Gravitational-wave astrophysics and cosmology

AST3101 Black Holes & Neutron Stars Lecture 6

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Building a Gravitational-Wave Catalog

Search data for interesting triggers and estimate their statistical significance —> list of confident events

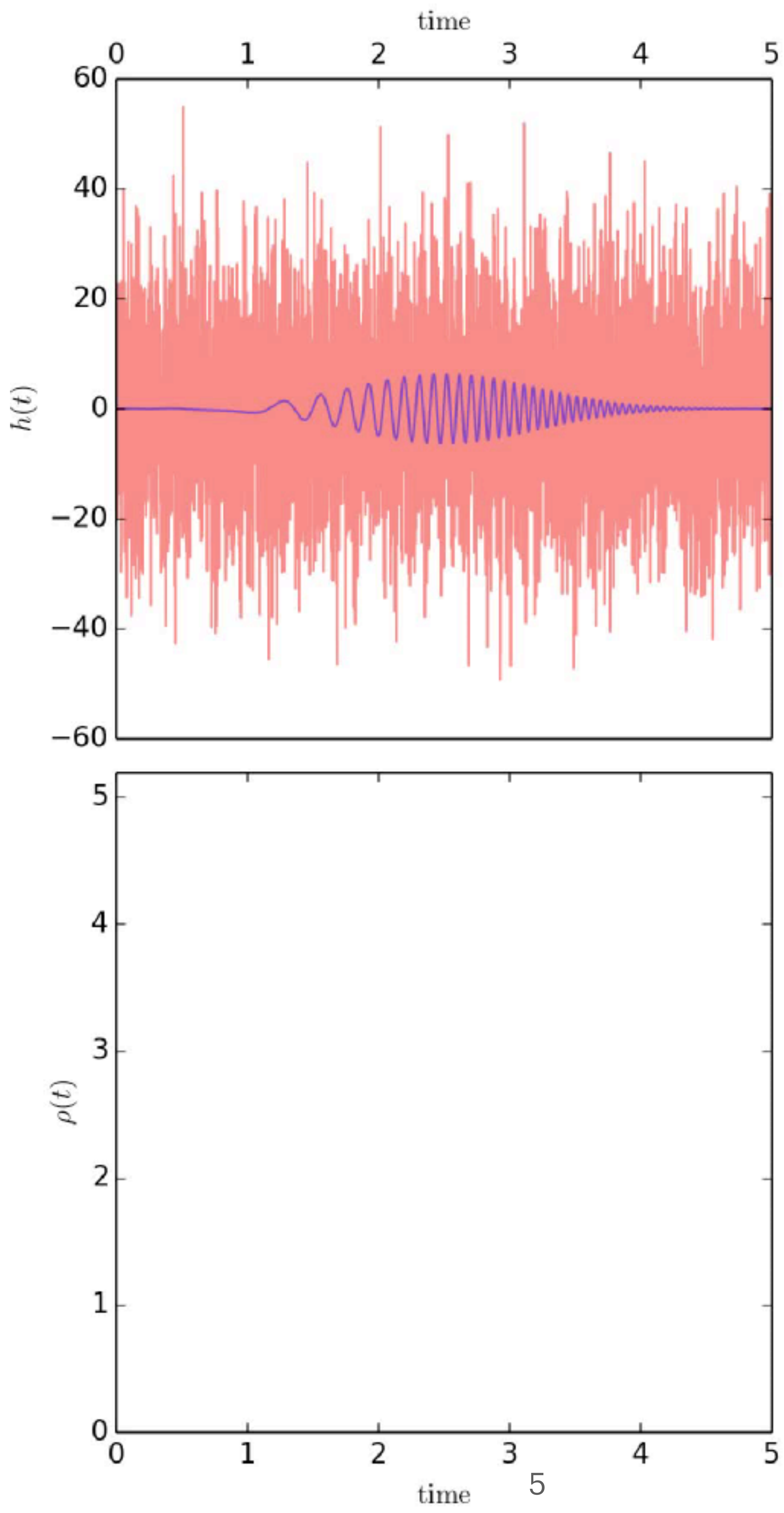
Parameter Estimation: estimate source parameters of events —> parameter estimation posteriors (assuming some default priors)

Do Science: combine events (hierarchical Bayesian inference) to infer physics of binary formation, measure cosmological parameters, test GR, etc.

(Matched-Filter) Searches
(covered in Lecture 3)

Matched-filter SNR timeseries

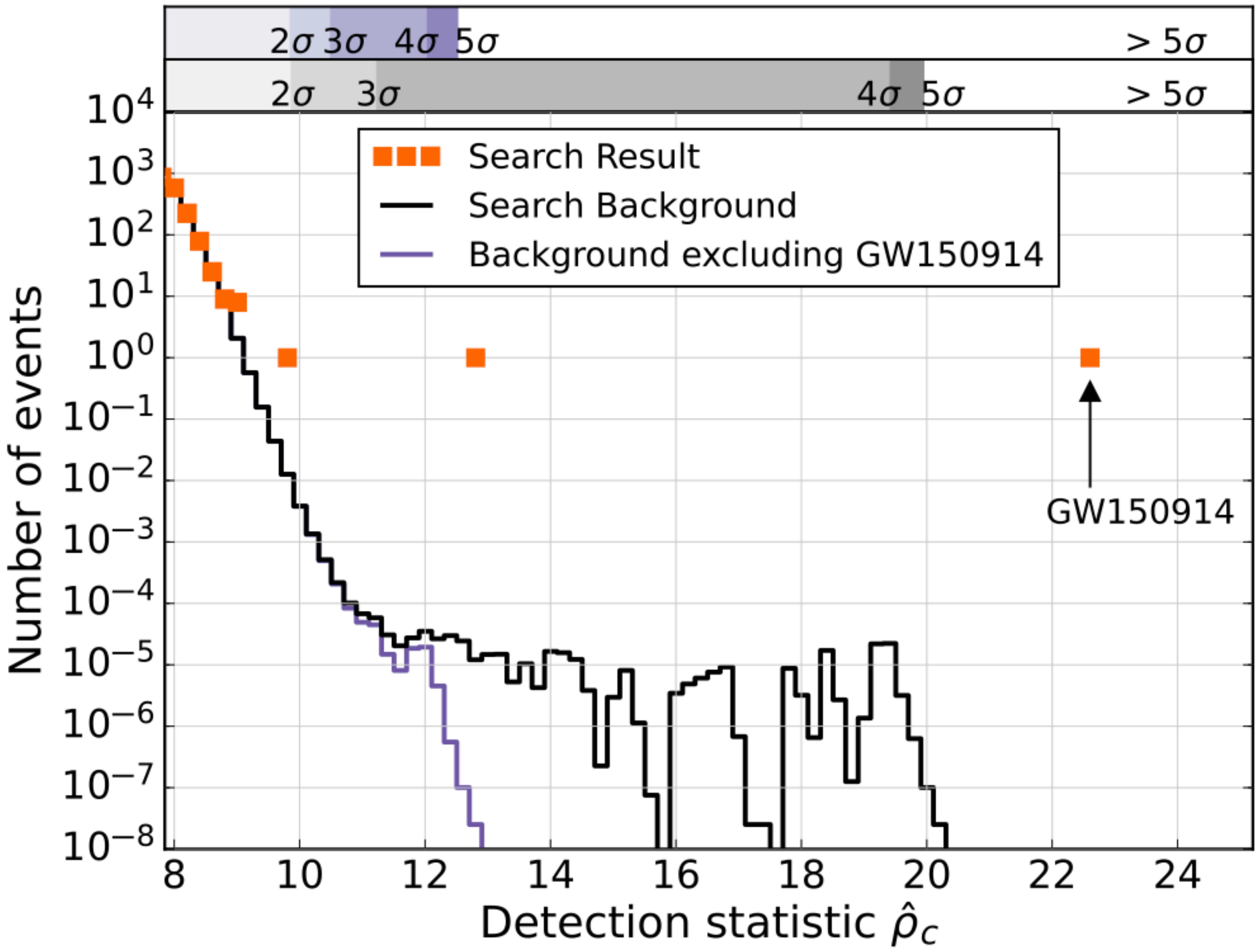
- When we do a search, we don't know the exact signal *s* or when it occurs, all we have is our datastream h(t) and a template bank consisting of templates T(t | ƛ) for different ƛ
- We "slide" the templates over the data and calculate the SNR as a function of the *time shift* between each template and the data
- A spike in the SNR timeseries is a "trigger" — a potential signal of interest



Movie credit: Reed C. Essick

Search significance

- Assign a ranking statistic to triggers, usually resembles the matched-filter signal-to-noise ratio
- How often can noise produce trigger of similar or higher ranking statistic?
- Noise background has to be determined empirically — challenging because we only have a finite observing time and we cannot isolate the noise and collect data without gravitational-waves!
- Determine background using time slides — shift data between detectors by 0.1 seconds, greater than the 10 ms intersite propagation time

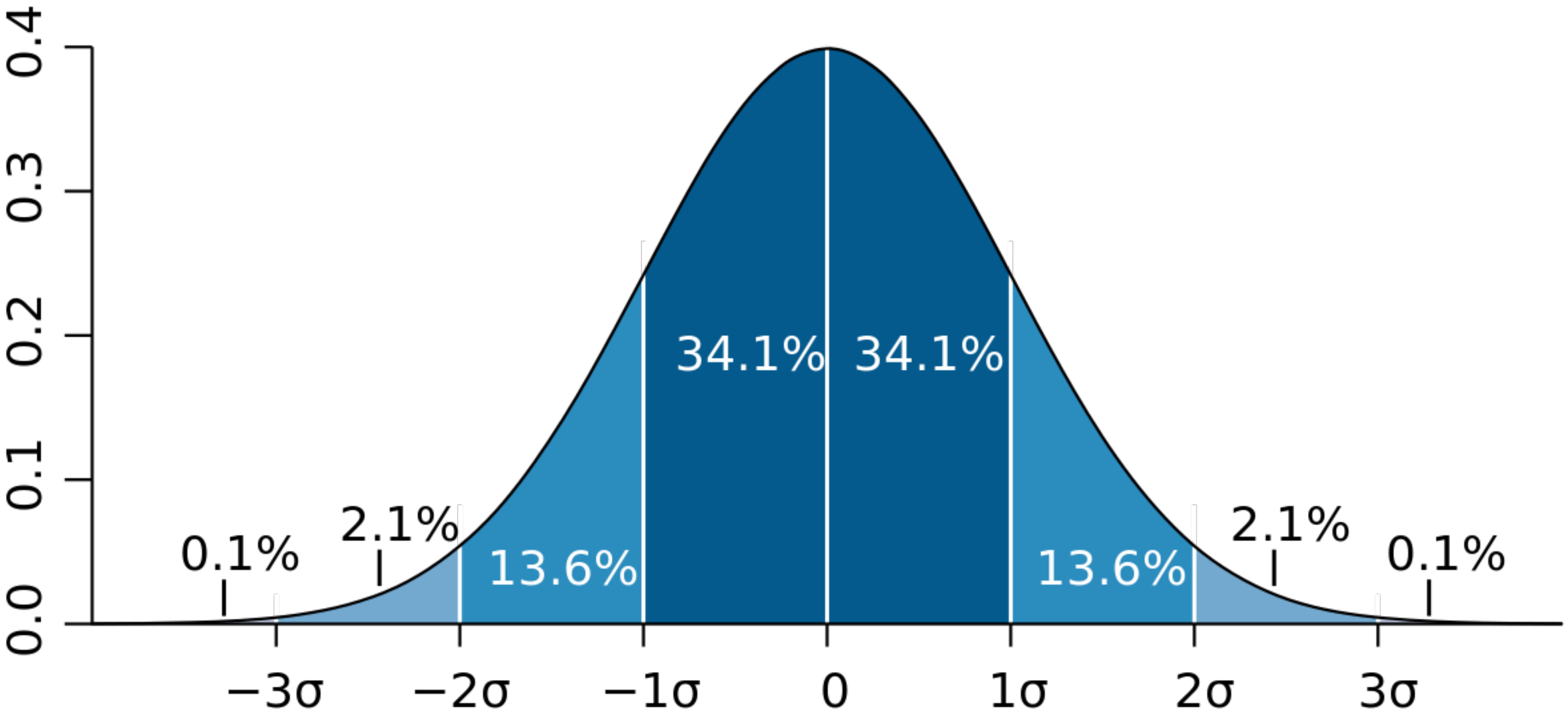


LVC, Phys Rev X 6, 041015 (2016), arXiv:1606.04856

False alarm rate (FAR) and false alarm probability (FAP)

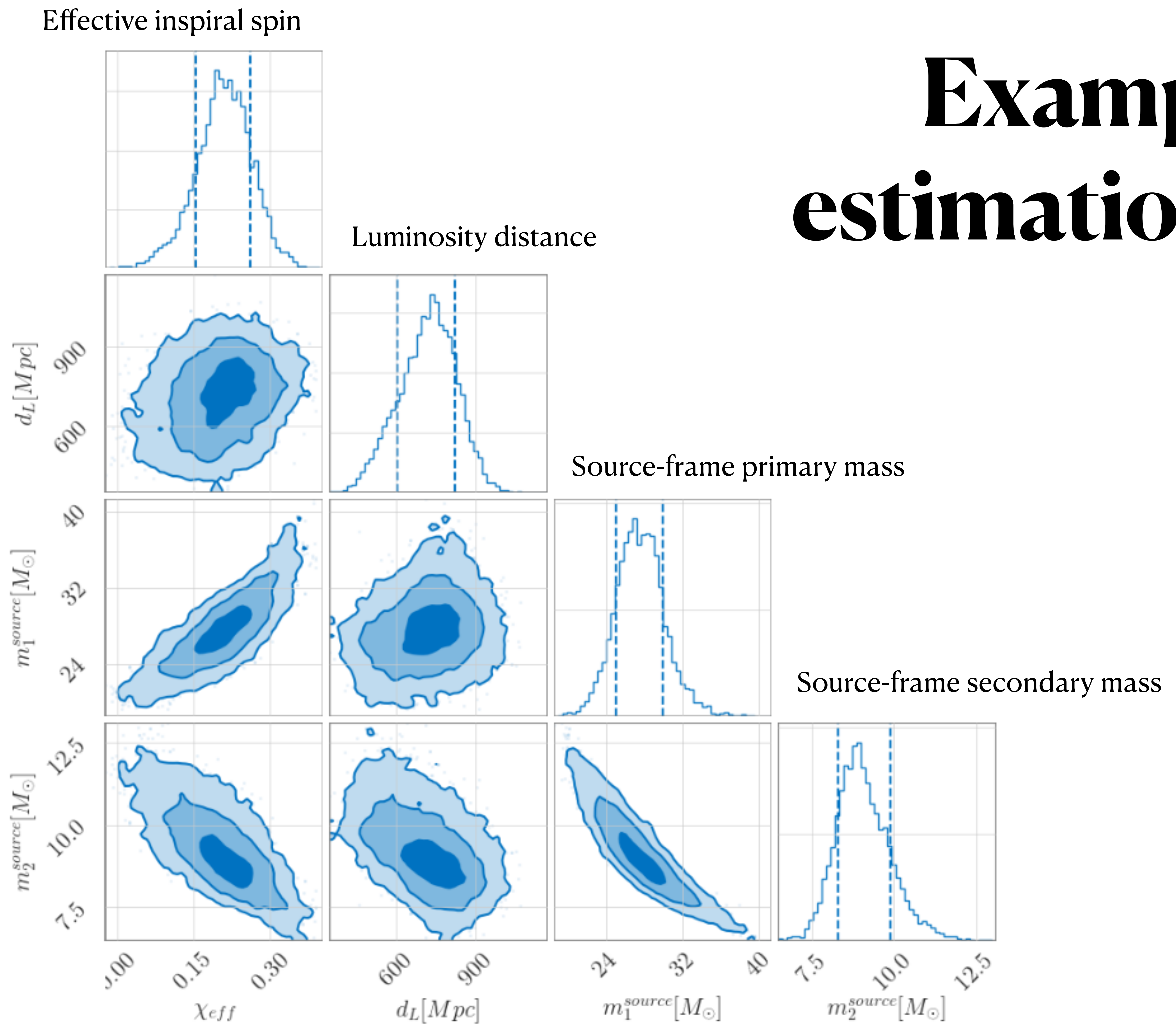
- Null hypothesis: dataset has no GW signal
- If the null hypothesis is true, the rate at which our detectors produce noise triggers of equal to or higher ranking statistics is the FAR (in units of 1/time)
- False alarm probability: takes into account how long we were observing, multiply FAR by observing time.

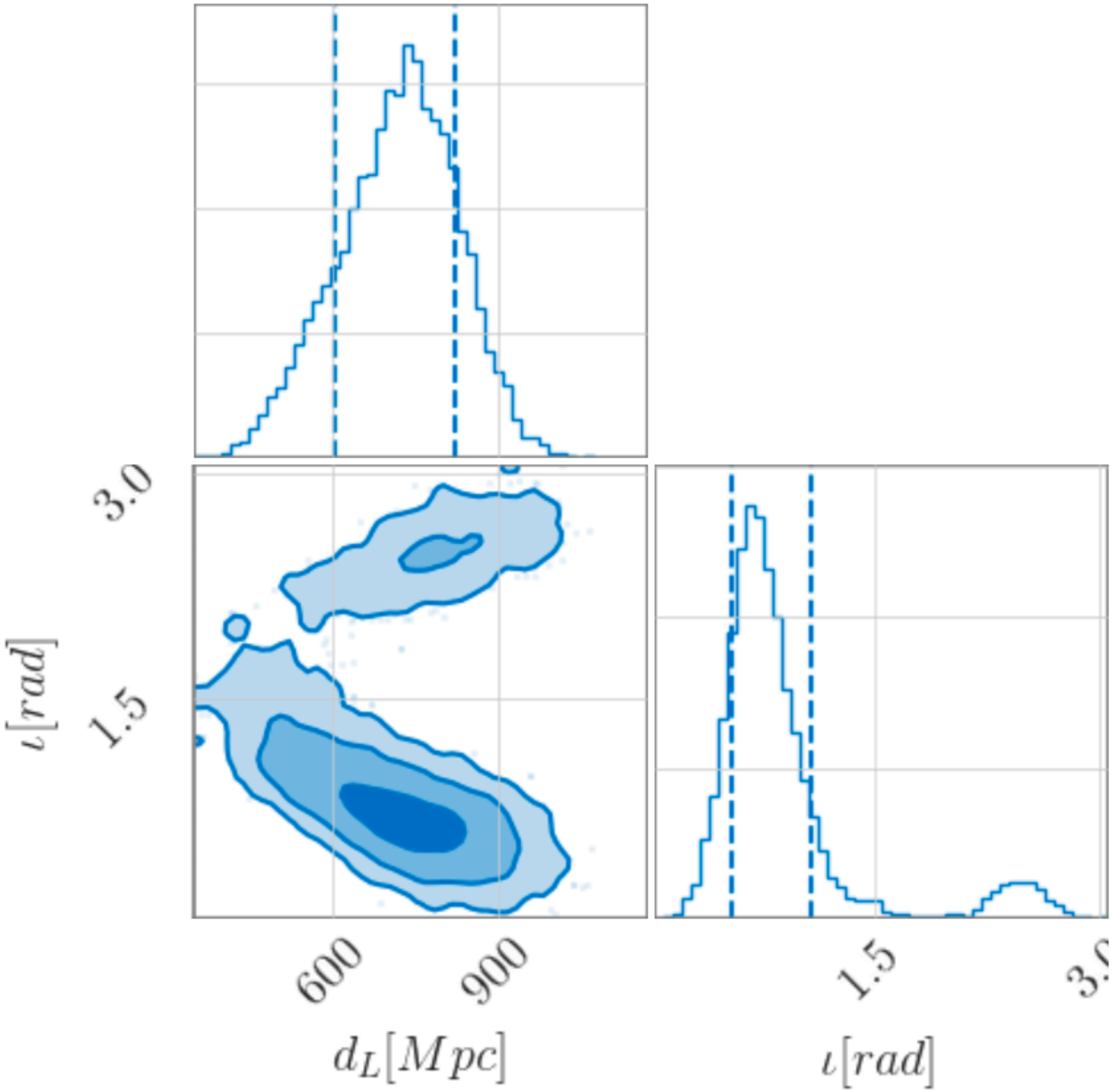
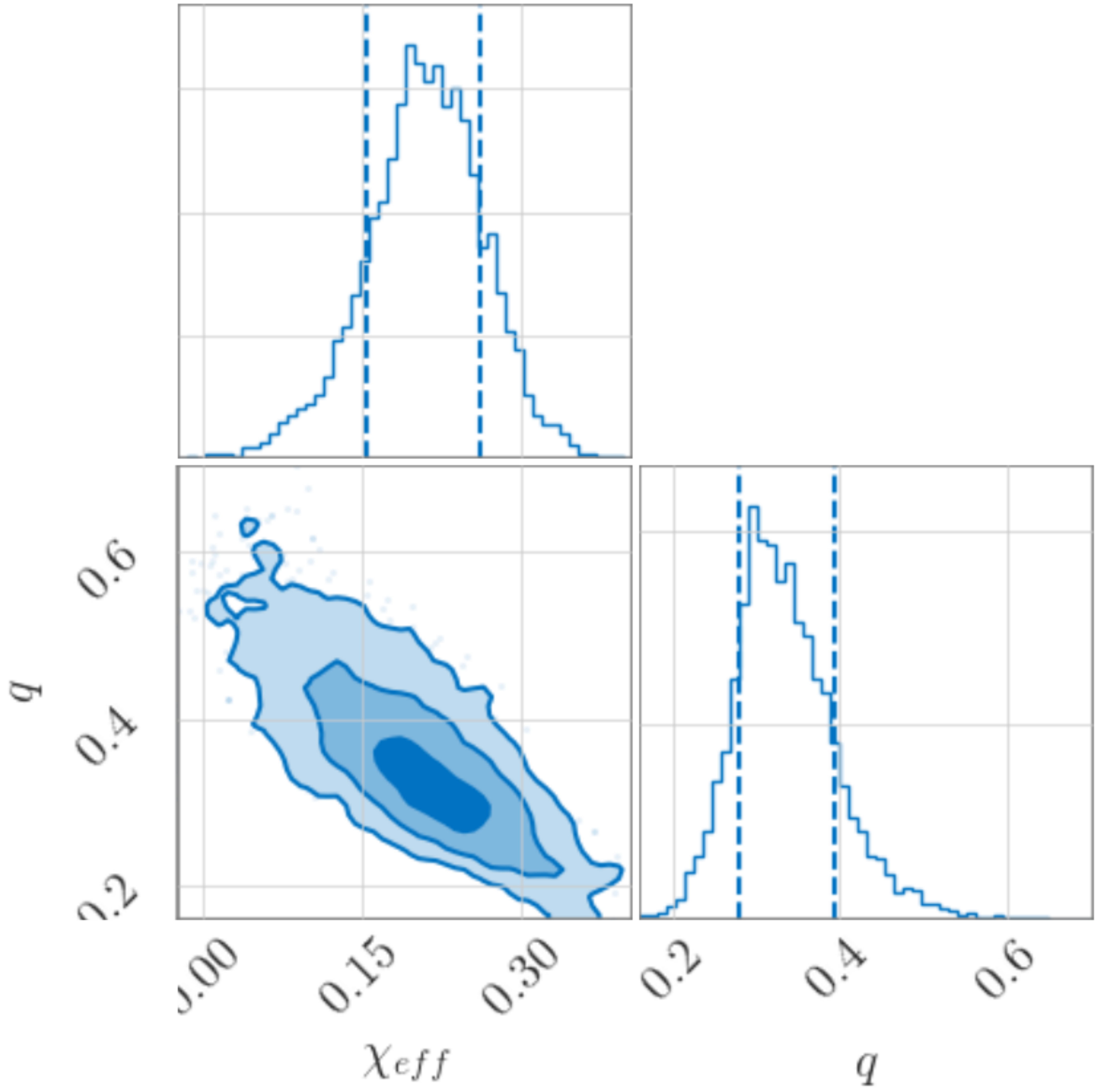
From FAP to a “sigma” statement



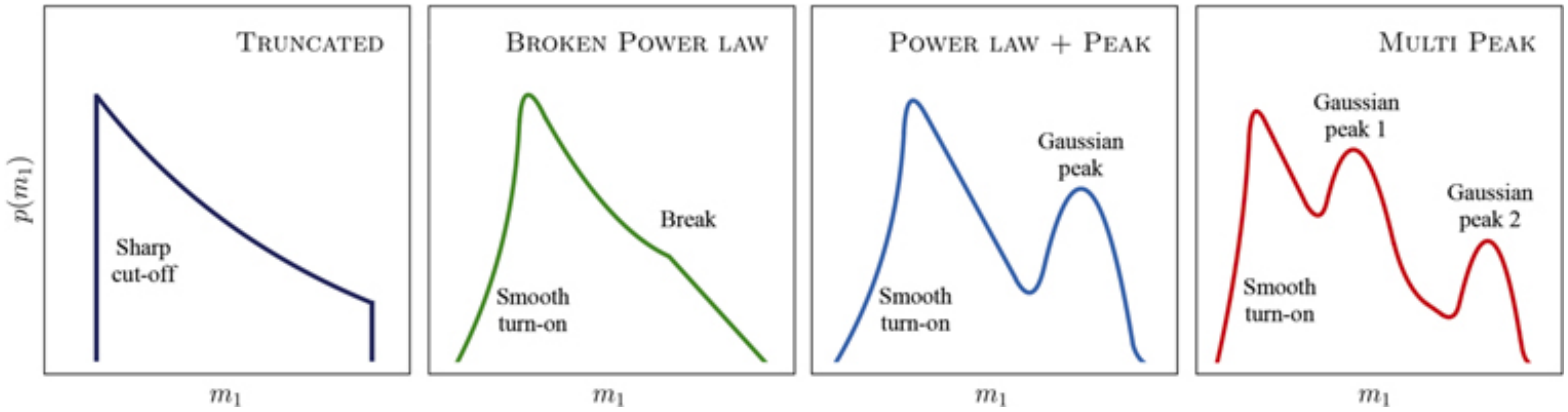
Parameter estimation (Covered in Lecture 4)

Example parameter estimation for GW190412

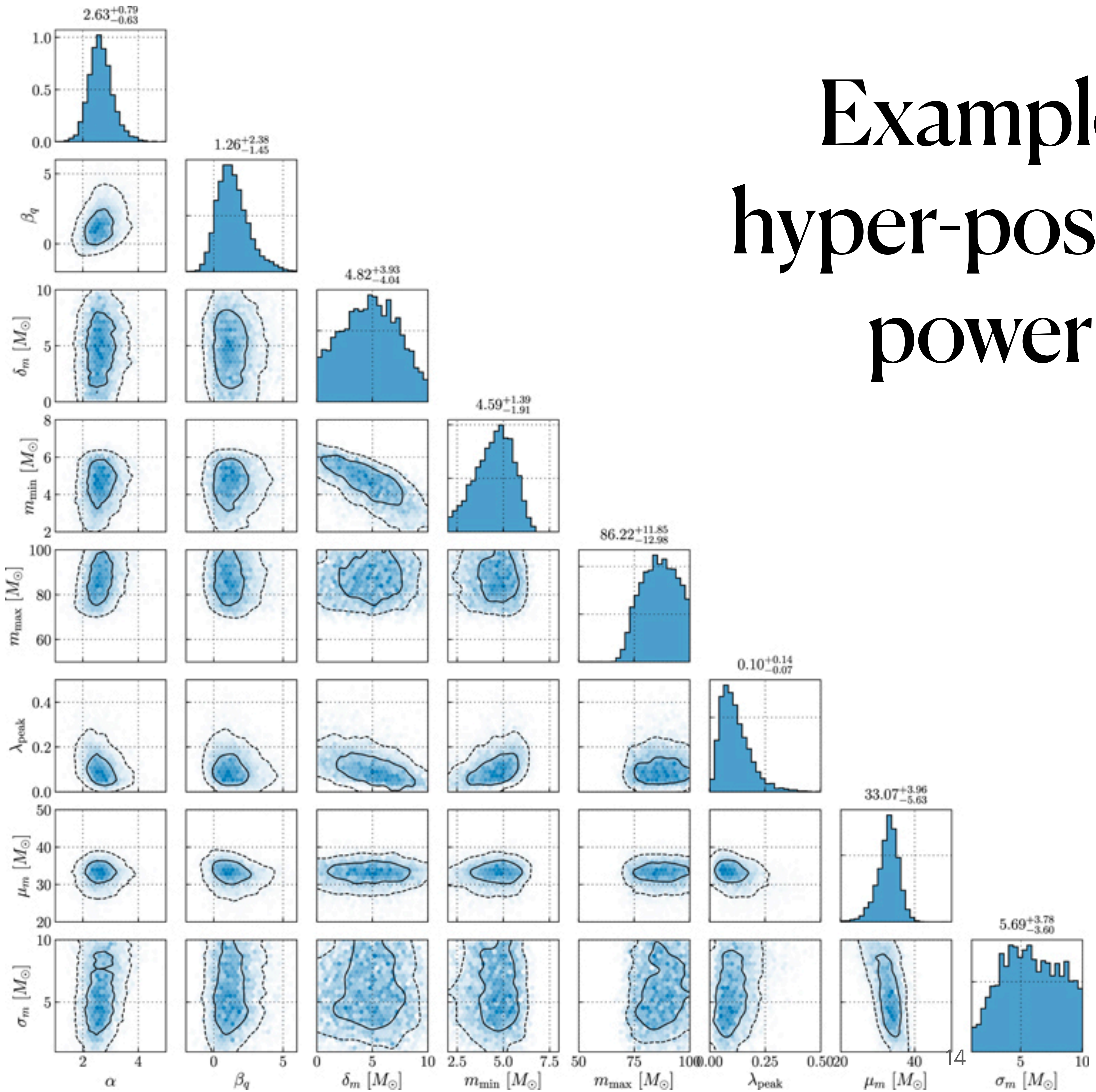



3.0
1.5
ι[rad]
600
900
d_L[Mpc]
1.5
ι[rad]

0.6
0.4
q
0.15
0.30
χ_eff
0.2
0.4
0.6
q

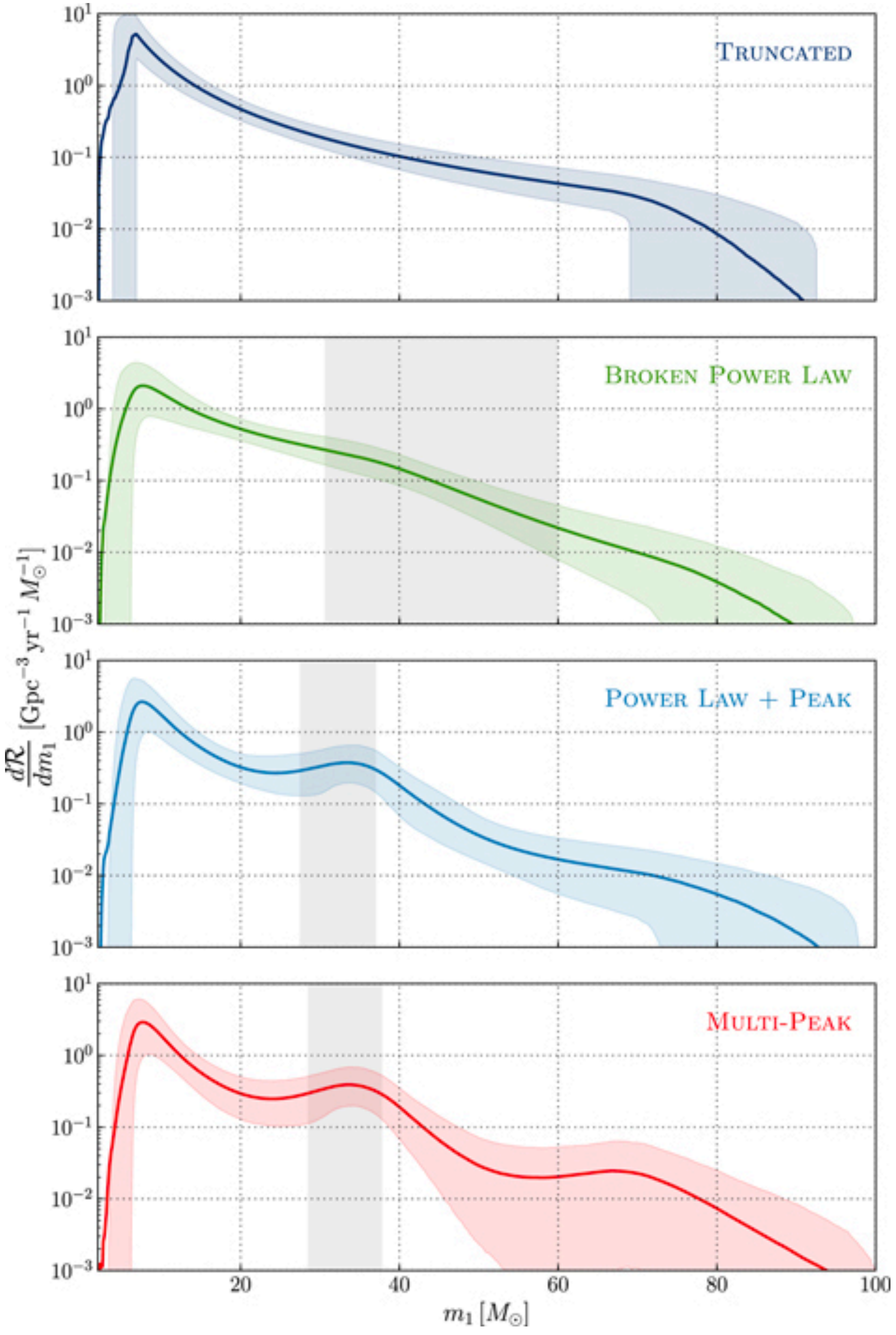
Hierarchical Bayesian Inference



Example mass distribution hyper-posterior with GWTC-2, power law + peak model



Inferred merger rate per primary mass with GWTC-2



Cosmology with Compact Binary Coalescences

Gravitational-wave mergers as cosmological probes

Standard Sirens: Binary coalescences provide a direct measurement of the luminosity distance (Schutz 1986)…

frequency

position and orientation

GW strain

$$h(t) = \frac{\mathcal{M}_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos(\Phi(t))$$

phase

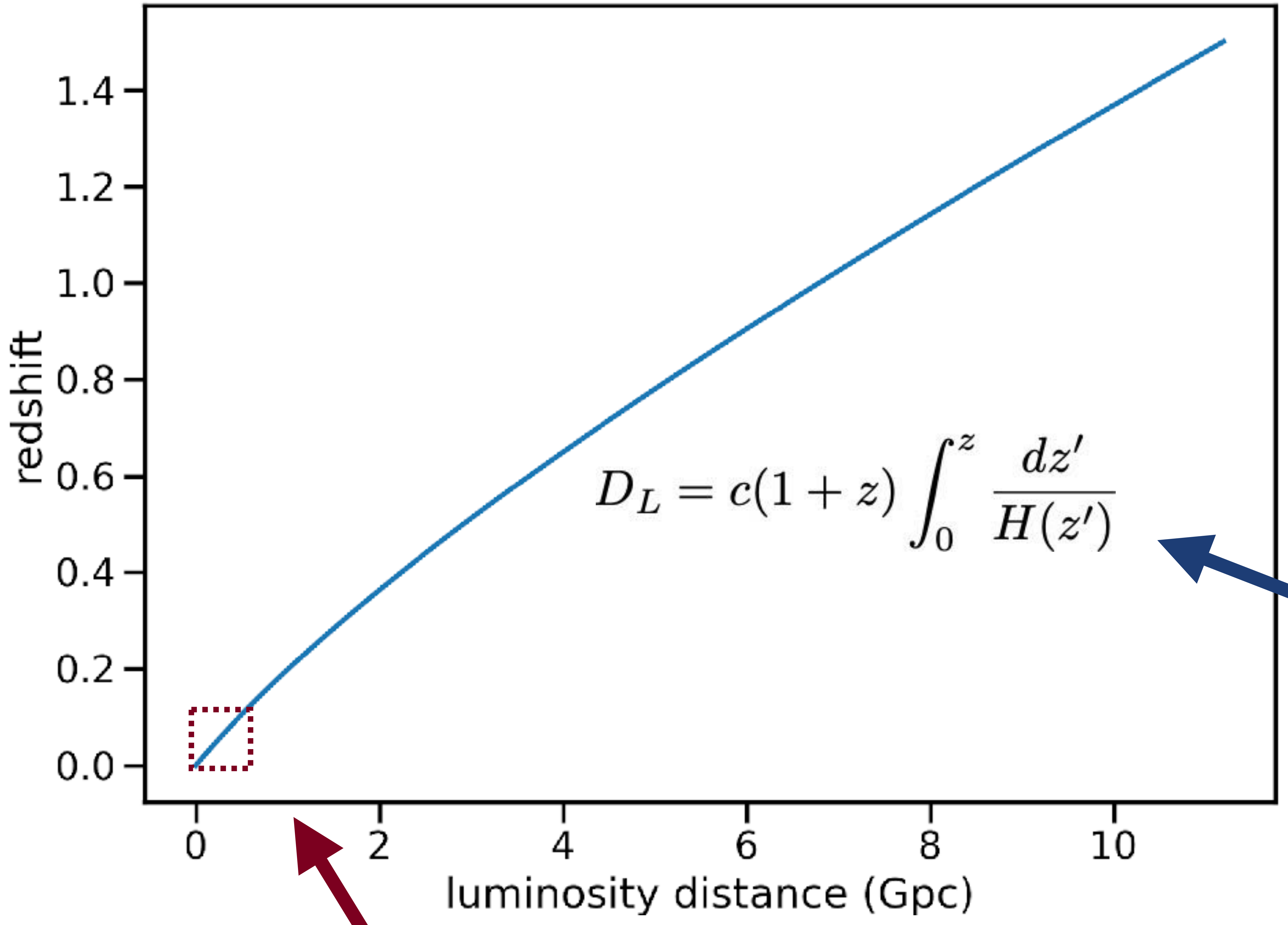
luminosity distance

redshifted chirp mass

$$\mathcal{M}_z = \left(\frac{5}{96} \pi^{-8/3} \left(f(t)\right)^{-11/3} \dot{f}(t) \right)^{3/5}$$

…but the redshift is degenerate with mass.

Goal: measure the redshift—distance relation



And thereby infer cosmological parameters

Depends on constituents of the Universe: matter density, dark energy density, dark energy equation of state

Local slope is the *Hubble constant*

GW170817: A standard siren with an electromagnetic counterpart

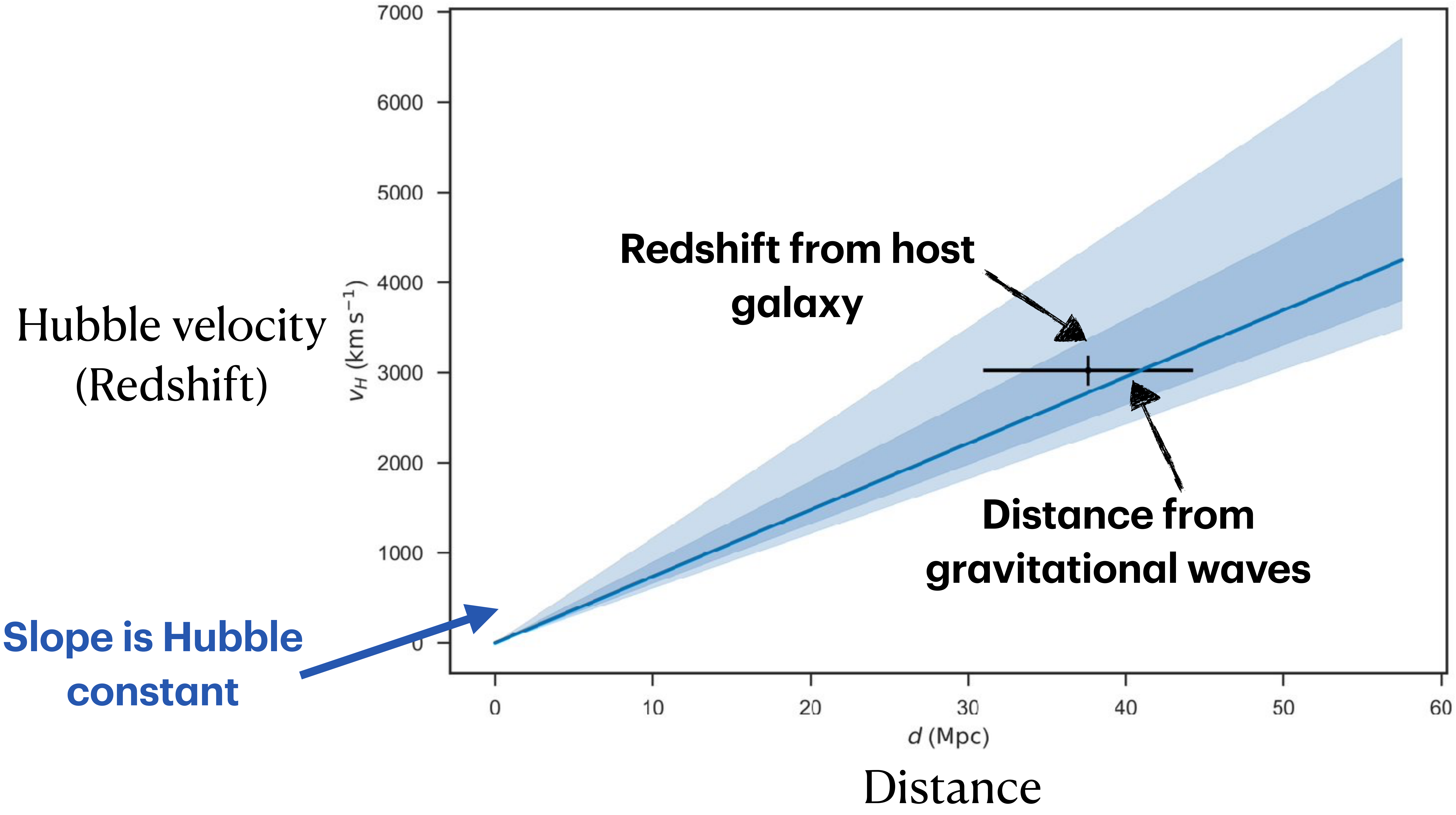
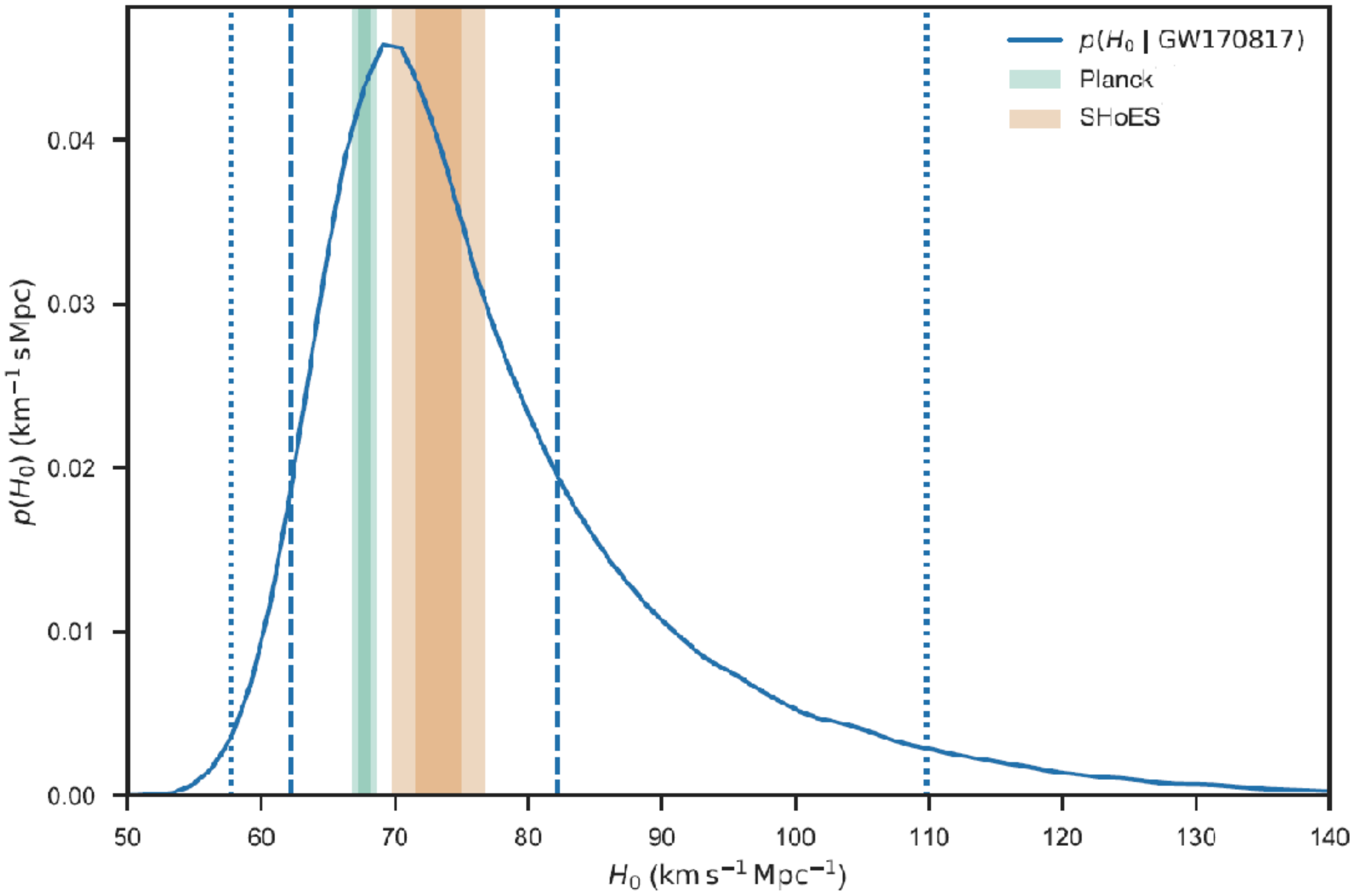


Figure Credit: Will Farr/ LIGO Scientific Collaboration

Hubble constant measurement from GW170817

$$H_0 = 70^{+12}_{-8}\ \mathrm{km/s/Mpc}$$



Abbott et al. *Nature* 551, 85-88 (2017)

Standard Siren Flavors

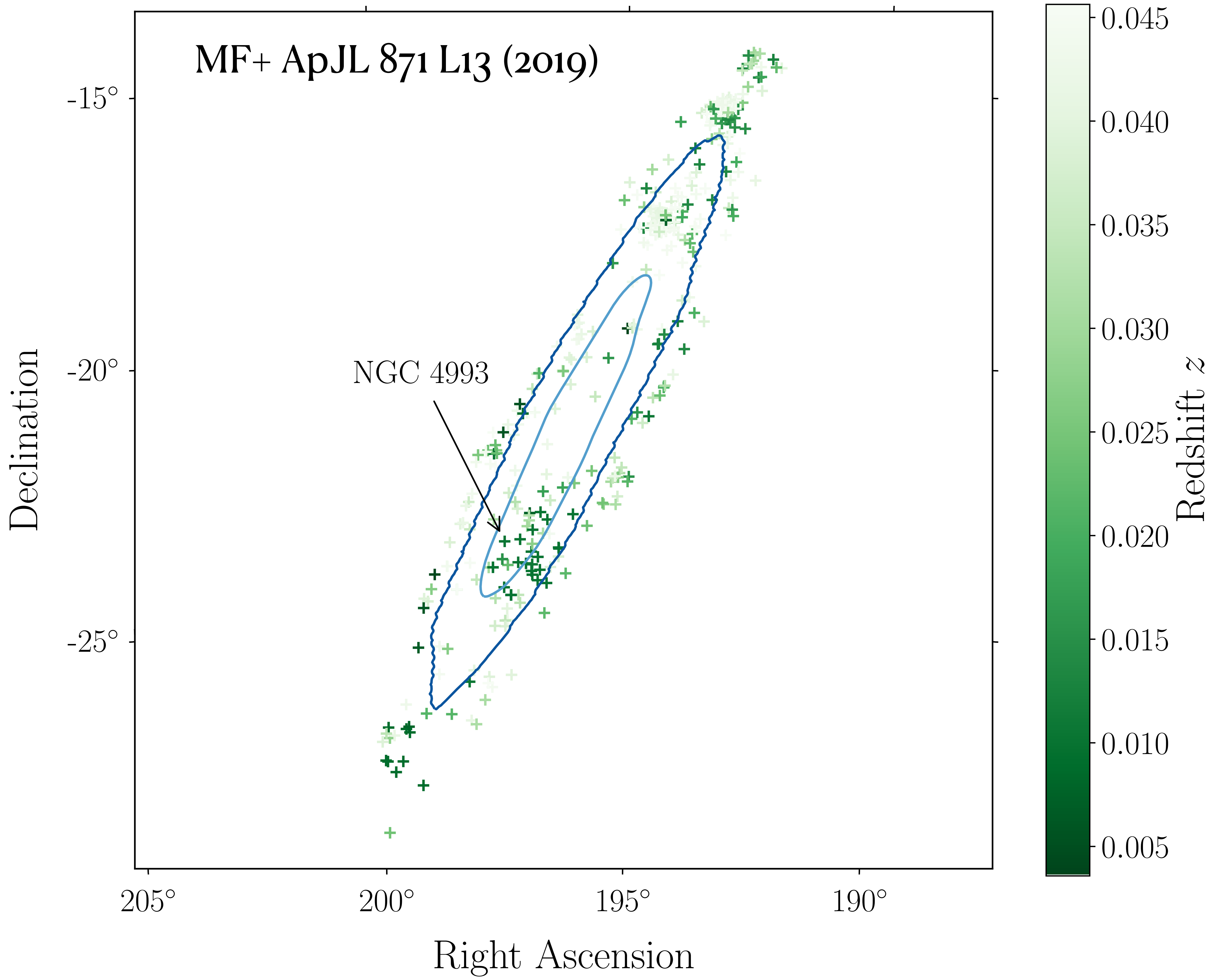
How can we learn the source redshift?

- **Bright:** unique host galaxy
- **Dark:** statistical distribution of redshifts
- **Spectral:** features in source-frame mass distribution

Dark Sirens

Statistical distribution of redshifts

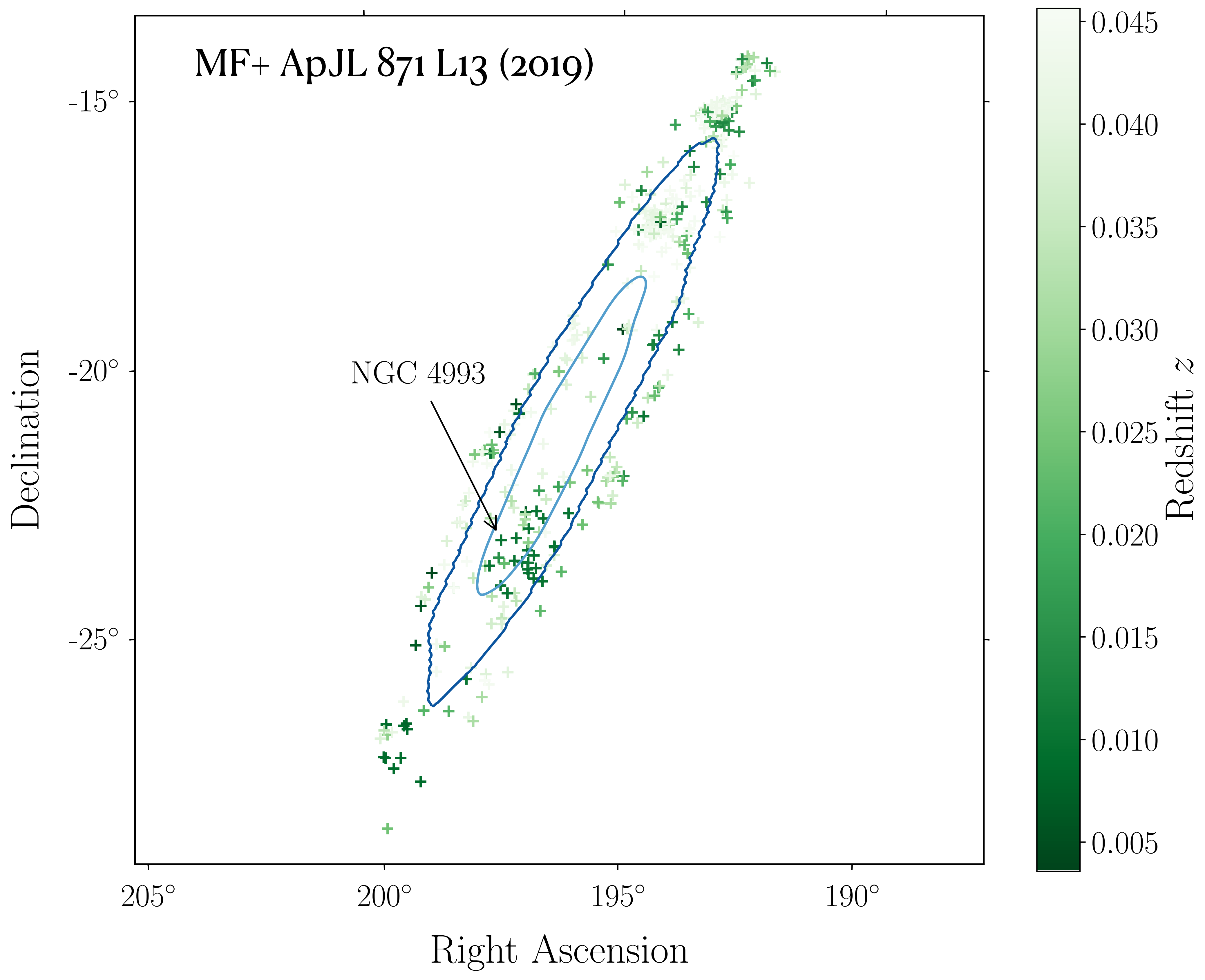
- Host galaxy catalog
- Large scale structure
- External knowledge of merger rate evolution with redshift



Standard sirens with galaxy catalogs

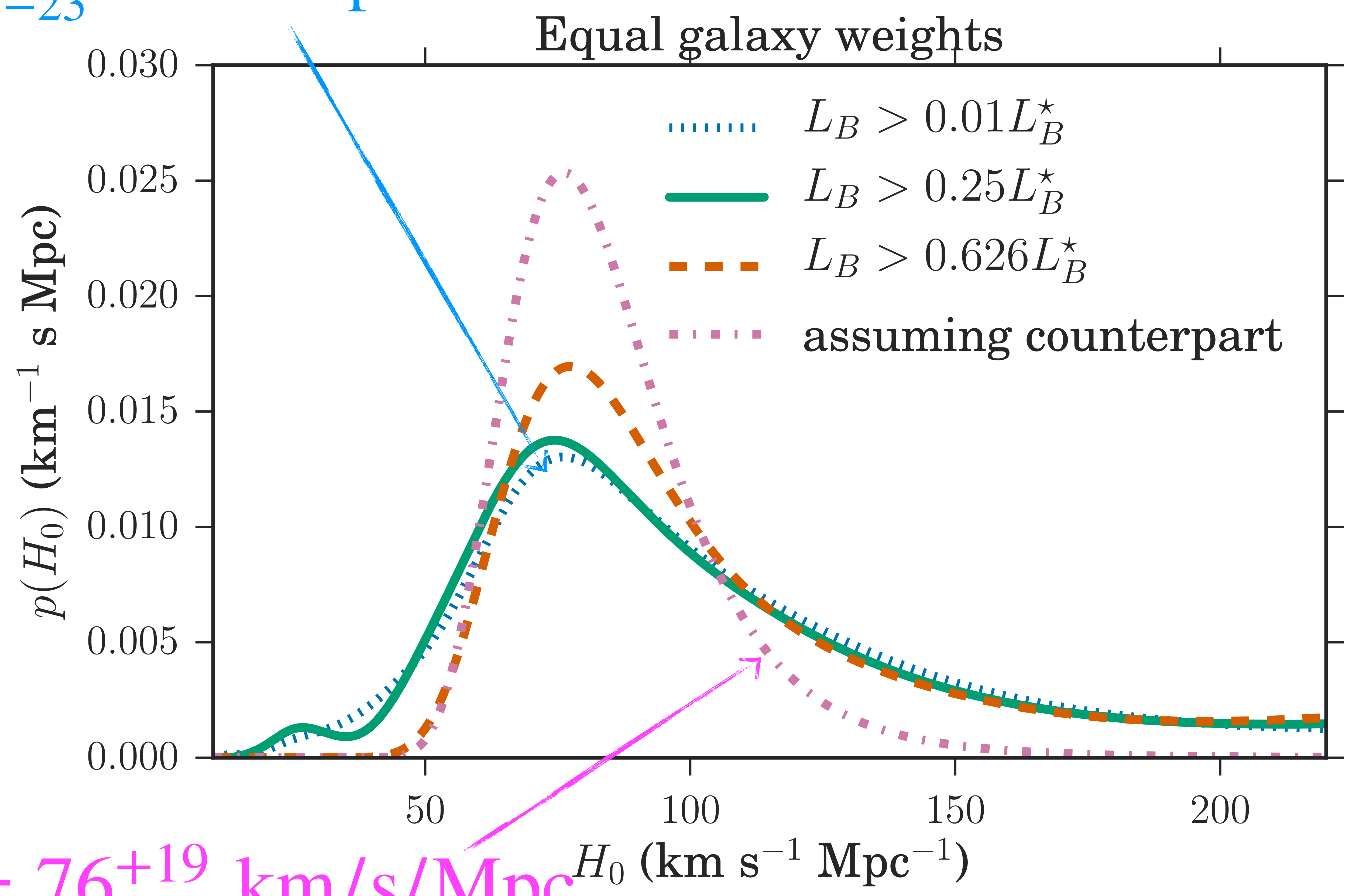
What if we didn’t know GW170817’s host galaxy?

- From GW data, 90% sky localization of 16 sq. deg
- Consider all ~400 galaxies in GW localization volume
- Most of the galaxies belong to a single group, containing NGC 4993



(Exceptionally) informative Hubble constant measurement

$H_0 = 76^{+48}_{-23}$ km/s/Mpc



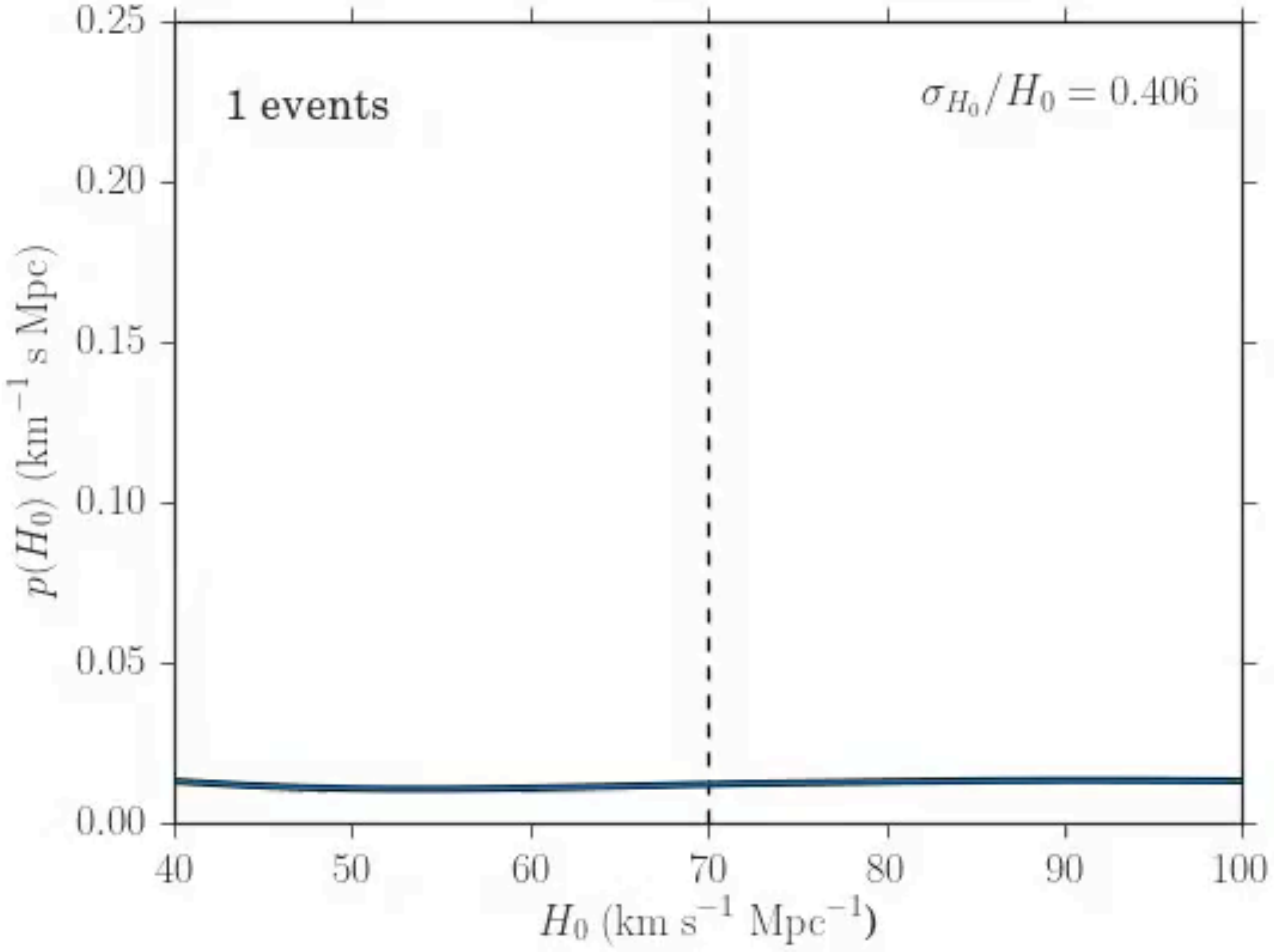
$H_0 = 76^{+19}_{-13}$ km/s/Mpc

MF+ ApJL 871 L13 (2019)

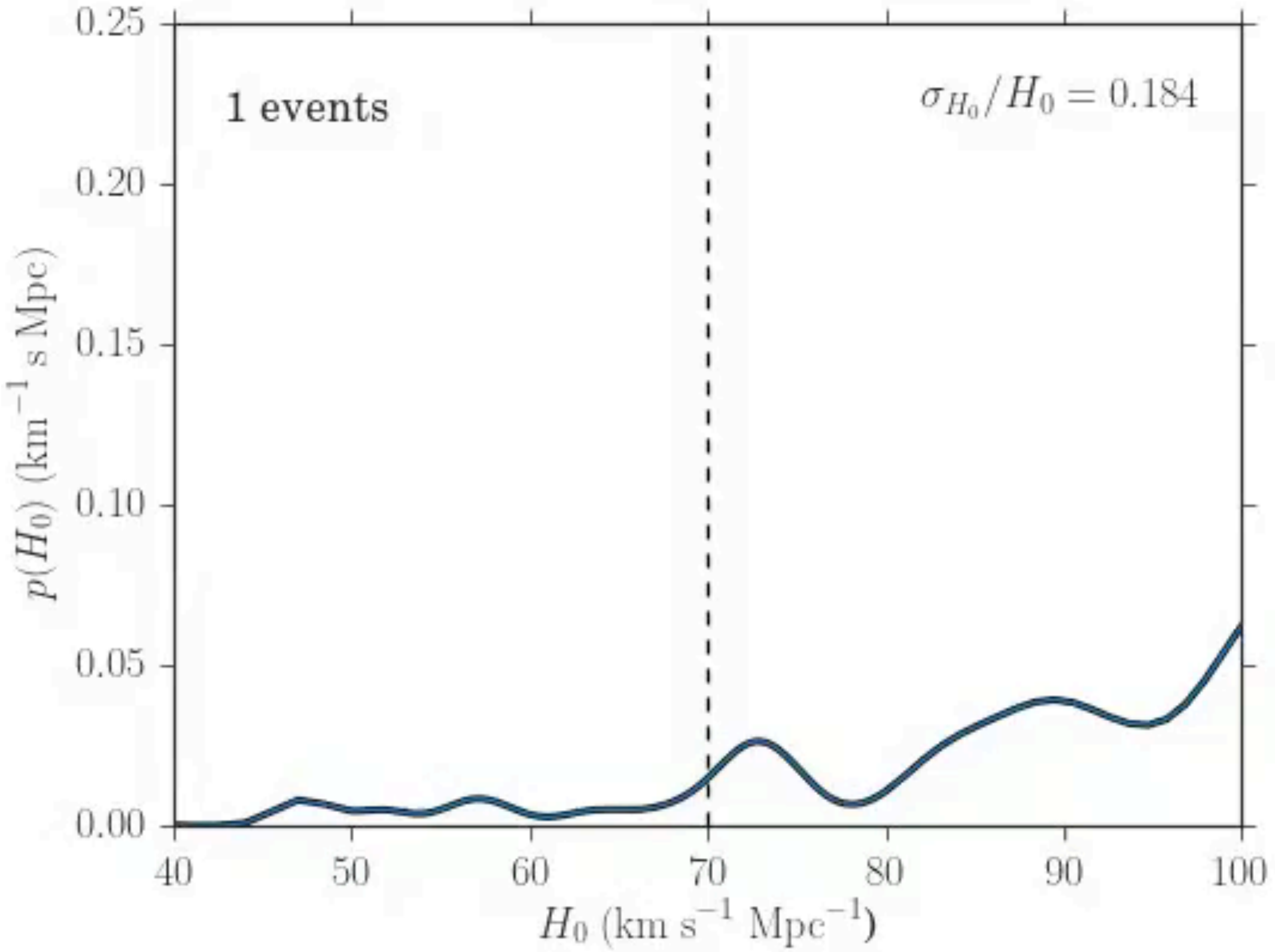
Comparing the galaxy catalog to the counterpart method

For binary neutron stars, convergence is ~7 times slower with galaxy catalog compared to unique host. For black holes, convergence is slower because localization volumes are bigger.

Statistical



Counterpart

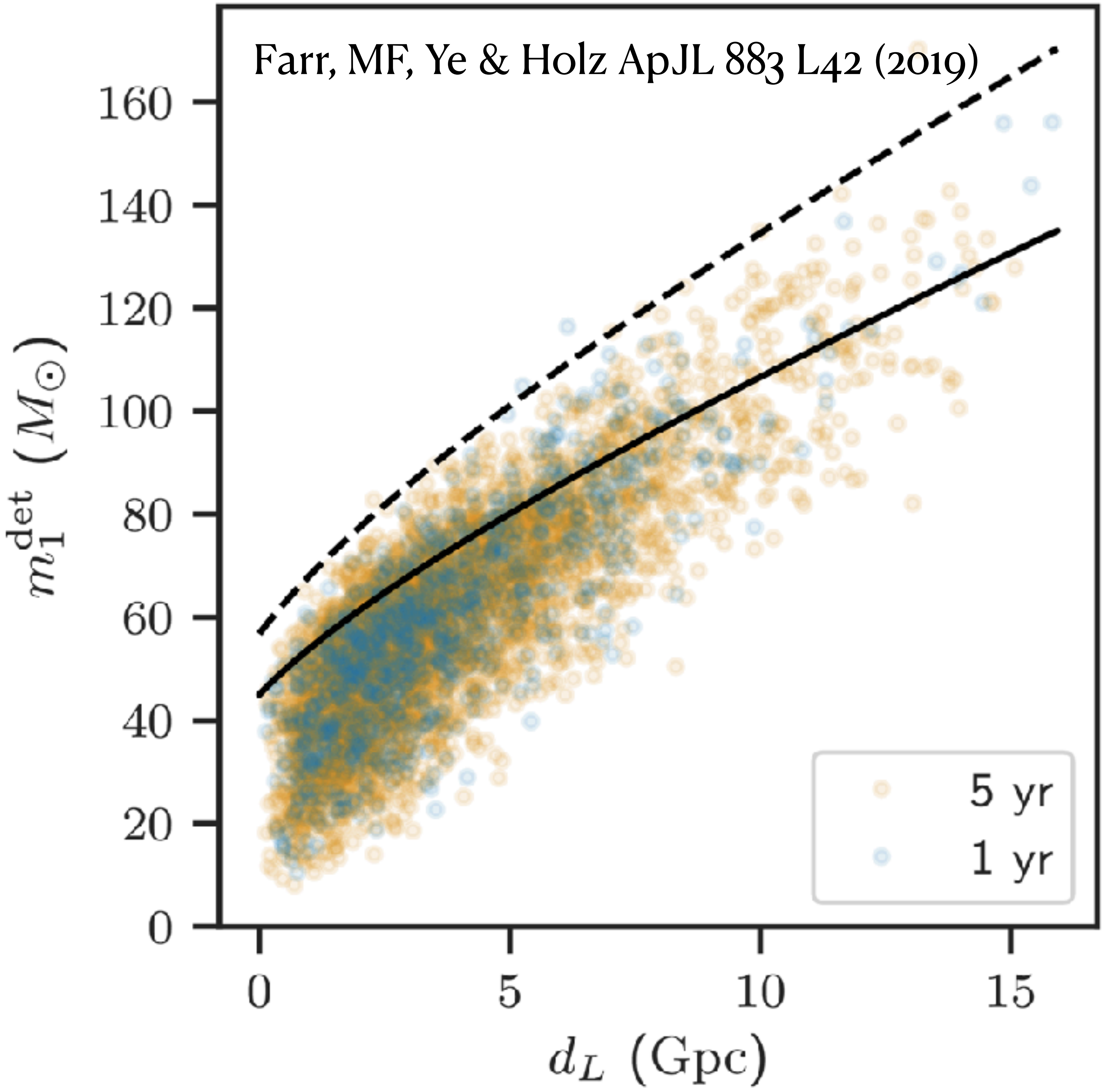


Combined measurement with N events converges as ~40%/√N compared to ~15%/√N for sources with a counterpart

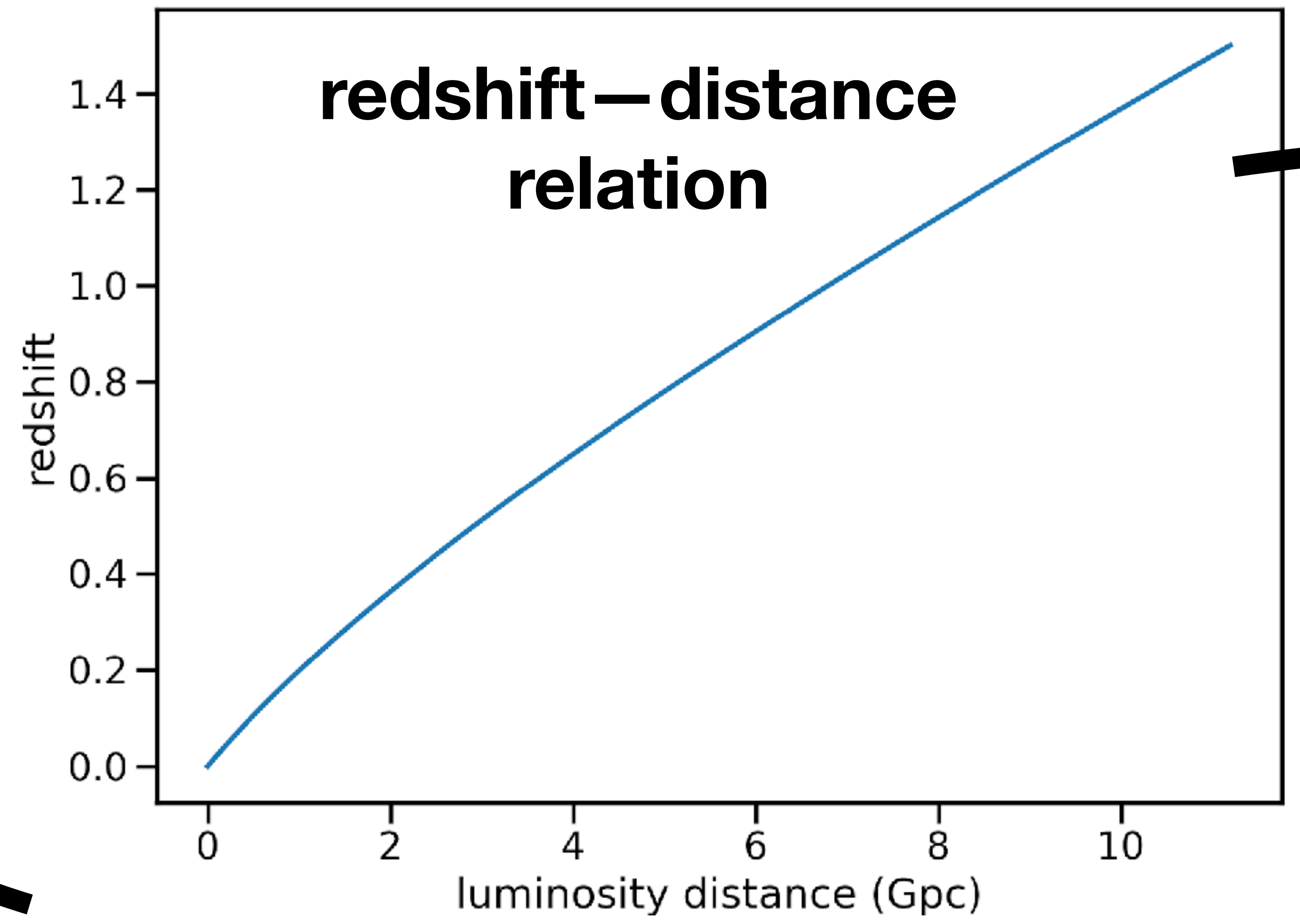
Chen, MF & Holz Nature 562 545 (2018)
MF+ ApJL 871 L13 (2019)

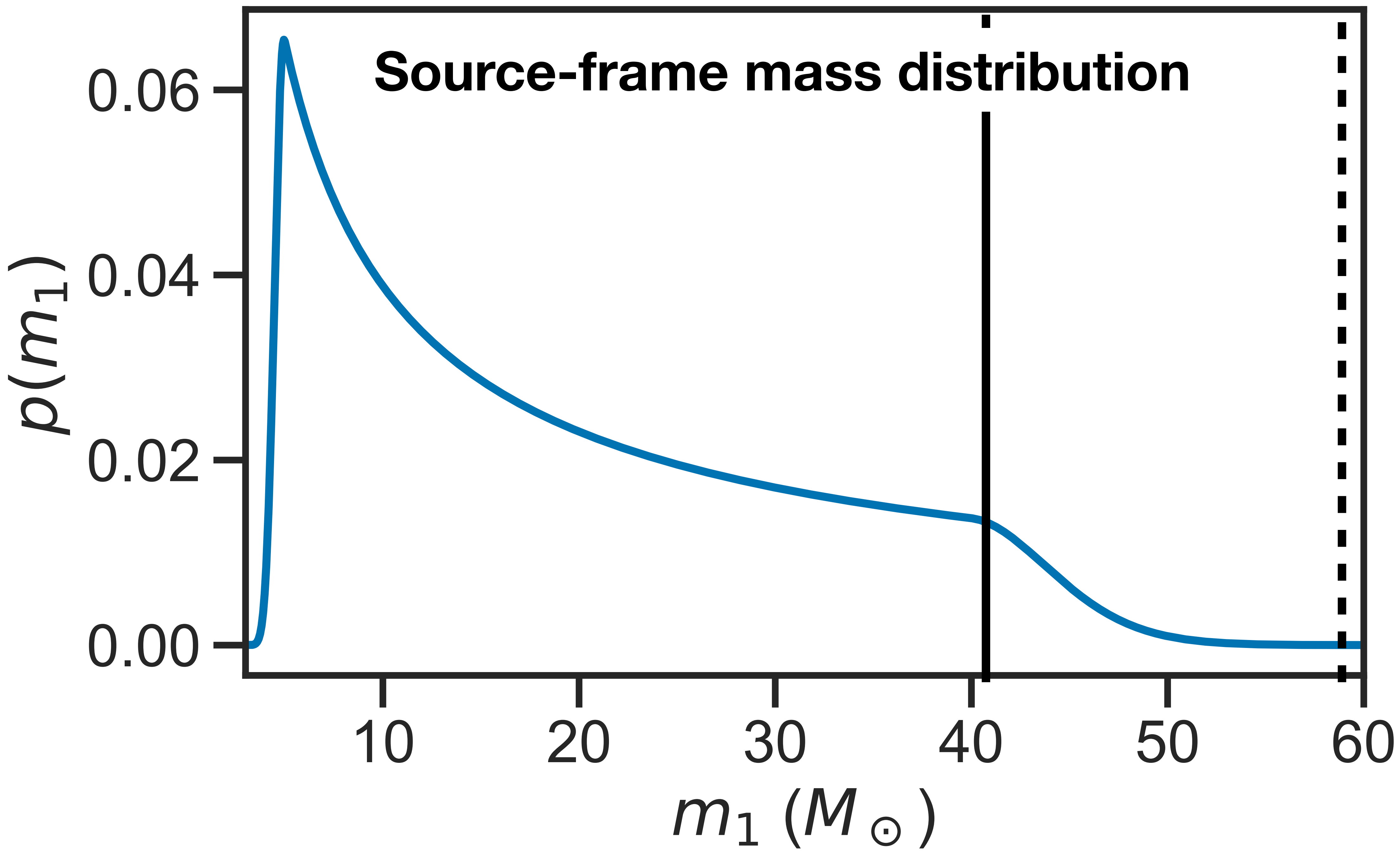
Spectral Sirens

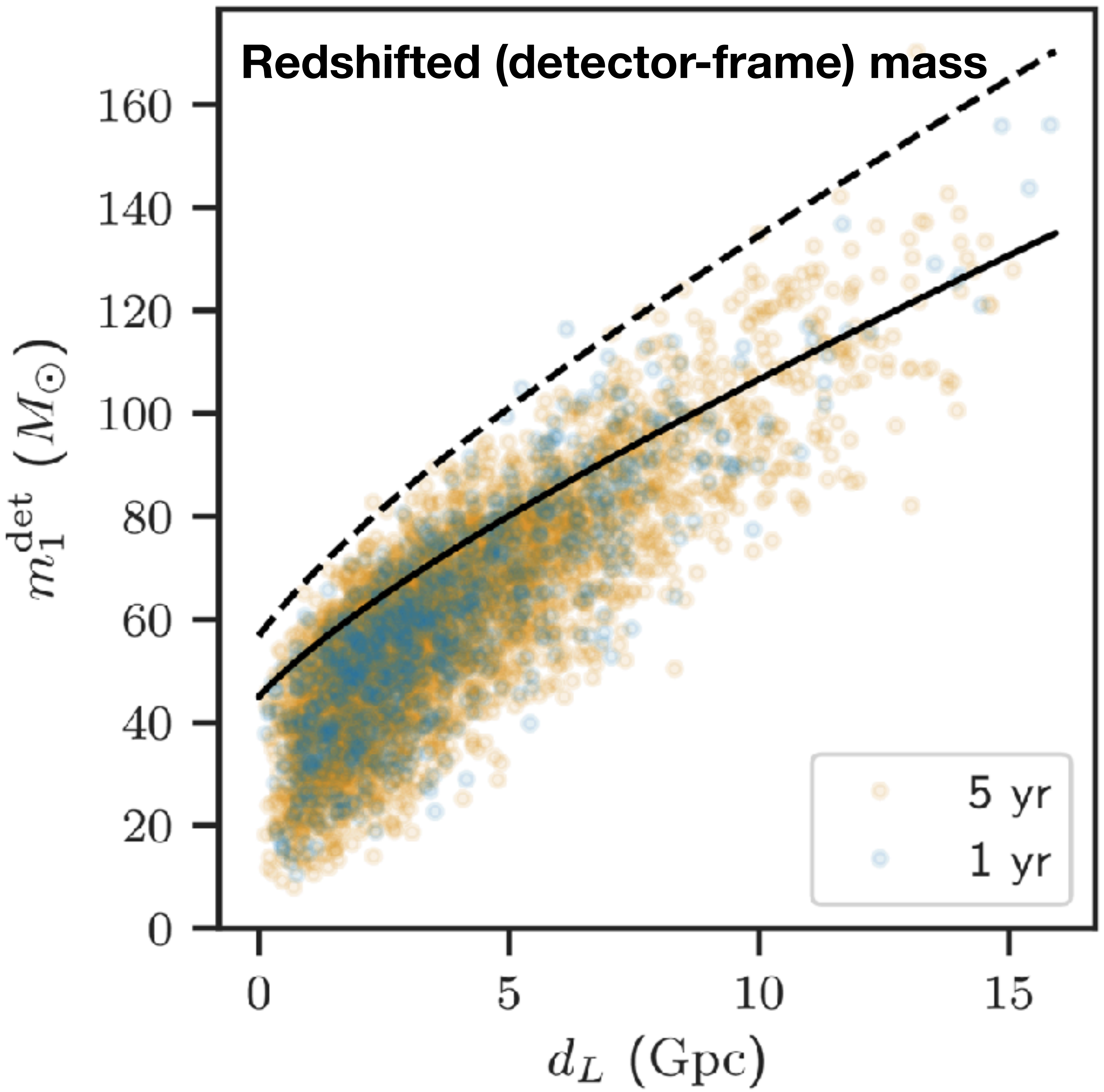
Features in the source-frame spectrum get redshifted



Simultaneously infer source population and redshift—distance relation







Farr, MF, Ye & Holz ApJL 883 L42 (2019)

Distinguish dynamical assembly and isolated binary evolution with spin statistics

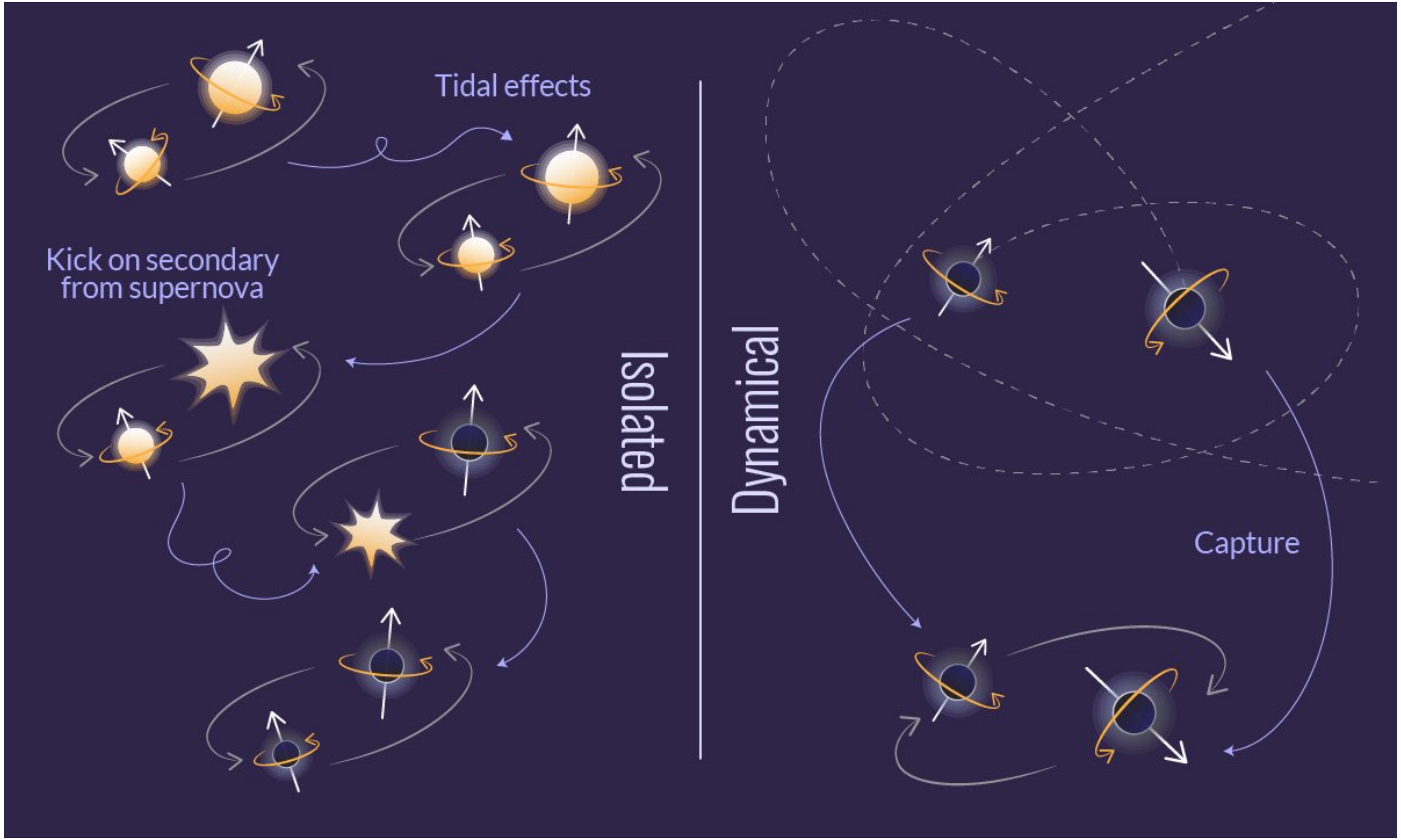
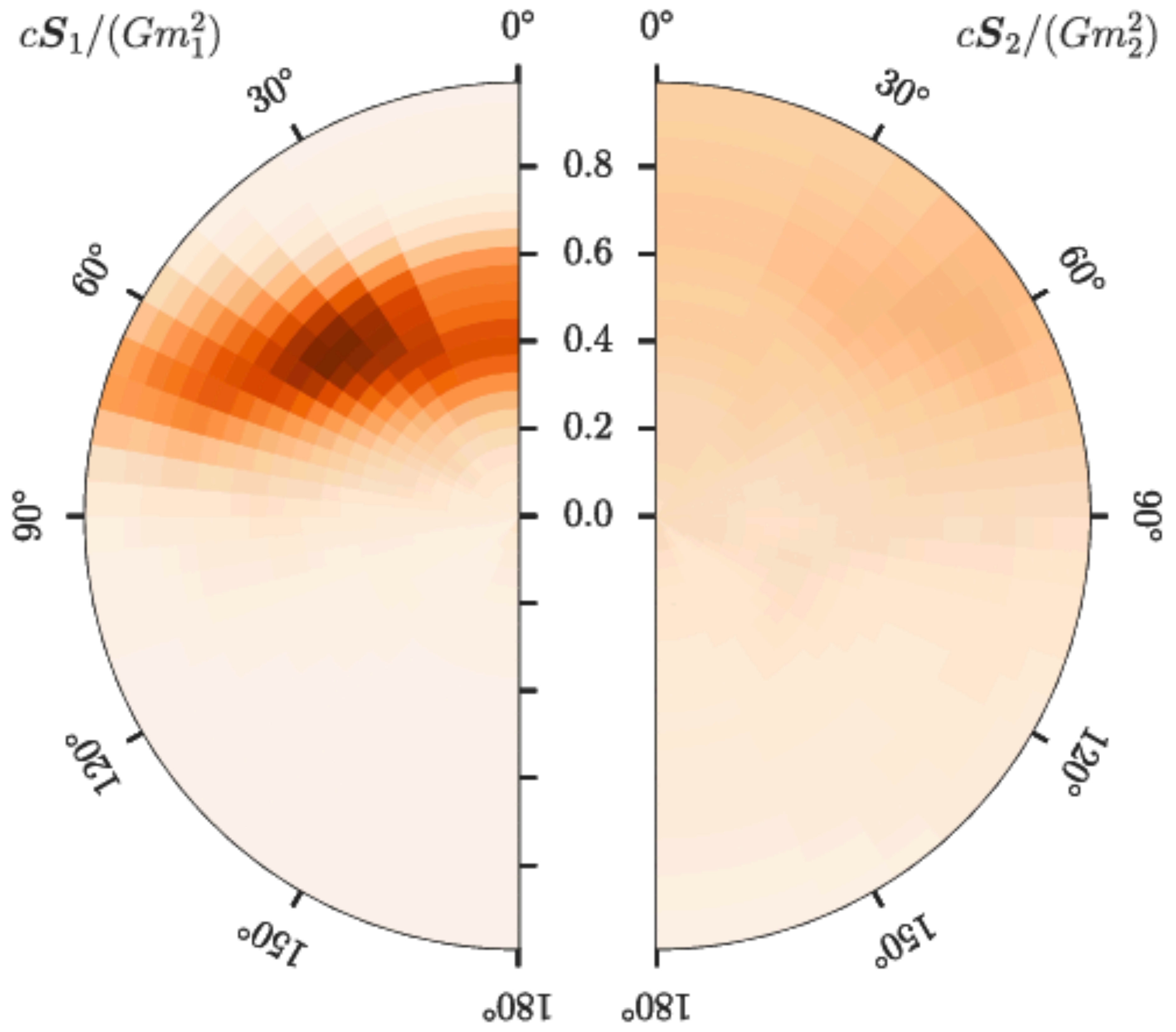
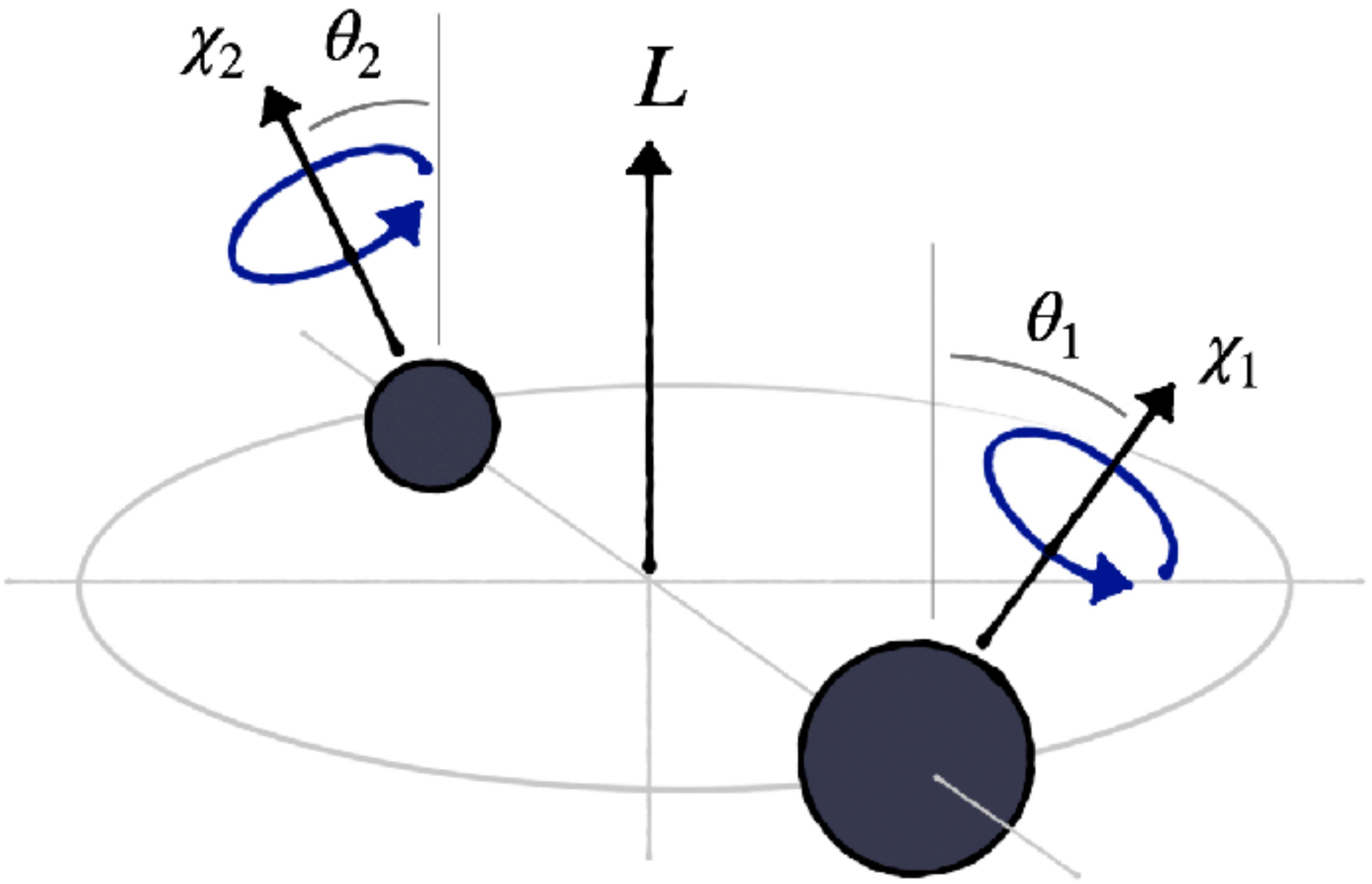


Figure credit: Shanika Galaudage

Spin measurements for individual events



LIGO-Virgo 2016



Credit: Thomas Callister

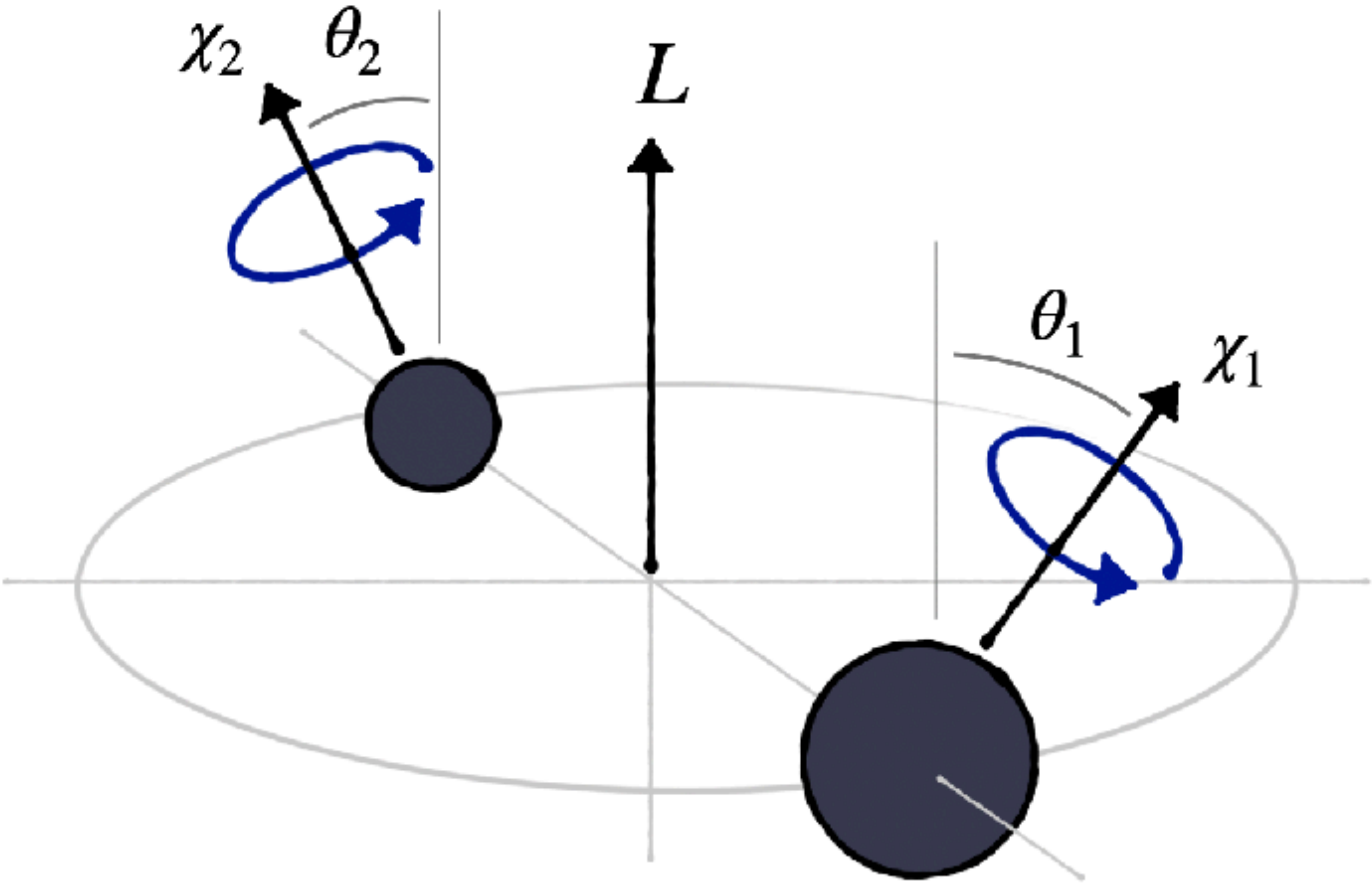
Spin Orientation Statistics

Effective inspiral spin $\chi_{\rm eff}$ is the mass-weighted spin along the orbital angular momentum axis

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

Negative $\chi_{\rm eff}$ implies spin tilts larger than 90 degrees — easier to accomplish via dynamical assembly than from isolated binary evolution

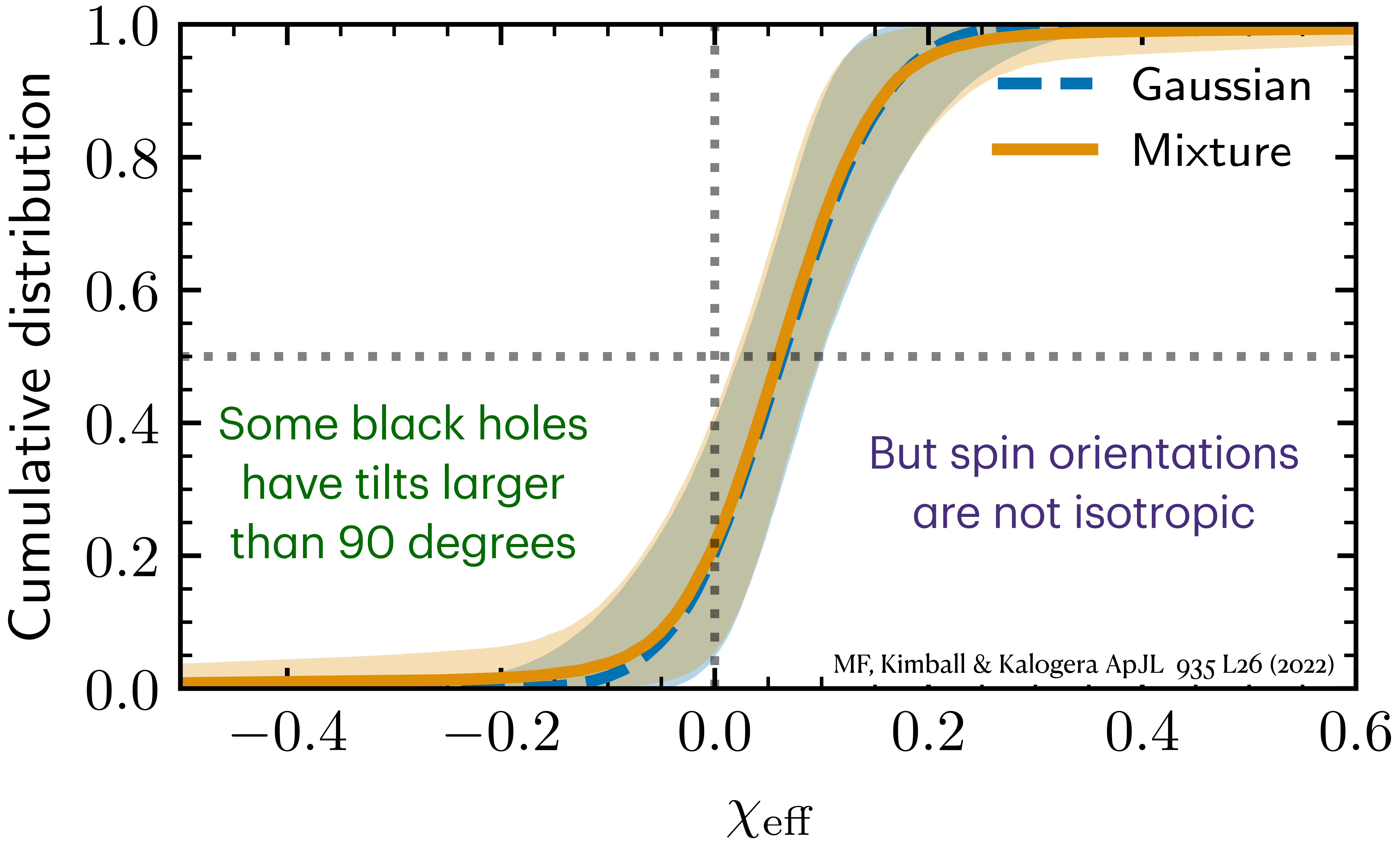
Isotropically oriented spins (as predicted by dynamical assembly in e.g. globular clusters) imply $\chi_{\rm eff}$ distribution is centered at zero



Credit: Thomas Callister

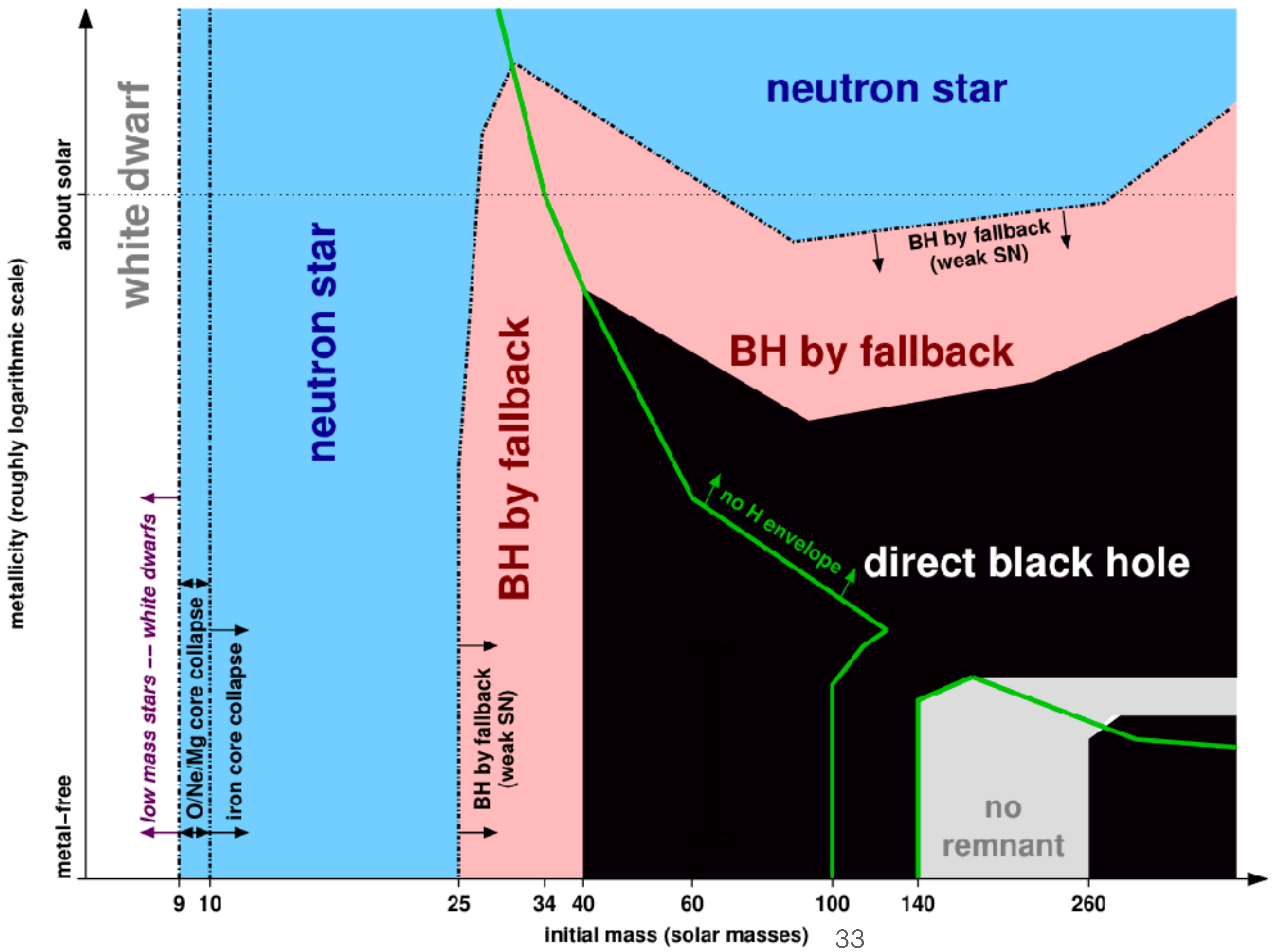
Latest binary black hole spin measurements:

Some, but *not all*, black hole mergers are dynamically assembled



Effective inspiral black hole spin

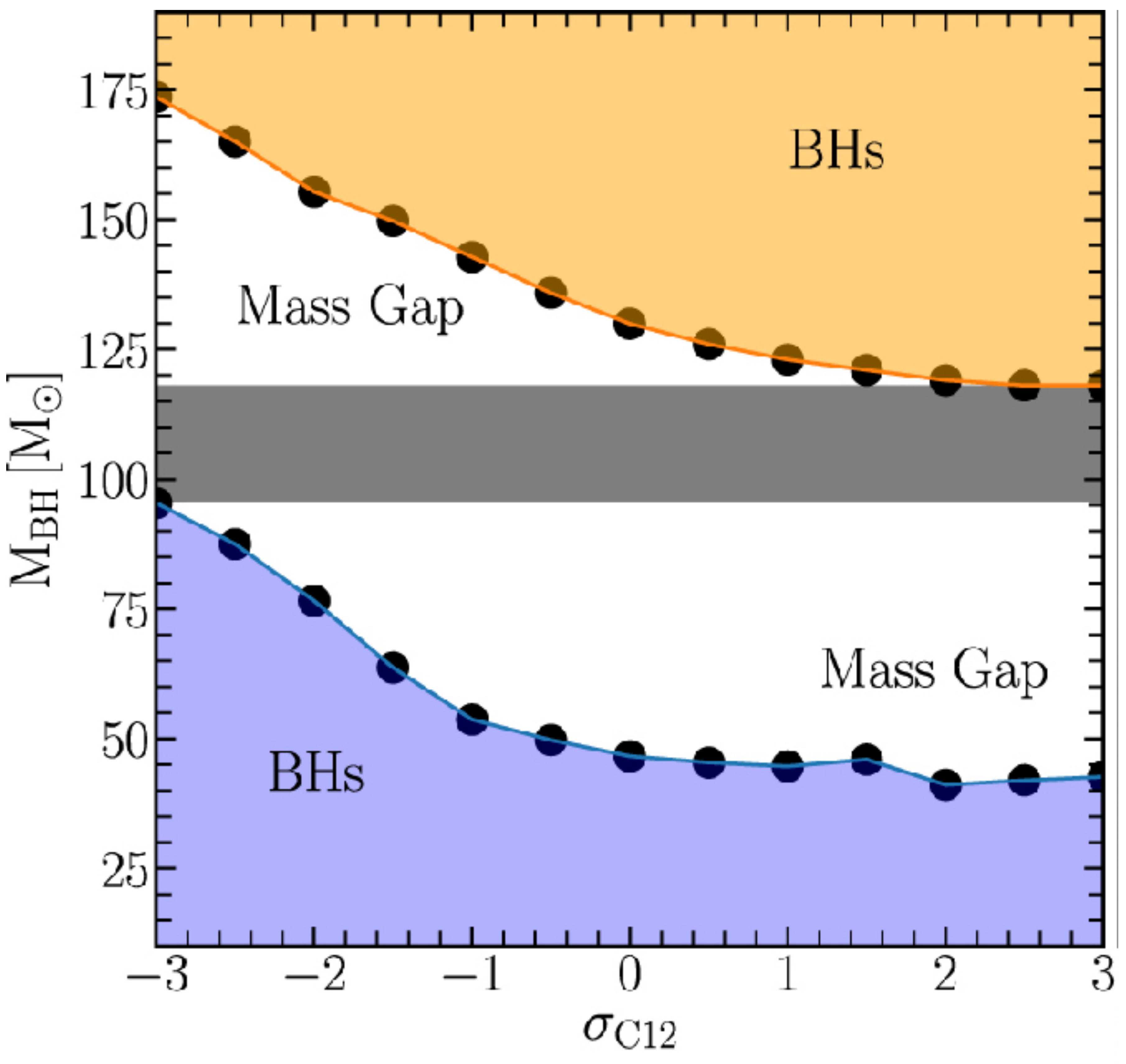
Pair-instability supernovae



Heger et al. 2023

Predicted pair-instability black hole mass gap

- (Pulsational) pair-instability supernovae predict an absence of stellar remnant black holes in the range $\sim 40 - 120\, M_{\odot}$
- Is the gap contaminated with non-stellar origin black holes?
- Are there black holes above the gap?



Standard deviations from the median $^{12}C(\alpha, \gamma)^{16}O$ reaction rate

Farmer, Renzo, de Mink, MF & Justham 2020

Pair-instability and the black hole mass distribution

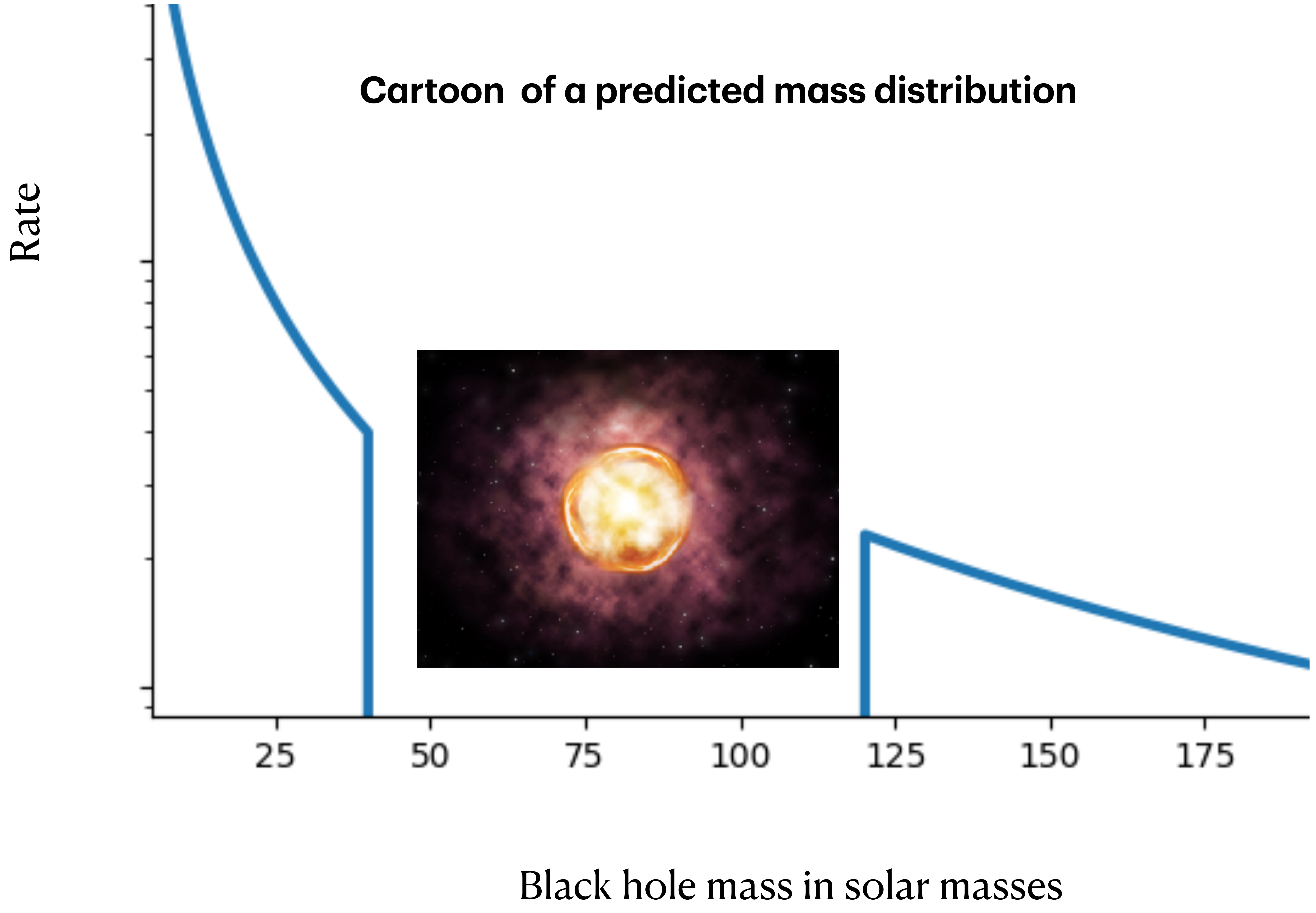
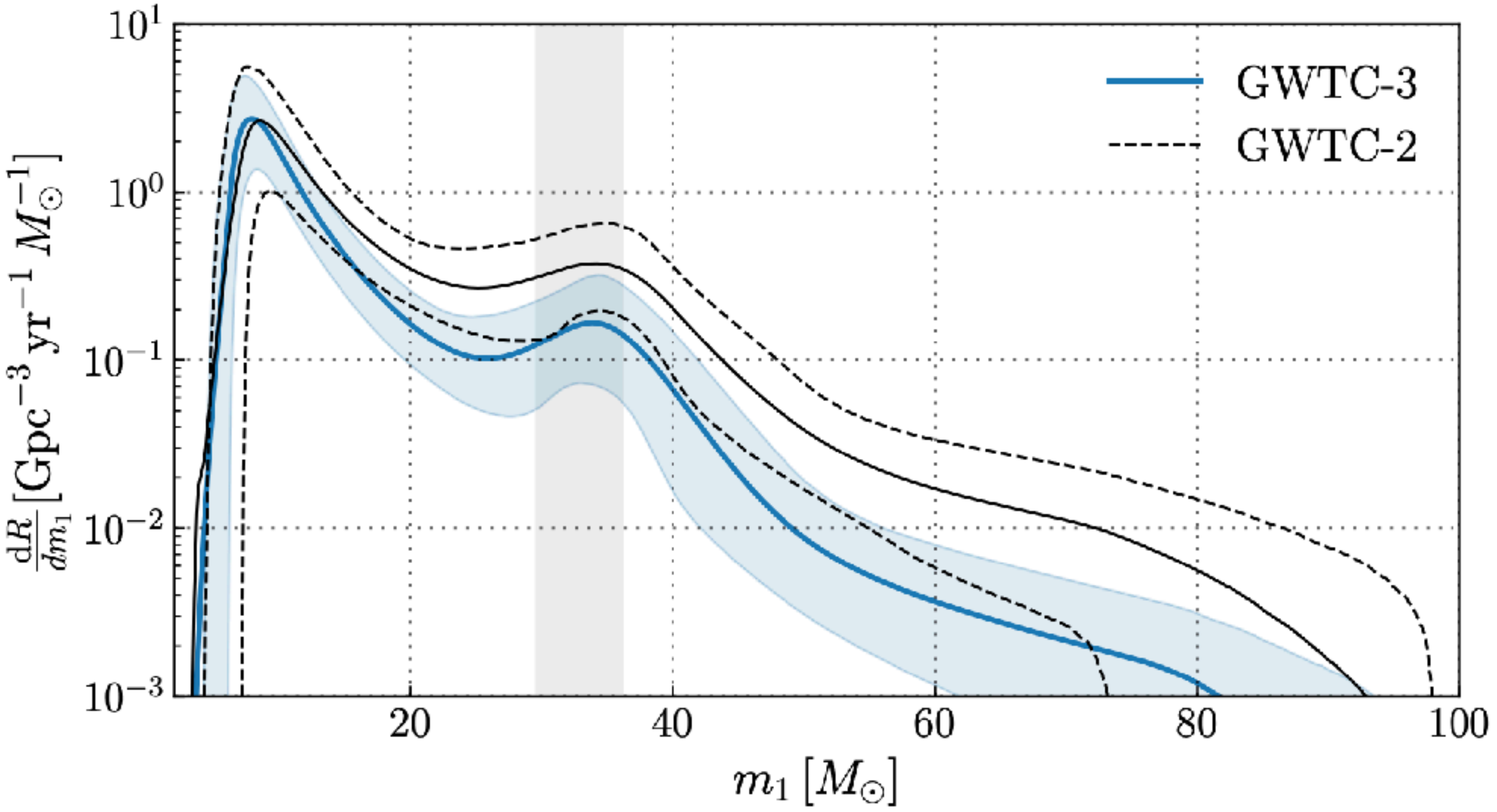


Image credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

Inferred Black Hole Mass Distribution

Where is the mass gap?

Merger rate

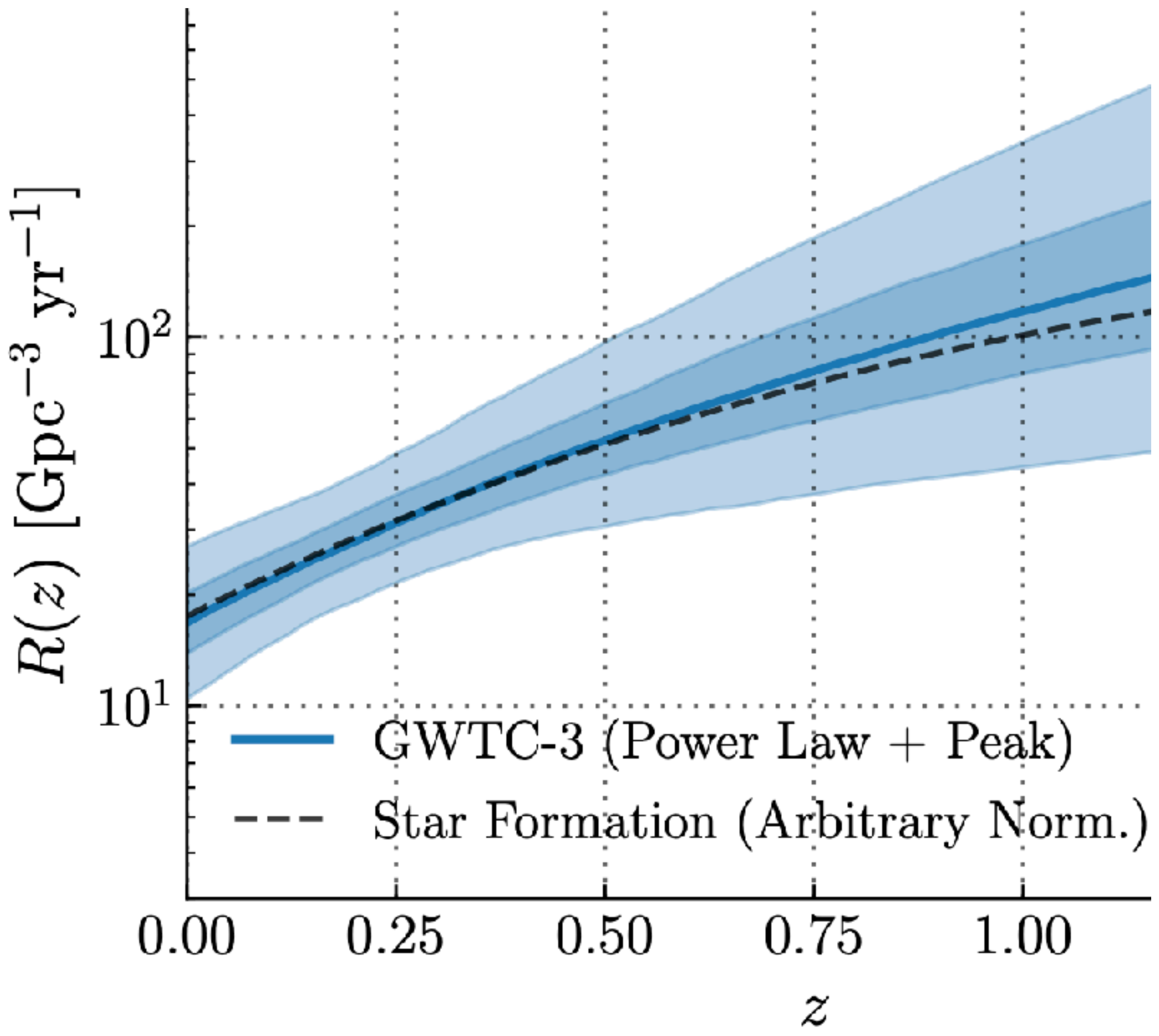


Primary mass in solar masses

LVK 2021 ApJL 913 L7 (GWTC -2)
LVK arXiv:2111.03634 (GWTC-3)

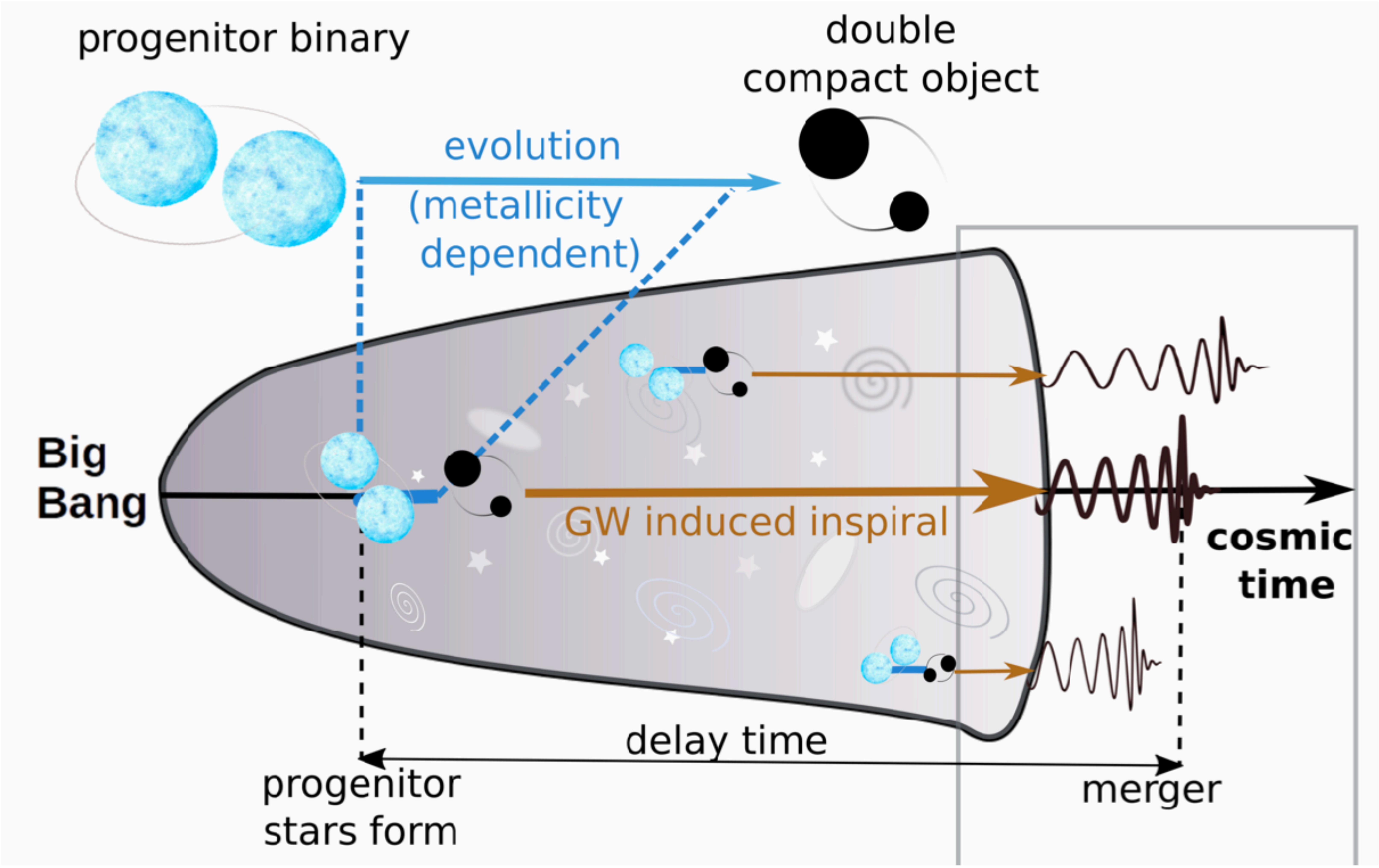
Probing the star formation history

Black hole merger rate evolves with redshift



LVK arXiv:2111.03634

Merger rate follows progenitor formation + delay time

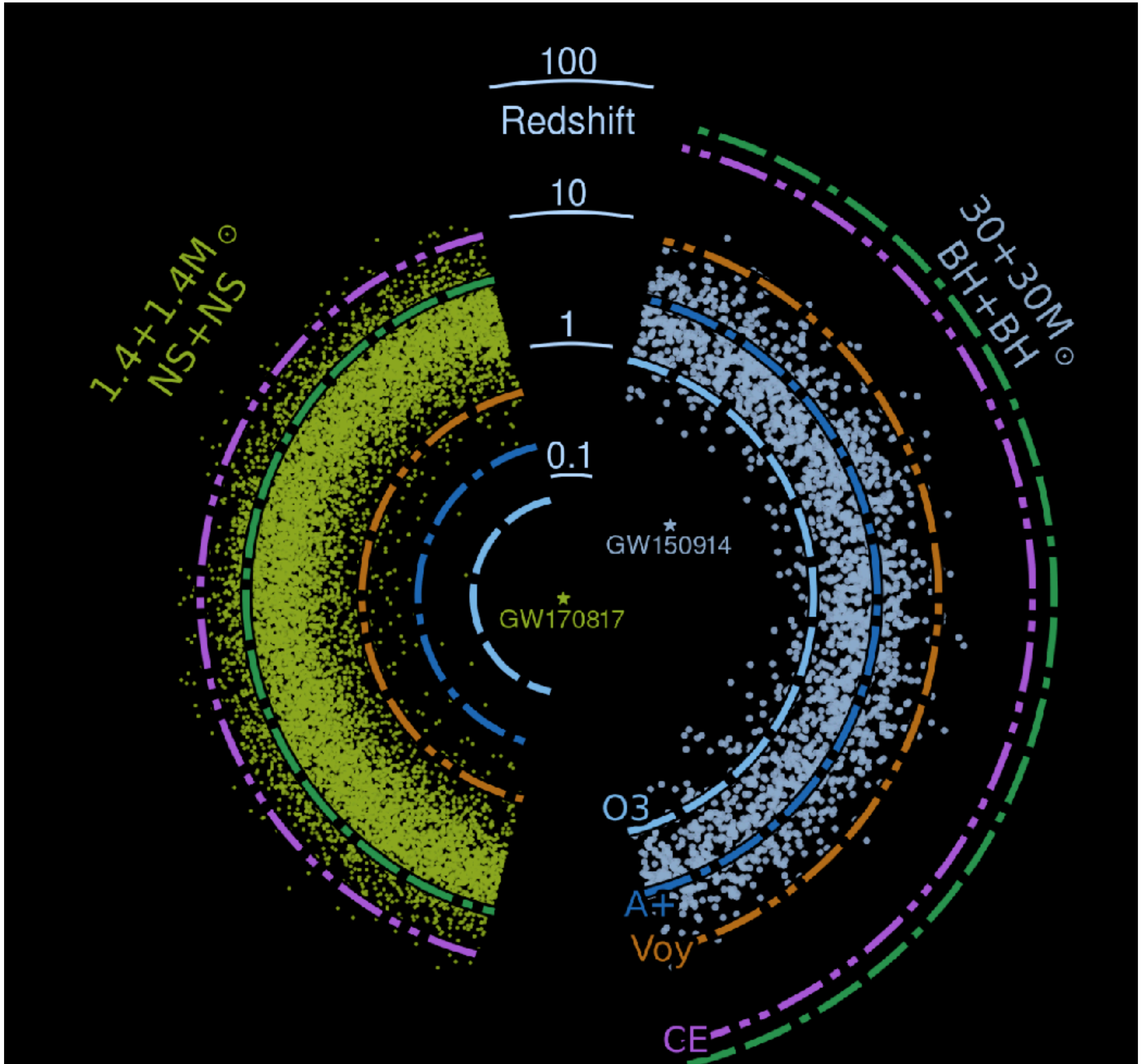


Chruslinska arXiv:2206.10622

Next generation gravitational-wave detectors

Mapping the black hole merger rate across *all* of cosmic time, from the very first black holes

Also map the redshift evolution of the mass distribution (e.g. MF+ 2021) and spin distribution (e.g. Bavera, MF+ 2022)



Evans et al., arXiv:2109.09882