What have we really learned about the nuclear equation of state from GW170817 (Part 1)?

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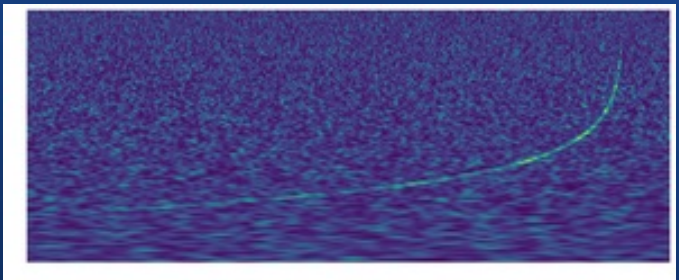
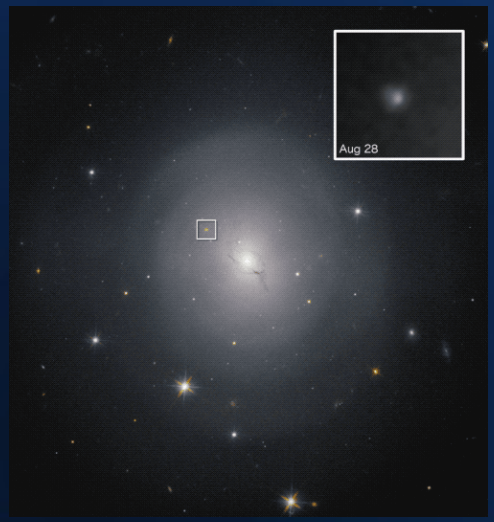
GW170817: First multimessenger detection of a compact binary with at least one neutron star

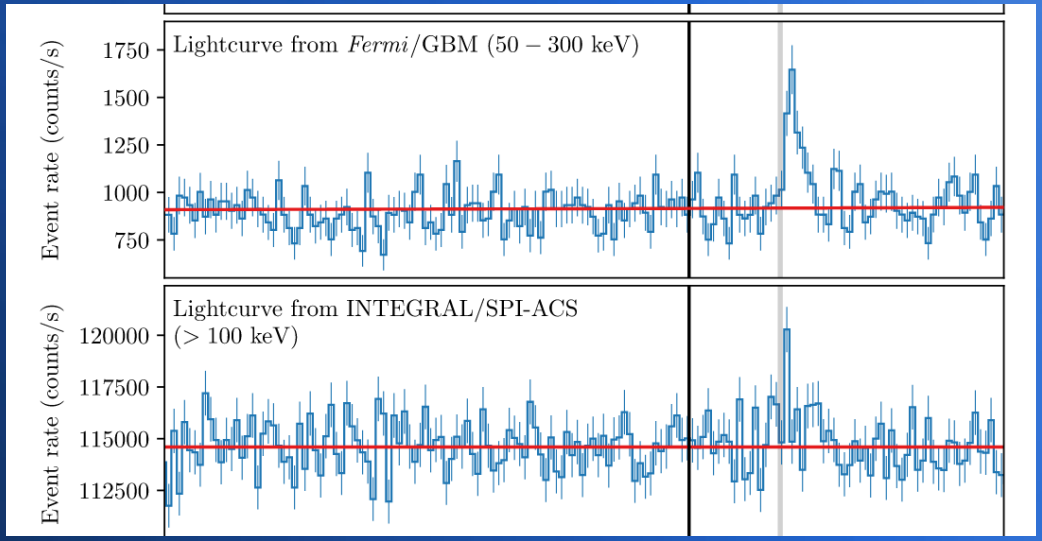
GWs: LIGO/Virgo



Kilonova AT2017gfo



GRB170817A: Fermi-GBM/Integral



A successful binary compact object model must explain all observations!

The observations can constrain the parameter space of models.

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GW170817: open questions

- Was it a binary neutron star or a binary black hole neutron star (BHNS)?
  - What constraints on the EOS in the BHNS scenario?
- Assuming a binary neutron star
  - How strong are the constraints from GWs?
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  - How do hybrid hadron-quark EOSs modify the story?

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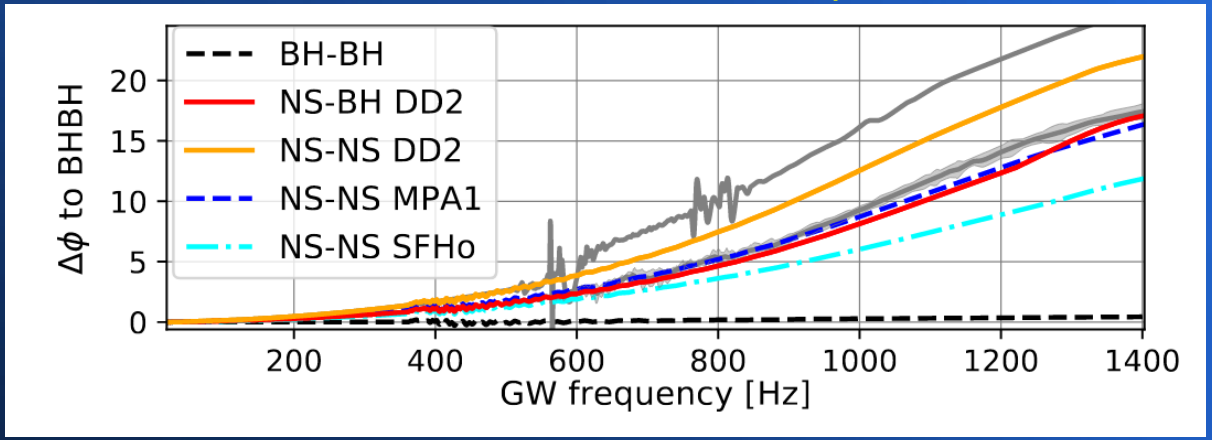
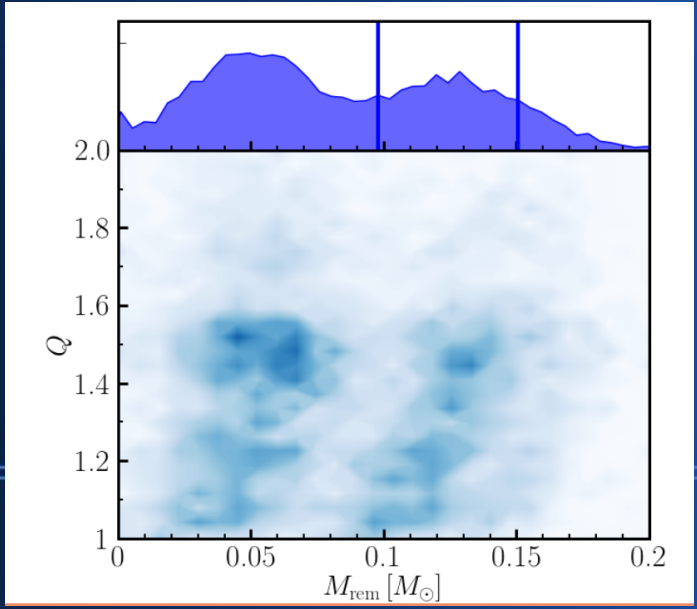
Was GW170817 a BHNS?

- BHNS GWs are compatible with GW170817 (Hinderer et al. 2018)



- About 40% of the GW parameters (C=M/R, Q, χ_{BH}) are compatible with EM

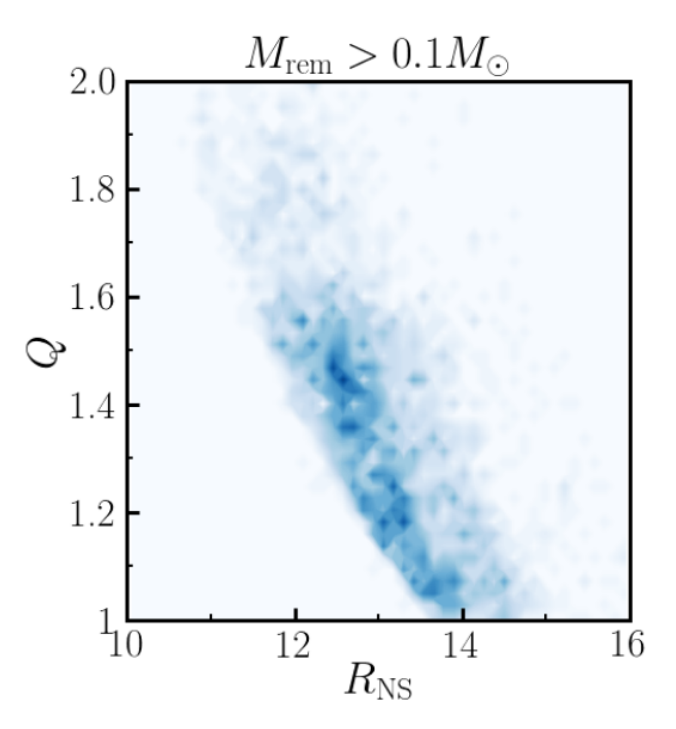


GW170817 is compatible with BHNS: EOS constraints?

- If GW170817 is BHNS → no constraint on the maximum TOV mass

  → no constraint on radius from threshold mass for prompt collapse in BNS scenario

- GW parameters (C=M/R, Q, χ_{BH}) and EM → joint constraint on Q, R_{NS}



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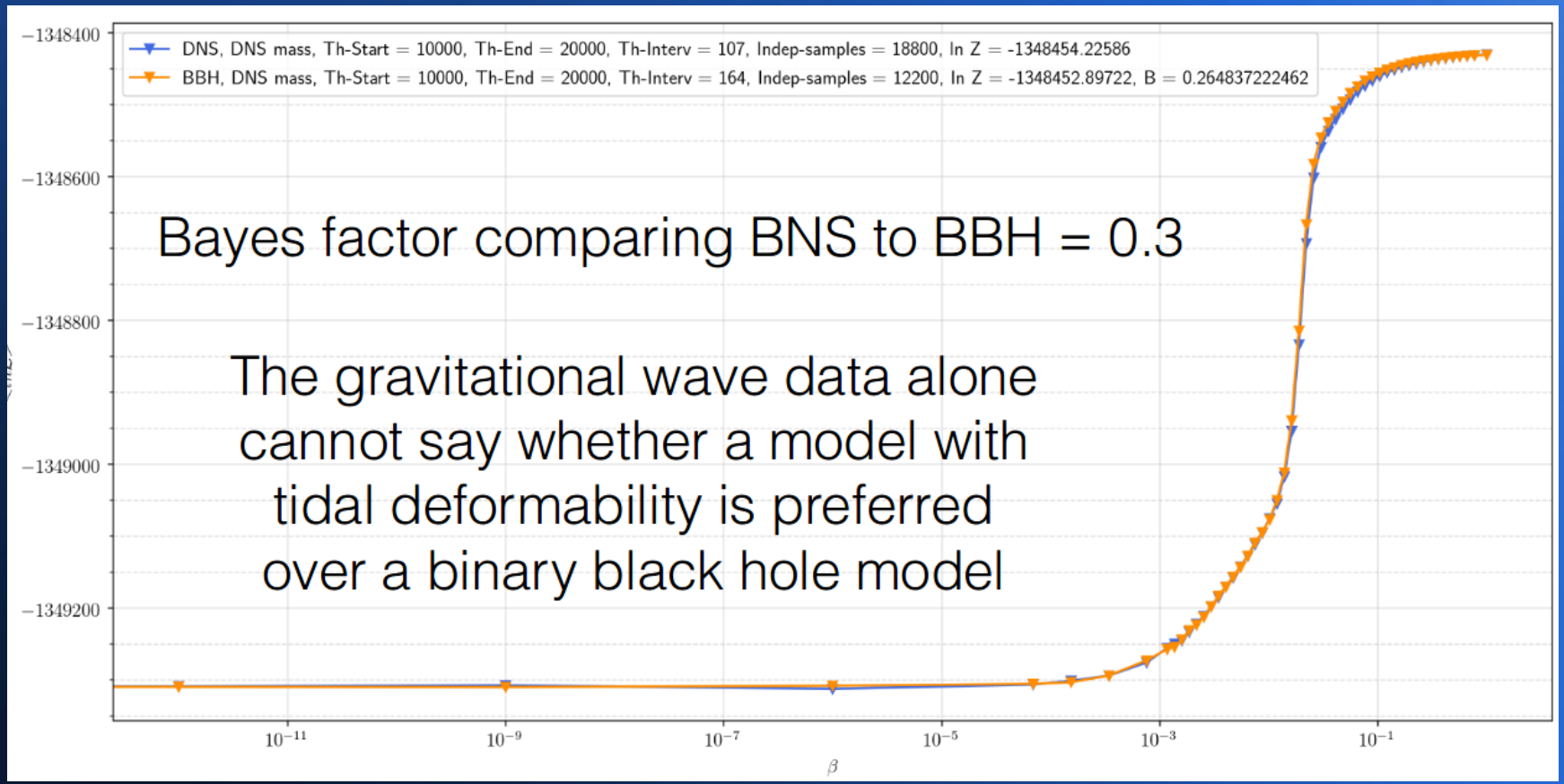
Does GW170817 favor BNS over BHBH?



Brown 2019 APS April Meeting

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Does GW170817 favor BNS over BHBH?

If model selection does not favor BNS over BHBH, how can we trust GW170817 tidal deformability constraints → EOS/radius constraints based on GWs alone?

How strong are the EOS constraints from GWs?

GW170817: open questions

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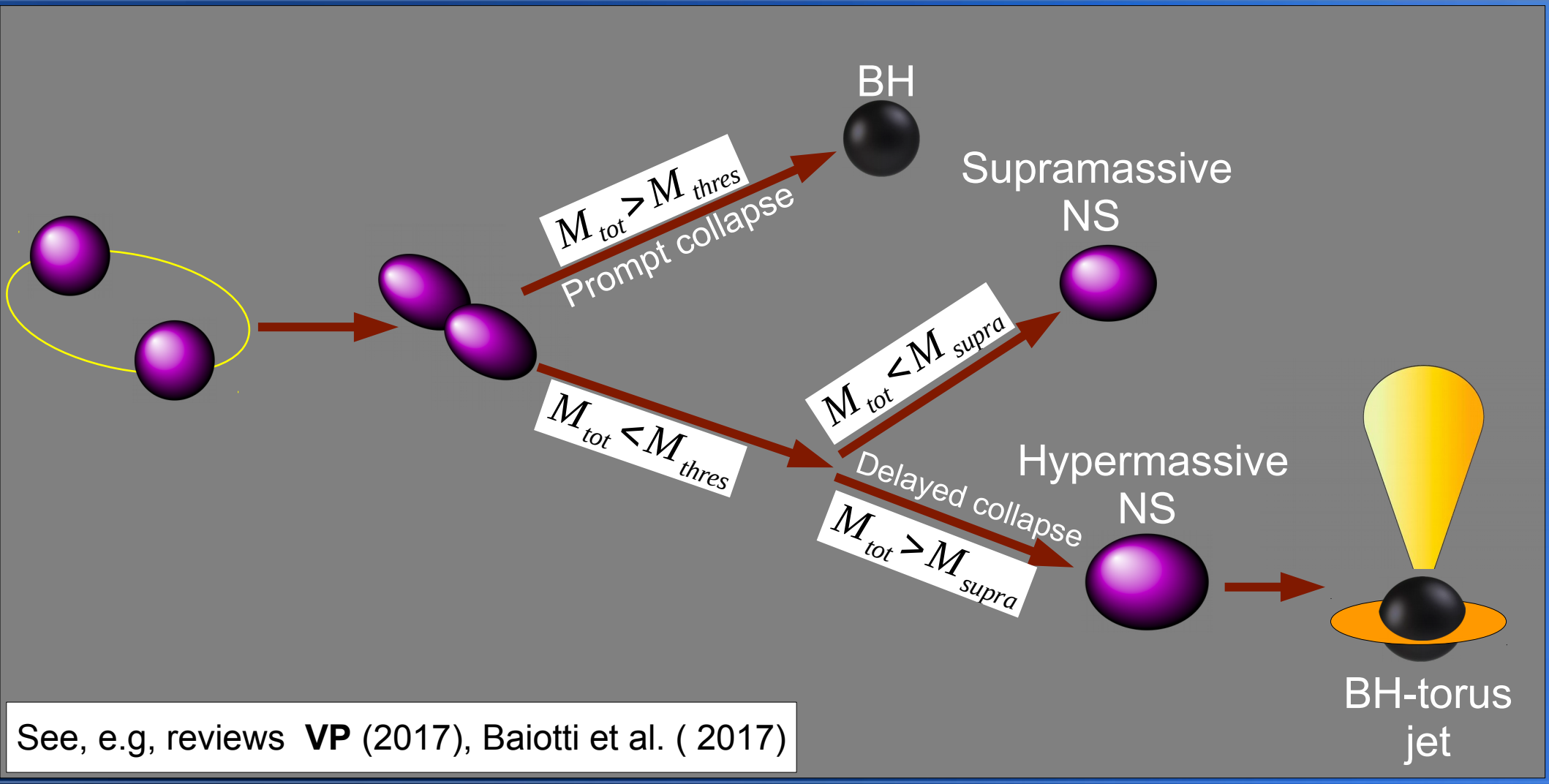
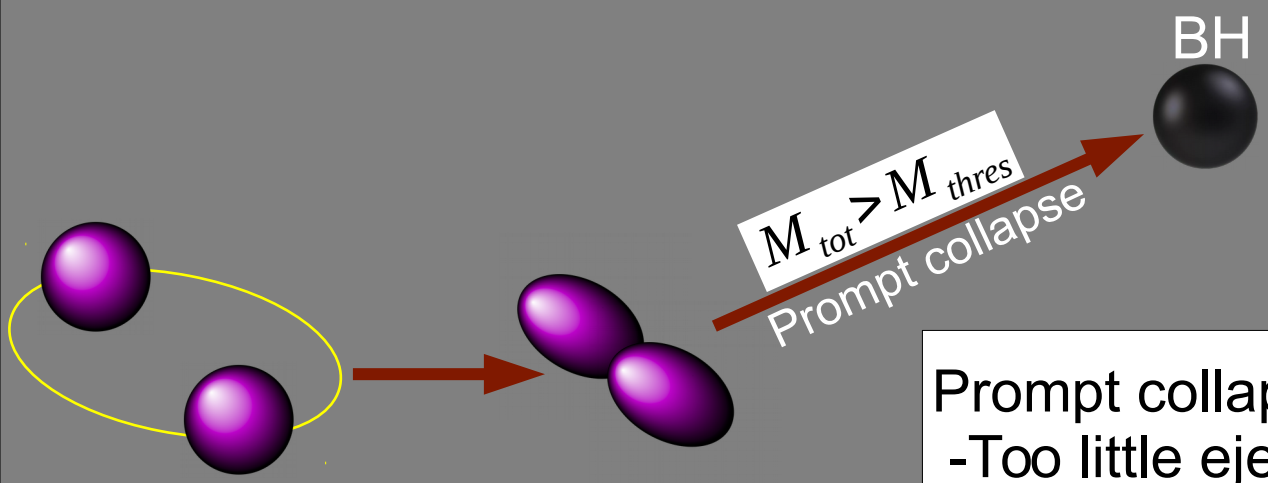
Binary neutron star (BNS) merger outcomes: a decade of computational gravity



See, e.g, reviews **VP** (2017), Baiotti et al. (2017)

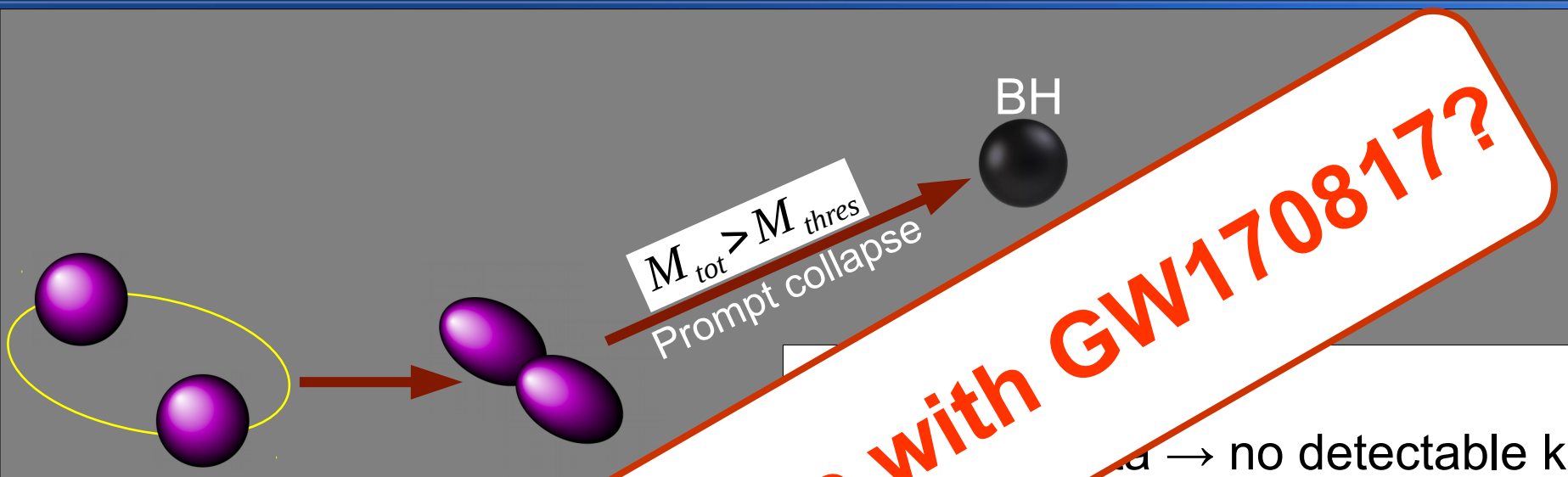
Prompt collapse to BH?



Prompt collapse:
-Too little ejecta → no detectable kilonova

- No B-field amplification + tiny disk →
No jets → No GRBs (Ruiz et al. (2017)

Prompt collapse to BH?



Incompatible with GW170817?

→ no detectable kilonova

-field amplification + tiny disk →
No jets → No GRBs (Ruiz et al. (2017)

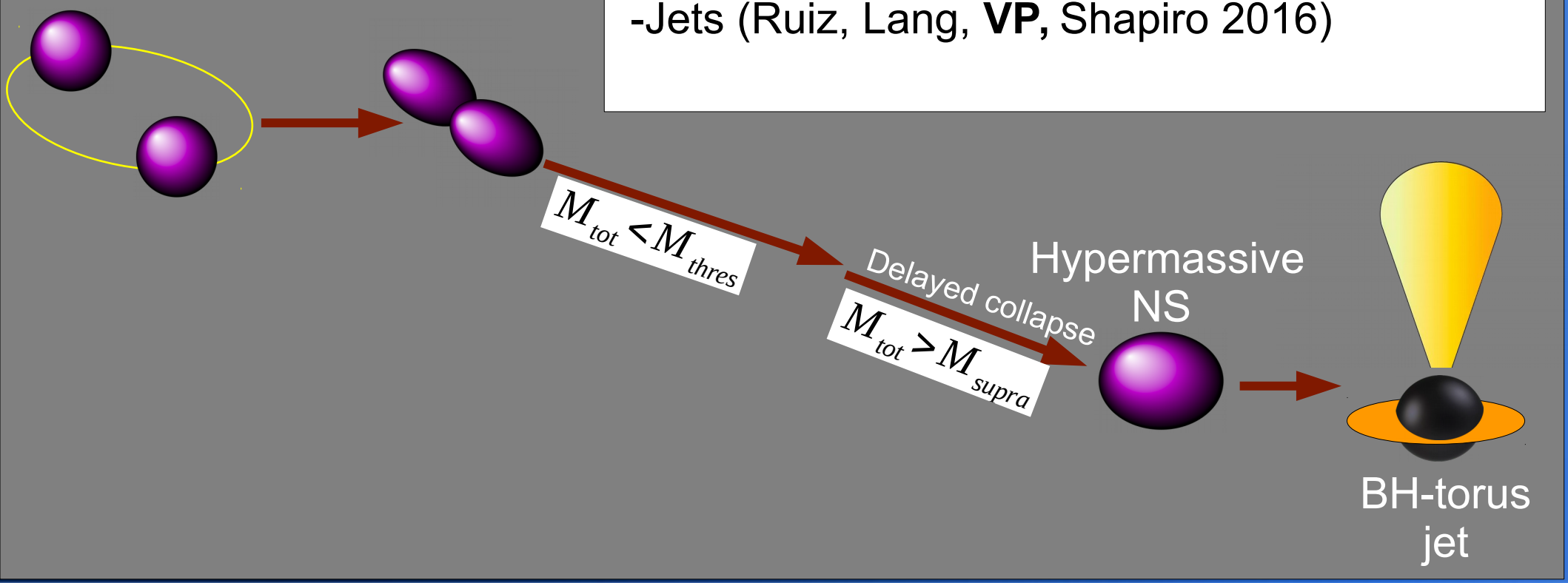
Constraint

$$M_{tot} < M_{thres}$$

Delayed collapse scenario?

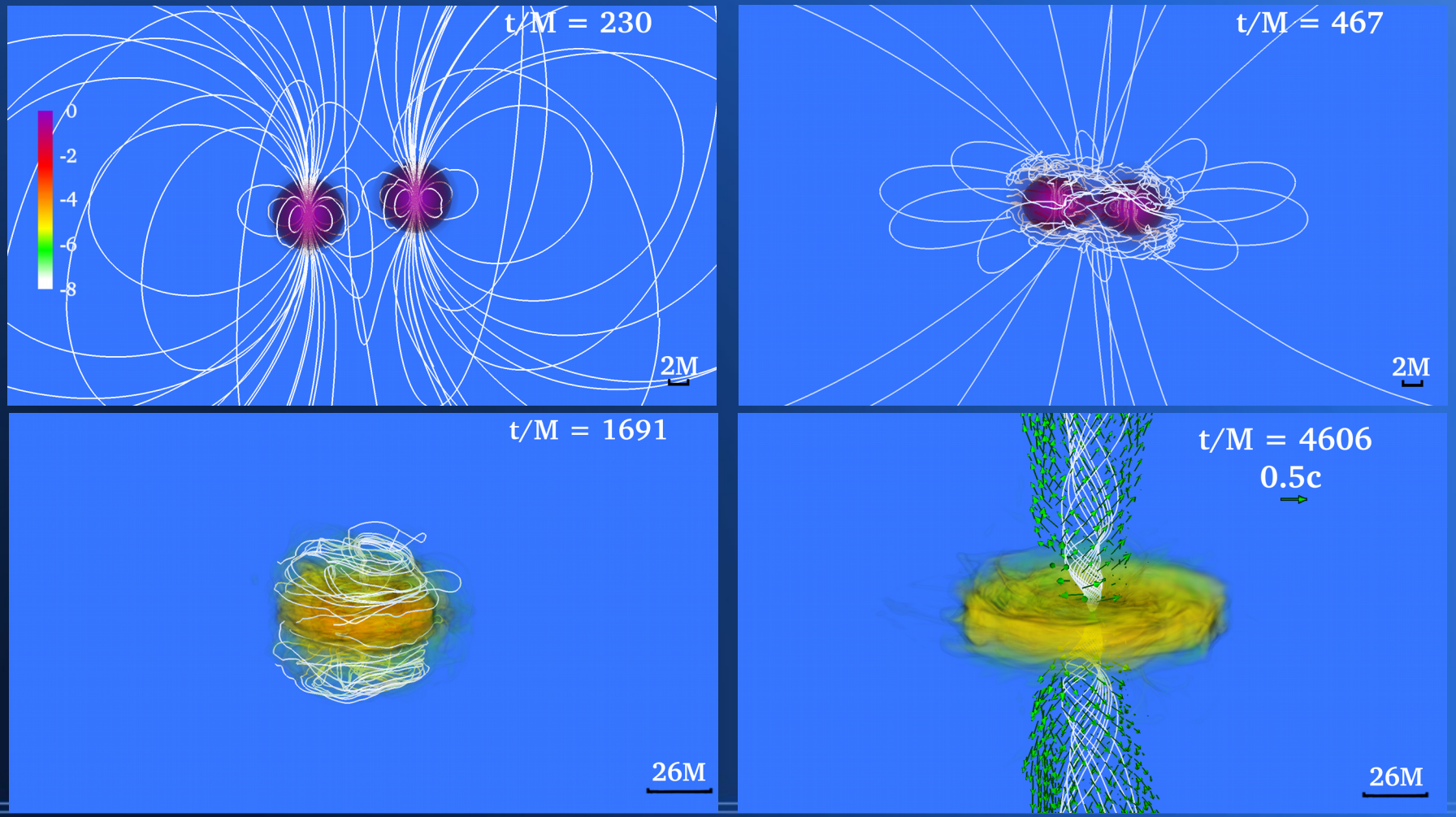
-Right amount of ejecta
(Shibata et al. 2017, Radice et al. 2017...)

-Jets (Ruiz, Lang, **VP,** Shapiro 2016)

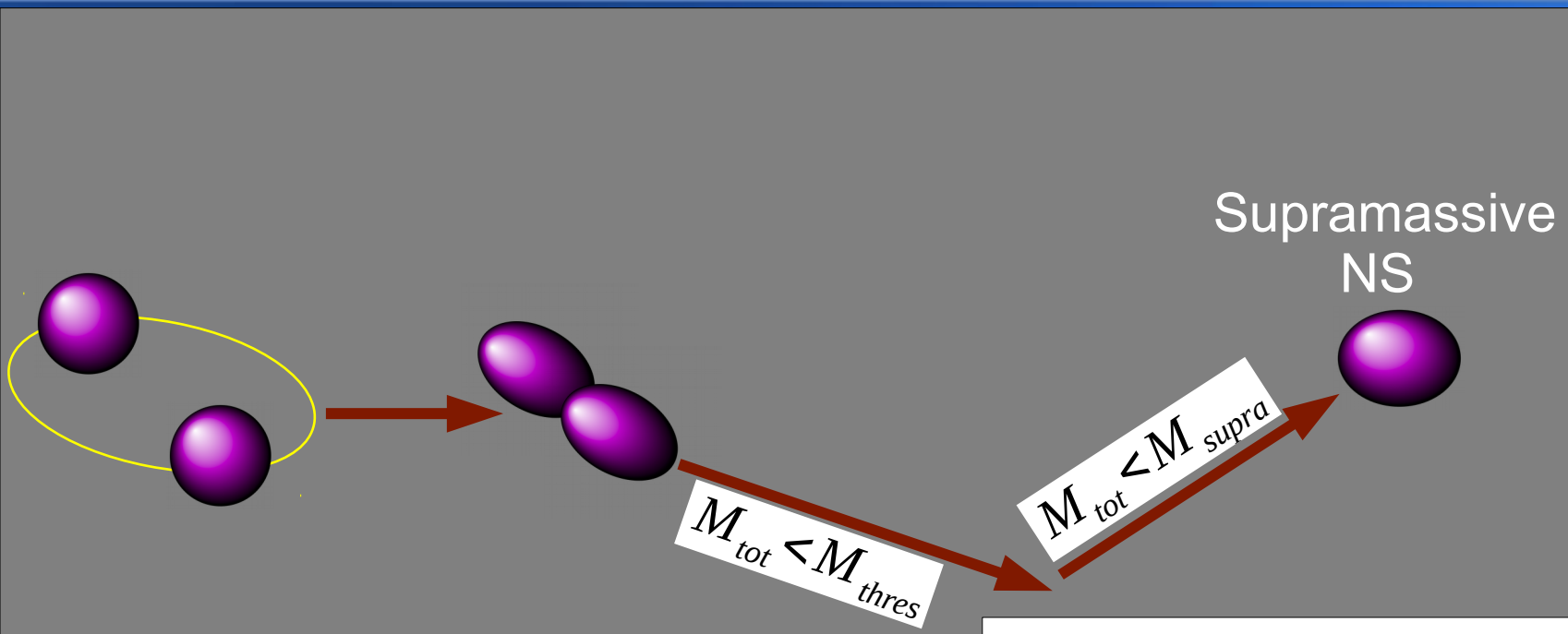


Incipient jets from delayed collapse → sGRBs

- Ruiz, Lang, VP, Shapiro (2016)



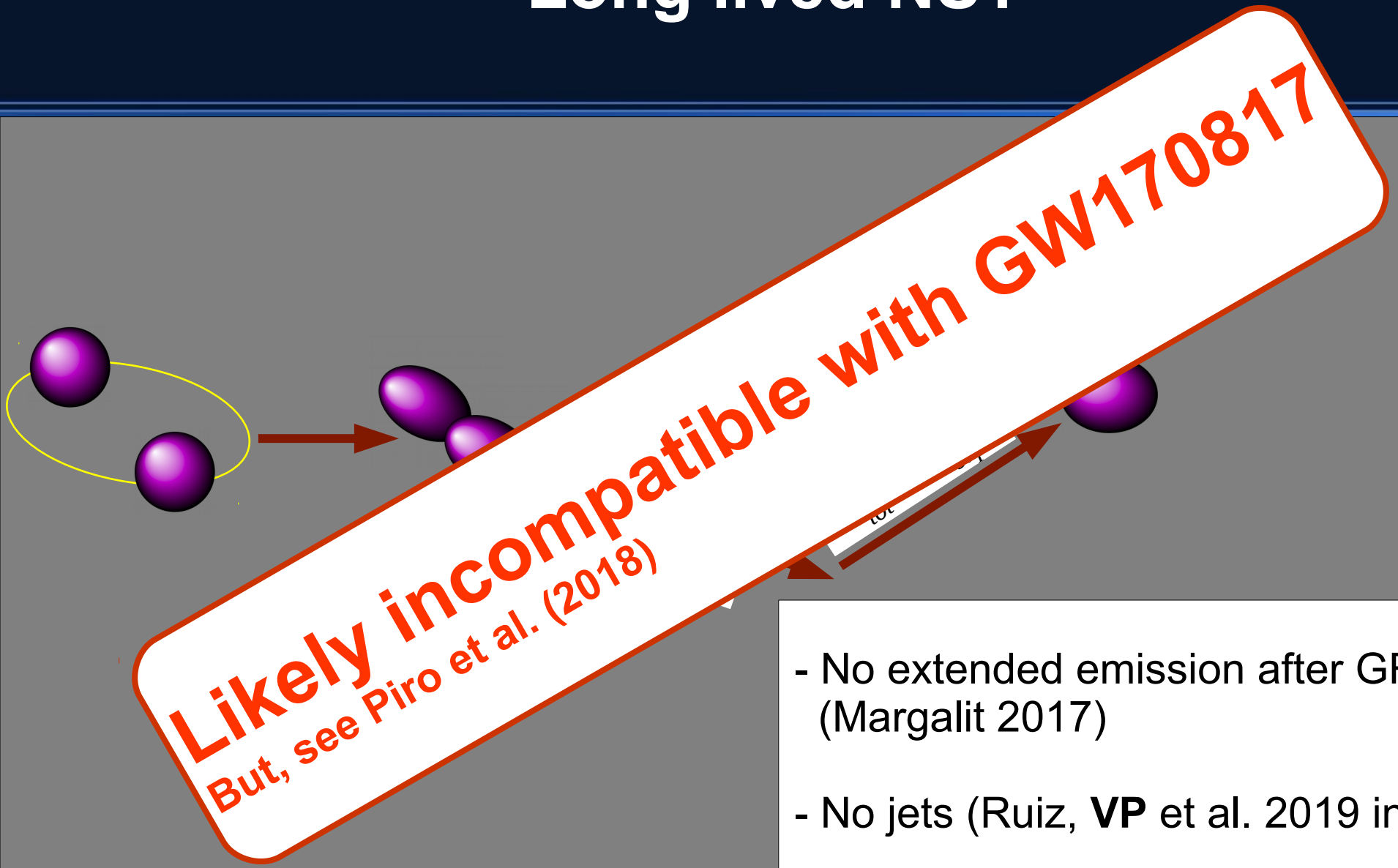
Long lived NS?



- No extended emission after GRB (Margalit 2017)

- No jets (Ruiz, **VP** et al. 2019 in prep.)

Long lived NS?



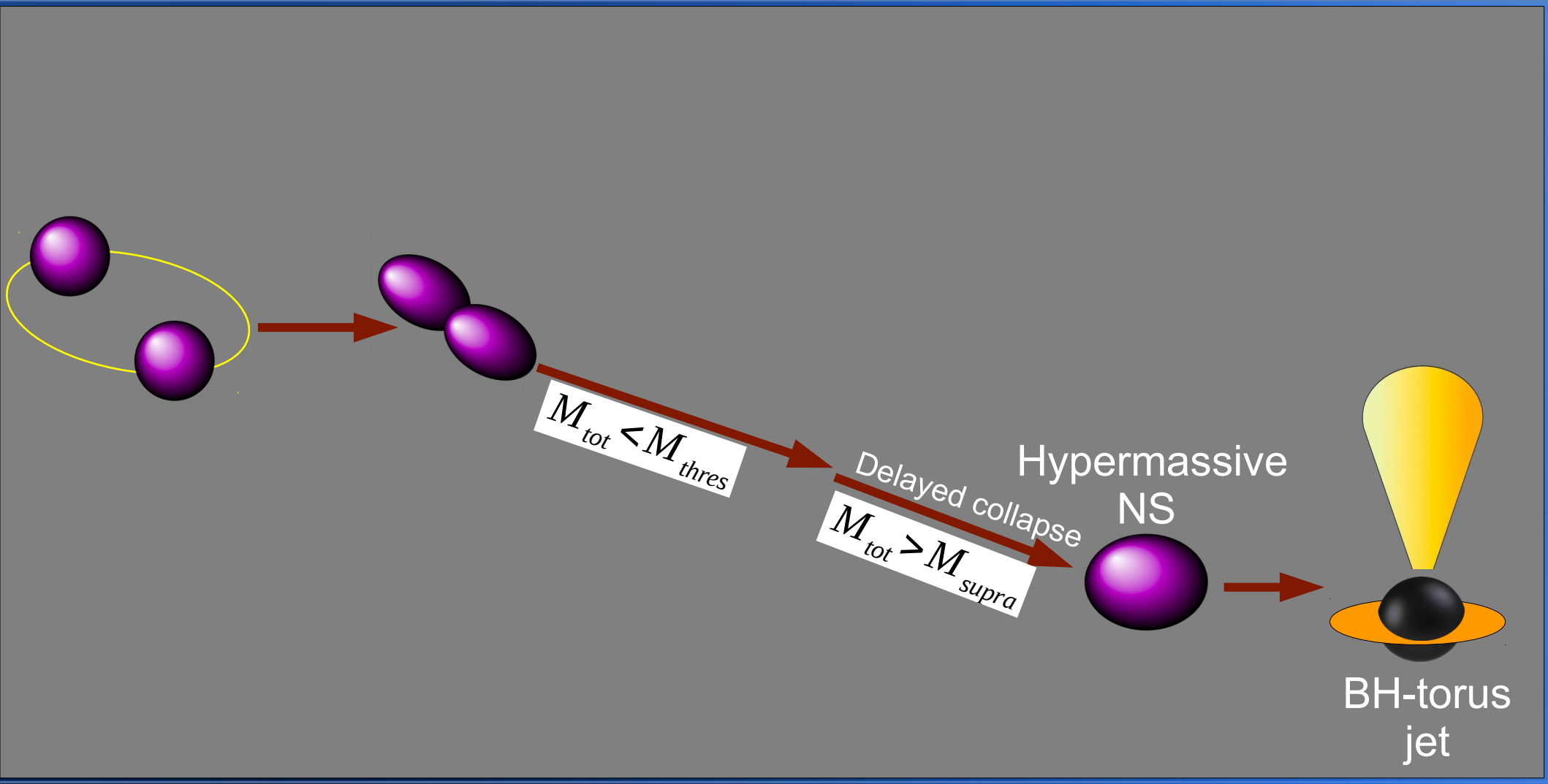
Likely incompatible with GW170817

But, see Piro et al. (2018)

- No extended emission after GRB (Margalit 2017)

- No jets (Ruiz, **VP** et al. 2019 in prep.)

Likely scenario for GW170817: delayed collapse



Constraint from GW170817

$$M_{tot} > M_{supra}$$

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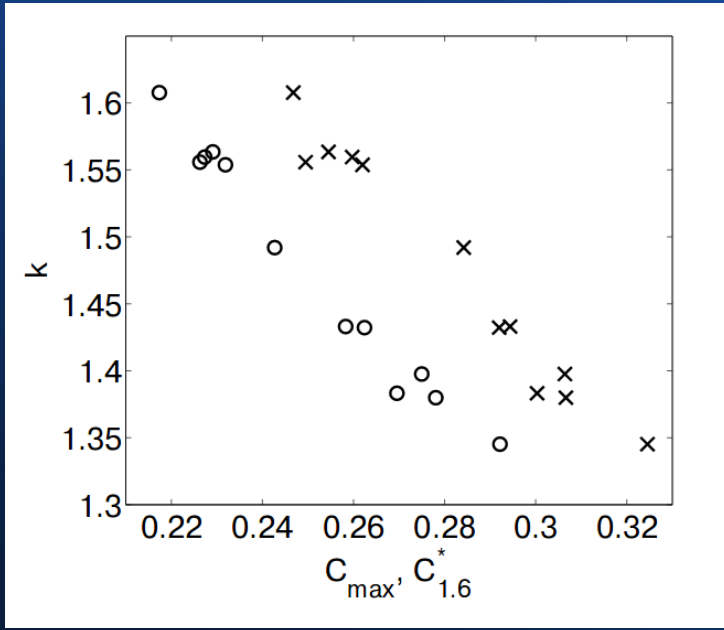
Constraint

$$M_{tot} < M_{thres}$$

Universal Relation for M_{thres}

- Bauswein, Baumgarte, Janka (2013)



$$k = M_{thres} / M_{max}$$

$$C_{max} = M_{max} / R_{max}$$

$$C_{1.6} = M_{max} / R_{1.6}$$

$$M_{thres} = \left(-3.606\, M_{max} / R_{1.6} + 2.38\right) M_{max}$$

$$M_{thres} = \left(-3.38\, M_{max} / R_{max} + 2.43\right) M_{max}$$

Constraints on neutron star radii from GW170817

- Bauswein, Just, Janka, Stergioulas (2017)

$$M_{thres} = \left(-3.606 \frac{M_{max}}{R_{1.6}} + 2.38 \right) M_{max}$$

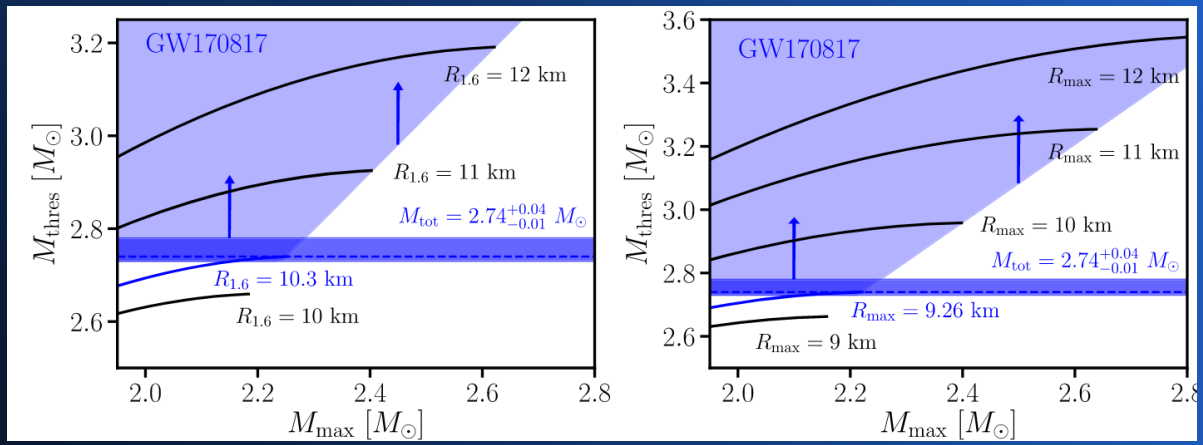
$$M_{thres} = \left(-3.38 \frac{M_{max}}{R_{max}} + 2.43 \right) M_{max}$$

Empirical

$$M_{max} \leqslant \frac{R_{1.6}}{3.10}$$

$$M_{thres} \gtrsim 2.70\, M_{\odot}$$

$$M_{max} \leqslant \frac{R_{max}}{2.82}$$



$$R_{1.6} \gtrsim 10.6\, km$$

$$R_{max} \gtrsim 9.6\, km$$

Constraint from GW170817

$$M_{tot} > M_{supra}$$

Universal relation and maximum mass constraint

- Ruiz et al. (2017), Rezzolla et al. (2017)

$$M_{supra} \simeq 1.2\, M_{max}$$

Universal relation and maximum mass constraint

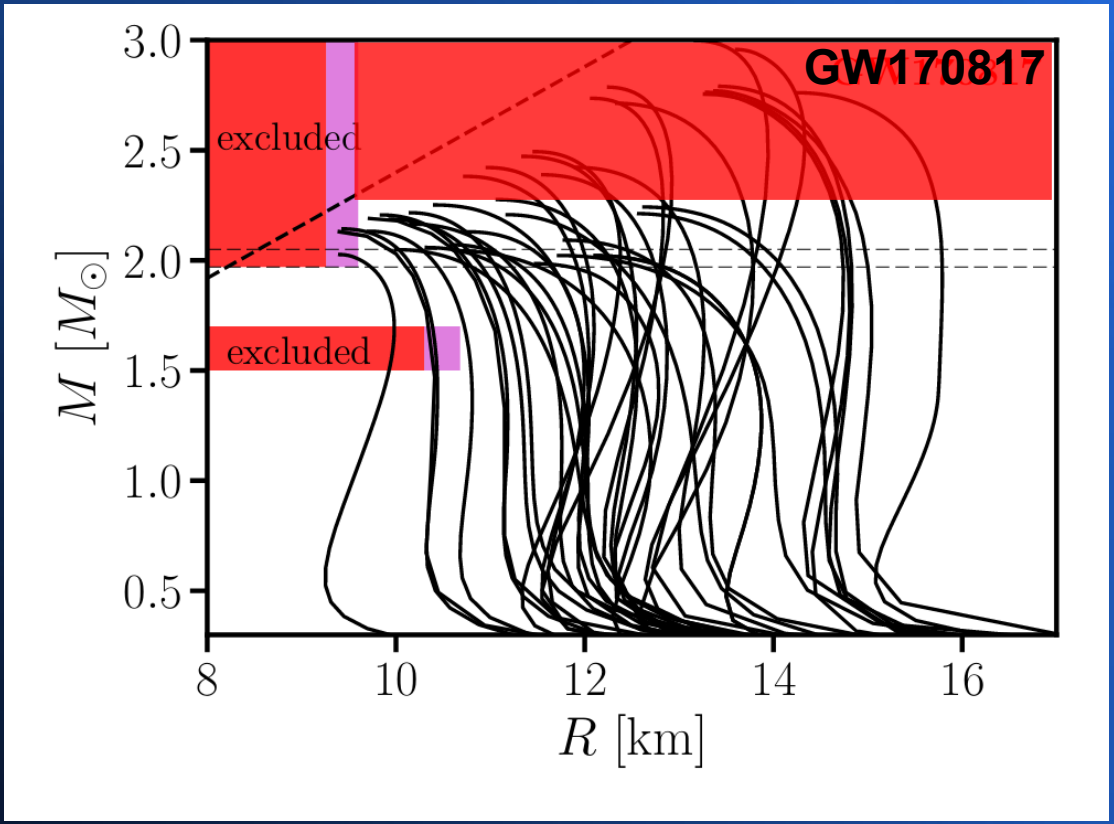
- Ruiz et al. (2017), Rezzolla et al. (2017)

$$M_{supra} \simeq 1.2\, M_{max}$$

$$M_{supra} \lesssim 2.7\, M_{\odot}$$

$$M_{max} \lesssim M_{tot}/1.2 \simeq 2.32\, M_{\odot}$$

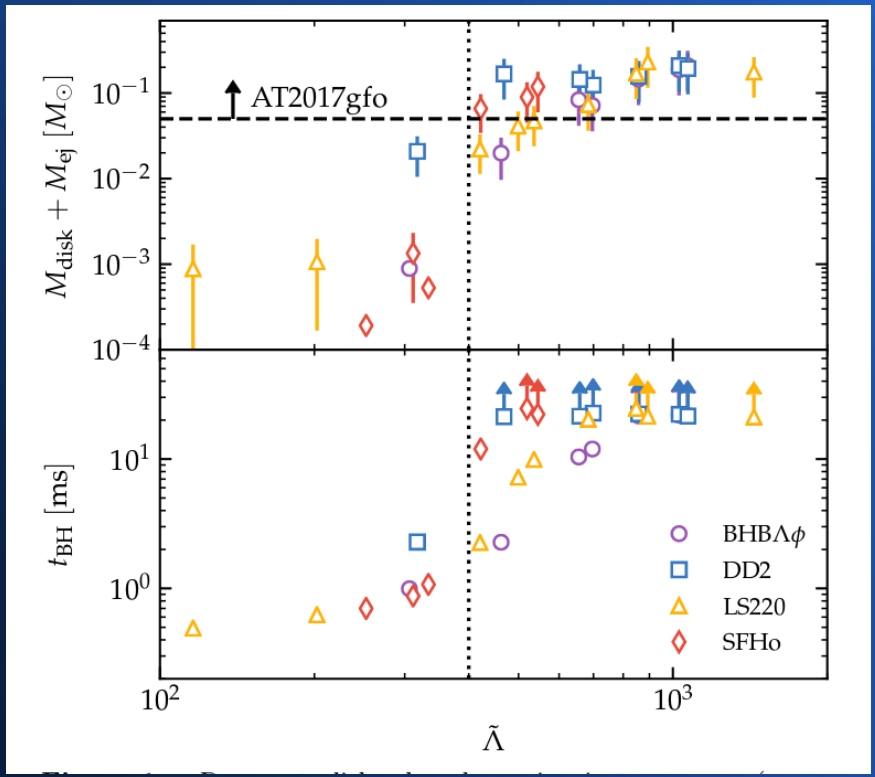
Constraints on the NS EOS



Original figure from Bauswein et al. 2017

GW+EM constraint on $\tilde{\Lambda}$

- Radice et al 2017 (equal mass, irrotational BNS simulations, BH collapse within 10-20 ms)



$$\tilde{\Lambda} \gtrsim 400$$

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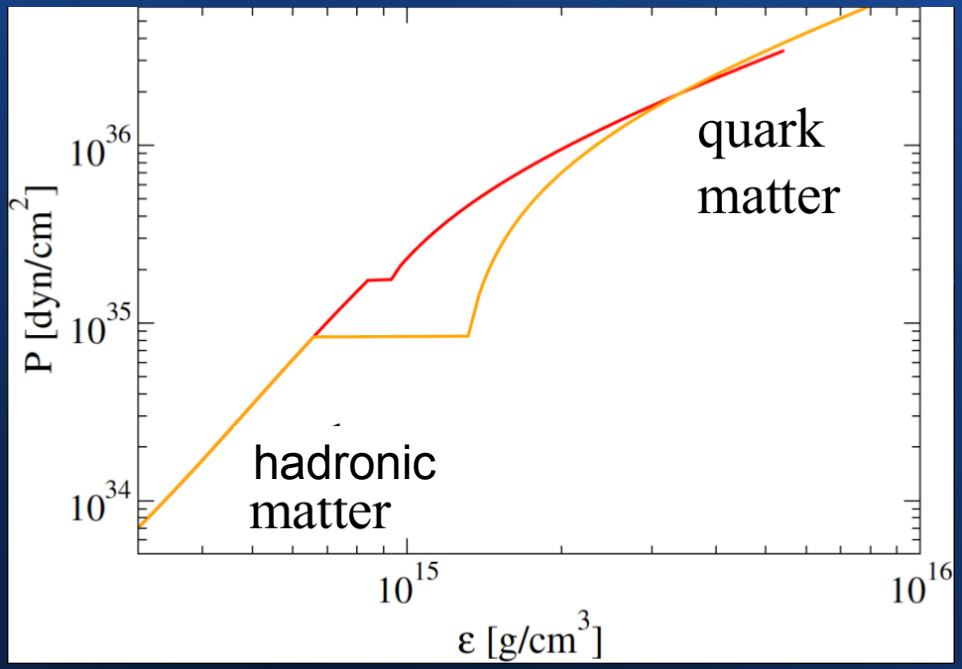
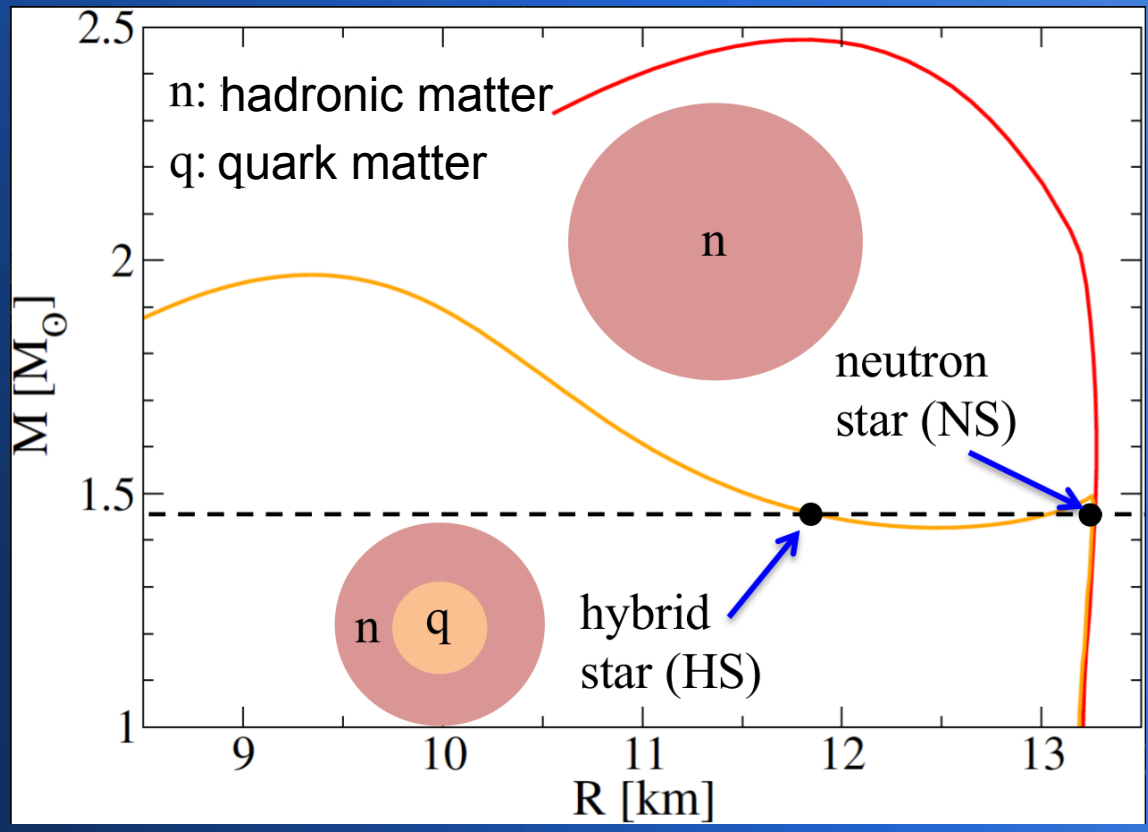
How universal is $M_{supra} \simeq 1.2\, M_{max}$?

Hybrid hadron-quark stars are compatible with GW170817

Hybrid quark-hadron stars (HS): the third family of compact objects

- Equations of state with a phase transition [Gerlach (1968)]

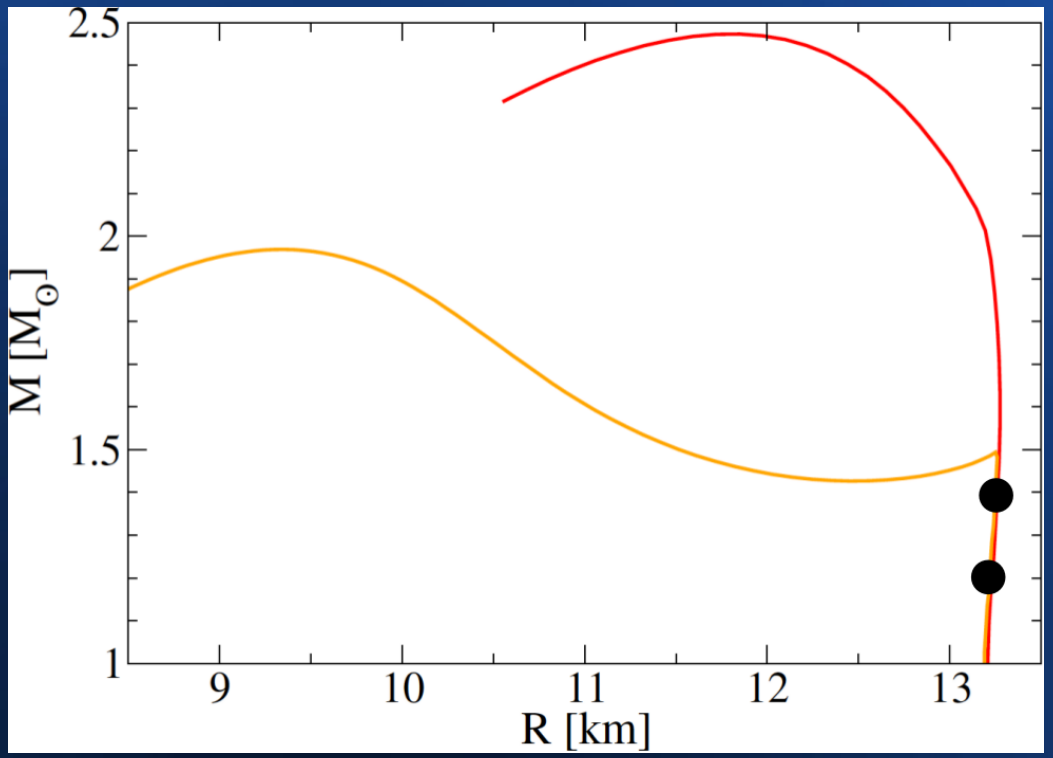


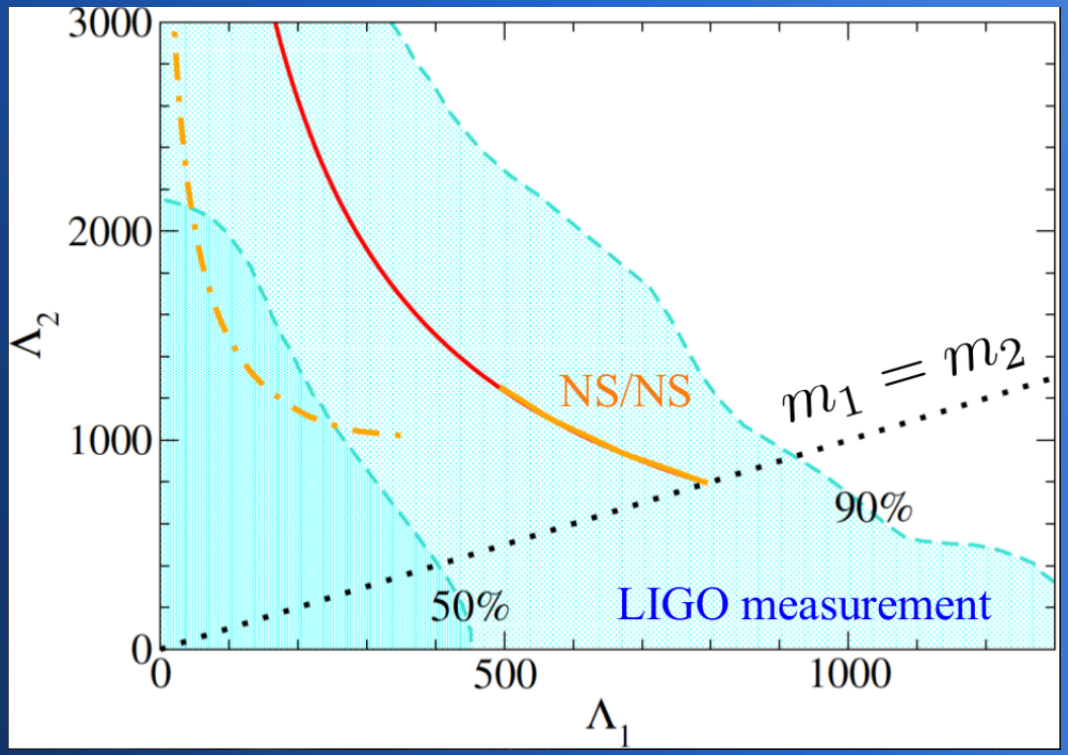


Glendenning and C. Kettner, 2000,
Twin star phenomenon: HS and NS
same mass, different radii

GW170817: consistent with NS/NS

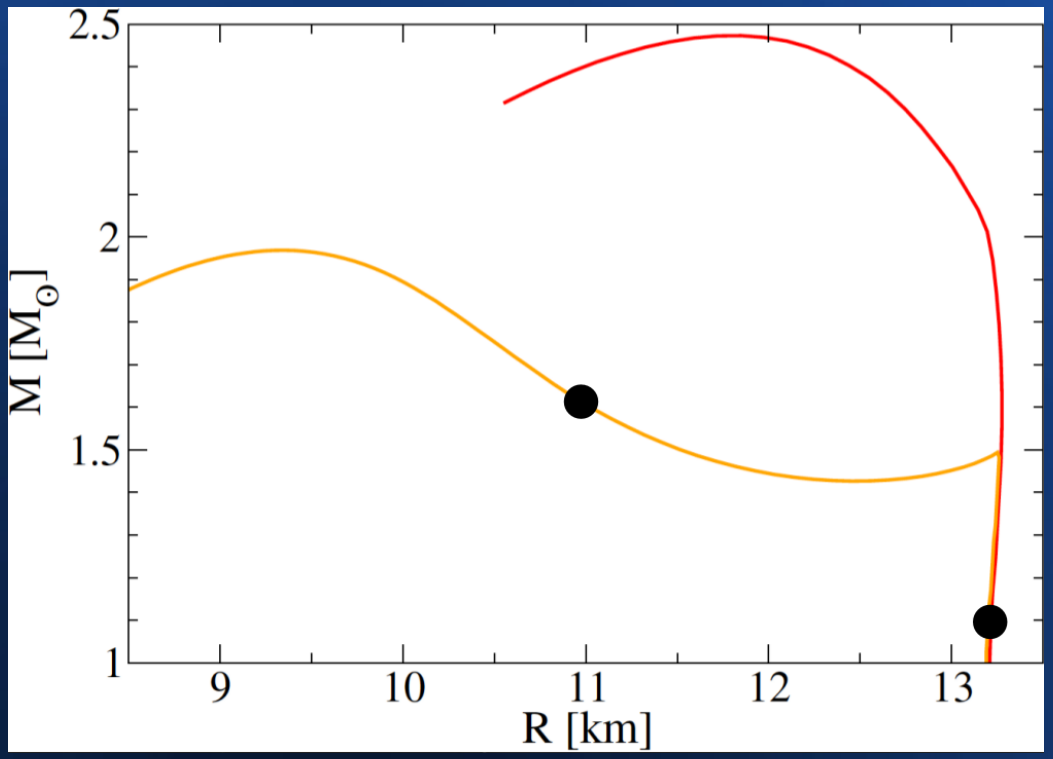
VP, Yagi et al. (2017)

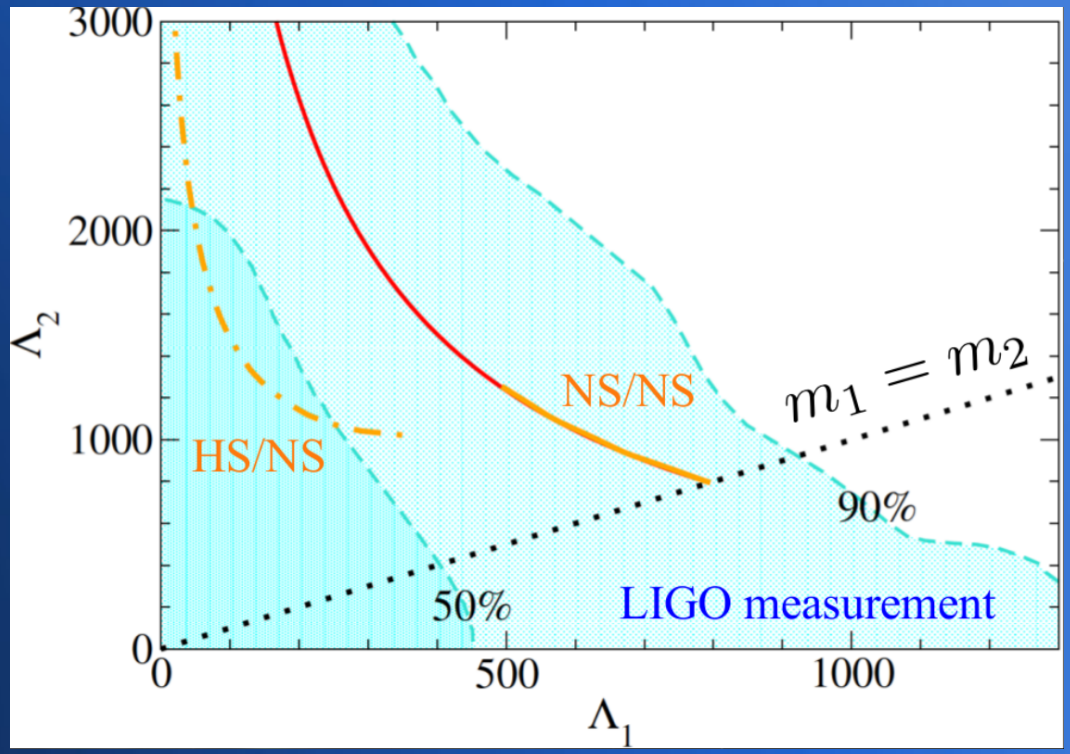




GW170817: consistent with HS/NS

VP, Yagi et al. (2017)

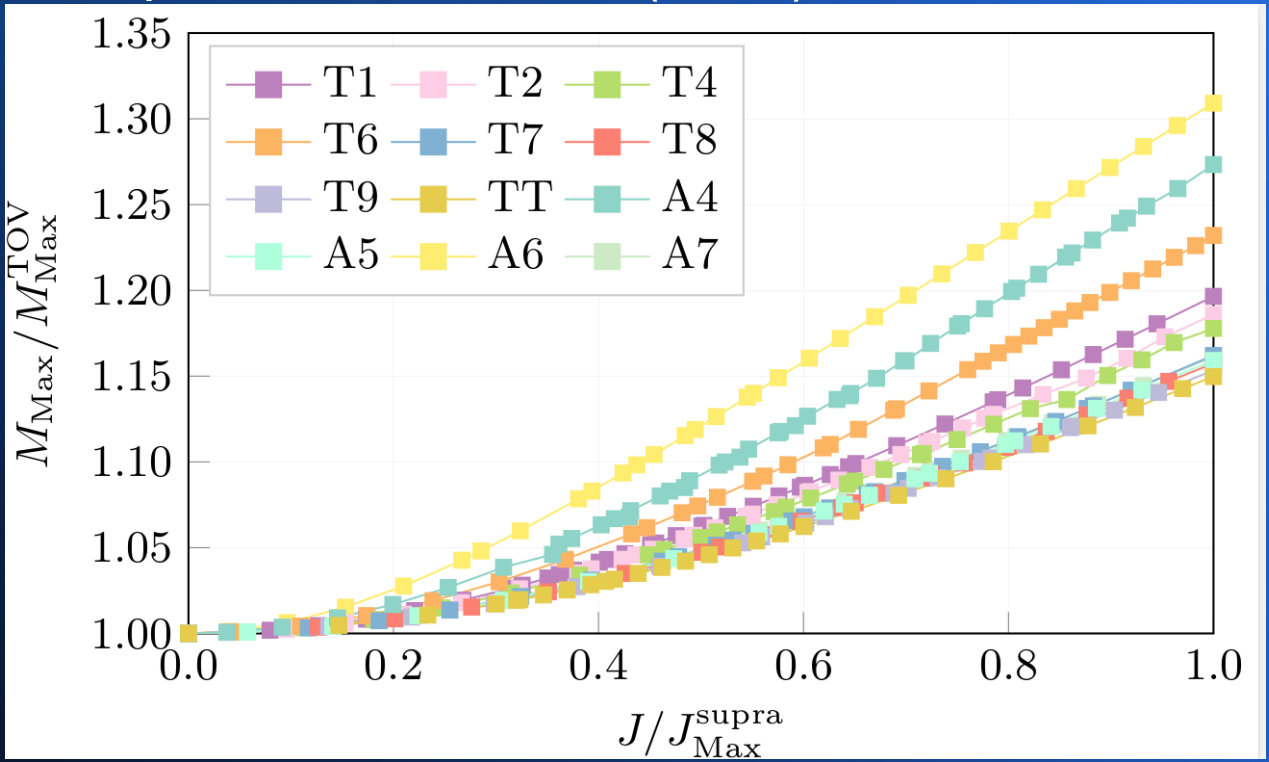




More consistent with HS/NS?

How universal is $M_{supra} \simeq 1.2\, M_{max}$?

G. Bozzola, P. Espino, C. Lewin, VP (2019)



How universal is $M_{supra} \simeq 1.2\, M_{max}$?

G. Bozzola, P. Espino, C. Lewin, VP (2019)

$$1.15 \leqslant \frac{M_{supra}}{M_{max}} \leqslant 1.31$$

- Using a single value for this ratio is not appropriate.
- At the very least, constraints on M_{max} using a single value for the ratio do not apply to all nuclear physics models.

Further challenges to existing constraints

Is prompt collapse ruled out?

$$M_{tot} < M_{thres}\ ?$$

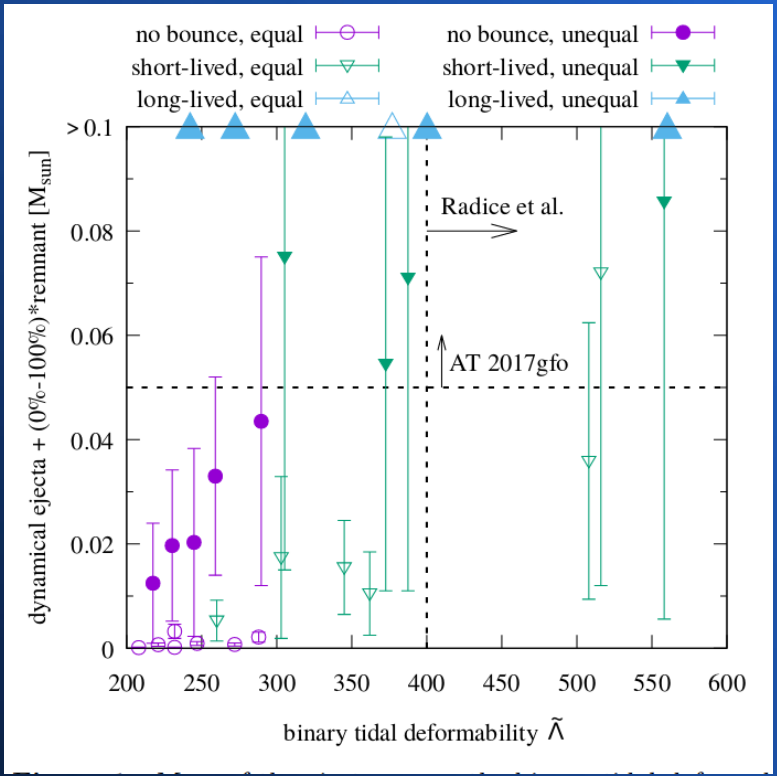
- Kiuchi et al. 2019 (irrotational BNS simulations equal and unequal mass)

Γ	$\log P_{14.7}$ (dyne cm^{-2})	$R_{1.35}$ (km)	$M_{\max}$ $[M_\odot]$	q	$\tilde{\Lambda}$	type	$M_{\rm dyn}$ $[M_\odot]$	$M_{\rm bd}$ $[M_\odot]$
3.765	34.1	10.4	2.00	1	208	no bounce	$< 10^{-3}$	$< 10^{-3}$
				0.774	218	no bounce	$< 10^{-3}$	0.023
3.887	34.1	10.5	2.05	1	221	no bounce	$< 10^{-3}$	$< 10^{-3}$
				0.774	230	no bounce	5.2×10^{-3}	0.029
4.007	34.1	10.5	2.10	1	232	no bounce	1.9×10^{-3}	2.7×10^{-3}
				0.774	242	long	0.013	—
3.446	34.2	10.6	2.00	1	232	no bounce	$< 10^{-3}$	$< 10^{-3}$
				0.774	245	no bounce	2.3×10^{-3}	0.036
3.568	34.2	10.7	2.05	1	247	no bounce	$< 10^{-3}$	$< 10^{-3}$
				0.774	259	no bounce	0.014	0.038
3.687	34.2	10.8	2.10	1	260	short	1.4×10^{-3}	7.8×10^{-3}
				0.774	272	long	0.011	—
3.132	34.3	11.0	2.00	1	272	no bounce	$< 10^{-3}$	$< 10^{-3}$
				0.774	290	no bounce	0.012	0.063
3.252	34.3	11.1	2.05	1	288	no bounce	1.2×10^{-3}	1.9×10^{-3}

- Ruling out prompt collapse not trivial → Bauswein et al. constrain weak

Is $\tilde{\Lambda} \gtrsim 400$ necessary to explain AT2017gfo?

- Kiuchi et al (2019)



- For unequal-mass BNSs enough matter can remain outside the remnant BH for

$$\tilde{\Lambda} \gtrsim 240$$

How well is M_{tot} constraned for GW170817?

- Depending on the spin priors

$$2.7\,M_{\odot} \lesssim M_{tot} \lesssim 3.3\,M_{\odot}$$

- GW170817 left the NS spins unrestricted.
- Using the high mass end, constraints on maximum mass become very weak
- NS spins can be up to

How well is M_{tot} constraned for GW170817?

- Maximal spins of NS are in the range $0.63 \lesssim J_{NS}/M_{NS}^2 \lesssim 0.77$

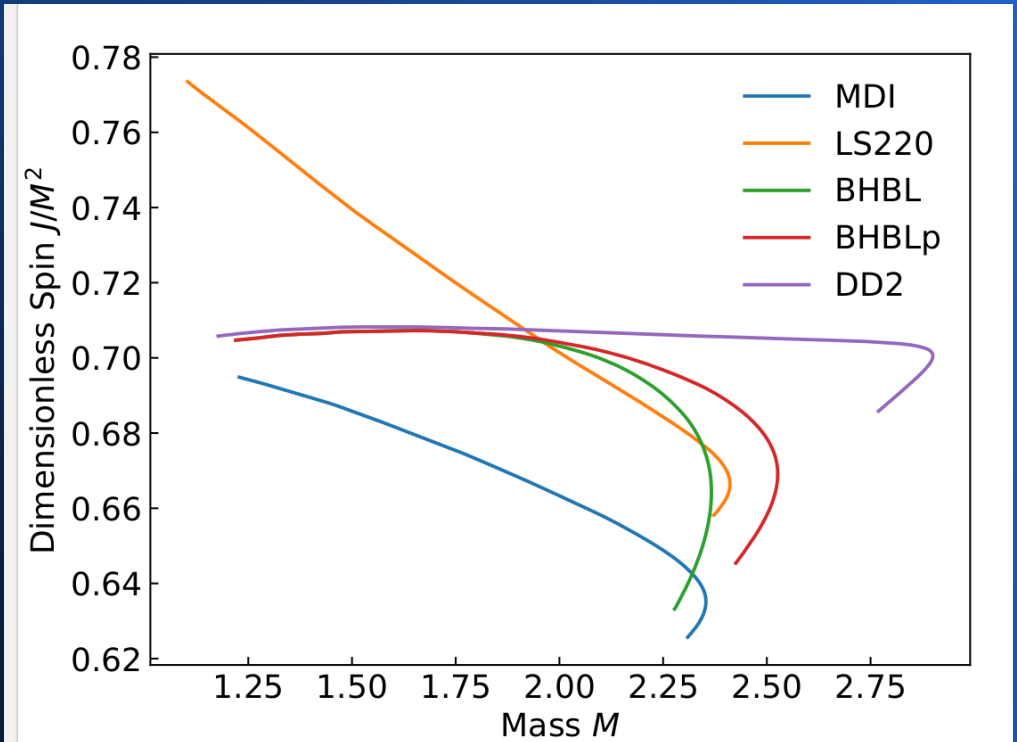


Image: courtesy of G. Bozzola

- The upper end of the GW170817 mass corresponds to spin priors < 0.89

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Impact of spin in BNS simulations?

- NS spins can be up to $J_{NS}/M_{NS}^2 \simeq 0.77$
- Spins of order 0.2-0.3 + magnetic fields can increase the disk mass outside the remnant BH by a factor of 5 (Ruiz, Tsokaros, VP, Shapiro 2019)!
- In hydro sims spins of order 0.3 double the disk mass outside a MNS

EOS	$a_{\rm NS}$	Spin state	$M_{0,\rm disk}$	$R_{\rm disk}$	$M_{0,\rm u}$	$\langle v_\infty \rangle$	$E_{\rm kin,50}$	$t_{\rm peak}$	L_{41}
ENG	-0.13	SP	14	3.1	1.55	0.20	7.88	0.37	1.98
ENG	0.00	IR	13	2.0	0.68	0.17	2.36	0.23	1.20
ENG	0.17	SP	15	1.2	0.05	0.12	0.08	0.05	0.28
ENG	0.17	CO	17	1.3	0.09	0.12	0.15	0.07	0.37
ENG	0.25	SP	25	1.2	0.09	0.14	0.19	0.07	0.39
ENG	0.33	SP	26	1.1	0.49	0.12	0.81	0.17	0.88

East, VP, Pretorius, Tsokaros (In prep.)

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Impact of spin in BNS simulations?

The increased disk mass in BNS simulations with increasing NS spin is likely to lower the lower bound on the tidal deformability even further.

In the relation for M_{thres}/M_{TOV} universal?

- Should depend on pre-merger NS spins.
- Since this is a threshold quantity, even small spins can change M_{thres}

Take away message

- Existing constraints on the EOS from GW170817 make a number of (plausible) assumptions
- GW170817 could be a BHNS
- Assuming BNS, the fate of the remnant is not 100% certain
- The methods developed for constraining the EOS in the BNS scenario are brilliant!
- BUT, existing EOS constraints are weak

THANK YOU!