Constraining core-collapse supernova engine with Einstein Telescope

SN2025gw, 25 July 2025

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Why are we talking about binary merger rates ?

Motivation: Thought process

Several evolutionary parameters for compact binary evolution still highly unconstrained.

↓

Multiple degeneracies still exist.

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Dynamics of engine behind core-collapse supernovae: Effect imprinted on the merger rate density evolution with redshift.

↓

GW observations can constrain merger rate density function for compact binaries.

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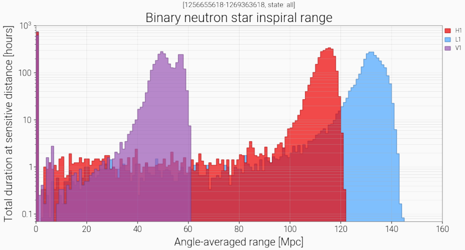
Strong constraints in-turn help to break the degeneracy between evolutionary parameters.

TLDR: Constrain the engine by excluding binary population evolution models !

Reason for Scepticism: Current sensitivities

O3b



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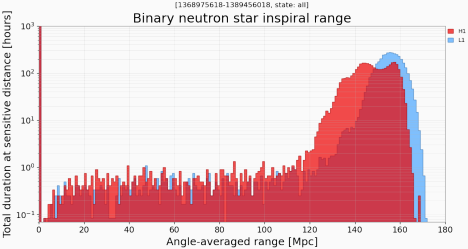

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Reason for Scepticism: Current sensitivities

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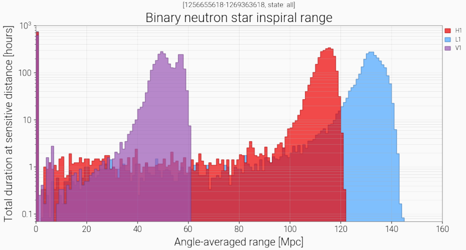

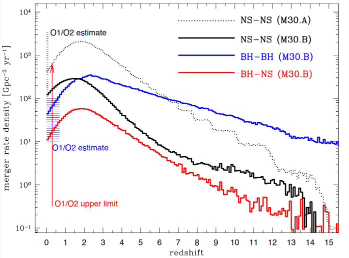

Belczynski et al. (2020)

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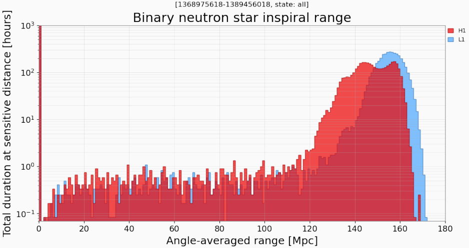

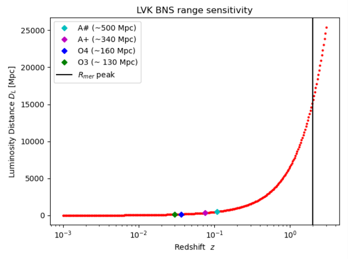

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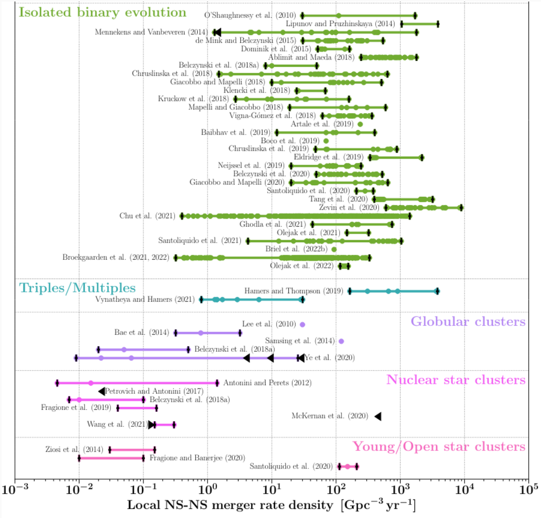
Future projections from Masayuki Nakano's talk

Local merger rate density: Predictions

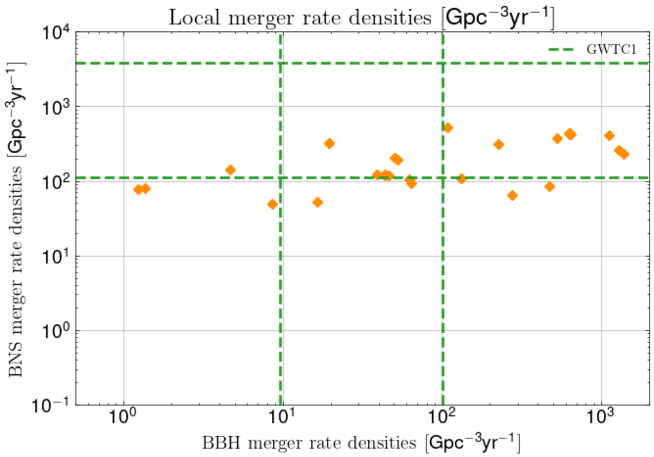


Rates from 2010 to present: Mandel & Broekgaarden Living Reviews 2022

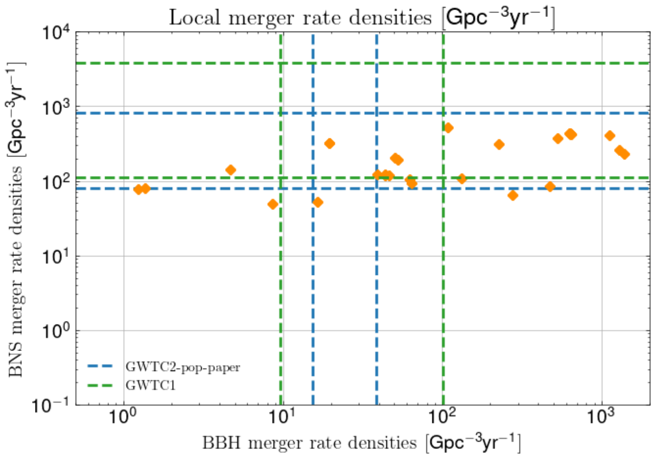
Points to ponder

- Local rates vary by orders of magnitude.
- What is the probability that a combination of parameters will result is exact merger rate density for $0 \leqslant z \lesssim 10$?

Constraints on population models



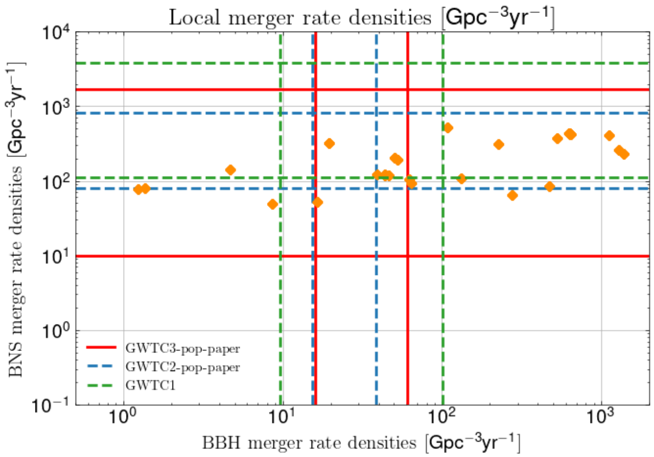
Constraints on population models



- The models satisfying the local rate may not reproduce the rates at larger redshifts.

Belczynski et al. 2020

Constraints on population models



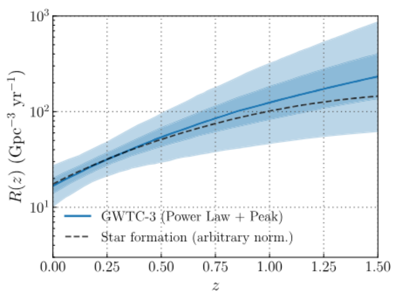
- The models satisfying the local rate may not reproduce the rates at larger redshifts.

Belczynski et al. 2020

Constraints on population models

	BNS	NSBH	BBH	NS gap	BBH gap	Full
	$m_1 \in [1, 2.5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 50]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 100]M_\odot$ $m_2 \in [2.5, 100]M_\odot$	$m_1 \in [2.5, 5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 100]M_\odot$ $m_2 \in [2.5, 5]M_\odot$	$m_1 \in [1, 100]M_\odot$ $m_2 \in [1, 100]M_\odot$
PDB (pair)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$	19^{+28}_{-13}	$9.3^{+15.7}_{-7.2}$	240^{+270}_{-140}
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$	$12^{+18}_{-9.0}$	$9.7^{+11.3}_{-7.0}$	150^{+170}_{-71}
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}	$3.7^{+35.3}_{-3.4}$	$0.12^{+24.88}_{-0.12}$	770^{+1030}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$	$1.7^{+30.0}_{-1.7}$	$5.2^{+12.0}_{-4.1}$	$180.0^{+270.0}_{-110.0}$
MERGED	10–1700	7.8–140	16–61	0.02–39	$9.4 \times 10^{-5} - 25$	72–1800

R. Abbot et al. 2023: Assuming merger rates per unit comoving volume are redshift independent.



- PDB: POWER LAW + DIP + BREAK model
- MS: MULTI SOURCE model
- BGP: BINNED GAUSSIAN PROCESS model

Constraints on the evolution of the BBH merger rate with redshift. Central 50% (dark blue) and 90% (light blue) credible bounds on the BBH merger rate density. The dashed line, for reference, is proportional to the rate of cosmic star formation. R. Abbot et al. 2023

Constraints on population models

- Current GW observations provide weak constraints on local merger rate density.
- The evolution of merger rate density ($z \lesssim 1.5$) is dependent on assumed mass distribution models.
- Given the reach of detectors, no constraints at higher redshift.
- Still a long way to go to confidently exclude population models with current detectors. Can ET do better??

Population Models: probing the multi dimensional parametric space

Model	Main features
M10	2016 standard input physics: – Rapid SNa BH masses Fryer et al. (2012) – With strong PPSN and with PSN – 10% neutrino mass loss at BH/NS formation – Low-to-no BH natal kicks (set by fallback) – High NS kicks: $\sigma = 265\,\mathrm{km\,s^{-1}}$ with fallback – 50% non-conservative RLOF – 10% Bondi-Hoyle accretion onto NS/BH in CE – Efficient accretion onto BH in stable MT/winds – No effects of rotation on stellar evolution [(a)] – Initial binary parameters: Sana et al. (2012) – Massive star winds: Vink et al. (2001) + LBV [(b)] – BH spins: Geneva models (Eq. (3)) – SFRD(z) and Z(z): Madau & Dickinson (2014) – Solar metallicity: $Z_\odot = 0.02$
M13	As in M10, but with: – High BH/NS natal kicks: $\sigma = 265\,\mathrm{km\,s^{-1}}$
M20	Modified input physics, as in M10, but with: – 80% non-conservative RLOF (Appendix A.7) – 5% Bondi-Hoyle accretion onto NS/BH in CE – Rotation increases CO core mass (by 20%)
M26	As in M20, but with: – Small BH/NS natal kicks: $\sigma = 70\,\mathrm{km\,s^{-1}}$
M25	As in M20, but with: – Intermediate BH/NS natal kicks: $\sigma = 130\,\mathrm{km\,s^{-1}}$
M23	As in M20, but with: – High BH/NS natal kicks: $\sigma = 265\,\mathrm{km\,s^{-1}}$
M30	2019 standard input physics: – Rapid SNa BH masses Fryer et al. (2012) – With weak PPSN and with PSN – 1% neutrino mass loss at BH formation – 10% neutrino mass loss at NS formation – Low-to-no BH natal kicks (set by fallback) – High NS kicks: $\sigma = 265\,\mathrm{km\,s^{-1}}$ with fallback – 50% non-conservative RLOF – 5% Bondi-Hoyle accretion onto NS/BH in CE – Inefficient accretion onto BH in stable MT/winds – No effects of rotation on stellar evolution [(a)] – Initial binary parameters: Sana et al. (2012) – Massive star winds: Vink et al. (2001) + LBV [(b)] – BH spins: MESA models (Eq. (4)) – SFRD(z) and Z(z): Madau & Fragos (2017) – Solar metallicity: $Z_\odot = 0.014$
M33	As in M30, but with: – High BH/NS natal kicks: $\sigma = 265\,\mathrm{km\,s^{-1}}$
M35	As in M30, but with: – Intermediate BH/NS natal kicks: $\sigma = 130\,\mathrm{km\,s^{-1}}$
M40	As in M30, but with: – BH spins: Fuller model (Eq. (5))
M43	As in M40, but with: – High BH/NS natal kicks: $\sigma = 265\,\mathrm{km\,s^{-1}}$
M50	As in M30, but with: – 30% of wind mass loss rates for all stars

- M13A, M23A, M25B, M30B, M43A, M50B
- Rapid supernova engine model for NS/BH mass from Fryer et al. (2012)

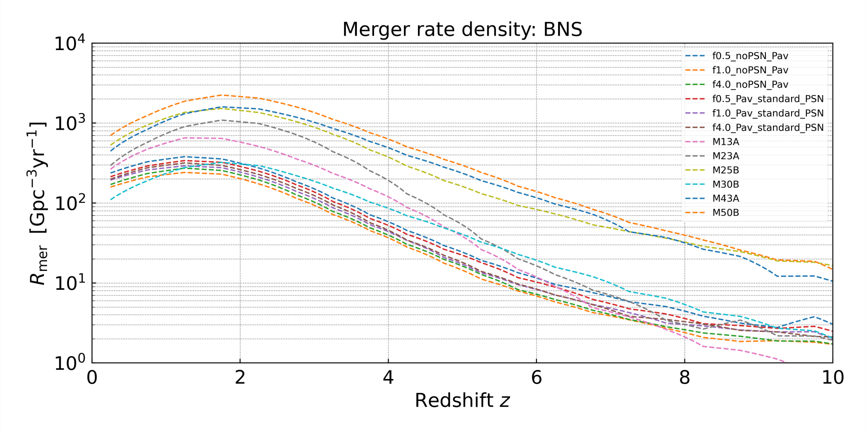
Belczynski et al. (2020)

No.	CE criteria	PSN limit	SN model
	GWTC-3 $z\sim0.2$		
1.	Standard	Revised	$f_{\rm mix} = 0.5$
2.	Standard	Revised	$f_{\rm mix} = 1.0$
3.	Standard	Revised	$f_{\rm mix} = 4.0$
4.	Standard	Strong	$f_{\rm mix} = 0.5$
5.	Standard	Strong	$f_{\rm mix} = 1.0$
6.	Standard	Strong	$f_{\rm mix} = 4.0$
7.	Revised	Revised	$f_{\rm mix} = 0.5$
8.	Revised	Revised	$f_{\rm mix} = 1.0$
9.	Revised	Revised	$f_{\rm mix} = 4.0$
10.	Revised	Strong	$f_{\rm mix} = 0.5$
11.	Revised	Strong	$f_{\rm mix} = 1.0$
12.	Revised	Strong	$f_{\rm mix} = 4.0$

- Revised CE with $f_{\rm mix}$: 0.5, 1.0, 4.0
- New formulas for remnant masses (Fryer et al. (2022))

Olejak et al 2022

Effect of Supernova engine on binary merger rate densities: BNS



- Chosen population models for this work: M30B, f0.5_Pav_standard_PSN
- The changes in convection growth time (inversely proportional to mixing fraction) affect the binary merger rate density evolution with redshift.
- Can we constrain them??

Parameter estimation with ET

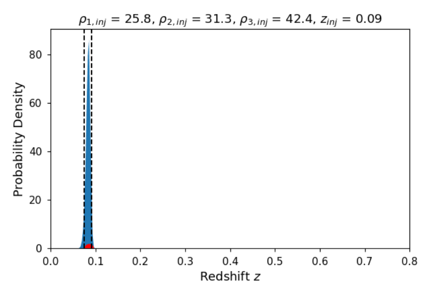
Construct a mock population

↓

Establish a detection threshold

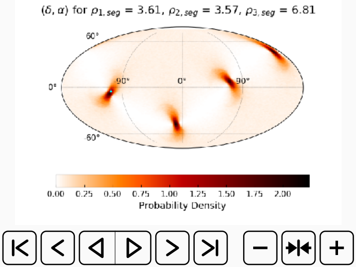
↓

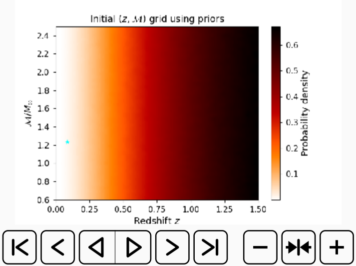
Estimate the parameters of the detected events



Singh et al. 2022 Phys. Rev. D 106, 123014

Bayesian parameter estimation

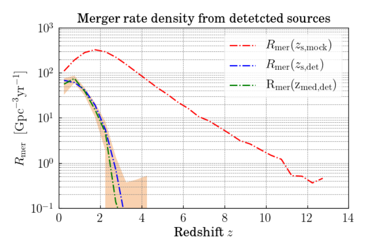




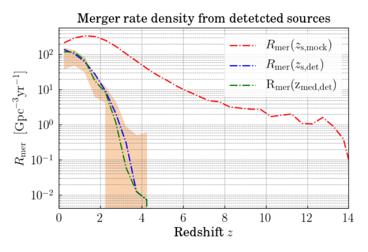
Merger rate estimation

- Threshold value of accumulated effective S/N $\rho_{eff} > 8$, and the S/N for i^{th} segment in the j^{th} detector $\rho^i_j > 3$ in at least one segment for $j = (1, 2, 3)$.
- Only $\sim 15\%$ BNS cross the threshold.
- We need an accurate estimate of detection efficiency. (Fraction of detected sources in a given redshift bin.)

M30B



f0.5_Pav_standard_PSN



True merger rate: Population-independent method

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

True merger rate

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

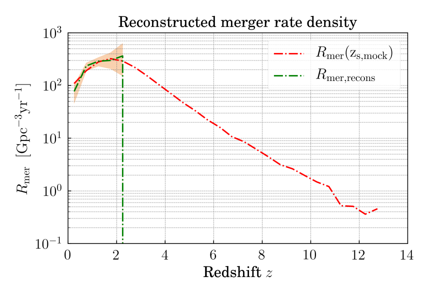
- $\mathcal{D}(z_i, z_{i+1}) = \left[\frac{N_{\rm sec,det}}{N_{\rm sec}}\right]_{(z_i, z_{i+1})}$
- $R_{\rm mer,recon}(z_i, z_{i+1}) = \left[\frac{R_{\rm mer}(z_{\rm med,det})}{\mathcal{D}}\right]_{(z_i, z_{i+1})}$

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

Singh et al. 2024 A&A 681, A56 "Reconstructing the star formation rate for compact binary populations with the Einstein telescope"

Reconstructed rates

M30B

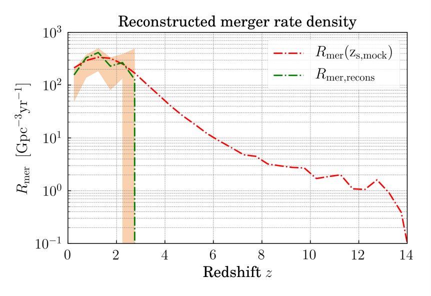


Observation time of $\sim$ 7.69 yrs

Poisson error for 0.54 months

Singh et al. 2025

f0.5_Pav_standard_PSN

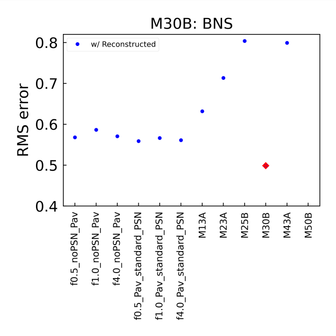


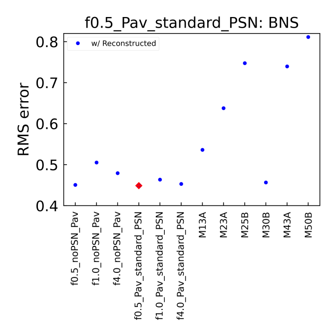
Observation time of $\sim$ 6.2 yrs

Poisson error for 0.46 months

- Get the Root mean square error on rate ratios, $\frac{\rm R_{mer,recon}}{\rm R_{mer,model}}$

Root mean square error on rate ratios






```
rms error:
f0.5_noPSN_Pav: 0.5679119981829039
f1.0_noPSN_Pav: 0.5864067362671391
f4.0_noPSN_Pav: 0.5707538412346541
f0.5_Pav_standard_PSN: 0.5589819613044525
f1.0_Pav_standard_PSN: 0.5663126899262241
f4.0_Pav_standard_PSN: 0.5611357905563583
M13A: 0.6317555569416484
M23A: 0.7134505230183692
M25B: 0.8036178215206121
M30B: 0.49876075508439843
M43A: 0.7991717044899596
M50B: 0.8553351113240178
```

```
rms error:
f0.5_noPSN_Pav: 0.4505528765747622
f1.0_noPSN_Pav: 0.5051725975146959
f4.0_noPSN_Pav: 0.47943925824486616
f0.5_Pav_standard_PSN: 0.4486711116540557
f1.0_Pav_standard_PSN: 0.4634706144268692
f4.0_Pav_standard_PSN: 0.4530006052482371
M13A: 0.536030723729045
M23A: 0.6377857949559512
M25B: 0.7475354790589286
M30B: 0.4567854849472954
M43A: 0.7396718716788437
M50B: 0.8112838027452101
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Conclusions

- Binary merger rate density evolution with redshift using ET can provide indirect constraints population evolution parameters including CCSN engine parameters.
- Rate constraints can be used to exclude parameter space more confidentiality, since we constrain the evolution of binary merger rate density as a function of redshift.
- Need population models with more densely sampled parameter space.
- Ongoing work looking into constraints using BBH and NSBH merger rate densities in addition to BNS.

Thank you

Acknowledgement

This work was supported by the Universitat de les Illes Balears (UIB); the Spanish Agencia Estatal de Investigación grants CNS2022-135440, PID2022-138626NB-I00, RED2022-134204-E, RED2022-134411-T, funded by MICIU/AEI/10.13039/501100011033, and the European Union NextGenerationEU/PRTR, and the ERDF/EU; and Comunitat Autònoma de les Illes Balears through the Conselleria d'Educació i Universitats with funds from the European Union - NextGeneration EU/PRTR-C17.I1 (SINCO2022/6719) and from the European Union - European Regional Development Fund (ERDF) (SINCO2022/18146).

EXTRA SLIDES