwells' equations, and also the contribution of the electromagnetic stress-energy tensor to the gravitational field.
- Cabral and Lobo report on obtaining electric and magnetic field oscillations fully induced by a GW traveling along the z-axis. A non-zero longitudinal mode in electromagnetic radiation can in general be induced by gravitational radiation.

Cabral F, Lobo FSN. Gravitational waves and electrodynamics: new perspectives. *Eur Phys J C Part Fields*. 2017;77(4):237. doi:10.1140/epjc/s10052-017-4791-z

LISA

Laser Interferometer Space Antenna





- Eventually 3 spacecraft separated by millions of miles.
- Pathfinder is the proof-of-concept mission with free-falling test masses.
- LISA operates in the low frequency range, between 0.1 mHz to 1 Hz (compared to LIGO's frequency of 10 Hz to 1000 Hz).
- The difference means that the waves LISA is looking for have a much longer wavelength, corresponding to objects in much wider orbits and potentially much heavier than those that LIGO is searching for, opening up the detection realm to a wider range of gravitational wave sources.
- The gravitational wave sources that LISA would discover include ultra-compact binaries in our Galaxy, supermassive black hole mergers, and extreme mass ratio inspirals.

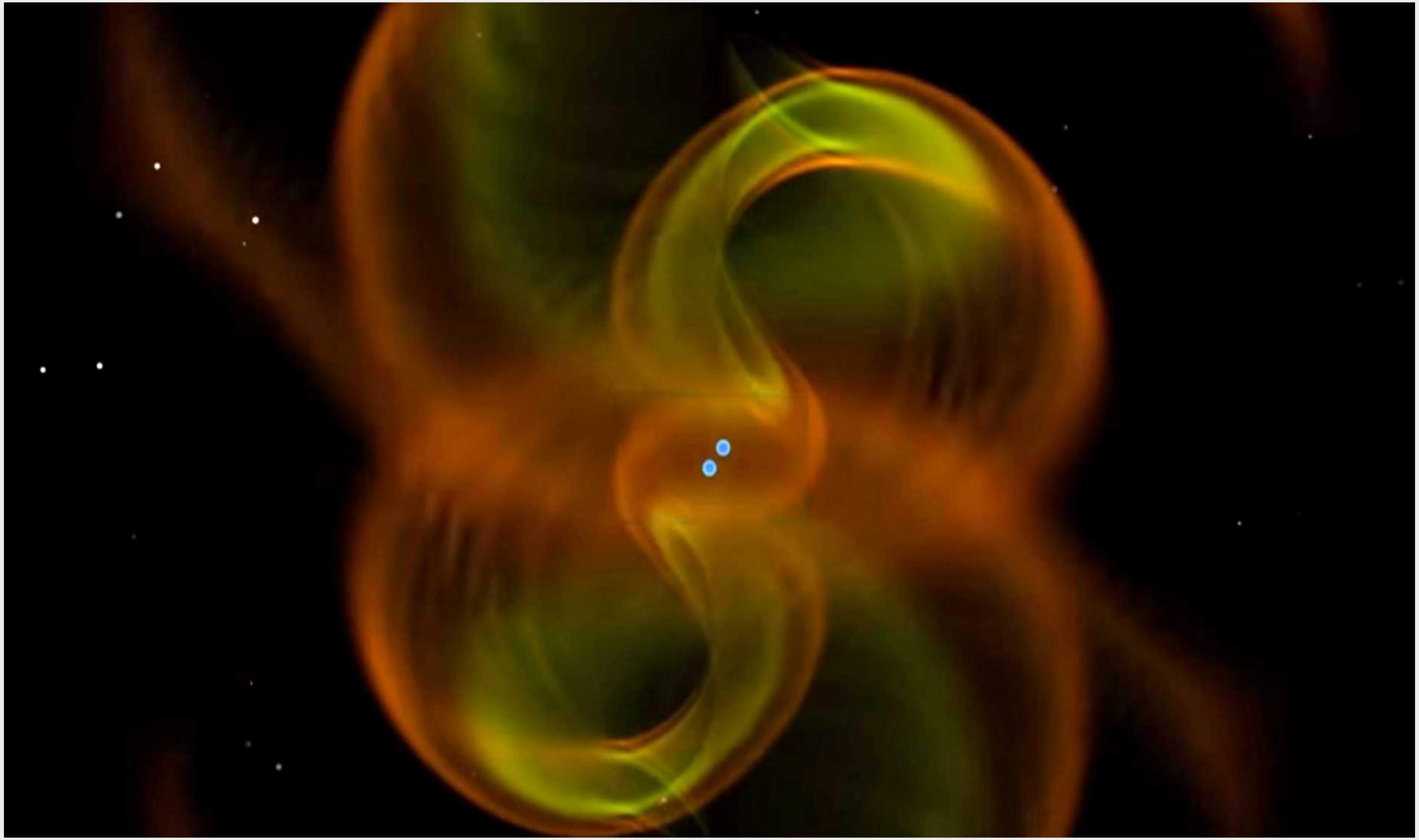
https://lisa.nasa.gov/

LISA at the 236th meeting of the American Astronomical Society (AAS 236)

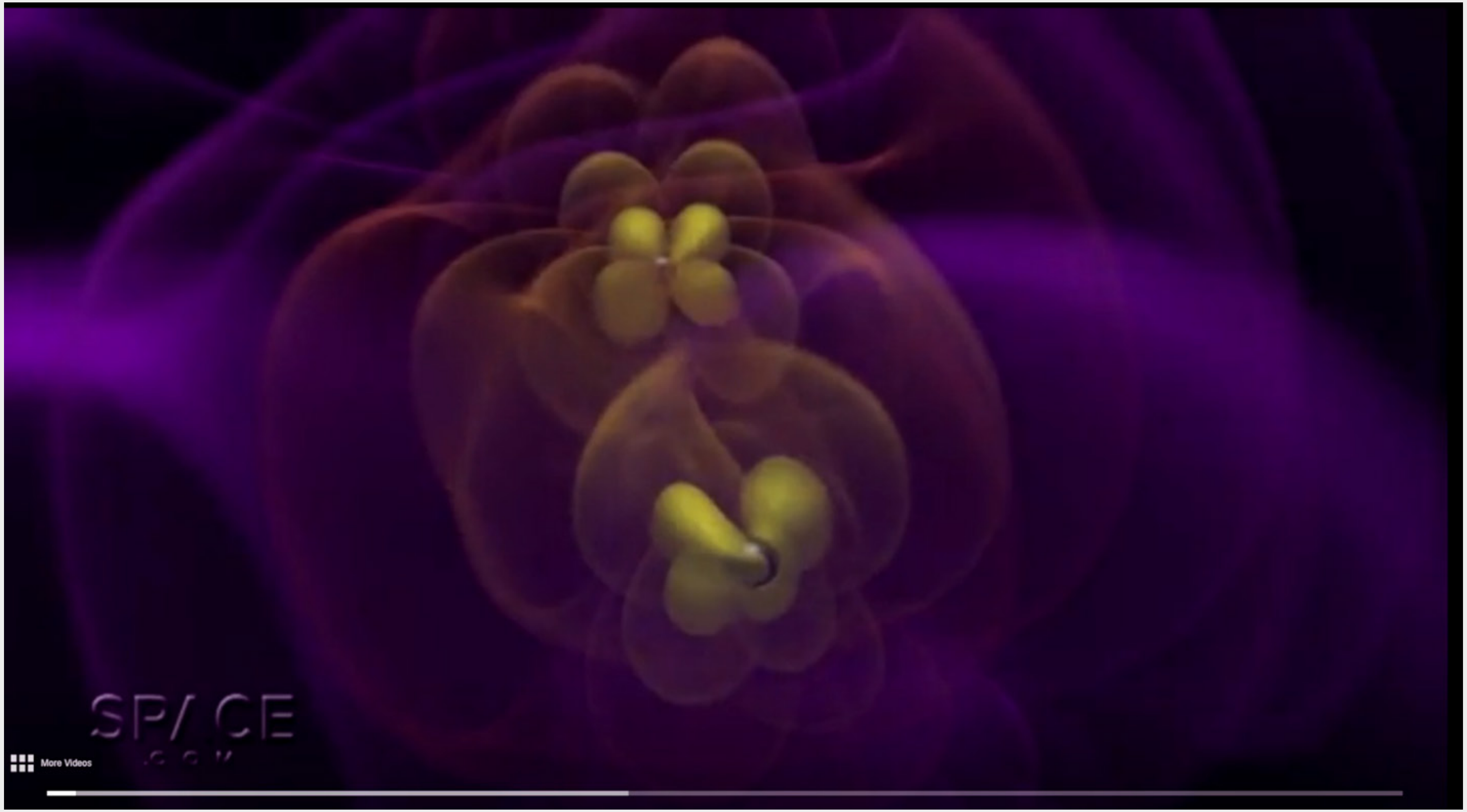
LISA

The first gravitational wave observatory in space

https://youtu.be/h_ApNry_jN0



Simulation of the neutron star coalescence GW190425, Max Planck Institute for Gravitational Physics https://youtu.be/853sZWxVto4



https://www.space.com/38816-gravitational-waves-fifth-ligo-black-hole-crash.html,
https://cdn.jwplayer.com/previews/Rh3FKvt0

Realtime & Interactive Links

Masses in the Stellar Graveyard Interactive Chart

https://ligo.northwestern.edu/media/mass-plot/index.html

Detector Status Portal: **Daily summary of detector performance:**

https://www.gw-openscience.org/detector_status/

GWIStat: **Real-time detector up/down status:**

https://ldas-jobs.ligo.caltech.edu/~gwistat/gwistat/gwistat.html

LIGO Data Grid Status: **Live dashboard showing up/down status of the detectors and online analyses. Status of the LIGO/Virgo alert pipeline is indicated by the "EMFollow" box:**

https://monitor.ligo.org/gwstatus

Gravitational Wave Quickview:

https://gw-quickview.streamlit.app/

Waveform Filter:

https://data.cardiffgravity.org/waveform-fitter/

Gravitational Wave Transiet Catalog:

https://www.gw-openscience.org/eventapi/