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An overview of the LIGO-Virgo-Kagra observational science and results

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on behalf of the LIGO-Virgo-Kagra Collaboration

26/08/2024

LIGO VIRGO KAGRA

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Summary

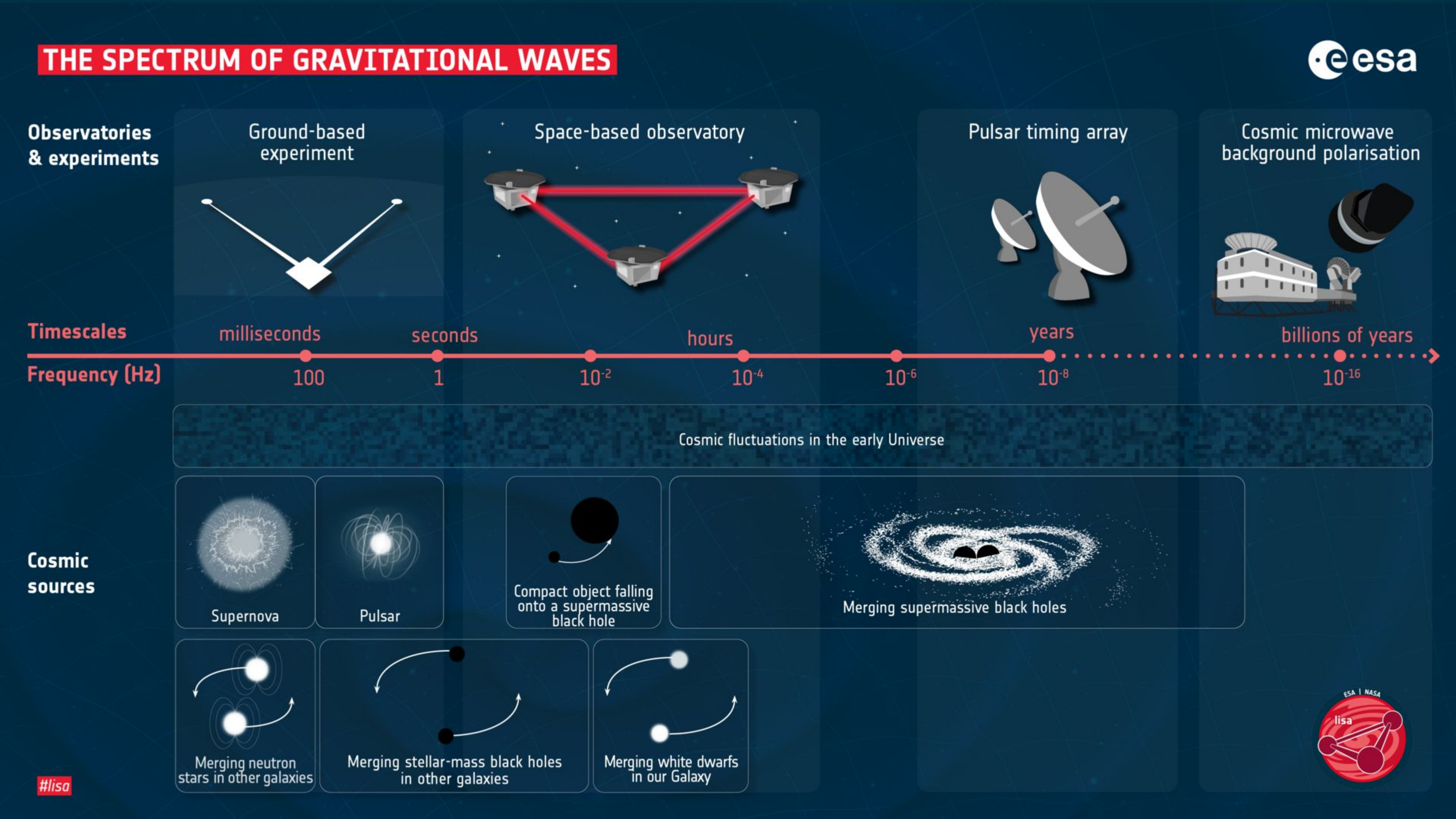
A *<u>brief, biased, limited</u>* overview on gravitational wave (GW) science and results

LIGO-Virgo-Kagra (LVK) Collaboration: more than 2000 scientists from >200 groups all over the world

A lot of science and results:

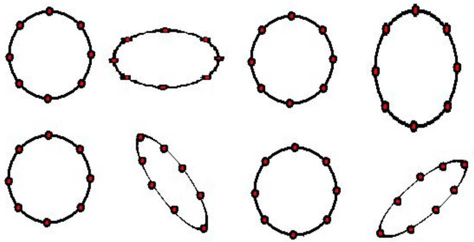
- opened a new “window” on the Universe
- first detection in run O1, first three detector event and first multimessenger event in O2
- from the last observing run (O3) → 52 LVK papers
- O4 run on-going → first released papers, lots of analysis on-going!

GraCeDB: public alerts, skymaps, FAR, events time, probabilities
GWOSC: release of data for specific event

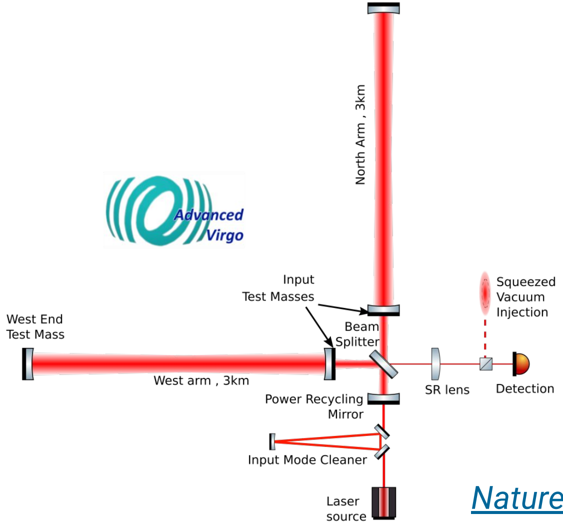


THE SPECTRUM OF GRAVITATIONAL WAVES
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations 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

GW ground-based detectors



- GWs admit two polarizations in GR and are transverse to the direction of propagation.
- GWs create a differential change in the distance between free falling masses
- Interferometers are good transducers to convert differential displacements into optical signals

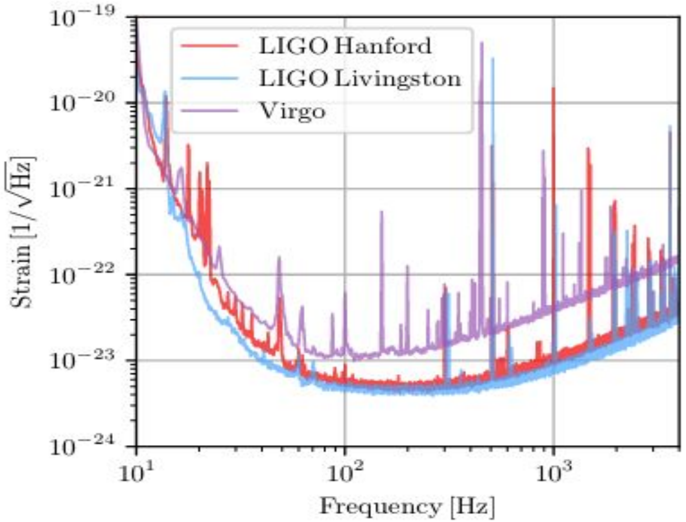


DARM displacement:

$$\Delta L_{\mathrm{free}} = \Delta L_x(t) - \Delta L_y(t)$$

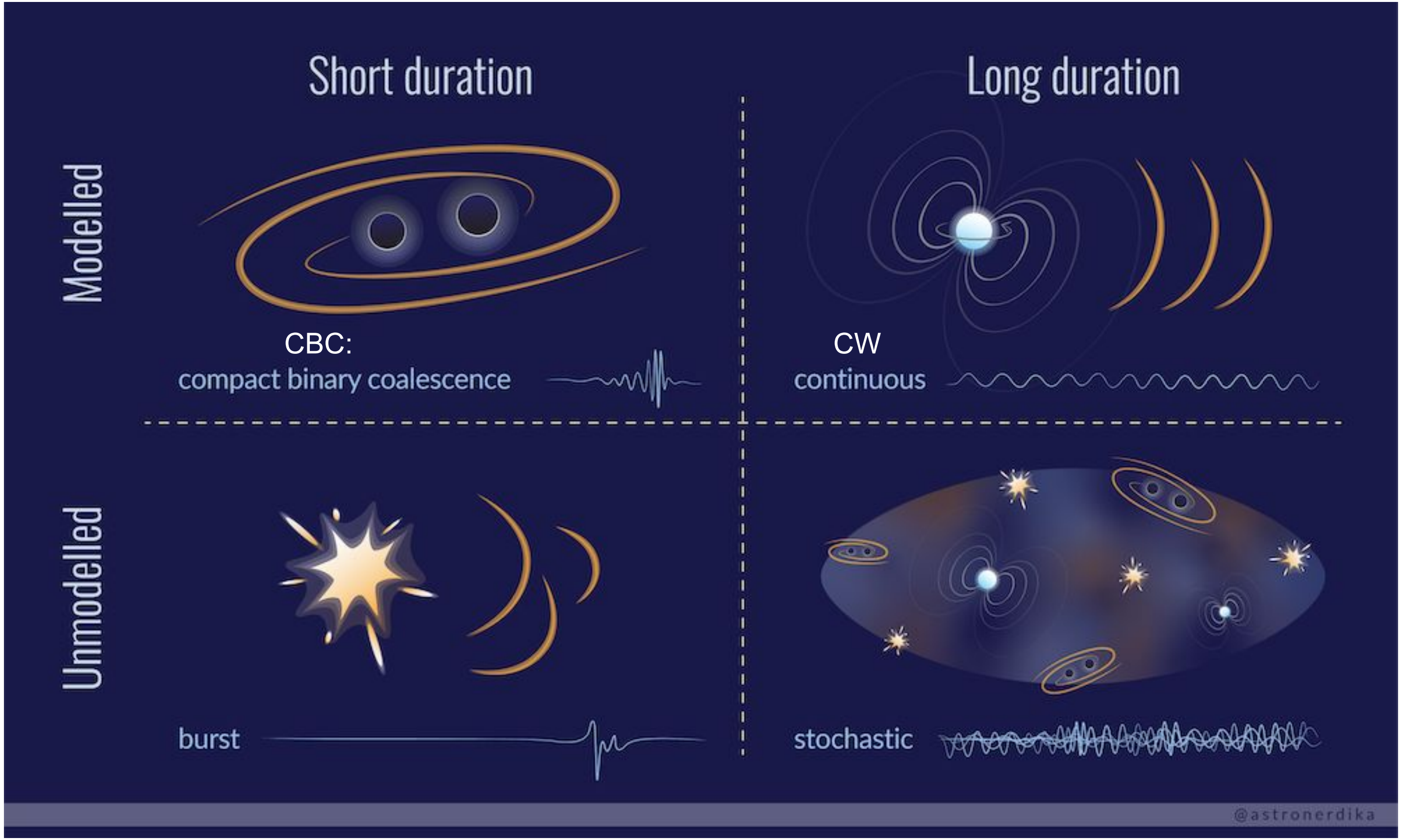
$$h(t) = \frac{\Delta L_{\mathrm{free}}(t)}{L}$$

$$L = (L_x + L_y)/2$$



Nature Reviews Physics 3, 344–366 (2021)

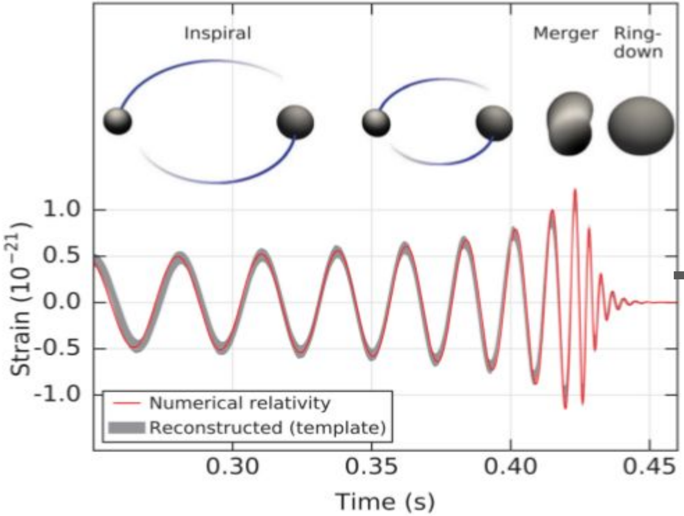
GW sources for ground-based detectors



Credit: Shanika Galaudage

CBC signals

Credit to *Phys. Rev. Lett. 116, 061102*



Binary Black Holes (BBHs)/Neutron stars(BNS), or BH-NS

Precise waveform models obtained from combining analytical, perturbative and numerical relativity methods.

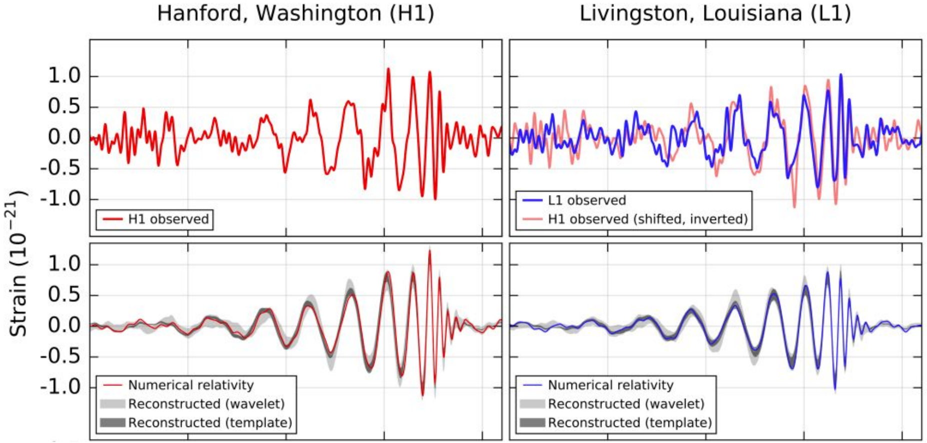
Stellar-mass BHs O(3–100 $M_\odot$):

we observe the final moments of the inspiral, then the merger, and the ringdown.

The first detection: **GW150914**

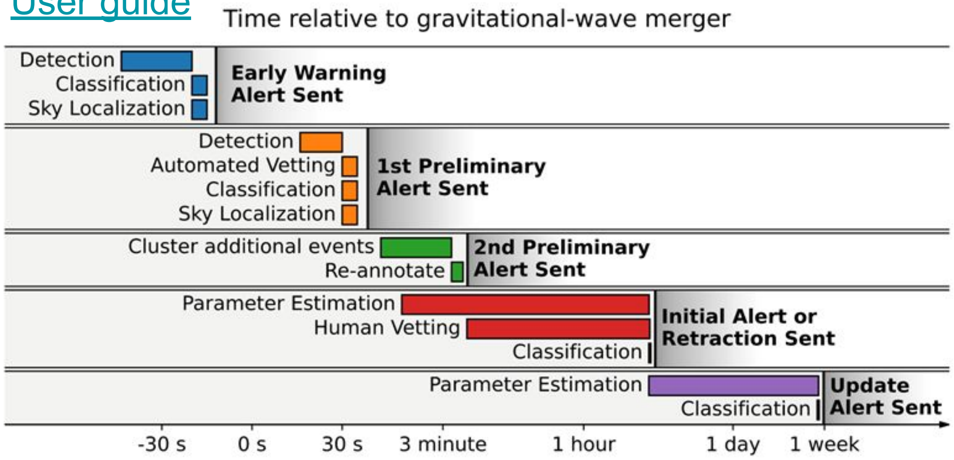
m1 ≈ 36 $M_\odot$; m2 ≈ 29 $M_\odot$

First observational evidence that BBH actually form in nature, with properties such that they merge in the local universe.



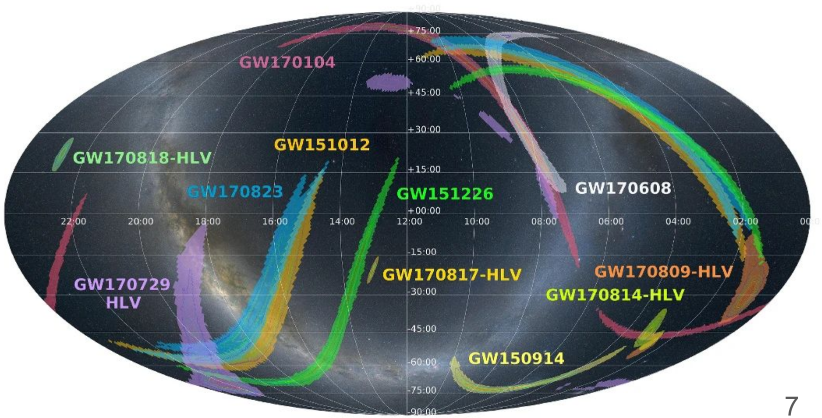
Sky localization and public alerts

User guide

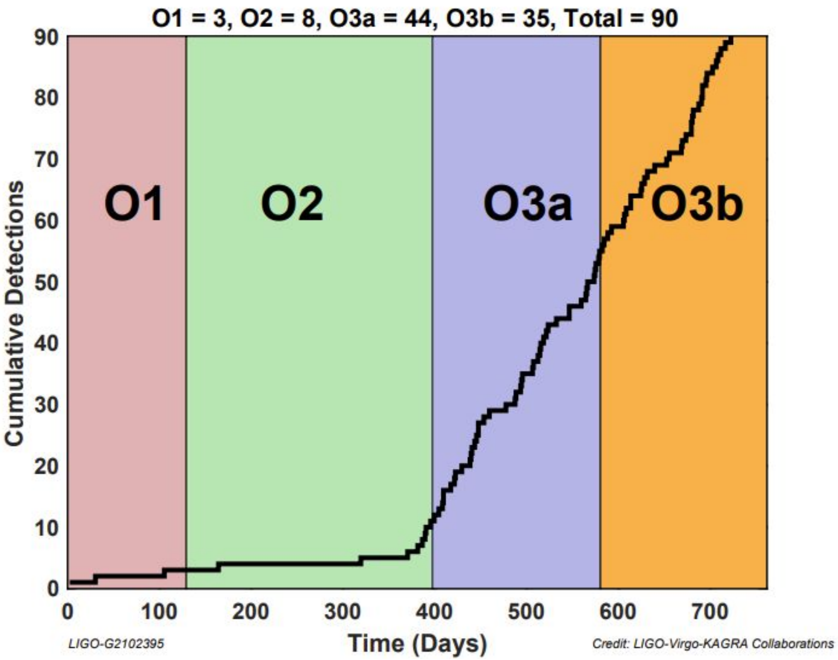


to quickly send out alerts to the global array of ground- and space-based telescopes via the NASA's Gamma-ray Coordinates Network (GCN)

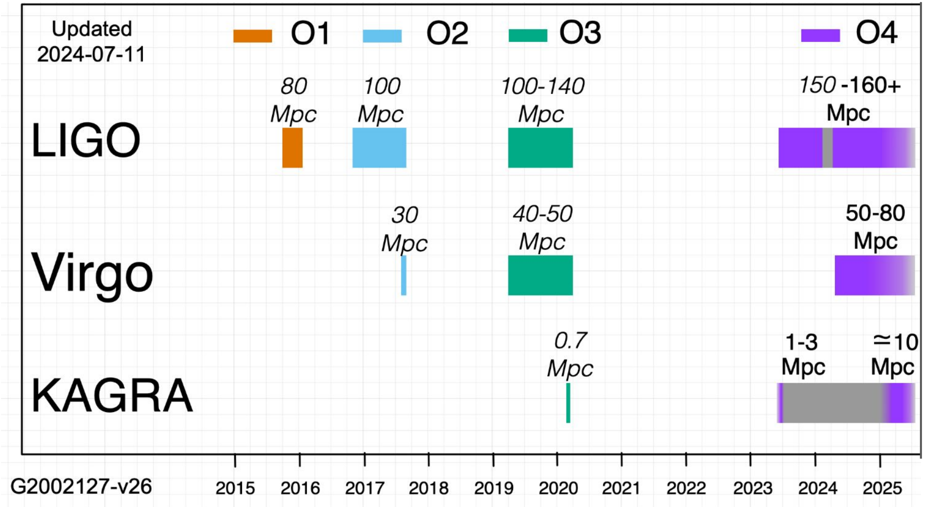
HasNS: The mass of at least one of the binary components is consistent with a NS.
HasRemnant: A non-zero amount of NS material remained outside the final remnant compact object
HasMassGap: The mass of at least one of the binary components lies in the hypothetical "mass gap" between NS and BH



The state of the art



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

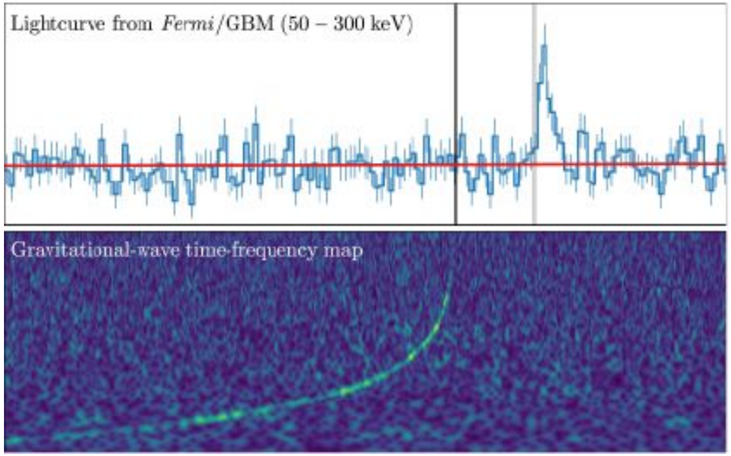


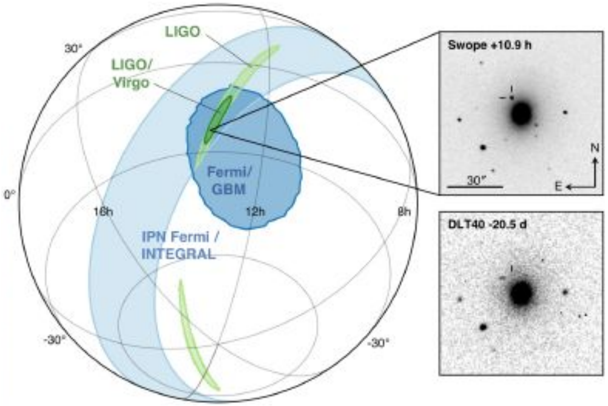
- several “special events”, such as GW170817, GW190521
- the last GW catalogue: GWTC-3 in PRD, 109, 022001 (2024)
  - population analysis, cosmology

The golden event: GW170817

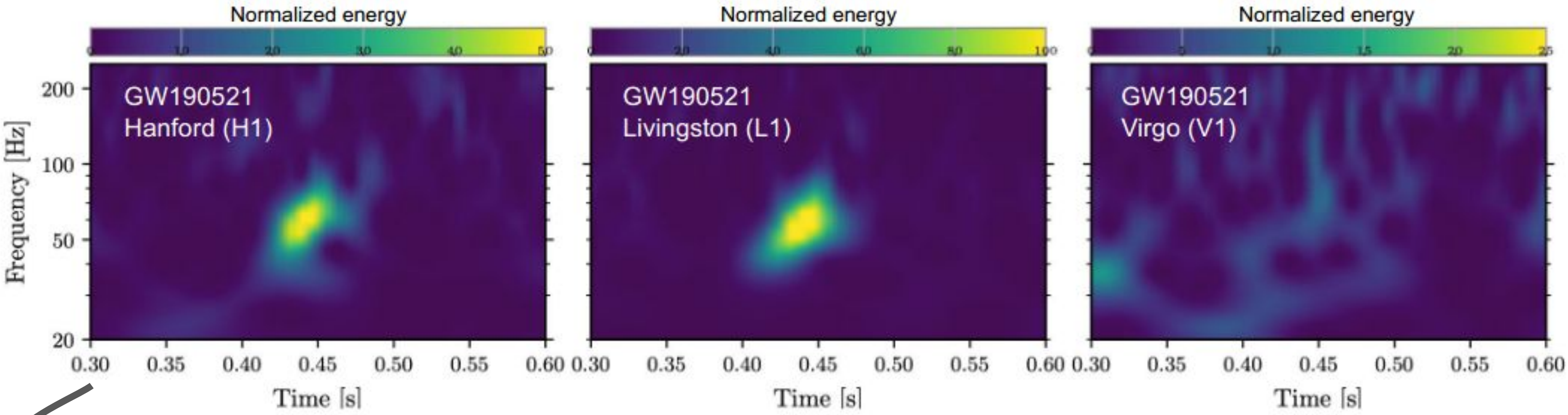
LIGO-Virgo detection and GRB coincidence

- first multimessenger event!
- first “standard siren” measurement of the Hubble constant (see slide 13)
- speed of gravity ≈ speed of light
- constraints on tidal deformability: neutron star maximum mass, equation of state of nuclear matter at extreme densities
- BNS mergers as prime source of heavy elements in the Universe



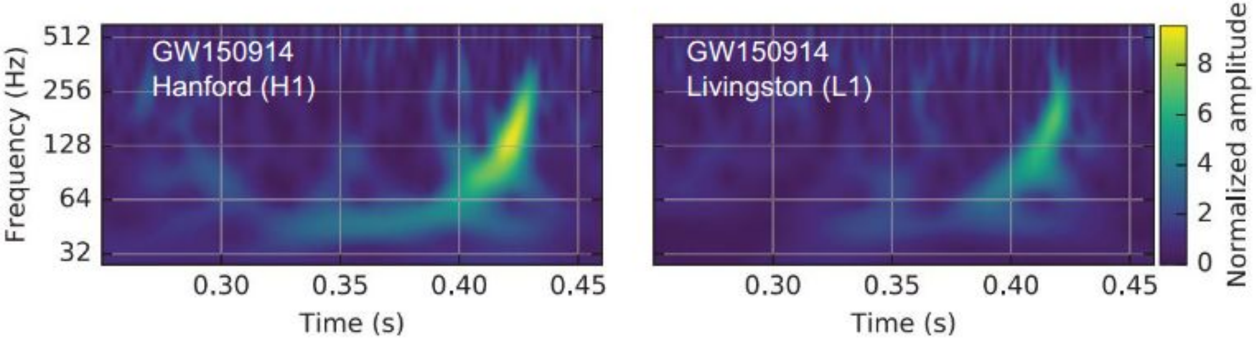


The “massive” event: GW190521



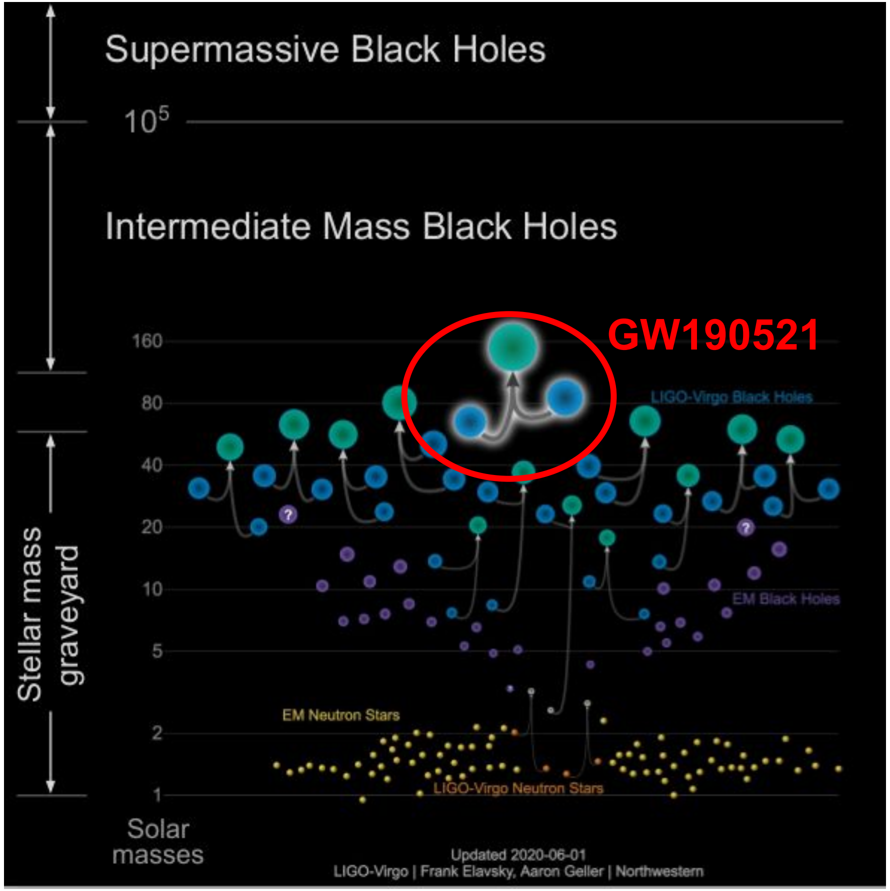
85 and 66 $M_\odot$ →144 $M_\odot$

Compared to the first event (36 and 29 $M_\odot$)

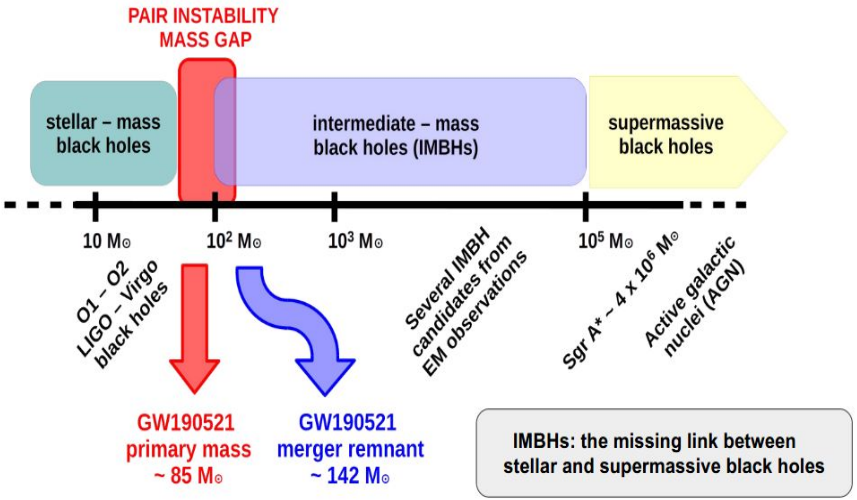


Spectrogram heat map computed using Q transform (Class.Quant.Grav. 21,S1809-S1818 (2004))

The “massive” event: GW190521



- First confident inference of an intermediate mass BH
- The primary mass falls in the Pair Instability mass gap → Challenges for stellar evolution

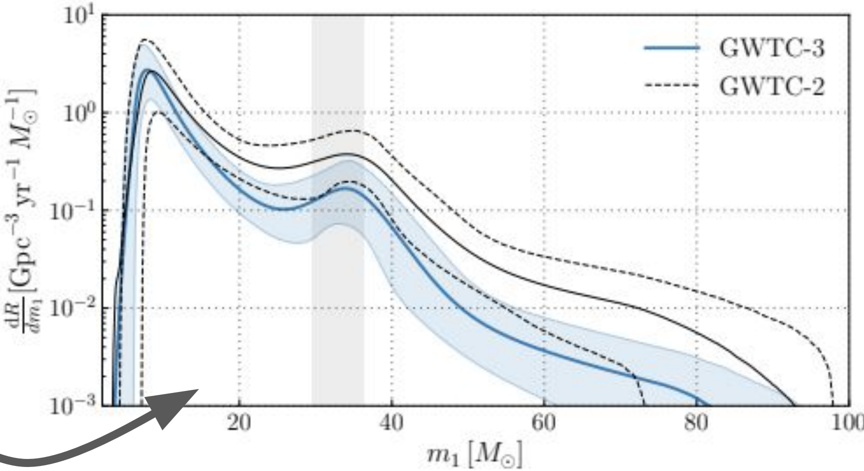


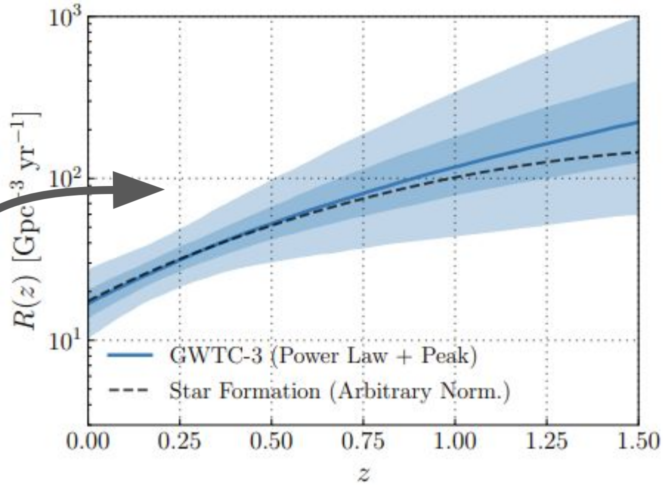
Population analysis

From the full set of events, we can infer some population parameters/distribution:

- BBH mass distribution is non-uniform, with over densities at BH masses of 10 $M_\odot$ and 35 $M_\odot$
    - No evidence for an upper mass gap
- Broad mass distribution for NSs extends up to $2.0^{+0.3}_{-0.3}$ $M_\odot$
- Observed BH spins are typically small (half less than 0.25).
- Spin-orbit misalignment is observed
- BBH merger rate likely increases with redshift

LVK PRX13,011048 (2023)

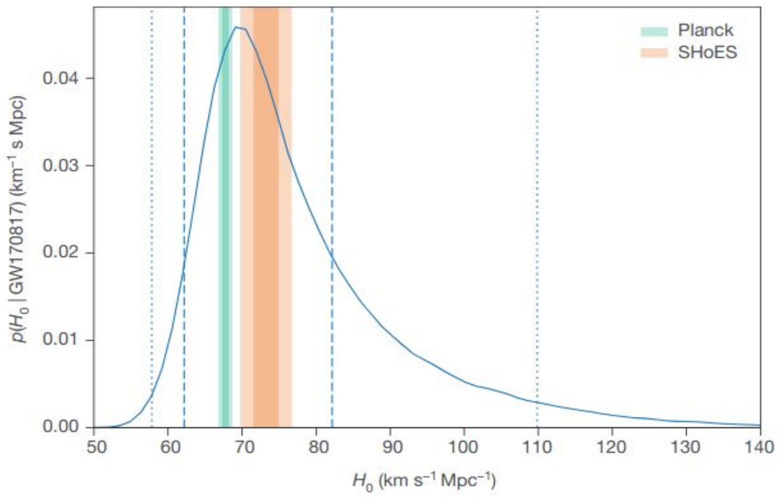




Cosmology

recessional velocity determined from EM observations (host galaxy identification) ← $v = H_0 \cdot d$ → GWs give you luminosity distance

- GW170817 measurements achieve <15% 1-sigma uncertainty in H0 with a SINGLE measurement (!)
- The fractional H0 uncertainty will scale roughly as 15% / √N Chen et al 2018 with N=BNS detections with counterpart

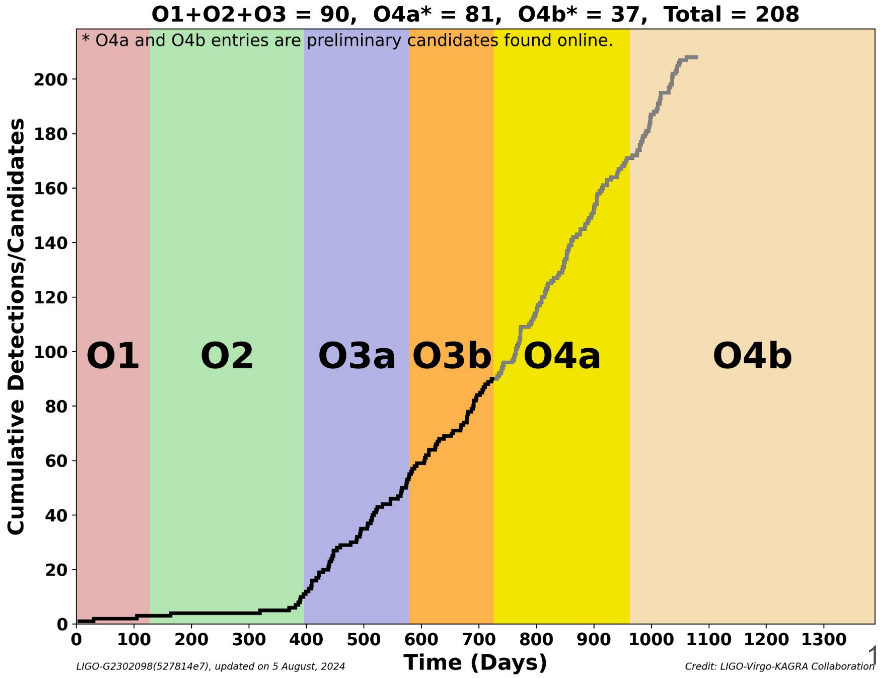


DARK SIRENS → Establishing a statistical association between the source, and those galaxies in a catalog that match the source sky location and luminosity distance as inferred from GW data.

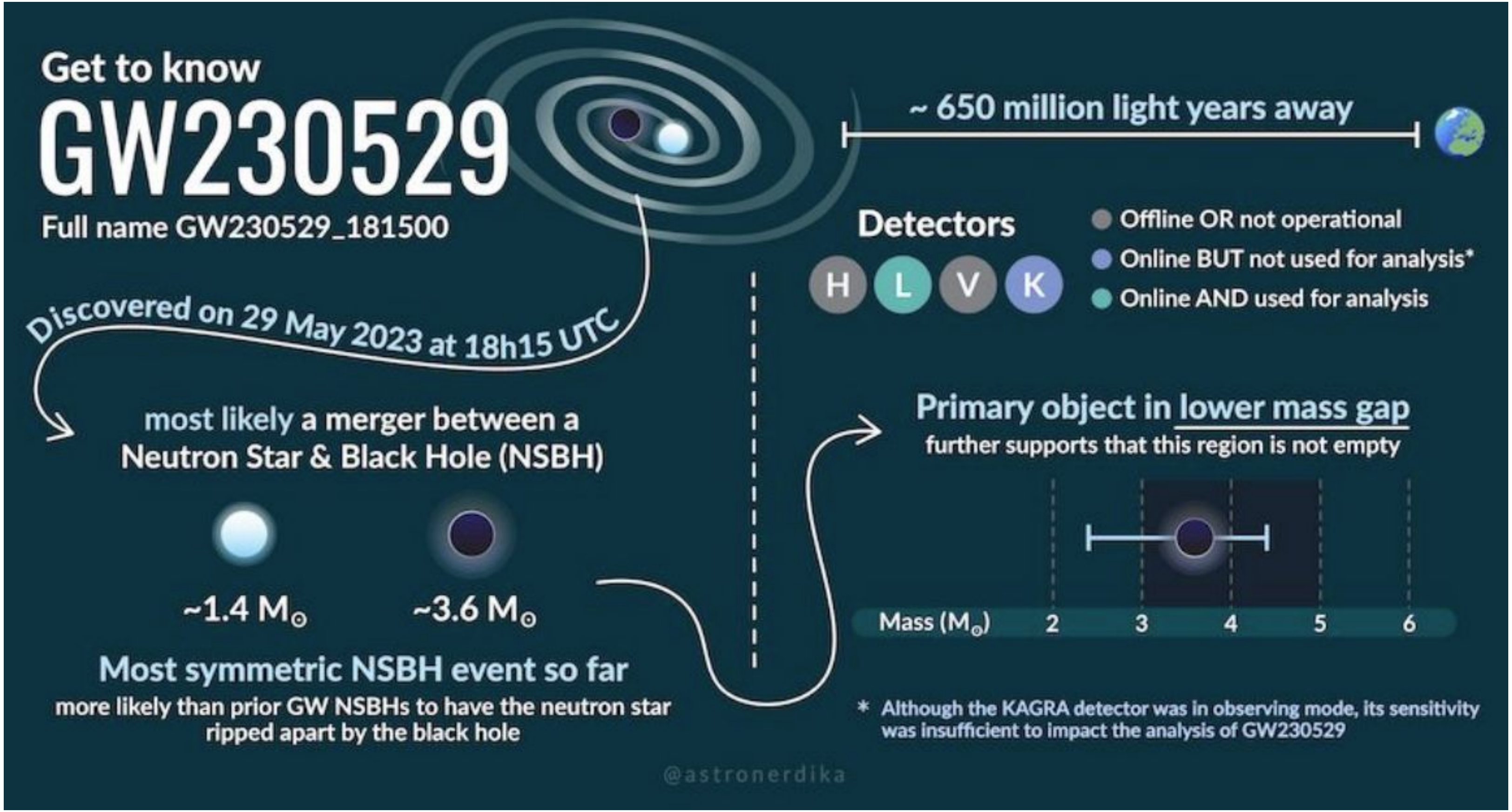
O4 on going

- The two LIGO detectors are now running with a sensitivity of 140-180 Mpc, and with duty cycles of 70-80%
- Virgo is running with a sensitivity of 50-55 Mpc, and with duty cycle of ~ 80%
- (so far) 81 significant detection candidates (almost all BBHs; no BNS; most likely a NS-BH)

10 August 2024 update
“LIGO, Virgo, and KAGRA have adopted a change to the end date for the O4 observing run, which previously had been set as February 2025. It has been decided to extend the O4 run, to allow for greater preparation of upgrade hardware that will be installed for O5. The new end date for O4 is ***9 June 2025.****”*



First O4 result: GW230529

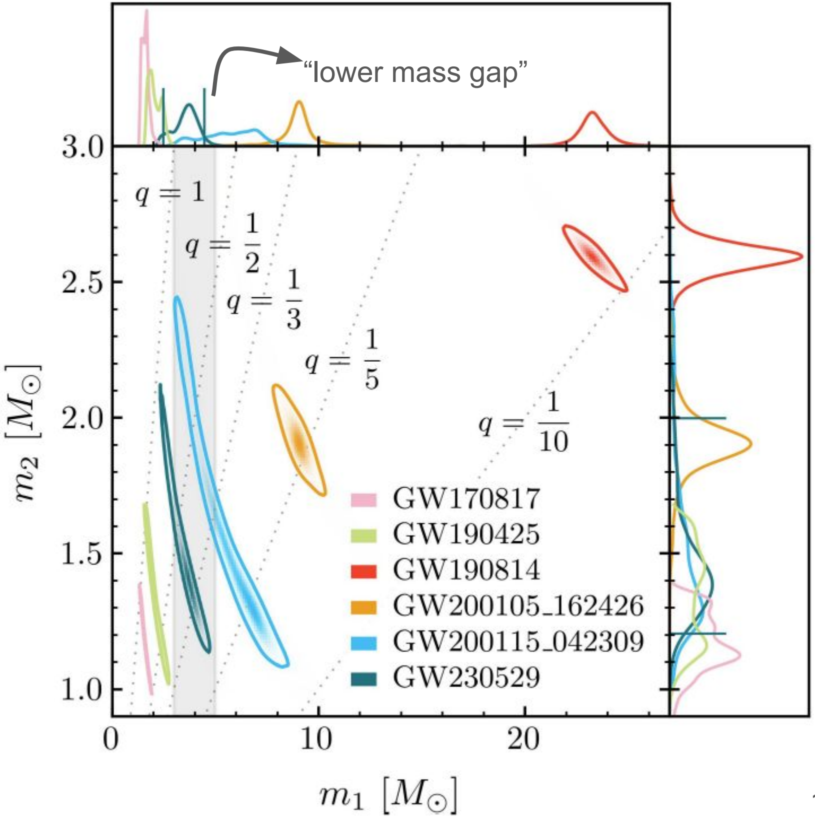


arXiv:2404.04248

First O4 result: GW230529

- Evidence for compact objects existing within the lower mass gap (mass between the most massive NS and the least massive BHs observed in the Galaxy)
- More symmetric masses → more susceptible to tidal disruption ⇒ EM counterpart
  - No confirmed EM counterpart, no clear tidal constraints
- BUT not possible to rule out that GW230529 is a BNS

https://arxiv.org/abs/2404.04248



The unseen, so far…

Burst GW from Core-collapse of massive stars/Coalescences

- other GW transients not well-modelled

Continuous GW, quasi-monochromatic radiation from non axisymmetric spinning neutron stars (or exotic sources) → different strategies according to the source knowledge

Stochastic GW background Superposition of large number of distant (weak) sources or relic from inflation / hot early Universe

- astrophysical or cosmological

New frontiers with GWs

Indirect or direct detection of particle dark matter, exotic compact objects, primordial BH, GW lensing, effects of modified gravity…

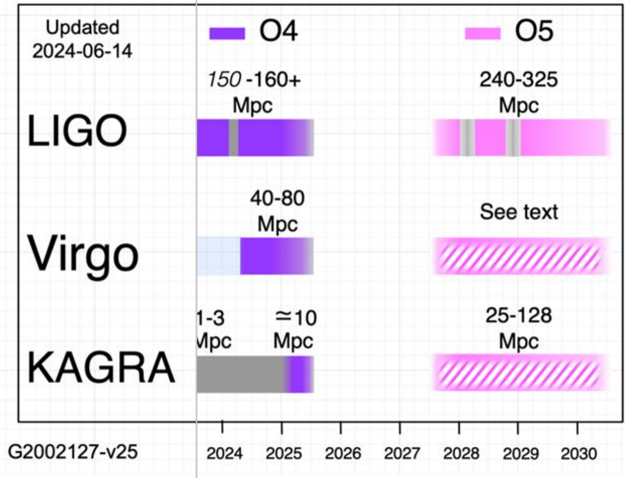
What's next?

O4 providing the best sensitivity and longest run duration yet: stay tuned for new results!

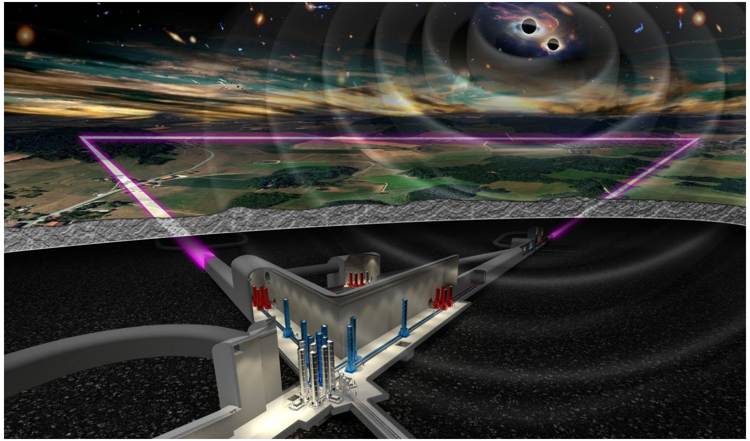
The global detector network continues to improve and grow; future detectors will push cosmic frontiers.

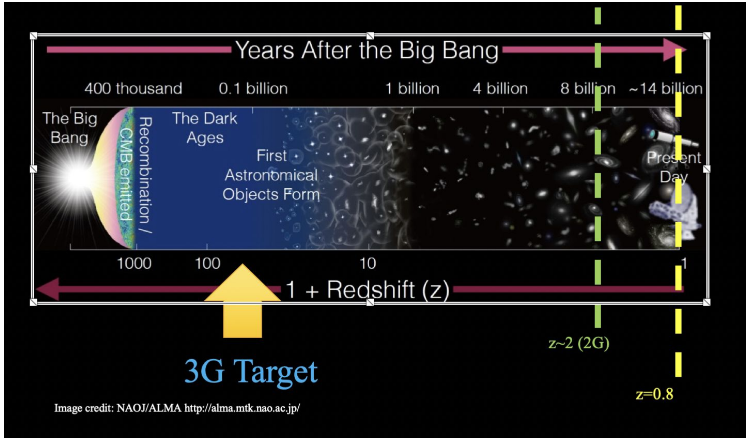
O5 and post-O5

[IGWN | Observing Plans (ligo.org)]



3G-detector





Acknowledgments

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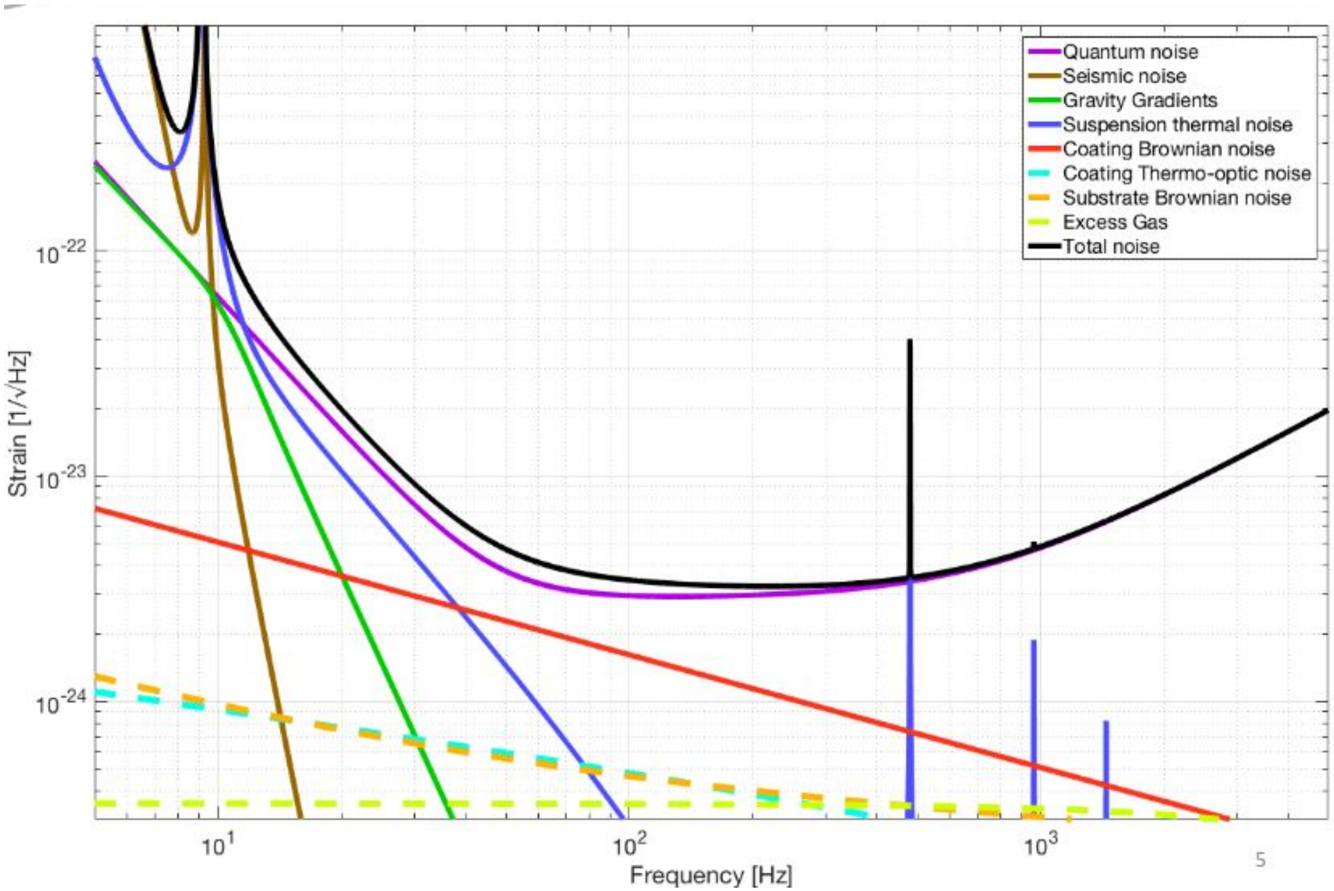
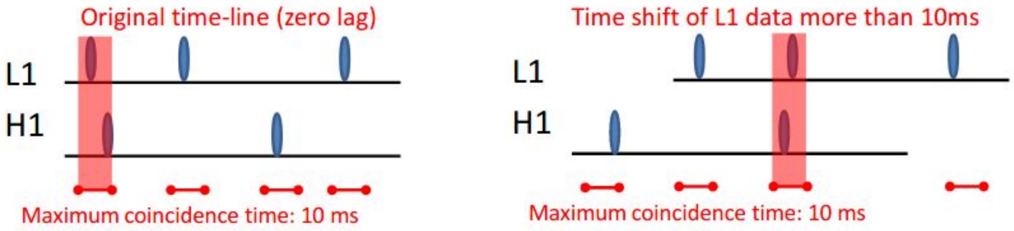
Thank you!

Noise budget



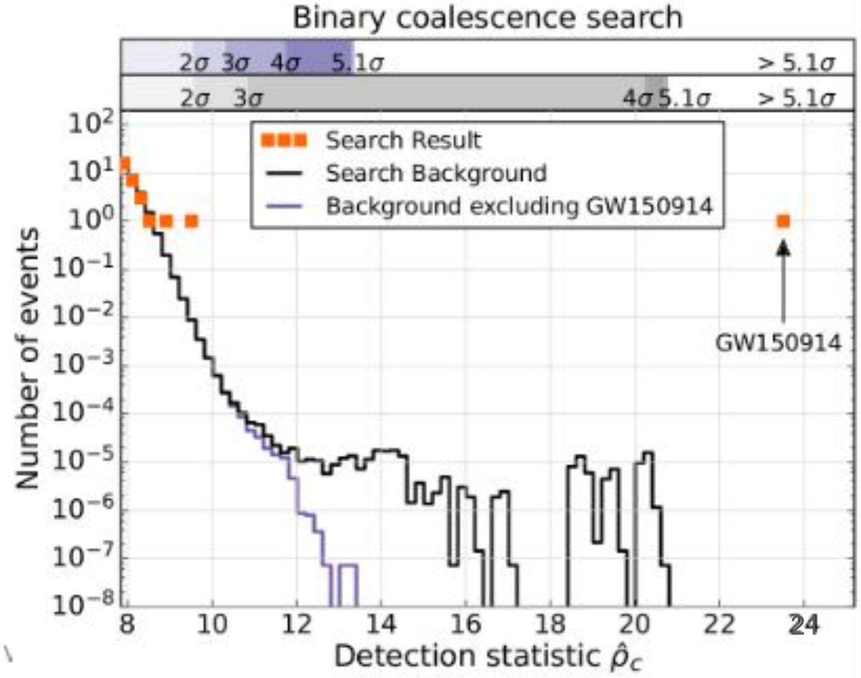
Significance and timeslide



The tail in the black-line background is due to random coincidences of GW150914 in one detector with noise in the other detector.

time-shift technique: the time stamps of one detector's data are artificially shifted by an offset that is large compared to the intersite propagation time, and a new set of events is produced based on this time-shifted data set.

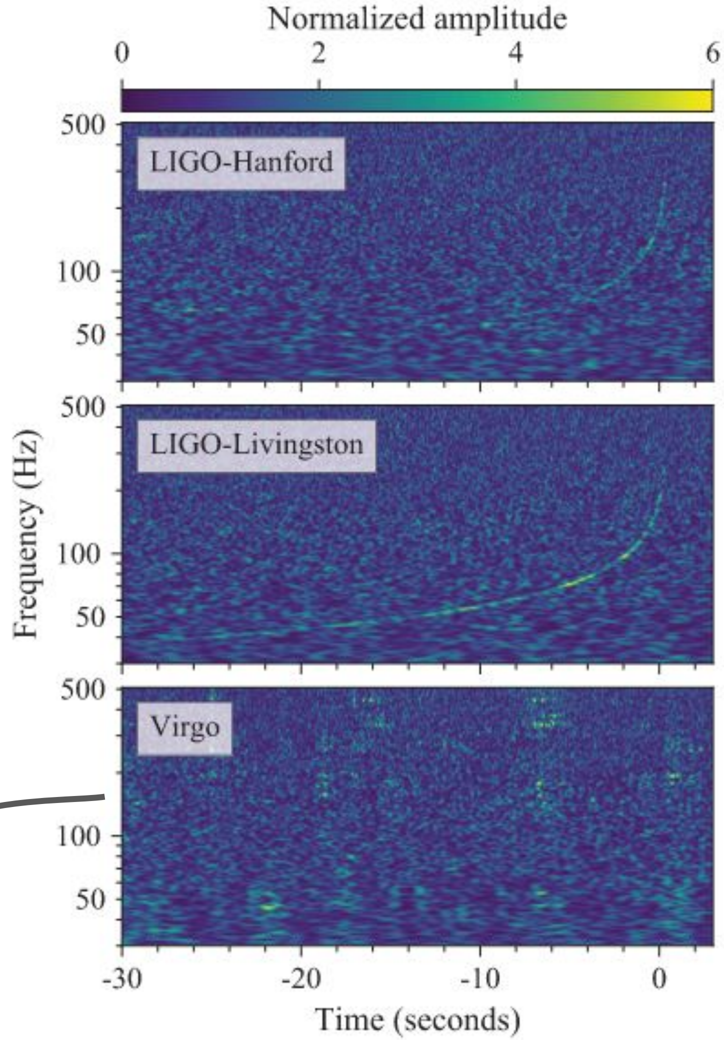
the search background = the rate at which detector noise produces events with a detection-statistic value equal to or higher than the candidate event
noise background analysis time equivalent to 608 000 years (upper bound on FAR ~ is 1 in 203 000 years.)



GW170817

the first joint detection of gravitational and electromagn radiation

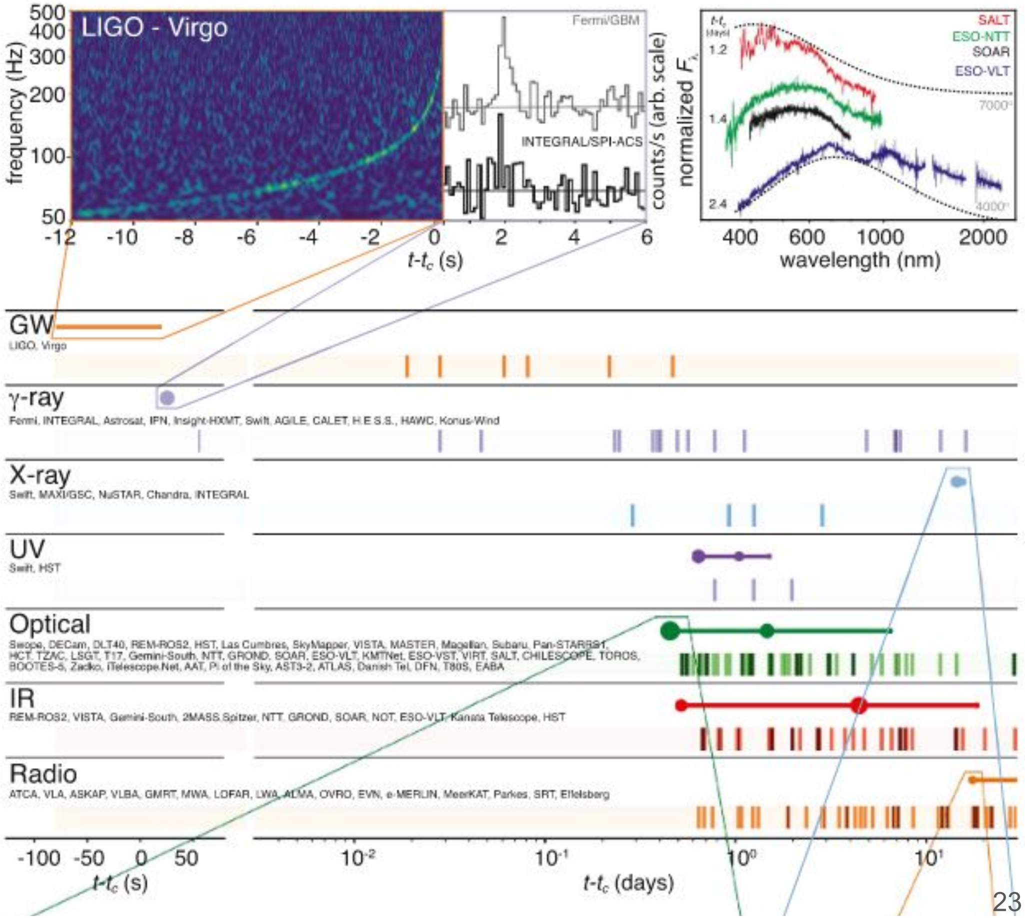
- First binary neutron star detected with gravitational waves
- four decades after Hulse and Taylor discovered the first neutron star binary, PSR B1913+16
- long-duration chirp signal in time-frequency representations of the detector strain data for ~100 seconds
- Total SNR=32.4!
- In Virgo's blind spot, crucial for localization!



low BNS range + direction of the source with respect to the detector's antenna pattern => SNR=2

Multi-messenger detection

- ~11h after: ultraviolet, optical, and infrared transient (kilonova), which allows for the identification of the host galaxy and is associated with the aftermath of the BNS merger
- delayed X-ray and radio counterparts that provide information on the environment of the binary
- No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches



[Multi-messenger Observations of a Binary Neutron Star Merger, The Astrophysical Journal Letters,848:L12(59pp), 2017 October 20]

Kilonova detection

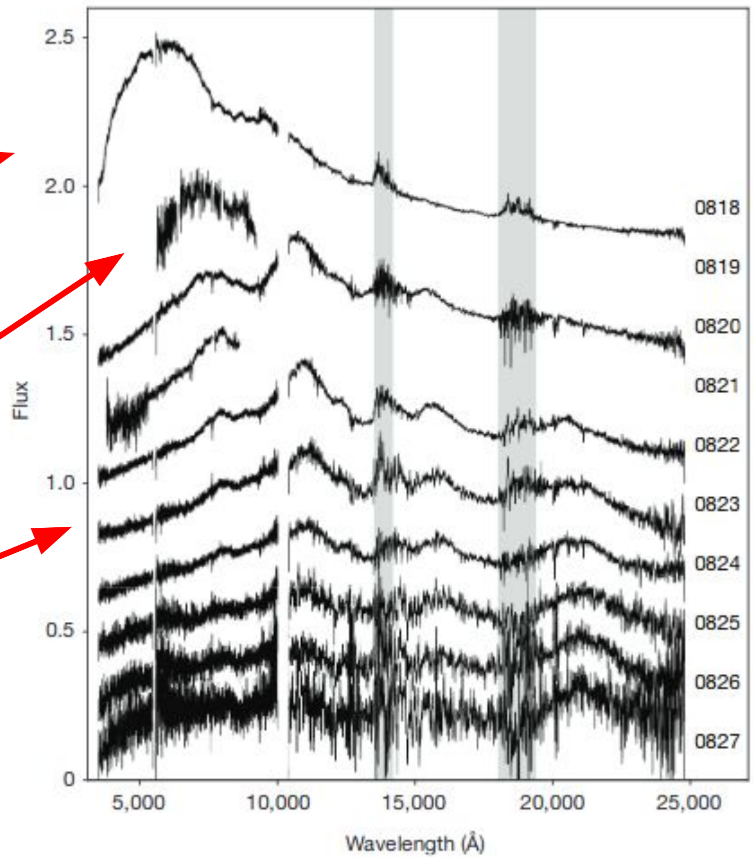
Kilonovae are thermal supernova-like transients lasting days to weeks, which are powered by the radioactive decay of heavy neutron-rich elements synthesized in the expanding merger ejecta

The first X-shooter spectrum shows a bright, blue continuum across the entire wavelength coverage that can be fitted with the spectrum of a blackbody of temperature 5000 ± 200 K

At the second epoch, one day later, when the spectrum covered only the optical range, the maximum moved to longer wavelengths, indicating rapid cooling.

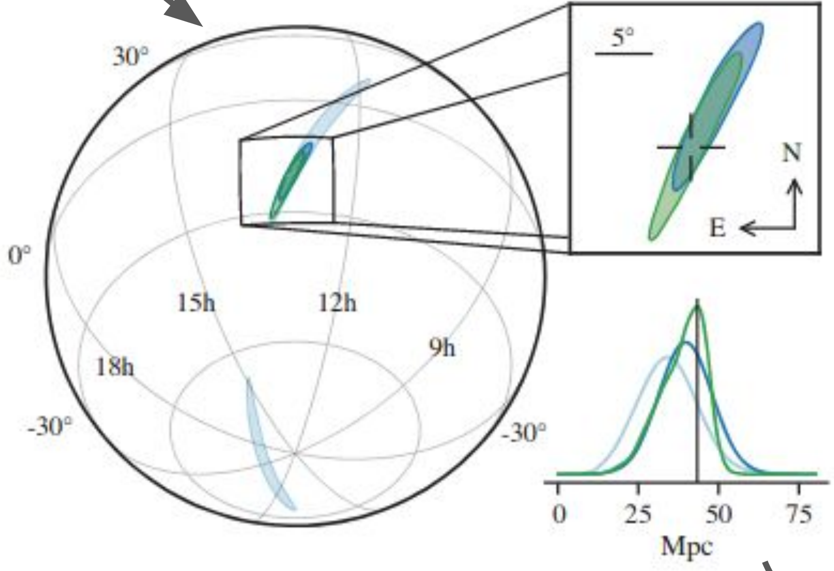
These rapid changes are not consistent with supernova time evolution and are attributed to a kilonova

BNS mergers as producers of heavy elements confirmed (abs. lines)!



Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. *Nature* **551**, 67–70 (2017).

Rapid localization algorithm from a Hanford-Livingston (190deg2,light blue contours) and Hanford-Livingston-Virgo (31deg2,dark blue contours) analysis (improved to 28deg2, green contours).



The reticle marks the position of the apparent host galaxy NGC 4993, distance ~ 40Mpc (local universe)

“The third detector, Virgo, was essential in localizing the source to a single region of the sky. The small sky area triggered a successful follow-up campaign that identified an electro-magnetic counterpart”

luminosity distance a posteriori using GWs compared with distance of NGC 4993 (vertical line)

Hubble constant

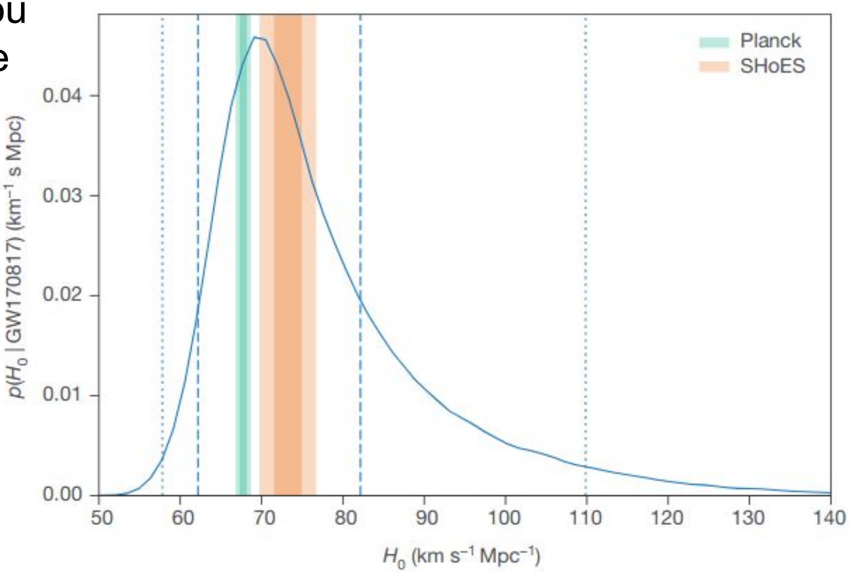
Compact mergers are **standard sirens** for GWs
Combining distance with host galaxy identification gives you Hubble constant (no prior assumptions on H0, no “distance ladder”)

$$v = H_0 \cdot d$$

velocity determined from EM observations (host galaxy identification)

GWs give you luminosity distance

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

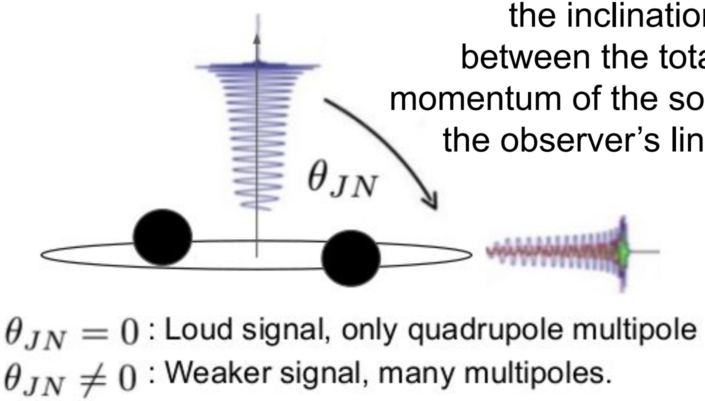


- One of the main sources of uncertainty in this measurement of H0 is due to the degeneracy between distance and inclination. EM info improving GW H0 estimate
- Measurement of the Hubble constant also using a GW detection of a BBH merger

Abbott, B., Abbott, R. *et al.* A gravitational-wave standard siren measurement of the Hubble constant. *Nature* **551**, 85–88 (2017).

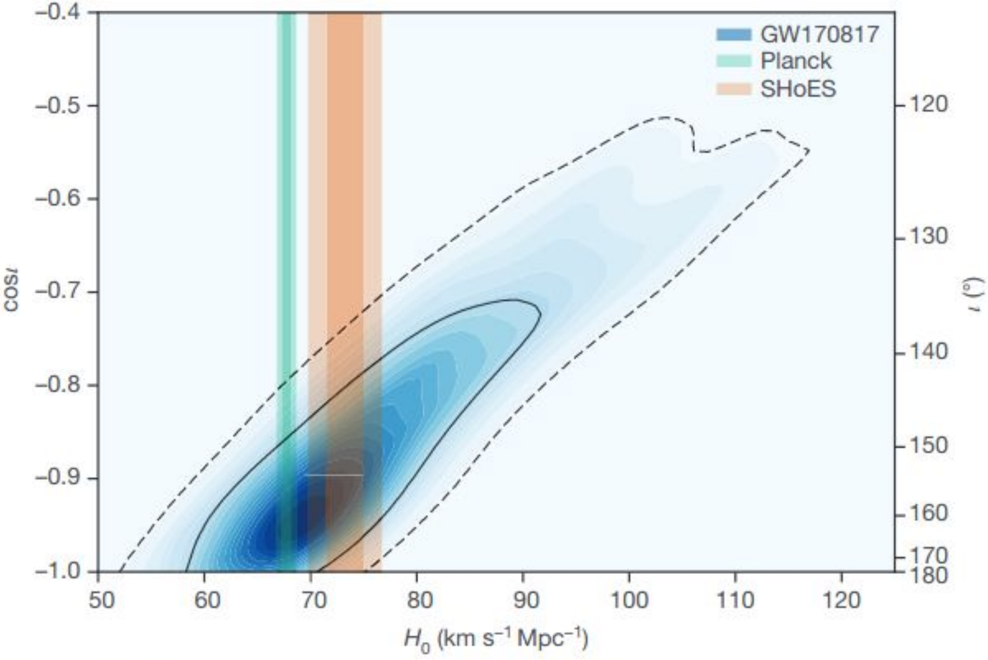
- One of the main sources of uncertainty in this measurement of H0 is due to the degeneracy between distance and inclination. EM info improving GW H0 estimate

the inclination angle is between the total angular momentum of the source, and the observer's line-of-sight



DEGENERACY :

GW emission is strongest along the orbital angular momentum direction, so face-on sources at larger distances produce similar signals to edge-on sources closer by.



The unseen, so far…

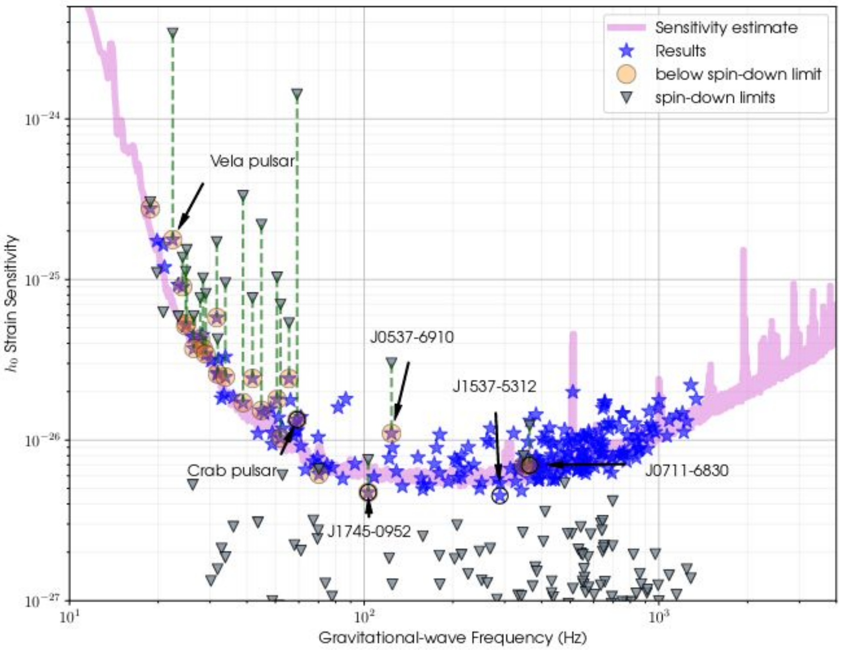
Continuous GW [1], quasi-monochromatic radiation from non axisymmetric spinning neutron stars (or exotic sources) → different strategies according to the source knowledge

Simplest but most sensitive → *targeted search*

➔ full coherent analysis and matched filter techniques

➔ model-dependent

➔ For CWs, a detection may help constrain the physics of NS matter and understand the NS population better



[1] Recent review:

*Riles, K. Searches for continuous-wave gravitational radiation. Living Rev Relativ **26**, 3 (2023).*

Different searches from pulsars

➔ Narrow-band analysis

Relax phase-locking between GW and EM to allow different emission mechanisms.
*R. Abbott et al 2022 ApJ **932** 133* 18 isolated pulsars, Spin-down limit surpassed for 7/18 pulsars.
R. Abbott et al., PRD 105, 022002 20 accreting millisecond x-ray pulsars

➔ Post-glitches pulsar search : Long CW-like transients

Models suggest change in quadrupole moment *Yim & Jones 2007.05893*
*R. Abbott et al 2022 ApJ **932** 133* : searches for 9 glitches from 6 targets in O3

➔ R-modes from J0537-6910 : The “Big Glitcher”

Coriolis-driven oscillations of the inner fluid. Extension of narrow-band to inter-glitch quiet periods
*R. Abbott et al 2021 ApJ **922** 71* LVK O3 search

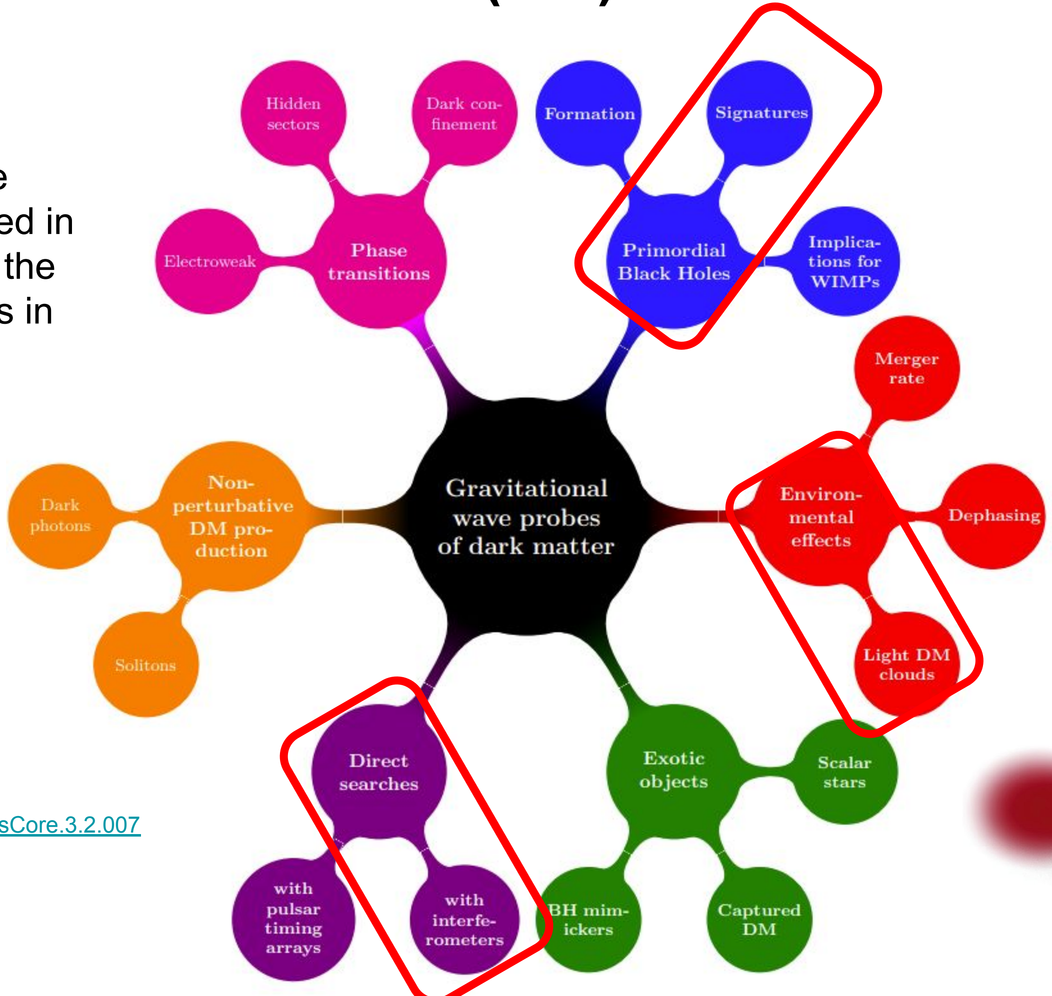
Non-LVK searches : *Nieder et al 2020 ApJL 902 L46*, *Papa 2020 ApJ 895 11*, *Clark et al 2023 MNRAS 519,4, …*

➔ Directed searches

where sky location is known while frequency and frequency derivatives are unknown
(e.g. Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters)

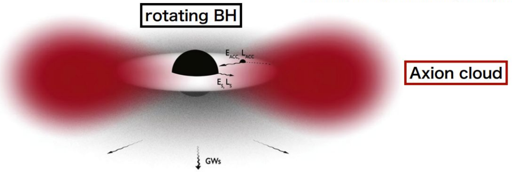
Dark matter (DM) searches

In many cases GW data analysis methods can be directly applied or adapted in a straightforward way to the search of DM fingerprints in GW data



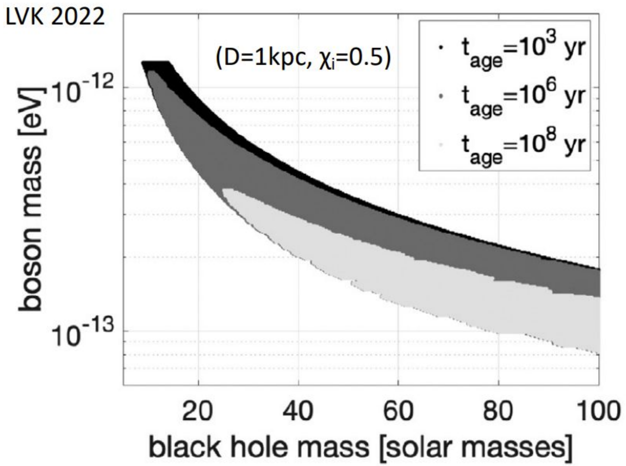
https://doi.org/10.21468/SciPostPhysCore.3.2.007

Arvanitaki *et al.*, PRD 81, 123530 (2010)
Brito *et al.*, Class. Quantum Grav. 32, 134001 (2015)



Dark matter (DM) searches

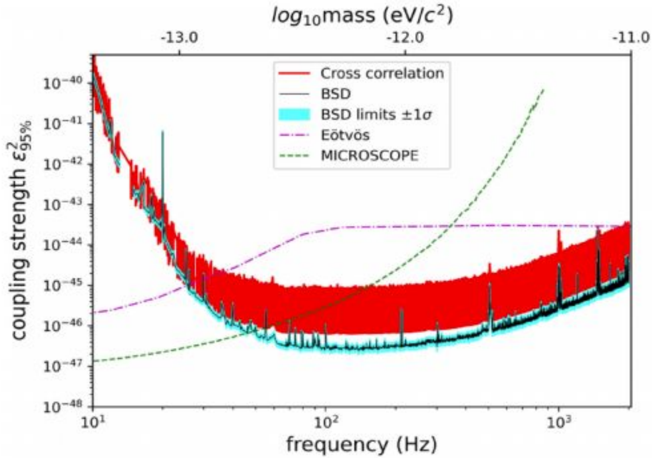
DM indirect detection:
CWs from depleting scalar boson clouds around Kerr BHs
long-transients from sub-solar mass BBH(<0.1M)



DM direct detection: interaction with the GW detectors
Vector DM (or so-called dark photon DM) interacts with test masses of the interferometer, for example, via a coupling to the baryon (B) or baryon minus lepton (B−L) number current

Phys. Rev. D 105, 063030, 2022 → O3 search

Abac+ (LVK) arXiv:2403.03004 • KAGRA particularly promising for vector dark matter coupled to the "B-L channel"



CBC: Test of GR and lensing

GW observations probe the relativistic, strong field regime

All events detected so far fit very well to waveforms predicted by GR.
Many ways to constrain alternative theories of gravity with GWs:

https://doi.org/10.48550/arXiv.2112.06861

- residual tests (We subtract the maximum-likelihood GR waveform from the data to verify the consistency of the residuals with detector noise)
- inspiral-merger-ringdown consistency
- parameterized tests of GW generation and GW dispersion relation
- polarization tests (We searched for non-GR polarization modes)

No evidence for deviations, increasingly strong constraints.

Also searching for signatures of gravitational lensing of GWs – no evidence yet. [LVC ApJ923:14 (2021), arXiv:2304.08393]