Universitat de les Illes Balears
IAC3 Institute of Applied Computing & Community Code.

Re-analysis of GWTC-1 with a new generation of phenomenological waveform models.

Goal: systematic Bayesian inference for O1 & O2 with higher modes and precession
include convergence studies and calibration uncertainty
=> state of the art parameter estimation for black hole events in GWTC-1

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Waveform models: Phenom 4th generation

- Non-precessing sector calibrated to NR, precession based on “twisting up approximation”
- Frequency domain IMRPhenomXPHM (includes XAS/XHM non-prec. and XP - no HMs)
  - Thorough update of IMRPhenom[D|HM|Pv2|Pv3|Pv3HM]
  - Modes in a co-precessing frame: [(2,|2|), (2,|1|), (3,|3|), (3,|2|), (4,|4|)]
- Time domain IMRPhenomTPHM (includes T/THM non-prec. and TP - no HMs)
  - “Take IMRPhenom FD techniques to TD”. Details: talk by Héctor at 15:35
  - Modes in co-precessing frame: [(2,|2|), (2,|1|), (3,|3|), (4,|4|), (5,|5|)]
  - Several improvements in the treatment of precession (including dropping SPA)

    => improves precession for inspiral/merger/ringdown
  - But: inspiral phase not yet as accurate as IMRPhenomX

    => improvement only for precessing + high-masses
- The fastest inspiral-merger-ringdown FD and TD models in LAL.
  - Faster models allow more systematic studies: sampler settings, priors, waveform systematics ...

GWTC-1 re-analysis: PE settings

Event	Trigger time	Duration	Low frequency	Sampling rate
GW150914	1126259462.4	8	20	2048
GW151012	1128678900.4	8	20	2048/4096
GW151226	1135136350.6	8	20	2048/4096
GW170104	1167559936.6	4	20	2048
GW170608	1180922494.5	16	20	2048/4096
GW170729*	1185389807.3	4	20	2048
GW170809*	1186302519.7	4	20	2048
GW170814*	1186741861.5	4	20	2048
GW170818*	1187058327.1	4	16	2048
GW170823	1187529256.5	4	10	2048

Tab. I: Data settings for each BBH event where * indicates that three det. data is used.

- *GWOSC data* from GWTC-1 release:
  - frame files, PSDs and cal. env.
  - Low mass events -> |m| = 3,4 can reach freq. > *1024 Hz*.
    - PSDs: BayesWave with 16kHz data @ sampling rate 4096 Hz.
    - Calibration Envelopes: Extrapolation to 2kHz (O1) + plot extract. from public DCC (O2).
    - Our GW151226 results are in tension with Chia+ and Nitz+ who use lower sampling rate.
- Performed *364* runs (slurm on RES machines) using different PhX* and PhT* waveform models - automatisation code.
- Sampling settings:
  - Parallel Bilby (PB)/Dynesty *with dist. marg.,* default: *nlive = 2048, nact = 30 (+ convergence tests). (walks = 200, maxmcmc = 15k)*
  - For low mass events we cross-check our results with LALInference/MCMC (LI) with 60 chains.
- Our priors mix choices from LVC + bilby catalogs. Also test cosmological distance prior for selected events and 1/q and q ≤ 0.4 (GW151226) mass priors to increase resolution for very unequal masses.

GWTC-1 re-analysis: BBH summary

- Differences between IMRPhenomPv2 and IMRPhenomXPHM are small but also interesting (*JS divergence < 0.045 bits*).
- In our new runs, there is a small *shift toward positive χ_{eff}* values for events which have negative or small positive χ_{eff}.
- Broad consistency with previous HM results for GW170729, but TPHM has higher BF and shifts support toward more *unequal masses.*

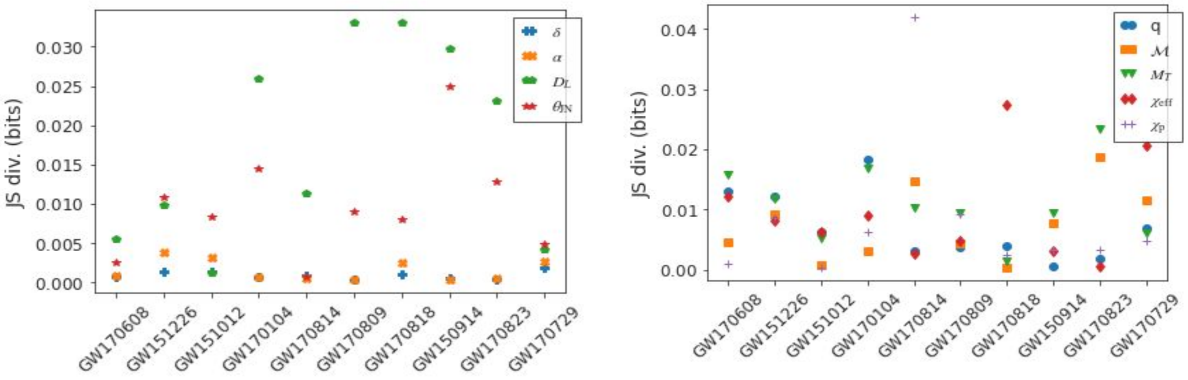


Fig. I: JS div. comparison between PhPv2 and PHXPHM posteriors.

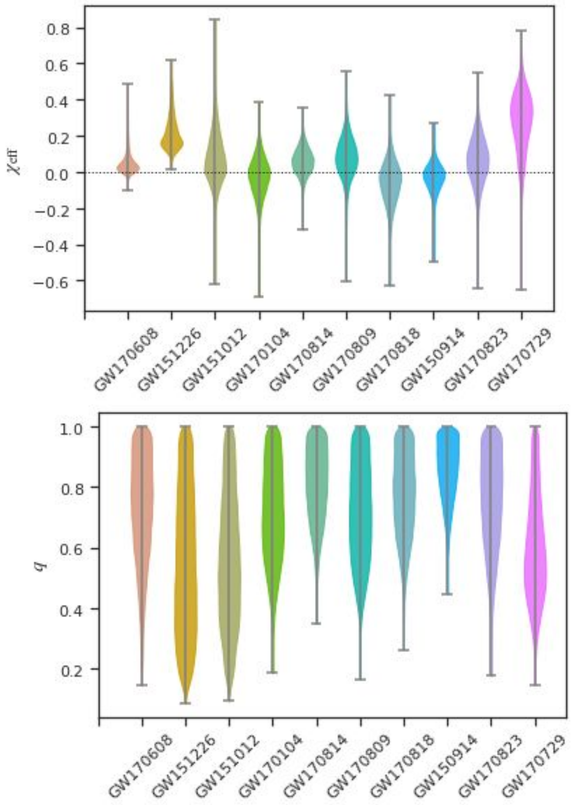


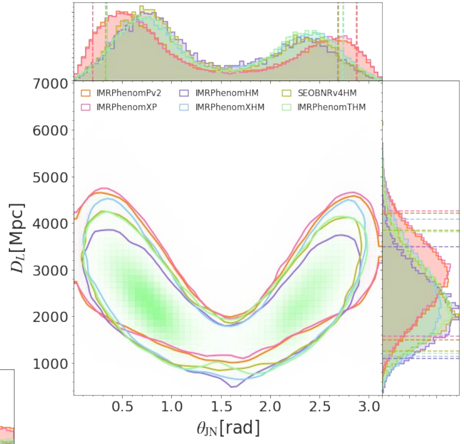
Fig. II: Violin plots of χ_{eff} and mass ratio PhXPHM posteriors.

GW170729 I

Hypotheses	Model properties	PhenomX	PhenomT/X
HM vs $\ell = 2 = \lvert m \rvert$	aligned	$2.27^{+0.48}_{-0.40}$	$2.43^{+0.51}_{-0.42}$
	precessing	$1.35^{+0.29}_{-0.24}$	$2.92^{+0.63}_{-0.52}$

Tab. II: BF table comparison between HM and dominant models for GW170729.

- Most massive and distant event of the 1st catalog.
- First systematic study of *HM content* with different models in *Chatziioannou+*
  - *22-mode* WF recovers *lower q and D_L* values.
  - *HM + Precessing* WF recover more evidence for *unequal masses* - especially TPHM.
- *TPHM*: *likelihood* values and *BF* higher than XPHM, BF = $2.16^{+0.47}_{-0.39}$.



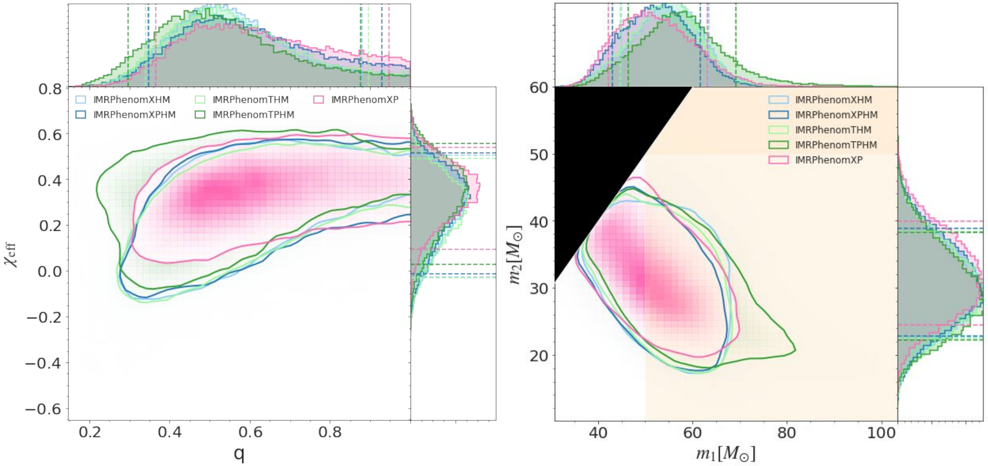
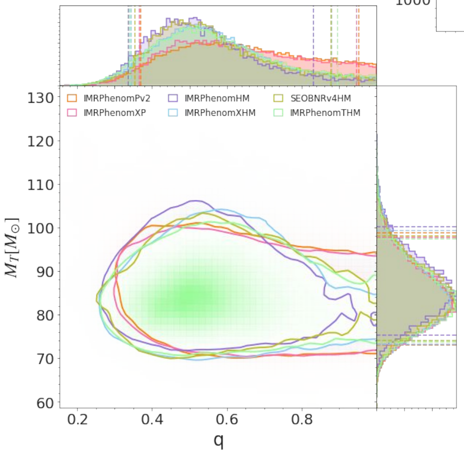


Fig. III: Posterior distributions of GW170729.



GW170729 II

- Study the influence of the distance and mass prior choices in higher mass events in order to check for similar multimodalities as in GW190521 - see Marta's talk.*
  - Distance priors:
    - Proportional to D_L^2 - expansion of the universe neglected.
    - Uniform in the comoving volume and source frame time.
  - Mass priors:
    - Uniform in component masses - LI sampling
    - Flat in component masses.
    - Flat in mass ratio $m_1/m_2 \geq 1$ and detector frame total mass.*

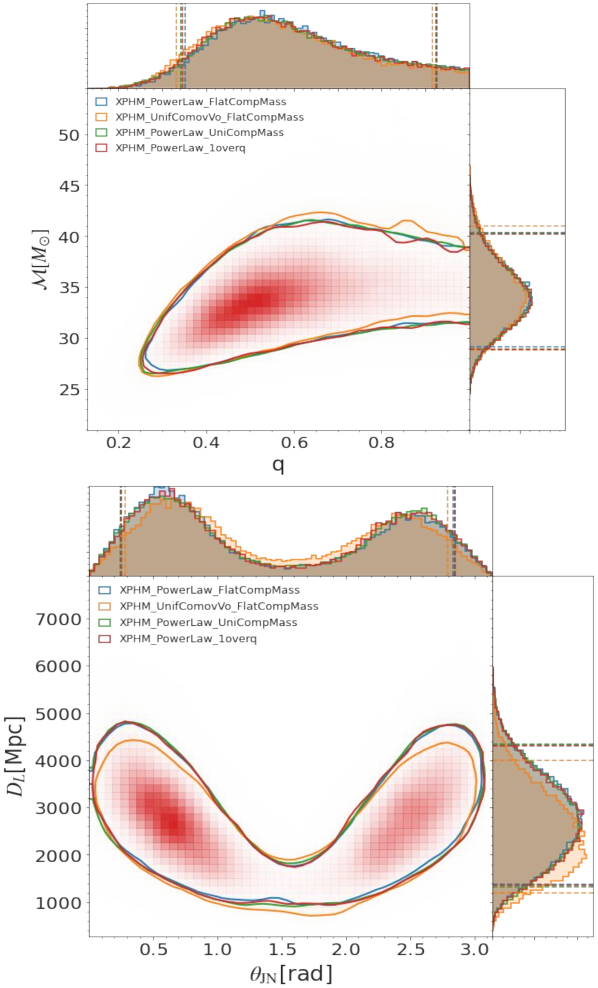


Fig. IV: Comparison between different prior choices for GW170729..

GW151226

- Chia+ (srate=1024 Hz) and Nitz+ (srate=2048 Hz) reported multimodal posteriors in tension with our results (also mutually in tension).
- Are we lacking resolution on our nested sampling?
- Cross-check of convergence: confirm our standard PB runs with mcmc LI. Also differences between sampling rates are broadly consistent with Nitz et al. results (labeled as 3-OGC). Comparing results using different PSDs estimations would be interesting.

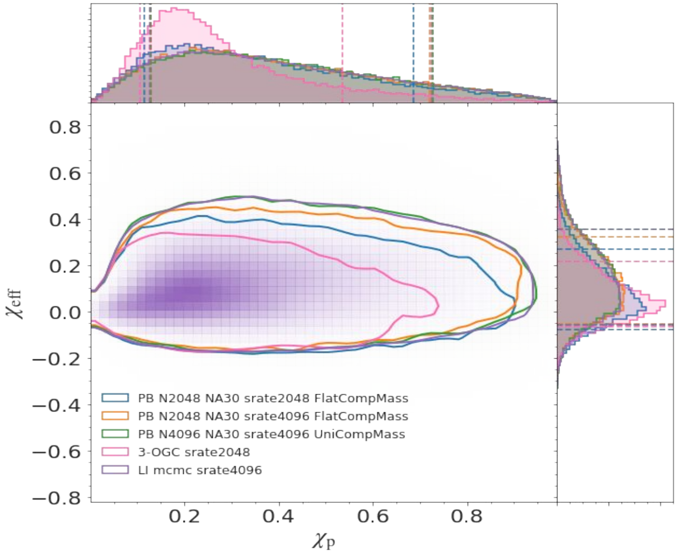


Fig. V: LI and PB posterior distributions for χ_{eff} and χ_p of GW151226 comparing srates.

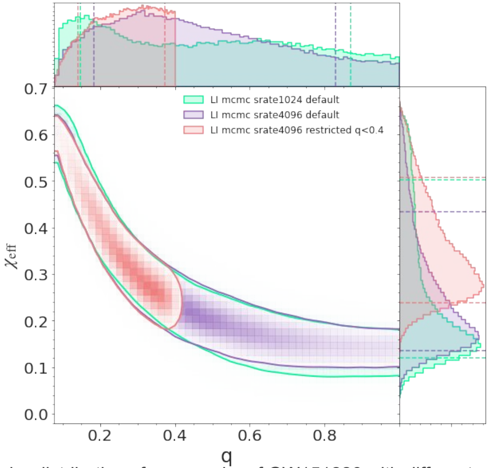


Fig. VI: LI posterior distributions for χ_{eff} and q of GW151226 with different priors and srates.

- Finally we reproduce Chia+ bimodalities in the mass ratio with LI mcmc lowing the srate to 1024 Hz. Restricting the prior to q ≤ 0.4 to improve the sampling in the more unequal mass ratios, gives support to higher spins but does not produce a secondary peak in the mass ratio.

Precession?

- Adding HM GW151226 shifts χ_p toward higher values.
- In GW170814 PhTPHM recovers higher χ_p and χ_{eff} . Also gets higher BF comparing to PhXPHM.
- In the LVC paper GW170818 has $\chi_{eff}<0$. Using PhX* and PhT*, χ_{eff} is *shifted toward zero.*

Tab. III: BF table comparison.

	GW151226	GW170814	GW170818
XP vs XAS	$3.63^{+0.86}_{-0.69}$	$0.77^{+0.18}_{-0.15}$	$2.27^{+0.53}_{-0.43}$
XPHM vs XHM	$3.85^{+0.92}_{-0.74}$	$0.80^{+0.19}_{-0.16}$	$2.54^{+0.60}_{-0.48}$
TPHM vs THM	-	$3.66^{+0.89}_{-0.71}$	$2.22^{+0.52}_{-0.42}$
TPHM vs XPHM	-	$3.48^{+0.85}_{-0.68}$	$0.63^{+0.15}_{-0.12}$

Mild support for precession.

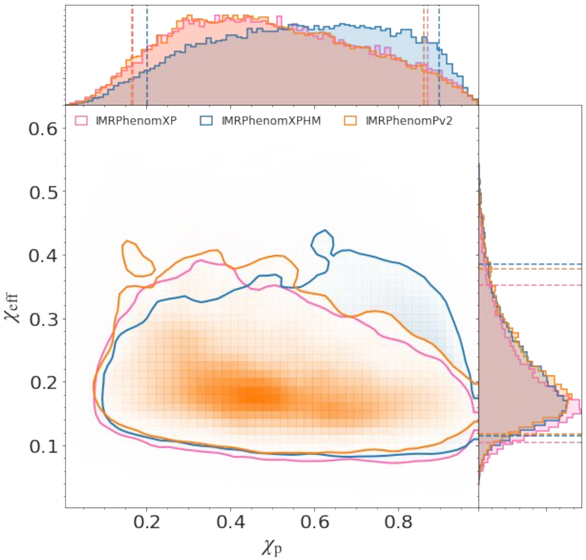


Fig. VII: Posterior distributions for the χ_{eff} and χ_p of GW151226.

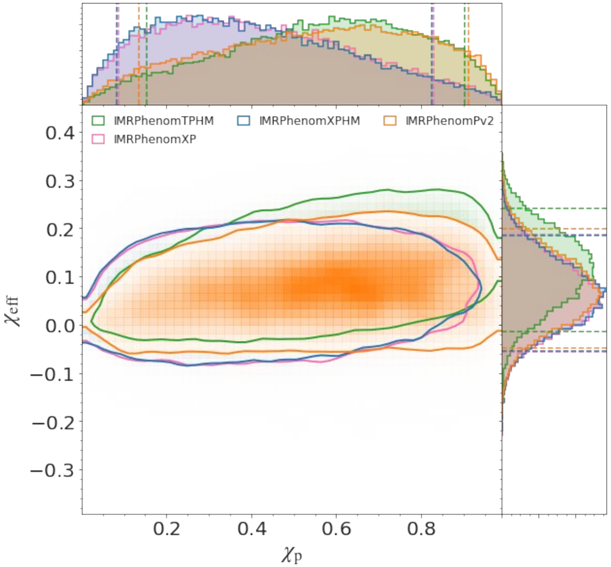


Fig. VIII: Posterior distributions for χ_{eff} and χ_p of GW170814.

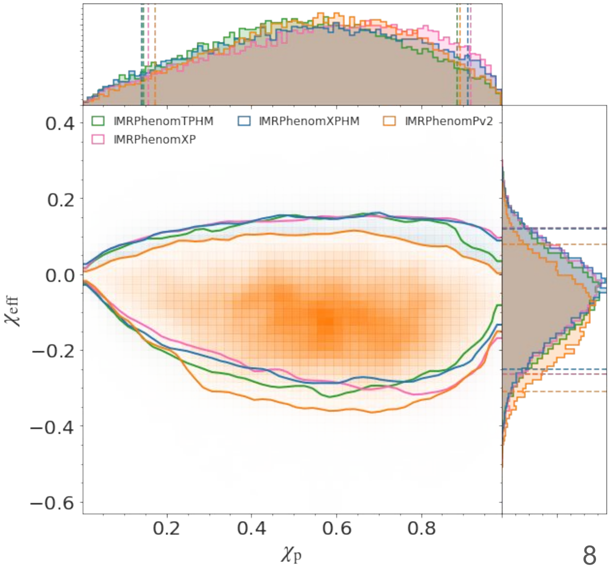
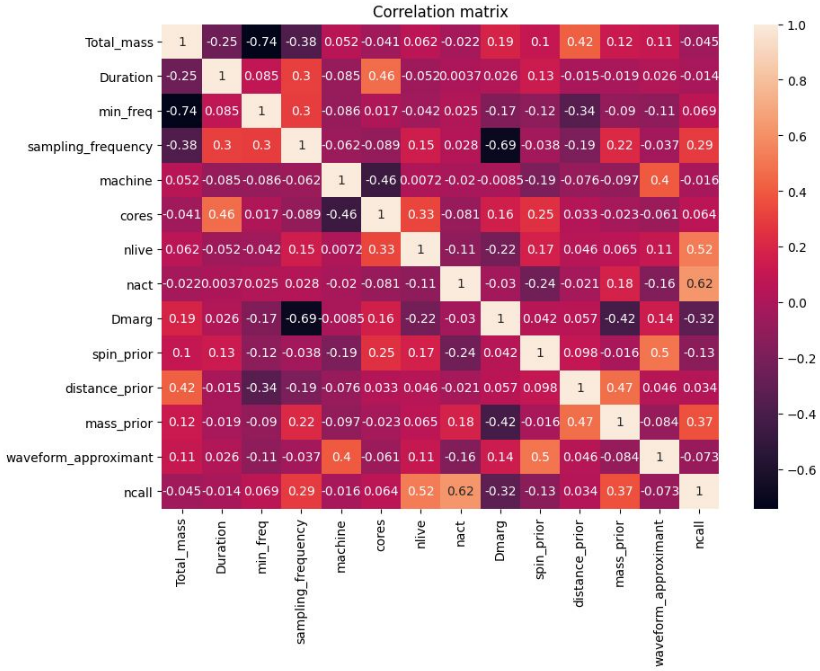


Fig. IX: Posterior distributions for χ_{eff} and χ_p of GW170818.

Better understanding of the PE samplers

- Predicting the number of likelihood evaluations of future runs using a ML regressor model - helps to *optimise the queue time* requests.
- Using a dataset of 471 PE Bilby runs (GWTC-1, GW190412 and GW190521 re-analysis) of 4 seeds each - a total of *1884 examples*.
- Correlated features:
    1. Total mass of the event.
    2. The machine and number of cores used in the parallelisation.
    3. Sampler settings (nlive, nact, marginalisation).
    4. Priors used.
    5. Waveform model, sampling rate, minimum frequency and duration.

Fig. X: Correlation matrix between features and labels.



BaggingRegressor(n_estimators=1000, cv=5) Training dataset (90%) - test dataset (10%)

Mean Relative Error: 7%

Conclusions

- Presented state of the art PE results for GWTC-1 BBHs - HMs + precession.
- Using these new accurate and fast WF model we can compare different prior choices and study the sampling convergence.
- We also perform extensive comparisons of PhenomX (incl. different precession versions) and PhenomT. PhenomXPHM gives slightly larger BF for smaller masses, TPHM favored for more massive events due to improved treatment of precessing merger/ringdown: GW170729 and also GW170814 (support for prec.)
- The results overall is very consistent with previous PhenomPv2. Some interesting deviations with higher modes/model updates, e.g. increased χ_{eff} for events with previously negative χ_{eff}.
- A reduced sampling rate implies a lower cutoff frequency corresponding to the Nyquist frequency and will reduce the mode content, e.g. in GW151226 produces bimodalities in the results.
- We build a large dataset useful to understand the behaviour of PE samplers.

Aknowledgments

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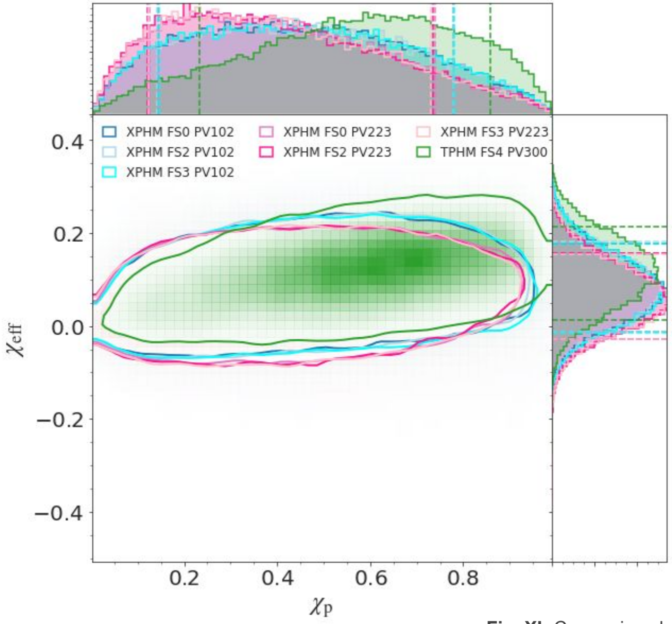
Extra slides - IMRPhenomXPHM versions

- IMRPhenomXPHM implementation has several final spin prescriptions and two different Euler angles approximations, MSA (PV = 223, default) and NNLO (PV = 102). We test them for all the events.
- For GW170814 we found that the NNLO Euler angles recover higher χ_p and BF comparing to the default MSA.



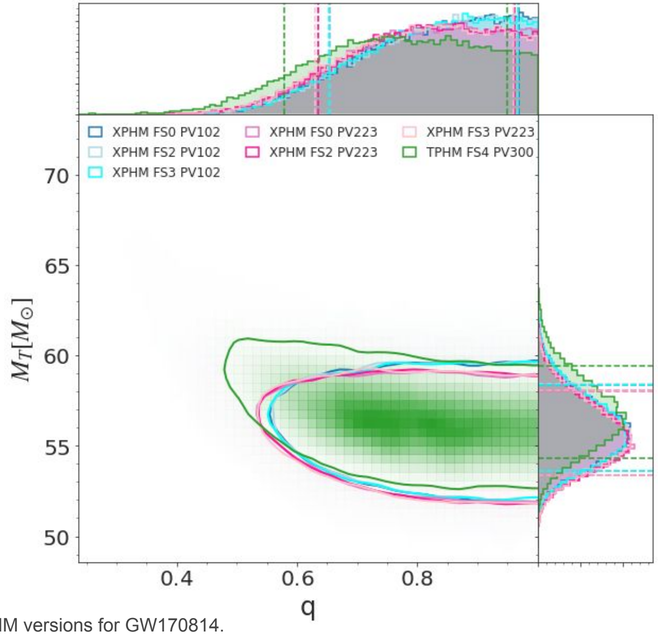


Fig. XI: Comparison between IMRPhenomXPHM versions for GW170814.

Extra slides - Multibanding interpolation

- IMRPhenomXPHM implement the multibanding (MB) interpolation method which controls the accuracy of the non-precessing modes and PMB which controls the accuracy of the Euler angles evaluation.
- This interpolation accelerates the evaluation of the model but with less accuracy.

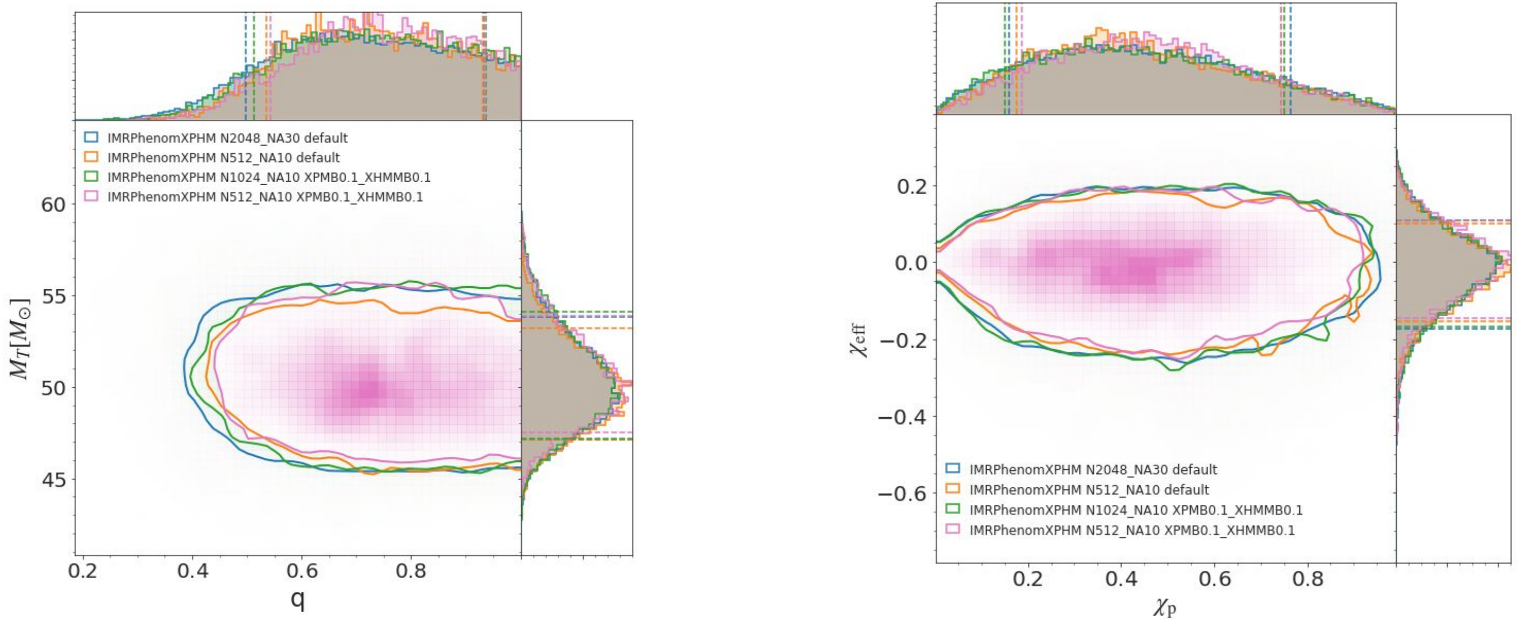


Fig. XII: Comparison between different MB thresholds