Rotating NSs/QSs
and recent astrophysical observations

ANG LI (李昂)

with

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B. Zhang (UNLV)
J.-B. Wang (Urumqi)
N.-B. Zhang & B. Qi (Weihai)
T. Liu (Xiamen)

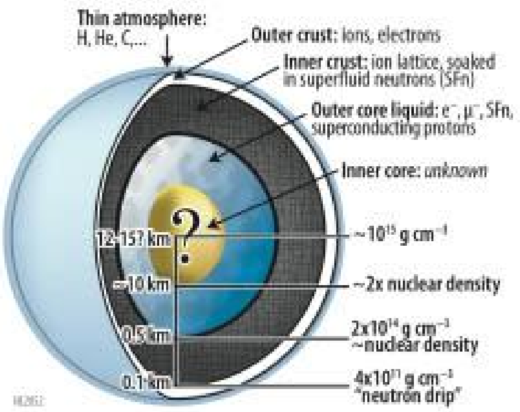
AL, Dong, Wang, Xu, ApJS 223, 16 (2016)
AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon

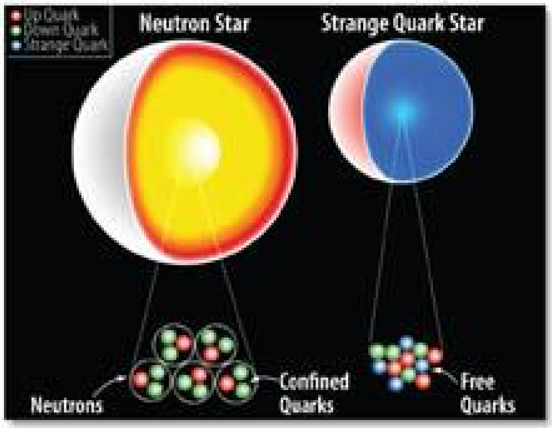
Outline

- **Introduction**
- **Rotating NS/QS configurations**
    - Slow: Glitch
    - Fast: Short GRBs
- **Summary**

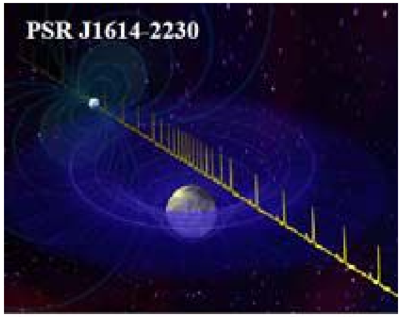
Introduction

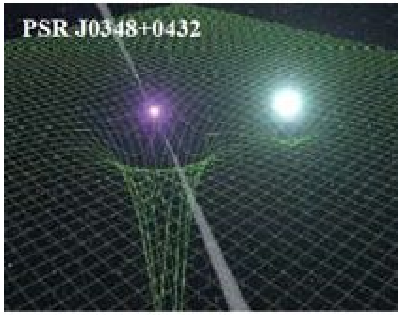
- NS's inner core? NS/QS?



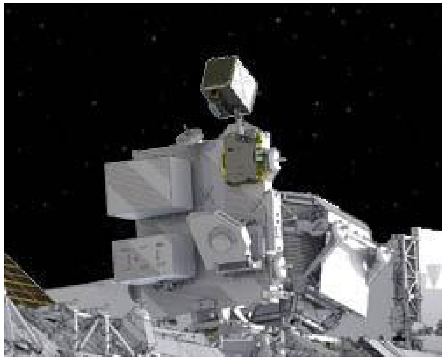


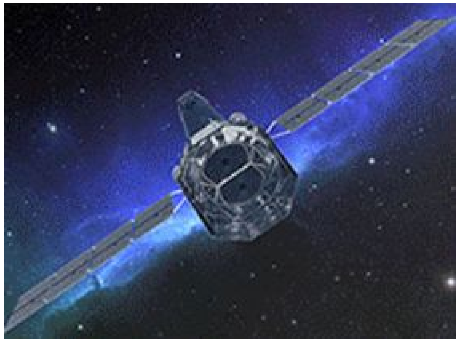
- 2-solar-mass

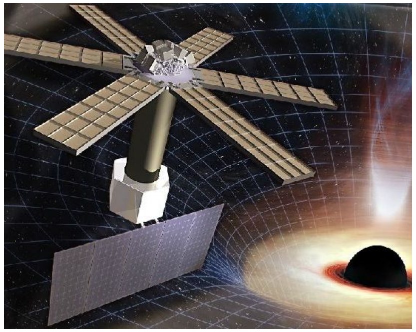




- Forthcoming NICER, Athena, and LOFT-like missions

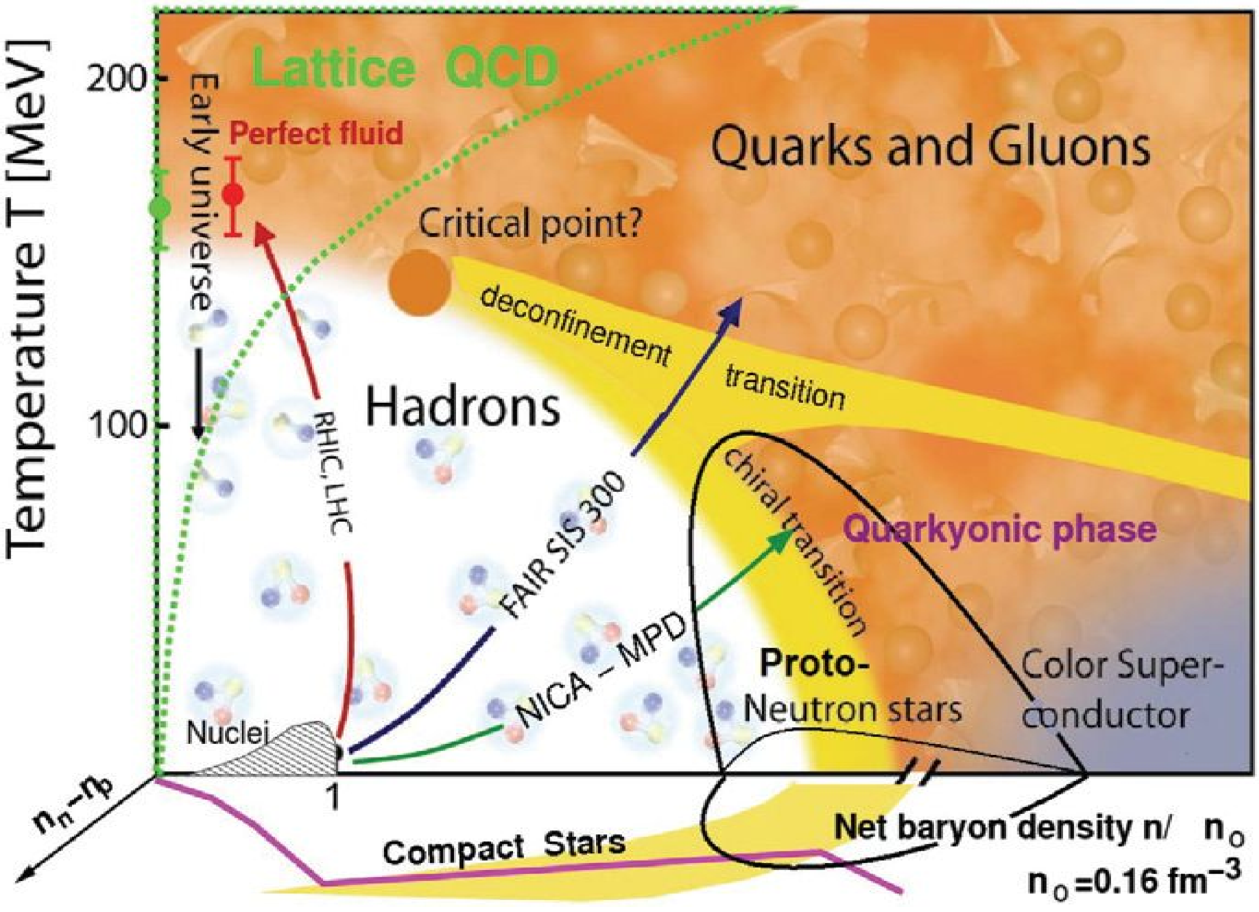






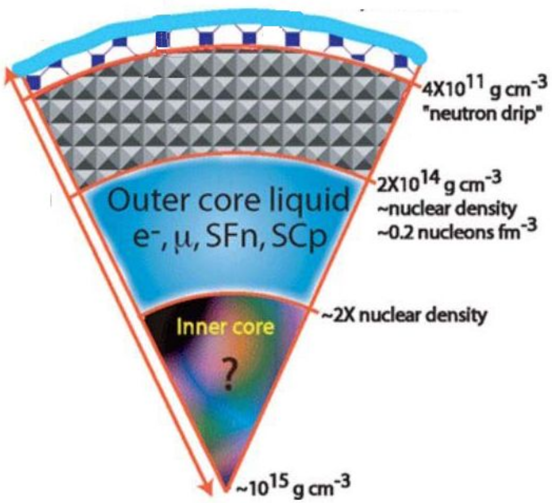
Introduction

- ❑ **Heavy-ion flow investigations**
- ❑ **Ab-initio lattice QCD simulations**



D. P. Menezes (2016) JPCS

Unified NS EoS



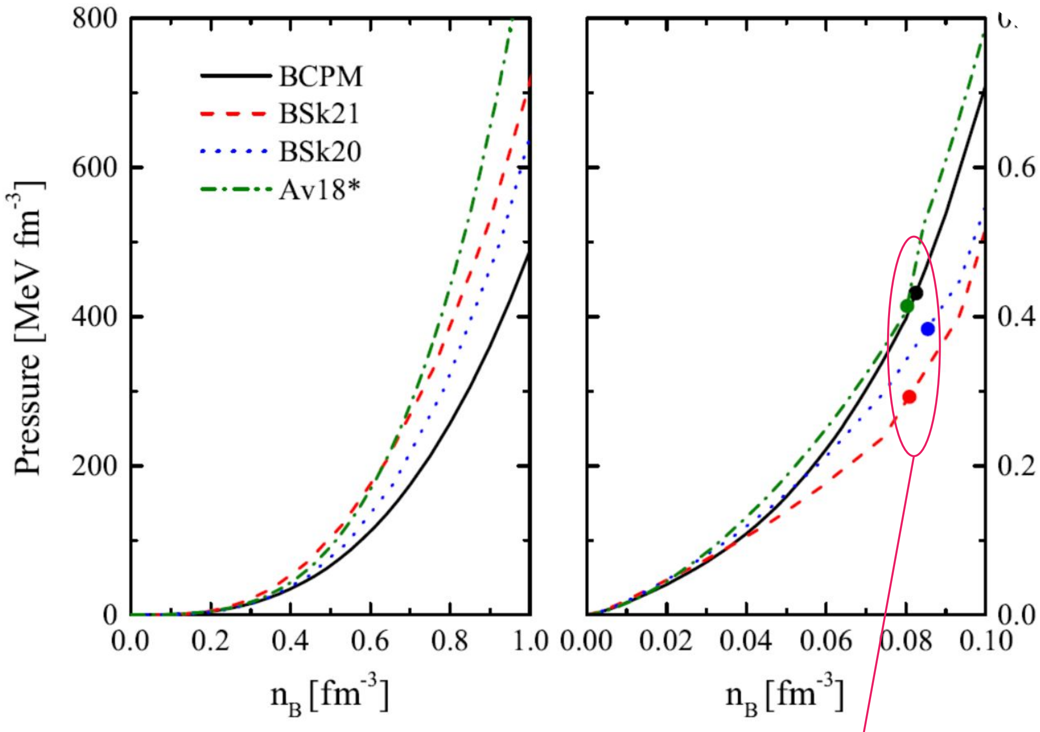
- ***BCPM (Barcelona-Catania-Paris-Madrid):***

A bulk part obtained from the **BHF** calculations for matter,
added in usual ways:
the phenomenological surface part,
the Coulomb part,
the spin-orbit part,
the pairing contributions.

(Baldo et al. 2008, 2010, 2013, Sharma et al. 2015)

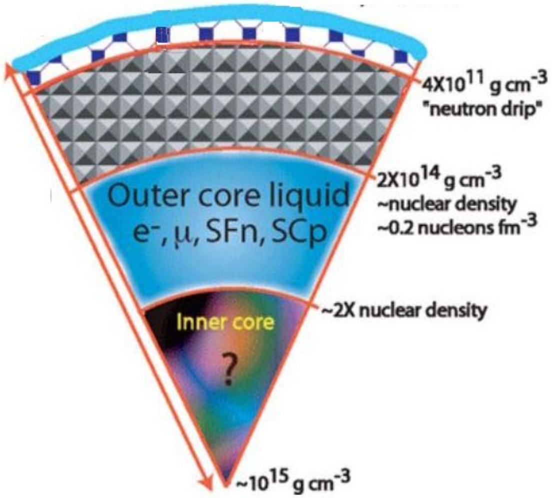
- ***BSk20,21:***

Skyrme-type unified EoSs from Brussels-Montreal group
(Chamel et al. 2011;
Pearson et al. 2012;
Fantina et al. 2013;
Potekhin et al. 2013)



Crust-core transition

Unified NS EoS



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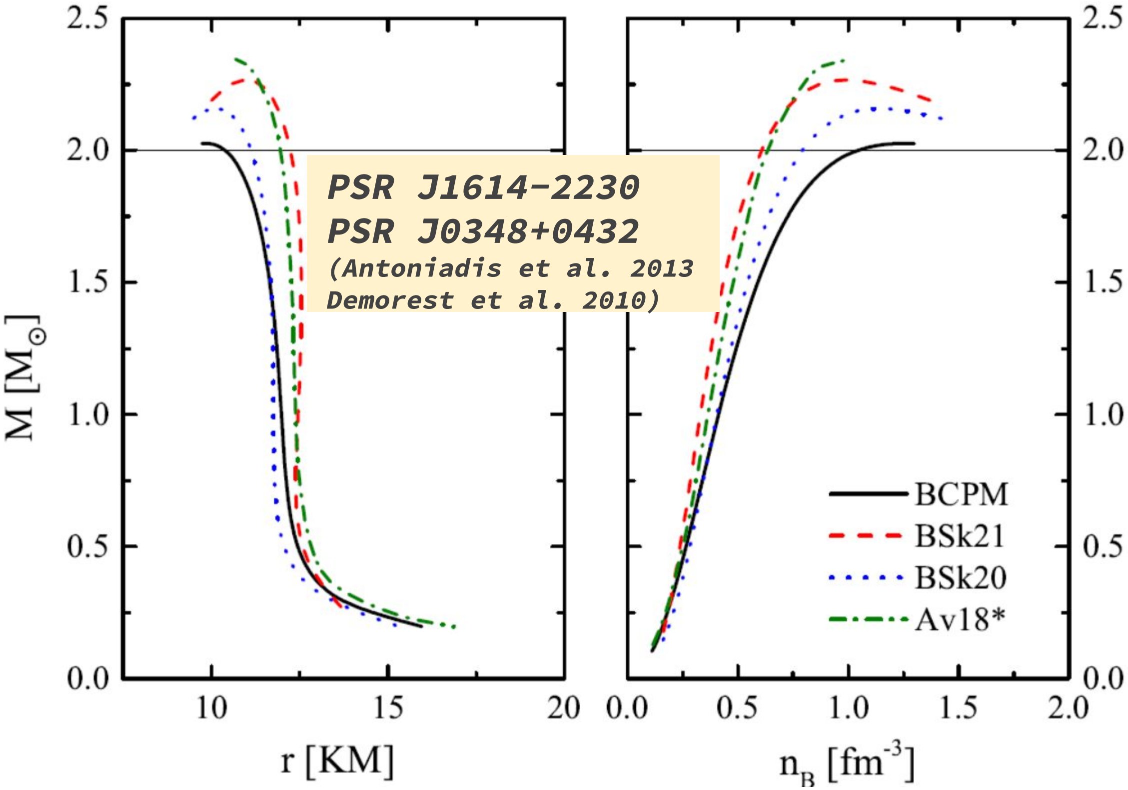

PSR J1614-2230
PSR J0348+0432
(Antoniadis et al. 2013 Demorest et al. 2010)

Unified NS EoS

- ***BCPM (Barcelona-Catania-Paris-Madrid):***

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(Baldo et al. 2008, 2010, 2013,
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(Chamel et al. 2011;
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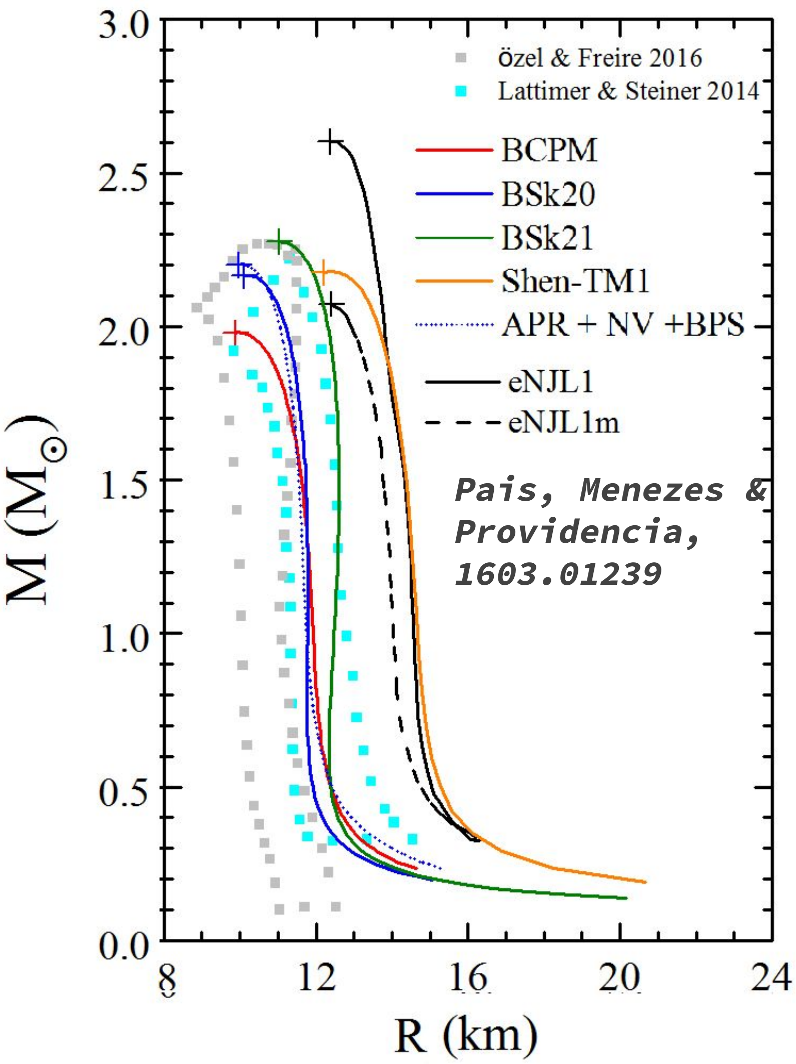
- ***Shen-TM1***

Relativistic Mean field (**RMF**)
model (Shen et al. 1998)



Pais, Menezes & Providencia, 1603.01239

Updated QS EoS

Fowler, et al. 1981;
Chakrabarty, et al. 1989,1991,1993,1996;
Peng, et al. 2000
Xia, et al. 2014

CDDM (Confined-density-dependent-mass) model

CIDDM (Confined-isospin-density-dependent-mass) model

Chu & Chen, 2014
Qauli & Sulaksono, 2016

$$H_{\mathrm{QCD}}=H_k+\sum_q m_{q0}\bar{q}q+H_{\mathrm{I}},$$

The variation of the quark mass with density mimics the strong interaction between quarks.

$$H_{\mathrm{eqv}}=H_k+\sum_q m_q\bar{q}q$$

$$m_q=m_{q0}+\frac{\langle H_{\mathrm{I}}\rangle_{n_b}-\langle H_{\mathrm{I}}\rangle_0}{\sum_q\left[\langle\bar{q}q\rangle_{n_b}-\langle\bar{q}q\rangle_0\right]}$$

$$\equiv m_{q0}+m_{\mathrm{I}},$$

Quark confinement

$$\lim_{n_b\to 0} m_{\mathrm{I}}=\infty$$

Asymptotic freedom

$$\lim_{n_b\to\infty} m_{\mathrm{I}}=0$$

$$m_{\mathrm{I}}=\frac{D}{n_b^z}$$

$$\boxed{m_{\mathrm{I}}=\frac{D}{n_{\mathrm{B}}^{1/3}}+Cn_{\mathrm{B}}^{1/3}}$$

D term: linear confinement;

***C* term: leading-order perturbative interactions**
(or ***the Coulomb term***).

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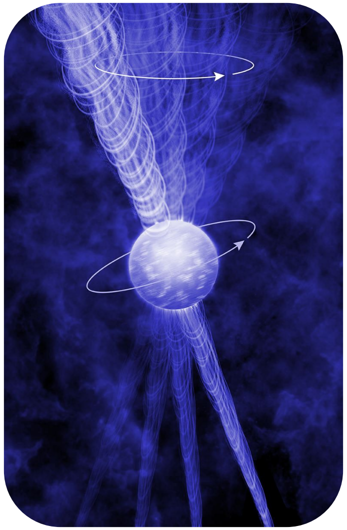
- Introduction
- **Rotating NS/QS configurations**
  - Slow: Glitch

    1> Why study glitches?

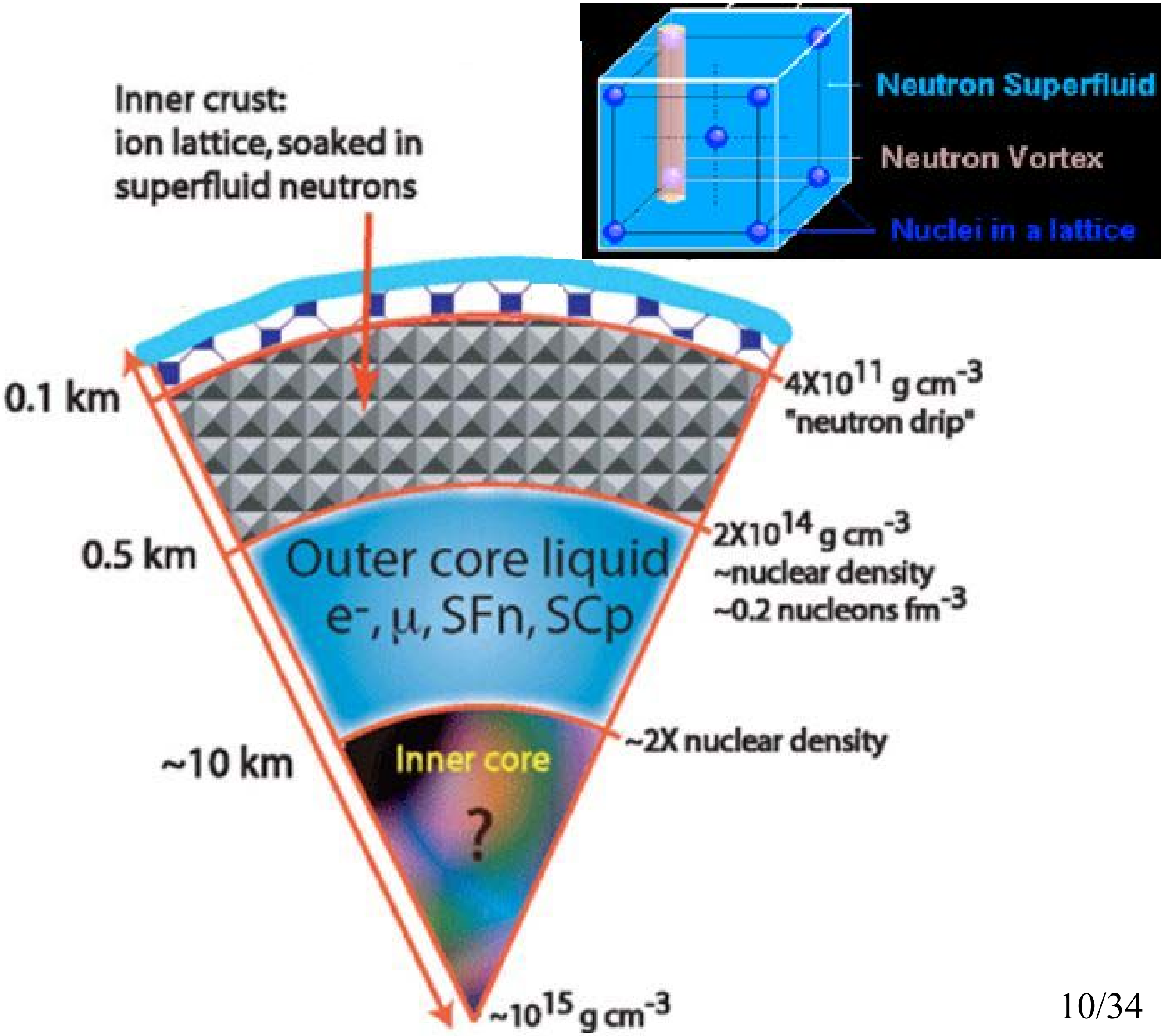
    2> Vela pulsar and glitch crisis
  - Fast: Short GRBs
- **Summary**

Rotating NS/QS



1> Why study glitches?

A glitch may arise from the inner crust of a neutron star.



Rotating NS/QS

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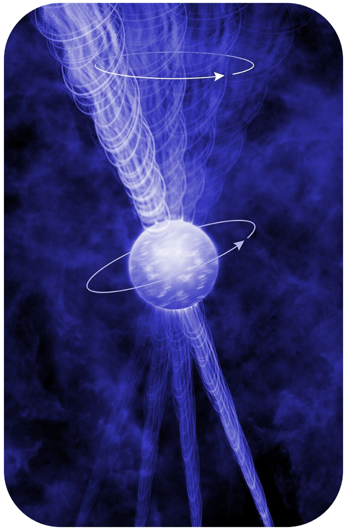
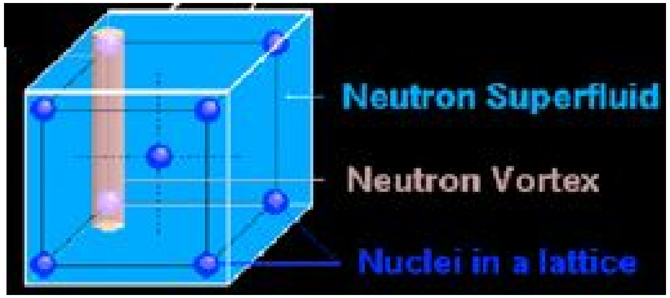




Two-component model

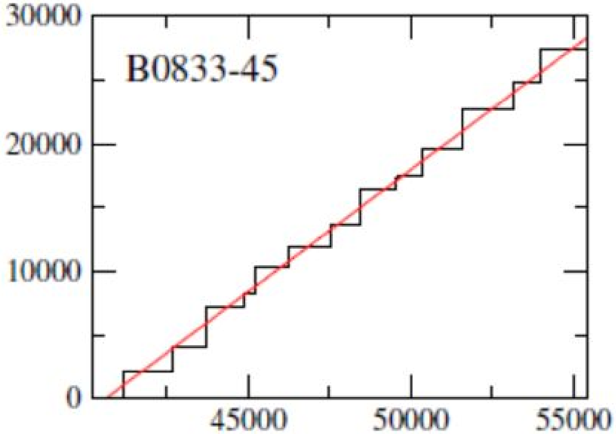
Normally, crustal superfluid are pinned to the crustal nuclei;

↓

Superfluid's angular velocity will lag that of the crust;

↓

Pinned vortices will give crust stress, until vortex unpinned catastrophically (Anderson & Itoh)



The accumulated $\sum_i \Delta\Omega_p^i/\Omega_p$ ($\times 10^{-9}$) as a function of the modified Julian date

From glitch observations to EoS

$$I_n/I \approx 2\tau_c \mathcal{A},$$

$$\text{where } \mathcal{A} = \frac{1}{t_{\text{obs}}}\left(\sum_i \Delta\Omega_p^i/\Omega_p\right).$$

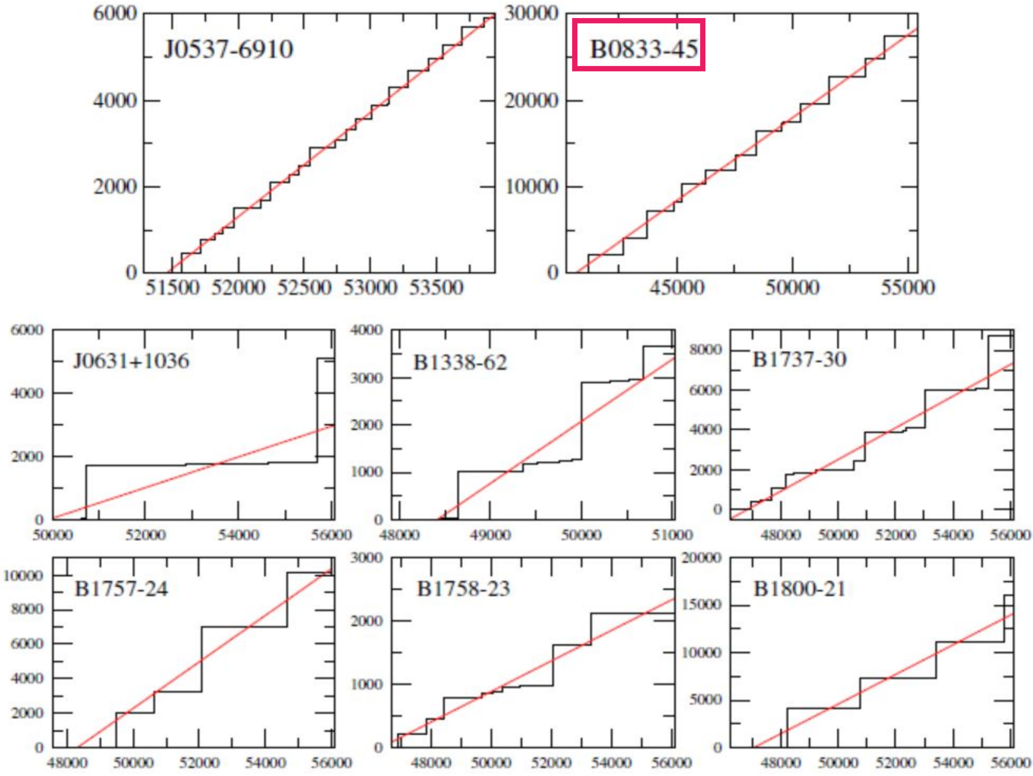
From glitch observations to EoS $I_c/I \geq 1.6\%$

$$I_n/I \approx 2\tau_c \mathcal{A},$$

$$\text{where } \mathcal{A} = \frac{1}{t_{\text{obs}}}\left(\sum_i \Delta\Omega_p^i/\Omega_p\right).$$

PSR	τ_c (kyr)	$\mathcal{A}$ $(\times 10^{-9}/d)$	I_n/I (%)
J0537-6910	4.93	2.40	0.9
B0833-45 (Vela)	11.3	1.91	1.6
J0631+1036	43.6	0.48	1.5
B1338-62	12.1	1.31	1.2
B1737-30	20.6	0.79	1.2
B1757-24	15.5	1.35	1.5
B1758-23	58.4	0.24	1.0
B1800-21	15.8	1.57	1.8
B1823-13	21.5	0.78	1.2
B1930+22	38.8	0.95	2.7
J2229+6114	10.5	0.63	0.5

Andersson et al. 2012, PRL



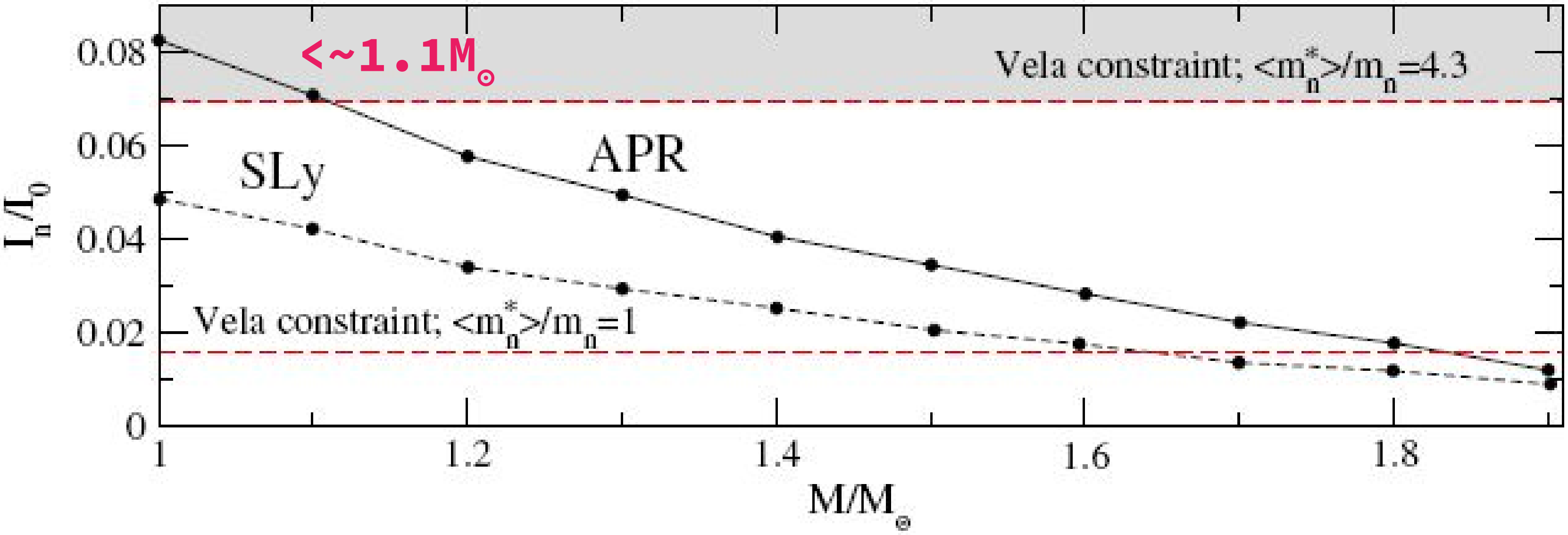
- **Vela** pulsar may provide the most severe problems of two-component model, because...

Glitch crisis (2012-present)

$$I_c/I \geq 1.6\% \longrightarrow I_c/I \geq 7\%$$

$$I_n/I \approx 2\tau_c \mathcal{A}, \longrightarrow \frac{I_n}{I} \approx 2\tau_c \mathcal{A} \frac{\langle m_n^* \rangle}{m_n}$$

Many neurons are **entrained** **by the crust**——neutrons move as if they had an effective mass m_n^* ($m_n < m_n^*$).



<~$1.1M_\odot$

- ❑ **Allowed NS mass too low !**

Andersson et al. 2012, PRL
Chamel N., 2013, PRL

Glitch crisis (2012-present) ?

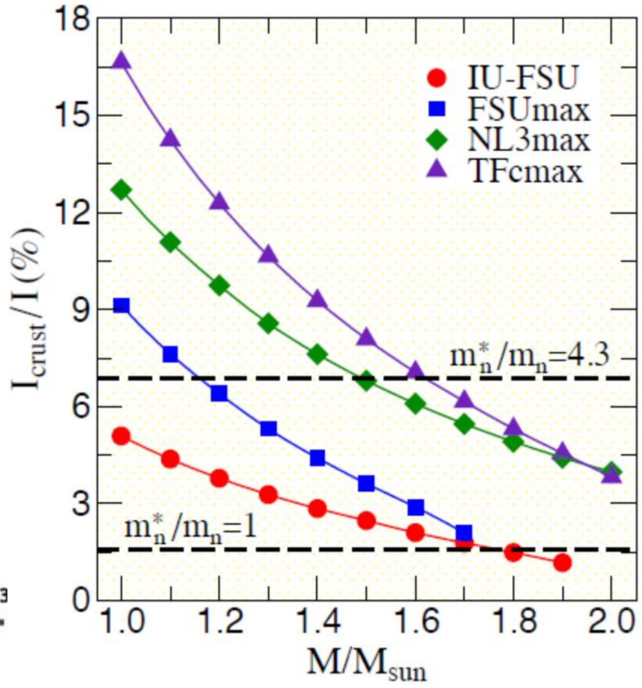
- The amount of superfluid in the crust **cannot explain** the changes in angular momentum required to account for the glitches.

Andersson et al. 2012, PRL
Chamel N., 2013, PRL

- Uncertainties in EoS and core-crust interface provide **enough** flexibility

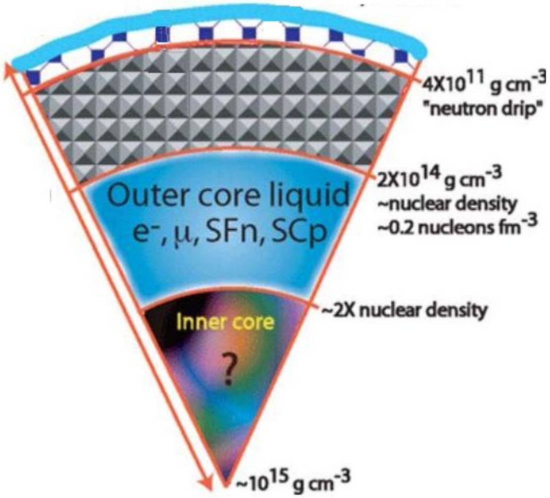
(RMF + polytropic interpolation + BPS)

Piekarewicz et al. 2014



Two points to be improved:

- Microscopic NS EoS;
- Unified NS EoS.



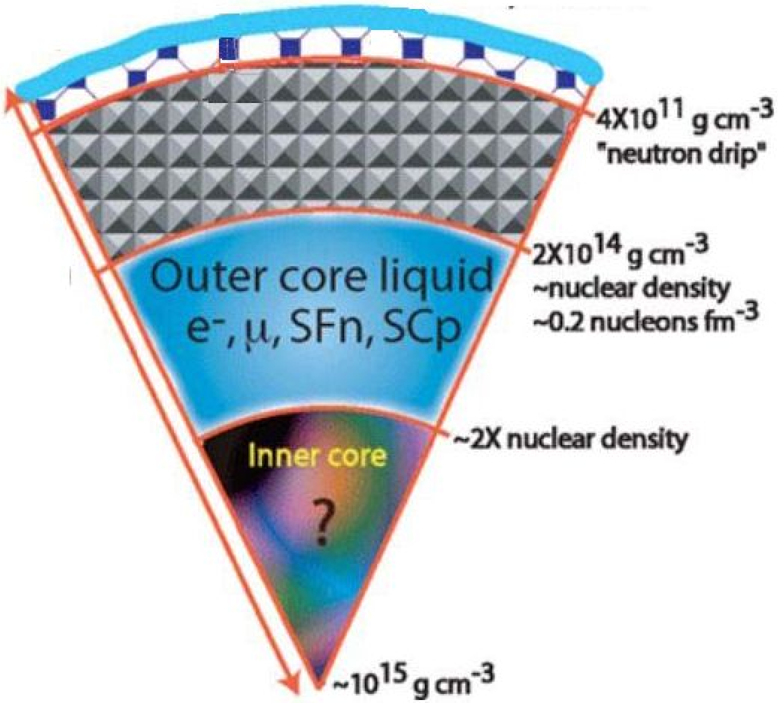
Two points to be improved:

- ➢ Microscopic NS EoS;
- ➢ Unified NS EoS.

Microscopic unified NS EoS

BCPM (Barcelona-Catania-Paris-Madrid)

(Baldo et al. 2008b, 2010, 2013, Sharma et al. 2015)



$$\Omega << \Omega_{max} \approx \sqrt{GM/R^3}$$

- ❑ Adopting **slow** rotation approximation for Vela (P = 89.33 milliseconds) **(Spherical-symmetry metric + Axis-symmetry perturbation)**

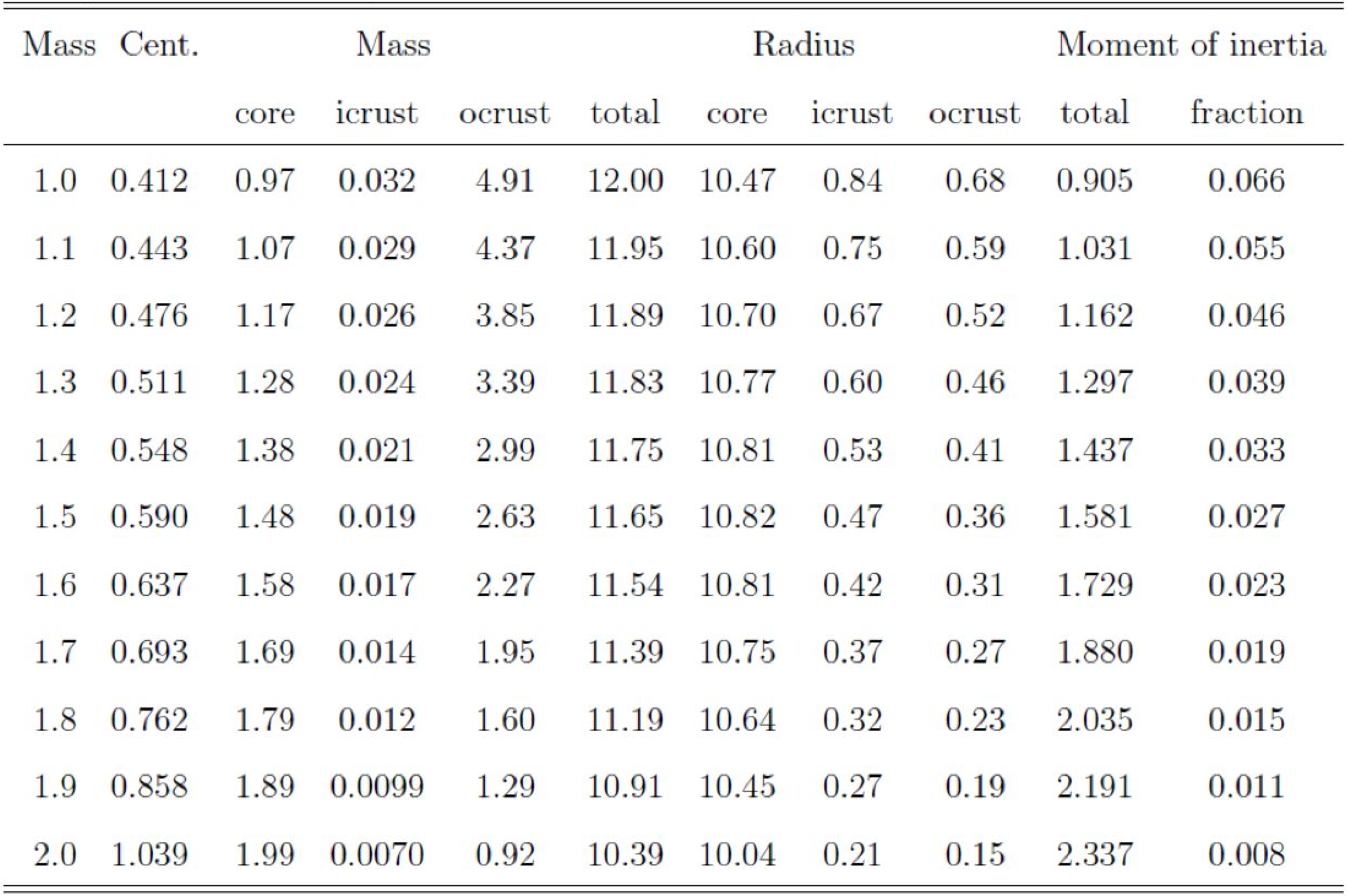
Hartle & Thorne 1968

$$I = \frac{8\pi}{3}\int_0^R r^4 e^{-\nu(r)} \frac{\bar{\omega}(r)}{\Omega} \frac{(\varepsilon(r) + P(r))}{\sqrt{1 - 2GM(r)/r}} \mathrm{d}r$$

$$I_c = \frac{8\pi}{3}\int_{R_c}^R r^4 e^{-\nu(r)} \frac{\bar{\omega}(r)}{\Omega} \frac{(\varepsilon(r) + P(r))}{\sqrt{1 - 2GM(r)/r}} \mathrm{d}r$$

2> Vela pulsar structure

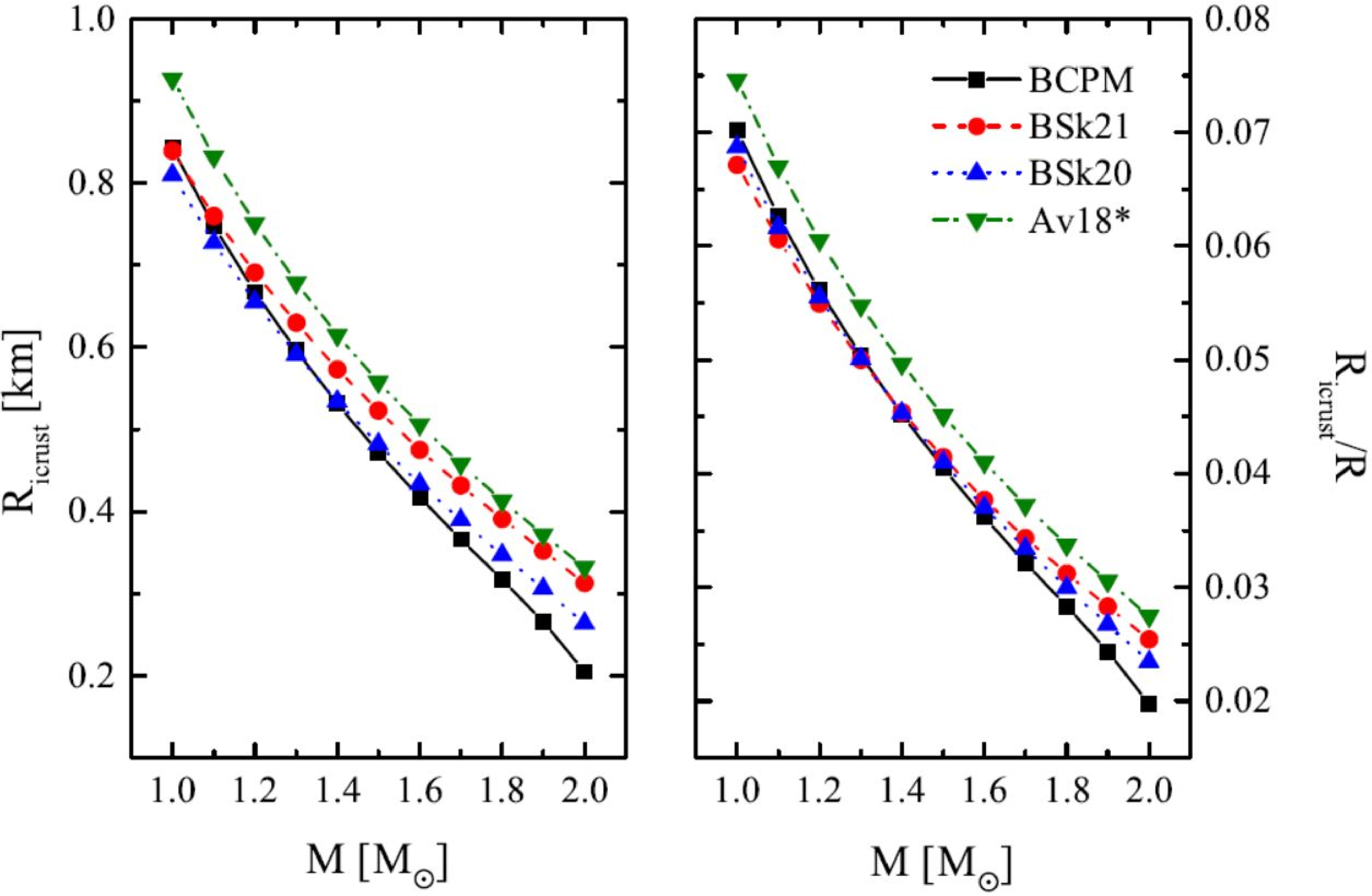
AL, Dong, Wang, Xu, ApJS 2016



Mass	Cent.	Mass			Radius				Moment of inertia	
		core	icrust	ocrust	total	core	icrust	ocrust	total	fraction
1.0	0.412	0.97	0.032	4.91	12.00	10.47	0.84	0.68	0.905	0.066
1.1	0.443	1.07	0.029	4.37	11.95	10.60	0.75	0.59	1.031	0.055
1.2	0.476	1.17	0.026	3.85	11.89	10.70	0.67	0.52	1.162	0.046
1.3	0.511	1.28	0.024	3.39	11.83	10.77	0.60	0.46	1.297	0.039
1.4	0.548	1.38	0.021	2.99	11.75	10.81	0.53	0.41	1.437	0.033
1.5	0.590	1.48	0.019	2.63	11.65	10.82	0.47	0.36	1.581	0.027
1.6	0.637	1.58	0.017	2.27	11.54	10.81	0.42	0.31	1.729	0.023
1.7	0.693	1.69	0.014	1.95	11.39	10.75	0.37	0.27	1.880	0.019
1.8	0.762	1.79	0.012	1.60	11.19	10.64	0.32	0.23	2.035	0.015
1.9	0.858	1.89	0.0099	1.29	10.91	10.45	0.27	0.19	2.191	0.011
2.0	1.039	1.99	0.0070	0.92	10.39	10.04	0.21	0.15	2.337	0.008

Inner crust: Directly related to glitch

AL, Dong, Wang, Xu, ApJS 2016



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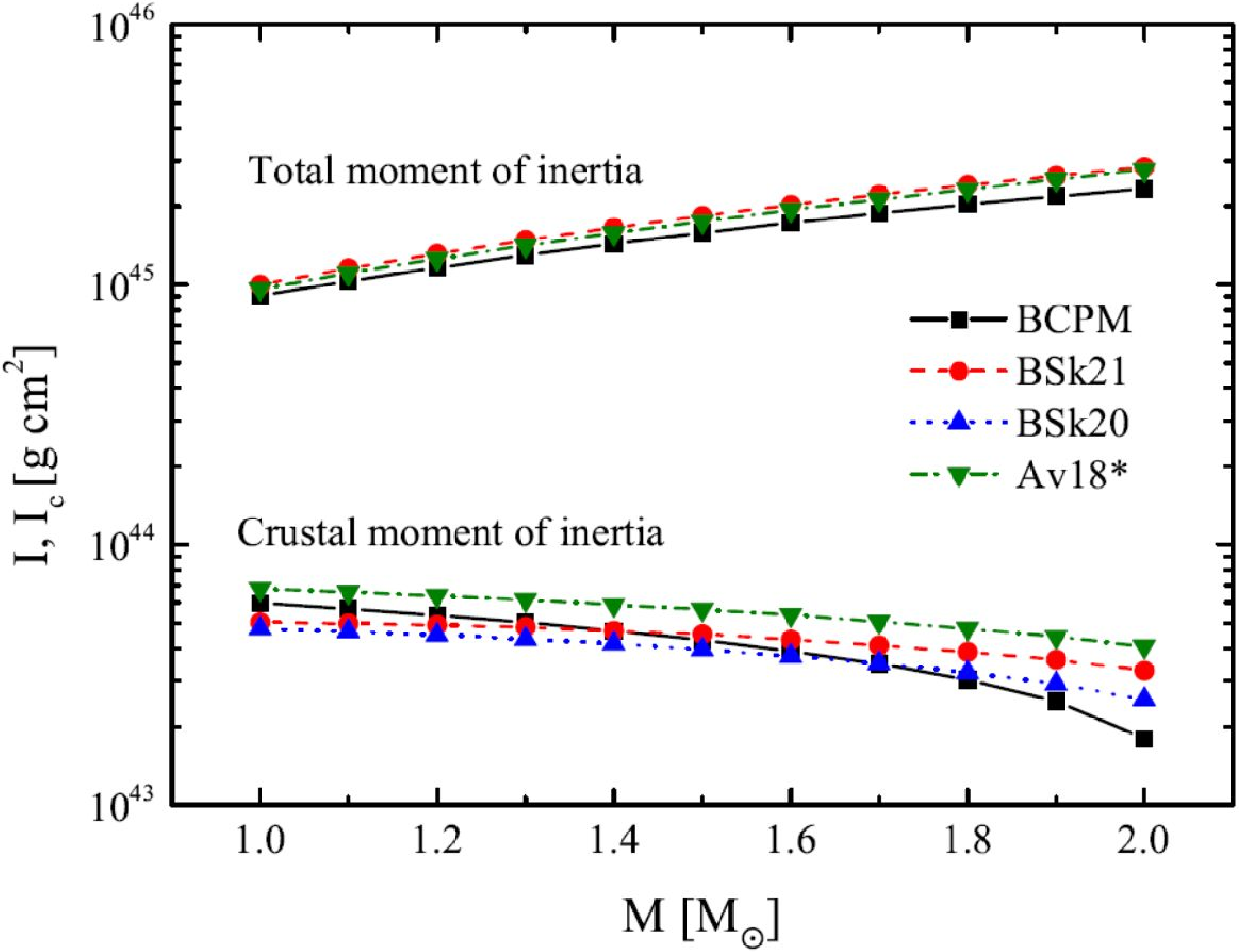
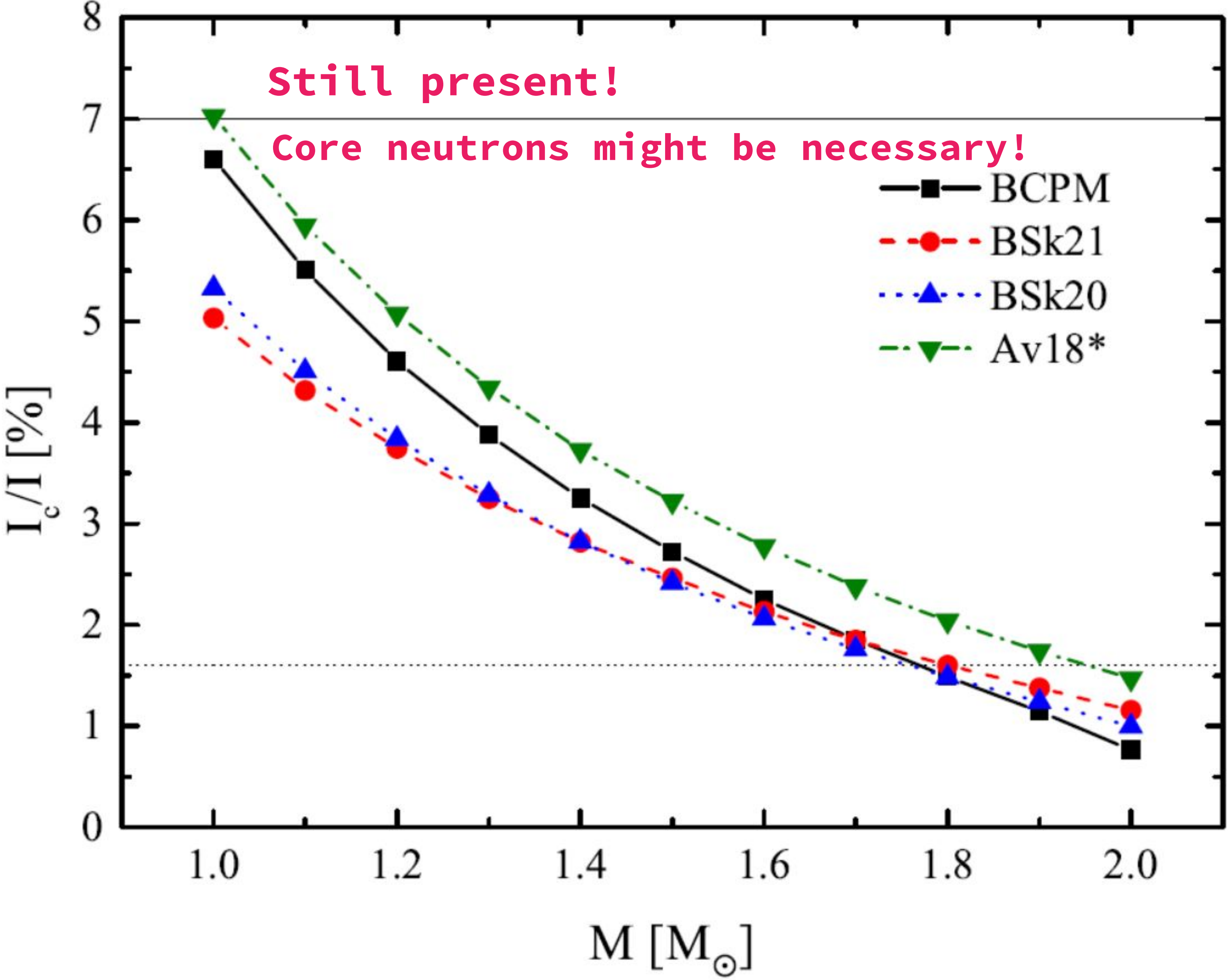


2> Glitch crisis

Fractional momenta of inertia:
Confronted with Vela glitch data

AL, Dong, Wang, Xu, ApJS 2016



Still present!

Core neutrons might be necessary!

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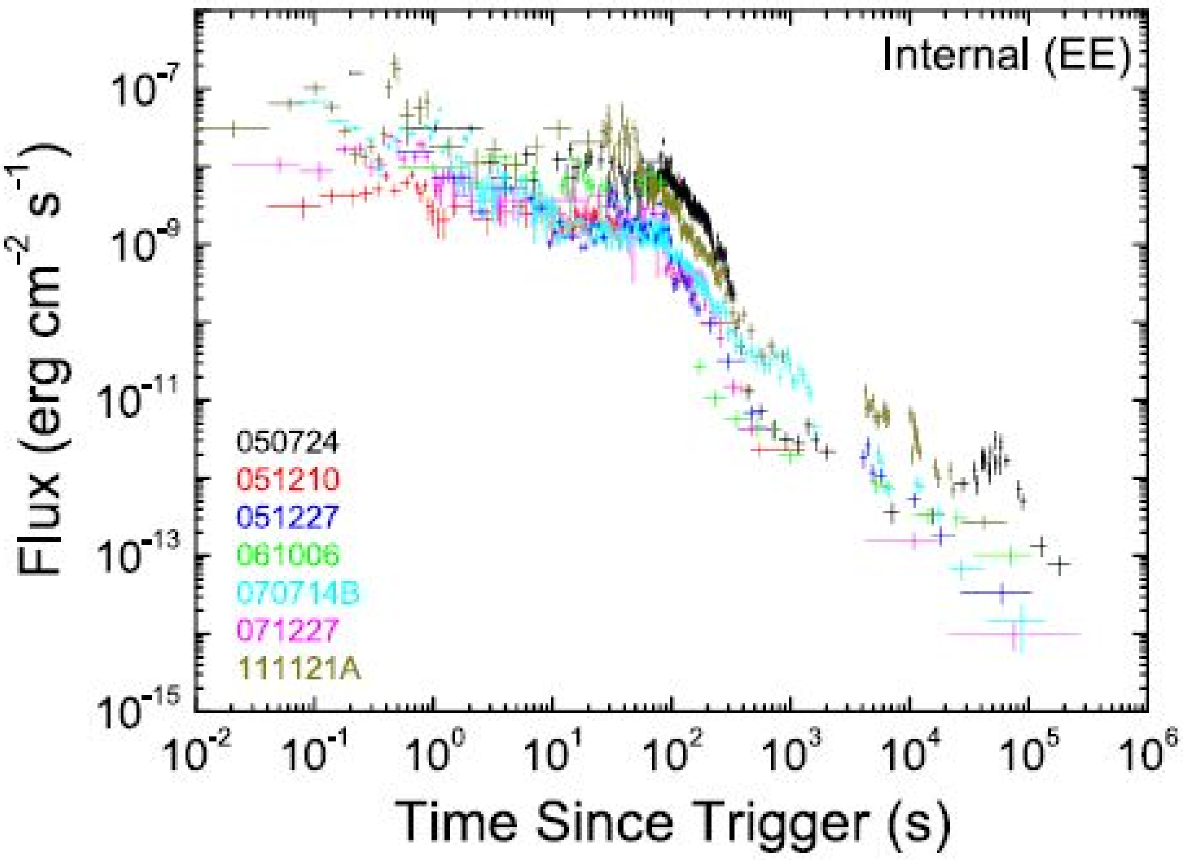
    - 1> **Why this related to glitches?**
    - 2> **Vela pulsar and glitch crisis**
  - Fast: Short GRBs
    - 1> **Internal X-ray plateau**
    - 2> **QS (instead of NS) central engine model**
- **Summary**

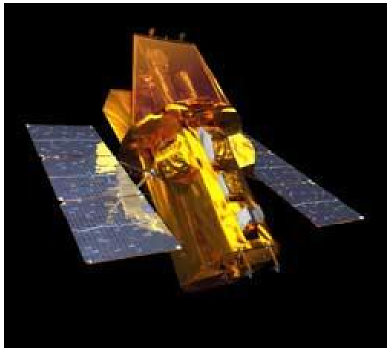
1> Internal X-ray plateau in short GRBs

(Rowlinson et al. 2010, 2013, MNRAS)

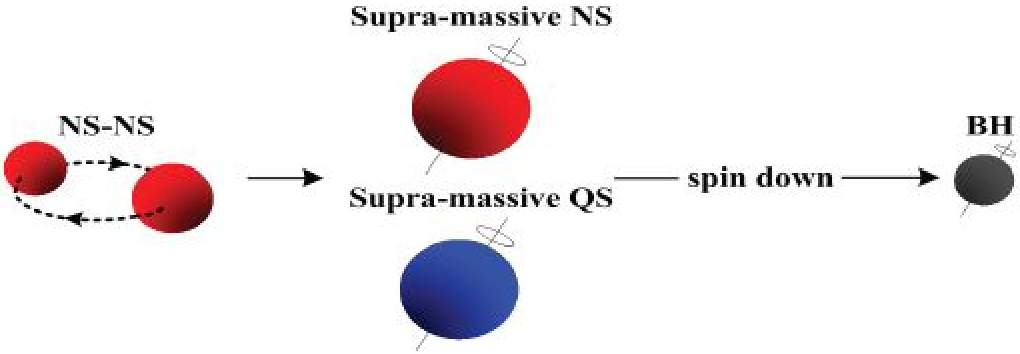


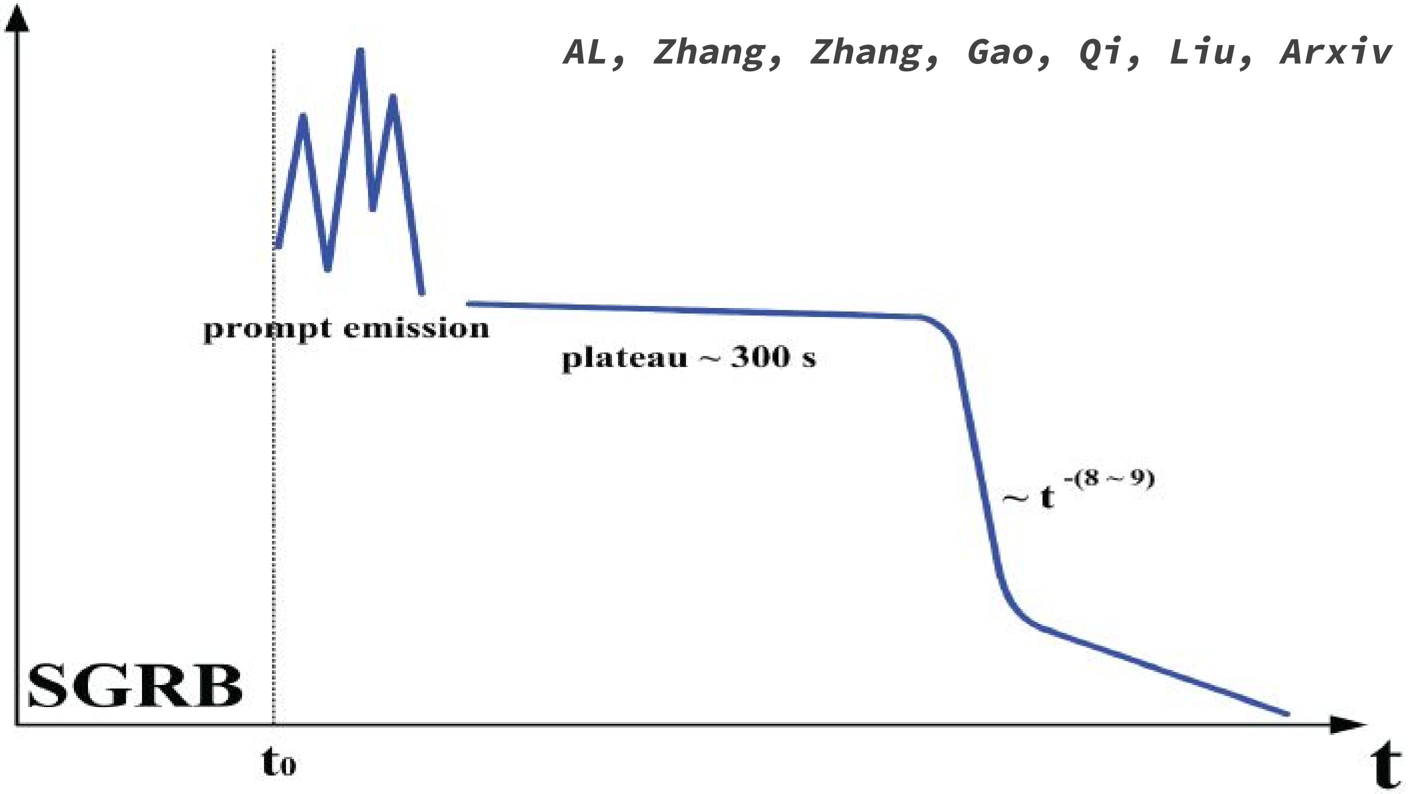
Lü, et al. 2015, ApJ
Lasky,et al. 2014, PRD

- ❑ **21 SGRB plateau sample with SWIFT** (2005/01-2015/10)
  (Gao, et al., 2016, PRD)



Spindown-induced collapse of a NS/QS to a BH

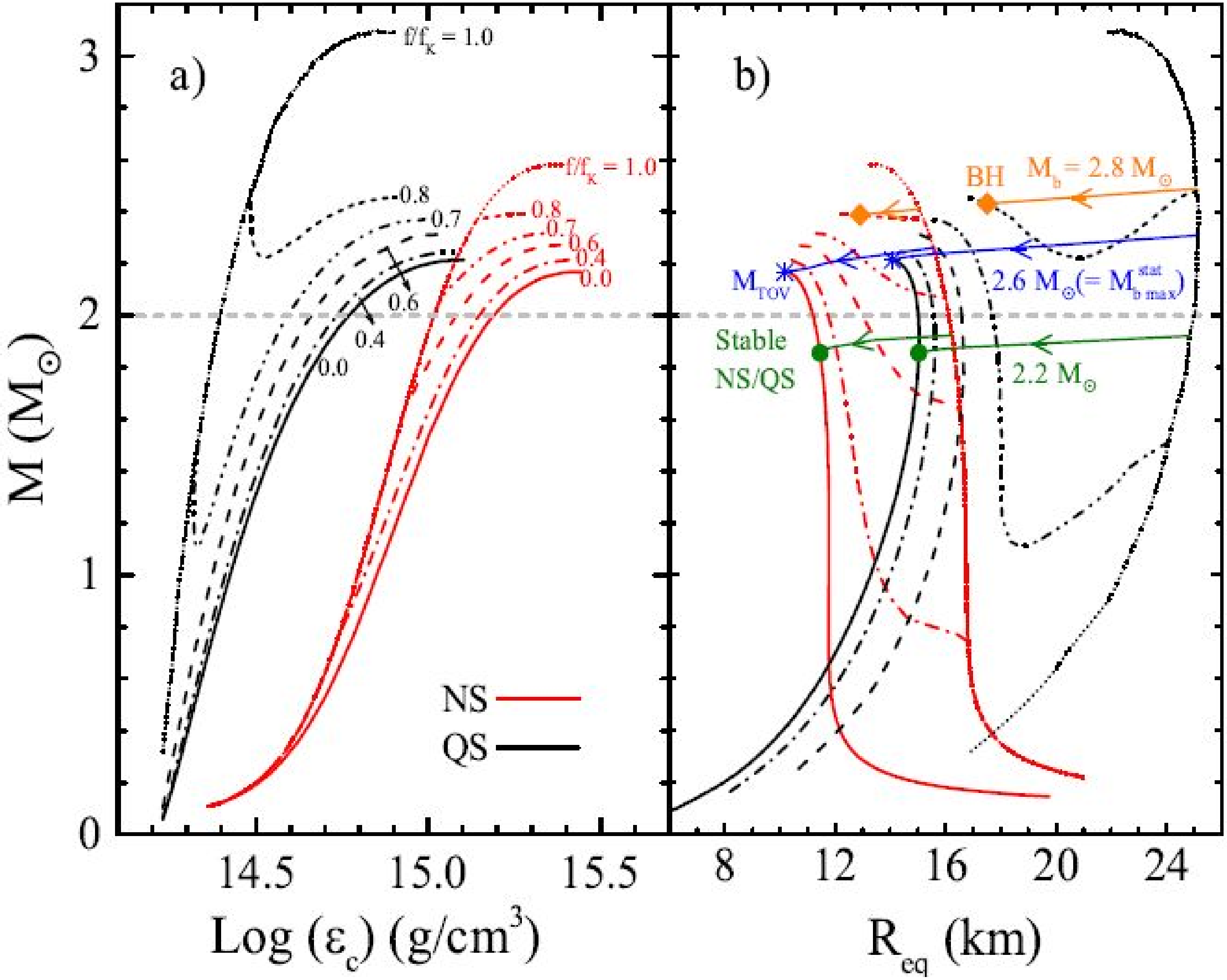




AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon

Supramassive NS/QS: Doomed to collapse

AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon

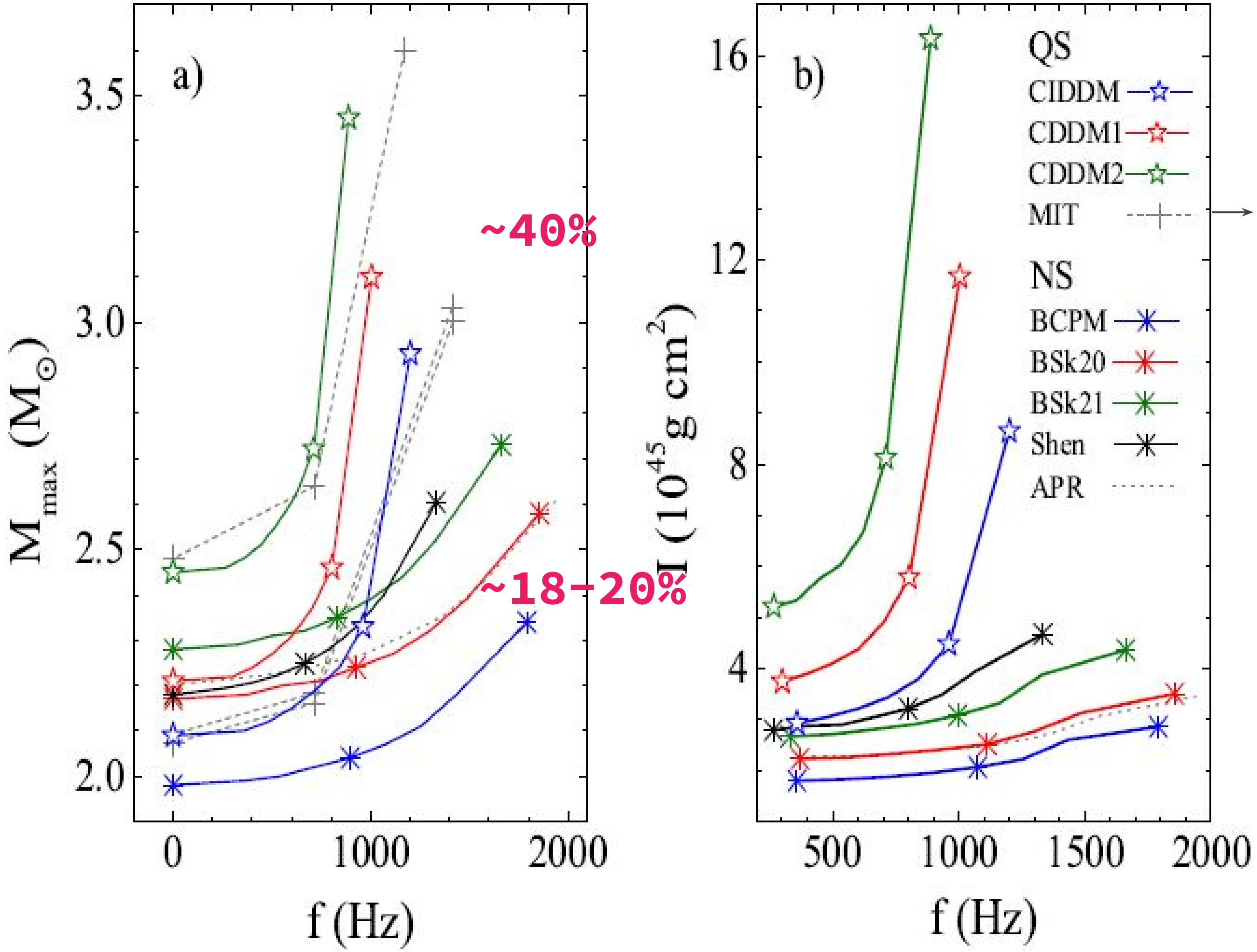


Uniformly fast-rotating supramassive NS/QS

from rns code

AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon

(Komatsu, et. al. 1989
Cook et al. 1994,
Stergiouslas, at al. 1995)



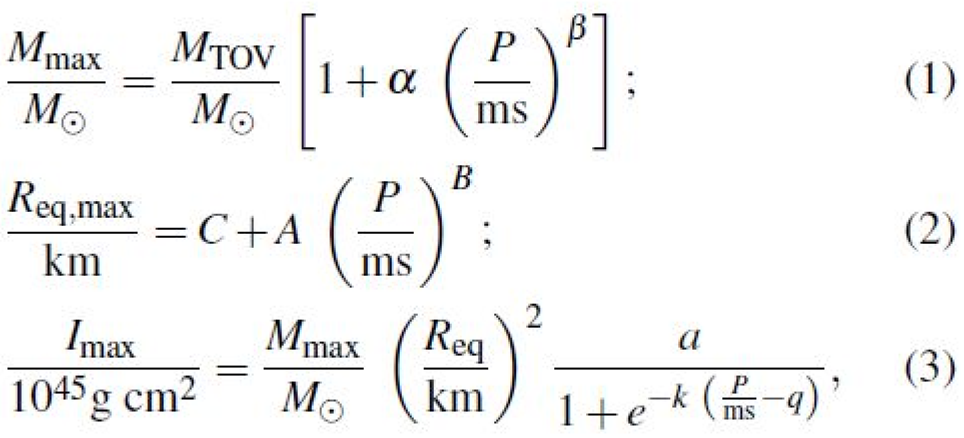
~40%

~18-20%

→ *Bhattacharyya, Bombaci, Logoteta, Thampan, 2016 MNRAS*

Data prepared

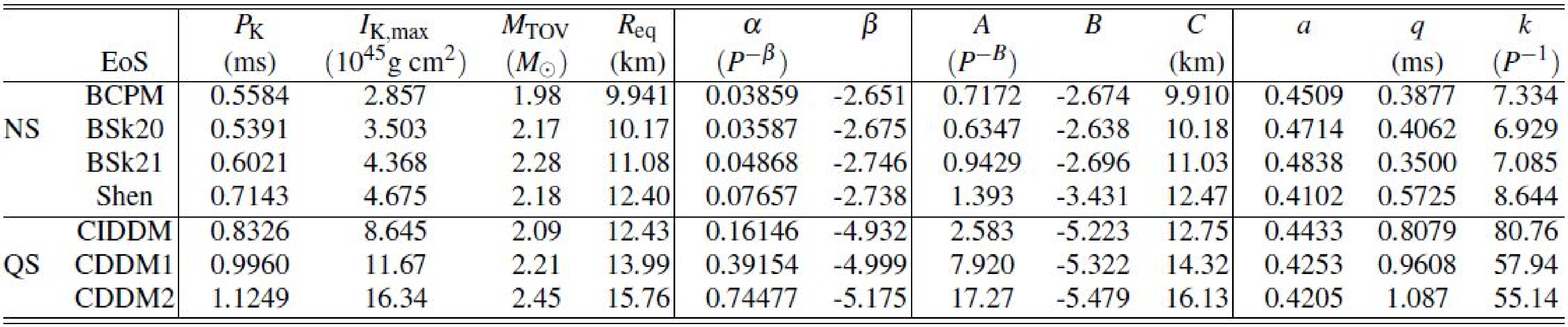
AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon



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

$$\frac{R_{\rm eq,max}}{\rm km} = C + A\left(\frac{P}{\rm ms}\right)^{B}; \quad (2)$$

$$\frac{I_{\rm max}}{10^{45}{\rm g\,cm^2}} = \frac{M_{\rm max}}{M_\odot}\left(\frac{R_{\rm eq}}{\rm km}\right)^2 \frac{a}{1+e^{-k\left(\frac{P}{\rm ms}-q\right)}}, \quad (3)$$



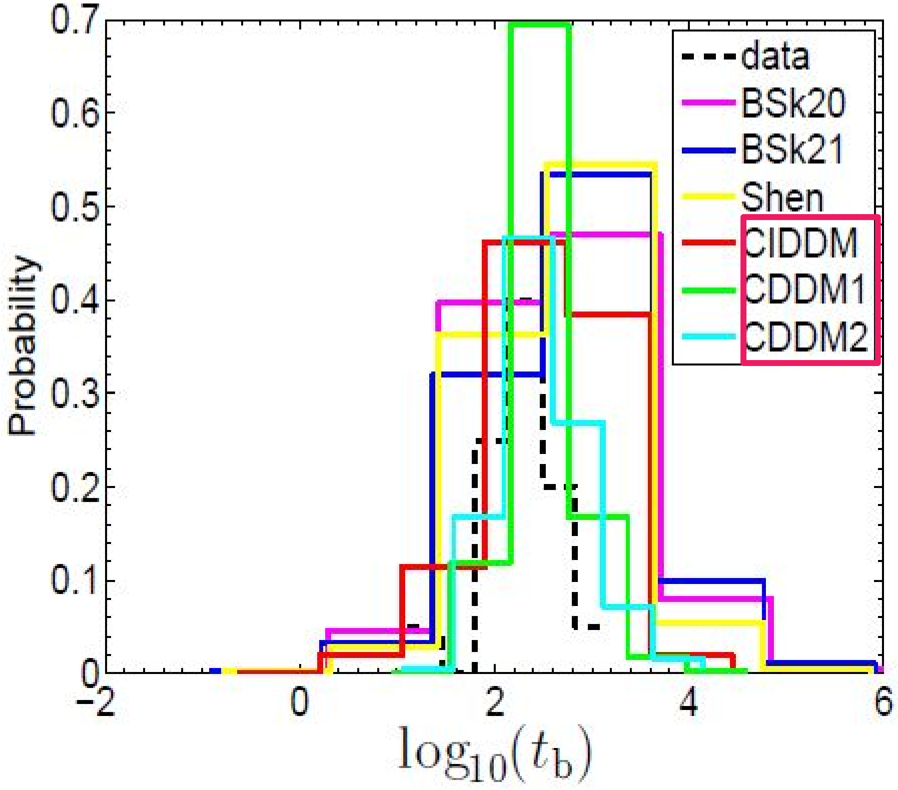
	EoS	$P_{\rm K}$ (ms)	$I_{\rm K,max}$ (10^{45}g cm^2)	$M_{\rm TOV}$ ($M_\odot$)	$R_{\rm eq}$ (km)	α ($P^{-\beta}$)	β	A (P^{-B})	B	C (km)	a	q (ms)	k (P^{-1})
NS	BCPM	0.5584	2.857	1.98	9.941	0.03859	-2.651	0.7172	-2.674	9.910	0.4509	0.3877	7.334
	BSk20	0.5391	3.503	2.17	10.17	0.03587	-2.675	0.6347	-2.638	10.18	0.4714	0.4062	6.929
	BSk21	0.6021	4.368	2.28	11.08	0.04868	-2.746	0.9429	-2.696	11.03	0.4838	0.3500	7.085
	Shen	0.7143	4.675	2.18	12.40	0.07657	-2.738	1.393	-3.431	12.47	0.4102	0.5725	8.644
QS	CIDDM	0.8326	8.645	2.09	12.43	0.16146	-4.932	2.583	-5.223	12.75	0.4433	0.8079	80.76
	CDDM1	0.9960	11.67	2.21	13.99	0.39154	-4.999	7.920	-5.322	14.32	0.4253	0.9608	57.94
	CDDM2	1.1249	16.34	2.45	15.76	0.74477	-5.175	17.27	-5.479	16.13	0.4205	1.087	55.14

MC simulation

AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon

- ❑ Reproducing simultaneously all three observed distributions (Break time t_b, Break time luminosity L_b, Total electromagnetic energy E_{total});

  Eg., time simulation
- ❑ Including both EM and GW;
- ❑ Constraining parameter ranges of stars (Ellipticity ε, Initial spin P_i, Surface dipole magnetic field B_p);
- ❑ NS vs. QS



	ε	P_i (ms)	B_p (G)	η	P_{best} (t_b)
BSk20	0.002	0.70 – 0.75 (0.75)	$N(\mu_{Bp} = 10^{14.8-15.4}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.2)]$	0.5 – 1 (0.9)	0.20
BSk21	0.002	0.60 – 0.80 (0.70)	$N(\mu_{Bp} = 10^{14.7-15.1}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{15.0}, \sigma_{Bp} = 0.2)]$	0.7 – 1 (0.9)	0.29
Shen	0.002 – 0.003 (0.002)	0.70 – 0.90 (0.70)	$N(\mu_{Bp} = 10^{14.6-15.0}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{14.6}, \sigma_{Bp} = 0.2)]$	0.5 – 1 (0.9)	0.41
CIDDM	0.001	0.95 – 1.05 (0.95)	$N(\mu_{Bp} = 10^{14.8-15.4}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{15.0}, \sigma_{Bp} = 0.2)]$	0.5 – 1(0.5)	0.44
CDDM1	0.002 – 0.003 (0.003)	1.00 – 1.40 (1.0)	$N(\mu_{Bp} = 10^{14.7-15.1}, \sigma_{Bp} \leq 0.3)$ $[N(\mu_{Bp} = 10^{14.7}, \sigma_{Bp} = 0.2)]$	0.5 – 1(1)	0.65
CDDM2	0.004 – 0.007 (0.005)	1.10 – 1.70 (1.3)	$N(\mu_{Bp} = 10^{14.8-15.3}, \sigma_{Bp} \leq 0.4)$ $[N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.4)]$	0.5 – 1(1)	0.84

Efficiency related to the conversion of the dipole spin-down luminosity to the observed X-ray luminosity.

Outline

- **Introduction**
- **Rotating NS/QS configurations**
  - Slow: Glitch
    - 1> Why this related to glitches?
    - 2> Vela pulsar and glitch crisis
  - Fast: Short GRBs
    - 1> Internal X-ray plateau
    - 2> NS/QS central engine model
- **Summary**

Summary

AL, Dong, Wang, Xu, ApJS 2016
AL, Zhang, Zhang, Gao, Qi, Liu, Arxiv soon

- **Rotating NS configurations (fast/slow) are presented with recently-constructed unified NS EoS;**
- **Glitch still a “crisis”;**
- **Calculations for pure quark star (QS) are also done;**
- ***Internal X-ray plateau in SGRBs could be a signature of fast-rotating QS, instead of NS.***

Thank you very much!

Glitch crisis (2012-present)

❑ Unresolved physics:

→ Pinning force between vortex and lattice (vortex unpin and moving);

→ Core-crust coupling during glitch rising.

❑ Next plans:

Pinning Force (with Shang, Lv)

The Ginzburg-Landau theory

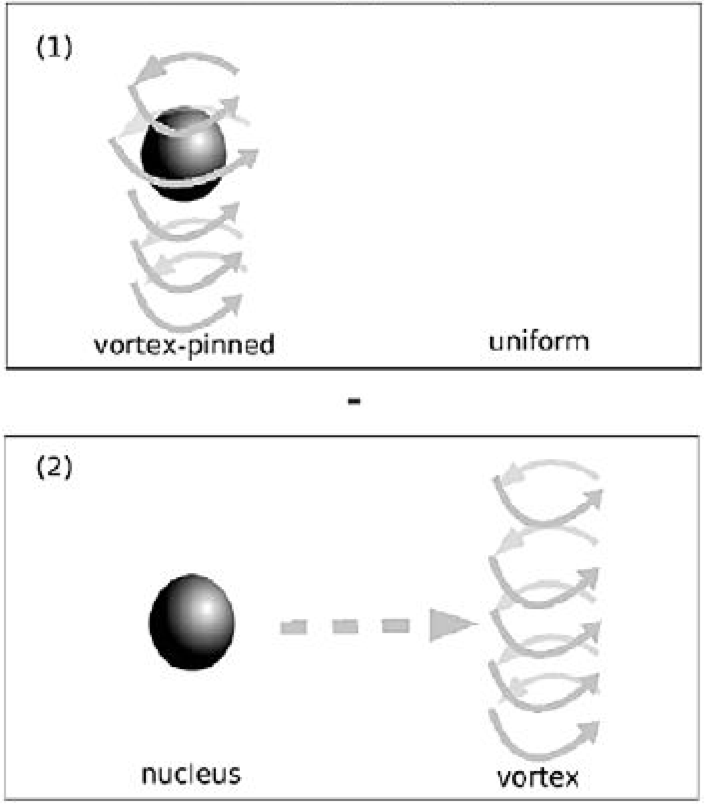
$$F_{\mathrm{GL}} = \int \left[\frac{\hbar^2 |\nabla\psi|^2}{4m_n} + f(|\psi|^2) \right] d^3r \,,$$

$$f(|\psi|^2) = A|\psi|^2 + \frac{B}{2}|\psi|^4 \,,$$

(A and B is from BHF+BCS)

$$\psi(\vec{r}) = \varphi(r) e^{im\theta} e^{iqz}$$ Column coordinate

$$E_{pinning} = E_{(1)} - E_{(2)}$$



To study the whole picture of glitch.