Image: Carl Knox, OzGrav-Swinburne University of Technology

Current status and future prospects of gravitational-wave observations

Soichiro Morisaki

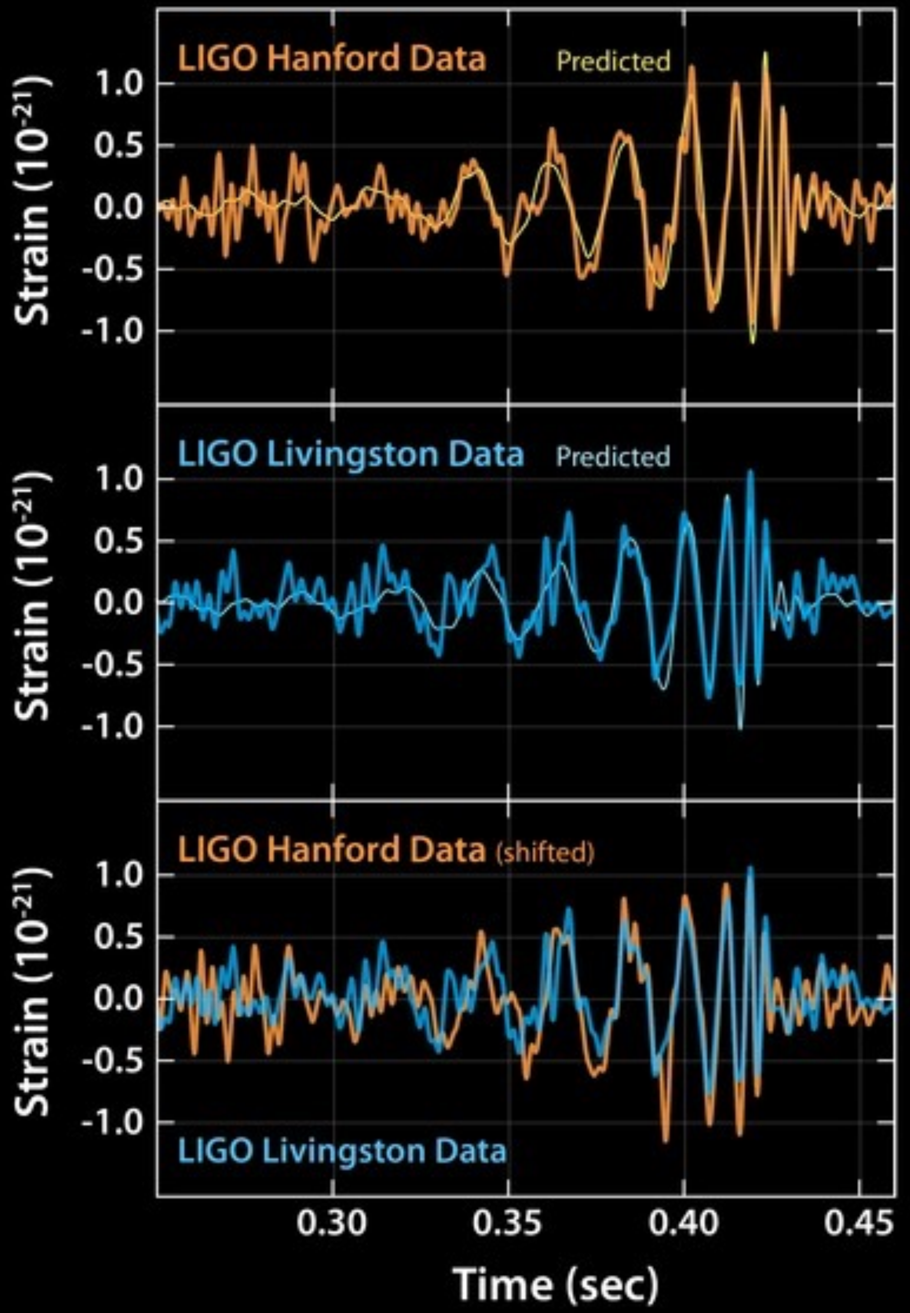
ICRR/University of Tokyo

Feb. 6, 2023

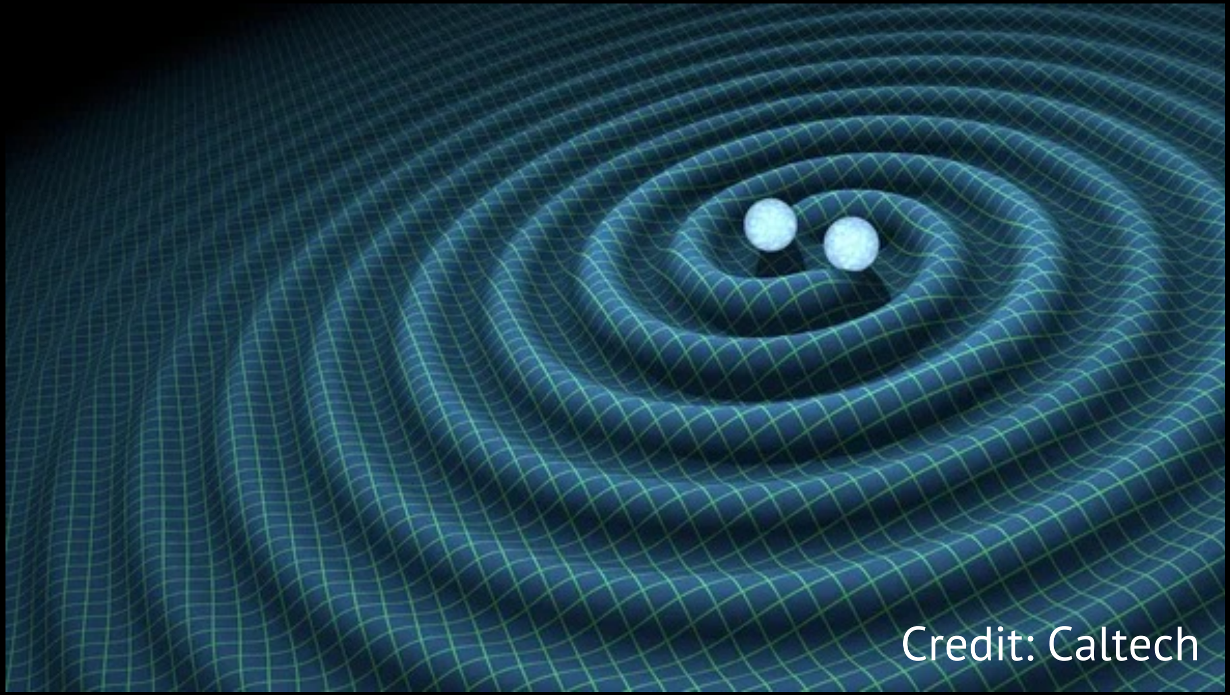
The extreme Universe viewed in very-high-energy gamma-rays 2022

Credit: Caltech/MIT/LIGO Lab

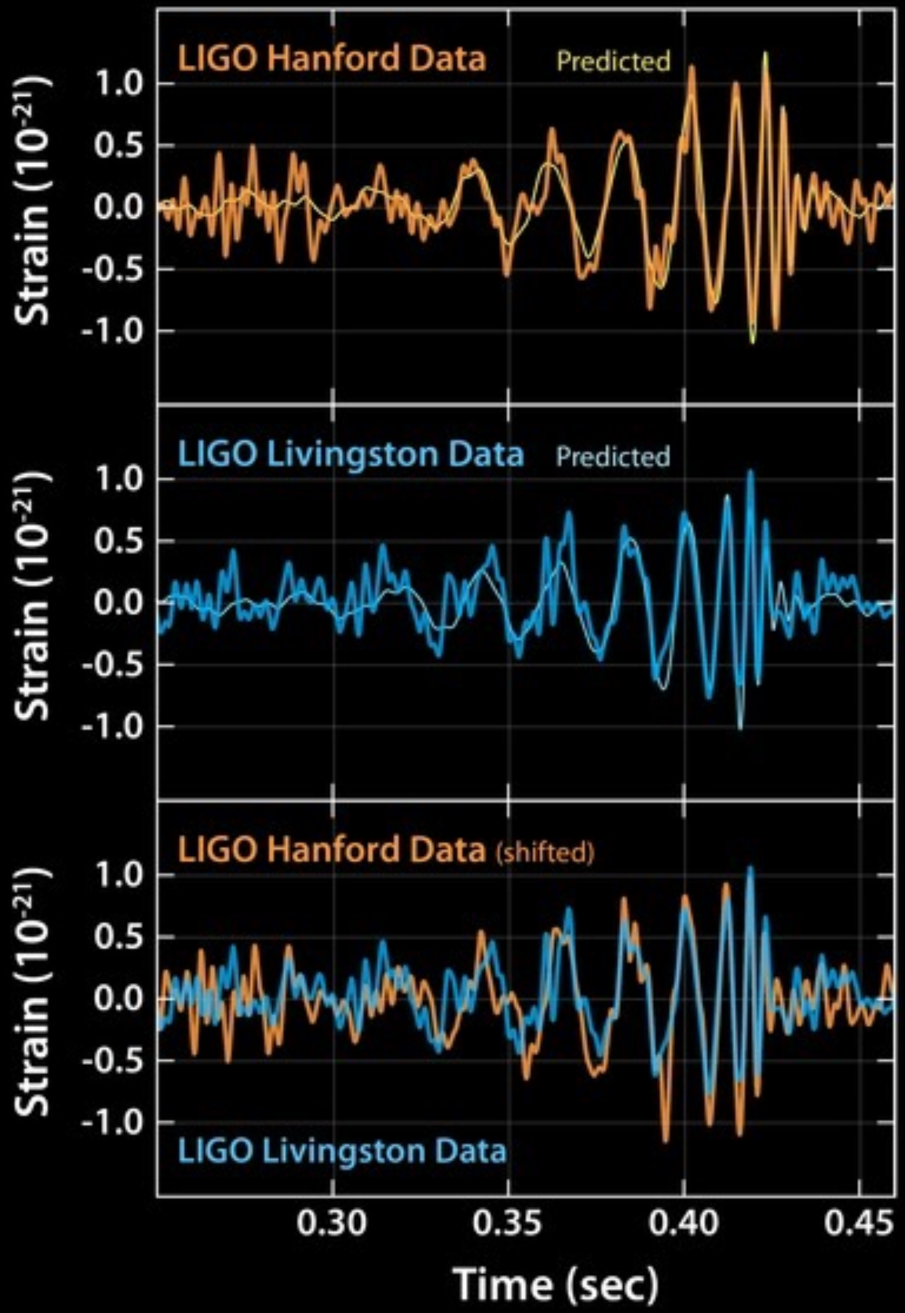
**On September 14, 2015,
the first direct detection of
gravitational waves was achieved.**



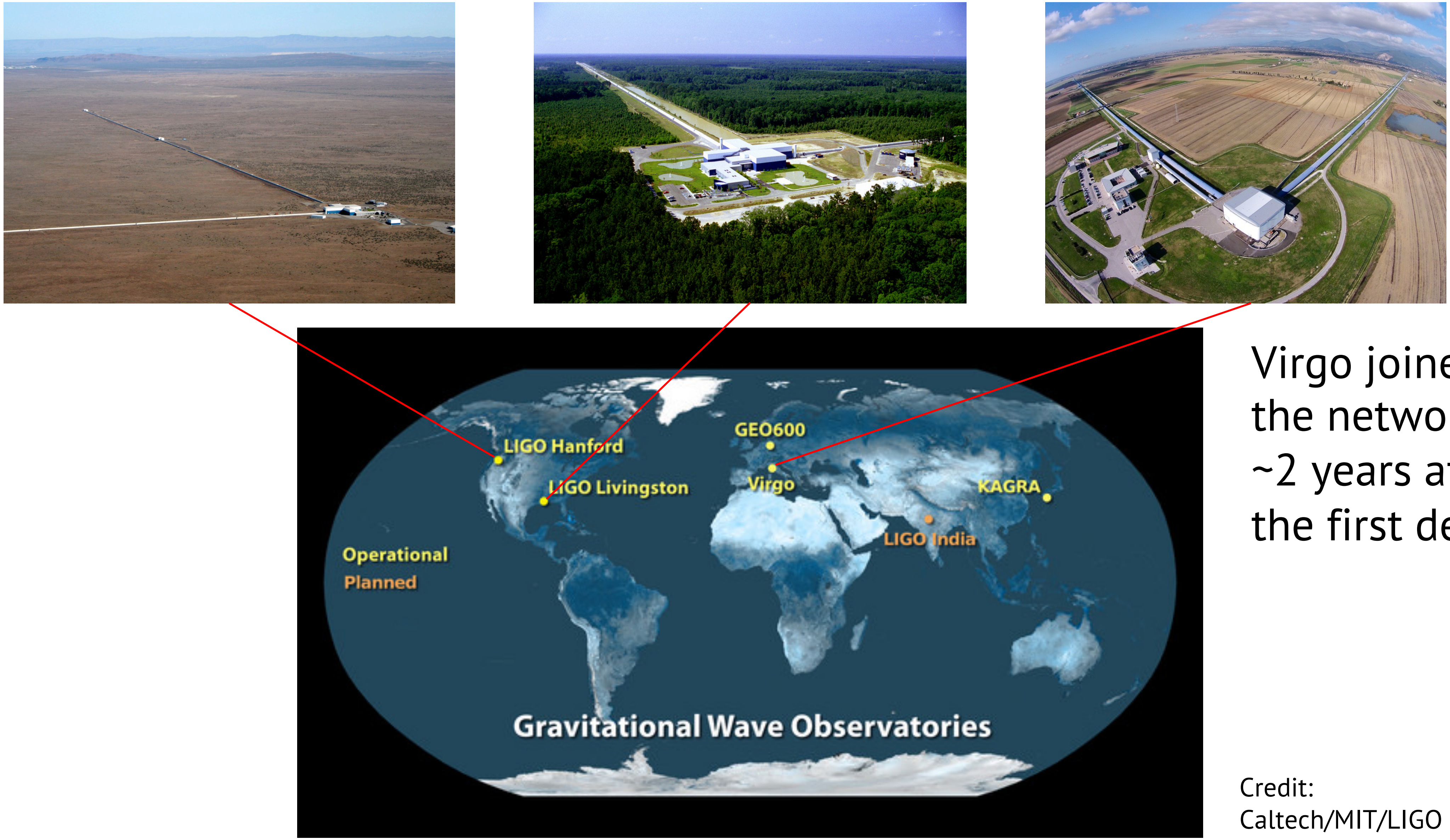
The signal is consistent with **binary black hole merger** with $m_1 = 36^{+5}_{-4}\,M_{\odot},\ m_2 = 29^{+4}_{-4}\,M_{\odot}.$



Credit: Caltech/MIT/LIGO Lab



Gravitational-wave observatories



Virgo joined the network ~2 years after the first detection.

Credit: Caltech/MIT/LIGO Lab

Future observations

So far, LIGO-Virgo has conducted three observing runs (O1, O2, O3).

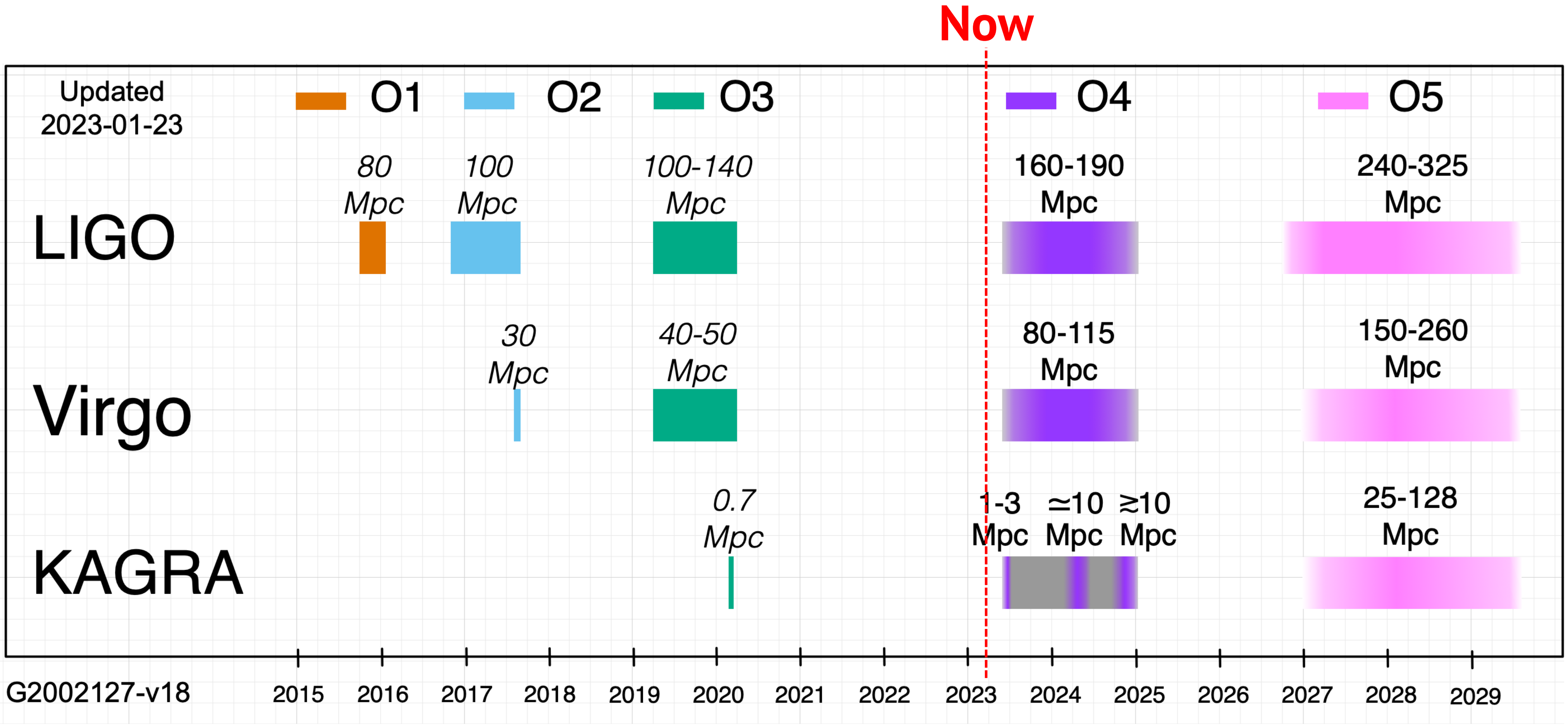


Figure: Observing plan (https://observing.docs.ligo.org/plan/)

GW170817

B. P. Abbott et al., Phys. Rev. Lett. **119**, no.16, 161101 (2017).
B. P. Abbott et al., Astrophys. J. Lett. **848**, no.2, L12 (2017).

- First detection of binary neutron star in O2: $m_1 = 1.36 — 1.60 M_{\odot}, m_2 = 0.86 — 1.36 M_{\odot}$.
- Electromagnetic (EM) counterparts from radio to gamma-ray
  → Multimessenger astronomy with GWs

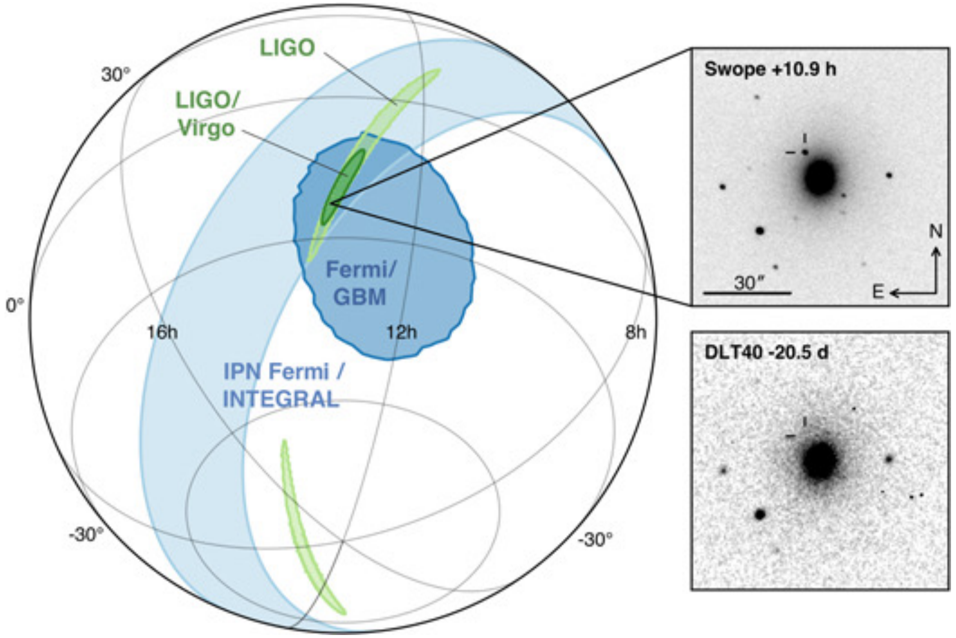


Figure:
Localization of GW, gamma-ray, and optical signal

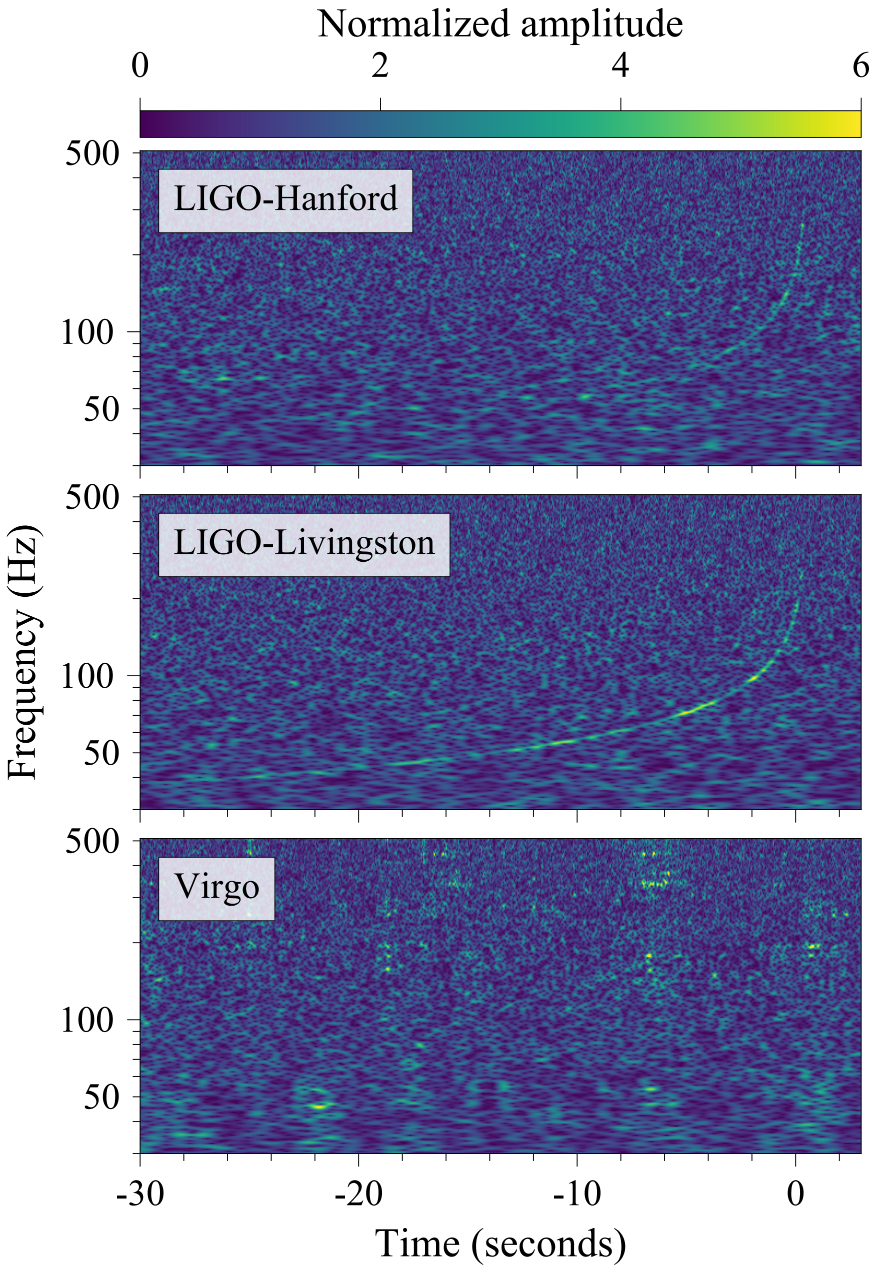


Figure: Time-frequency plot

Public alert

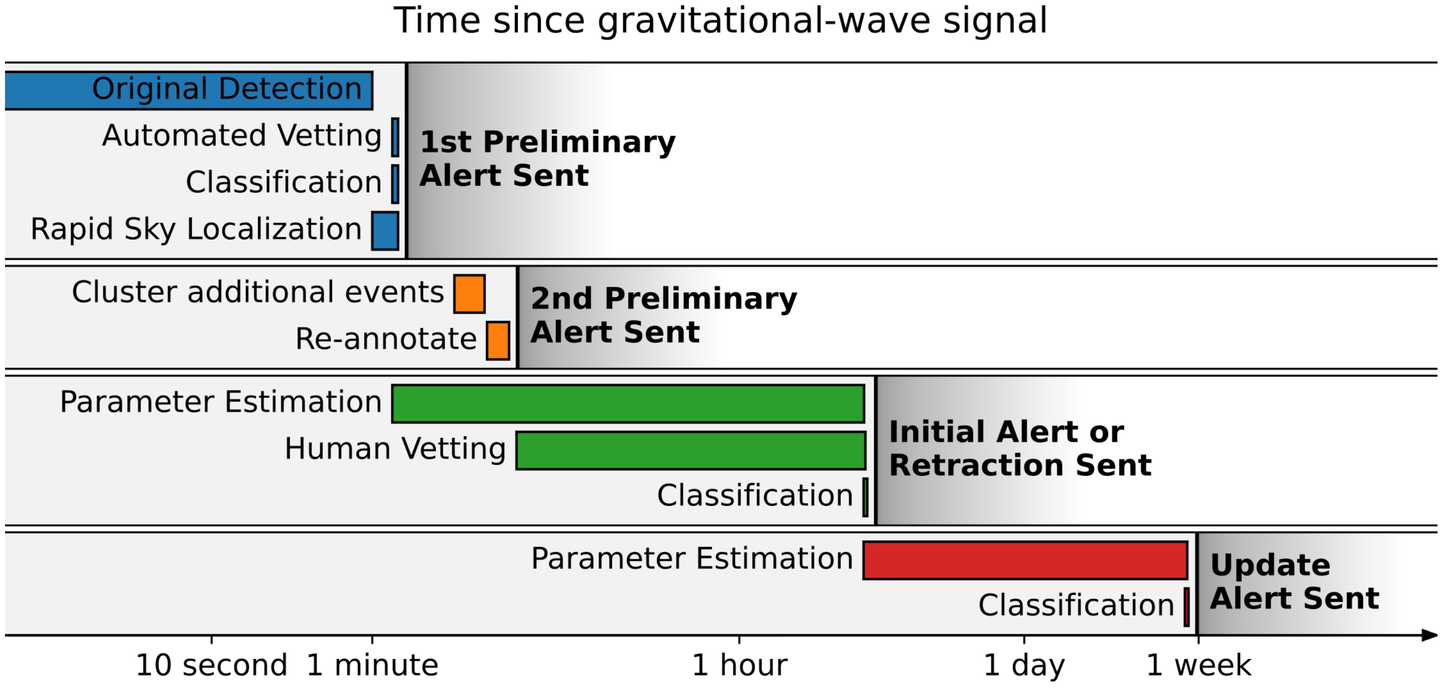


Figure: Timeline of public alert

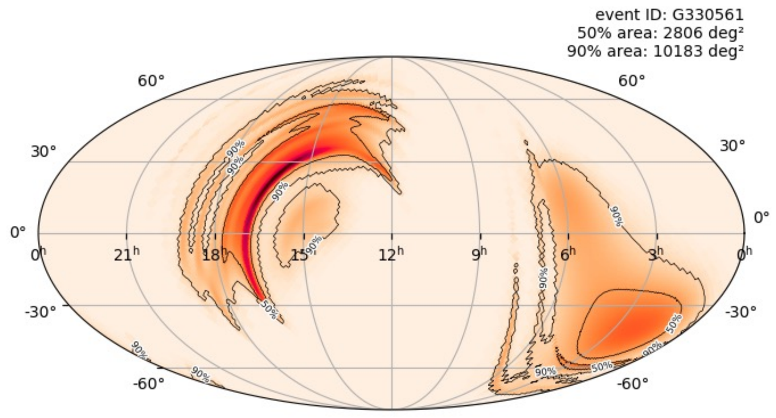
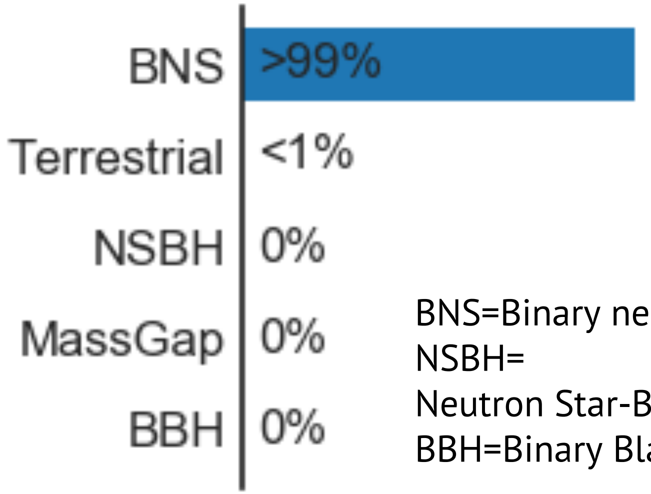


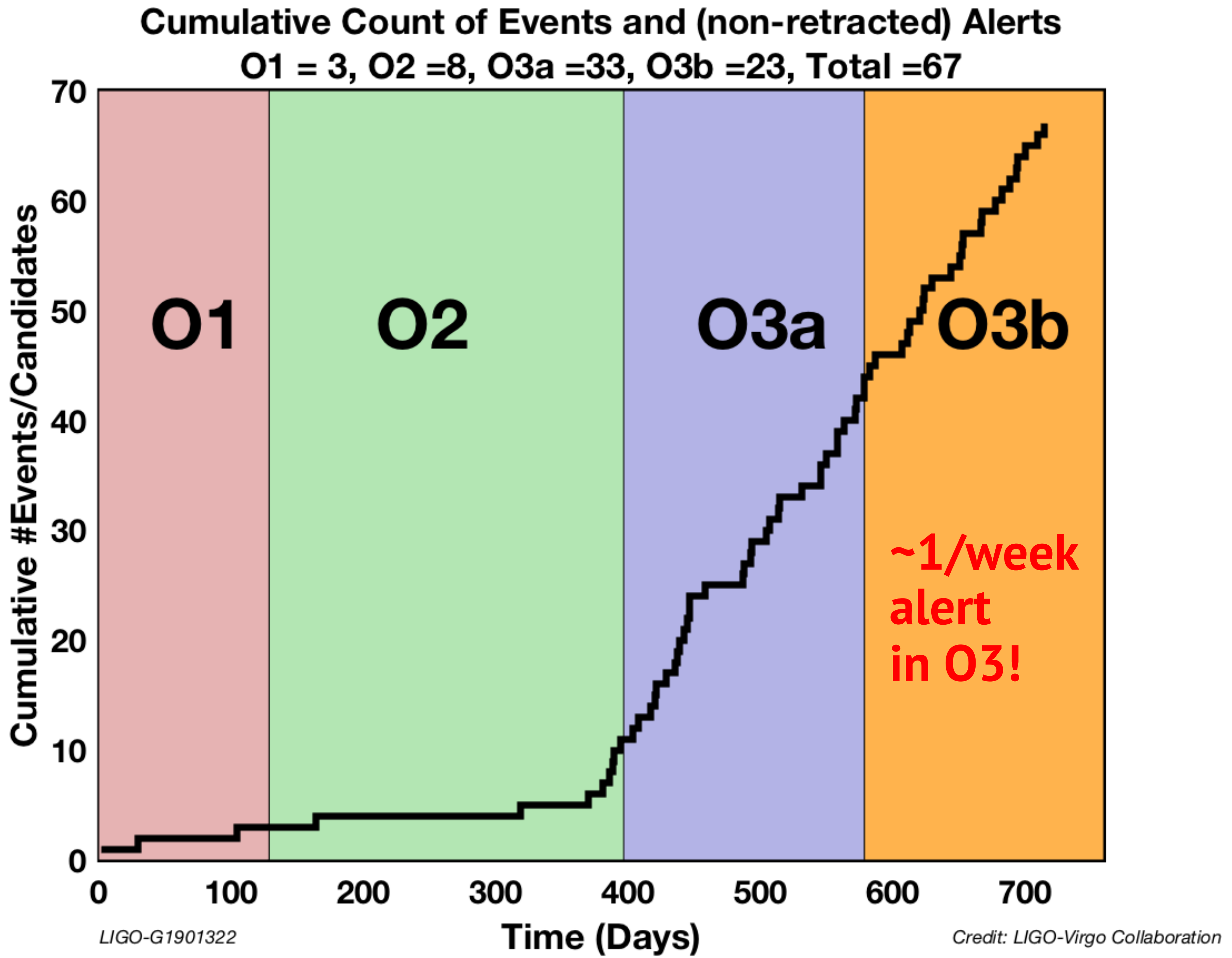
Figure: Estimated source localization of GW190425



BNS=Binary neutron star
NSBH= Neutron Star-Black Hole
BBH=Binary Black Hole

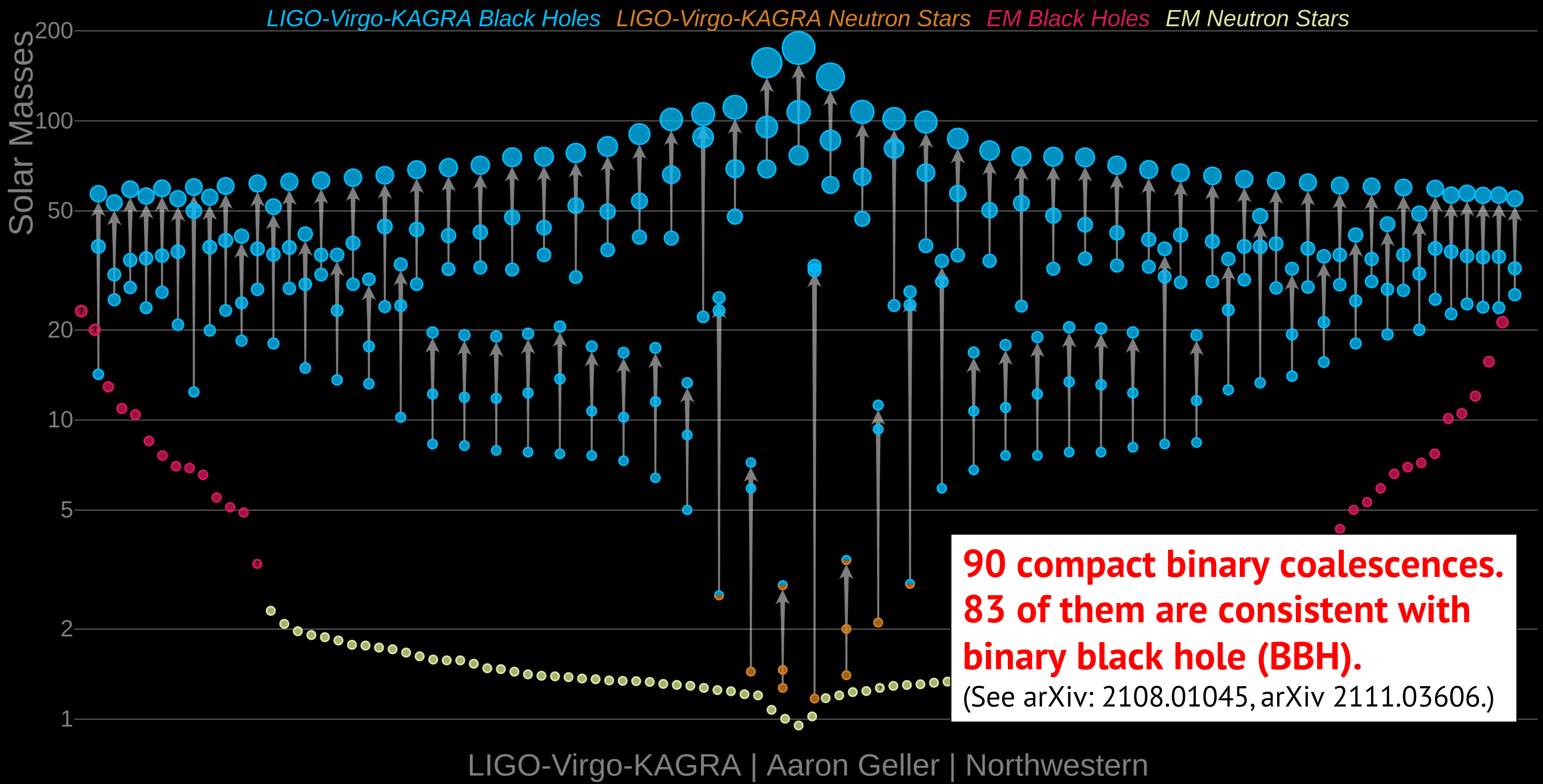
Figure: Classification of GW190425

- Automated public alert from O3.
- False alarm rate threshold for compact binary coalescence: 1/(10 months)



Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67
Cumulative #Events/Candidates
Time (Days)
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
O1
O2
O3a
O3b
~1/week
alert
in O3!
LIGO-G1901322
Credit: LIGO-Virgo Collaboration

Masses in the Stellar Graveyard



90 compact binary coalescences. 83 of them are consistent with binary black hole (BBH).
(See arXiv: 2108.01045, arXiv 2111.03606.)

GW190412 R. Abbott et al., Phys. Rev. D **102**, no. 4, 043015 (2020).

- Asymmetric BBH: $m_1 = 30.1^{+4.6}_{-5.3} M_\odot,\ m_2 = 8.3^{+1.6}_{-0.9} M_\odot$.
- Strong evidence of higher-order moments ($p \le 6\times10^{-4}$)

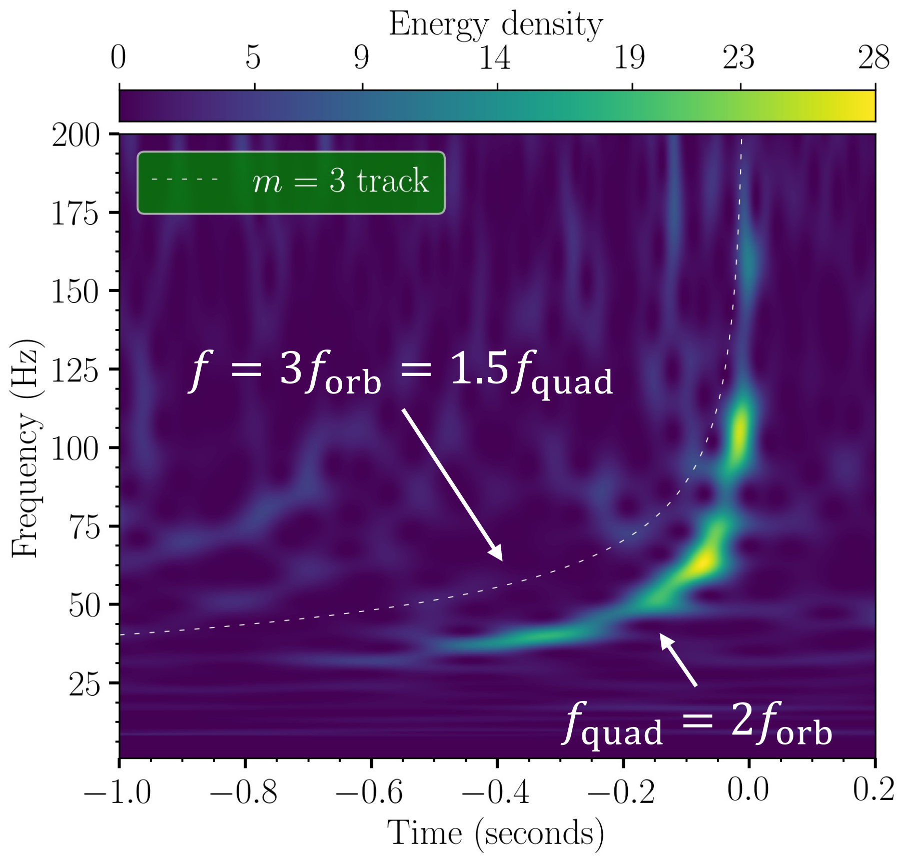


Figure: Time-frequency plot of LIGO-Livingston data

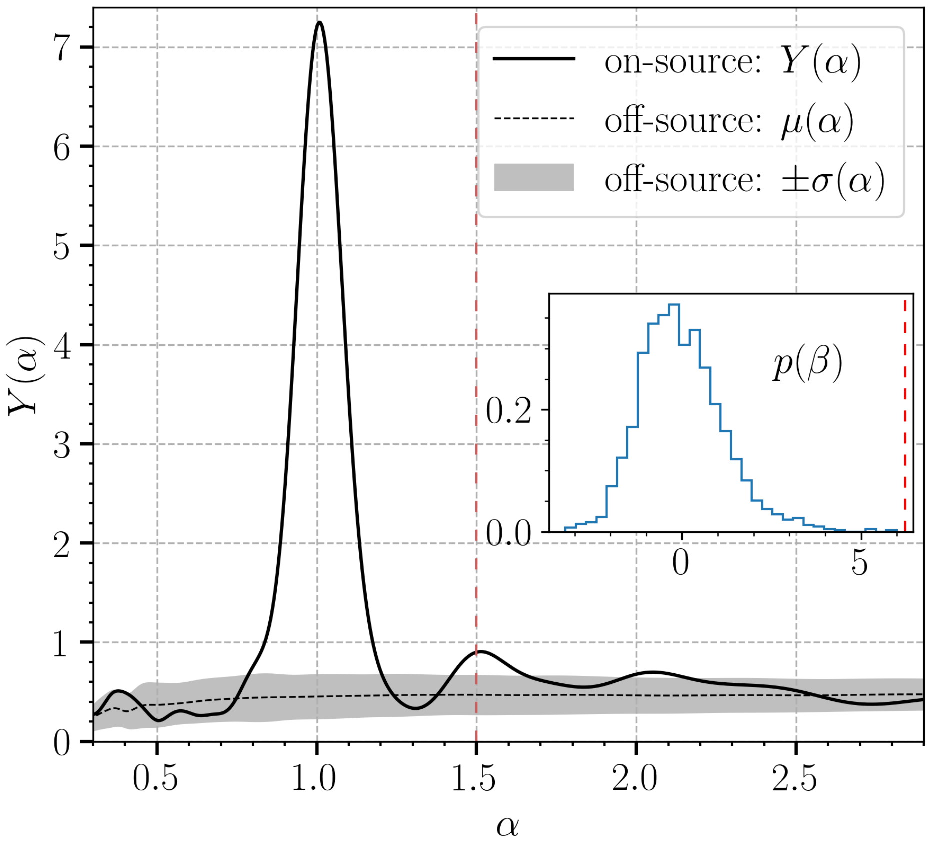


Figure: Energy stacked along $f(t) = \alpha f_{\rm quad}(t)$, $Y(\alpha)$.

GW190814 R. Abbott et al., Astrophys. J. Lett. **896**, no.2, L44 (202

- Asymmetric binary:
  $m_1 = 23.2^{+1.1}_{-1.0} M_\odot$, $m_2 = 2.59^{+0.08}_{-0.09} M_\odot$.

- The secondary object can be
  the heaviest NS or the lightest BH.

- Strong evidence of higher-order moments
  ($p < 2.5\times10^{-4}$)

- No electro-magnetic counterparts.

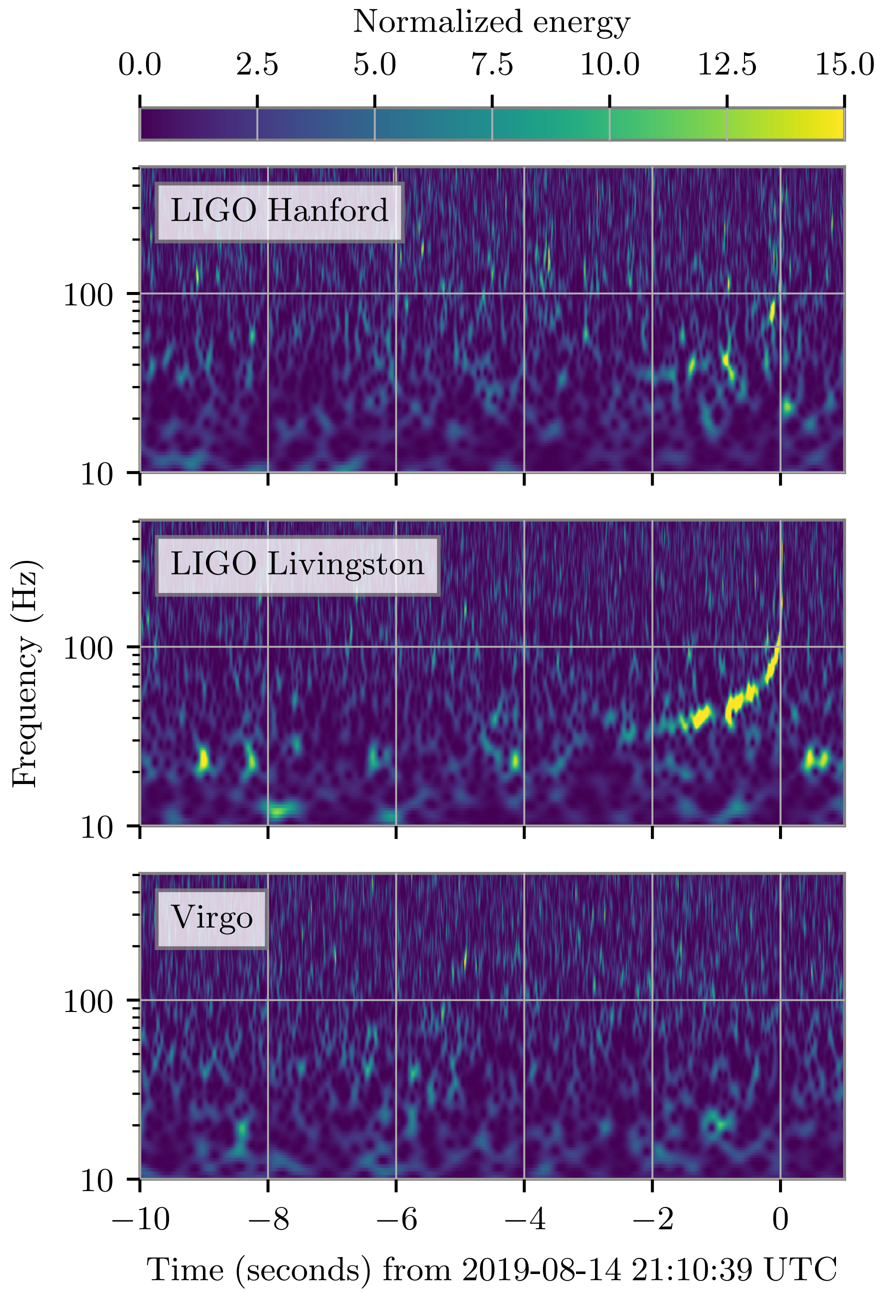


Figure: Time-frequency plot

GW190521

R. Abbott et al., Phys. Rev. Lett. **125**, no.10, 101102 (2020),
R. Abbott et al., Astrophys. J. Lett. **900**, no.1, L13 (2020).

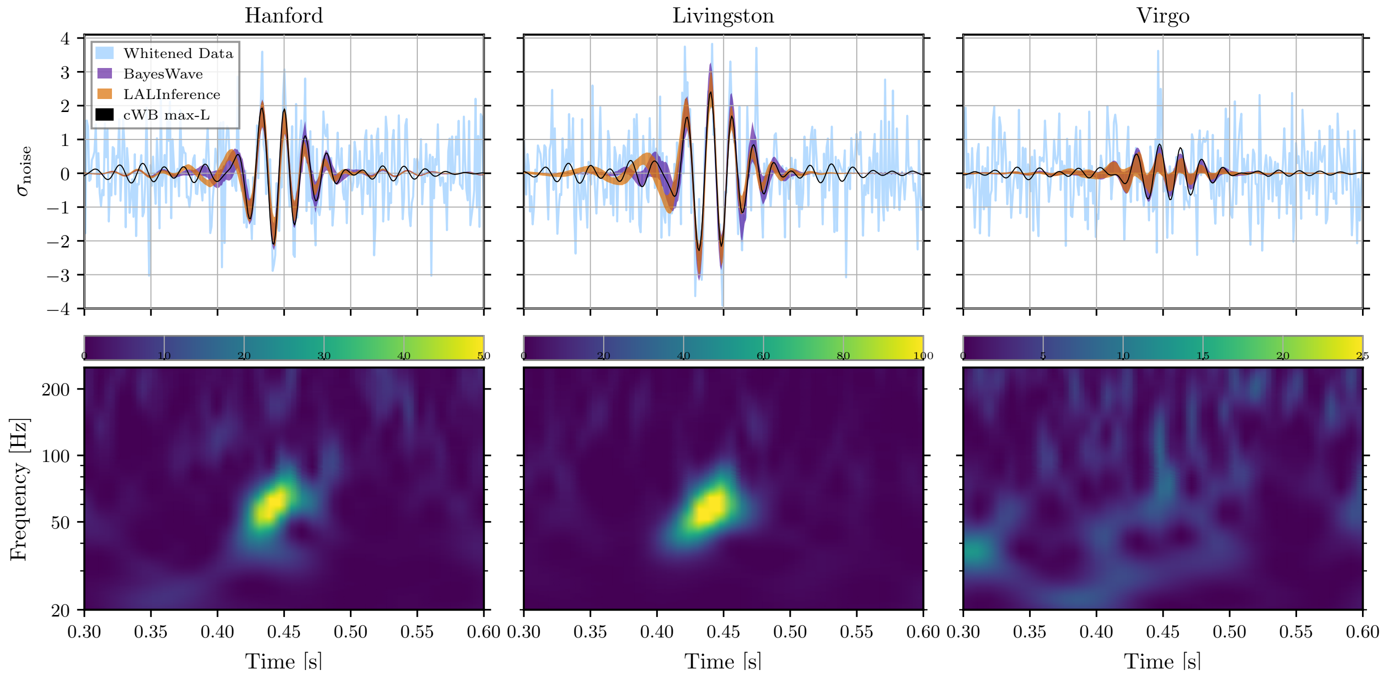


Figure: Time-Frequency plot

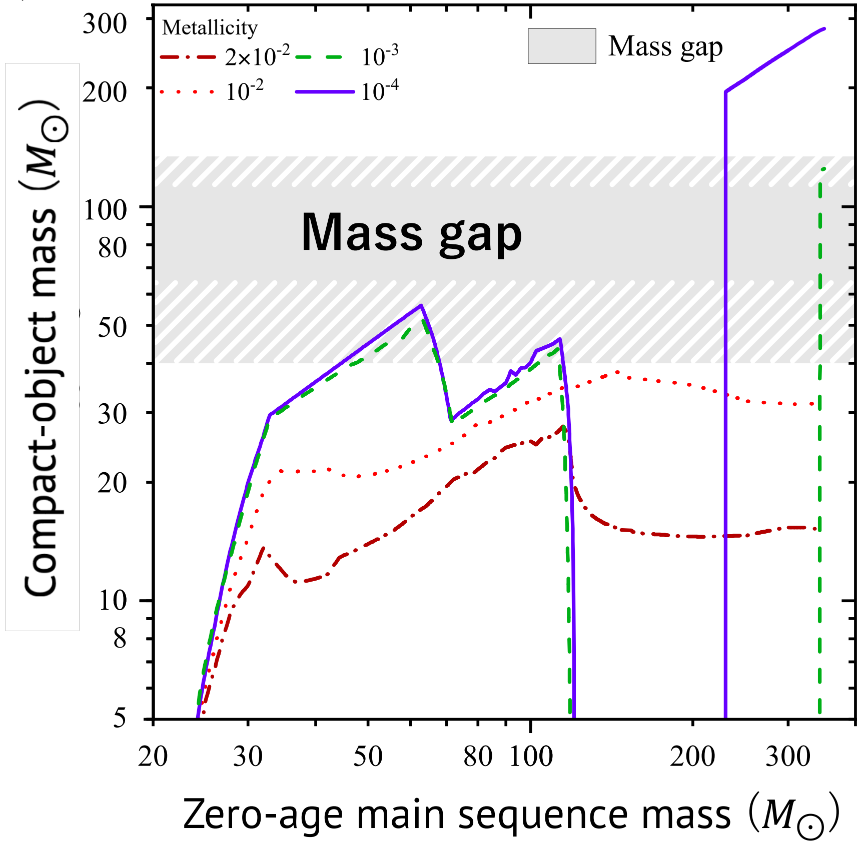


Figure: Compact-object mass from supernovae

- Heavy BBH: $m_1 = 85^{+21}_{-14} M_\odot$, $m_2 = 66^{+17}_{-18} M_\odot$.
- The primary mass m_1 is in the pair-instability mass gap ($65 - 120 M_\odot$).
- The remnant is an intermediate mass black hole: $M_f = 142^{+28}_{-16} M_\odot$.

GW190521

- Possible association of optical EM counterpart detected by Zwicky Transient Facility (ZTF) (False positive probability of 0.1%).

  M. J. Graham et al., Phys. Rev. Lett. **124**, no.25, 251102 (2020).

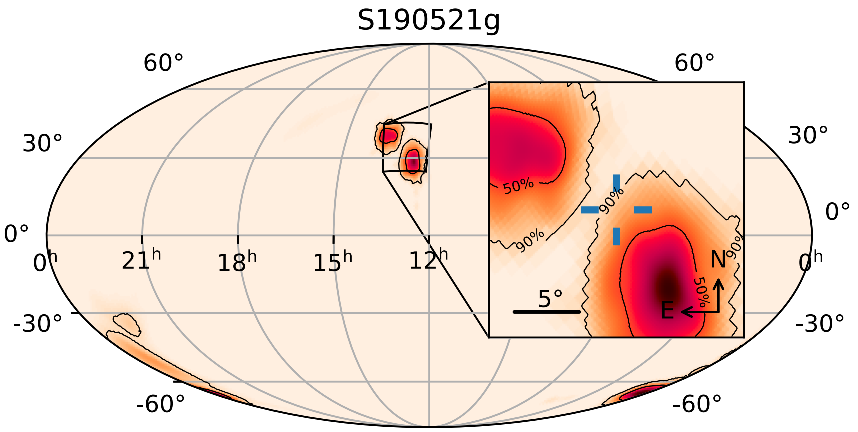


Figure: Estimated location of GW190521 (red region) and ZTF19abanrhr (reticle)

- The association still uncertain.
  - Other studies found the association is not significant enough.

    G. Ashton et al., Class. Quant. Grav. **38**, 23, 235004 (2021).
    A. Palmese et al., Astrophys. J. Lett. **914**, 2, L34 (2021).

  - Estimated distance of GW190521 depends on waveform model, and the overlap is uncertain.

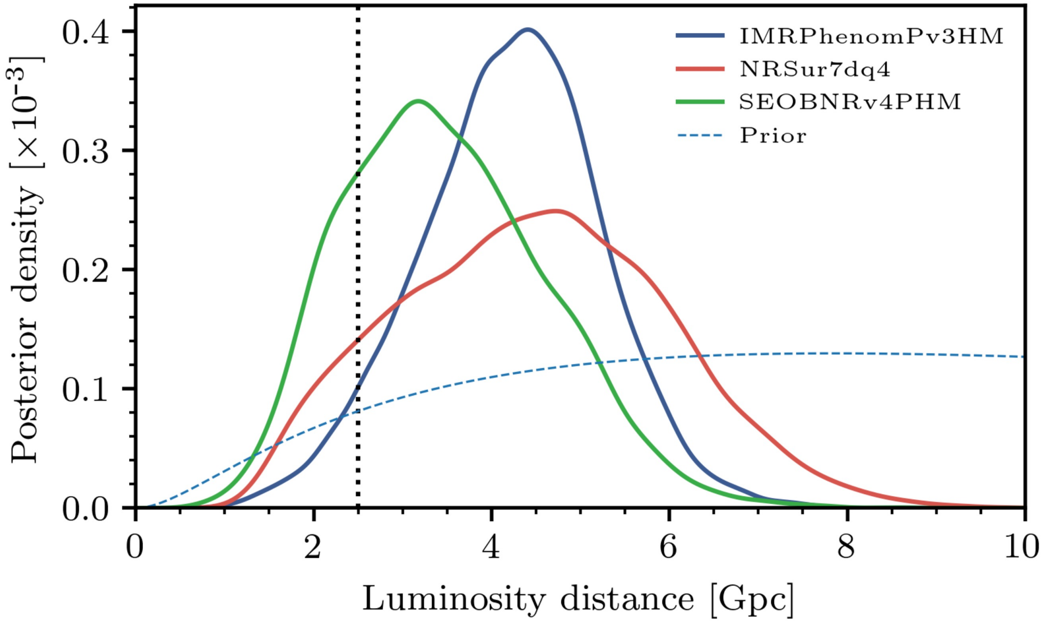


Figure: Estimated luminosity distance to GW190521 from various waveform models and ZTF19abanrhr (dashed vertical line) (taken from G. Ashton et al., Class. Quant. Grav. **38**, 23, 235004 (2021).)

BBH population: Mass

R. Abbott et al., arXiv: 2111.03634.

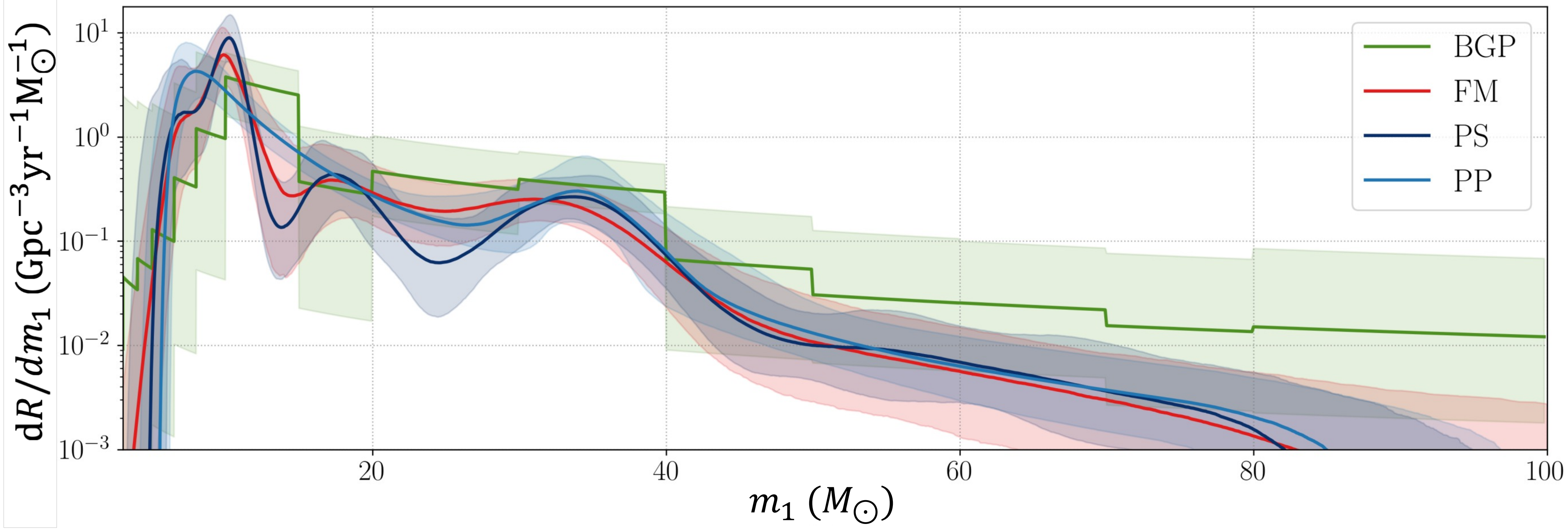


Figure: Differential event rate, dR/dm_1, from various population models

- Local maxima at $m_1 \sim 10M_\odot$ and $m_1 \sim 35M_\odot$ ($>$ 99% credibility)
- Inconclusive evidence for pair-instability mass gap $(65 - 120M_\odot)$.

BBH population: Redshift

R. Abbott et al., arXiv: 2111.03634.

- Merger rate increases with redshift z.
- Merger rate $\propto (1+z)^{\kappa}$, with $\kappa > 0$ (at 99.6%).
- $\kappa = 2.9^{+1.7}_{-1.8}$ (90% CI)
- No evidence that mass distribution varies with redshift.

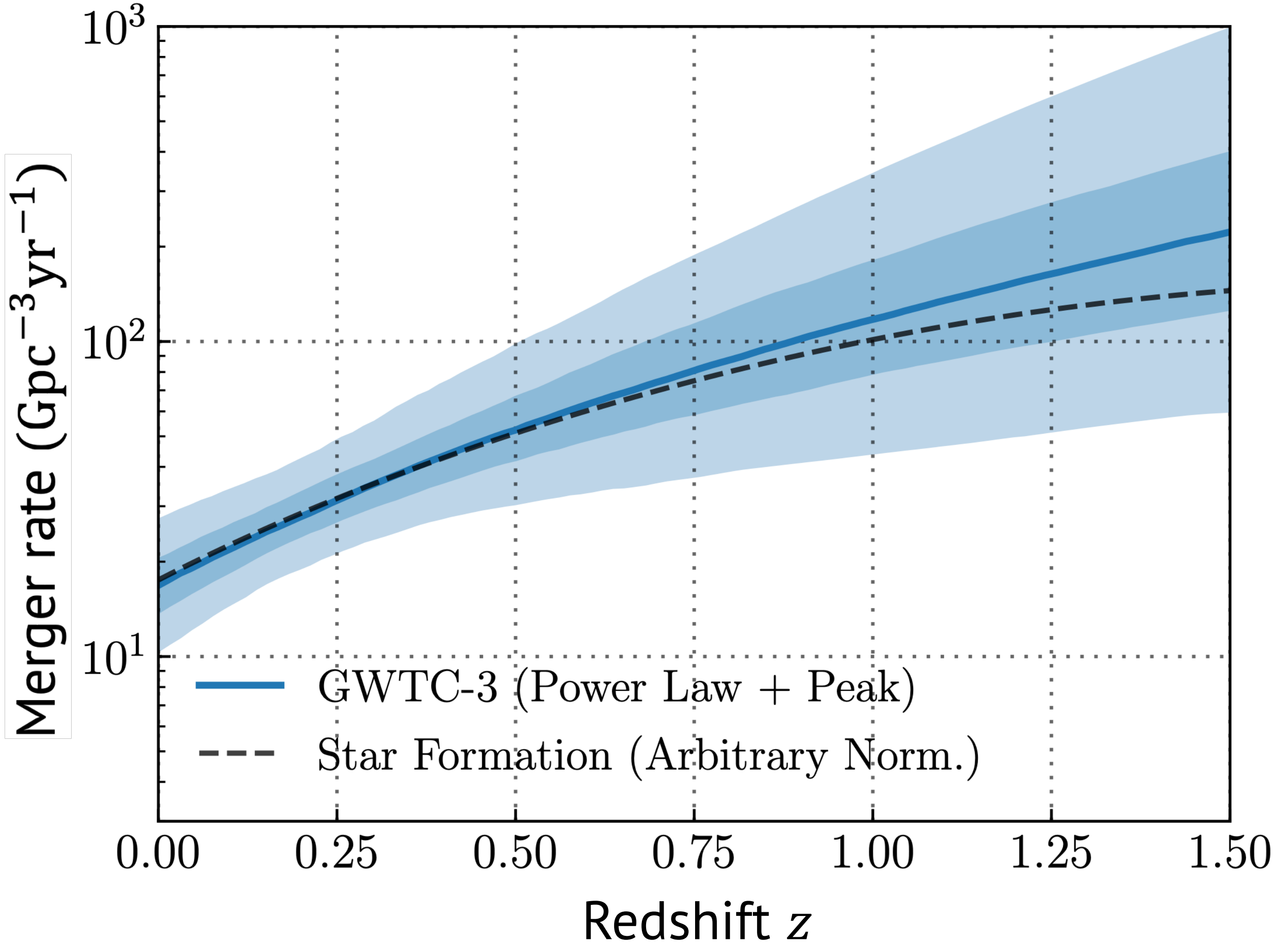
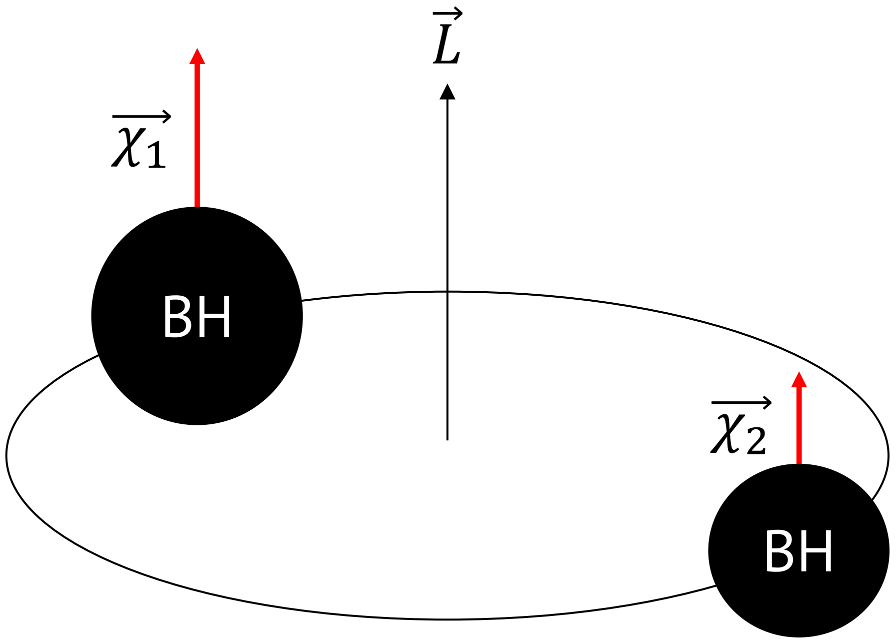


Figure: Redshift evolution of merger rate

BBH population: Spin

Frequency evolution is predominantly affected by $\chi_{\parallel}$, a spin component aligned with orbital angular momentum $\vec{L}$.

C. Cutler and E. E. Flanagan, PRD 49, 2658 (1994).



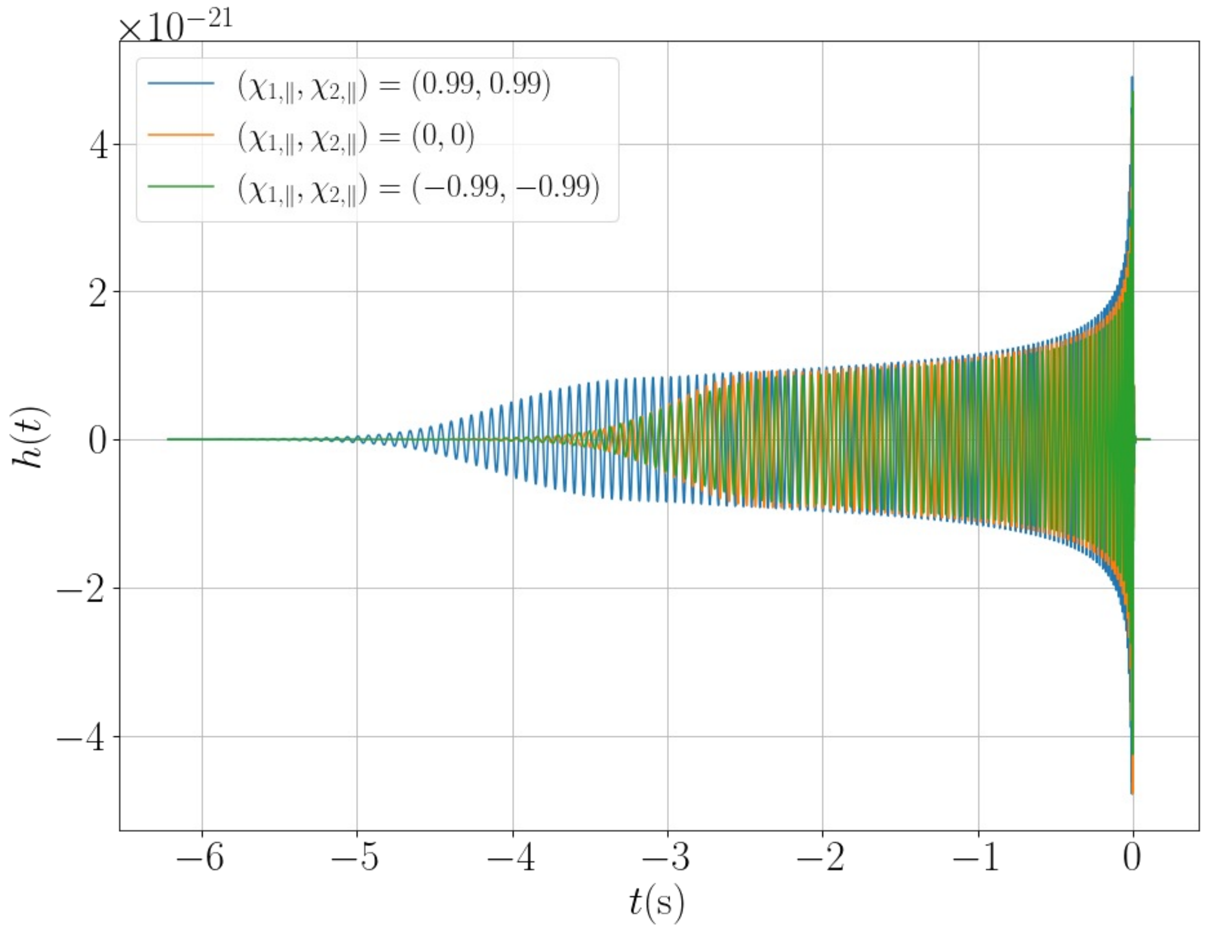
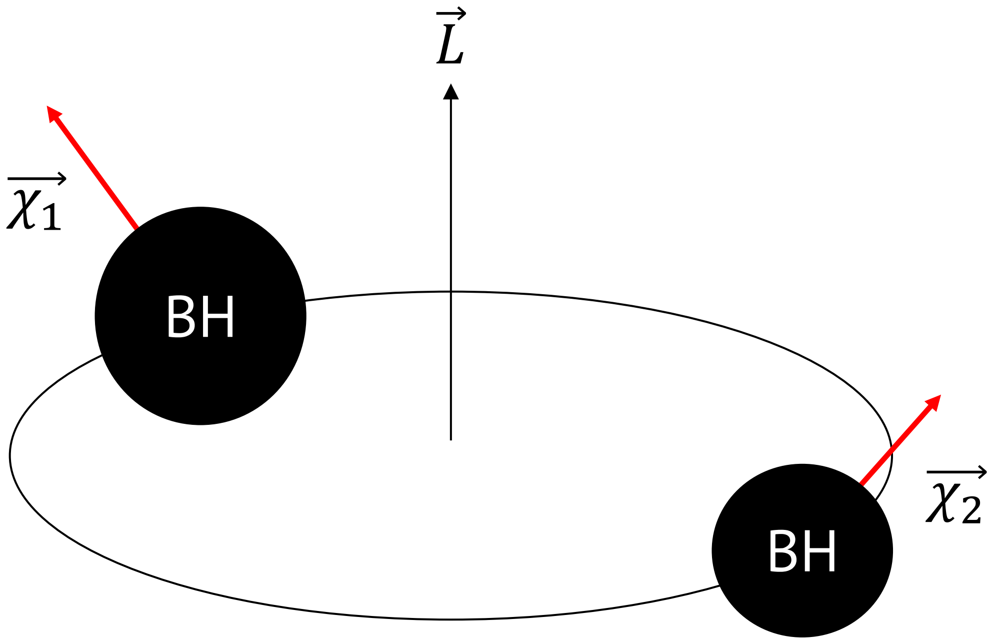


Figure: Gravitational waves with various $\chi_{\parallel}$ values, $(m_1, m_2) = (20M_{\odot}, 20M_{\odot})$

BBH population: Spin

Perpendicular spin components, $\chi_{1,\perp}$ and $\chi_{2,\perp}$, cause precession of the orbital plane, which induces signal amplitude modulation.

T. A. Apostolatos et al., PRD 49, 6274 (1994).



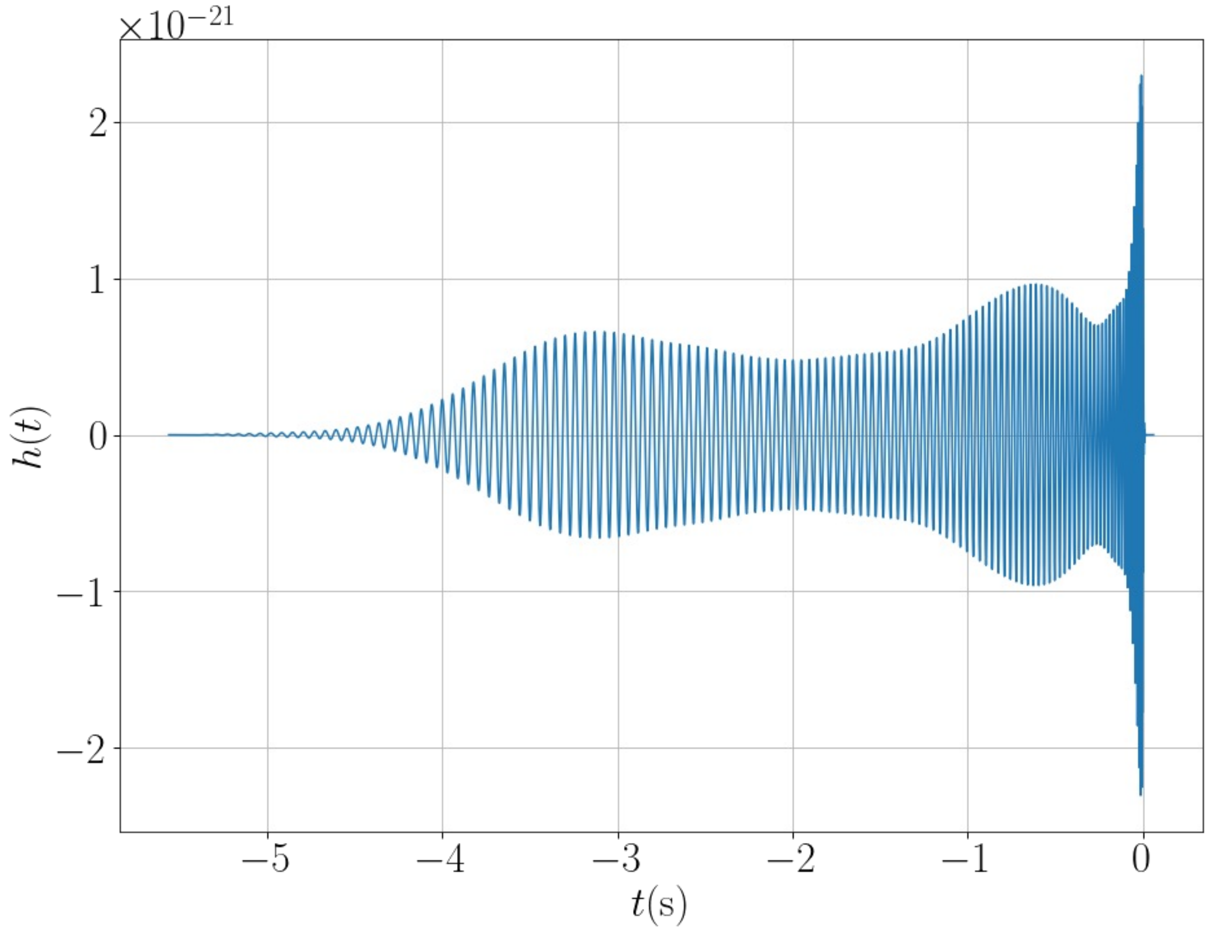


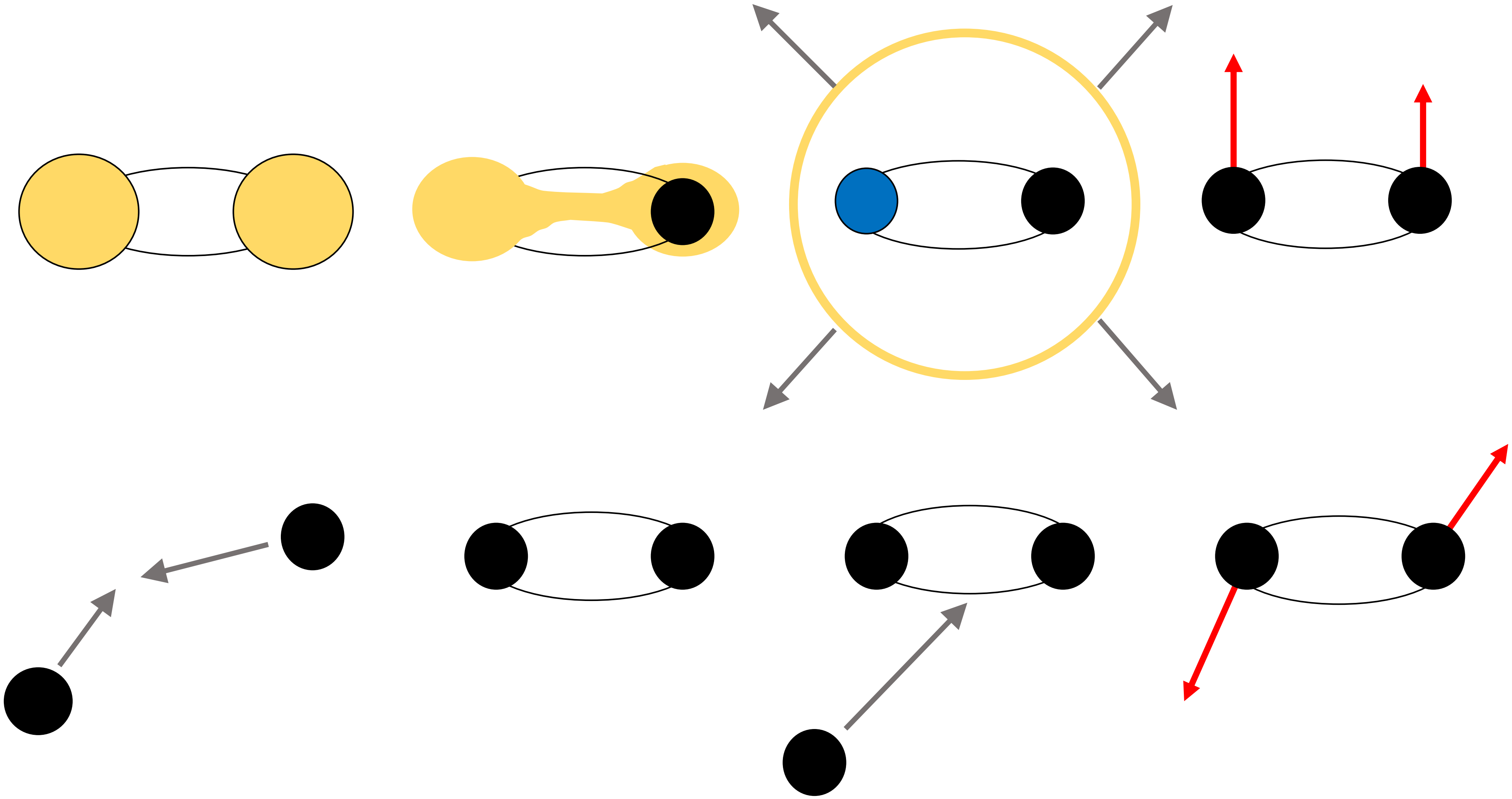
Figure: Gravitational waves with $(m_1, m_2, \chi_{1,\perp}) = (30M_\odot, 10M_\odot, 0.7)$

BBH population: Spin

e.g. I. Mandel and A. Farmer, arXiv: 1806.05820

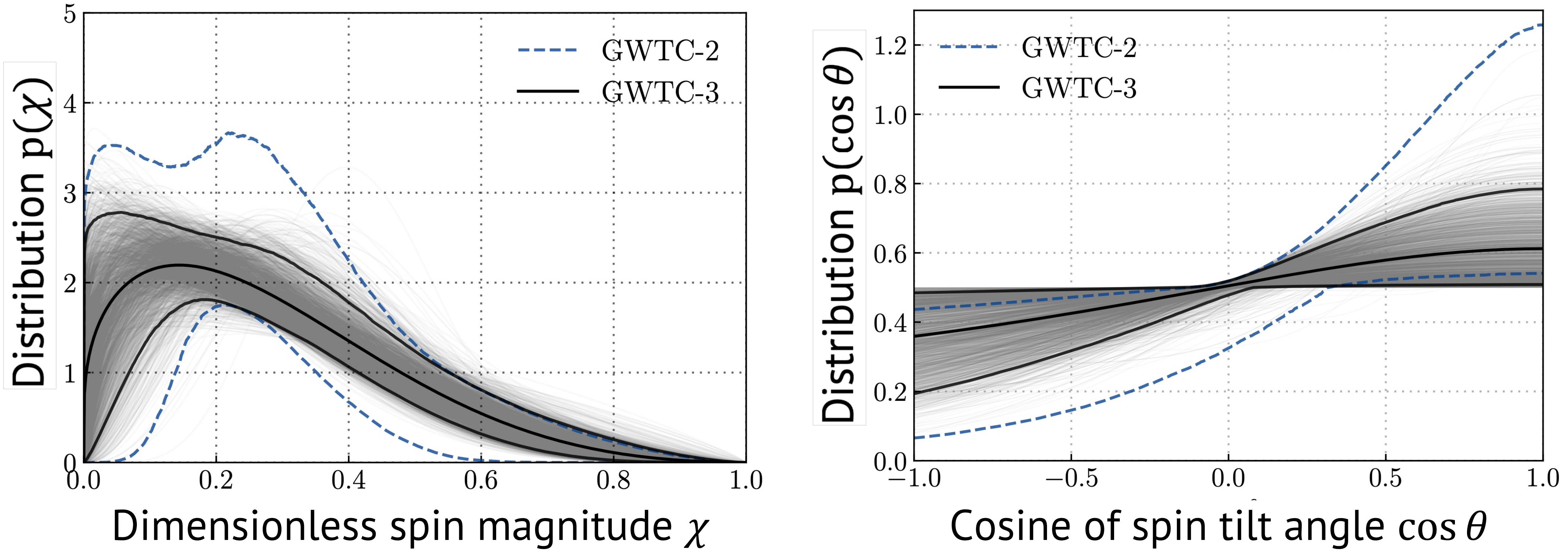
Isolated field binaries

Dynamical formation



BBH population: Spin

R. Abbott et al., arXiv: 2111.03634.



- Spin magnitude generally small ($\chi \lesssim 0.4$), but not-vanishing.
- Significant spin-orbit misalignment, but $\cos\theta = 1$ preferred.

GW190425

B. P. Abbott et al., Astrophys. J. Lett. **892**, no.1, L3 (2020).

- Heavy binary neutron star (BNS):
  $m_1 = 1.61 - 2.52 M_\odot,\ m_2 = 1.12 - 1.68 M_\odot$.

- LIGO-Hanford was not observing.
  → Large localization uncertainties ($\sim 16\%$ of the whole sky). The source is also distant ($90 - 230$ Mpc).

- No EM or neutrino counterparts.

- The heaviest merging BNS observed so far.

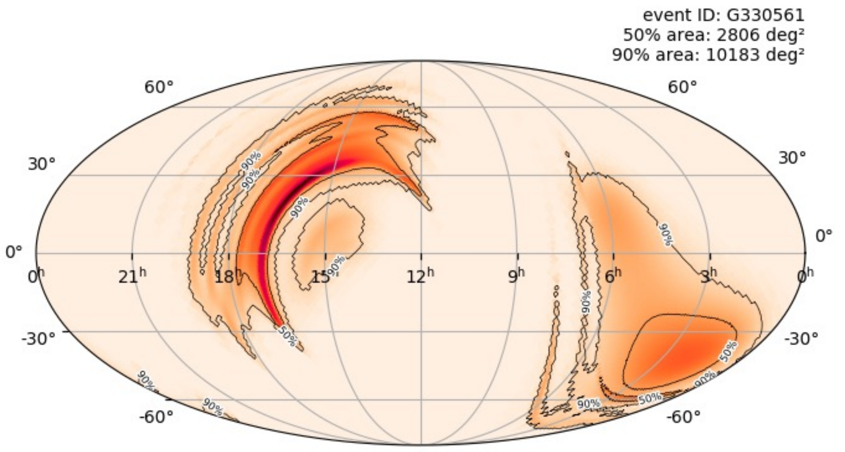


Figure: 2D Localization of GW190425

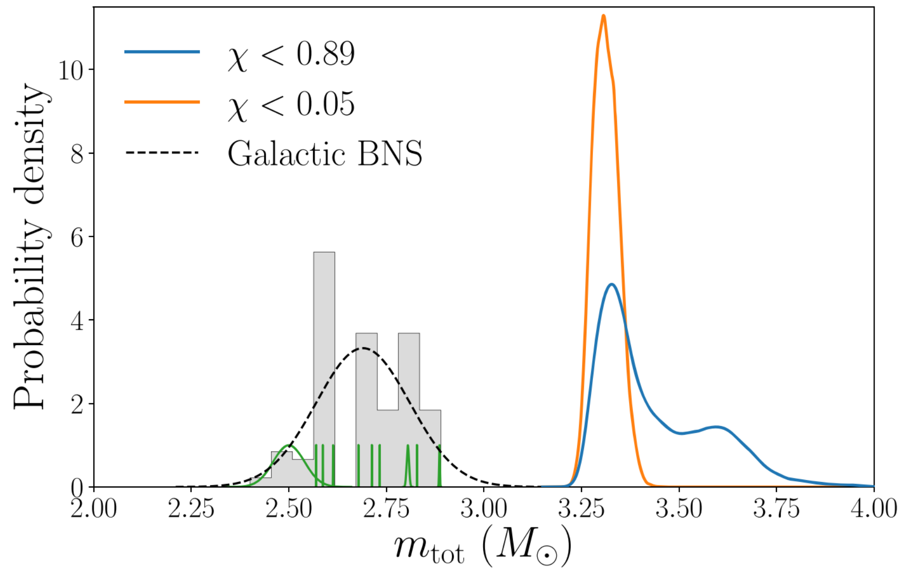
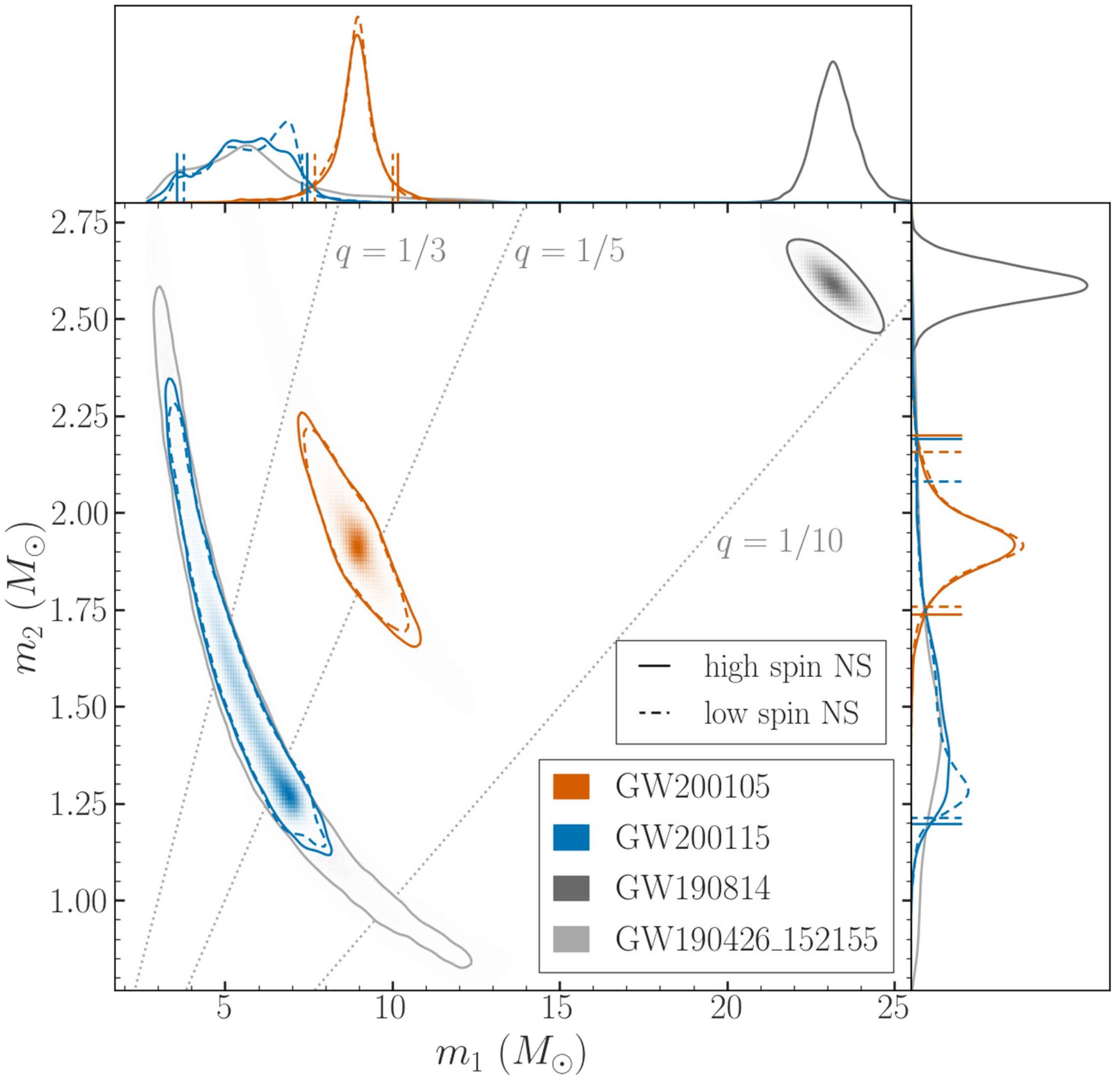


Figure: Total masses of galactic merging BNSs (gray) and GW190425 (orange, blue)

GW200105 & GW200115

R. Abbott et al., Astrophys. J. Lett. **915**, no.1, L5 (2021).



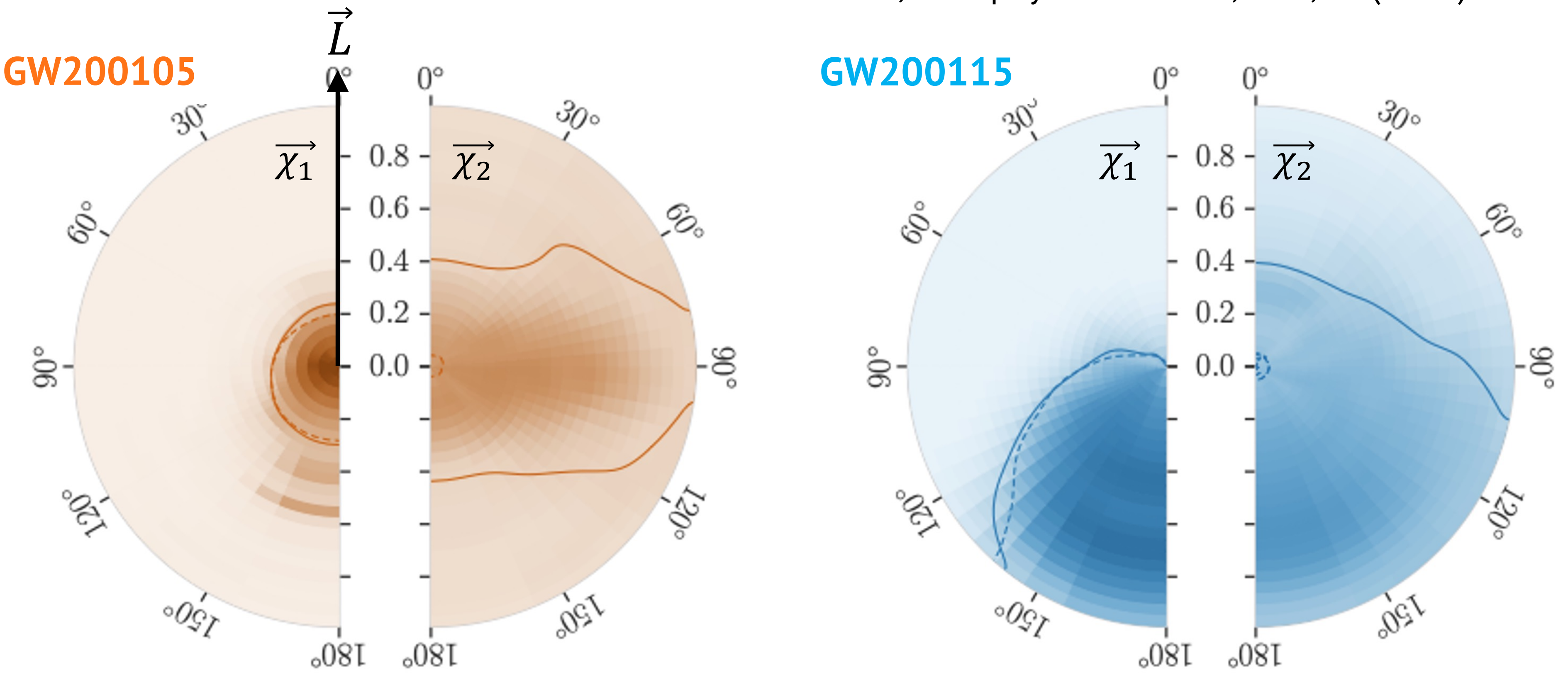
	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

90% credible intervals centered at the medians

- Masses consistent with neutron star-black hole (NSBH)
- No direct evidence of secondary objects being neutron stars (No EM counterparts, no tidal information)

GW200105 & GW200115

R. Abbott et al., Astrophys. J. Lett. **915**, no.1, L5 (2021).

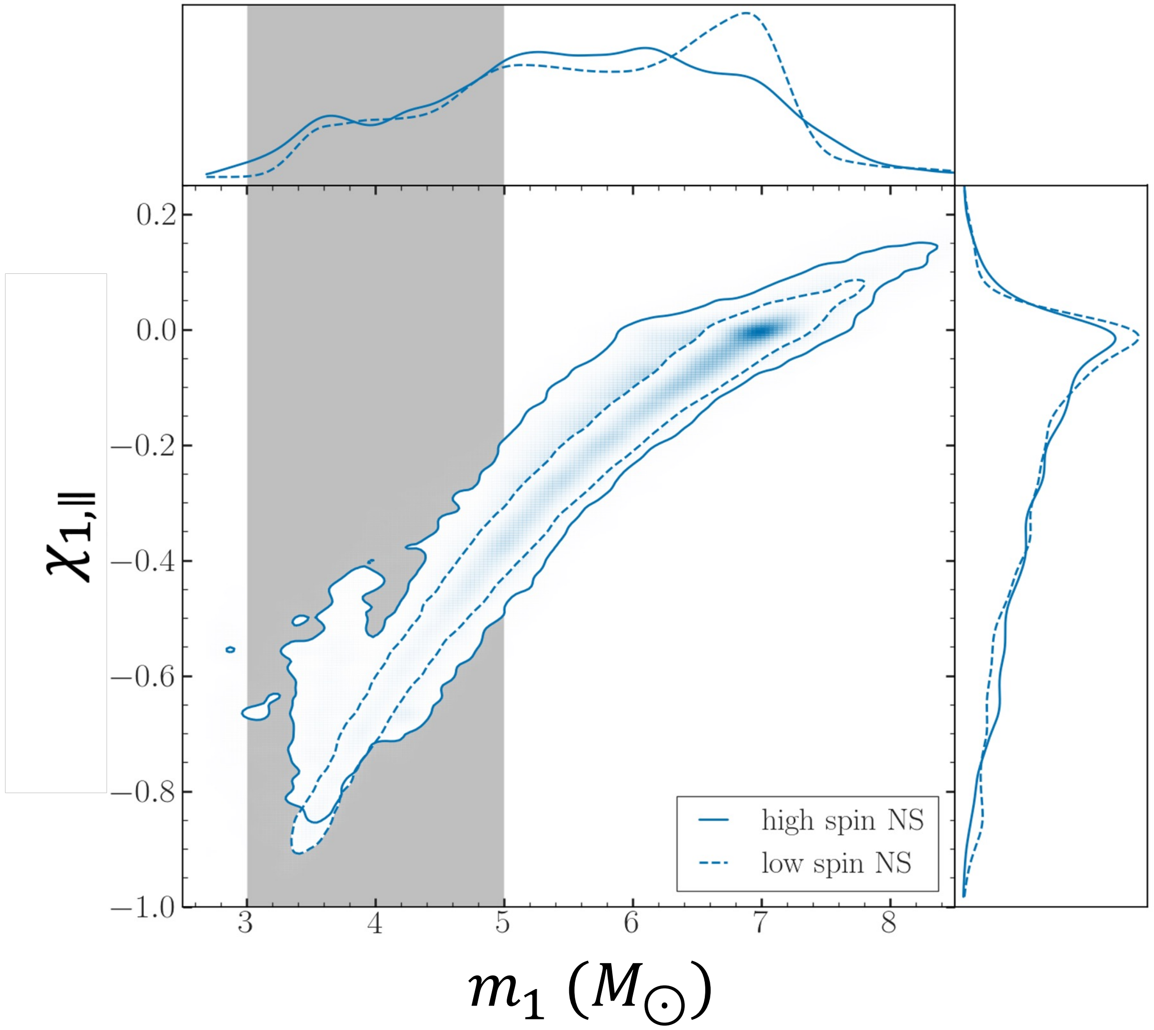


	GW200105	GW200115
$\vec{\chi}_1$	$\lvert\vec{\chi}_1\rvert < 0.23$ (90% confidence)	$\chi_{1,\parallel} = -0.19^{+0.24}_{-0.50}$ $P(\chi_{1,\parallel} < 0) = 88\%$
$\vec{\chi}_2$	Unconstrained	Unconstrained

GW200105 & GW200115

R. Abbott et al., Astrophys. J. Lett. **915**, no.1, L5 (2021).

GW200115



- Negative $\chi_{1,\parallel}$ is correlated with the low value of the primary mass m_1, which is in the lower mass gap $3M_\odot \leq m_1 \leq 5M_\odot$.
- $P\left(3M_\odot \leq m_1 \leq 5M_\odot\right) = 30\%$.

Event rate

BNS:

$10\ \mathrm{Gpc^{-3}yr^{-1}}$ - $1700\ \mathrm{Gpc^{-3}yr^{-1}}$

NSBH:

$7.8\ \mathrm{Gpc^{-3}yr^{-1}}$ – $140\ \mathrm{Gpc^{-3}yr^{-1}}$

BBH (at $z = 0.2$):

$17.9\ \mathrm{Gpc^{-3}yr^{-1}}$ - $44\ \mathrm{Gpc^{-3}yr^{-1}}$

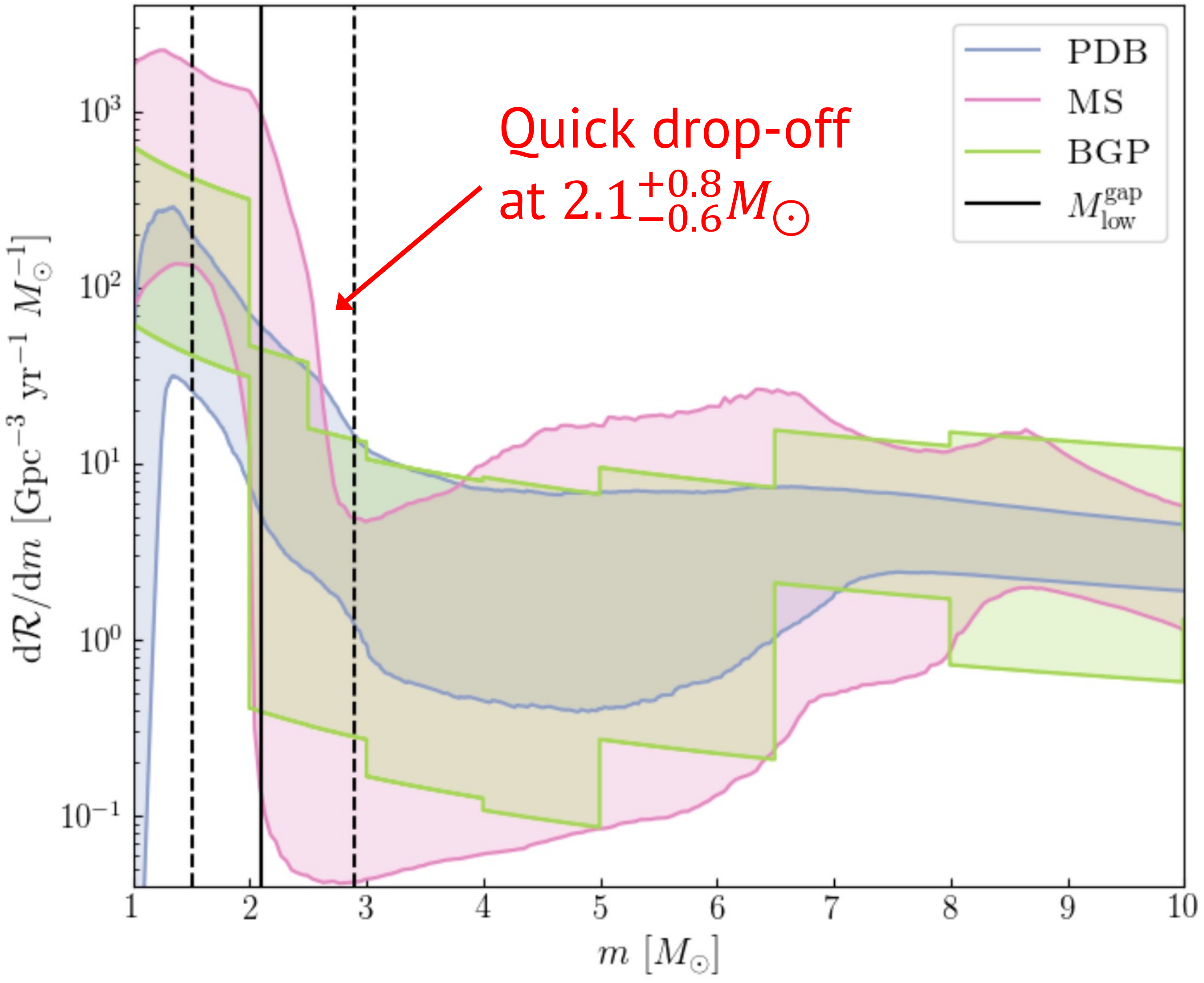


Figure: Differential merger rate as a function of component mass

Future observations

The fourth observing run (O4) will start on **May 24**. The duration is **18 months**.

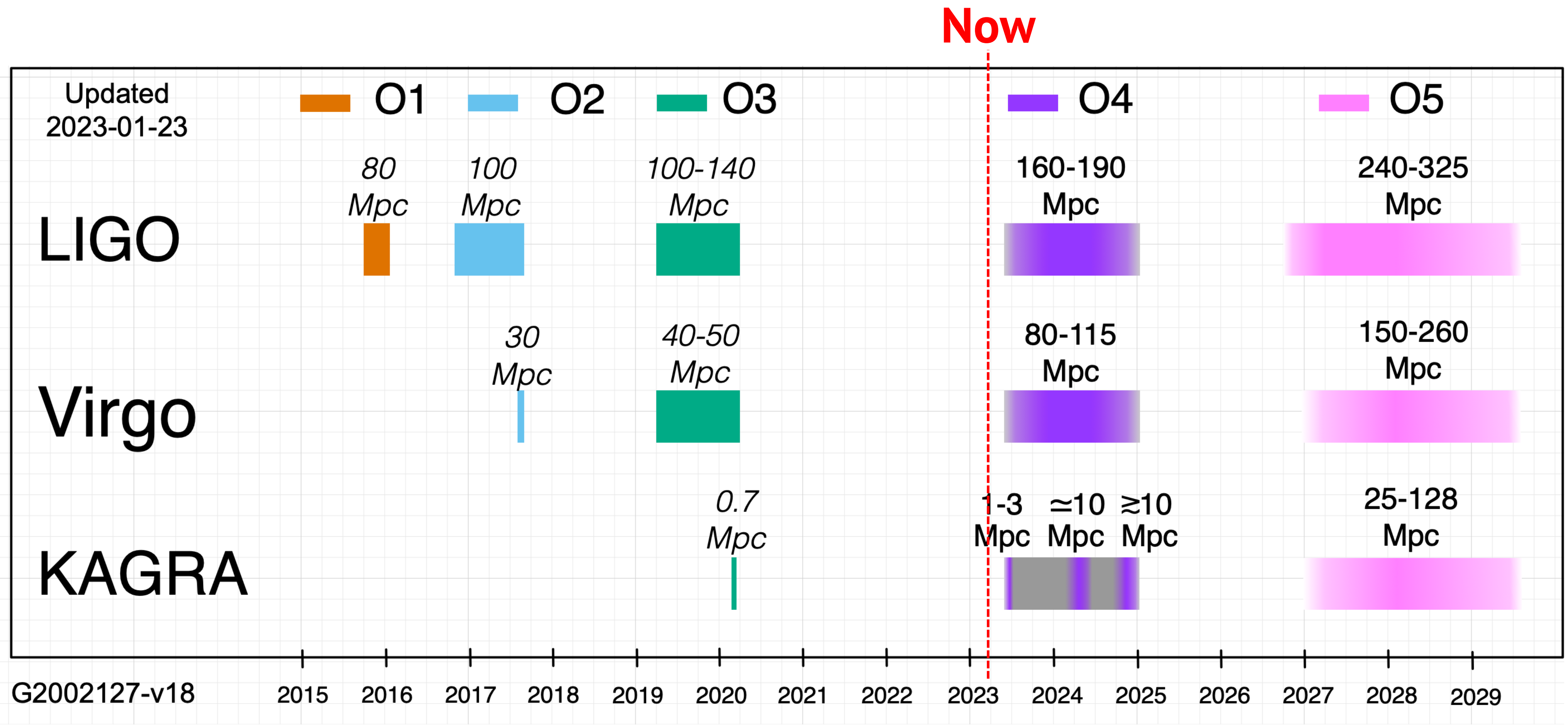


Figure: Observing plan (https://observing.docs.ligo.org/plan/)

Public alert in O4: New FAR threshold

The false alarm rate threshold for public alerts will be lowered to **2/day**.

There will be two classes of alerts:

- **Significant** gravitational-wave alerts with false alarm rate less than 1/ month for compact binary coalescence (CBC) and 1/year for burst that pass automated and manual verification tests.
- **Low Significance** gravitational-wave alerts with false alarm rate between 1/months – 2/day for CBC and 1/year – 2/day for burst.

See https://dcc.ligo.org/LIGO-G2300151/public for more details.

Public alert in O4: Early Warnings

R. Magee et al., ApJL **910** L21 (2021).

1-10/yr early warnings expected 1s before merger if no system latencies.

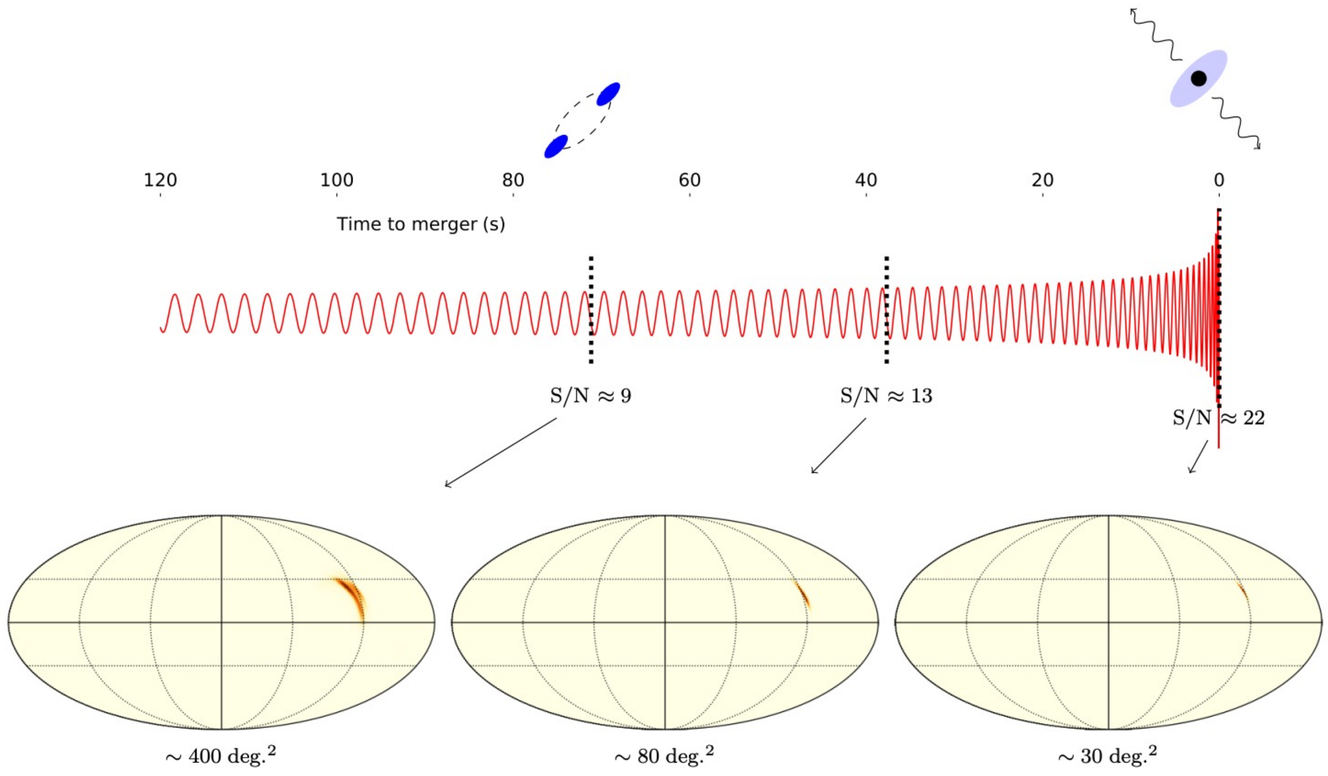


Figure: Illustration of early warning

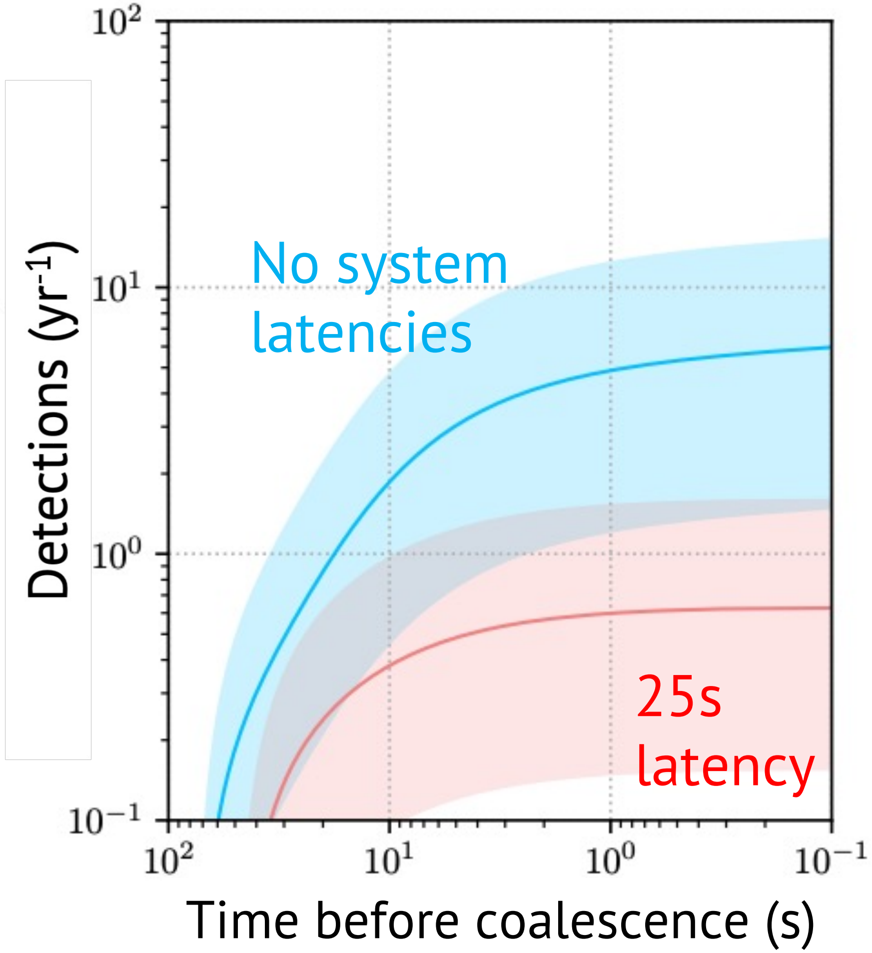
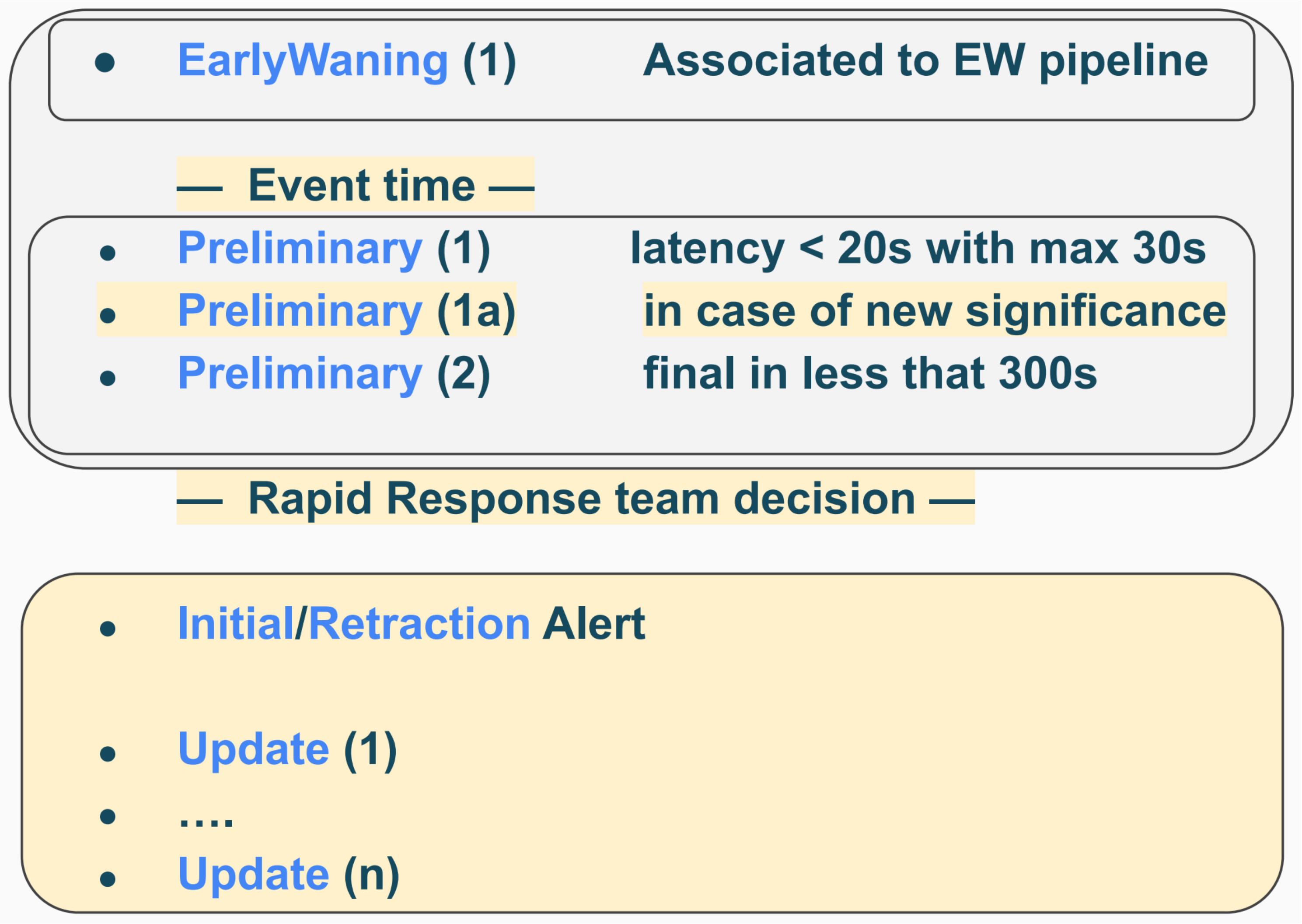


Figure: O4 early warning capability

Public alert in O4: Alert timeline



- Preliminary 1a alert when significance is updated.
- “Significant” alerts will be followed by Rapid Response team discussions, automated and manual verification tests, parameter estimation updates, etc.

Public alert in O4: External trigger search

Searches for coincidence between GWs and external triggers.

- **RAVEN [1]** will search for temporal/space-time coincidence with gamma-ray bursts from Fermi, Swift and AGILE, as well as supernova alerts from the SNEWS. It computes coincident FAR if any coincidence.

- **LLAMA [2, 3]** will search for coincidence with High Energy Neutrino triggers from IceCube.

[1] Urban, A. L. 2016, Ph.D. Thesis. https://dc.uwm.edu/etd/1218/
[2] Bartos, I., Veske, D., Keivani, A., et al. 2019, PRD **100**, 083017.
[3] Countryman, S., Keivani, A., Bartos, I., et al. 2019. arXiv: 1901.05486

Expectation

- Based on the best possible sensitivity and SNR threshold of 8.

- More realistic values will be available once engineering run is performed.

- Detections can be ~1/day in O4

		BNS	NSBH	BBH
Annual number of public alerts (log-normal merger rate uncertainty $\times$ Poisson counting uncertainty)				
O4	HKLV	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	HKLV	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}
Median luminosity distance (Mpc, Monte Carlo uncertainty)				
O4	HKLV	398^{+15}_{-14}	770^{+67}_{-70}	2685^{+53}_{-40}
O5	HKLV	738^{+30}_{-25}	1318^{+71}_{-100}	4607^{+77}_{-82}
Median 90% credible area (deg^2, Monte Carlo uncertainty)				
O4	HKLV	1860^{+250}_{-170}	2140^{+480}_{-530}	1428^{+60}_{-55}
O5	HKLV	2050^{+120}_{-120}	2000^{+350}_{-220}	1256^{+48}_{-53}

(Taken from https://emfollow.docs.ligo.org/userguide/capabilities.html)

Summary

- 90 compact binary coalescences detected.
  - Exceptional events: asymmetric BBH, mass gaps (low and high), heavy BNS, NSBH
  - BBH population: structure in mass distribution, merger rate increases with redshift, significant spin-orbit misalignment (but not necessarily isotropic)

- Public alert in O4
  - New false alarm rate threshold: 2/day
  - Early warnings
  - Coincidence with external triggers

- Detections can be ~1/day in O4!

Extra slides

Public alert in O4: New FAR threshold

```
{   "alert_type": "PRELIMINARY",
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    "superevent_id": "MS181101ab",
    "urls": { "gracedb": "https://example.org/superevents/MS181101ab/view/" },
    "event": {
        "time": "2018-11-01T22:22:46.654Z",
        "far": 9.11069936486e-14,
        "significance": "low significance"  # 2/day > FAR > (1/month CBC and 1/year BURST)
                        "significant"       # (1/month CBC and 1/year BURST) > FAR
        "instruments": [ "H1", "L1", "V1"],
        "group": "CBC",
        "pipeline": "gstlal",
        "search": "MDC",
        "classification": { "BNS": 0.95, "NSBH": 0.01, "BBH": 0.03, "Terrestrial": 0.01},
        "properties": { "HasNS": 0.95, "HasRemnant": 0.91, "HasMassGap": 0.01},
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         },
    "external_coinc": null }
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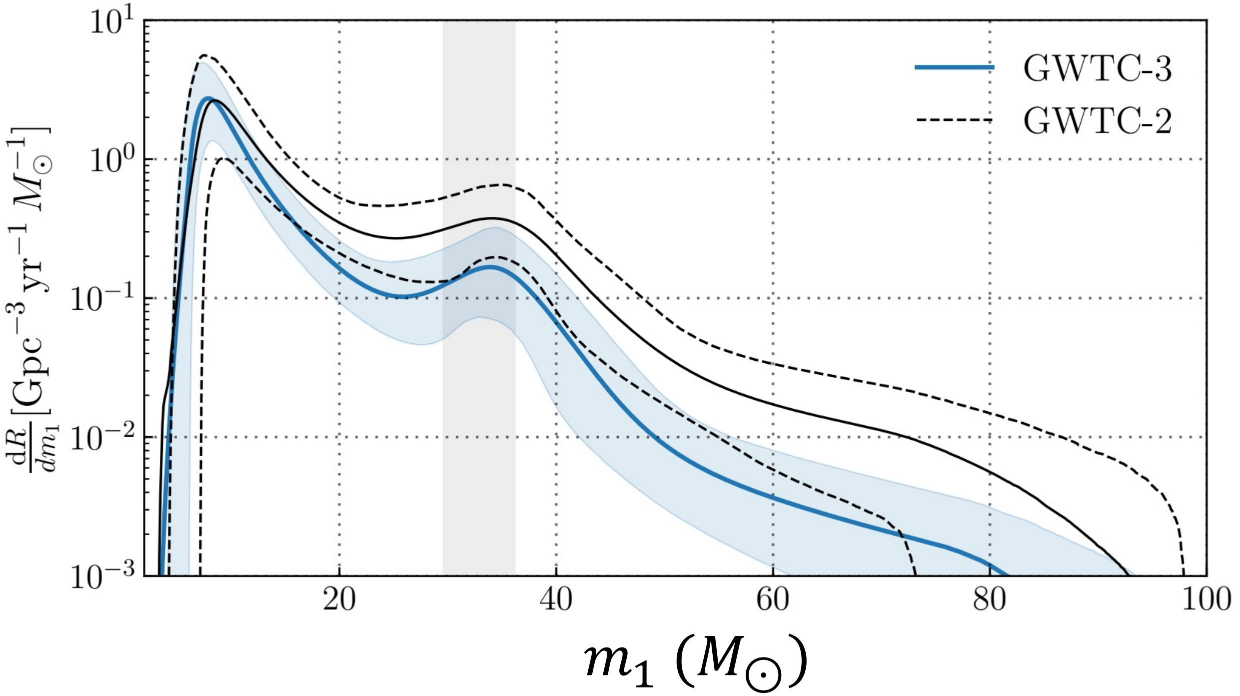
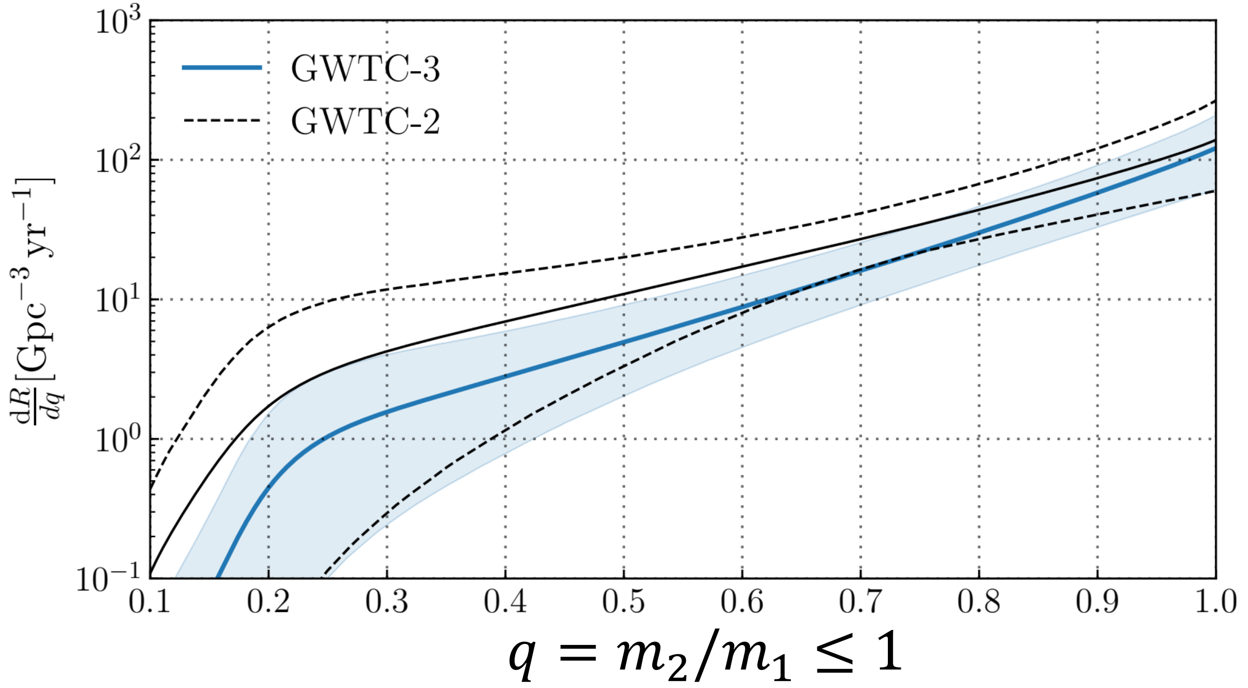
BBH population: Mass





- Gaussian peak at $m_1 = 34^{+9.2}_{-5.1}\ M_\odot$
- Equal-mass favored $p(q) \propto q^\beta$, with $\beta = 1.1^{+1.7}_{-1.3}$.

Discovery paper

The Astrophysical Journal Letters, 915:L5 (24pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac082e

Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

Abstract

We report the observation of gravitational waves from two compact binary coalescences in LIGO's and Virgo's third observing run with properties consistent with neutron star–black hole (NSBH) binaries. The two events are named GW200105_162426 and GW200115_042309, abbreviated as GW200105 and GW200115; the first was observed by LIGO Livingston and Virgo and the second by all three LIGO–Virgo detectors. The source of GW200105 has component masses $8.9^{+1.2}_{-1.5}$ and $1.9^{+0.3}_{-0.2}\,M_\odot$, whereas the source of GW200115 has component masses $5.7^{+1.8}_{-2.1}$ and $1.5^{+0.7}_{-0.3}\,M_\odot$ (all measurements quoted at the 90% credible level). The probability that the secondary's mass is below the maximal mass of a neutron star is 89%–96% and 87%–98%, respectively, for GW200105 and GW200115, with the ranges arising from different astrophysical assumptions. The source luminosity distances are 280^{+110}_{-110} and 300^{+150}_{-100} Mpc, respectively. The magnitude of the primary spin of GW200105 is less than 0.23 at the 90% credible level, and its orientation is unconstrained. For GW200115, the primary spin has a negative spin projection onto the orbital angular momentum at 88% probability. We are unable to constrain the spin or tidal deformation of the secondary component for either event. We infer an NSBH merger rate density of $45^{+75}_{-33}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ when assuming that GW200105 and GW200115 are representative of the NSBH population or $130^{+112}_{-69}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ under the assumption of a broader distribution of component masses.

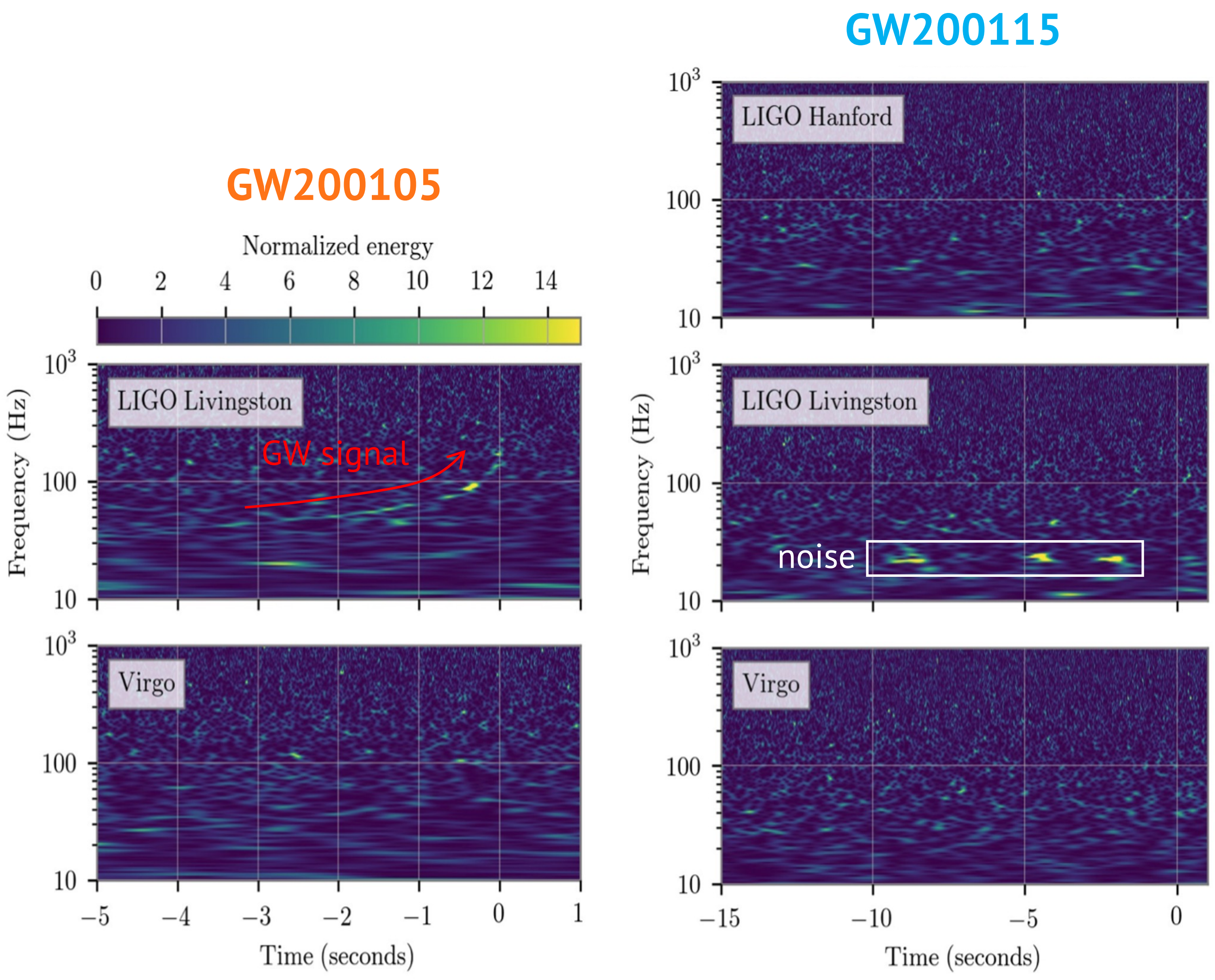
R. Abbott et al., 2021 ApJL **915** L5, arXiv: 2106.15163.

Detector network

- Detector ranges
  LIGO-Hanford: ~120 Mpc
  LIGO-Livingston: ~130-140 Mpc
  Virgo: ~50 Mpc

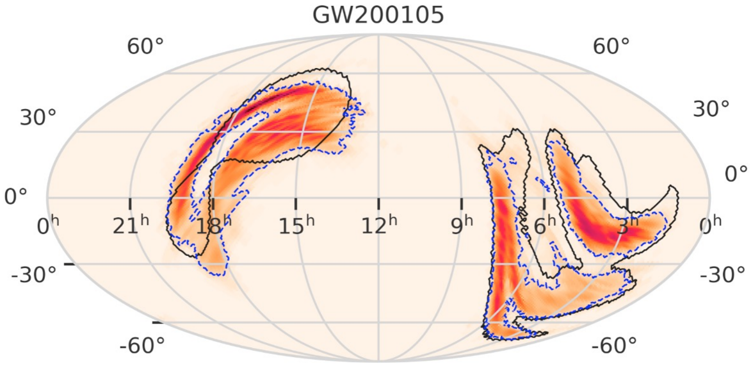
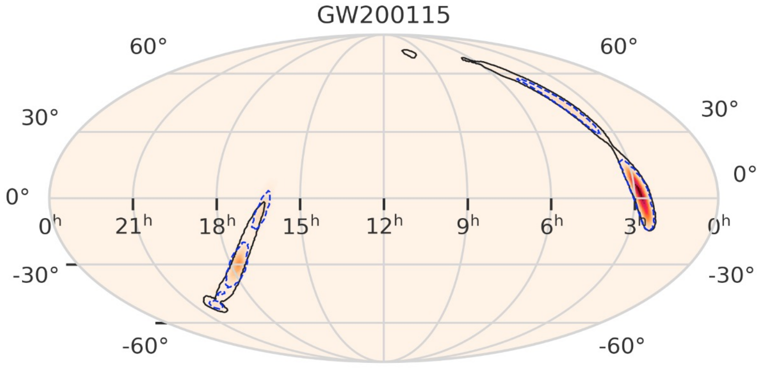
- LIGO-Hanford was not operating at the time of GW200105.

- Noise excess at ~20 Hz in Livingston for GW200115
  → exclude data below 25Hz in parameter estimation



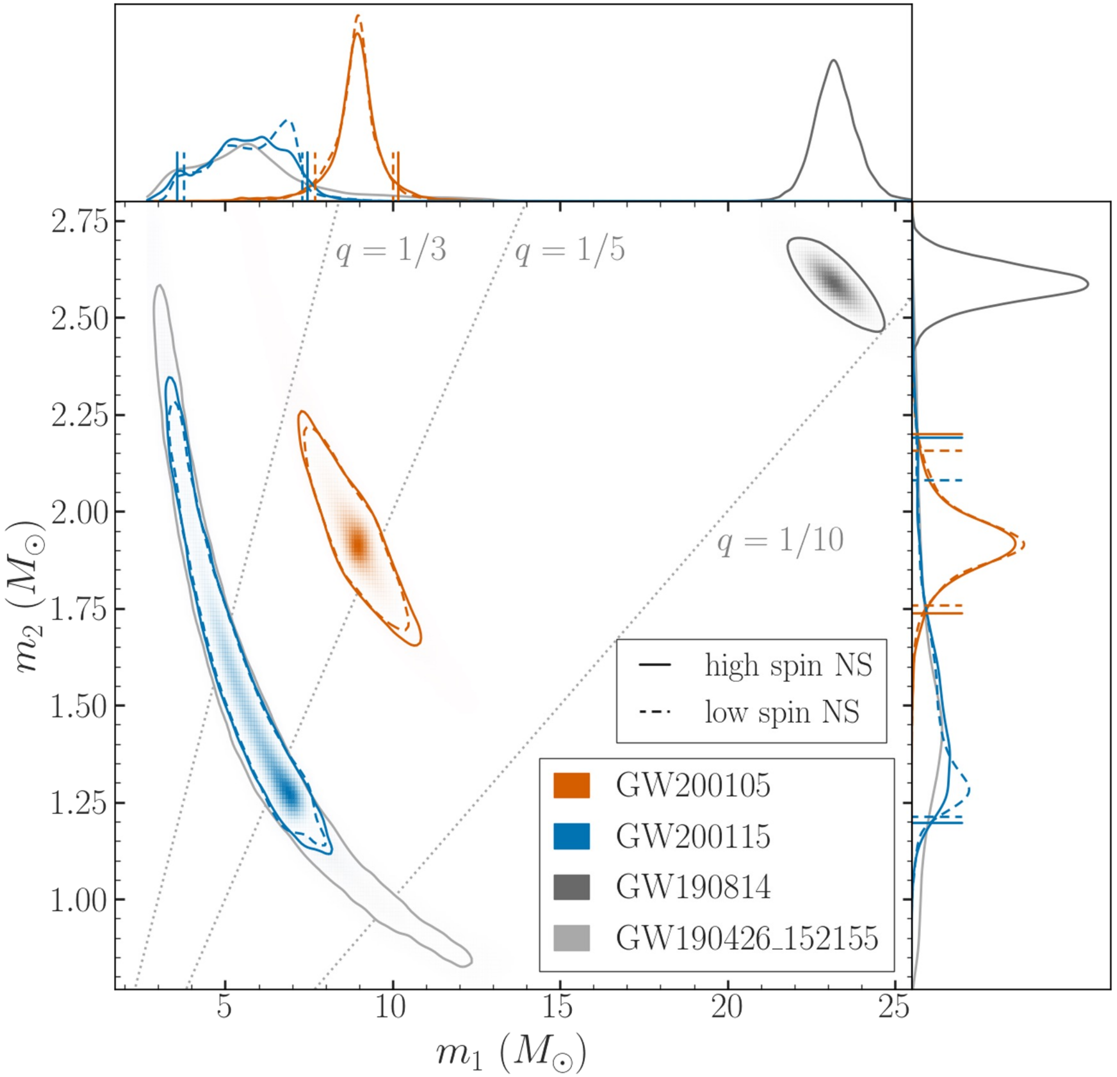
Time-frequency maps of data containing GW200105 (left) and GW200115 (right)

Detection summary

Event	GW200105	GW200115
Signal-to-Noise Ratio (H, L, V)	N/A, 13.6, 2.7 (Livingston-only)	6.9, 8.6, 2.9 (HL coincidence)
False Alarm Rate	low latency: 1/(15 days) offline: 1/(2.8 yr)	low latency: 1/(1513 yr) offline: From 1/(182 yr) to < 1/(10^5 yr)
GCN Notice Latency	More than 1 day	After 6 mins
Sky localization	7700 deg^2 (low latency) 	900 deg^2 (low latency) 
Distance	~265 Mpc (low latency)	~330 Mpc (low latency)
# Follow-up GCNs	21 (**No EM/neutrino counterparts**, e.g. [1])	31 (**No EM/neutrino counterparts**)

[1] S. Anand et al., Nature Astron. **5**, 46 (2021).

Masses



	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

All measurements quoted at the 90% credible level

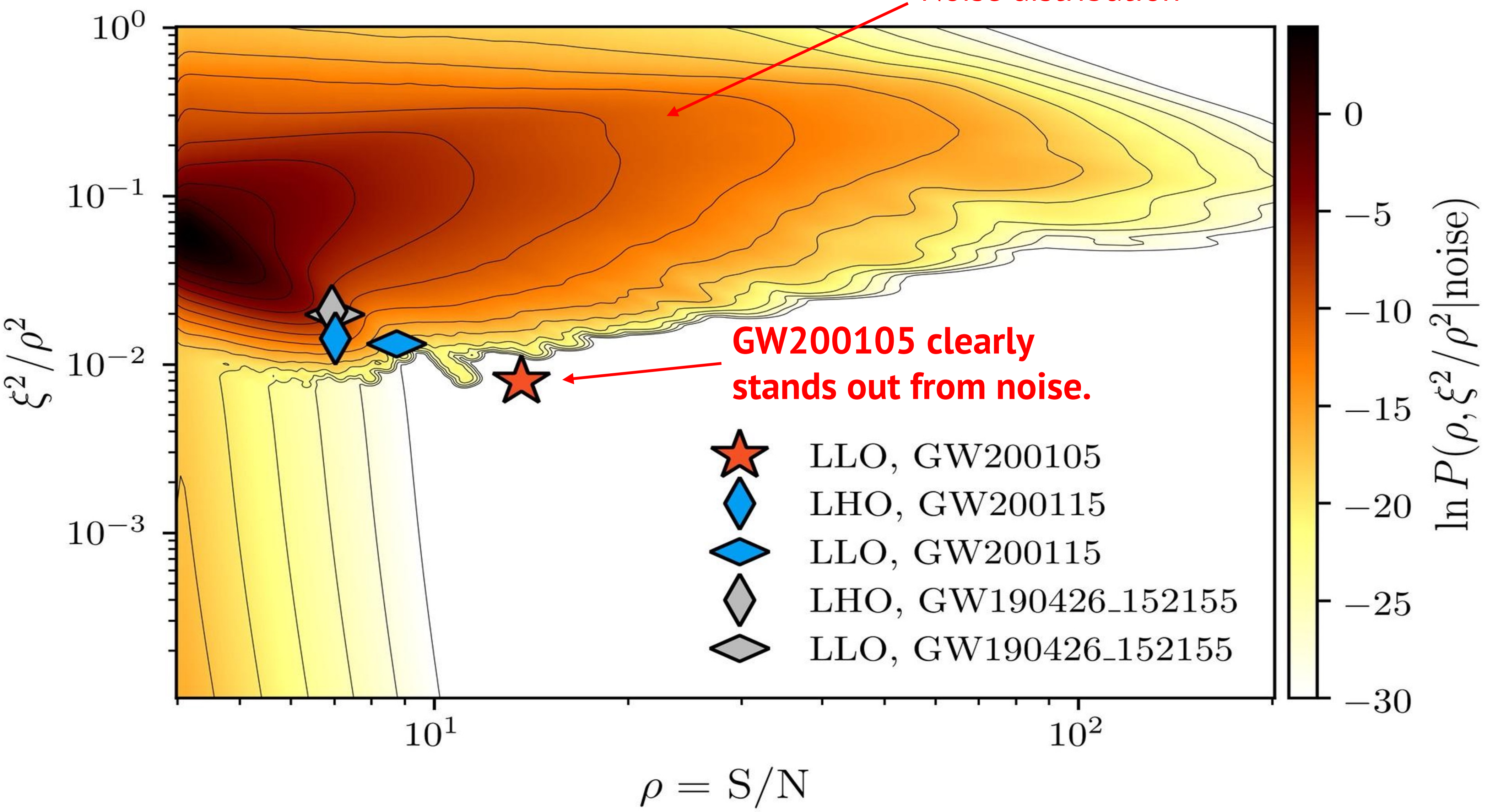
Plausible neutron stars

Modest support for GW200115's primary being in lower mass gap,

$$P(3M_\odot \le m_1 \le 5M_\odot) = 30\%.$$

GW200105: single-detector event

Noise distribution



Waveform consistency

GW200105 clearly stands out from noise.

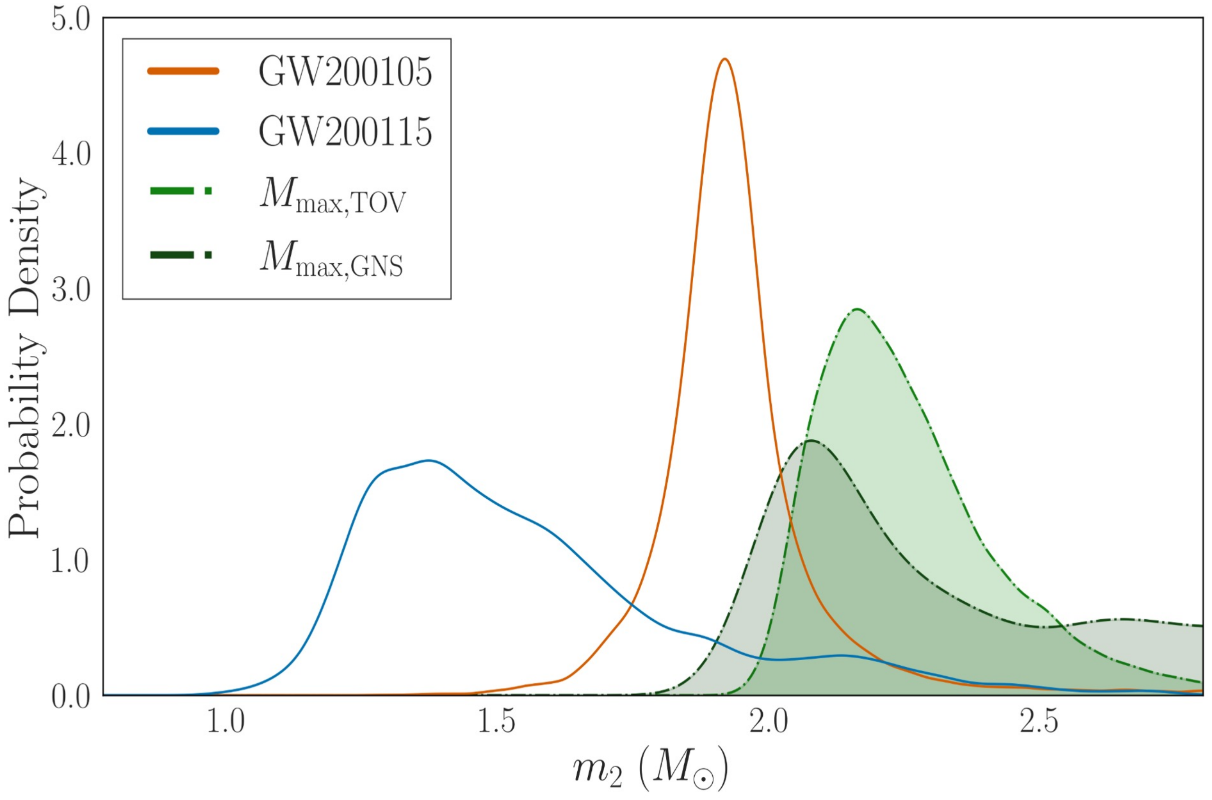
Signal-to-noise ratio

Are the secondary objects neutron stars?

Comparison with the maximum mass of a neutron star (NS)

- $M_{\mathrm{max,TOV}}$ Equation of state inferred from radio, GW and X-ray observations (Landry, Essick & Chatziioannou 2020)
- $M_{\mathrm{max,GNS}}$ Fit to Galactic NS population (Farr & Chatziioannou 2020)
- $M_{\mathrm{max}}(\mathrm{spin})$ Allows for potentially large NS spins (not shown)

$p(m_2 < M_{\mathrm{max}}) \sim 95\%$ for either case.



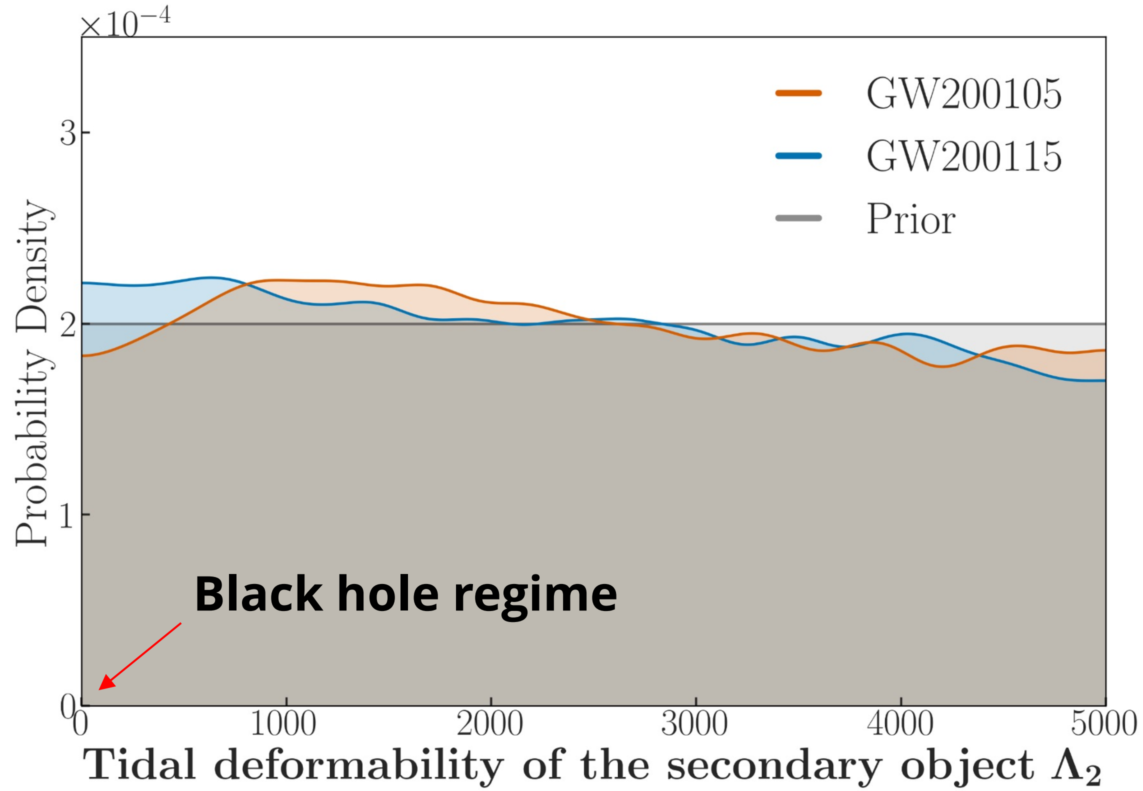
Estimated masses of secondary objects in comparison with the maximum NS mass

Are the secondary objects neutron stars?

No detections of matter signatures.

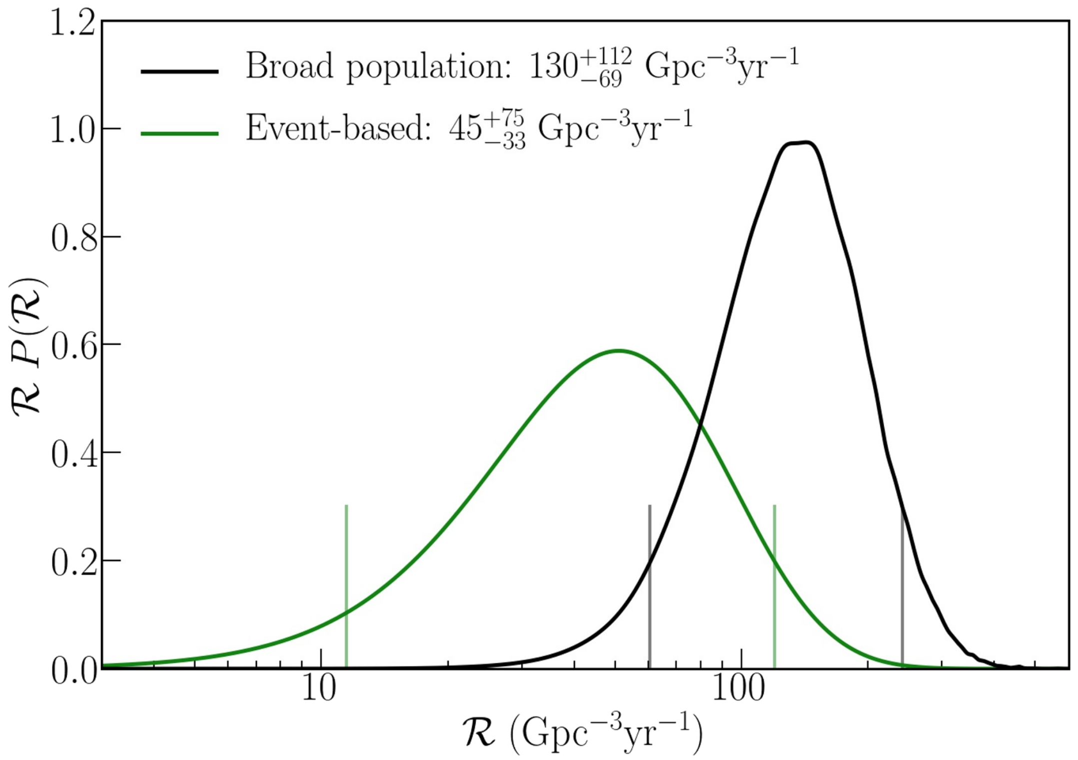
- No associated EM counterparts
- No information on tidal deformability from GWs (See the right figure)

→Do not exclude light black holes (e.g. primordial black holes).



Estimated tidal deformabilities of secondary objects

Merger rate



Event-based rate

- Assumes 1 count each from GW200105/GW200115-like population
- **12-120 Gpc^{-3}yr^{-1}**

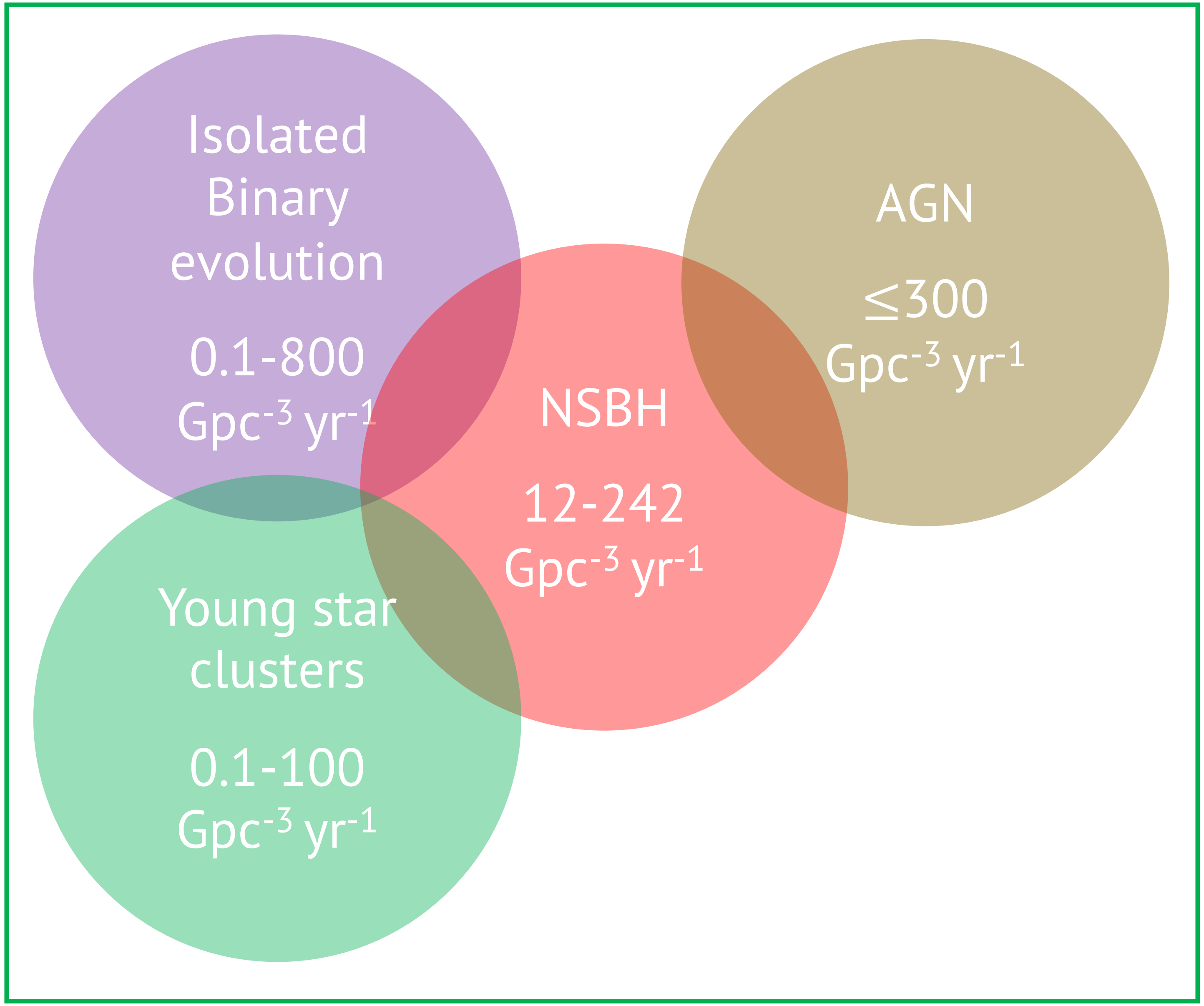
Broad population rate

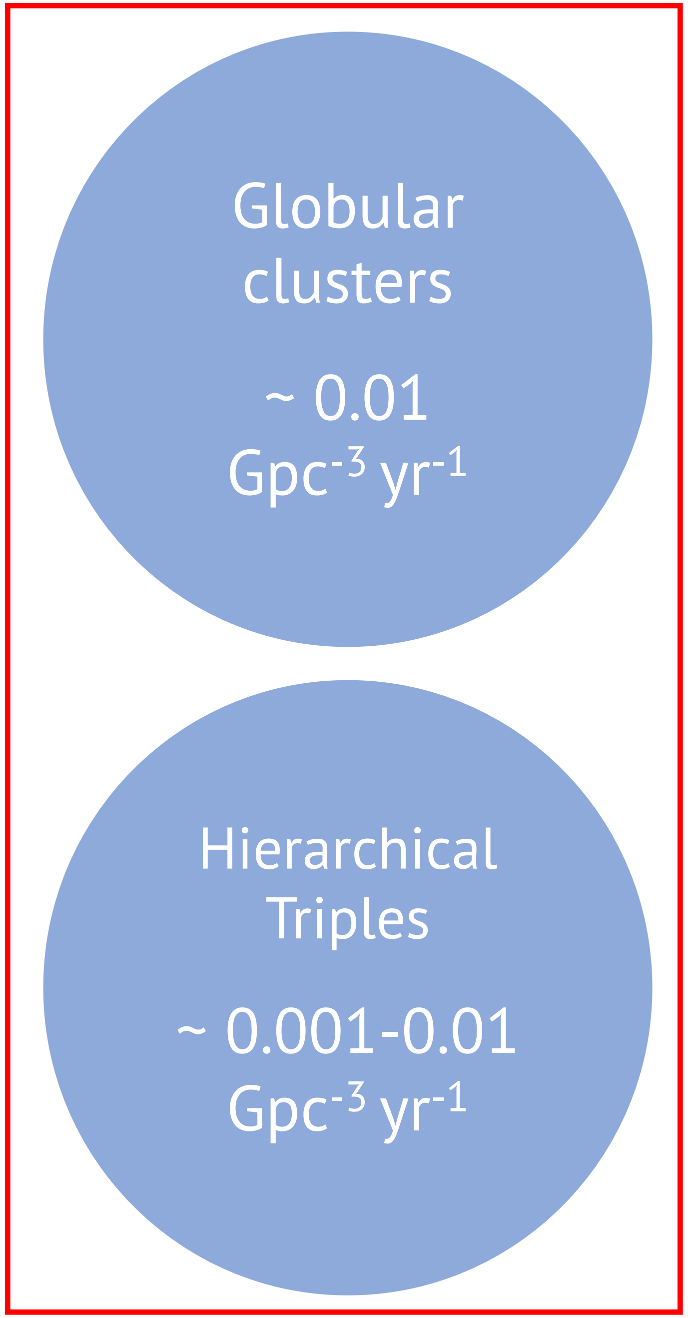
- Includes all foreground triggers in NSBH regime ($m_1 \in [2.5, 40] M_\odot$ and $m_2 \in [1, 3] M_\odot$)
- **61-242 Gpc^{-3}yr^{-1}**

All merger rates now empirically measured:

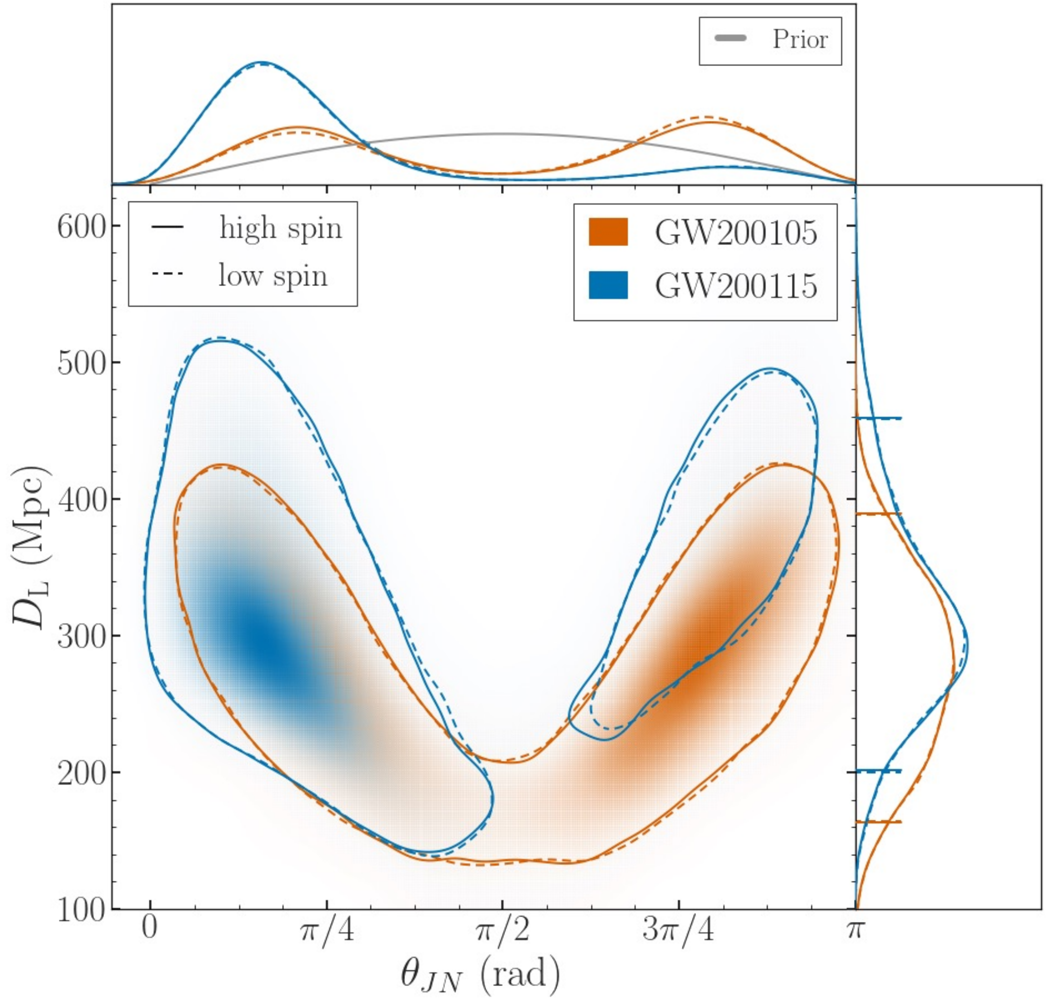
NSBH	BNS	BBH
12-242 Gpc^{-3}yr^{-1}	80-810 Gpc^{-3}yr^{-1}	15-38 Gpc^{-3}yr^{-1}

Formation scenario





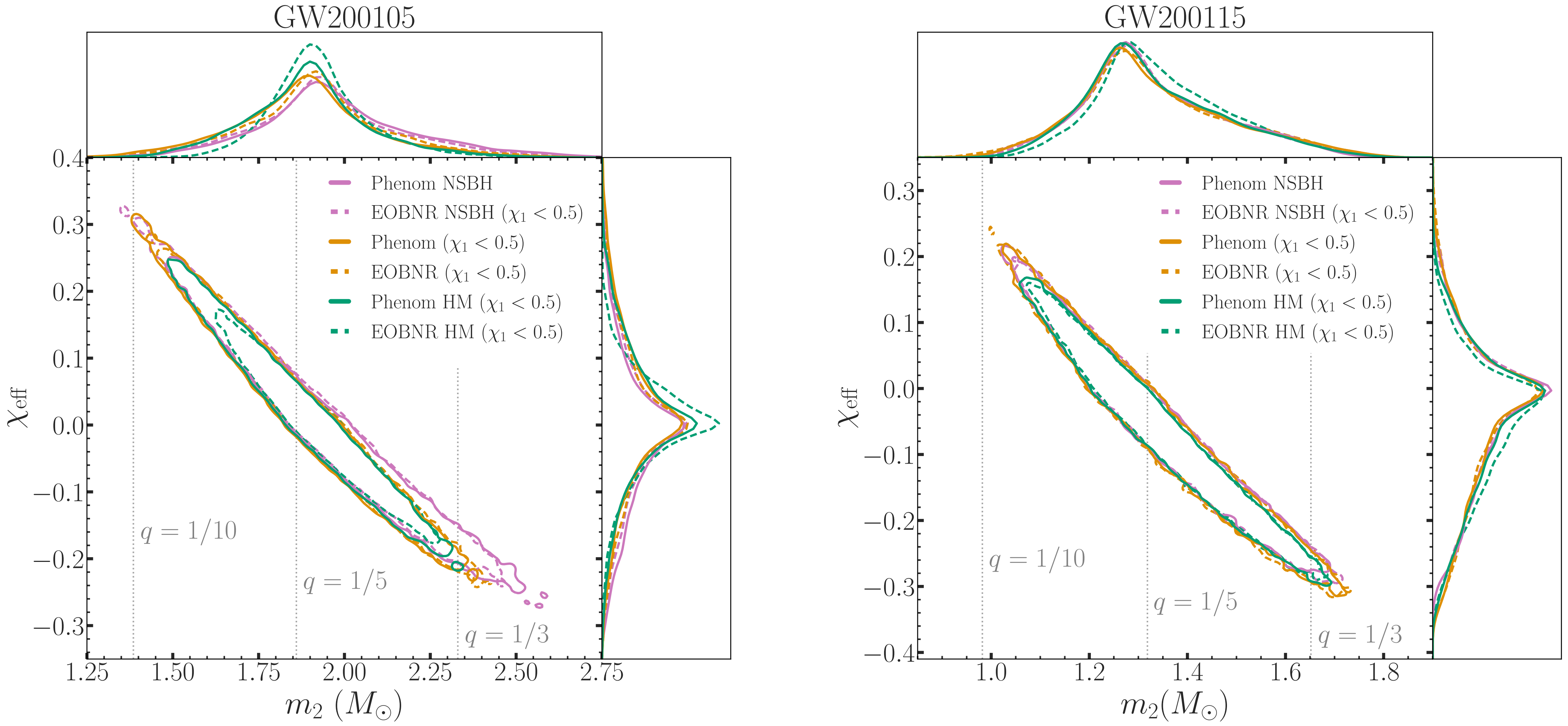
Distance-inclination



- Distance
  GW200105: 280^{+110}_{-110} Mpc
  GW200115: 300^{+150}_{-100} Mpc
  (c.f. 40 Mpc for GW170817)

- Inclination
  Both events disfavor $\theta_{JN} \sim 90°$, suppressing higher-order moments.

Waveform systematics



Miscellaneous properties

- Remnant objects
  Mass

$$M_{\mathrm{f}} = \begin{cases} 10.4^{+2.7}_{-2.0}\ M_{\odot} & \text{(GW200105)} \\ 7.8^{+1.4}_{-1.6}\ M_{\odot} & \text{(GW200115)} \end{cases}$$

  Spin

$$\chi_{\mathrm{f}} = \begin{cases} 0.43^{+0.04}_{-0.03} & \text{(GW200105)} \\ 0.38^{+0.04}_{-0.02} & \text{(GW200115)} \end{cases}$$

- Test of general relativity

  Less stringent constraints than the current ones due to the weak signals.

- Higher-order modes

  Inconclusive

- Precession effect

  Inconclusive

- Lensing scenario unlikely for GW200105 and GW200115, as masses do not overlap.

Masses

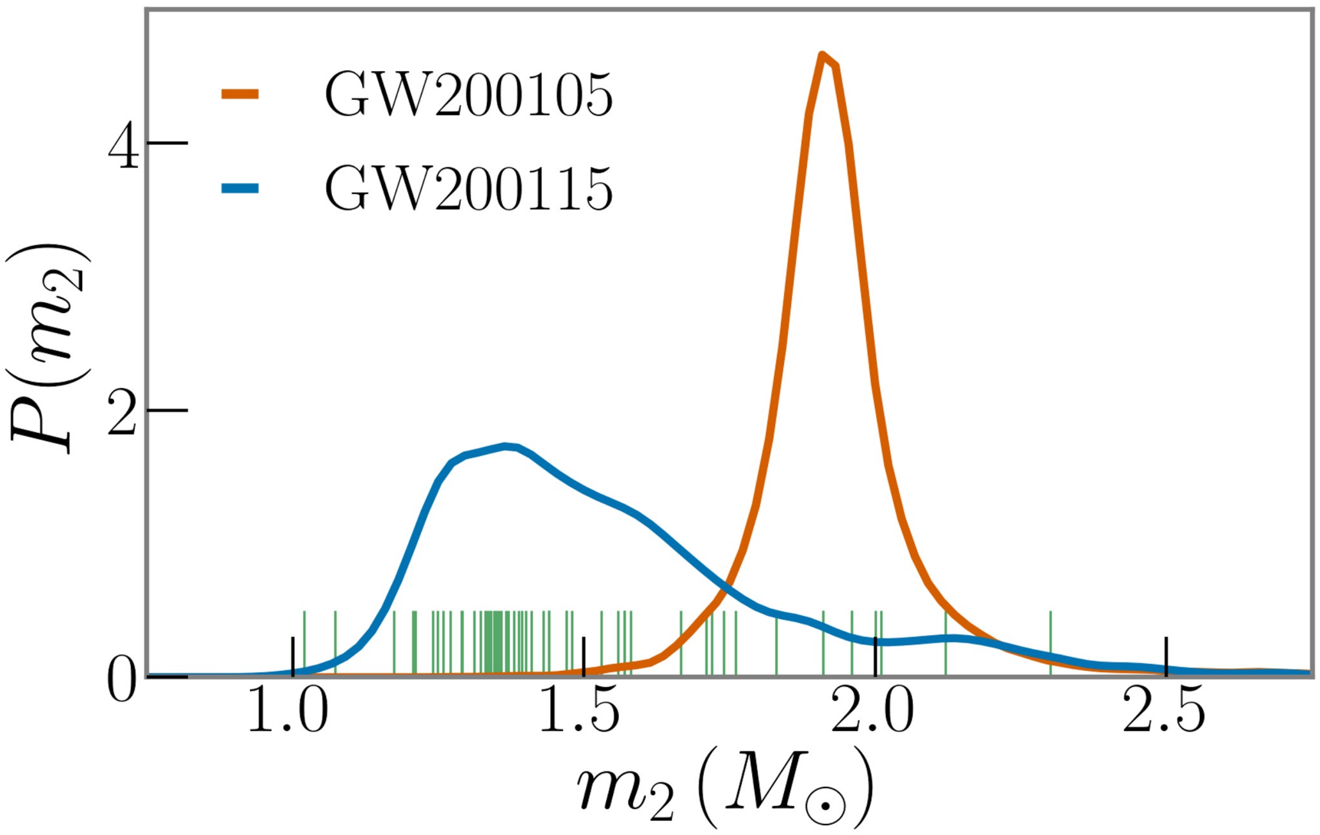
Neutron star masses

Consistent with Galactic NS population from EM observations

Black hole masses

GW200115 BH may be in the lower mass gap

- $P(3M_\odot \leq m_1 \leq 5M_\odot) = 30\%$
- Correlated with negatively-aligned primary spin



Galactic NS masses from Alsing et al. 2018, MNRAS **478**, no.1, 1377-1391

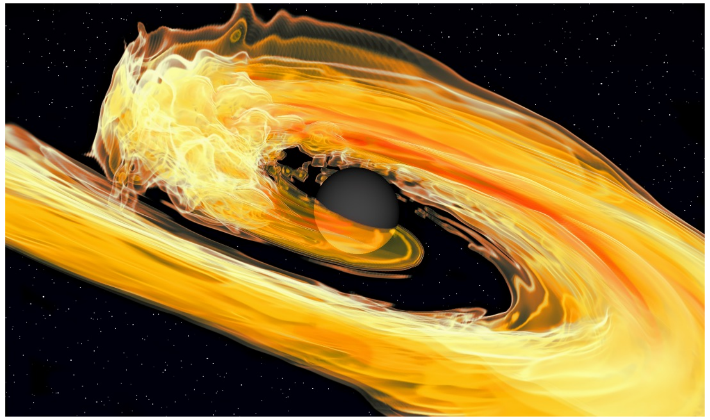
Electromagnetic observations

No significant detections of electromagnetic counterparts for both events.

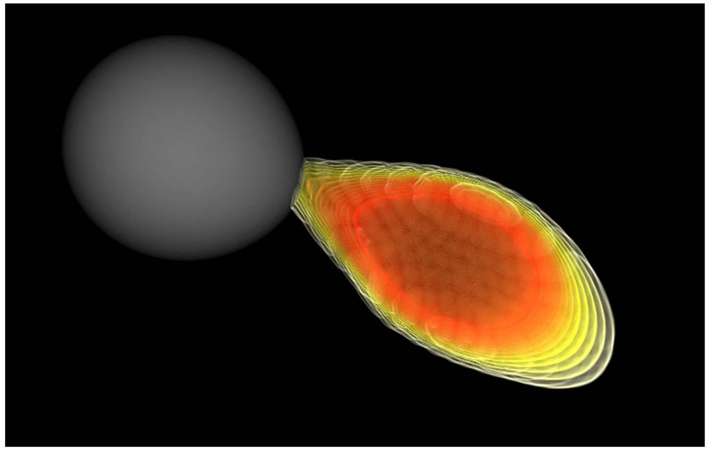
e.g. S. Anand et al., Nature Astron. **5**, 46 (2021).

This is consistent with

- **No** tidal disruption expected due to highly asymmetric masses (and negative spins for GW200115) ✗



- The large distances (~7 times more distant than GW170817) and large uncertainties of their sky localization ✓



Summary

- Observation of GW inspirals consistent with neutron star−black hole binaries:

  GW200105: $9M_\odot + 1.9M_\odot$ (single-detector detection)
  GW200115: $6M_\odot + 1.5M_\odot$ (coincident detection)

- Estimated masses *suggest* they are neutron star−black hole binaries.
  - Secondary masses smaller than the maximum mass of a neutron star.
  - However, no detections of matter signatures in GW or EM observations.

- Estimated merger rate of $\sim 100\ \mathrm{Gpc^{-3}yr^{-1}}$ consistent with several formation scenarios.

Stay tuned for more O3b results!

Tidal deformability

The combination enters the leading tidal effect:

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}.$$

For NSBH ($\Lambda_1 = 0$),

$$\tilde{\Lambda} = \frac{16}{13}\frac{12 + q}{(1 + q)^5}q^4\Lambda_2, \qquad \left(q \equiv \frac{m_2}{m_1}\right)$$

which becomes vanishing for highly asymmetric masses ($q \to 0$).

Expected stochastic GW background

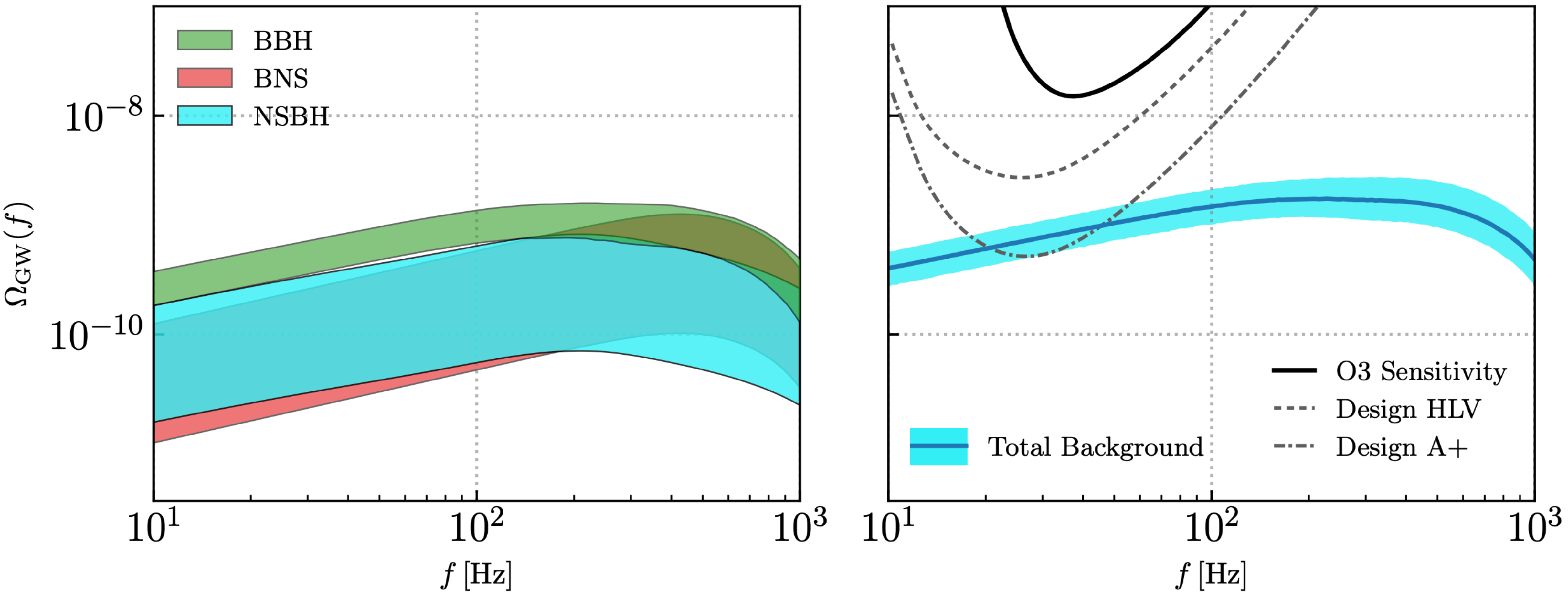


Figure: Expected stochastic gravitational-wave background (Taken from R. Abbott et al., arXiv: 2111.03634).