

Configurations of the SMNS in BNS mergers

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Outline

- The role of the supra-/hyper-MNS in BNS mergers
- Axisymmetric **RNS** & **RQS** configurations
- Triaxial **RNS** & **RQS** configurations
- Discussions

BNS merger in GW era

BNS mergers are more interesting..

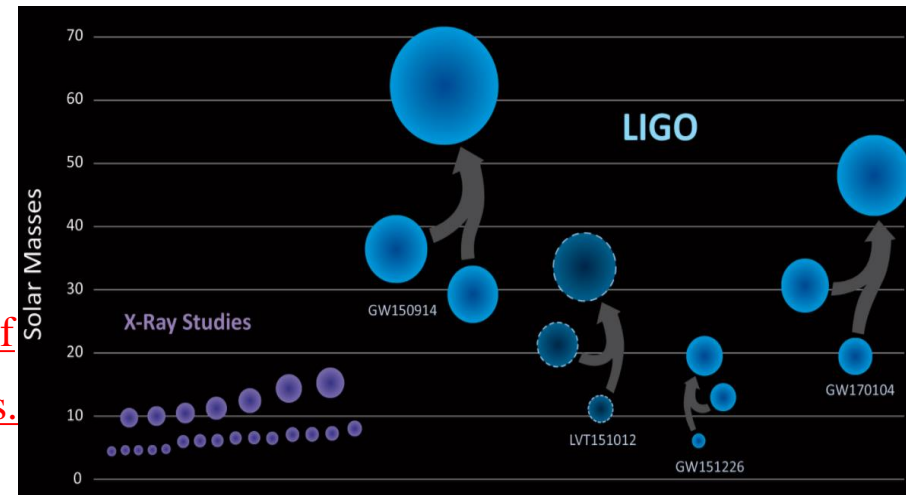
➤ **Strong interaction:** $T \sim 0$, $\rho > \rho_0 \rightarrow \alpha_s > 1$

- Testing different EoS by pulsar observations can give us information about Non-perturbative QCD

➤ **Gravity:** $C_{NS} \sim 0.5 C_{BH}$

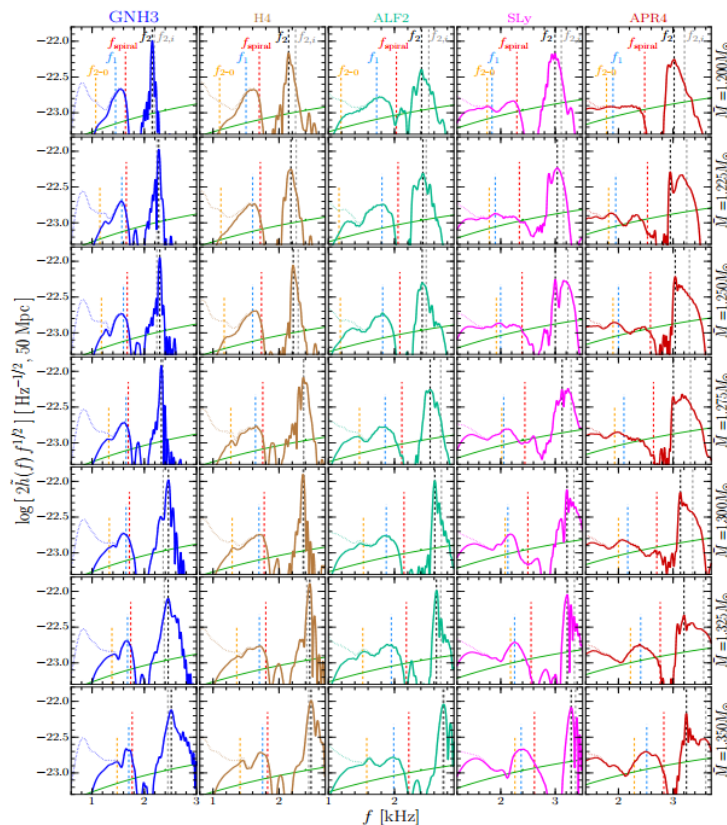
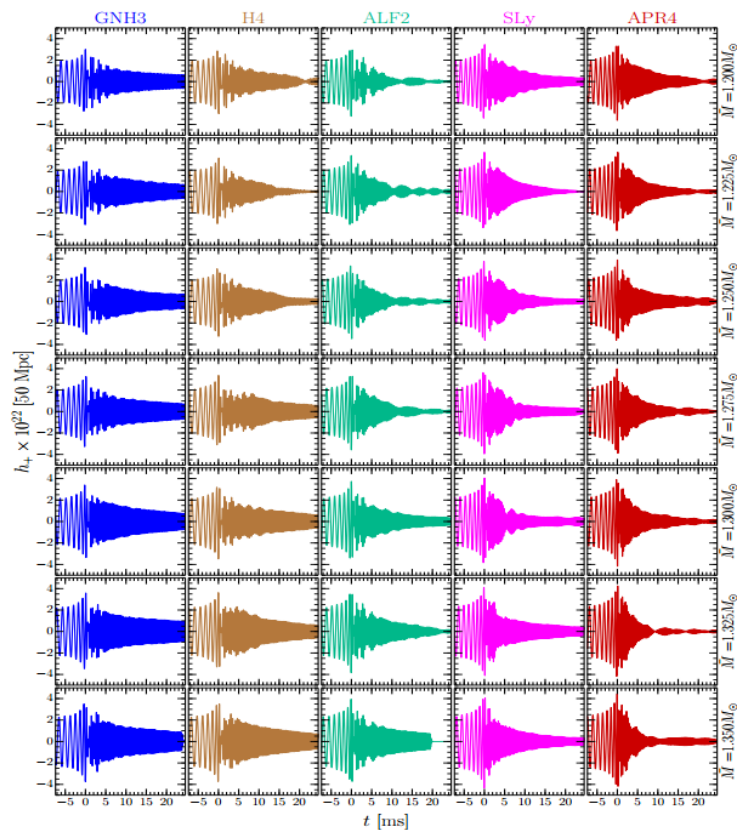
- BNS merger produces gravitational wave

The discovery of GW150914 opens a new era of gravitational wave astronomy, by the advantage of which we can also constrain EoS of compact stars.
NR needs to be invoked for this quest.



BNS merger in GW era

- NR & EoS of compact stars

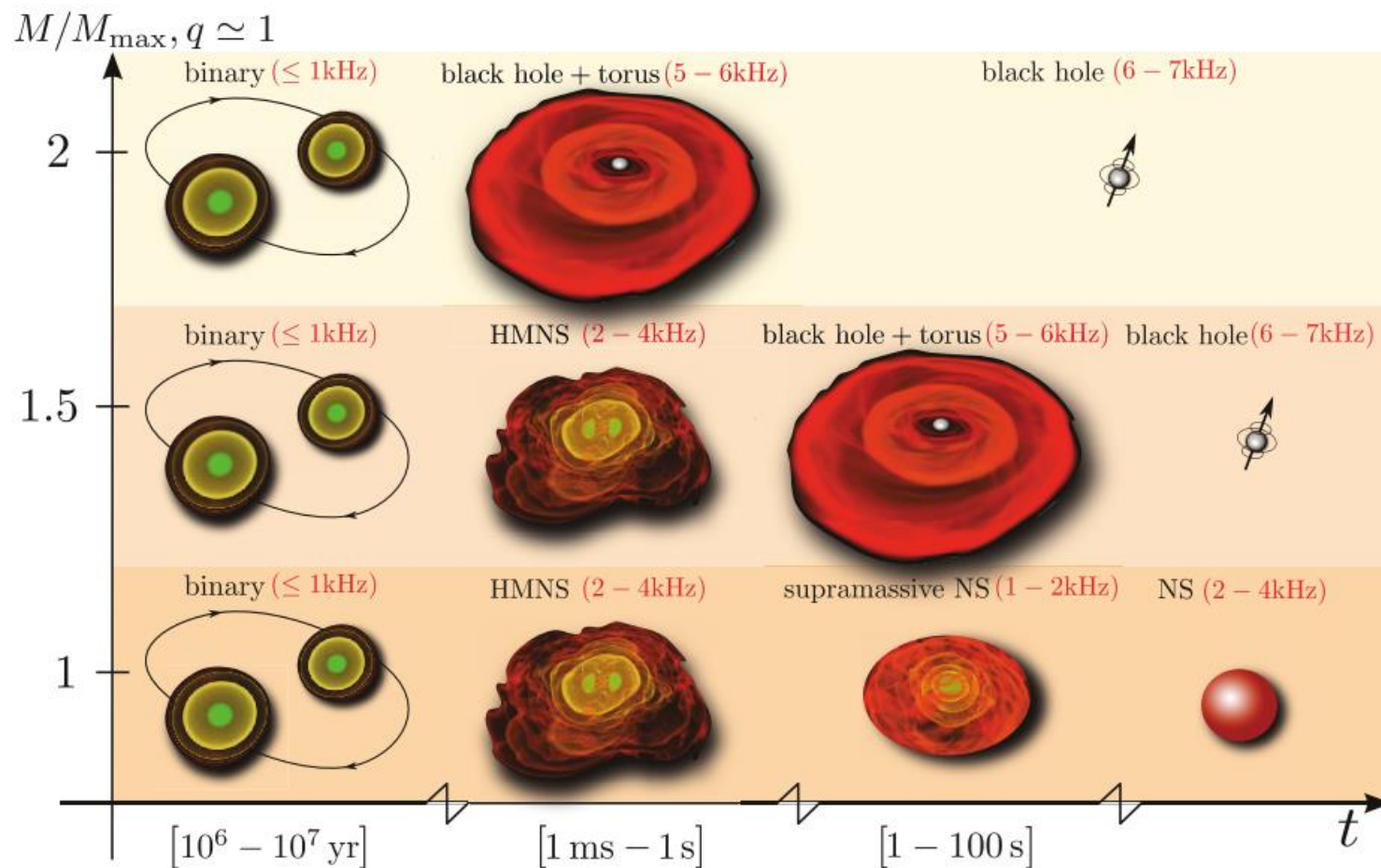


Waveforms and PDSs of GW radiation by BNS mergers with different EoSs (column) & different mass (row)

Rezzolla & Takami 2016

Supra-/hyper-MNS in BNS merger

- BNS as the possible central engine of short GRBs



Rezzolla & Zanotti
2013

M/M_{\max} and the configuration of the HMNS is very important to understand BNS merger and its EM counterpart.

Supra-/hyper-MNS in BNS merger

Table 1
Double Neutron Star Systems Known in the Galaxy

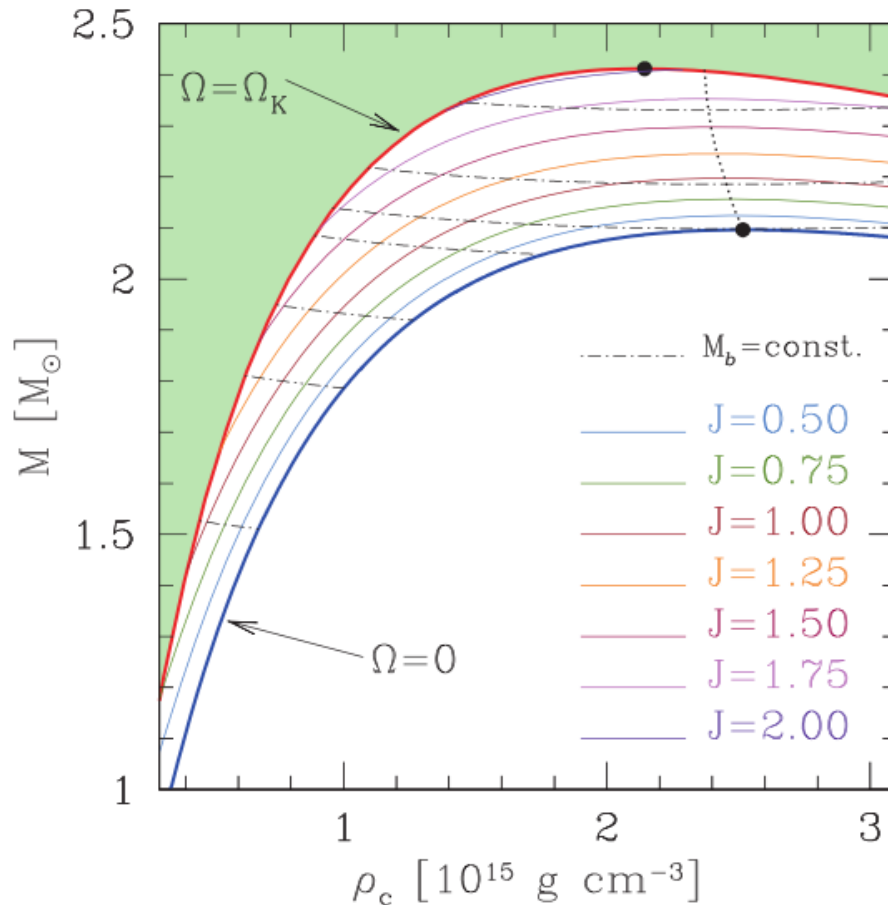
Pulsar	Period (ms)	P_b (days)	x (lt-s)	e	M (M_\odot)	M_p (M_\odot)	M_c (M_\odot)	References
J0737–3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	(1)
J0737–3039B	2773.461	...	1.516	...	...	...	...	...
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	...	...	(2)
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	(3)
J1753–2240	95.138	13.638	18.115	0.303582(10)	...	...	...	(4)
J1756–2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	(5)
J1811–1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	...	...	(6)
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	...	...	(7)
J1906+0746 ^a	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	(8)
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	(9)
J1930–1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	...	...	(10)
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This letter
Globular Cluster Systems								
J1807–2500B ^a	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	(12)
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	(13)

Martinez et al. 2015

The current mass constraint for NS is **2 solar mass** (PSR J0348+0432 & J1614-2230), which means a realistic nuclear EoS has to have a TOV maximum of 2 solar mass.

Therefore the known DNS systems in observations show not very high value of M/M_{\max} (**~ 1.3**). So it's very important to study the configuration of rotating compact stars, i.e., to study the maximum mass of a compact star at mass shedding limit.

Axisymmetric uniformly RNS

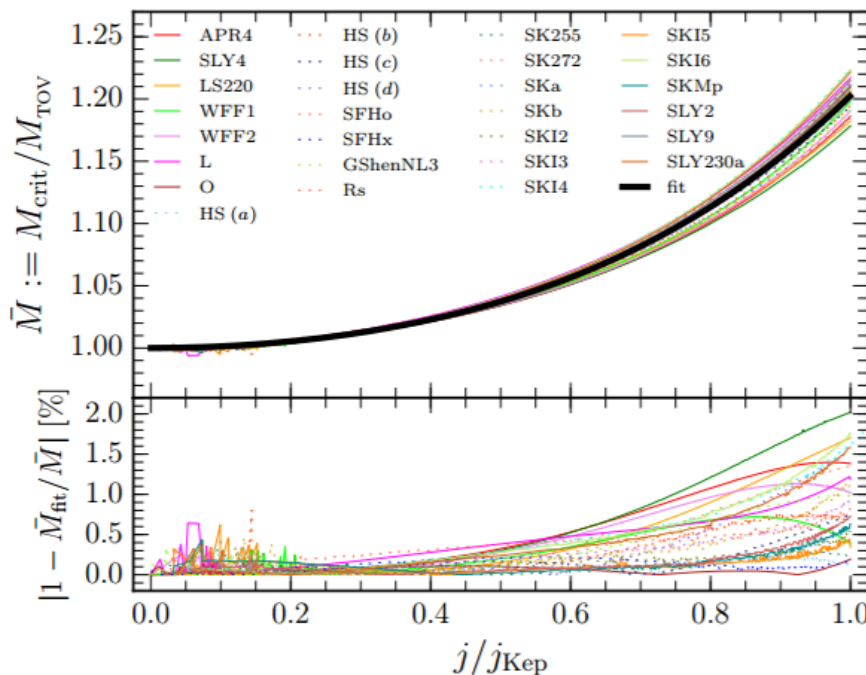


- NS move on the dashed-dotted lines which are the constant baryonic mass line when they spin down.
- Dotted line is the stable limit, for which $\frac{\partial M}{\partial \rho_c} \Big|_J = 0$
- A supramassive neutron star can either eventually collapse to a black hole (in magnetic braking timescale) or become a stable NS forever.

A textbook example with polytropic EoS of $\Gamma = 2$ Rezzolla & Zanotti 2013

Axisymmetric uniformly RNS

- Breu and Rezzolla have shown that quantities of rotating neutron stars depend very weakly on the EoSs:



$$\frac{M_{\text{crit}}}{M_{\text{TOV}}} = 1 + a_2 \left(\frac{j}{j_{\text{KEP}}}\right)^2 + a_4 \left(\frac{j}{j_{\text{KEP}}}\right)^4$$

$$a_2 = 0.1316$$

$$a_4 = 0.0711$$

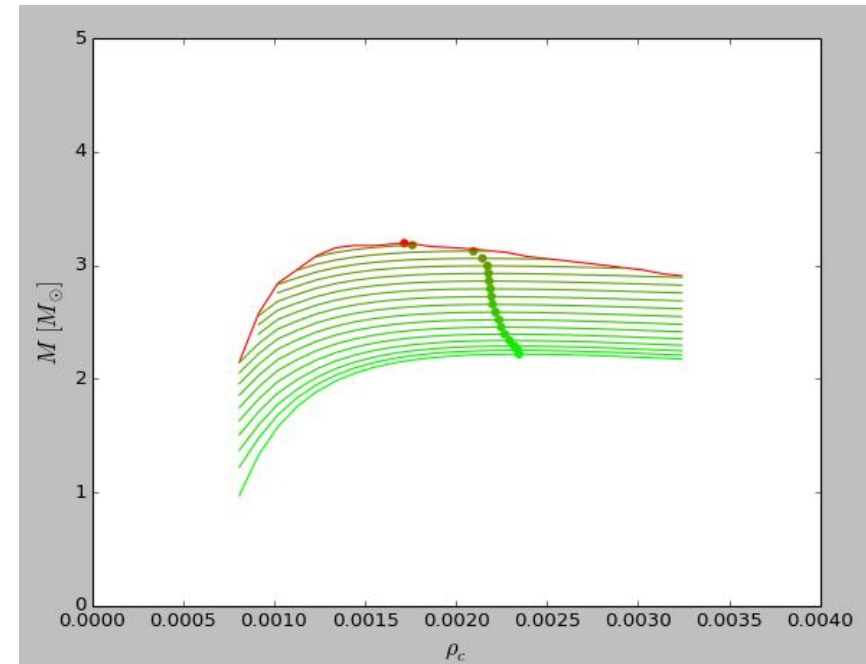
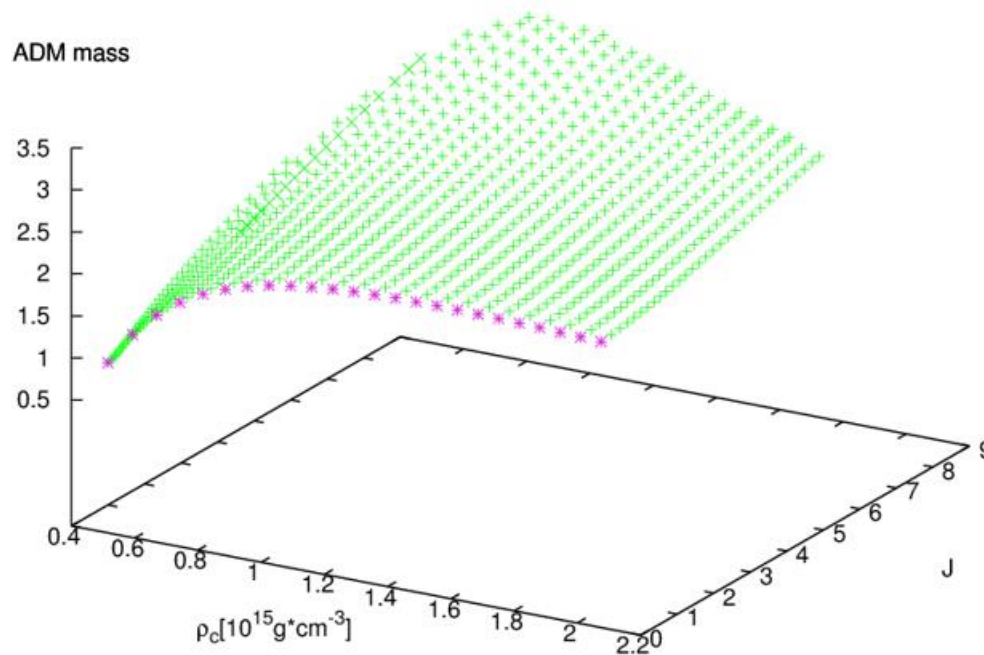
$$M_{\text{max}} = M_{\text{crit}}(j = j_{\text{kep}}) = (1 + a_2 + a_4)M_{\text{TOV}} \simeq 1.203M_{\text{TOV}}$$

Similar universality has also been found between quantities such as :
moment of inertia/ binding energy
and compactness.

In another word, for RNS, the maximum mass at mass shedding limit can be **20% larger** than TOV maximum.

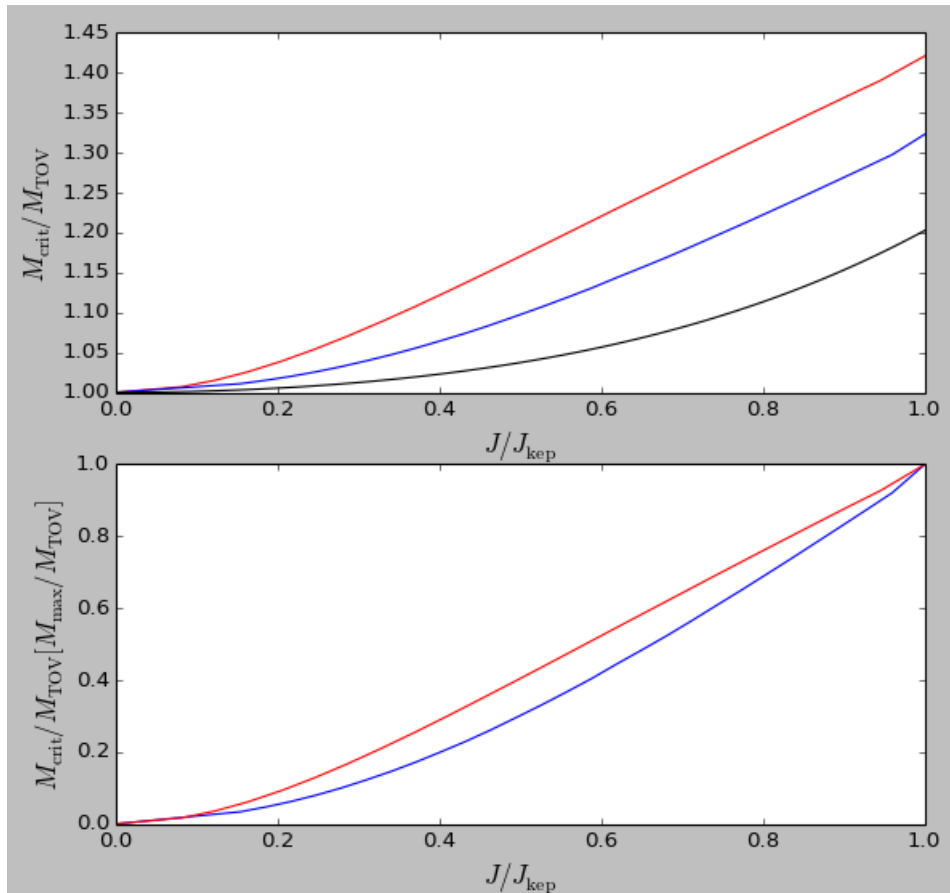
Axisymmetric uniformly RQS

- A series of RQS sequences has been created and studied with **COCAL** (an initial data code with **finite differencing method** and **conformally flat approximation, KEH approach**).



An axisymmetric RQS solution sequence example with MIT bag model
($B = 60 \text{MeVfm}^{-3}$)

Axisymmetric uniformly RQS

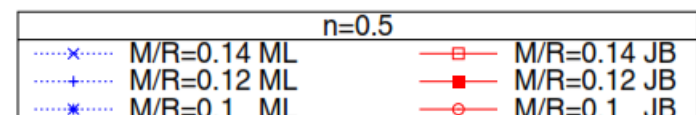
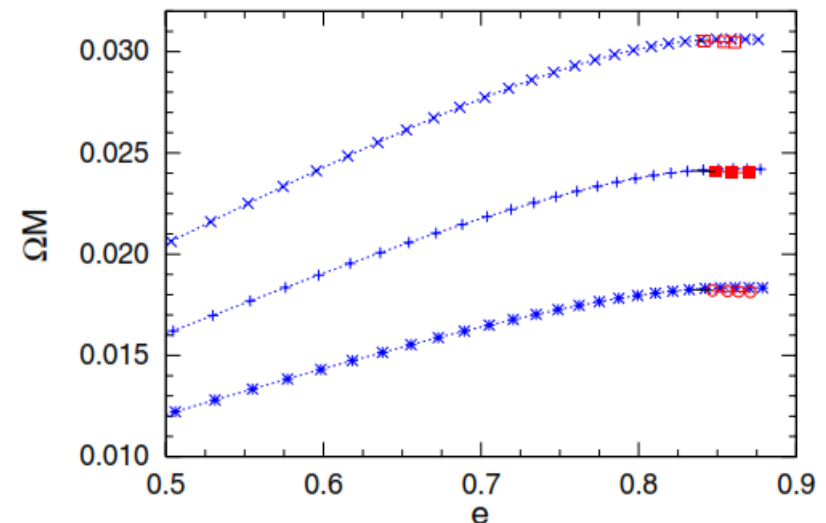
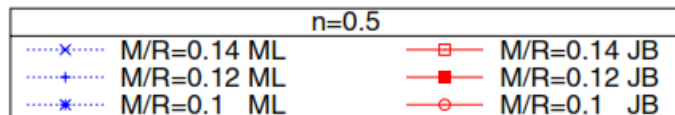
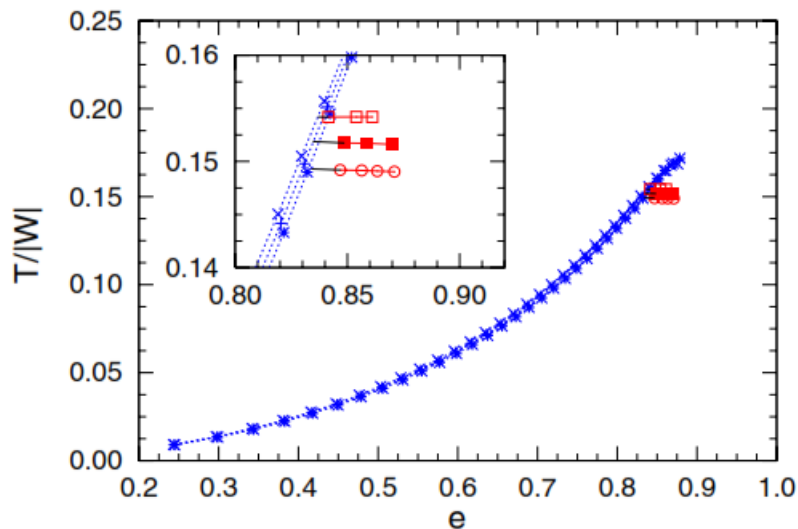


Unfortunately, the universality for RNS (black line) can't be extended to RQS, even RQS with different EoSs show large scattering in the quantities (red: LaiXu09 model, blue: MIT bag model).

But we found that RQS can be much heavier (40% heavier at Keplerian frequency) than non-rotating quark stars compared with RNS (20% heavier).

Triaxial uniformly RNS

- Since the HMNS formed in the post-merger phase is rapidly rotating, the secular instability could take place if the $T/|W|$ ratio exceeds a critical value (in Newtonian it's 0.1375).
- This has been studied by Huang et al. 2007 using COCAL.



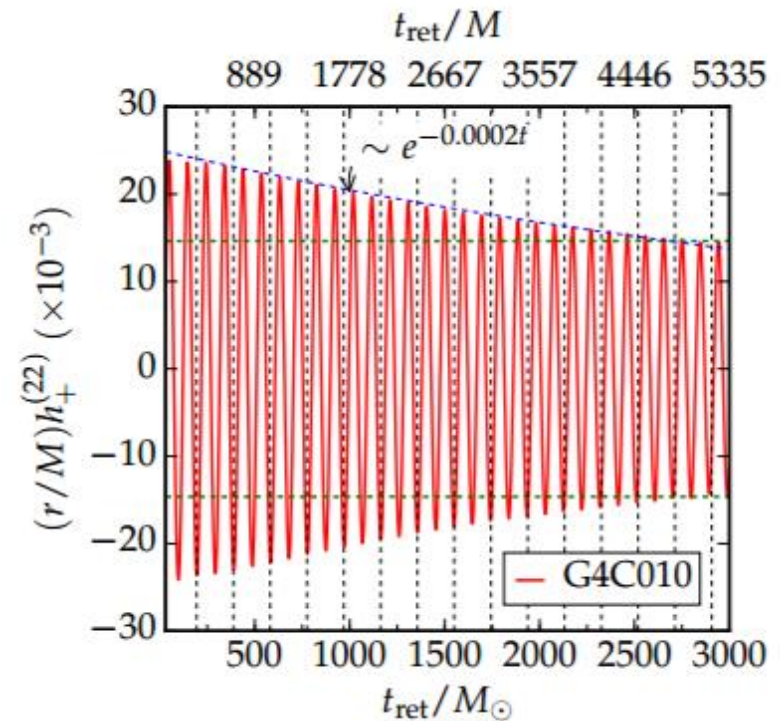
However, the triaxial sequence terminates at certain M/R for RNS !

Triaxial uniformly RNS

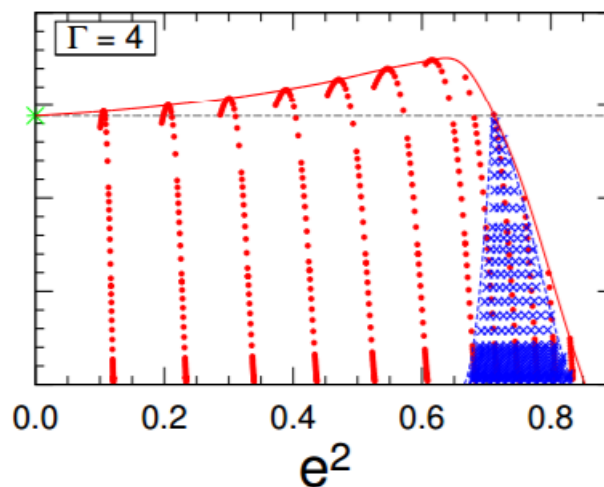
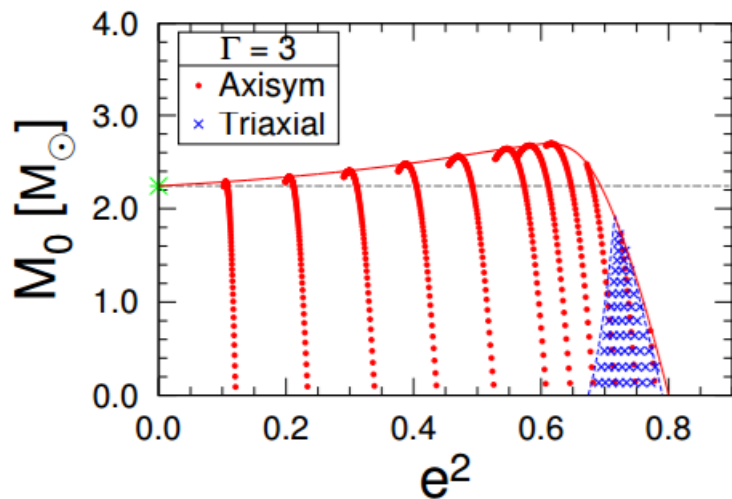
$$\frac{t_d}{M} \sim \frac{1}{\Omega M} \sim \left(\frac{M}{R}\right)^{-3/2}$$

Evolutions of such initial data show that such configuration of triaxial RNS are **dynamically stable**.

The frequency of the radiation (hence the rotating star) remains almost the same (slightly increase) when it loses angular momentum due to GW radiation.



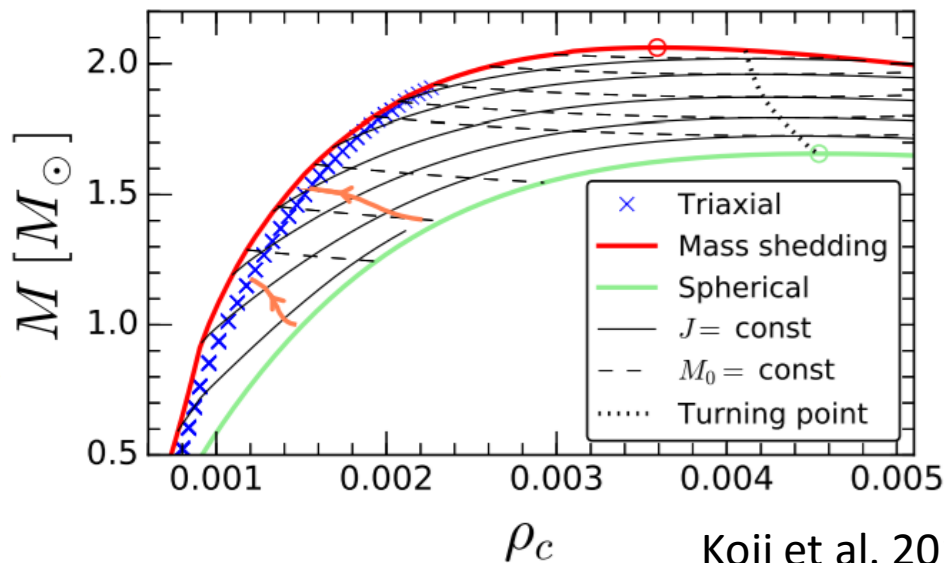
Triaxial uniformly RNS



Even for polytropic EoS with $\gamma=4$, we can hardly find supramassive triaxially RNS.

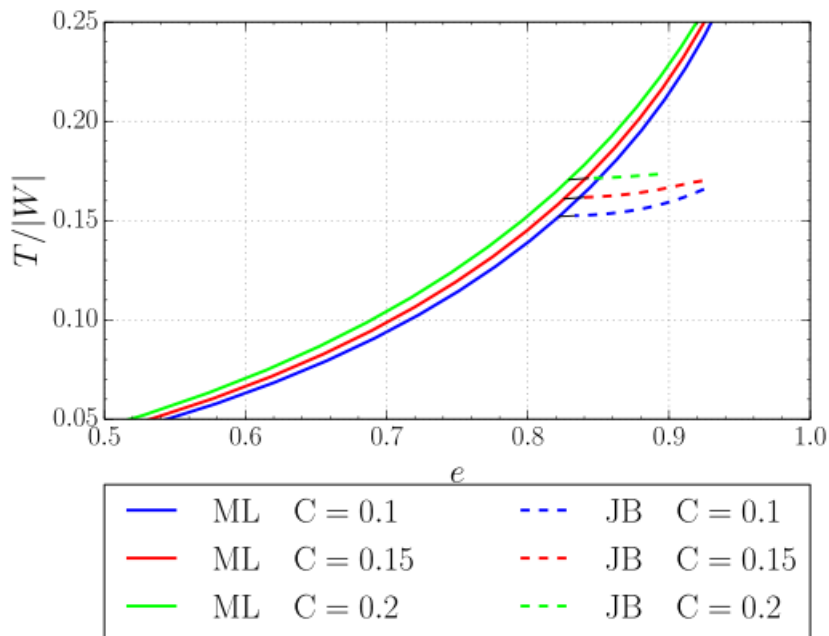
$$T/|W|_{\text{crit}} = T/|W|_{\text{crit,Newt}} + 0.148x(x+1)$$

T/W for RNS is too low!

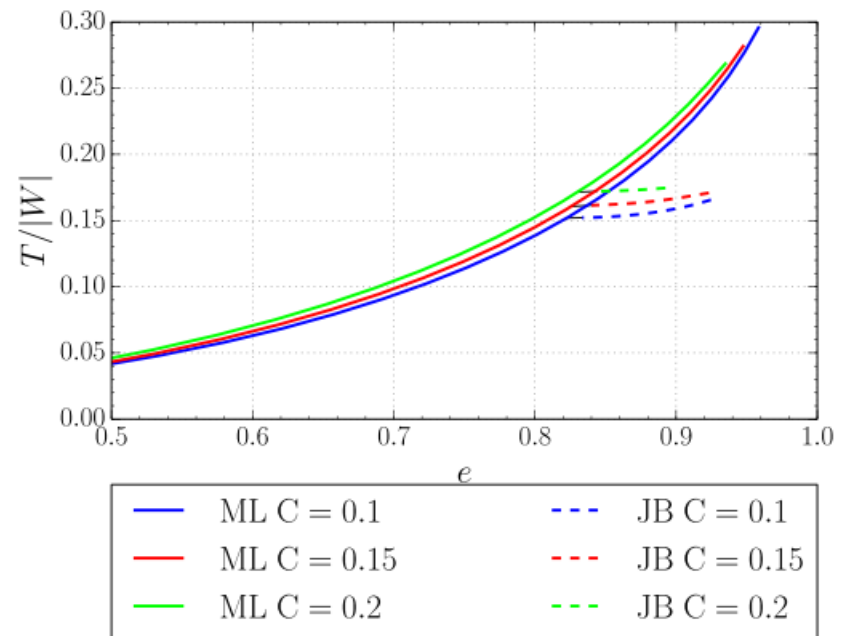


Triaxial uniformly RQS

- We have built triaxially RQS with COCAL, and found that the triaxially RQS sequence plays a more important role than RNS, because RQS can reach a much higher kinetic energy compared with RNS. (Zhou et al. in preparation)

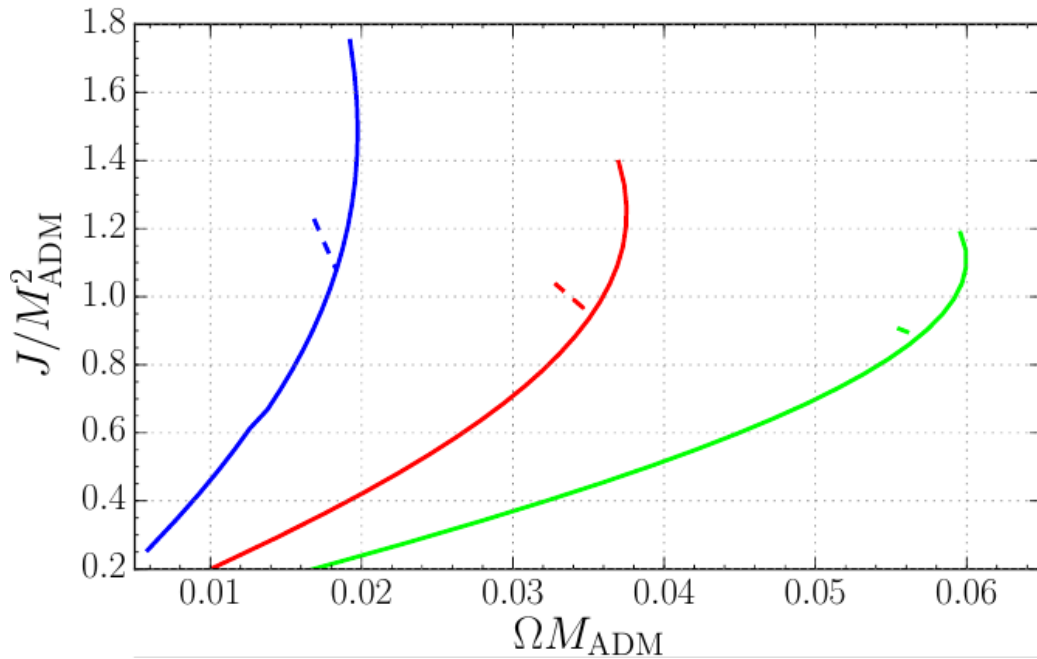


MIT bag model

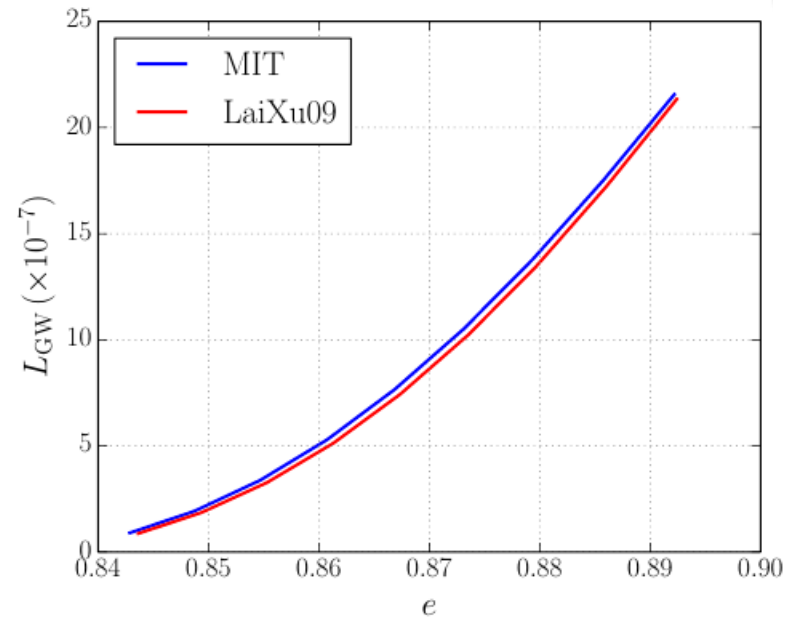
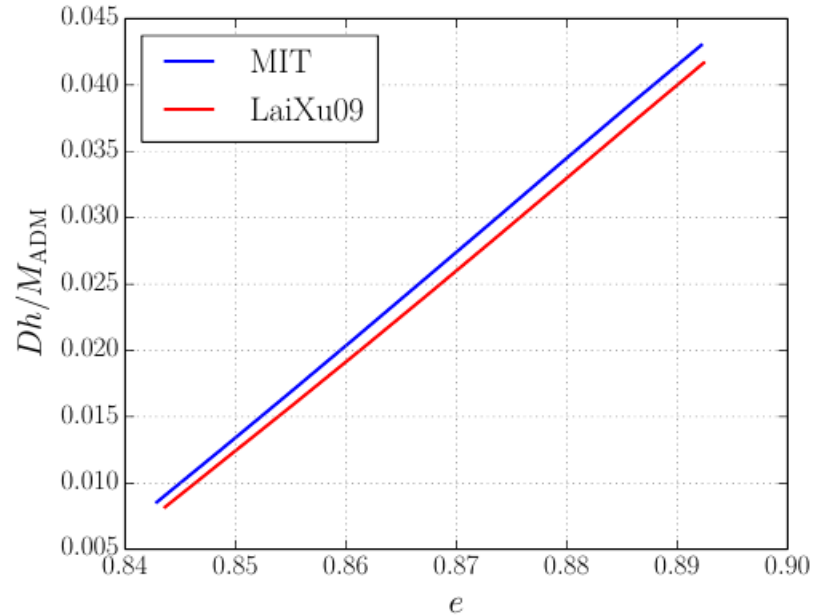


LaiXu09 model

Triaxial RQS



Therefore, if the HMCS is a QS, we could expect GW radiation from the triaxially rotating body ($h \sim 10^{-24}$ @ 30Mpc, $f \sim 2\text{kHz}$).



Discussion

- We expect different types of stars (hypermassive/supramassive) formed in a BNS merger, assuming different EoS (NS/QS). This might lead to **different fate** of the system or at least **different lifetime** of the merged compact object.
- We expect persistent GW signals from the triaxial rotating star if it's a quark star.
- Future work: differential rotating quark stars

Thanks!

