Rigid rotating NS as binary-neutron star-merger remnant

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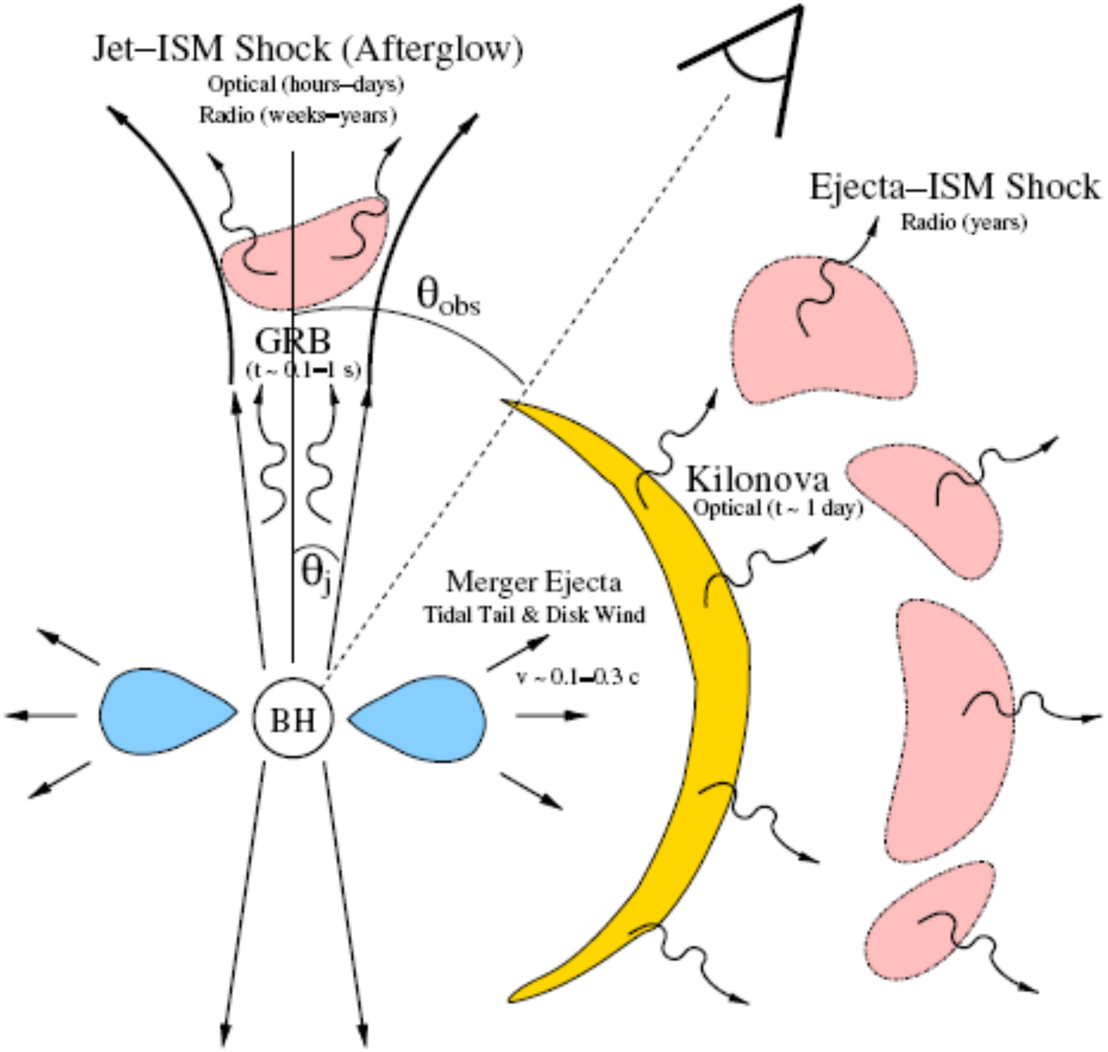
Classic binary-neutron-star EM counterparts

- **Short Gamma-ray burst**
- **Broadband sGRB afterglows**: From X-ray to radio
- **UV/optical/IR kilo-nova** peaks at ~ 1 day
- **Ejecta-ISM driven afterglows**

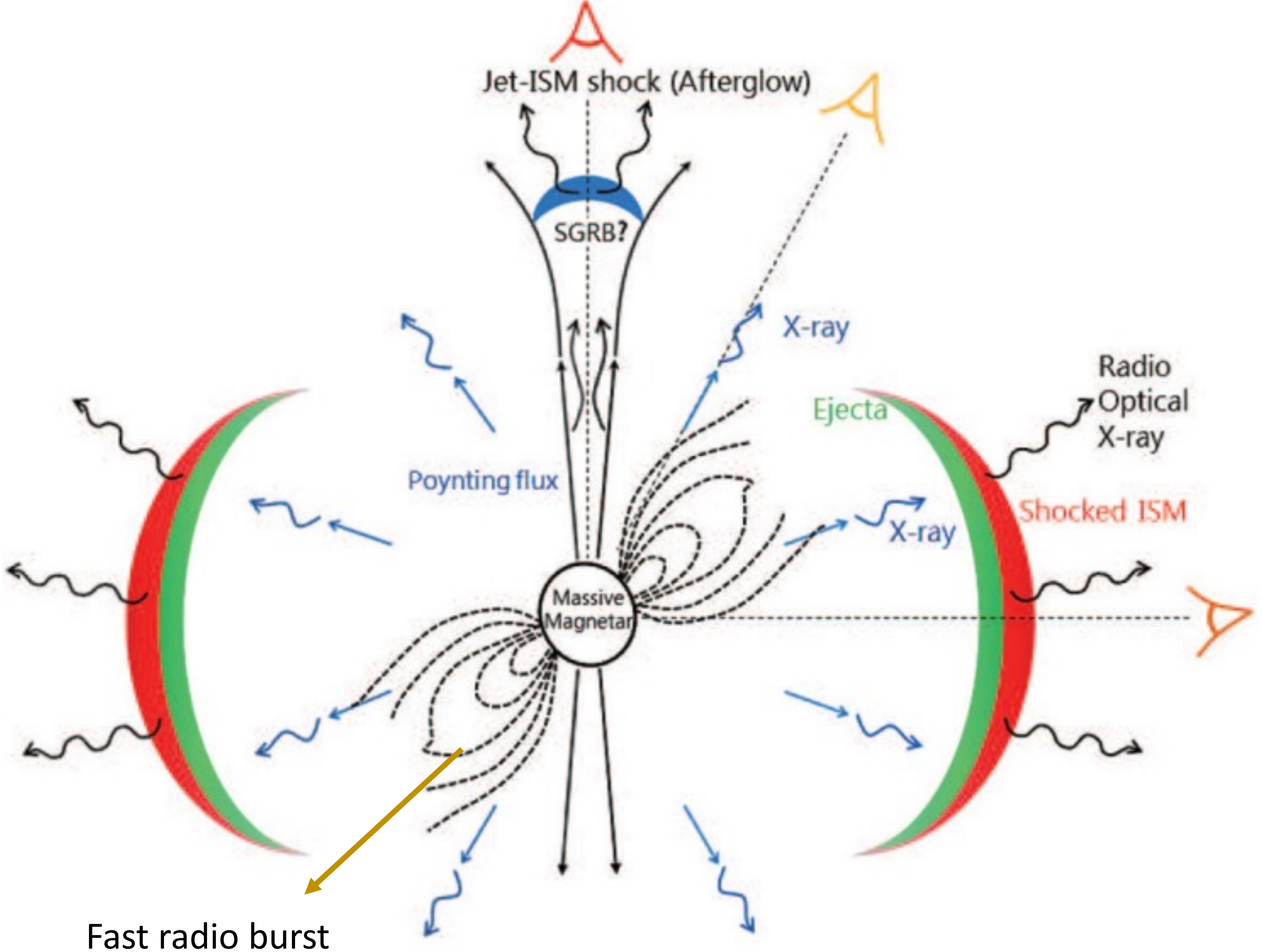


(Metzger & Berger 2012)

Magnetar-powered EM signals

- **Engine-fed kilonova (Mergernova)** (Yu et al. 2013, Ai et al. 2022)
- **Ejecta-ISM shock powered bright afterglow** (Gao et al. 2013)
- **(Short-GRB-less) X-ray internal plateau emission** (Zhang 2013)
- **Late-time X-ray flares** (Zhang 2006, Piro et al. 2019)
- **Fast radio burst induced by the collapse of the post-merger NS** (Zhang 2014, Falcke & Rezzolla 2014)

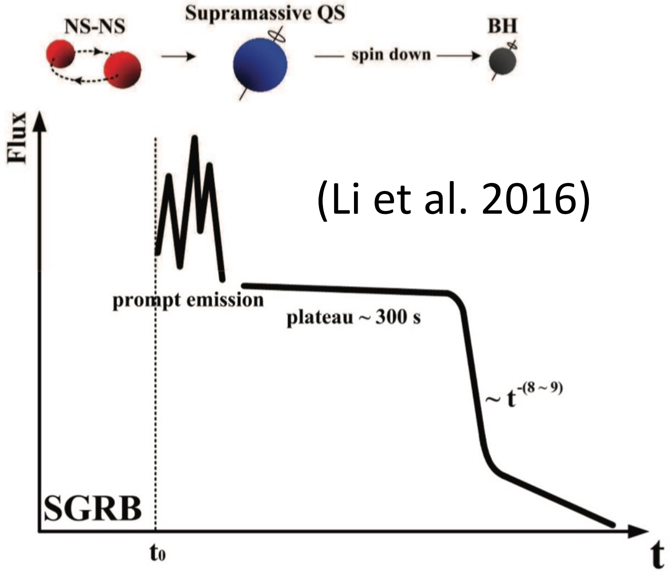
Jet can be launched with NS remnant (Ciolfi 2020)



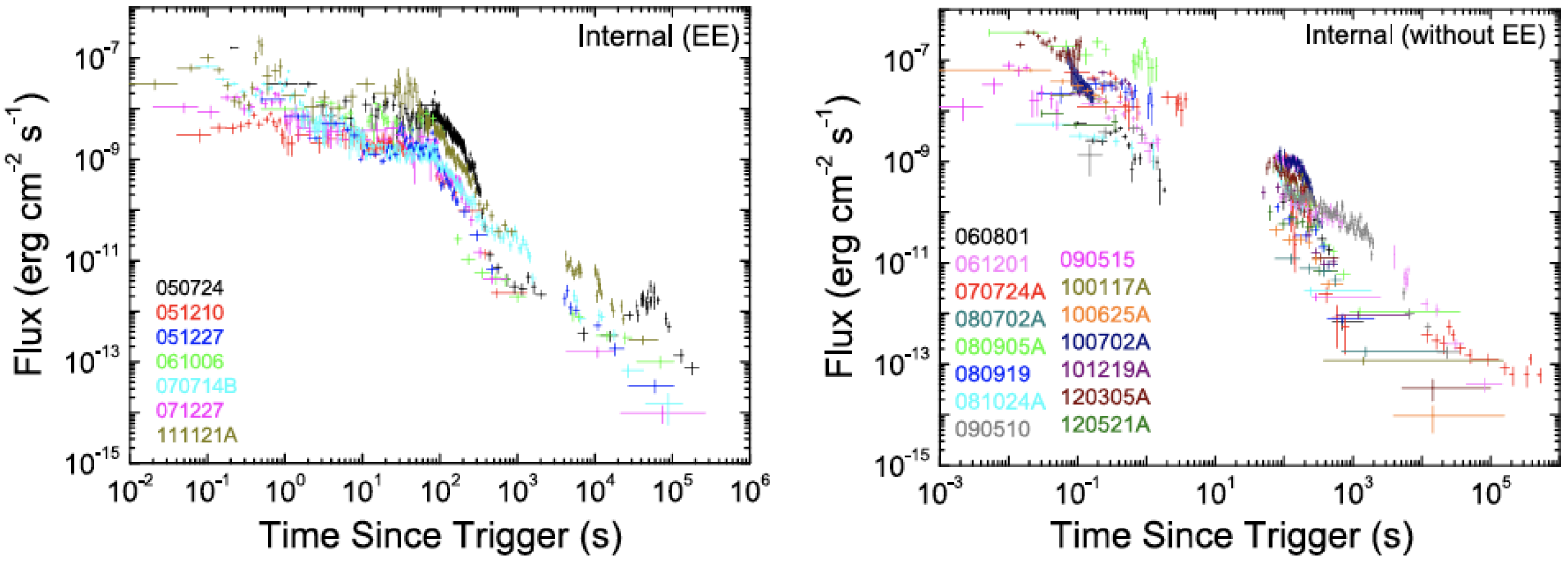
Fast radio burst

(Gao et al. 2013)

Magnetar-powered X-ray Internal Plateau



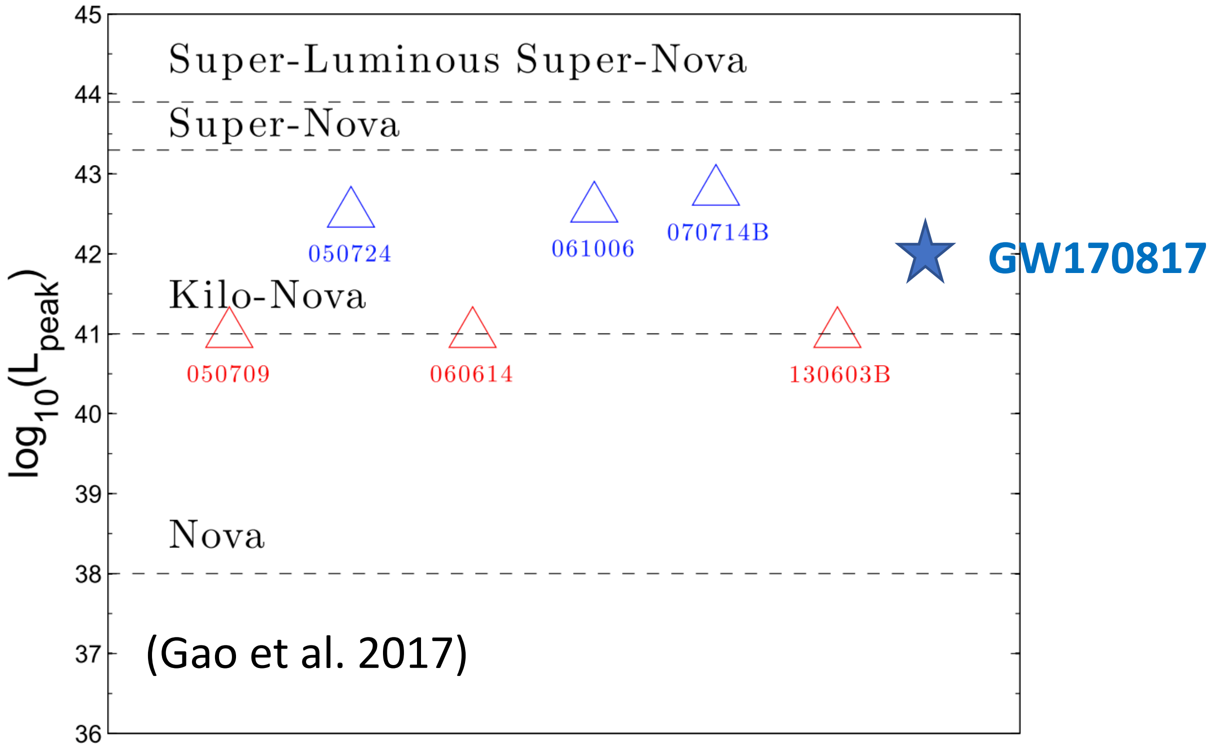
(Li et al. 2016)



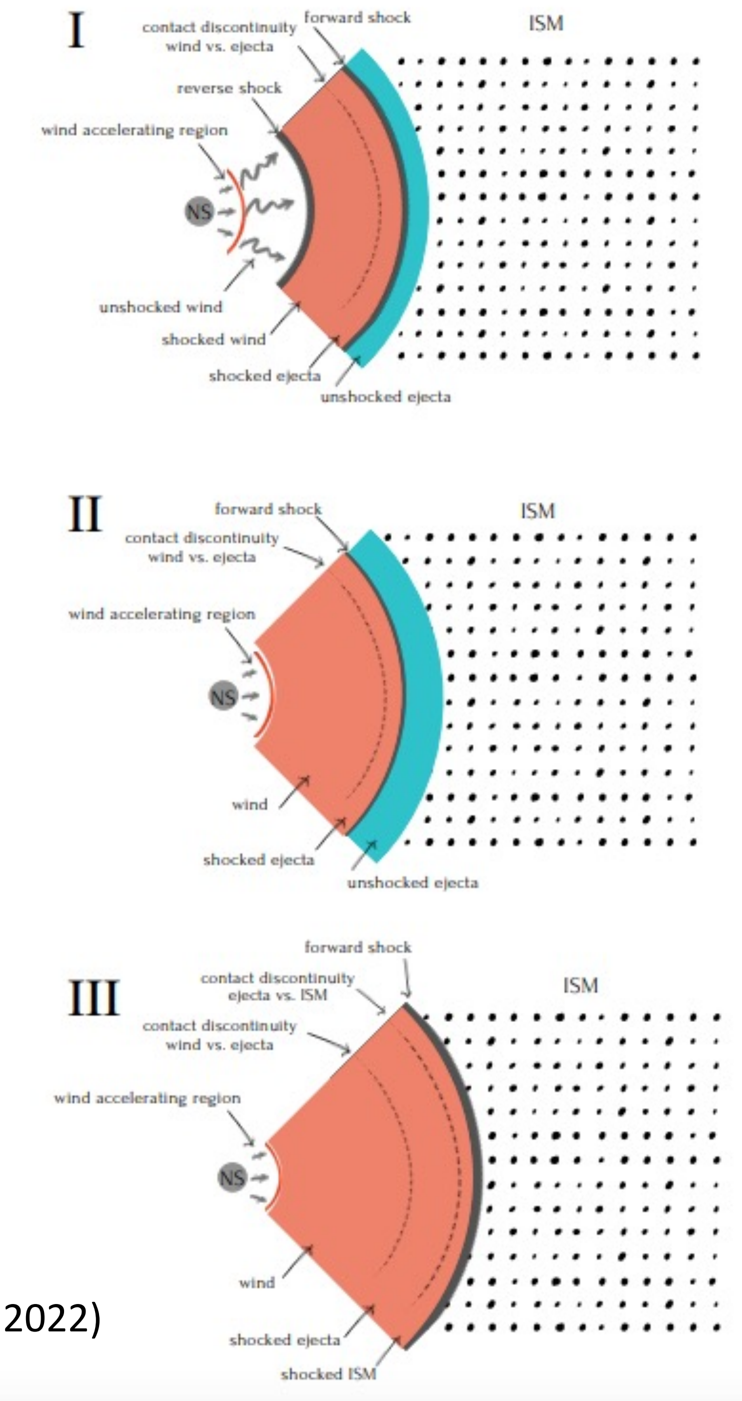
(Lü et al. 2015)

- X-ray plateau followed by a sharp decay ($F \propto 1/t^{>3}$)
- A long-live central engine is required to power the plateau
- Any external shock emission cannot have a decay slope steeper than 3 (Kumar & Panaitescu 2000; Kobayashi & Zhang 2007)
- The most straightforward interpretation: NS collapsing to BH

Magnetar-powered (engine-fed) kilonova



(Gao et al. 2017)



(Ai et al. 2022)

- For the kilonova associated with GW170817 $L_p \sim 10^{42}\mathrm{erg/s}$
  may be produced with short-lived Hyper-massive NS
- Some kilonova candidates have $L_p \sim 10^{43}\mathrm{erg/s}$.
  need long-lived magnetar as the central engine

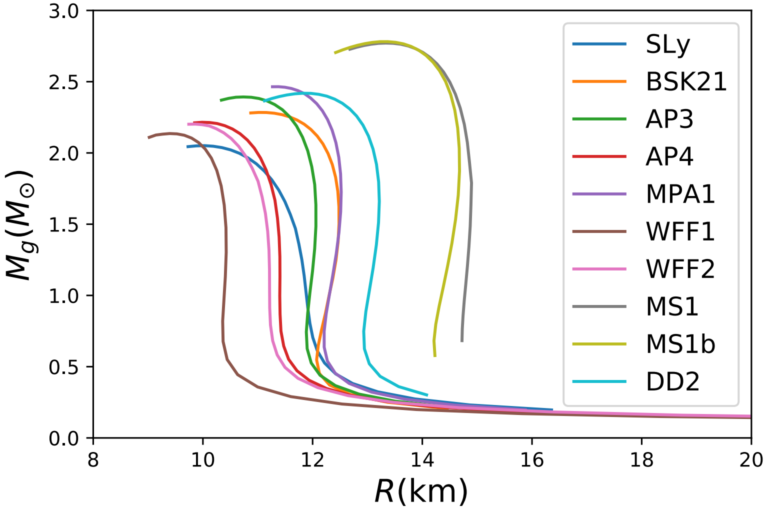
Rigid rotating NS as BNS merger remnant

- Two types of mass:
  Gravitational mass (M) vs. baryonic mass (M_b)
- Baryonic mass is conserved during the merger

$$M_1 + M_2 = \mathrm{M_{tot}} = 2.74\mathrm{M_\odot}$$

$$M_{b,1} + M_{b,2} = M_{b,rem} + M_{ej}$$

$$M_{rem,0}$$



GW170817

(Ai et al. 2020 APJ)

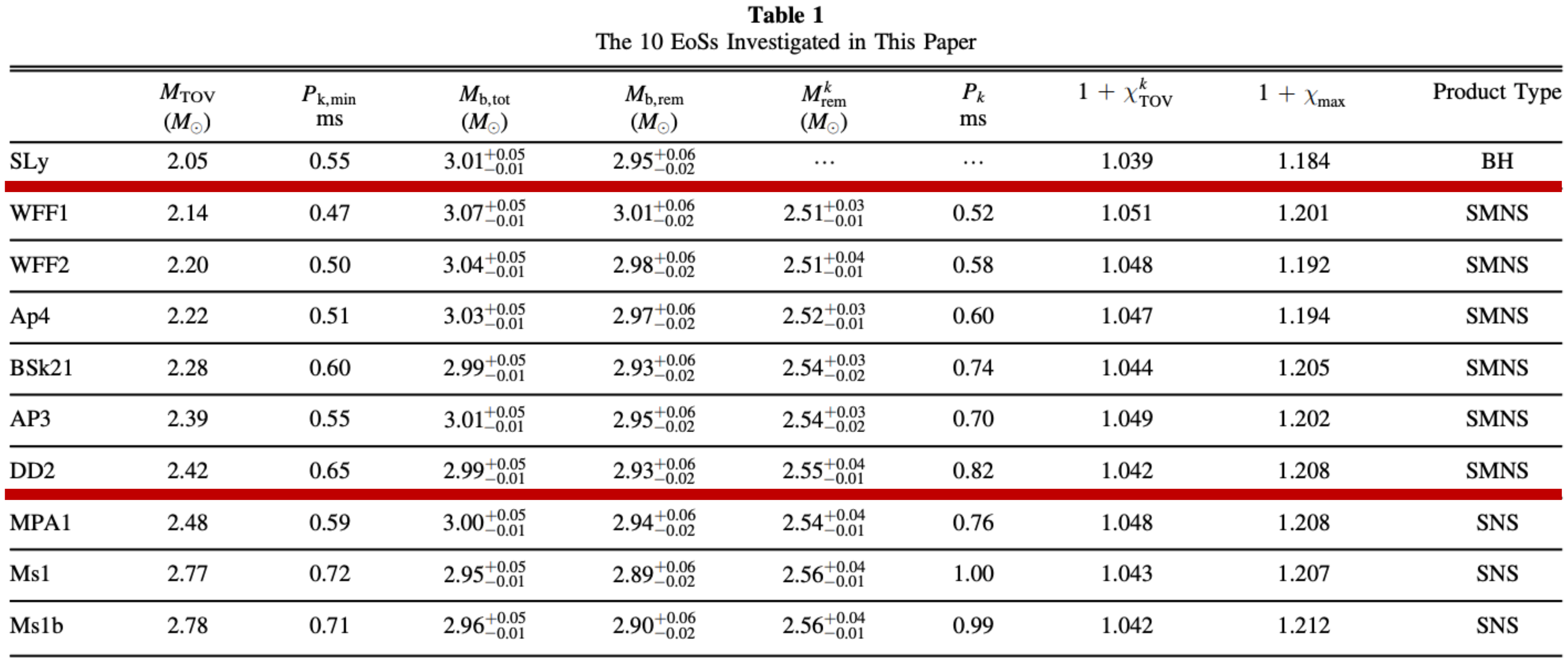


Table 1
The 10 EoSs Investigated in This Paper

	M_{TOV} ($M_\odot$)	$P_{\mathrm{k,min}}$ ms	$M_{\mathrm{b,tot}}$ ($M_\odot$)	$M_{\mathrm{b,rem}}$ ($M_\odot$)	M^k_{rem} ($M_\odot$)	P_k ms	$1+\chi^k_{\mathrm{TOV}}$	$1+\chi_{\mathrm{max}}$	Product Type
SLy	2.05	0.55	$3.01^{+0.05}_{-0.01}$	$2.95^{+0.06}_{-0.02}$	⋯	⋯	1.039	1.184	BH
WFF1	2.14	0.47	$3.07^{+0.05}_{-0.01}$	$3.01^{+0.06}_{-0.02}$	$2.51^{+0.03}_{-0.01}$	0.52	1.051	1.201	SMNS
WFF2	2.20	0.50	$3.04^{+0.05}_{-0.01}$	$2.98^{+0.06}_{-0.02}$	$2.51^{+0.04}_{-0.01}$	0.58	1.048	1.192	SMNS
Ap4	2.22	0.51	$3.03^{+0.05}_{-0.01}$	$2.97^{+0.06}_{-0.02}$	$2.52^{+0.03}_{-0.01}$	0.60	1.047	1.194	SMNS
BSk21	2.28	0.60	$2.99^{+0.05}_{-0.01}$	$2.93^{+0.06}_{-0.02}$	$2.54^{+0.03}_{-0.02}$	0.74	1.044	1.205	SMNS
AP3	2.39	0.55	$3.01^{+0.05}_{-0.01}$	$2.95^{+0.06}_{-0.02}$	$2.54^{+0.03}_{-0.02}$	0.70	1.049	1.202	SMNS
DD2	2.42	0.65	$2.99^{+0.05}_{-0.01}$	$2.93^{+0.06}_{-0.02}$	$2.55^{+0.04}_{-0.01}$	0.82	1.042	1.208	SMNS
MPA1	2.48	0.59	$3.00^{+0.05}_{-0.01}$	$2.94^{+0.06}_{-0.02}$	$2.54^{+0.04}_{-0.01}$	0.76	1.048	1.208	SNS
Ms1	2.77	0.72	$2.95^{+0.05}_{-0.01}$	$2.89^{+0.06}_{-0.02}$	$2.56^{+0.04}_{-0.01}$	1.00	1.043	1.207	SNS
Ms1b	2.78	0.71	$2.96^{+0.05}_{-0.01}$	$2.90^{+0.06}_{-0.02}$	$2.56^{+0.04}_{-0.01}$	0.99	1.042	1.212	SNS

Rigid rotating NS as NS-NS merger remnant

- Two types of mass:

  Gravitational mass (M) vs. baryonic mass (M_b)
- Baryonic mass is conserved during the merger

$$M_1 \quad + \quad M_2$$

$$\downarrow \qquad \downarrow$$

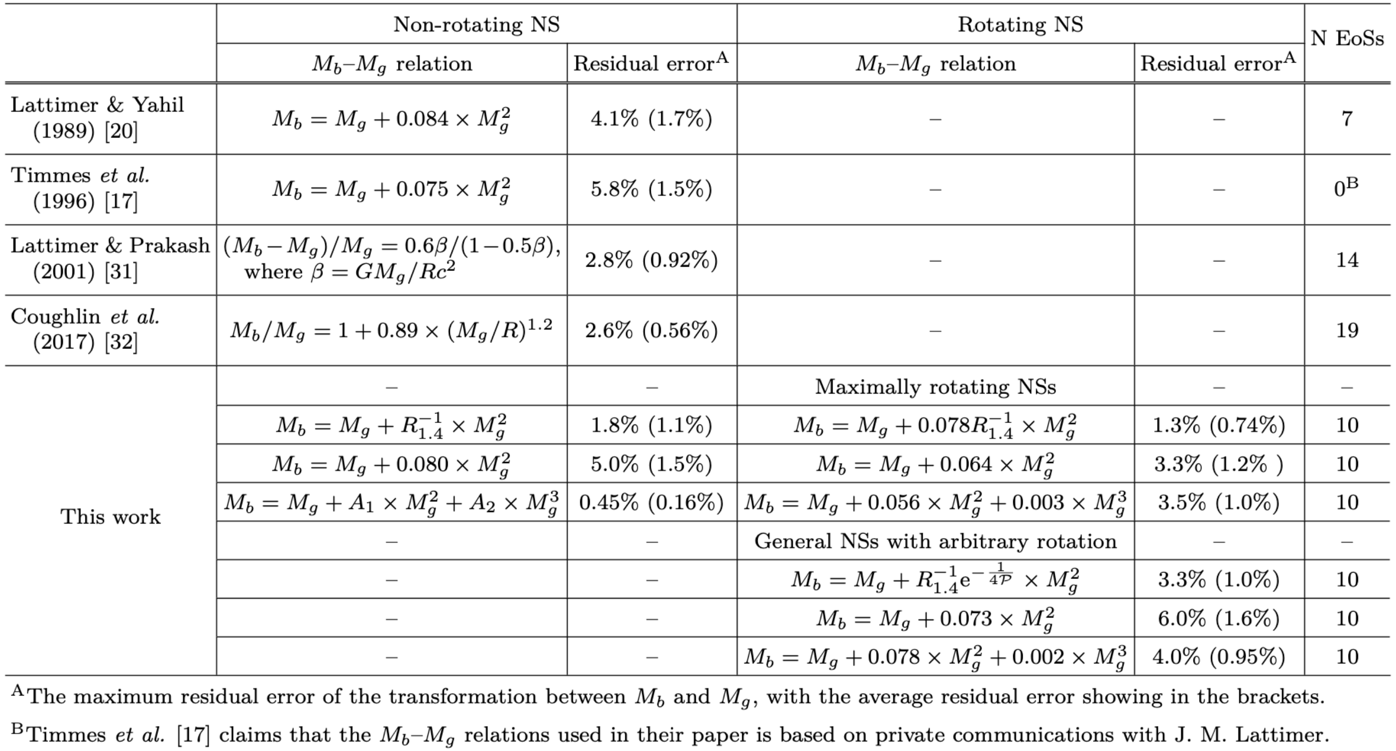
Universal relation For non(slowly)-rotating NSs $\boldsymbol{M_b = M + 0.080M^2}$

$$M_{b,1} + M_{b,2} = M_{b,rem} + M_{ej}$$

$$\downarrow$$

Universal relation For Keplerian rotating NSs $\boldsymbol{M_b = M + 0.064M^2}$

$$M_{rem,0}$$



	Non-rotating NS		Rotating NS		N EoSs
	M_b–M_g relation	Residual error^A	M_b–M_g relation	Residual error^A	
Lattimer & Yahil (1989) [20]	$M_b = M_g + 0.084 \times M_g^2$	4.1% (1.7%)	–	–	7
Timmes *et al.* (1996) [17]	$M_b = M_g + 0.075 \times M_g^2$	5.8% (1.5%)	–	–	0^B
Lattimer & Prakash (2001) [31]	$(M_b - M_g)/M_g = 0.6\beta/(1-0.5\beta)$, where $\beta = GM_g/Rc^2$	2.8% (0.92%)	–	–	14
Coughlin *et al.* (2017) [32]	$M_b/M_g = 1 + 0.89 \times (M_g/R)^{1.2}$	2.6% (0.56%)	–	–	19
This work	–	–	Maximally rotating NSs	–	–
	$M_b = M_g + R_{1.4}^{-1} \times M_g^2$	1.8% (1.1%)	$M_b = M_g + 0.078R_{1.4}^{-1} \times M_g^2$	1.3% (0.74%)	10
	$M_b = M_g + 0.080 \times M_g^2$	5.0% (1.5%)	$M_b = M_g + 0.064 \times M_g^2$	3.3% (1.2%)	10
	$M_b = M_g + A_1 \times M_g^2 + A_2 \times M_g^3$	0.45% (0.16%)	$M_b = M_g + 0.056 \times M_g^2 + 0.003 \times M_g^3$	3.5% (1.0%)	10
	–	–	General NSs with arbitrary rotation	–	–
	–	–	$M_b = M_g + R_{1.4}^{-1} e^{-\frac{1}{4P}} \times M_g^2$	3.3% (1.0%)	10
	–	–	$M_b = M_g + 0.073 \times M_g^2$	6.0% (1.6%)	10
	–	–	$M_b = M_g + 0.078 \times M_g^2 + 0.002 \times M_g^3$	4.0% (0.95%)	10

[A] The maximum residual error of the transformation between M_b and M_g, with the average residual error showing in the brackets.

[B] Timmes *et al.* [17] claims that the M_b–M_g relations used in their paper is based on private communications with J. M. Lattimer.

(Gao et al. 2020 Frontiers of Physics)

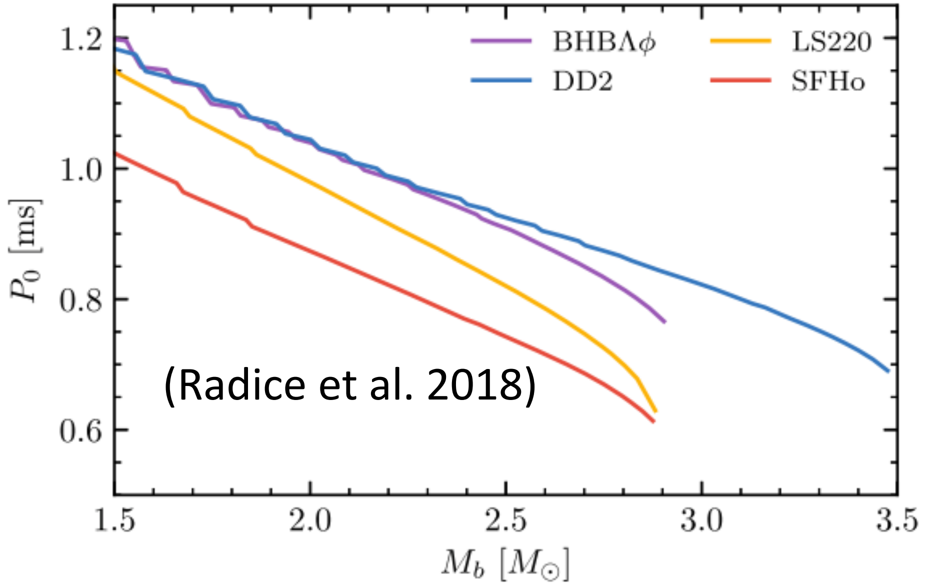
Rigid rotating NS as NS-NS merger remnant

- Two types of mass:
  Gravitational mass (M) vs. baryonic mass (M_b)
- Baryonic mass is conserved during the merger

$$\begin{tikzcd}
M_1 \arrow[d] & + & M_2 \arrow[d] & & & & \\
M_{b,1} & + & M_{b,2} & = & M_{b,rem} \arrow[d] & + & M_{ej} \\
 & & & & M_{rem,0} & &
\end{tikzcd}$$

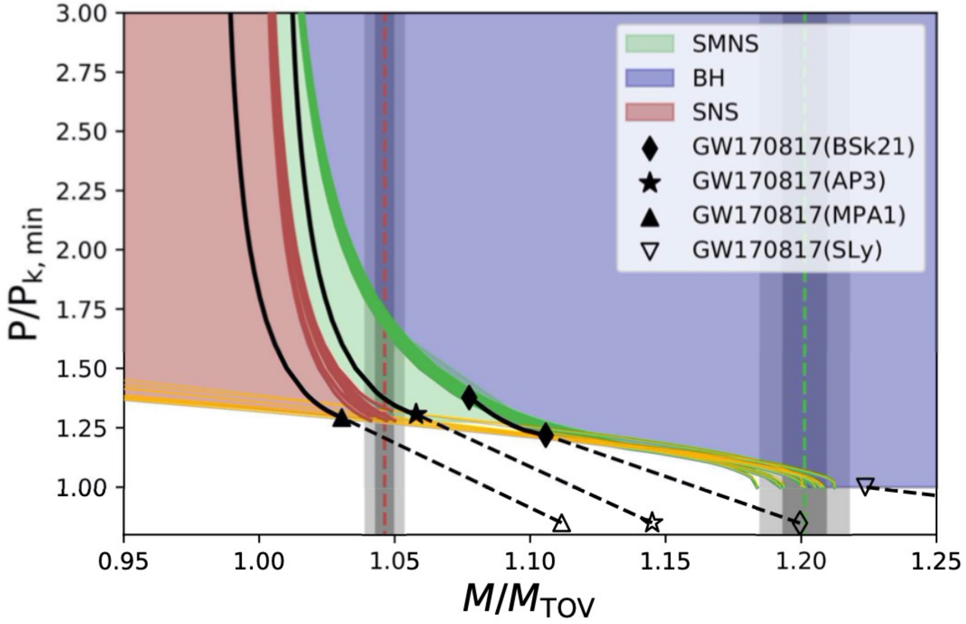
- Define $\chi_{max} = (M_{max} - M_{TOV})/M_{TOV}$
  $\chi_{TOV} = (M - M_{TOV})/M_{TOV}$, for $M = M(P = P_k,\ M_\infty = M_{TOV})$
- $\chi_{max} \approx 0.2;\ \chi_{TOV} \approx 0.05$

$\boldsymbol{M_{rem,0} > (1 + \chi_{max})M_{TOV}}$ → ***BH***
$\boldsymbol{(1 + \chi_{TOV})M_{TOV} < M_{rem,0} < (1 + \chi_{max})M_{TOV}}$ → ***SMNS***
$\boldsymbol{M_{rem,0} < (1 + \chi_{TOV})M_{TOV}}$ → ***SNS***

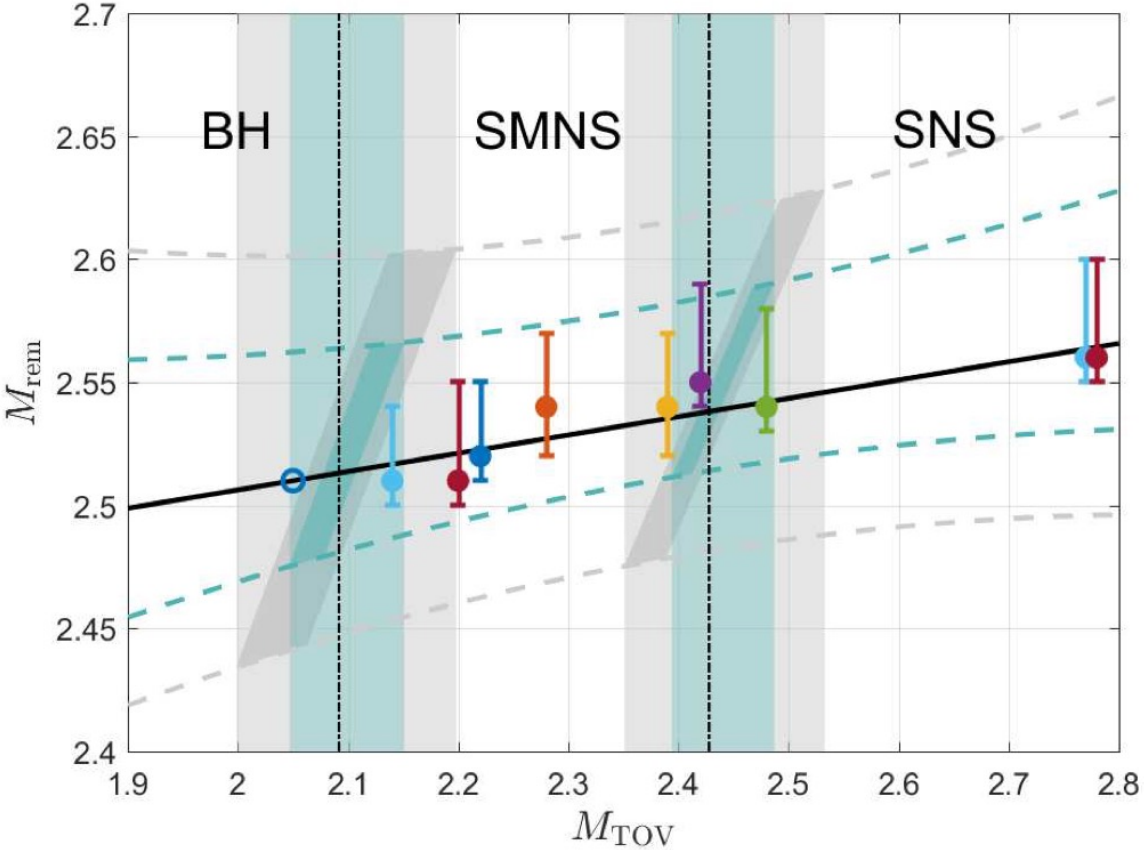


(Radice et al. 2018)

(Ai et al. 2020 APJ)

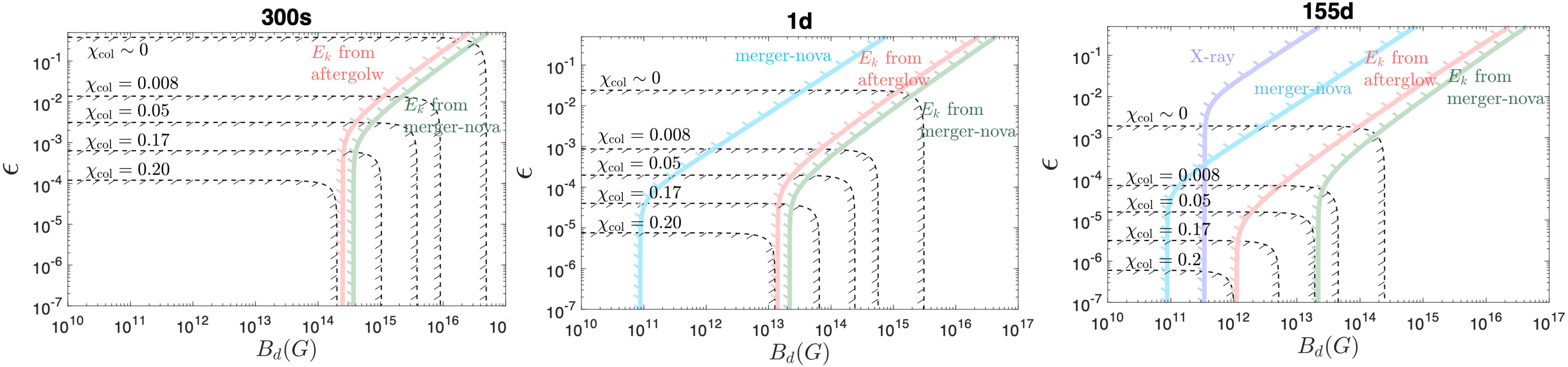


GW170817



- If a BH was formed directly after the HMNS, We have $M_{TOV} < 2.09^{+0.11}_{-0.09} M_\odot$
- If a SMNS was formed after the differentially rotating phase and finally collapses into a BH, We have $2.09^{+0.11}_{-0.09} M_\odot < M_{TOV} < 2.43^{+0.10}_{-0.08} M_\odot$
- If a SNS was formed, We have $M_{TOV} > 2.43^{+0.10}_{-0.08} M_\odot$. (2σ)

Constraints on the NS Properties in the MNS Cases



Following the spin period evolution of a SMNS, given its lifetime and M_{TOV}, constraints can be put on B (EM radiation) and ϵ (GW radiation).

(**Ai**, Gao & Zhang 2020, The *Astrophysical Journal*)

(**Ai** et al. 2018, The *Astrophysical Journal*)

Low B, NS hides in the center?

High B NS but quickly collapses or GW dominated spin-down?

What’s the merger product of GW170817?

- Hyper-massive NS → BH?

  $M_{TOV} <\sim 2.1 M_\odot$, close the mass of observed massive pulsars?

  PSR J1614-2230: $1.97 \pm 0.04 M_\odot$(Demorest et al. 2010)
  PSR J0348+0432: $2.01 \pm 0.04 M_\odot$ (Antoniadis et al. 2013)
  PSR J0740+6620: $2.14^{+0.10}_{-0.09} M_\odot$ (Cormartie et al. 2019)

  30% SGRBs have X-ray internal plateaus?

- Hyper-massive NS →Super-massive NS (→ BH)?

  short-lived SMNS? $M_{TOV} \sim 2.1 M_\odot$

  long-lived SMNS? High B, but GW dominated spin-down (✓)

  stable NS? High B, but GW dominated spin-down (✓)