MAX PLANCK INSTITUTE
FOR GRAVITATIONAL PHYSICS
(ALBERT EINSTEIN INSTITUTE)

Constraining M_{TOV} of NSs with GW170817

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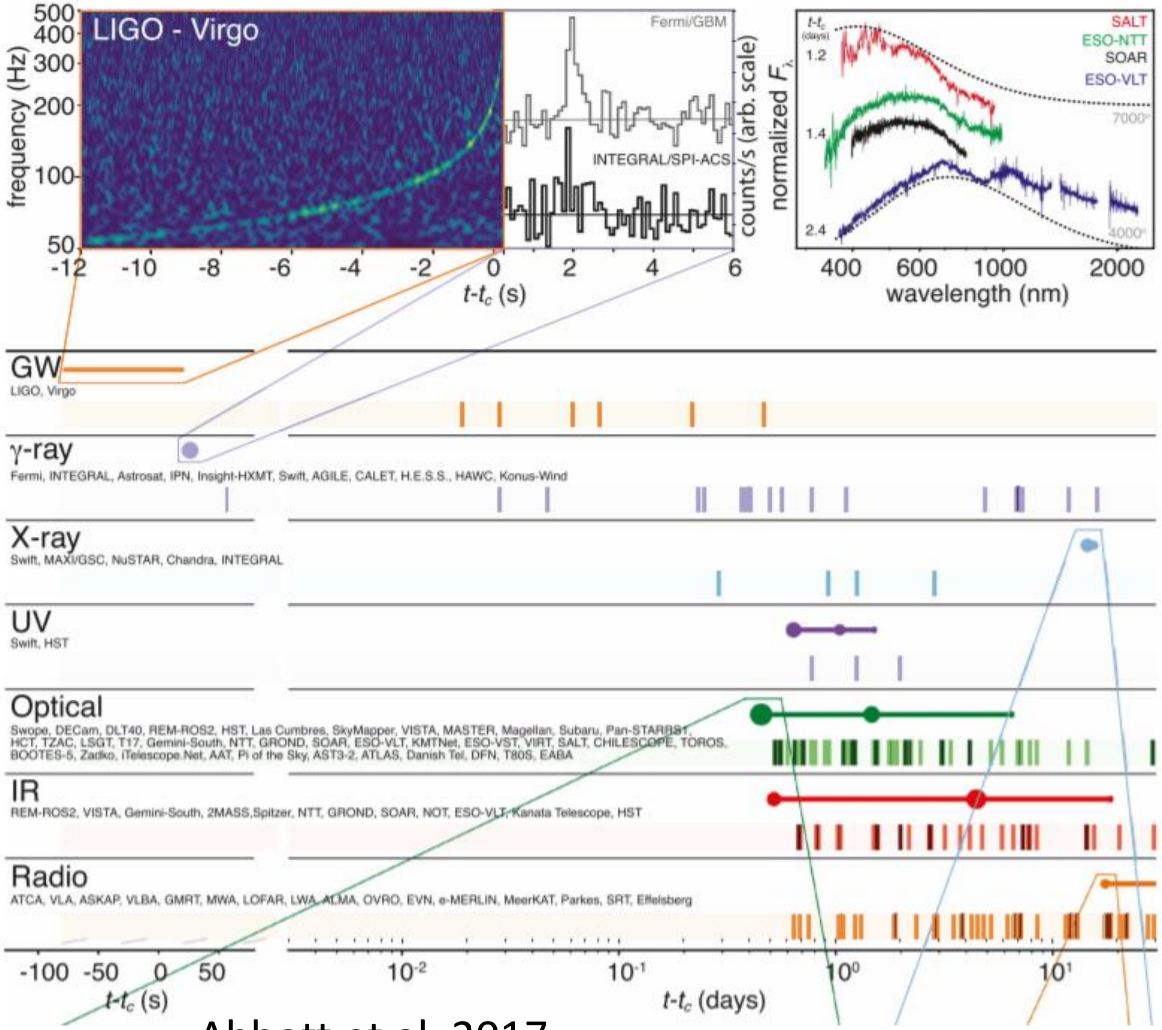
Overview: Constraining EOS in multimessenger era



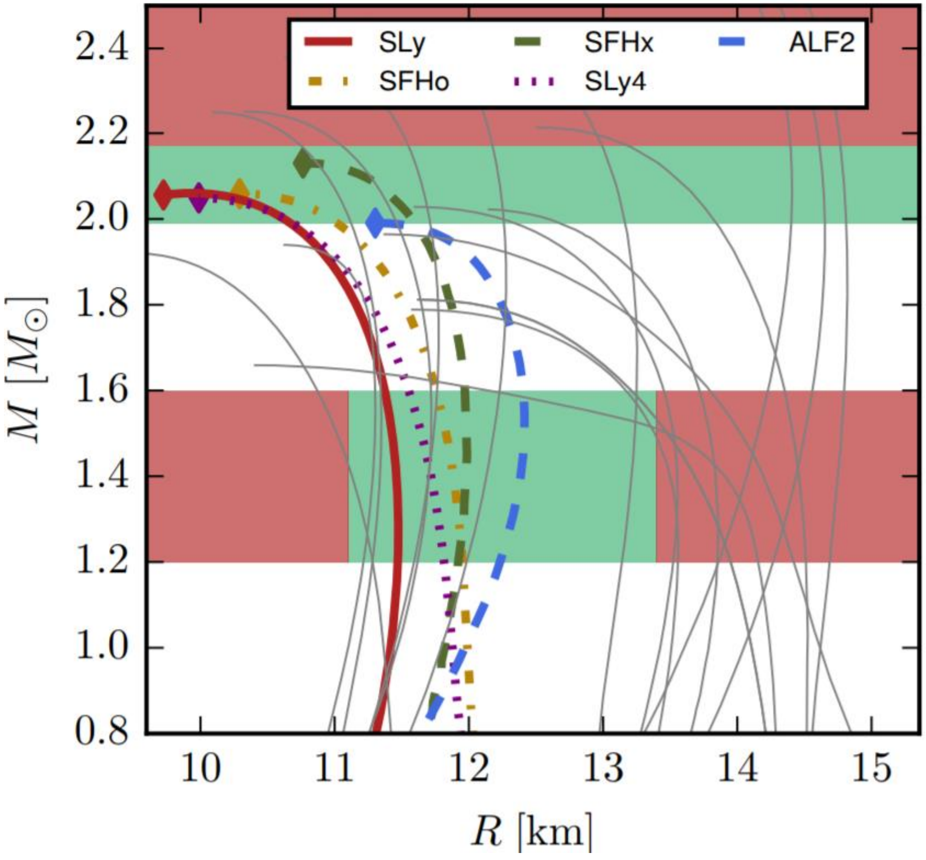
Abbott et al. 2017

GW:
Tidal deformability measurement (robust)

Op/IR/UV:
Kilonova (mass and velocity of the ejecta, model dependent)

Gamma Ray:
Off-axis sGRB (formation of a BH, model dependent)

Overview: Constraining EOS in multimessenger era

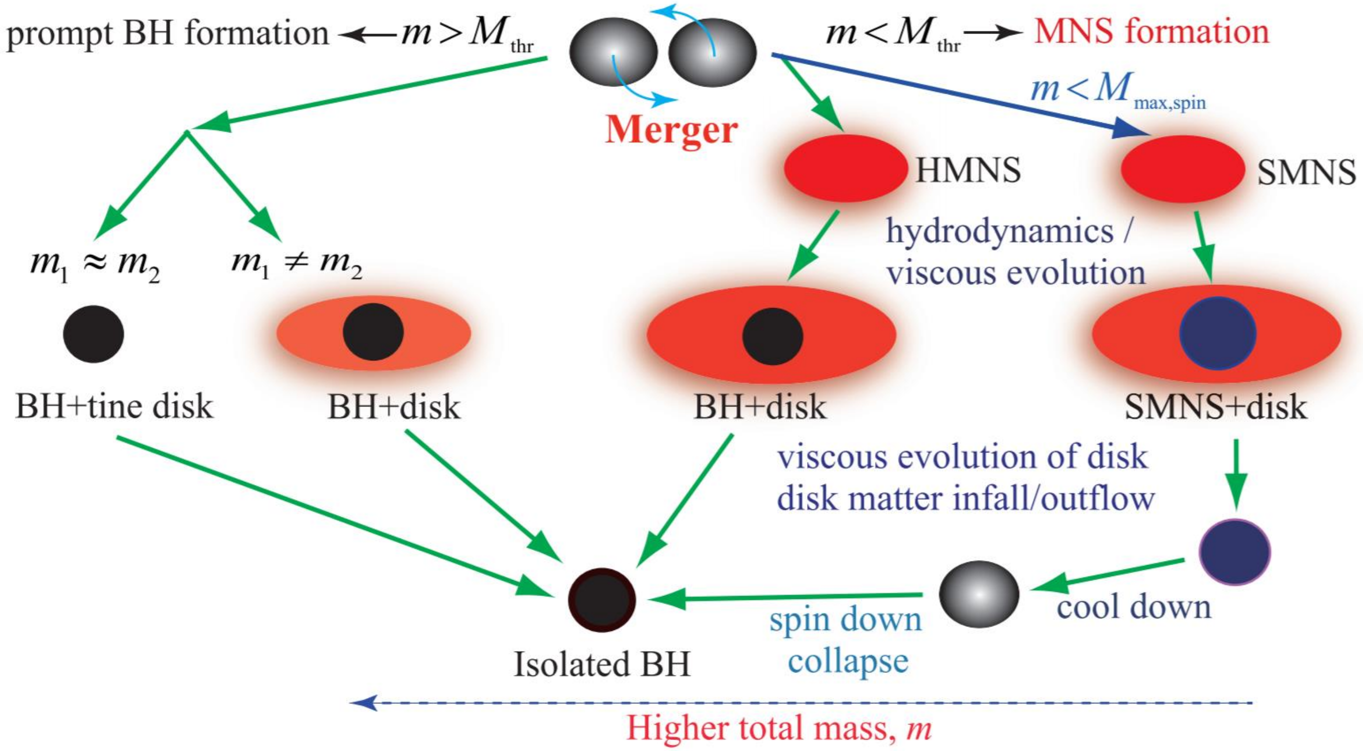


Coughlin et al 2019

Merger product -> Mtov constraint ?

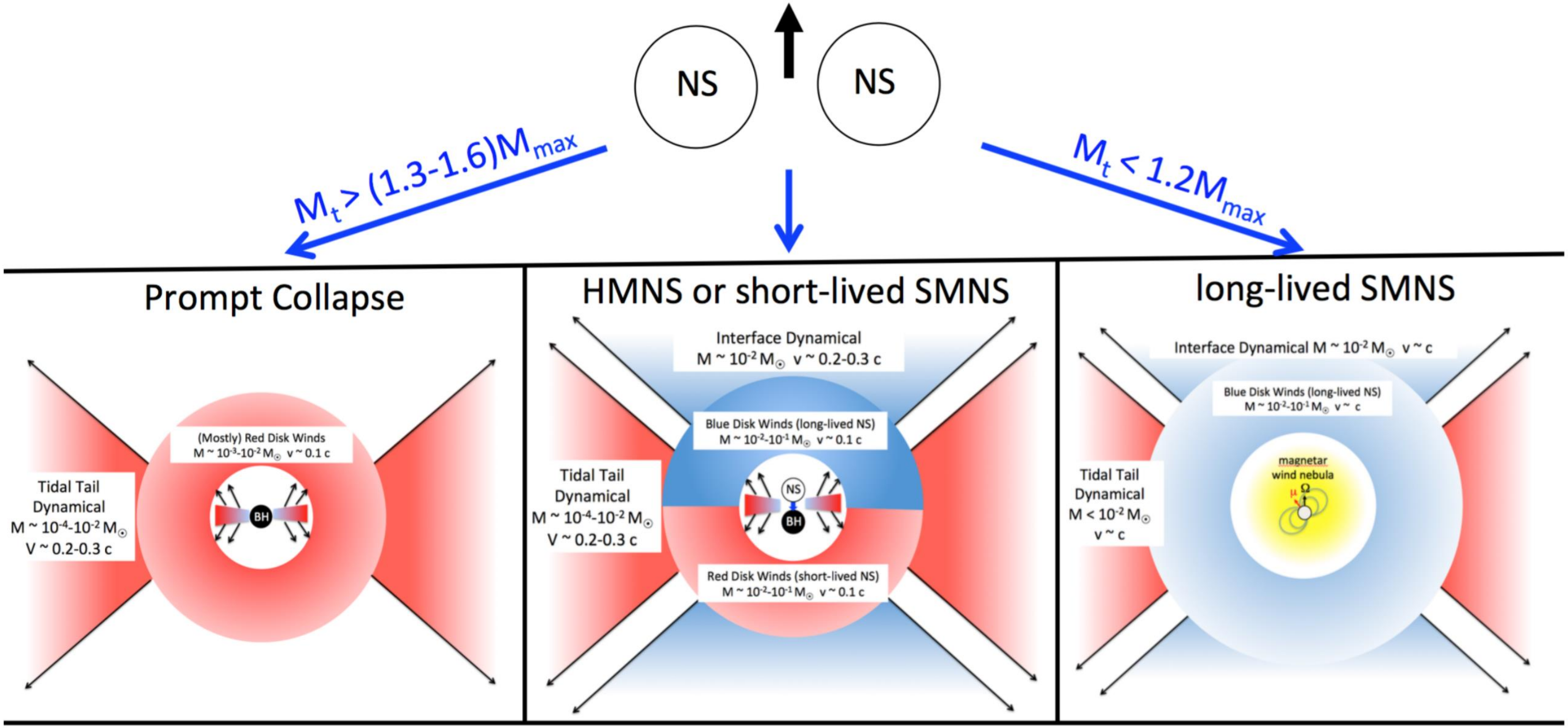
Tidal deformability -> Radius constraint
No prompt collapse -> Radius constraint

Merger products -> Mtov



Shibata & Hotokezaka 2019

EM counterparts -> Merger products

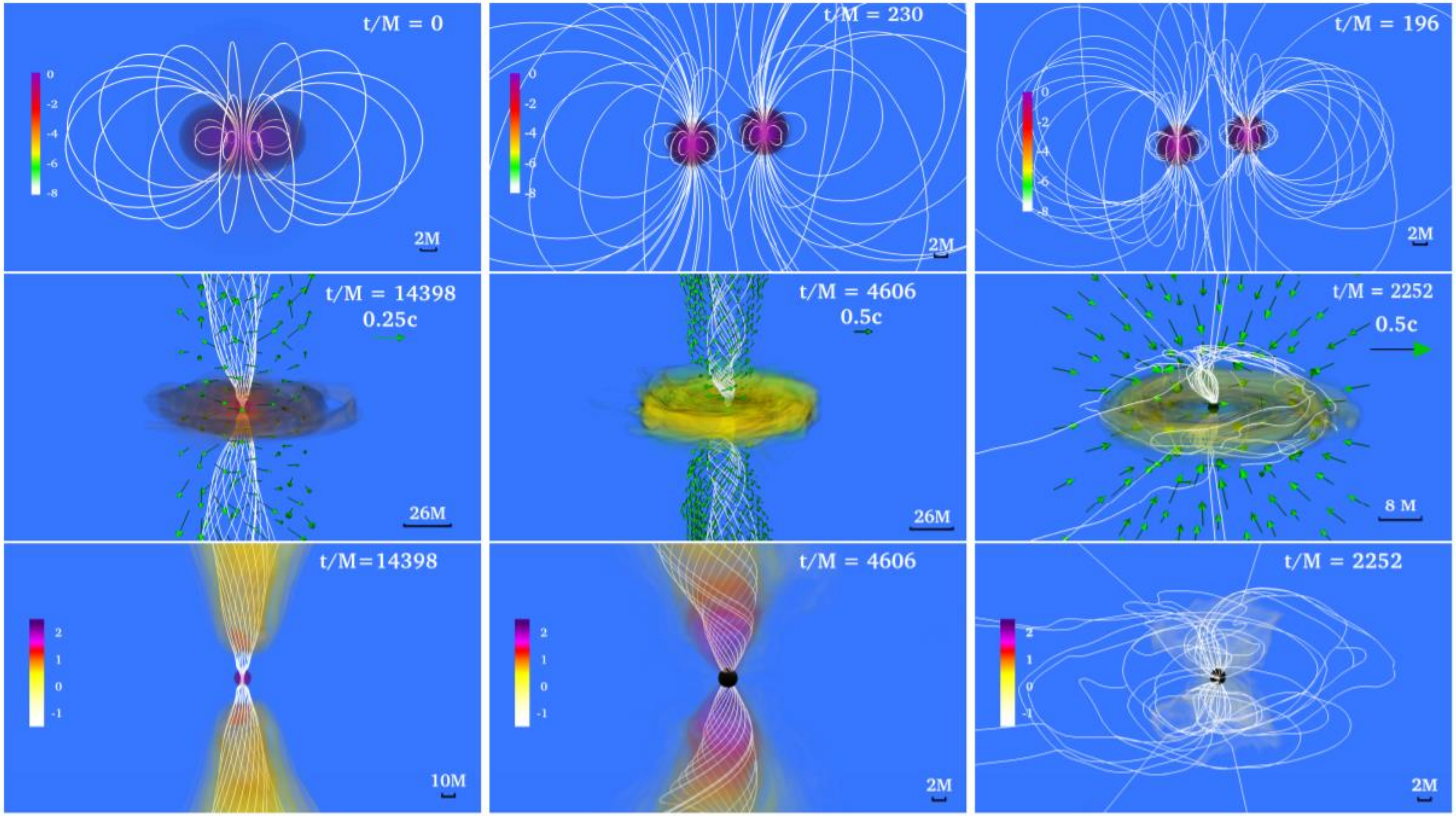


Margalit & Metzger 2017

Negligible shock driven ejecta
Negligible disk ouflow
Red KN dominated

Injection of spin down power
Abnormally large expansion speed of ejecta and L_{GRB}

EM counterparts -> Merger products



Ruiz et al. 2018

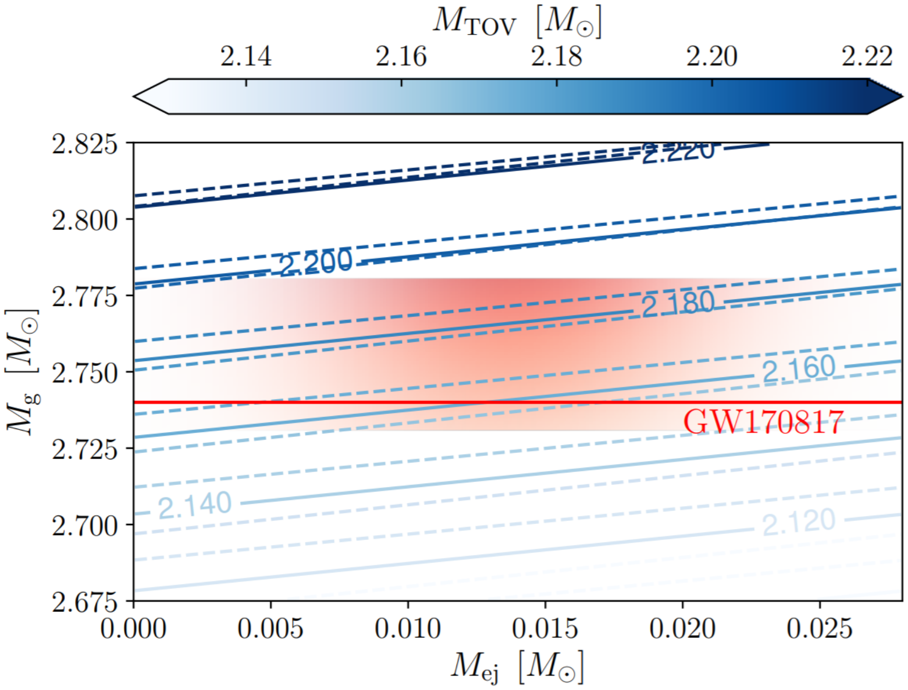
Long lived remnant
No BH -> No GRB

HMNS
BH formation + strong B

Prompt collapse
Low B field -> No GRB

Previous constraints on Mtov

- GW170817 most likely result in a short-lived merger remnant, which collapse to BH shortly after its differential rotation is dissipated.
- For NSs, $M_{\mathrm{Kep}} \sim 1.2 M_{\mathrm{TOV}}$



Rezzolla et al. 2018

Motivation for a new analysis

- GRB = BH ?
- Is the remnant really at the mass shedding limit when it collapses to a BH??

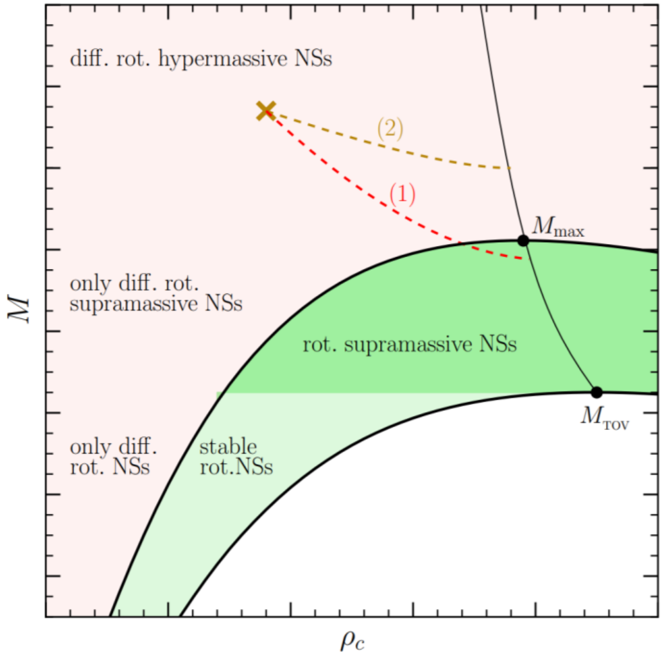
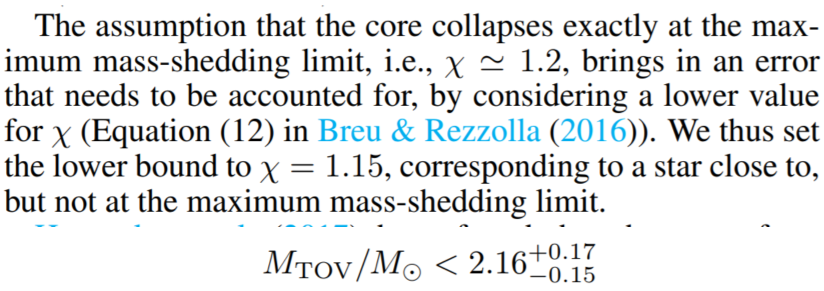


FIG. 1.— Schematic diagram of the different types of equilibrium models for neutron stars. The golden cross marks the initial position of the BMP and the dashed lines its possible trajectories in the (M, ρ_c) plane before it collapses to a black hole.

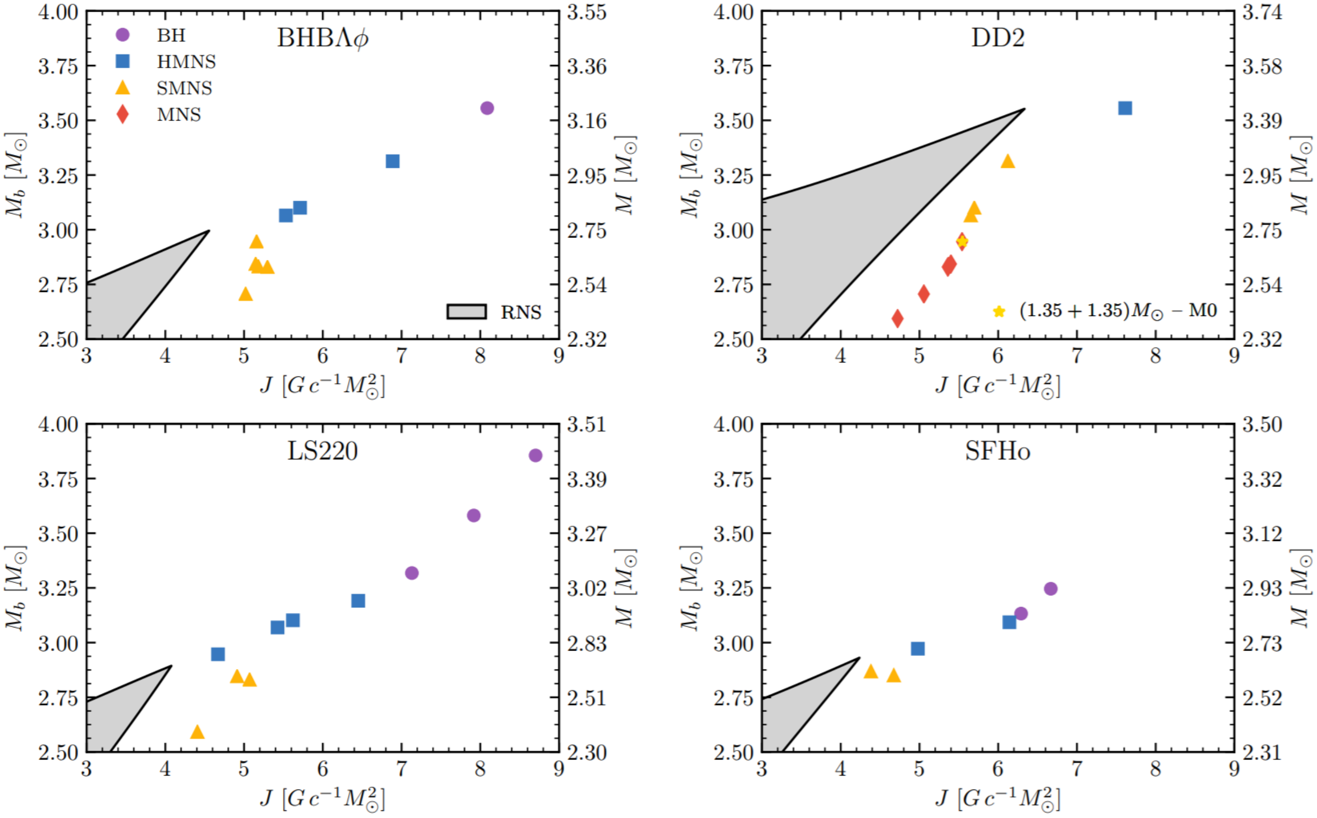


The assumption that the core collapses exactly at the maximum mass-shedding limit, i.e., $\chi \simeq 1.2$, brings in an error that needs to be accounted for, by considering a lower value for χ (Equation (12) in Breu & Rezzolla (2016)). We thus set the lower bound to $\chi = 1.15$, corresponding to a star close to, but not at the maximum mass-shedding limit.

$$M_{\rm TOV}/M_\odot < 2.16^{+0.17}_{-0.15}$$

Rezzolla et al. 2018

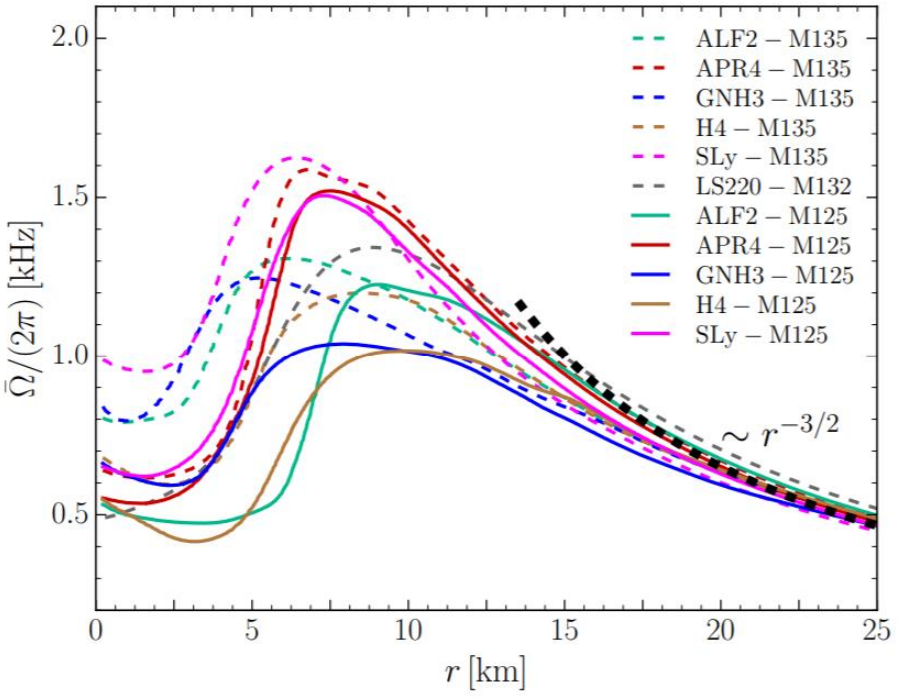
Motivation for a new analysis



Radice et al. 2018 argues that the merger remnant has enough angular momentum such that the remnant should collapse at the mass shedding limit.

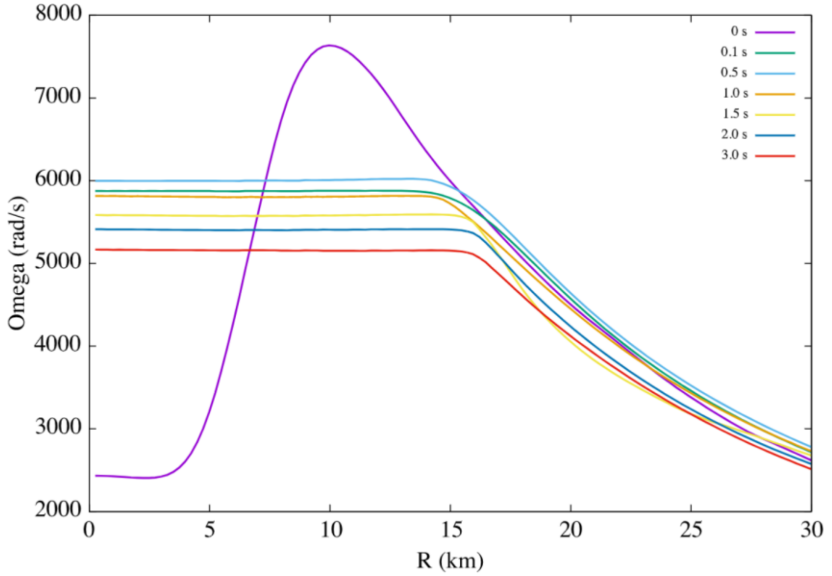
However, this paper doesn't account for angular momentum loss by neutrino emission, ejecta and the rotational profile.

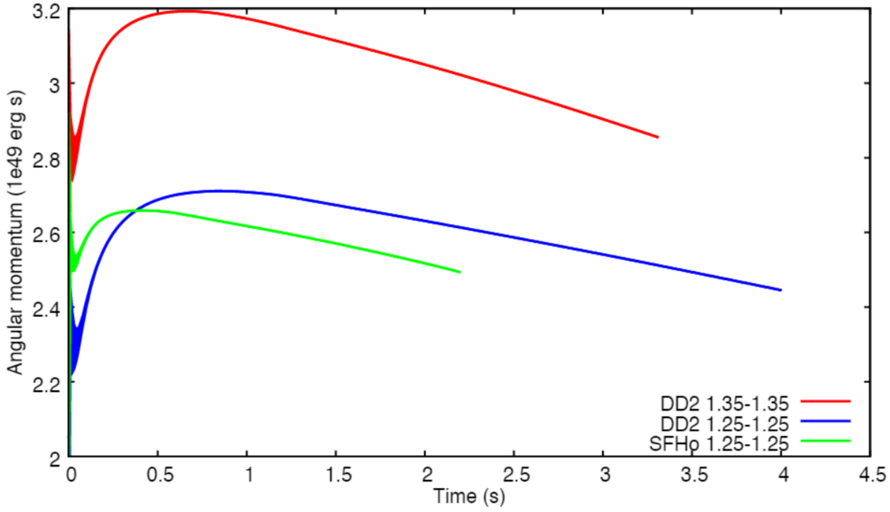
Motivation of a new analysis



Hanauske et al. 2017

Conclusion: it’s very likely that the collapsing core is not at mass shedding limit when it collapses!





Simulation data from Fujibayashi

New analysis: the model

- Conservation of rest mass

$$M_{b,0} = M_{b,f} + M_{eje} + M_{out}$$

- Conservation of energy

$$M_{g,0} = M_{g,f} + E_{gw,i} + E_{gw,p} + E_{\nu} + M_{eje} + M_{out}$$

- Conservation of angular momentum

$$J_0 = J_f + J_{gw,p} + J_{\nu} + J_{eje} + J_{out}$$

There are in total 15 variables! But we only have 3 relation…
Needs to find more relations!

Details in
Shibata, Zhou, Kiuchi, Fujibayashi
PRD 100, 023015 (2019)

New analysis: the model

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$$J_0 = J_f + J_{gw,p} + J_{\nu} + J_{eje} + J_{out}$$

From GW170817 observation, we have initial gravitational mass

New analysis: the model

- Conservation of rest mass

$$M_{b,0} = M_{b,f} + M_{eje} + M_{out}$$

- Conservation of energy

$$M_{g,0} = M_{g,f} + E_{gw,i} + E_{gw,p} + E_{\nu} + M_{eje} + M_{out}$$

- Conservation of angular momentum

$$J_0 = J_f + J_{gw,p} + J_{\nu} + J_{eje} + J_{out}$$

When certain EoS is assumed, M_b can be related to M_g (for any given mass) , $M_{b,0}$ and $M_{g,0}$ is related by the factor f_0 in our paper.
By constructing initial data with this certain EoS and perform a simulation until merger, J_0 and $E_{gw,i}$ are determined simultaneously.

New analysis: the model

- Conservation of rest mass

$$M_{b,0} = M_{b,f} + M_{eje} + M_{out}$$

- Conservation of energy

$$M_{g,0} = M_{g,f} + E_{gw,i} + E_{gw,p} + E_{\nu} + M_{eje} + M_{out}$$

- Conservation of angular momentum

$$J_0 = J_f + J_{gw,p} + J_{\nu} + J_{eje} + J_{out}$$

$$J_\nu \approx (2/3)c^{-2}R_{\mathrm{MNS}}^2\Omega E_\nu$$

$$J_{\mathrm{out}} \approx M_{\mathrm{out}}\sqrt{GM_{\mathrm{MNS}}R_{\mathrm{out}}}$$

$$J_{\mathrm{eje}} \approx M_{\mathrm{eje}}\sqrt{GM_{\mathrm{MNS}}R_{\mathrm{eje}}}$$

$$J_{\mathrm{GW,p}} \approx \frac{E_{\mathrm{GW,p}}}{\pi f}$$

The d.o.f of this equation system is 6 at the moment

New analysis: the model

- Conservation of rest mass

$$M_{b,0} = M_{b,f} + M_{eje} + M_{out}$$

- Conservation of energy

$$M_{g,0} = M_{g,f} + E_{gw,i} + E_{gw,p} + E_{\nu} + M_{eje} + M_{out}$$

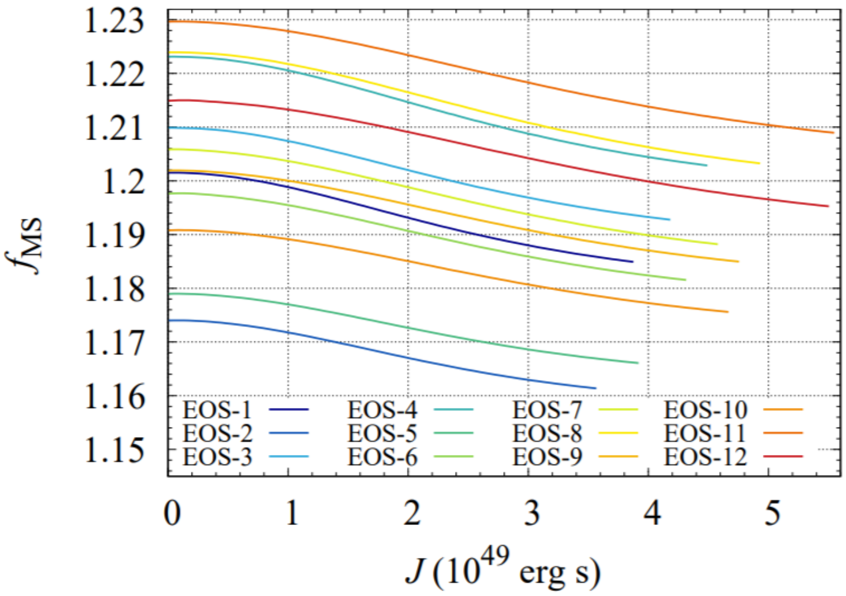
- Conservation of angular momentum

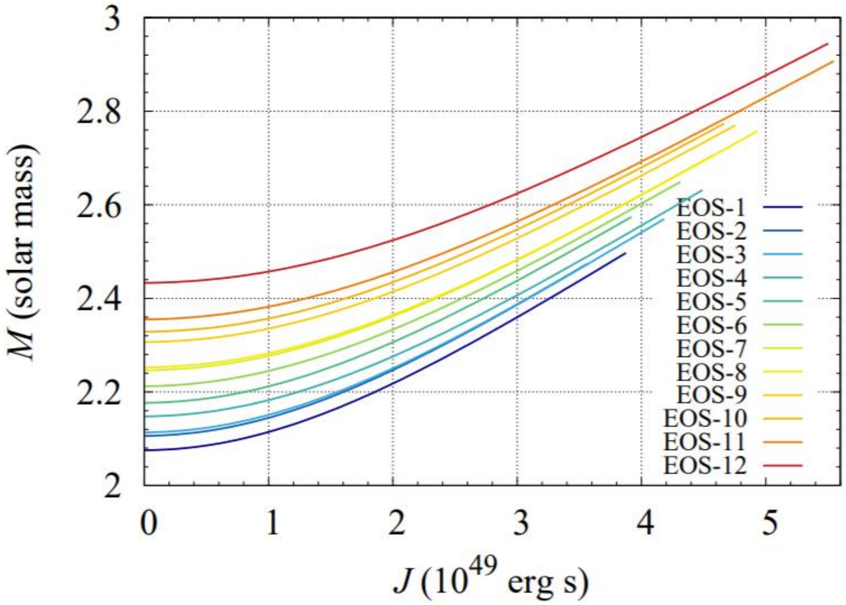
$$J_0 = J_f + J_{gw,p} + J_{\nu} + J_{eje} + J_{out}$$

$M_{b,f}$ can be solved from 1st equation now

$M_{g,f}$ and J_f are related to it!

New analysis: the model





$J, M_{g,f}$ and $M_{b,f}$ are related by constructing rotating solutions and find out the quantities of the turning points.

New analysis: the model

- Conservation of rest mass

$$M_{b,0} = M_{b,f} + M_{eje} + M_{out}$$

- Conservation of energy

$$M_{g,0} = M_{g,f} + E_{gw,i} + E_{gw,p} + E_{\nu} + M_{eje} + M_{out}$$

- Conservation of angular momentum

$$J_0 = J_f + J_{gw,p} + J_{\nu} + J_{eje} + J_{out}$$

Blue values are from the observation
Purple values are from the simulations
Red values can be determined once a value of $M_{eje} + M_{out}$ is chosen
Then, with 2nd and 3rd equation, $E_{gw,p}$ and E_{ν} as well as $J_{gw,p}$ and J_{ν} can be solved.
Then a consistency check can be done

New analysis: the model

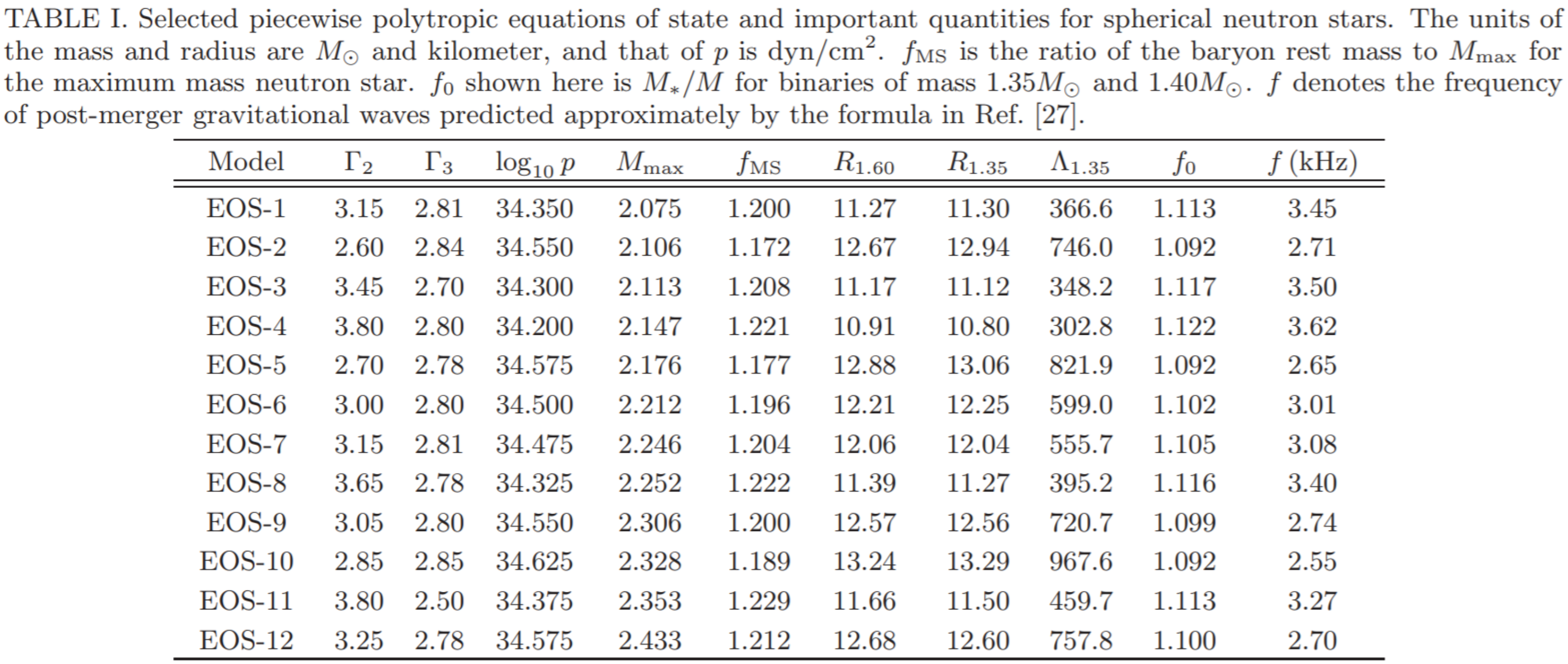
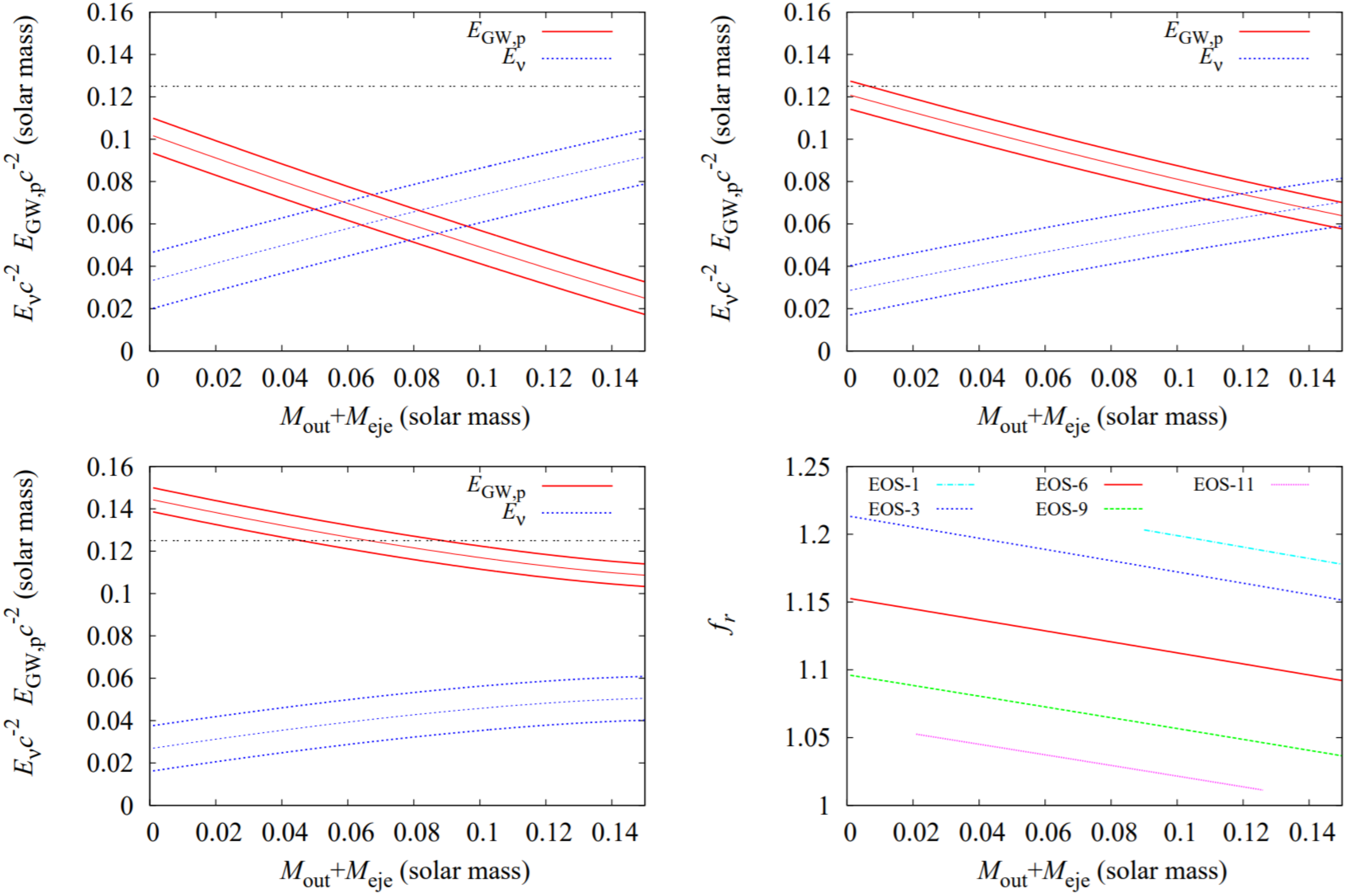


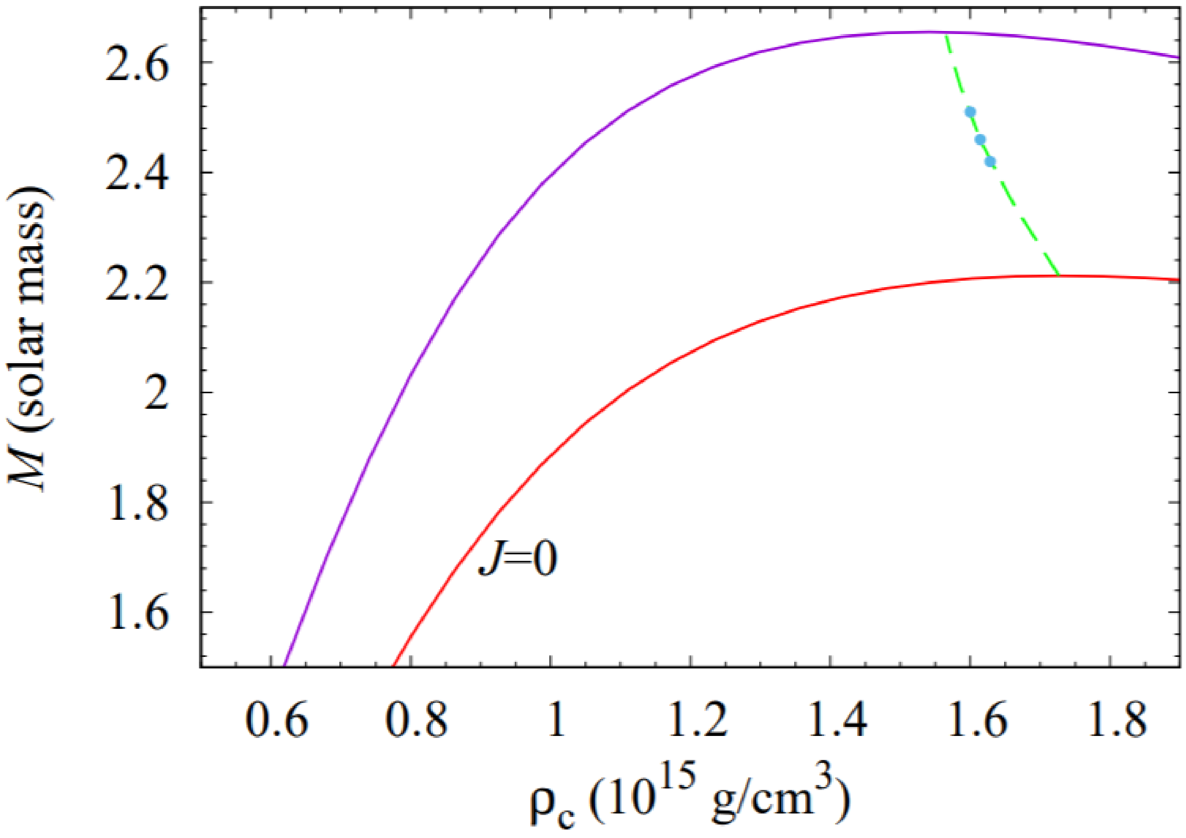
TABLE I. Selected piecewise polytropic equations of state and important quantities for spherical neutron stars. The units of the mass and radius are $M_\odot$ and kilometer, and that of p is dyn/cm^2. $f_{\rm MS}$ is the ratio of the baryon rest mass to $M_{\rm max}$ for the maximum mass neutron star. f_0 shown here is M_*/M for binaries of mass $1.35M_\odot$ and $1.40M_\odot$. f denotes the frequency of post-merger gravitational waves predicted approximately by the formula in Ref. [27].

Model	Γ_2	Γ_3	$\log_{10} p$	$M_{\rm max}$	$f_{\rm MS}$	$R_{1.60}$	$R_{1.35}$	$\Lambda_{1.35}$	f_0	f (kHz)
EOS-1	3.15	2.81	34.350	2.075	1.200	11.27	11.30	366.6	1.113	3.45
EOS-2	2.60	2.84	34.550	2.106	1.172	12.67	12.94	746.0	1.092	2.71
EOS-3	3.45	2.70	34.300	2.113	1.208	11.17	11.12	348.2	1.117	3.50
EOS-4	3.80	2.80	34.200	2.147	1.221	10.91	10.80	302.8	1.122	3.62
EOS-5	2.70	2.78	34.575	2.176	1.177	12.88	13.06	821.9	1.092	2.65
EOS-6	3.00	2.80	34.500	2.212	1.196	12.21	12.25	599.0	1.102	3.01
EOS-7	3.15	2.81	34.475	2.246	1.204	12.06	12.04	555.7	1.105	3.08
EOS-8	3.65	2.78	34.325	2.252	1.222	11.39	11.27	395.2	1.116	3.40
EOS-9	3.05	2.80	34.550	2.306	1.200	12.57	12.56	720.7	1.099	2.74
EOS-10	2.85	2.85	34.625	2.328	1.189	13.24	13.29	967.6	1.092	2.55
EOS-11	3.80	2.50	34.375	2.353	1.229	11.66	11.50	459.7	1.113	3.27
EOS-12	3.25	2.78	34.575	2.433	1.212	12.68	12.60	757.8	1.100	2.70

New analysis: the results



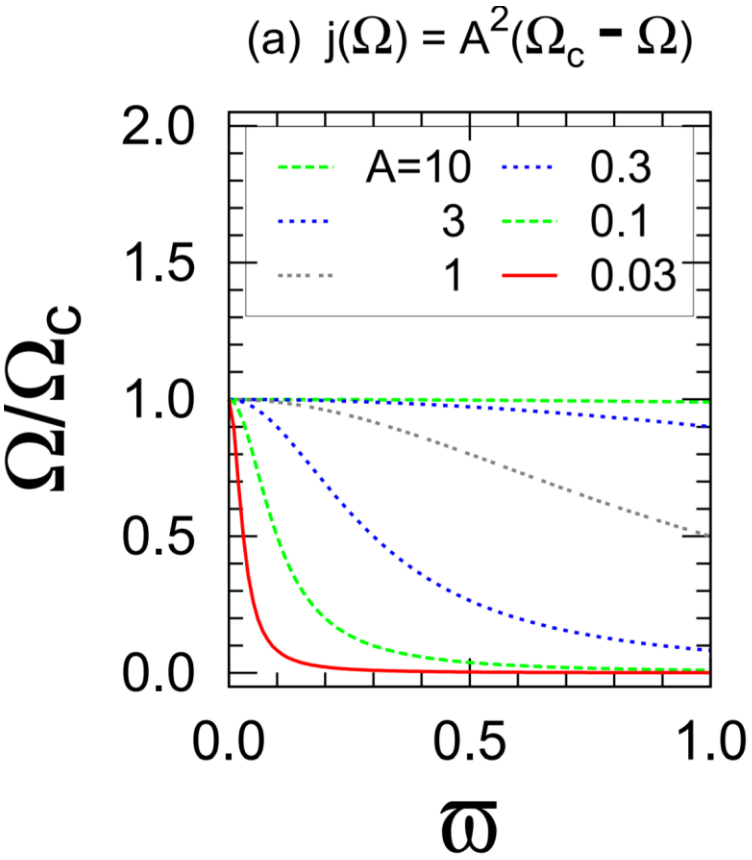
New analysis: the results



Note that the matter outside the star can be constrained from observations and simulations, so we can roughly know where the star is on the marginally stable line when it collaspes to BH. (example for EOS 6)

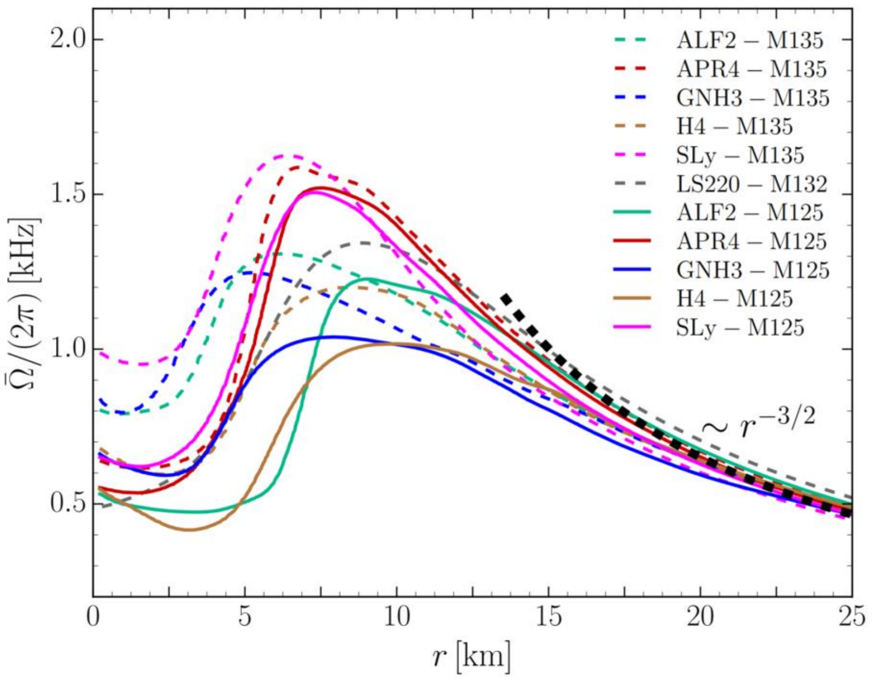
Influence of drot at collapse

Previous studies are not realistic



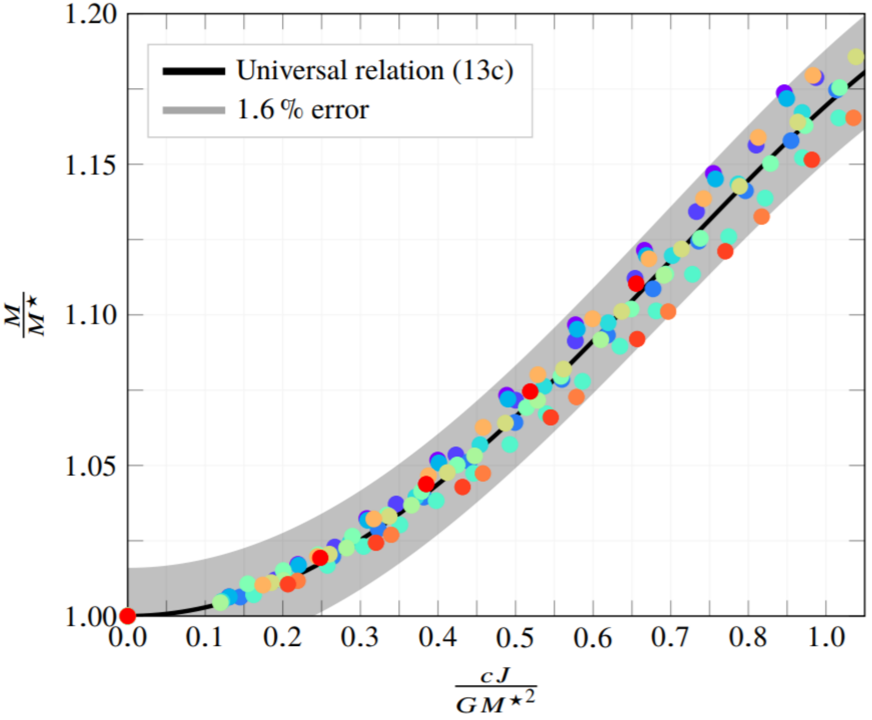
J-const law used in previous studies.
A monotonic omega profile

$$\Omega = \Omega_c \frac{1 + (j/B^2\Omega_c)^p}{1 + (j/A^2\Omega_c)^{q+p}}$$



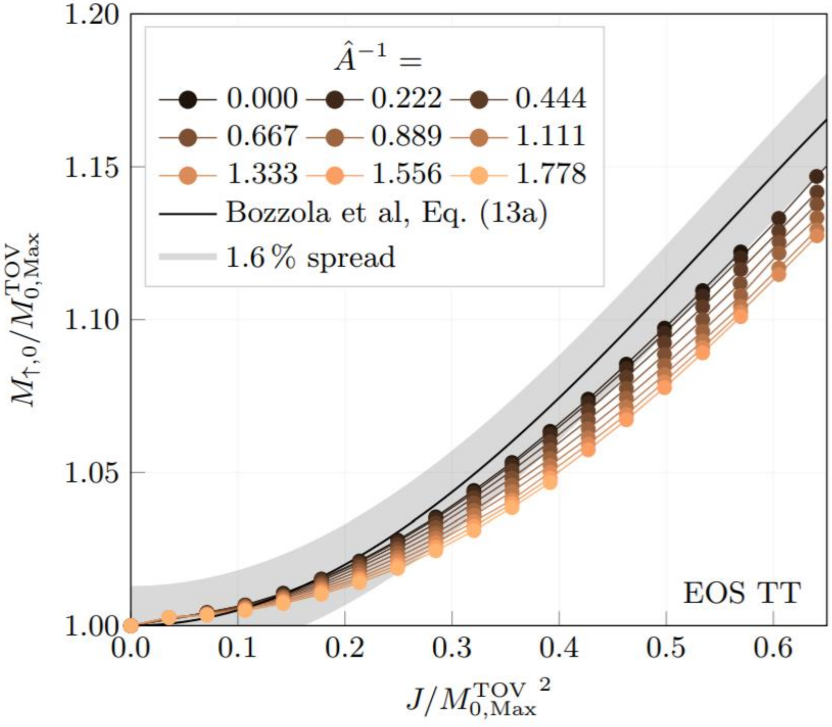
Actual omega profile seen in NR simulations
Hanauske et al. 2016

Influence of drot at collapse



Bozzola et al. 2017

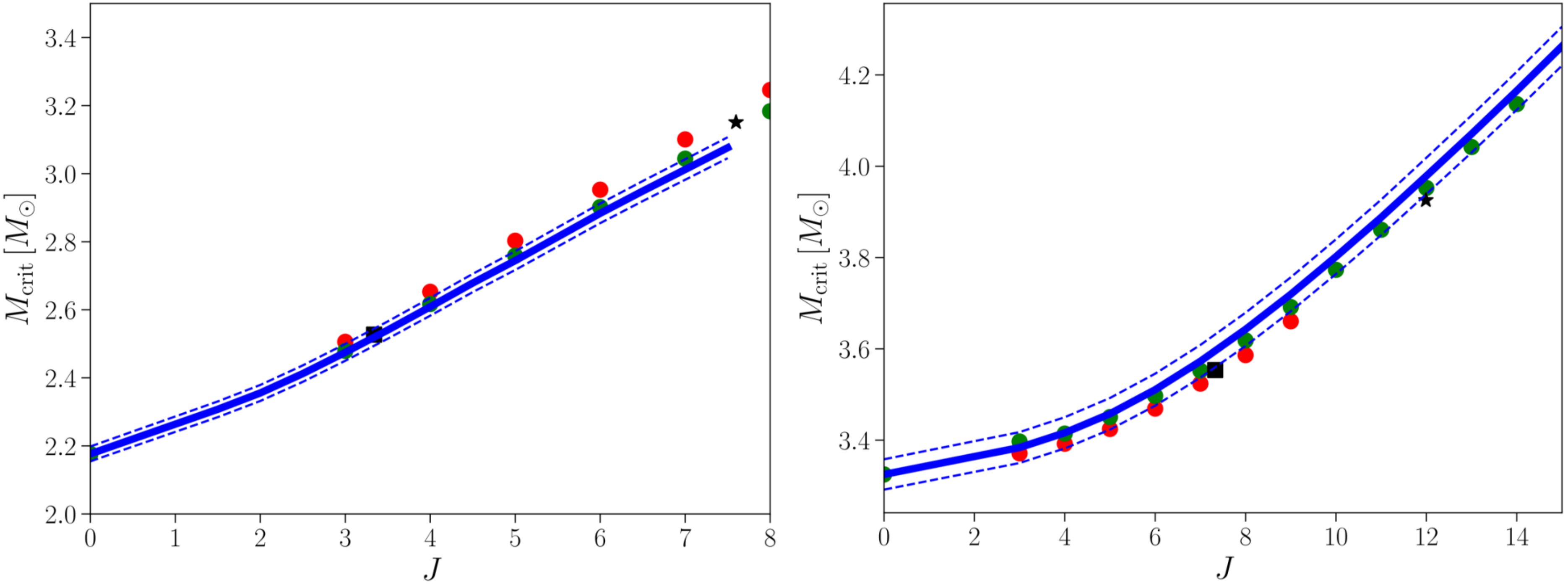
EoS-independent relation for j-const law



Bozzola et al. 2019

Deviations realized when hybrid stars are considered

Influence of drot at collapse



Zhou et al. 2019

For 2 different QS models as well as the new drot law

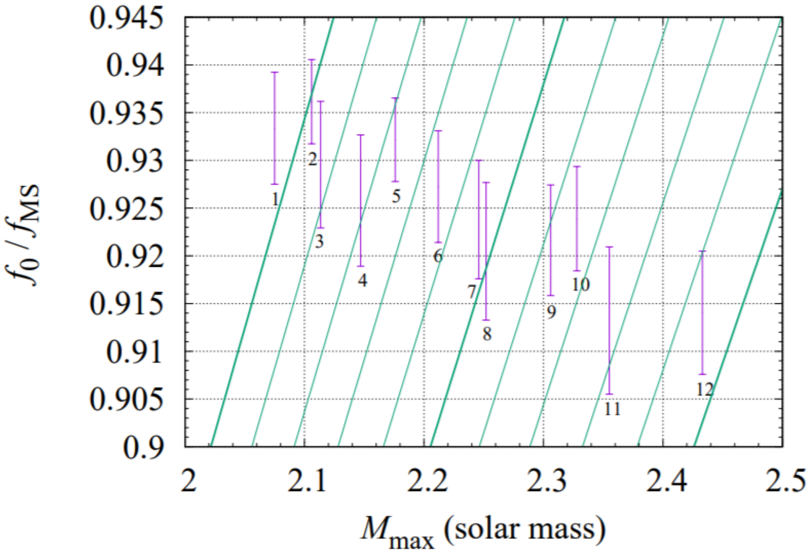
Therefore, it’s safe to use the uniform rotation marginally stable line, even if the remnant still rotates differentially at the time of collapse

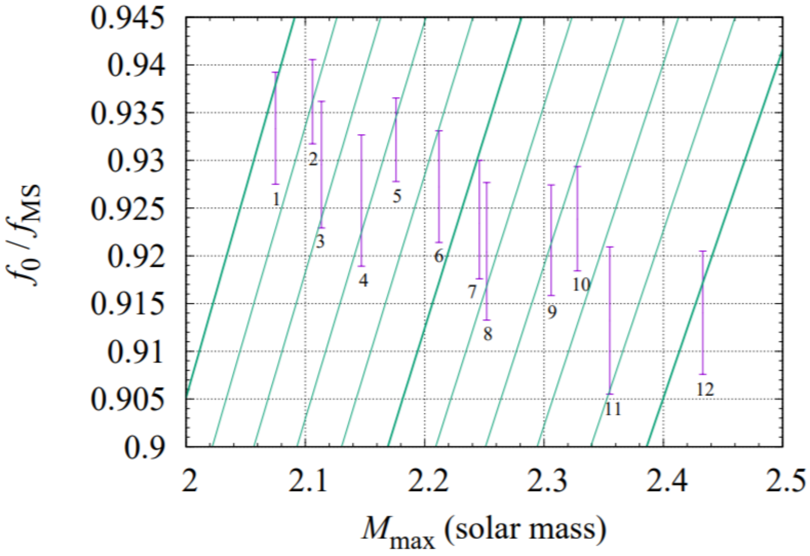
New analysis: the results

$$M_f = \frac{f_0}{f_{\rm MS}} M - \frac{M_{\rm out} + M_{\rm eje}}{f_{\rm MS}}$$

$$\frac{f_0}{f_{\rm MS}} = \frac{M_{\rm out} + M_{\rm eje}}{f_{\rm MS} M} + \frac{f_r M_{\rm max}}{M}.$$

$$f_r M_{\rm max} = M_f$$





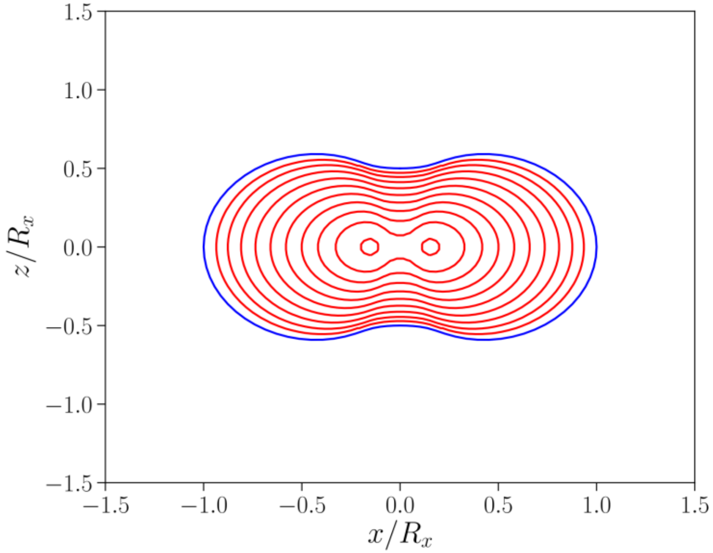
Future prospects

Magnetar model?

- requires high E_gw,p
- requires relatively low B field
- requires larger Mtov (M_supra) but should not violate tidal deformability constraint.

Zhou et al. 2019

QSs (e.g. MIT bag model) might be a suitable model candidate for the magnetar scenario.



Future prospects

- Indeed, in order to move one step forward from the simplest approximation, we have to make more approximations since we are touching more details. This can be improved in the future by better study of long term post-merger simulations.
- Future observation of post-merger GW signal as well as neutrino (i.e., exact time of collapse) will significantly improve our constraint on EoS models.