# Uncovering hidden structure in the binary black hole population with gravitational-waves

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SPINS

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LIGO VIRGO KAGRA

# What is LIGO?

Ground-based gravitational-wave detectors

Two perpendicular arms, each 4 km long

Measures differential strain



LIGO Hanford, WA.



LIGO Livingston, LA.

Sensitive to binary black holes, binary neutron stars, black hole-neutron star binaries, and more!



B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), “GW150914: The advanced LIGO detectors in the era of first discoveries”, Phys. Rev. Lett. 116, 131103 (2016).

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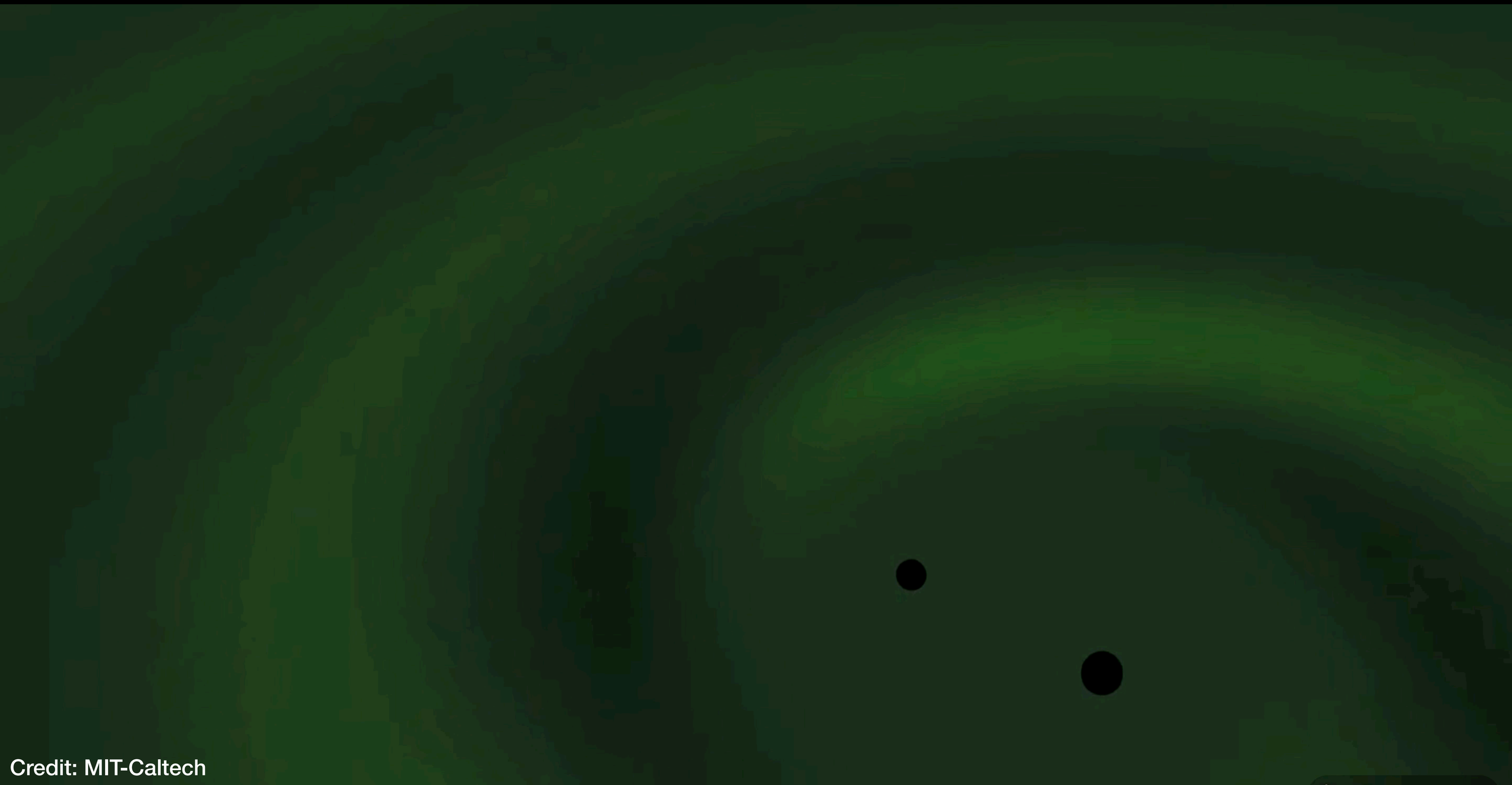

Credit: MIT-Caltech

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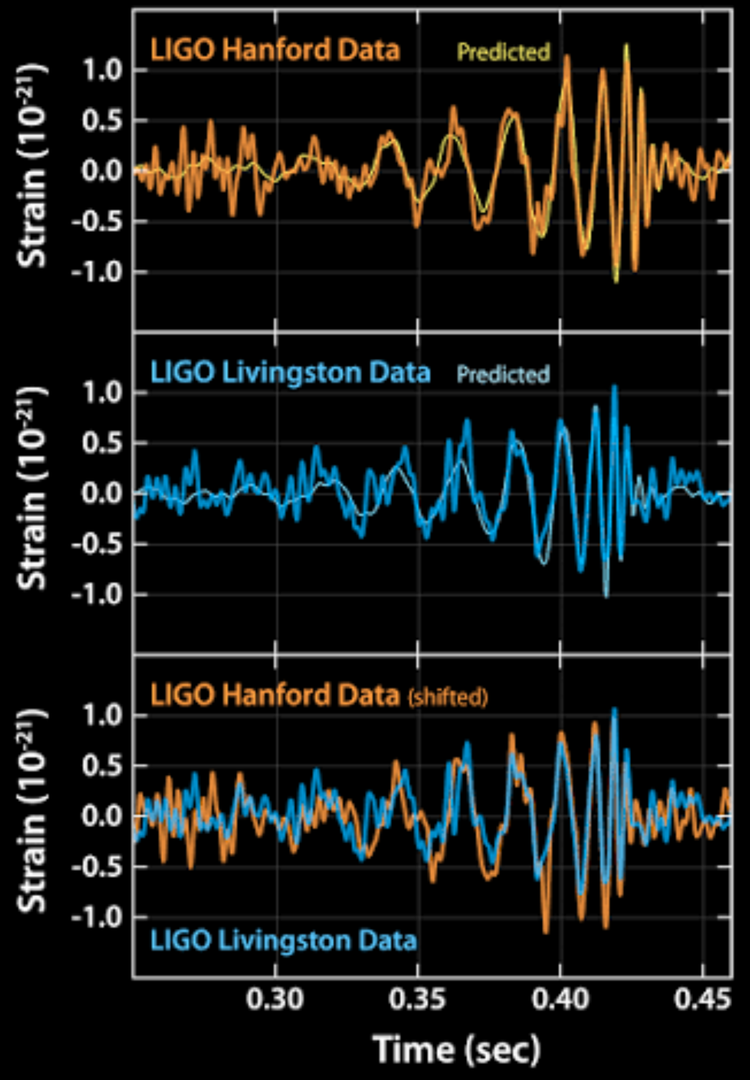
# Happy birthday, GW150914!

- First direct detection of gravitational-waves
- First observation of a binary black hole merger.
- September 14 2015, 11 years ago this week!




Credit: Caltech LIGO lab

Abbott+16

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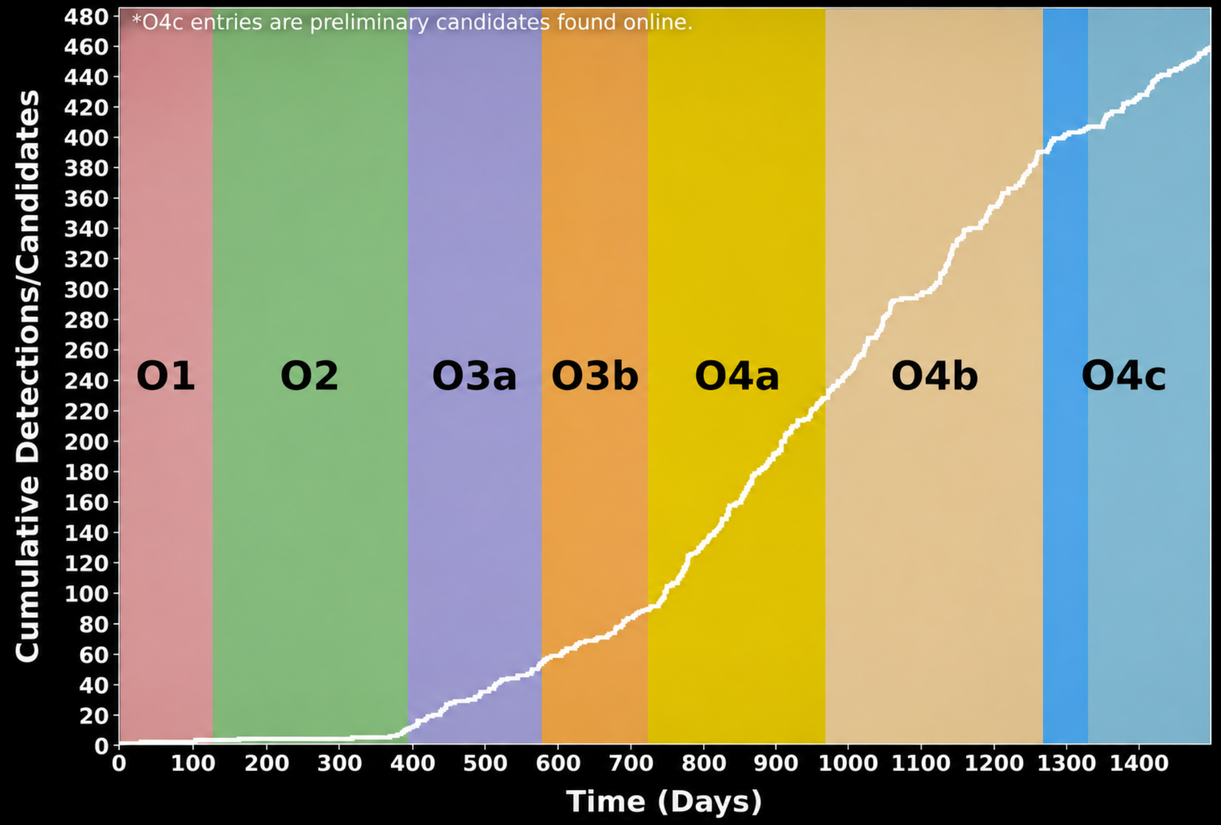
# Where are we?

- Four observing runs over the last decade.
- Detectors have steadily increased sensitivity.
- We have detected more than 390 binary mergers!
  - Mostly binary black holes (259 confident detections)
  - Two neutron star binaries
  - Six neutron star - black hole binaries.




https://ligo.org/science-summaries/o4b_catalog_omnibus/



Abac+25

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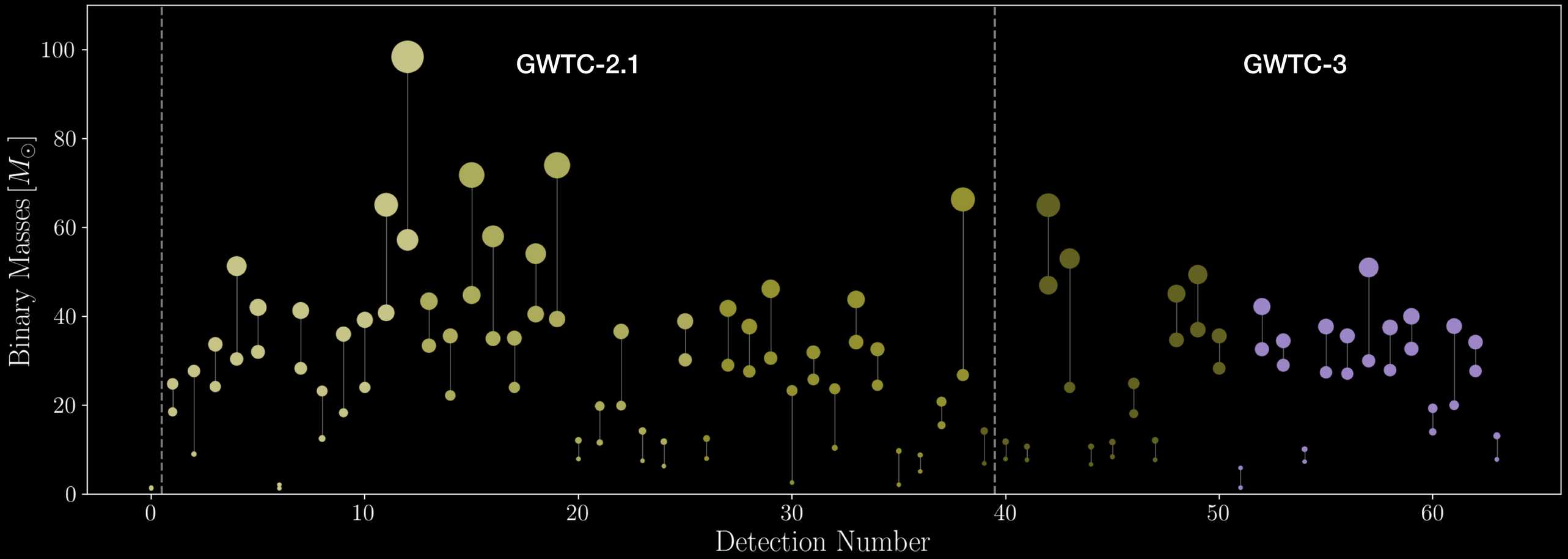
# Where we were: GWTC-3




Abbot+21



With inspiration from Tom Callister

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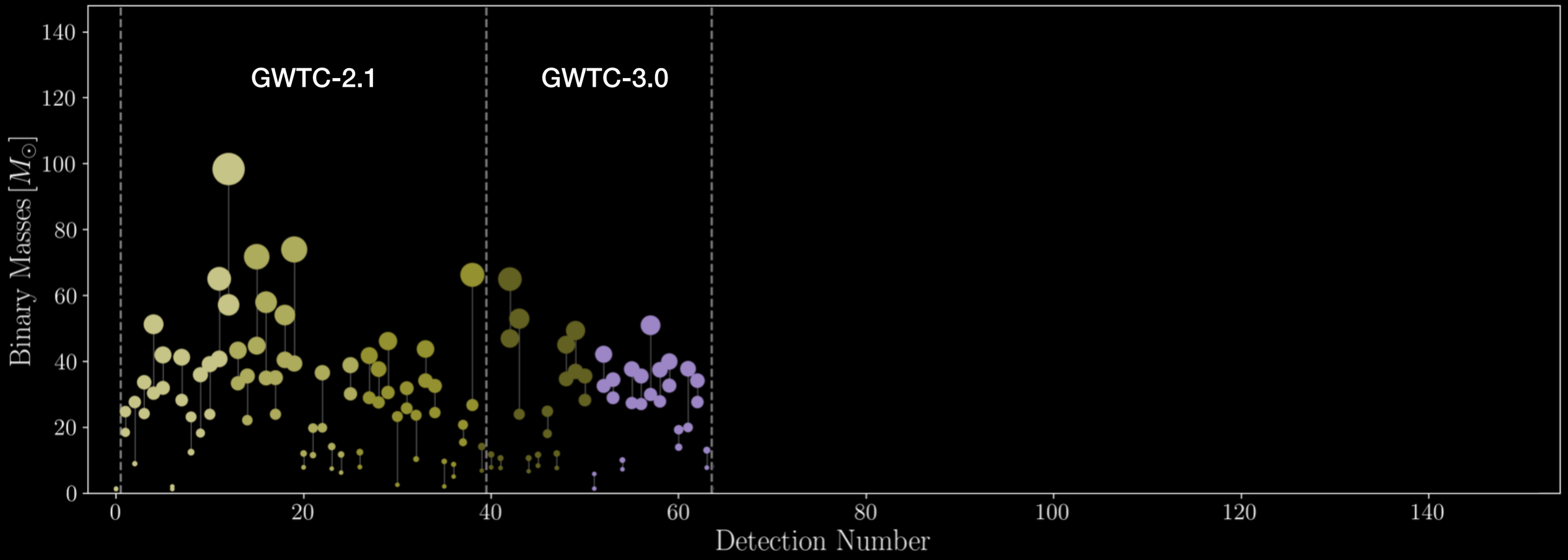
# Where we were: GWTC-4




Abac+25



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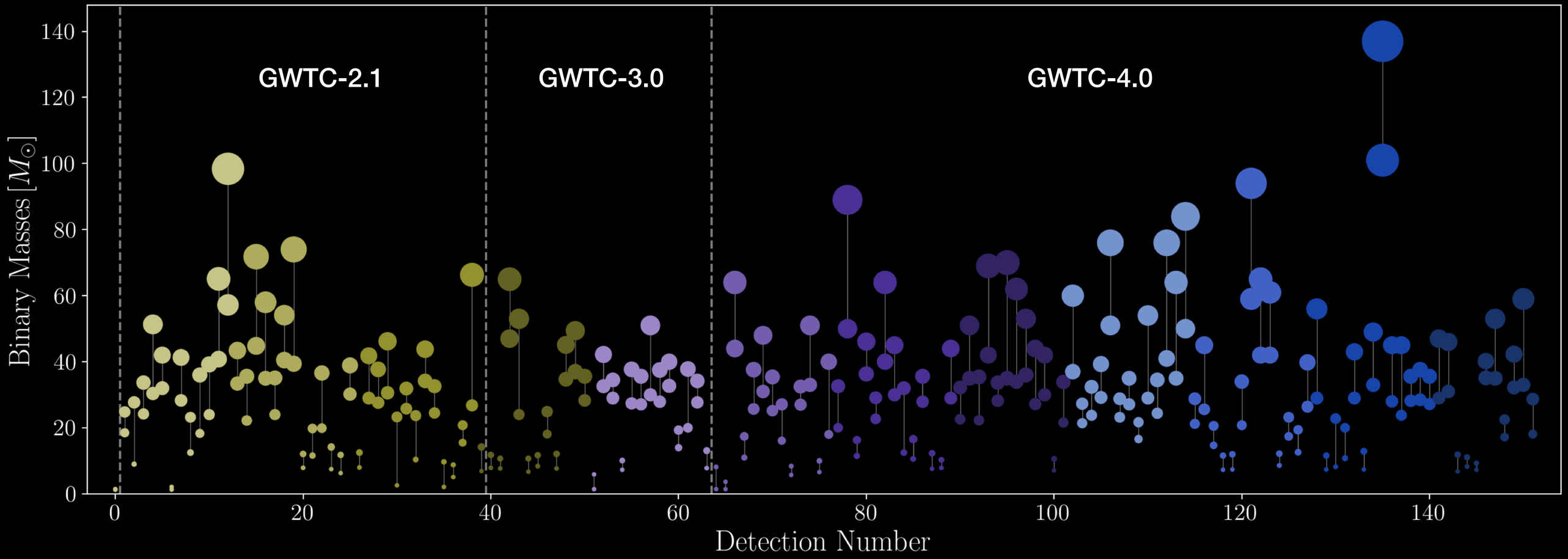
# Where we were: GWTC-4




Abac+25



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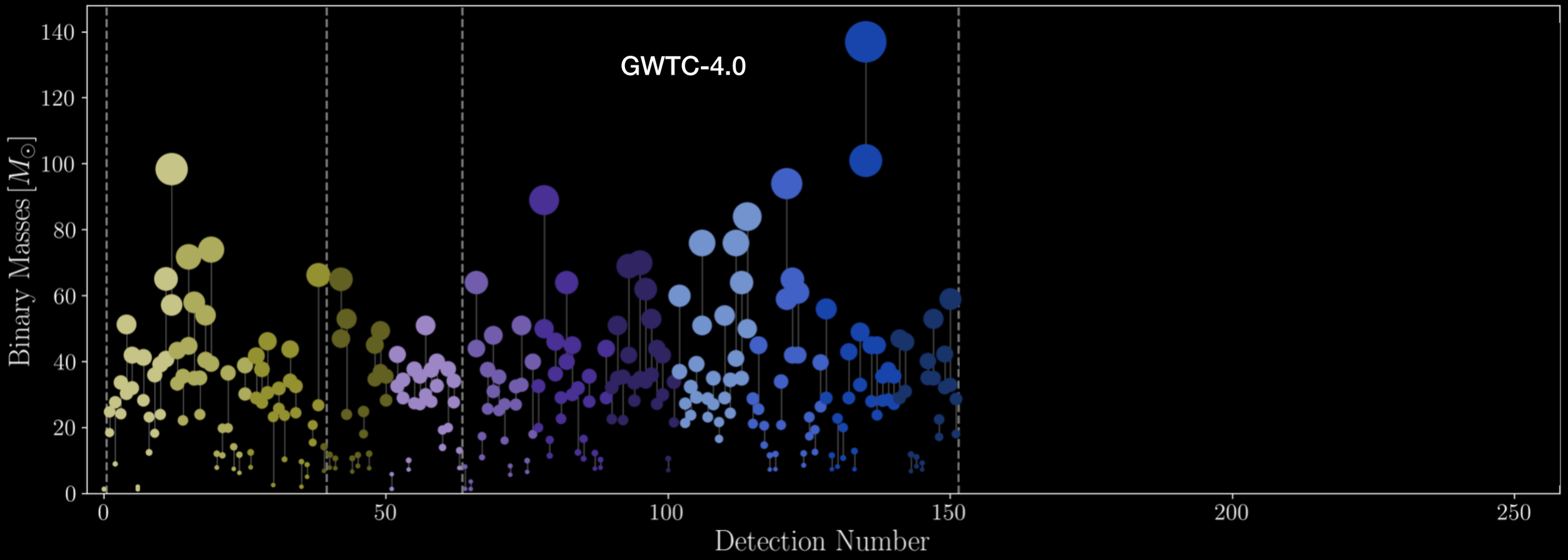
# Where we are: GWTC-5




Abac+26



With inspiration from Tom Callister

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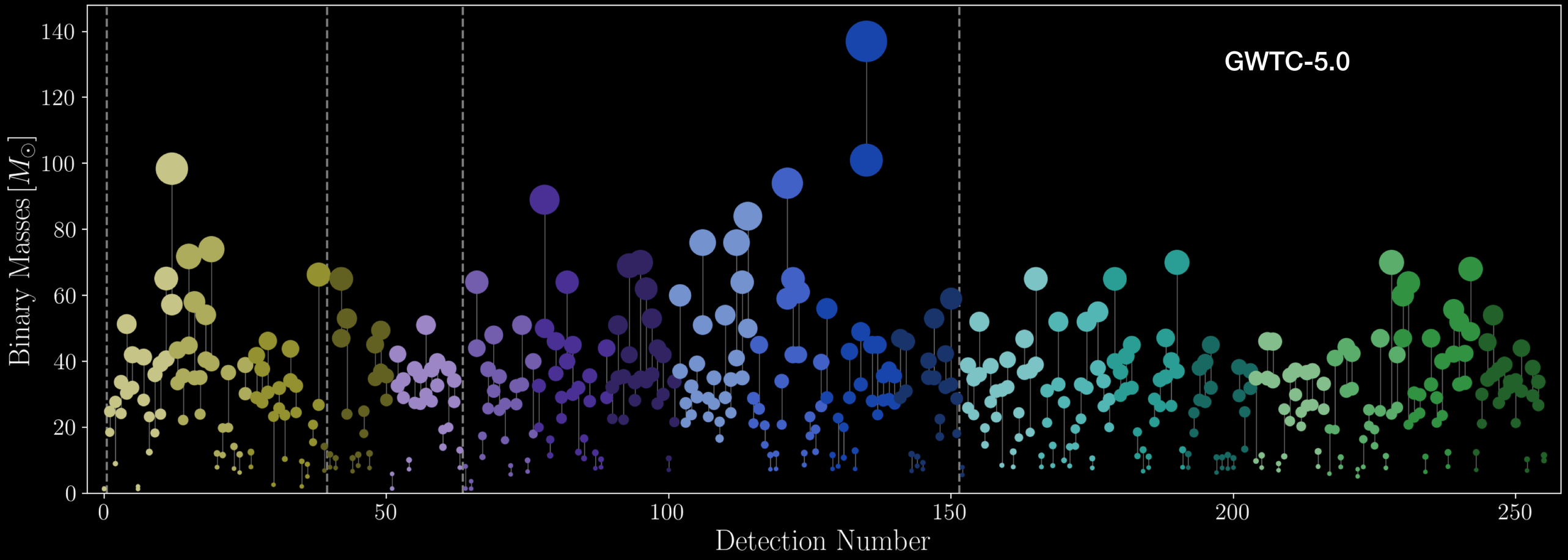
# We have 259 confident BBH detections in GWTC-5!




Abac+26



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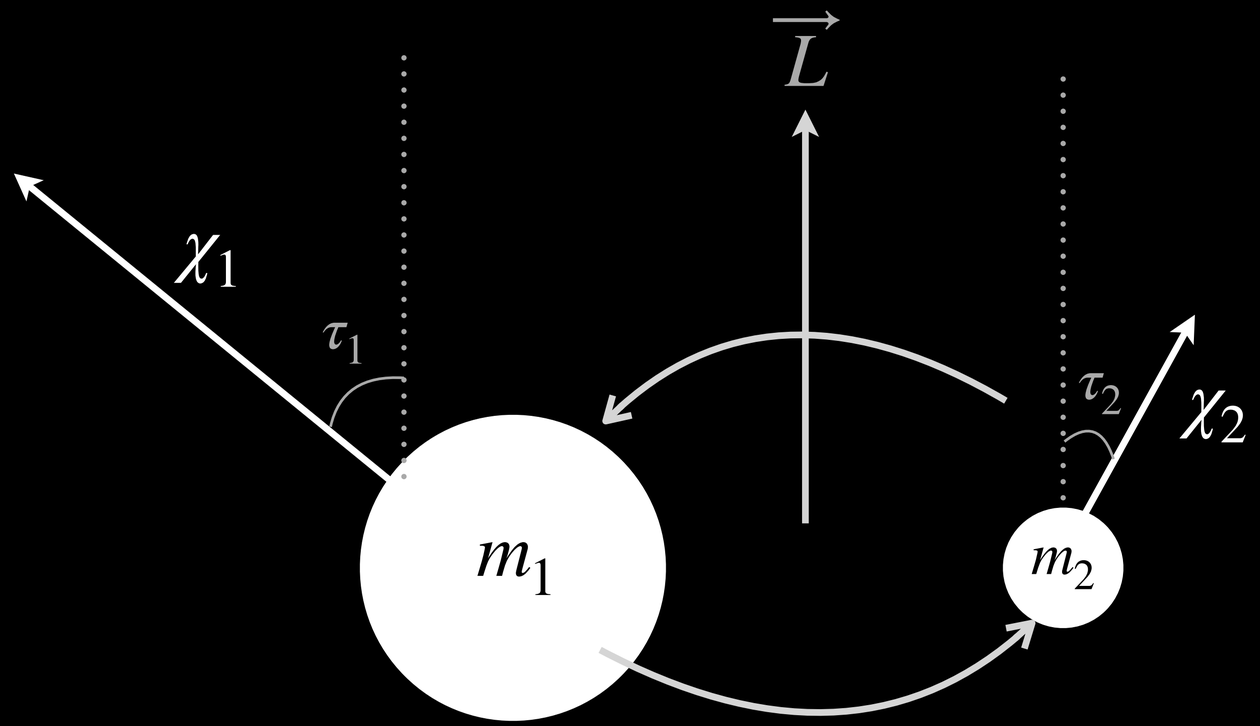
# Each source has unique properties that can teach us about its story, encoded in the gravitational-wave signals we measure




Index 1 = most massive object



Inspired on Salvo's slides!

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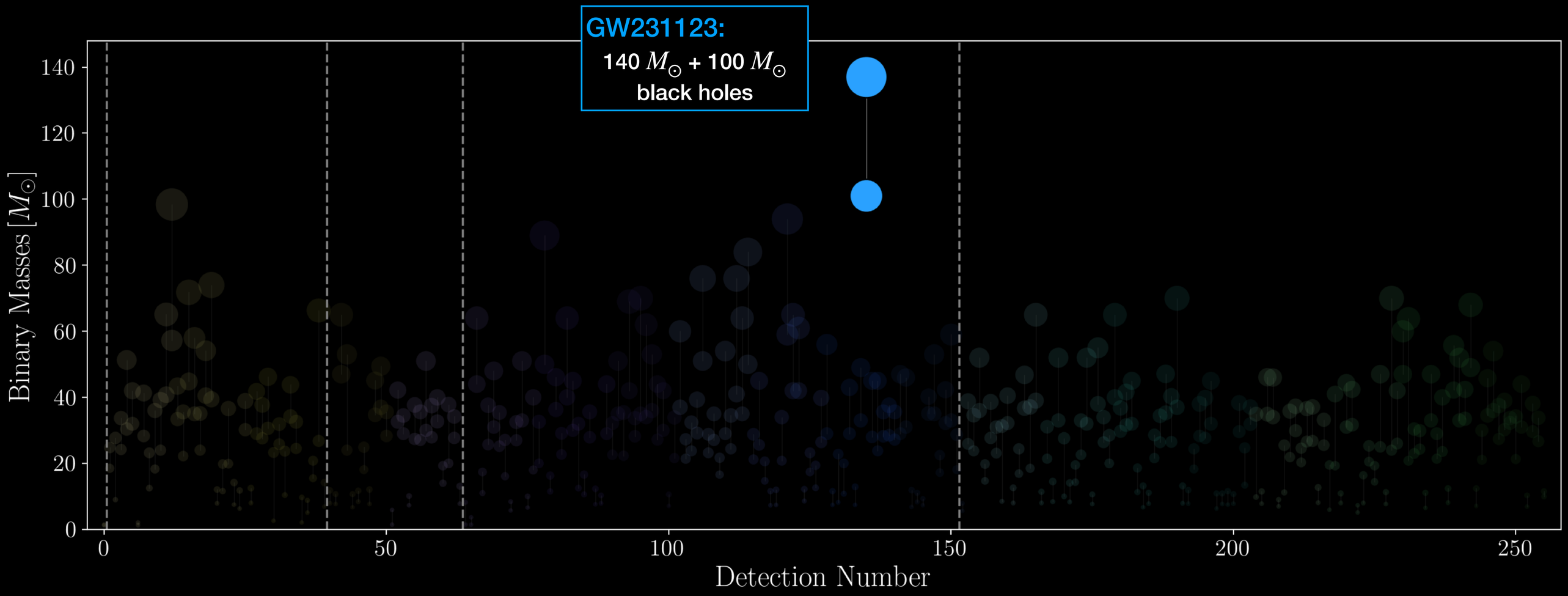
# Exceptional stories in GWTC-4.0 and GWTC-5.0

## GW231123: most massive BBH to date






Abac+23, Abac+25, Abac+26

# From black hole stories to formation histories

With hundreds of detections, we can start learning about the underlying astrophysical populations of compact binary coalescences.

However…

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The detected population is not the astrophysical population

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However…

The detected population is not the astrophysical population

1. Our measurements of the properties of individual binary black hole systems are uncertain.

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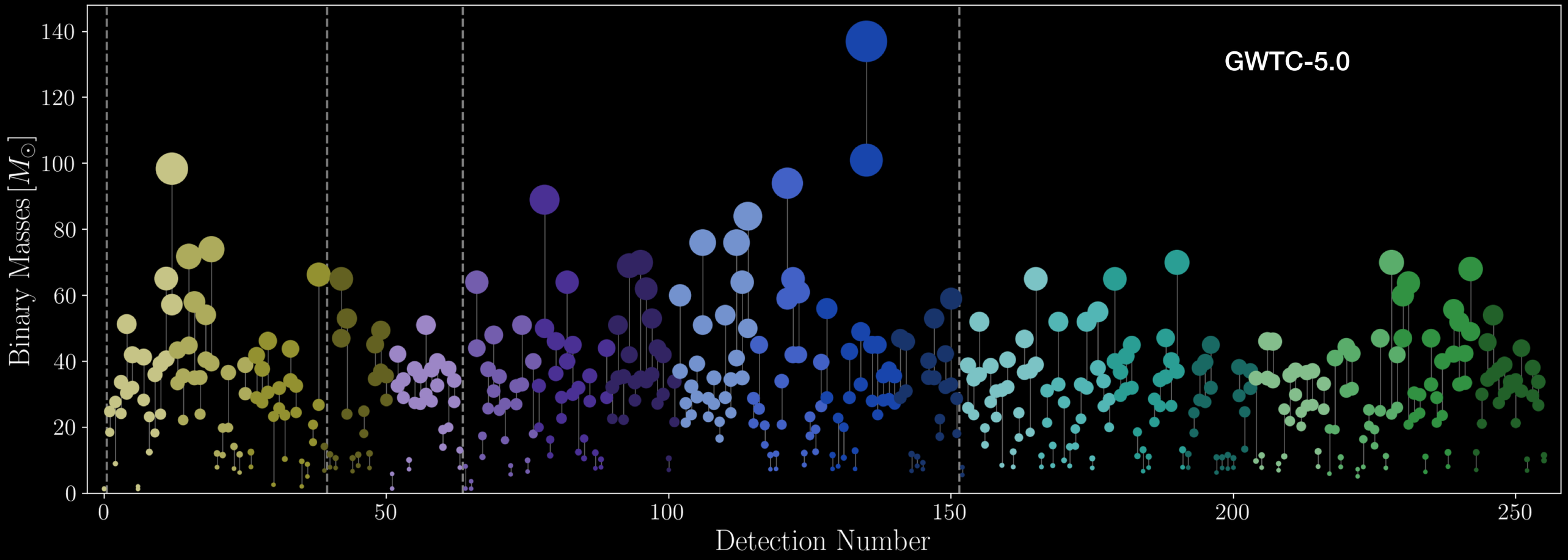
# Instead of “perfect” measurements (e.g., of the mass)…



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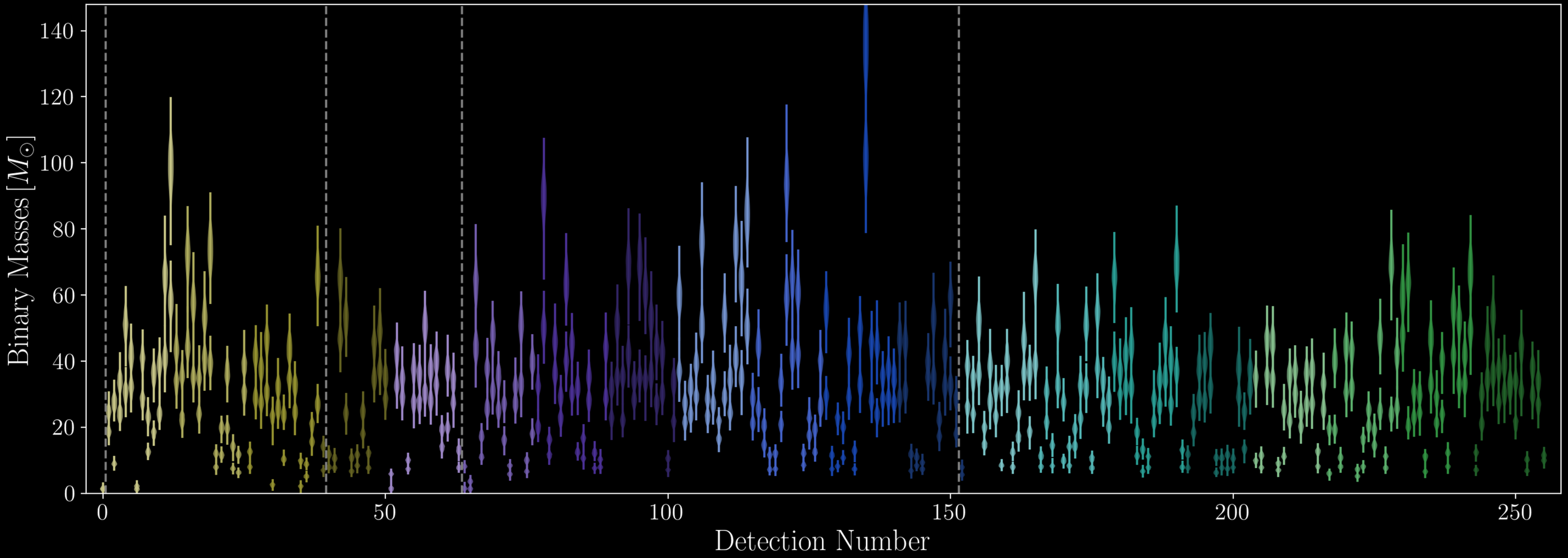
# Our measurements of binary black hole properties are uncertain



# From black hole stories to formation histories

With hundreds of detections, we can start learning about the underlying astrophysical populations of compact binary coalescences.

However…

The detected population is not the astrophysical population

1. Our measurements on the properties of individual binary black hole systems are uncertain.

2. Selection effects: some binaries are easier to detect than others

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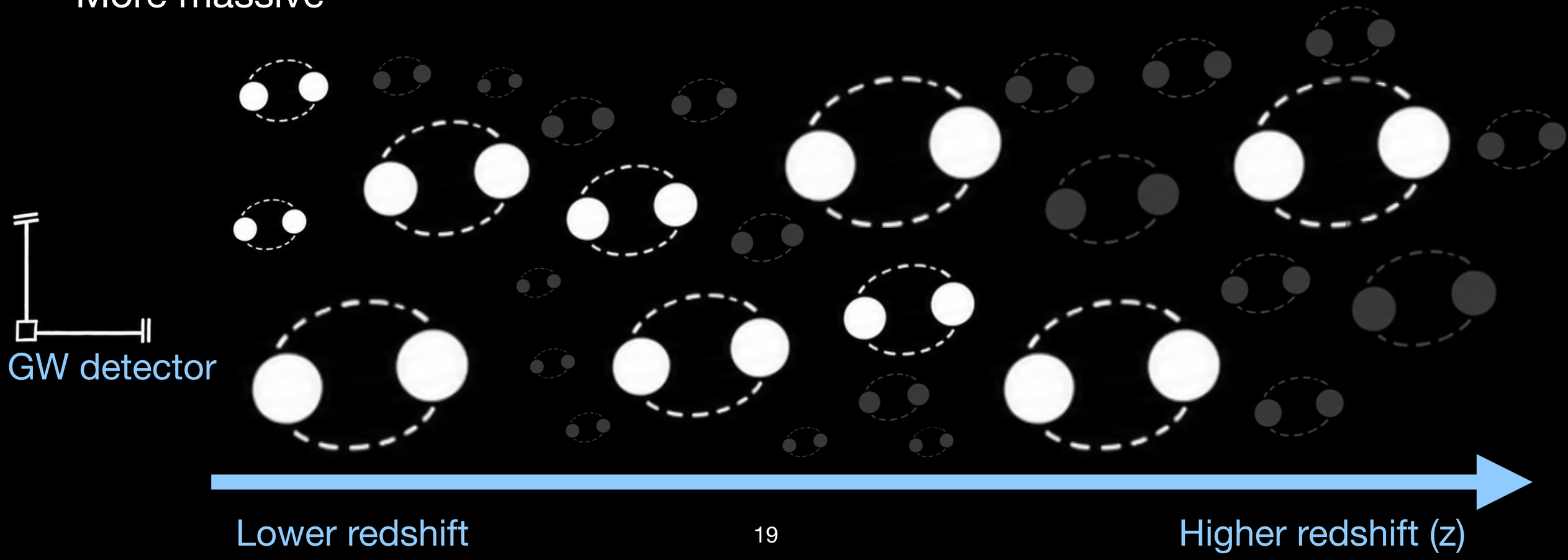
# LVK is more sensitive to binary black holes that are:

- Closer to Earth (i.e., lower redshift)
- More massive



# From black hole stories to formation histories

With hundreds of detections, we can start learning about the underlying astrophysical populations of compact binary coalescences.

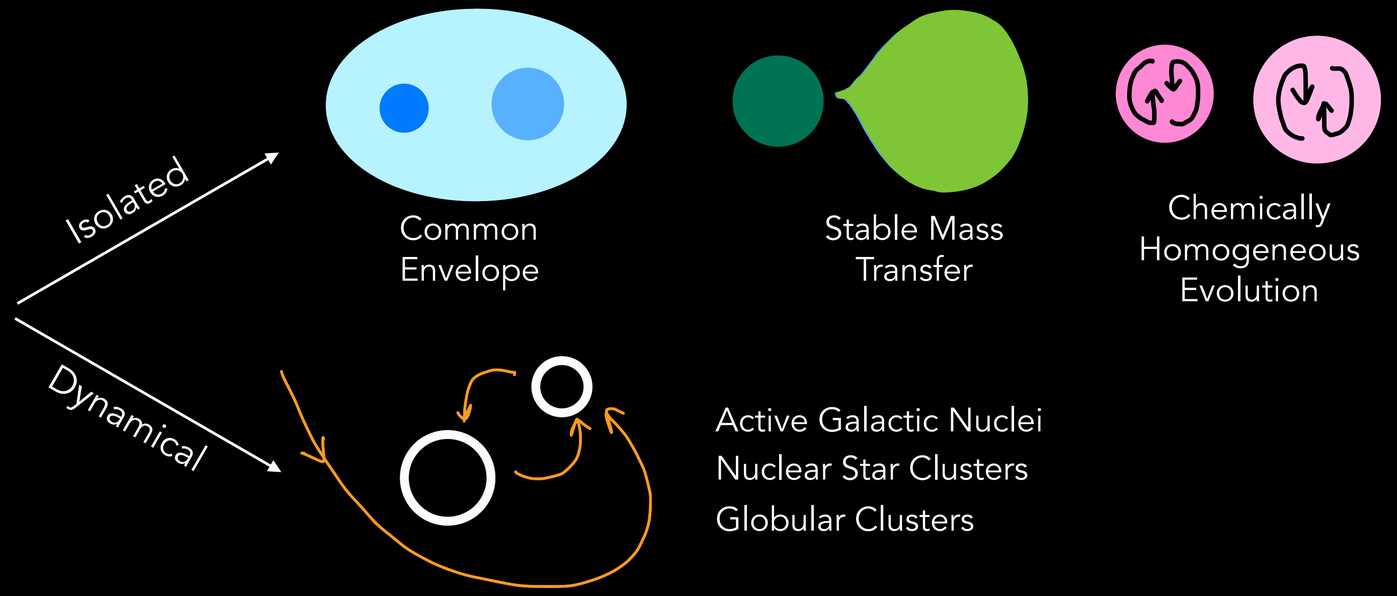
Why do we care?

We want to learn how much black hole formation history is hidden in the GW catalog

# Binary black holes may form through a diverse range of astrophysical formation channels

We expect nature to be a superposition of (at least) some of these formation channels.

e.g., Mapelli+19,20, Ivanova+13, Bavera+21, Gerosa-Fishbach 21, Mandel-Broekgaarden 22, Gallegos-Garcia+21




Each formation channel is governed by complex astrophysical processes, which may leave fingerprints in the BBH population and correlations between source parameters.

e.g., Bavera+20,21,22, Santini+23, Baibhav+23, van Son+22, Zevin+22, Broekgaarden+22.

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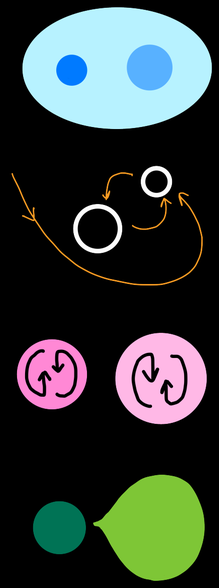
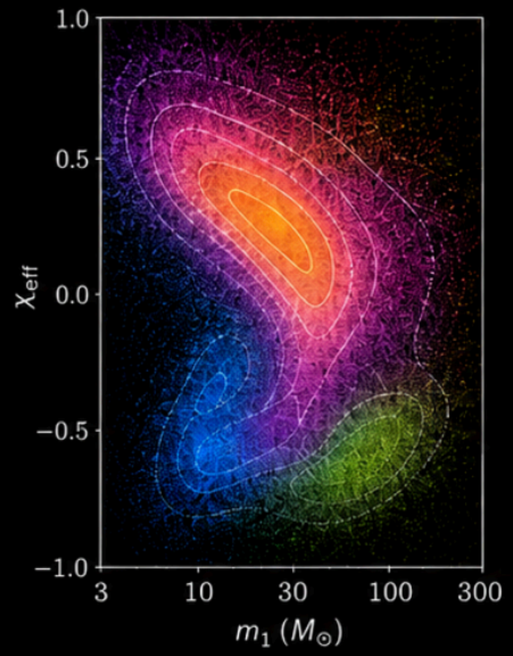
# Inferring the population properties

## 1. Formation pathways



and more!

## 2. True binary black hole population




Masses, spins, mass ratios, redshifts, correlations imprinted from progenitors

PopSynth: Posydon, Andrews et al. 2024; MESA, Paxton et al. 2015; COMPAS Stevenson et al. 2017; CMC, Rodriguez+ 2021

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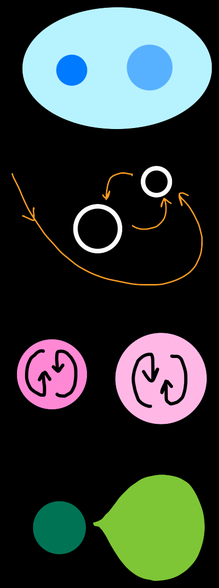

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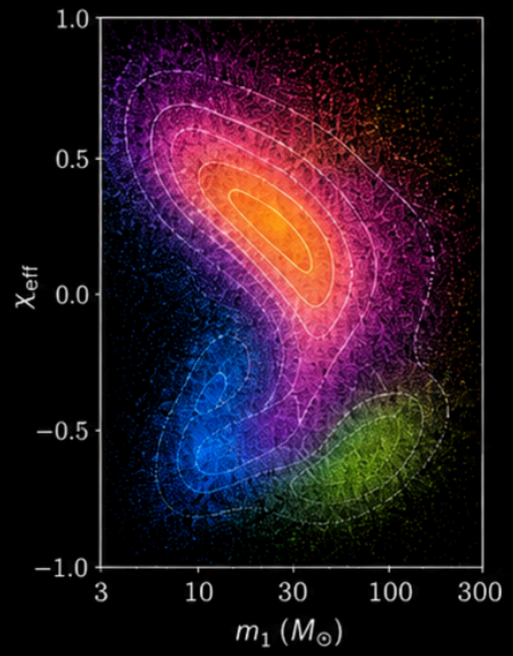


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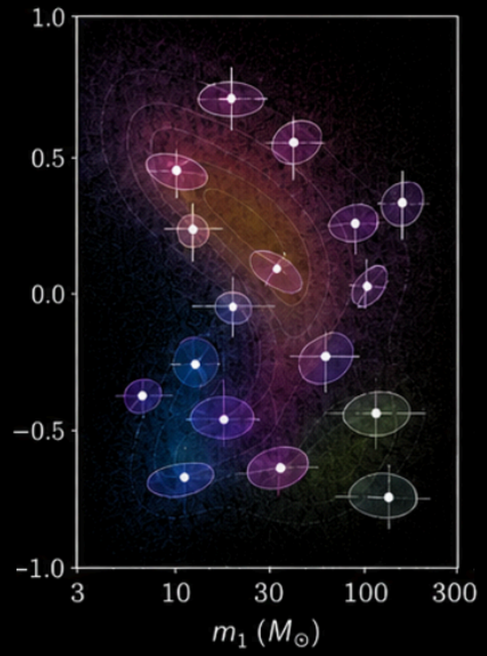
## 3. We detect *some* with LIGO




Incomplete catalog, uncertain measurements

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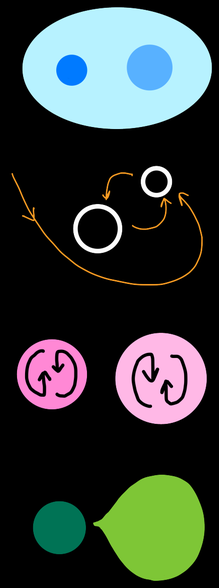

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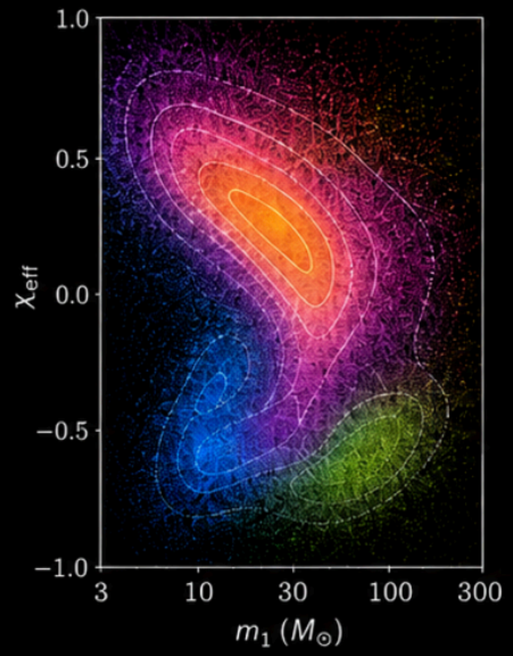


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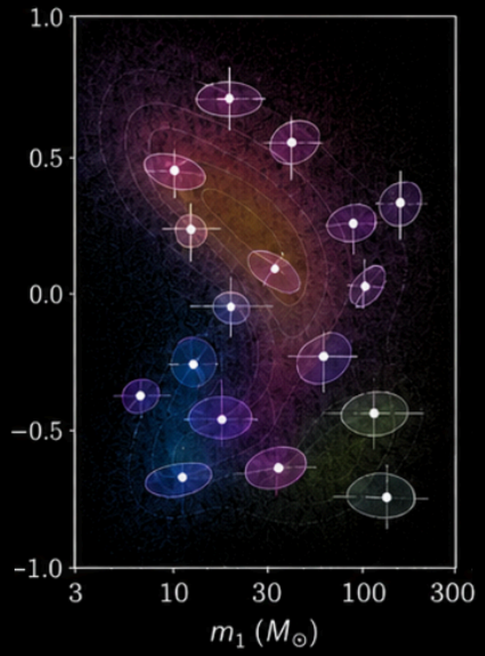


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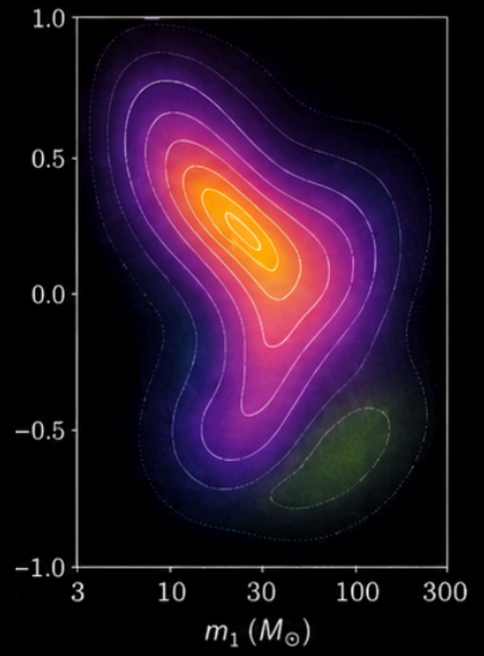


Need to account for selection effects, need a model

PopSynth: Posydon, Andrews et al. 2024; MESA, Paxton et al. 2015; COMPAS Stevenson et al. 2017; CMC, Rodriguez+ 2021

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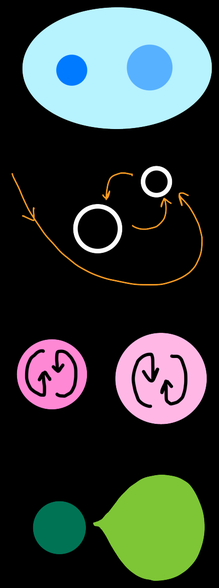

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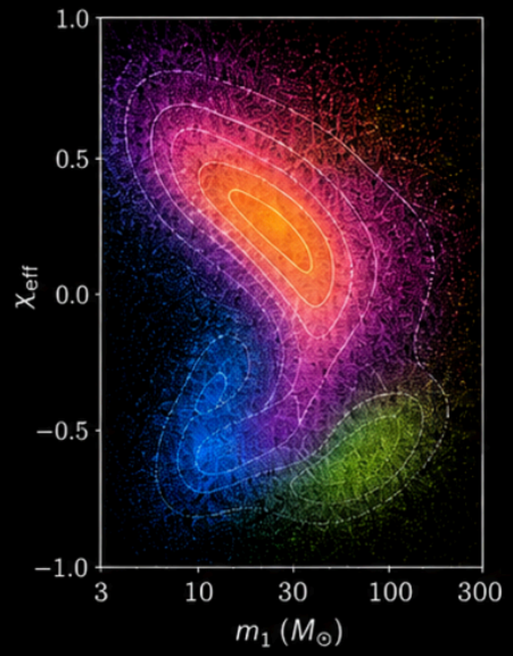


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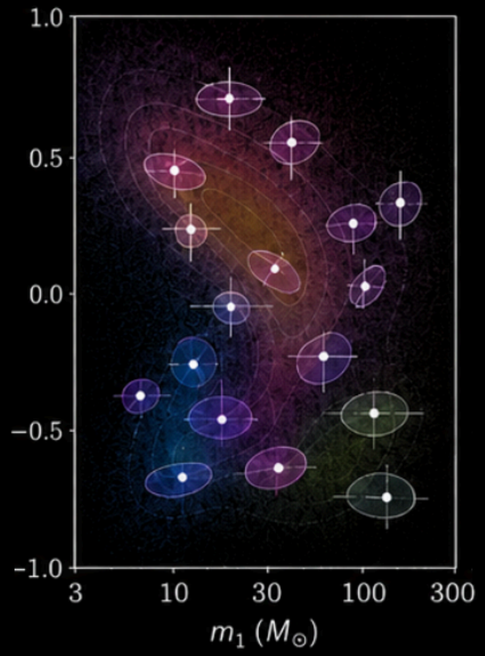


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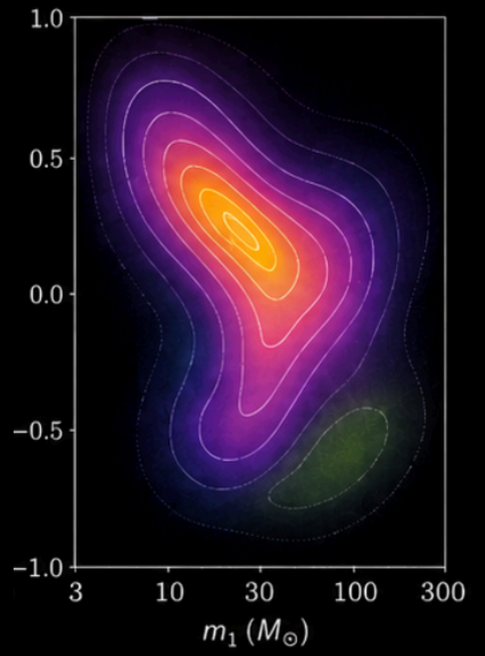


Need a model and need to account for selection effects

5. Understand in light of the theory!

COMPAS

CMC Cluster Monte Carlo

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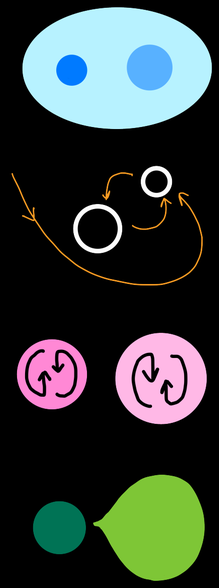

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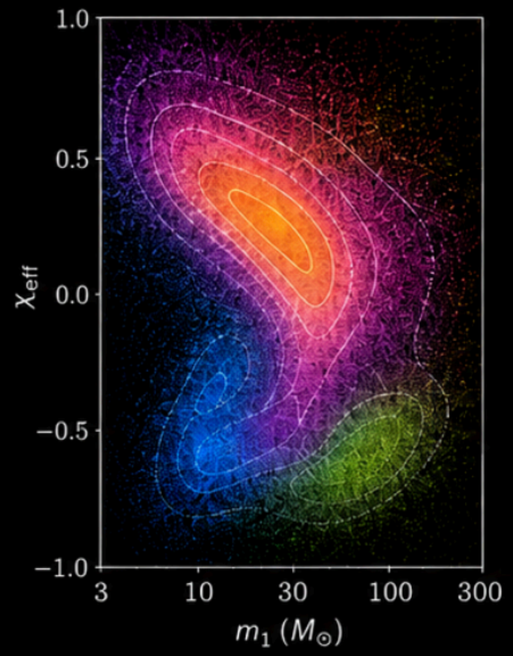


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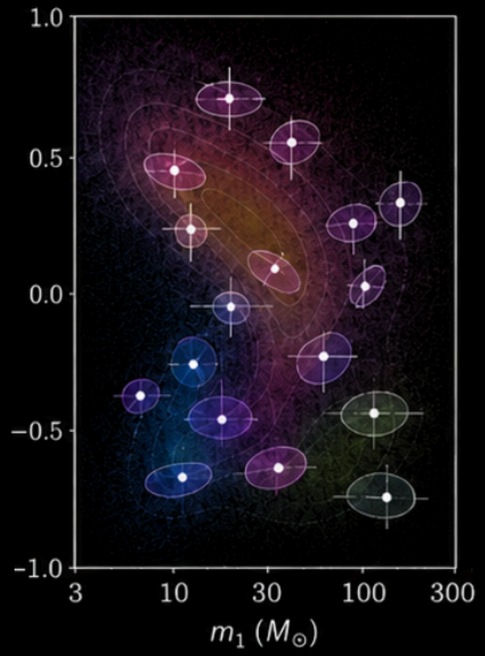


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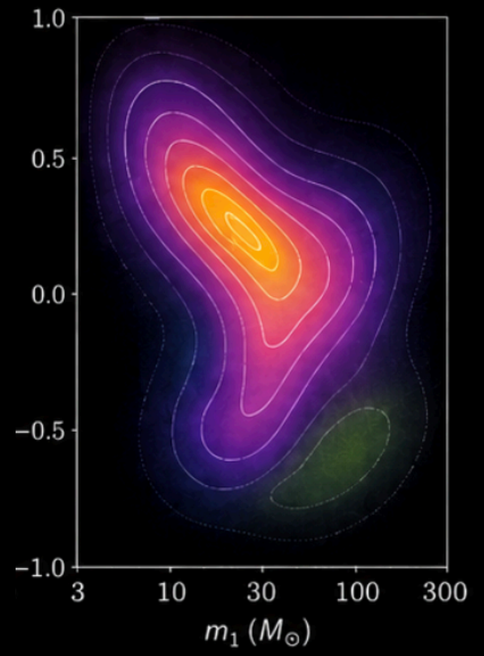


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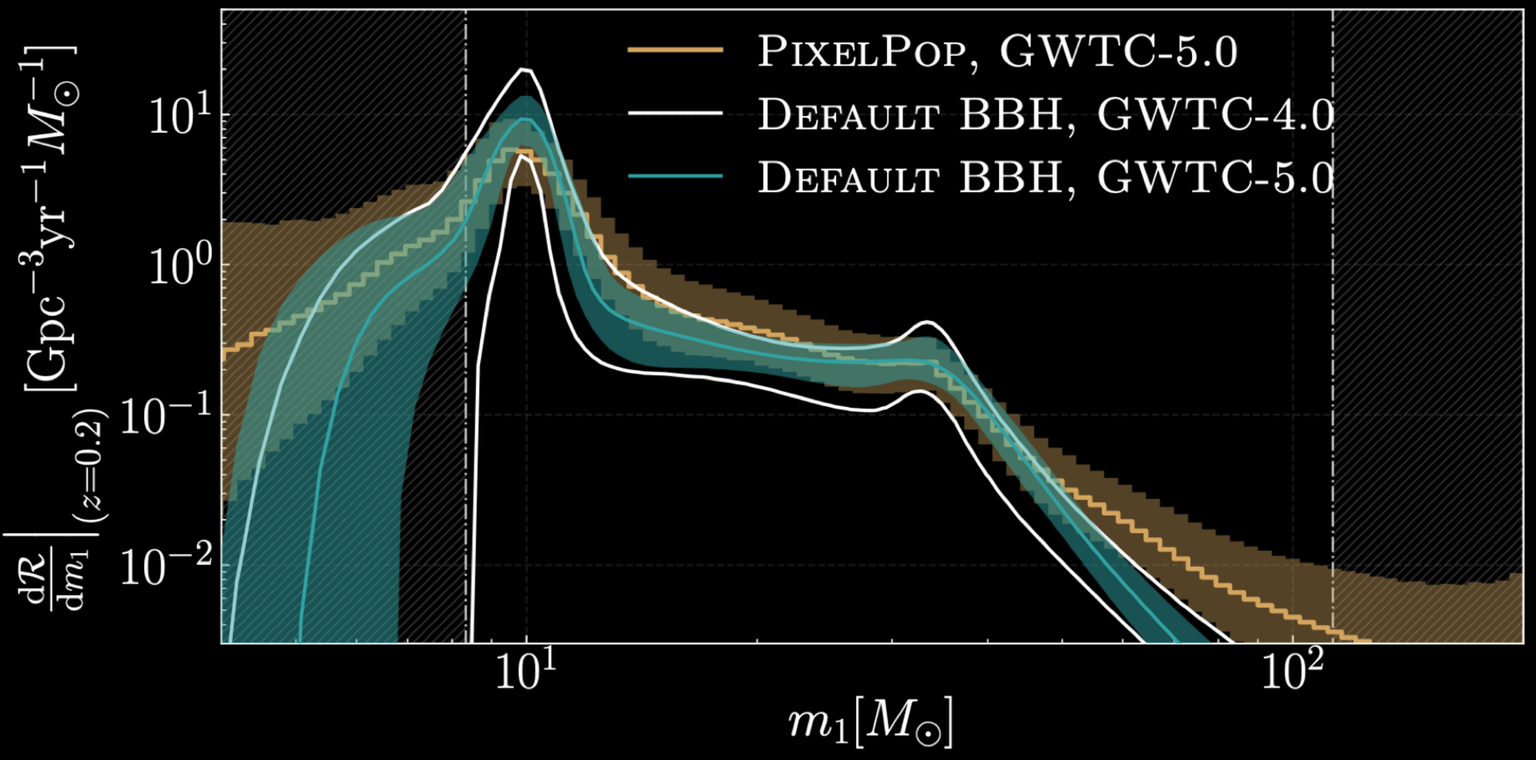
# What have we learned about BH masses in GWTC-5.0?

- **Masses:** global peak at $\sim 10\,M_\odot$, secondary peak at $\sim 35\,M_\odot$.




$\sim 10\,M_\odot$ peak consistent with isolated binary evolution (slowly spinning BHs)

Change in slope after the $\sim 35\,M_\odot$ peak: less BBHs at higher masses, but if there is a (P)PISN mass gap, it is not empty!

Abac+ 2026, Dominik+2015, Belczynski+2020, Giacobbo & Mapelli 2018, van Son+2022

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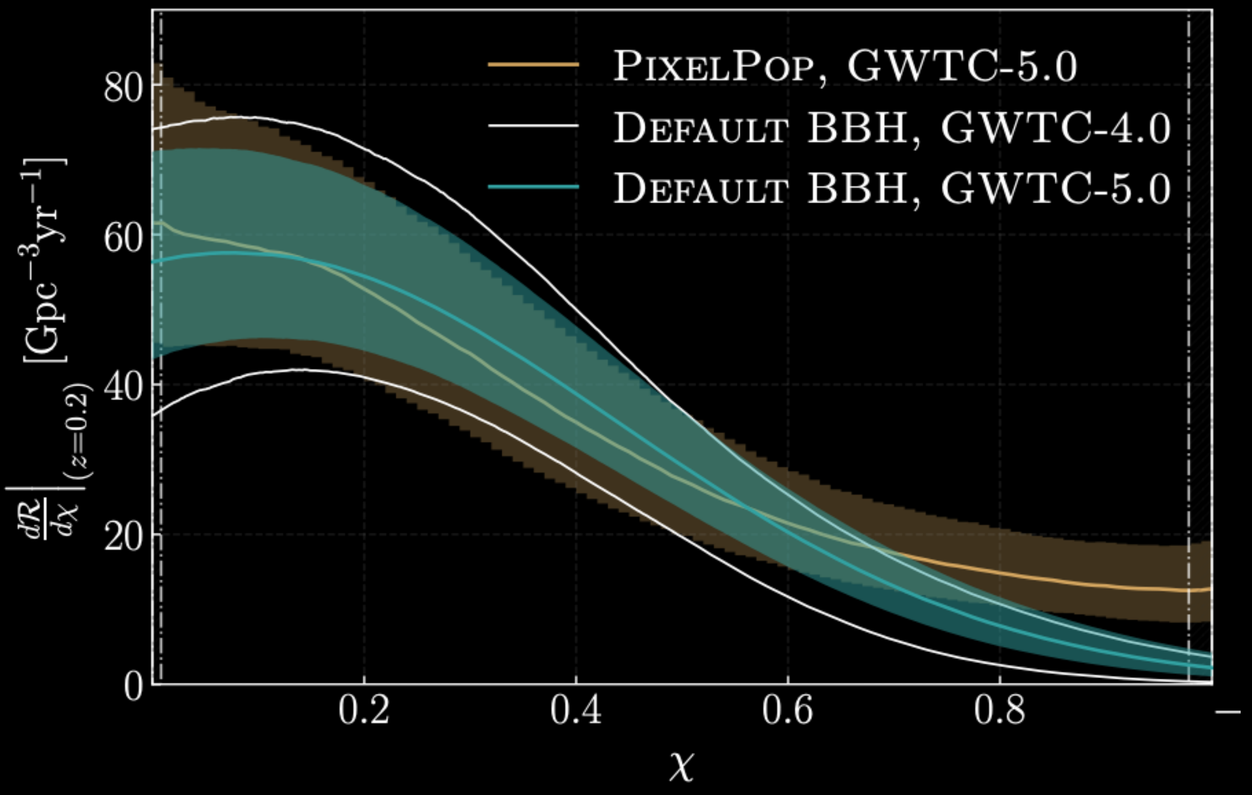
# What have we learned about BH spins in GWTC-5.0?

- **Spins:** Generally small, but some are large and misaligned!
- Spin tilts are very poorly constrained




Abac+ 2026, Dominik+2015, Belczynski+2020, Giacobbo & Mapelli 2018, van Son+2022, Wolfe+2026

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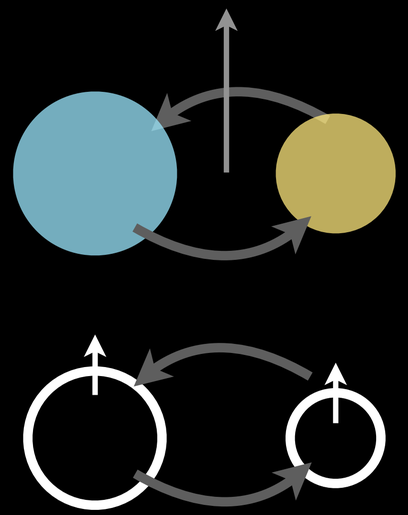
# Spin allows us to distinguish between major formation channels

## Isolated binary evolution

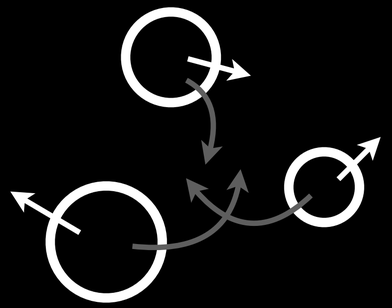
Stellar binary: born together
die together



**small** spins **aligned** with the orbital angular momentum

## Dynamical formation

Dense stellar environments
→ dynamical capture



**1G: small** spins **isotropically oriented**



Inspired on Cailin Plunkett's slides!

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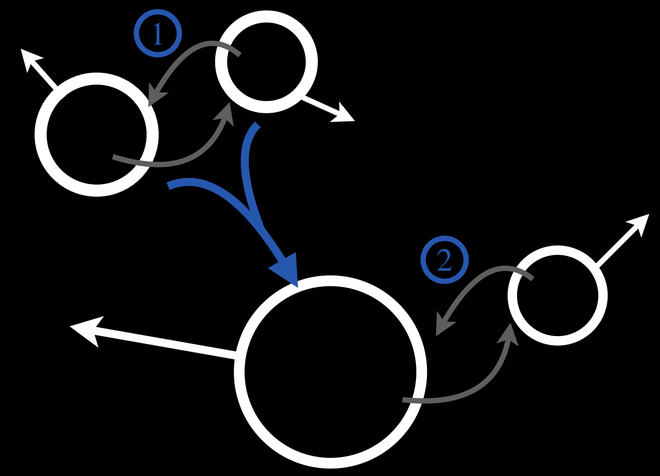
# Dynamical formation channels

## Hierarchical assembly



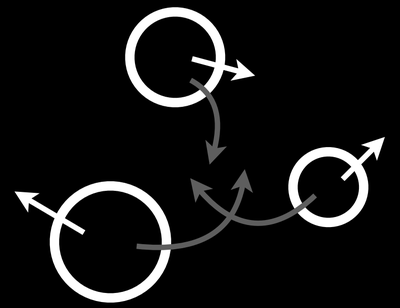

merger remnants can be **retained** and participate in additional mergers

"2G" BH characteristically have

1. **higher masses** (they are merger remnants)
2. **isotropic** spin tilts
3. **spin magnitudes** $\chi \approx 0.7$

## Dynamical formation

Dense stellar environments
→ dynamical capture



**1G: small** spins **isotropically oriented**

Inspired on Cailin Plunkett's slides!

e.g. Pretorius 2005, Buonanno+ 0709.3839, Rodriguez+ 1609.05916, Alvarez+ 2404.00720, Borchers+ 2503.21278

# However…

- Spin tilts are hard to measure because they are related to precession, which doesn’t imprint a lot of information into the amplitude and phase modulation of the signal.
- Effects are hard to see, especially because we detect mostly face-on systems (Easier to detect), where precession signatures are suppressed.
- Also there are degeneracies with spin magnitudes!



e.g. Wolfe+25

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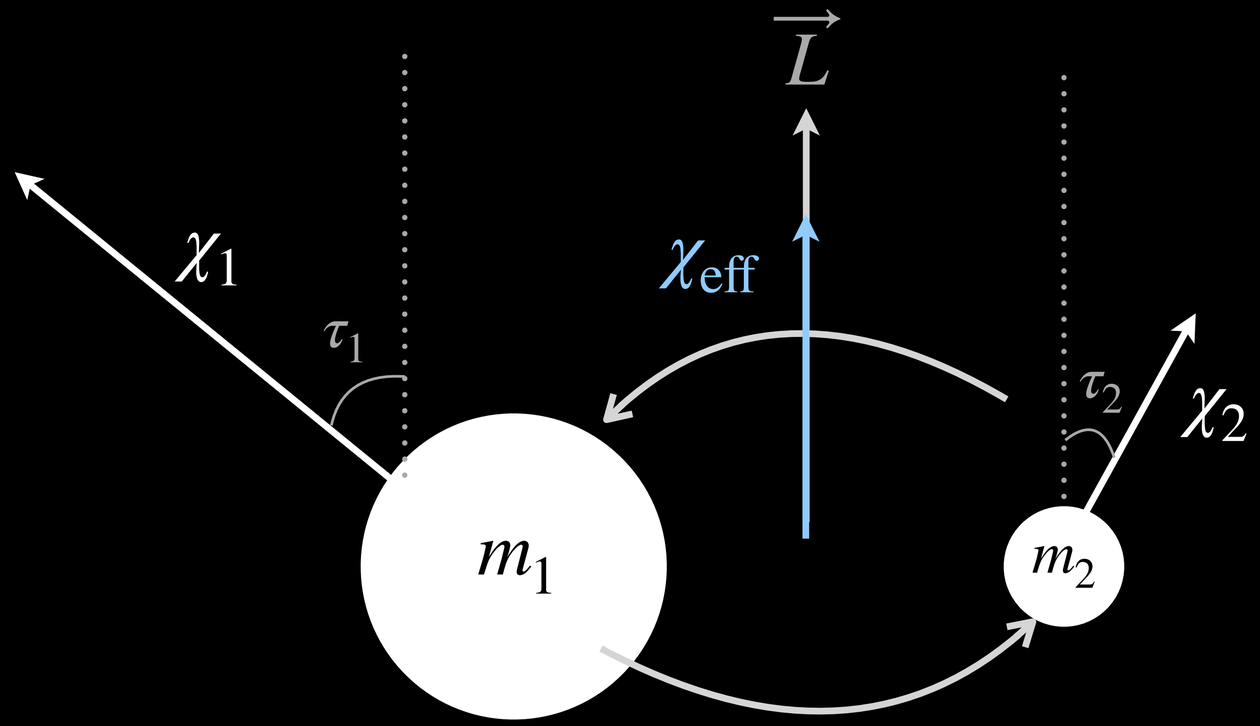
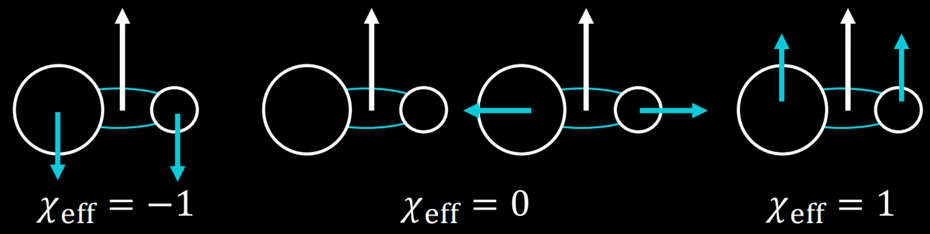
# We may get better population constraints using the effective spin, which is typically better measured than components (magnitudes, tilts)




$$\chi_{\rm eff} = \frac{m_1\chi_1 \cos\tau_1 + m_2\chi_2 \cos\tau_2}{m_1 + m_2}$$




Index 1 = most massive object



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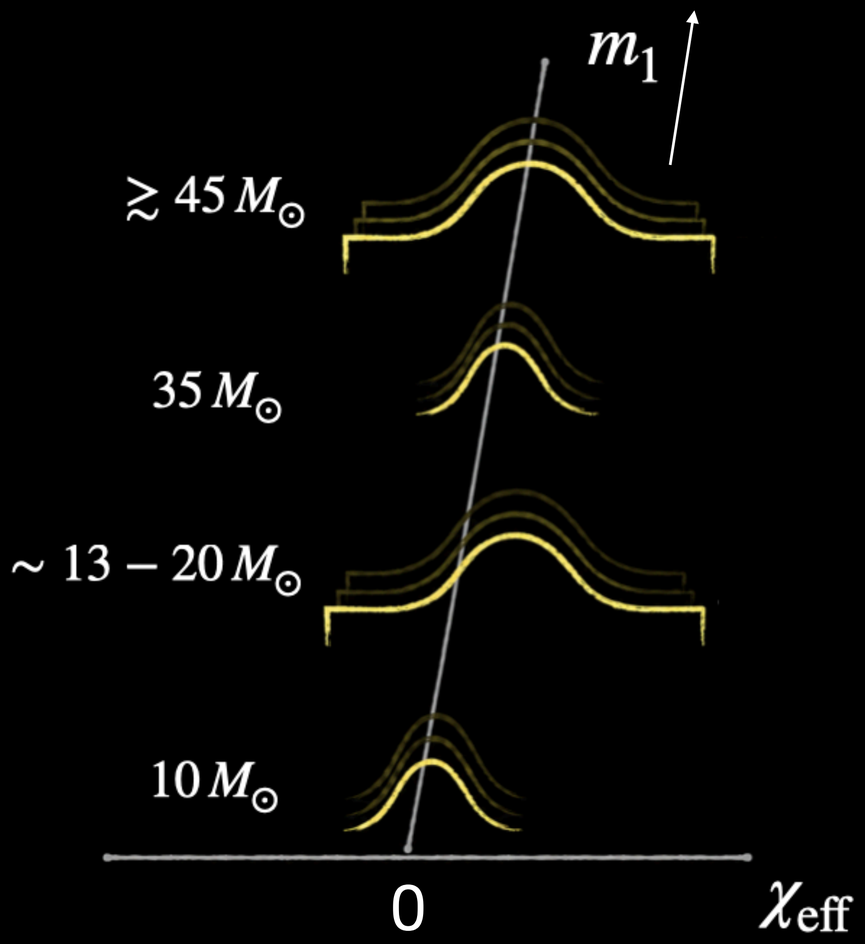
# Recently, many papers (including the LVK) have claimed that the $\chi_{\rm eff}$ distribution (as a function of mass) looks like this:




Broad, (quasi)-uniform $\chi_{\rm eff}$ component interpreted as smoking gun of hierarchical mergers of binary black holes in dense stellar clusters

# However, we show that these conclusions might not be the full picture!

Álvarez-López+ 2606.12205



See a nice summary of our paper by Floor Broekgaarden!
https://floorbroekgaarden.github.io/research-blog/#alvarezlopez2026spins

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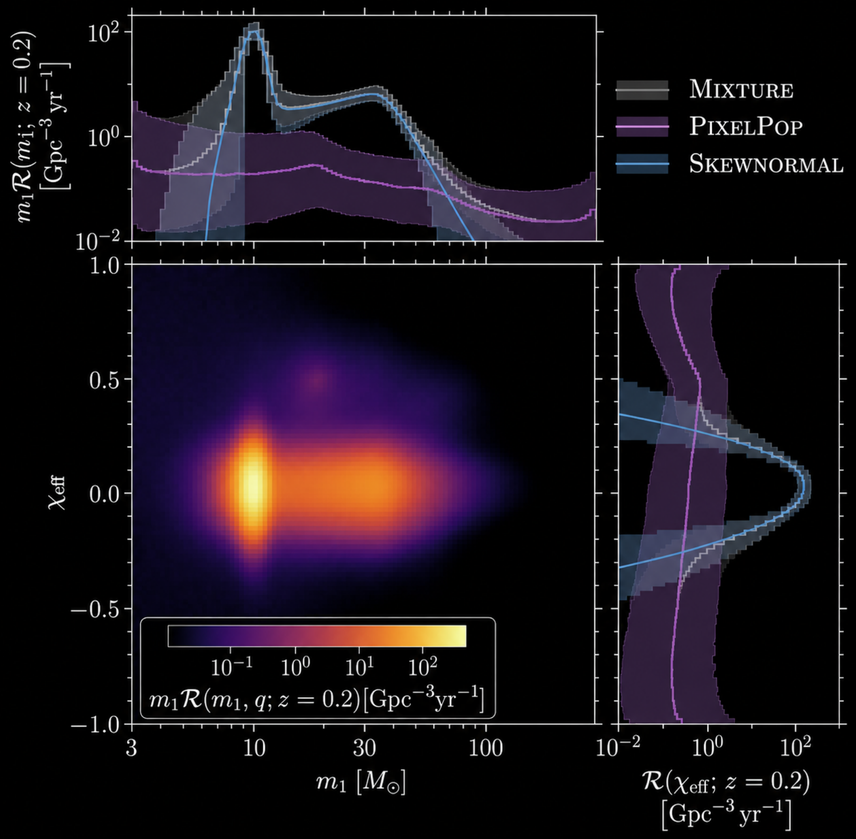


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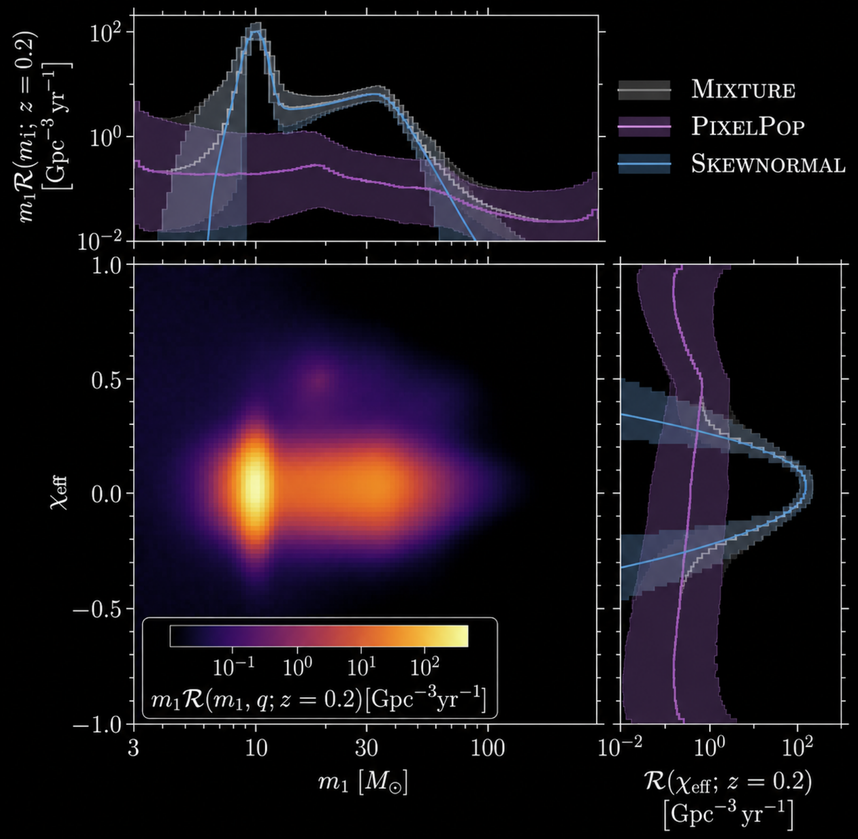


While we do find (with a very flexible model with little prior assumptions):

Most systems live in a slowly-spinning bulk,

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Sofía Álvarez-López | sofiaal@mit.edu

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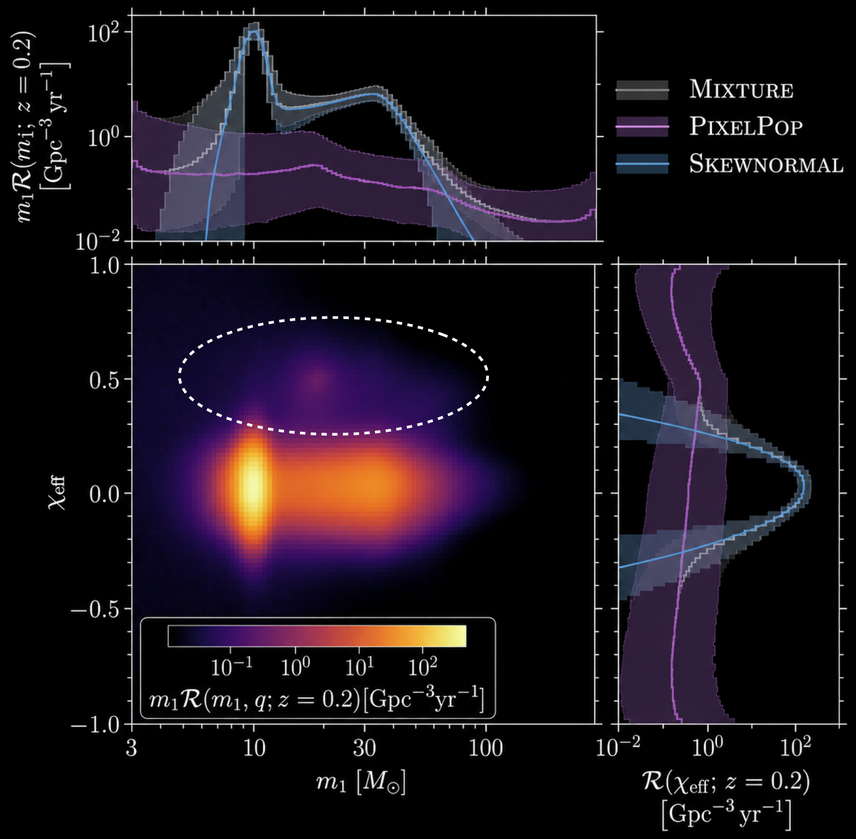


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Most systems live in a slowly-spinning bulk,

Mass-dependent residual structure in the $\chi_{\mathrm{eff}}$ distribution

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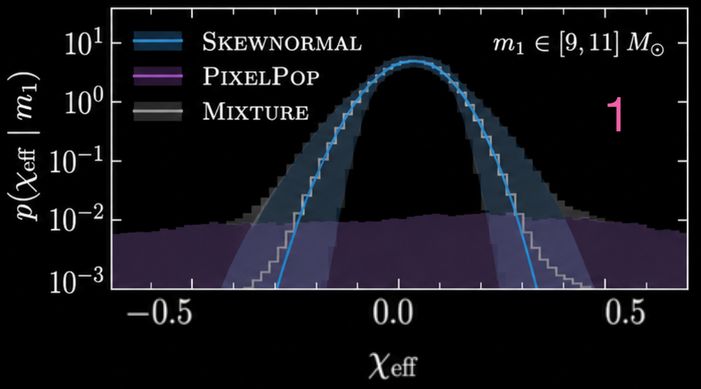
# We find that the residual $\chi_{\rm eff}$ structure is not required to be symmetric around zero!




1. No residual structure around $\sim 10\, M_\odot$

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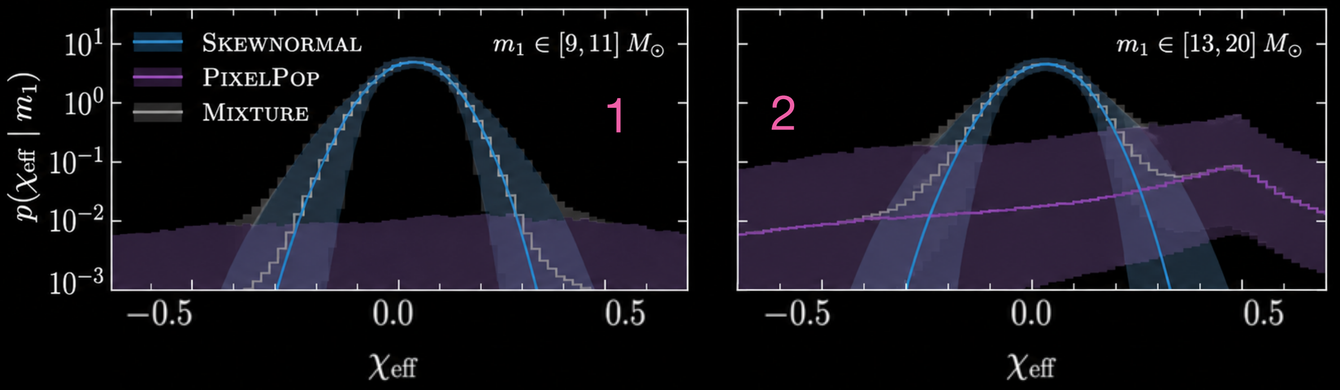


1. No residual structure around $\sim 10\, M_\odot$
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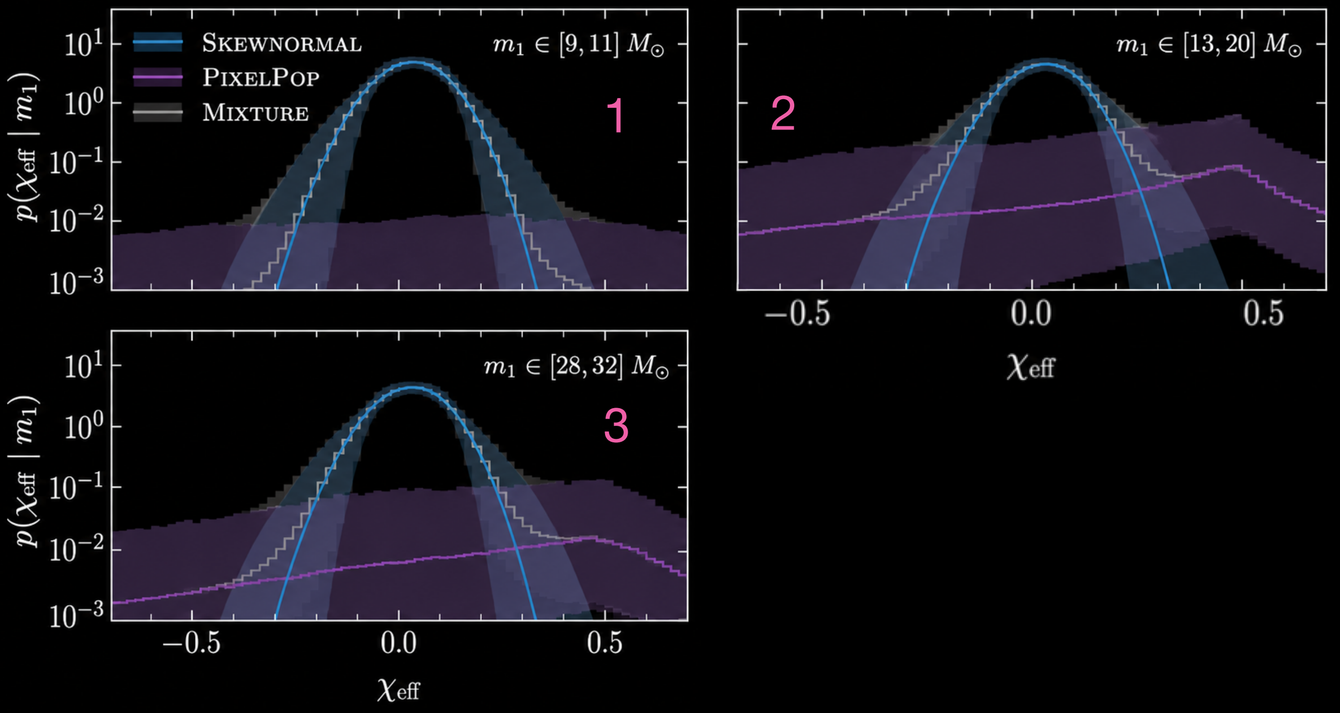


1. No residual structure around $\sim 10\, M_\odot$
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3. Potentially a small excess of positive $\chi_{\rm eff}$ at $\sim 30\, M_\odot$.

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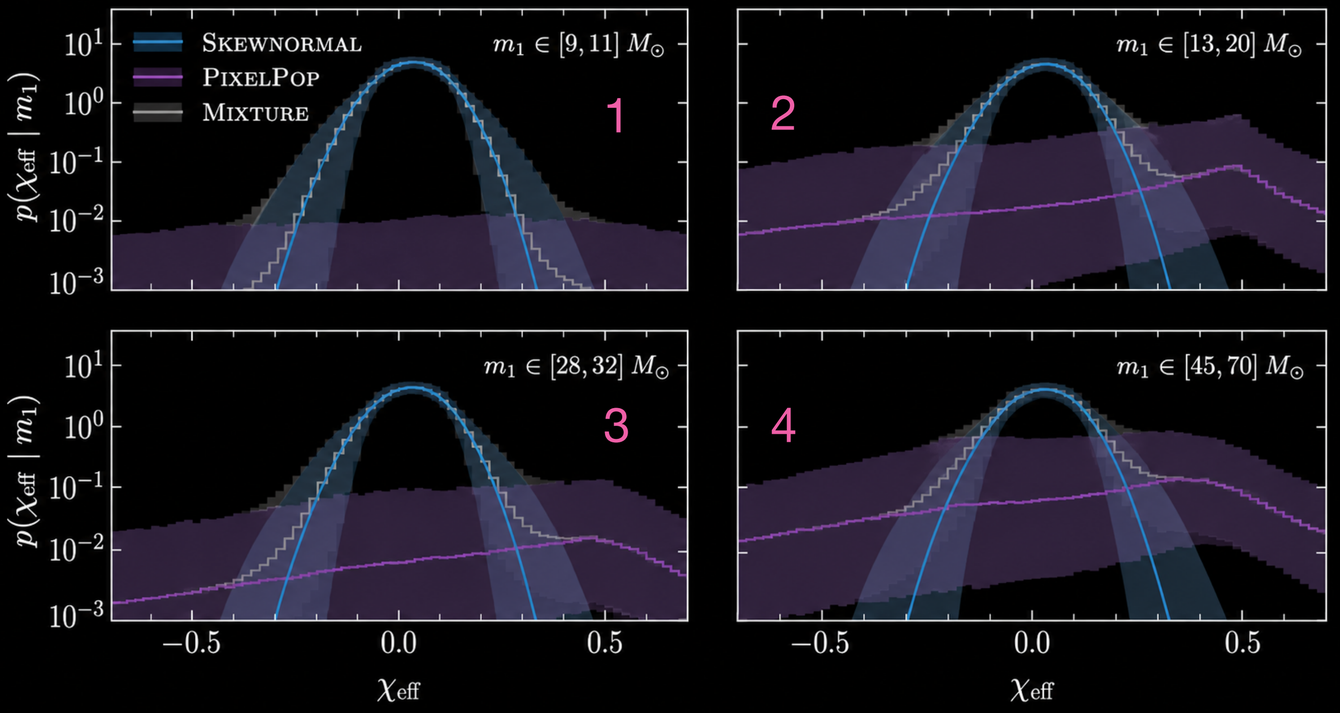


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3. Potentially a small excess of positive $\chi_{\rm eff}$ at $\sim 30\,M_\odot$.
4. Some potential positive $\chi_{\rm eff}$ excess, negative $\chi_{\rm eff}$ component might become relevant.

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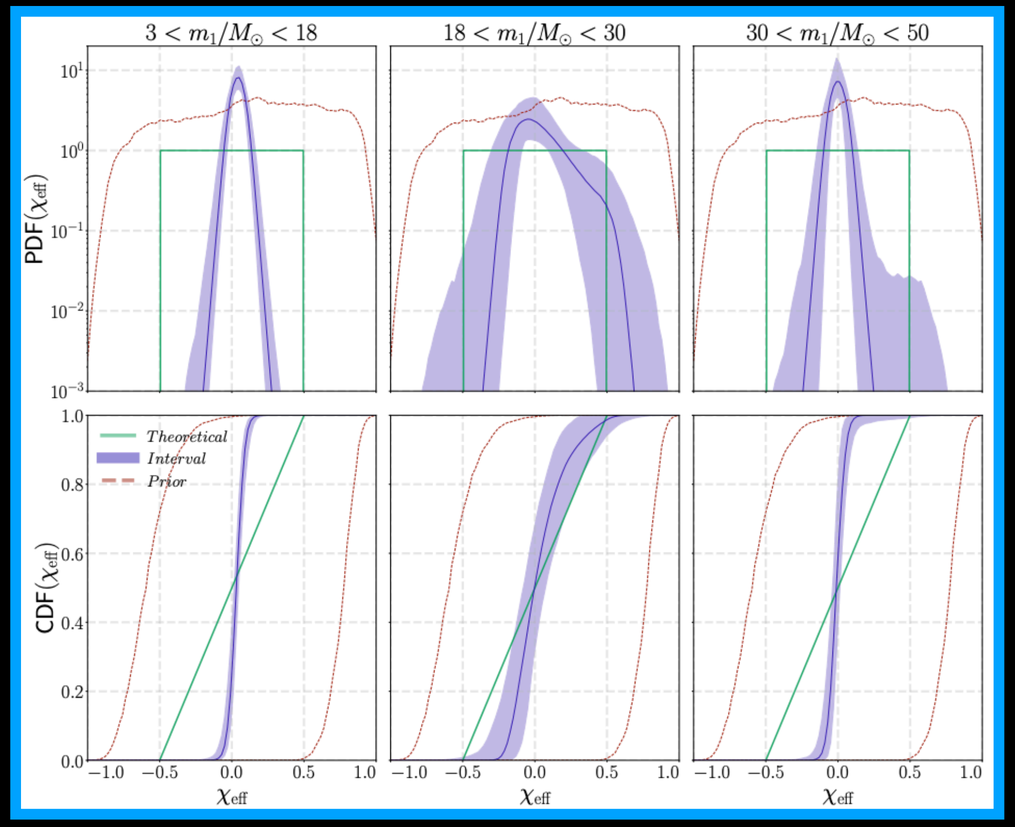
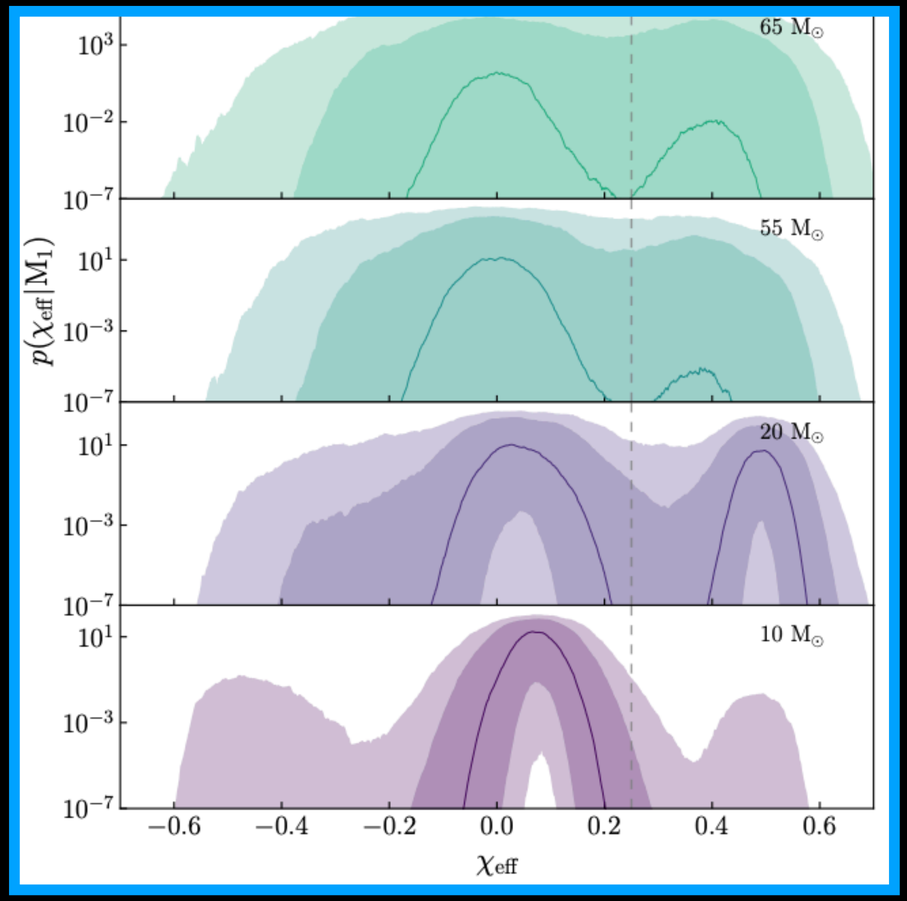
# Mass-dependent asymmetric structure consistent with subsequent work on GWTC-5.0!




Flanagan+ 2606.14472




Rinaldi+2606.23305

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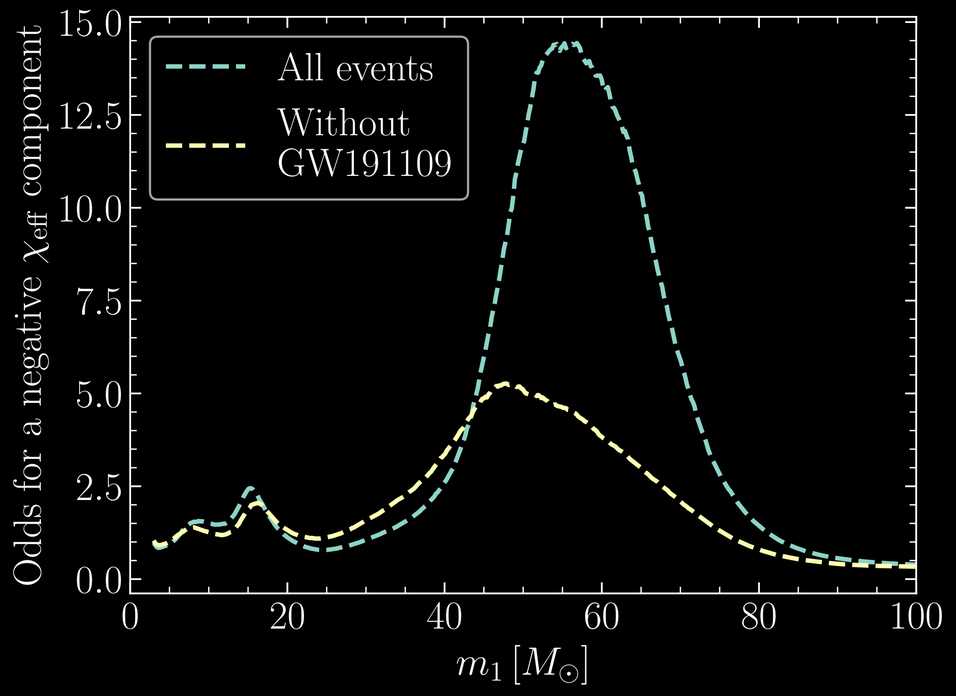
# Are the odds in favor of a negative $\chi_{\rm eff}$ component high enough to provide evidence for such a component?




- In our analysis, we find only a mild statistical preference for a negative $\chi_{\rm eff}$ component, while we find strong evidence for a positive $\chi_{\rm eff}$ component.
- Preference is highest at $m_1 \in [47,65]\,M_\odot$ (13:1 odds in favor of a negative $\chi_{\rm eff}$ component).
- This preference reduces significantly (5:1 odds) when removing GW191109 (which has data quality issues).

**No robust evidence for a negative $\chi_{\rm eff}$ component, so we can't uniquely identify hierarchical mergers as producing the structure we're seeing in $\chi_{\rm eff}$.**

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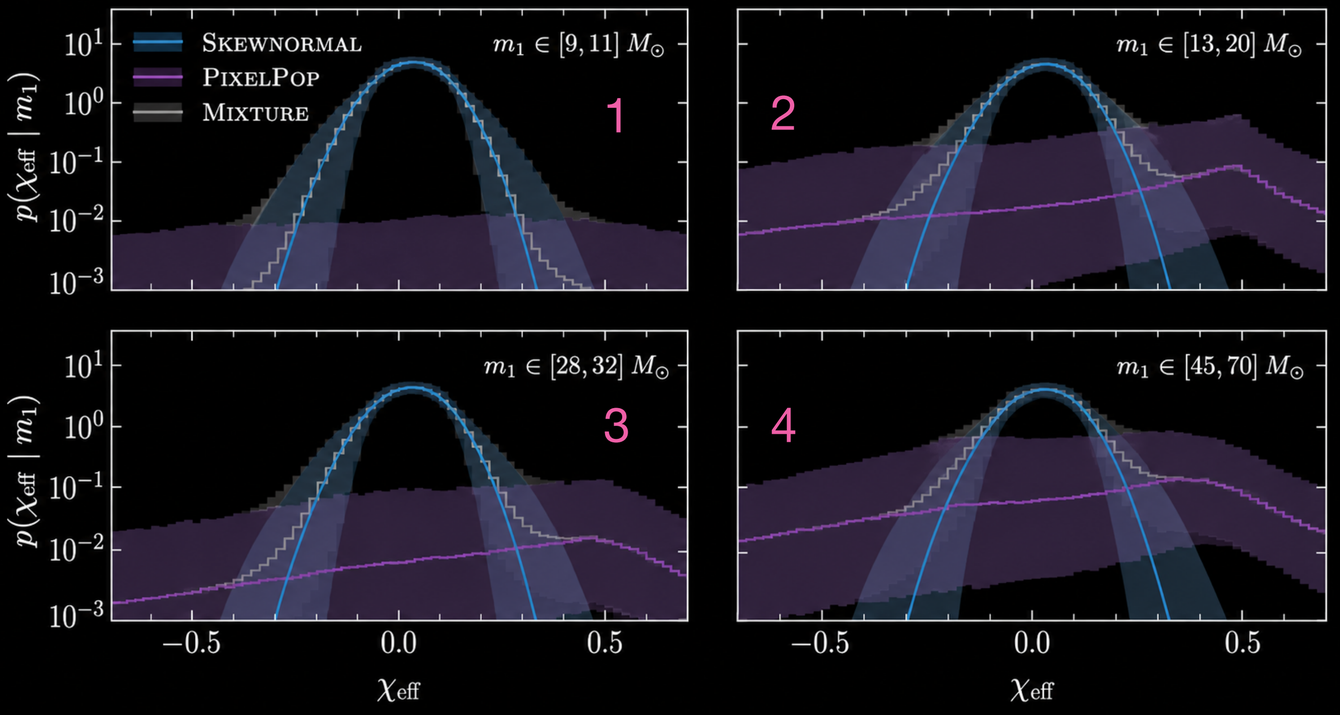
# We find that the residual $\chi_{\rm eff}$ structure is not required to be symmetric around zero!




1. No residual structure around $\sim 10\,M_\odot$
2. Excess of positive $\chi_{\rm eff}$ at $\sim 13 - 20\,M_\odot$.

   No negative $\chi_{\rm eff}$ component required.
3. Potentially a small excess of positive $\chi_{\rm eff}$ at $\sim 30\,M_\odot$.
4. Some potential positive $\chi_{\rm eff}$ excess

   Negative $\chi_{\rm eff}$ component mildly favored, but highly dependent on event with known data quality issues.

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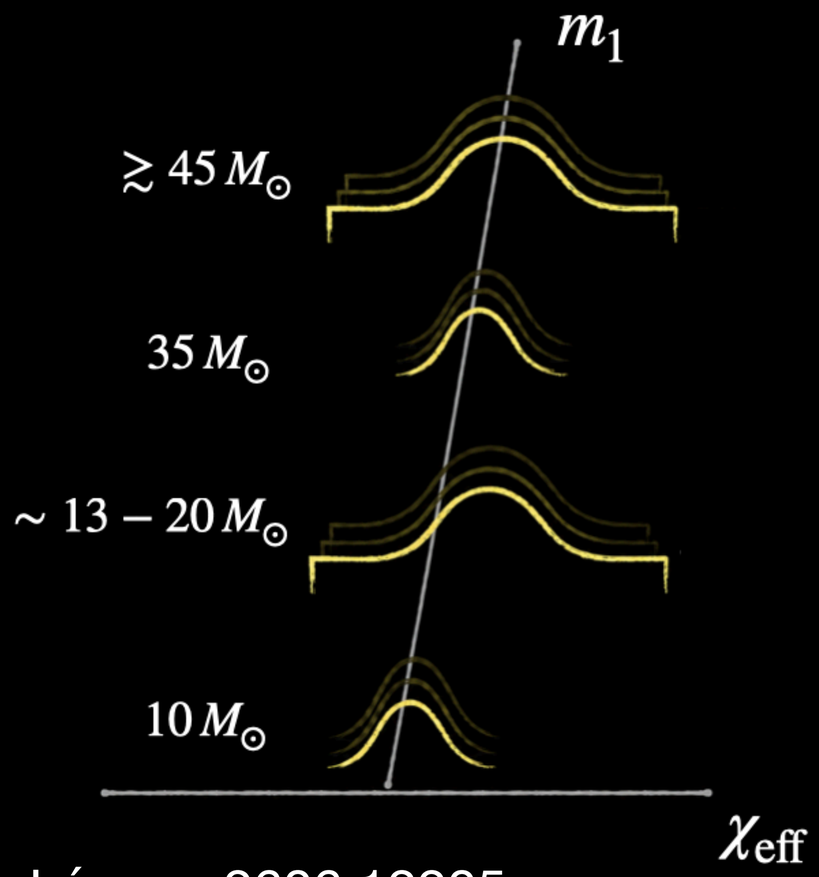
# If highly spinning binary black holes are formed (only) via hierarchical mergers in dense stellar clusters, we should expect a symmetric distribution

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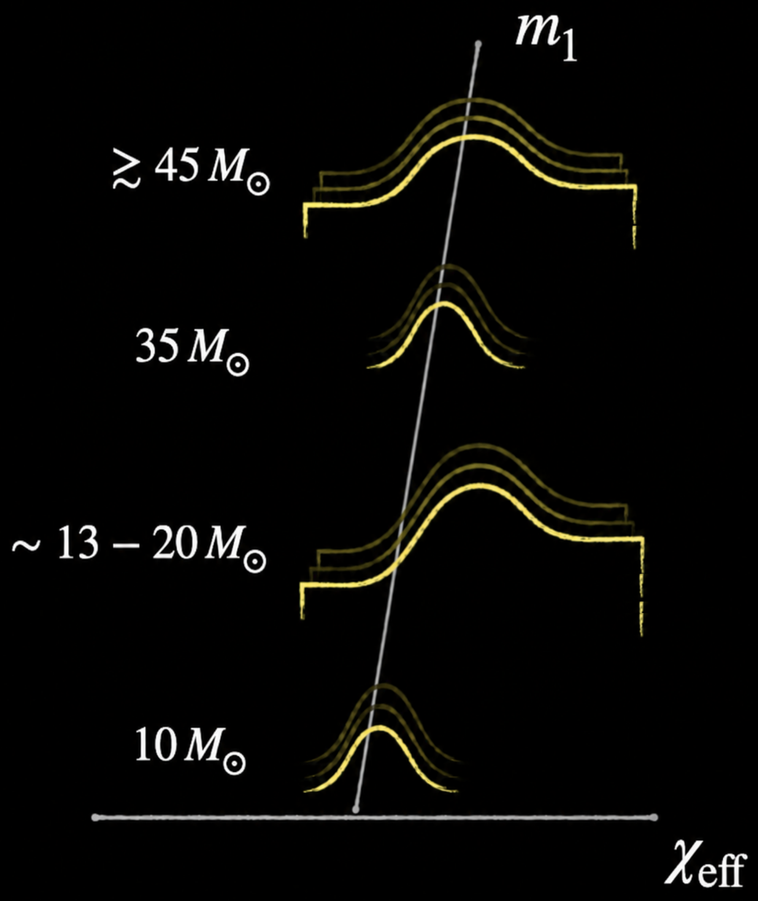


However, we find only a mild statistical preference for a negative $\chi_{\rm eff}$ component and suggestive evidence for an **asymmetric** distribution…

Suggestive of formation channels beyond assembly in stellar clusters contributing to the overall merger rate

But which formation channels?

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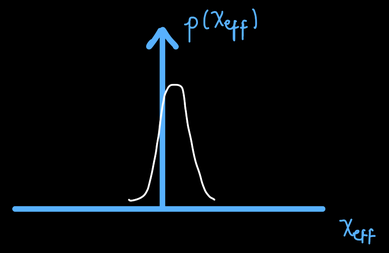
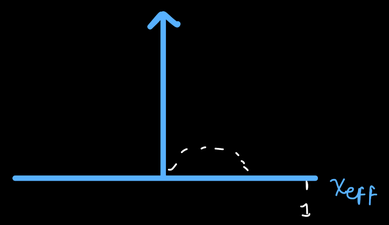
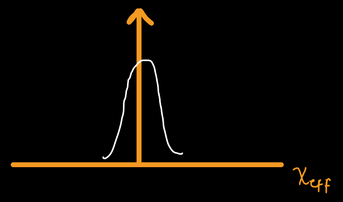
# Hard to know! $\chi_{\rm eff}$ signatures from different formation channels overlap significantly



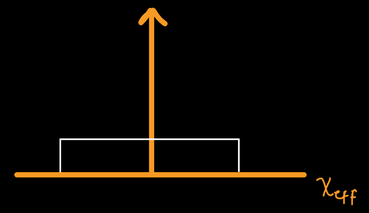

Isolated binary evolution



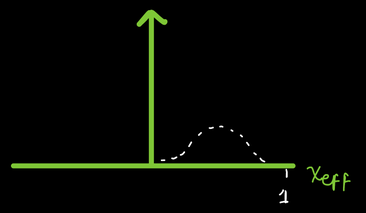

e.g., CHE/tidally spun up binaries




1G mergers in dynamical environments




Hierarchical mergers in clusters




Mergers in AGN disks

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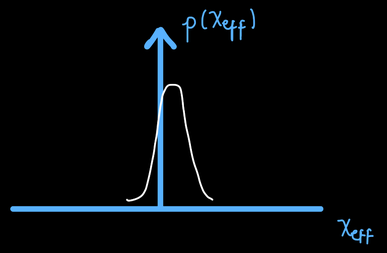


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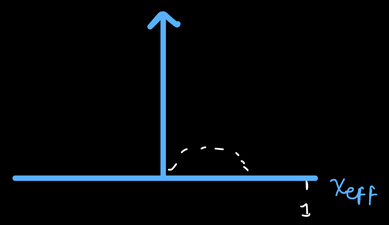


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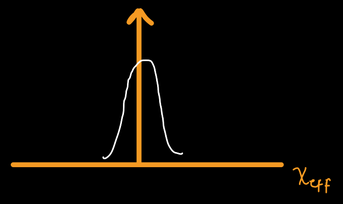


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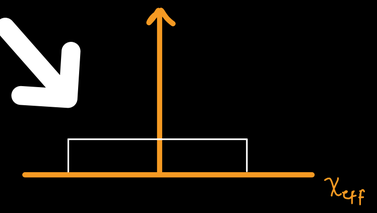


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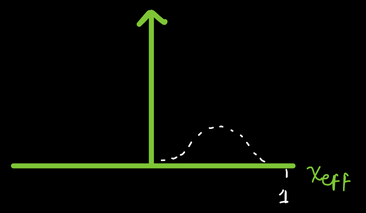


Mergers in AGN disks

Only channel where we would have a clear, smoking-gun evidence is hierarchical mergers in clusters: a broad, negative $\chi_{\rm eff}$ component is a distinctive signature.

However, the data does not require (robustly) a negative component at any given mass yet.

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# There's still a lot of information to uncover!

There is mass-dependent structure beyond the slowly-spinning Gaussian bulk which is likely asymmetric, pointing to an excess of binary black holes with positive $\chi_{\rm eff}$ (vs negative $\chi_{\rm eff}$).

Suggestive of formation channels beyond stellar cluster hierarchical assembly.

Which formation channels contribute at which masses? There is still information hiding in the population! Look at more dimensions?

At high masses, we cannot yet uniquely identify hierarchical mergers: evidence for $\chi_{\rm eff} < 0$ is still mild.

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# Nowhere left to hide: revealing realistic gravitational-wave populations in high dimensions

Álvarez-López+ ApJL 1006 (2026) 1, L5

# Nowhere left to hide: revealing realistic gravitational-wave populations in high dimensions

Formation channels imprint high-dimensional correlations between source parameters!

→

Yet, most of our analyses have been restricted to a couple of dimensions at a time

Want multi-dimensional!

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Want multi-dimensional!

Many models impose restrictive assumptions

→

Hard to distinguish between data-driven and model-driven features

Want flexible!

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# Nowhere left to hide: revealing realistic gravitational-wave populations in high dimensions

Formation channels imprint high-dimensional correlations between source parameters!

→

Yet, most of our analyses have been restricted to a couple of dimensions at a time

Want multi-dimensional!

Many models are too “strong”

→

Hard to distinguish between data-driven and model-driven features

Want flexible!

Heinzel+24 (incl. Álvarez-López)

Álvarez-López+ ApJL 1006 (2026) 1, L5

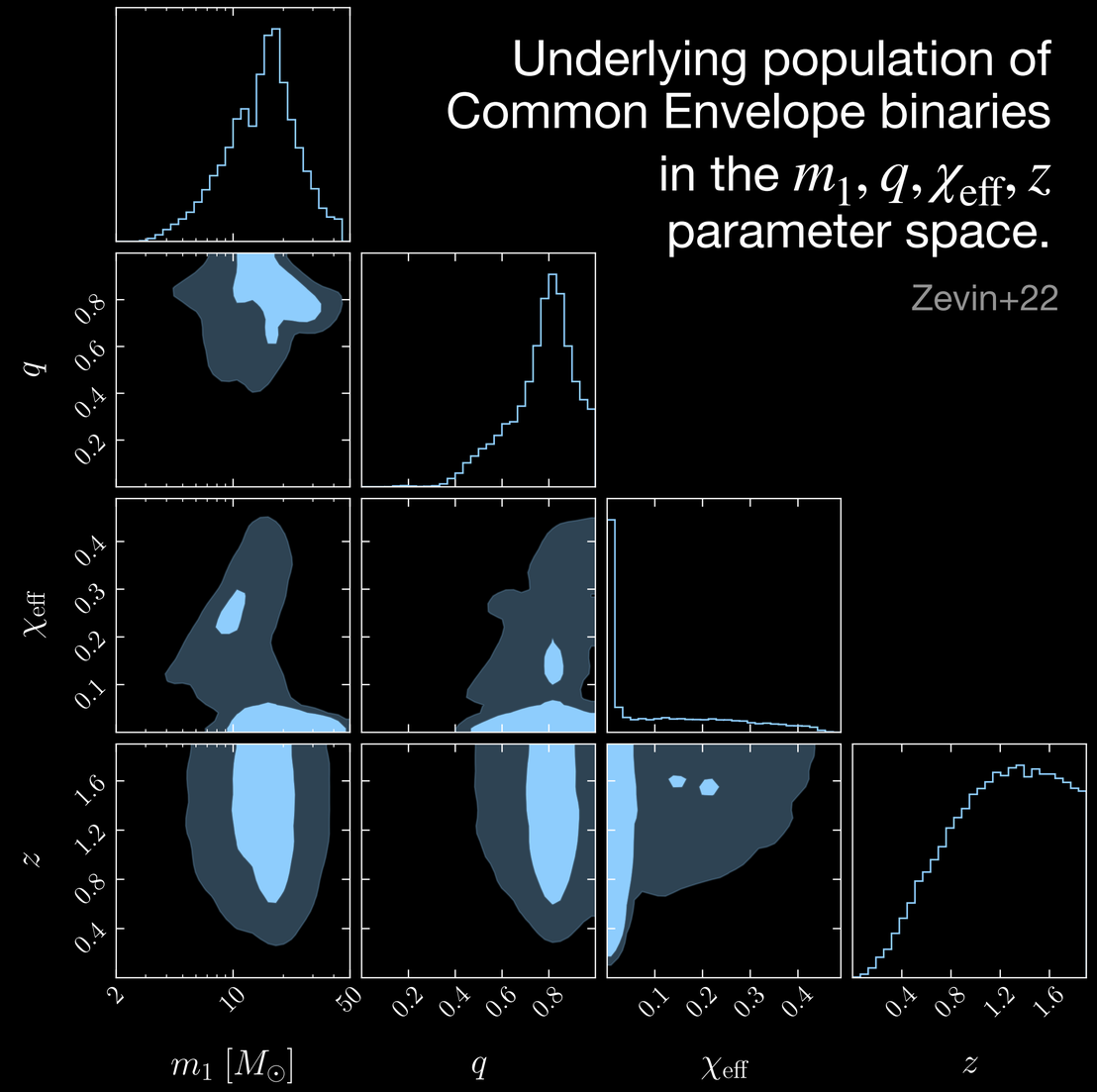


PixelPop

Sofía Álvarez-López | sofiaal@mit.edu

# A simulated population

- Simulate a Universe where all binaries undergo at least one common envelope episode, as predicted by pop-synth.
    - Note in the real Universe we have many formation channels at the same time!
- Highly non-trivial and high-dimensional correlations, probably representative of correlations in nature!




Underlying population of Common Envelope binaries in the $m_1, q, \chi_{\rm eff}, z$ parameter space.

Zevin+22

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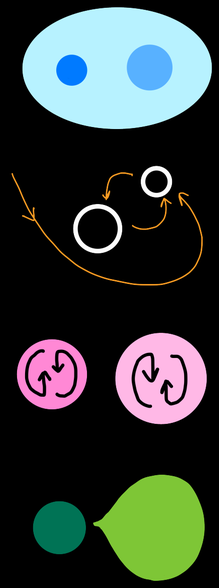
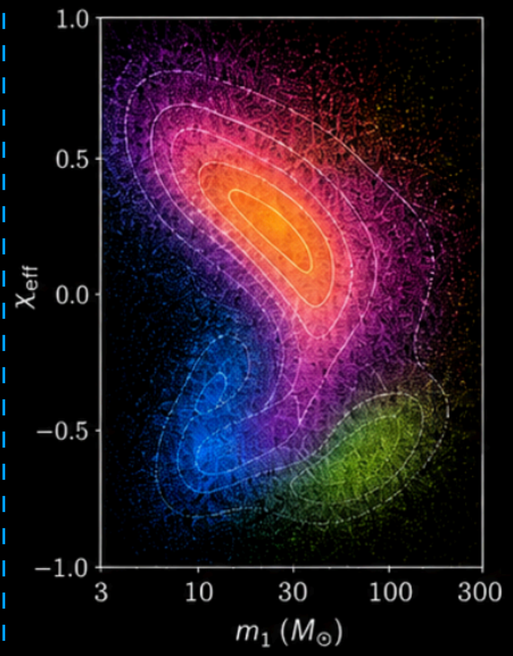
# Inferring the population properties

1. Formation pathways



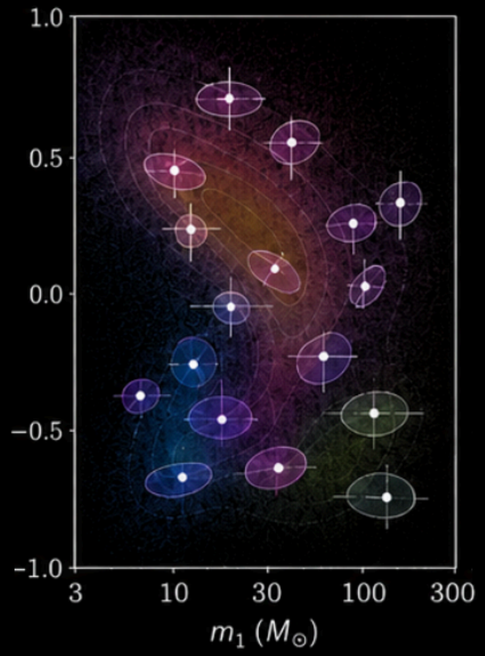
and more!

2. True binary black hole population



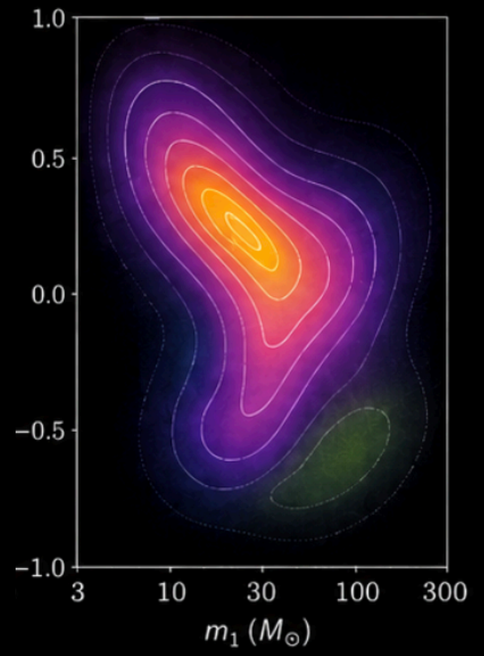

Masses, spins, mass ratios, redshifts, correlations imprinted from progenitors

3. We detect *some* with LIGO




Incomplete catalog, uncertain measurements

4. We infer the true population




Need a model and need to account for selection effects

5. Understand in light of the theory!

MESA

COMPAS

POSYDON

CMC Cluster Monte Carlo

PopSynth: Posydon, Andrews et al. 2024; MESA, Paxton et al. 2015; COMPAS Stevenson et al. 2017; CMC, Rodriguez+ 2021

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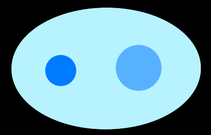

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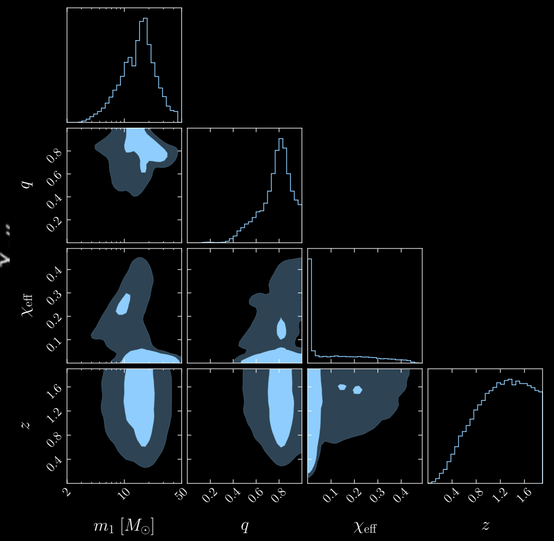


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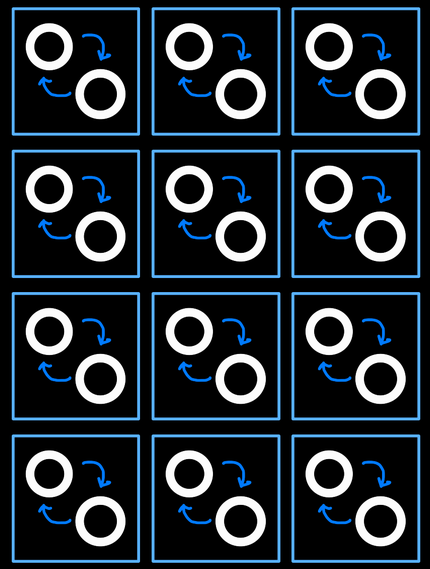


Incomplete catalog, uncertain measurements

4. We infer the true population

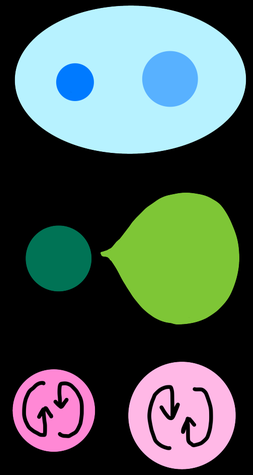
Using our flexible model

PixelPop

Need a model and need to account for selection effects

5. Can we distinguish where these sources came from?

Compare with predictions



From pop-synth

PopSynth: Posydon, Andrews et al. 2024; MESA, Paxton et al. 2015; COMPAS Stevenson et al. 2017; CMC, Rodriguez+ 2021

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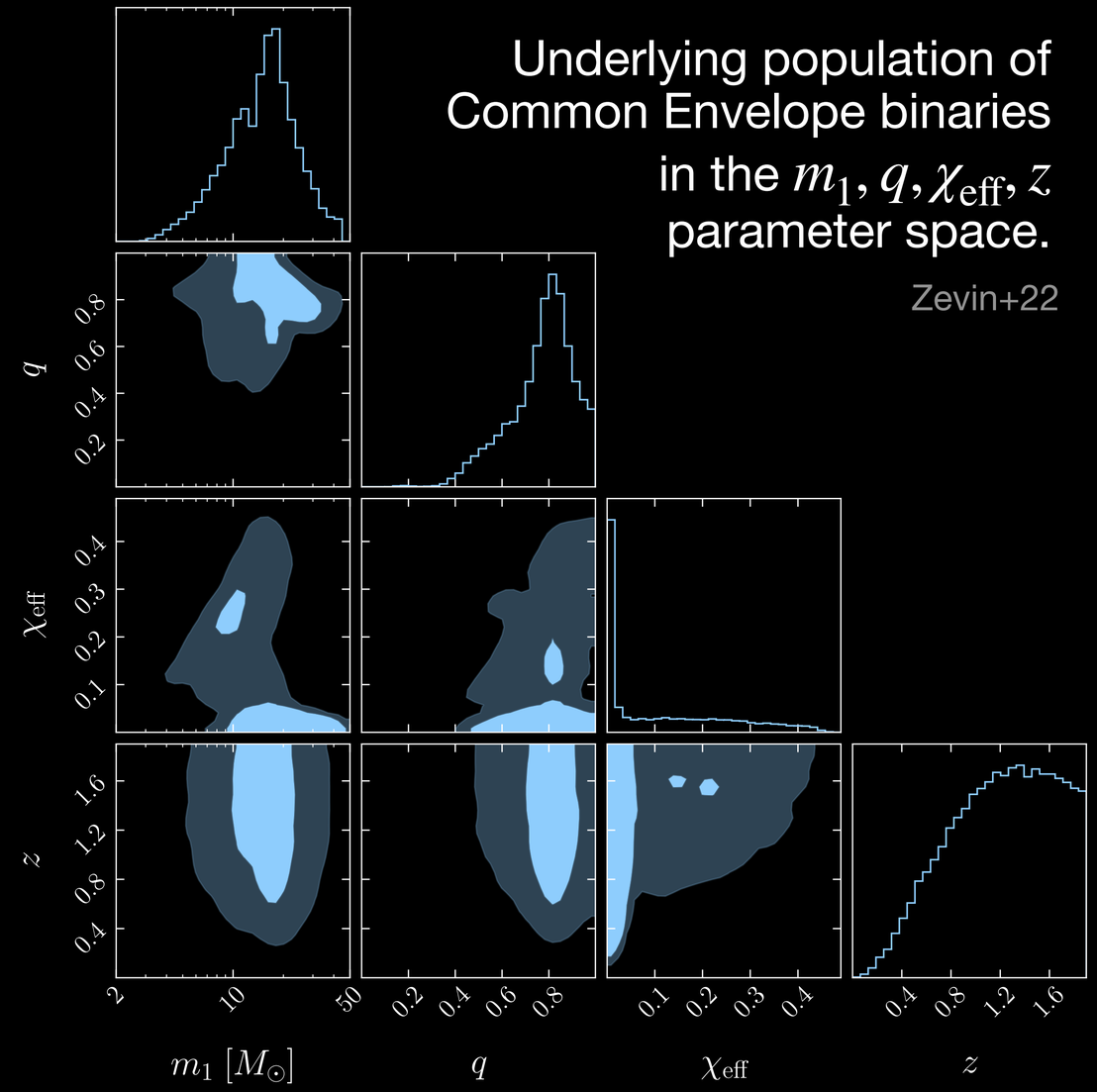


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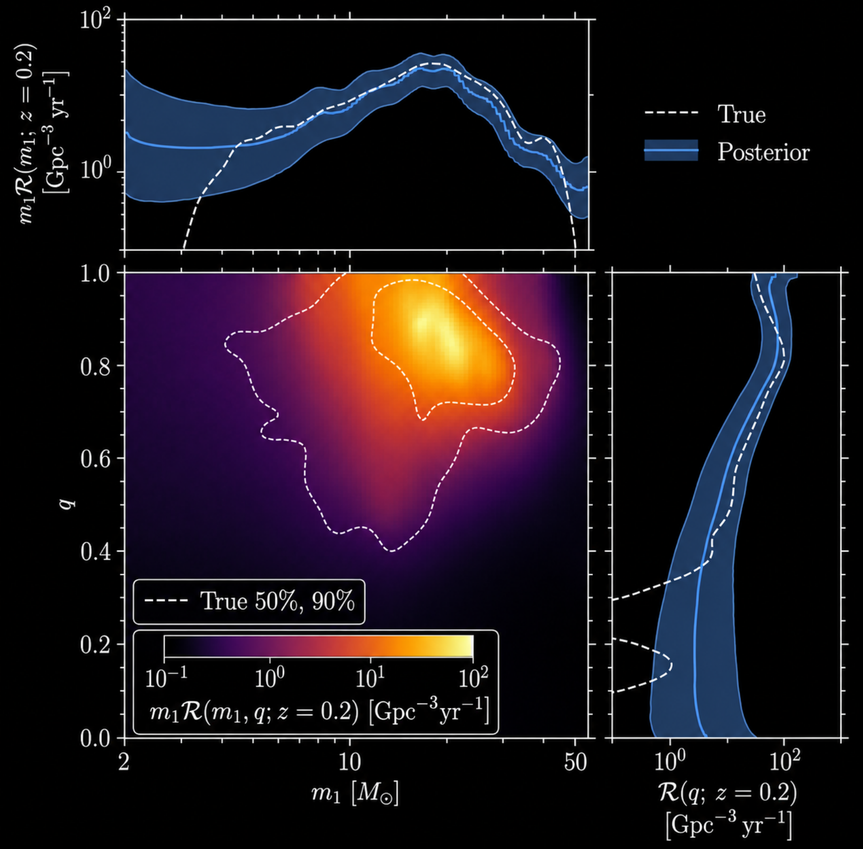
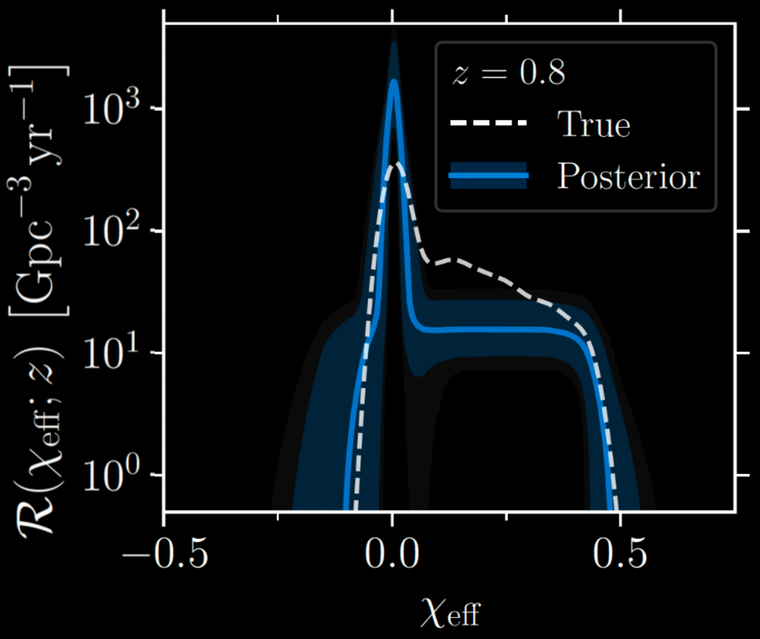
# Take the two highest-correlated parameters: A simple 2-D correlation is insufficient!

- Model $m_1/q$ with PixelPop, model $z/\chi_{\rm eff}$ independently.

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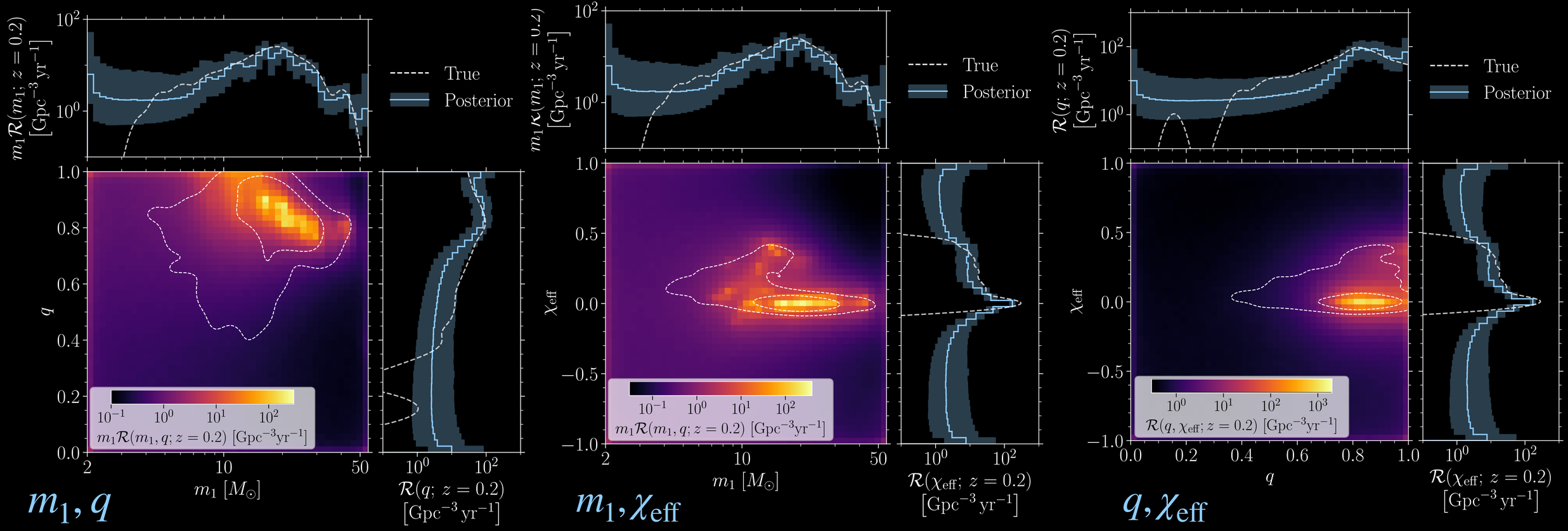
# Take the three highest-correlated parameters: A ~~2-D~~ 3D correlation is insufficient too!

- Model $m_1/q/\chi_{\rm eff}$ with PixelPop, model $z$ independently.

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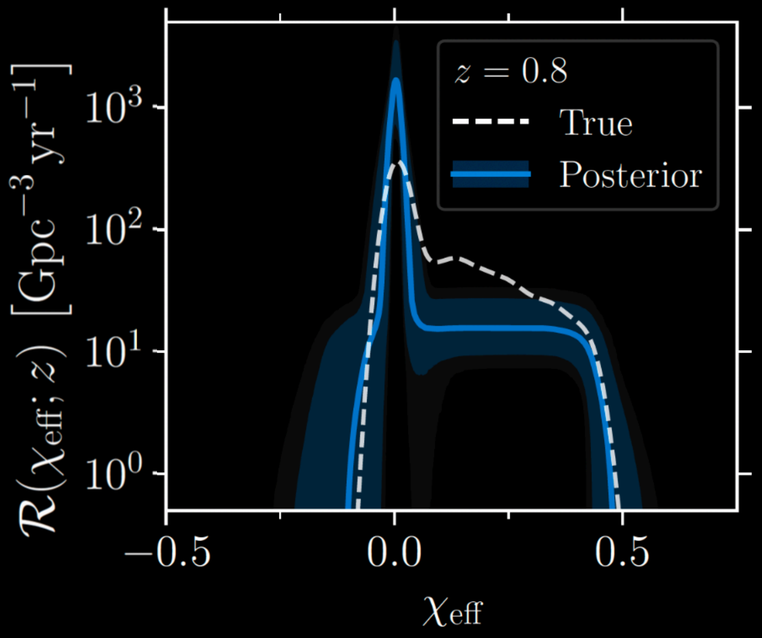
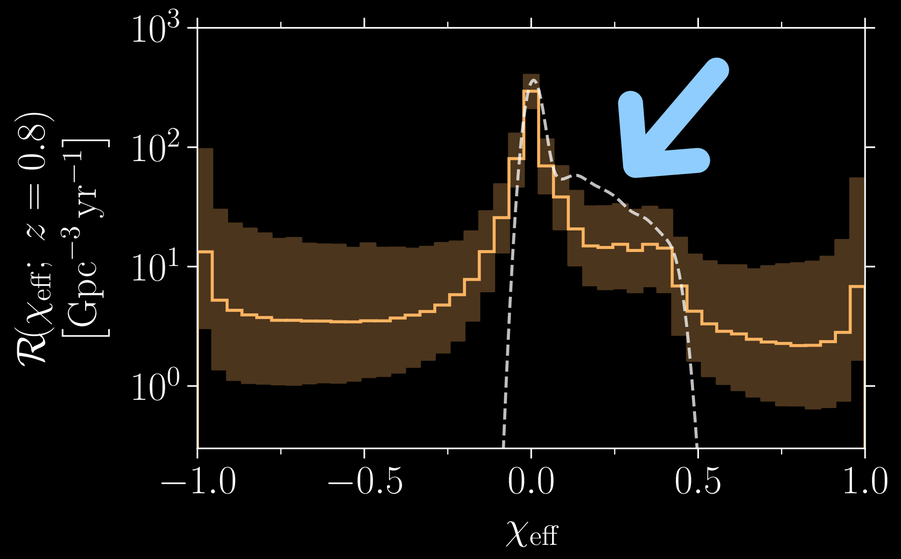
# A 4D correlated model is needed to avoid biases

- Model $m_1/q/\chi_{\rm eff}$ with PixelPop, model $z$ independently.

2D model




3D model

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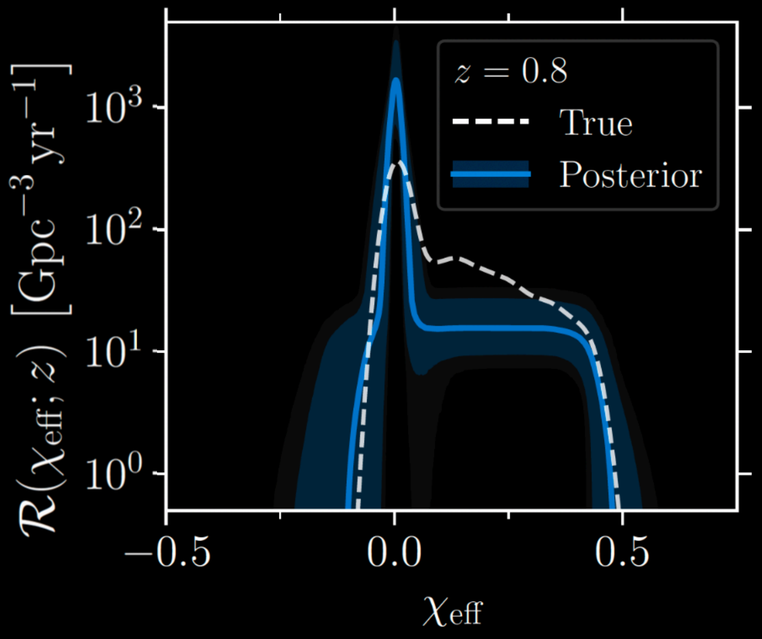
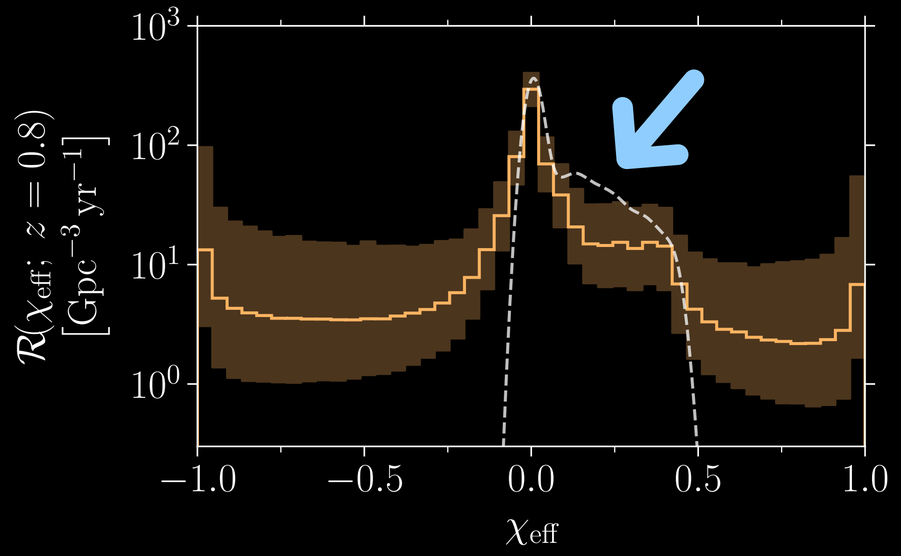
# A 4D correlated model is needed to avoid biases

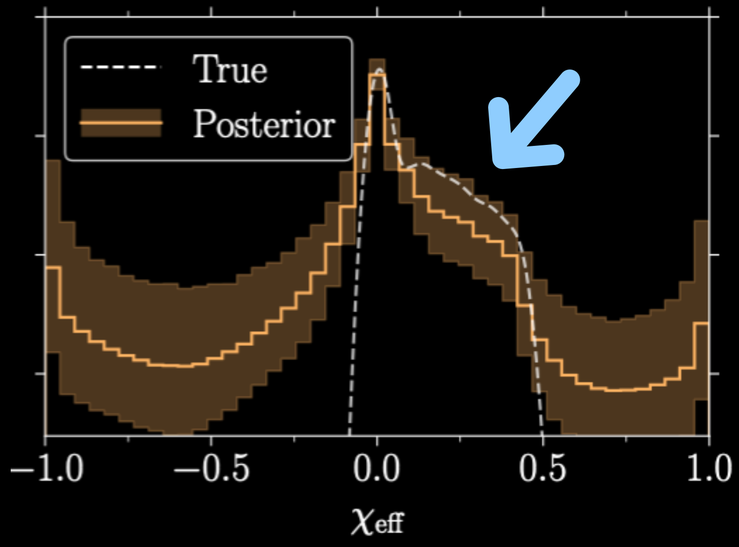
2D model




3D model




4D model

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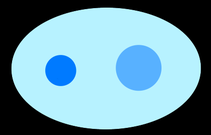
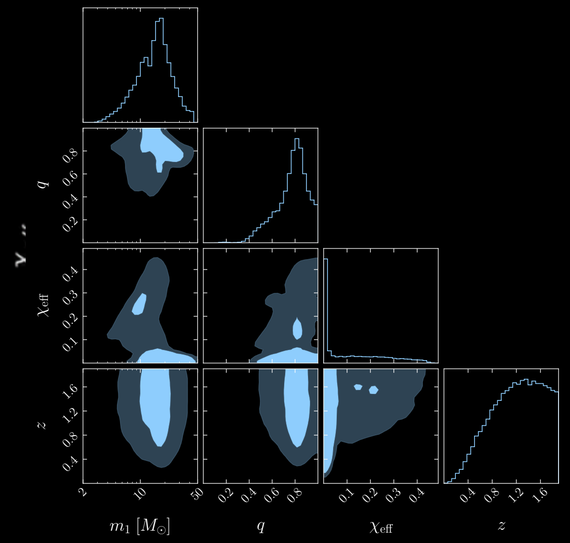
# Inferring the population properties

1. Formation pathways

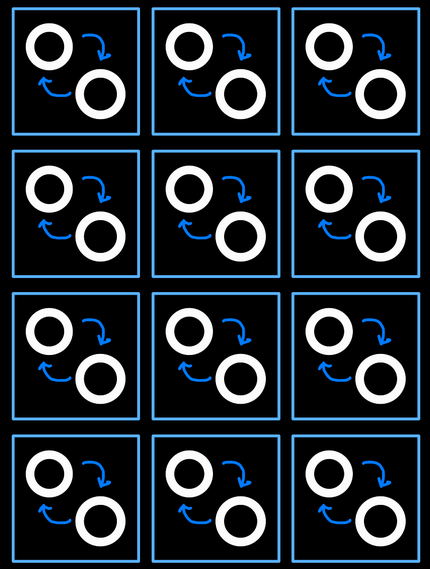


2. True binary black hole population




Masses, spins, mass ratios, redshifts, correlations imprinted from progenitors

3. We detect *some* with LIGO



Incomplete catalog, uncertain measurements

4. We infer the true population

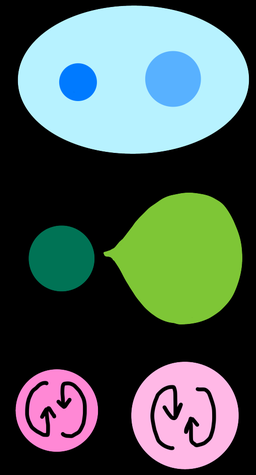
Using our flexible model

PixelPop

Need a model and need to account for selection effects

5. Can we distinguish where these sources came from?

Compare with predictions



From pop-synth

PopSynth: Posydon, Andrews et al. 2024; MESA, Paxton et al. 2015; COMPAS Stevenson et al. 2017; CMC, Rodriguez+ 2021



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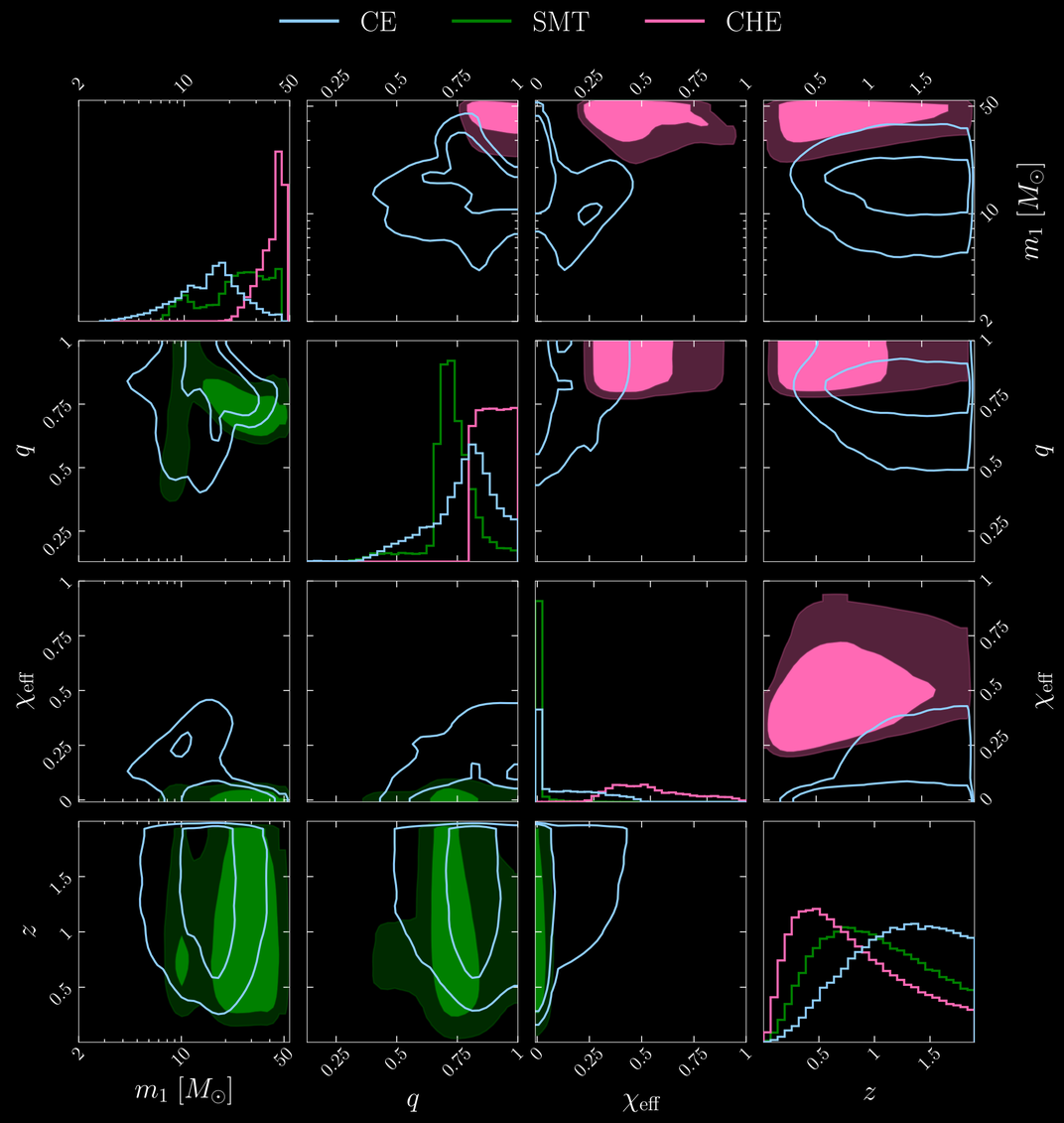
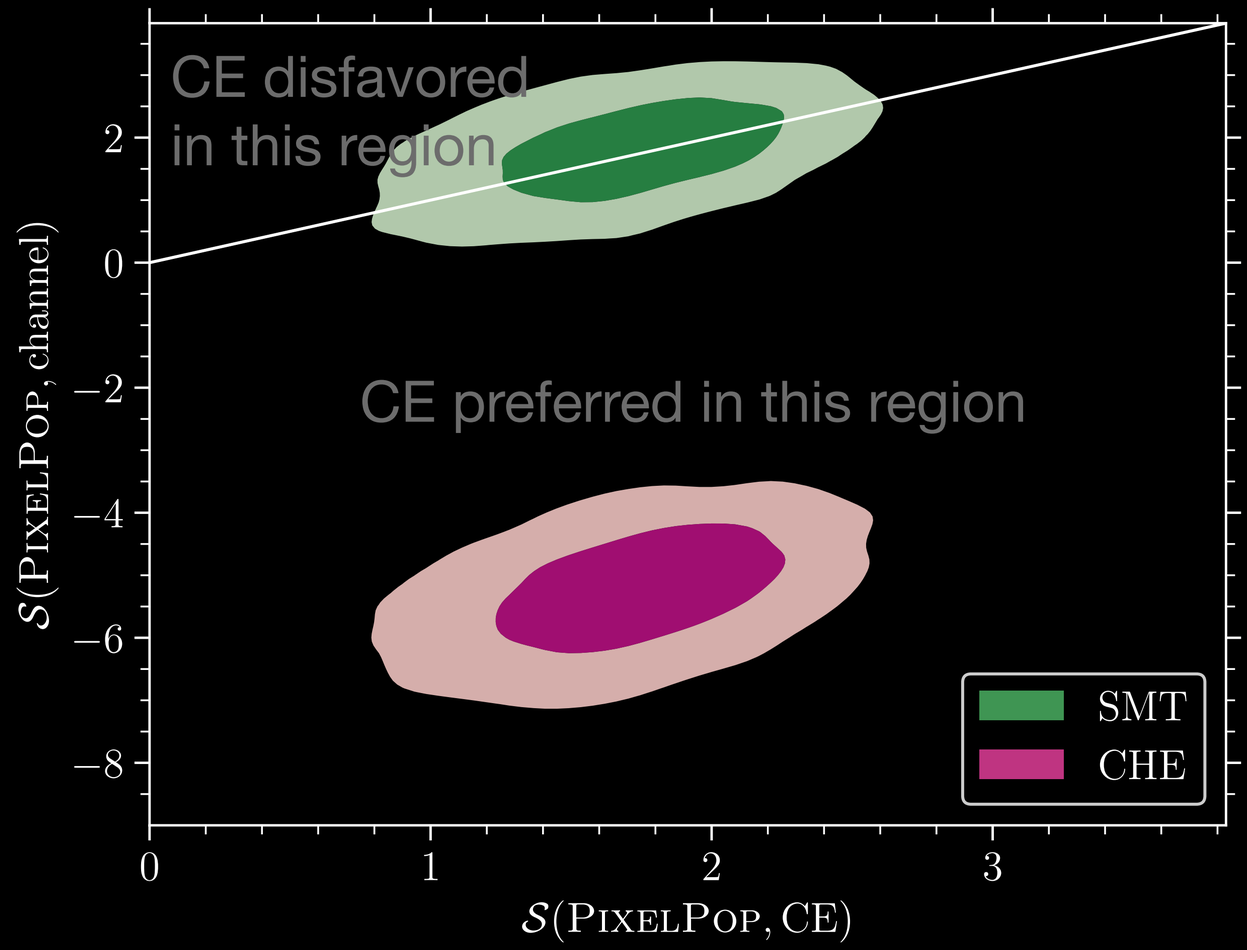
# Can we actually distinguish formation channels?

- Easy with strong models (but be careful with biases!)
- Less trivial with flexible models.
- We used our population results and measured the “similarity” between Common Envelope predictions (i.e., the truth) and the two other filed channels from Zevin+
- Note high-dimensional overlap between CE and SMT.



# Can we actually distinguish formation channels?

- With 400 sources all from CE, we can exclude they all came from CHE.
- We can’t exclude they all came from SMT.
- While PixelPop accounts for all correlations in the population (without biases), distinguishing between some formation channels is harder.



# Main takeaways

We are moving toward **precision demographics** of binary black holes, with 250+ published to date!

We have found additional mass-dependent structure in the BBH population. However, distinguishing between formation channels is still quite complicated at current sensitivities (i.e., we need to be careful about over-interpreting the data!)

If we want to learn more (and more accurately) about the binary black hole population, we need to look at multiple dimensions, where correlations between source parameters might tell us a lot more about formation channels!

Álvarez-López+ 2606.12205

Álvarez-López+ ApJL 1006 (2026) 1, L5

# Extra slides!

# Hierarchical Bayesian inference

# BH stories: GW231123, GW241011, GW241110

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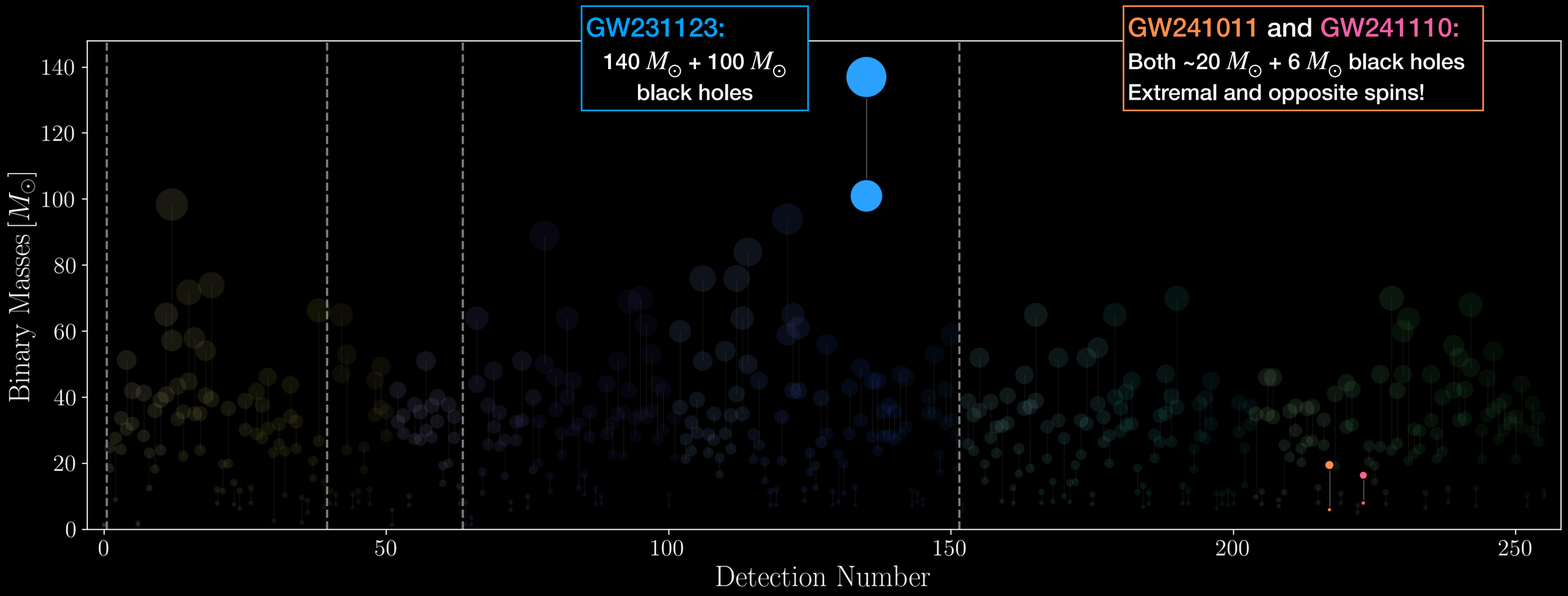
# Exceptional stories in GWTC-4.0 and GWTC-5.0

## GW241011 and GW241110: extremal and opposite spins






Abac+23, Abac+25, Abac+26

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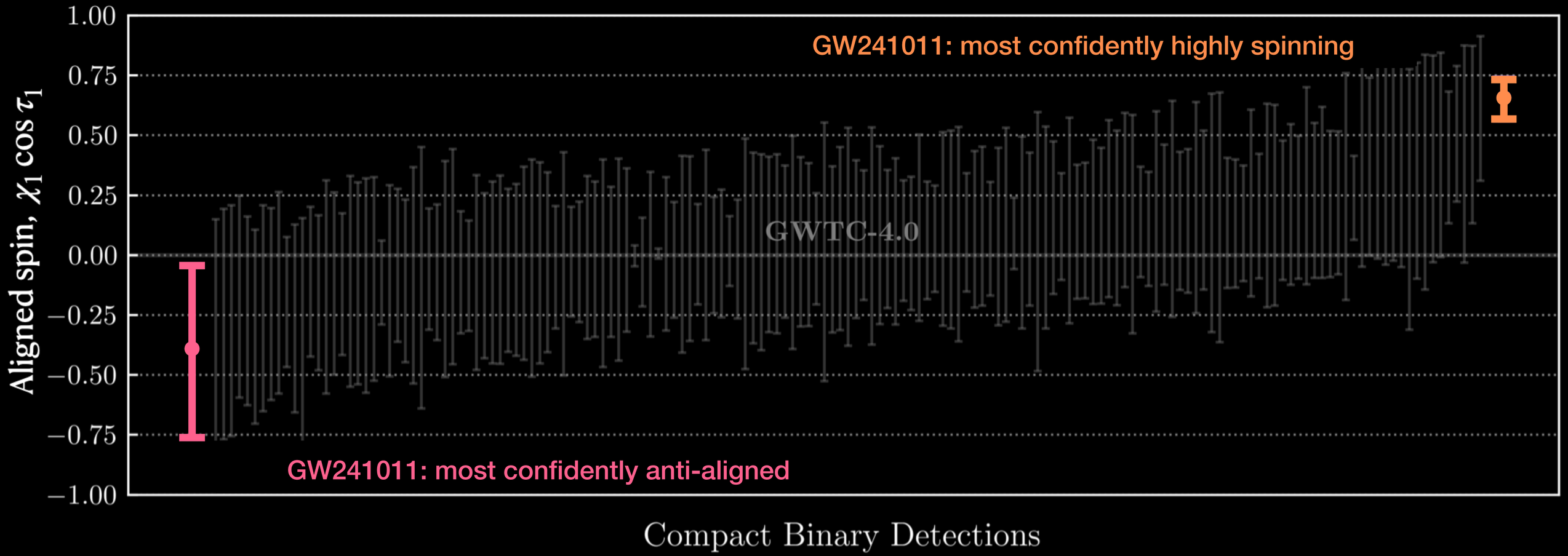
# GW241011 and GW241110: extremal and opposite spins






Abac+25

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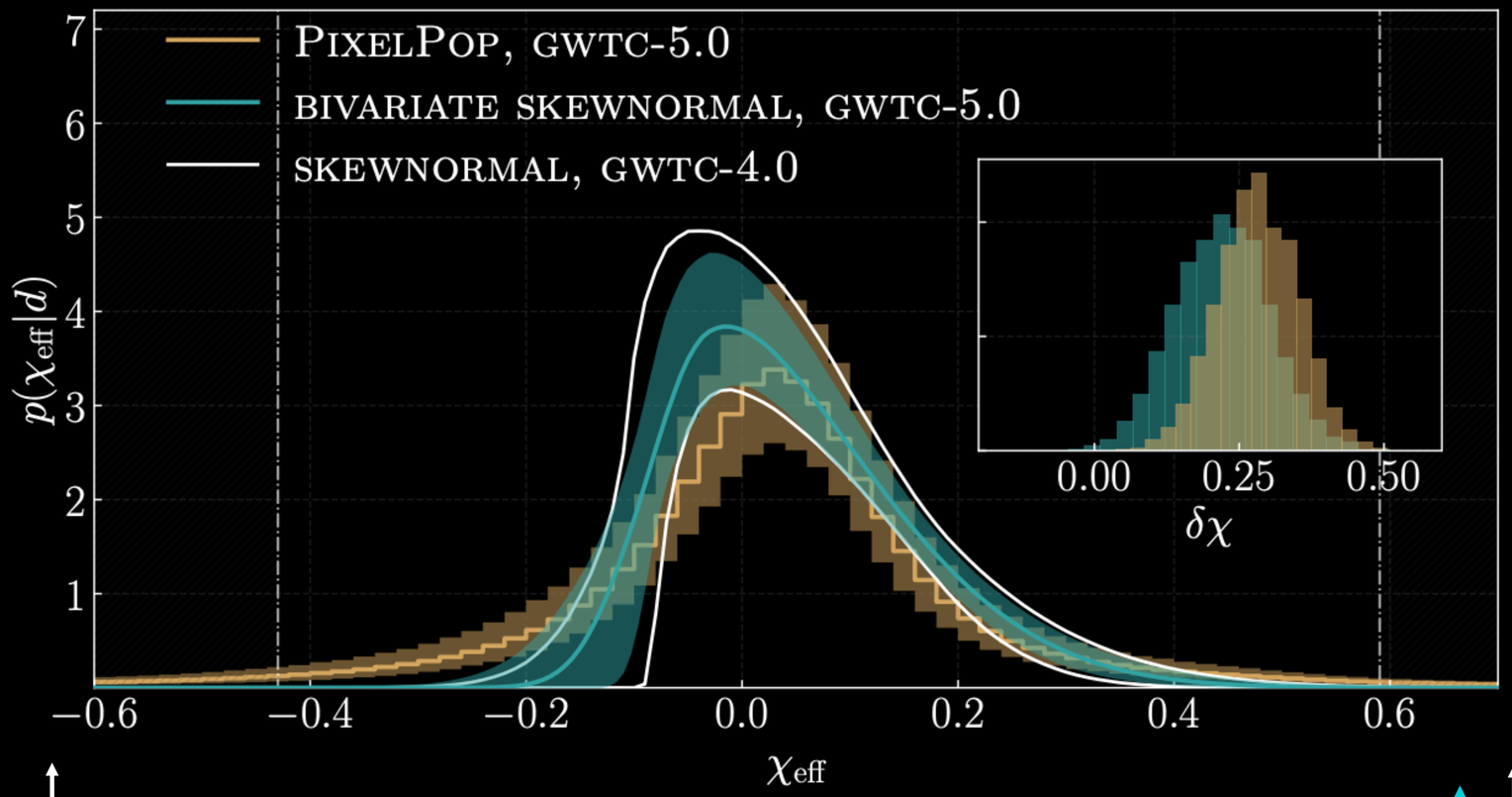
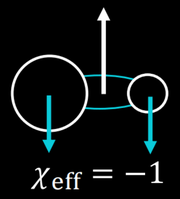
# Effective spin distribution in GWTC-5.0

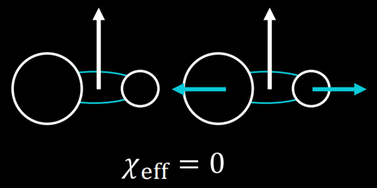


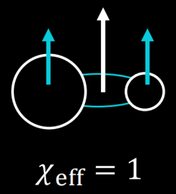

Peaks about zero

~25% more positive than negative $\chi_{\rm eff}$

Skewness is a model-dependent feature!



# Models: parametric vs agnostic

# Inferring the population properties

- Given the catalog of gravitational-wave sources, we need a way of extracting the population properties.
- We rely on hierarchical Bayesian inference, which requires:
    - Posterior samples from individual events.
    - Accounting for selection effects.
    - A model for the distribution of parameters

# Inferring the population properties

- Broadly speaking, we use two approaches to write the population distribution:
  - Phenomenological (“strong”) models
  - Agnostic models

# Population models lie on a spectrum




**Parametric**

- Strong functional forms.
- Usually astrophysically motivated.
- Easier to interpret?
- Prone to biases.

**Non-parametric**

- Flexible.
- Astrophysics agnostic.
- Harder to interpret.
- Less prone to biases.

# Population models lie on a spectrum




**Parametric**

Strong functional forms.

Usually astrophysically motivated.

Easier to interpret?

Prone to biases.

**Non-parametric**

Flexible.

Astrophysics agnostic.

Harder to interpret.

Less prone to biases.

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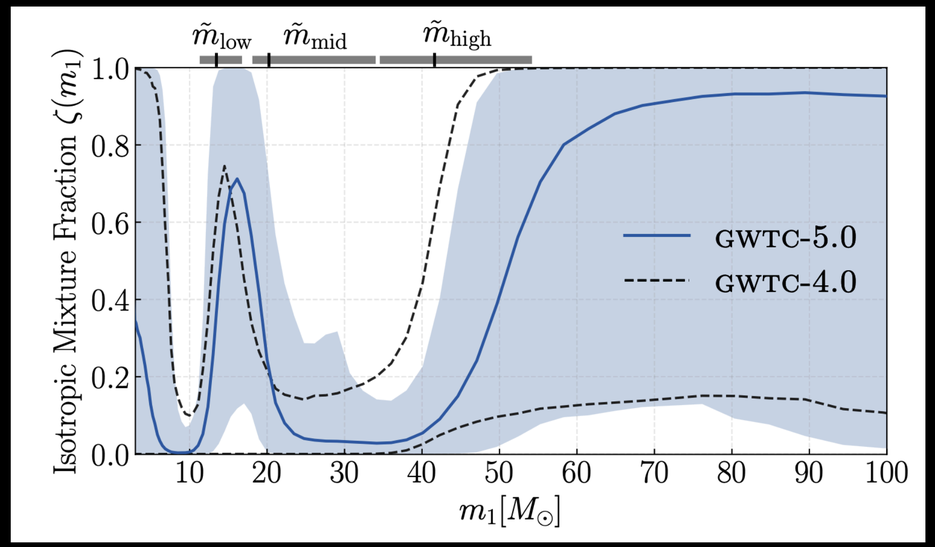
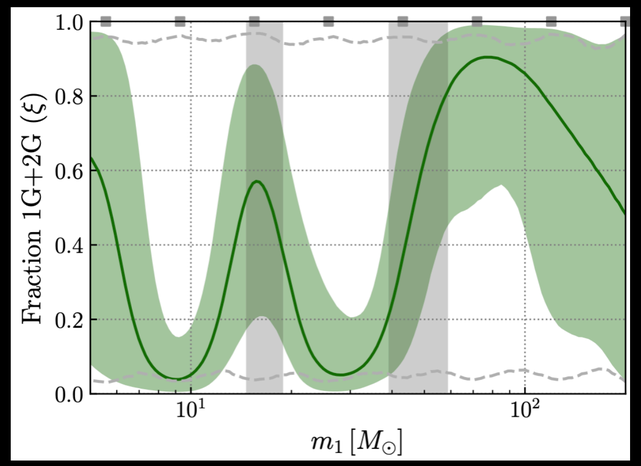
# Mixing fractions

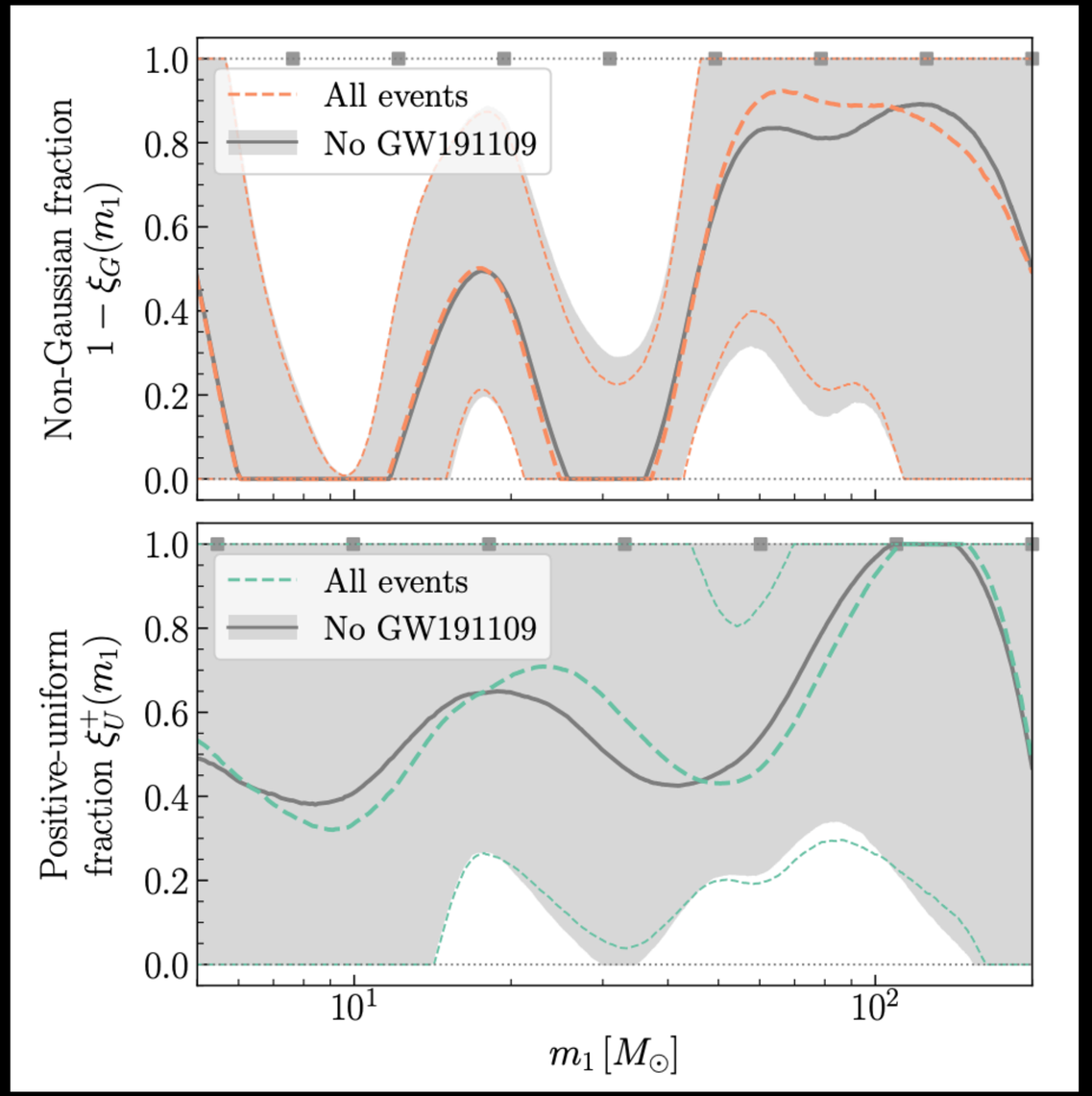



Abac+ 2605.27226, using model from Antonini+ 2406.19044;

see also Antonini+ 2509.04637, Tong+ 2511.05316




Plunkett+ 2601.07908



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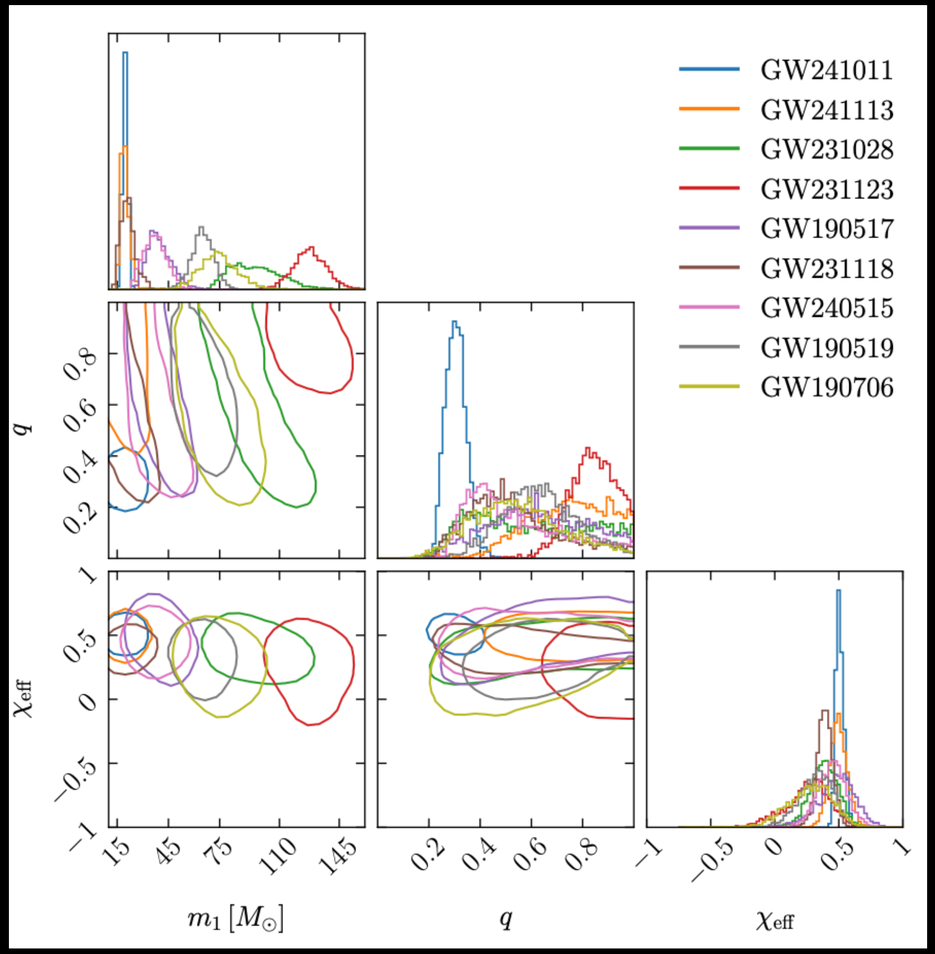
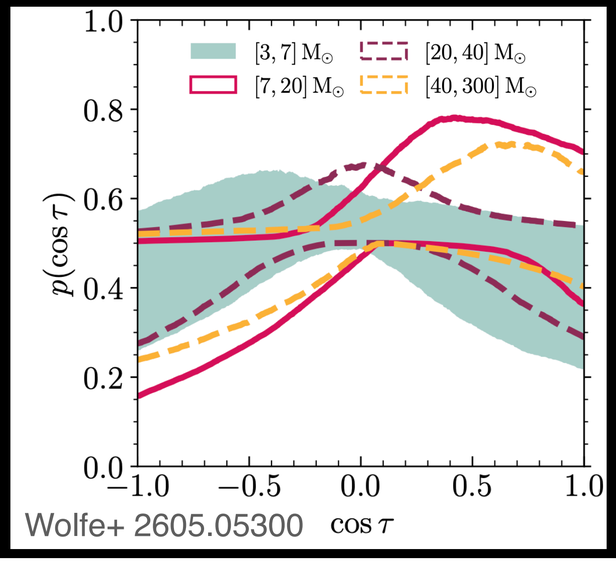
# Mass ratios are poorly constrained

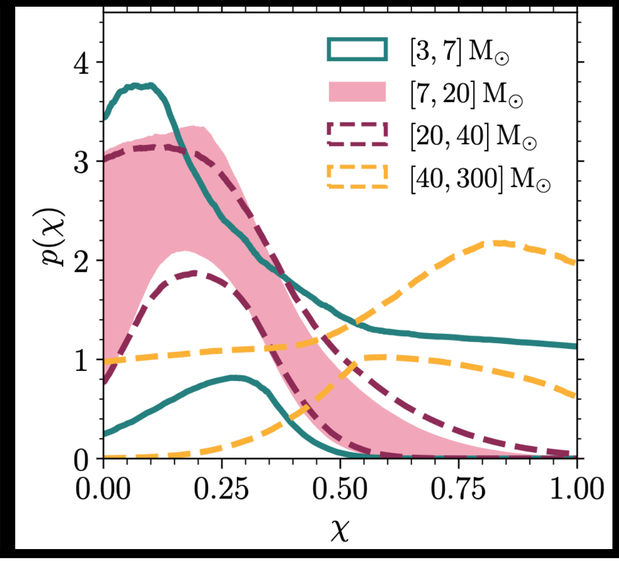


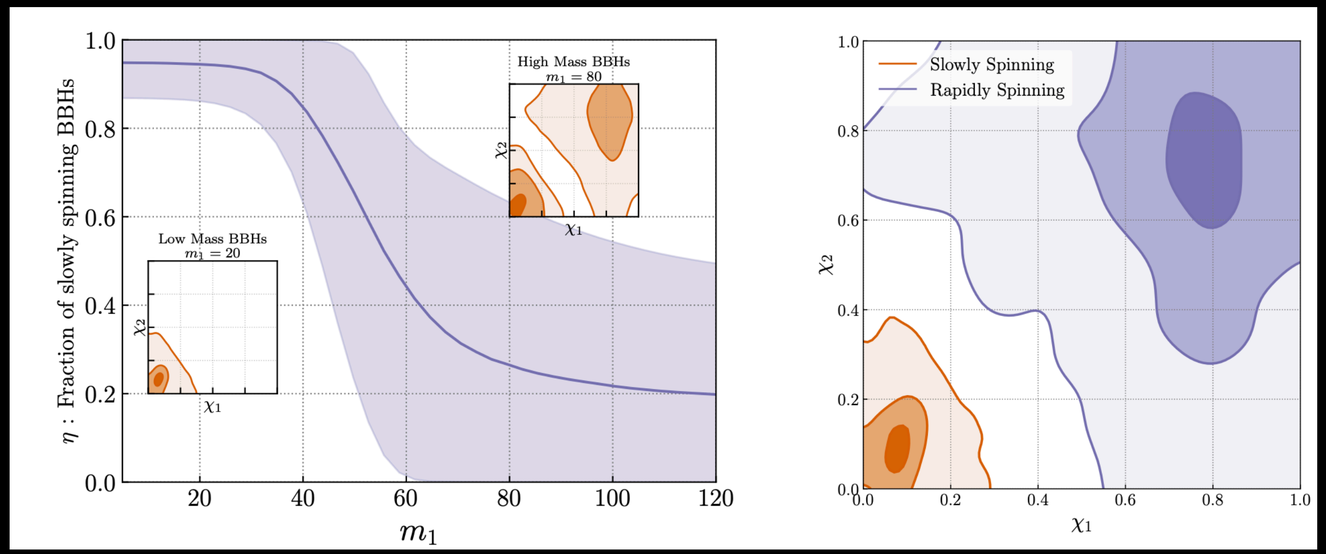
# Further evidence for mass-spin substructure

- Analyses in **component spin magnitudes & tilts** yield a more complicated story: *tilts remain difficult, but spin magnitudes are more telling*
- No confident correlations between tilts and mass
- Wolfe+ confirms spin magnitude – mass correlation with coarse-grained approach
- Hussain+ finds evidence for *both BH spinning*, rather than only the primary




Wolfe+ 2605.05300




Hussain+ 2605.24281

# A bit more about LIGO

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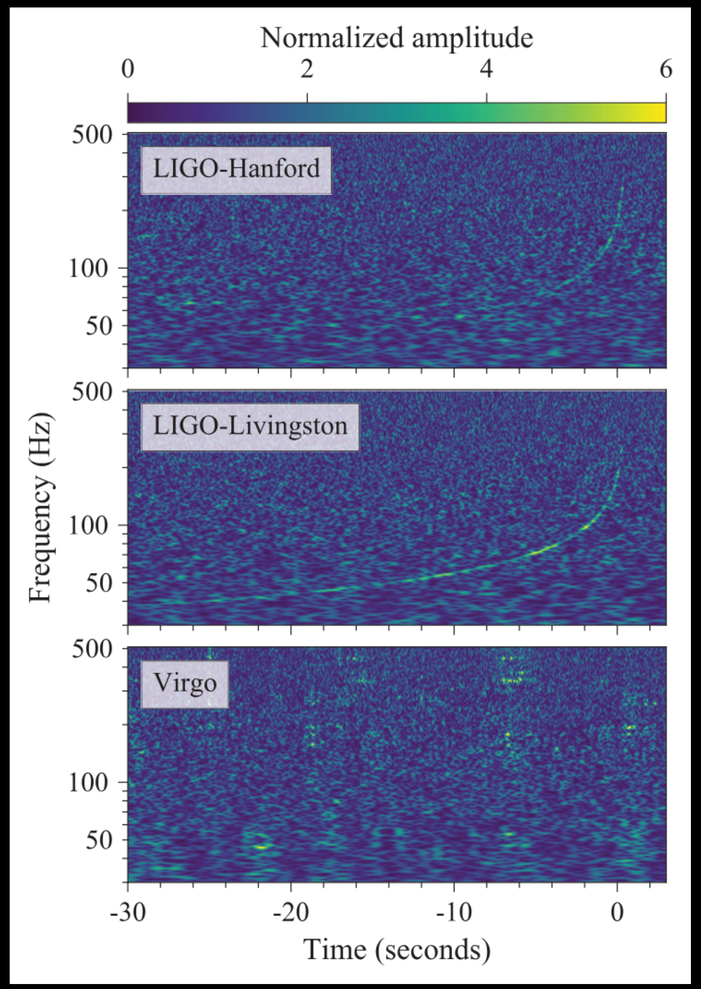
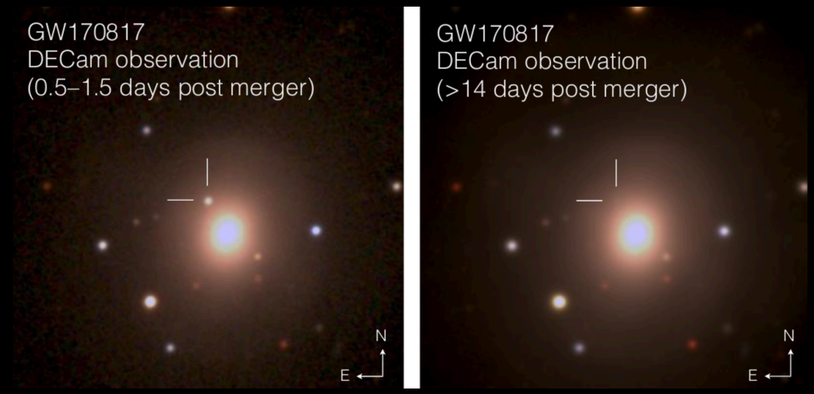
# Multi-messenger astronomy!




Abbott+2017

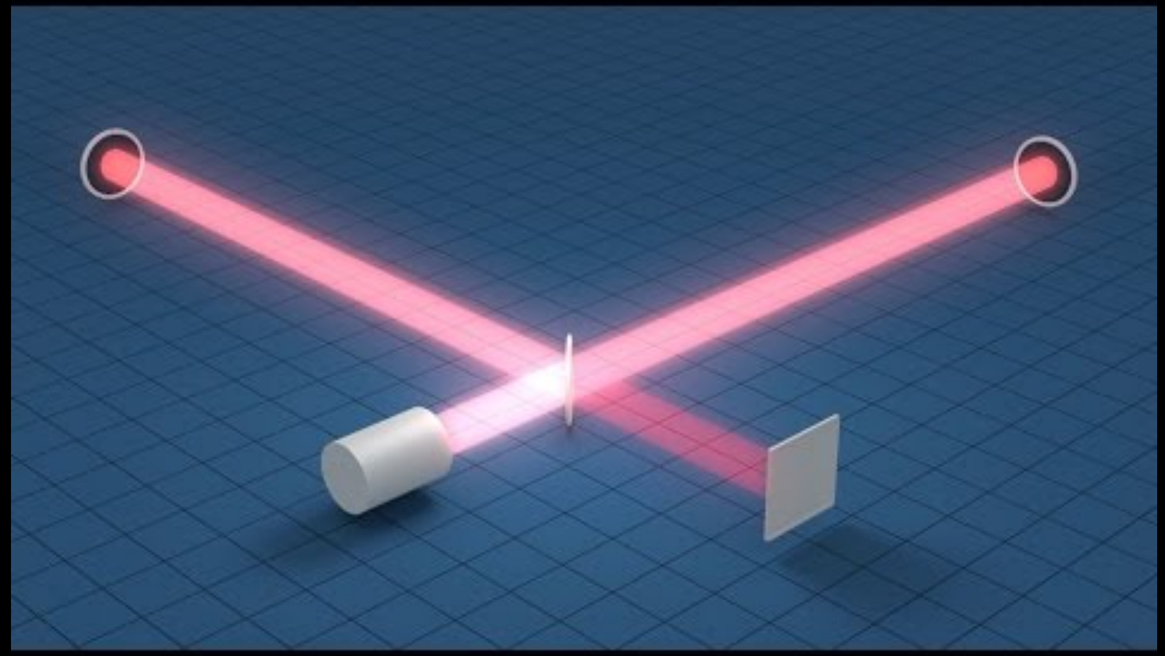



Chandra:




https://chandra.harvard.edu/photo/2018/gw170817/

# Detecting gravitational-waves with LIGO



# Measuring spins

- Spin changes the orbital dynamics of the binary, leaving an imprint on the gravitational-wave signature.
- Then, we compare waveform models with different masses and spins to the data using Bayesian parameter estimation to get estimates of the source parameters.

# Slide resources

