Start time 21:00 UTC

Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog

LIGO Scientific Collaboration and Virgo Collaboration

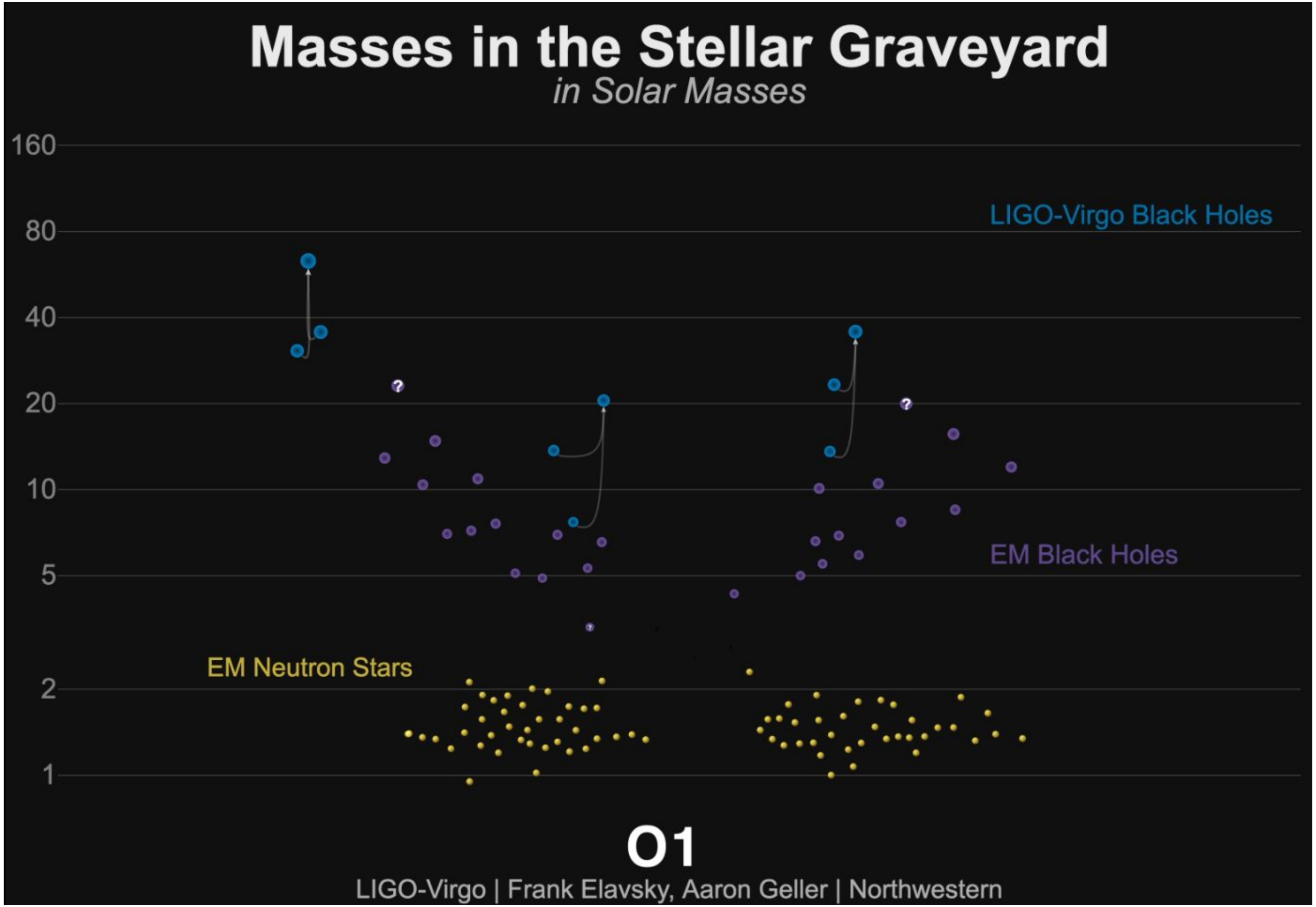
O3a population paper:
dcc.ligo.org/LIGO-P2000077/public
arXiv: 2010.14533

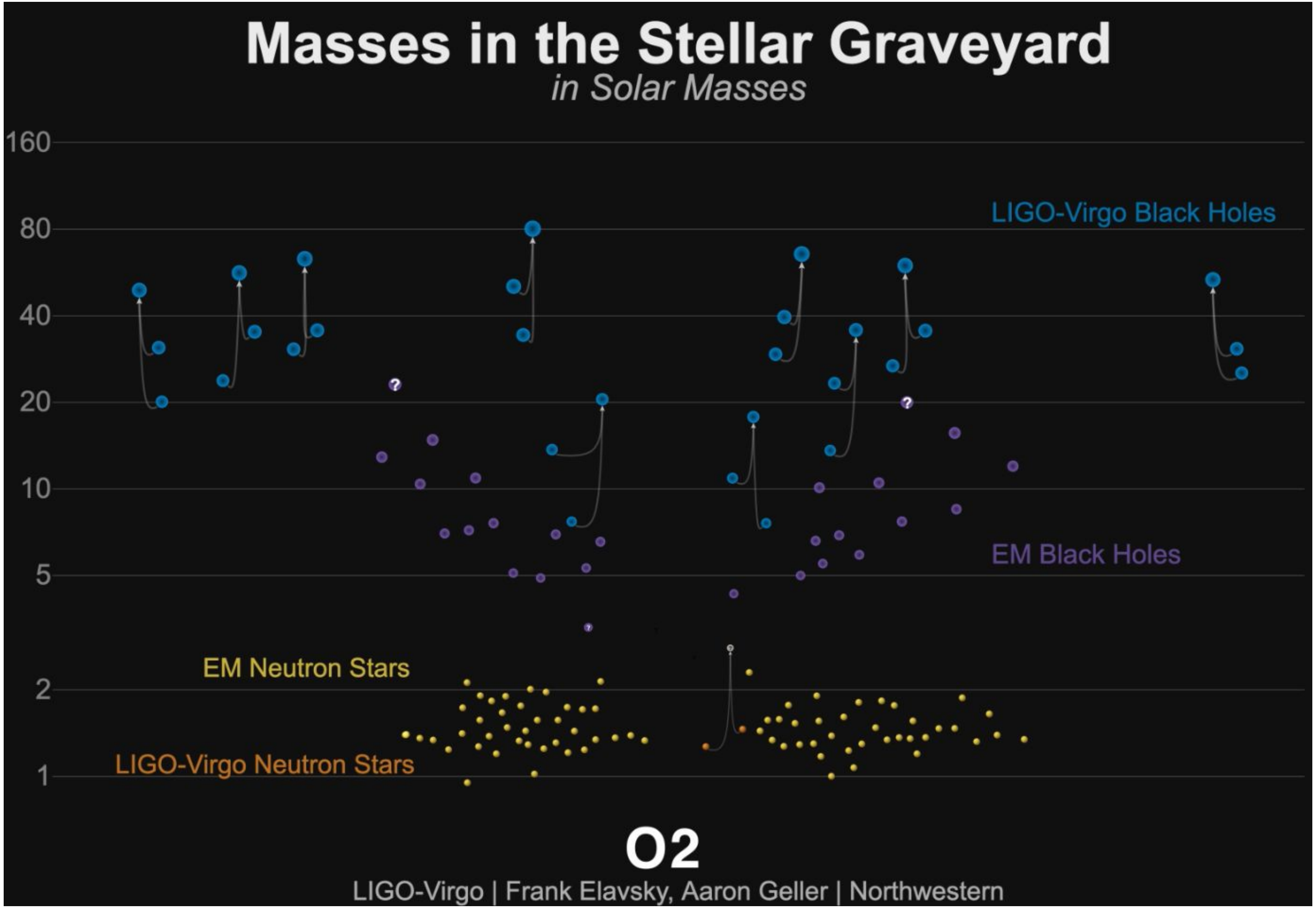
Data distribution:
dcc.ligo.org/LIGO-P2000434/public
Science summary

Slides
dcc.ligo.org/LIGO-G2001970/public

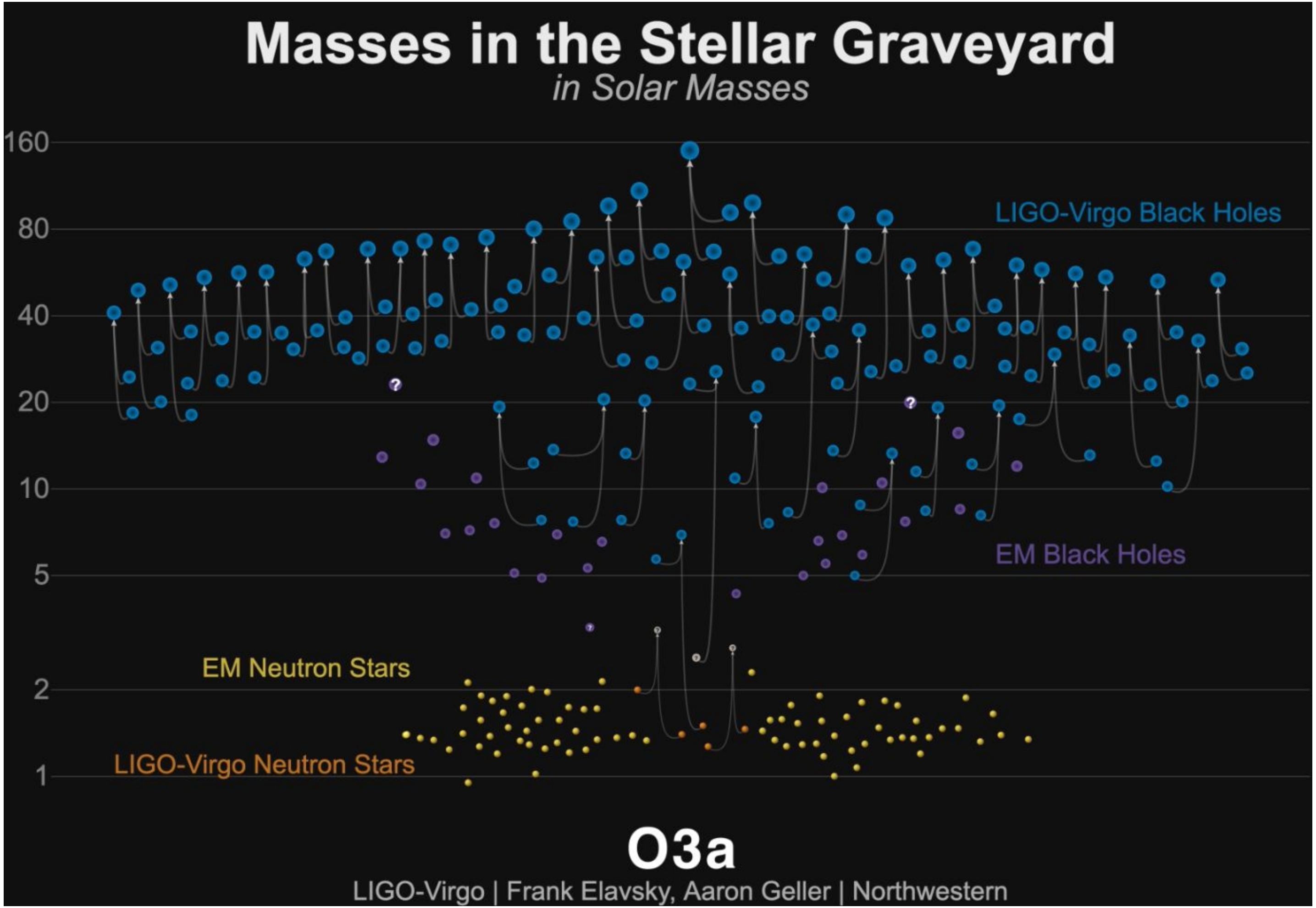
GWTC-2 catalog paper:
dcc.ligo.org/P2000061/public
arXiv: 2010.14527

GWTC-2 Tests of GR paper:
dcc.ligo.org/LIGO-P2000091/public
arXiv: 2010.14529


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
?
?
?
O1
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern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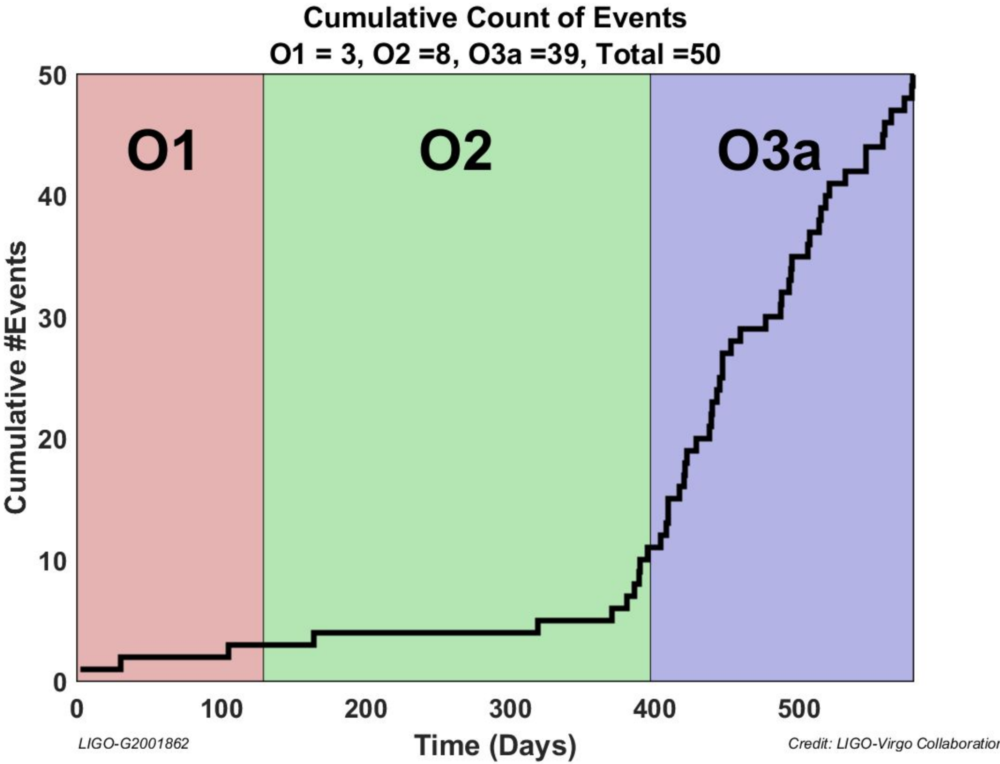
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

A Population of GW sources from GWTC-1 and GWTC-2

As we improve our detectors we are detecting more and more GW events

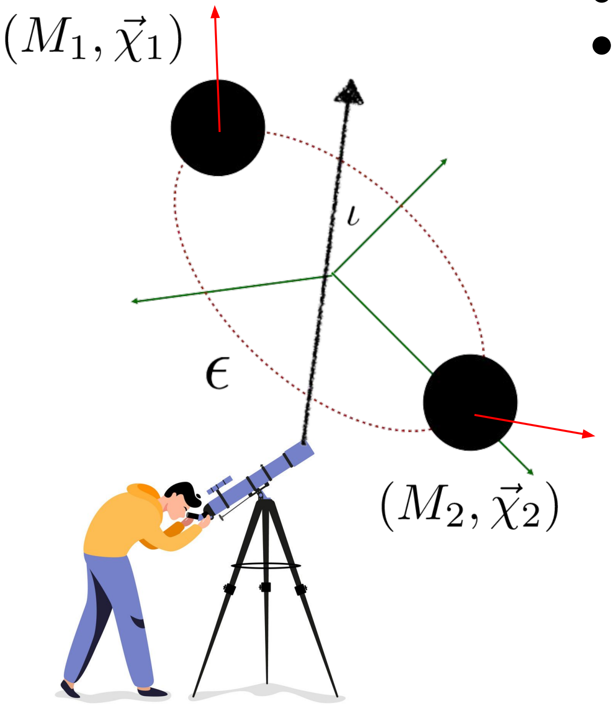
- **During O1 (~4 months)**:
  - 3 confident BBHs
- **During O2 (~8 months):**
  - 7 confident BBHs
  - 1 confident BNS
- **During O3a (~6 months)**:
  - 1 consistent with BNS masses (GW190425)
  - 2 BH+lighter object (GW190814, GW190426_152155)
  - 36 consistent with BBHs



LIGO-G2001862

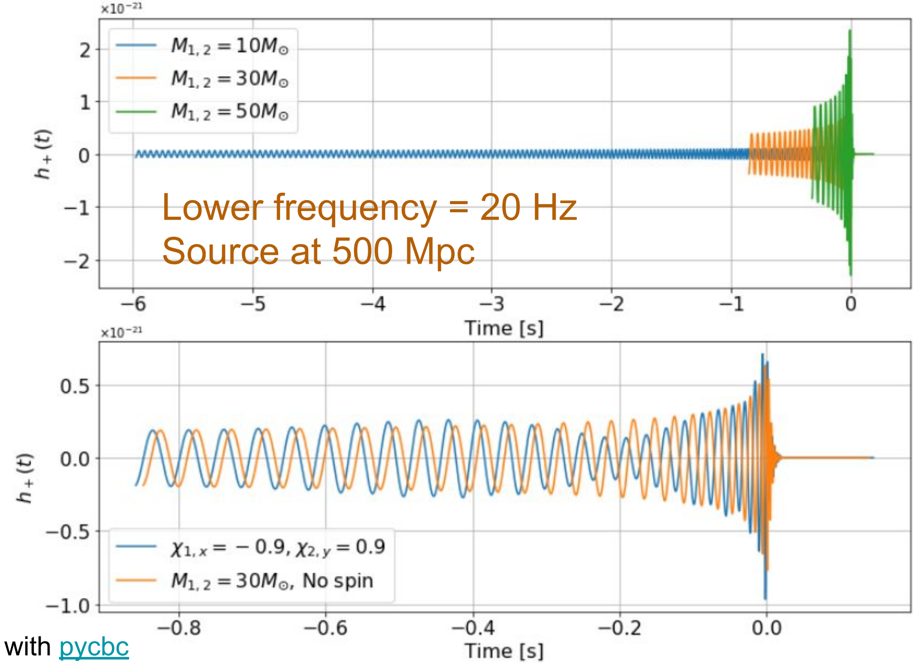
Credit: LIGO-Virgo Collaboratior

A Population of GW sources from GWTC-1 and GWTC-2



The parameters:

- **Intrinsic:** Spins, Masses, tidal deformability, ellipticity
- **Extrinsic:** Time, reference phase, sky position, luminosity distance, orbital orientation

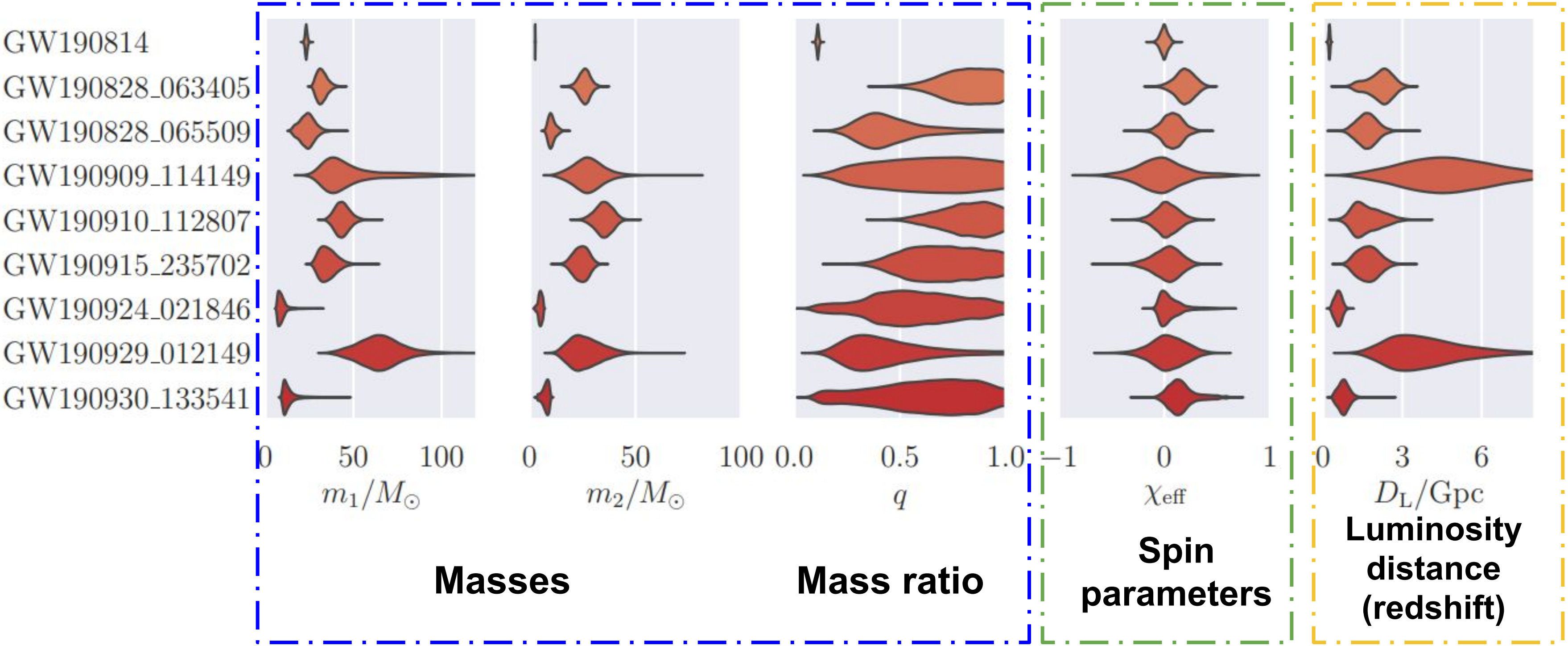


Lower frequency = 20 Hz
Source at 500 Mpc

Generated with pycbc

A Population of GW sources from GWTC-1 and GWTC-2

Key quantities for population inference



Masses

Mass ratio

Spin parameters

Luminosity distance (redshift)

Data analysis method and events used

- We select all the events from **GWTC-1** and **GWTC-2** with a *False Alarm Rate* (**FAR**) < 1 yr^{-1}. We use a total of:
    - 2 BNS events
    - BH+lighter object (GW190814)
    - **44 confident BBH events** (the focus of this presentation)
- We use a ***hierarchical Bayesian analysis*** using various priors on masses, spins, redshift distributions and rate.
    - 4 mass population models
    - 3 spin population models
    - 1 redshift evolution model
- We model and take into account ***selection effects for the detection of GW events***.

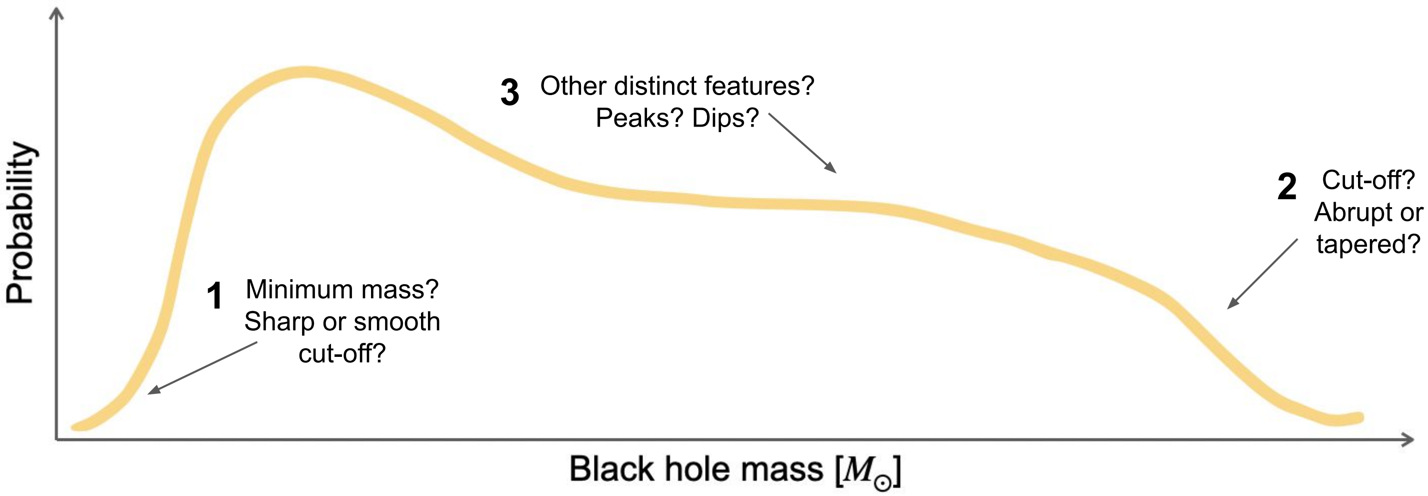
Questions that we answer in this paper

- *Are there BBH systems with component masses higher than 45 Msun?*
- *What is the minimum mass of BH?*
- *Is there a preference to form nearly equal mass binaries?*
- *How fast and how misaligned BBHs spin?*
- *Does the merger rate evolve with redshift?*

Important for understanding the formation channel of binaries and the nature of ‘’exceptional events’’

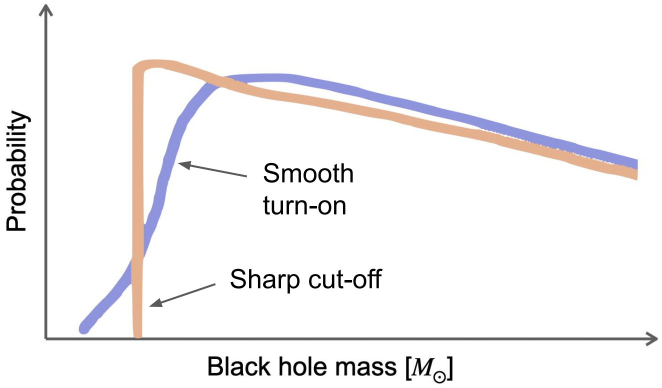
Black hole **mass distribution** can give us hints on stellar evolution.

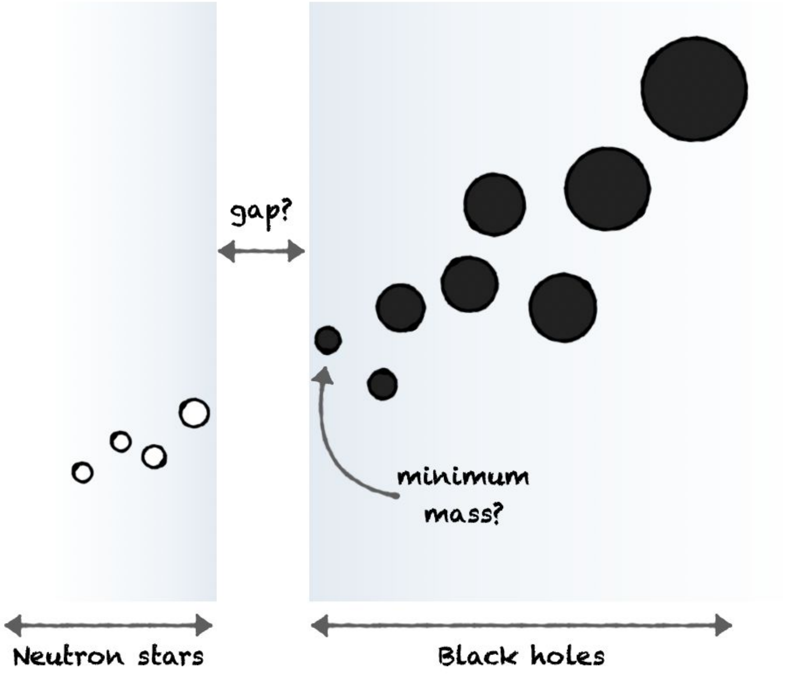
- Features in the mass distribution can help us probe how black holes formed. We can compare results to expectations from theories for stellar evolution.
- Models used in population analysis motivated by these theories.



Mass distribution: low-mass features

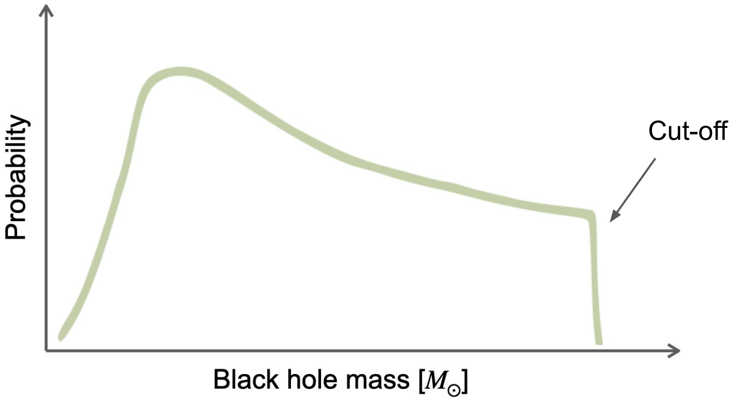
- What is the minimum mass black hole?
- Does the distribution have a smooth or sharp cut-off at low-mass end? Is there evidence for a low mass gap?

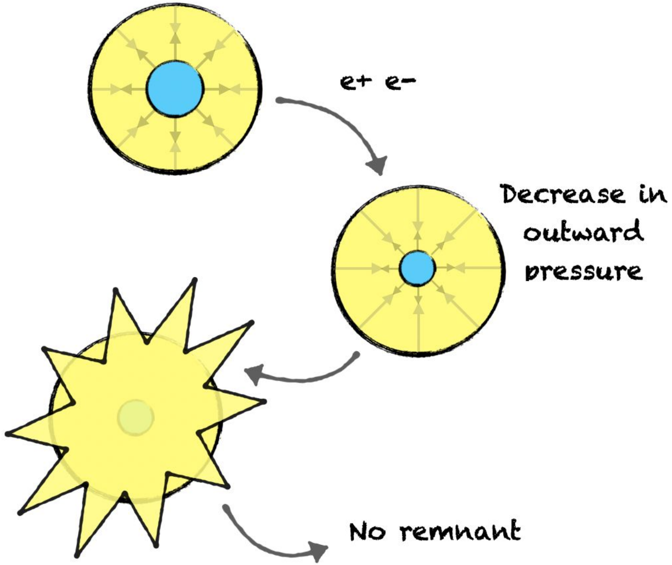




Pair-instability supernova: upper mass cut-off

- Very massive stars leave behind no remnant after a supernova.
- No black holes formed beyond a certain mass, suggests a cut-off in the mass distribution



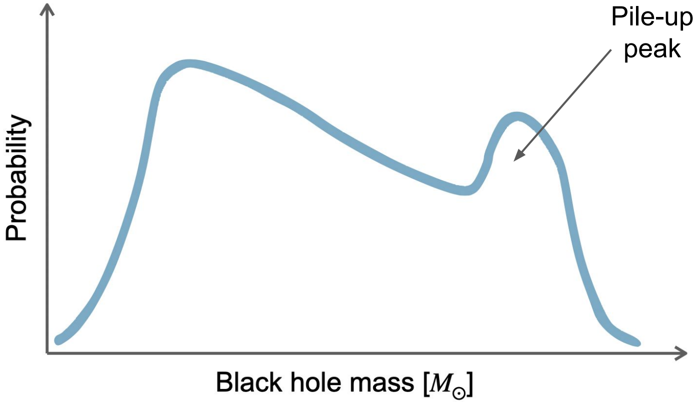


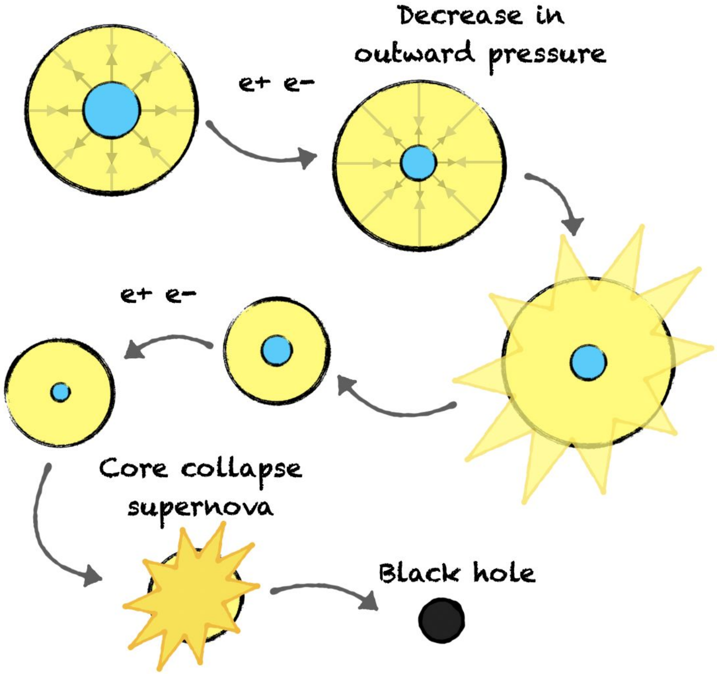
Stars of masses $> 130 M_\odot$ at ZAMS

(ZAMS = Zero Age Main Sequence ~ original mass of star)

Pulsational pair instability: black hole pile up

- Massive stars shed mass in ‘pulses’.
- Produce stars of similar mass, which collapse to form black holes around ~ 35 to 45 $M_\odot$

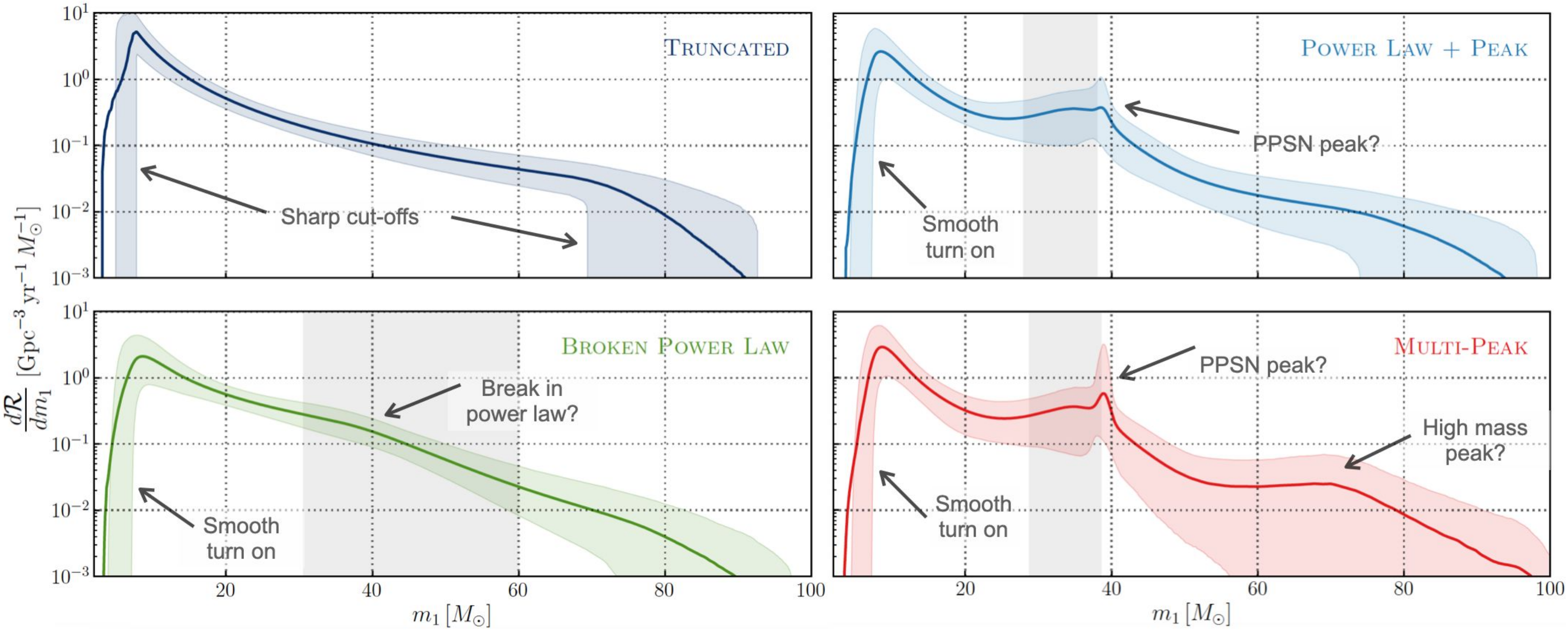




Stars of masses $\sim 80 M_\odot \rightarrow 130 M_\odot$ at ZAMS

(ZAMS = Zero Age Main Sequence ~ original mass of star)

Mass results in GWTC-2: what features do we see?



Analysis with 44 confident BBH. Primary mass distribution: Solid curve - mean; Shaded region - 90% credible interval

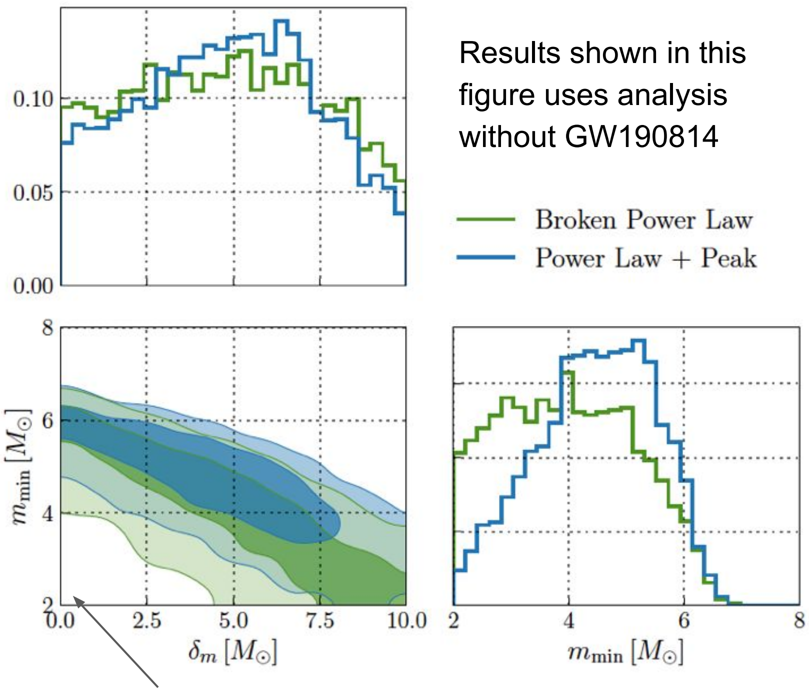
Low mass distribution features

- We rule out the combination of a small minimum black hole mass (~ 2 $M_\odot$) and a sharp low-mass cut-off.

- We are beginning to resolve the low-mass end of distribution.

- Additional study performed including GW190814. Low-mass end of distribution pulled from ~6 to ~2 $M_\odot$. GW190814 is an outlier in the BBH distribution -- only 0.02% chance of GW190814-like event in analysis with 44 confident BBH population.

GW190814 - arXiv:2006.12611

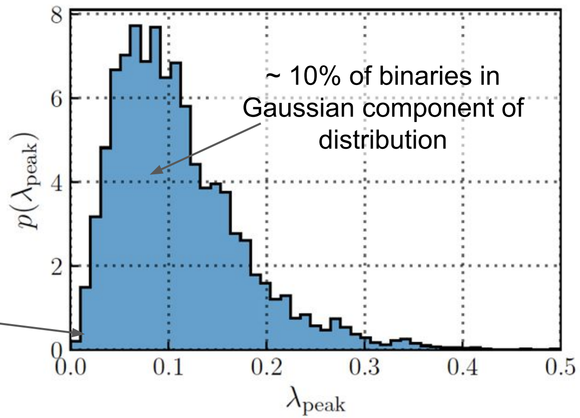


Results shown in this figure uses analysis without GW190814

Excludes low mass + sharp cut-off

Structure beyond a power law

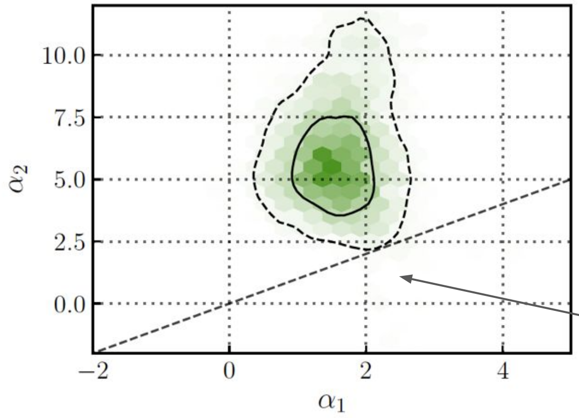
- Support for Gaussian component in distribution (most favoured model Power law + peak).
- Power-laws have different slopes (Broken power law slightly less favoured; by factor of 8).



Power law + peak model

~ 10% of binaries in Gaussian component of distribution

Zoomed in, Excludes zero



Broken power law model

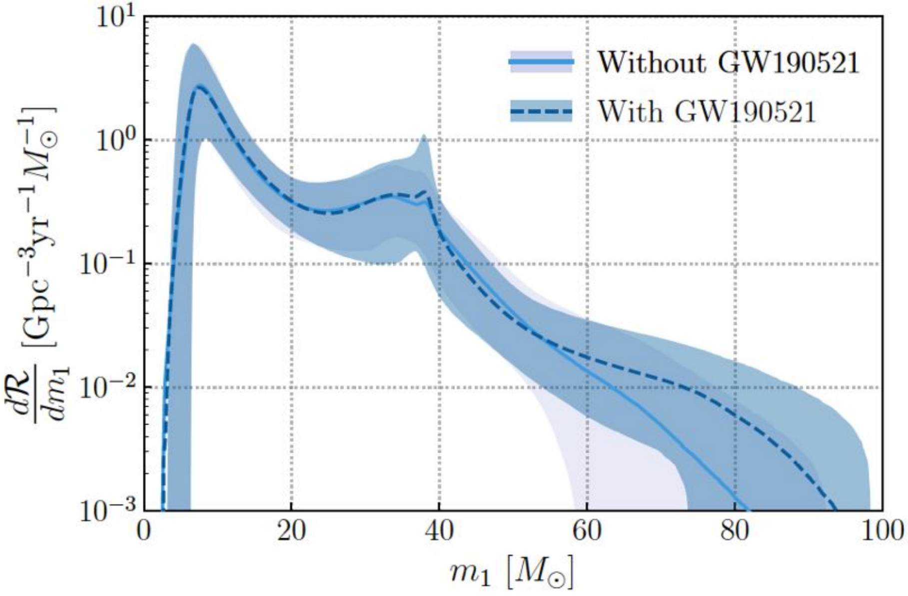
Excludes equal index for power law slopes

- A simple power law with sharp-cutoffs (Truncated model) is disfavoured (by factor 100 compared to Power law + peak).

Masses beyond 45 $M_\odot$

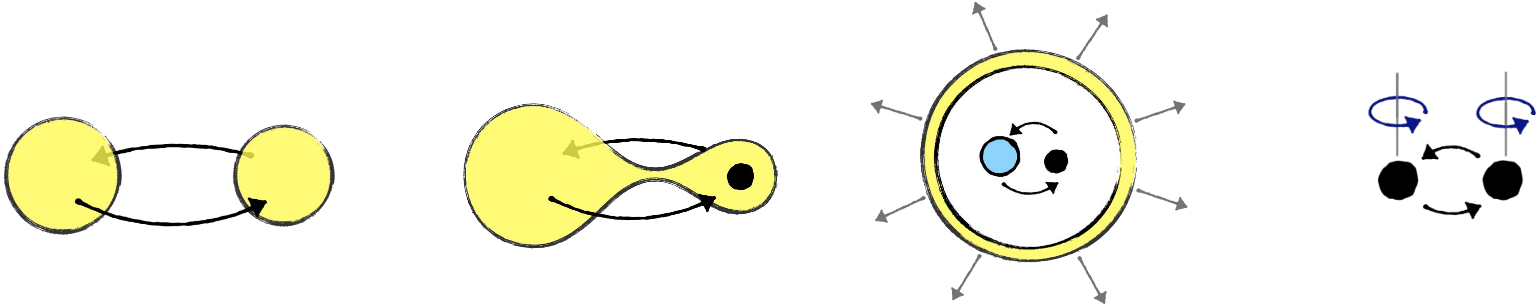
- No cut-off feature around 45 $M_\odot$
- Masses extend beyond 45 $M_\odot$ with and without GW190521. This event appears to be consistent with the population.
- Unable to conclude whether GW190521 is in the tail of the distribution, or a separate subpopulation (e.g. hierarchical mergers)

GW190521 - arXiv:2009.01075 & arXiv:2009.01190

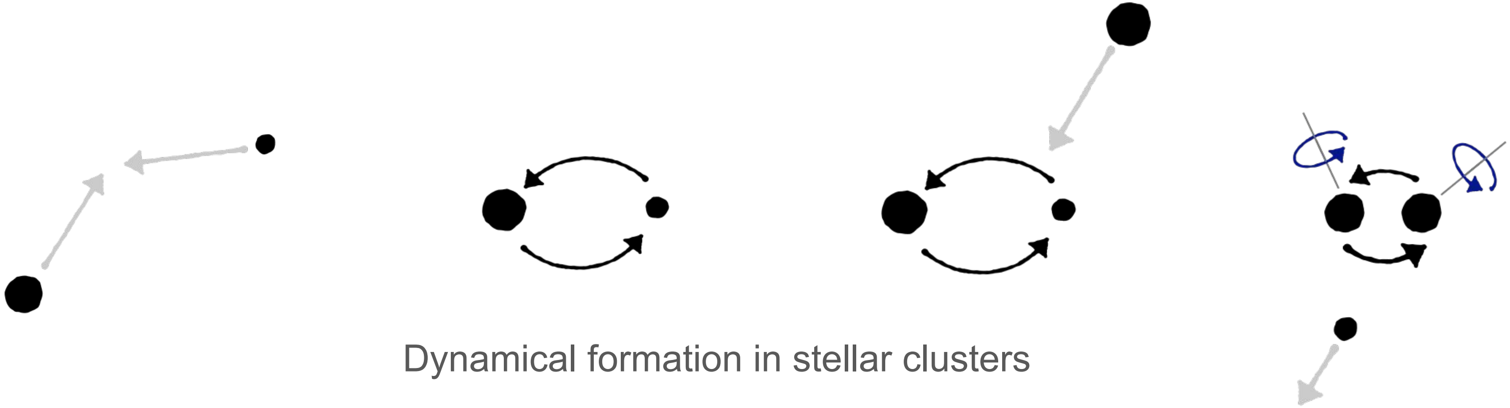


Primary mass distribution: Solid/dashed curves - mean;
Shaded region - 90% credible interval
(results from Power law + peak model)

Black hole spin orientations as probes of binary formation



Isolated common envelope evolution



Dynamical formation in stellar clusters

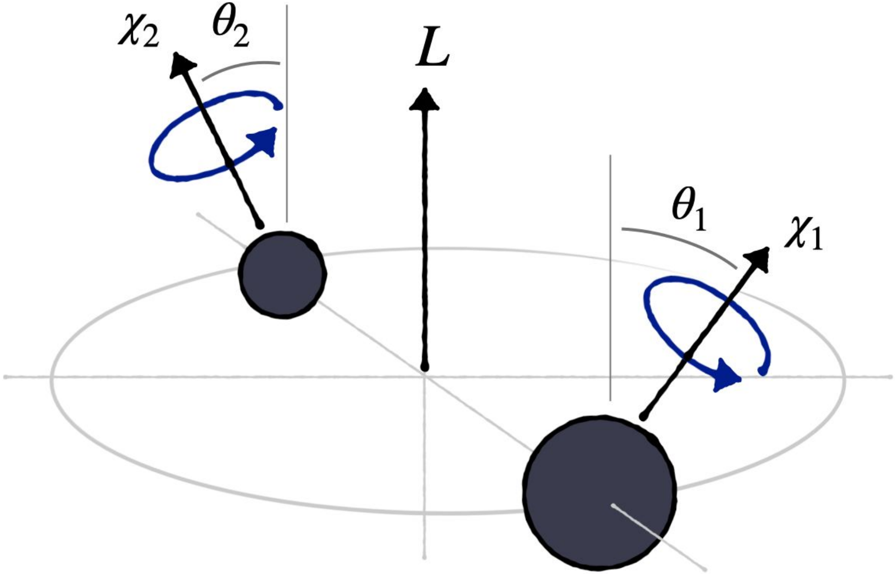
GW signals can be parameterized by two “effective spins”

Effective inspiral spin quantifies total spin parallel to a binary’s orbital angular momentum:

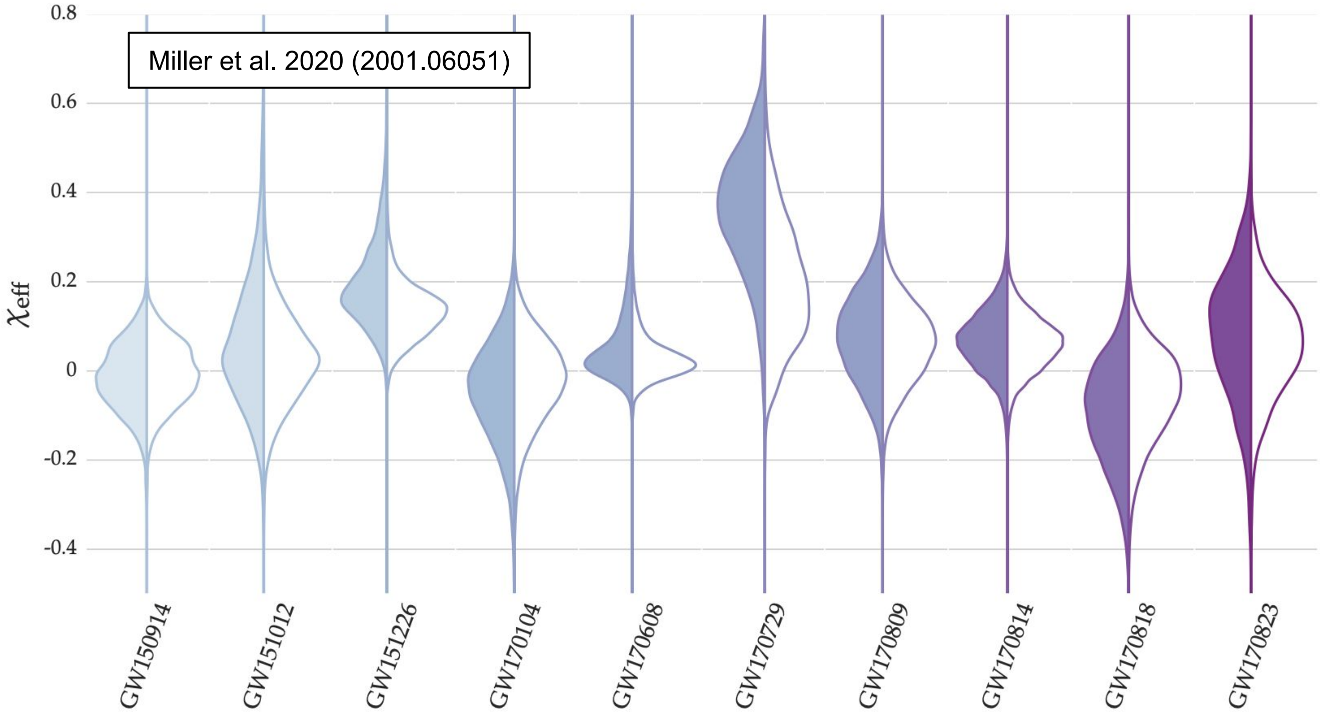
$$\chi_{\mathrm{eff}} = \frac{m_1\,\chi_1 \cos\theta_1 + m_2\,\chi_2 \cos\theta_2}{m_1 + m_2}$$

Effective precessing spin is related to degree of spin *perpendicular* to orbit:

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

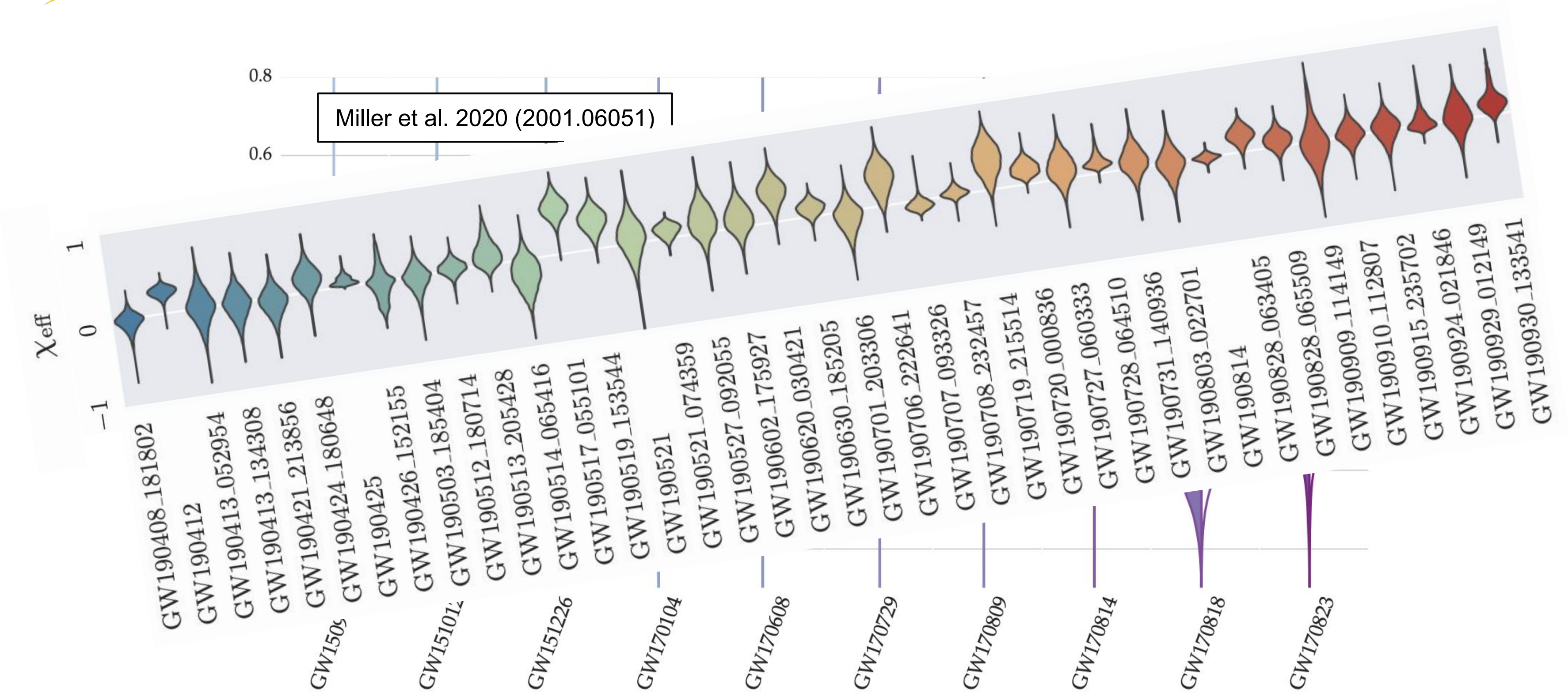


BBH spins before GWTC-2:
Small magnitudes, but ***unknown orientations***



Miller et al. 2020 (2001.06051)

BBH spins before GWTC-2: *Small magnitudes*, but *unknown orientations*


Miller et al. 2020 (2001.06051)

We take three different approaches in measuring the distribution of BBH spins

Default model:

Measure the physical ***spin magnitude*** and ***spin tilt distributions*** of binary black hole systems

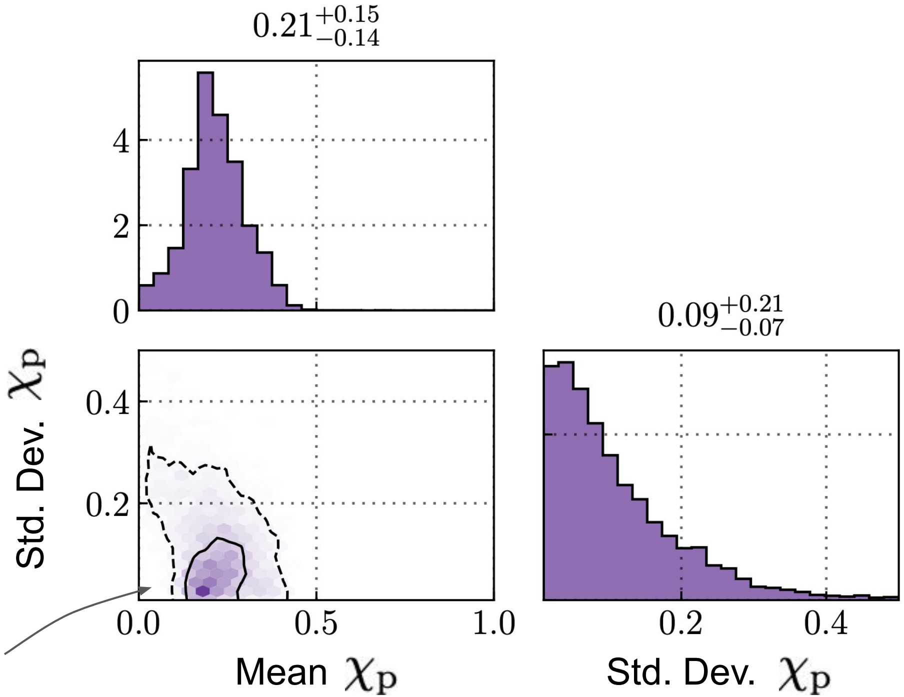
Gaussian model:

Measure the distribution of phenomenological χ_{eff} and χ_{p} parameters

Multi-spin model:

Do high and low-mass BBHs exhibit different spin distributions?

In-plane spin components are present among the BBH population



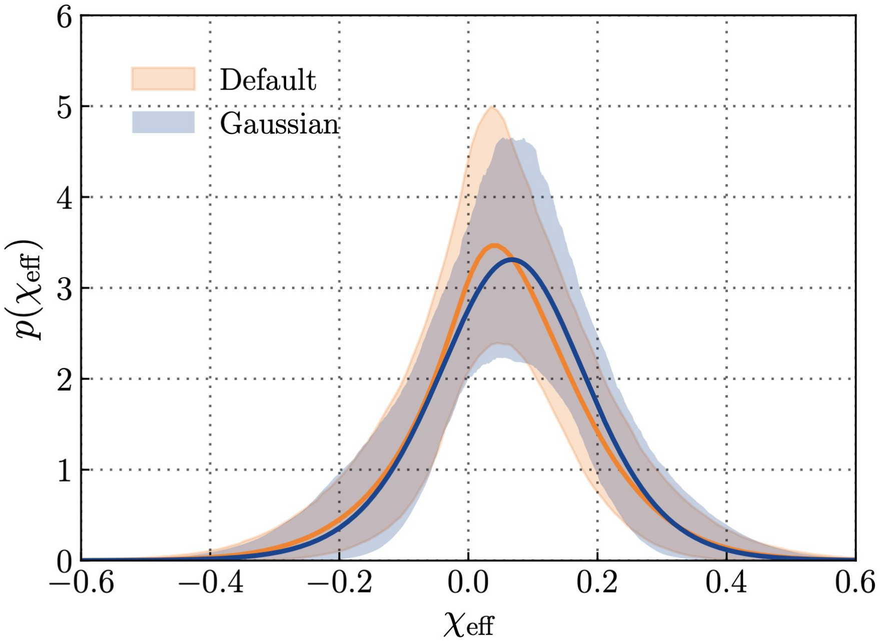
Exclude a delta-function at $\chi_\mathrm{p} = 0$

At least some events have negative effective spin

- Negative χ_{eff} implies **spins tilted by more than $90°$** relative to their orbital angular momentum

- Between 12% and 44% of BBHs have negative effective spins

- If we attribute negative χ_{eff} to dynamics, then **between 25% and 93% of events originate in dynamical channels**



Merger Rates

Binary Neutron Stars: With two confident observations of binary neutron stars in GWTC-2, we infer that the local merger rate of binary neutron stars is:

$$\mathcal{R}_{\mathrm{BNS}} = 320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

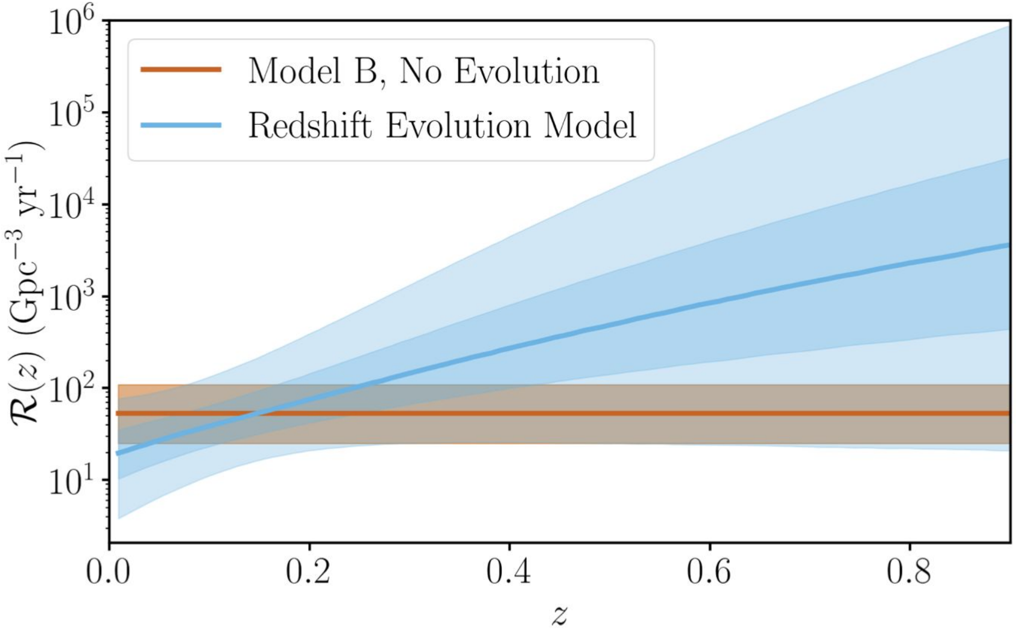
Binary Black Holes: For binary black holes, we simultaneously fit for the mass, spin and merger rate. Assuming a merger rate density that is constant across cosmic time:

$$\mathcal{R}_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Merger Rate of Binary Black Holes Across Cosmic Time

Allowing the merger rate to evolve with redshift, GWTC-1 found:

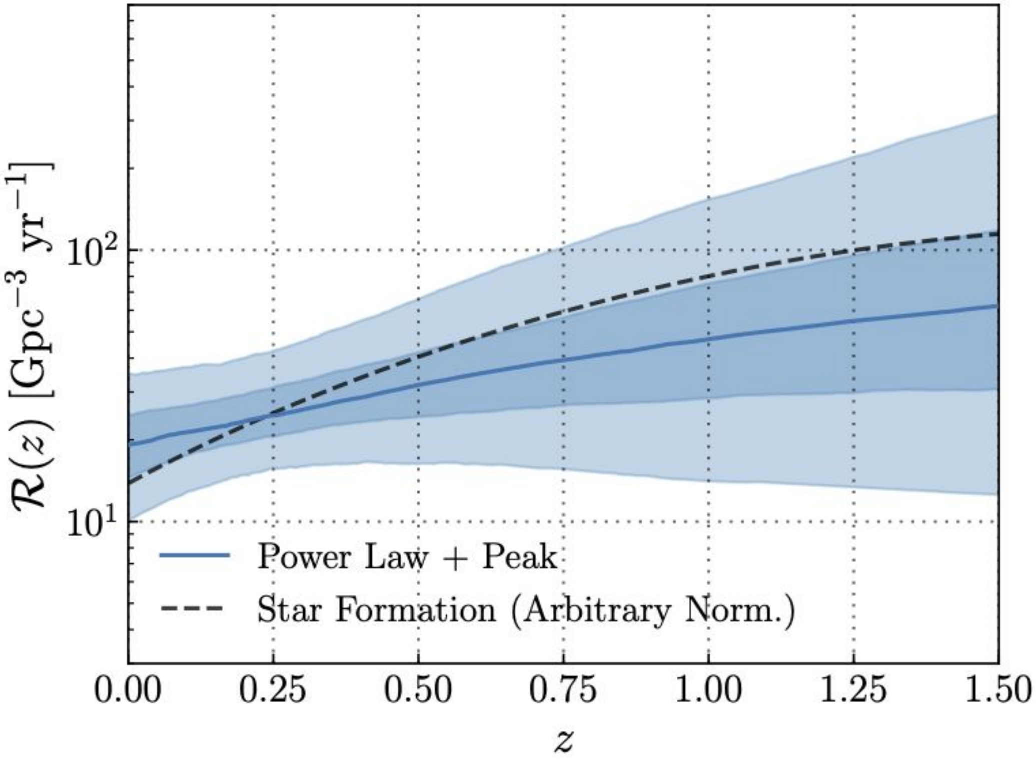
- Today (*z = 0)*, the merger rate is between [4, 77] Gpc^{-3} yr^{-1}
- 8 billion years ago (*z = 1)*, the merger rate was probably higher, but uncertain by more than 4 orders of magnitude



Merger Rate of Binary Black Holes Across Cosmic Time

With GWTC-2, we now know:

- Today ($z = 0$), the binary black hole merger rate is between [10, 35] Gpc^{-3} yr^{-1}
- 8 billion years ago ($z = 1$), the binary black hole merger rate was between 0.6 and 10 times its present rate

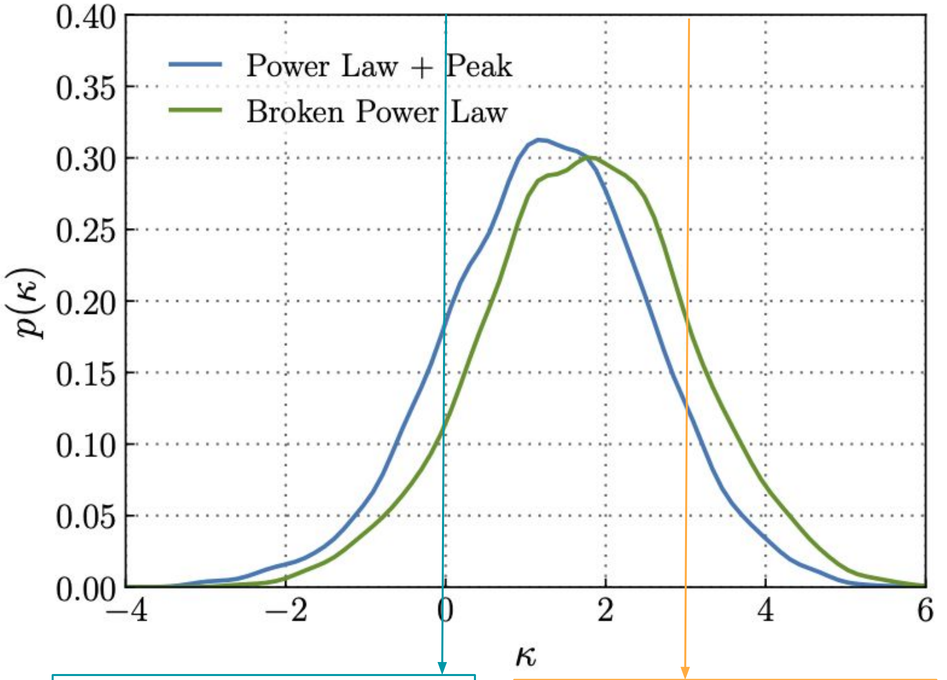


The merger rate probably evolves, but slower than the star formation rate

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)



Constant rate at all redshifts

Evolution that tracks the star-formation rate

Astrophysical Lessons from GWTC-2: 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.)

Astrophysical Lessons from GWTC-2: 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.**

Astrophysical Lessons from GWTC-2: Rates

- In the local universe, the average **binary black hole merger rate is between 15 and 40 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 $z = 1$.

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?

Thank you!