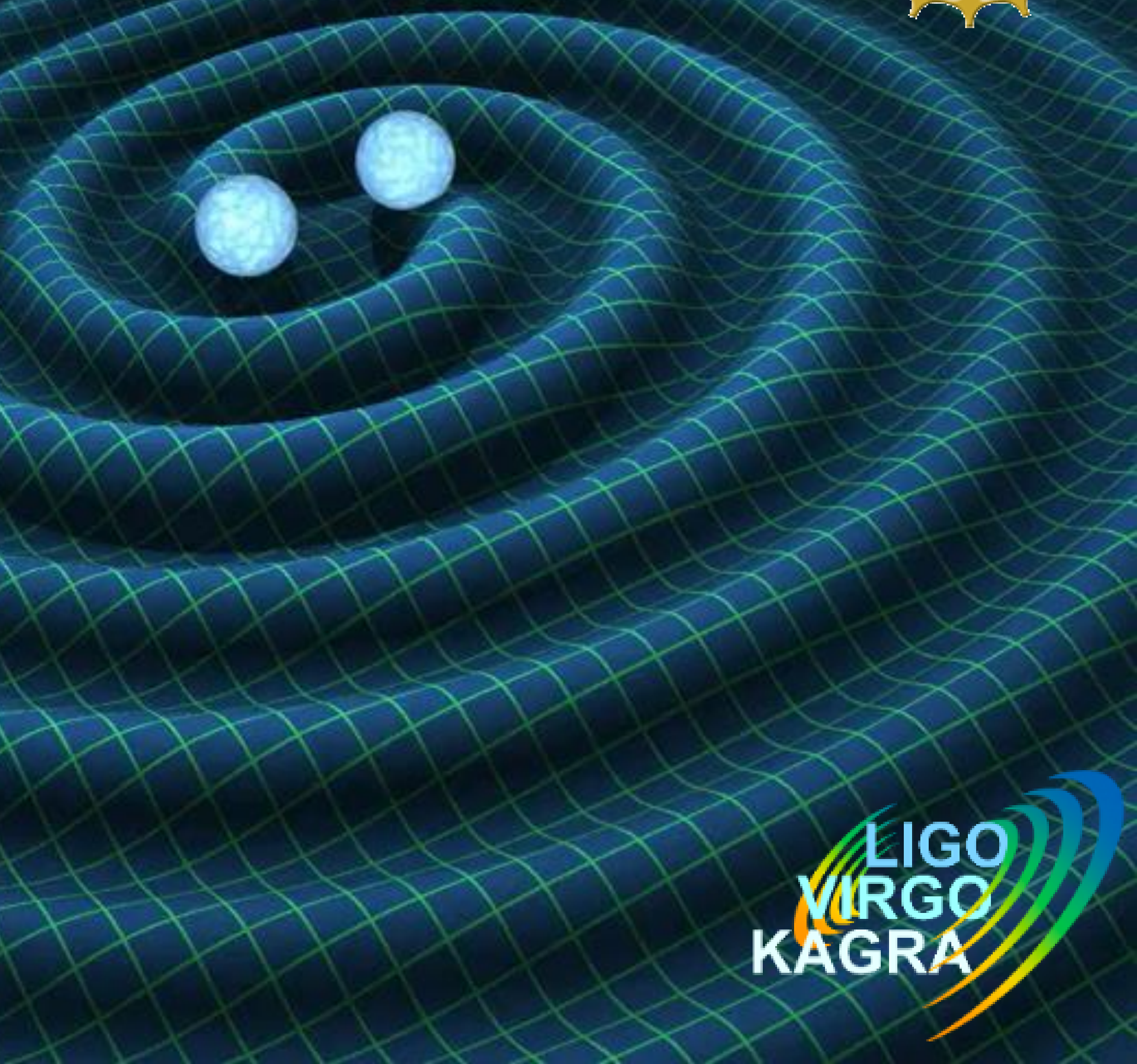
Interferometric Experimental Techniques: Squeezing in LIGO

Victoria Xu

Assistant Professor, Physics, UC Berkeley

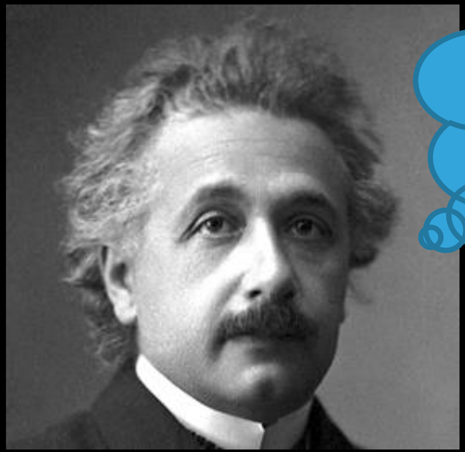
2026 SLAC Summer School

August 14, 2026



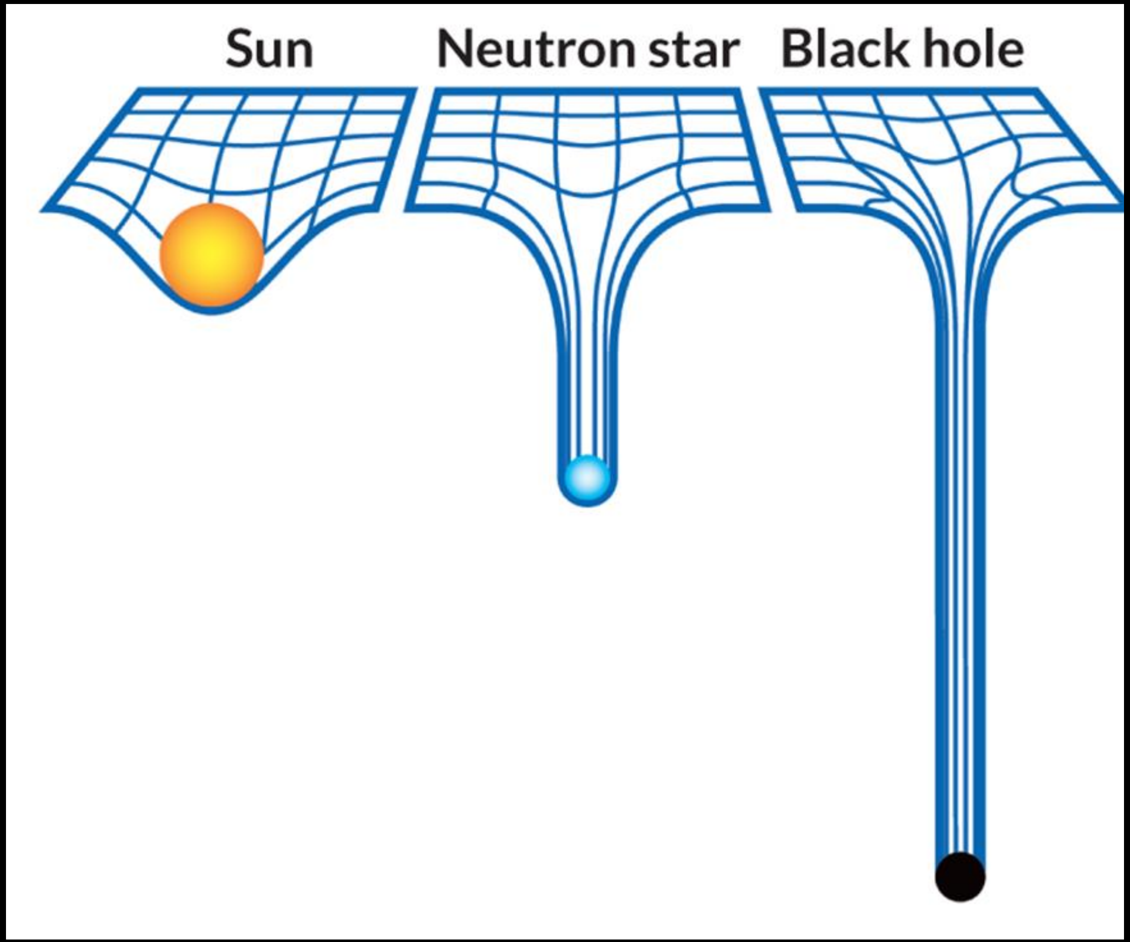
Credits: R. Hurt - Caltech / JPL

GRAVITATION



Albert Einstein

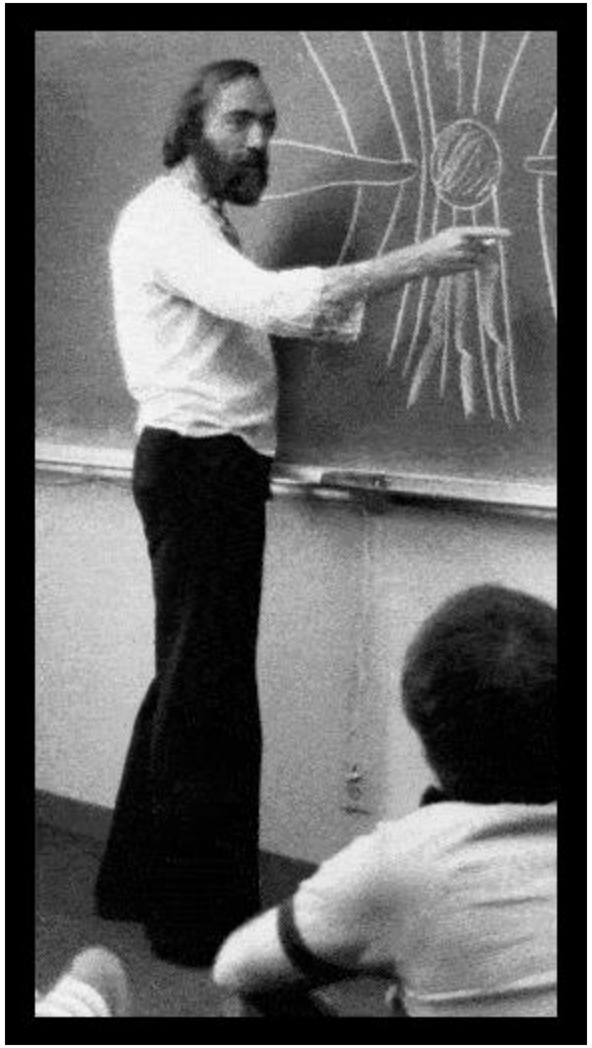
General relativity!



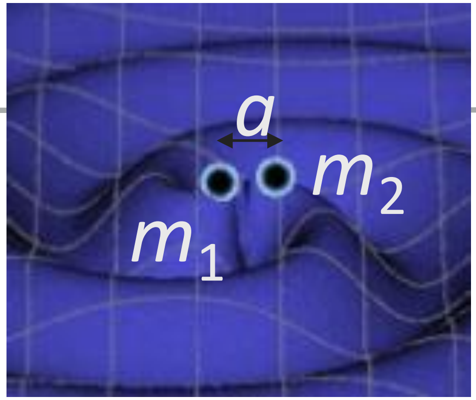
Spacetime tells matter how to move; matter tells spacetime how to curve.

- John Wheeler

GRAVITATIONAL WAVES



Kip Thorne



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} = \begin{bmatrix} -1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{bmatrix} + h \begin{bmatrix} 0 & & & \\ & 1 & & \\ & & -1 & \\ & & & 0 \end{bmatrix}$$

$$h \approx \frac{r_{S1} r_{S2}}{a} \frac{1}{r}$$

$$h = \frac{(90\text{ km})(90\text{ km})}{350\text{ km}} \frac{1}{(400)(3 \times 10^{19}\text{ km})} \sim 10^{-21}$$

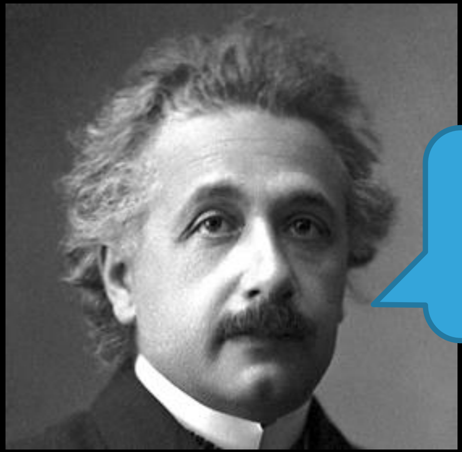
$$\Delta L = hL \sim 10^{-21}\text{ m}$$

Need long baseline L to get even close to an "observable" displacement ΔL

slide credit: W.Jia

GRAVITATION

"Quantum sensing" – when signal is smaller than quantum fluctuations, we need new tricks

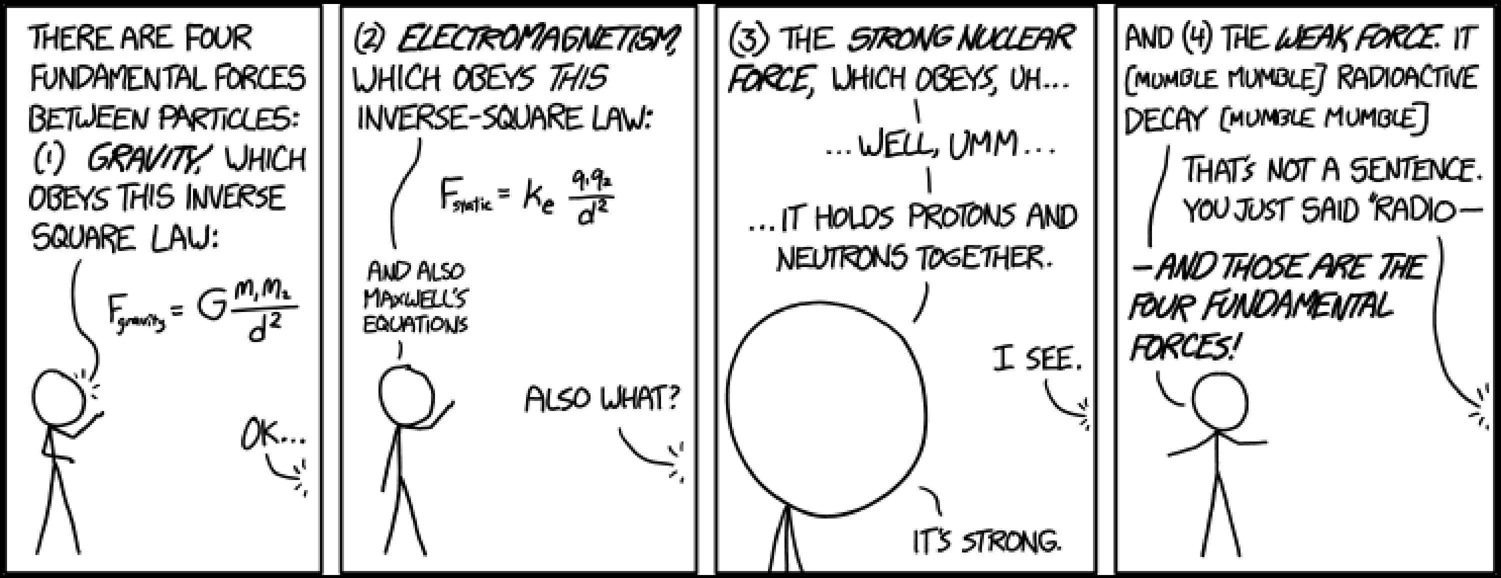


Albert Einstein

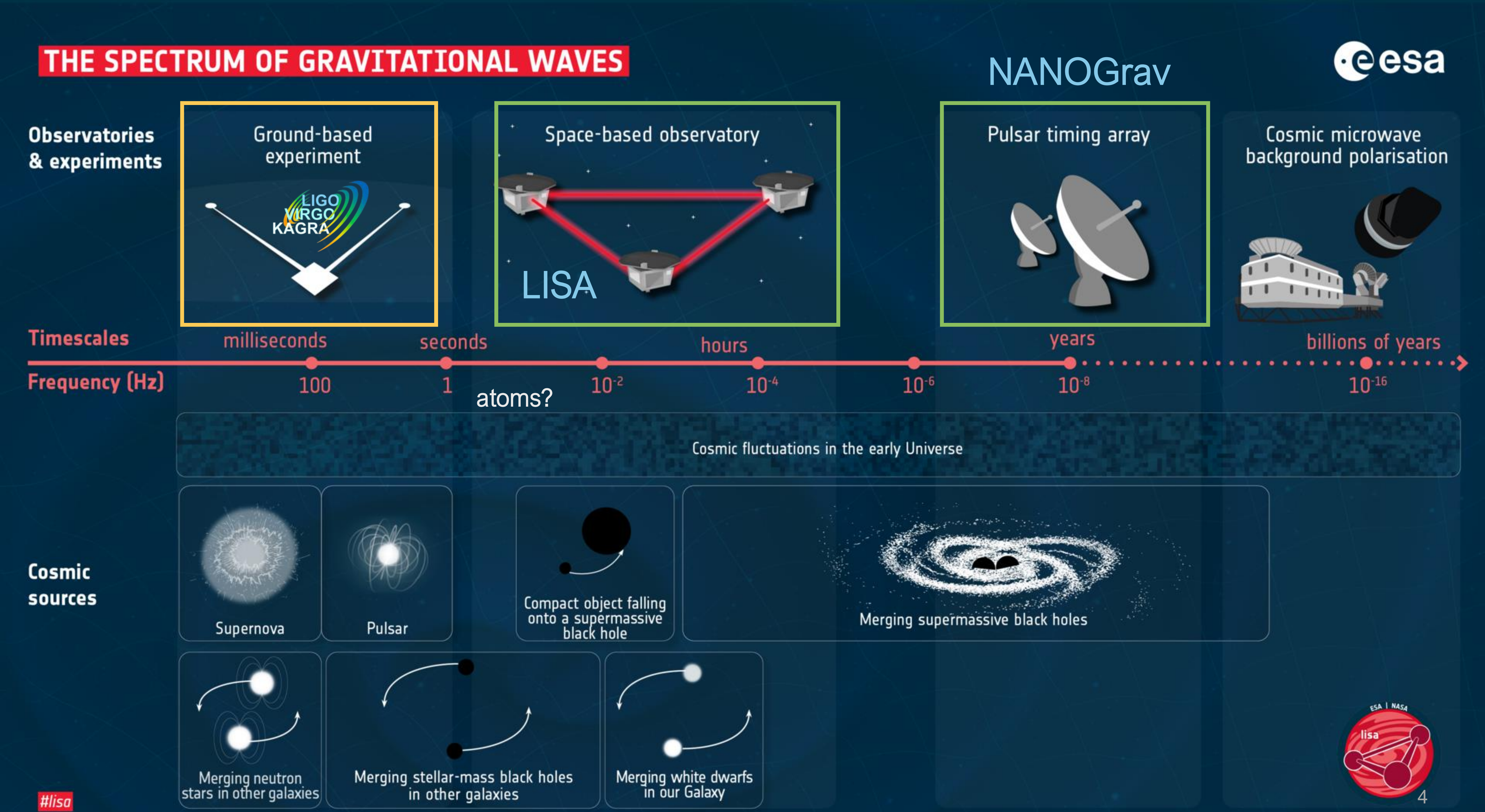
…one can see that (GW) must have a practically vanishing value in all conceivable cases.

A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. 1, 688 (1916)

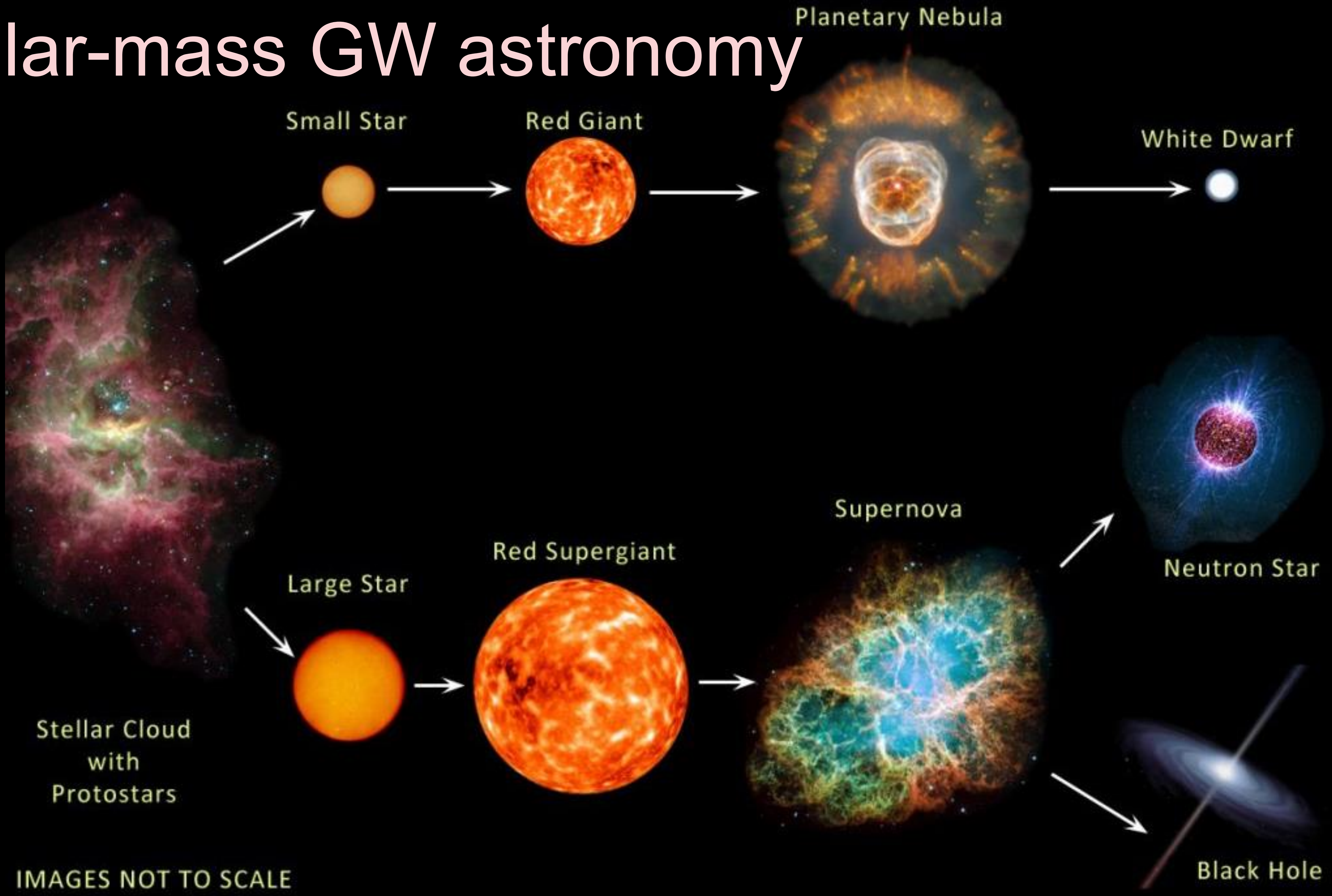
Relative strength:	strong	> electromagnetic	> weak	>> gravitation
	100	1	10^{-3}	10^{-36}



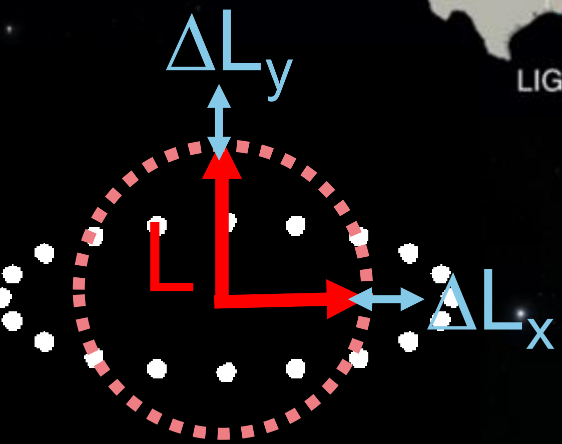
…and the one we understand least is gravity

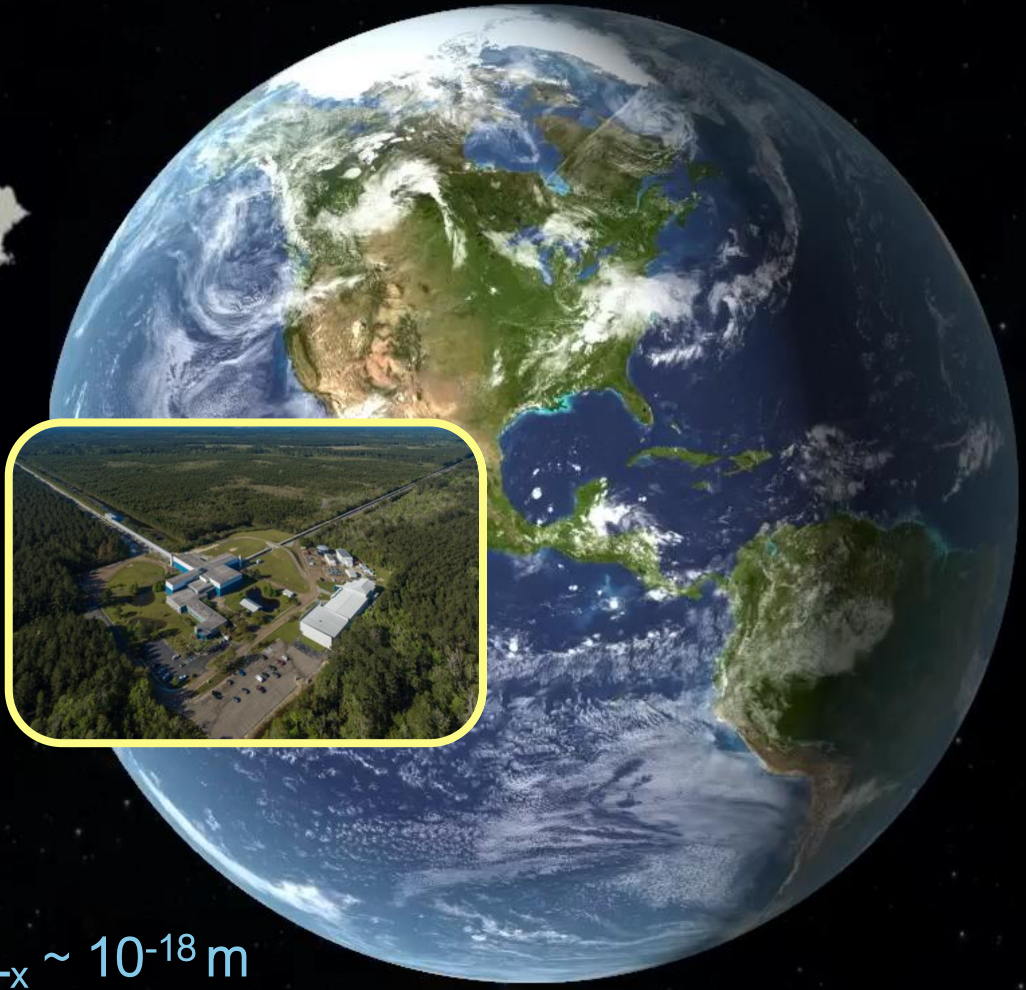

THE SPECTRUM OF GRAVITATIONAL WAVES
esa
NANOGrav
Observatories & experiments
Ground-based experiment
LIGO
VIRGO
KAGRA
Space-based observatory
LISA
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
atoms?
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
ESA | NASA
lisa

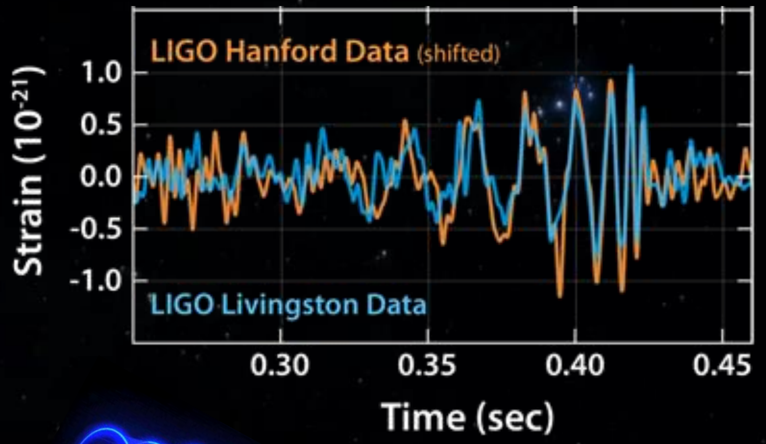
Stellar-mass GW astronomy

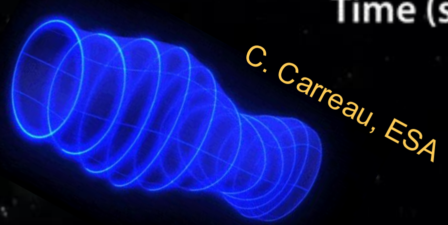


GRAVITATIONAL WAVES





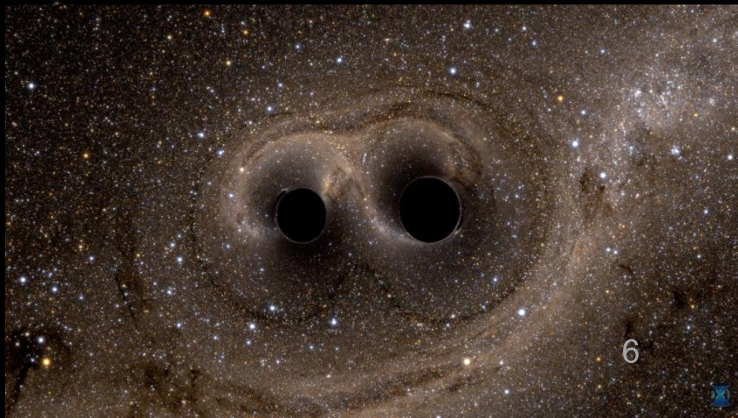




$$\text{Strain } h \sim 10^{-21} \sim \frac{\Delta L = \Delta L_y - \Delta L_x \sim 10^{-18}\text{ m}}{L \sim 4000\text{ m (2.5 miles)}}$$

Scale of Effect Vastly Exaggerated

Credit: LIGO/R. Hurt

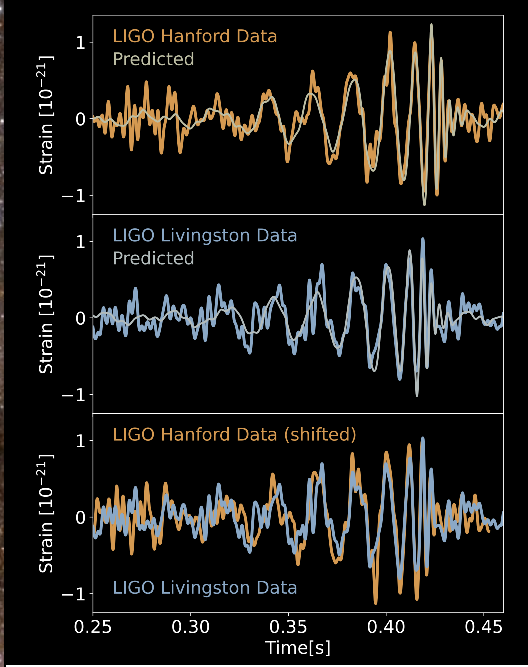


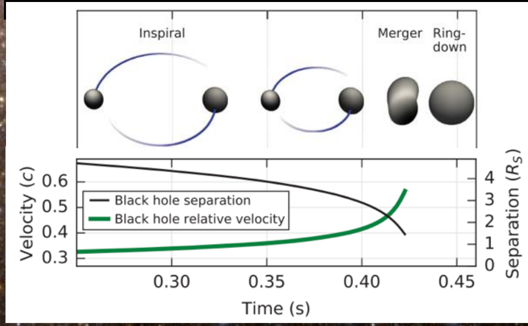
The dawn of gravitational wave astrophysics GW150914

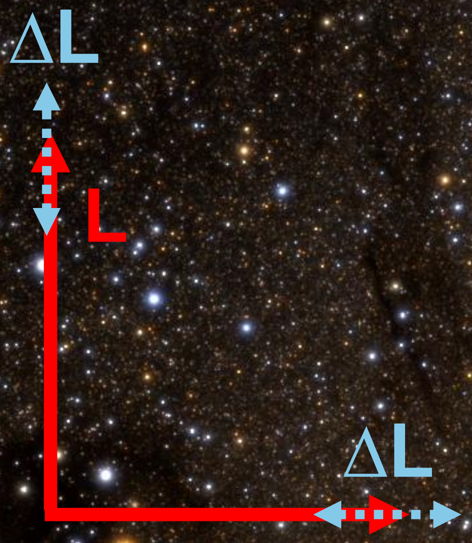
Featured in Physics | Editors' Suggestion | Open Access

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102 – Published 11 February 2016







$h \sim 10^{-21} \sim \frac{\Delta L \sim 10^{-18}\ \text{m}}{L \sim 4000\ \text{m (2.5 miles)}}$

$M \approx 29\ \&\ 36\ M_{sun}$

$D \approx$ 1.3 billion l.y. (410 Mpc)

$\Delta E \approx 3\ M_{sun}$

Video Credits: Simulating eXtreme Spacetimes (SXS) project

Stellar remnants – neutron stars

Neutron stars are supernova remnants, with the mass of 1.5x suns in ~12 miles.

*** Very high density, like 4 x 10^{17} kg/m^3 ! a spoonful weighs as much as a mountain!

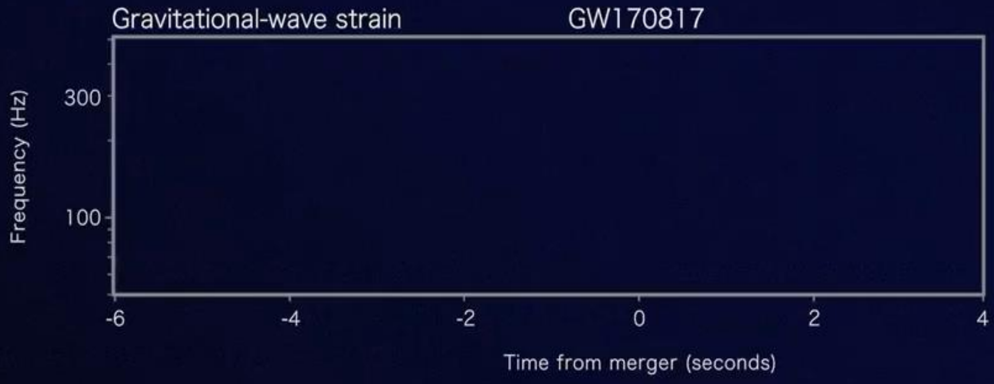
Video Credits: LIGO / Caltech / MIT / Fermilab

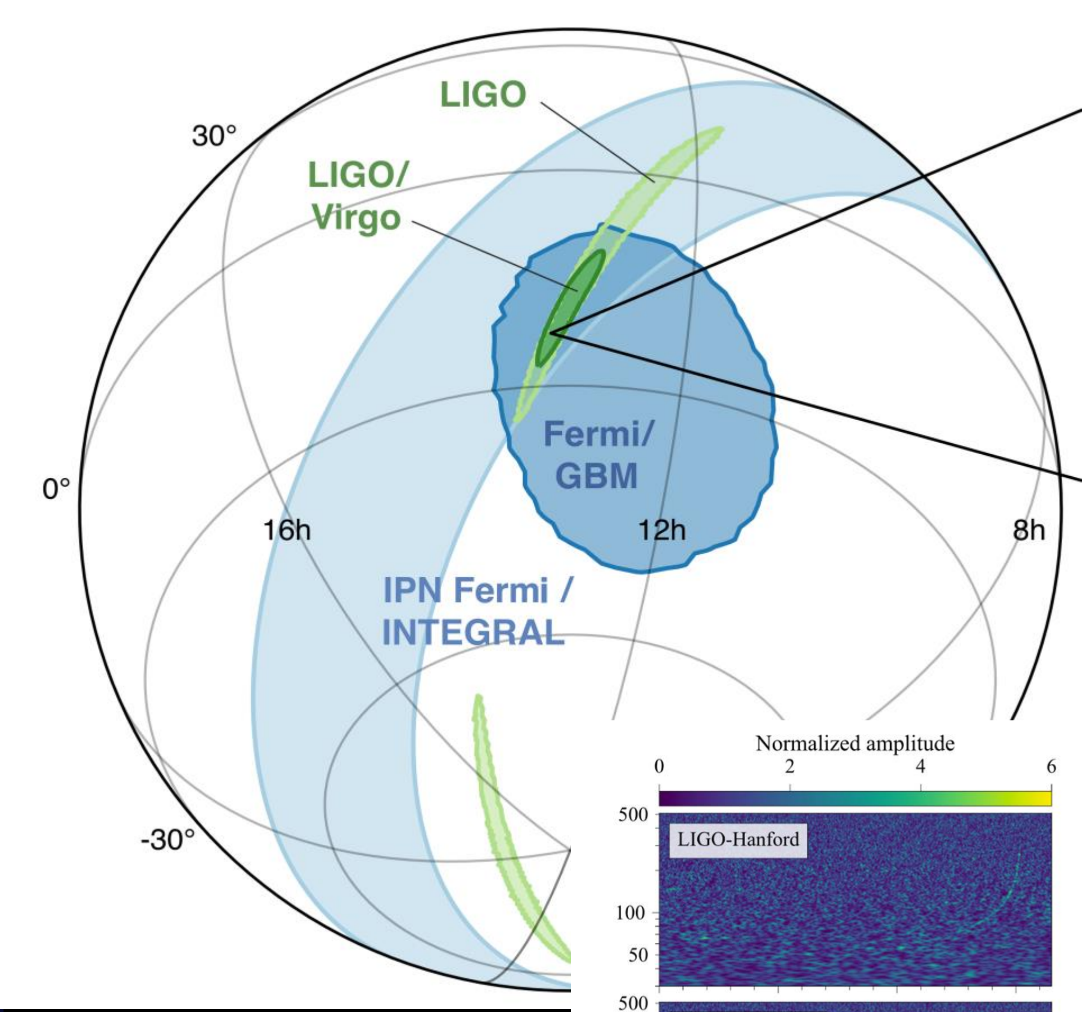
NEUTRON STAR MERGERS

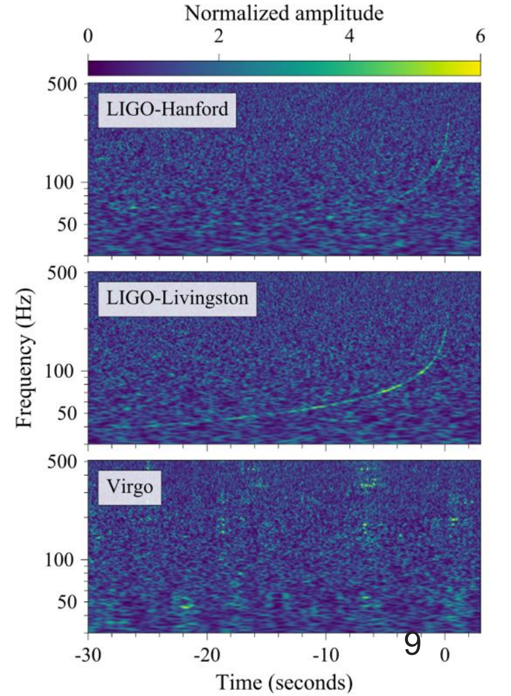
Neutron stars are supernova remnants, with the mass of 1.5x suns in ~12 miles.

Fermi

LIGO







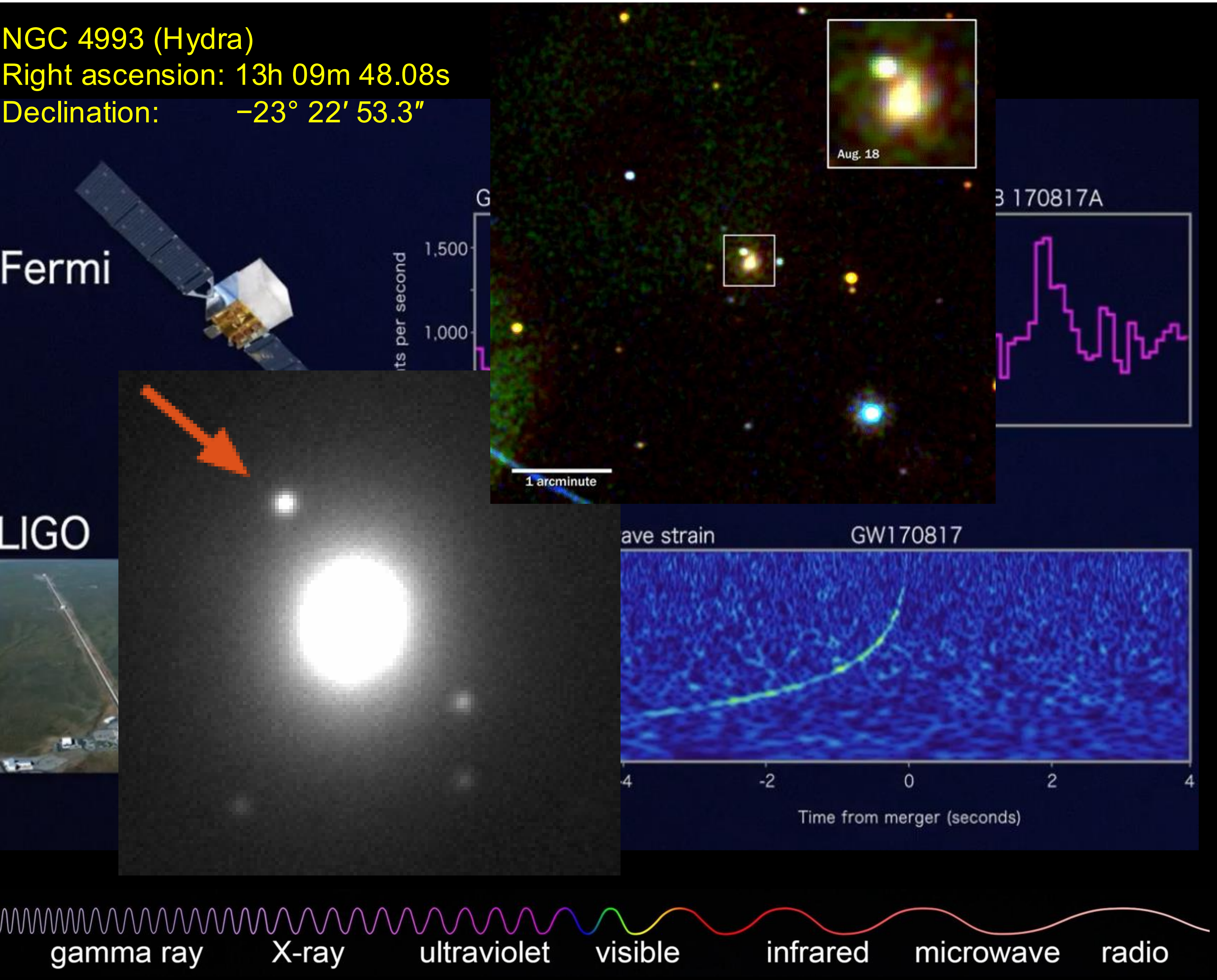
“Multi-messenger Observations of a Binary Neutron Star Merger”, The Astrophysical Journal Letters 848, L12 (2017)

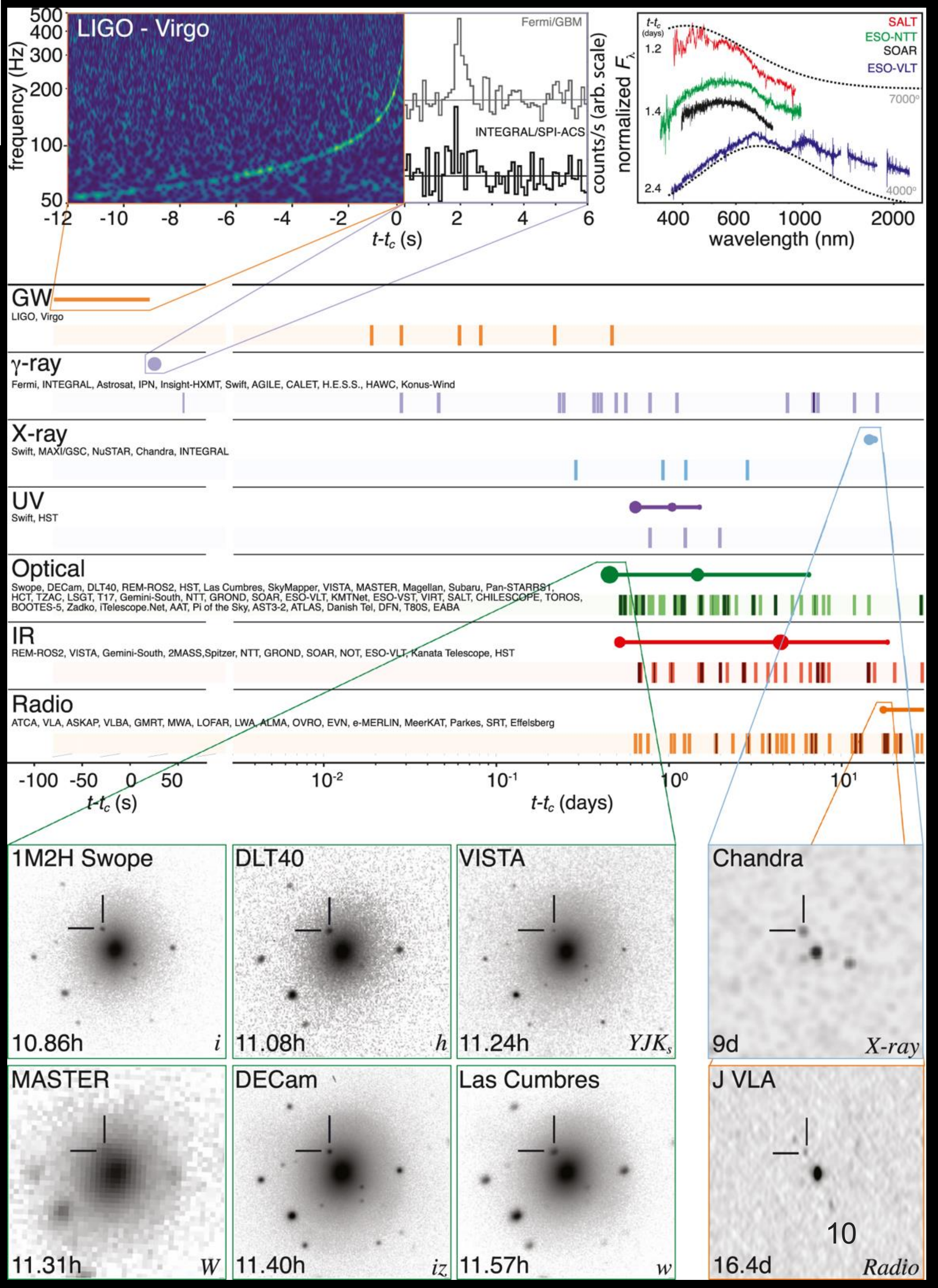
THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

Multi-messenger Observations of a Binary Neutron Star Merger*

NGC 4993 (Hydra)
Right ascension: 13h 09m 48.08s
Declination: −23° 22′ 53.3″

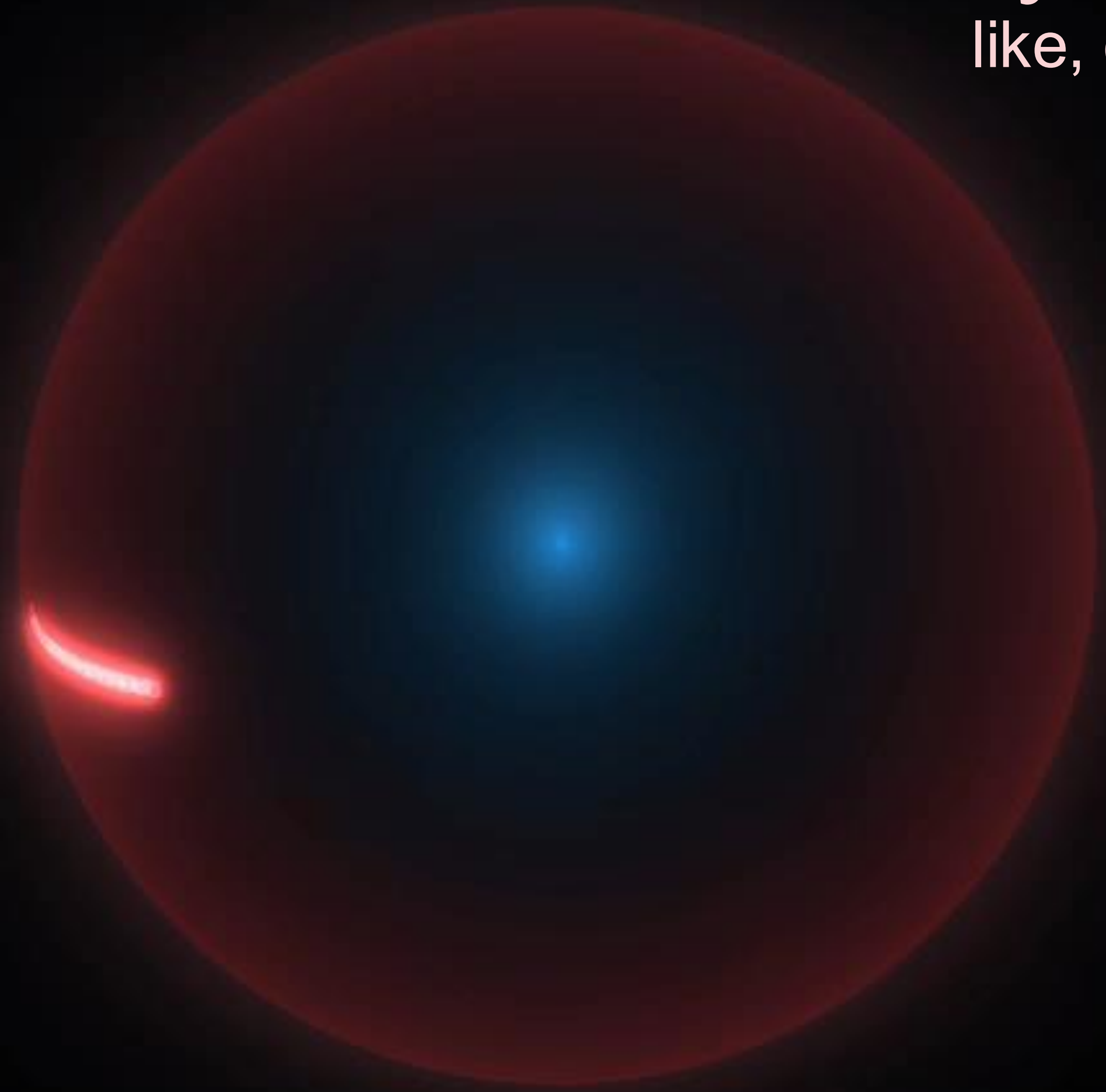




“Multi-messenger Observations of a Binary Neutron Star Merger”, The Astrophysical Journal Letters 848, L12 (2017)

How small is it really

like, compared to an atom?



At this scale, quantum effects are huge!

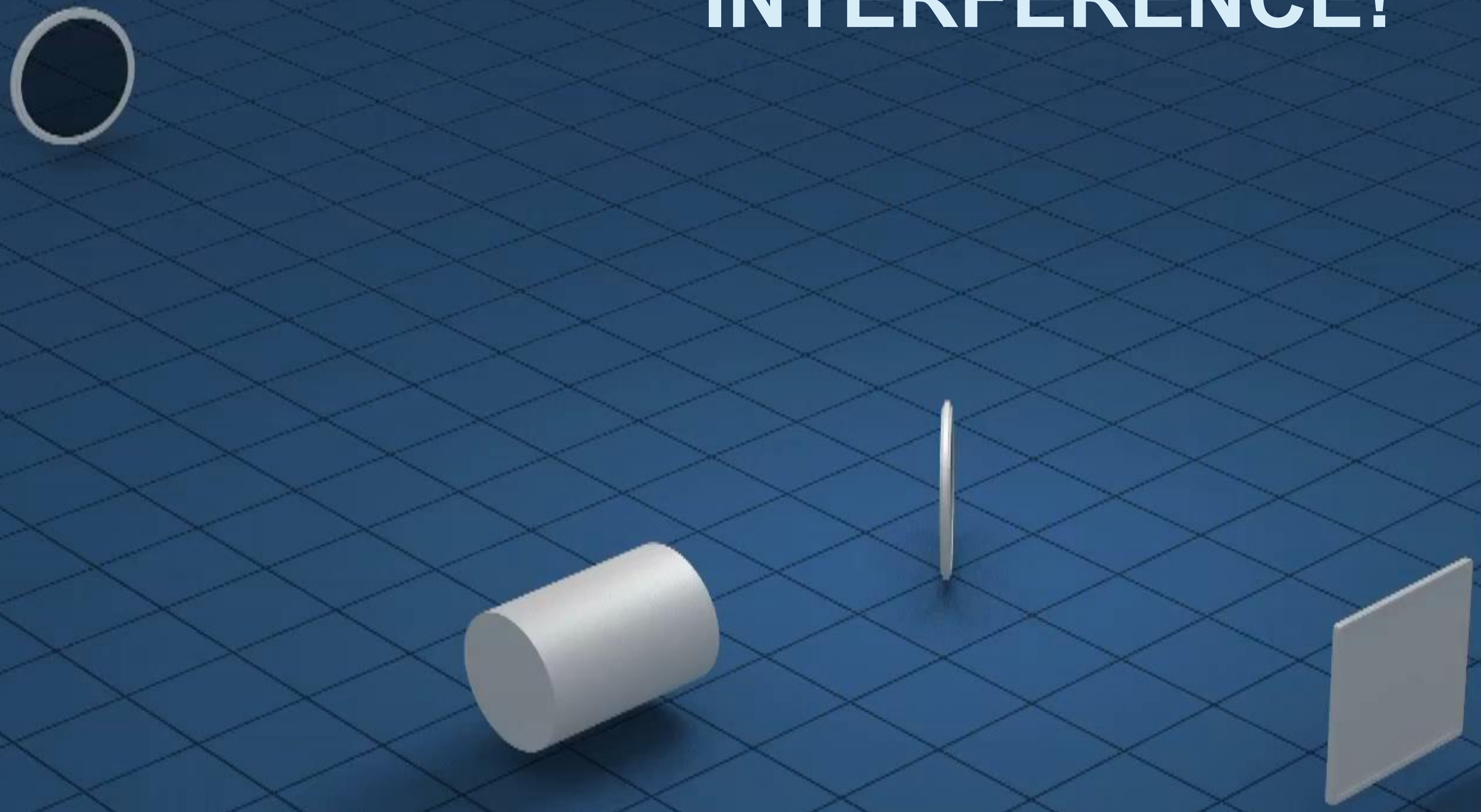
< 0.1% of a proton…so, really small.

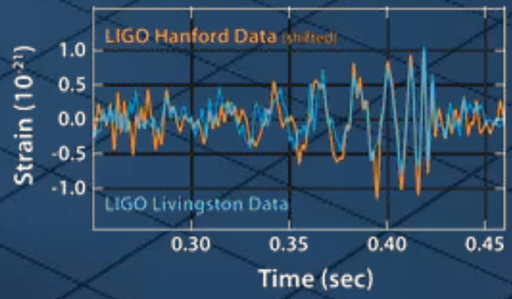
SIMULATION

Video Credits: LIGO / Caltech / MIT

HOW TO DETECT GRAVITATIONAL WAVES?

INTERFERENCE!





Interferometry for precision measurements

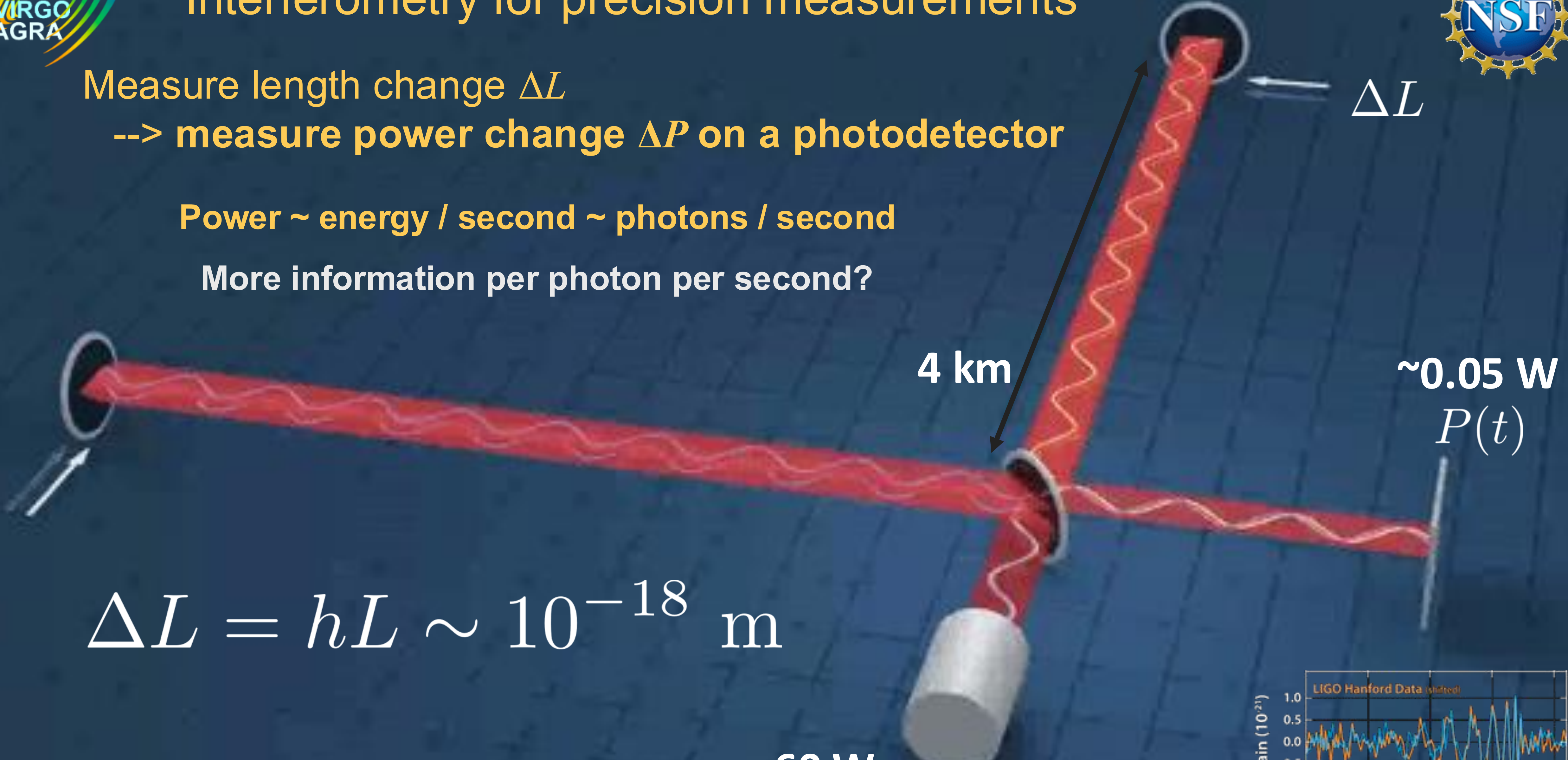
Measure length change ΔL

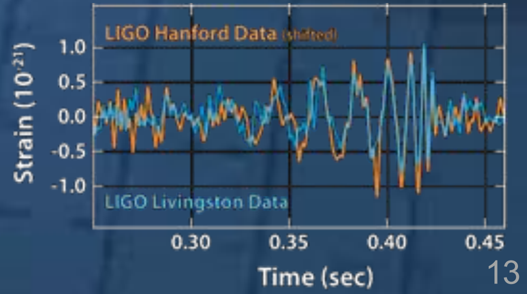
--> **measure power change ΔP on a photodetector**

Power ~ energy / second ~ photons / second

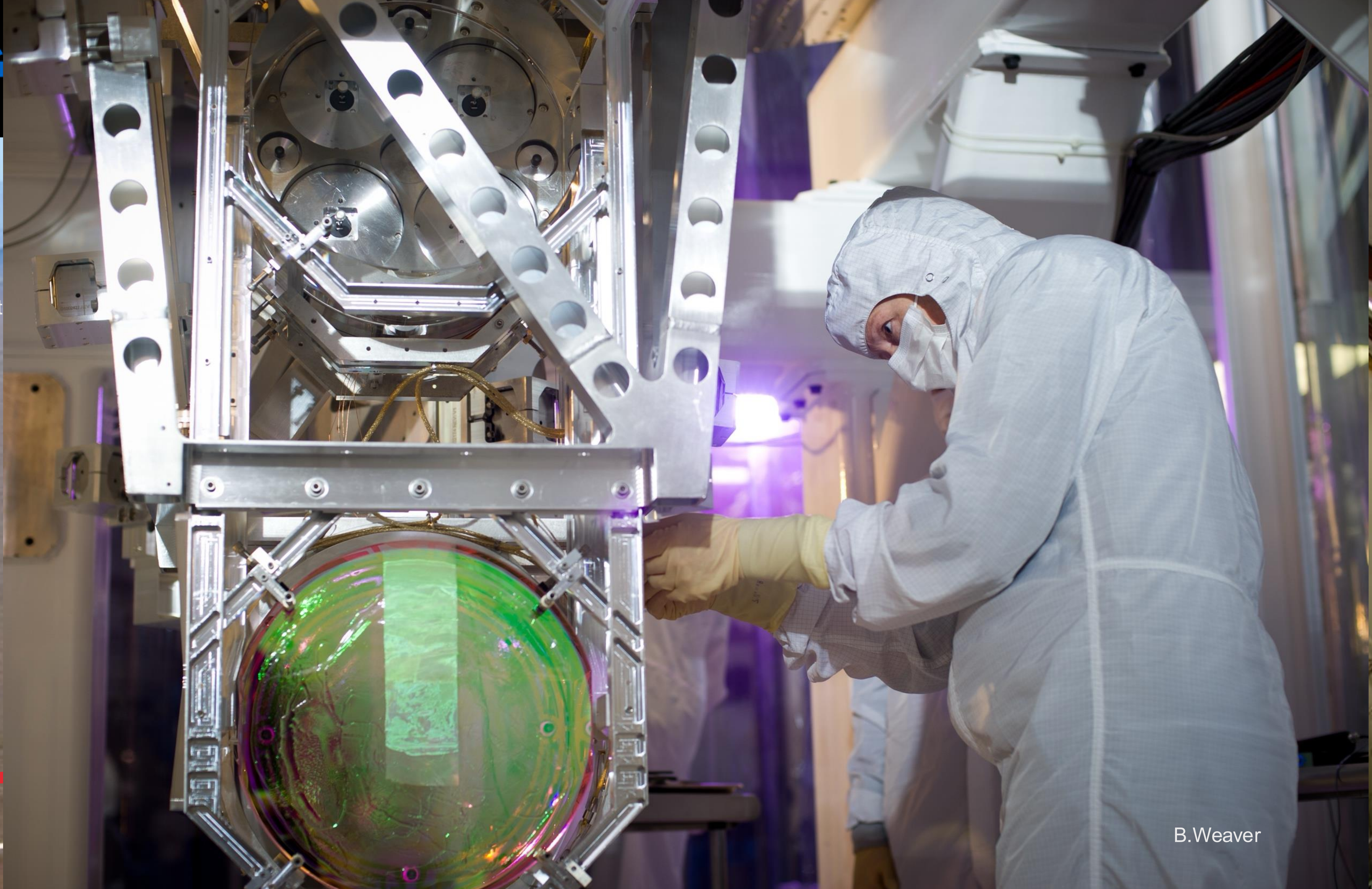
More information per photon per second?

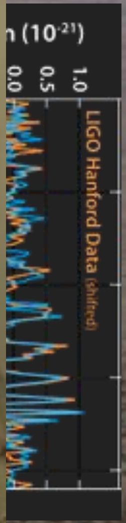
$$\Delta L = hL \sim 10^{-18}\ \mathrm{m}$$





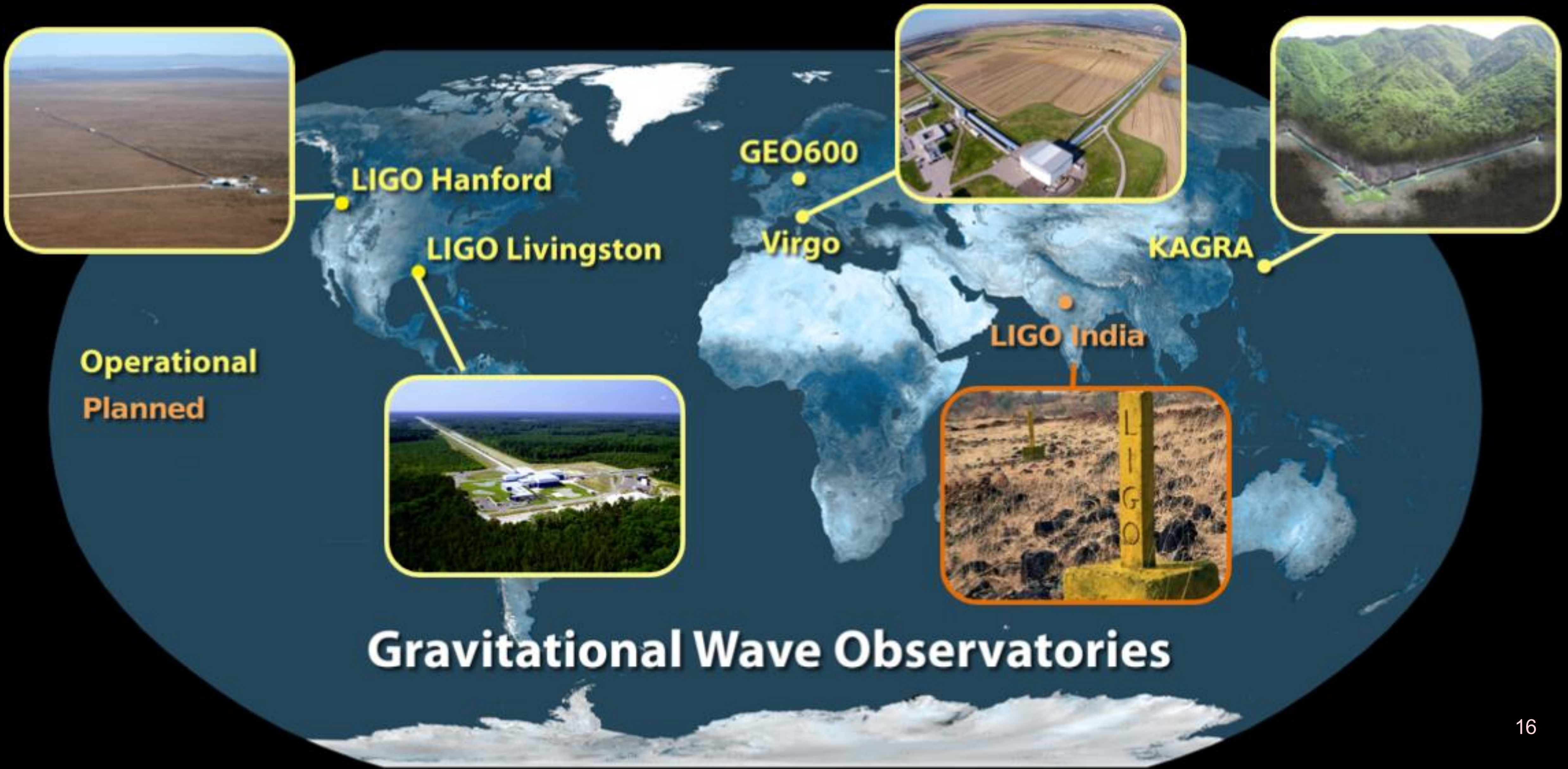
Slide credit … GO Lab

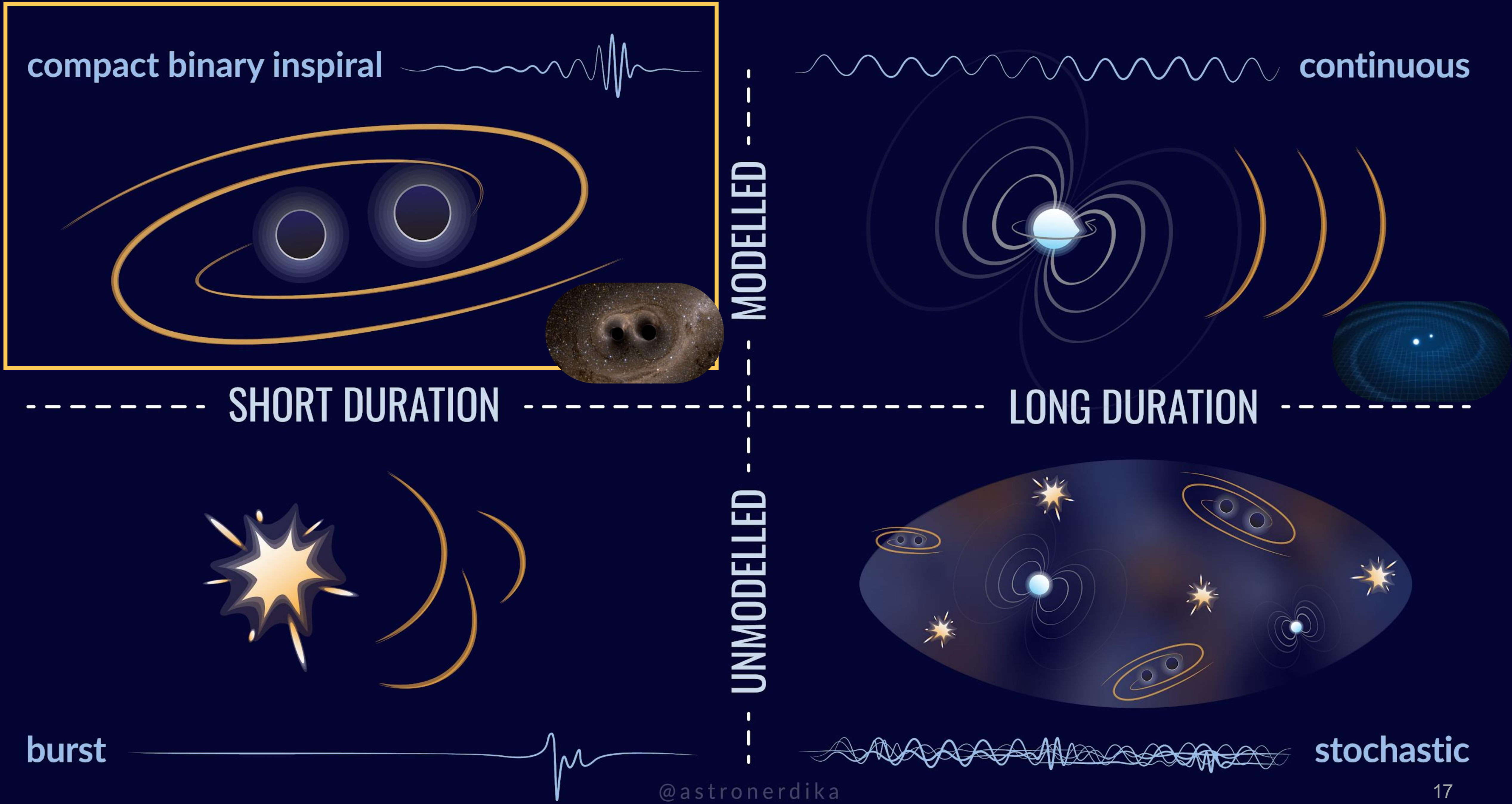




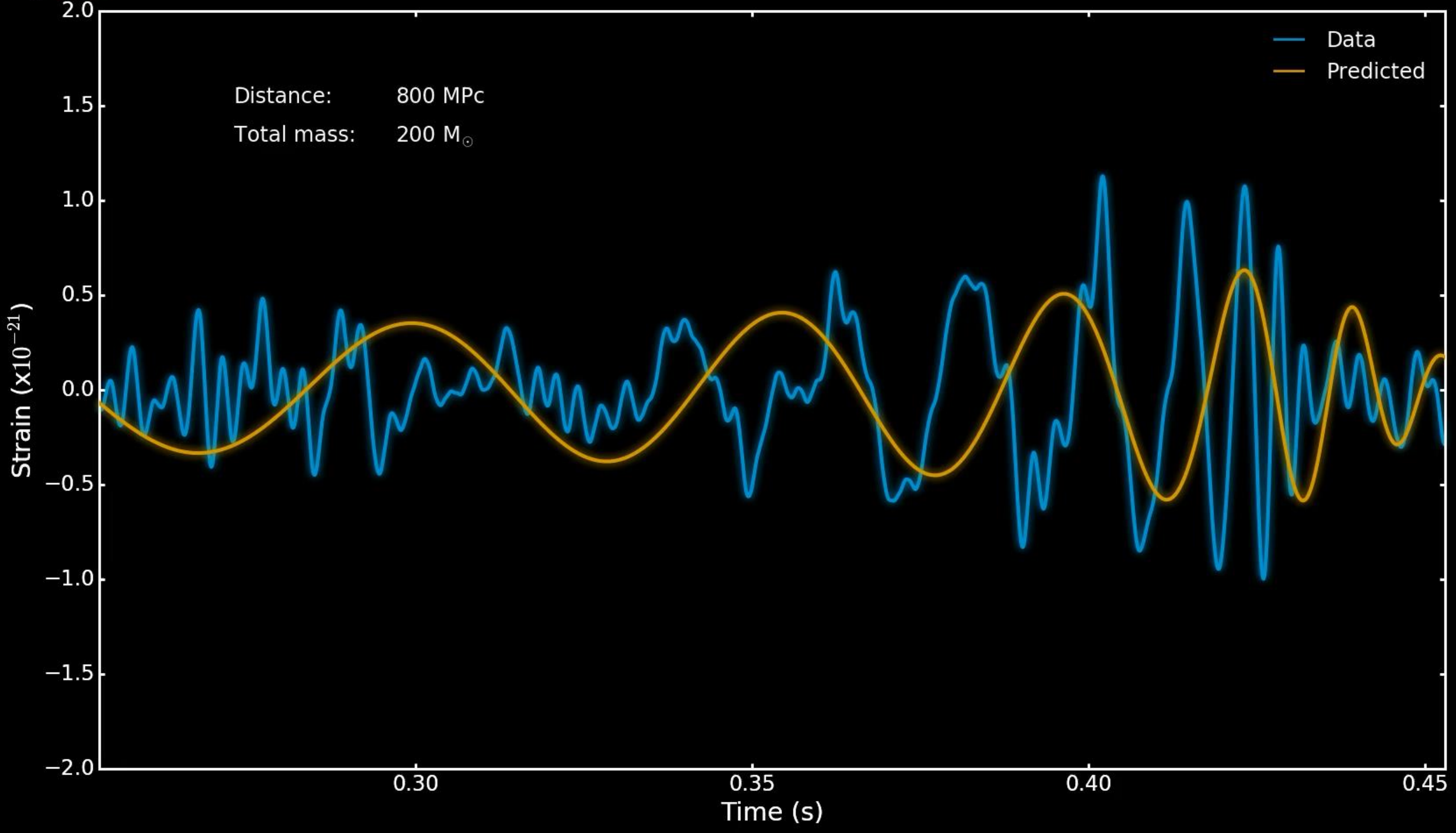
Video Credits: LIGO / Caltech / MIT

A WORLDWIDE EFFORT




compact binary inspiral
continuous
MODELLED
SHORT DURATION
LONG DURATION
UNMODELLED
burst
stochastic
@astronerdika

HOW DO WE KNOW WHAT IT WAS?



GW Strain

(quadrupole)

h(t) ~ 1/D ~ M

$$h(t) \propto \frac{1}{D}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f(t)}{c}\right)^{2/3}$$

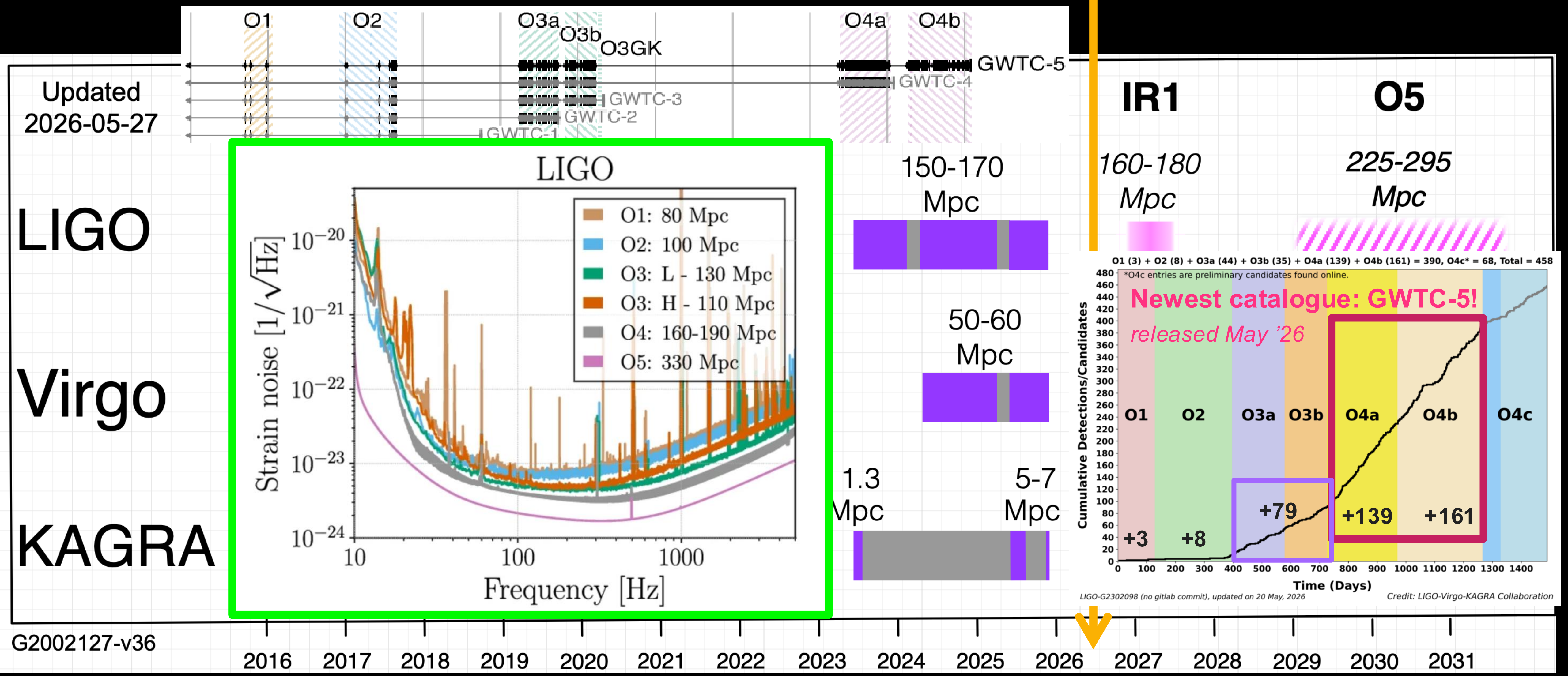
GW Frequency

f ~ 1/mass

$$f(t) = \frac{1}{8\pi}\left(\frac{5}{t_c - t}\right)^{3/8}\left(\frac{1}{\mathcal{M}}\right)^{5/8}$$

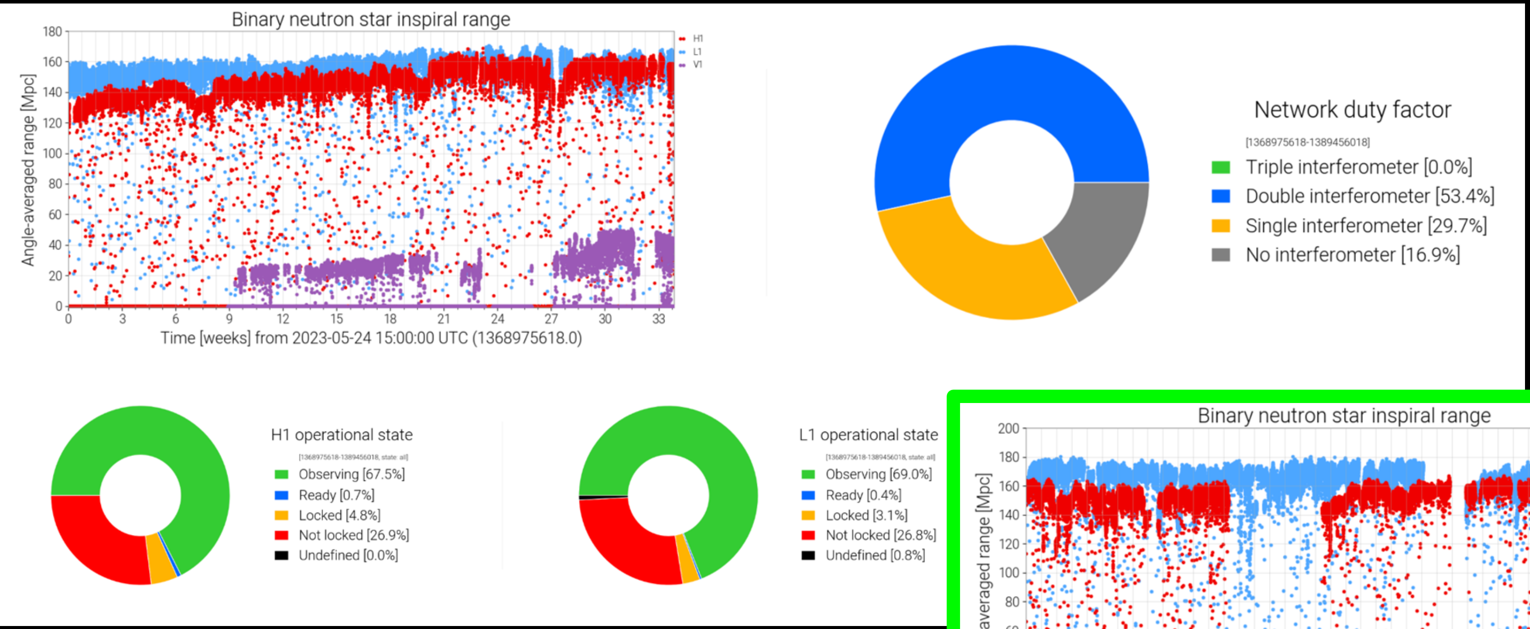
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

THE LVK TODAY



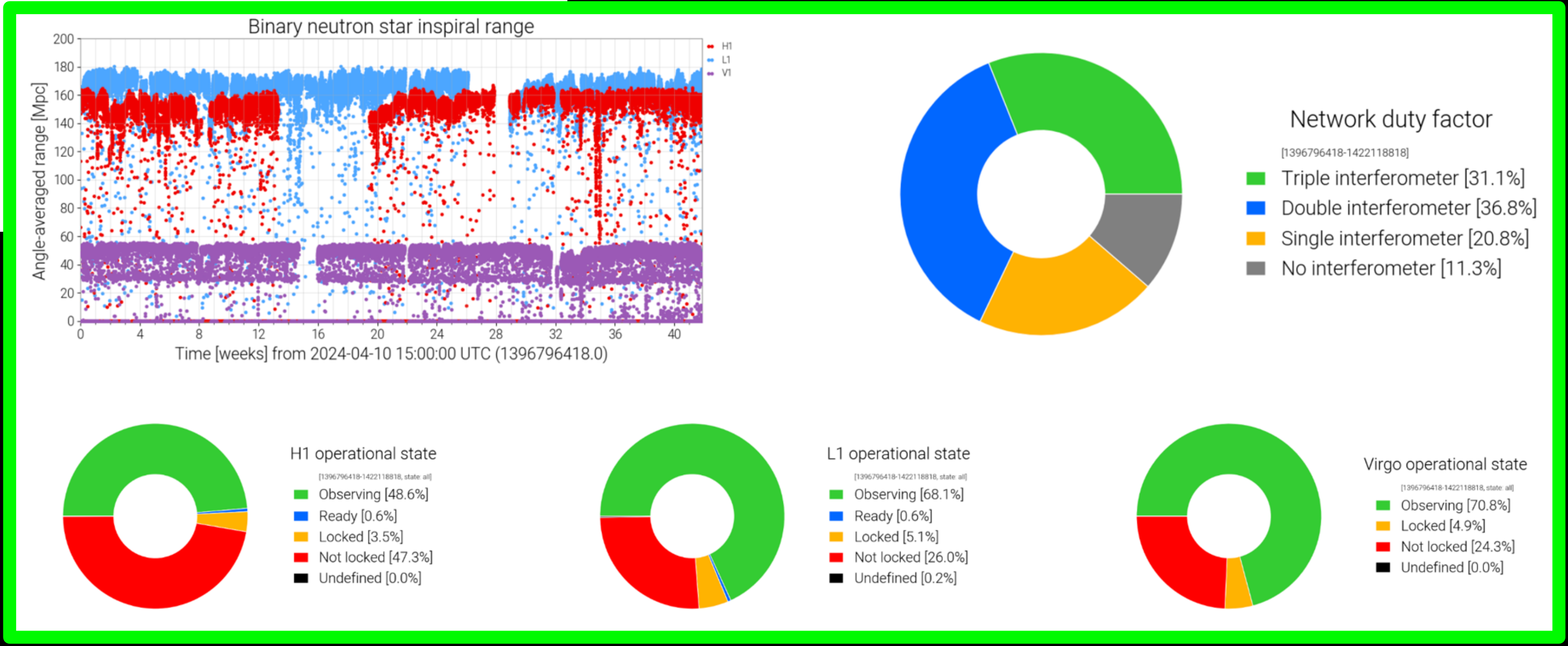
https://observing.docs.ligo.org/plan/#timeline
https://arxiv.org/abs/2605.27223, GWTC-5.0: An Introduction to Version 5.0 of the Gravitational-Wave Transient Catalog
https://link.springer.com/article/10.1007/s41114-020-00026-9

LVK: O4a TO O4b



O4b

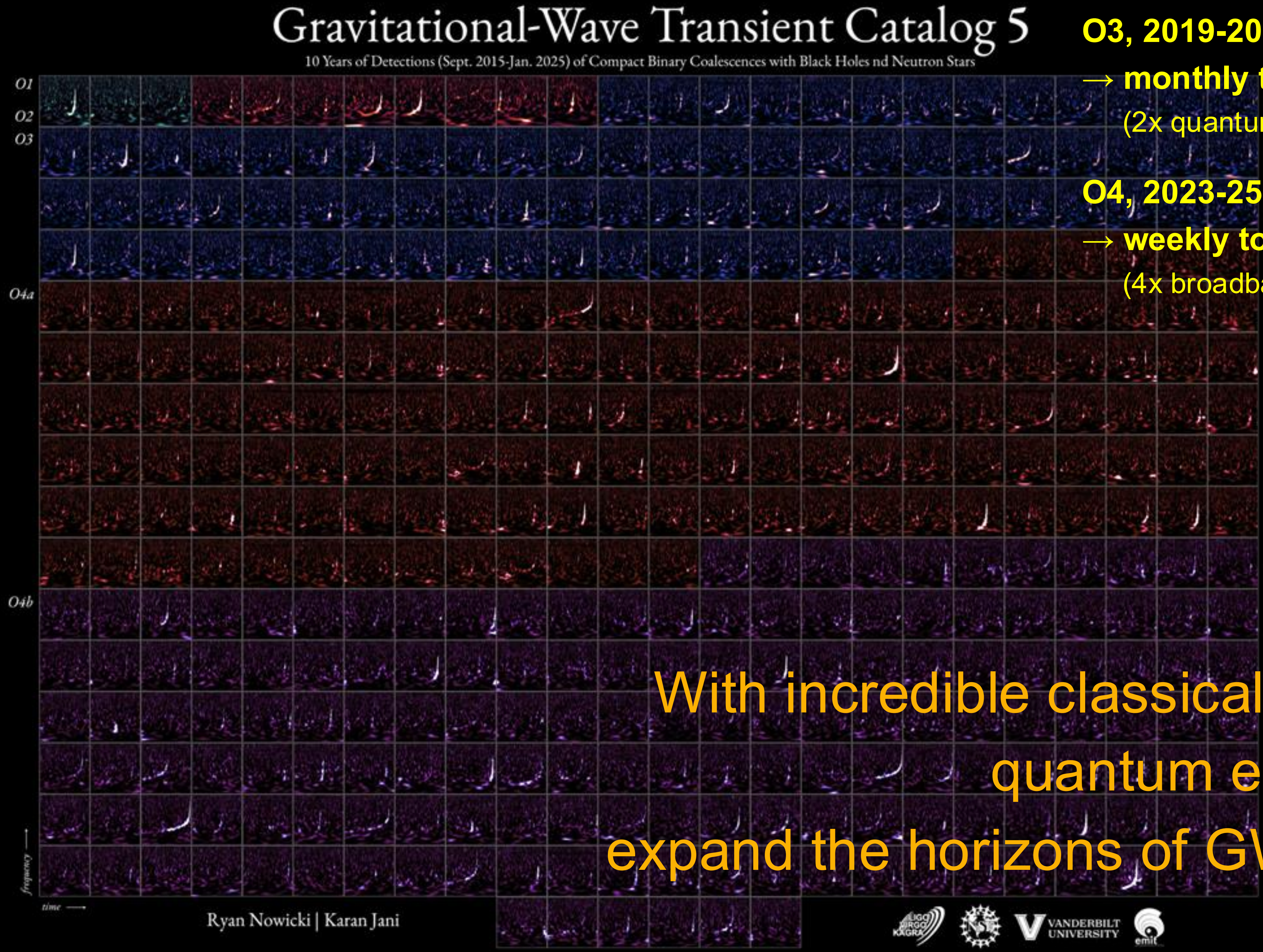
LIGO (LHO/LLO) + Virgo



O4a

LIGO (LHO+LLO) + KAGRA

https://ldas-jobs.ligo.caltech.edu/~detchar/summary/O4b/ - LVK summary pages



O3, 2019-20

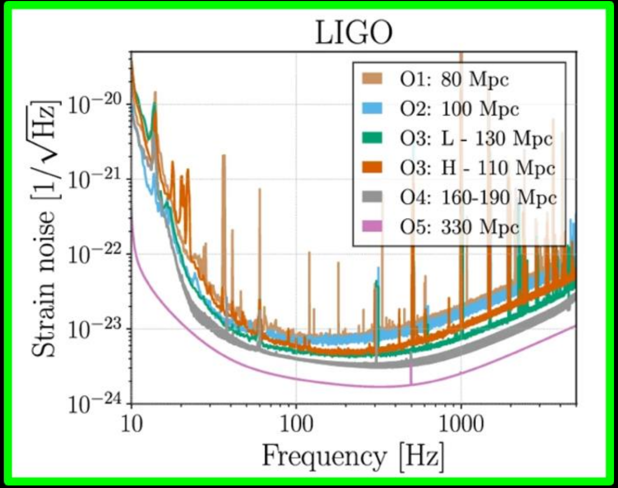
→ monthly to ~weekly

(2x quantum noise reduction)

O4, 2023-25

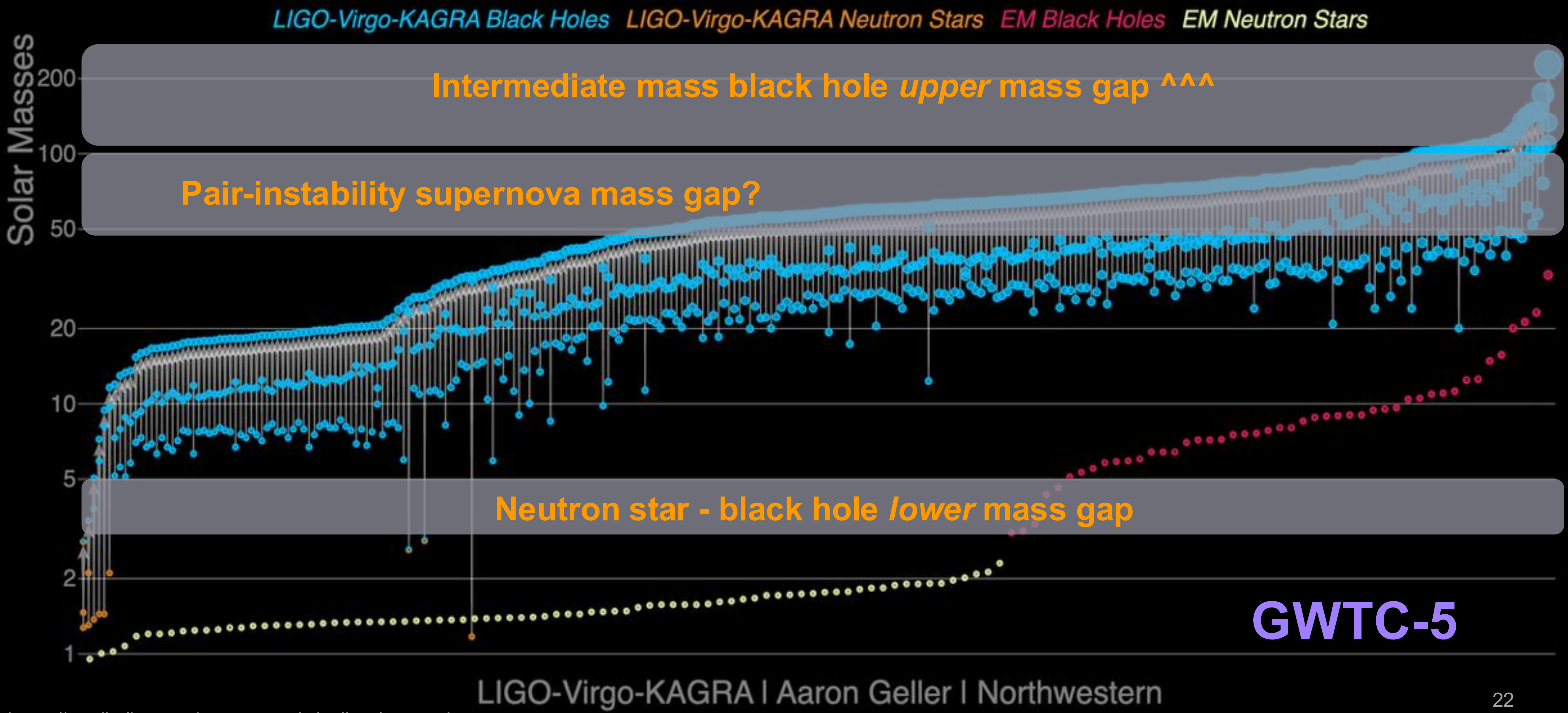
→ weekly to ~daily

(4x broadband quantum noise reduction)



With incredible classical engineering…
quantum engineering can
expand the horizons of GW astrophysics

Masses in the Stellar Graveyard



https://media.ligo.northwestern.edu/gallery/mass-plot

Population-scale GW astronomy

Black hole mass distribution

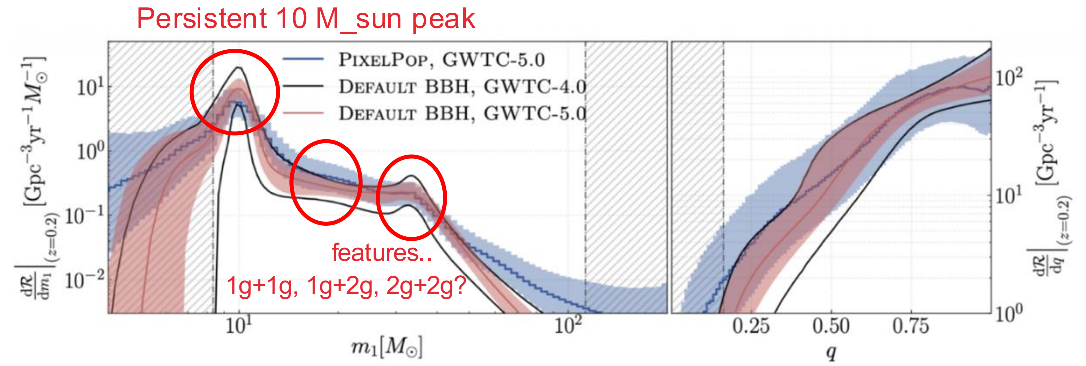
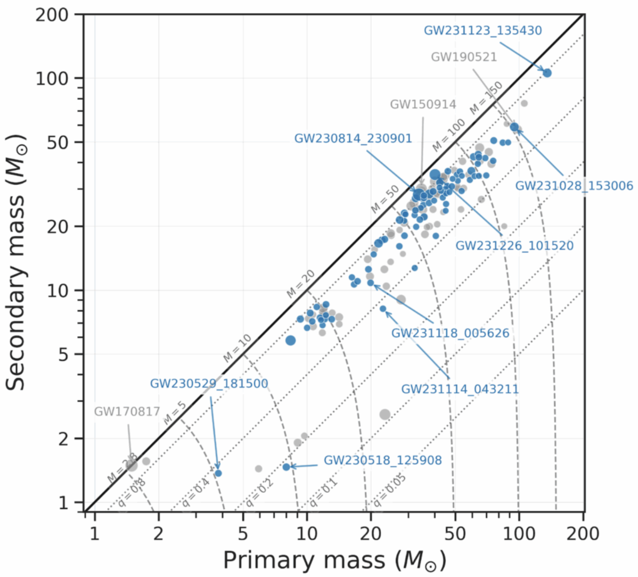


Figure 1 (Fig. 2 in our paper). Left panel: the distribution of the primary mass (i.e., the more massive component) in the binary black hole population. The GWTC-5.0 results (blue and red) retain the overall structure seen in GWTC-4.0 (solid black), with persistent features around 10 M⊙ and 35 M⊙. Right panel: the distribution of mass ratio, q, which probes how black holes pair with each other. A mass ratio of $q = 1$ indicates a black hole paired with a companion of the same mass.

mass ratio



Star formation rate across cosmic time

$R(z) \propto (1+z)^\kappa$

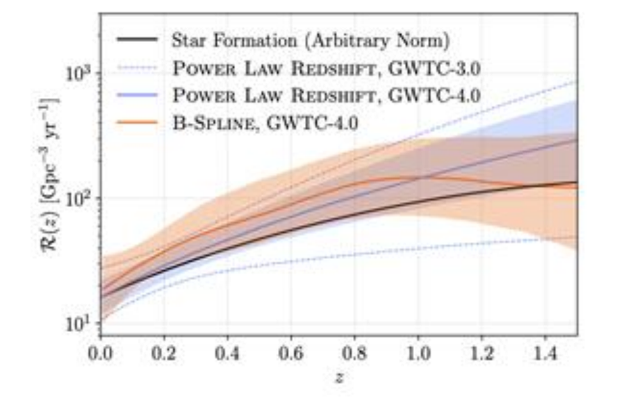
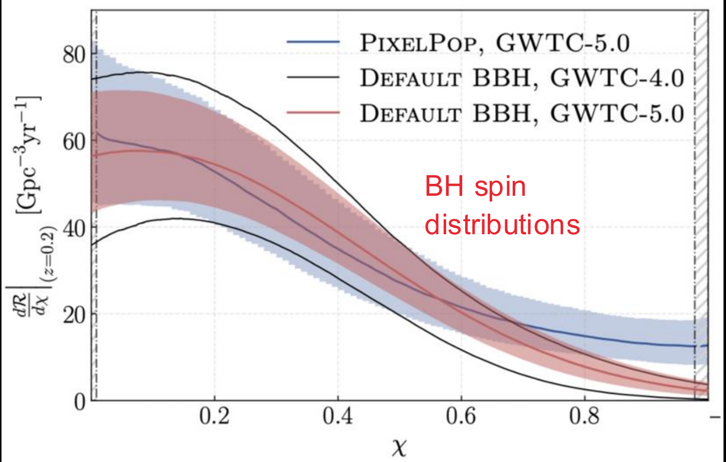


Figure 10. Comparison of redshift models between GWTC-3.0 and GWTC-4.0. *Top:* Posterior on the κ parameter for the Power Law Redshift model. GWTC-4.0 shows increased support for positive values. *Bottom:* Median ... regions for the comoving source frame rate ... Redshift model. We also show a com... ...er Law Redshift model and the weakly ... model and a scaled cosmic star formation ...u & Dickinson 2014), which are consistent ...es ($\kappa_{SFR} = 2.7$).



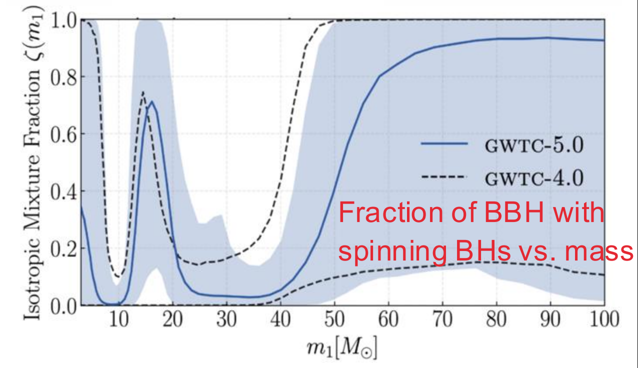
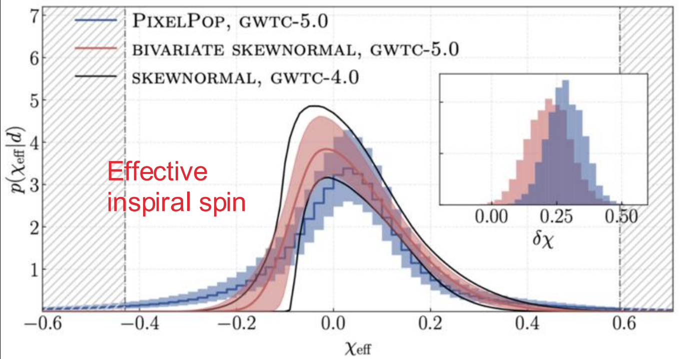


Figure 4 (adapted from Fig. 10 of our paper): The fraction of systems with a rapidly-spinning black hole as a function of mass. Black holes with rapid spins either seem to have masses in the approximate range 10–20 M⊙ or above 45 M⊙. The solid blue line shows the median fraction inferred from GWTC-5.0 and the shaded blue region shows the corresponding 90% credible interval for this fraction.

Black hole spins

distorts BH shape and GW emission



Slide adapted from D.Singh

https://ligo.org/science-summaries/O4b_Astro_Distrib/

LVK, GWTC-4.0: Population Properties of Merging Compact Binaries, https://arxiv.org/abs/2508.18083

LVK, GWTC-5.0: Population Properties of Merging Compact Binaries, https://arxiv.org/abs/2605.27226

Highest SNR – black hole spectroscopy – test GR, Hawking's area law

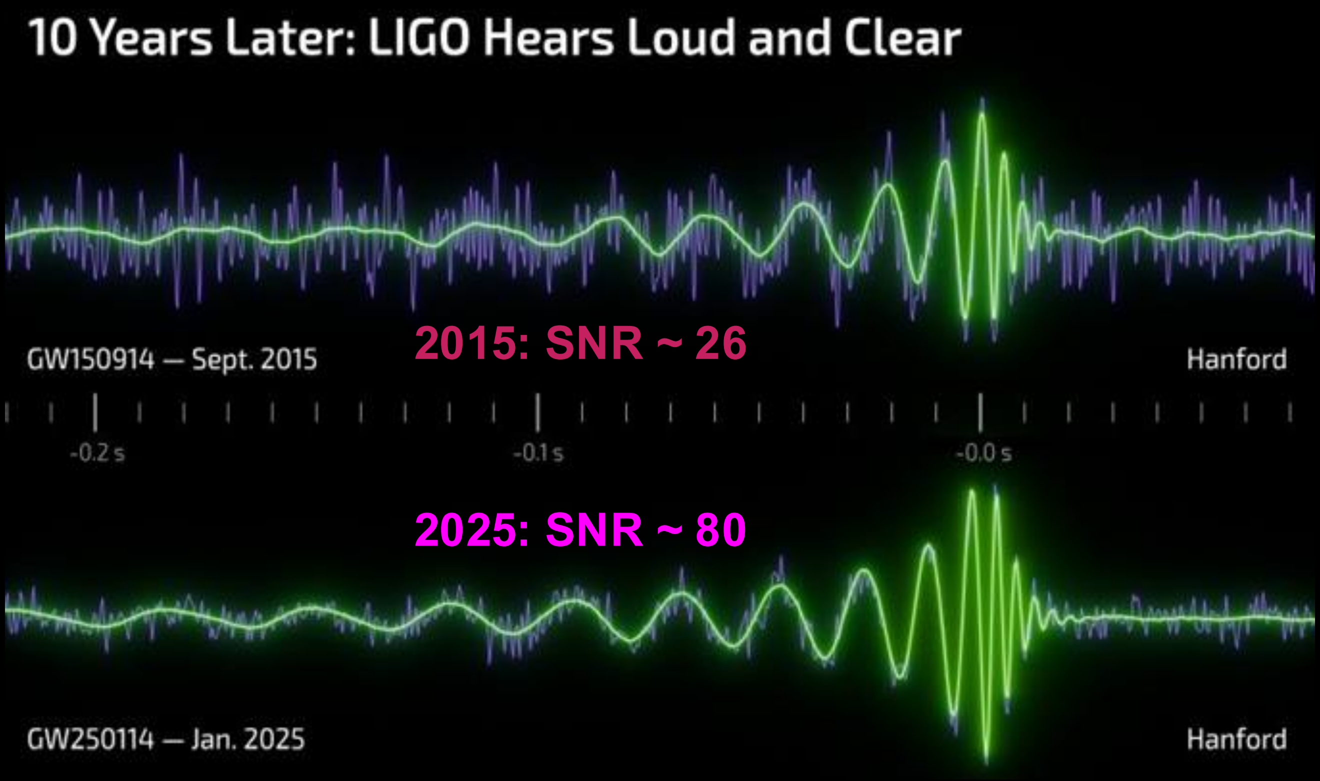
PHYSICAL REVIEW LETTERS 135, 111403 (2025)

Editors' Suggestion | Featured in Physics

GW250114: Testing Hawking's Area Law and the Kerr Nature of Black Holes

A. G. Abac *et al.**
(LIGO Scientific, Virgo, and KAGRA Collaborations)

(Received 13 August 2025; revised 25 August 2025; accepted 26 August 2025; published 10 September 2025)



2015: SNR ~ 26

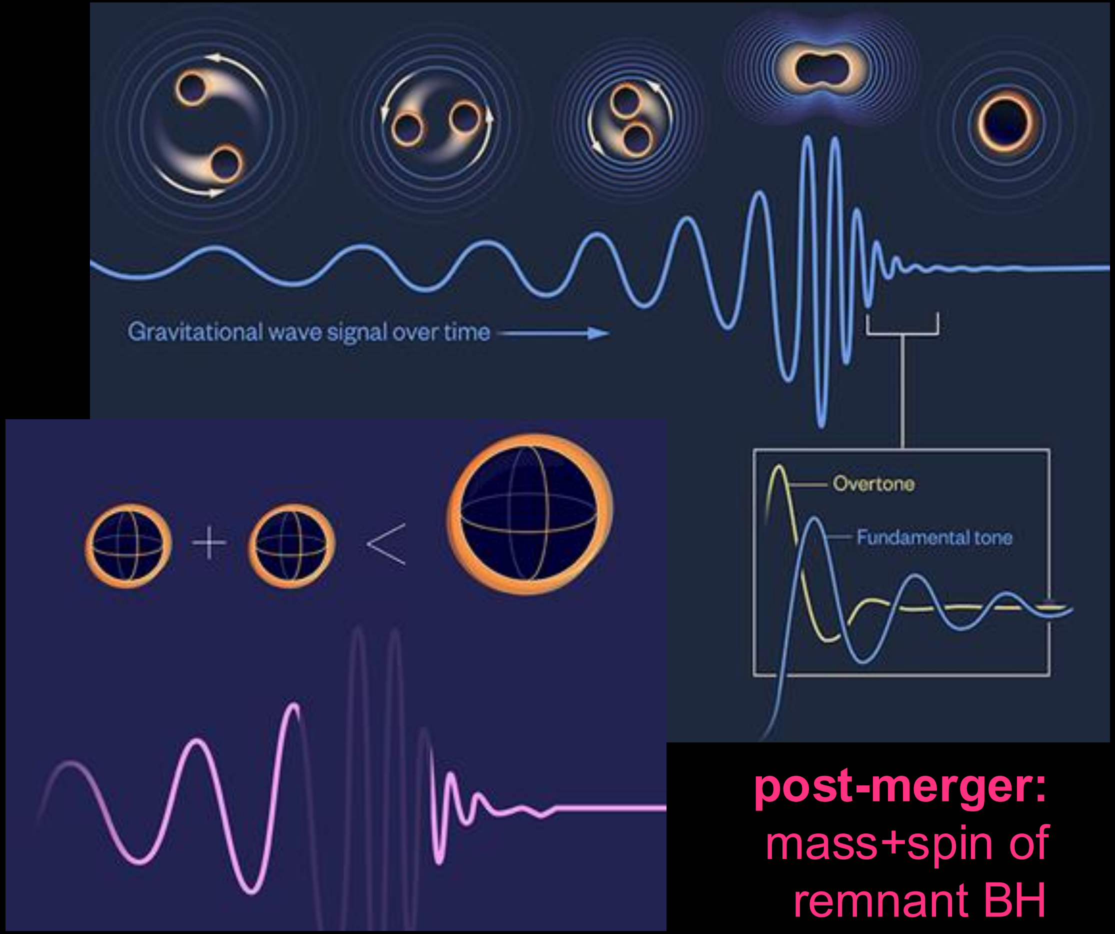
2025: SNR ~ 80

https://www.ligo.caltech.edu/news/ligo20250910

Chatziioannou, Clarke, Hanna, Harry, Isi, Tissino, et al, LVK, PRL 135, 111403 (2025)

Hawking's area law

Remnant black hole has greater surface area than two initial black holes combined (despite GW radiation)!



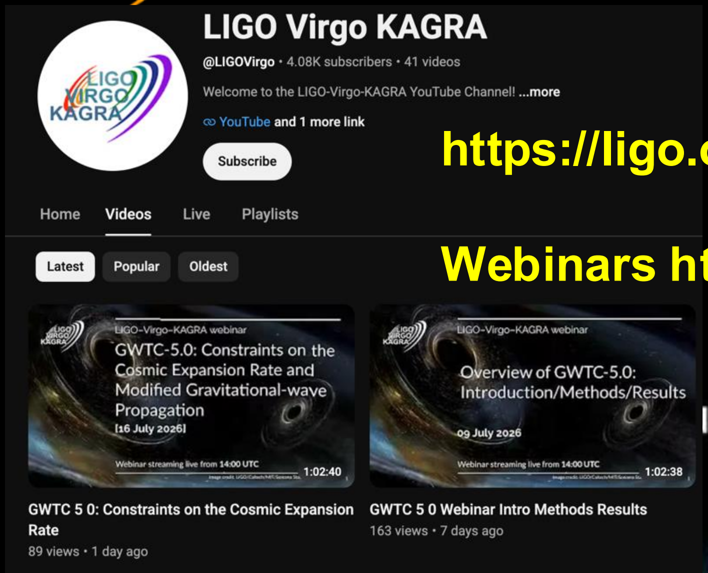
post-merger: mass+spin of remnant BH

pre-merger: mass+spin of component BHs

Yes, this dark star is a Kerr (spinning) BH from GR!

LSC Science summaries

O4c analysis in progress



https://ligo.org/science-summaries/

Webinars https://www.youtube.com/@LIGOVirgo/videos

2015: SNR ~ 26

2025: SNR ~ 80

https://www.ligo.caltech.edu/news/ligo20250910

Chatziioannou, Clarke, Hanna, Harry, Isi, Tissino, et al, LVK, PRL 135, 111403 (2025)

2026

▼ Testing general relativity with the latest compact binary merger observations
2026-03-19 PDF: [en] [es] [it] [ja] [pt] [vi]

▼ Neutron stars: smoother than billiard balls – unfortunately
2026-03-17 PDF: [en] [ja]

▼ What do our latest searches for a background of gravitational waves mean for cosmology and high-energy physics?
2026-02-04 PDF: [en] [ca] [ja]

▼ Deep multi-messenger search for joint sources of gravitational waves and high-energy neutrinos
2026-01-15 PDF: [en] [ja] [zh-Hant]

2025

▼ When a pulsar hiccups, can we hear that with gravitational waves?
2025-12-25 PDF: [en] [ca] [es] [it] [ja] [ma]

▼ GWTC-4.0: Searches for gravitational lensing of gravitational waves
2025-12-19 PDF: [en] [ca] [es] [it] [ja] [pt]

▼ Searching for dancing pulsars amid the Universe's gravitational symphony
2025-11-26 PDF: [en] [ca] [es] [gl] [ja] [pt]

▼ Searching for planetary-mass black holes from the early Universe
2025-11-26 PDF: [en] [es] [gl] [ja] [pt]

▼ Searching for elusive ultralight dark matter
2025-11-07 PDF: [en] [ja] [pt]

▼ Probing the Universe for persistent gravitational waves
2025-10-29 PDF: [en] [hi] [ja] [pt]

▼ GW241011 and GW241110: A pair of rapidly spinning, unequal mass black hole mergers detected with gravitational waves
2025-10-28 PDF: [en] [it] [ja] [pl] [pt] [vi]

▼ Can we detect gravitational waves from vector boson clouds?
2025-09-10 PDF: [en] [it] [ja] [pt]

▼ Black hole spectroscopy and tests of general relativity with GW250114
2025-09-10 PDF: [en] [ca] [es] [gl] [it] [ja] [pt]

▼ GW250114: Cosmic carillon of chaos
2025-09-10 PDF: [en] [da] [el] [es] [gl] [it] [ja] [pt] [zh-Hant]

▼ GW230814: A loud gravitational-wave signal detected by LIGO Livingston
2025-09-09 PDF: [en] [es] [hi] [it] [ja] [pt] [ta]

▼ New constraints on the cosmic expansion and general relativity with gravitational waves
2025-09-08 PDF: [en] [ca] [it] [ja] [pt]

▼ Upper limits on the isotropic gravitational-wave background from LIGO, Virgo, and KAGRA's fourth observing run
2025-09-06 PDF: [en] [es] [ja] [pt]

▼ GWTC-4.0: Population properties of merging compact binaries
2025-08-26 PDF: [en] [it] [ja] [pt]

▼ Open data from LIGO Virgo and KAGRA through the first part of the fourth observing run
2025-08-26 PDF: [en] [fr] [it] [ja] [zh-Hant]

▼ GWTC-4.0: Updating the catalog with observations from the first part of the fourth LIGO-Virgo-KAGRA observing run
2025-08-26 PDF: [en] [de] [fr] [it] [ja] [nl] [pl] [pt] [zh-Hans] [zh-Hant]

▼ Looking for short-duration gravitational wave sources in the deep dark sky
2025-07-22 PDF: [en] [it] [ja] [vi]

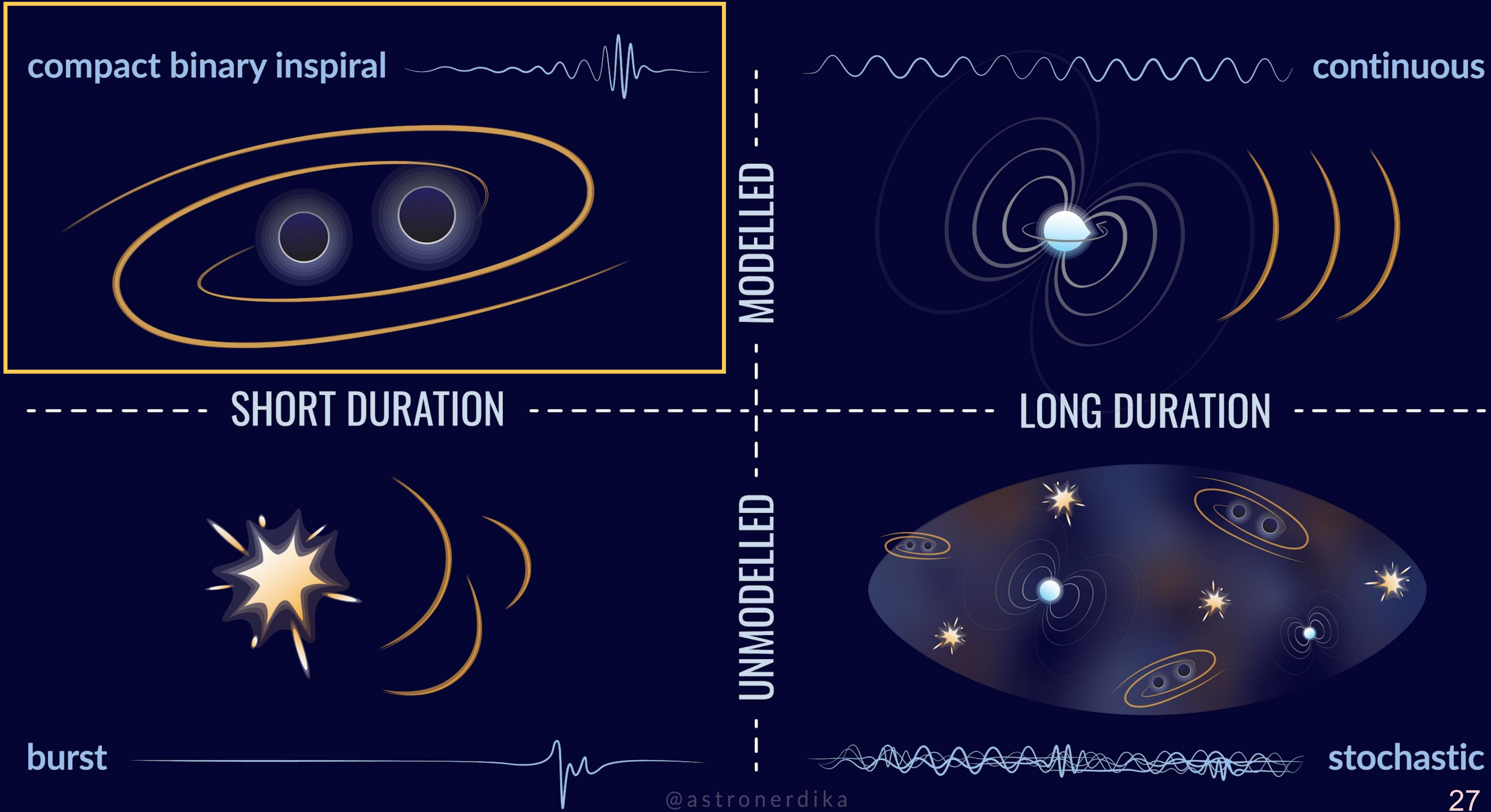
▼ All-sky search for long-duration gravitational-wave transients in the first eight months of the fourth Advanced LIGO-Virgo-KAGRA observing run
2025-07-22 PDF: [en] [ca] [es] [it] [ja] [pt] [vi] [zh-Hant]

▼ GW231123: The most massive black hole binary detected through gravitational waves
2025-07-14
PDF: [en] [bn] [ca] [da] [de] [el] [es] [fi] [fr] [hi] [it] [ja] [ma] [mr] [pt] [ta] [vi] [zh-Hans]

▼ No continuous gravitational waves from 45 known pulsars in O4a data
2025-01-10 PDF: [en] [ca] [de] [es] [gl] [it] [ja] [nl] [pt] [ro] [vi] [zh-Hant]

How to we make such sensitive measurements?

“sensitivity” = ***signal-to-noise*** *ratio*


compact binary inspiral
continuous
MODELLED
SHORT DURATION
LONG DURATION
UNMODELLED
burst
stochastic
@astronerdika

LIGO **signal**-to-noise

BBH #1!
(36+29, ~100ms)

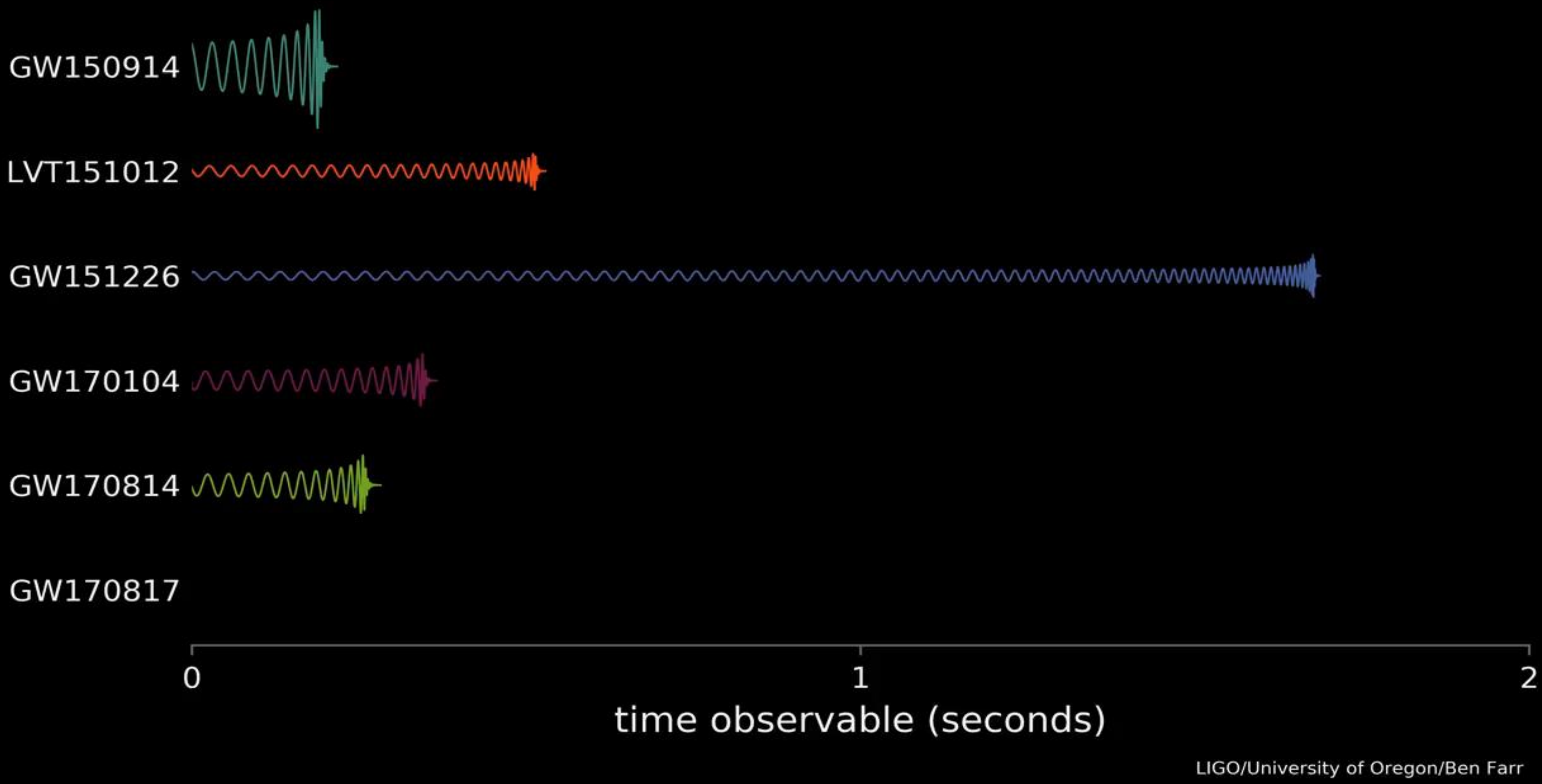
~BBH (23+13)

BBH #2 (14+8)

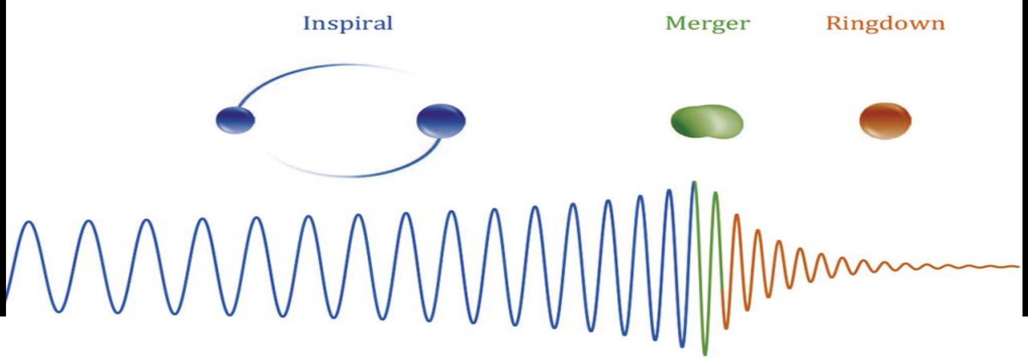
BBH (31+20, *z*~0.2)

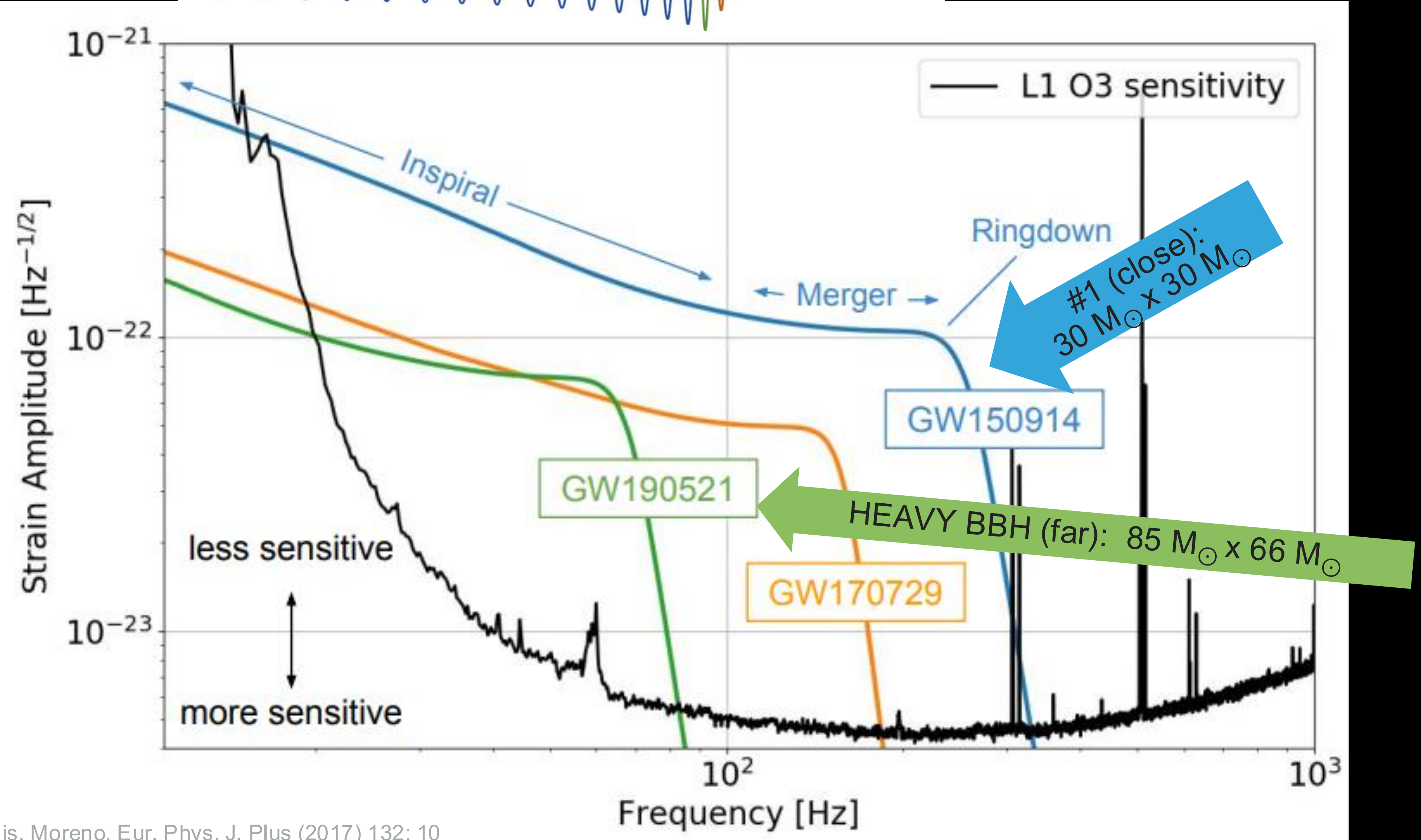
BBH (30+25)

BNS! (1.4+1.4, ~100s)



LIGO signal-to-noise

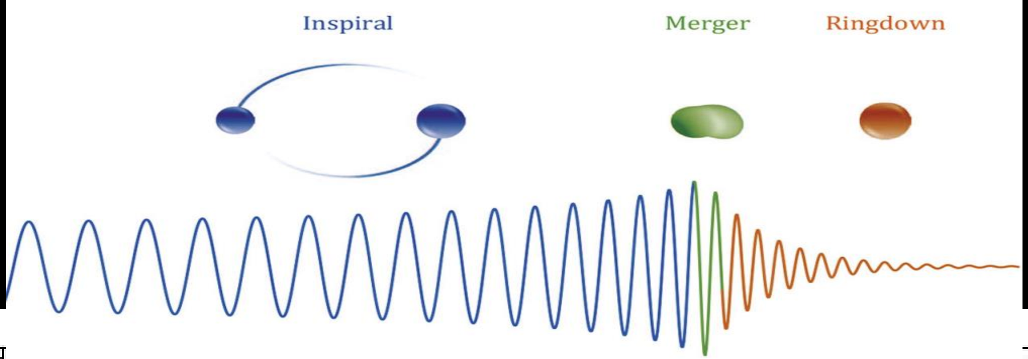


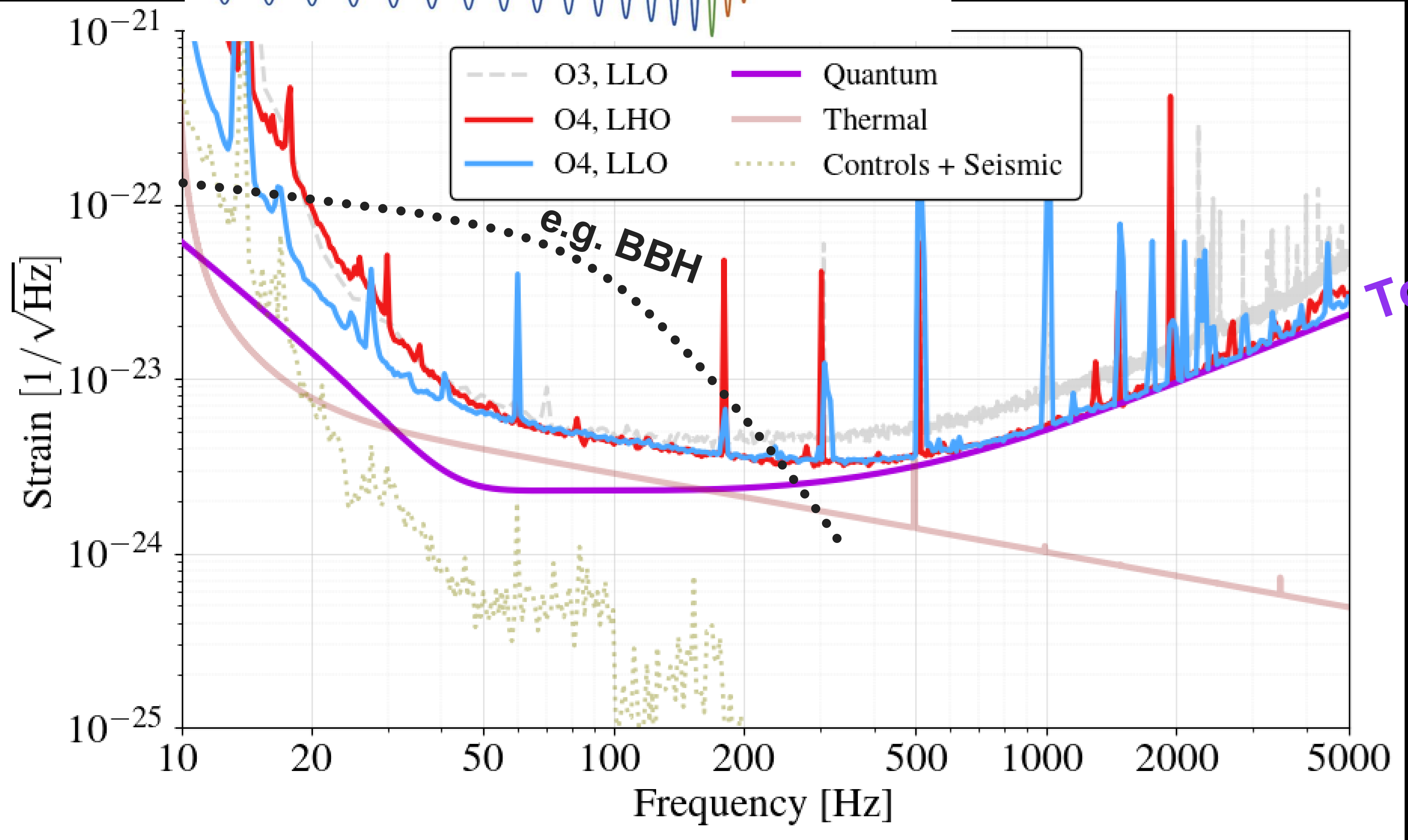


Antelis, Moreno, Eur. Phys. J. Plus (2017) 132: 10

LIGO signal-to-**noise**

Quantum noise broadly limits sensitivity





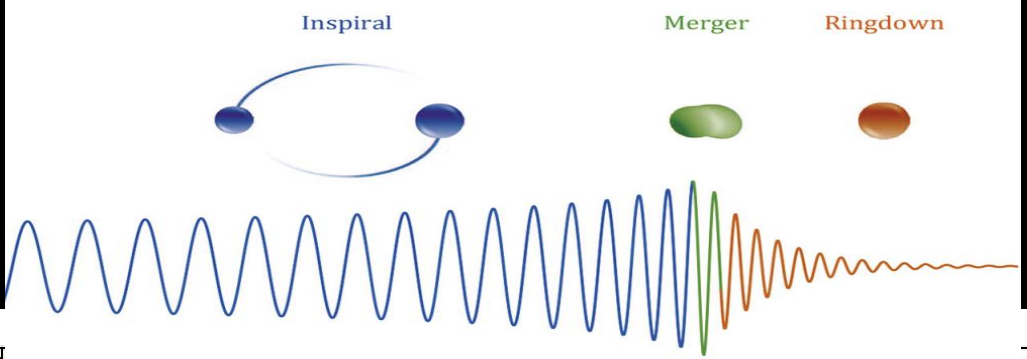
Total quantum noise

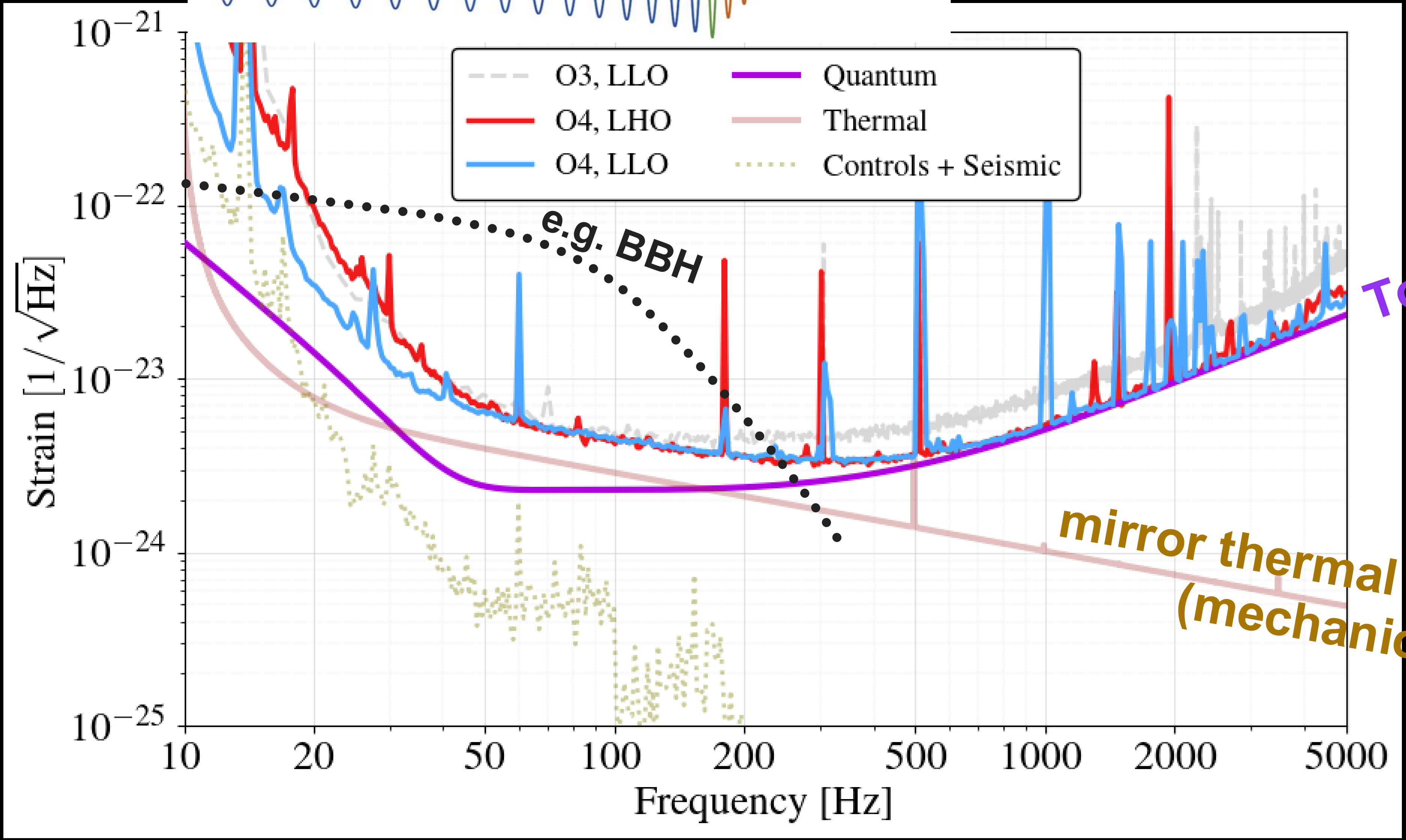
Heisenberg uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

LIGO signal-to-**noise**

Quantum noise broadly limits sensitivity





Total quantum noise

Heisenberg uncertainty principle

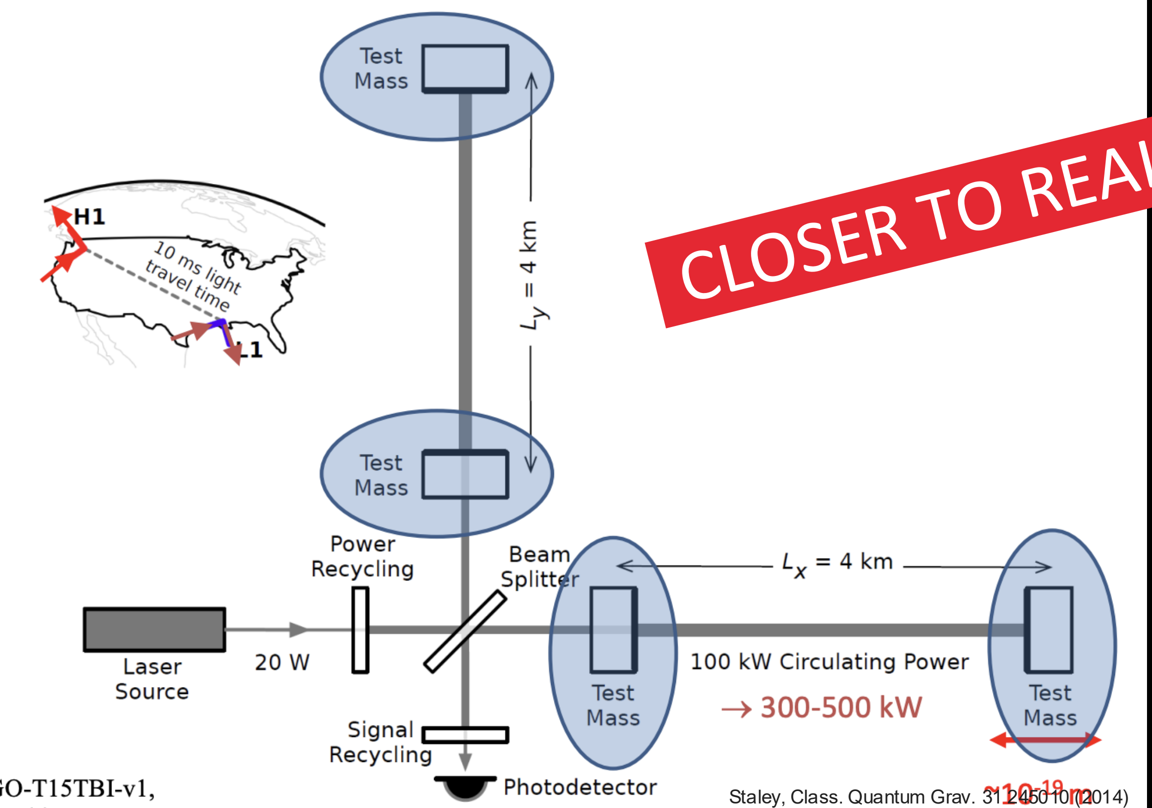
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

mirror thermal coating noise (mechanical loss)

ADVANCED LIGO OPTICAL LAYOUT

Dual-recycled, Fabry-Perot Michelson Laser Interferometer

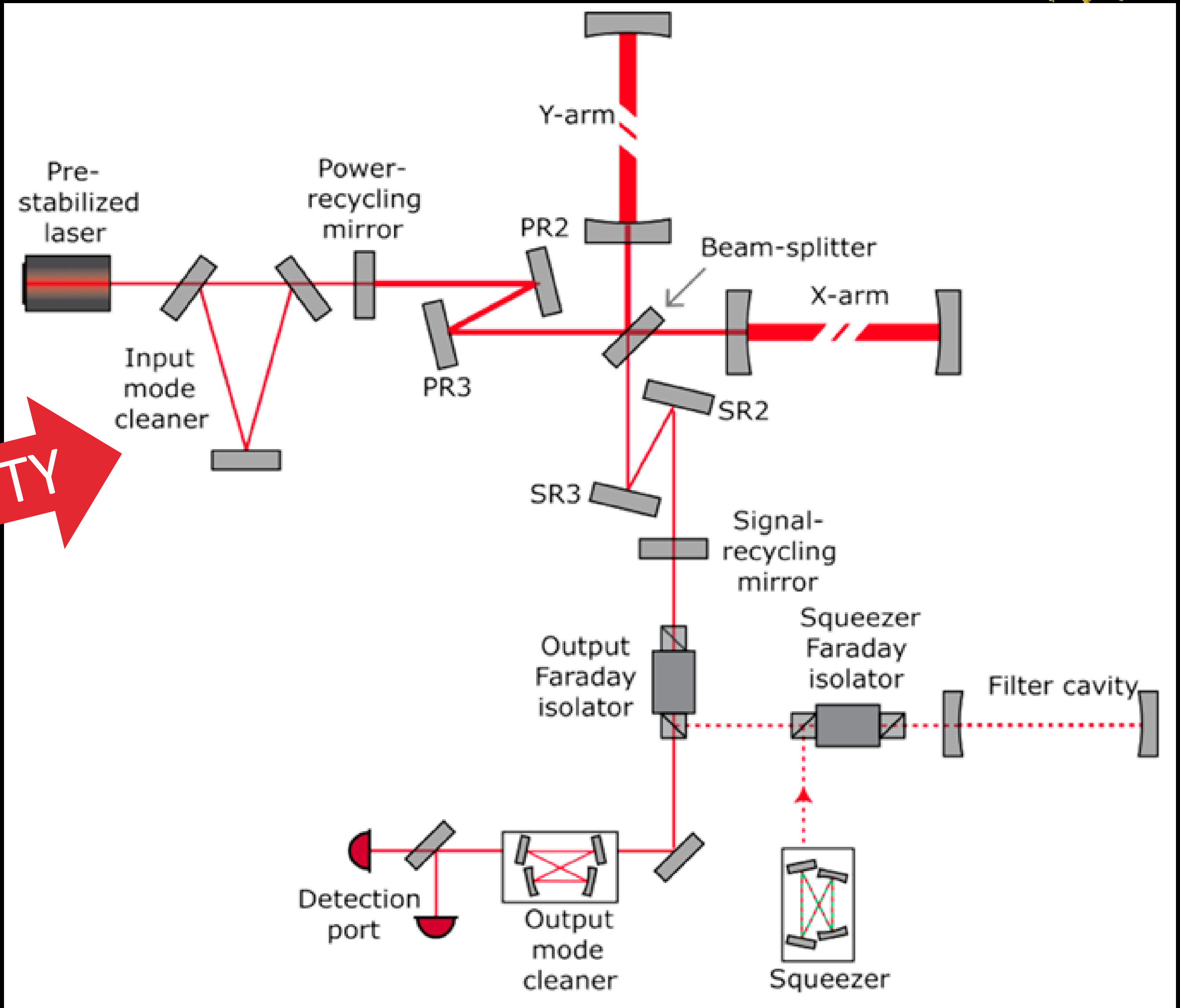
Gravitational Wave Interferometry
Fabry-Perot Michelson Interferometer



LIGO-T15TBI-v1,
I.S. White Paper

Staley, Class. Quantum Grav. 31 245010 (2014)
Achieving resonance in the Advanced LIGO gravitational-wave interferometer

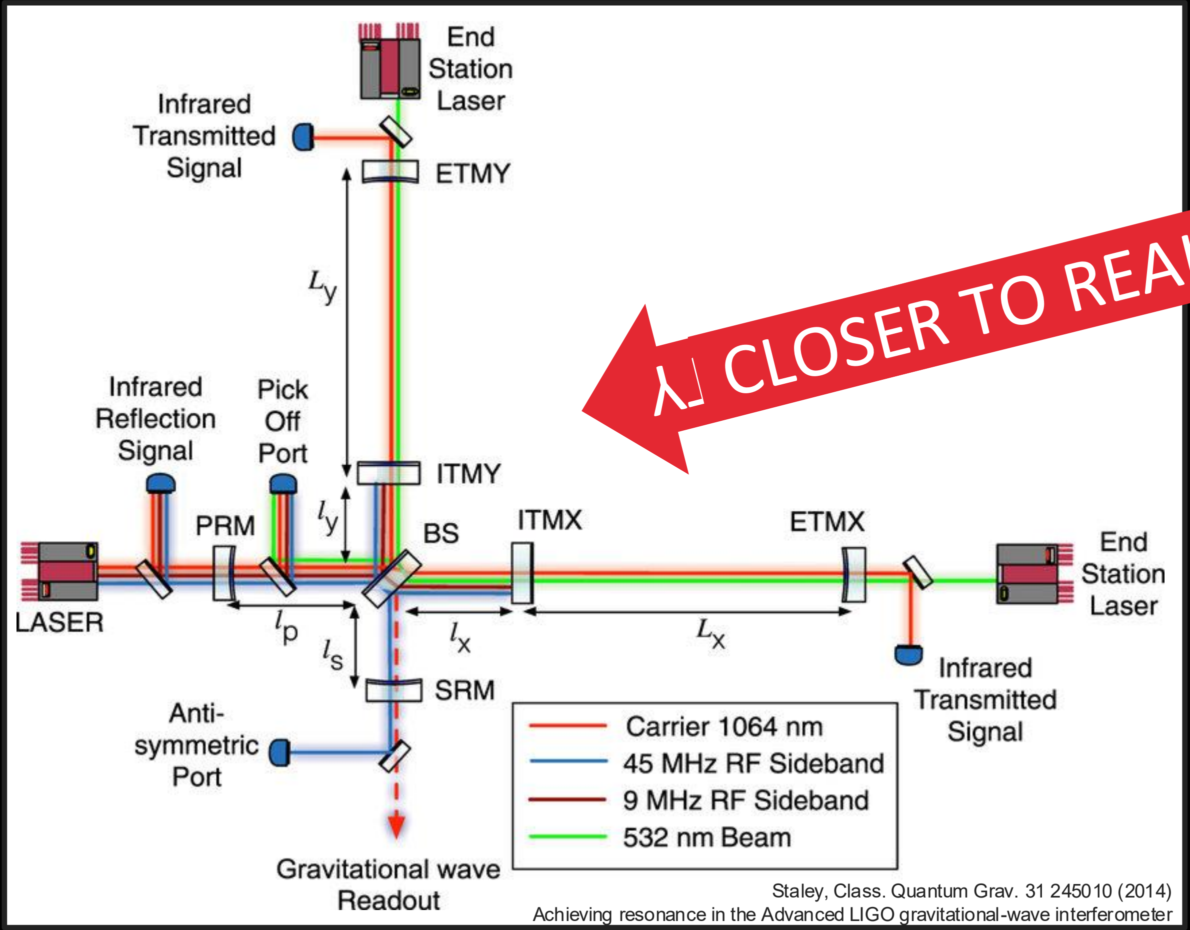
CLOSER TO REALITY



Capote, LIGO O4 instrument scientists, PRD ***111****, 062002 (2025)*

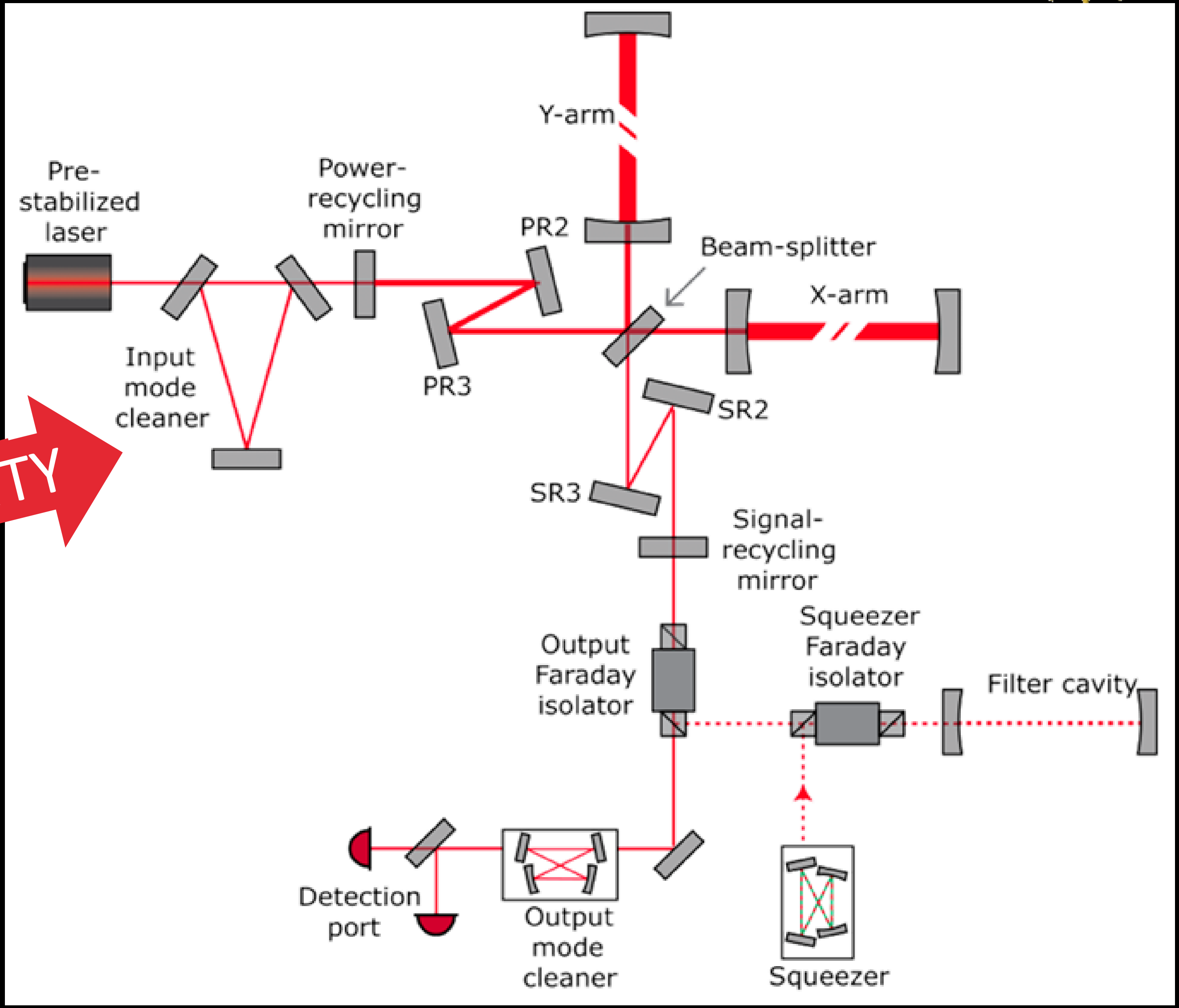
ADVANCED LIGO OPTICAL LAYOUT

Dual-recycled, Fabry-Perot Michelson Laser Interferometer



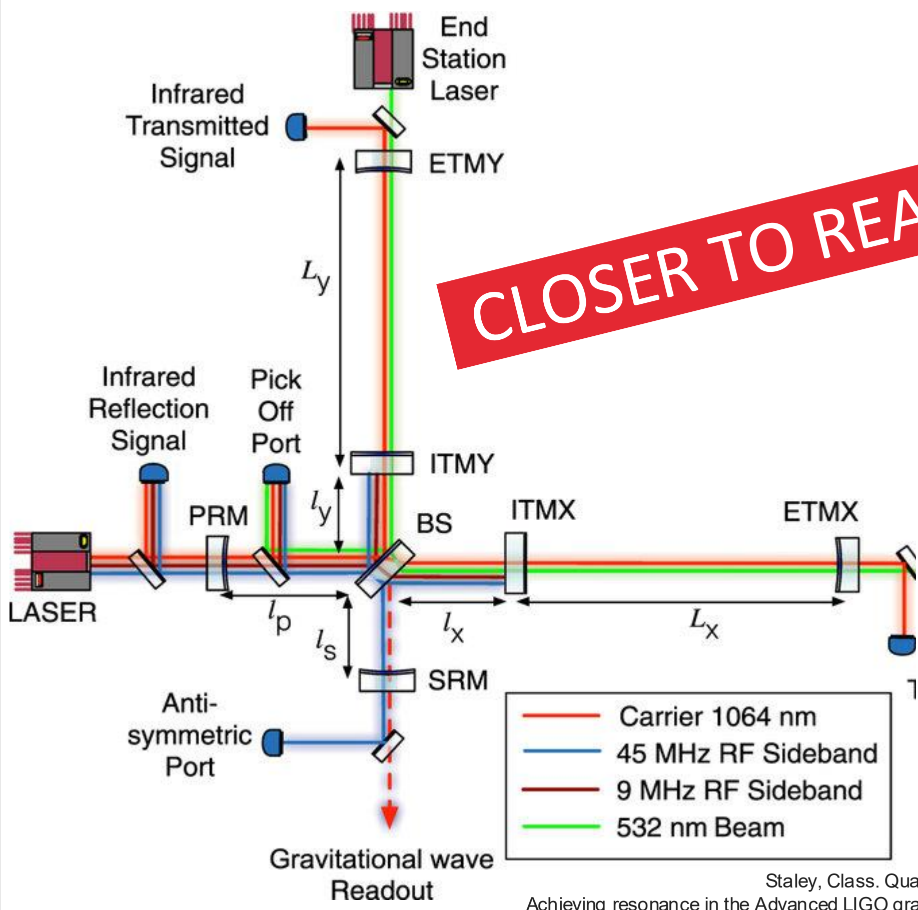
Staley, Class. Quantum Grav. 31 245010 (2014)
Achieving resonance in the Advanced LIGO gravitational-wave interferometer

CLOSER TO REALITY



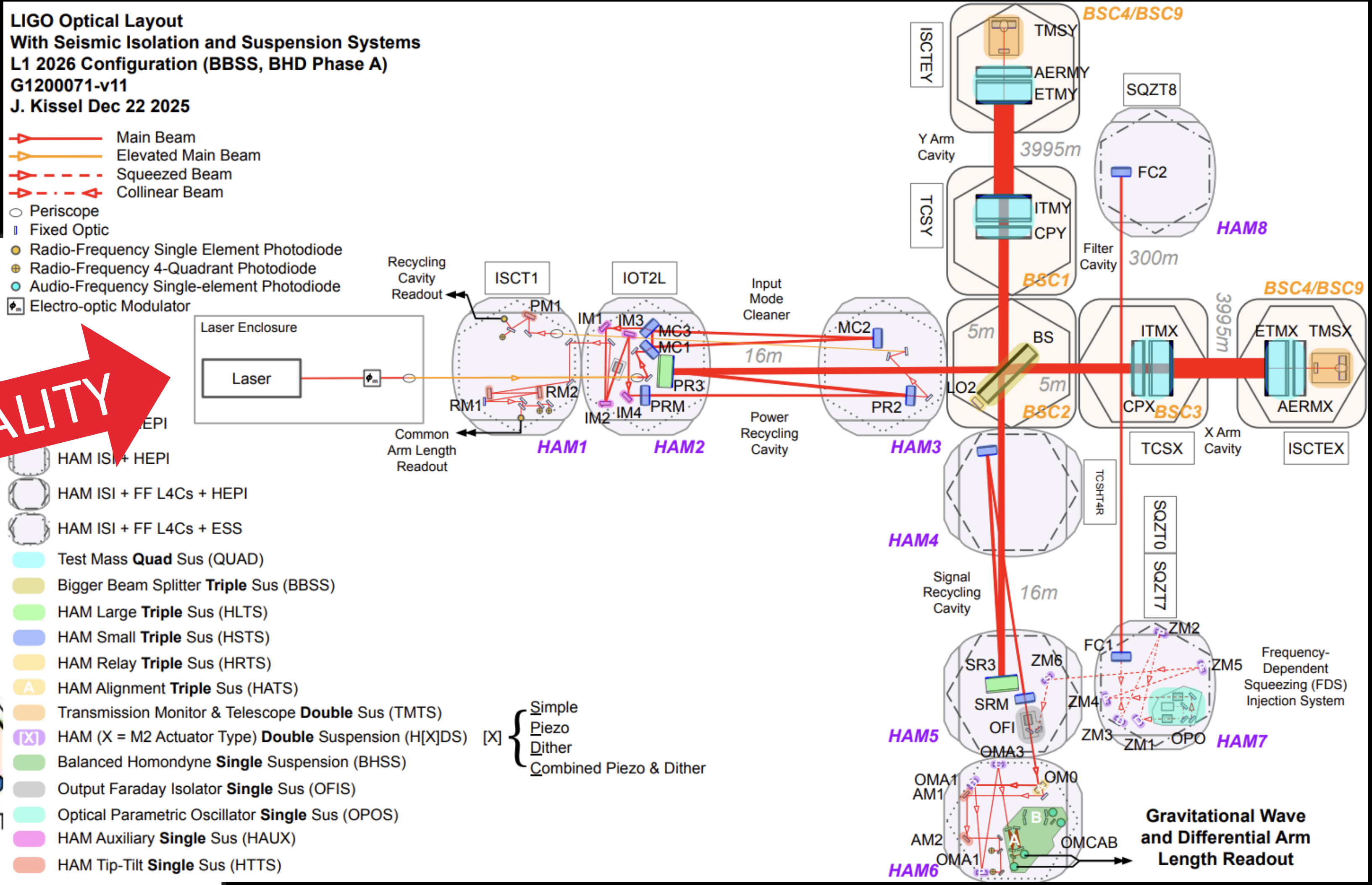
*Capote, LIGO O4 instrument scientists, PRD **111**, 062002 (2025)*

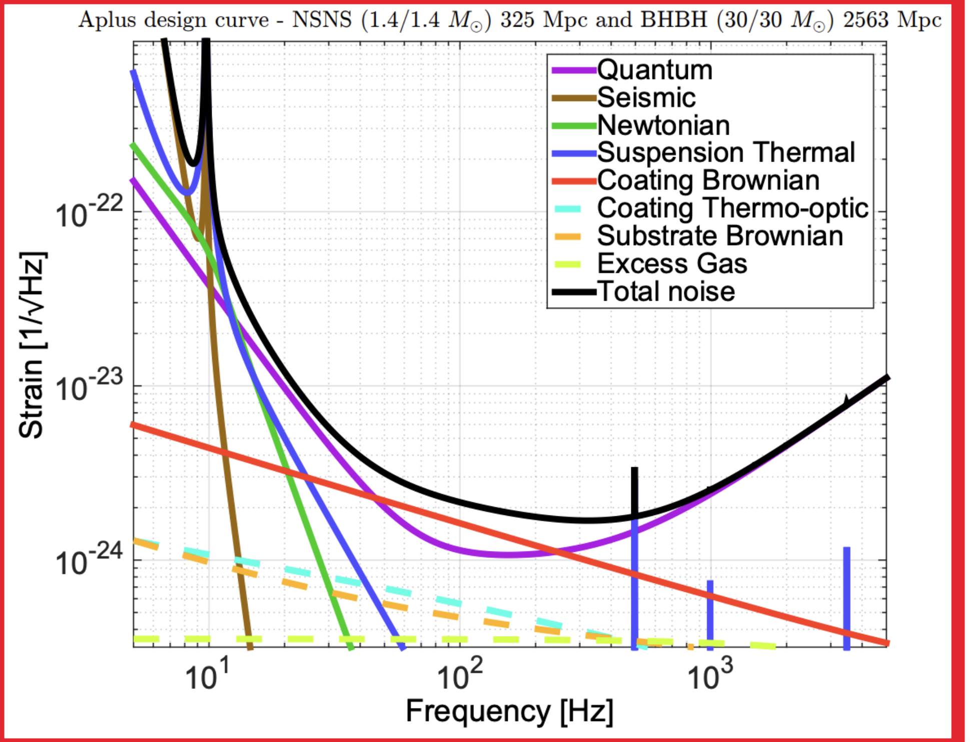
ADVANCED LIGO OPTICAL LAYOUT



Staley, Class. Quantum Grav. 31 245010 (2014)
Achieving resonance in the Advanced LIGO gravitational-wave interferometer

CLOSER TO REALITY

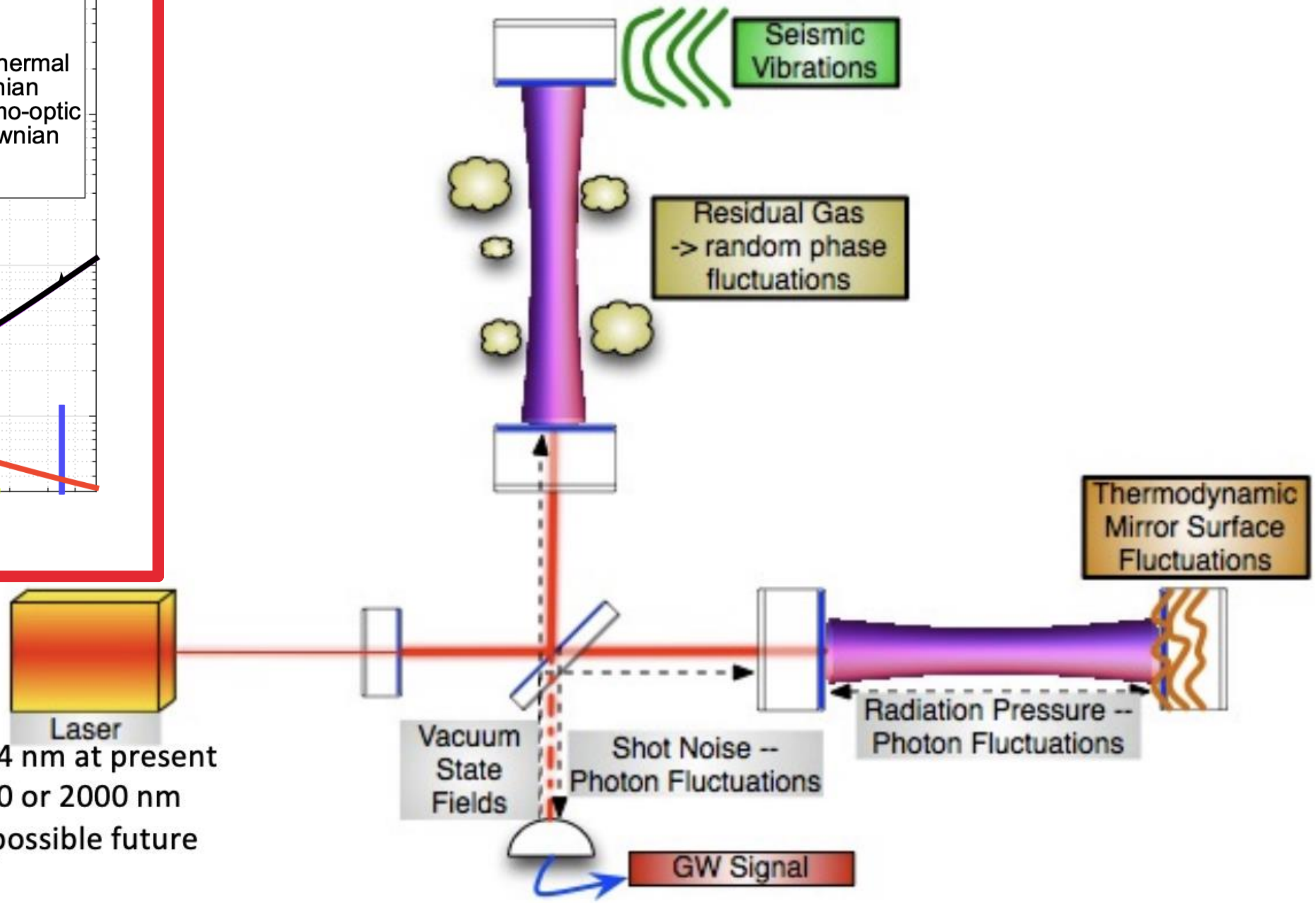




LIGO-T1800042-v4 The A+ design curve
L. Barsotti, L. McCuller, M.Evans, P. Fritschel

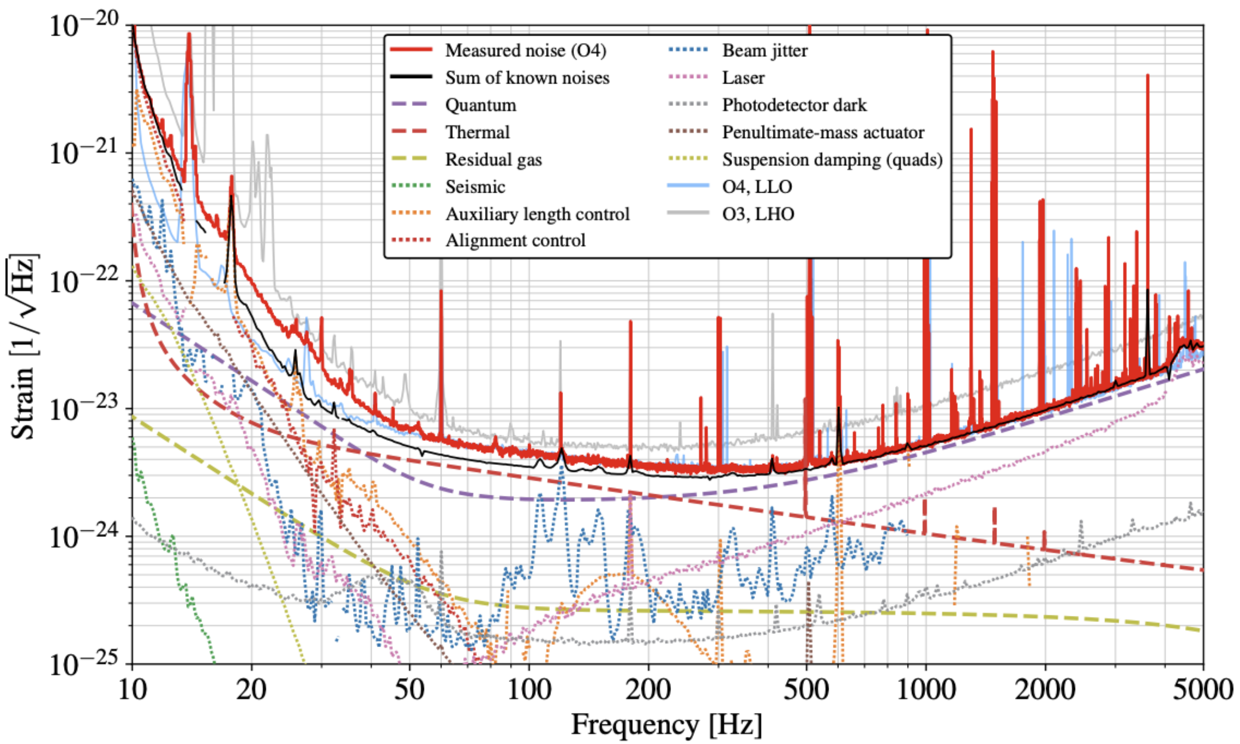
LIGO: Major Sources of Noise

From Rana Adhikari Caltech LIGO SURF talk

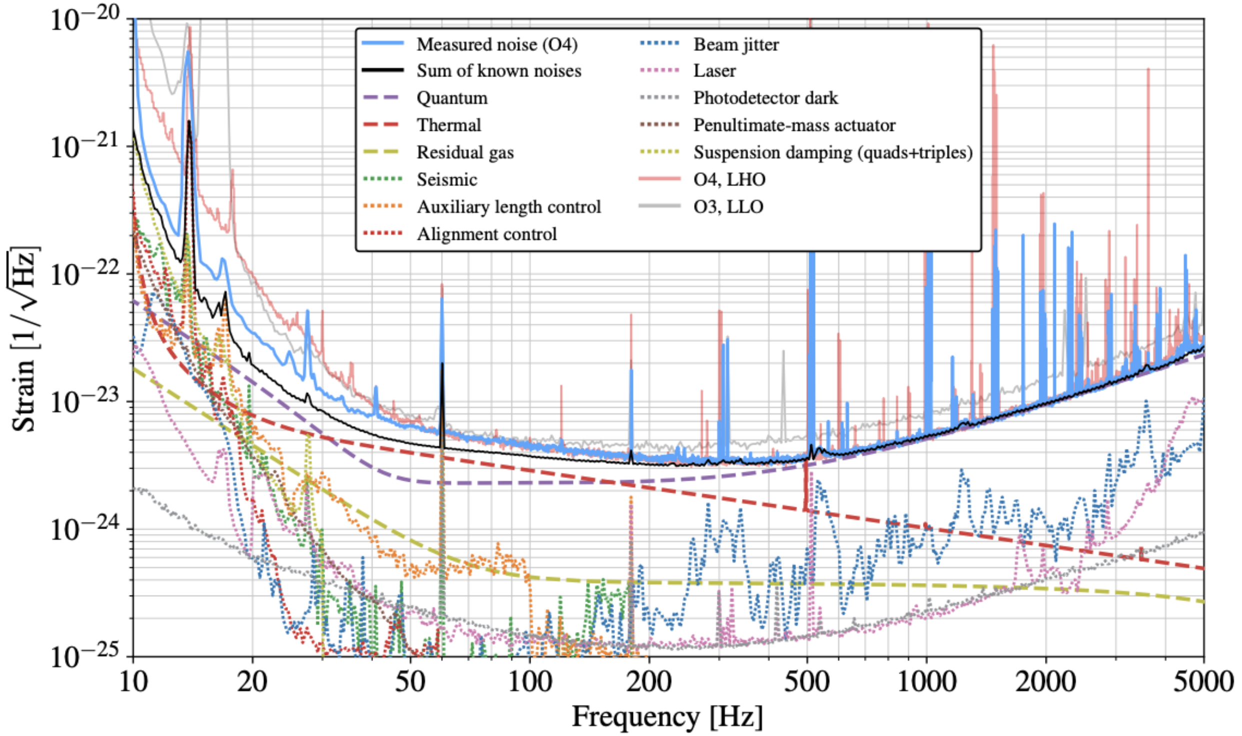


1064 nm at present
1550 or 2000 nm
possible future

O4a – NOISE BUDGET



(a) Noise budget for the LIGO Hanford Observatory, as of December 2023.



(b) Noise budget for the LIGO Livingston Observatory, as of October 2023.

Capote, LIGO O4 instrument scientists, *PRD* ***111***, 062002 (2025)

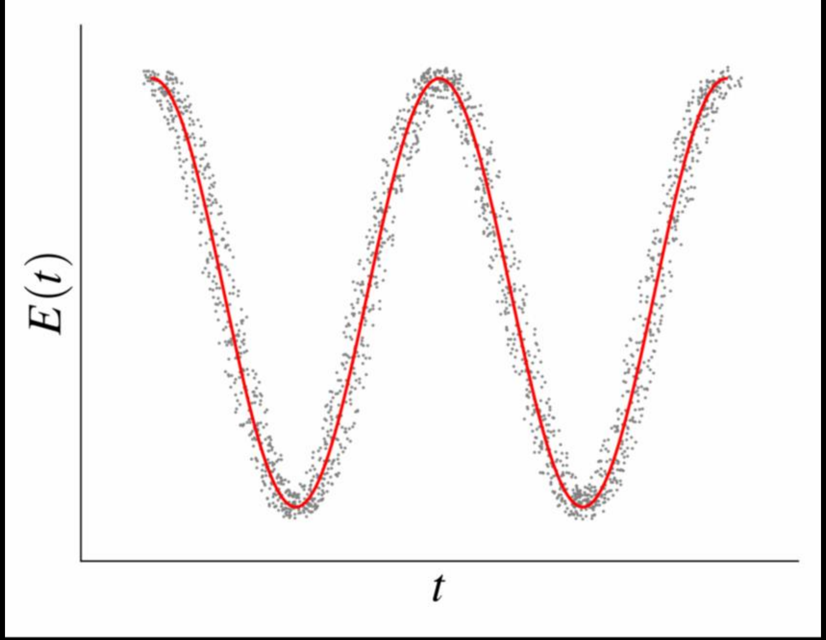
- What limits our LIGO detectors noise now?
  - Quantum & thermal noise (improve sqz loss and control, improve mirror coatings)
  - Mystery low-frequency noise (improve baffling for scatter reduction, improve seismic controls, isolation, and sensors, improve optics)

- Circulating powers: achieved LHO ~350 kW, LLO ~290 kW, limited by thermal instabilities and related effects.
- SQZ target 4.5 FDS → OK.
- Coating thermal noise, challenging

Quantum noise (EM vacuum fluctuations)

In the electromagnetic field, there is a minimum noise power at every frequency: zero point energy, $E_{vac} = \hbar\omega/2$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



Credit: W.Jia

Heisenberg uncertainty principle

for simultaneous measurement of 2 non-commuting observables (e.g., photon position & momentum, field amplitude & phase)

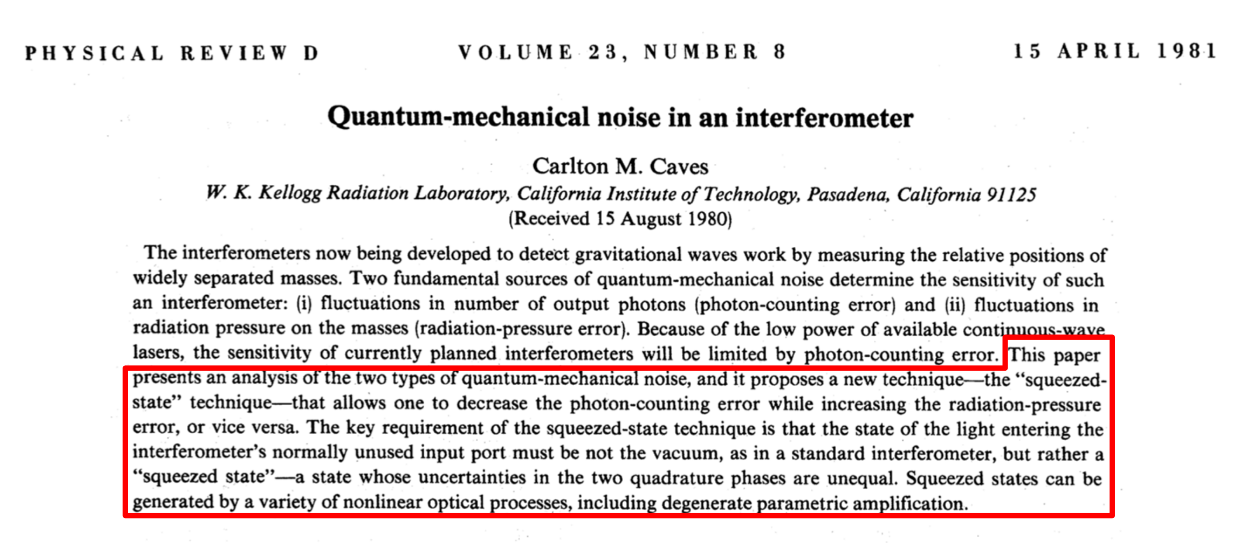
→ photon position (field phase) & momentum (field amplitude) can't be measured infinitely precisely + simultaneously!

Measuring *x* or *p* too well disturbs the other observable.

Quantum noise in an *interferometer*

Carlton Caves (1980) –

Interferometer quantum noise originates from vacuum fluctuations at the output port



PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

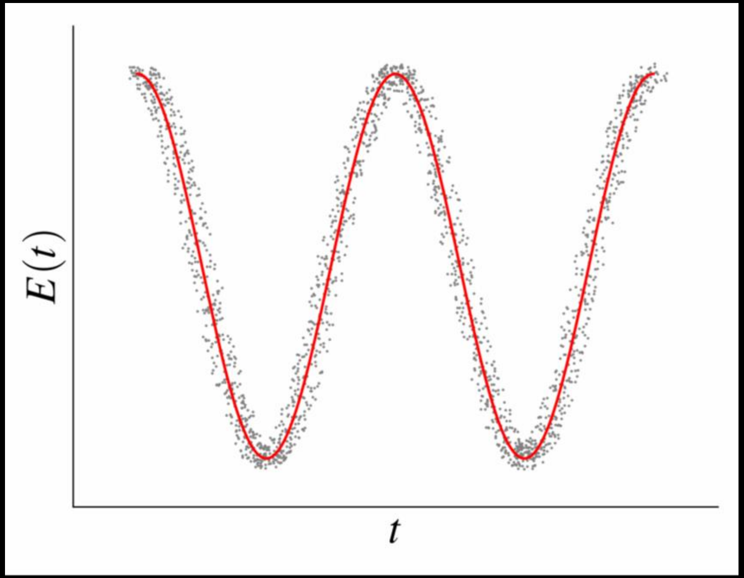
(Received 15 August 1980)

The interferometers now being developed to detect gravitational waves work by measuring the relative positions of widely separated masses. Two fundamental sources of quantum-mechanical noise determine the sensitivity of such an interferometer: (i) fluctuations in number of output photons (photon-counting error) and (ii) fluctuations in radiation pressure on the masses (radiation-pressure error). Because of the low power of available continuous-wave lasers, the sensitivity of currently planned interferometers will be limited by photon-counting error. This paper presents an analysis of the two types of quantum-mechanical noise, and it proposes a new technique—the "squeezed-state" technique—that allows one to decrease the photon-counting error while increasing the radiation-pressure error, or vice versa. The key requirement of the squeezed-state technique is that the state of the light entering the interferometer's normally unused input port must be not the vacuum, as in a standard interferometer, but rather a "squeezed state"—a state whose uncertainties in the two quadrature phases are unequal. Squeezed states can be generated by a variety of nonlinear optical processes, including degenerate parametric amplification.

Heisenberg uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Regular EM vacuum has equal phase and amplitude noise:



Cannot beat Heisenberg uncertainty, but squeezed states *redistribute* uncertainty

between Δx and Δp, while conserving total noise!

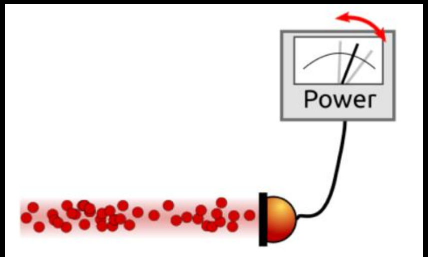
1. Shot noise Δx: photons arrive randomly @ photodetector

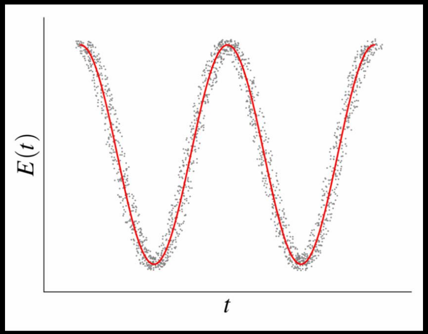
→ Imagine a night time video: too dark. Can't use long exposures because source moves. At night, can't get more signal photons ... **shot-noise-limited, SNR~1/sqrt[N]**

→ **Need more signal photons, or reduced shot noise per photon, to improve sensitivity**

Vacuum phase flucutations
= Photons randomly arrive at the detector
= Power fluctuations in time

Signal ~ N photons , Shot noise ~ $\sqrt{N}$ → SNR ~ $\frac{N}{\sqrt{N}} \sim \sqrt{N}$





https://en.wikipedia.org/wiki/Shot_noise

2. Quantum radiation pressure Δp: mirrors randomly kicked

Mirrors randomly driven by **vacuum amplitude fluctuations** beating with main laser

Power fluctuation of the laser beam due to **vacuum amplitude fluctuations**

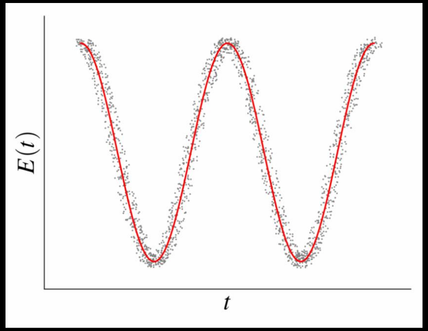
$$P(\Omega) = \sqrt{2\hbar\omega_0} A_0 \hat{a}_1(\Omega)$$

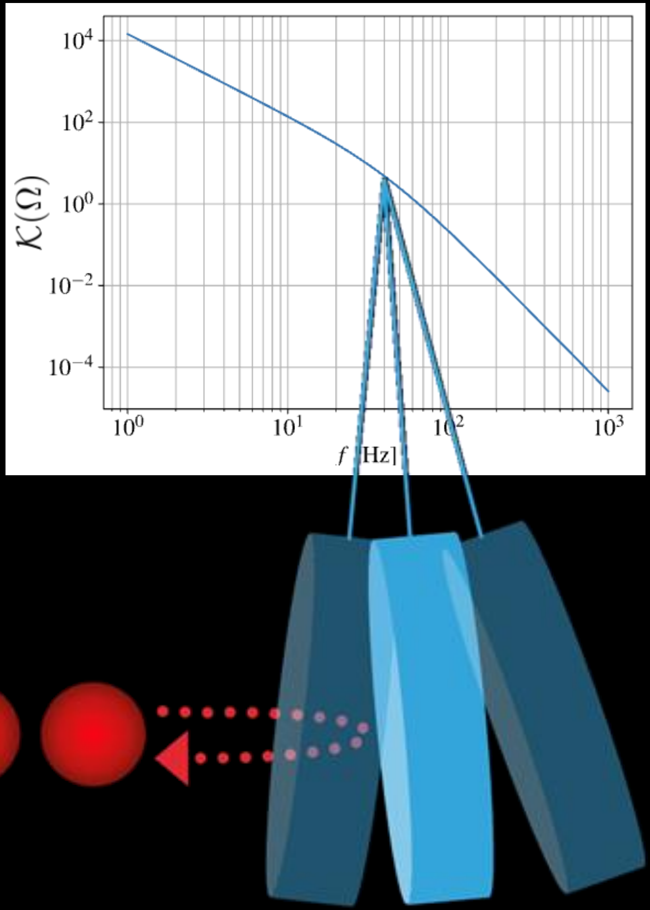
Position fluctuation of the mirror

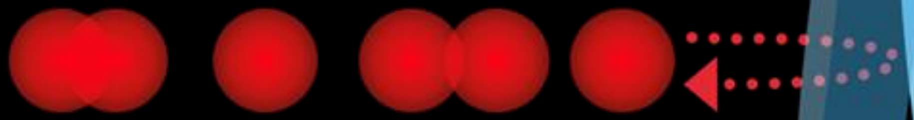
$$\delta L(\Omega)$$

Additional phase fluctuation → phase noise

$$\hat{a}_2(\Omega) \to \hat{a}_2(\Omega) + \mathcal{K}(\Omega)\hat{a}_1(\Omega)$$







Mitigation strategies:

1. Extremely heavy mirrors so mirrors don't recoil and displace as far.
   With 40-kg fused silica mirrors… ***classical QRPN reduction***
2. Quantum engineering to squeeze vacuum amplitude noise… ***quantum QRPN reduction***

“Standard” quantum limit (SQL)

“imprecision noise”

coherent state limit, uncorrelated sum of shot noise + QRPN

$$S(\Omega) = \frac{h^2_{\rm SQL}(\Omega)}{2}\left[\mathcal{K}(\Omega) + \frac{1}{\mathcal{K}(\Omega)}\right]$$

“backaction noise”

mirrors recoil from laser light:

$$\mathcal{K}(\Omega) = \frac{16 k_0 P_{\rm arm}}{m \gamma_0 L_{\rm arm}} \frac{1}{\Omega^2}\left(1 + \frac{\Omega^2}{\gamma_0^2}\right)^{-1}$$

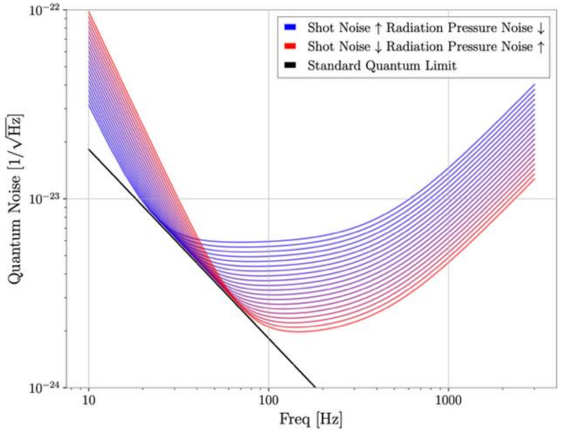
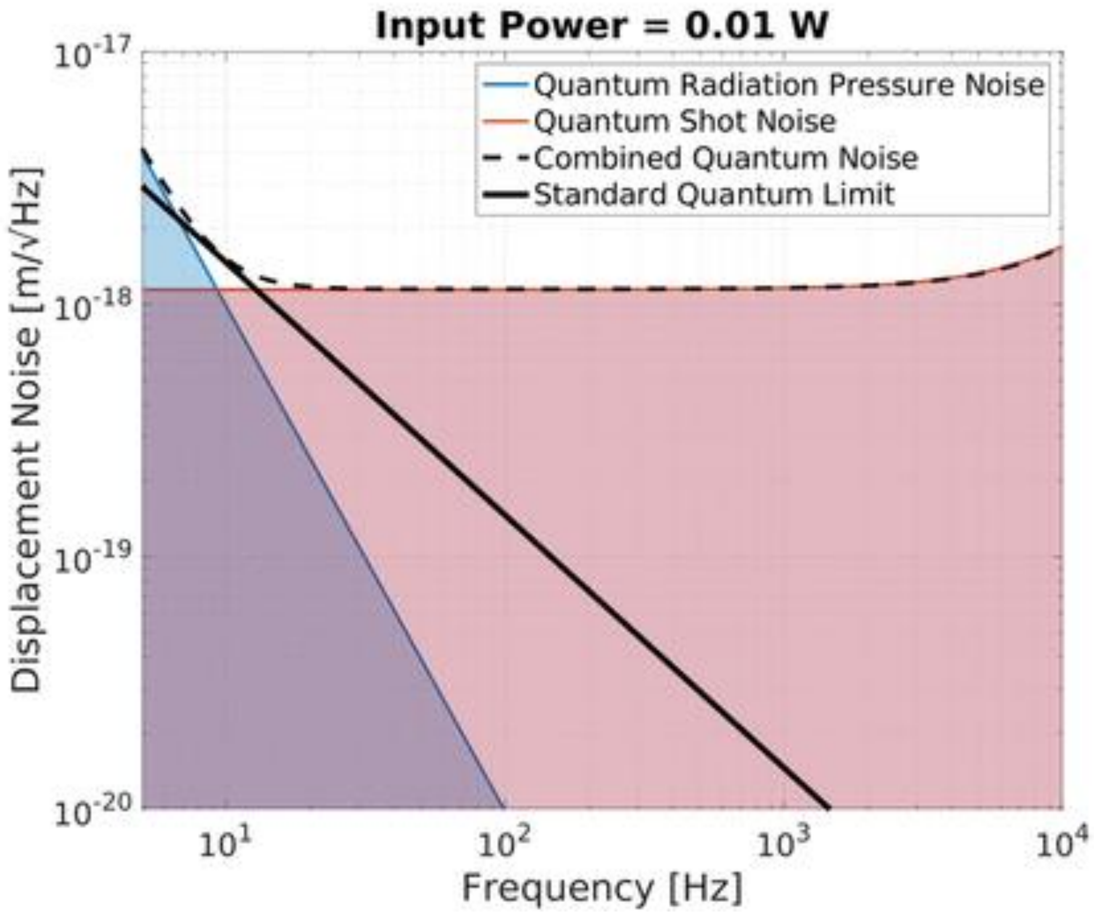
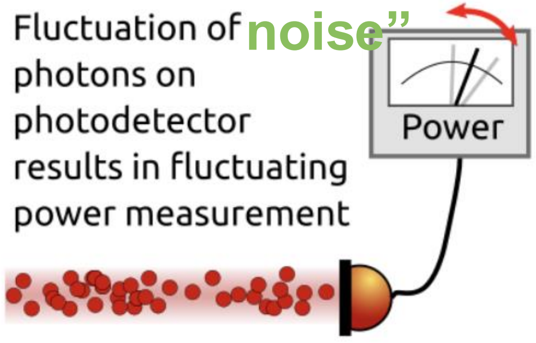


Figure 1.4: The standard quantum limit



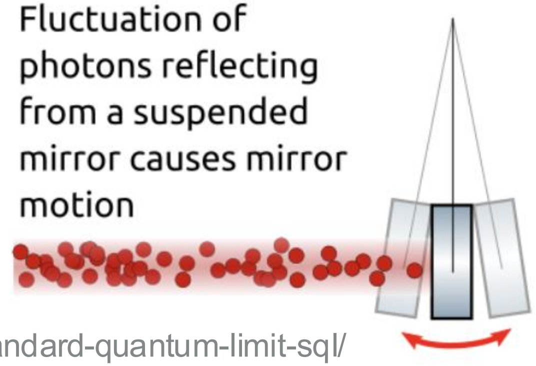
Shot noise
“imprecision noise”

Fluctuation of photons on photodetector results in fluctuating power measurement



QRPN
“backaction noise”

Fluctuation of photons reflecting from a suspended mirror causes mirror motion



https://10m.aei.mpg.de/standard-quantum-limit-sql/

$$S_{\rm SQL}(\Omega) = \frac{8\hbar}{m\Omega^2 L^2}. \approx 1.8 \times 10^{-24}\left(\frac{2\pi \times 100\ {\rm Hz}}{\Omega}\right)\frac{1}{\sqrt{\rm Hz}}$$

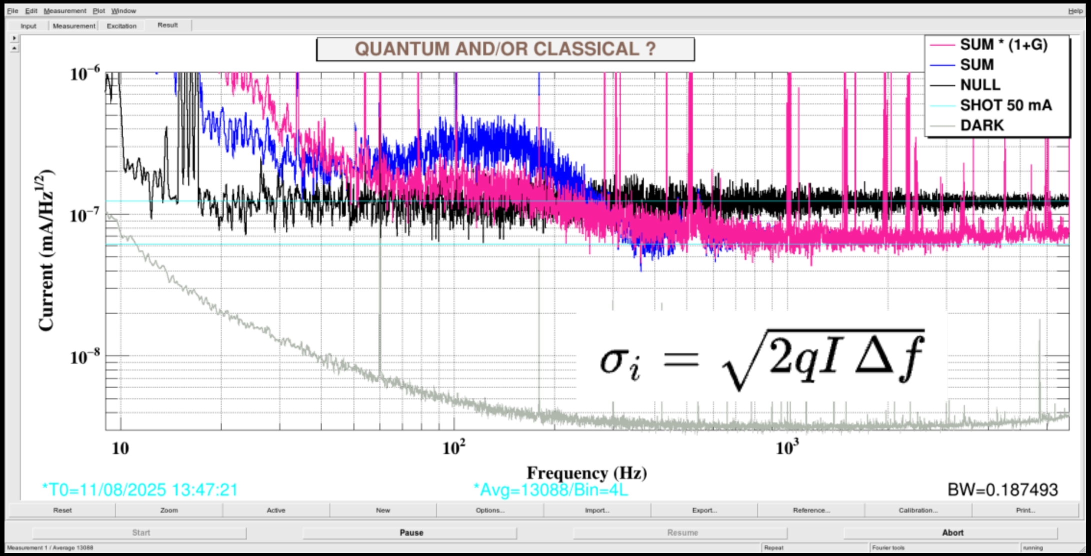
...barely sufficient for astrophysics,

which is why LIGO mirrors are 40 kg heavy: a classical way to lower the “standard quantum limit”.

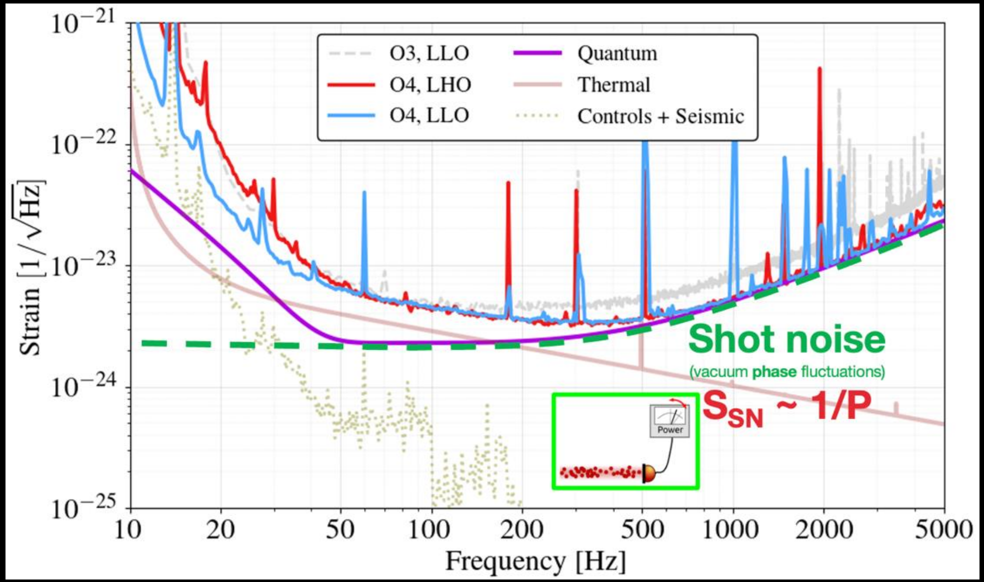
LIGO shot noise to strain noise

Photocurrent noise spectrum (mA/rtHz)

e.g. photocurrent shot noise: $\frac{\sigma_i}{\sqrt{\Delta f}}$ = sqrt(2*e*(50mA)) ~ 1.3e-7 mA/rtHz

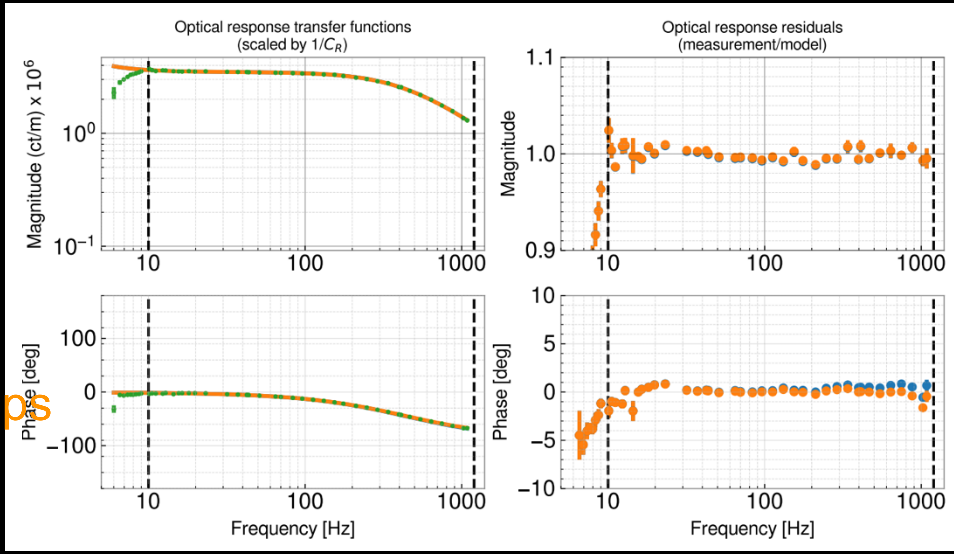


Strain noise ASD



=

/

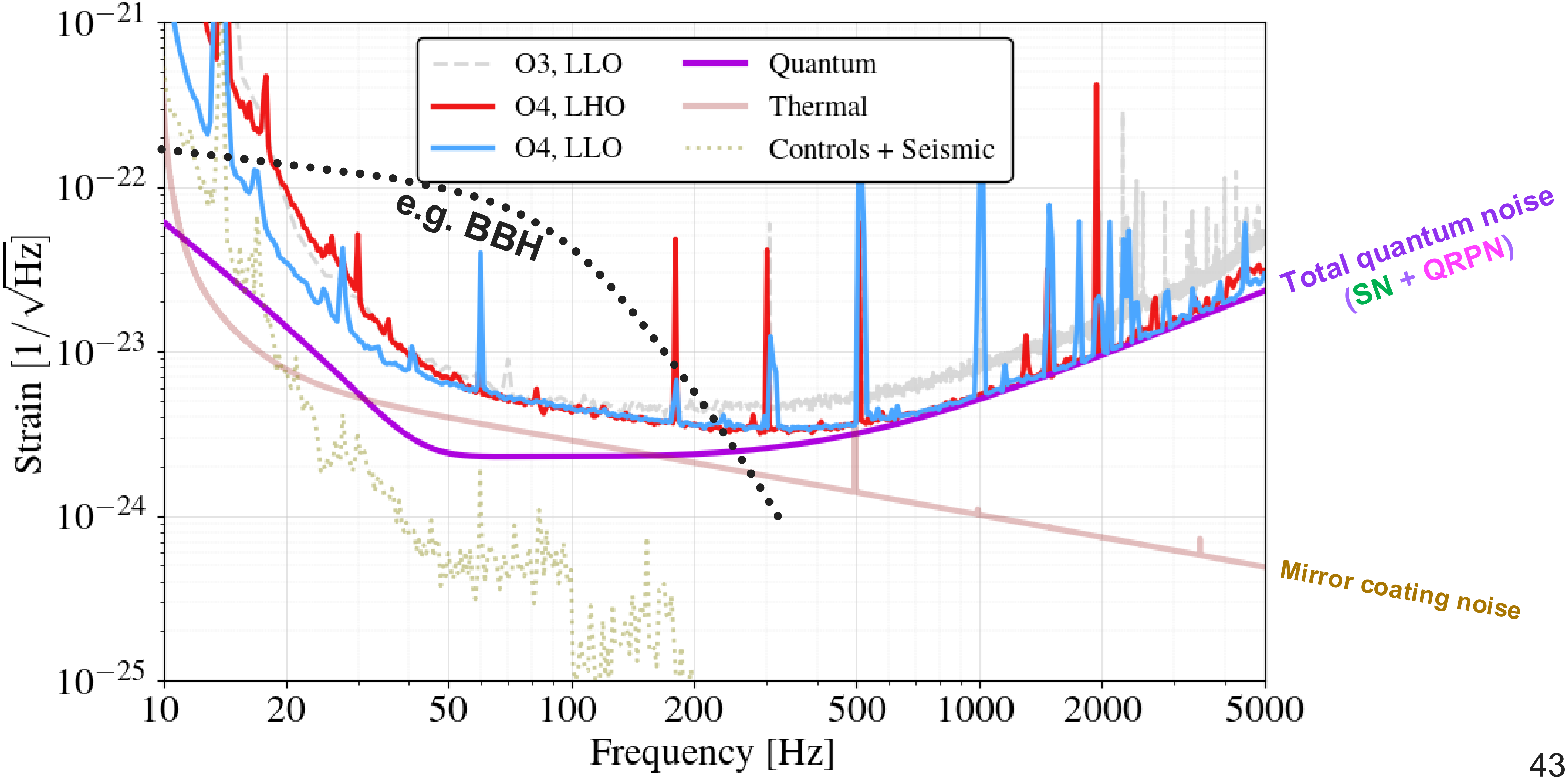


Calibrate current to meters (~mA/pm)

Detector opto-mechanical transfer function from digitized milliamps ("counts") to meters of interferometer displacement.

LIGO signal-to-**noise**

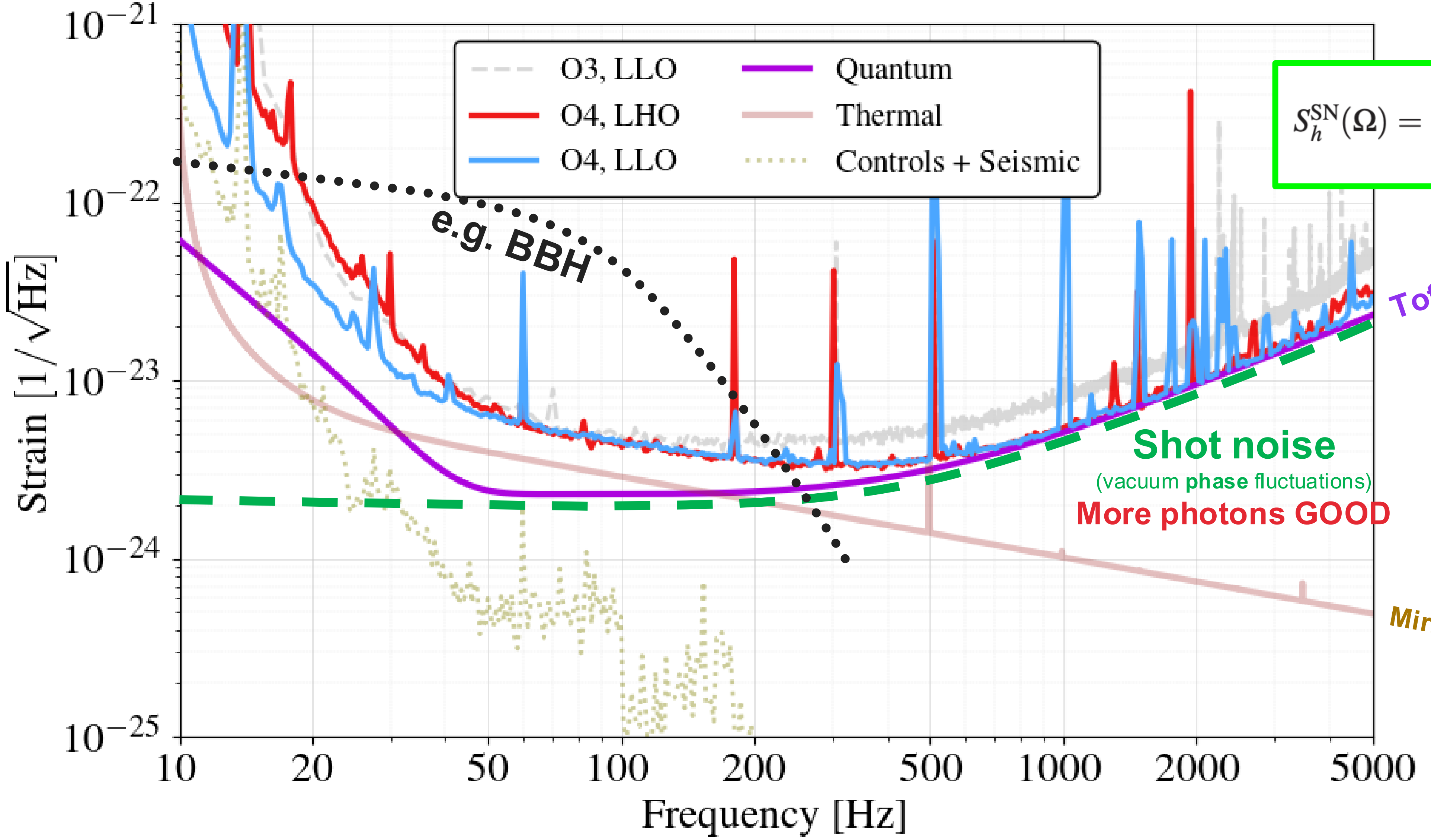
Quantum noise broadly limits total sensitivity



PRX **13**, 041021 (2023)

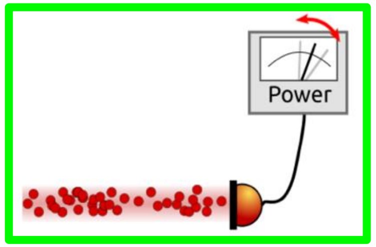
LIGO signal-to-**noise**

Quantum noise broadly limits total sensitivity



$$S_h^{\mathrm{SN}}(\Omega) = \frac{\hbar\gamma}{4kLP}\left(1 + \frac{\Omega^2}{\gamma^2}\right)$$

Total quantum noise (SN + QRPN)

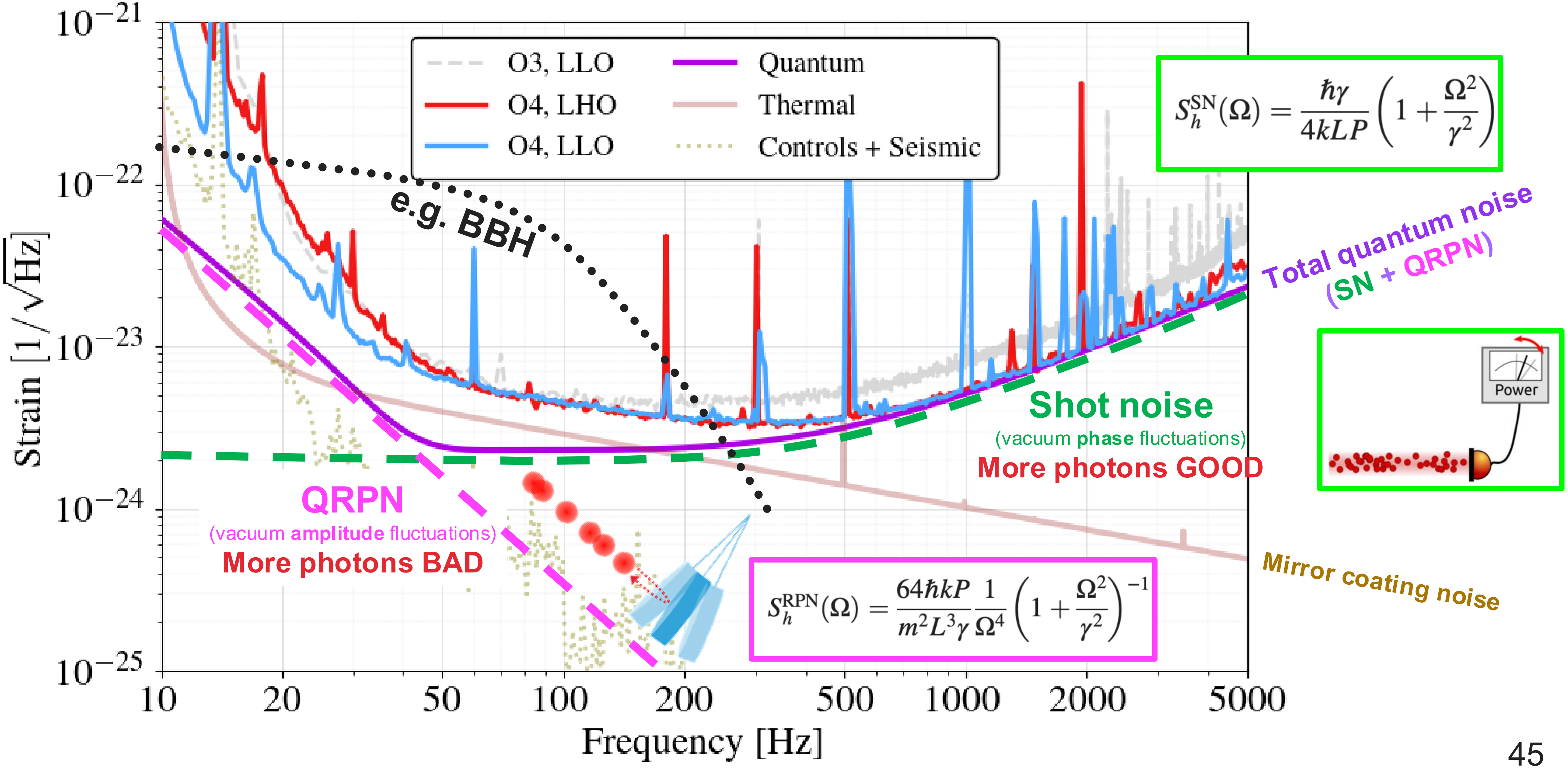


Mirror coating noise

PRX **13**, 041021 (2023)

LIGO signal-to-**noise**

Quantum noise broadly limits total sensitivity



$$S_h^{\mathrm{SN}}(\Omega) = \frac{\hbar\gamma}{4kLP}\left(1+\frac{\Omega^2}{\gamma^2}\right)$$

$$S_h^{\mathrm{RPN}}(\Omega) = \frac{64\hbar kP}{m^2L^3\gamma}\frac{1}{\Omega^4}\left(1+\frac{\Omega^2}{\gamma^2}\right)^{-1}$$

PRX **13**, 041021 (2023)

LIGO signal-to-noise

Quantum noise broadly limits total sensitivity

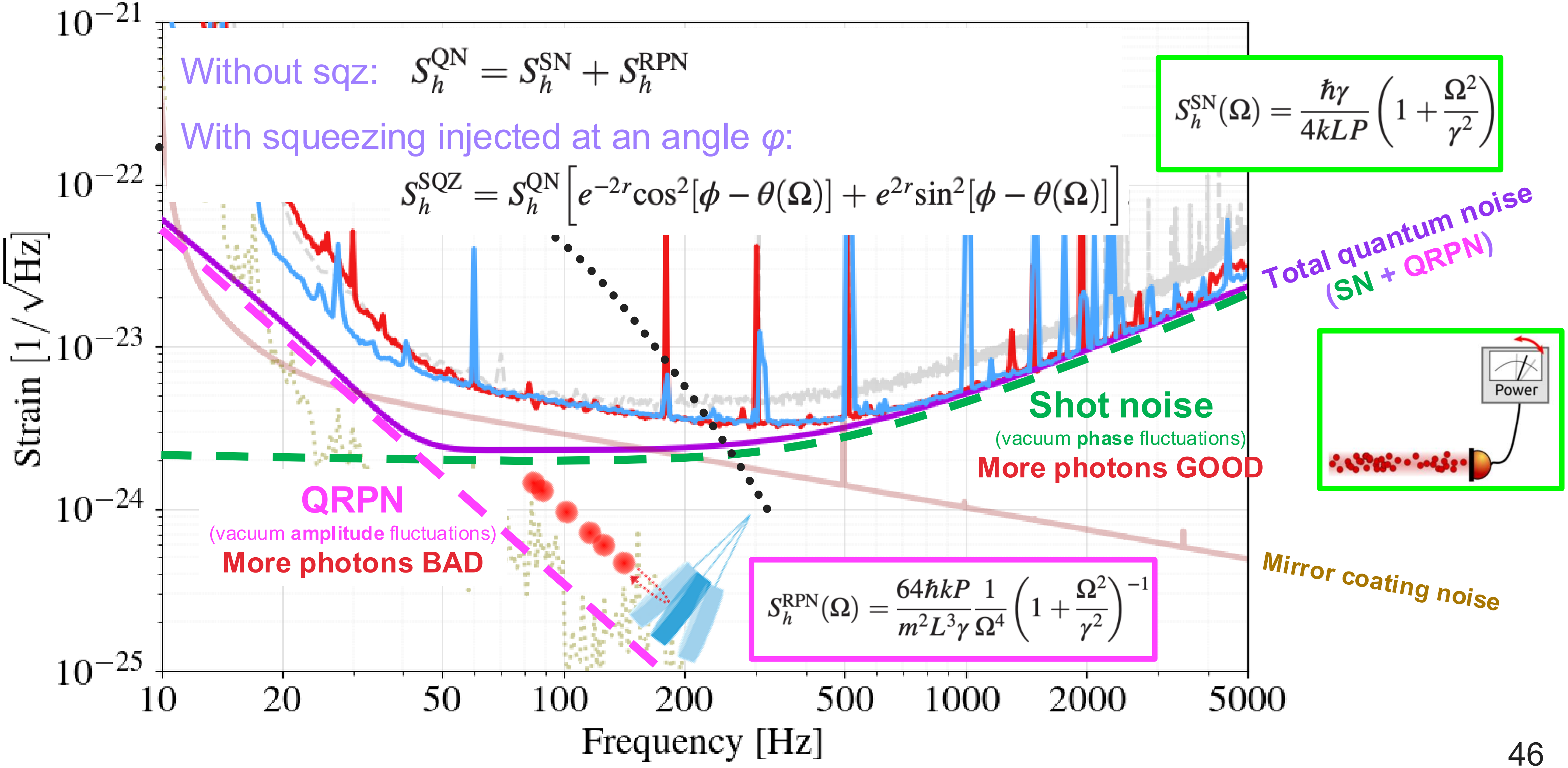
Without sqz: $S_h^{QN} = S_h^{SN} + S_h^{RPN}$

With squeezing injected at an angle φ:

$$S_h^{SQZ} = S_h^{QN}\left[e^{-2r}\cos^2[\phi - \theta(\Omega)] + e^{2r}\sin^2[\phi - \theta(\Omega)]\right]$$

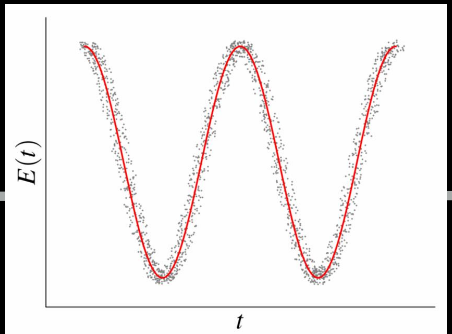
$$S_h^{SN}(\Omega) = \frac{\hbar\gamma}{4kLP}\left(1 + \frac{\Omega^2}{\gamma^2}\right)$$

$$S_h^{RPN}(\Omega) = \frac{64\hbar kP}{m^2L^3\gamma}\frac{1}{\Omega^4}\left(1 + \frac{\Omega^2}{\gamma^2}\right)^{-1}$$



PRX **13**, 041021 (2023)

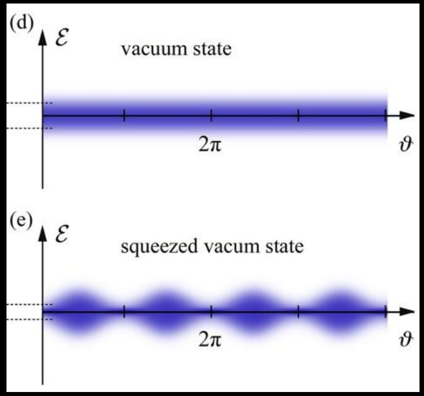
Squeezed “vacuum”

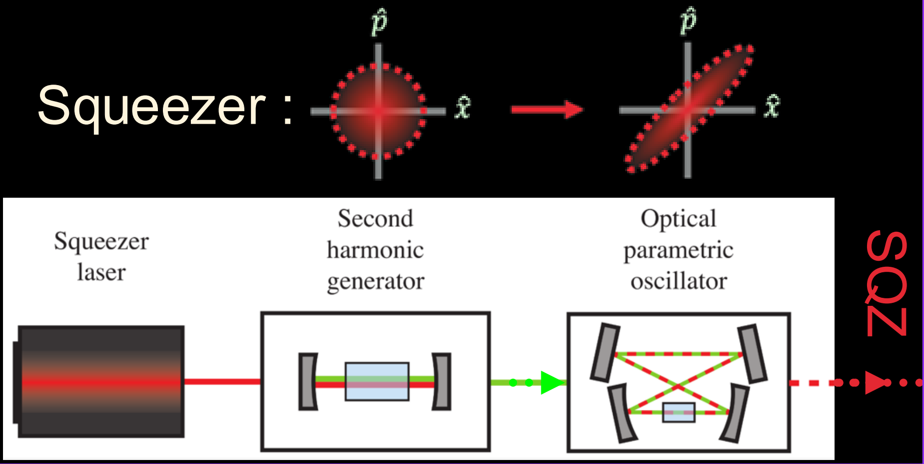


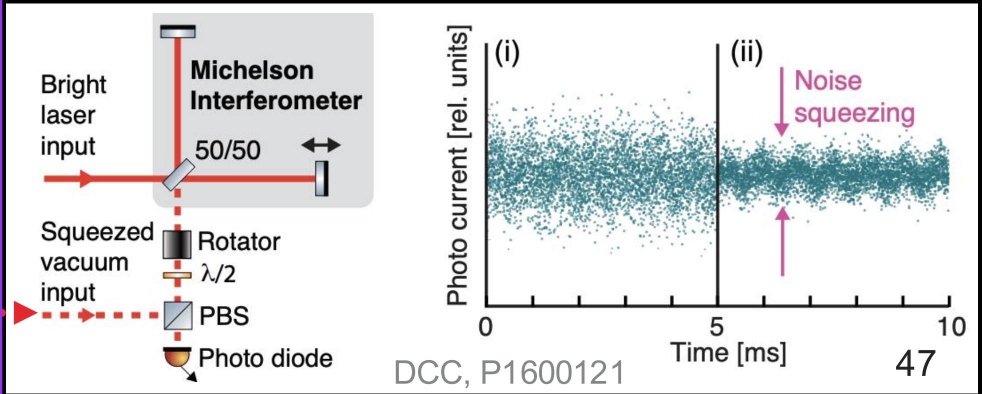
Zero-point energy is finite,
SQZ trades one noise for another

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Optical parametric amplification to generate squeezed vacuum







DCC, P1600121

EM field is quantized like a harmonic oscillator

Quantize EM field from phasors a(t)

$$E(t) = \tfrac{1}{2}[a(t) + a^*(t)]$$

into quadrature operators x, p (equiv, X1,X2):

$$a = x + ip$$

→ (re) $x = (a + a^*)/2$

→ (im) $p = (a - a^*)/(2i)$

$$E(t) = x \cos \omega t + p \sin \omega t$$

Quadratures: demod_I, demod_Q

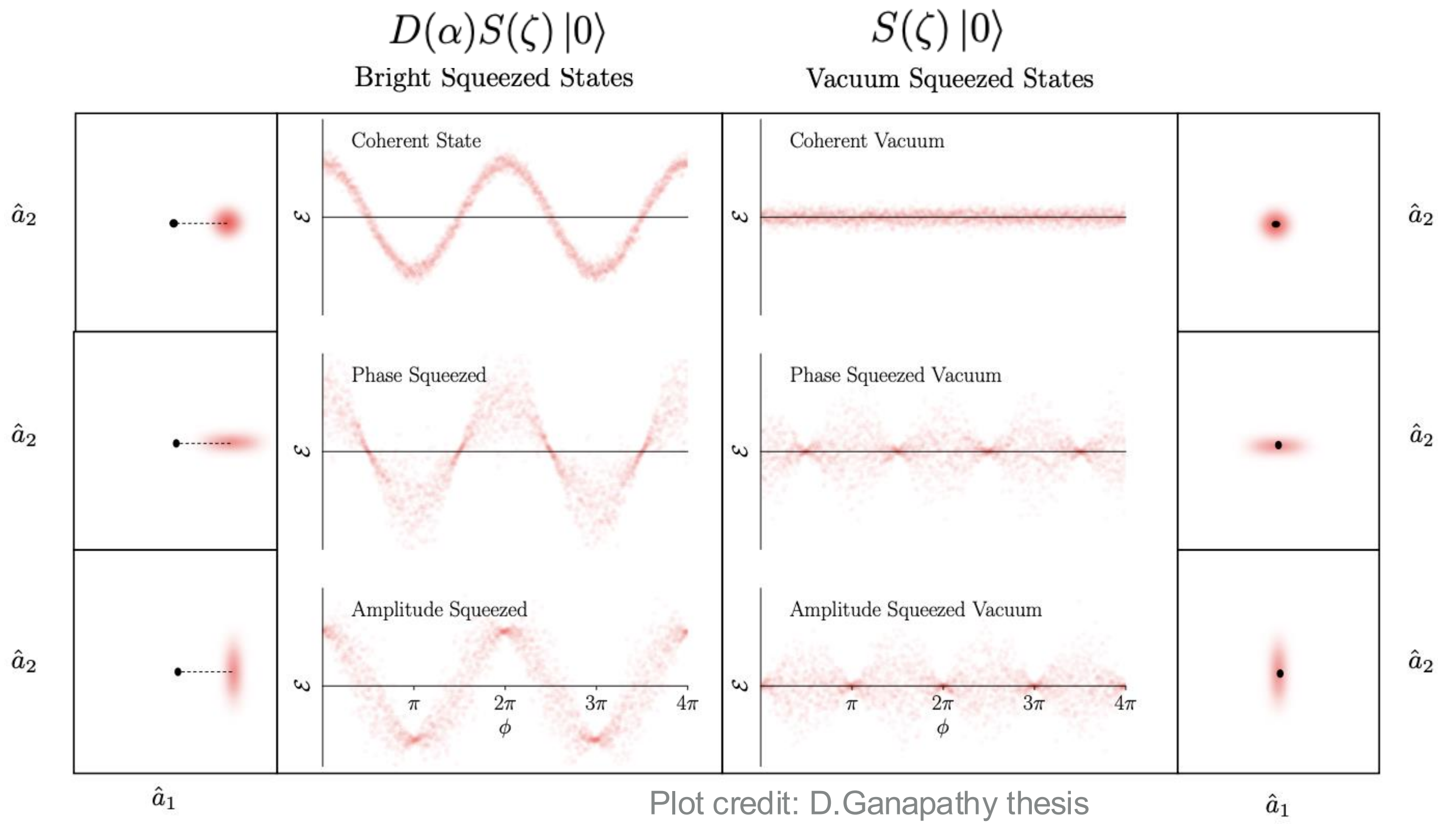
(aka, demodulate photodetector with LO cos φ, LO sin φ, to readout {x, p} non-commuting field quadratures)

$$[x, p] = \frac{i}{2} \qquad \sigma_x \sigma_p \geq \frac{1}{4}$$

$$[a(t), a^\dagger(t)] = a(t)a^\dagger(t) - a^\dagger(t)a(t) = 1$$

Recognize a quantum harmonic oscillator:
(vacuum field, n=0, average energy = hw/2)

Squeeze operator $S(\zeta) = \exp\left((\zeta^* a^2 - \zeta a^{\dagger 2})/2\right)$



Plot credit: D.Ganapathy thesis

average energy in the quantum mode is $\hbar\omega(\langle n \rangle + \frac{1}{2})$

SQUEEZED "VACUUM", "QUADRATURE SQUEEZING"

From a mathematical point of view, a field in a minimum uncertainty state can be quadrature squeezed by multiplying its x-component by the factor e^{-r} and its p-component by the factor e^{r}. The quantity r is called the 'squeeze parameter'. It is convenient to include a phase factor $e^{i\xi}$ in one of the quadratures so that

$$E_s(t) = xe^{-r}e^{i\xi}\cos\omega t + pe^{r}\sin\omega t\,. \qquad (11)$$

The net result of this operation is to squeeze the x-component uncertainty σ_x down to $e^{-r}\sigma_x$ and simultaneously to stretch the p-component uncertainty σ_p up to $e^{r}\sigma_p$. As

Mean photon number is coherent field + sqz field

$$\langle n\rangle = |\alpha|^2 + \sinh^2 r$$

about 10^{16} (40mW) + 24 photons

Mean photon number for 20 dB of squeezed vacuum is ~24 photons

$$\langle n\rangle = \sinh^2 r > 0$$

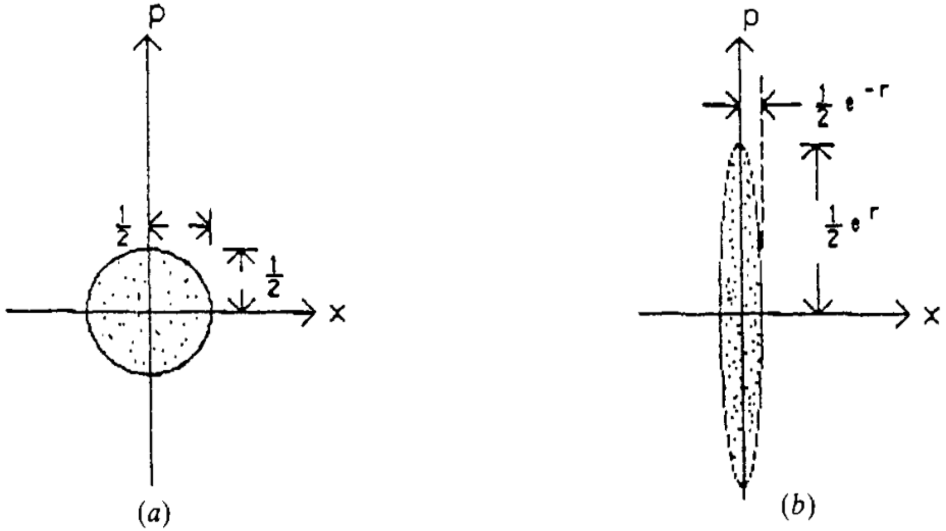


Figure 9. Comparison of quadrature-component uncertainties for the vacuum and squeezed vacuum states: (*a*) vacuum state, (*b*) squeezed vacuum state.

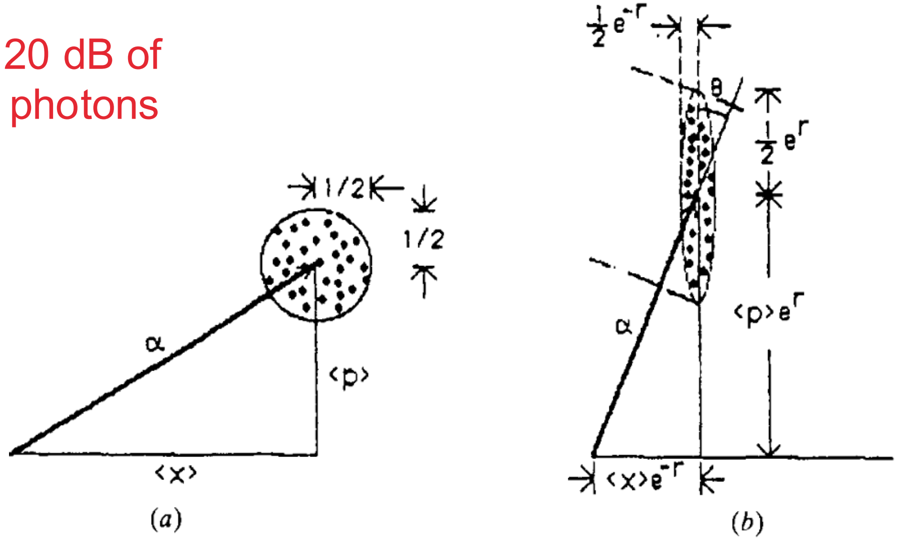
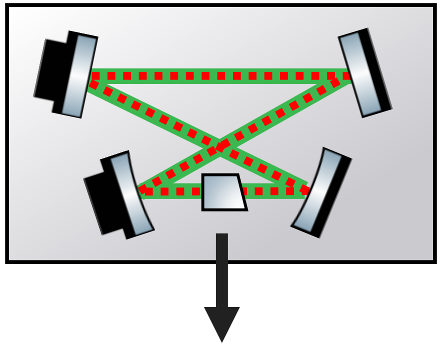


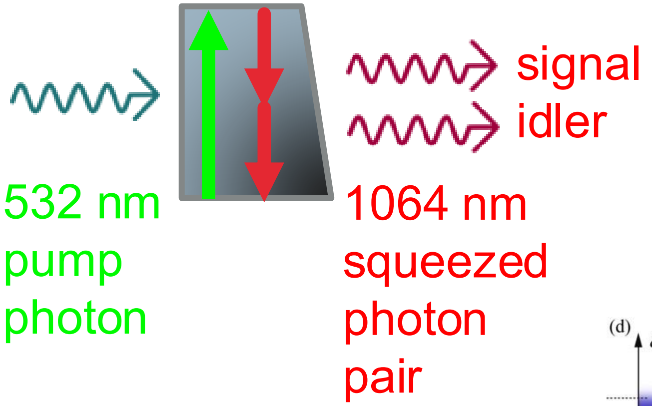
Figure 10. Comparison of quadrature-component uncertainties for the coherent and squeezed coherent states: (*a*) coherent state, (*b*) squeezed coherent state.

SQUEEZED VACUUM SOURCE



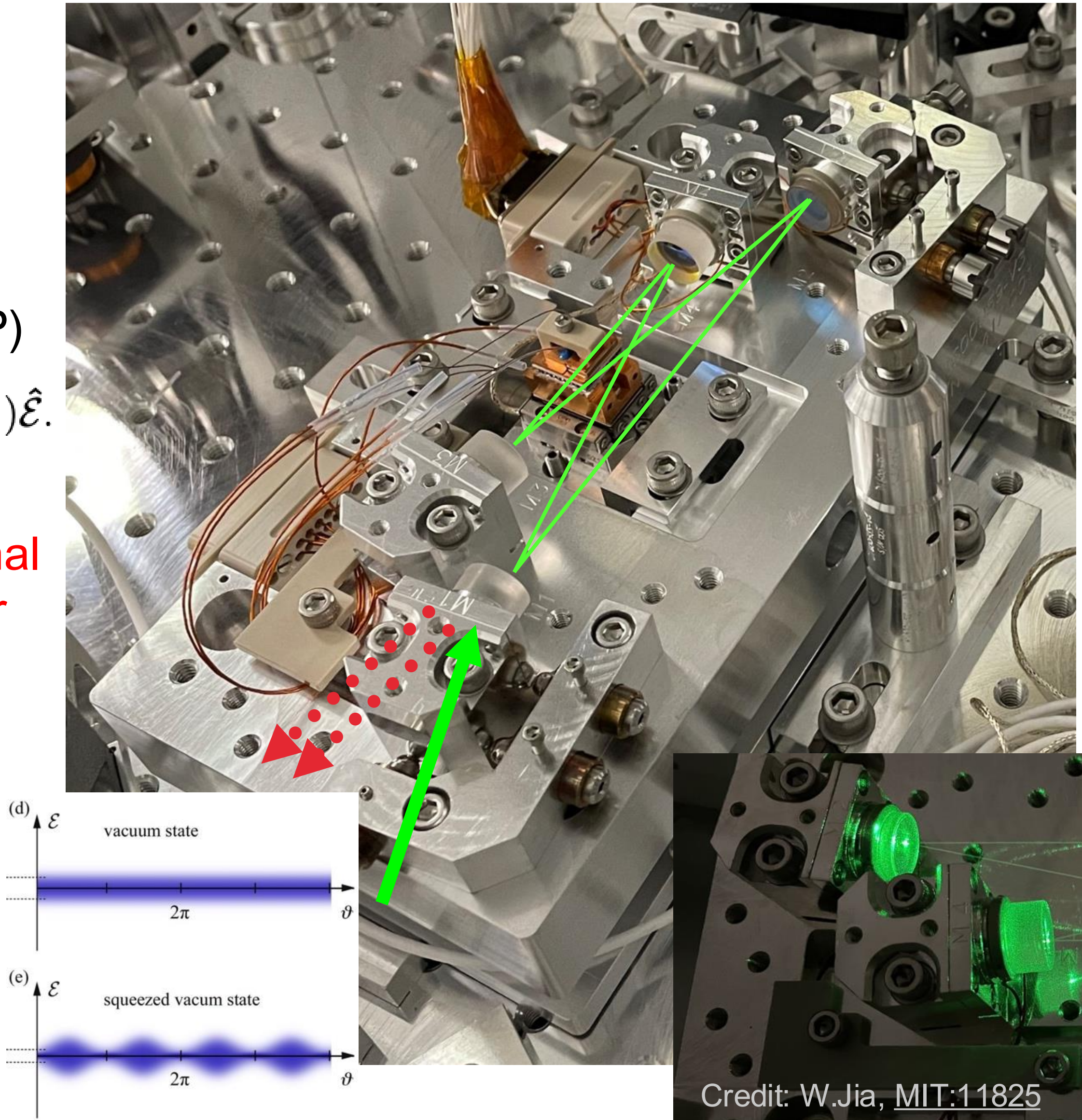
Nonlinear $\chi^{(2)}$ crystal (PPKTP)

$$\mathbf{P} = \epsilon_0(\chi^{(1)} + \chi^{(2)}|\mathcal{E}| + \chi^{(3)}|\mathcal{E}|^2 + ...)\hat{\mathcal{E}}.$$

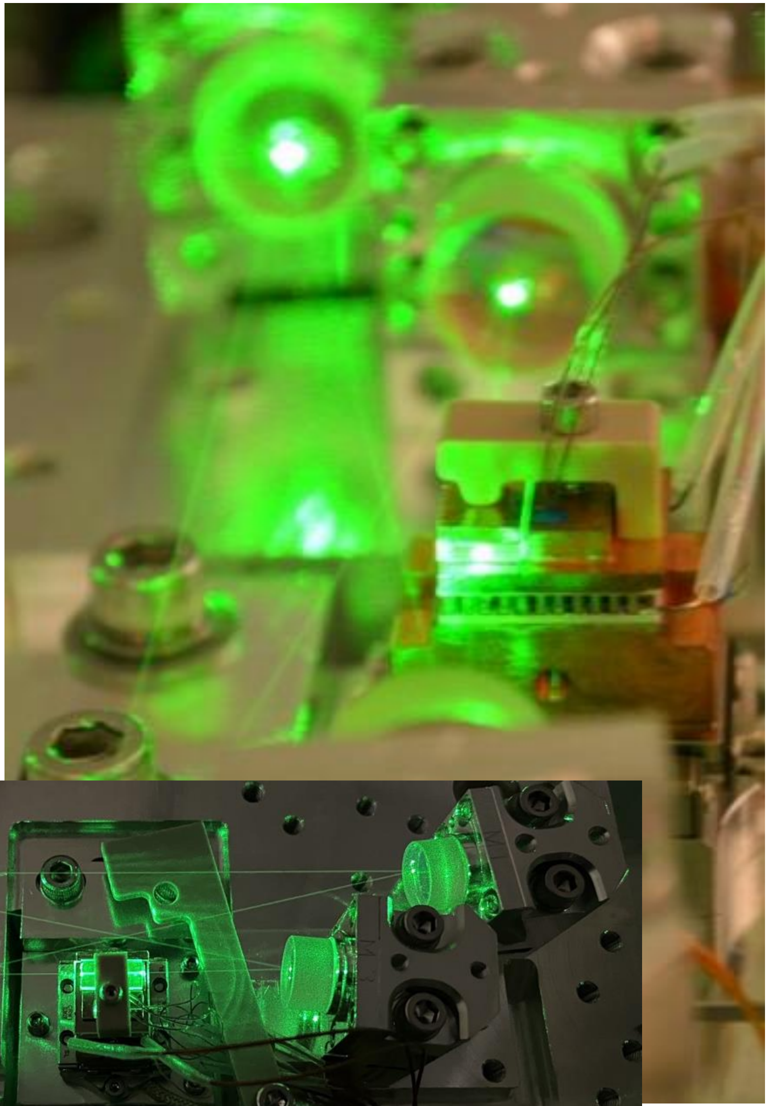


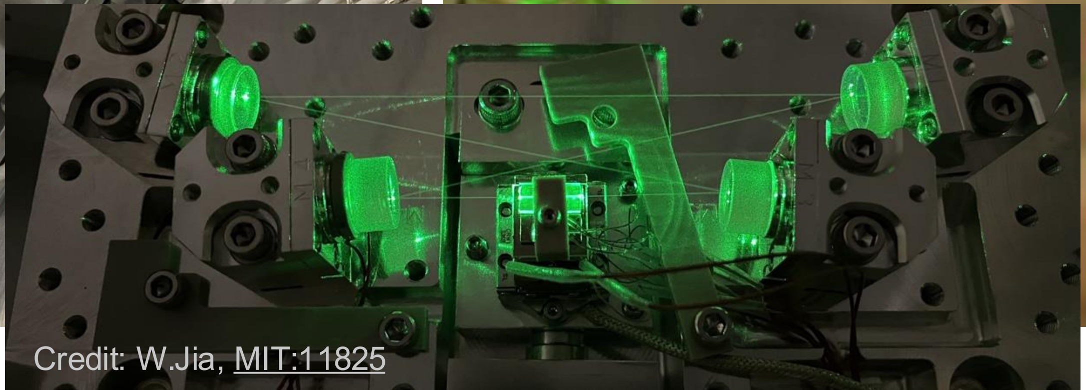
Spontaneous parametric down-conversion Type 0

llo55528



G2300668

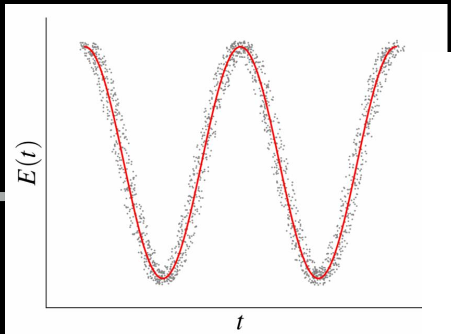


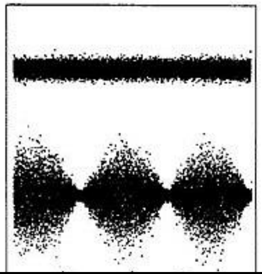


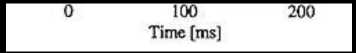
Credit: W.Jia, MIT:11825

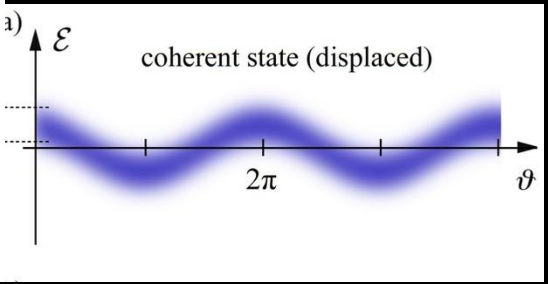
Squeezing quantum noise

Electric field of "squeezed" light:





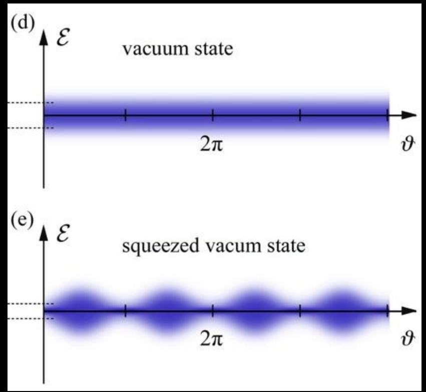




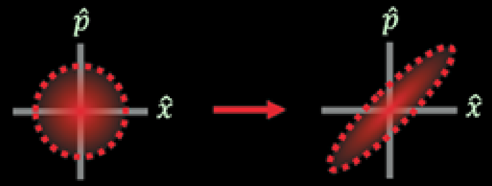
Zero-point energy is finite,
SQZ trades one noise for another

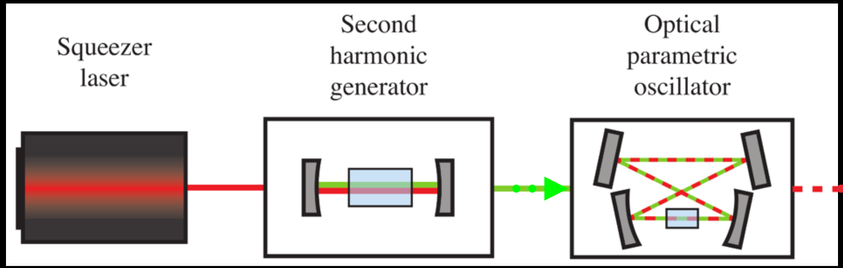
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Credit: Wikipedia, R.Schnabel

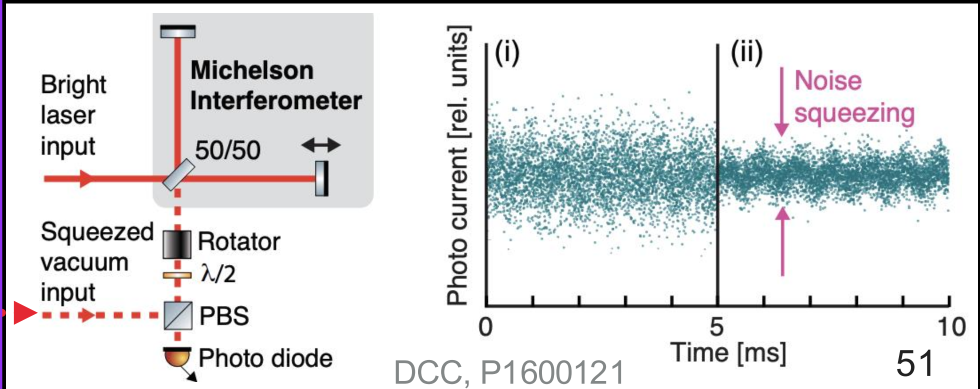


Squeezer :





SQZ



DCC, P1600121

O3: Frequency-*independent* squeezing

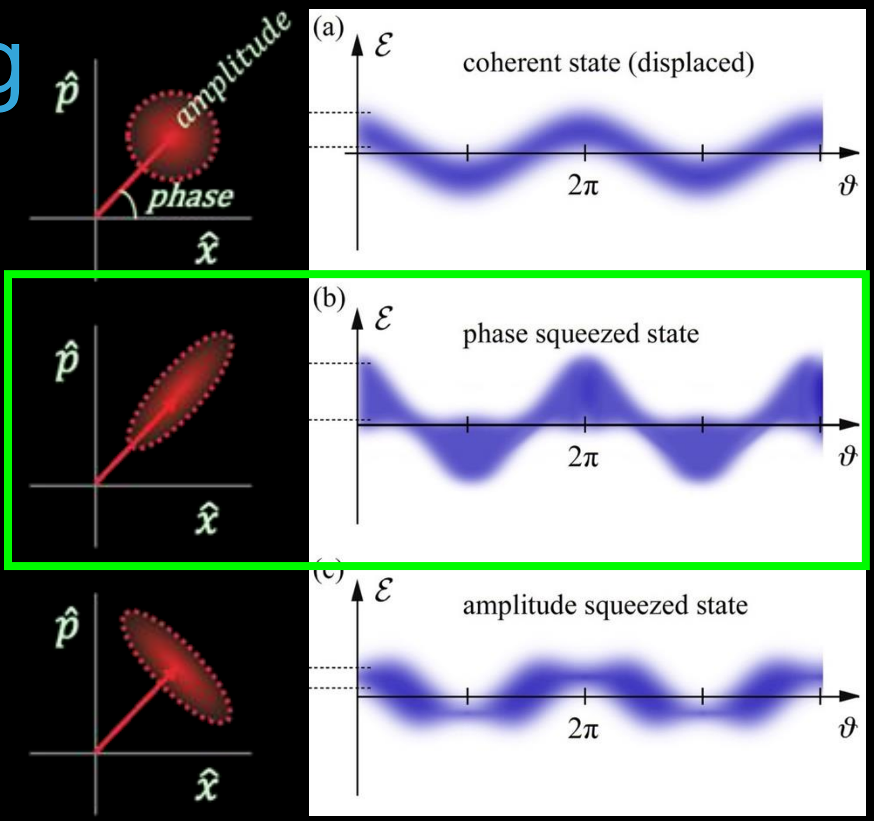
SQZ trades one noise for another – a compromise

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

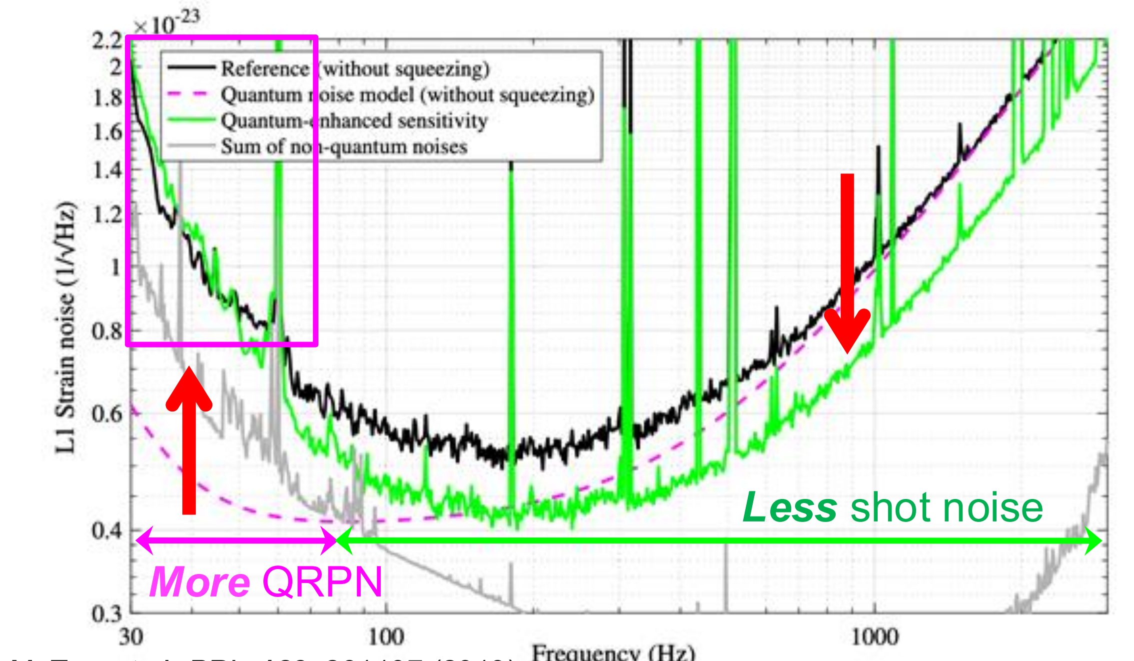
Δx → Shot noise ✓ O3, O4

Δp → Quantum radiation pressure noise ✓ O4

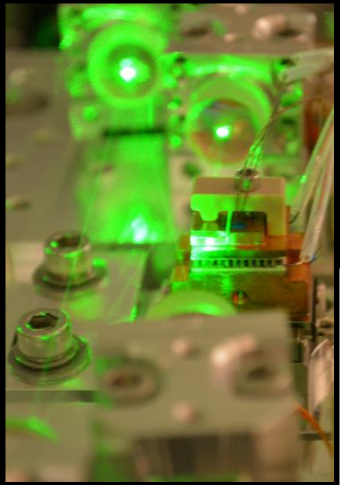
Electric field of "squeezed" light:

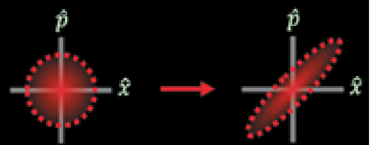


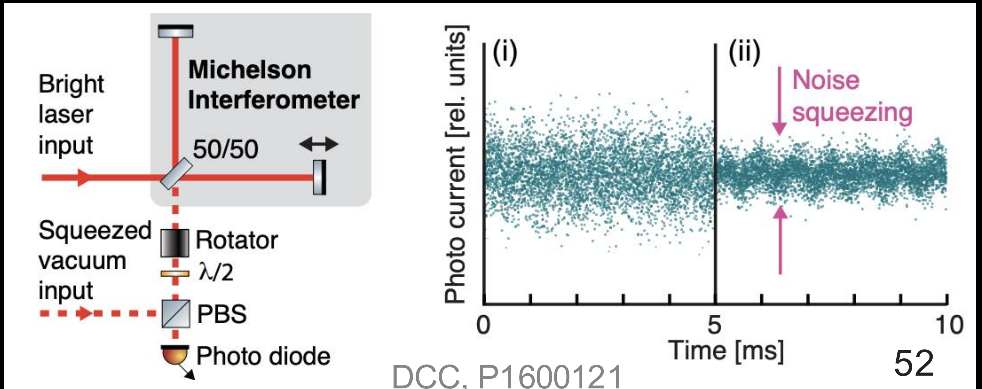
Credit: Wikipedia, R.Schnabel



M. Tse, et al, *PRL*, **123**, 231107 (2019)







DCC, P1600121

O4: Frequency-*dependent* squeezing

Amplitude SQZ at **low** frequency

Phase SQZ at **high** frequency

Reflect SQZ off a **detuned filter cavity** for freq-dep SQZ

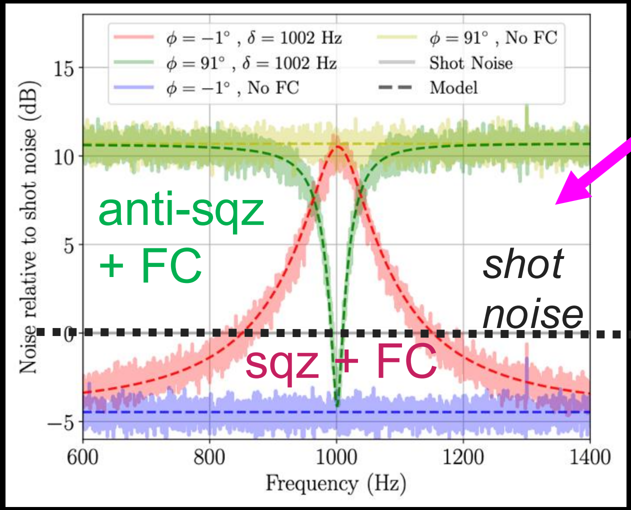
FC reflection gives asymmetric, frequency-dependent phase shift to the upper vs. lower sideband → SQZ rotation around FC resonance

→ Delaying signal vs idler photons with Δf~100 Hz requires a **long photon storage time of >3 ms!!**

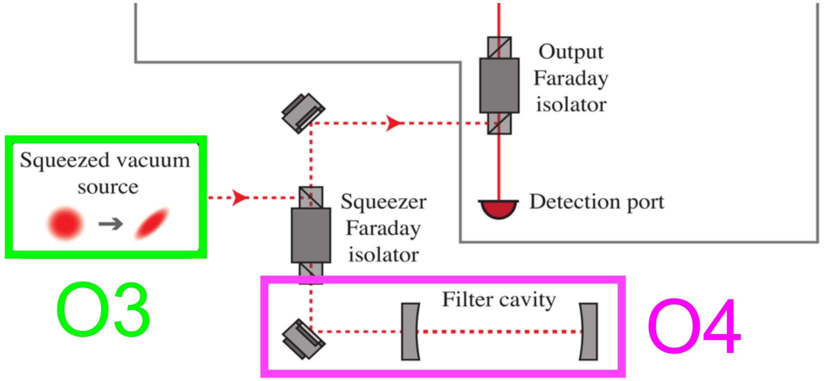
* FC Length ~ 297 m

* FC Finesse ~ 6700

SQZ rotation @ 1 kHz:
(on a diagnostic homodyne)



Ganapathy, LIGO instrument scientists, *PRX* **13**, 041021 (2023)



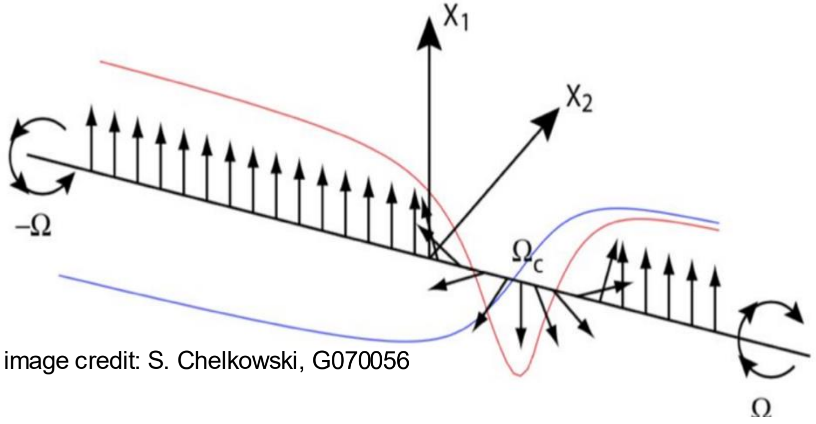
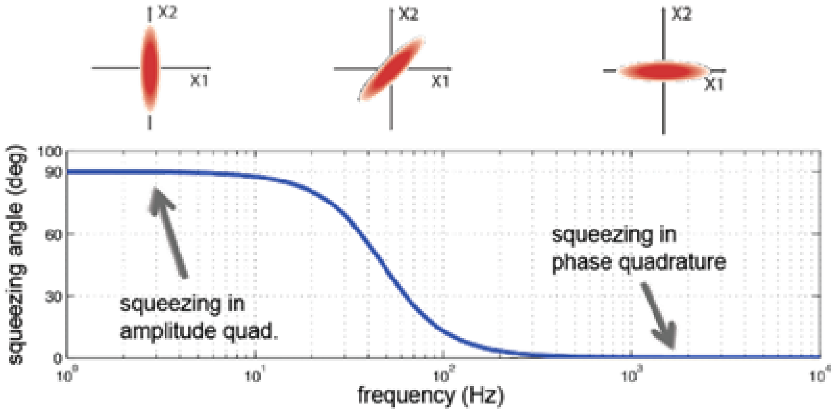


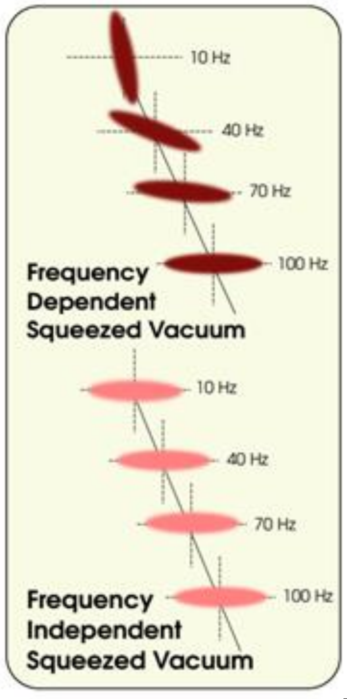
image credit: S. Chelkowski, G070056

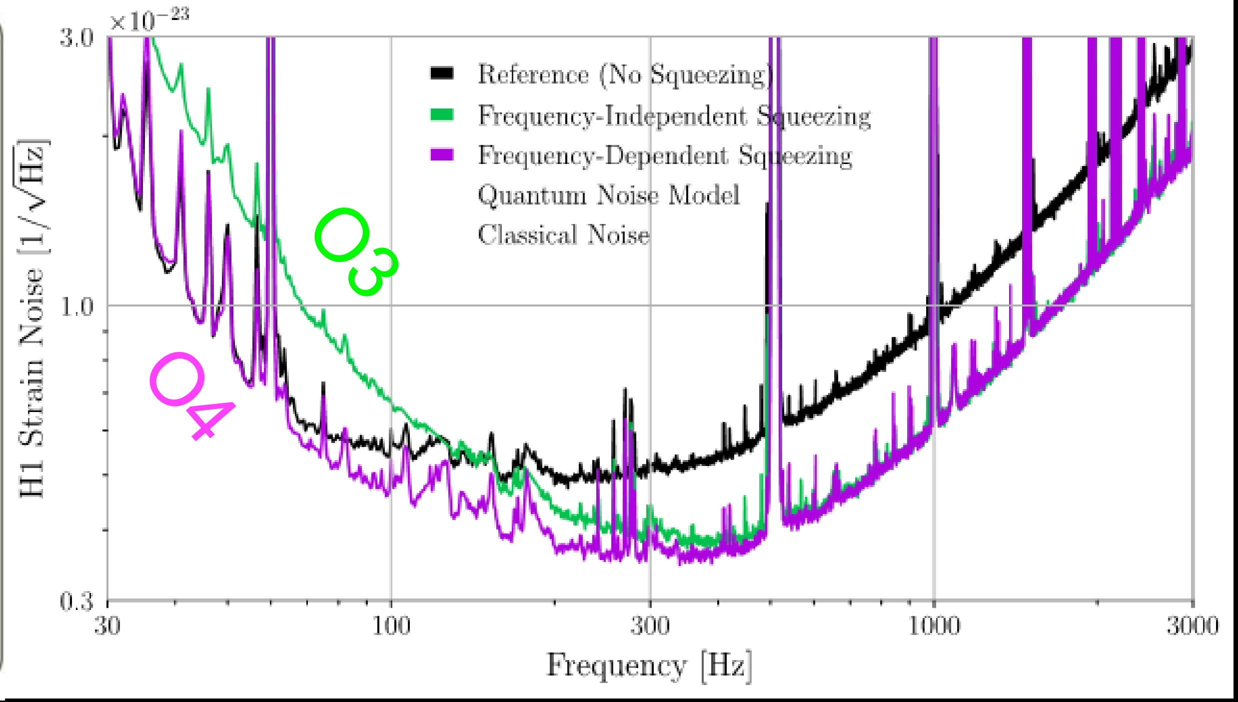


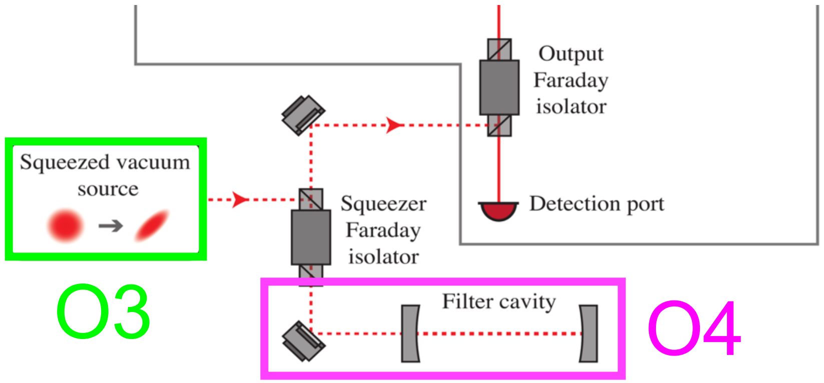
O4: Frequency-*dependent* squeezing

Amplitude SQZ at **low** frequency

Phase SQZ at **high** frequency







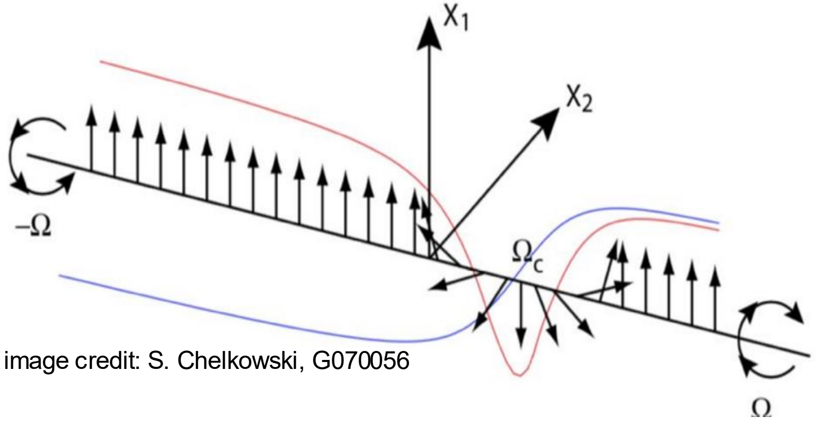
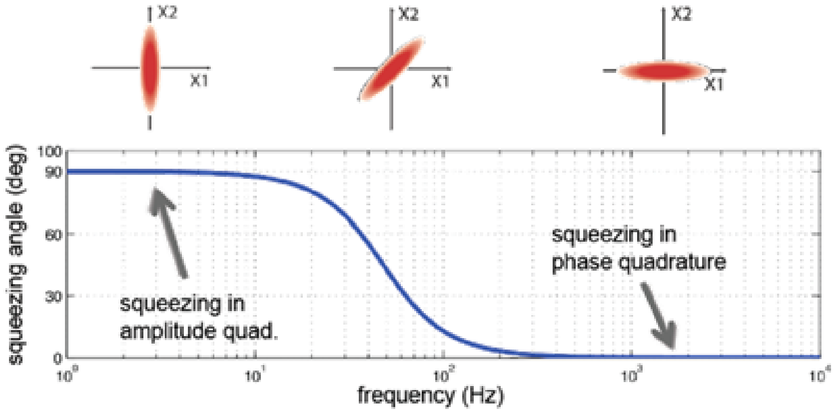


image credit: S. Chelkowski, G070056



All the SQZ + All the astrophysics!

PRX **13**, 041021 (2023)

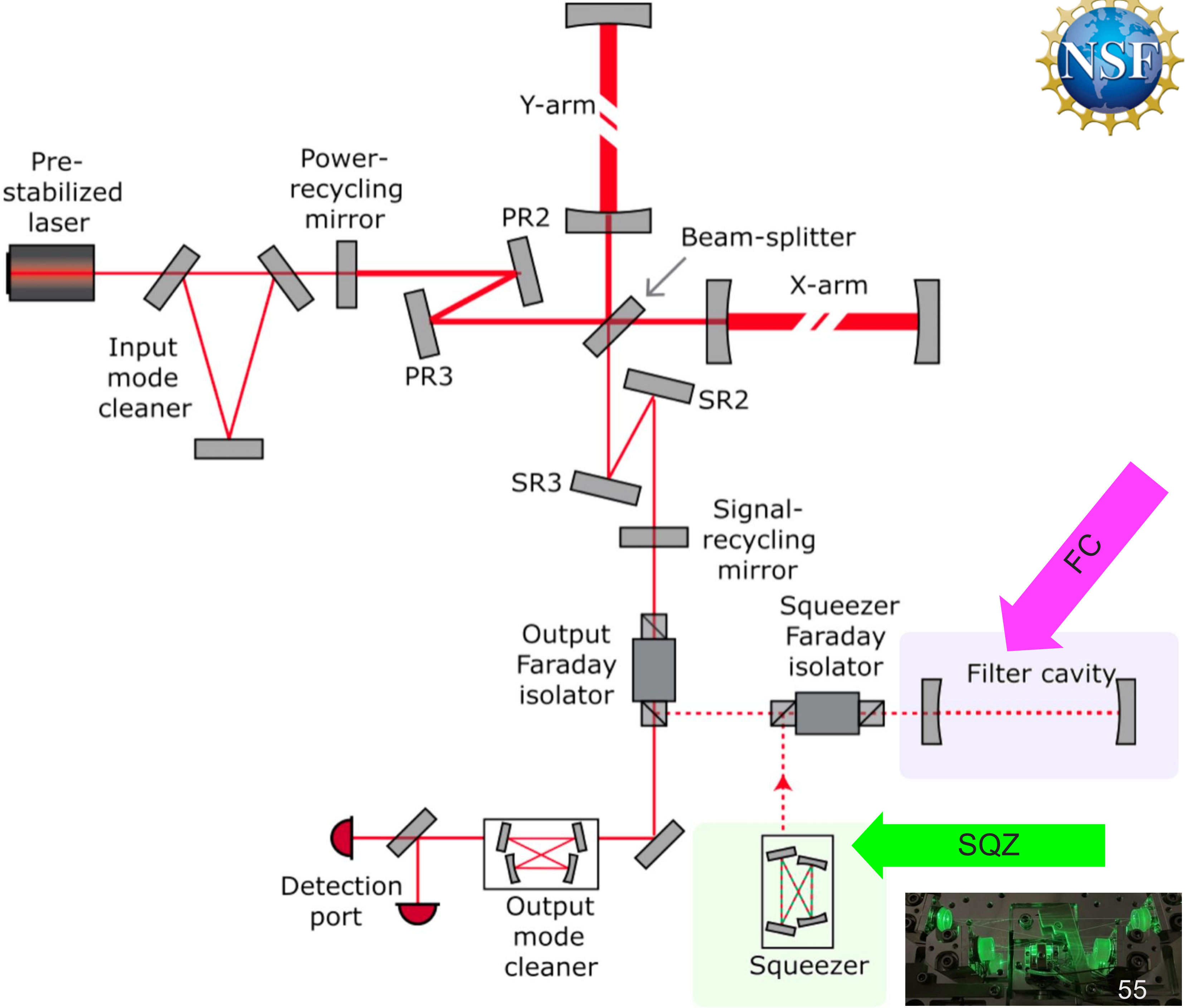
O4 SQZ UPGRADE

SQZ: Phase SQZ
at **high** frequencies

FC: amplitude SQZ
at **low** frequencies

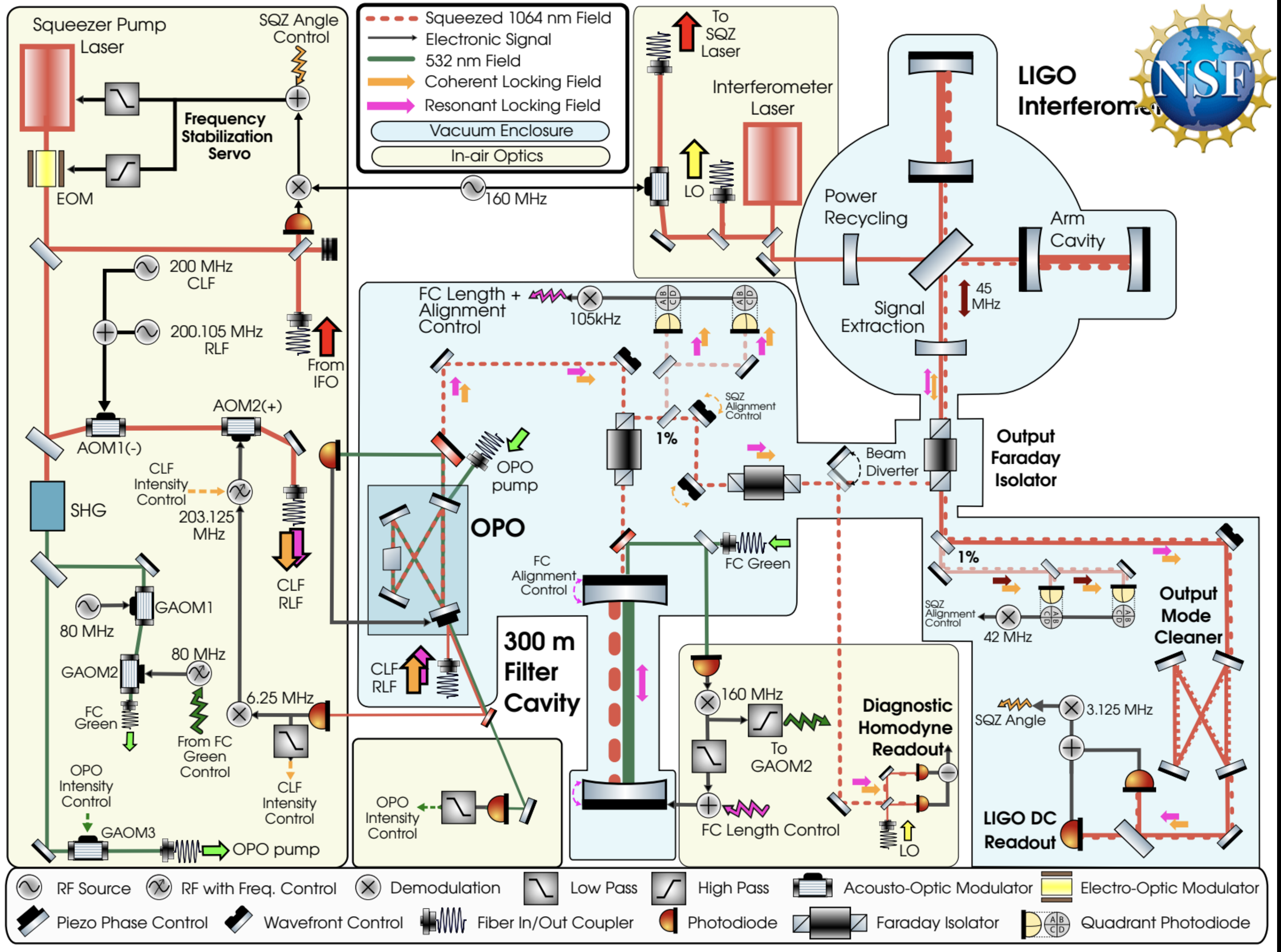
Reduce limiting quantum noise
at all frequencies

→ **Broadband quantum noise reduction!**



Capote, LIGO O4 detector list, PRD (2025)

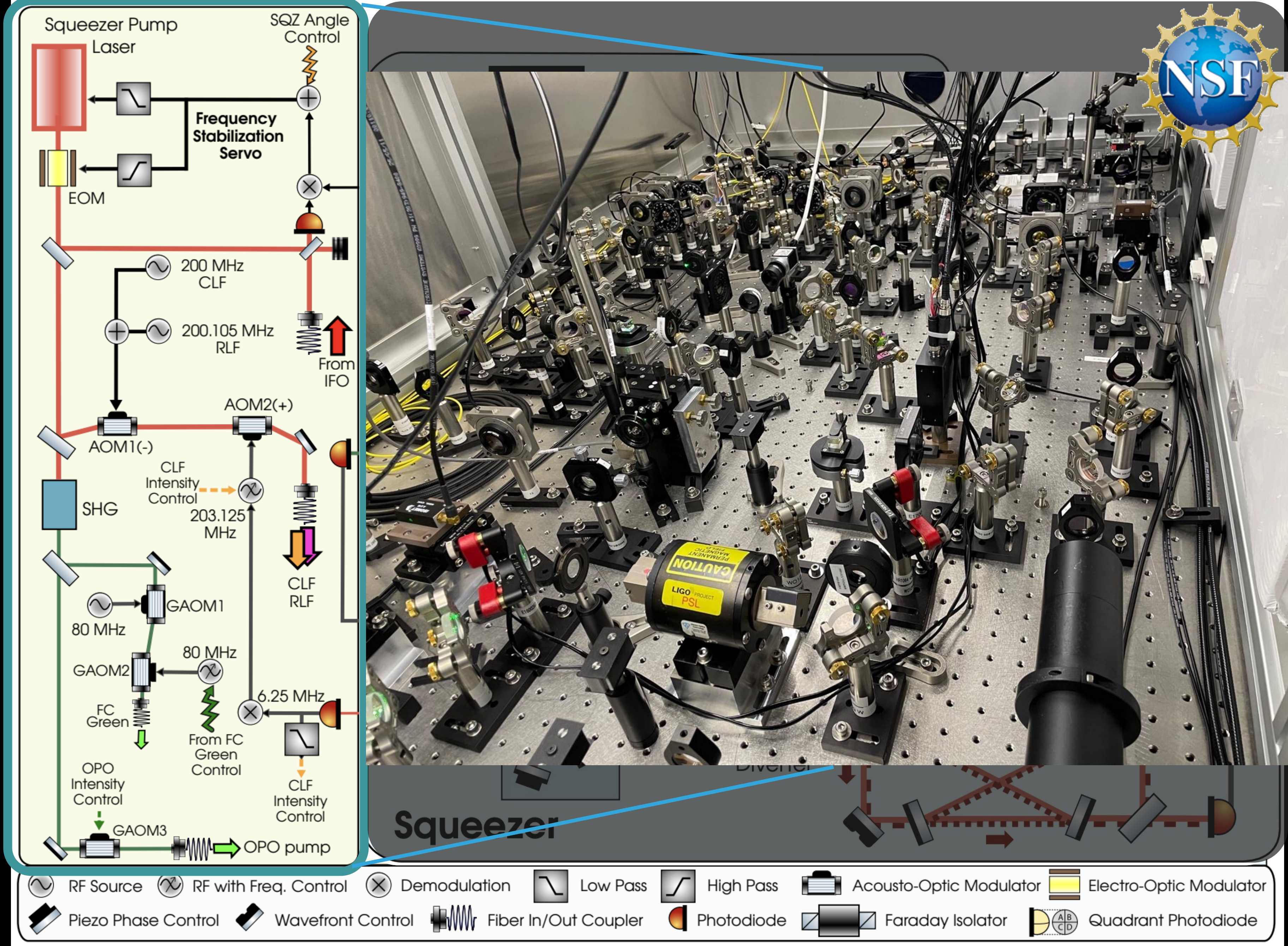
O4 SQZ UPGRADE



Ganapathy*,Jia*,Nakano*,Xu*,LIGO O4 instrument scientists,
Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, PRX 13, 041021 (2023)

O4 SQZ UPGRADE

In-air optical tables to prepare the squeezing pump and control tones



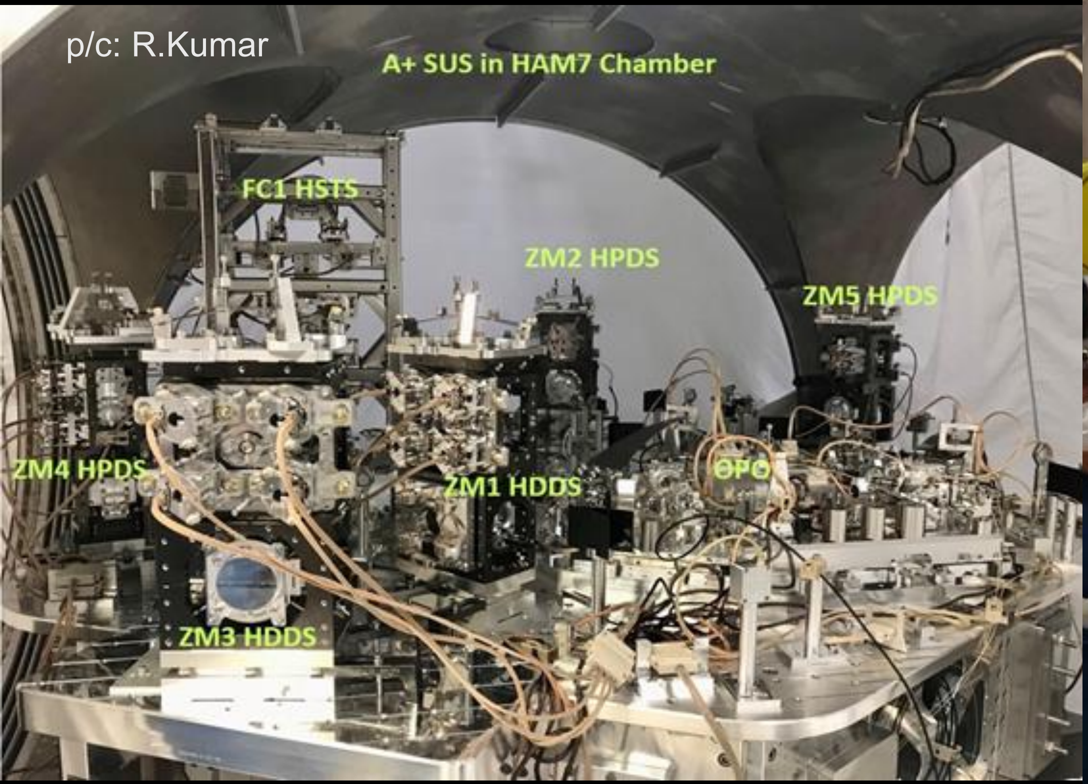
Ganapathy*,Jia*,Nakano*,Xu*,LIGO O4 instrument scientists,
Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, PRX 13, 041021 (2023)

O4 SQZ UPGRADE

LATE-2021 LHO:60854, LLO:57774, 57911, 58012

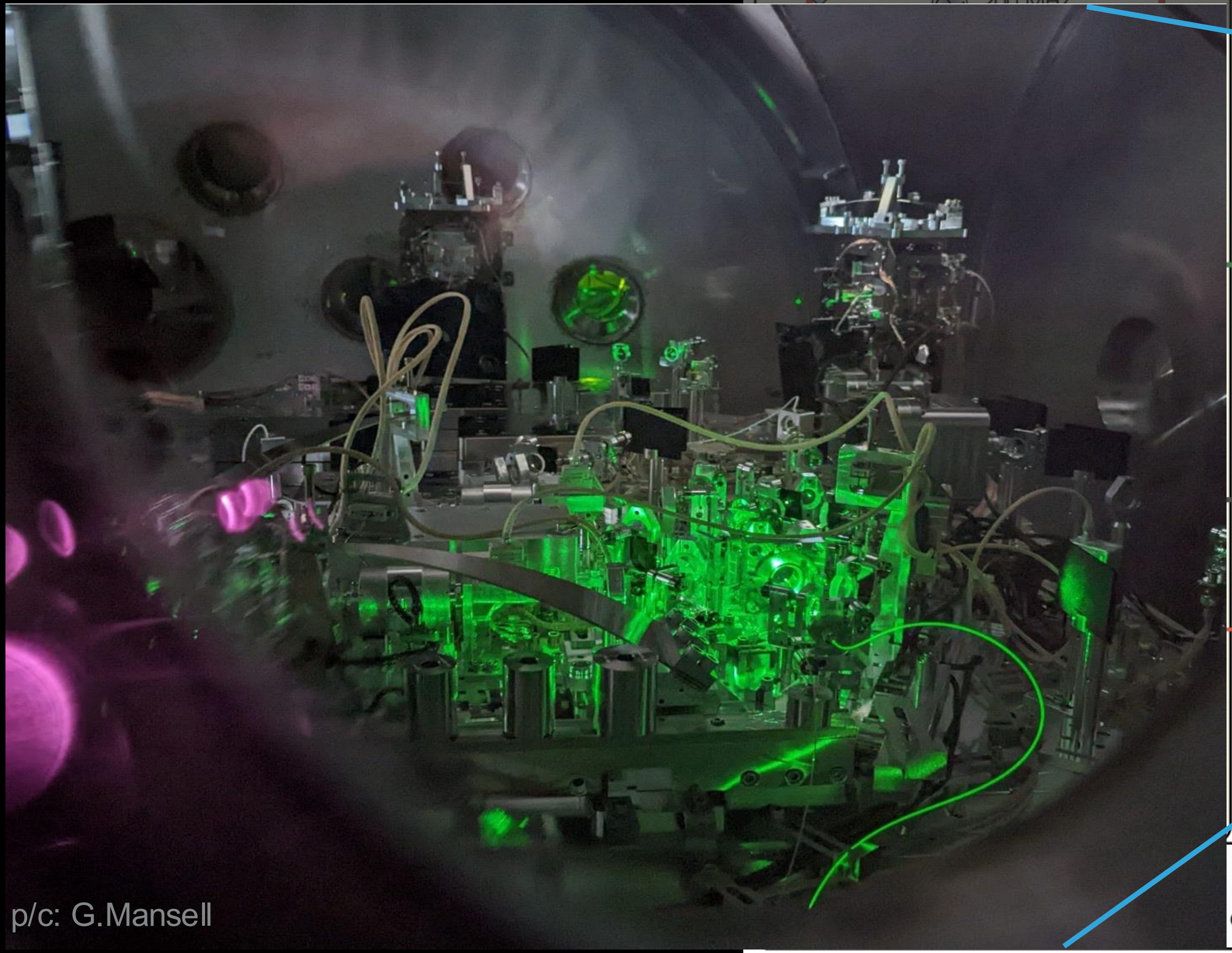
ALL CREDIT TO ON-SITE CREWS

p/c: R.Kumar

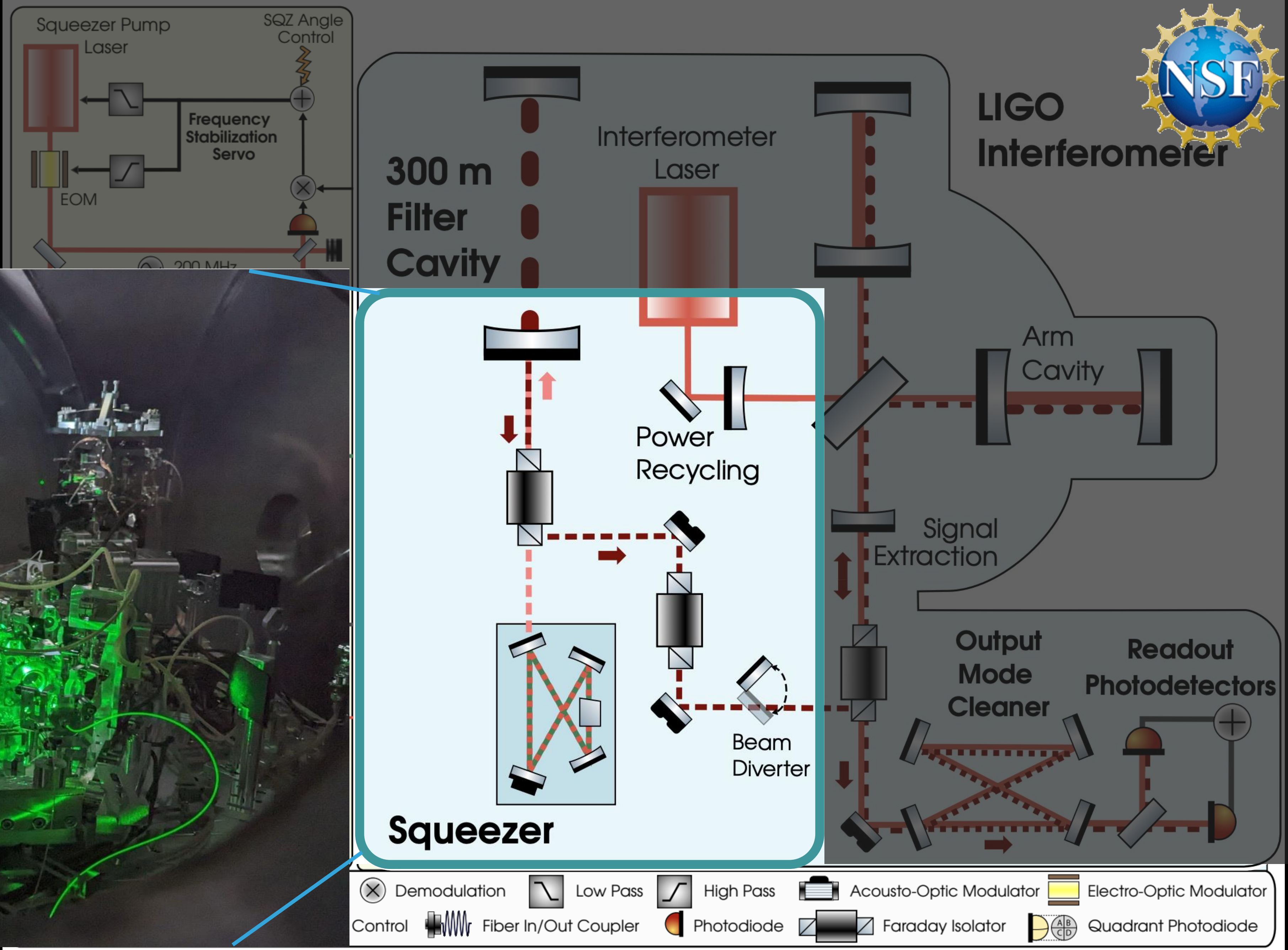


Epic video of HAM7-ISI install @ LLO:57774

O4 SQZ UPGRADE

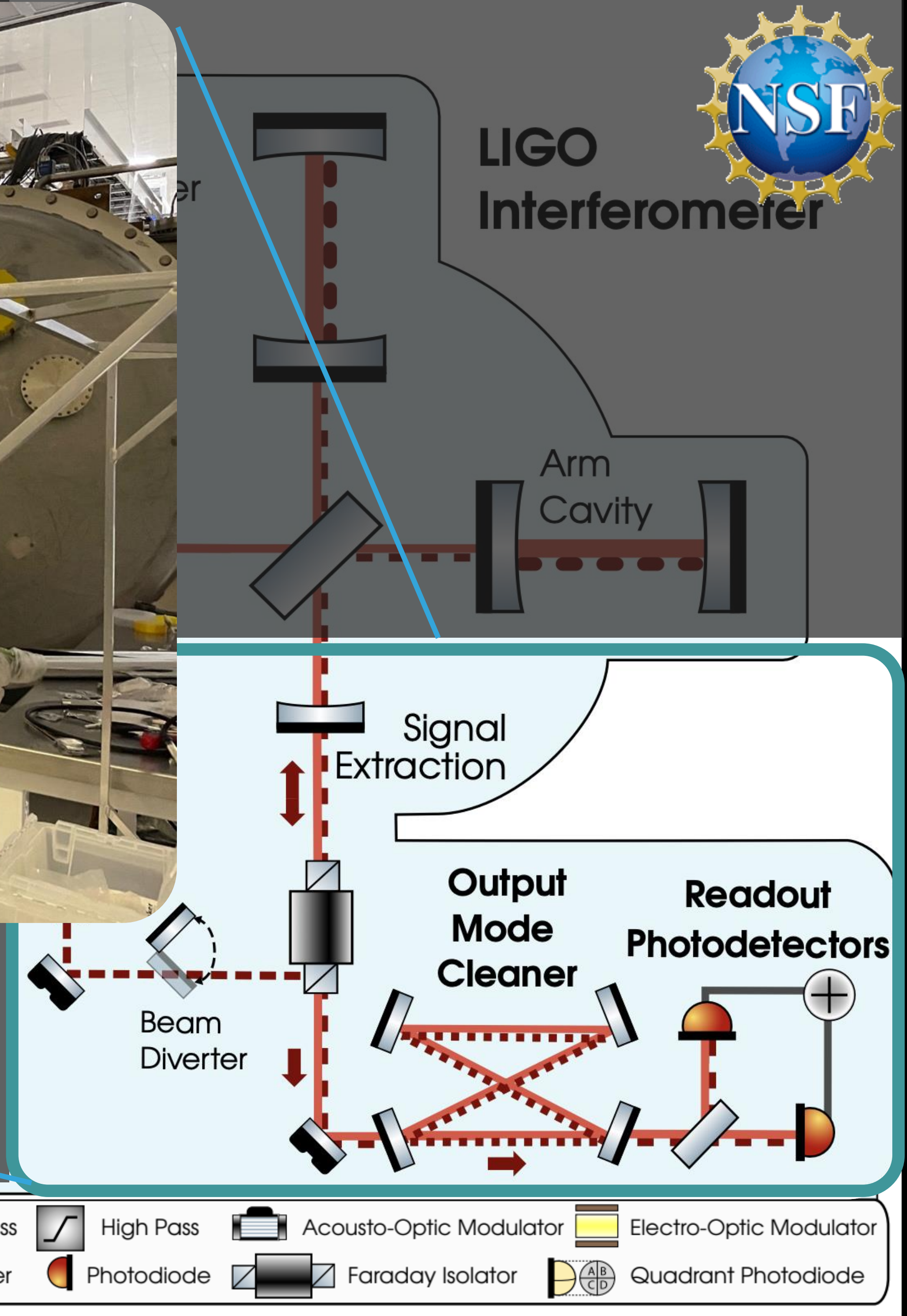


p/c: G.Mansell



Ganapathy*,Jia*,Nakano*,Xu*,LIGO O4 instrument scientists,
Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, PRX 13, 041021 (2023)

O4 SQZ UPGRADE



In-vacuum squeezed light injection into the interferometer

Ganapathy*,Jia*,Nakano*,Xu*,LIGO O4 instrument scientists,
Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, PRX 13, 041021 (2023)

October 2021, LHO
LHO
(alog 60149)

January 2022, LLO

(alog 57505)

HAM shack!

p/c Timothy Nelson, LLO

February 2022,

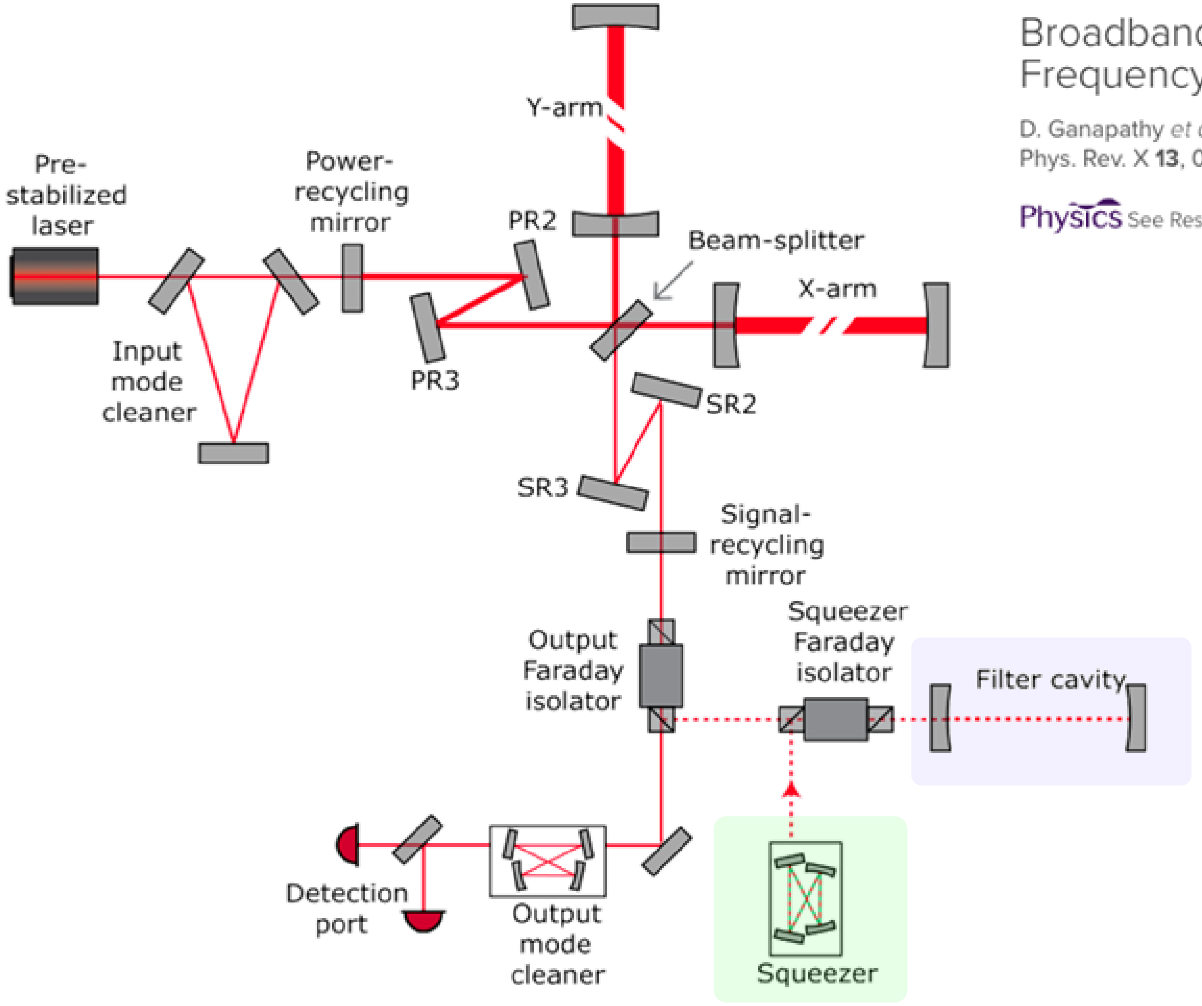
(alog

p/c Bubba Gately, LHO

300-m Filter cavity install @ LHO, LLO

TJ O'Hanlon [alog61193]

O4: Broadband quantum noise reduction



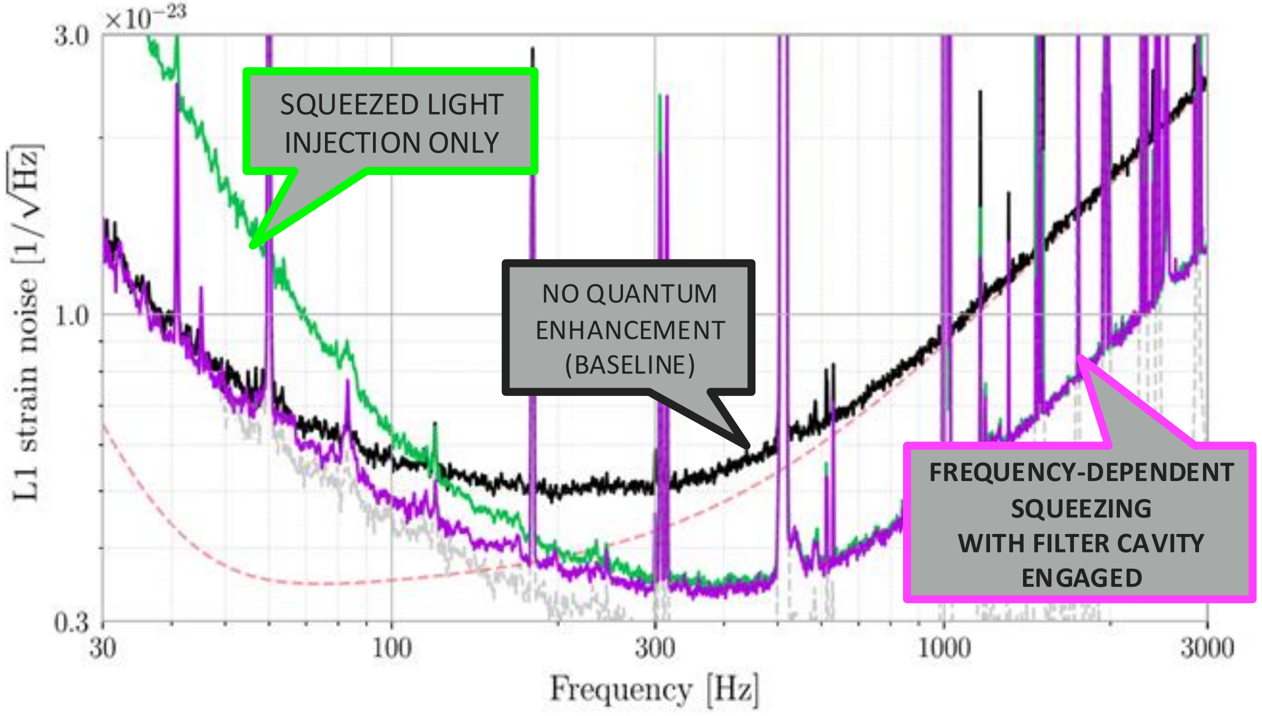
Featured in Physics Open Access

Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing

D. Ganapathy *et al.* (LIGO O4 Detector Collaboration)
Phys. Rev. X **13**, 041021 – Published 30 October 2023

Physics See Research News: Quieting Noise in Gravitational-Wave Detectors

Grad: Dhruva Ganapathy



*Capote, LIGO O4 instrument scientists, PRD **111**, 062002 (2025)*
*Ganapathy, LIGO O4 instrument scientists, PRX **13**, 041021 (2023)*

O4: Broadband quantum noise reduction

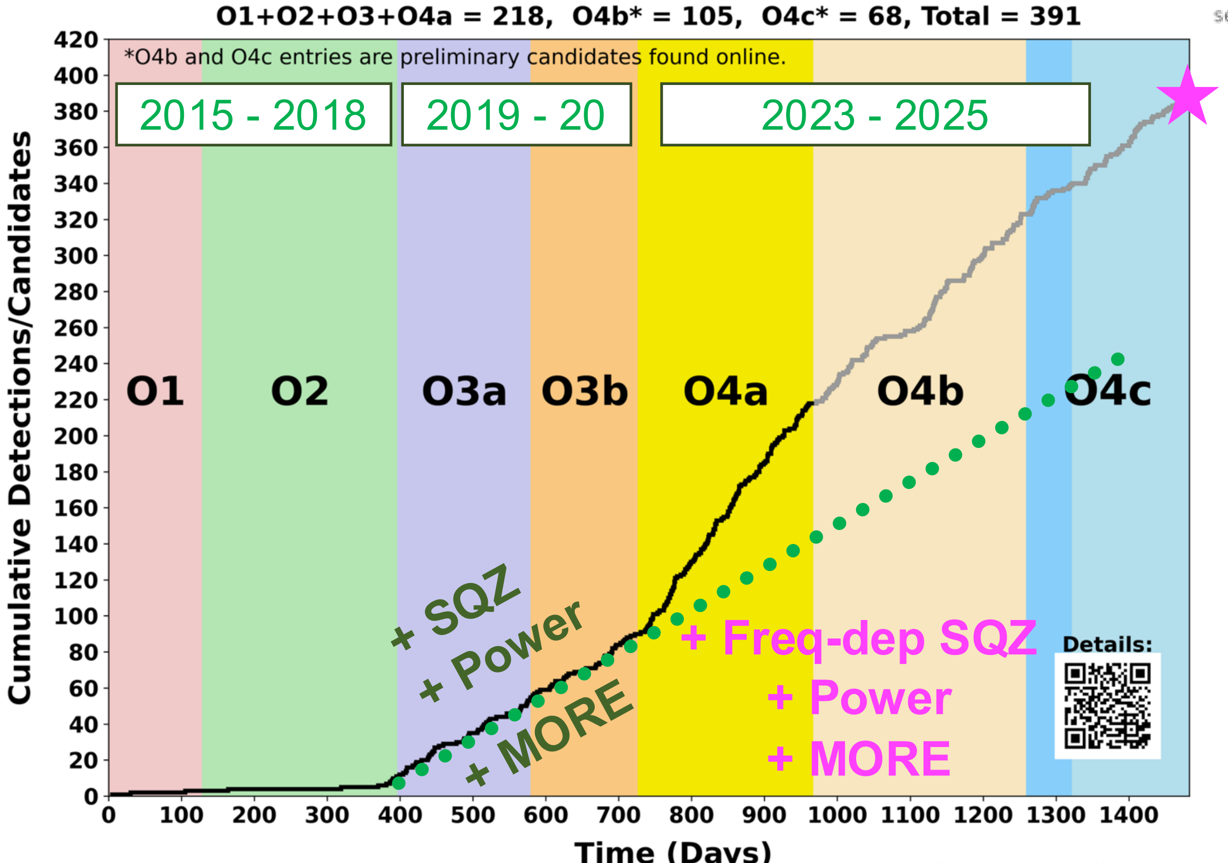
Featured in Physics | Open Access

Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing

D. Ganapathy *et al.* (LIGO O4 Detector Collaboration)
Phys. Rev. X **13**, 041021 – Published 30 October 2023

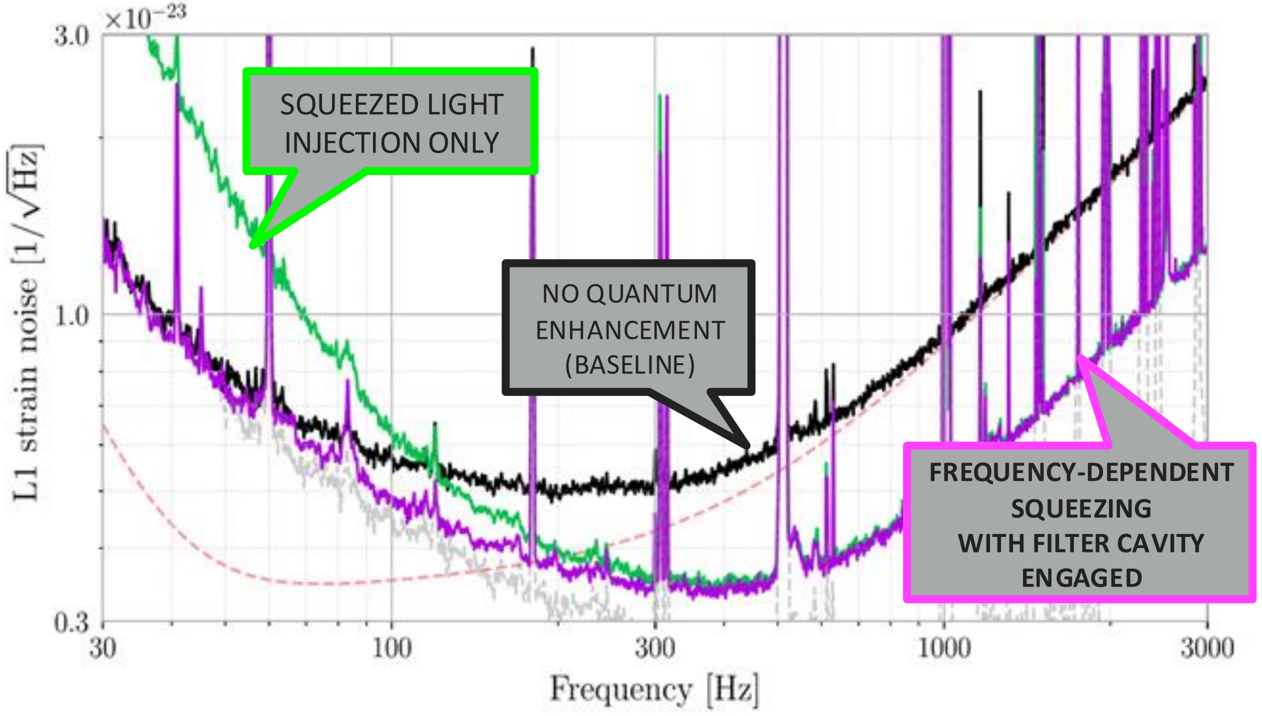
search News: Quieting Noise in Gravitational-Wave Detectors

Grad: Dhruva Ganapathy



LIGO-G2302098(b84be9c4), updated on 18 November, 2025

Credit: LIGO-Virgo-KAGRA Collaboration



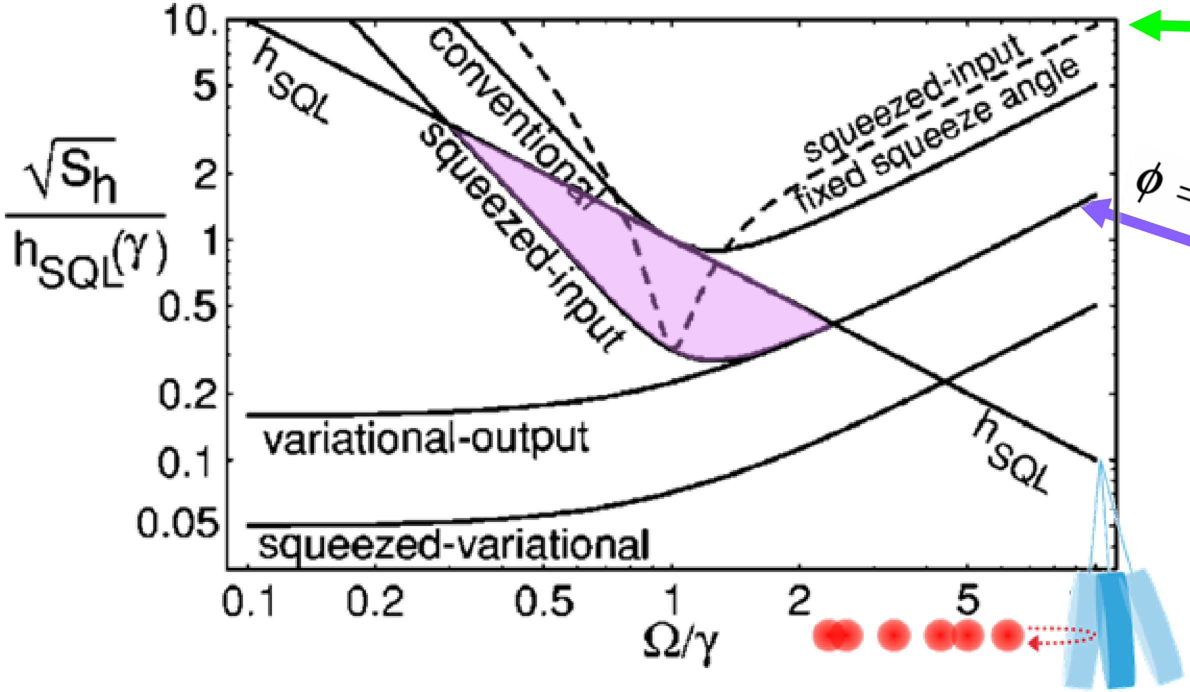
*Capote, LIGO O4 instrument scientists, PRD **111**, 062002 (2025)*
*Ganapathy, LIGO O4 instrument scientists, PRX **13**, 041021 (2023)*

LIGO A+ upgrade to quantum

PHYSICAL REVIEW D, VOLUME 65, 022002

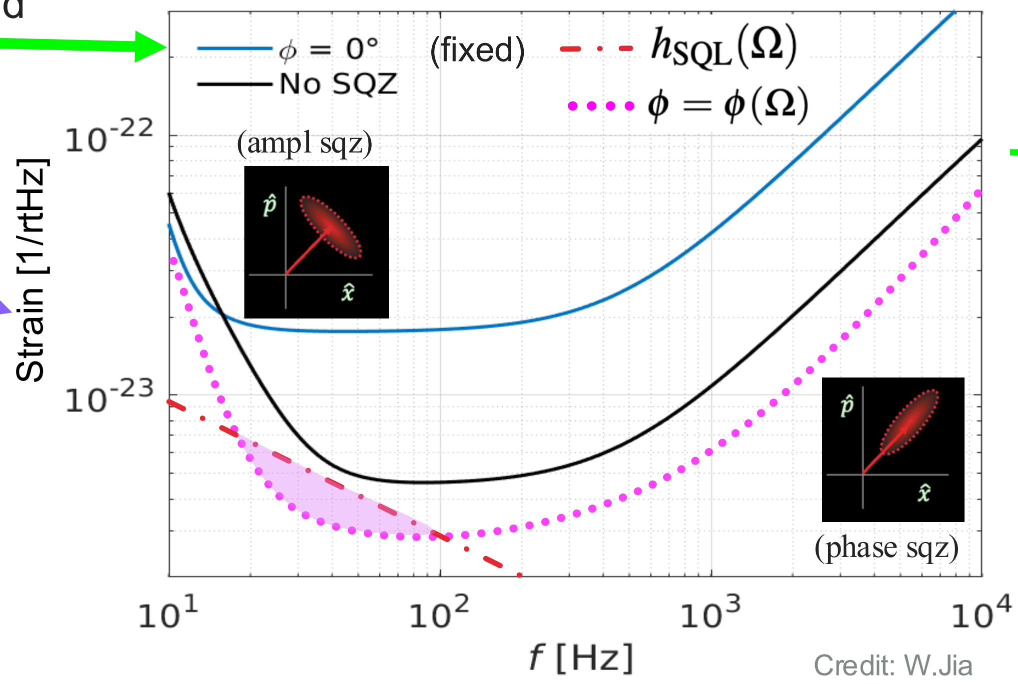
Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics

H. J. Kimble,[1] Yuri Levin,[2,*] Andrey B. Matsko,[3] Kip S. Thorne,[2] and Sergey P. Vyatchanin[4]
[1]Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125
[2]Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
[3]Department of Physics, Texas A&M University, College Station, Texas 77843-4242
[4]Physics Faculty, Moscow State University, Moscow, 119899, Russia
(Received 11 August 2000; published 26 December 2001)



ϕ fixed

$\phi = \phi(\Omega)$



O3 +SQZ

O4 +FC

Kimble, Levin, Matsko, Thorne, Vyatchanin, Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics, PRD 65, 022002 (**2001**)

$$h_{SQL}(\Omega) \approx 1.8 \times 10^{-24} \left(\frac{2\pi \times 100\ \mathrm{Hz}}{\Omega} \right) \frac{1}{\sqrt{\mathrm{Hz}}} \quad \text{(for 4x 40 kg test masses)}$$

PHYSICAL REVIEW D, VOLUME 65, 022002

Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics

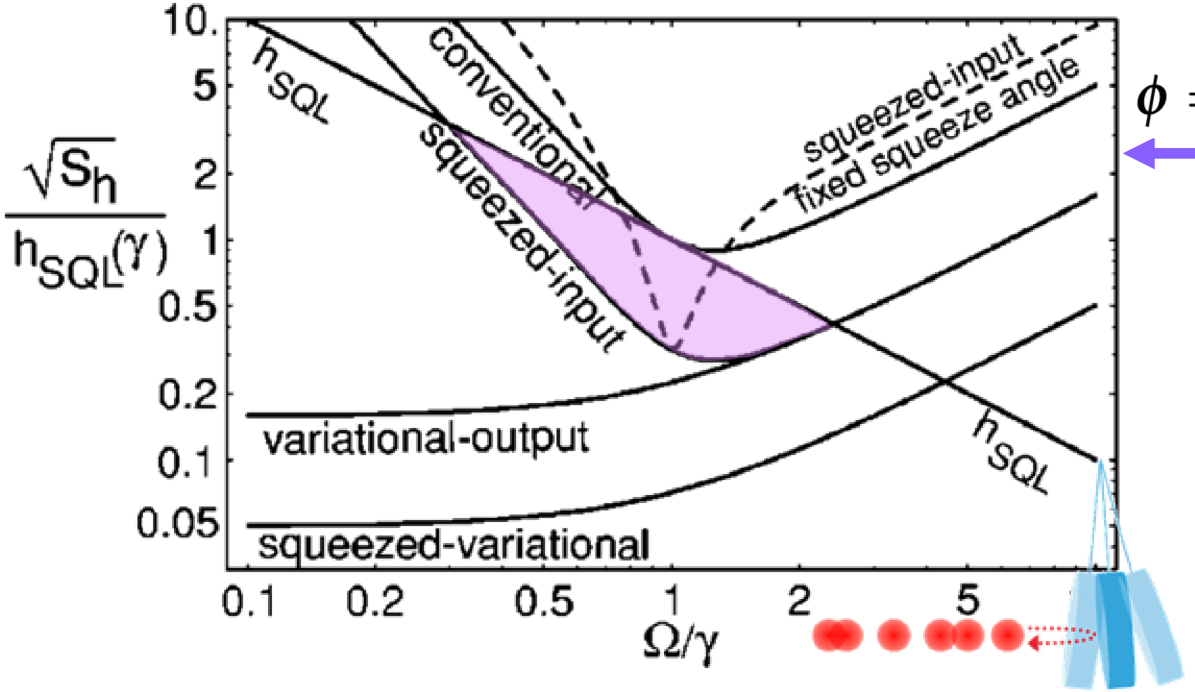
H. J. Kimble,[1] Yuri Levin,[2,*] Andrey B. Matsko,[3] Kip S. Thorne,[2] and Sergey P. Vyatchanin[4]
[1]Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125
[2]Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
[3]Department of Physics, Texas A&M University, College Station, Texas 77843-4242
[4]Physics Faculty, Moscow State University, Moscow, 119899, Russia
(Received 11 August 2000; published 26 December 2001)

Squeezing the quantum noise of a gravitational-wave detector below the standard quantum limit

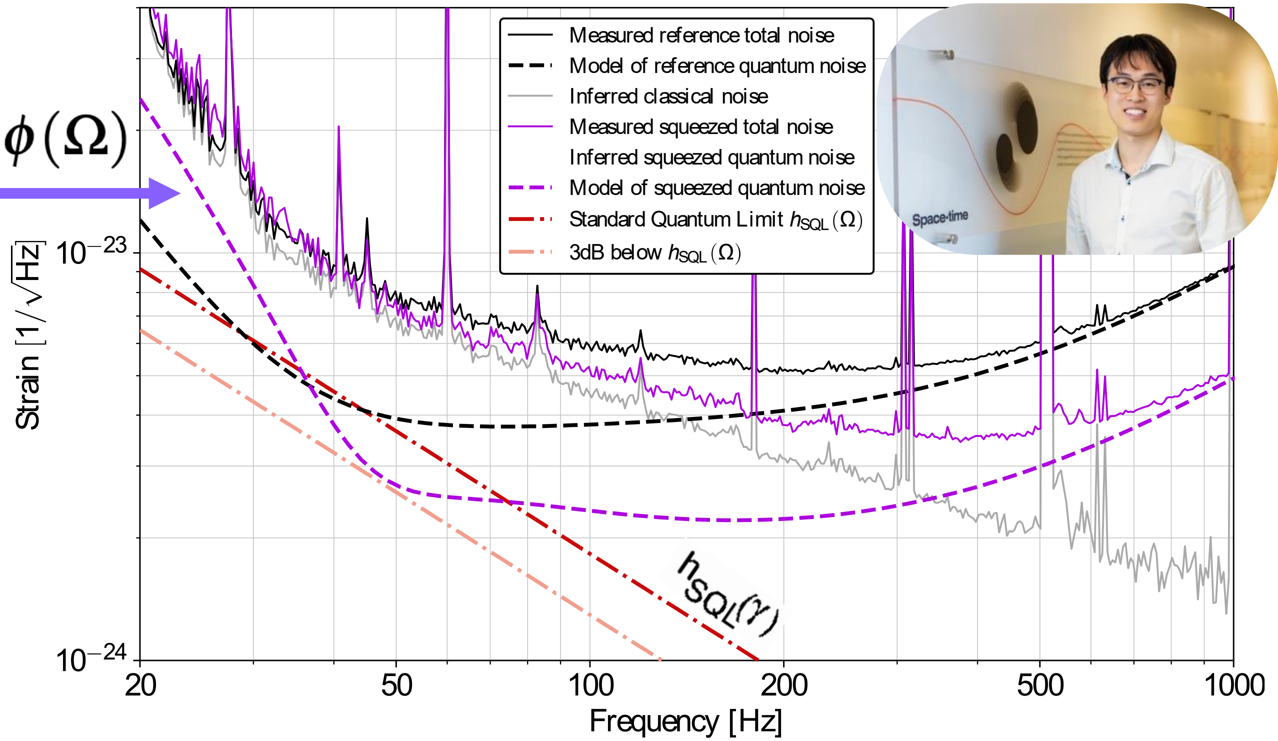
WENXUAN JIA, VICTORIA XU, KEVIN KUNS, MASAYUKI NAKANO, LISA BARSOTTI, MATTHEW EVANS, NERGIS MAVALVALA, AND MEMBERS OF THE LIGO SCIENTIFIC COLLABORATION Authors Info & Affiliations

SCIENCE • 19 Sep 2024 • Vol 385, Issue 6715 • pp. 1318-1321 • DOI: 10.1126/science.ado8069

while observing!



$\phi = \phi(\Omega)$

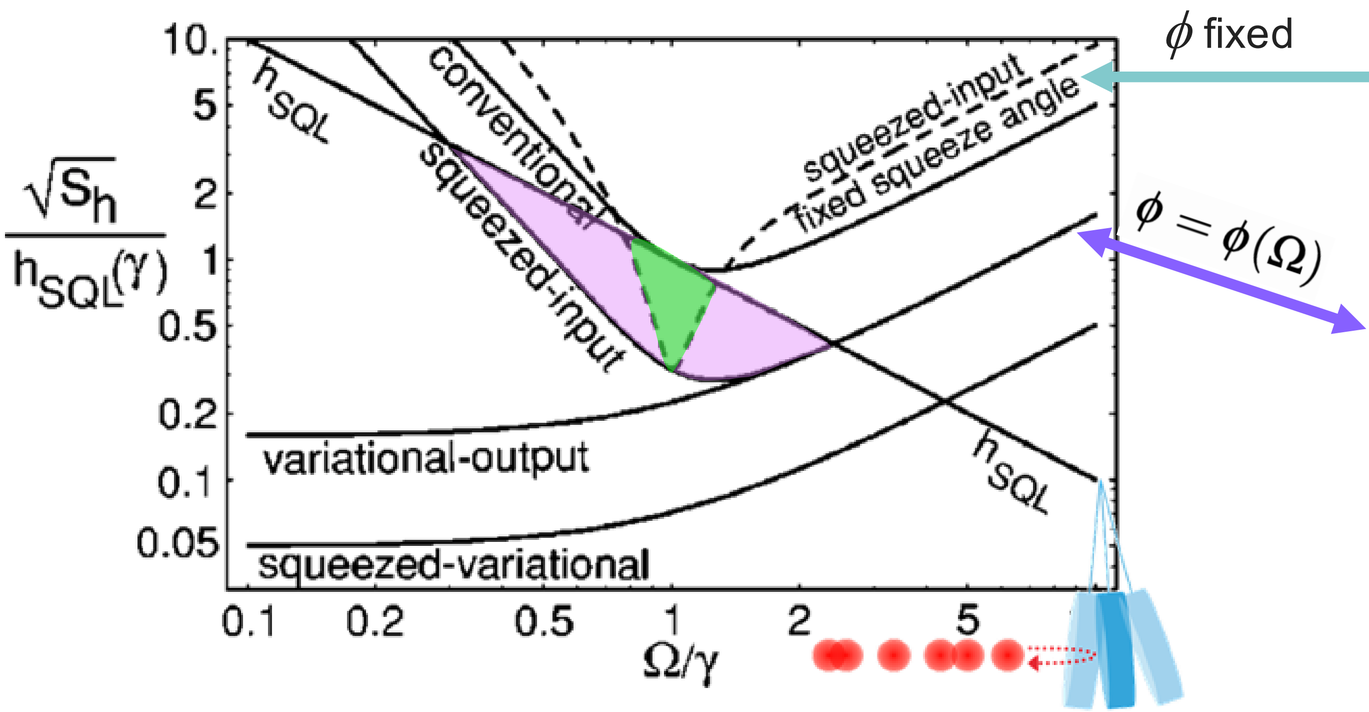


Kimble, Levin, Matsko, Thorne, Vyatchanin, Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics, PRD 65, 022002 (**2001**)

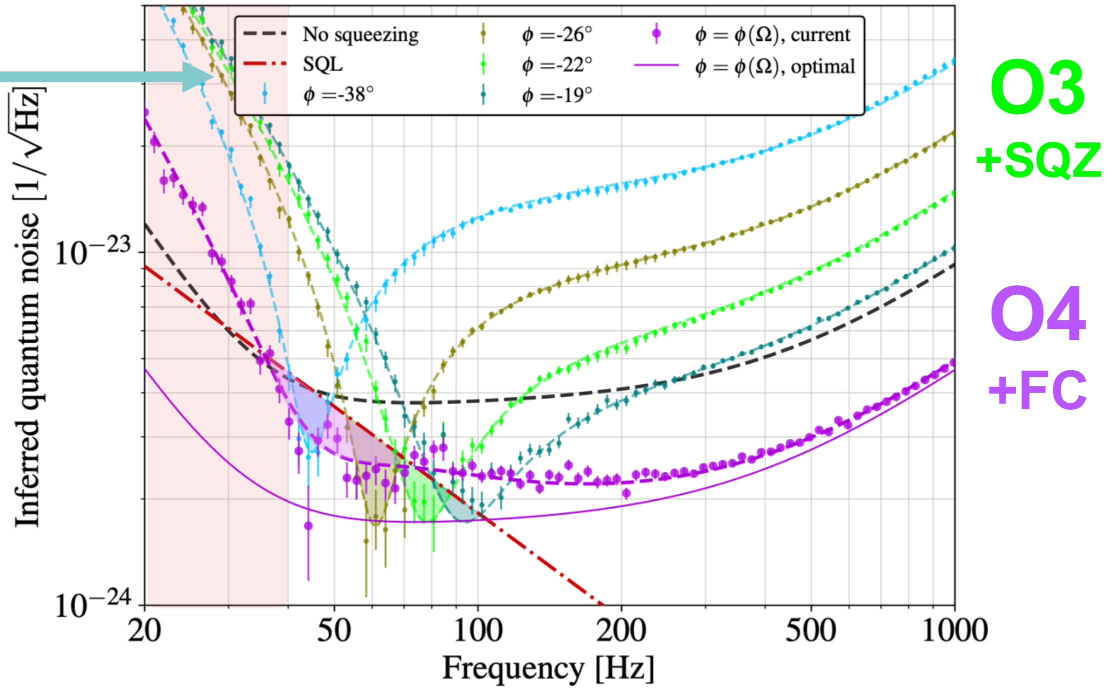
Jia, LIGO O4 instrument scientists, *Science* **385**, 1318-1321 (2024)

$$h_{SQL}(\Omega) \approx 1.8 \times 10^{-24} \left(\frac{2\pi \times 100\ \text{Hz}}{\Omega}\right) \frac{1}{\sqrt{\text{Hz}}} \quad \text{(for 4x 40 kg test masses)}$$

LIGO A+ as of O4:
beyond the standard quantum limit



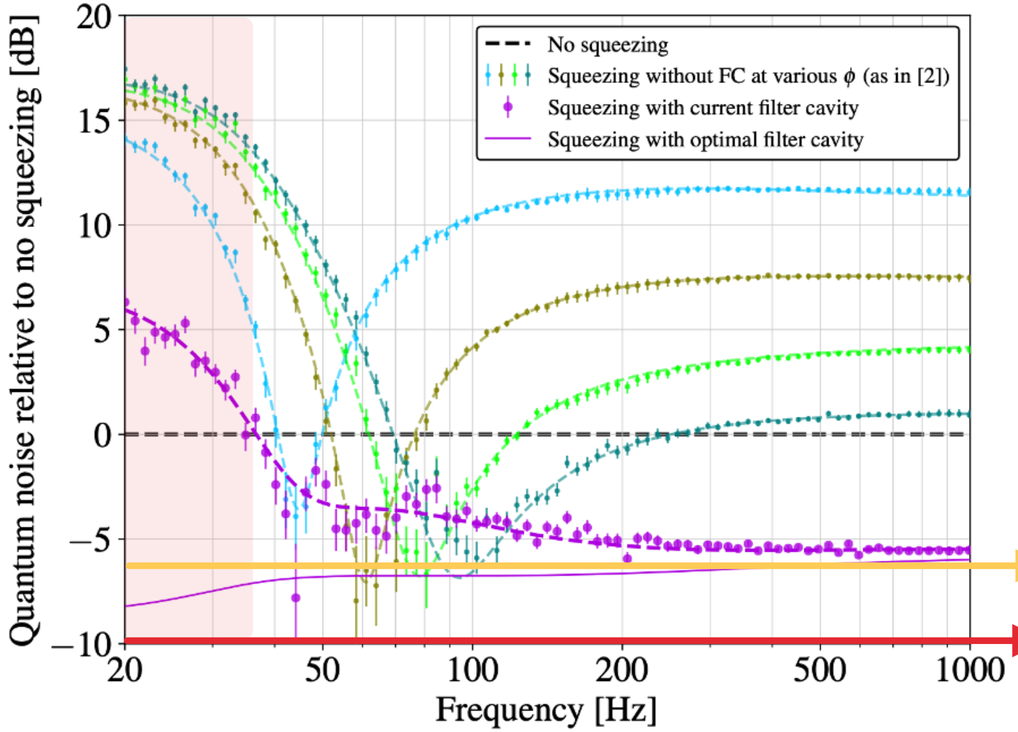
Kimble, Levin, Matsko, Thorne, Vyatchanin, Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics, PRD 65, 022002 (**2001**)



Jia, LIGO O4 instrument scientists, *Science* **385**, 1318-1321 (2024)

Squeezed light as a quantum noise injection for detector diagnostics & optimization

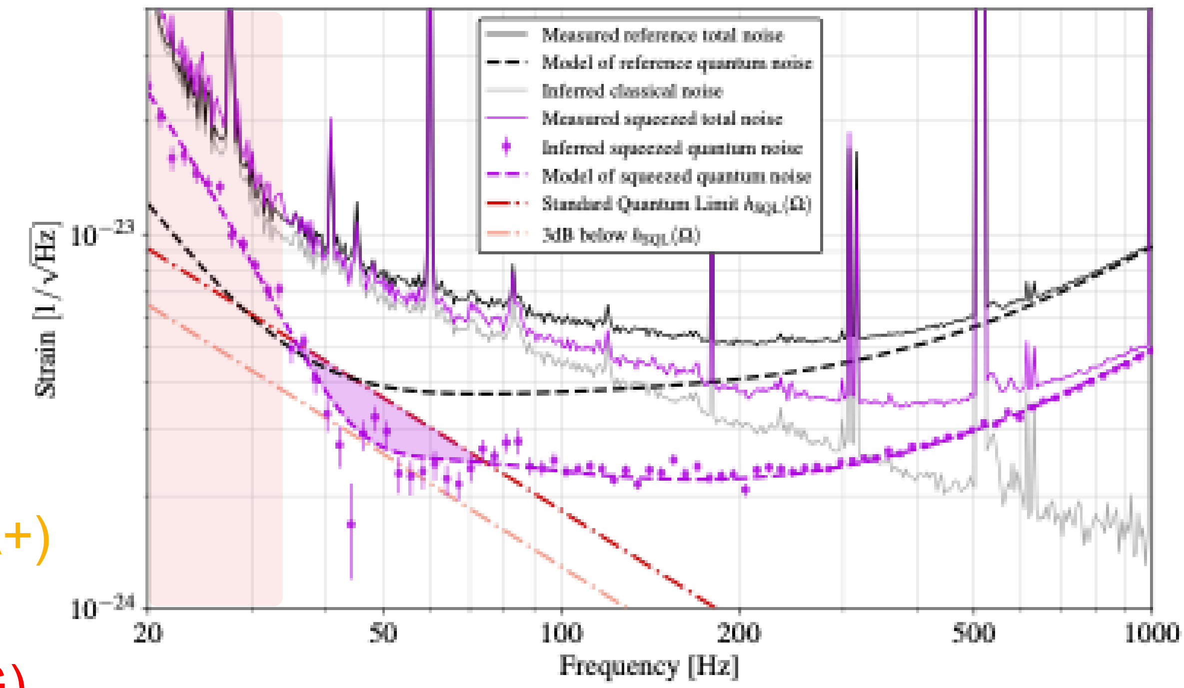
What's next,
beyond the standard quantum limit?



6 dB (A+)

10 dB (A#, XG)

Compared to total detector noise, ***it matters***



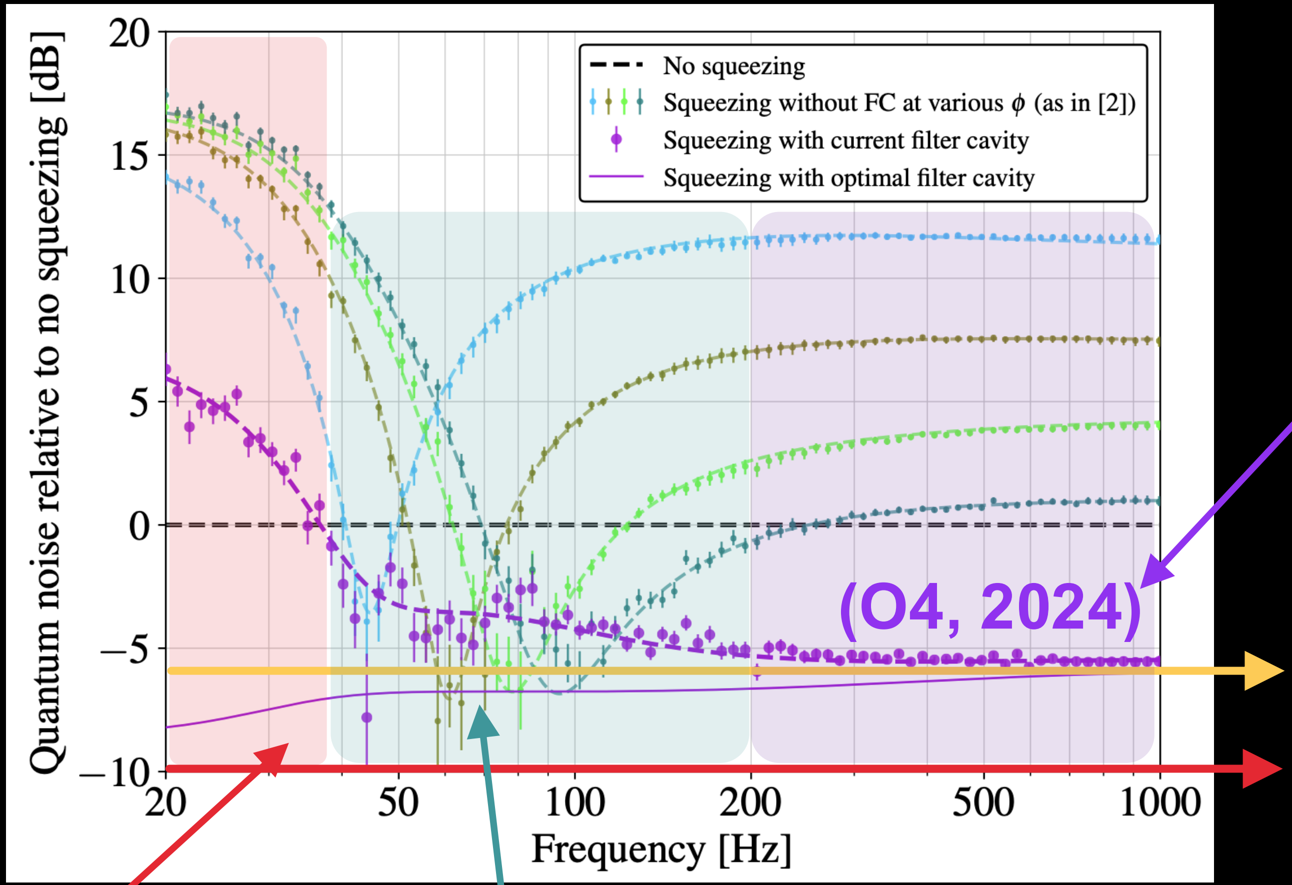
Jia, LIGO O4 instrument scientists, *Science* **385**, 1318-1321 (2024)

Towards 10 dB broadband squeezing 24/7 for A#, XG

for interferometers at 3-5x higher power, with up to 10x longer baselines..

TOWARDS 10 dB

O4 SQZ LIMITATIONS



Loss-limited
(lower loss optics and crystals, mode-mismatch, misalignment, etc..)

Residual back-action (QRPN)
(filter cavity loss, sideband dephasing, fc bandwidth)

??? mid-band – commissioning
(thermalization, detuning, mode-matching, alignment… improve sqz diagnostics)

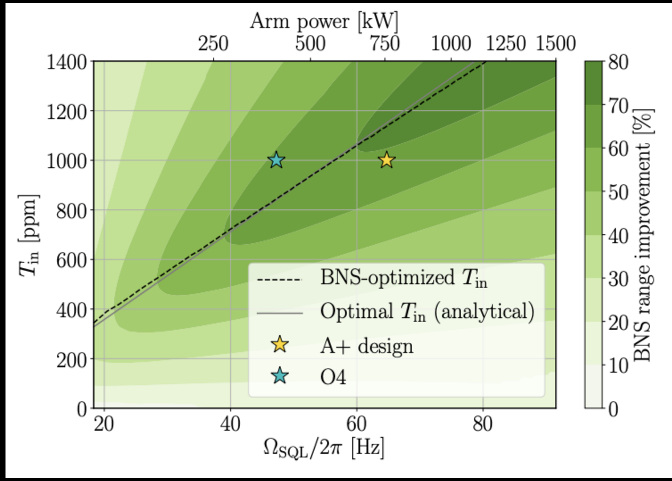
Critical astrophysical frequencies!!

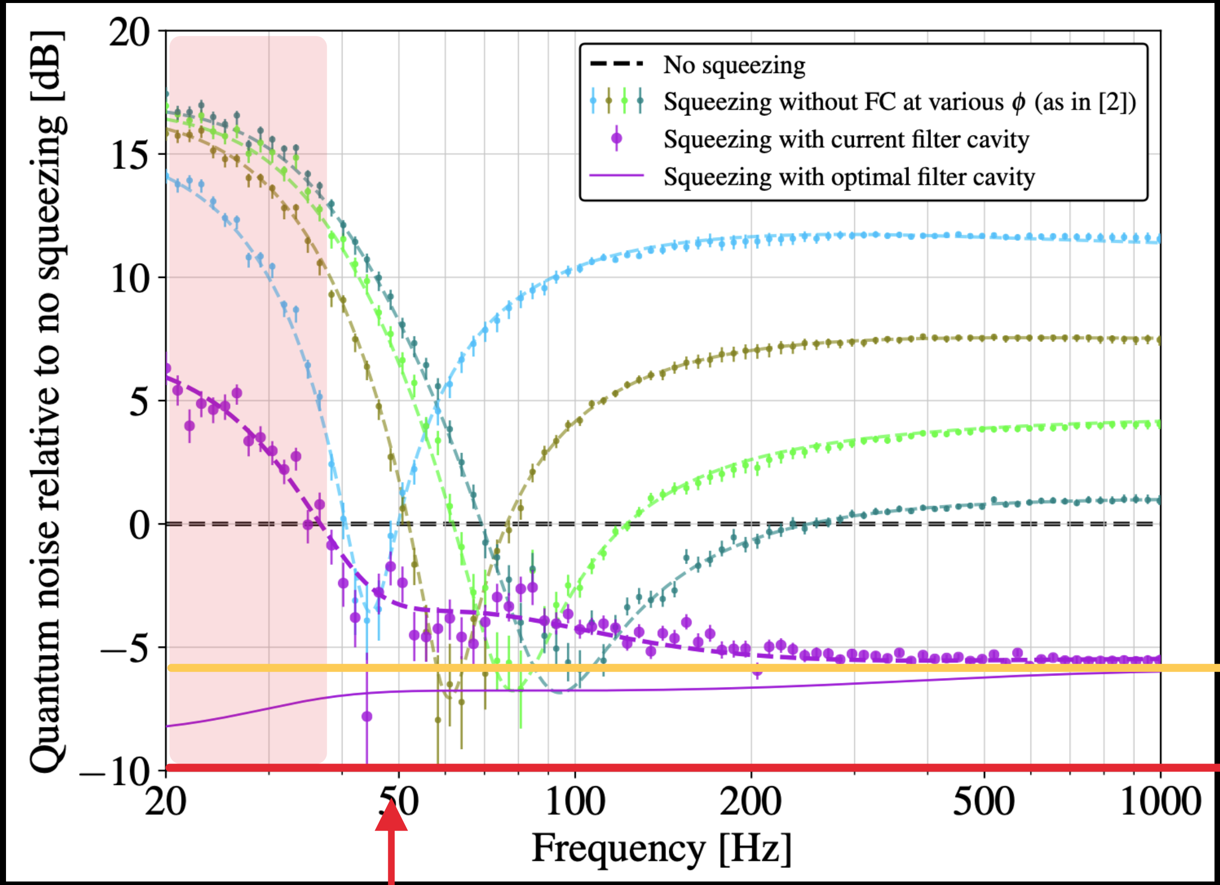
Jia, LIGO O4 instrument scientists, *Science* **385**, 1318-1321 (2024)

RESIDUAL QRPN CONTROL

- optimal FC bandwidth depends on circulating power in the arm cavities

$$\theta(\Omega) = \tan^{-1}\left[\frac{16kP}{mL\gamma}\frac{1}{\Omega^2}\left(1+\frac{\Omega^2}{\gamma^2}\right)^{-1}\right]$$





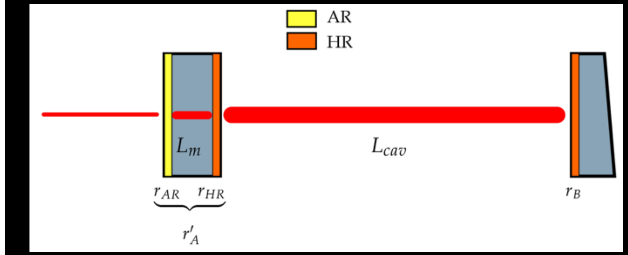
6 dB (A+)

10 dB (A#, XG)

Residual back-action noise (QRPN)

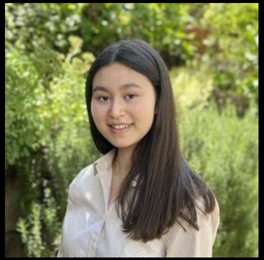
(filter cavity loss, sideband dephasing, fc bandwidth)

@ Berkeley towards 10 dB tunable FDS

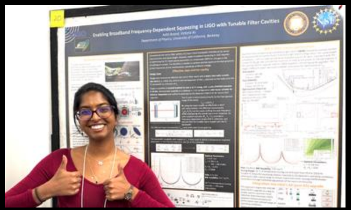


K. Gray

C. Virador



A. Anand



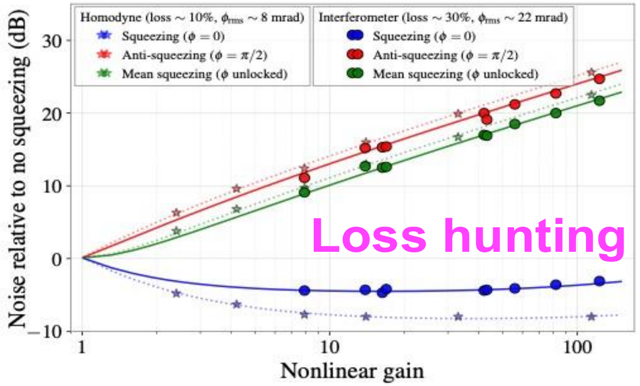
Jia et al, *Science* **385**, 1318-1321 (2024)
Whittle et al, Phys. Rev. D 102, 102002 (2020)
Brooks et al, Galaxies 2020, 8(4), 80 (2020)

SQZ DEGRADATIONS

SQZ dB ~ $10 \log_{10} (\Lambda + 2\theta)$

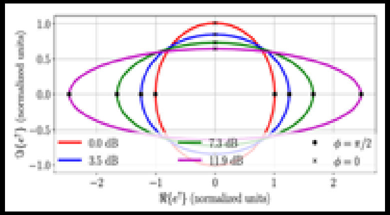
O4 Loss Budget		
Squeezer cavity loss	1.5%	7.5% Squeezing injection
Faraday Isolators (5x 1% loss/pass)	5%	
Optical pickoffs	3.5%	7.5% Detector readout
OMC cavity losses	2-5%	
PD quantum efficiency	2-4%	
Total known loss	**~15%**	**~7 dB possible**

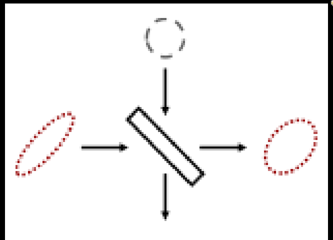
Only 5-6 dB observed, equivalent to 5-15% extra loss



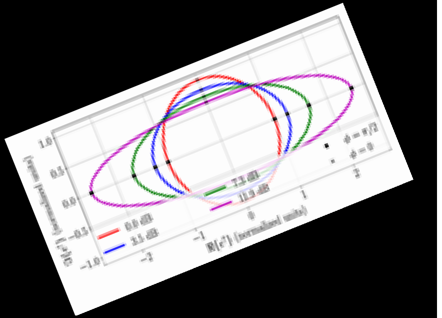
Capote, LIGO O4 instrument scientists, *PRD* **111**, 062002 (2025)

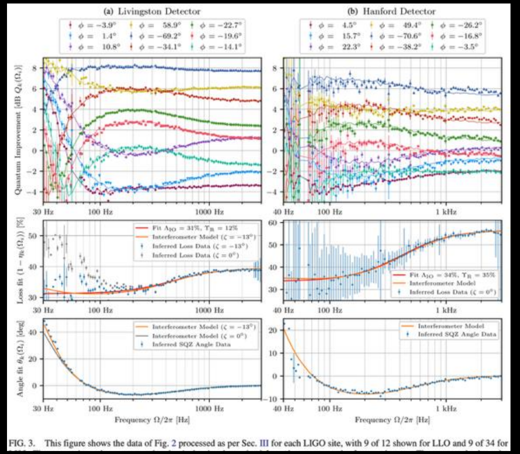
Loss (Λ)





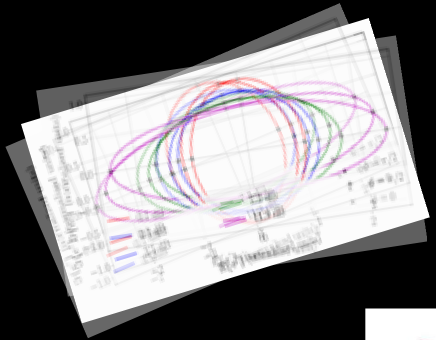
Rotation (θ)

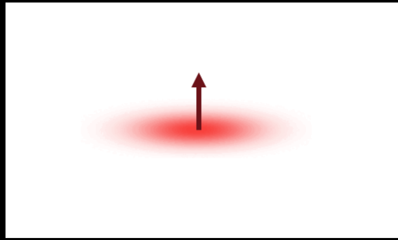




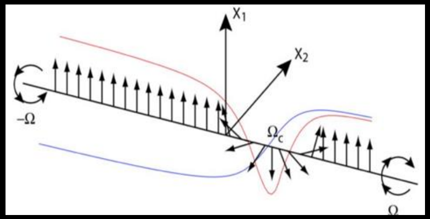
McCuller et al, PRD 104, 062006 (2021)

Phase noise ($\tilde{\theta}$)





Sideband loss, dephasing

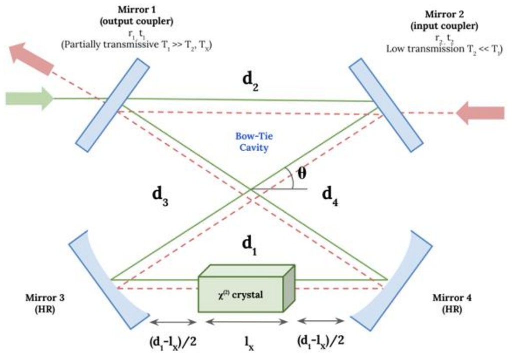


SQZ DEGRADATIONS

SQZ dB ~ 10 $\log_{10}(\Lambda+2\theta)$

O4 Loss Budget		
Squeezer cavity loss	1.5%	7.5% Squeezing injection
Faraday Isolators (5x 1% loss/pass)	5%	
Optical pickoffs	3.5%	7.5% Detector readout
OMC cavity losses	2-5%	
PD quantum efficiency	2-4%	
Total known loss	**~15%**	**~7 dB possible**

Only 5-6 dB observed, equivalent to 5-15% extra loss

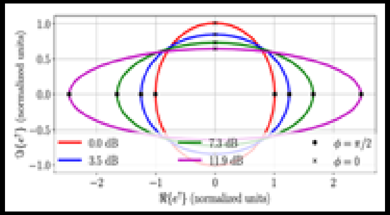


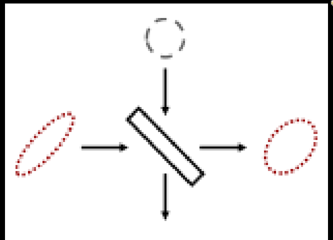
New SQZ light source
- Greater escape efficiency
- Less astigmatism
- Less green pump power
- Fiber SHG for pump: robustness

Capote, LIGO O4 instrument scientists, *PRD* ***111***, 062002 (2025)

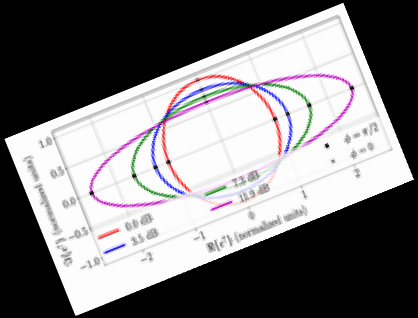
k.gray j.alvarez

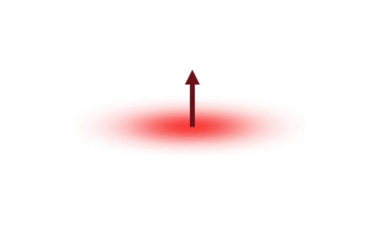
Loss (Λ)



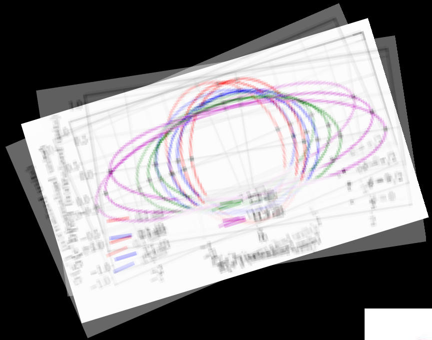


Rotation (θ)

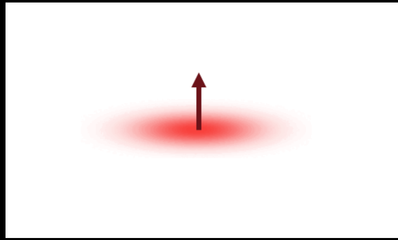


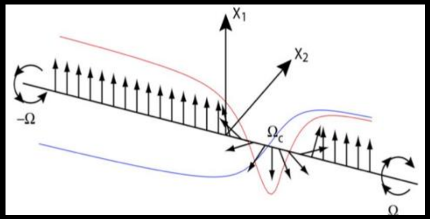


Phase noise ($\tilde{\theta}$)



McCuller et al, PRD 104, 062006 (2021)



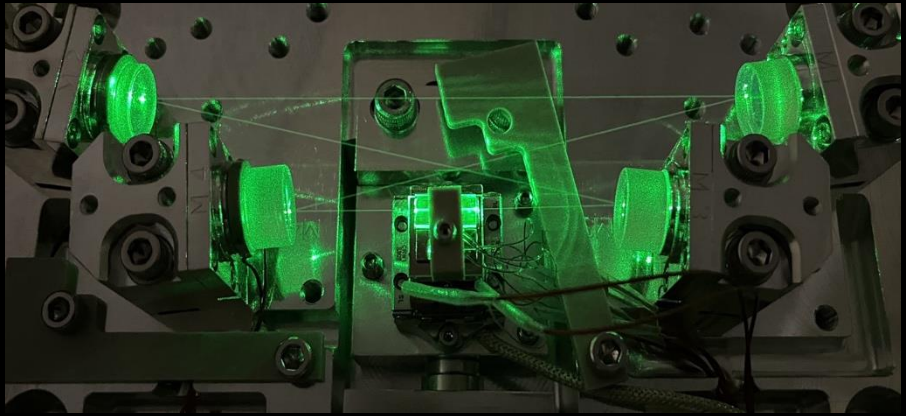


O4a SQZ STABILITY – H1 & L1

Quantum noise can be decisive to astrophysical range

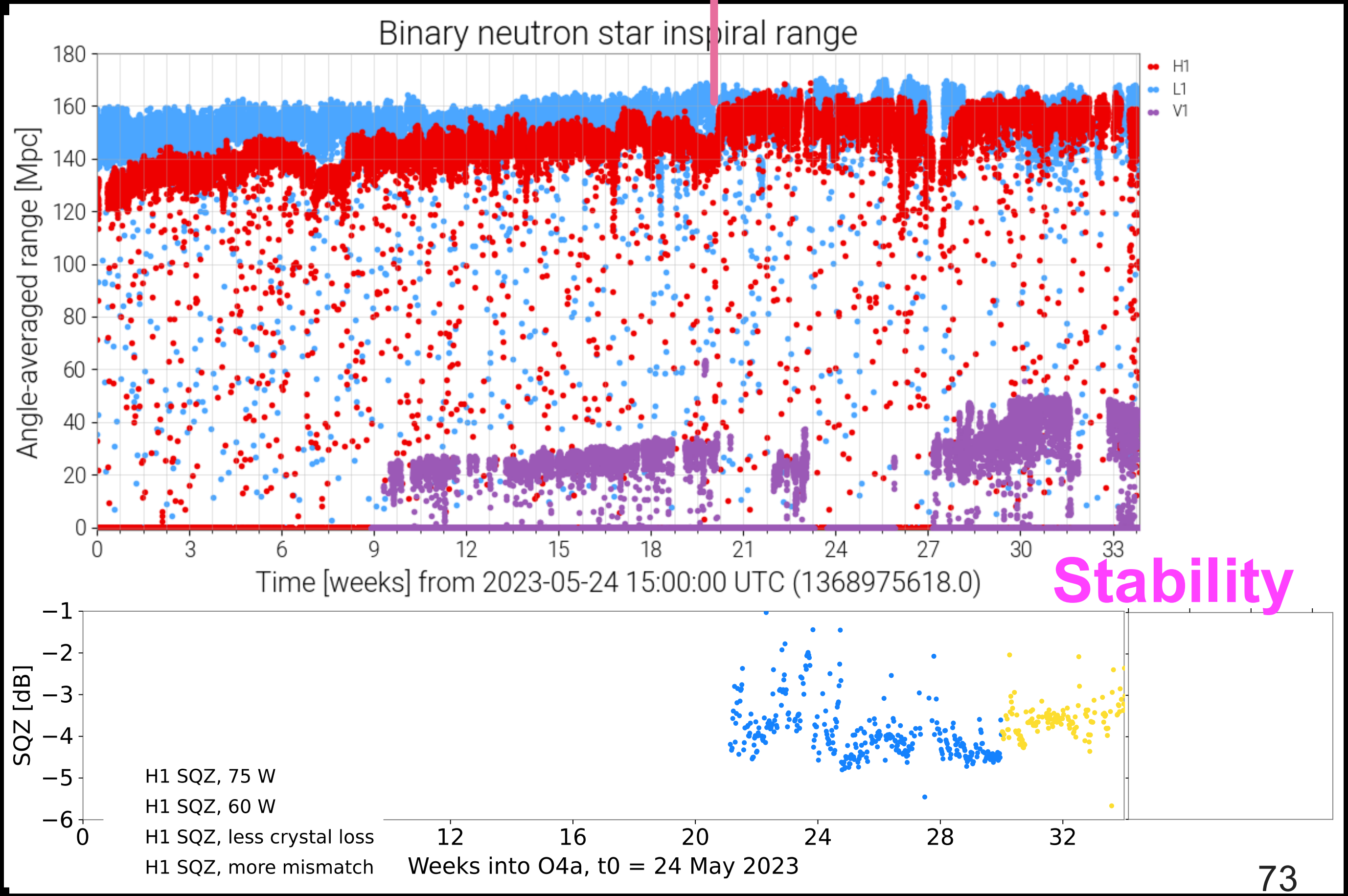
– see H1 O4a experience

Recovered 8% sqz cavity loss
(few mm crystal move ⟶ +10 Mpc)
→ 8 dB homodyne SQZ



J.Alvarez

Berkeley
Physics ugrad



Stability

Astro cheat sheet

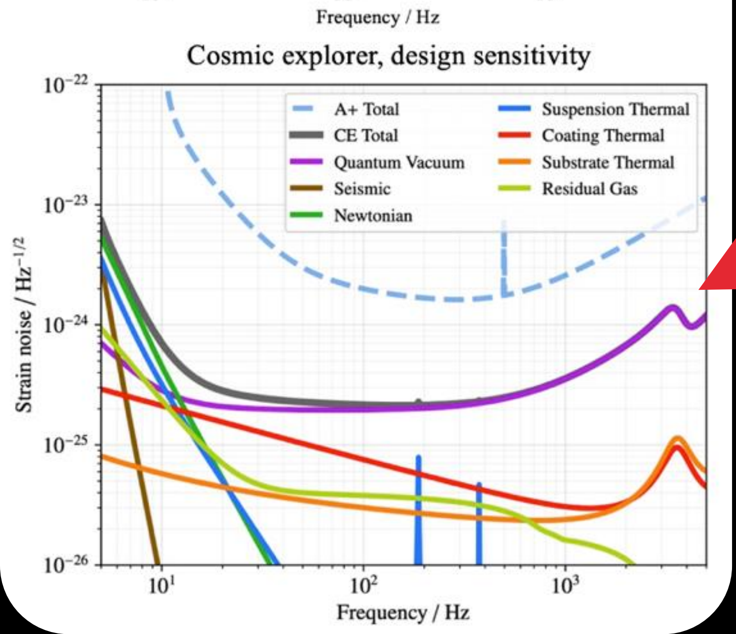
1 Mpc = 3.26 million light years

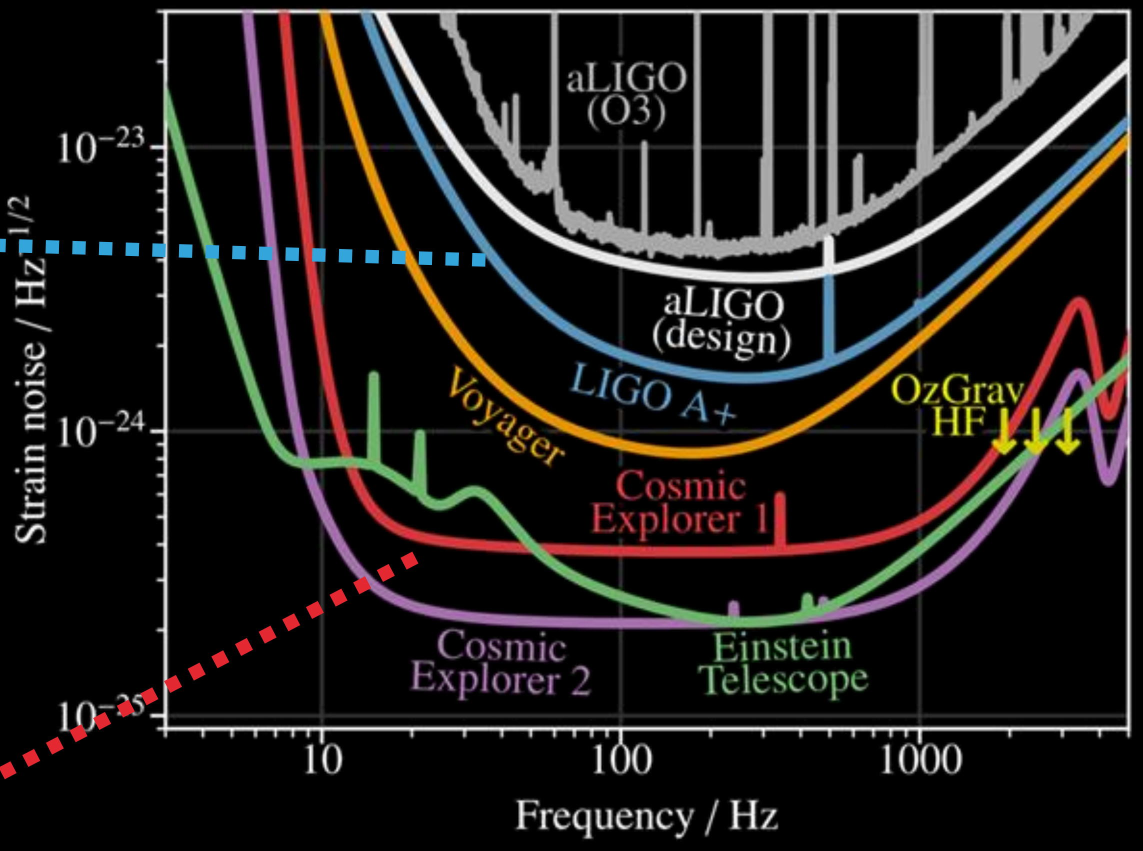
- ~ 0.03 Mpc Milky Way diameter
- ~ 0.8 Mpc to Andromeda
- ~ 3 Mpc Local Group diameter
- ~ 33 Mpc diameter of Local Supercluster (>100 galaxy groups, clusters)
- ~ 90 Mpc, e.g. to Coma supercluster

FUTURE DETECTORS WANT 10 dB SQUEEZING

We could observe GWs to the edge of the visible Universe,

and black holes from the very first stars.





Squeezing limited by optical losses **Λ**, + phase noise θ, + mode-mismatch

dB ~ $10 \log_{10} (2\theta + \Lambda)$

FOR 10 dB —

- ❑ **known loss / 2**
- ❑ **no excess loss**
- ❑ **phase noise / 3**

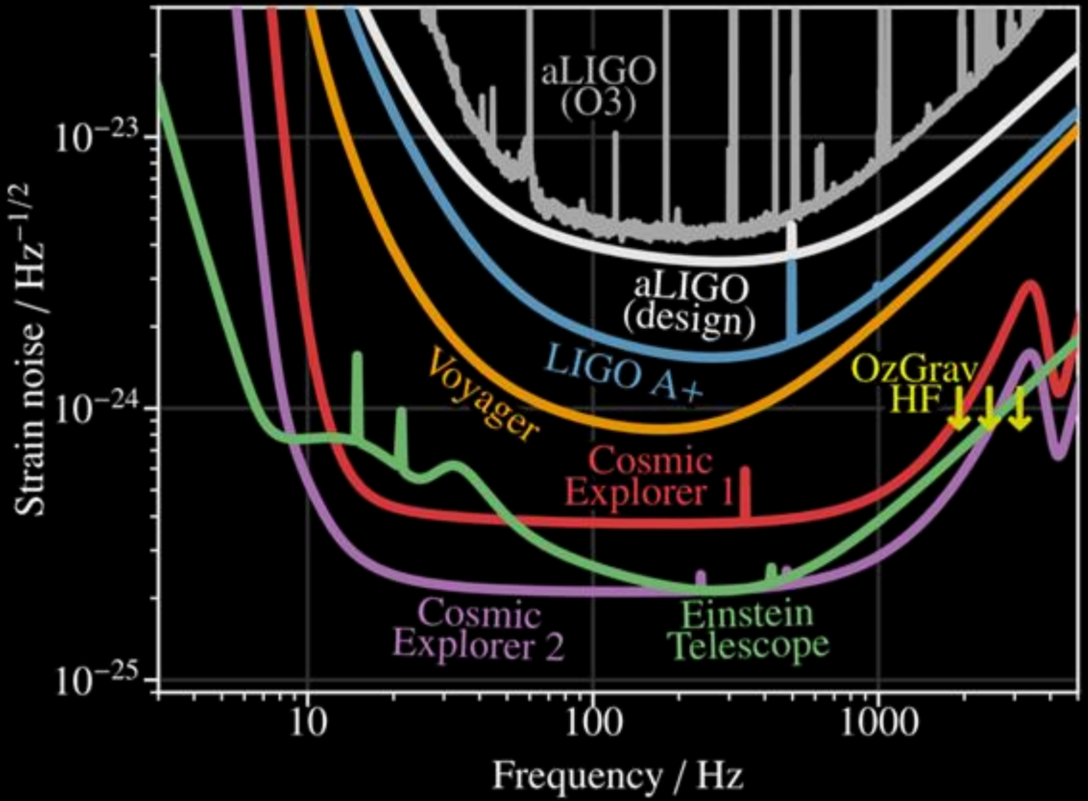
O3 ✓	FIS 3 dB (50%)	~50% loss
O4 (2023) ✓	FDS 4.5 dB (65%)	30% loss, 30 mrad
A+ (O5, 2028)	FDS 6 dB (75%)	20% loss, 30 mrad
A#, CE	FDS 10 dB (90%)	8% loss, 10 mrad

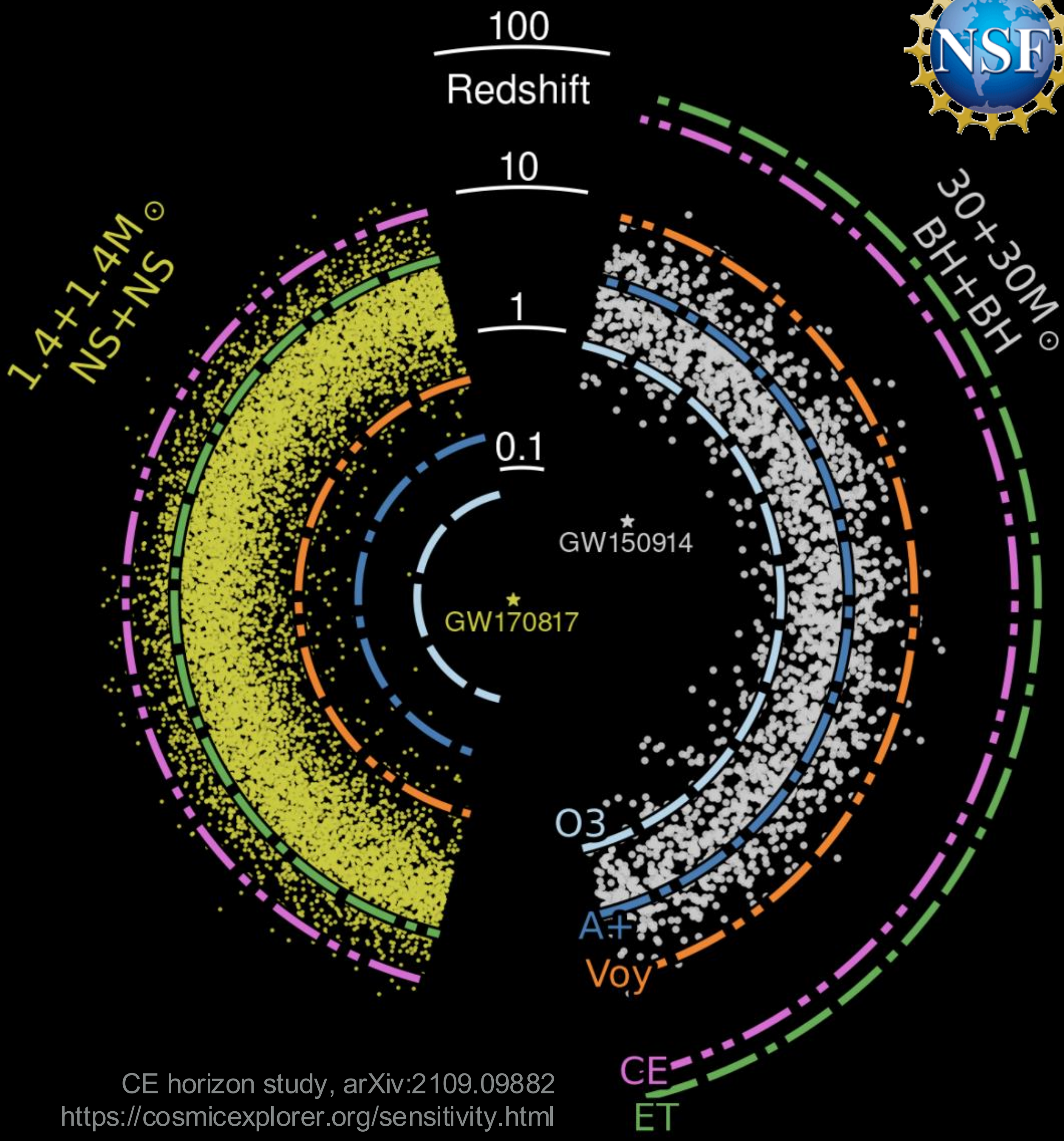
need…
low-loss optics & materials,
robust optical & quantum noise models,
in-situ diagnostics,
QRPN back-action control

CE horizon study, arXiv:2109.09882

PROPOSED XG GROUND-BASED GRAVITATIONAL-WAVE DETECTORS

US Cosmic Explorer;
EU Einstein Telescope





CE horizon study, arXiv:2109.09882
https://cosmicexplorer.org/sensitivity.html

LIGO Scientific Collaboration

>1600 members, >130 institutions, 20 countries

The material presented here is based upon work supported by NSF's LIGO Laboratory, which is a major facility fully funded by the National Science Foundation.

LIGO Scientific Collaboration

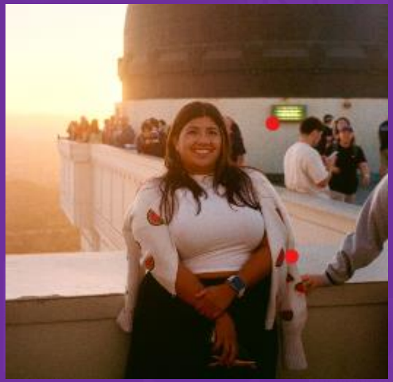
>1600 members, >130 institutions, 20 countries

Berkeley - LIGO

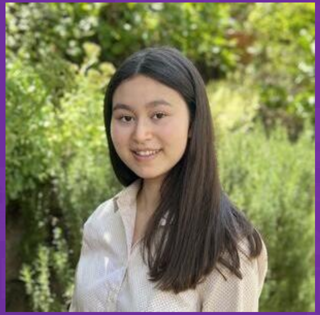
PI
- Frances Hellman
- Victoria Xu (q-ifo.github.io)

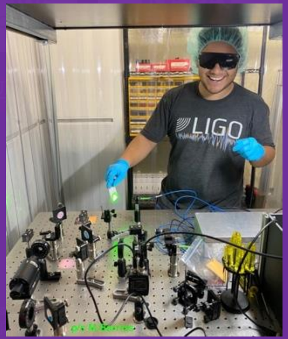
Quantum Interferometry Lab (PI: Xu)

Postdoc:
Dr. Maryrose Barrios



Physics PhDs: Katie Gray, Celeste Virador, Aditi Anand (fall 26-), Mark Zhu (fall 26-)





Efforts to begin in trapped atom interferometry for quantum tests in gravitational physics & fundamental physics!

Undergraduates:
Jaime Alvarez (→ MIT),
Max Umminger, Lauren Lee

The material presented here is based upon work supported by NSF's LIGO Laboratory, which is a major facility fully funded by the National Science Foundation.

Thank you!