What gravitational-wave observations can and have revealed about the population of compact binaries

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What can we learn from gravitational waves?

- Cosmology

- General relativity

- Stellar/binary astrophysics

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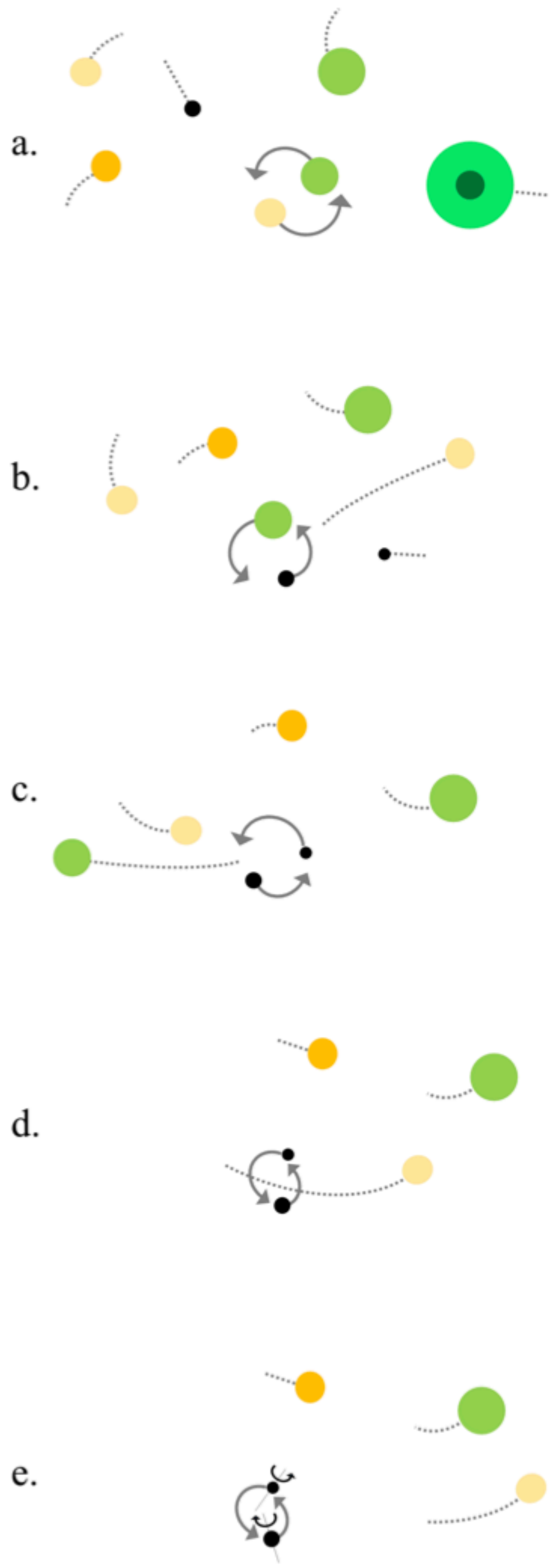
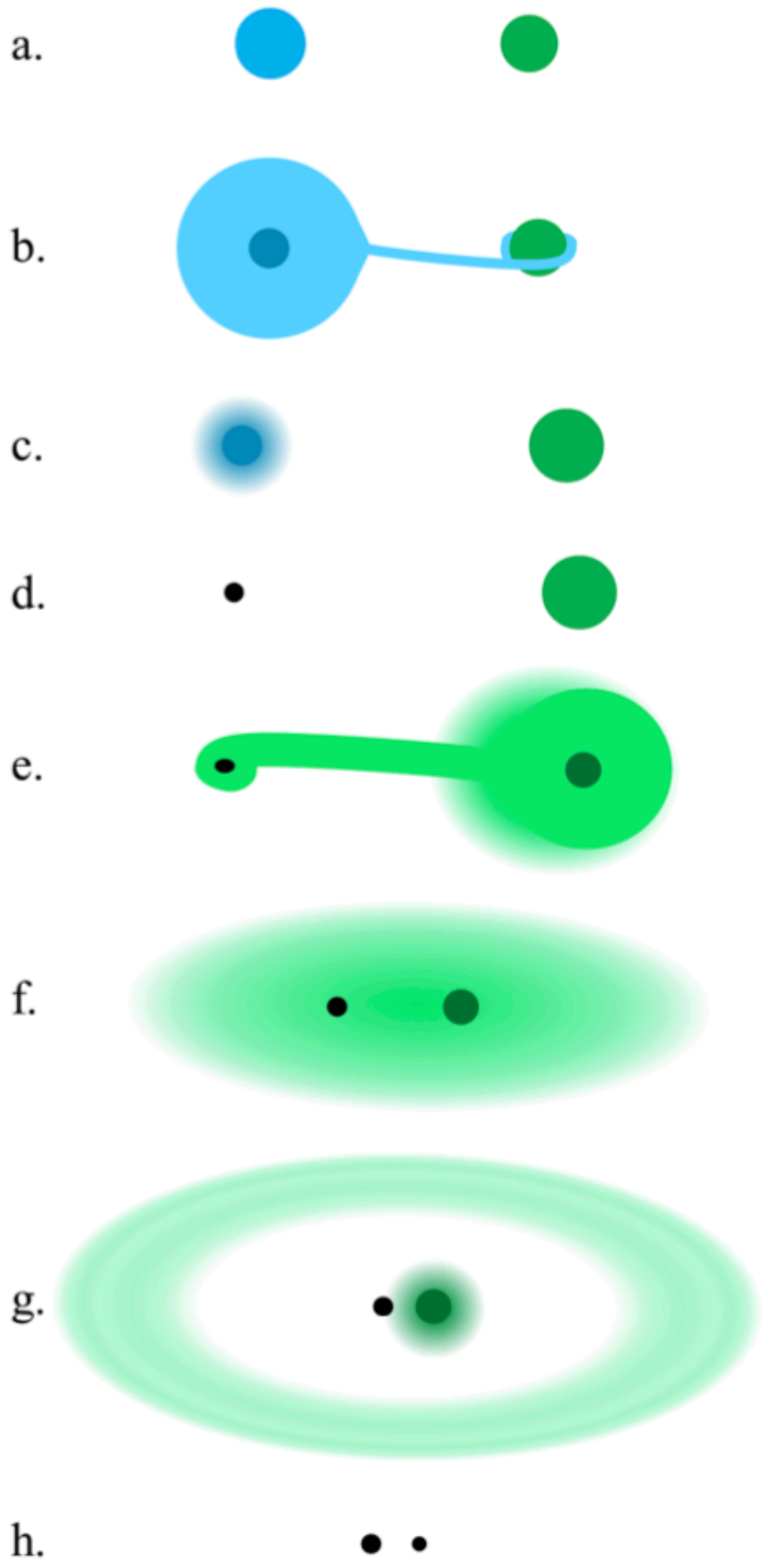
The lives and deaths of stellar binaries

Mergers driven via **dynamical** interactions in dense environments





Binaries in intermediate stages observable electromagnetically

Mergers driven via mass transfer for **isolated/field** binaries

Mandel & Farmer, PR, 2018

What can we learn from gravitational waves?

- How do black holes form?
  - Stellar winds
  - Supernova physics

- How do binaries form, evolve, and merge?
  - Binary evolution vs dynamical formation
  - Tidal interactions
  - Mass transfer
  - Common envelope evolution

What can we learn about stars?

- How do black holes form?
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  - **Supernova physics**

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How can we learn about stars?

- The mass distribution of main sequence stars is well described by a power law
- Our observational selection bias is very well understood (and is approximately a power law)
- Any deviations from a power law distribution of black hole masses must be driven by stellar/binary effects
  - Look for features in the black hole mass distribution
- Other imprints can be left on spins and the distribution of redshifts

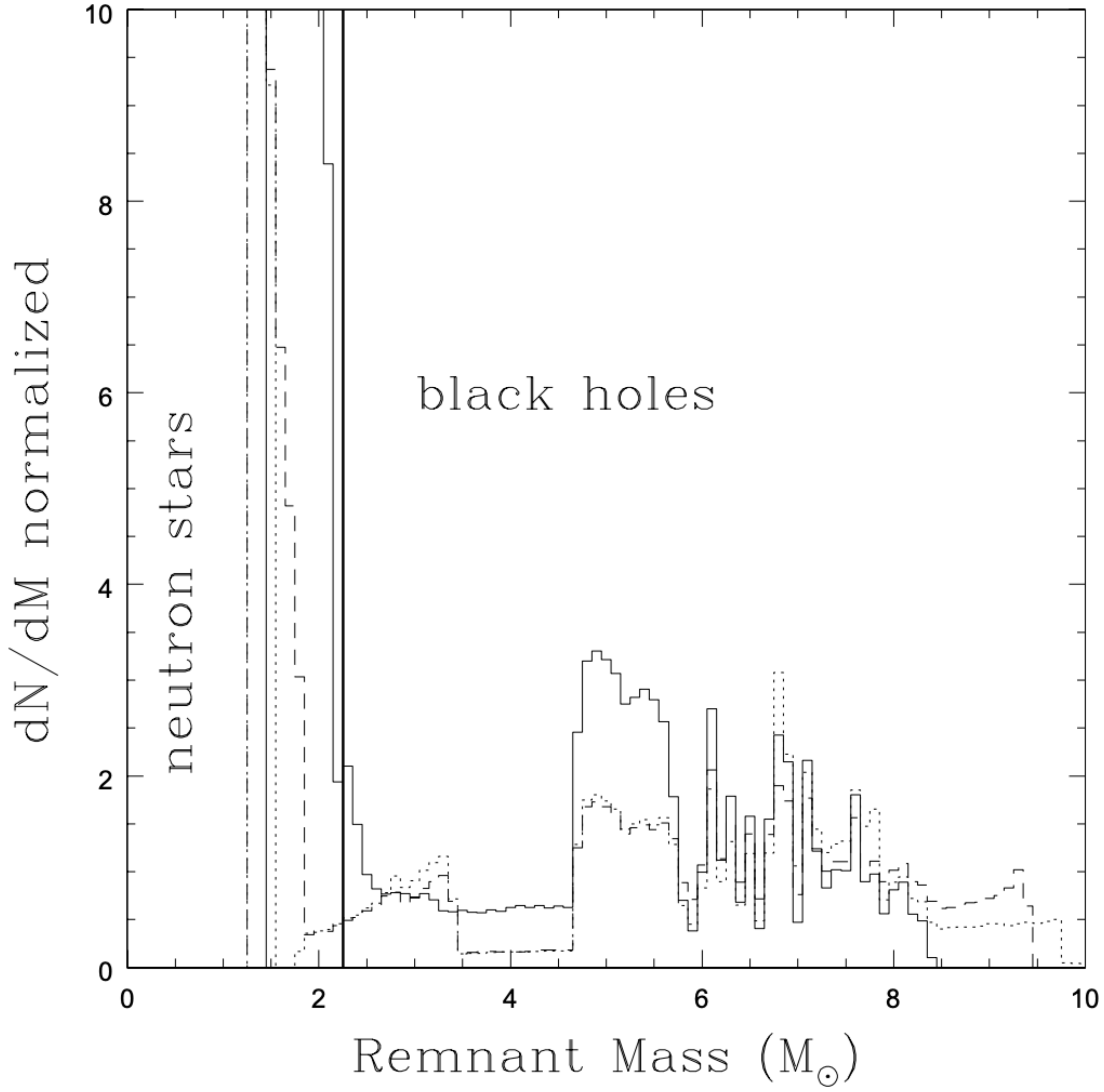
What can we learn about supernovae?

Failed supernovae

- Possible mass gap between neutron stars and black holes and an excess below 10 solar masses

- Theoretical explanation:

  - Stars in the 16-25 solar mass range fail to explode

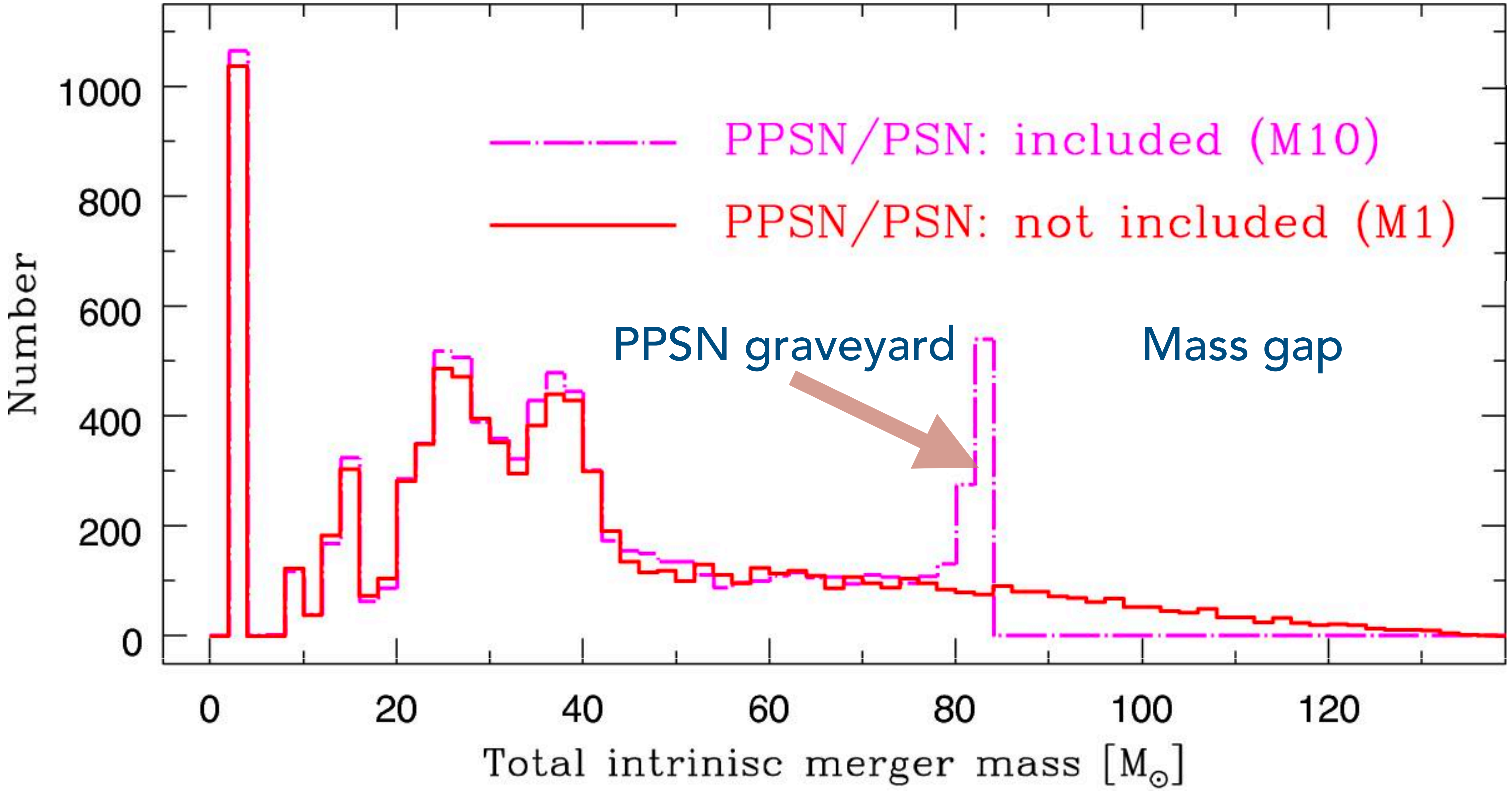


Kochanek, ApJL, arXiv:1308.0013

What can we learn about supernovae?

(Pulsational) pair instability supernovae

- Stars initially between ~150-250 solar masses go through periods of unstable pair production
- Star either completely disrupted (no remnant) or loses lots of mass



Belczynski *et al.*, A&A, arXiv:1607.03116

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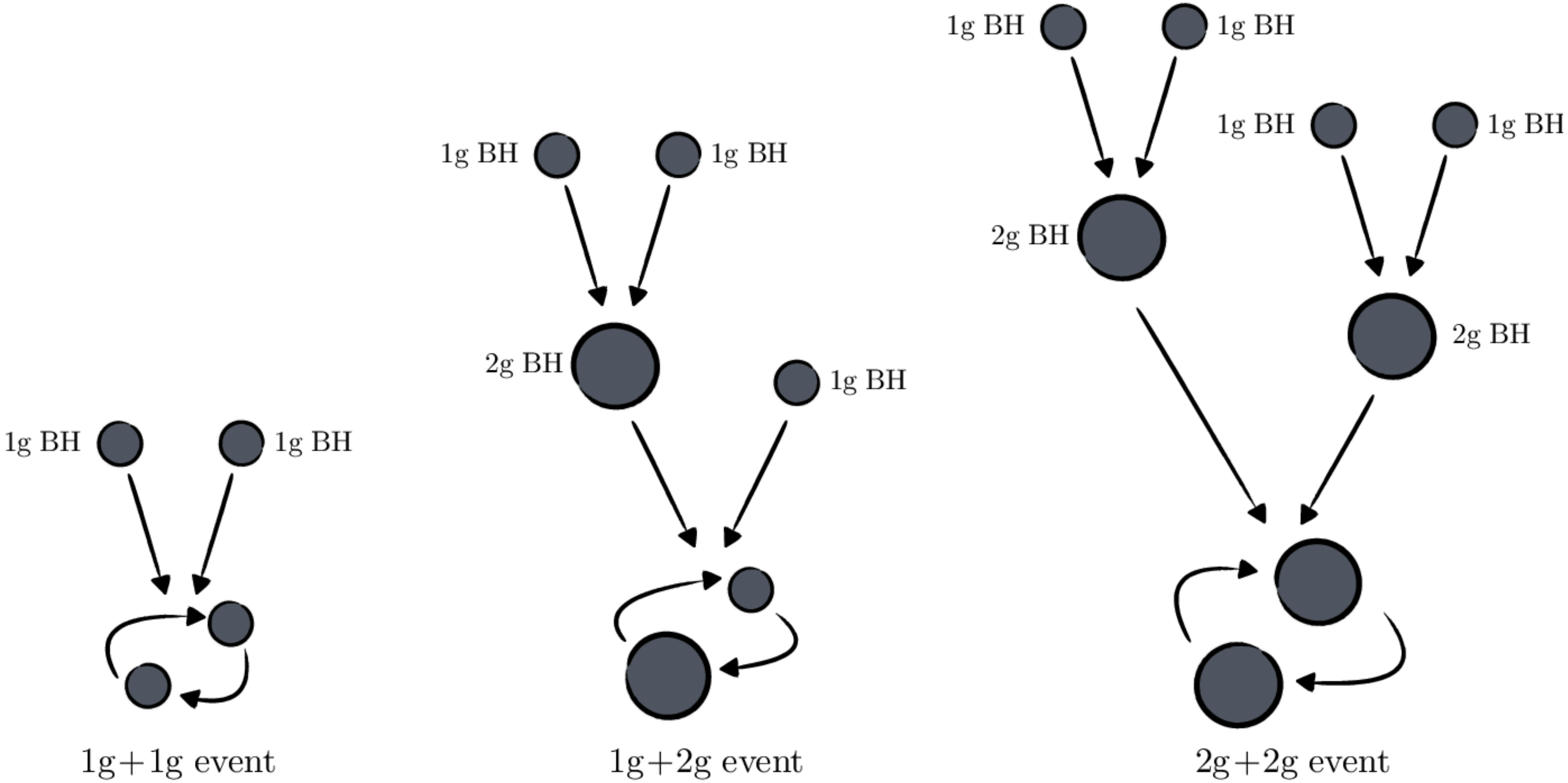
How can we learn about formation channels?

Repeated “hierarchical” mergers



Gerosa & Berti, PRD, arXiv:1703.06223

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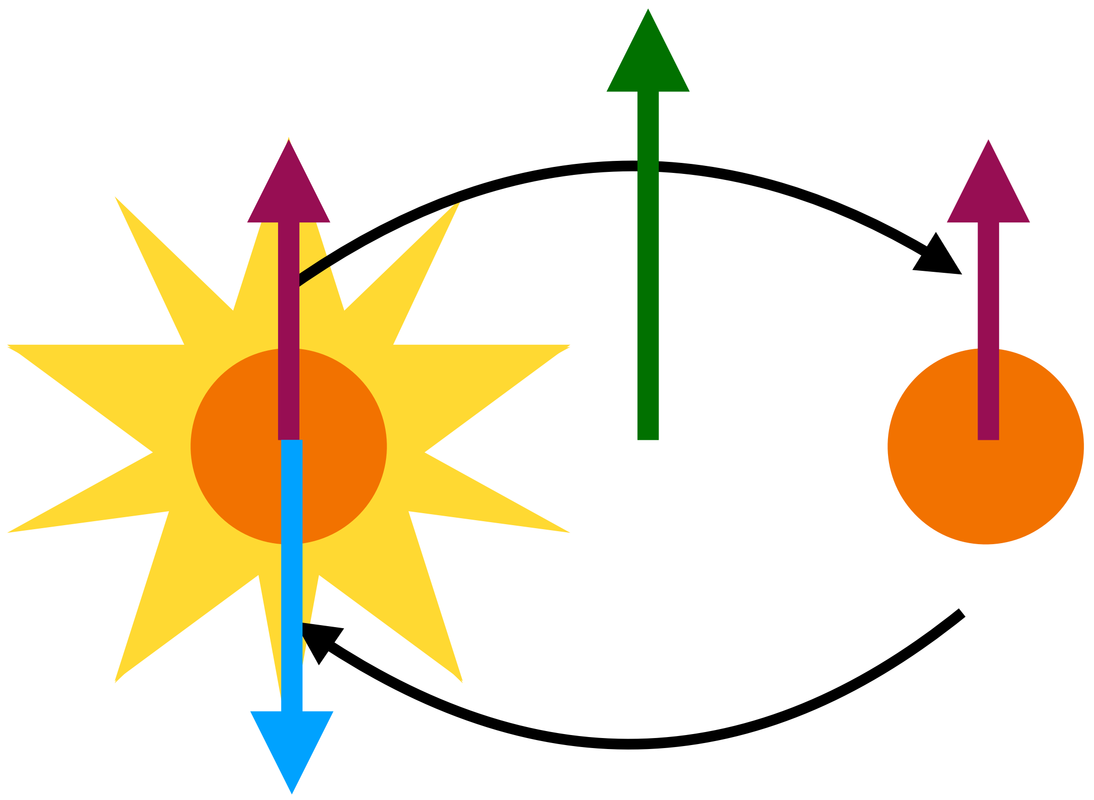
What spins do we expect to see?

Spin orientations

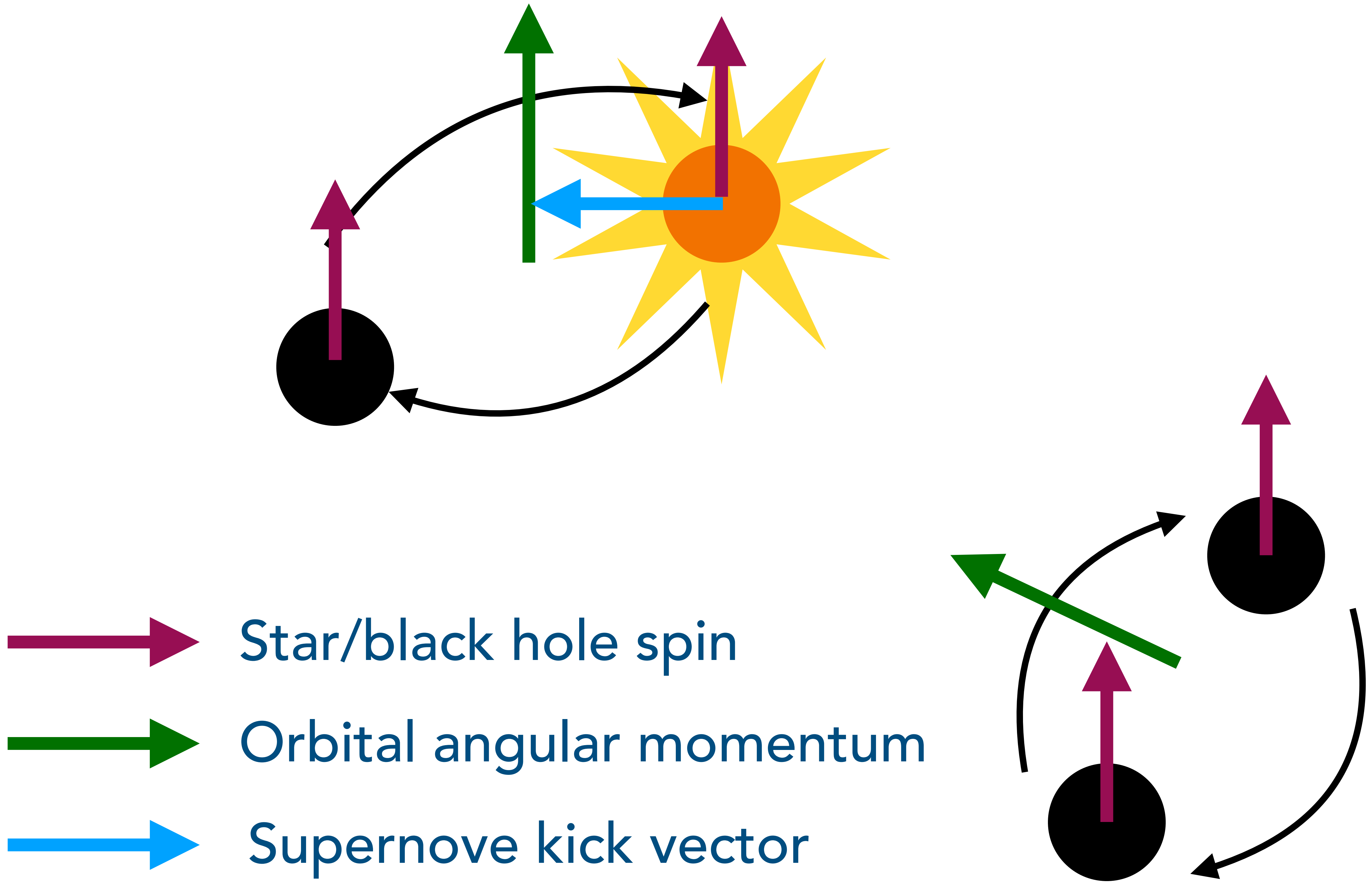


Dynamically formed

- Random spin orientations

Stellar binary evolution

- Supernova asymmetry can lead to misalignment
- Tidal interactions and mass transfer episodes align stellar spins



How do we go from observations to astrophysics?

Building models

Theoretical

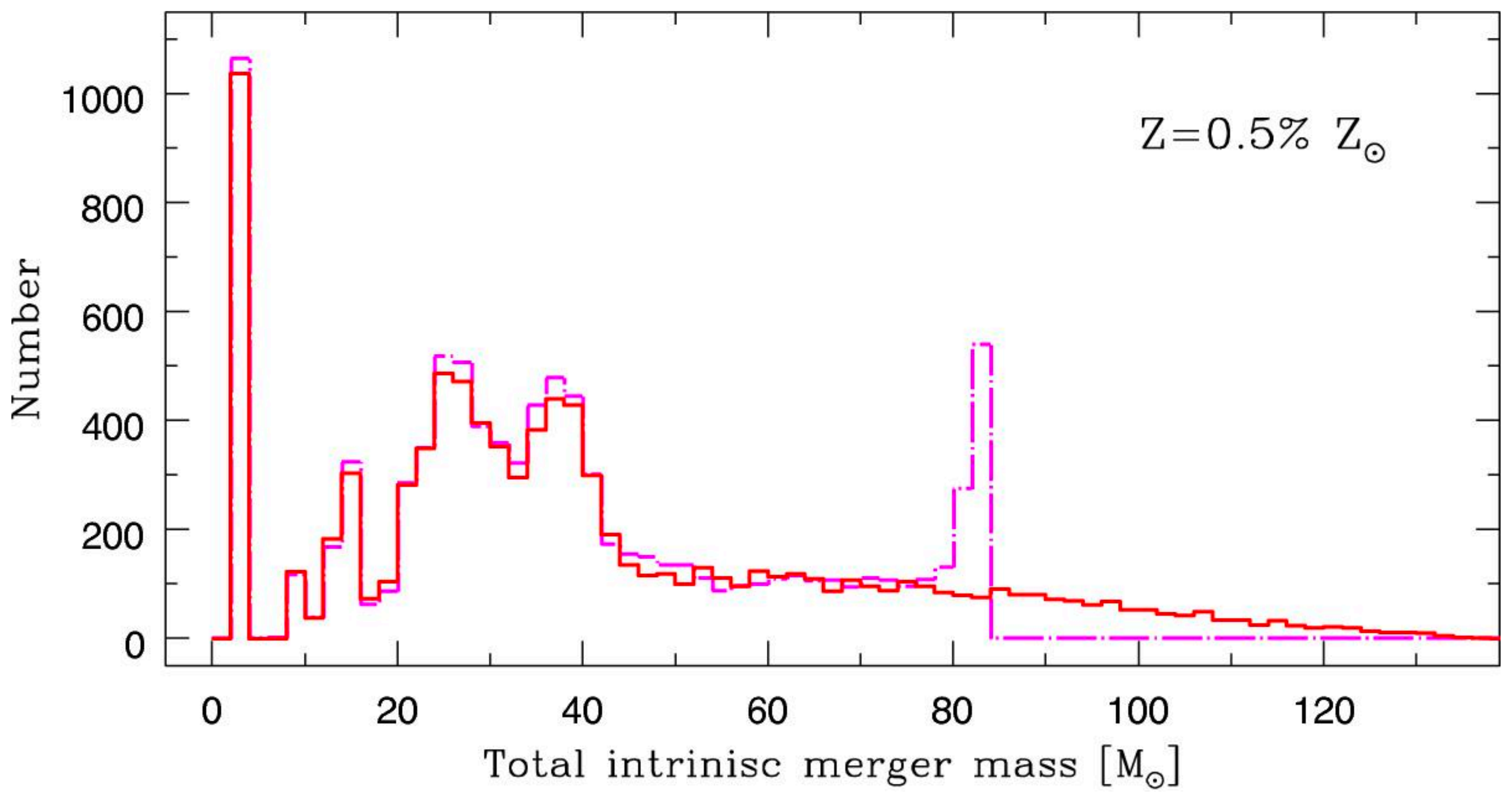
Easy to interpret

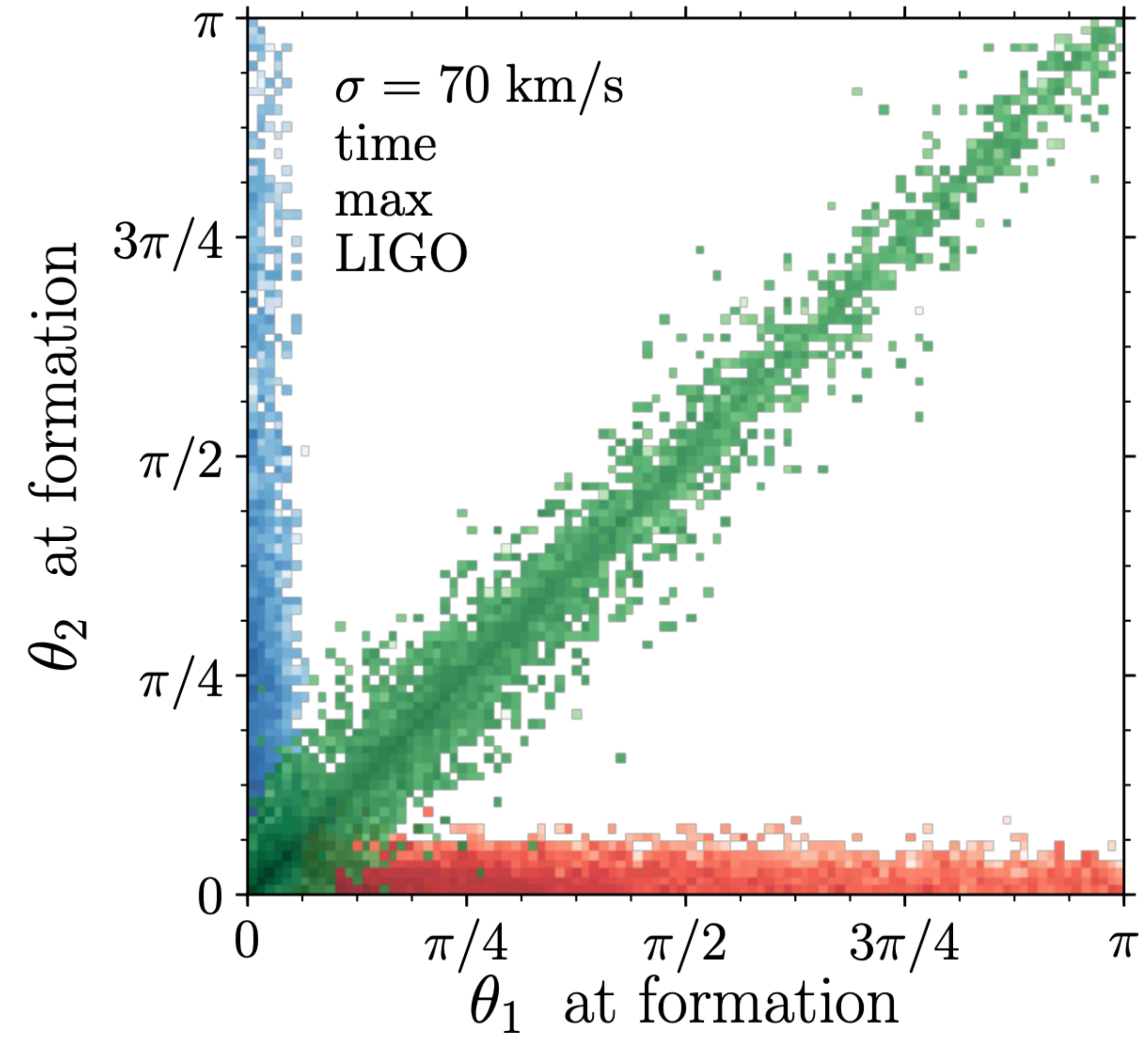
Naturally amounts for both GW and EM sources

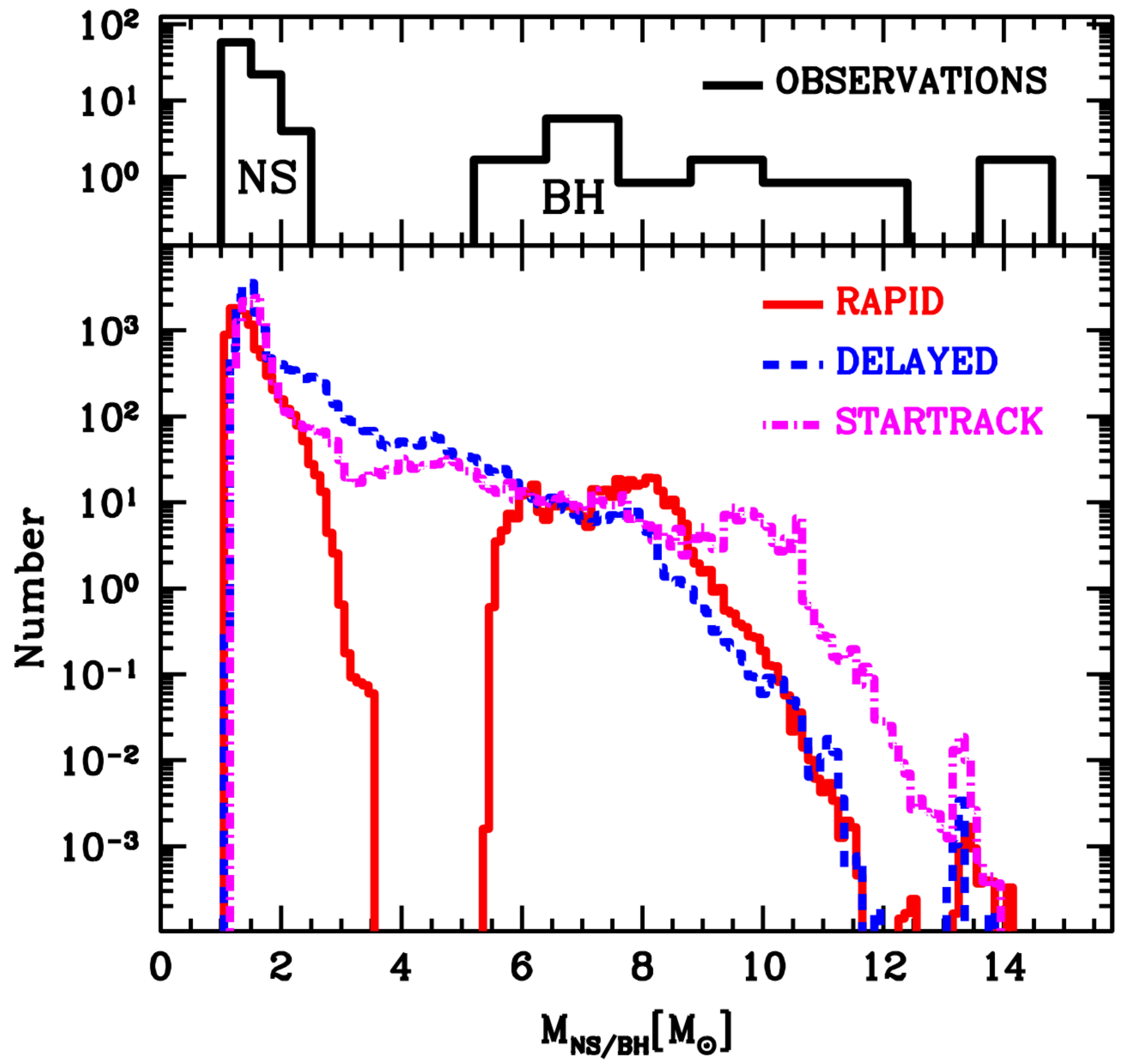
Needs reliable theory

Very sensitive to systematics

Computationally expensive







Gerosa *et al.*, PRD, arXiv:1808.02491

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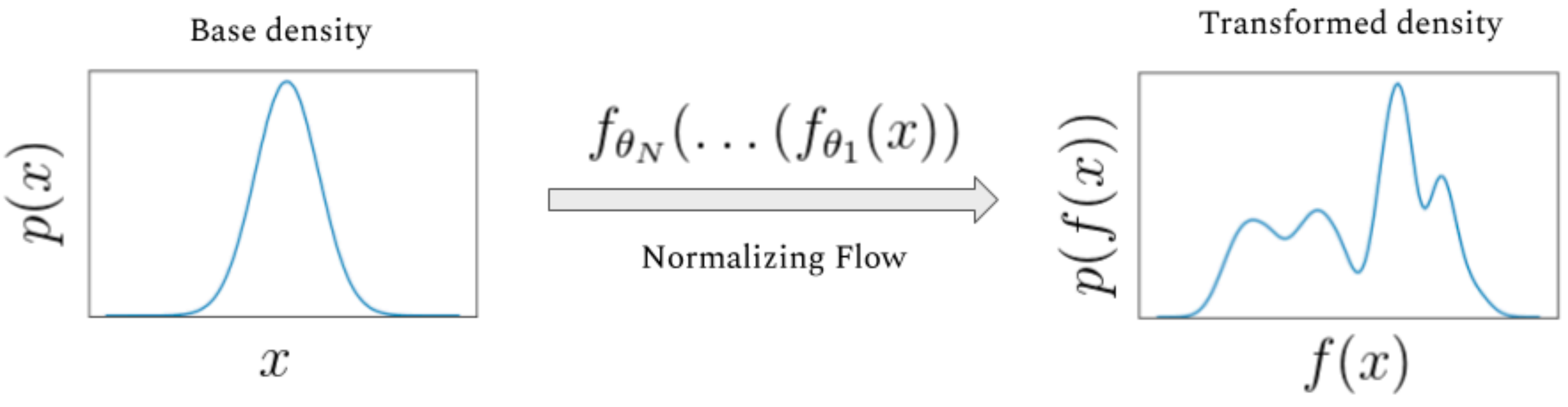
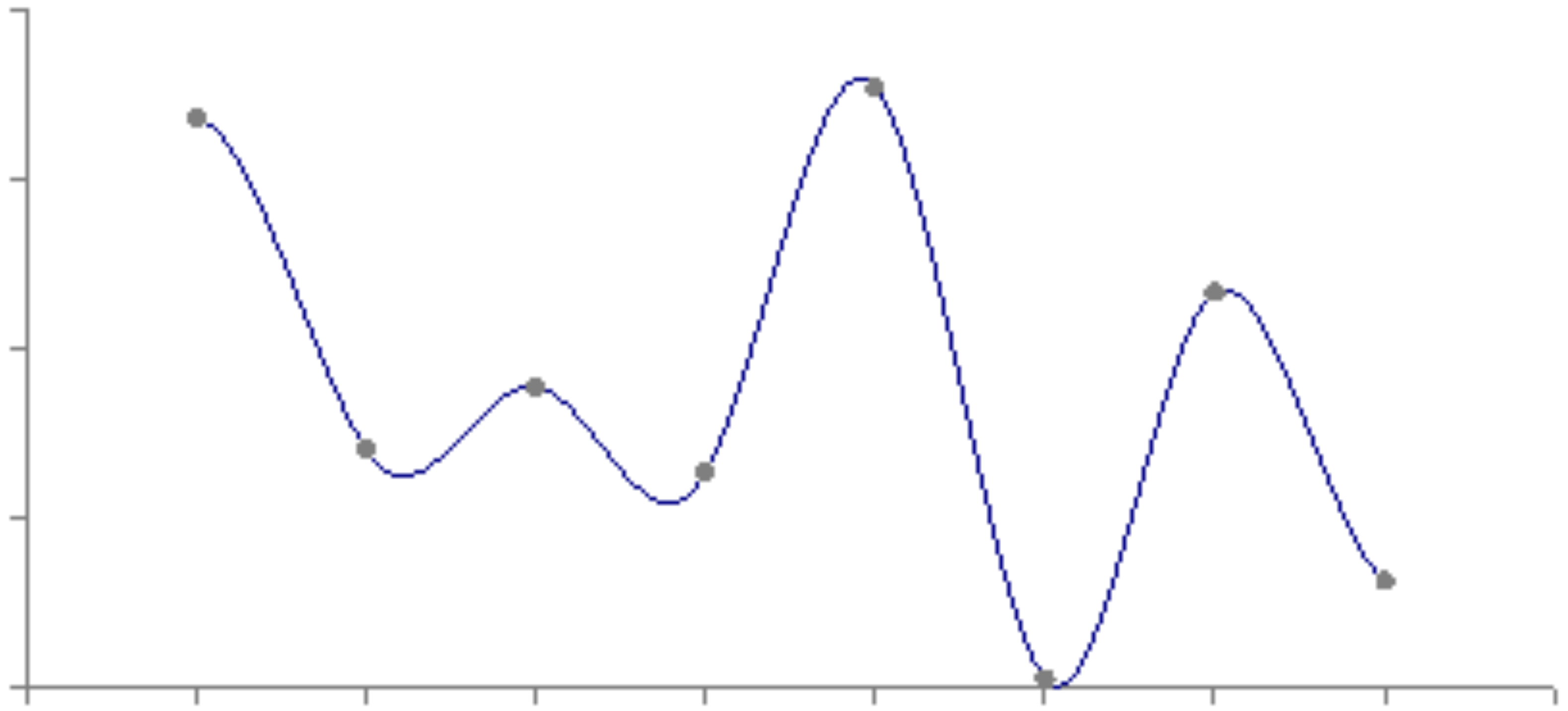
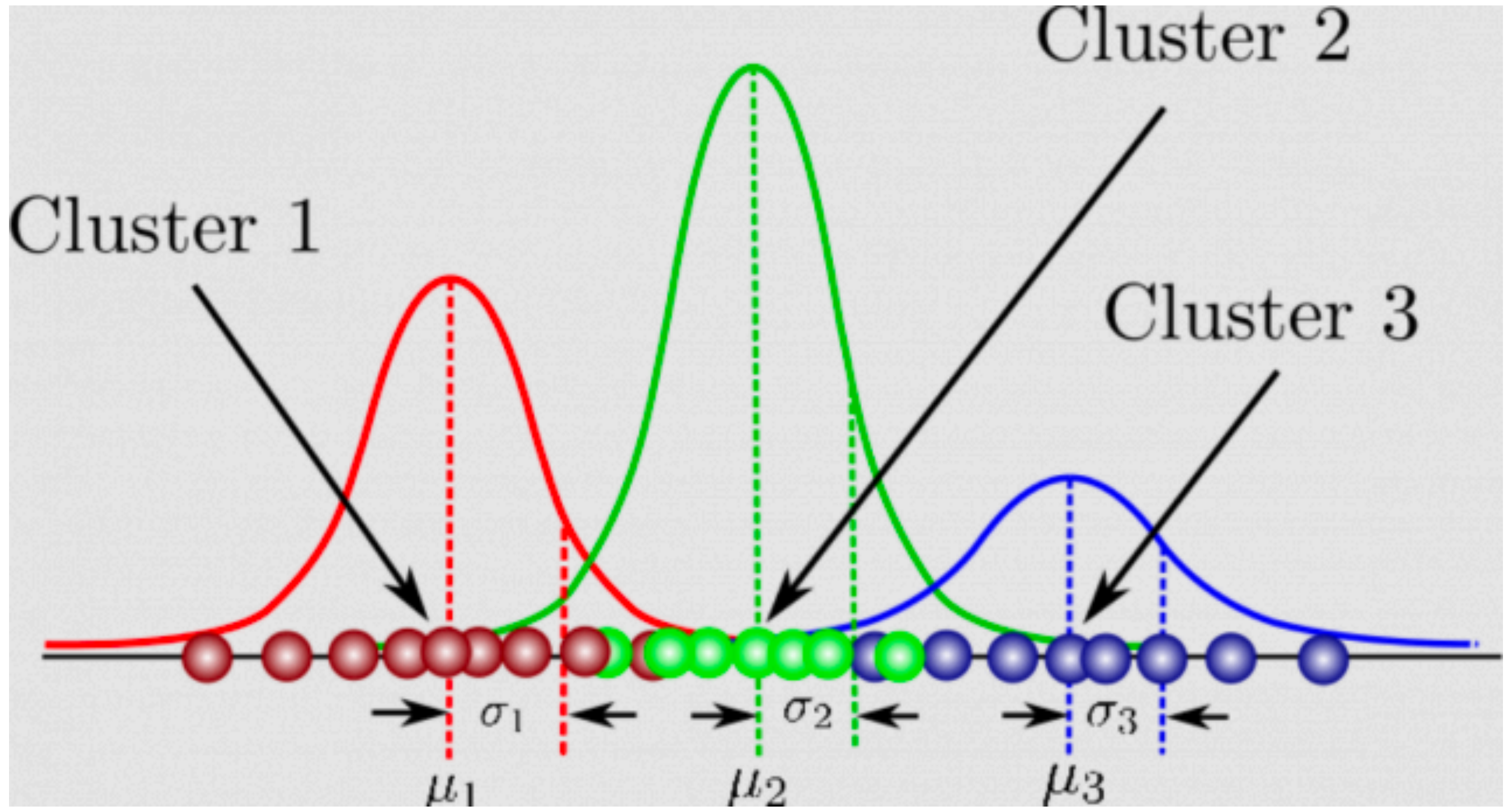






vitalflux.com/gaussian-mixture-models-what-are-they-when-to-use

siboehm.com/articles/19/normalizing-flow-network

paulbourke.net/miscellaneous/interpolation

Data driven

Less sensitive to modelling systematics

Needs lots of data

Difficult to interpret

How do we go from observations to astrophysics?

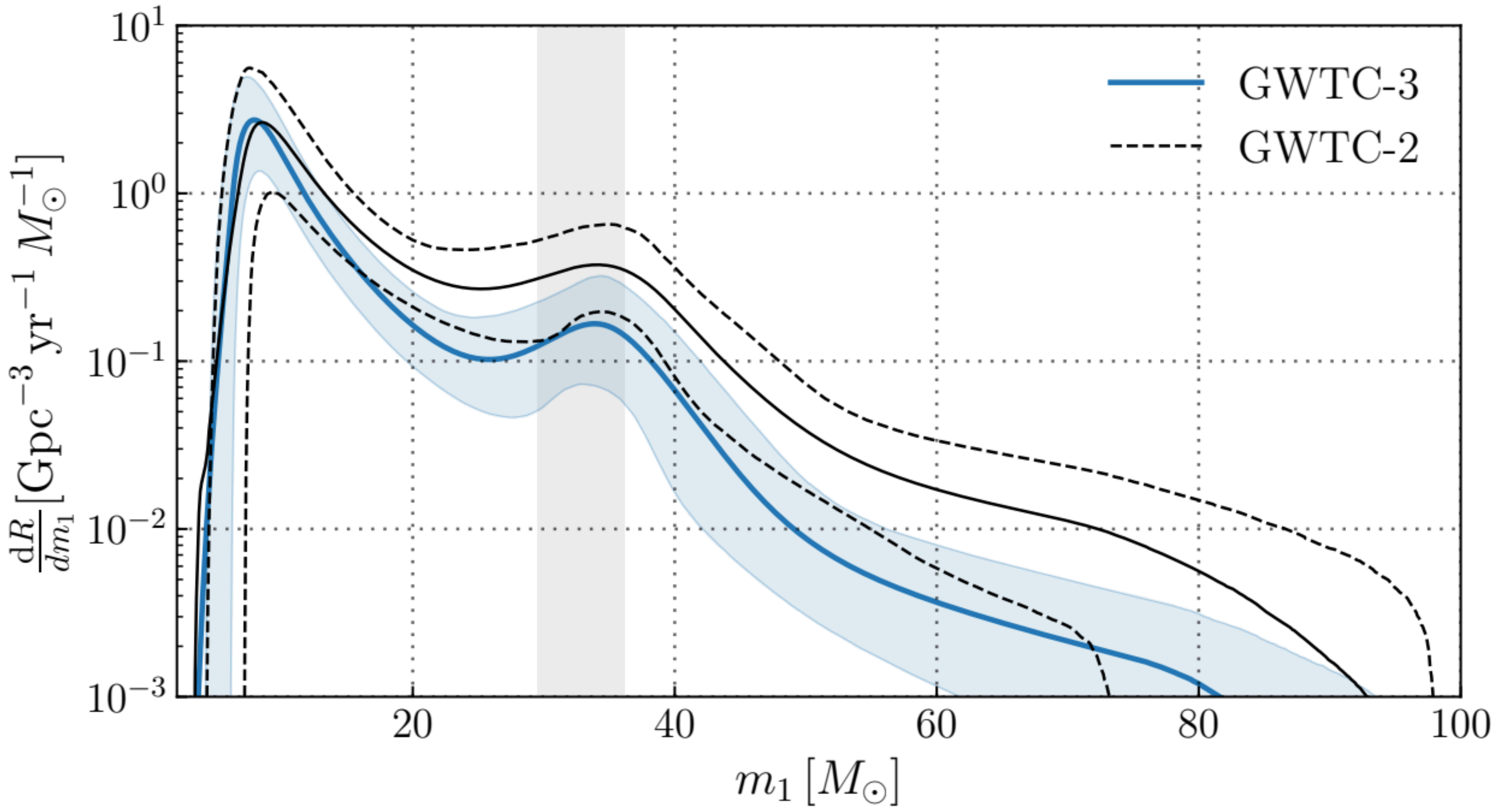
Building models

Phenomenological

Identify qualitative features

Extendable as more data becomes available

Limited by modellers ingenuity



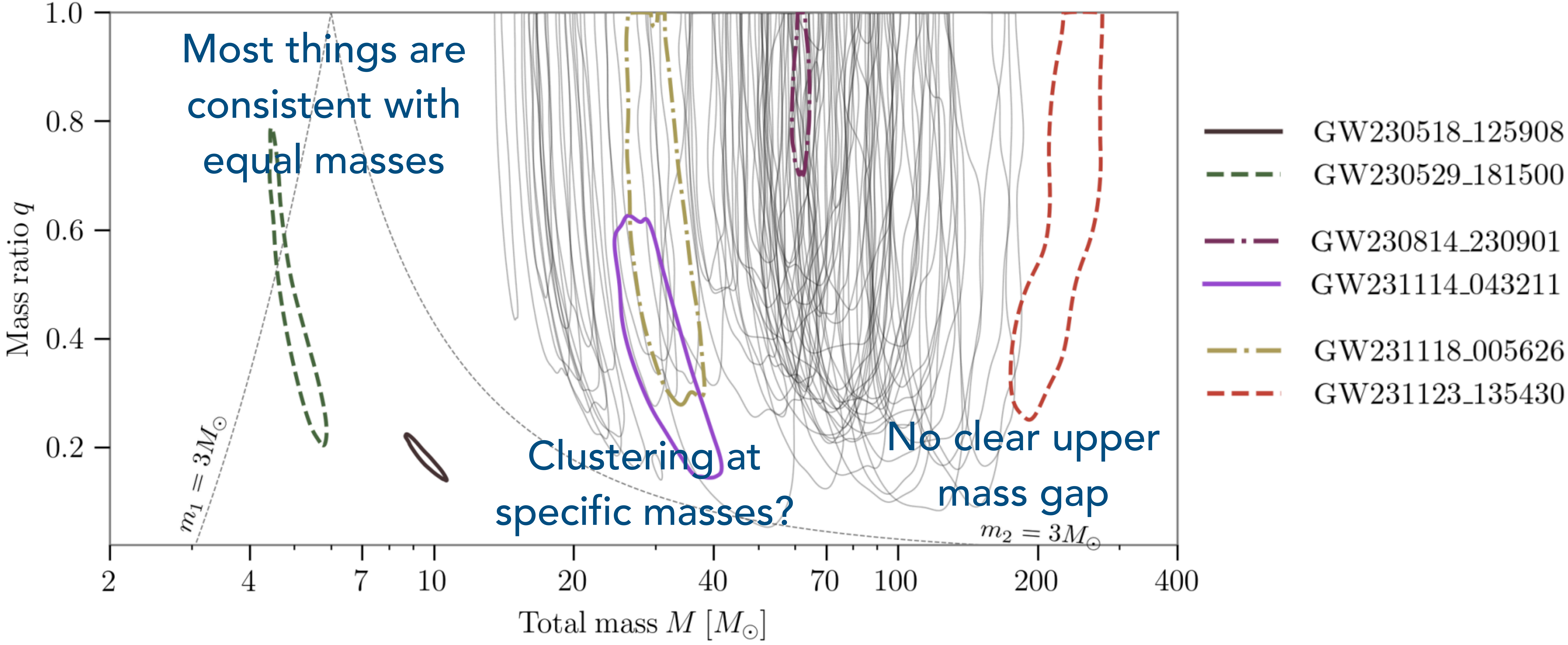
CT & Thrane, arXiv:1801.02699, LVK Collaboration (inc. **CT**) 2021

How do we go from observations to astrophysics?

Building models

Theoretical	Phenomenological	Data driven
Easy to interpret	Identify qualitative features	Less sensitive to modelling systematics
Naturally accounts for both GW and EM sources	Extendable as more data becomes available	Needs lots of data
Needs reliable theory	Limited by modellers ingenuity	Difficult to interpret
Very sensitive to systematics		
Computationally expensive		

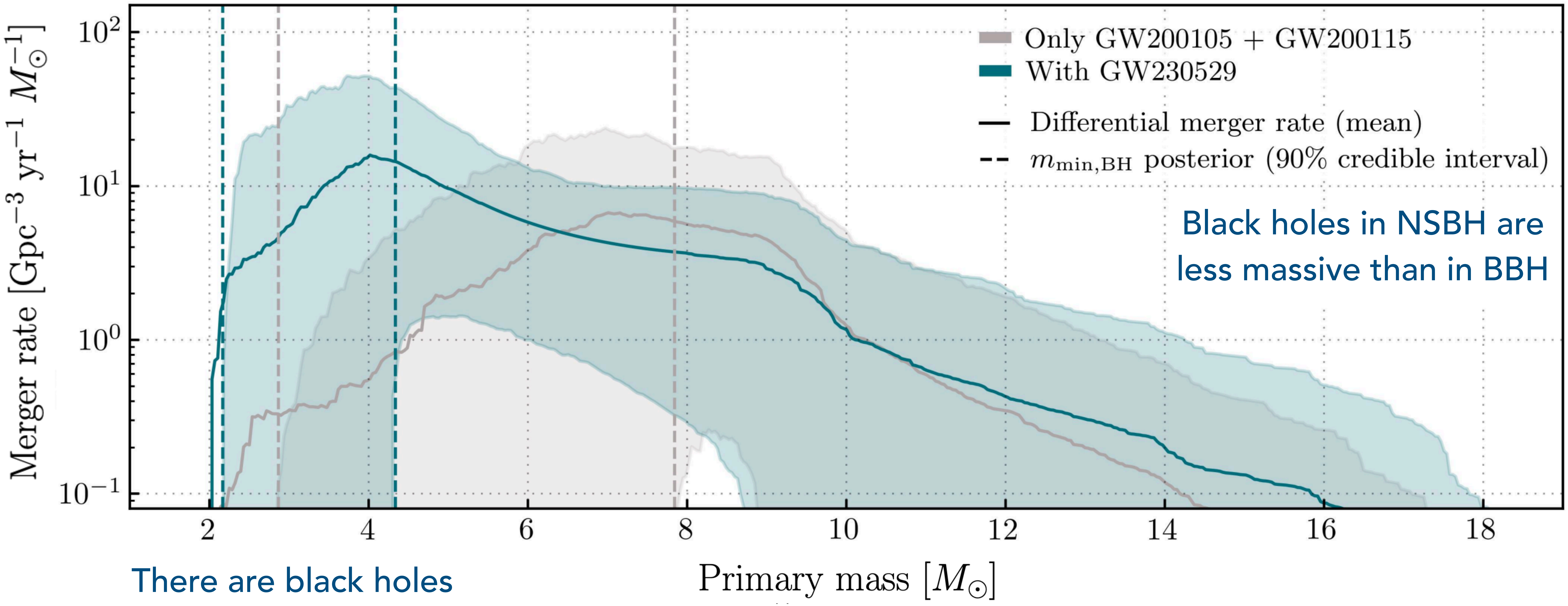
What merging objects we seen so far?



LVK Collaboration (inc. **CT**) 2025

What have we learned about masses?

NSBH



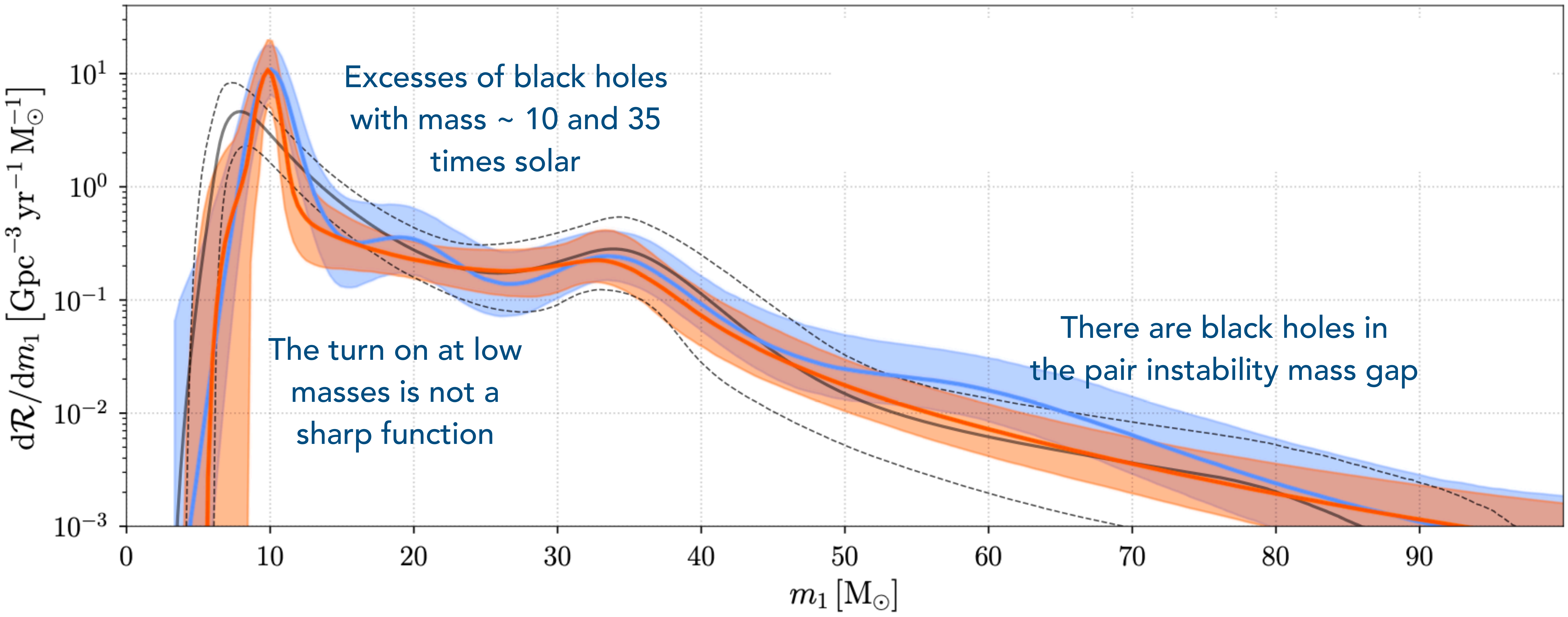
Black holes in NSBH are less massive than in BBH

There are black holes In the lower mass gap

LVK Collaboration (inc. **CT**) 2024

What have we learned about masses?

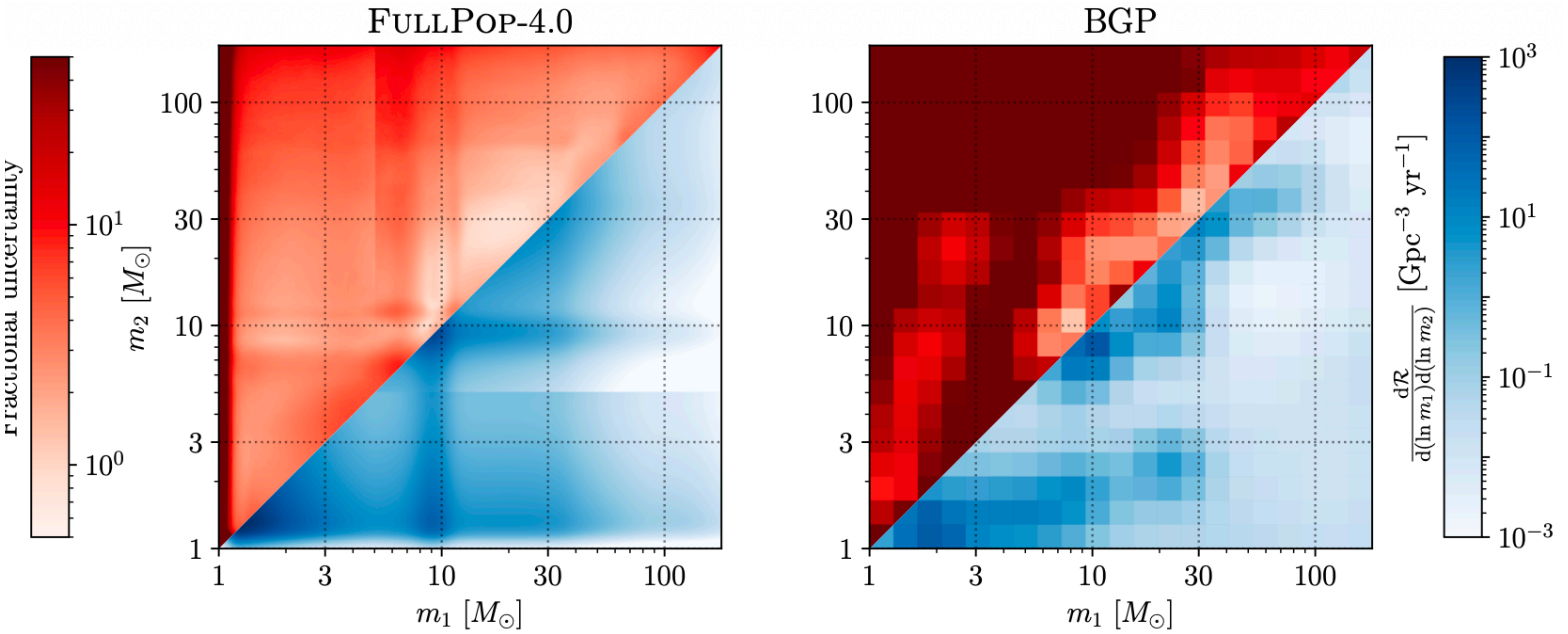
Primary mass



LVK Collaboration (inc. **CT**) 2021

What have we learned about masses?

Data-driven modelling



LVK, inc. **CT**, ApJL, arXiv:2508.18083

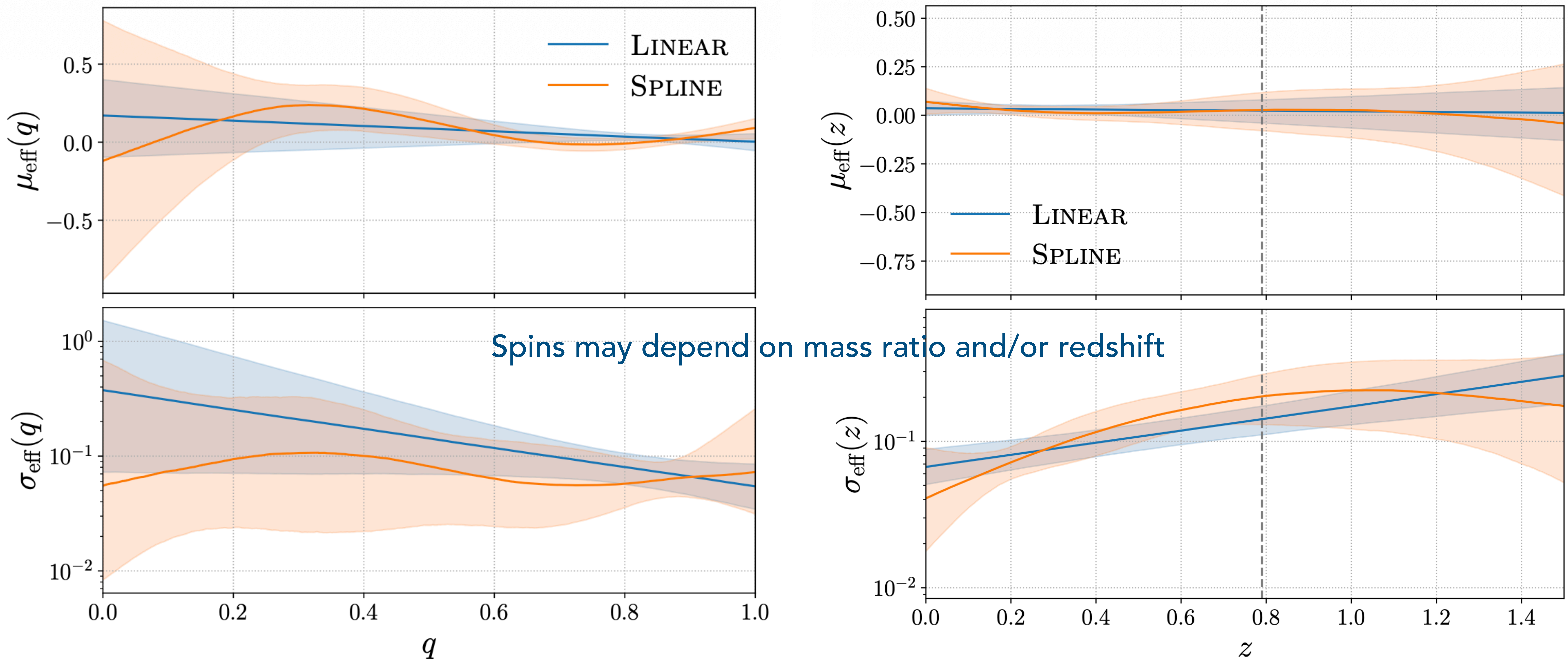
What have we learned about spins?

Data-driven modelling

LVK, inc. **CT**, ApJL, arXiv:2508.18083

What about correlations?

Looking for correlations between parameters

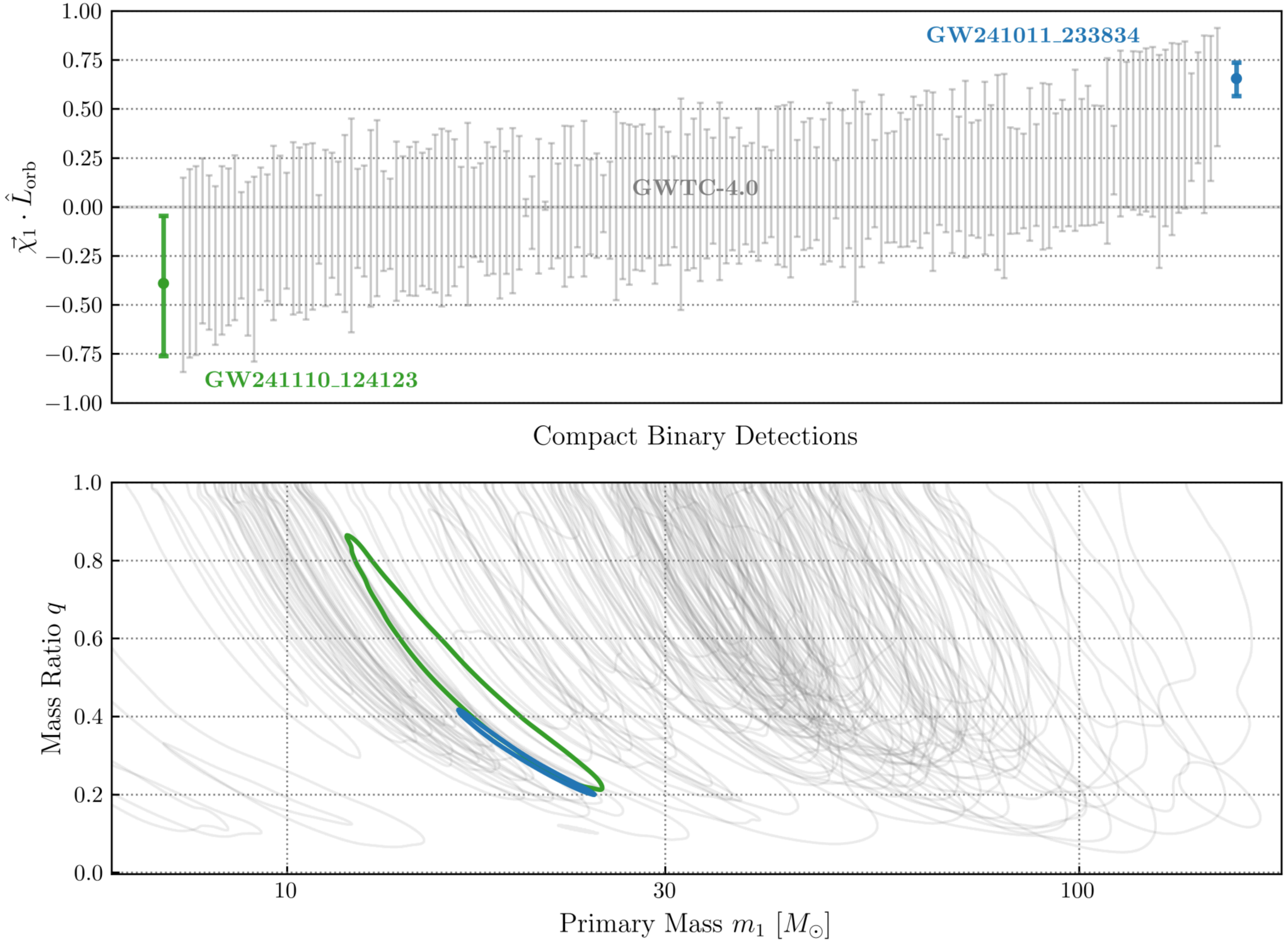


Spins may depend on mass ratio and/or redshift

LVK, inc. **CT**, ApJL, arXiv:2508.18083

What have we learned?

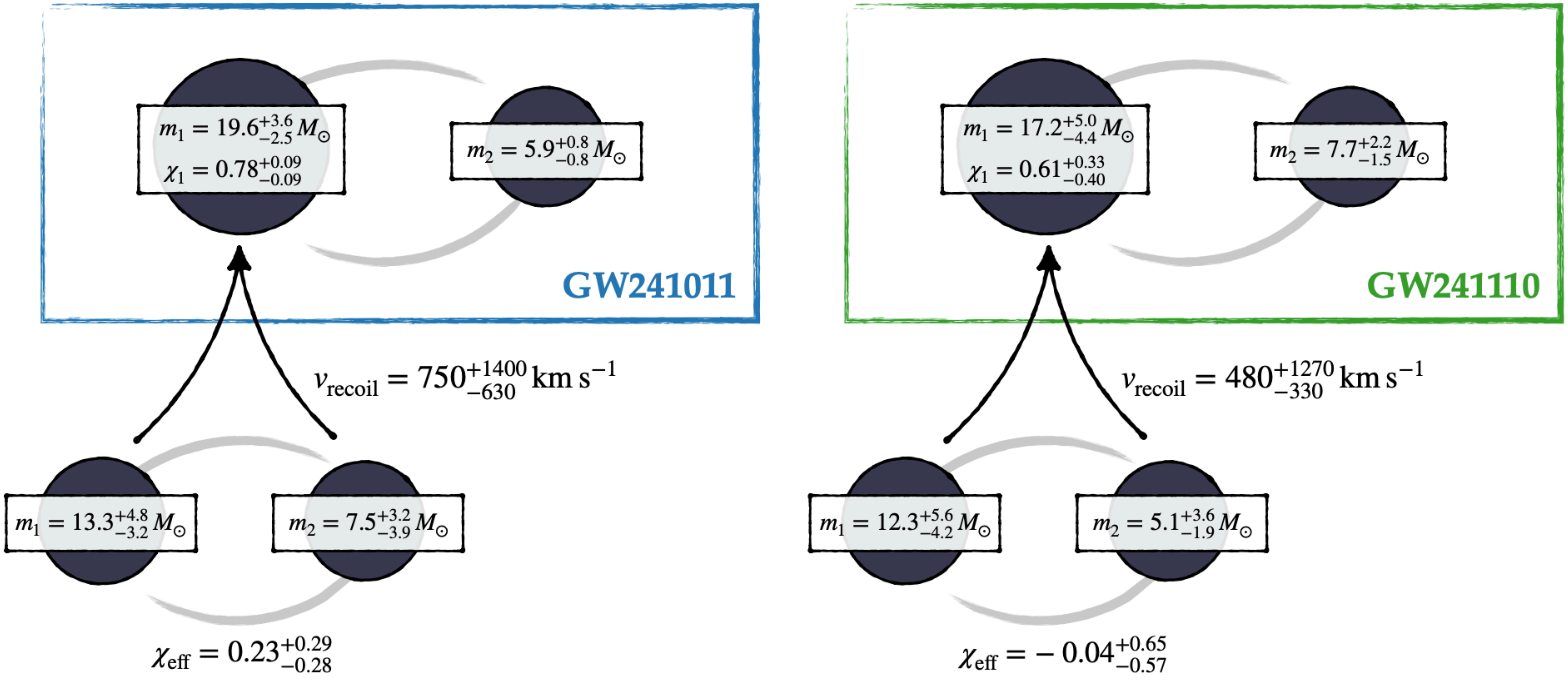
The twins: GW241011 and GW241110



LVK, inc. **CT**, ApJL, arXiv:2510.26931

What have we learned?

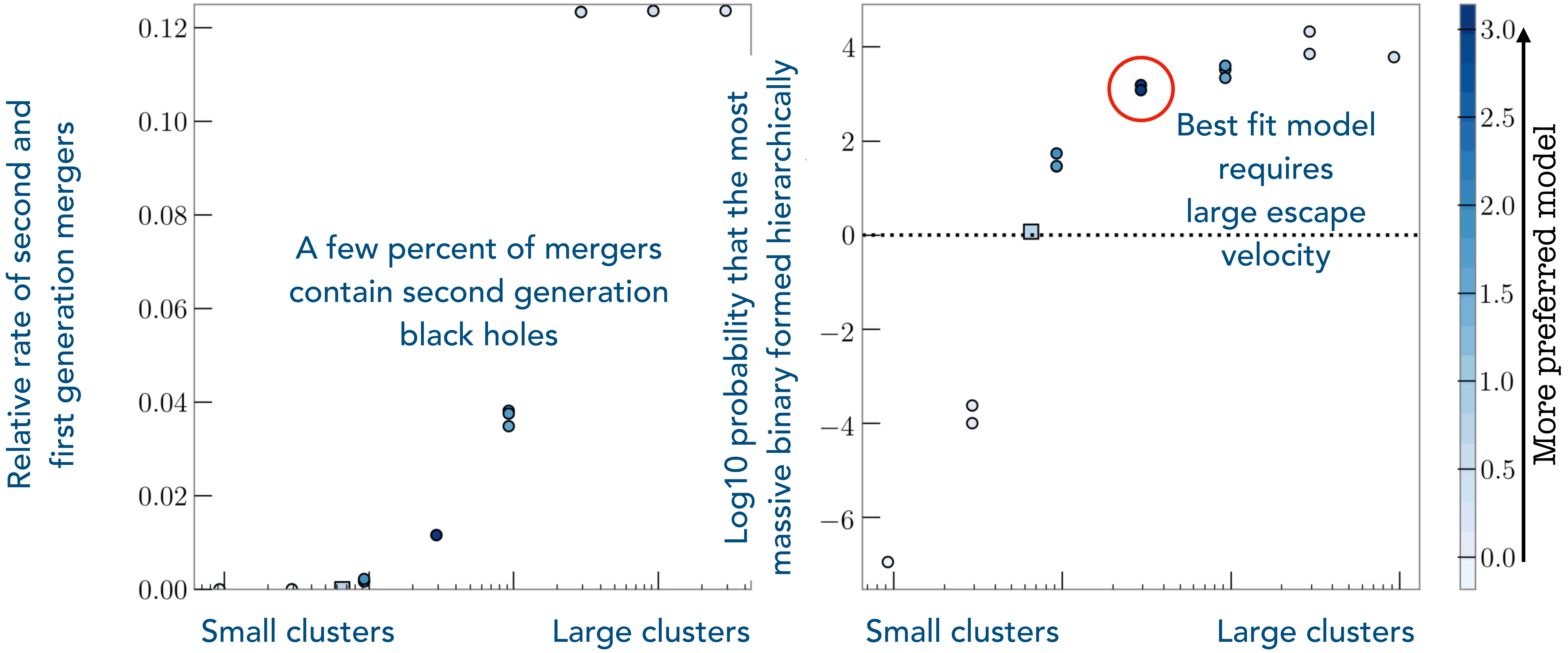
There multiple generations of merging black holes



LVK, inc. **CT**, ApJL, arXiv:2510.26931

What have we learned?

Are there too many hierarchical formed black holes?



Kimball, **CT**, *et al.*, ApJL, arXiv:2011.05332

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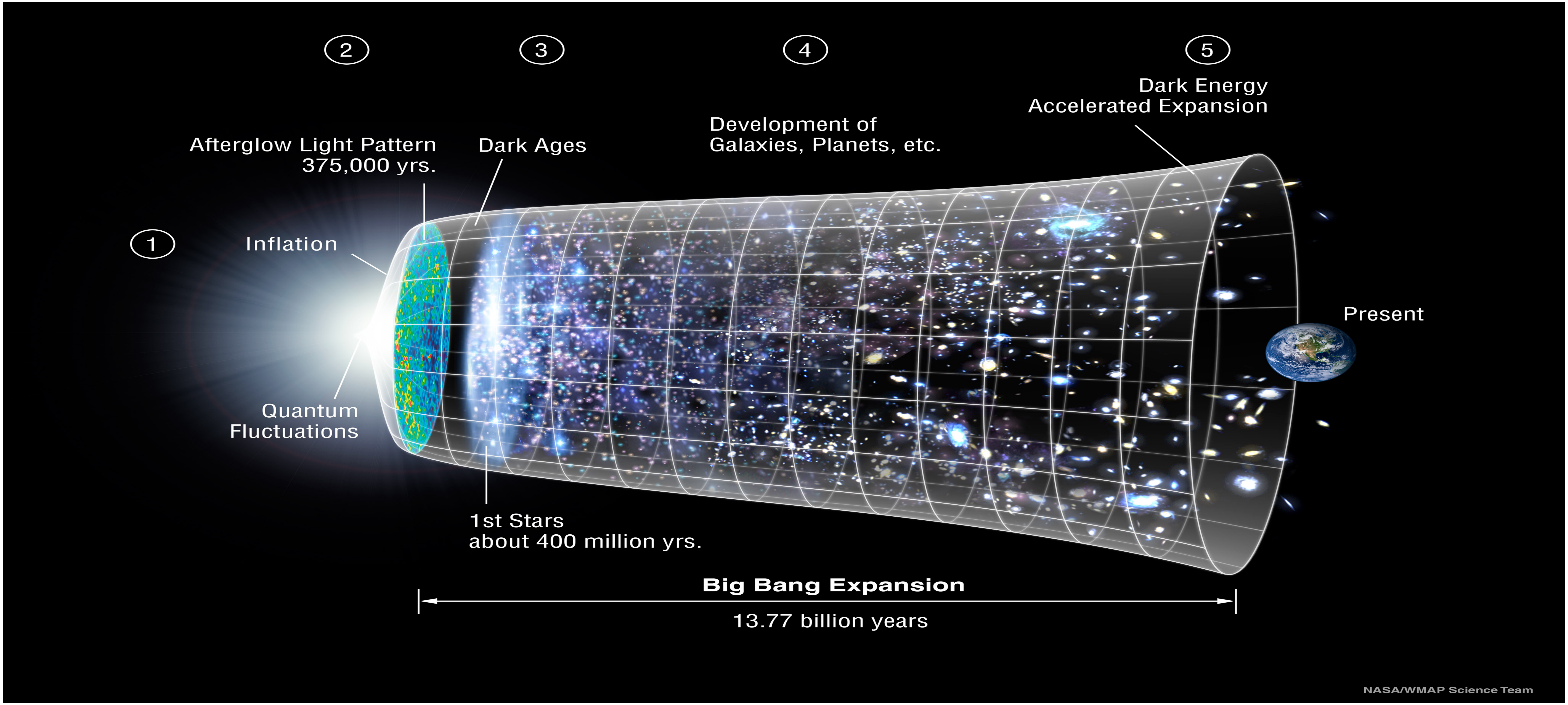
What is cosmology? (Or what do I mean by cosmology)



What can we learn about cosmology?

- The local expansion rate (a.k.a., the Hubble constant H0)
- The matter energy density (a.k.a., Omega m)
    - By extension the dark energy energy density (a.k.a., Omega Lambda)

$$H(z; H_0, \Omega) = H_0\sqrt{\Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})(1+z)^{3(1+w_0)}}$$

$$H(z; H_0, \Omega) = H_0 E(z; H_0, \Omega)$$

How can we learn about cosmology?

- Measure mapping between luminosity distance and redshift

$$d_L = (1+z)d_H \int_0^z \frac{dz'}{E(z'; \Omega_{m,0}, w_0)}$$

- Gravitational waves from compact binaries provide an absolute measurement of luminosity distance
  - They are “standard sirens”
- How can we measure the redshift?

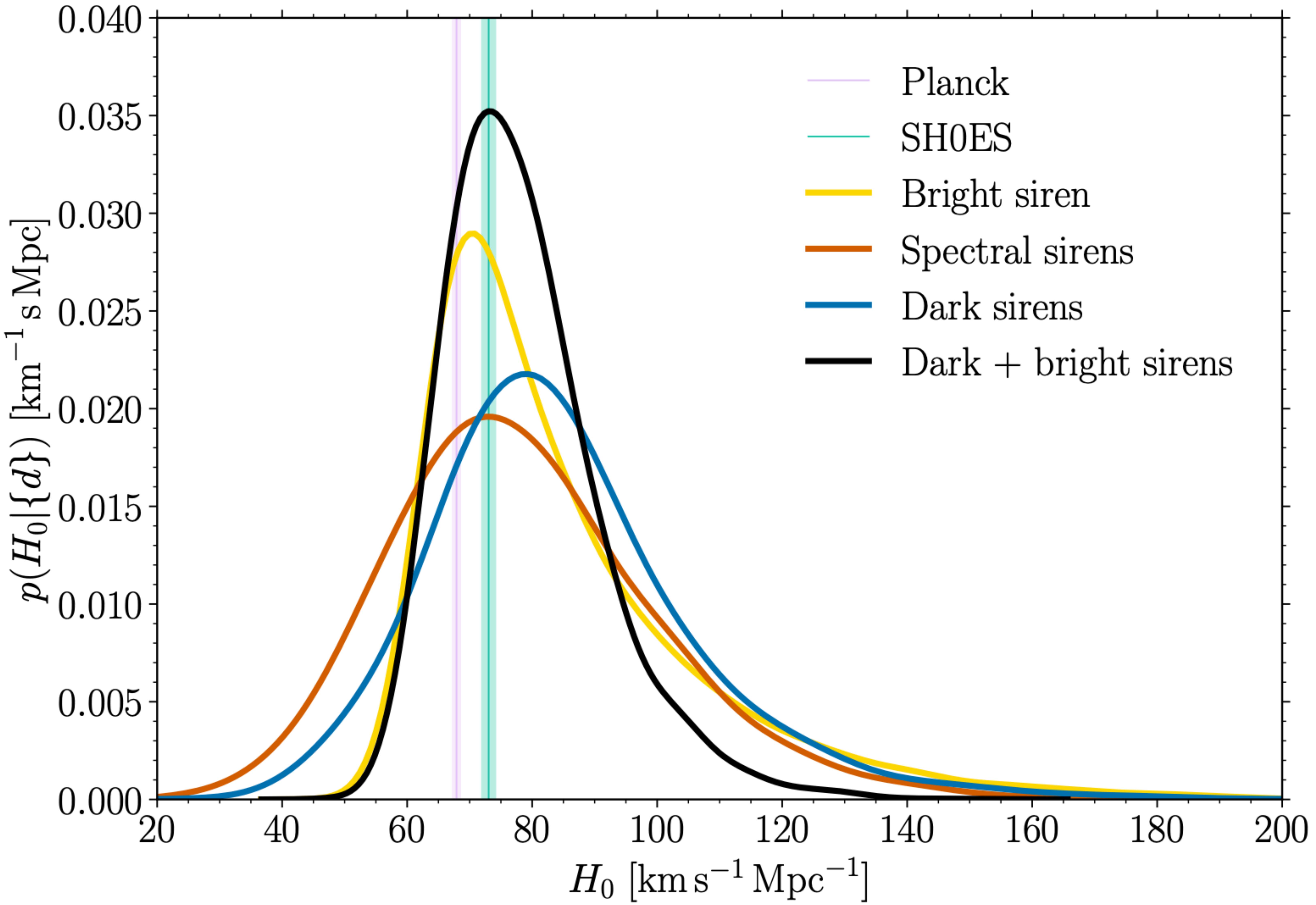
How can we measure the redshift?

- Bright sirens (e.g., GW170817)
  - Redshifts from electromagnetic observations of the source
- Dark sirens
  - Correlate observations with catalogs of known galaxies
- Spectral sirens
  - Measure how the population evolves with distance/redshift
- Love sirens (a.k.a., tidal sirens)
  - Tidal effects are determined by source-frame mass and equation of state
- Stochastic sirens
  - Use upper bound on the astrophysical background to constrain cosmology

Spectral siren cosmology

- We measure luminosity distance and detector-frame masses for individual events
- Jointly model the distribution of source-frame quantities and cosmological parameters
- Everything else is the same
- Caveat:
  - We need to assume something about the redshift dependence of the astrophysical population.

What have we learned about cosmology?



LVK, inc. **CT**, ApJL, arXiv:2509.04348

What is coming?

- The gravitational-wave transient catalog will have several hundred candidates by the release of the last O4 data.

- Future runs will accumulate events much more rapidly.

- We need better analysis methods.

What did I miss?

- Lots of results from LVK analyses…
- All the results from non-LVK work!
- How we do these analyses
- Our current methods won't scale to the catalog sizes we expect in the coming years.
- How we could do better

Summary

- Examining the gravitational wave transient catalog as a whole can reveal information about the formation processes of compact binaries
- We are already seeing structure in the observed population and hints of correlations between mass, spin, and distance
- There seem to be hierarchically formed merging binary black hole systems

Summary

- Examining the gravitational wave transient catalog as a whole can reveal information about the formation processes of compact binaries
- We are already seeing structure in the observed population and hints of correlations between mass, spin, and distance
- There seem to be hierarchically formed merging binary black hole systems