Title: Astrophysical Lessons from the Fourth Gravitational Wave Transient Catalog.

Speakers: Maya Fishbach

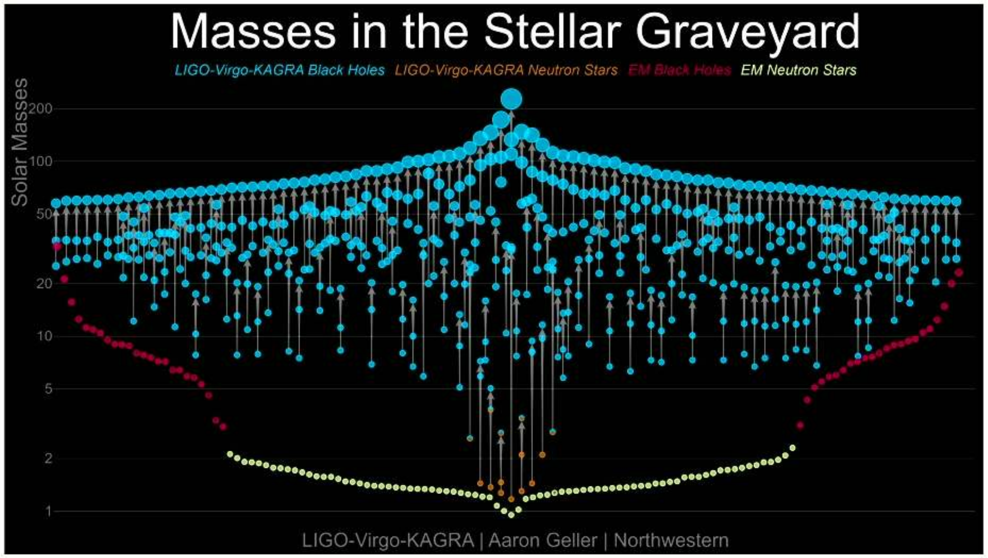
Collection/Series: Charting the Future Symposium

Subject: Cosmology, Particle Physics, Strong Gravity

Date: August 26, 2025 - 10:00 AM

URL: https://pirsa.org/25080020

Evidence for a Black Hole Mass Gap from the Fourth Gravitational Wave Transient Catalog



Maya Fishbach (she/her)
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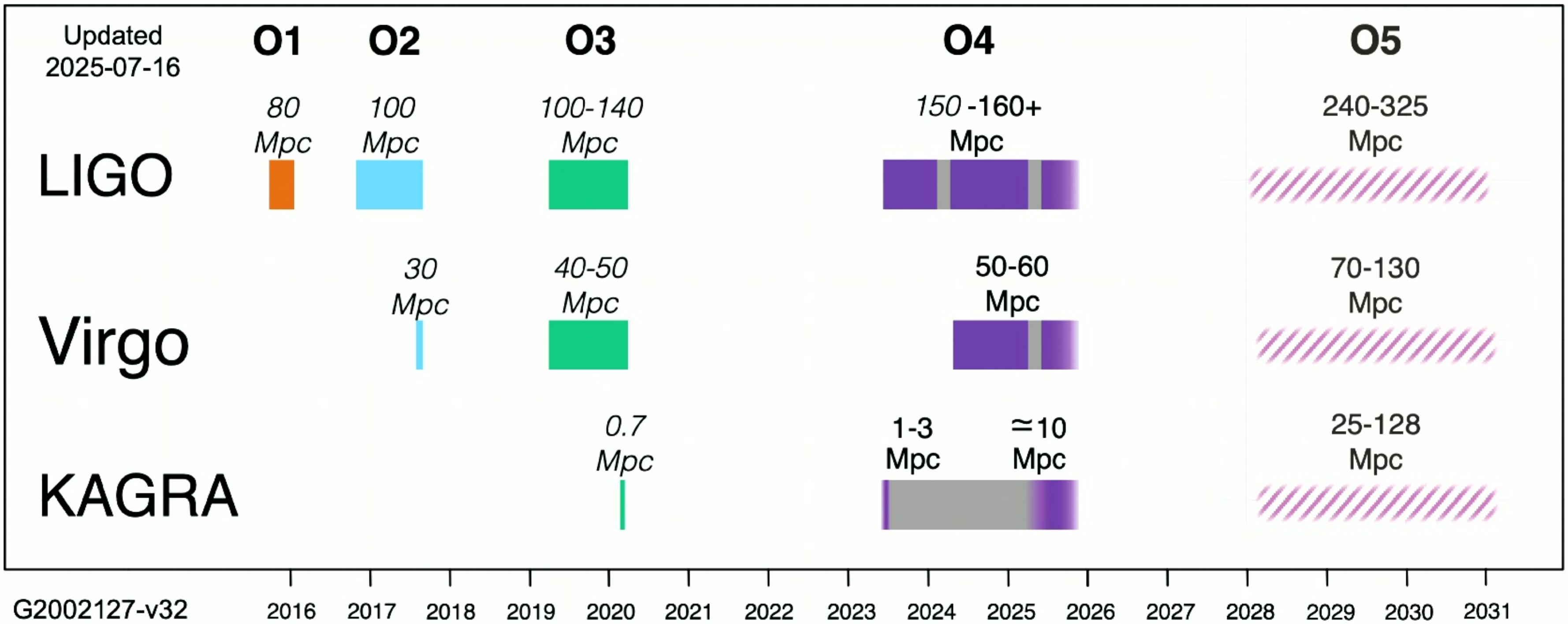
Charting the Future Symposium 2025

CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

UNIVERSITY OF TORONTO

Observing Timeline



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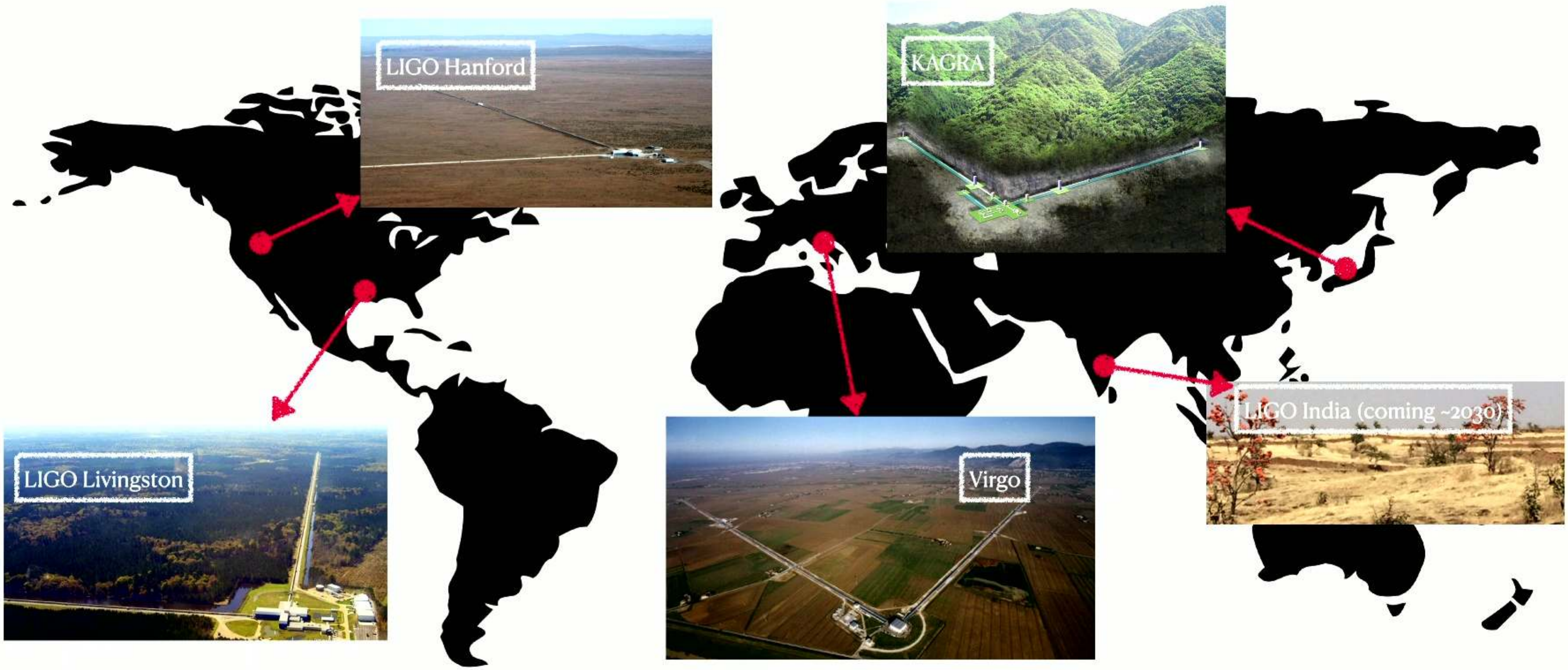
Gravitational-wave observatories



GWTC-4.0: The Fourth Gravitational Wave Transient Catalog

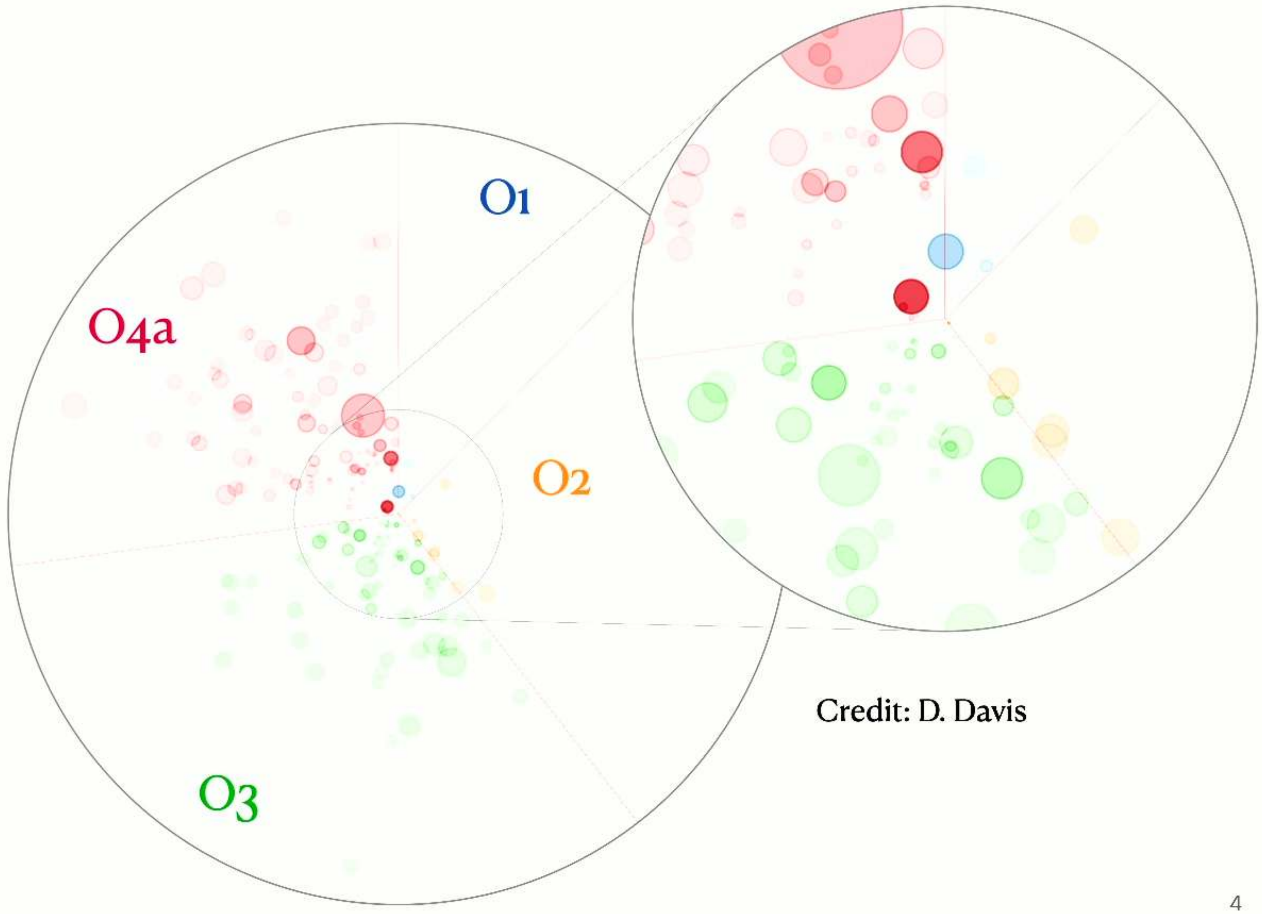
Catalog - Introduction: 2508.18080

Catalog - Methods: 2508.18081

Catalog - Results: 2508.18082

Astrophysical populations: 2508.18083

Open data: 2508.18079

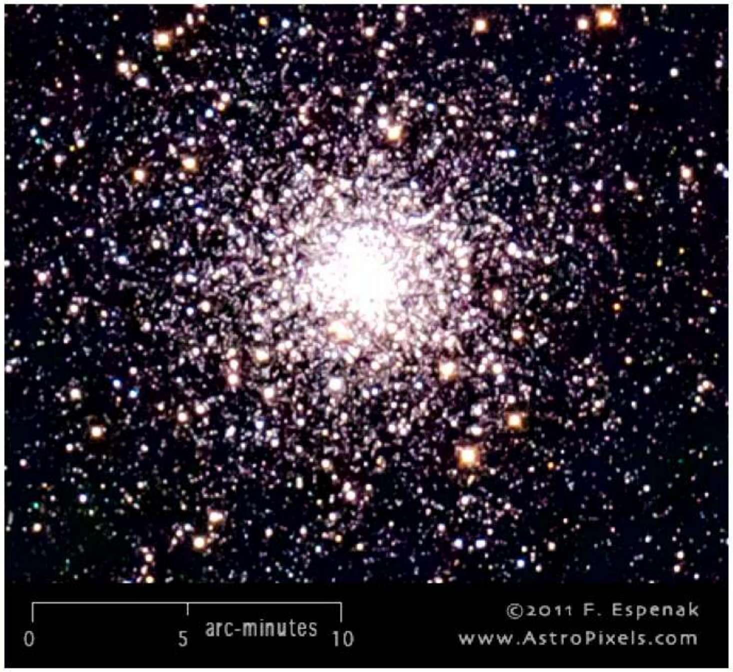


Credit: D. Davis

How are merging binary black holes made?

Isolated Binary Stars

Dense Star Clusters



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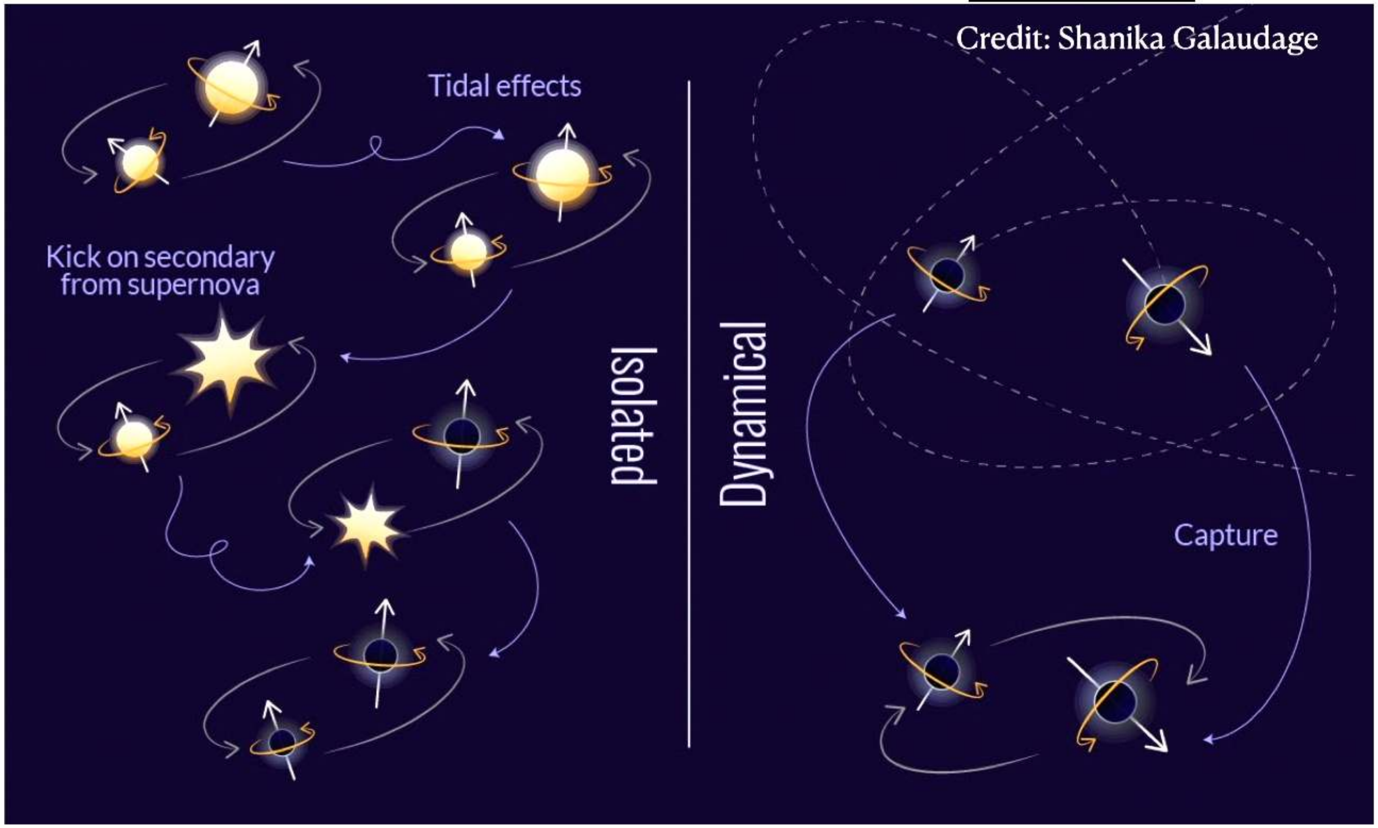
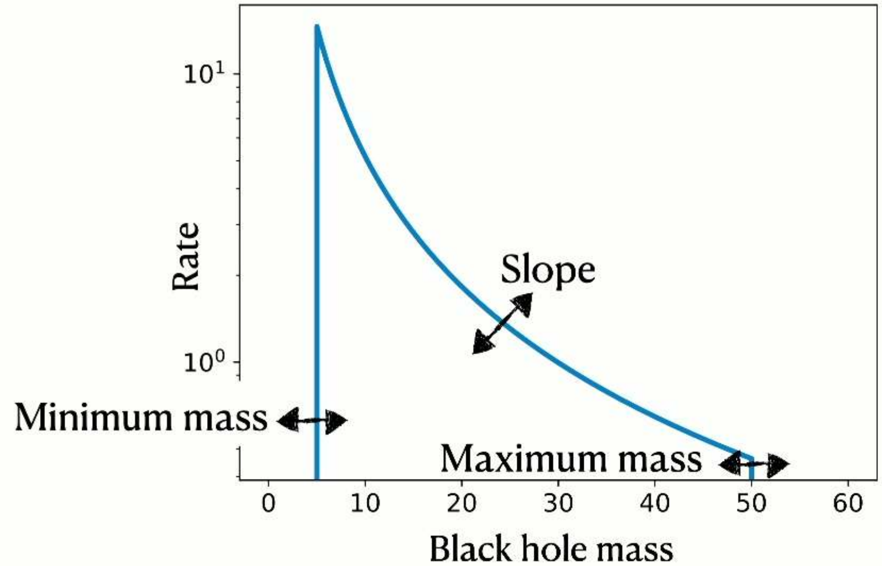

Credit: Shanika Galaudage
Tidal effects
Kick on secondary from supernova
Isolated
Dynamical
Capture

From Single Events to a Population

- Introduce a population model that describes the **distributions** of masses, spins, redshifts across **multiple events**.
- Example: Fit a power law to black hole masses.
- Take into account **measurement uncertainty** and **selection effects** (see Reed's talk).
    - Don't just fit the "detected distribution!" (Essick & MF 2024)



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Black Hole Mass Gap

For stellar collapse, **(pulsational) pair-instability supernovae** predict an absence of black hole remnants between $\sim 50 - 130\, M_{\odot}$ (see, e.g., Renzo & Smith 2024 for a review)

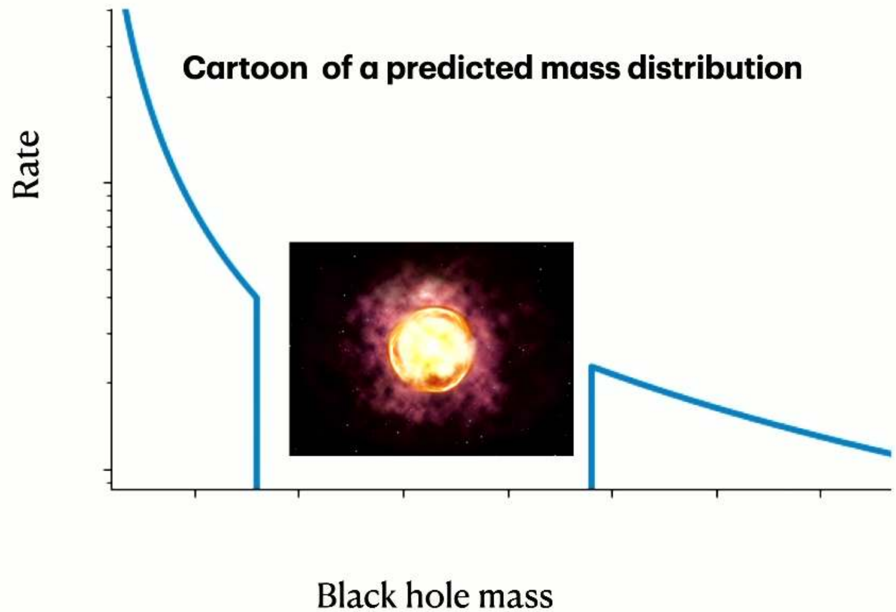
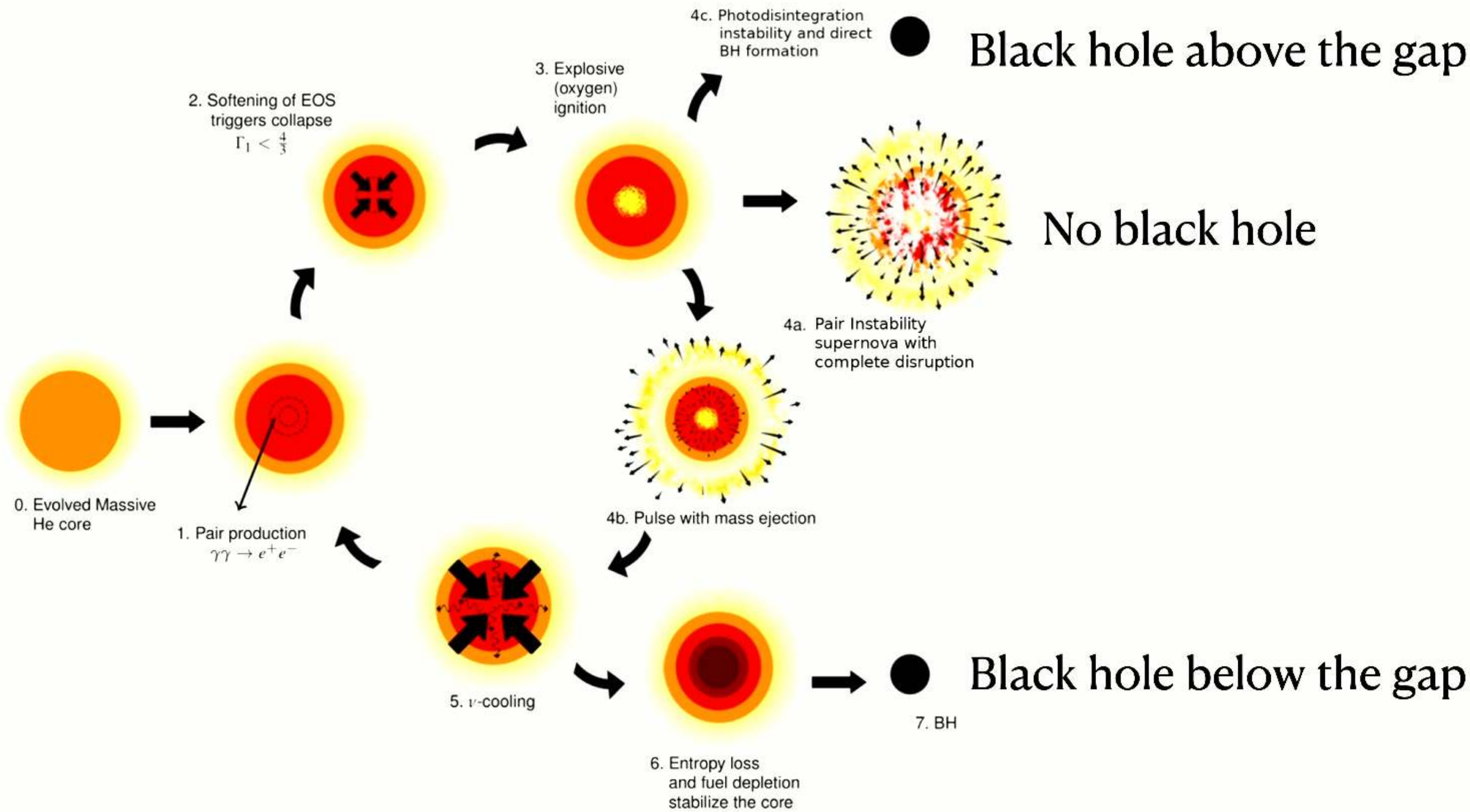


Image credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

Pair Instability Supernovae



Renzo & Smith (2024), from Renzo+ (2020)

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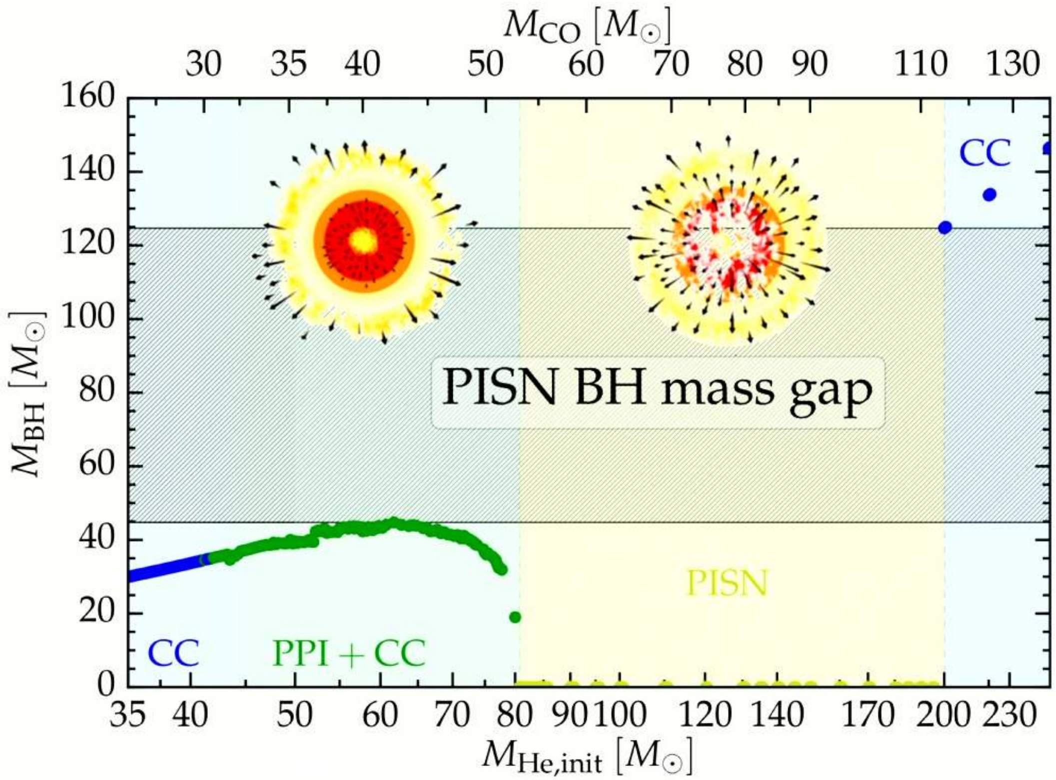
Pair Instability Mass Gap



Renzo & Smith (2024), from Renzo+ (2020)

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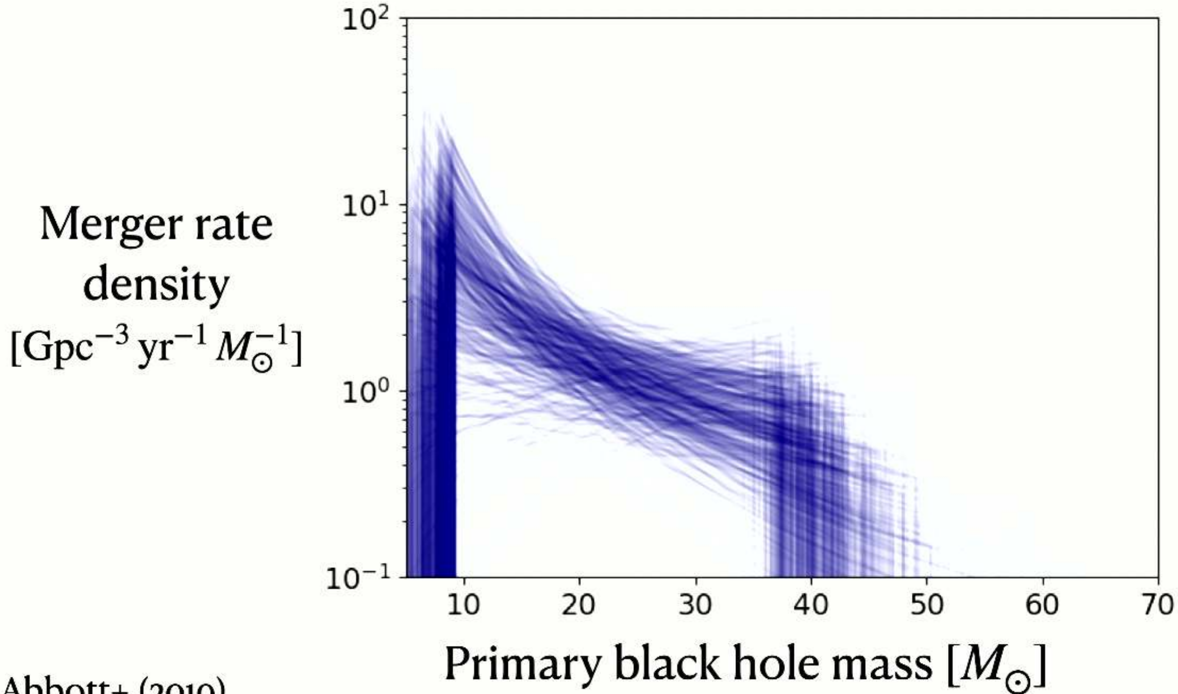
We thought we found the lower edge of the mass gap in O2

With the first 10 binary black holes, black hole primary masses were consistent with a truncated power law distribution with a cutoff at ~45 solar masses



MF & Holz (2017), Abbott+ (2019)

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But in O3, we discovered bigger black holes

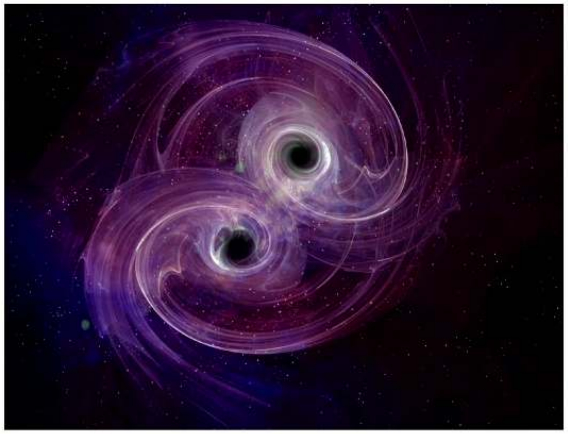
The New York Times

OUT THERE

These Black Holes Shouldn't Exist, but There They Are

On the far side of the universe, a collision of dark giants sheds light on an invisible process of cosmic growth.

GW190521



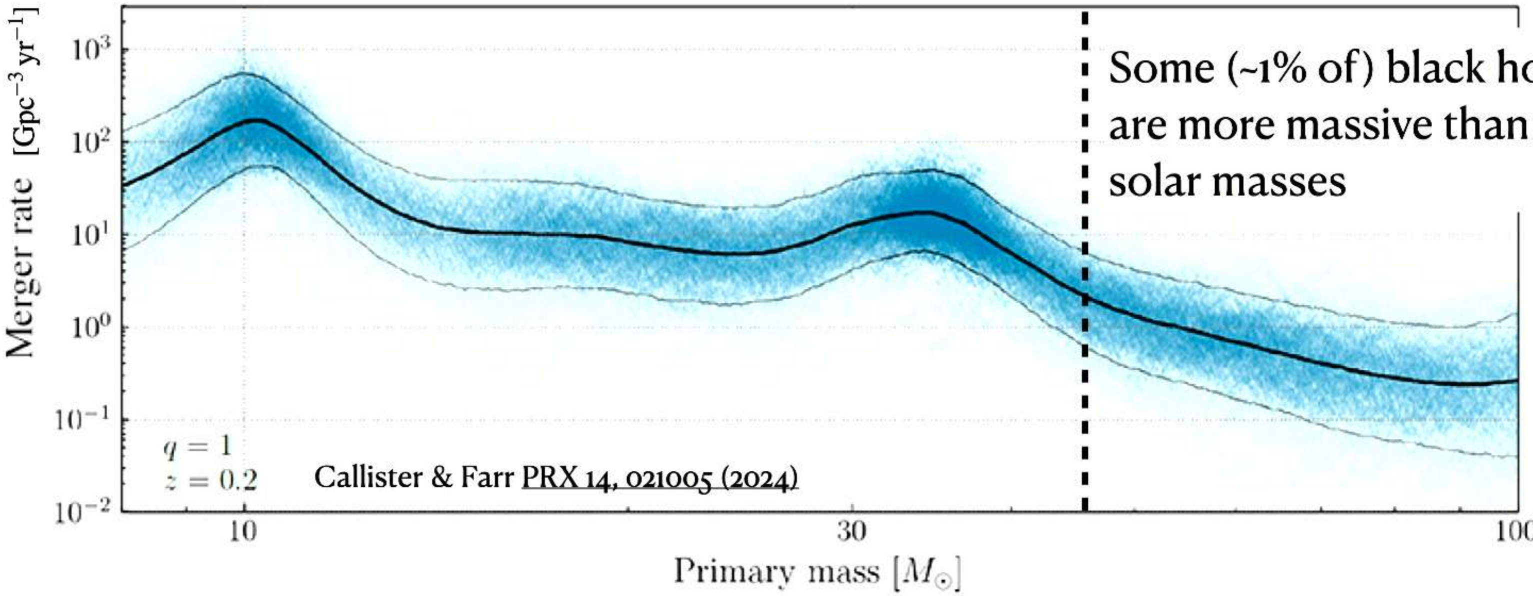
NEWS · 02 SEPTEMBER 2020

'It's mindboggling!': astronomers detect most powerful black-hole collision yet

Gravitational-wave detections suggest merging black holes fell into 'forbidden' range of masses.

Abbott+ PRL 125, 101102

O3 revealed a *population* of big black holes with primary masses above the ~45 solar mass limit



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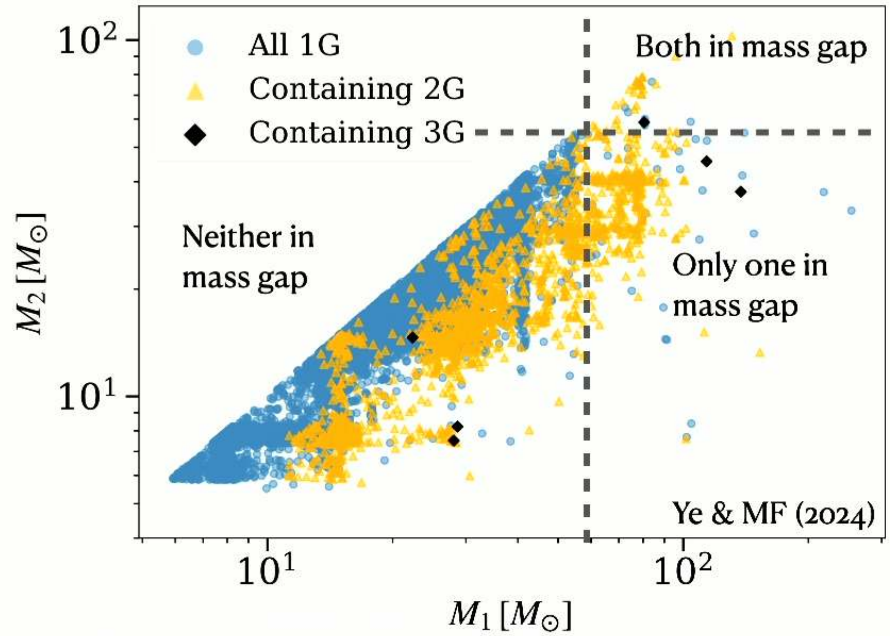
Possible Origins of Black Holes in the Mass Gap

- **Hierarchical black hole mergers**
  - Two black holes of stellar origin merge into a second-generation black hole, which then participates in another merger (e.g. Gerosa & MF 2021 for a review)
- **Black hole growth via accretion**
  - From binary companion (e.g. van Son+ 2020), merger with star in dense cluster (e.g. Kıroğlu+ 2025), dense gas in AGN disk (e.g. McKernan+ 2012), Pop III stars embedded in dense gas (e.g. Safarzadeh & Haiman 2020)
- **Product of stellar mergers**
  - Small stellar core but oversized envelope (e.g. Di Carlo+ 2019, Renzo+ 2020)
- **Non-stellar origin** (e.g., primordial black holes; Bird+ 2016)
- **Mass gap starts at much higher masses** than previously thought
  - Different nuclear reaction rates? Exotic particles in stellar cores?

Are there binaries with *both* black holes in the mass gap?

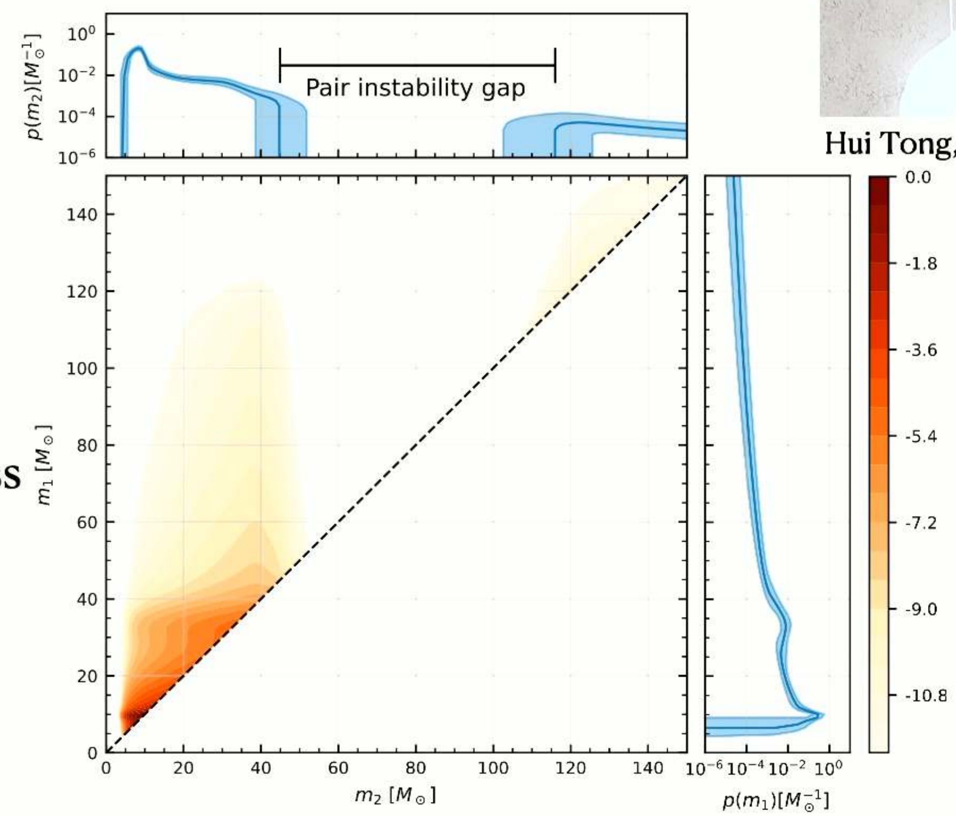
Claire Ye, CITA Fellow

- If mass-gap black holes are rare, we would expect 2 mass-gap black holes in the same binary to be even rarer
- For example, in dense star clusters, only a small fraction of second-generation (2g) black holes are retained
  - The 2g+2g merger rate is an order of magnitude lower than the 1g+2g rate (Rodriguez+ 2019)



Evidence for the Pair Instability Gap in the Distribution of Black Hole *Secondary* Masses

Fit to the mass distribution using 153 confident binary black holes in GWTC-4.0



Primary mass

Secondary mass

Hui Tong, PhD @Monash

Tong, MF, Thrane+ *in prep*

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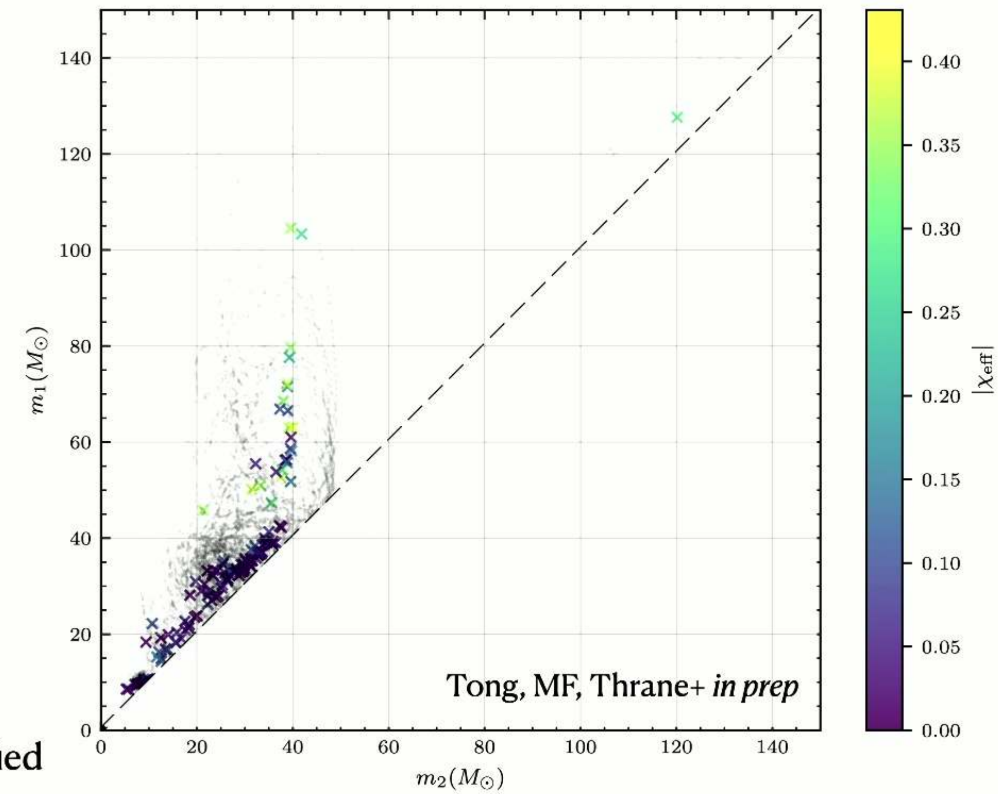
Primary black holes in the gap also *spin* more rapidly

Primary mass



Effective inspiral spin (mass-weighted spins aligned with orbital angular momentum axis)

Secondary mass

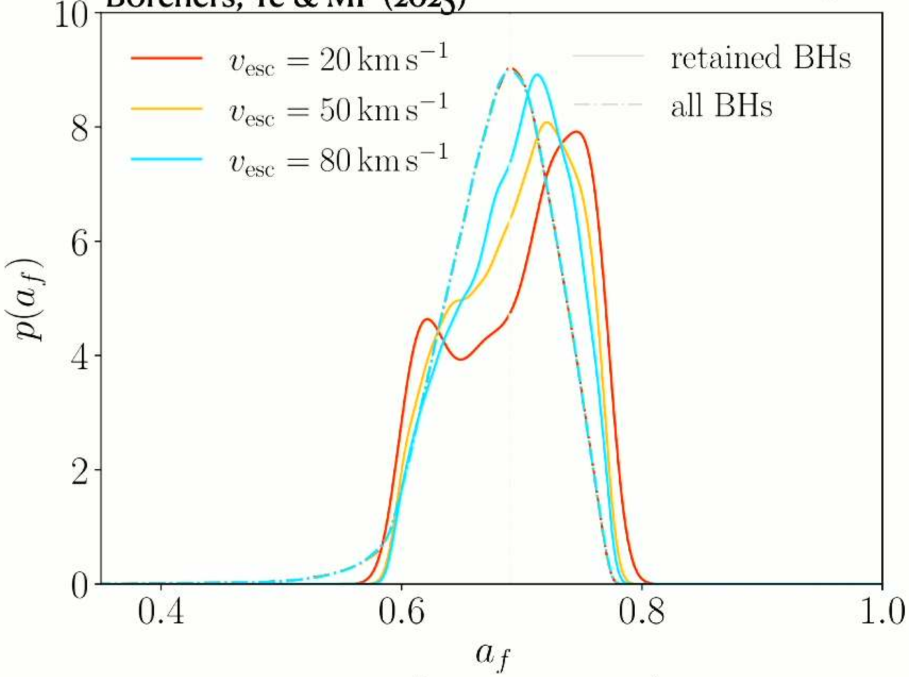
Spin transition previously identified in: Li+ (2024), Pierra+ (2024), Antonini+ (2025)

Spins consistent with 2g+1g hierarchical mergers contaminating the mass gap

Angela Borchers Pascual,
PhD@ AEI Hannover

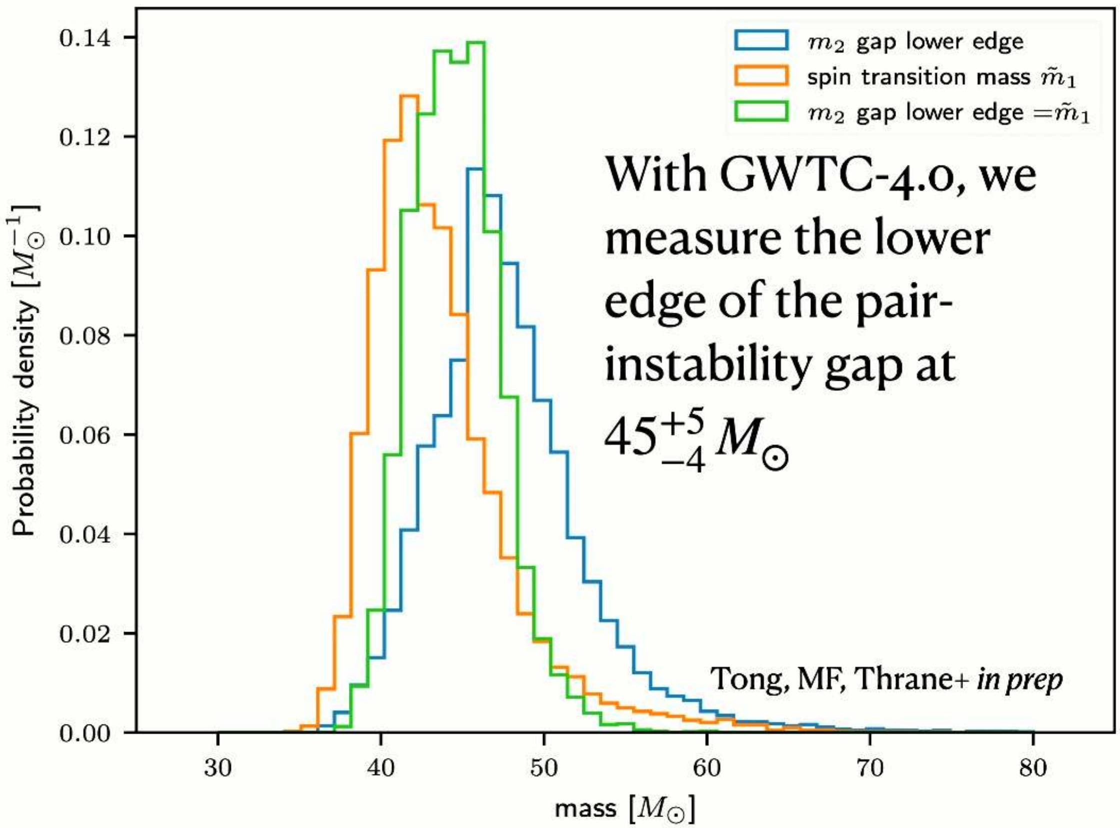
- 2g black holes tend to spin at dimensionless spin magnitude ~0.7 (e.g., MF, Farr & Holz 2017)
- Additional detailed features in the distribution imprinted by the environmental escape speed

Borchers, Ye & MF (2025)



Spin of merger product

Measuring the lower edge of the pair-instability gap



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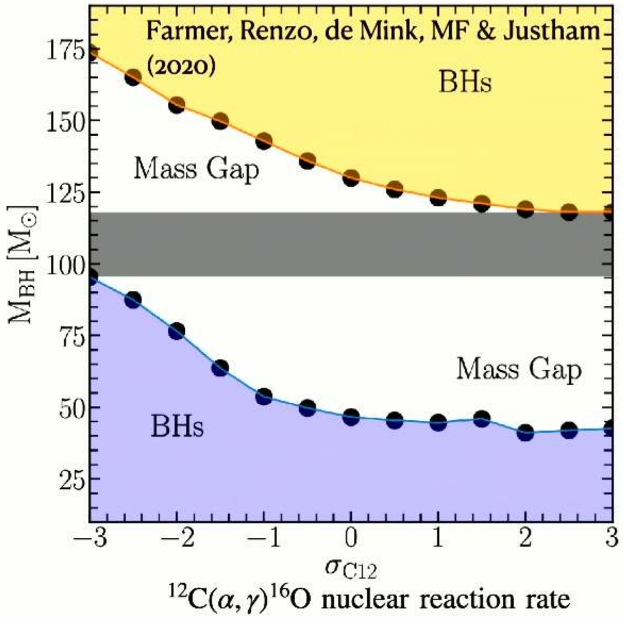
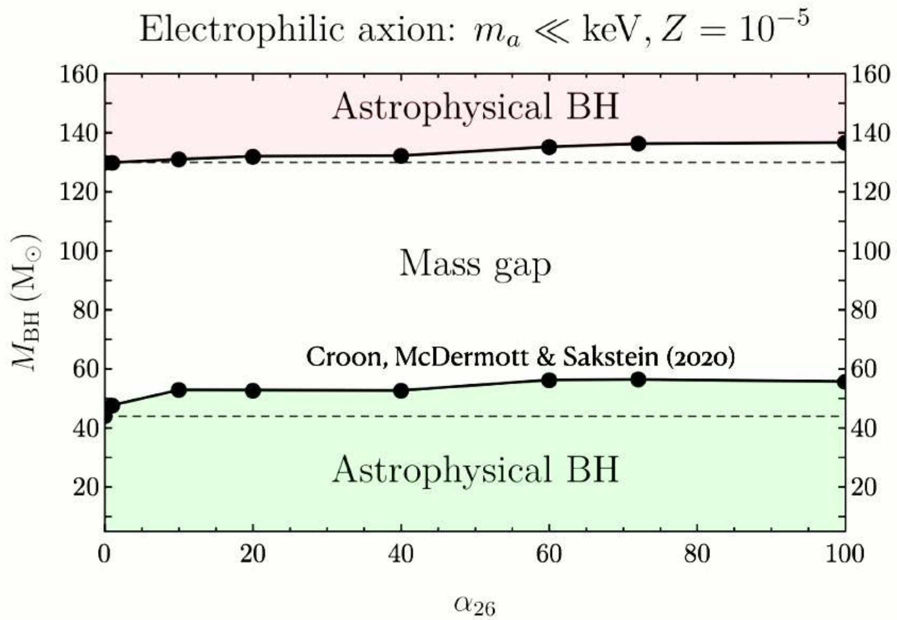
Measuring the location of the pair-instability gap constrains uncertain physics

Uncertain nuclear physics



(standard deviations from the measured median)

Possible beyond-standard model physics



Electron-axion coupling

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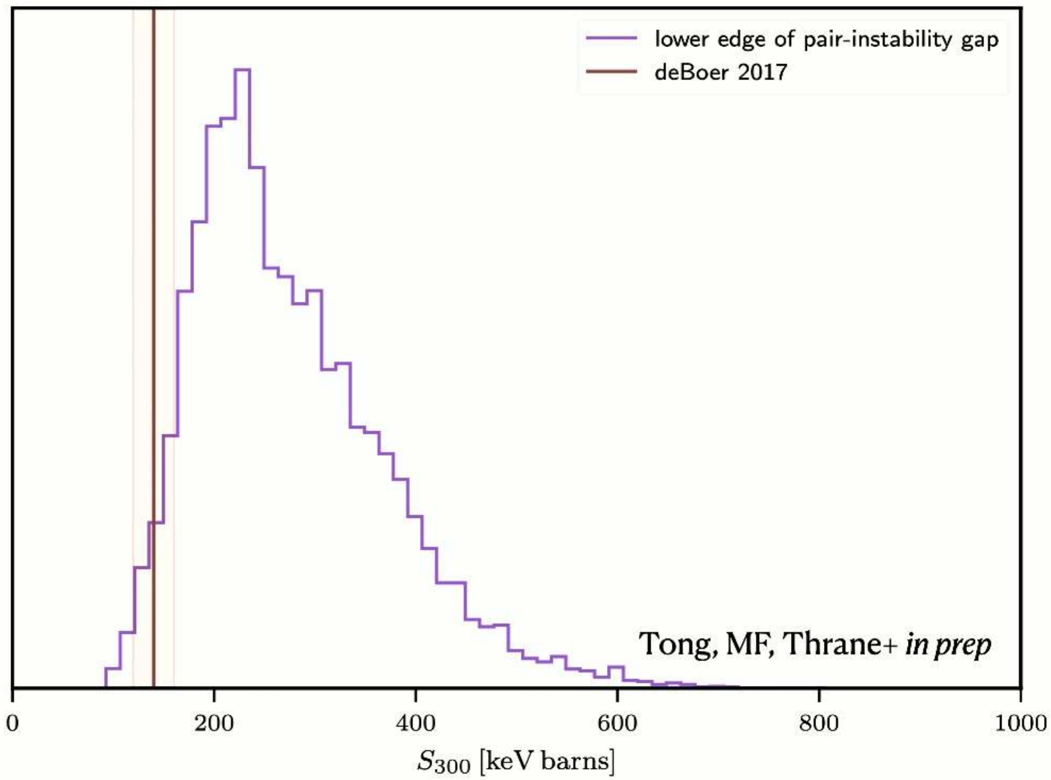
The $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction rate

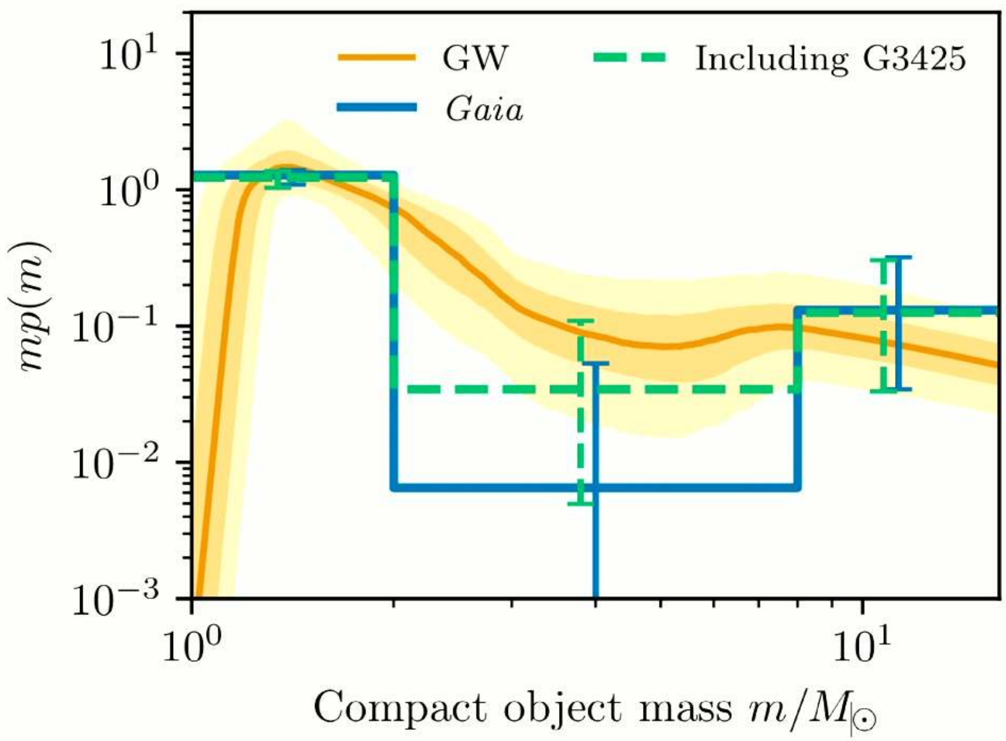


Astrophysical S-factor (rescaled reaction cross section) at 300 keV

Bonus: What about the “lower” mass gap between neutron stars and black holes?

Where are *Gaia*’s small black holes?

MAYA FISHBACH,[1,2,3] KATELYN BREIVIK,[4] REINHOLD WILLCOX,[5,6] AND
L. A. C. VAN SON[7,8,9]



arXiv:2508.08986

Evidence for a pair-instability gap in black hole masses from GWTC-4

- GWTC-4.0: new catalog from the LIGO-Virgo-KAGRA Collaboration with 80+ new gravitational-wave events, doubling the size of the previous catalog
- The black hole mass, spin and redshift distribution encodes their unknown evolutionary histories & uncertain physical processes
- (Pulsational) pair-instability supernovae are predicted to cause a gap in the black hole mass distribution
- **We have found evidence for this gap in the black hole *secondary* mass distribution**, placing an upper limit on the merger rate of binaries with *both* black holes in the mass gap
- There exist binaries with *one* black hole in the mass gap; their **spins are consistent with hierarchical mergers**
- Implications for black hole formation channels, transient astronomy, stellar evolution, nuclear physics, particle physics, and cosmology

Could supernova kicks cause the mass gap?

If *Gaia*'s progenitor binaries are less tightly bound than GW progenitor binaries, they could be preferentially disrupted by large kicks imparted on low-mass black holes