Probing the connection between short gamma ray bursts and binary coalescing systems through gravitational waves

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Motivation for study

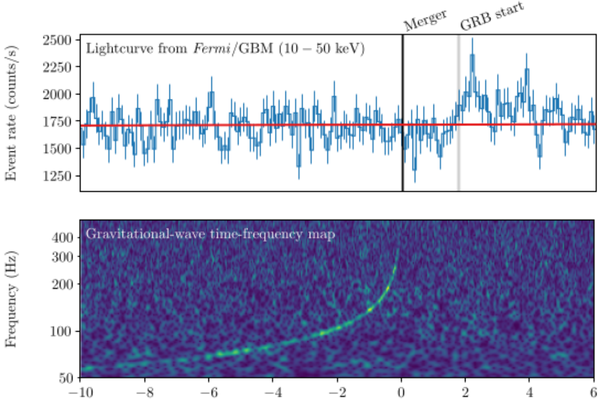
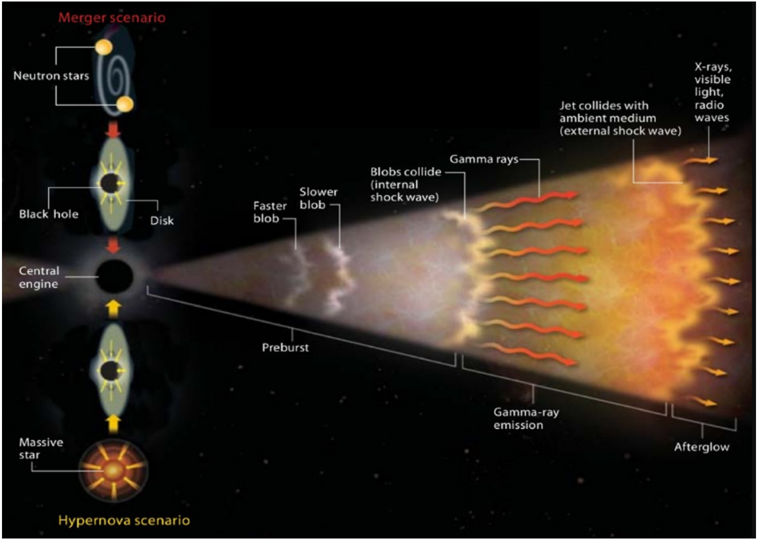


Figure: Fermi GBM light curve of GRB170817A above a time frequency map of GW170817 generated from LIGO Hanford and Livingston. A joint detection rate of 0.1 - 1.4 yr^{-1} between LIGO and Fermi GBM was predicted. At LIGO's design sensitivity this climbed to 0.3 - 1.7 yr^{-1}data.[1]

Motivation for study

- To date, the events of GW170817/GRB170817A has been the only joint detection of its kind so far.
- During LIGOS 2nd and 3rd observing runs O2 and O3, a second BNS merger GW190425 and Black Hole Neutron Star (BHNS) mergers GW200115_042309, GW200210_092254, GW190917_114636 were detected[2]. All of these events could be possible sources for a GRB. No EM counterpart for these events were detected.
- This study aims to find an explanation for the lack of joint detections through the O2 and O3 runs.

The Hypothesis



Gravitational waves

- Gravitational waves are travelling perturbations in spacetime caused by the acceleration of massive bodies. General relativity predicts the existence of 2 tensor polarisation modes:

$$h_+(t) = -\frac{1+\cos^2\iota}{2}\left(\frac{\mathcal{G}\mathcal{M}}{c^2 D}\right)\left(\frac{t_c - t}{5\mathcal{G}\mathcal{M}/c^3}\right)^{-1/4}\cos(2\phi_c - 2\phi(t-t_c;M,\mu))$$

$$h_\times = -\cos\iota\left(\frac{\mathcal{G}\mathcal{M}}{c^2 D}\right)\left(\frac{t_c - t}{5\mathcal{G}\mathcal{M}/c^3}\right)^{-1/4}\sin(2\phi_c + 2\phi(t-t_c;M,\mu))$$

- The GW strain as seen by a particular detector is given by

$$h(t) = h_+(t-t_c-t_0)F_+(\alpha,\delta,\Psi,t) + h_\times t - t_c - t_0)F_\times(\alpha,\delta,\Psi,t) \qquad (1)$$

1

[1] reference [3]

Gravitational waves

- For short duration signal F_+ and $F_\times$ are nearly constant. The GW strain seen by a particular detector can then be written as

$$h(t) = -\left(\frac{\mathcal{GM}}{c^2 D_{eff}}\right)\left(\frac{t_0 - t}{5\mathcal{GM}/c^3}\right)^{-1/4} \cos(2\phi_0 + 2\phi(t - t_0; M, \mu)) \qquad (2)$$

- ϕ_0 is the termination phase which is given by the relation

$$2\phi_0 = 2\phi_c - \arctan\left(\frac{F_\times}{F_+}\frac{2\cos\iota}{1+\cos^2\iota}\right) \qquad (3)$$

- and D_{eff} is the effective distance given by

$$D_{eff} = D\left[F_+^2\left(\frac{1+\cos^2\iota}{2}\right)^2 + F_\times \cos^2\iota\right]^{-1/2} \qquad (4)$$

2

[2] reference [3]

Analysing detector data

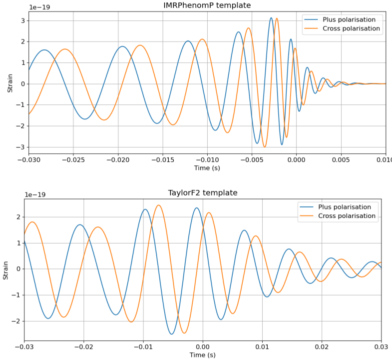


Figure: Gravitational waveform templates used in this study

Bayes theorem

- For a set of observations $\mathbf{d} = (d_1, ..., d_n)$ and set of unknown parameters $\boldsymbol{\theta} = (\theta_1, ..., \theta_n)$, the probability density of the values of $\boldsymbol{\theta}$ given the data $\mathbf{d}$ is given by:

$$p(\boldsymbol{\theta}|\mathbf{d}) = \frac{L(\mathbf{d}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\mathcal{Z}} = \frac{L(\mathbf{d}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\int L(\mathbf{d}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})d\boldsymbol{\theta}} \tag{5}$$

- where $L(\mathbf{d}|\boldsymbol{\theta})$ is the likelihood function of $\mathbf{d}$ given $\boldsymbol{\theta}$. $\pi(\boldsymbol{\theta})$ is the prior probability density functions and $\mathcal{Z}$ is the marginalised likelihood .
- By choosing a likelihood, a model for the GW is implicitly chosen. For example, a Gaussian likelihood for GW astronomy is given by

$$L(\mathbf{d}|\boldsymbol{\theta}) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2}\frac{(\mathbf{d} - h(\boldsymbol{\theta})^2}{\sigma^2}\right) \tag{6}$$

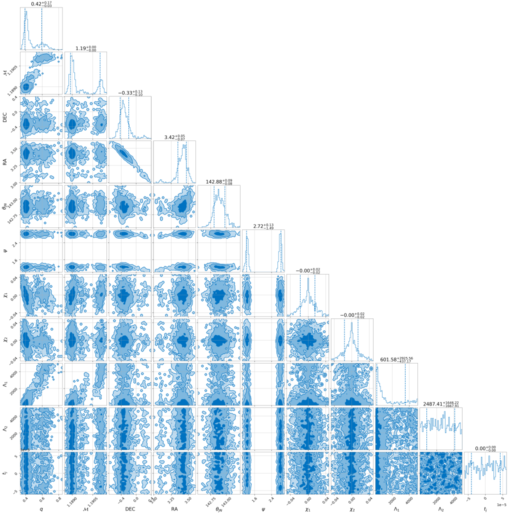
3

[3] reference [4]

Methodology

- For this study we performed Bayesian inference on the following GW events: GW170817, GW190425 (BNS events), GW190917_114636, GW200210_092254, GW2000115_042309 (BHNS events)
- We perform Bayesian inference using Bilby which is python based Bayesian inference library for GW astronomy [5]
- GW170817 has an observed EM counterpart GRB170817A. As a result, the inclination angle is well constrained. To test how effective pure GW analysis is using Bilby, we aim to obtain similar values for the inclination angle through pure GW analysis.
- In order to perform Bayesian analysis, we define a prior giving the distribution of the waveform parameters. Following convention, we set up two priors that represent a low spin and high spin case for the merger.

GW170817: Results (TaylorF2_Lowspin)



GW190425

- This is a BNS mereger detected by a single detector (Livingston). The Hanford detector was offline during the event
- Component masses are $m_1 = 2.1 \pm^{0.5}_{0.4}\ \mathrm{M}_{\odot}$ and $m_2 = 1.3 \pm^{0.3}_{0.2}$
- No trigger in the Virgo detector
- To analyse this event, the same set of waveform templates used on GW170817 were utilised(TaylorF2,IMRPhenomP,IMRPhenomD).
- 2 different low spin case priors were used with one having a uniform distribution between 0° and 90°
- For the high spin case a uniform distribution between 0° and 180° was chosen.

GW200115 and GW190917

- GW200115_042309 and GW190917 are BHNS events detected all through the LVC network with component masses.
- To analyse the signal a high or low spin prior case was not considered. Instead we considered a case of precessing spins with no consideration for tidal deformities in the neutron star.
- In this study we only made use of the gravitational waveform IMRPhenomP which is a waveform template that allows spin precession
- A new prior accommodating spin precession as well as the distance considerations was then set up

Summary of results

Gravitational wave	Waveform	$\mathcal{M}$ $(\mathrm{M}_\odot)$	mass ratio
GW170817	IMRPhenomP	$1.20^{+0.0}_{-0.0}$	$0.83^{+0.11}_{-0.11}$
	TaylorF2	$1.19^{+0.0}_{-0.0}$	$0.42^{+0.17}_{-0.03}$
	IMRPhenomD	$1.20^{+0.0}_{0.0}$	$0.83^{+0.11}_{-0.11}$
	LIGO result	1.19	$(0.4, 0.8)$
GW190425	IMRPhenomP	$1.47^{+0.02}_{-0.0}$	$0.43^{+0.40}_{-0.05}$
	TaylorF2	$1.47^{+0.00}_{-0.03}$	$0.45^{+0.39}_{-0.05}$
	IMRPhenomD	$1.47^{+0.02}_{-0.0}$	$0.45^{+0.42}_{-0.06}$
GW190917	IMRPhenomP	$2.59^{+0.39}_{-0.17}$	$0.33^{0.19}_{0.07}$
	LIIGO Result	$3.7^{+0.2}_{-0.2}$	-
GW200115	IMRPhenomP	$2.55^{+0.01}_{-0.00}$	$0.34^{+0.15}_{-0.12}$
	LIGO Result	$2.43^{+0.05}_{-0.07}$	-

Table: Chirp Mass and mass ratios estimated for events GW170817, GW190425, GW190917, GW200115

Summary of results

Gravitational wave	Waveform	Low spin	High spin
GW170817	IMRPhenomP	$155.28^{\circ}{}^{+15.99}_{-18.57}$	$152.6^{\circ}{}^{+18.65}_{-16.01}$
	TaylorF2	$142.88^{\circ}{}^{+0.9}_{-0.8}$	$152.41^{\circ}{}^{+18.65}_{-15.82}$
	IMRPhenomD	$155.21^{\circ}{}^{+15.98}_{-18.56}$	$155.57^{\circ}{}^{+15.62}_{18.82}$
	LIGO result	$146^{\circ}{}^{+25}_{-27}$	$152^{\circ}{}^{+21}_{-27}$
GW190425	IMRPhenomP	$46.54^{\circ}{}^{+28.96}_{-30.54}$	$89.04^{\circ}{}^{+63.11}_{-60.36}$
	TaylorF2	$44.64^{\circ}{}^{+29.94}_{-28.45}$	$98.03^{\circ}{}^{+58}_{-63.39}$
	IMRPhenomD	$46.09^{\circ}{}^{+30.65}_{-32.38}$	$87.95^{\circ}{}^{+62.85}_{-63.11}$
GW190917	IMRPhenomP	$107.14^{\circ}{}^{+34.37}_{67.18}$	
GW200115	IMRPhenomP	$64.74^{\circ}{}^{+63.59}_{-40}$	

Table: Inclination angles estimated for events GW170817, GW190425, GW190917, GW200115

Discussions and conclusion

- The current set of results suggests that the binaries were orientated such that detection of the emitted GRB was not possible. The hypothesis still holds
- From existing joint detection predictions, 1 in 8 BNS mergers detected by the LVC network should have a GRB counterpart. Our current set of results is still in agreement with this prediction.
- Parameter degeneracies present the biggest challenges when it comes to parameter inference (e.g mass and spin degeneracy, luminosity distance and inclination angle degeneracy)
- to overcome these degeneracies, an independent observation of the parameter through a different messenger breaks the degeneracy
- In this study, without stricter constraints on either the luminosity distance or a smaller parameter space for the parameter of interest, reducing the uncertainty in the inferred value is not possible.

References I

[1] B.P Abbott et al. "*Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A*". In: *The Astrophysical Journal Letters* 848.2 (2017), p. L13.

[2] *GWTC event portal*. Last accessed 19 April 2023. 2023. URL: https://gwosc.org/eventapi/html/GWTC/.

[3] B Allen et al. "*FINDCHIRP: An algorithm for detection of gravitational waves from inspiraling compact binaries*". In: *Physical Review D* 85.12 (2012), p. 122006.

[4] Benjamin P Abbott et al. "A guide to LIGO–Virgo detector noise and extraction of transient gravitational-wave signals". In: *Classical and Quantum Gravity* 37.5 (2020), p. 055002.

References II

[5] G Ashton et al. "BILBY: A user-friendly Bayesian inference library for gravitational-wave astronomy". In: *The Astrophysical Journal Supplement Series* 241.2 (2019), p. 27.