Improving the understanding of evolution of binary neutron stars with Einstein Telescope

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Outline

- Mass Distribution of Neutron stars (NSs)
  - Parameters leading to differences in the mass distribution.
  - Predictions from population synthesis of binaries.
  - Differences among different systems
  - Implications
- Role of merger rate density
  - How can it constrain the parameters.
  - Ability of Einstein Telescope.
- Conclusion

Survival and disruption

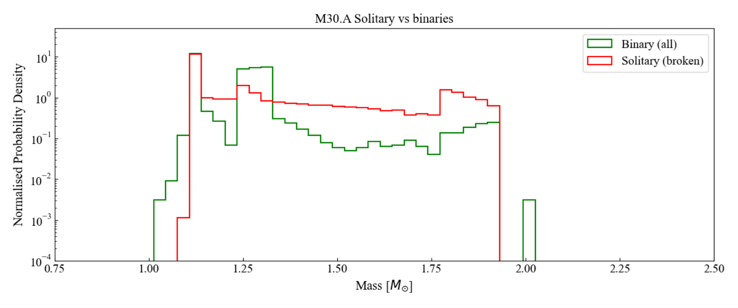
NS in a binary or solitary

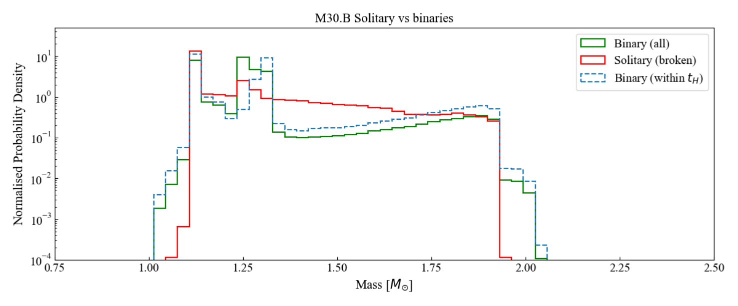
- Mass profile different for solitary NSs compared to those in binary.
- The disruption of a binary system may occur
    - asymmetric SN explosions.
    - Blaauw kick associated with symmetric mass loss leading to change in the mass ratio and in the orbital parameters.

We revisit the models generated by Belczynski et al. 2020

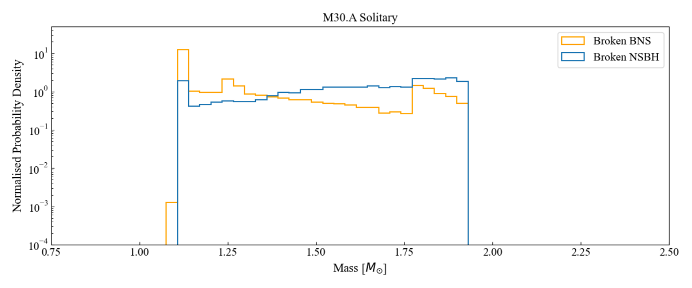
- Model M30 re-simulated to understand the disruption and the survival of BNSs.

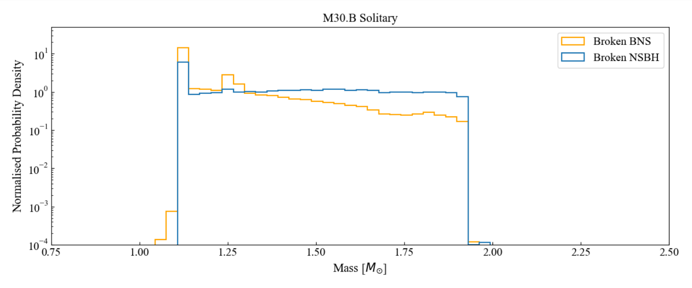
Comparison of NS mass distribution for solitary and binary





Comparison of NS mass distribution for BNS and NSBH





Note: These plots do not show evolution of mass with redshift.

Ratio of solitary(broken) binaries

Number of NSs in broken systems vs in those in a binary

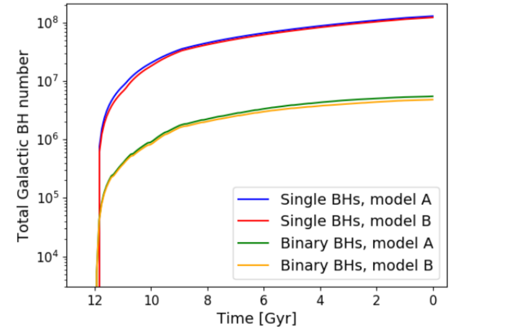
- M30.A:
  - NS(broken system) $\approx 41 \times$ NS(in all binaries)
- M30.B:
  - NS(broken system) $\approx 53 \times$ NS(in all binaries)

- Bulk of the NS population is composed of solitary (broken) neutron stars.
- Constraints on evolutionary models required to estimate the density of solitary NSs.

Solitary(broken) binaries

Similar ratios predicted by simulation for black holes in the Milky Way

- The Milky Way (disk+bulge+halo) expected to have $\sim 1.2 \times 10^8$ single BHs, and $\sim 9.3 \times 10^6$ BHs in binary systems.
- Here "single star" category single stars evolving as singular, mergers, and broken binaries.

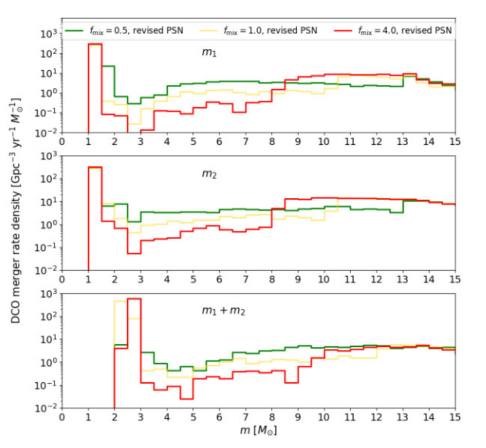


Olejak et al. (2020)

Effect of SN engine

Role of Supernova (SN) engine

- Fraction of compact objects within the lower mass gap range varies by one to two orders of magnitude with different mixing efficiencies.
- Significant parameter in understanding the origin of massive NS systems like GW190425.



Olejak et al. (2022)

Implication of these distributions

- Helps understand the formation scenarios
- Also used to constrain EOS (Holmbeck et al. (2022.))

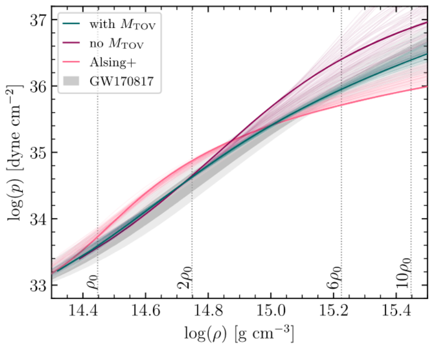


Figure 5. Posterior samples (thin lines) and maximum likelihood (thick lines) NS EOSs for the case in which a constraint on $M_{\rm TOV}$ is used (teal) and when there is no such constraint (pink). The gray band indicates the 50% (darker) and 90% (lighter) confidence intervals for the EOS inferred from GW170817.

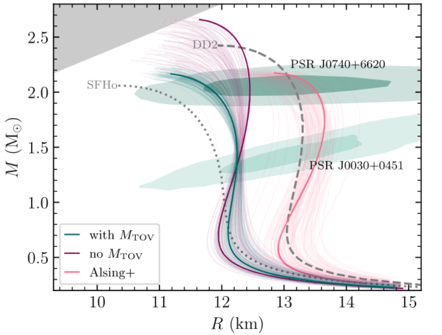


Figure 6. Posterior samples (thin lines) and maximum likelihood (thick lines) mass–radius curves for the case in which a constraint on $M_{\rm TOV}$ is used (teal) and when there is no such constraint (pink). For comparison, two existing theoretical EOSs (SFHO, dotted, and DD2, dashed) are shown, along with recent pulsar measurements from NICER (shaded contours). The upper-left gray shaded region indicates where causality is violated ($R > 2.9\,GM$).

How to constrain the evolutionary parameters

Thought process

Effect of evolutionary parameters imprinted on the mass distributions of both, solitary and binaries. Multiple degeneracies still exist.

↓

They also lead to variation of merger rate density with redshift for merging compact binaries.

↓

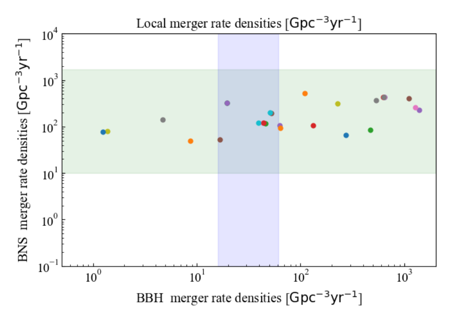
Constraining merger rate density function for binaries

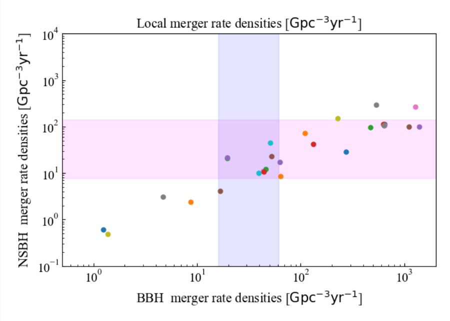
↓

Strong constraints in-turn help to break the degeneracy between evolutionary parameters

Singh et al. (2024)

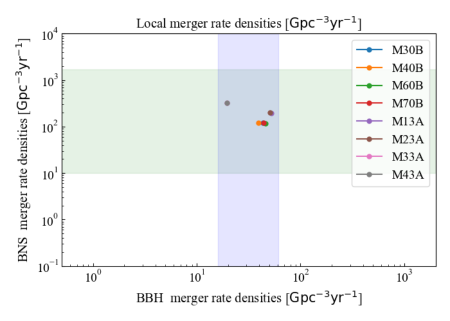
Local merger rate density: an example

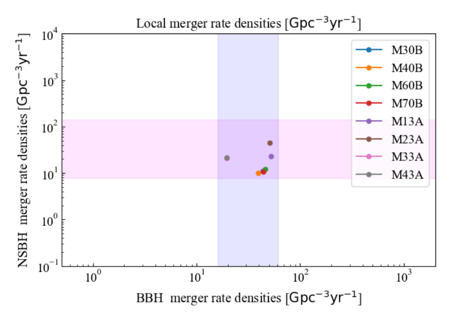




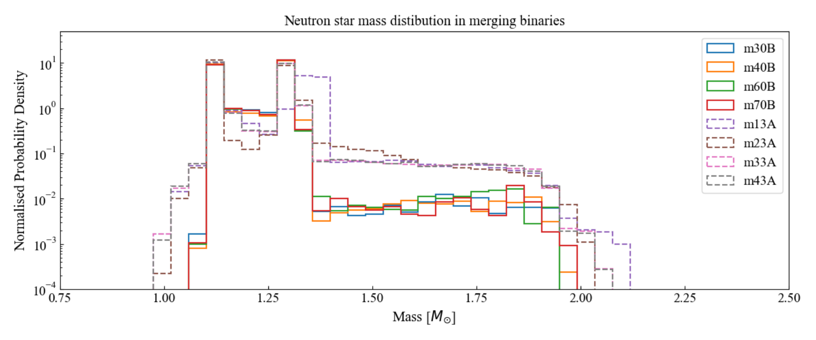
- The local merger rate density predictions from GWTC-3
- The models generated by Belczynski et al. 2020

Local merger rate density: an example





NS masses in binary systems: an example of allowed models



- A and B represent different scenarios for a binary system with a Hertzsprung gap donor star in the CE phase.(Belczynski et al. (2020)).
- In model B binaries are assumed to merge during the CE phase.
- In model A the system is assumed to have survived the CE phase.
- It is currently not well known which scenario prevails.
- Clear difference in A/B for higher mass distribution in binaries merging within t_H.

NS masses in binary systems: an example: caveats

- These particular rates assume binary fraction $f_b = 1$.
- It means that all the mass in IMF is assumed to be in binary stars.
- The rates are essentially an upper limit for the model
- Exclusion using LVK local predictions is not strong enough
  - The models predicting higher merger rate may still be *allowed* since f_b is unknown.
  - The models allowed by the the local merger rate density predictions by LVK detections, do not correctly reproduce merger rate density in older galaxies.
- Tensions between predictions still persist

Will 3G detectors be able to provide better understanding of stellar evolution?

CW search for binary neutron star

Based on Generalised Frequency-Hough in $2 - 20$ Hz regime, since the signal from a low mass could spend months at $\sim 2 - 3\text{Hz}$

Pros:

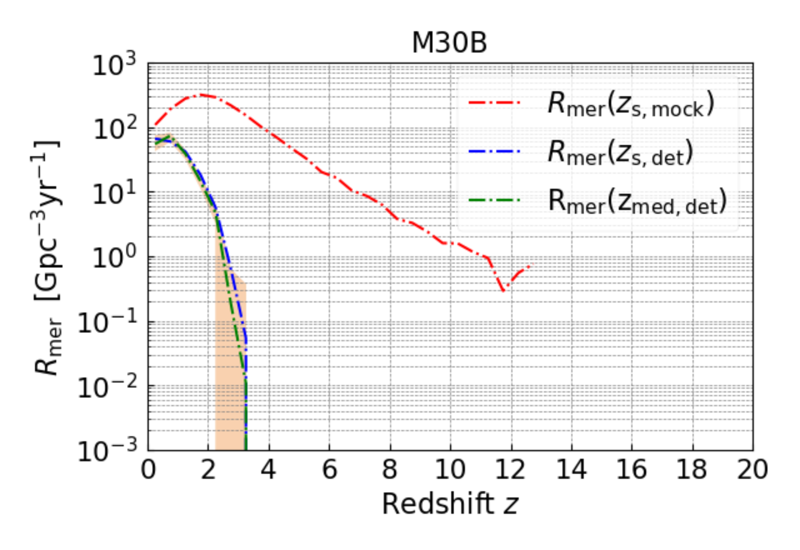
- Can warn astronomers $\sim$ 2.5 hours before a GW170817-like merger at 40 Mpc.
- Can enable multi-messenger astronomy, using only low frequencies (2 - 20 Hz),
- Would be possible to begin excluding some of the BNS models.

Cons:

- Can only provide the merger rate density upper limit up-to redshift of $z \sim 0.08$.
- Will need to observe for at least 15 years to start excluding models.

Miller et al. (2024)

CBC based search



Singh et al. (2022)

Method

True merger rate: Population-independent method

Estimate the merger-redshift of the detected population

↓

Estimate the merger rate density of the detected population

↓

Estimate the detection efficiency (How??)

↓

Estimate the true merger rate density

The detected sources provide the priors for detection efficiency estimate

Singh et al. (2024)

Method

Priors for constructing secondary population

- $p(\mathcal{M}_{\rm sec}) \propto p(\mathcal{M}_{\rm med,det})$
- $p(z_{\rm sec}) \propto p(z_{\rm med,det})$
- $M_{\rm sec} = \mathcal{M}_{\rm sec} \left[\frac{q_{\rm sec}}{(1+q_{\rm sec})^2}\right]^{-3/5}$

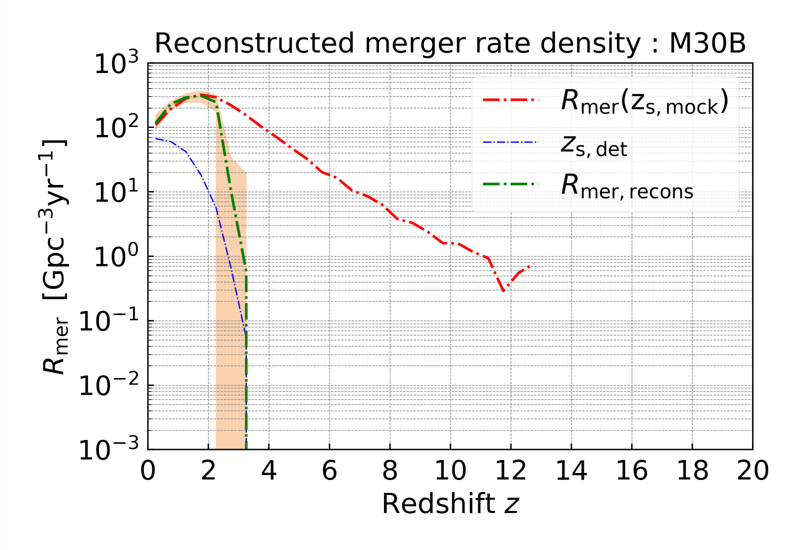
Estimating detection efficiency

- $\mathcal{D}(z_i, z_{i+1}) = \left[\frac{N_{\rm sec,det}}{N_{\rm sec}}\right]_{(z_i, z_{i+1})}$
- $R_{\rm mer,recon}(z_i, z_{i+1}) = \left[\frac{R_{\rm mer}(z_{\rm med,det})}{\mathcal{D}}\right]_{(z_i, z_{i+1})}$

Caveat: We assume that the population which is *'detected'* with the set threshold represents the true underlying population.

Singh et al. (2024)

Result



Reconstructed merger rate density : M30B
$R_{\rm mer}$ [Gpc^{-3}yr^{-1}]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10
12
14
16
18
20
Redshift z
$R_{\rm mer}(z_{\rm s,\,mock})$
$z_{\rm s,\,det}$
$R_{\rm mer,\,recons}$

Conclusion

- A population-independent method, to estimate true merger rate
- Estimates constrain models upto redshift $z \sim 2$.
- Strong constraints possible with only half an year of data.
- Model selection possible with much shorter observation time, compared to CW methods already tested.
- Stronger constraints on both solitary and binary mass distribution.
- Improved understanding of differences in evolution of BNS and NSBH evolution.
- Model selection will help in understanding SN engine, EOS, natal kicks, to name a few.

Thank you

Acknowledgement

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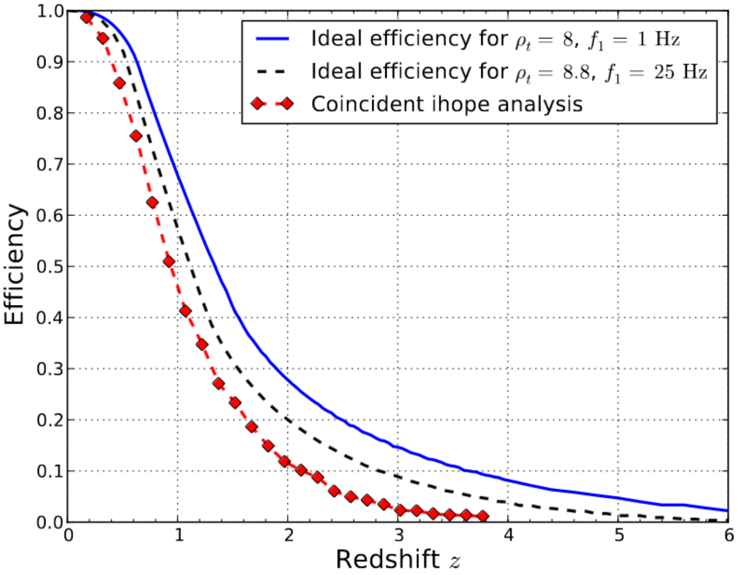
EXTRA SLIDES

Einstein Telescope: Sensitivity Curve



Einstein Telescope: Astrophysical reach

- The coalescence of compact binaries with total mass 20 - 100 $M_\odot$, as typical of BH-BH or BH-NS binaries, will be visible up to redshift $z \approx 20$ and higher.
- Facilitate probing the dark era of the Universe preceding the birth of the first stars.
- It will be able to detect BHs with masses up to several times $10^3 M_\odot$, out to $z \approx 1 - 5$.
- For NS-NS binaries, whose total mass is $\approx 3M_\odot$, ET will reach $z \approx 2 - 3$.
- **The corresponding detection rates will be, of order $10^5 - 10^6$ BH-BH and 7×10^4 NS-NS coalescences per year.**

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Useful instrument for population studies !!

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Useful instrument for population studies !!

Need to break $\mathcal{M} - z$ degeneracy

Michele Maggiore et al JCAP03(2020)050

Compact Binaries: Strain

The strain in the detector :

$$h(t) = F_+\left(\boldsymbol{\theta}, \boldsymbol{\phi}, \boldsymbol{\psi}, t\right) h_+(t + t_c - t_0) + F_\times\left(\boldsymbol{\theta}, \boldsymbol{\phi}, \boldsymbol{\psi}, t\right) h_\times(t + t_c - t_0)$$

$$\mathcal{M} = (m_1 m_2)^{3/5} / M^{1/5} \;\; ; \;\; M = m_1 + m_2$$

t_0: time of coalescence in the detector frame.

$t_0 - t_c$: the travel time from the source to the detector.

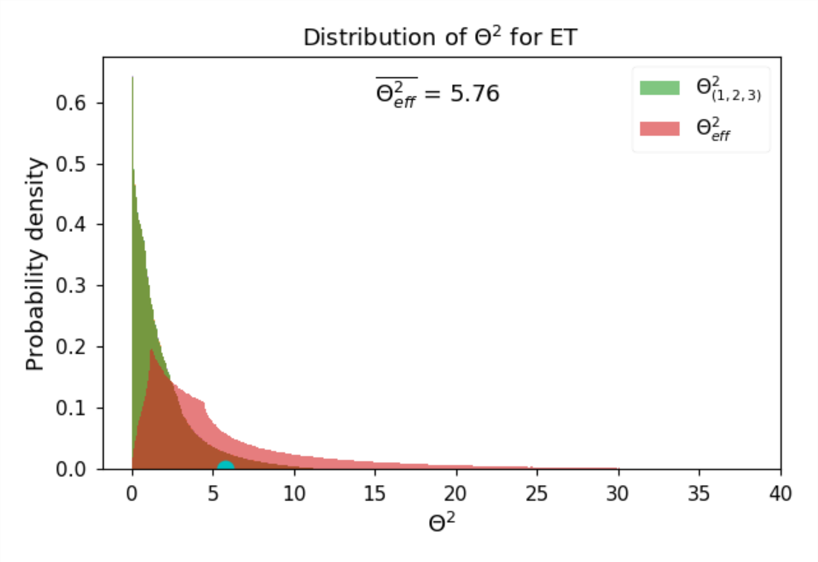
Compact Binaries: Angular parameters $(\theta, \phi, \iota, \psi)$

$$|\tilde{h}(f)| = \frac{2c}{D_L}\left(\frac{5G\mu}{96c^3}\right)^{1/2}\left(\frac{GM}{\pi^2c^3}\right)^{1/3}\left(\frac{\Theta}{4}\right)f^{-7/6}$$

$$\Theta(\boldsymbol{\theta}, \boldsymbol{\phi}, \boldsymbol{\iota}, \boldsymbol{\psi}) \equiv 2\left[F_+^2\left(1+\cos^2\boldsymbol{\iota}\right)^2 + 4F_\times^2\cos^2\boldsymbol{\iota}\right]^{1/2}$$

$$\Theta_{eff} = \left(\Theta_1^2 + \Theta_2^2 + \Theta_3^2\right)^{1/2}$$

Compact Binaries: $\Theta\left(\theta, \phi, \iota, \psi\right)$



Compact Binaries: Signal to Noise Ratio (SNR)

$$\rho_i \approx 8\Theta_i \frac{r_0}{D_L} \left(\frac{\mathcal{M}_z}{\mathcal{M}_{BNS}} \right)^{5/6} \sqrt{\zeta\left(f_{max}\right)}$$

f_{max} is the frequency at the end of the inspiral. $f_{max} = 785 \left(\frac{M_{BNS}}{M(1+z)} \right)$ Hz

$$D_L = 8\Theta_{eff} \frac{r_0}{\rho_{eff}} \left(\frac{\mathcal{M}_z}{1.2 M_\odot} \right)^{5/6} \sqrt{\zeta\left(f_{max}\right)}$$

Compact Binaries: Estimates

Constraining Θ, without triangulation

$$\rho_i \approx 8\Theta_i \frac{r_0}{D_L} \left(\frac{\mathcal{M}_z}{\mathcal{M}_{BNS}} \right)^{5/6} \sqrt{\zeta\left(f_{max}\right)}$$

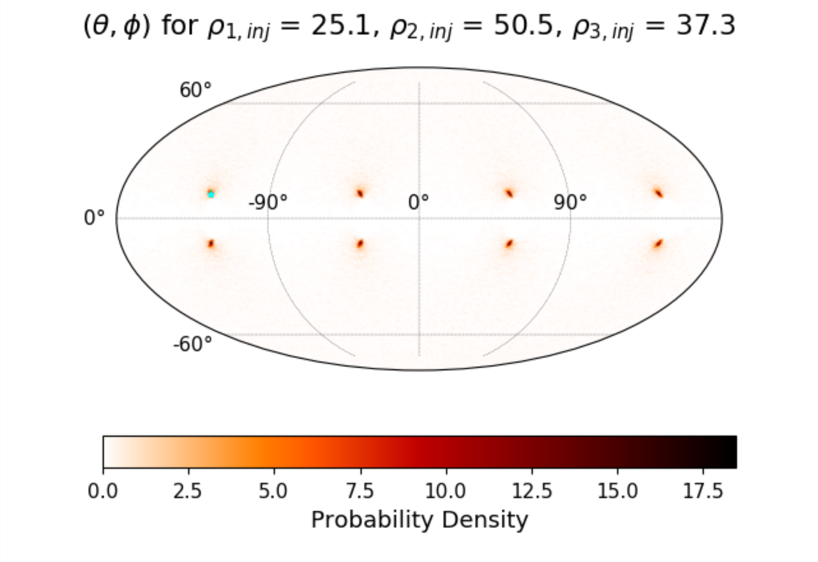
$$\downarrow$$

$$\frac{\rho_2}{\rho_1} = \frac{\Theta_2}{\Theta_1} \equiv \Theta_{21} \quad \text{and} \qquad \frac{\rho_3}{\rho_1} = \frac{\Theta_3}{\Theta_1} \equiv \Theta_{31}$$

$$\downarrow$$

$$\boldsymbol{\Theta}_{eff}$$

Compact Binaries: Estimates from short signals



Phys. Rev. D 104, 043014

Compact Binaries: Estimates from short signals

Constraining $\mathcal{M}, z, D_L, M, q$

Information about Θ

$+$

Information from detection

$(\mathcal{M}_z, f_{max}, \rho_i)$

$+$

Priors

$\Longrightarrow$

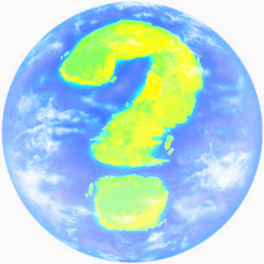
$\mathcal{M}, z, D_L, M, q$

Breaking the $\mathcal{M}, z$ degeneracy !!

Phys. Rev. D 104, 043014

BNS

- Signals from coalescing low mass compact binary systems.
- The BNS or NSBH signals can stay in the detectable band for a few minutes to several days.
- Necessary to take into account, the effect of rotation of Earth on the response function.



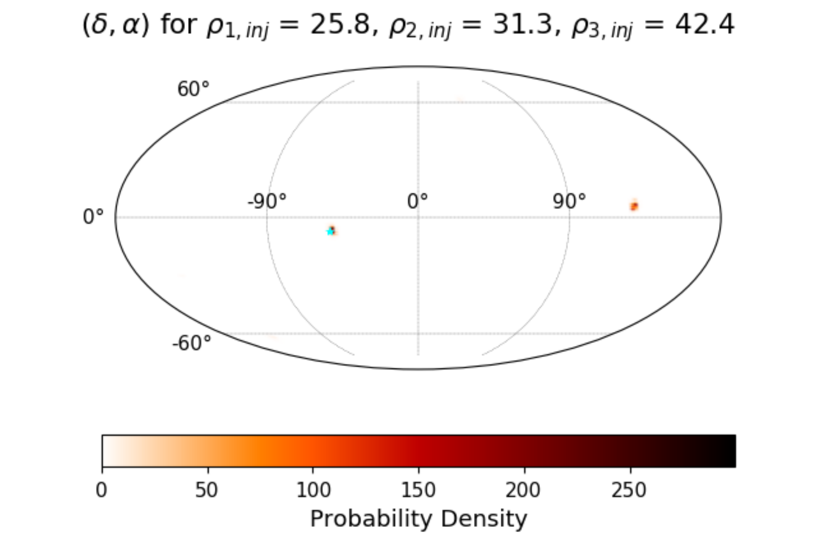
Compact Binaries: Estimates from long signals

$$\Lambda \equiv \left(\frac{8 r_0}{D_L} \left(\frac{\mathcal{M}_z}{\mathcal{M}_{BNS}} \right)^{5/6} \right)^{-1} \approx \frac{\Theta^i_{eff} \sqrt{\zeta^i \left(f_{i-1}, f_i \right)}}{\rho^i_{eff}}$$

red: Θ^i_{eff}, $\zeta^i \left(f_{i-1}, f_i \right)$, ρ^i_{eff}, characteristic for each segment.

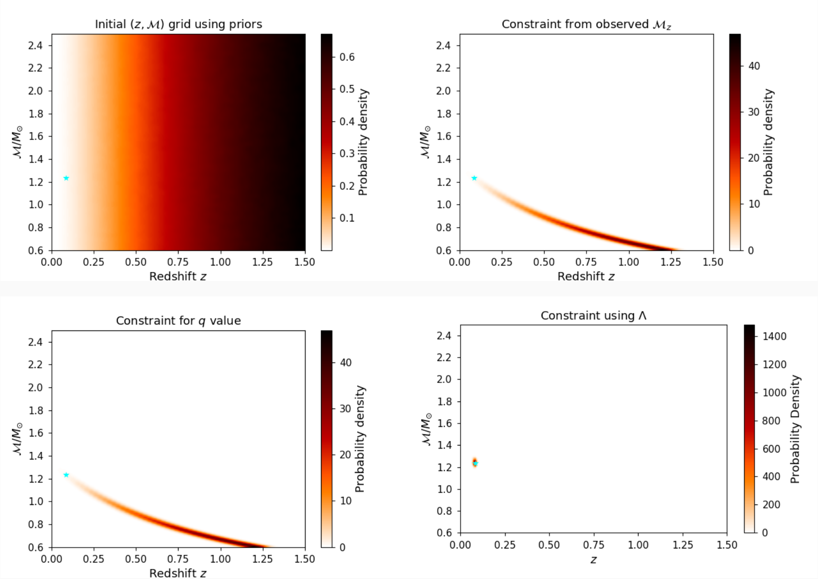
blue: Characterised by the source

Compact Binaries: Estimates from long signals

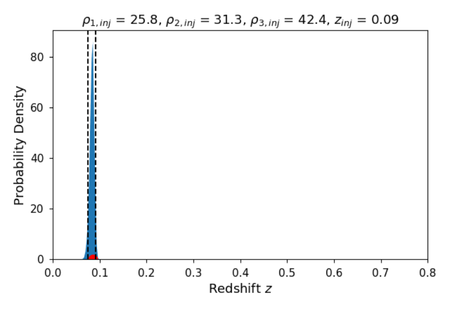


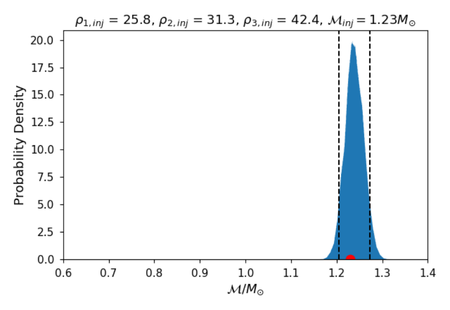
arXiv:2107.11198

Compact Binaries: Estimates from long signals



Compact Binaries: Estimates from long signals





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