No Detectable Kilonova Counterpart is Expected for O3 Neutron Star–Black Hole Candidates

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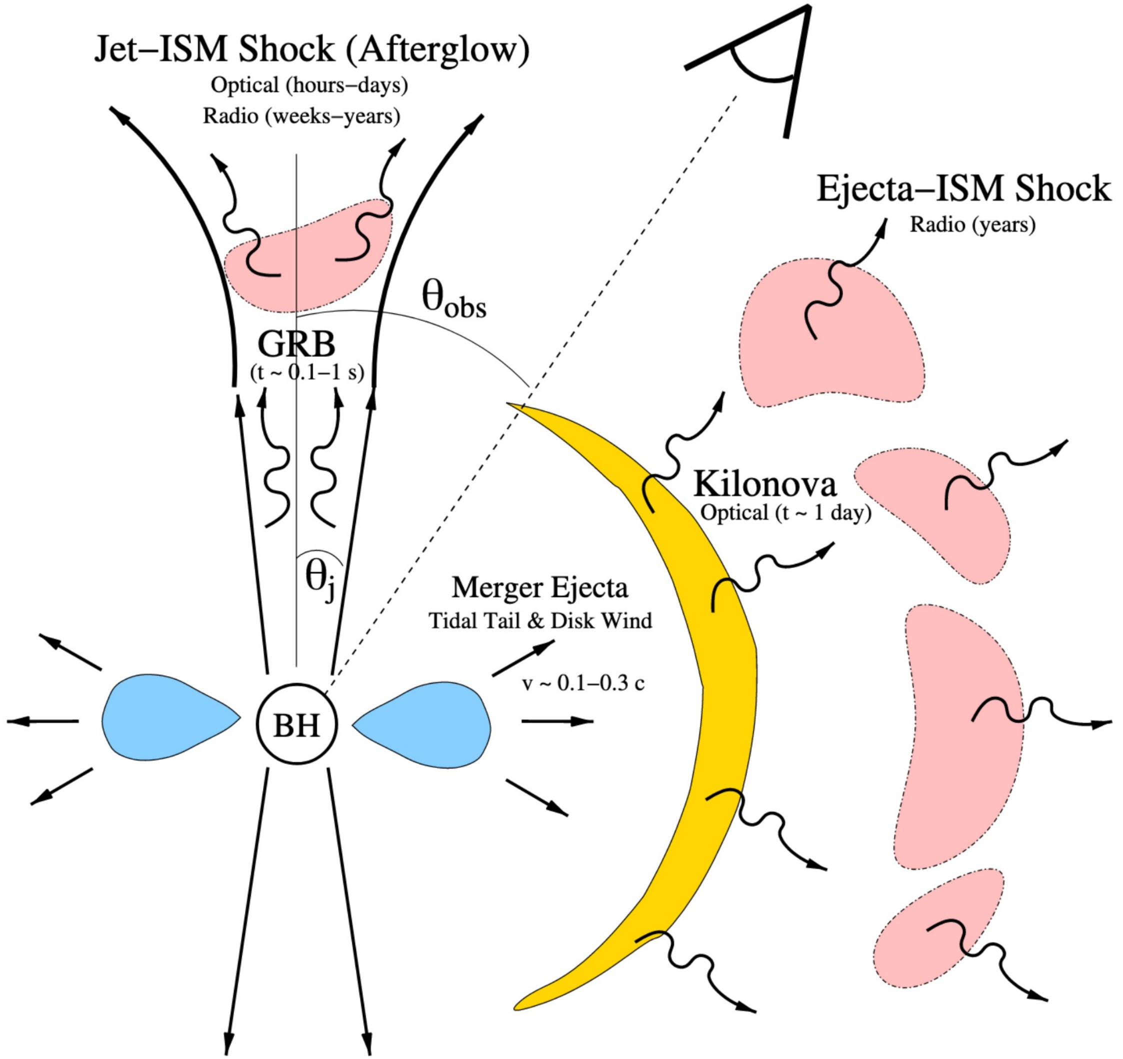
ABSTRACT

We analyse the tidal disruption probability of potential neutron star–black hole (NSBH) merger gravitational wave (GW) events, including GW190426_152155, GW190814, GW200105_162426 and GW200115_042309, detected during the third observing run of the LIGO/Virgo Collaboration, and the detectability of kilonova emission in connection with these events. The posterior distributions of GW190814 and GW200105_162426 show that they must be plunging events and hence no kilonova signal is expected from these events. With the stiffest NS equation of state allowed by the constraint of GW170817 taken into account, the probability that GW190426_152155 and GW200115_042309 can make tidal disruption is $\sim 24\%$ and $\sim 3\%$, respectively. However, the predicted kilonova brightness is too faint to be detected for present follow-up search campaigns, which explains the lack of electromagnetic (EM) counterpart detection after triggers of these GW events. Based on the best constrained population synthesis simulation results, we find that disrupted events account for only $\lesssim 20\%$ of cosmological NSBH mergers since most of the primary BHs could have low spins. The associated kilonovae for those disrupted events are still difficult to be discovered by LSST after GW triggers in the future, because of their low brightness and larger distances. For future GW-triggered multi-messenger observations, potential short-duration gamma-ray bursts and afterglows are more probable EM counterparts of NSBH GW events.

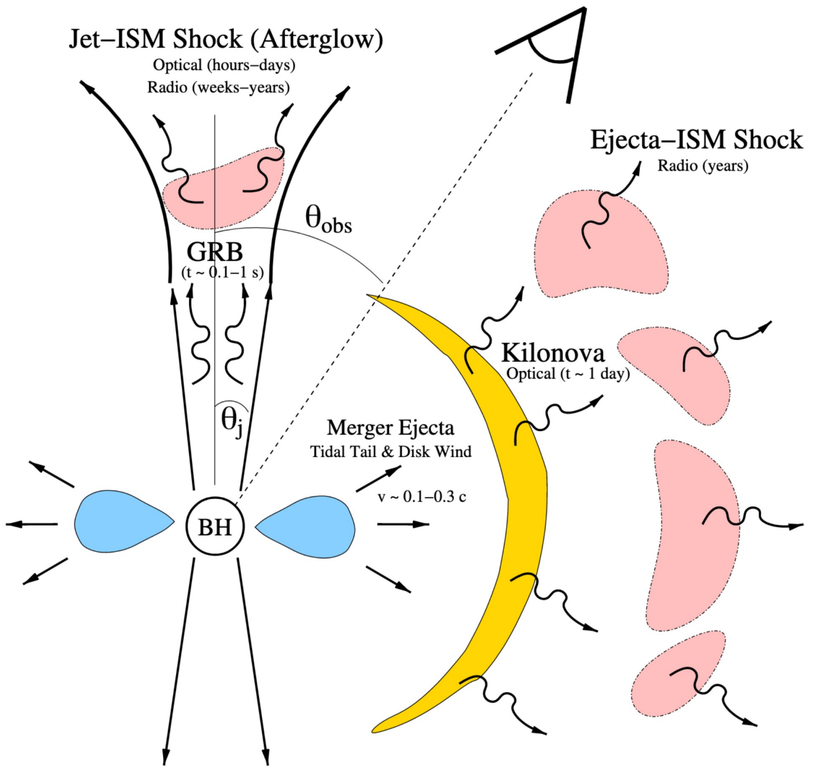
1. Introduction

Context: BNS mergers



Metzger & Berger 2012

Context: BNS mergers



Metzger & Berger 2012

Question: Can we expect a similar physical setup for a NSBH merger?

Context: O3 observing run

- No confirmed EM counterpart candidate identified (see 8 references in article)
- Potential sub-threshold GRB (GBM-190816) associated with sub-threshold LVC GW signal (Goldstein et al. 2019a, Yang et al. 2020, Li & Shen 2021)
- 2 possible explanations:
  - EM searches too shallow
  - EM counterparts intrinsically missing (plunging events)

Context: Four NSBH GW candidates (O3a)

Table 1. Source properties for potential NSBH events

GW Event	GW190426	GW190814	GW200105	GW200115
Primary mass $M_1/M_\odot$	$5.7^{+3.9}_{-2.3}$	$23.2^{+1.1}_{-1.0}$	$8.9^{+1.1}_{-1.3}$	$5.9^{+1.4}_{-2.1}$
Secondary mass $M_2/M_\odot$	$1.5^{+0.8}_{-0.5}$	$2.59^{+0.08}_{-0.09}$	$1.9^{+0.2}_{-0.2}$	$1.4^{+0.6}_{-0.2}$
Mass ratio $Q = M_1/M_2$	$4.2^{+6.7}_{-2.7}$	$8.9^{+0.8}_{-0.6}$	$4.8^{+1.1}_{-1.1}$	$4.2^{+2.1}_{-2.3}$
Effective inspiral spin $\chi_{\rm eff}$	$-0.03^{+0.32}_{-0.30}$	$-0.002^{+0.060}_{-0.061}$	$-0.01^{+0.08}_{-0.12}$	$-0.14^{+0.17}_{-0.34}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	370^{+190}_{-160}	241^{+41}_{-45}	280^{+110}_{-110}	310^{+150}_{-110}

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Follow-up observations: no possible EM counterpart

Why?

Tidal disruption probability + Kilonova detectability

2. Tidal disruption and kilonova detectability

Is a NS tidally disrupted?

A comparison between

$$\widetilde{R}_{\rm ISCO} = c^2 R_{\rm ISCO}/GM_{\rm BH}$$

$$\widetilde{R}_{\rm ISCO} = 3 + Z_2 - {\rm sign}(\chi_{\rm BH})\sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)}$$

$$Z_1 = 1 + (1 - \chi_{\rm BH}^2)^{1/3}[(1 + \chi_{\rm BH})^{1/3} + (1 - \chi_{\rm BH})^{1/3}]$$

$$Z_2 = \sqrt{3\chi_{\rm BH}^2 + Z_1^2}$$

And

$$R_{\rm tidal} \sim R_{\rm NS}(3M_{\rm BH}/M_{\rm NS})^{1/3}$$

(Depends on the EoS)

Remnant mass

Foucart et al. 2018:

Out of 75 NR simulations, the total remnant mass is:

$$\frac{M_{\rm total,fit}}{M^{\rm b}_{\rm NS}} = \left[\max\left(\alpha\frac{1-2C_{\rm NS}}{\eta^{1/3}} - \beta\widetilde{R}_{\rm ISCO}\frac{C_{\rm NS}}{\eta} + \gamma, 0\right)\right]^{\delta}$$

Similar formula with different coefs. from Zhu et al. 2020a

Dynamical ejecta mass

Only a fraction of the remnant mass is unbound and ejected

This info is obtained with independent NR data

Final empirical mass of dynamical ejecta:

$$M_{\rm d} = \min(M_{\rm d,fit}, f_{\rm max} M_{\rm total,fit})$$

From
- Zhu et al. 2020 (Z20)
- Kawaguchi et al. 2016 (K16)
- Krüger & Foucart 2020 (KF20)

f_{max} = 0.5: upper limit on max. dynamical ejecta mass

Observational data

Note: To compute M_d, you need to know χ_{BH} and the EoS

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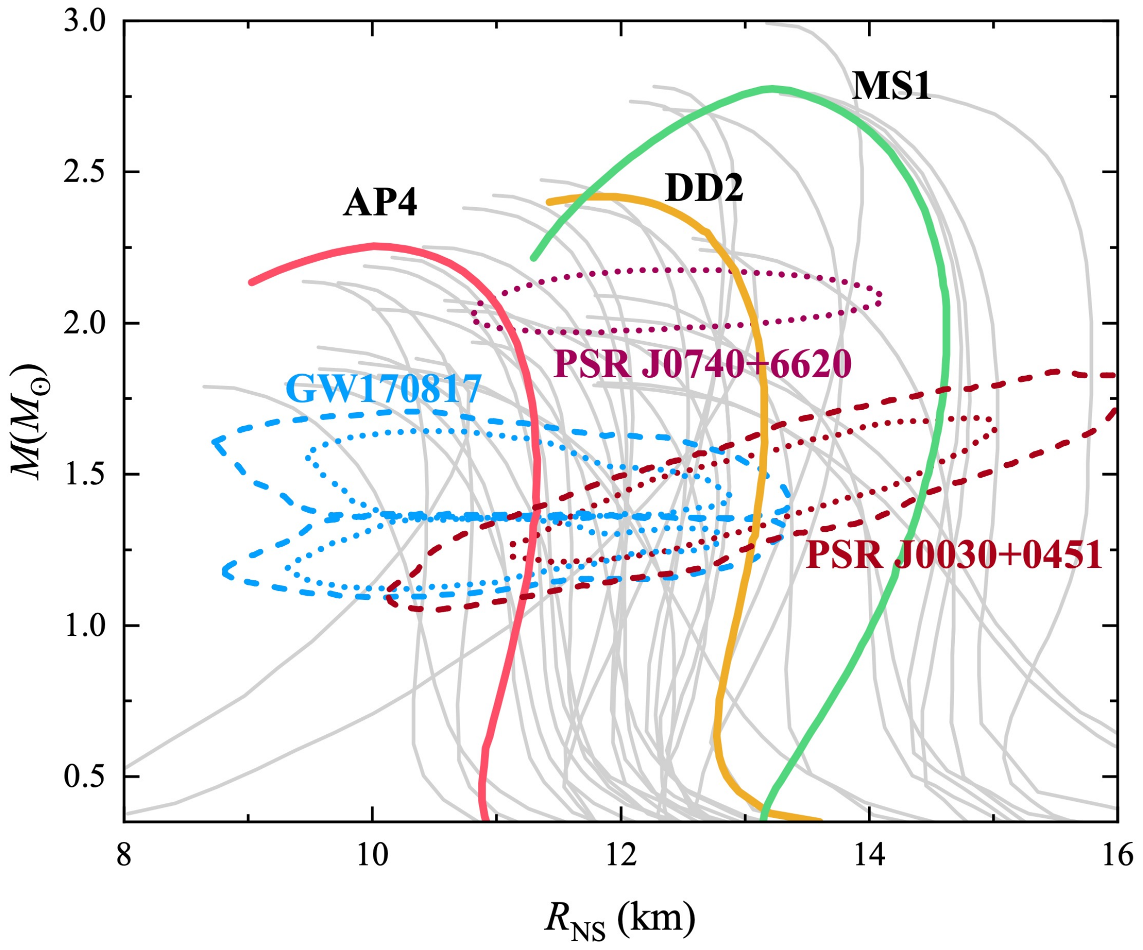
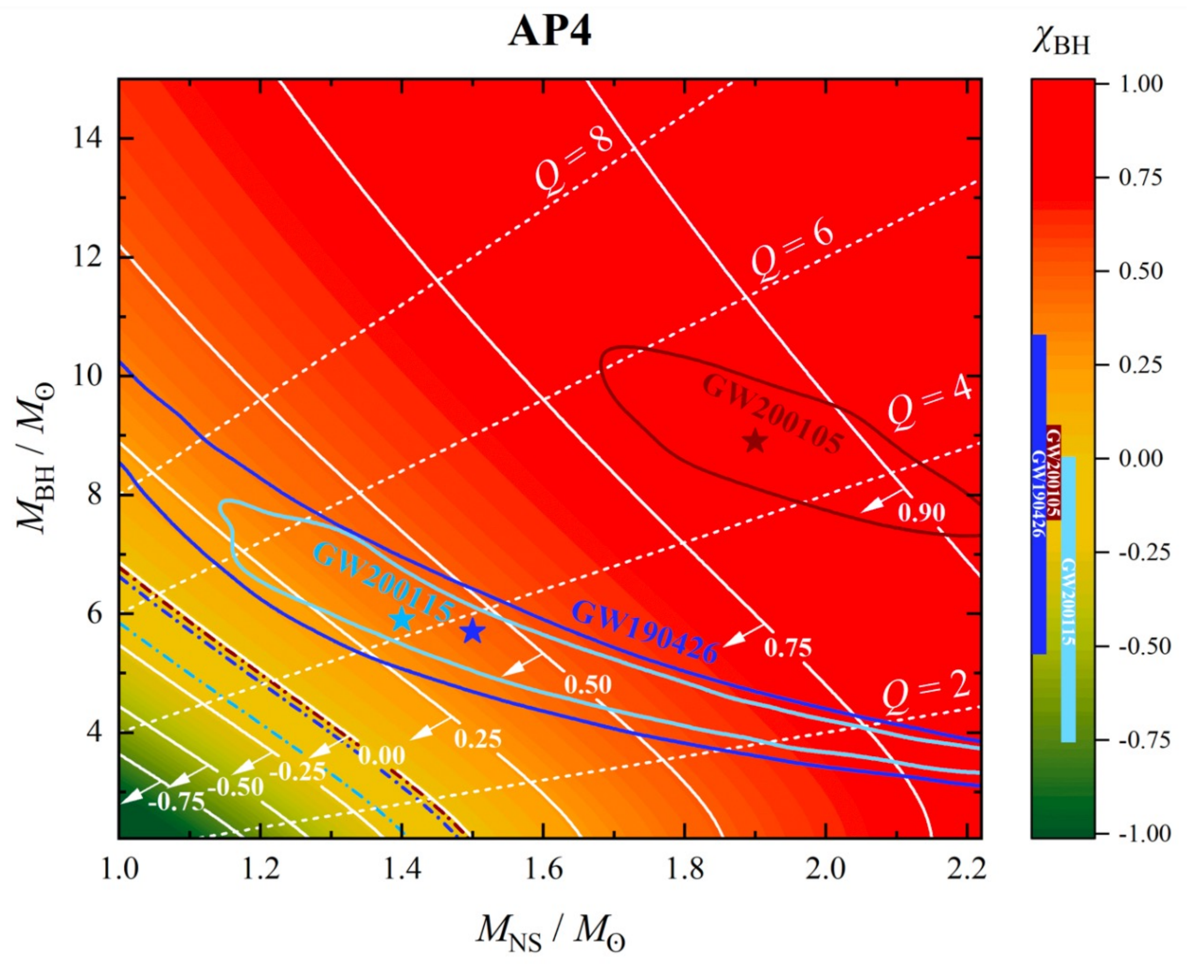
→ χ_{BH}

Selected Equations of State

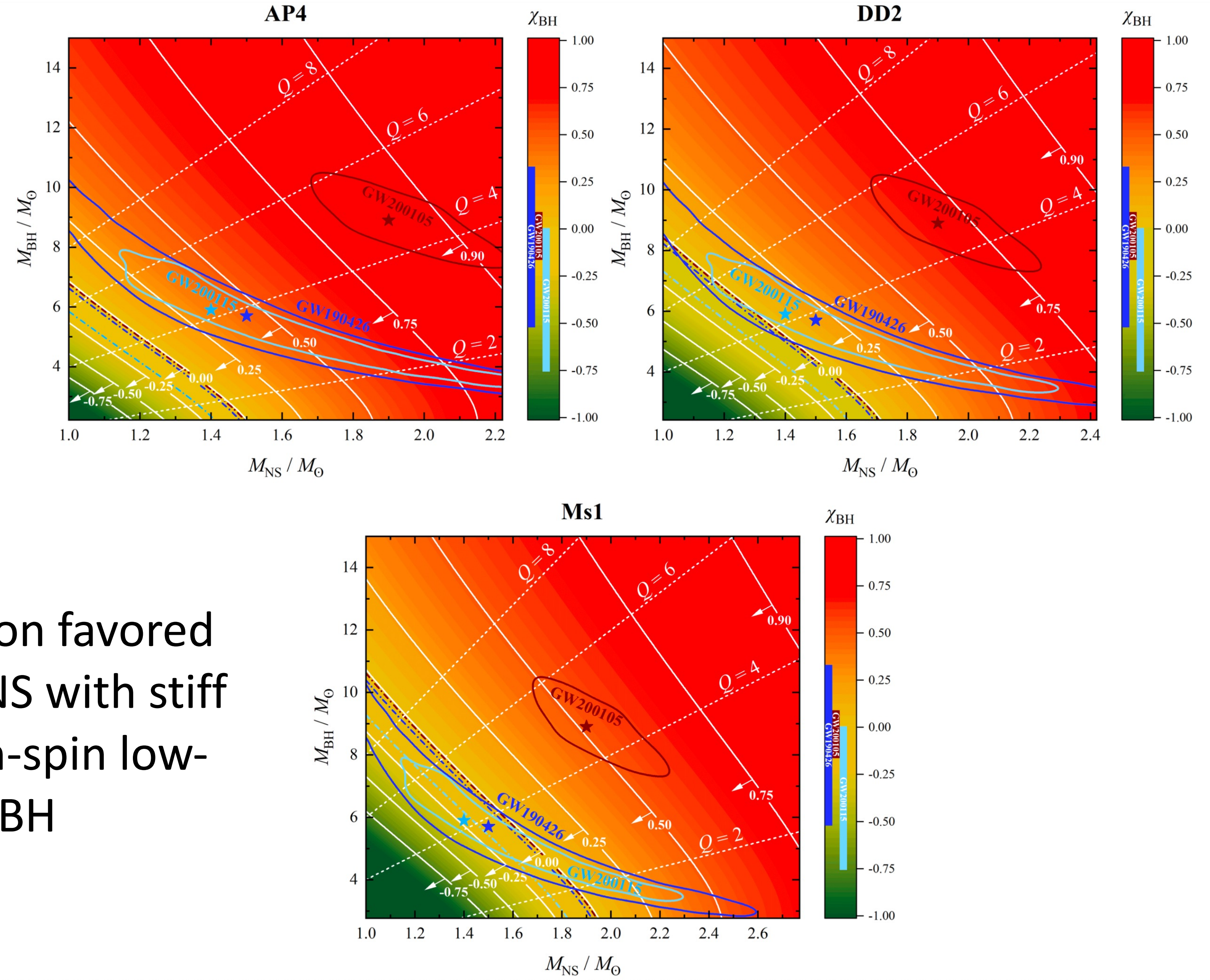


3 EoS selected (from soft to stiff)

Parameter space for tidal disruption



Parameter space for tidal disruption



Tidal disruption favored by low-mass NS with stiff EoS, and high-spin low-mass BH

Tidal disruption probability

GW Event	EoS	P_{NSBH} [a]	Tidal Disruption Probability
			F18
GW190426	AP4	94.4%	5.95%
	DD2	97.6%	24.3%
	Ms1	99.8%	65.2%
GW190814	AP4	0%	–
	DD2	0.30%	0%
	Ms1	99.9%	0%
GW200105	AP4	97.0%	0%
	DD2	99.1%	0%
	Ms1	99.8%	0%
GW200115	AP4	98.1%	0%
	DD2	100%	2.76%
	Ms1	100%	49.9%

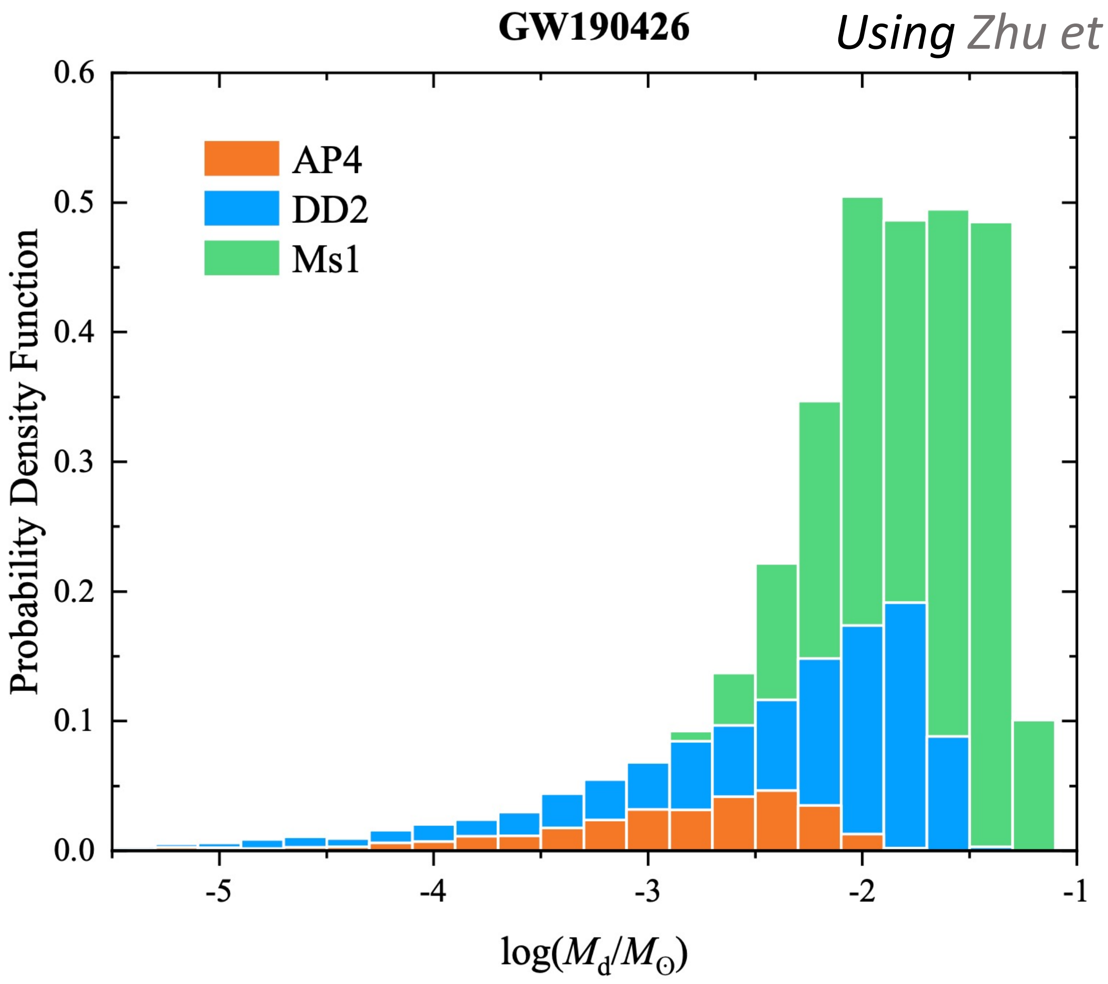
$M_{NS} = 2.59\ M_{sun}$

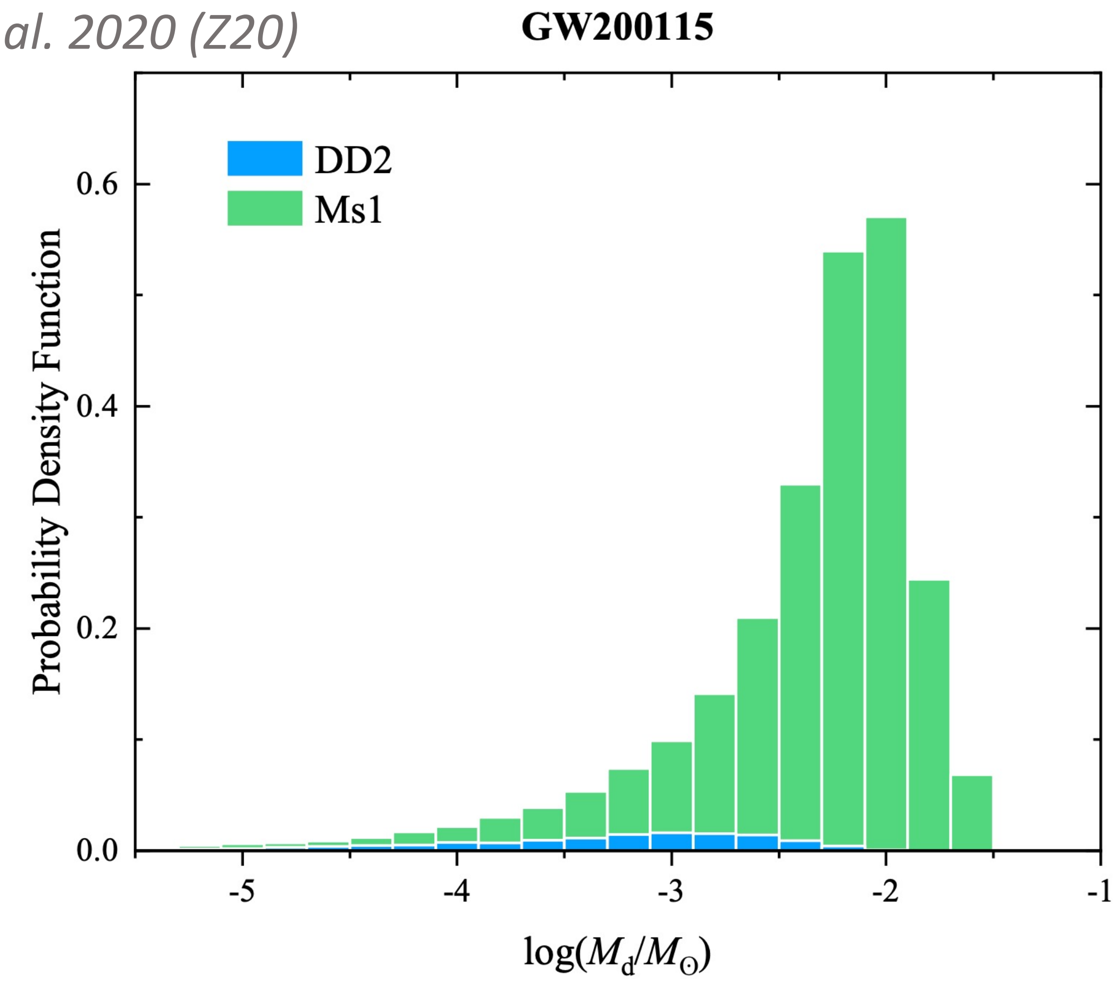
Primary mass too high

Stiffer EoS: Tidal disruption more likely

Ejecta mass

Using Zhu et al. 2020 (Z20)





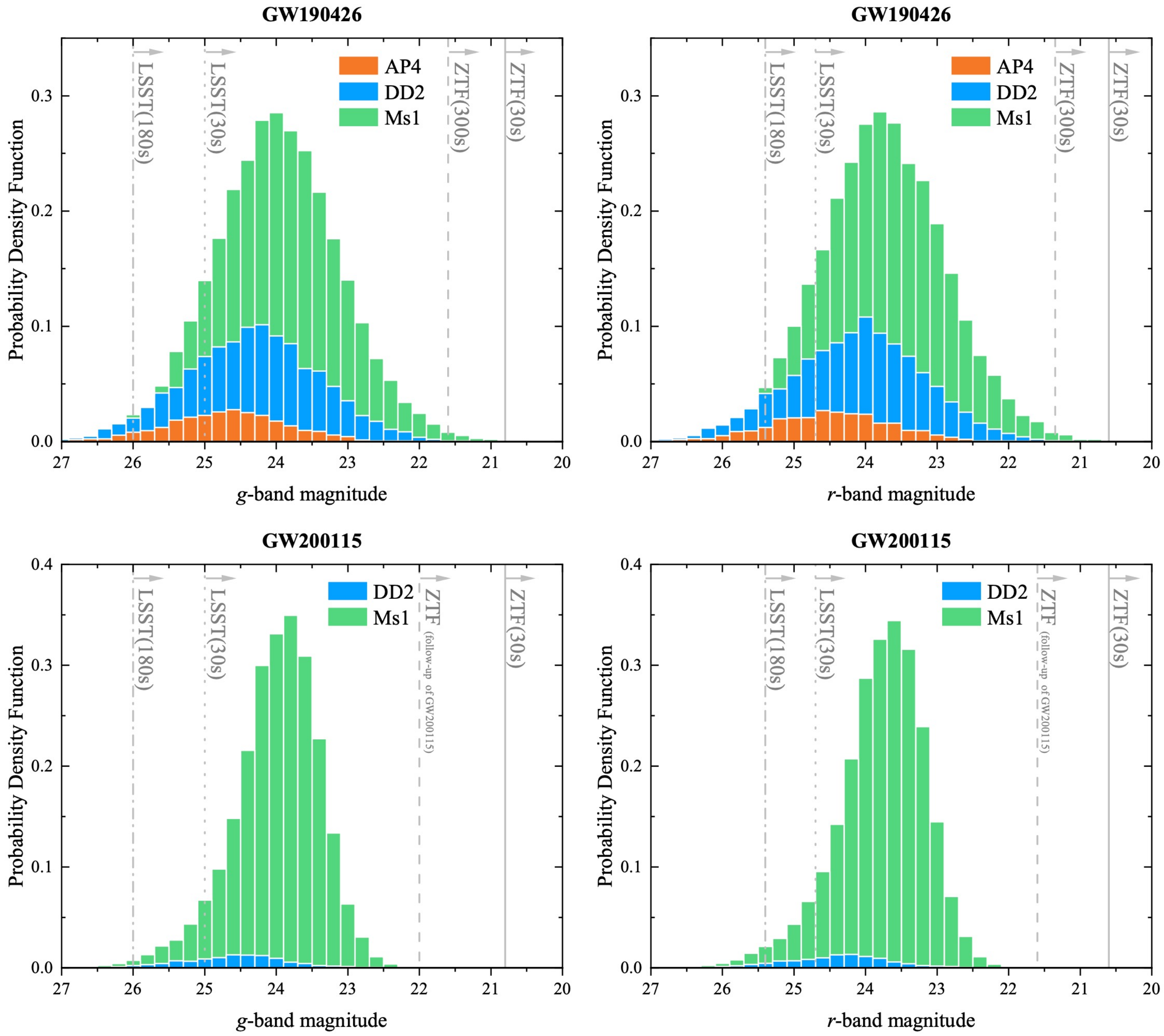
Ejecta mass

GW170817 ejecta mass: 0.01-0.05 M_{sun}

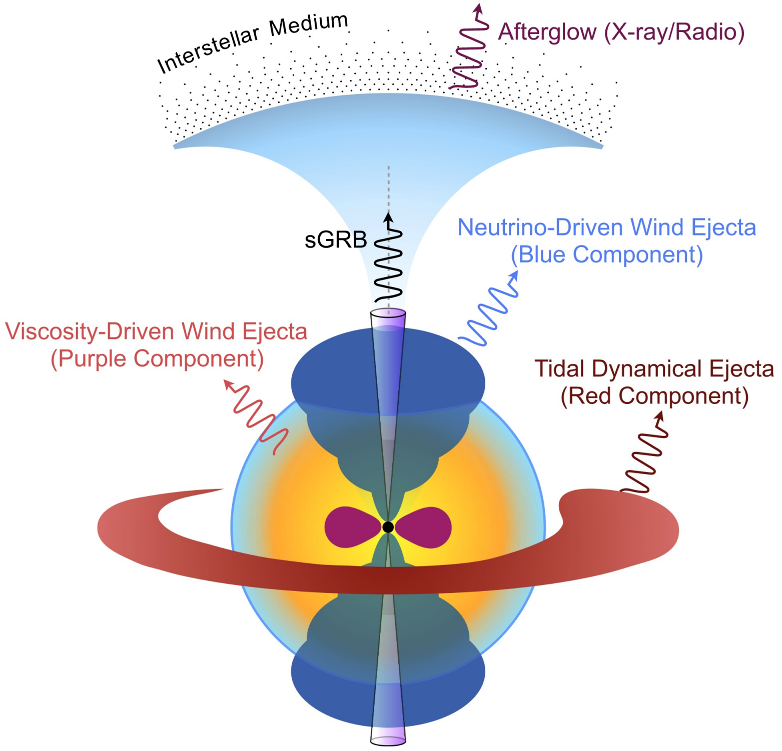
GW Event	EoS	$P_{\rm NSBH}$ [a]	Tidal Disruption Probability	Dynamical Ejecta Mass [b]		
			F18	K16	KF20	Z20
GW190426	AP4	94.4%	5.95%	$1.9^{+6.1}_{-1.8} \times 10^{-3} M_\odot$	$5.3^{+8.7}_{-4.8} \times 10^{-3} M_\odot$	$1.7^{+6.2}_{-1.7} \times 10^{-3} M_\odot$
	DD2	97.6%	24.3%	$7^{+16}_{-6} \times 10^{-3} M_\odot$	$10^{+14}_{-9} \times 10^{-3} M_\odot$	$5^{+17}_{-5} \times 10^{-3} M_\odot$
	Ms1	99.8%	65.2%	$1.5^{+3.3}_{-1.3} \times 10^{-2} M_\odot$	$1.5^{+3.4}_{-1.2} \times 10^{-2} M_\odot$	$1.3^{+3.4}_{-1.2} \times 10^{-2} M_\odot$
GW190814	AP4	0%	–	–	–	–
	DD2	0.30%	0%	0	0	0
	Ms1	99.9%	0%	0	0	0
GW200105	AP4	97.0%	0%	0	0	0
	DD2	99.1%	0%	0	0	0
	Ms1	99.8%	0%	0	0	0
GW200115	AP4	98.1%	0%	0	0	0
	DD2	100%	2.76%	$6^{+39}_{-6} \times 10^{-4} M_\odot$	$34^{+41}_{-33} \times 10^{-4} M_\odot$	$6^{+39}_{-6} \times 10^{-4} M_\odot$
	Ms1	100%	49.9%	$6^{+11}_{-6} \times 10^{-3} M_\odot$	$7^{+11}_{-5} \times 10^{-3} M_\odot$	$6^{+11}_{-6} \times 10^{-3} M_\odot$

KF20 predict a slightly larger value for dynamical ejecta

Kilonova apparent magnitudes



Viewing-angle dependent NSBH kilonova model from Zhu et al. 2020a



3. Implications from population synthesis results

Parameter space for tidal disruption with population synthesis

From GW detections (LVC 2020b):

$$\mathcal{R}_{BNS} = 320^{+490}_{-240}\ Gpc^{-3}yr^{-1}$$

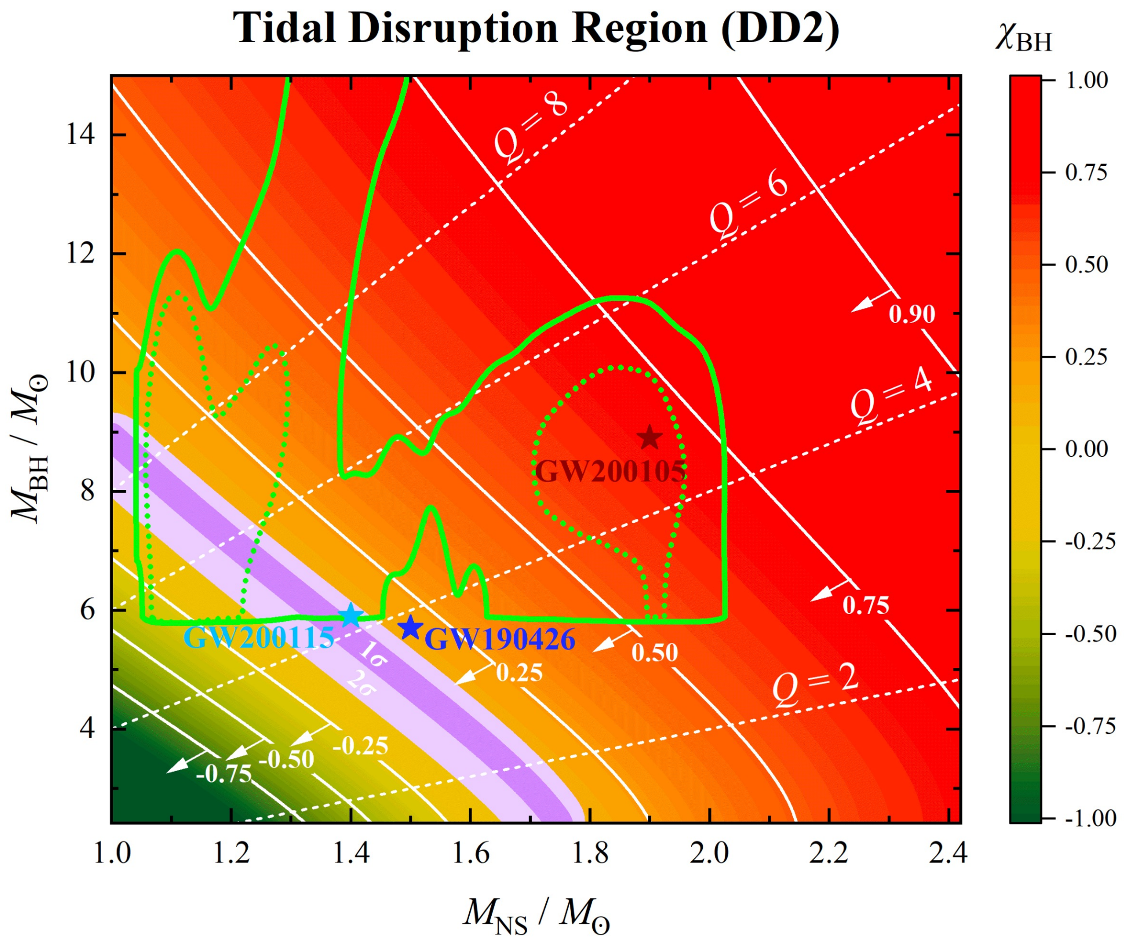
$$\mathcal{R}_{NSBH} = 45^{+75}_{-33}\ Gpc^{-3}yr^{-1}$$

$$\mathcal{R}_{BBH} = 24^{+14}_{-9}\ Gpc^{-3}yr^{-1}$$

Abbott et al. 2021:

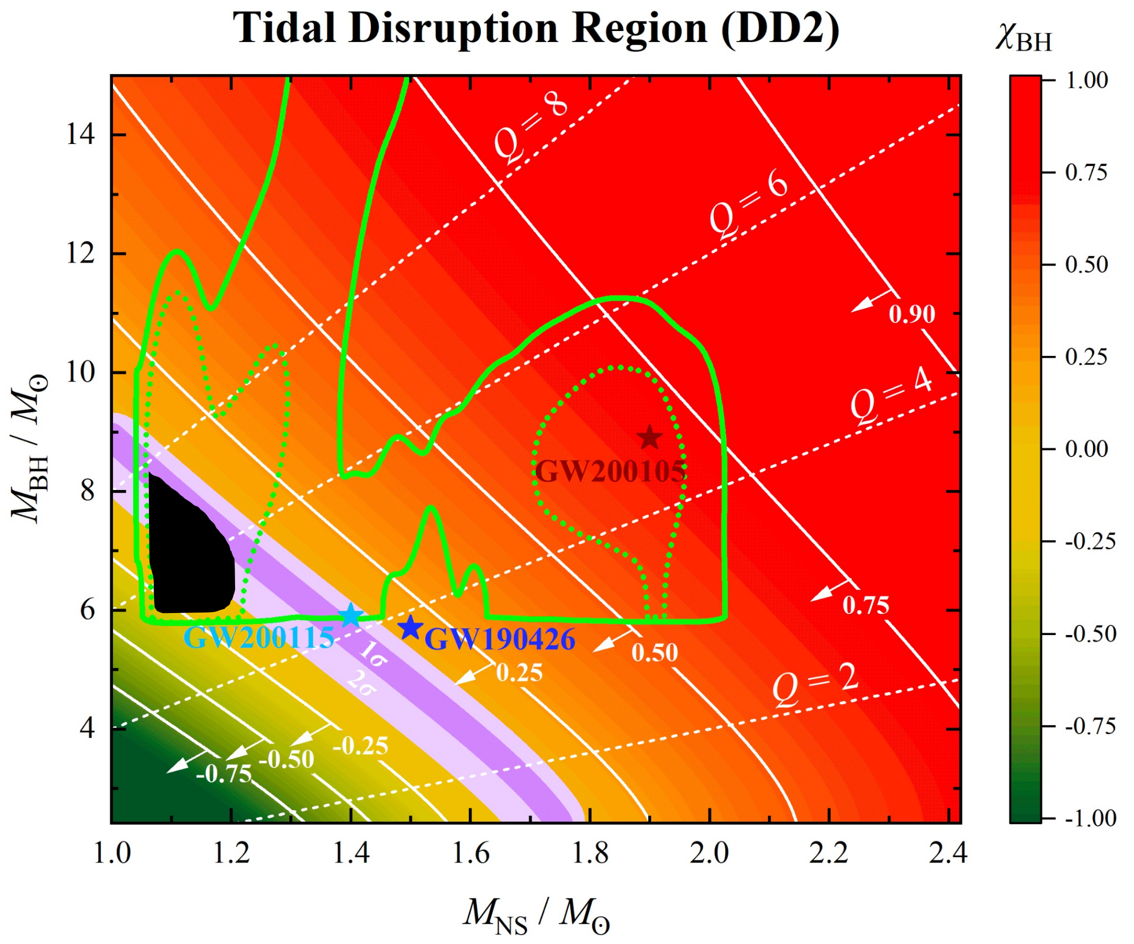
$$\mathcal{R}_{NSBH} = 130^{+112}_{-69}\ Gpc^{-3}yr^{-1}$$

Belczynski et al. 2020 try several population synthesis models. Here the authors focus on those that manage to reproduce the observed rates



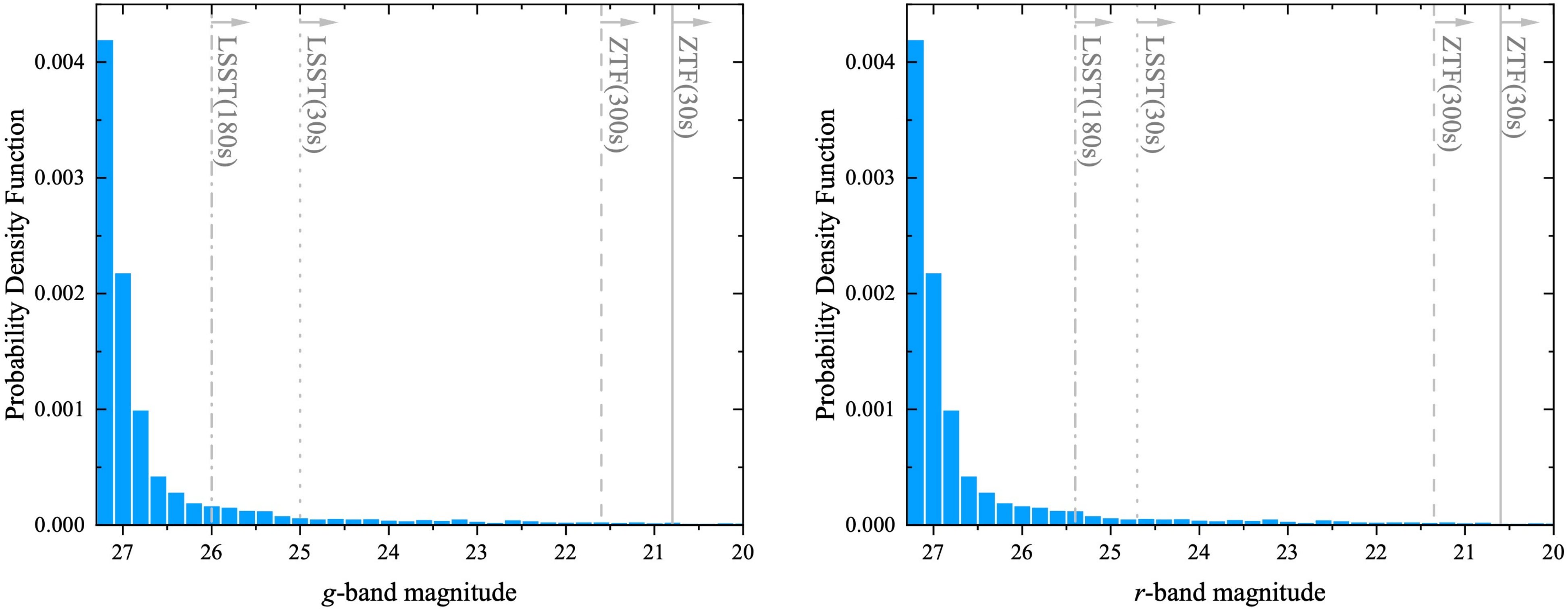
Parameter space for tidal disruption with population synthesis

Only ~20% NSBH mergers can allow tidal disruption and produce bright kilonovae



Distribution of apparent magnitudes

Obtained with 5 x 10^6 NSBH mergers mapping distributions of peak *g*-band and *r*-band apparent magnitudes



4. Conclusions and discussion

Concerning tidal disruptions of the four O3 events

GW Event	EoS	P_{NSBH} [a]	Tidal Disruption Probability	Dynamical Ejecta Mass [b]		
			F18	K16	KF20	Z20
GW190426	AP4	94.4%	5.95%	$1.9^{+6.1}_{-1.8} \times 10^{-3} M_\odot$	$5.3^{+8.7}_{-4.8} \times 10^{-3} M_\odot$	$1.7^{+6.2}_{-1.7} \times 10^{-3} M_\odot$
	DD2	97.6%	24.3%	$7^{+16}_{-6} \times 10^{-3} M_\odot$	$10^{+14}_{-9} \times 10^{-3} M_\odot$	$5^{+17}_{-5} \times 10^{-3} M_\odot$
	Ms1	99.8%	65.2%	$1.5^{+3.3}_{-1.3} \times 10^{-2} M_\odot$	$1.5^{+3.4}_{-1.2} \times 10^{-2} M_\odot$	$1.3^{+3.4}_{-1.2} \times 10^{-2} M_\odot$
GW190814	AP4	0%	–	–	–	–
	DD2	0.30%	0%	0	0	0
	Ms1	99.9%	0%	0	0	0
GW200105	AP4	97.0%	0%	0	0	0
	DD2	99.1%	0%	0	0	0
	Ms1	99.8%	0%	0	0	0
GW200115	AP4	98.1%	0%	0	0	0
	DD2	100%	2.76%	$6^{+39}_{-6} \times 10^{-4} M_\odot$	$34^{+41}_{-33} \times 10^{-4} M_\odot$	$6^{+39}_{-6} \times 10^{-4} M_\odot$
	Ms1	100%	49.9%	$6^{+11}_{-6} \times 10^{-3} M_\odot$	$7^{+11}_{-5} \times 10^{-3} M_\odot$	$6^{+11}_{-6} \times 10^{-3} M_\odot$

No tidal disruption (GW190814, GW200105)

Low probability of tidal disruption + low brightness (undetectable by ZTF) (highlighted: GW190426 and GW200115 F18 values)

Concerning population models

- Only $\sim$20% NSBH mergers can allow tidal disruption and produce bright kilonovae
- “Most” of them undetectable by LSST (Only considering volume effects)
- sGRB & afterglow more “ideal” EM counterparts to search

Discussion on the models and perspectives

- More luminous kilonovae possible with higher electron fraction in the wind
- Depending on the model, peak luminosity differs by up to a factor 2 (~1mag uncertainty)
- FRB or short-duration X-ray burst can be expected (Zhang 2019, Dai 2019, Sridhar et al. 2021)
- NSBHs in AGN discs can be found with cocoon shock breakout