Numerical configurations of the supra-/hyper-MNS 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
- Differential RNS & RQS configurations
- Discussions

BNS merger in GW era

BNS mergers are more interesting..

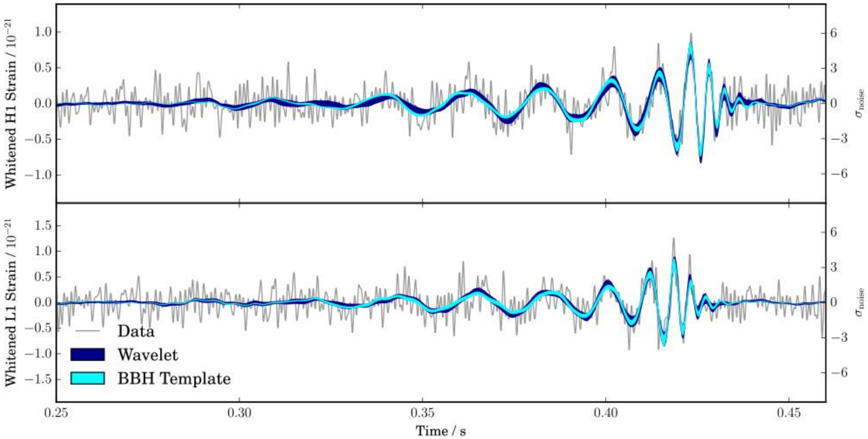
➢**Strong interaction**: $T \sim 0, \quad \rho > \rho_0 \quad \rightarrow \quad \alpha_s > 1$

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

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

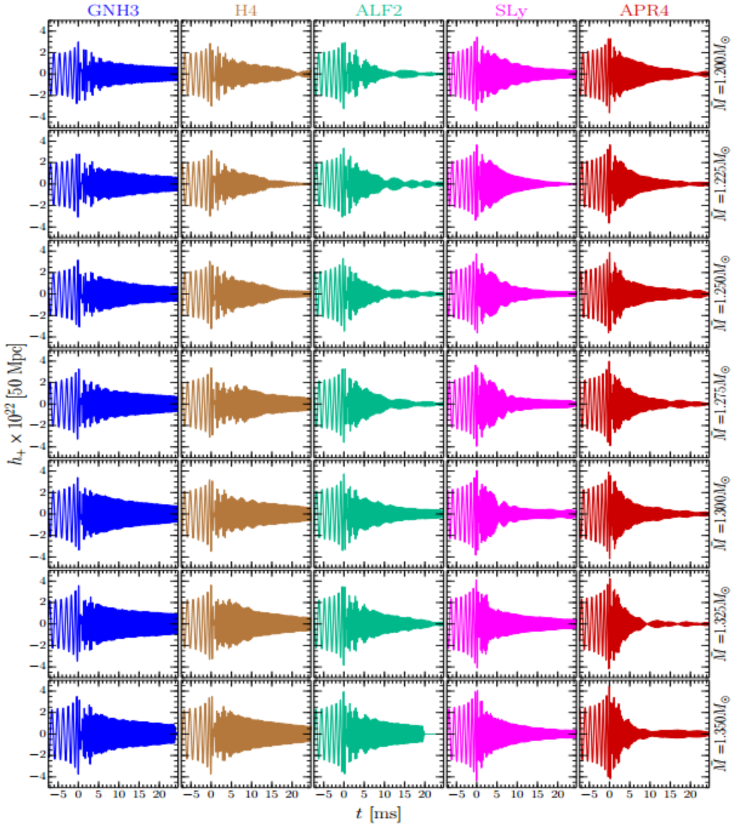
- BNS merger produces gravitational wave

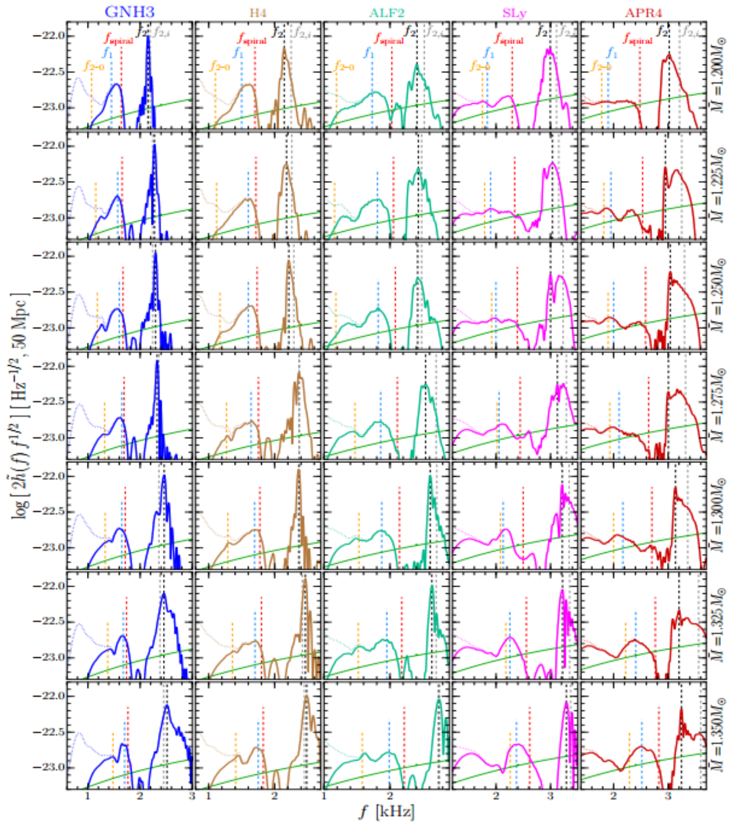
The discovery of GW150914 opens a new era of gravitational wave astronomy, by the advantage of which we can also constrain EoS of compact stars. NR needs to be invoked for this quest.



BNS merger in GW era

- NR & EoS of compact stars



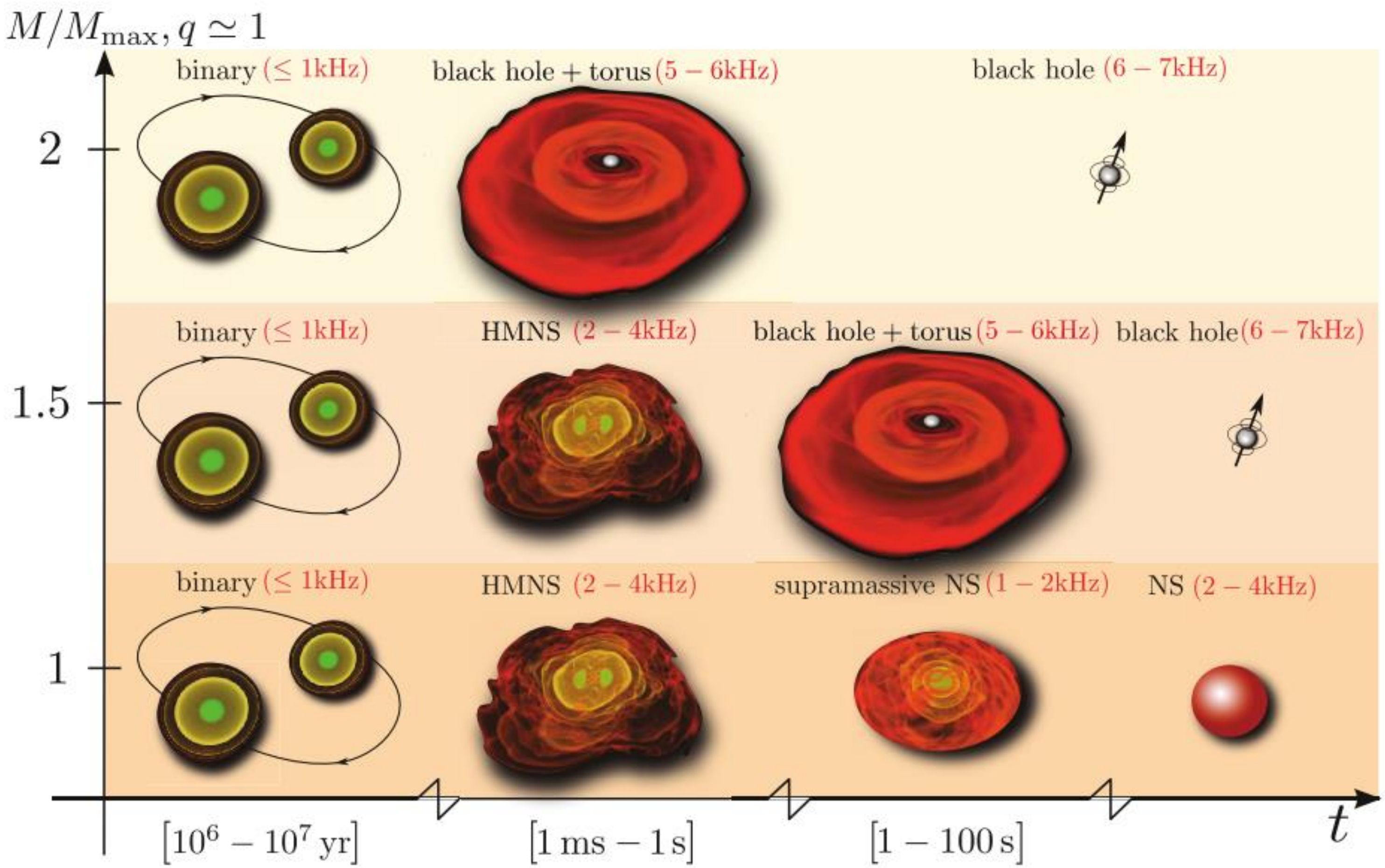


Waveforms and PDSs of GW radiation by BNS mergers with different EoSs (column) & different mass (row)

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

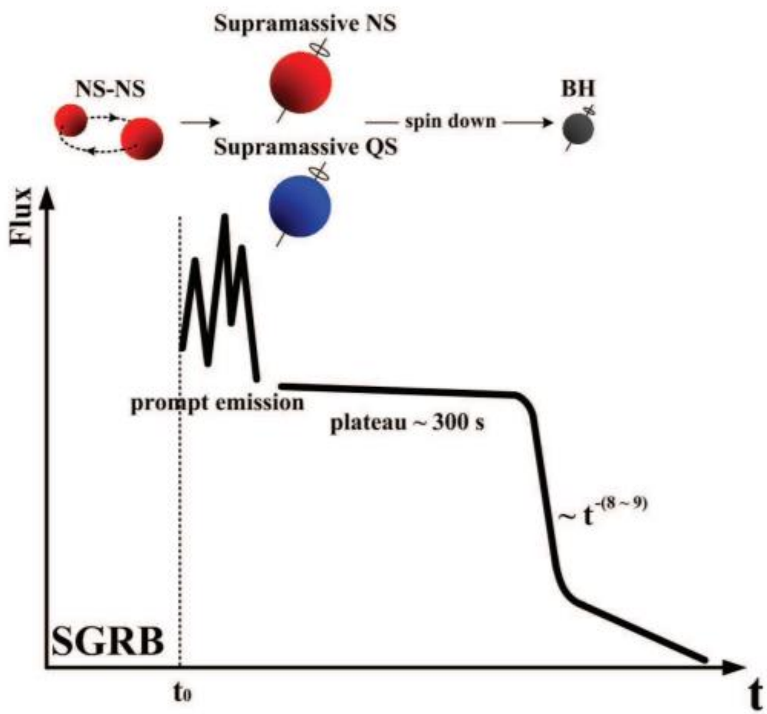
Table 1
Double Neutron Star Systems Known in the Galaxy

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.

Supra-/hyper-MNS in BNS merger



Li & Dong 2017 as an illustration for the magnetar model of sGRBs

In either model, the property of the supra-/hyper-MNS is very crucial to the understand the observations:

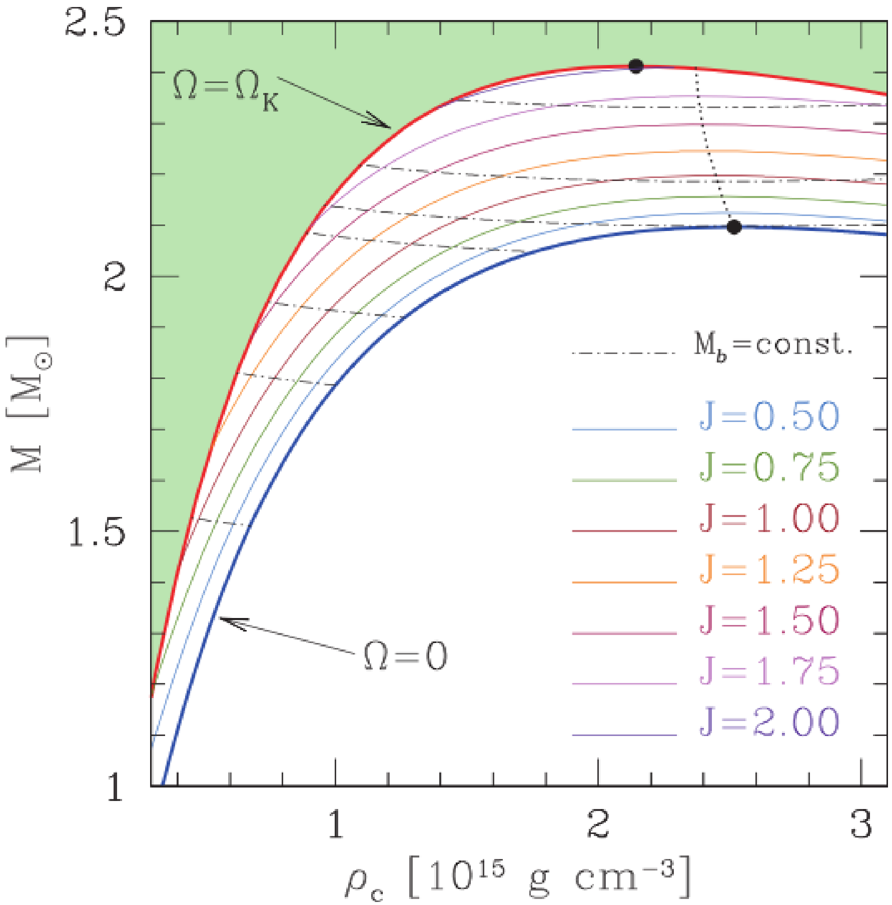
- Whether or not the sGRB triggered and the time-delay
- Whether or not the X-ray plateau detected and the duration

In sGRB studies (e.g. Li et al. 2016; Sun et al. 2016), a relationship of

$$\frac{M_{\rm max}}{M_\odot} = \frac{M_{\rm TOV}}{M_\odot}\left[1+\alpha\,\left(\frac{P}{\rm ms}\right)^{\beta}\right]$$

is usually fitted to imply the evolution of the SMNS . This can be improved by invoking NR.

Axisymmetric uniformly RNS

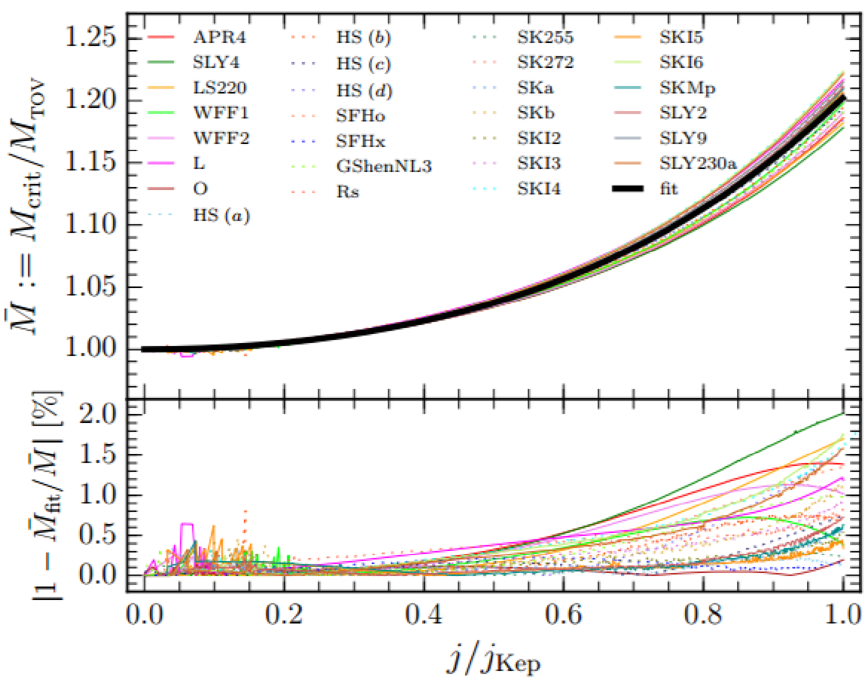


A textbook example with polytropic EoS of $\Gamma = 2$ Rezzolla & Zanotti 2013

- 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 $\frac{\partial M}{\partial \rho_c}|_J = 0$
- A supramassive neutron star can either eventually collapse to a black hole (in magnetic braking timescale) or become a stable NS forever.

Axisymmetric uniformly RNS

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



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

$a_2 = 0.1316$ $\quad$ $a_4 = 0.0711$

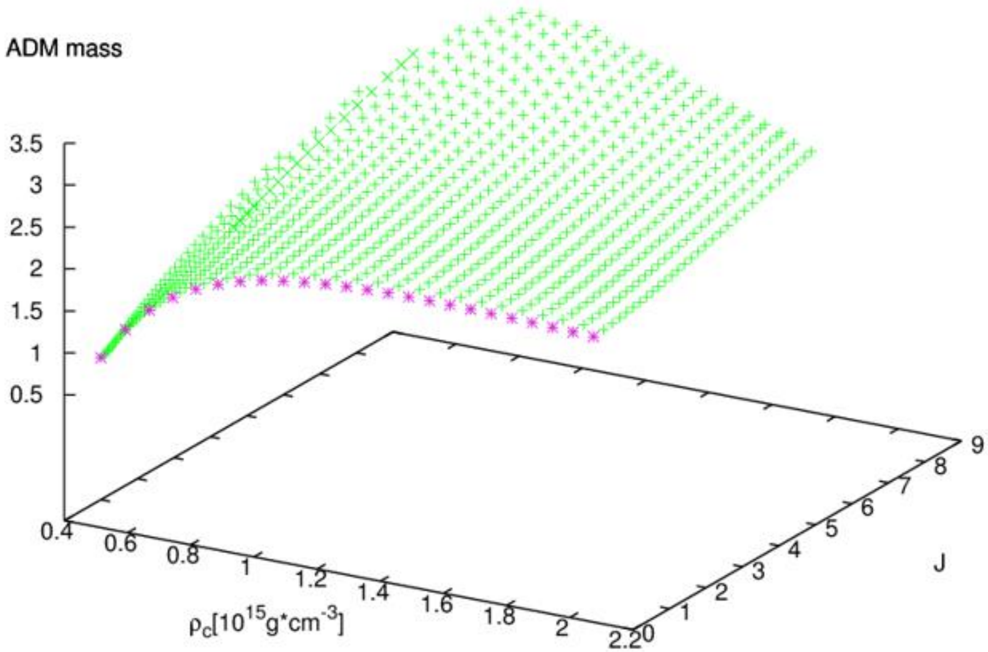
$$M_{\rm max} = M_{\rm crit}(j = j_{\rm kep}) = (1 + a_2 + a_4)M_{\rm TOV} \simeq 1.203 M_{\rm TOV}$$

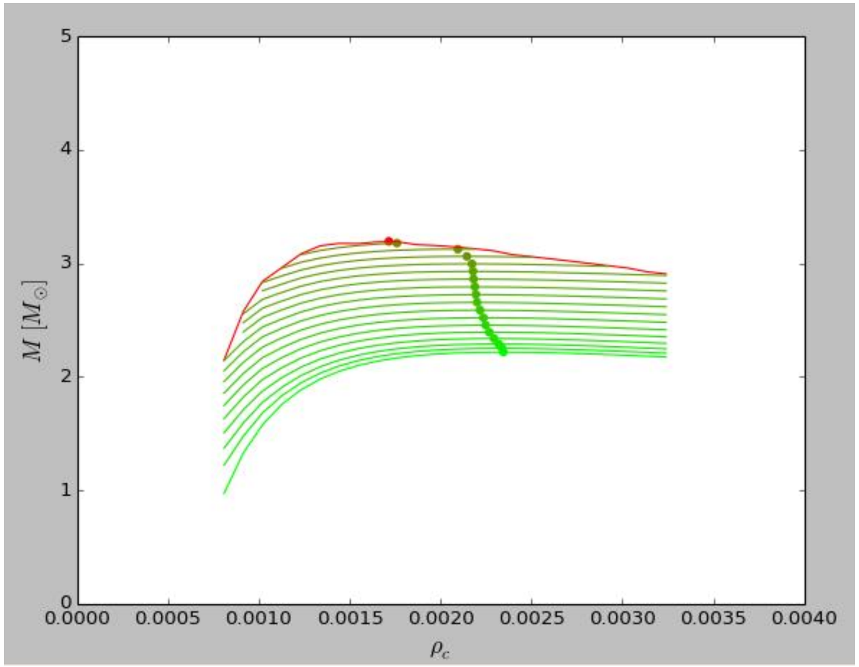
Similar universality has also been found between quantities such as : moment of inertia/ binding energy and compactness.

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

Axisymmetric uniformly RQS

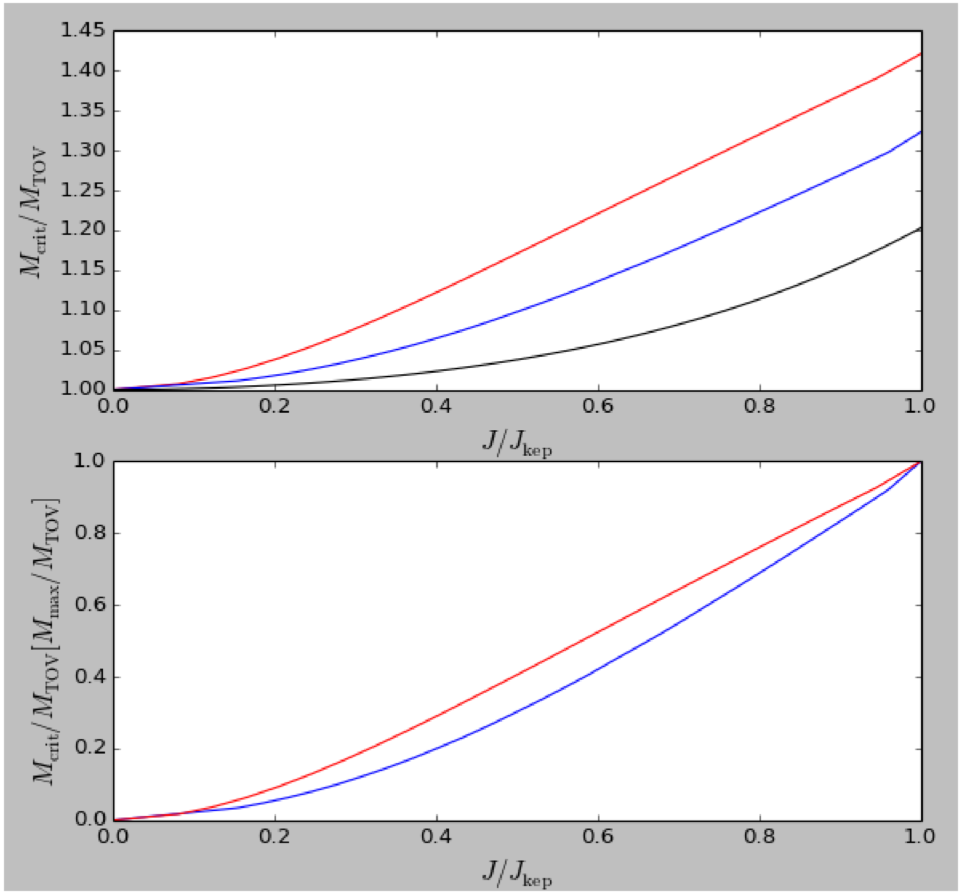
- A series of RQS sequences has been created and studied with COCAL (an initial data code with finite differencing method and conformally flat approximation, KEH approach).





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

Axisymmetric uniformly RQS

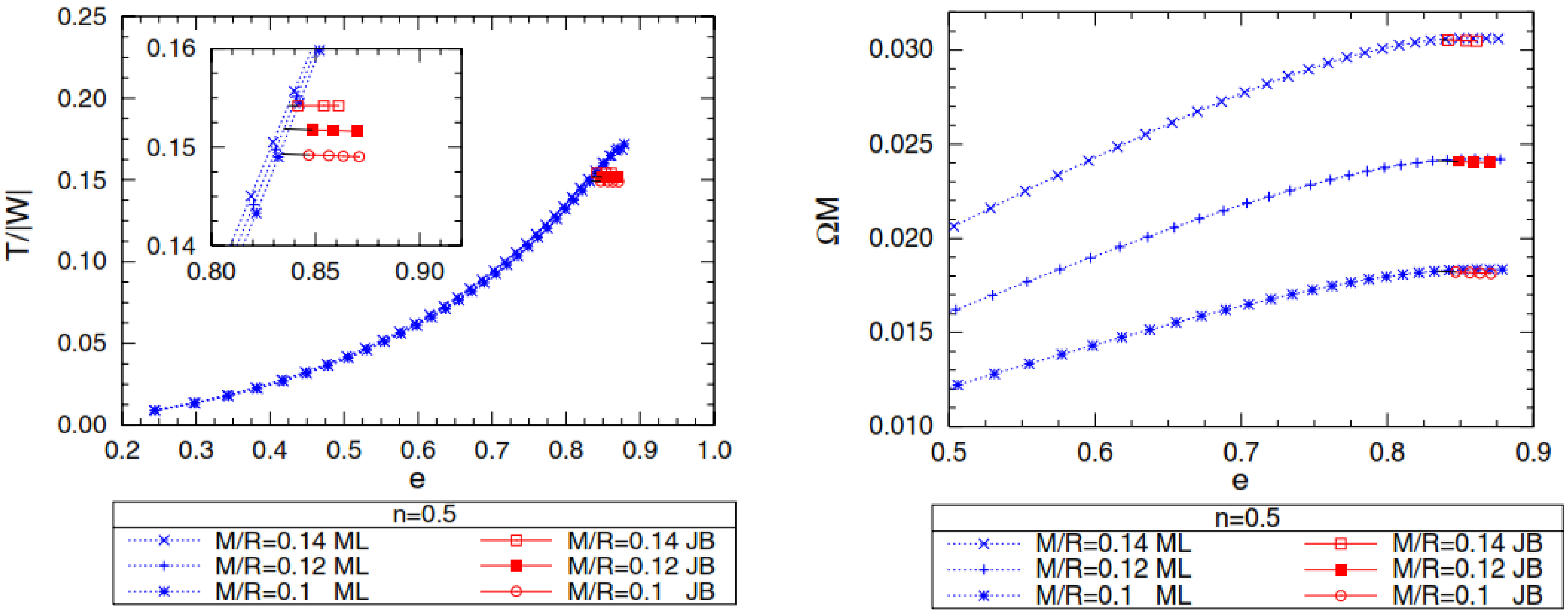


Unfortunately, the universality for RNS (black line) can't be extended to RQS, even RQS with different EoSs show large scattering in the quantities (red:LaiXu09 model, blue: MIT bag model).

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

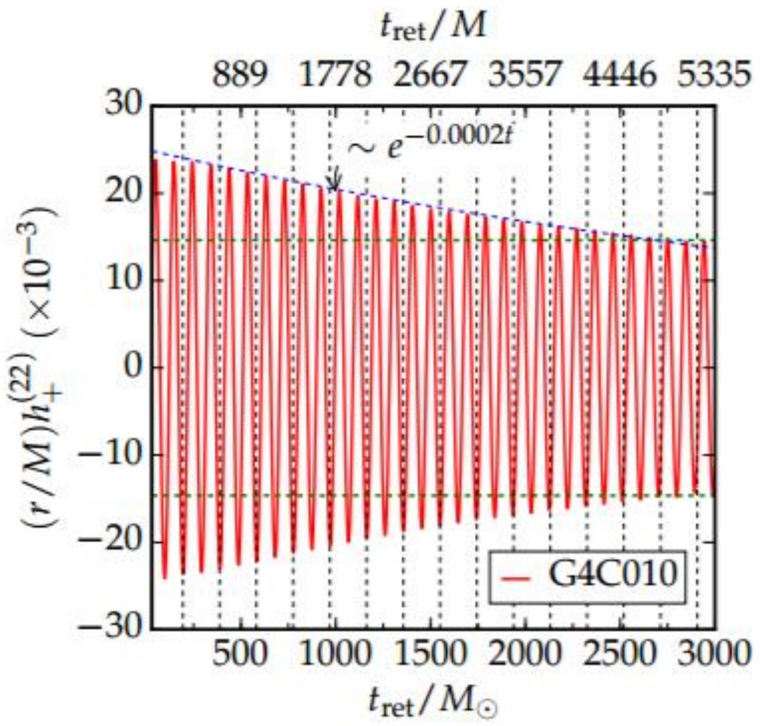
$$\frac{t_d}{M} \sim \frac{1}{\Omega M} \sim \left(\frac{M}{R}\right)^{-3/2}$$

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

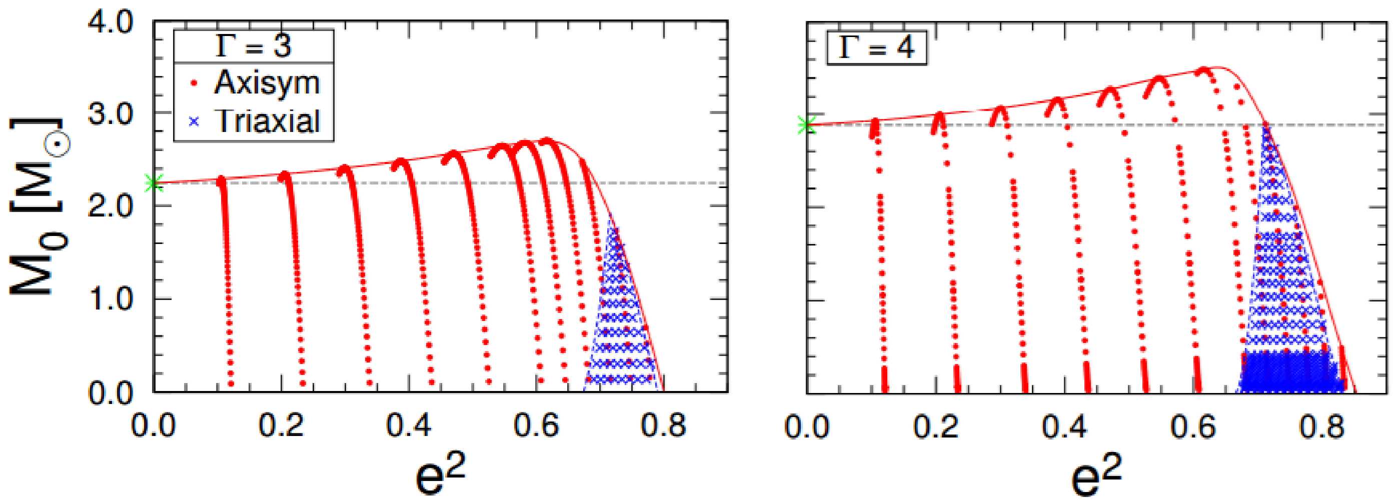
The frequency of the radiation (hence the rotating star) remains almost the same (slightly increase) when it loses angular momentum due to GW radiation.

Affect the EM radiation light-curve?

$$L_{\mathrm{X,free}}(t) = \eta L_{\mathrm{sd}} = \frac{\eta B_p^2 R^6 \Omega^4(t)}{6c^3}$$



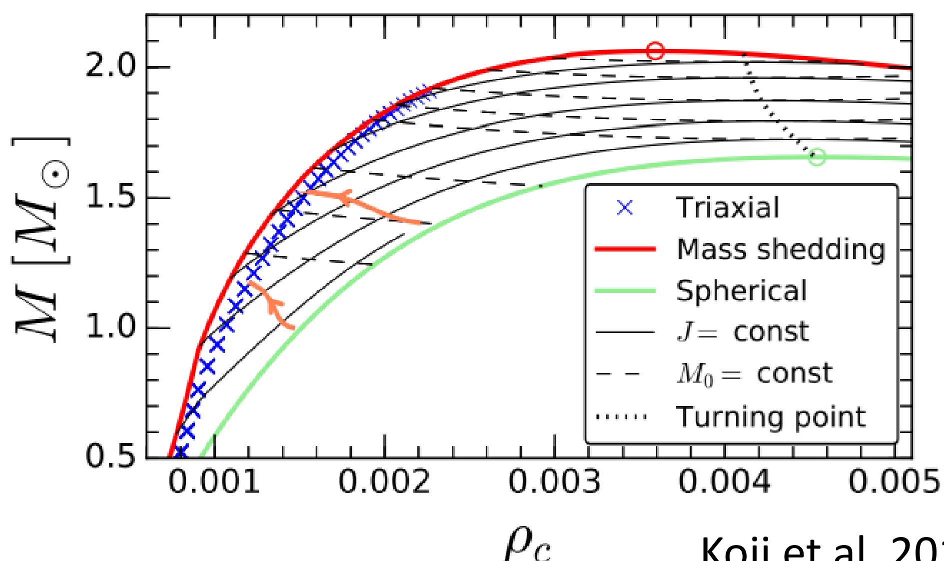
Triaxial uniformly RNS



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

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

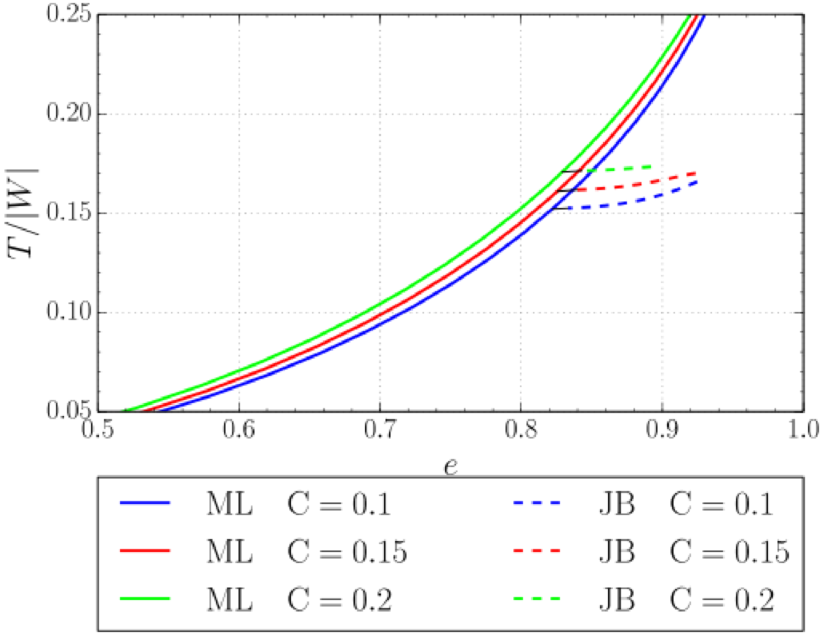
T/W for RNS is too low!



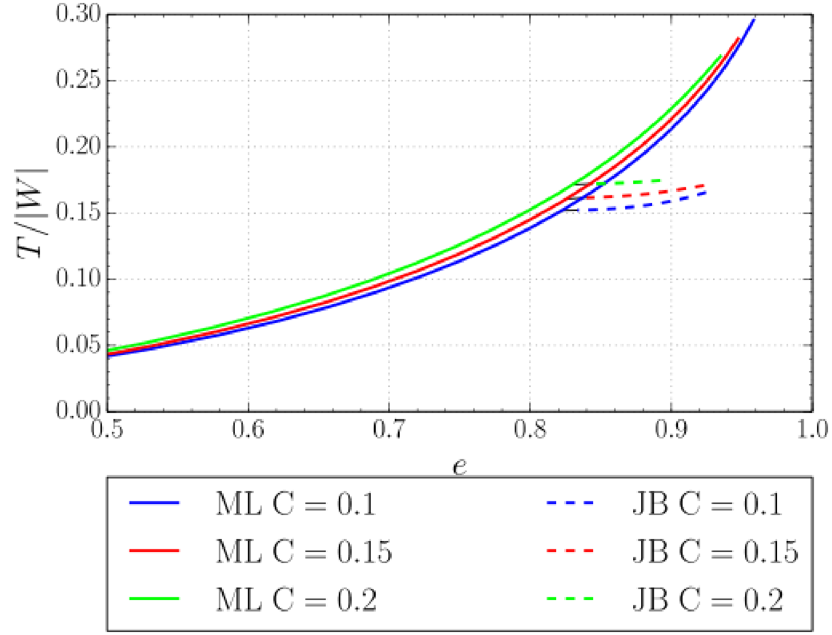
Koji et al. 2016

Triaxial uniformly RQS

- We have built triaxilly 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)

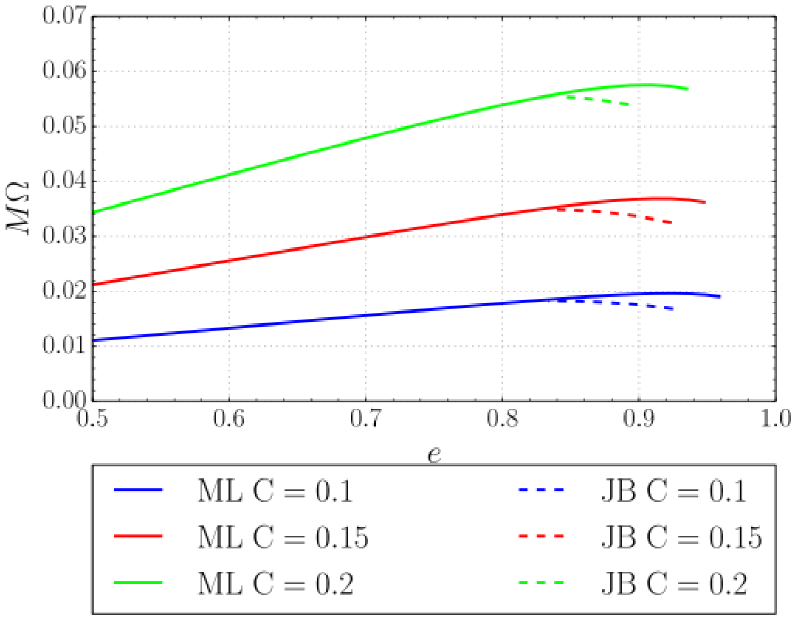


MIT bag model

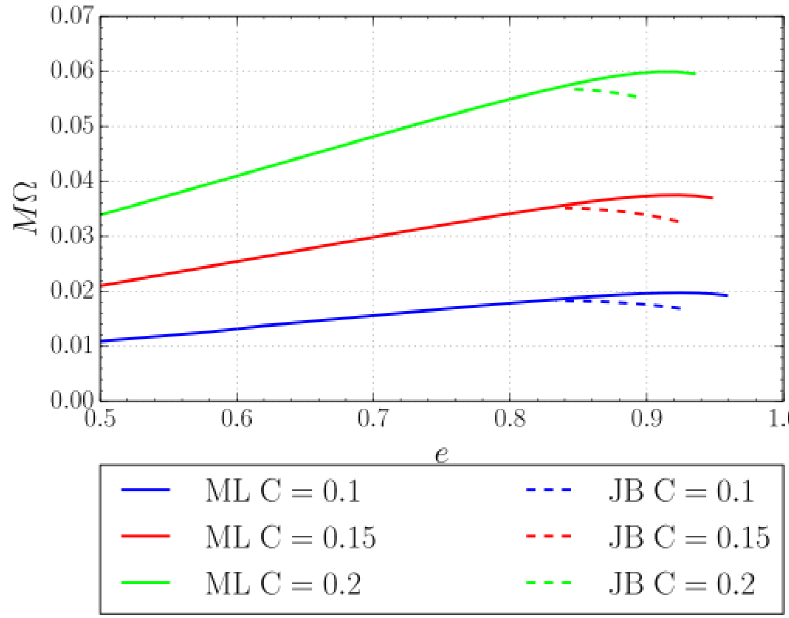


LaiXu09 model

Triaxial uniformly RQS



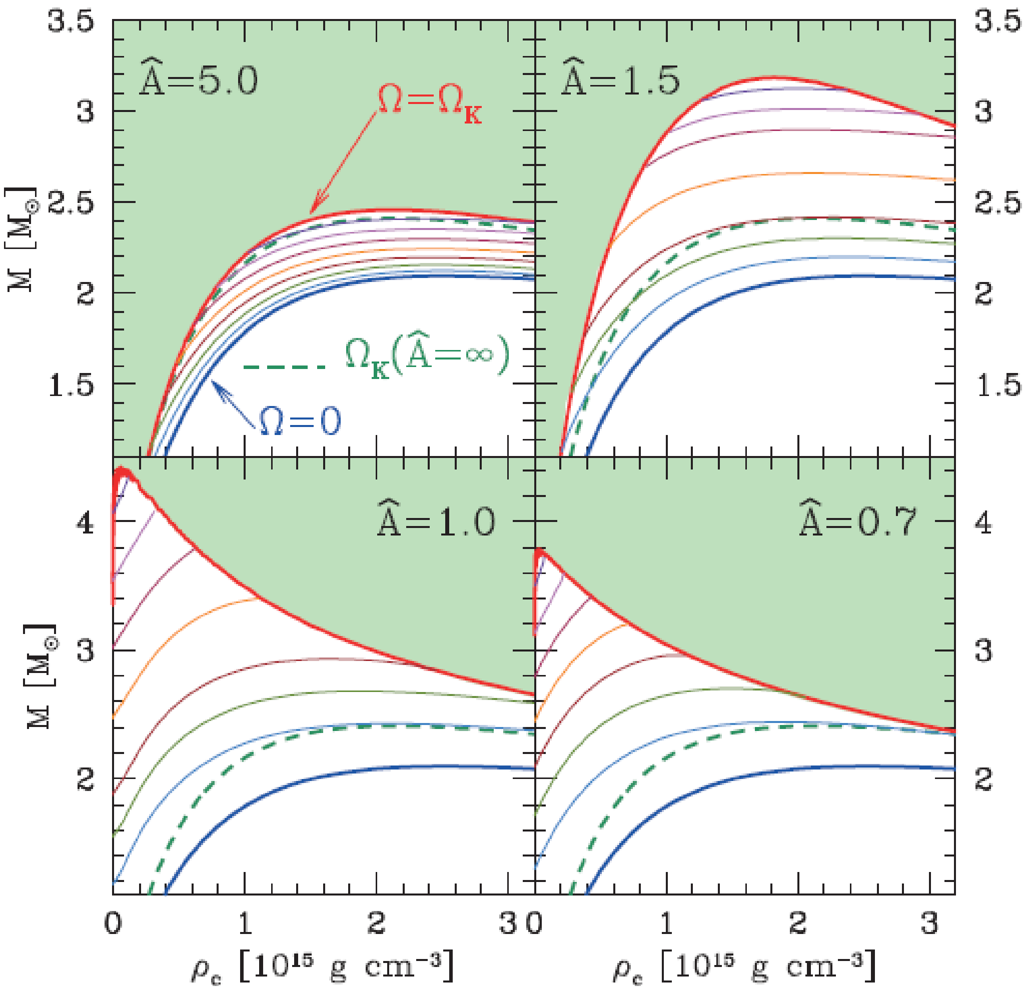
MIT bag model



LaiXu09 model

Therefore, if the HMCS is a QS, we could expect GW radiation from the triaxially rotating body (h~10^-24 @ 30Mpc, f~2kHz).
And we have found supramassive triaxially rotating quark star solutions for both MIT bag model and LaiXu09 model.

Differentially RNS

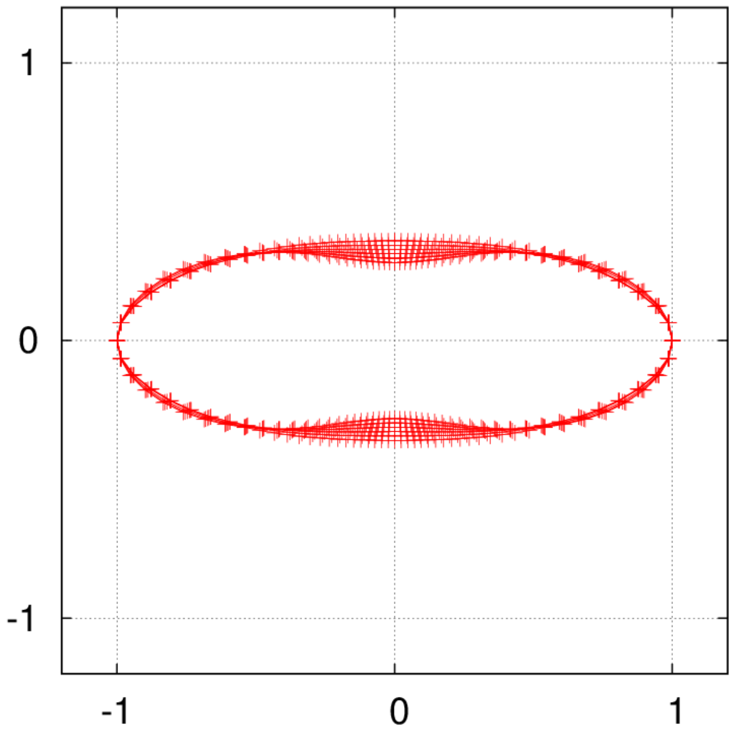


Differentially rotation law (Newtonian limit):

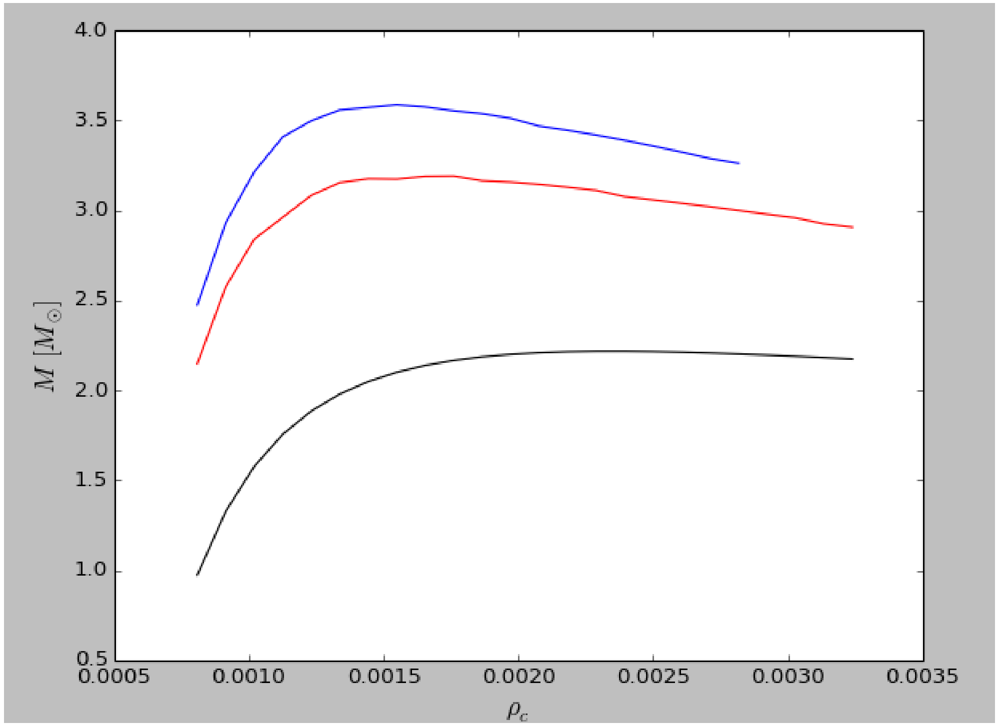
$$\Omega_c - \Omega = \frac{\Omega_c r^2 \sin^2\theta}{\widehat{A}^2 r_e^2 + r^2 \sin^2\theta}\,.$$

For stable differentially RNS configurations, the maximum mass is 54% more than TOV maximum
(Weih et al. 2017)

Differentially RQS



The bifurcation into an unstable 'donut shape' branch of the differentially rotating QS with LaiXu09 model. The mass at the bifurcation solution is 4.27 solar mass.



Parameter space of uniformly RQS and differentially RQS with MIT bag model as the EoS.

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.
- We have found a 4 solar mass star for differentially rotating LaiXu09 model star
- Future work: different amount of mass

ejected in BNS/BQS mergers

Thanks!