Neutron star matter EOS in RMF with multi-body couplings

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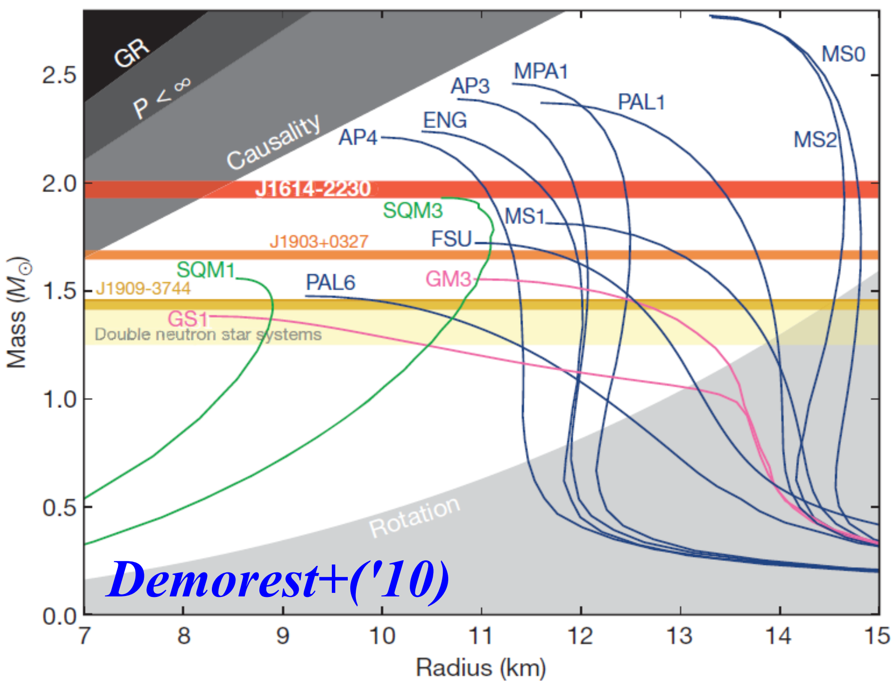
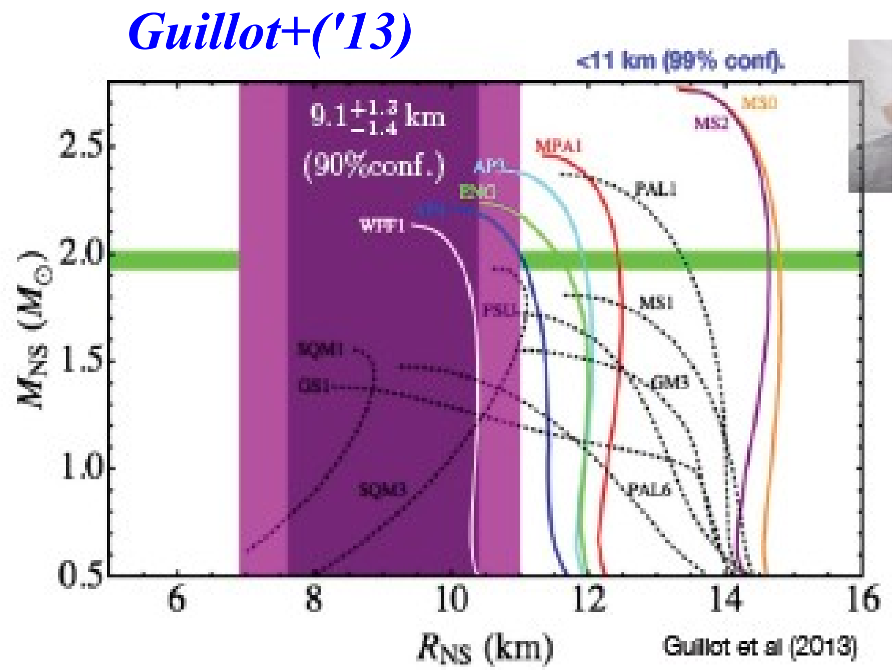
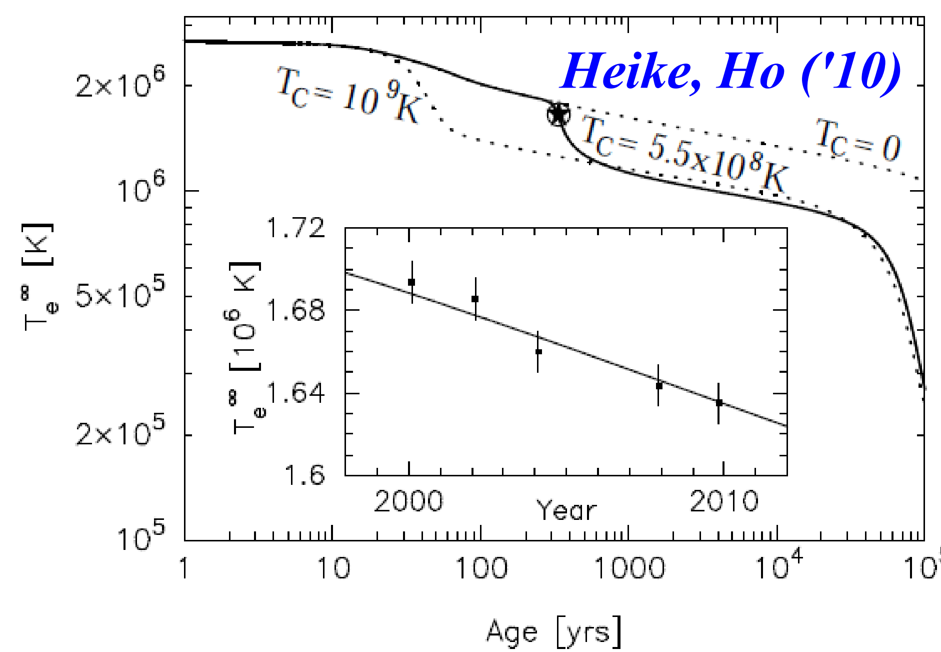
Current Big Puzzles of NS

- **Massive NS puzzle (2 Msun NS puzzle), Compact NS puzzle (9 km NS puzzle), Rapid NS cooling puzzle (CasA puzzle)**

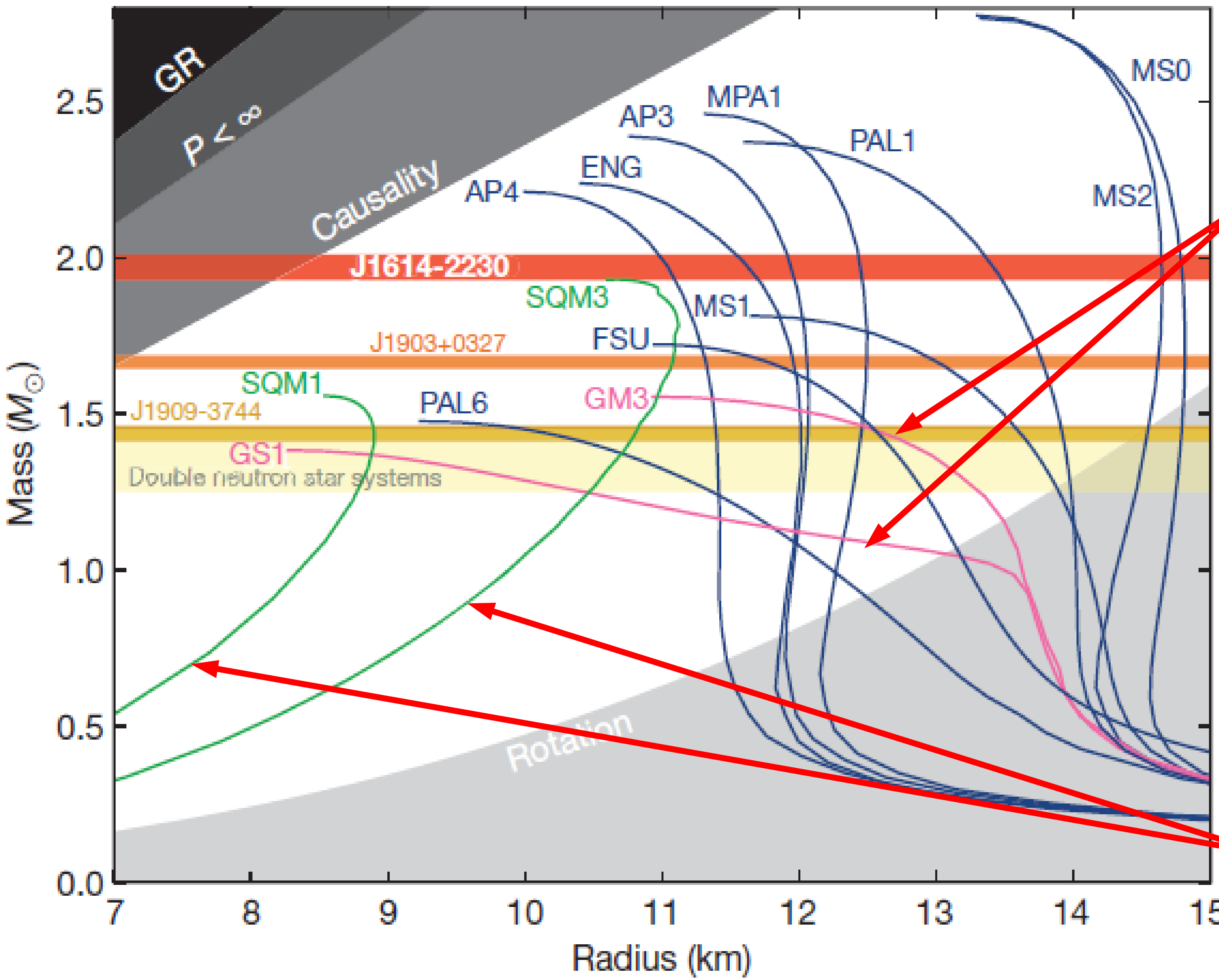






$1.97 \pm 0.04\ M_{\odot}$ Neutron Star

Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



EOS with hyperons or Kaons

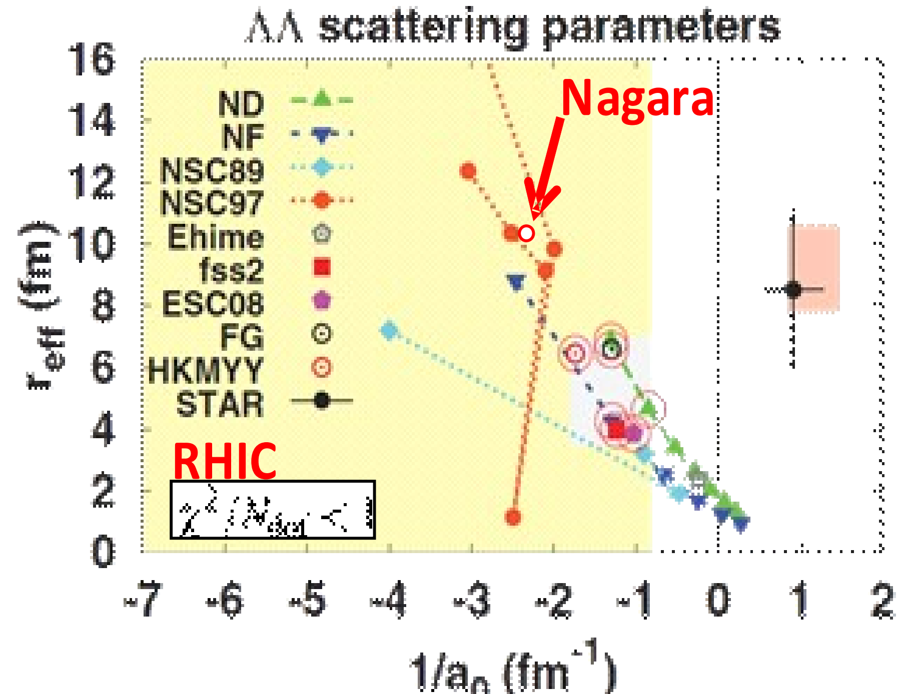
Quark matter EOS

Three Baryon Force (3BF)

- Three-Baryon Force (3BF)
  - 3NF is necessary to reproduce (ρ_0, E/A) in most of ab initio cal.
  - 3BF incl. YNN, YYN and YYY should exist and contribute to EOS (Nishizaki, Takatsuka, Yamamoto ('02))
- "Ab initio" EOS with 3NF
  - FP, APR, DBHF, G-matrix (MPP, Chiral EFT), Variational (Togashi et al.), ….
- Other recent approaches
  - Quark-Meson Coupling model (Miyatsu et al., Thomas)
  - Nπ FRG (Weise)

3BF including Hyperons

- **Bare 3BF including hyperons (YNN, YYN, YYY)**
  - **Chiral EFT, Multi-Pomeron exch., Quark Pauli, Lattice 3BF, SJ, ..**
    Kohno('10); Heidenbauer+('13); Yamamoto+('14); Nakamoto; Doi+(HALQCD,'12); Tamagaki('08); …
  - **Caveat: Missing data**



- **Alternative method: "Ab initio" Nucl. Matter EOS + Y phen.**
  - **Fit "Ab initio" EOSs in a phen. model,**
  - **Include hyperons, and explain hypernuclear data.**

We fit ab initio EOS in RMF with multi-body couplings, and introduce hyperons.

Relativistic Mean Field with Multi-body couplings

σωρ model +std. non-linear terms + multi-body couplings

$$\mathcal{L}_N = \bar{\psi}\left(i\gamma^\mu \partial_\mu - M_N - U_s - \gamma^\mu U_\mu\right)\psi + \mathcal{L}_{\sigma\omega\rho}$$

$$\mathcal{L}_{\sigma\omega\rho} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}R_{\mu\nu}\cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho}$$

$$U_s = -g_\sigma\,\sigma\,[1 + r_{\sigma\sigma}(1-\sigma/f_\pi)] + g_\sigma\omega^\mu\omega_\mu/f_\pi\,[r_{\omega\omega} + r_{\sigma\omega\omega}(1-\sigma/f_\pi)]$$

$$U_\mu = g_\omega\,\omega_\mu\,[1 - r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2] + g_\rho\,\tau\cdot R_\mu\,[1 - r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2]$$

$$\mathcal{V}_{\sigma\omega\rho} = \frac{1}{2}m_\sigma^2\sigma^2 - a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma4}\left(\sigma^4 - 4f_\pi\sigma^3\right) - \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu[1 - c_{\sigma\omega}\sigma/f_\pi] - \frac{1}{4}c_{\omega4}(\omega^\mu\omega_\mu)^2 - \frac{1}{2}m_\rho^2 R^\mu\cdot R_\mu[1 - c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu\omega_\mu/f_\pi^2] - \frac{1}{4}c_{\rho4}(R^\mu\cdot R_\mu)^2$$

$$f_{\log}(x) = \log(1-x) + x + \frac{1}{2}x^2 \qquad a_\sigma = f_\pi^2(m_\sigma^2 - m_\pi^2)/2 - f_\pi^4 c_{\sigma4}$$

RMF with many-body coupling

- **Naive dimensional analysis (NDA) and naturalness**

  Manohar, Georgi ('84)

  The vertex is called "natural" if C ~ 1.

$$L_{\rm int} \sim (f_\pi \Lambda)^2 \sum_{l,m,n,p} \frac{C_{lmnp}}{m!\,n!\,p!} \left(\frac{\bar{\psi}\Gamma\psi}{f_\pi^2 \Lambda} \right)^l \left(\frac{\sigma}{f_\pi} \right)^m \left(\frac{\omega}{f_\pi} \right)^n \left(\frac{R}{f_\pi} \right)^p$$

  → Consistent with the idea that the vertex is generated by loop diagrams under the assumption that the QCD coupling is small.

- **FST truncation**

  R. J. Furnstahl, B. D. Serot, H. B. Tang, NPA615 ('97)441.

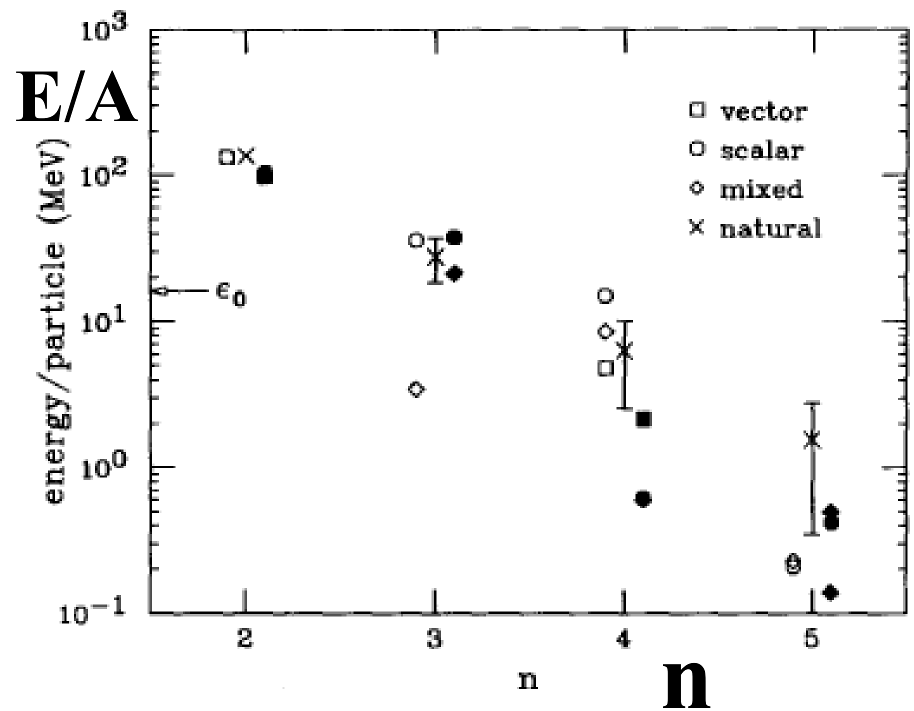
  At a given density, we can truncate the Lagrangian by the index

  n = B/2 + M + D

  (B: baryon field, M: Non NG boson, D: derivatives)

  Naturalness → V ~ $\rho^n/n!$

  → small for large n

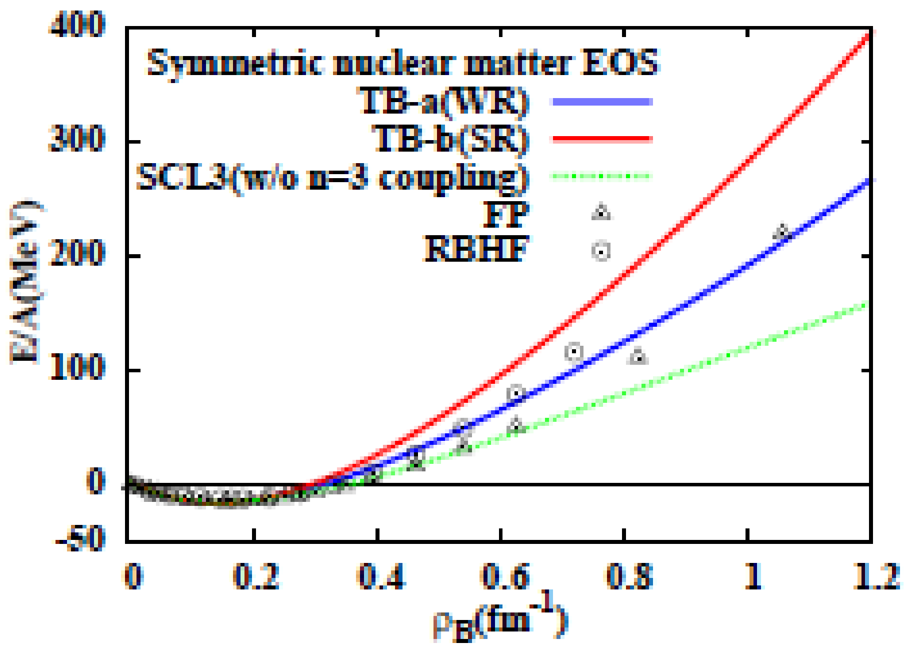


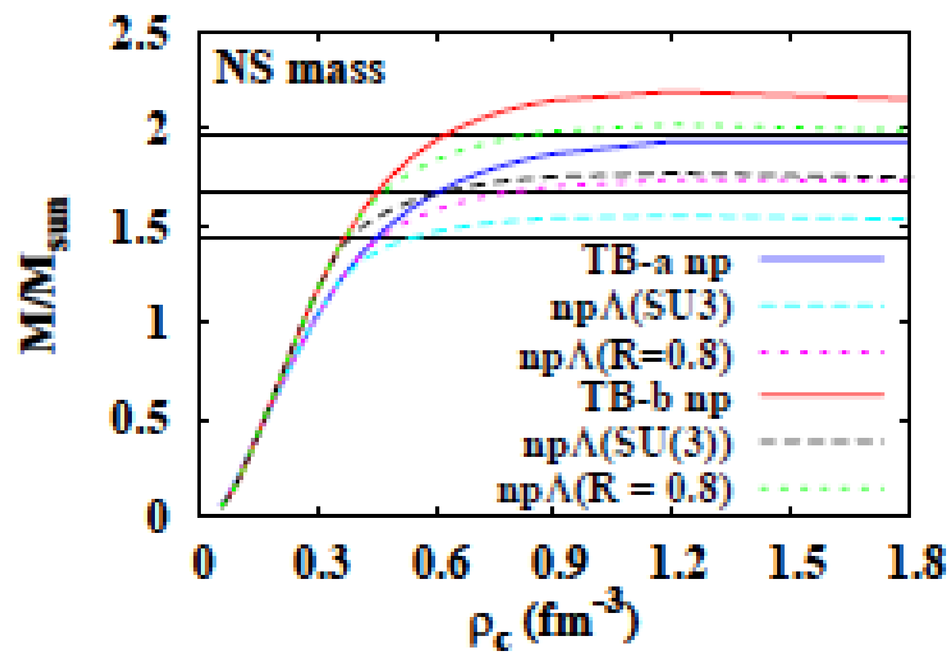
n=3 coupling terms

- **RMF with n=3 terms**
  - **n=B/2+M+D; baryon, meson, derivative**

$$\mathcal{L}^{\sigma\omega}_{n=3} = -\frac{1}{f_\pi}\sum_B \bar{\psi}_B\left[g_{\sigma\sigma B}\sigma^2 + g_{\omega\omega B}\omega_\mu\omega^\mu - g_{\sigma\omega B}\sigma\omega_\mu\gamma^\mu\right]\psi_B - c_{\sigma\omega\omega}\, f_\pi\sigma\omega_\mu\omega^\mu$$

  - **$g_{\sigma\Lambda}/ g_{\sigma N} \sim 0.8 > 2/3 \to 2\ M_\odot$ NS**
  - **Parameter fitting: (ρ_0, E/A), Vector pot. in DBHF, S_0, L, ...**

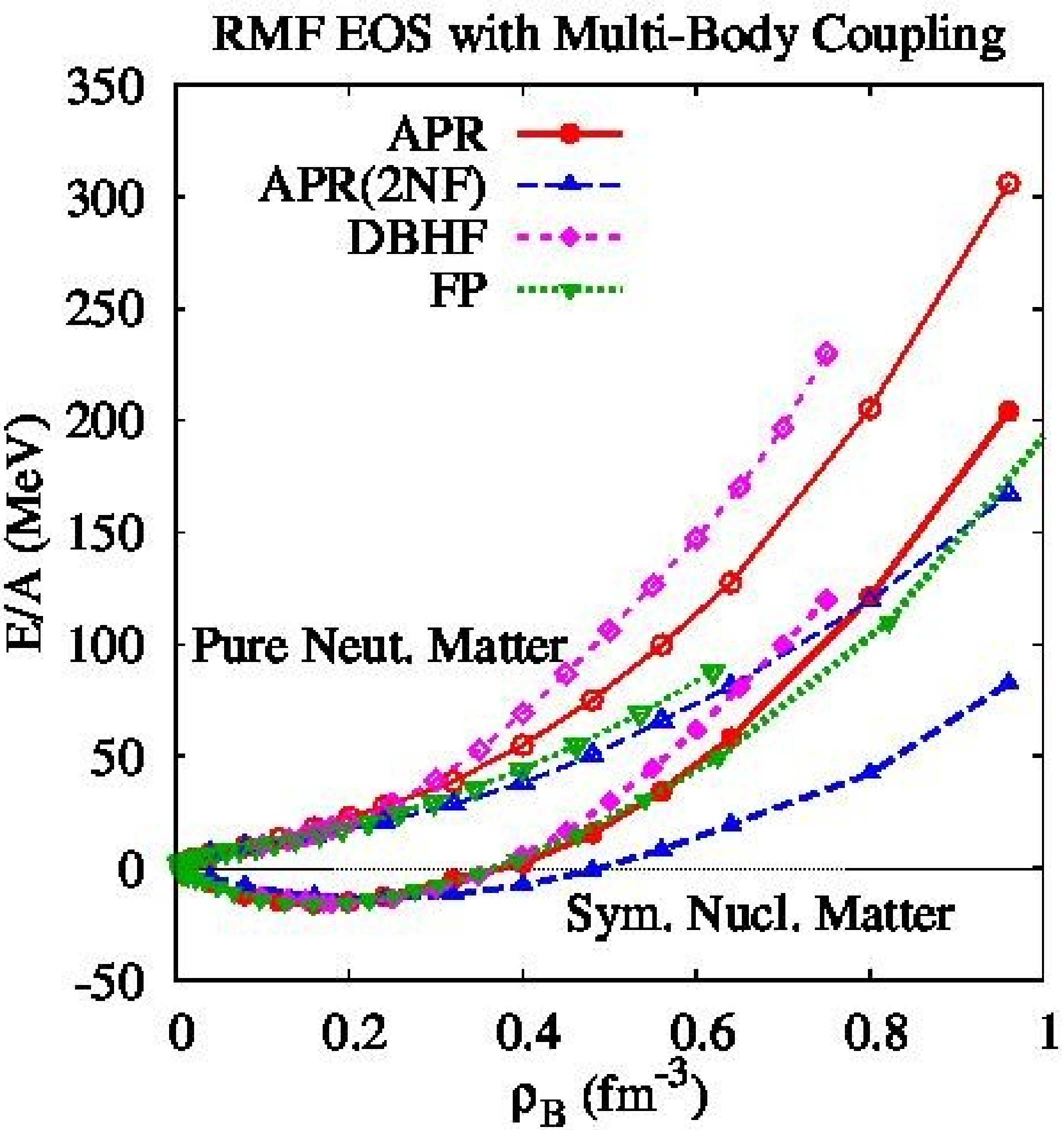




Tsubakihara, AO, NPA914 ('13), 438.

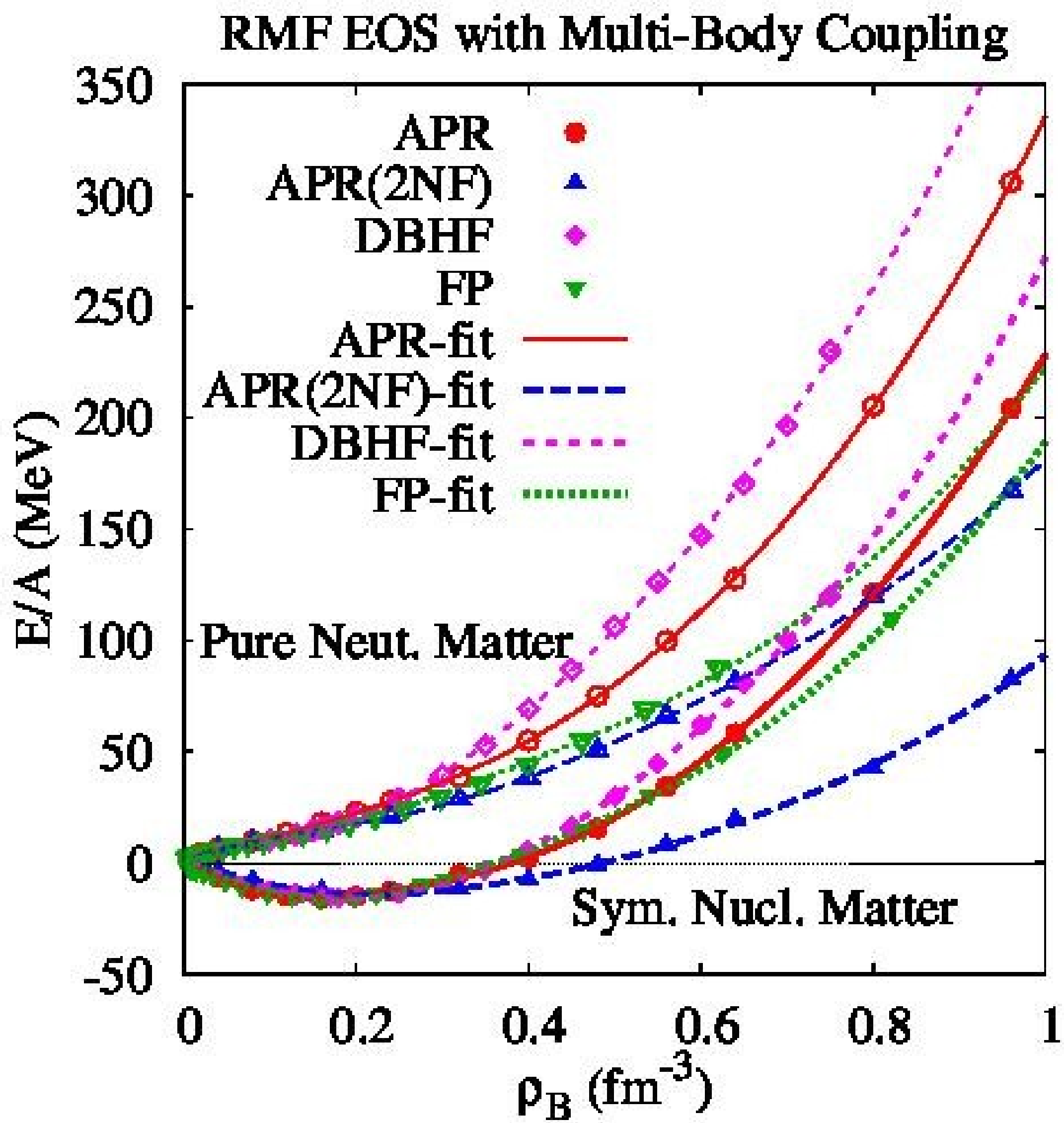
"Ab initio" EOS

- "Ab initio" EOS under consideration
  - FP: Variational calc. (Av14+3NF(att.+repl.))
    B. Friedman, V.R. Pandharipande, NPA361('81)502.
  - APR: Variational chain summation (Av18+rel. corr. ; Av18+ rel. corr.+3NF)
    A. Akmal, V.R.Pandharipande, D.G. Ravenhall, PRC58('98)1804.
  - DBHF: Dirac Bruckner approach (Bonn A)
    G. Q. Li, R. Machleidt, R. Brockmann, PRC45('92)2782



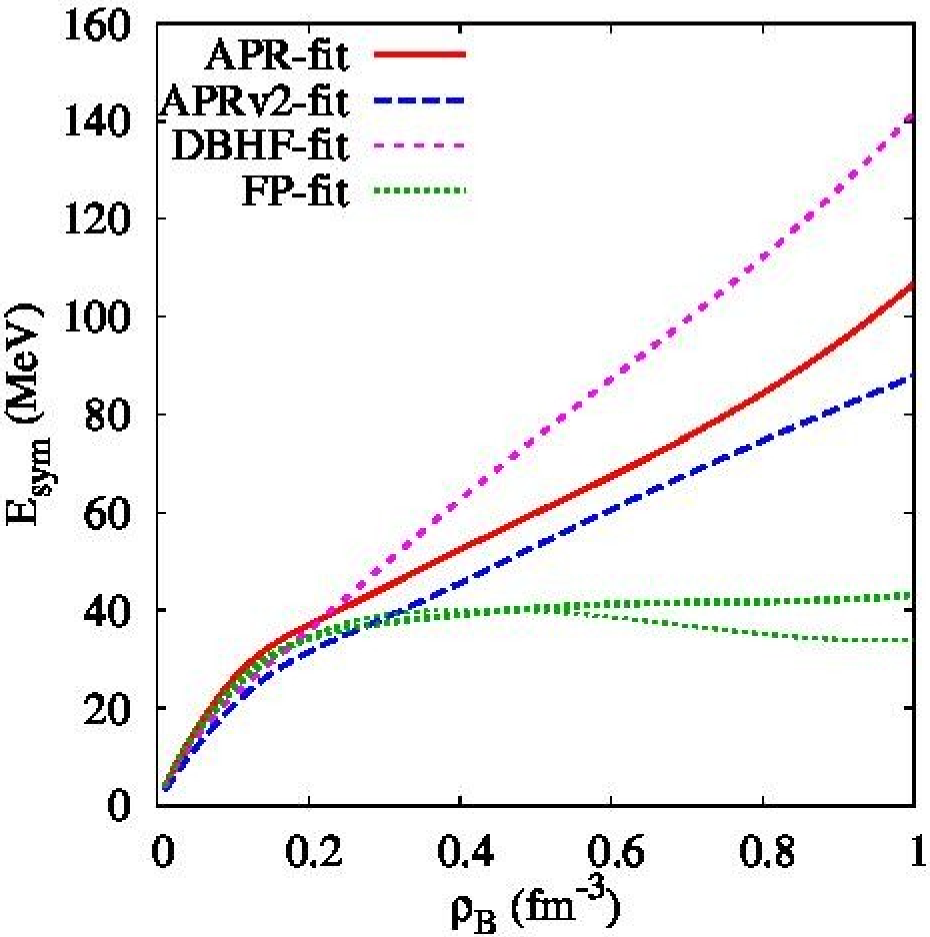
Fitting "Ab initio" EOS via RMF

- RMF with multi-body couplings: 15 parameters
  - Working hypothesis
    σ self-energy: SCL2 model
    Tsubakihara, AO ('07)
    $M_N \to 0$ @ $\sigma \to f_\pi$
- Markov Chain Monte-Carlo (MCMC)-like parameter search
  - Langevin type shift +Metropolis judge
  - Simultaneous fit of SNM and PNM is essential.
  - std. dev=0.5-0.7 MeV



Symmetry Energy

- Symmetry E. = E(PNM)-E(SNM)
  - APR-fit: (S_0, L)=(32, 47) MeV
  - APRv2-fit: (S_0, L)=(33, 47) MeV
  - DBHF-fit: (S_0, L)=(35, 75) MeV
  - FP-fit: (S_0, L)=(32, 40) MeV

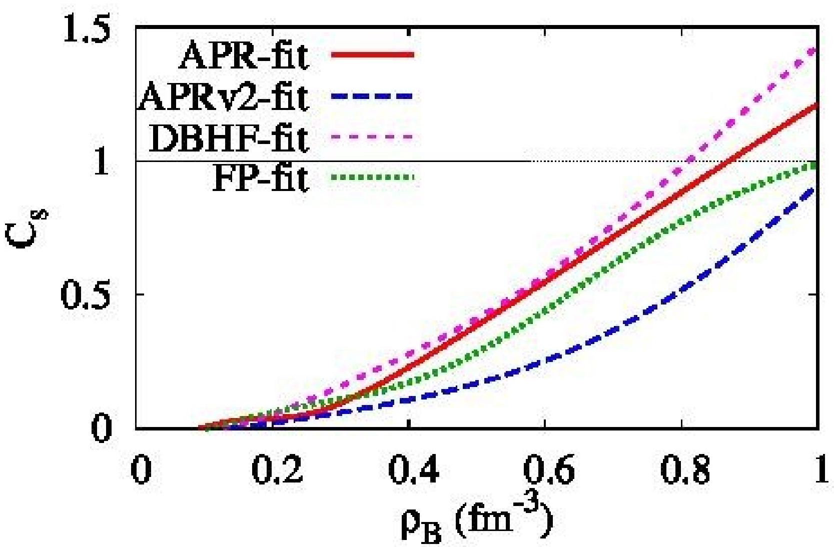


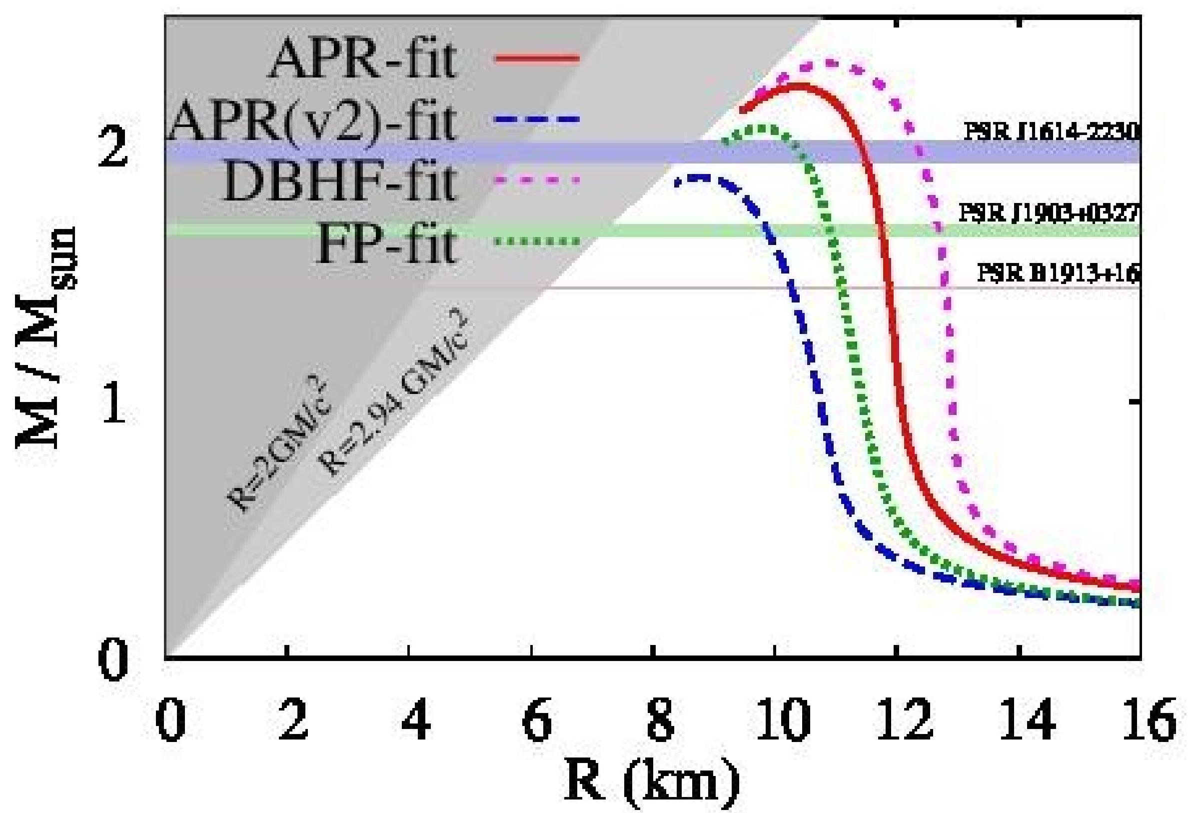
Neutron Star Matter EOS

- **Asymmetric Nuclear Matter EOS**
  $E_{ANM}(\rho)=E_{SNM}(\rho)+\delta^2 S(\rho)$
  β-equilibrium condition → NS matter EOS
- **Max. mass in the fit EOS deviates from the original one by ~ 0.1 $M_\odot$.**

$\eta=(KL^2)^{1/3}$?
Sotani et al.(2014)

- **Caveat:**
  $c_s > c$ at high density





Summary

- In order to solve the massive NS puzzle (hyperon crisis), we need to determine
  two-baryon (YN, YY) and three-baryon (YNN, YYN, YYY)
  based on laboratory experiments and/or QCD.
- One of the ways would be to combine
  "Ab Initio" nuclear matter EOS
  and Hypernuclear physics phenomenology.
- We have fitted several "ab initio" EOS in RMF with multi-body coupling by using MCMC-like procedure.
- To do
  - To tune "ab initio"-fit EOS to explain finite nuclei and recent data,
  - To introduce hyperons, and to examine hypernuclear properties,
  - To improve the parametrization to avoid acausal EOS
  - and to give MR curves with systematic (theoretical) error bars.

研究会世話人より

- 講演者の皆さん、参加者の皆さん、ありがとうございました。
- スライドは公開させていただきます。
  (公開できない版をいただいた方、公開可能版を送ってください。)
- 世話人: 大西明 (京大基研) 、森田健司 (京大基研) 、椿原康介 (大阪電通大) 、池野なつ美 (東北大 / 京大基研) 、李東奎 (京大基研) 、原田融 (大阪電通大) 、中田仁 (千葉大) 、飯田圭 (高知大) 、小野章 (東北大) 、田村裕和 (東北大) 、
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Thank you !