Neutron star matter EOS in RMF with multi-body couplings

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work in progress with
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--- Effective theories and Lattice ---
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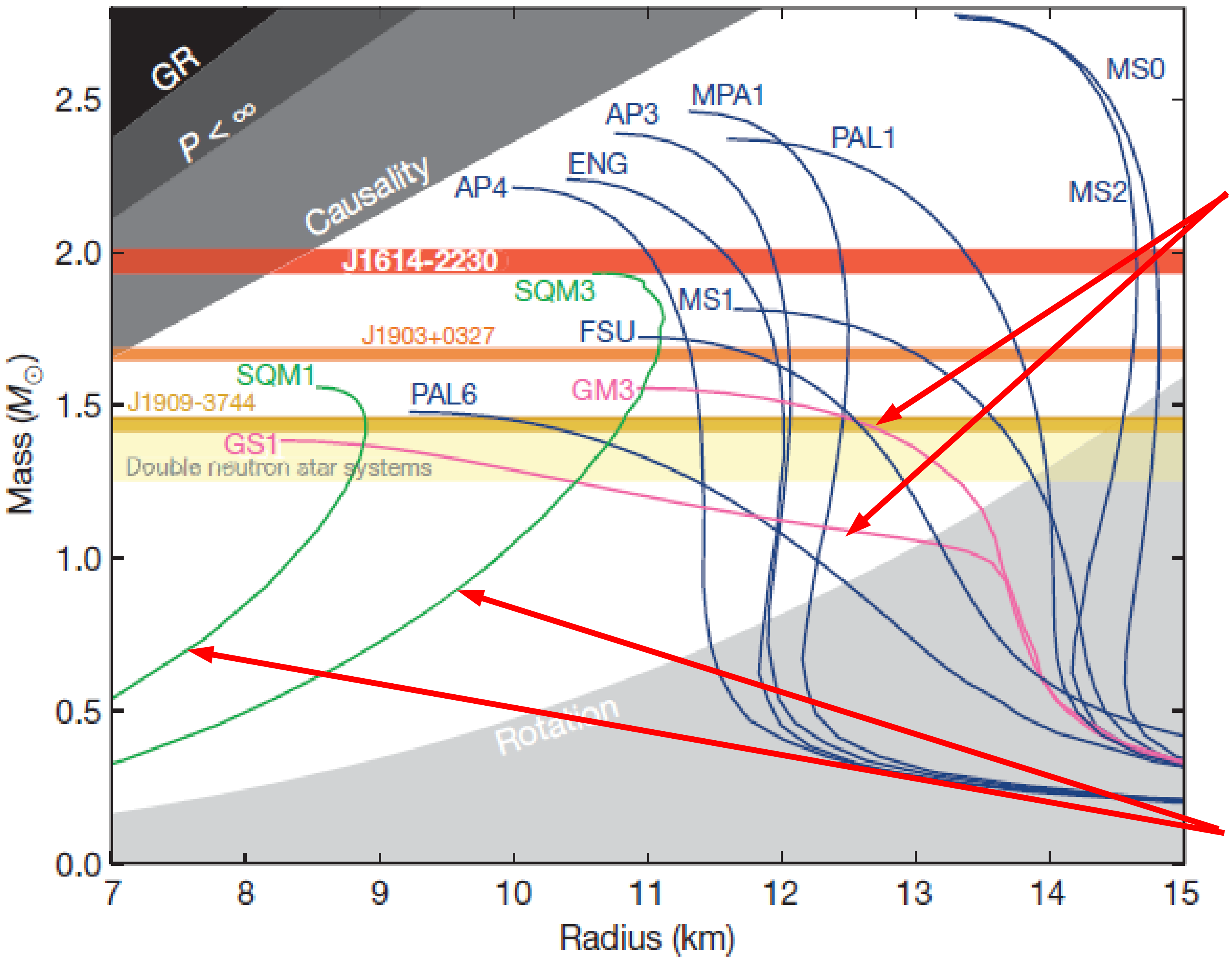
K. Tsubakihara, AO, NPA914 ('13), 438.
K. Tsubakihara, T. Harada, AO, arXiv:1402.0979
K. Tsubakihara, T. Harada, AO, work in progress

Massive NS Puzzle (or Hyperon Crisis)

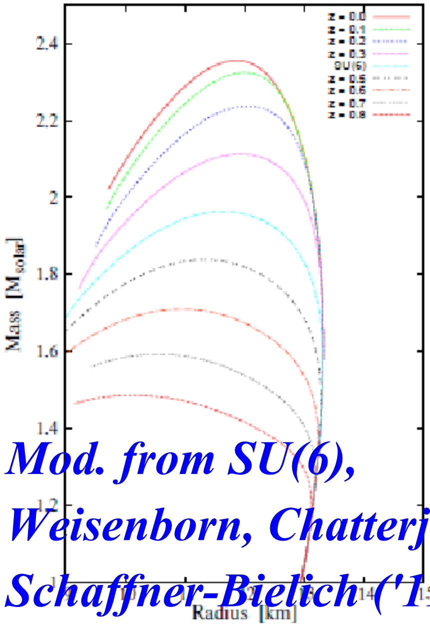
Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



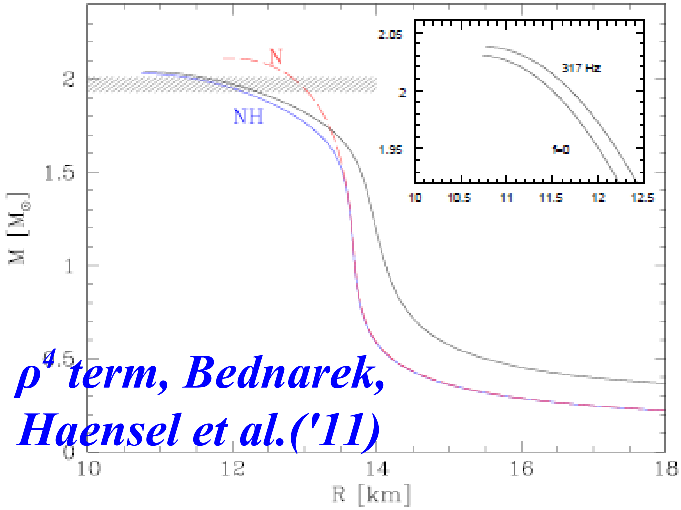
EOS with hyperons or Kaons

Quark matter EOS

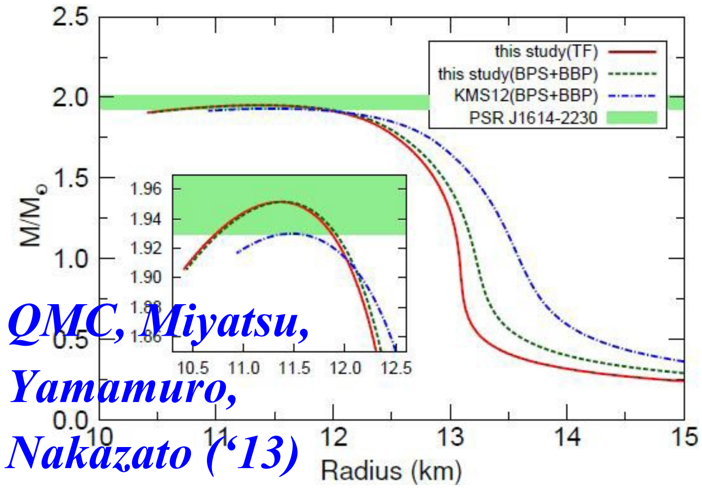
Massive Neutron Stars with Hyperons



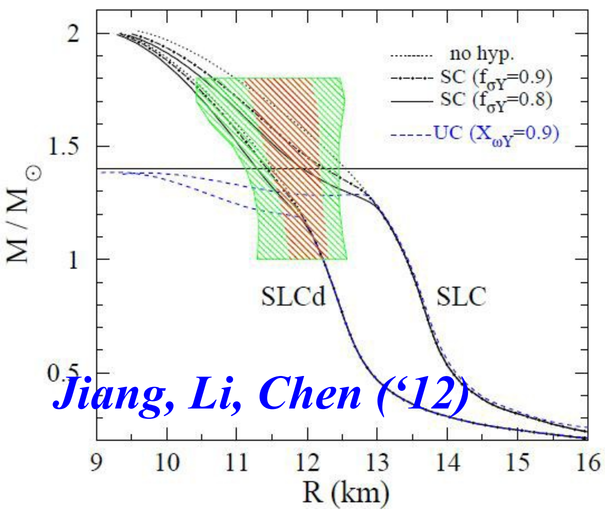
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



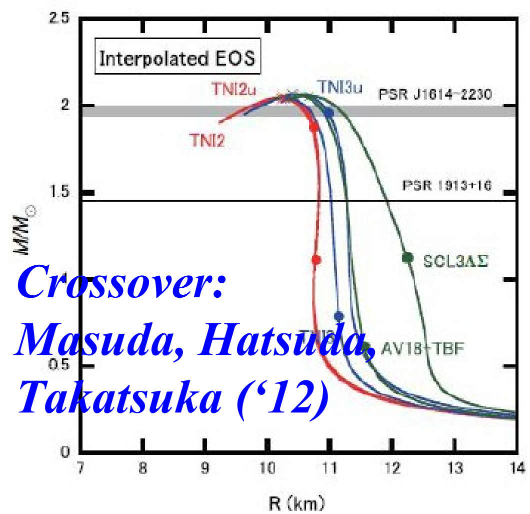
ρ^4 term, Bednarek, Haensel et al.('11)



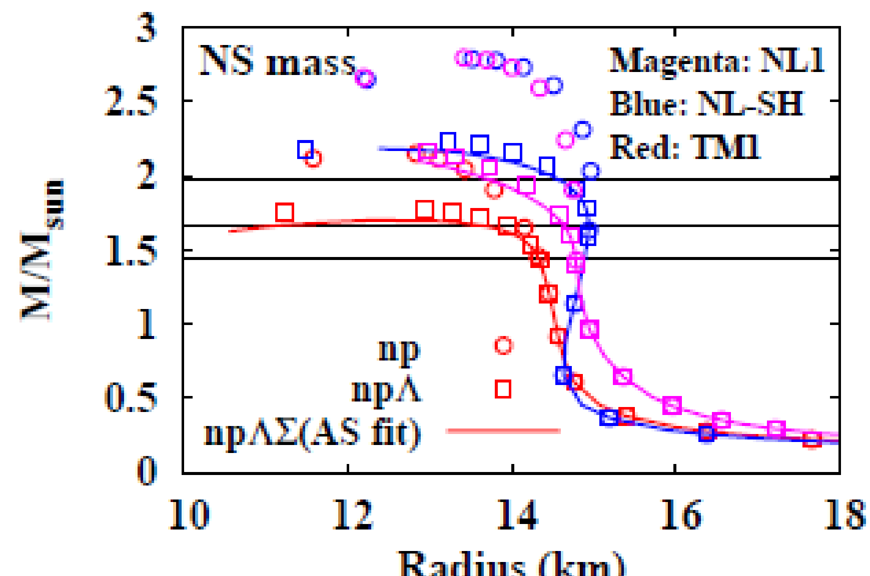
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

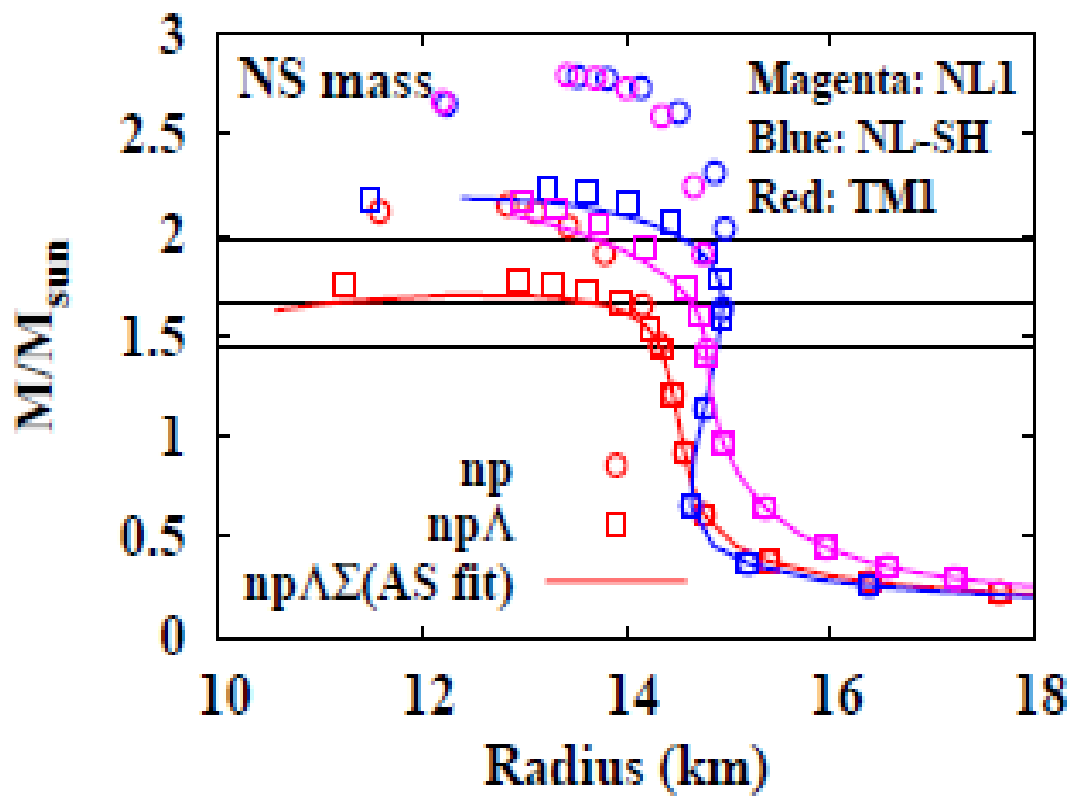


Tsubakihara, Harada, AO, arXiv:1402.0979

Massive Neutron Stars with Hyperons

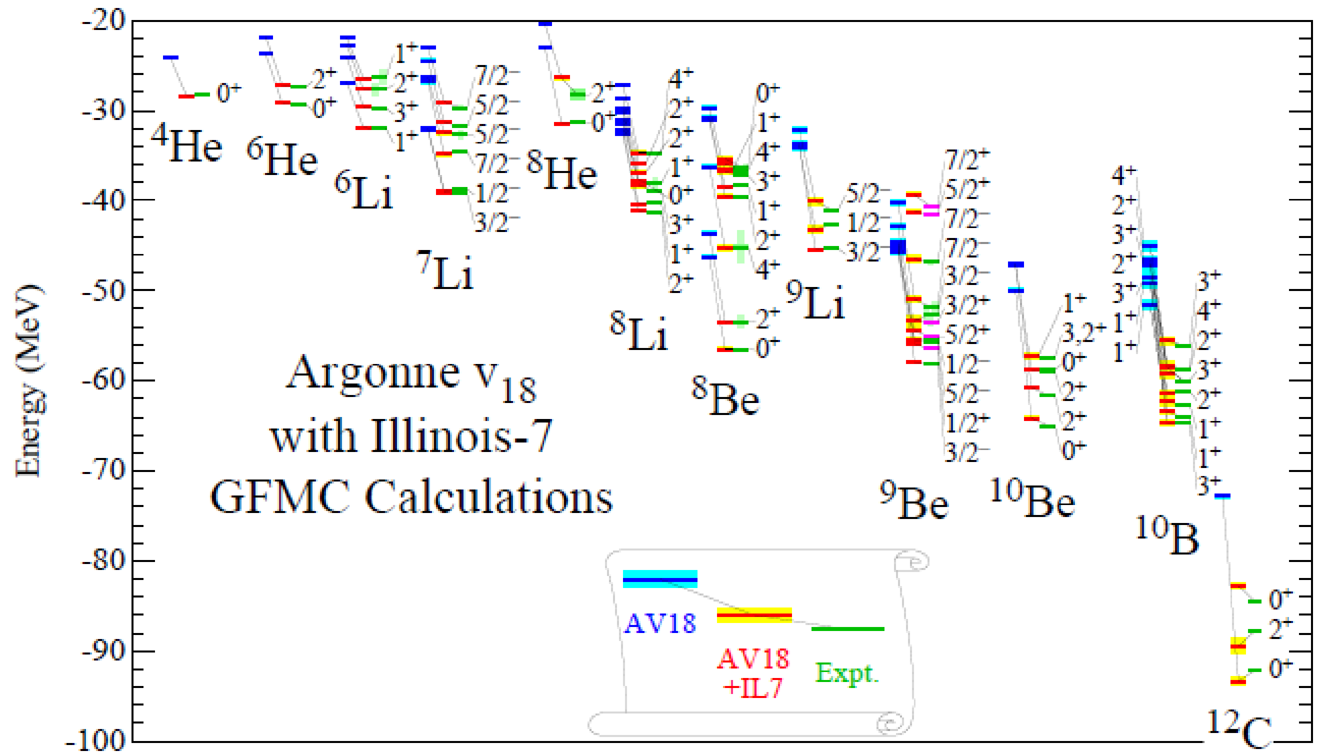
Tsubakihara, Harada, AO, arXiv:1402.0979

- **Ruled-out EOS with hyperons = GM3 Glendenning & Moszkowski (1991)**
- **We did NOTHING special and find 2 $M_\odot$ NS can be supported.**
  - **"Typical" RMF for nucl. matter NL1, NL-SH, TM1**
    Reinhardt et al. ('86); Sharma, Nagarajan, Ring ('93); Sugahara, Toki ('94).
  - **$s\bar{s}$ mesons are introduced**
  - **Hypernuclear data**
    Λ, ΛΛ hypernuclei
    Σ atomic shifts
    SU(3) relation to isoscalar -vector couplings



What is necessary to solve the massive NS puzzle ?

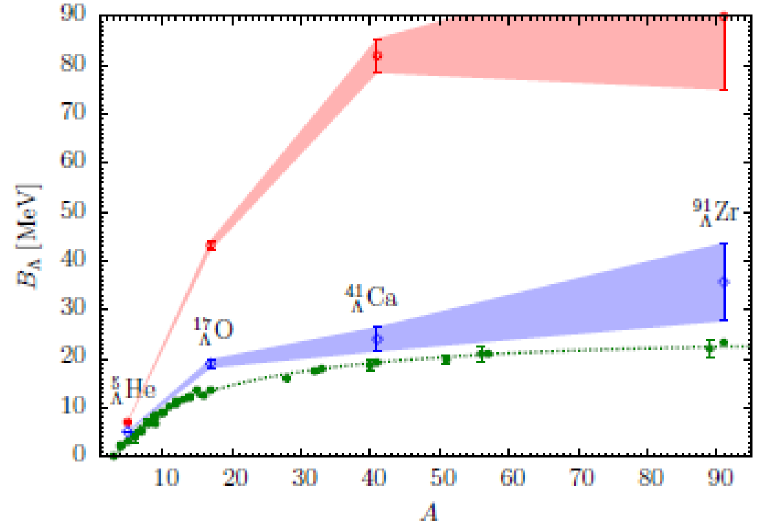
- **There are many “model” solutions.**
- **Ab initio calculation including three-baryon force (3BF)**
  - **Bare 2NF+Phen. 3NF(UIX, IL2-7) + many-body theory (verified in light nuclei).**
  - **Chiral EFT (2NF+3NF) + many-body theory**
  - **Dirac-Bruckner-HF (no 3NF)**

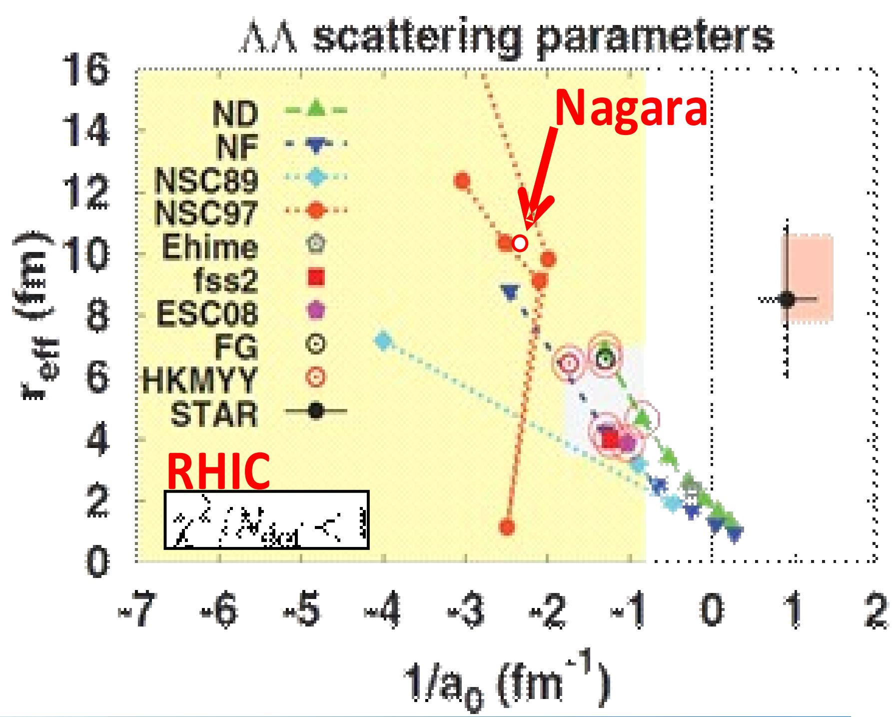


J. Carlson et al. ('14)

3BF including Hyperons

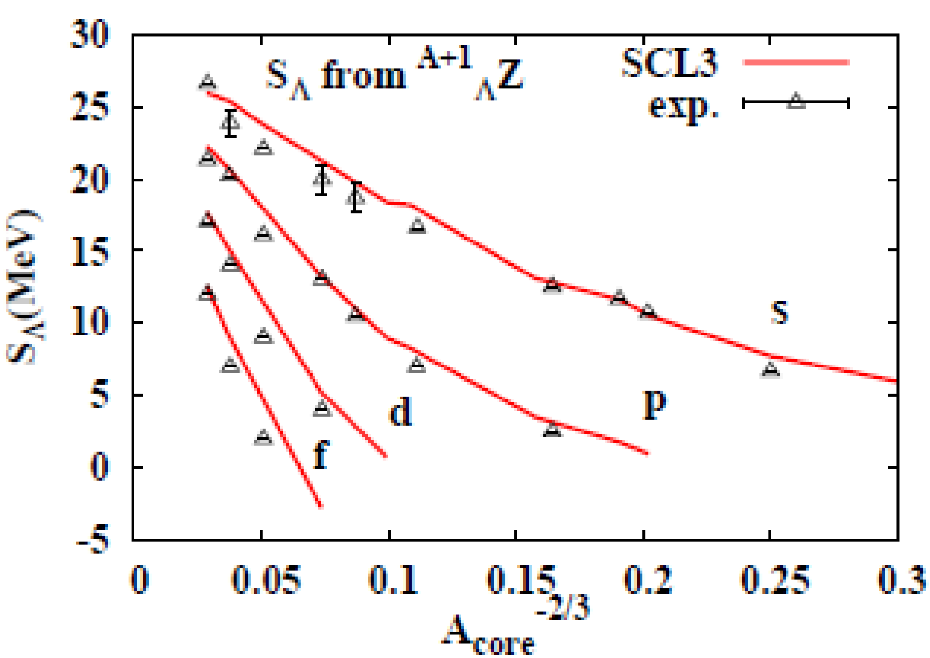
- **3BF incl. YNN, YYN and YYY should exist and contribute to EOS.**
  Nishizaki, Takatsuka, Yamamoto ('02)
  - **Chiral EFT, Multi-Pomeron exch., Quark Pauli, Lattice 3BF, SJ, ..**
    Kohno('10); Heidenbauer+('13); Yamamoto+('14); Nakamoto, Suzuki; Doi+(HALQCD,'12); Tamagaki('08); …
  - **Quant. MC study** *Lonardoni et al.('14)*
  - **Quark Meson Coupling**
    Miyatsu et al.; Thomas (HHIQCD)
  - **ΛΛN** *K. Morita, T. Furumoto, AO, PRC91('15)024916*
- **Caveat: Missing data**



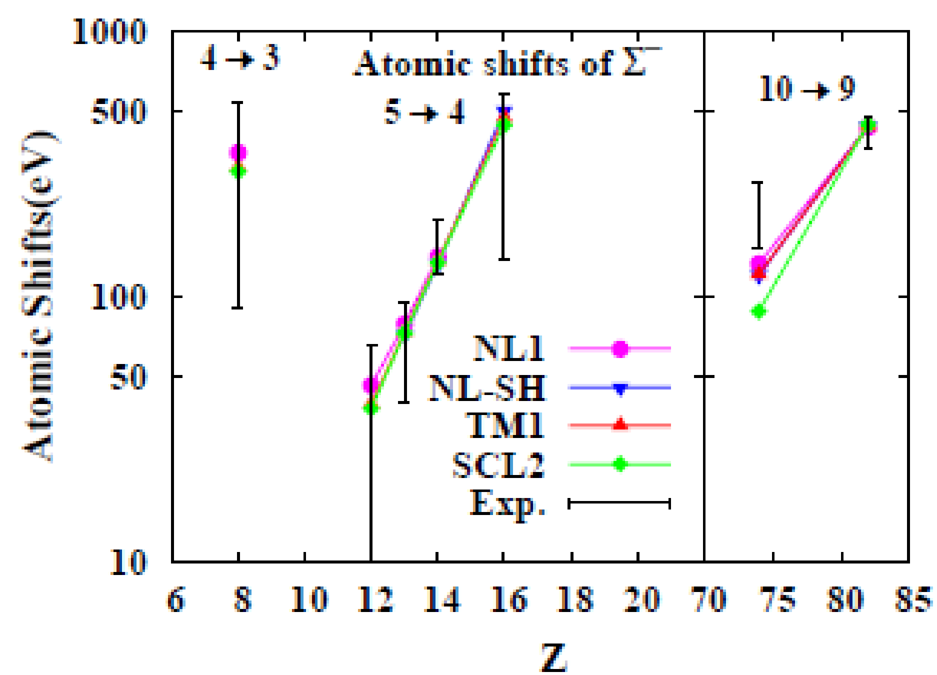


Alternative approach

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



Tsubakihara et al., PRC81('10)065206



Tsubakihara, Harada, AO, arXiv:1402.0979

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

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

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

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

$$U_\mu = g_\omega\omega_\mu\left[1 - r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2\right] + g_\rho\boldsymbol{\tau}\cdot\boldsymbol{R}_\mu\left[1 - r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2\right]$$

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

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

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.

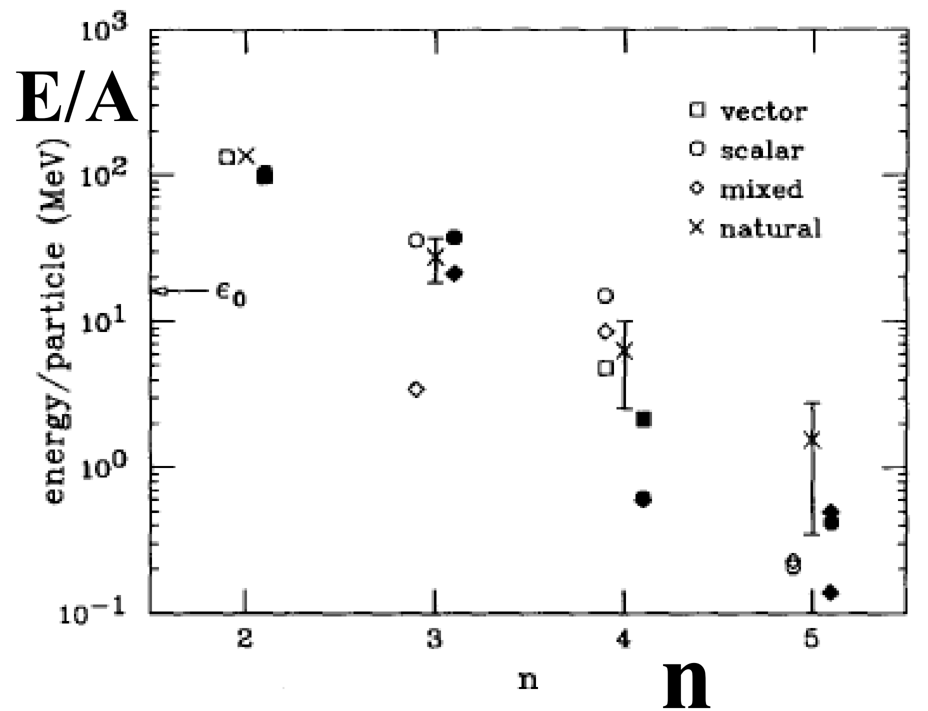
  At a given density, we can truncate the Lagrangian by the index

  n = B/2 + M + D

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

  Naturalness → V ~ $\rho^n/n!$

  → small for large n

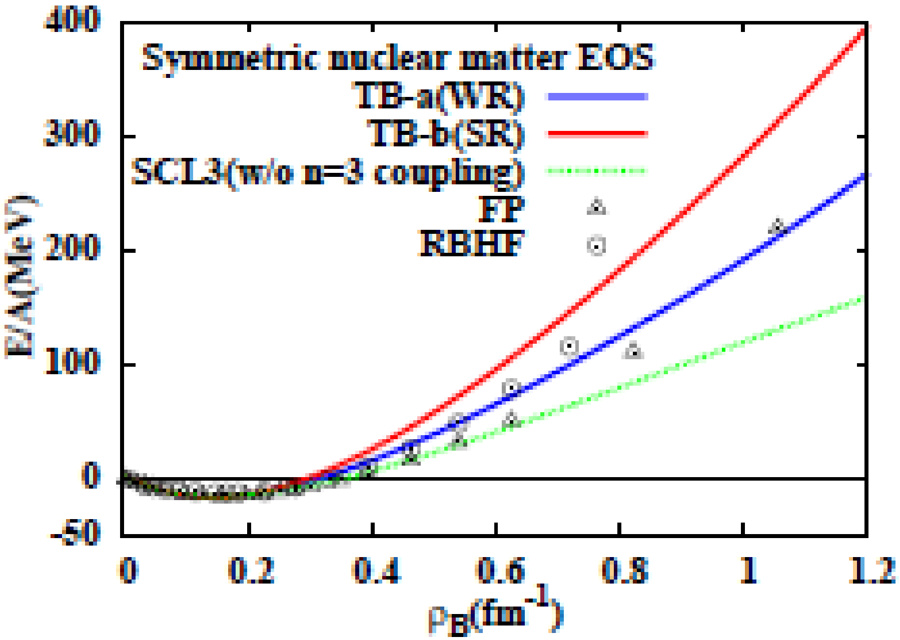


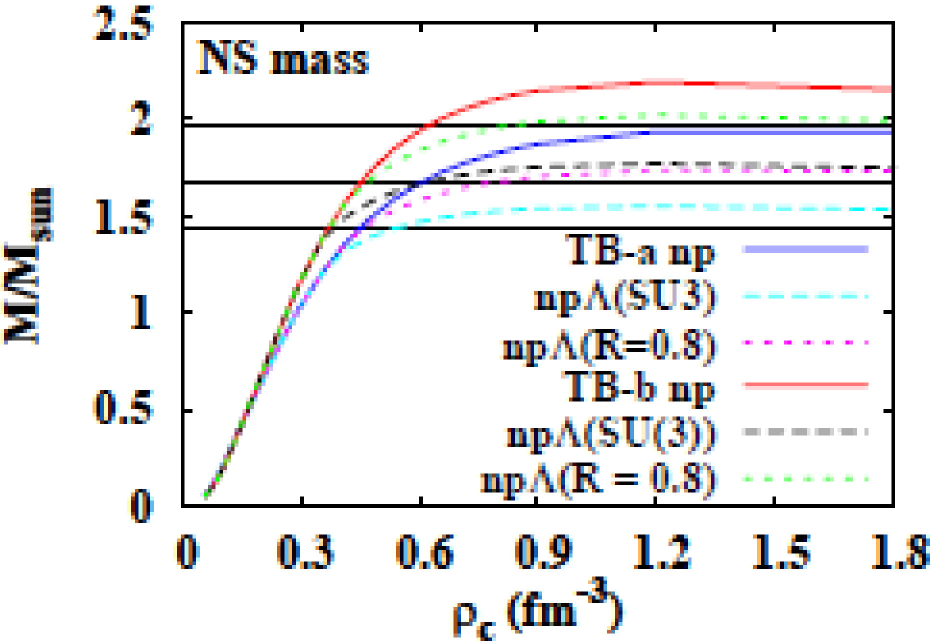
n=3 coupling terms

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

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

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

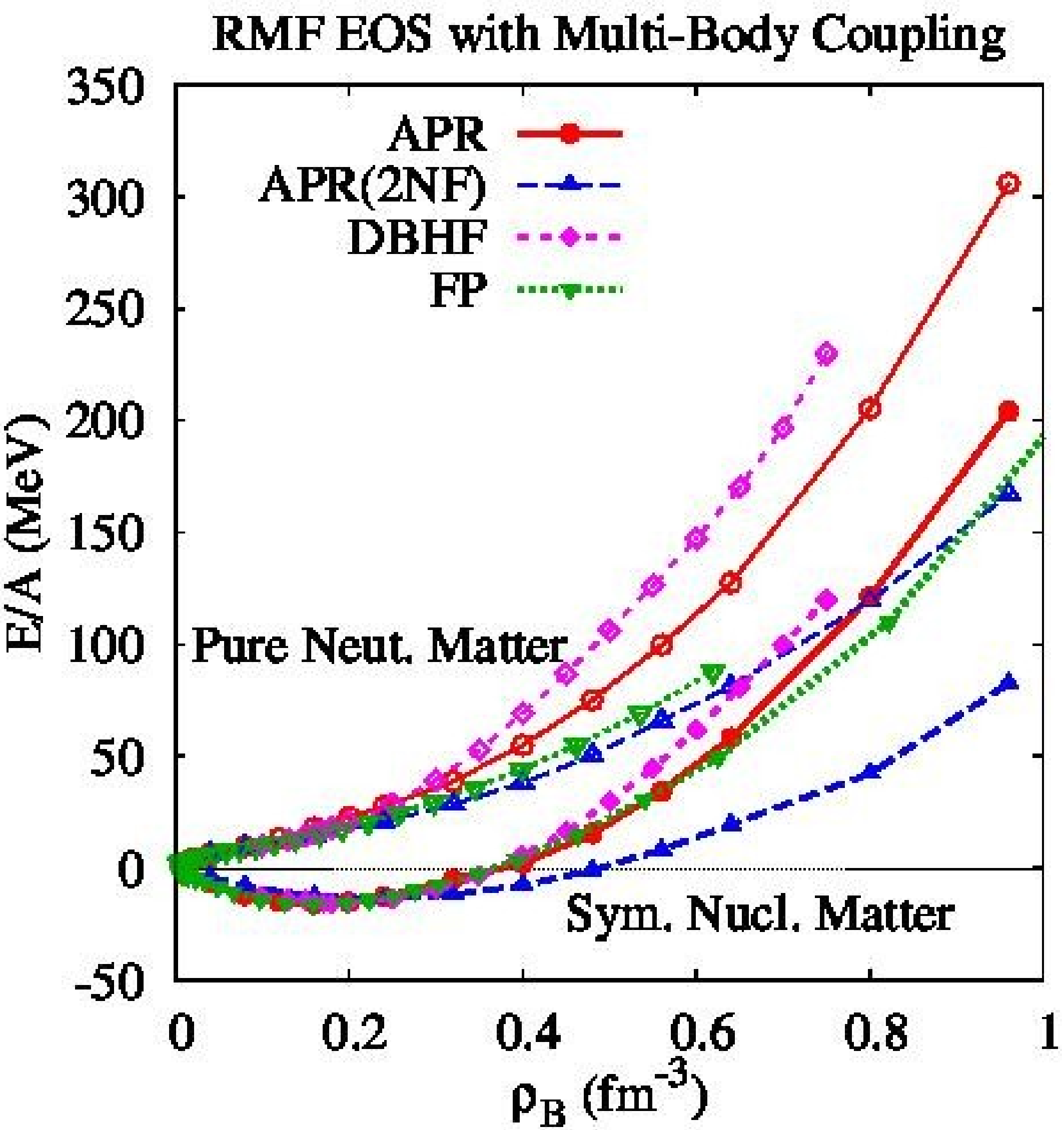




Tsubakihara, AO, NPA914 ('13), 438.

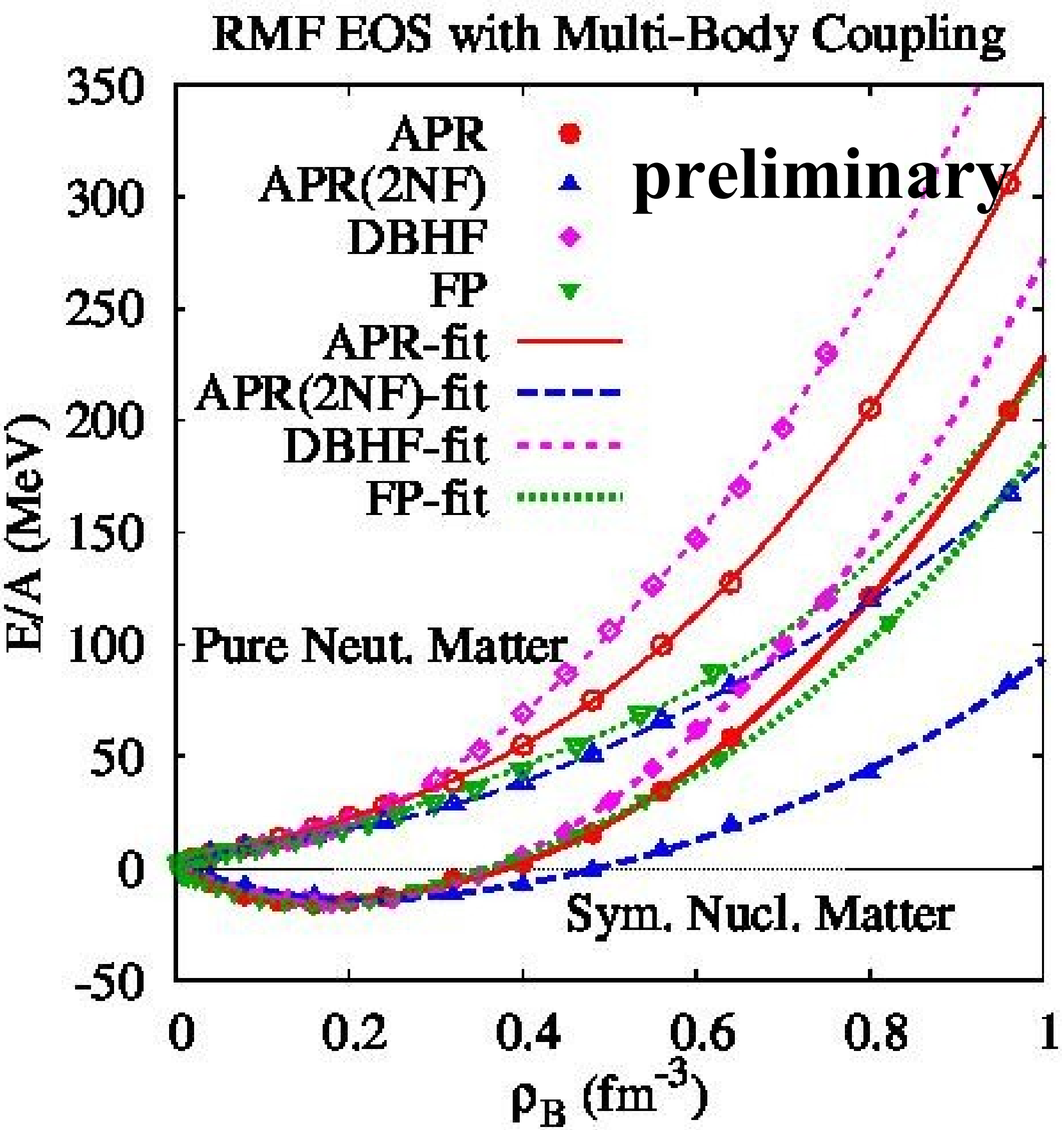
"Ab initio" EOS

- **"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

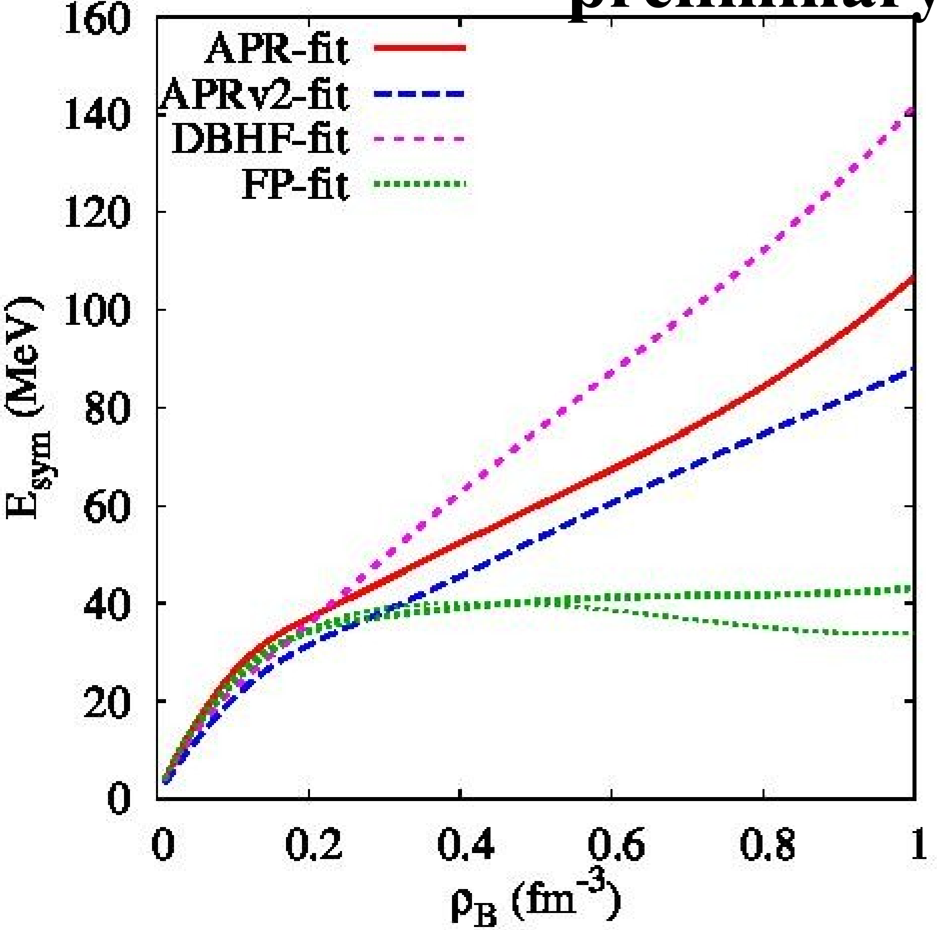
- RMF with multi-body couplings: 15 parameters
  - Working hypothesis
    σ self-energy: SCL2 model
    Tsubakihara, AO ('07)
    $M_N \to 0$ @ $\sigma \to f_\pi$
- Markov Chain Monte-Carlo (MCMC)-like parameter search
  - Langevin type shift +Metropolis judge
  - Simultaneous fit of SNM and PNM is essential.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

preliminary

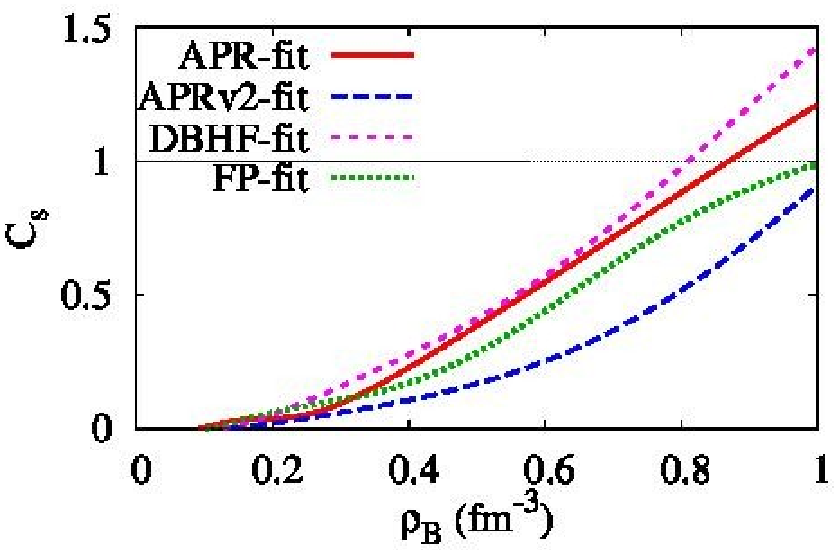


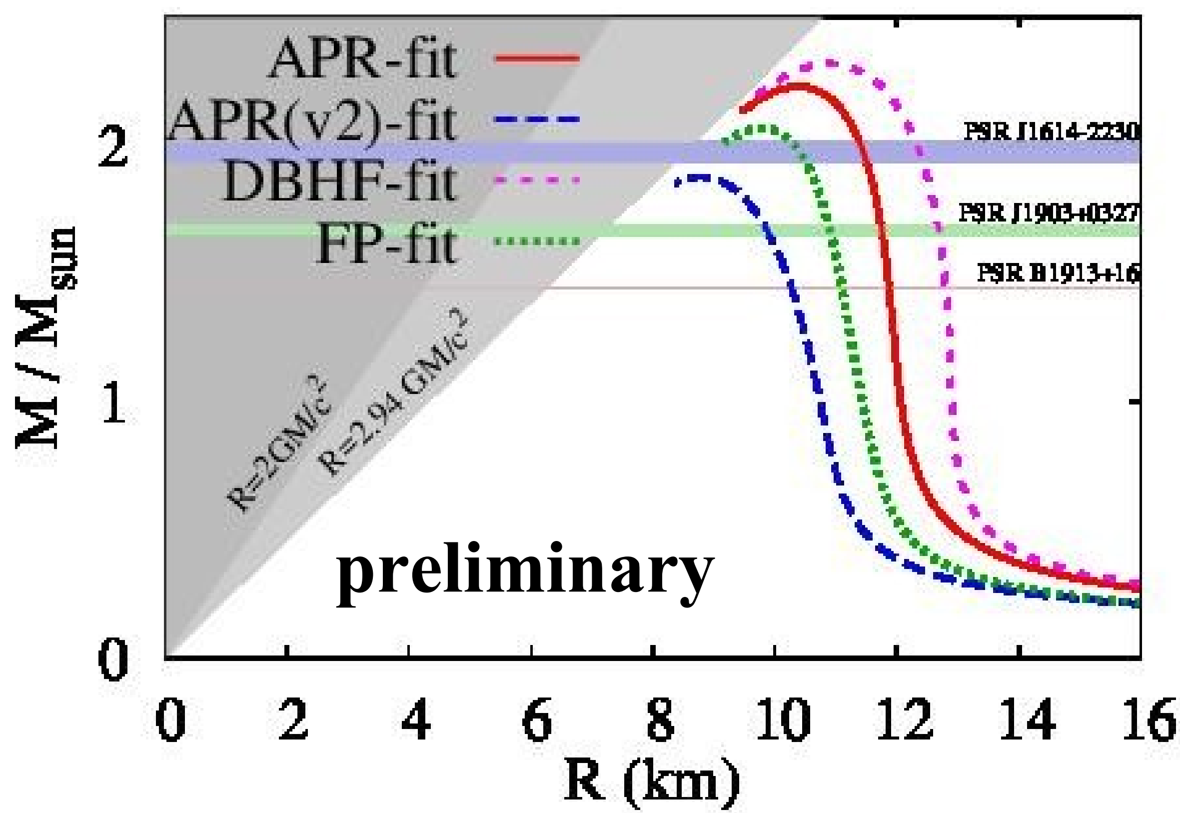
Neutron Star Matter EOS

- **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)

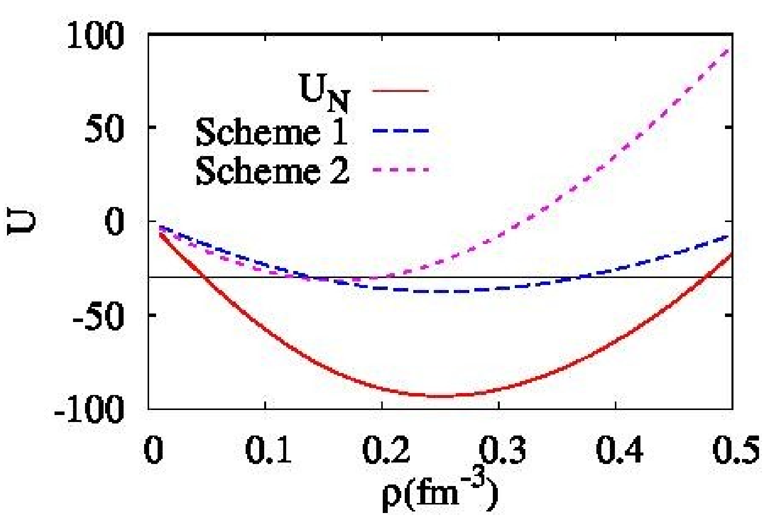
- **Caveat:**
  $c_s > c$ at high density

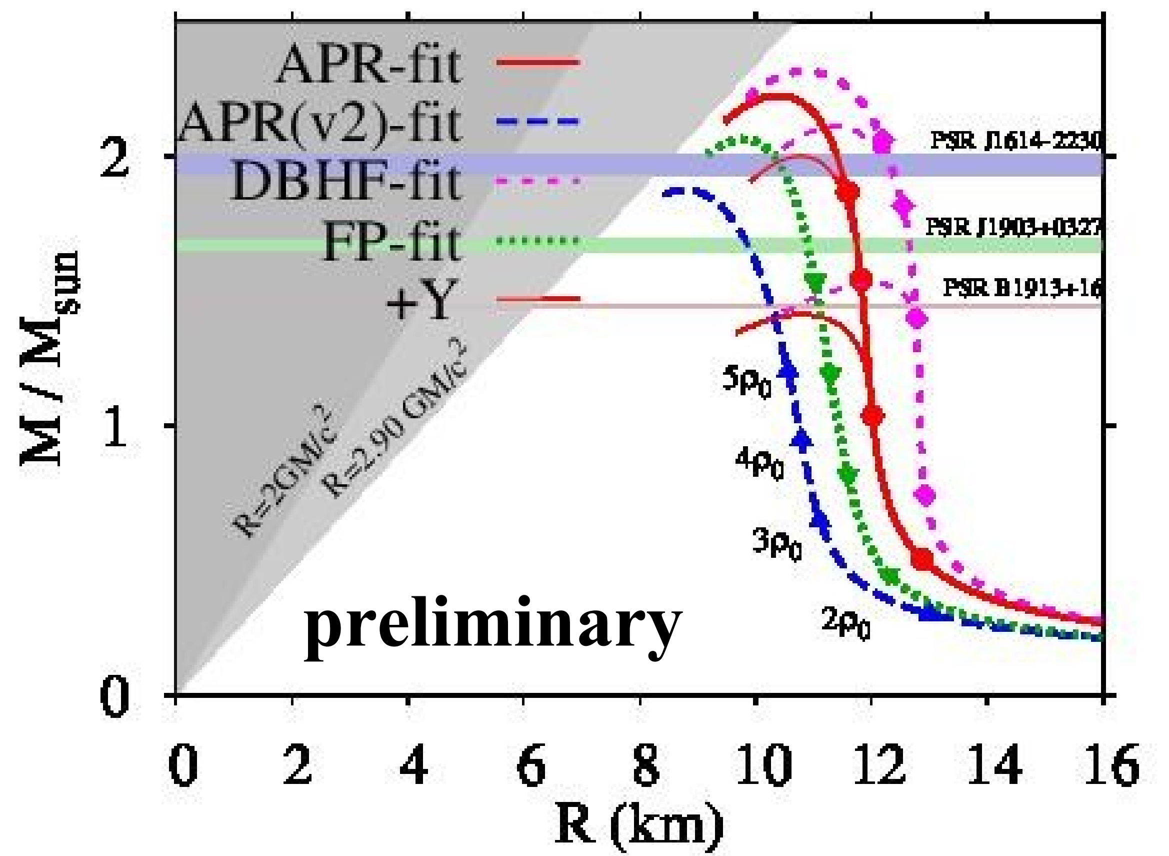




NS matter in "ab initio"-fit + Λ

- **Λ potential in nuclear matter at $\rho_0 \sim -30$ MeV**
  - **Scheme 1: $U_\Lambda(\rho) = \alpha\, U_N(\rho)$**
  - **Scheme 2: $U_\Lambda(\rho) = 2/3\, U^{n=2}_N(\rho) + \beta\, U^{n>2}_N(\rho)$**





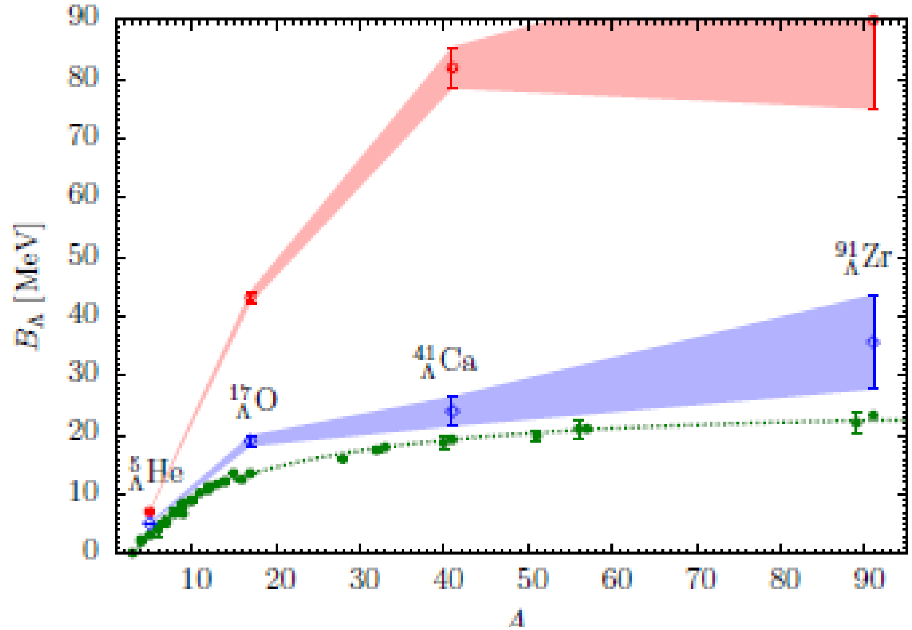
Summary

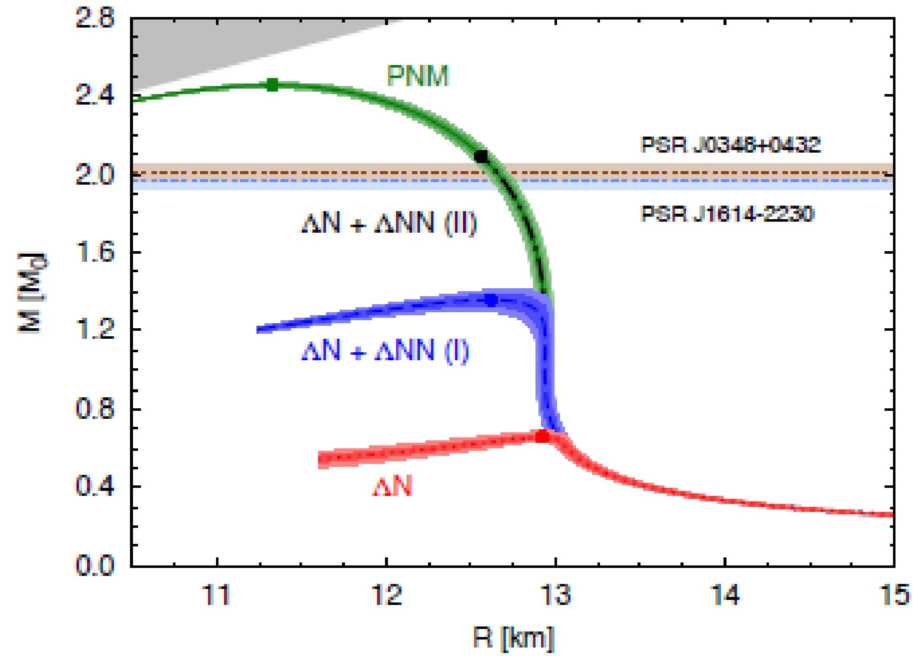
- **In order to solve the massive NS puzzle (hyperon crisis), we need to determine**
  two-baryon (YN, YY) and three-baryon (YNN, YYN, YYY)
  based on laboratory experiments and/or QCD.
- **One of the ways would be to combine**
  "Ab Initio" nuclear matter EOS
  and Hypernuclear physics phenomenology.
- **We have fitted several "ab initio" EOS in RMF with multi-body coupling by using MCMC-like procedure, and included Λ with -30 MeV potential at ρ_0.**
- **To do**
  - **Finite nuclei (normal and hyper), recent Esym data, Causality,**
  - **MR curves with systematic (theoretical) error bars.**

Thank you !

3BF including hyperons

- *Lonardoni et al.('14)*
- **2BF results show - 80 MeV potential.**





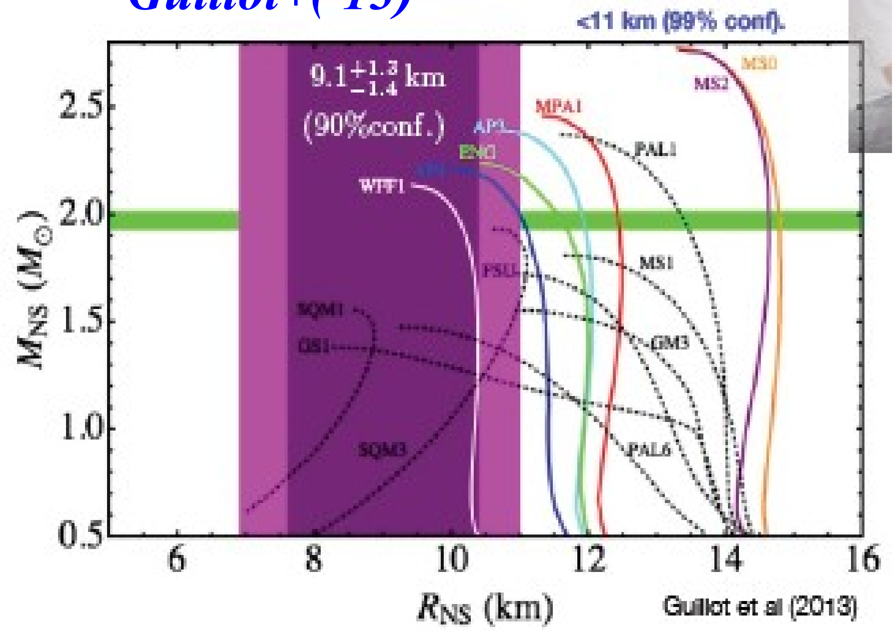
Three Baryon Force (3BF)

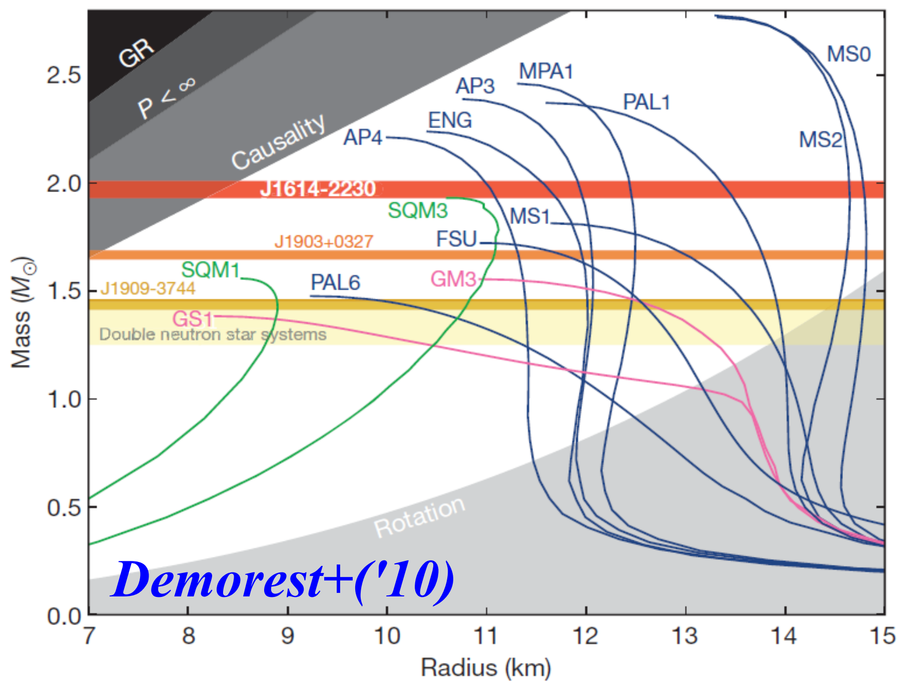
- **Three-Baryon Force (3BF)**
  - **3NF is necessary to reproduce (ρ_0, E/A) in most of ab initio cal.**
  - **3BF incl. YNN, YYN and YYY should exist and contribute to EOS (Nishizaki, Takatsuka, Yamamoto ('02))**
- **"Ab initio" EOS with 3NF**
  - **FP, APR, DBHF, G-matrix (MPP, Chiral EFT), Variational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

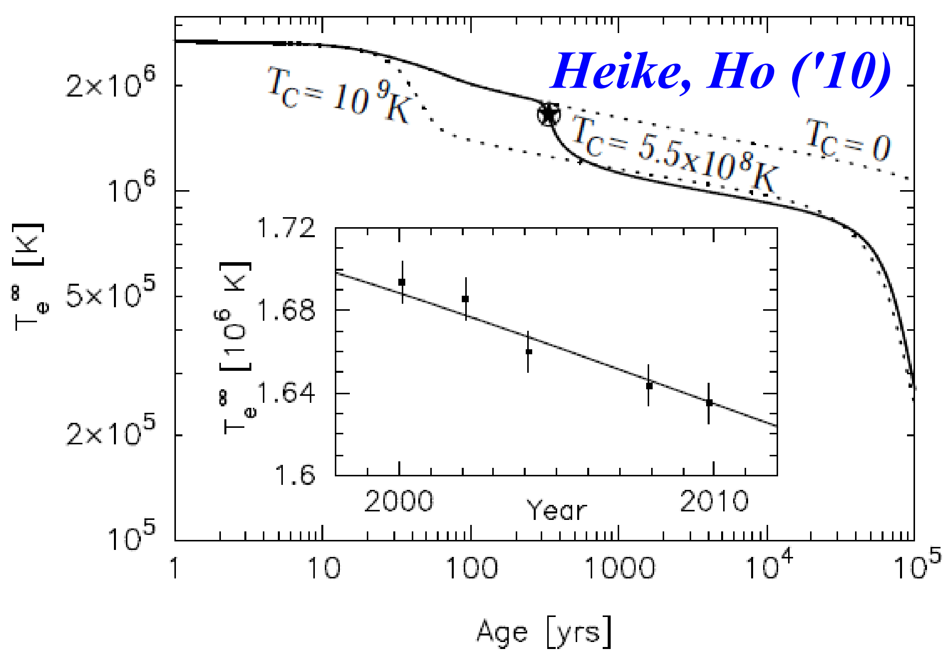
Current Big Puzzles of NS

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

Guillot+('13)




Demorest+('10)


Heike, Ho ('10)