FAST/Future Pulsar Symposium 14

Symmetry energy effect on hot nuclear matter and proto-neutron stars

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Outline

- Introduction
- Theoretical framework
- Numerical results
- Summary

Introduction

temperature (T):

0 ~ 100 MeV

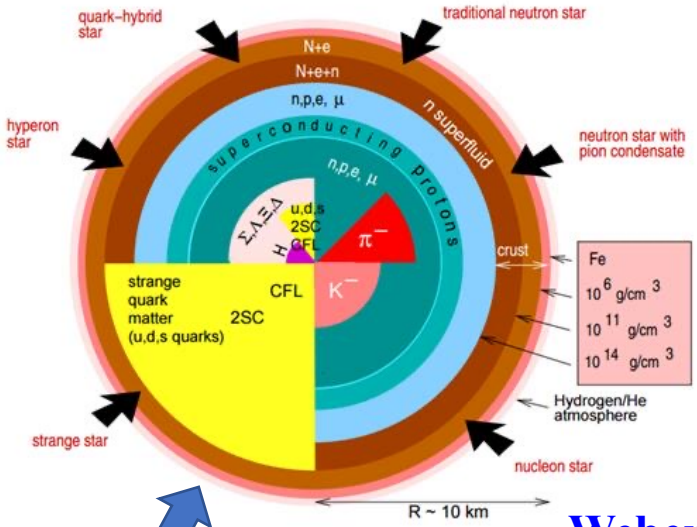
proton fraction (Yp or YL):

0 ~ 0.5

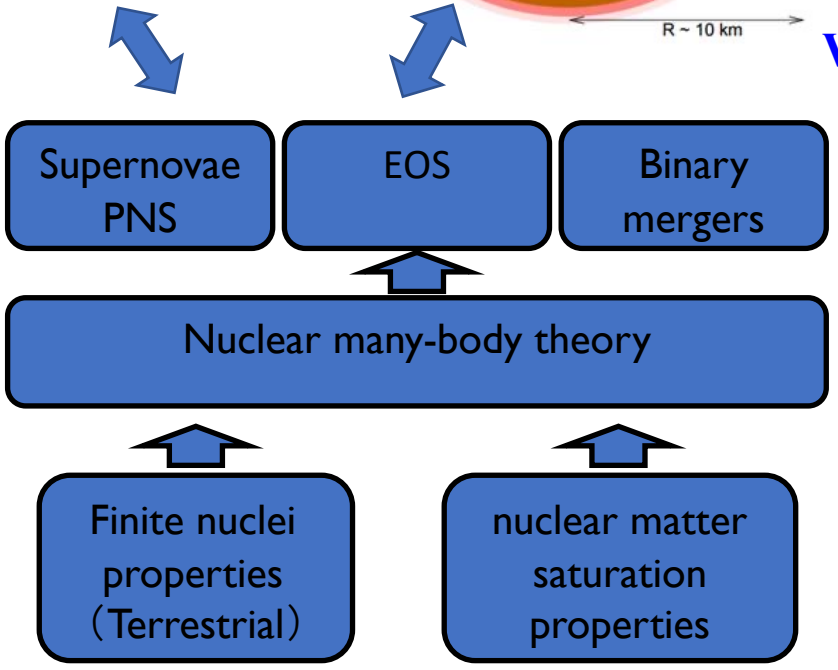
Rapid spin (Period)

10^{-3}-$10^{1.5}$s

Pulsar structures



Weber 2005



Observations and Constraints:

- **Massive neutron stars:**

PSR J1614-2230 $(1.928 \pm 0.0017 M_\odot)$
P. B. Demorest et al., Nature. 467, 108 (2010)

PSR J0384+0432 $(2.01 \pm 0.04 M_\odot)$
E. Fonseca et al., Astrophys. J. 832, 167 (2016)

PSR J0740+6620 $(2.14 \pm 0.10 M_\odot)$
P. J. Antoniadis et al., Science 340, 1233232 (2020)

PSR J2215+5135 $(2.27^{+0.17}_{-0.15} M_\odot)$
M. Linares et al., Astrophys. J. 859, 54 (2018)

- **Mass-radius measurements by NICER:**

PSR J0740+6620

$R = 12.39^{+1.3}_{-1.5}$ km, $M = 2.072^{+0.067}_{-0.066} M_\odot$

$R = 13.70^{+2.7}_{-1.5}$ km, $M = 2.08 M_\odot$

M. C. Miller et al., Astrophys. J. Lett., 887, L24 (2019).
T. E. Riley et al., Astrophys. J. Lett., 887, L21 (2019).

PSR J0030+0451

$R = 12.71^{+1.14}_{-1.19}$ km, $M = 1.34^{+0.15}_{-0.16} M_\odot$

$R = 13.02^{+1.24}_{-1.06}$ km, $M = 1.44^{+0.15}_{-0.14} M_\odot$

M. C. Miller et al., Astrophys. J. Lett., 918, L28 (2021).
T. E. Riley et al., Astrophys. J. Lett., 918, L27 (2021).

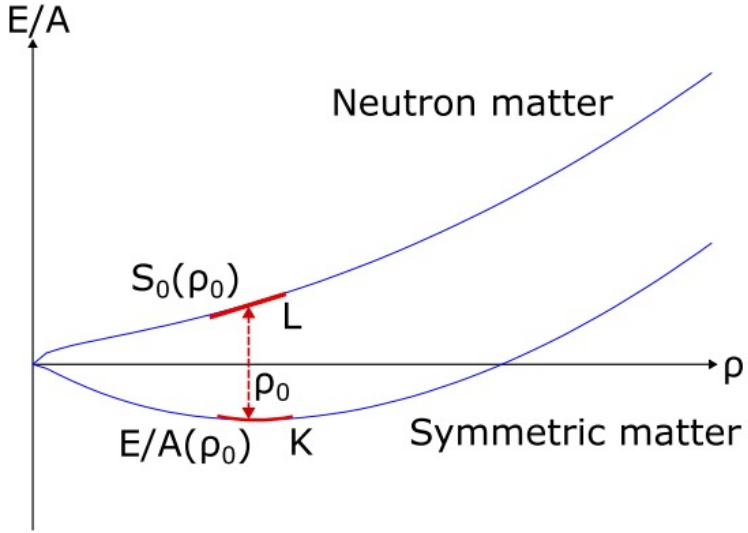
- **NS multimessenger observations:**

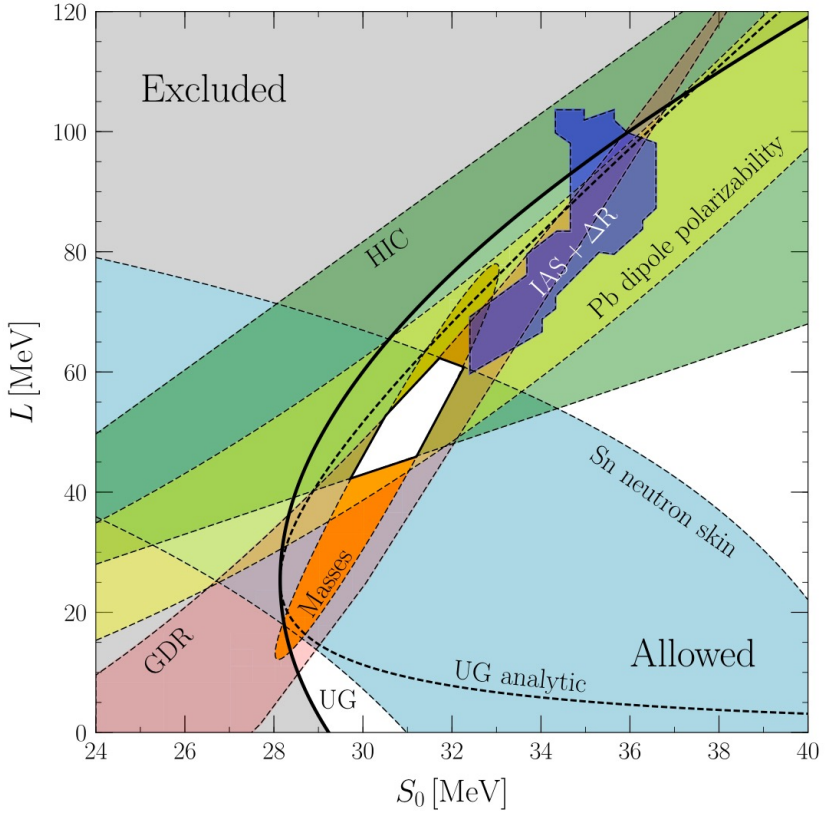
GW170817: Tidal deformability: $\Lambda_{1.4} = 190^{+390}_{-120}$,
Total mass: 1.0-$1.89 M_\odot$,
Radius: 11.9 ± 1.4 km.

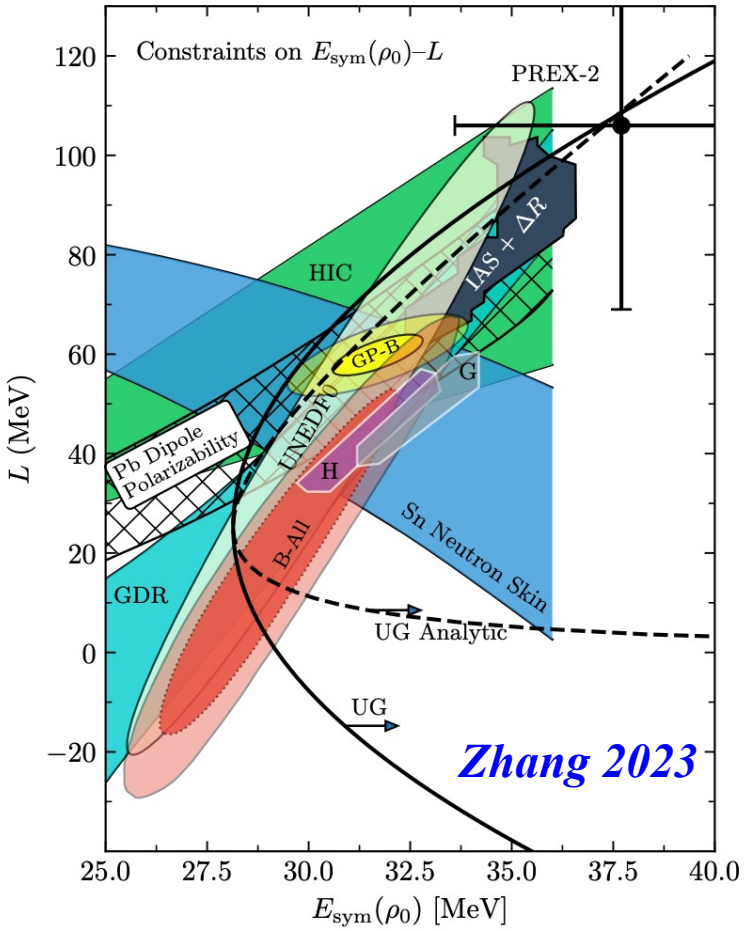
GW190814: 2.6 solar mass object?

Introduction (S and L)

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L(\frac{\rho-\rho_0}{3\rho_0}) + \frac{K_{\rm sym}}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{J_{\rm sym}}{6}(\frac{\rho-\rho_0}{3\rho_0})^3$$







$S(\rho_0) = 31.7 \pm 3.2$ MeV

$L = 58.7 \pm 28.1$ MeV

Oertel 2017

Tews 2017

$S(\rho_0) = 31 \pm 1.3$ MeV

$L = 52.5 \pm 10$ MeV

L(PREX2) = 76~165 MeV

L(CREX) = 0~51 MeV

strong tension between PREX-II and CREX results

Tagami 2022

Theoretical Framework

$$\mathcal{L}_{\mathrm{RMF}} = \sum_{i=p,n} \bar{\psi}_{\mathrm{i}} \left\{ \mathrm{i}\gamma_\mu \partial^\mu - (M + g_\sigma \sigma) \right.$$
$$\left. -\gamma_\mu \left[g_\omega \omega^\mu + \frac{g_\rho}{2} \tau_a \rho^{a\mu} \right] \right\} \psi_i$$
$$+ \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4$$
$$- \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4} c_3 \left(\omega_\mu \omega^\mu \right)^2$$
$$- \frac{1}{4} R^a_{\mu\nu} R^{a\mu\nu} + \frac{1}{2} m_\rho^2 \rho^a_\mu \rho^{a\mu}$$
$$+ \Lambda_{\mathrm{v}} \left(g_\omega^2 \omega_\mu \omega^\mu \right) \left(g_\rho^2 \rho^a_\mu \rho^{a\mu} \right)$$
$$+ \sum_{l=e,\mu} \bar{\psi}_l \left(\mathrm{i}\gamma_\mu \partial^\mu - m_l \right) \psi_l,$$

isothermy,
isentropy,
fixed lepton fractions

$$\mu_n = \mu_p + \mu_e + \mu_{\bar{\nu}_e}$$

$$Y_L = \frac{n_e + n_{\nu_e} + n_\mu + n_{\nu_\mu}}{n_b}$$

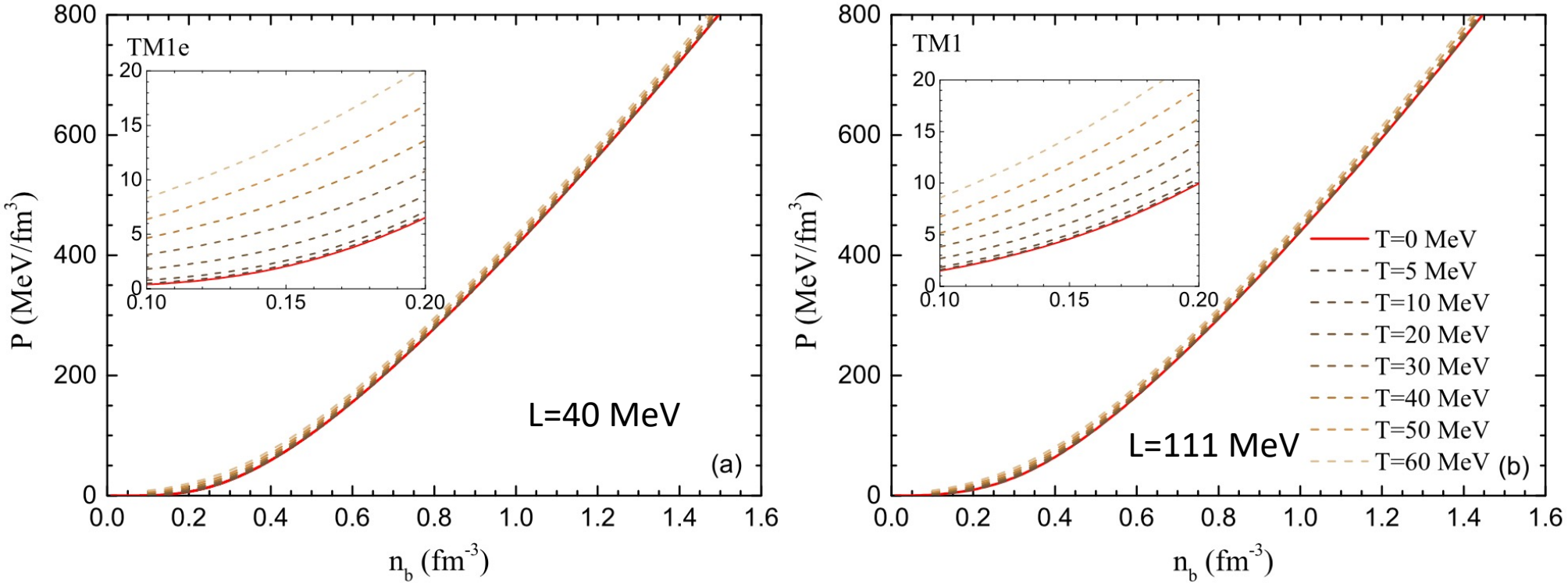
Results (PNS)

isothermy

The EOSs

Model	M	m_σ	m_ω	m_ρ	g_σ	g_ω	g_ρ	g_2 /fm^{-1}	g_3	c_3	Λ_v
TM1	938.000	511.198	783.000	770.000	10.0289	12.6139	9.2644	7.2325	0.6183	71.3075	0
TM1e	938.000	511.198	783.000	770.000	10.0289	12.6139	13.9714	7.2325	0.6183	71.3075	0.0429

With same isoscalar properties



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Results (PNS)

isothermy

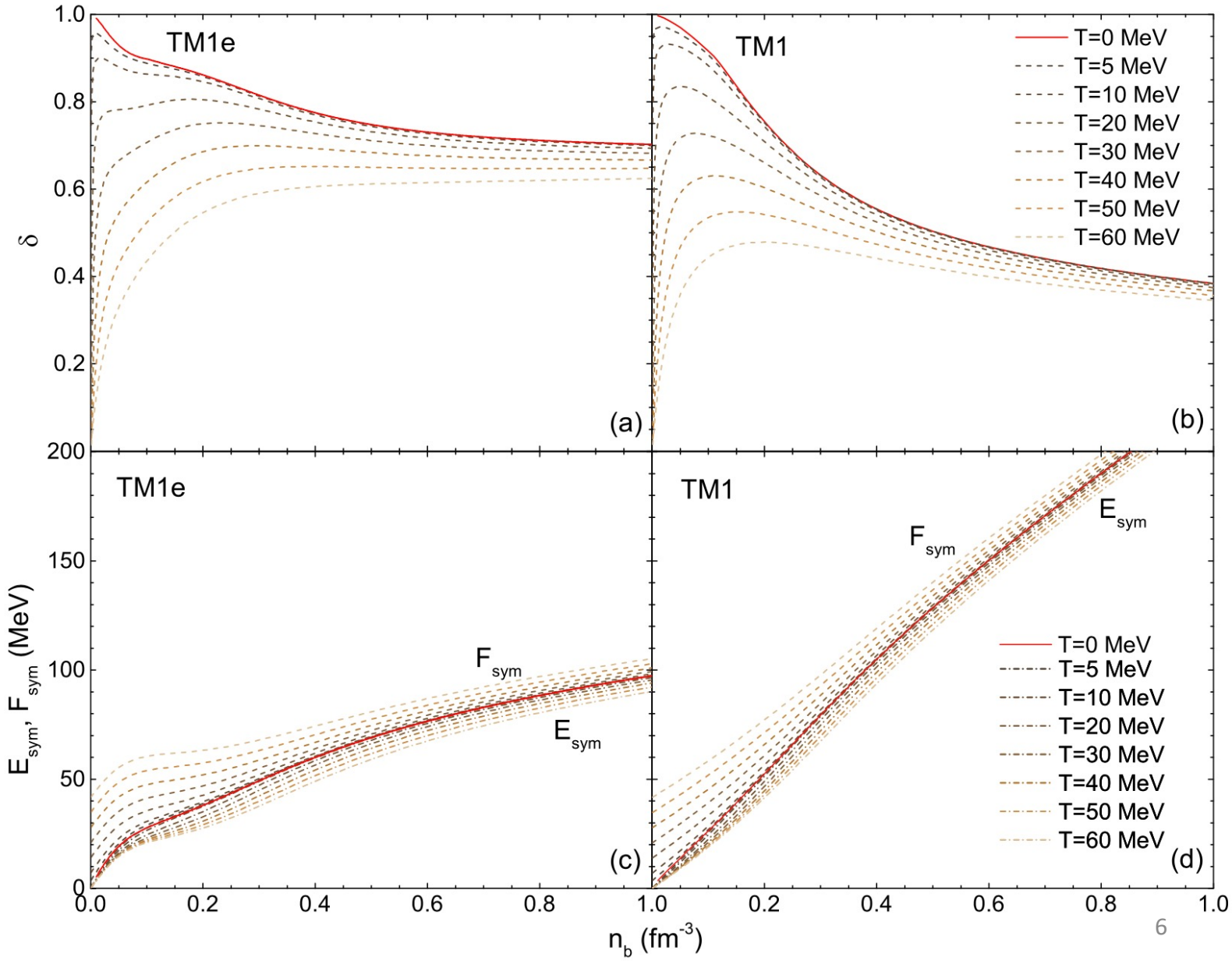
Isospin asymmetry
Symmetry energy
Symmetry free energy

$$\delta = \frac{n_n - n_p}{n_n + n_p}$$

$$f = \varepsilon - Ts$$

$$F_{\mathrm{sym}} = \frac{f}{n_b}(\delta = 1) - \frac{f}{n_b}(\delta = 0)$$

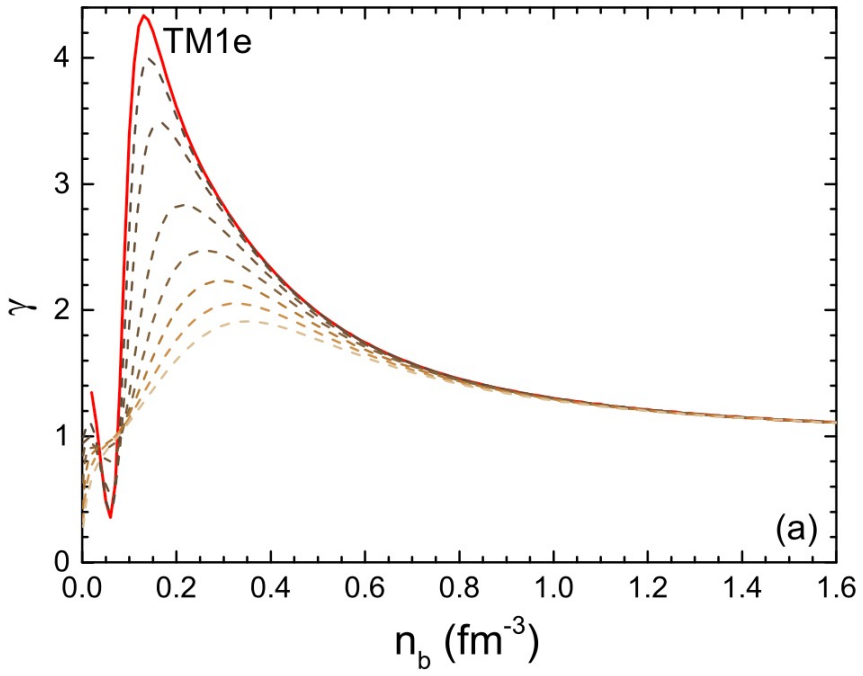
$$E_{\mathrm{sym}} = \frac{\varepsilon}{n_b}(\delta = 1) - \frac{\varepsilon}{n_b}(\delta = 0)$$

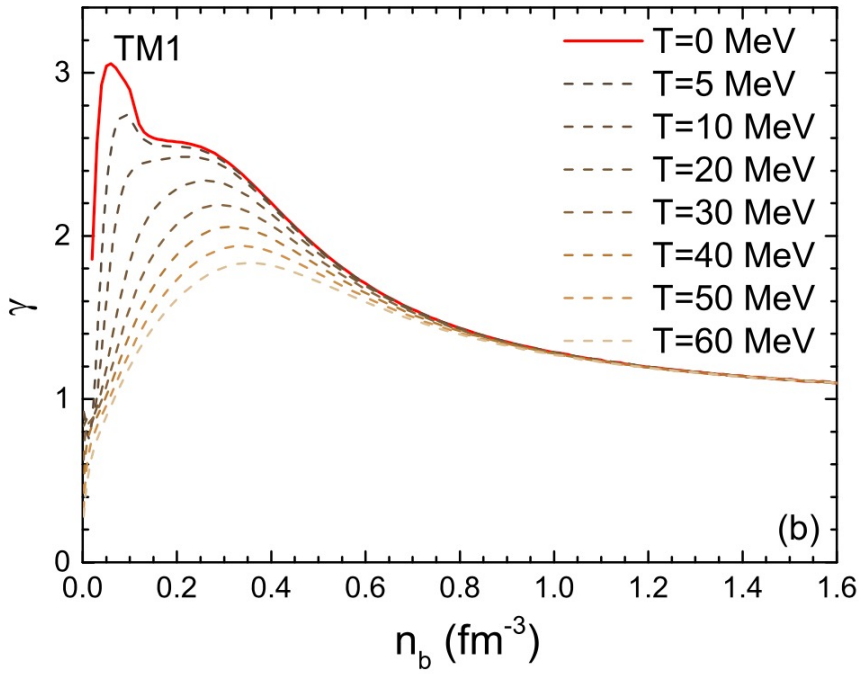


Results (PNS)

isothermy

Polytropic index





T/MeV		M_{max} /$M_\odot$
0	TM1e	2.121
5		2.125
10		2.129
20		2.147
30		2.192

T/MeV		M_{max} /$M_\odot$
0	TM1	2.178
5		2.180
10		2.185
20		2.206
30		2.259

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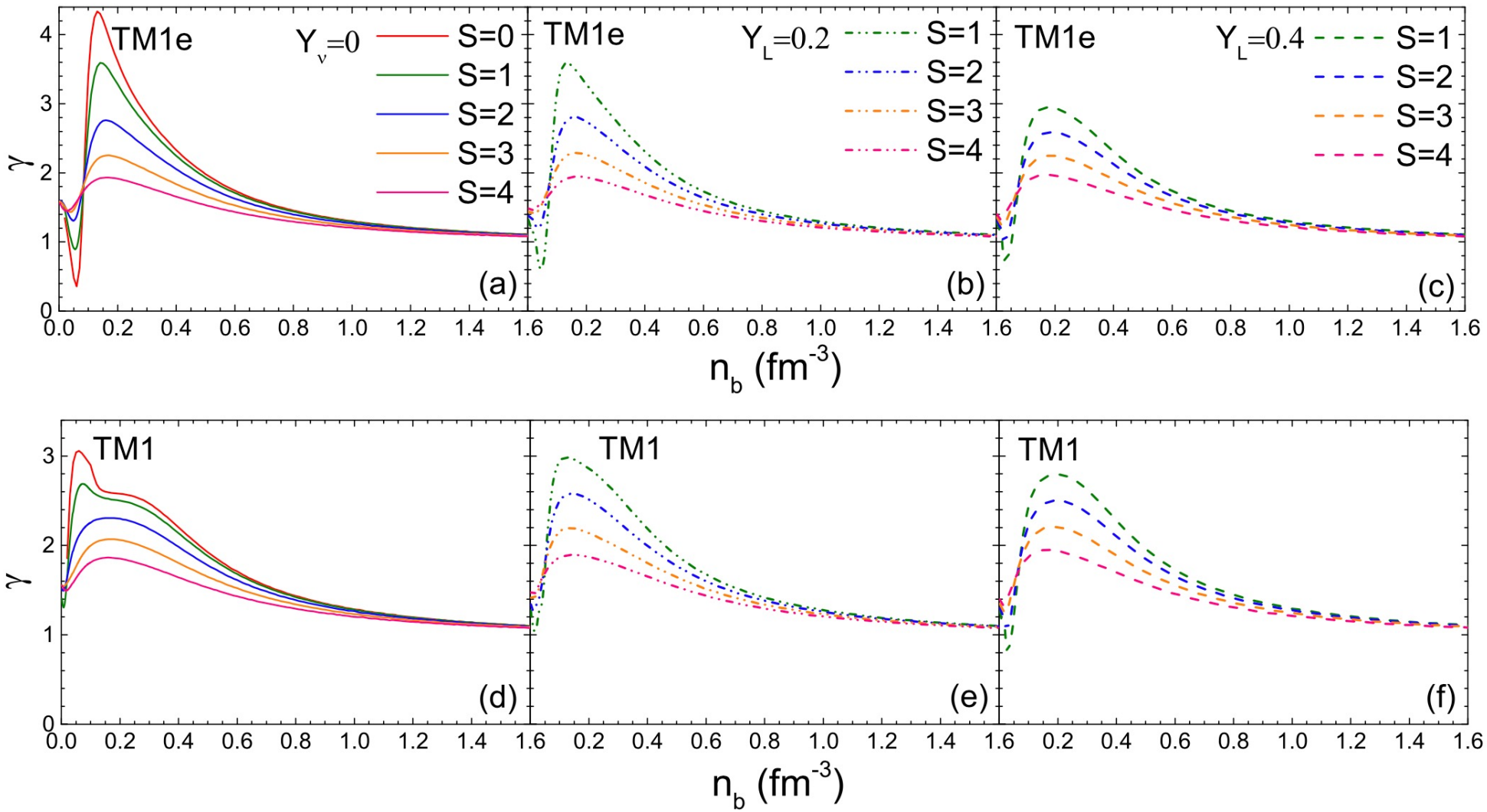
Results (PNS)

isentropy

Polytropic index

TM1e

Y_L	S/k_B	$M_{\max}/M_\odot$
	0	2.121
ν	1	2.140
free	2	2.194
	3	2.296
	1	2.120
0.2	2	2.179
	3	2.281
	1	2.107
0.4	2	2.157
	3	2.230

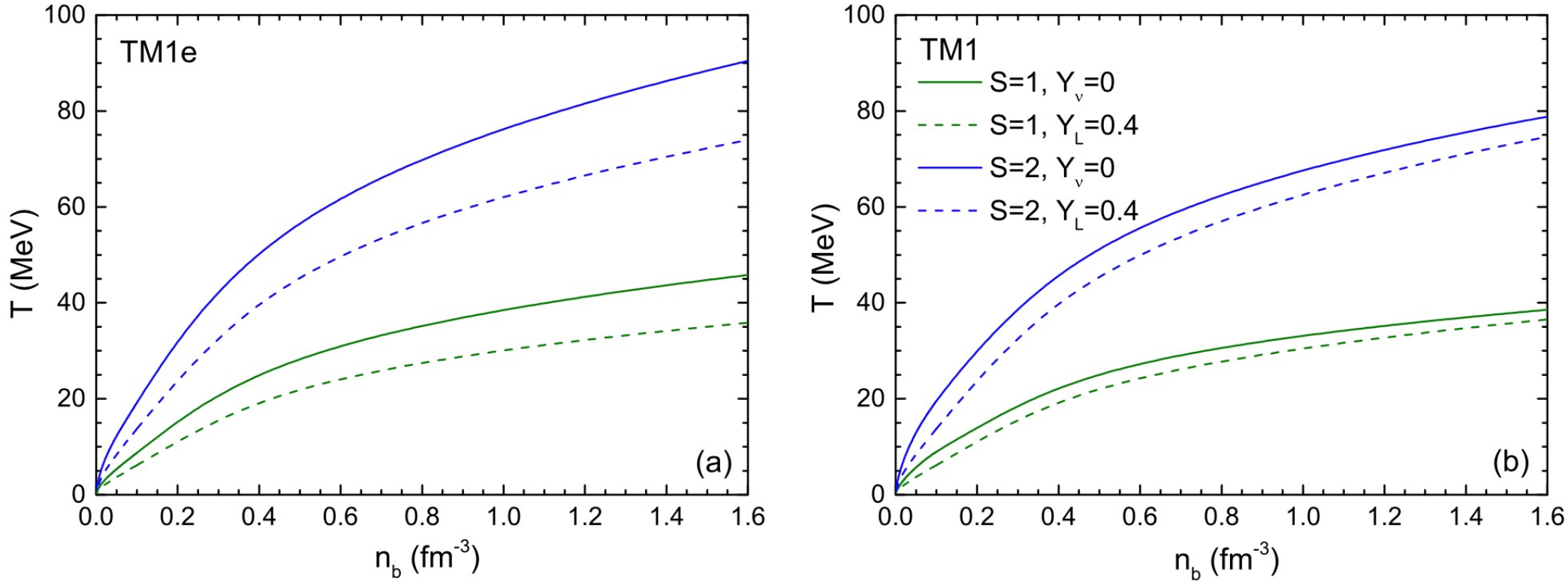


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Results (PNS)

isentropy

Temperature

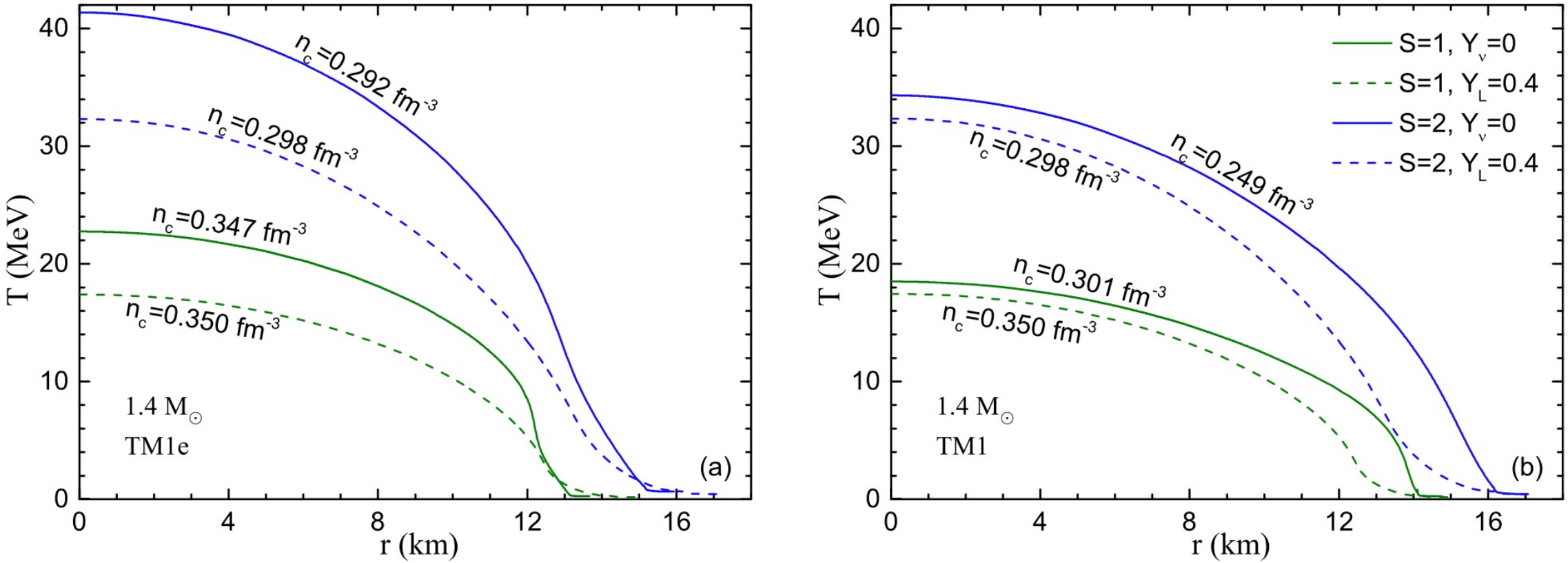


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Results (PNS)

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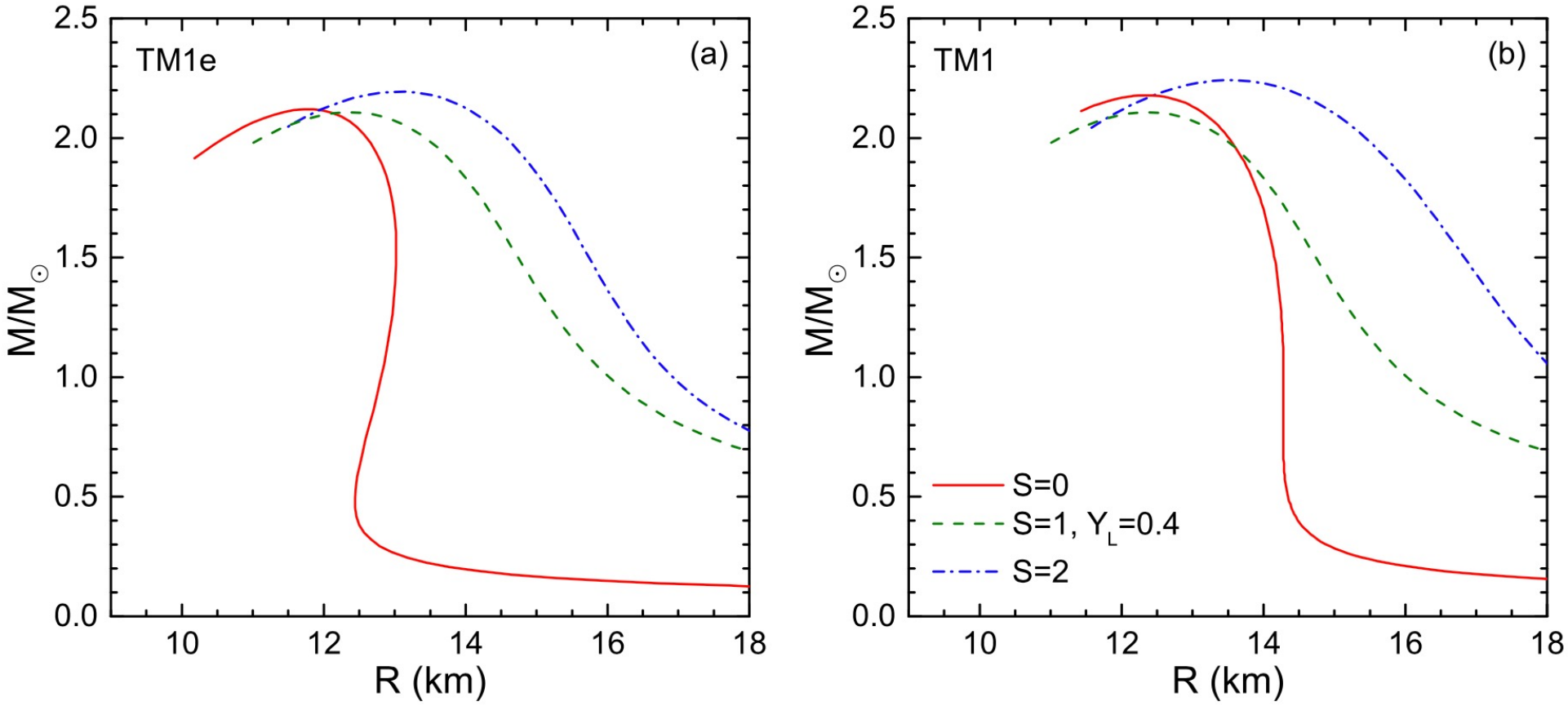
T in the canonical 1.4 $M_\odot$ stars



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Results (PNS)

M-R relations



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Summary and Perspective

- L lessly affect EOS, but affect isospin, Polytropic index, T distribution, more effective with same NS mass

- Finite T affect more at low densities
- NS properties depend on L, more clear at low Yp (YL)

- Any Quantitative relation between γ and Mmax ?

Thanks!

To Do: Quark star, Hybrid star, Strangeon star; Moment of inertia of the crust; Ksym, Qsym