LIGO-Virgo-KAGRA Latest Achievements and O4

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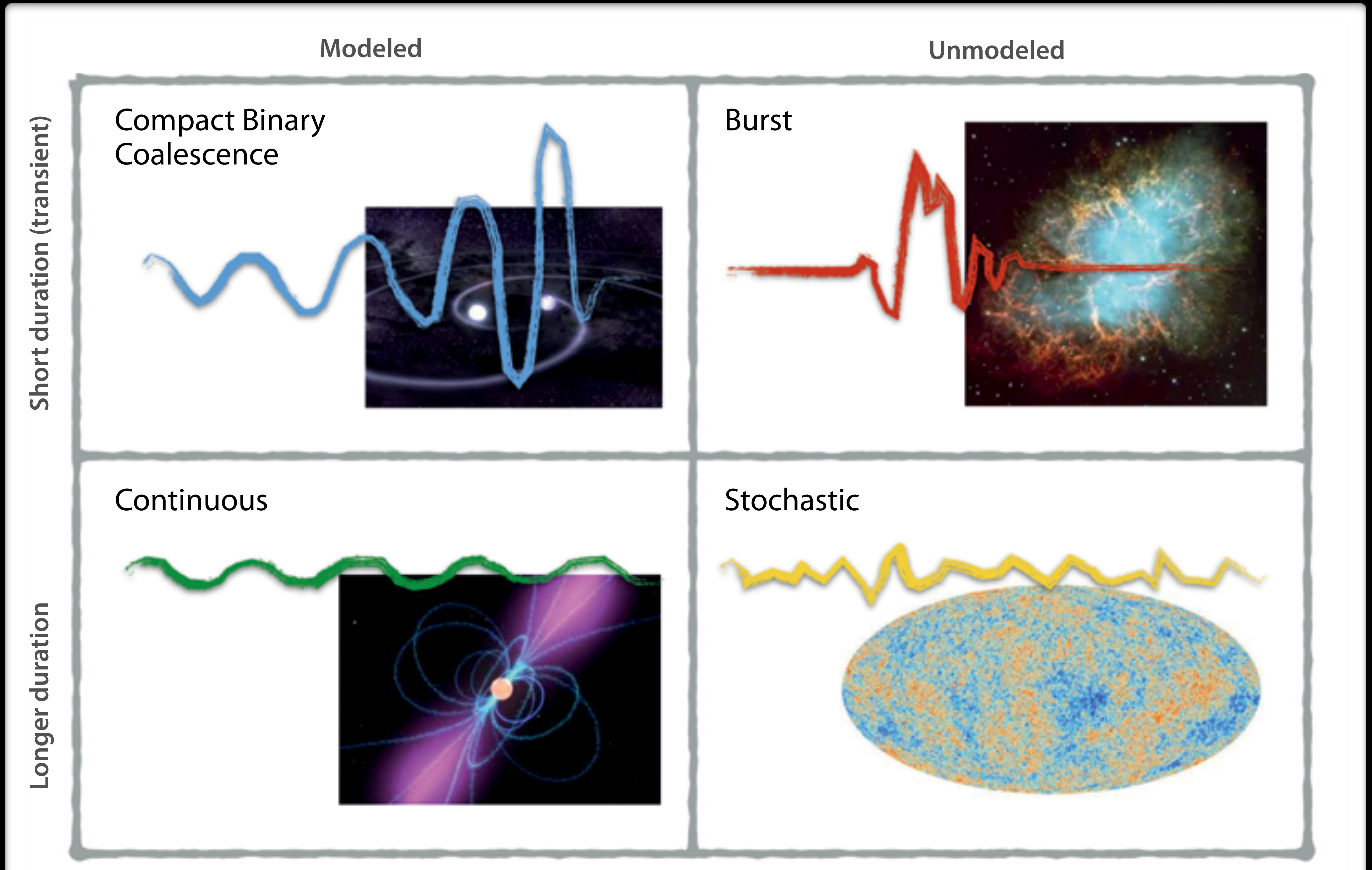
on behalf of the LIGO-Virgo-KAGRA Collaboration

Einstein Telescope Symposium – May 11, 2023

[LIGO DCC: G2300982]

[Virgo TDS: VIR-0444A-23]



[Credit: LIGO Magazine, issue 14]

90 compact binary coalescences observed

- What have we learned from these observations?
- What else have we looked for and learned?

Fourth Observing Run (O4) planned to start on May 24

- What is happening in preparation for this run?

  [Detectors are covered in the talks after this one]

Observing Runs and Gravitational-Wave Transient Catalog Releases

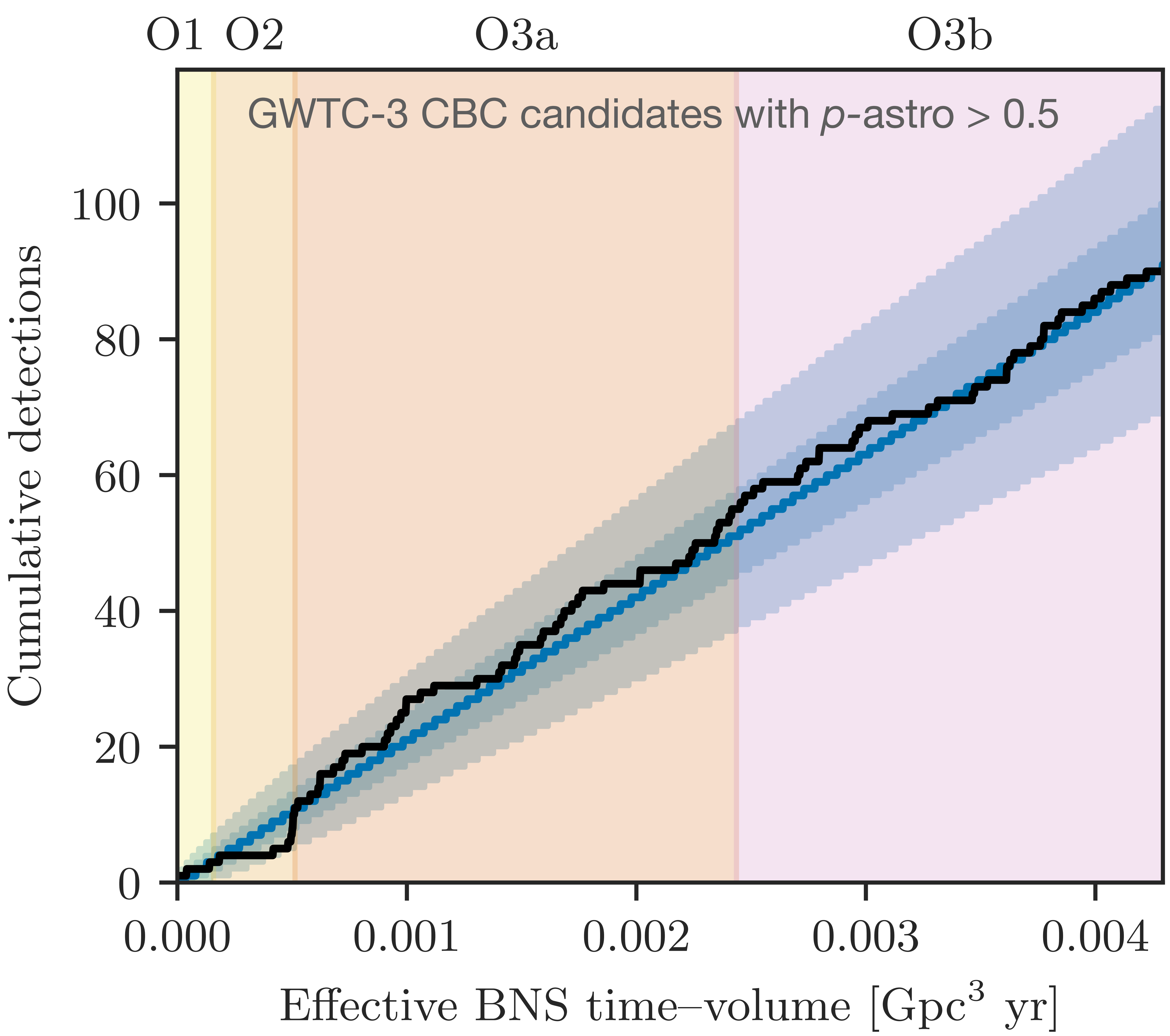
OBSERVING RUNS

- O1: 2015–2016
- O2: 2016–2017
- O3: 2019–2020

Most are binary black holes (BBHs)

Some are neutron star–black hole binaries (NSBHs)

Two are binary neutron stars (BNSs)



CATALOG RELEASES

- **GWTC-1 (O1+O2)**
  arXiv:1811.12907
- **GWTC-2 (O3a)**
  arXiv:2010.14527
  youtu.be/nJD3DAaEkxs
- **GWTC-2.1 (O3a)**
  arXiv:2108.01045
  youtu.be/tD36nX_rzic
- **GWTC-3 (O3b)**
  arXiv:2111.03606
  youtu.be/MUyOVX1HqB8

[arXiv:2111.03606]

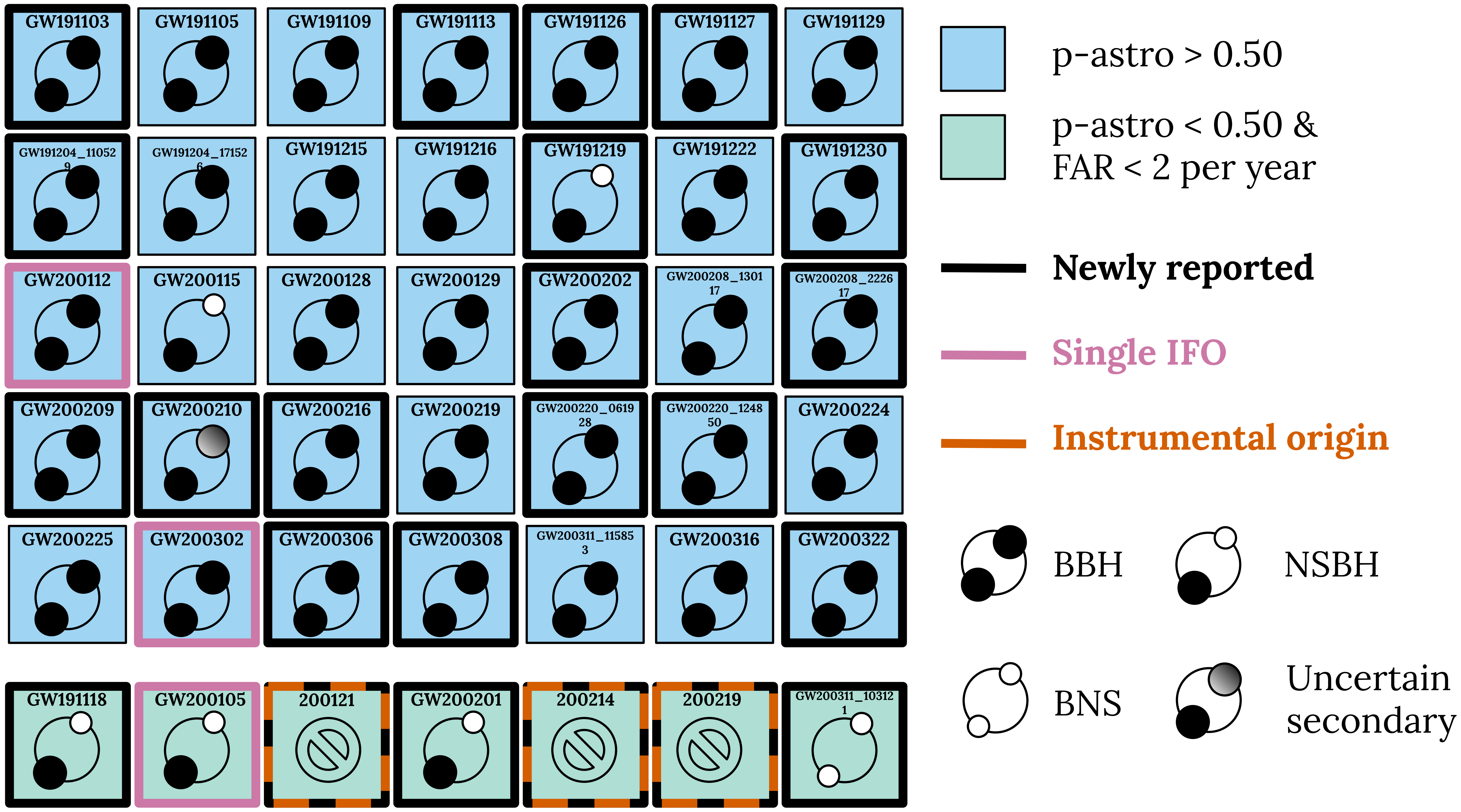
GWTC-3 Candidate List

35 events with *p*-astro > 0.5

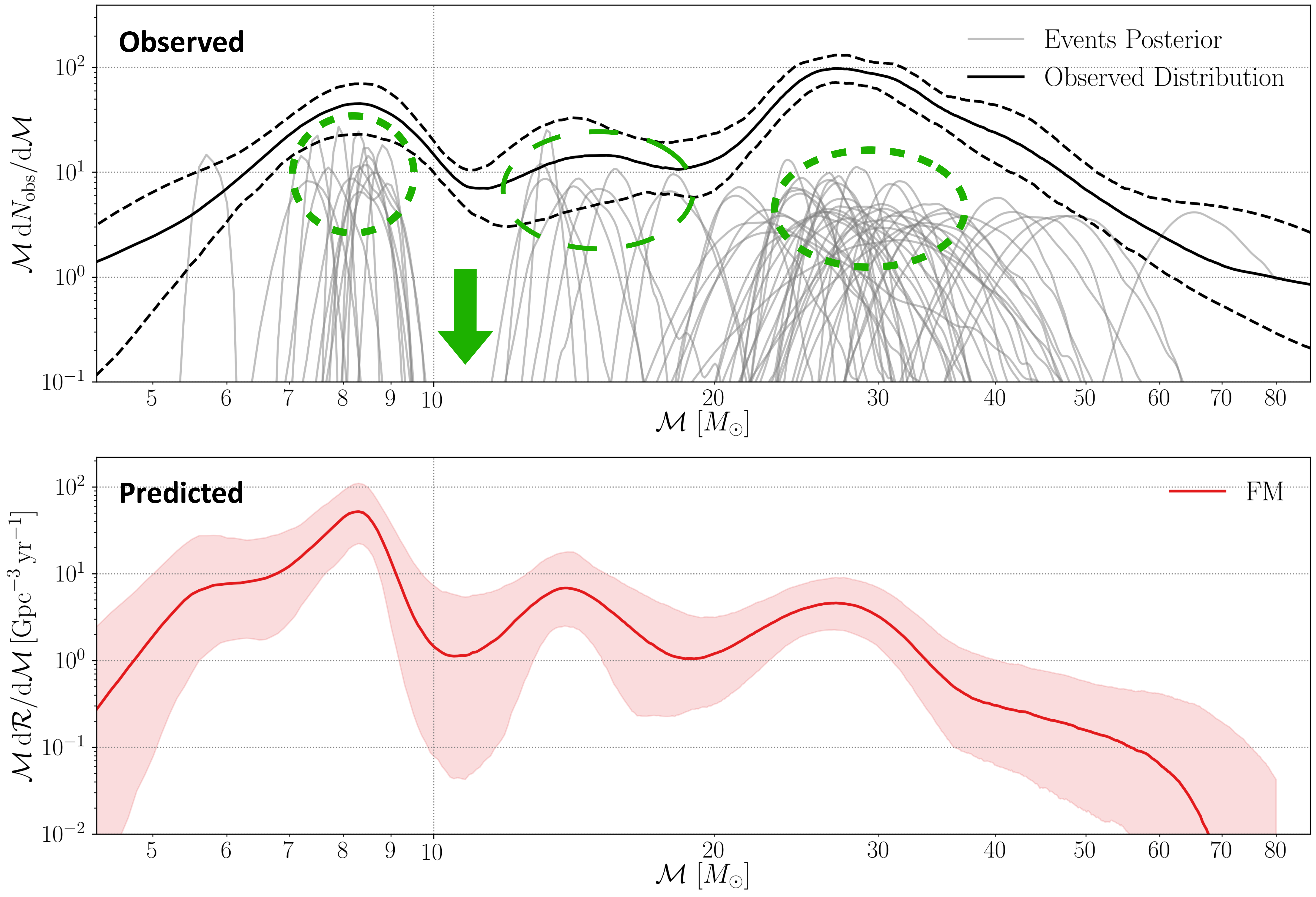
3 NSBH (or potential NSBH)
+ **GW200105**

3 marginal candidates with identified instrumental origin (including unmodeled search only event 200214)

2 single detector candidates + **GW200105**



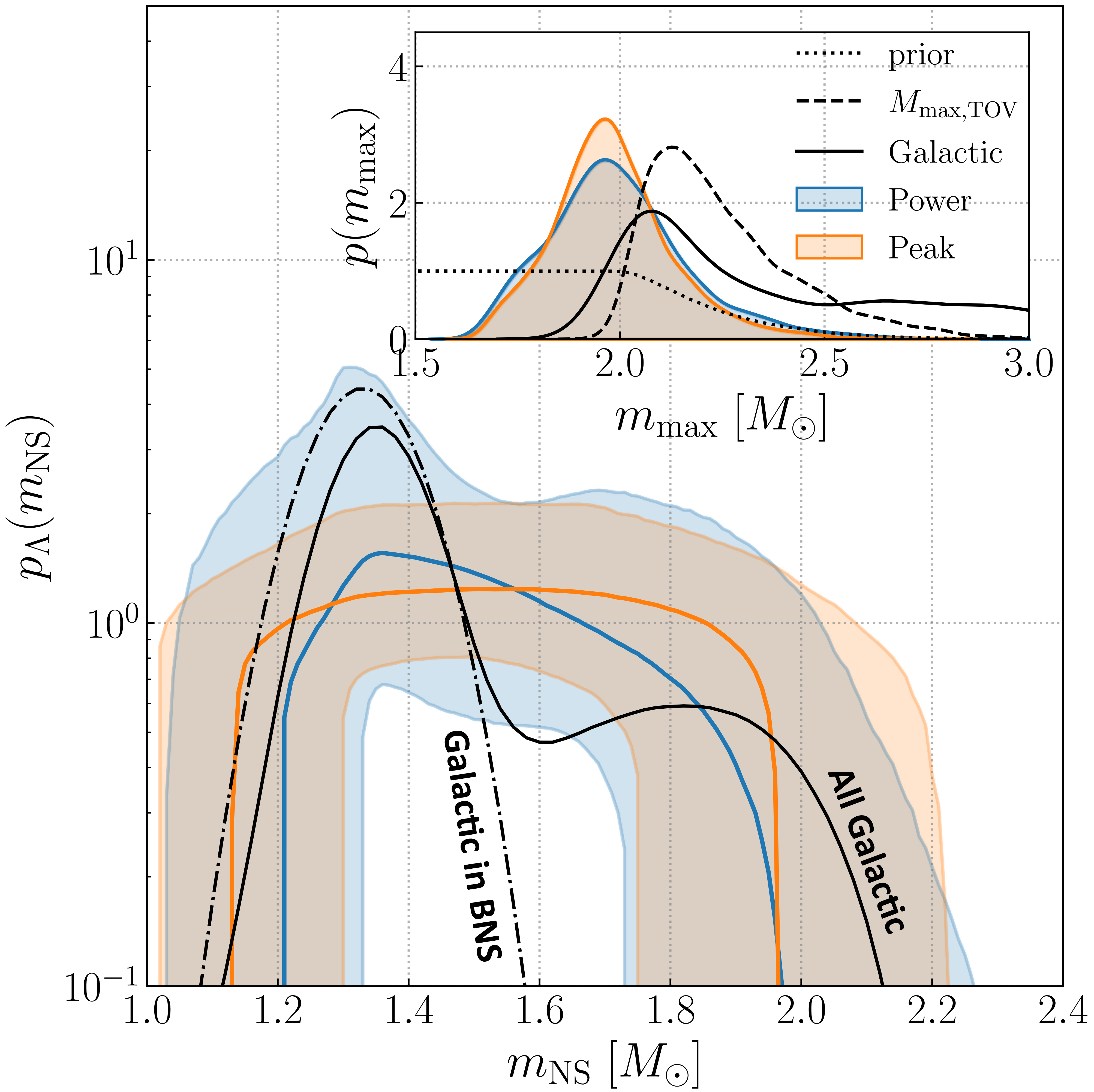
Mass Distribution of Binary Black Holes



- Highly significant structure in the chirp mass distribution
- Localized peaks in the component mass distribution, e.g., overdensities in the merger rate as a function of the primary mass when compared to a power law $10^{+0.29}_{-0.59}\,M_\odot$ and $35^{+1.7}_{-2.9}\,M_\odot$
- Inconclusive evidence for upper mass gap
- No evidence that mass varies with redshift, but BBH merger rate is observed to increase with redshift as $(1+z)^\kappa$, where $\kappa = 2.9^{+1.7}_{-1.8}$

[Abbott et al., Phys. Rev. X 13, 011048 (2023)]

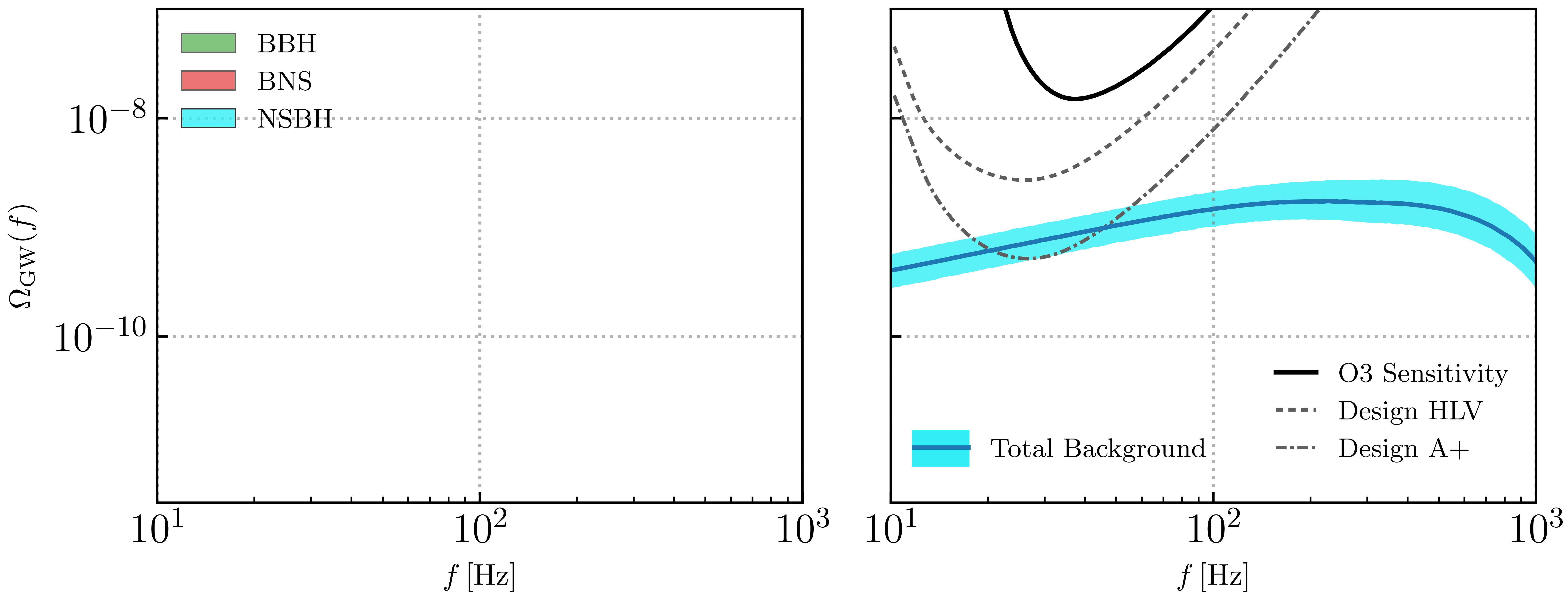
Neutron Star Mass Distribution



- No support for mass distribution with a pronounced single peak
- Neutron stars as heavy as the equation of state can support can end up in merging compact binaries
- Maximum mass: $2.0^{+0.3}_{-0.3}\,M_\odot$ ($2.0^{+0.2}_{-0.2}\,M_\odot$) vs $2.2^{+0.8}_{-0.2}\,M_\odot$ inferred from the Galactic neutron stars
- These medians are shifted by $0.7 - 0.8\,M_\odot$ when GW190814 is folded in the analysis and an upper bound on the neutron star mass is not enforced

[Abbott et al., Phys. Rev. X 13, 011048 (2023)]

Forecast of Astrophysical GW Background Due to Binary Mergers



- *Left*: individual contributions expected from BNS, NSBH and BBH mergers. Uncertainties on the energy-density due to BNS and NSBH are due to Poisson uncertainties in their rates, while the BBH forecast also includes systematic uncertainties associated with their imperfectly known mass distribution

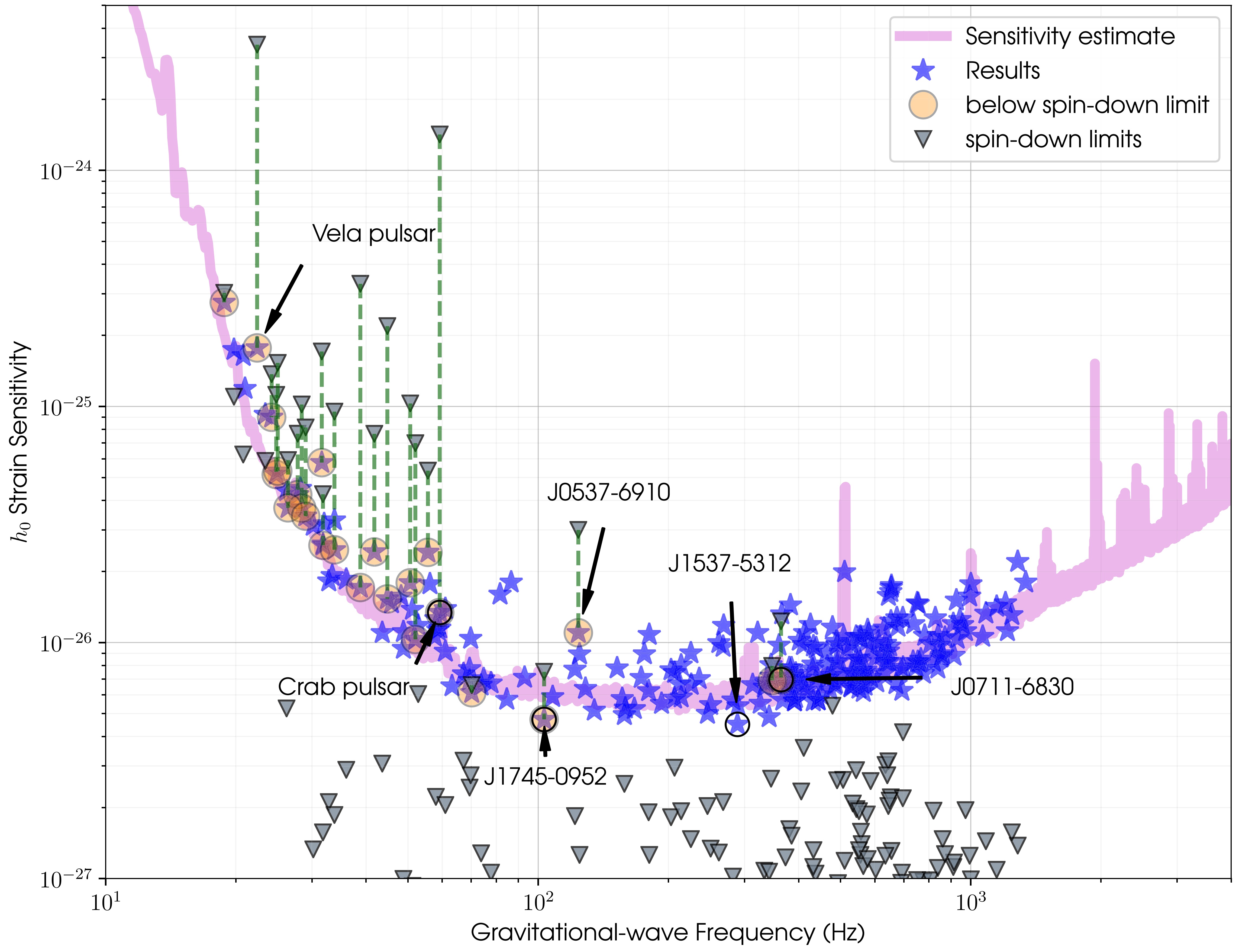
- *Right*: estimate of the total GW background (blue)

[Abbott et al., Phys. Rev. X 13, 011048 (2023); Phys. Rev. D 104, 022004 (2021)]

Continuous Waves

- Upper limits were obtained in a multitude of searches for continuous GWs
  - Targeted searches: *known* frequency evolution and sky location (e.g., pulsars)
  - Narrow-band searches: *known* sky location, search over a small frequency band
  - Directed searches: *known* location (e.g., supernova remnant, Galactic Center), *unknown* frequency evolution, (some) *unknown* binary parameters
  - All-sky (or blind) searches: *unknown* location, frequency evolution, binary parameters
- The outlook for the first detection of continuous GWs is highly uncertain, mostly due to large uncertainties on expected non-axisymmetries
  - When detections are made they will likely provide persistent sources (unlike the transient ones discussed so far) that can be studied with increasing precision for decades

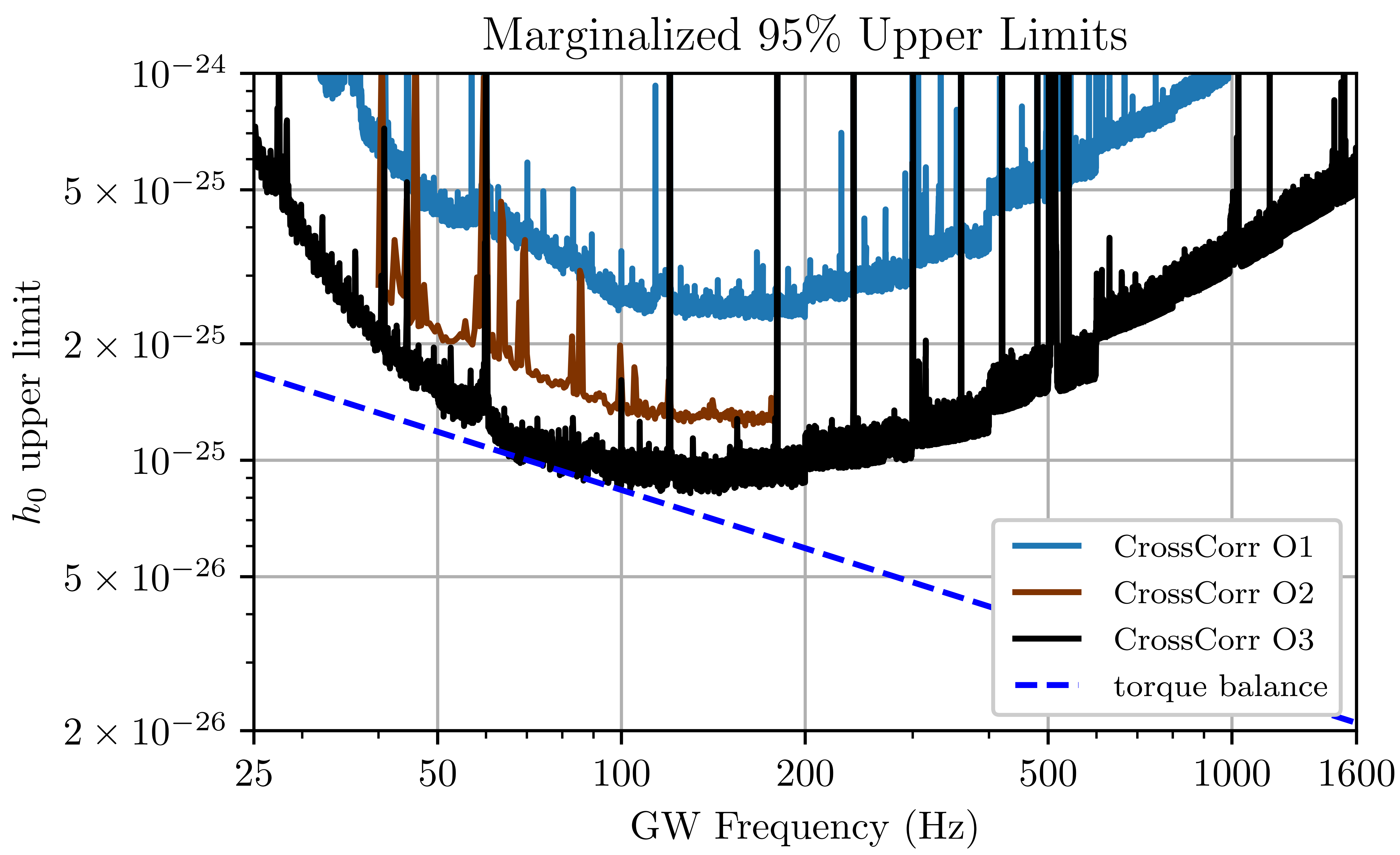
Continuous Waves: Targeted Search Results



- 95% credible upper limits from targeted searches for 236 known pulsars
- Best strain upper limit $\sim 5 \cdot 10^{-27}$
- Benchmark: indirect upper limit on strain by ascribing to GW emission all rotational kinetic energy loss inferred from frequency spin-down
- In 23 cases, direct upper limits are more stringent than this benchmark

[Abbott et al., ApJ 935, 1 (2022)]

Continuous Waves: Directed Search Results for Scorpius X-1



- Scorpius X-1 is a low-mass X-ray binary system undergoing accretion
- Strain upper limit after marginalizing over spin inclination, assuming an isotropic prior
- $\sim 10^{-25}$ as the spin frequency is unknown, and orbital parameters have substantial uncertainties
- Benchmark: equate the angular momentum lost to GW emission and that gained from accretion (torque balance strain limit vs. frequency)

[Abbott et al., ApJL 941, L30 (2022)]

Public Data is also an Achievement

- A. H. Nitz, C. Capano, A. B. Nielsen, S. Reyes, R. White, D. A. Brown, and B. Krishnan, *1-OGC: The First Open Gravitational-Wave Catalog of Binary Mergers from Analysis of Public Advanced LIGO Data*, Astrophys. J. 872, 195 (2019)
- T. Venumadhav, B. Zackay, J. Roulet, L. Dai, and M. Zaldarriaga, *New Search Pipeline for Compact Binary Mergers: Results for Binary Black Holes in the First Observing Run of Advanced LIGO*, Phys. Rev. D 100, 023011 (2019)
- T. Venumadhav, B. Zackay, J. Roulet, L. Dai, and M. Zaldarriaga, *New Binary Black Hole Mergers in the Second Observing Run of Advanced LIGO and Advanced Virgo*, Phys. Rev. D 101, 083030 (2020)
- B. Zackay, T. Venumadhav, L. Dai, J. Roulet, and M. Zaldarriaga, *Highly Spinning and Aligned Binary Black Hole Merger in the Advanced LIGO First Observing Run*, Phys. Rev. D 100, 023007 (2019)
- A. H. Nitz, T. Dent, G. S. Davies, S. Kumar, C. D. Capano, I. Harry, S. Mozzon, L. Nuttall, A. Lundgren, and M. Tápai, *2-OGC: Open Gravitational-Wave Catalog of Binary Mergers from Analysis of Public Advanced LIGO and Virgo Data*, Astrophys. J. 891, 123 (2020)
- A. H. Nitz, C. D. Capano, S. Kumar, Y.-F. Wang, S. Kastha, M. Schäfer, R. Dhurkunde, and M. Cabero, *3-OGC: Catalog of Gravitational Waves from Compact- Binary Mergers*, Astrophys. J. 922, 76 (2021)
- A. H. Nitz, S. Kumar, Y.-F. Wang, S. Kastha, S. Wu, M. Schäfer, R. Dhurkunde, C. D. Capano, *4-OGC: Catalog of gravitational waves from compact-binary mergers*, arXiv:2112.06878

Fourth Observing Run (O4)

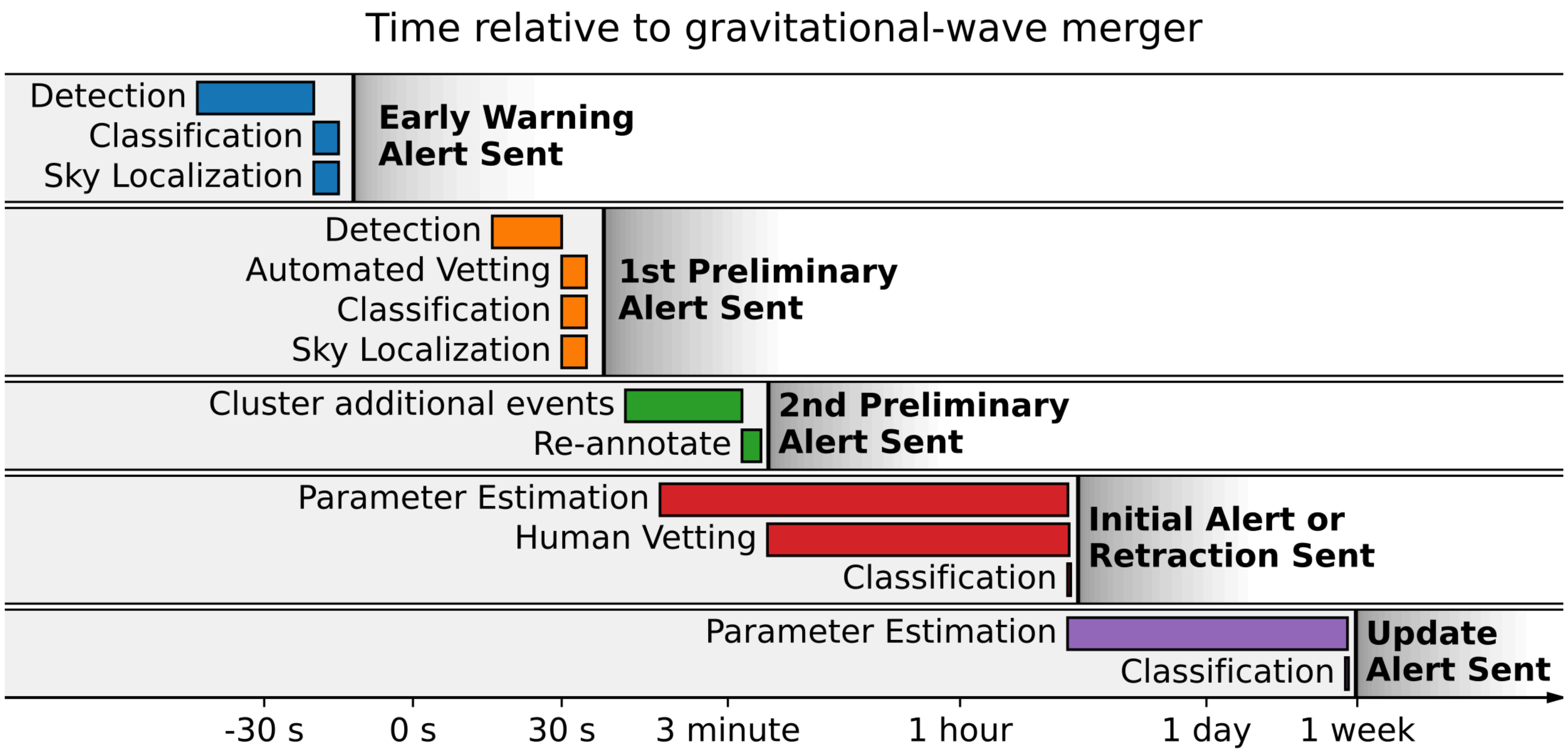
- Planned to begin on May 24, with 18 months of active observing time + short commissioning breaks
- Detectors currently engaged in a collaborative engineering run to test upgraded instruments in real time and systems required for observing
- If exceptional candidate events occur during an engineering run, they may be released to the scientific community and studied further

O4 False Alarm Rate (FAR) threshold to release automatic alerts: **2/day**

Low-significance GW alerts	**Significant** GW alerts
▸ CBC searches: 1/month < FAR < 2/day	▸ CBC searches: FAR < 1/month
▸ Unmodeled searches: 1/yr < FAR < 2/day	▸ Unmodeled searches: FAR < 1/yr
▸ Only automated data quality checks	▸ Automated data quality checks and human vetting

[https://emfollow.docs.ligo.org/userguide/analysis/index.html]

O4 Public Alerts: Timeline



- Fully automatic

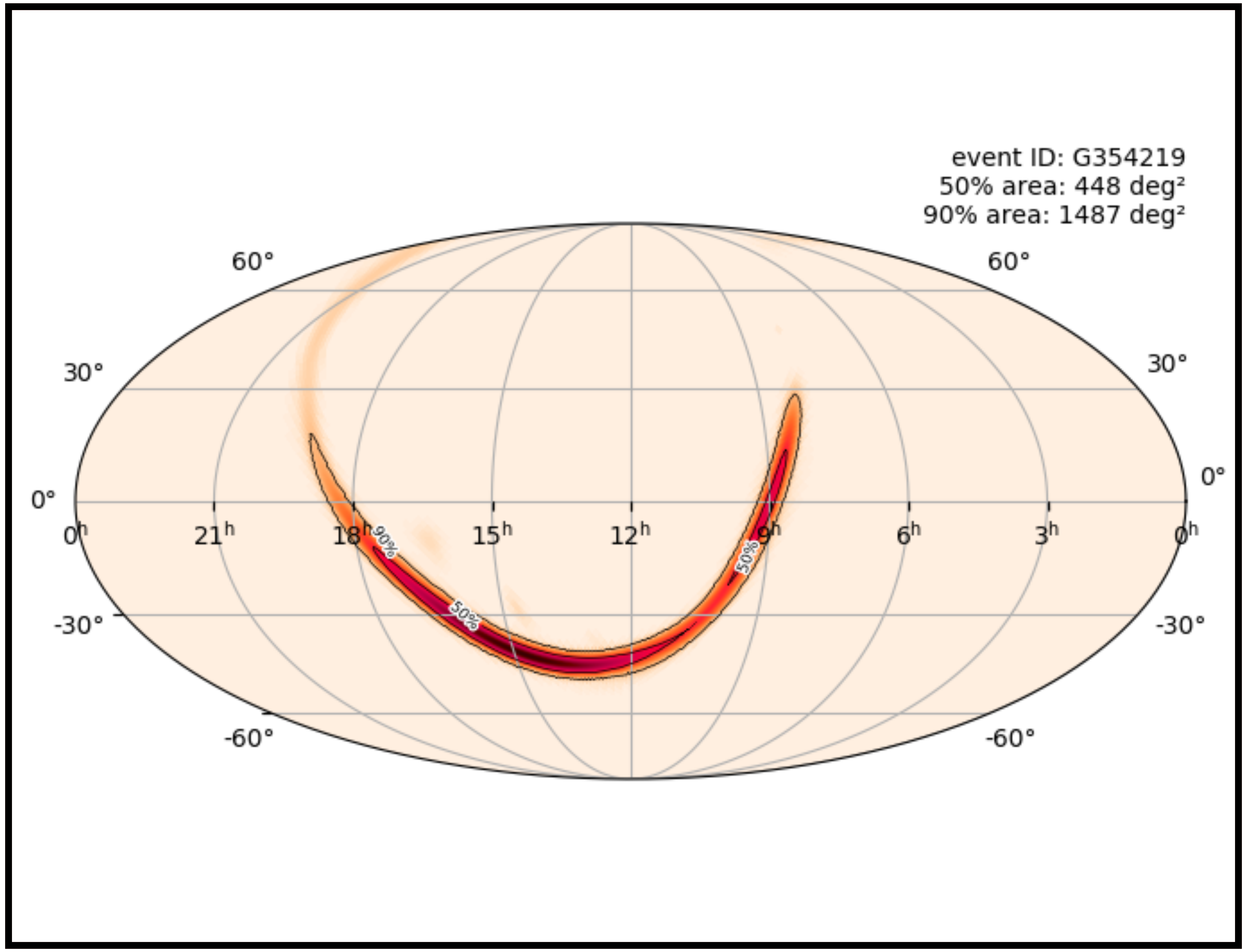
- Fully automatic
- Another issued if low-significance → significant
- Final issued when all searches completed

- Updates issued when improved parameter estimation results are available

[https://emfollow.docs.ligo.org/userguide/early_warning.html]

O4 Public Alerts: Content

- FAR estimate
- “Significant” field (new)
- Event time and sky localization (2D skymaps)
- Unmodeled search candidates:
  - Central frequency
  - Duration
- Modeled (CBC) search candidates:
  - 3D skymaps with direction-dependent luminosity distance [Singer et al. 2016]
  - Luminosity Distance marginalized over the whole sky
  - Source *Classification* and *Properties*



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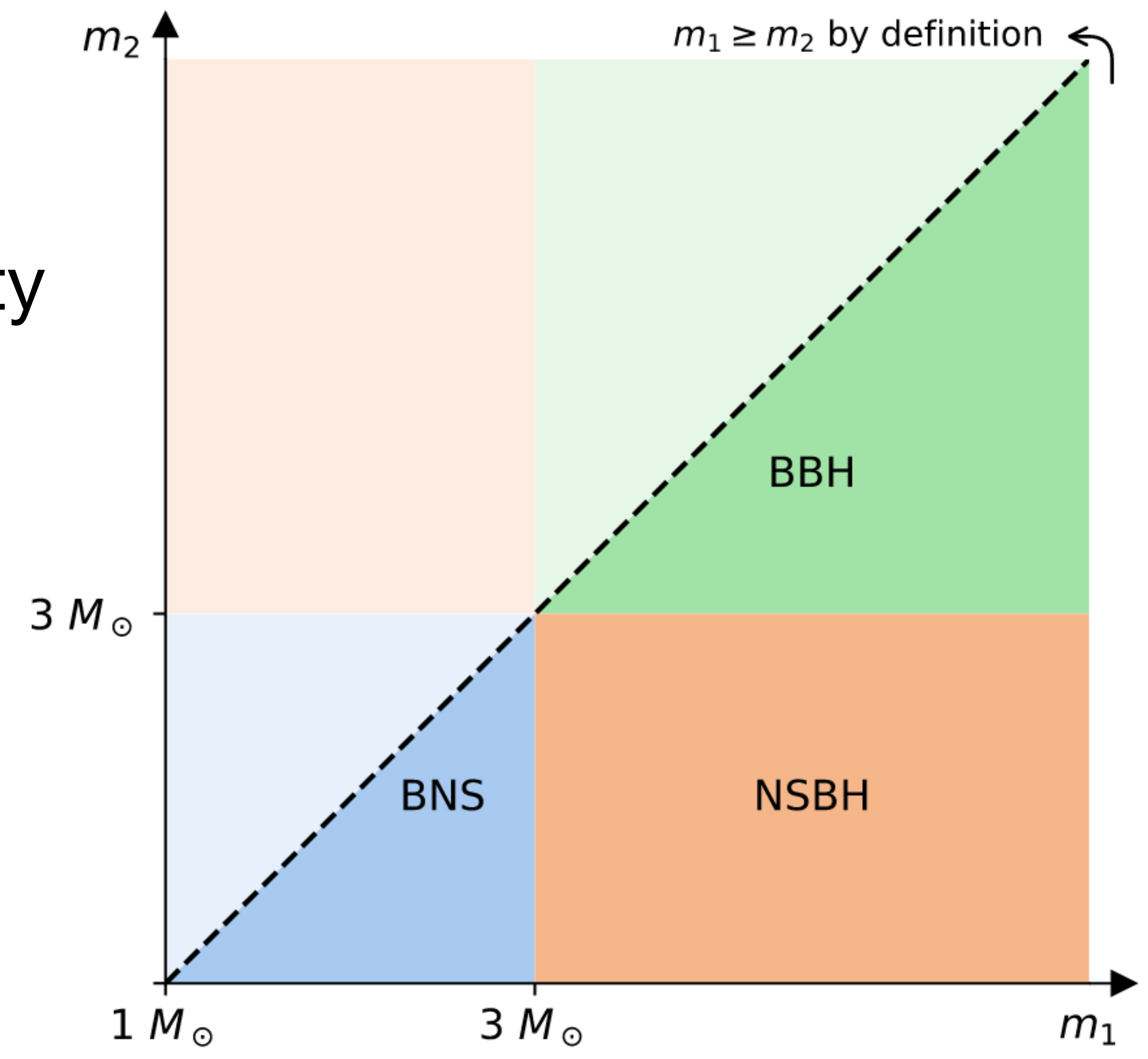
Classification

***p*-astro**: probability that the source is astrophysical



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Properties

HasNS: probability that at least one of the compact objects is a neutron star ($m < 3M_{\odot}$)

HasRemnant: probability that a non-zero amount of neutron star matter is around the central objects [Pannarale & Ohme 2014, Foucart et al. 2018]

HasMassGap: probability that one or both compact objects have $3M_{\odot} \leq m \leq 5M_{\odot}$

[https://emfollow.docs.ligo.org/userguide/content.html]

Final Remarks

- 90 transient candidates with *p*-astro > 0.5 plus several lower probability candidates (notably GW200105): 35 O3b candidates from improved detector sensitivities and data analysis techniques
  - No support for neutron star mass distribution with a pronounced single peak
  - Highly significant structure in the mass distribution: benchmark for population synthesis and/or constraints on fundamental physics if the census includes primordial black holes
  - Binary black hole merger rate grows into the past
  - Spins of black holes are low but nonzero and $29^{+15}_{-13}\,\%$ of binaries have $\chi_{\mathrm{eff}} < 0$
  - Observation of correlation between mass ratio and spins of binary black holes
- Upper limits from searches not yielding observations are becoming more stringent and informative
- An exciting new observing run is ahead shortly and infrastructure is in place to broadcast candidates outside the LIGO-Virgo-KAGRA Collaboration

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[https://dcc.ligo.org/LIGO-P2100218/public]