Core-crust transition density with symmetry energy in the nonlinear relativistic Hartree approximation

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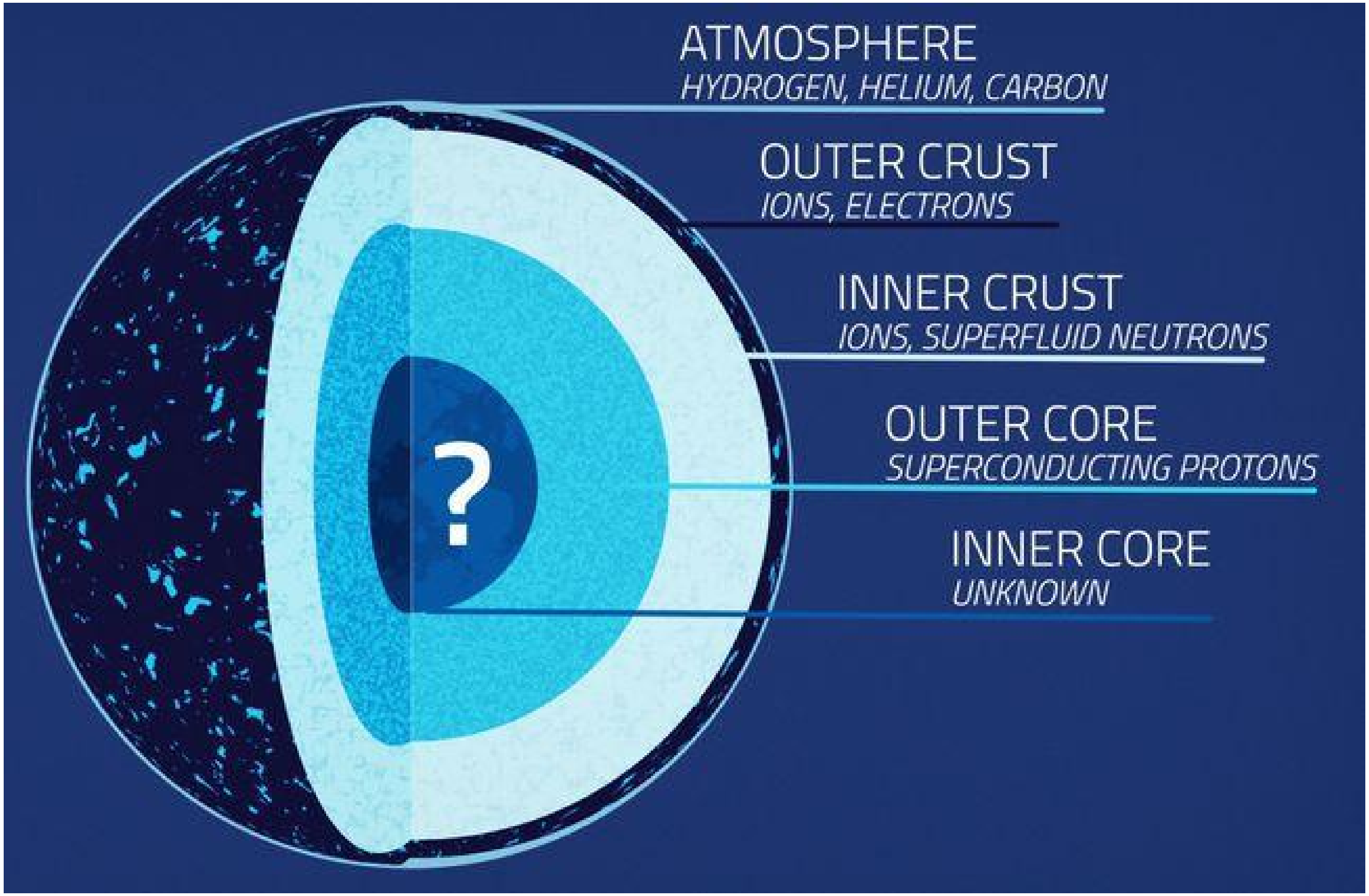
Contents

Core-crust transition density



➢**core-crust transition density**：When the density lower than a specific value, the outer core of neutron star becomes unstable under the density fluctuation.

Core-crust transition density

- The neutron star radius

  M. Fortin, etl. Phys. Rev. C 94 (2016) 035804.

- Pulsar glitches

  J.M. Lattimer, et al., Phys. Rep. 442 (2007) 109.
  N. Chamel, et al., Phys. Rev. C 85 (2012) 035801.
  N. Andersson, et al., Phys. Rev. Lett. 109 (2012) 241103.
  J. Piekarewicz, et al., Phys. Rev. C 90 (2014) 015803.
  S-N. Wei, et al., Chin. Phys. C 42 (2018) 74.

- Crust meltdown in inspiraling binary neutron stars

  Z. Pan, et al., Phys. Rev. Lett. 125 (2020) 201102.

- Asteroseismology from giant magnetar flares

  A.T. Deibel, et al., Phys. Rev. C 90 (2014) 025802.

Core-crust transition density

- Hydrodynamic method: Vlasov equation, Master equation

  Chomaz et al PR389,263(04), Ducoin, et al.NPA 789, 403 (07),
  Zheng & Chen, PRD 85, 043013(12)

- Thermodynamic method: P&μ instability condition

  Douchin & Haensel, PLB 485, 107 (00),
  Li, et al, NPA 699, 493 (02), Kubis, PRC 76, 025801 (07).

- Relativistic RPA: Dyson equation

  Lim &Horowitz, NPA 501, 729(89),
  Carriere, Horowitz, et al, ApJ 593, 463 (03);
  Ma, et al, NPA 686, 173 (01)

No vacuum effect or no self-consistent vacuum treatment

Contents

RRPA method in nonlinear RHA

- The interacting Lagrangian is written as:

$$\mathcal{L}_{\rm int} = \overline{\psi}[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu - g_\rho\boldsymbol{\tau}\cdot\boldsymbol{b}^\mu + \frac{e}{2}(1+\tau_3)A^\mu) - (M - g_\sigma\phi)]\psi + 4g_\rho^2 b_\mu\cdot b^\mu\Lambda_v g_\omega^2\omega_\mu\omega^\mu - U(\phi,\omega),$$

Where

$$U(\phi,\omega) = -\tfrac{1}{2}g_{\sigma\omega}\omega^2\phi^2 + g_2\phi^3/3! + g_3\phi^4/4!$$

The Lagrangian counterterms* to renormalize the infinite nucleon self-energy is

$$\mathcal{L}_{CT} = \sum_{n=1}^{4}\frac{\alpha_n}{n!}\phi^n$$

* S. A. Chin, Ann. Phys. 108: 301 (1977)

RRPA method in nonlinear RHA

$$U(\phi,\omega) = -\tfrac{1}{2} g_{\sigma\omega}\omega^2\phi^2 + g_2\phi^3/3! + g_3\phi^4/4!$$

⇓

$$U^{Ren.}(\phi,\omega) = -\frac{1}{2} g_{\sigma\omega}\omega^2\phi^2 + \frac{1}{3!} g_2\phi^3 + \frac{1}{4!} g_3\phi^4 + \frac{1}{(8\pi)^2}\Big[-\big(g_2\phi + \frac{g_3\phi^2}{2}\big)\tilde{m}_\sigma^2$$
$$+ \frac{1}{12}\frac{g_2^4\phi^4}{\tilde{m}_\sigma^4} + \big(\tilde{m}_\sigma^2 + g_2\phi + \frac{g_3\phi^2}{2}\big)^2 \ln\Big(1 + \frac{g_2\phi + \frac{g_3\phi^2}{2}}{\tilde{m}_\sigma^2}\Big)$$
$$- \frac{3}{2}\big(g_2\phi + \frac{g_3\phi^2}{2}\big)^2 - \frac{(g_2\phi)^2}{3\tilde{m}_\sigma^2}\big(g_2\phi + \frac{3g_3\phi^2}{2}\big)\Big],$$

where $\tilde{m}_\sigma^2 = m_\sigma^2 - g_{\sigma\omega}\omega^2$.

* D. B. Serot and J. D. Walecka, Adv. Nucl. Phys. 16: 1 (1986)

RRPA method in nonlinear RHA

- The interacting polarization is determined through the Dyson equation :

$$\widetilde{\Pi}_L = \Pi_L + \widetilde{\Pi}_L D_L \Pi_L$$

$$\widetilde{\Pi}_L = (1 - D_L \Pi_L)^{-1} \Pi_L$$

Dielectric function: $\epsilon_L = \det(1 - D_L \Pi_L)$

- The transition density ρ_t, the largest density determined by

$$\epsilon_L = \det[1 - D_L(q)\Pi_L(q, q_0 = 0)] \leq 0,$$

RRPA method in nonlinear RHA

$$\Pi_L = \begin{pmatrix} \Pi^e_{00D} & 0 & 0 & 0 \\ 0 & \Pi^n_{sD} + \Pi^p_{sD} & \Pi^p_m & \Pi^n_m \\ 0 & \Pi^p_m & \Pi^p_{00D} & 0 \\ 0 & \Pi^n_m & 0 & \Pi^n_{00D} \end{pmatrix}$$

$$\Pi_L = \begin{pmatrix} \Pi^e_{00D} + \Pi^e_{00f} & 0 & 0 & 0 \\ 0 & \Pi^n_{sD} + \Pi^p_{sD} + \Pi^n_{sf} + \Pi^p_{sf} & \Pi^p_m & \Pi^n_m \\ 0 & \Pi^p_m & \Pi^p_{00D} + \Pi^p_{00f} & 0 \\ 0 & \Pi^n_m & 0 & \Pi^n_{00D} + \Pi^n_{00f} \end{pmatrix}$$

$$\Pi^0_{sf} = \frac{1}{\pi^2} \sum_{i=p,n} [\frac{m_\sigma^2 - q^2}{8} - \frac{3}{4}\int_0^1 dx(M_i^{*2} + x(x-1)q^2) ln \frac{x(x-1)q^2 + M_i^{*2}}{x(x-1)m_\sigma^2 + M_i^2}$$

$$- \frac{3}{4}\int_0^1 dx(M_i^{*2} - M_i^2) ln(1 + \frac{x(x-1)m_\sigma^2}{M_i^2}) - \frac{1}{2}(3M_i\Sigma_s - \frac{9}{2}\Sigma_s^2)]$$

where $\Sigma_s = M_i - M_i^*$.

Renormalization at $q^2 = 0$, m_σ^2?

RRPA method in nonlinear RHA

$$D_L^0 = \begin{pmatrix} d_g & 0 & -d_g & 0 \\ 0 & -d_s^0 & 0 & 0 \\ -d_g & 0 & d_g + d_v^0 + d_\rho^0 & d_v^0 - d_\rho^0 \\ 0 & 0 & d_v^0 - d_\rho^0 & d_v^0 + d_\rho^0 \end{pmatrix}$$

⇓

$$D_L = \begin{pmatrix} d_g & 0 & -d_g & 0 \\ 0 & -d_\sigma & \mathrm{d}_{\sigma\omega} & \mathrm{d}_{\sigma\omega} \\ -d_g & \mathrm{d}_{\sigma\omega} & d_g + d_V + 2\mathrm{d}_{\omega\rho} & d_I \\ 0 & \mathrm{d}_{\sigma\omega} & d_I & d_V - 2\mathrm{d}_{\omega\rho} \end{pmatrix};$$

with $d_V = d_\omega + d_\rho$, and $d_I = d_\omega - d_\rho$.

Contents

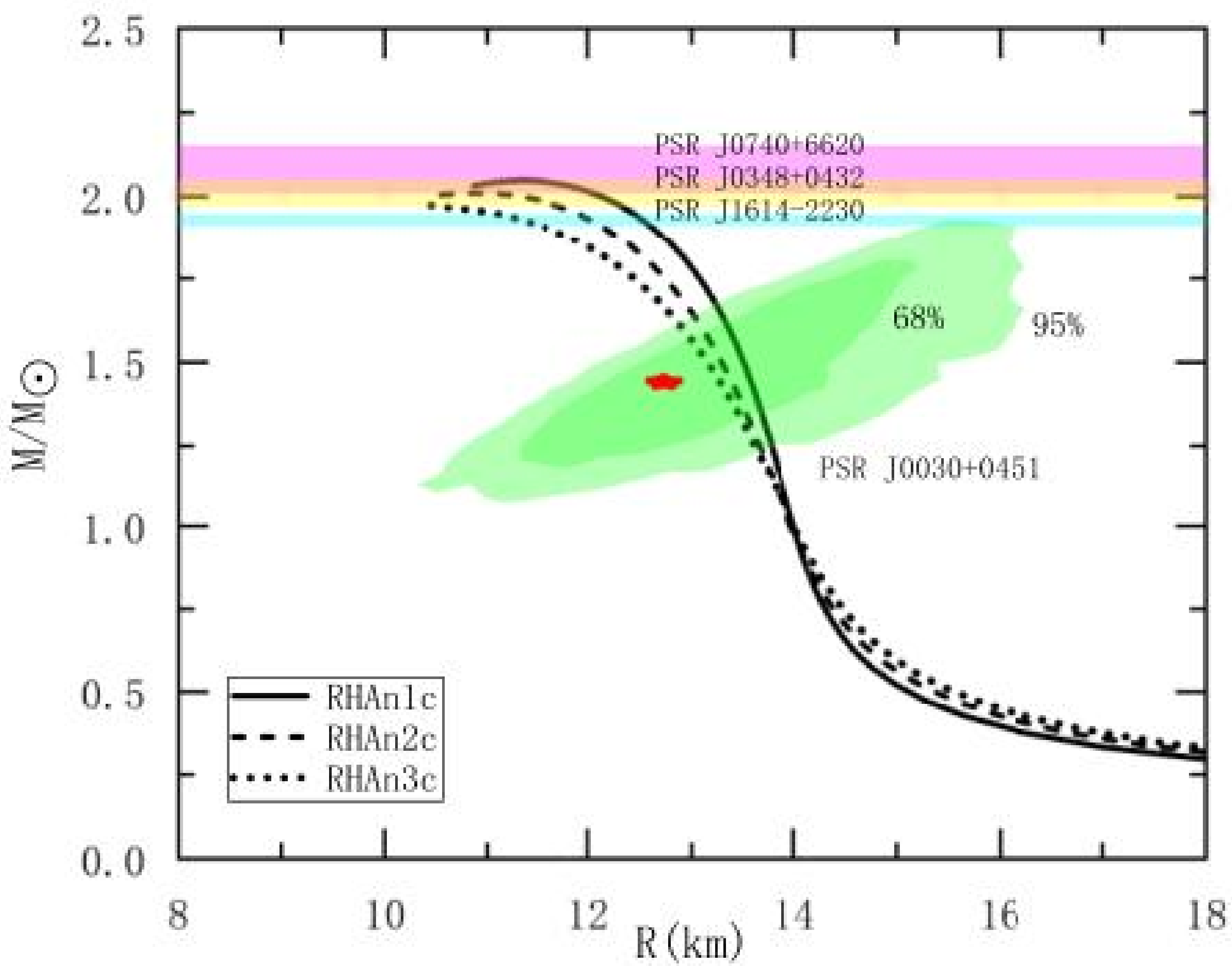
1. Core-crust transition density
2. RRPA method in nonlinear RHA
3. Results and discussion
4. Summary

Results and discussion

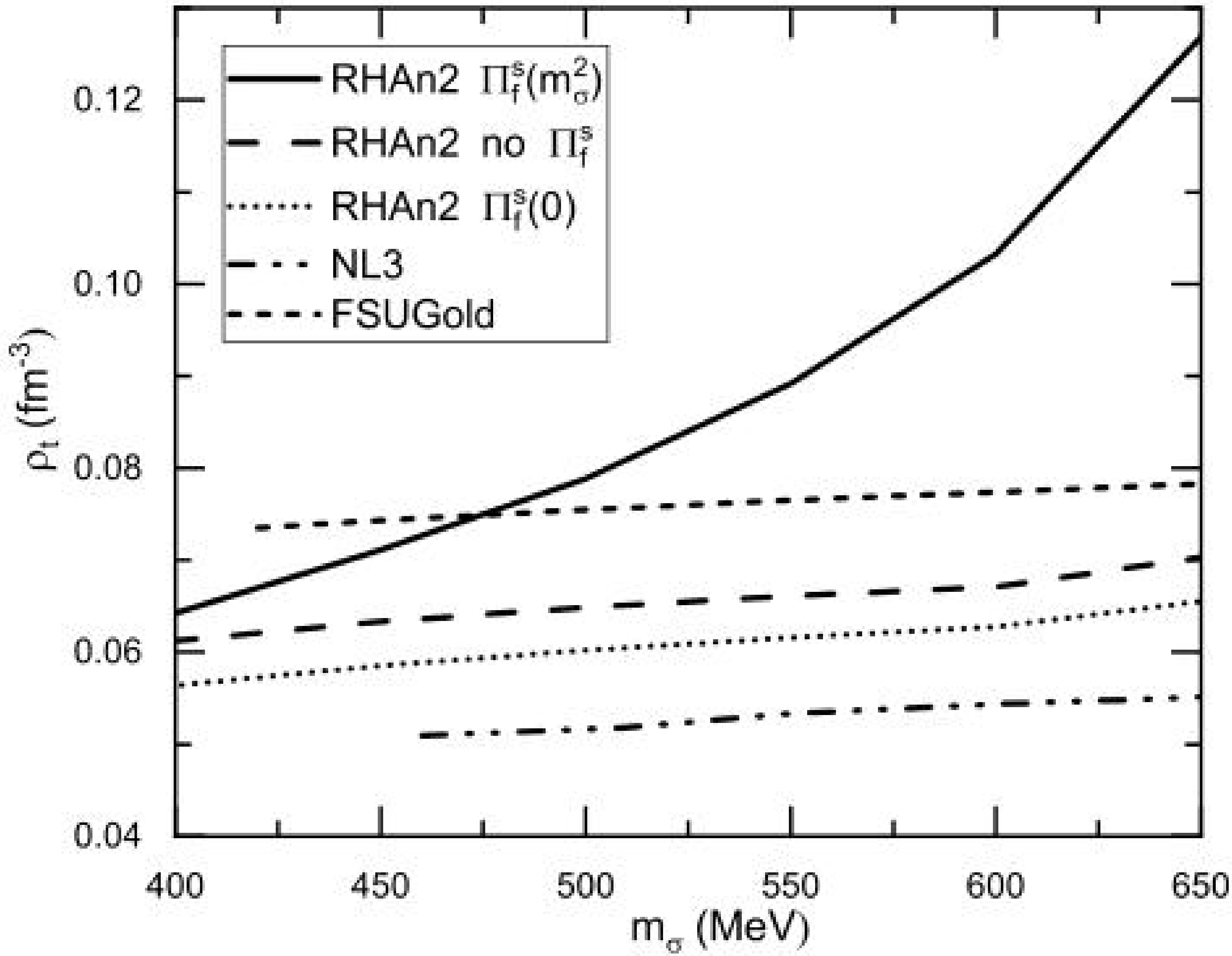
Model	g_σ	g_ρ	g_ω	g_2	g_3	$g_{\sigma\omega}$	c_3	M^*/M	ρ_t	κ	$R_{1.4}$	$M_{NS}^{max}/M_\odot$	$M_{NS}^{max*}/M_\odot$
RHAn1c	7.72	4.03	8.45	25.19	21.16	0.5	0.0	0.782	0.081	300	13.62	2.048	2.03
RHAn2c	7.59	4.06	7.96	35.58	39.24	0.5	-4.3	0.800	0.081	270	13.44	2.012	1.91
RHAn3c	7.47	4.10	7.39	51.11	88.90	7.0	-9.0	0.820	0.079	240	13.35	1.975	1.72

: Main parameters of RHAnc Models and properties of nuclear matters and neutron stars. M_{NS}^{max*} is the maximum neutron star mass in RHAn Models without $g_{\sigma\omega}$. The masses of σ, ω, and ρ mesons are 512, 783, and 770 MeV, respectively. The saturation density $\rho_0 = 0.16 fm^{-3}$ and binding energy per nucleon $E_b = -16$ MeV at saturation. The transition density ρ_t, incompressibility κ, and radius $R_{1.4}$ of $1.4M_\odot$ star are in units of fm^{-3}, MeV, and km, respectively.

Results and discussion



Results and discussion



Results and discussion

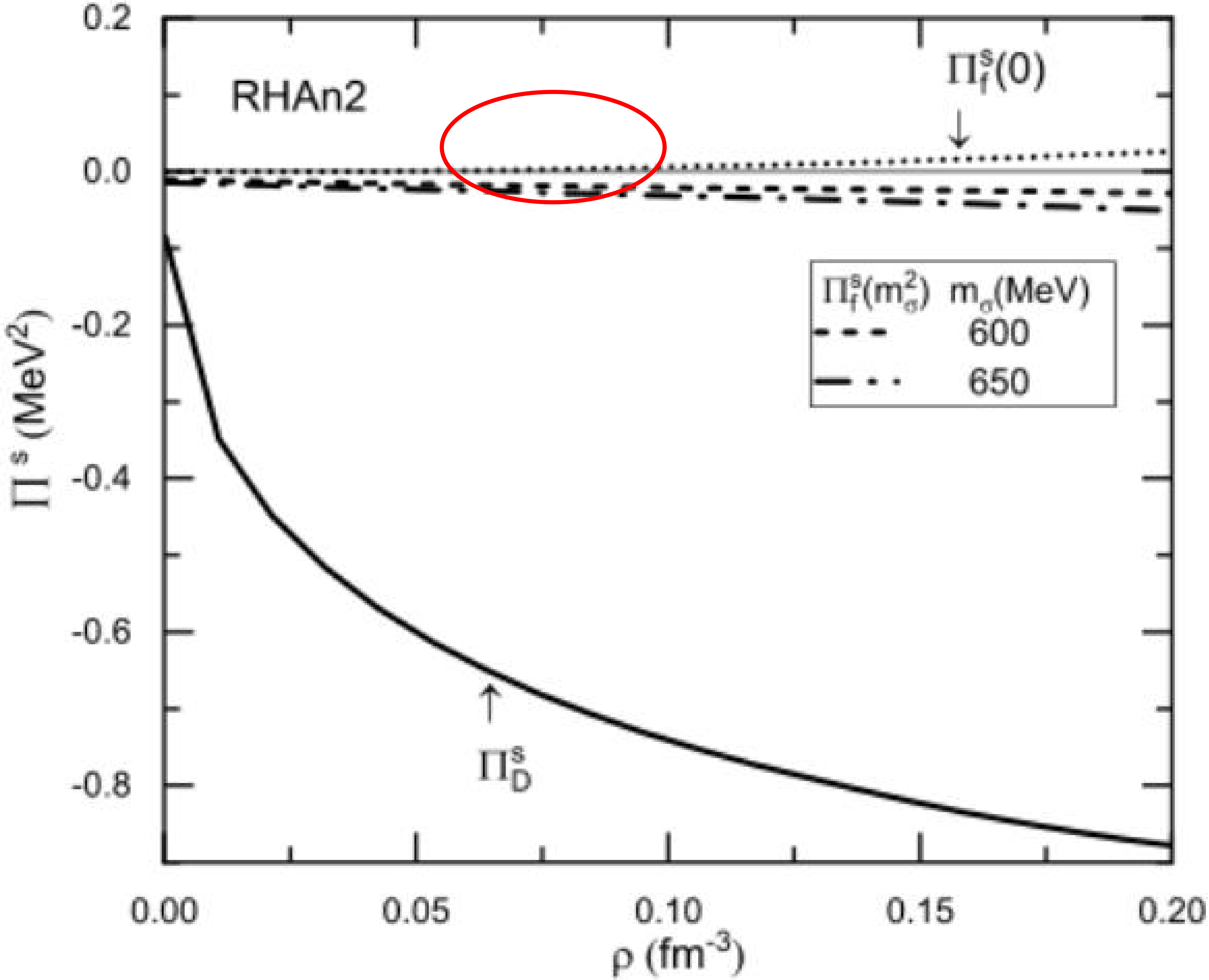
- A simplified ϵ_L by neglecting the Coulomb interaction , photon polarization and the crossing coupling terms

$$\epsilon_L = [1 + d_s(\Pi_D^s + \Pi_f^s)] \cdot [1 + 4d_\omega d_\rho \Pi_L^2 + 2(d_\omega + d_\rho)\Pi_L] - 4(1 + 2d_\rho \Pi_L) d_s d_\omega \Pi_M^2,$$

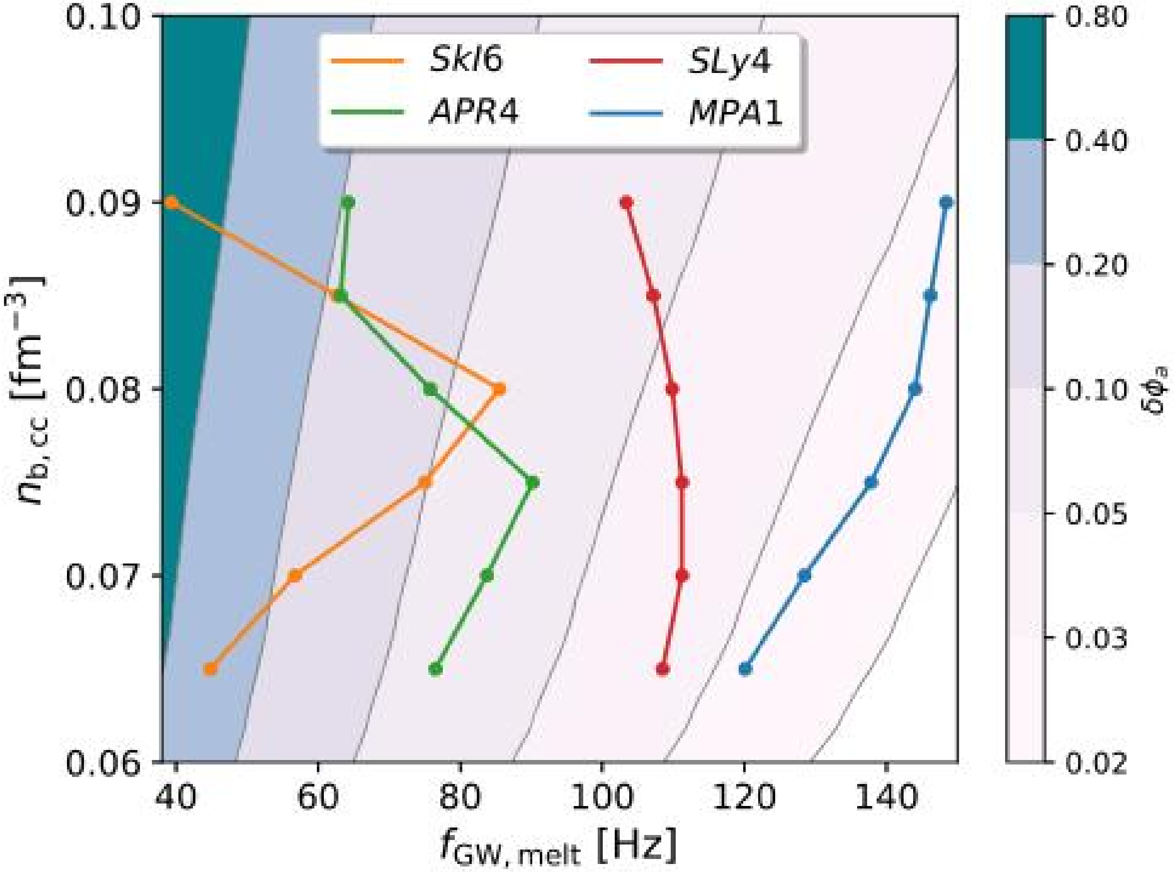
- The difference between $\Pi_f^s(q^2)$ at q^2=0 and m_σ^2 is not small, their effects on the ρ_t depart in sharp contrast.

- $\Pi_f^s(m_\sigma^2)$, which is of the same sign of Π_D^s, shifts the zero point of the dielectric function to a larger density, that is, the transition density ρ_t grows clearly with the rise of m_σ.

Results and discussion



Results and discussion



Z. Pan, et al., Phys. Rev. Lett. 125 (2020) 201102.

The crust melting induced phase change $\delta\phi_a$ in GWs of a BNS merger with each star of M*=1.3 /M ☉ and R=12.5/11.3/11.7 /12.7 km for the EOS SkI6/APR4/SLy4/MPA1. The core-crust transition density is $n_{b;cc}$.

Results and discussion

- The fraction of the crustal moment of inertia ΔI/I can be derived as*:

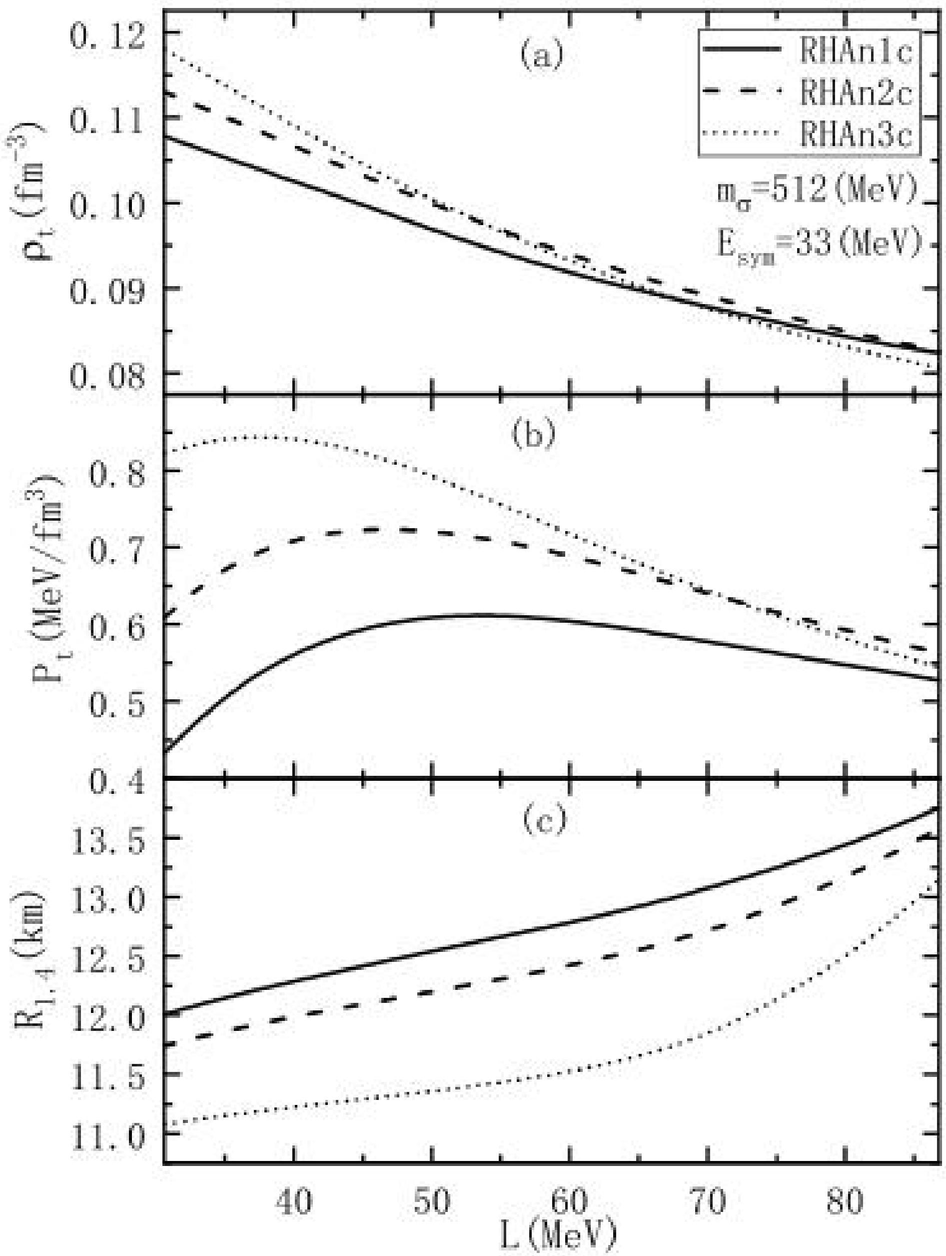
$$\frac{\Delta I}{I} \simeq \frac{28\pi P_t R^3}{3M_{NS} \cdot c^2} \frac{(1 - 1.67\beta - 0.6\beta^2)}{\beta} \times [1 + \frac{2P_t(1 + 5\beta - 14\beta^2)}{\rho_t M c^2 \beta^2}]^{-1}, \quad (7)$$

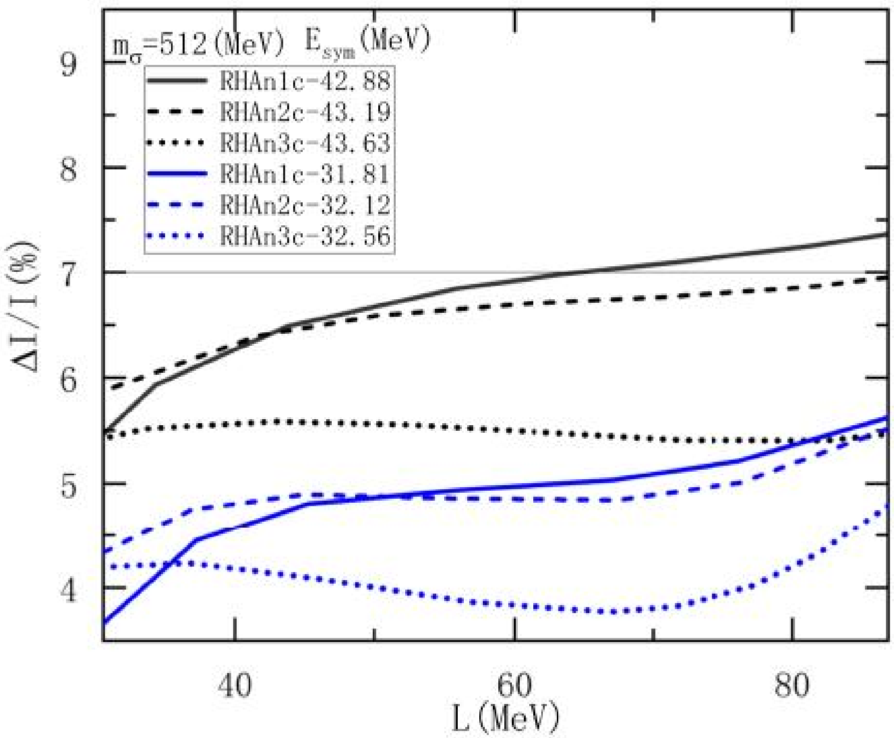
where ΔI is the crustal moment of inertia, I is the total moment of inertia, $\beta = GM_{NS}/Rc^2$ is the compactness parameter, and M_{NS} and R are the neutron star mass and radius, respectively.

Reproducing the pulsar glitch condition: ΔI/I>=7%

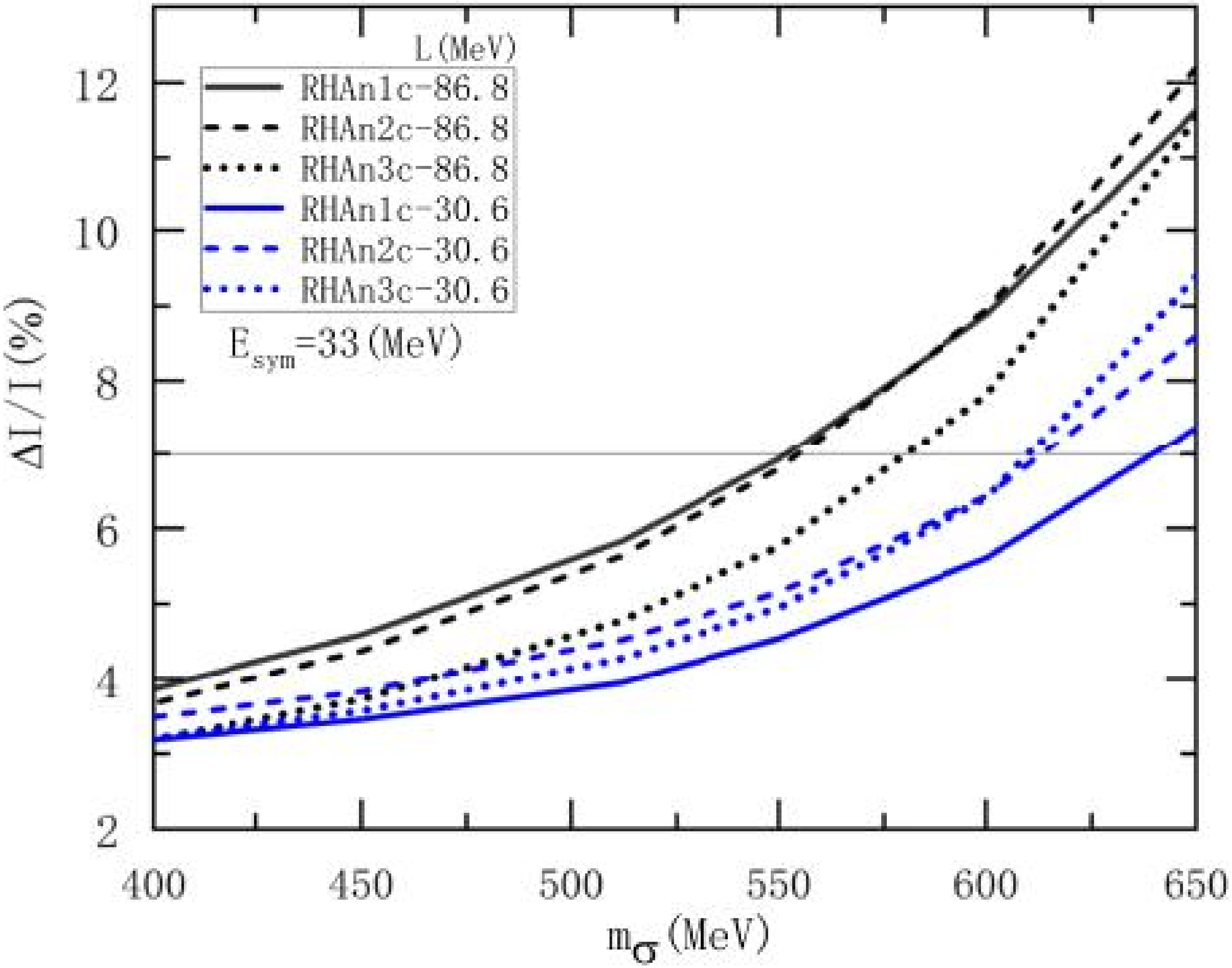
* J. M. Lattimer and M. Prakash. Phys. Rep., 333: 121 (2000)

Results and discussion





Results and discussion



Contents

Summary

- A strong correlation between m_σ and ρ_t overwhelming the uncertainty of the nuclear EOS in the RHAn models;

- Our research indicates that merely adjusting the symmetry energy and/or slope within reasonable regions is difficult to achieve $\Delta I/I \geq 7\%$; Increasing m_σ makes it easier to achieve this goal.

- The nonlinear RHA models generally consistent with astrophysical observations and can be further improved.

Thank you ！