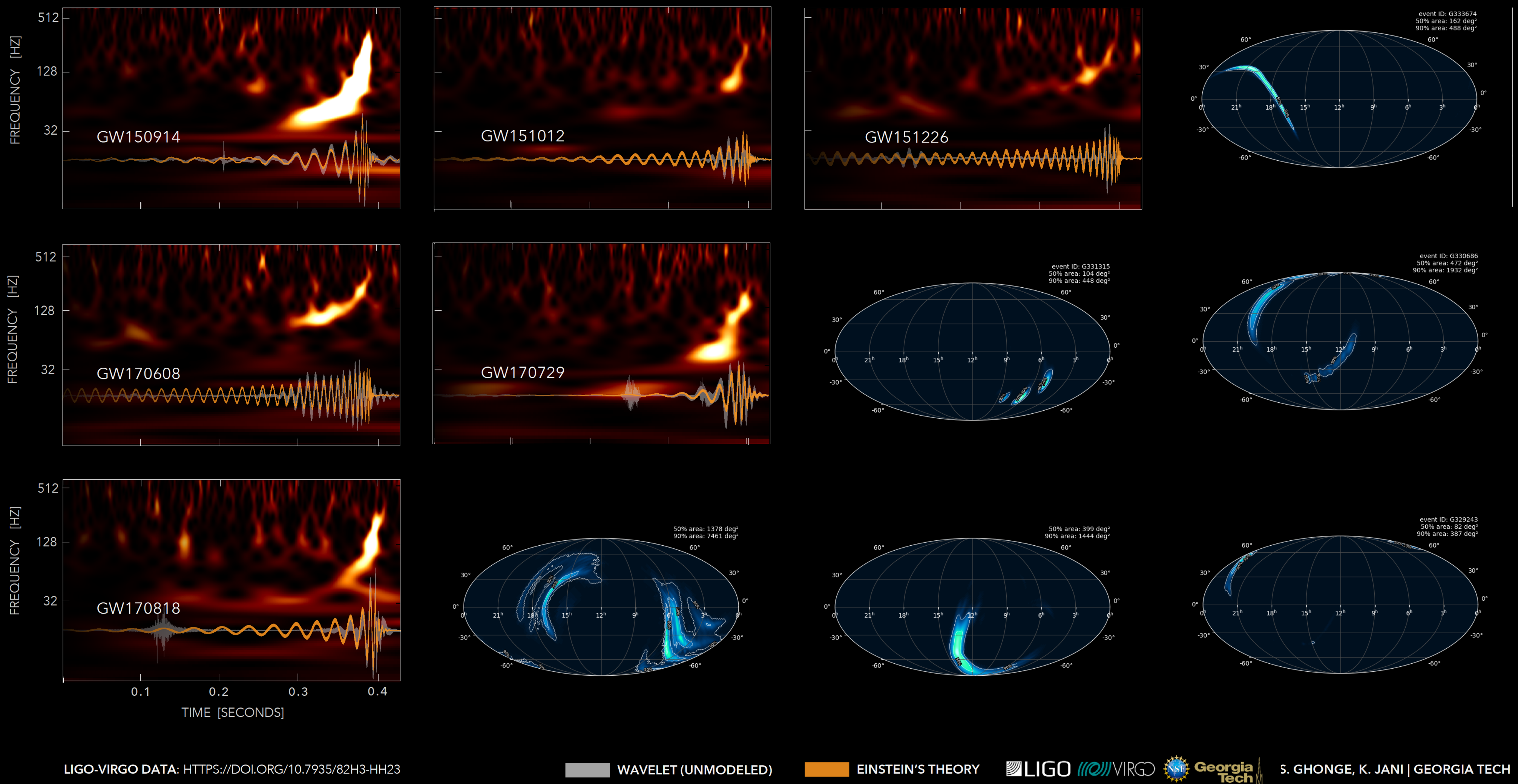
LIGO-Virgo's 3rd Observing Run (so far)



Ben Farr

LIGO-G2000092

Status of Ground-Based GW Astronomy

O3 began on April 1, 2019.

Mid-run commissioning break started Oct 2019 at 15:00:00 UTC.

- Scattered light mitigation.
- Hanford squeezing improvements.
- Virgo power increased from 18W to 26W.

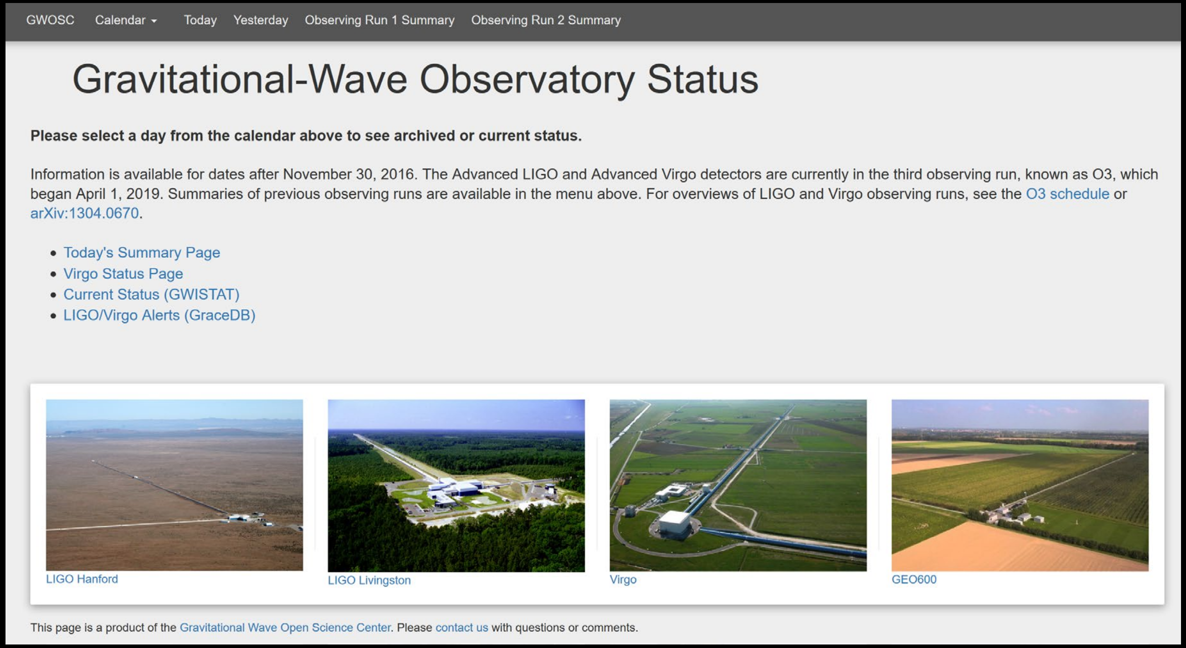
LIGO/Virgo/KAGRA Memorandum of Agreement signed Oct 4.

O3b began Nov 1 at 15:00:00 UTC.

Status of Ground-Based GW Astronomy

https://monitor.ligo.org/gwstatus

https://www.gw-openscience.org/detector_status/



https://gracedb.ligo.org/

GraceDB — Gravitational-Wave Candidate Event Database

http://chirp.sr.bham.ac.uk/

Chirp

GET IT ON Google Play

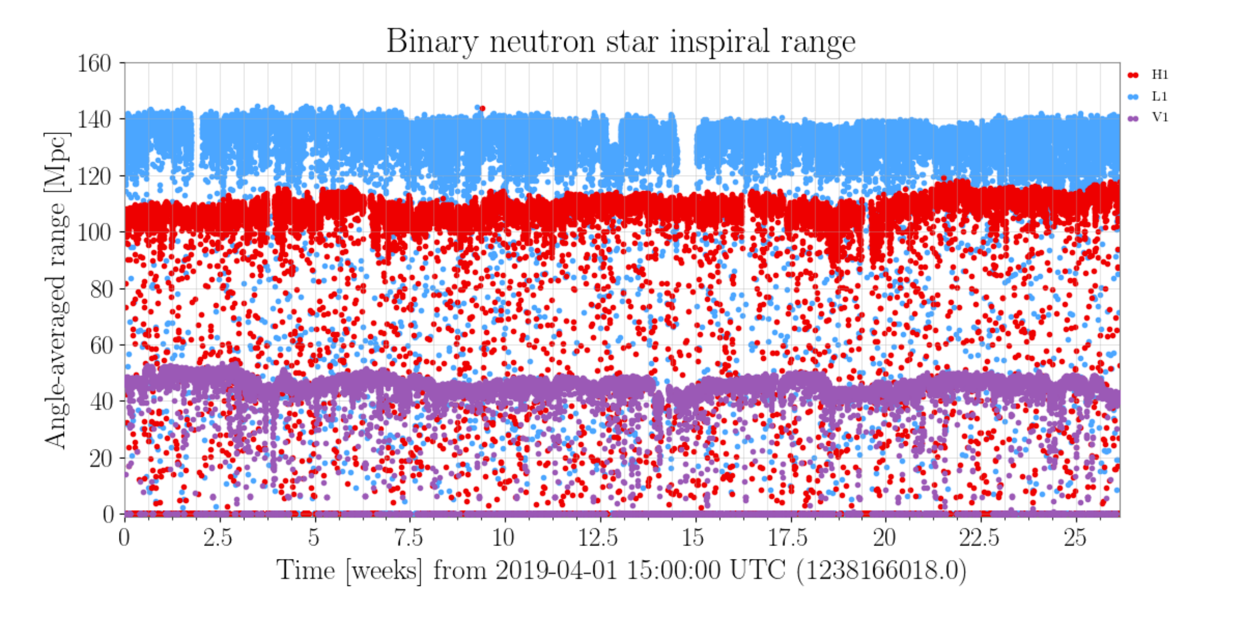
Download on the App Store

Gravitational Wave Events

Download on the App Store

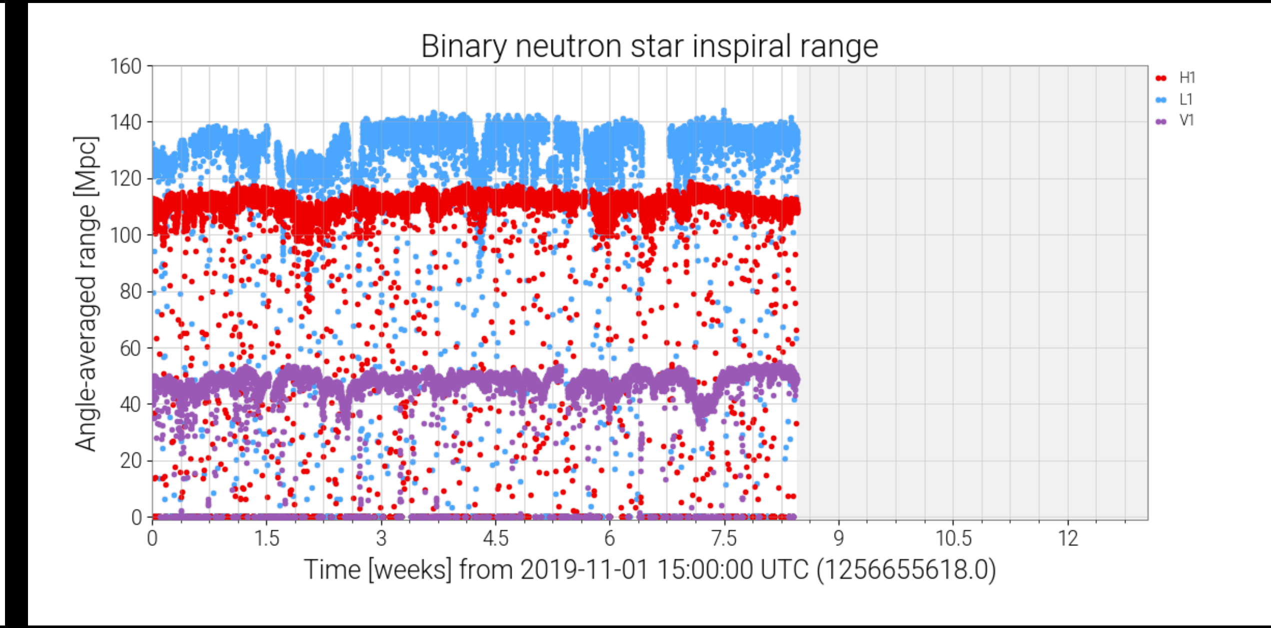
LIGO-Virgo's 3rd Observation Run

O3a



April 1 – October 1, 2019

O3b

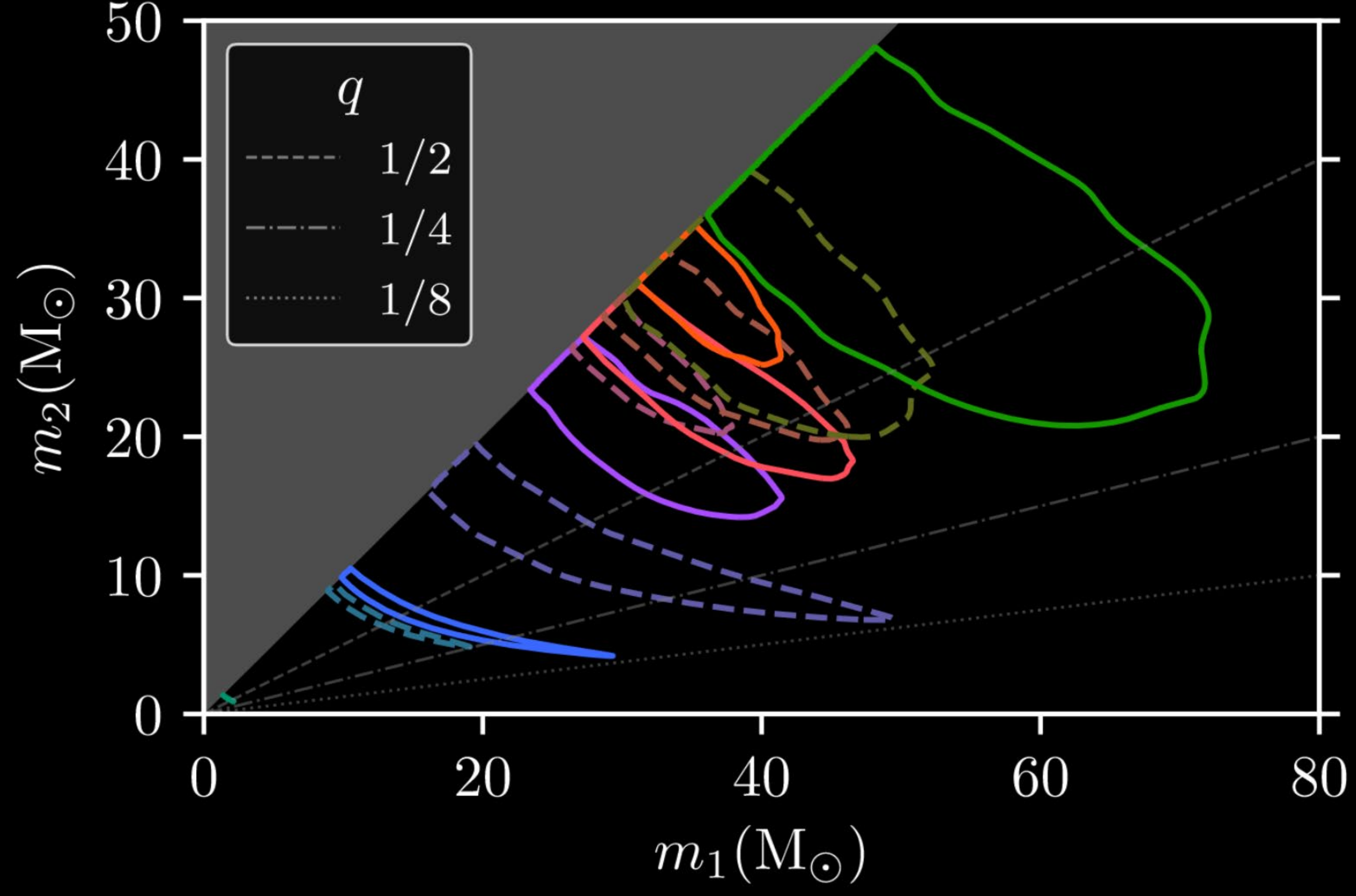


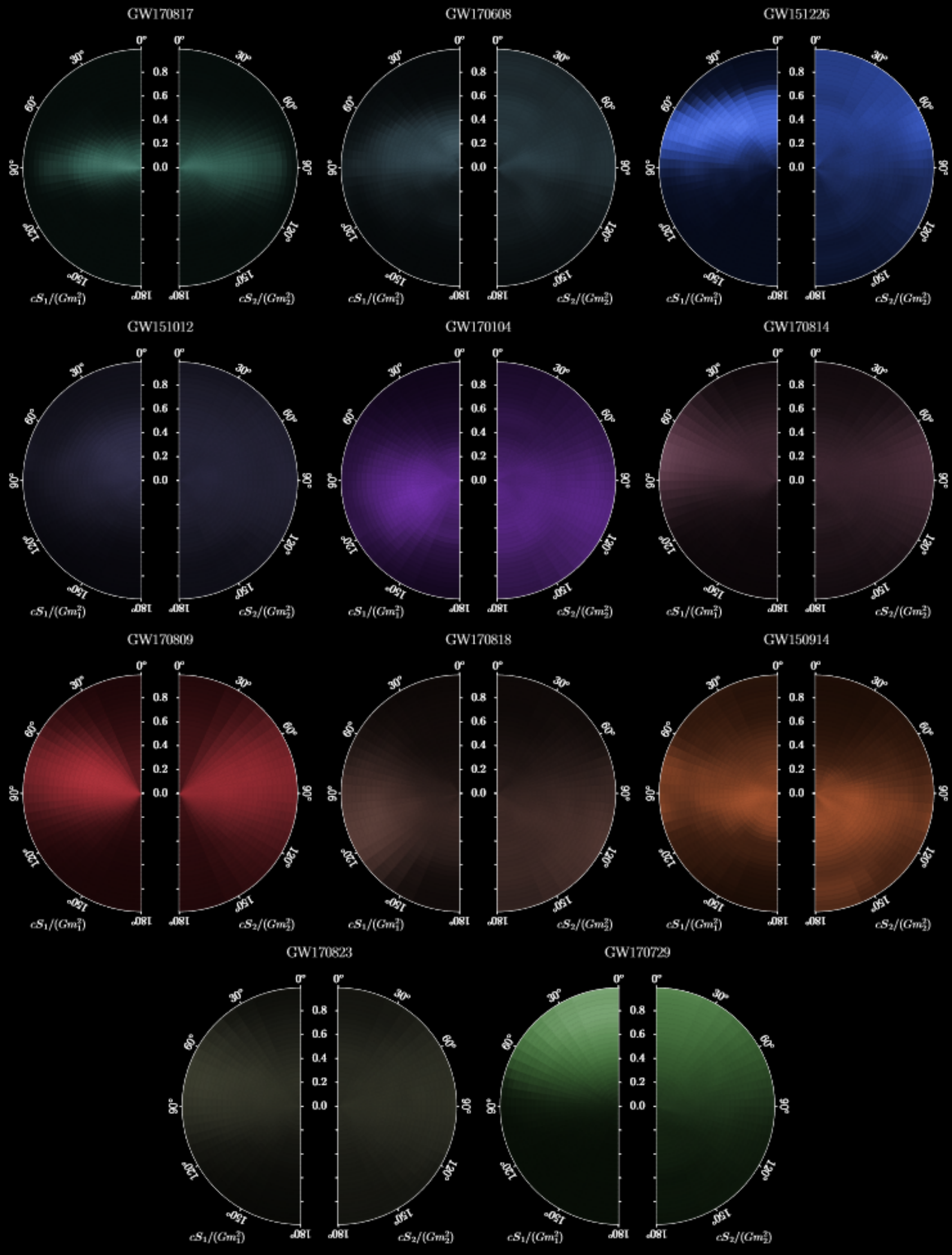
November 1, 2019 – April 2020

https://www.gw-openscience.org/detector_status/

GWTC-1

What we've learned so far

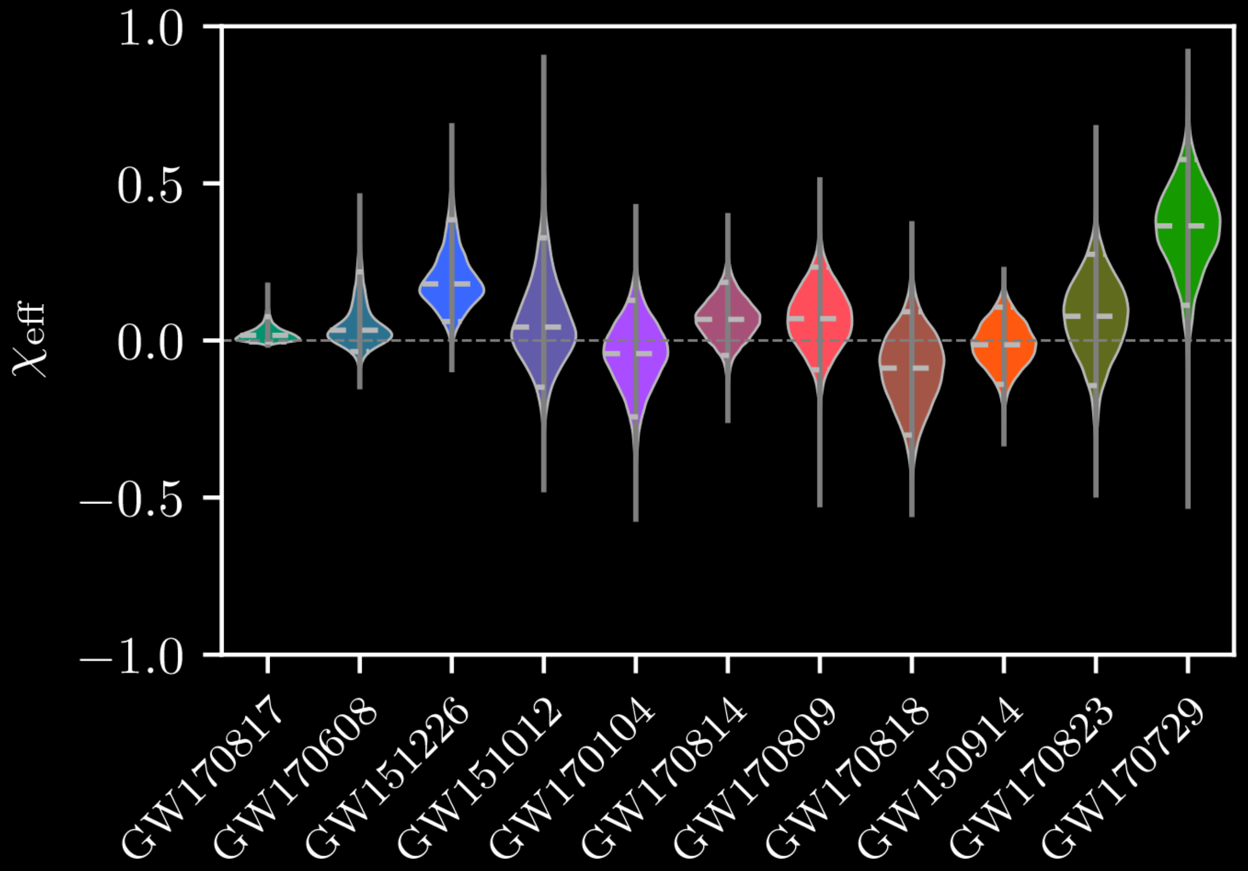




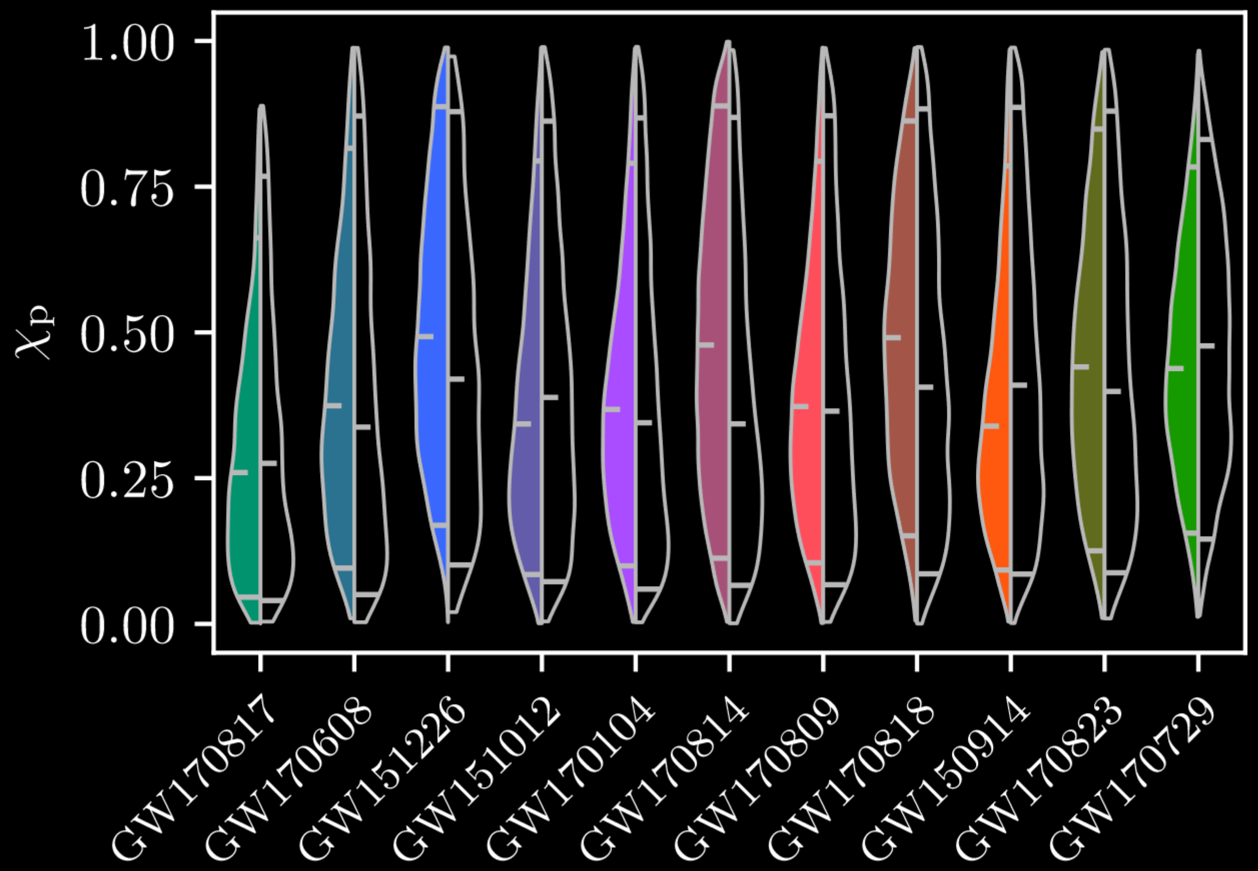
Abbott *et al* 2018 **arXiv:1811.12907 (GWTC-1)**

What we've learned so far

$$\chi_{\text{eff}} = \frac{(m_1\vec{s}_1 + m_2\vec{s}_2)\cdot\hat{L}_N}{m_1 + m_2}$$



$$\chi_{\text{p}} = \frac{1}{B_1 m_1^2}\max(B_1 s_{1\perp}, B_2 s_{2\perp})$$



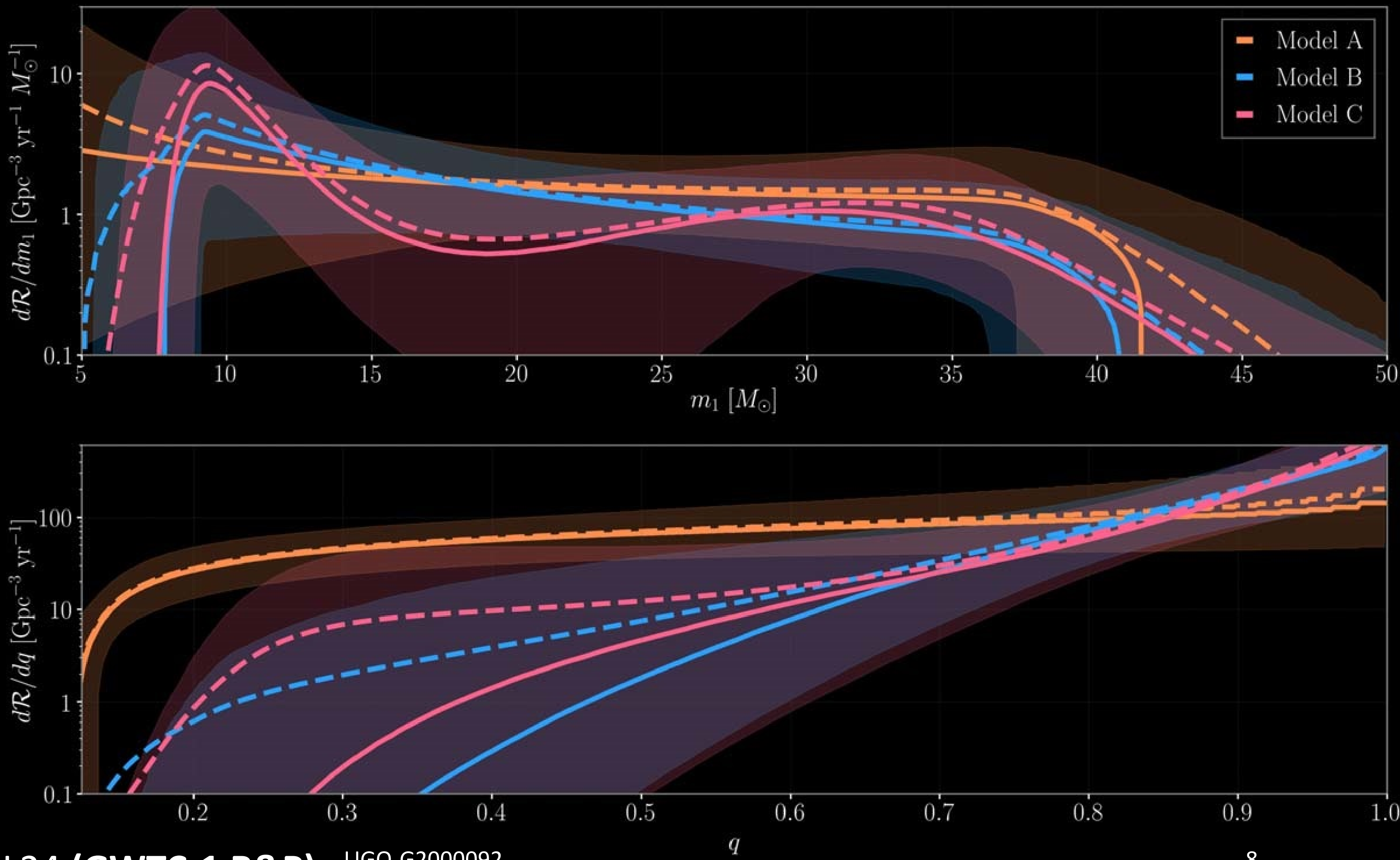
Abbott *et al* 2018 **arXiv:1811.12907 (GWTC-1)**

What we've learned about **BH masses** so far

Model A
- Max. BH mass
- Mass power-law index
- Min. BH mass = 5 $M_\odot$
- Mass ratio power-law index = 0

Model B
- Min. BH mass
- Max. BH mass
- Mass power-law index
- Mass ratio power-law index

Model C
- Model B
- Gaussian high-mass comp.
- Tapering at edges



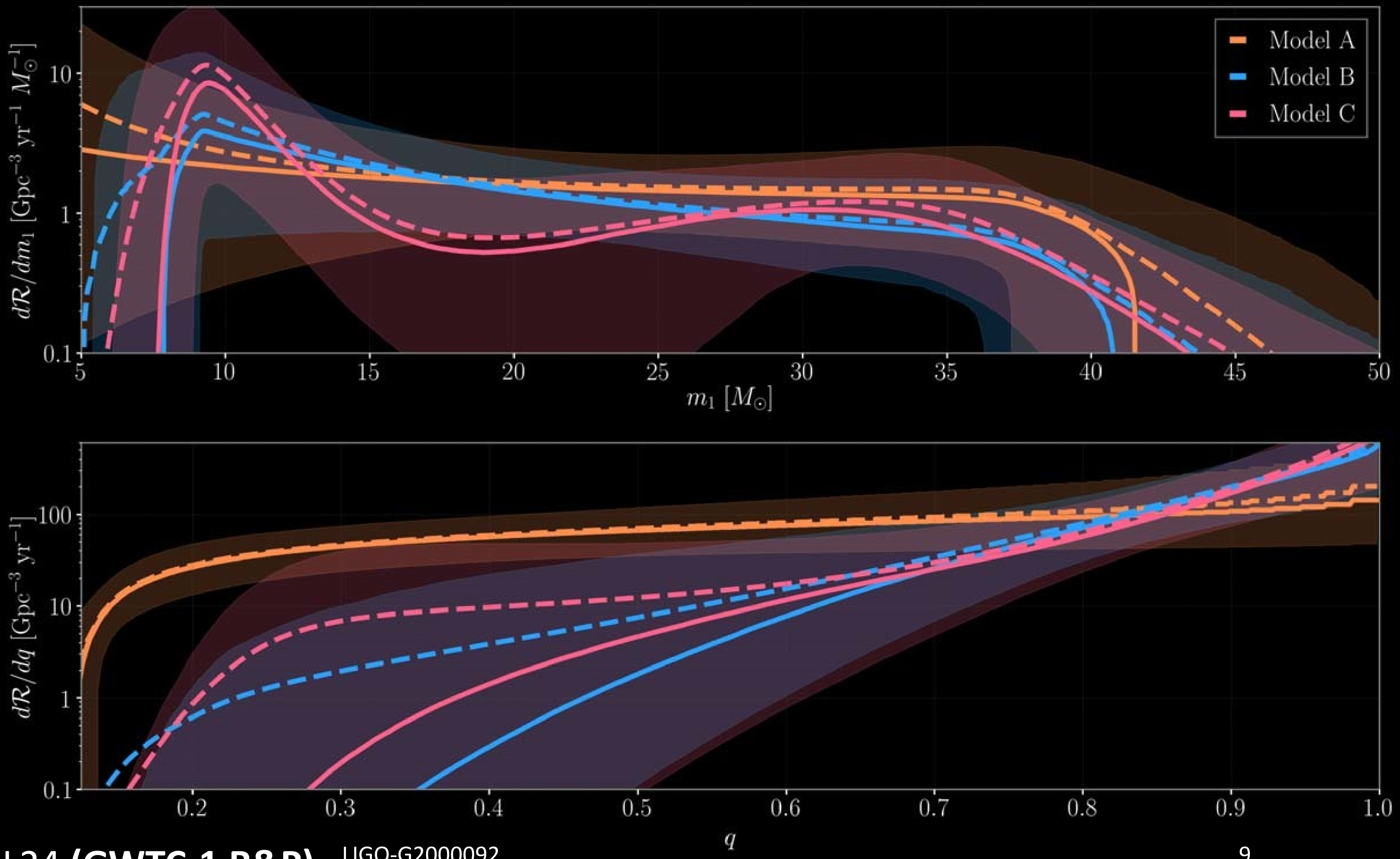
B. P. Abbott *et al* 2019 *ApJL* **882** L24 **(GWTC-1 R&P)**

What we've learned about **BH masses** so far

Model A
- Min. BH mass = 5 $M_\odot$
- Mass ratio power-law index = 0
- Mass power-law index $0.4^{+1.3}_{-1.9}$
- Max. BH mass $41.6^{+9.0}_{-4.5}$ $M_\odot$

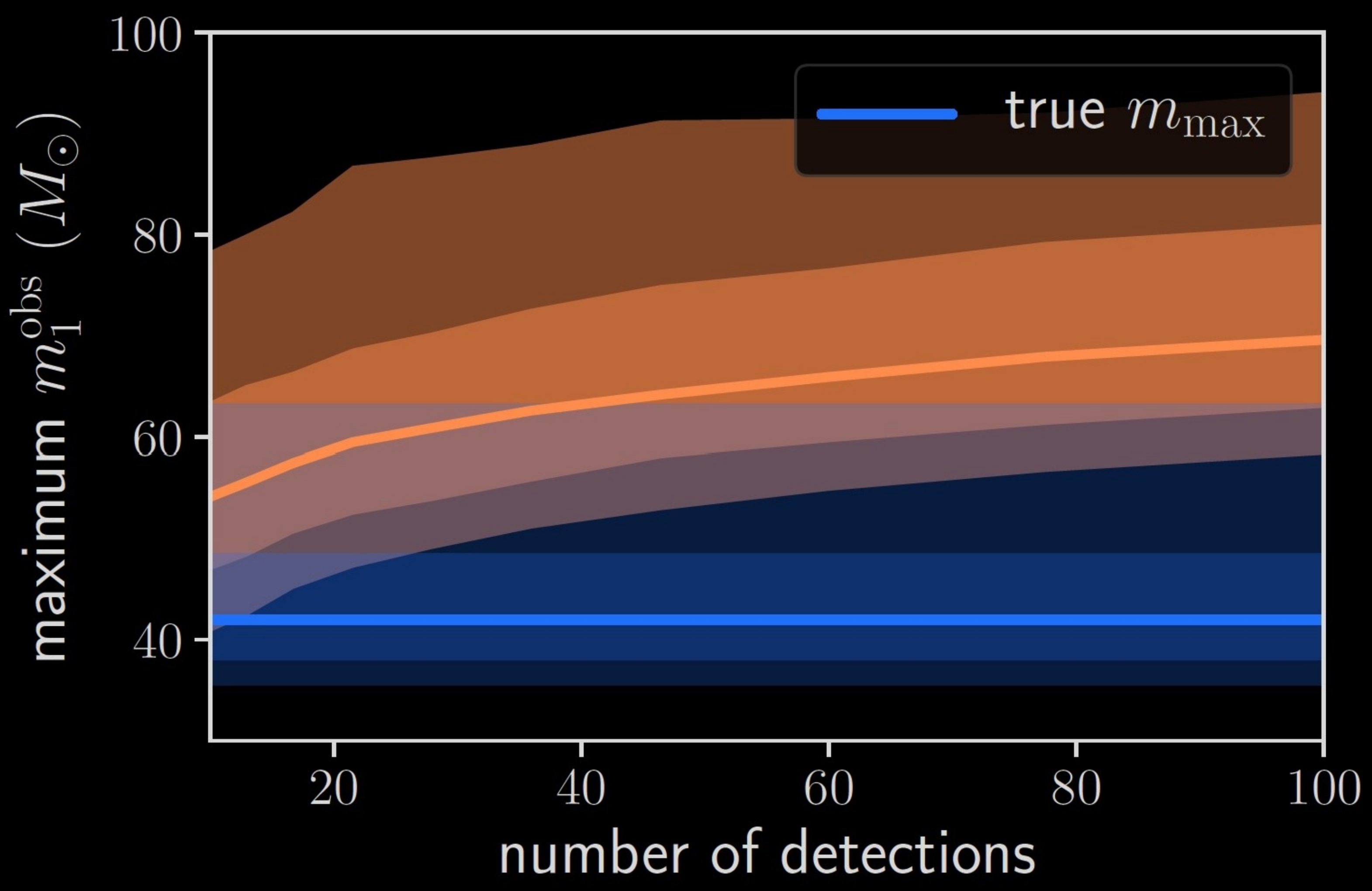
Model B
- Min. BH mass $7.9^{+1.2}_{-2.5}$ $M_\odot$
- Mass ratio power-law index = 0
- Mass power-law index $1.6^{+1.5}_{-1.7}$
- Max. BH mass $42.0^{+15.0}_{-5.7}$ $M_\odot$

Model C
- Gaussian comp. w/ mean $30.1^{+4.5}_{-6.9}$ $M_\odot$ and std. deviation $5.5^{+3.8}_{-4.0}$ $M_\odot$
- Power-law index $7.3^{+4.2}_{-4.6}$
- Cannot constrain max. mass



B. P. Abbott *et al* 2019 *ApJL* **882** L24 **(GWTC-1 R&P)**

A Word of Caution



Mass estimates must be done in the context of the population.

Ignoring population for large samples leads to apparent outliers.

E.g., For GW170729

Single-event analysis:

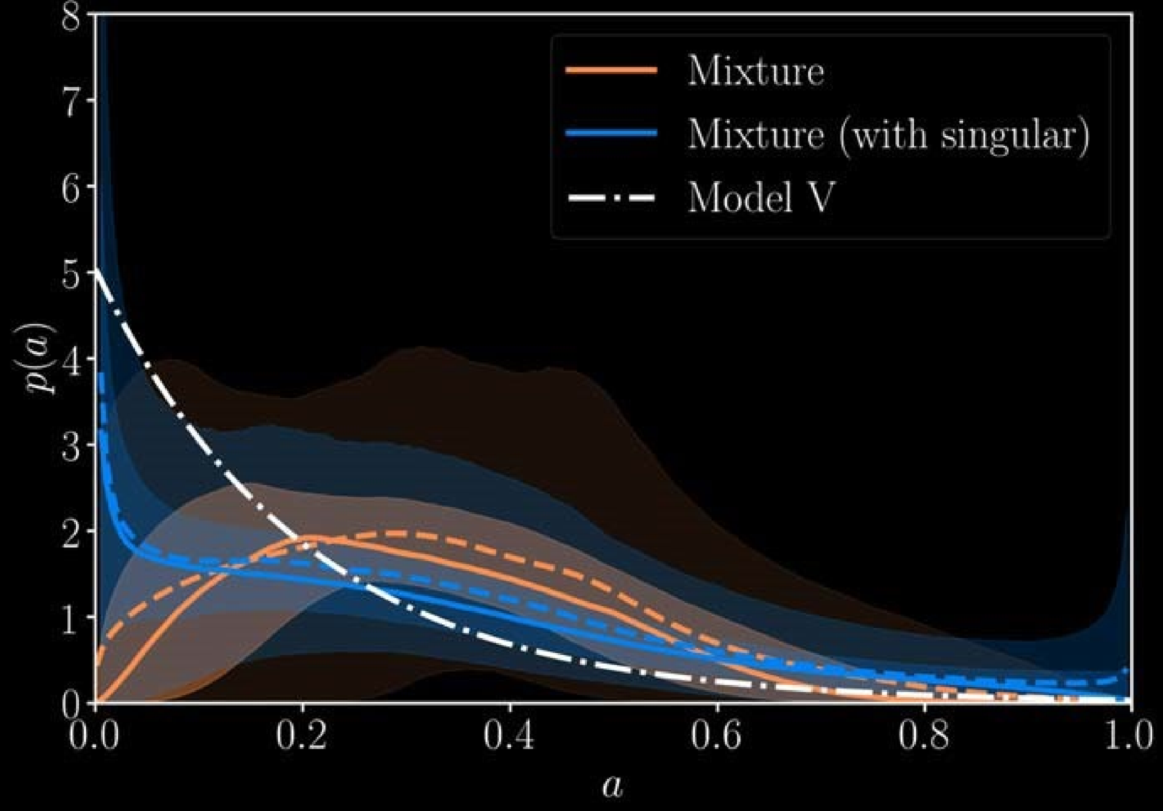
$$m_1 = 51.2^{+16.2}_{-11.0} M_\odot$$

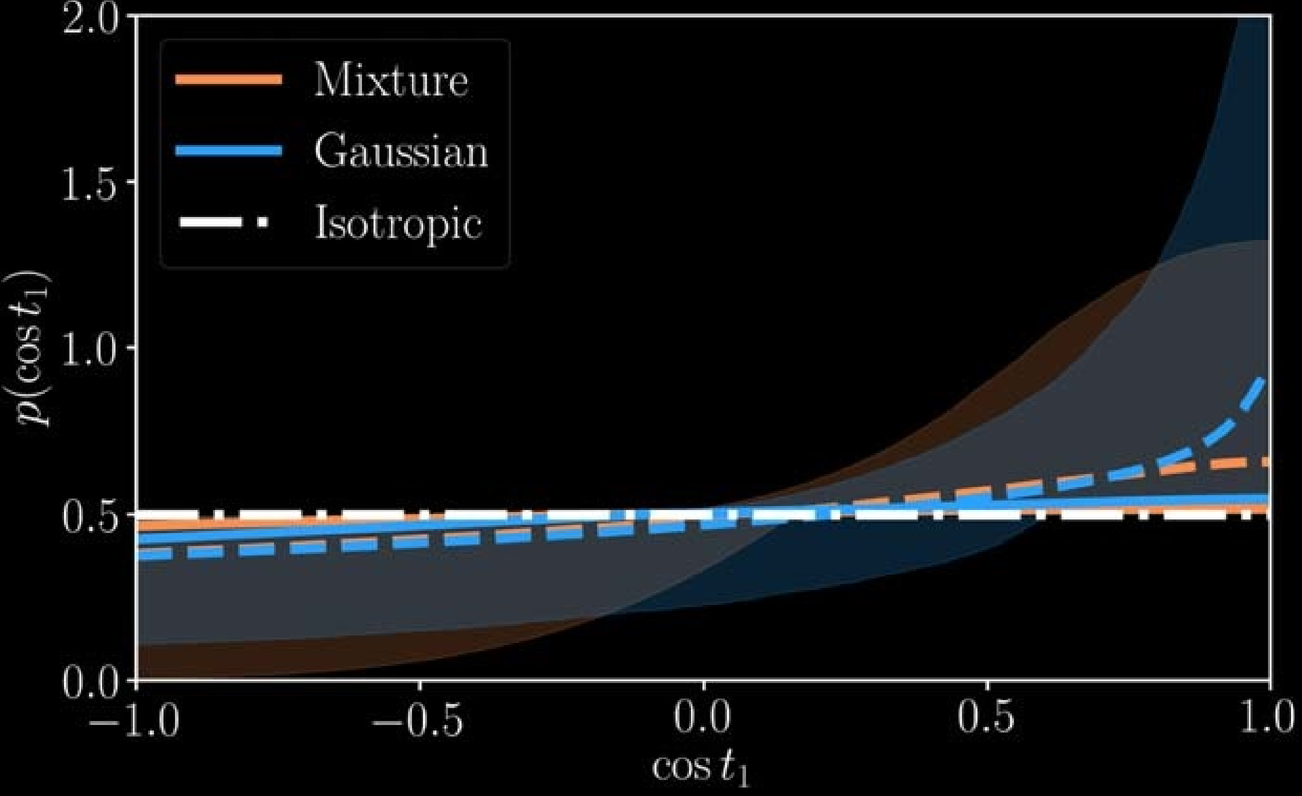
Hierarchical analysis:

$$m_1 = 38.9^{+7.3}_{-4.5} M_\odot$$

Fishbach *et al* 2019 **arXiv:1911.05882**

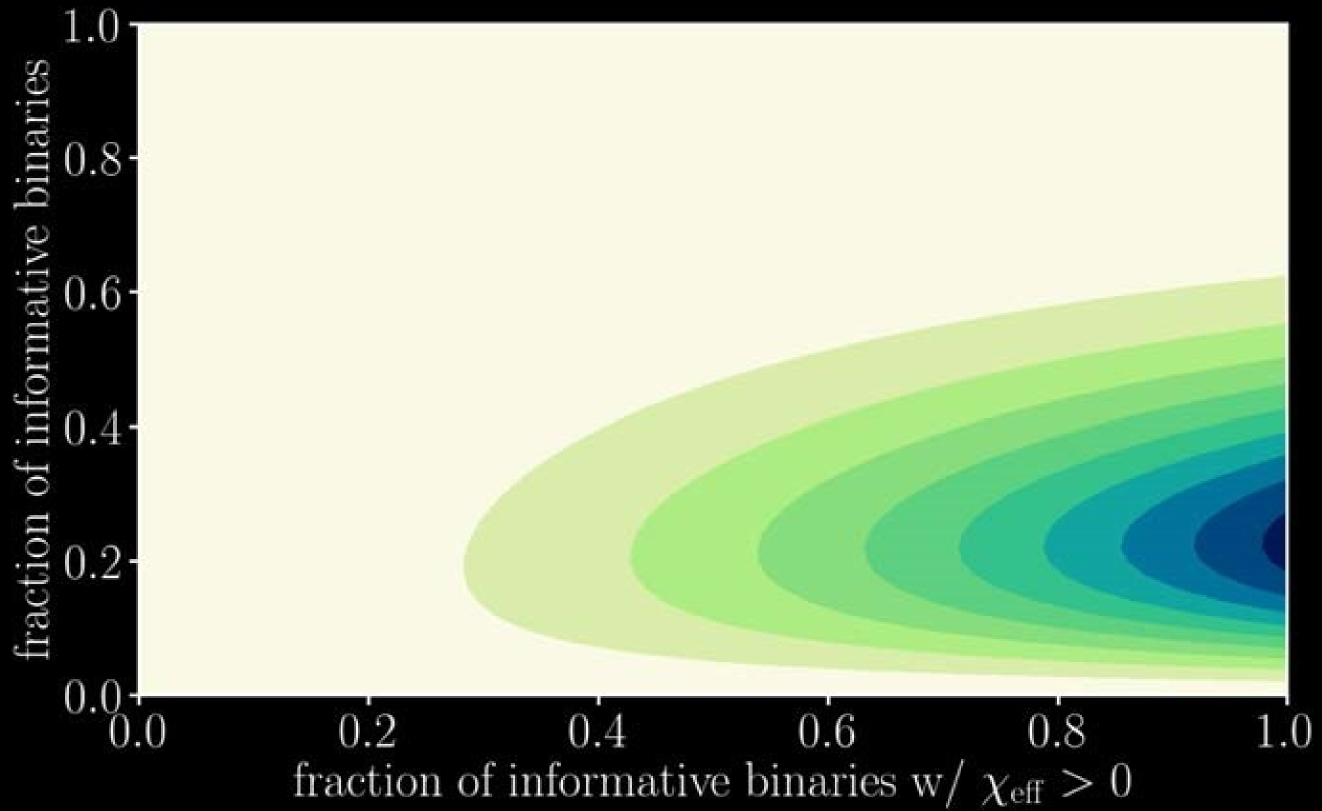
What we've learned about **BH spins** so far

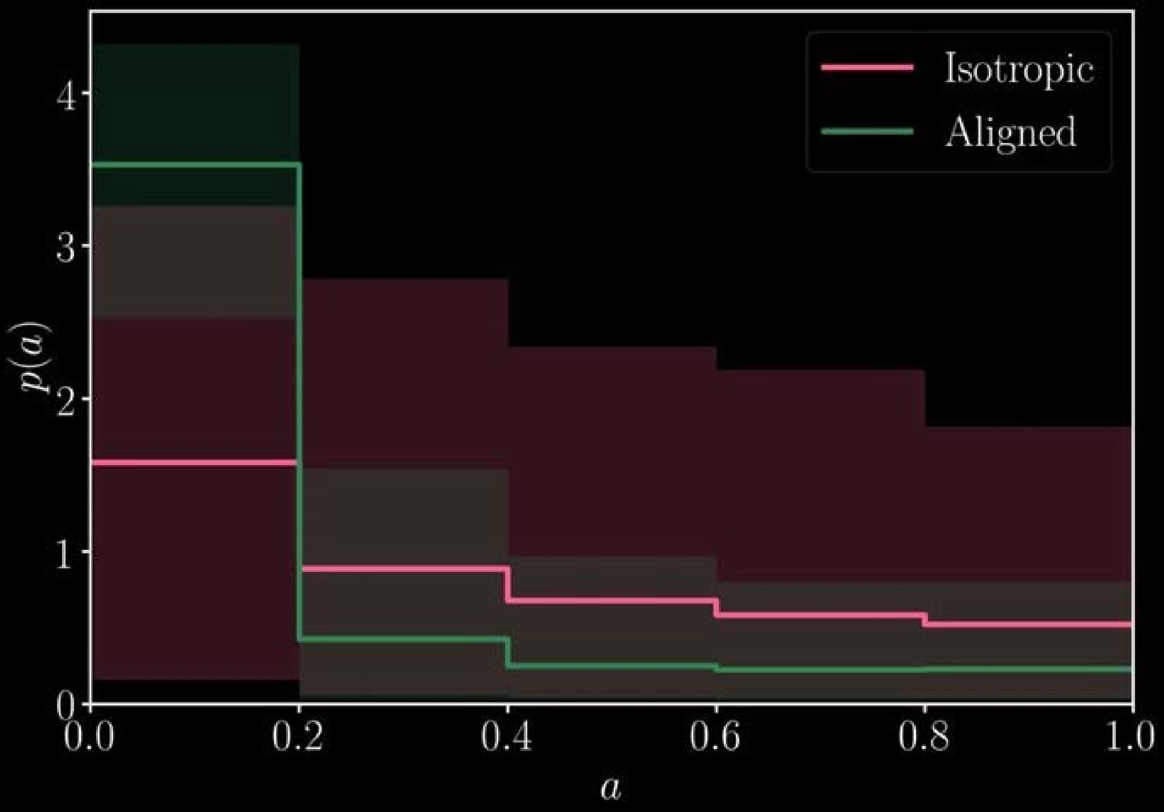




B. P. Abbott *et al* 2019 *ApJL* **882** L24 **(GWTC-1 R&P)**

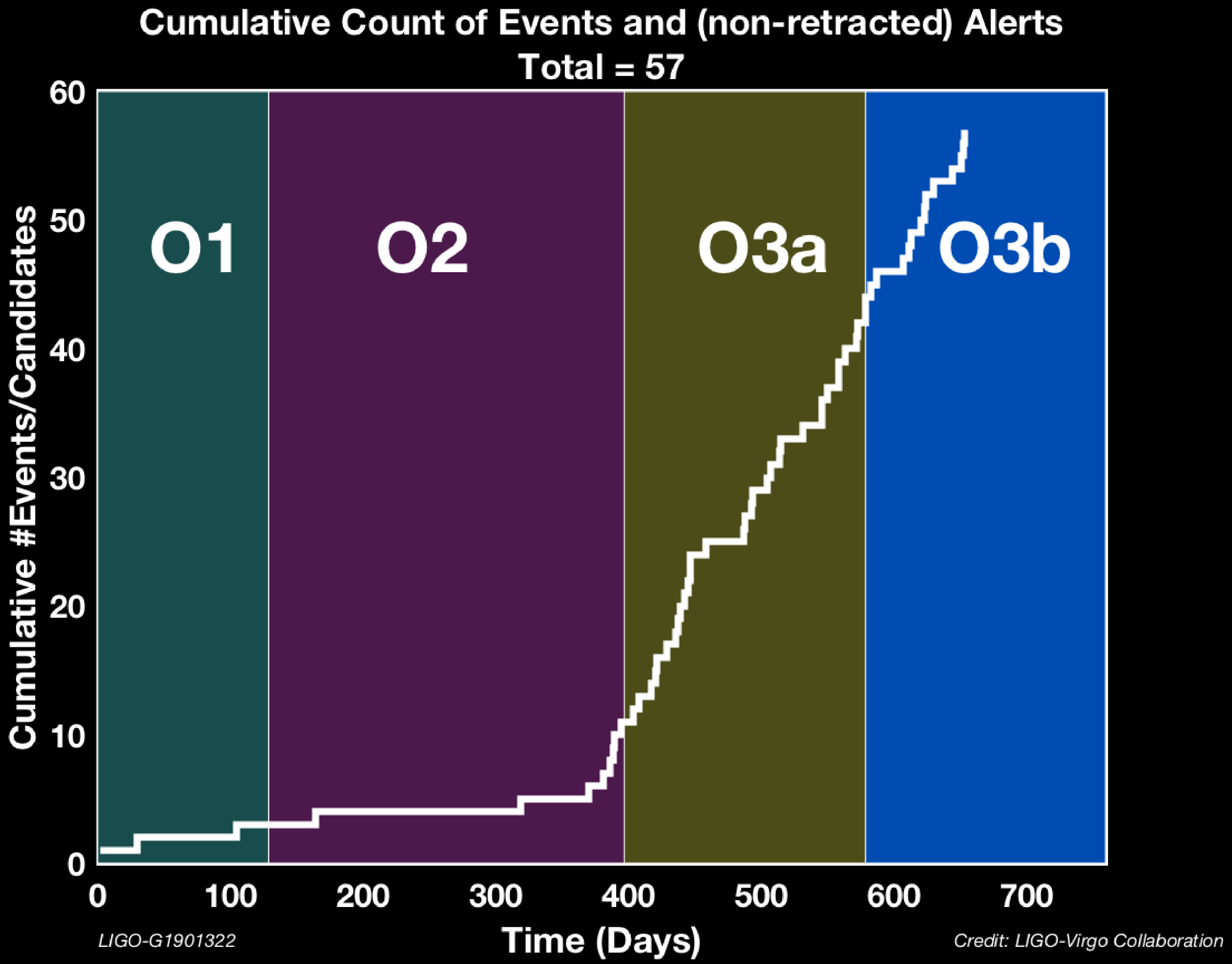
What we've learned about **BH spins** so far





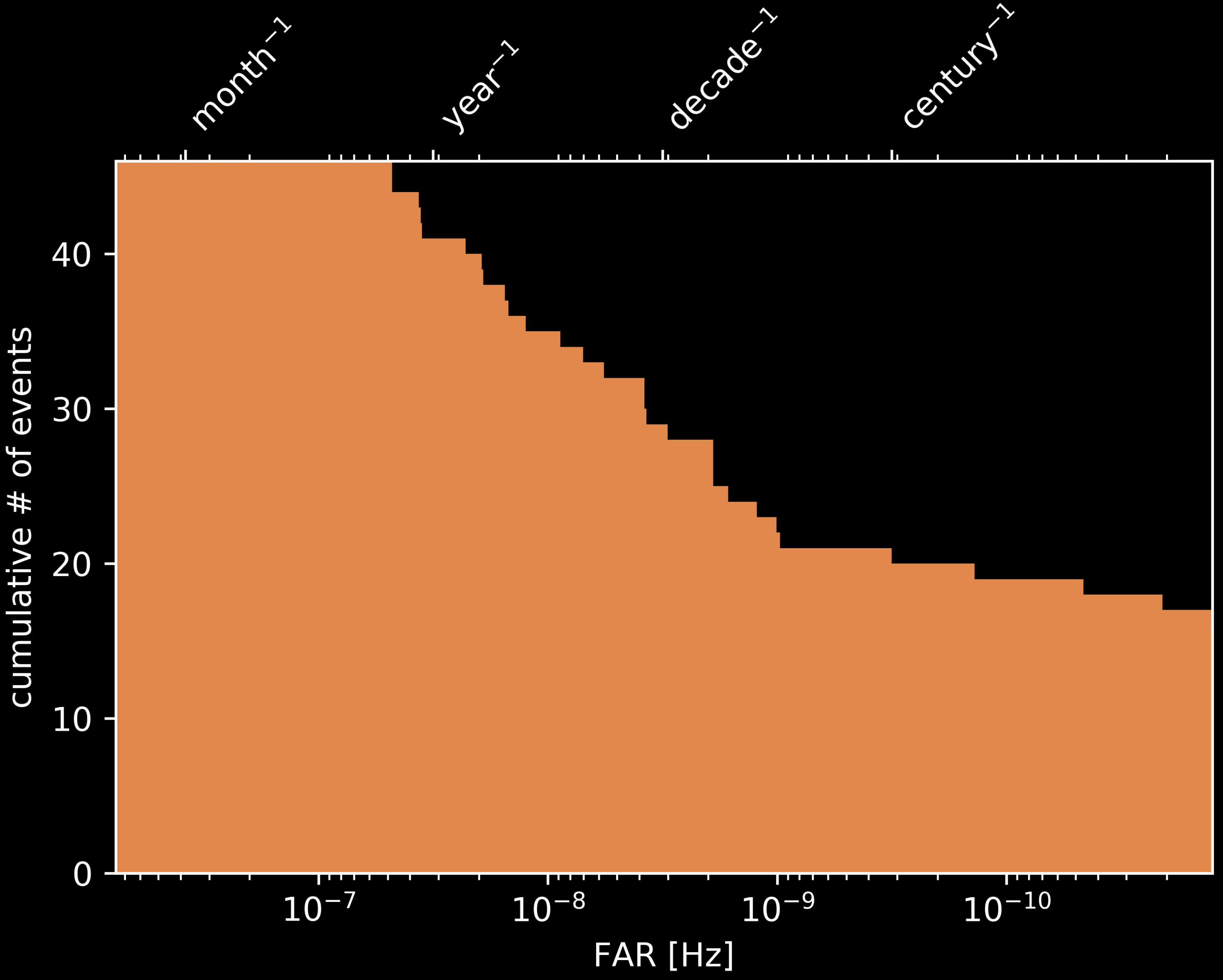
B. P. Abbott *et al* 2019 *ApJL* **882** L24 **(GWTC-1 R&P)**

O3

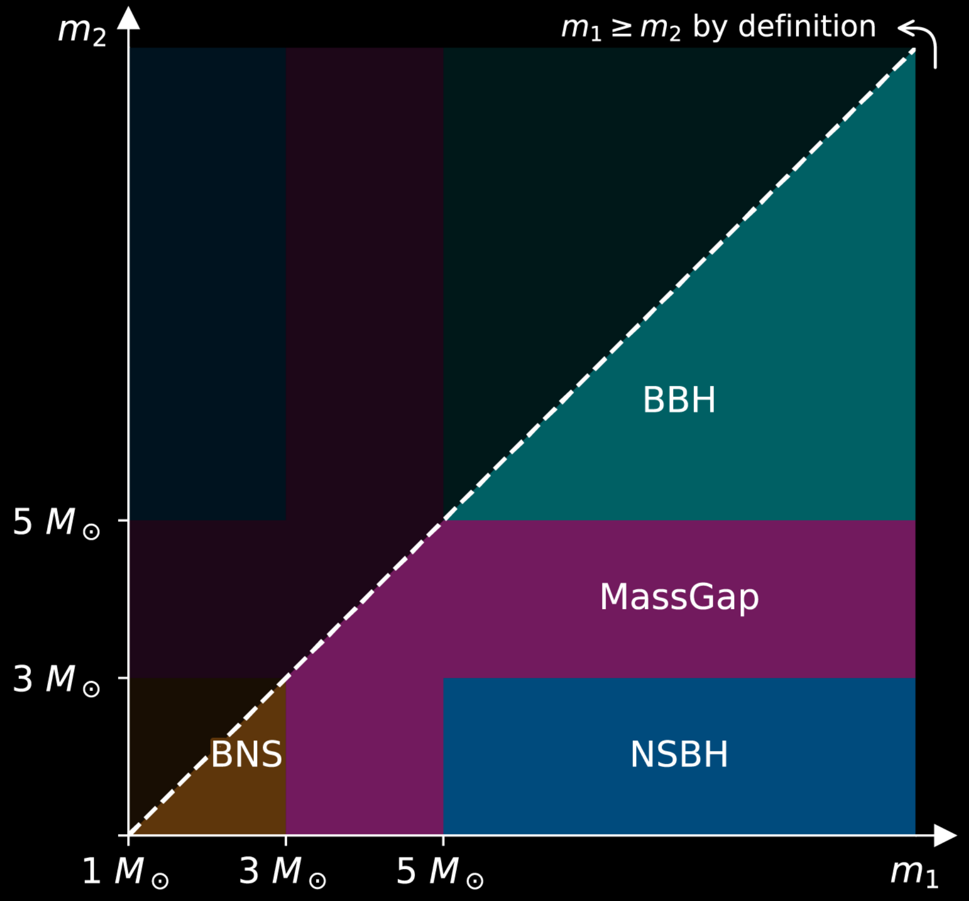

Cumulative Count of Events and (non-retracted) Alerts
Total = 57
Cumulative #Events/Candidates
Time (Days)
O1
O2
O3a
O3b
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
LIGO-G1901322
Credit: LIGO-Virgo Collaboration

O3 so far

https://gracedb.ligo.org/latest



Source Classifications



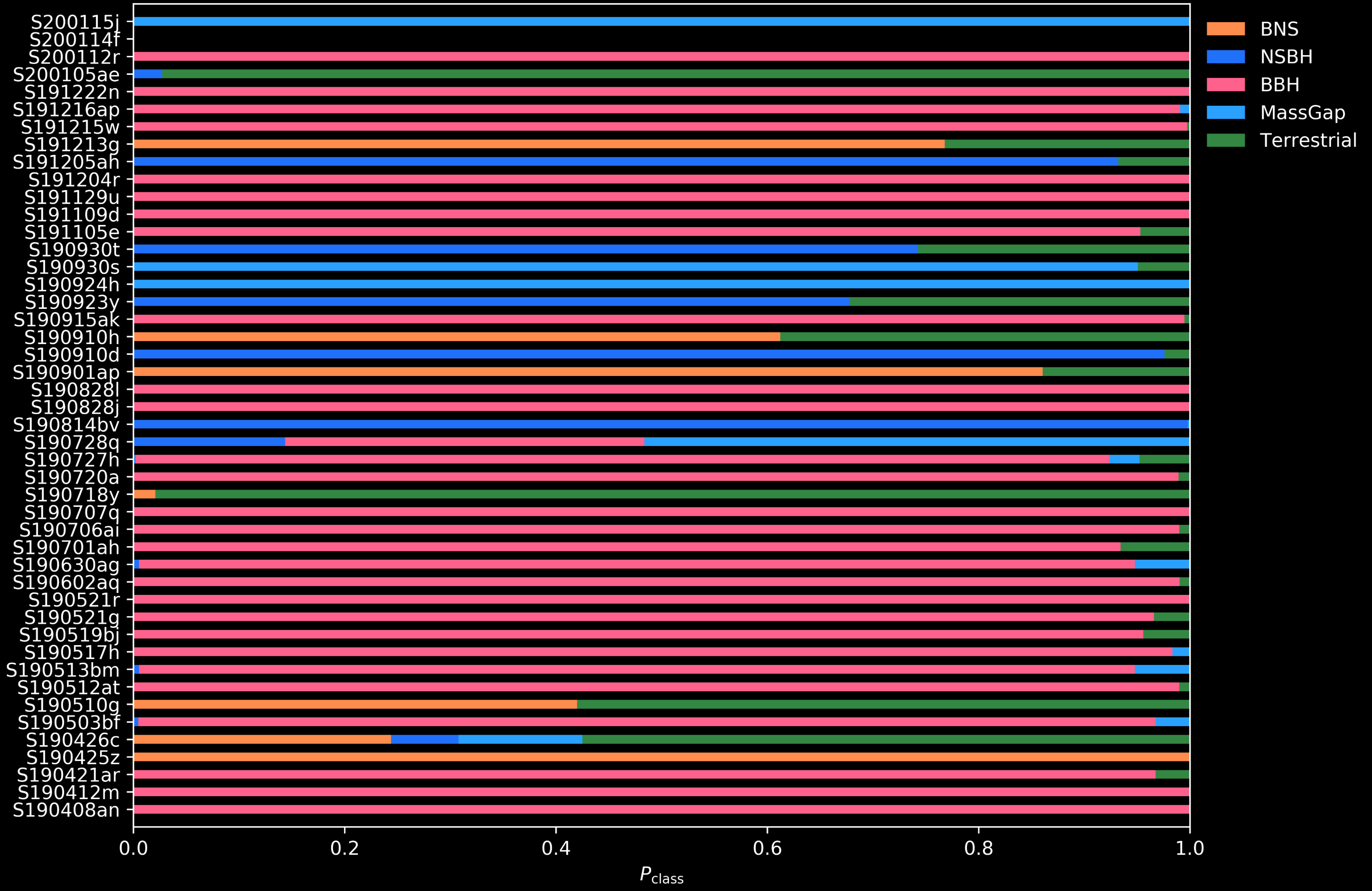
LIGO/Virgo Public Alerts User Guide

https://emfollow.docs.ligo.org/userguide/

O3 so far

https://gracedb.ligo.org/latest

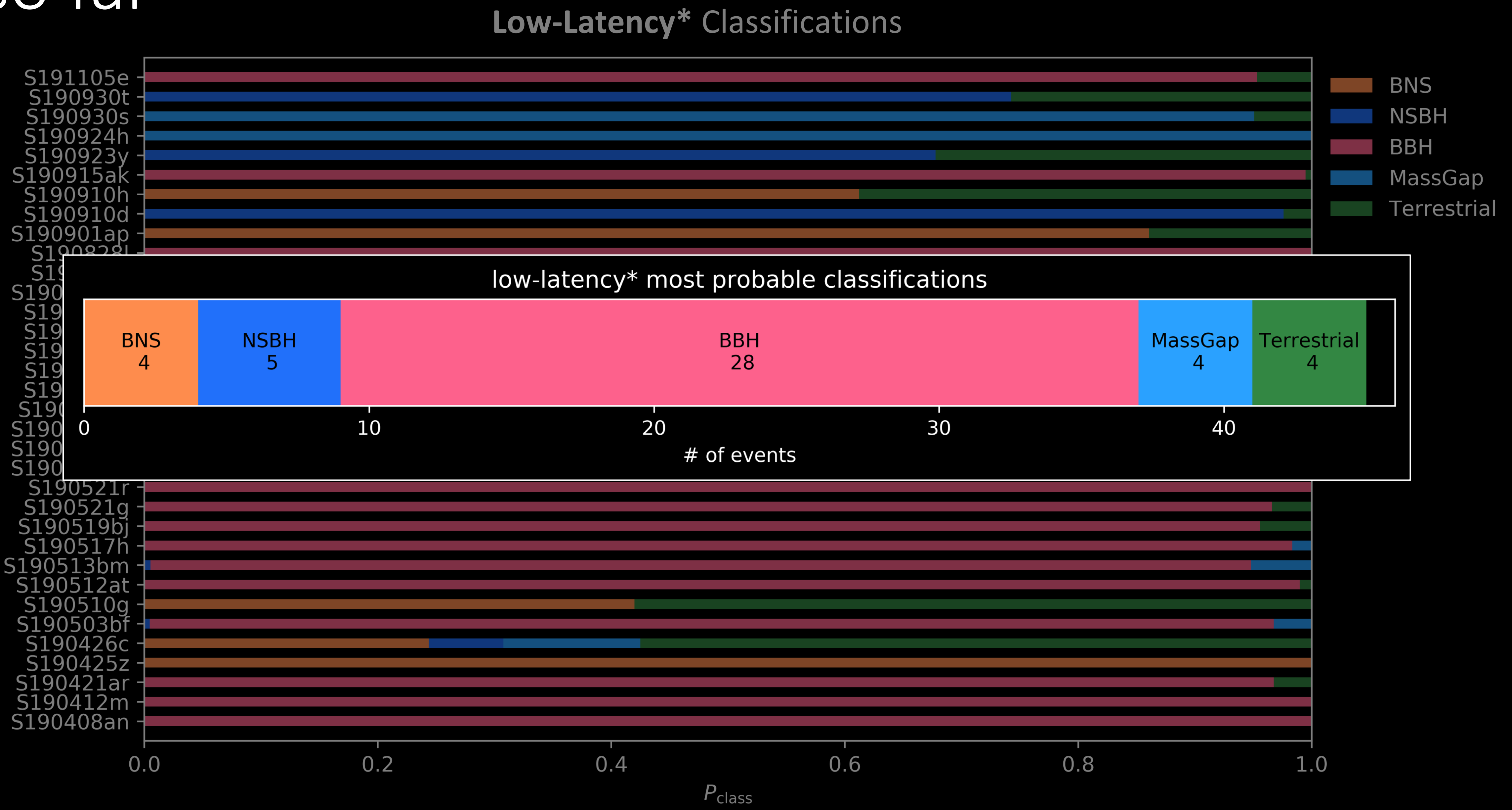
Low-Latency* Classifications



* Preliminary classifications produced in low-latency to facilitate follow-up efforts

O3 so far

https://gracedb.ligo.org/latest



* Preliminary classifications produced in low-latency to facilitate follow-up efforts

BBH Conclusions from O1 + O2

- O1 + O2 suggest stellar BH masses top out around 45 $M_{\odot}$.
- Haven't yet probed low-mass mass gap.
- Not enough events to disentangle models (yet).

CBC Conclusions from O3

- ~40 interesting events in the first 6 months.
- Rates are ~consistent with predictions from O2.
- Population statements will continue to get more interesting.

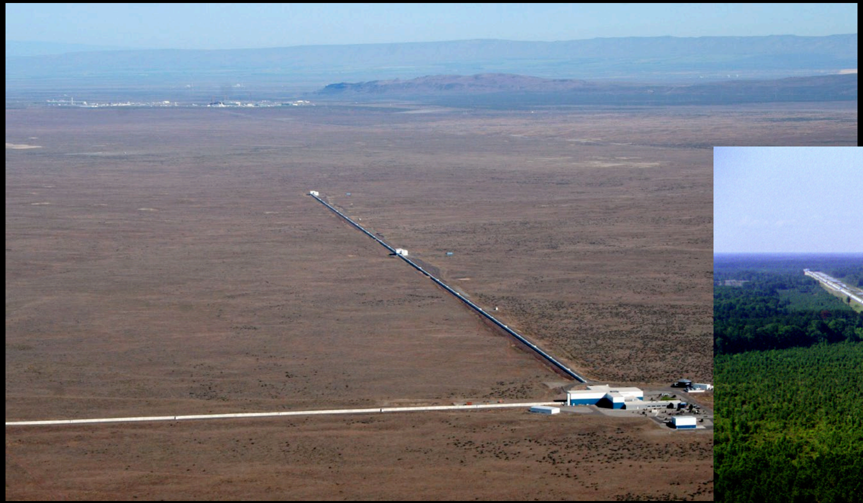
GW190425: Observation of a compact binary coalescence with total mass $\sim 3.4\,M_\odot$

The LIGO Scientific Collaboration,[1] The Virgo Collaboration,[2]

Image: Aurore Simonnet

GW190425: Network State

LIGO Hanford



Offline for 2h

LIGO Livingston

Online for 30h

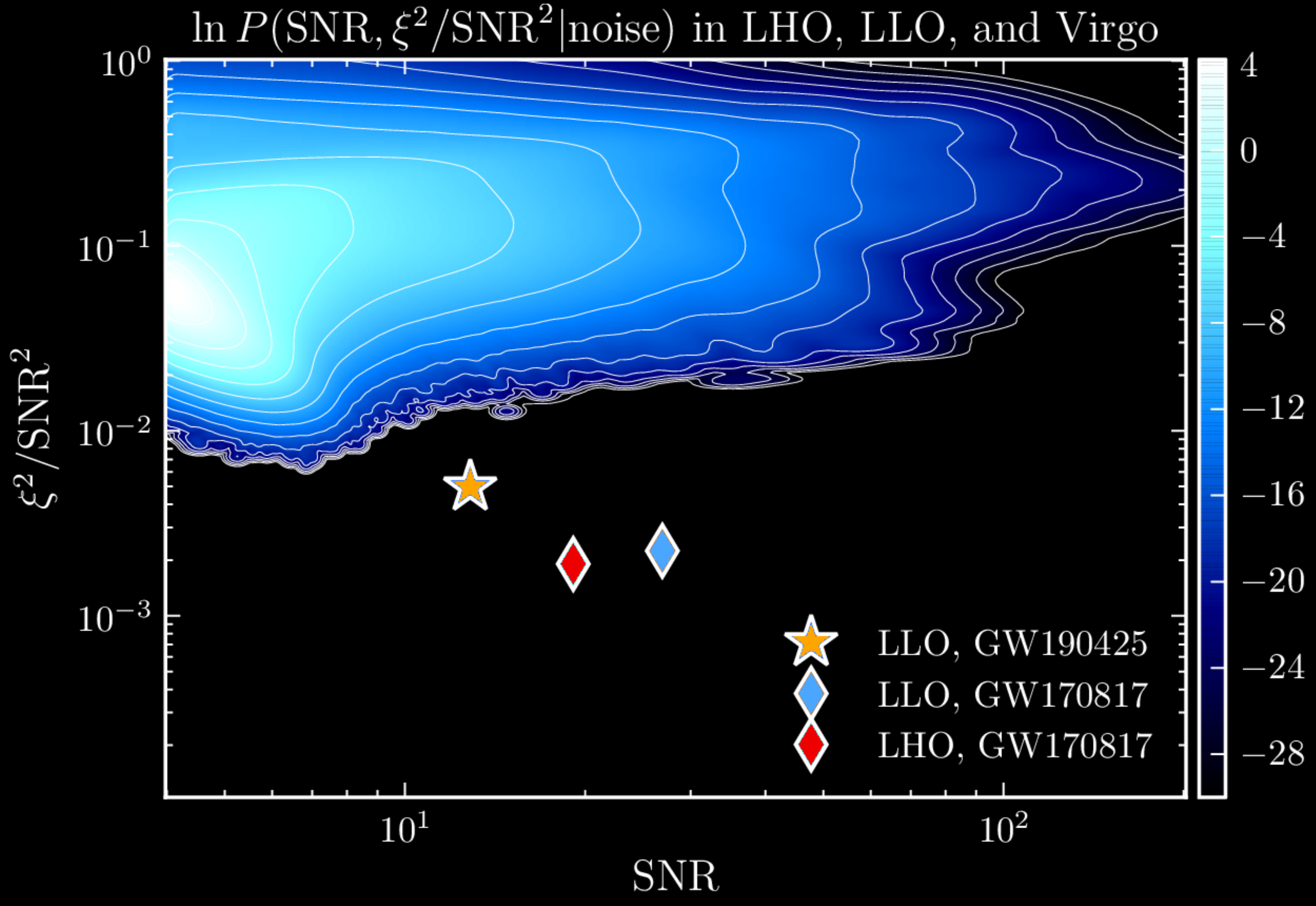
BNS Range: 135 Mpc

Virgo

Online for 14h

BNS Range: 48 Mpc

GW190425: Confidence



SNR

LIGO Livingston: 12.9

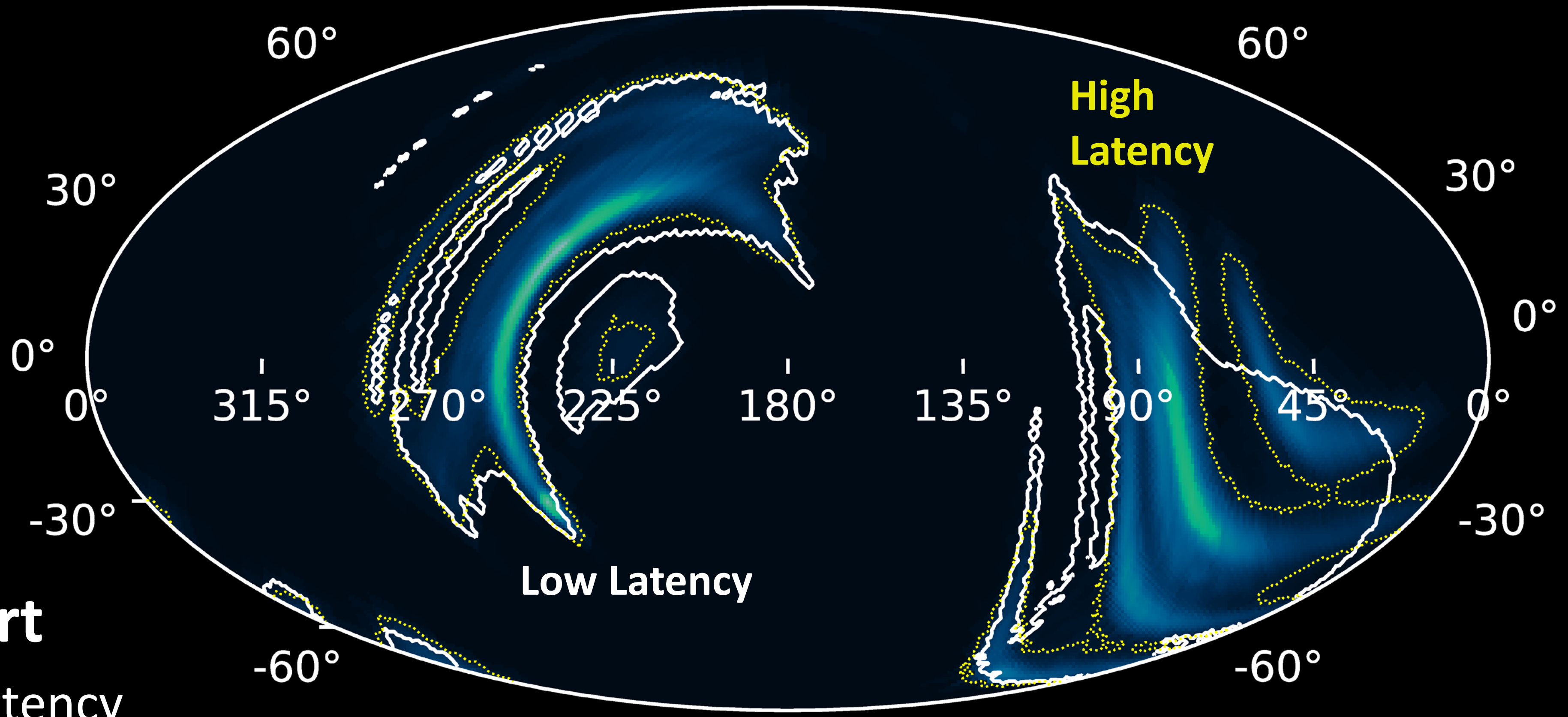
Virgo: 2.5

Low-latency FAR

1 per 69,000 years

No comparable background events in the advanced-detector era.

GW190425: Localization



Initial Alert

43 minute latency

BNS w/ >99% probability

90% region: **10,200 sq. deg.**

Distance: **110 – 200 Mpc**

Update

31 hour latency

90% region: **7,461 sq. deg.**

Distance: **115 – 197 Mpc**

Final

90% region: **8,284 sq. deg.**

Distance: 88 – 228 Mpc

GW190425: Follow-up

Final localization:

8,284 sq. deg.

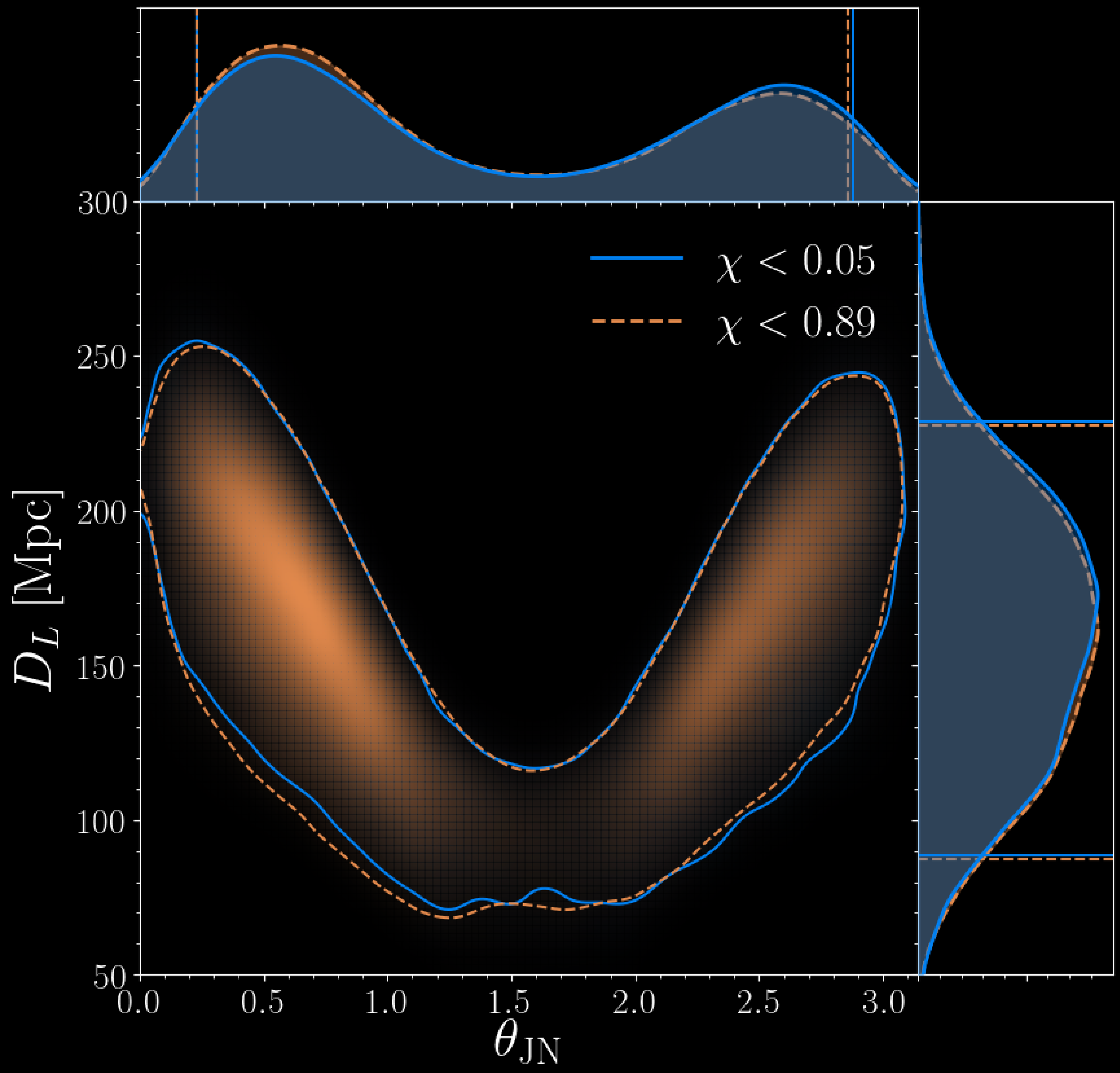
88 – 228 Mpc

Extensive follow-up efforts:

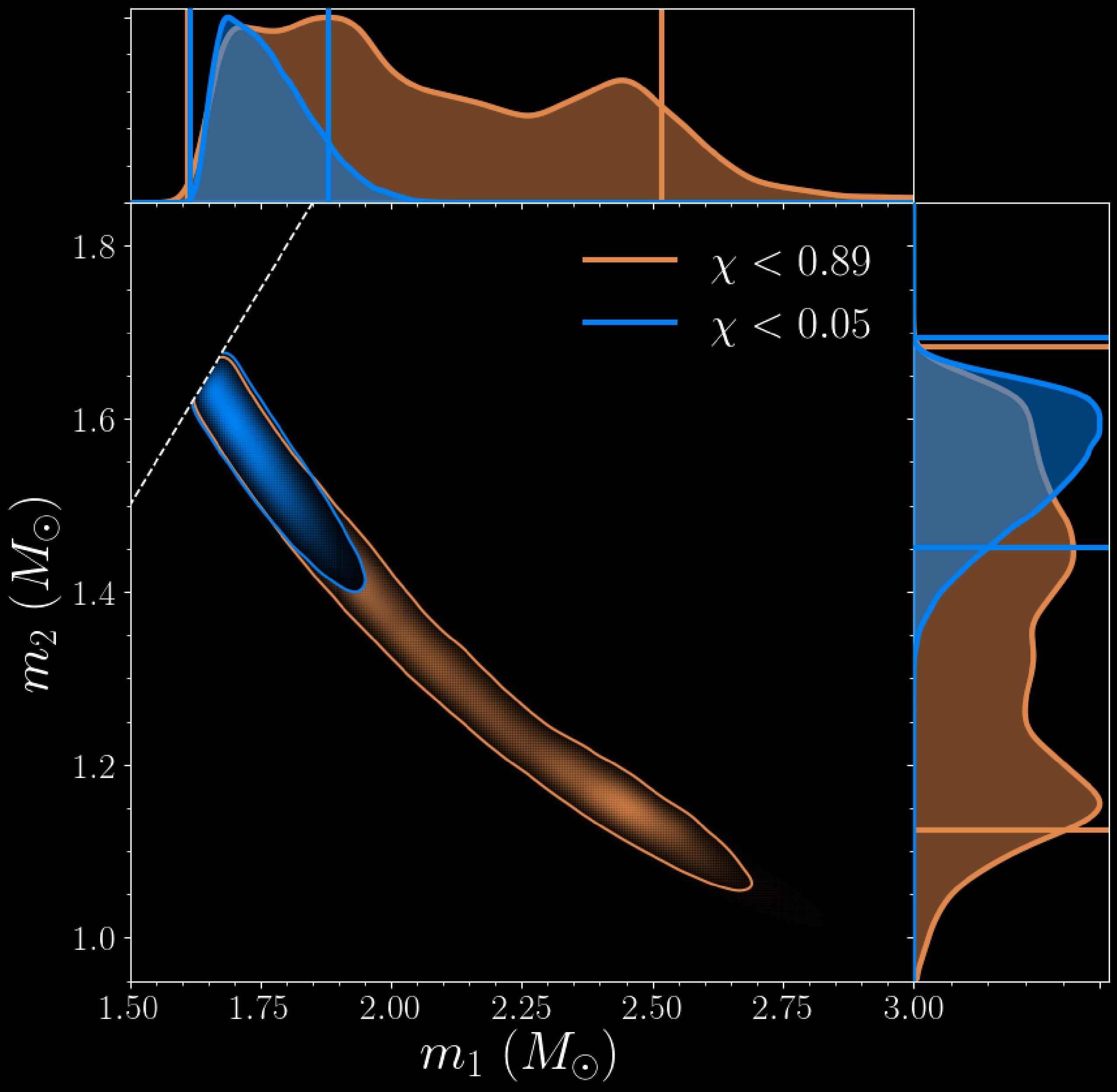
118 circulars

No reported EM transients appear to be associated with GW190425

No constraints on inclination from GW



GW190425: Masses



Primary

Low-spin prior: 1.62 – 1.88 $M_\odot$

High-spin prior: 1.61 – 2.52 $M_\odot$

Secondary

Low-spin prior: 1.45 – 1.69 $M_\odot$

High-spin prior: 1.12 – 1.68 $M_\odot$

GW190425: Masses

Assuming a BNS…
@ **5σ** of galactic BNS population

Field Formation

Might suggest a BNS pop. formed w/ sub-hour orbital periods.

Belczynski *et al.* 2002 *ApJ* **572** 407

Ivanova *et al.* 2003 *ApJ* **592** 475

Dewi & Pols 2003 *MNRAS* 344 629

Dynamical Formation

MS pulsars up to 2 $M_\odot$ found in globular clusters

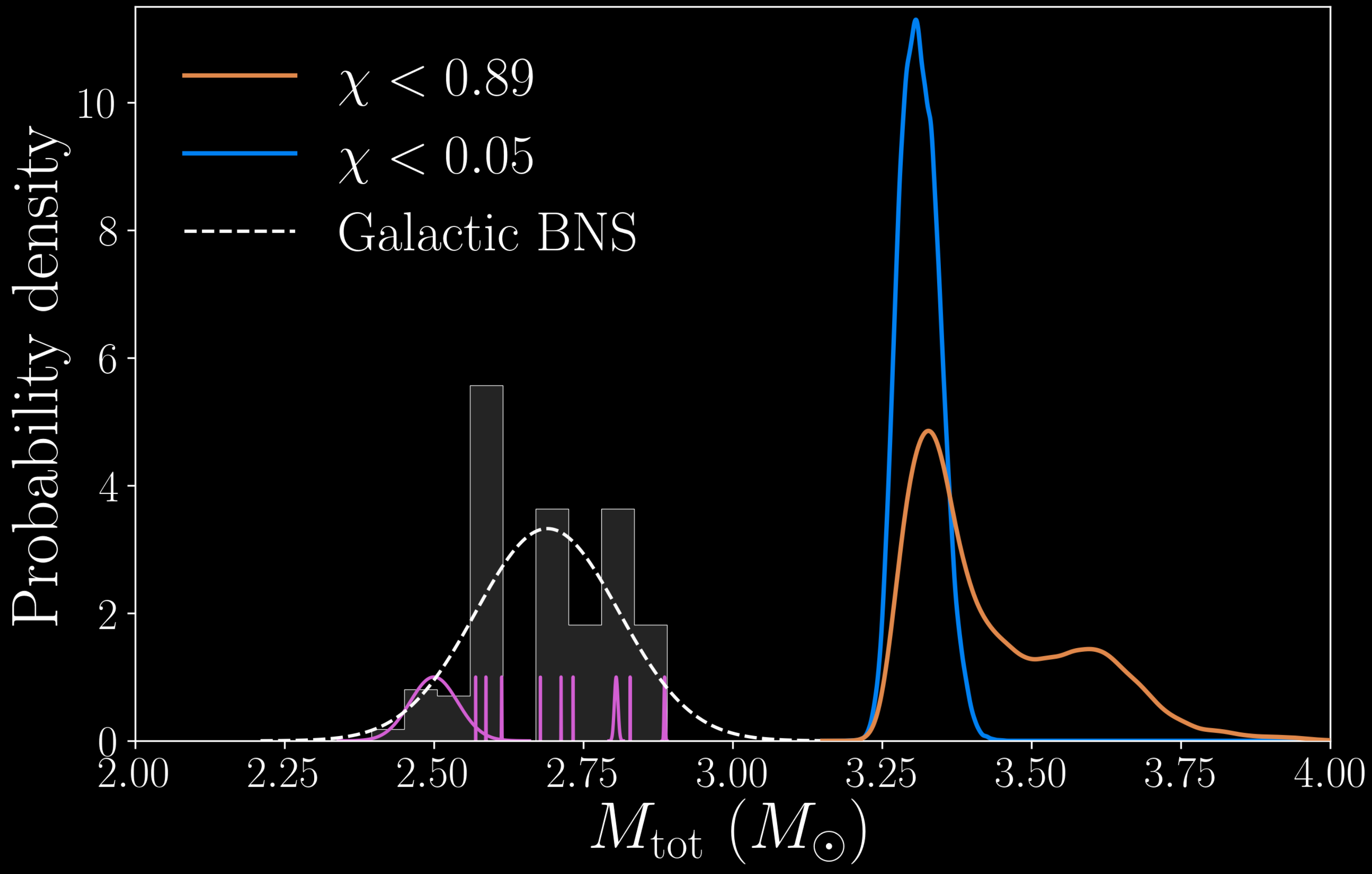
Ransom *et al.* 2005 *Science* **307** 892

Freire *et al.* 2008 *ApJ* **679** 1433

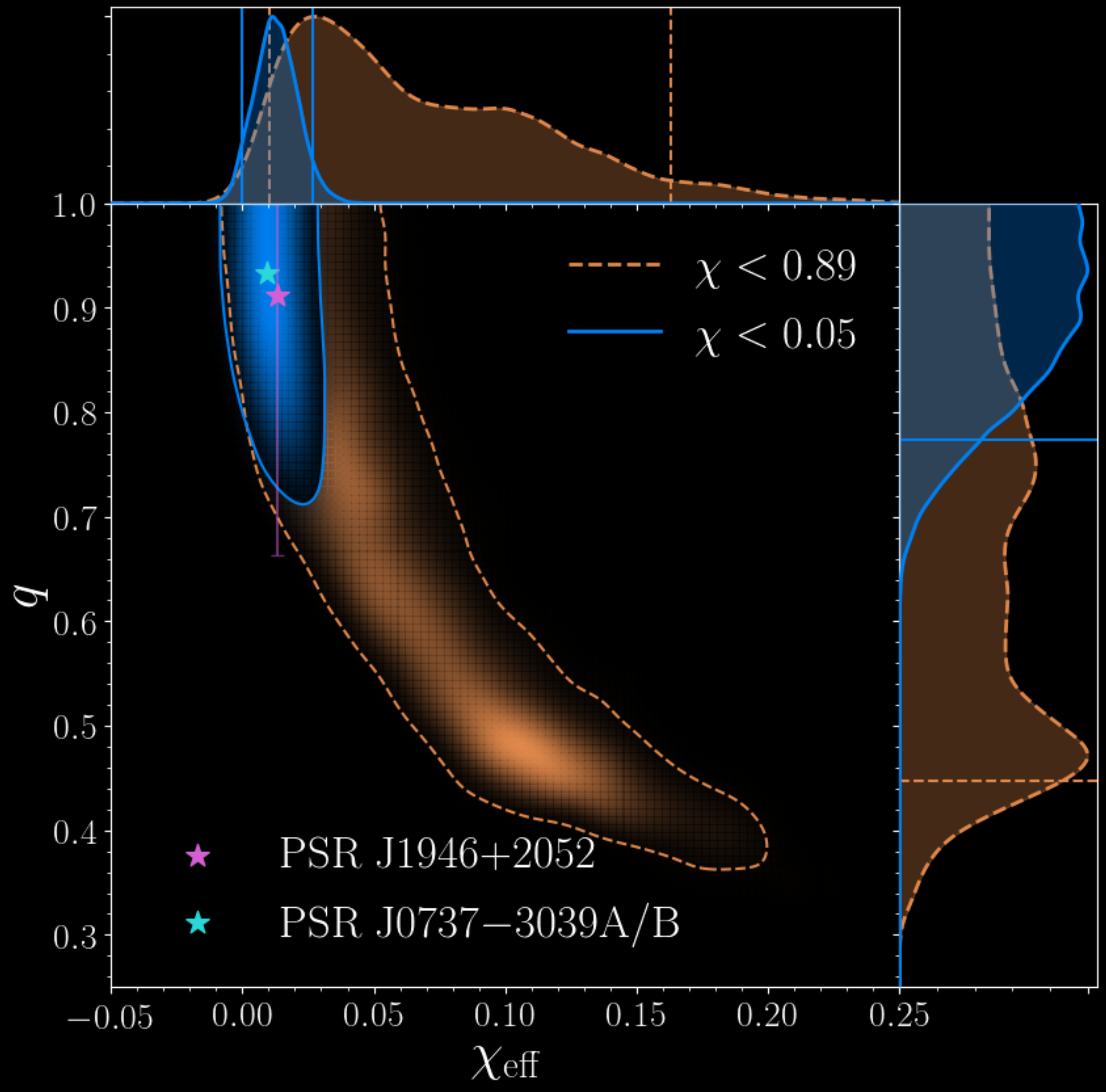
BNS contributions expected to be minimal

Belczynski *et al.* 2018 *A&A* **615** A91

Ye et al. 2019 arXiv:1910.10740



GW190425: Spins

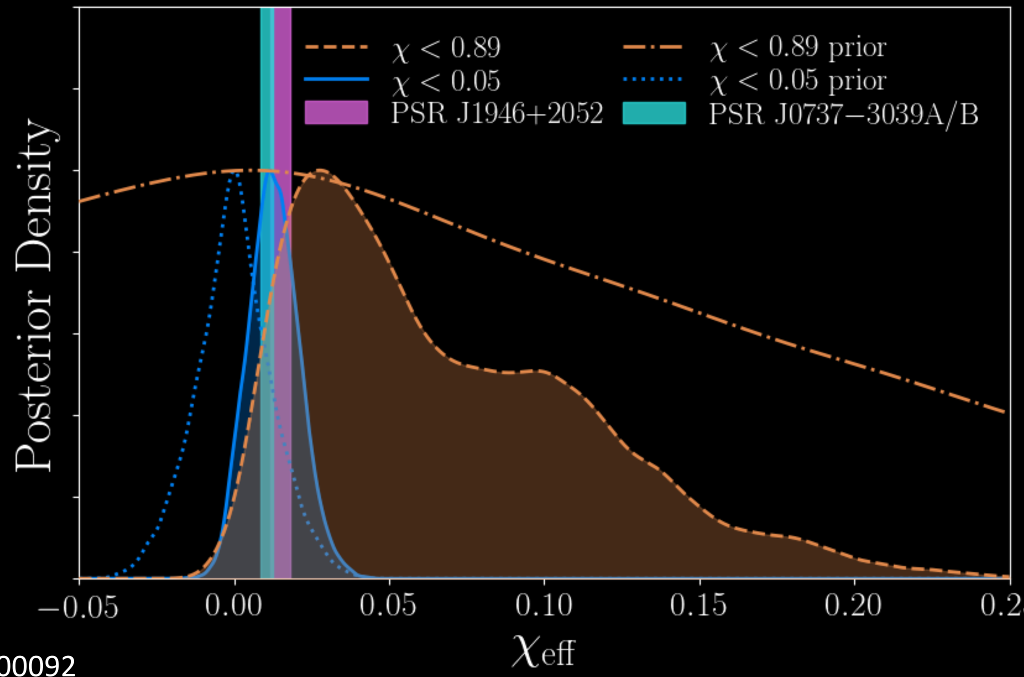


Effective spin

$$\chi_{\mathrm{eff}} = \frac{(m_1\vec{s}_1 + m_2\vec{s}_2)\cdot\hat{L}_N}{m_1 + m_2}$$

Broad spin priors allow for a large mass ratio

Data consistent with negligible spin



GW190425: Astrophysical Rates

BNS merger rate from GWTC-1:

$R_{\text{GWTC-1}}$ = 110 – 2520 $\text{Gpc}^{-3}\text{yr}^{-1}$

Assuming GW190425 & GW170817 from same uniform-in-component mass dist.:

R = 250 – 2470 $\text{Gpc}^{-3}\text{yr}^{-1}$

Treating GW190425 & GW170817 independently (a la Kim *et al.* 2003 *ApJ* **584** 985)

R_{170817} = 110 – 2500 $\text{Gpc}^{-3}\text{yr}^{-1}$
R_{190425} = 70 – 1510 $\text{Gpc}^{-3}\text{yr}^{-1}$

$R = R_{170817} + R_{190425}$ = 290 – 2810 $\text{Gpc}^{-3}\text{yr}^{-1}$

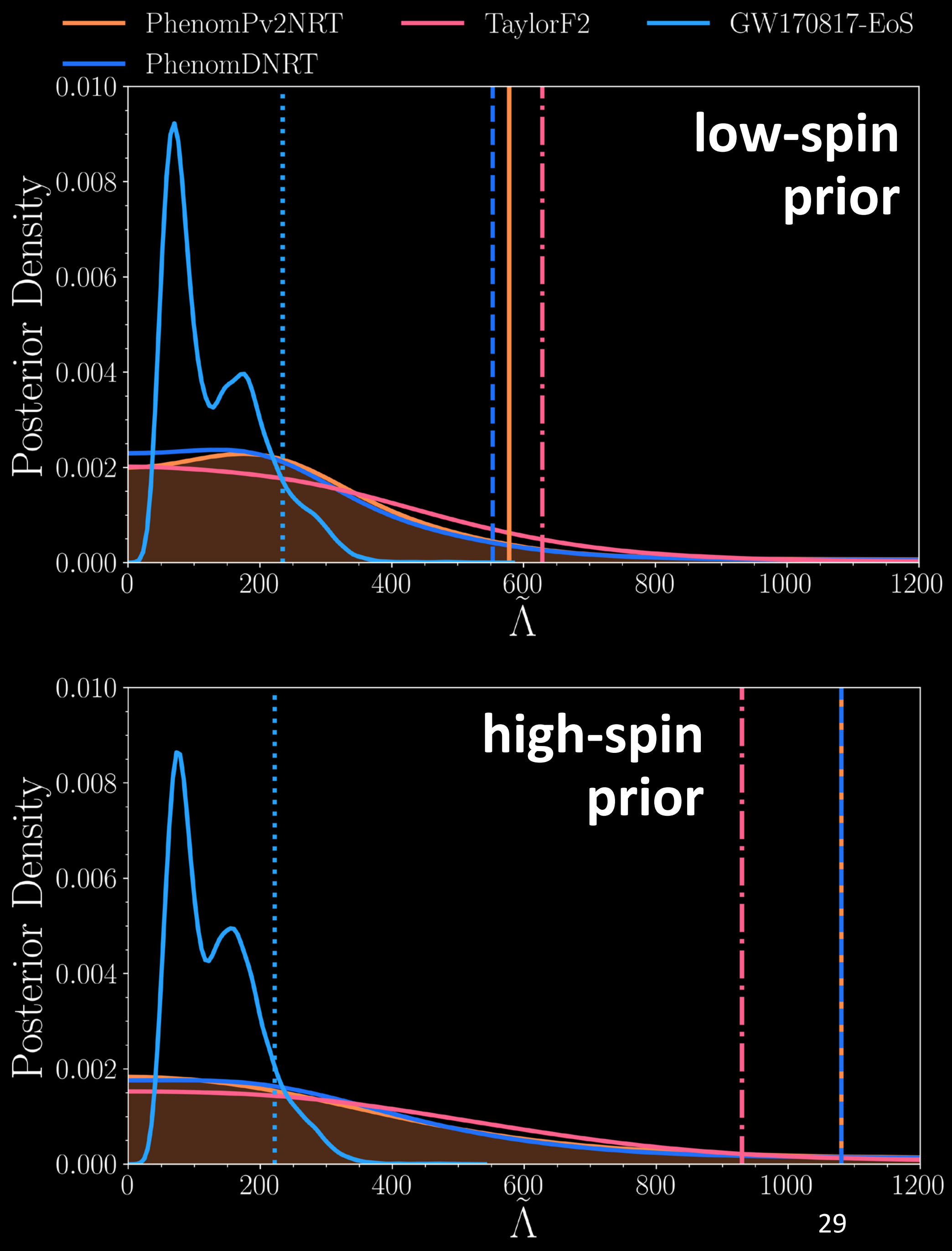
GW190425: Matter Effects

No confident detection of matter effects
 i.e., can't rule out point-particle model

Constraints poorer than GW170817

No additional information on EoS

No sensitivity to post-merger signal



Conclusions

GW190425 is…

the first demonstration of single-detector detection.

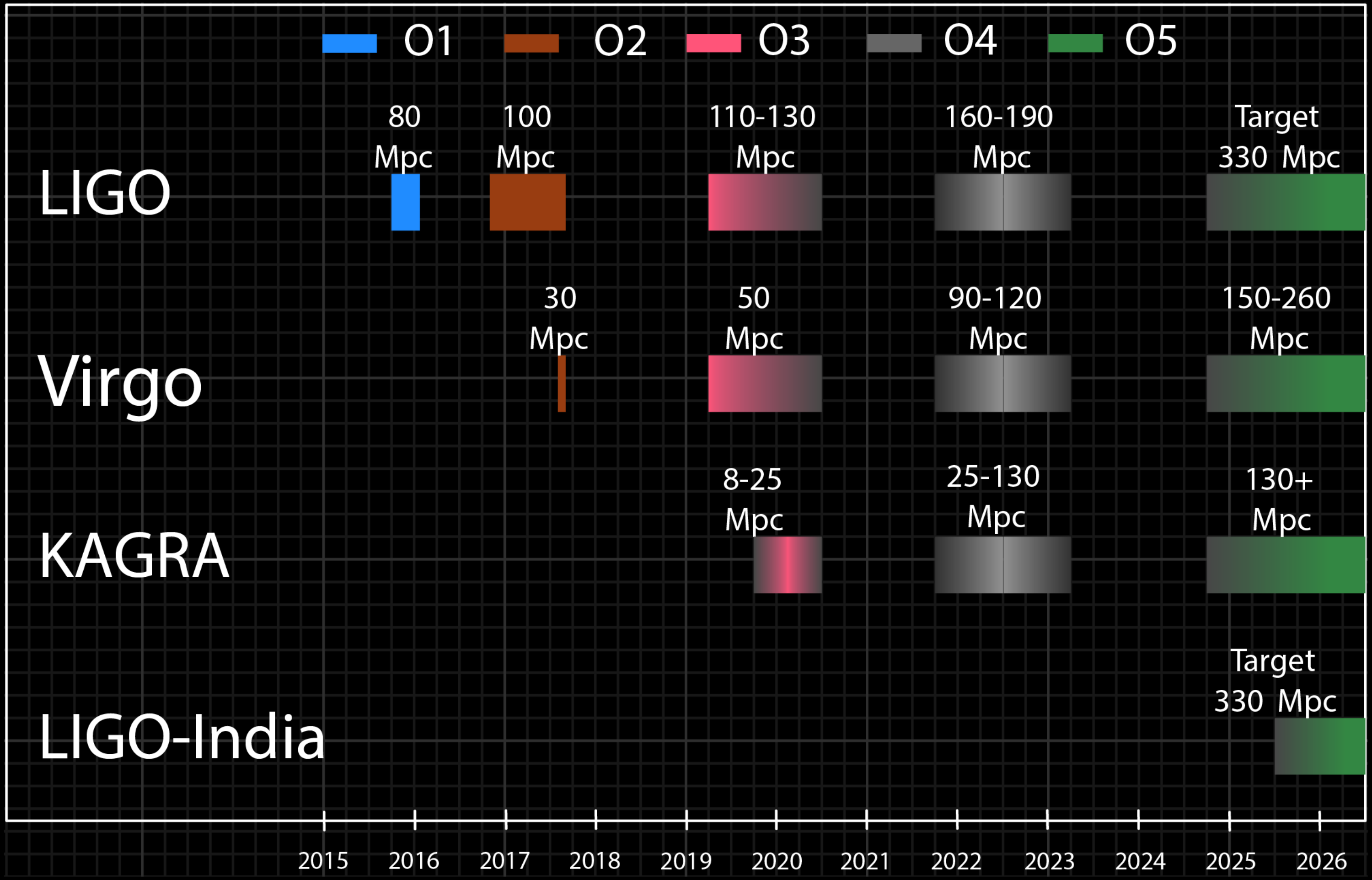
likely the second BNS detection with gravitational waves.

an outlier of observed galactic BNS population.

More to come…

Beyond

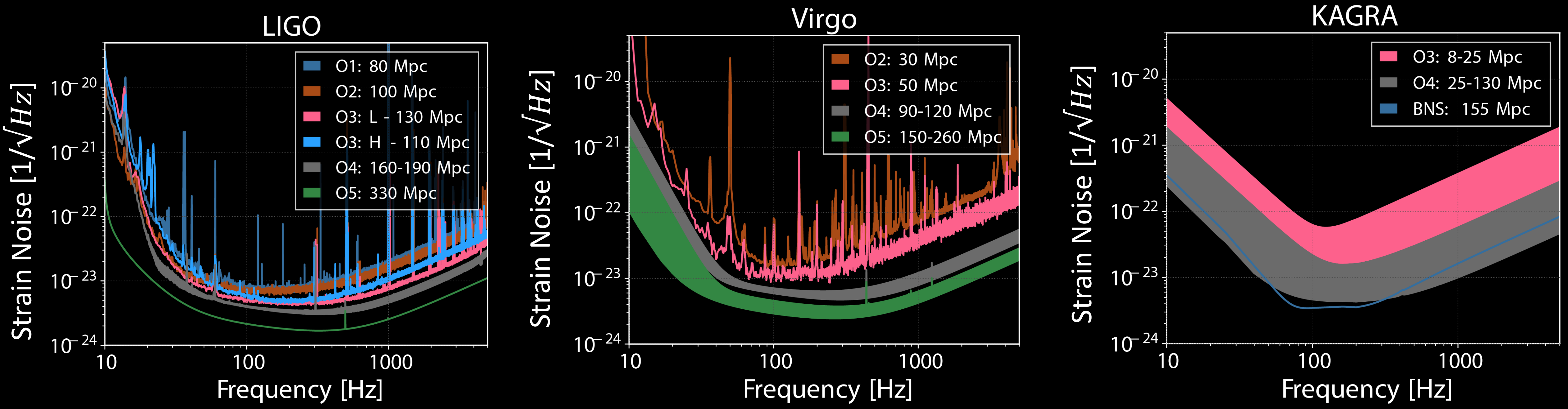
Observing Schedule



Abbott, B.P. Living Rev Relativ (2018) 21: 3.
arXiv:1304.0670

Thank you

Expected Sensitivities



Abbott, B.P. Living Rev Relativ (2018) 21: 3.
arXiv:1304.0670

Expected Ranges

		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+

Abbott, B.P. Living Rev Relativ (2018) 21: 3.
arXiv:1304.0670

Expected Detections

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	250 – 310	310 – 390	250 – 340
O4	HLVK	29 – 48	48 – 69	33 – 47

		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	90 – 130	590 – 1000	11000 – 19000
O4	HLVK	43 – 71	400 – 560	6400 – 10000

Abbott, B.P. Living Rev Relativ (2018) 21: 3.
arXiv:1304.0670