A detailed analysis of GW190521 with phenomenological waveform models

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GW190521 : Why is it special?

- Mass estimate of remnant puts it in the IMBH range
- LVC analysis confidently placed primary within the pair-instability supernova mass-gap, in contrast with population previously observed by LIGO
- Evidence of in-plane spins
- Properties might point to a dynamical formation channel (Kimball+20, Gerosa+21)

Anatomy of the signal

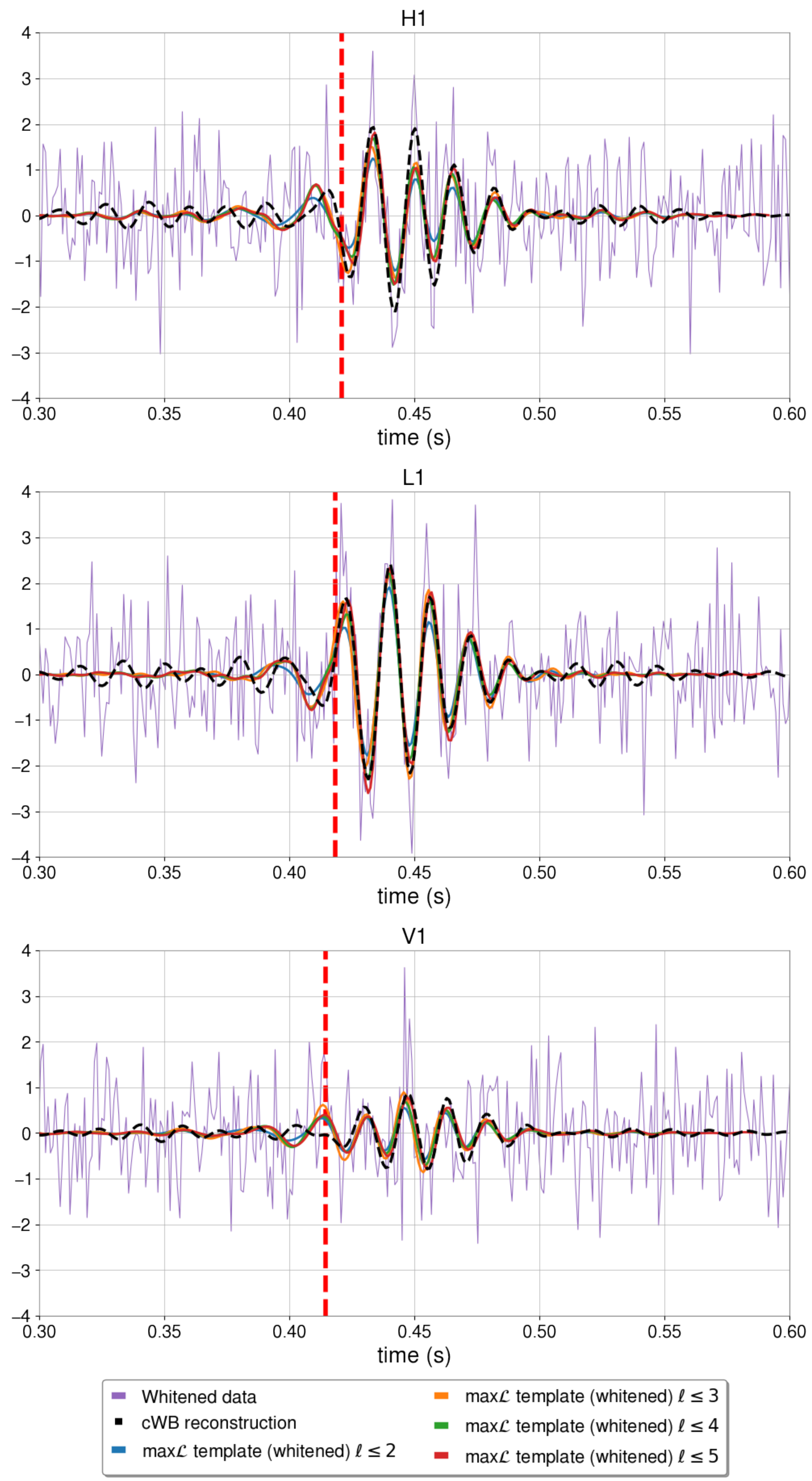
- Short signal of approximately 0.1 s

- Very few cycles: prone to degeneracies

- Strong suppression of inspiral cycles: quasi-circular templates recover strong in-plane spins to model this feature.

- *However*, several possible alternative explanations have been put forward! (see also Juan's talk)

  - Dynamical capture in dense stellar environment (Gayathri+ 20, Romero-Shaw+ 20, Gamba+ 21)
  - Head-on collision (Bustillo + 20)
  - Exotic objects (Bustillo +20)



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Our perspective

- We stick to the quasi-circular coalescence assumption
- Investigate the effects of waveform systematics on special events
- As detector sensitivity improves, we can expect more non-vanilla events: need to understand limits of current QC BBH baselines and differences related to specific modelling approximations

Waveform models for QC BBH inspirals

- **NR Surrogates**: “interpolation” of NR waveforms (Field+13, NRSur7dq2: Blackman+ 17, NRSur7dq4: Varma+ 19)
    - Highest faithfulness against NR simulations, but relatively short waveforms (around 20 orbits) before merger —> imply limitations of minimum frequency and total mass models can handle
- **SEOB models** (Taracchini+ 13, Pan+ 14, latest additions: SEOBNRv4HM (Cotesta+ 18), SEOBNRv4PHM (Ossokine+ 20))
    - Precession: not directly calibrated to NR. Twist-up aligned spin model, solving EOB precession equations
    - Precessing models track consistently precession dynamics, at the price of solving expensive differential equations —> high computational cost!
- **Phenom models** (Ajith+ 07, Khan+15, London+16, Khan+19, Pratten+20, García-Quirós+20, Estellés+20, Estellés +21…)
    - split a compact-binary coalescence into three regions and fit amplitude and phase to hybrid EOB/NR waveforms in each
    - Traditionally built in FD, but now also constructed in TD (see Héctor’s talk)

Latest generation of Phenom models

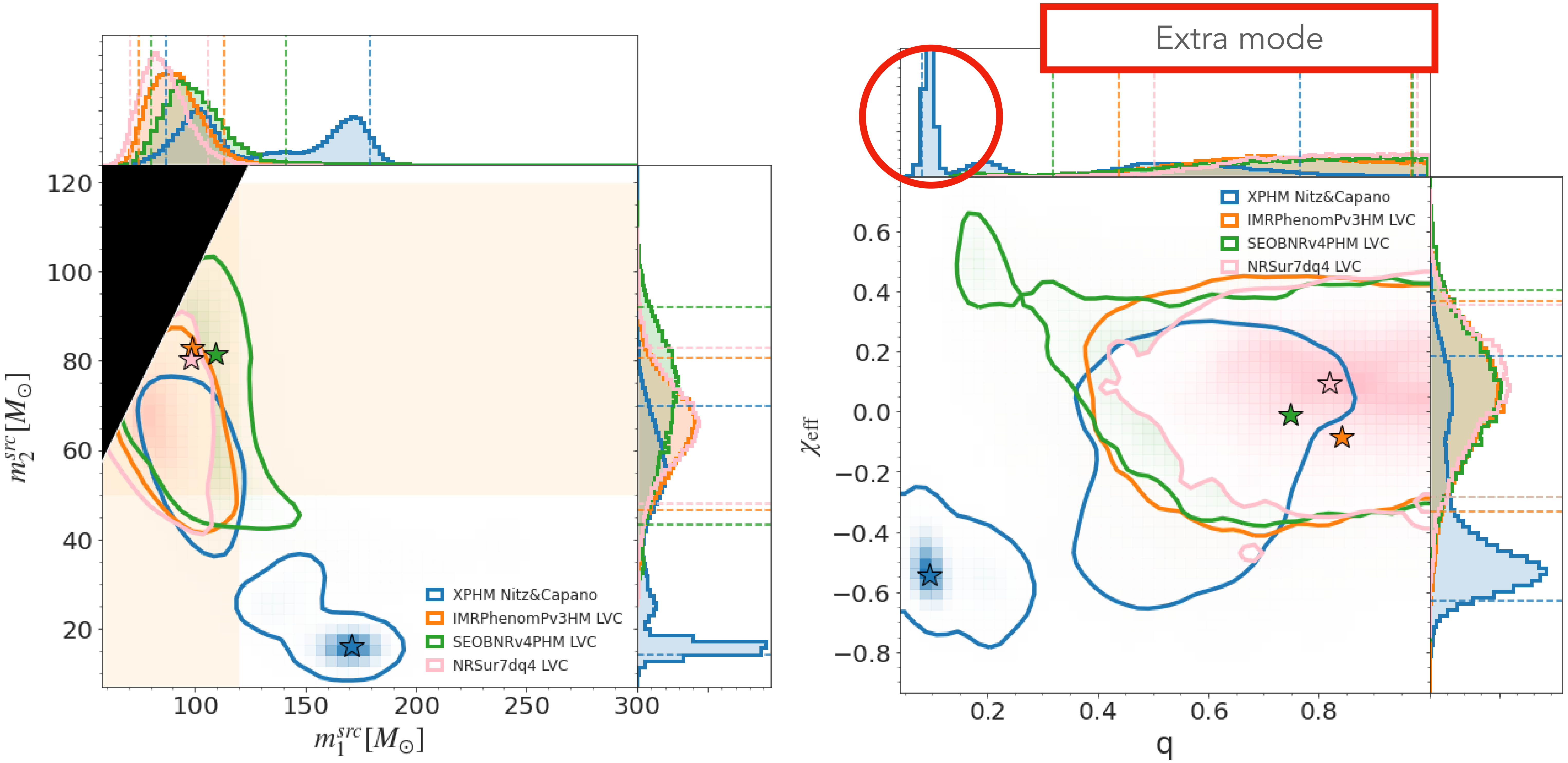
We have developed two complementary phenomenological models:

- a **frequency-domain** family (IMRPhenomX* (Pratten+ 19, Garcia-Quirós+ 19, Pratten+ 20))
    - Accurate phasing of aligned spin model
    - Artificially prolong inspiral description of transfer functions into merger-RD
    - a **time-domain** family: IMRPhenomT* (Estellés+ 20, Estellés+ 21))
    - Does not rely on SPA and offer a better RD description (O'Shaughnessy,+ 13)

Cheap enough to allow systematic studies of effects of priors, sampler settings, specific model approximations, etc…(see Maite's talk)

Was it an intermediate mass-ratio inspiral?

- Mass prior had a hard cut on mass ratio, to adjust to the validity domain of one of the approximants used (NRSur7dq4): $q \geq 0.17$, where $q \leq 1$
- This implies modes in the posterior with yet more unequal masses are excluded.
- A later reanalysis of public data with PhenomXPHM by Nitz&Capano found that, by extending the LVC prior bounds, additional small mass ratio modes could be found



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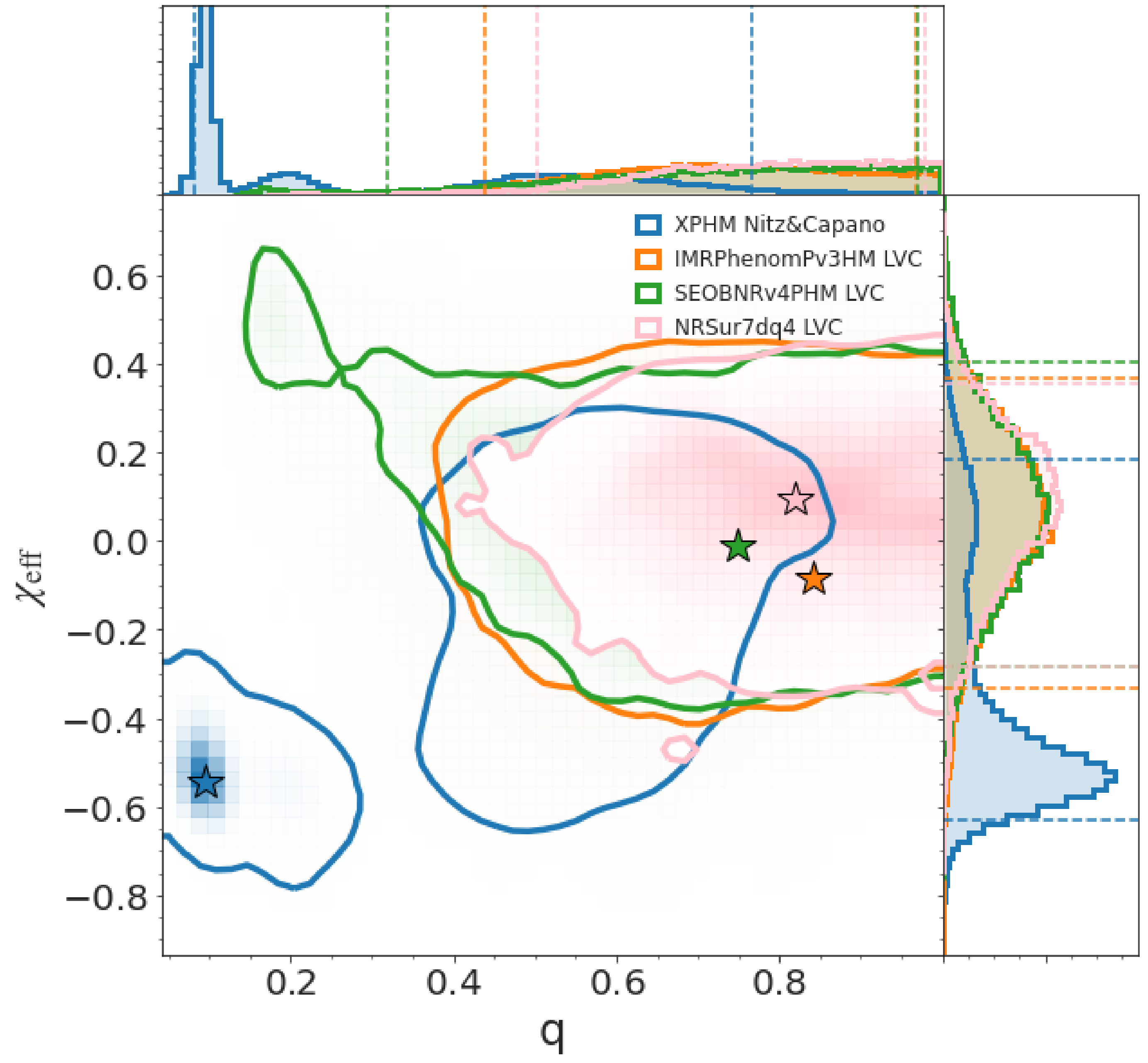
A different picture?

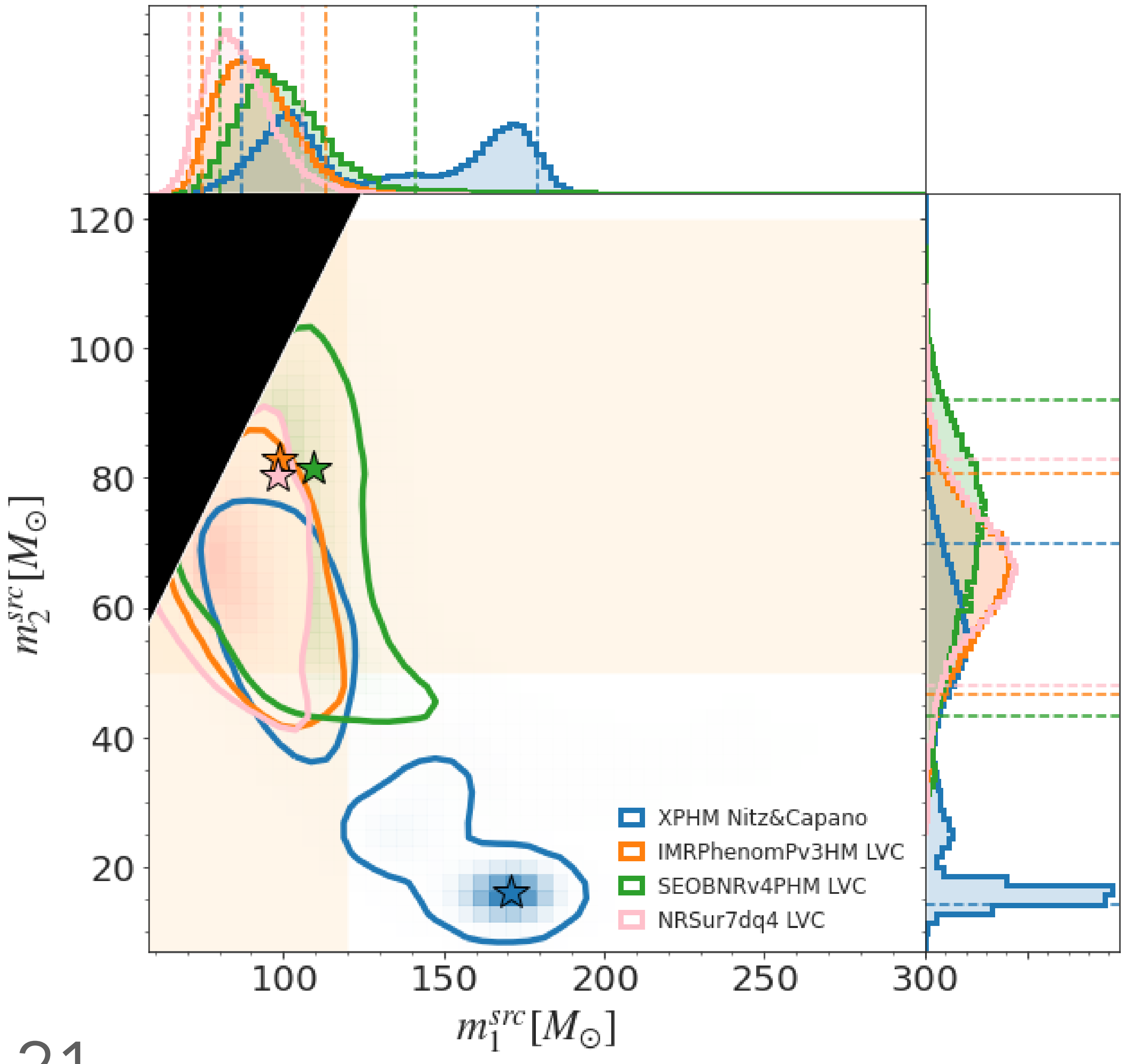
- New analysis finds additional modes and max likelihood sample around q~0.1
- These modes correlates with a strongly negative $\chi_{\rm eff}$
- The source masses of the small-q modes lie outside the PISN mass gap
- Question: how much of this depends on choice of

  - priors

  - specific waveform model

  - sampler settings





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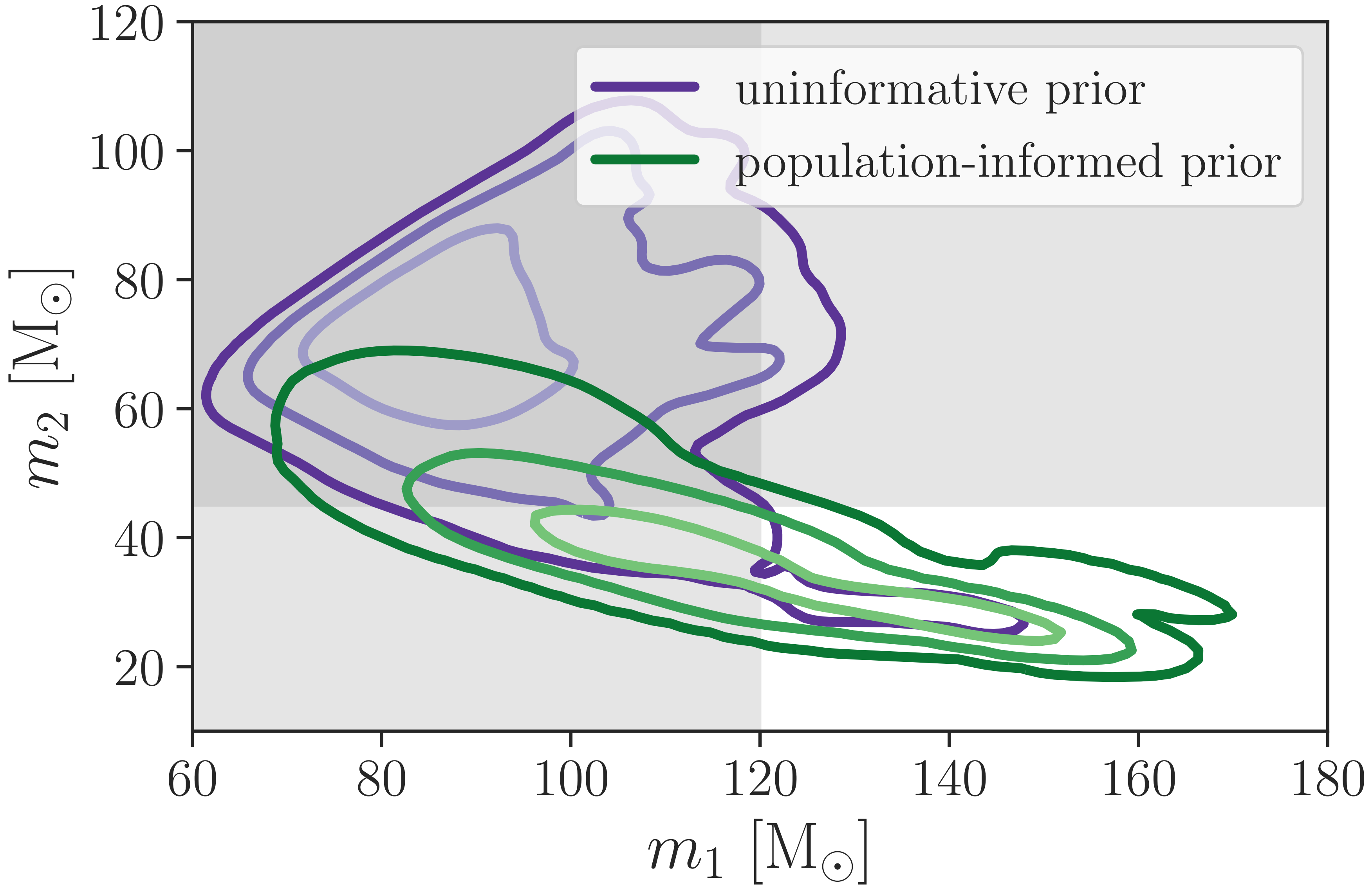
The importance of priors

- *Nitz&Capano*: priors used in early analyses led to undersample small-q region
- *Fishbach&Holz*: merger rate of systems involving a mass-gap component is expected to be very low → impose a population-informed prior: assume the secondary belongs to previously observed population → components can no longer confidently placed inside PISN mass-gap
- Need also to consider the presence of 2G generation BHs! (Kimball + 20, depend on cluster escape velocity)

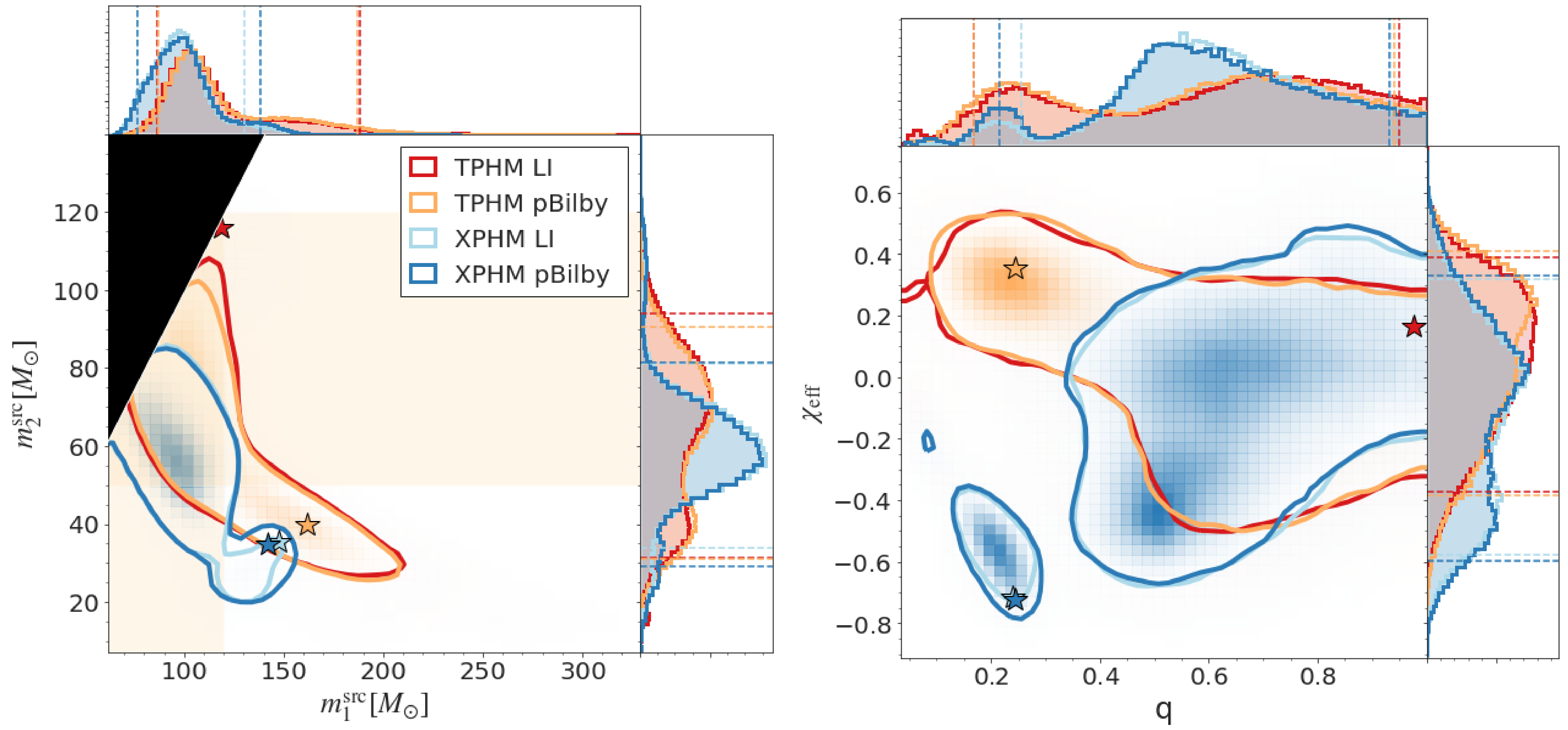


Fishbach&Holz, 2020 *ApJL* **904** L26

Analysis settings

- Study the effect of different priors. E.g. different mass ratio priors, some of which enhance the small-q region of par space (restricted priors, uniform in 1/q)
- Reweight posteriors to meaningfully compare different results
- Repeat the runs with different sampling codes (LALInference and pBilby), varying sampler settings to test robustness

TD-FD comparison



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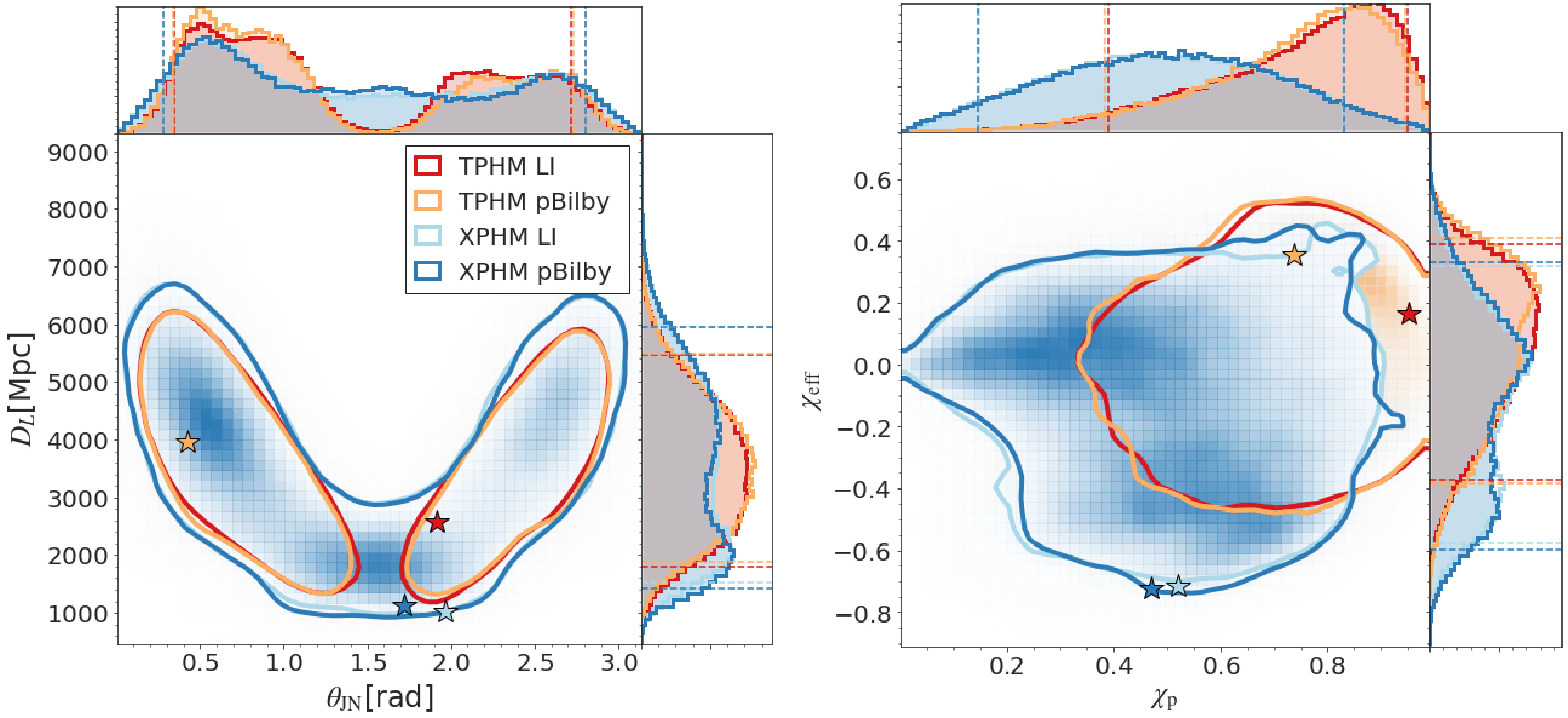
- We have analysed the event both with TD and FD Phenom models
- We find evidence for a $q \approx 0.2$ mode that correlates with positive (negative) effective spins when running TD (FD) models: no clear support for more extreme mass ratios
- Position of $\max \mathscr{L}$ sample highly variable

Comparison TD-FD cc.ed



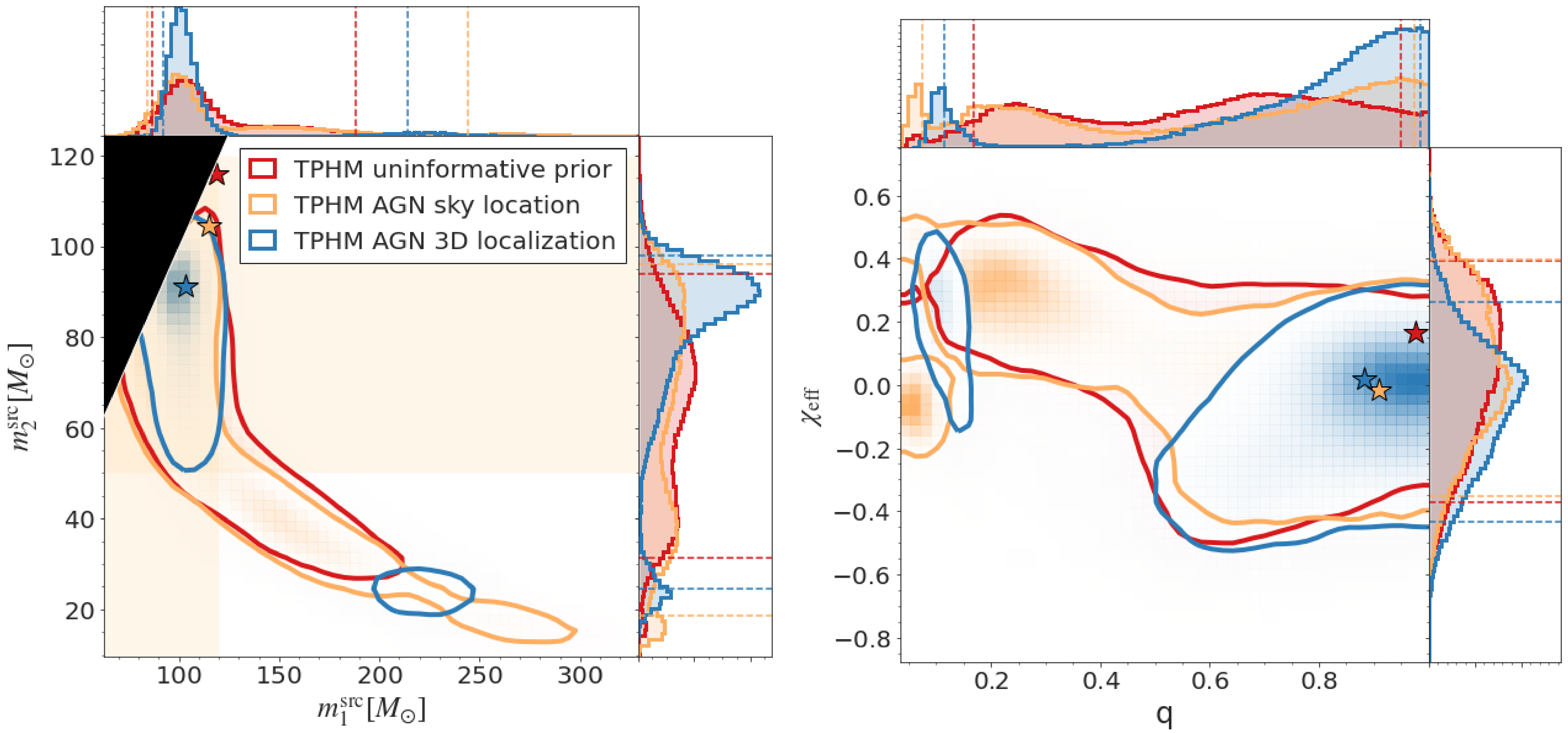
- Adding precession helps to break the degeneracy between distance and inclination only for the TD model (and also in a higher BF)
- TD model predicts rather high precession spin!

Association with an AGN flare

- There was a tentative association between GW190521 and the flare ZTF19abanrhr (Graham+ 20), generally deemed inconclusive (Ashton+ 20, Palmese+20)

- Nonetheless, we study the impact on posteriors of constraining the source sky localisation (interesting in the prospect of future multi-messenger observations)

- We confirm the results of Ashton et al.: only mild evidence of association



Mass-gap hypothesis

Waveform Model	NRSur7dq4	Pv3HM	v4PHM	XPHM (NC)	XPHM	TPHM $\ell \leq 4$	TPHM $\ell \leq 5$
Primary BH mass m_1	85^{+21}_{-14}	90^{+23}_{-16}	99^{+42}_{-19}	129^{+46}_{-37}	97^{+34}_{-21}	109^{+80}_{-22}	107^{+68}_{-20}
Secondary BH mass m_2	66^{+17}_{-18}	65^{+16}_{-18}	71^{+21}_{-28}	32^{+33}_{-17}	59^{+22}_{-25}	65^{+28}_{-34}	68^{+26}_{-33}
Total BBH mass M	150^{+29}_{-17}	154^{+25}_{-16}	170^{+36}_{-23}	169^{+23}_{-20}	154^{+35}_{-16}	181^{+44}_{-27}	179^{+39}_{-25}
Binary chirp mass $\mathcal{M}$	64^{+13}_{-8}	65^{+11}_{-7}	71^{+15}_{-10}	55^{+14}_{-16}	64^{+15}_{-10}	71^{+16}_{-11}	72^{+16}_{-11}
Mass-ratio $q = m_2/m_1$	$0.79^{+0.19}_{-0.29}$	$0.73^{+0.24}_{-0.29}$	$0.74^{+0.23}_{-0.42}$	$0.23^{+0.46}_{-0.14}$	$0.61^{+0.32}_{-0.36}$	$0.63^{+0.32}_{-0.46}$	$0.66^{+0.29}_{-0.46}$

- Intrinsic difficulty: boundaries of the gap are very uncertain, complex dependence on reaction rates and aspects of stellar evolution and dynamics (Woosley 2016, Farmer +20, Woosley&Heger 21,Mehta+ 21).
- We test two possible ranges, a "low" gap $[50,120]M_\odot$ and a "high" gap $\approx [70,160]M_\odot$
- Probability of at least one mass in the gap is generally above 70% for the "low" gap and and above 85% for the "high gap"

Conclusions

- We do expect systematic differences among different template families, due to specific modelling assumptions: need to understand better their extent and impact on PE (more injections, waveform comparison etc…)
- Strong motivation to develop models incorporating more physics: e.g. eccentricity (see Toni's talk)
- Phenomenological models are under constant improvement: stay tuned!