Neutron star matter EOS in RMF with multi-body couplings

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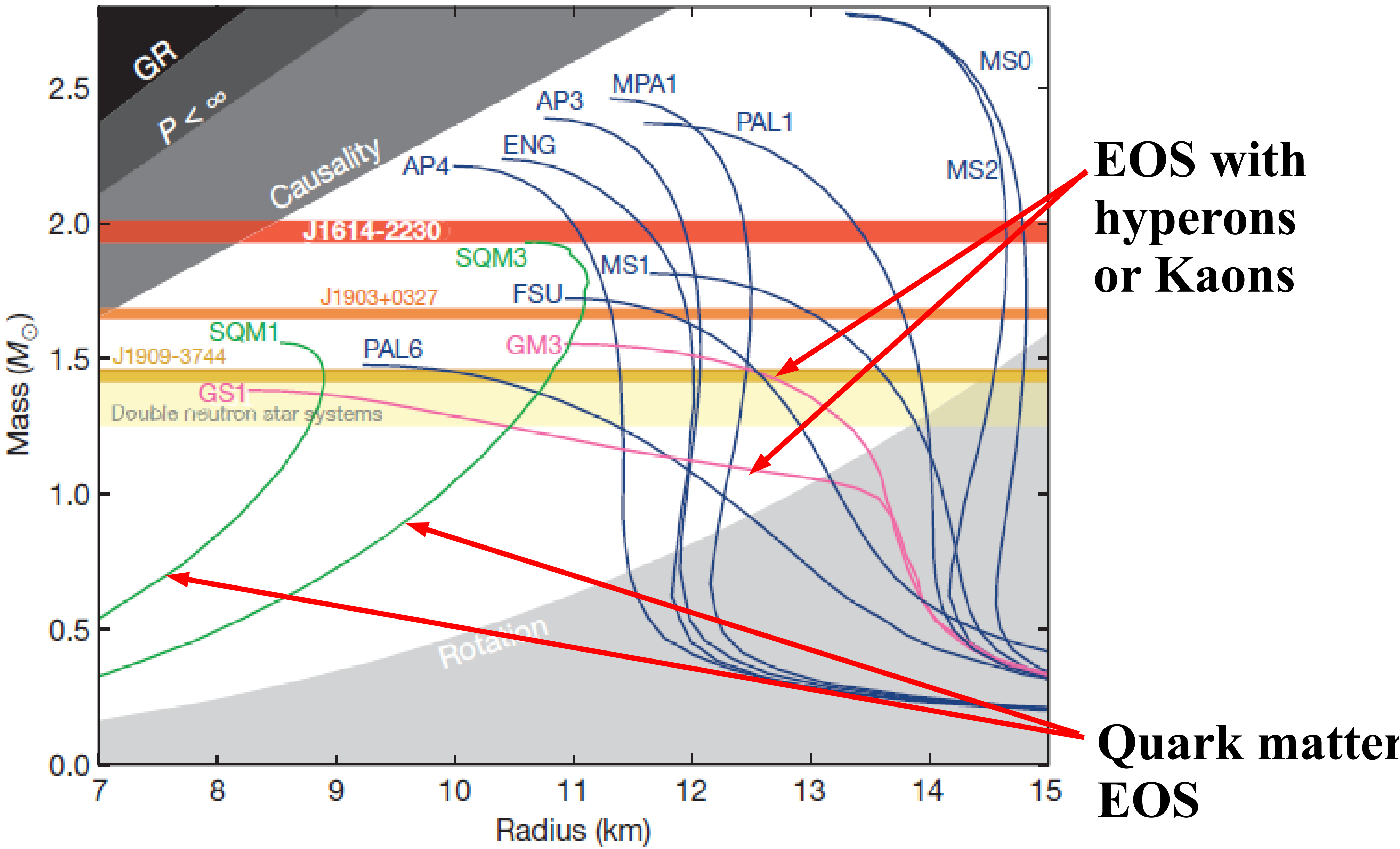
Nuclei in the Cosmos XIV,
Jun.19-24, Toki Messe, Niigata, Japan.

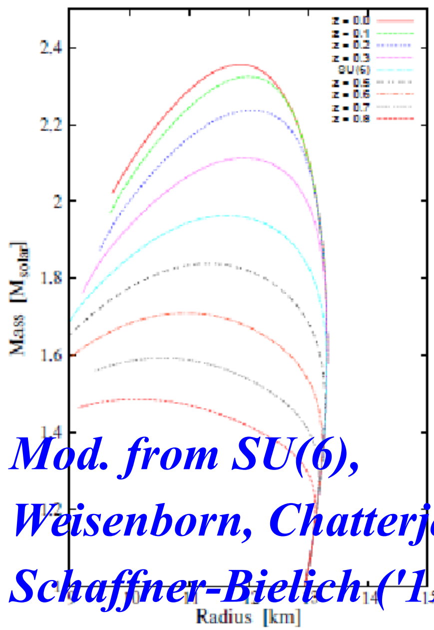
K. Tsubakihara, AO, NPA914 ('13), 438.
K. Tsubakihara, T. Harada, AO, arXiv:1402.0979
K. Tsubakihara, T. Harada, AO, work in progress

Massive NS Puzzle (or Hyperon Crisis)

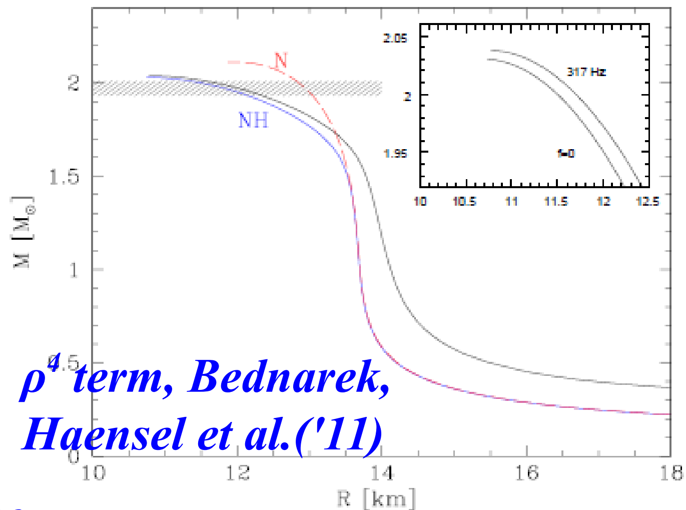
Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



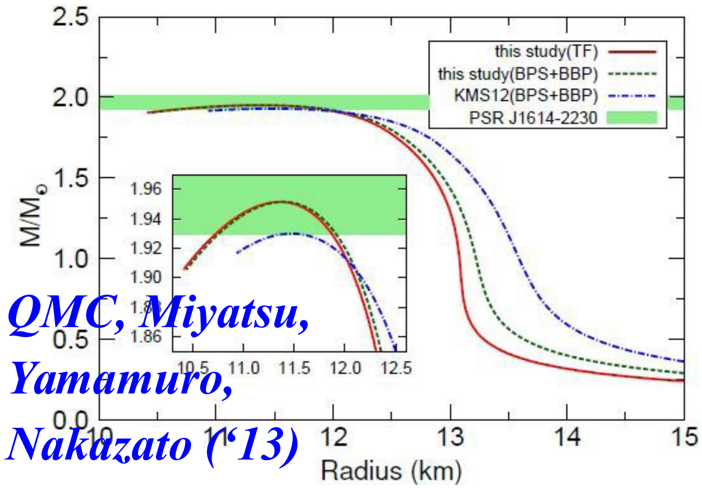
Massive Neutron Stars with Hyperons



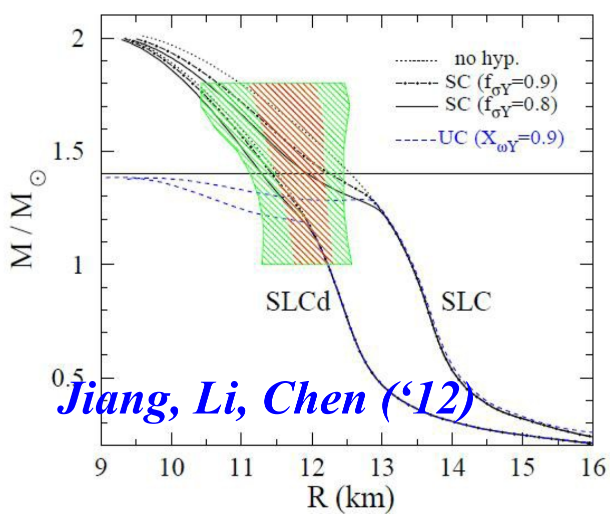
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



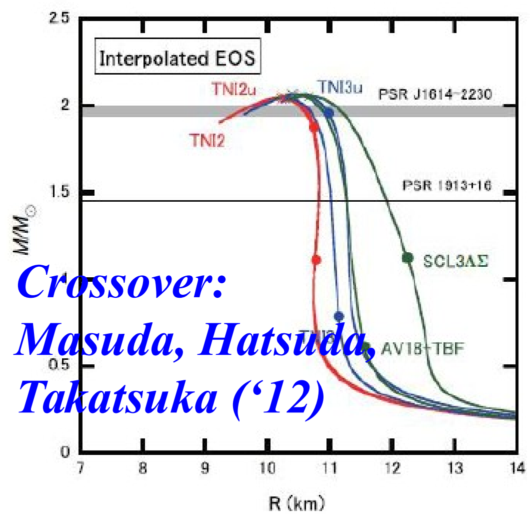
ρ^4 term, Bednarek, Haensel et al.('11)



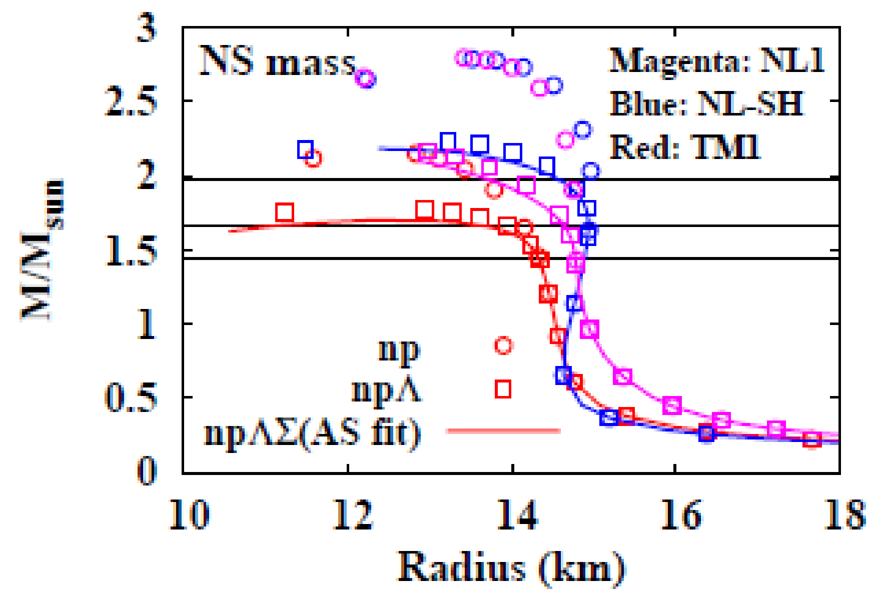
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

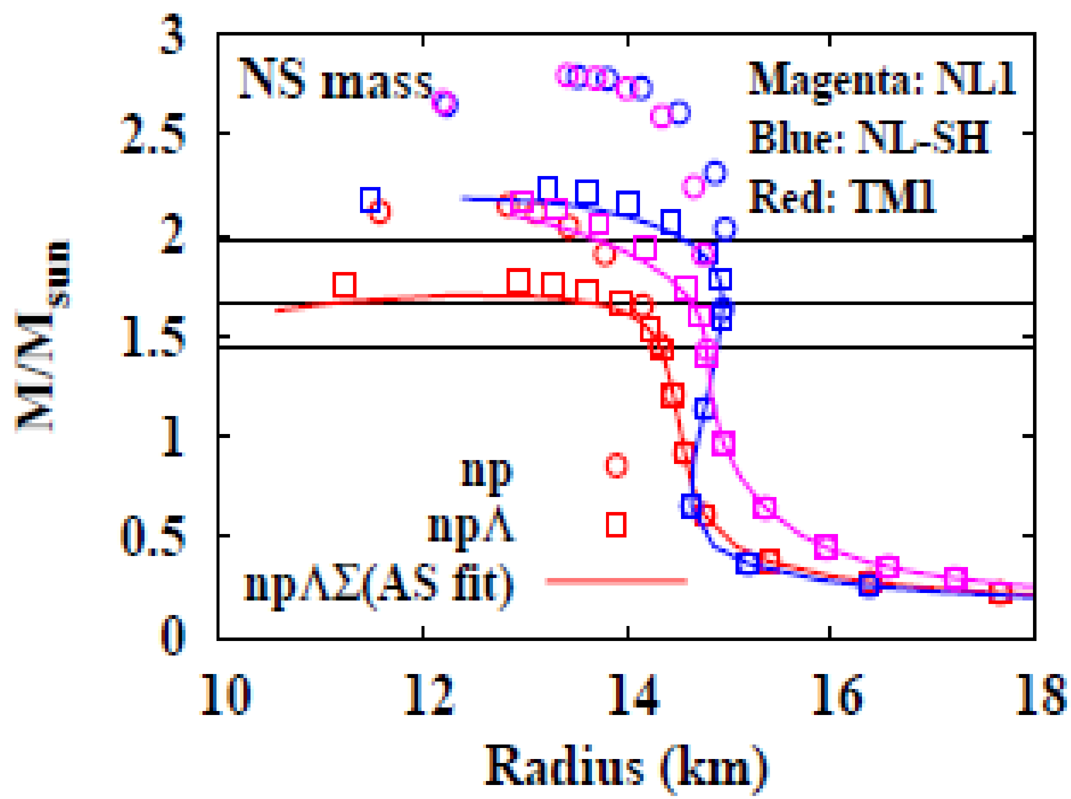


Tsubakihara, Harada, AO, arXiv:1402.0979

Massive Neutron Stars with Hyperons

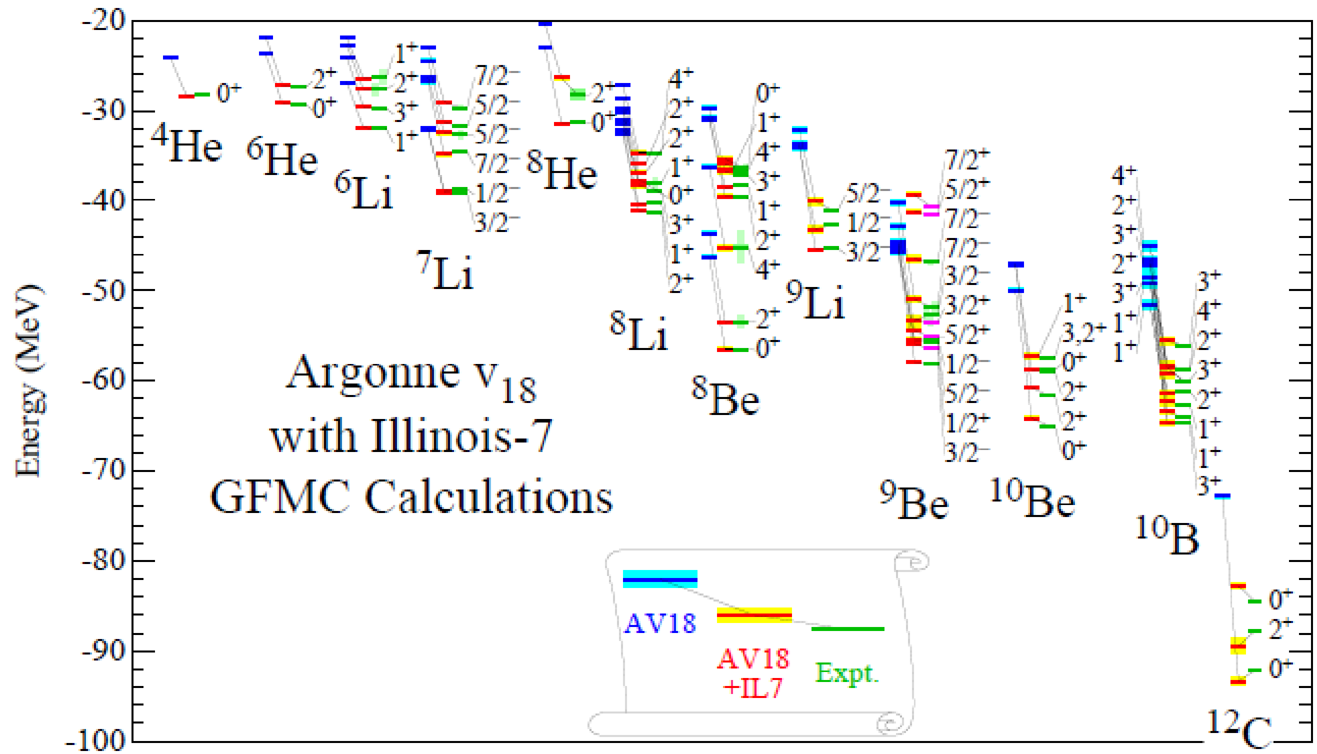
Tsubakihara, Harada, AO, arXiv:1402.0979

- **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 ?

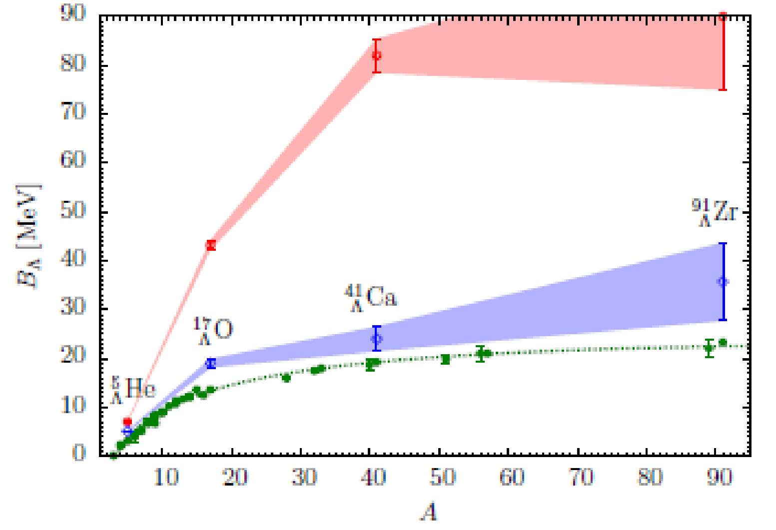
- **There are many "model" solutions.**
- **Ab initio calculation including three-baryon force (3BF)**
  - **Bare 2NF+Phen. 3NF(UIX, IL2-7) + many-body theory (verified in light nuclei).**
  - **Chiral EFT (2NF+3NF) + many-body theory**
  - **Dirac-Bruckner-HF (no 3NF)**

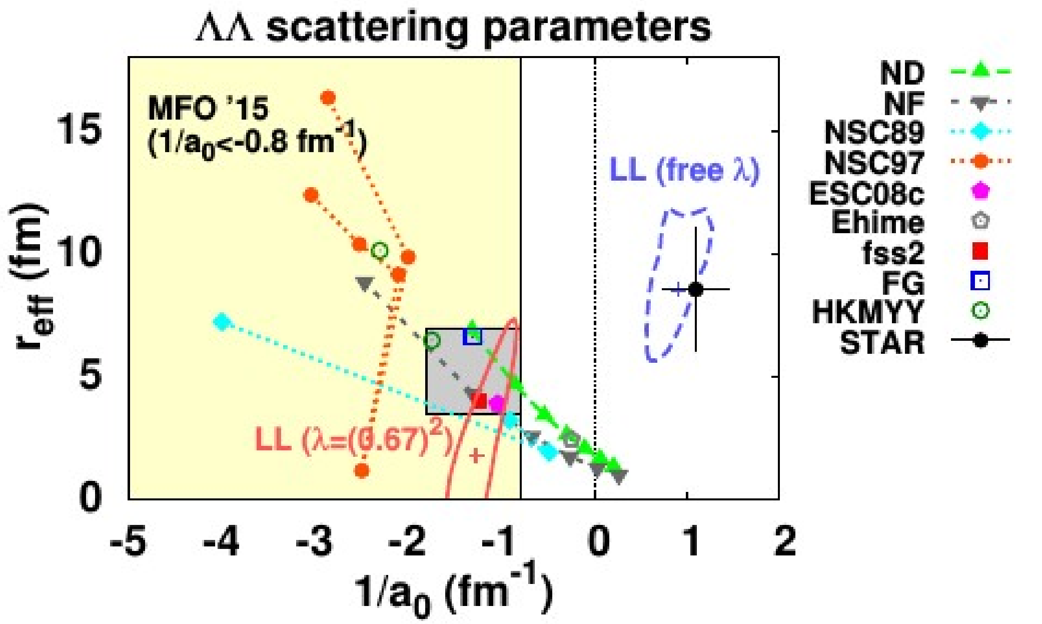


J. Carlson et al. ('14)

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*





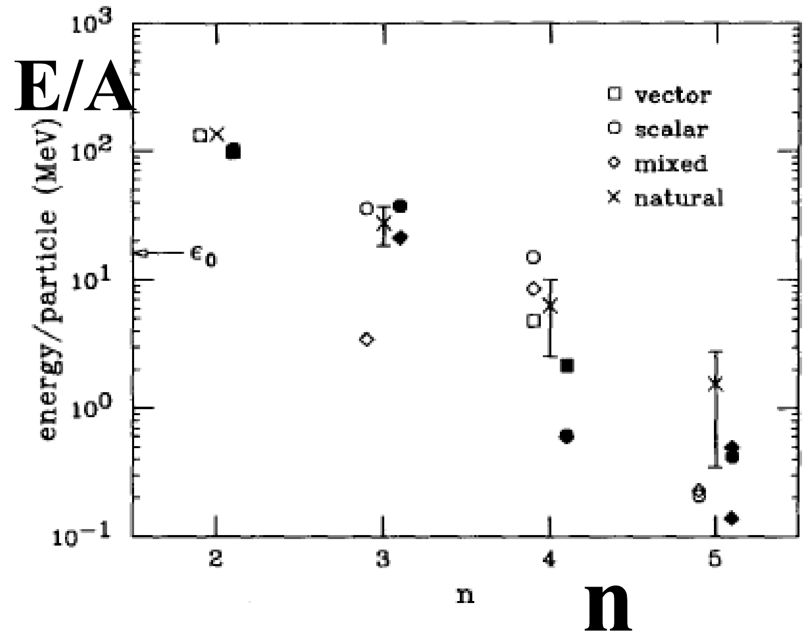
Caveat: Missing data

Alternative approach: Nuclear "Ab initio"+ Y phen.

- **We fit RMF with multi-body coupling to ab initio EOS, and introduce hyperons.**
- **Phen. model = RMF w/ Multi-body coupling**
  - **Naive dimensional analysis (NDA) and naturalness**
    Manohar, Georgi ('84)
    The vertex is called "natural" if C ~ 1 (consistent with pQCD).

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

  - **FST truncation**
    R. J. Furnstahl, B. D. Serot, H. B. Tang, NPA615 ('97)441.
    Truncation the index
    n = B/2 + M + D
    (B: baryon, M: Non NG boson, D: derivatives)
    Natural → V ~ $\rho^n/n!$
    → small for large n



Relativistic Mean Field with Multi-body couplings

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

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

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

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

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

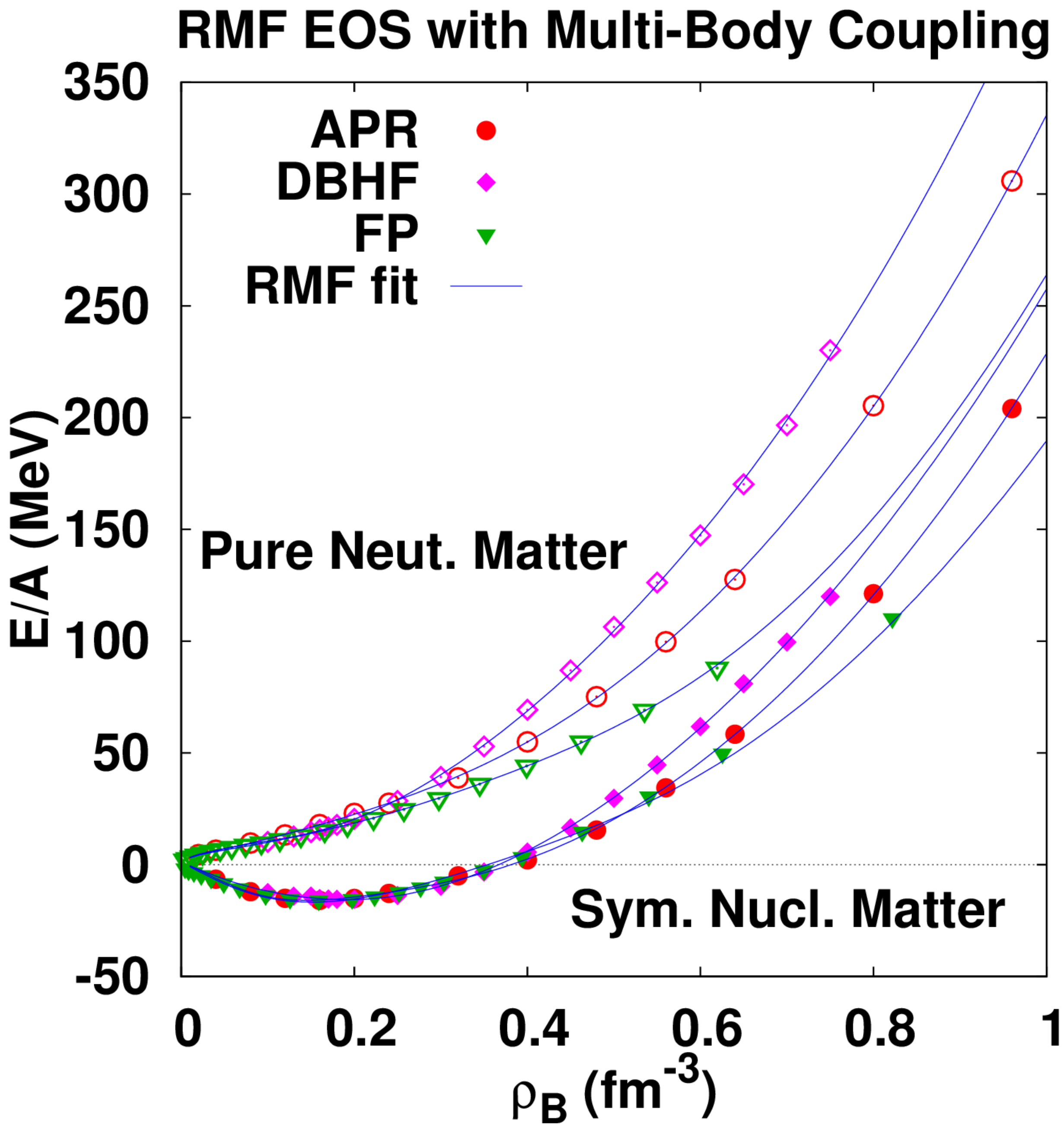
$$\mathcal{V}_{\sigma\omega\rho} = \frac{1}{2}m_\sigma^2\,\sigma^2 - a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\left(\sigma^4 - 4f_\pi\sigma^3\right) - \frac{1}{2}m_\omega^2\,\omega^\mu\omega_\mu\left[1 - c_{\sigma\omega}\,\sigma/f_\pi\right] - \frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2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

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

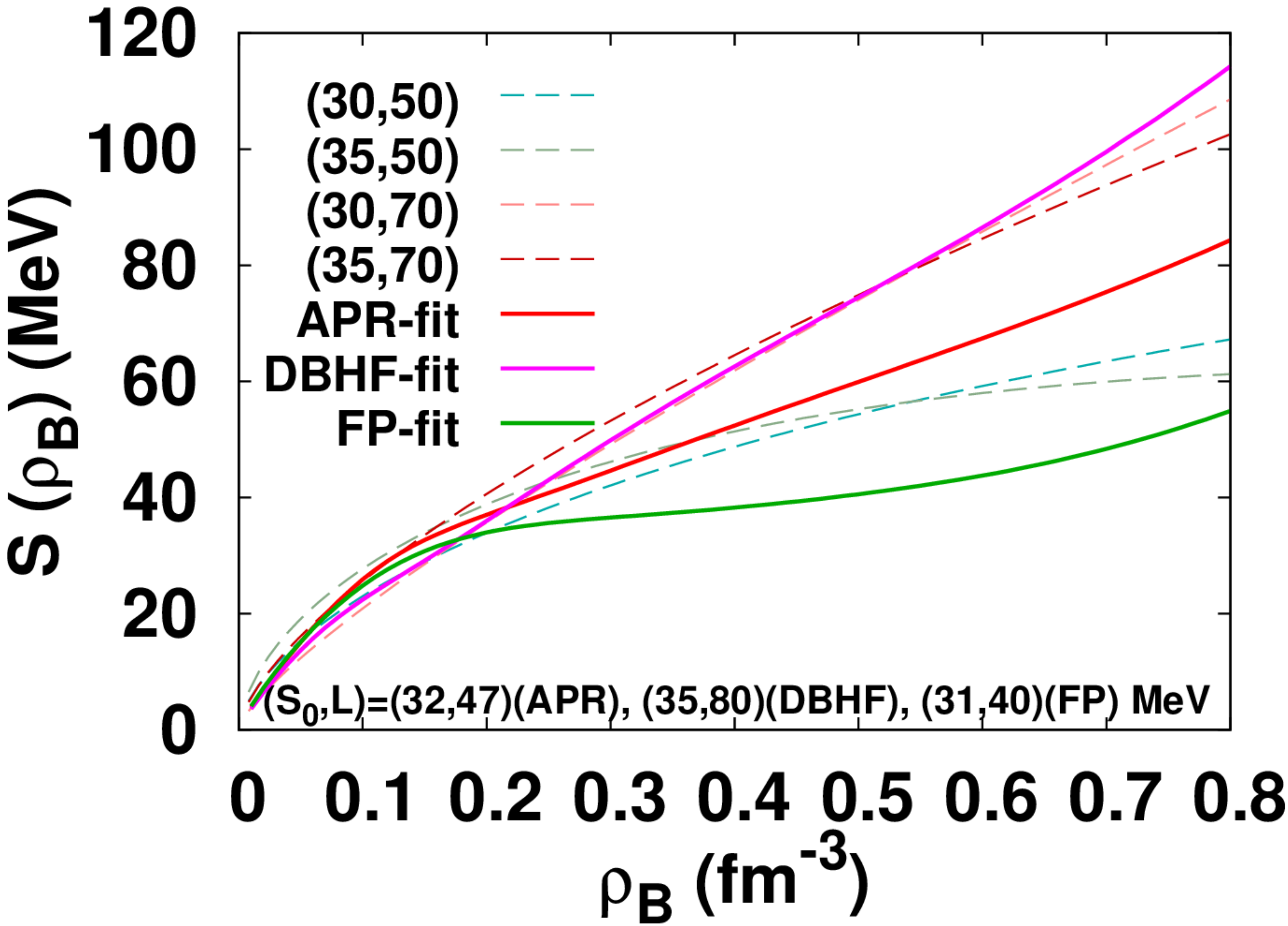
Fitting "Ab initio" EOS via RMF

- "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.+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
- RMF with multi-body couplings: 16 parameters
  - n=3 *Tsubakihara, AO, NPA914 ('13), 438.*
  - 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 → std. dev=0.5-1.0 MeV

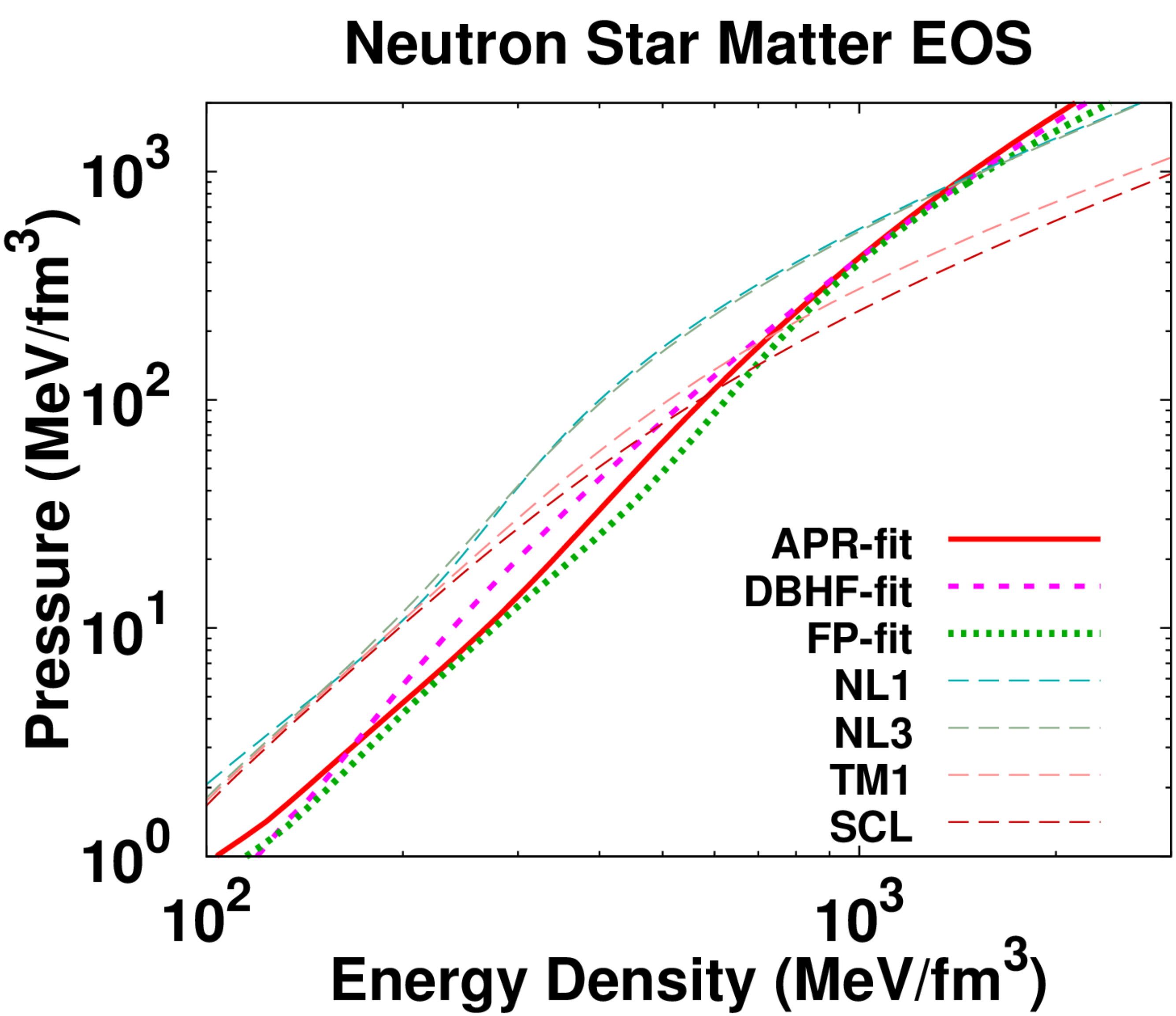
Fitting "Ab initio" EOS via RMF

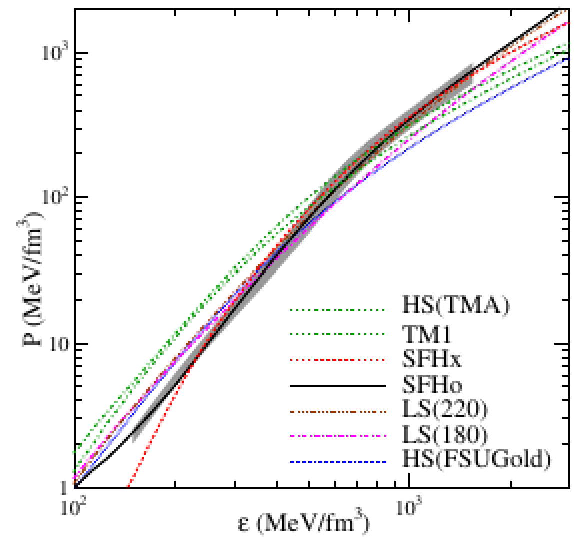


Symmetry Energy



Neutron Star Matter EOS

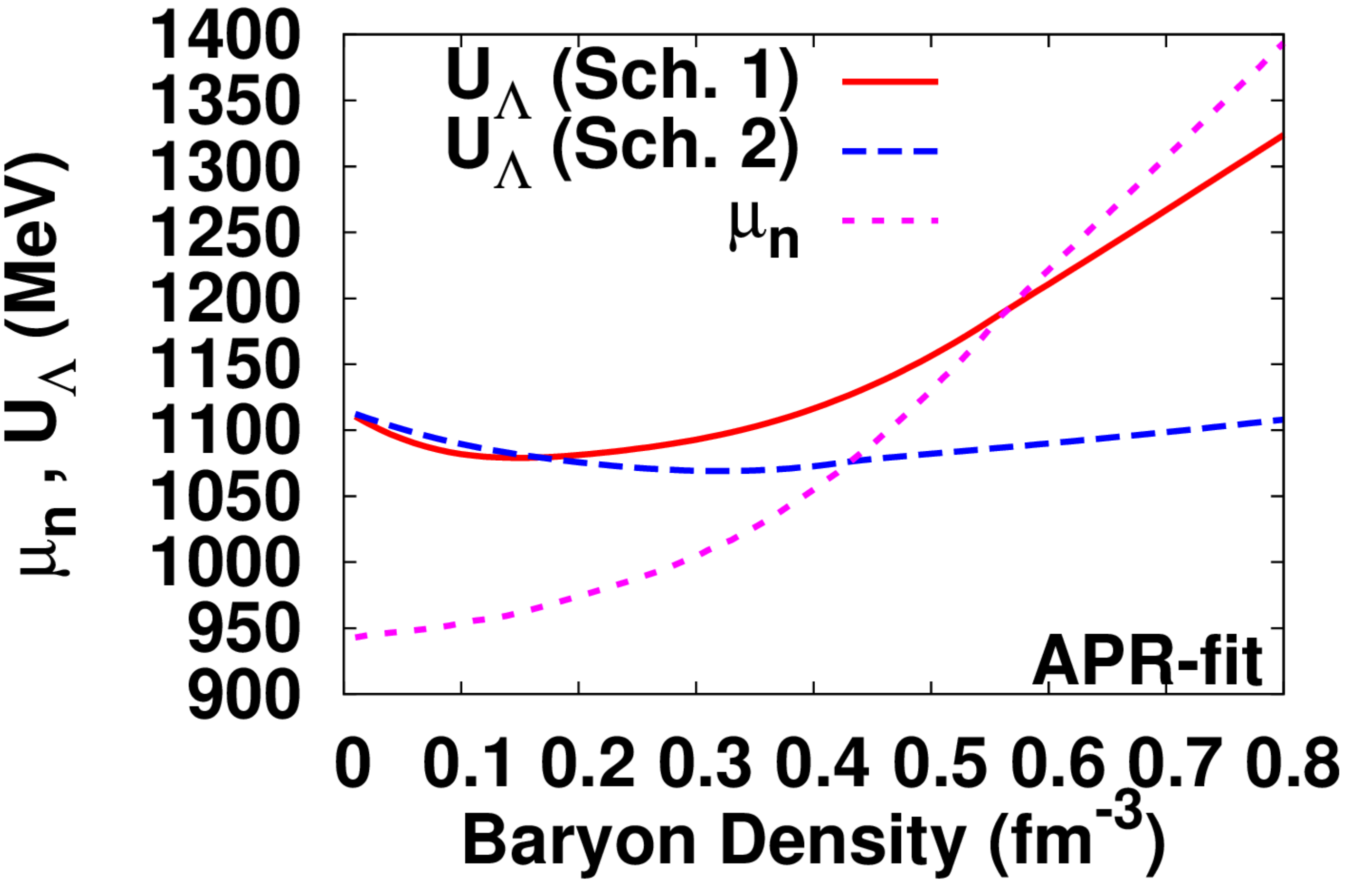




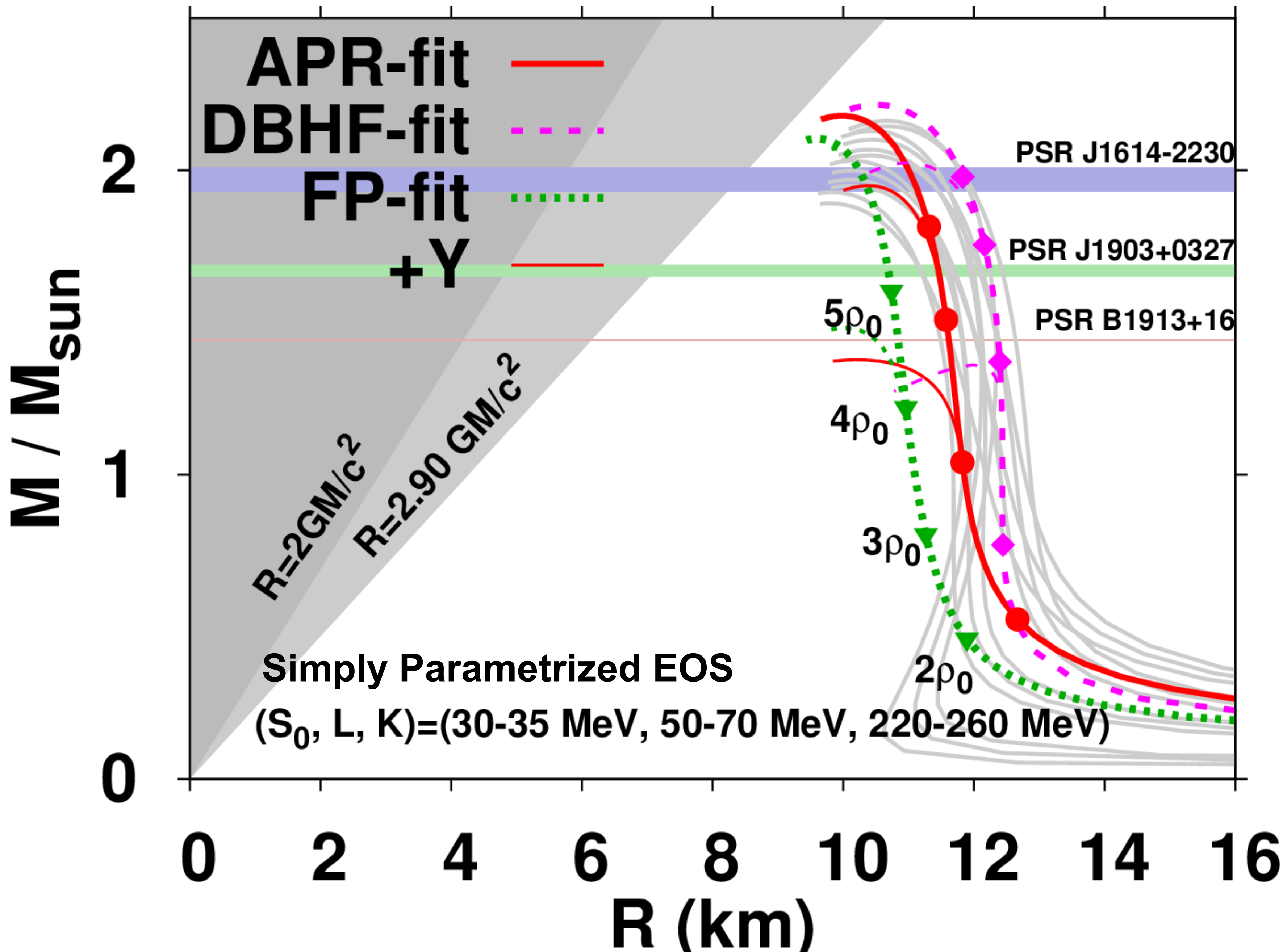
A. W. Steiner, M. Hempel, T. Fischer, ApJ 774 (2013) 17 (TMA+NSE w/ excl. vol.)

NS matter in "ab initio"-fit + Λ

- Λ potential in nuclear matter at ρ_0 ~ -30 MeV
  - Scheme 1: $U_\Lambda(\rho) = \alpha\, U_N(\rho)$
  - Scheme 2: $U_\Lambda(\rho) = 2/3\, U^{n=2}_N(\rho) + \beta\, U^{n>2}_N(\rho)$



M-R curve of Neutron Stars



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.