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)
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.
A different picture?

- New analysis finds additional modes and max likelihood sample around \( q \approx 0.1 \)
- These modes correlate with a strongly negative \( \chi_{\text{eff}} \)
- 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
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)
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

- 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 $\mathcal{L}$ sample highly variable
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$^{+14}_{-14}$ | 90$^{+21}_{-16}$ | 99$^{+42}_{-19}$ | 129$^{+26}_{-37}$ | 97$^{+24}_{-21}$ | 100$^{+30}_{-22}$ | 107$^{+48}_{-28}$ |
| 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 $M$           | 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$^{+0.32}_{-0.36}$ | 0.65$^{+0.32}_{-0.46}$ | 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!