Astrophysical Lessons from LIGO/Virgo's Black Holes

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ICERM - Statistical Methods for the Detection, Classification and Inference of Relativistic Objects

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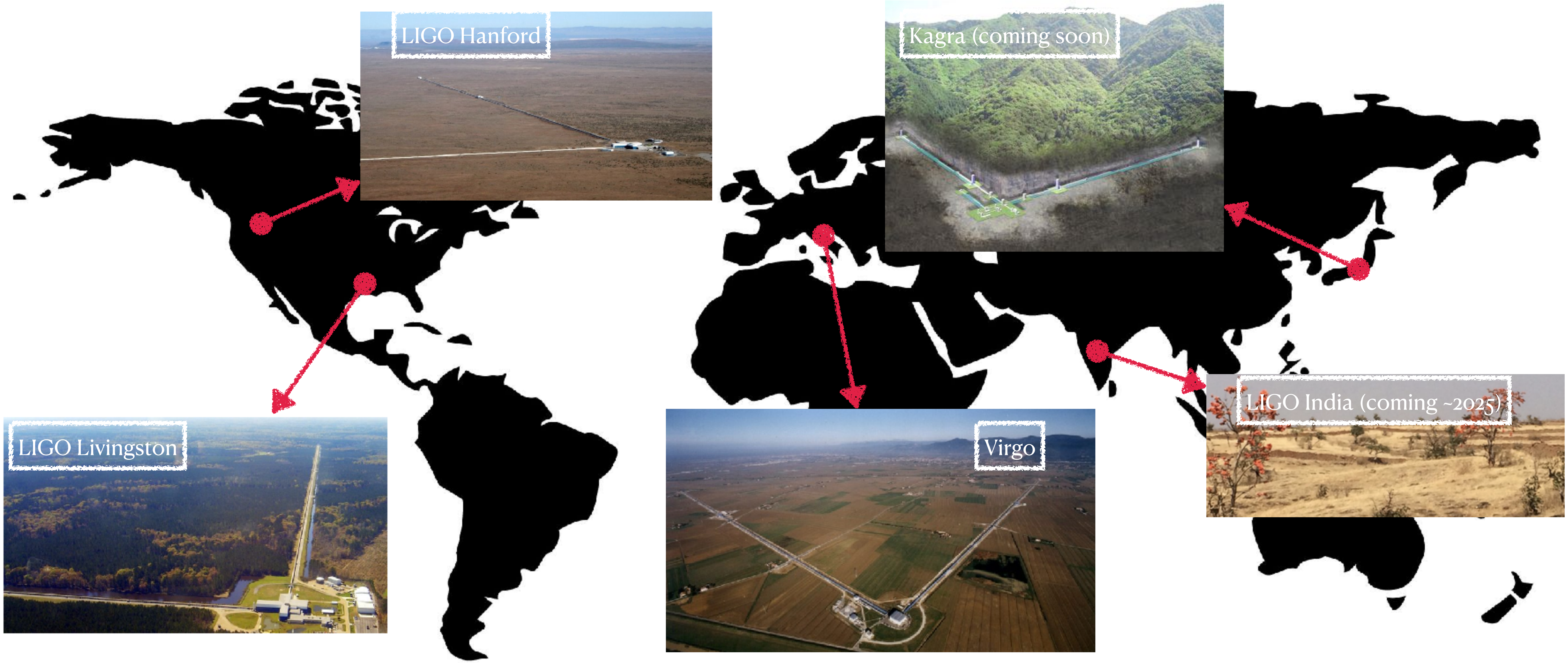
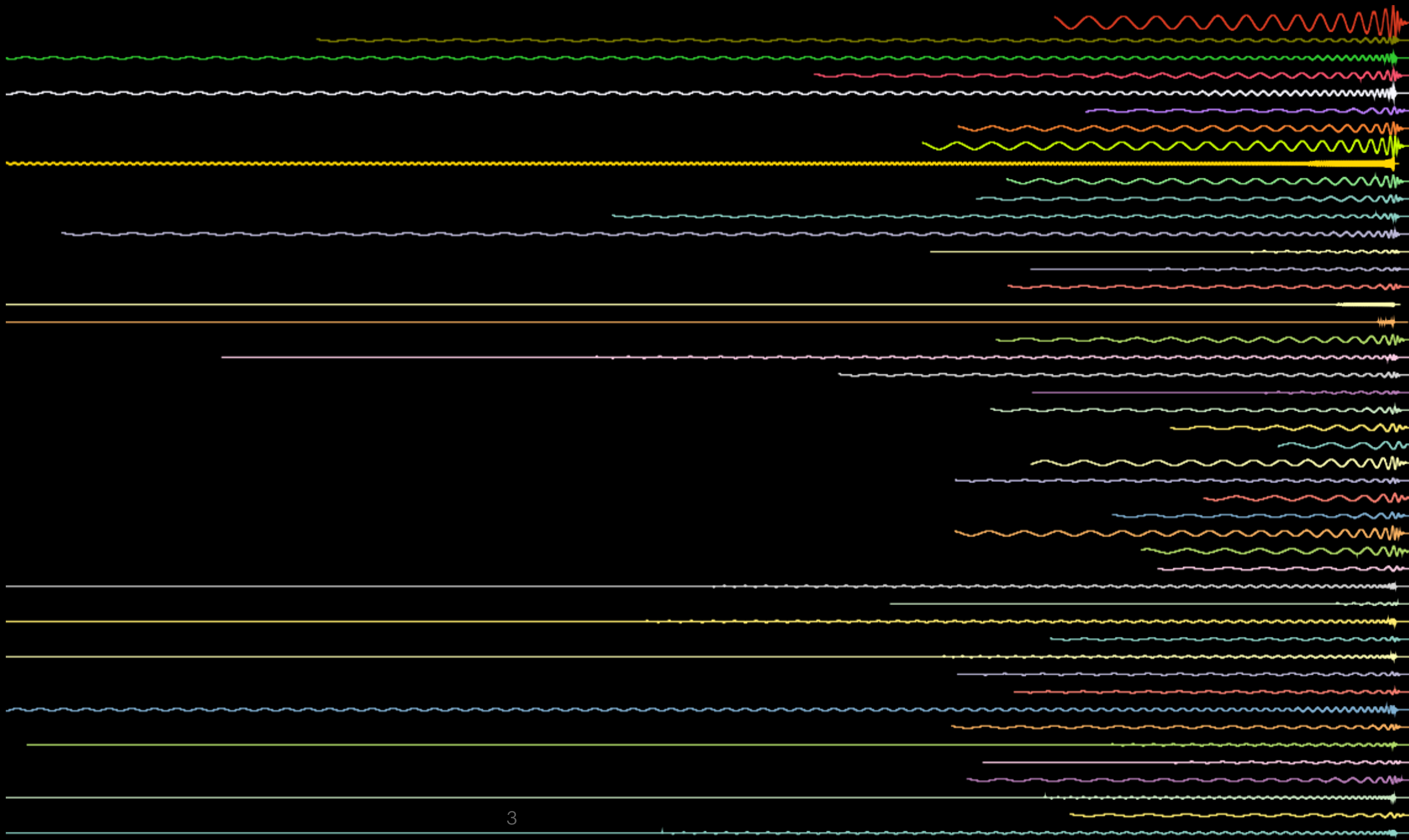
CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

NHFP
NASA Hubble Fellowship Program

World-wide network of gravitational-wave detectors



LIGO and Virgo have observed gravitational waves from ~50 mergers



Credit: Chris North & Stuart Lowe,
https://waveview.cardiffgravity.org

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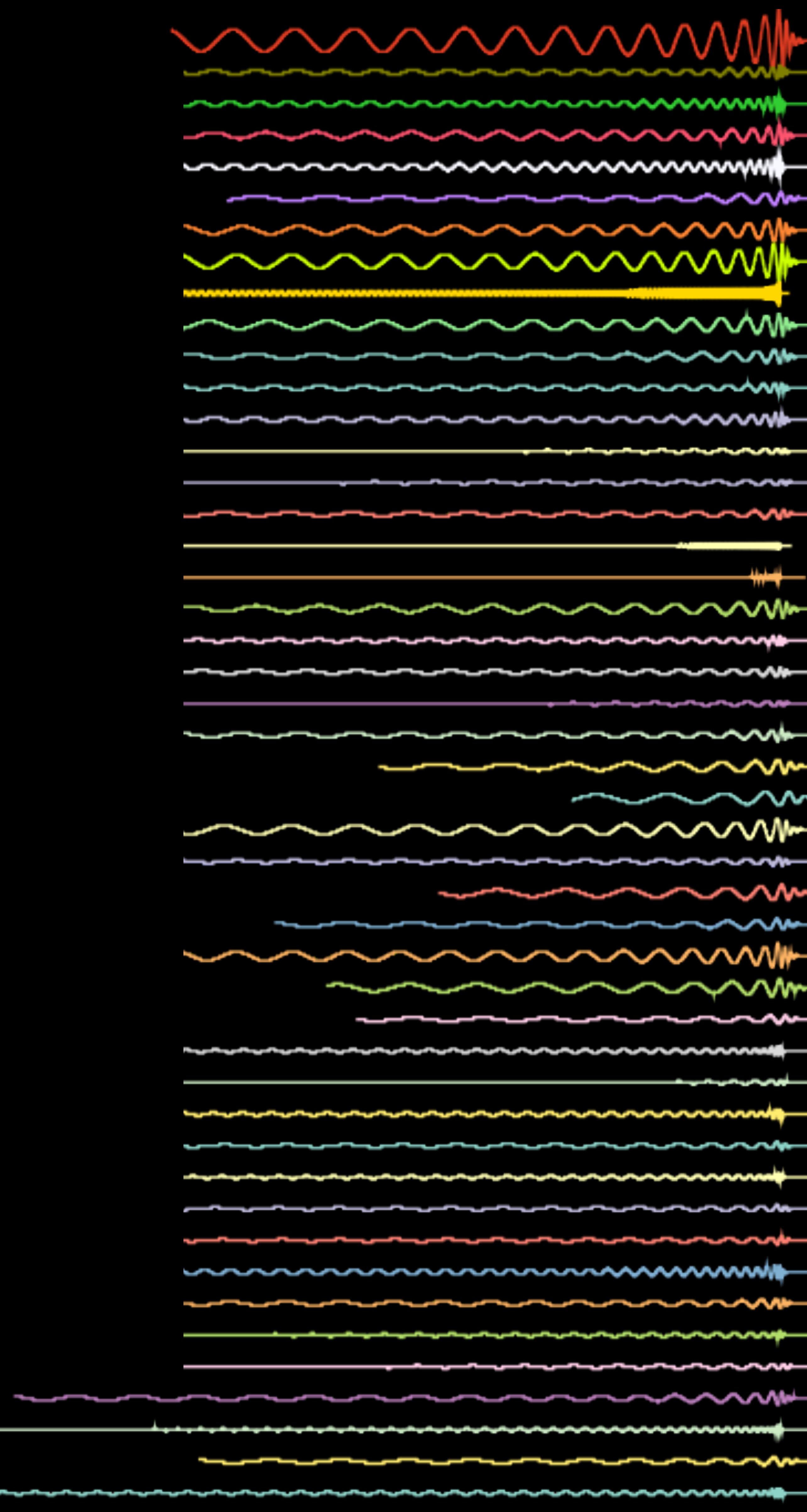


GWTC-2 papers:

Catalog:
dcc.ligo.org/P2000061/public
arXiv: 2010.14527

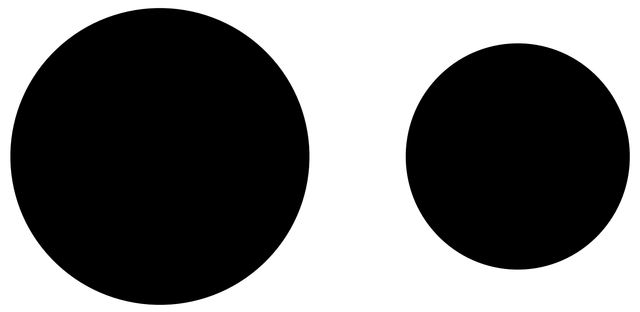
Population paper:
dcc.ligo.org/LIGO-P2000077/public
arXiv: 2010.14533

Tests of GR paper:
dcc.ligo.org/LIGO-P2000091/public
arXiv: 2010.14529

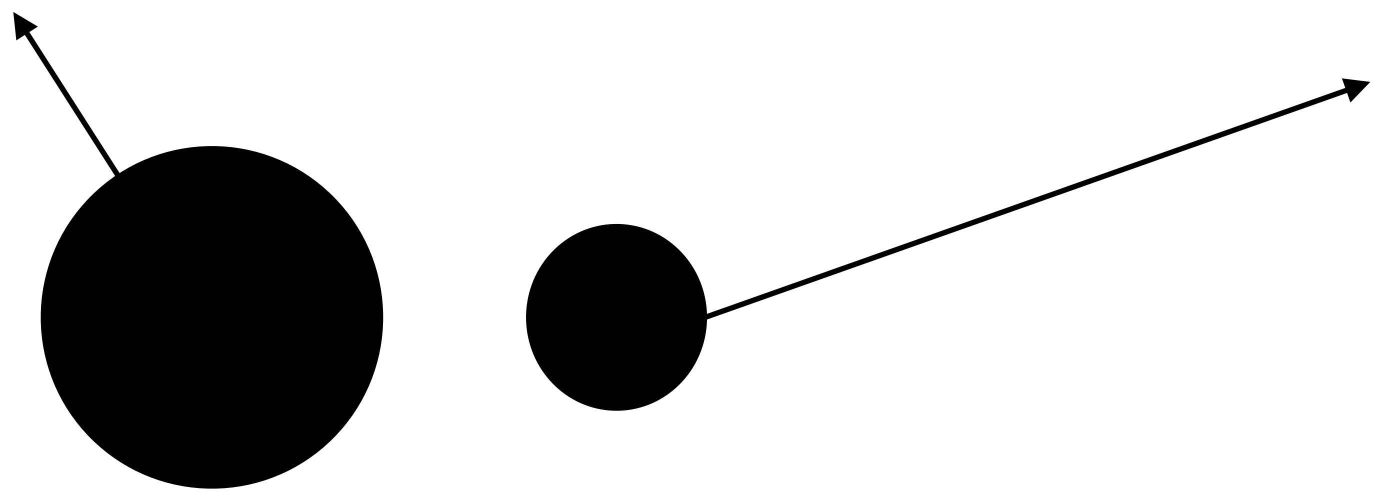
Credit: Chris North & Stuart Lowe,
https://waveview.cardiffgravity.org

For each binary black hole merger, the gravitational-wave signal encodes:

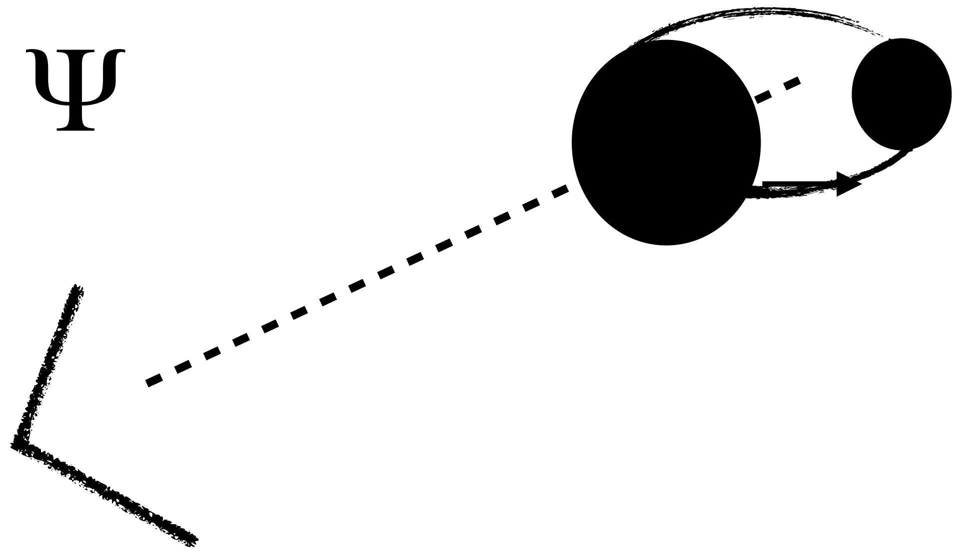
- The masses of the two components $m_1 \geq m_2$



- The component spins a_1, a_2



- Distance d_L, sky position α, δ, inclination ι, polarization Ψ



Measuring these parameters for each event is known as *parameter estimation*

Masses in the Stellar Graveyard

in Solar Masses

GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Parameter estimation

For individual events, measurement uncertainties are large, and our inferred *posterior* depends on the *prior*

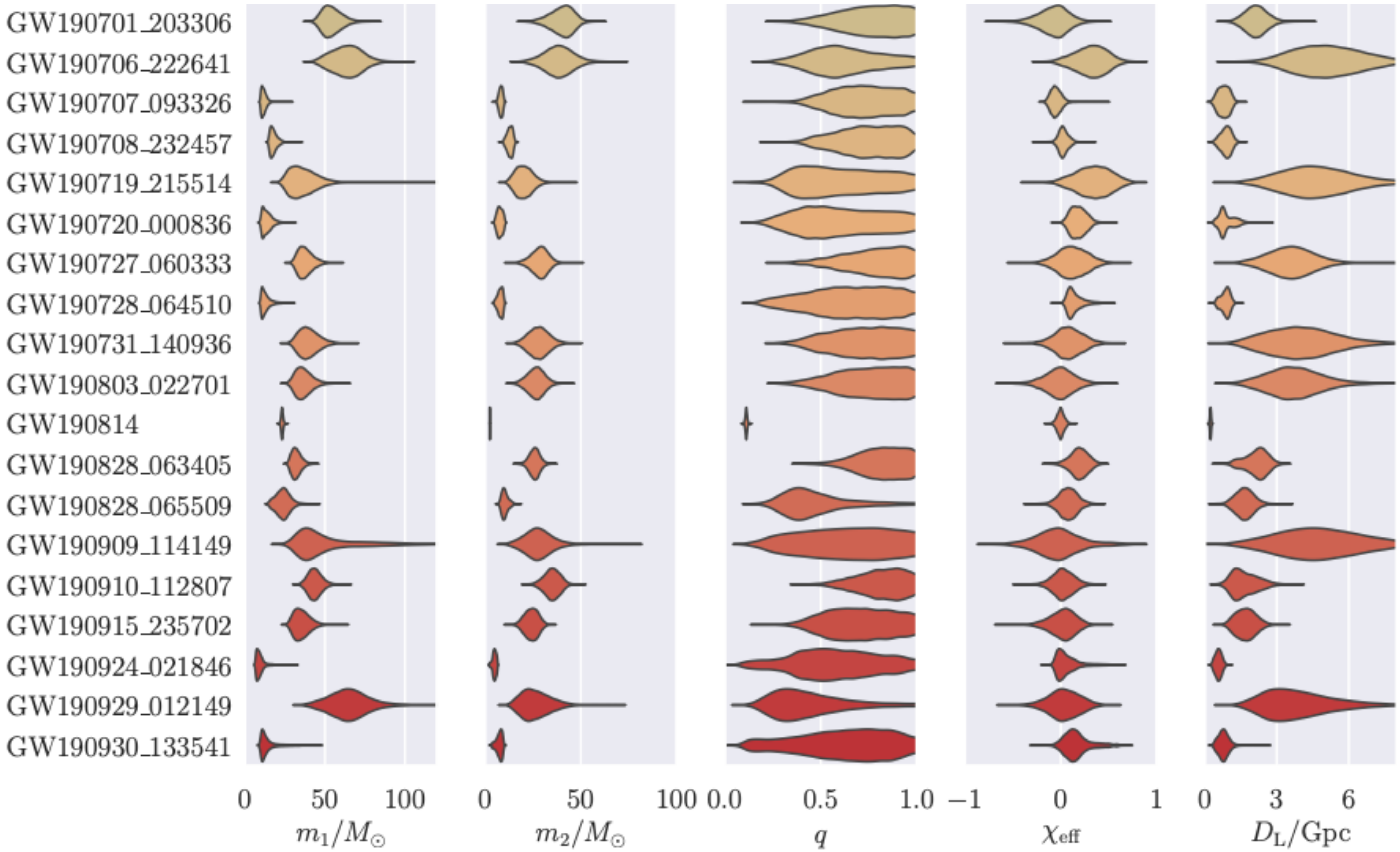
$$p(m_1, m_2 \mid \text{data}) \propto p(\text{data} \mid m_1, m_2) p_0(m_1, m_2)$$

Posterior Likelihood Prior

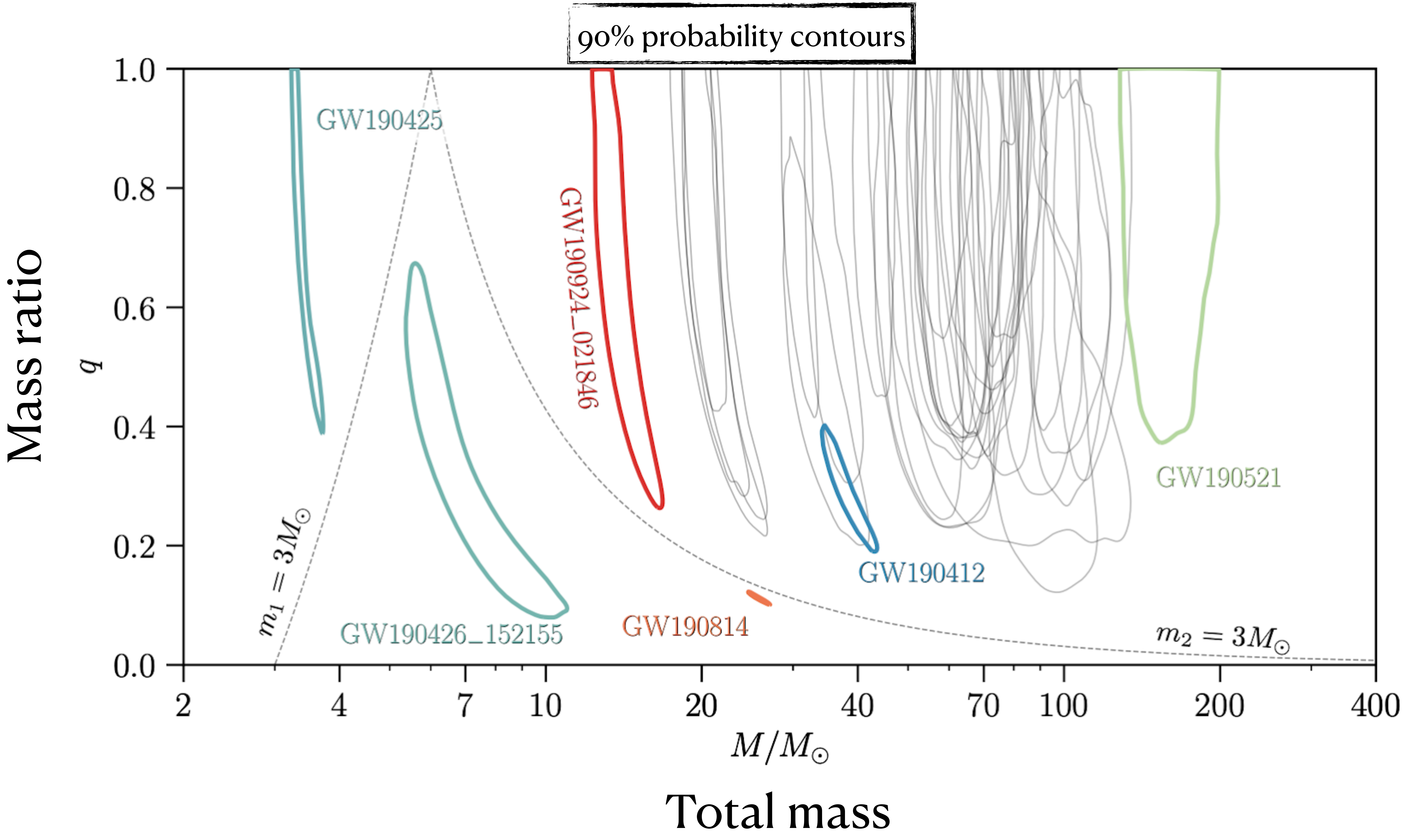
LIGO/Virgo prior: *flat* in (detector-frame) masses

Measurements of individual events' parameters

Subset of events in GWTC-2



Primary mass Secondary mass Mass ratio Effective inspiral spin Distance (redshift)


90% probability contours
Mass ratio
q
Total mass
$M/M_\odot$
GW190425
GW190426_152155
GW190924_021846
GW190814
GW190412
GW190521
$m_1 = 3M_\odot$
$m_2 = 3M_\odot$
1.0
0.8
0.6
0.4
0.2
0.0
2
4
7
10
20
40
70
100
200
400

From Single Events to a Population

- Introduce a set of population **hyper-parameters** that describe the **distributions** of masses, spins, redshifts across multiple events
- Example: Fit a power-law model to the mass distribution of black holes, $p(\text{mass} \mid a) \propto \text{mass}^{-a}$
- Take into account **measurement uncertainty** and **selection effects**

Population analysis

Find the "best" prior to use for individual events

$$p(m_1, m_2 \mid \alpha)$$

Population model, common to all systems

Parameter estimation likelihood for event *i*

$$p(\mathrm{data} \mid \alpha) = \prod_i \frac{\int p(\mathrm{data}_i \mid m_1, m_2)\, p(m_1, m_2 \mid \alpha)\, \mathrm{d}m_1 \mathrm{d}m_2}{\beta(\alpha)}$$

Likelihood given population hyperparameters

Selection effects: fraction of detectable systems in the population

Mandel, Farr & Gair arXiv:1809.02063

Three Astrophysical Lessons

The population properties of binary black holes reveal how these systems are made

1. A feature in the mass distribution at ~40 solar masses
2. Misaligned black hole spins
3. Black hole merger rate across cosmic time

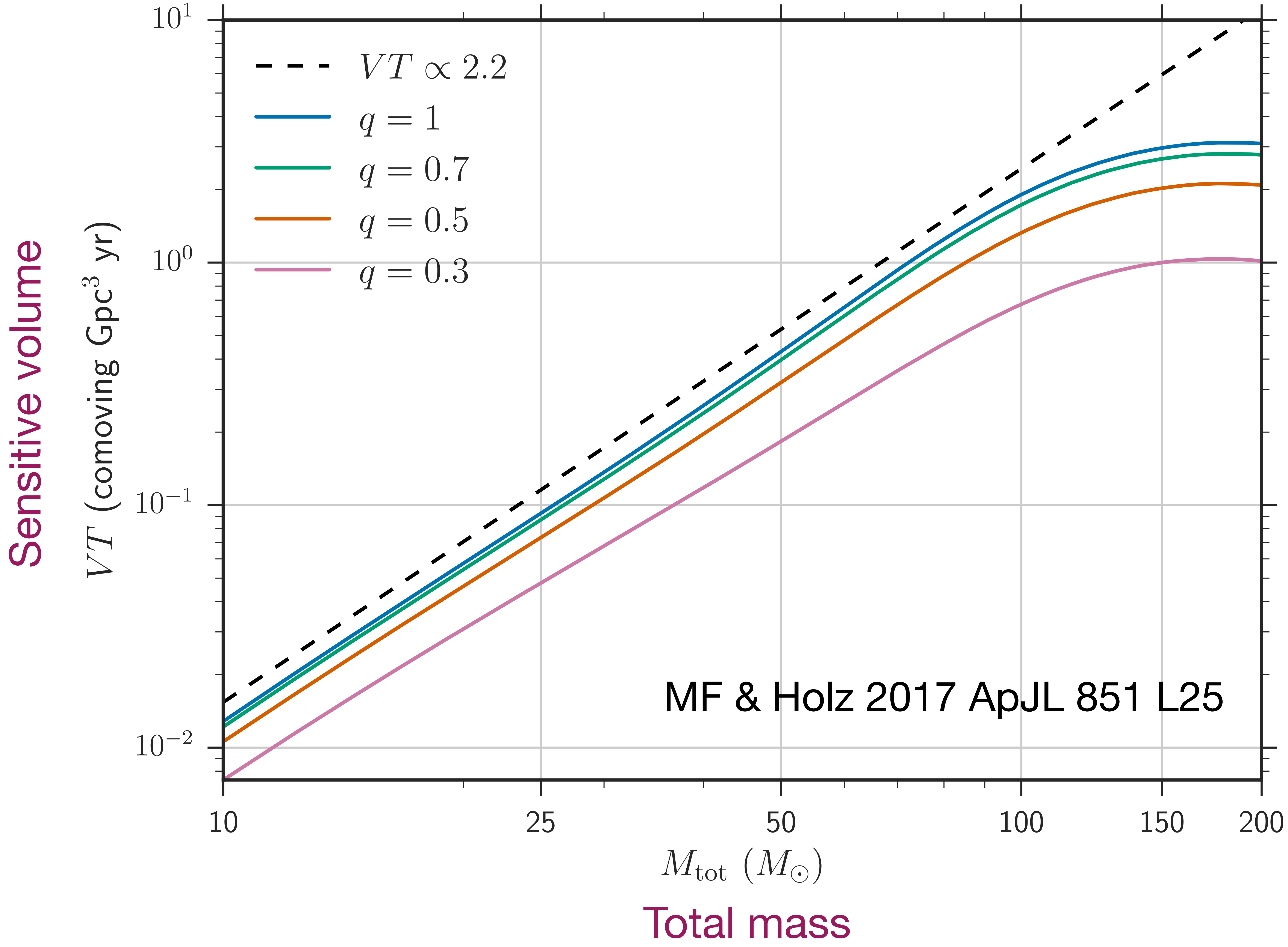
Three Challenges

To account for when recovering the population distribution of binary black holes

1. The parameters of individual systems are uncertain
2. Some systems are easier to detect than others (selection effects)
3. Our models may not match the true population distribution (necessitates model checking)

Example of selection effects:

Big black holes are louder than small black holes

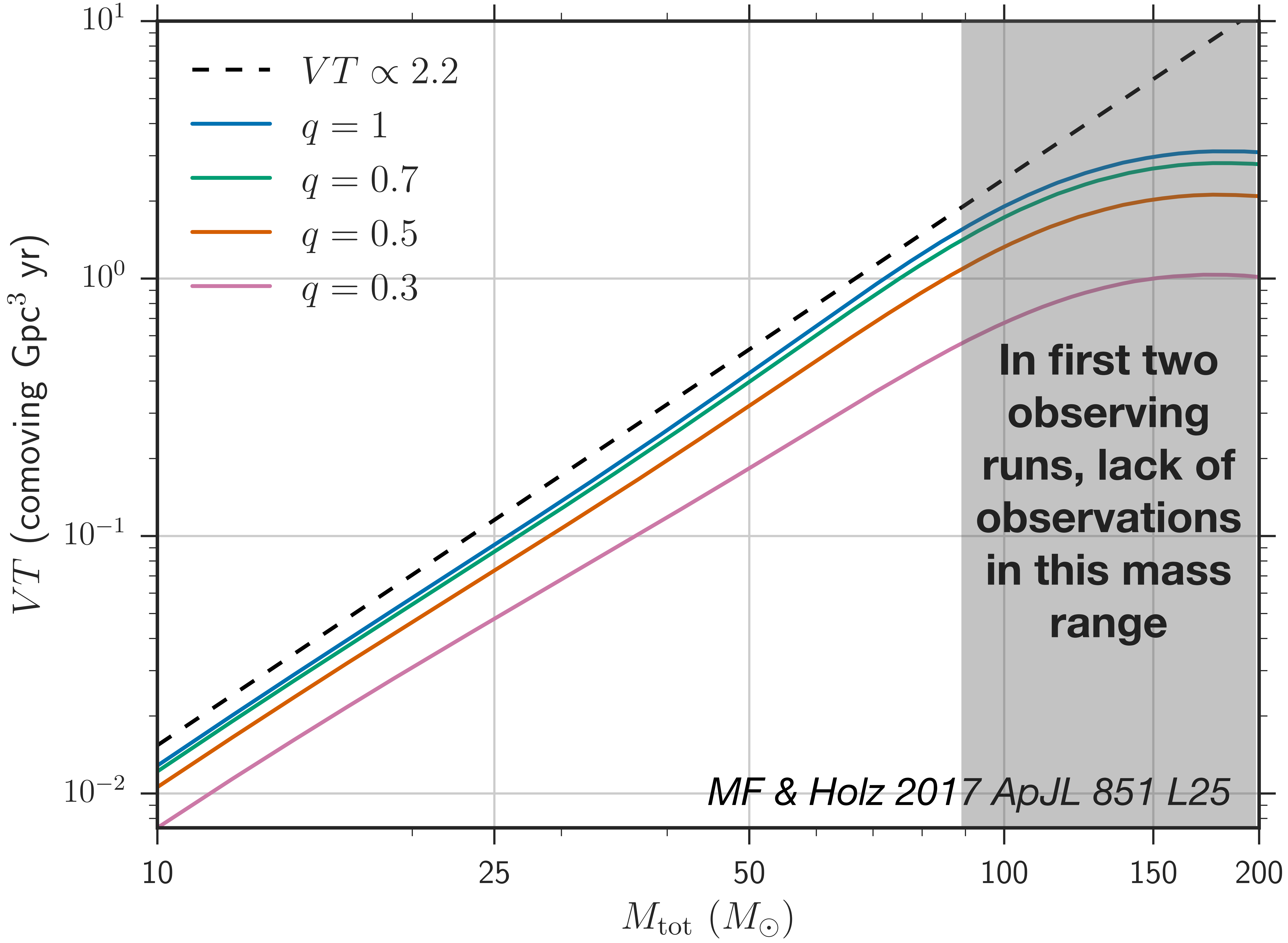


Astrophysical Lesson #1:
Dearth of big black holes in the black hole population

Where are LIGO's big black holes?

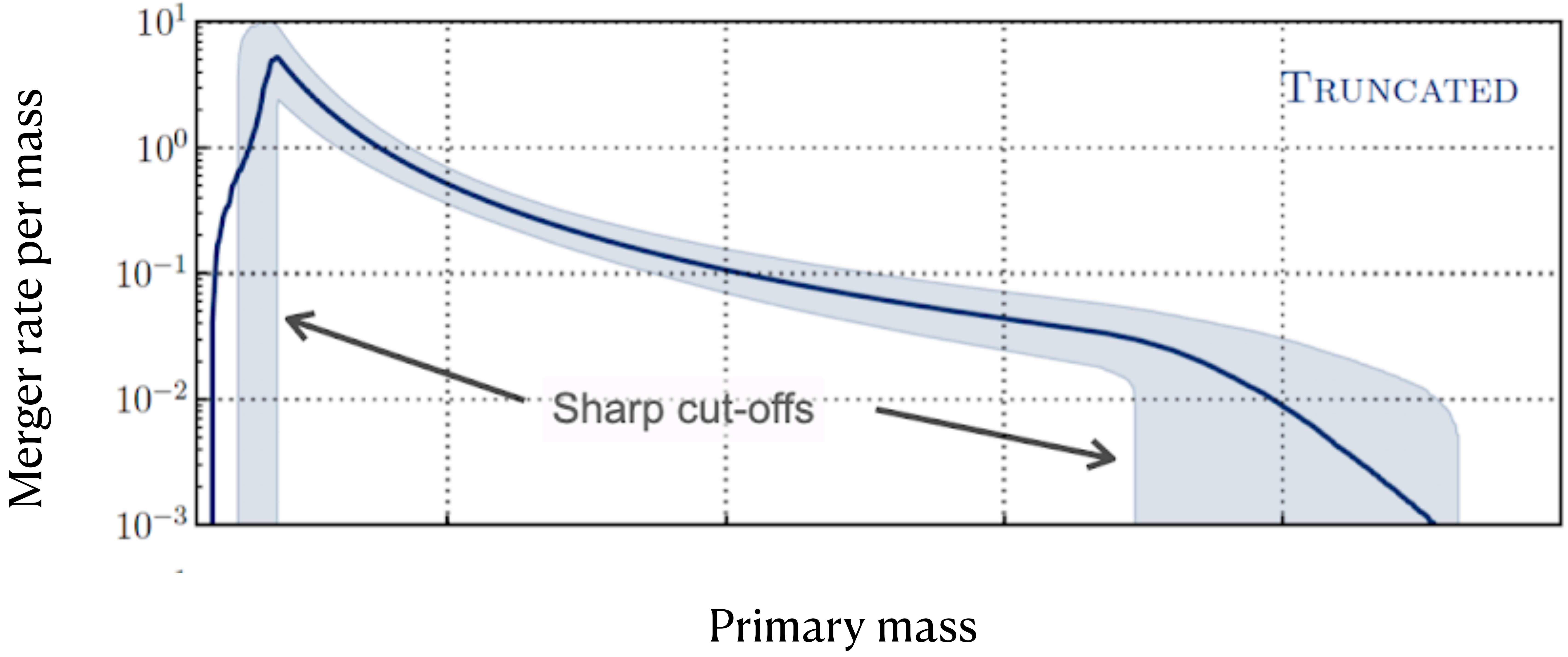
Big black holes are very loud, and yet we did not see any binary black holes with component masses above ~45 solar masses in the first two observing runs.

→ *These systems must be rare in the underlying population.*



With the first 10 binary black holes, we measured the maximum black hole mass to be ~40 solar masses

The black hole masses we observed were consistent with coming from a truncated power law distribution



Abbott+ arXiv:2010.14533

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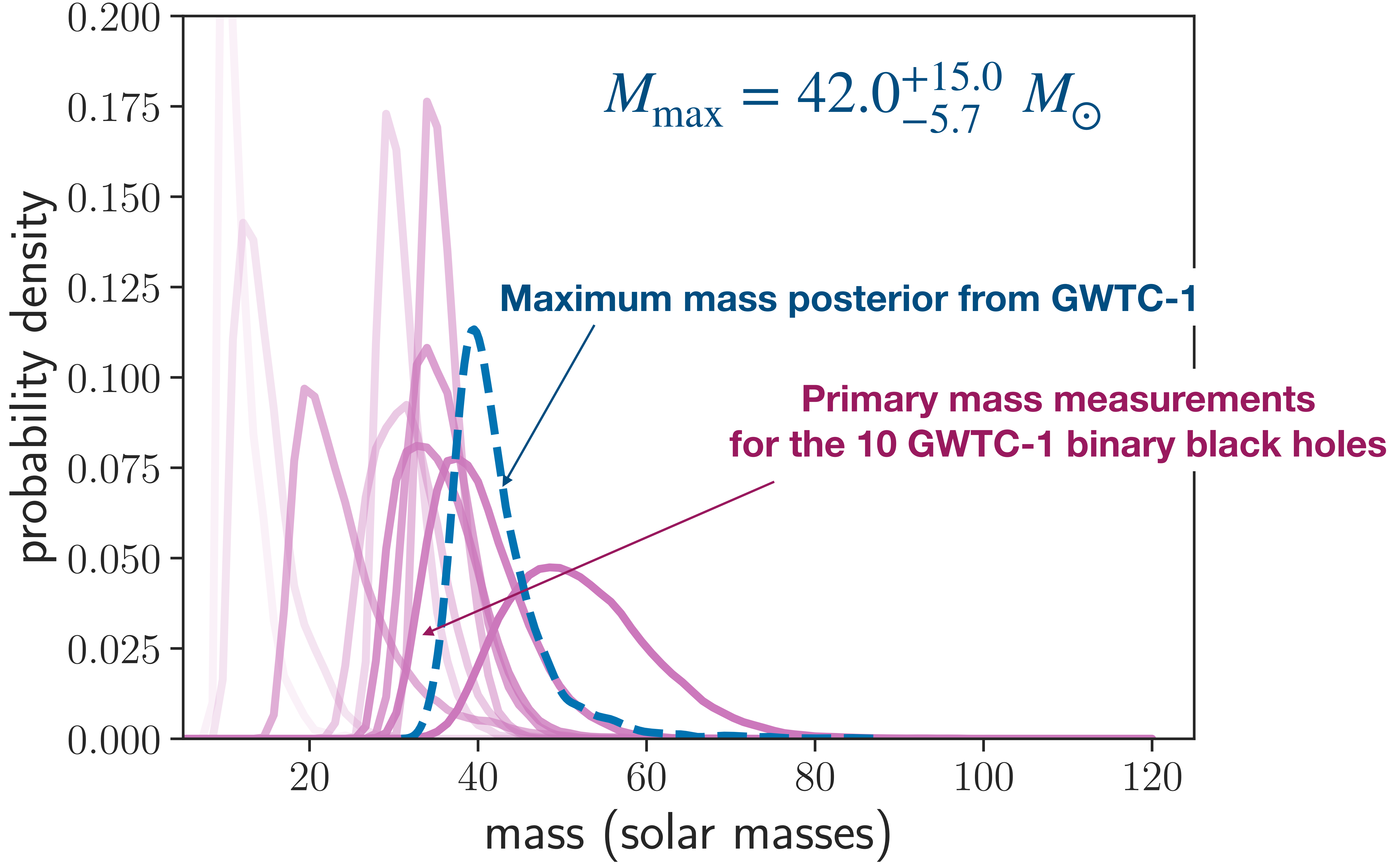
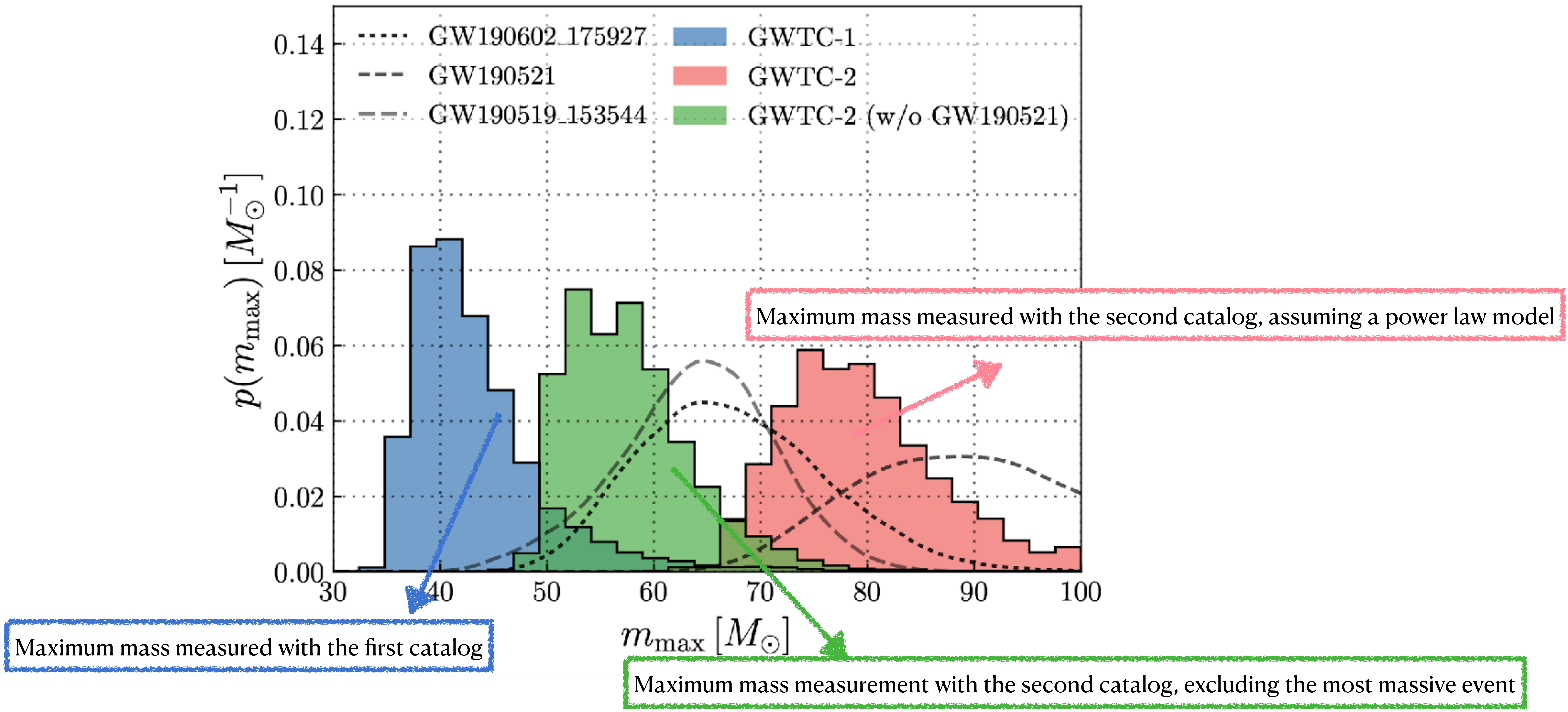


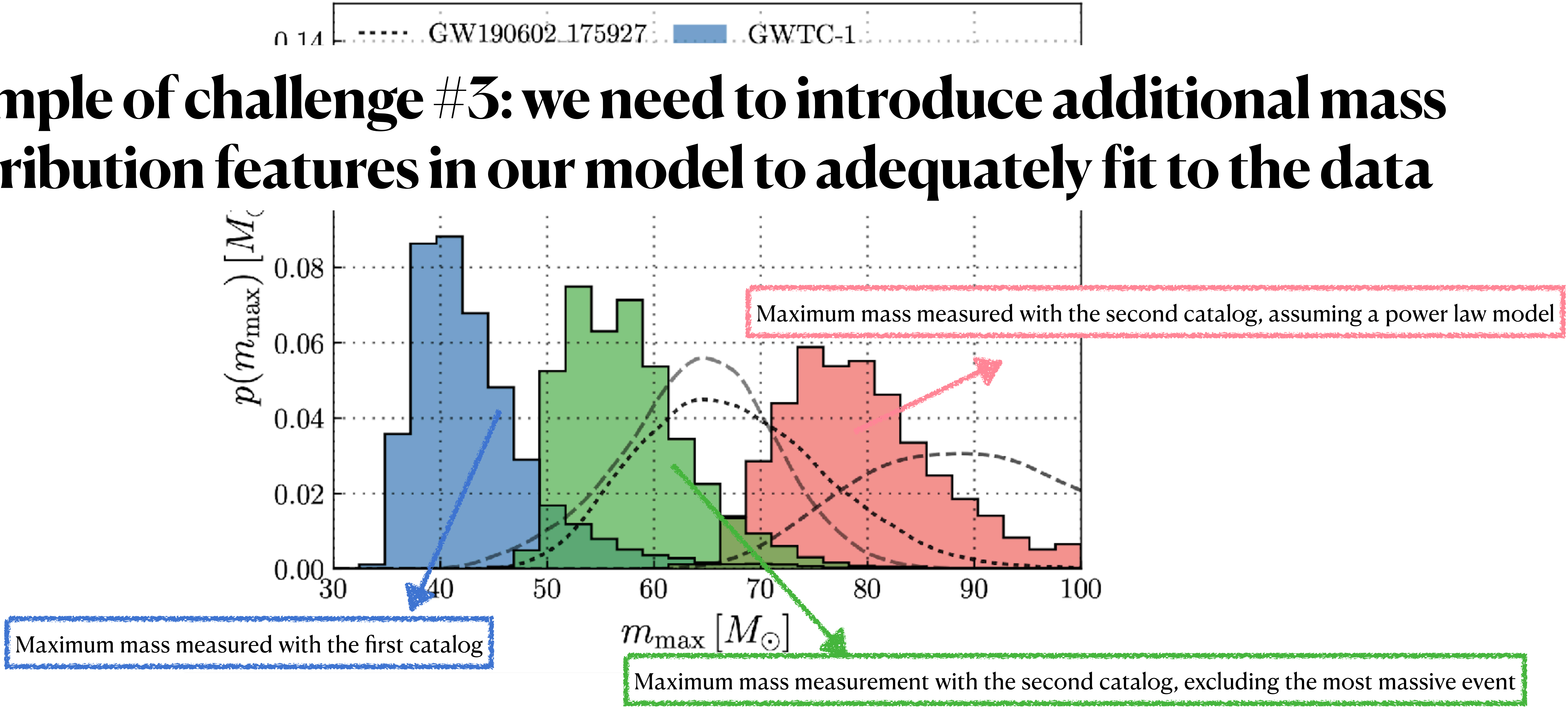
We now know that ~40 solar masses is not a sharp limit: there are bigger black holes out there!



Abbott+ arXiv:2010.14533

We now know that ~40 solar masses is not a sharp limit: there are bigger black holes out there!

Example of challenge #3: we need to introduce additional mass distribution features in our model to adequately fit to the data

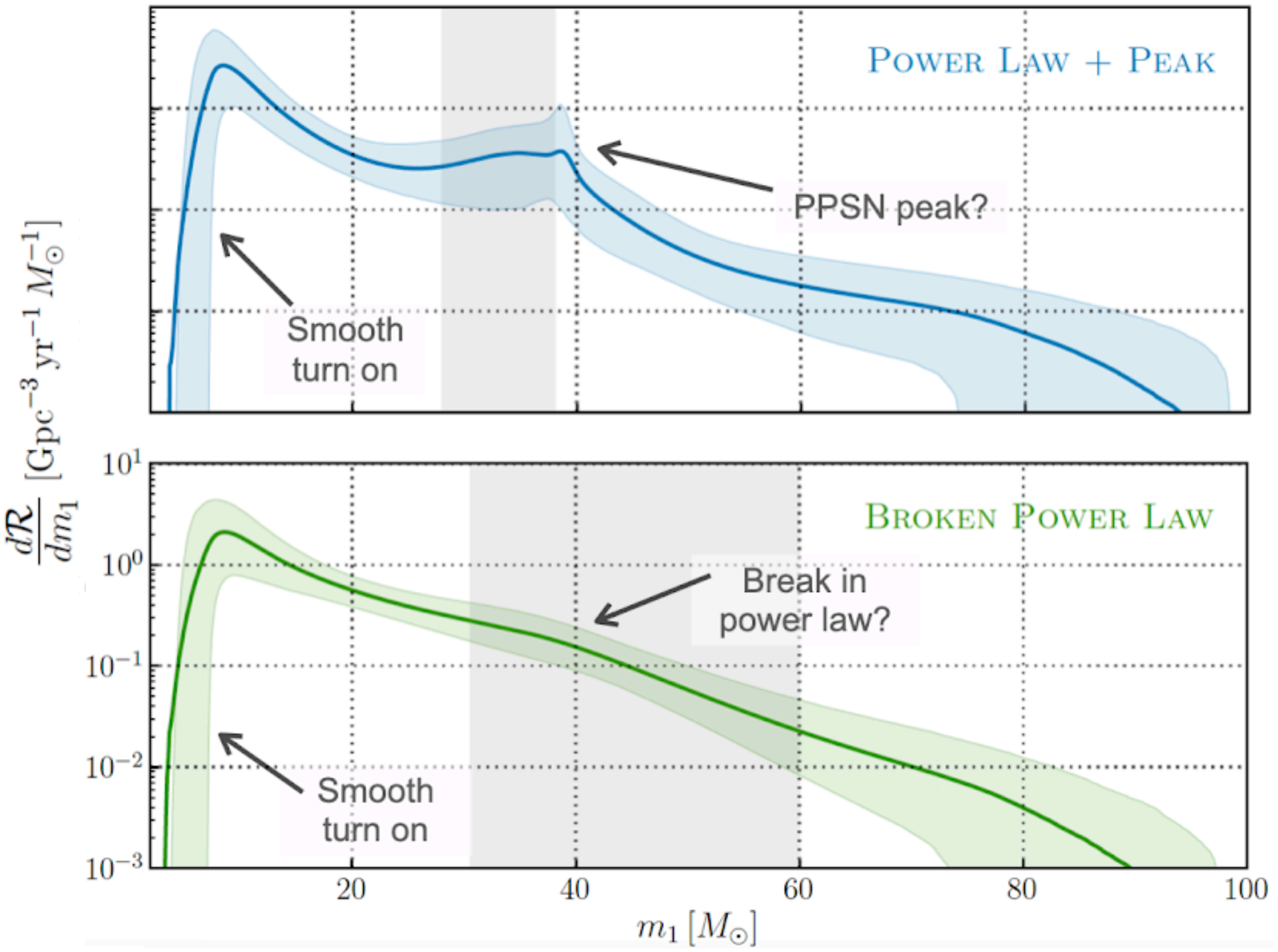


Abbott+ arXiv:2010.14533

Nevertheless, there is a feature in the black hole mass distribution at ~40 solar masses

With the third observing run, we know that big black holes are not *absent*, but they are *rare*

- A truncated power law with sharp cutoffs fails to fit the data
- We must introduce additional features, like a *Gaussian peak* or a *break* in the power law
- The black hole mass distribution steepens at ~40 solar masses



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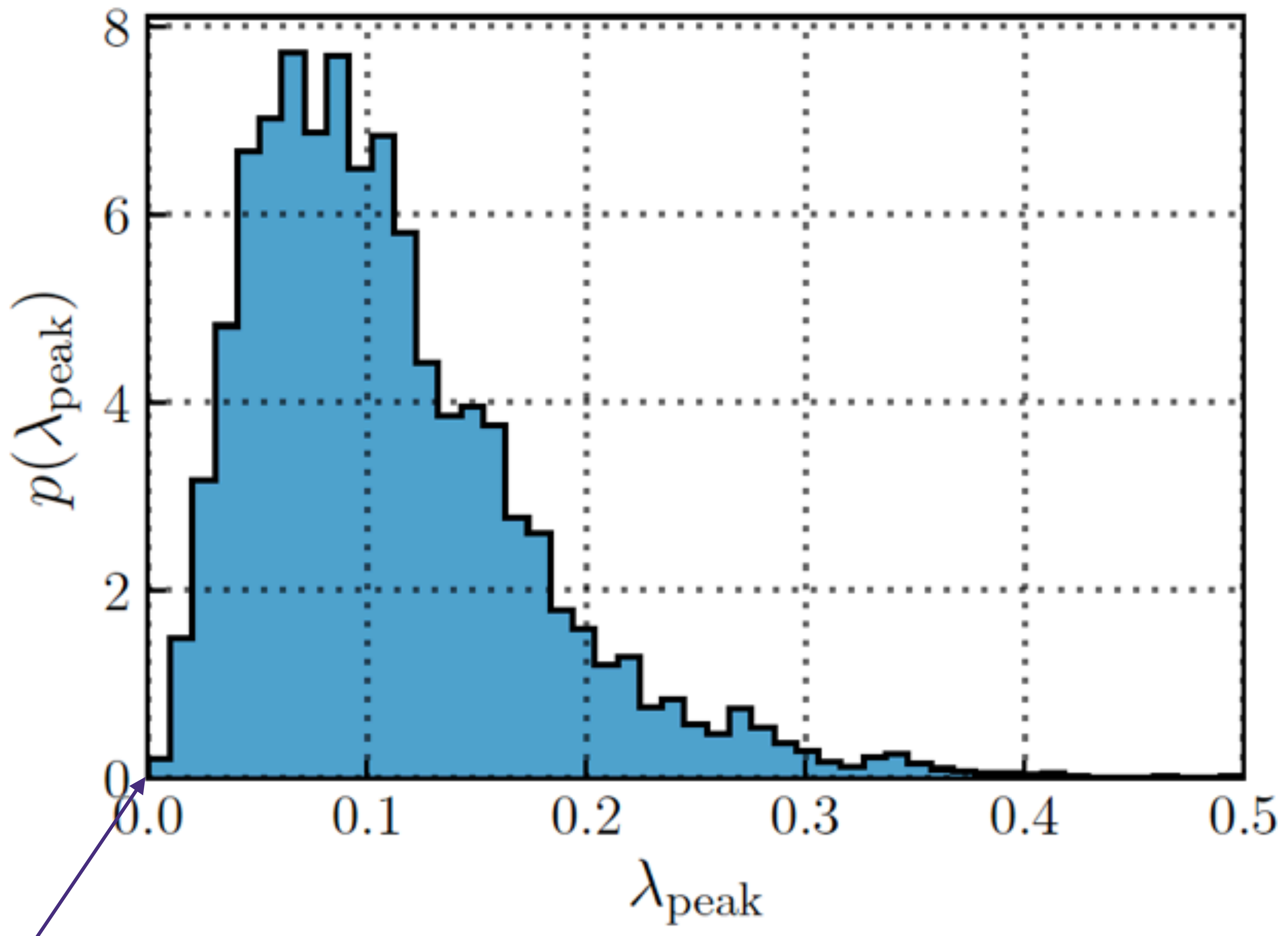
Multiple observations allow us to resolve detailed features of the black hole mass distribution

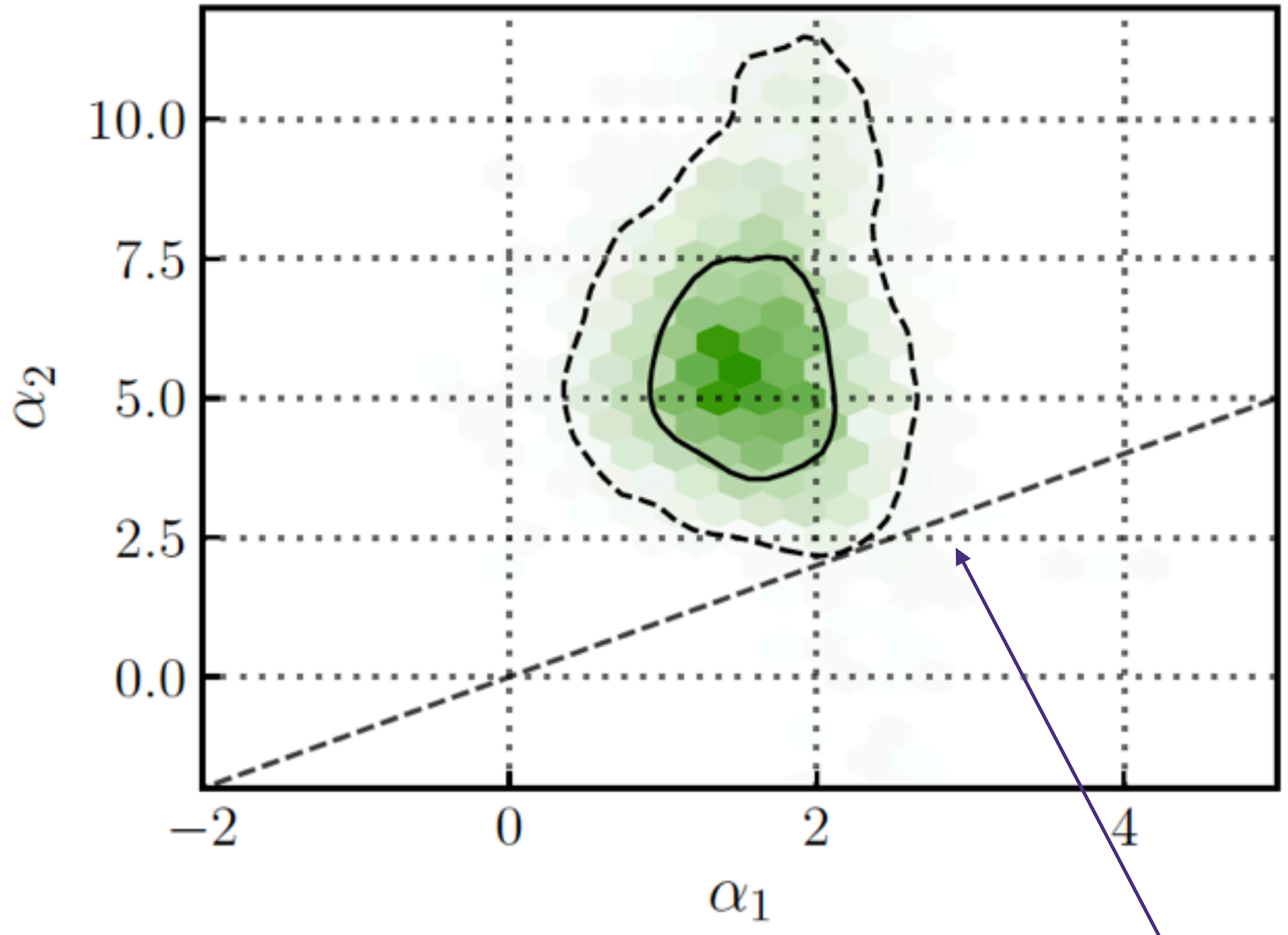
Power law + peak



Fraction of black holes in the Gaussian component

Excludes 0

Broken power law



Power law index above the break

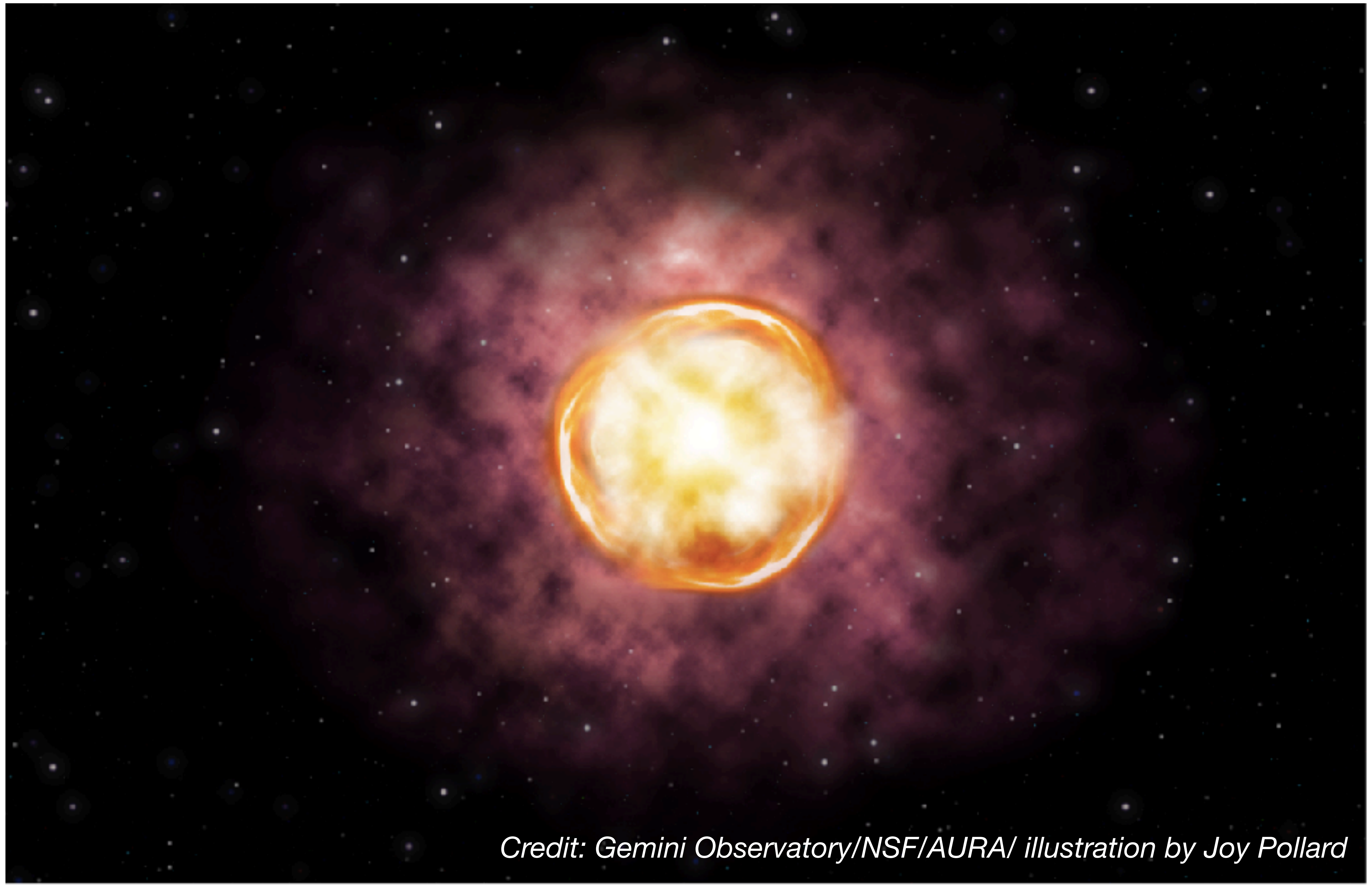
Power law index below the break

Excludes a single power law (equal indices)

Abbott+ arXiv:2010.14533

Astrophysical Implications:
Feature at ~40 solar masses caused by pair-instability supernova?

- (Pulsational) pair-instability supernovae predict an absence of black holes in the range ~40 - 120 solar masses
- Applies to black holes formed from stellar collapse
- Are black holes above this limit formed via a different channel? (E.g., from smaller black holes?) Or perhaps the limit is not as sharp as we thought? Further measurements will help us resolve this question.



Credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

Astrophysical Lesson #2:

Black hole spins are not always aligned with the orbital angular momentum

- The gravitational-wave signal can be parameterized by two "effective" spins:
  - The effective inspiral spin measures the total spin along the orbital angular momentum axis

$$\chi_{\rm eff} = \frac{m_1\,\chi_1 \cos\theta_1 + m_2\,\chi_2 \cos\theta_2}{m_1 + m_2}$$

  - The effective precessing spin measures the spin in the orbital plane, perpendicular to orbital angular momentum axis

$$\chi_{\rm p} \sim \chi_1 \sin\theta_1$$

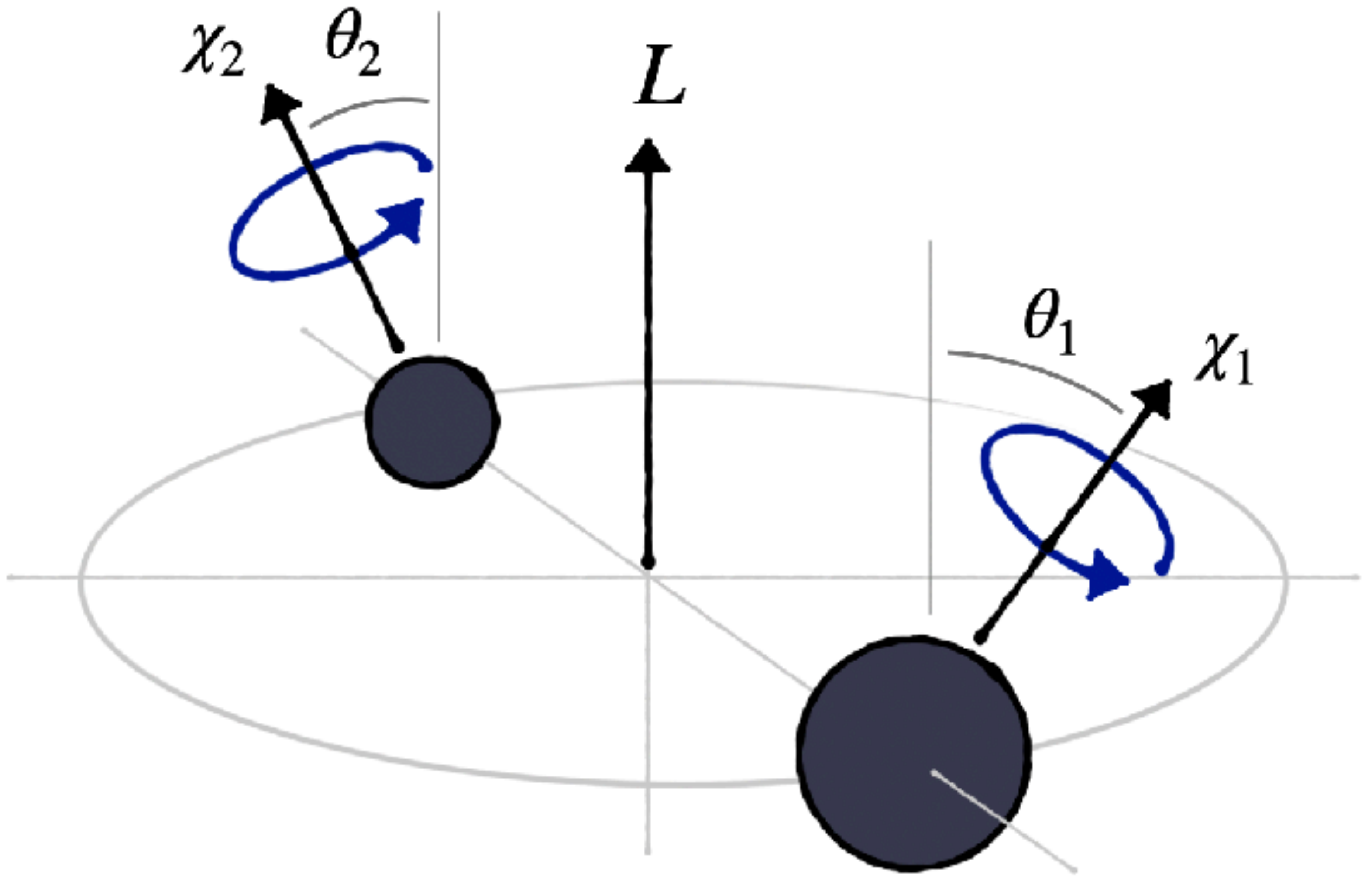
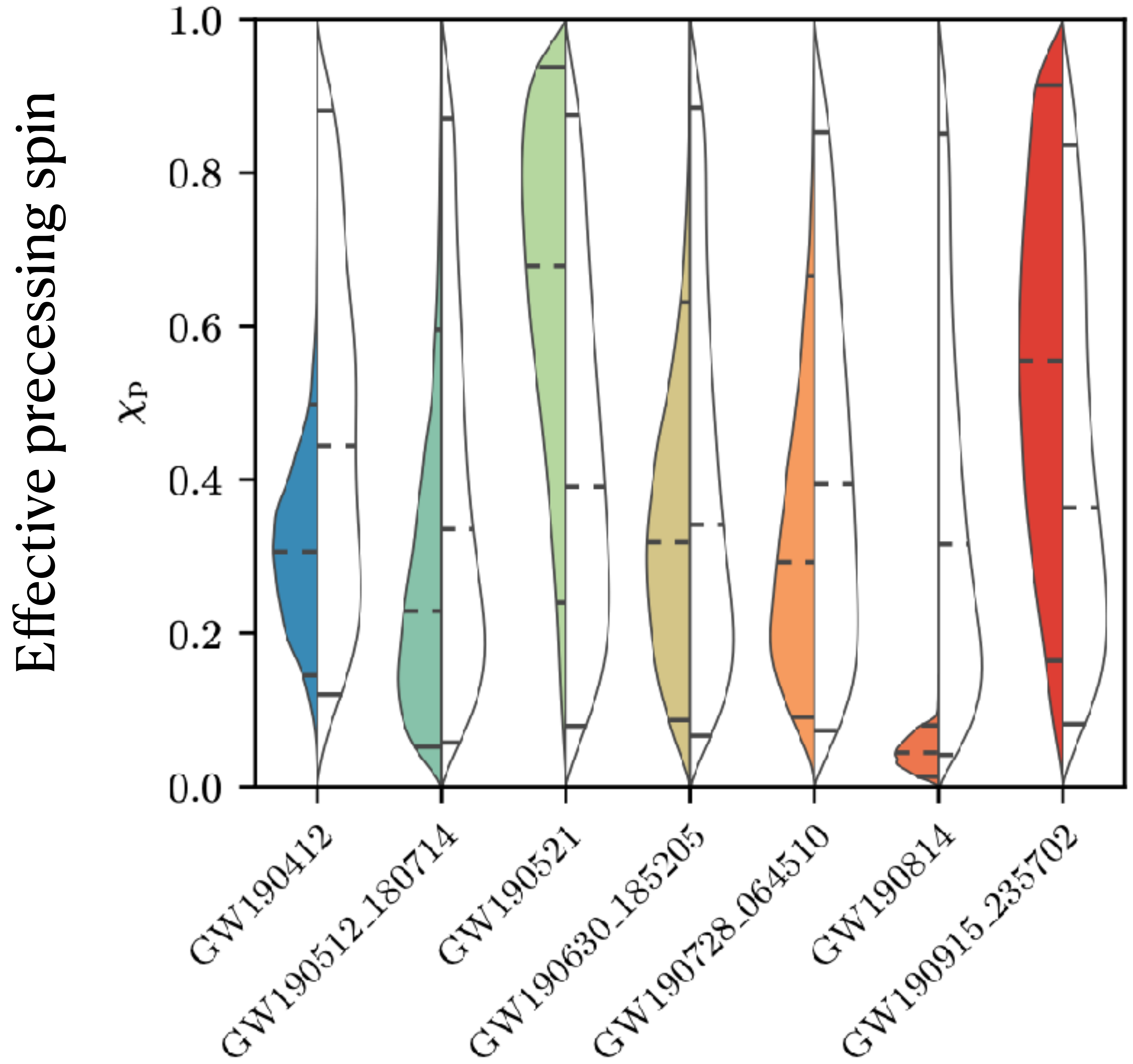


Figure credit: Thomas Callister

For individual events, in-plane spins tend to be poorly constrained

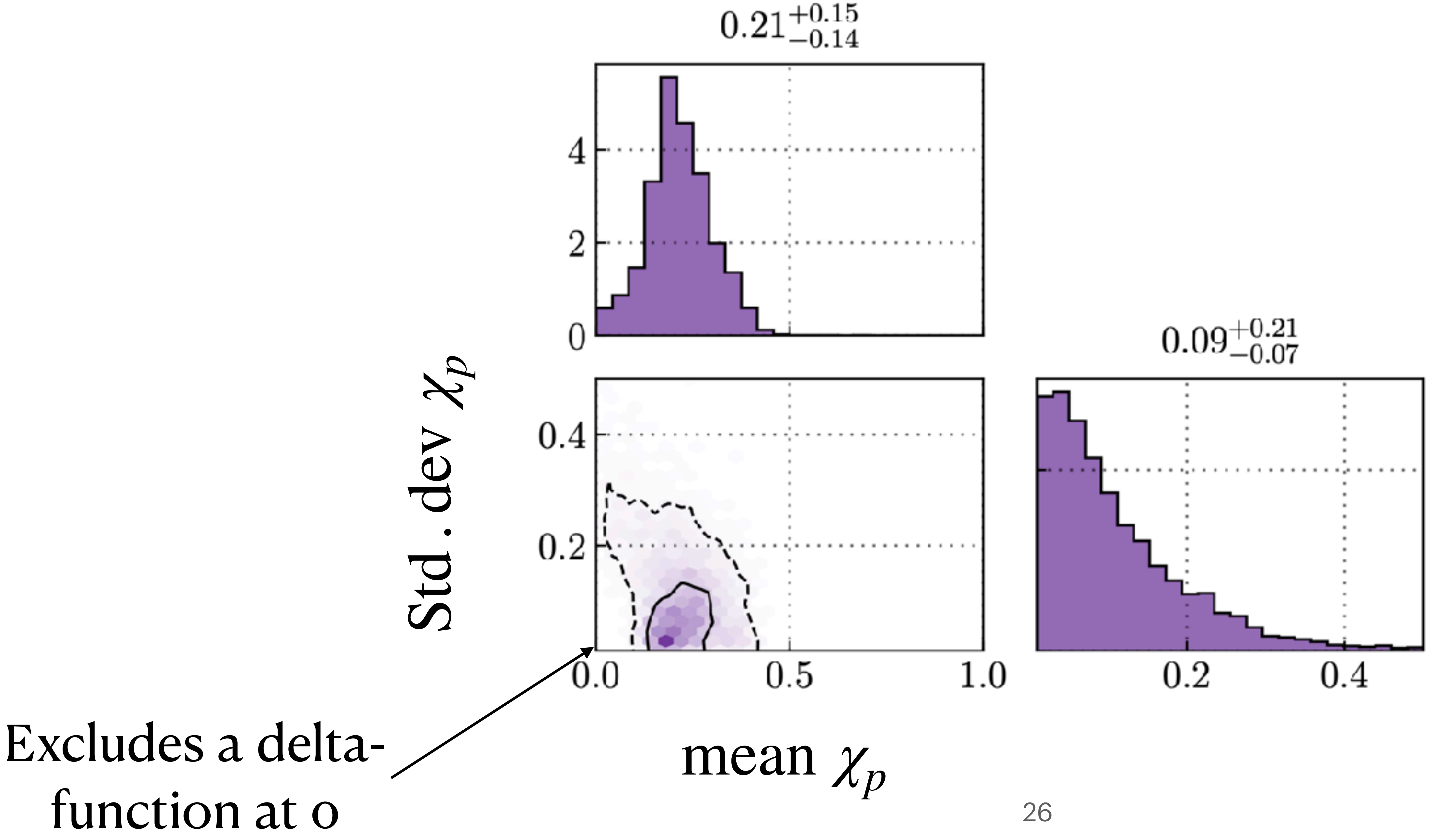
Individually, no system shows strong evidence for in-plane spins



Abbott+ arXiv: 2010.14527

On a population level, we find that some systems have in-plane spins ($\chi_p > 0$)

We measure the *mean* and *standard deviation* of the distribution of χ_p across all events, assuming a Gaussian distribution



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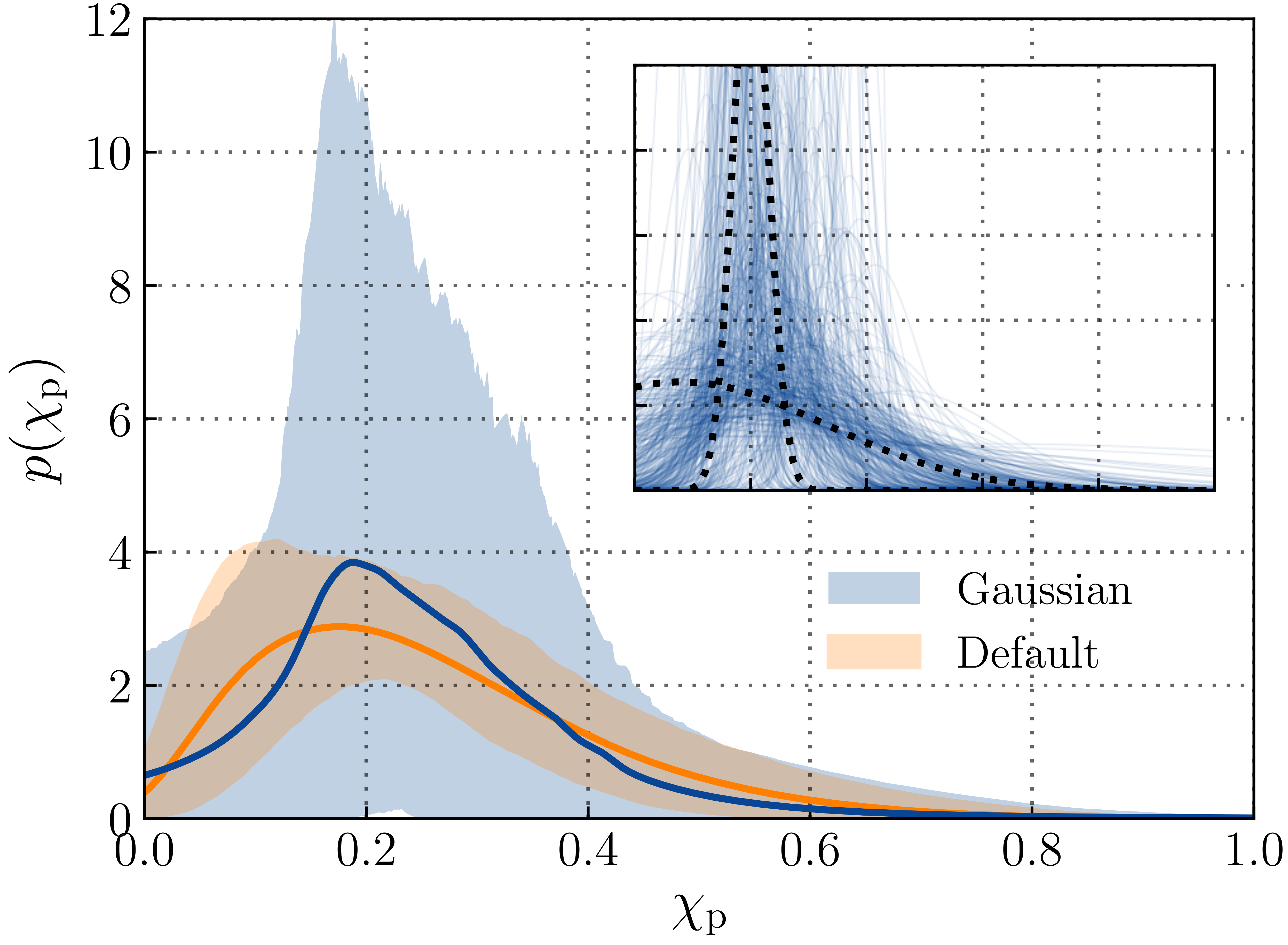


Abbott+ arXiv:2010.14533

Astrophysical Implications of Misaligned Spins

Spin misalignments can be used to distinguish formation channels

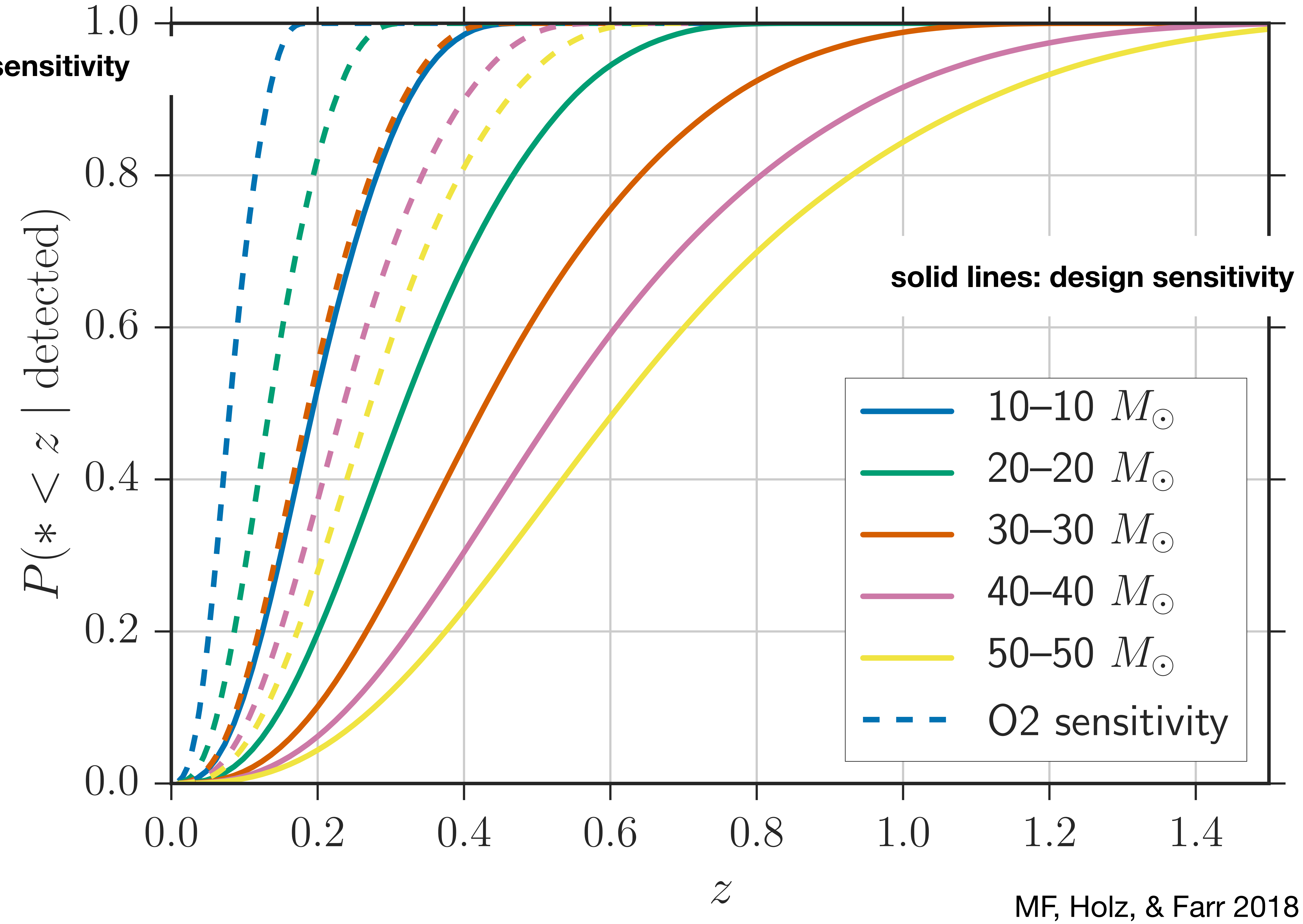
- **Isolated field formation:** typically difficult to get large misalignments, but depends on uncertain physics like black hole natal kicks, efficiency of tides
- **Dynamical assembly:** typically expect random spin orientations, but this can depend on whether the environment is gaseous (e.g. AGN disks)

Astrophysical Lesson #3:

Measuring the black hole merger rate across cosmic time

dashed lines: O2 sensitivity

cumulative distribution in redshift for detected binaries of a fixed mass



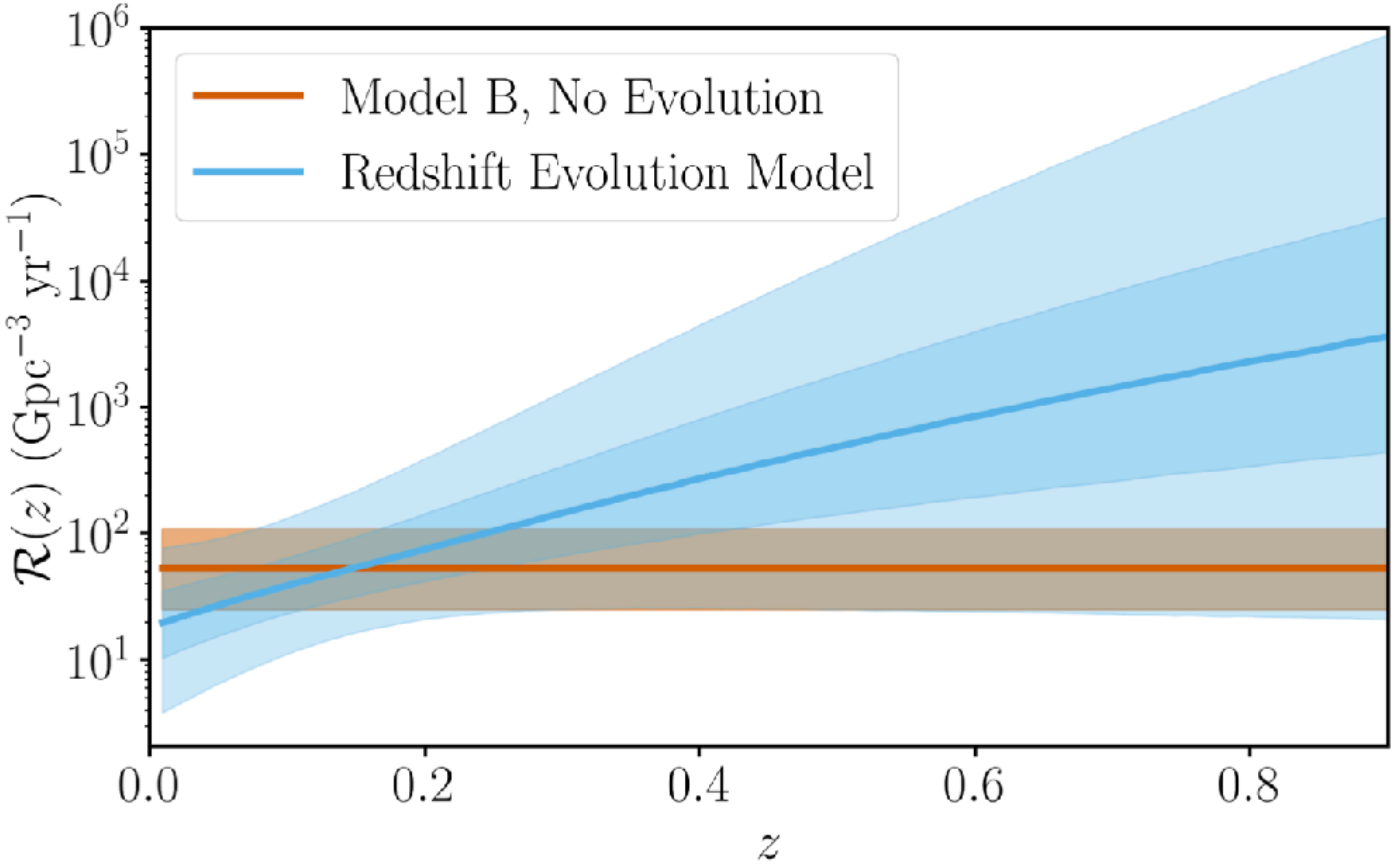
solid lines: design sensitivity

MF, Holz, & Farr 2018 ApJL 863 L41

Merger rate of black hole mergers across cosmic time:

Inference from the first 10 binary black holes

- Allowing the merger rate to evolve with redshift, GWTC-1 found:
  - Today ($z = 0$), the merger rate is between [4, 77] $Gpc^{-3}\ yr^{-1}$
  - 8 billion years ago *($z = 1$)*, the merger rate was higher, but uncertain by more than 4 orders of magnitude

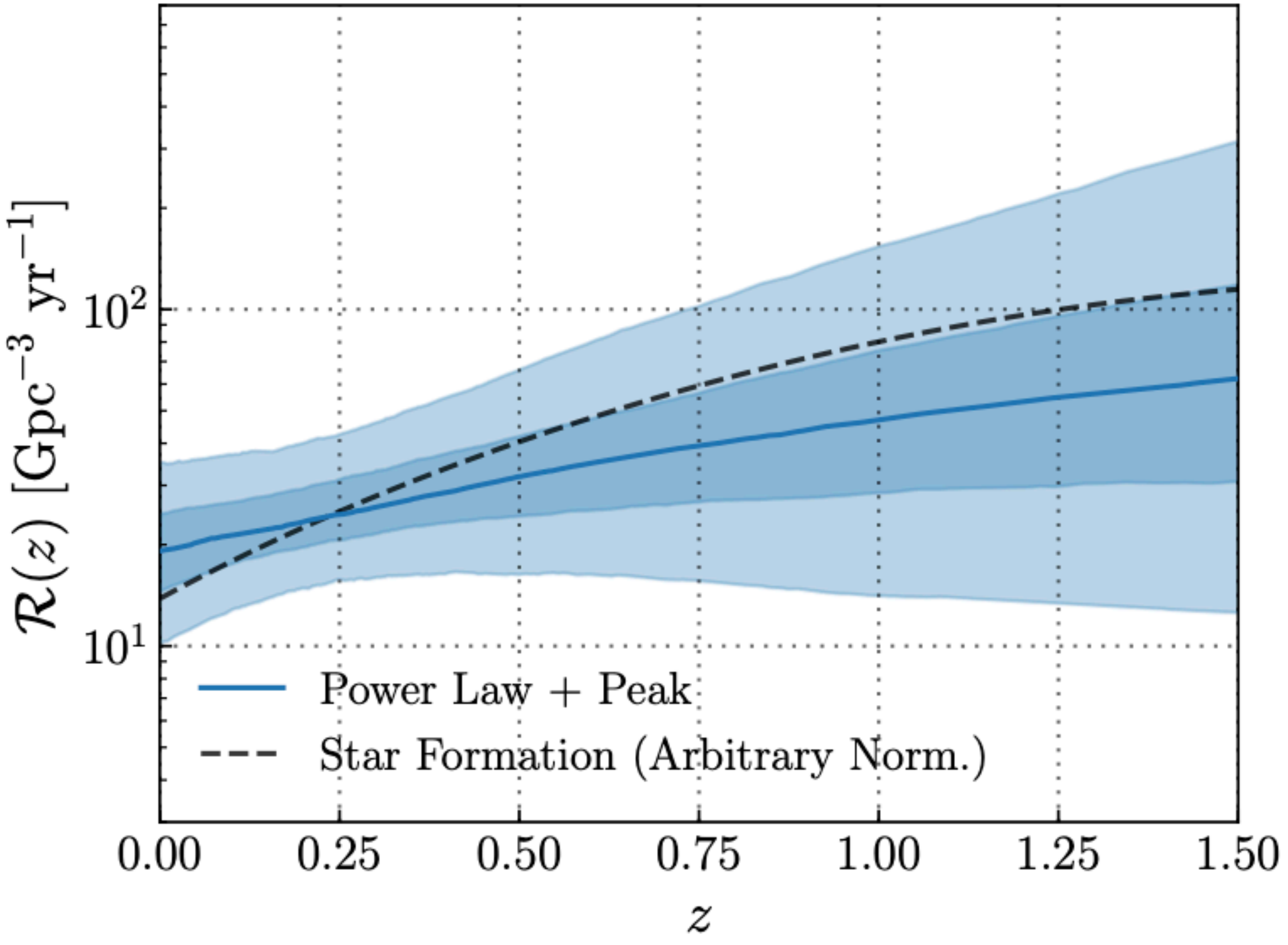


Abbott+ 2019 *ApJL* **882** L24

Merger rate of black hole mergers across cosmic time:

Updated inference from GWTC-2

- With GWTC-2, we now know:
  - Today (z = 0), the merger rate is between [10, 35] $Gpc^{-3}\ yr^{-1}$
  - 8 billion years ago *(z = 1),* the merger rate was between 0.6 and 10 times its present rate — a significant improvement in the measurement from GWTC-1!

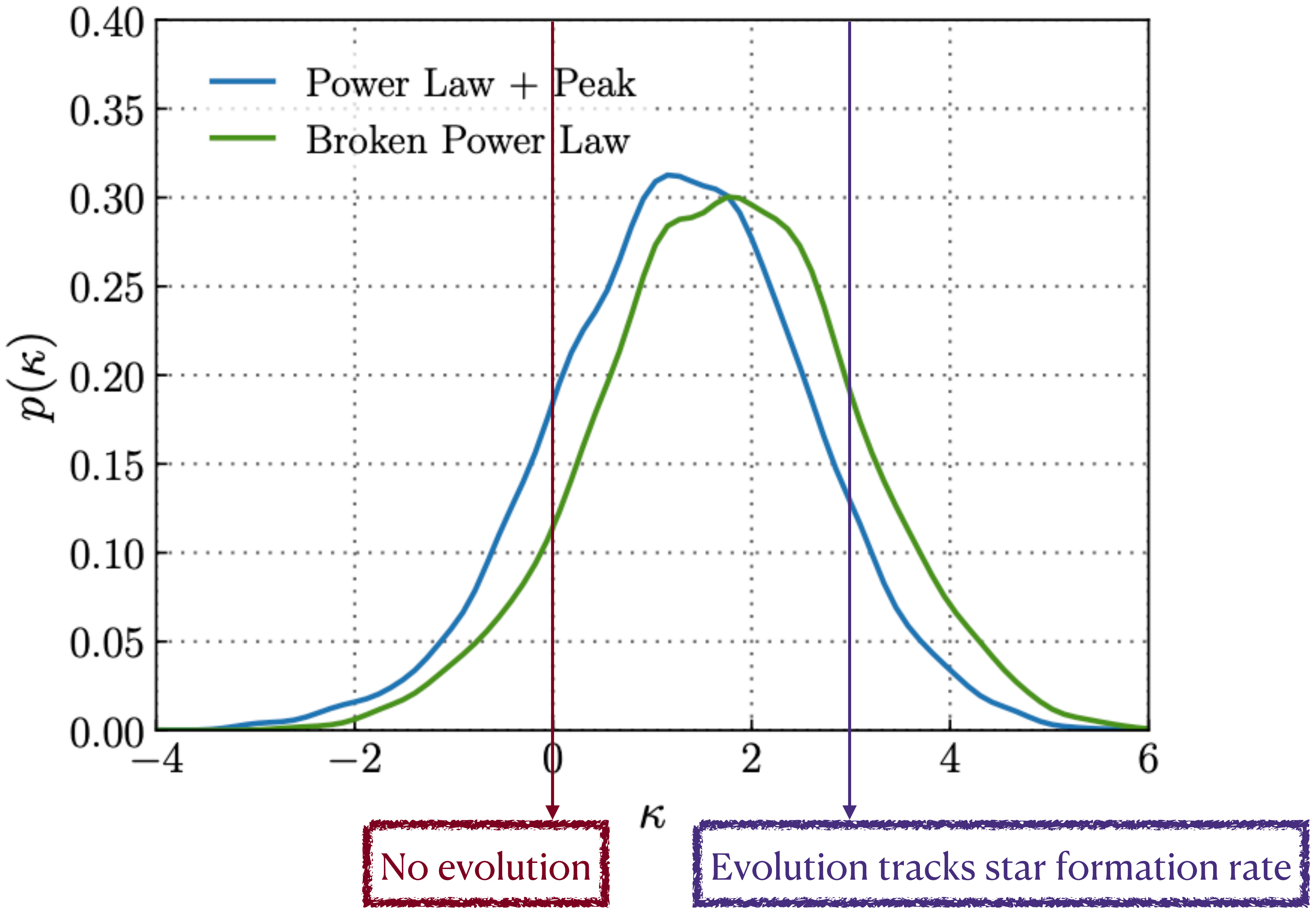


Abbott+ arXiv:2010.14533

Astrophysical Implications:

The binary black hole merger rate evolves, but slower than the star formation rate

- Assume that the rate ***R*** as a function of redshift z is described by $\boldsymbol{R}(z) = (1+z)^K$
- Measure the slope K
- The most likely values are between 0 (no evolution) and 2.7 (approximating the star-formation rate)



Other astrophysical lessons in the gravitational wave data so far

Masses

- **The black hole mass spectrum *does not* terminate abruptly at 45 solar masses**, but *does* show a feature at ~40 solar masses, which can be represented by a *break* in the power law or a Gaussian *peak*.
- **There is a dearth of low-mass black holes** between 2.6 solar masses and ~6 solar masses.
- **The distribution of mass ratios is broad** in the range ~0.3-1, with a mild preference for equal-mass pairings. (GW190814 is an outlier.)

Spins

- Some binary black holes have measurable in-plane spin components, leading to **precession of the orbital plane**.
- Some binary black holes have spins **misaligned by more than 90 degrees**, but the distribution of spin tilts is not perfectly isotropic.
- There are hints, but **no clear evidence that the spin distribution varies with mass**.

Rate across cosmic time

- In the local universe, the average **binary black hole merger rate is between 15 and 40 $\mathrm{Gpc^{-3}\,yr^{-1}}$**
- The binary black hole merger rate **probably evolves with redshift, but slower than the star-formation rate**, increasing by a factor of ~2.5 between $z = 0$ and $z = 1$.

Challenges to keep in mind

- **Parameter estimation**: The parameters of individual events are uncertain due to noise, and possibly due to systematics in our waveform models. (Aside: measuring the population distribution allows us to better infer the individual event parameters as well, by employing a population-informed prior.)
- **Selection effects**: We must quantify the sensitivity of our searches to gravitational-wave sources across parameter space, e.g. via an injection campaign.
- **Modeling systematics**: We must check that our population models adequately fit the data, by e.g. carrying out posterior predictive checks, checking robustness to outliers.

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Thank you! Questions?