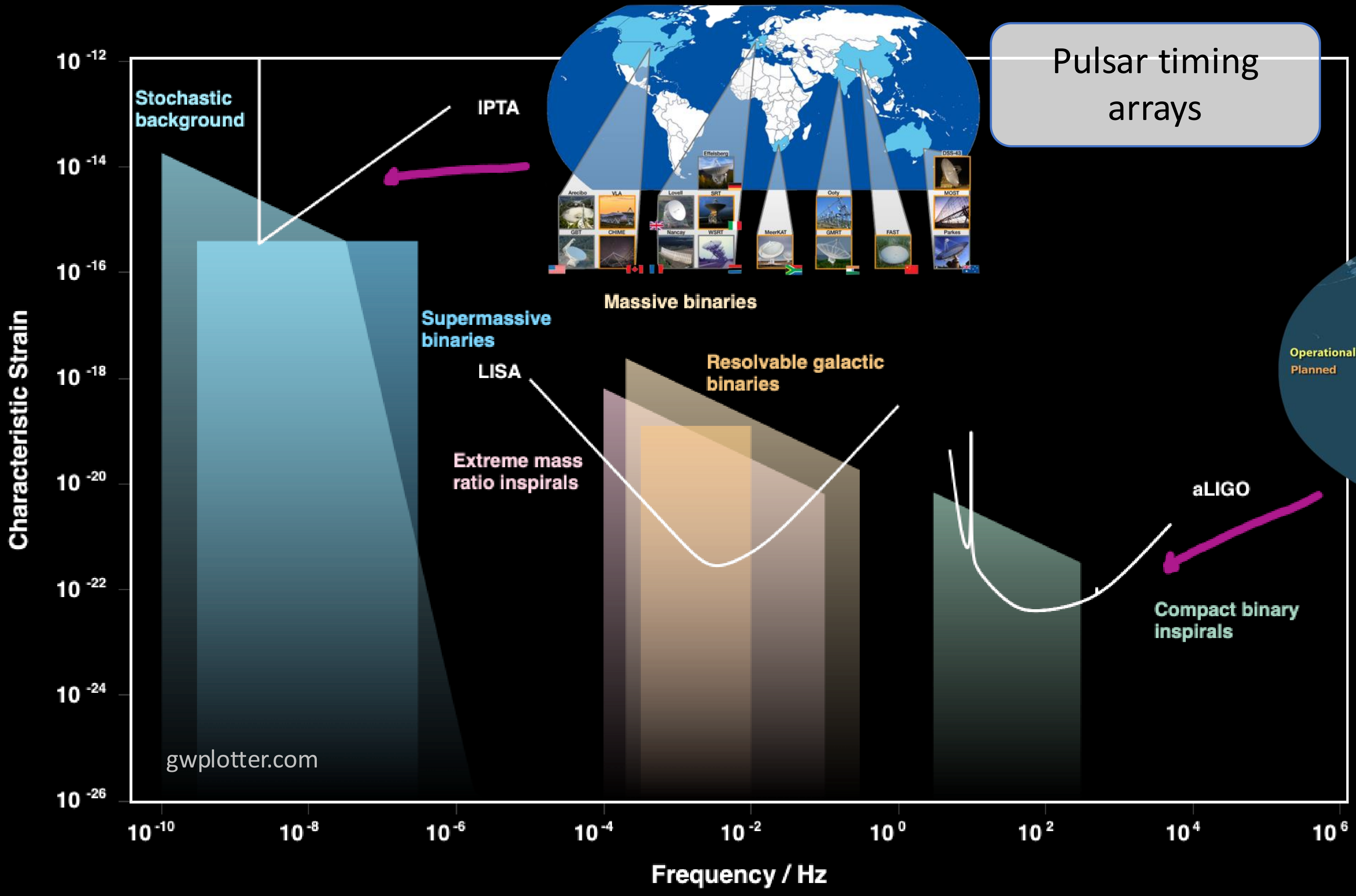
Image: LIGO / Caltech / MIT / Sonoma State (Aurore Simonnet)

Gravitational-wave observations and multimessenger implications

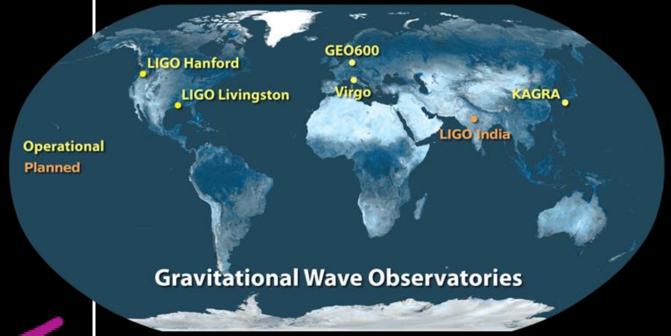
Sylvia Biscoveanu

TeVPA 2026

Our observational landscape



Pulsar timing arrays

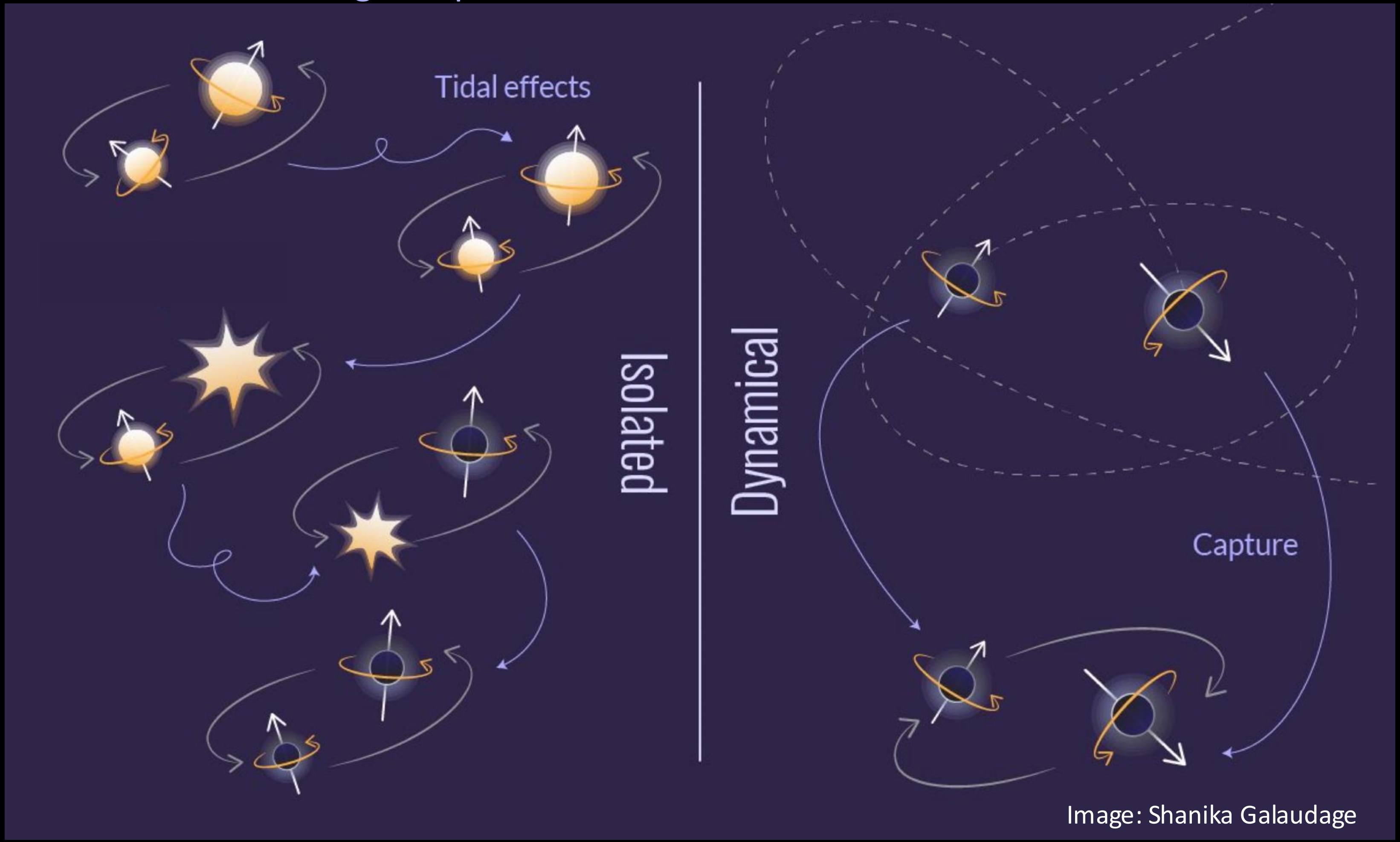


Ground-based interferometers

How do compact-object binaries form?

Lifelong companions

Social butterflies



How do compact-object binaries form?

Lifelong companions

Social butterflies

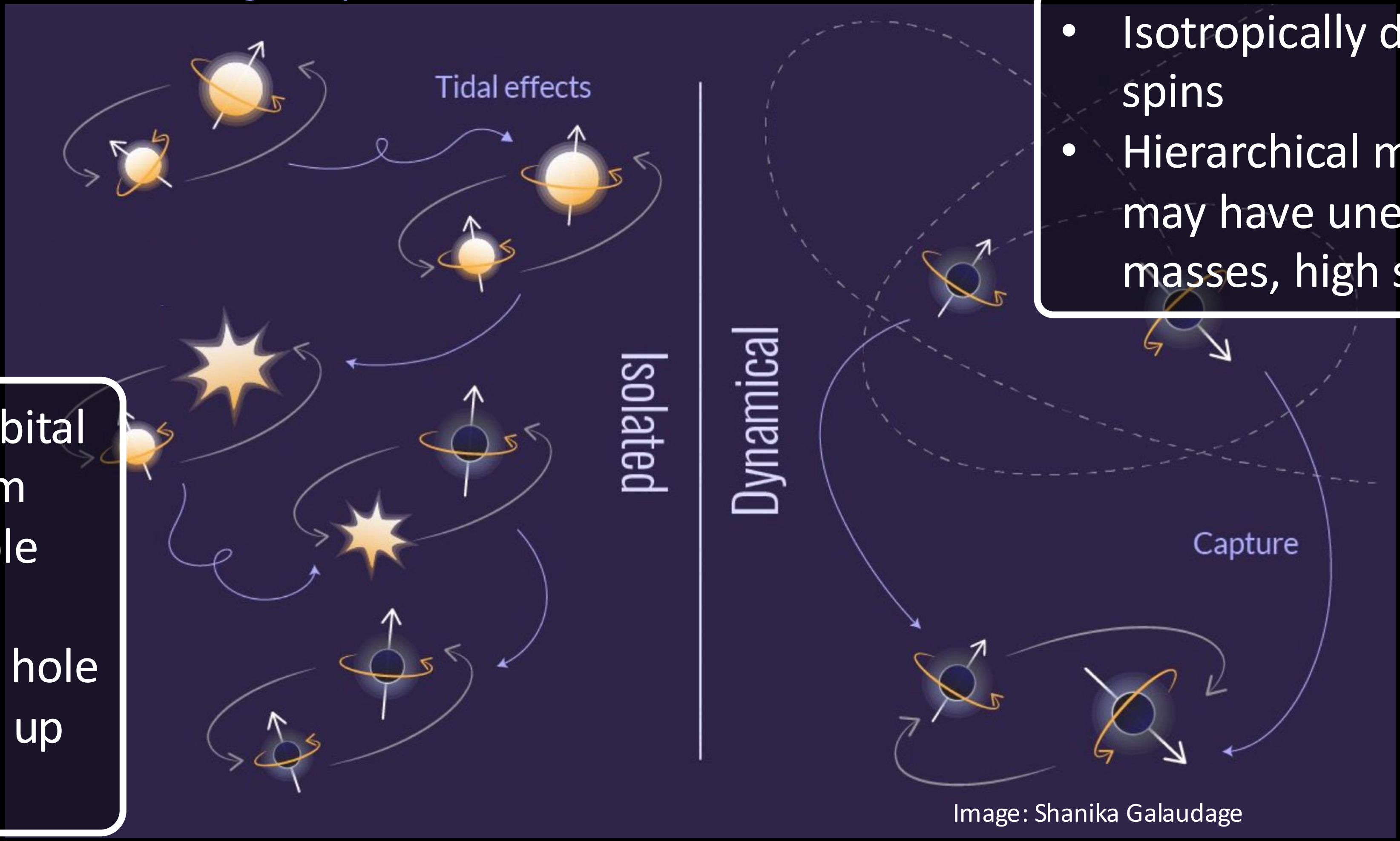
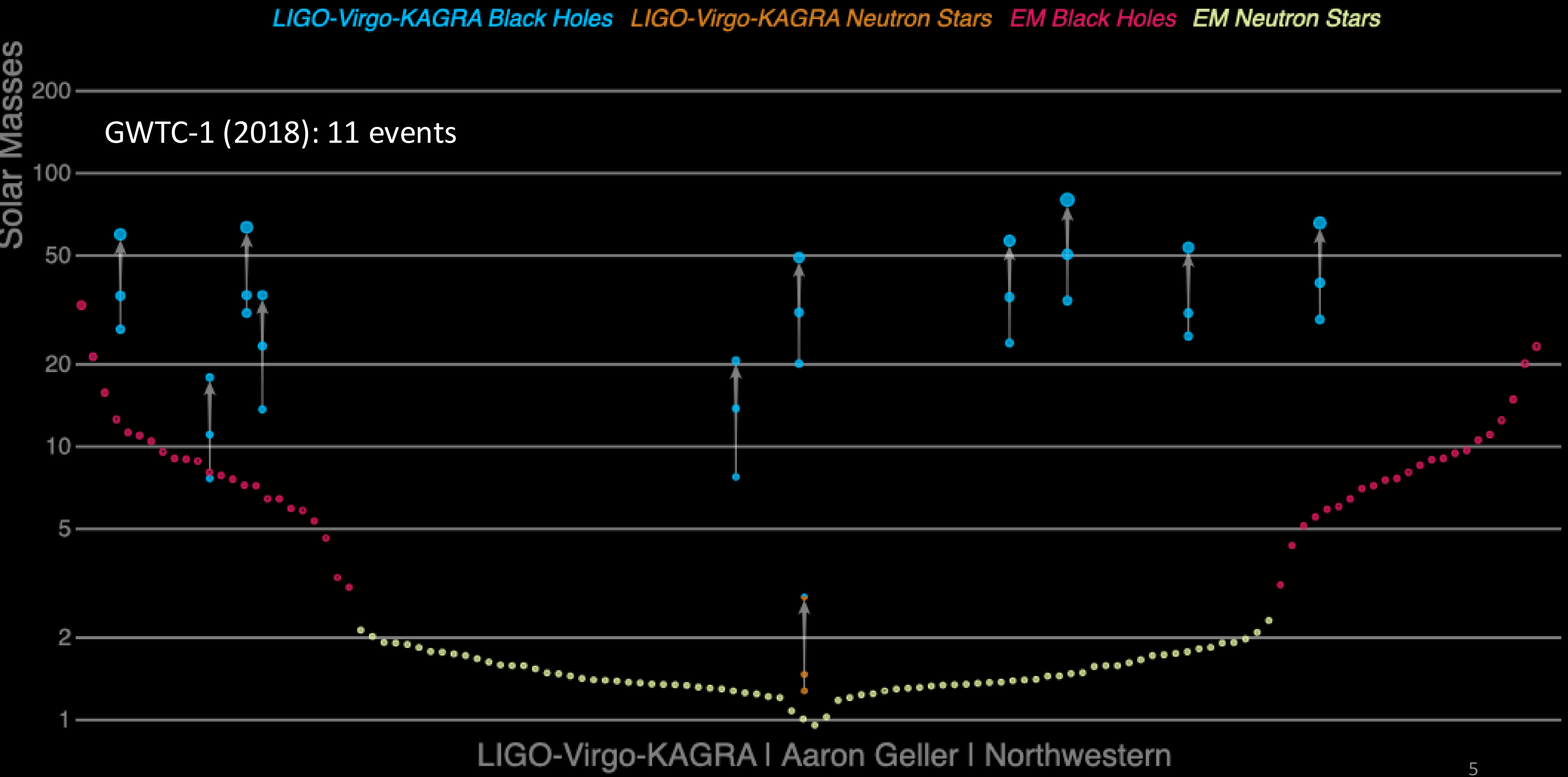


Image: Shanika Galaudage

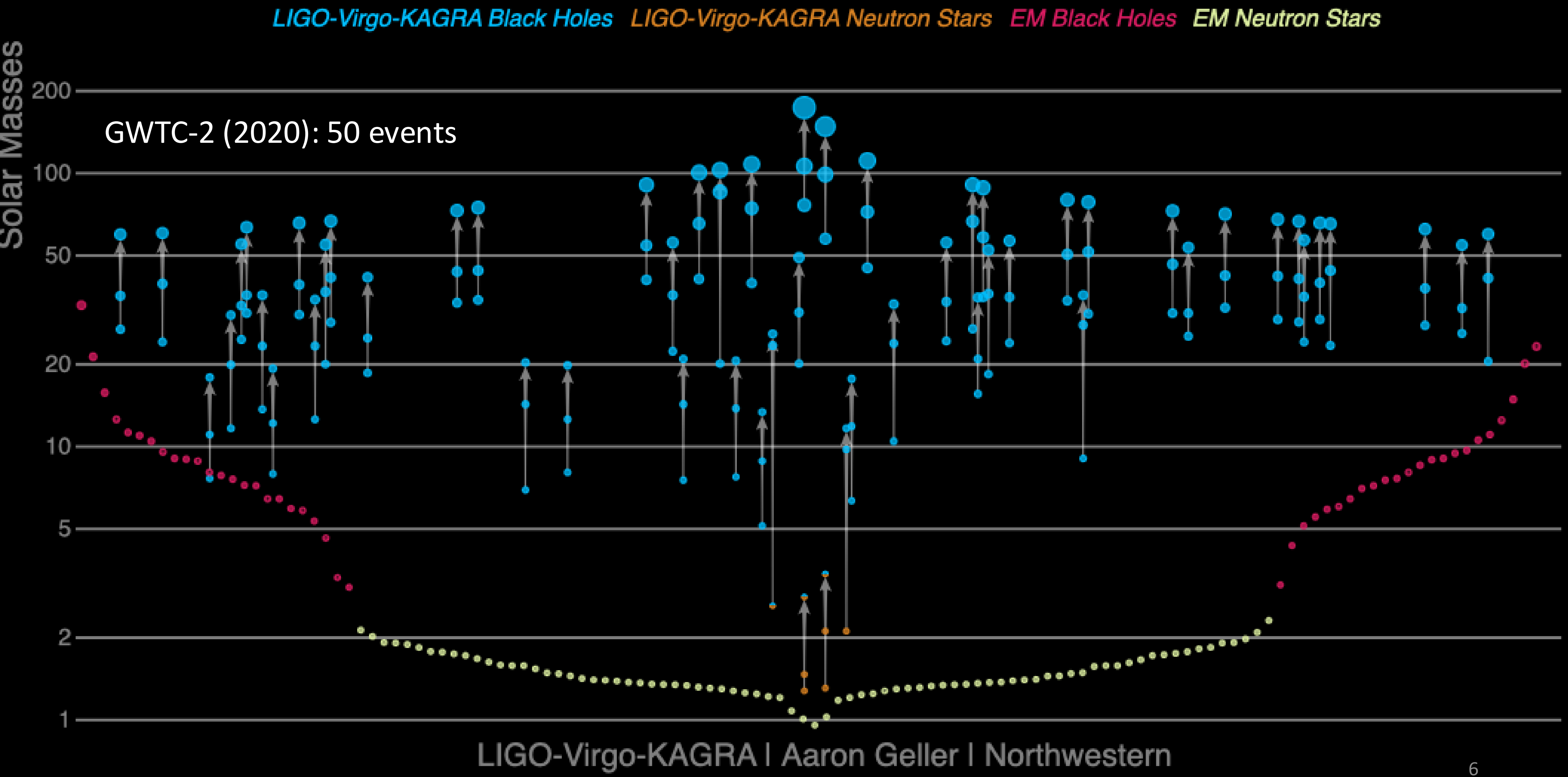
- Isotropically distributed spins
- Hierarchical mergers may have unequal masses, high spin

- Spins aligned to orbital angular momentum
- First-born black hole has small spin
- Second-born black hole can be tidally spun up

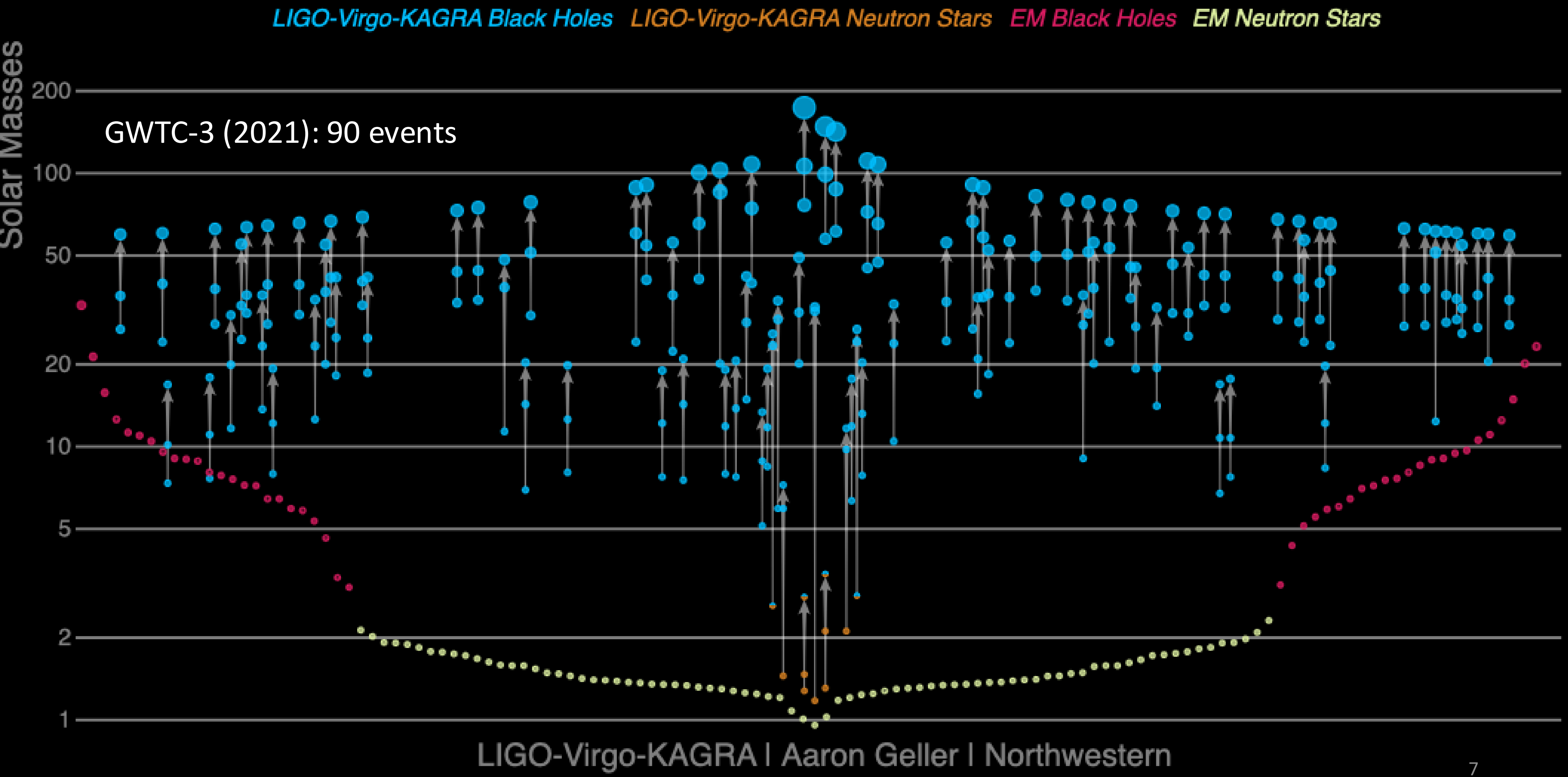
Masses in the Stellar Graveyard



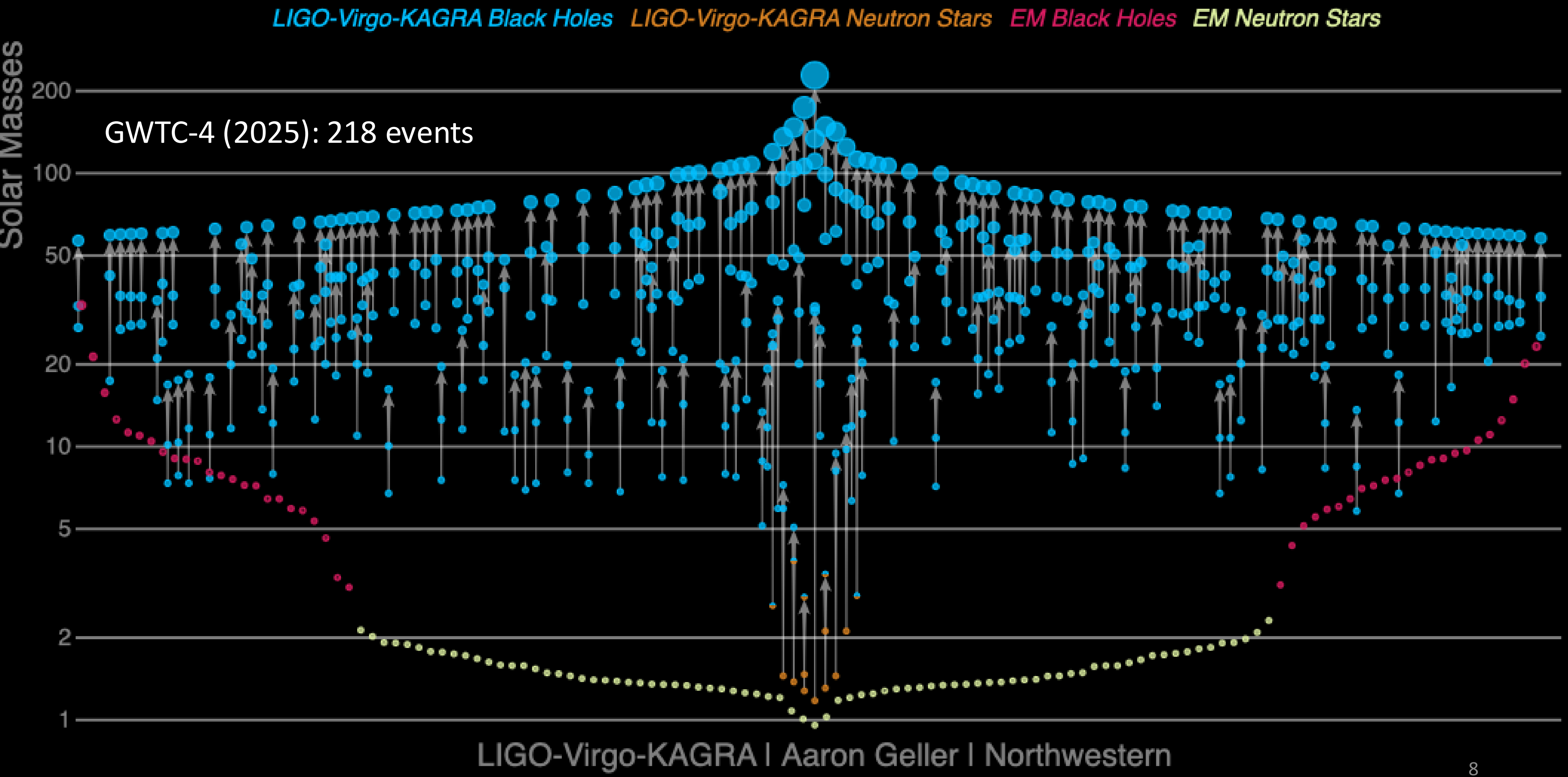
Masses in the Stellar Graveyard

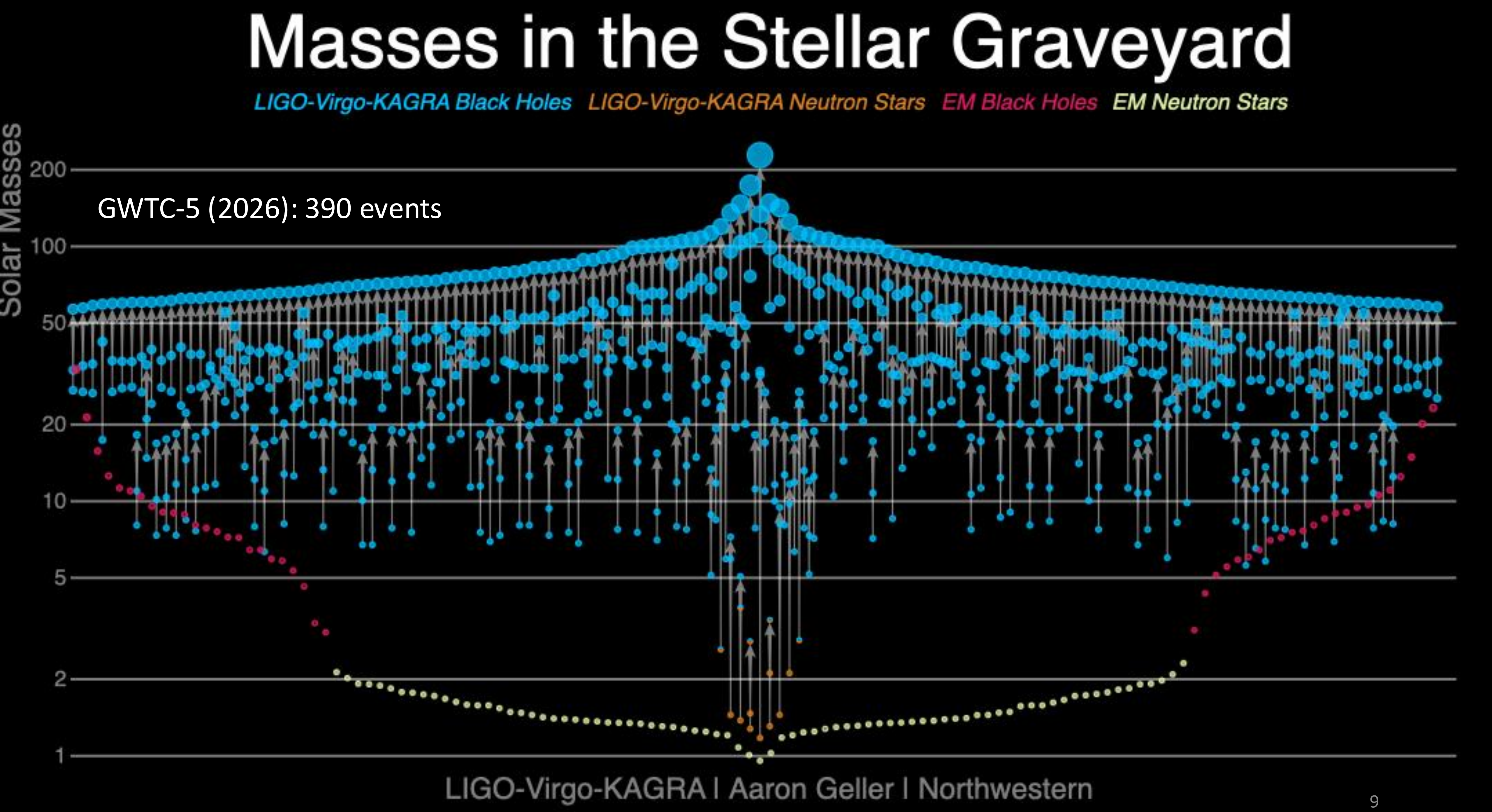


Masses in the Stellar Graveyard



Masses in the Stellar Graveyard



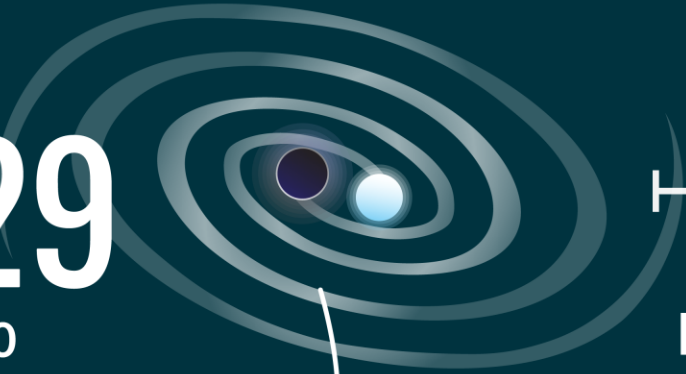


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
GWTC-5 (2026): 390 events
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Get to know

GW230529

Full name GW230529_181500



~ 650 million light years away

Detectors

H L V K

- Offline OR not operational
- Online BUT not used for analysis*
- Online AND used for analysis

most likely a merger between a Neutron Star & Black Hole (NSBH)

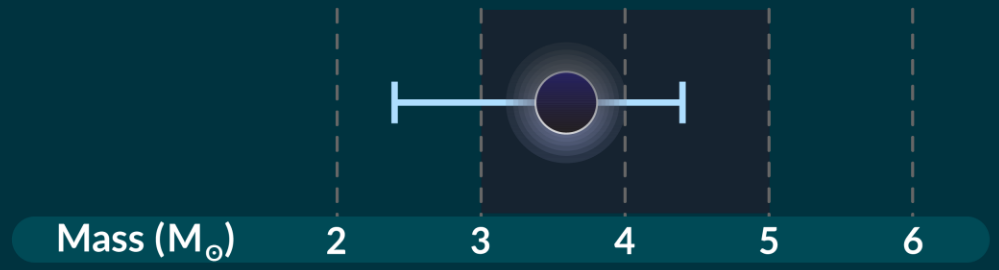
~1.4 $M_\odot$ ~3.6 $M_\odot$

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

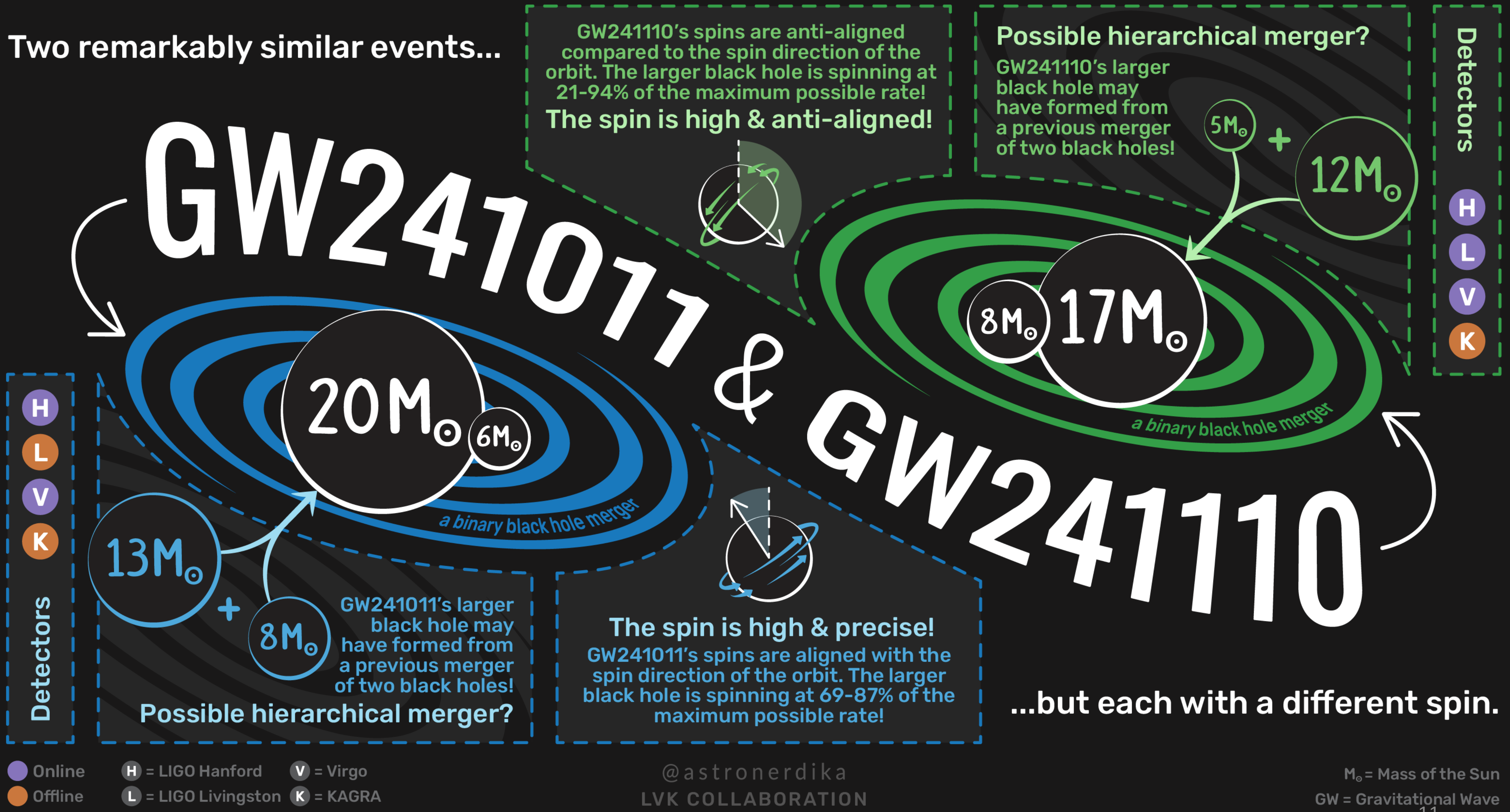
Primary object in lower mass gap

further supports that this region is not empty

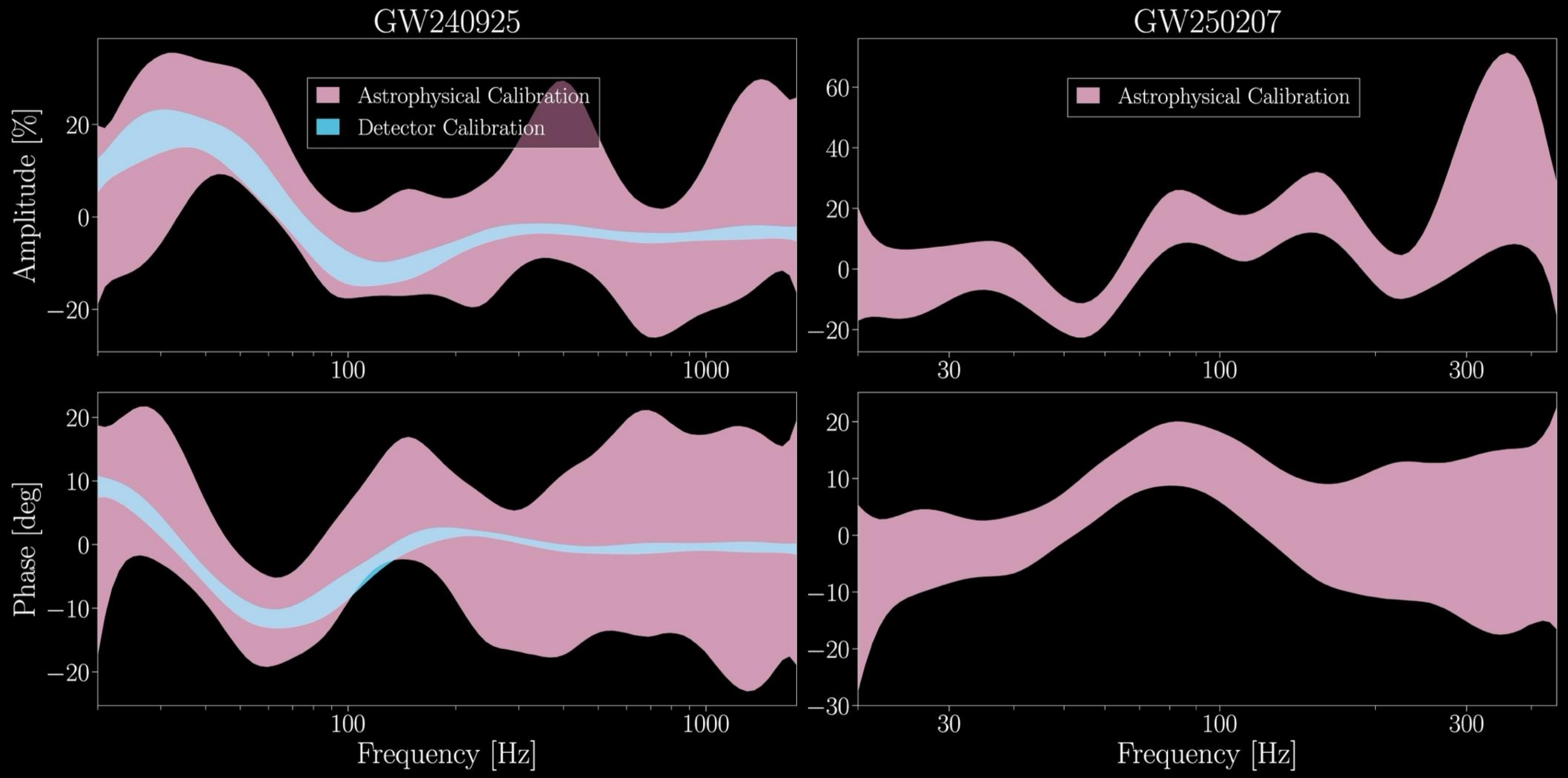


* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

LVK ApJL 2024
inc **SB** as paper manager


Two remarkably similar events...
GW241011 & GW241110
GW241110's spins are anti-aligned compared to the spin direction of the orbit. The larger black hole is spinning at 21-94% of the maximum possible rate!
The spin is high & anti-aligned!
Possible hierarchical merger?
GW241110's larger black hole may have formed from a previous merger of two black holes!
5M☉
+
12M☉
8M☉
17M☉
a binary black hole merger
Detectors
H
L
V
K
20M☉
6M☉
a binary black hole merger
13M☉
+
8M☉
GW241011's larger black hole may have formed from a previous merger of two black holes!
Possible hierarchical merger?
The spin is high & precise!
GW241011's spins are aligned with the spin direction of the orbit. The larger black hole is spinning at 69-87% of the maximum possible rate!
...but each with a different spin.
Online
Offline
H = LIGO Hanford
L = LIGO Livingston
V = Virgo
K = KAGRA
@astronerdika
LVK COLLABORATION
M☉ = Mass of the Sun
GW = Gravitational Wave

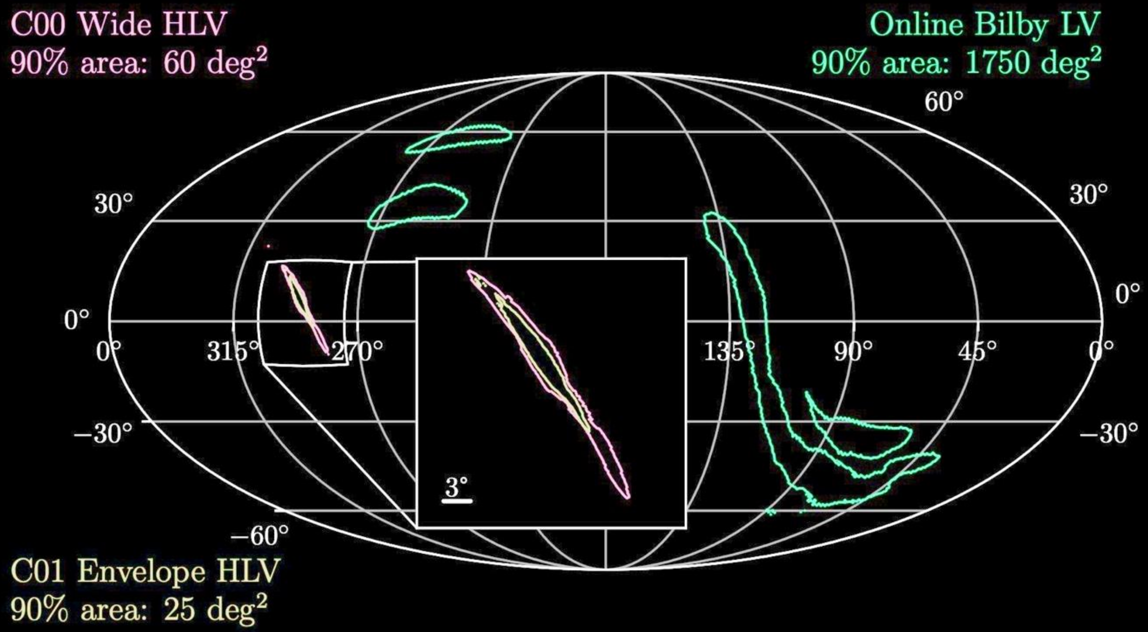
Astrophysical calibration of GW detectors



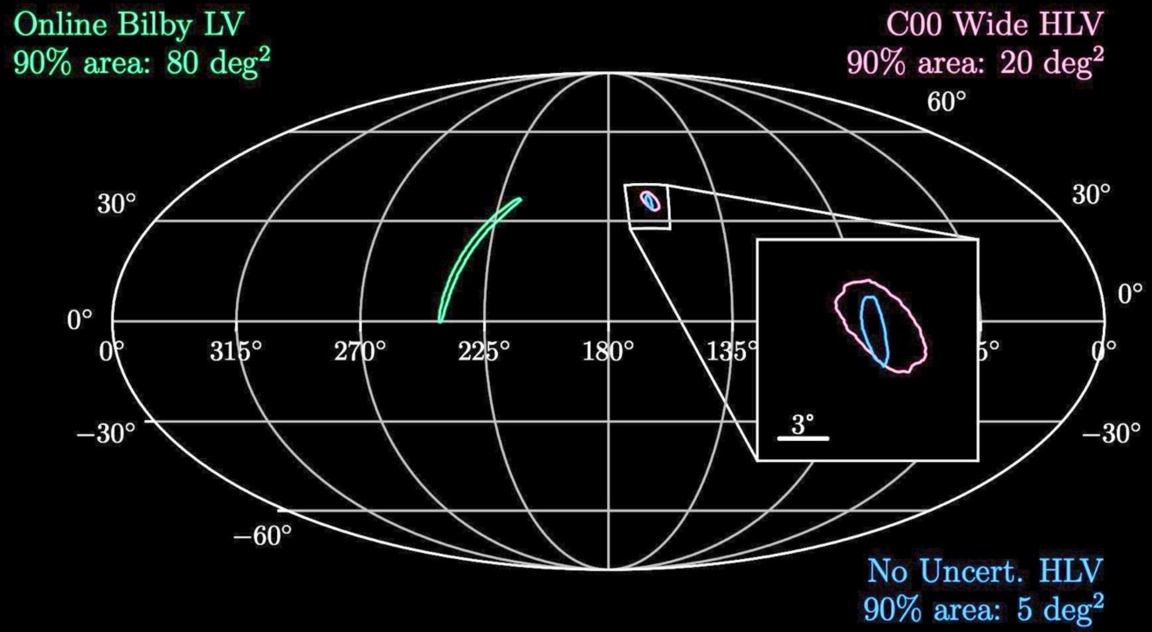
LVK PRL 2026
inc **SB** as lead analyst

Astrophysical calibration of GW detectors

GW240925

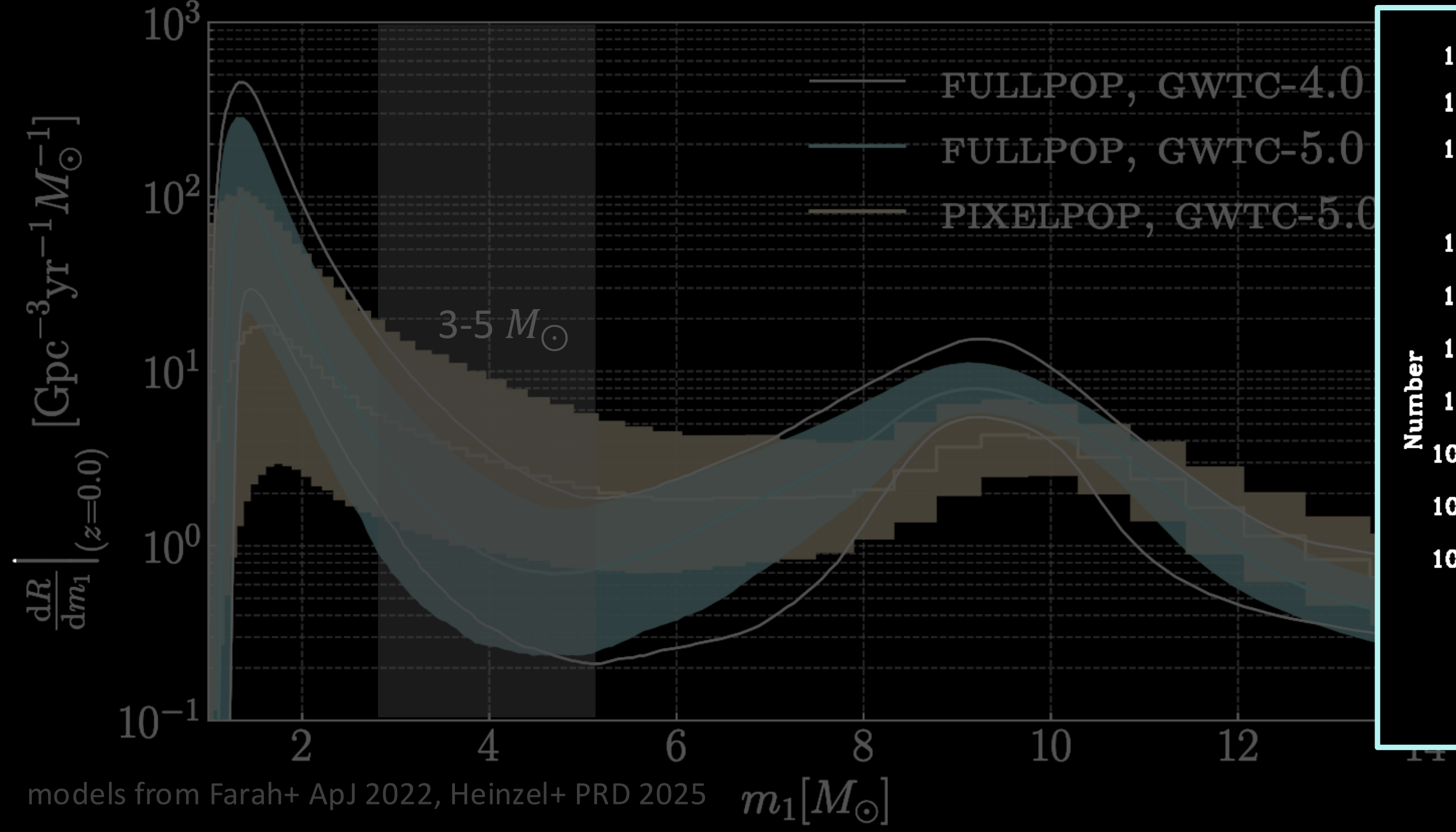


GW250207

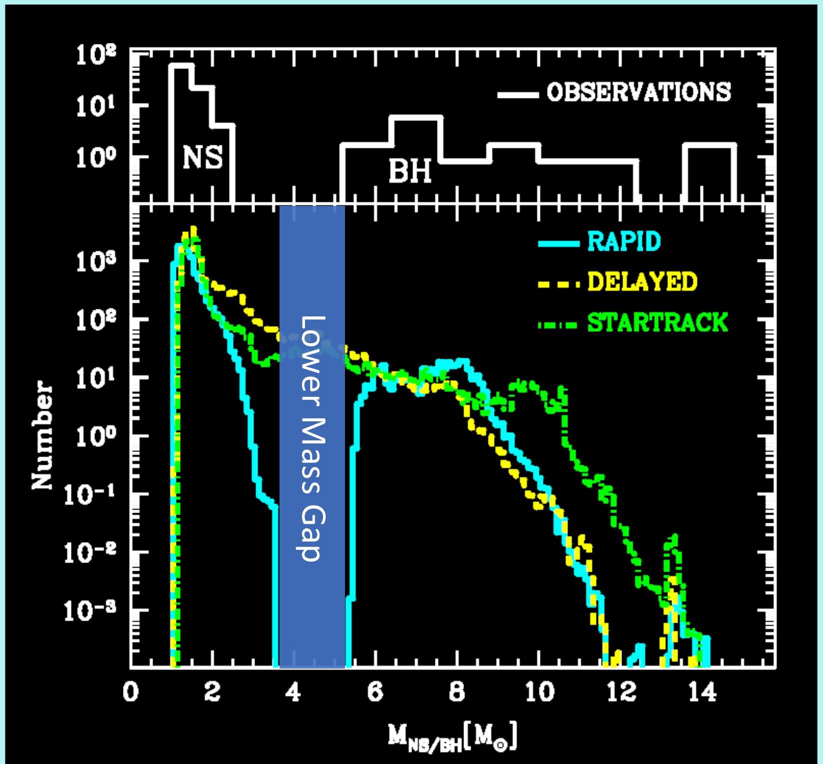


LVK PRL 2026
inc **SB** as lead analyst

Probing supernova physics with the lower mass gap between neutron stars and black holes



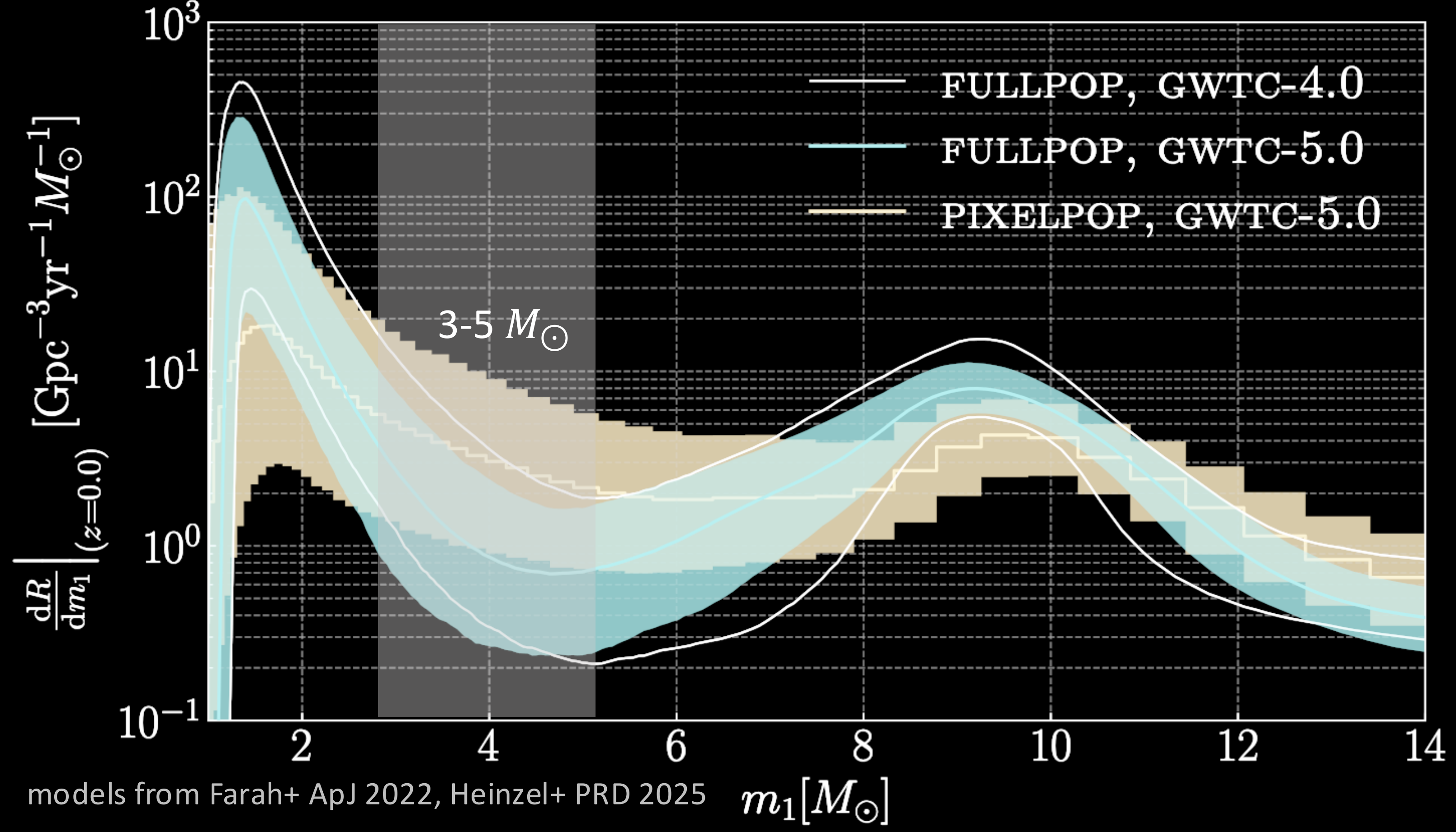
models from Farah+ ApJ 2022, Heinzel+ PRD 2025



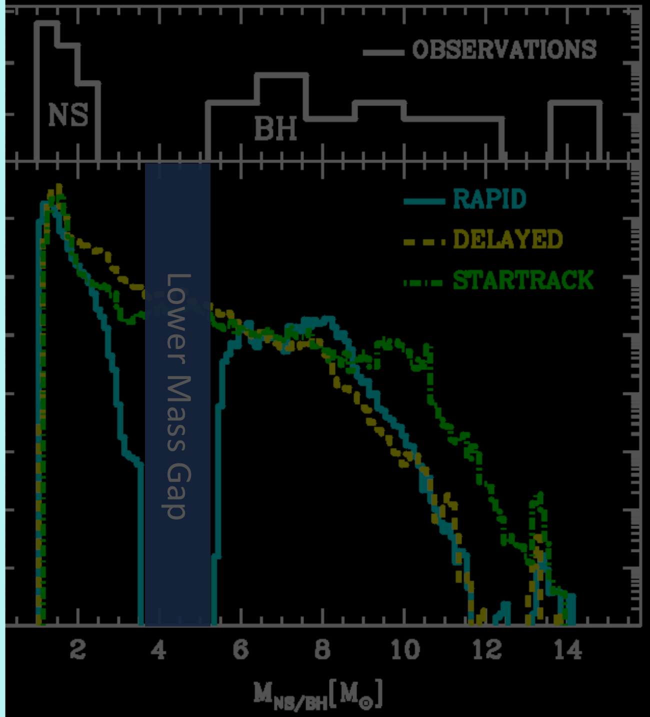
Belczynski + ApJ 2012

LVK 2605.27226

Probing supernova physics with the lower mass gap between neutron stars and black holes



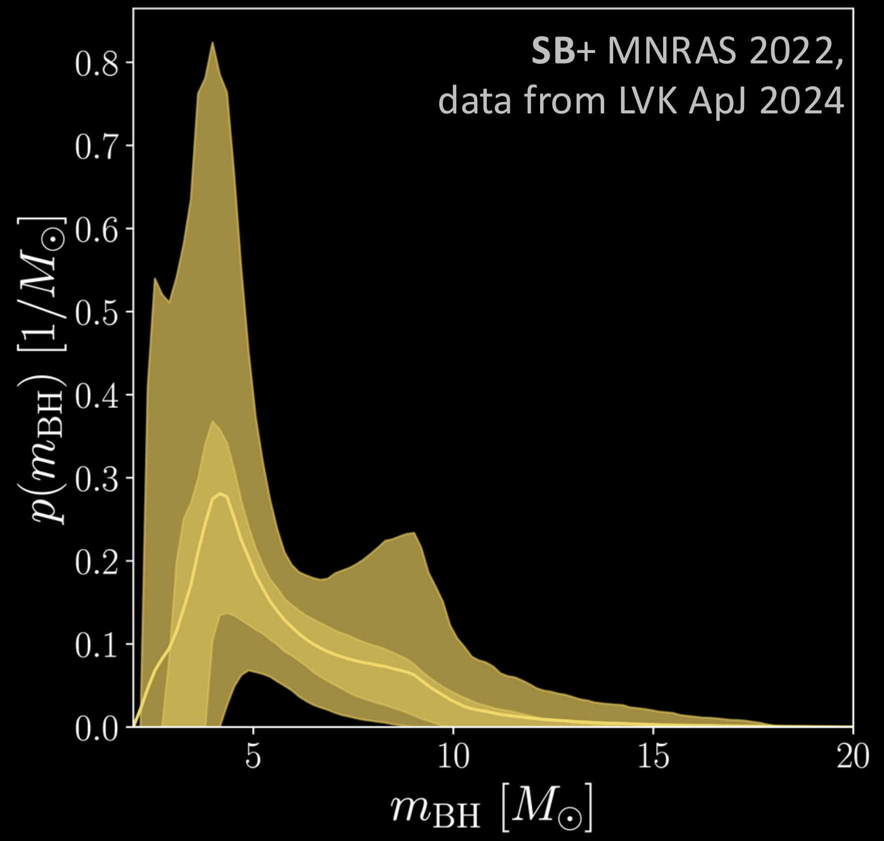
models from Farah+ ApJ 2022, Heinzel+ PRD 2025



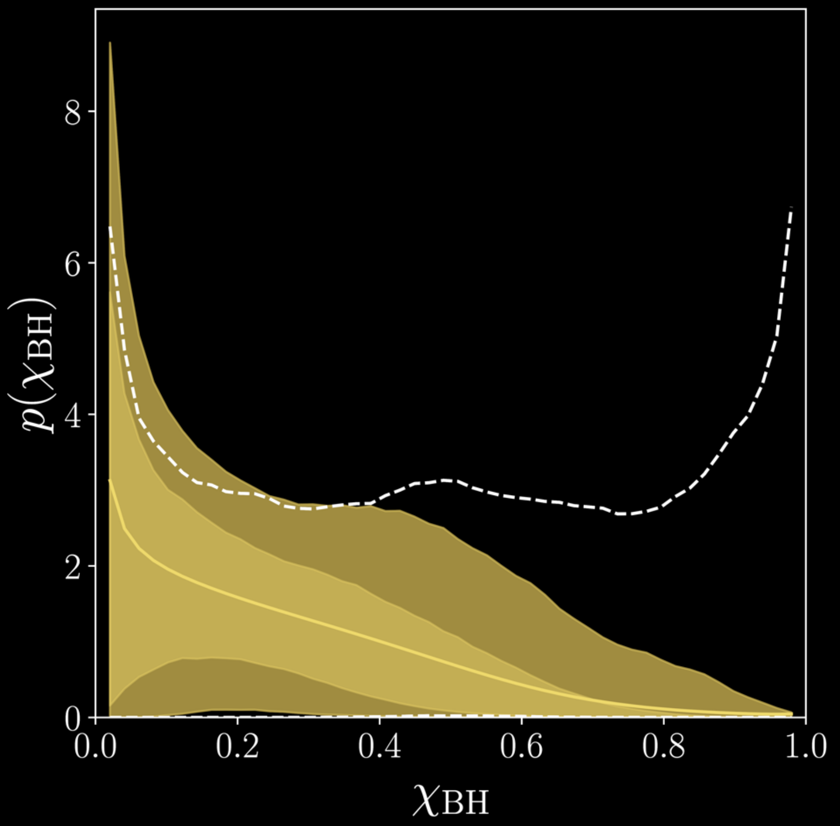
Belczynski + ApJ 2012

LVK 2605.27226

Black holes paired with neutron stars are less massive…



And likely more slowly spinning than those paired with black holes



Evolve from different stellar progenitors

Neutron star-black hole mergers are unlikely multimessenger sources

- < 18% with EM counterparts
  - Unequal mass ratios and low black hole spins

- < 2-20% of all short GRBs have NSBH progenitors

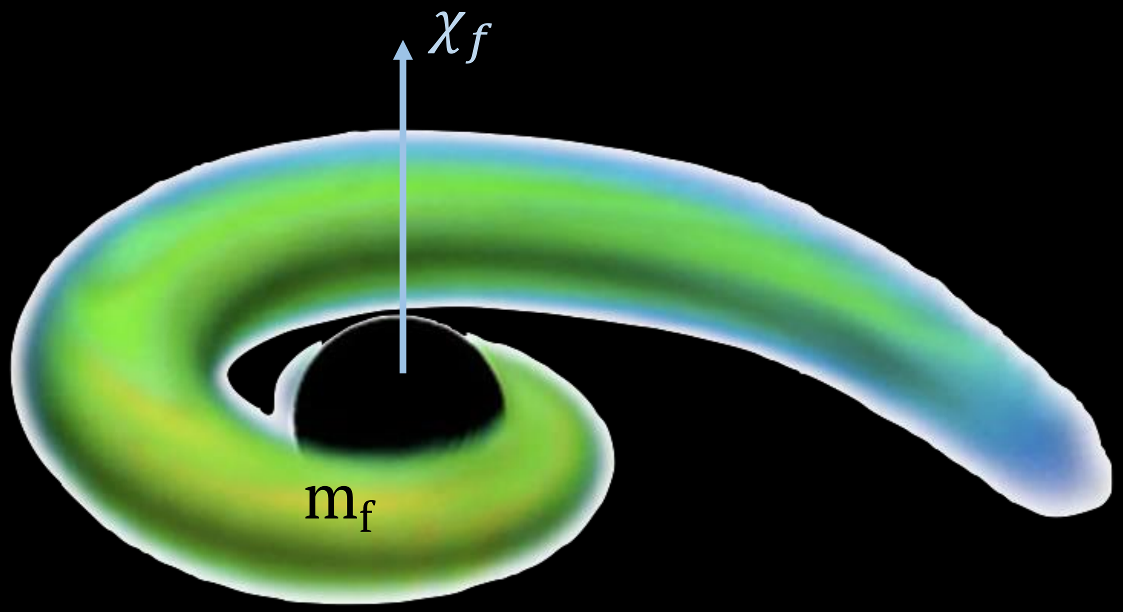
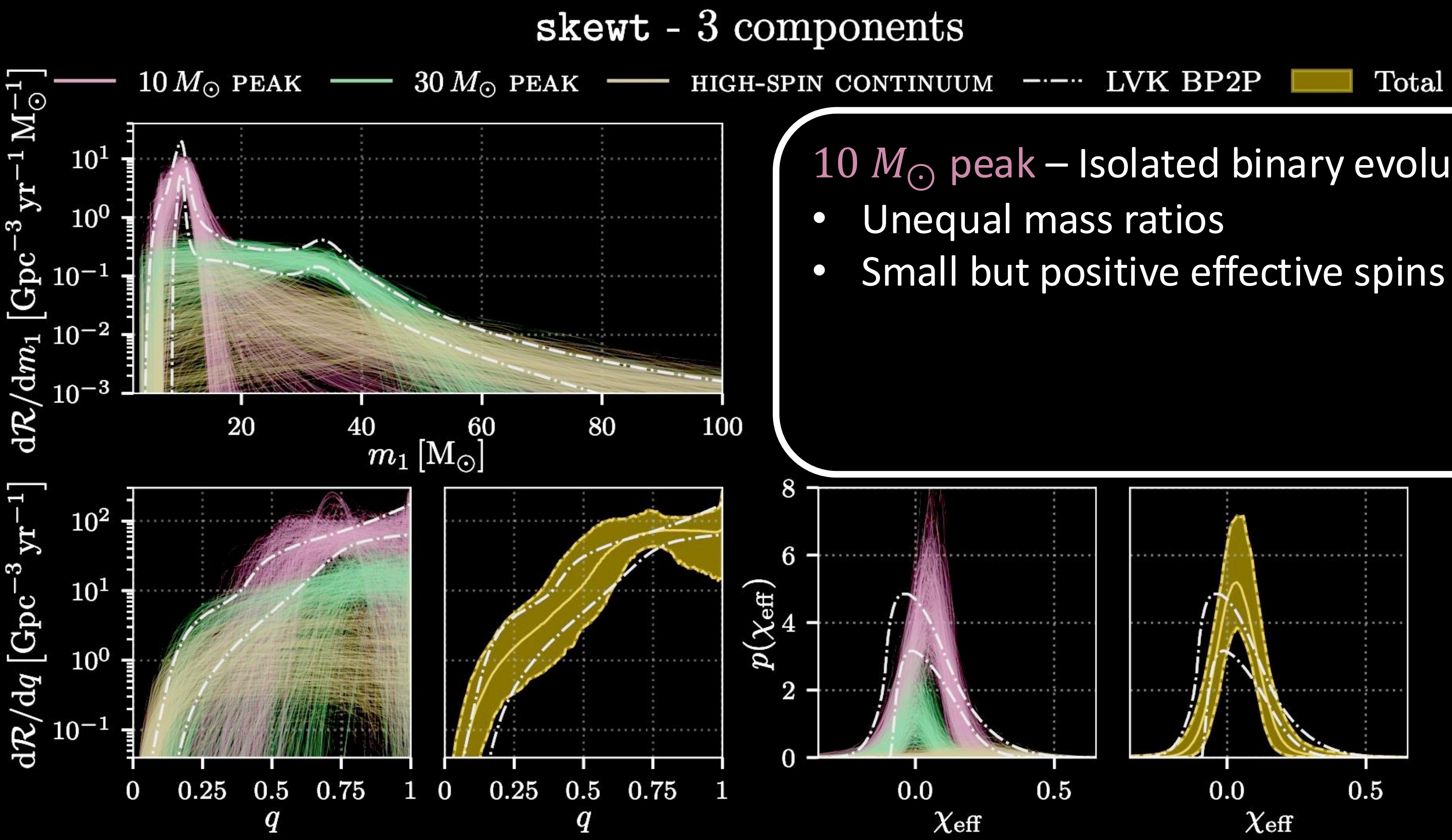


Image: Foucart FrASS 2020

LVK ApJ 2024
SB+ MNRAS 2022,
SB+ RNAAS 2023

Three subpopulations of binary black holes

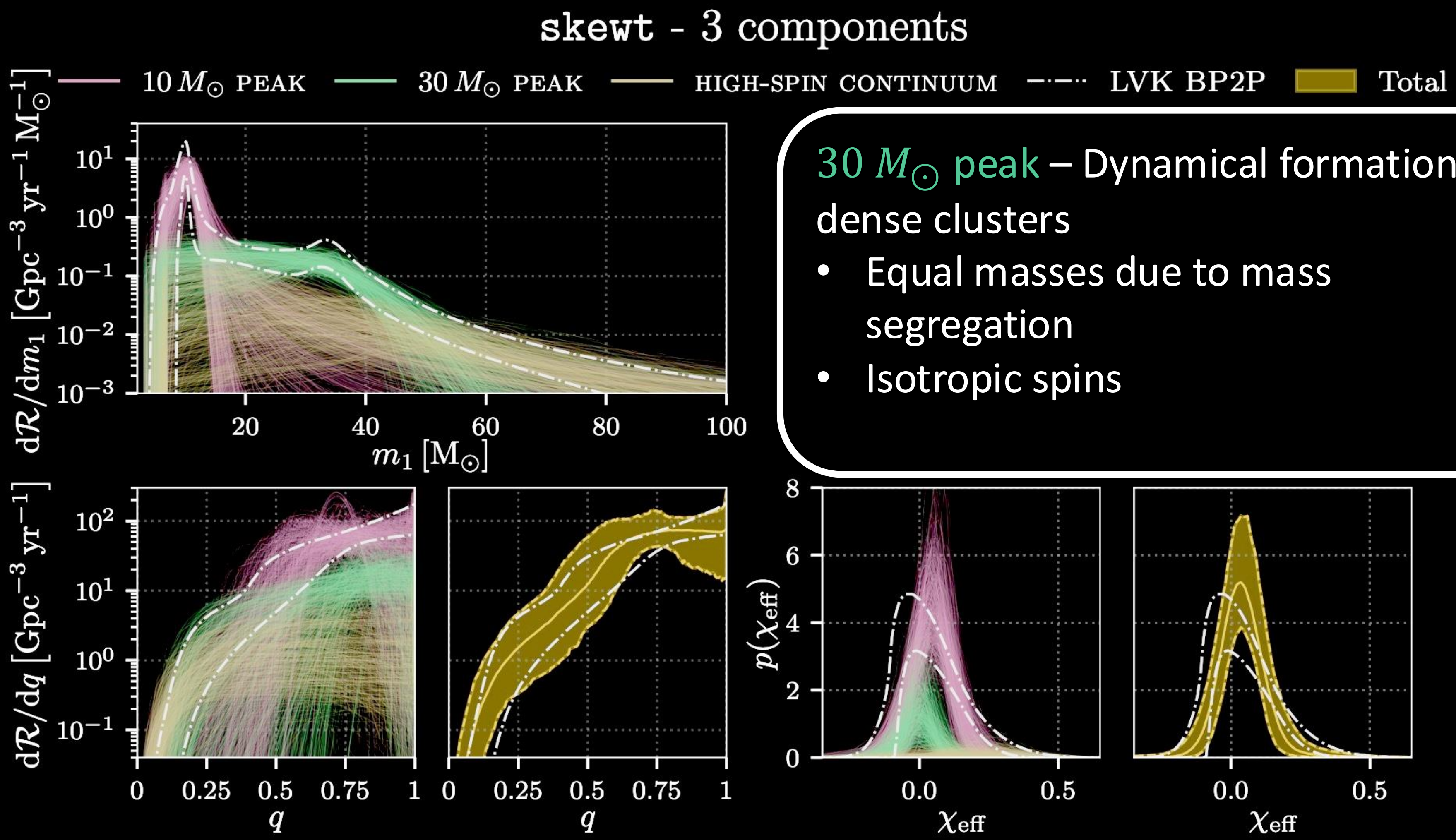


$10\ M_\odot$ peak – Isolated binary evolution

- Unequal mass ratios
- Small but positive effective spins

Cheng+ inc **SB** 2605.25980; see also Li+ ApJ 2024; Banagiri+ PRL 2026; Ray+ ApJL 2026; Galaudage 2026

Three subpopulations of binary black holes

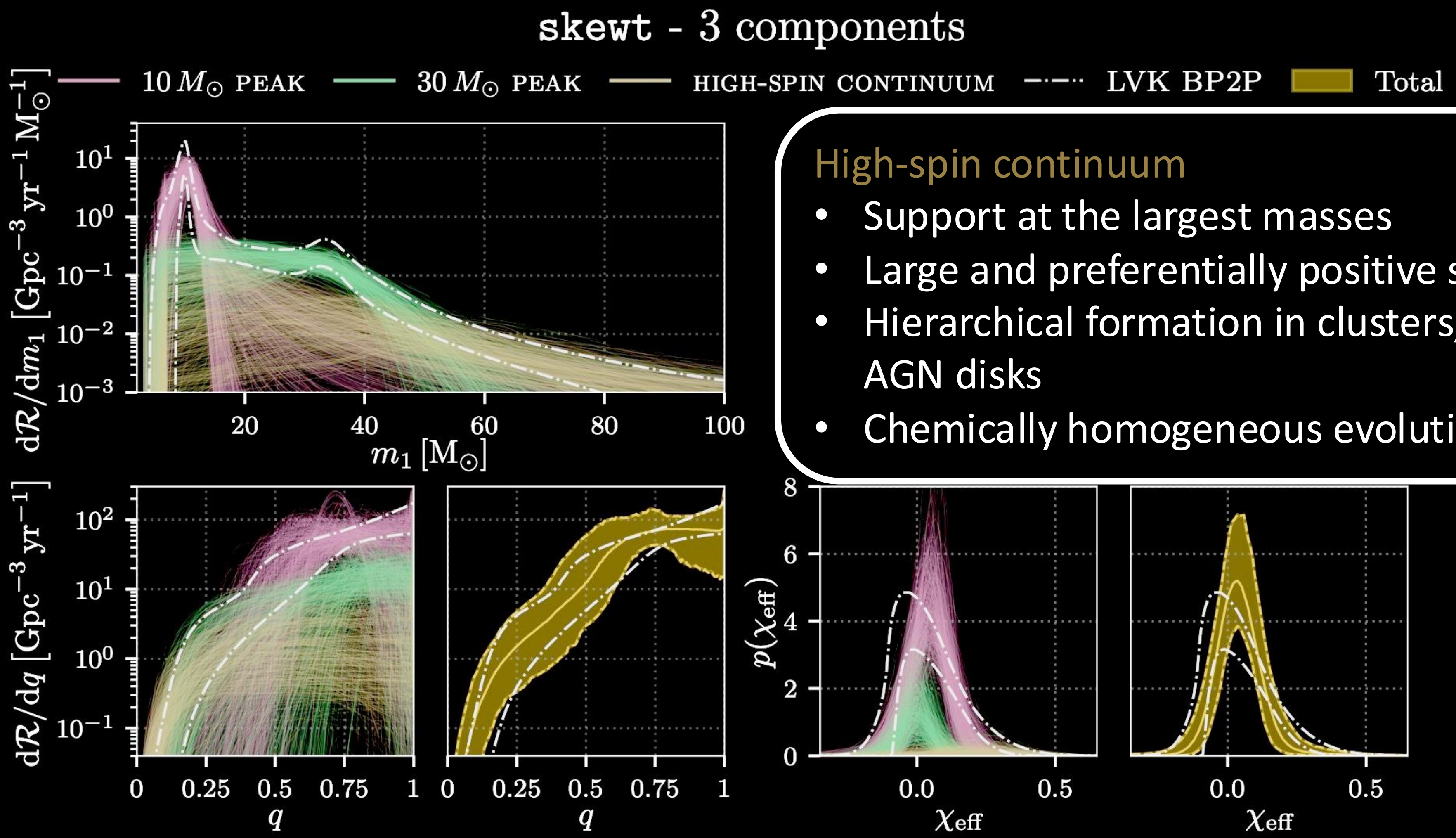


30 $M_\odot$ peak – Dynamical formation in dense clusters

- Equal masses due to mass segregation
- Isotropic spins

Cheng+ inc **SB** 2605.25980; see also Li+ ApJ 2024; Banagiri+ PRL 2026; Ray+ ApJL 2026; Galaudage 2026

Three subpopulations of binary black holes



High-spin continuum

- Support at the largest masses
- Large and preferentially positive spins
- Hierarchical formation in clusters, AGN disks
- Chemically homogeneous evolution

Cheng+ inc **SB** 2605.25980; see also Li+ ApJ 2024; Banagiri+ PRL 2026; Ray+ ApJL 2026; Galaudage 2026

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Summary

- Supernova physics: No evidence for lower mass gap between neutron stars and black holes
- Multimessenger prospects
  - BNS are rarer than expected based on earlier observations
  - NSBH mergers are unlikely multimessenger sources
- Formation channels: (At least) three subpopulations of binary black holes including isolated and dynamical evolution

Backup

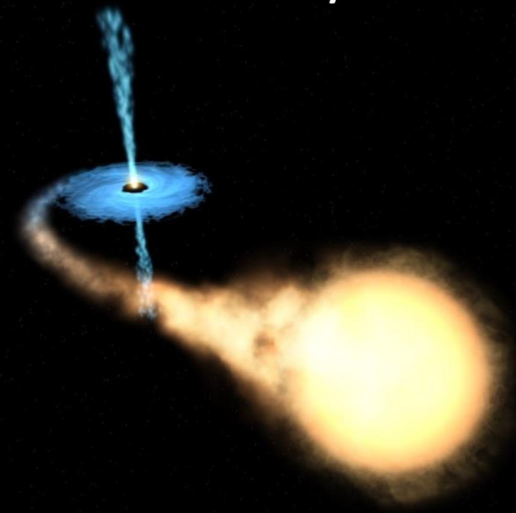
The fates of massive stars

Neutron stars

- Progenitors initially $\sim 9 - 25\ M_\odot$
- $m \sim 1.5\ M_\odot,\ R \sim 10\ \mathrm{km}$
- Unknown equation of state
- Observed as pulsars

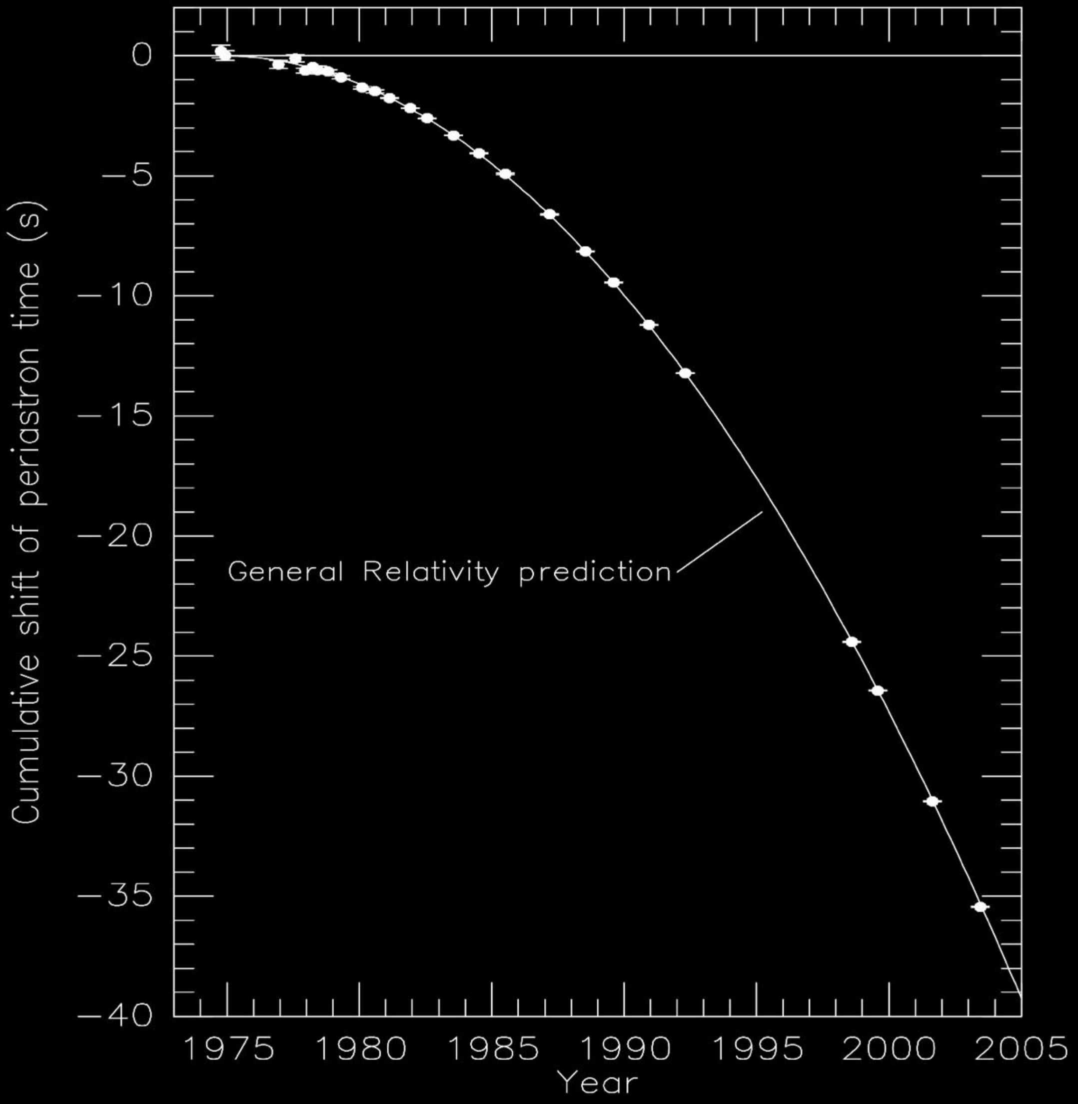
Black holes

- Progenitors initially $\gtrsim 25^*\ M_\odot$
- $m \gtrsim 5\ M_\odot$
- No hair
- Observed as X-ray binaries



Indirect evidence

- Hulse-Taylor Binary discovered in 1974
  - First binary pulsar
  - First binary neutron star
- Rate of orbital decay confirmed to be consistent with prediction from the emission of gravitational waves in 1979

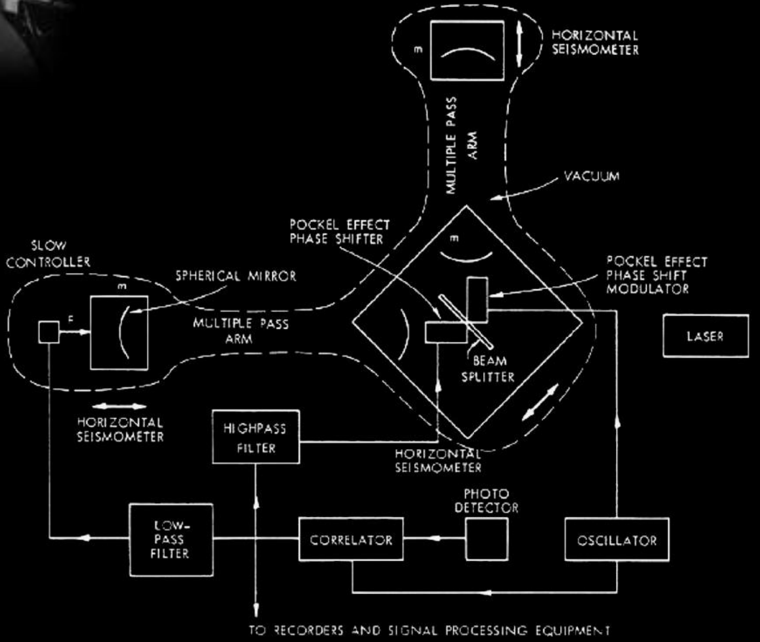


Weisberg & Taylor, ISP Conf Ser 2004
Taylor & Weisberg ApJ 1982
Taylor, Fowler, McCulloch Nature 1979

Gravitational-wave detection

1960s – Joe Weber develops the resonant bar detector and claims to detect gravitational waves

1970s – first interferometric gravitational-wave detectors proposed
1984 – Ron Drever, Rai Weiss, and Kip Thorne found LIGO



Weiss Tech Report 1972

- 1990 – NSF approves LIGO construction
- 2002-2010 – First searches for gravitational waves using initial LIGO (six science runs)
- 2008 – NSF approves funding for Advanced LIGO
- 2015 – Advanced LIGO observing begins

What can we learn with gravitational waves?

Fundamental Physics:

Strong-field tests of General Relativity

Neutron star equation of state

Cosmology:

Measurement of ΛCDM parameters

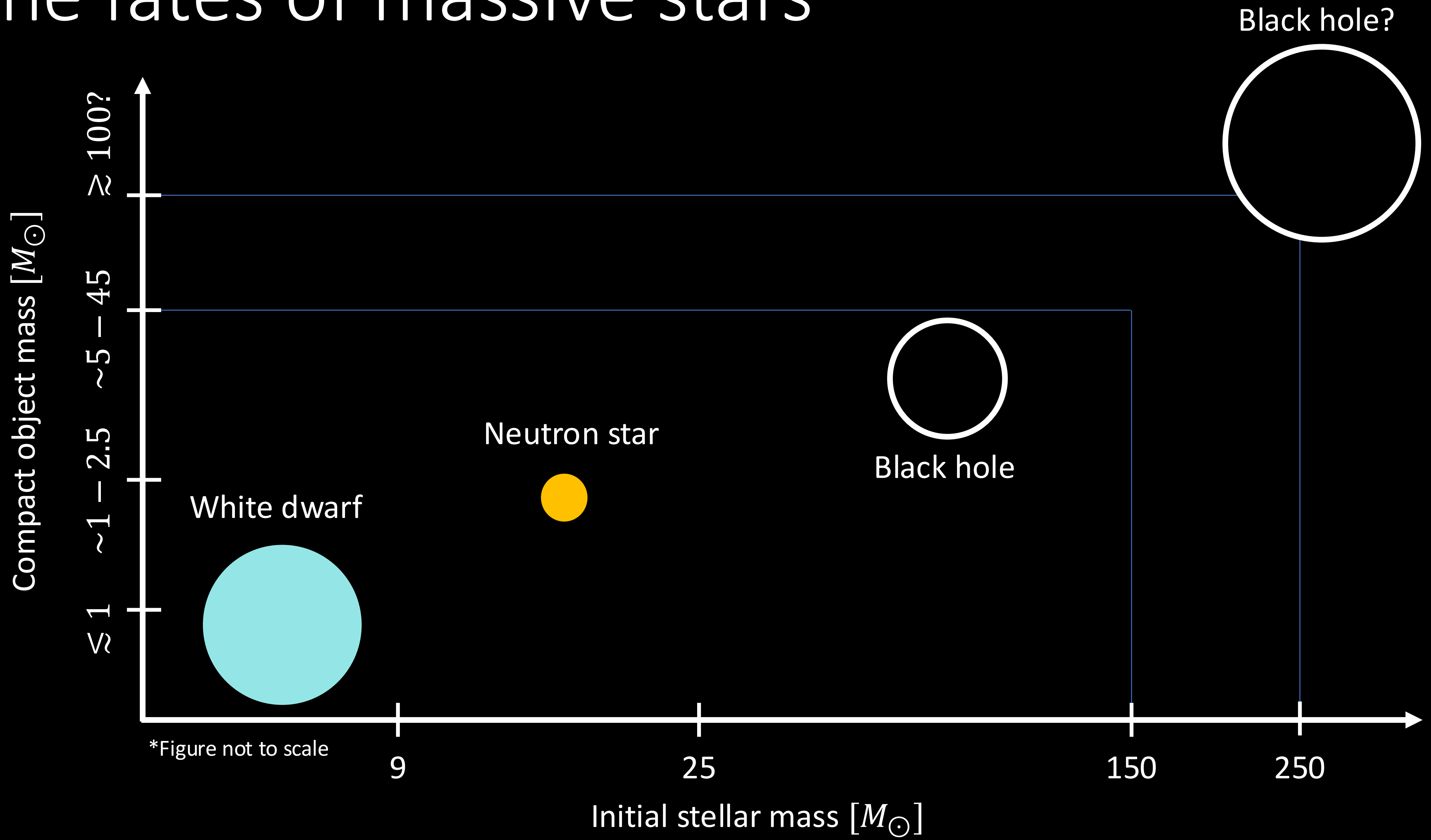
Early-universe phenomena

Astrophysics:

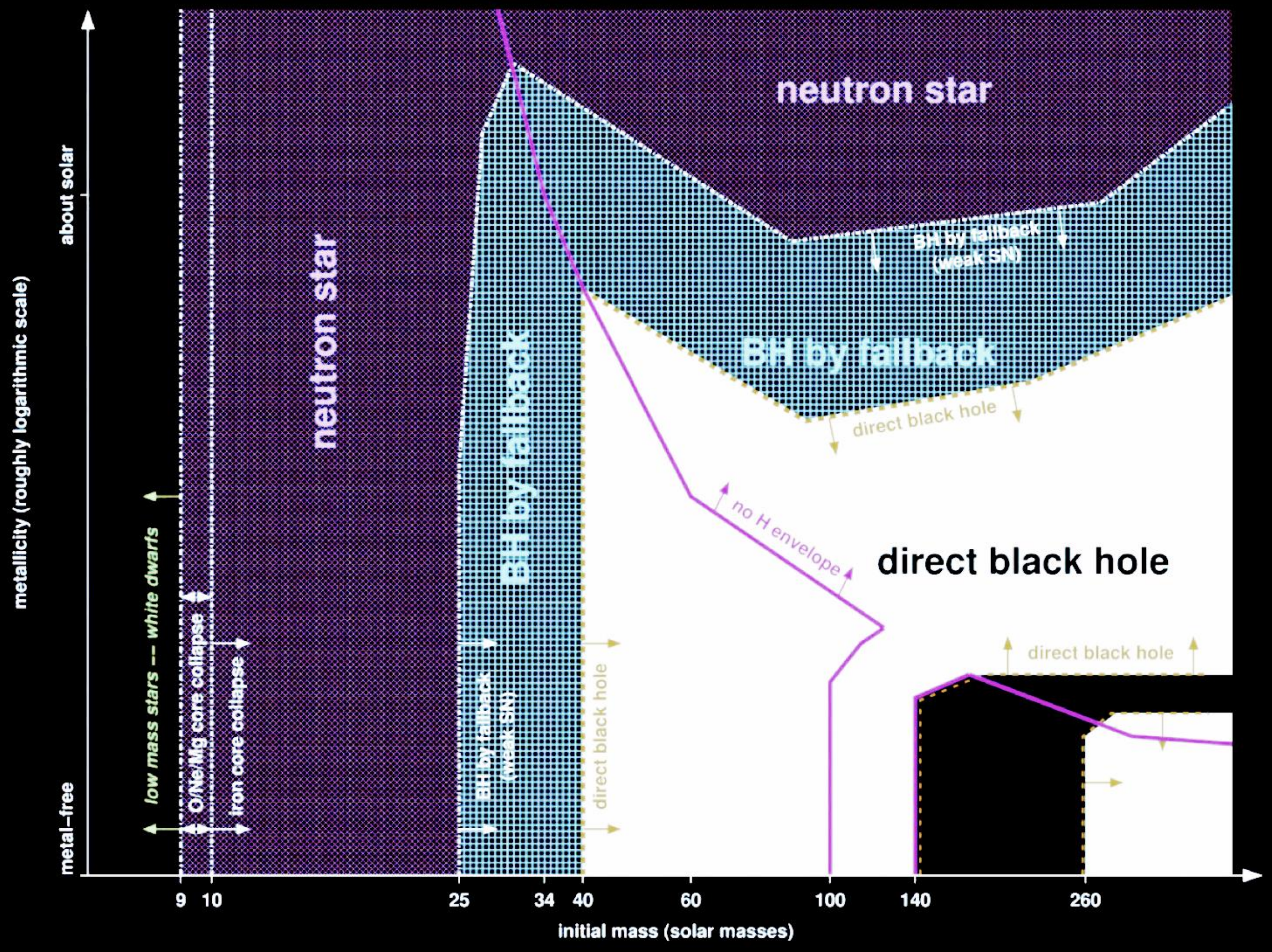
Binary formation and evolution

Supernova physics

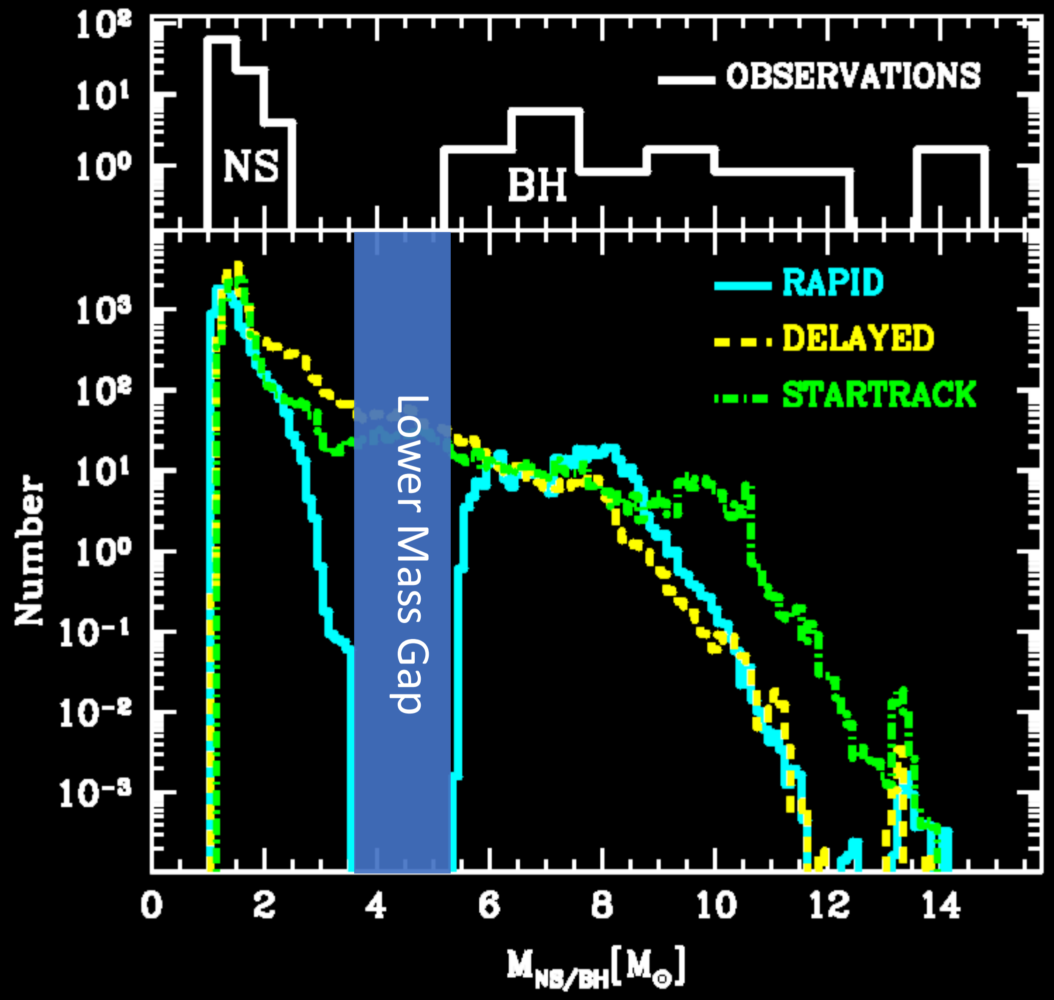
The fates of massive stars



The fates of massive stars



Heger + 2003



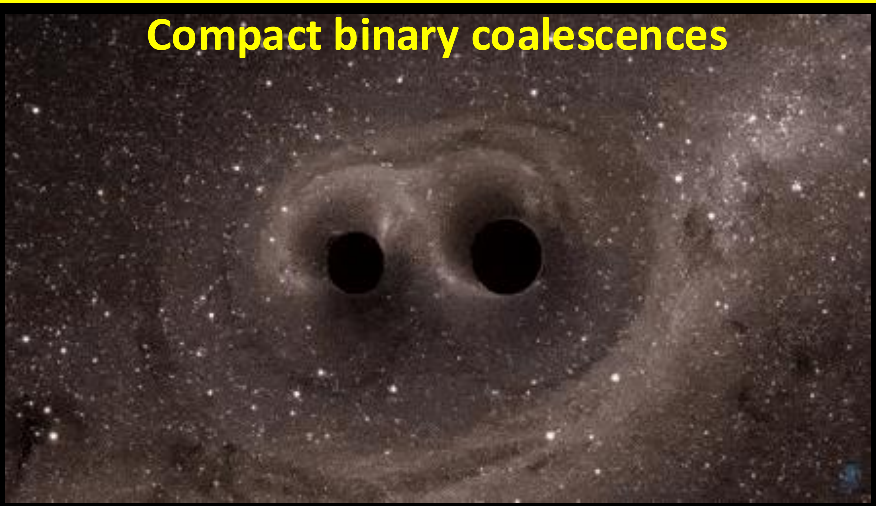
Belczynski + 2011

Sources of gravitational waves

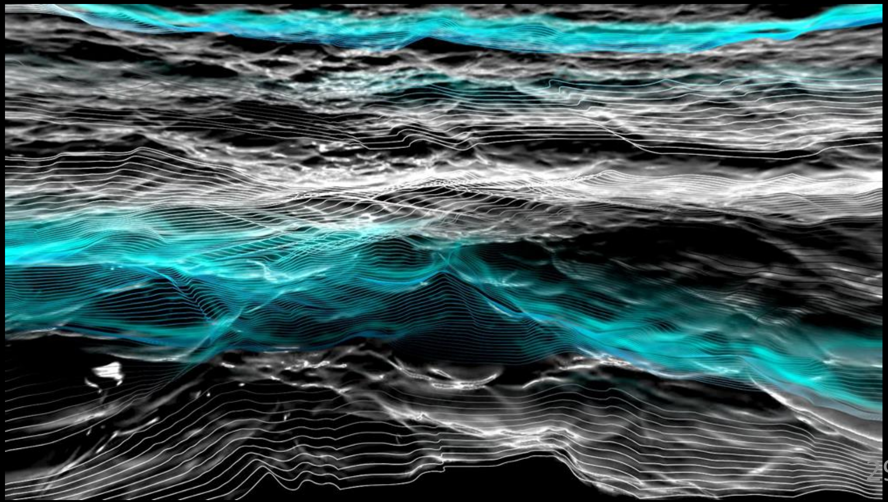
Modeled

Unmodeled

Transient

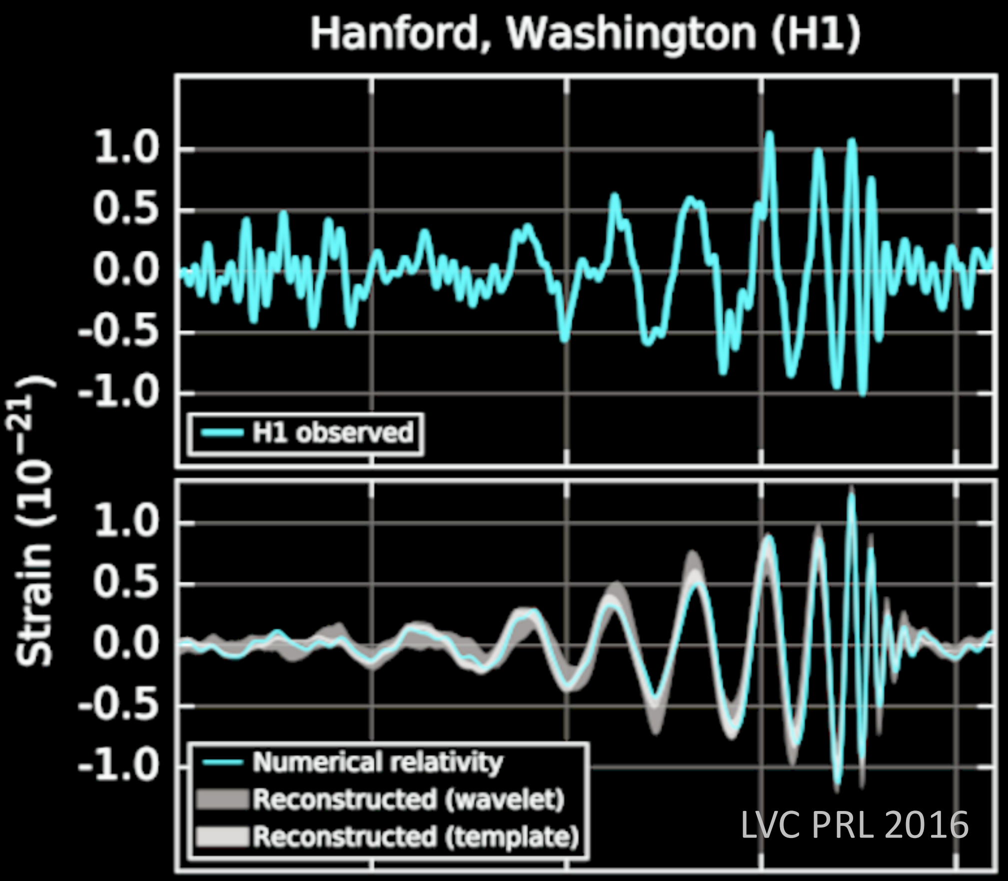


Persistent



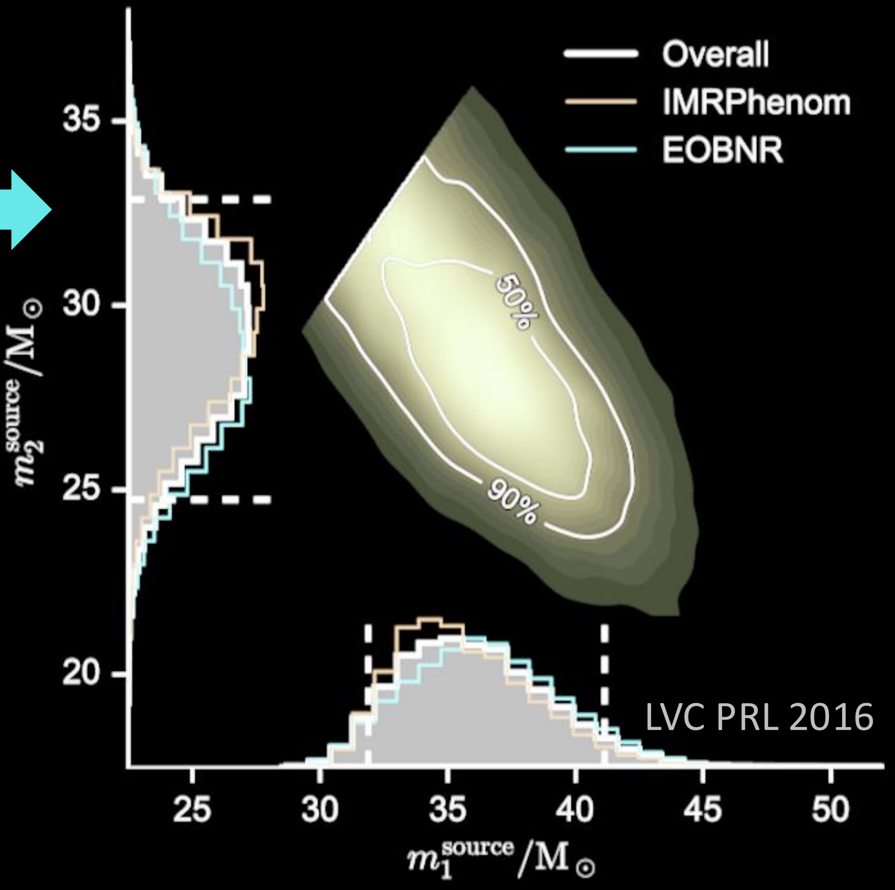
How do we go from…

Strain



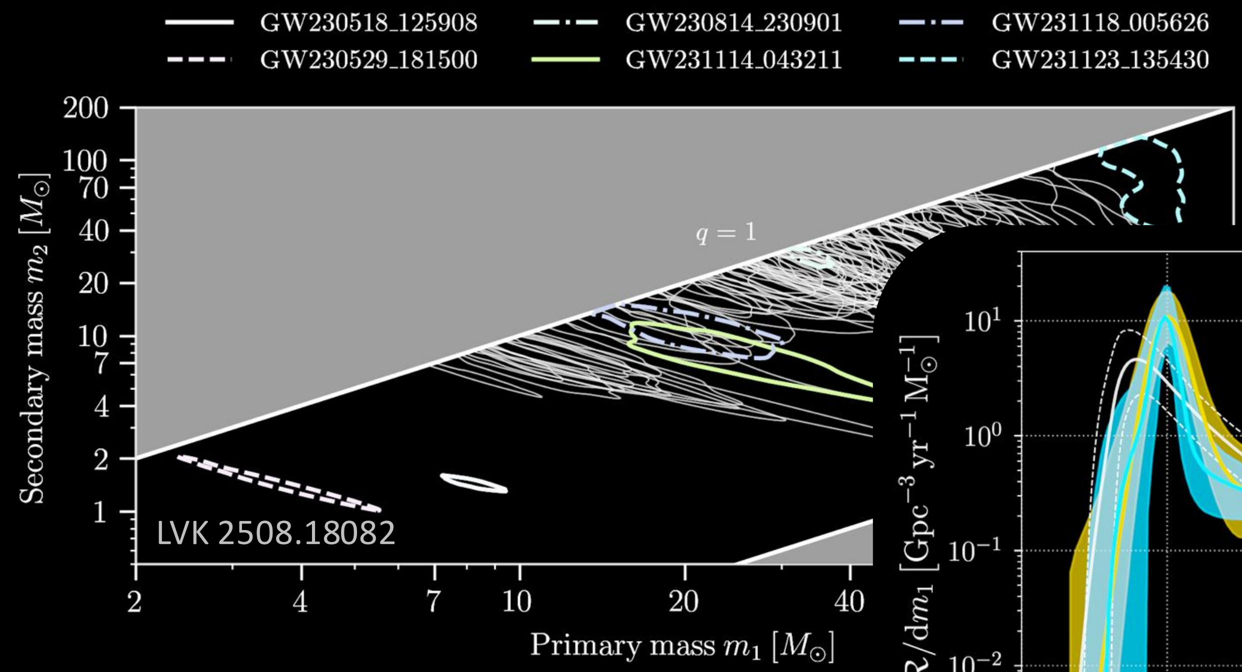
Time

To individual-event parameters?

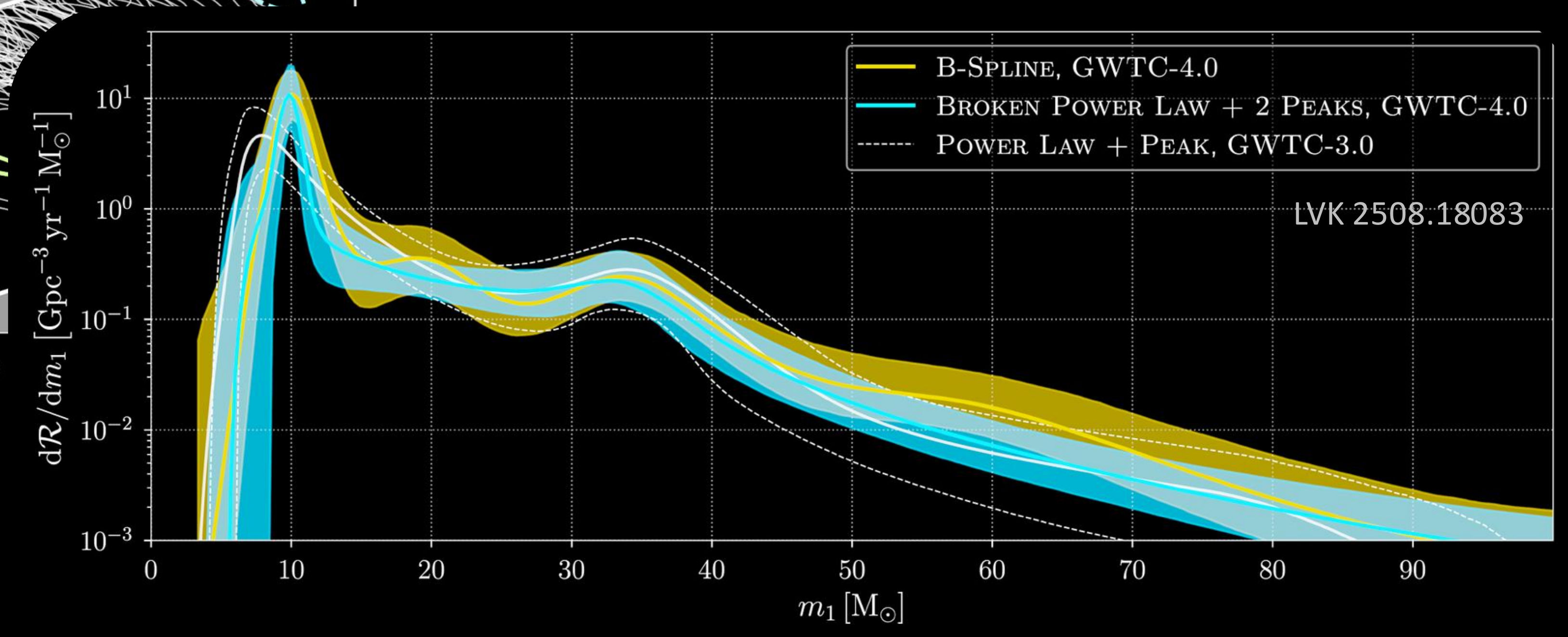


And then from…

Individual-event parameters



To population properties (astrophysics)?



Detection and parameter estimation

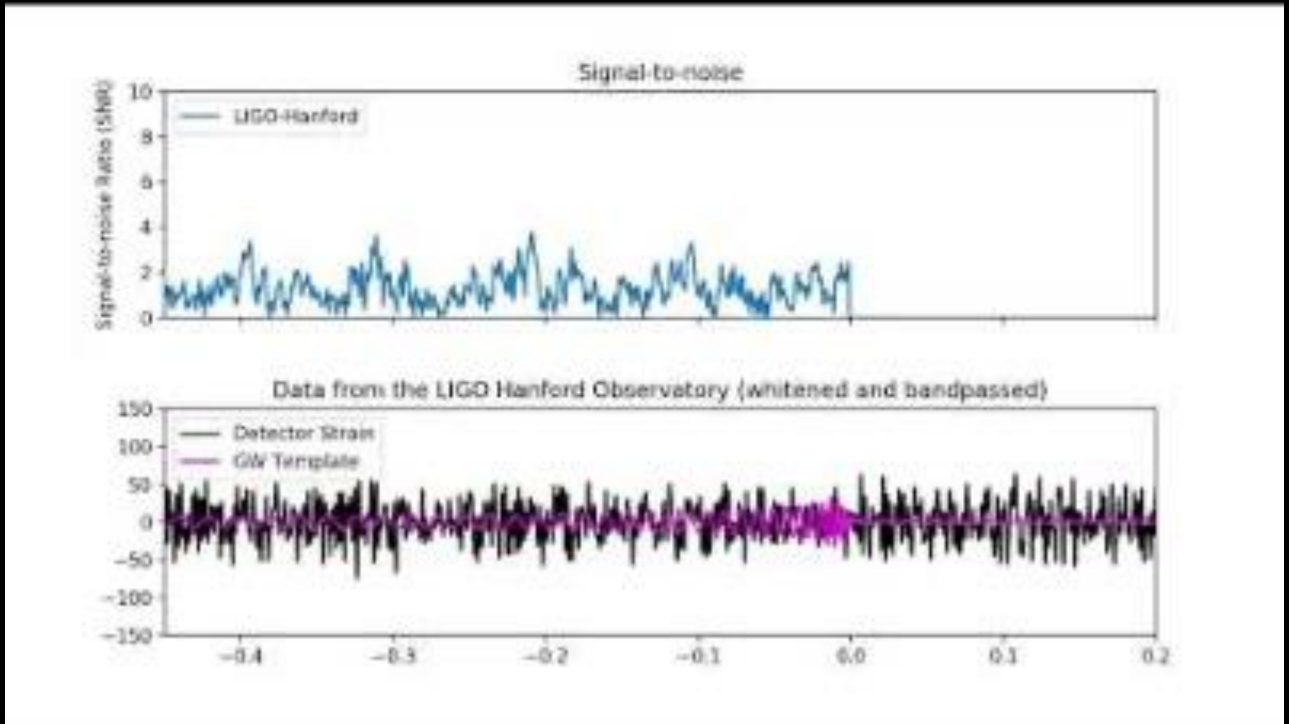
- Matched filtering – compare gravitational-wave signals from a fixed template bank to the strain data, maximize the “match”
  - Best match gives us a point estimate for the binary parameters
  - LVK 2508.18081, Allen+ PRD 2012

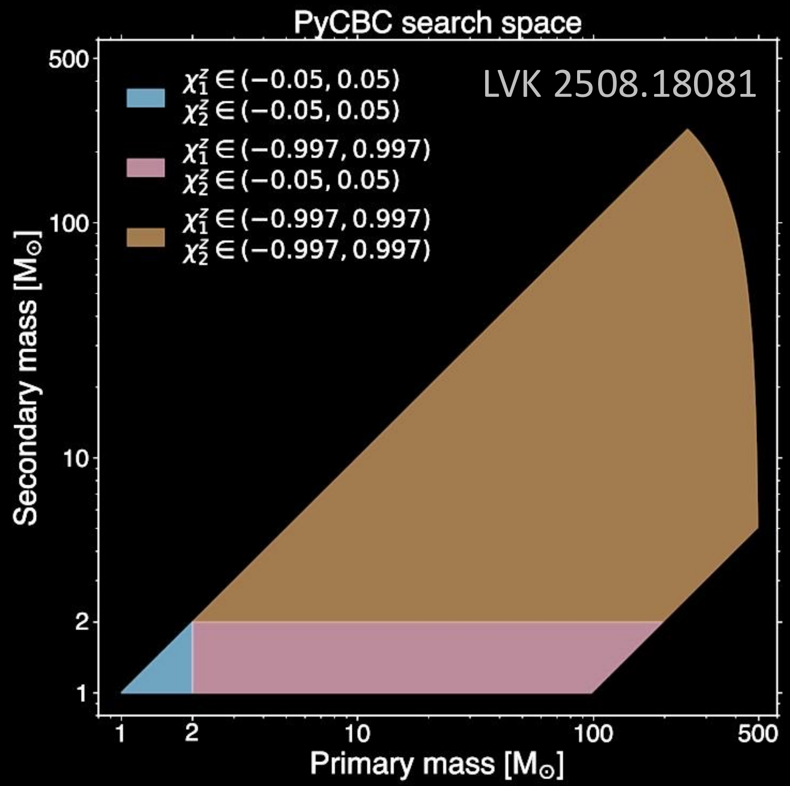
- Use Bayesian inference to sample across the whole 17-dimensional binary parameter space and obtain posterior probability distributions
  - Christensen & Meyer, RvMP 2022
  - Thrane & Talbot, PASA 2019

Ashton+ (inc **S. Biscoveanu**) ApJS 2019
Romero-Shaw, Talbot, **S. Biscoveanu**+ MNRAS 2020

Gravitational-wave detection

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





Parameter estimation

- Matched filtering gives us a point estimate for the binary parameters
  - Template bank does not include all relevant physics (tidal deformability, spin precession)
- Use Bayesian inference to sample across the whole 15-dimensional binary parameter space and obtain posterior probability distributions

likelihood prior

posterior

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

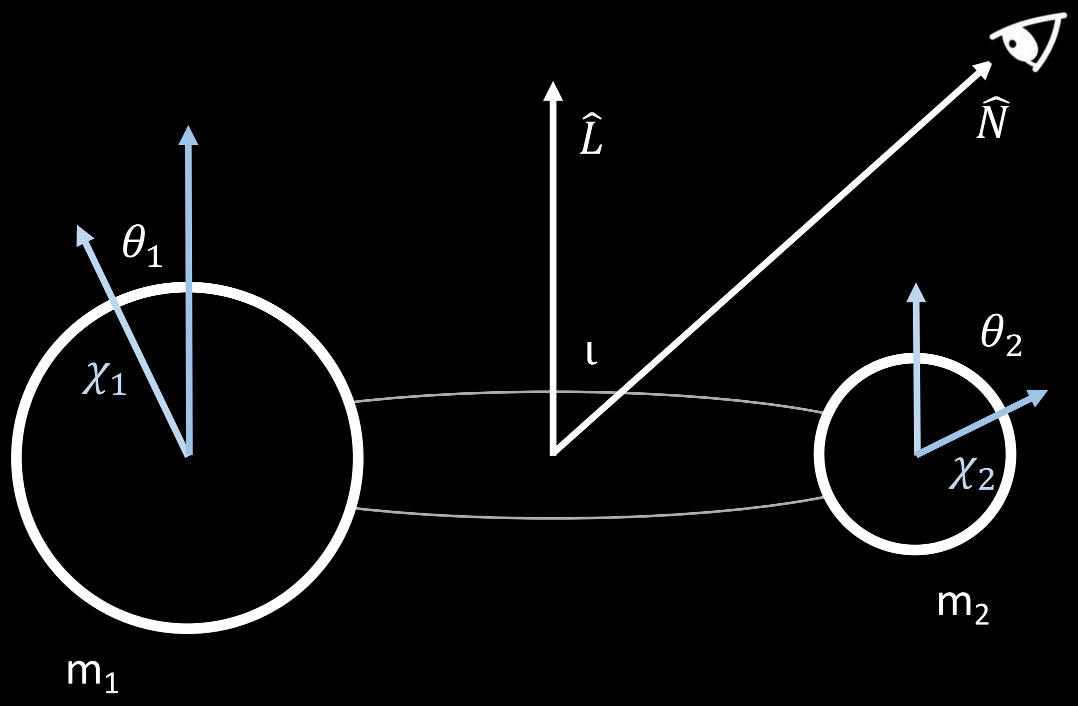
evidence

parameters data model

Veitch+ PRD 2015; Cornish & Littenberg CQG 2015; Ashton+ ApJS 2019; Romero-Shaw+ MNRAS 2020

Compact object binary parameters

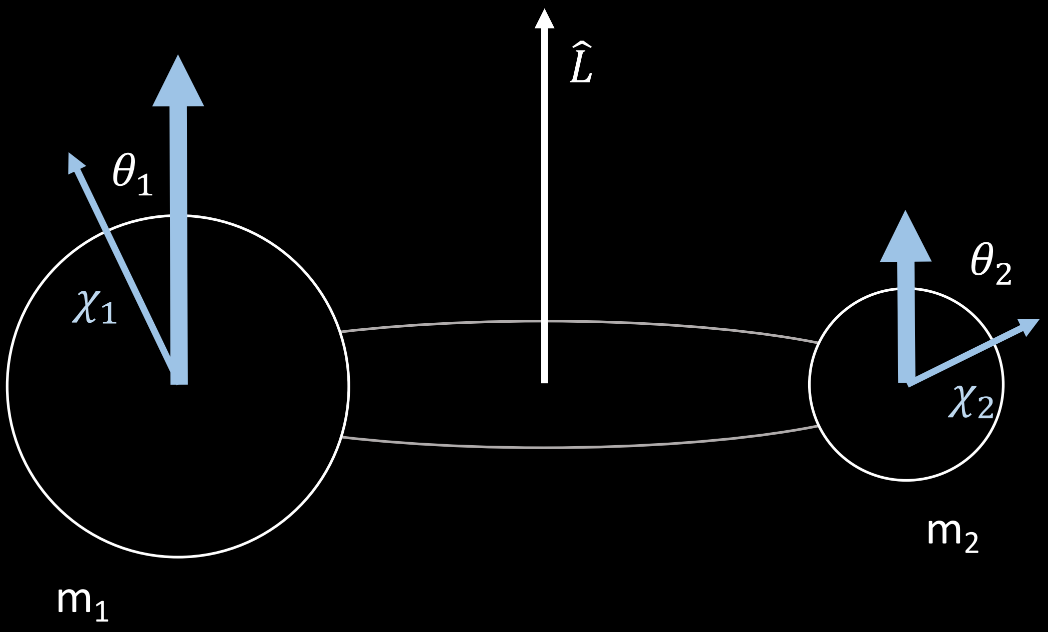
- Mass
- Spin – parameterized in terms of:
    - Dimensionless spin magnitude
    - Tilt angle relative to orbital angular momentum
    - Azimuthal angle
- Tidal deformability
    - depends on neutron star equation of state
- Extrinsic parameters
    - Sky position
    - Distance (redshift)
    - Inclination angle relative to observer
    - Time, phase, and polarization at coalescence



Spin Parameters

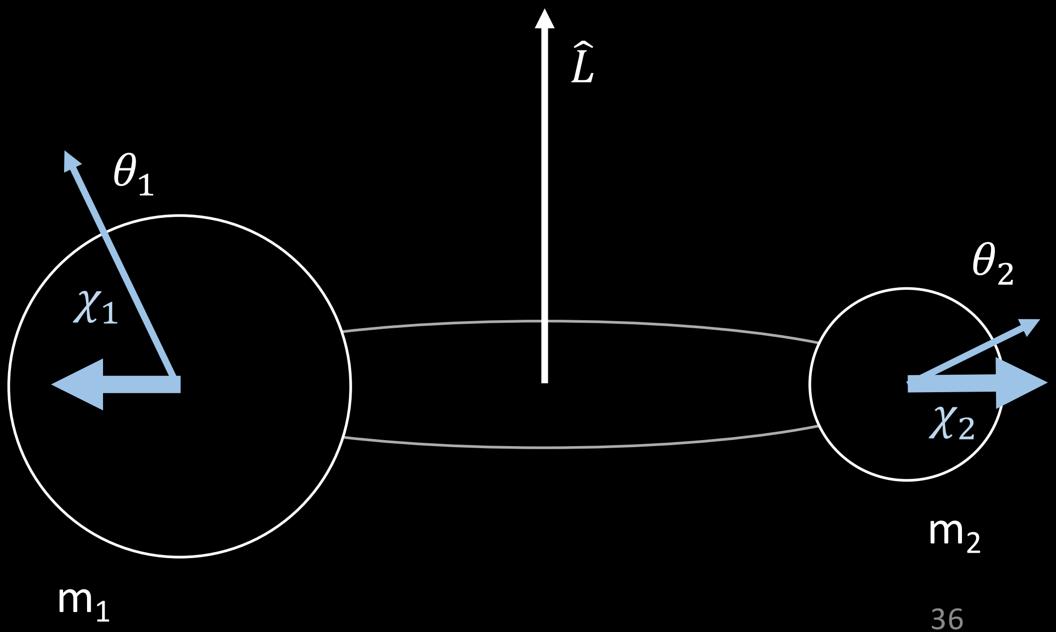
- χ_{eff} - best measured spin parameter with gravitational waves, mass-weighted spin aligned with the orbital angular momentum

$$\chi_{\text{eff}} = \frac{\chi_1 \cos\theta_1 + q\chi_2 \cos\theta_2}{1+q}$$



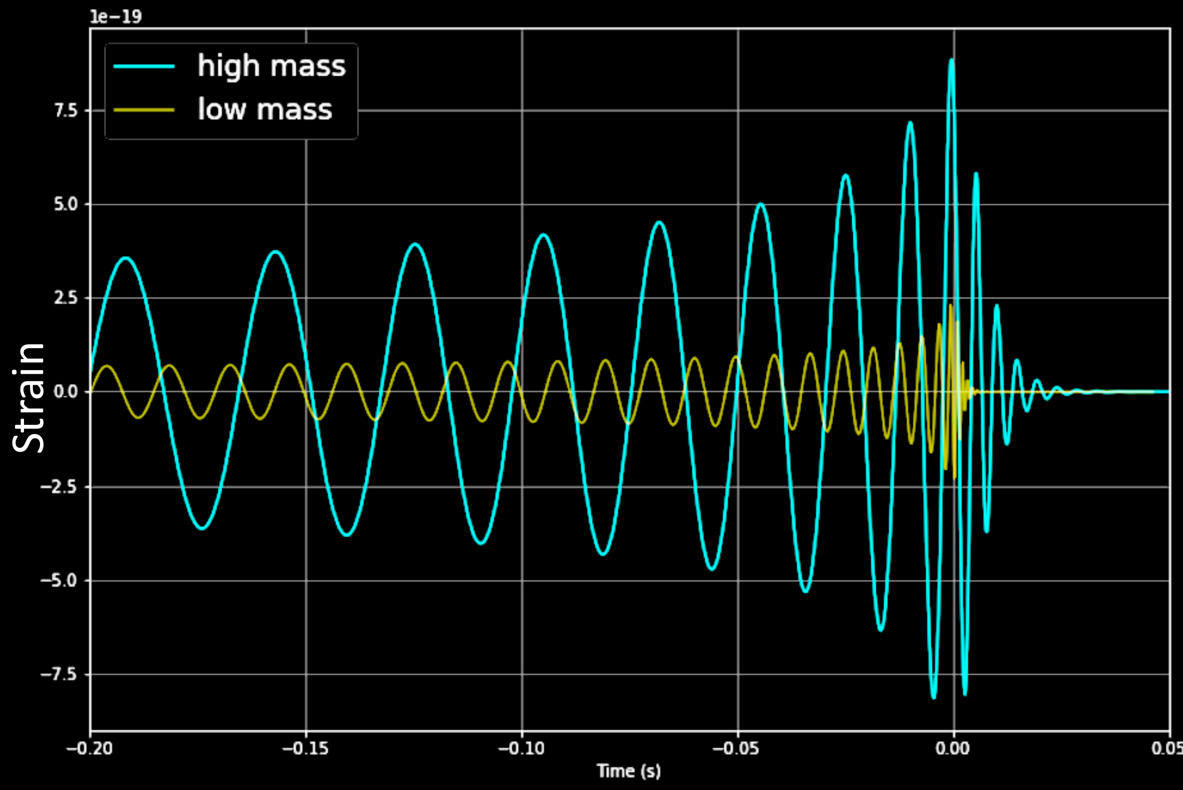
- χ_p - effective precessing spin, mass-weighted spin projection onto the orbital plane

$$\chi_p = \max\left(\chi_1 \sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q\chi_2 \sin\theta_2\right)$$



The gravitational-wave signal

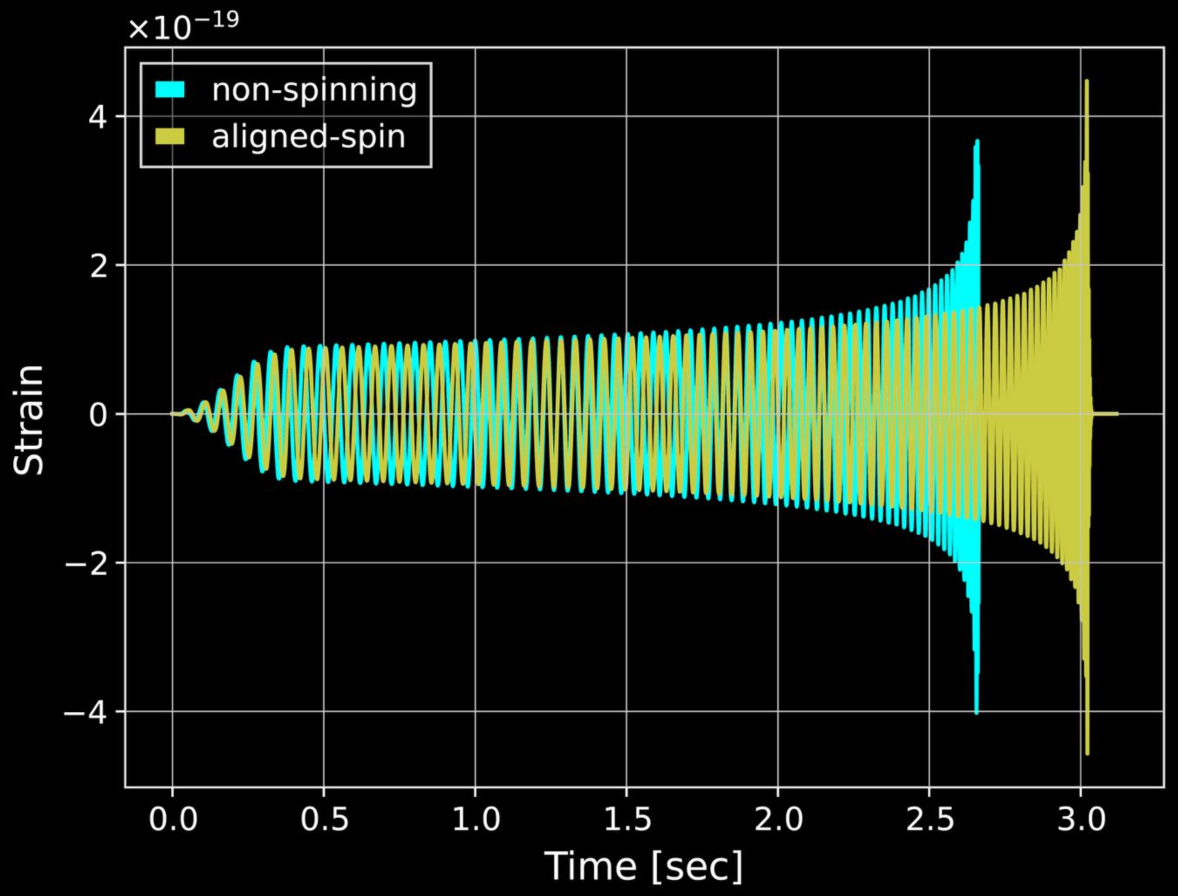
- General relativity predicts a unique gravitational "waveform" for each set of binary parameters
- Amplitude and frequency both increase in time as merger approaches
- More massive systems merge at lower frequency → spend less time in LIGO's sensitive band
- More massive, larger amplitude at fixed distance



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

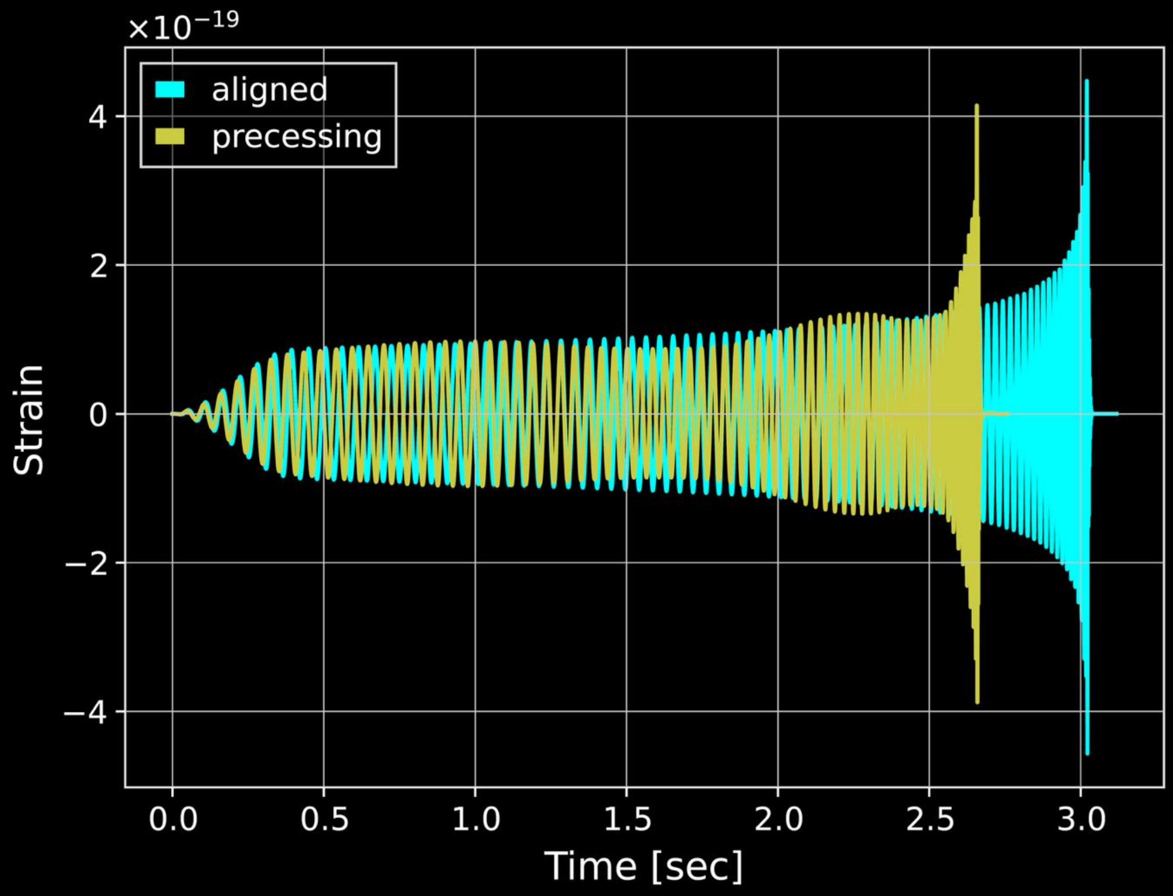
The gravitational-wave signal

- 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



LIGO Noise Properties

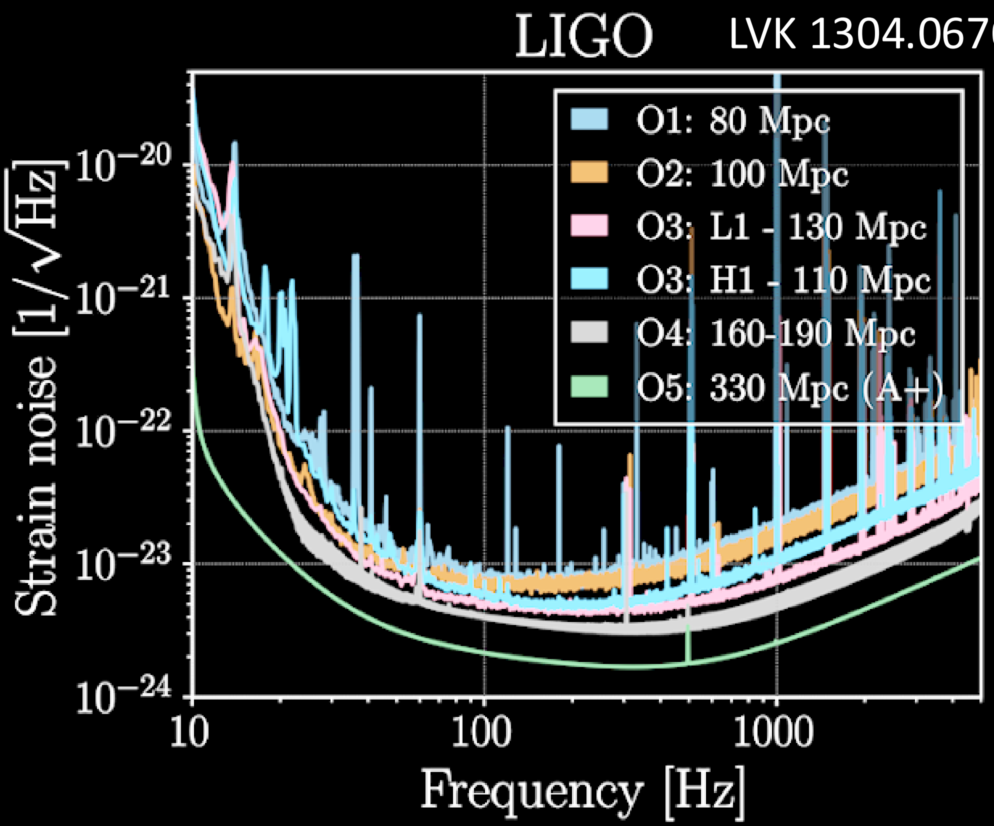
- Assume data has both a gravitational-wave signal component and a noise component:

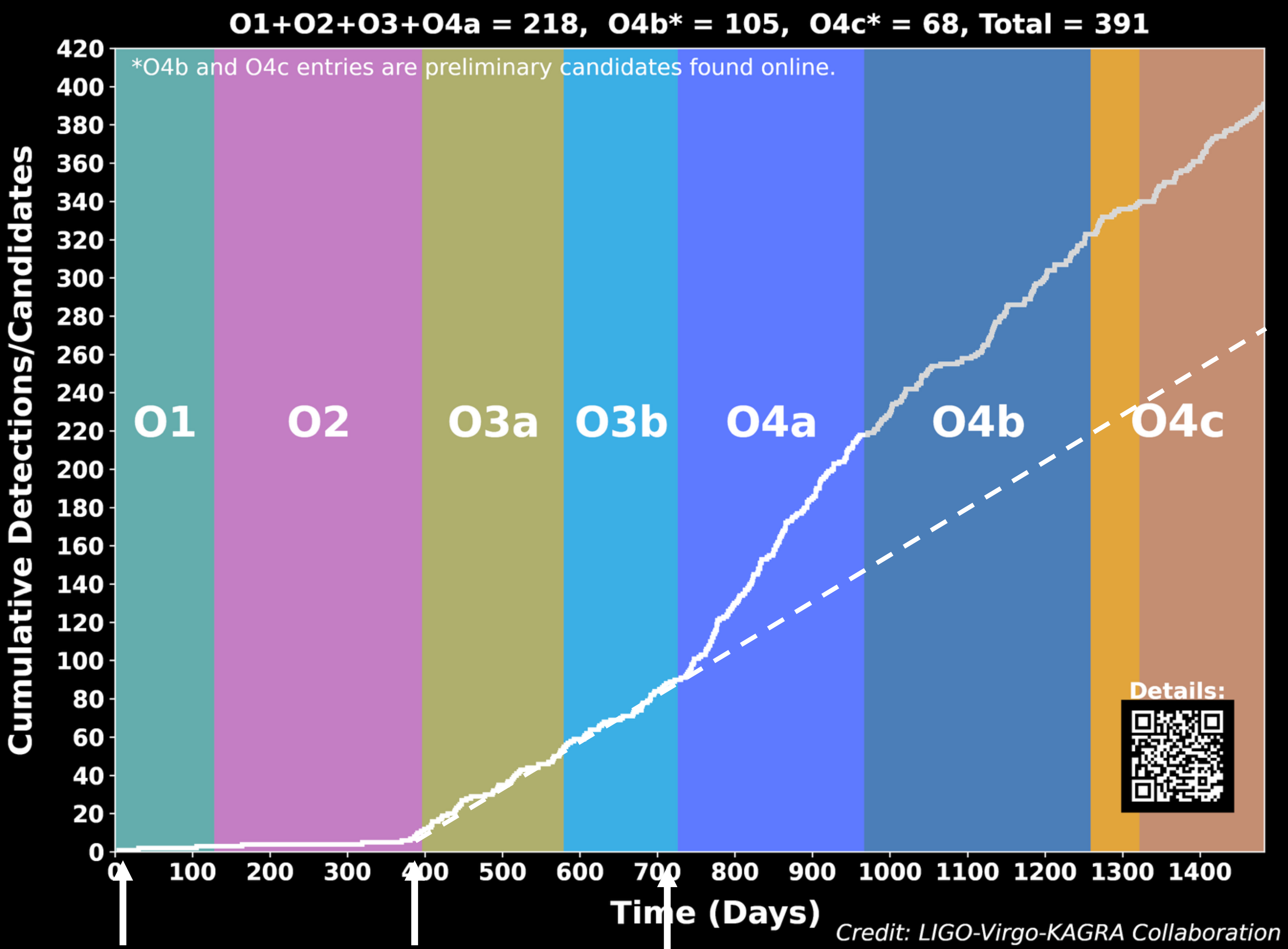
$$d = h + n$$

- 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





GW150914: first binary black hole

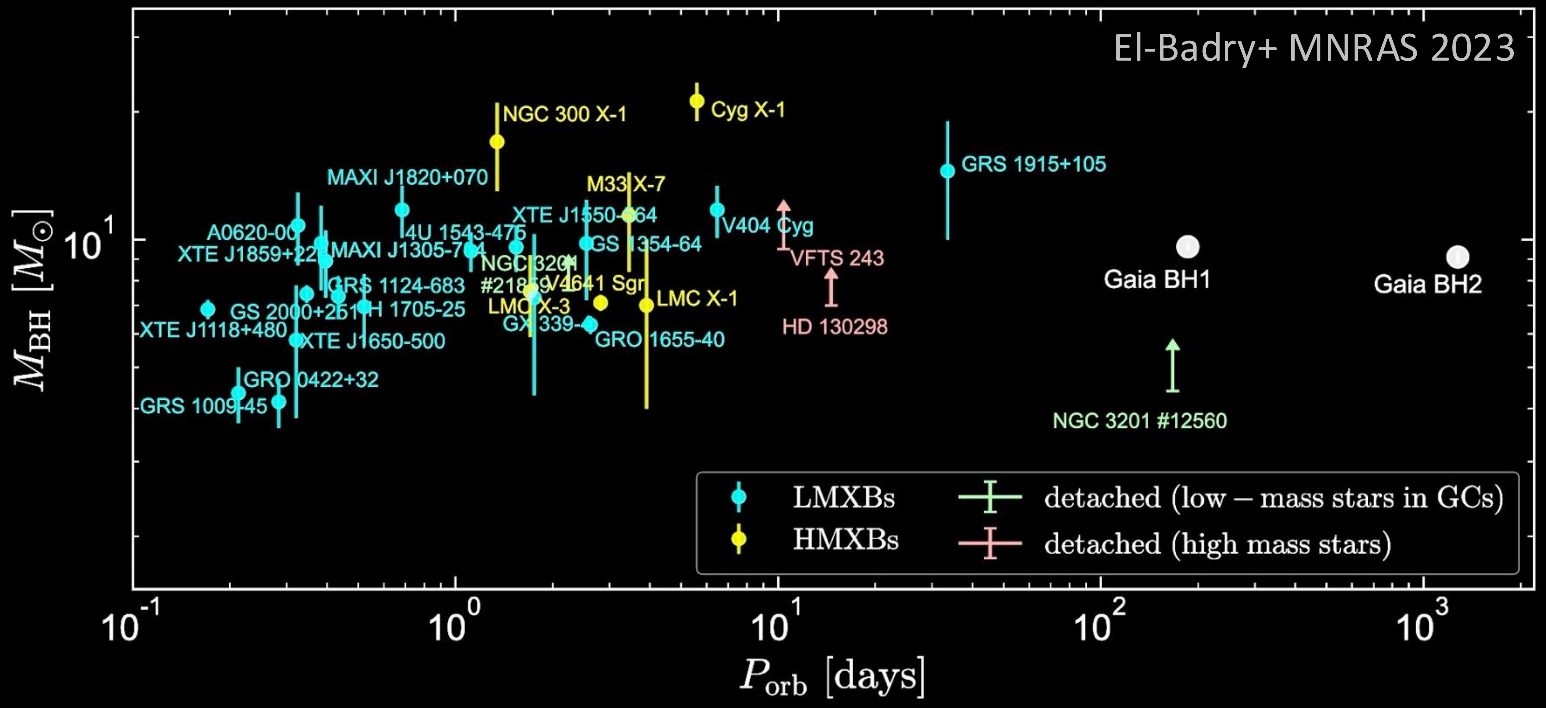
GW170817: first binary neutron star (multimessenger)

GW200105 and GW200115: first neutron star-black hole mergers

GW150914

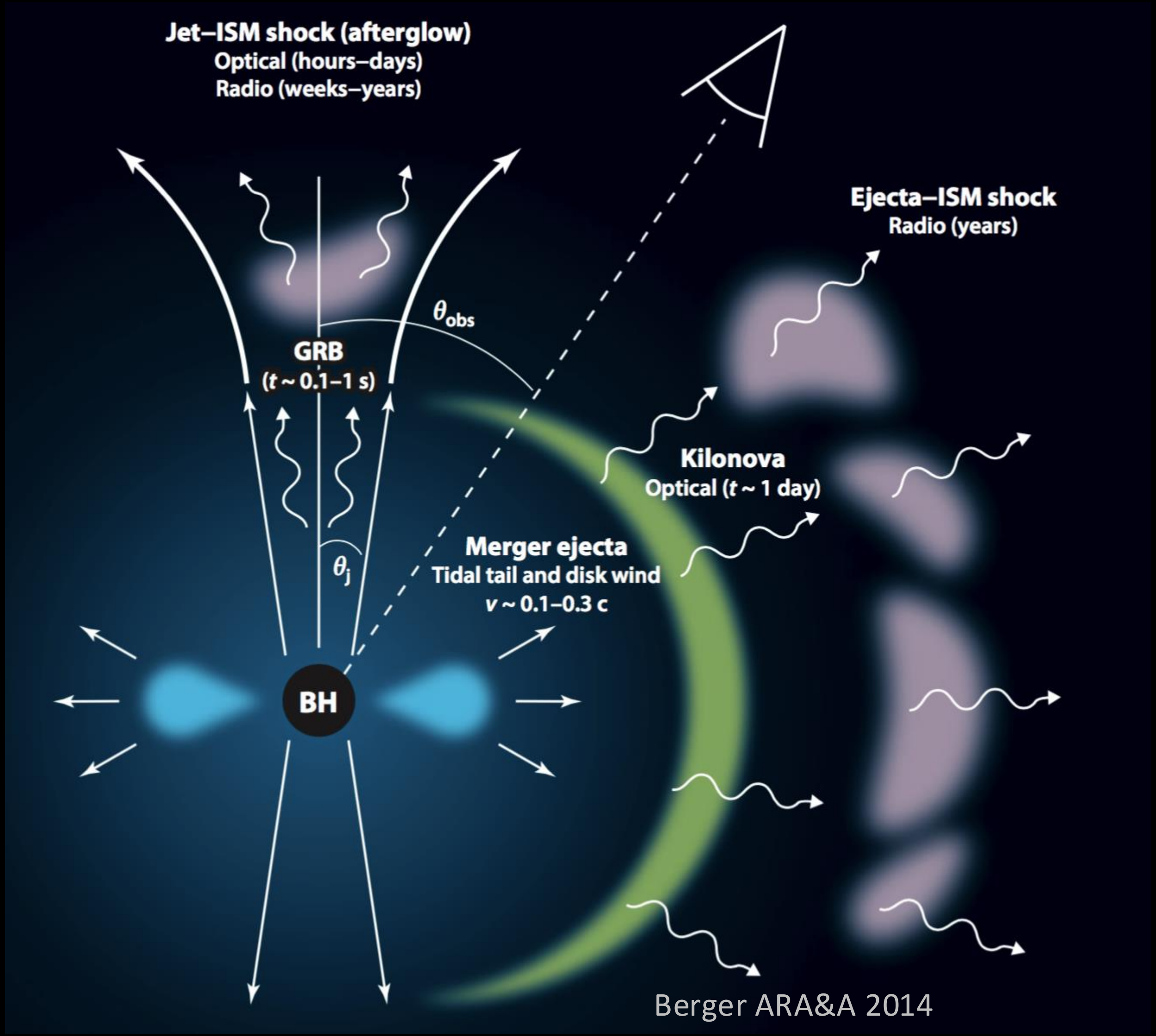
- Binary black holes exist and merge within the age of the Universe
- Tens of times more massive than the sun
- Small spins

Electromagnetically-detected black holes



GW170817

- Progenitors of some short gamma-ray bursts
- Site of heavy element nucleosynthesis
- Neutron star radii are small

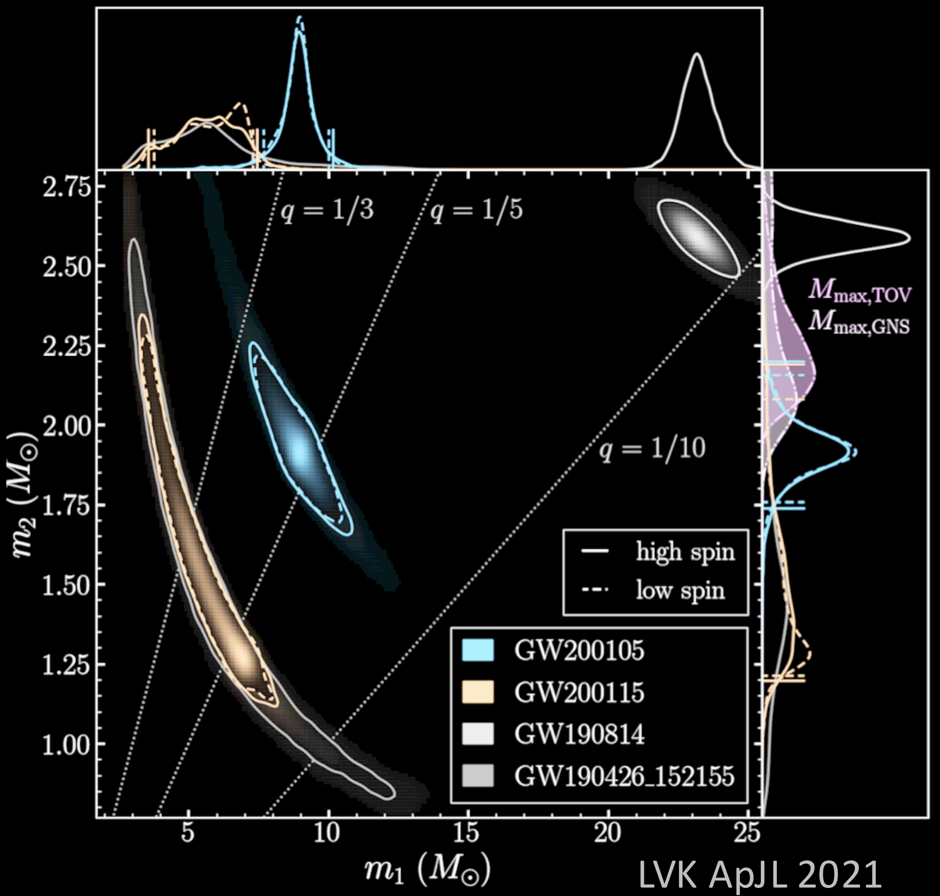


Berger ARA&A 2014

LVC PRL 2017
LVC + MMA ApJL 2017

GW200105 and GW200115

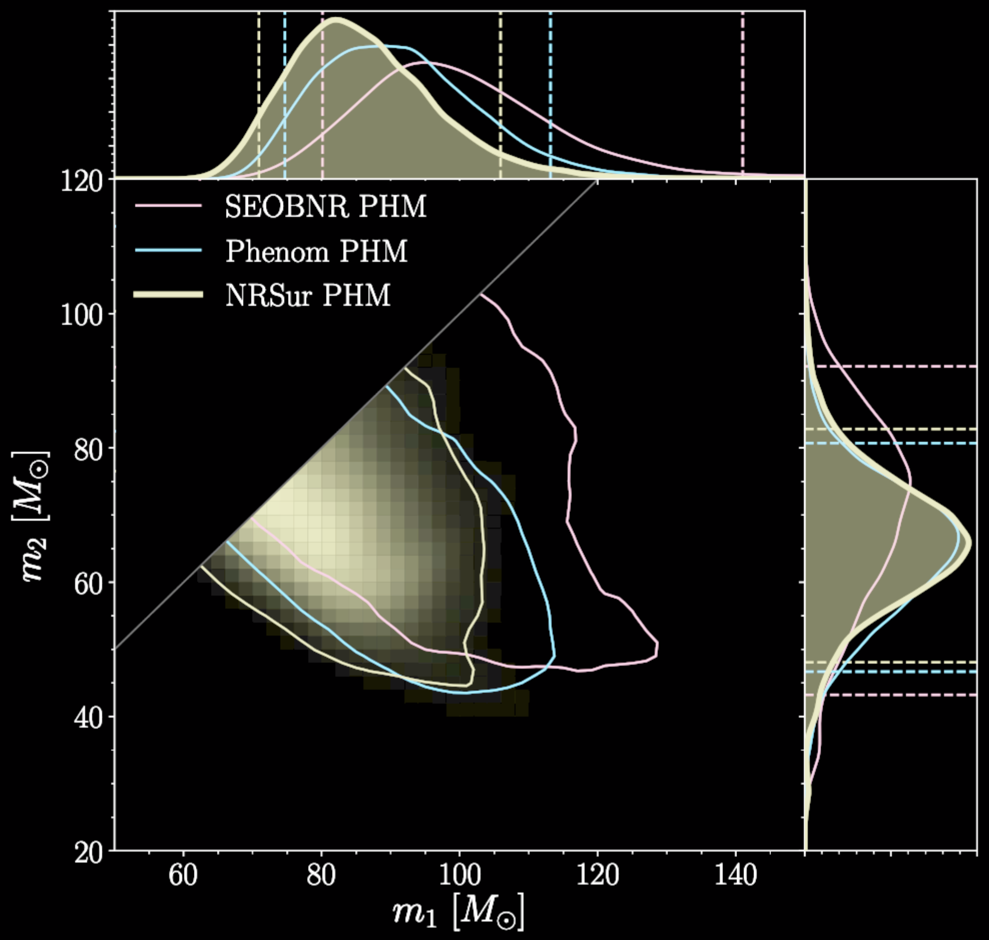
- First neutron star-black hole binaries
- Merge about as frequently as binary black holes
- Have smaller spins and are less massive than binary black holes
  - **S. Biscoveanu**+ MNRAS 2023, Zhu+ 2021



LVK ApJL 2021

GW190521

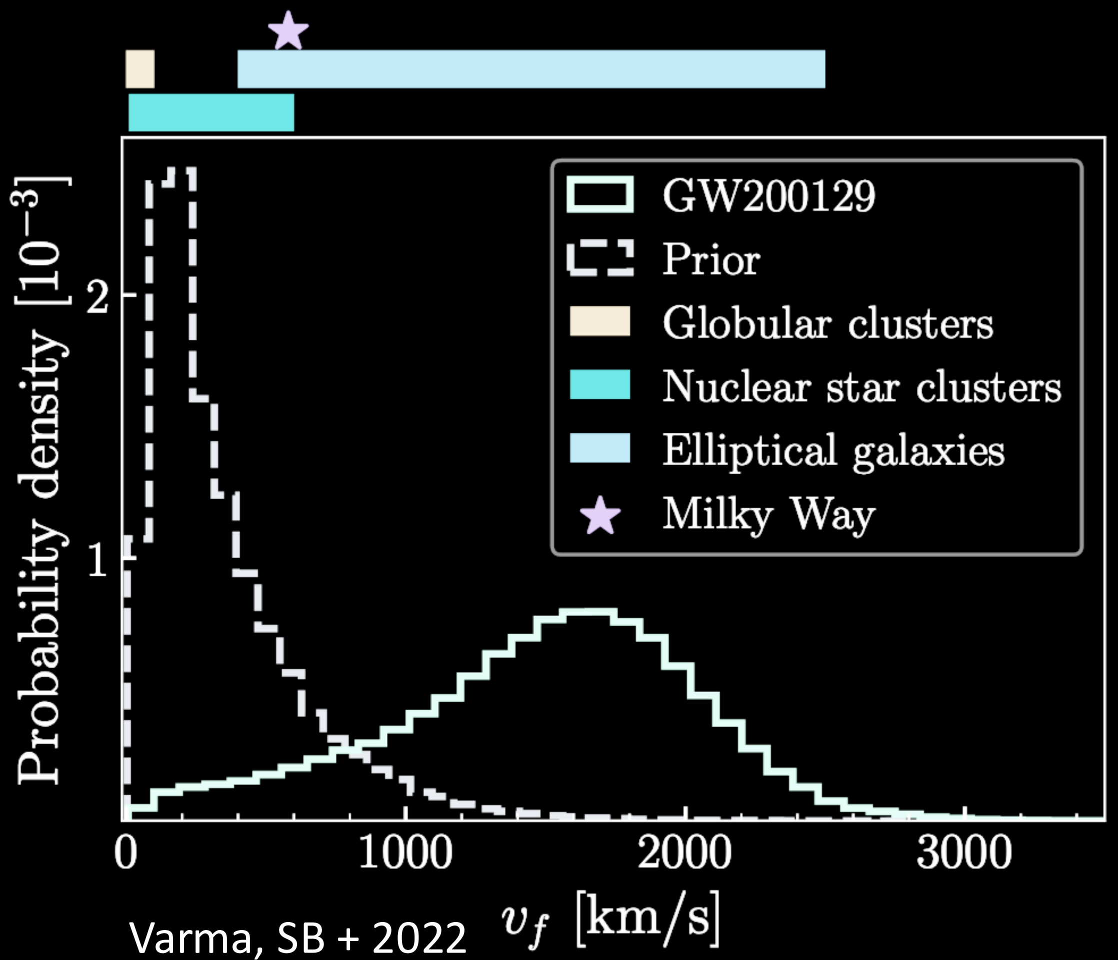
- The heaviest binary black hole merger detected
  - Primary mass in upper mass gap
  - Hint of spin precession
  - Signatures of dynamical formation!
- Spin information for massive events like GW190521 is driven by merger and ringdown rather than inspiral (SB + 2106.06492)



LVC 2009.01075

Some special events

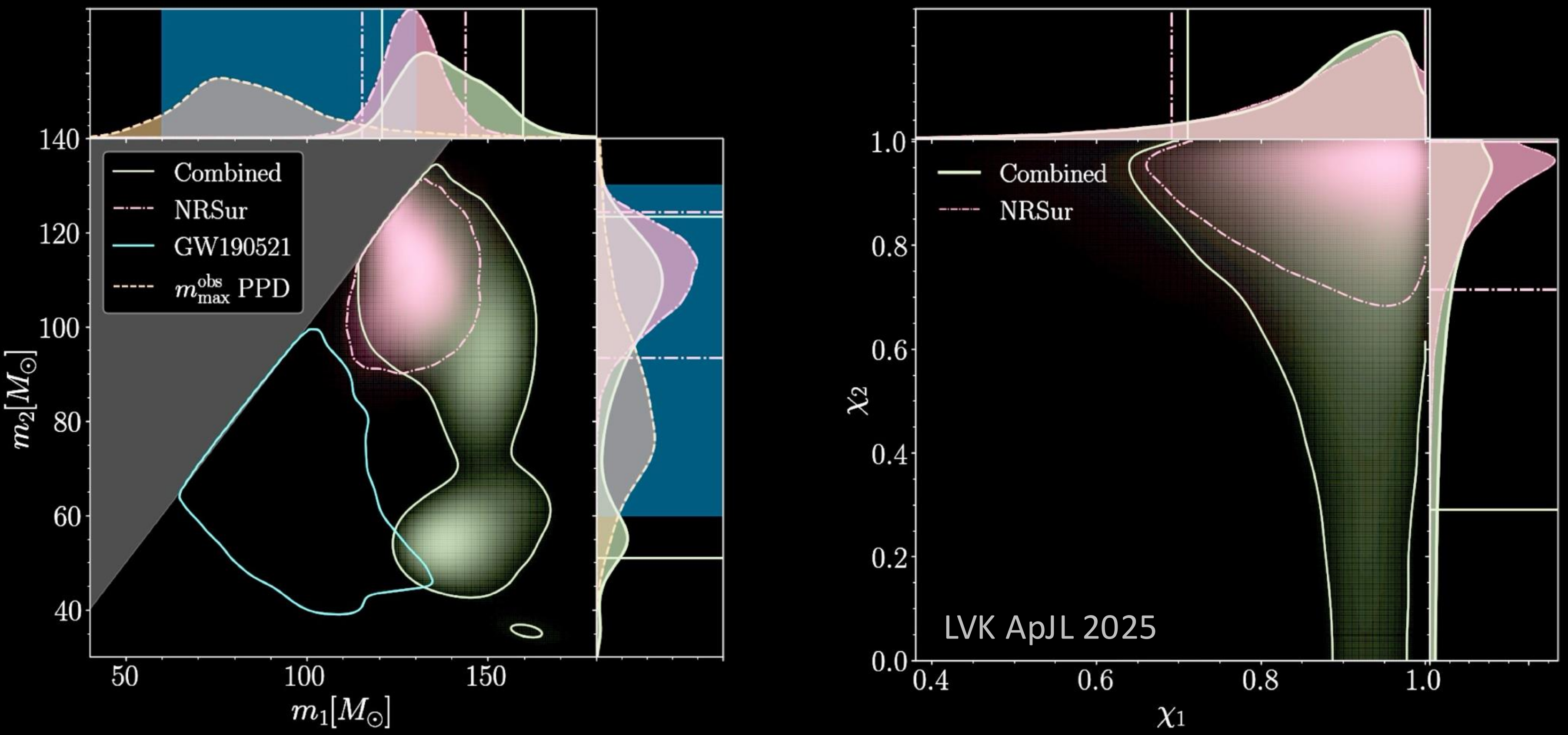
- GW200129 – significant evidence for precession (Hannam + 2021)
    - Merger remnant received a recoil kick velocity of ~1700 km/s
    - Likely ejected from host environment so unable to merge again



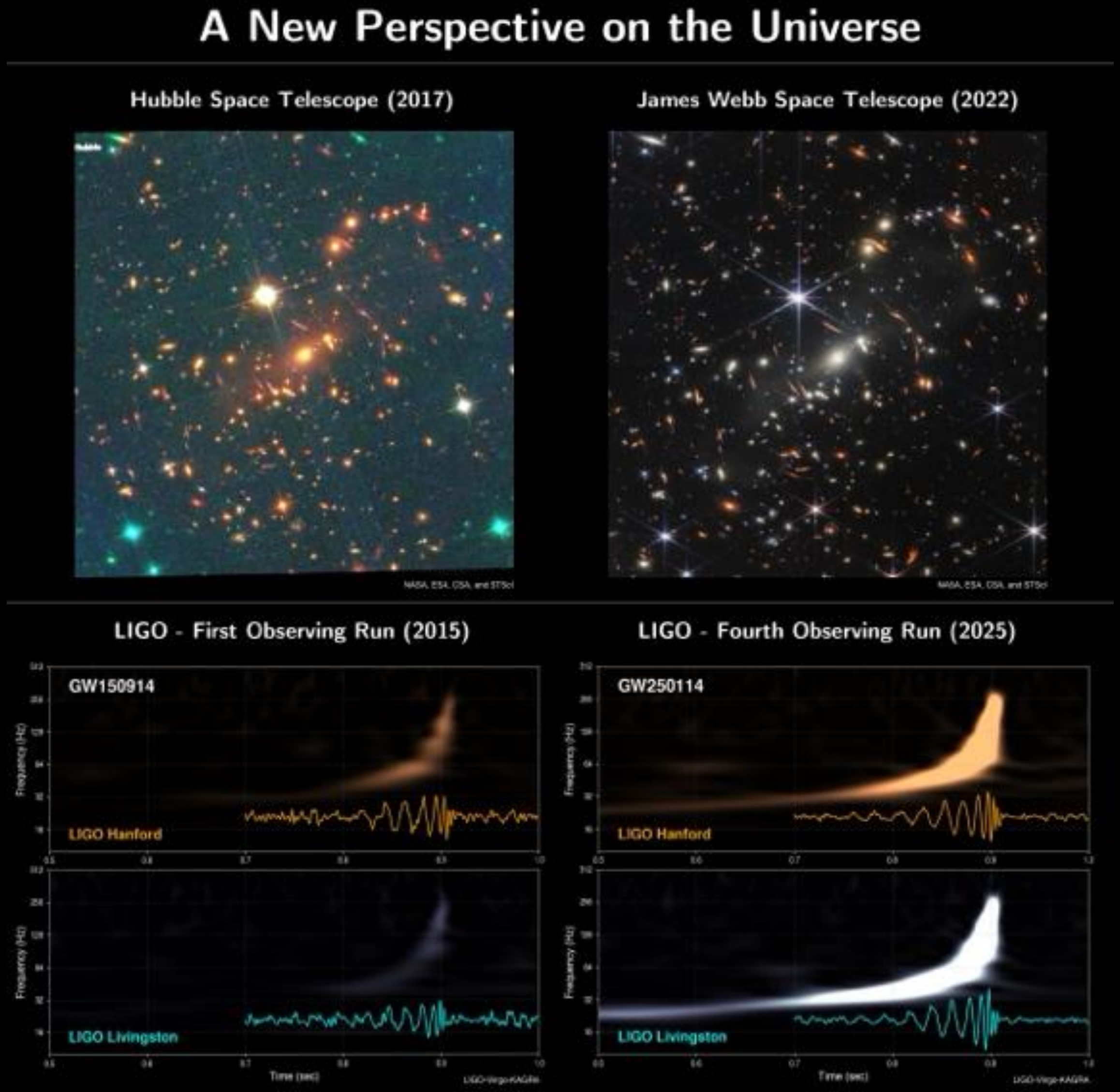
Varma, SB + 2022

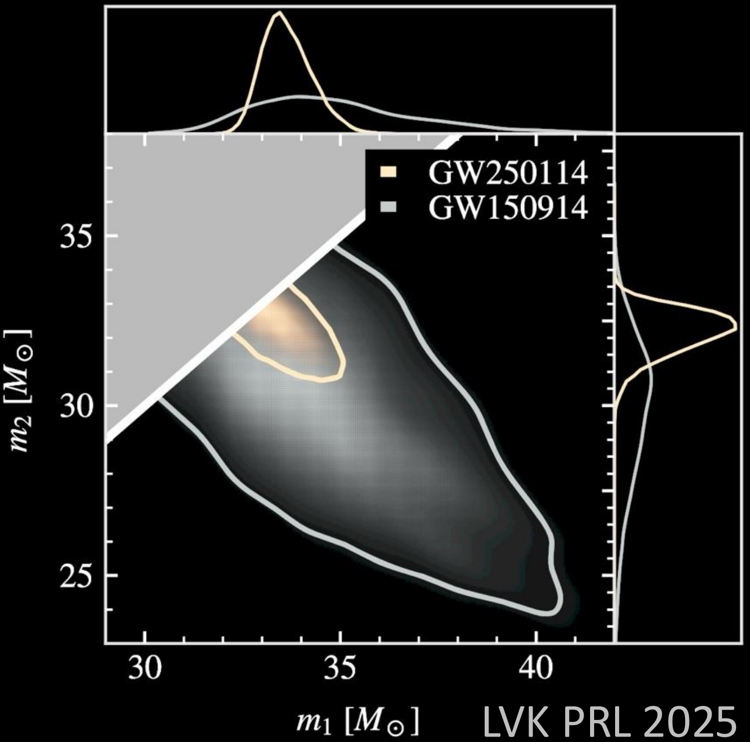
GW231123

The most massive and likely most rapidly spinning binary black hole merger



GW250114, the twin of GW150914 ten years later

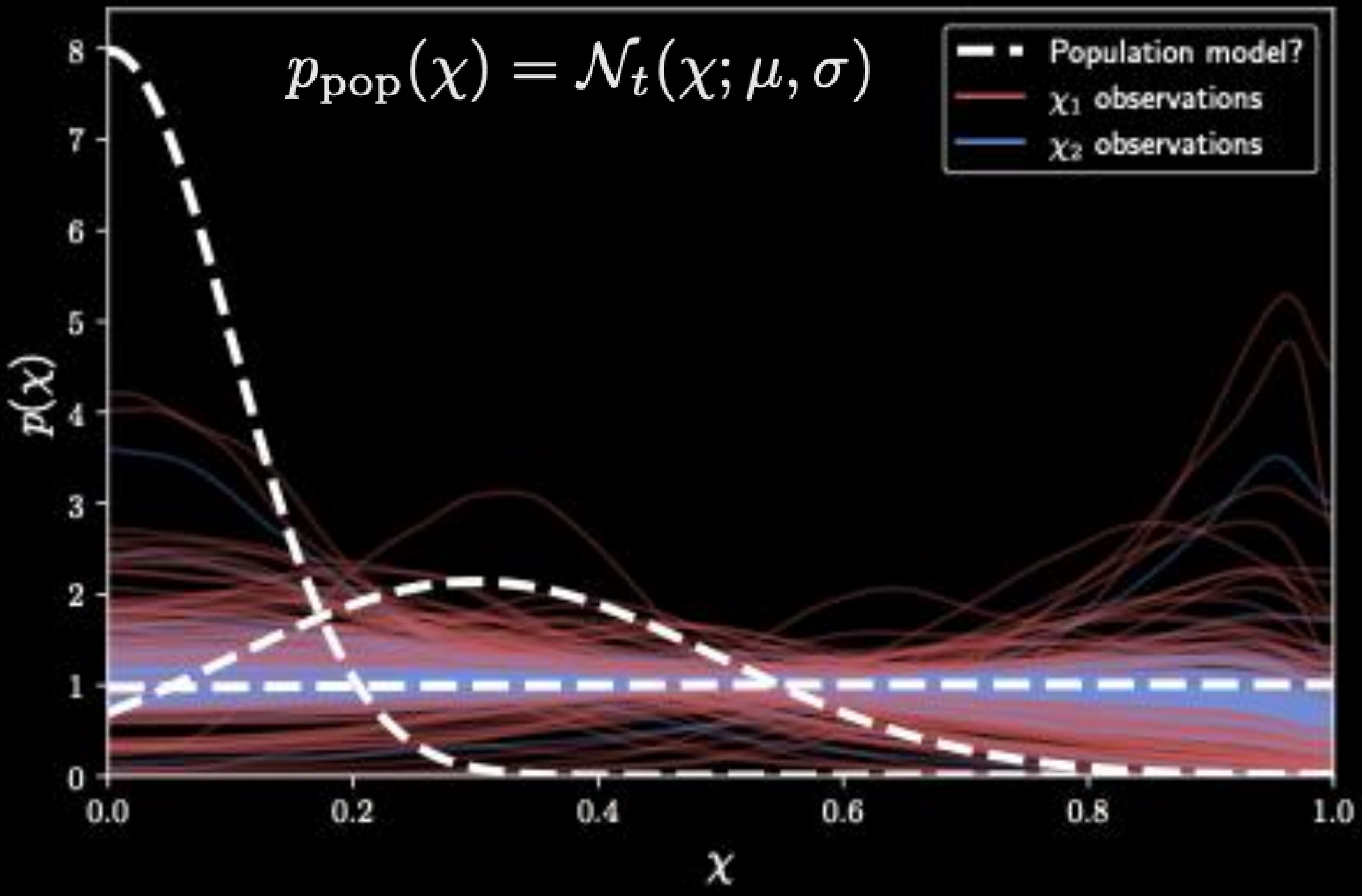




LVK PRL 2025

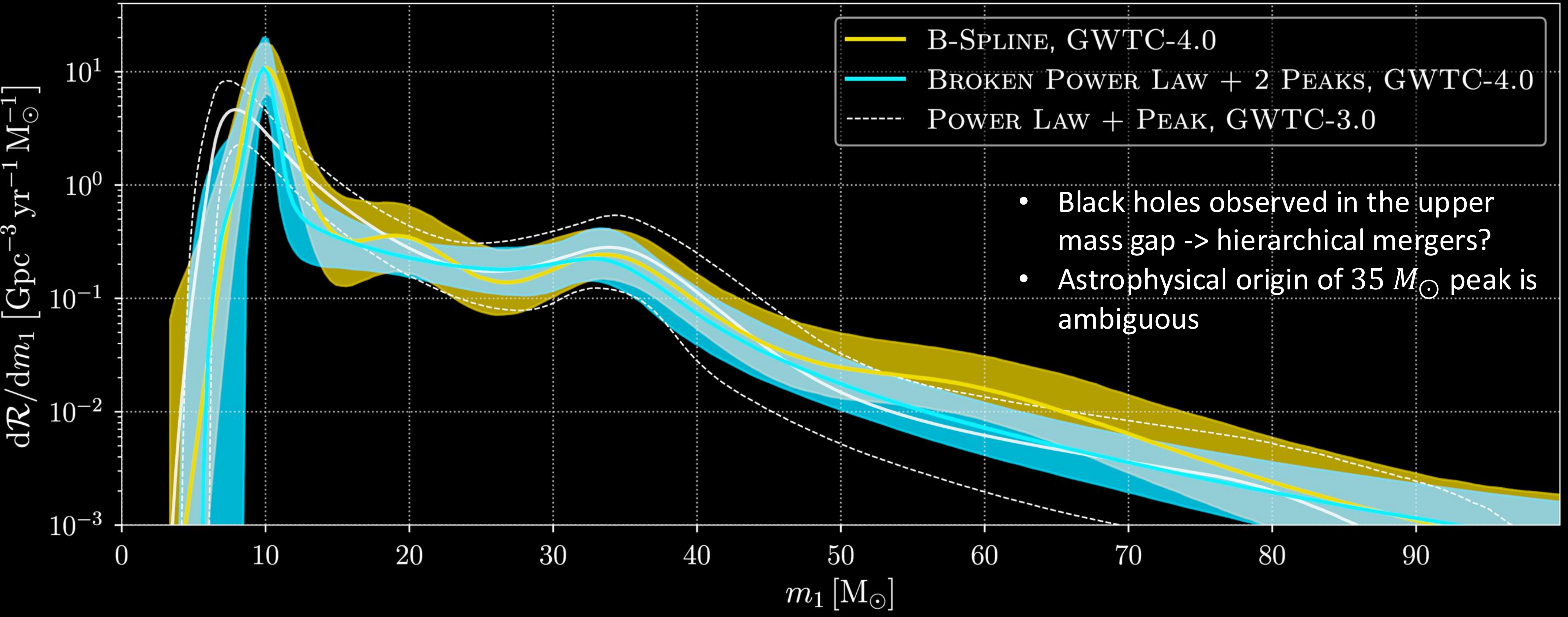
SNR 80 allows for precision tests of general relativity

From individual events to the population with hierarchical Bayesian inference



Thrane & Talbot, PASA 2019; Mandel+ MNRAS 2019; Vitale+ Springer, 2022

Mass distribution of heavier black hole has two peaks and evolves differently at high and low masses



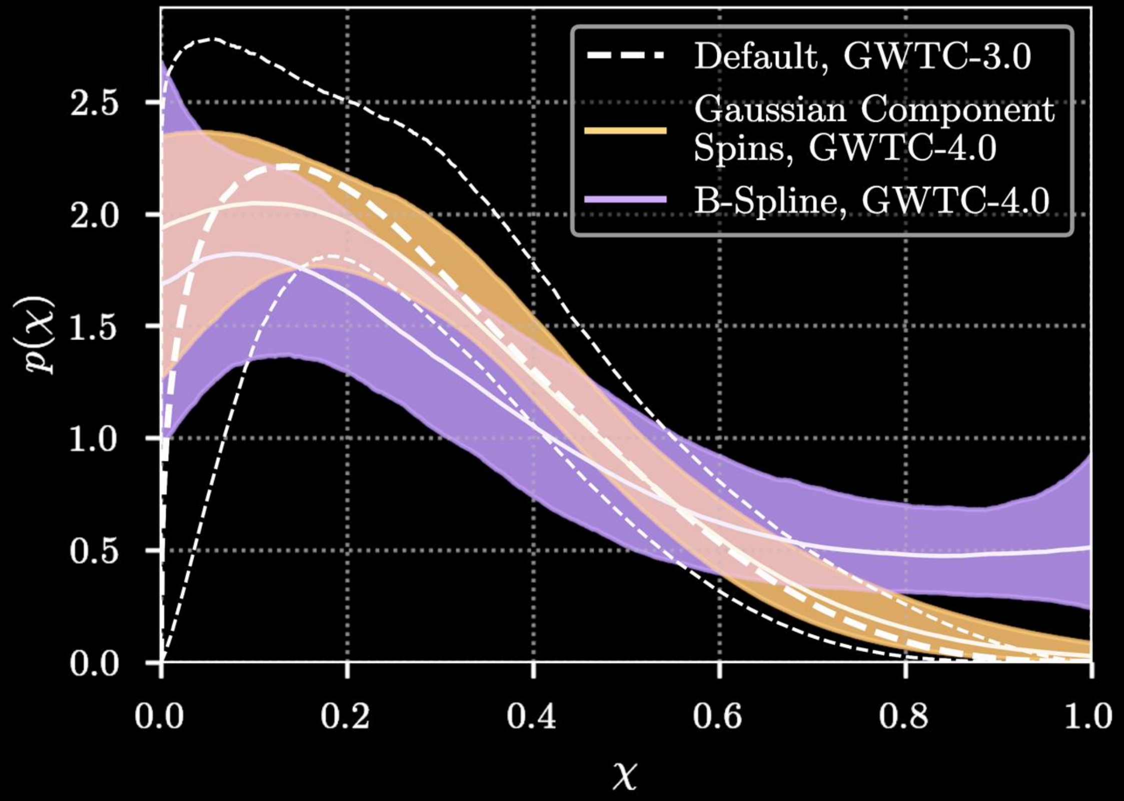
- Black holes observed in the upper mass gap -> hierarchical mergers?
- Astrophysical origin of 35 $M_\odot$ peak is ambiguous

LVK 2508.18083, Edelman+ PRD 2023,
Talbot & Thrane ApJ 2018, Fishbach & Holz ApJ 2017

Binary black hole spin magnitudes are small

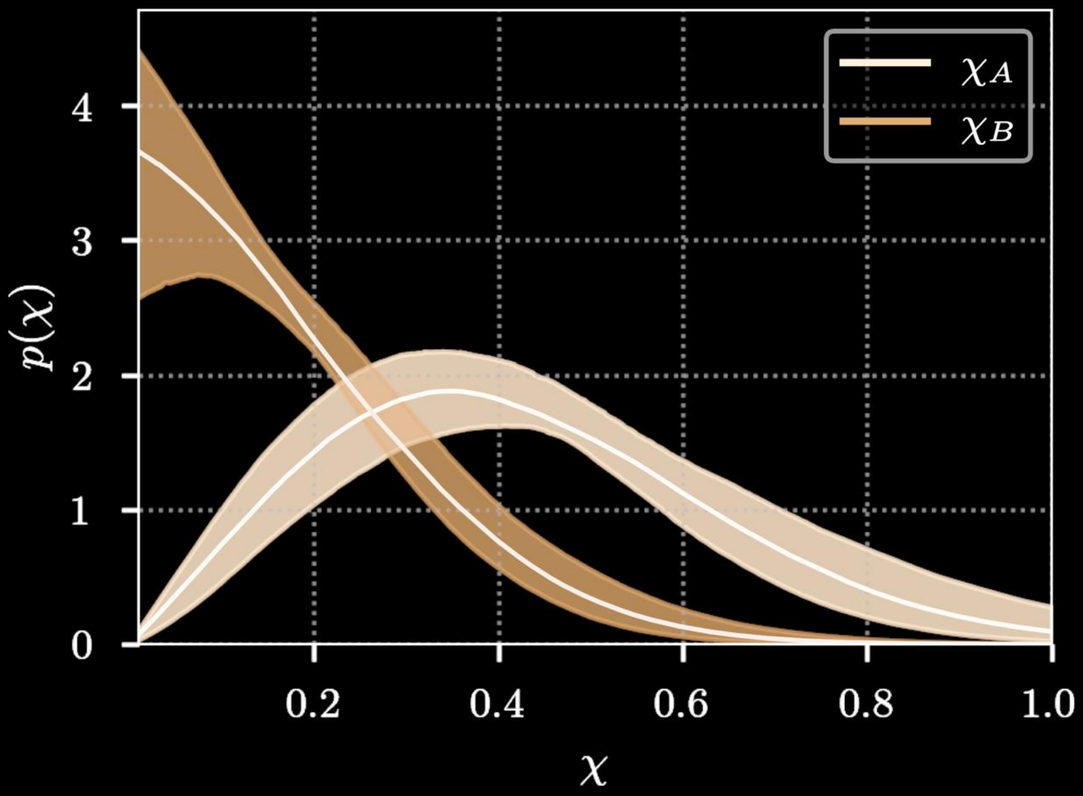
But not negligibly small across the whole population

LVK 2508.18083; Edelman+ PRD 202; Wysocki+ PRD 2019



Angular momentum transport in massive stars is efficient

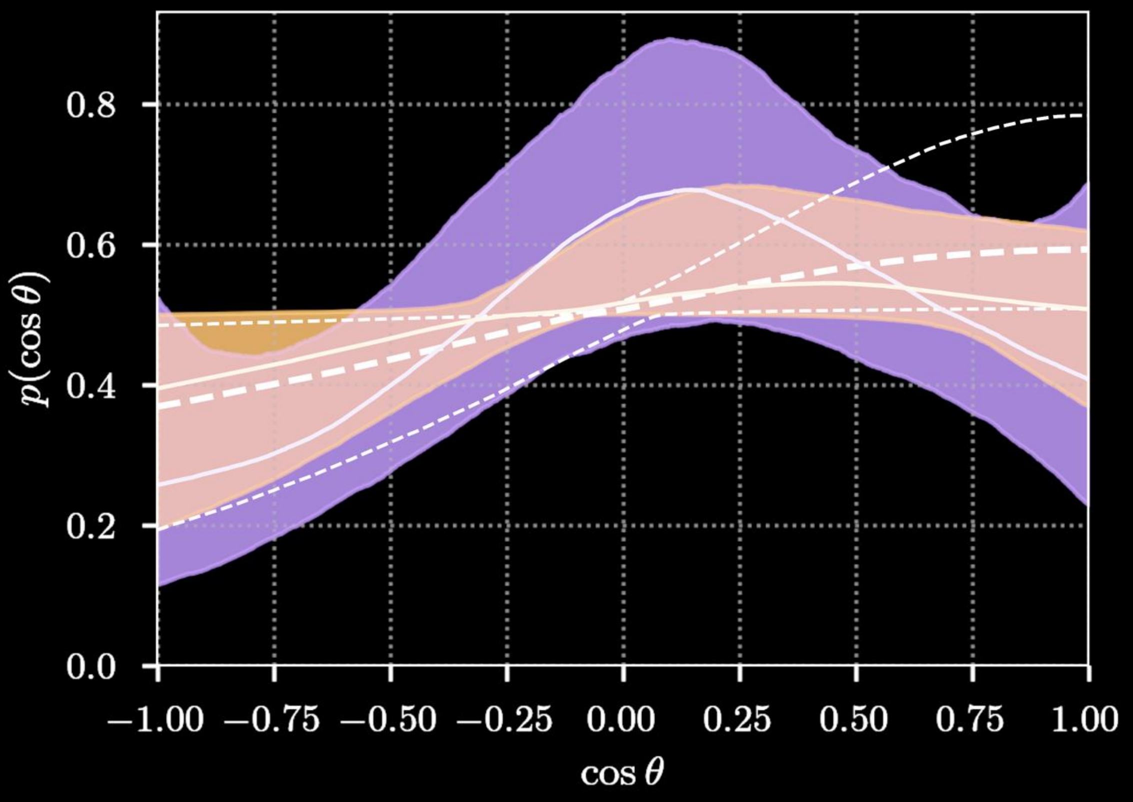
SB+ PRL 2020; Szemraj & **SB** CQG 2026



At most 80% of sources are nonspinning using spin sorting

Tilts are sometimes significantly misaligned

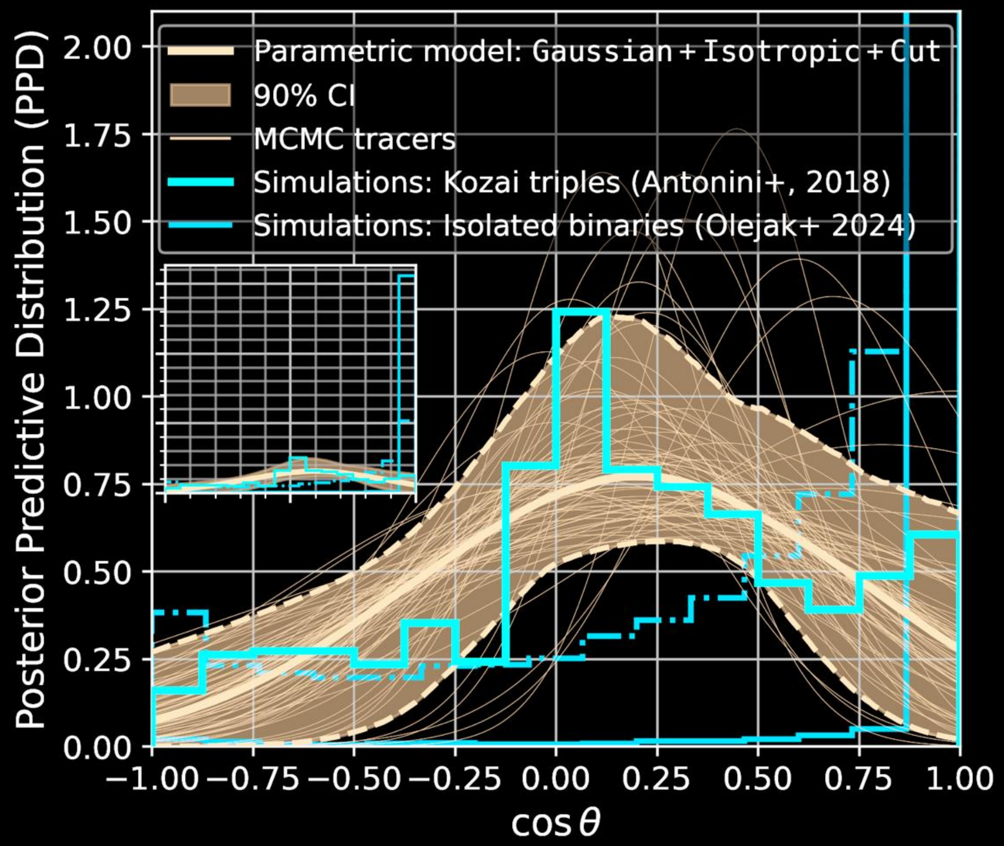
LVK 2508.18083, Edelman+ PRD 2023, Vitale, **SB**+ A&A 2022, Talbot & Thrane ApJ 2018



Some binaries form dynamically…

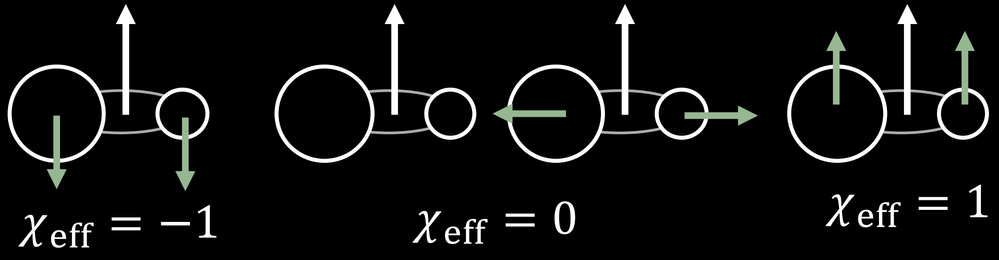
With a potential excess of in-plane spins

Stegmann+ inc **SB** ApJ 2026

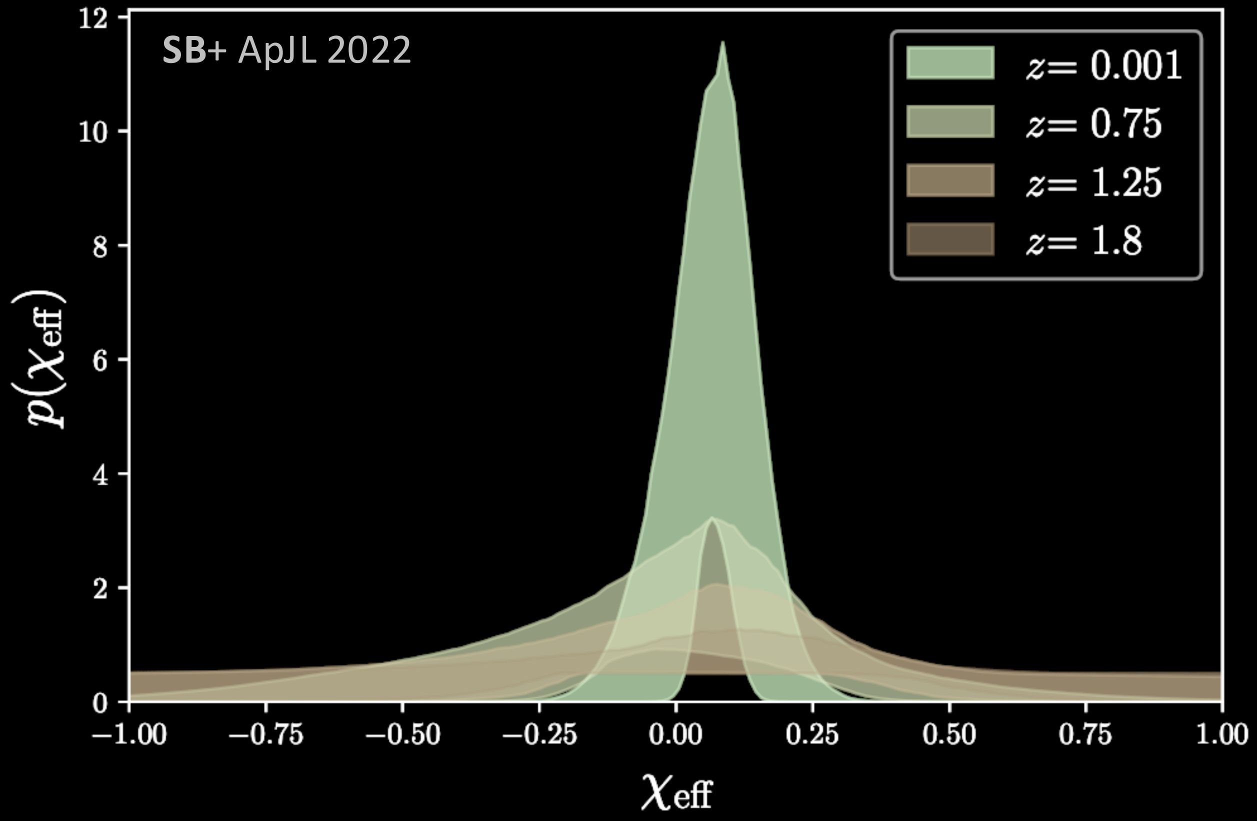


And in stellar triples!

The binary black hole spin distribution likely broadens with redshift



- "Effective aligned spin"- mass-weighted spin projected onto the orbital angular momentum
- Allow mean and width of χ_{eff} distribution to evolve with redshift
- Black holes were born with larger spin in the cosmic past



Correlation is robust against model choice

$$p_{\rm pop}(\chi_{\rm eff}) = \mathcal{N}(\chi_{\rm eff}; \mu, \sigma)$$

$$\mu(z) = {\rm Line}(z)$$

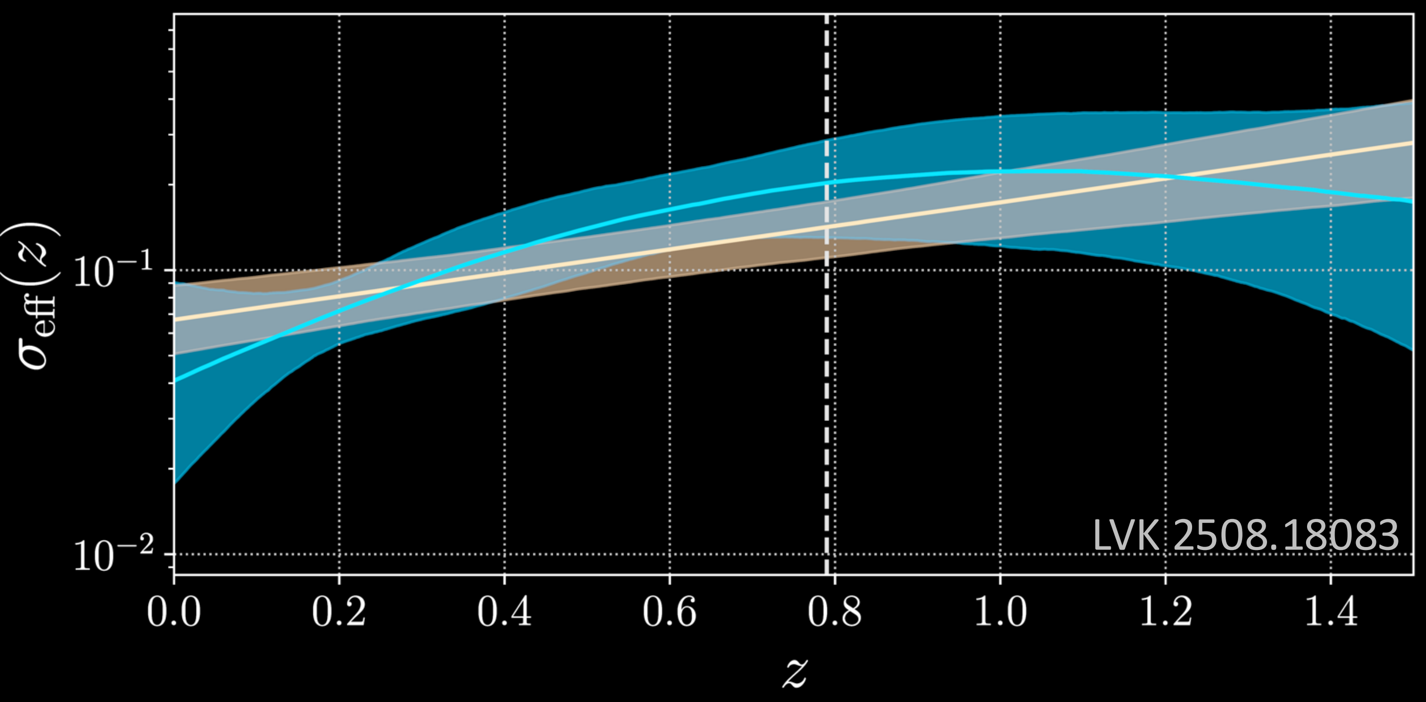
$$\sigma(z) = {\rm Line}(z)$$

↓

$$\mu(z) = {\rm Spline}(z)$$

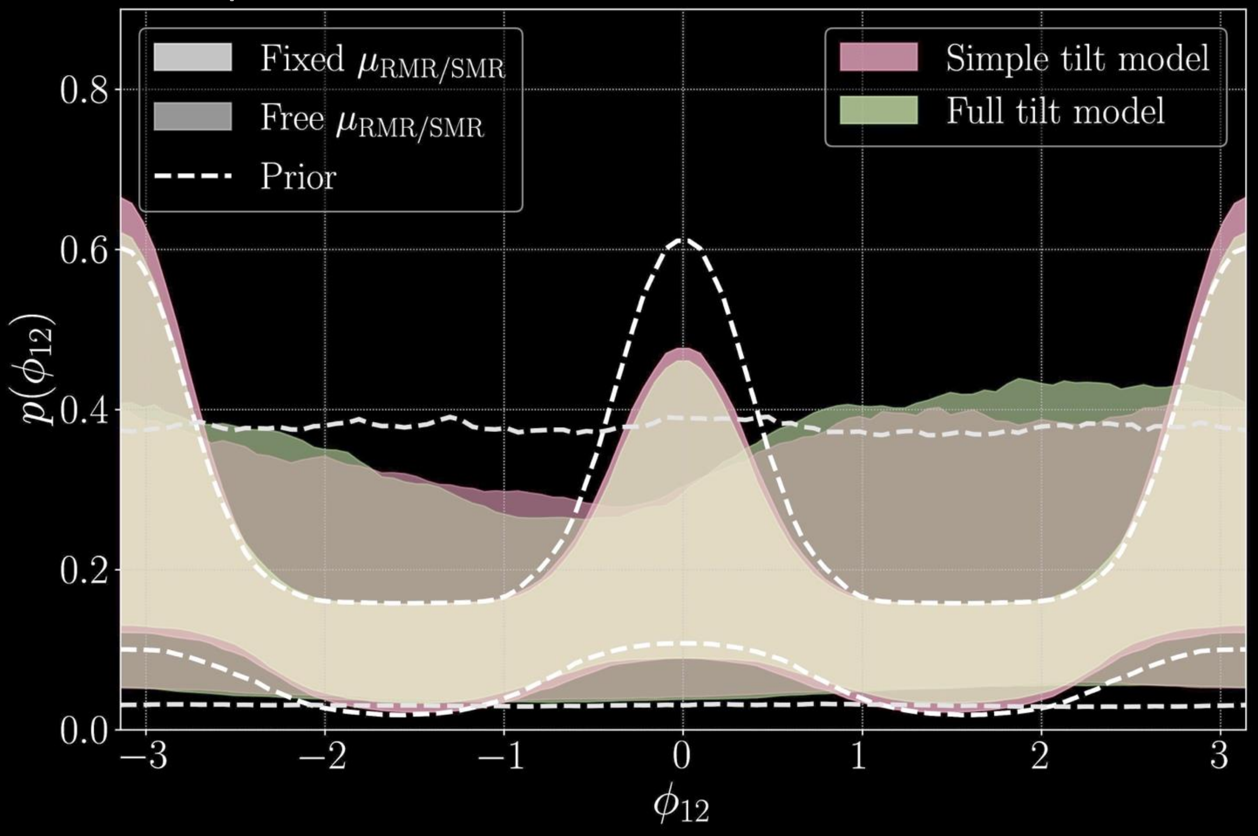
$$\sigma(z) = {\rm Spline}(z)$$

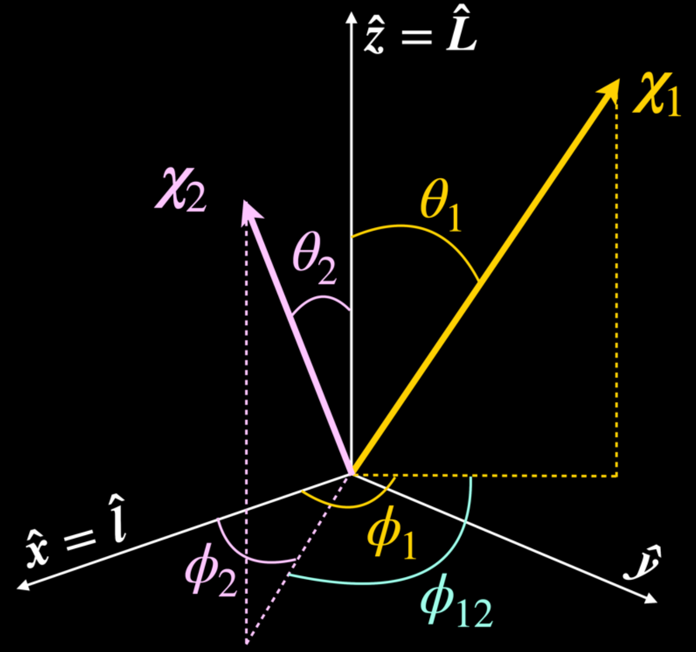
Heinzel, **SB**+ PRD 2024



Azimuthal spin angle encodes binary dynamics, formation channels, and mass transfer history

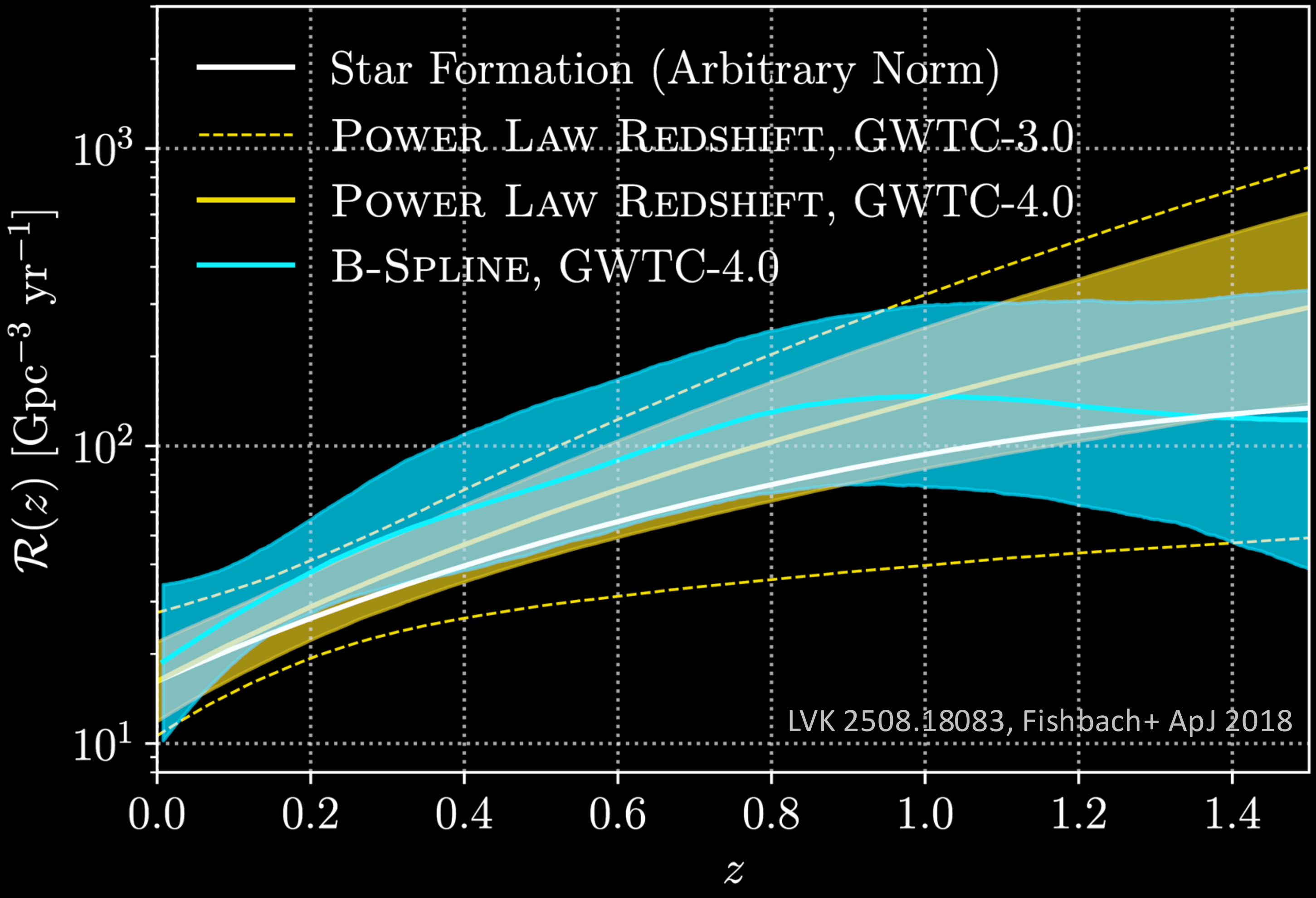
SB ApJ 2026





Spin-orbit resonances lead to peaks at $\phi_{12} = 0, \pm\pi$

Binary black holes merged more often in the cosmic past

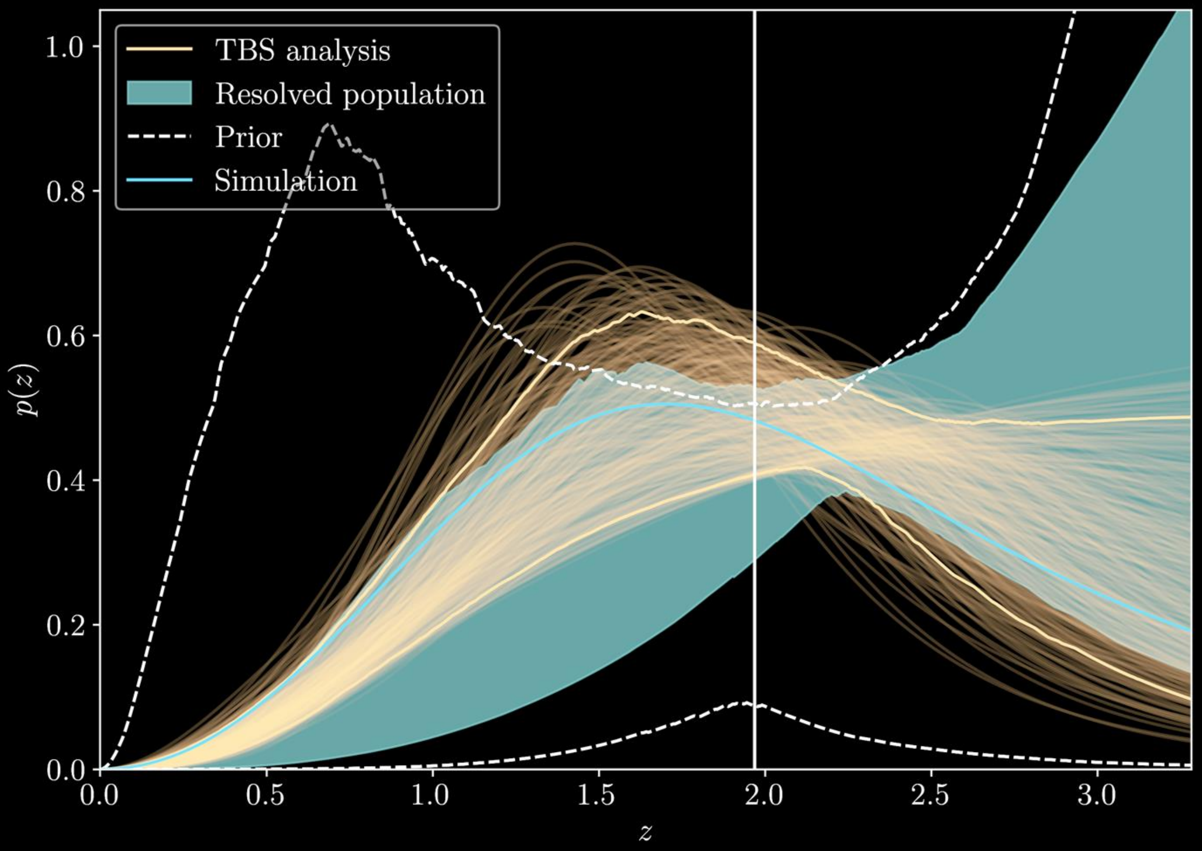


Redshift distribution of the merger rate may evolve faster than star formation

Expanding our redshift horizon with the stochastic background

Bers & **SB** ApJ 2026

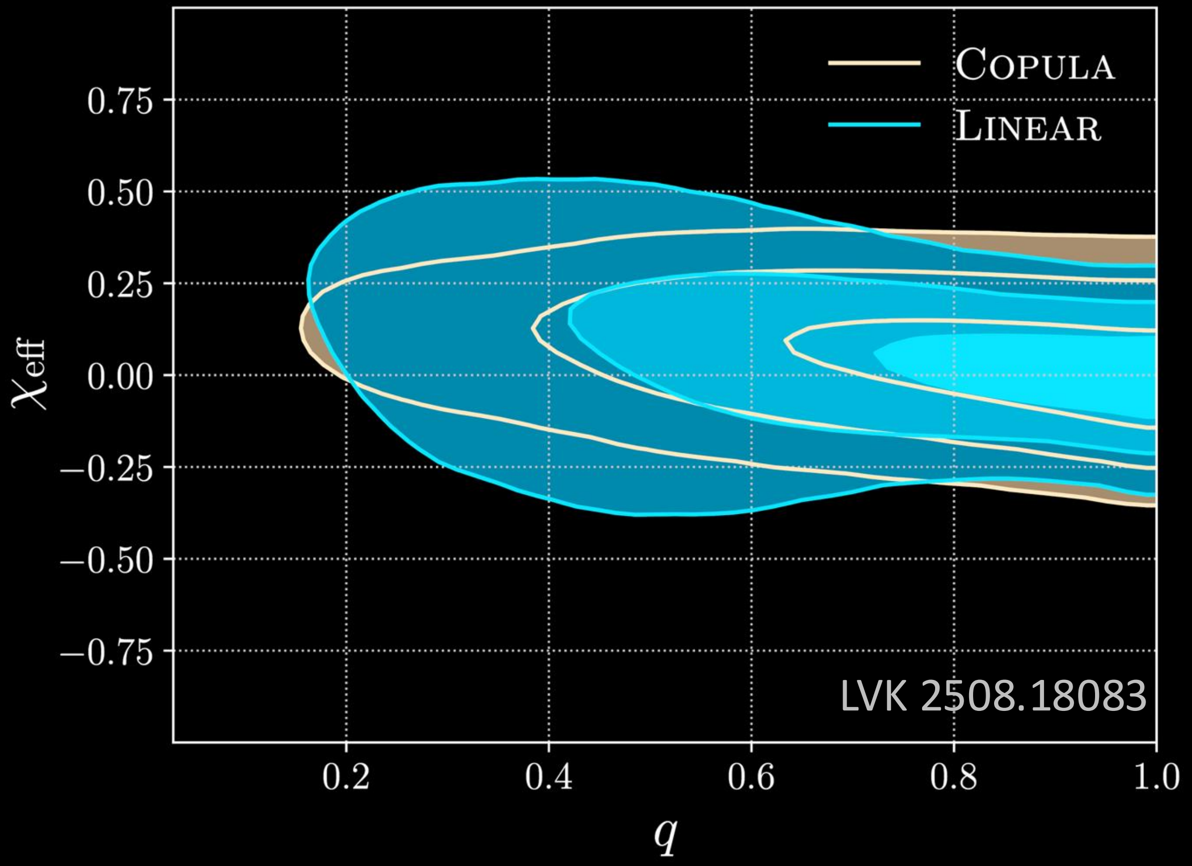
- Population analysis without thresholds (Smith & Thrane PRX 2018)
  - No distinction between foreground and background
- Can potentially constrain the shape of BBH merger rate out to redshifts beyond the peak of star formation using detectors at current sensitivity



Weaker evidence for a correlation between mass ratio and effective spin

- Evidence for anticorrelation between mass ratio and mean $\chi_{\rm eff}$ decreases from 98% to 82% credibility between GWTC-3/4
- Evidence for correlation with *either* mean or width found at > 99% credibility

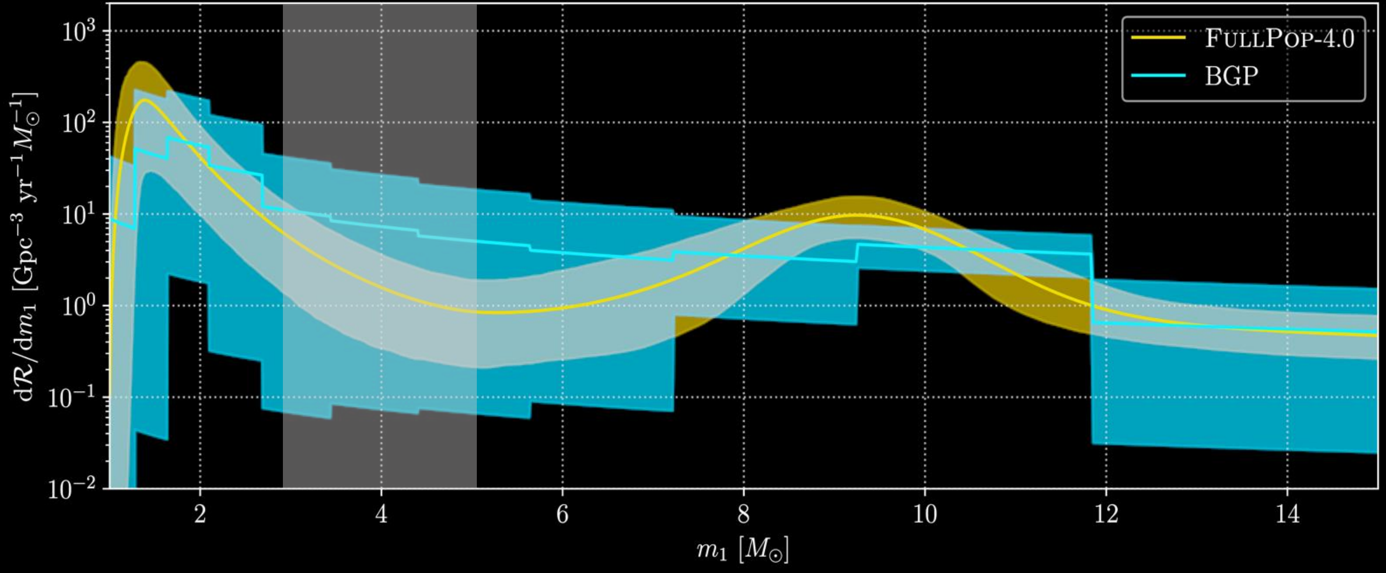
Callister+ ApJL 2021; Adamcewicz+ ApJ 2023



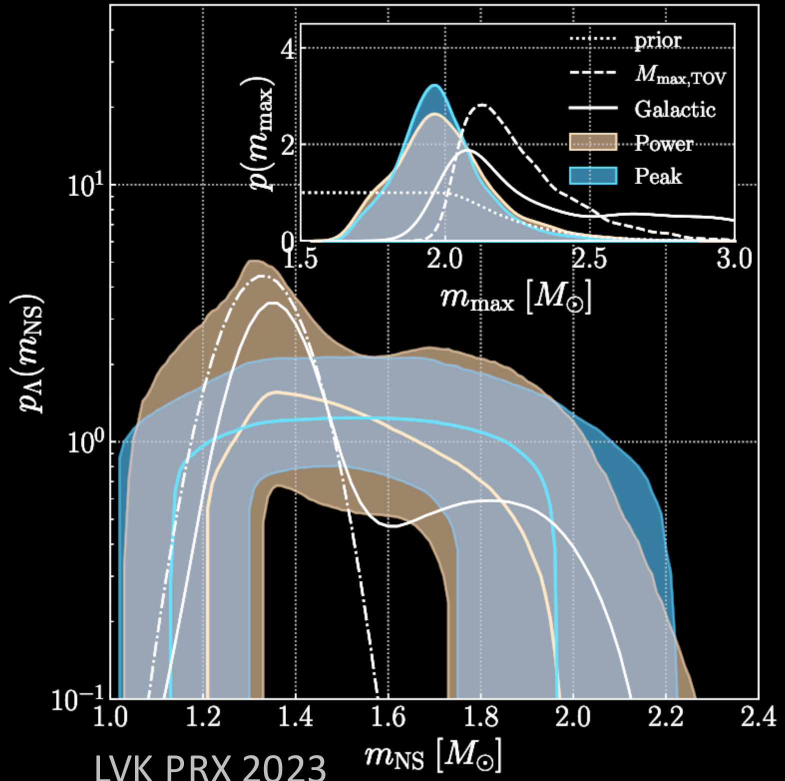
Binaries with neutron stars have distinct properties from those observed electromagnetically

No evidence for a gap between neutron star and black hole masses

LVK 2508.18083, Farah+ ApJ 2022, Ray+ ApJ 2023



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

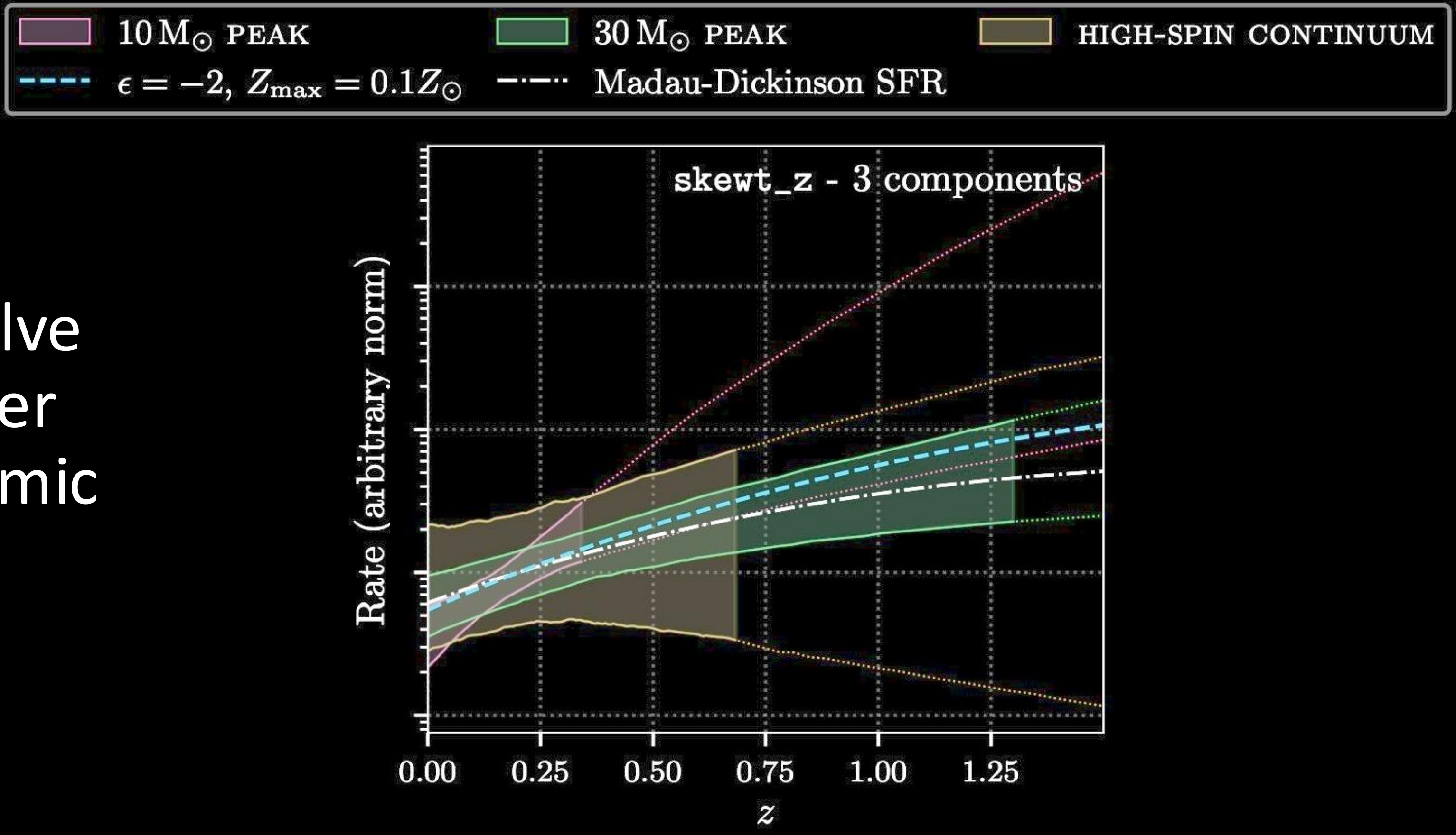


LVK PRX 2023

Landry & Read ApJL 2023

With hints of different redshift evolution

10 Msun peak may evolve more quickly than other subpopulations and cosmic star formation rate



Cheng+ inc **SB** 2605.25980; see also Guo+ ApJ 2024; Gennari+ 2026; Farah+ 2026

Merger rates

No new significant BNS mergers since 2019

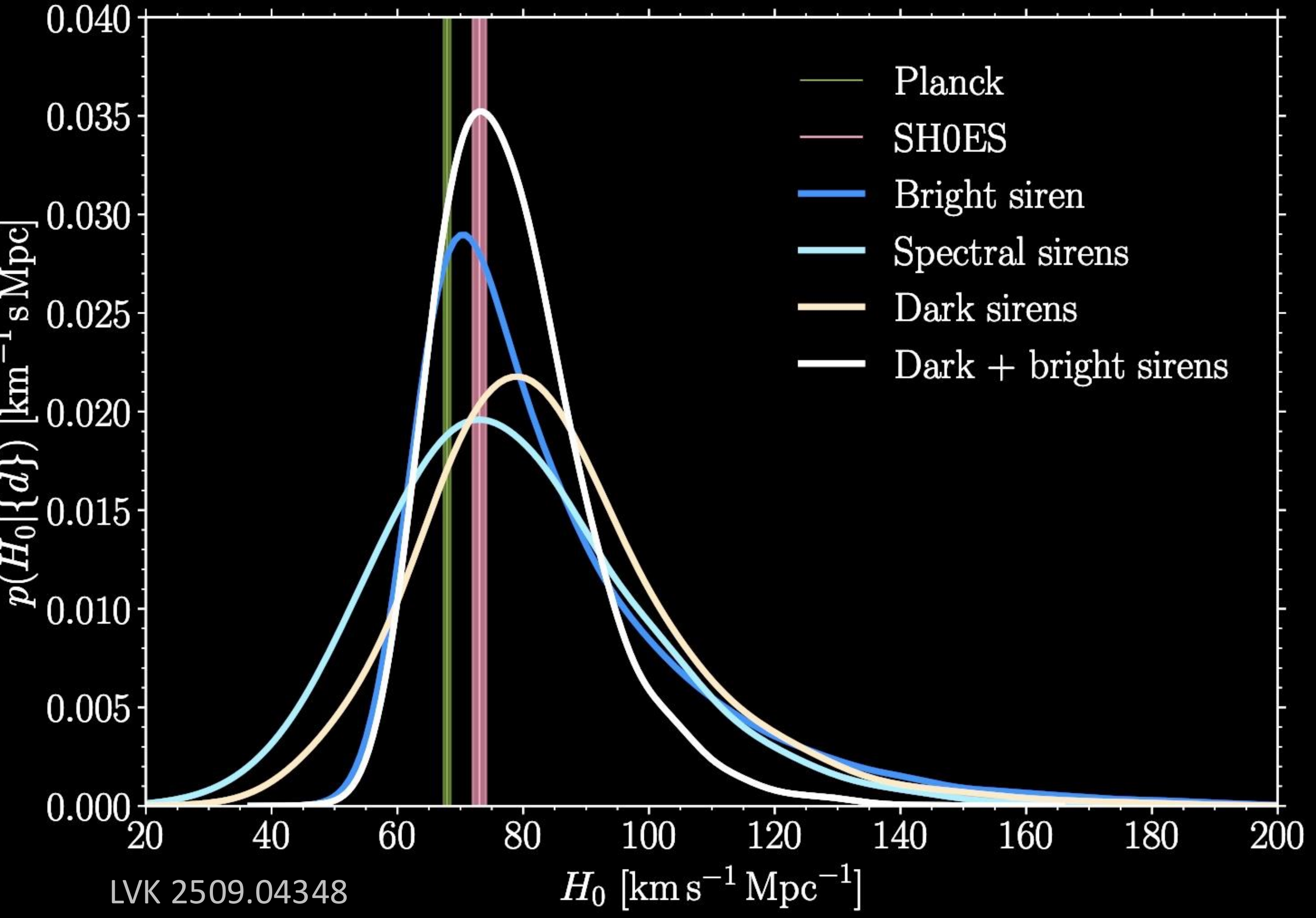
BNS rate 5.1–154.7 $Gpc^{-3}\ yr^{-1}$

NSBH rate 6.7–32.8 $Gpc^{-3}\ yr^{-1}$

BBH rate 27.5–49.4 $Gpc^{-3}\ yr^{-1}$

LVK 2605.27226

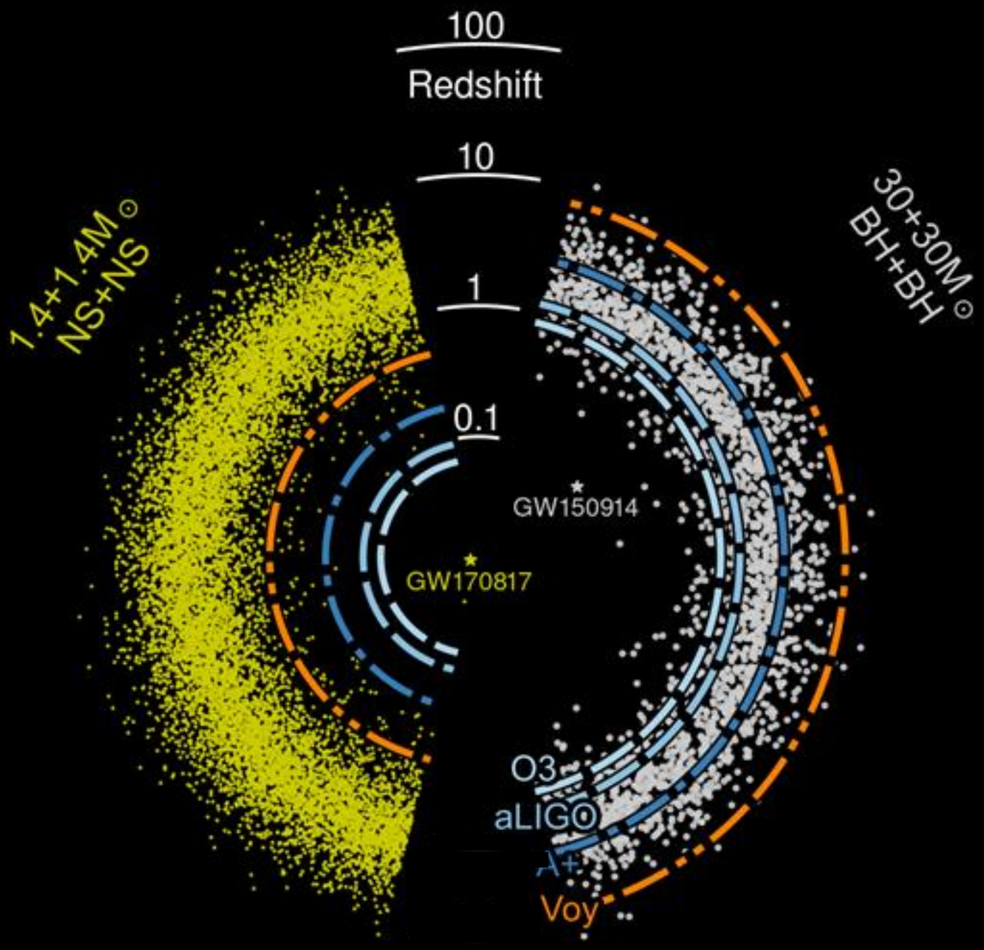
Constraints on the cosmic expansion history



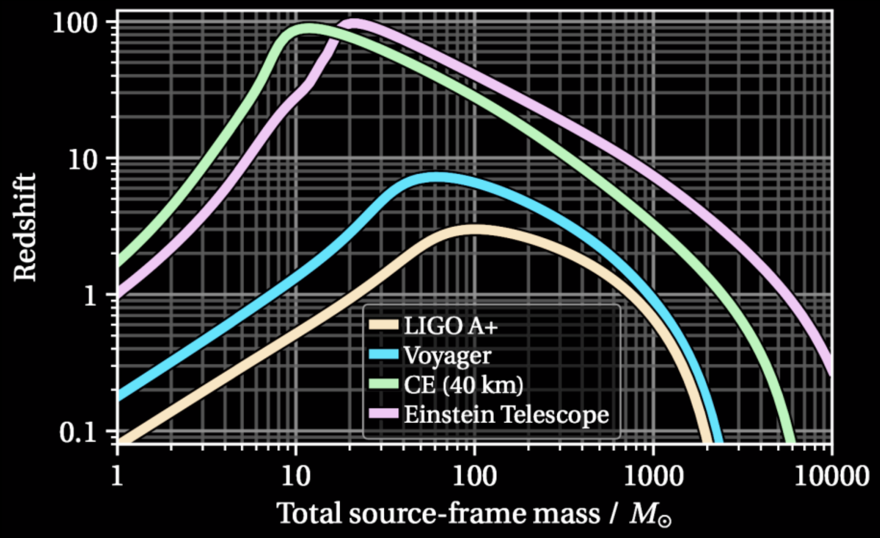
LVK 2509.04348

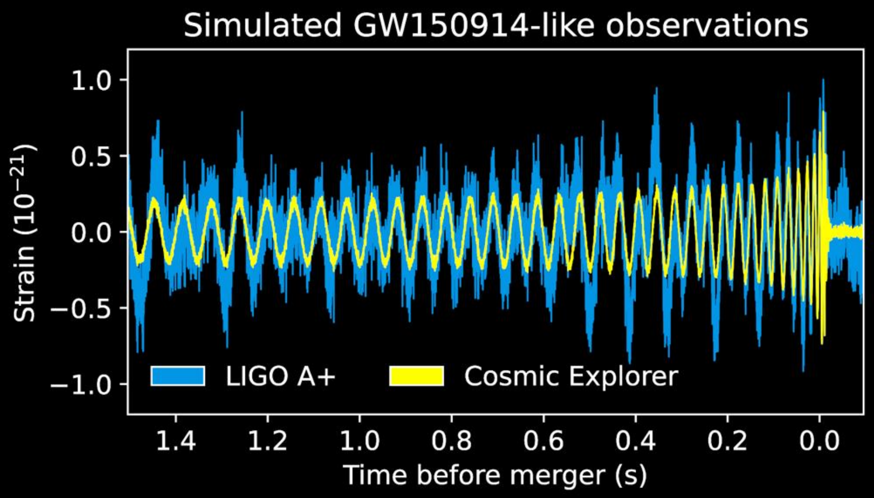
What we can't learn… *yet*

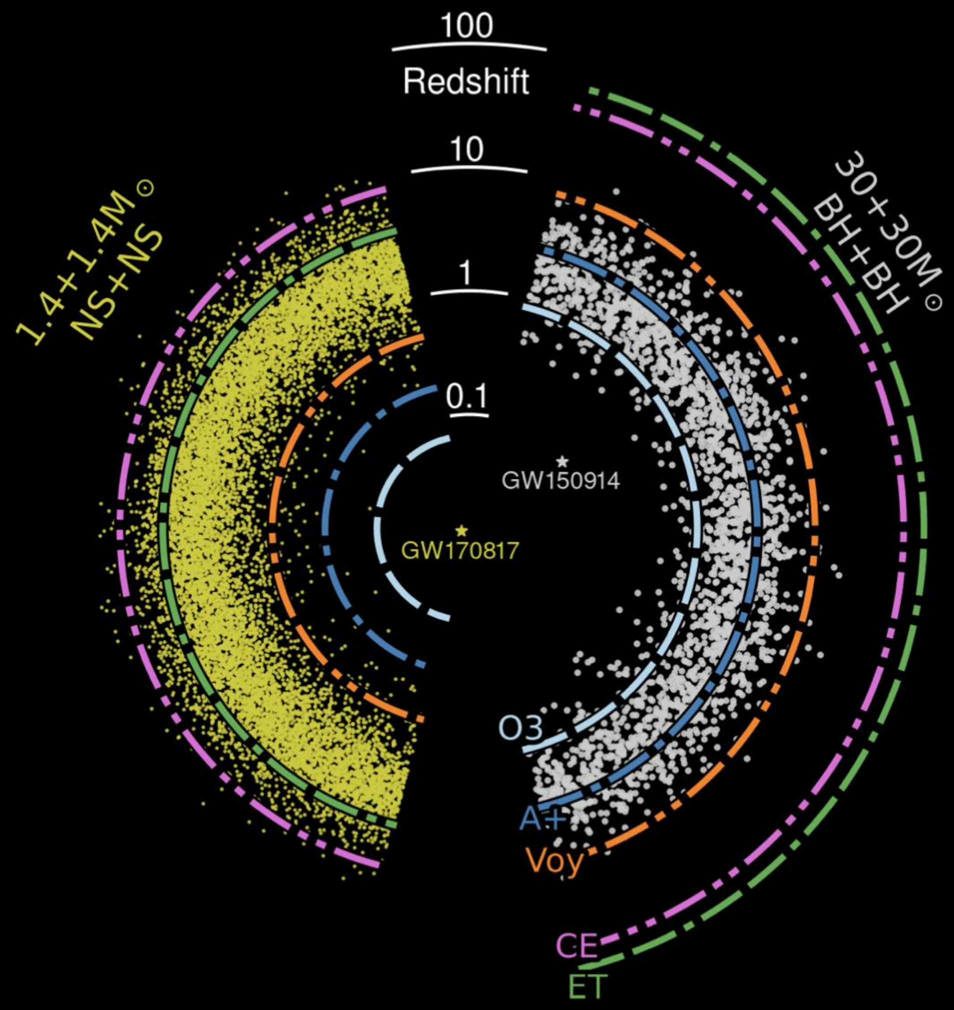
- Binary neutron star mergers beyond cosmic noon
- Precision measurements of the neutron star equation of state
- Binary neutron star postmerger signal
- Binary mergers including Population III and primordial black holes
- Cosmological stochastic gravitational-wave backgrounds



Cosmic Explorer: the next generation







Evans + (inc SB) 2109.09882