Astrophysical Lessons from LIGO/Virgo's Black Holes

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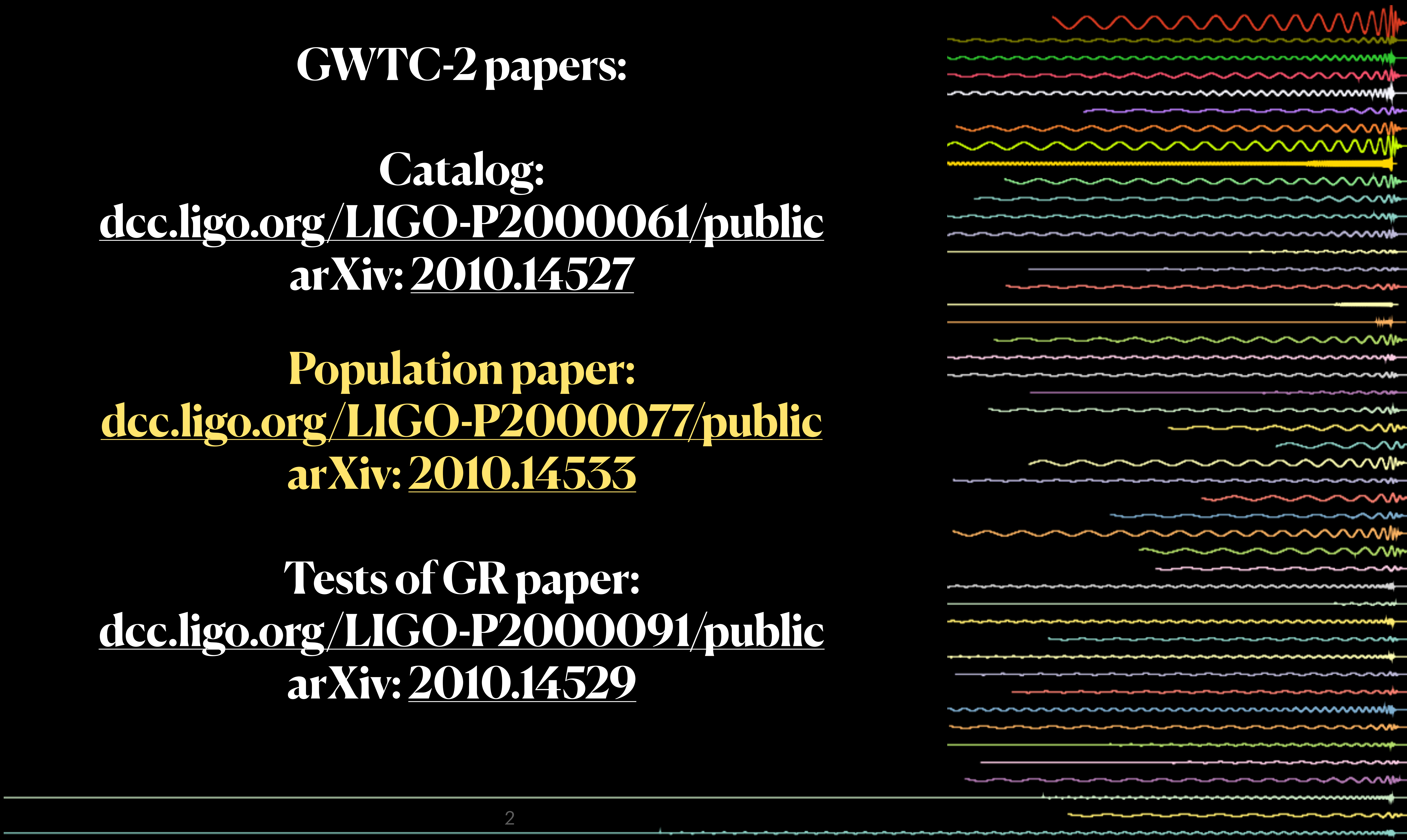
LIGO and Virgo have observed gravitational waves from ~50 mergers



GWTC-2 papers:

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

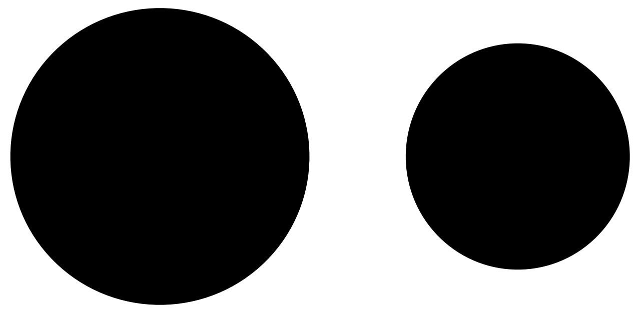
Population paper:
dcc.ligo.org/LIGO-P2000077/public
arXiv: 2010.14533

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

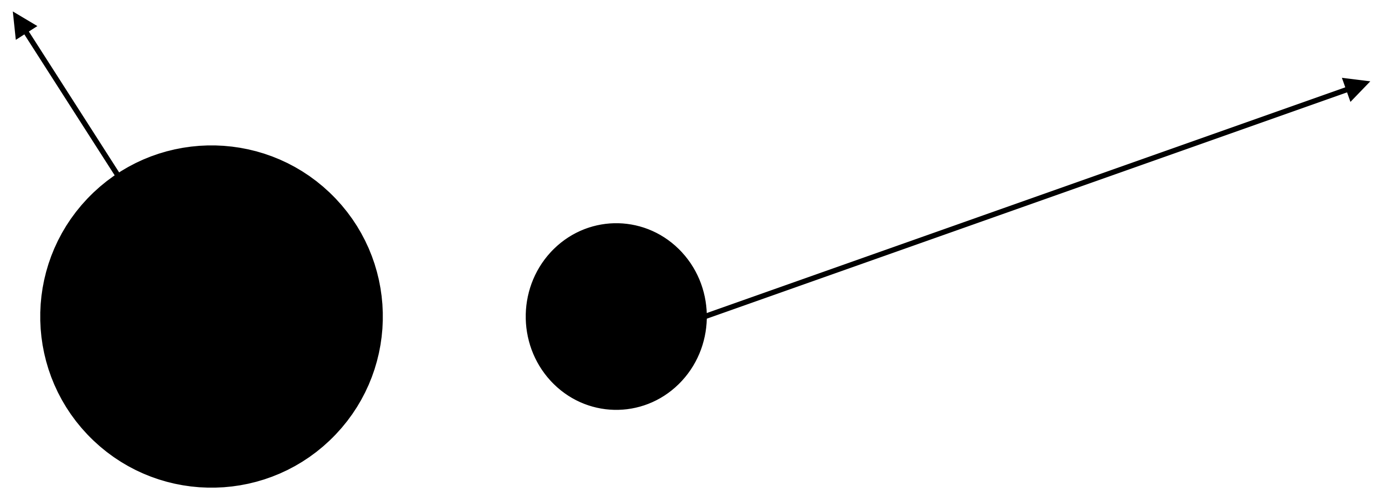
Credit: Chris North & Stuart Lowe,
https://waveview.cardiffgravity.org

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

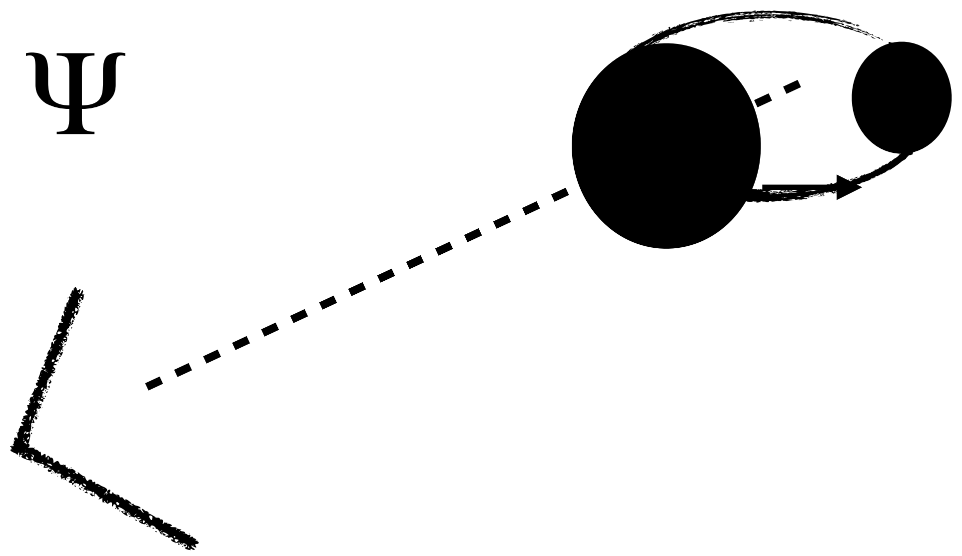
- The masses of the two components $m_1 \geq m_2$



- 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*

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**

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**.

Merger rate across cosmic time

- In the local universe, the average **binary black hole merger rate is between 15 and 40 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$**
- 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 $z = 1$.

Three Astrophysical Lessons

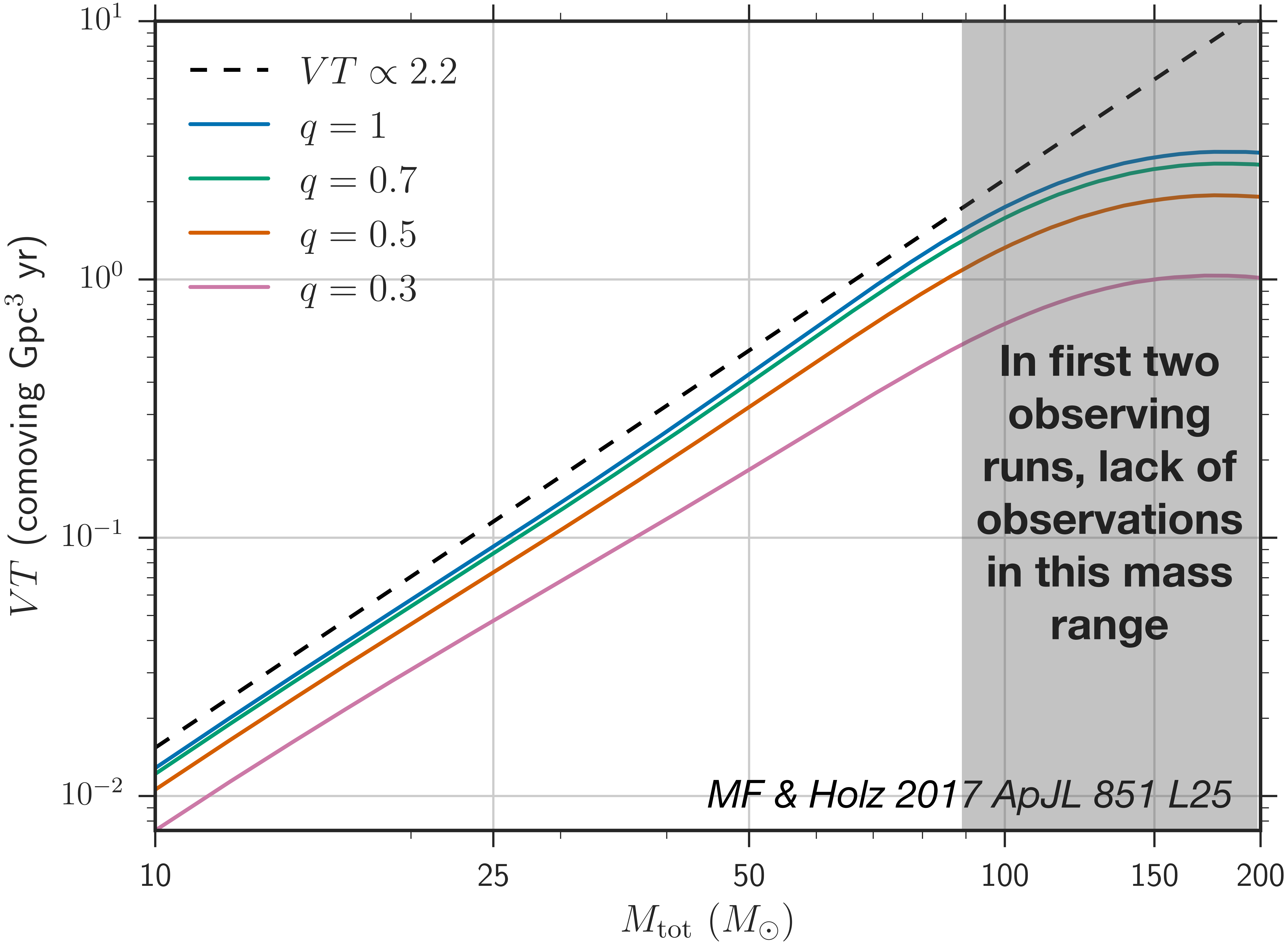
1. A feature in the mass distribution at ~40 solar masses
2. Highly misaligned black hole spins
3. Black hole merger rate across cosmic time

Astrophysical Lesson #1:
Feature at ~40 solar masses

Where are LIGO's big black holes?

Big black holes are very loud, and yet in GWTC-1, we did not see any binary black holes with component masses above ~45 solar masses

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

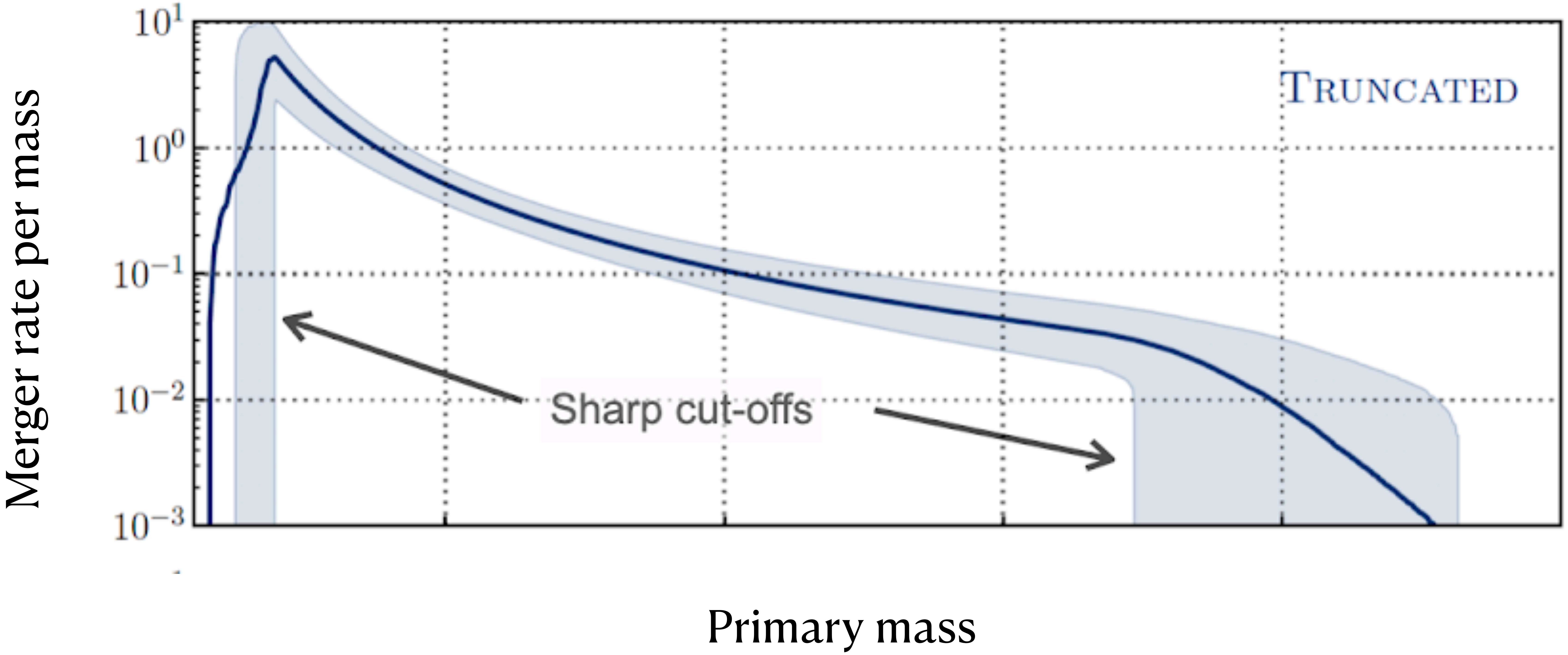


In first two observing runs, lack of observations in this mass range

MF & Holz 2017 ApJL 851 L25

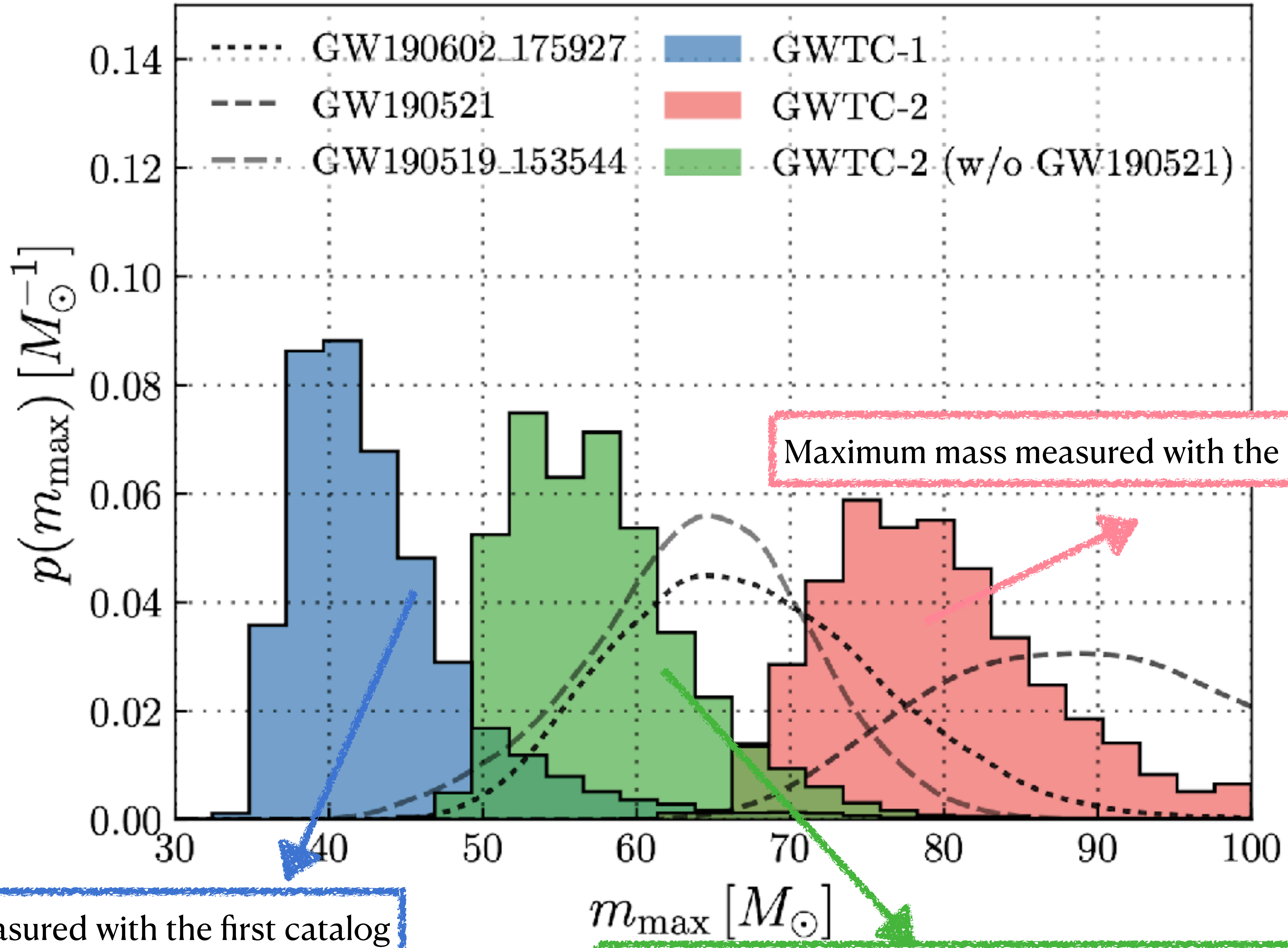
With the first 10 binary black holes, we measured the maximum black hole mass to be ~40 solar masses

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



Abbott+ arXiv:2010.14533

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



Maximum mass measured with the second catalog, assuming a power law model

Maximum mass measured with the first catalog

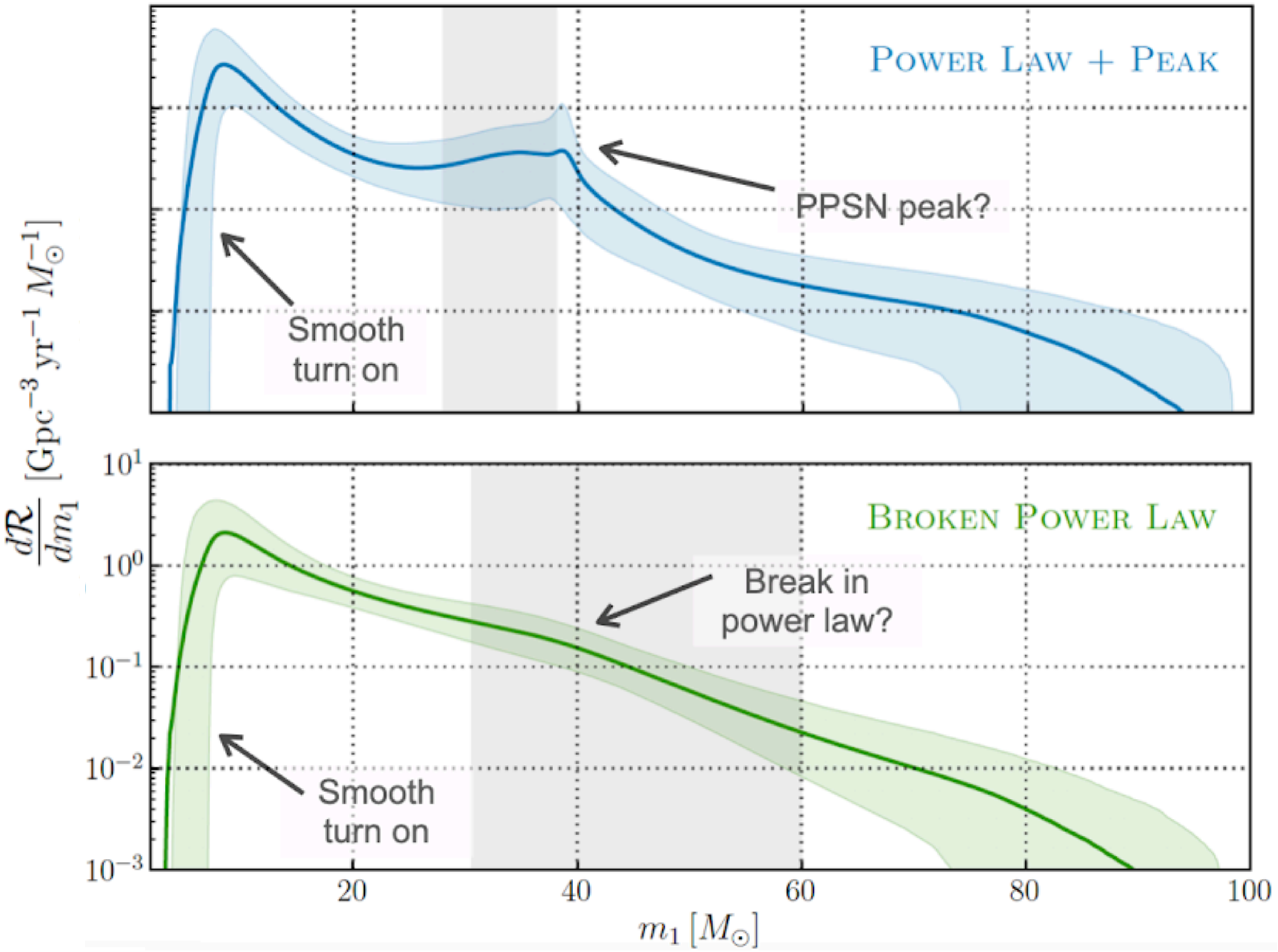
Maximum mass measurement with the second catalog, excluding the most massive event

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*

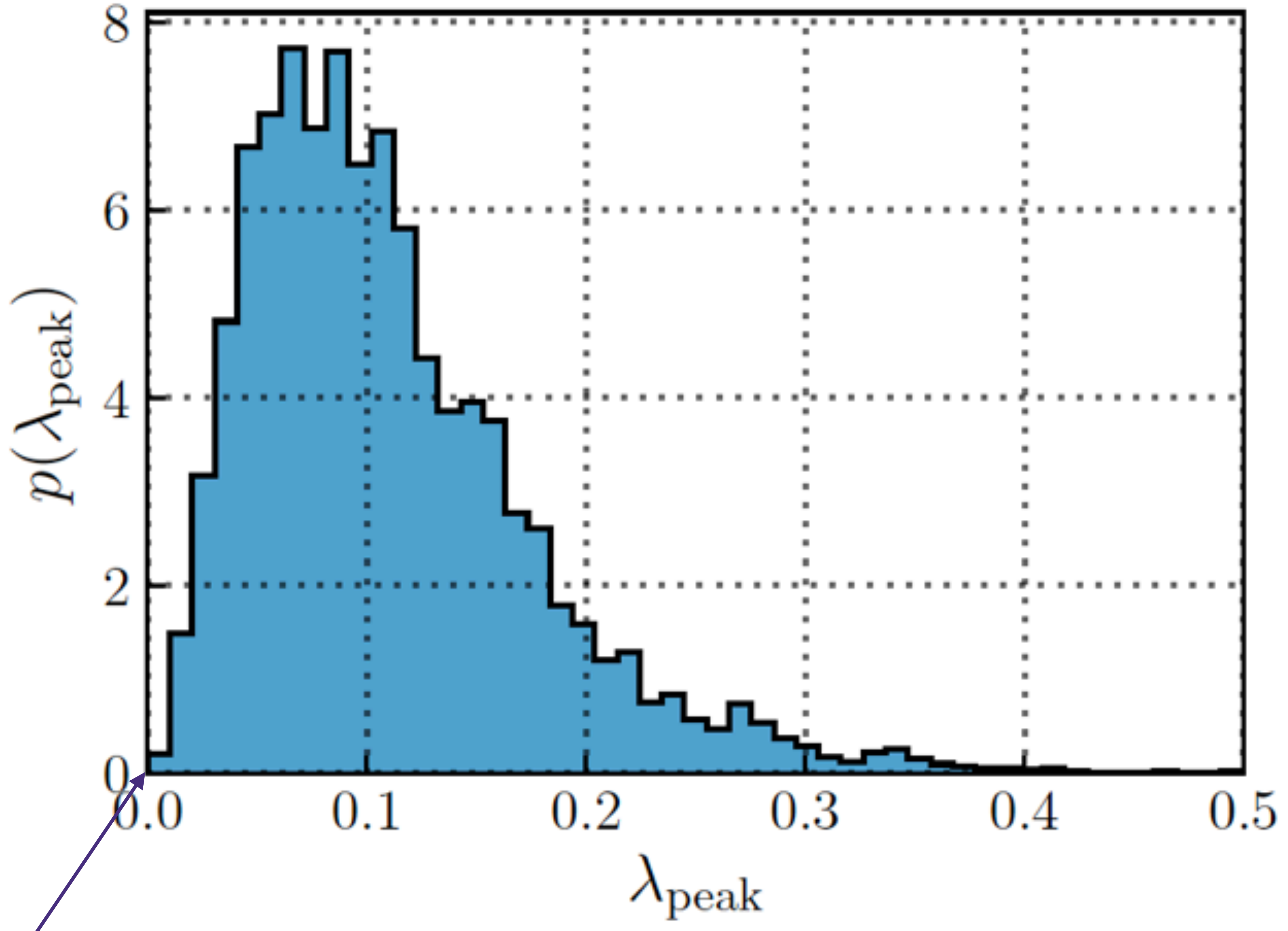
- A truncated power law with sharp cutoffs fails to fit the data
- We must introduce additional features, like a *Gaussian peak* or a *break* in the power law
- The black hole mass distribution steepens at ~40 solar masses



Abbott+ arXiv:2010.14533

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

Power law + peak

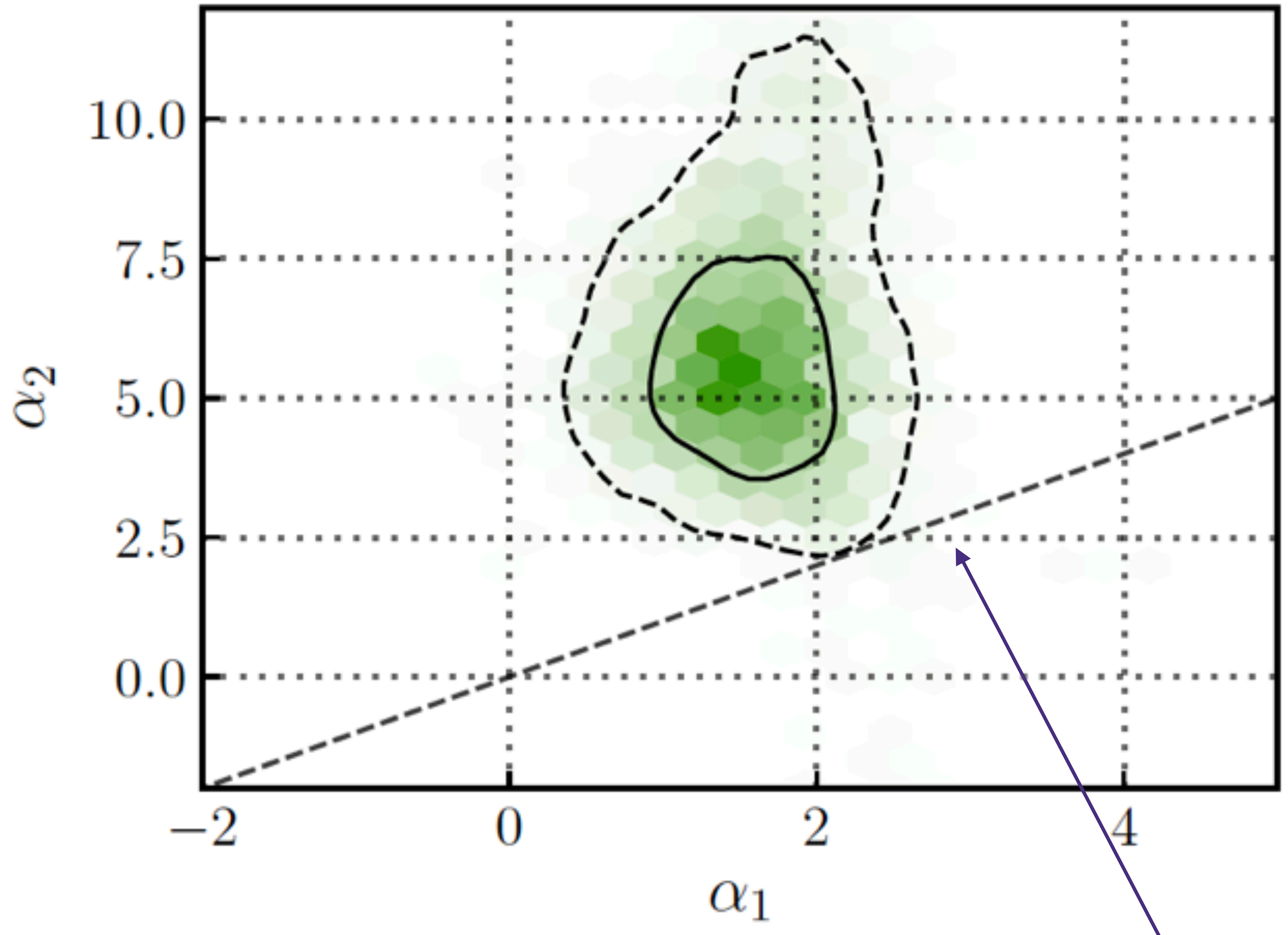


Fraction of black holes in the Gaussian component

Excludes 0

Broken power law

Power law index above the break



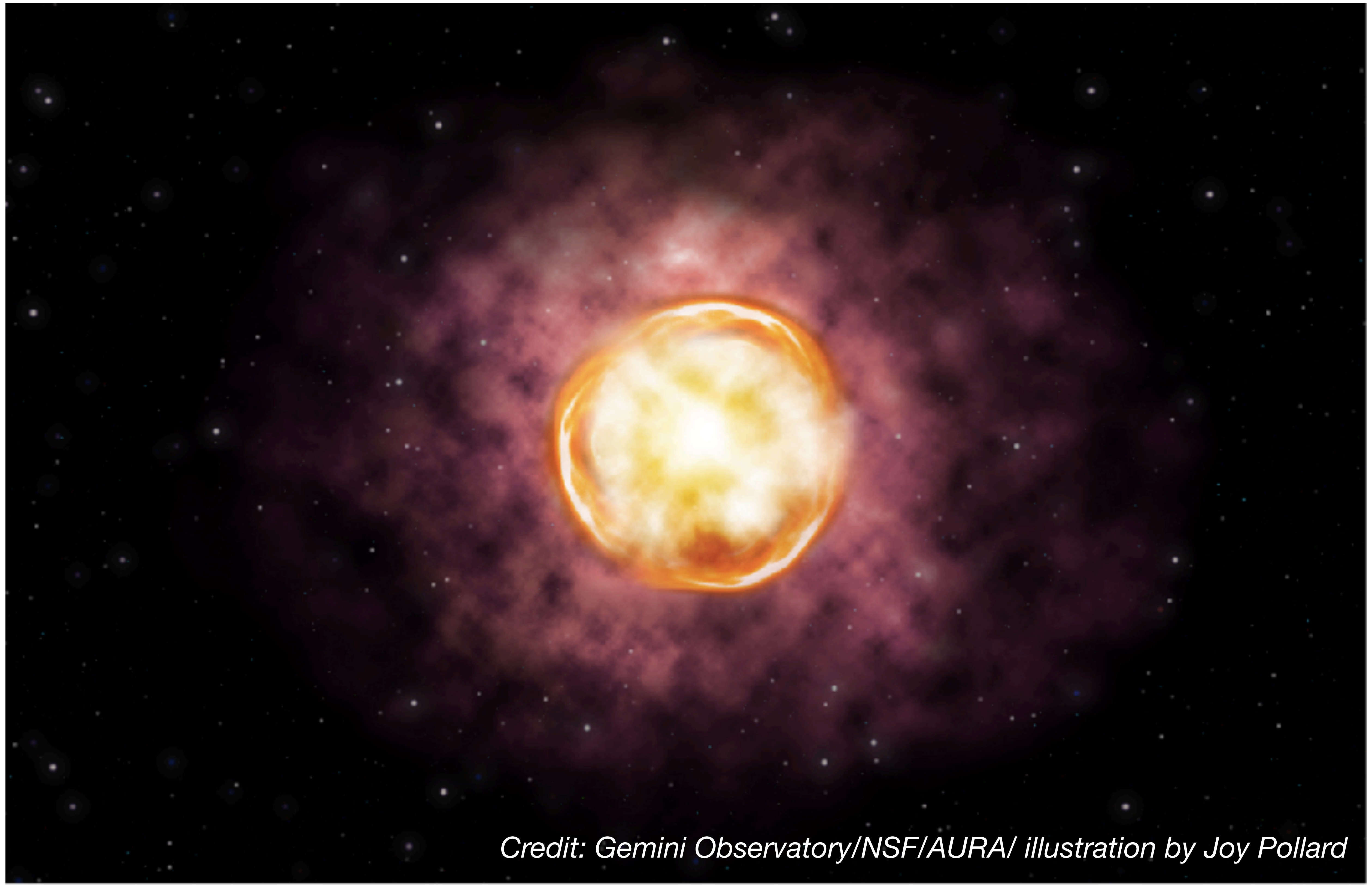
Power law index below the break

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

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

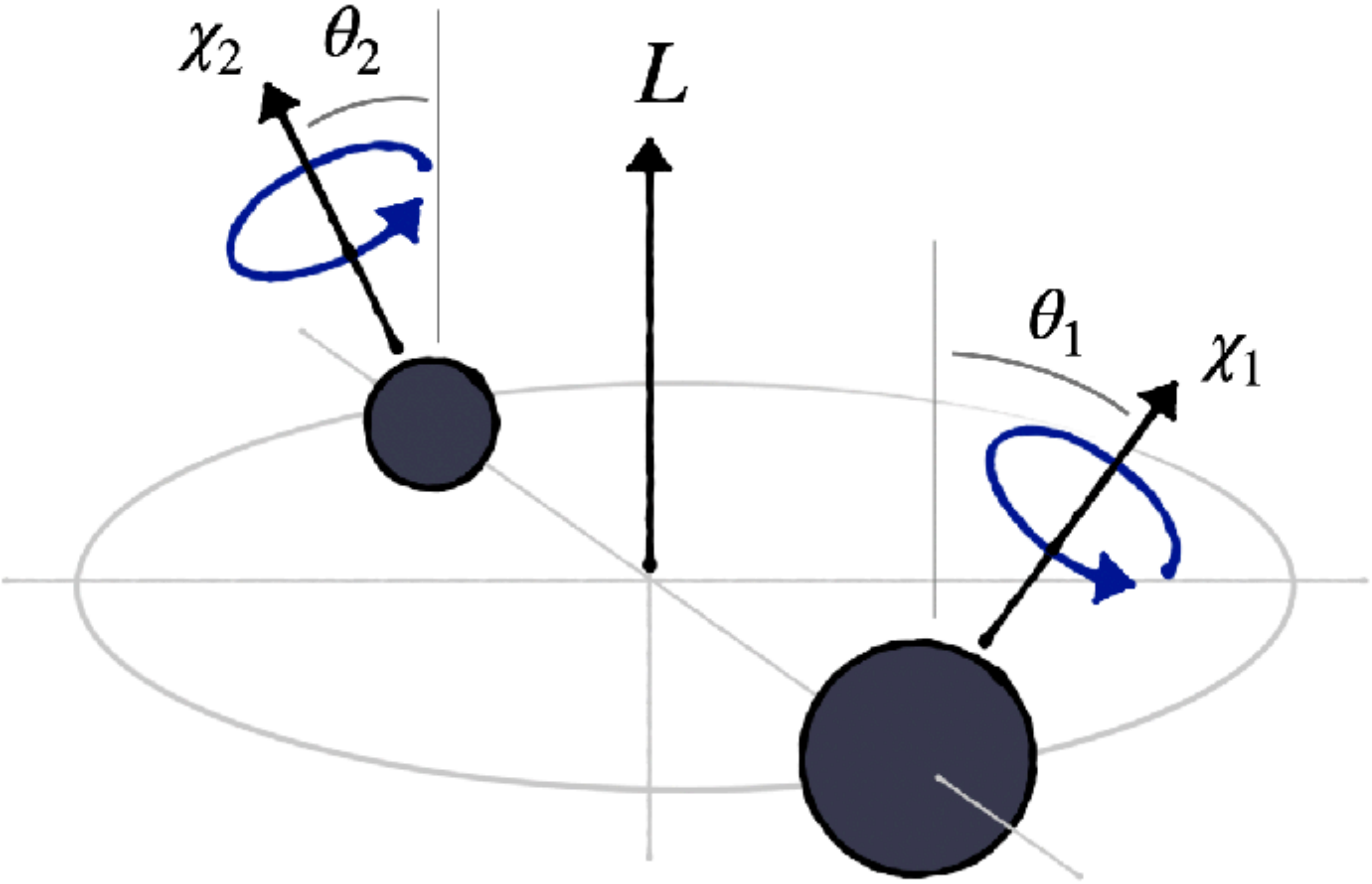
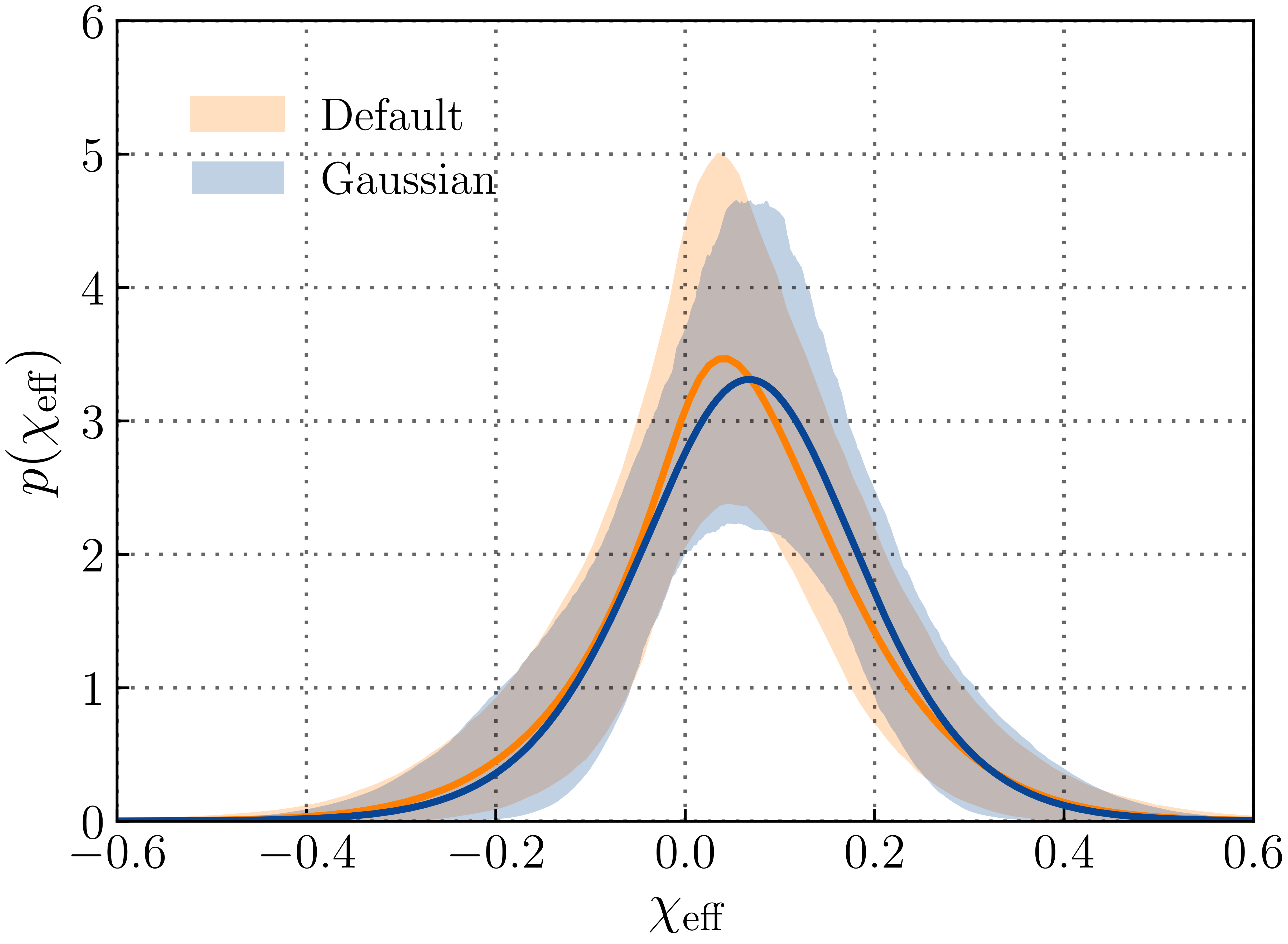


Figure credit: Thomas Callister

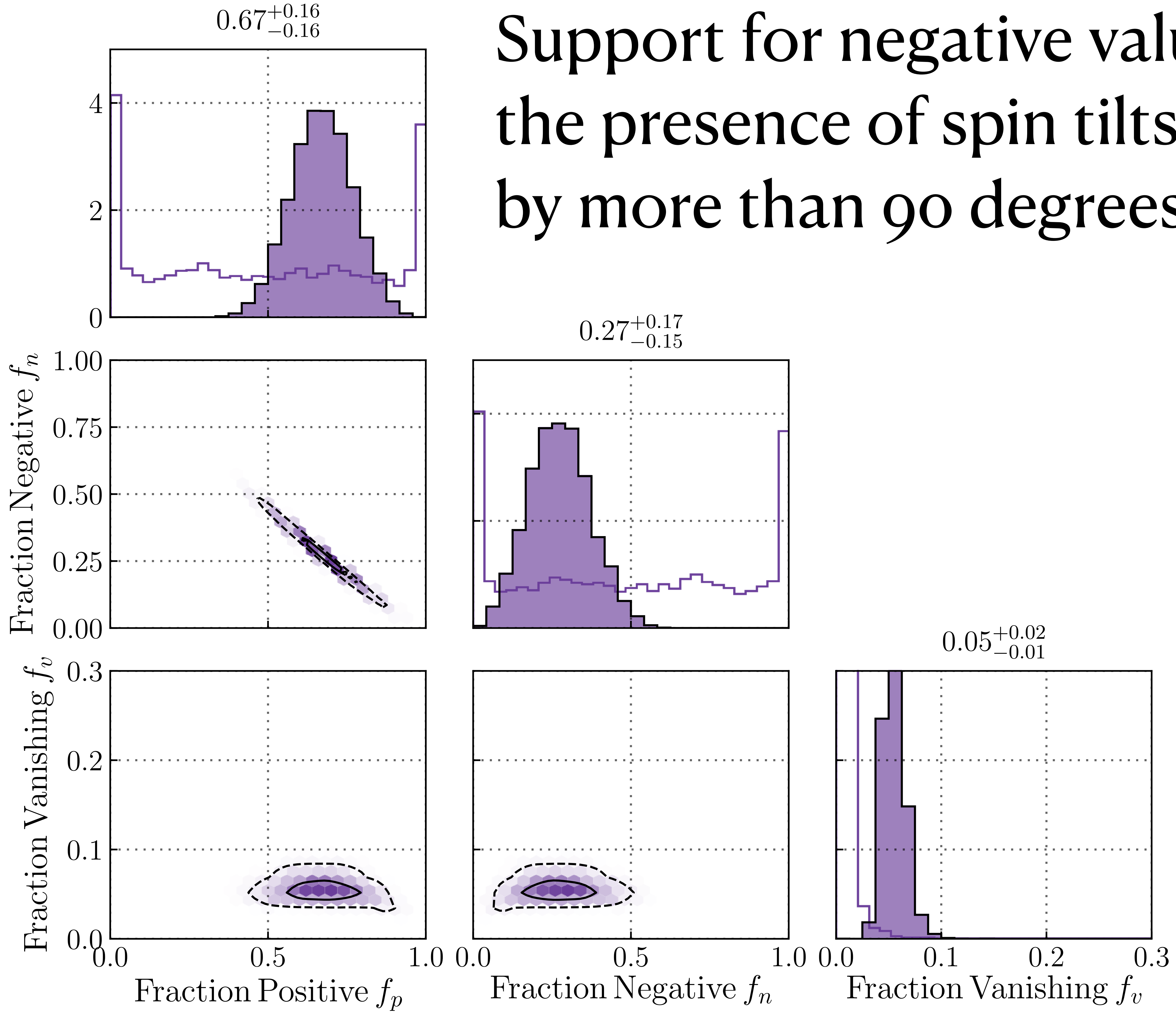
Fitting the effective spin distribution

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



Support for negative values implies the presence of spin tilts misaligned by more than 90 degrees

Evidence for multiple formation channels?



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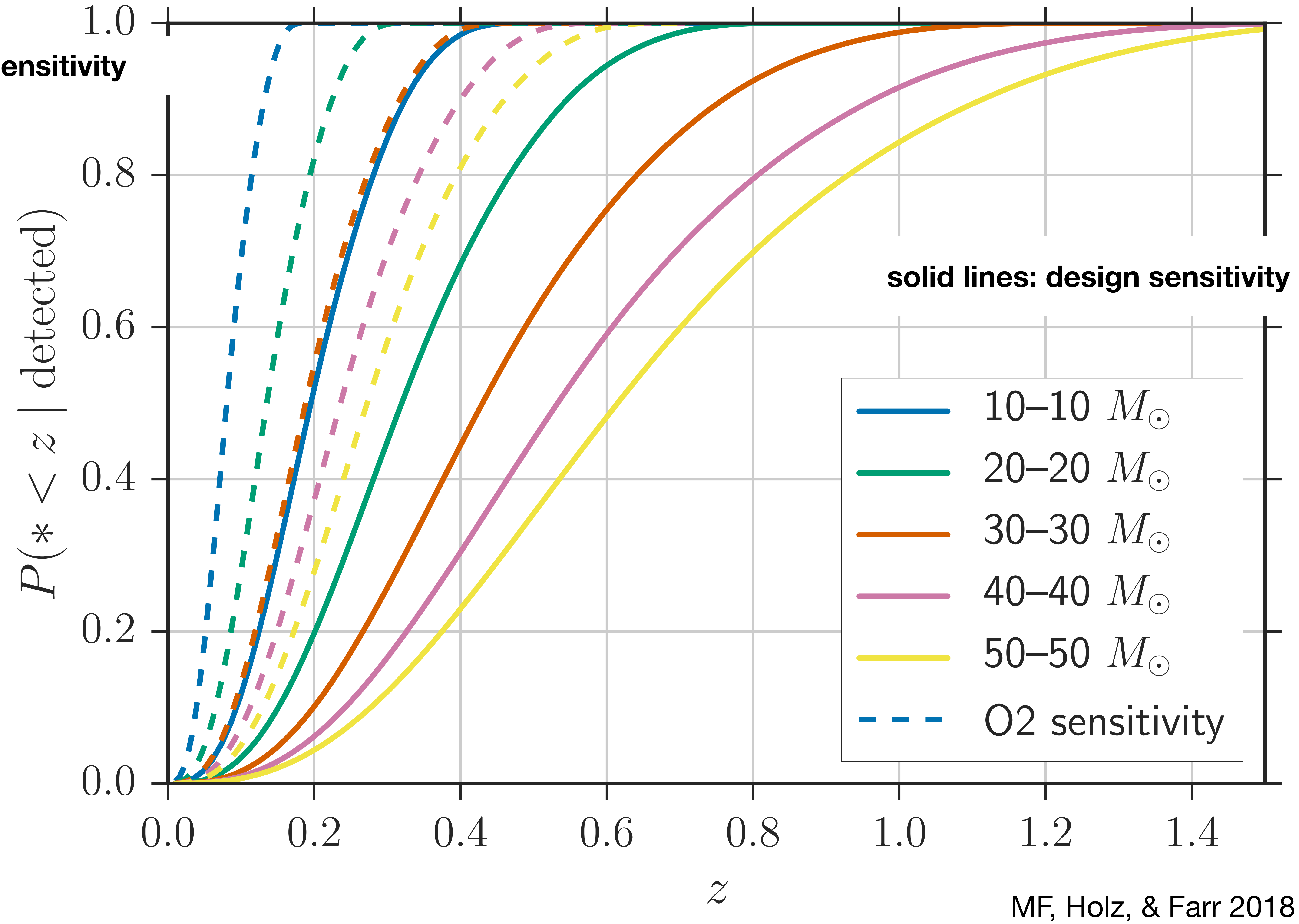
Diagonal $f_n = f_p$ is excluded, implying that the distribution of spin tilts is not isotropic

Astrophysical Lesson #3:

Measuring the black hole merger rate across cosmic time



dashed lines: O2 sensitivity

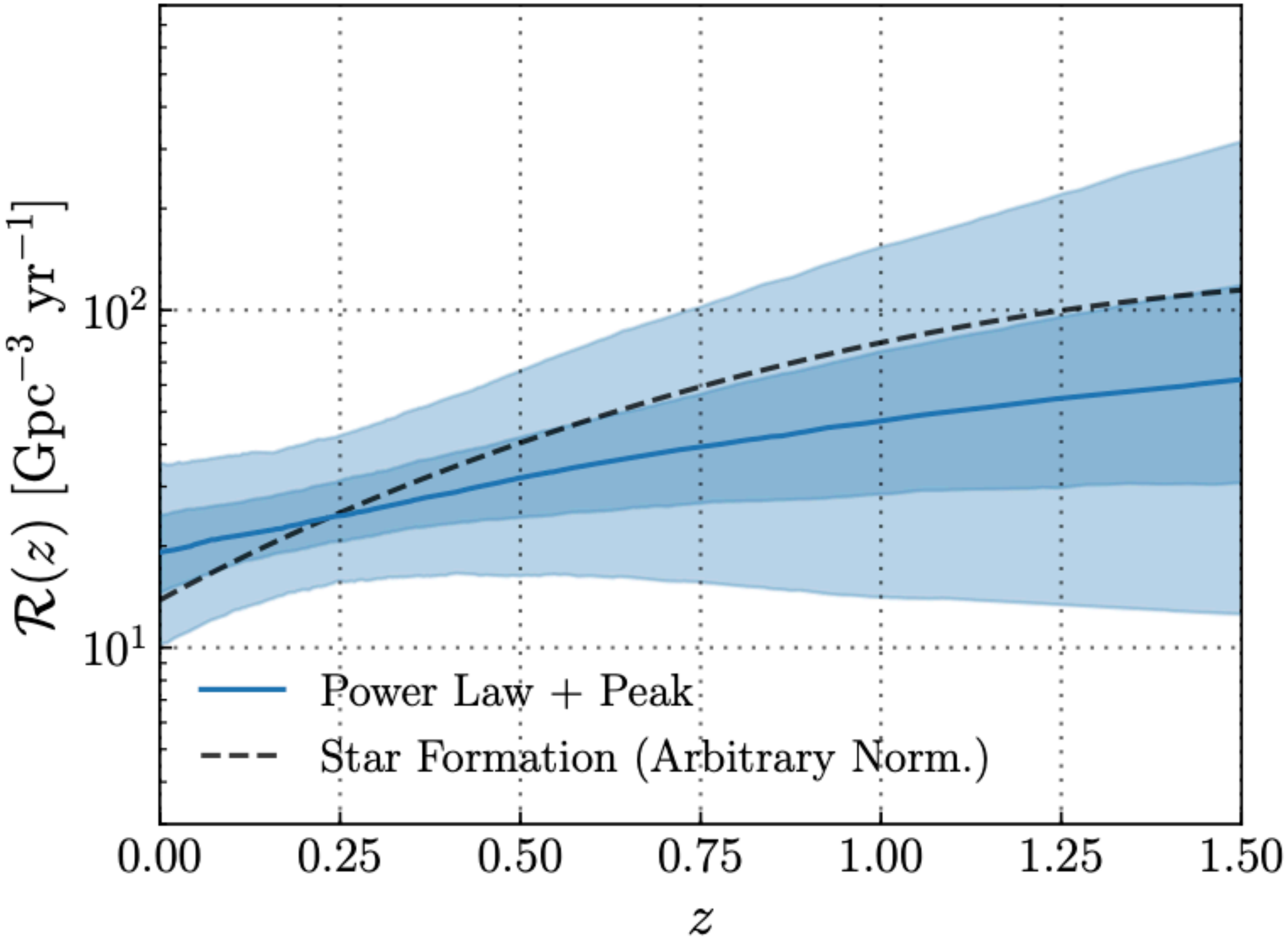
solid lines: design sensitivity

cumulative distribution in redshift for detected binaries of a fixed mass

MF, Holz, & Farr 2018 ApJL 863 L41

Merger rate of black hole mergers across cosmic time

- Today ($z = 0$), the merger rate is between [10, 35] $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- 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!

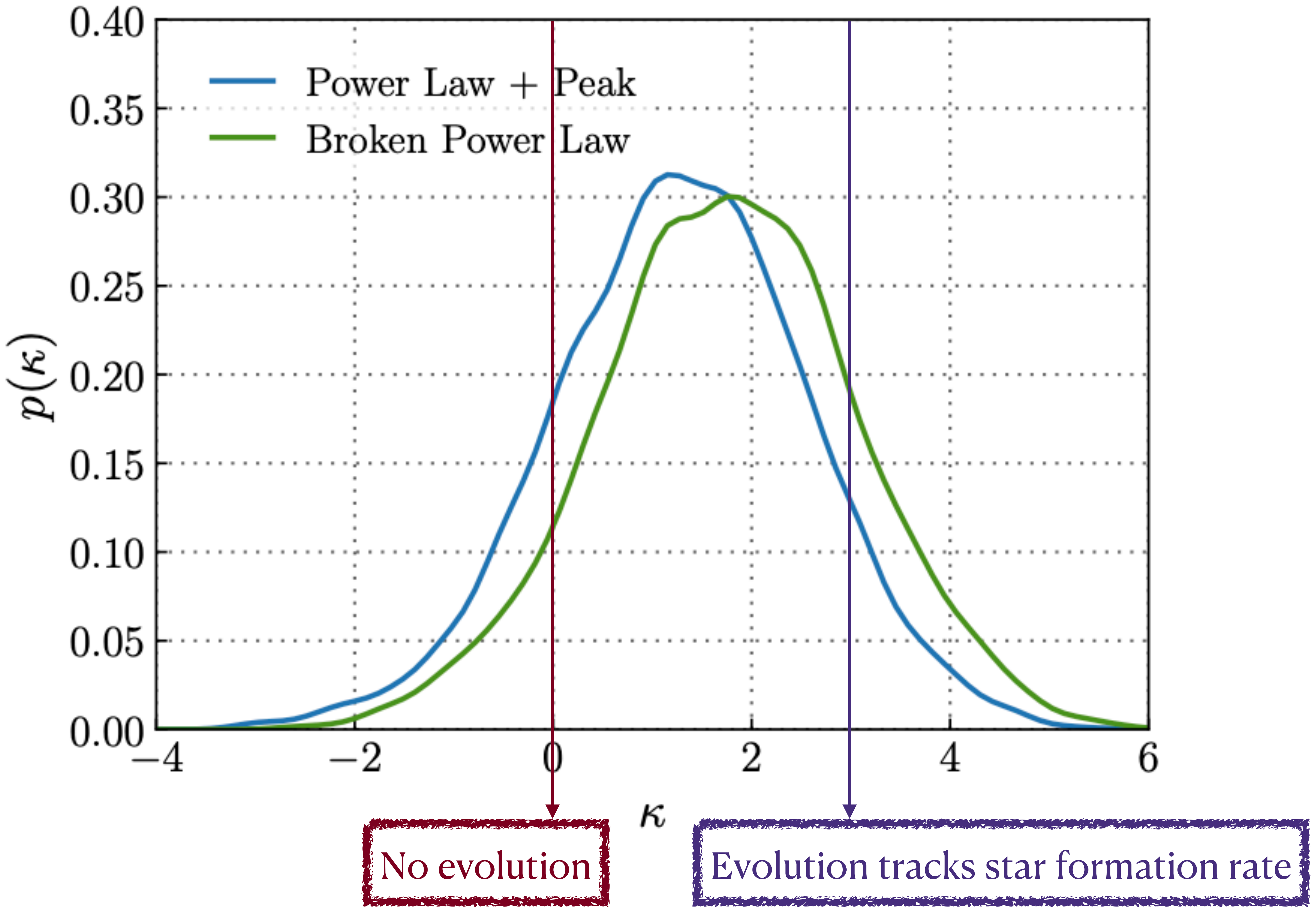


Abbott+ arXiv:2010.14533

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)



No evolution

Evolution tracks star formation rate

Abbott+ arXiv:2010.14533

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Open Questions

- What is the physical origin for the feature at ~40 solar masses?
- What is the origin of black holes with masses above 45 solar masses?
- Is there a mass gap between neutron stars and black holes?
- What is the nature of the 2.6 solar mass object in GW190814?
- Are the systems with misaligned spins the result of dynamical assembly?
- Are we observing binary black holes from multiple formation channels?
- Other questions?