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

11th Iberian GW meeting
June 2021

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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

- **GWOSC data** from GWTC-1 release:
  - frame files, PSDs and cal. env.
  - Low mass events -> $|m| = 3,4$ can reach freq. $> 1024 \text{ Hz}$.
    - PSDs: BayesWave with 16kHz data @ sampling rate 4096 Hz.
    - Calibration: 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 $q \leq 0.4$ (GW151226) mass priors to increase resolution for very unequal masses.

<table>
<thead>
<tr>
<th>Event</th>
<th>Trigger time</th>
<th>Duration</th>
<th>Low frequency</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>1126259462.4</td>
<td>8</td>
<td>20</td>
<td>2048</td>
</tr>
<tr>
<td>GW151012</td>
<td>1128678900.4</td>
<td>8</td>
<td>20</td>
<td>2048/4096</td>
</tr>
<tr>
<td>GW151226</td>
<td>113513650.6</td>
<td>8</td>
<td>20</td>
<td>2048/4096</td>
</tr>
<tr>
<td>GW170104</td>
<td>1167559936.6</td>
<td>4</td>
<td>20</td>
<td>2048</td>
</tr>
<tr>
<td>GW170608</td>
<td>1180922494.5</td>
<td>16</td>
<td>20</td>
<td>2048/4096</td>
</tr>
<tr>
<td>GW170729</td>
<td>1185389807.3</td>
<td>4</td>
<td>20</td>
<td>2048</td>
</tr>
<tr>
<td>GW170809</td>
<td>1186302519.7</td>
<td>4</td>
<td>20</td>
<td>2048</td>
</tr>
<tr>
<td>GW170814</td>
<td>1186741861.5</td>
<td>4</td>
<td>20</td>
<td>2048</td>
</tr>
<tr>
<td>GW170818</td>
<td>1187058327.1</td>
<td>4</td>
<td>16</td>
<td>2048</td>
</tr>
<tr>
<td>GW170823</td>
<td>1187529256.5</td>
<td>4</td>
<td>10</td>
<td>2048</td>
</tr>
</tbody>
</table>

* indicates that three det. data is used.

**Envelopes:**
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 $\chi_{\text{eff}}$ values for events which have negative or small positive $\chi_{\text{eff}}$.
- 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 $\chi_{\text{eff}}$ and mass ratio PhXPHM posteriors.
GW170729 I

- 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 = $2.16^{+0.47}_{-0.39}$.

<table>
<thead>
<tr>
<th>Hypotheses</th>
<th>Model properties</th>
<th>PhenomX</th>
<th>PhenomT/X</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM vs $\ell = 2 =</td>
<td>m</td>
<td>$</td>
<td>aligned</td>
</tr>
<tr>
<td></td>
<td>precessing</td>
<td>$1.35^{+0.59}_{-0.24}$</td>
<td>$2.92^{+0.63}_{-0.52}$</td>
</tr>
</tbody>
</table>

*Fig. III: Posterior distributions of GW170729.*

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

- Finally we **reproduce** Chia+ bimodalities in the mass ratio with LI mcmc lowing the srate to 1024 Hz. Restricting the prior to $q \leq 0.4$ 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 $x_p$ toward higher values.
- In GW170814 PhTPHM recovers higher $x_p$ and $x_{\text{eff}}$. Also gets higher BF comparing to PhXPHM.
- In the LVC paper GW170818 has $x_{\text{eff}} < 0$. Using PhX* and PhT*, $x_{\text{eff}}$ is shifted toward zero.

**Fig. VII:** Posterior distributions for the $x_{\text{eff}}$ and $x_p$ of GW151226.

**Fig. VIII:** Posterior distributions for $x_{\text{eff}}$ and $x_p$ of GW170814.

**Fig. IX:** Posterior distributions for $x_{\text{eff}}$ and $x_p$ of GW170818.

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**Tab. III: BF table comparison.**

<table>
<thead>
<tr>
<th></th>
<th>GW151226</th>
<th>GW170814</th>
<th>GW170818</th>
</tr>
</thead>
<tbody>
<tr>
<td>XP vs XAS</td>
<td>3.63$^{+0.86}_{-0.89}$</td>
<td>0.77$^{+0.18}_{-0.15}$</td>
<td>2.27$^{+0.55}_{-0.43}$</td>
</tr>
<tr>
<td>XPHM vs XHM</td>
<td>3.85$^{+0.62}_{-0.74}$</td>
<td>0.80$^{+0.19}_{-0.16}$</td>
<td>2.54$^{+0.48}_{-0.48}$</td>
</tr>
<tr>
<td>TPHM vs THM</td>
<td>3.66$^{+0.89}_{-0.74}$</td>
<td>2.27$^{+0.55}_{-0.43}$</td>
<td>3.48$^{+0.85}_{-0.66}$</td>
</tr>
<tr>
<td>TPHM vs XPHM</td>
<td>-</td>
<td>3.48$^{+0.85}_{-0.66}$</td>
<td>0.63$^{+0.15}_{-0.12}$</td>
</tr>
</tbody>
</table>

Mild support for precession.
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**.

![Correlation matrix between features and labels.](image)

**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 $\chi_{\text{eff}}$ for events with previously negative $\chi_{\text{eff}}$.
- 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.
Acknowledgments

This work was supported by European Union FEDER funds, the Ministry of Science, Innovation and Universities and the Spanish Agencia Estatal de Investigación grants FPA2016-76821-P, RED2018-102661-T, RED2018-102573-E, FPA2017-90687-REDC, Vicepresidència i Conselleria d’Innovació, Recerca i Turisme, Conselleria d’Educació, i Universitats del Govern de les Illes Balears i Fons Social Europeu, Generalitat Valenciana (PROMETEO/2019/071), EU COST Actions CA18108, CA17137, CA16214, and CA16104, and the Spanish Ministry of Education, Culture and Sport grants FPU15/03344 and FPU15/01319. M.C. acknowledges funding from the European Union’s Horizon 2020 research and innovation programme, under the Marie Skłodowska-Curie grant agreement No. 751492 and from the Spanish Agencia Estatal de Investigación, grant IJC2019-041385. D.K. is supported by the Spanish Ministerio de Ciencia, Innovación y Universidades (ref. BEAGAL 18/00148) and cofinanced by the Universitat de les Illes Balears. The authors thankfully acknowledge the computer resources at MareNostrum and the technical support provided by Barcelona Supercomputing Center (BSC) through Grants No. AECT-2019-2-0010, AECT-2019-1-0022, from the Red Española de Supercomputación (RES). Authors also acknowledge the computational resources at the cluster CIT provided by LIGO Laboratory and supported by National Science Foundation Grants PHY-0757058 and PHY-0823459. This research has made use of data obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO is funded by the U.S. National Science Foundation. Virgo is funded by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale della Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by Polish and Hungarian institutes.
**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 $\chi_r$ 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