Explicit three-body couplings in RMF and its effects on symmetry energy

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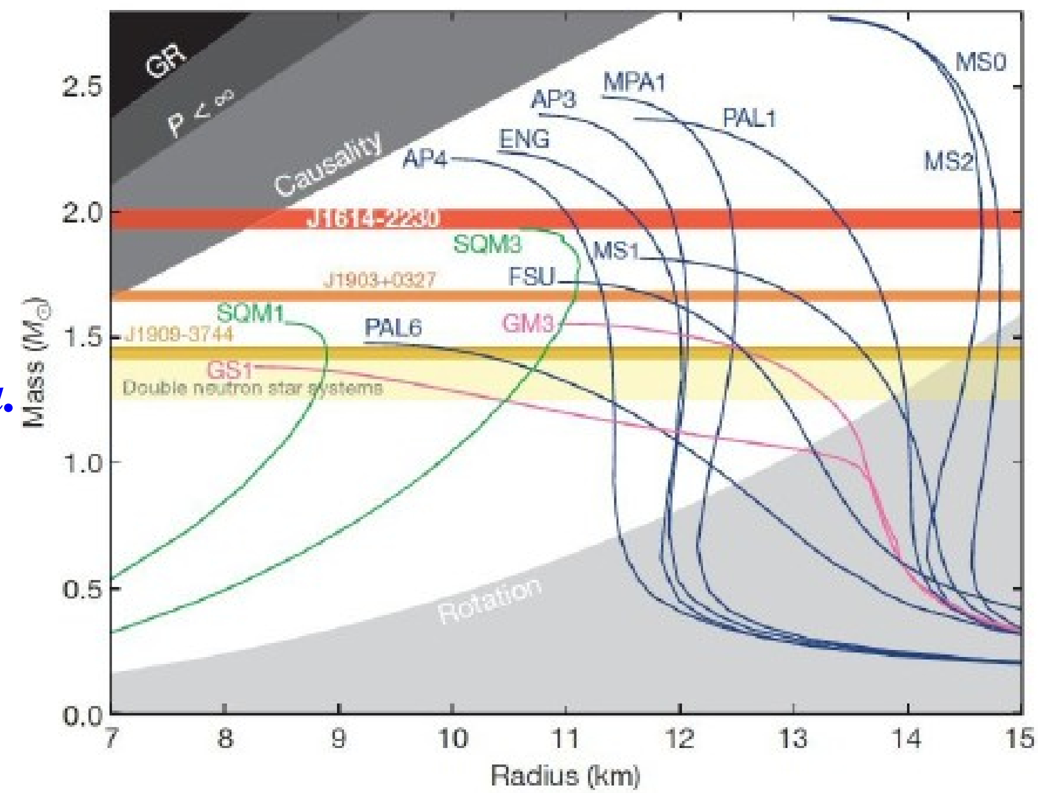
Massive Neutron Star Puzzle

- **PSR J1614-2230 (NS-WD binary), M=1.97 ± 0.04 Msun**
  Demorest et al., Nature 467 (2010) 1081.
- **Something is wrong ! → Massive Neutron Star Puzzle**
  - **Hypernuclear data suggest hyperons should appear in NS.**
  - **EOS with hyperons cannot support 2 Msun NS.**
- **Possible solutions**
  - **Modify YN interaction**
    S. Weissenborn, I. Sagert, et al., ApJ 740 (2011) L14.
  - **Transition to quark matter**
    Vidana; Masuda, Hatsuda, Takatsuka.
  - **Three-body force**
    S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703; K.Tsubakihara, AO, arXiv:1211.7208.

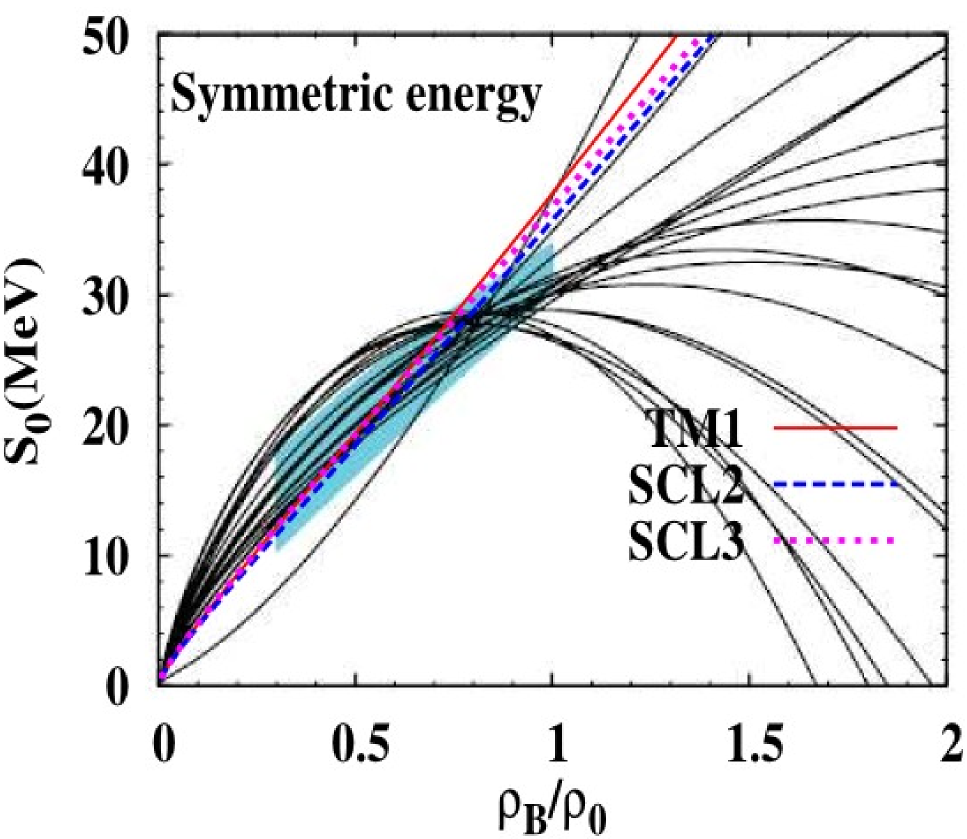


Symmetry Energy

- **NuSym11 results S_0 = 31-34 MeV, L = 50-110 MeV**
  http://www.smith.edu/nusym11
- **Symmetry energy in simple RMF: Esym(ρ_B) $\propto$ ρ_B → L ~ 3 S_0**
  → Asy Stiff EOS
- **Why ?**
  - **Symmetry energy is dominated by ρ meson.**

$$U_{sym} = g_{\rho N} R = \frac{g_{\rho N}^2}{m_\rho^2}(\rho_n - \rho_p)$$

→ We need to include higher order terms or density dep. ρ coupling.



M. B. Tsang et al., Phys. Rev. C 86 (2012) 015803.

Three-body coupling in RMF and Sym. E.

- **We discuss three-body coupling in RMF.**
  - **Towards a consistent understanding of**
    Neutron Star, Hypernuclei, Symmetry Energy,
    RMF is a useful tool.
  - **We need to introduce**
    non-linear terms or density dependent coupling
    in isovector channels in order to control Esym(ρ).
  - **Truncation scheme is necessary to include higher order terms.**
- **By using the RMF with three-body coupling, we examine Esym (ρ_B) and neutron star mass-radius (M-R) relation.**

RMF with Three-Body Coupling

RMF with non-linear terms

- **"Linear" RMF = σω model + ρ meson**

$$L_{\sigma\omega\rho} = \bar\psi_B \left(i\gamma^\mu \partial_\mu - M + g_{\sigma B}\sigma - g_{\omega B}\gamma^\mu \omega_\mu - g_{\rho B}\gamma^\mu \tau_a R^a_\mu \right)\psi_B$$
$$+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma\sigma^2 - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}\omega^\mu\omega_\mu - \frac{1}{4}R^{\mu\nu}_a R^a_{\mu\nu} + \frac{1}{2}R^\mu_a R^a_\mu$$

- **Renormalizable higher order terms terms (σ^3, σ^4, ω^4)**
  - **Reasonable compressibility, density dependence of vector potential.**
    NL1, NL3, TM1, ...
- **Further terms**
  → *RMF an effective theory (Covariant DensityFunctional)*
  - **Vertex in RMF appears from loop diagrams,**
    and to be treated in the tree (mean field) level.
  - **Any term satisfying required symmetry is allowed,**
    and we need a good truncation scheme.

→ *Furnstahl-Serot-Tang (FST) truncation scheme.*

FST truncation

- **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.

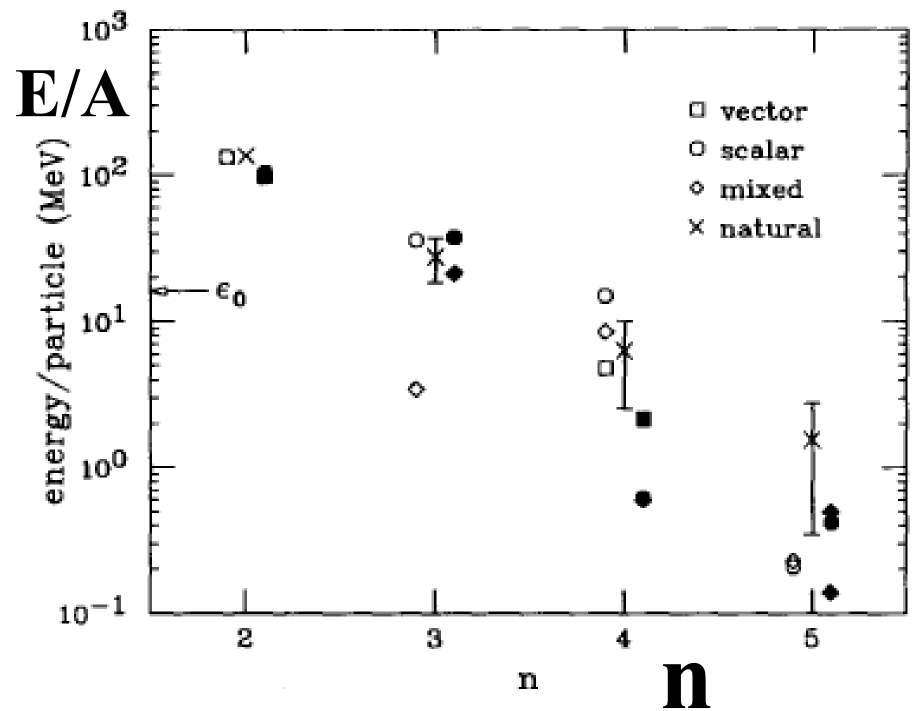
  At a given density, we can truncate the Lagrangian by the index

  n = B/2 + M + D

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

  Naturalness → V ~ $\rho^n/n!$

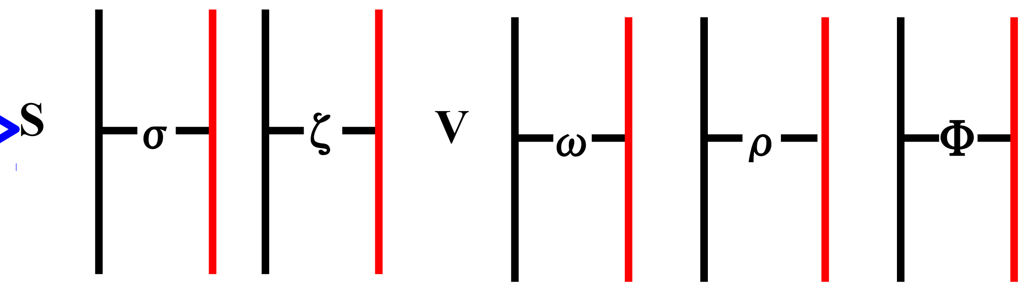
  → small for large n



n=2 and n=3 terms in RMF

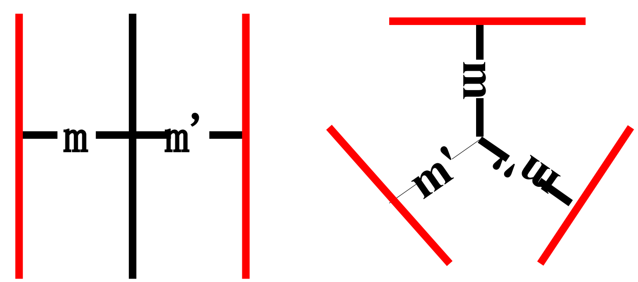
- n=B/2+M+D=<u>2</u> RMF model (+ effective pot.) →<u>2</u>-body interaction (and rel. 3-body corr.)

$$\bar{\Psi}_B g_{mB} m \Psi_B \Longleftrightarrow$$



- n=3 model → 3-body coupling

$$g_{mm'B}\bar{\Psi} m m' \Psi$$
$$c_{mm'm''} m m' m'' \Longleftrightarrow$$



Bmm terms are ignored in FST paper (field redefinitions).

RMF Lagrangian with n=3 coupling terms

$$L = L_{\mathrm{free}}(\bar{B}, B, \sigma, \omega, \rho, \zeta, \phi) - \bar{B}(S_B + \gamma_\mu V_B^\mu)B - V_M$$

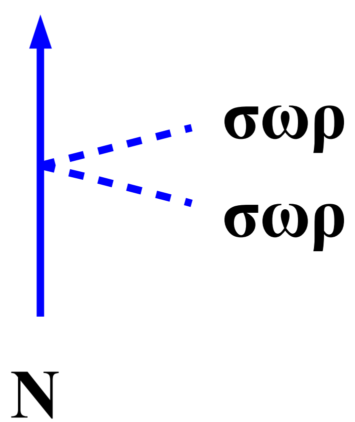
$$S_N = -g_{\sigma N}\sigma + \left(g_{\sigma\sigma N}\sigma^2 + g_{\omega\omega N}\omega^2 + g_{\rho\rho N}R^2 + g_{\omega\rho N}\omega_\mu R^\mu\right)/f_\pi$$

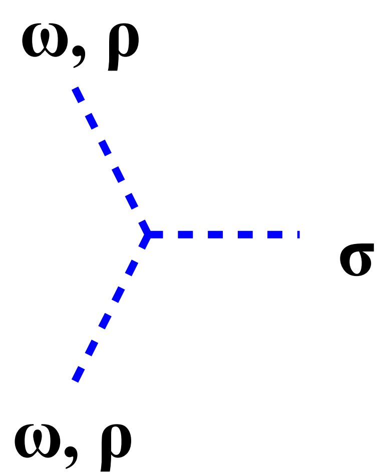
$$V_N = g_{\omega N}\omega + g_{\rho N}R - \left[g_{\sigma\omega N}\sigma\omega + g_{\sigma\rho N}\sigma R\right]/f_\pi$$

$$V_M = V_{\sigma\zeta} - \frac{1}{4}c_\omega(\omega_\mu\omega^\mu)^2 + \frac{1}{2}c_{\sigma\omega}f_\pi\sigma\omega^2 + \frac{1}{2}c_{\sigma\rho}f_\pi\sigma R^2$$

n=3 terms

$(R = \tau_a R_a^\mu$ represents ρ meson$)$





B/2	σ	ω	ρ	Coupling
1	2	0	0	gσσ
1	1	1	0	gσω
1	0	2	0	gωω
0	1	2	0	cσω
1	1	0	1	gσρ
1	0	1	1	gωρ
1	0	0	2	gρρ
0	1	0	2	cσρ
2,3	i	j	k	Not yet

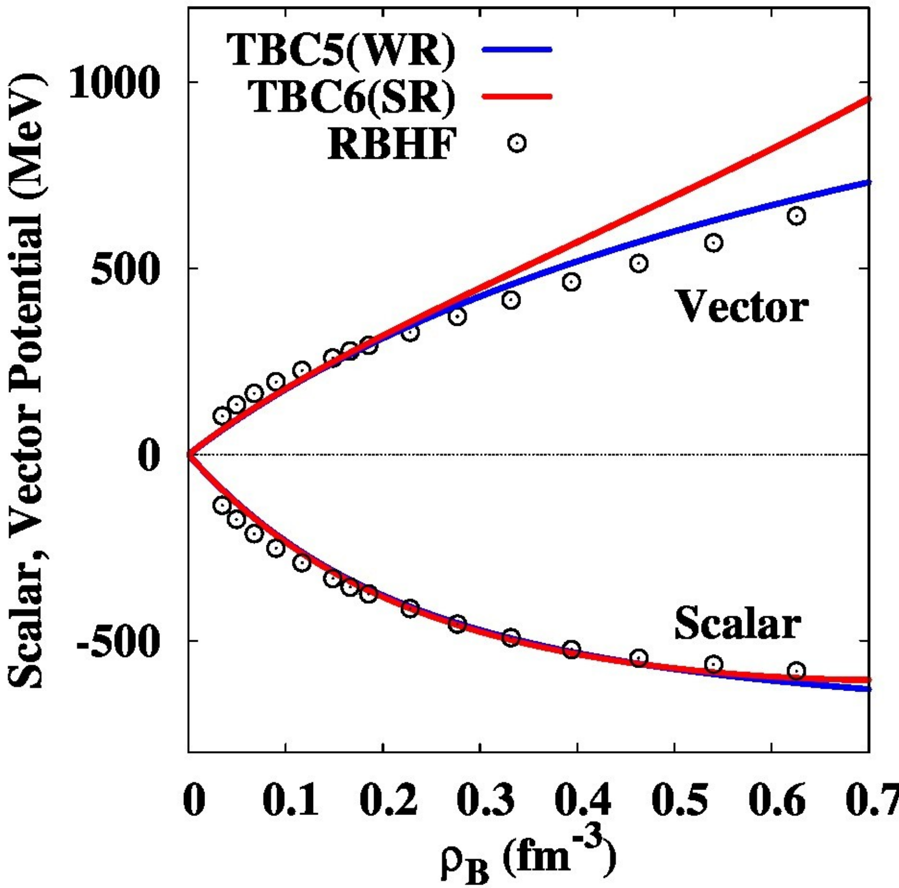
How to fix parameters (in nuclear matter)

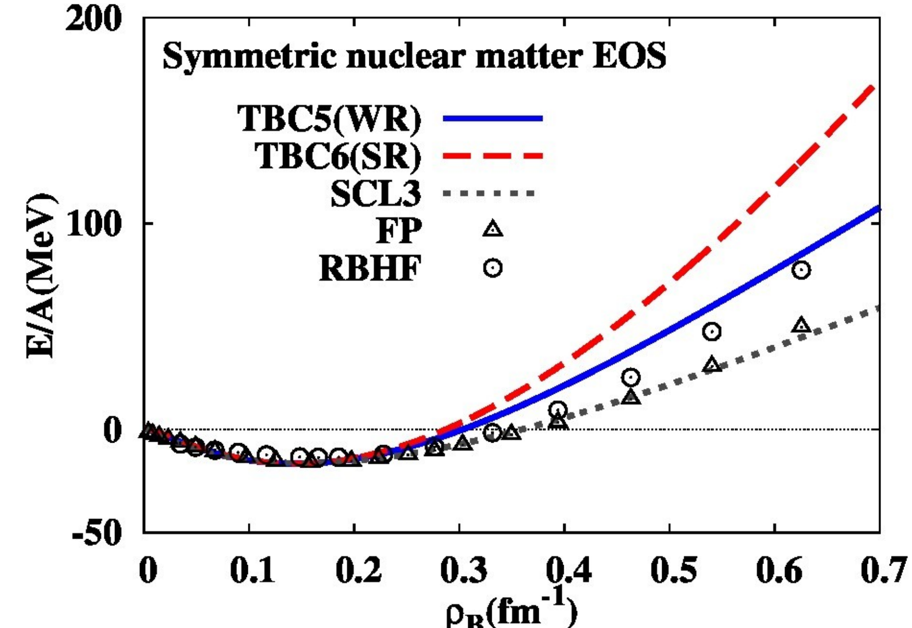
- **Vacuum part: Logarithmic σ and ζ potential**
  Tsubakihara, AO ('08), Tsubakihara et al.('10)
  - **Stability against variation of σ and ζ fields.**
    (Polynomial σ potential is unstable at large values of σ).
- **Symmetric matter**
  - **Adjustable parameters: g_ω, c_ω, $g_{\sigma\sigma}$, $g_{\sigma\omega}$, $c_{\sigma\omega}$**
  - **Fit saturation point, Simulate vector potential in RBHF,**
    Require M_N=0 at $\sigma=f_\pi$
    → 1 parameters are left free, and two sets are prepared.
- **Isovector (IV) part**
  - **Adjustable parameters: g_ρ, $g_{\sigma\rho}$, $g_{\omega\rho}$, $g_{\rho\rho}$, $c_{\sigma\rho}$**
  - **For a given set of (g_ρ, $g_{\omega\rho}$, $c_{\sigma\rho}$), S_0 and L values are fitted via g_ρ and $g_{\rho\rho}$ (not yet complete)**
  - **We adopt those sets which fit BEs of Sn and Pb isotopes**

EOS, Symmetry Energy, and Neutron Star M-R in RMF with Three-Body Coupling

Results (1): Symmetric matter

- Symmetric nuclear matter EoS

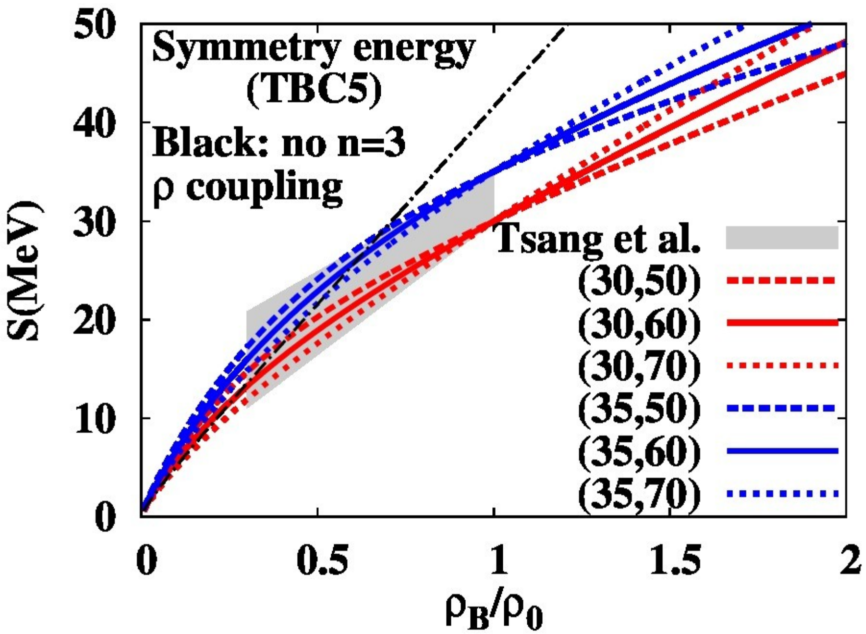


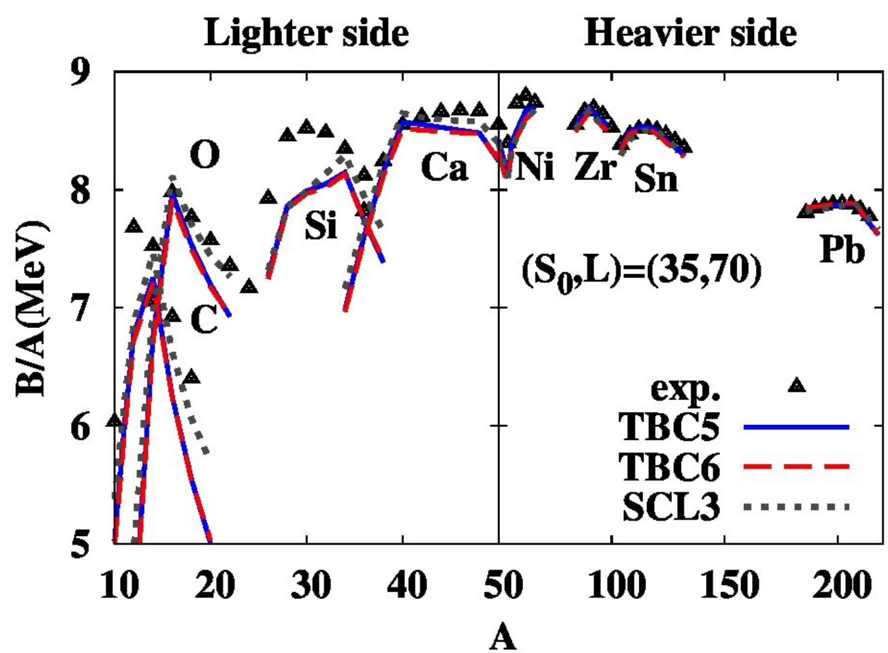


TBC5: determined so as to reporuce RBHF calc.
TBC6: More repulsive parameter set than TBC5

Results(2): Symmetry energy

- Symmetry energy w or w/o n=3 ρ coupling

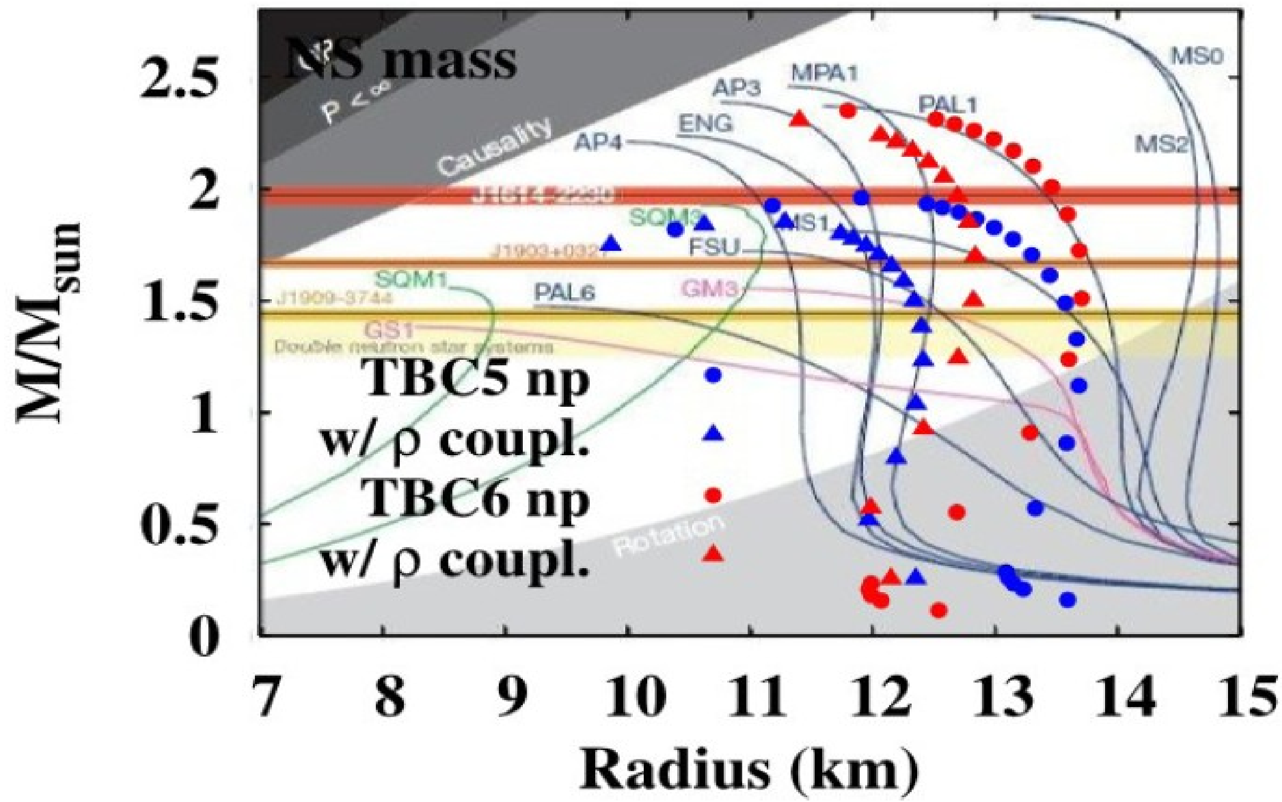




- n=3 ρ couplings: reasonably constrained by (S_0,L)
- Symmetry Energy: good agreement with HIC suggestion
- B/A of heavy nuclei: well-reproduced even if we modify sym. E from n=3 IV type couplings

Results (3): NS-MR

- M-R curve on TBC parameter sets

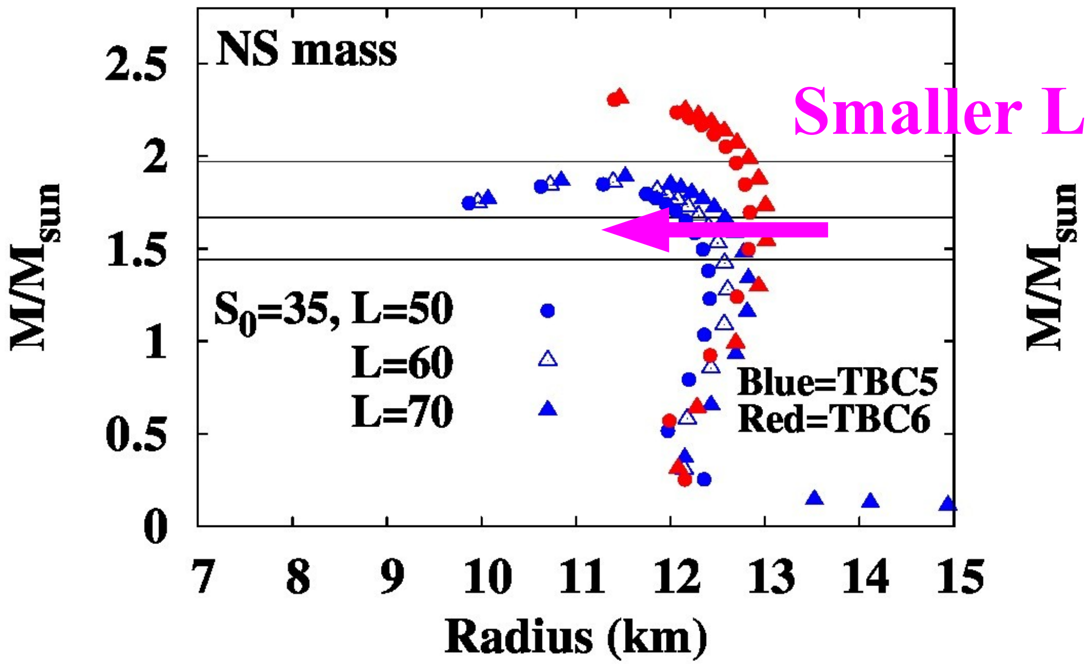


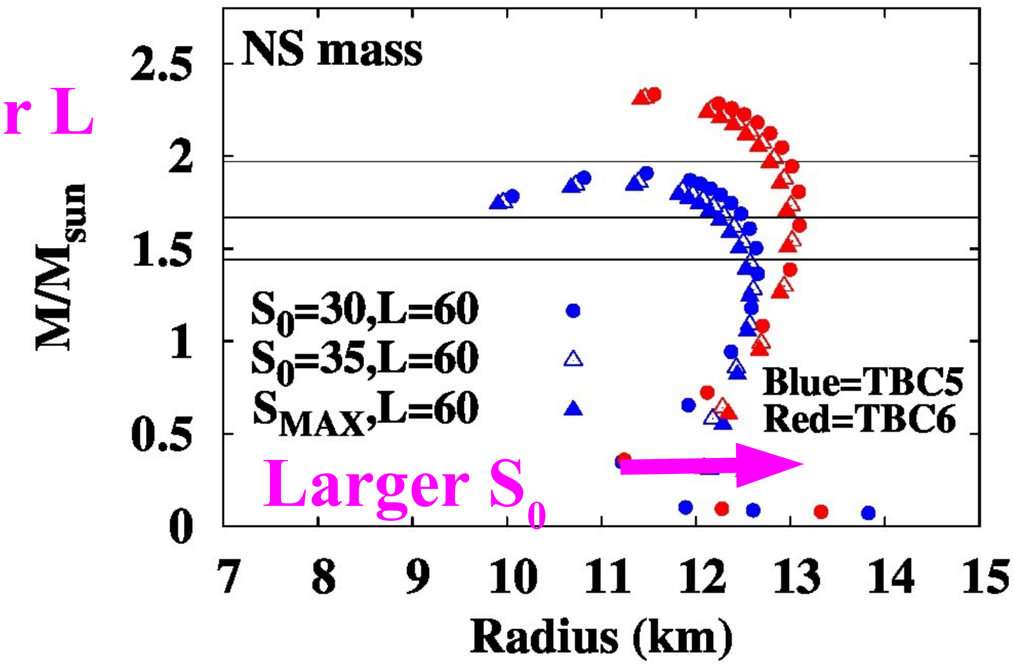
•Symmetry energy: controllable by introducing IV type n=3 couplings
(TBC5: $S_0 \sim$ 41.5MeV >> 35MeV, L $\sim$ 120MeV >>50MeV)

•Large modification to the M-R relation; not to maximum mass of NS

Results (4): (S_0, L) in M-R curves

- Effects of S_0 and L to calculated NS mass

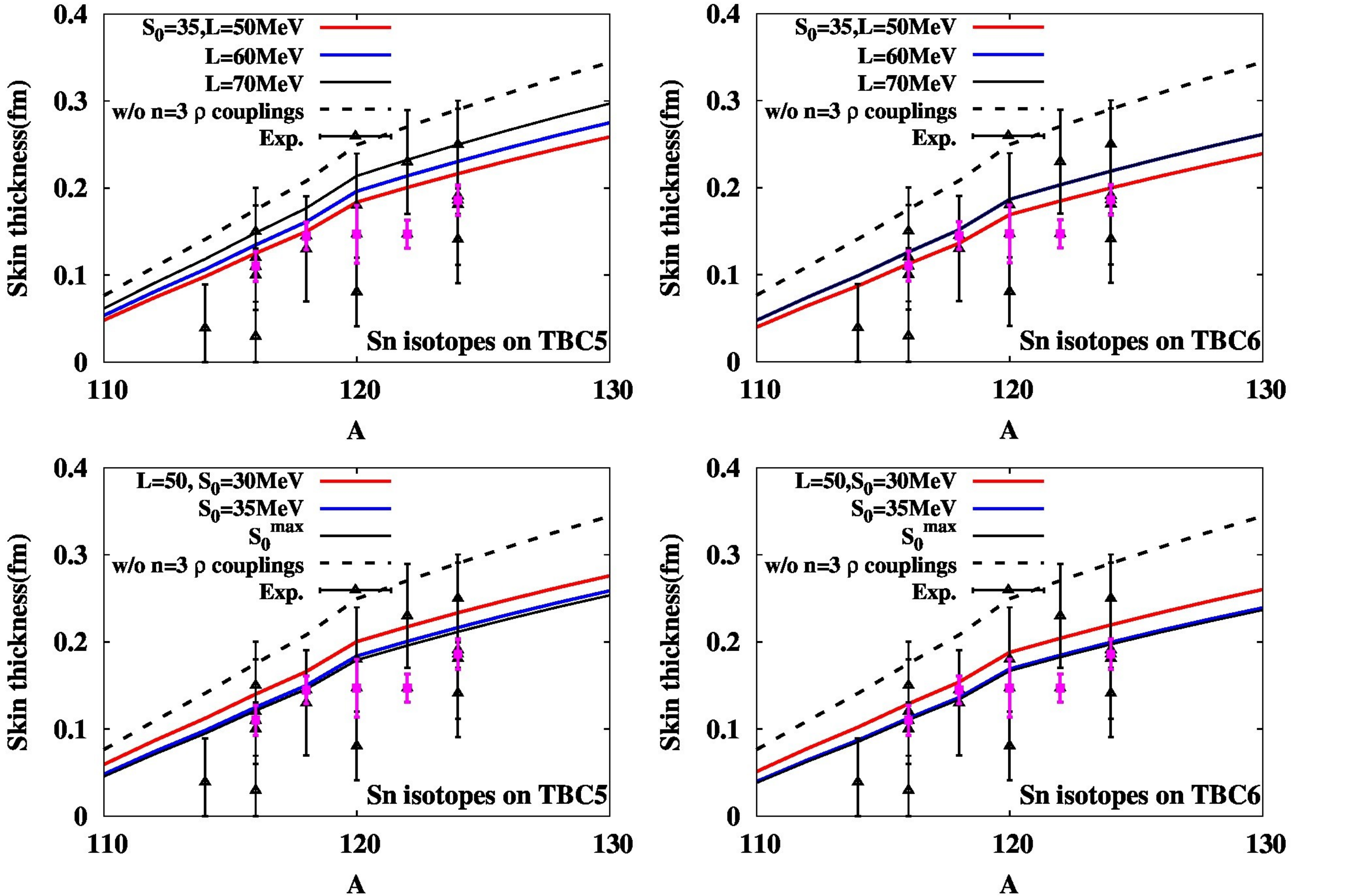




M-R curve: modified by......
L→Higher mass region
S_0→lower mass region

Note: Low density EOS is also given by uniform RMF

Results (5): Neutron skin in Sn



Highlighted RCNP data: Terashima et al. PRC 77 024317

Summary

- **Massive neutron star puzzle and symmetry energy require improvement of RMF.**
  - **EOS at high density should be stiff enough even with hyperons.**
  - **Devistion of Esym(ρ_B) from $\propto \rho_B$ needs other isovector terms.**
- **RMF with Three-Body Coupling (TBC) would provide a possible solution of the above two problems.**
  - **The massive NS can be supported in EOS with hyperons, when TBC is introduced and YN interaction is moderately stiffened.**
    Tsubakihara, AO, arXiv:1211.7208 (HYP XI proc.)
  - **We can respect NuSYM 11 results of Esym in TBC-RMF.**
    Tsubakihara, Harada, AO, in preparation.
  - **Other term such as $\omega^2\rho^2$ (n=4) terms may be also useful to improve density dependence of Esym.** *I. Bednarek et al., arXiv:1111.6942.*
- **S_0 and L effects on NS radius and skin thickness are examined.**

Thanks for your attention !

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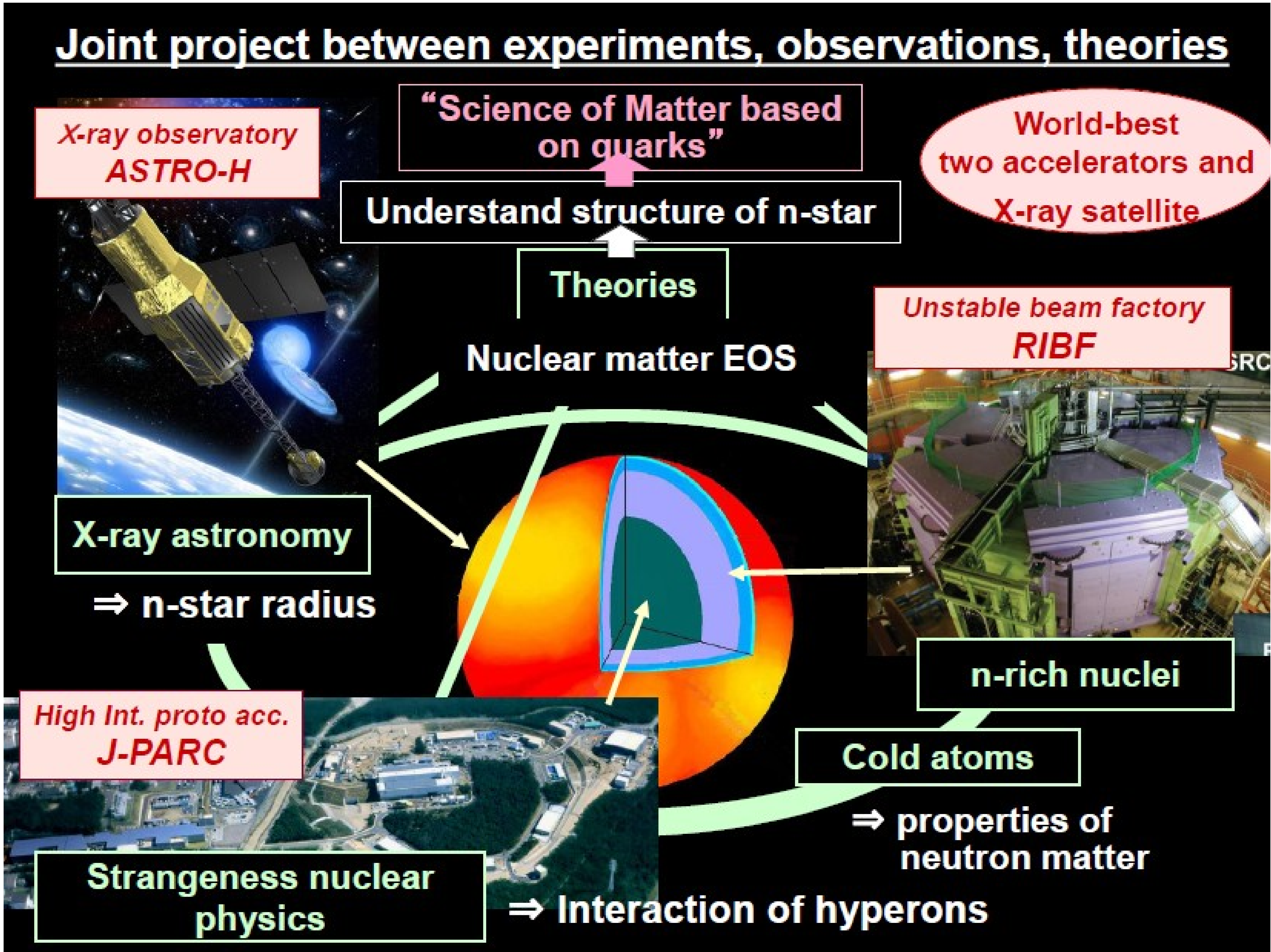
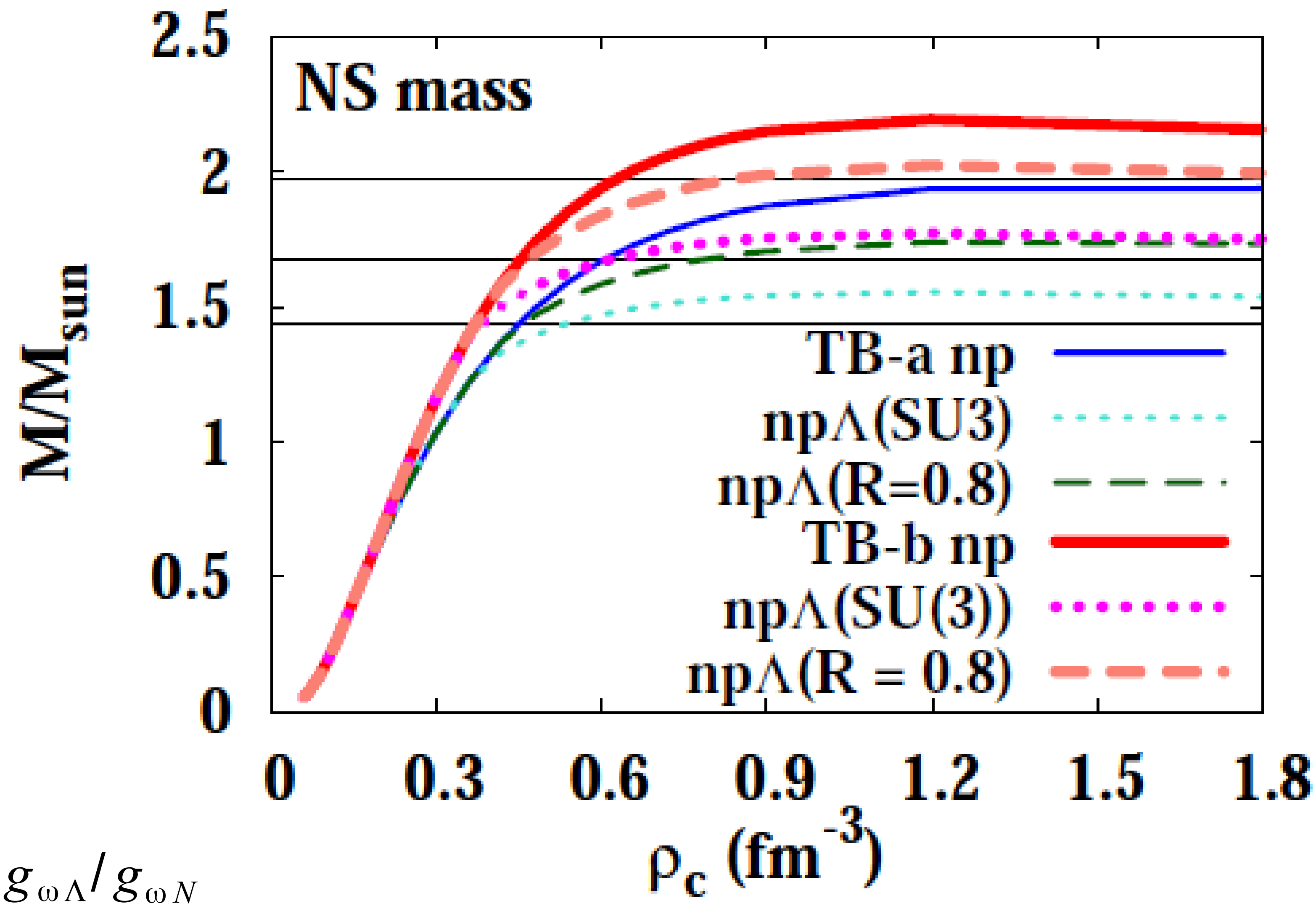


Joint project between experiments, observations, theories
"Science of Matter based on quarks"
Understand structure of n-star
Theories
Nuclear matter EOS
World-best two accelerators and X-ray satellite
X-ray observatory
ASTRO-H
X-ray astronomy
⇒ n-star radius
Unstable beam factory
RIBF
n-rich nuclei
Cold atoms
⇒ properties of neutron matter
High Int. proto acc.
J-PARC
Strangeness nuclear physics
⇒ Interaction of hyperons

NS mass with Hyperons in TBC



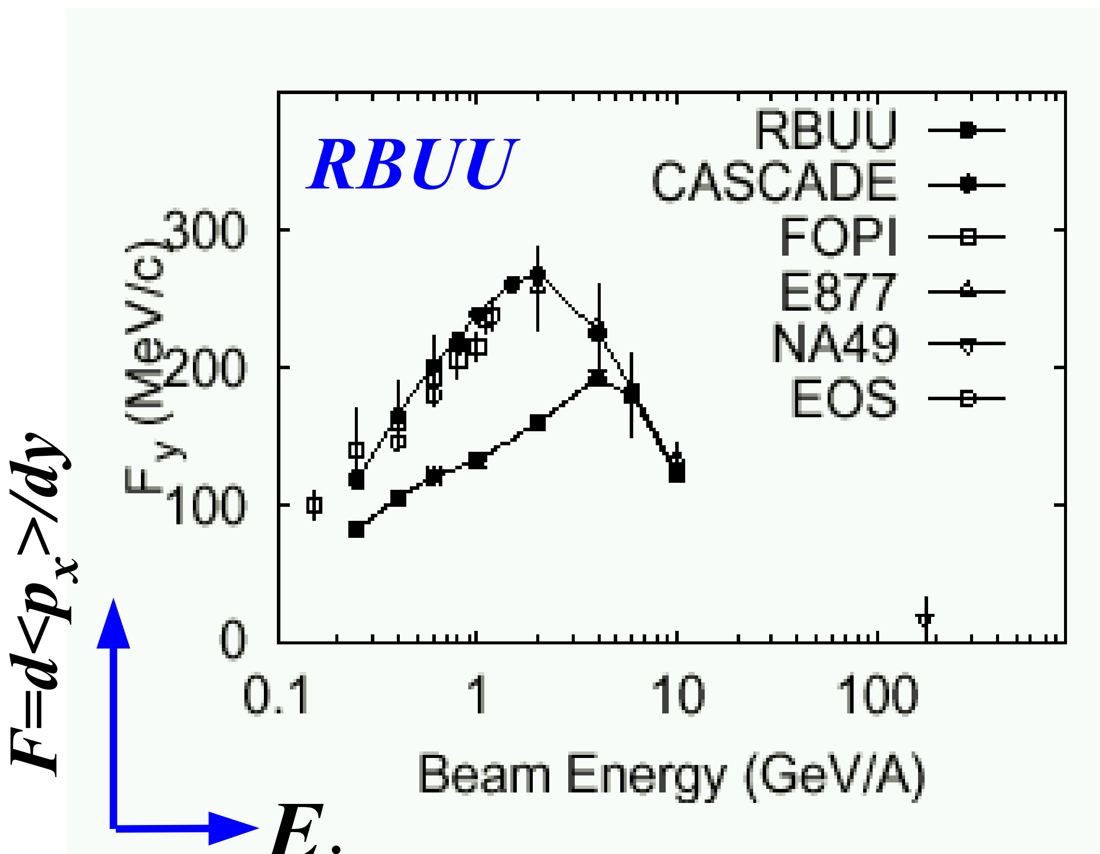
$R = g_{\omega\Lambda} / g_{\omega N}$

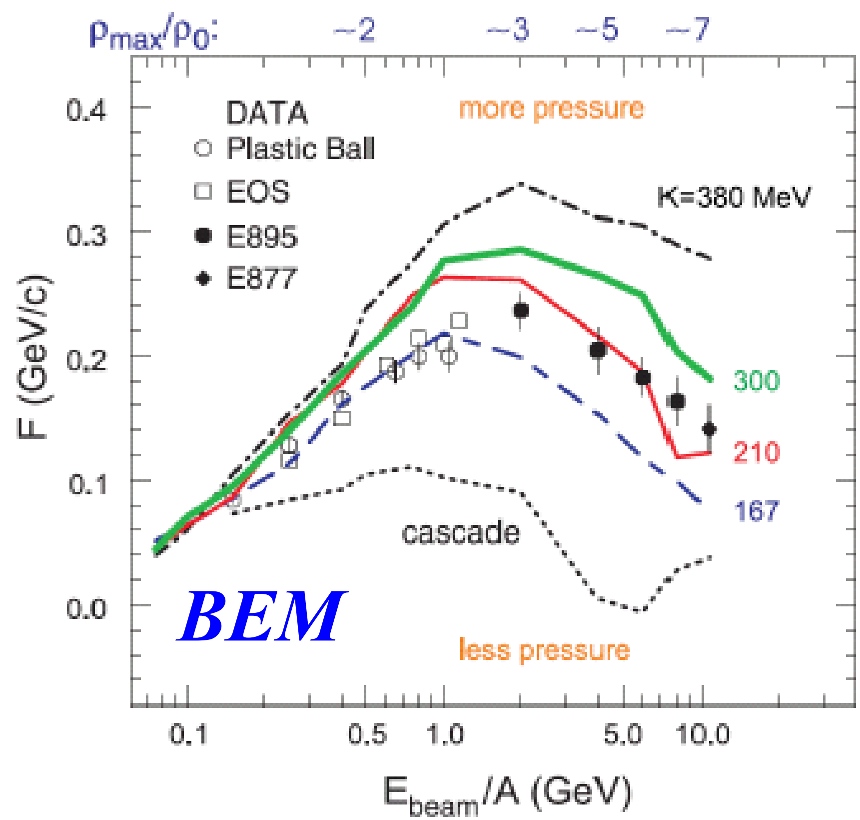
$R(SU(3)) \sim 2/3$

Tsubakihara, AO, arXiv:1211.7208 (HYP XI proc.)

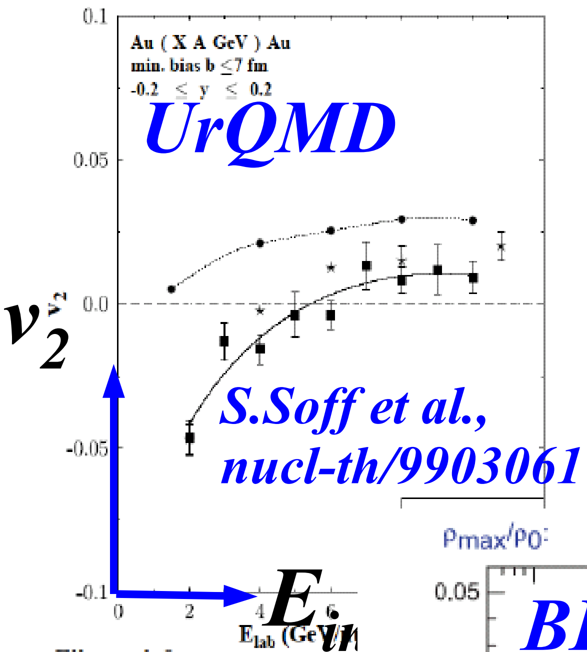
Side Flow at AGS Energies

- **Relativistic BUU (RBUU) model: *K ~ 300 MeV***
  (Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)
- **Boltzmann Equation Model (BEM): *K=167~210 MeV***
  (P. Danielewicz, R. Lacey, W.G. Lynch, Science 298(2002), 1592.)

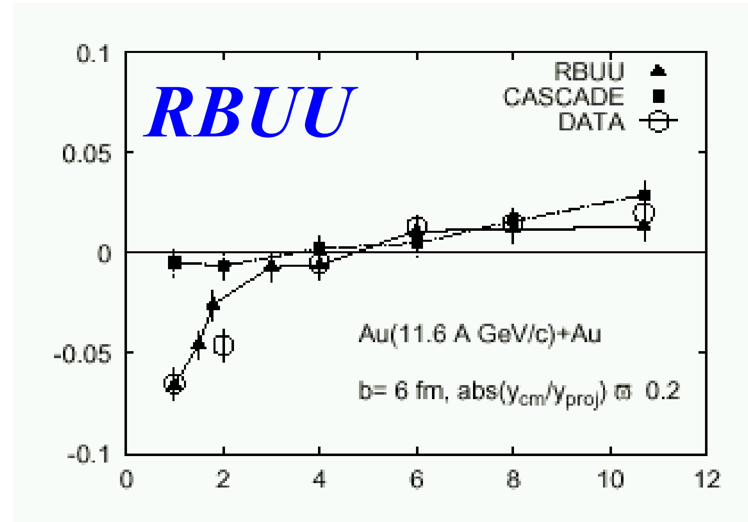




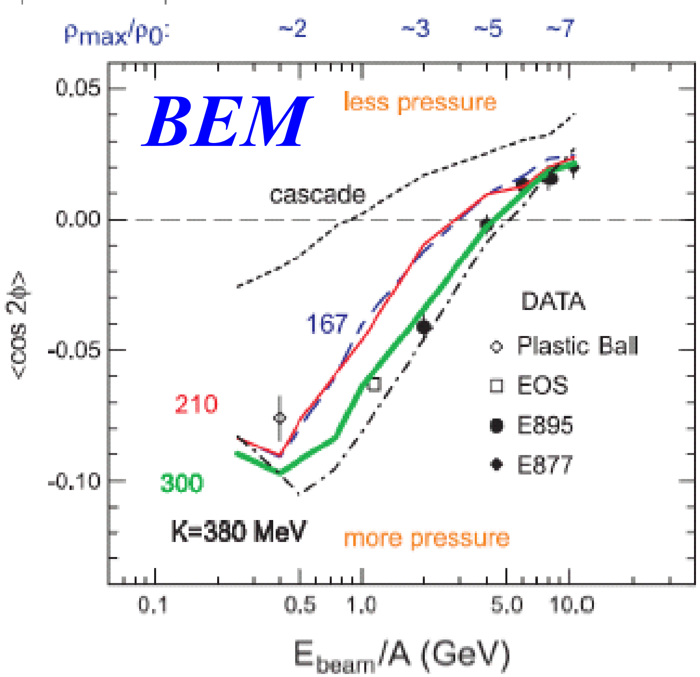
Elliptic Flow at SIS-AGS-SPS Energies



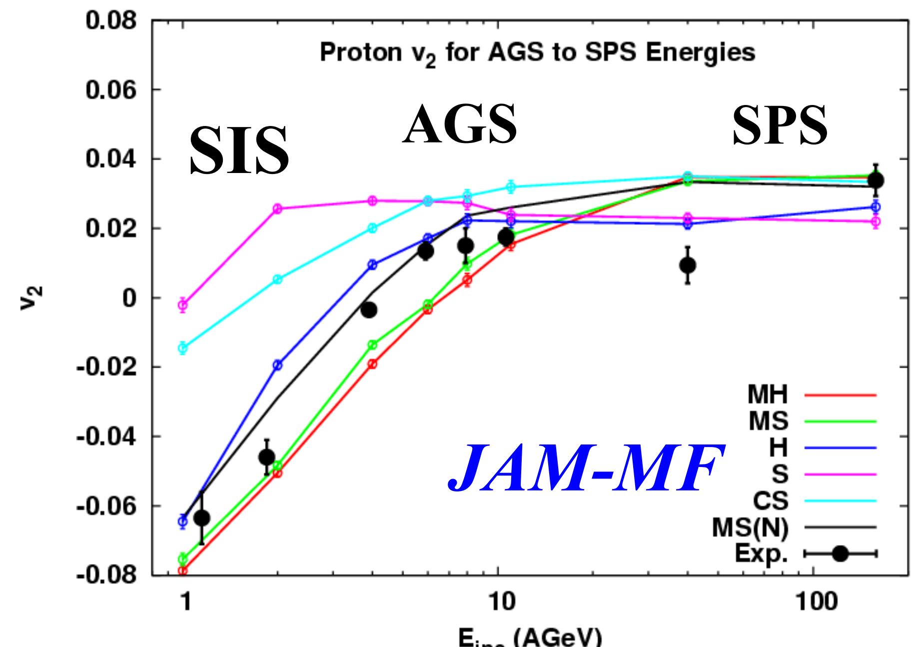
S.Soff et al., nucl-th/9903061



Sahu, Cassing, Mosel, AO ('00)



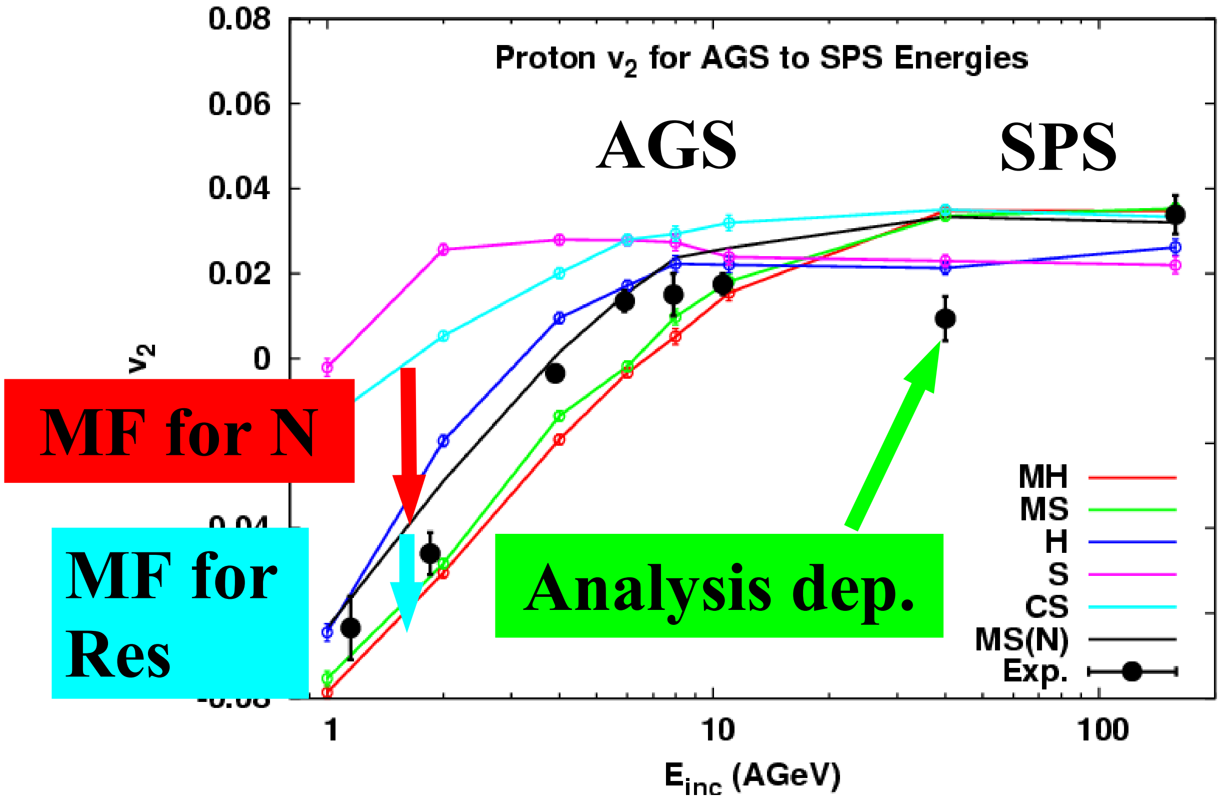
P.Danielewicz, R.Lacey, W.G.Lynch, Science 298(2002), 1592.)



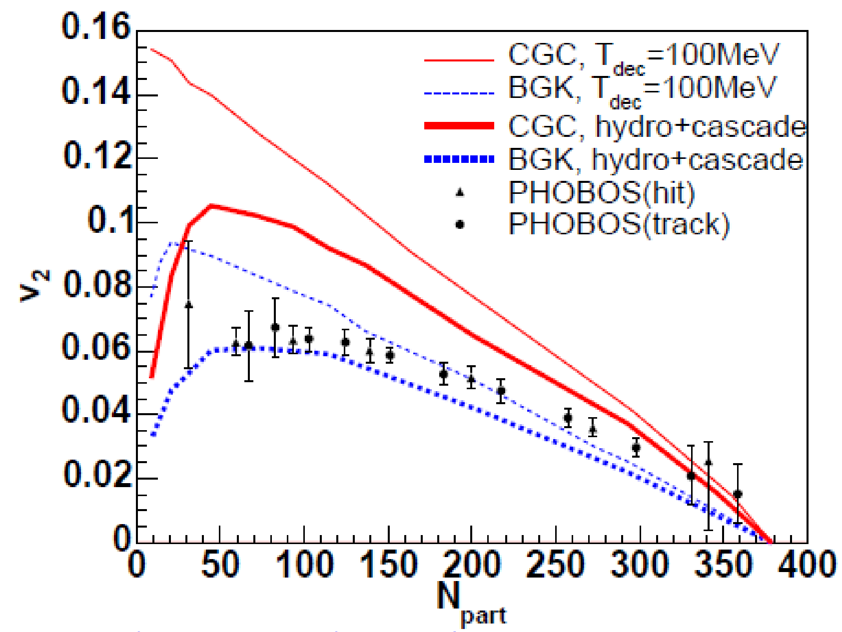
Isse, AO, Otuka, Sahu, Nara, PRC72(2005)064908.

Elliptic Flow at GSI, AGS and SPS Energies

- **JAM-MF with p dep. MF explains proton v2 at 1-158 A GeV (from SIS to SPS energies)**
- **Hydro+JAM Hybrid model explains v_2 at RHIC.**



Isse, AO, Otuka, Sahu, Nara, PRC72(2005)064908.



Hirano,Heinz,Kharzeev, Lacey, Nara,PLB636 ('06)299.