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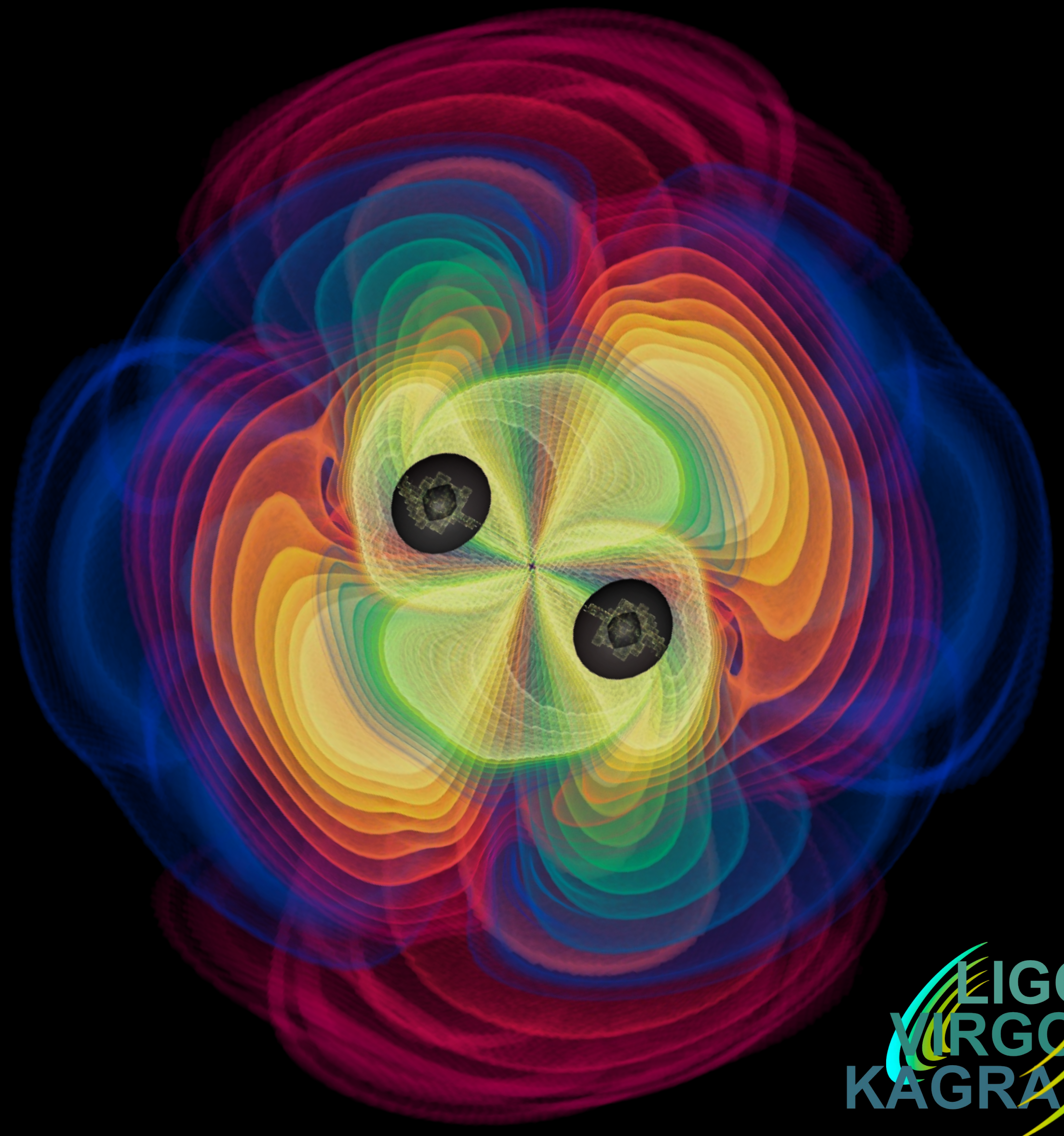

# Astrophysical insights from the compact-object mass distribution inferred with gravitational waves

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NHFP Symposium 2024

LIGO VIRGO KAGRA

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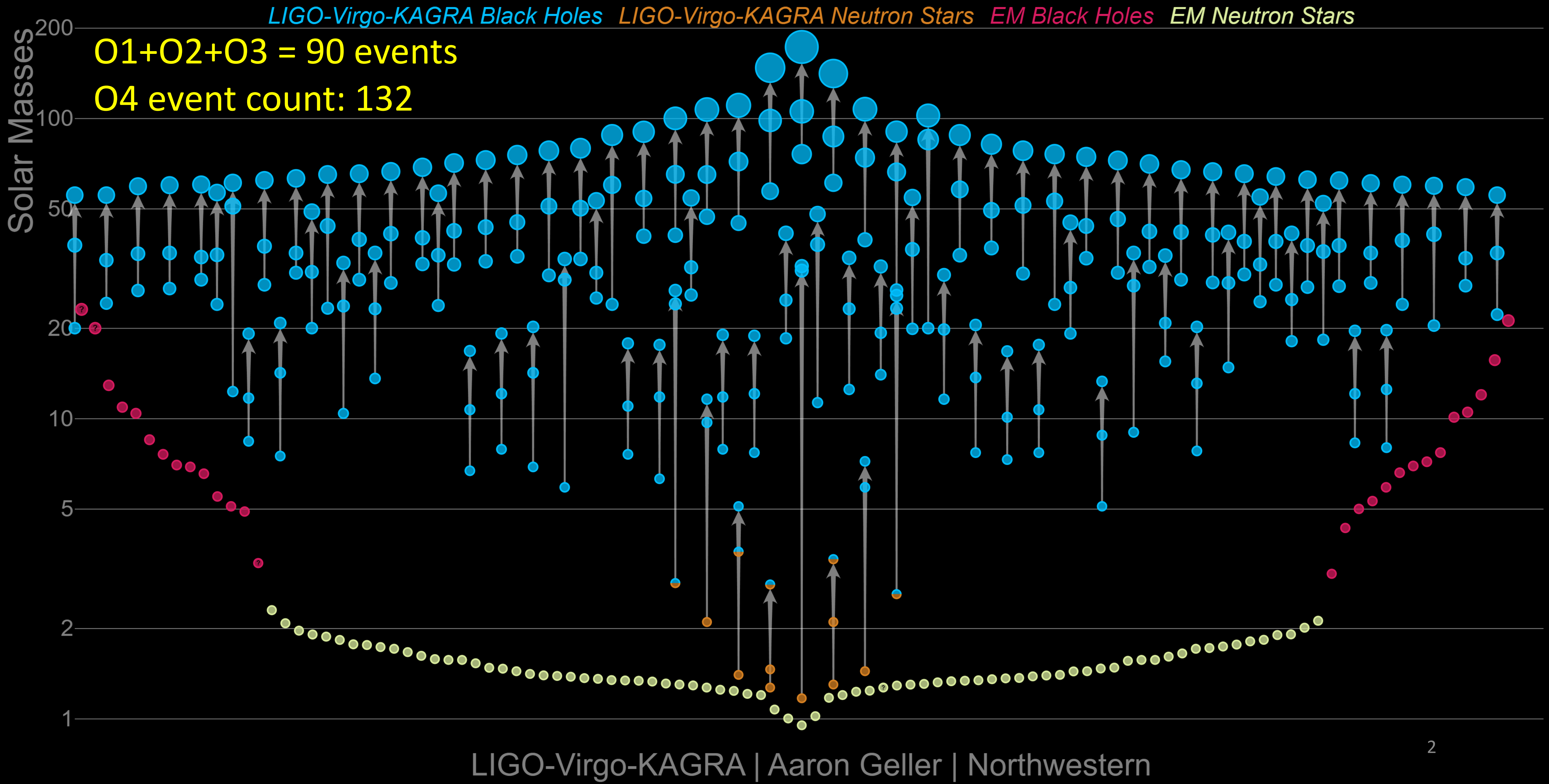
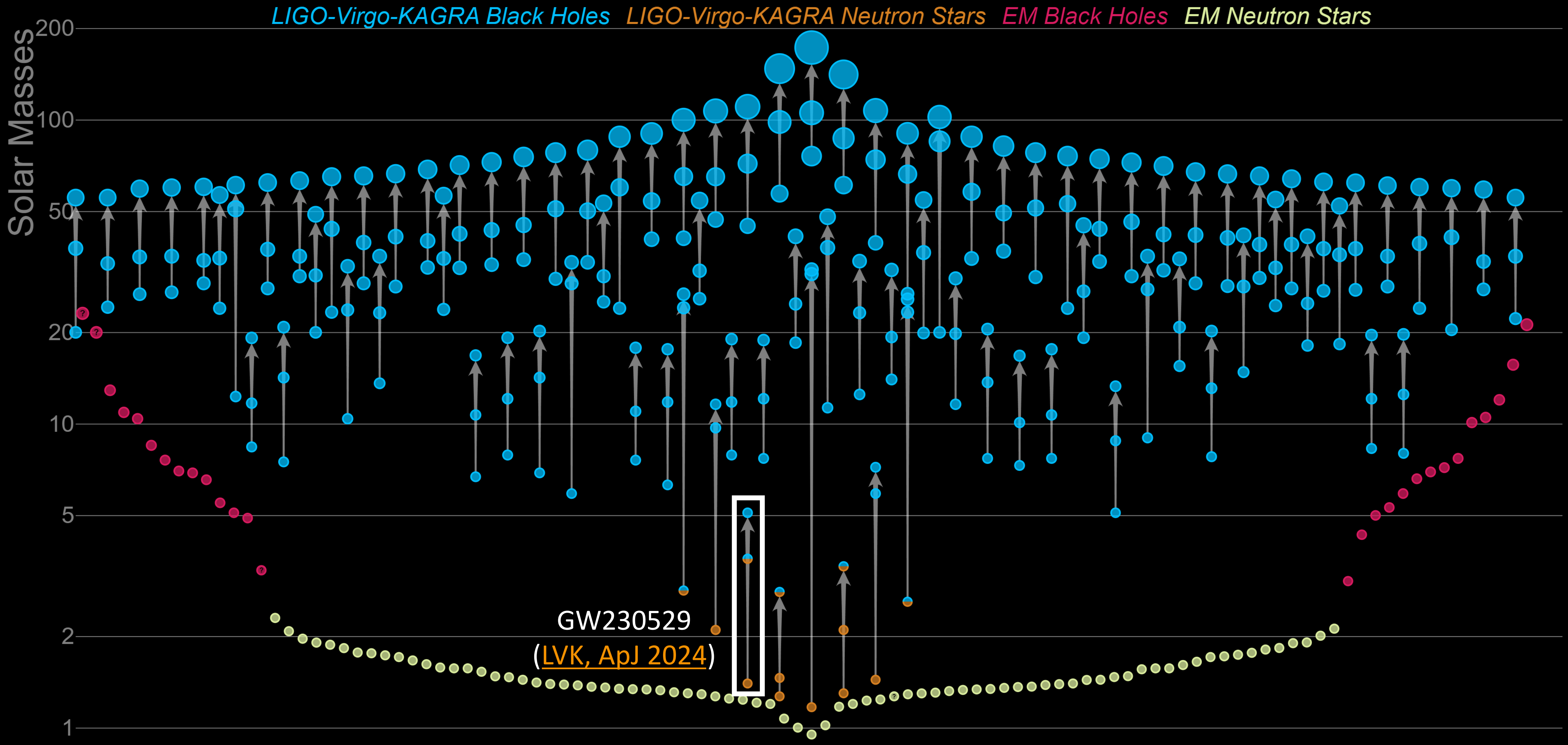
NHFP
NASA Hubble Fellowship Program

Image: Ed Seidel (AEI) and Werner Benger (ZIB, AEI)

# Masses in the Stellar Graveyard



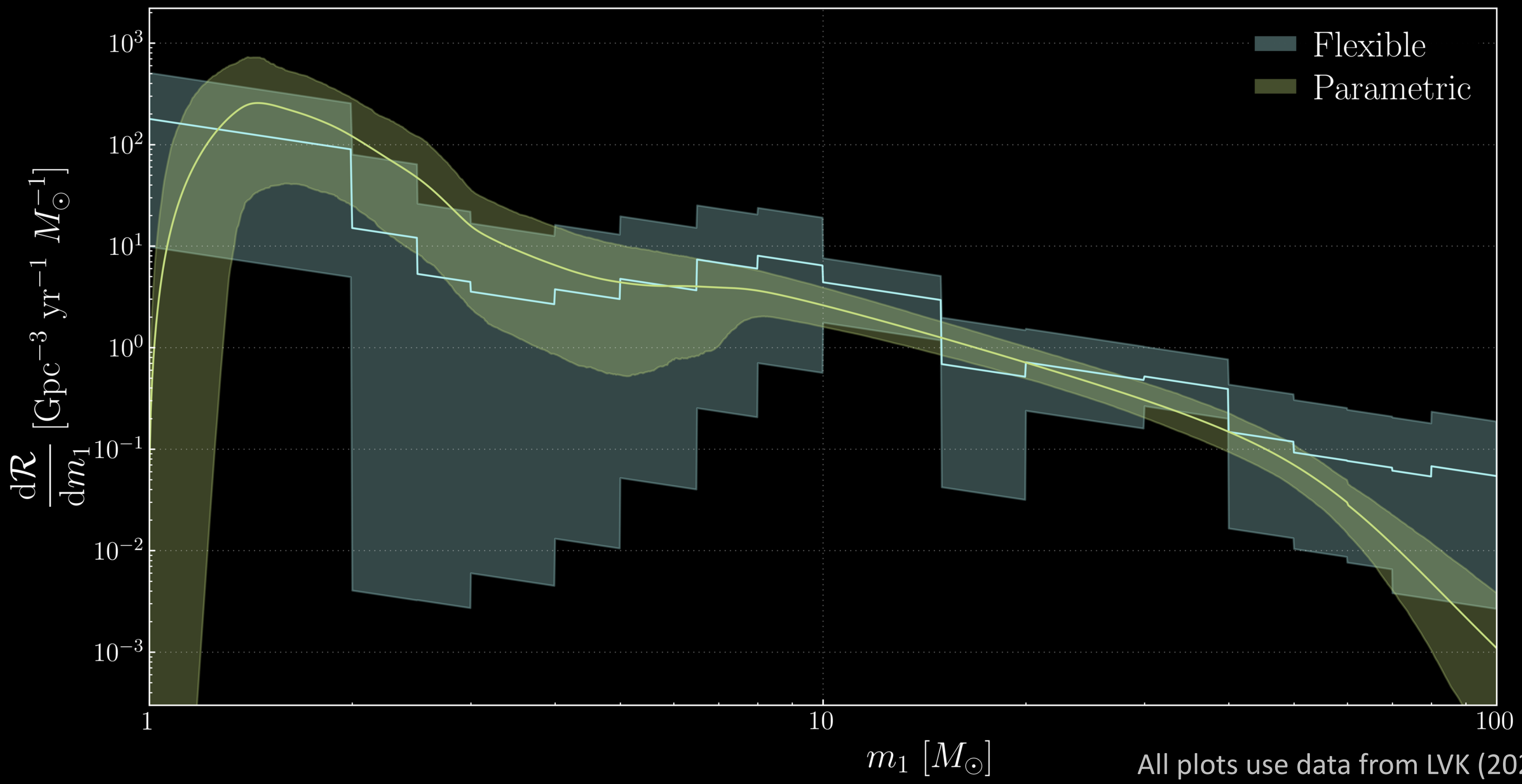
# Masses in the Stellar Graveyard





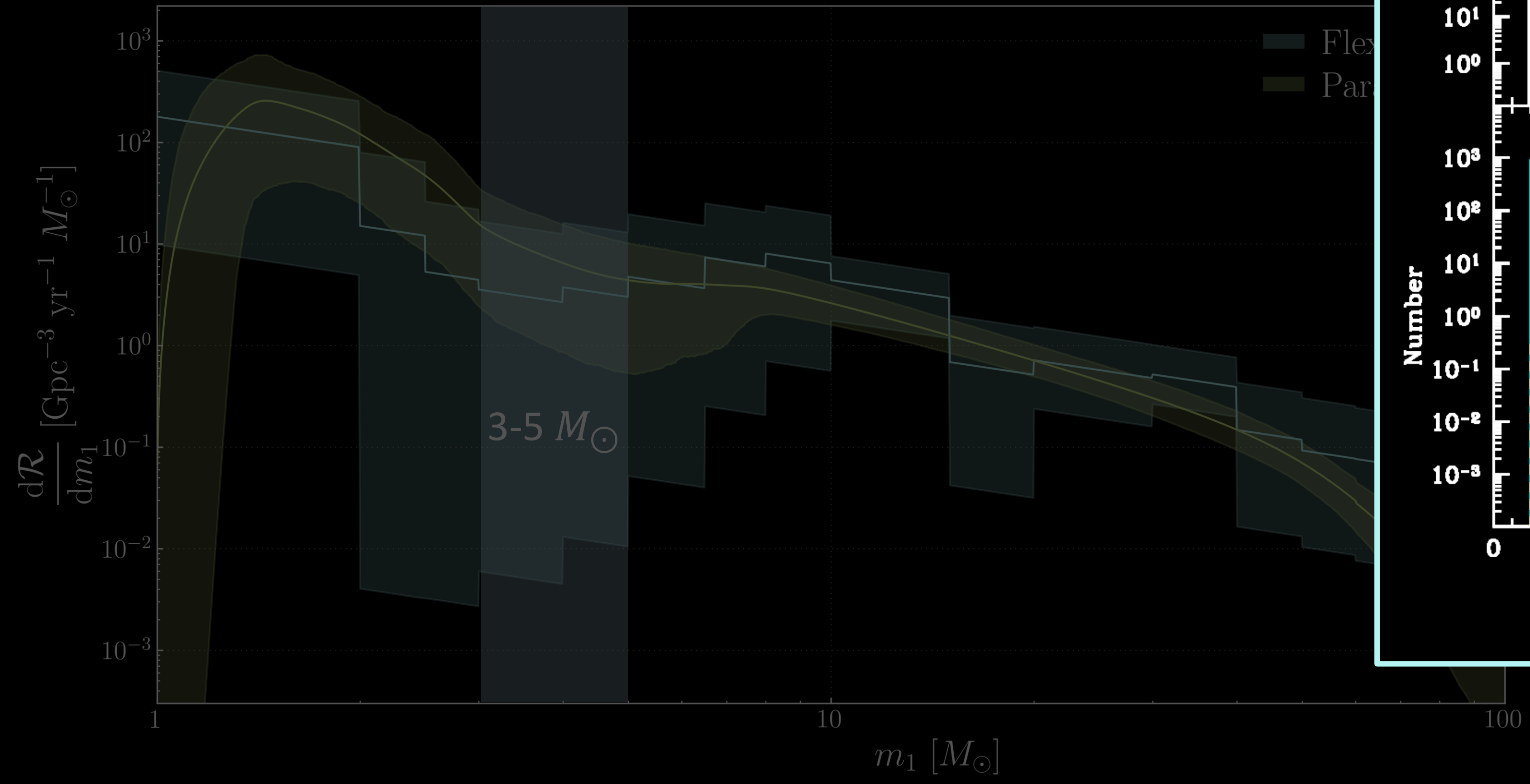

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

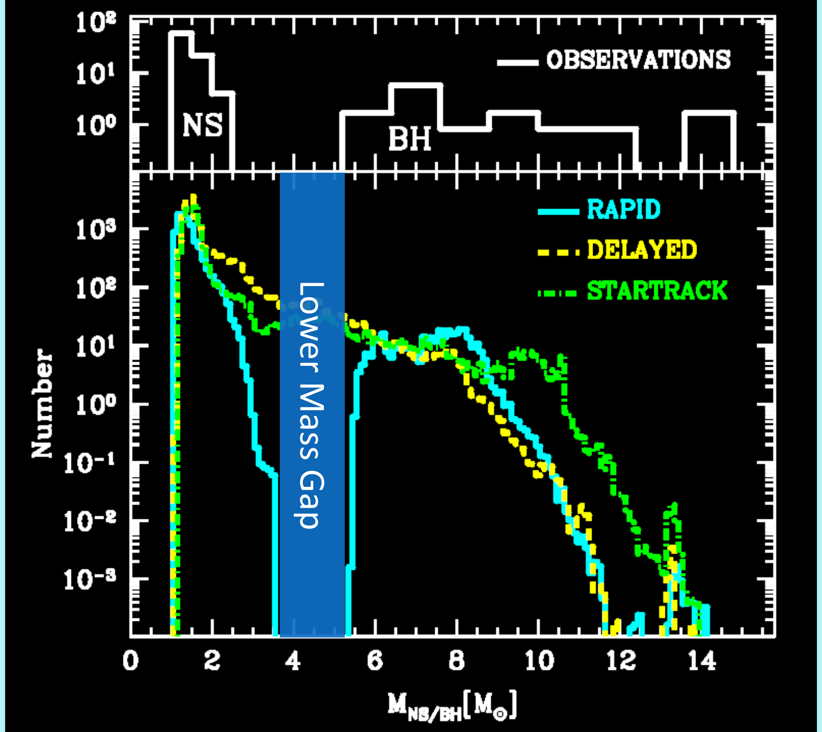
# The compact object mass distribution provides key astrophysical insights:




All plots use data from LVK (2024) unless otherwise noted

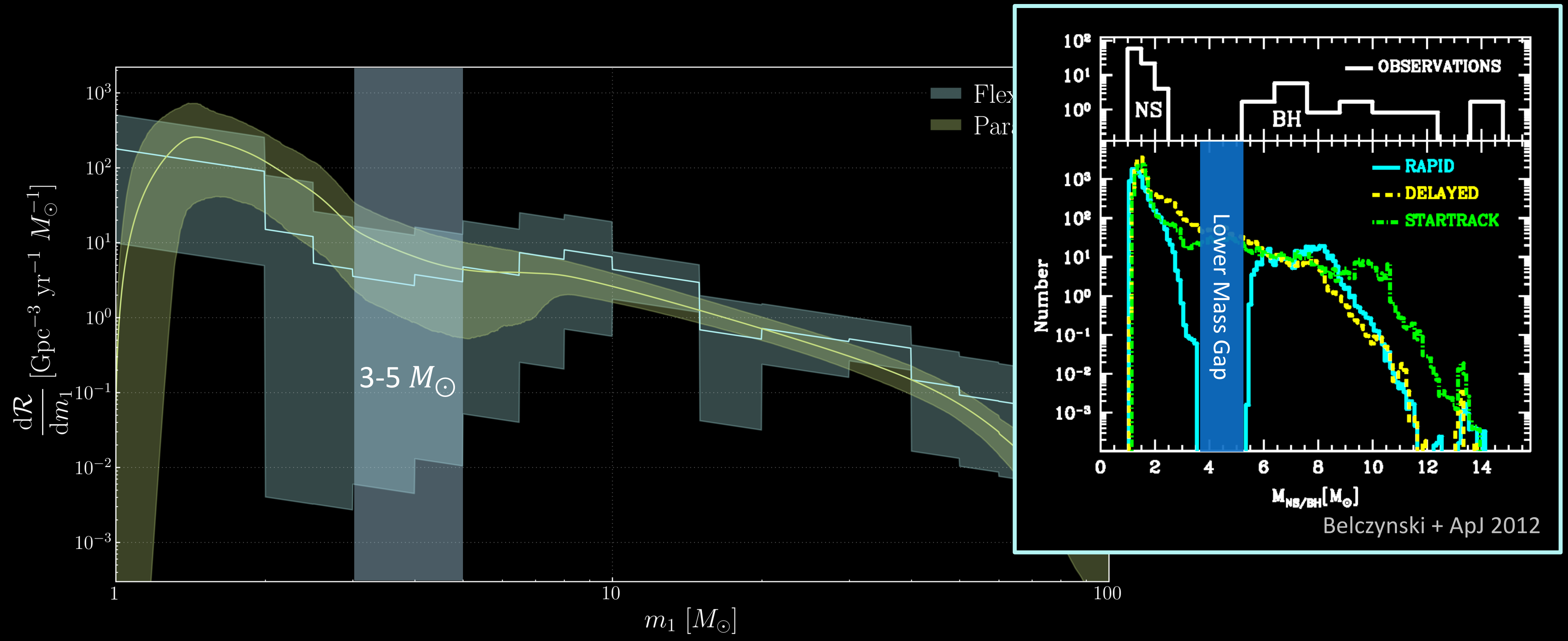
# Evidence for a gap between the most massive neutron stars and least massive black holes?



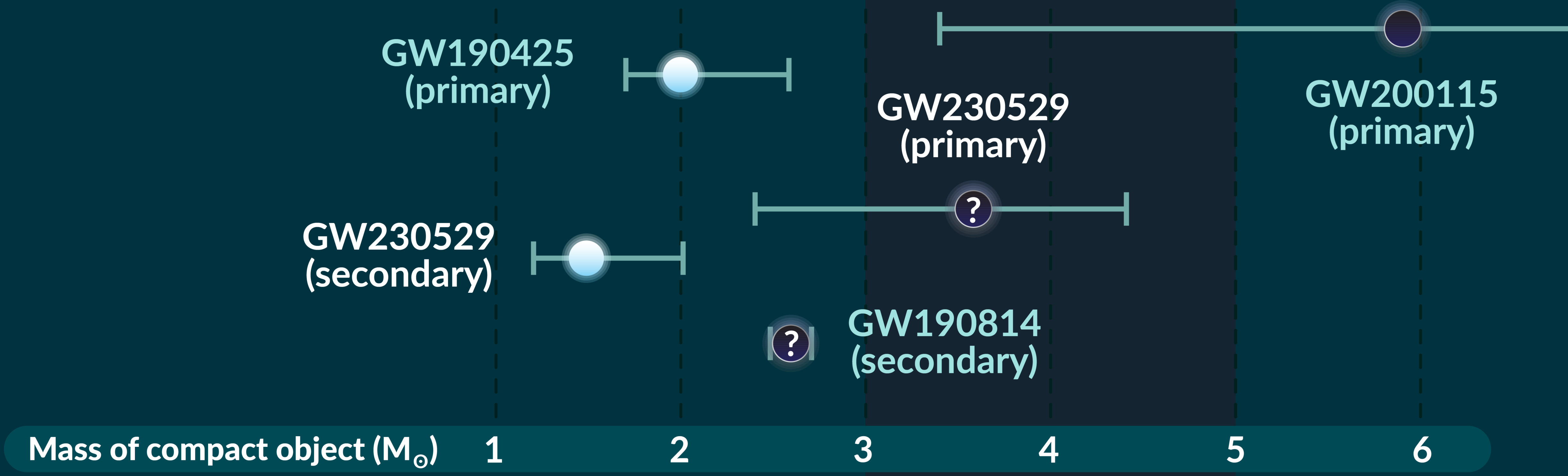

Belczynski + ApJ 2012

# Evidence for a gap between the most massive neutron stars and least massive black holes?



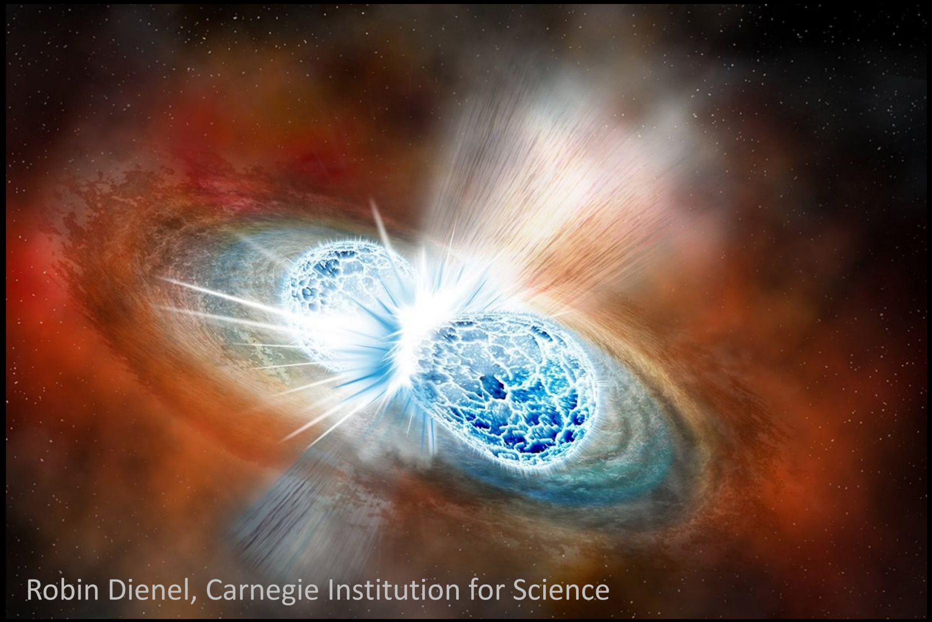
# FILLING THE MASS ⟷ GAP

*with observations of compact binaries from gravitational waves*




Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

# GW230529: the merger of a neutron star with a lower-mass-gap object

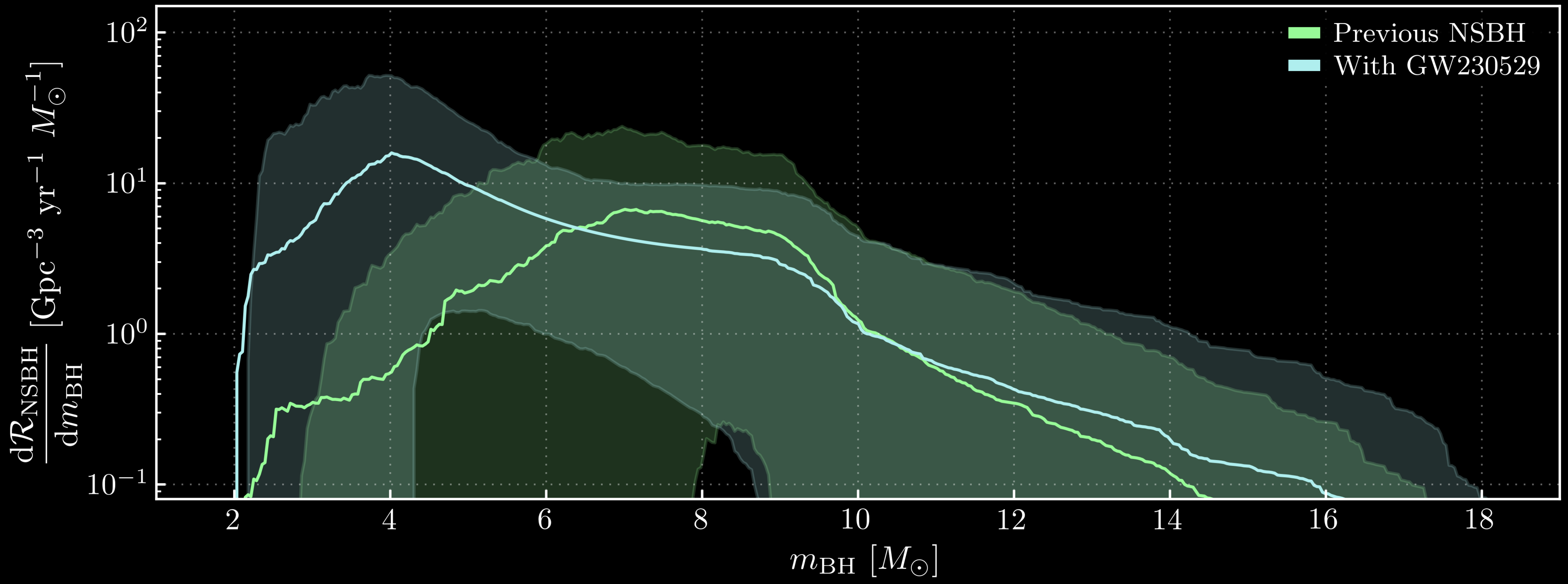



Heavy binary neutron star merger

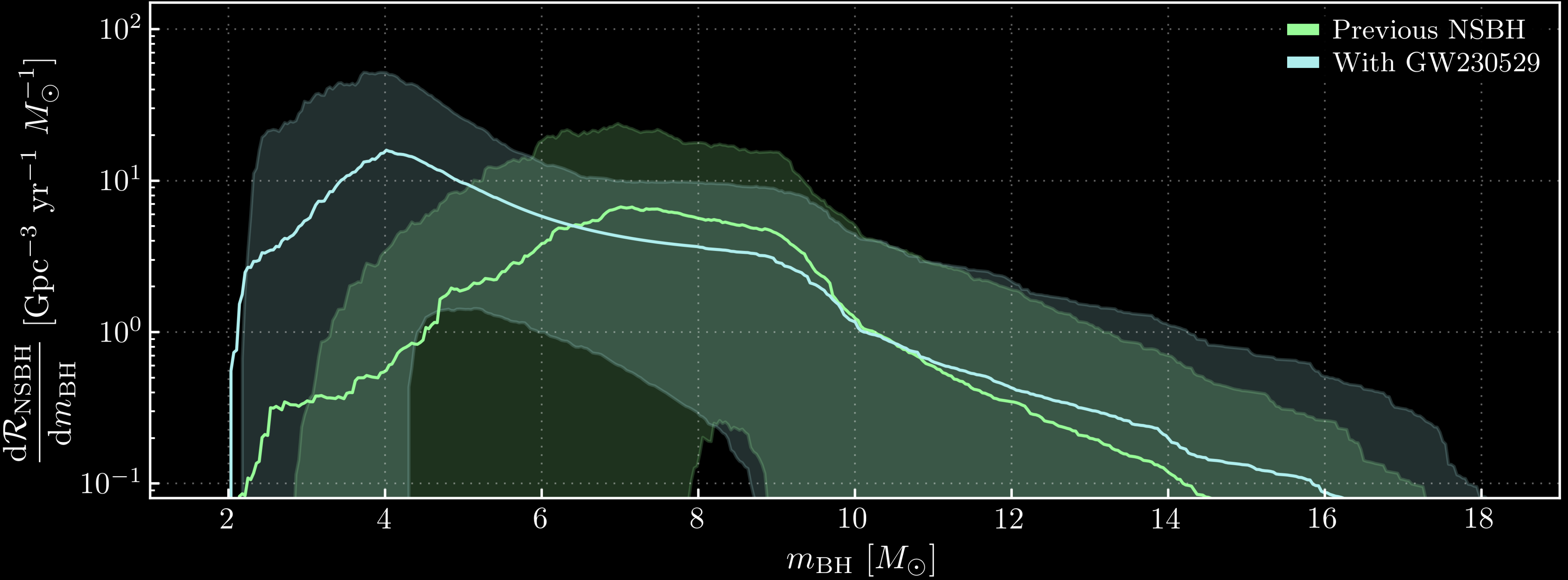
OR


Neutron star merging with low-mass black hole

# Including GW230529 decreases the minimum mass of black holes in the NSBH population



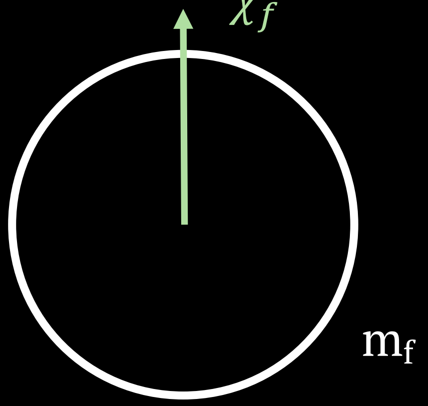
# Including GW230529 decreases the minimum mass of black holes in the NSBH population




Probability of the existence of a mass gap (in NSBH) decreases from 98.6% to 7.2%

# Merger outcome depends on binary properties

## Black hole swallows neutron star




Rigid neutron stars, unequal mass ratios, small black hole spins

## Neutron star tidally disrupted outside ISCO

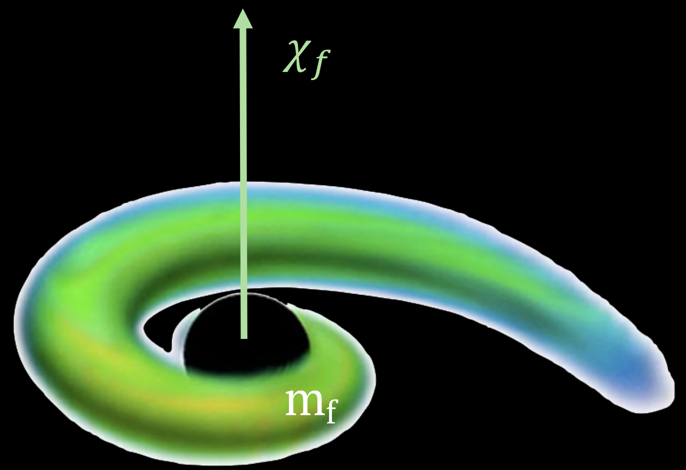
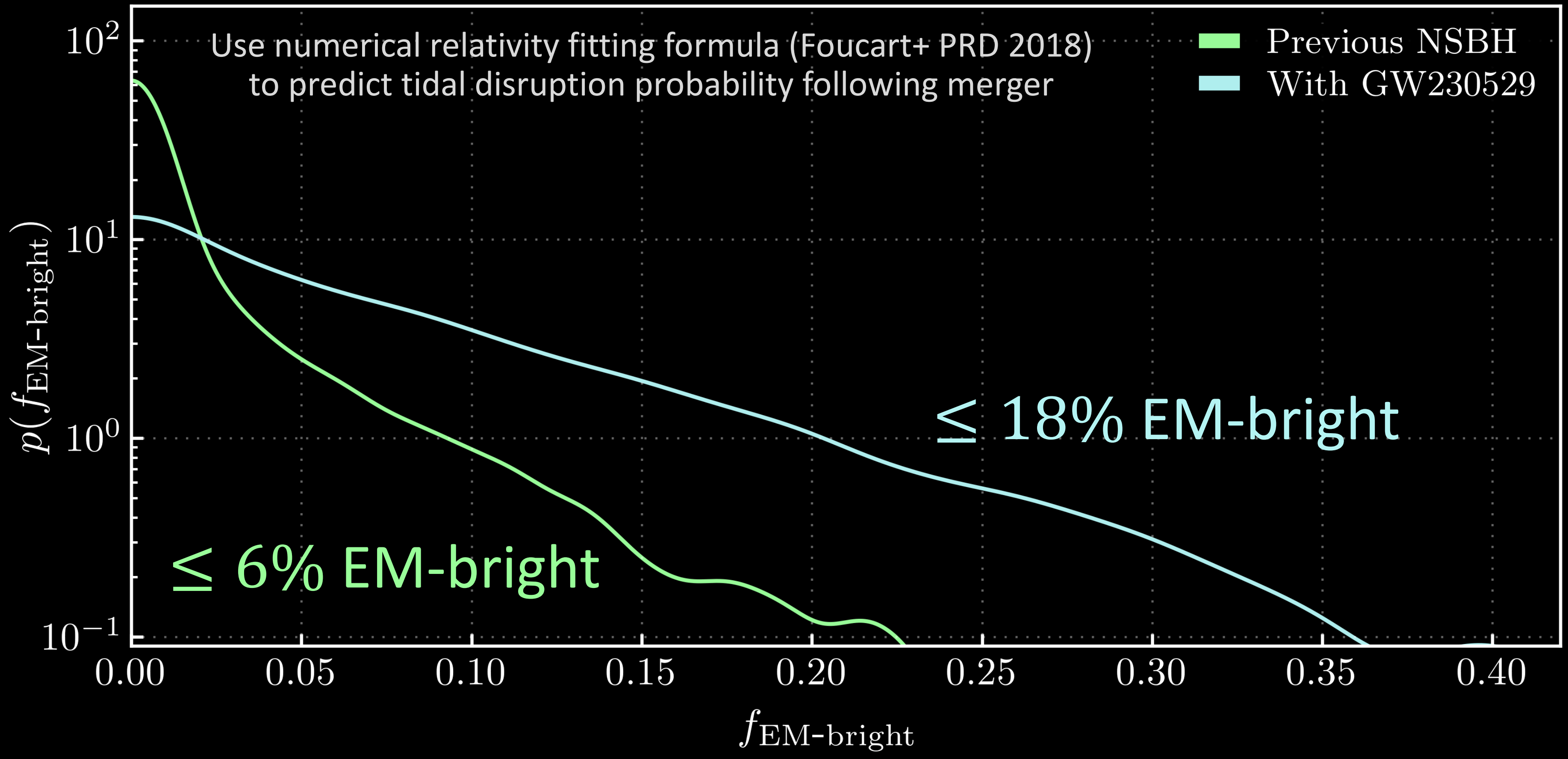



Image: Foucart FrASS 2020

Deformable neutron stars, equal mass ratios, large prograde spins

# The detection of GW230529 means that NSBH mergers are more likely to be multimessenger sources



# GW230529 Summary

Likely the merger of a neutron star with a mass-gap black hole

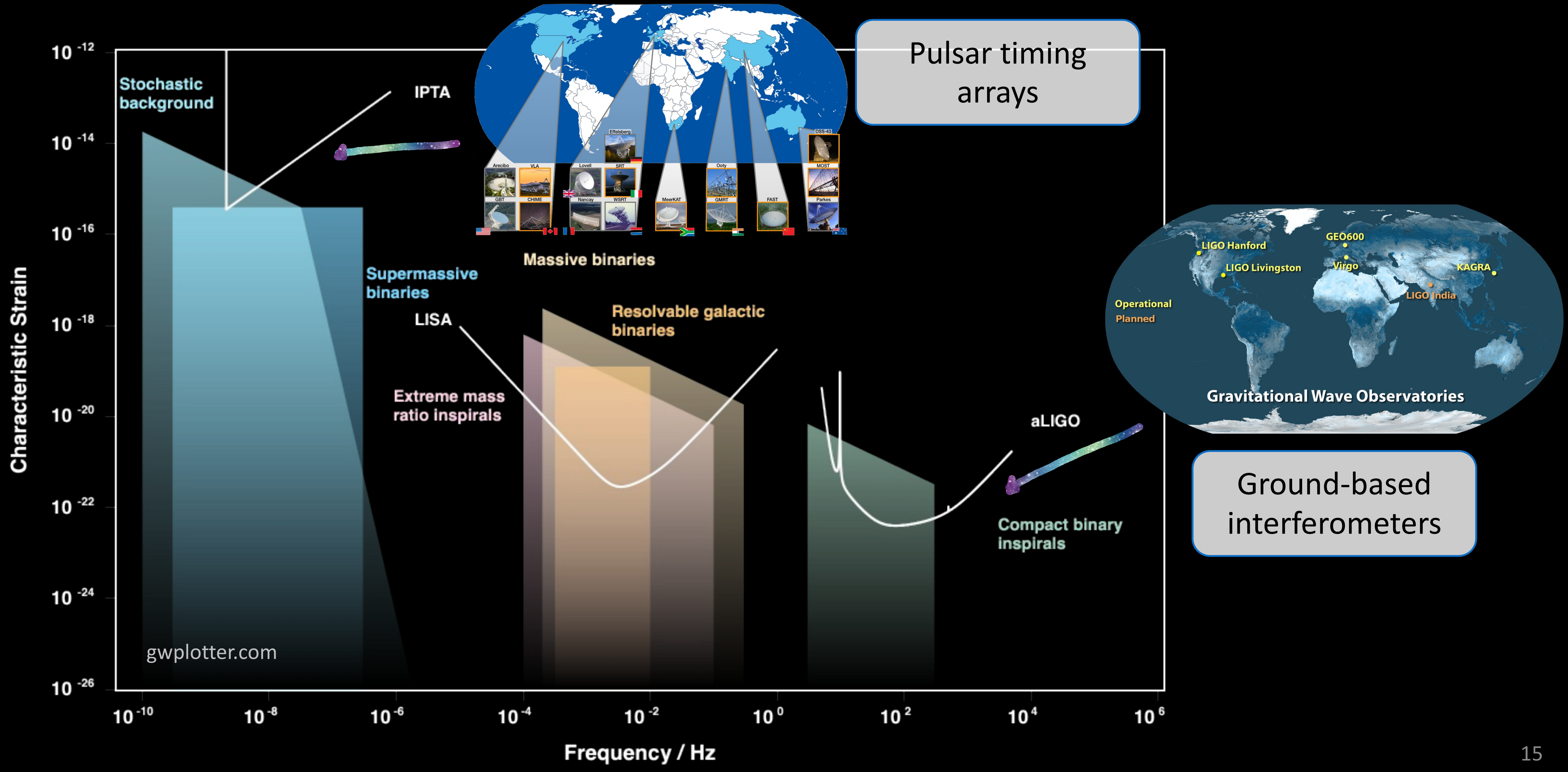
Challenges compact object formation paradigms

Enhances multimessenger prospects for neutron star-black hole mergers

Raises questions about X-ray binary selection selection effects

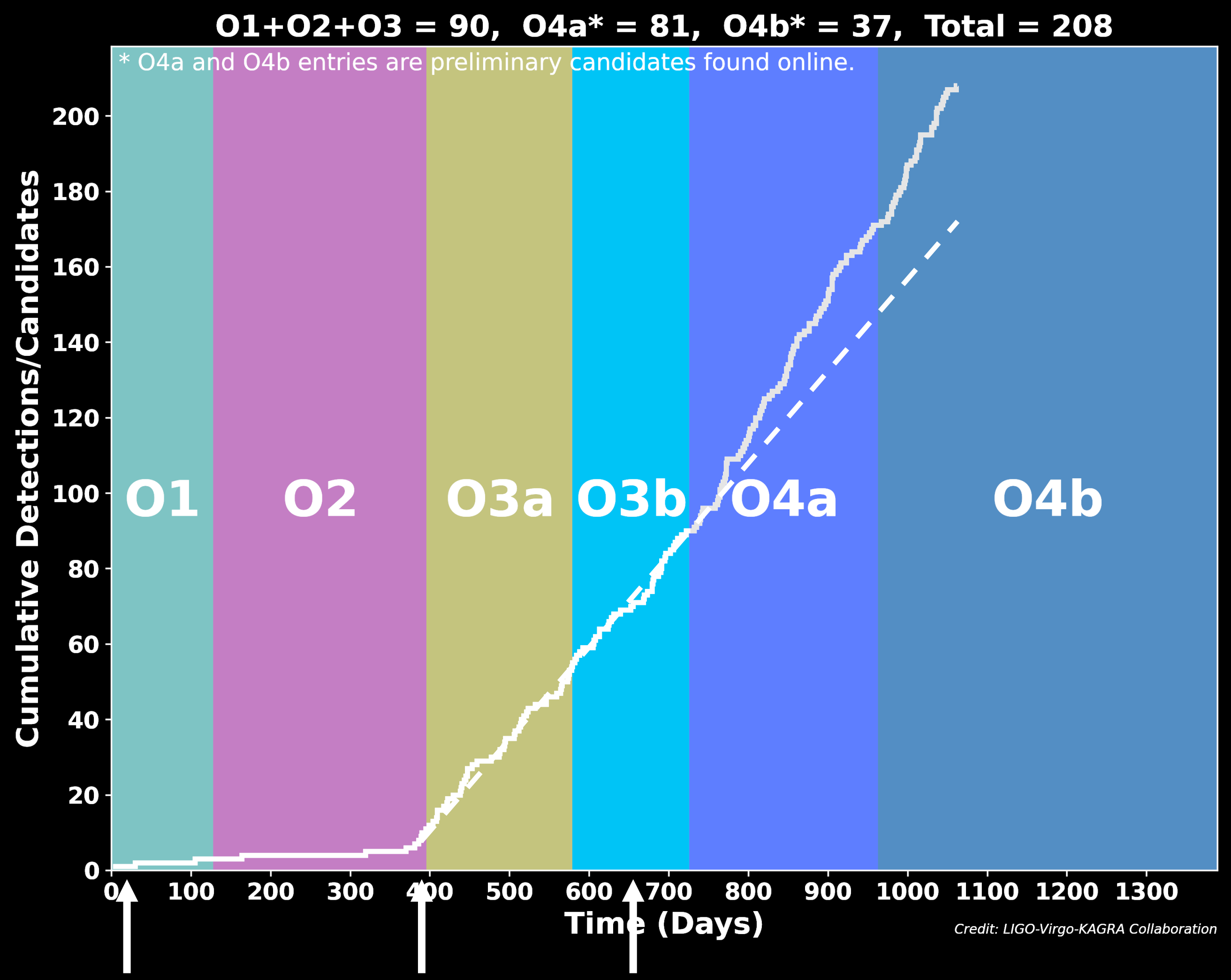
# Backup

# Our observational landscape




Pulsar timing arrays

Ground-based interferometers




GW150914: first binary black hole

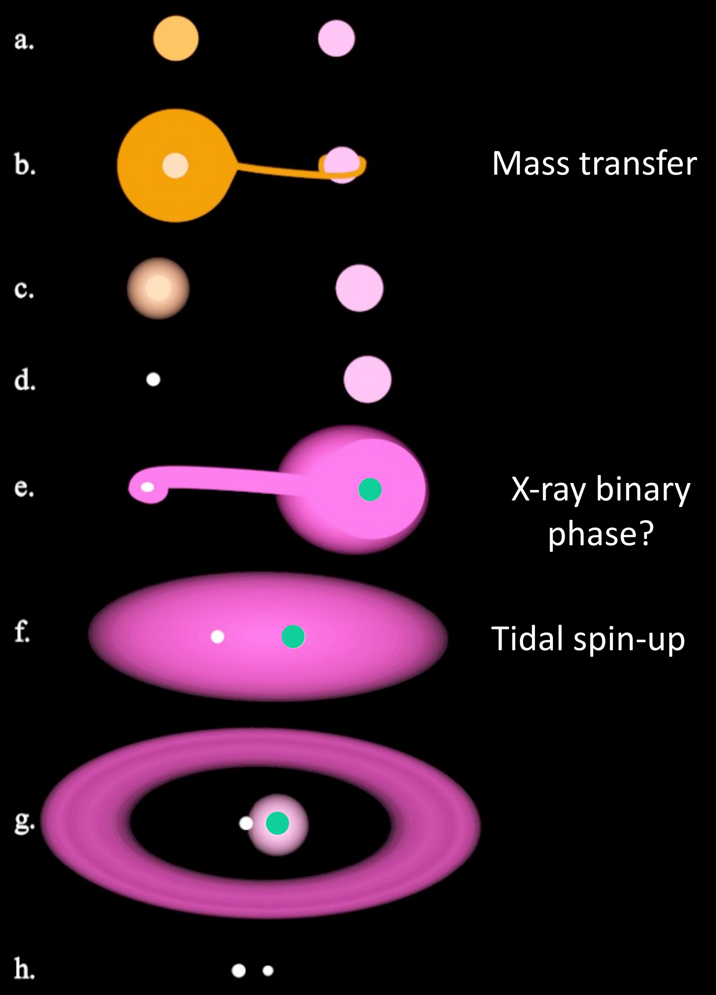
GW170817: first binary neutron star (multimessenger)

GW200105 and GW200115: first neutron star-black hole mergers

# Compact-object binary formation

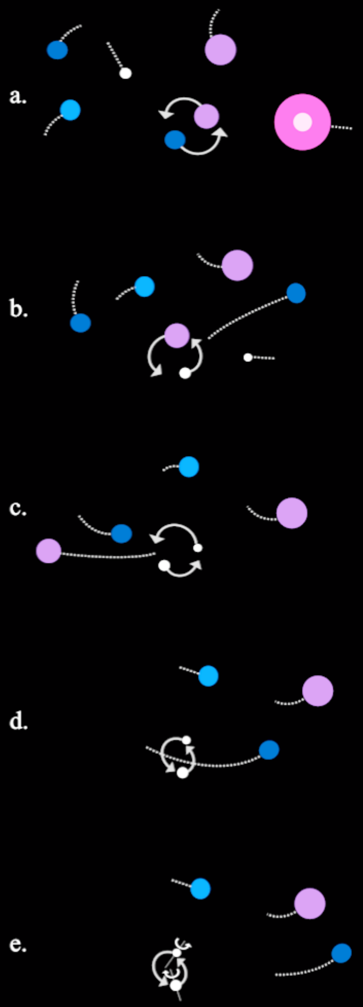
Isolated binary evolution

- Spins aligned to orbital angular momentum
- First-born black hole has small spin
- Second-born black hole can be spun up
- Masses set by supernova physics




Mandel & Farmer 1806.05820

# Compact-object binary formation

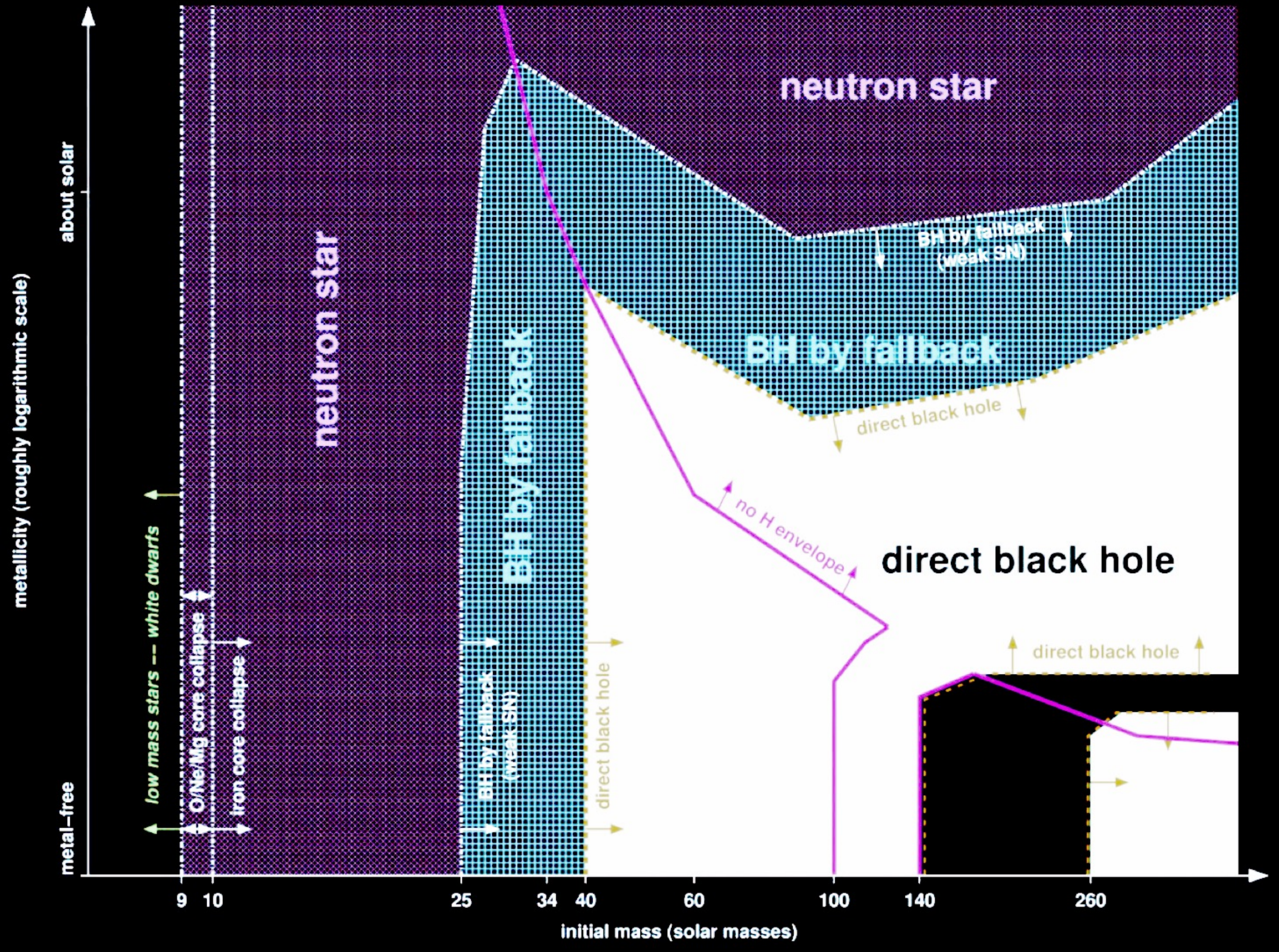



Dynamical assembly

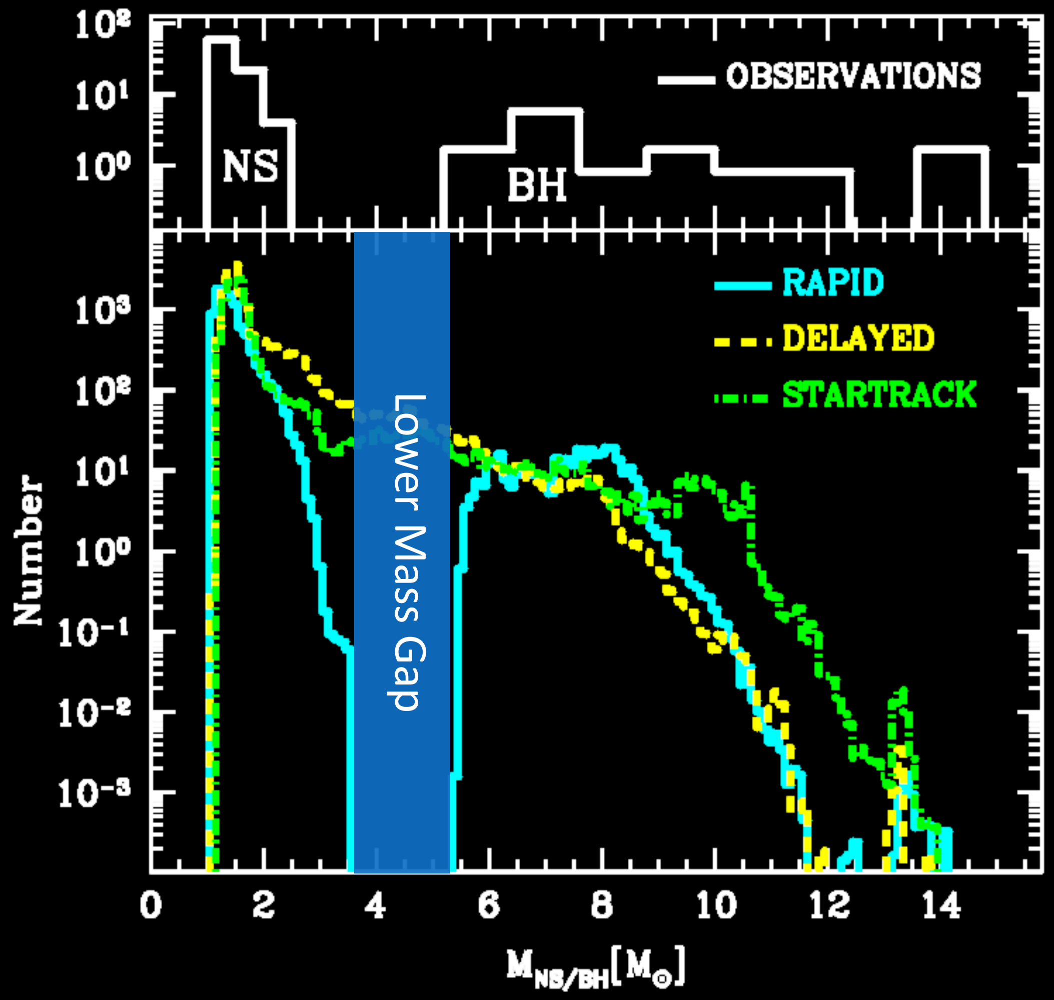
- Isotropically distributed spins
- Low spins except for hierarchical mergers
- Hierarchical mergers can populate mass gaps

Mandel & Farmer 1806.05820

# The fates of massive stars

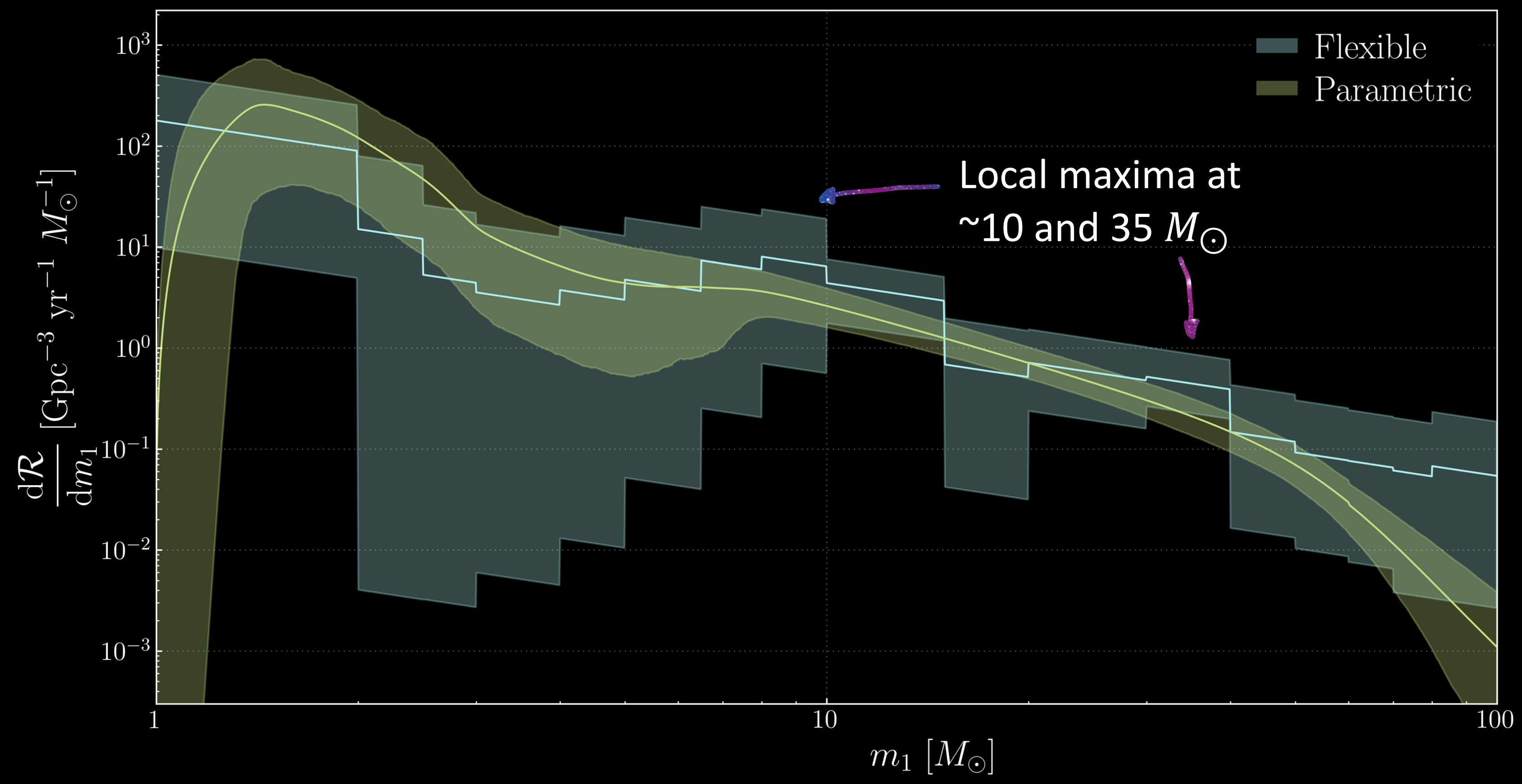



Heger + 2003

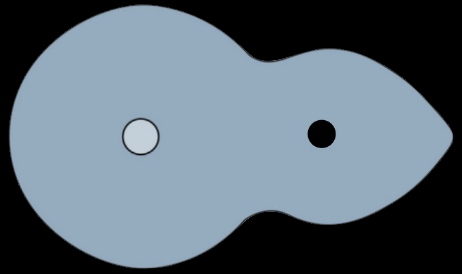



Belczynski + 2011

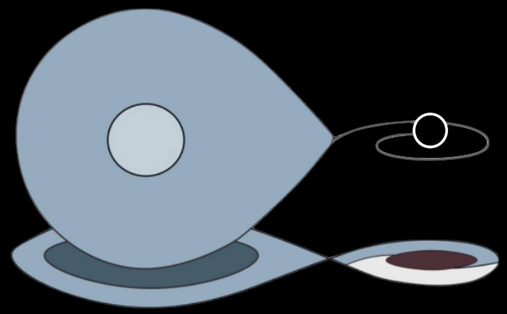
# Features from different formation channels?




Common envelope

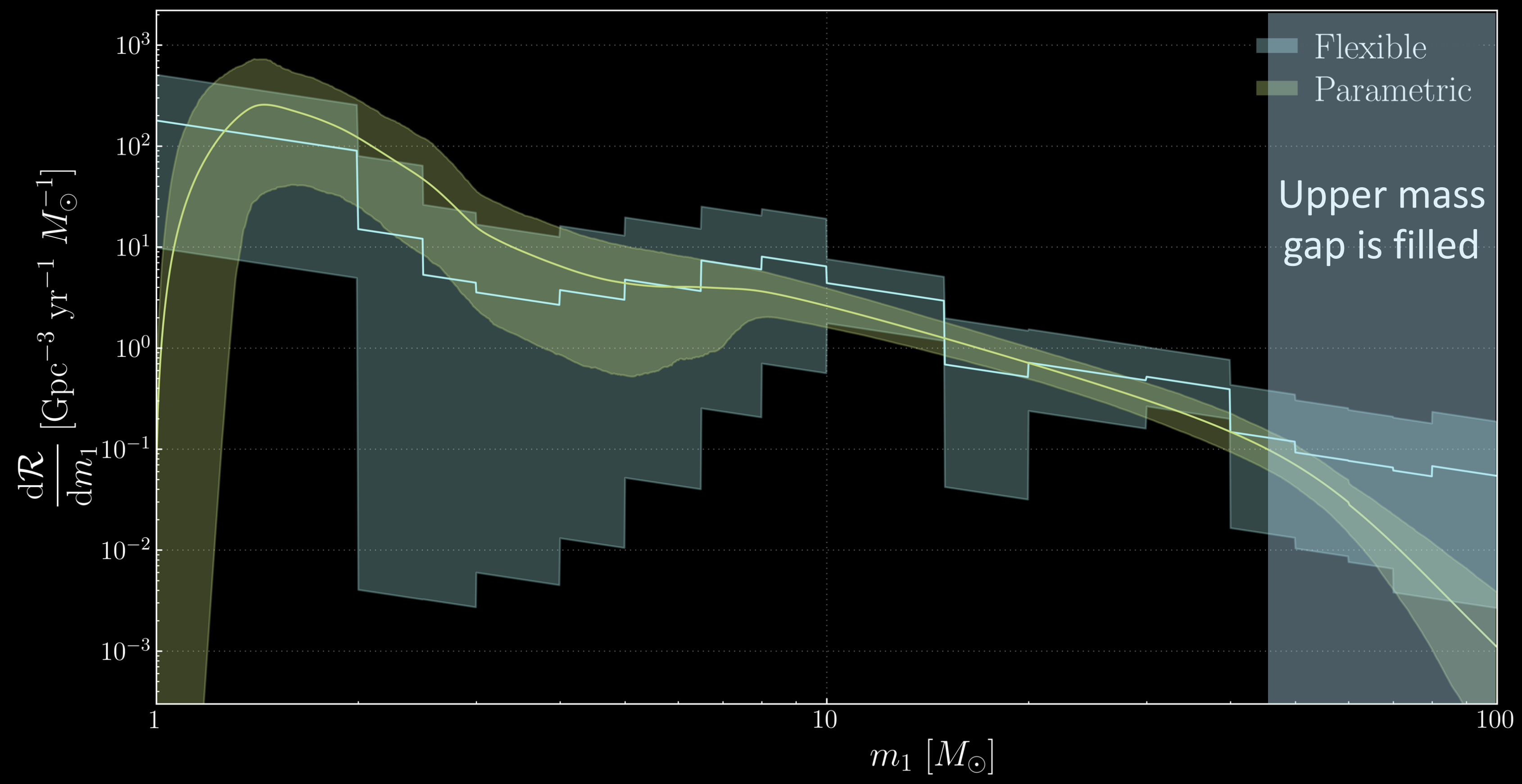


Stable mass transfer



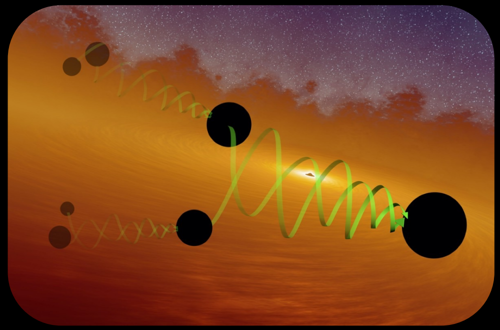
Illustrations by Dean Kousiounelos

# Clues to the formation of the most massive stellar-mass black holes?



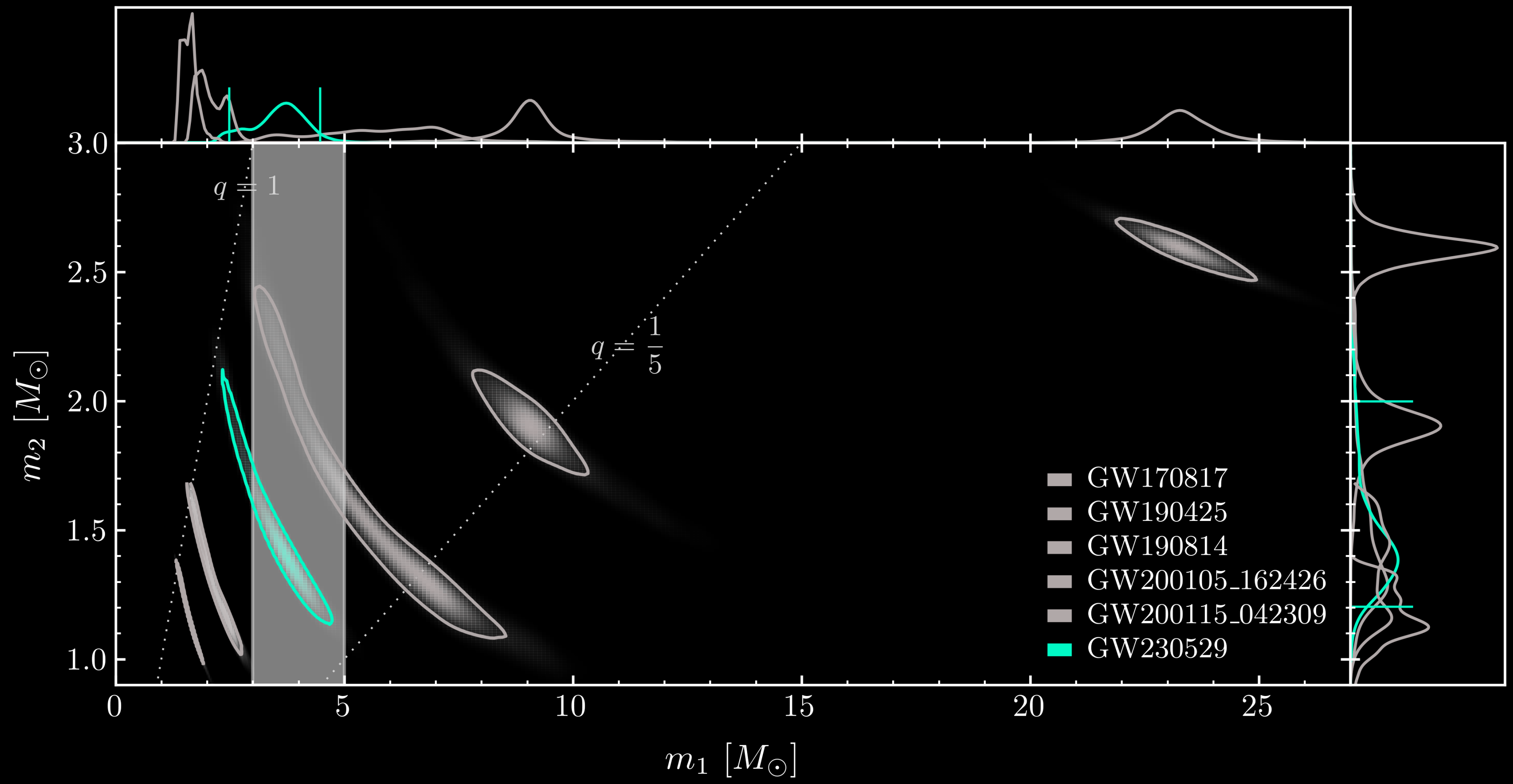

(Pulsational) pair instability supernovae

Hierarchical mergers

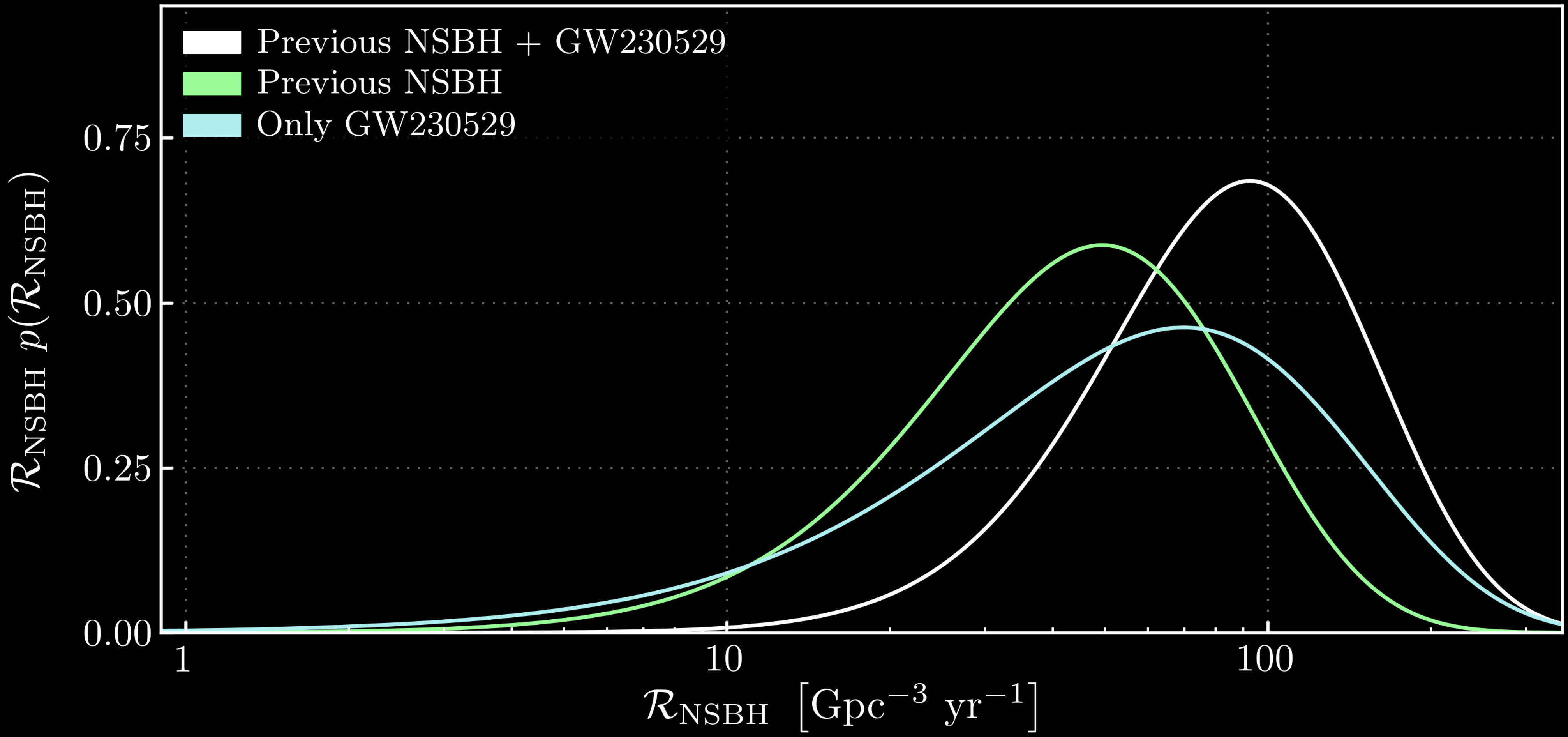


arxiv - 2404.04248

# GW230529 is the most equal-mass neutron star-black hole merger observed to date

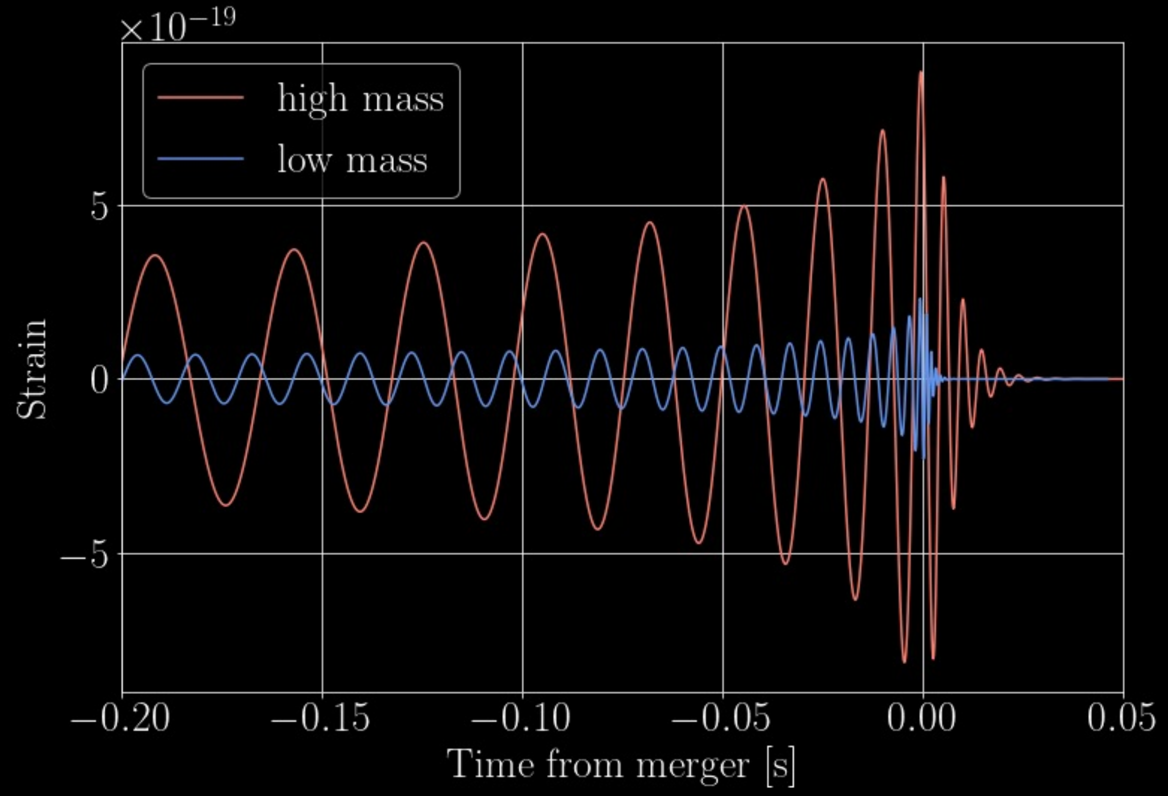


# GW230529 is at least as common as more "vanilla" unequal-mass NSBH



# The gravitational-wave signal

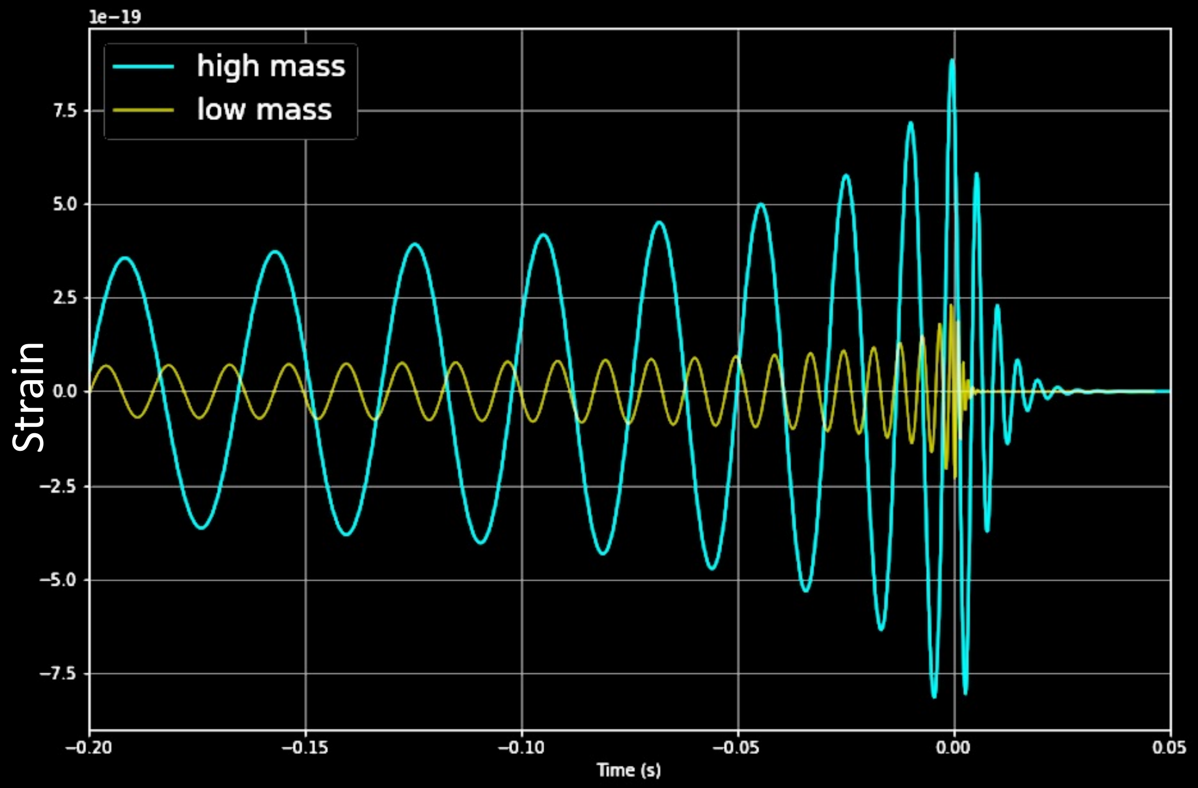
- General relativity predicts a unique gravitational waveform for each set of binary parameters
- Use different "approximant" waveforms to reduce computational cost of full solution



# The gravitational-wave signal

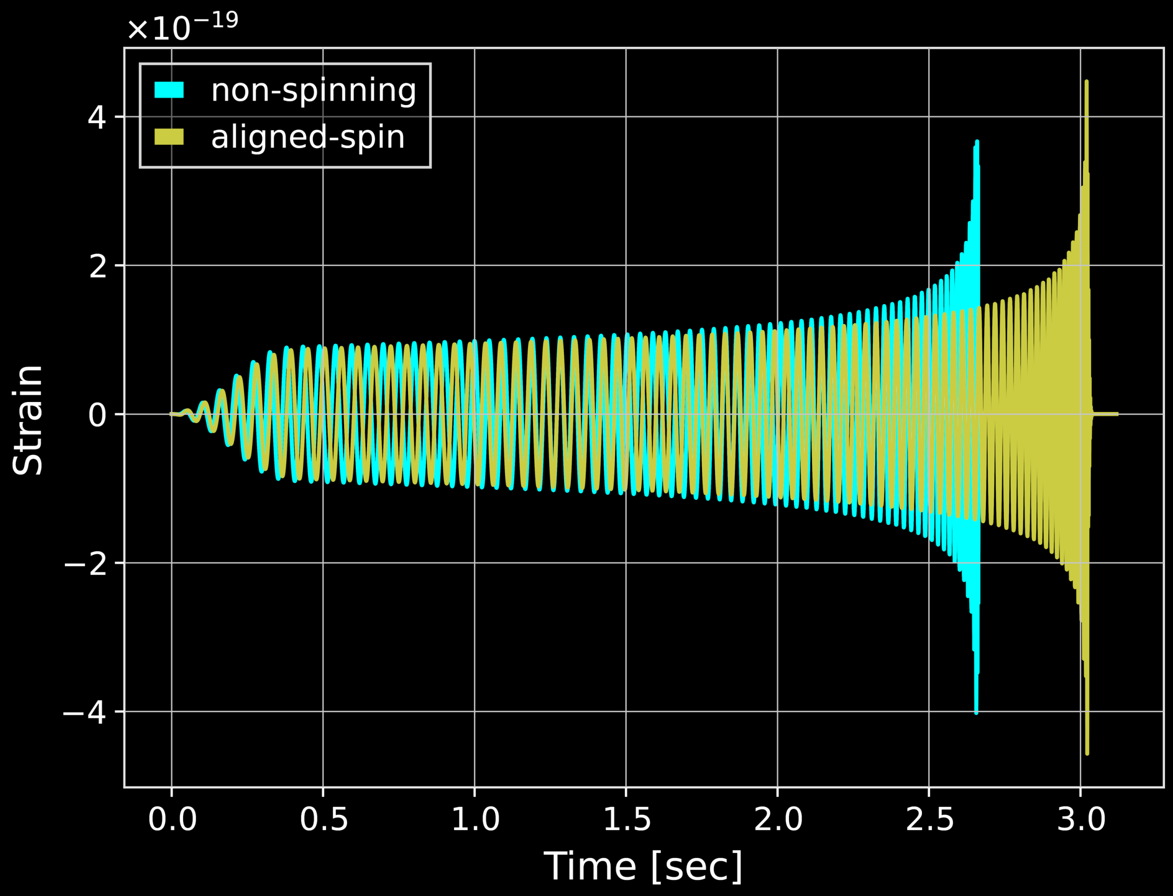
- More massive systems merge at lower frequency → spend less time in LIGO's sensitive band
- More massive, larger amplitude at fixed distance

$$\mathcal{A}_{\mathrm{GW}} \propto \frac{\mathcal{M}^{5/6} f^{-7/6}}{d_L}$$



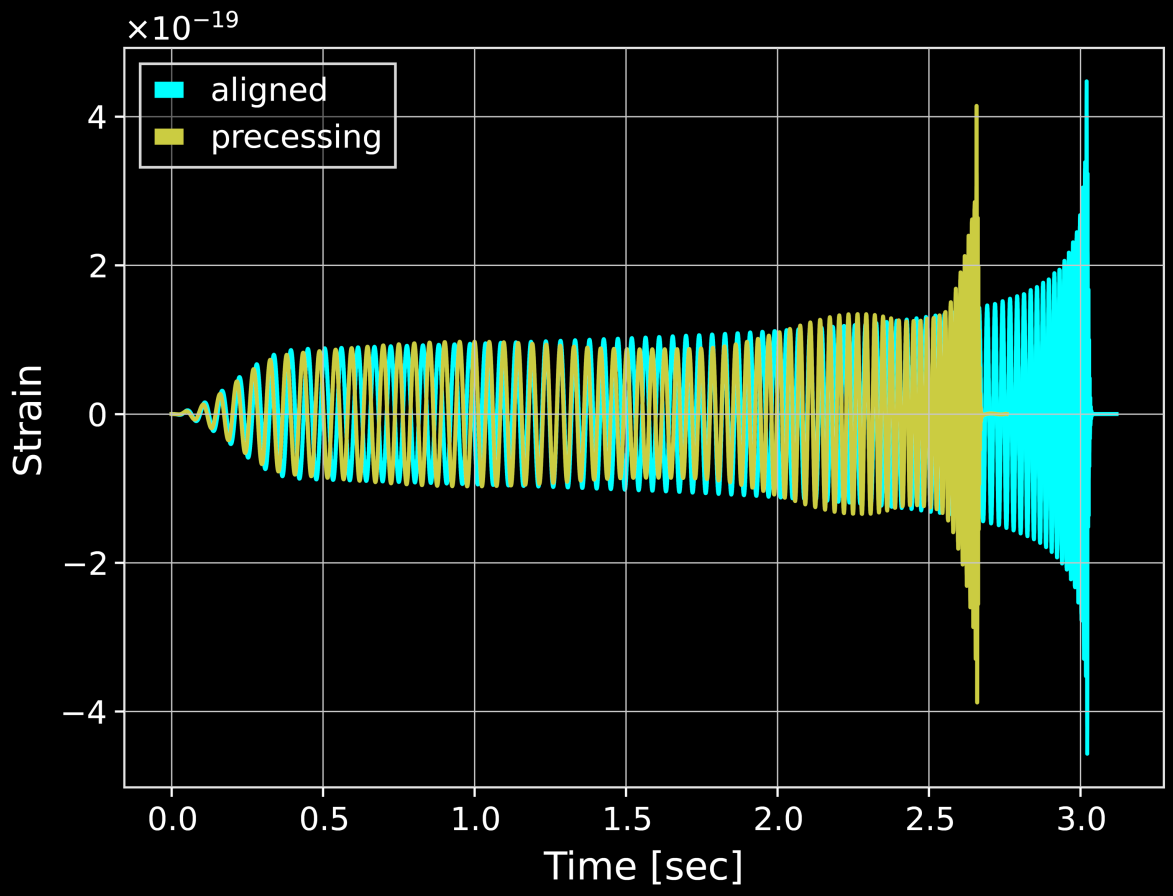
# The gravitational-wave signal

- General relativity predicts a unique gravitational "waveform" for each set of binary parameters
- Amplitude and frequency both increase in time as merger approaches
- More rapidly spinning systems spend more time in LIGO's sensitive band due to "orbital hangup effect"



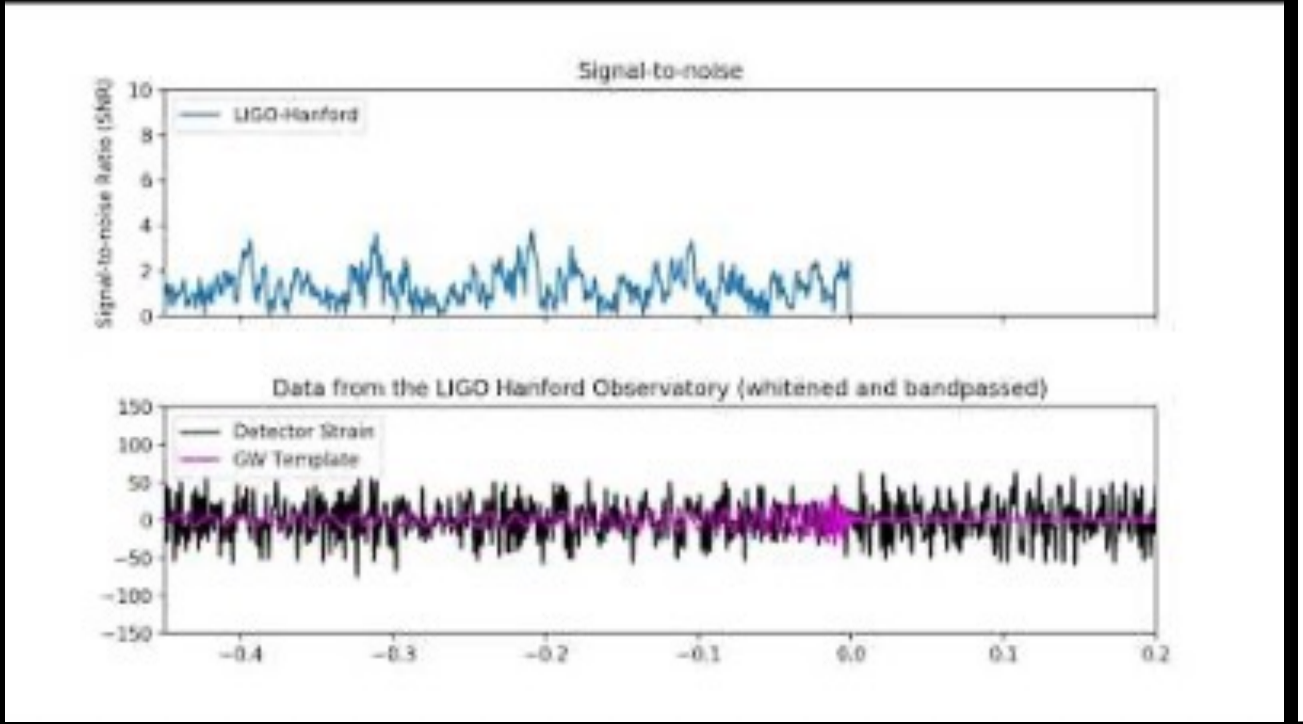
# The gravitational-wave signal

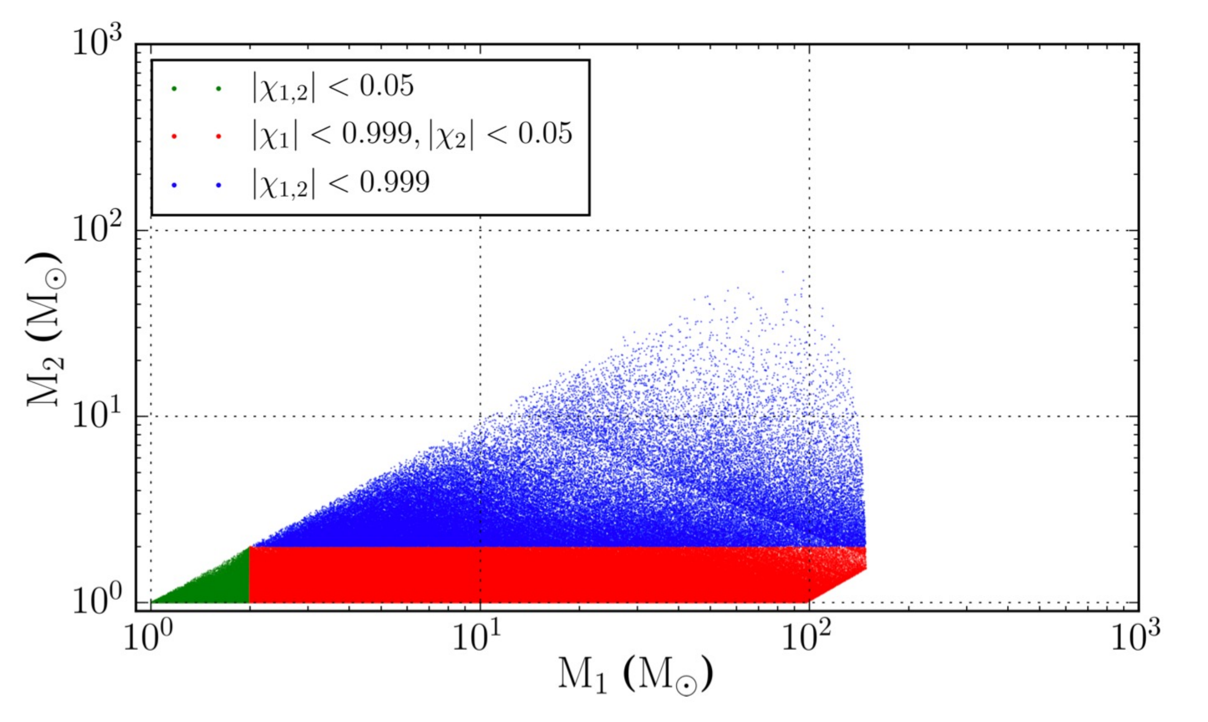
- General relativity predicts a unique gravitational “waveform” for each set of binary parameters
- Amplitude and frequency both increase in time as merger approaches
- Systems with spin vectors misaligned to the orbital angular momentum exhibit general relativistic “precession”
- Modulation of the waveform due to precession of the orbital plane



# Gravitational-wave detection

- Matched filtering – compare gravitational-wave signals from a fixed template bank to the strain data, maximize the "match"




arxiv - 2404.04248

Mukherjee + 1812.05121

# Parameter estimation

- Use Bayesian inference to sample across the whole 15-dimensional binary parameter space and obtain posterior probability distributions
- Requirements:
  - Likelihood of observing the data given a certain model
  - Prior probability of each binary parameter

likelihood prior

posterior

$$p(\boldsymbol{\theta}|d, H) = \frac{p(d|\boldsymbol{\theta}, H)\,p(\boldsymbol{\theta}|H)}{p(d|H)}$$

parameters data model

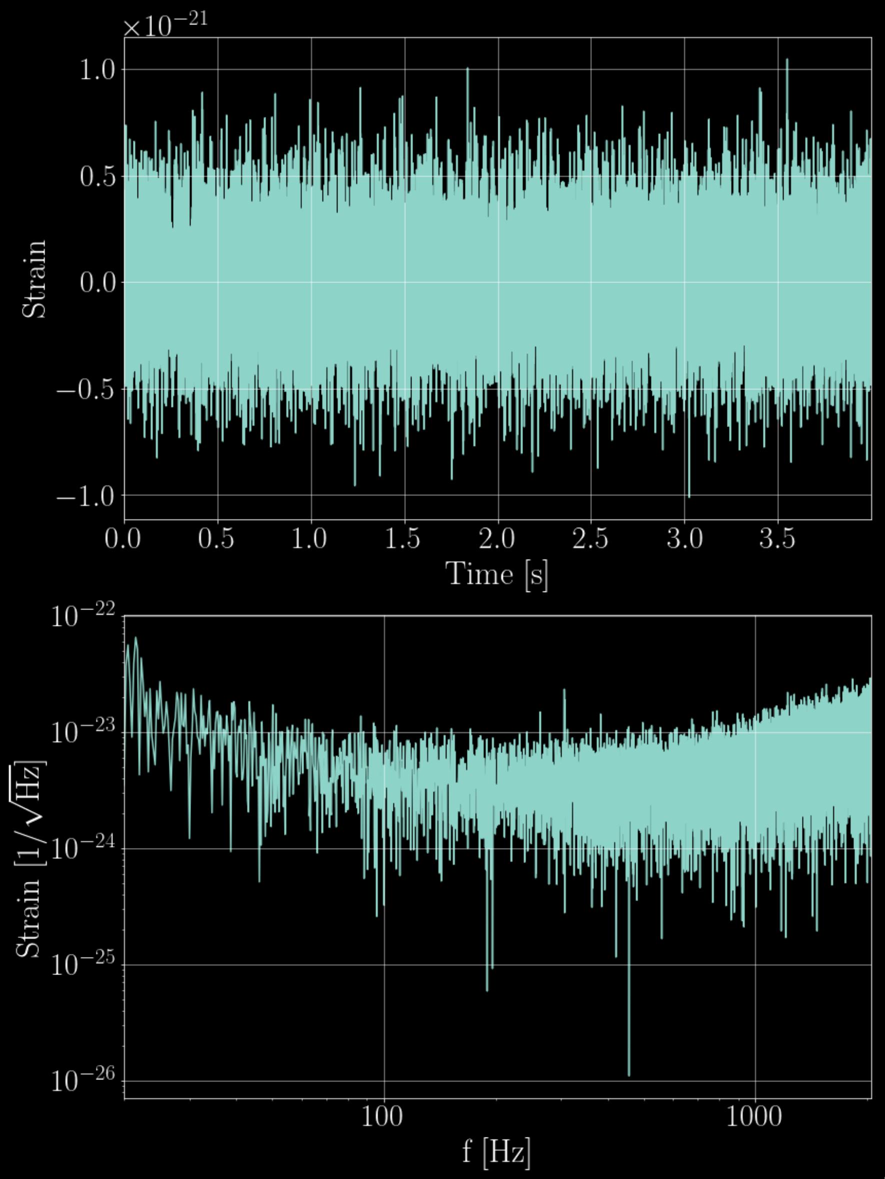
evidence

# LIGO Noise Properties

- Assume data has both a gravitational-wave signal component and a noise component:

$$d = h + n$$

- Observe dimensionless strain time-series, Fourier transform into frequency domain



# LIGO Noise Properties

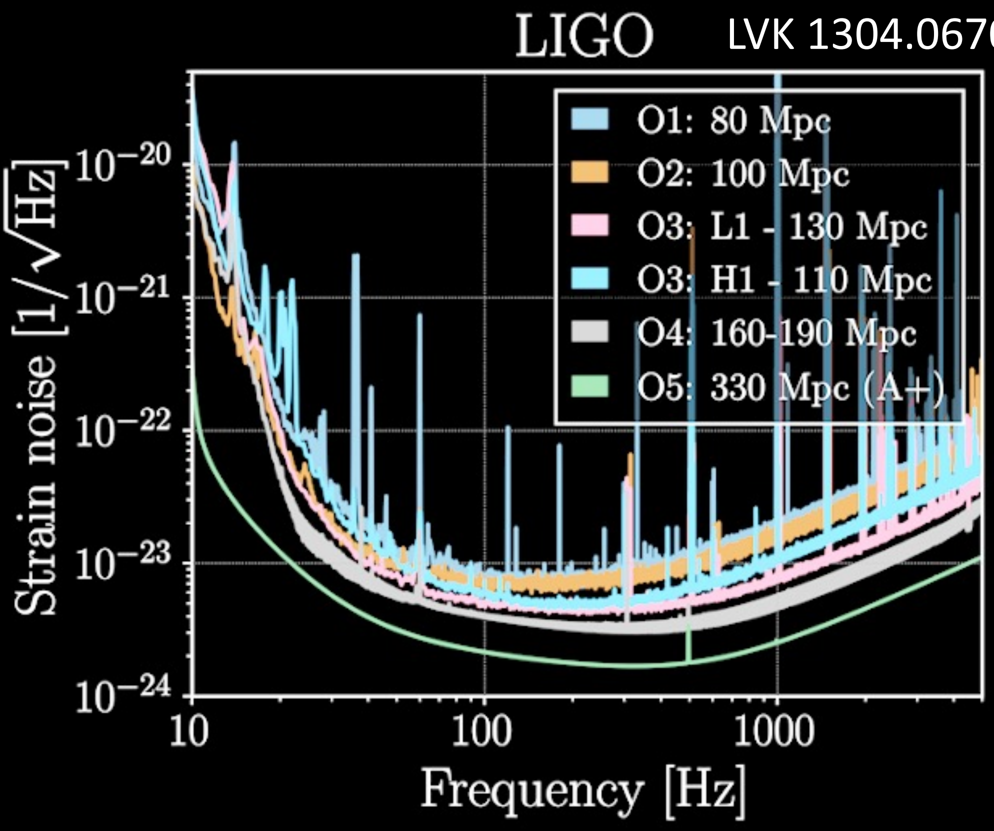
- Assume data has both a gravitational-wave signal component and a noise component:

$$d = h + n$$

- Well-behaved data in the absence of a signal is gaussian about the "amplitude spectral density" (ASD) or "strain noise" → Gaussian likelihood

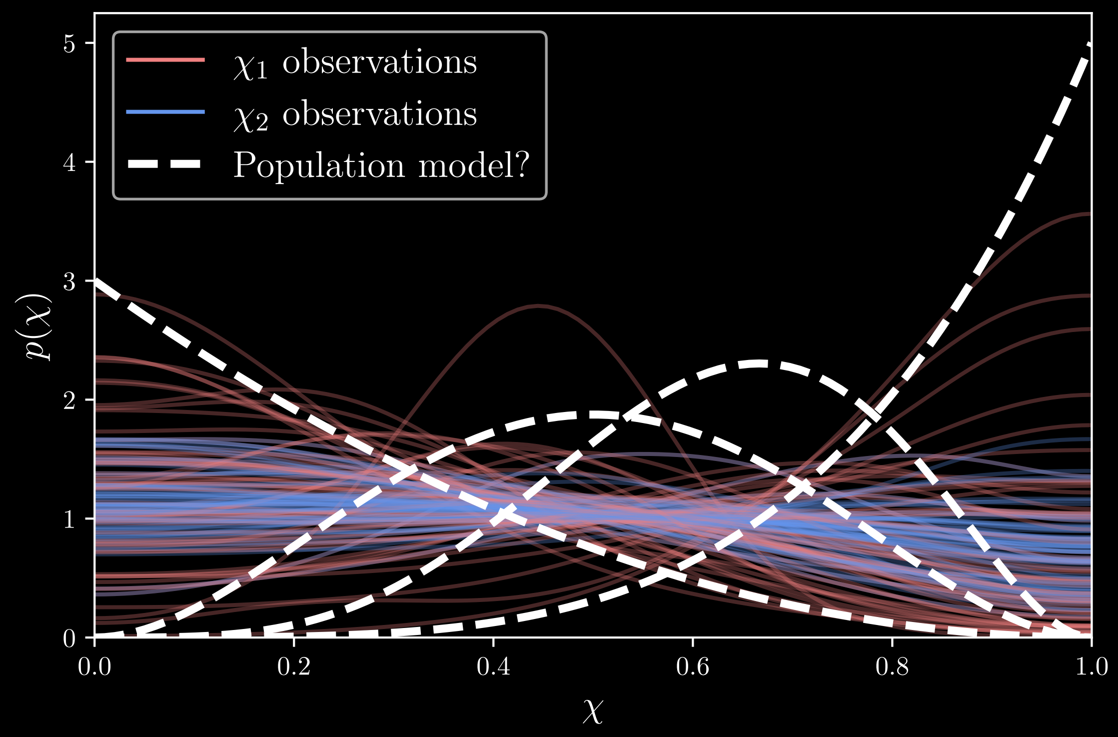
$$p(d\,|\boldsymbol{\theta}) \propto \frac{(d-h)^2}{2\mathrm{ASD}^2}$$

LVK 1304.0670



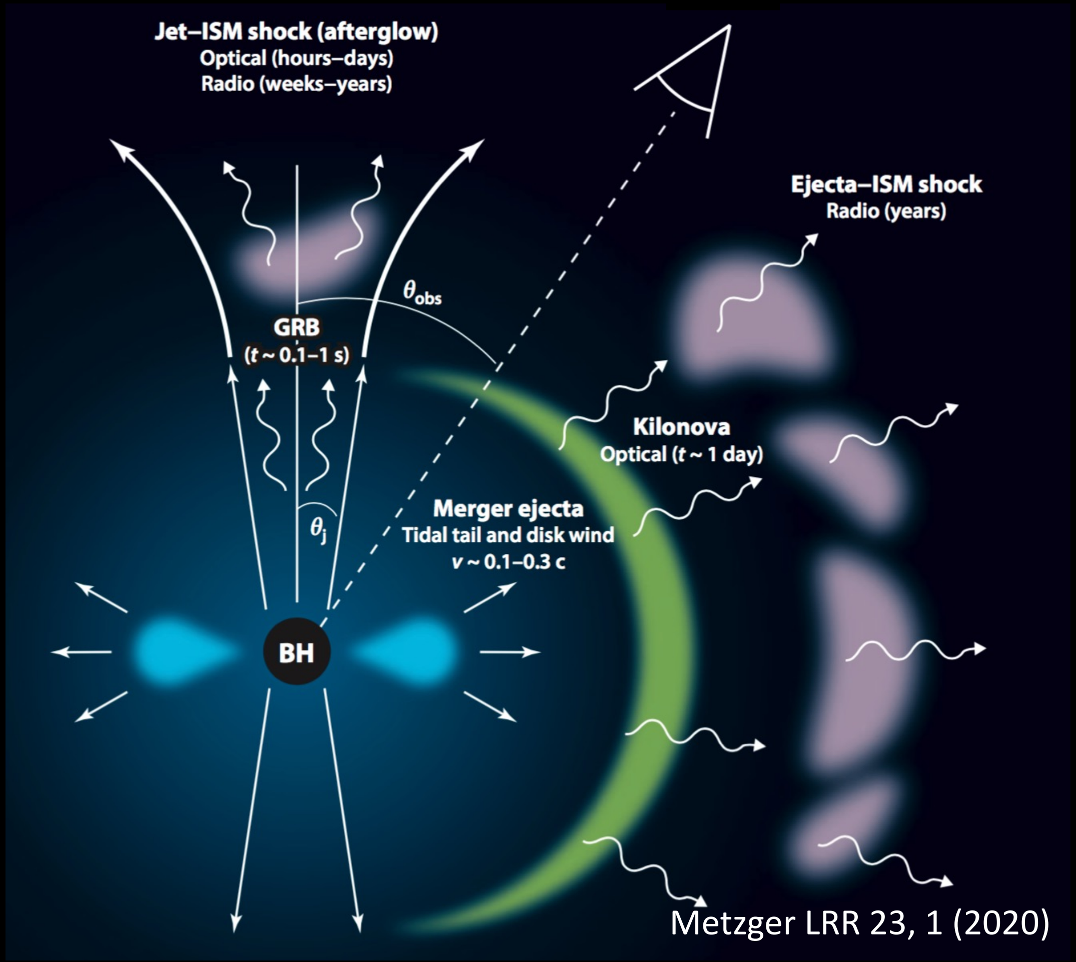
# Population analysis

- By combining our $\mathcal{O}(100)$ events, we can estimate the parameters governing the distributions from which they are drawn using hierarchical Bayesian inference
- Account for individual-event statistical uncertainty and for selection effects
- Ex: assume spin magnitude is a Beta distribution characterized by an unknown mean and width
  - Wysocki+ PRD 100, 043012 (2019)



# Electromagnetic counterparts

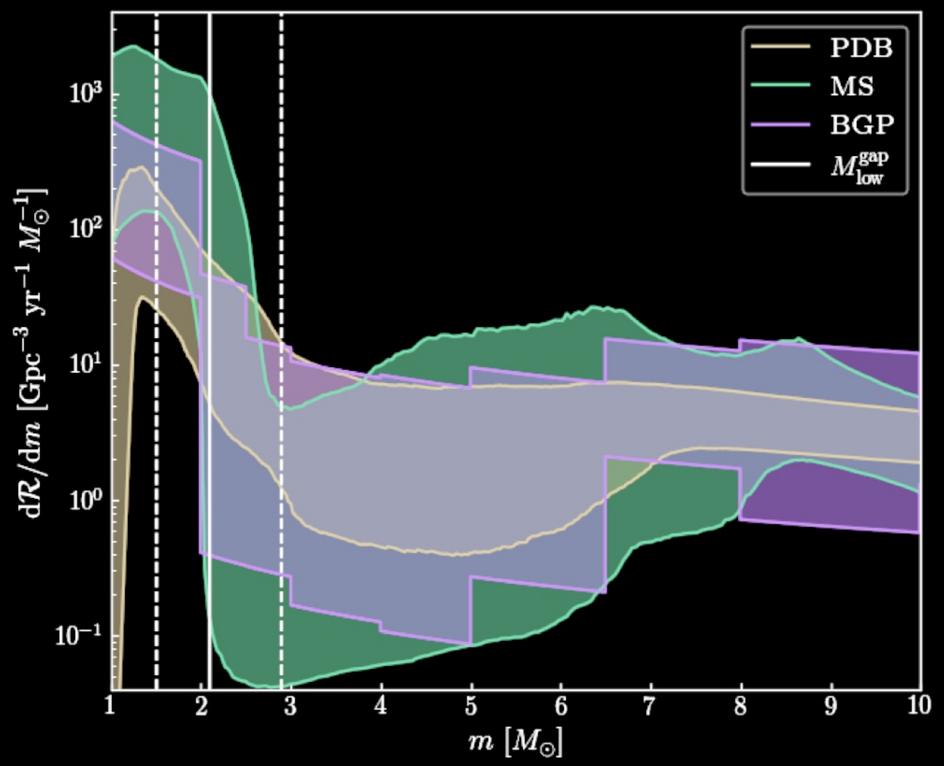
- Fate of the merger remnant and electromagnetic counterpart depends on the properties of the component objects
- *Gamma-ray burst:* most energetic electromagnetic explosions observed in the universe
- *Kilonova:* optical emission powered by the radioactive decay of freshly synthesized heavy elements



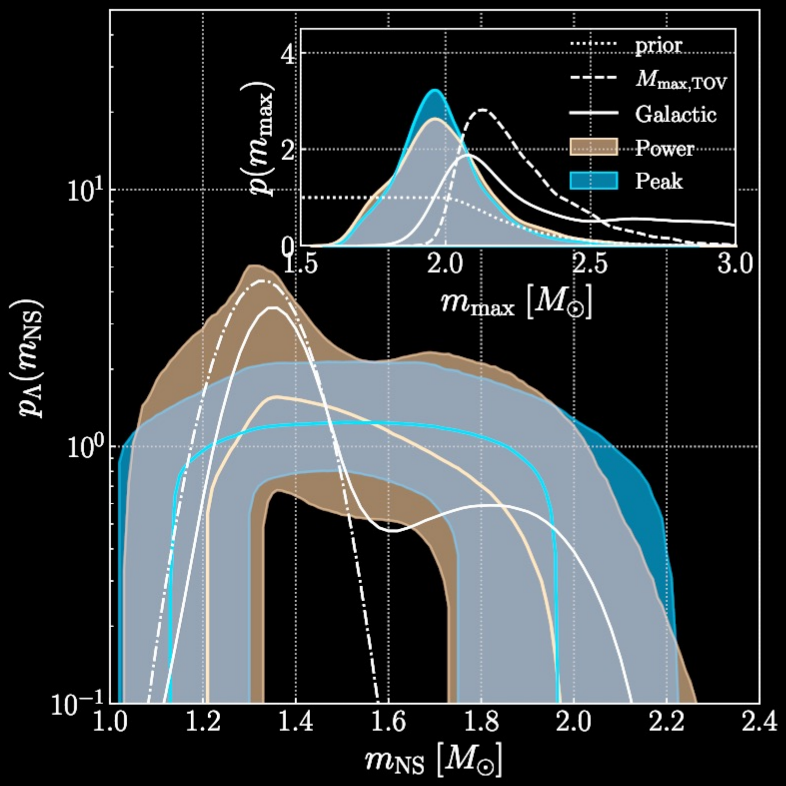
Metzger LRR 23, 1 (2020)

# Astrophysical population inference

No evidence for lower mass gap between neutron stars and black holes

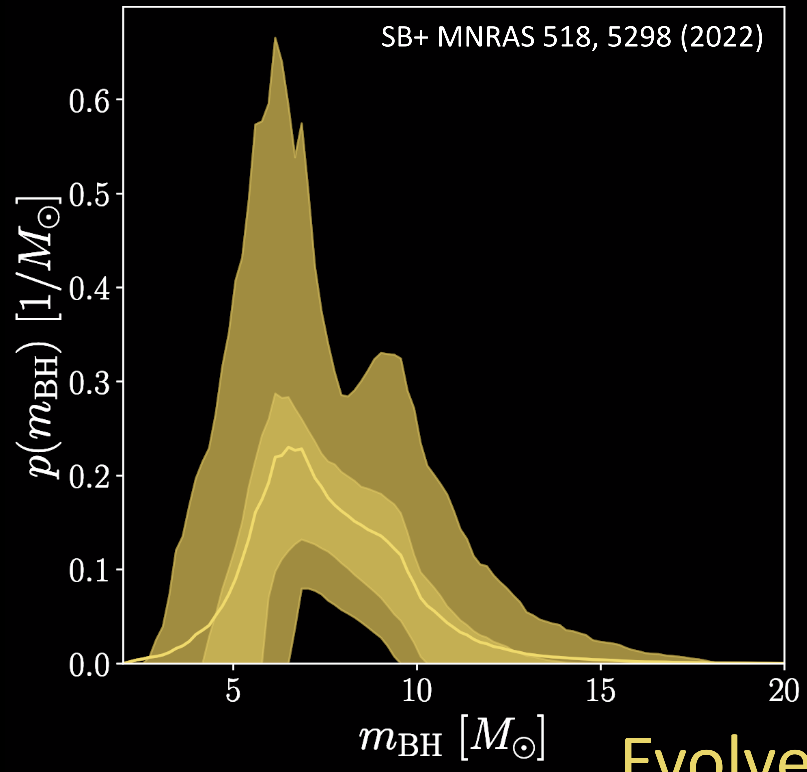



Neutron stars detected in GWs are more massive than those detected as pulsars in our galaxy

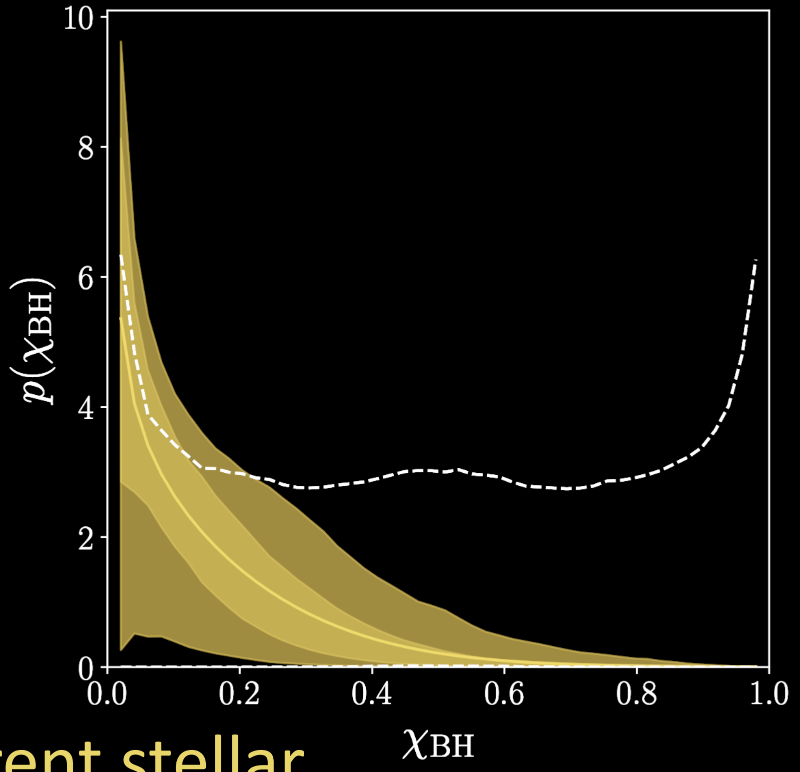


# Neutron star-black hole mergers

The black holes are less massive than those in black hole binaries

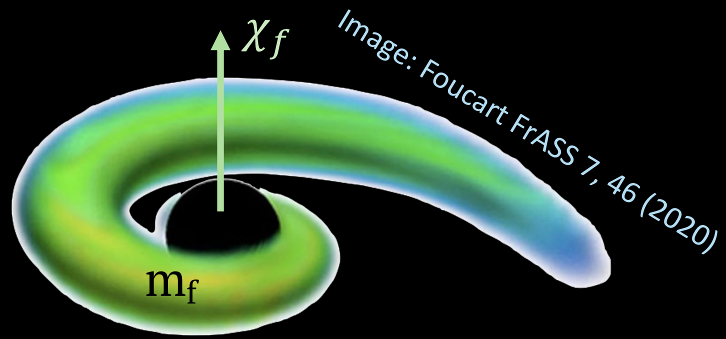



And more slowly spinning

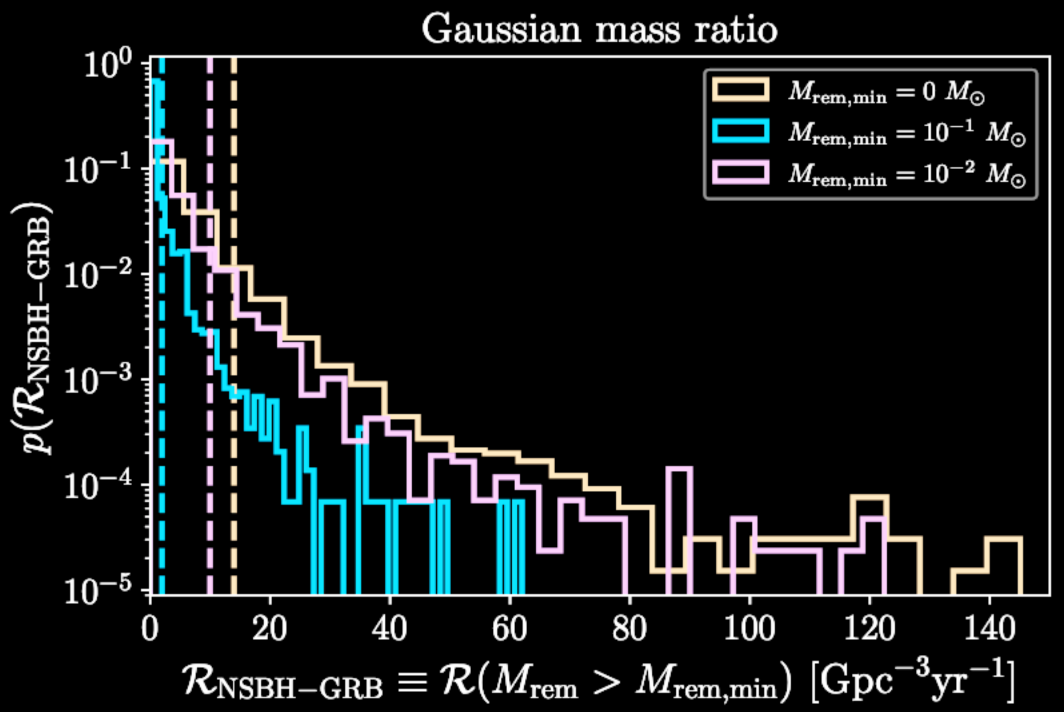



Evolve from different stellar progenitors

# Multimessenger prospects



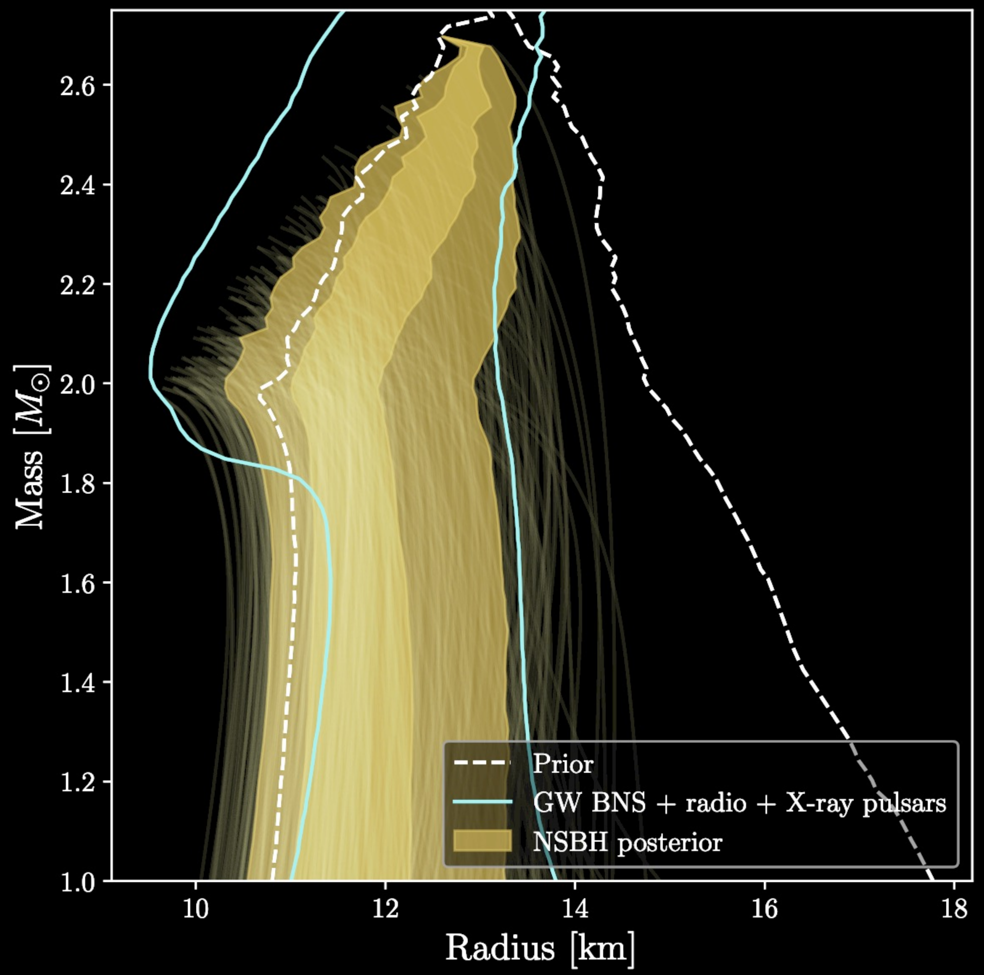

- Neutron-star black hole mergers are unlikely to produce electromagnetic counterparts
  - Unequal mass ratios and low black hole spins
- Upper limit of 20 $Gpc^{-3}\,yr^{-1}$ GRBs from NSBH mergers at 90% credibility (underlying beaming-corrected rate)




SB+ RNAAS 7, 136 (2023)

# Neutron star-black hole mergers

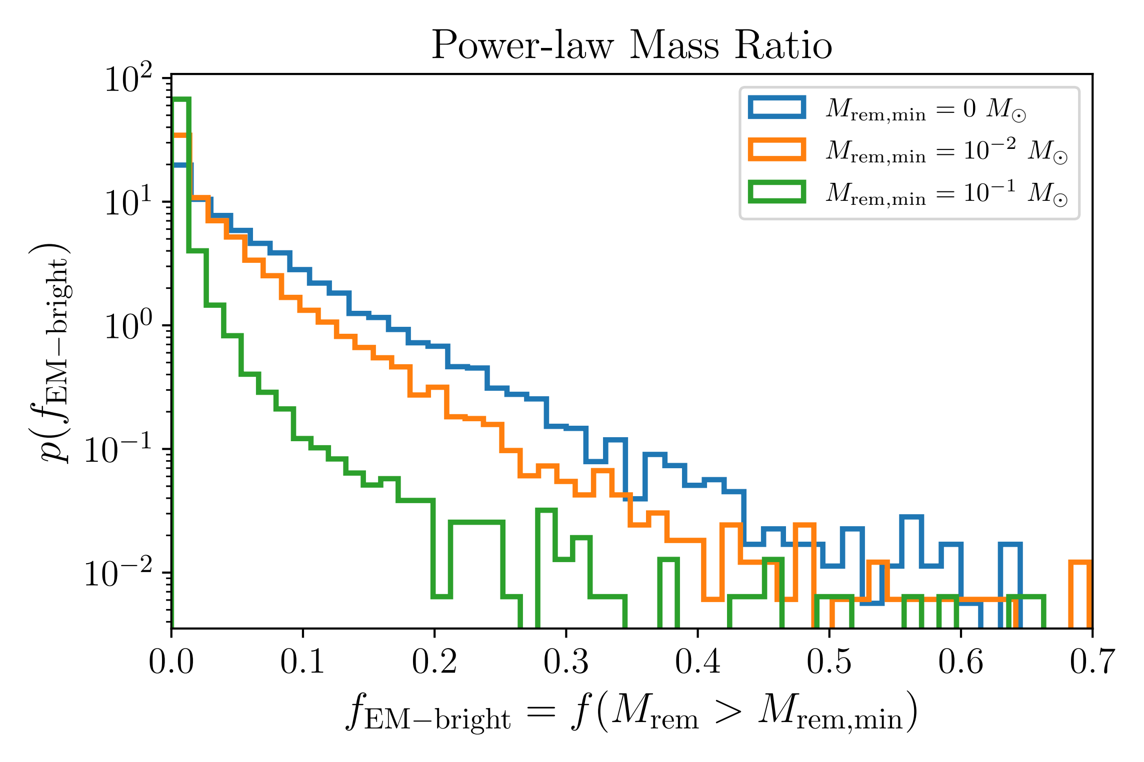
- For small neutron star radii, extreme mass ratios, and low black hole spin, the neutron star is more likely to plunge directly into the black hole → no electromagnetic counterpart
- Based on the observed population, at most 14% of mergers detectable in gravitational waves may be electromagnetically bright
- Fold in counterpart non-detection into Bayesian framework to constrain the neutron star equation of state



# Electromagnetically-bright fraction

- At most 14% of NSBH sources may have an associated electromagnetic counterpart
- 99% probability that none of the four NSBH candidates we consider were electromagnetically bright

➢ Use this constraint to inform the population properties and measure the neutron star equation of state




observed remnant mass = 0

remnant mass predicted by fitting formula

equation of state piecewise polytrope parameters

$$p(M_{\rm rem}|q, m_{\rm NS}, \chi_{{\rm BH},z}, \mathbf{\Lambda}_{\rm EoS}) = \delta(\hat{M}_{\rm rem}(q, m_{\rm NS}, \chi_{\rm NS}, \chi_{{\rm BH},z}, \mathbf{\Lambda}_{\rm EoS}))$$

# Hierarchical Modeling

- The new likelihood is the original likelihood marginalized over the original parameters:

$$\mathcal{L}(d|\boldsymbol{\Lambda}) = \int d\boldsymbol{\theta} \mathcal{L}(d|\boldsymbol{\theta}, \boldsymbol{\Lambda}) \pi(\boldsymbol{\theta}|\boldsymbol{\Lambda})$$

$$= \int d\boldsymbol{\theta} \mathcal{L}(d|\boldsymbol{\theta}) \pi(\boldsymbol{\theta}|\boldsymbol{\Lambda})$$

$$= \int d\boldsymbol{\theta} \frac{p(\boldsymbol{\theta}|d) \mathcal{Z}_{\theta}}{\pi_0(\boldsymbol{\theta})} \pi(\boldsymbol{\theta}|\boldsymbol{\Lambda})$$

Hyper-prior

Original likelihood (doesn't depend on hyper-parameters)

Original evidence

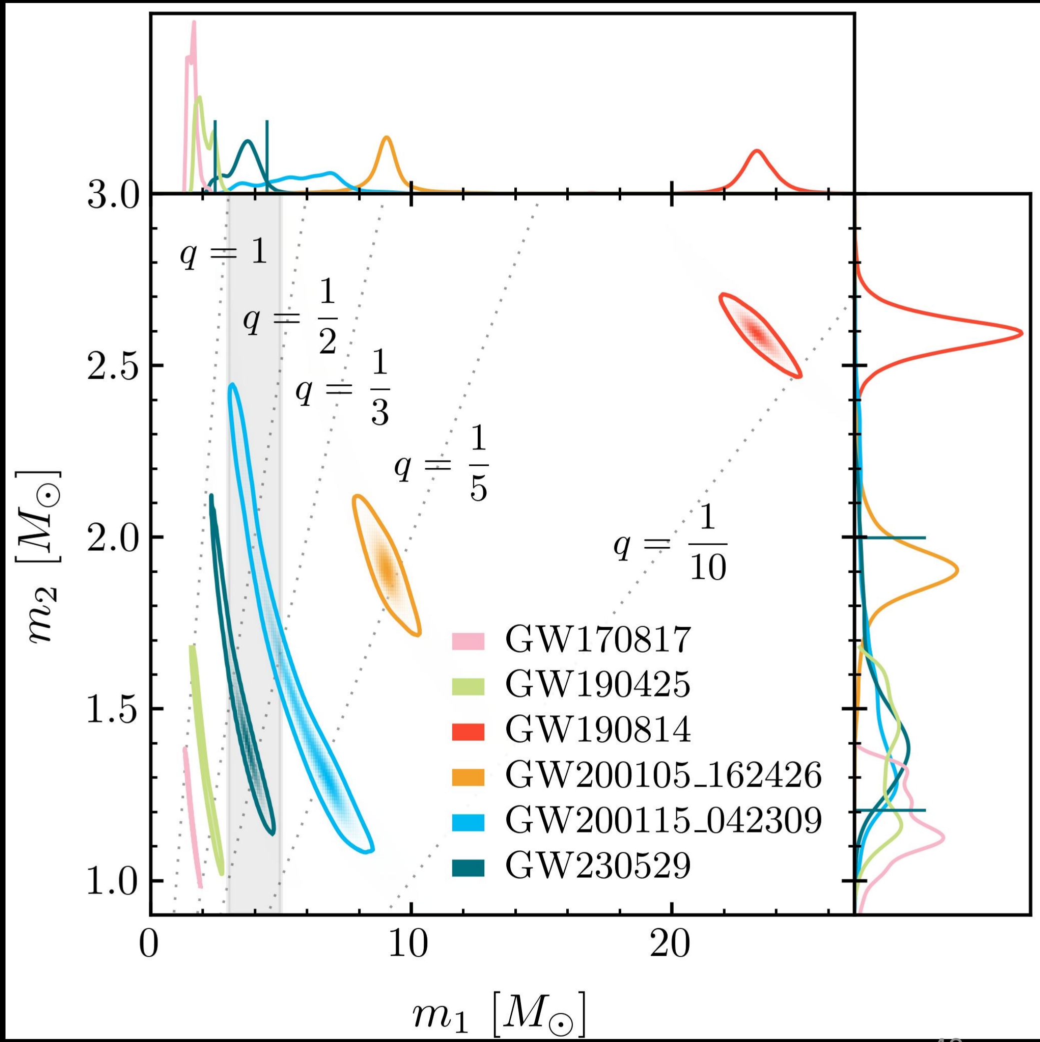
Original prior

# GW230529

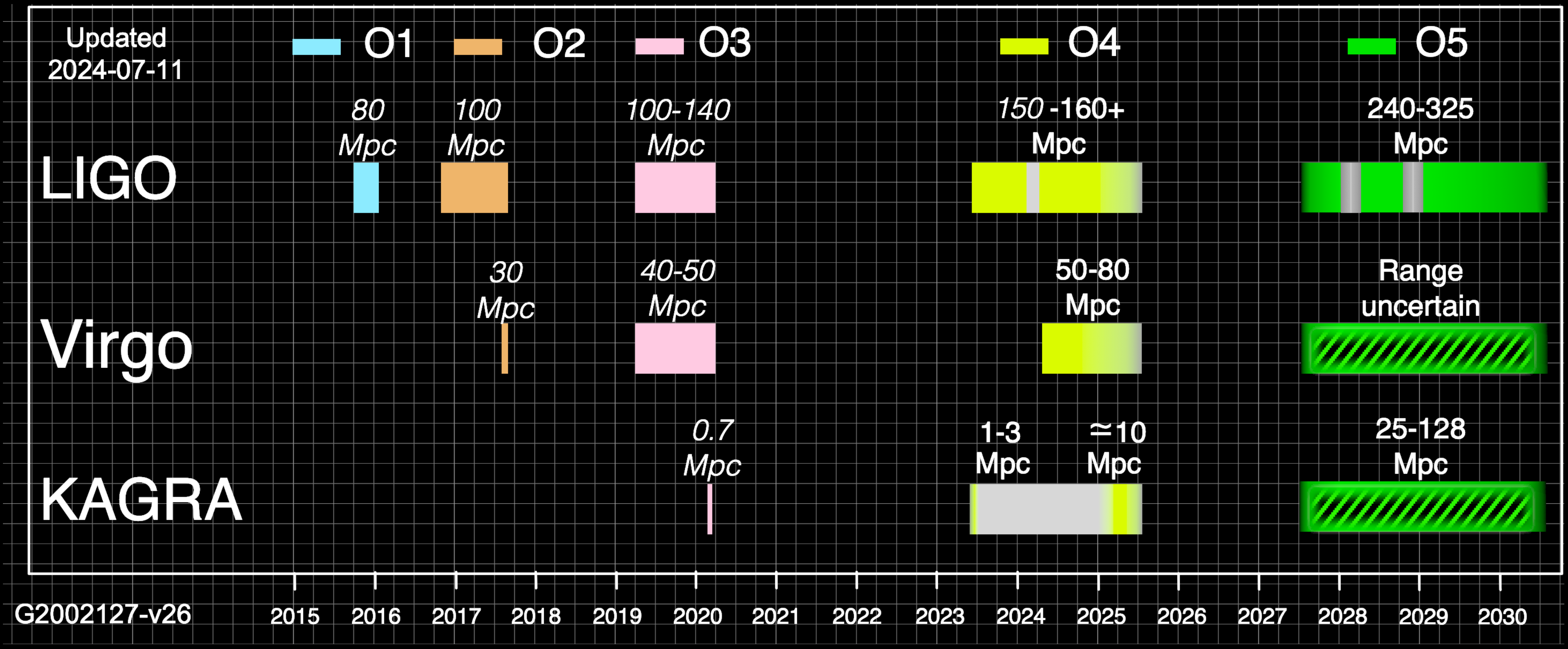
- Observed by LIGO Livingston only – significant detection by three independent search pipelines

| | GstLAL | MBTA | PyCBC |
|---|---|---|---|
| Online S/N | 11.3 | 11.4 | 11.6 |
| Online inverse FAR (yr) | 1.1 | 1.1 | 160.4 |
| Offline inverse FAR (yr) | 60.3 | >1000 | >1000 |

- Mass of the primary staunchly in 3-5 $M_\odot$ range
- Support for either very high-mass neutron star or low-mass black hole



# What's next?


Updated
2024-07-11
O1
O2
O3
O4
O5
LIGO
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150 -160+
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KAGRA
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