A Decade of Gravitational-Wave Astronomy
Discoveries and Instrumental Evolution

KMI2026: The 7th KMI International Symposium
LIGO-G2602387

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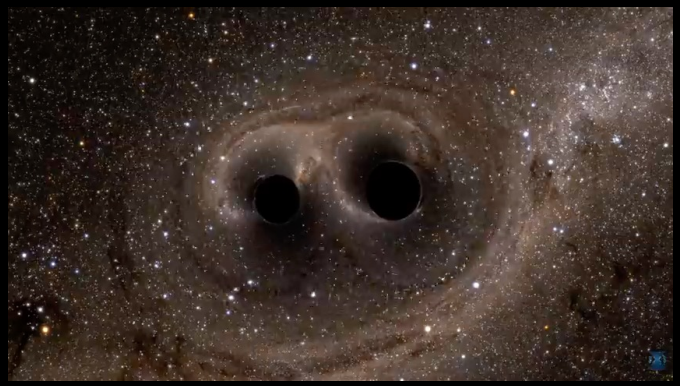
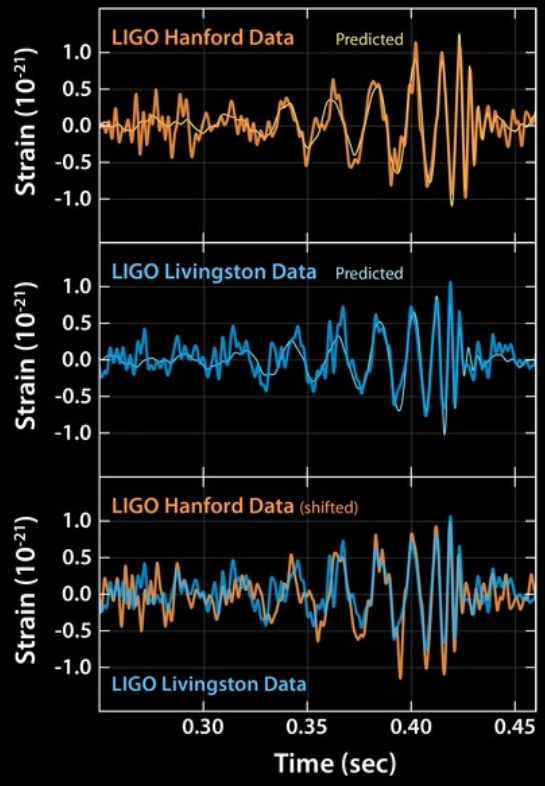
Gravity Exploration Institute, Cardiff University

The First Gravitational Wave Detection in 2015

Black hole binary coalescence (image)

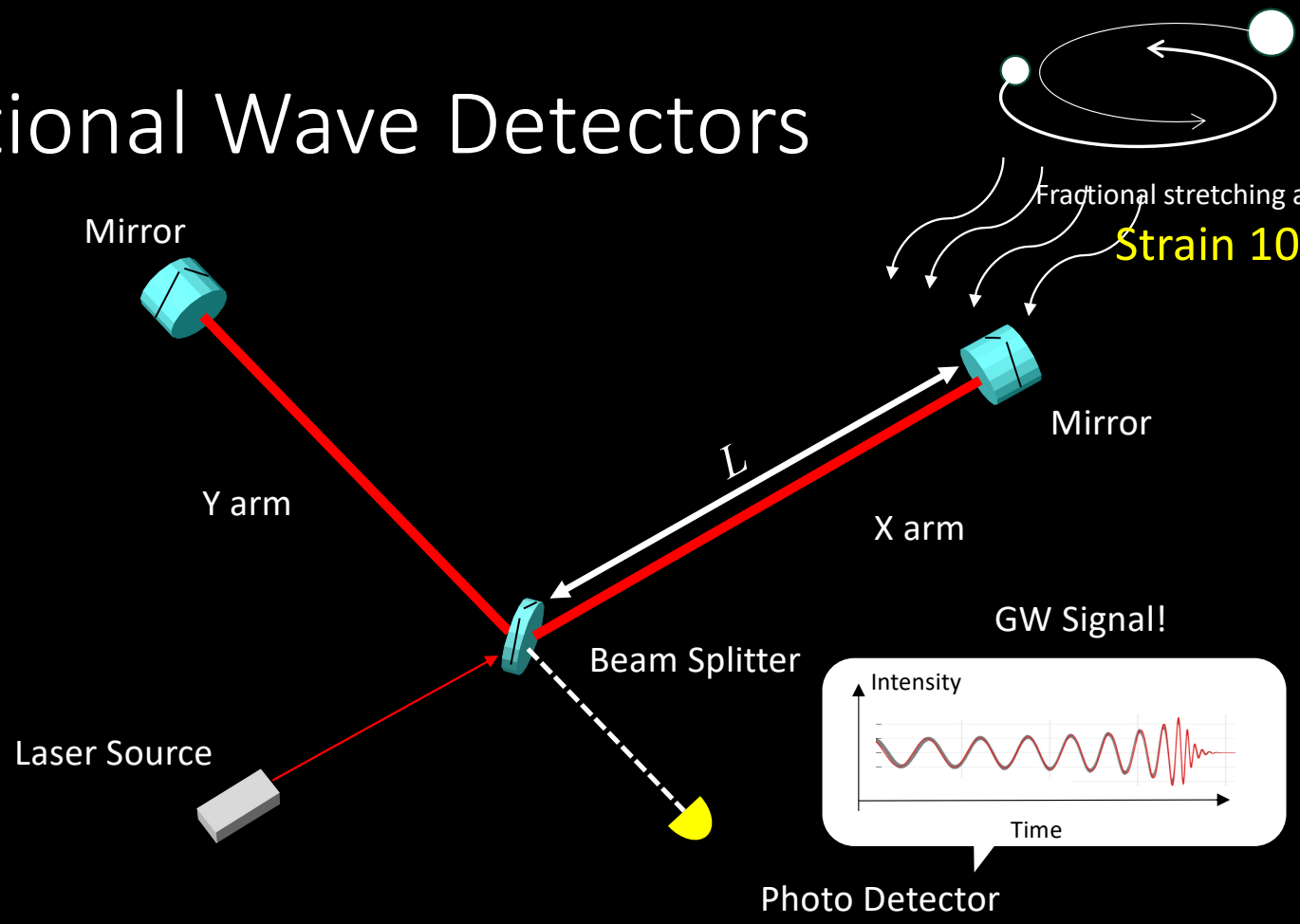


Credit: LIGO Scientific Collaboration



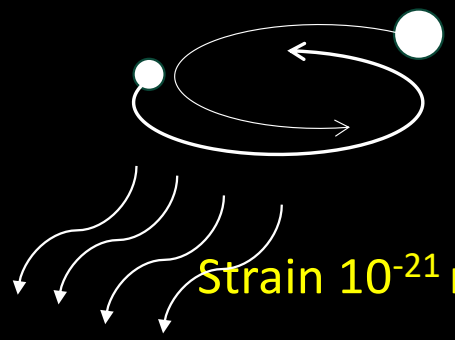
- First direct detection of spacetime distortions produced by gravitational waves
- Verification that Einstein's general relativity remains valid even in extremely strong gravitational fields
- First observation of a binary black hole system
- Captured the moment when two black holes merged into a single black hole for the first time
- First confirmation of the existence of ~30-solar-mass black holes

Gravitational Wave Detectors

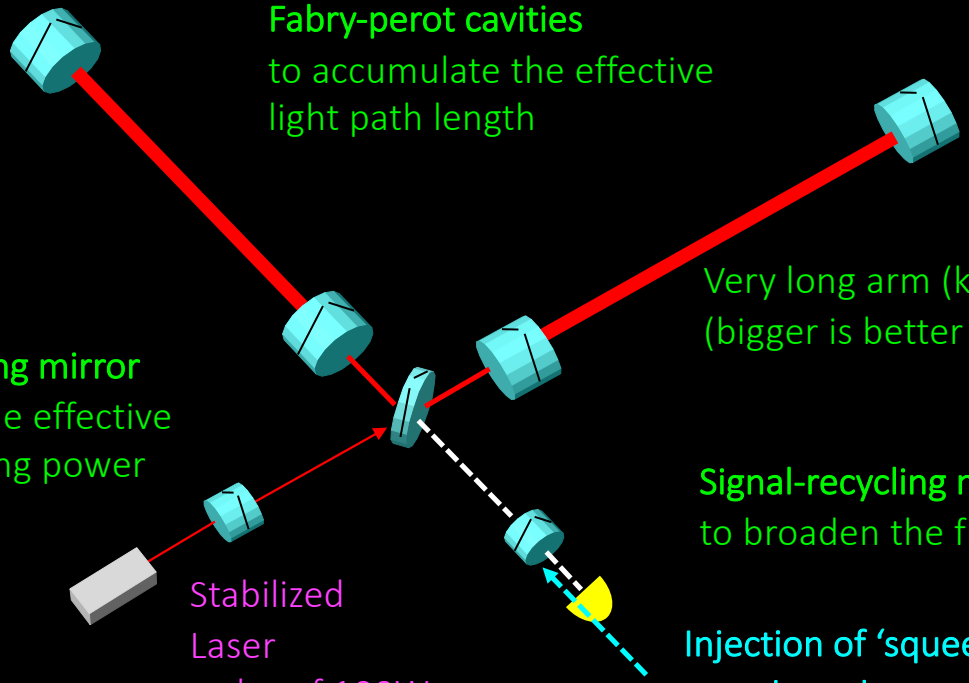


Optical sensor detecting the length difference between X and Y arms

Actual “Advanced” Detectors



Strain 10^{-21} m/m



Fabry-perot cavities
to accumulate the effective light path length

Very long arm (km)
(bigger is better!)

$$dL \propto L$$

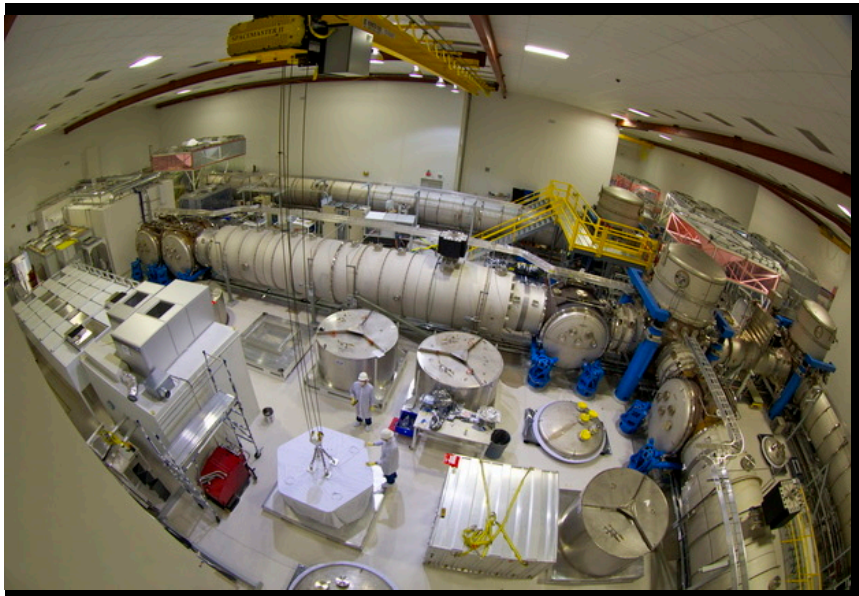
Power-recycling mirror
to enhance the effective laser circulating power

Signal-recycling mirror
to broaden the frequency response to the GW

Stabilized
Laser
order of 100W

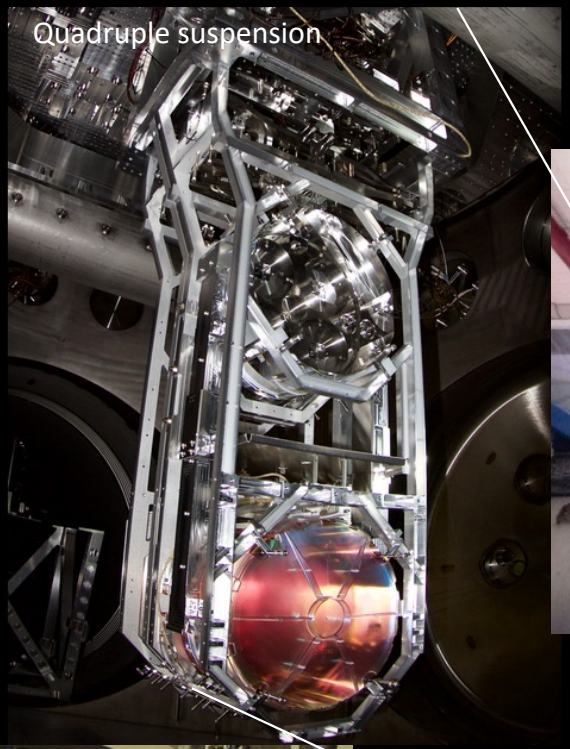
Injection of ‘squeezed vacuum’
to reduce the quantum noise

all photo credit: Caltech/MIT/LIGO Lab

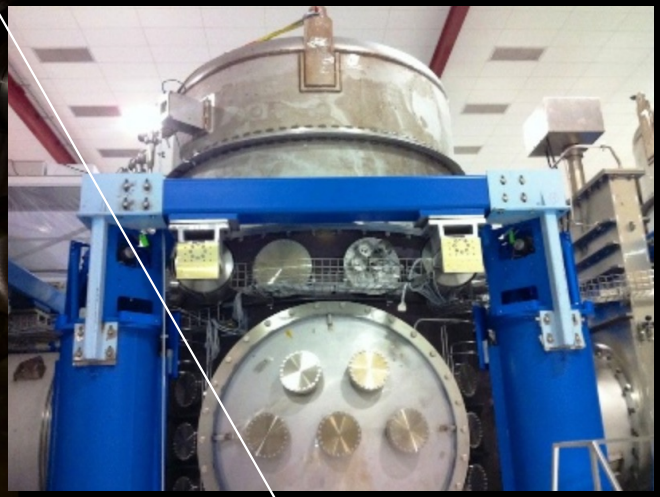


Electronics for detector control and data acquisition

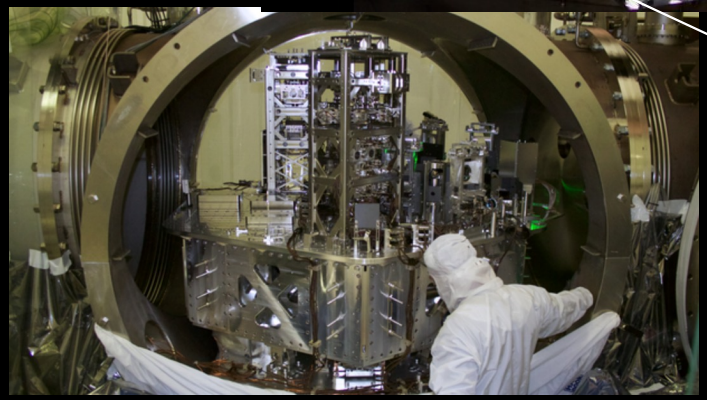


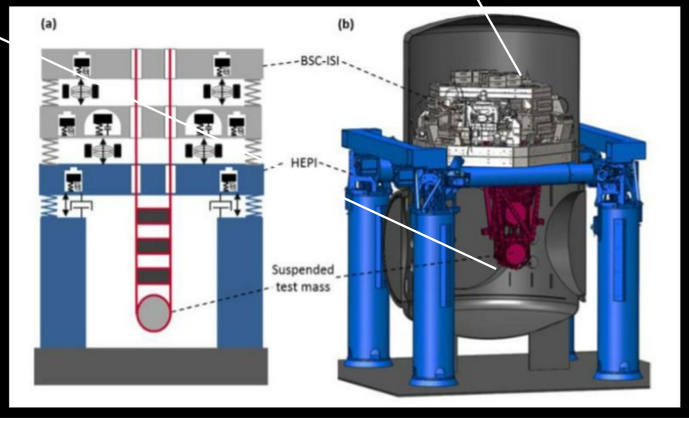


Quadruple suspension



Seismic isolation stage

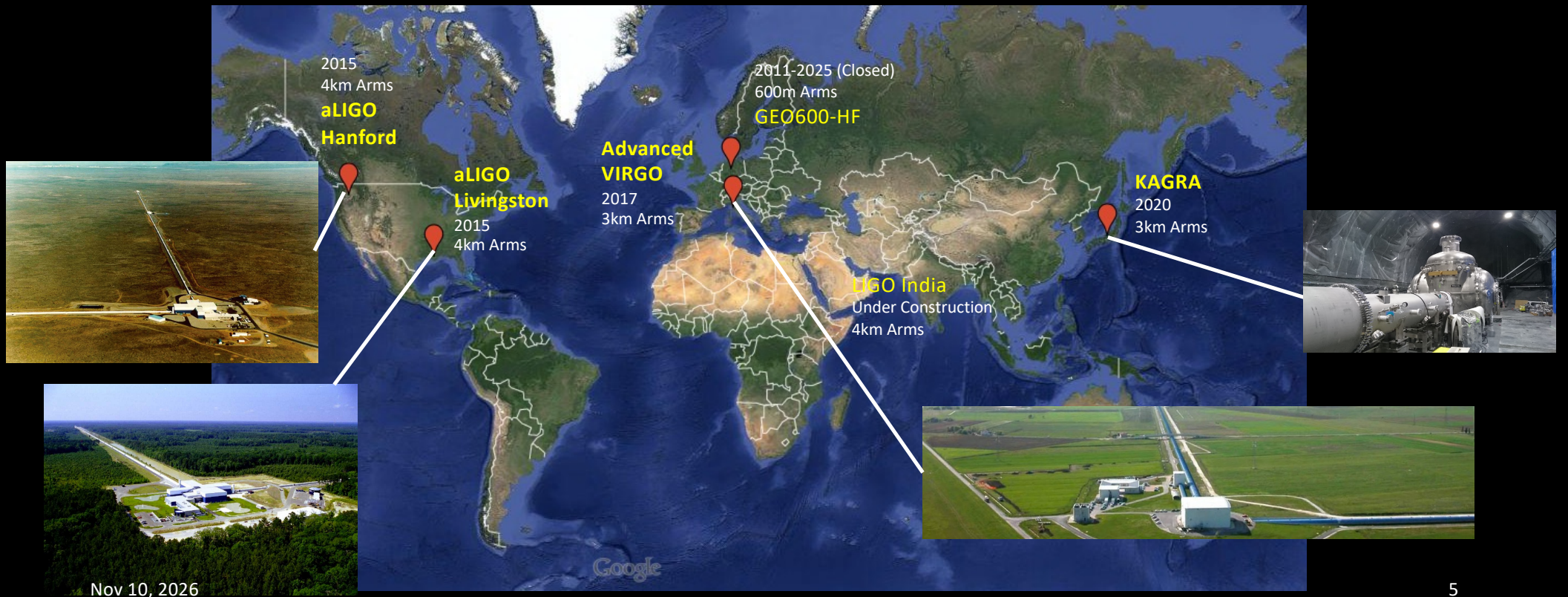




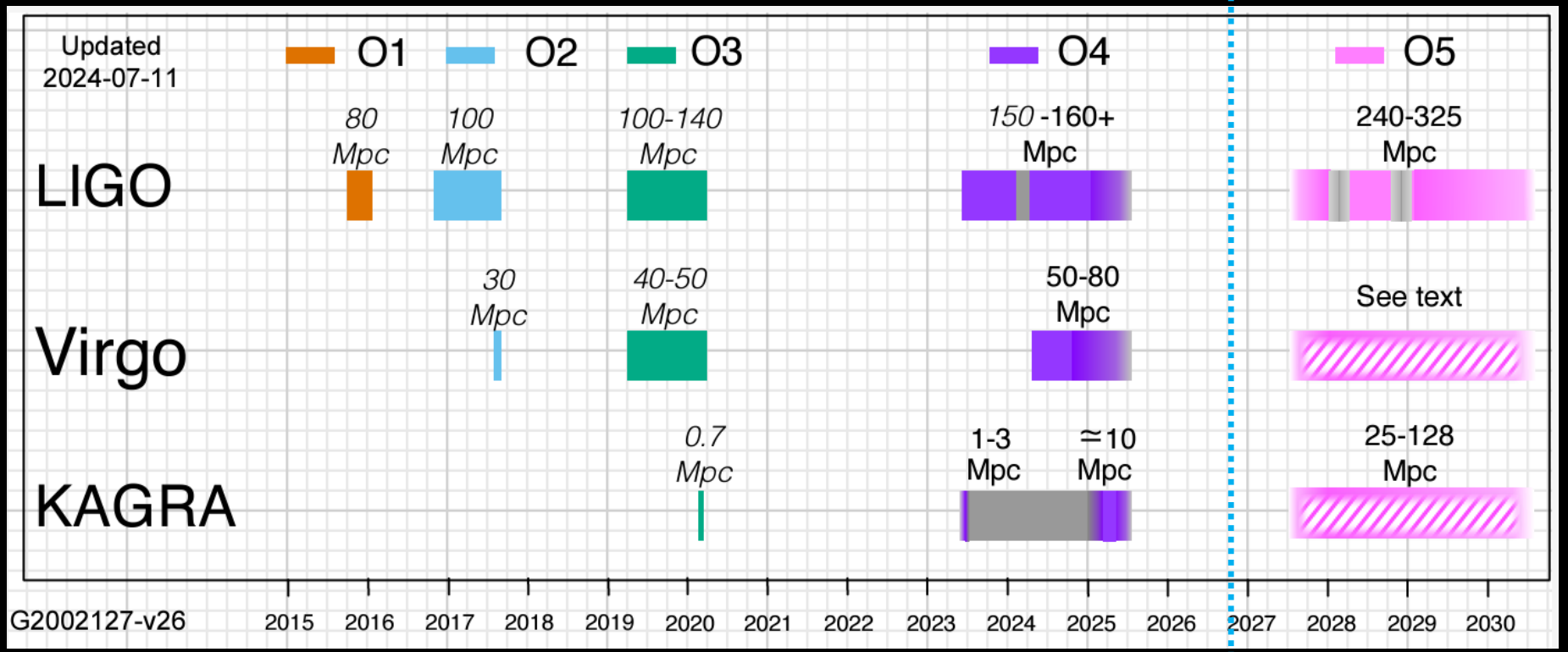
Nov 10, 2026

Worldwide Detector Network

Detector network is essential for source localization, as the source position is determined using the differences in arrival times of the signals at each detector



Observation Timeline



Cycles of Detector Upgrades

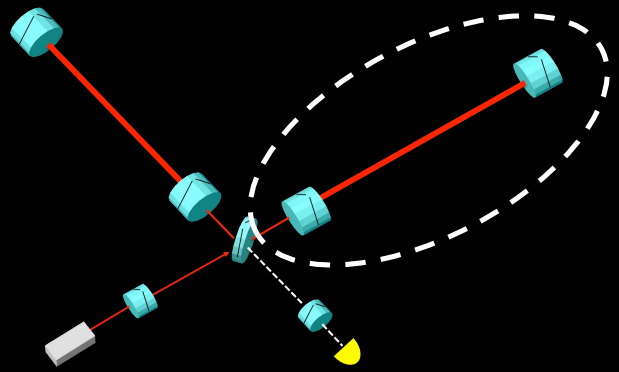
image credit: LIGO/Virgo/KAGRA

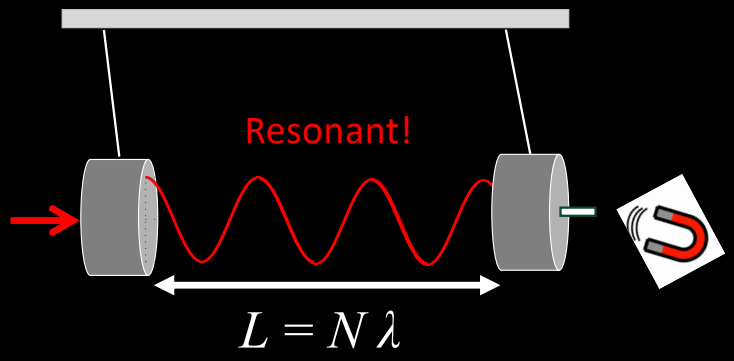


The first challenge before O1

- Integrating all the subsystems together as one detector and bringing the ifo into resonance so that it can operate as a GW detector (called commissioning)
- Stable operation was first achieved in 2014

Staley et al., CQG 2014
D. V. Martynov et al., PRD 2016





Actuated
by coil magnets or
electro-static drivers

The mirrors are controlled with sub-wavelength (λ =1064nm) precision

Detector Upgrades for O2

- 6-month commissioning period
- Doubling the input laser power to 50 W
- Replacement of vacuum components, e.g., output mode cleaner (lower loss) and photodetector (better quantum efficiency)
- Installing dampers for test mass mechanical mode
- …
- Achieved a BNS range of approximately 100 Mpc at LLO

O2 : Neutron Start Binary Merger

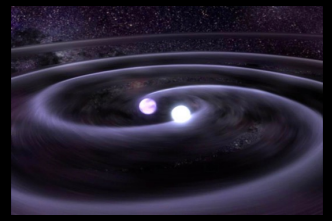
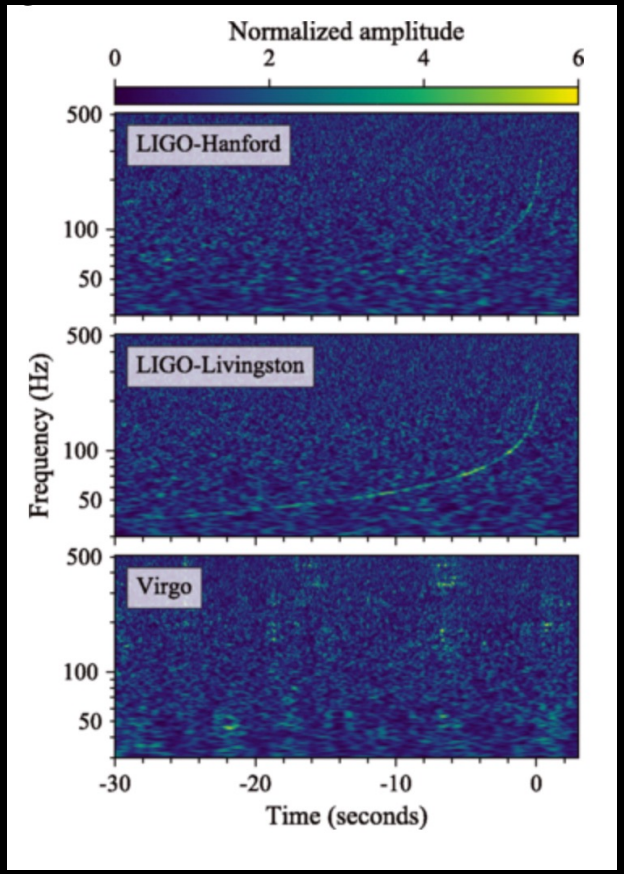
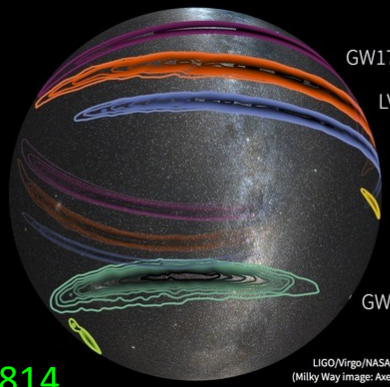


Figure: Phys. Rev. Lett. 119, 161101 (2017)



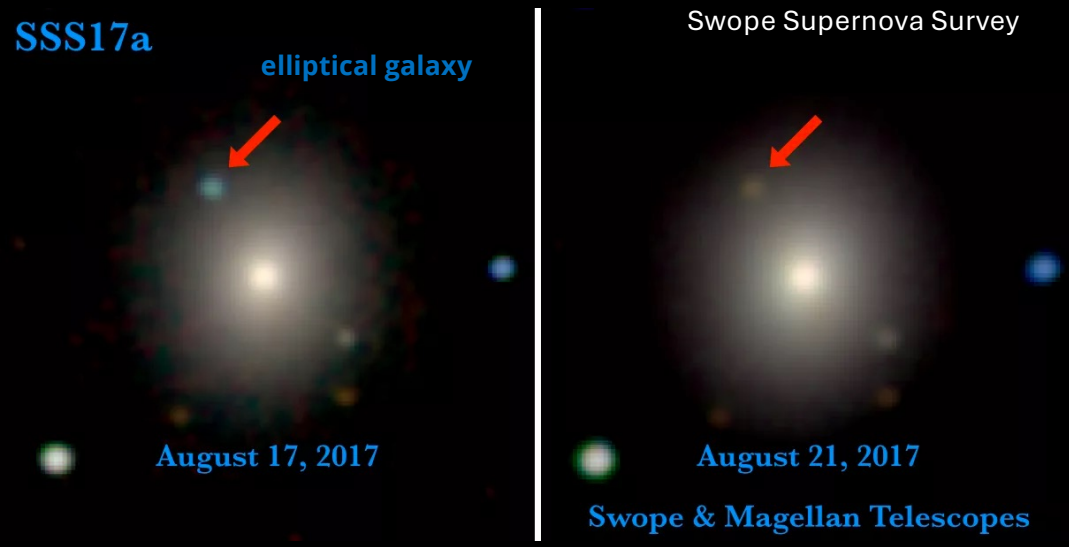


Better Sky Localization with VIRGO!

(image)

Figure: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

First GW Multimessenger Observation



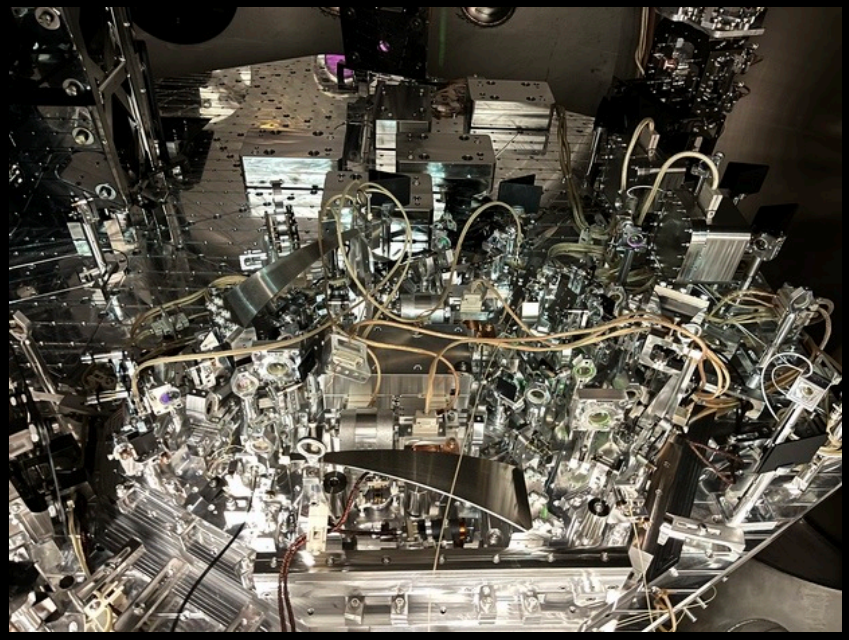
- Kilonova was observed by EM telescopes
- The Fermi Gamma-ray Space Telescope detected a gamma-ray burst 1.7 seconds later
- Extensive worldwide follow-up observing campaign followed

Multimessenger Observation

- Confirmed that kilonovae are produced by binary neutron star mergers
- Confirmed that gravitational waves travel at the speed of light, providing a key test of general relativity
- Provided an independent measurement of the Hubble constant $(70^{+12}_{-8}\ \mathrm{km\,s^{-1}\ Mpc^{-1}})$
- Binary neutron star mergers had long been considered a candidate for the production of heavy elements such as gold and platinum. This observation provided strong evidence that such mergers are a major origin of the heavy elements found in the Universe today.

Detector Upgrade Highlights for O3

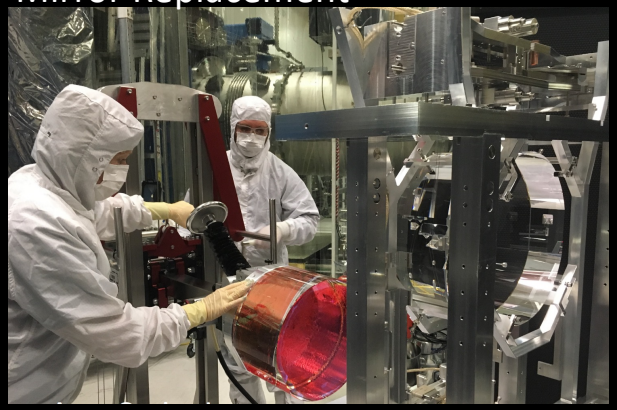
Installation of “squeezer”

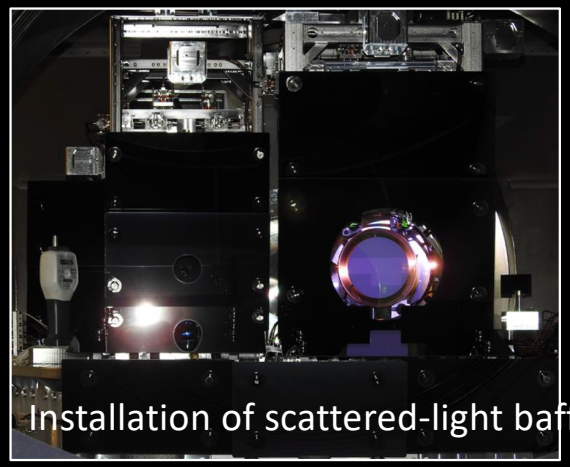


D. GANAPATHY PRX (2023)

Wenxuan Jia/MIT

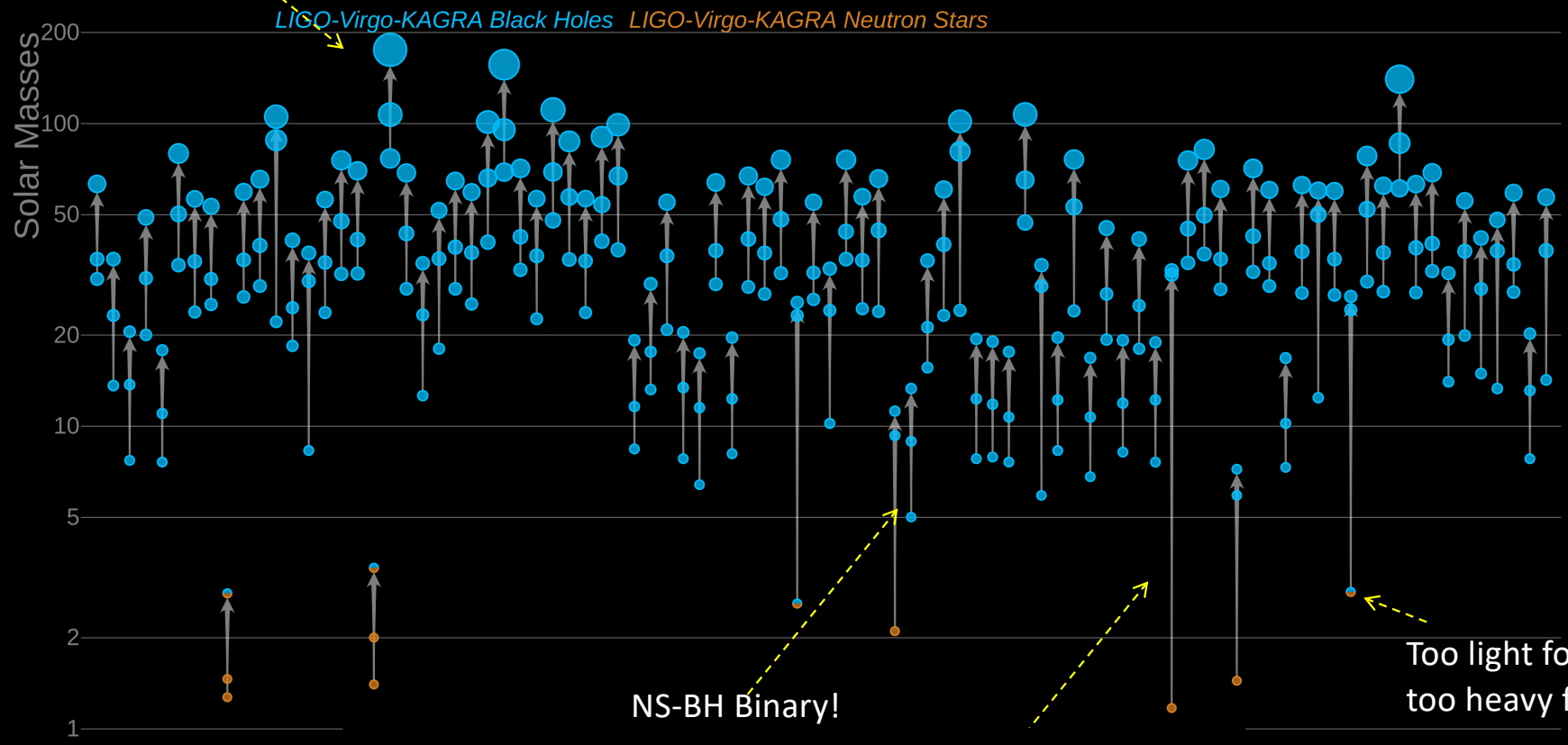
Mirror Replacement





Installation of scattered-light baffles

O3: Start Gaining Statistical View



Asymmetric mass (1:30) binary

Distribution of Charp Mass

Mass of the heavier one

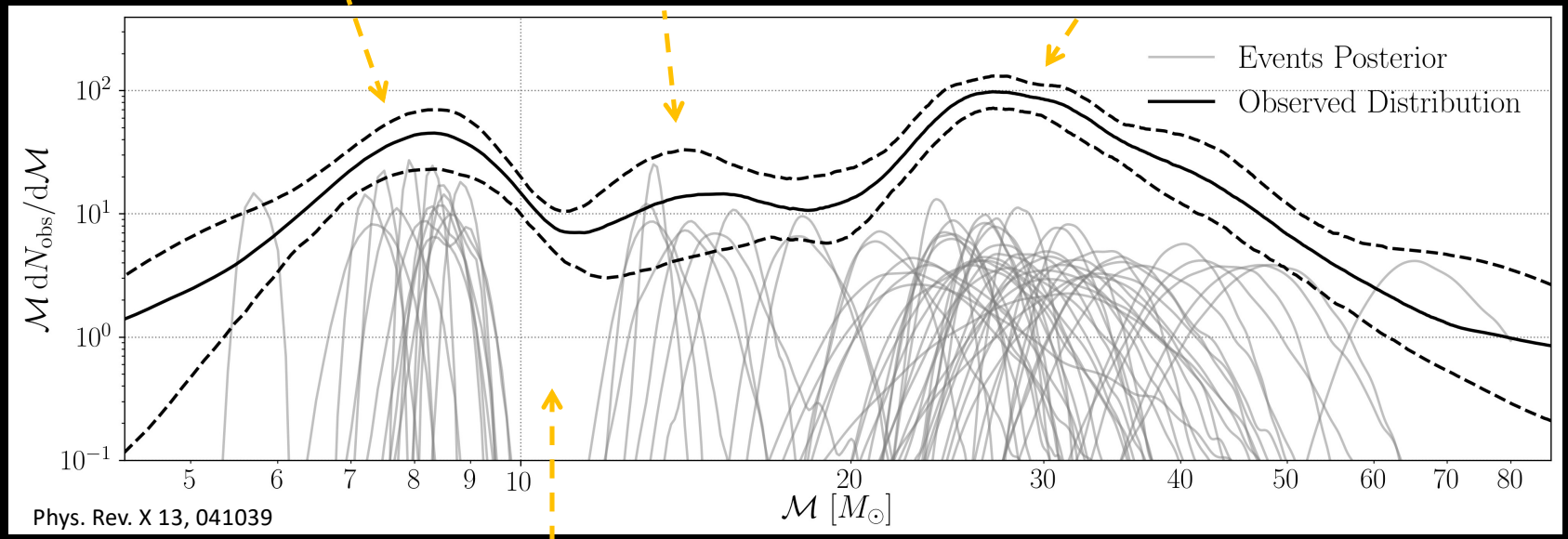
Mass of the lighter one

$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}\,.$$

Peak at 8-10 Msol

Weak peak?

Another peak at 35 Msol



Phys. Rev. X 13, 041039

Dip (no mergers?)

Detector Upgrade Highlights for O4 (1)

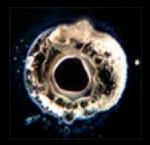
- Commissioning Period: 2020-2023/5
- Installation of 300 m filter cavity for frequency-dependent squeezing
- Higher circulating power (320 kW)

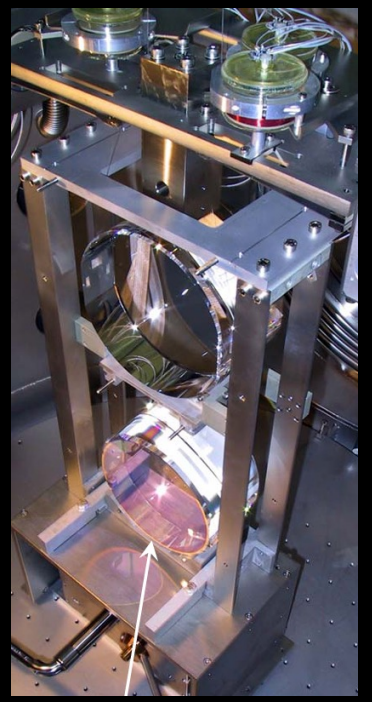
Credit: MJ Doherty



New filter cavity vacuum tube

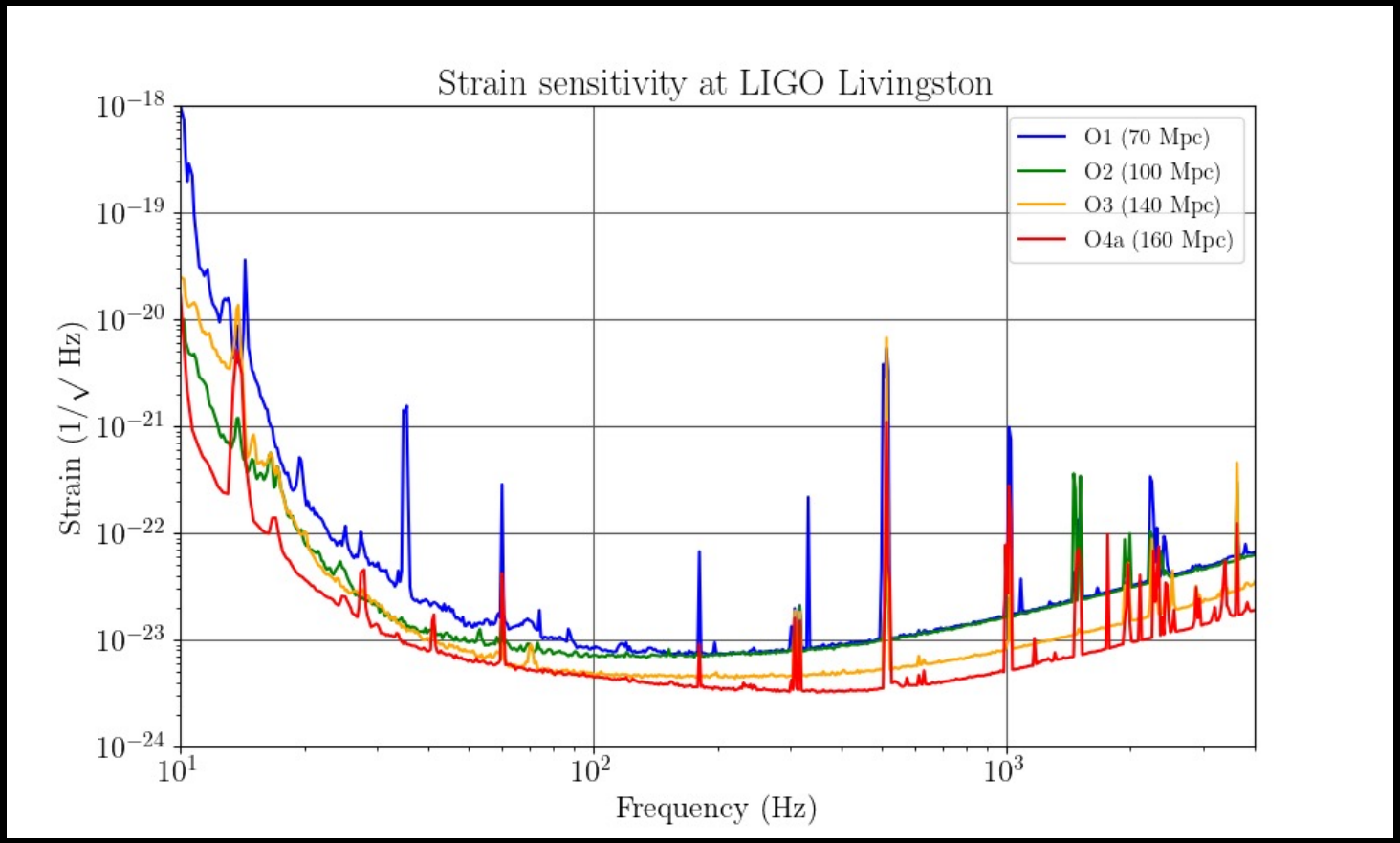






LIGO-G080468-00-R
A Brooks, Applied Optics (2021)

Evolution of Detector Sensitivity



Bad

Sensitivity

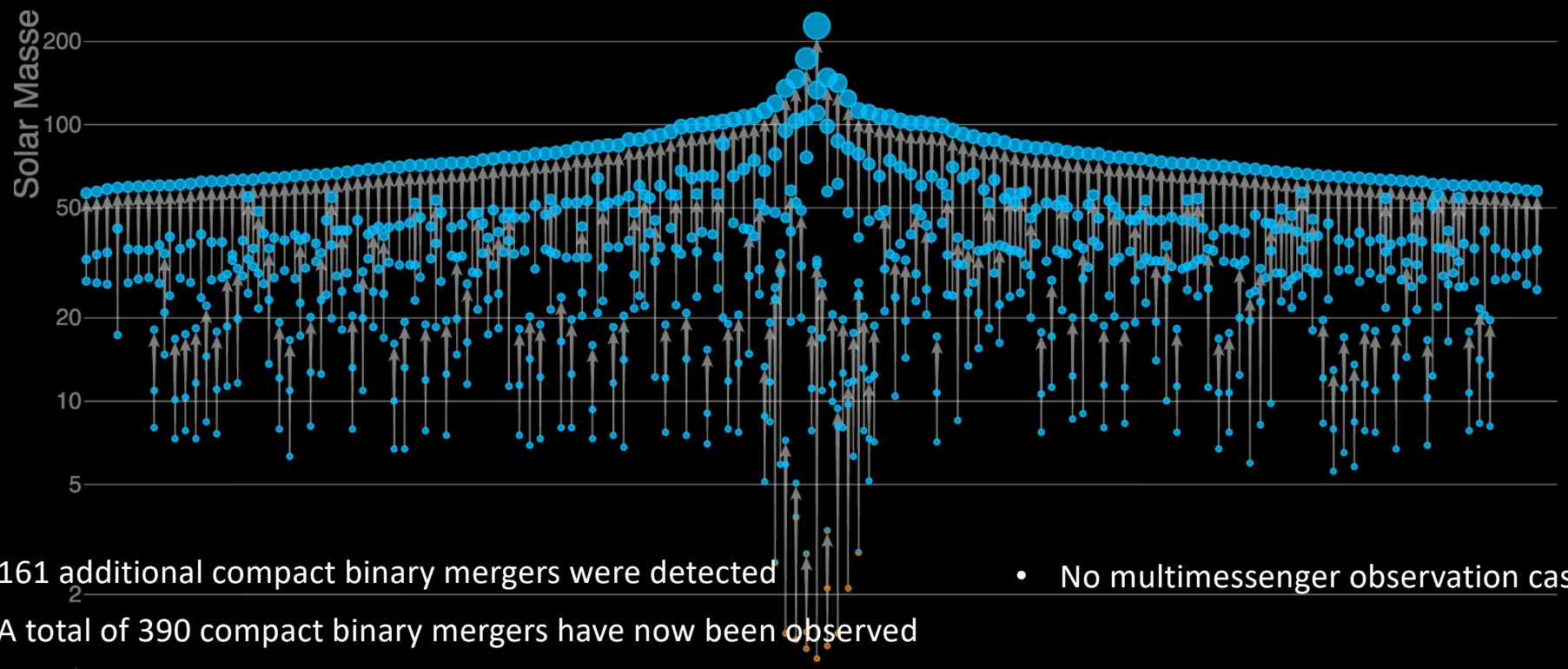
Good

Low
Heavier GW sources

Frequency of the GW signals

High
Lighter GW sources

O4 Run has finished in Nov 2025



- 161 additional compact binary mergers were detected
- A total of 390 compact binary mergers have now been observed
- The figure shows the publicly available data through O4b
- Results based on the full O4 dataset (GWTC-5) are expected to be released in December

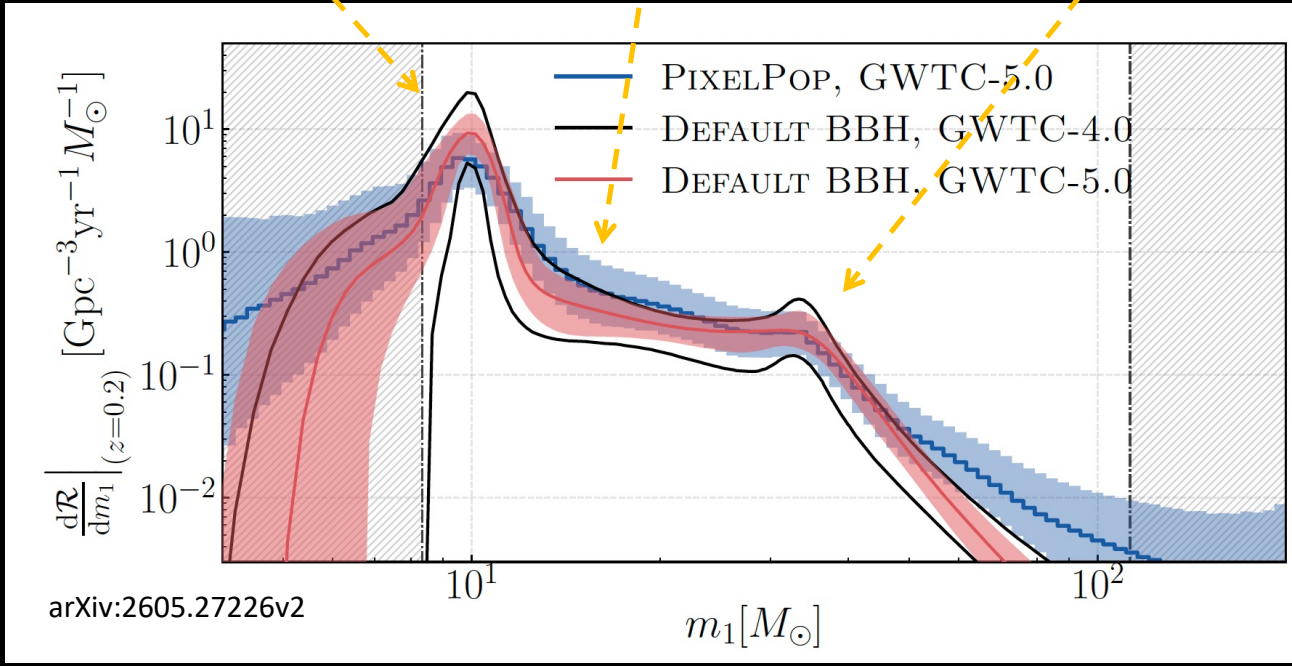
- No multimessenger observation case

Statistical View being Updated

Peak at 8-10 Msol

No weak peak

Around 35 Msol, a change in slope rather than a distinct peak



arXiv:2605.27226v2

More (MANY) results are found here!
https://www.youtube.com/@LIGOVirgo
And more coming in December

Ongoing Detector Commissioning for O5

Effler, LIGO-G2600895

- About 2 years obs. break for installations and commissioning
- The design sensitivity will be achieved
- Higher laser power (Max 750 kW in the arm cavities)
- Bigger beamsplitter (from 37 cm to 45 cm diameter)
- Balanced homodyne readout scheme
- Installation of Jitter attenuation cavity
- New thermal compensation system (CHETA)
- Advanced VIRGO will also be upgraded

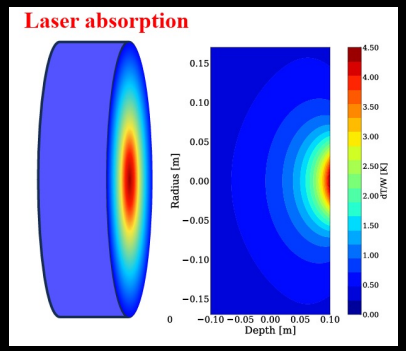


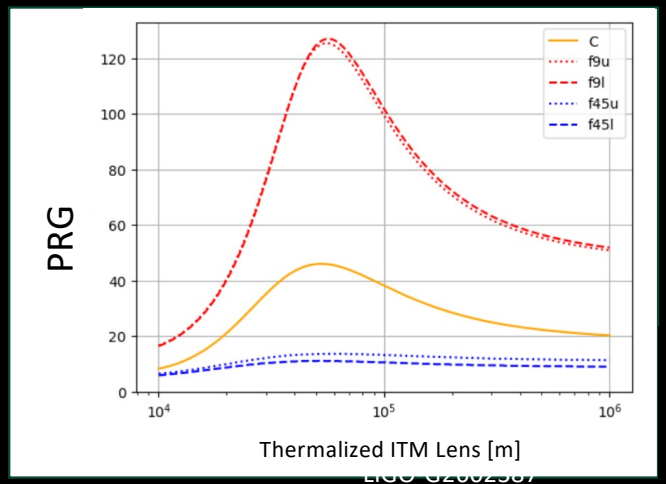
Instagram @japullin

Instrumental Research at Nagoya University

Modeling for ‘Thermalized’ Interferometer

- Increasing the laser power reduces shot noise, but it also heats the mirrors, causing thermal lensing and deformation of the mirror surfaces
- These thermal effects make the interferometer more difficult to control, limiting further laser power increases during the O4 observing run (< 300 kW in the arms) We use numerical and analytical modeling to investigate how thermally induced mirror distortions affect interferometer control (e.g., PRG)









Kenji Tsuji
MSc Thesis,
LIGO-G2602259-v1,
LIGO-G2601058-v1

Summary

- Gravitational-wave astronomy is a young field that began in 2015. Since then, our understanding of compact binaries has steadily improved
- To gain more statistical understanding, many more gravitational-wave observations will be needed
- Gravitational-wave detectors are among the most advanced scientific instruments ever built, and their development is itself a major area of research
- Improving detector sensitivity and maintaining stable observations are also large-scale scientific and engineering challenges