Astrophysical lessons from merging black holes through gravitational-wave detections

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OzGrav
ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY

We observe the ending, not the story

A gravitational-wave event is the last page of a much longer astrophysical history.

The merger signal is brief, but it carries the imprint of stellar evolution, binary formation, and the environment in which the black holes lived.

1 Hidden history

Massive stars evolve, collapse, and form black holes over millions to billions of years.

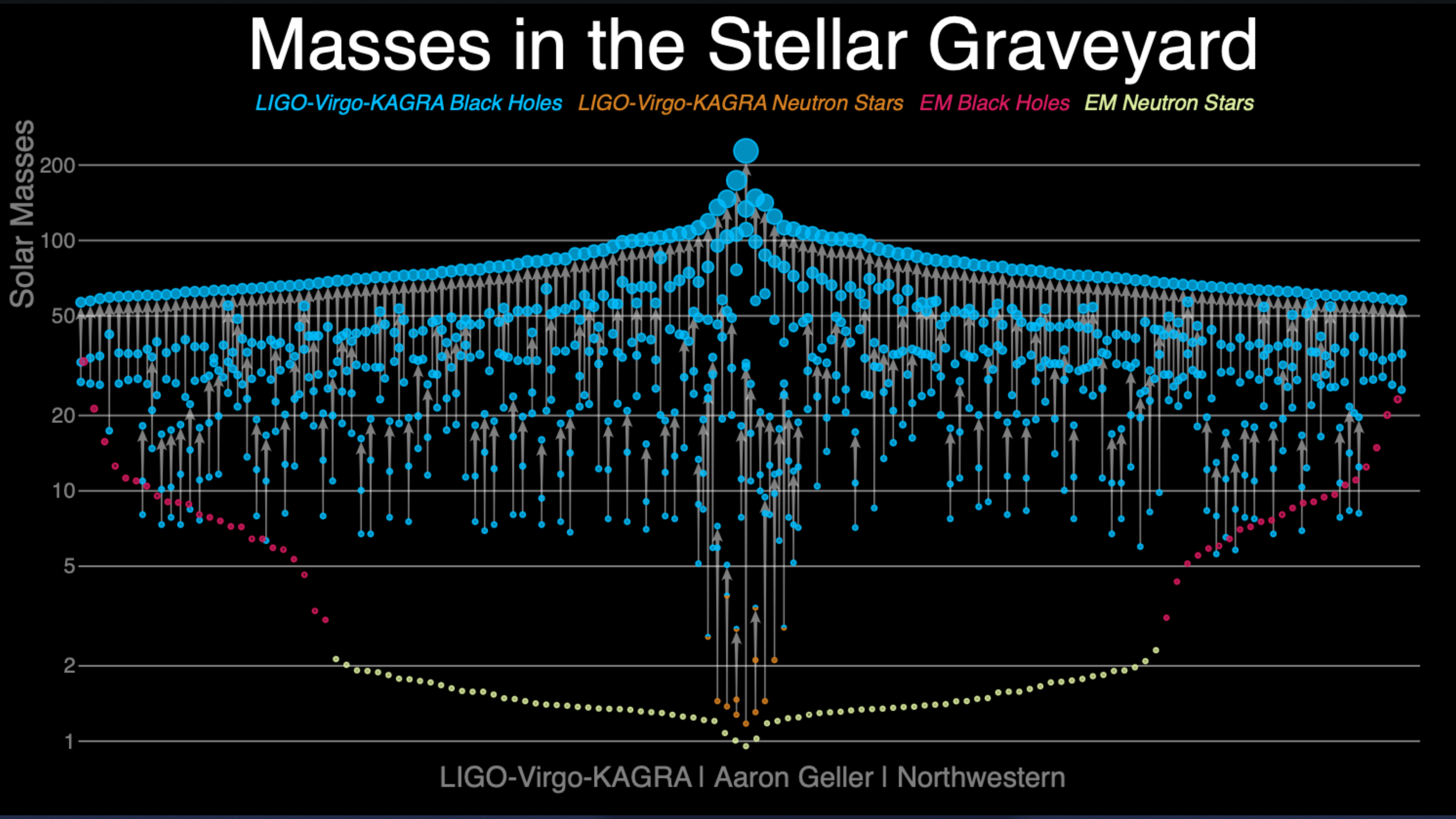
2 What we observe

LIGO-Virgo-KAGRA detect the final gravitational-wave chirp from the merger.

3 What we infer

The waveform gives masses, spins, distance, and clues to the formation history.

Can the ending reveal the story before it?


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

From detections to astrophysical lessons

Population inference turns measurements into astrophysics.

Masses, spins, and merger rates connect gravitational-wave observations to broader questions.

1 How do massive stars die?

Black-hole mass spectrum
Pair-instability mass gap
Stellar and nuclear physics

2 Where do binaries form?

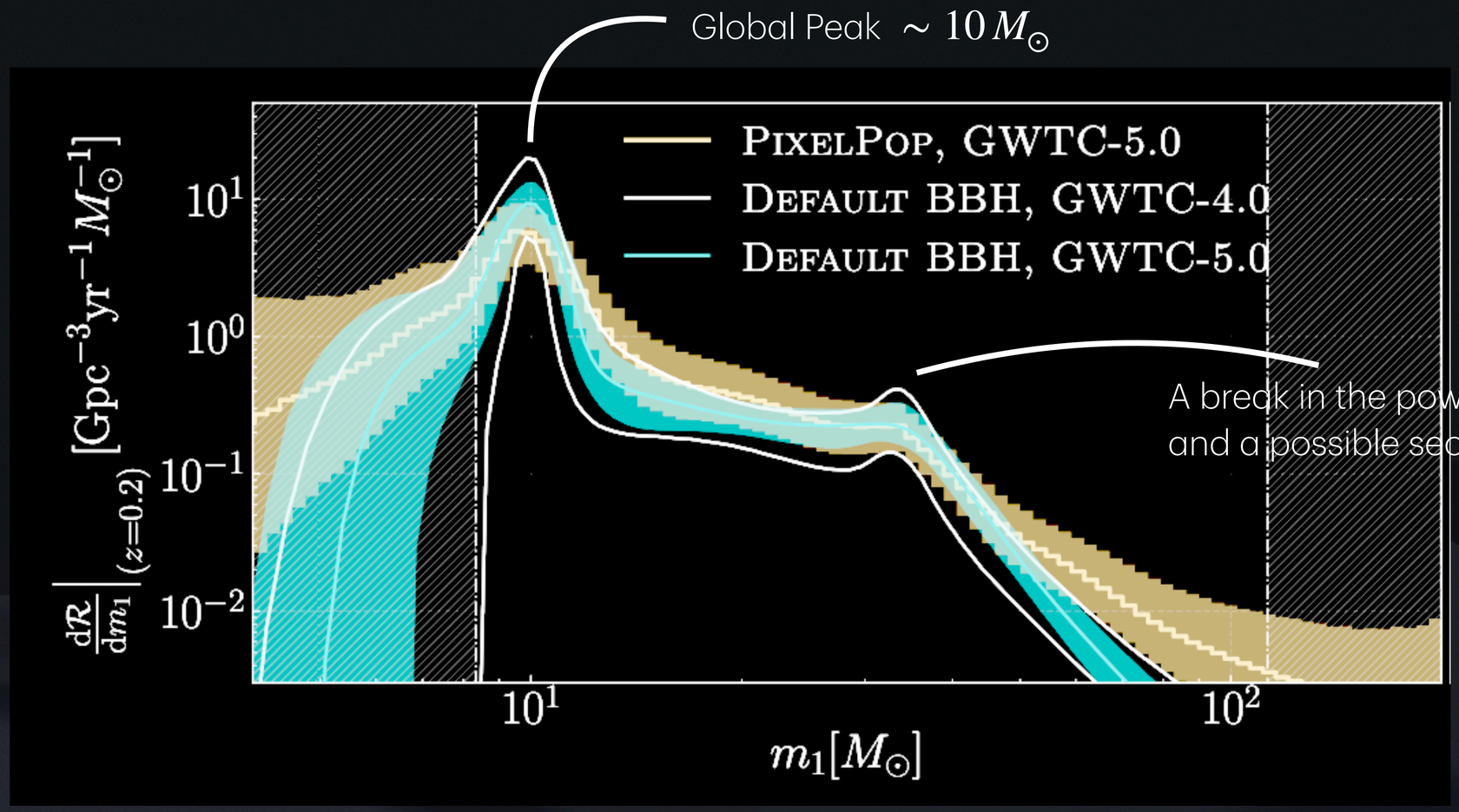
Isolated binaries or dense clusters
Spin signatures
Hierarchical mergers

3 What can they tell us about the Universe?

Cosmic evolution
Standard sirens
Expansion of the Universe

Masses, spins, and rates bridge the lives of stars, black-hole formation environments, and cosmic history.

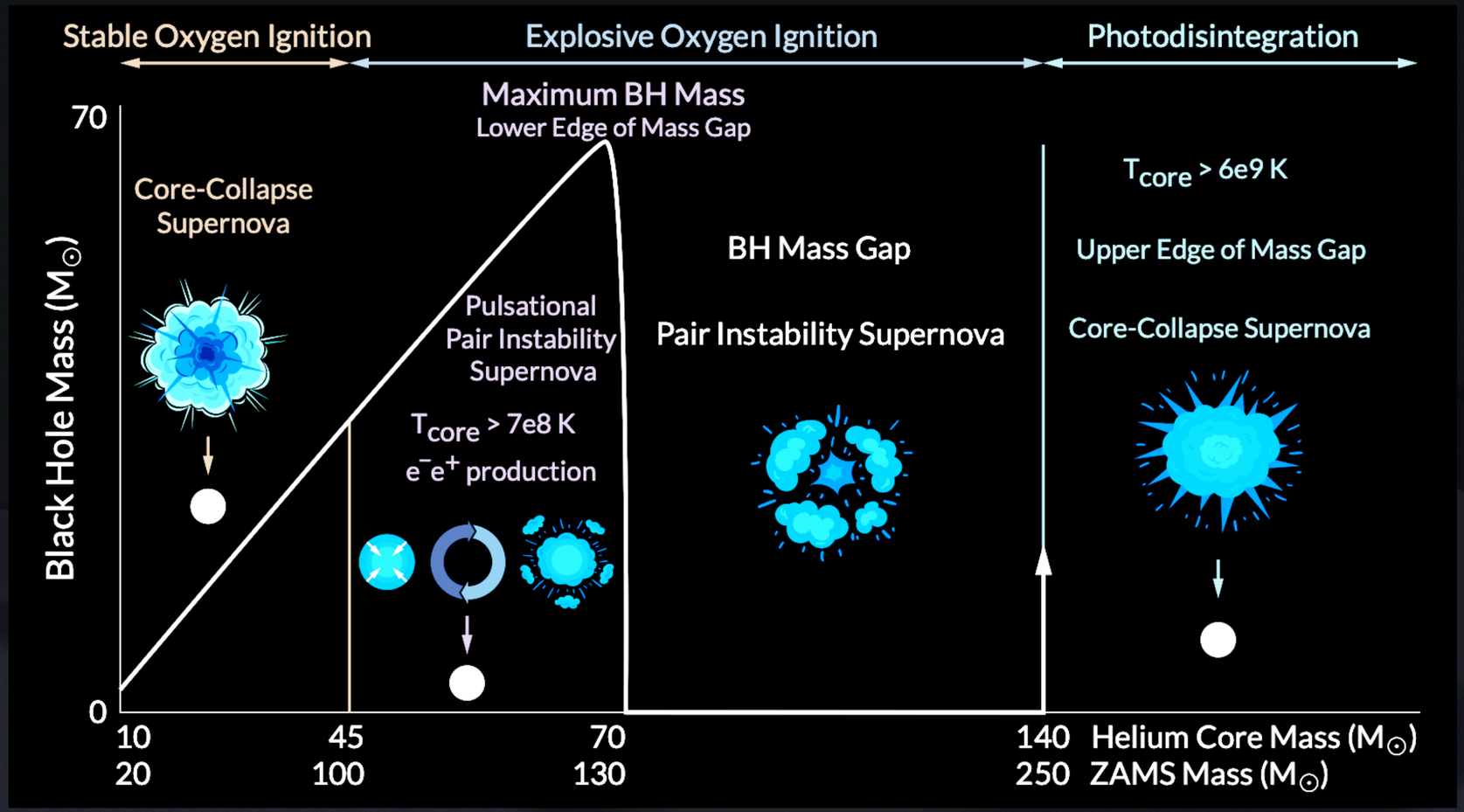
Global Mass Distribution



Abac et al. 2026, arxiv: 2605.27226

Pair-instability gap

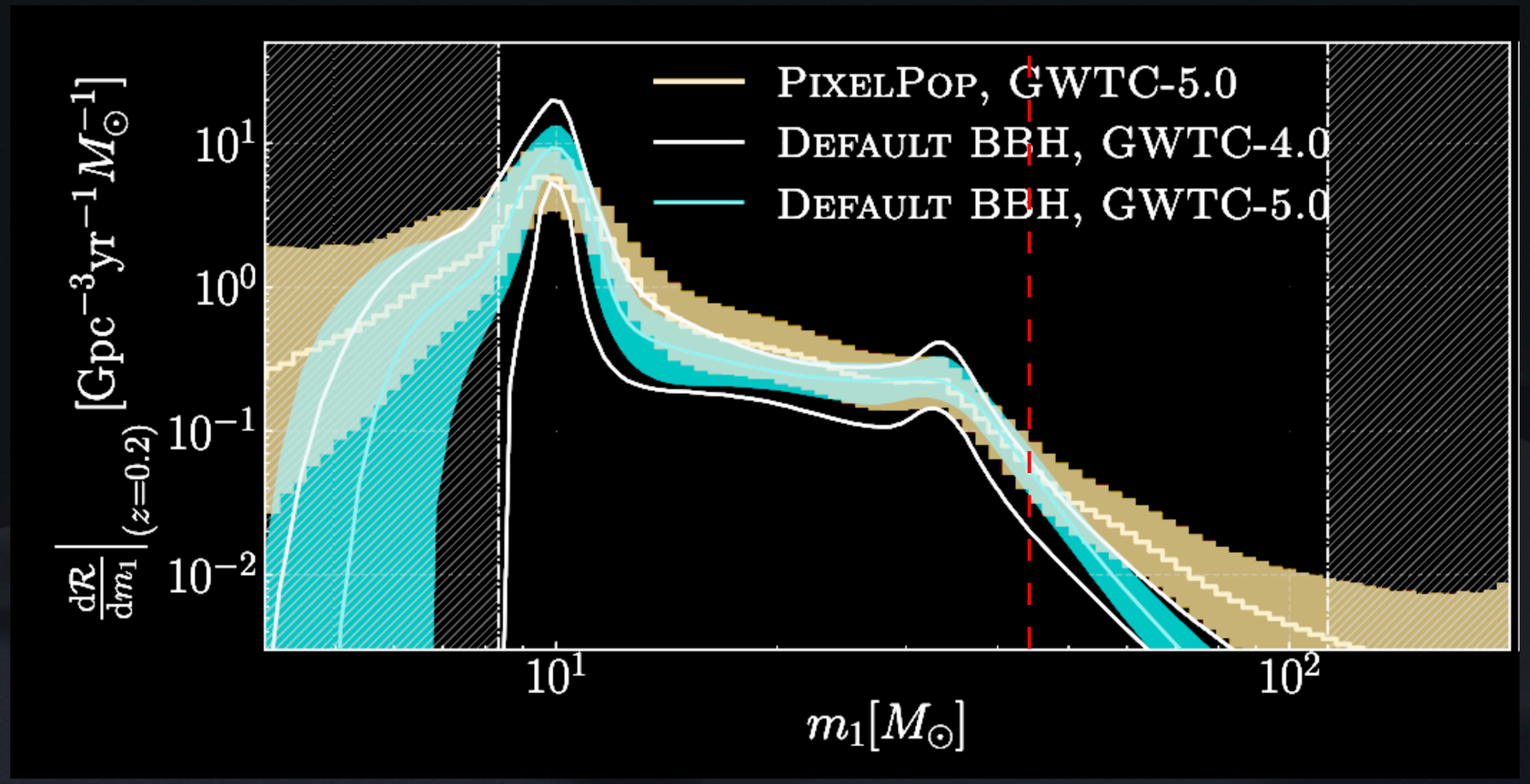
Stellar evolution theory predicts a lack of remnant black holes with certain masses due to (pulsational) pair instability supernova.



Farag et al. 2022

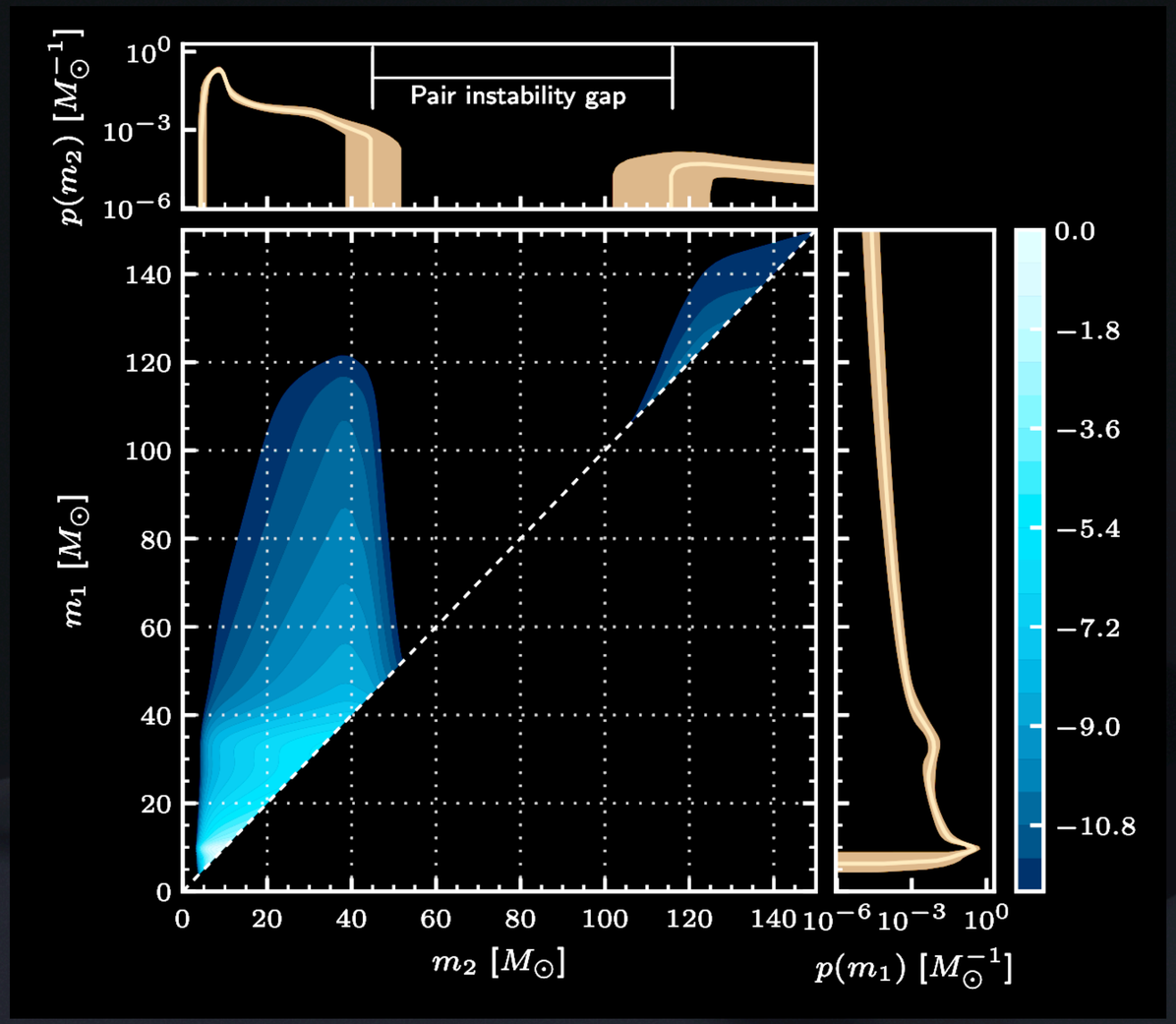
Pair-instability gap

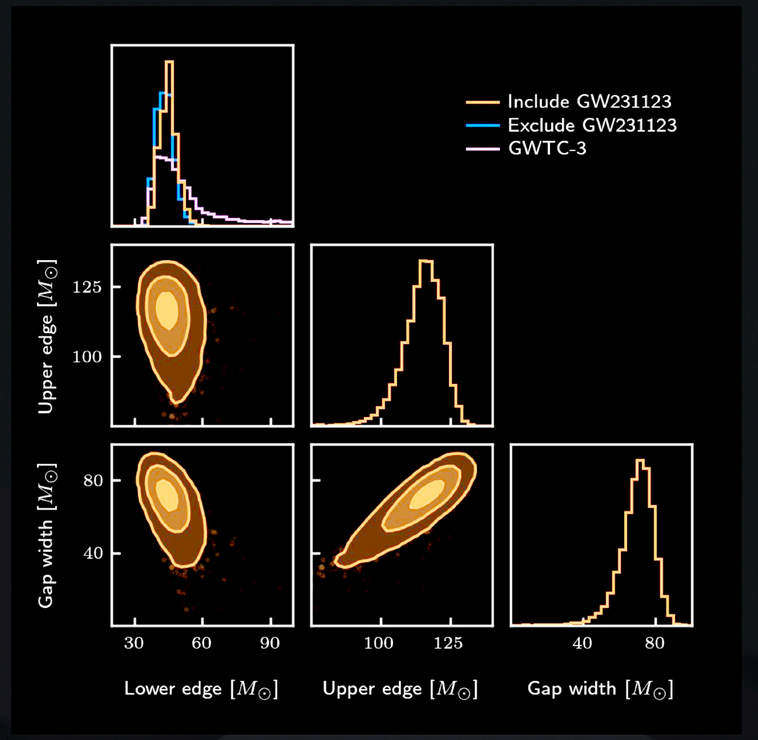
Some ($\gtrsim$ 1% of) black holes are more massive than 45 solar masses in BBH population inferred by GWTC-5.



Abac et al. 2026, arxiv: 2605.27226

A mass measurement of PISN



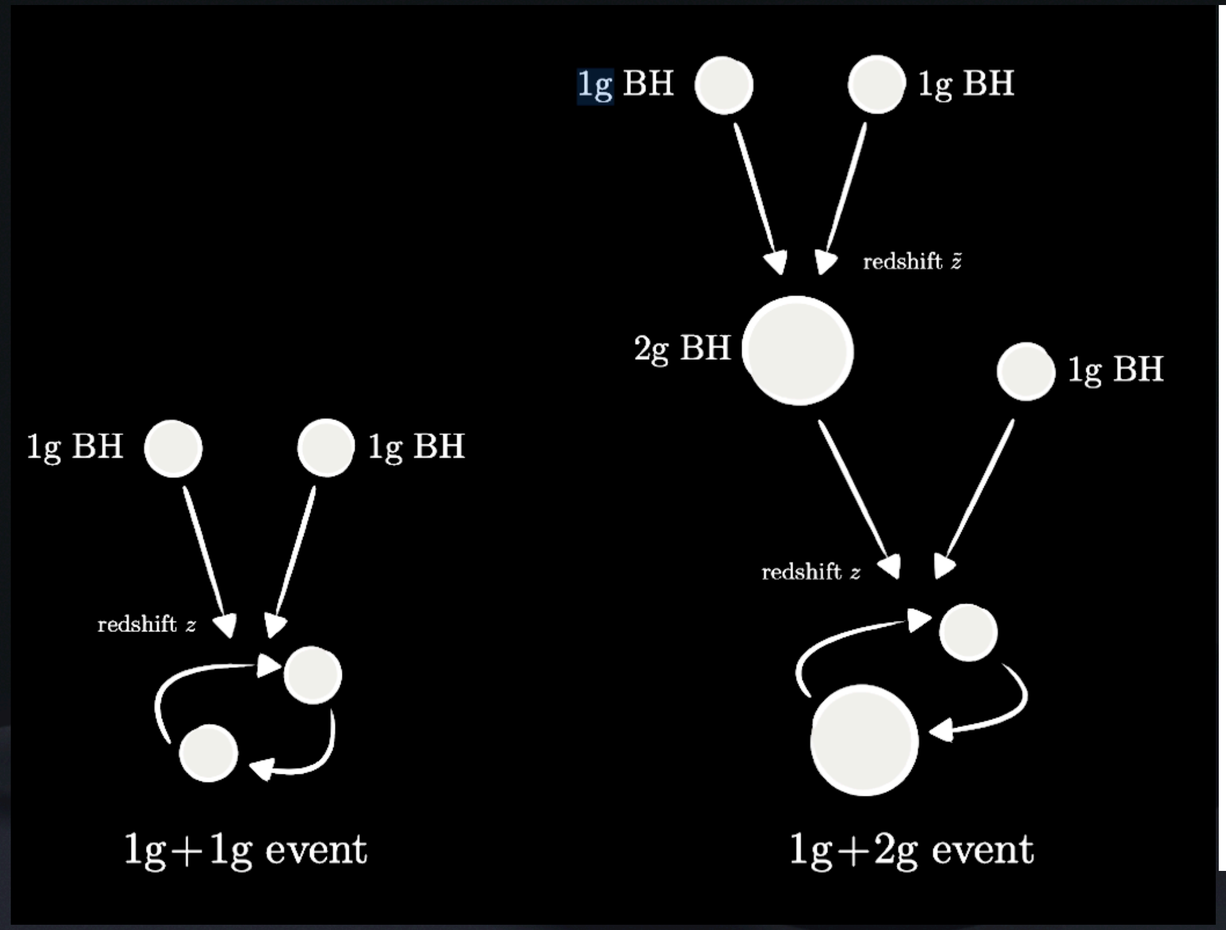


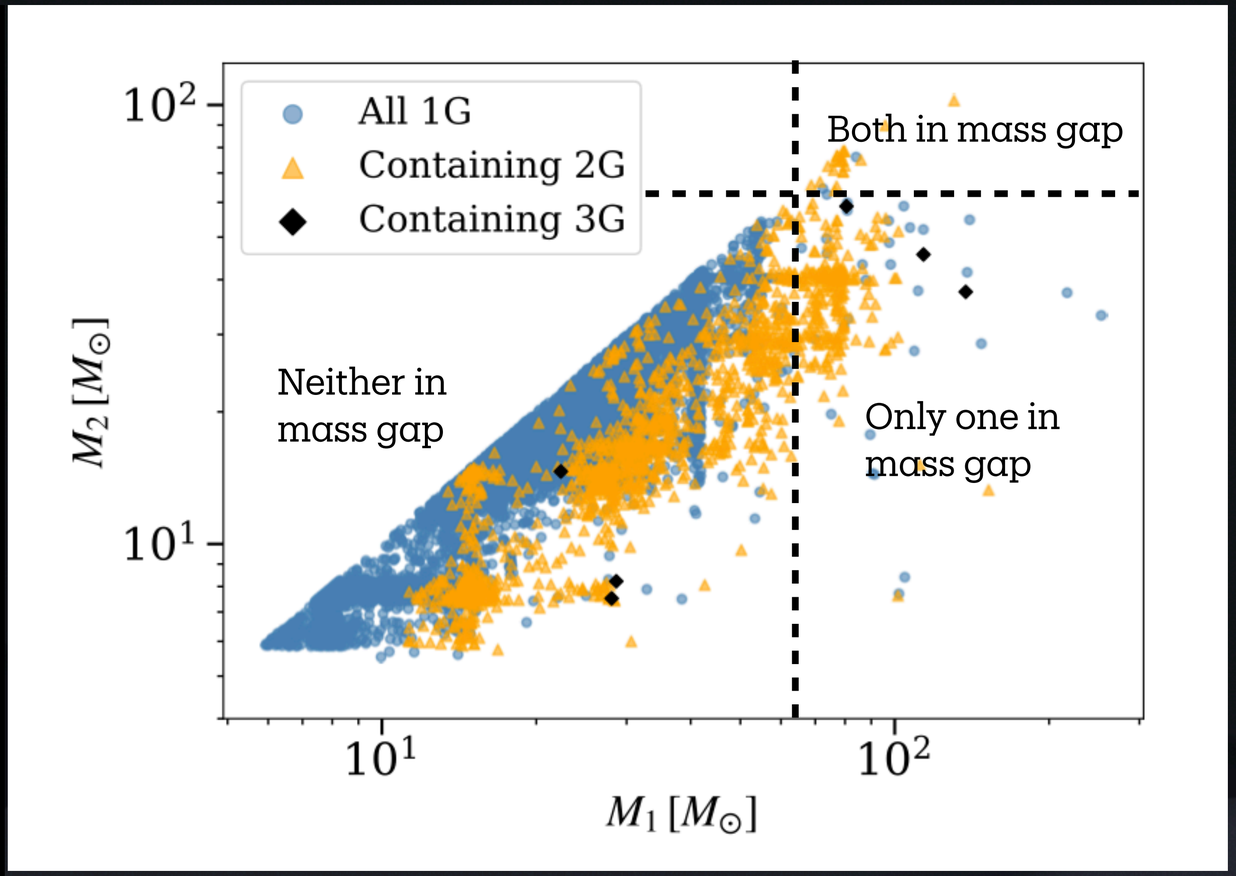
While the gap is not present in the distribution of primary masses m_1, it appears unambiguously in the distribution of secondary masses m_2.

Tong et al., Nature (2026)

Hierarchical mergers

Gerosa & Berti, 2017

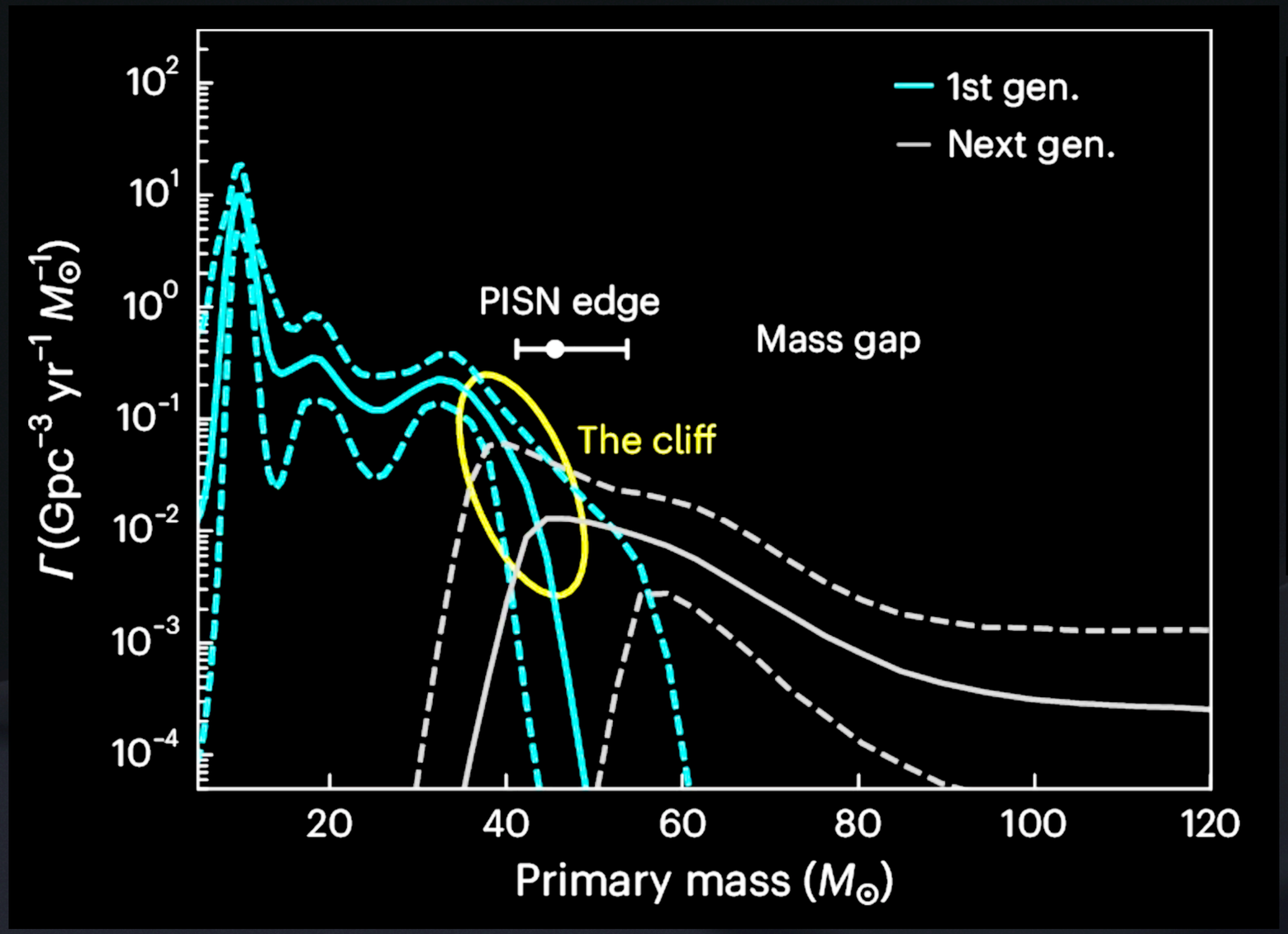


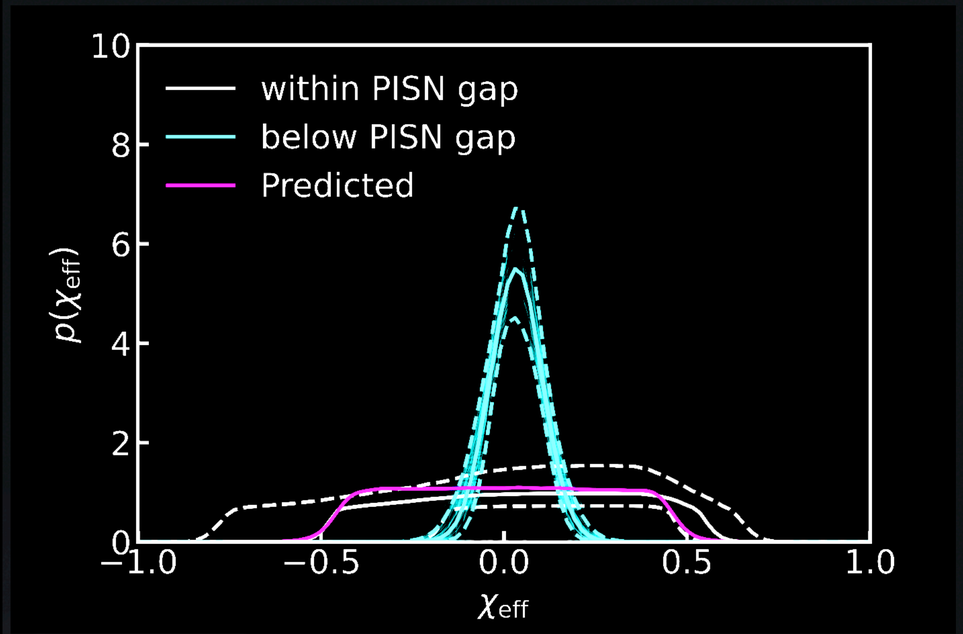


Ye & Fishbach, 2024

A merger remnant typically has $\chi \sim 0.7$

A spin measurement of PISN



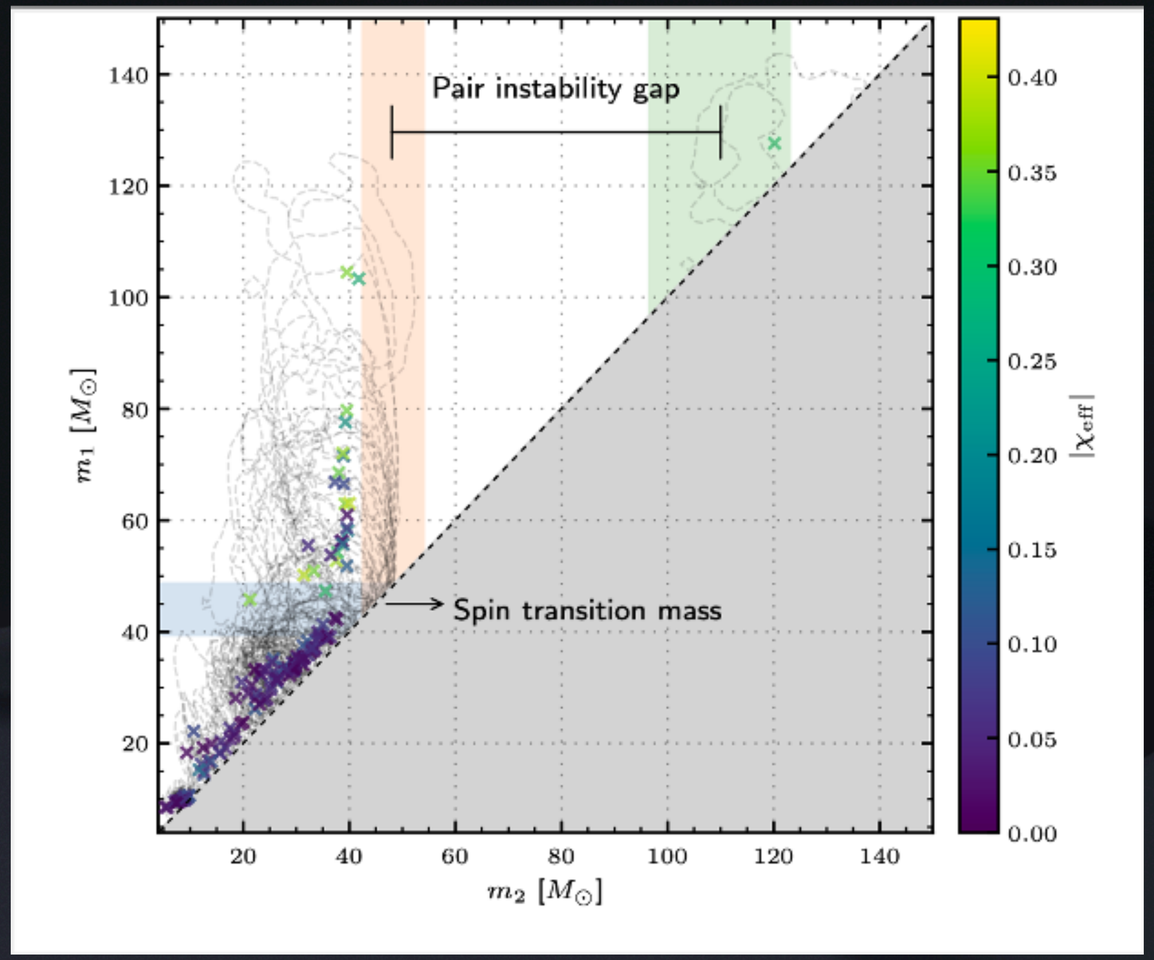


Effective inspiral spin $\chi_{\rm eff}$: mass-weighted spins aligned with orbital angular momentum axis

Antonini et al., 2026

Evidence for the pair instability gap in GWTC-4

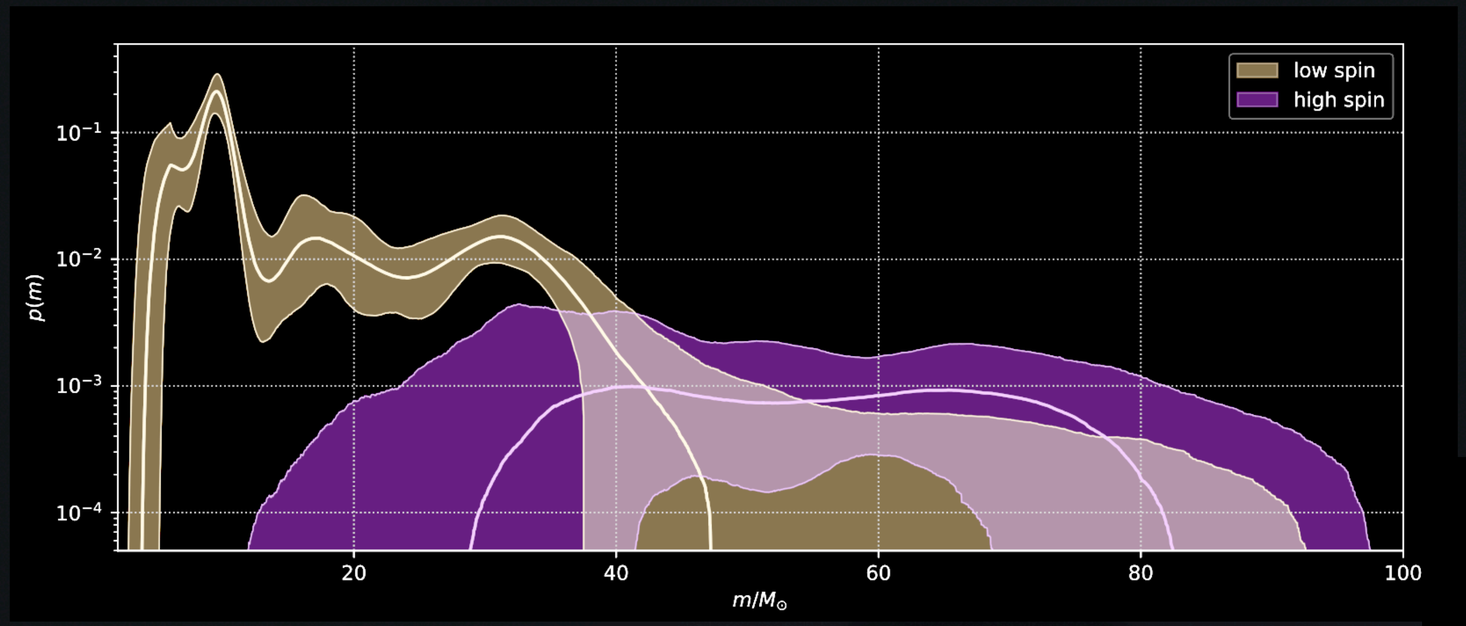
The location of the gap lines up well with the transition in the binary black-hole spin distribution.



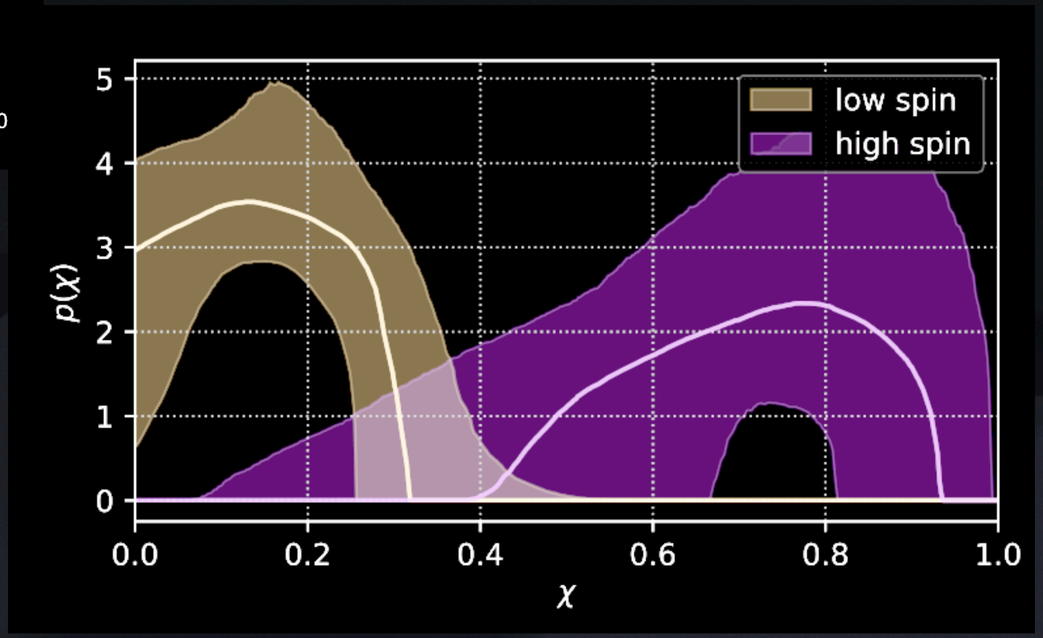
Binaries with *primary* components in the gap tend to spin more rapidly than those below the gap.

Tong et al., Nature (2026)

Spin for high mass mergers



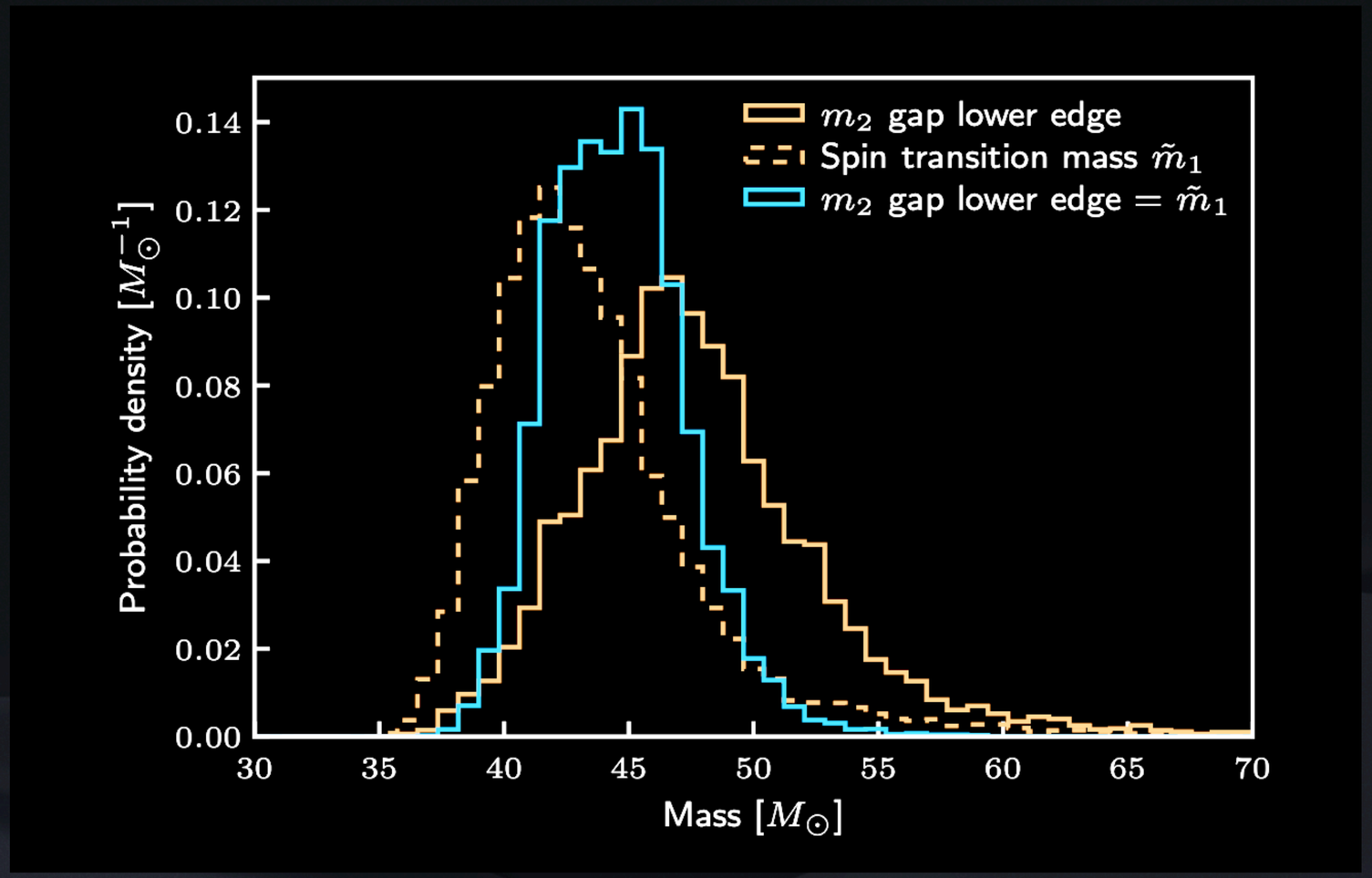
Li et al., 2024



There are two subpopulations of black holes.

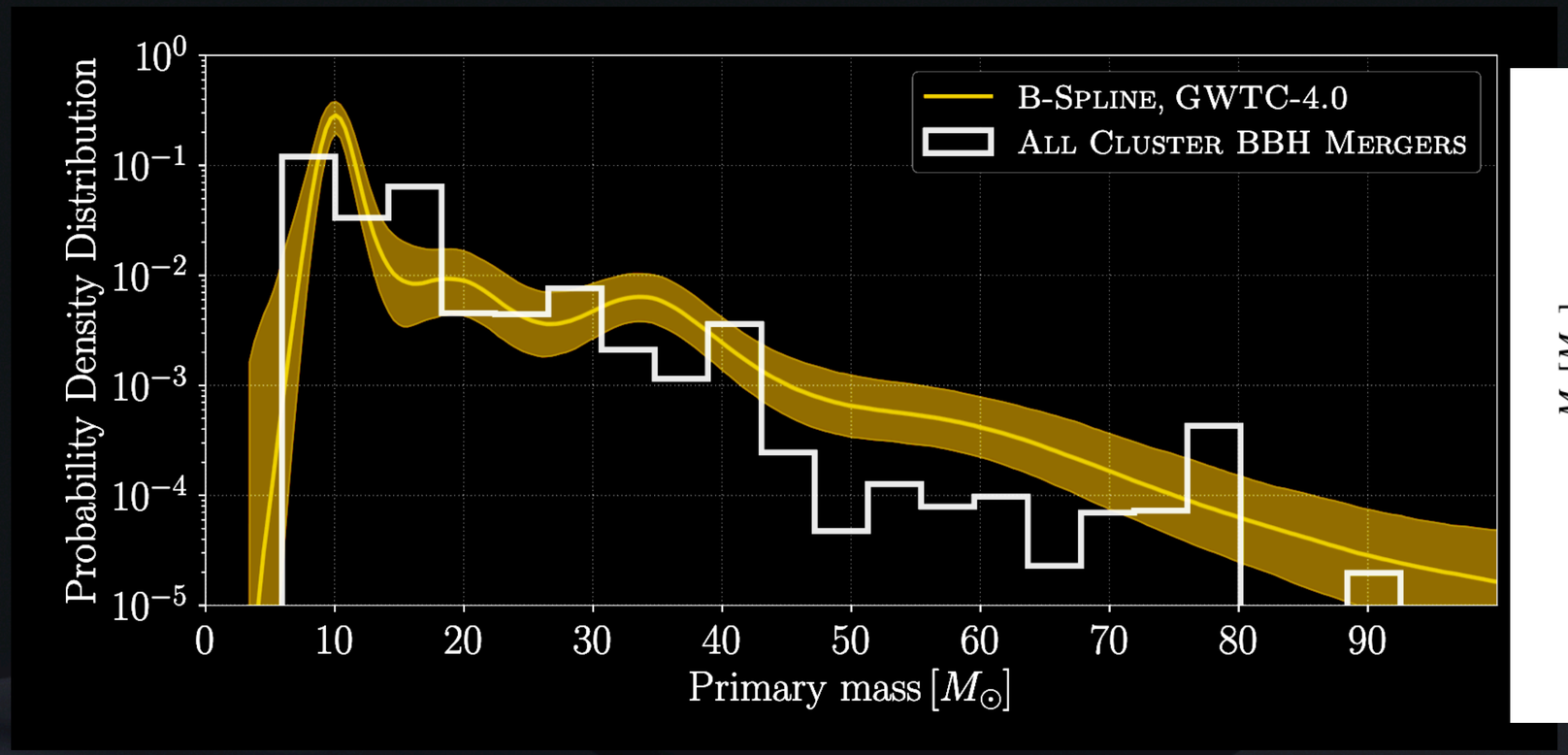
High mass black holes have $\chi \sim 0.7$.

Agreement between the spin transition and the m_2 gap

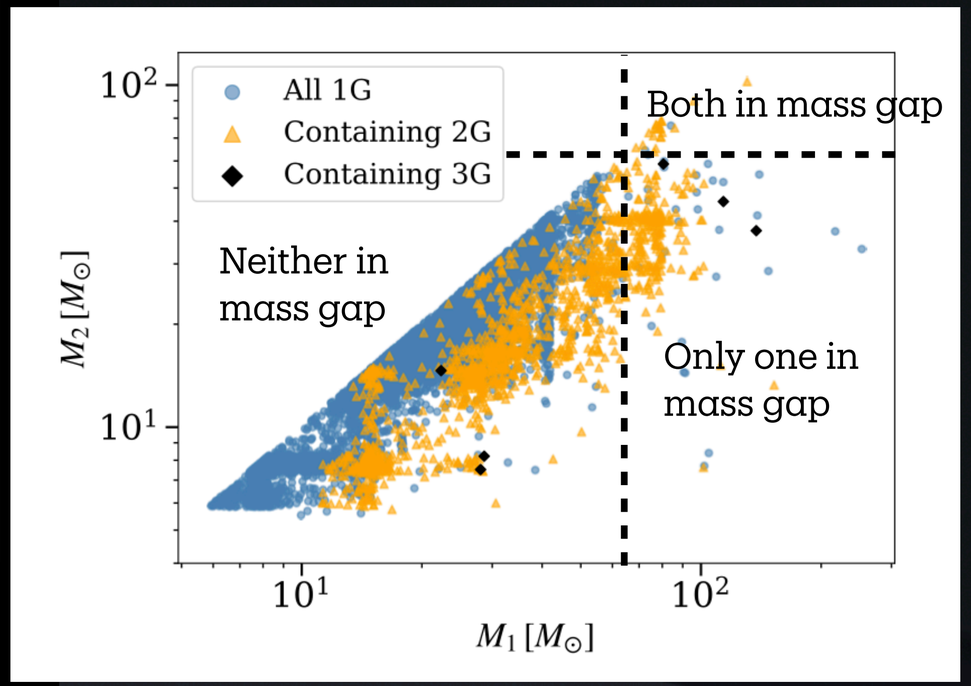


Tong et al., Nature (2026)

Hierarchical mergers at low masses

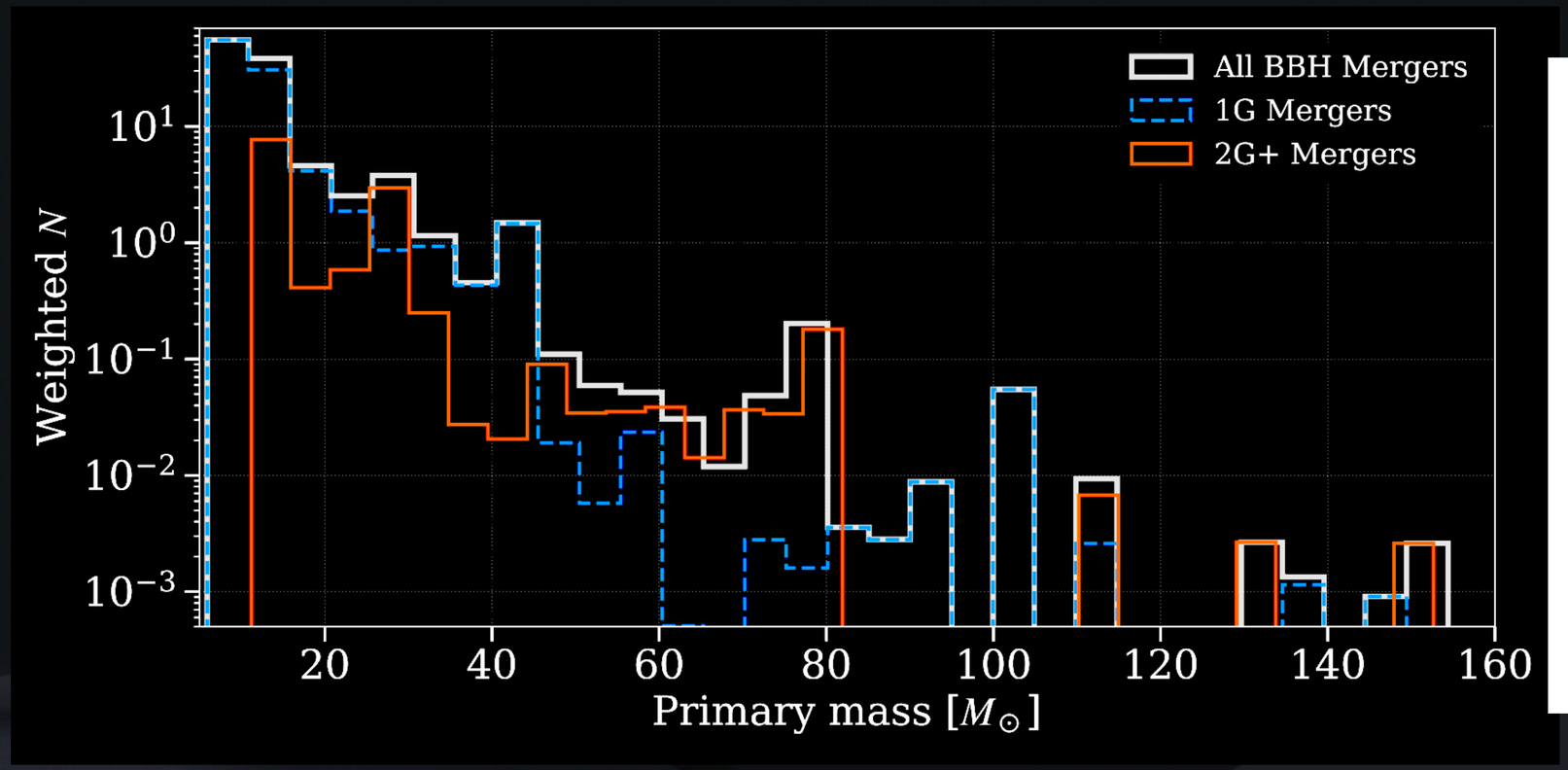


Ye et al., 2026

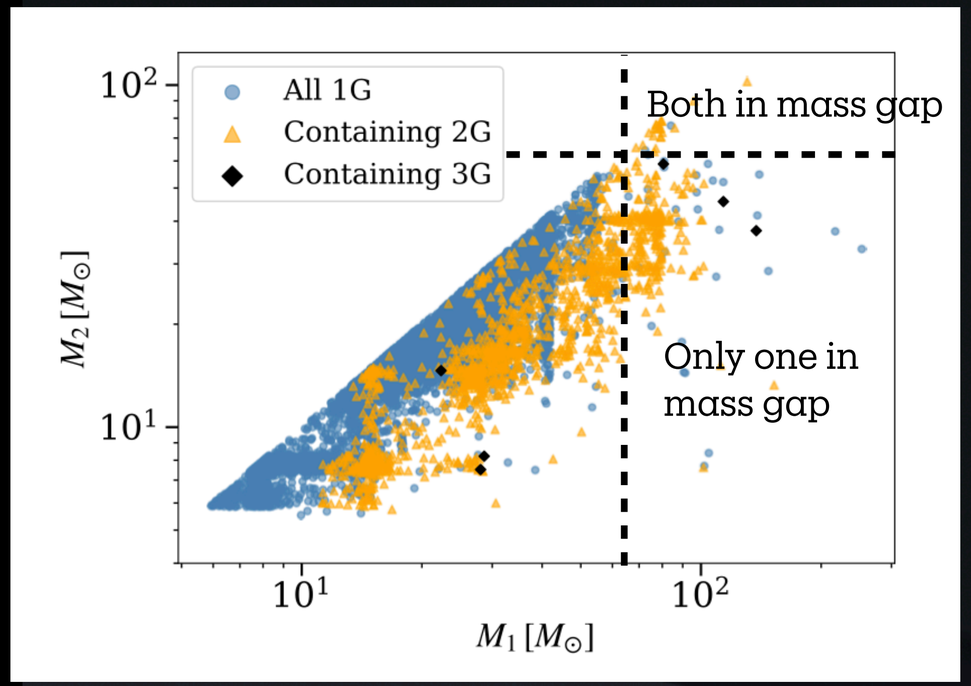


Ye & Fishbach, 2024

Hierarchical mergers at low masses



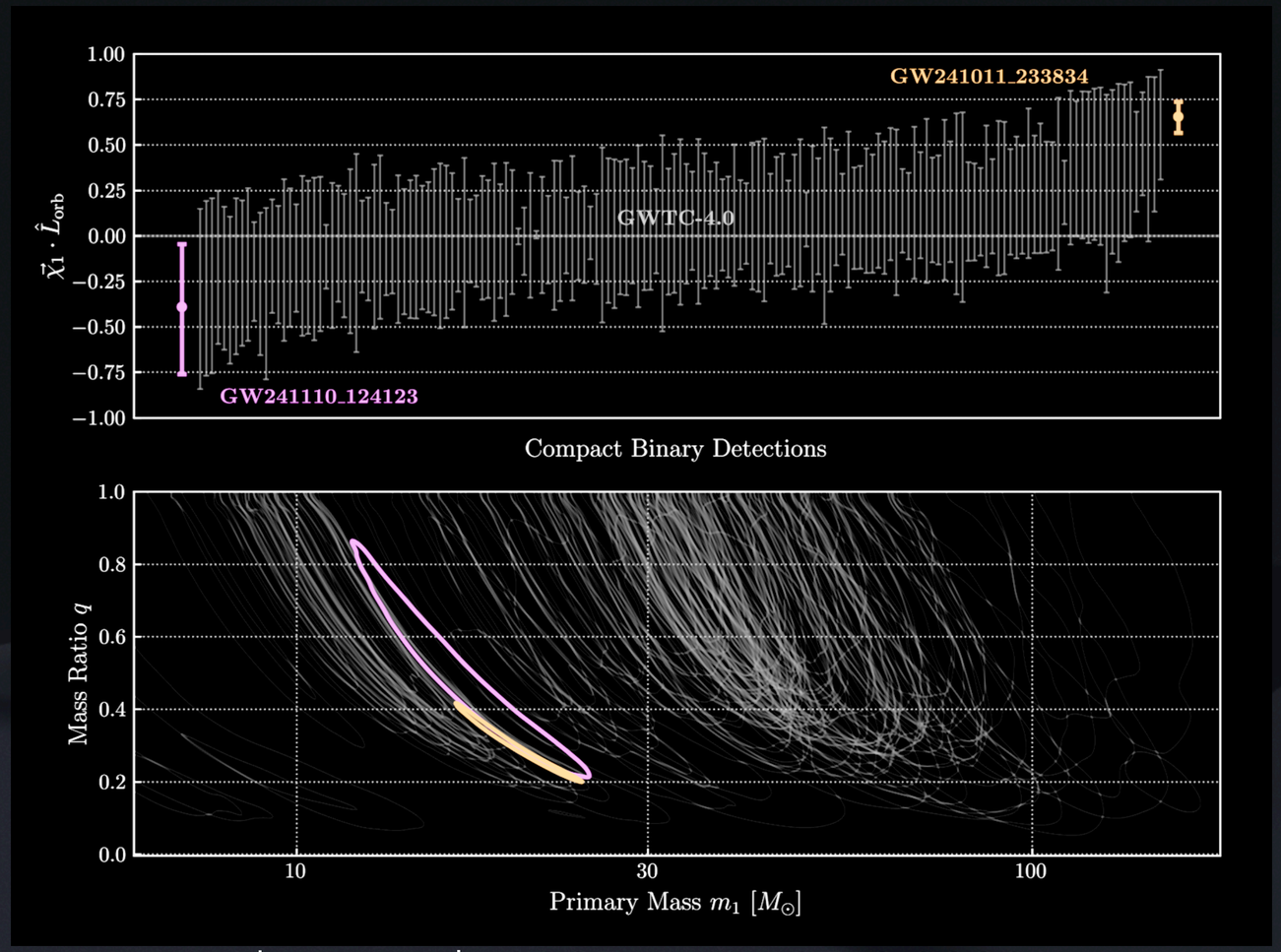
Ye et al., 2026



Ye & Fishbach, 2024

The most promising hierarchical merger candidates?

GW241011 & GW241110



GW241011

$\chi_1 = 0.78^{+0.09}_{-0.09},$

$q = 0.30^{+0.09}_{-0.08},$

$\theta = 31^{+11}_{-14}\text{deg},$

GW241110

$\chi_1 = 0.61^{+0.33}_{-0.40},$

$q = 0.45^{+0.32}_{-0.17},$

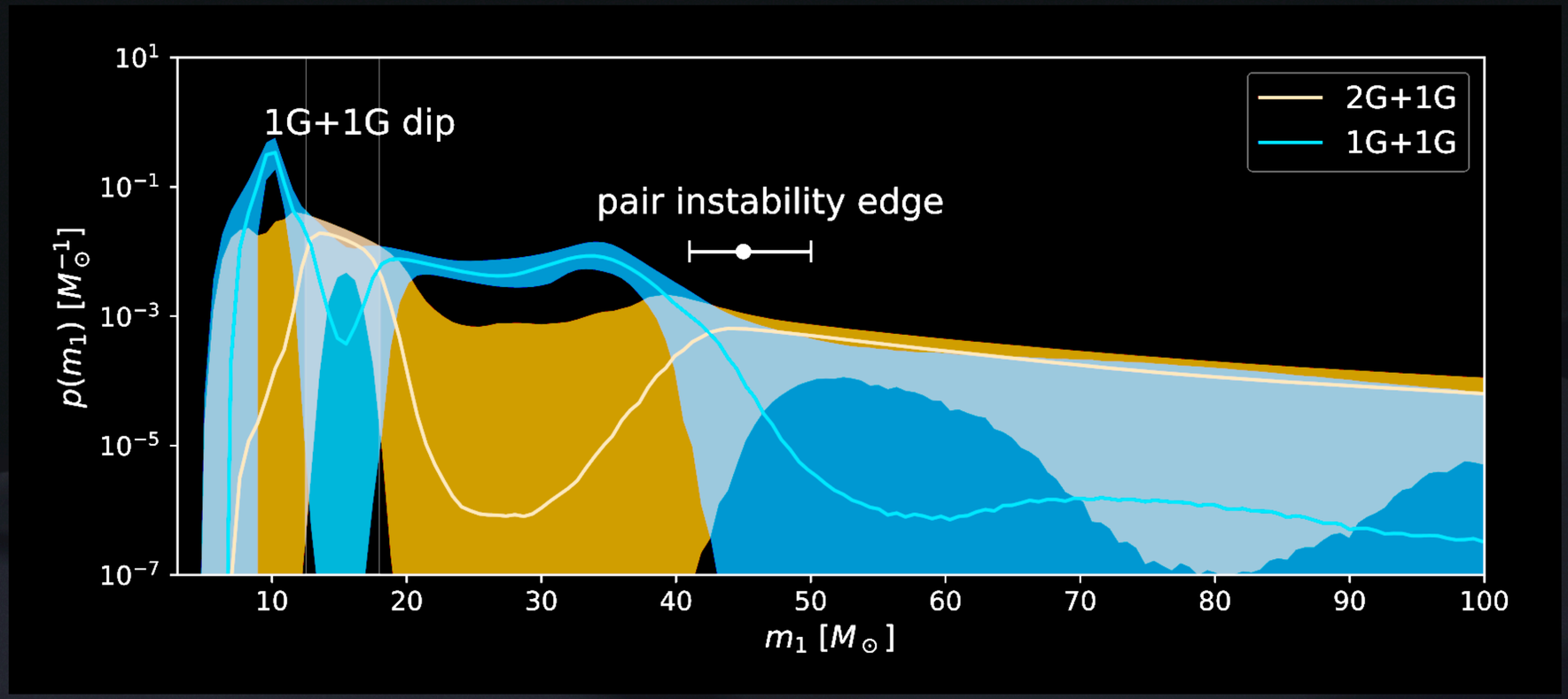
$\theta = 133^{+47}_{-25}\text{deg},$

Abac et al., 2025, arxiv: 2510.26931

A subpopulation low-mass, spinning black hole

There are more than just GW241011 and GW241110.

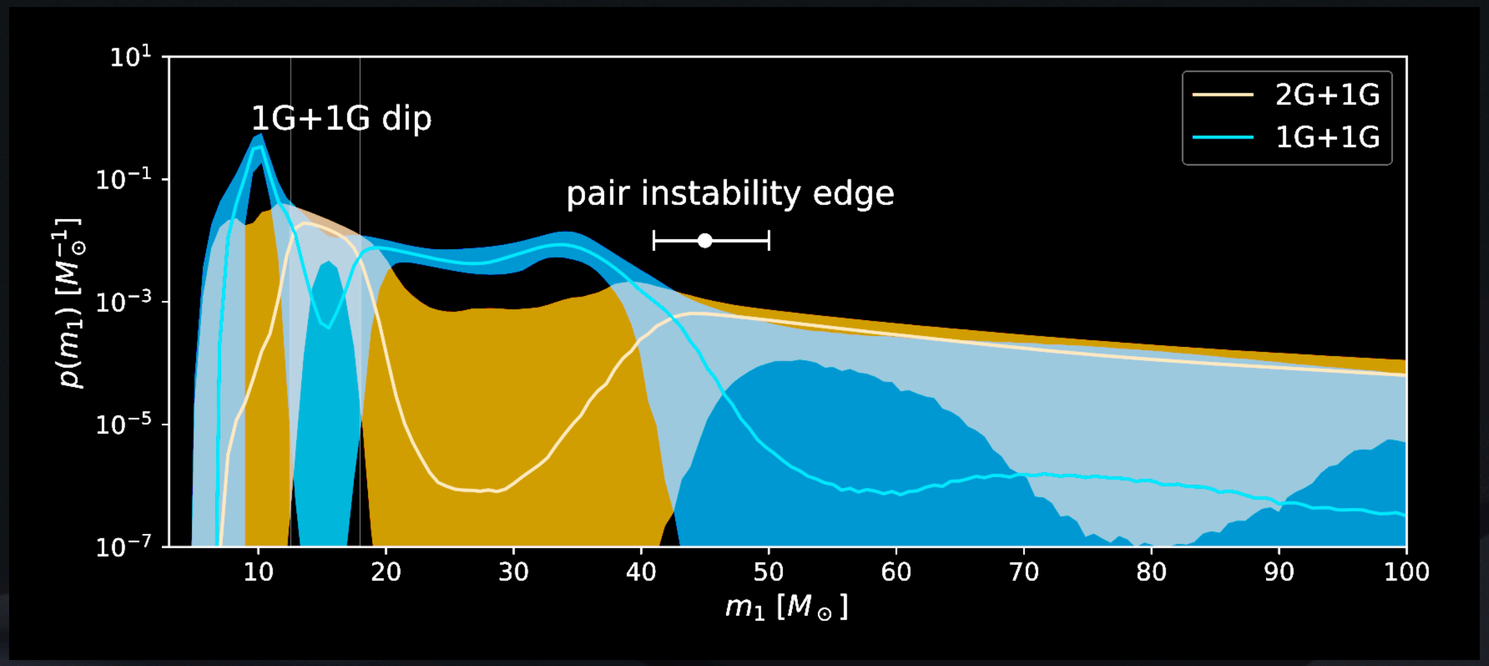
Tong et al., PRD (2026)

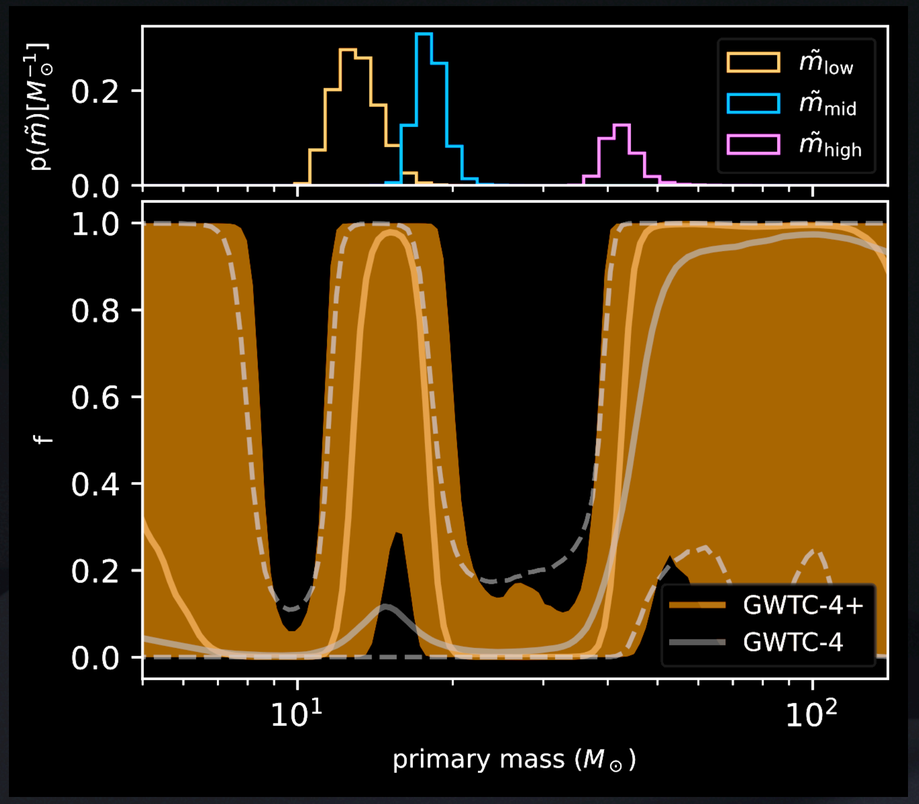


Possible candidates:
GW241011
GW231118_005626
GW241110
GW230723_101834?
GW230706_104333?

The primary mass distribution of 2G+1G mergers may have a global peak around $16M_\odot$.

A subpopulation low-mass, spinning black hole

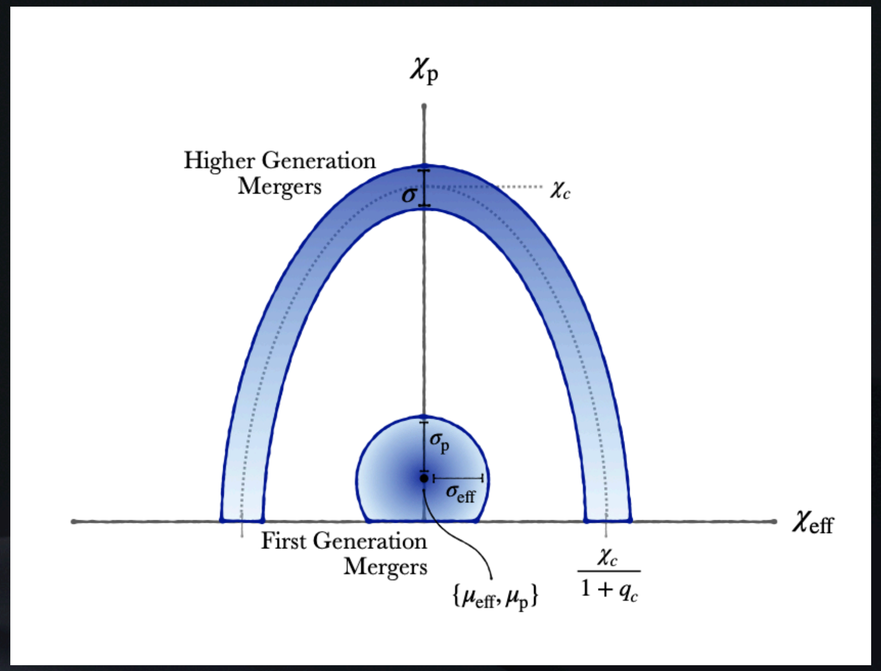


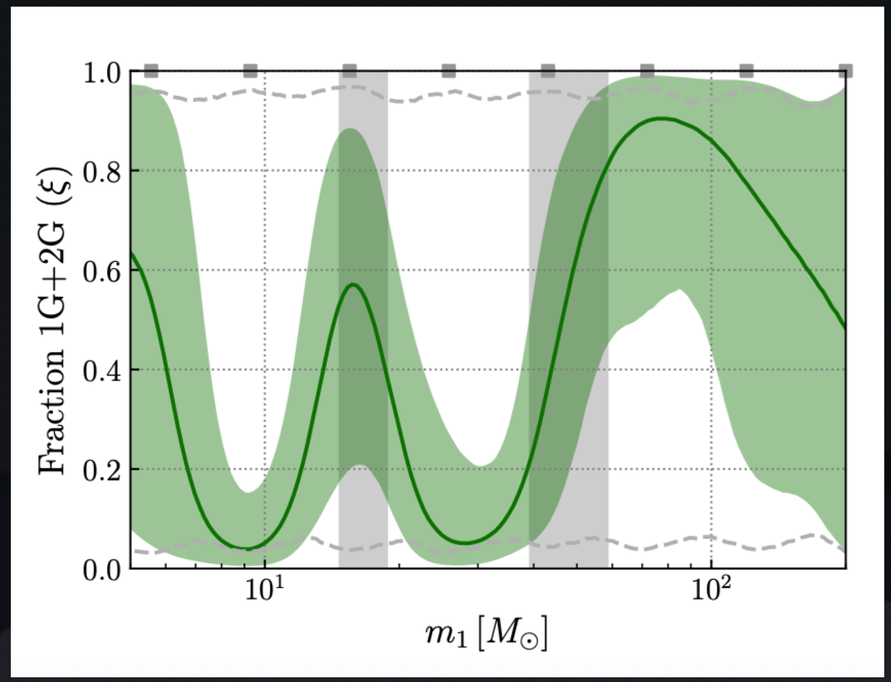


The primary mass distribution of 2G+1G mergers may have a global peak around 16$M_\odot$.

A subpopulation low-mass, spinning black hole subpopulation

This is supported by a follow-up study which incorporates in-plane spin information.





Plunkett et al., 2026

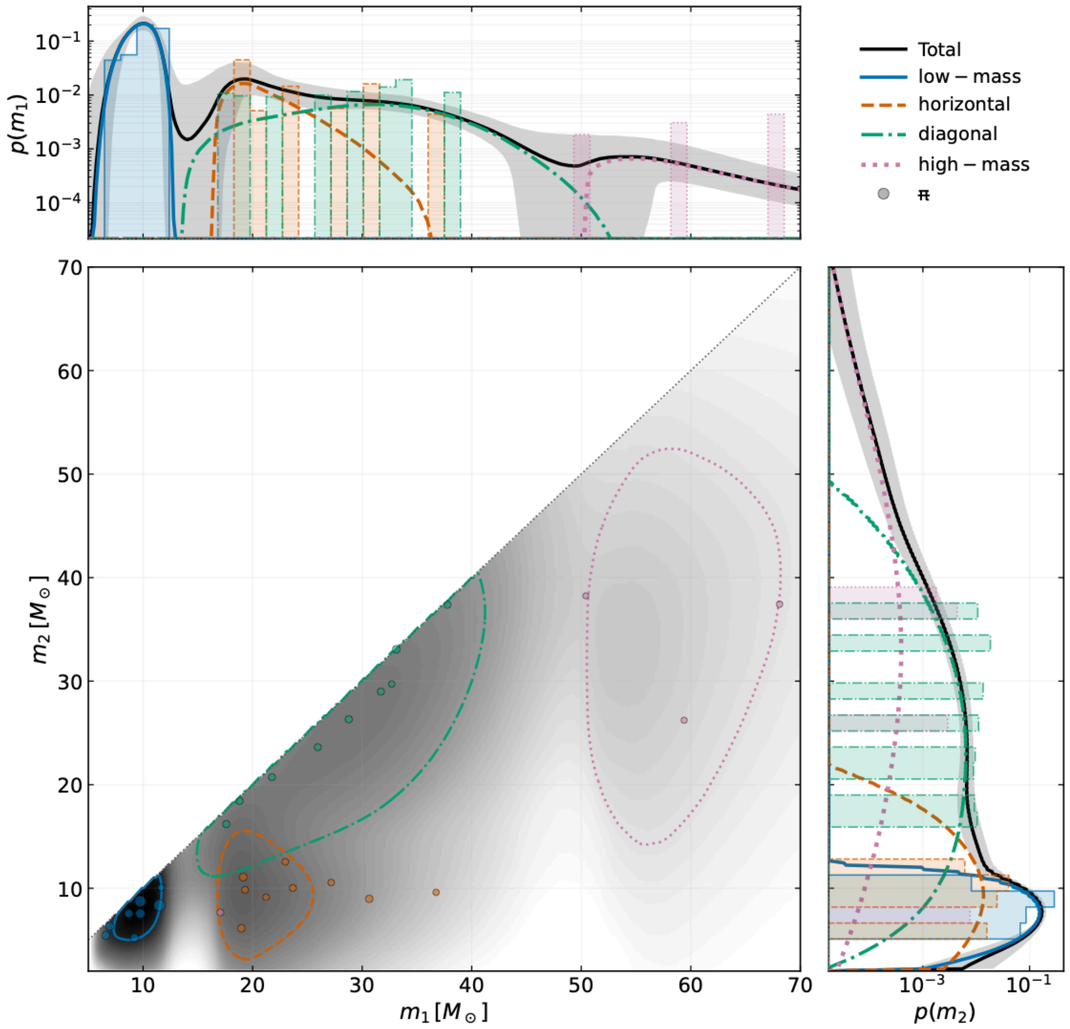
The overdensity of low mass mergers through dynamical assembly might suggest the contribution from metal-rich stellar environments.

Conclusions

- Gravitational-wave detections enable inference of the astrophysical population of BBHs.
- Features in the BBH distribution provide direct insight into massive stellar evolution and supernova physics.
  - We constrain the pair-instability gap at $\sim 45\,M_{\odot}$.
- Signatures of black hole properties can probe the formation channels and environments of BBHs as well.
  - The existence of low mass hierarchical mergers suggests the dense, metal rich stellar environments as GW source factories.

Extra slides

A Data-Driven Method



Guttman et al., 2026