Parameter Estimation of the most significant subsolar mass candidate in O2

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Based on arXiv:2301.11619

Zooming in on PBHs

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General Motivation for SSM

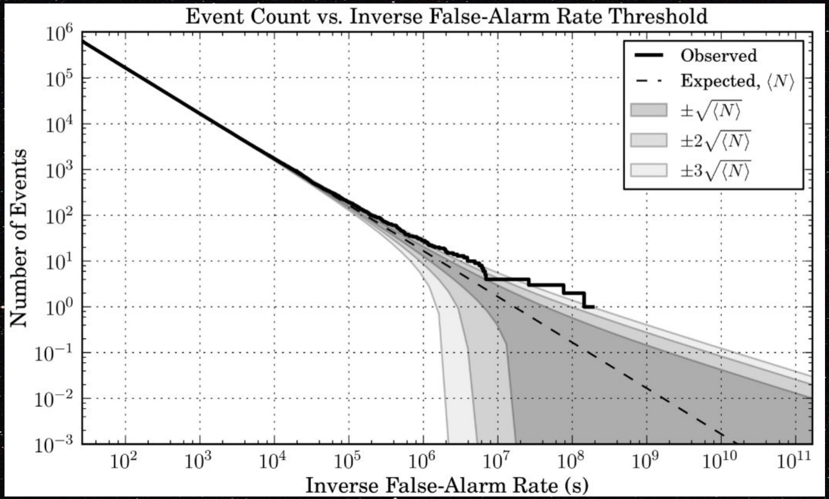
- LIGO-Virgo are sensitive to the GWs emitted by CBCs with SSM components. We should look for them!

- No widely accepted astrophysical channels predict the formation of subsolar-mass (SSM) objects significantly more compact than white dwarfs

- Detection of SSM compact objects would be a smoking gun for new physics. Some possible scenarios are:
  - Primordial Black Holes (PBHs)
  - "Dark" black holes formed by collapse of dissipative particle dark matter
  - Boson stars, which are ultralight bosonic fields clumped together in compact objects. If $m_B \gtrsim 10^{-10} eV/c^2$, they have to be subsolar

Motivation & Search

- Proof of readiness for PE in subsolar region
- Follow up to the SSM search of Phukon et al. (2021)
- GstLAL search in O2 data extending the LVK SSM search to more extreme mass ratios (q≥0.1)
- Investigate lowest FAR multiple detector trigger using
  - Improved modelling (TaylorF2 ⟶ IMRPhenomXPHM)
  - More data (45Hz/12s ⟶ 20Hz/128s)
  - Clean data & BayesWave PSD



FAR [yr^{-1}]	$\ln \mathcal{L}$	UTC time	mass 1 [$M_\odot$]	mass 2 [$M_\odot$]	spin1z	spin2z	Network SNR	H1 SNR	L1 SNR
0.1674	8.457	2017-03-15 15:51:30	3.062	0.9281	0.08254	-0.09841	8.527	8.527	-
0.2193	8.2	2017-07-10 17:52:43	2.106	0.2759	0.08703	0.0753	8.157	-	8.157
0.4134	7.585	2017-04-01 01:43:34	4.897	0.7795	-0.05488	-0.04856	8.672	6.319	5.939
1.2148	6.589	2017-03-08 07:07:18	2.257	0.6997	-0.03655	-0.04473	8.535	6.321	5.736

Significance of SSM170401

- The candidate was found in data taken on April 1st 2017, during O2
- Network signal-to-noise ratio (SNR) of 8.67 and false-alarm rate (FAR) of $0.4134\mathrm{yr}^{-1}$
  This gives a FAP of

$$\mathrm{FAP} = 1 - \exp\{-\mathrm{FAR} \cdot T_{\mathrm{obs}}\} = 0.12$$

- We can estimate upper bound for P_{CBC} using O3 SSM event rates (arXiv:2212.01477)
  $\mathcal{R}_{90} \sim 2 \times 10^2 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, and the volume-time surveyed for these masses is
  $\langle VT \rangle \sim 3 \times 10^{-3} \mathrm{Gpc}^3\mathrm{yr}$. Using the fact that the arrival of GW to the detectors is Poisson distributed with parameter $\mu = \mathcal{R}\langle VT \rangle$ and the probability of finding n events

$$P(n) = \frac{\mu^n}{n!} e^{-\mu}$$

  the probability of finding one or more events at 90% C.L. is

$$1 - P_{90}(0) \sim 0.45$$

Candidate SSM170401

- Chirp mass reported by the search: $\mathcal{M} = 1.57\mathrm{M}_{\odot}$

- Predicted time in the detector from 20Hz: 104s $\longrightarrow$ We analyze 128s of H1 and L1 data

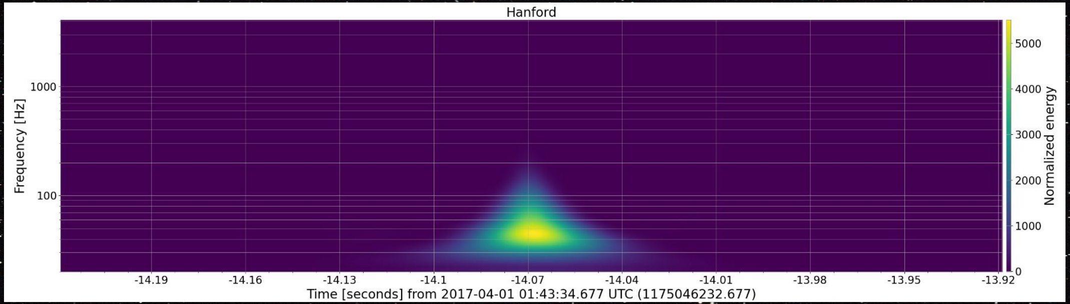
- The search chirp mass is very similar to a vanilla BNS. If we want to investigate the SSM nature we have to precisely determine the mass ratio (we need $q<0.28$ to have an SSM component)

- We use standard BBH priors, uniform in component masses and comoving volume

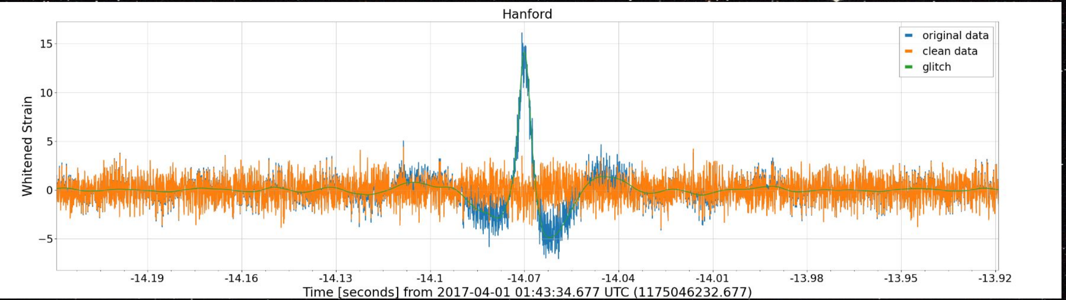
- There was a large blip glitch in Hanford 14s before coalescence. It didn't (probably) affect the search as the template duration was 12s, however for PE it has to be removed since we study 128s of data

Glitch identification & subtraction

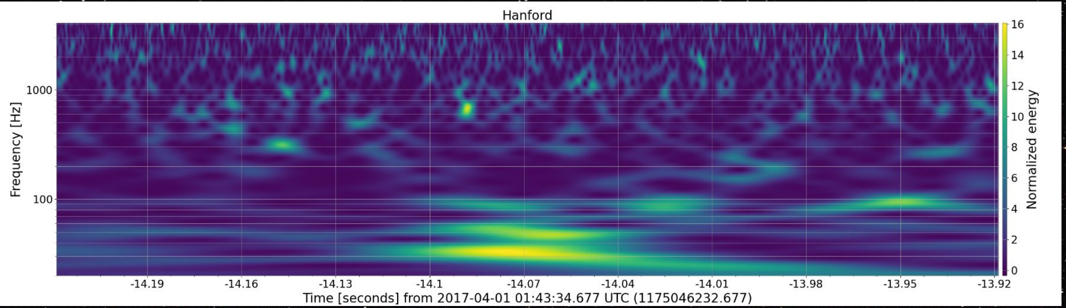
- Original spectrogram:



- Bayeswave subtraction:

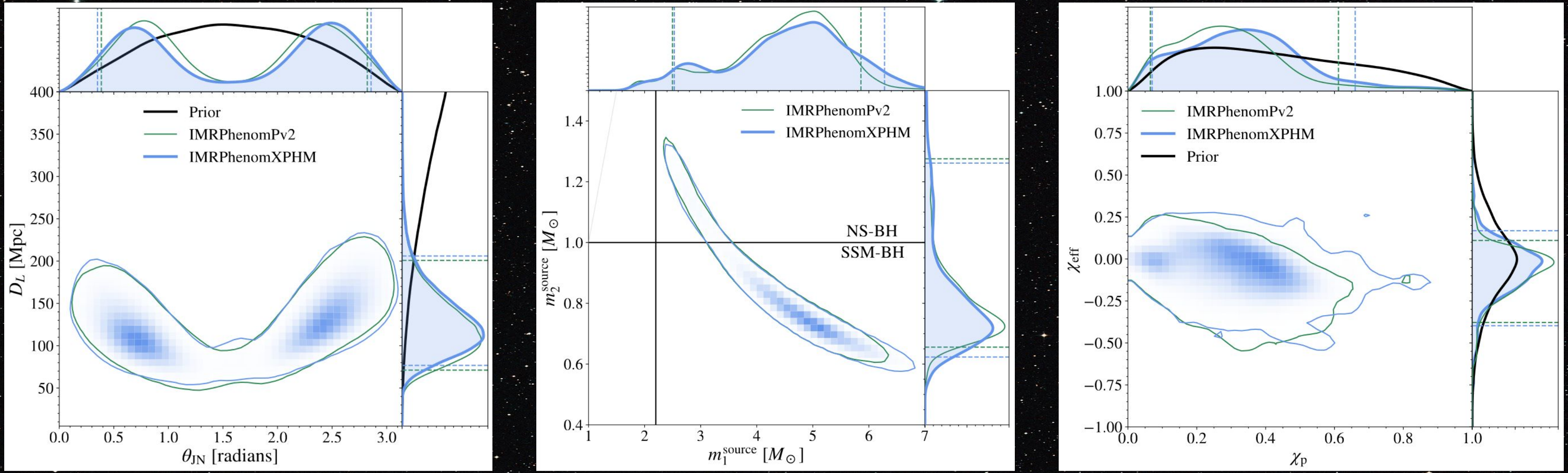


- Clean spectrogram:



Posterior PDFs

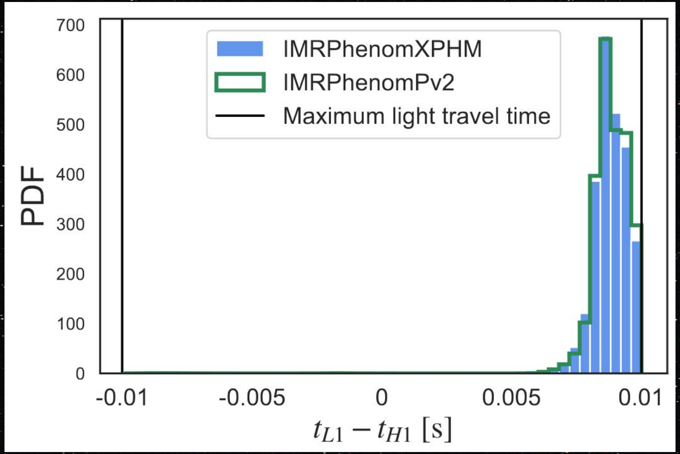
- Using ***LALInference_mcmc***, median Network matched filter SNR ~ 8
- Posterior probability of m_2 being subsolar is 84% in XPHM and 86% in Pv2
- Luminosity distance posterior peaked at ~120Mpc
- Spins largely unconstrained, with slight preference for low spins

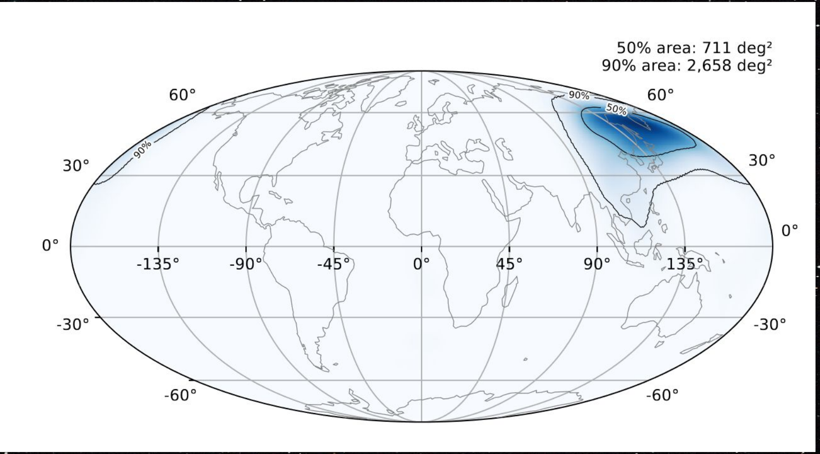


Position in the sky & time delay

- Unusual blob-like shape (Position in the sky usually has ring-like shape for H1L1 detections)
- Time delay between L1 and H1 close to maximum light travel time ($\theta = \pi/2$)

$$\Delta t_{L-H} = \frac{\vec{d}_{H-L} \cdot \hat{n}}{c} = \frac{d_{H-L}}{c} \cos\theta$$





Coherence test

- Test proposed in Veitch 2010
- Use individual detector data to obtain

$$\mathcal{B}^{(i)} = Z^{(i)} / Z^{(i)}_{\text{noise}}$$

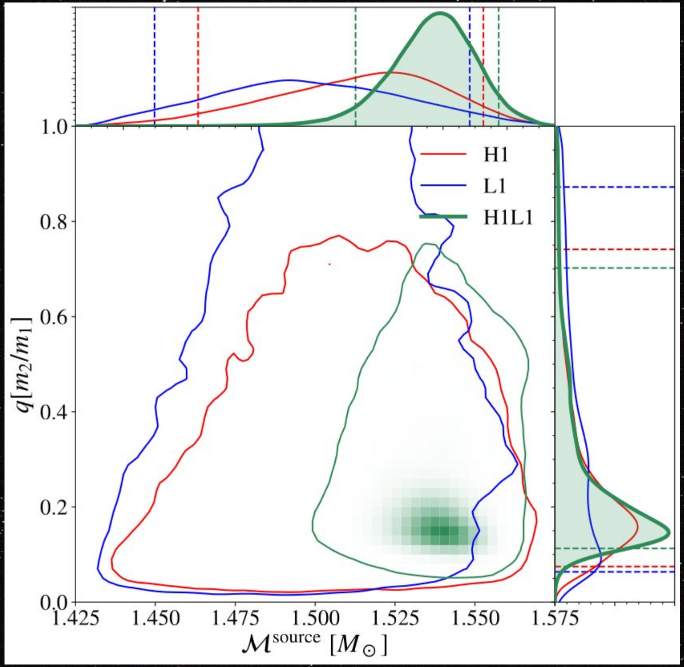
- Use data from all detectors simultaneously to calculate

$$\mathcal{B}_{\text{coh}} = Z_{\text{coh}} / \prod_{i=1}^{N} Z^{(i)}_{\text{noise}}$$

- Compute coherent vs incoherent evidence

$$\mathcal{B}_{\text{coh,inc}} = \frac{\mathcal{B}_{\text{coh}}}{\prod_{i=1}^{N} \mathcal{B}^{(i)}}$$

- H1 and L1 posteriors compatible with H1L1
- Strong evidence for coherence



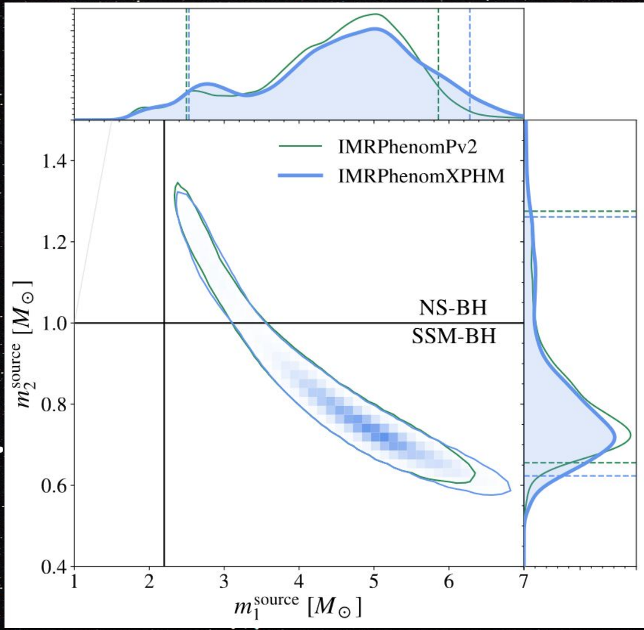
Posteriors using {H1,L1,H1L1}

$\log \mathcal{B}_{H1L1}$	$\log \mathcal{B}_{H1}$	$\log \mathcal{B}_{L1}$	$\log \mathcal{B}_{\text{coh,inc}}$
7.00 ± 0.10	1.56 ± 0.07	0.48 ± 0.06	4.96 ± 0.13

Table with results

Possible interpretation

- For 16% of the posterior we have $m_1 > 2.2M_\odot$ and $m_2 > 1.0M_\odot$, i.e. masses compatible with an NS-BH.
  - The primary would be a BH in the mass gap
  - The secondary could be a NS or a BH



- For 84% of the posterior we have $m_1 > 2.2M_\odot$ and $m_2 < 1.0M_\odot$, i.e. masses compatible with an SSM-BH.
  - The primary can be in the mass gap or above
  - The secondary is an SSM black hole.

- In all cases, astrophysical models have problems generating a system with these masses

Conclusion

- We perform PE follow up to the most significant candidate of the SSM search of Phukon et al. (2021)
- PE parameters show broad agreement with the search and compatibility with a SSM candidate
- Posterior probability of m_2 being subsolar is 84% in XPHM and 86% in Pv2
- Strong evidence for coherent signal in H1L1
- Show readiness of pipelines to perform PE on subsolar candidates!

Backup slides

Gelman-Rubin $\hat{R}$ diagnostics

- As implemented in the ArviZ package based on the paper: arXiv:1903.08008
- The diagnostic is computed by:

$$\hat{R} = \frac{\hat{V}}{W}$$

where $\hat{W}$ is the within-chain variance and $\hat{V}$ is the posterior variance estimate for the pooled rank-traces. This is the potential scale reduction factor, which converges to unity when each of the traces is a sample from the target posterior. Values greater than one indicate that one or more chains have not yet converged.

- The empirical threshold usually employed is $\hat{R} \leq 1.01$