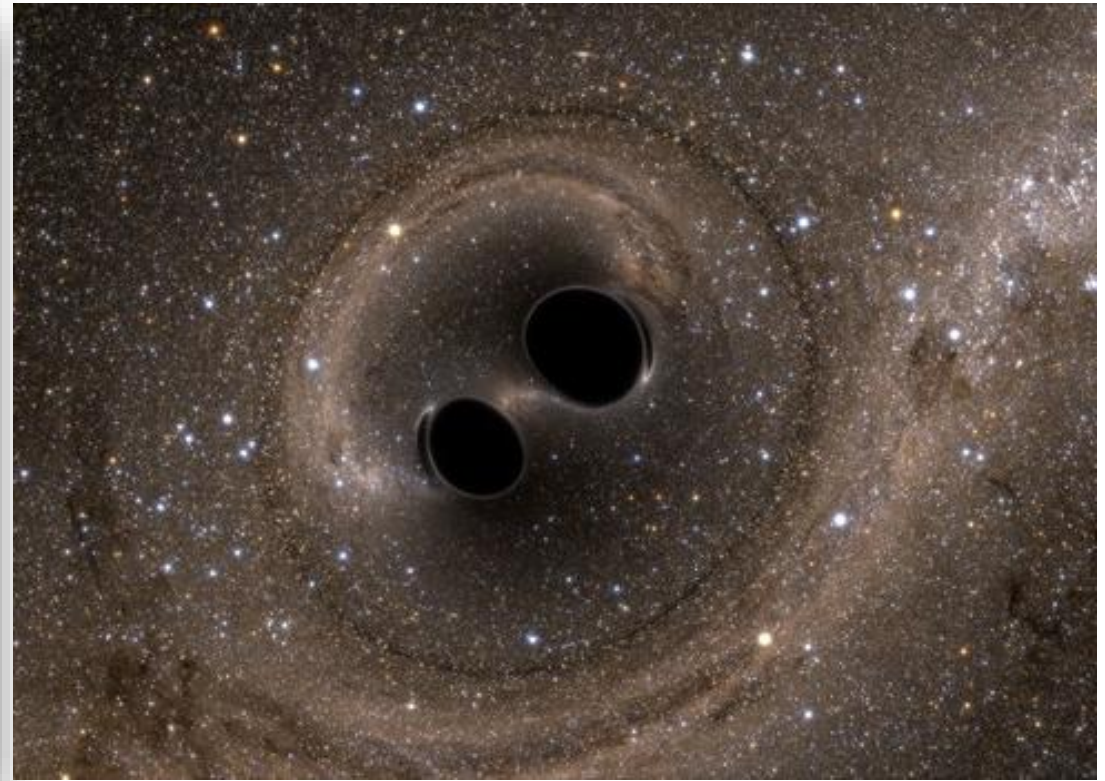
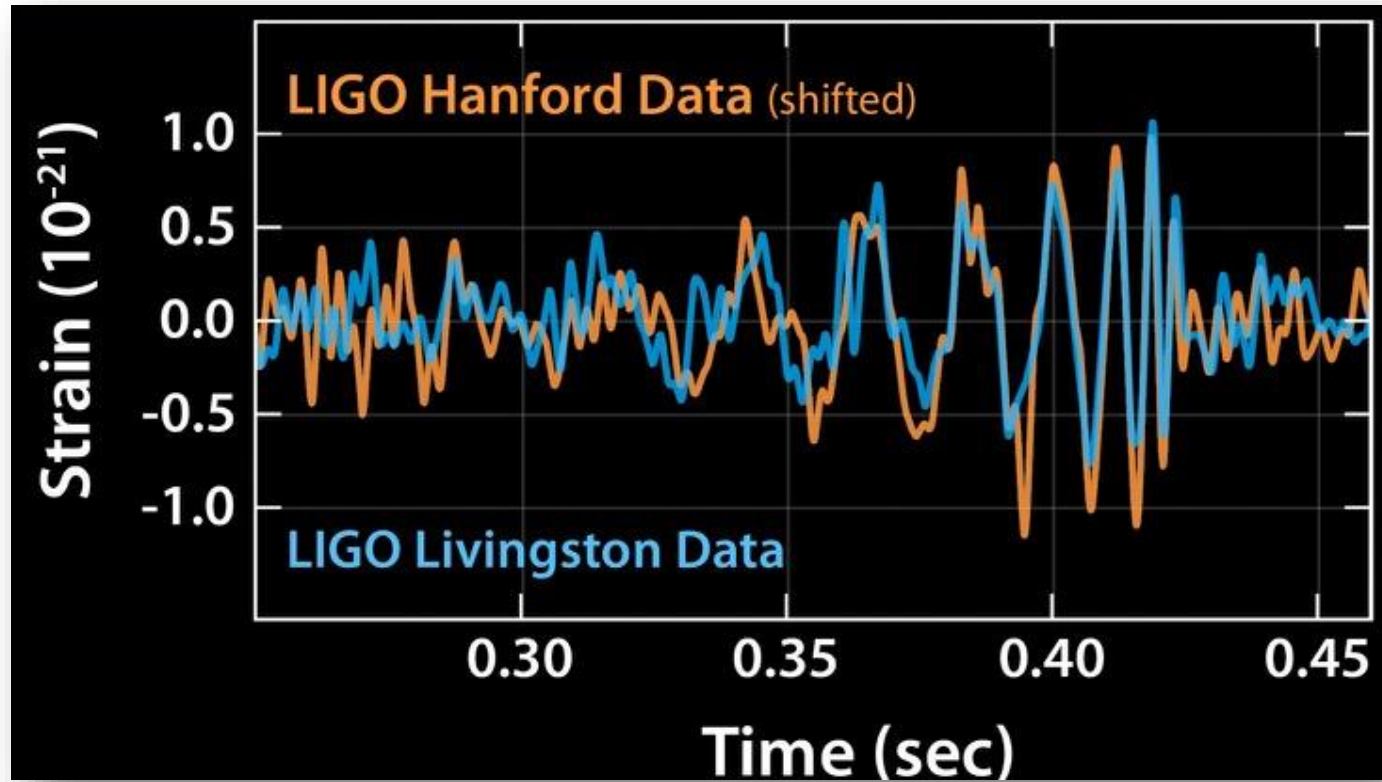


Ten years of Gravitational Wave Observations

Stephen Fairhurst

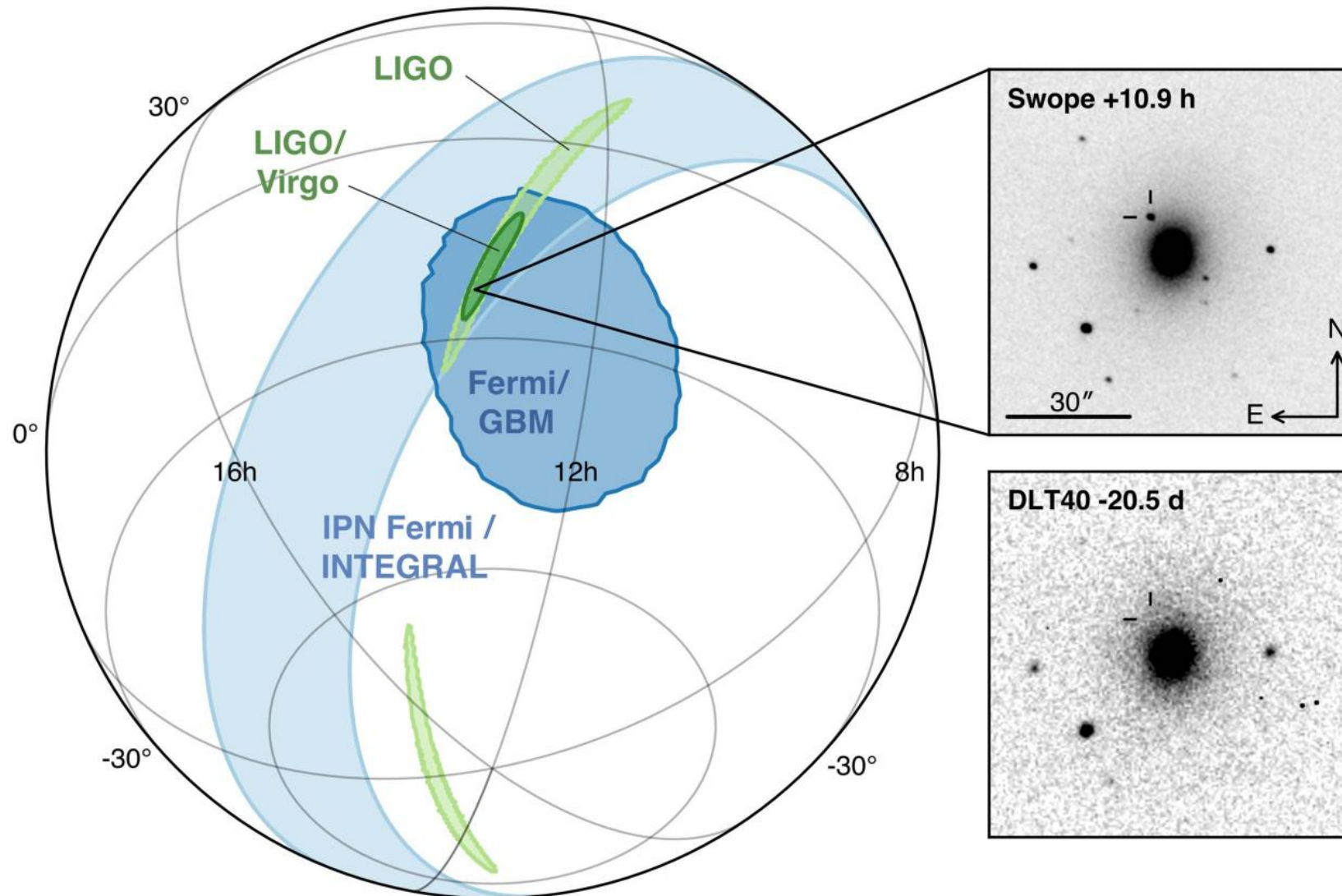
<https://dcc.ligo.org/G2601298>

Ten years ago: First Detection – GW150914



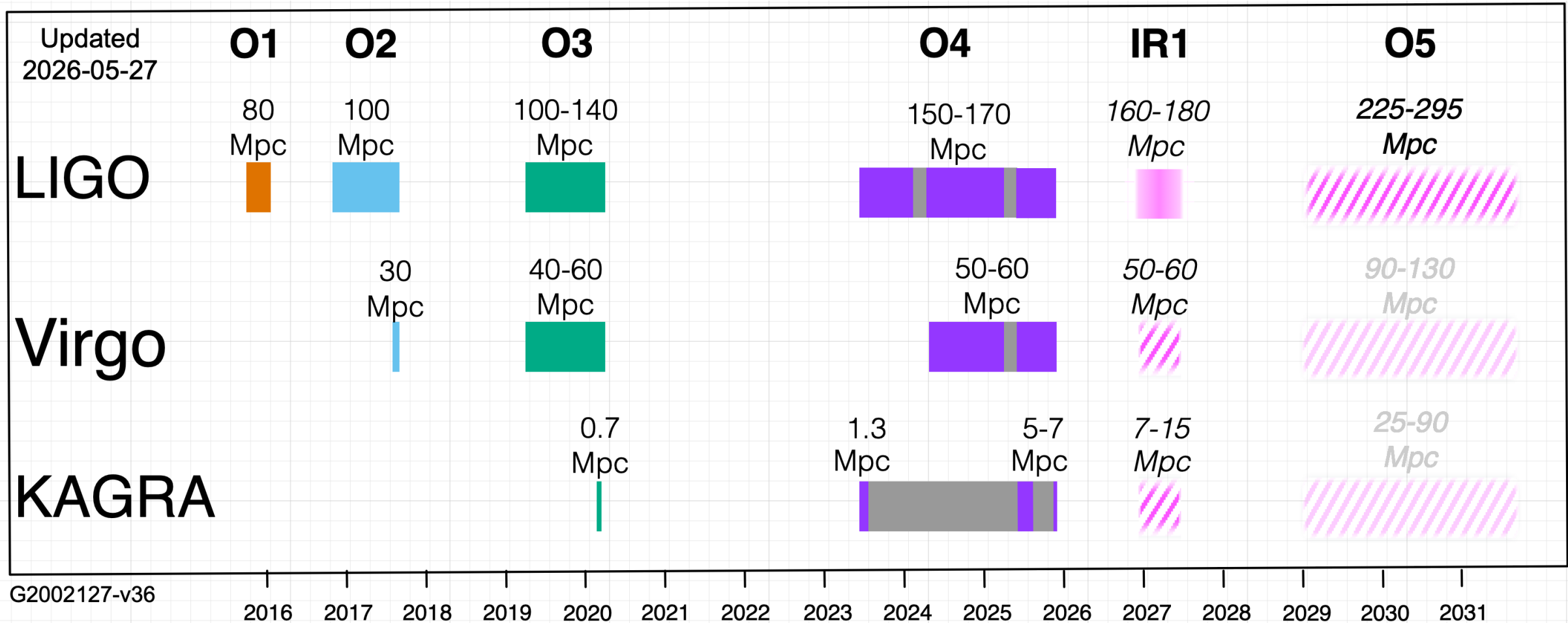
Abbott et al, arXiv:[1602.03837](https://arxiv.org/abs/1602.03837), "Observation of Gravitational Waves from a Binary Black Hole Merger"

Multi-messenger observation – GW170817



LIGO, Virgo and KAGRA Observing Runs

(from <https://observing.docs.ligo.org/plan/>)





Images from <https://www.ligo.caltech.edu>, Credit Caltech/MIT/LIGO Lab



Advanced LIGO in O4

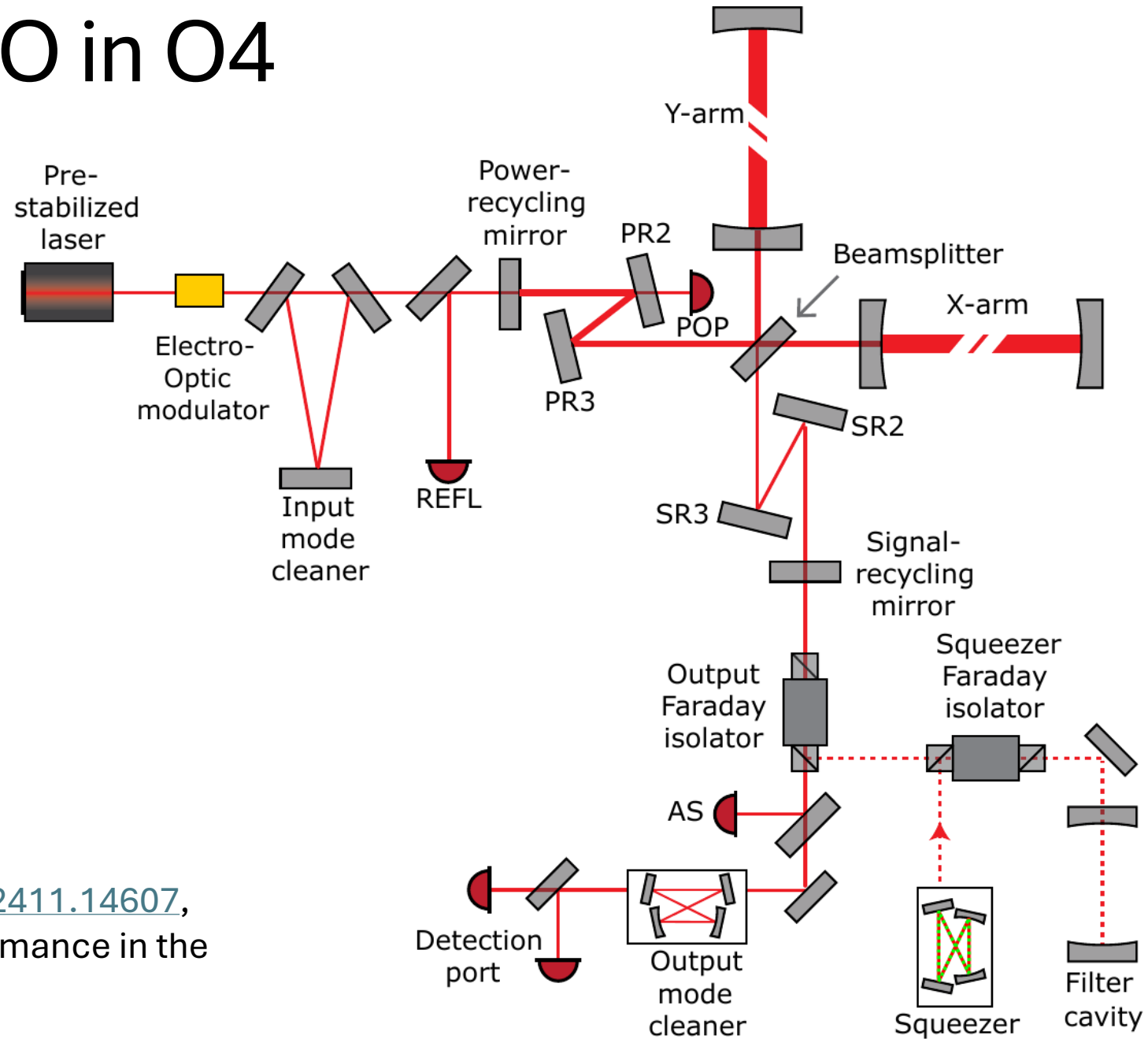


Figure from: Capote et al, [arXiv:2411.14607](https://arxiv.org/abs/2411.14607),
“Advanced LIGO detector performance in the fourth observing run”

Advanced LIGO in O4

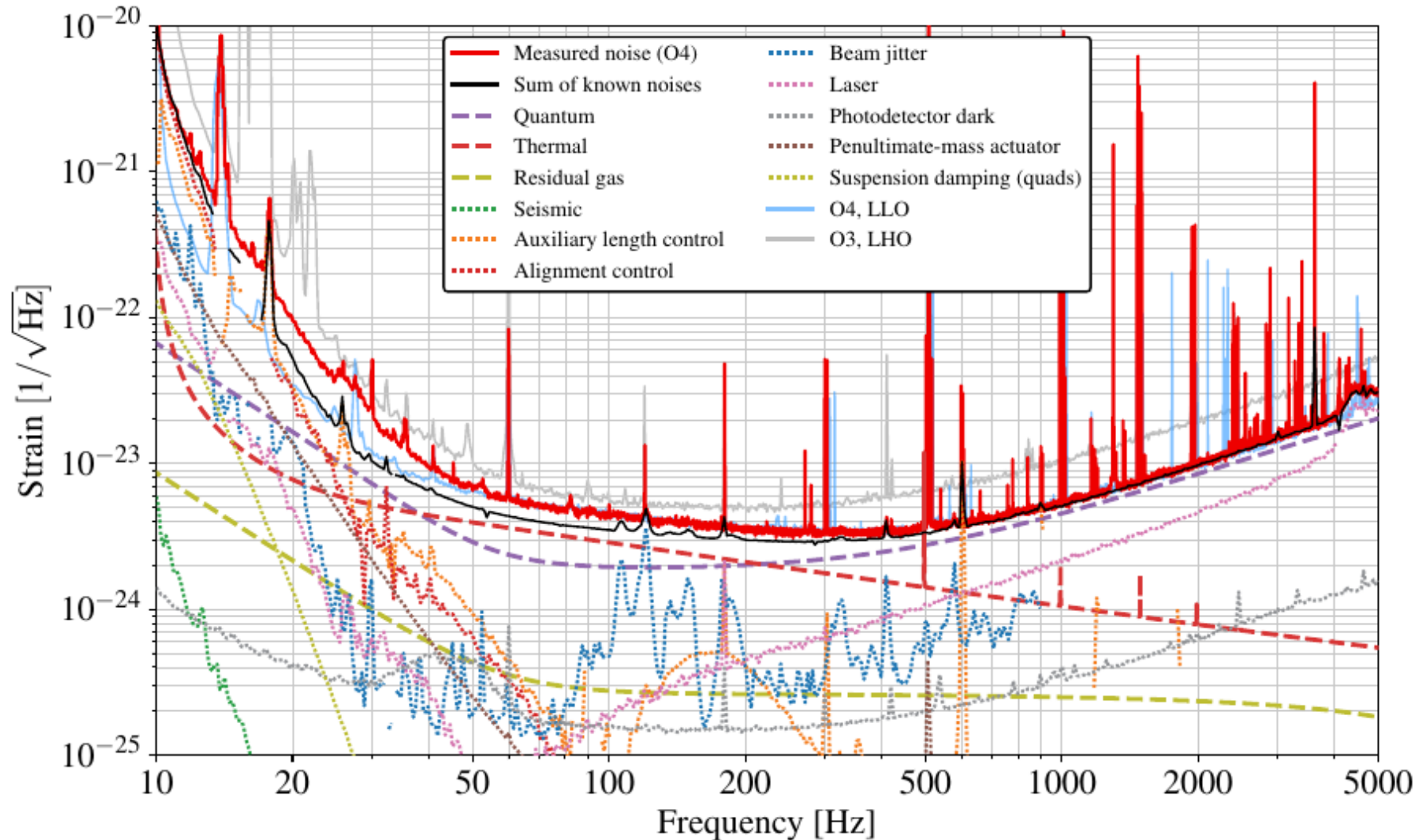
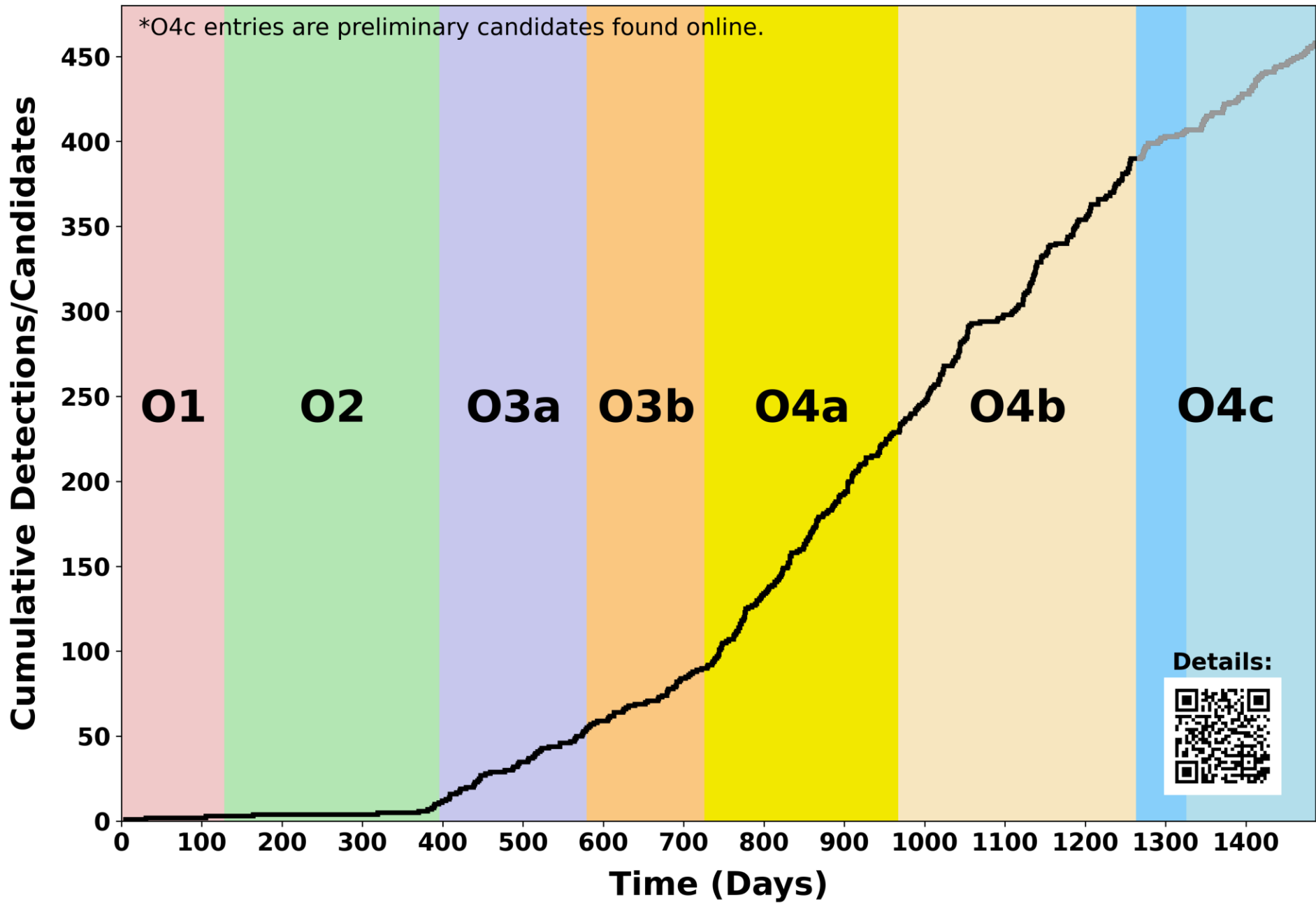


Figure from: Capote et al, [arXiv:2411.14607](https://arxiv.org/abs/2411.14607)

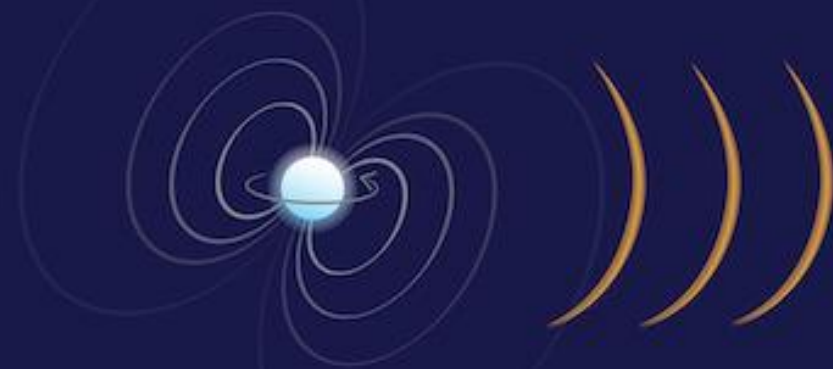
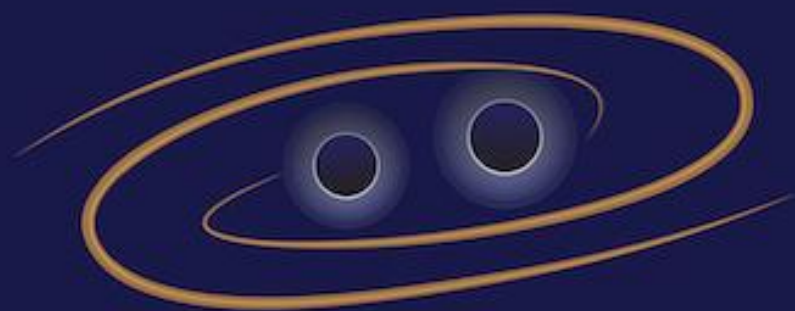
O1 (3) + O2 (8) + O3a (44) + O3b (35) + O4a (139) + O4b (161) = 390, O4c* = 68, Total = 458



Short duration

Long duration

Modelled



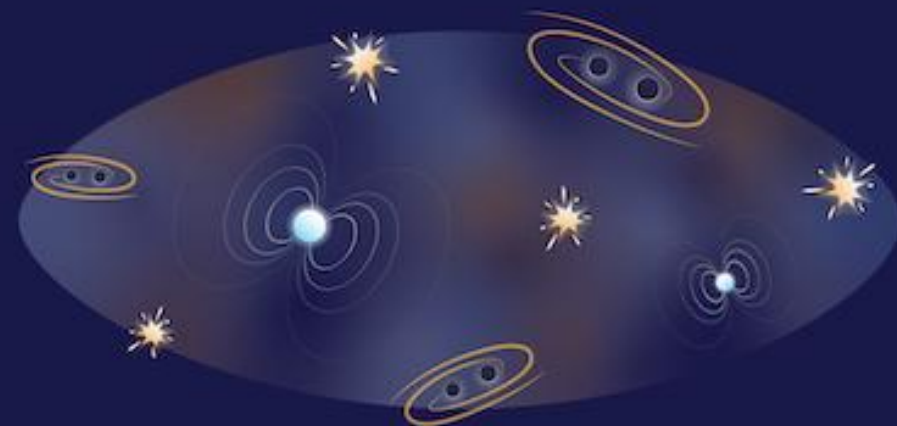
compact binary coalescence



continuous



Unmodelled



burst

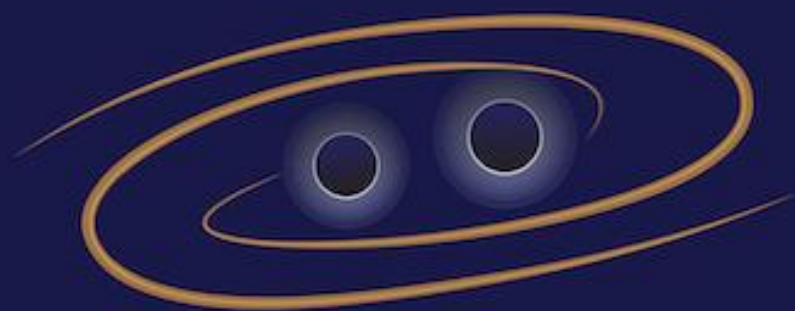


stochastic



Short duration

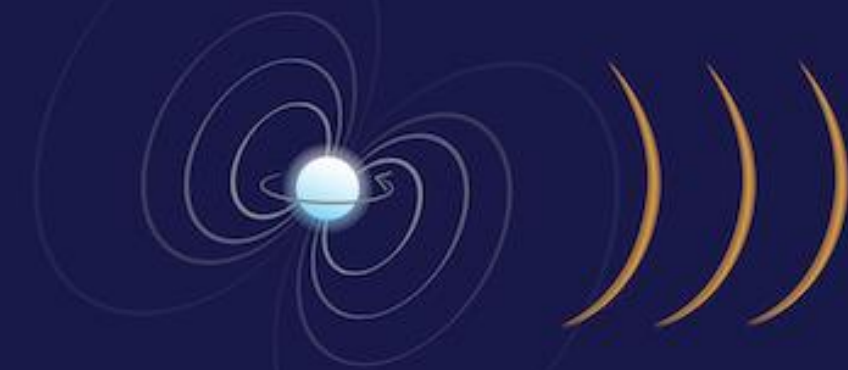
Modelled



compact binary coalescence



Long duration



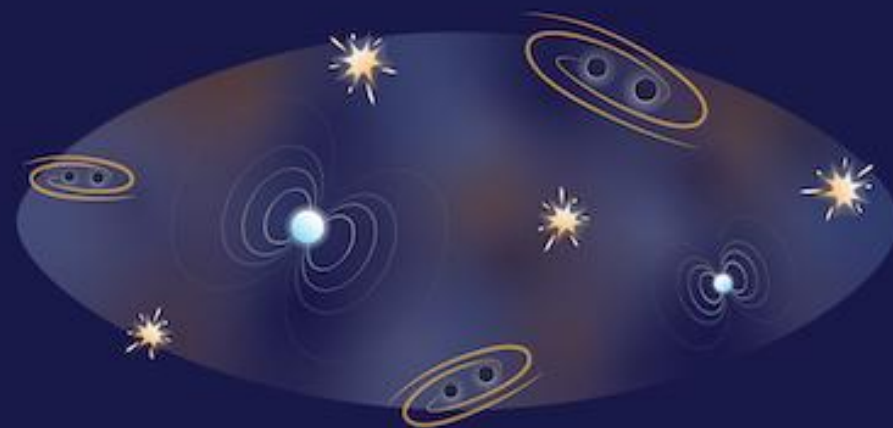
continuous



Unmodelled



burst



stochastic

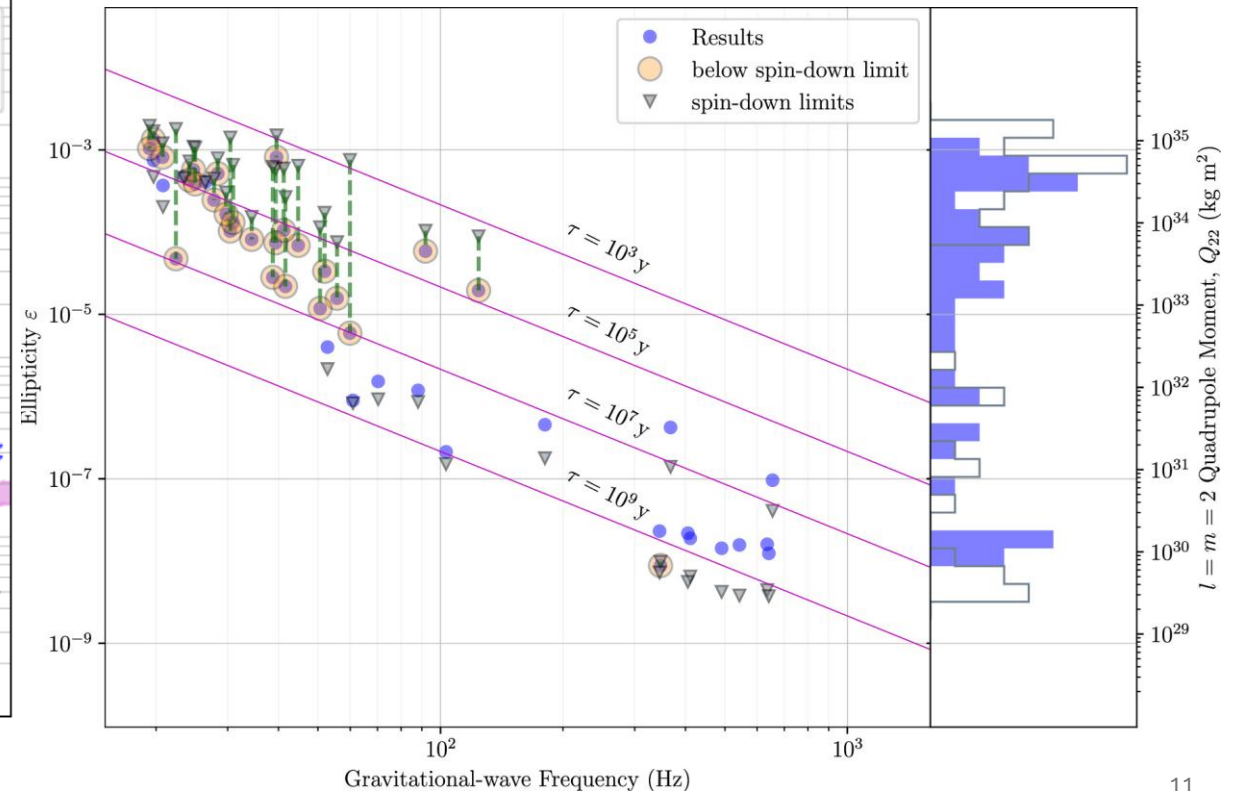
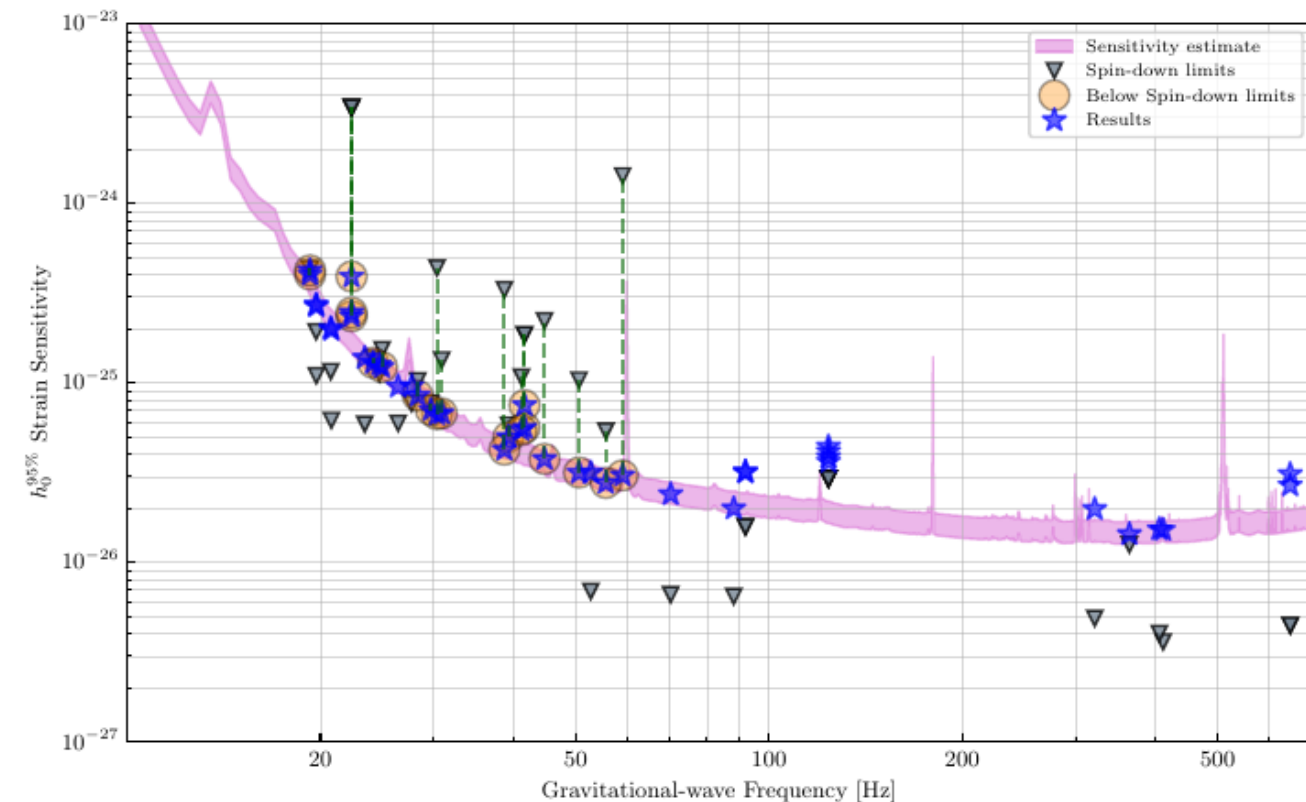


Continuous Gravitational Waves

Search for GWs from known pulsars

Figures from Abac et al, [arXiv:2603.25938](https://arxiv.org/abs/2603.25938)

Also search for signals from unknown neutron stars, both isolated (Abac et al, [arXiv:2603.14168](https://arxiv.org/abs/2603.14168)) and in binary systems (Abac et al, [arXiv:2511.16863](https://arxiv.org/abs/2511.16863))

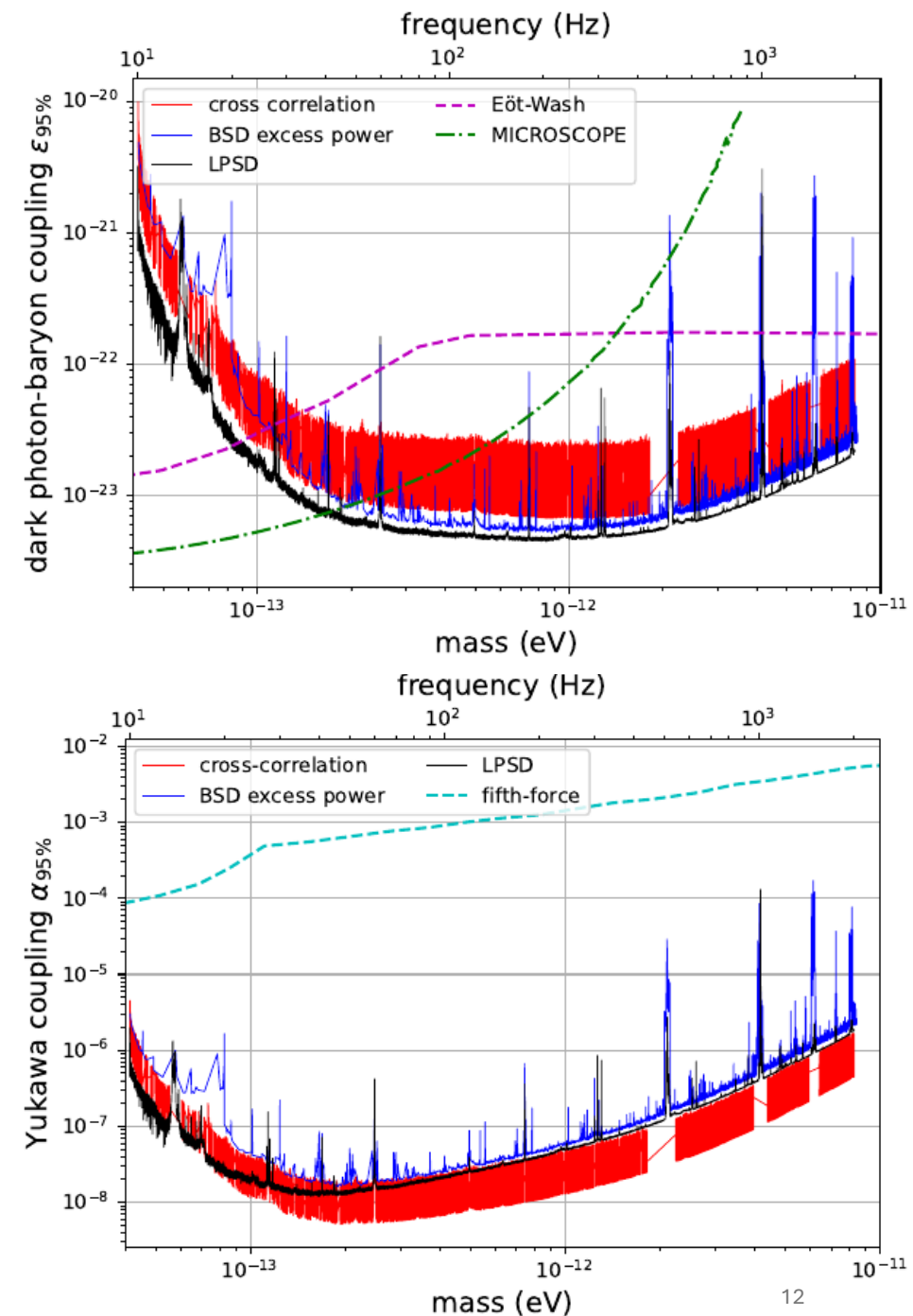


Searching for Dark Matter

GW Interferometers are sensitive to different kinds of Ultra Light Dark Matter that directly interact with the detector:

- Scalar dark matter (spin 0): Expand/Contract mirrors
- Dark photon dark matter (spin 1): Accelerate mirrors
- Tensor dark matter (spin 2): Modify gravity

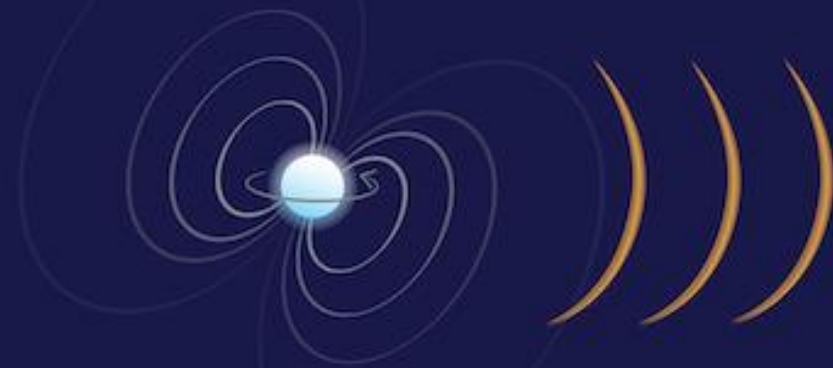
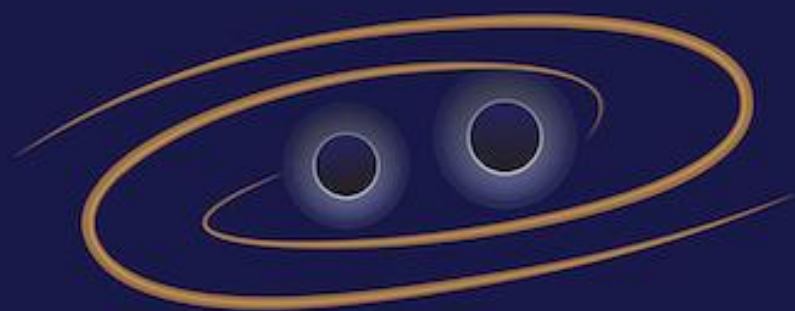
Figures from Abac et al, [arXiv:2510.27022](https://arxiv.org/abs/2510.27022),



Short duration

Long duration

Modelled



compact binary coalescence



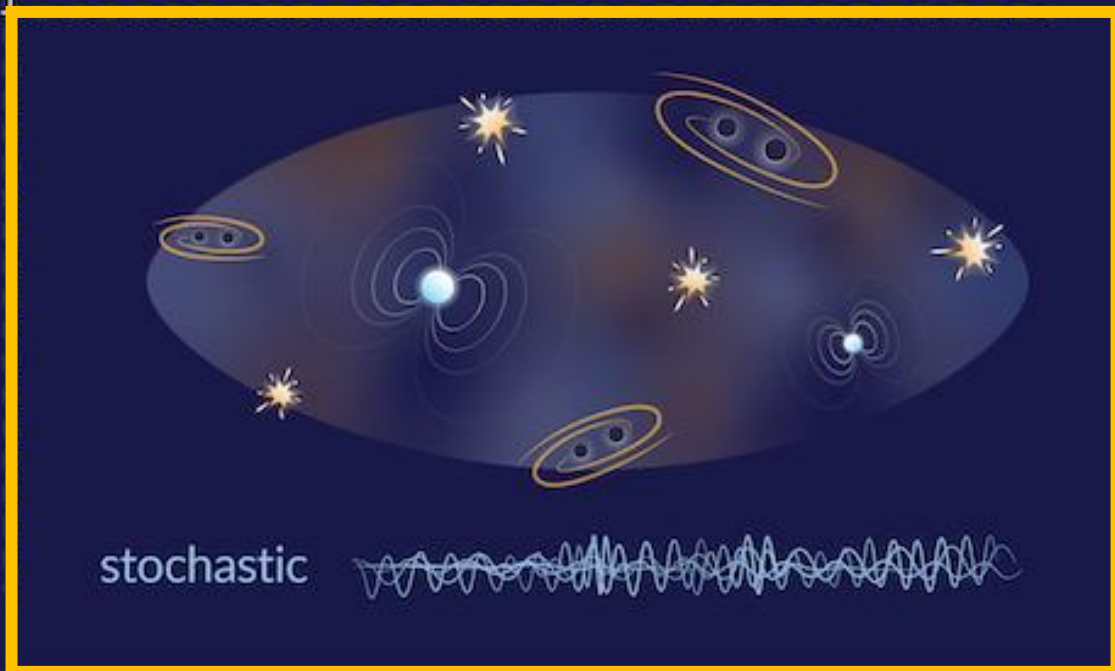
continuous



Unmodelled



burst

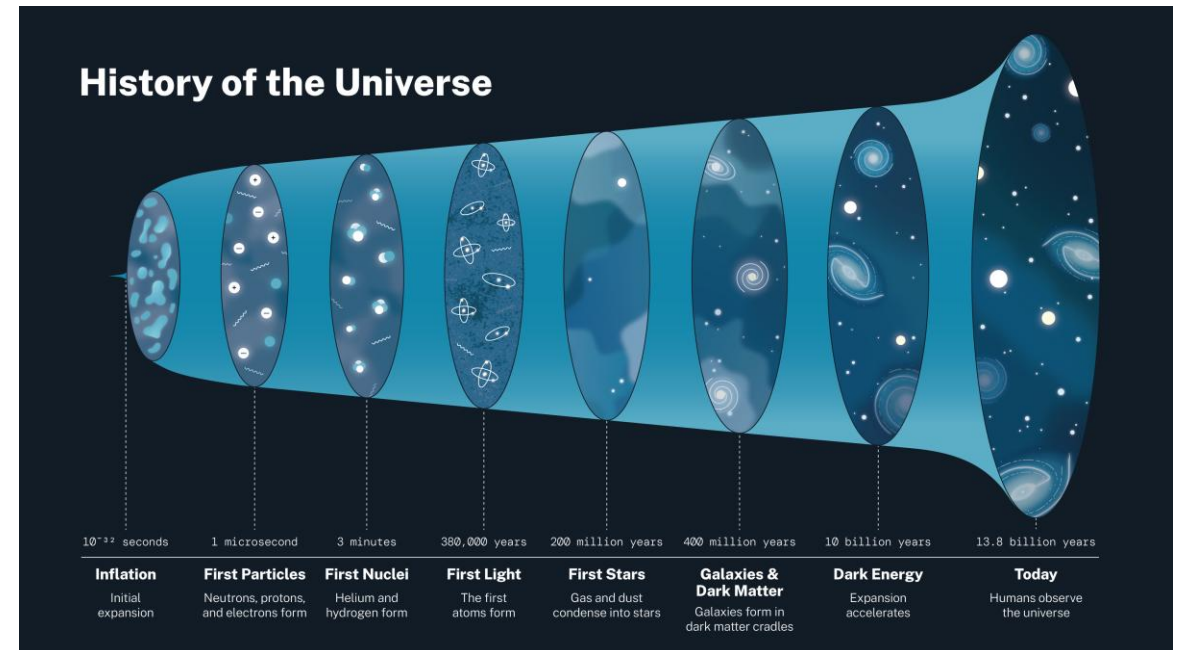


stochastic



Stochastic GW background

- A cosmological background of gravitational waves could be generated in the early universe
- Alternatively, an astrophysical background would arise from a population of gravitational-wave sources which are too weak to observe individually
- Search for both isotropic and directional persistent GW background.
- Characterize the strength of the signal as a fraction of the total energy density of the universe, Ω_{GW}

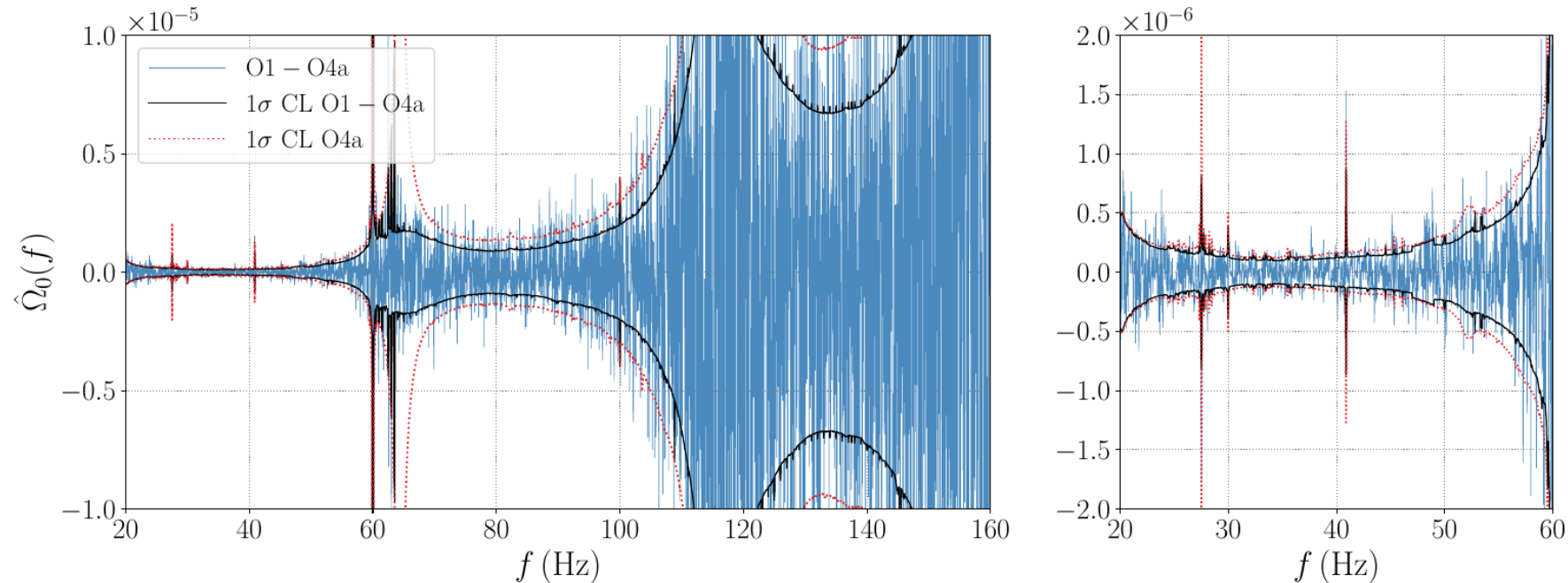


From: <https://science.nasa.gov/universe/overview/>

Stochastic GW background

- Search for both isotropic and directional persistent GW background.
- No observable signal to date. Constrain $\Omega_{\text{GW}}(f)$

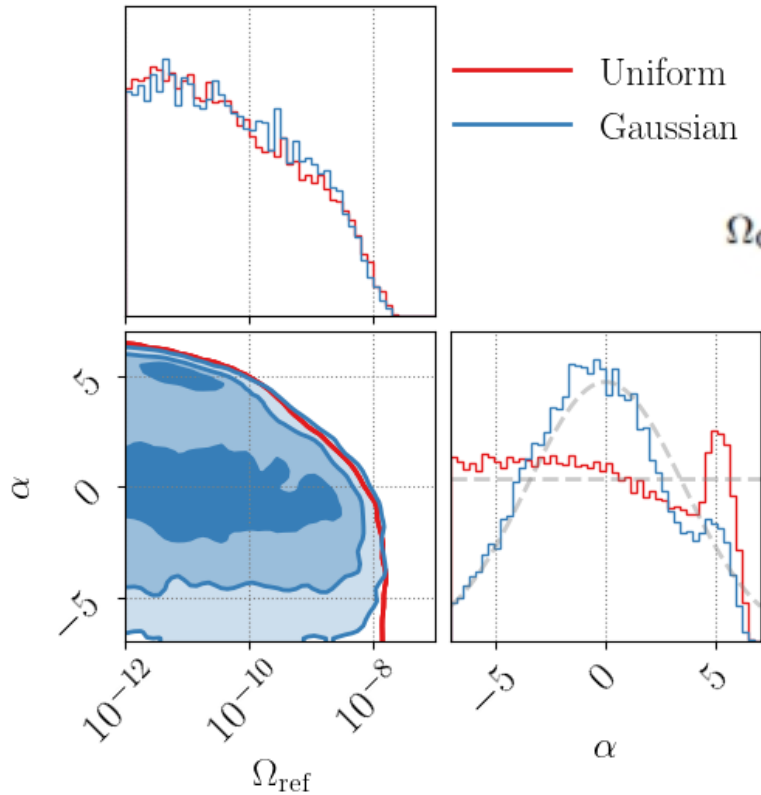
Figures from Abac et al, arXiv:[2508.20721](https://arxiv.org/abs/2508.20721)



Stochastic GW background

Place constraints on

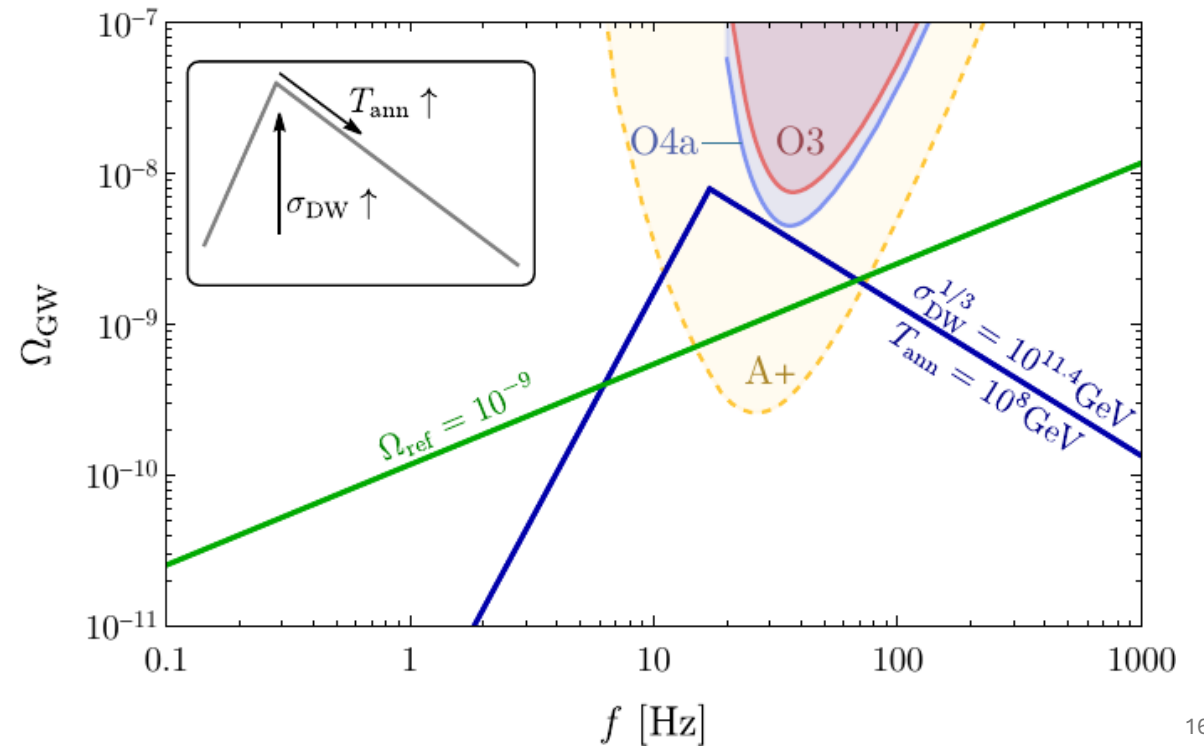
- Ω_{GW} and power law index α from Abac et al, [arXiv:2508.20721](https://arxiv.org/abs/2508.20721)



$$\Omega_{\text{GW}}(f) = \Omega_{\text{ref}} F_{\alpha, \text{ref}}(f),$$

$$F_{\alpha, \text{ref}}(f) = \left(\frac{f}{f_{\text{ref}}} \right)^\alpha$$

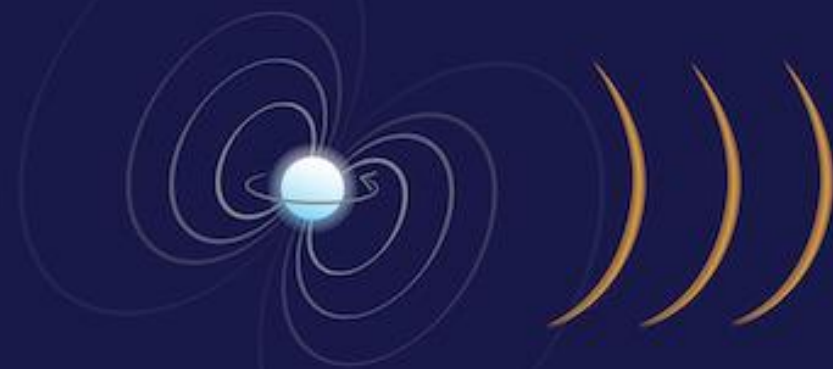
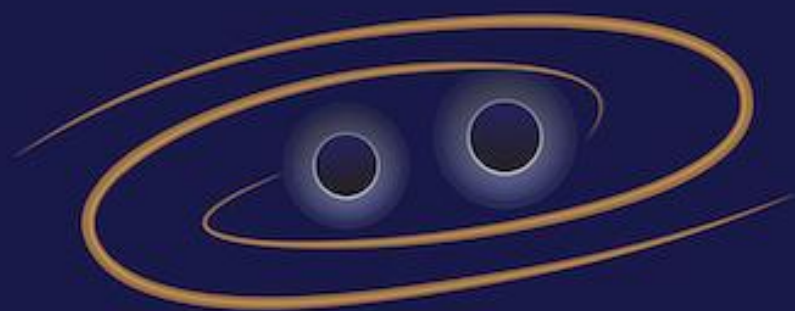
- Various cosmological models which predict GW backgrounds, from Abac et al, [arXiv:2510.26848](https://arxiv.org/abs/2510.26848)
- e.g. domain walls



Short duration

Long duration

Modelled



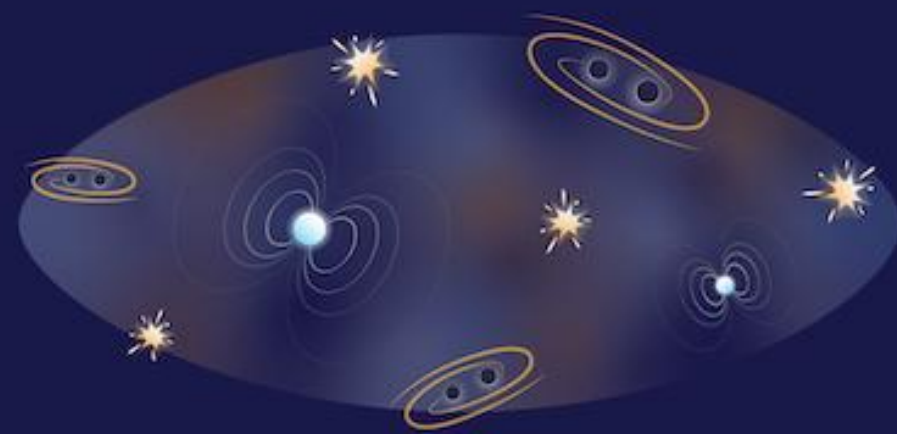
compact binary coalescence



continuous



Unmodelled



burst

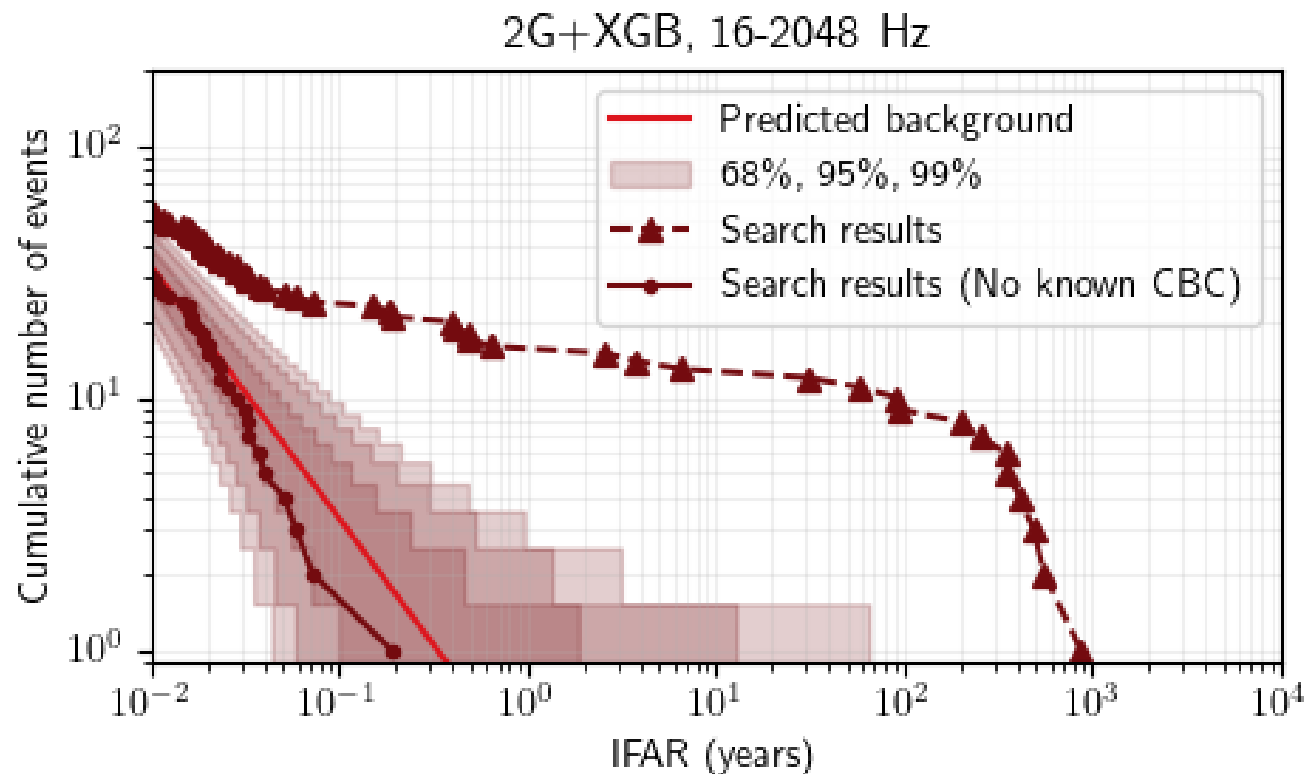


stochastic



Unmodelled transients

- Searches for short- and long-duration transients (bursts)
- Analyses to date identify a subset of the observed BBH mergers, but no other significant transients
- Short bursts:
Abac et al, [arXiv:2507.12374](https://arxiv.org/abs/2507.12374)
- Long duration transients:
Abac et al, [arXiv:2507.12282](https://arxiv.org/abs/2507.12282)

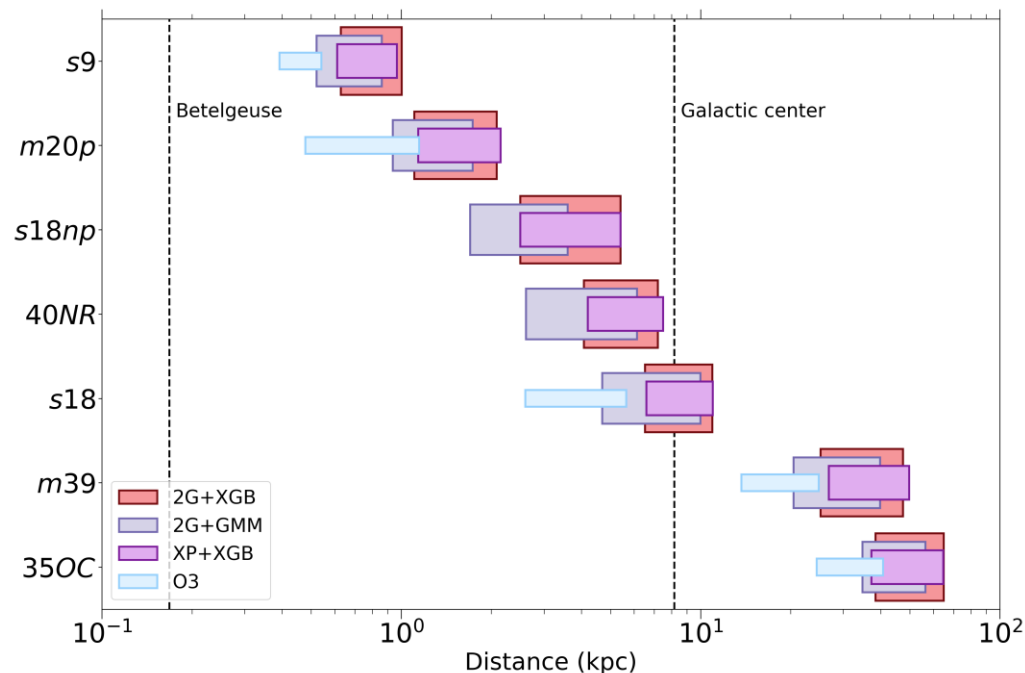


Short transients

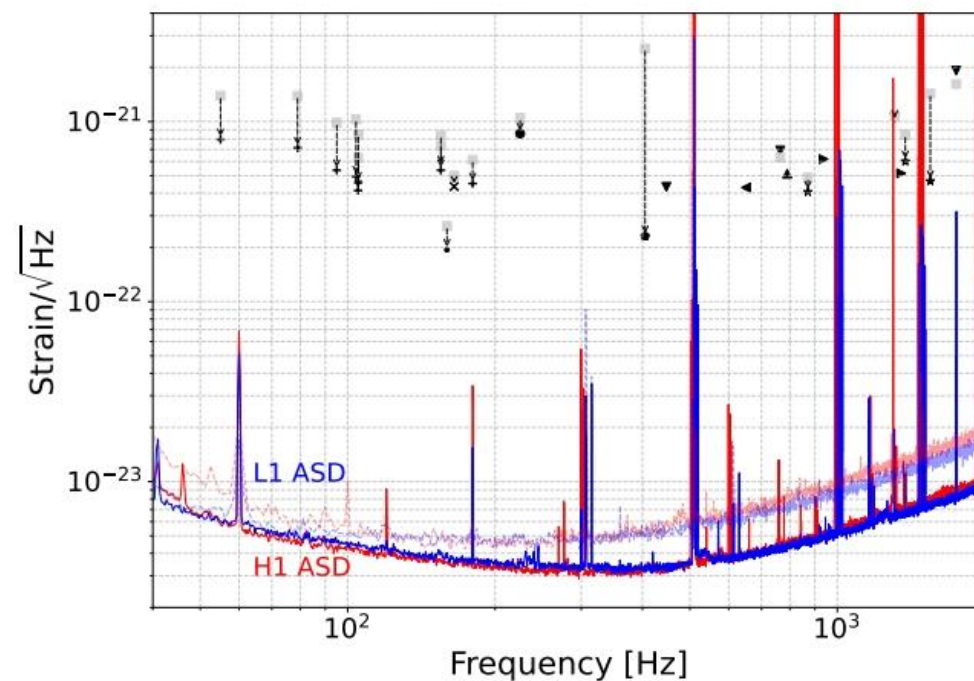
Unmodelled transients

- Searches for short- and long-duration transients (bursts)
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Abac et al, [arXiv:2507.12374](https://arxiv.org/abs/2507.12374)
- Long duration transients:
Abac et al, [arXiv:2507.12282](https://arxiv.org/abs/2507.12282)

Supernova
sensitivity

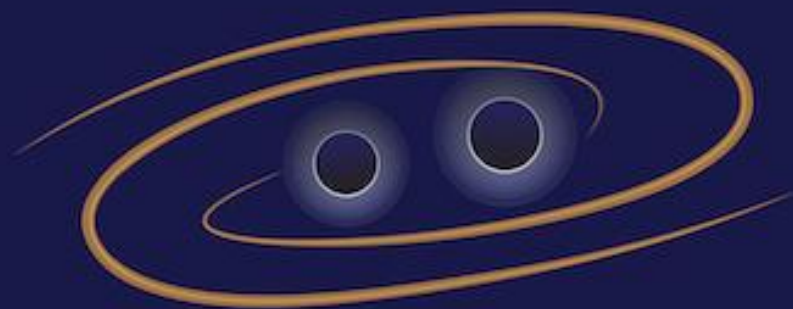


Long
Transient
sensitivity



Modelled

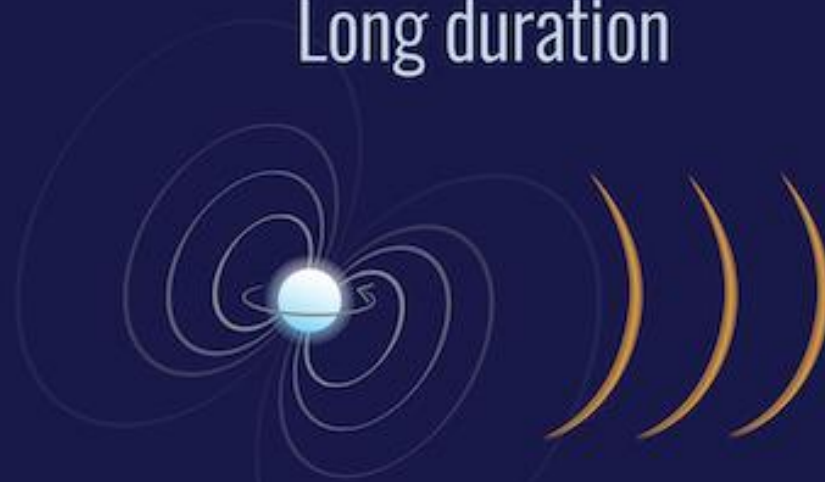
Short duration



compact binary coalescence



Long duration



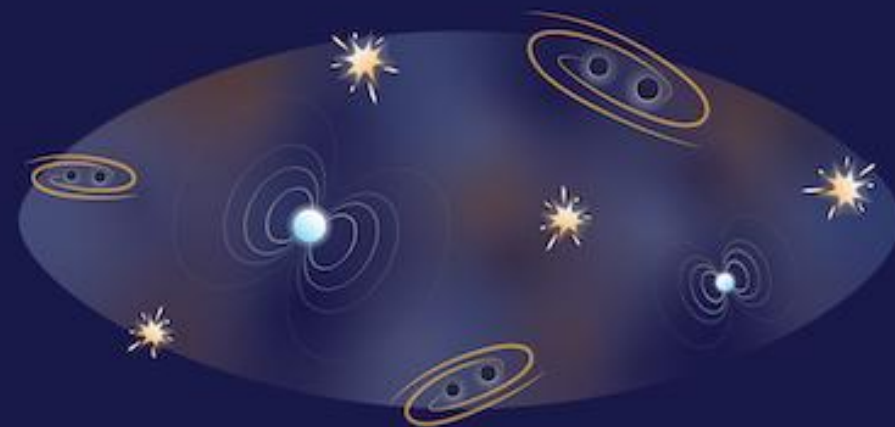
continuous



Unmodelled



burst

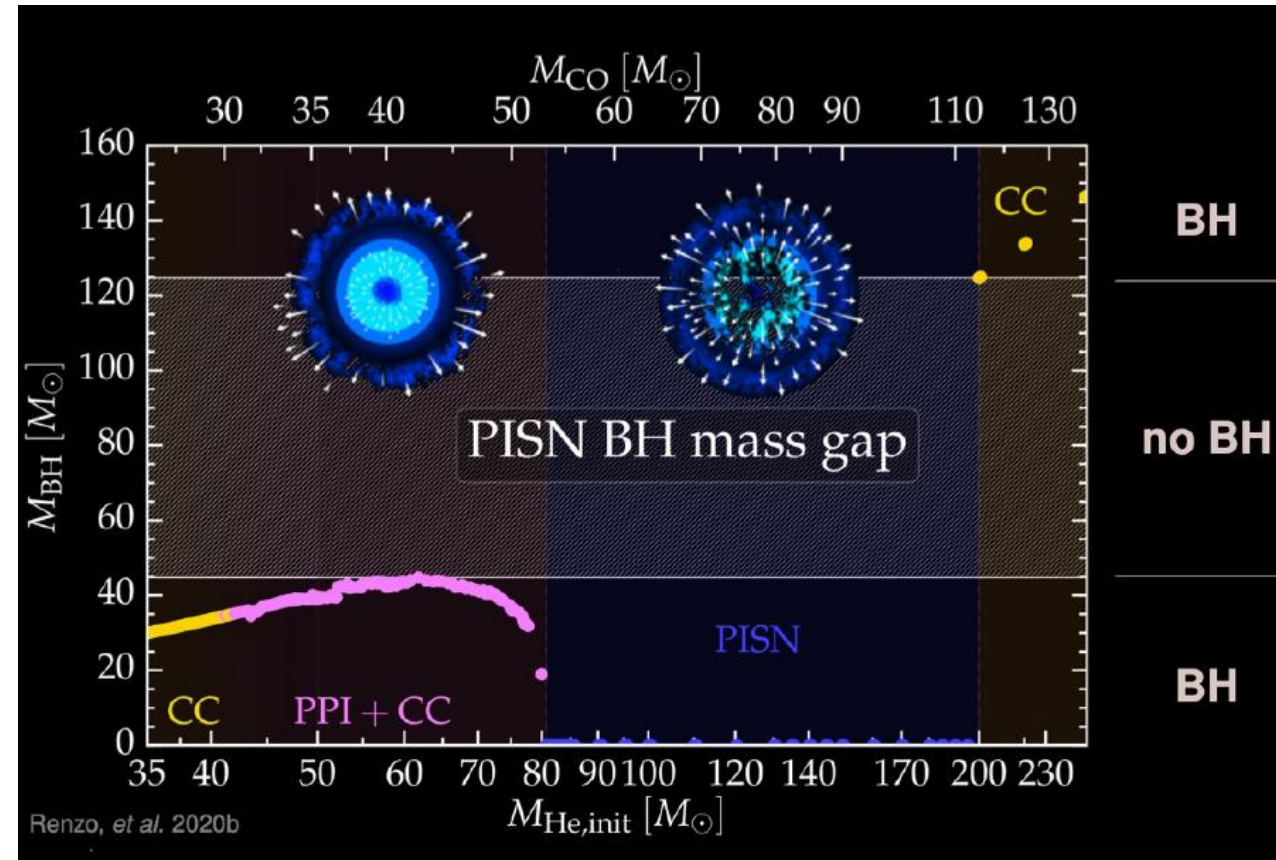


stochastic

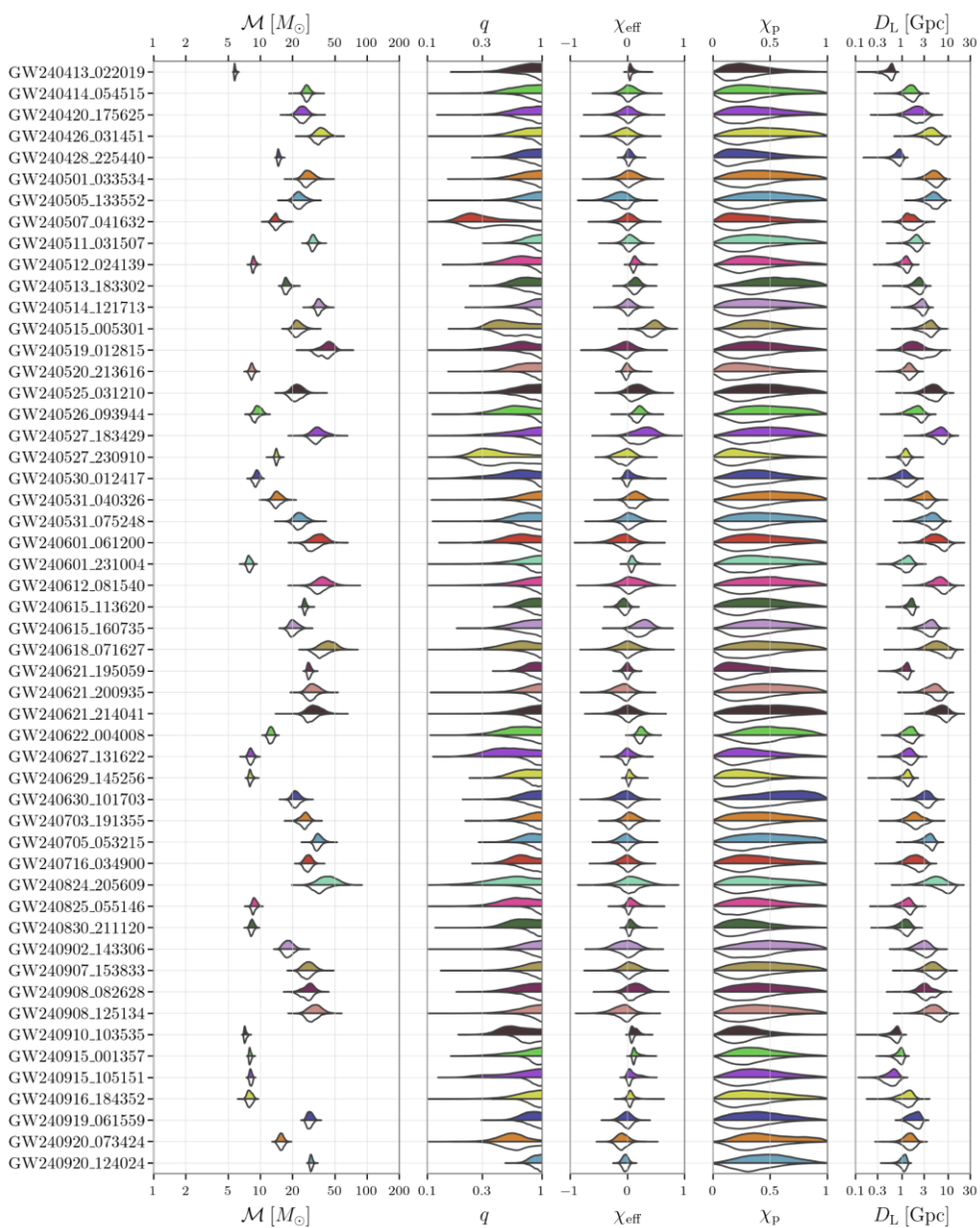


What was expected?

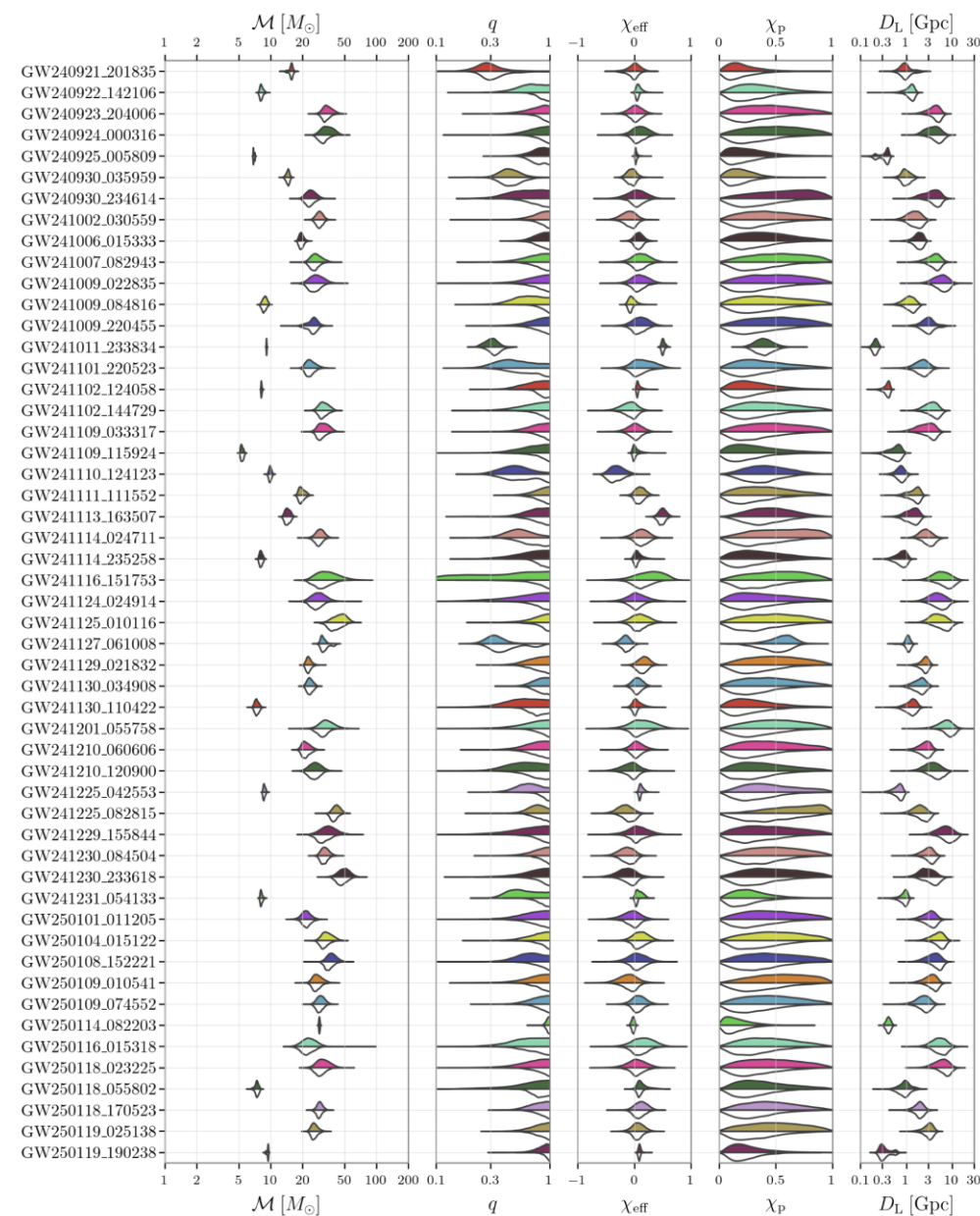
- High rate of neutron star mergers, as high as 40 observations per year
- Wildly uncertain black hole merger rates, from zero to hundreds per year
- Most massive black holes around $40M_{\odot}$, due to pair instability supernovae
- No black holes below $5 M_{\odot}$, a “mass gap” between neutron stars and lightest black holes
- Highly spinning black holes



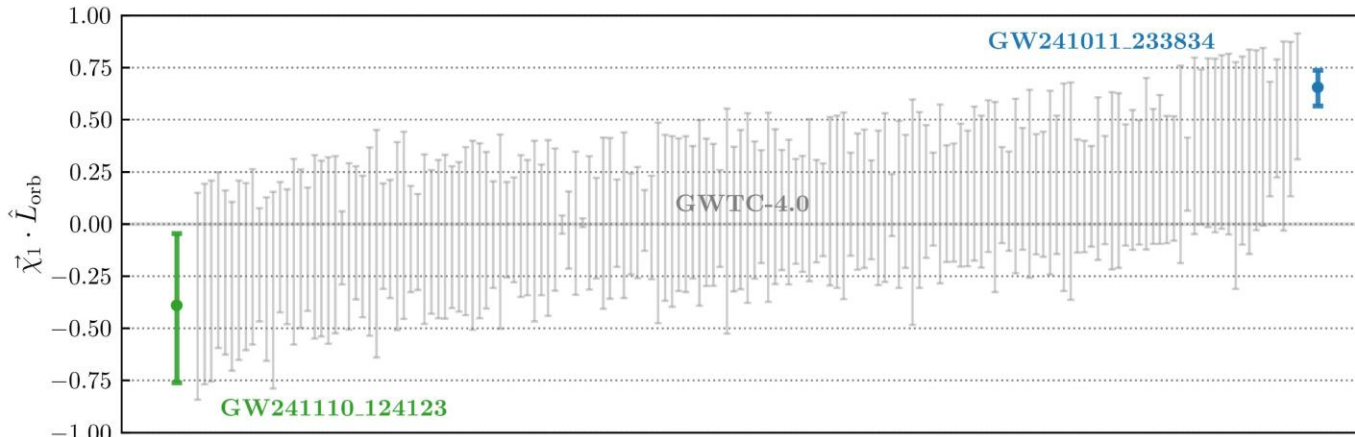
GWTC-5.0



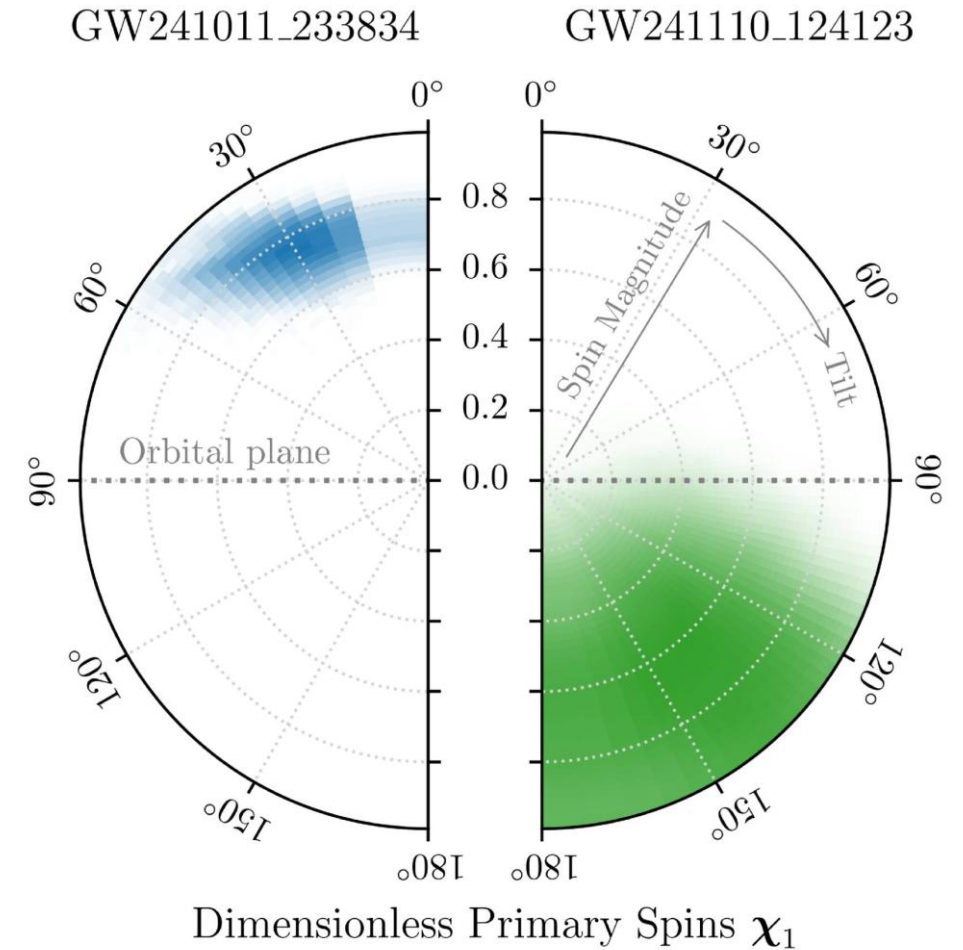
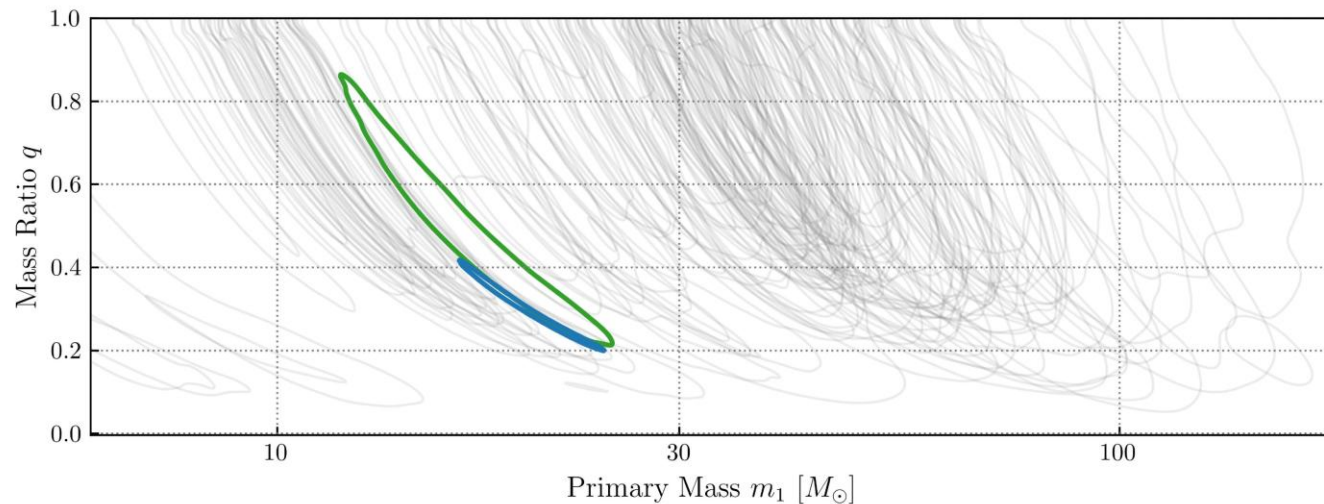
- Six papers released on 26 May describing O4b data and new observations
- “This brings the total number of transients in the cumulative GWTC having $p_{\text{astro}} > 0.5$ to 390”
- From Abac et al, [arXiv:2605.27225](https://arxiv.org/abs/2605.27225)
- Final O4 data and updated catalog will be released on 16 December 2026



GW241011 and GW241110



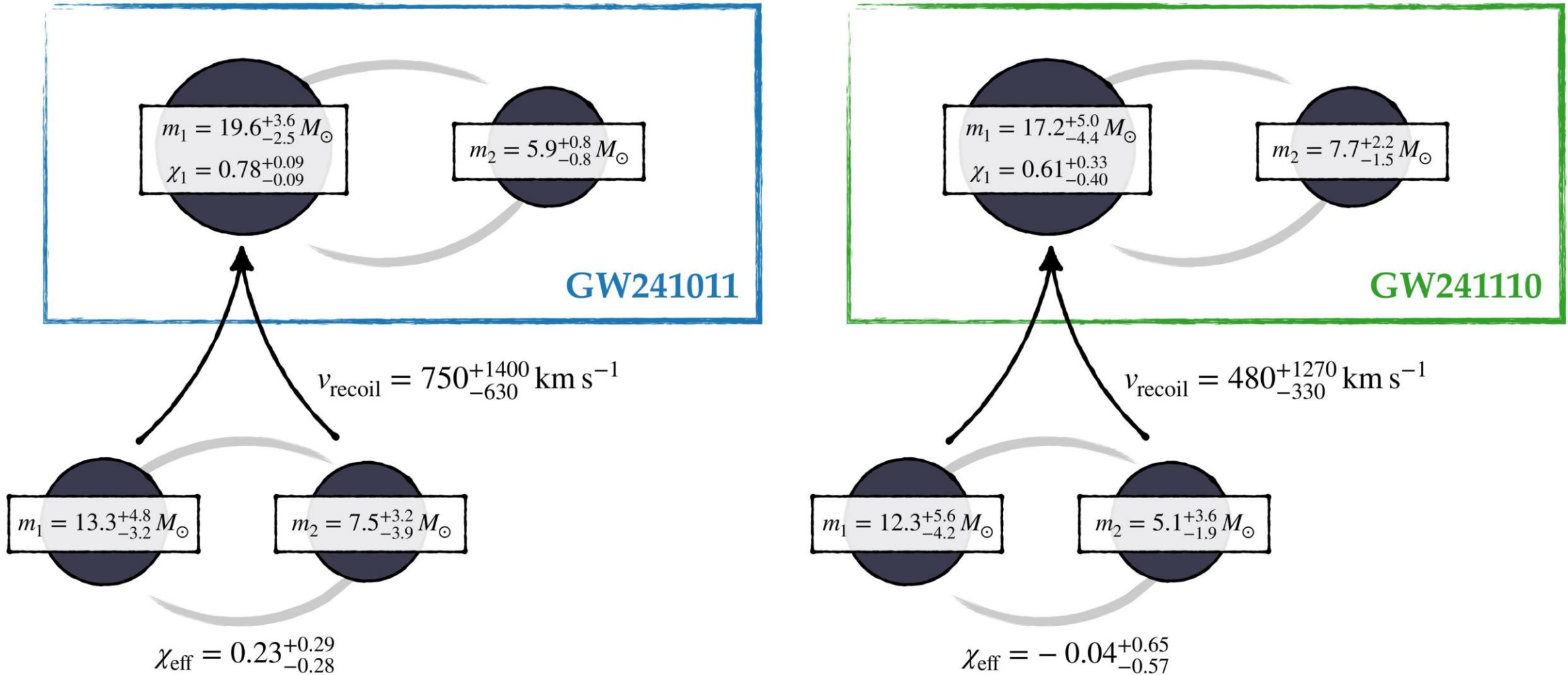
Compact Binary Detections



Dimensionless Primary Spins χ_1

From Abac et al, [arXiv:2510.26931](https://arxiv.org/abs/2510.26931), “GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-Spin Black Hole Coalescence”

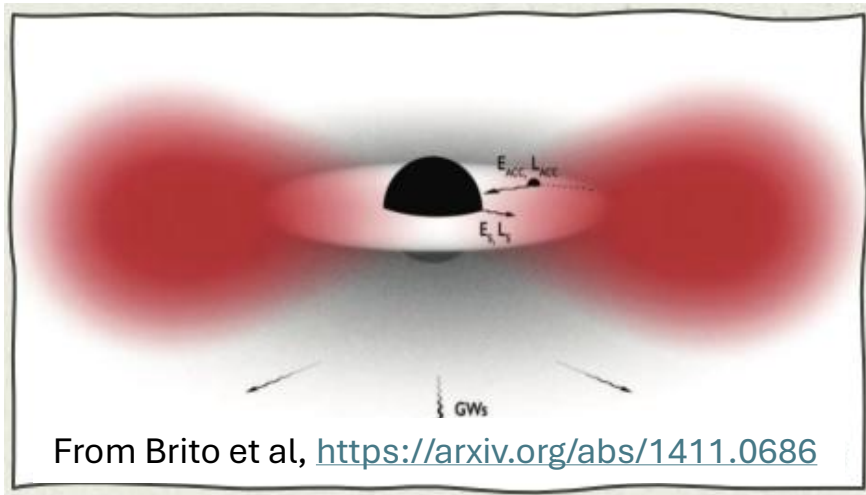
GW241011 and GW241110 as hierarchical mergers



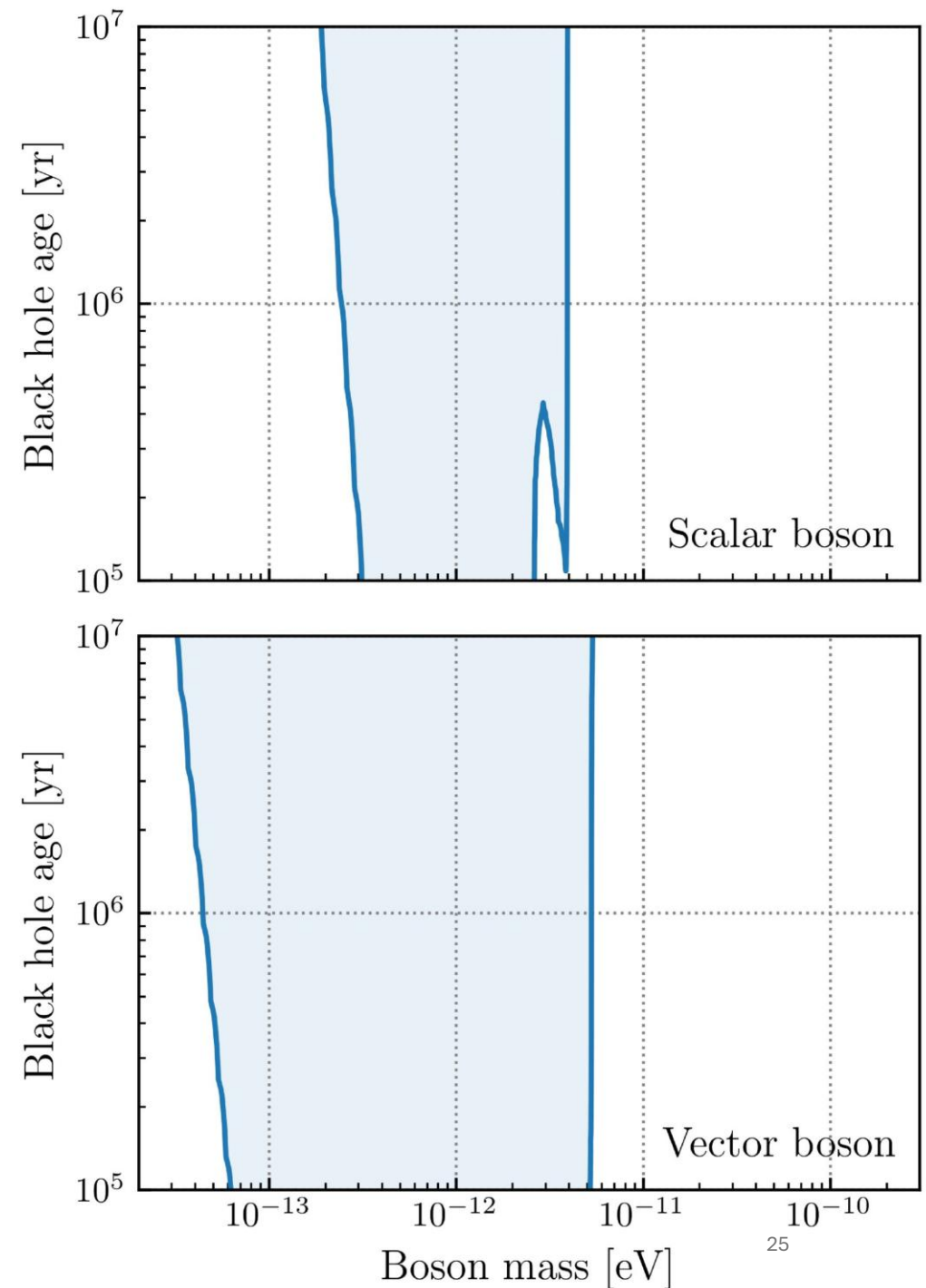
From Abac et al, [arXiv:2510.26931](https://arxiv.org/abs/2510.26931), “GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-Spin Black Hole Coalescence”

Constraining Dark Matter

- Vector boson clouds around black holes would spin-down the black holes
- Observation of high spins enables constraints on these fields



From Abac et al, [arXiv:2510.26931](https://arxiv.org/abs/2510.26931)



10 Years Later: LIGO Hears Loud and Clear

[News](#) | [Ten Years Later, LIGO is a Black-Hole Hunting Machine](#) | [LIGO Lab](#) | [Caltech](#)



GW150914 — Sept. 2015

Hanford

-0.2 s

-0.1 s

-0.0 s



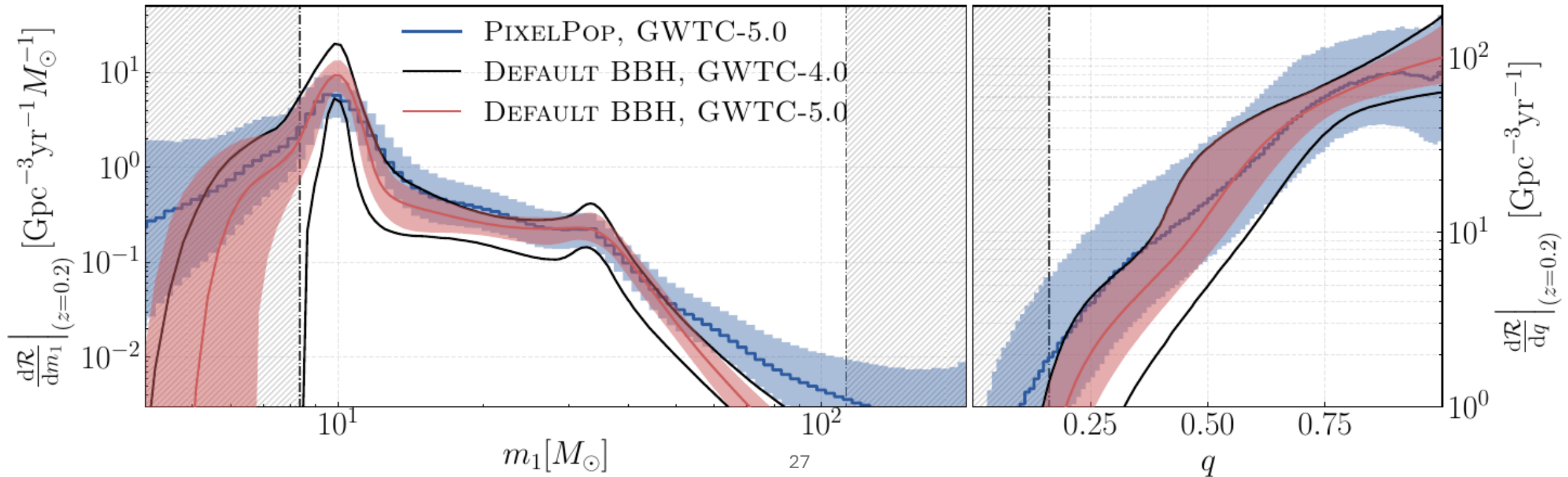
GW250114 — Jan. 2025

Hanford

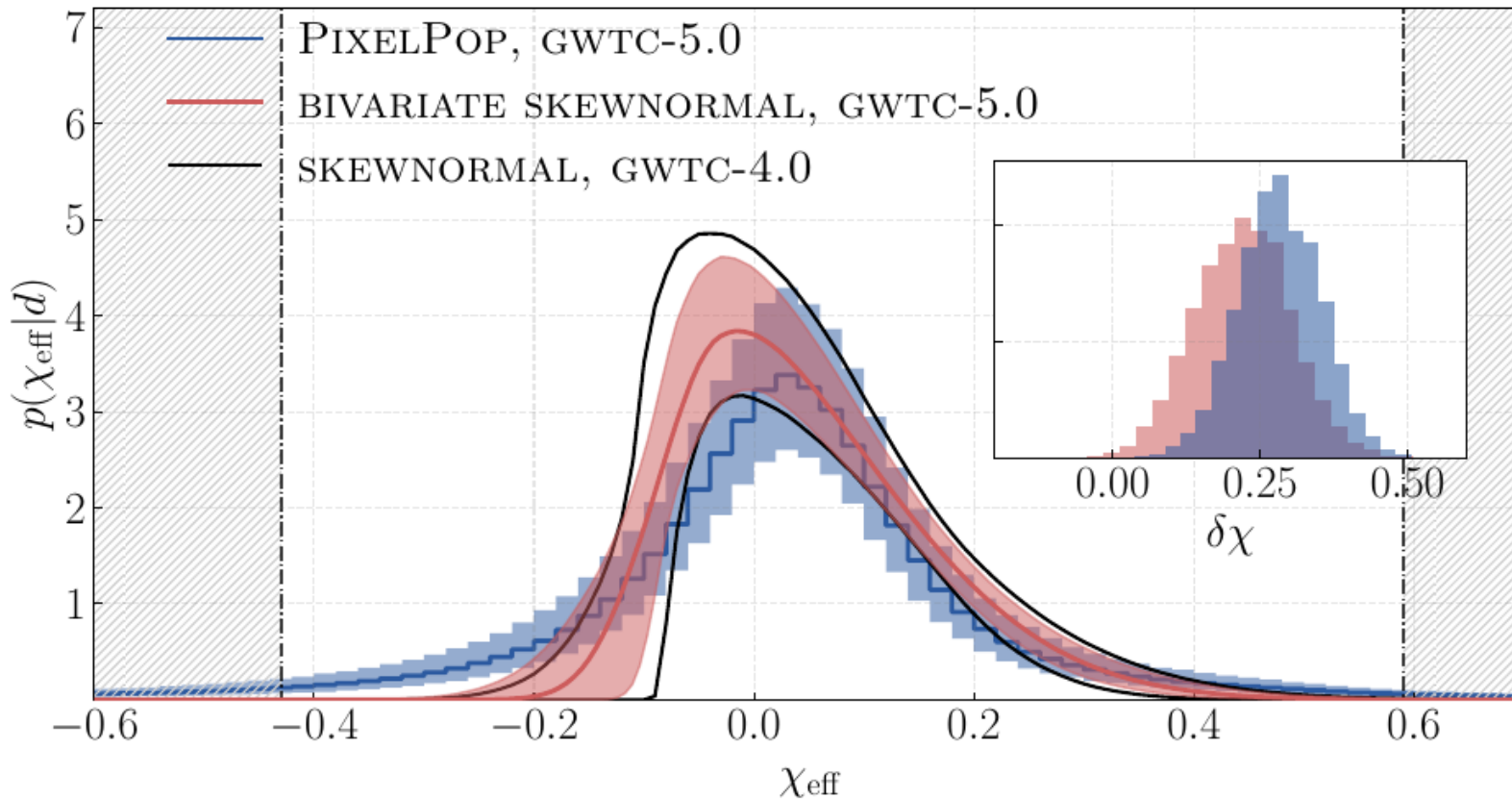
GWTC-5.0: The astrophysical population

Infer the population of black hole/neutron star mergers from GW observations

Fit both **strongly parametrized** and **weakly parametrized [PixelPop]** models.
From Abac et al, [arXiv:2605.27226](https://arxiv.org/abs/2605.27226)



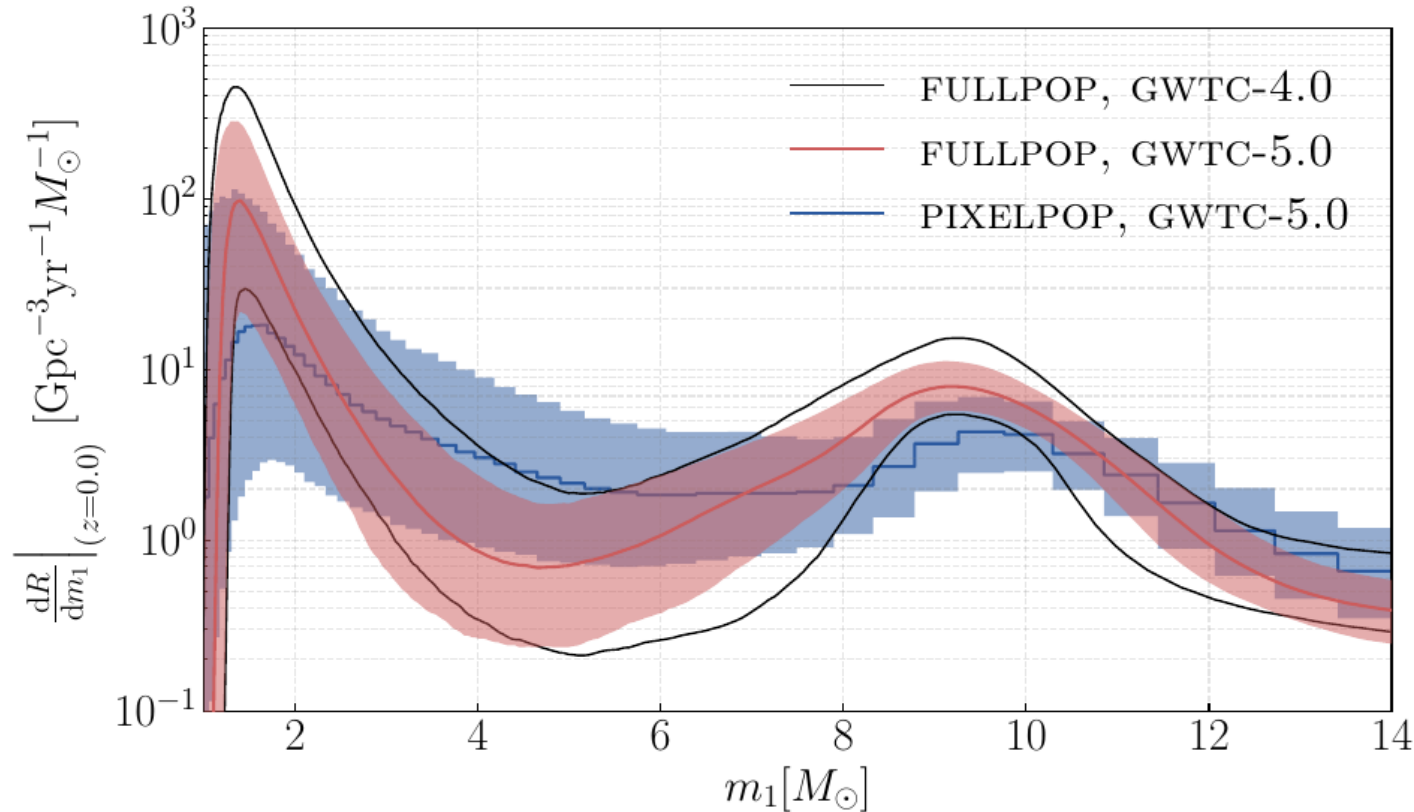
GWTC-5.0: The astrophysical population



- Black hole spins are predominantly non-extremal with 85% belonging to a small spin population ($\chi < 0.25$)
- Identify a high-spin population ($\chi \sim 0.25$)
- Spins preferentially aligned, rather than misaligned, with orbital angular momentum

From Abac et al, [arXiv:2605.27226](https://arxiv.org/abs/2605.27226)

GWTC-5.0: The astrophysical population



No new Binary Neutron Star mergers observed

- After GW170817,
 $R = 1540 (+3200/-1220) \text{ Gpc}^{-3} \text{ yr}^{-1}$
- With GWTC-5,
 $R = 59.3 (+95.4/-43.9) \text{ Gpc}^{-3} \text{ yr}^{-1}$

Rule out a “mass gap”
between 3 and 5 M_{\odot}

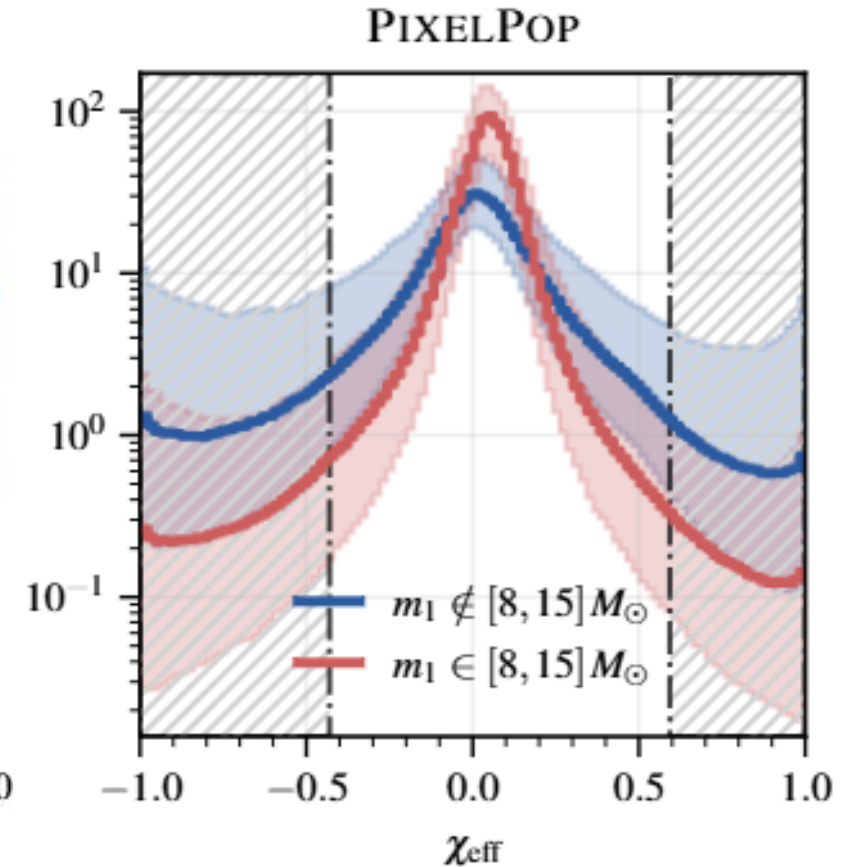
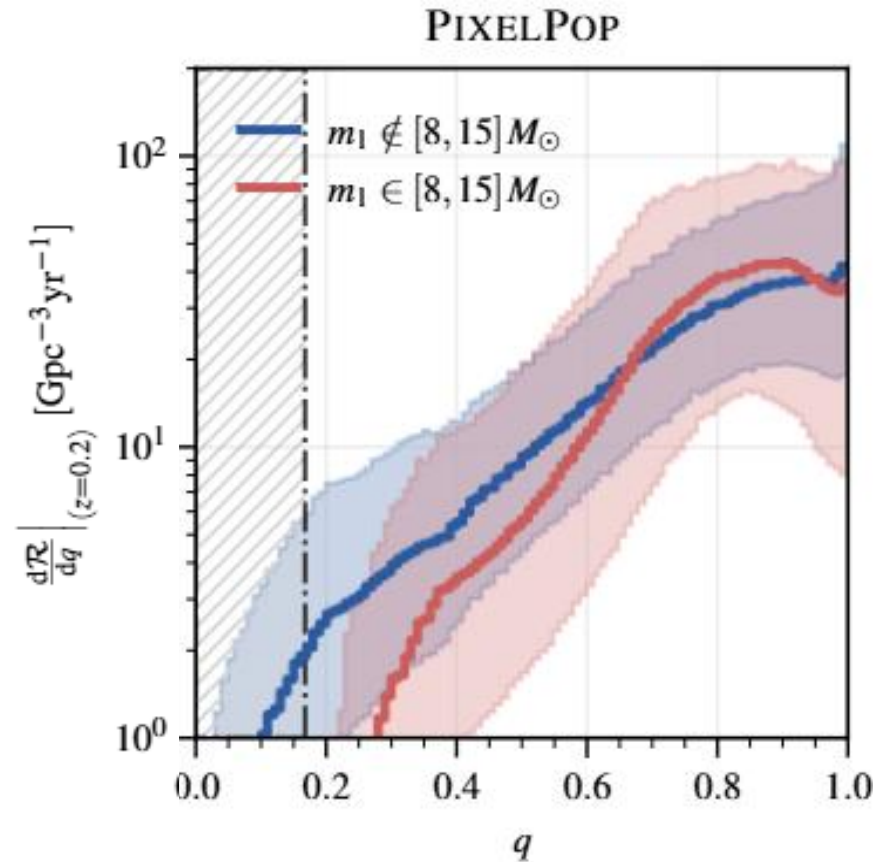
From Abac et al, [arXiv:2605.27226](https://arxiv.org/abs/2605.27226)

GWTC-5.0: Subpopulations

Evidence for a low-mass subpopulation

- Preference for close to equal masses
- Lower effective spins

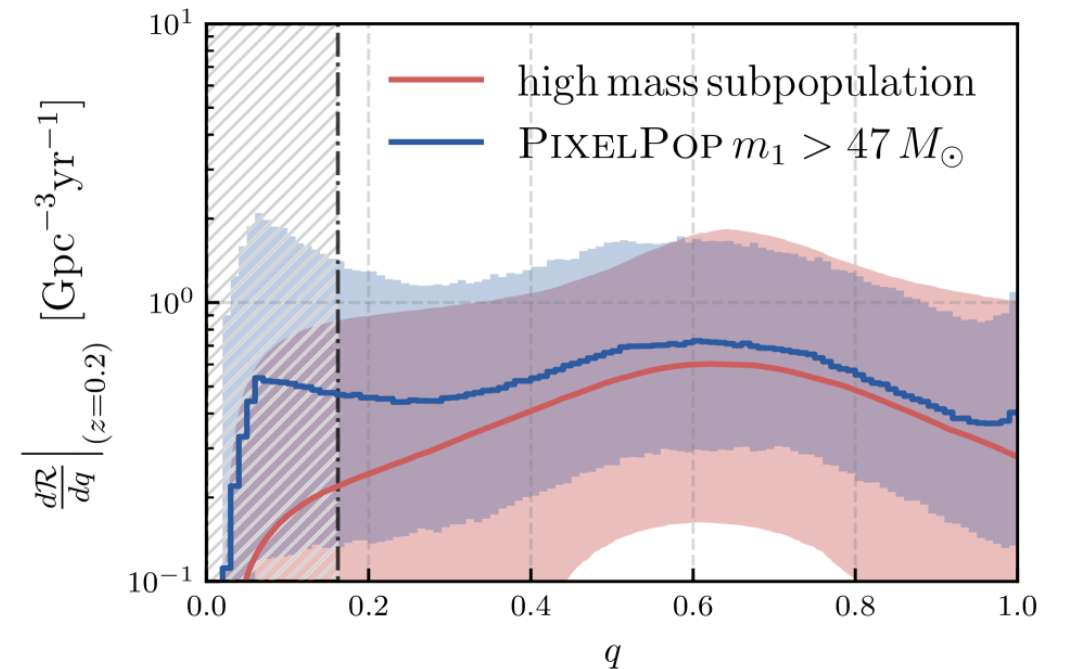
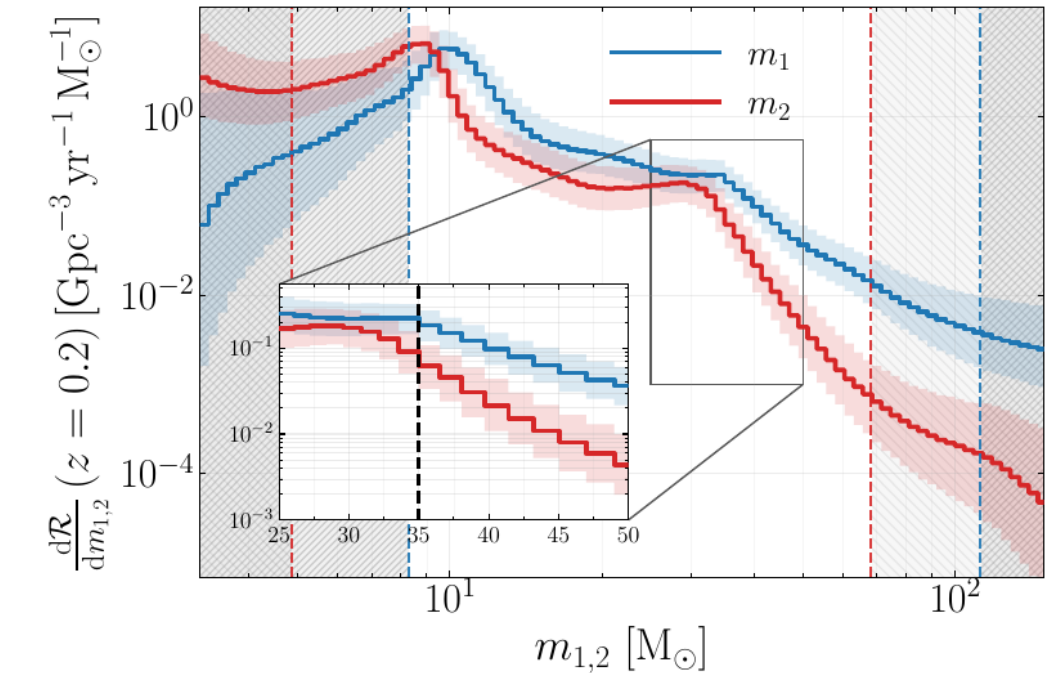
From Abac et al, [arXiv:2605.27](https://arxiv.org/abs/2605.27)



GWTC-5.0: Subpopulations

- Difference in inferred distributions of primary and secondary above $40 M_{\odot}$
- Very broad mass ratio distribution
- Possible evidence of a population of hierarchical mergers

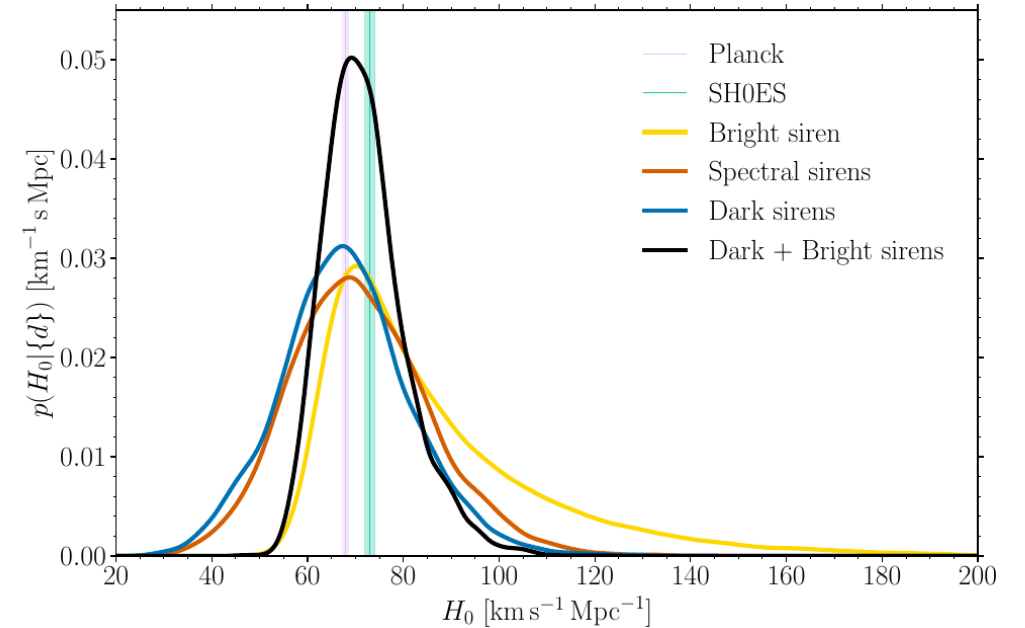
From Abac et al, [arXiv:2605.27226](https://arxiv.org/abs/2605.27226)



GWTC-5.0: Cosmology

- “Bright sirens”: require observation of GW and EM signal, as in GW170817
- “Spectral sirens”: joint inference of cosmological and population properties
- “Dark sirens”: include statistical overlap with potential host galaxies

From Abac et al, [arXiv2605.27227](https://arxiv.org/abs/2605.27227)



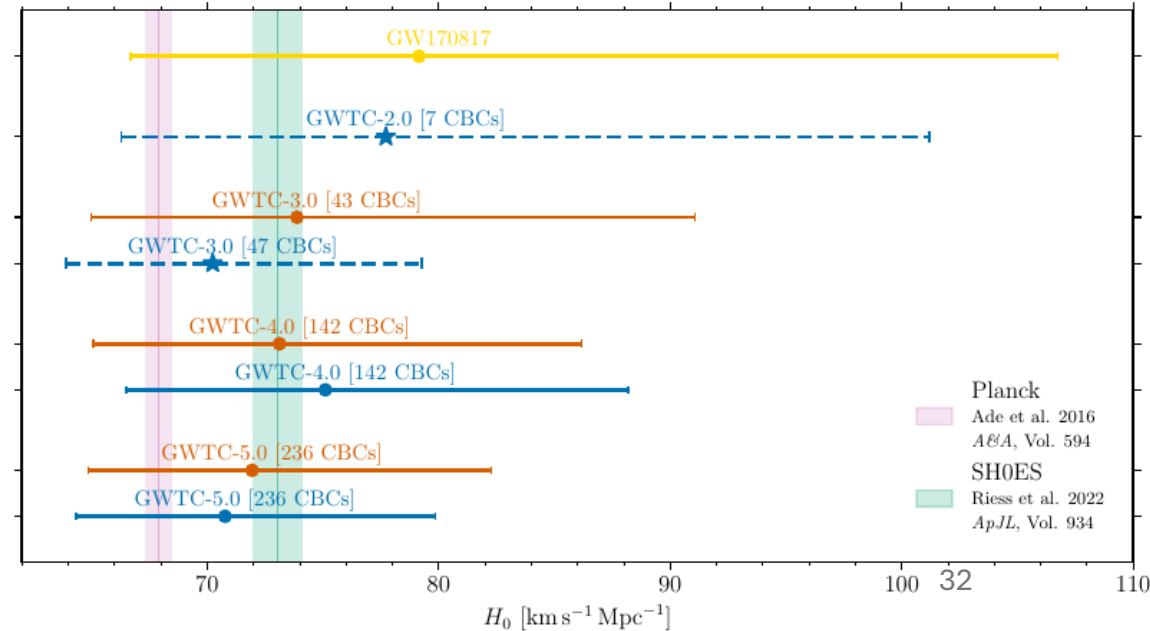
This work (Updated)

Abbott et al. 2021
ApJ, Vol. 909, No2

Abbott et al. 2023
ApJ, Vol. 949, No2

Abac et. al 2025
arxiv 2509.04348

This work



Planck
Ade et al. 2016
A&A, Vol. 594
SH0ES
Riess et al. 2022
ApJL, Vol. 934

Planned Sensitivity Evolution

Low Frequency Sensitivity

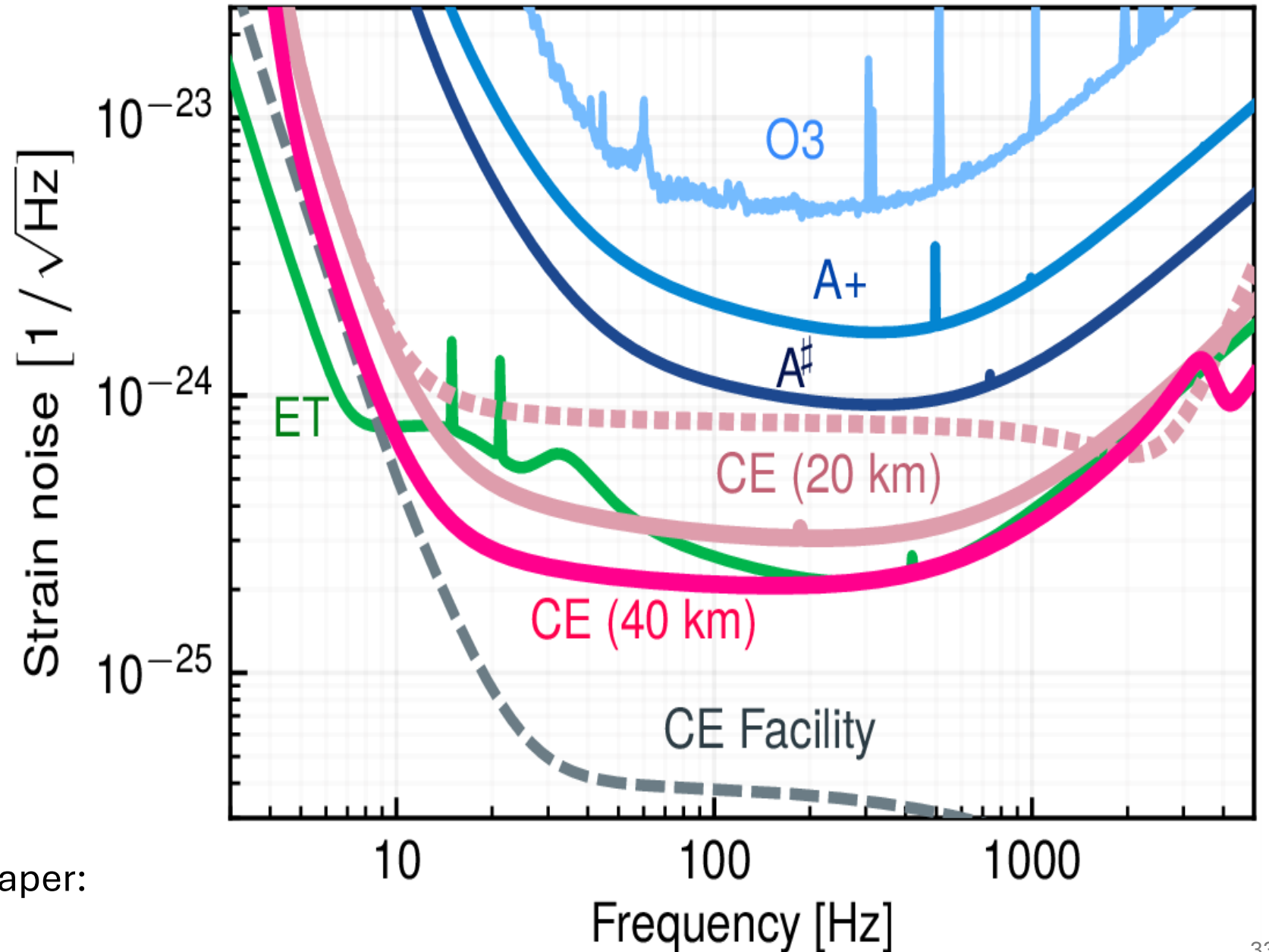
- Longer signals (early warning)
- Sensitive to higher masses

“Bucket” Sensitivity

- Greater reach
- Higher SNR

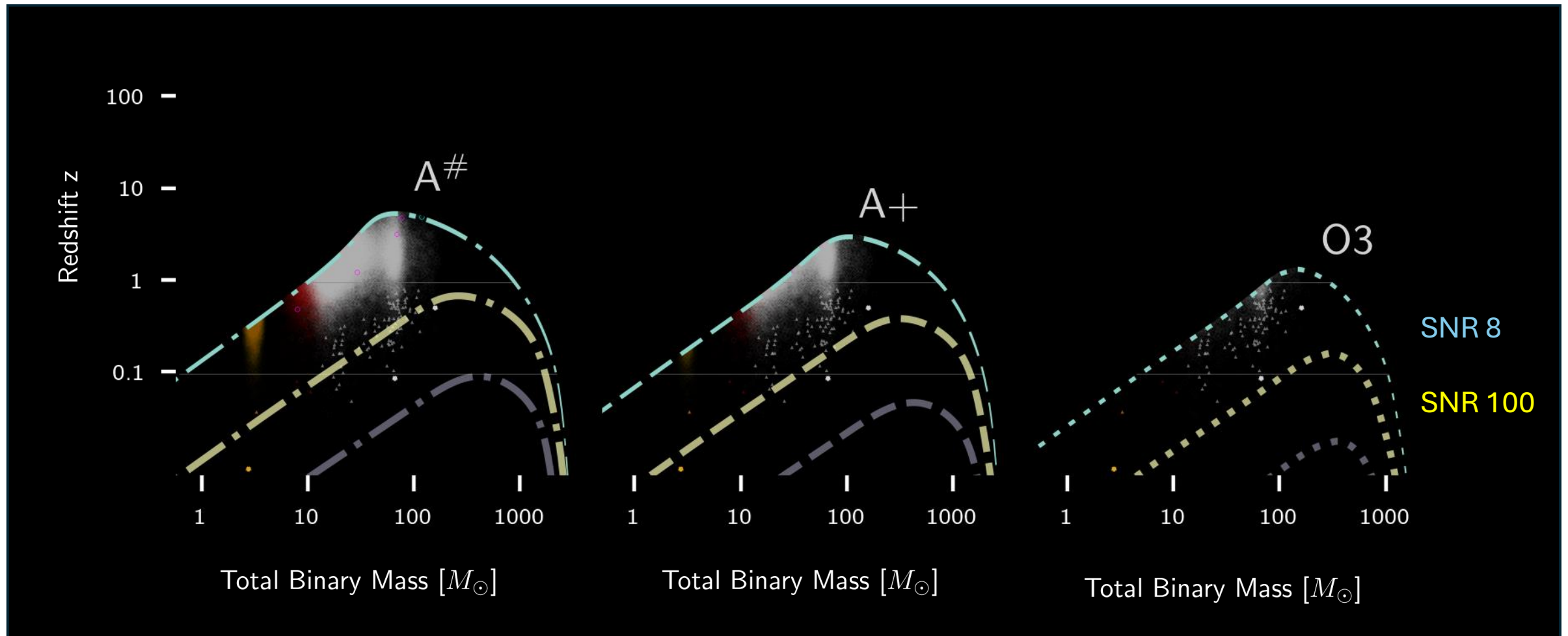
High Frequency Sensitivity

- Sensitivity to merger and post-merger signals
- Sensitivity to Supernovae



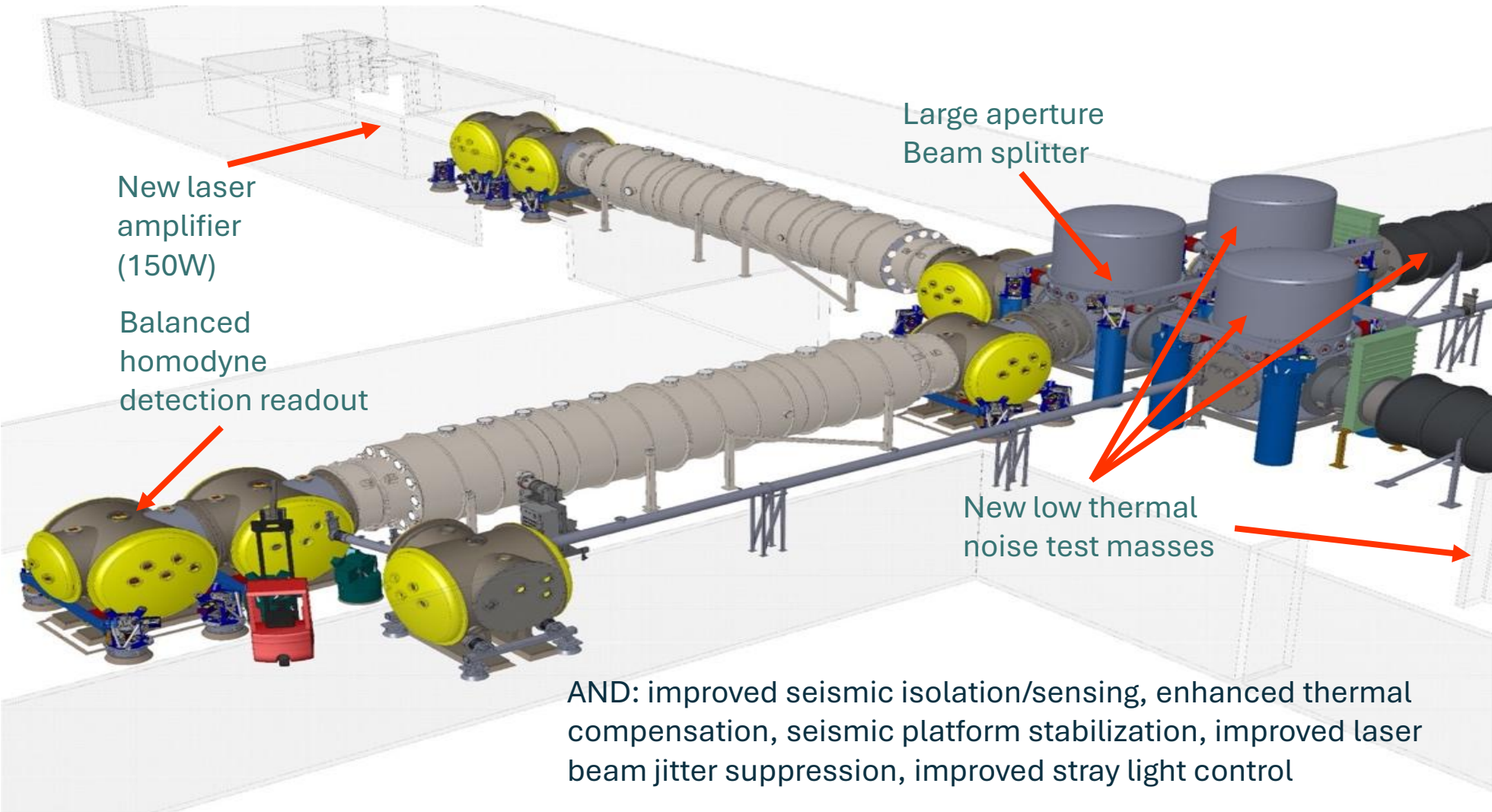
From Cosmic Explorer white paper:
Evans et al, [arXiv:2306.13745](https://arxiv.org/abs/2306.13745)

Expanding reach of current observatories



From Cosmic Explorer white paper: Evans et al, [arXiv:2306.13745](https://arxiv.org/abs/2306.13745)

Completing the LIGO A+ upgrade



New laser amplifier (150W)

Balanced homodyne detection readout

Large aperture Beam splitter

New low thermal noise test masses

AND: improved seismic isolation/sensing, enhanced thermal compensation, seismic platform stabilization, improved laser beam jitter suppression, improved stray light control

LIGO India

The LIGO India project obtained approval in February 2016.

- The LIGO Laboratory is providing the hardware for a complete LIGO interferometer, including technical data on its design, installation and commissioning
- India is providing the site, the vacuum system, and other infrastructure required to house and operate the interferometer.

On 23 May 2026, There was a ground-breaking ceremony at the LIGO-India site,

<https://www.ligo.caltech.edu/news/ligo20260423>



LIGO A# Upgrade

Improved low frequency sensitivity requires:

- Larger test masses, improvements to test mass suspensions
- Improved seismic isolation and subtraction of Newtonian noise

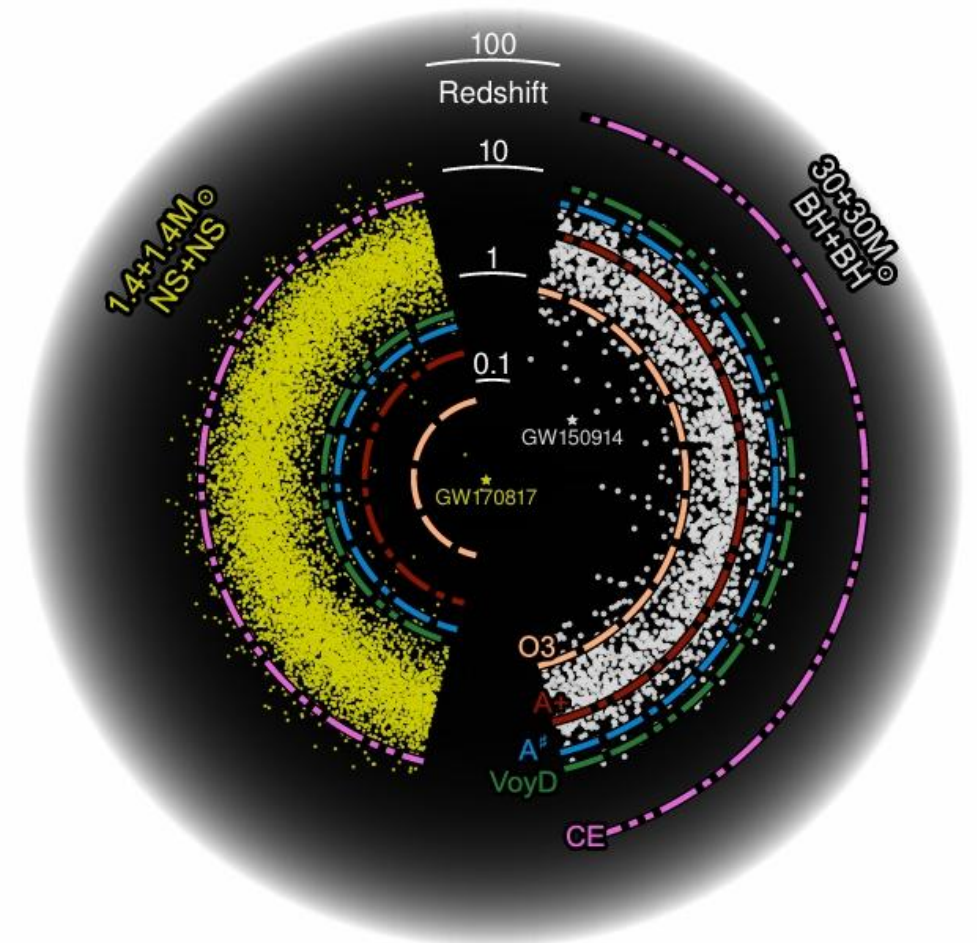
Improved mid-frequency sensitivity requires:

- Lower thermal noise coatings for the test masses.

Improved high frequency sensitivity requires:

- Laser power increase to 1.5 MW arm power
- Squeezing increase to 10 dB broadband

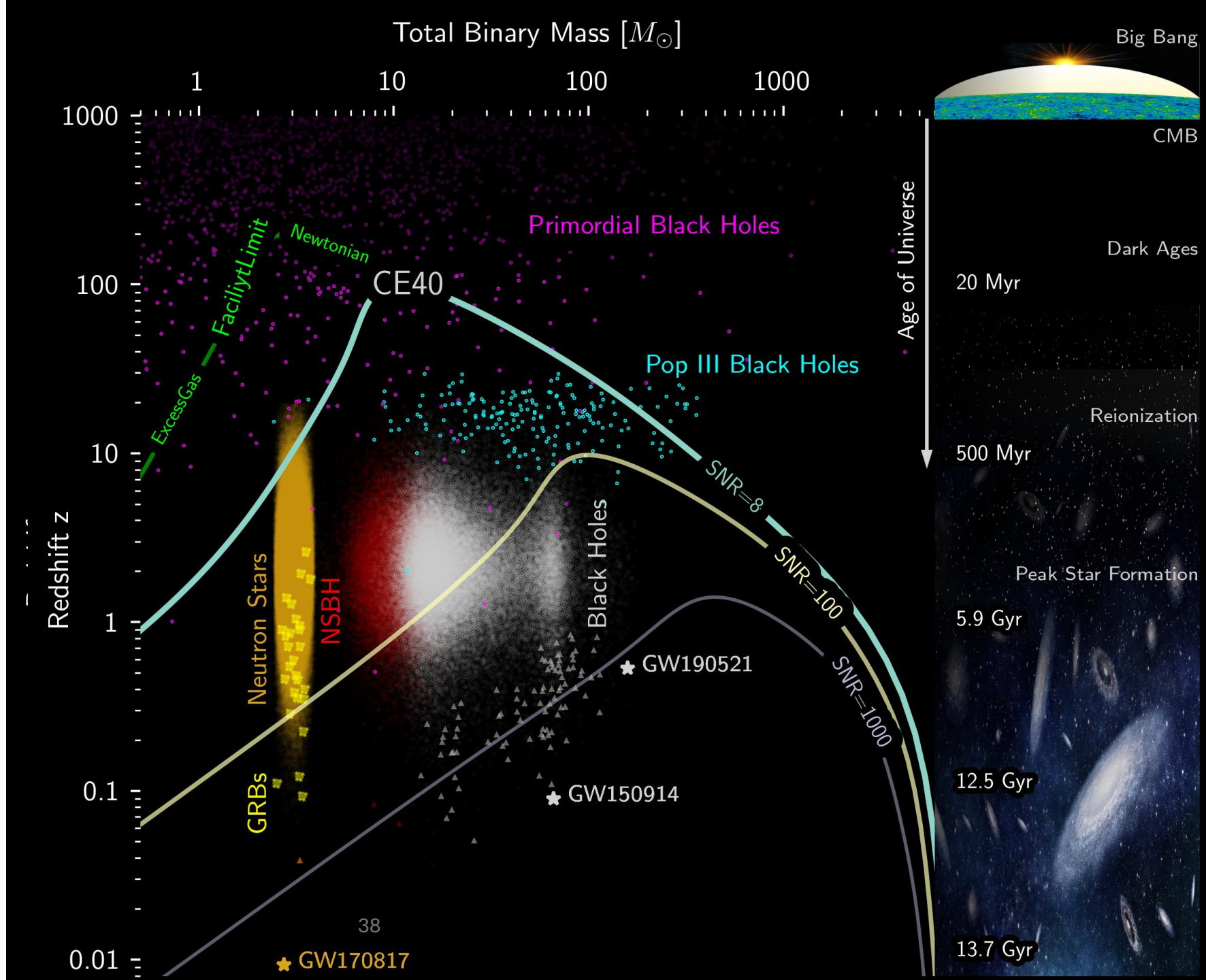
This is the best sensitivity we think we can achieve in the 4km LIGO detectors



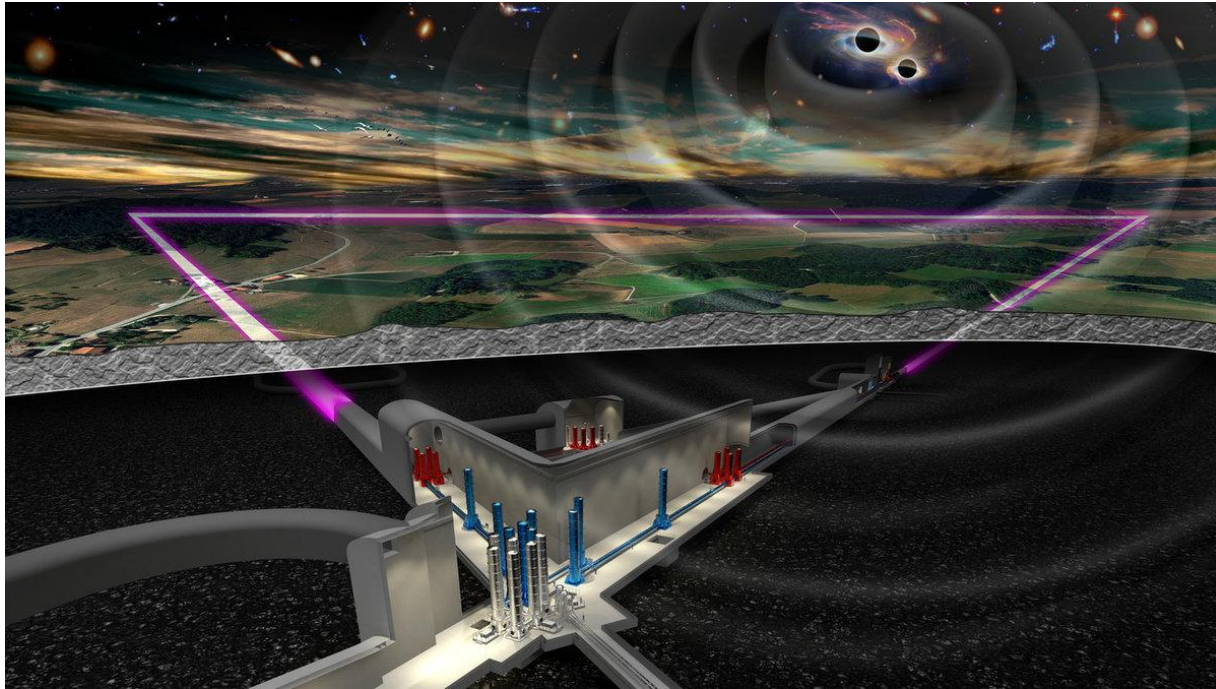
From: [LIGO-T2200287-v3: Report of the LSC Post-O5 Study Group](#)

Science Reach of Next Generation Observatories

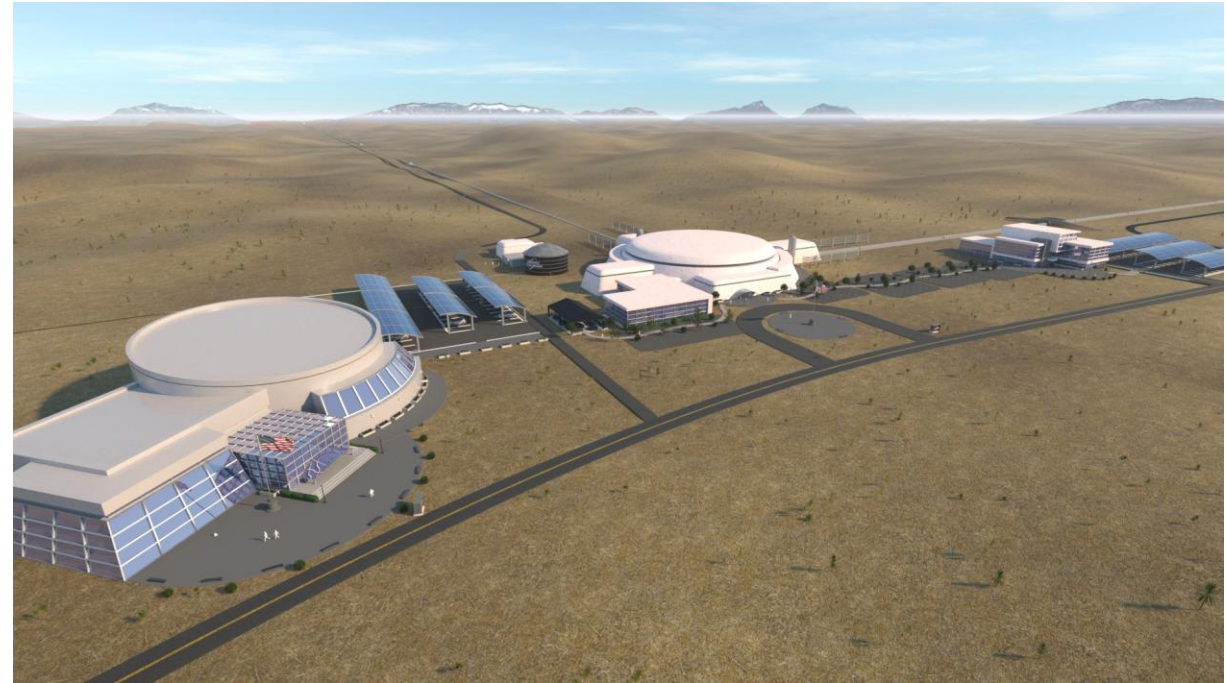
From Cosmic Explorer white paper: Evans et al, [arXiv:2306.13745](https://arxiv.org/abs/2306.13745)



Einstein Telescope and Cosmic Explorer



Maggiore et al. <https://arxiv.org/abs/1912.02622>

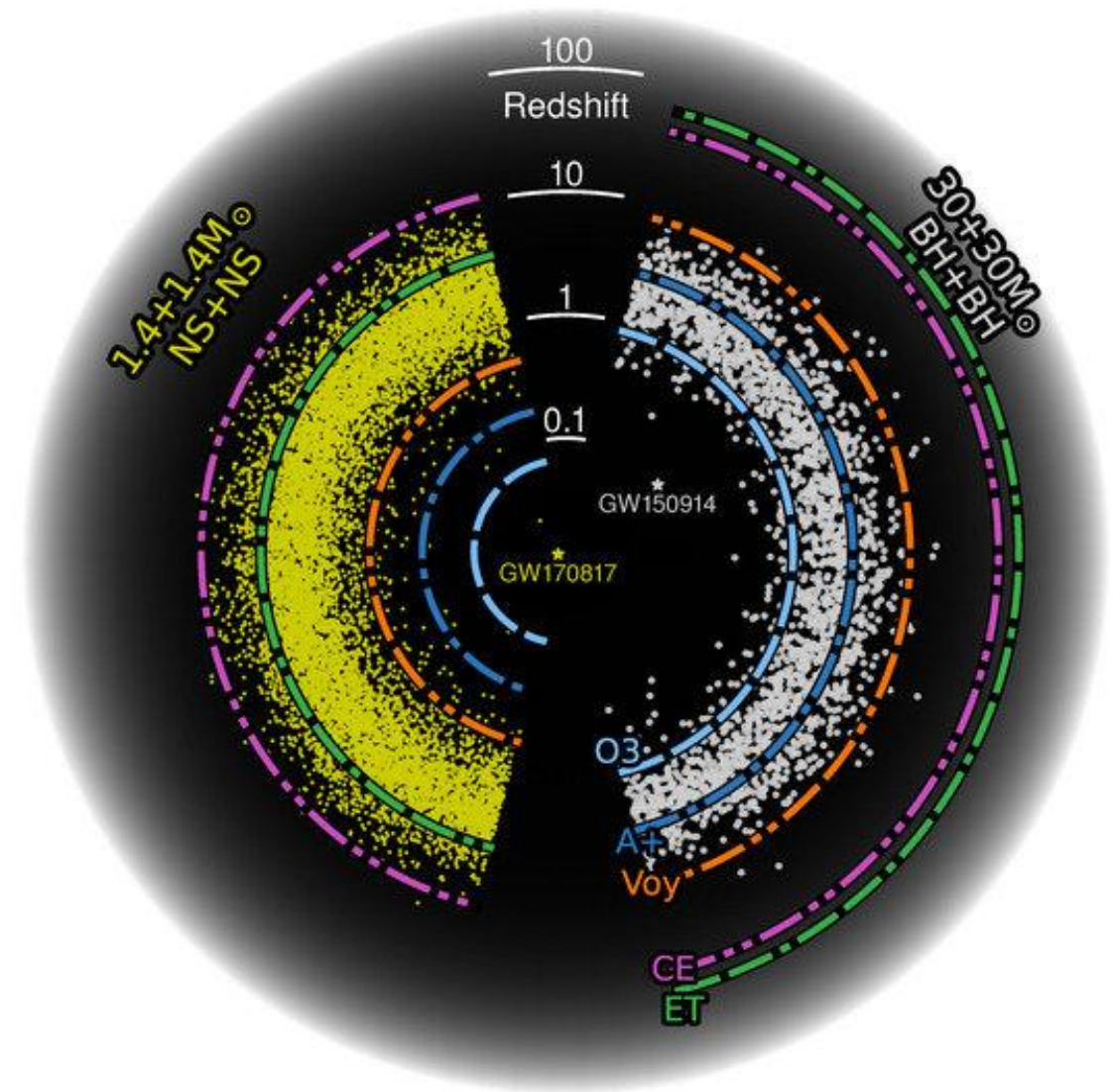


Evans et al. <https://arxiv.org/abs/2109.09882>

Next Generation GW Observatory Science Book
<https://gwic.ligo.org/3Gsubcomm/documents.html>

Summary

- It is just over ten years since the first gravitational wave observation
- We have observed several hundred signals from merging black holes and neutron stars
 - Beginning to unveil the properties of the population, and identify sub-populations
- Upgrades to existing facilities and new GW observatories will enhance the gravitational wave view of the universe



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