Effective hadronic models applied to compact stars

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ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Set, 27th 2023

Outline

- Motivation
- Combined analysis of the modelling reproducing low energy nuclear data
- Impact of the groups on the symmetry energy and its slope correlation
- Neutron star global properties
- Conclusions

PHYSICAL REVIEW C **107**, 035805 (2023)

Low-energy nuclear physics and global neutron star properties

Brett V. Carlson[1] Mariana Dutra[1,2] Odilon Lourenço[1,2] and Jérôme Margueron[2]
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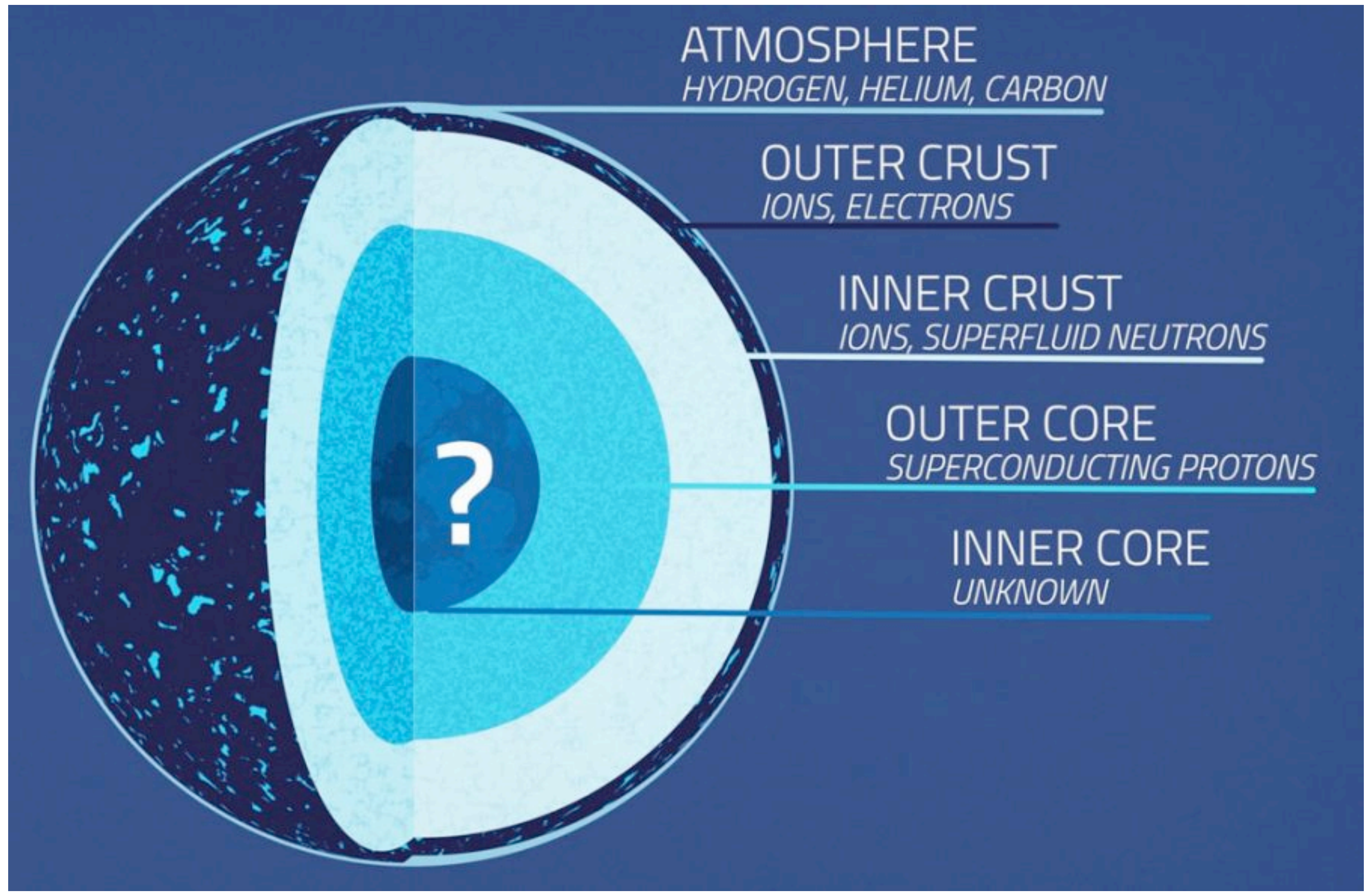
Motivation

- The understanding of observational data:
  - gravitational waves (emitted from binary NSs)
  - x-ray emissions (from milli-second pulsars)
    - require for the most part the understanding of the NS core.

NS core → $n_{\text{sat}} \approx 2.7 \times 10^{14}\ \text{g cm}^{-3}$

Neutron star (NS) layers



Credit: NASA's Goddard Space Flight Center / Conceptual Image Lab

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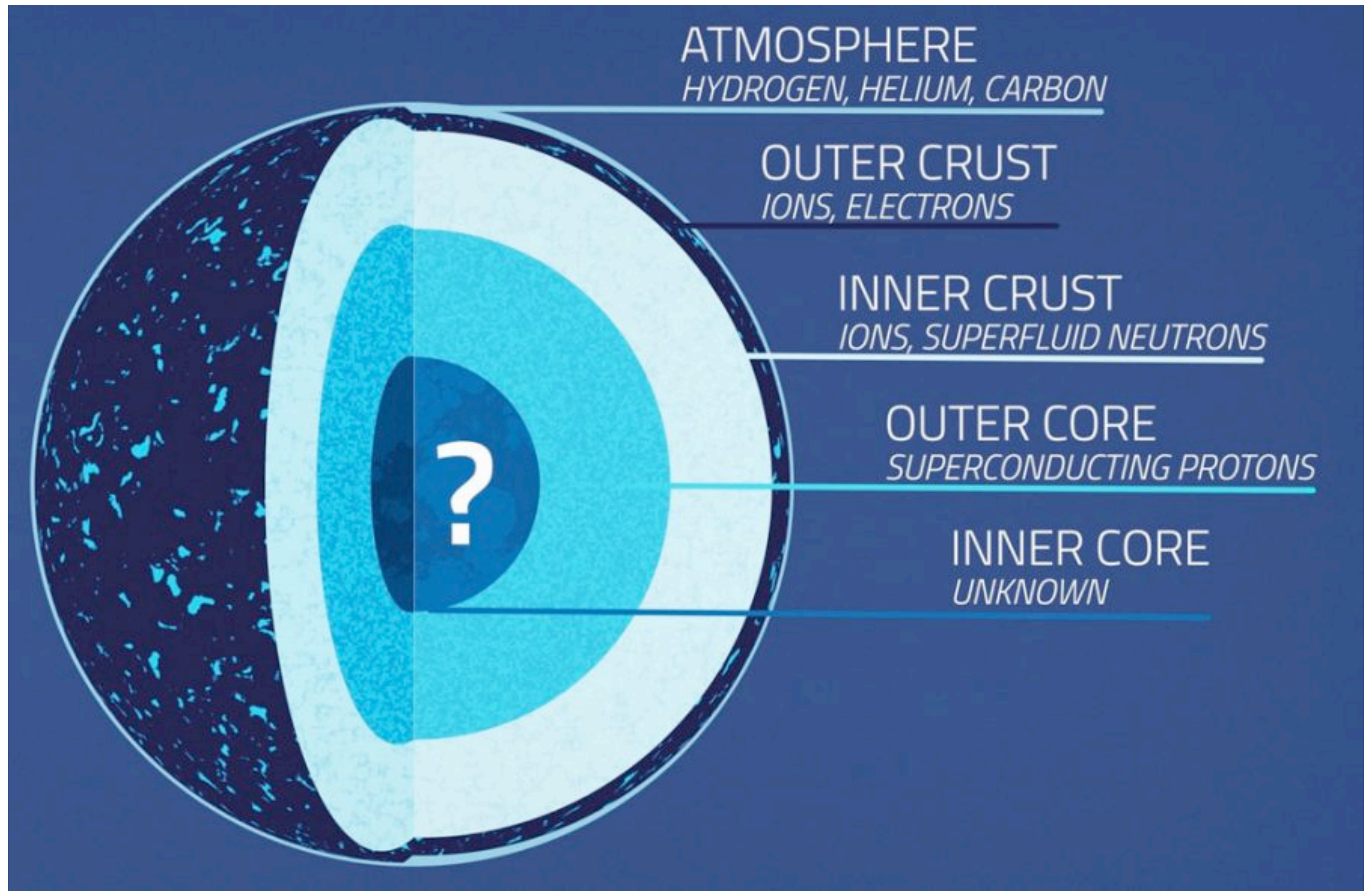

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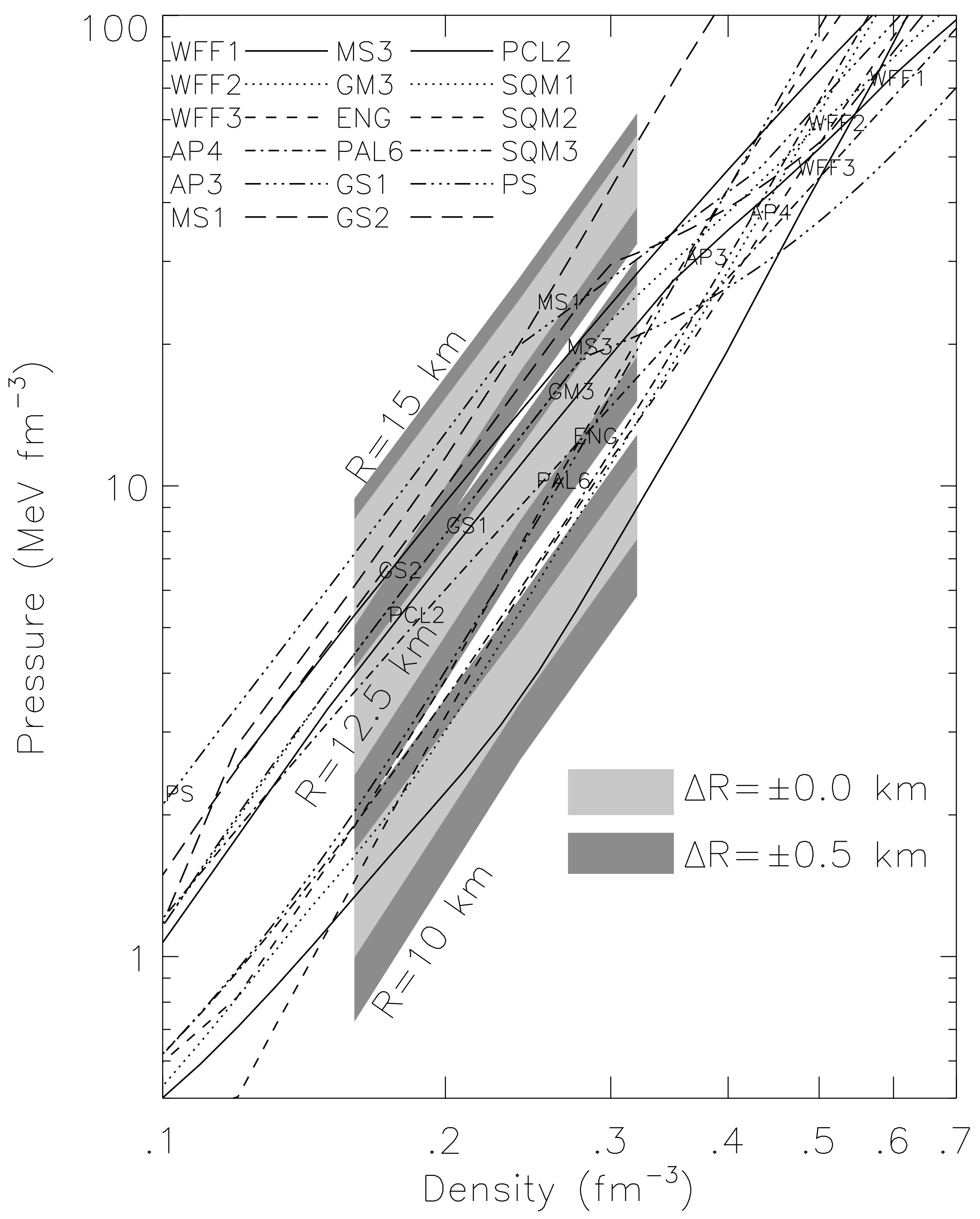
NS core → $n_{\mathrm{sat}} \approx 2.7 \times 10^{14}$ g cm^{-3}

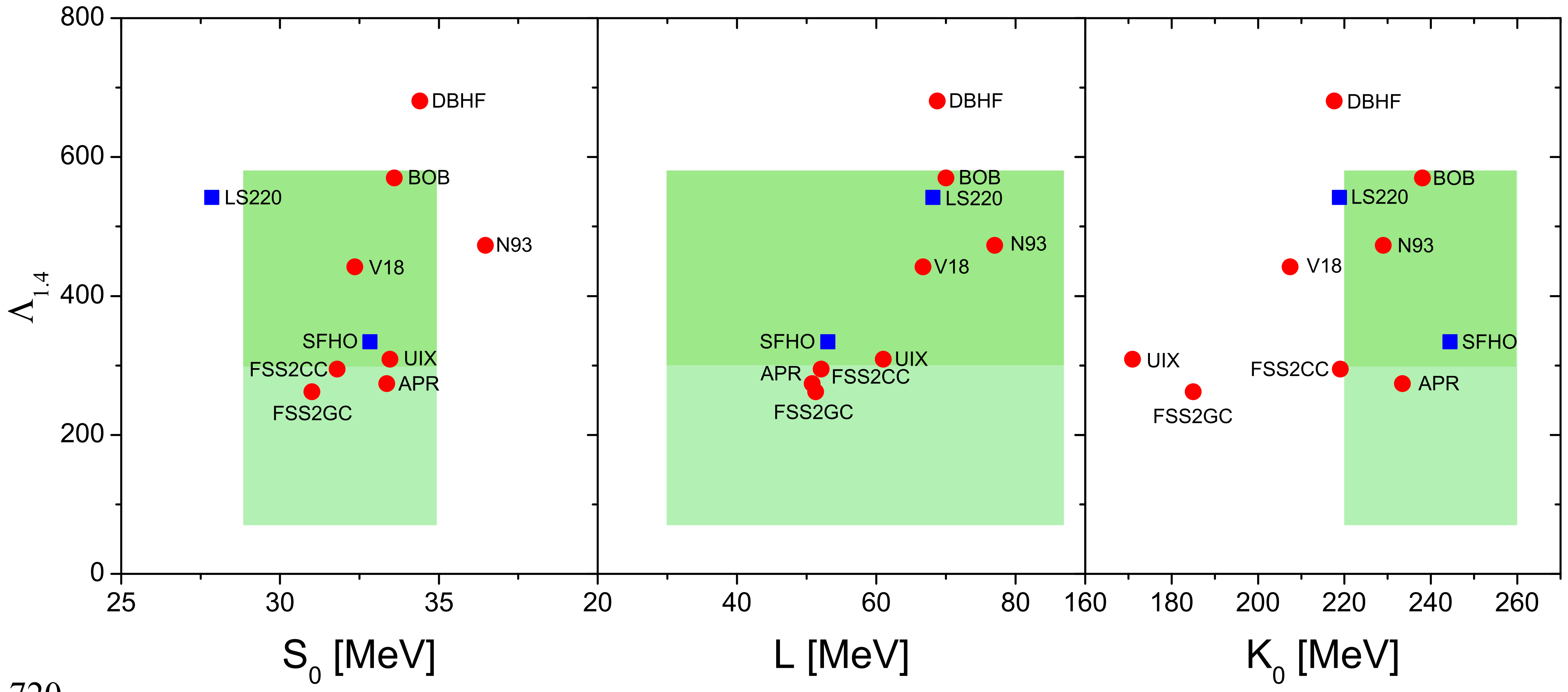
To what extent do global properties of NSs require accurate experimental nuclear data as complementary constraints?

Is the extrapolation of nuclear physics models to higher densities predominantly controlled by nuclear physics data at saturation density?

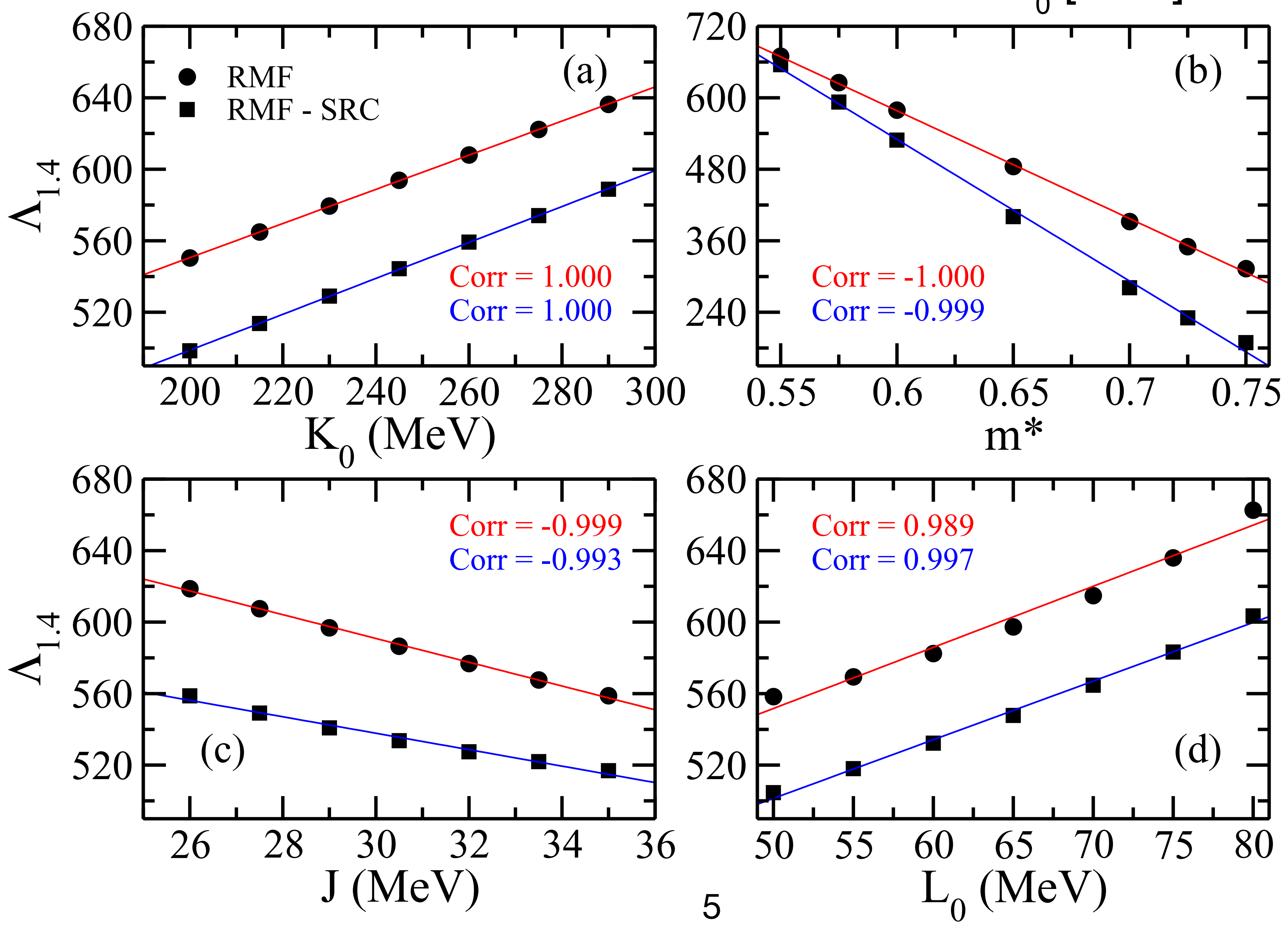
Motivation



[J. M. Lattimer et al., APJ 550, 426 (2001)]

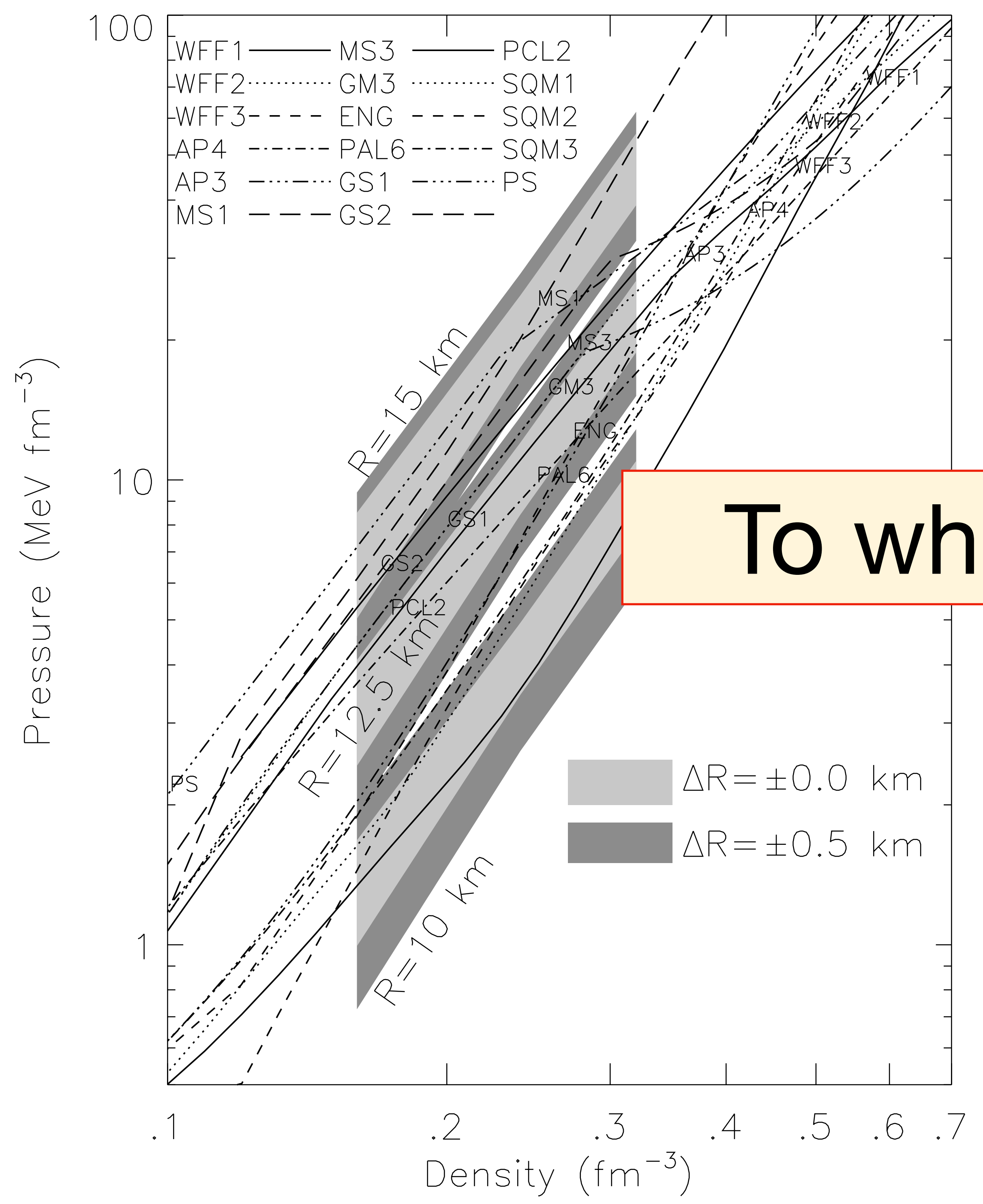


[Jin-Biau Wei et al., EPJA 56, 63 (2020)]



[L. A.Souza et al., PRC101, 065202 (2020)]

Motivation



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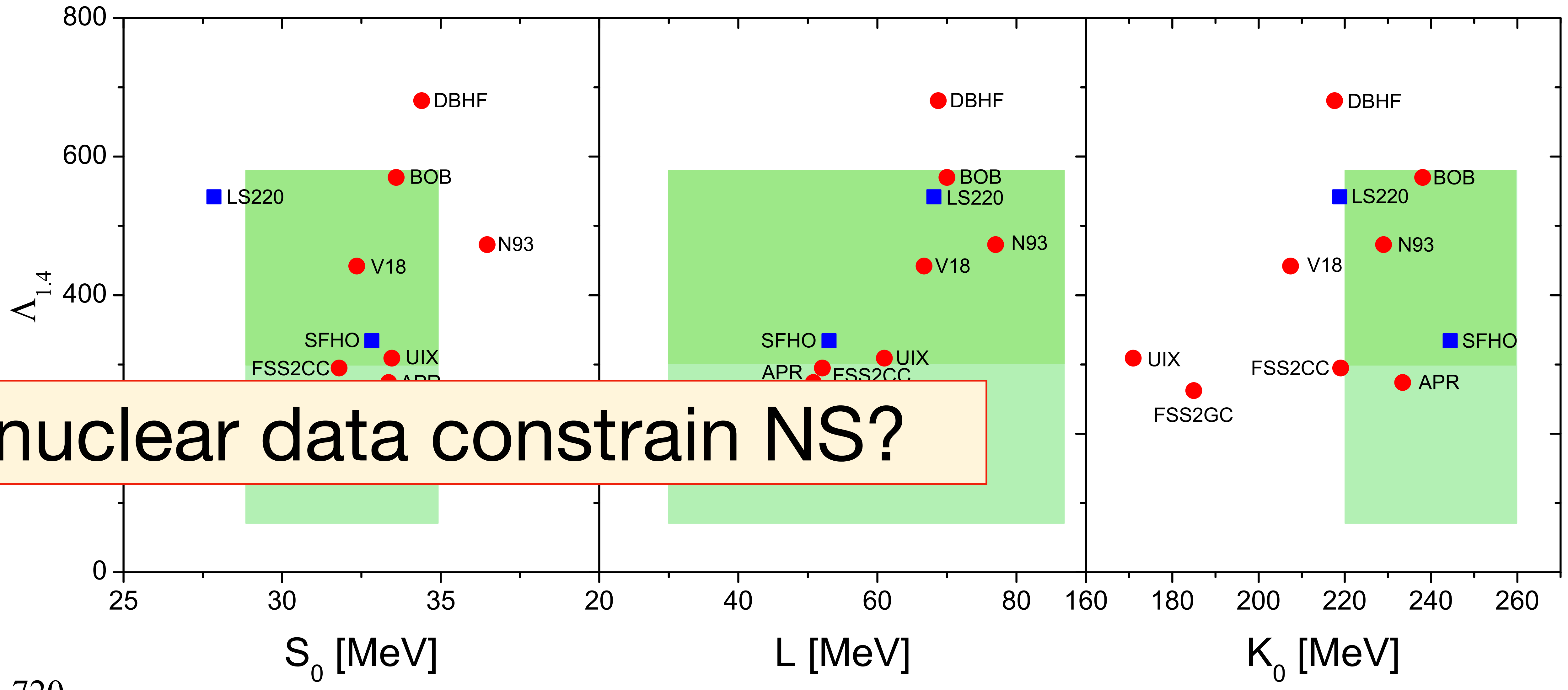
To what extend low-energy nuclear data constrain NS?



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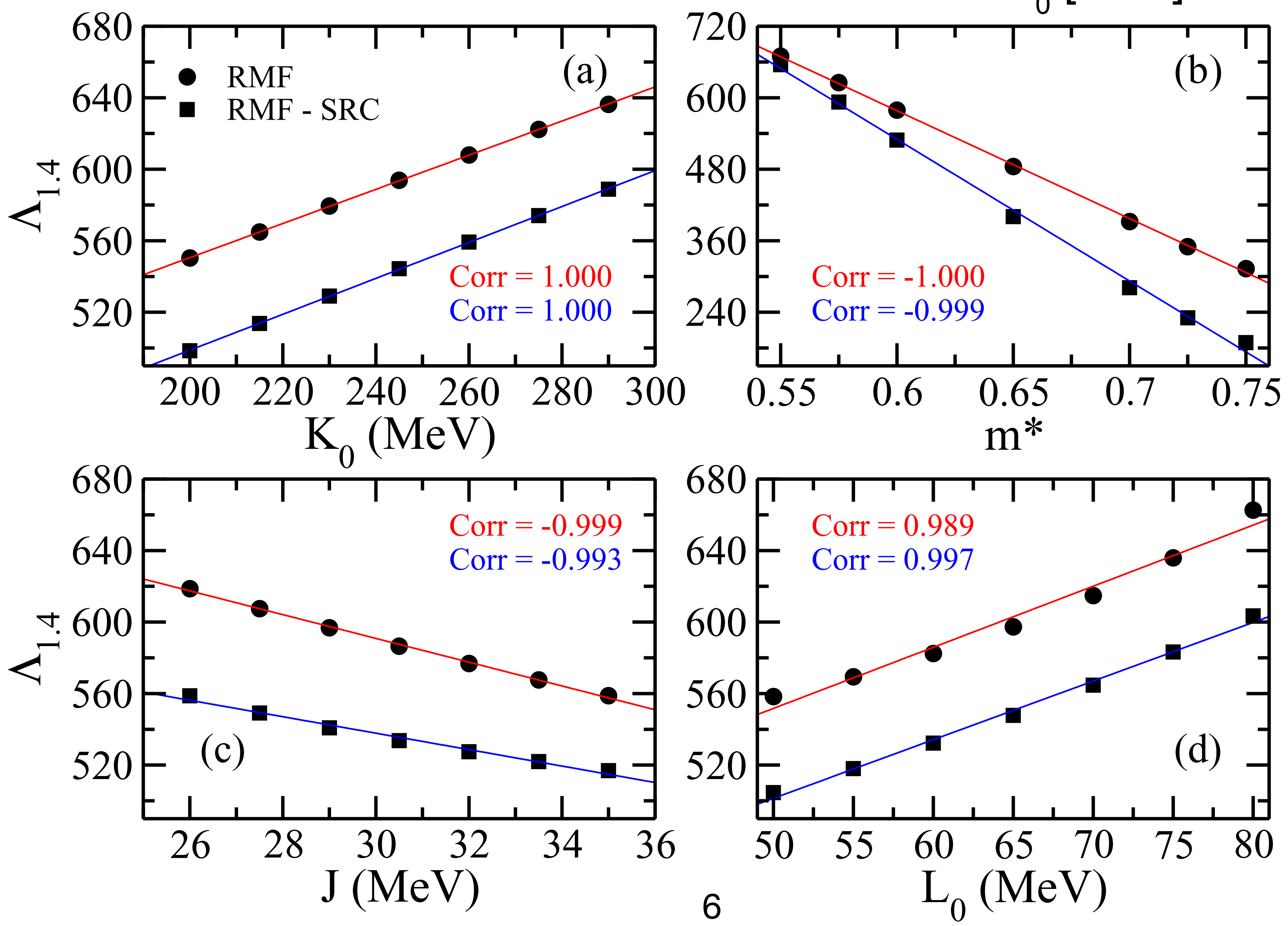

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Combined analysis of the modelling reproducing low energy nuclear data

To what extend low-energy nuclear data constrain NS?

Combined analysis of the modelling reproducing low energy nuclear data

To what extend low-energy nuclear data constrain NS?

- 415 nuclear physics models
  - Skyrme
  - Relativistic Mean-Filed (RMF)
    - with nonlinear couplings (RMF-NL)
    - with density dependence coupling (RMF-DD)

- We assess the capacity of these models according to their ability to reproduce low-energy nuclear physics data.
  - binding energies, charge radii, giant monopole energy + constraint in symmetry energy.

Combined analysis of the modelling reproducing low energy nuclear data

- Nuclear experimental data

Z	N	Nucleus	B (MeV)
8	8	^{16}O	−127.6193(–)
14	20	^{34}Si	−283.4289(140)
20	20	^{40}Ca	−342.0521(–)
20	28	^{48}Ca	−416.0009(1)
20	32	^{52}Ca	−438.3279(7)
20	34	^{54}Ca	−445.3642(500)
28	20	^{48}Ni$^{\#}$	−348.7275(5000)
28	28	^{56}Ni	−483.9956(4)
28	50	^{78}Ni$^{\#}$	−641.5470(6000)
40	50	^{90}Zr	−783.8972(1)
50	50	^{100}Sn	−825.2944(3000)
50	82	^{132}Sn	−1102.8430(20)
82	126	^{208}Pb	−1636.4301(11)

[G. Audi et al., CPC 41, 030001 (2017)]

Z	N	Nucleus	$E^{\text{exp.}}_{\text{GMR}}$ (MeV) $\sqrt{m_1/m_{-1}}$
82	126	^{208}Pb	13.50(10)

[U. Garg et al., PPNP 101, 55 (2018)]

Z	N	nucleus	R_{ch} (fm)
8	8	^{16}O	2.6991(52)
20	20	^{40}Ca	3.4776(19)
20	28	^{48}Ca	3.4771(20)
40	50	^{90}Zr	4.2694(10)
50	82	^{132}Sn	4.7093(76)
82	126	^{208}Pb	5.5012(13)

[I. Angeli et al., ADNDT 99, 57 (2013)]

Combined analysis of the modelling reproducing low energy nuclear data

- Combined Analysis

G_i : global assessment → all nuclei contribute equally to the variance

$$\sigma_B^2 = \frac{1}{N_B} \sum_i \left[\frac{B_i(\exp) - B_i(\text{model})}{\delta_B} \right]^2$$

$$\sigma_{R_{ch}}^2 = \frac{1}{N_{R_{ch}}} \sum_i \left[\frac{R_{ch,i}(\exp) - R_{ch,i}(\text{model})}{\delta_{R_{ch}}(A_i)} \right]^2$$

$$\sigma_{\text{ISGMR}}^2 = \frac{1}{N_{\text{ISGMR}}} \sum_i \left[\frac{E_{\text{ISGMR},i}(\exp) - E_{\text{ISGMR},i}(\text{model})}{\delta_{\text{ISGMR}}} \right]^2$$

$i =$	B	R_{ch}	E_{ISGMR}
N_i	13	6	1
δ_i	2.0 (MeV)	$0.1A^{-1/3}$ (fm)	0.7 (MeV)

Combined analysis of the modelling reproducing low energy nuclear data

- Combined Analysis

D_i : detailed approach ⟶ the variances (B *and* R_{ch}) of the symmetric $N = Z$ and asymmetric $N \neq Z$ nuclei are accumulated separately. The E_{ISGMR} remains the same.

$$\sigma^2_{B,S} = \frac{1}{N_{B,S}} \sum_{i \in S} \left[\frac{B_i(\text{exp}) - B_i(\text{model})}{\delta_B} \right]^2$$

(B, S): ^{16}O, ^{40}Ca, ^{56}Ni, ^{100}Sn

$$\sigma^2_{R_{ch},S} = \frac{1}{N_{R_{ch},S}} \sum_{i \in S} \left[\frac{R_{ch,i}(\text{exp}) - R_{ch,i}(\text{model})}{\delta_{R_{ch}}(A_i)} \right]^2$$

(R_{ch}, S): ^{16}O, ^{40}Ca

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D_i : detailed approach ⟶ the variances (B *and* R_{ch}) of the symmetric $N = Z$ and asymmetric $N \neq Z$ nuclei are accumulated separately. The E_{ISGMR} remains the same.

$$\sigma^2_{B,A} = \frac{1}{N_{B,A}} \sum_{i \in A} \left[\frac{B_i(\exp) - B_i(\text{model})}{\delta_B} \right]^2$$

(B, A): ^{34}Si, ^{48}Ca, ^{52}Ca, ^{54}Ca, ^{48}Ni, ^{78}Ni, ^{90}Zr, ^{132}Sn, ^{208}Pb.

$$\sigma^2_{R_{ch},A} = \frac{1}{N_{R_{ch},A}} \sum_{i \in A} \left[\frac{R_{ch,i}(\exp) - R_{ch,i}(\text{model})}{\delta_{R_{ch}}(A_i)} \right]^2$$

(R_{ch}, A): ^{48}Ca, ^{90}Zr, ^{132}Sn, ^{208}Pb

Combined analysis of the modelling reproducing low energy nuclear data

- Combined Analysis

$i =$		B	R_{ch}
S	N_i	4	2
	δ_i	2.0 (MeV)	$0.1A^{-1/3}$ (fm)
A	N_i	9	4
	δ_i	2.0 (MeV)	$0.1A^{-1/3}$ (fm)

Combined analysis of the modelling reproducing low energy nuclear data

- Combined Analysis

$$
\begin{aligned}
&\text{(i)} \quad L = A \text{ if } \sigma < 1,\\
&\text{(ii)} \quad L = B \text{ if } 1 < \sigma < 2,\\
&\text{(iii)} \quad L = C \text{ if } 2 < \sigma < 3,\\
&\text{(iv)} \quad L = D \text{ if } \sigma > 3.
\end{aligned}
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SLy4: BBA, BB:BB:A

Combined analysis of the modelling reproducing low energy nuclear data

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	G_0 / D_0	G_1 / D_1	G_2 / D_2	G_3 / D_3	G_4 / D_4
L	*	A to C	A or B	A or B	A or B
types of data	all	all	bind energy	bind energy and charge radii	bind energy, charge radii, and GMR energy

* discarded interactions with: (i) negative values of the sound speed above n_{sat} or (ii) negative value of the pressure in stellar matter

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SLy4: BBA, BB:BB:A

	D_0/G_0	D_1	G_1	D_2	G_2	D_3	G_3	D_4	G_4
Total	374	81	90	66	74	61	74	45	54

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Impact of the groups on the symmetry energy and its slope correlation

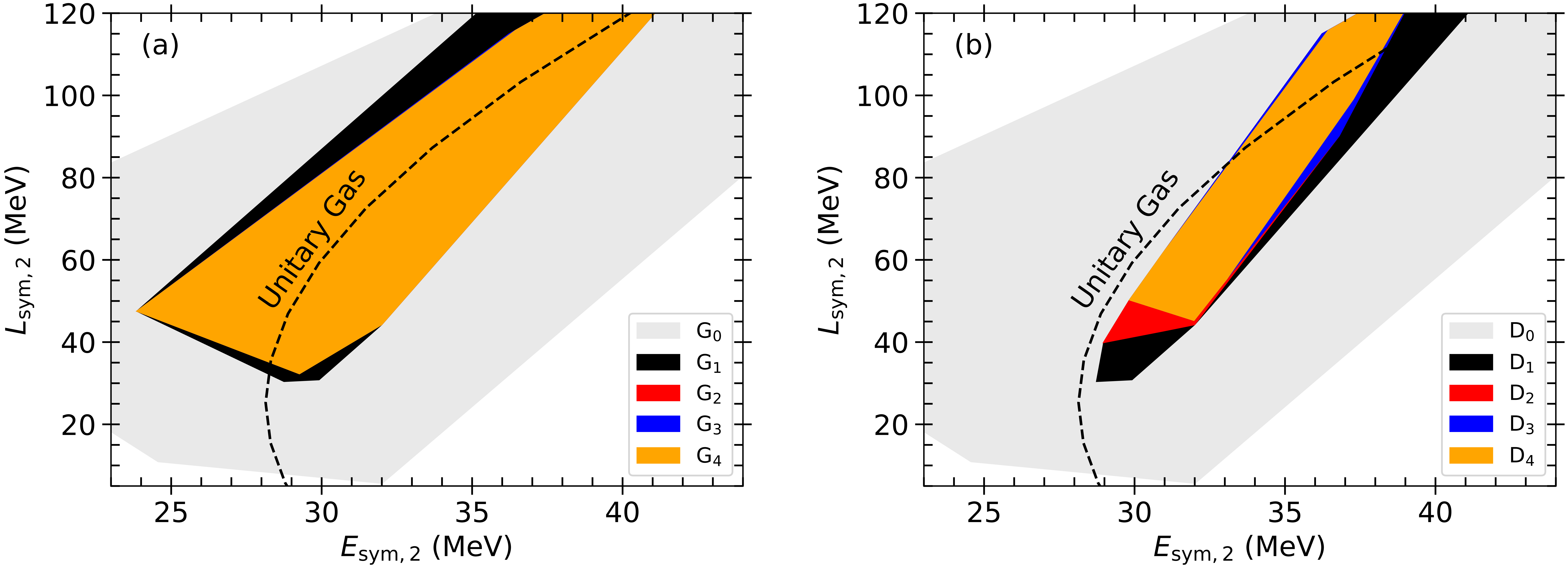
$$E_{\mathrm{sym},2}(n) = \frac{1}{2}\frac{\partial^2 e(n,\delta)}{\partial\delta^2}\Big|_{\delta=0}$$

$$e_{\mathrm{sym},2}(n) = E_{\mathrm{sym},2} + L_{\mathrm{sym},2}\,x + \frac{1}{2}K_{\mathrm{sym},2}\,x^2 + \frac{1}{6}Q_{\mathrm{sym},2}\,x^3 + \ldots,$$

with $x = (n - n_{\mathrm{sat}})/3n_{\mathrm{sat}}$ and $\delta = (n_n - n_p)/n\,.$

$$L_{\mathrm{sym},2}(n) = 3n_0\frac{\partial E_{\mathrm{sym},2}(n)}{\partial n}$$

Impact of the groups on the symmetry energy and its slope correlation



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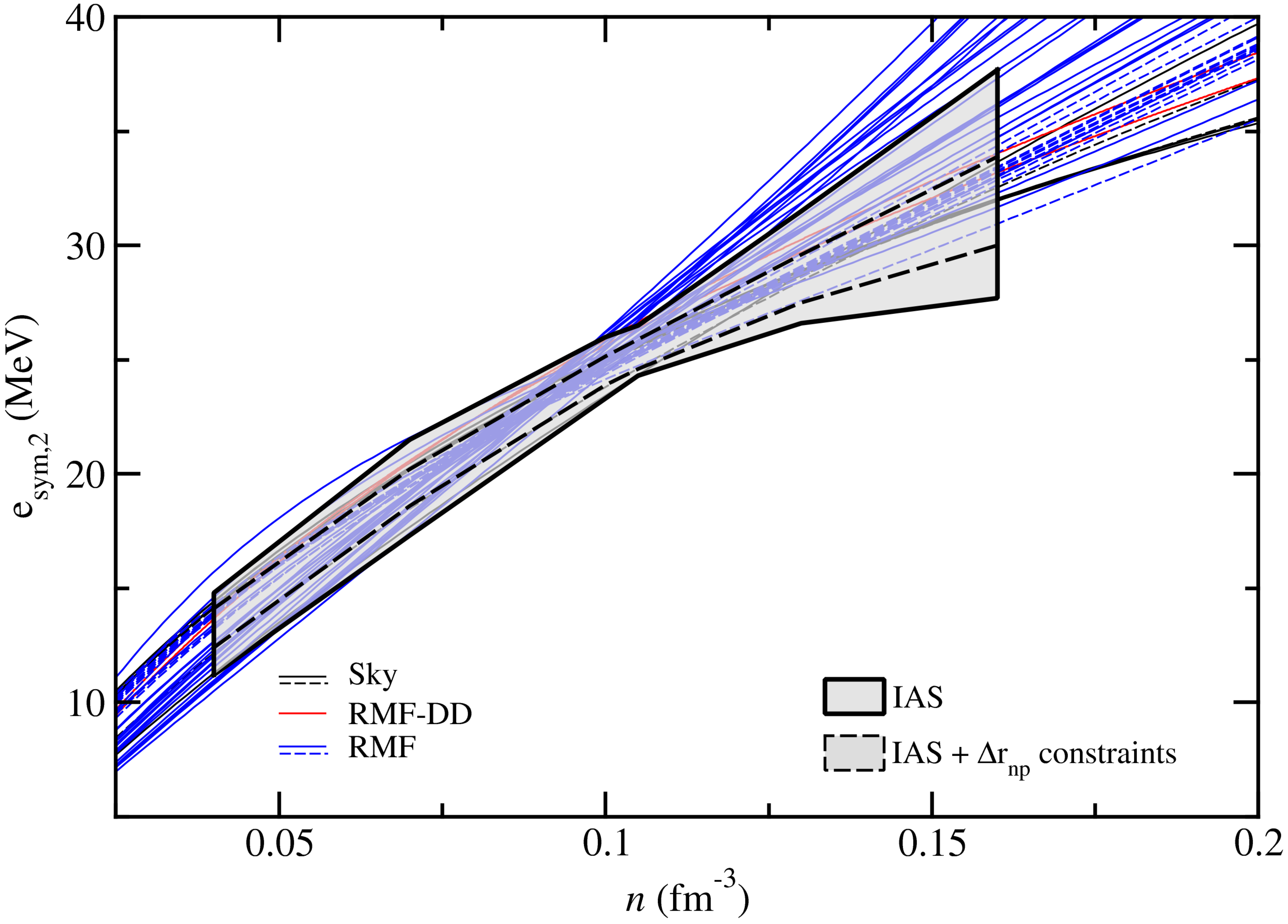

$$\chi^2 = \frac{1}{N} \sum_i \frac{[e^{av}_{sym,2}(i) - e^{model}_{sym,2}]^2}{[\Delta e_{sym,2}(i)]^2}$$

$$\chi^2 < 1$$

	D_0/G_0	D_1	G_1	D_2	G_2	D_3	G_3	D_4	G_4	D_{4sym}
Total	374	81	90	66	74	61	74	45	54	22

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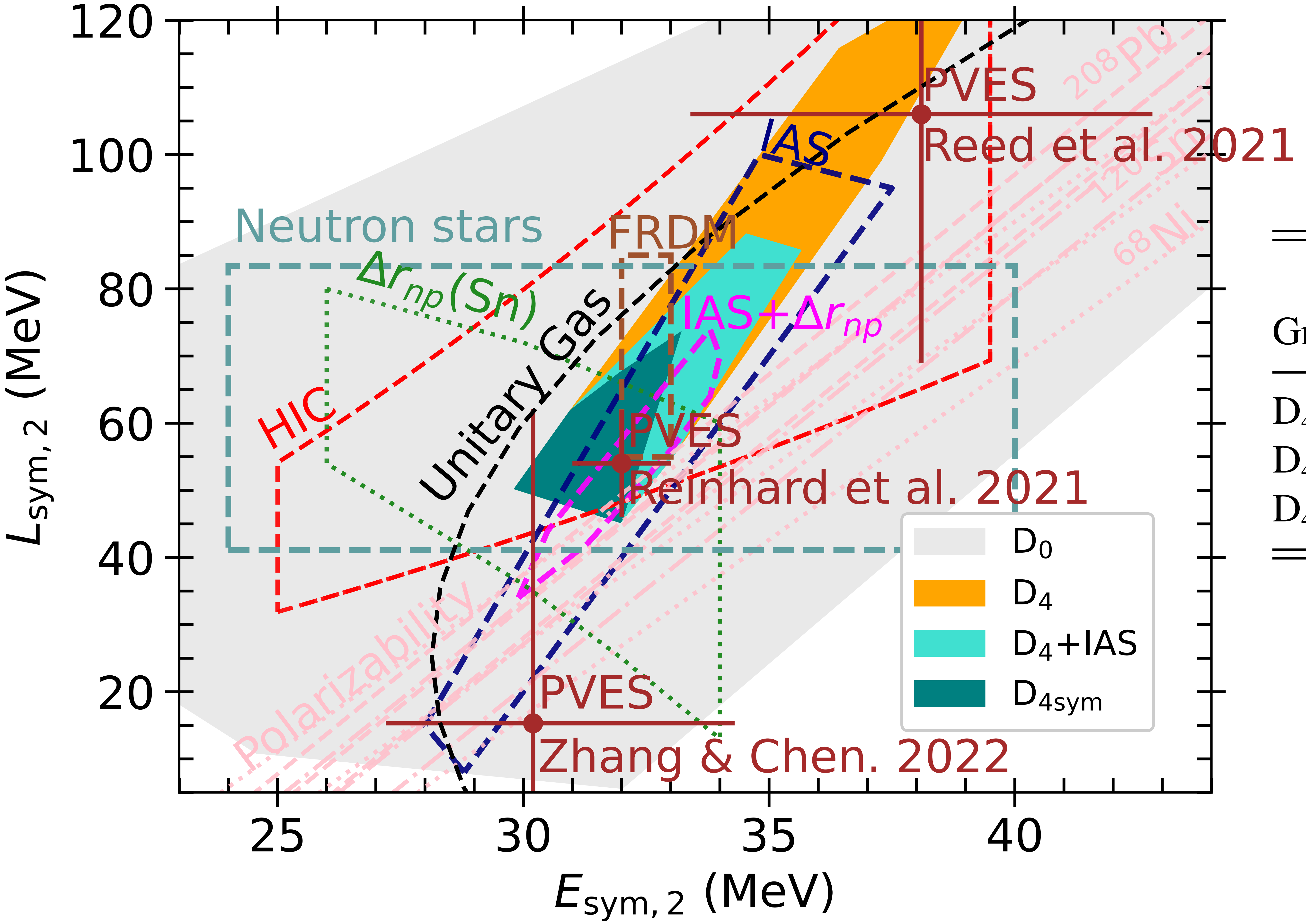

Group	$E_{sym,2}$ (MeV)	$L_{sym,2}$ (MeV)
D_4	33.5 ± 2.4	73.4 ± 23.3
D_4+IAS	32.3 ± 1.2	62.9 ± 12.3
D_{4sym}	31.8 ± 0.7	58.1 ± 9.0

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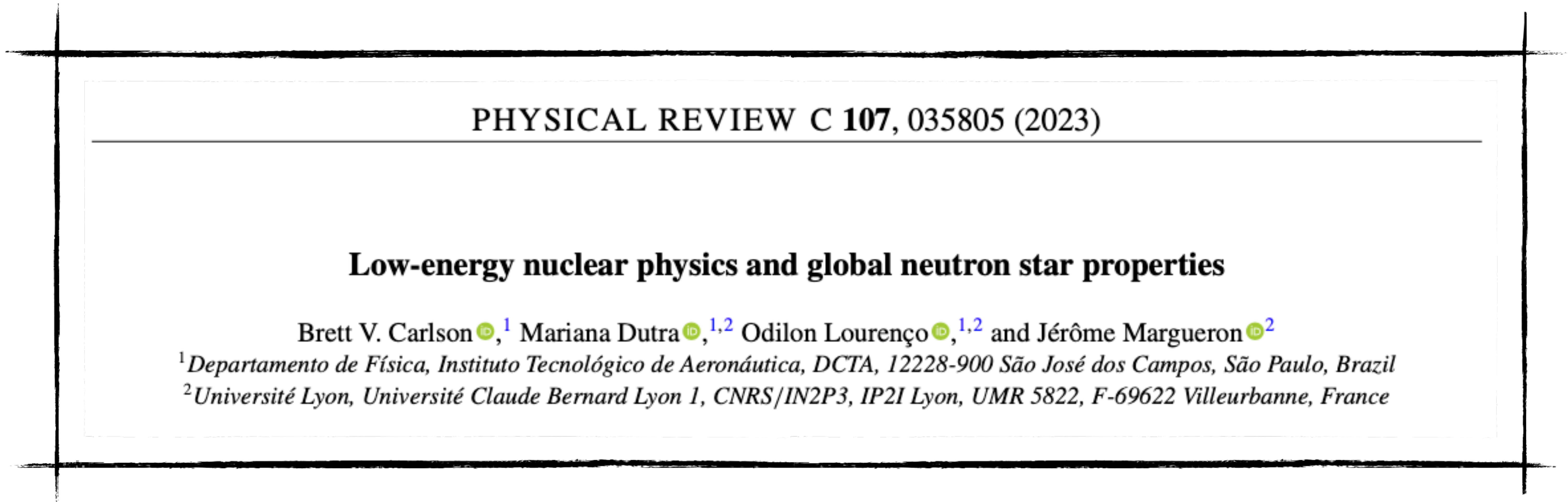
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Neutron star global properties

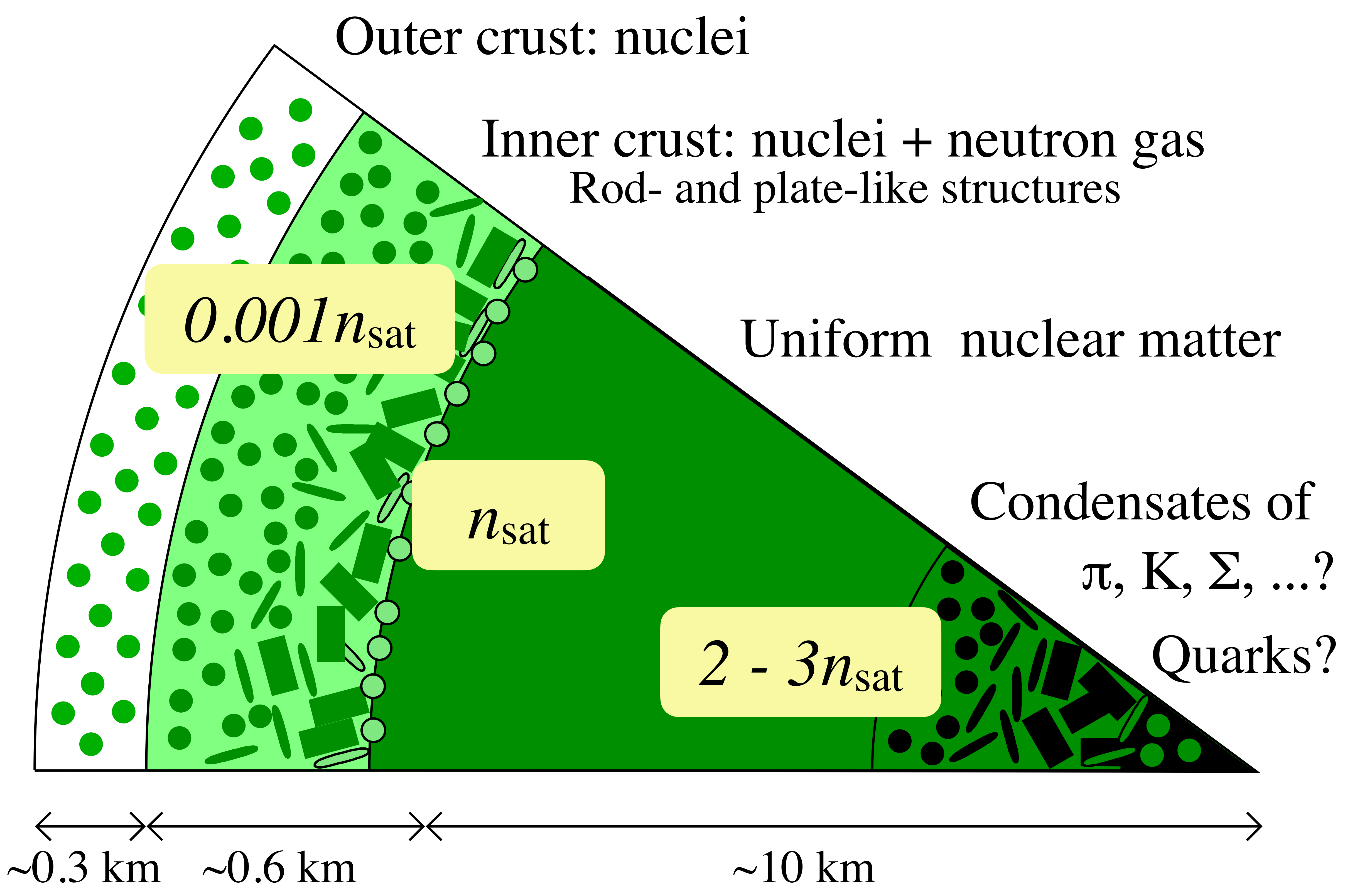
Main properties:

$M \approx 1.2 - 2.1\, M_\odot$

Average density $\approx 10^{15}\,\mathrm{g\,cm^{-3}}$

$R \approx 10 - 14\,\mathrm{km}$ $\quad B \approx 10^{12} - 10^{15}\,\mathrm{G}$

- Aftermath of a core-collapse supernovae,
- Isolated or in binary,
- Could be a pulsar: from radio to/or γ-rays,
- X-ray emission from accretion disk,
- Fast spinning.

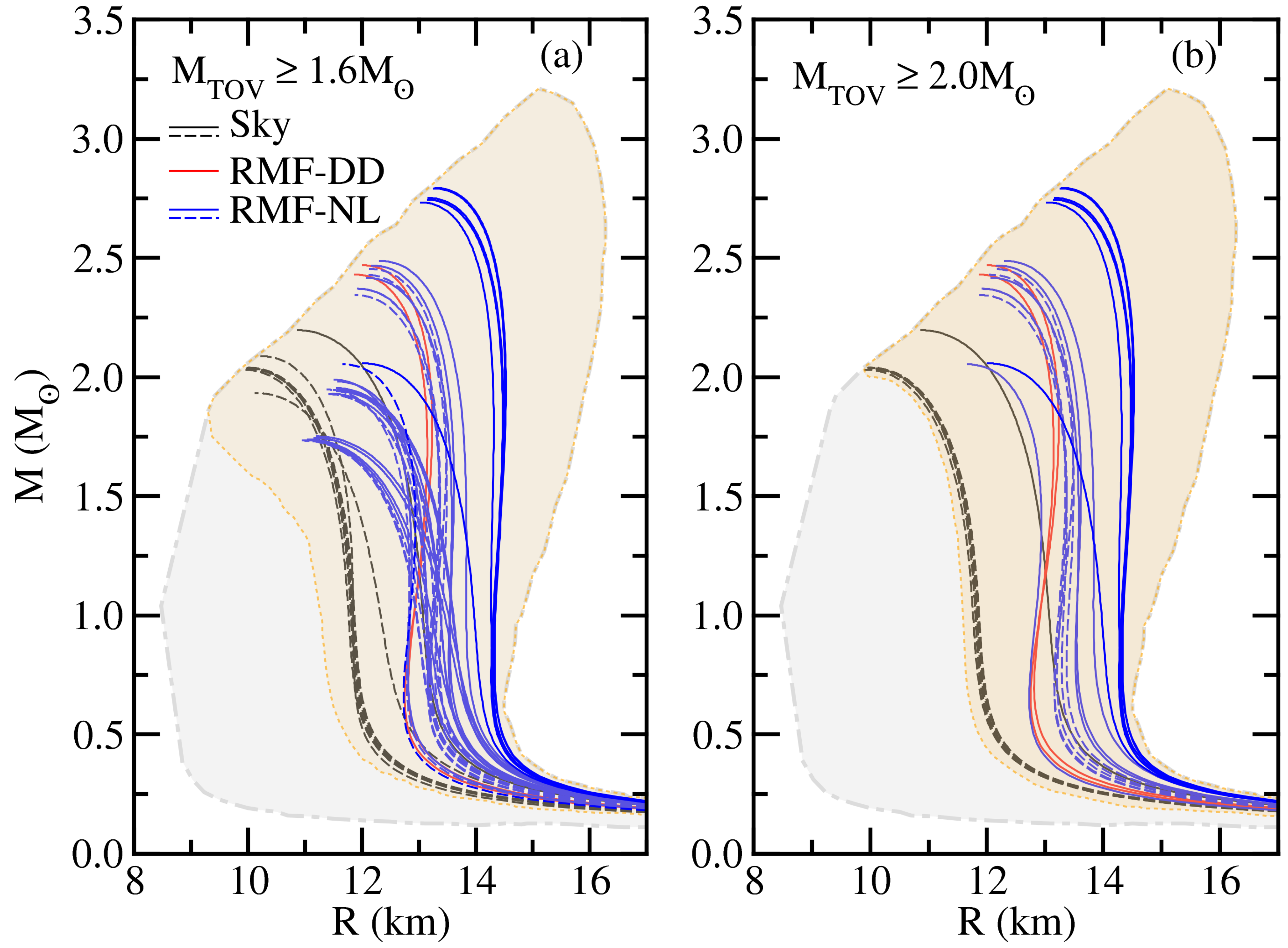


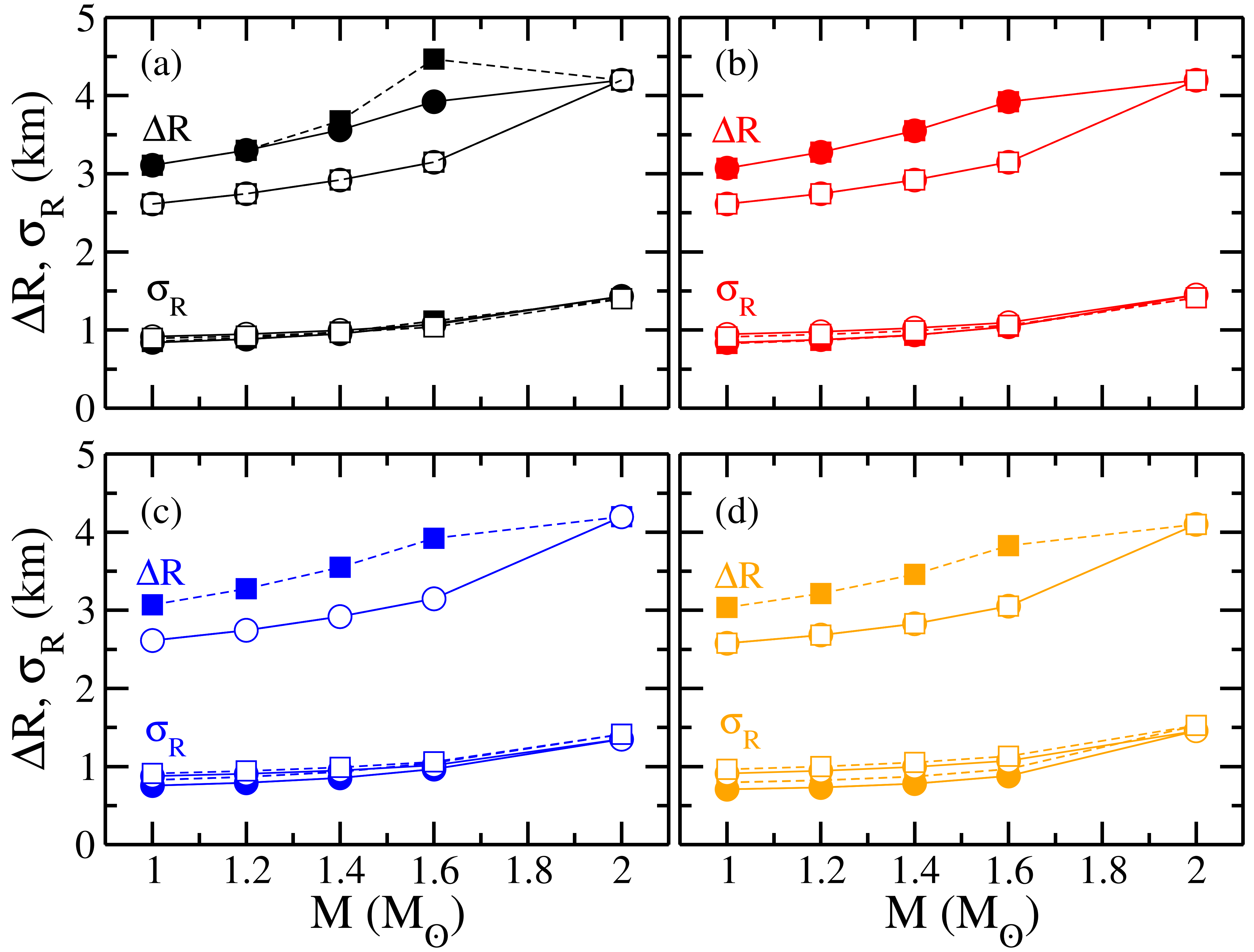
[H. Heiselberg, arXiv:astro-ph/0201465 (2002)]

Neutron star global properties

EoS → Tolmann-Oppenheimer-Volkov (TOV) GR equations

	D_0/G_0	D_1	G_1	D_2	G_2	D_3	G_3	D_4	G_4	D_{4sym}
Total	374	81	90	66	74	61	74	45	54	22
$M_{TOV} \geqslant 1.6 M_\odot$	312	77	85	65	72	61	72	45	52	22
$M_{TOV} \geqslant 2.0 M_\odot$	198	49	53	44	49	41	49	25	29	12





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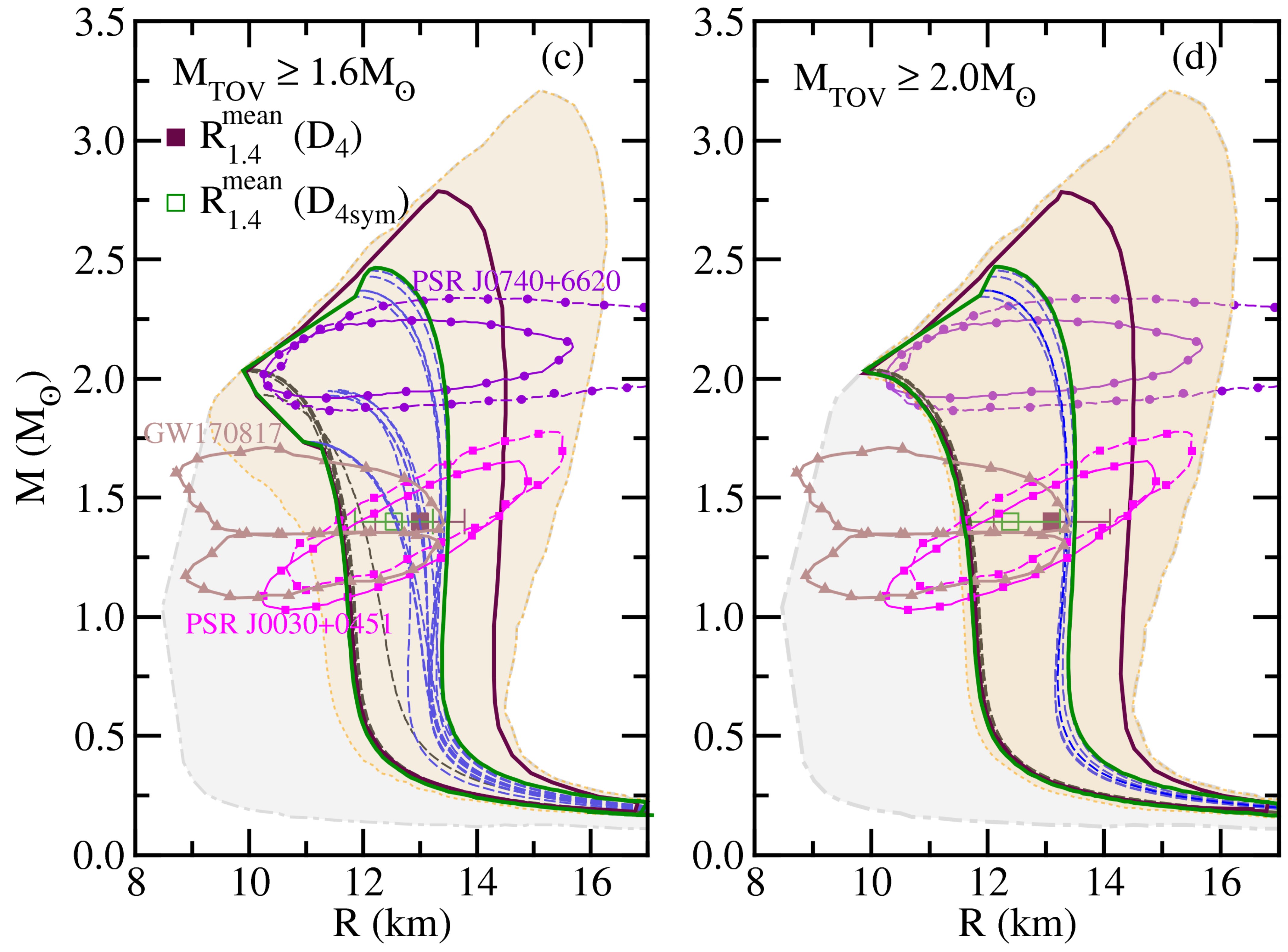

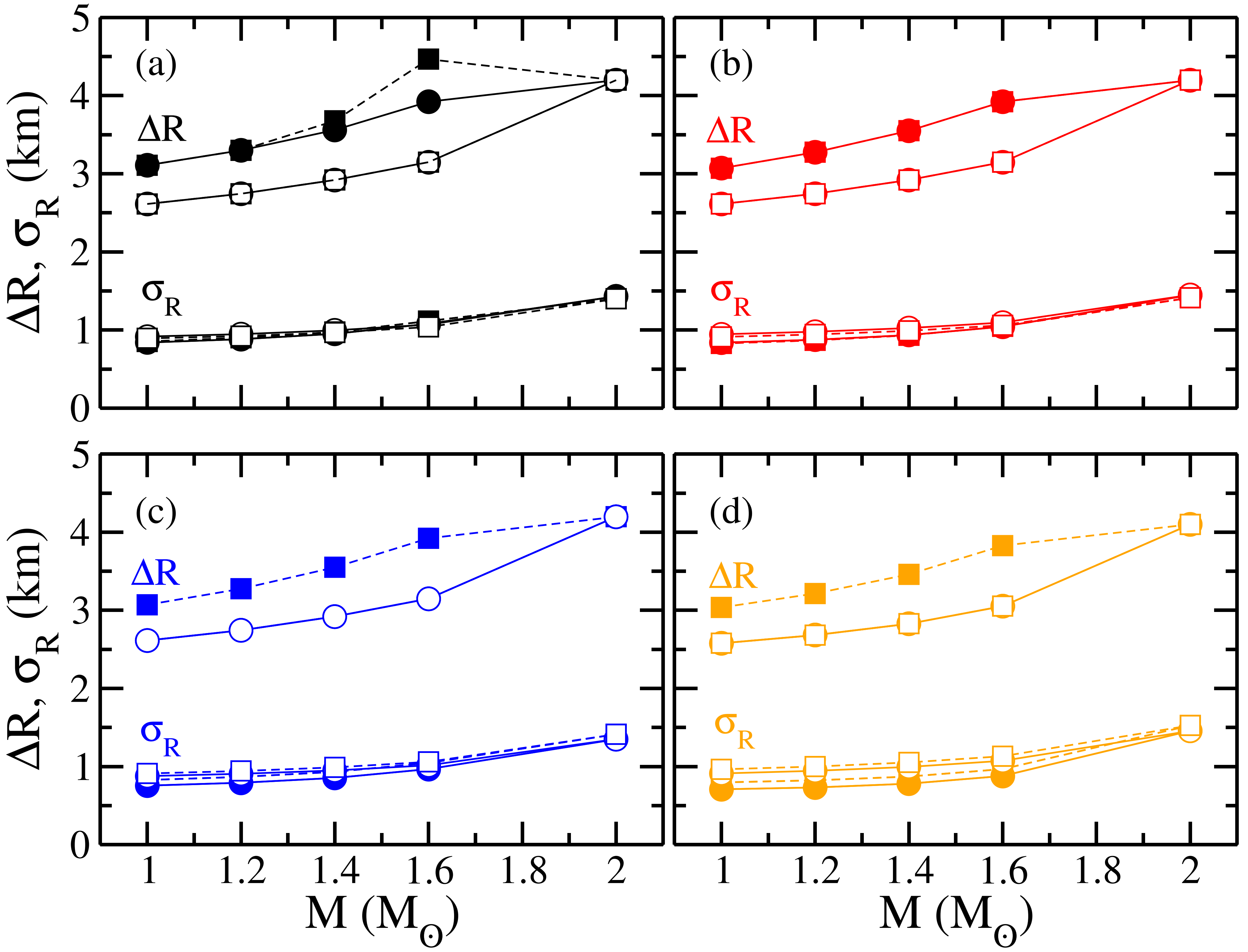

Neutron star global properties

- Tidal deformability

$$\Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3}k_2\frac{R^5}{m^5} = \frac{2}{3}k_2C^{-5}$$

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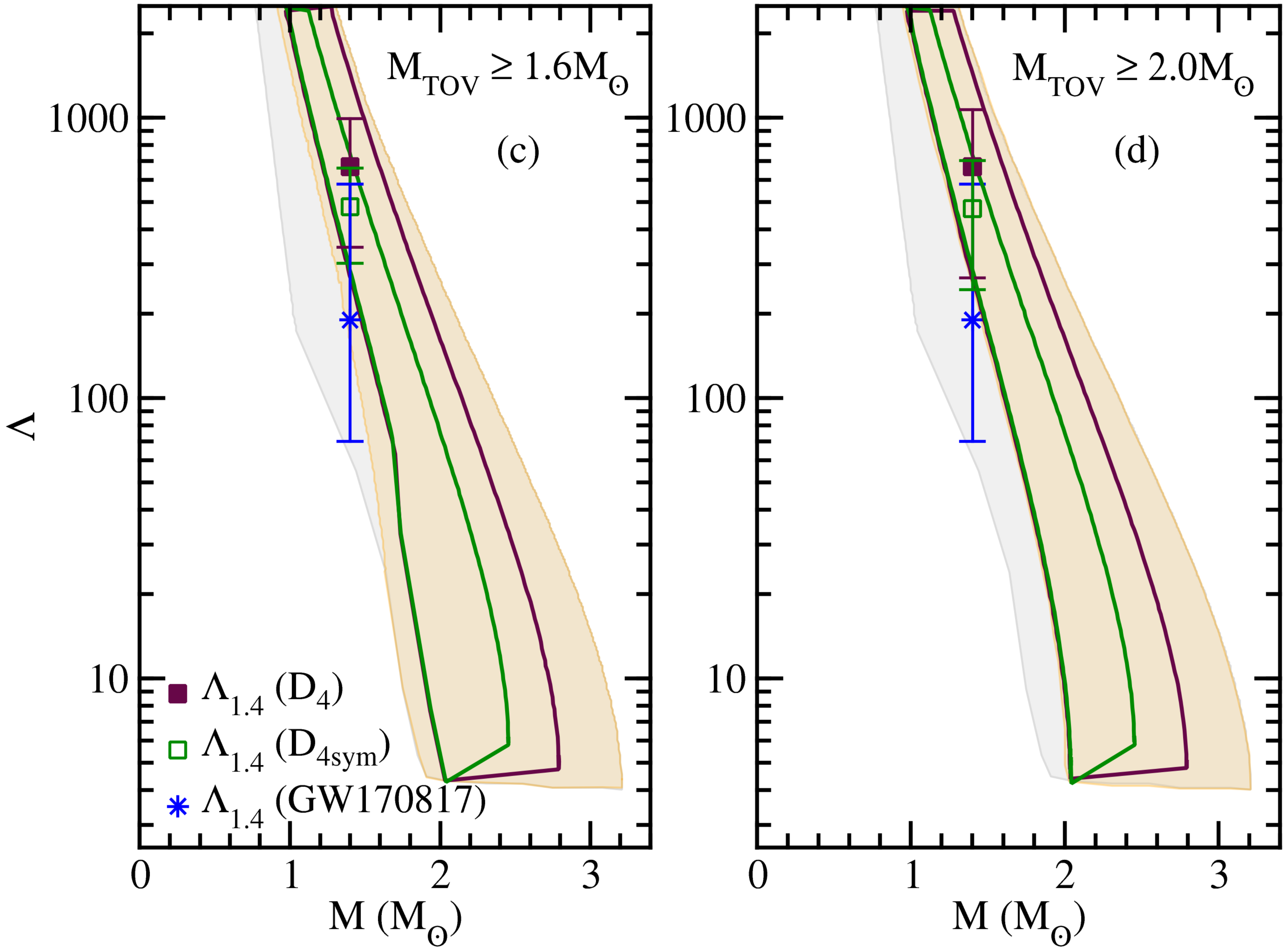

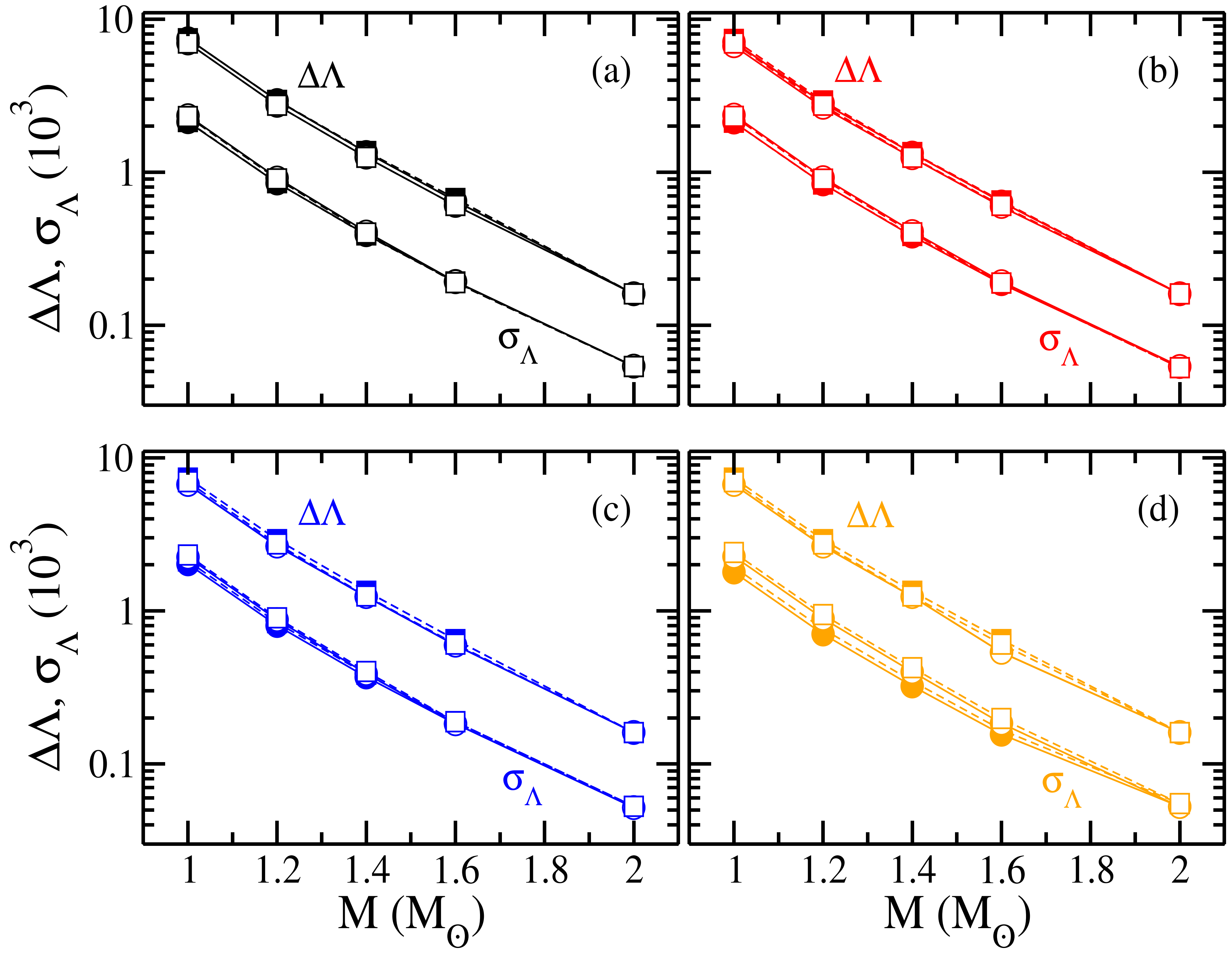

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Conclusions

- ✓ The group D_{4sym} that further reduces the uncertainty in the symmetry energy. We find $E_{sym,2} = 31.8 \pm 0.7\,\mathrm{MeV}$ and $L_{sym,2} = 58.1 \pm 0.9\,\mathrm{MeV}$.

- ✓ Better low energy nuclear properties may not improve predictions for NS global properties.

- ✓ The $1.4\,M_{\odot}$ NS radius lies between 12 and 14 km for the “better” nuclear interactions.

- ✓ We plan to perform a complementary analysis including data from heavy-ion collision exploring densities above n_{sat}, the saturation density of nuclear matter.

Thank you!

Backup slides

$$\left\langle R_{ch}^{\text{emp}}\right\rangle^2 \approx \left\langle R_p^2\right\rangle + 0.64\ \text{fm}^2$$

$$E_{\text{ISGMR}} = \sqrt{\frac{m_1}{m_{-1}}},$$

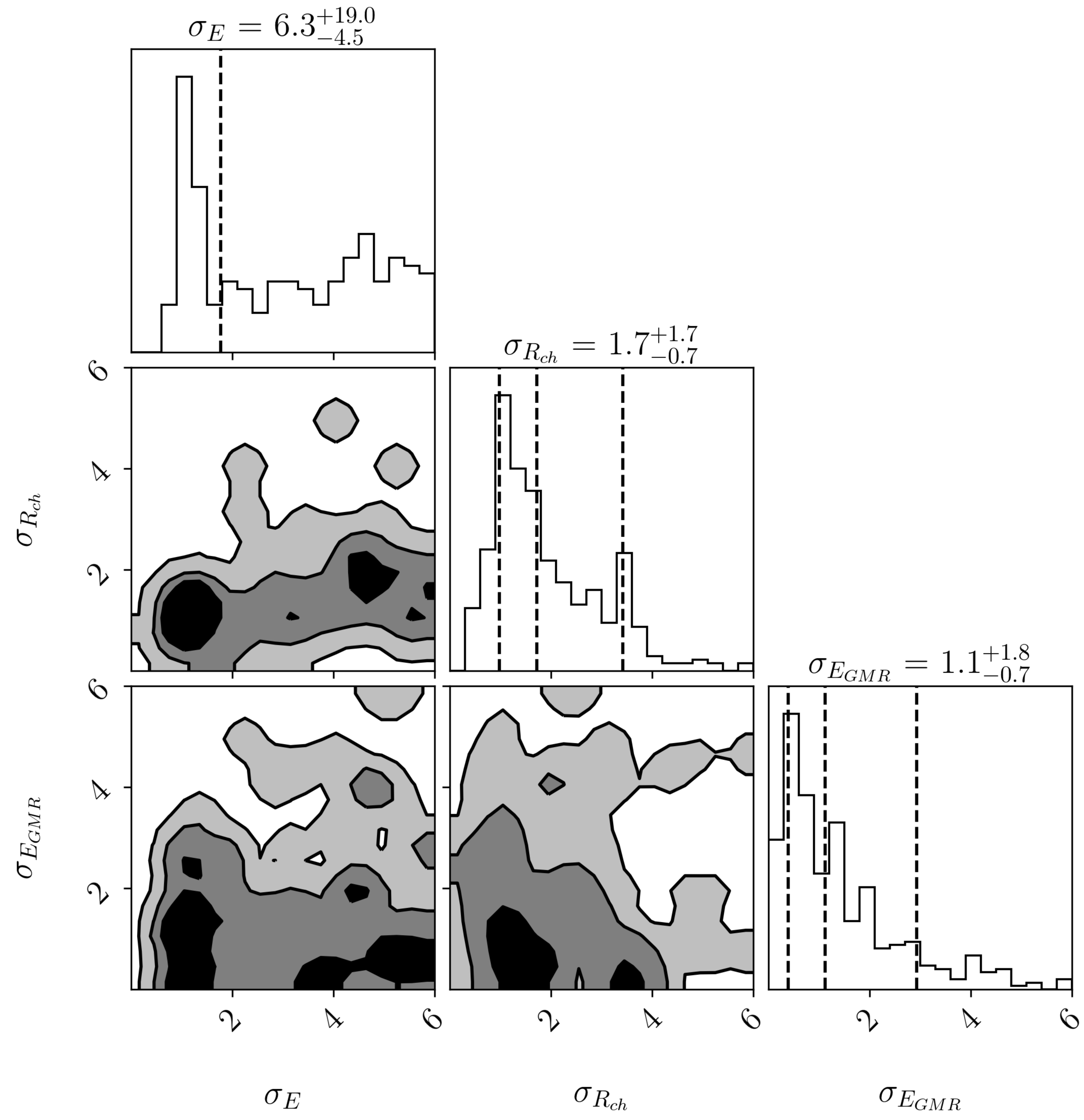
$$m_1 = 2A\frac{\hbar^2}{m_N}\langle r^2\rangle,$$

$$m_{-1} = -\frac{1}{2}\left[\frac{\partial}{\partial\lambda}\langle\lambda|\hat{Q}|\lambda\rangle\right]_{\lambda=0},$$

where $|\lambda\rangle$ is the ground-state energy of the constrained Hamiltonian,

$$\hat{H}_{\text{constr.}} = \hat{H} + \lambda\hat{Q}. \quad (11)$$

$\hat{Q} = \sum_{i=1}^{A} r_i^2$ isoscalar monopole transition operator.



$\sigma_E = 6.3^{+19.0}_{-4.5}$
$\sigma_{R_{ch}} = 1.7^{+1.7}_{-0.7}$
$\sigma_{E_{GMR}} = 1.1^{+1.8}_{-0.7}$
$\sigma_{R_{ch}}$
$\sigma_{E_{GMR}}$
σ_E
$\sigma_{R_{ch}}$
$\sigma_{E_{GMR}}$
2
4
6

Neutron star global properties

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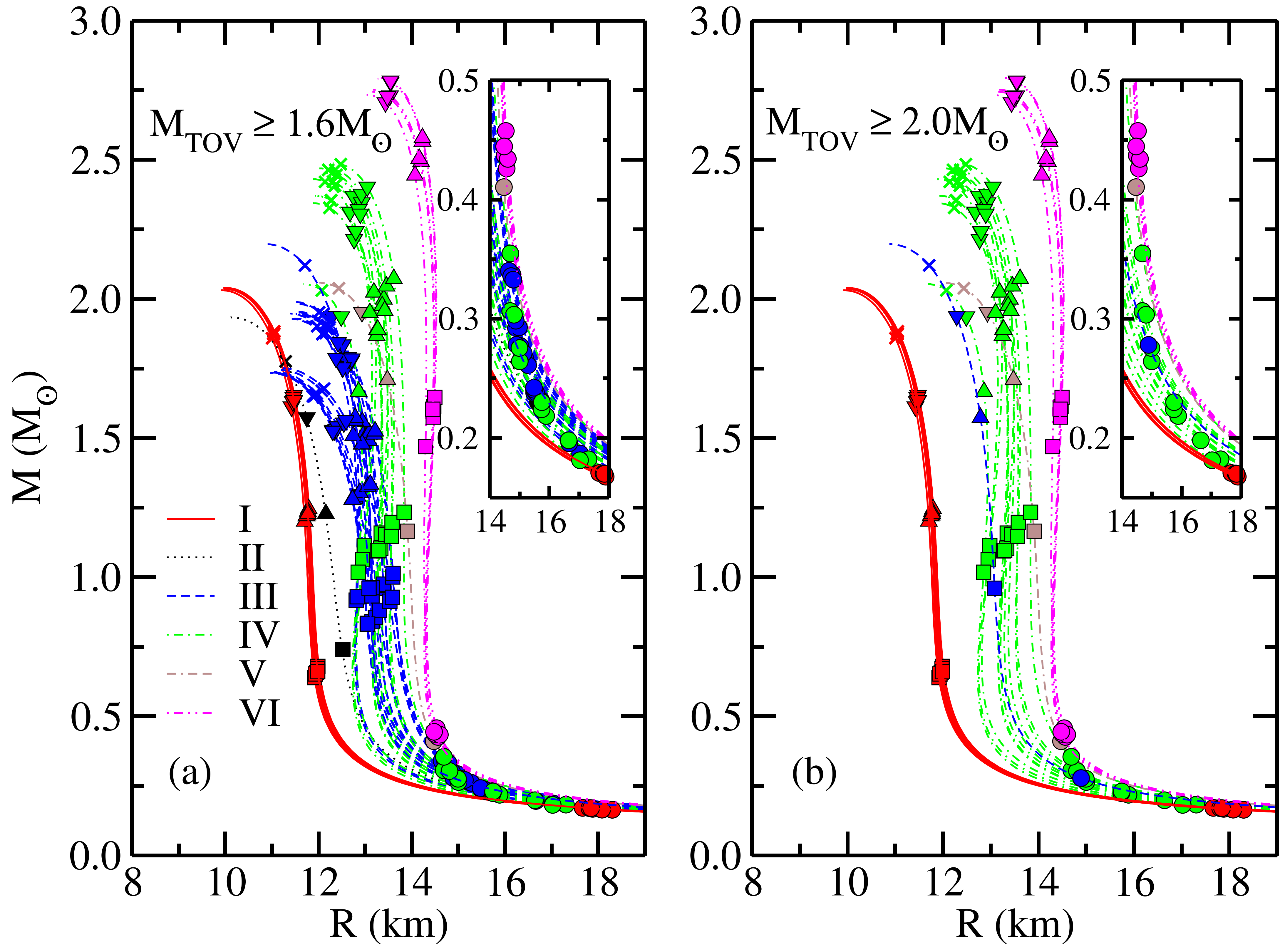
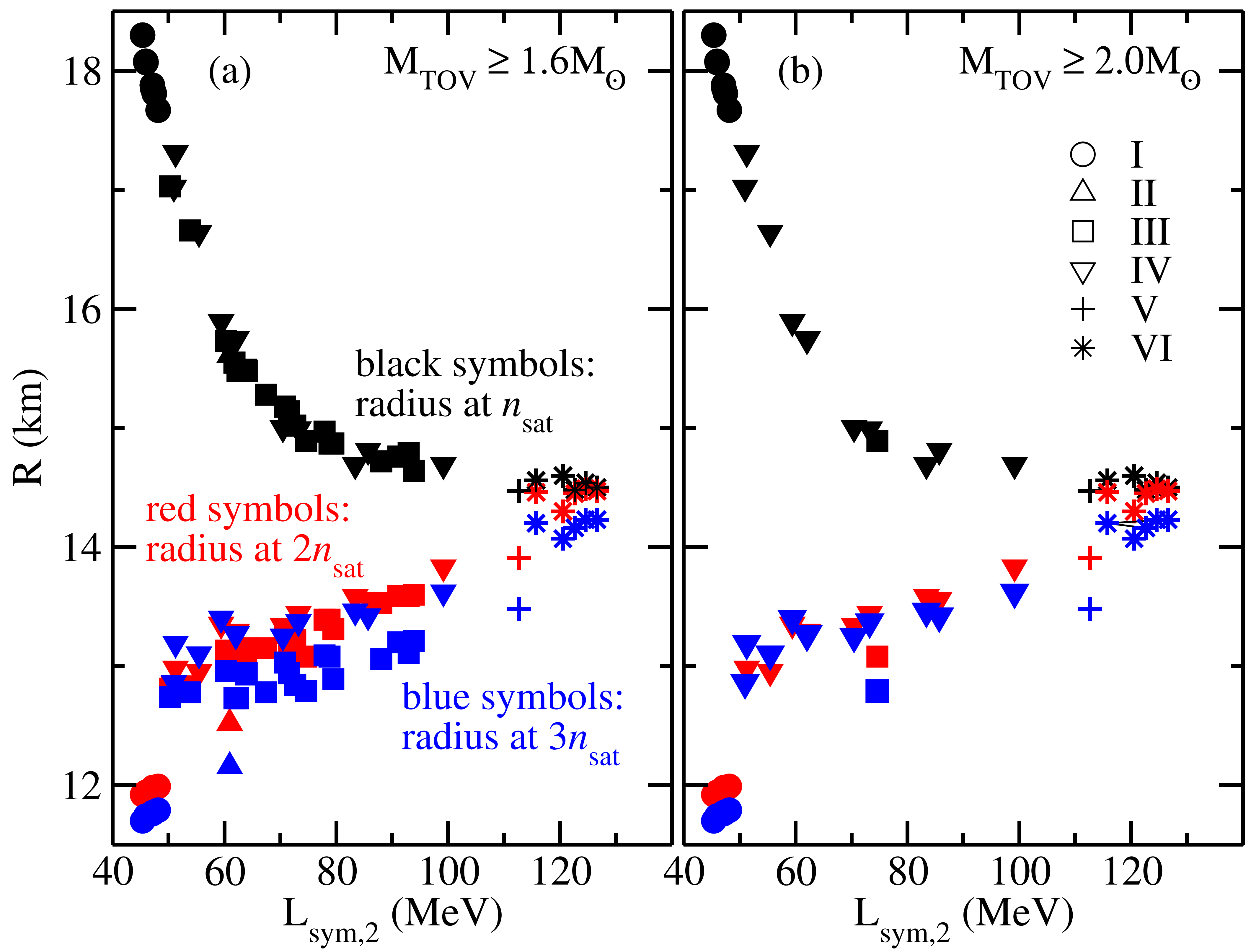
$M_{TOV} \geqslant 1.6M_\odot$	312	77	85	65	72	61	72	45	52	22
$M_{TOV} \geqslant 2.0M_\odot$	198	49	53	44	49	41	49	25	29	12





Neutron star global properties

	D_0/G_0	D_1	G_1	D_2	G_2	D_3	G_3	D_4	G_4	D_{4sym}
Total	374	81	90	66	74	61	74	45	54	22
$M_{TOV} \geqslant 1.6M_\odot$	312	77	85	65	72	61	72	45	52	22
$M_{TOV} \geqslant 2.0M_\odot$	198	49	53	44	49	41	49	25	29	12