On the Distribution of Effective Spins and Masses of Binary Black Holes from the LIGO and Virgo O1–O3a Observing Runs

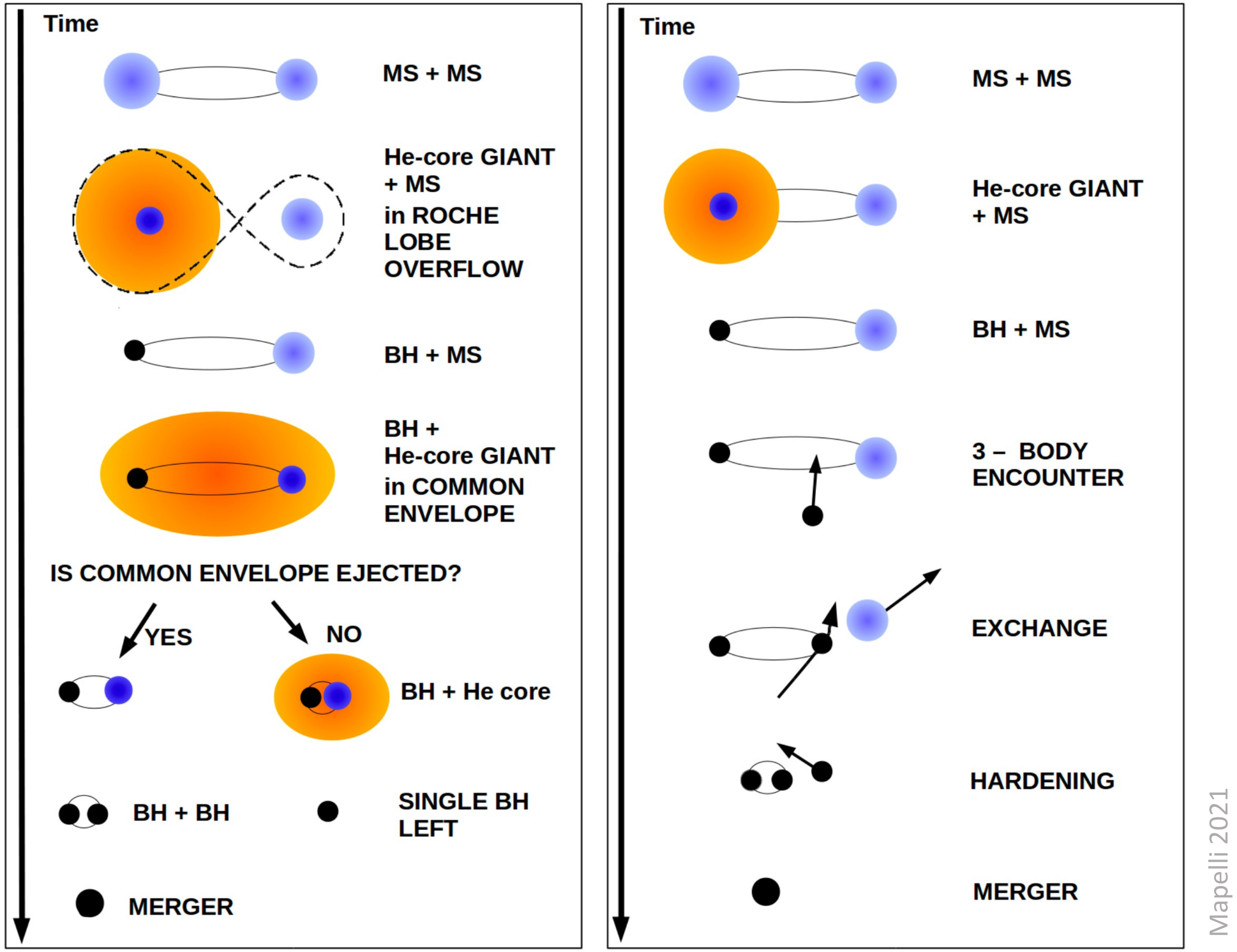
Roulet[1] et al. 2021

High-energy journal club June 3rd, 2021

[1] Department of Physics, Princeton University

Context

- Discriminate between isolated and dynamical formation channels of BBH

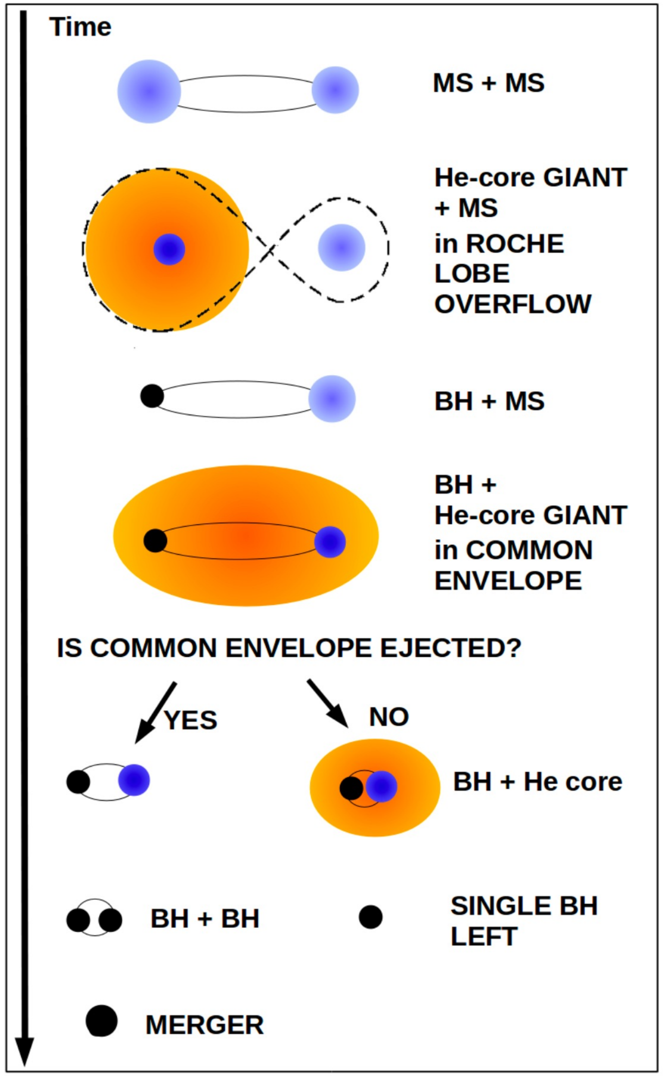


Isolated

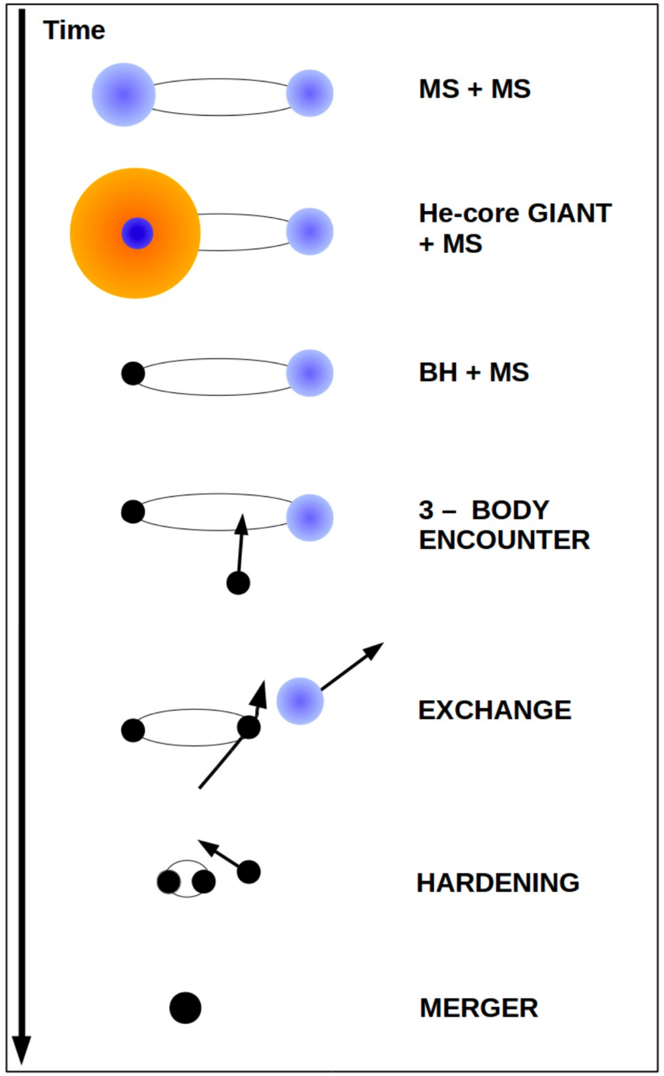
Dynamical

Context

- Isolated formation channels:
  - Correlations in BH spins and orbit directions due to mass transfer episodes or tidal interaction between component stars
- Dynamical formation channels:
  - Spins and orbits uncorrelated to each other, isotropically distributed



Isolated



Dynamical

Mapelli 2021

Context: spins

- Spin-orbit alignment characterized by

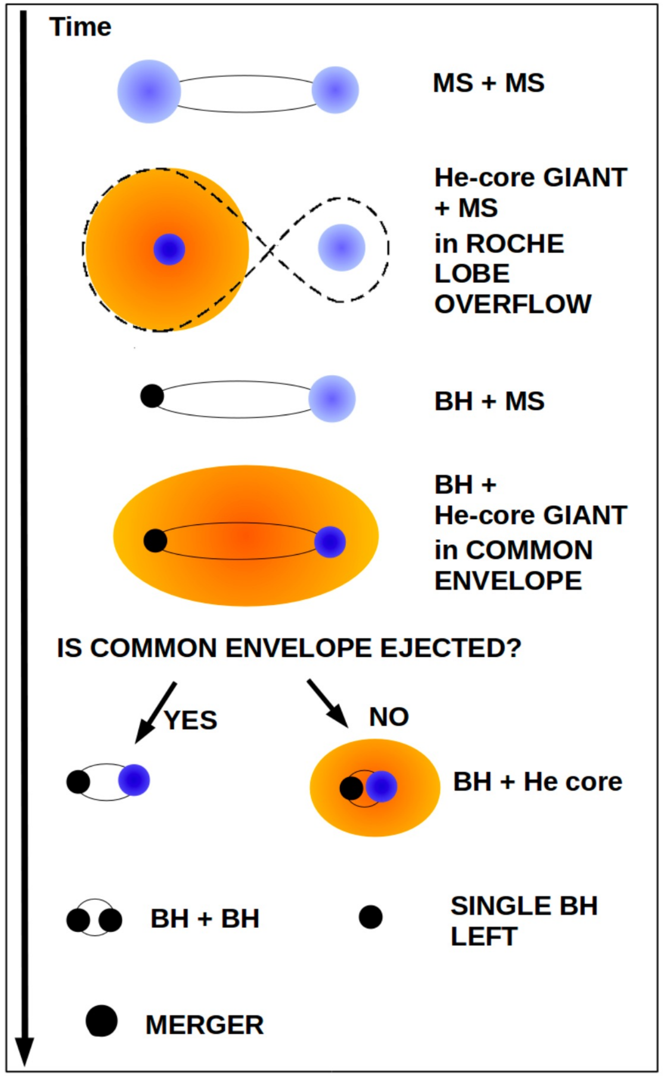
$$\chi_{\text{eff}} := \frac{\boldsymbol{\chi}_1 + q\,\boldsymbol{\chi}_2}{1+q} \cdot \hat{\boldsymbol{L}}$$

$q = m_2 / m_1 \leq 1$

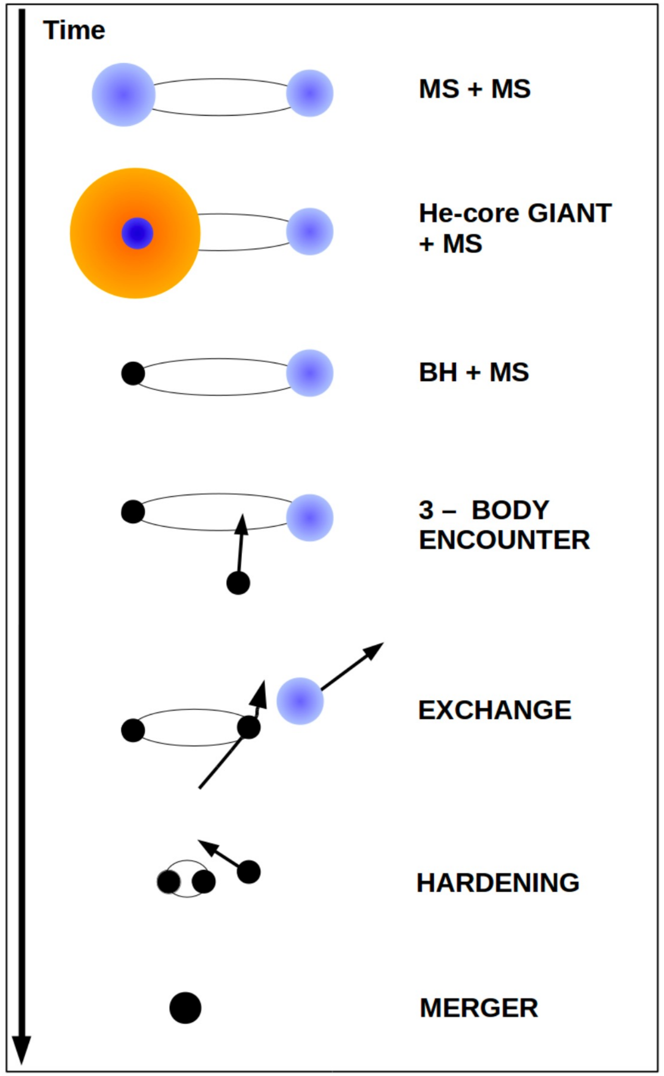
$\hat{\boldsymbol{L}}$ unit vector along Newtonian orbital angular momentum of the binary

$\chi_{\text{eff}} < 0$: spin-orbit misalignment

Isolated binary : little support at negative values



Isolated



Dynamical

Mapelli 2021

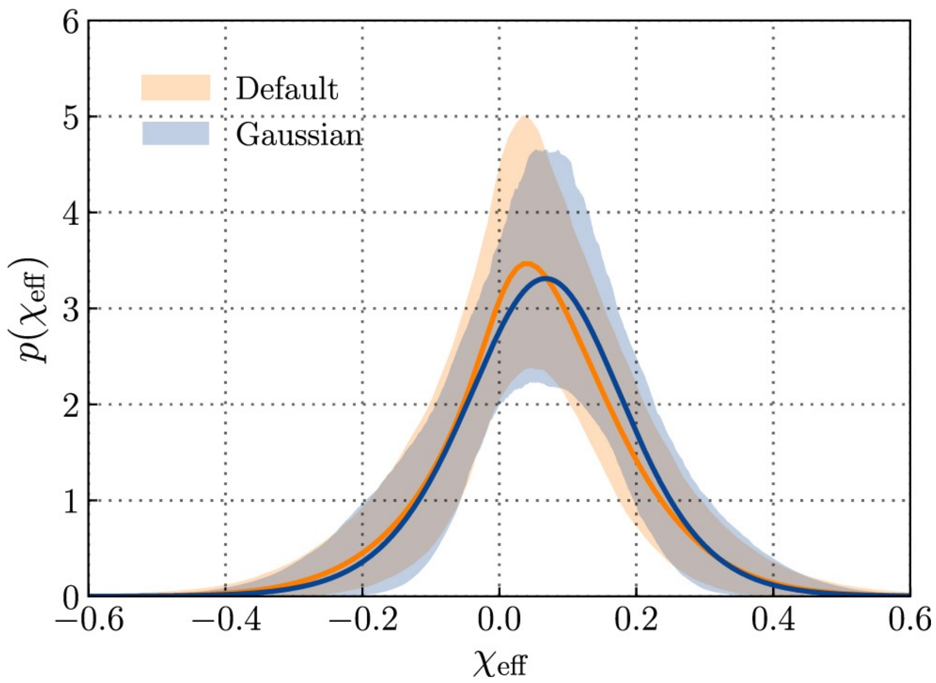
Context: spins

- In this work:
  - Study of the features of the χ_{eff} distribution: symmetry about 0 and support at negative values using 01 – 03a observations

- Difficulty:
  - Hard to test if χ_{eff} are small : small sample with measurable nonzero χ_{eff}

Context: spins

- This paper: a response to Abbott et al. 2021 : “Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog”



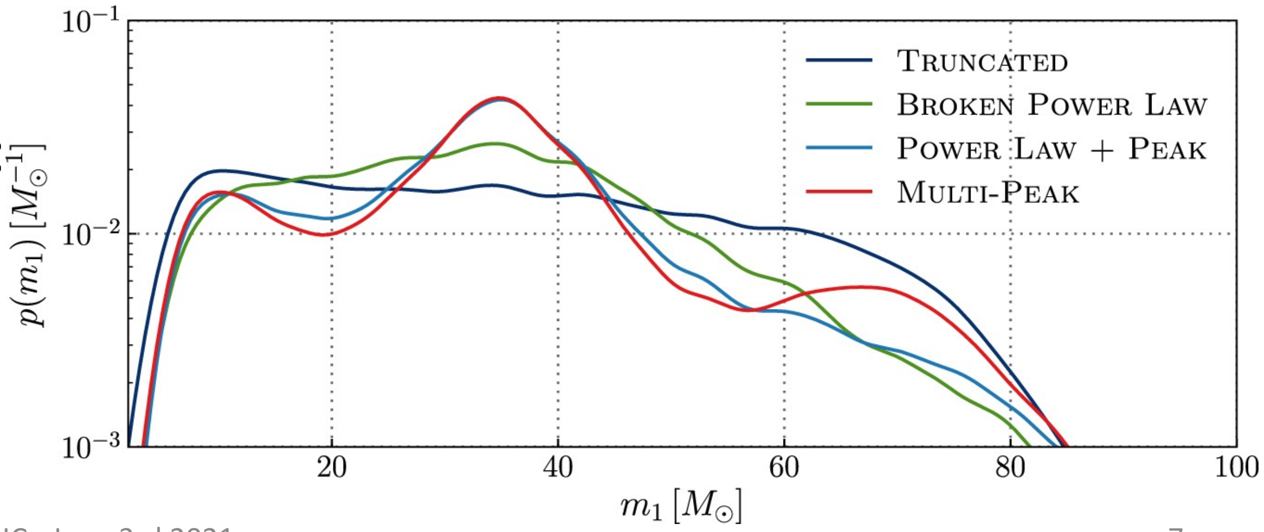
Abbott et al. 2021

Posterior distribution of χ_{eff} values

Their conclusions: positive mean and support at negative values
→ Neither dynamical nor isolated formation channels can explain the entirety of the detections

Context: masses

- High-mass end of the mass distribution:
  - Mass gap from (pulsational) pair instability supernovae from ~45$M_\odot$ to ~135$M_\odot$
  - BHs in this mass range: "second-generation" after mergers
  - Favoured if escape velocity is high (kicks inefficient) → in clusters but not in isolated binaries.
  - Analysis from Abbott et al. 2021:



Findings of the paper

- χ_{eff} distribution inconsistent with being symmetric about 0
  - Disfavours a scenario with an entire population with isotropically-distributed effective spins, as predicted by dynamical scenario

- No evidence for negative χ_{eff} in the population (contrary to Abbott et al. 2021)

- Primary-mass distribution distribution steepens at $\sim 45 M_{\odot}$ then flattens with an extended tail

Data

- LVC GWTC-1 & GWTC-2 : O1 ; O2 ; O3a GW events
- IAS O1-O2
- Exclude GW190814 ($23M_\odot$ - $2.6M_\odot$ merger) : not sure if secondary is NS or BH

- Some detection are more statistically significant → "gold sample"

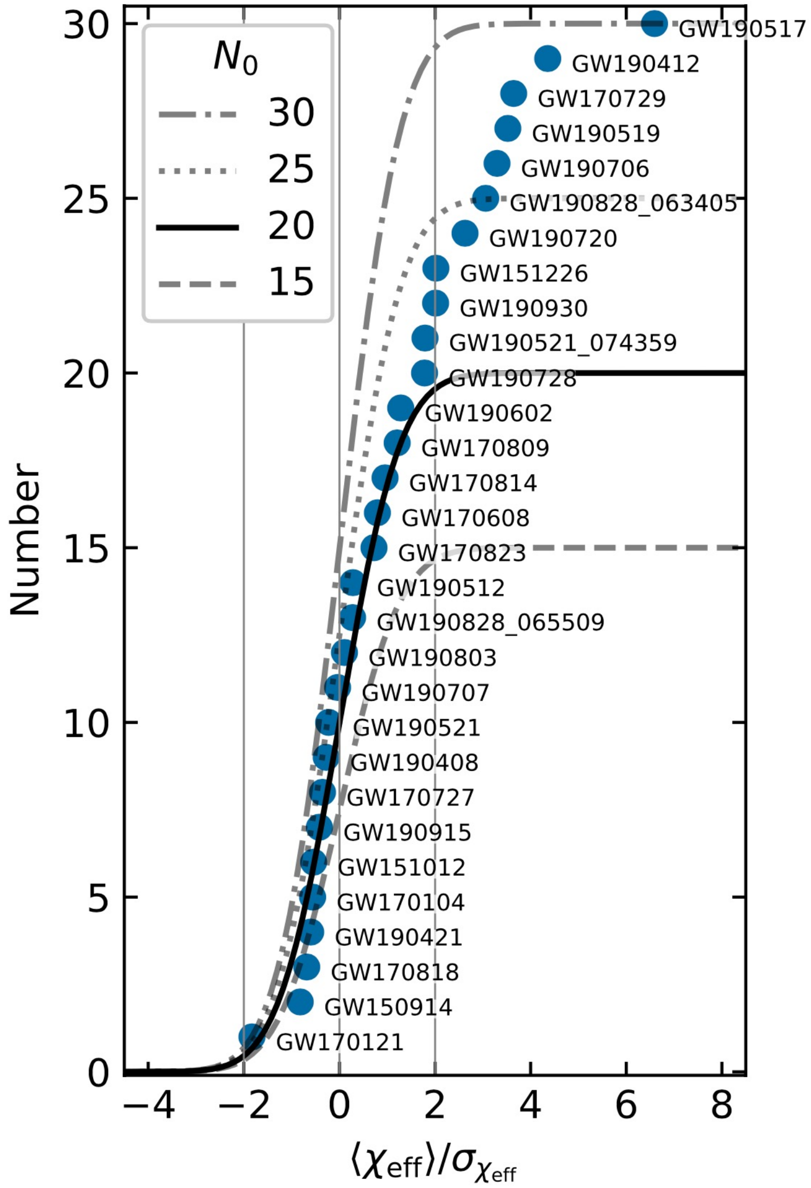
- 55 events, 33 in the gold sample

Data processing

- Waveform fitting for every event in the catalogue, with a quasi-circular orbit and taking into account spin-orbit precession in the signal and some (l, lml) harmonics
- Some events have non-gaussian transient noise → no mitigation efforts but they verify that they find similar results to Abbott et al. 2021

- Results consistent with LVC apart from GW151226 (more unequal mass ratio, larger χ_{eff}) & GW190521 (bimodal mass solution)

Model-free exploration: support for nonzero χ_{eff}



For each event, posterior distribution from waveform fitting gives $<\chi_{eff}>$ and $\sigma_{\chi eff}$

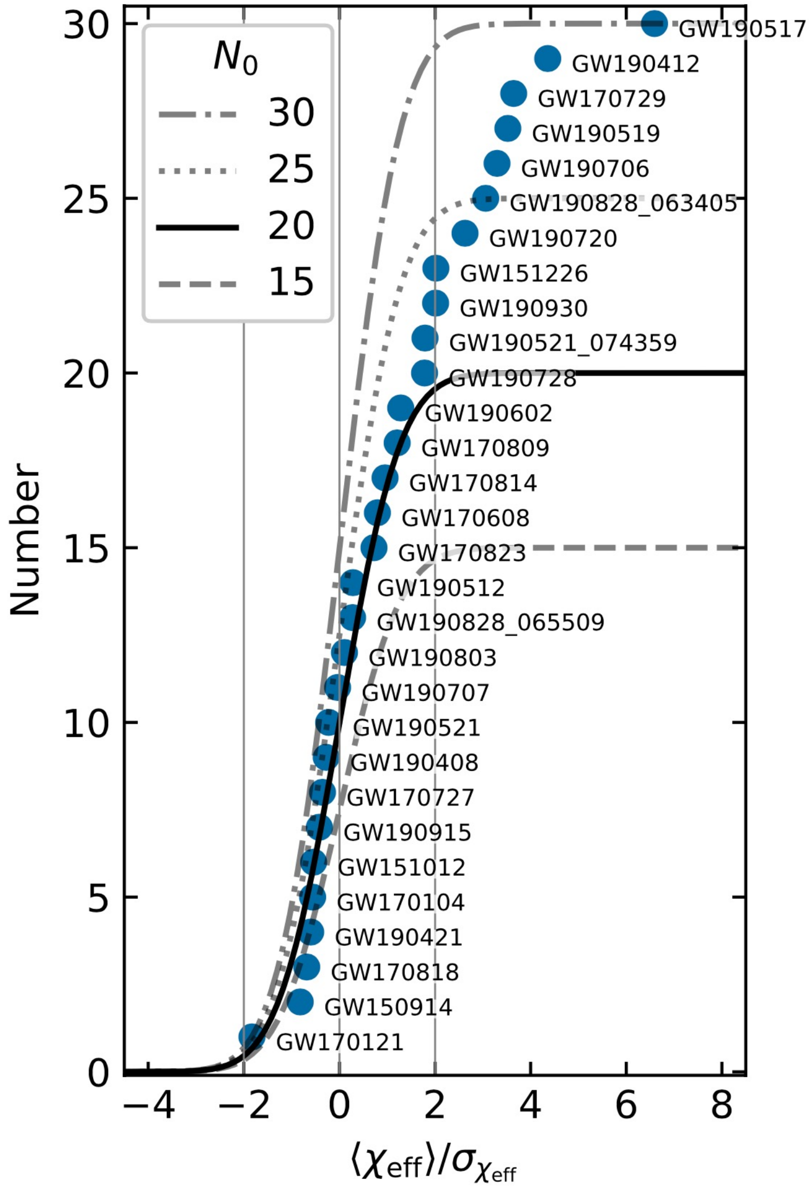
Lines : what we would expect from a noisy measurement of a $\chi_{eff} = 0$ population (cumulative of a standard Gaussian distribution with 0 mean and N_0 number of events in the distribution)

If $\chi_{eff} = 0$ for the real population:

- Data should match line for $N_0 = 30$
- No observations more than 2σ away from $\chi_{eff} = 0$

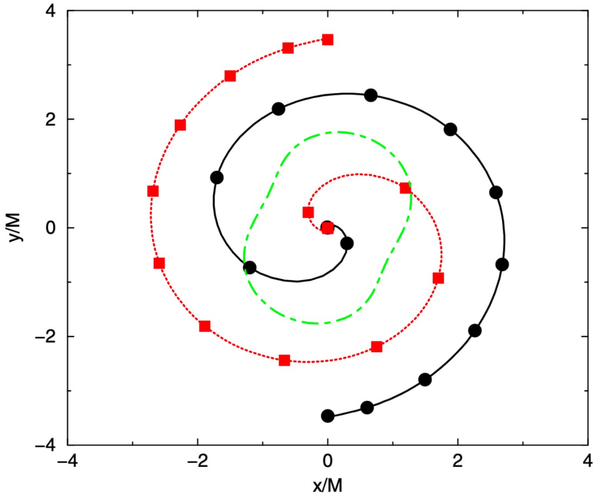
10 events with $\chi_{eff} > 0$ cannot be explained by measurement uncertainty, no such tail needed in the $\chi_{eff} < 0$ interval

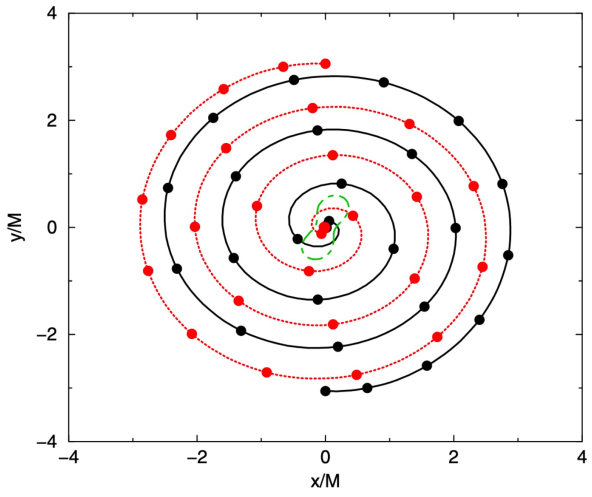
Model-free exploration: support for nonzero χ_{eff}



Warning : Selection bias!
Observed excess of $\chi_{eff} > 0$ relative to $\chi_{eff} < 0$ does not directly imply that the astrophysical population is asymmetric about $\chi_{eff} = 0$

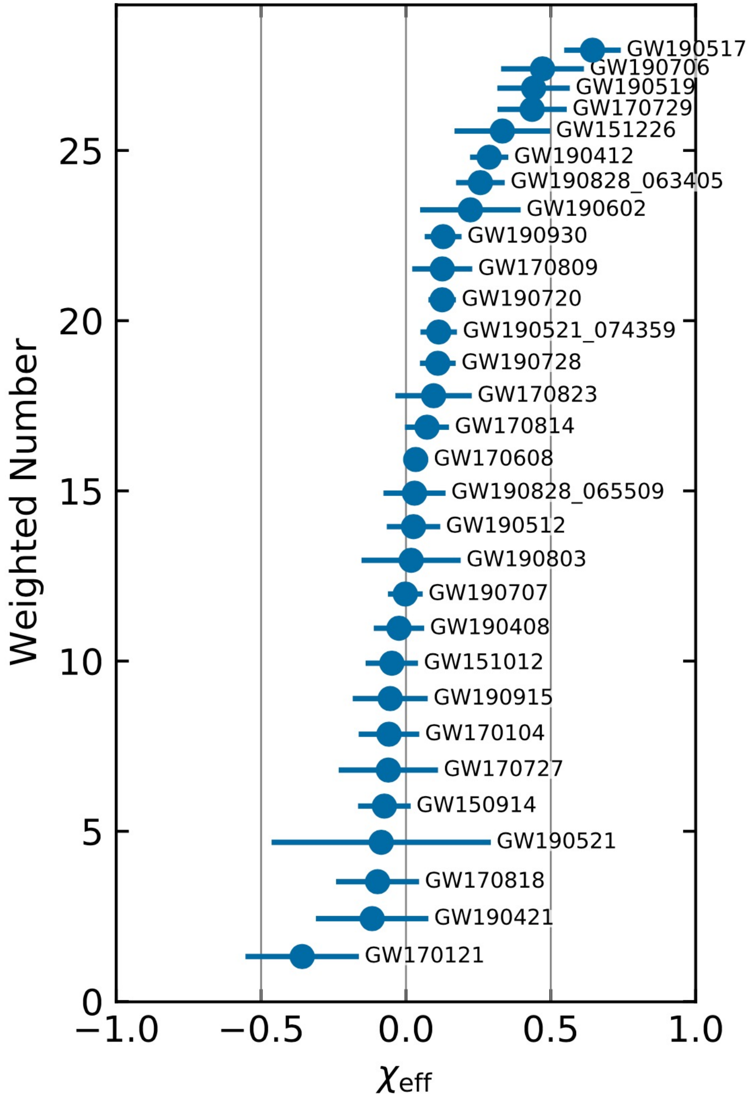
Mergers with large, positive χ_{eff} louder: "orbital hangup" effect





Campanelli et al. 2006

Model-free exploration: symmetry of the χ_{eff} distribution



Correction for observational bias: weight factor for each event:

w = <$V_{no\ spin}$ / V>

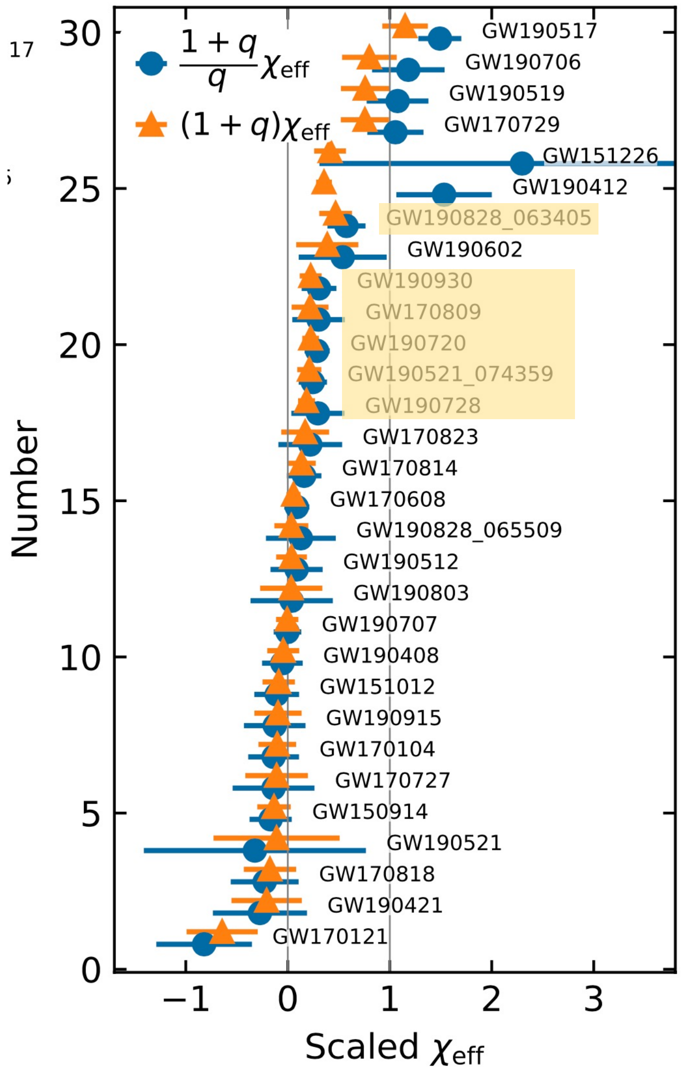
V: sensitive volume

If w is small: it is easier to miss a similar event with anti-aligned spins

This plot: vertical spacing from volume weight of the events.

Empirical effective spin distribution consistent with a distribution with no support for negative spins ; not very consistent with a distribution symmetric about $\chi_{eff} = 0$

Model-free exploration: testing tidal models



Can the events with $\chi_{\mathrm{eff}} > 0$ be explained by a simple model of tides acting on the progenitor of one of the component black holes?

χ_{eff} distribution should peak at:

- 0 — inefficient tides
- q / (1 + q) — tides torqued the progenitor of the secondary BH
- 1 / (1 + q) — tides torqued the progenitor of the primary BH
- 1 — tides torqued both BHs

Plot: Primary or secondary maximally spinning and aligned with orbit

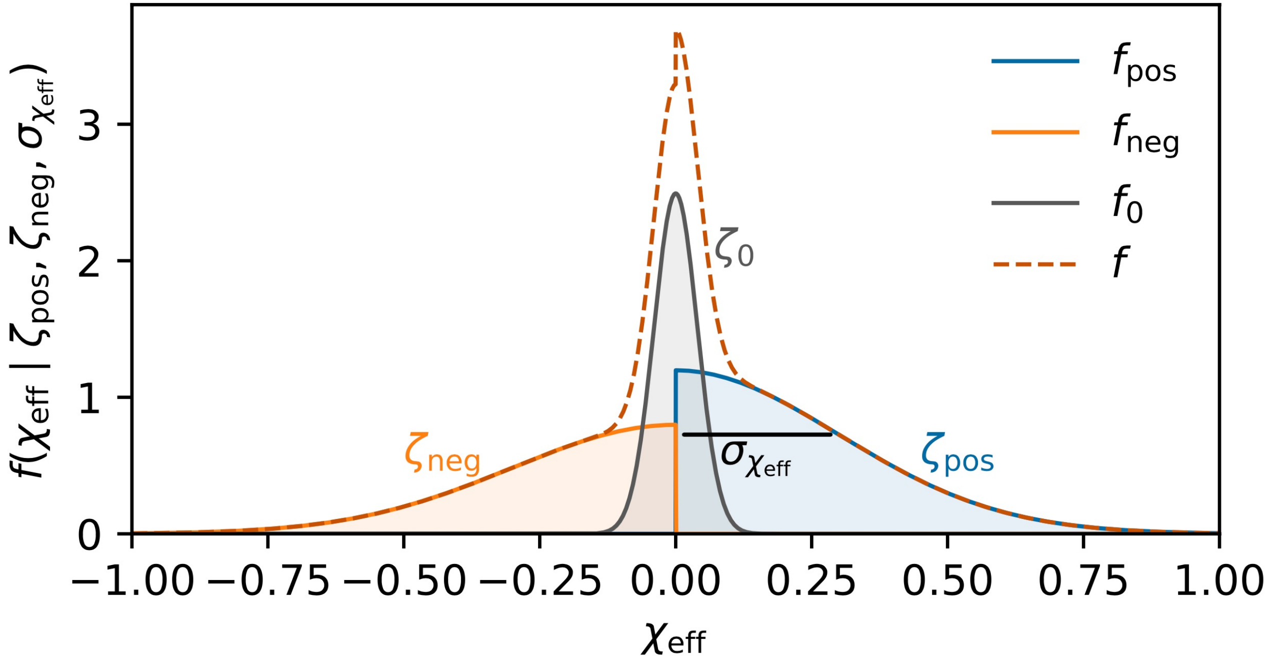
Events in yellow inconsistent with these hypotheses

Need for a less extreme model of tidal torques, or a distribution of natal spins with some dispersion

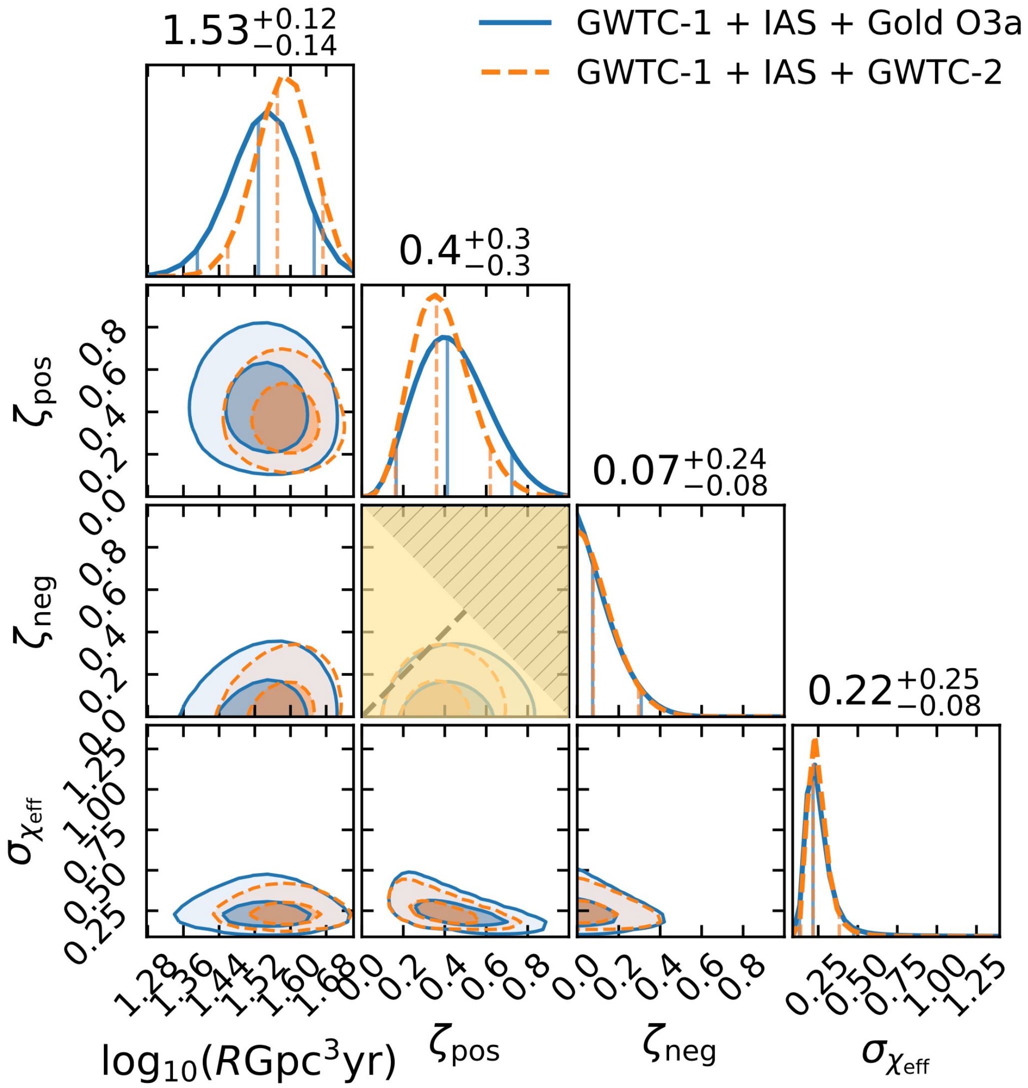
Model selection: Spin distribution

- Phenomenological model of effective spin distribution to explore symmetry and distribution about $\chi_{\mathrm{eff}} = 0$:

$$
\begin{aligned}
f_{\chi_{\mathrm{eff}}}(\chi_{\mathrm{eff}} \mid \zeta_{\mathrm{pos}}, \zeta_{\mathrm{neg}}, \sigma_{\chi_{\mathrm{eff}}}) = {} & \zeta_0 \mathcal{N}(\chi_{\mathrm{eff}}; \sigma_0 = 0.04) \\
& + \zeta_{\mathrm{neg}} \mathcal{N}_{<0}(\chi_{\mathrm{eff}}; \sigma_{\chi_{\mathrm{eff}}}) \\
& + \zeta_{\mathrm{pos}} \mathcal{N}_{>0}(\chi_{\mathrm{eff}}; \sigma_{\chi_{\mathrm{eff}}}) \, .
\end{aligned}
$$

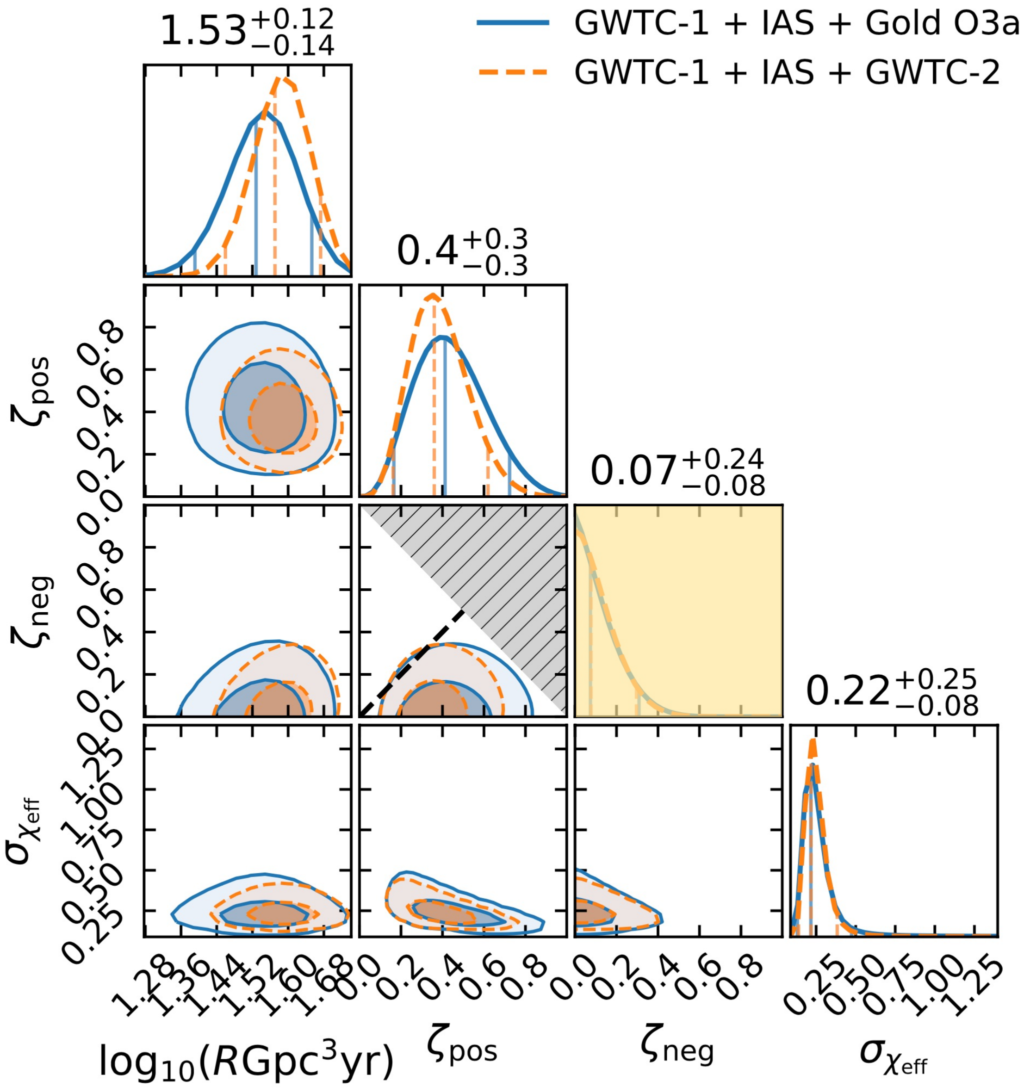


Model selection: Spin distribution



- 95% of the posterior at $\zeta_{pos} > \zeta_{neg}$
- Symmetric distribution $\zeta_{pos} = \zeta_{neg}$ (dashed line) disfavoured

Model selection: Spin distribution



- 95% of the posterior at $\zeta_{pos} > \zeta_{neg}$
- Symmetric distribution $\zeta_{pos} = \zeta_{neg}$ (dashed line) disfavoured

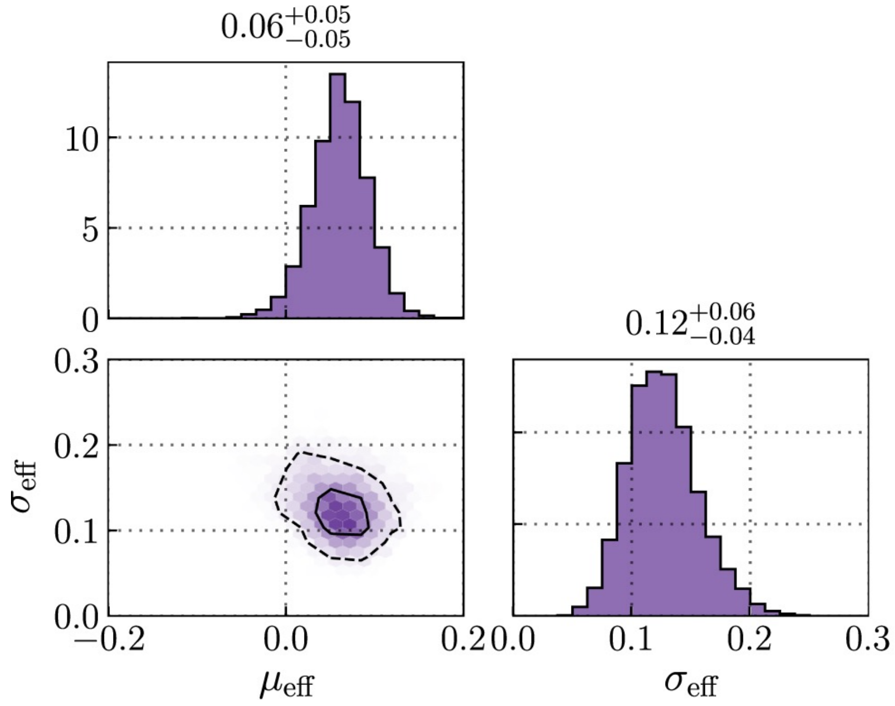
- Population consistent with $\zeta_{neg} = 0$ (no spins anti-aligned with binary orbit)

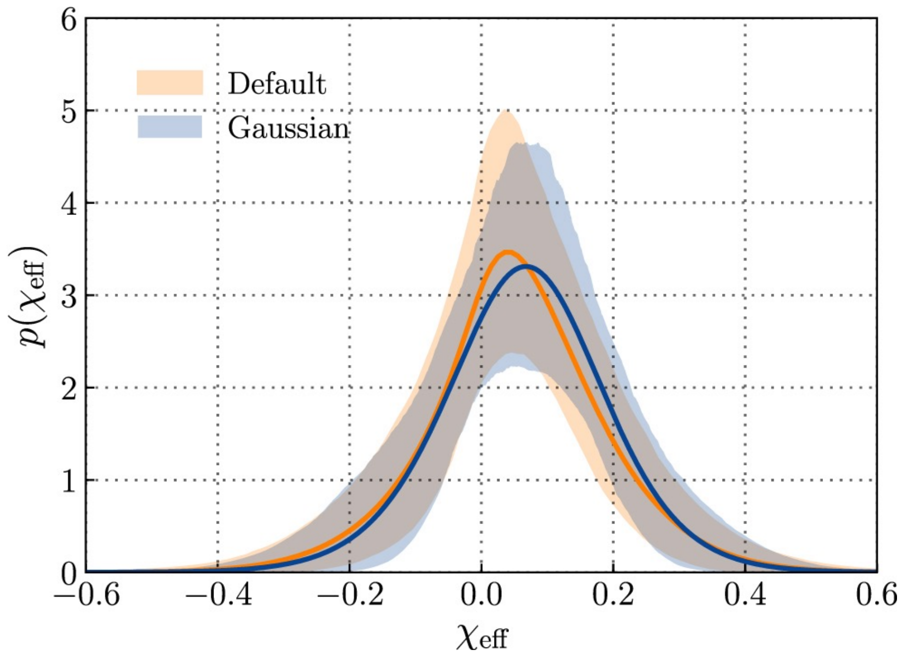
Reminder:

- Symmetric χ_{eff} model → Dynamical formation in clusters
- Positive χ_{eff} model → Isolated binaries

Model selection: Spin distribution

No evidence for negative χ_{eff} : in contrast with Abbott et al. 2021…

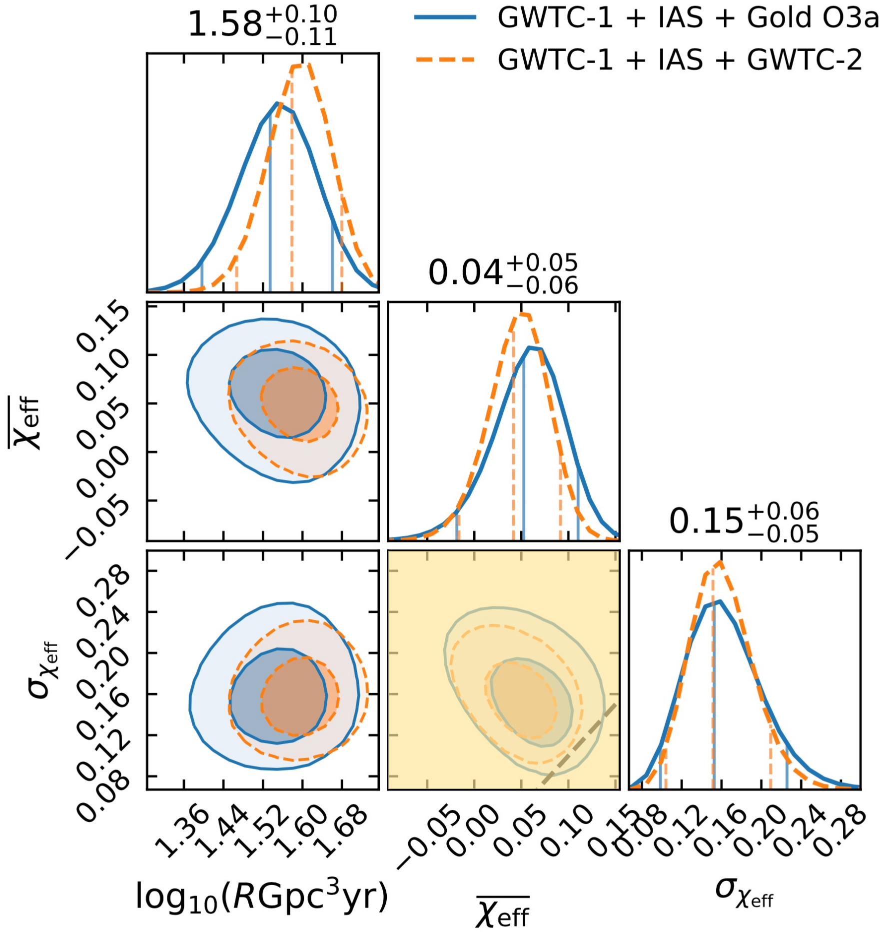


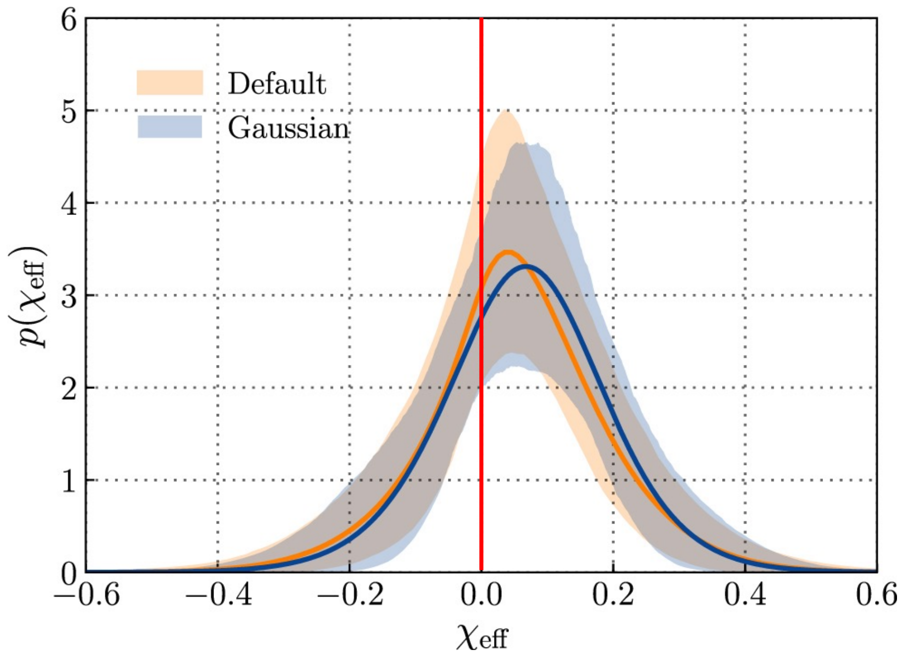


Abbott et al. 2021

Model selection: Spin distribution

… but if we parametrize the population as a Gaussian distribution, we retrieve a significant tail at $\chi_{eff} < 0$





Abbott et al. 2021

Model selection: Spin distribution

… but if we parametrize the population as a Gaussian distribution, we retrieve a significant tail at $\chi_{eff} < 0$

	Δ max ln L	Δ ln Z
Symmetric χ_{eff}	0	0
Positive χ_{eff}	$2.1^{+0.5}_{-0.4}$	$1.6^{+0.5}_{-0.3}$
Positive/Negative mixture χ_{eff}	$2.1^{+0.5}_{-0.4}$	$1.4^{+0.4}_{-0.2}$
Gaussian χ_{eff}	$0.2^{+0.7}_{-0.6}$	$-0.2^{+0.6}_{-0.8}$

Scores for models of the χ_{eff} distribution:
Gaussian model performs worse

"While it is certainly possible that there are negative χ_{eff} systems in the population, there is not enough evidence for them yet"

Model selection: Mass distribution

- O1 + O2: power-law truncated at $m_{max} \sim 45 M_{\odot}$
- O1 + O2 + O3a: tail extending to higher masses → broken power-law

- Statistics: With a finite number of events, one cannot probe the tail of a distribution arbitrarily far out. Constraints from the population = characterization of the bulk of the distribution

Model selection: Mass distribution

- Add the possibility for astrophysical trigger from a population with broad parameter distribution, with probability $\varepsilon = 0.05$:
  - No difference for the bulk of the population (enough statistics in this range)
  - Diagnostic that some specific events may be poorly accommodated by the parametrization chosen (if they are classified with high confidence as belonging to the other subpopulation: $p_{outlier}$)

- Compare how the parametrizations with $\varepsilon = 0$ and $\varepsilon = 0.05$ fit the data. If evidence doesn't increase significantly, initial model with $\varepsilon = 0$ is a good description

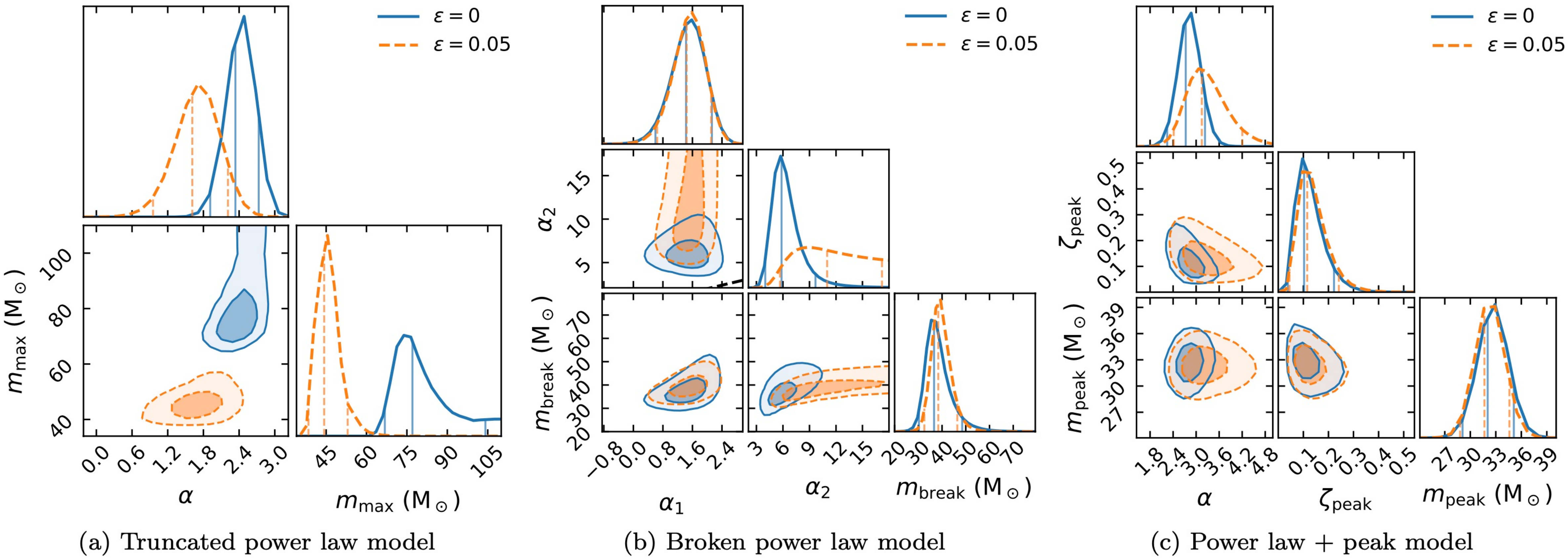
Model selection: Mass distribution

- Procedure applied to Truncated, Broken Power Law, Power Law + Peak mass distribution models

$$f_{m_{1s}}(m_{1s}) \propto \begin{cases} 0, & m_{1s} < 5\,\mathrm{M}_\odot \\ \left(\dfrac{m_{1s}}{m_{\mathrm{break}}}\right)^{-\alpha_1}, & 5\,\mathrm{M}_\odot < m_{1s} < m_{\mathrm{break}} \\ \left(\dfrac{m_{1s}}{m_{\mathrm{break}}}\right)^{-\alpha_2}, & m_{\mathrm{break}} < m_{1s}, \end{cases}$$

Model selection: Mass distribution

$$f_{m_{1s}}(m_{1s}) \propto \begin{cases} 0, & m_{1s} < 5\,\mathrm{M}_\odot \\ \left(\dfrac{m_{1s}}{m_{\rm break}}\right)^{-\alpha_1}, & 5\,\mathrm{M}_\odot < m_{1s} < m_{\rm break} \\ \left(\dfrac{m_{1s}}{m_{\rm break}}\right)^{-\alpha_2}, & m_{\rm break} < m_{1s}, \end{cases}$$



Model selection: Mass distribution

- Preferred models are those with small fraction of events in a broad tail that extends to high masses:
  - Truncated power-law with ε = 0.05
  - Broken power-law with ε = 0.05
- A few outlier events

	Truncated power law	Broken power law	Power law + peak
GW190521	1.00	0.94	0.68
GW190602_175927	0.95	0.72	0.66
GW190706_222641	0.88	0.72	0.75
GW190519_153544	0.76	0.54	0.59
GW190929_012149	0.57	0.46	0.51
GW190620_030421	0.43	0.34	0.47
GW190701_203306	0.33	0.19	0.29
GW190413_134308	0.27	0.25	0.31

$p_{outlier}$

Conclusions

- Parametric model of the χ_{eff} distribution with 3 components (positive, negative and zero).

- Dynamical formation scenarios → χ_{eff} distribution symmetric about 0
- Isolated binaries → negative χ_{eff} should be extremely rare

Conclusions

- Symmetric distribution disfavoured (more events with $\chi_{eff} > 0$ than $\chi_{eff} < 0$): not all BBH are dynamically assembled. O3b will settle the question.
- No evidence for negative χ_{eff} in the population, in tension with Abbott et al. 2021. Discrepancy due to the different parametrization. Gaussian model used in Abbott et al. 2021 fares worse at describing the concentration of events near 0.
- All events with $\chi_{eff} < 0$ are consistent with coming from a population with $\chi_{eff} = 0$.

Conclusions

- Primary masses distribution poorly described by a truncated power law

- Broken power law & Power law + peak models compare poorly to a model in which a small fraction of the events comes from a broad subpopulation. Tail of masses distribution therefore hides interesting features!