
Ground-based laser interferometer gravitational wave detectors: current status, latest results and future prospects

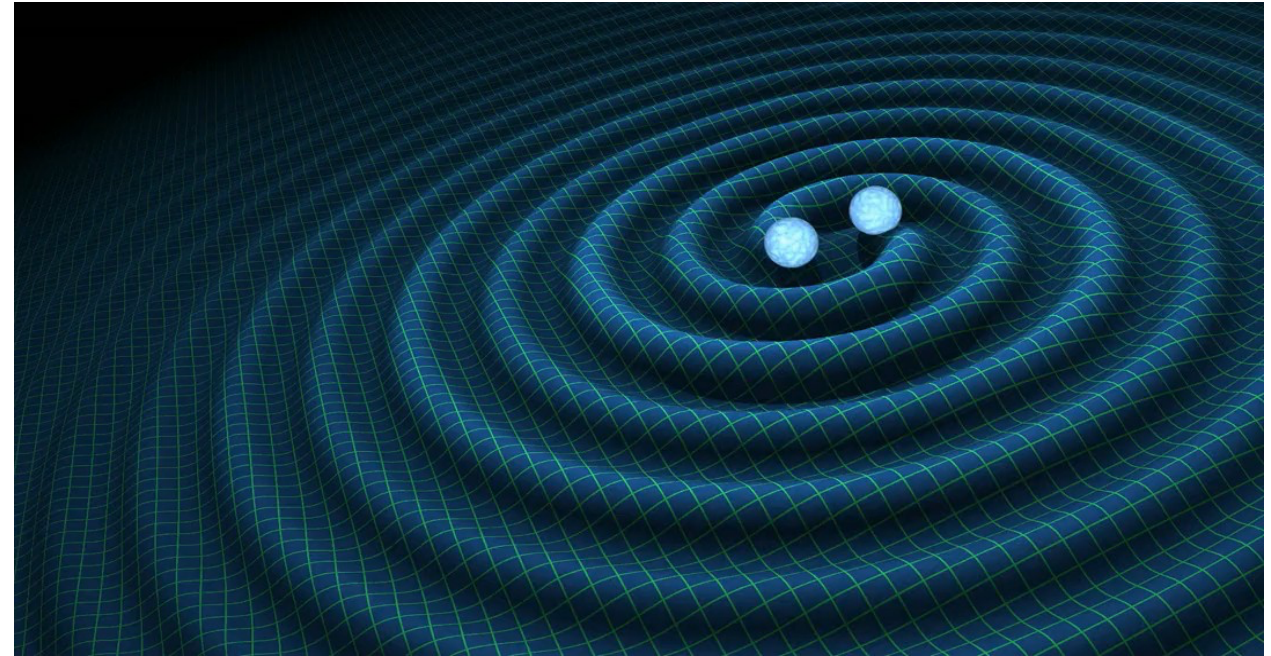
Raffaele Flaminio

CNRS/LAPP, Annecy, France

- Short introduction
- First results (O1 and O2 runs)
- Selection of latest results (O3 and O4 runs)
- Perspectives: 3G detectors
- Summary

Introduction and first results

- Gravitational wave generation
 - ◆ Acceleration of massive, compact and relativistic objects
- Quadrupolar emission
 - ◆ Second derivative of the source's quadrupole moment
- Typical sources
 - ◆ Compact binary stars involving black holes or neutron stars (BBH, BNS, NSBH)
 - ◆ Many others are possible
 - » Rotating neutron stars
 - » Star core collapses
 - »

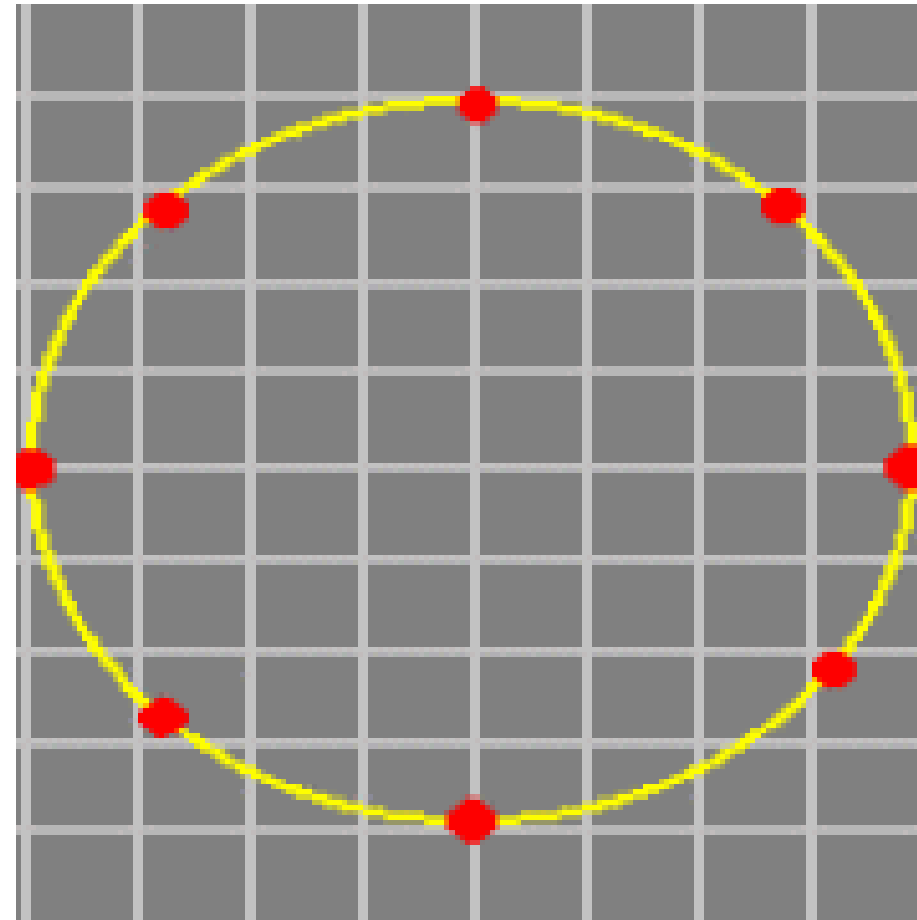
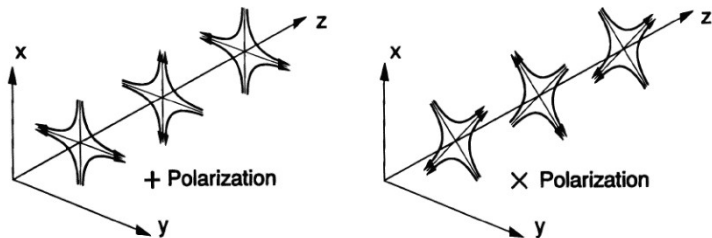


- Oscillations of space-time curvature

- ◆ Quadrupolar wave
- ◆ Tidal force
- ◆ Wave amplitude h

$$\delta L = h L$$

- ◆ Two polarizations



- The principle

Gravitational wave



Mirror displacement



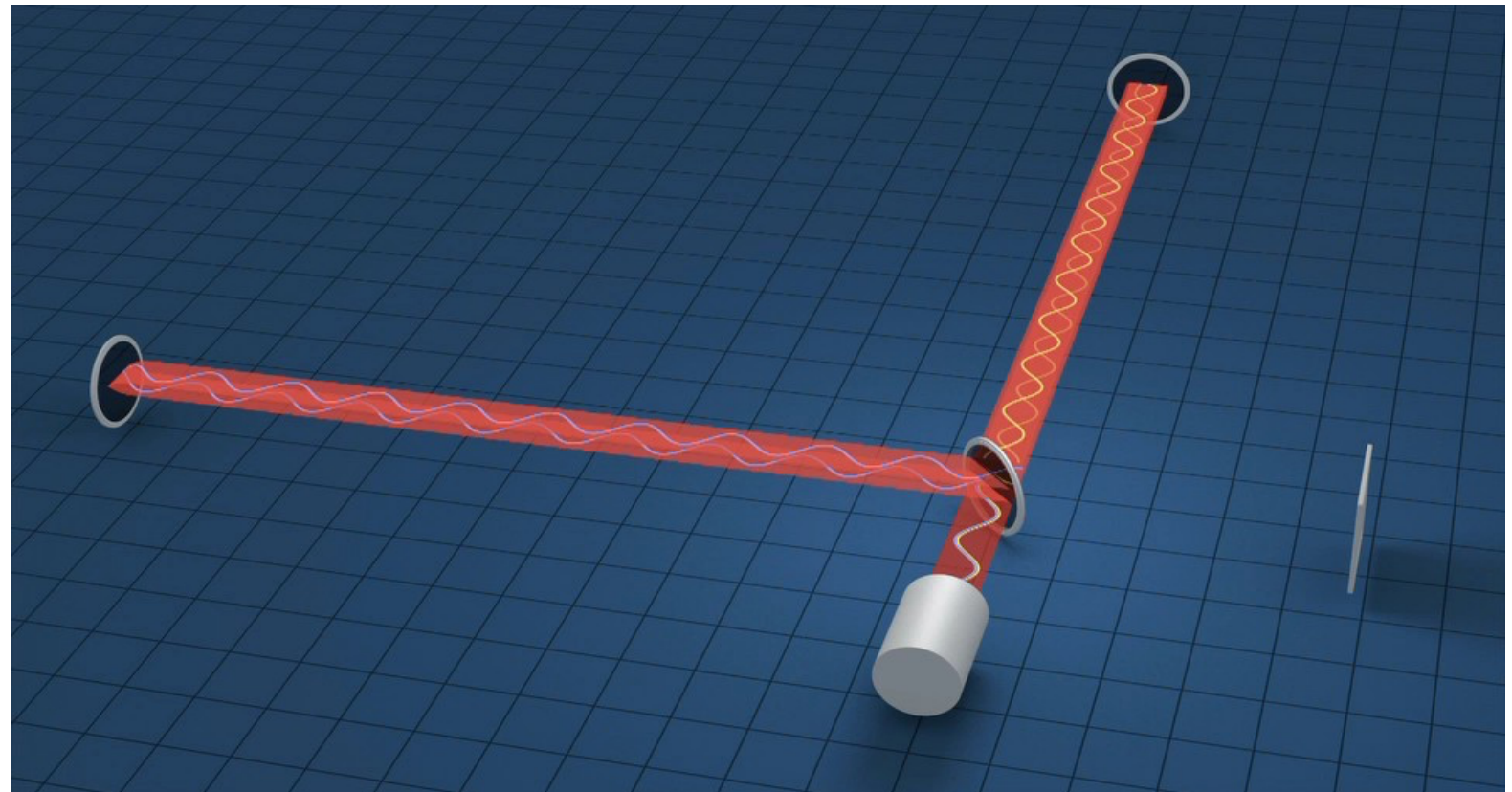
Light phase shift



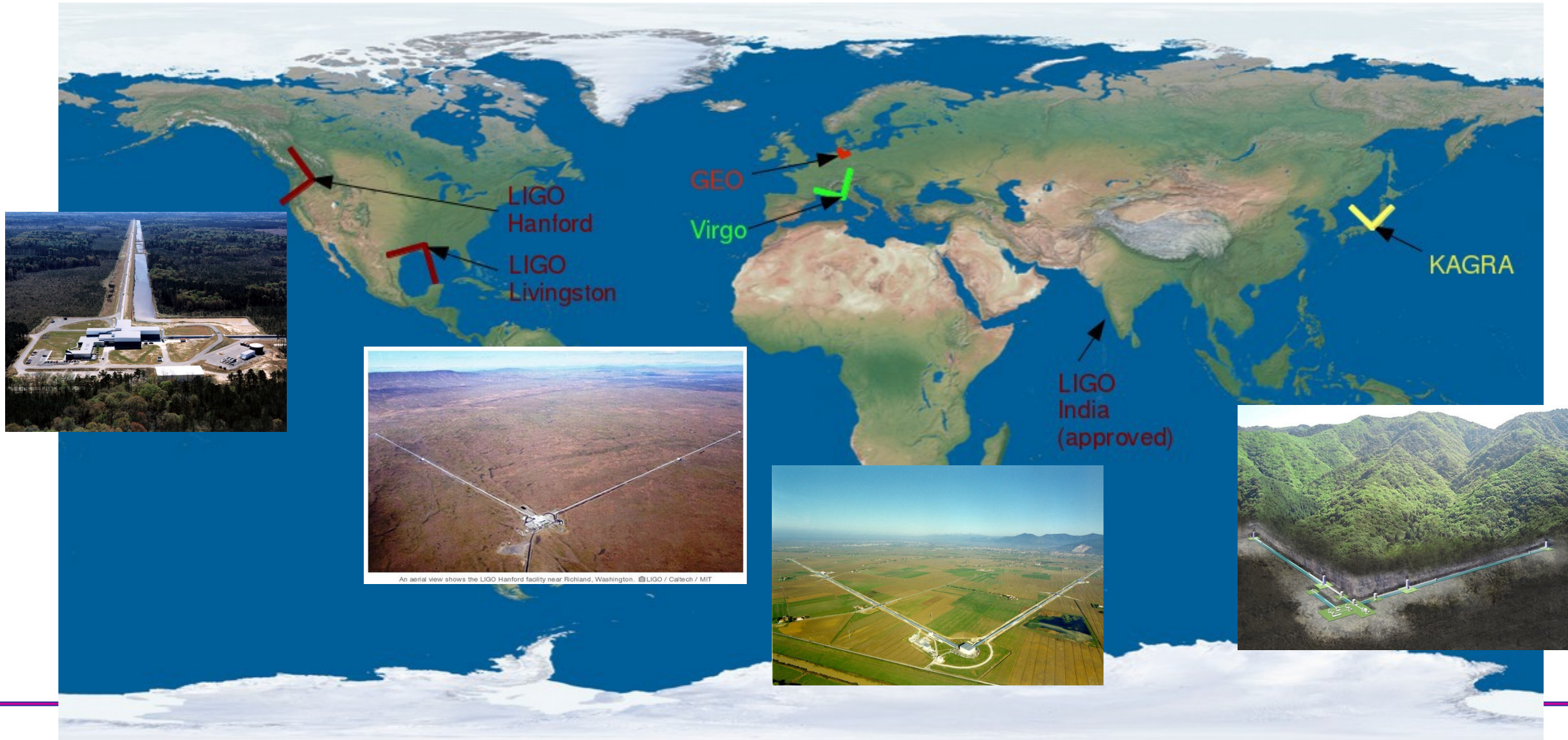
Light power variation

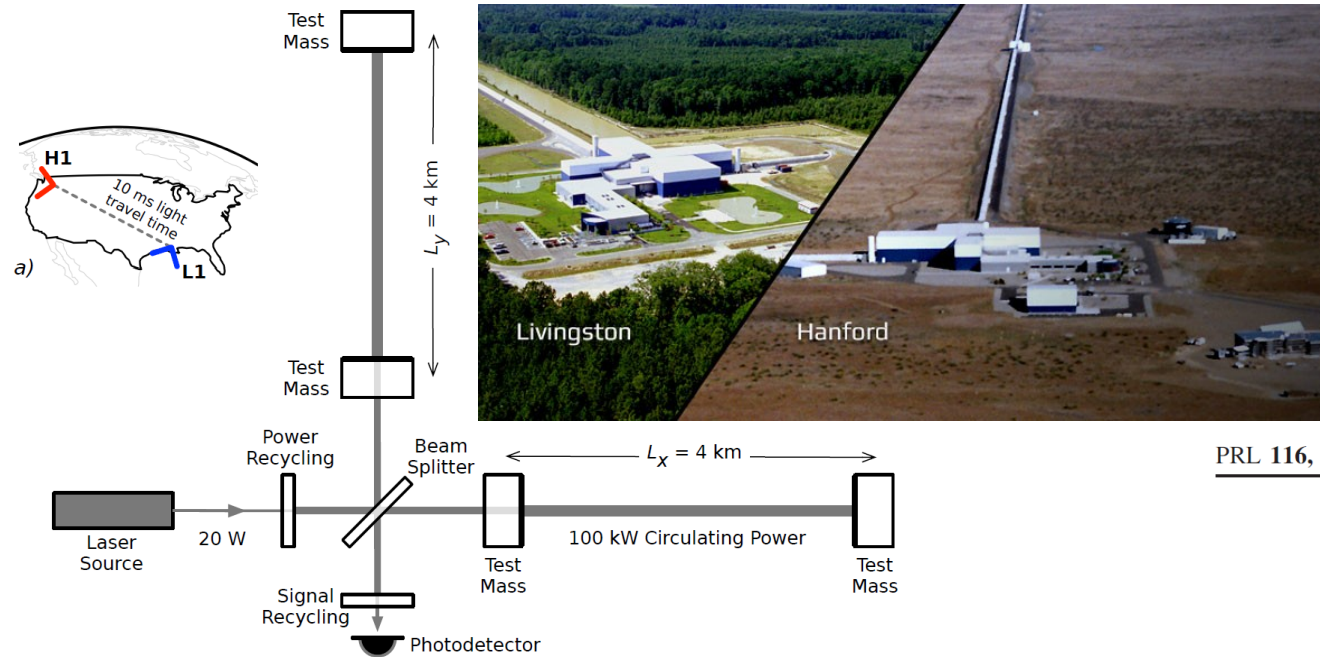
- The devil is in the details

- ◆ With 3 km arm length displacement $\sim 10^{-18}$ m
- ◆ Arm length is the key parameter



The LVK detectors network





PRL 116, 061102 (2016)

Selected for a Viewpoint in *Physics*
 PHYSICAL REVIEW LETTERS

week ending
 12 FEBRUARY 2016



Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

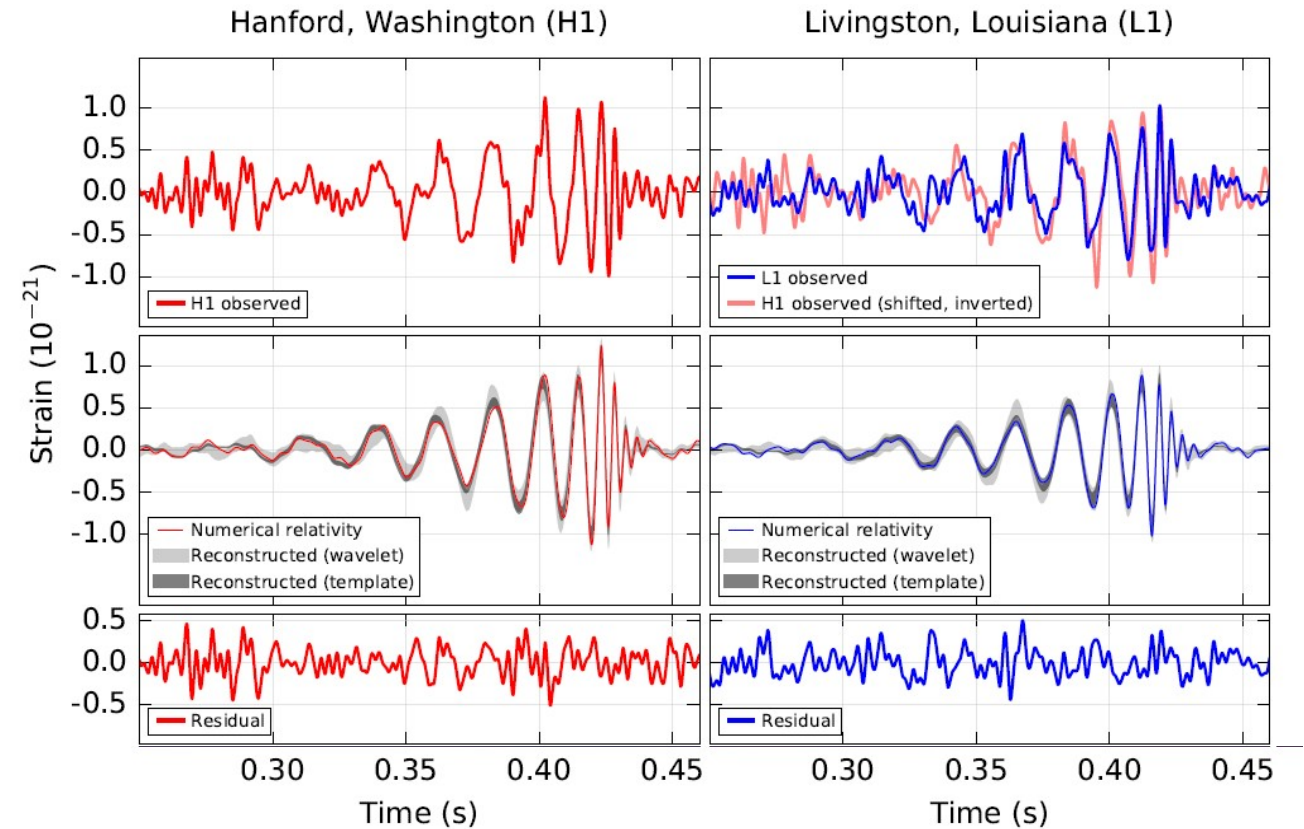
(LIGO Scientific Collaboration and Virgo Collaboration)
 (Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ . The source lies at a luminosity distance of 410_{-180}^{+160} Mpc corresponding to a redshift $z = 0.09_{-0.04}^{+0.03}$. In the source frame, the initial black hole masses are $36_{-4}^{+5} M_{\odot}$ and $29_{-4}^{+4} M_{\odot}$, and the final black hole mass is $62_{-4}^{+4} M_{\odot}$, with $3.0_{-0.5}^{+0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

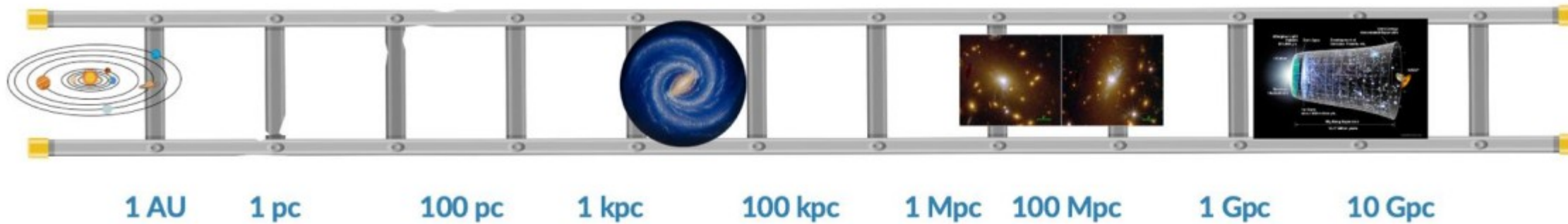
DOI: 10.1103/PhysRevLett.116.061102

- Orbital inspiral and merger of two black holes and ring-down of the final black hole

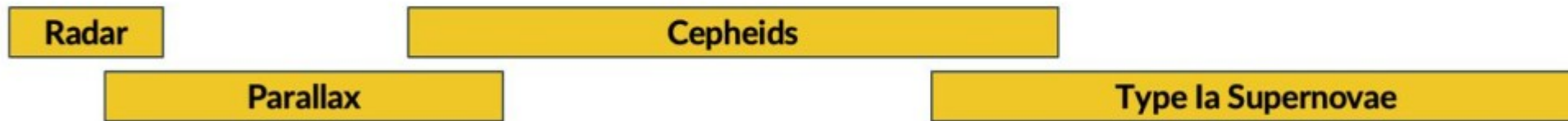
- Signal shape → Black hole masses
 - » Initial black hole masses: $36 M_{\odot}$ and $29 M_{\odot}$
 - » Final black hole mass: $62 M_{\odot}$
 - » Energy released: $3 M_{\odot} !!$
- Signal amplitude → Source distance
 - » 1 GLy
 - » At the peak it is brighter than the entire Universe
 - Energy flux at Earth larger than full moon



- A new and independent method to measure astronomical distances
- Can be used to study the $d(z)$ relationship i.e. to do cosmology
- Measurement of z requires source identification



Distances with Electromagnetic observations



Distances with GW observations



Figure credit:
S Mastrogiovanni

- The Earth is transparent to gravitational waves
- A network of gravitational wave detectors can provide the direction of the source by triangulation
 - From the differences in the wave arrival times
 - At least three detectors needed

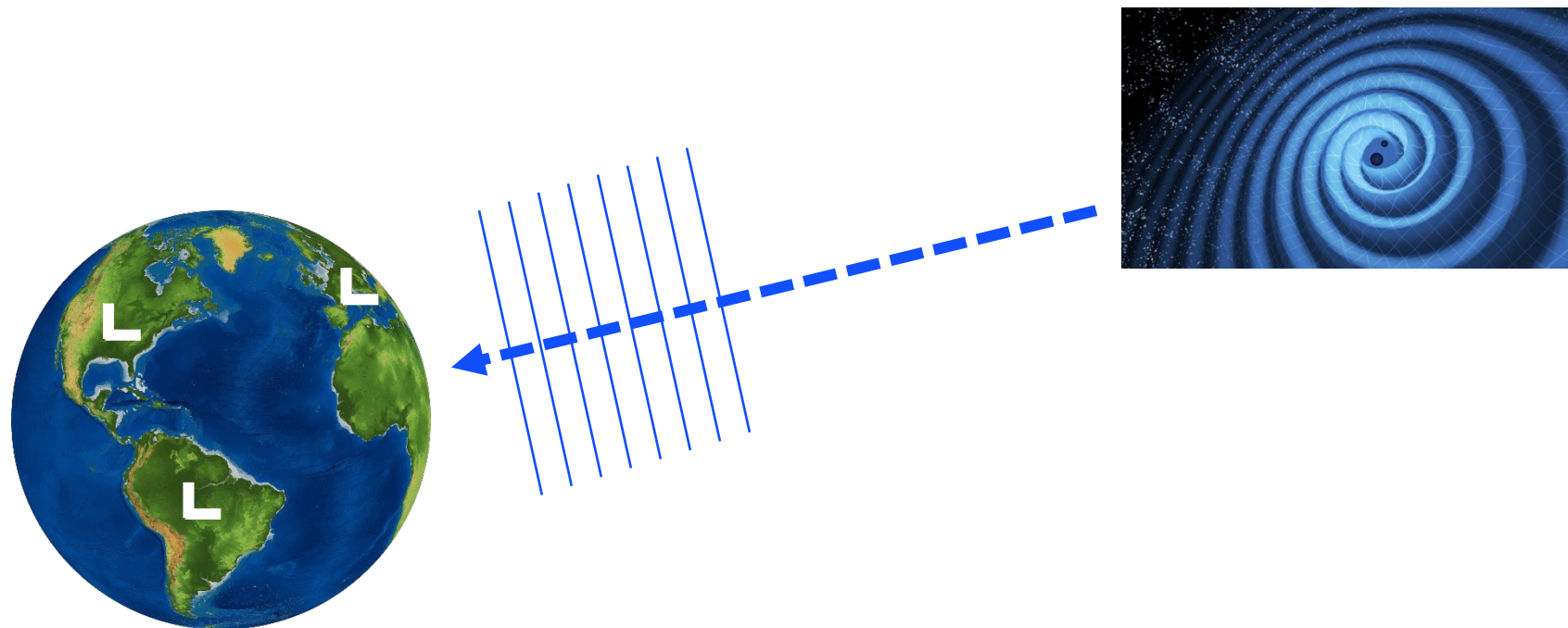
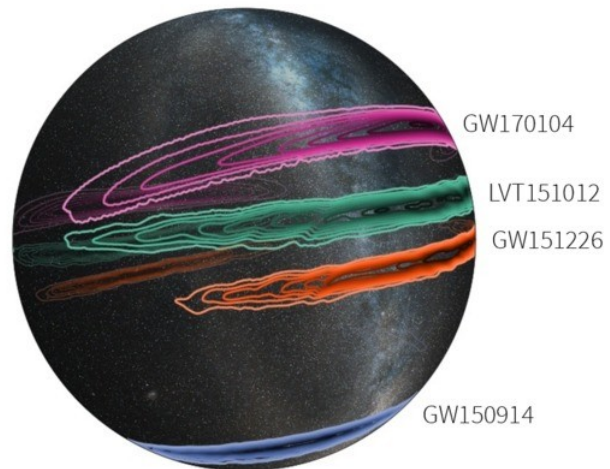


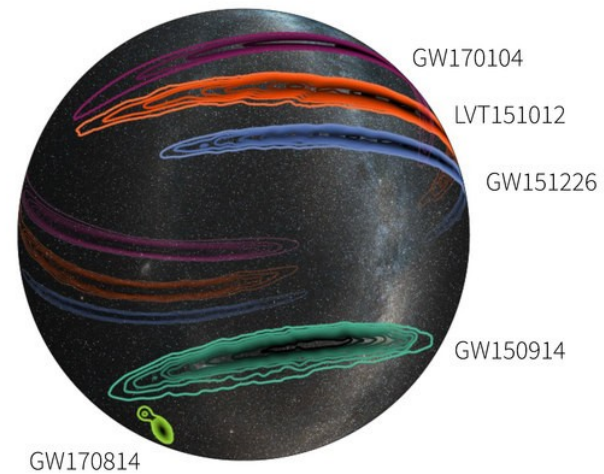
Image: Earth seen from the North Pole



Localization: before Virgo



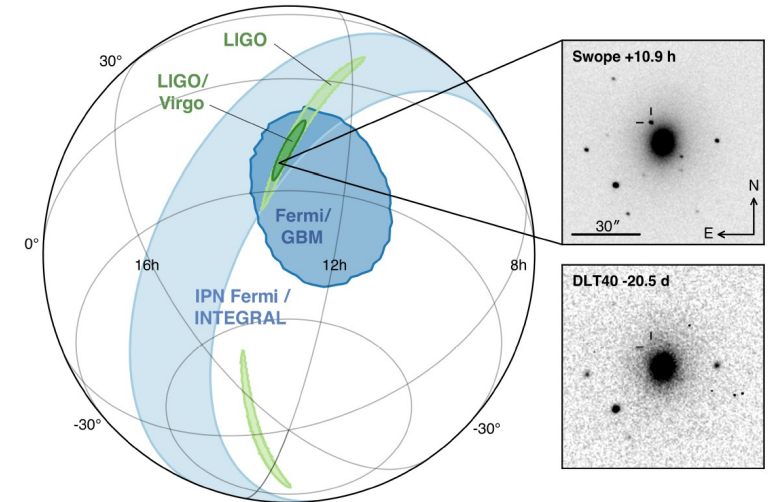
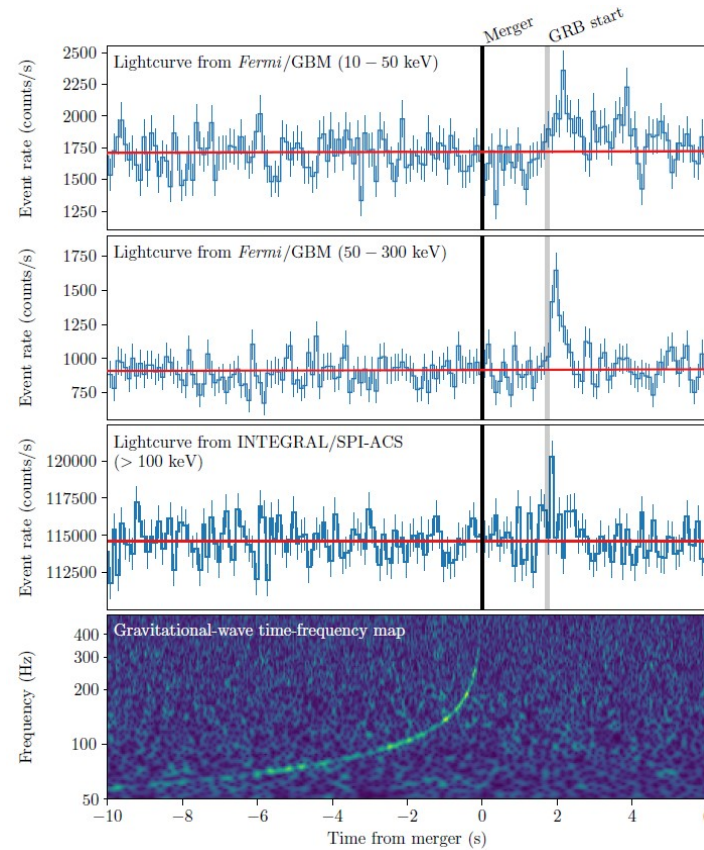
Localization: after Virgo



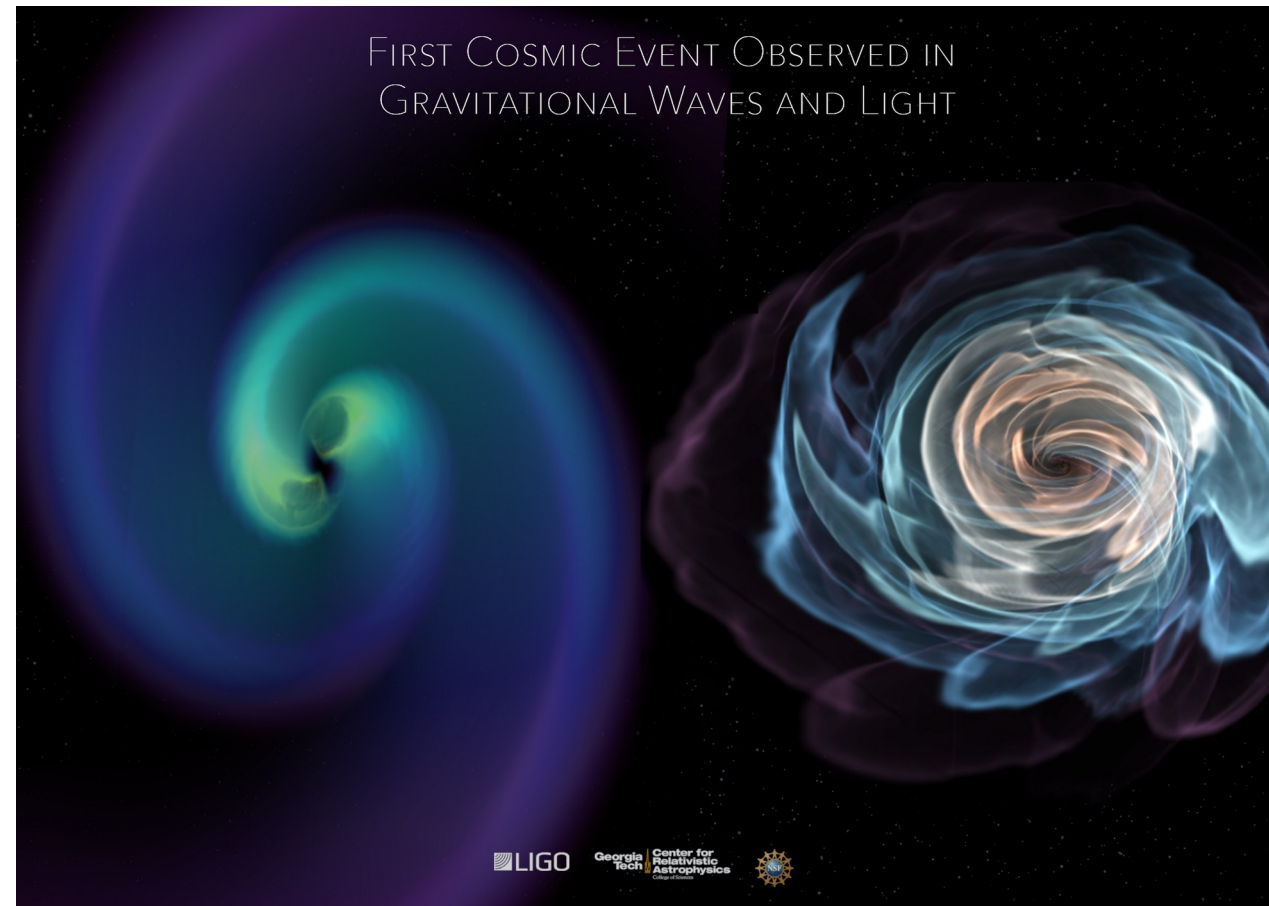
- Aug 17th, 2017 - GW170817: First detection of gravitational waves from a binary neutron star merger (BNS)

- ◆ Coincidence with the detection of a short gamma ray burst
- ◆ LIGO-Virgo localization
- ◆ Subsequent detection of the optical counterpart

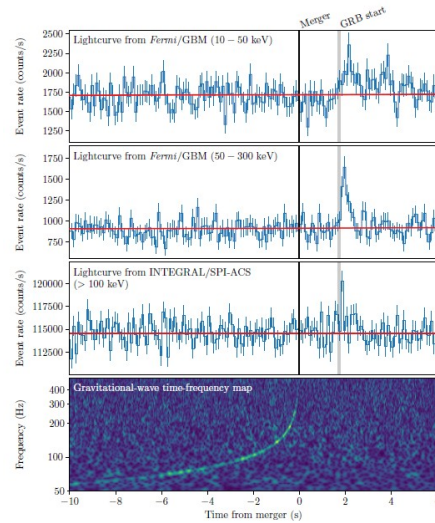
LIGO Scientific Collaboration and Virgo Collaboration
 Phys. Rev. Lett. 119, 161101 (2017)



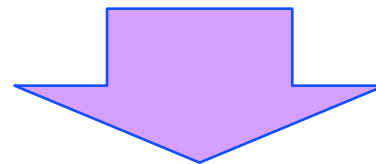
- The first combination of gravitational wave data and electro-magnetic observations allowed to gain insights in:
 - ◆ Fundamental physics
 - » Speed of gravitational waves
 - ◆ Astrophysics
 - » Gamma ray burst engine
 - » Kilonova, Heavy elements production
 - ◆ Cosmology
 - » First Hubble constant measurement with GW based distance measurement



- Gamma rays arrived 1.7 seconds after the gravitational wave

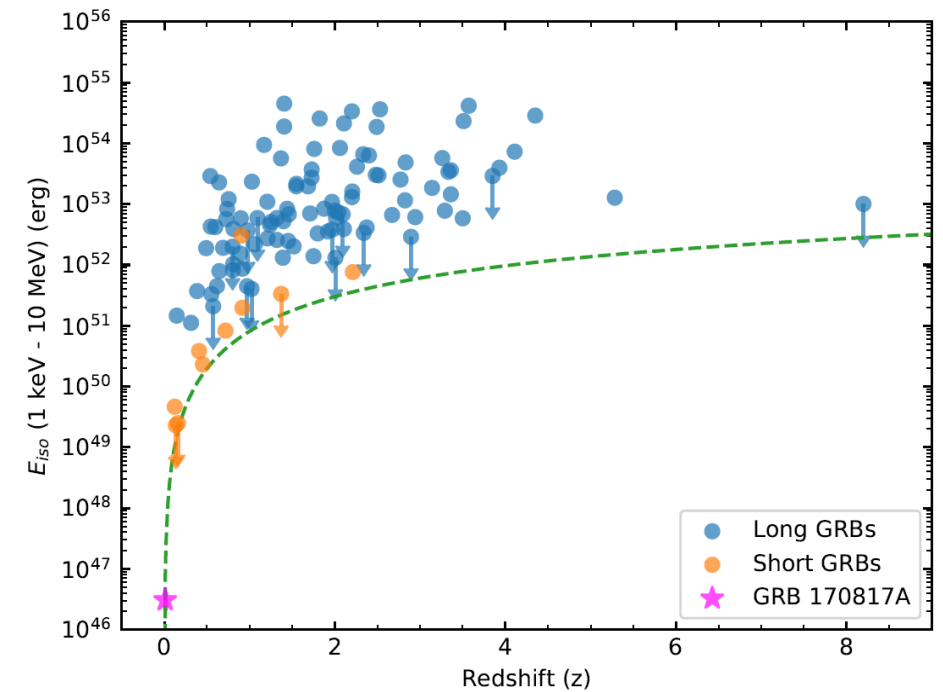
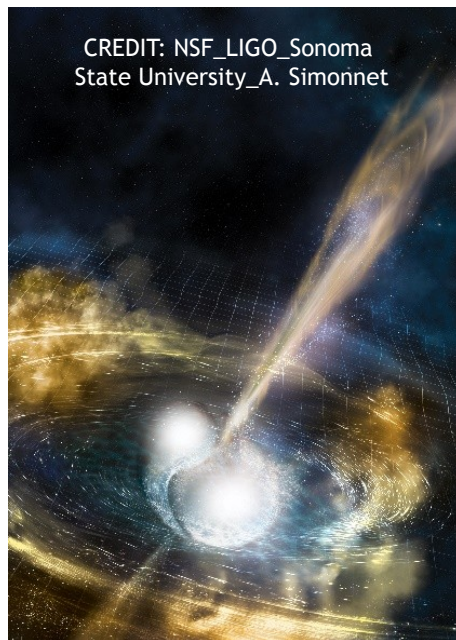


- Exact time of gamma rays emission not known within ~ 10 seconds
- But given the source distance, the “race” lasted 130 million years

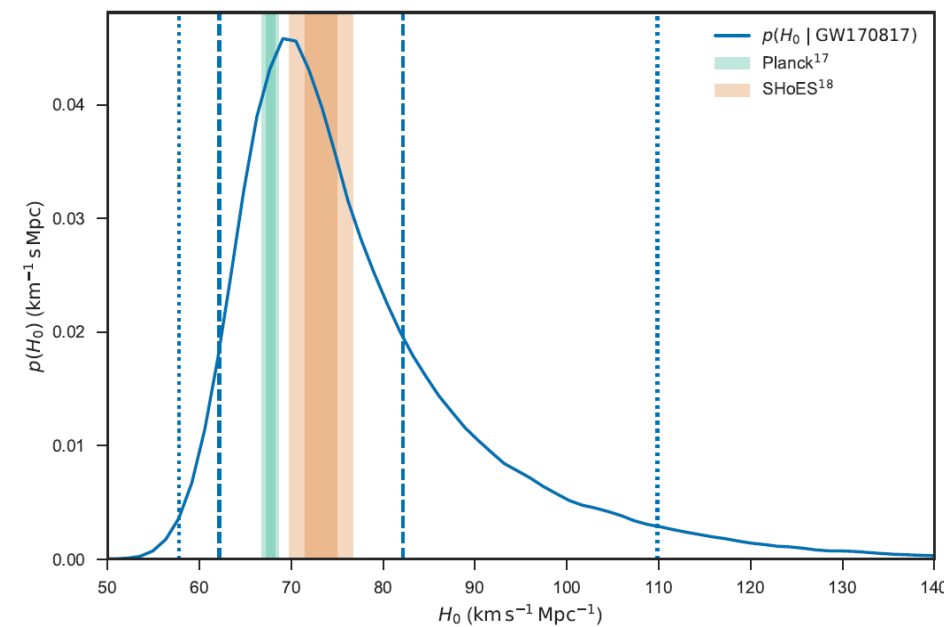


- Speed of Gravity \sim Speed of Light, within ~ 0.0000009 m/s

- Confirm that binary neutron stars mergers produce short gamma ray bursts
- This is the closest gamma-ray burst ever measured
- It is very faint: why?
 - ◆ Source inclination?
 - ◆ A new population of close and faint gamma ray bursts found?

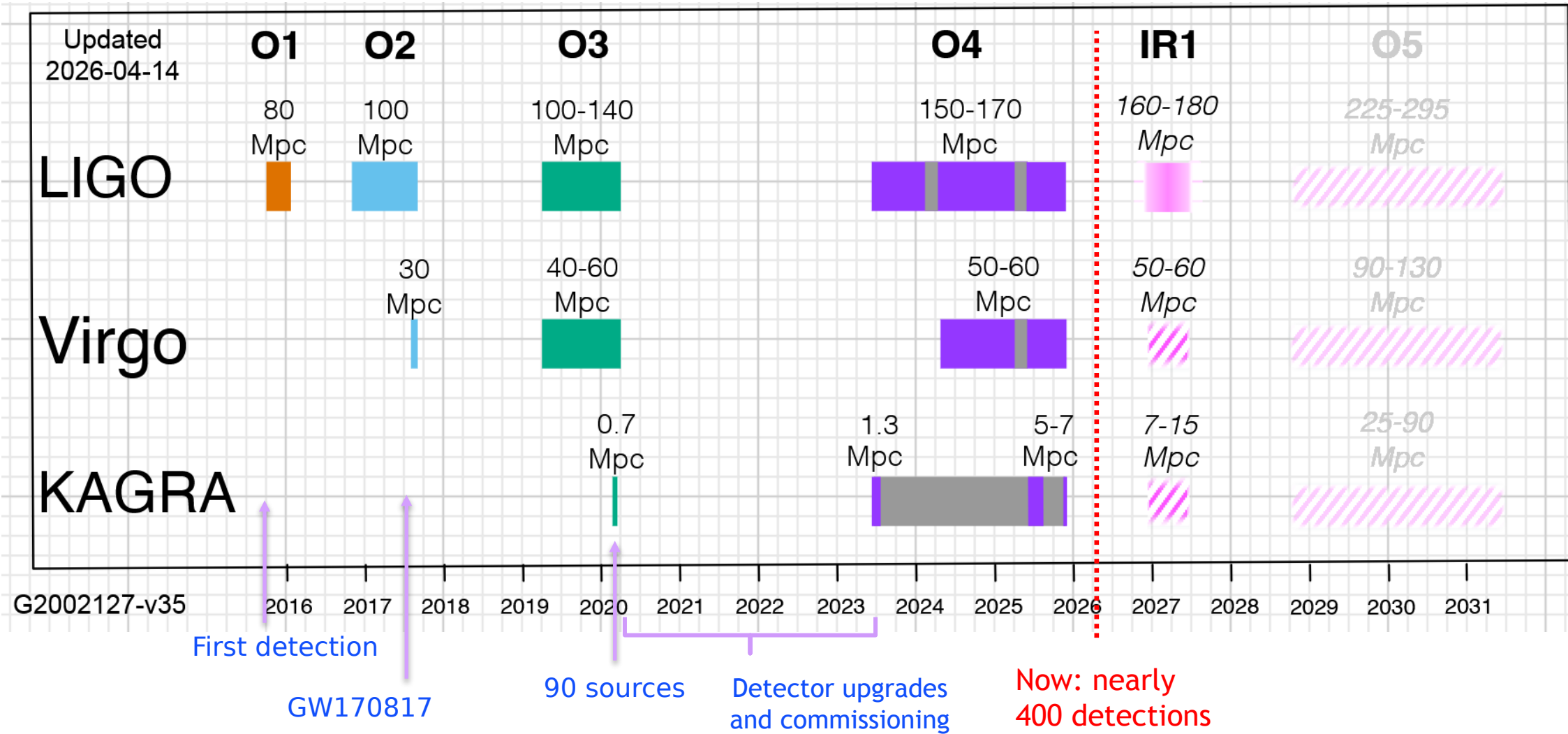


- From the gravitational waveform we know the source distance
 - New method to measure distances in astronomy
 - Result: $43.8_{-6.9}^{+2.9} \text{ Mpc}$
 - Precision will improve with more detectors
- From the optical observations we know the source velocity
 - Assuming it is part of NGC4993
- Measurement of the Hubble constant
 - $H_0 = 70.0_{-8}^{+12} \text{ km s}^{-1} \text{ Mpc}^{-1}$



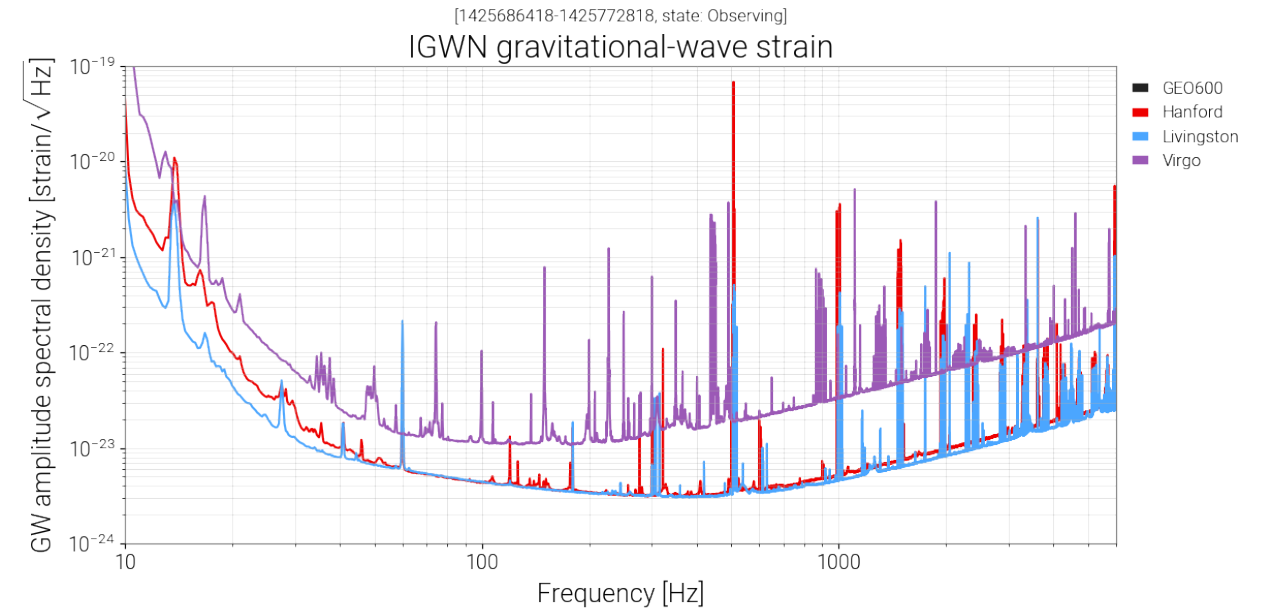
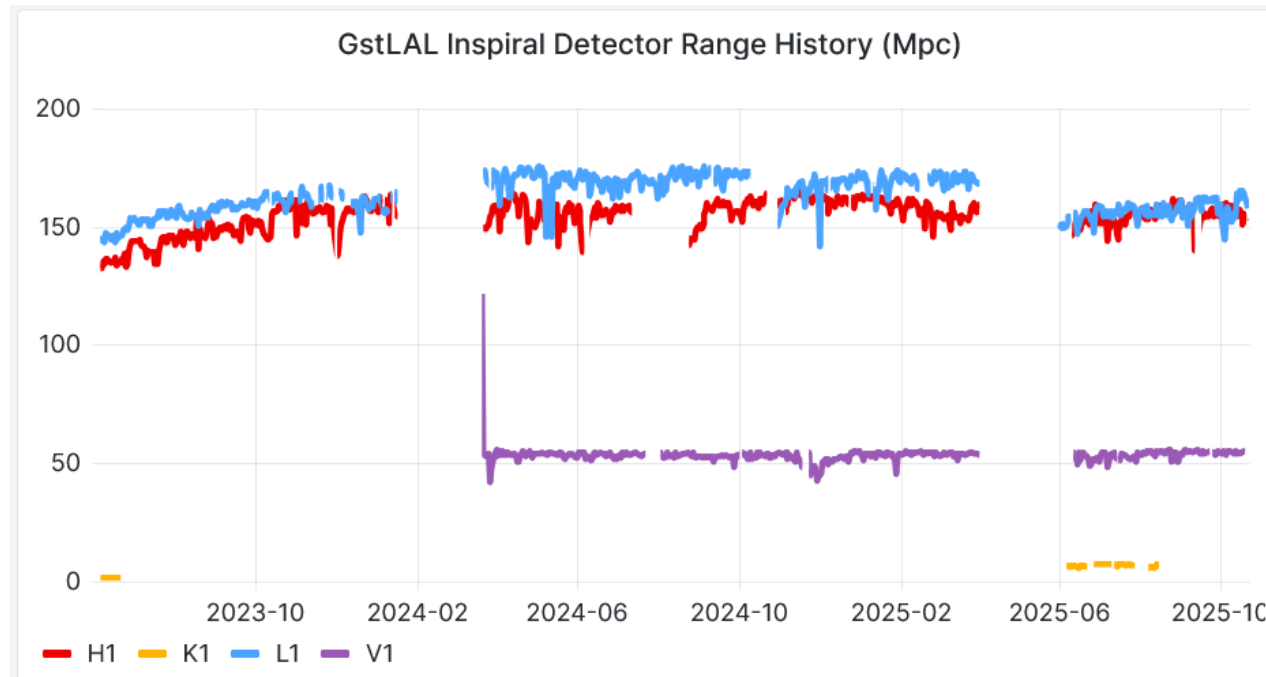
'A standard siren measurement of the Hubble constant with GW170817'
 The LIGO Scientific Collaboration & The Virgo Collaboration, et al.
 Nature, 16 October 2017.

Selection of latest results

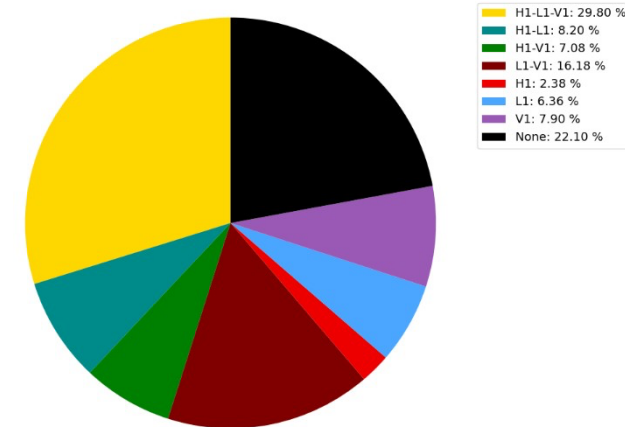


- O4 started on May 2023

- ◆ Initially with the two LIGO detectors
- ◆ Virgo joined since March 2024
- ◆ KAGRA now joining as well



plot_HLV_science_segments: Number of detectors online
2024-04-10 15:00:00+00:00 UTC -> 2025-10-20 19:00:03+00:00 UTC -- segments: DMT-ANALYSIS_READY (H1-L1), SCIENCE (V1)



- So far 254 significant detection candidates during O4 (283 Total - 29 Retracted)

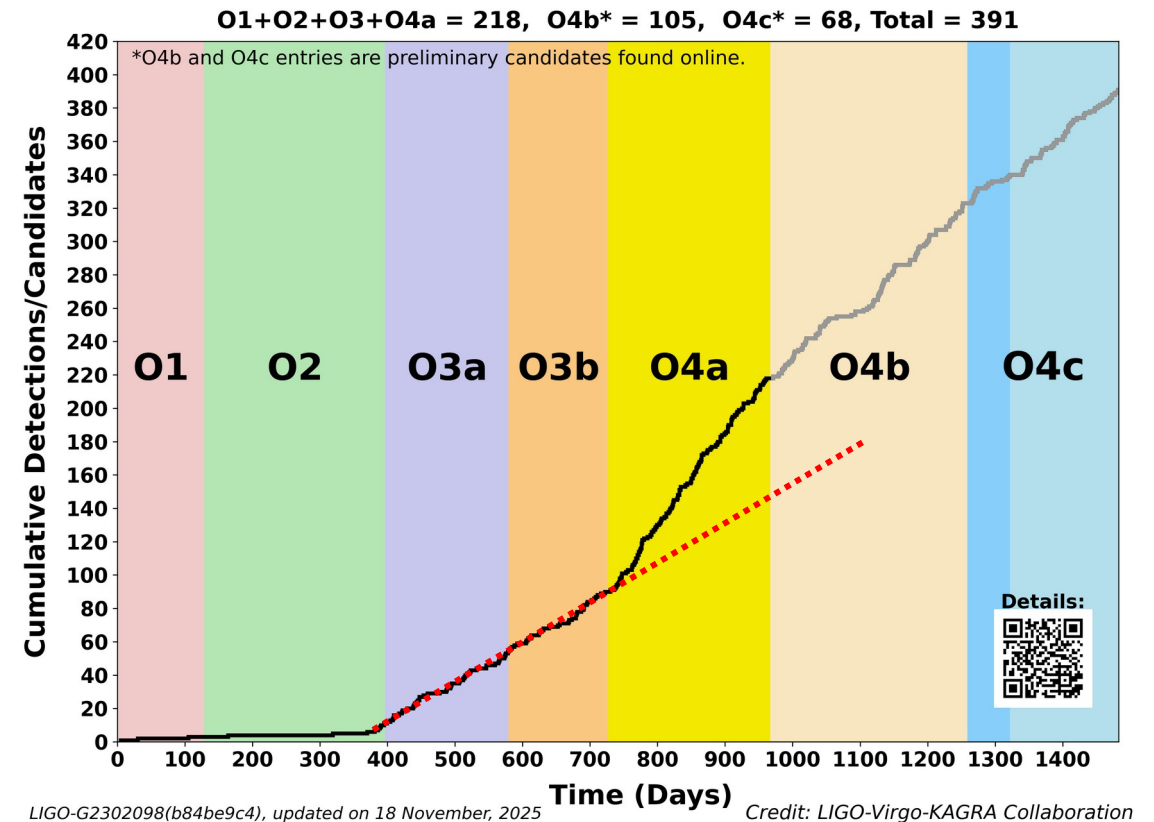
- ◆ See <https://gracedb.ligo.org/superevents/public/O4/>
- ◆ Event rate ~2.5/week, the advantage of upgrading

- Information provided

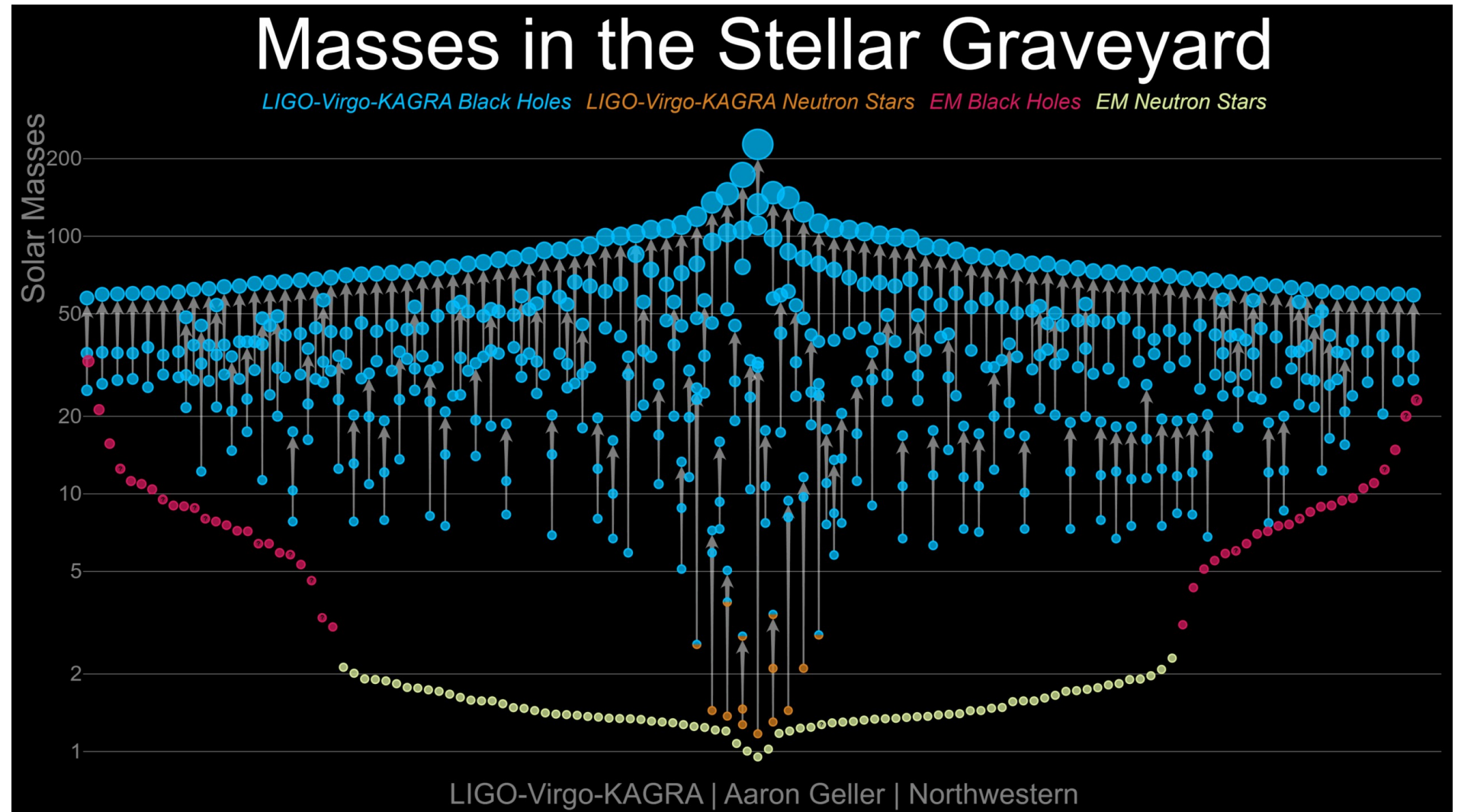
- ◆ Timing
- ◆ False alarm rate
- ◆ Localization/Distance
- ◆ Event type
 - » 1 NSBH (55%), BNS (37%) - S250206dm
 - » 1 NSBH (72%), BBH (28%) - S241109bn
 - » 1 NSBH (49%), BBH (48%) - S230627c
 - » 1 NSBH (62%), BNS (31%) - S230529ay
 - With BH in the Mass gap
 - » The others are BBH or most probably BBH

- Status

- ◆ O4 ended on Nov the 18th 2025
- ◆ O4a data released!



- O1+O2+O3+O4a
 - ◆ 218 events



- First neutron star - black hole mergers detected
 - ◆ GW200105 and GW200115
- No optical counterparts
 - ◆ Relatively far (several 100 Mpc)
 - ◆ Likely that black hole was massive enough to swallow the neutron star as a whole

LIGO Scientific Collaboration and Virgo Collaboration
Astrophys. J. Lett. 915, L5 (2021)



FACT SHEET GW200105 GW200115 First observation of neutron star-black hole (NSBH) binaries

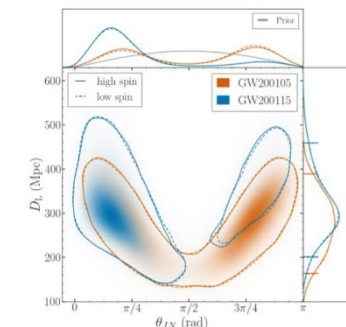
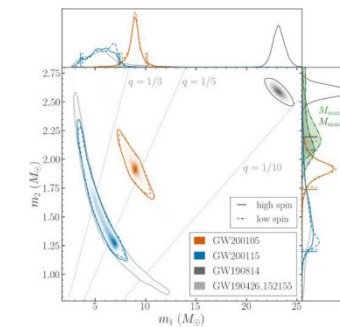
All parameter ranges correspond to 90% credible bounds. Quoted values are for high spin (<0.99) neutron-star priors

	GW200105	GW200115
observed by	LIGO Livingston and Virgo	LIGO Livingston & Hanford and Virgo
date, time	5 Jan 2020, 16:24:26 UTC	15 Jan 2020, 04:23:10 UTC
likely distance	170 to 390 Mpc	200 to 450 Mpc
source redshift	0.04 to 0.08	0.05 to 0.10
signal-to-noise ratio	13.9	11.6
false alarm rate	< 1 in 2.8 yr	< 1 in 100,000 yr
Source masses (M_{\odot})		
total mass	9.7 to 12.0	5.7 to 8.6
primary (BH)	7.4 to 10.1	3.6 to 7.5
secondary (NS)	1.7 to 2.2	1.2 to 2.2
mass ratio	0.18 to 0.30	0.16 to 0.61
BH spin	0.00 to 0.30	0.04 to 0.81
effective inspiral spin	-0.16 to 0.10	-0.54 to 0.04
effective precession spin	0.02 to 0.23	0.04 to 0.51

Inferred merger rate density of NSBH systems*: 12 to 120 $\text{yr}^{-1} \text{Gpc}^{-3}$

* Assuming GW200105 and GW200115 are representative of the NSBH population

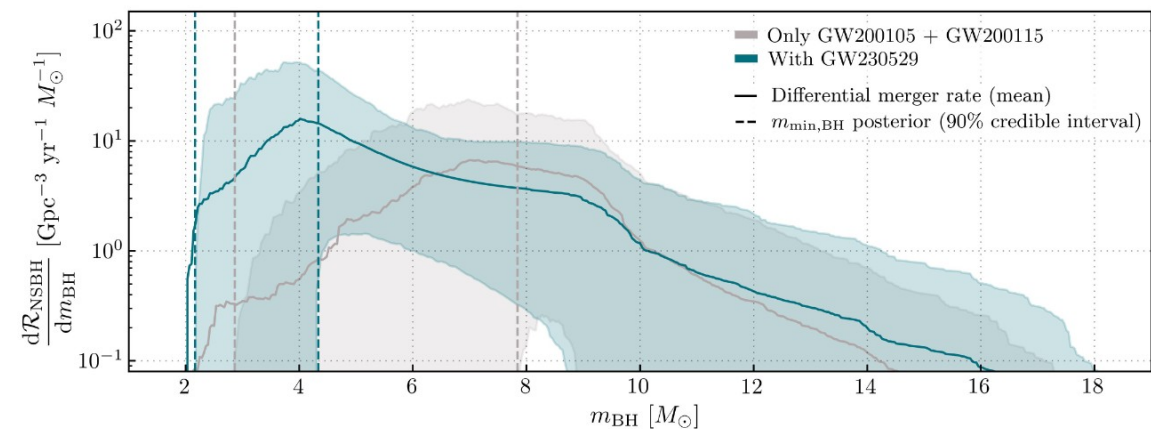
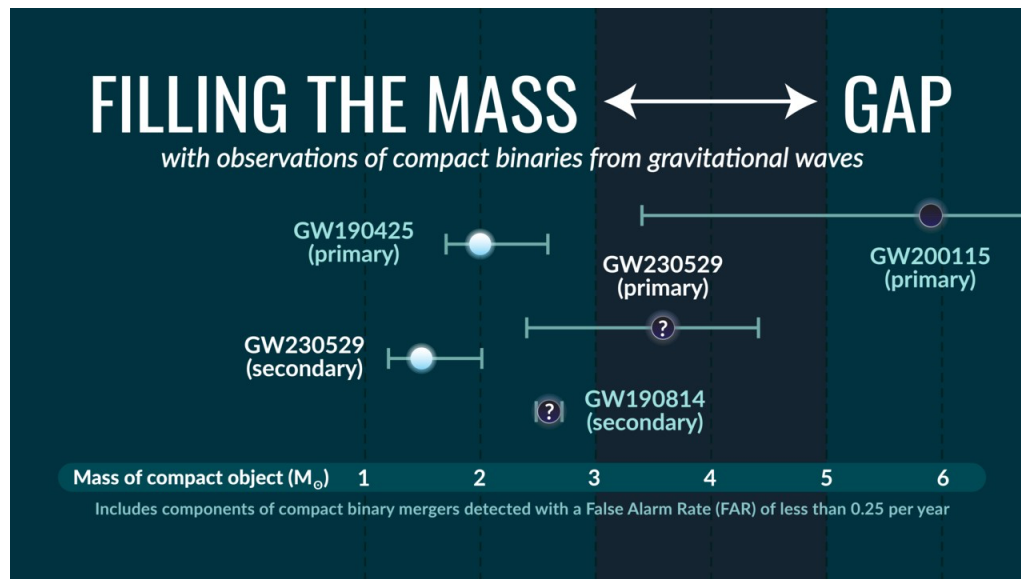
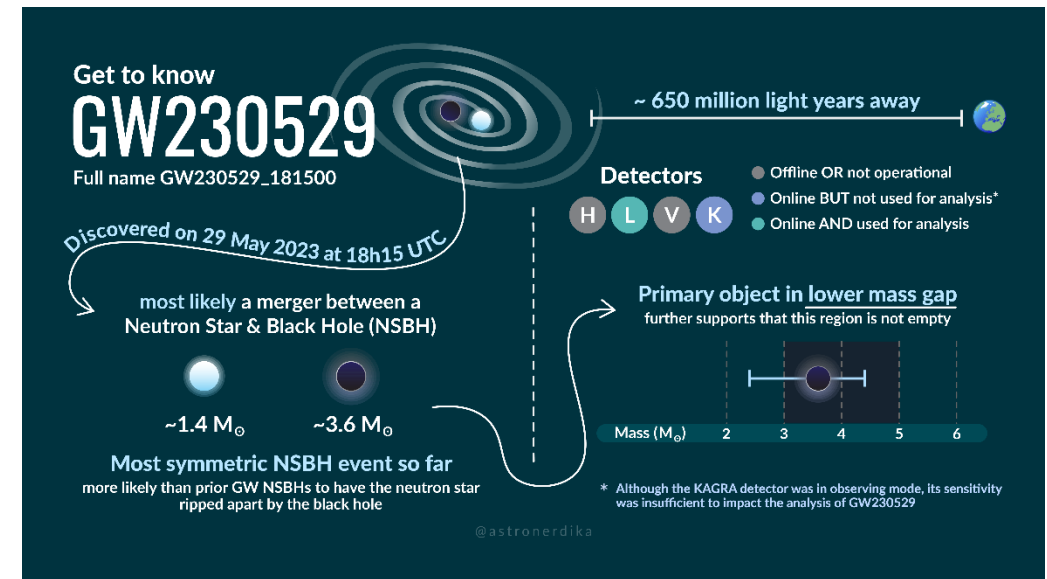
Images: companion masses (left), distance vs inclination (right), both with low (<0.05) and high (<0.99) spin priors for the neutron stars



Credits: B.S. Sathyaprakash, Penn State and Cardiff University

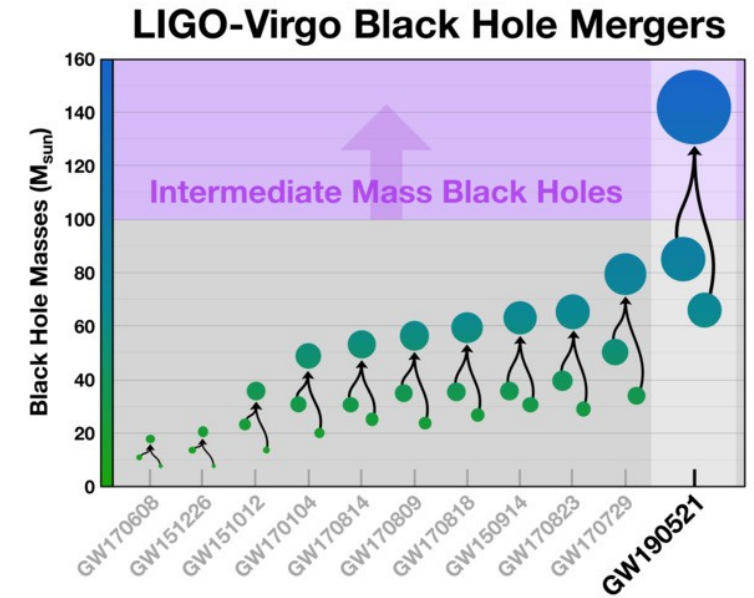
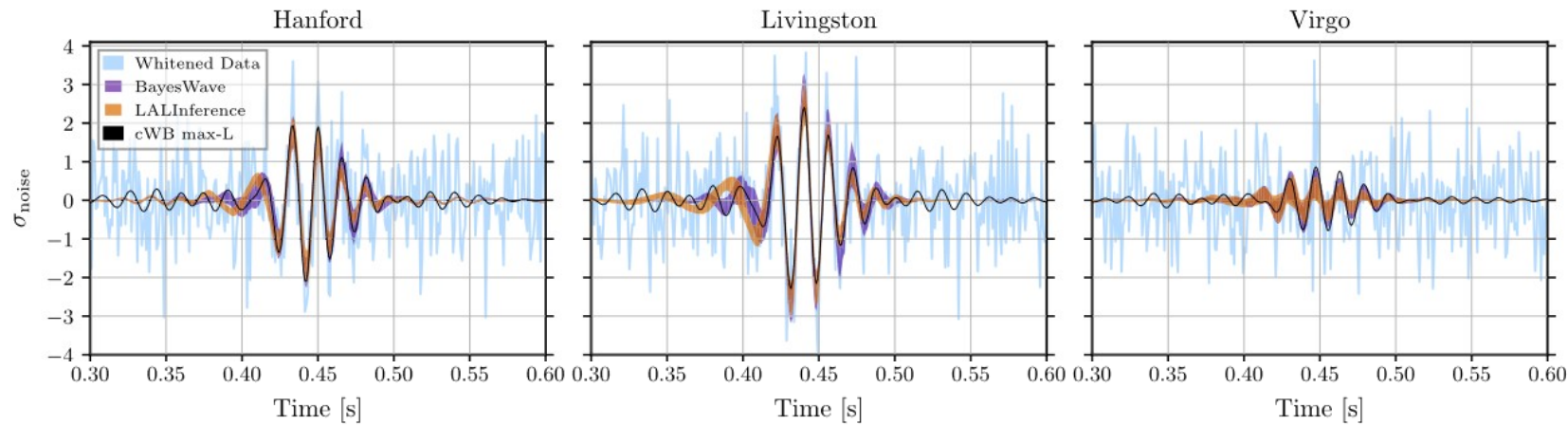
Merger of neutron star with black hole

- ◆ Black hole mass between $2.5 M_{\odot}$ and $5 M_{\odot}$
 - » In the so-called mass gap
- ◆ First of this type to involve a neutron star as secondary component
- ◆ Increase estimate of NSBH rate with small black hole
 - » Interesting for EM emission



- Merger of two black holes into a 142 M_{\odot} black hole

- ◆ First observation of IMBH
- ◆ Primary black hole mass $\sim 85 M_{\odot}$: in the pair instability mass gap
- ◆ Several scenarios considered for its formation

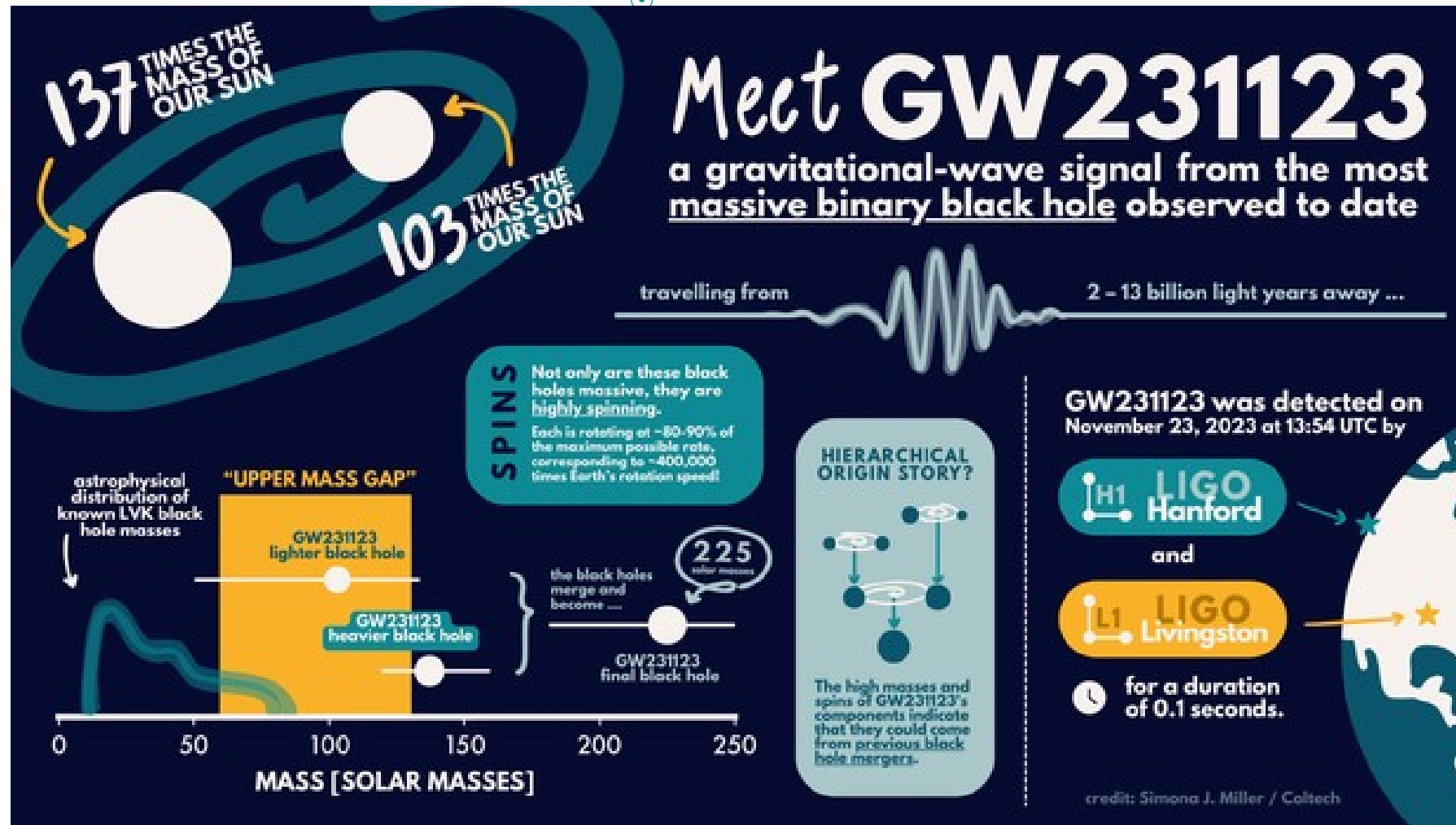


LIGO Scientific Collaboration and Virgo Collaboration
 Phys. Rev. Lett. 125, 101102 (2020)

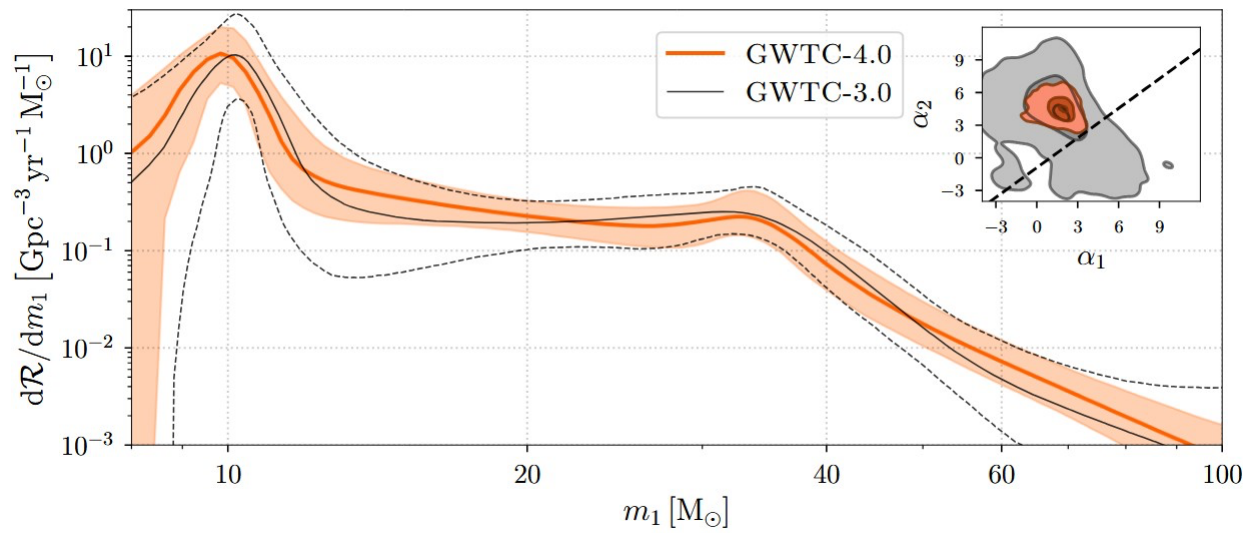
- Signal from exotic stars?

- ◆ Compatible with head-on collision of two horizonless vector boson stars (J.C. Bustillo et al. Phys. Rev. Lett. **126**, 081101)
- ◆ Only merger measured

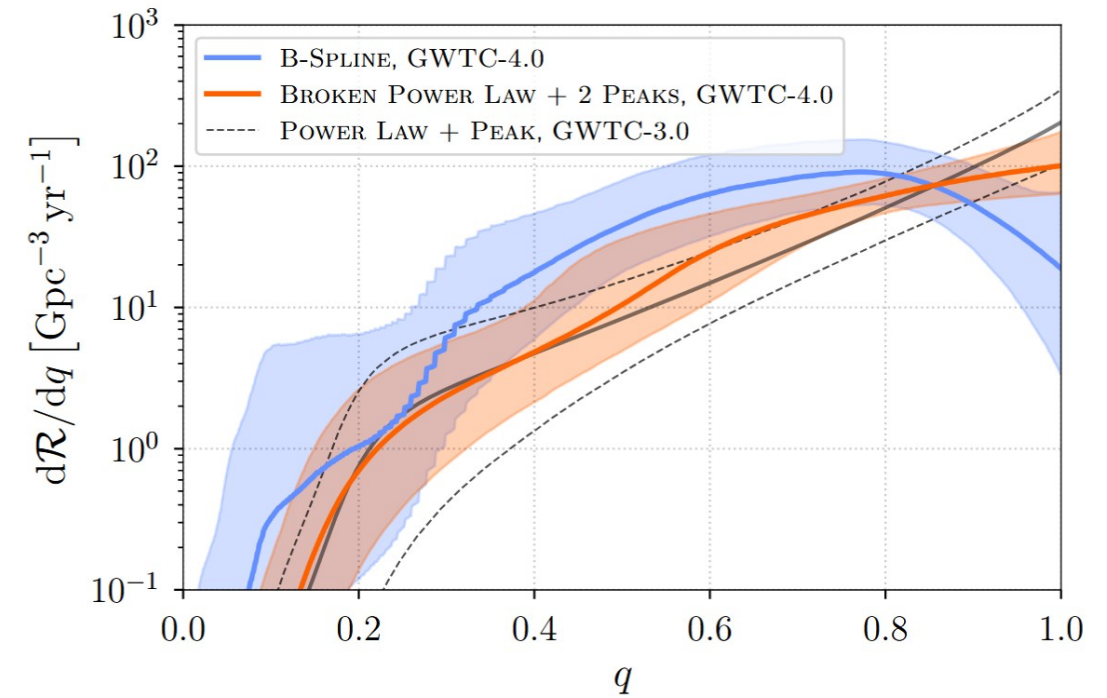
- Merger of two black holes into a 225 M_{\odot} black hole



- Larger number of detection allows population studies
- Peaks visible in the black hole mass distribution



Primary mass

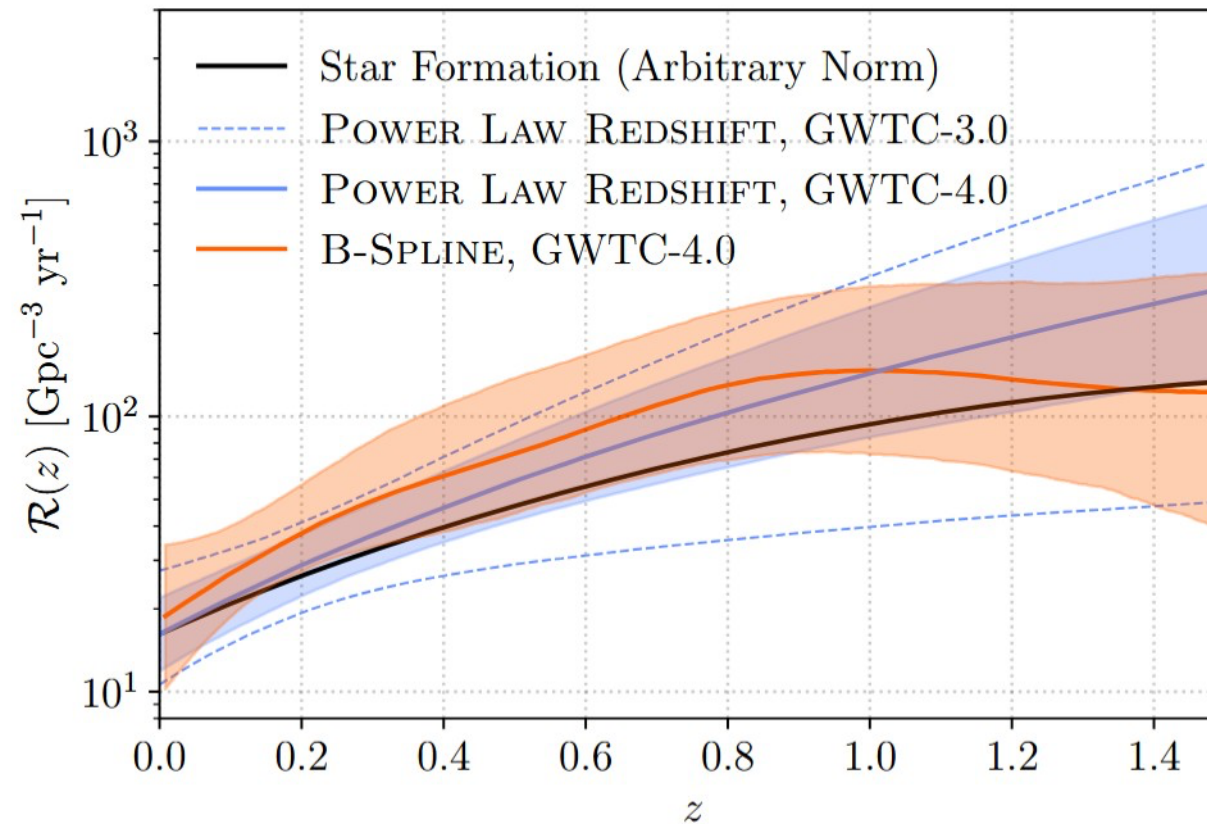


Mass ratio

LIGO Scientific Collaboration, Virgo Collaboration and KAGRA collaboration
arXiv:2508.18083 [astro-ph.HE] (2025)

● Evolution of merger rates with redshift

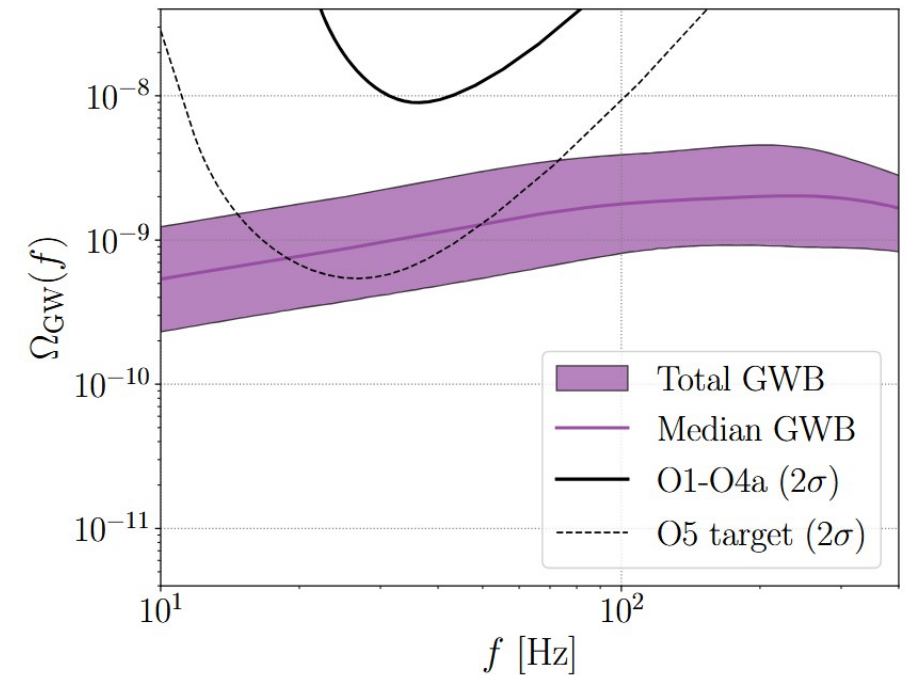
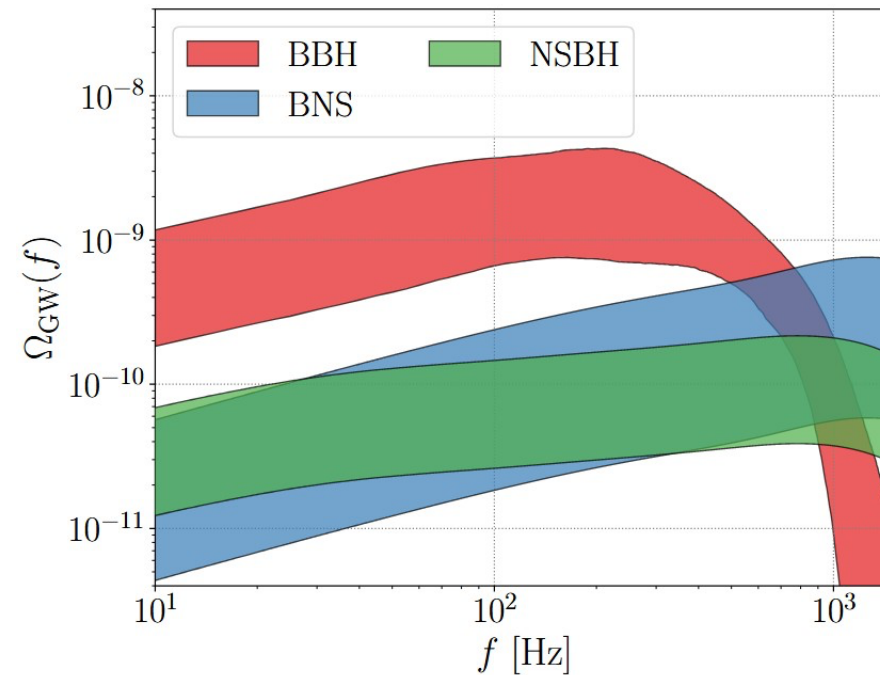
- ◆ Large merger rate at larger redshift
- ◆ Consistent with star formation rate



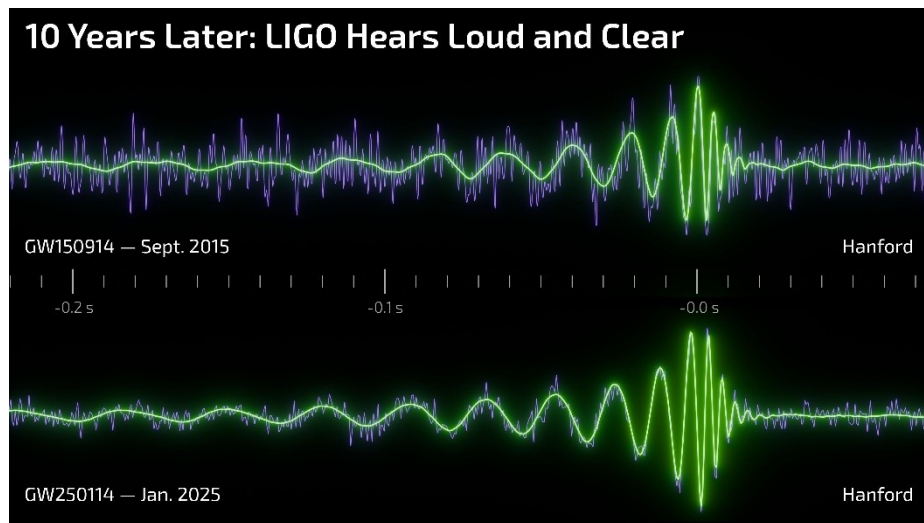
LIGO Scientific Collaboration, Virgo Collaboration and KAGRA
collaboration
arXiv:2508.18083 [astro-ph.HE] (2025)

- Upper limits so far
- From population studies to expected gravitational wave background due to superposition of all mergers in the Universe
 - ◆ Accessible to A+/Virgo_nEXT generation

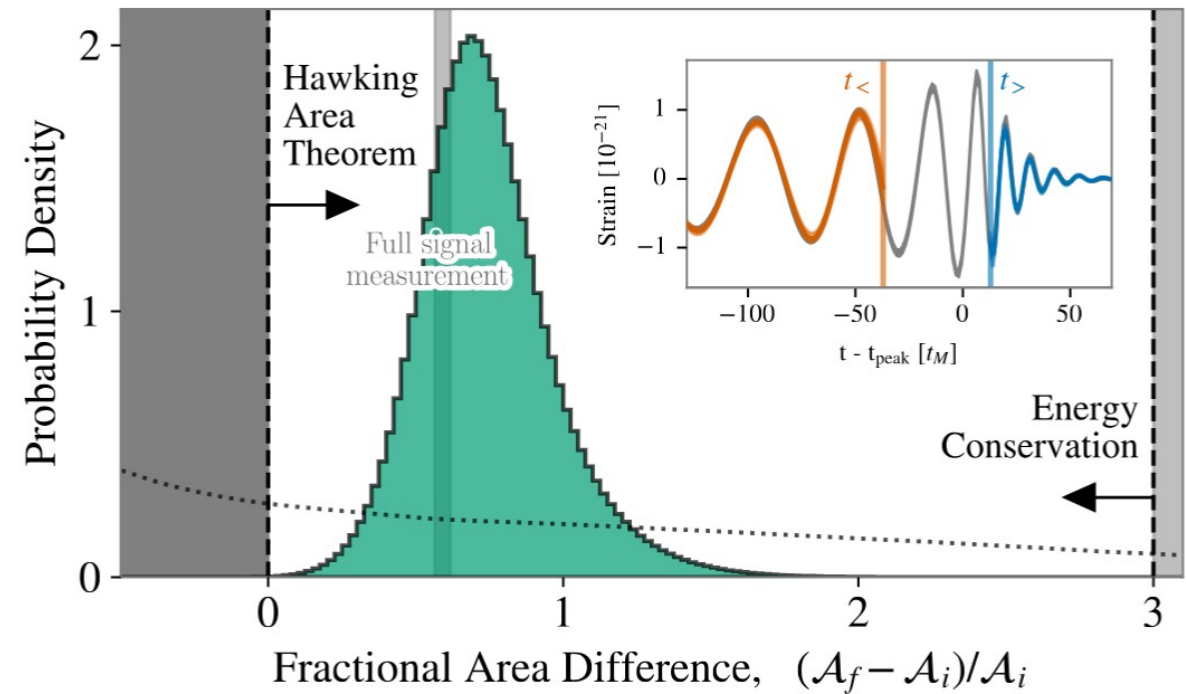
$$\Omega(f) = \frac{1}{\rho_c} \frac{d\rho}{d \ln f}$$



- From preliminary tests to precision tests
- Example:
 - ◆ GW250114
 - » Testing Hawking's Area Law and the Kerr Nature of Black Holes
 - ◆ Thanks to clean detection of final back hole ringing

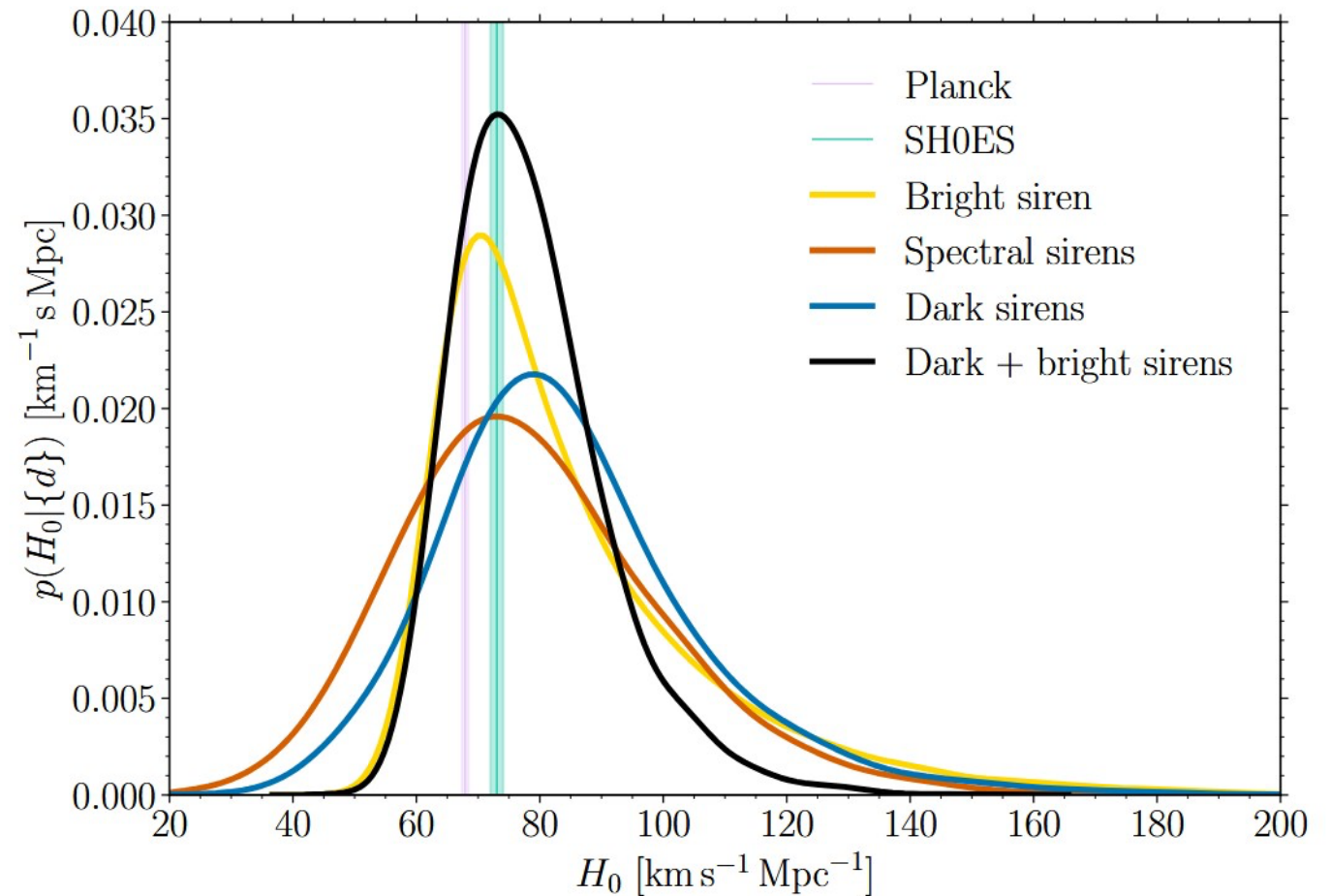


LIGO Scientific Collaboration, Virgo Collaboration and KAGRA collaboration
 Phys. Rev. Lett. 135, 111403 - Published 10 September, 2025
 arXiv:2509.08099 [gr-qc] (2025) submitted to PRL



- Use of GW signal to extract source distance
- Red-shift from:
 - ◆ Electromagnetic emission
 - » “bright siren”
 - » So far, only GW170817.
 - ◆ Features in source mass distribution
 - » “spectral siren”
 - ◆ Spectral siren + Galaxy catalog
 - » “dark siren”

LIGO Scientific Collaboration, Virgo Collaboration and KAGRA collaboration
arXiv:2509.04348 [astro-ph.CO] submitted to ApJL



- Direct detection of ultra-light bosons

- ◆ Ultra-light bosons (scalar, vector and tensors) interact with the detector
- ◆ Interesting limits placed in the energy range 10^{-12} - 10^{-13} eV
- ◆ See: LIGO Scientific Collaboration, Virgo Collaboration and KAGRA collaboration, arXiv:2510.27022 [astro-ph.CO] (2025)

- Indirect detection

- ◆ Ultralight vector bosons forming clouds around black holes
- ◆ Effects:
 - » Limit maximum black hole spin due to spin down
 - » Monochromatic GW emission from the boson clouds
 - » Effects on the binary black holes frequency chirp
- ◆ Searches in O4a data disfavor vector boson masses of the order of 10^{-13} eV
- ◆ See: LIGO Scientific Collaboration, Virgo Collaboration and KAGRA collaboration arXiv:2509.07352 [gr-qc] (2025)

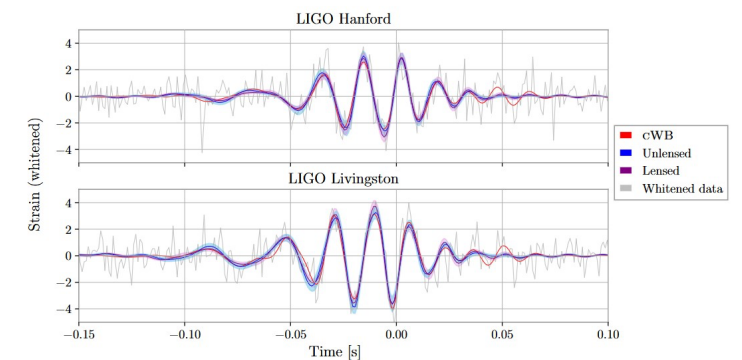
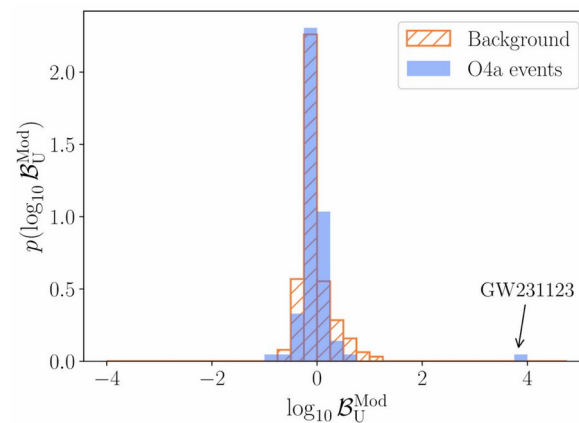
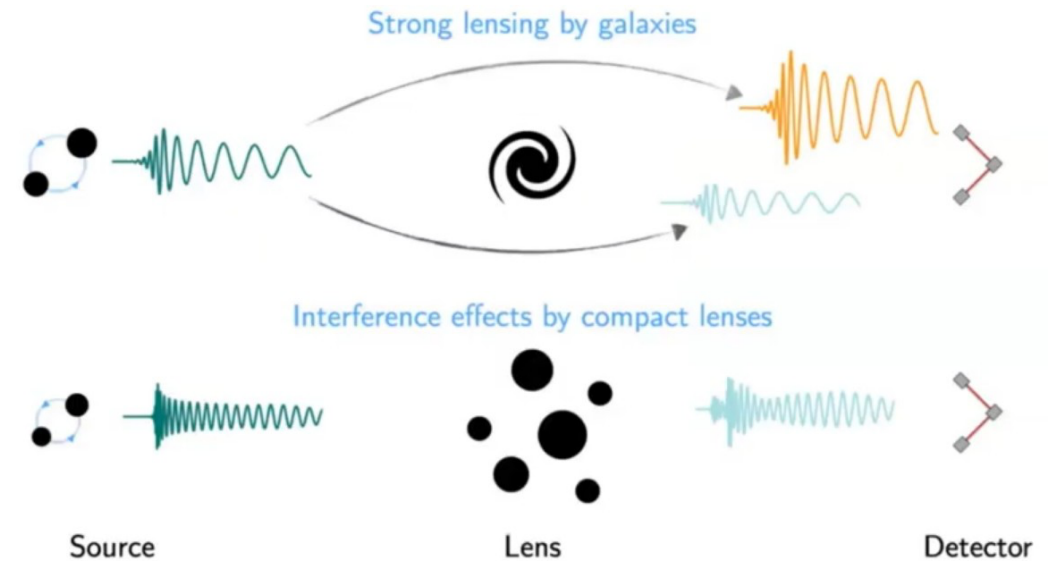
- Search done using BBH signals detected during O4a

- ◆ Strong-lensing searches with 3486 BBH pairs
- ◆ Search of sub-threshold lensed counterparts of 84 BBH
- ◆ Single-event analyses with an isolated point-mass lens mode
- ◆ No evidence of lensing

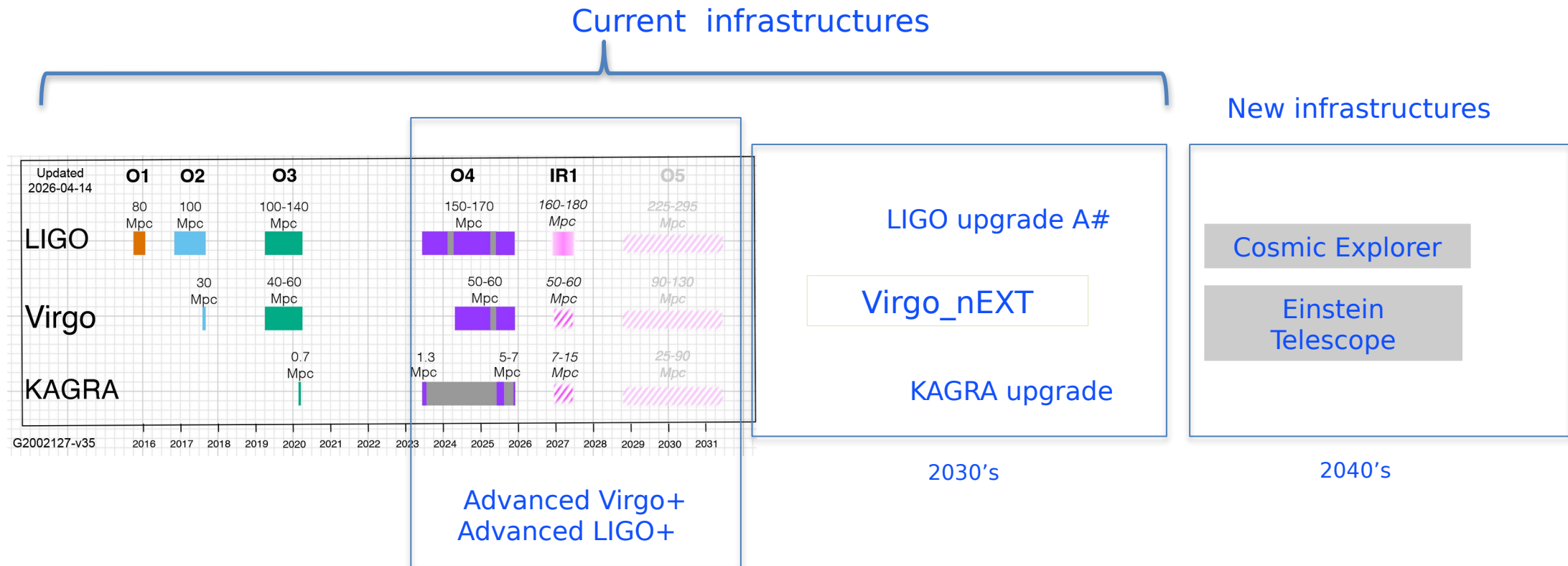
- GW231123

- ◆ Isolated point mass lens mode fits better than no-lensing
- ◆ But statistically not significant

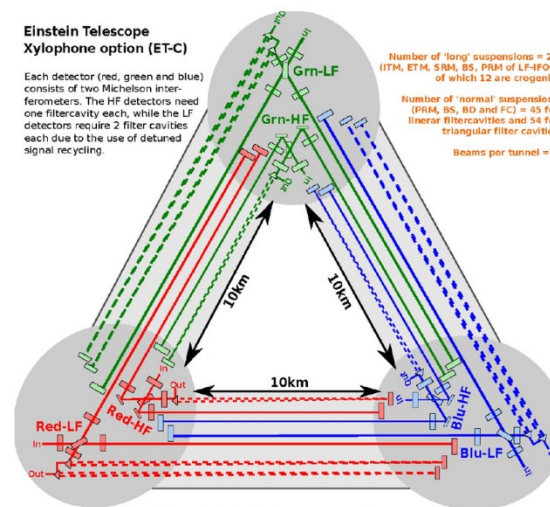
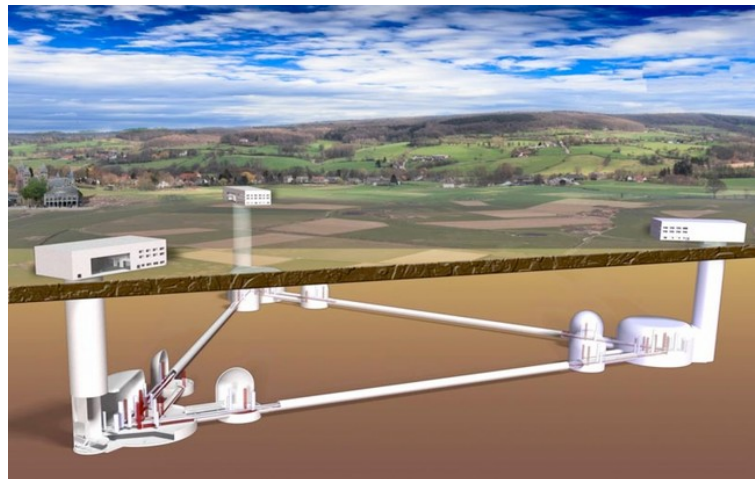
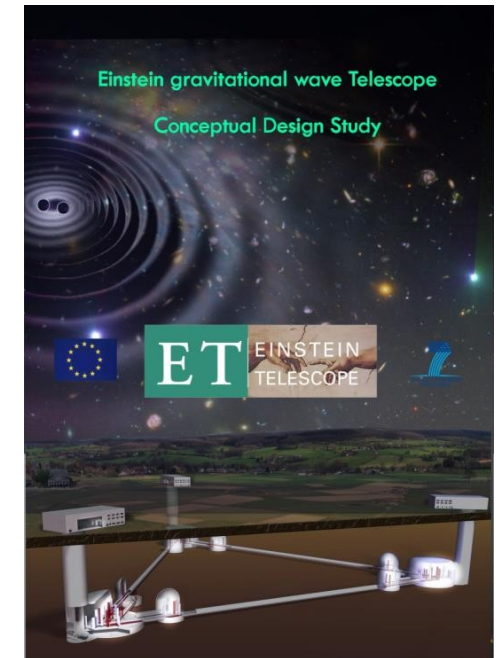
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 arXiv:2512.16347 [gr-qc] submitted to ApJL



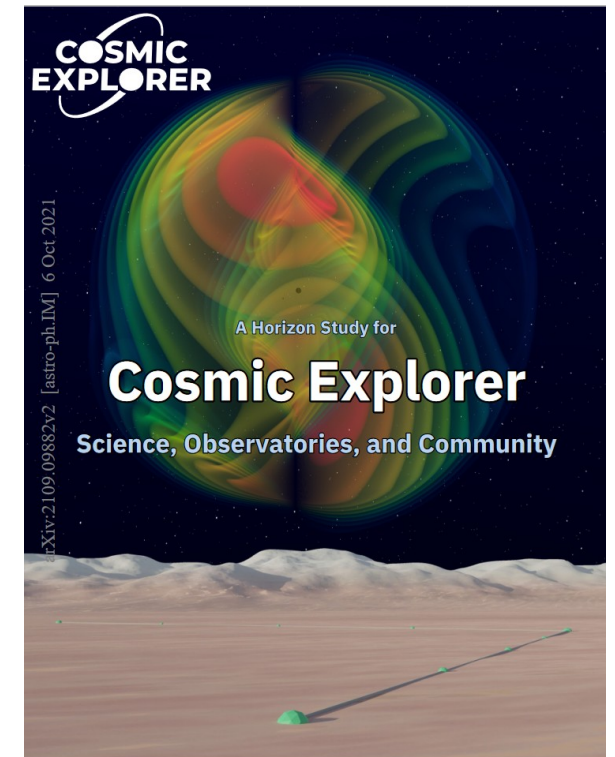
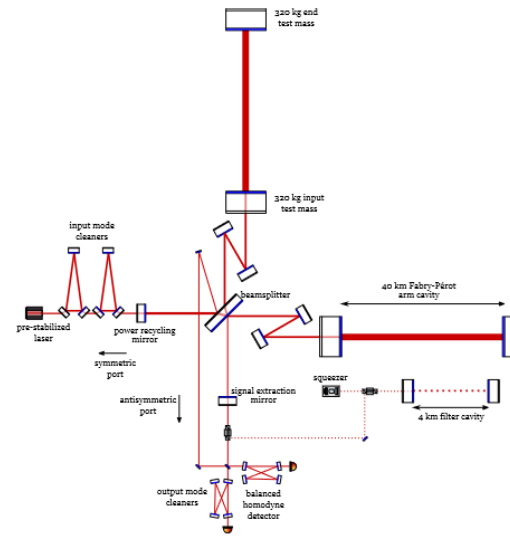
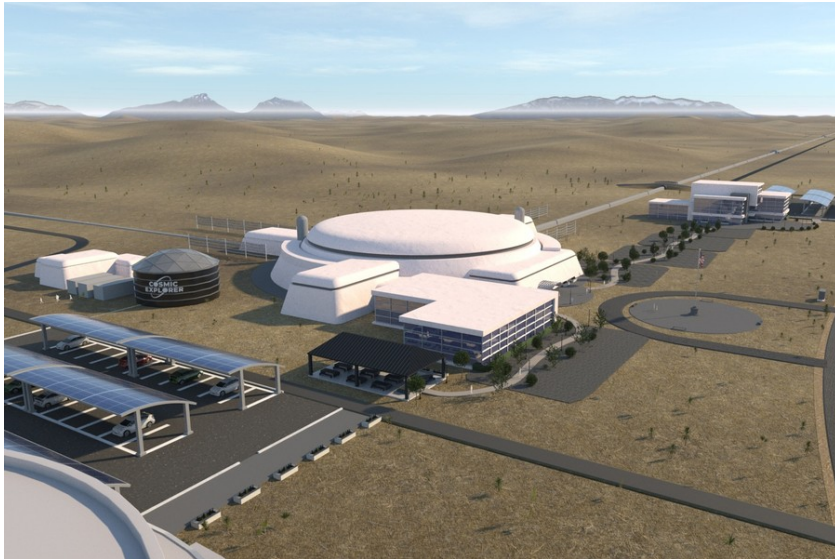
Perspectives

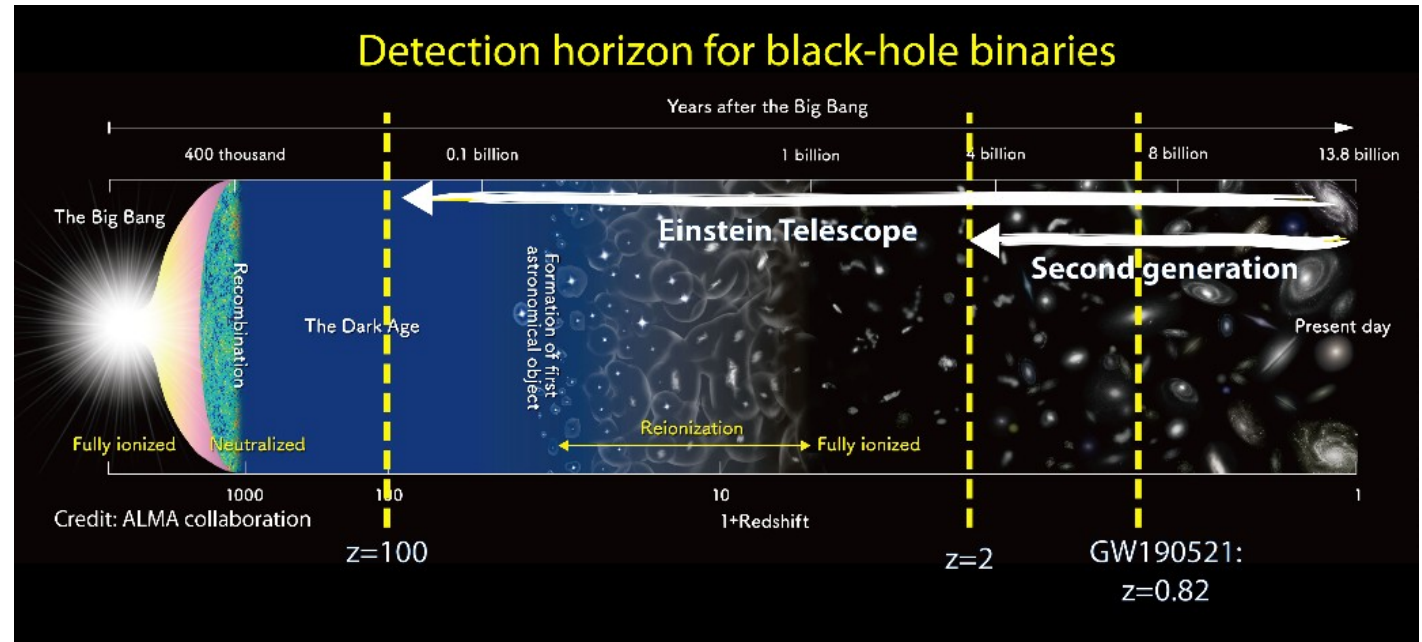
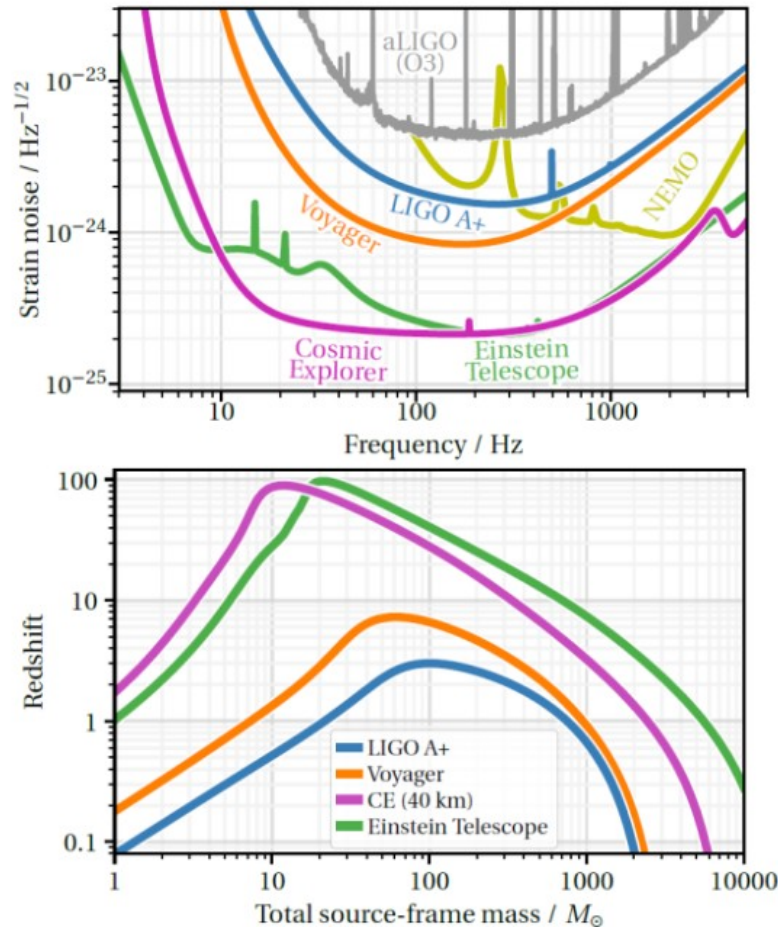


- A new European observatory for gravitational wave astronomy
 - ◆ Conceptual design established in 2011
 - ◆ Now part of ESFRI Roadmap (European Strategy Forum for Research Infrastructures)
- Main features
 - ◆ Underground
 - ◆ Triangular: three nested detectors 10 km long
 - ◆ Xylophone: two interferometers (one for low frequency and one for high frequency) for each detector
 - ◆ Cryogenic technology for the low frequency interferometer

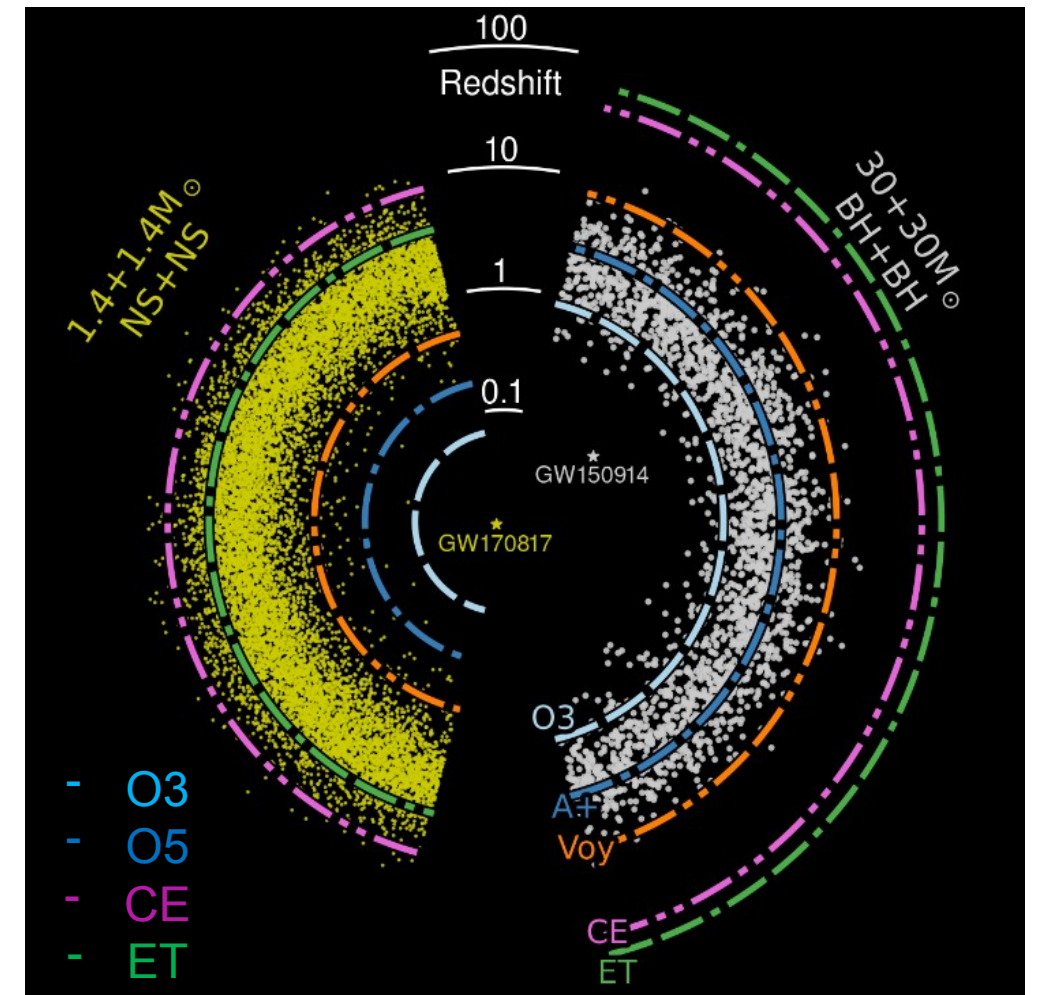


- A new infrastructure for gravitational wave astronomy in the US
 - ◆ A horizon study delivered to the NSF in 2021
- Main features
 - ◆ 2 L-shape, 40 km and 20 km long interferometers (ITF)
 - » Alternatives: one 40 km ITF, two 20 km ITF's
 - ◆ Based on LIGO technology but larger mirrors and suspensions
 - » Room temperature, same laser wavelength



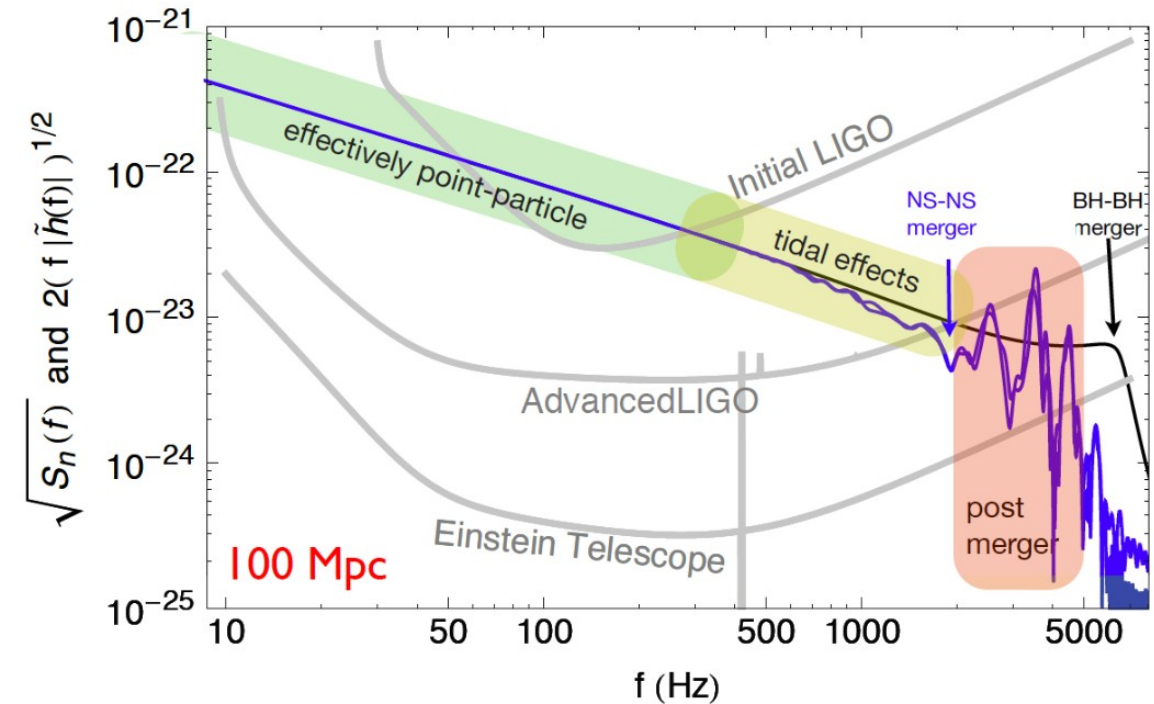


- Very high statistics
 - ◆ Several 10^5 BBH mergers per year
 - ◆ 10^5 BNS mergers per year
 - ◆ Several 10's of nearby well localized BNS mergers per year
- Black Holes and Neutron Stars Throughout Cosmic Time
 - ◆ Remnants of the First Stars (Pop III)
 - ◆ Seed Black Holes and Galaxy Formation
 - ◆ Formation and Evolution of Compact Objects



● Dynamics of Dense Matter

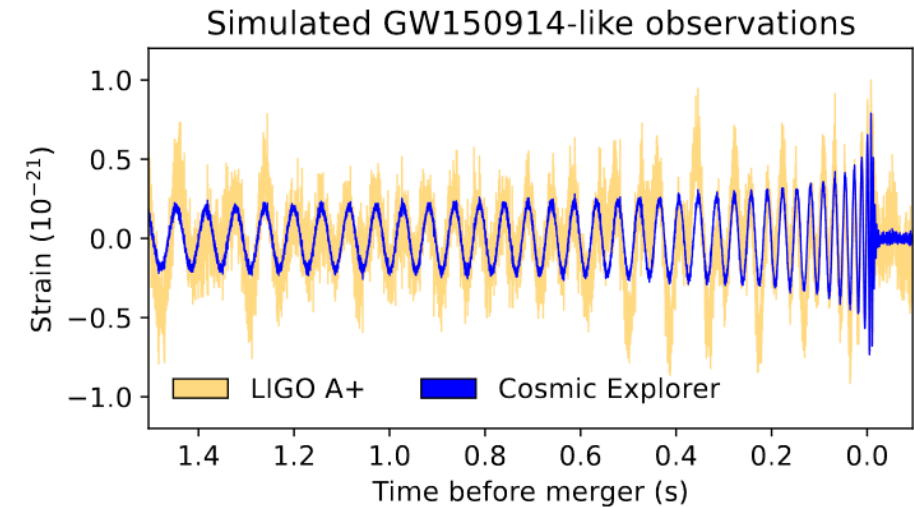
- ◆ Neutron Star Structure and Composition
 - » From BNS mergers
 - » From rotating neutron stars
- ◆ New Phases in Quantum Chromodynamics
 - » From BNS post-merger oscillations
 - » From supernovae or other burst type events
- ◆ Chemical Evolution of the Universe
 - » From a large number of kilonovae detections
 - » From BH mass distribution vs redshift
- ◆ Gamma-Ray Burst Jet Engine
 - » From BNS and NSBH orbit inclination measurements



M. Maggiore et al. JCAP 03 (2020) 050

● Fundamental Physics from Extreme Gravity

- ◆ Nature of Strong Gravity
 - » From precision tests of GR
 - » From search of extra polarizations
 - » From delays in γ -ray vs GW detections
- ◆ Unusual and Novel Compact Objects
 - » From rare uncommon mergers of BH's and NS's
 - » From exotic compact objects
- ◆ Dark Matter and Dark Energy
 - » From dark matter clouds around BH and NS
 - » From study of GW propagation
 - » From GW sources as standard candle
- ◆ Early Universe
 - » From gravitational wave background



[M. Evans et al. arXiv:2109.09882v2](https://arxiv.org/abs/2109.09882v2)

- General Introduction
- +
- Fundamental Physics with ET
- +
- Cosmology with ET
- +
- Population studies and astrophysical background
- +
- Multi-messenger observations in the ET era
- +
- Synergies of ET with other gravitational-wave obse
- +
- Subatomic Physics with ET
- +
- Stellar collapse and rotating neutron stars
- +
- Waveforms
- +
- Tools for assessing the scientific potentials of dete
- +
- Data Analysis
- Contributions
- Acknowledgments
- List of Acronyms

ET-0036C-25

The Science of the Einstein Telescope

Einstein Telescope collaboration

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5 Mar 2025

- The first detection of a binary black hole merger open the era of gravitational wave astronomy
- The first detection of a BNS merger in coincidence with the electromagnetic observation started the epoch of multi-messenger astronomy
- O3&O4 allow first black holes population studies and detection of more rare events
- Progresses made thanks to the reduction of noise in present detectors. They will reach the limitations due to the infrastructure during the next decade.
- This is just the beginning.
- 3G detectors will allow very high statistics and very large SNR, enabling the detection of most of the compact binaries mergers in the Universe
- Europe and the US have started building a plan for 3G. Some discussions in China.