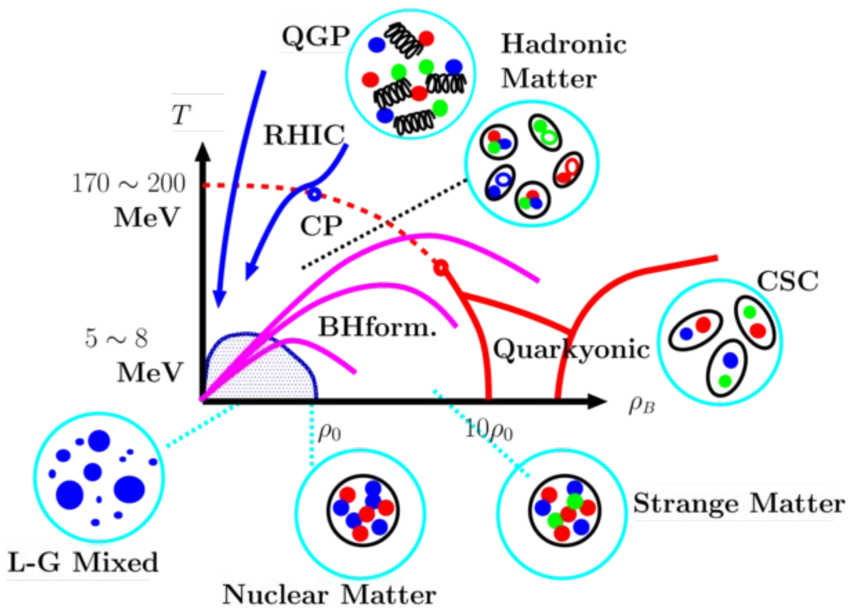
核多体系物理学

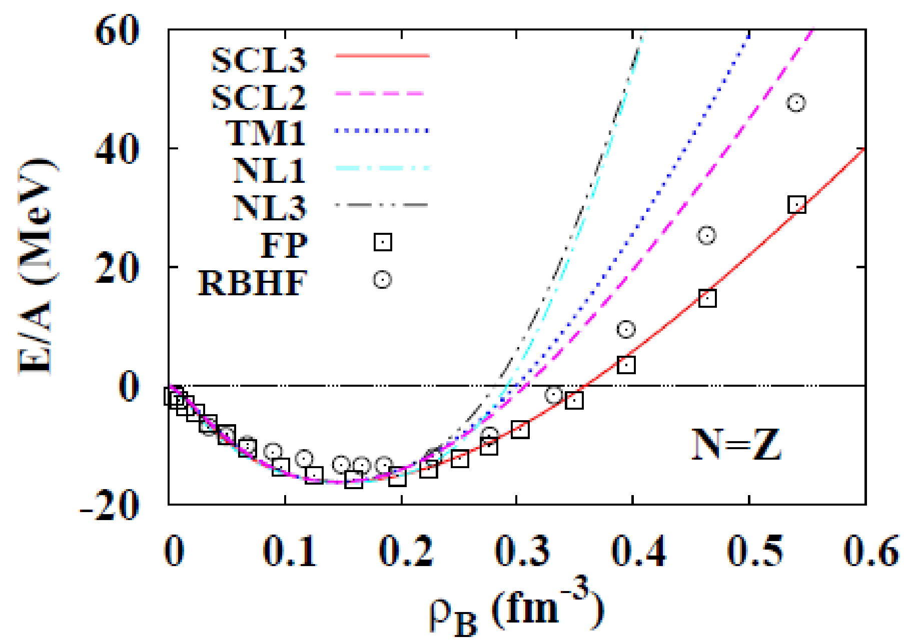
大西　明(基礎物理学研究所)

1. 直接反応理論
    1. 核子-核子散乱:核力と位相差
    2. ハドロン-核反応 (I): 光学模型
    3. ハドロン-核反応 (II): インパルス近似
    4. ハドロン-核反応 (III): グリーン関数法
    5. (高エネルギー核反応：グラウバー模型、ハドロン共鳴)
2. (輸送模型)
    1. 時間依存平均場理論(含:非相対論的平均場)
    2. 半古典輸送模型とボルツマン方程式
    3. 流体模型
3. 状態方程式を記述する理論模型
    1. 相対論的平均場理論
    2. 核子相関の役割 (G-matrix)
    3. 場の理論からのアプローチ:強結合格子 QCD

QCD Phase diagram and Nuclear Matter EOS

- **Phase diagram and EOS**
  = Two important aspects of Nuclear Matter
- **Dense nuclear matter has rich physics**
  → Many-body theory, Exotic compositions, CEP, Astrophysical applications, ...





Nuclear matter EOS
= Subjects in Nuclear, Quark-Hadron, Particle, Astro, and Condensed Matter Physics !

What is EOS ?

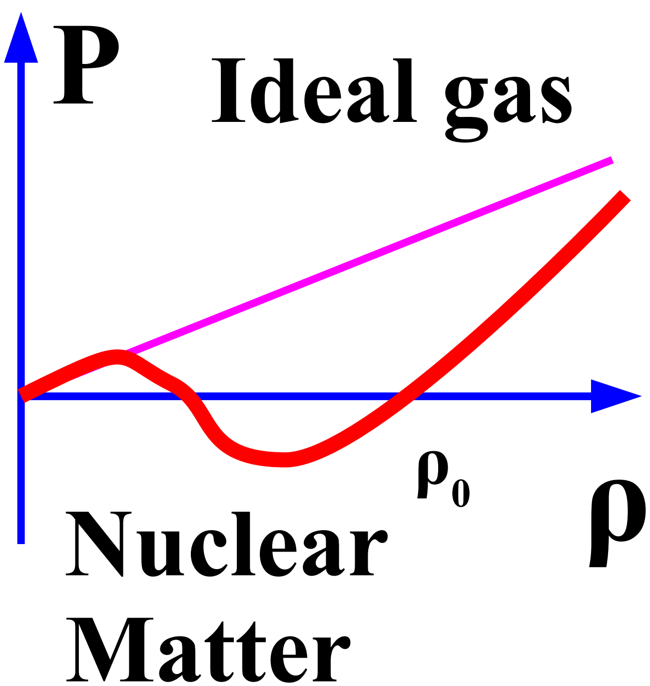
- **Equation of State (EOS) of Ideal Gas (理想気体の状態方程式)**

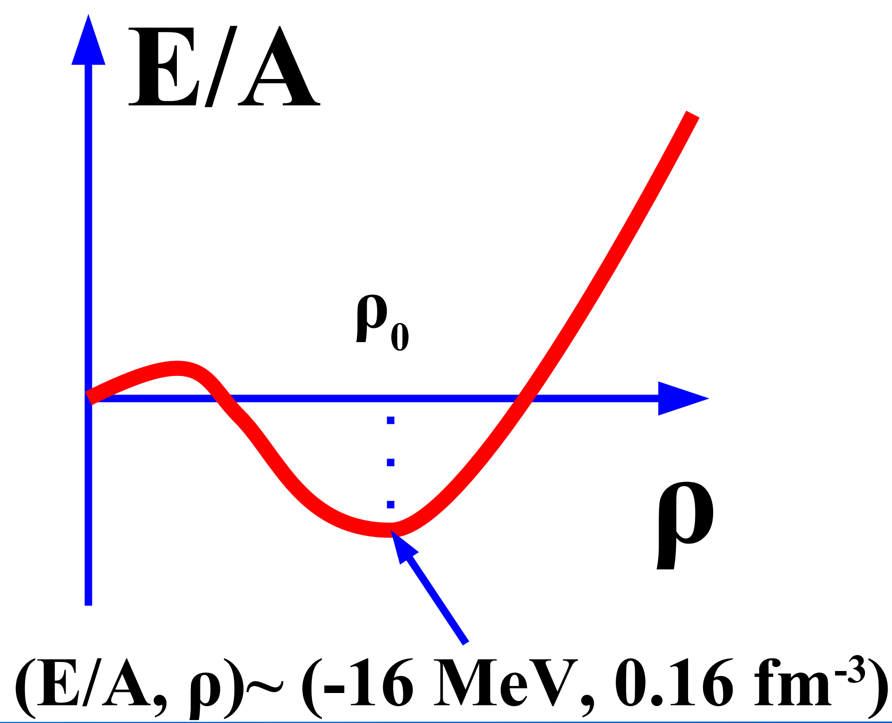
$$PV = NkT \rightarrow P = \rho T \quad (\rho = N/V, k = 1)$$

- **Self-binding system → Null pressure density (ρ_0) exists.**

$$P = P(\rho, T, \ldots), \quad E/A = -\epsilon_0 + \frac{K}{18\rho_0^2}(\rho - \rho_0)^2 + \cdots$$

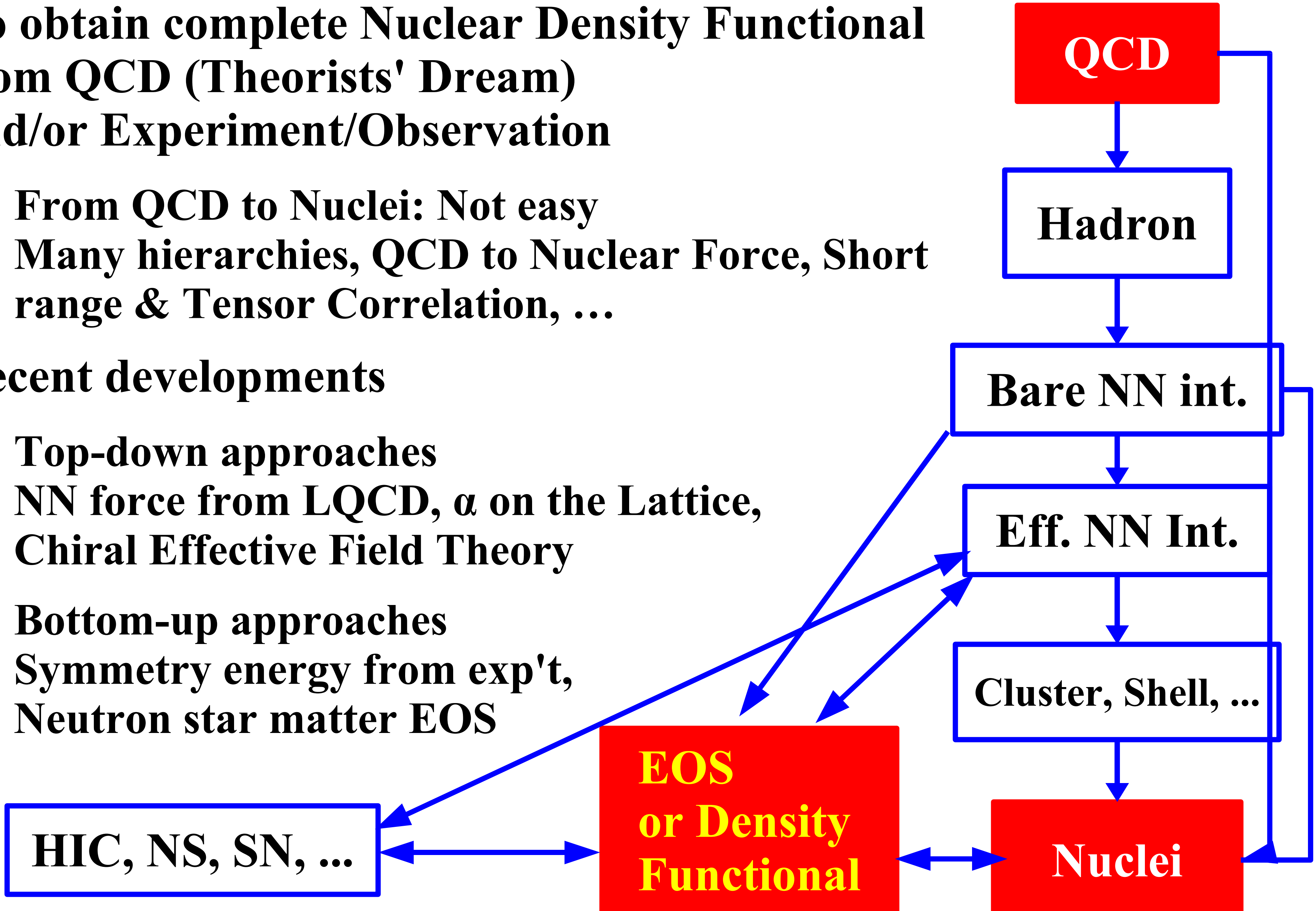
ε_0: Saturation E. (~ -16 MeV), ρ_0: Saturation density (~ 0.16 fm^{-3}), K: incompressibility (~ 200-300 MeV)





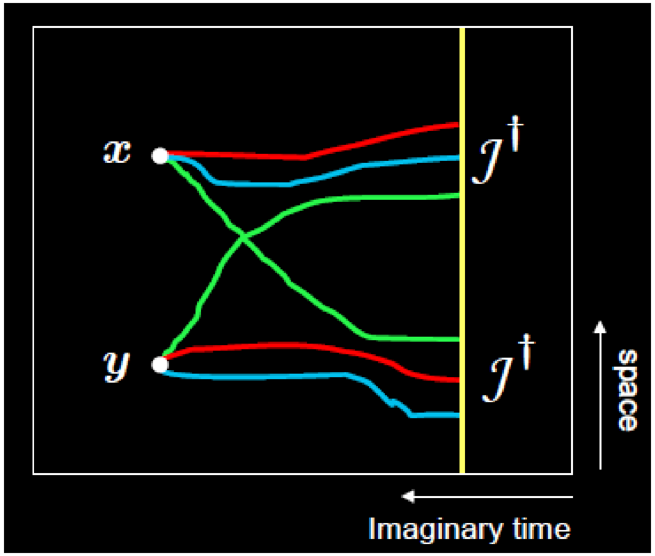
One of the "Ultimate" Goals in Nuclear Physics

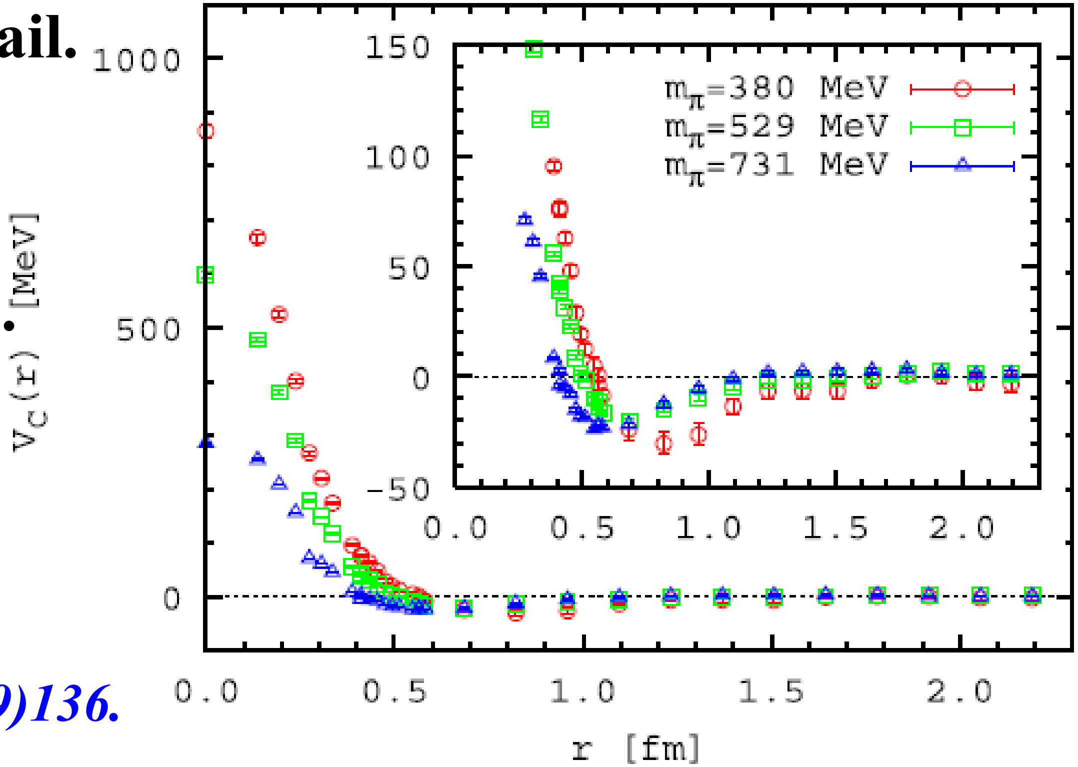
- **To obtain complete Nuclear Density Functional from QCD (Theorists' Dream) and/or Experiment/Observation**
  - **From QCD to Nuclei: Not easy**
    Many hierarchies, QCD to Nuclear Force, Short range & Tensor Correlation, …
- **Recent developments**
  - **Top-down approaches**
    NN force from LQCD, α on the Lattice, Chiral Effective Field Theory
  - **Bottom-up approaches**
    Symmetry energy from exp't, Neutron star matter EOS



Nuclear force on the Lattice

- **BS wave function → Lattice NN Pot.**
  - **Starting from wall source, and measure Bethe-Salpeter ampl.**
  - **By using Schrodinger-type Eq., NN potential is obtained.**
- **Lot of achievements !**
  - **One pion exchange potential tail.**
  - **Repulsive core from quark Pauli principle.**
  - **YN potential, MB potential, …**
- **Needs further studies for EOS**

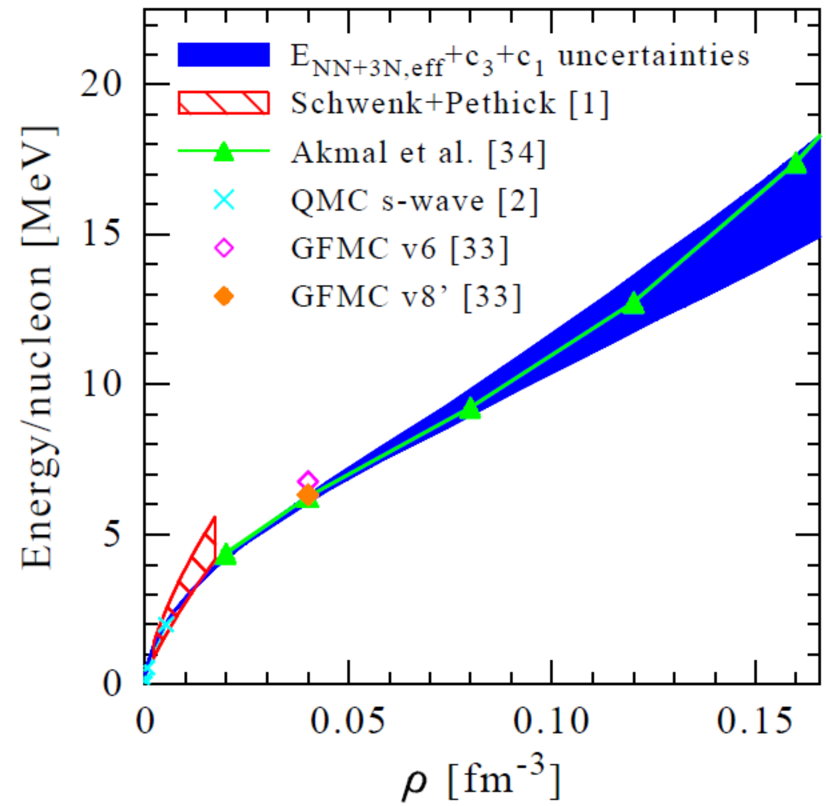




S. Aoki, T. Hatsuda, N. Ishii, PTP 123('10)89
Ishii, Aoki, Hatsuda, PRL 99 ('07) 022001
Nemura et al, arXiv:1005.5352 [hep-lat]
H. Nemura, Ishii, Aoki, Hatsuda, PLB673('09)136.

Ab Initio Calculations

- **Chiral EFT + RG evolution to low momenta**
  - **N3LO NN + NNLO 3N force**
    E. Epelbaum, H.-W. Hammer, U.-G. Meißner, RMP81('09)1773.
  - **3N force → ρ dep. NN force**
    S.K.Bogner, T.T.S.Kuo, A.Schwenk, PRep386('03)1.
- **Neutron matter results**
  - **Consistent with other "rigorous" results such as APR**
    A.Akmal, V.R.Pandharipande, D.G.Ravenhall, PRC58('98)1804.
    → Understanding of the origin of phen. 3-body repl. in APR.
- **Related work:**
  - **QMC on the lattice**
    T. Abe, R. Seki, PRC79('09)054002.
  - **3NF from Exp. (Sekiguchi)**



K. Hebeler, A. Schwenk, arXiv:0911.0483

Symmetry Energy (1)

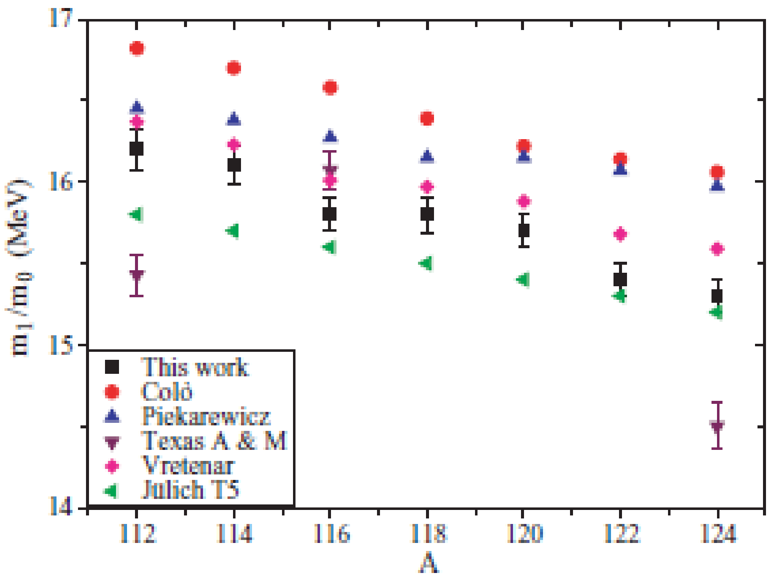
- **Recent data suggest that EOS becomes softer in asymmetric nuclear matter.**

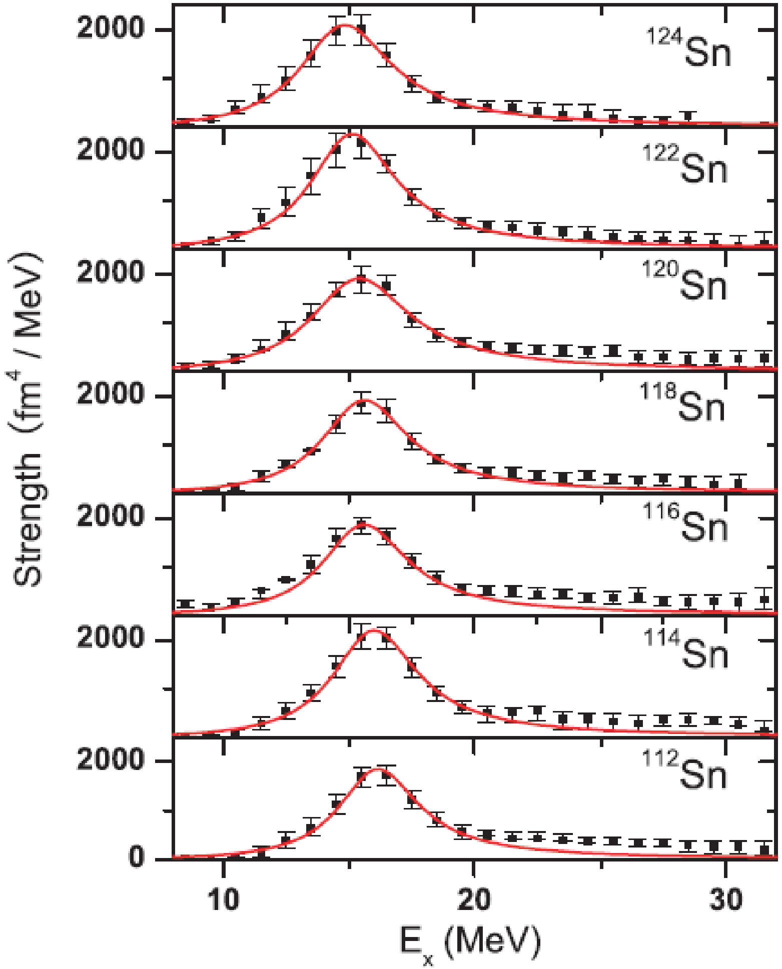
$$K = K_{sym} + K_{asy}\,\delta^2, \quad K_{asy} \sim -550\,\mathrm{MeV}$$

$$E_{sym} \simeq 31.6\,(\rho/\rho_0)^{1.05}\,\mathrm{MeV}$$

(c.f. E_{sym} ~ 23 MeV from Mass formula)

- **Isoscalar Giant Monopole Resonance (ISGMR) of Sn isotopes**
  - **ISGMR in Isotope chain (^{112}Sn ~ ^{124}Sn) is systematically studied.**





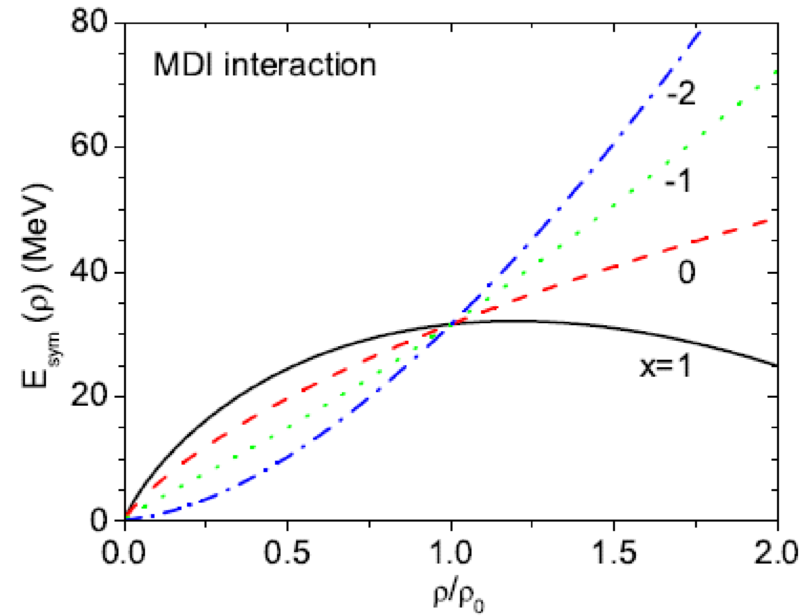
T. Li, U. Garg, et al., PRC81('10), 034309.

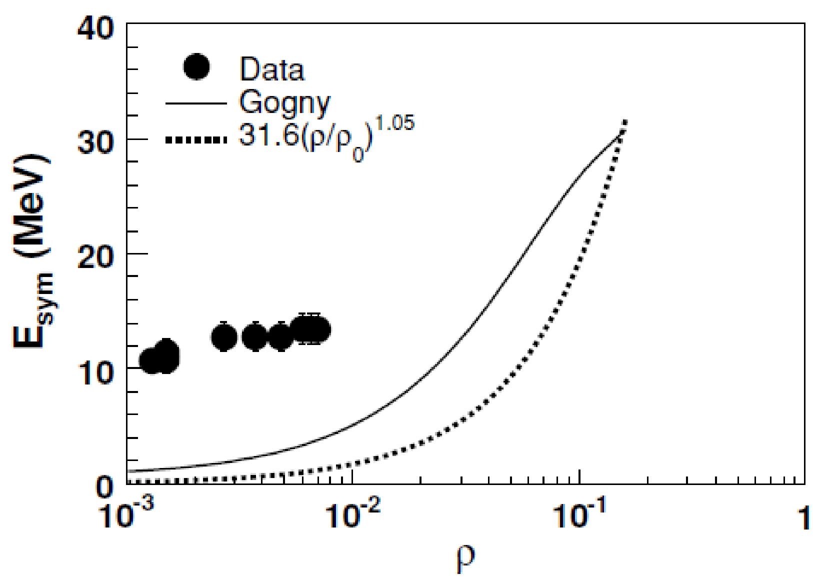
Symmetry Energy (2)

- **Symmetry energy in HIC**
  - **Isospin diffusion → K_{asy} ~ -550 MeV**

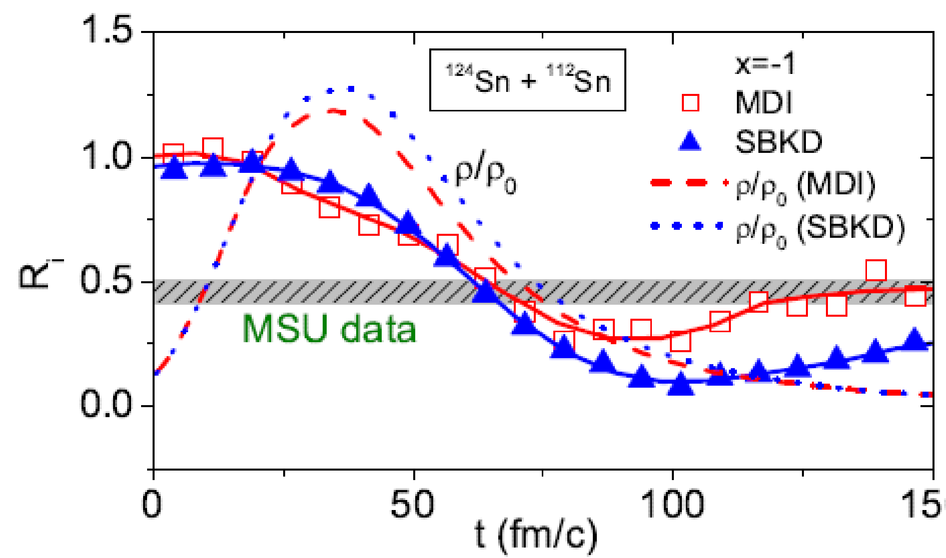
$$R_i = \frac{2X_{^{124}Sn+^{112}Sn} - X_{^{124}Sn+^{124}Sn} - X_{^{112}Sn+^{112}Sn}}{X_{^{124}Sn+^{124}Sn} - X_{^{112}Sn+^{112}Sn}}$$

  - **Light frag. dist.**
    → Larger Sym. E at low ρ





S. Kowalski, ..., A. Ono, PRC75('07)014601



L.W.Chen, C.M.Ko, B.A.Li, PRL94('05),032701.

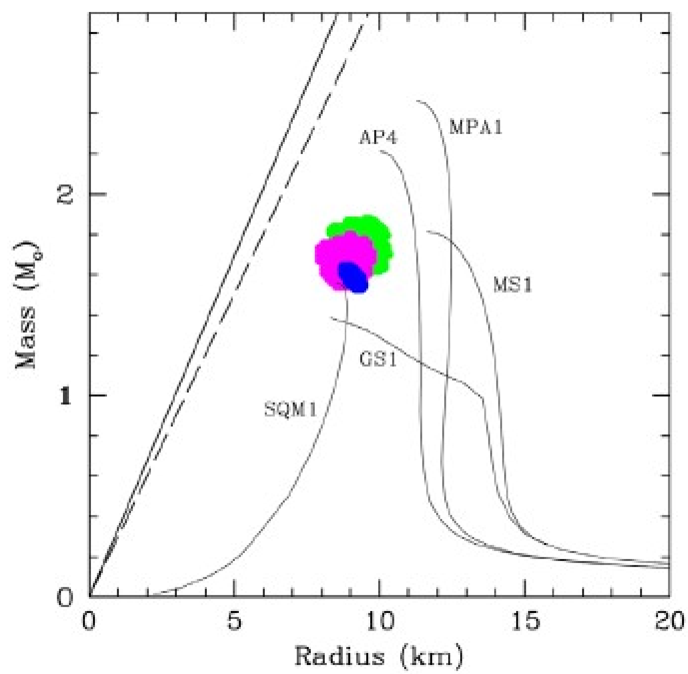
X-ray measurements of Neutron Stars

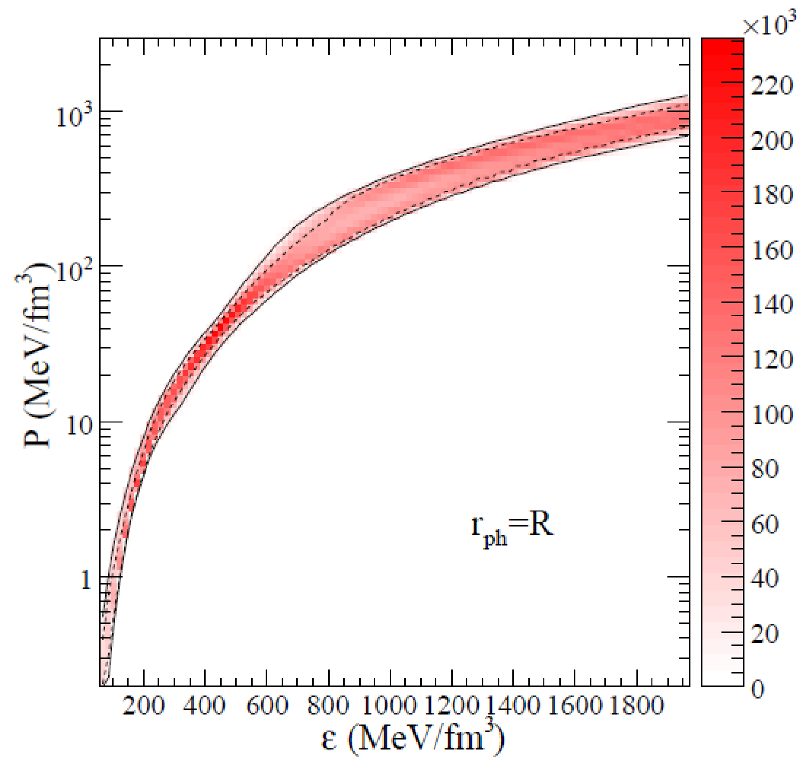
- **Neutron star mass (M)-radius (R) curve *uniquely*(*) determines NS matter EOS.**
  - **Radius measurement:**
    flux + temperature → apparent radius

$$\frac{R_\infty}{D} = \frac{R}{D}\frac{1}{\sqrt{1-2GM/Rc^2}}$$

  - **Eddington flux would give another info.**
  - **Bayesian TOV inversion → EOS**

Thermonuclear Burst in X-ray Binaries
4U 1608-248
EXO 1745-248
4U 1820-30



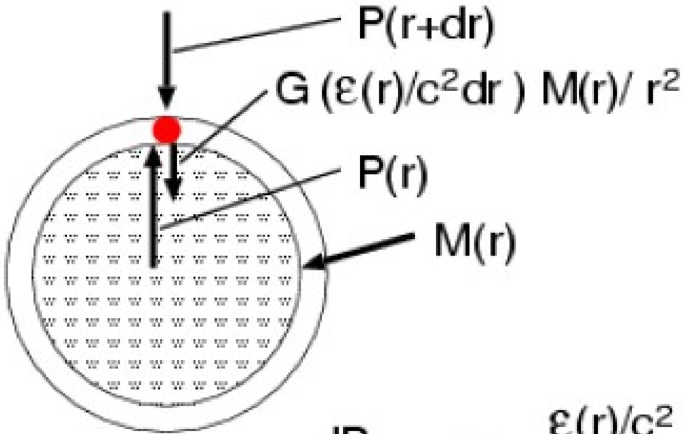


A. W. Steiner, J. M. Lattimer, Ed. Brown, arXiv:1005.0811

Ozel, Baym & Guver, arXiv: 1002.3153 [astro-ph.HE]

Tolman-Oppenheimer-Volkoff (TOV) equation

- **TOV Eq. = General Relativistic Balance of pressure and gravity**



Non-Rela. $\frac{dP}{dr} = -G \frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$

$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

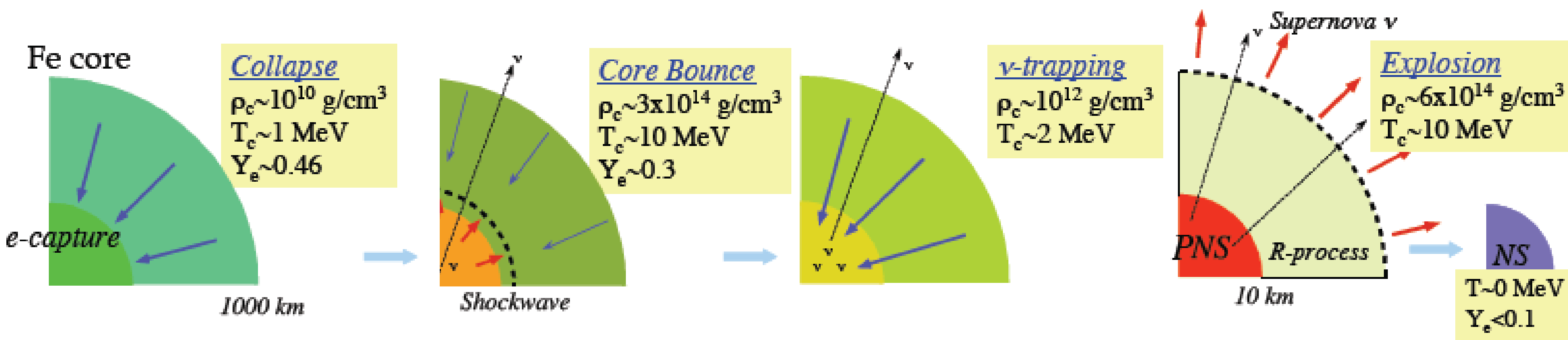
$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2 \;, \quad \frac{dP}{dr} = \frac{dP}{d\varepsilon}\frac{d\varepsilon}{dr}$$

$$P = P(\varepsilon) \;, \quad \frac{dP}{d\varepsilon} = \frac{dP}{d\varepsilon}(\varepsilon) \quad \text{(EOS)}$$

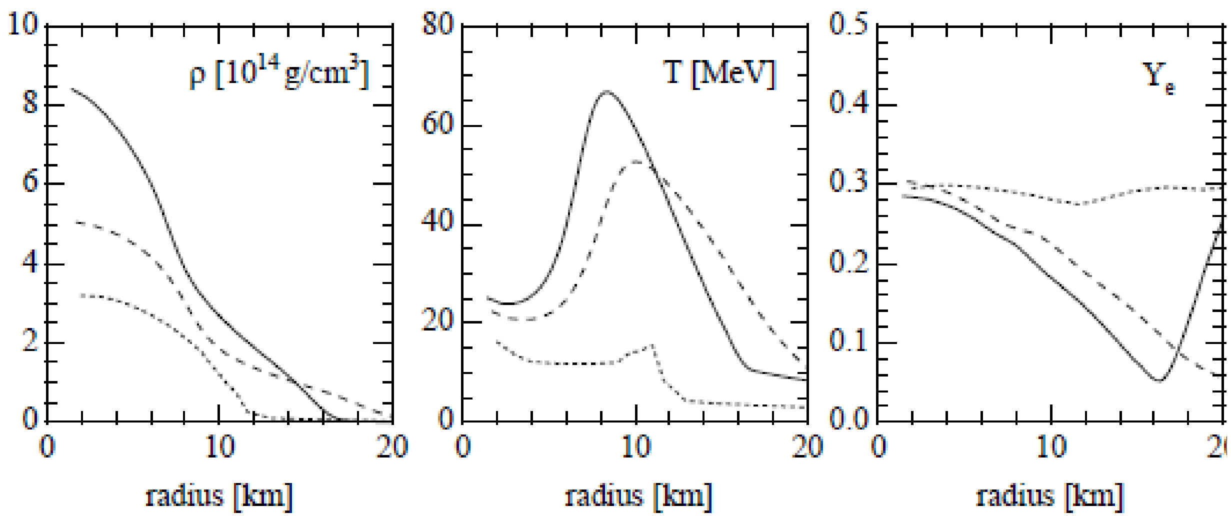
Neutron Star Mass = M(R) where P(R)=0

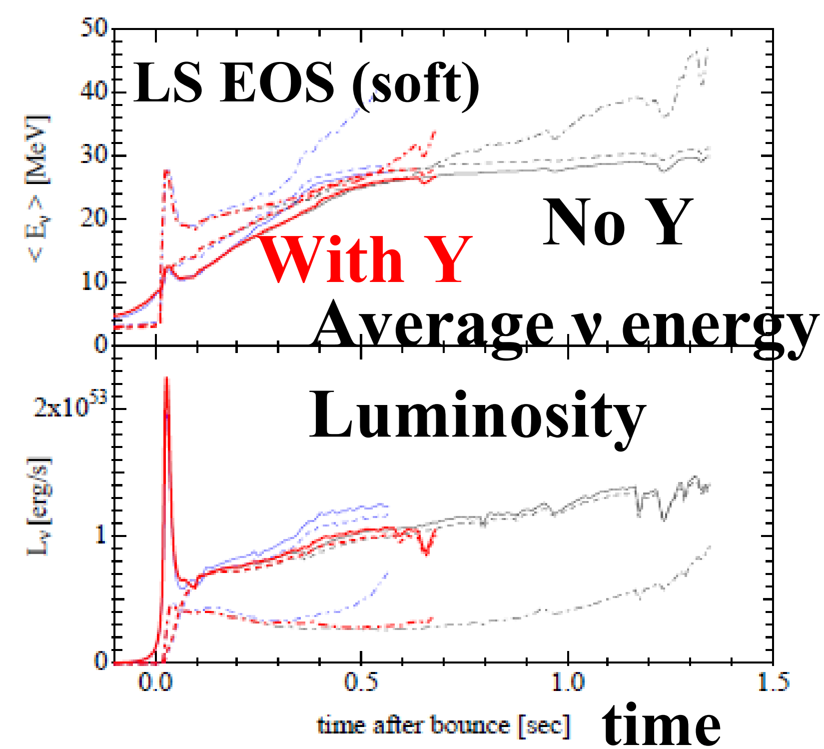
When you make a new EOS, please check the NS mass !

Black Hole Formation (Failed Supernova)



At bounce, 500 ms 680 ms (at BH form.)



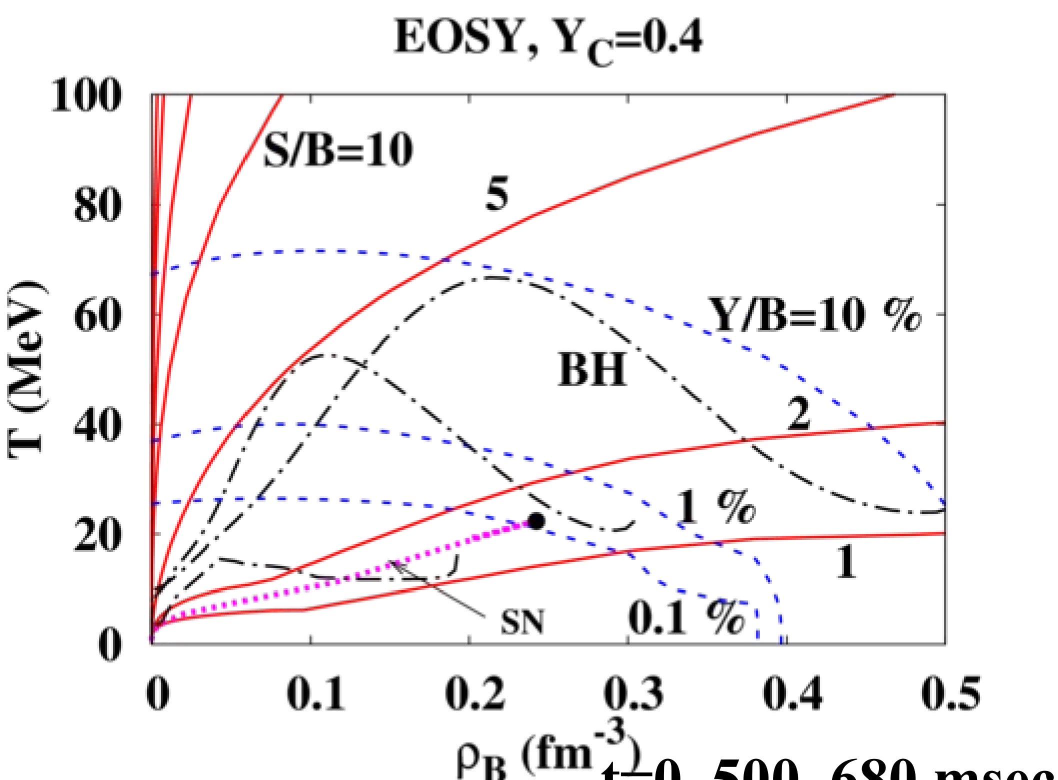


Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009

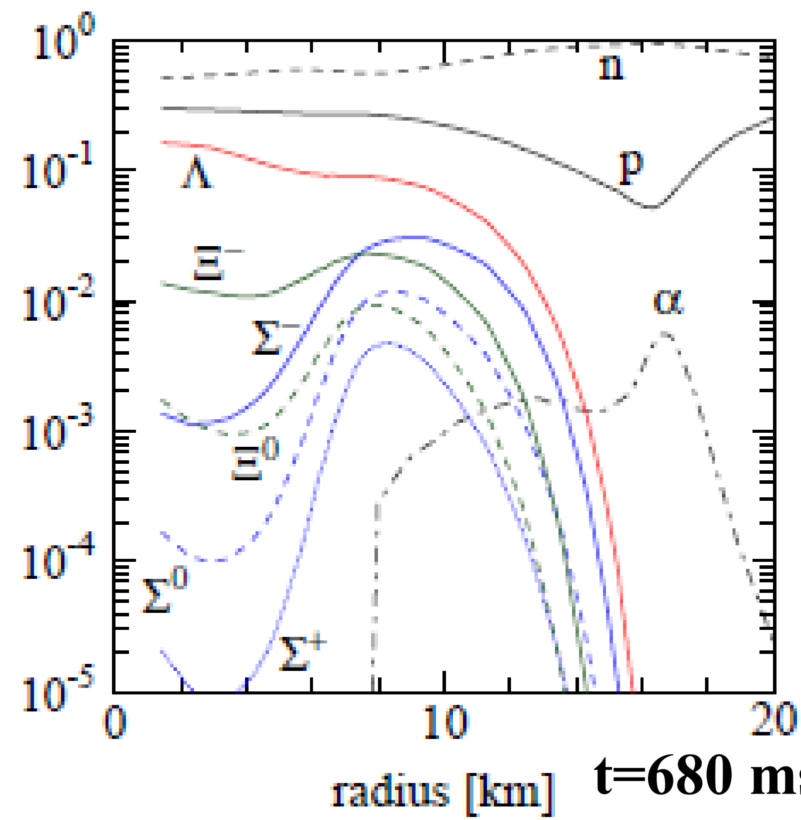
Black Hole Formation

- **Black Hole Formation: (ρ_B, T, Y_e) ~ (4 ρ_0, 70 MeV, 0.2)**
  → Hyperon fraction ~ 10 %

(K. Sumiyoshi, C. Ishizuka, AO, S. Yamada, H. Suzuki, ApJ690(09)L43)



t=0, 500, 680 msec



t=680 msec

Hyperons are abundantly formed during BH formation !
→ EOS softening, Early collapse, Short ν duration

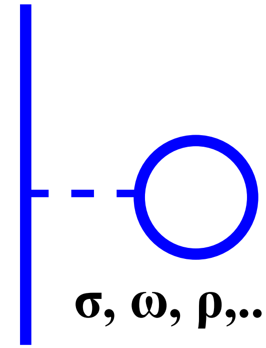
Relativistic Mean Field

Theories/Models for Nuclear Matter EOS

- **Ab initio Approach**
  - **LQCD, GFMC, Variational, DBHF, G-matrix**
    → Not easy to handle, Not satisfactory for phen. purposes
- **Mean Field from Effective Interactions ~ Nuclear Density Fuctionals**
  - **Skyrme Hartree-Fock(-Bogoliubov)**
    - **Non.-Rel.,Zero Range, Two-body + Three-body (or ρ-dep. two-body)**
    - **In HFB, Nuclear Mass is very well explained (Total B.E. ΔE ~ 0.6 MeV)**
    - **Causality is violated at very high densities.**
  - **Relativistic Mean Field**
    - **Relativistic, Meson-Baryon coupling, Meson self-energies**
    - **Successful in describing pA scatering (Dirac Phenomenology)**

Relativistic Mean Field (1)

- **Relativistic Mean Field**
  = Nuclear scalar and vector mean field generated by mesons
  → Why do we use relativistic framework ?



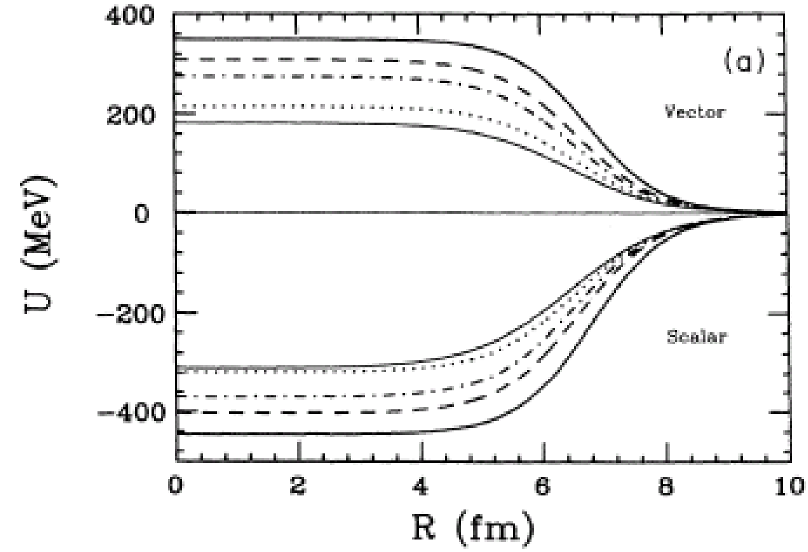
  - **Nuclear Force is mediated by mesons**
    → Let's consider meson-baryon system !
    (Entrance of Hadron Physics)
  - **We are also interested in Dense Matter EOS**
    → Sound velocity exceeds the Speed of Light (=c) with Non.-Rel. MF
  - **Success of "Dirac Phenomenology"**
    (Dirac Eq. for pA scattering → Spin Observables)
    → Strong Scalar and Vector Mean Fields are preferable to explain Spin Observables
  - **DBHF (Dirac-Brueckner-Hatree-Fock)**

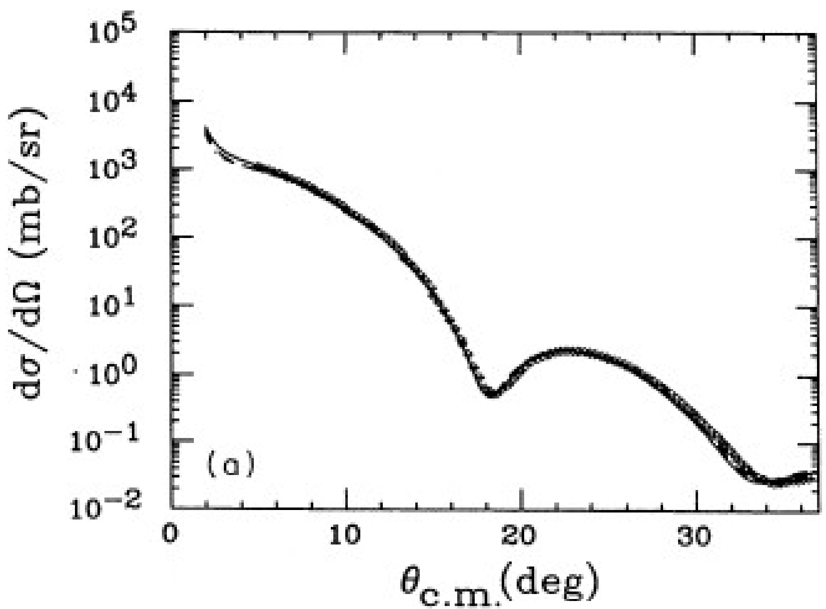
RMF is a good starting point as a framework of hadronic system including Nuclei and Nuclear Matter

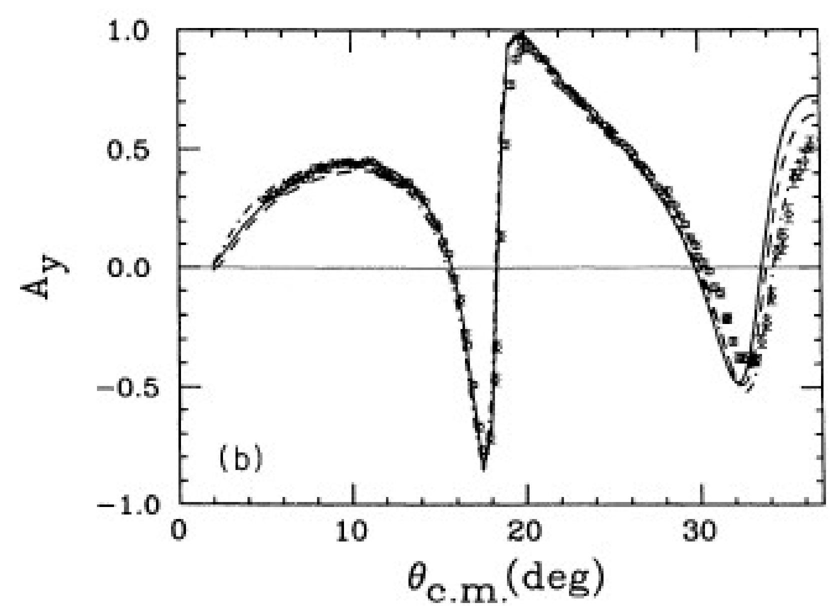
Dirac Phenomenology

E.D. Cooper, S. Hama, B.C. Clark, R.L. Mercer, PRC47('93),297

- **Dirac Eq. with**
  Scalar + Vector pA potential
  (-400 MeV + 350 MeV)
  → Cross Section, Spin Observable



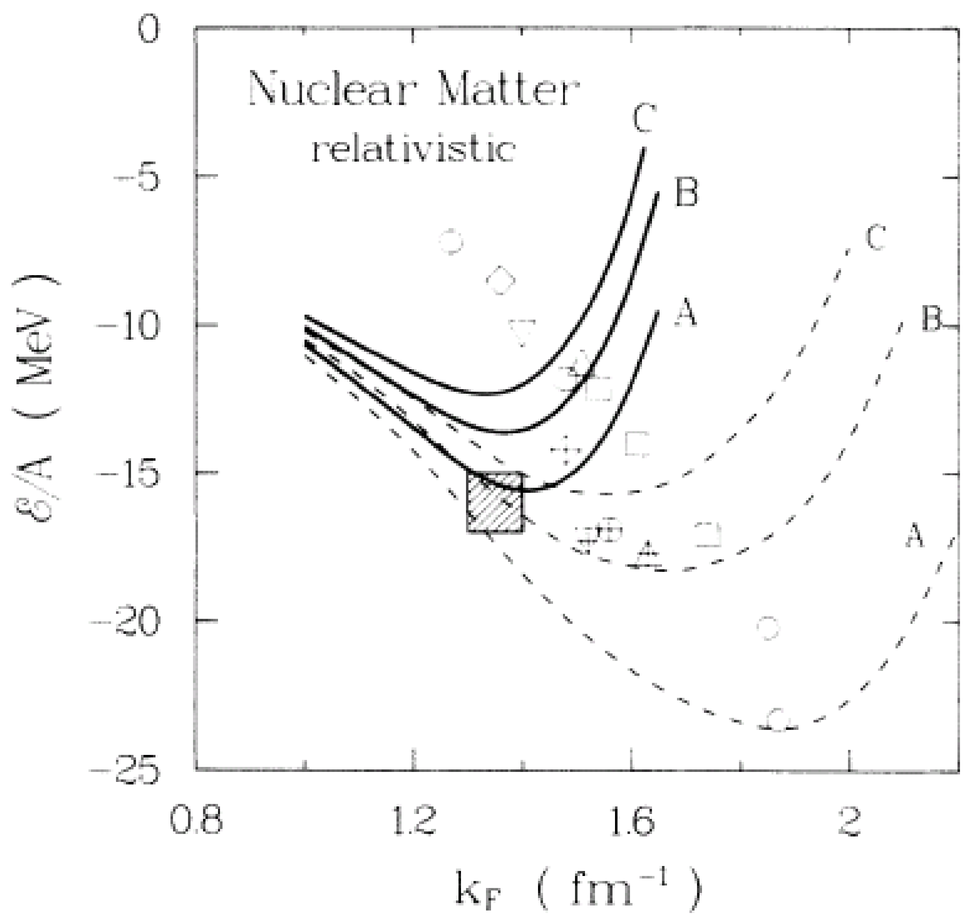




EOS in Dirac-Brueckner-Hartree-Fock

R. Brockmann, R. Machleidt, PRC42('90),1965

- **Non Relativistic Brueckner Calculation**
  → Nuclear Saturation Point cannot be reproduced (Coester Line)
- **Relativistic Approach (DBHF)**
  → Relativity gives additional repulsion, leading to successful description of the saturation point.



Relativistic Mean Field (2)

- Mean Field treatment of meson field operator
  = Meson ield operator is replaced with its expectation value
  $\varphi(r) \rightarrow \langle\varphi(r)\rangle$
  Ignoring fluctuations compared with the expectation value may be a good approximation at strong condensate.
- Which Hadrons should be included in RMF ?
  - Baryons (1/2+) p, n, Λ, Σ, Ξ, Δ, ...
  - Scalar Mesons (0+) σ(600), f_0(980), a_0(980), ...
  - Vector Mesons (1-) ω(783), ρ(770), ϕ(1020), ...
  - Pseuso Scalar (0-) π , K, η, η', ...
  - Axial Vector (1+) a_1, ...

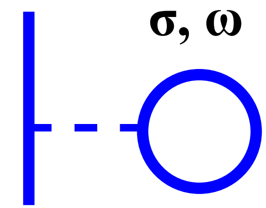
  We require that the meson field can have uniform expectation values in nuclear matter.
  → Scalar and Time-Component of Vector Mesons (σ , ω, ρ, ...)

σω Model (1)

Serot, Walecka, Adv.Nucl.Phys.16 (1986),1

- **Consider only σ and ω mesons**
- **Lagrangian**

$$L=\bar{\psi}\left(i\gamma^{\mu}\partial_{\mu}-M+g_s\sigma-g_v\omega\right)\psi$$
$$+\frac{1}{2}\partial_{\mu}\sigma\,\partial^{\mu}\sigma-\frac{1}{2}m_s^2\sigma^2-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{1}{2}m_v^2\omega_{\mu}\omega^{\mu}$$
$$\left(F_{\mu\nu}=\partial_{\mu}\omega_{\nu}-\partial_{\nu}\omega_{\mu}\right)$$



- **Equation of Motion**
  - **Euler-Lagrange Equation**

$$\frac{\partial}{\partial x^{\mu}}\left[\frac{\partial L}{\partial(\partial_{\mu}\phi_i)}\right]-\frac{\partial L}{\partial\phi_i}=0$$

$$\sigma:\left[\partial_{\mu}\partial^{\mu}+m_s^2\right]\sigma=g_s\bar{\psi}\psi$$

$$\omega:\partial_{\mu}F^{\mu\nu}+m_v^2\omega^{\nu}=g_v\bar{\psi}\gamma^{\nu}\psi \quad\rightarrow\quad \left[\partial_{\mu}\partial^{\mu}+m_v^2\right]\omega^{\nu}=g_v\bar{\psi}\gamma^{\nu}\psi$$

$$\psi:\left[\gamma^{\mu}\left(i\partial_{\mu}-g_vV_{\mu}\right)-\left(M-g_s\sigma\right)\right]\psi=0$$

EOM of ω (for beginners)

- **Euler-Lagrange Eq.**

$$\partial_\mu F^{\mu\nu} + m_v^2 \omega^\nu = g_v \bar{\psi} \gamma^\nu \psi$$

- **Divergence of LHS and RHS**

$$\partial_\nu \partial_\mu F^{\mu\nu} + m_v^2 (\partial_\nu \omega^\nu) = m_v^2 (\partial_\nu \omega^\nu) = g_v (\partial_\nu \bar{\psi} \gamma^\nu \psi) = 0$$

LHS: derivatives are sym. and $F_{\mu\nu}$ is anti-sym.

RHS: Baryon Current = Conserved Current

- **Put it in the Euler-Lagrange Eq.**

$$\partial_\mu F^{\mu\nu} = \partial_\mu (\partial^\mu \omega^\nu - \partial^\nu \omega^\mu) = \partial_\mu \partial^\mu \omega^\nu - \partial^\nu (\partial_\mu \omega^\mu) = \partial_\mu \partial^\mu \omega^\nu$$

- **Dirac Equation for Nucleons**

$$\left(i\gamma\partial-\gamma^0 U_V - M - U_S\right)\psi=0\ ,\quad U_V=g_\omega\omega\ ,\quad U_S=-g_\sigma\sigma$$

- **Decompose 4 spinor into Upper and Lower Components**

$$\begin{pmatrix} E-U_V-M-U_S & i\sigma\cdot\nabla \\ -i\sigma\cdot\nabla & -E+U_V-M-U_S \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix}=0$$

$$g=\frac{-i}{E+M+U_s-U_V}(\sigma\cdot\nabla)f$$

$$(E-M-U_v-U_s)f=-i(\sigma\cdot\nabla)g$$

- **Erase Lower Component (assuming spherical sym.)**

$$-i(\sigma\cdot\nabla)g=-(\sigma\cdot\nabla)\frac{1}{X}(\sigma\cdot\nabla)f=-\frac{1}{X}\nabla^2 f-\frac{1}{r}\left[\frac{d}{dr}\frac{1}{X}\right](\sigma\cdot r)(\sigma\cdot\nabla)f=-\nabla\frac{1}{X}\nabla f+\frac{1}{r}\left[\frac{d}{dr}\frac{1}{X}\right](\sigma\cdot l)f$$

$$(\sigma\cdot r)(\sigma\cdot\nabla)=(r\cdot\nabla)+i\sigma\cdot(r\times\nabla)=r\cdot\nabla-\sigma\cdot l$$

- **"Schroedinger-like" Eq. for Upper Component**

$$-\nabla\frac{1}{E+M+U_s-U_v}\nabla f+\left(U_s+U_v+U_{LS}(\sigma\cdot l)\right)f=(E-M)f$$

$$U_{LS}=\frac{1}{r}\left[\frac{d}{dr}\frac{1}{E+M+U_s-U_v}\right]<0 \quad \text{on surface}$$

(Us,Uv)~ (-350 MeV,280 MeV)→Small Central(Us+Uv), Large LS (Us-Uv)

Various Ways to Evaluate Non.-Rel. Potential

- **From Single Particle Energy**

$$\left(\gamma^0(E-U_v)+i\gamma\cdot\nabla-(M+U_s)\right)\psi=0 \;\rightarrow\; (E-U_v)^2=p^2+(M+U_s)^2$$

$$\rightarrow E=\sqrt{p^2+(M+U_s)^2}+U_v\approx E_p+\frac{M}{E_p}U_s+U_v+\frac{p^2}{2E_p^3}U_s^2$$

$$(E_p=\sqrt{p^2+M^2})$$

- **Schroedinger Equivalent Potential (Uniform matter)**

$$-\frac{\nabla^2}{2\mathrm{M}}f+\left[U_s+\frac{E}{M}U_v+\frac{U_s^2-U_v^2}{2\mathrm{M}}\right]f=\frac{E+M}{2\mathrm{M}}(E-M)f$$

$$U_{\mathrm{SEP}}\approx U_s+\frac{E}{M}U_v$$

Anyway, slow baryons feel Non.-Rel. Potential,

$$U\approx U_s+U_v=-g_s\sigma+g_v\omega$$

Nuclear Matter in σω Model

Serot, Walecka, Adv.Nucl.Phys.16 (1986),1

- **Uniform Nuclear Matter**

$$E/V = \gamma_N \int^{P_F} \frac{d^3p}{(2\pi)^2} E^* + \frac{1}{2} m_s^2 \sigma^2 - \frac{1}{2} m_v^2 \omega^2 + g_v \rho_B \omega$$

$$(M^* = M + U_s = M - g_s \sigma, \quad E^* = \sqrt{p^2 + M^{*2}})$$

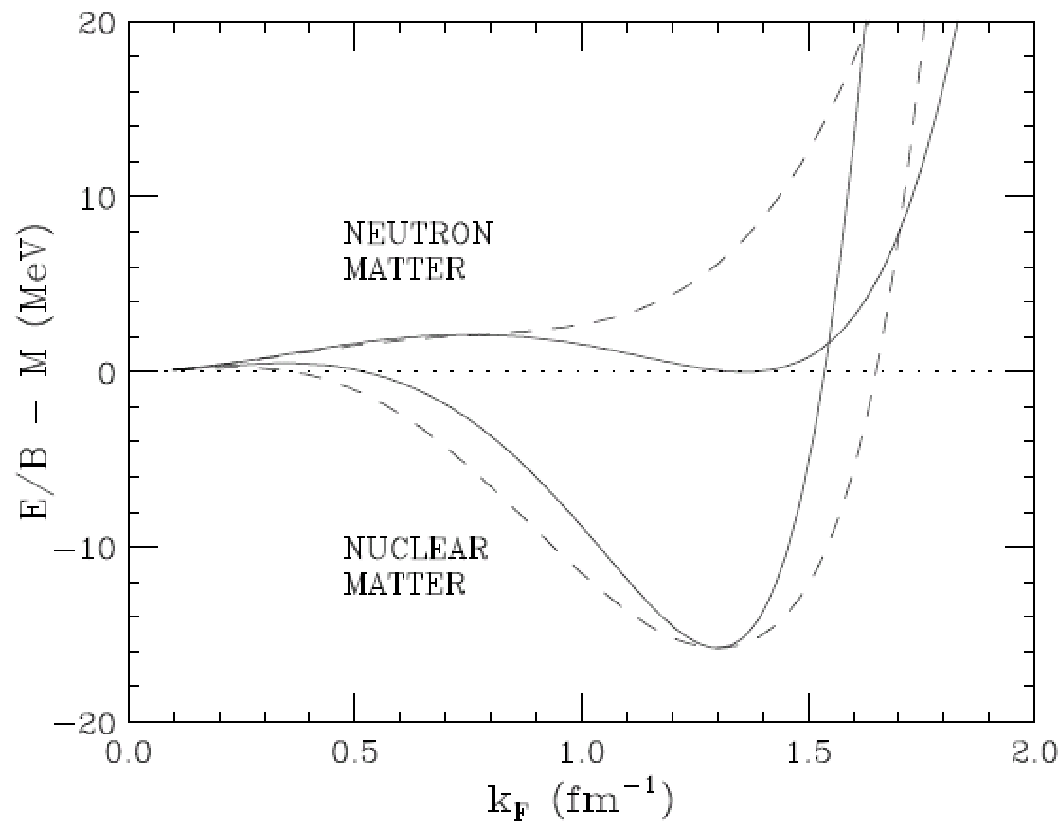
$$\sigma = \frac{g_s}{m_s^2} \rho_s = \frac{g_s}{m_s^2} \int^{P_F} \frac{\gamma_N \, d^3p}{(2\pi)^2} \frac{M^*}{E^*}$$

$$\omega = \frac{g_v}{m_v^2} \rho_B = \gamma_N \frac{g_v}{m_v^2} \int^{P_F} \frac{d^3p}{(2\pi)^3}$$

γ_N = Nucleon degeneracy

(=4 in sym. nuclear matte

Problem: EOS is too stiff
K ~ (500-600) MeV !
→ How can we solve ?

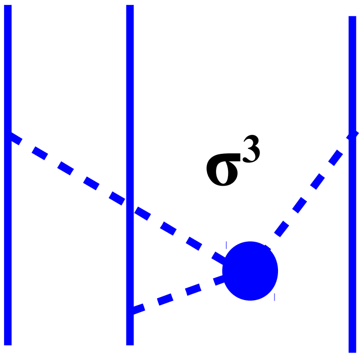


σ ω model --- pros and cons

- **Pros (merit)**
  - **Foundation is clear: based on the success of Dirac phen. and DBHF.**
  - **Simple description of scalar and vector potential in σ and ω mesons.**
  - **Saturation is well described in two parameters.**
  - **Natural explanation of large LS potential in nuclei.**
- **Cons (shortcomings)**
  - **Relation with the bare NN interaction is not clear.**
  - **Especially, pion effects are not included.**
  - **Symmetry energy is too small.**
  - **Incompressibility is too large (K ~ 600-700 MeV)**
    (c.f. Empirical value K ~ (200-300) MeV)
  - **Chiral symmetry is not respected.**

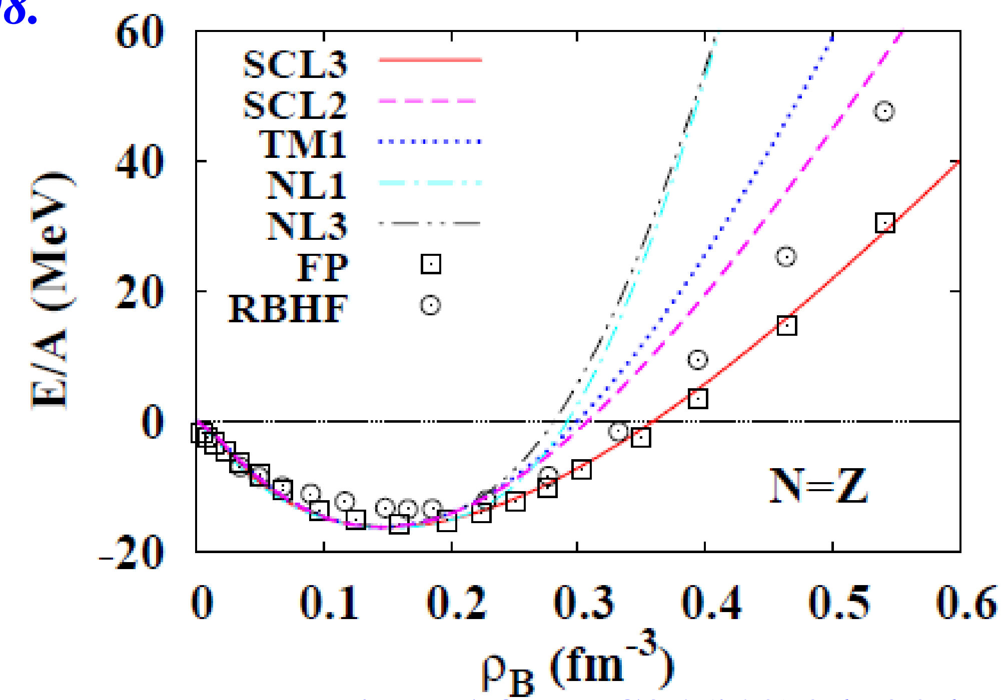
High Quality RMF models

- Variety of the RMF models
  → MB couplings, meson masses, meson self-energies



  - *σN*, *ωN*, *ρN* couplings are well determined
    → almost no model deps. in Sym. N.M. at low ρ
  - ω^4 term is introduced to simulate DBHF results of vector pot.
    TM: Y. Sugahara, H. Toki, NPA579('94)557; R. Brockmann, H. Toki, PRL68('92)3408.
  - σ^3 and σ^4 terms are introduced to soften EOS at ρ_0.
    J. Boguta, A.R.Bodmer NPA292('77)413, NL1:P.-G.Reinhardt, M.Rufa, J.Maruhn, W.Greiner, J.Friedrich, ZPA323('86)13. NL3: G.A.Lalazissis, J.Konig, P.Ring, PRC55('97)540.

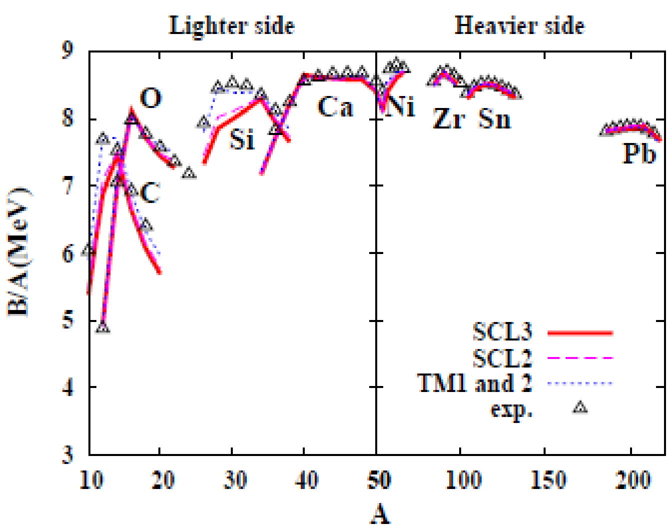
→ Large differences are found at high ρ

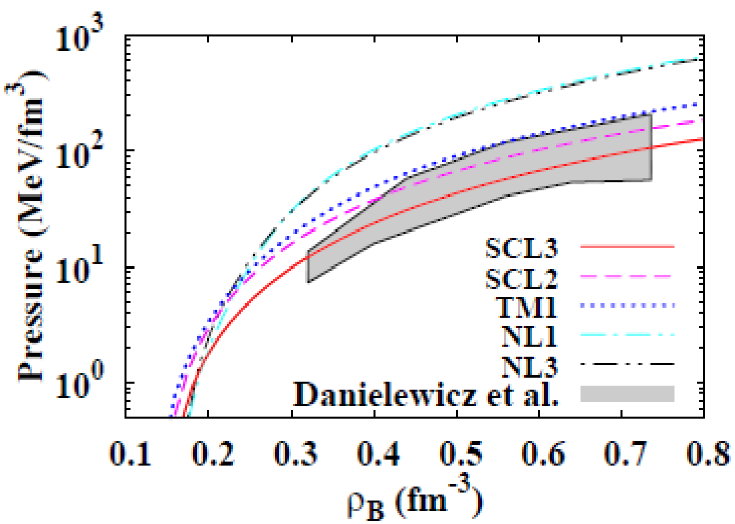


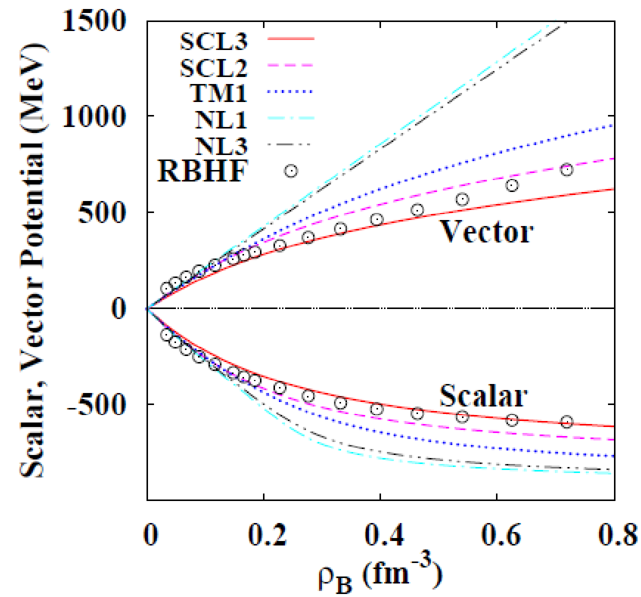
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

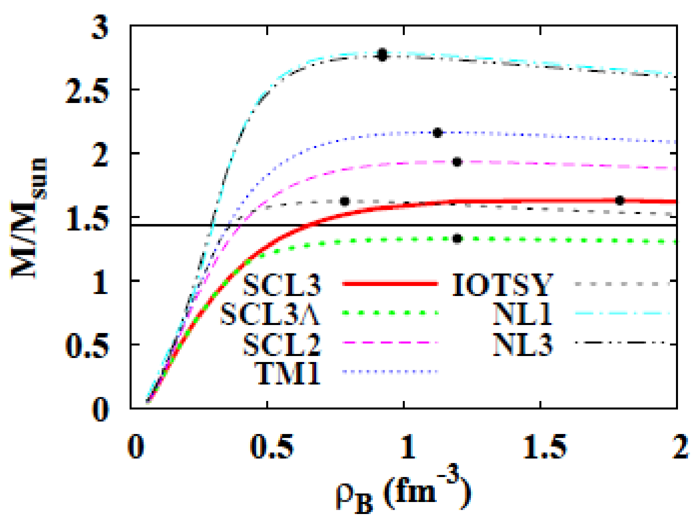
How to determine Non-Linear terms ? (1)

- **Method 1: Fit as many as known observables**
  - **EOS, Nuclear B.E., High density EOS from HIC, Vector potential in DBHF, Neutron Star, ...**





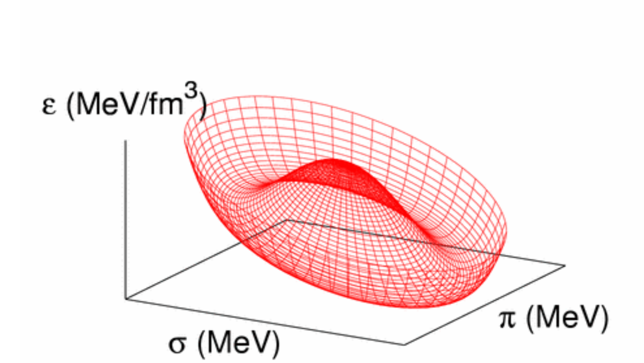


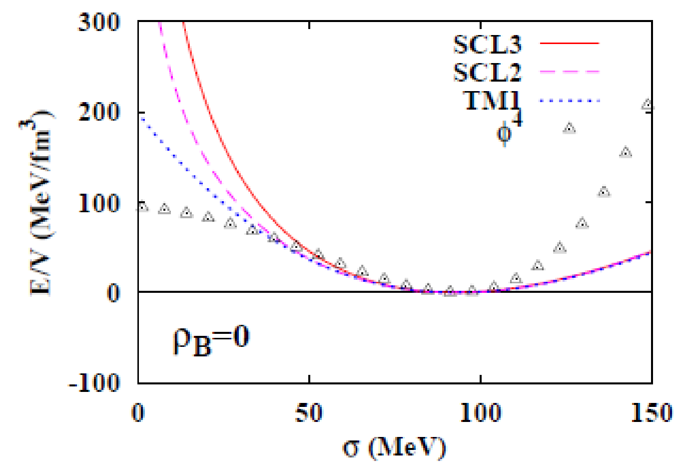


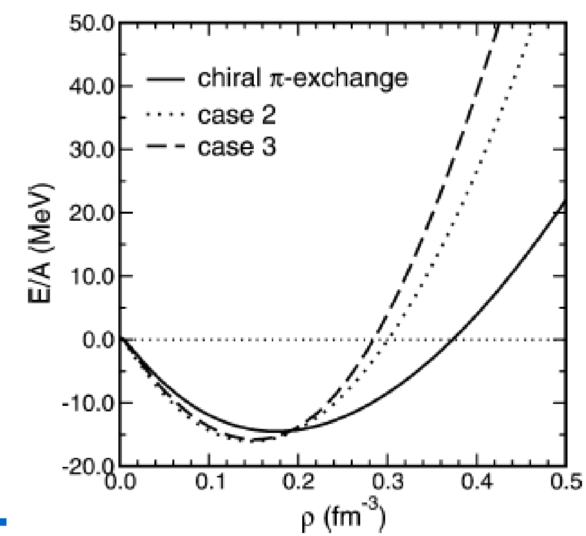
P. Danielewicz, R. Lacey, W. G. Lynch, Science298('02)1592.
R. Brockmann, R. Machleidt, PRC42('90)1965.
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

How to determine Non-Linear terms ? (2)

- **Method (2): Fix parameters by using symmetry, such as the *Chiral Symmetry***
- **Chiral Symmetry**
  - **Fundamental symmetry of massless QCD, and its spontaneous breaking generates hadron masses.**
    Nambu, Jona-Lasinio ('61)
  - **Many of the linear σ models are unstable against finite density (chiral collapse).**
    → Log type chiral potential
    Sahu, Tsubakihara,AO('10), Tsubakihara, AO('07), Tsubakihara et al.('10)
  - **Non-linear representation (chiral pert.) leads to density dependent coupling from one- and two-pion exchanges.**
    Kaiser, Fritsch, Weise ('02),
    Finelli, Kaiser, Vretener, Weise ('04)

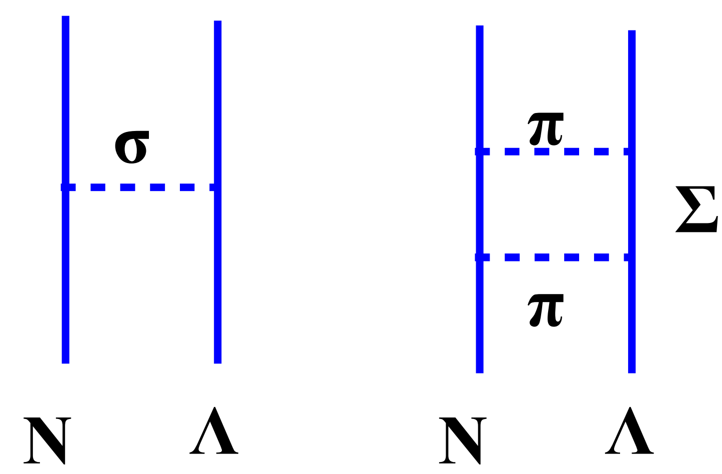




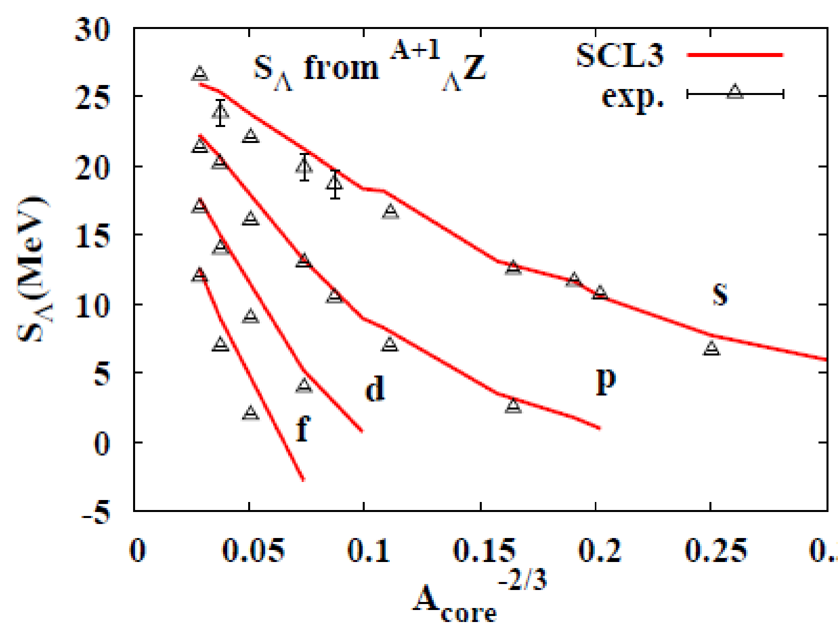


RMF with Hyperons --- Λ hypernuclei

- Why Λ ?
  - Λ is expected to appear in NS.
  - Coupling with π, σ, … are different
    → detailed study of Λ hypernnuclei will tell us what makes MF (OBEP or π)



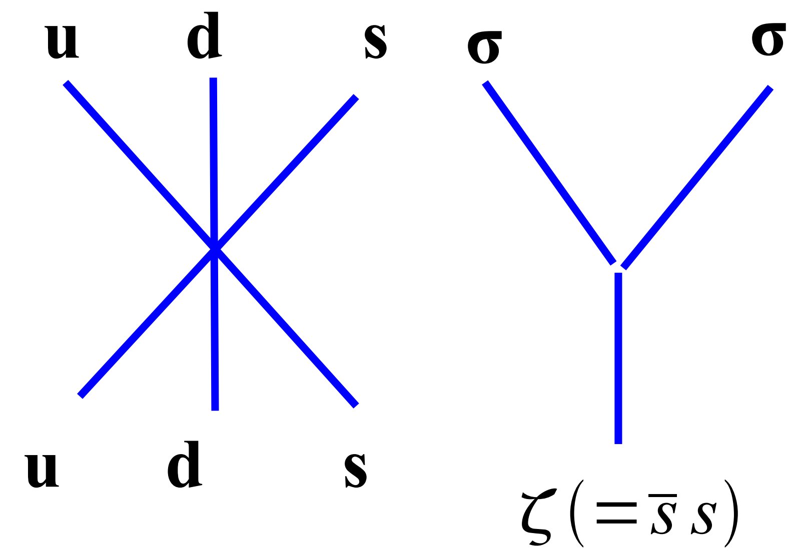
  - Coupling with mesons : $x_M = g_{M\Lambda}/g_{MN}$
    quark counting: $x_\sigma \sim 2/3$
    π exchanges: $x_\sigma \sim 1/3$
    → Which is true ?
- Single Λ hypernuclei
  - Λ Sep. E. → $U_\Lambda \sim$ -30 MeV ~ 2/3 U_N
    → We can fit them by changing $g_{\sigma\Lambda}$, $g_{\omega\Lambda}$, $g_{\zeta\Lambda}$, …

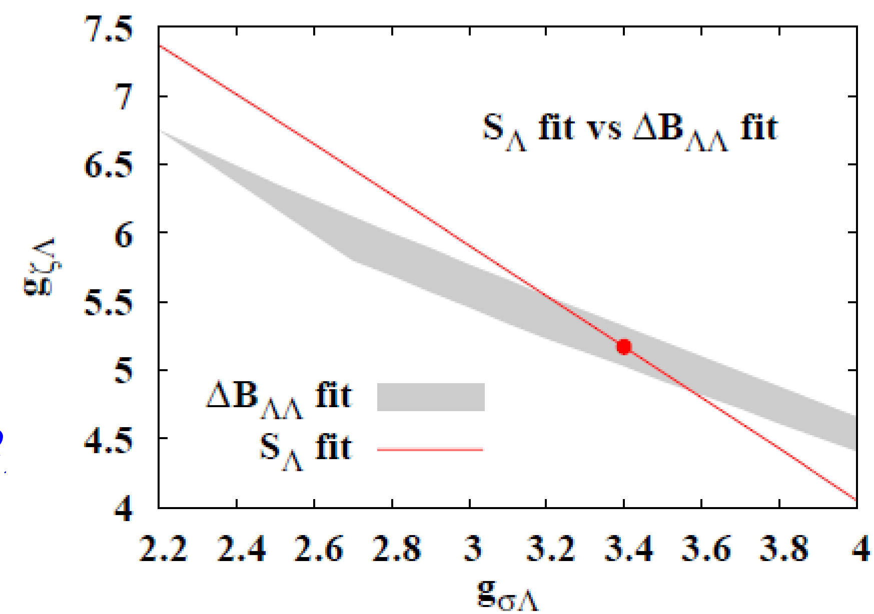


K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

RMF with Hyperons --- Double Λ hypernuclei

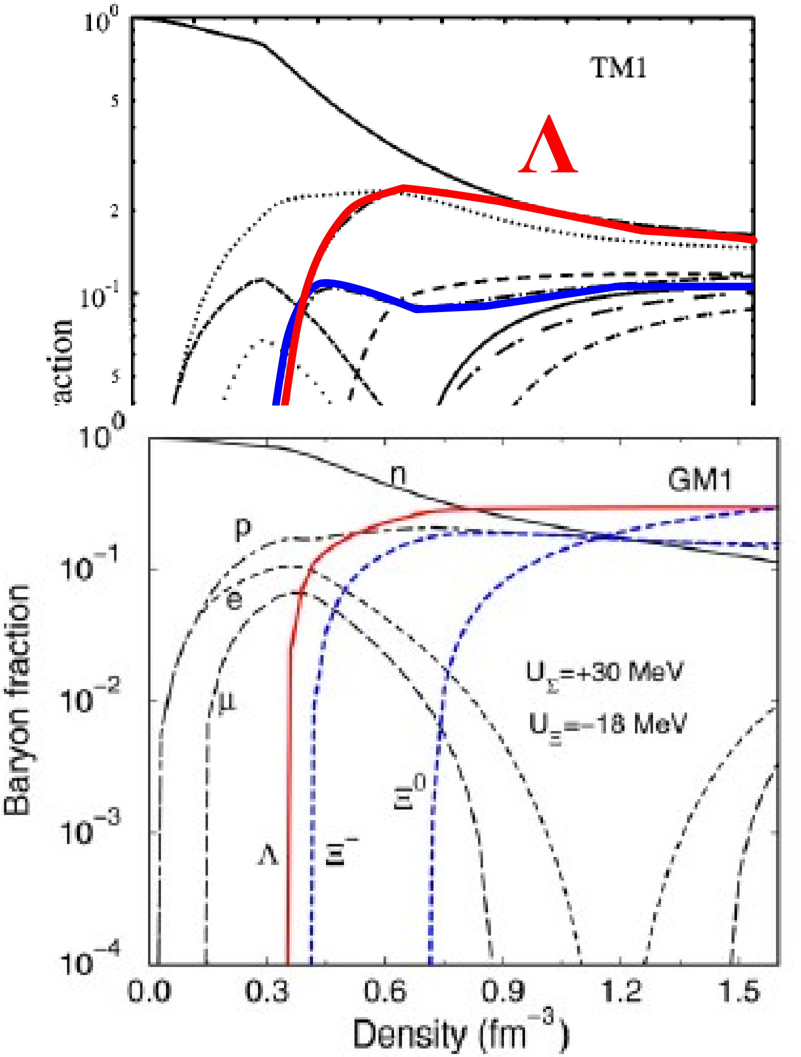
- **Nagara event $\Delta B_{\Lambda\Lambda} \sim 1.0$ MeV (weakly attractive)**
  - **TM & NL-SH based RMF**
    H. Shen, F. Yang, H. Toki, PTP115('06)325.
    Model 1: $x_\sigma = 0.621$, $x_\omega = 2/3$ (no ς, φ)
    Model 2: $R_\varsigma = g_{\varsigma\Lambda} / g_{\sigma N} = 0.56\text{-}0.57$,
    $R_\varphi = g_{\varphi\Lambda} / g_{\omega N} = -\sqrt{2}/3$
  - **Chiral SU(3) RMF**
    K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.
    $SU(3)_f$ for vector coupling
    $x_\omega = 0.64$, $R_\varphi = 0.504$
    Det. (KMT) int. mixes σ and ς
    M. Kobayashi, T. Maskawa, PTP44('70)1422
    G. 't Hooft, PRD14('76)3432.
    → $x_\sigma = 0.335$, $R_\varsigma = 0.509$





Hyperon Composition in Dense Matter

- **Hyperon start to emerge at (2-3)ρ_0 in Neutron Star Matter !**
- **Hyperon composition in NS is sensitive to Hyperon potential.**
  - **U_Λ ~ -30 MeV: Well-known**
  - **U_Ξ ~ -(12-15) MeV**
    (K^-,K^+) reaction, twin hypernuclei
    P. Khaustov et al. (E885),PRC61('00)054603;
    S. Aoki et al., PLB355('95)45.
  - **U_Σ~ -30 MeV (Old conjecture)**
    → Σ^- appears prior to Λ
  - **U_Σ > 0 (repulsive) → No Σ in NS**
    Σ atom (phen. fit), QF prod.
    H. Noumi et al., PRL89('02)072301;
    T. Harada, Y. Hirabayashi, NPA759('05)143;
    M. Kohno et al. PRC74('06)064613.

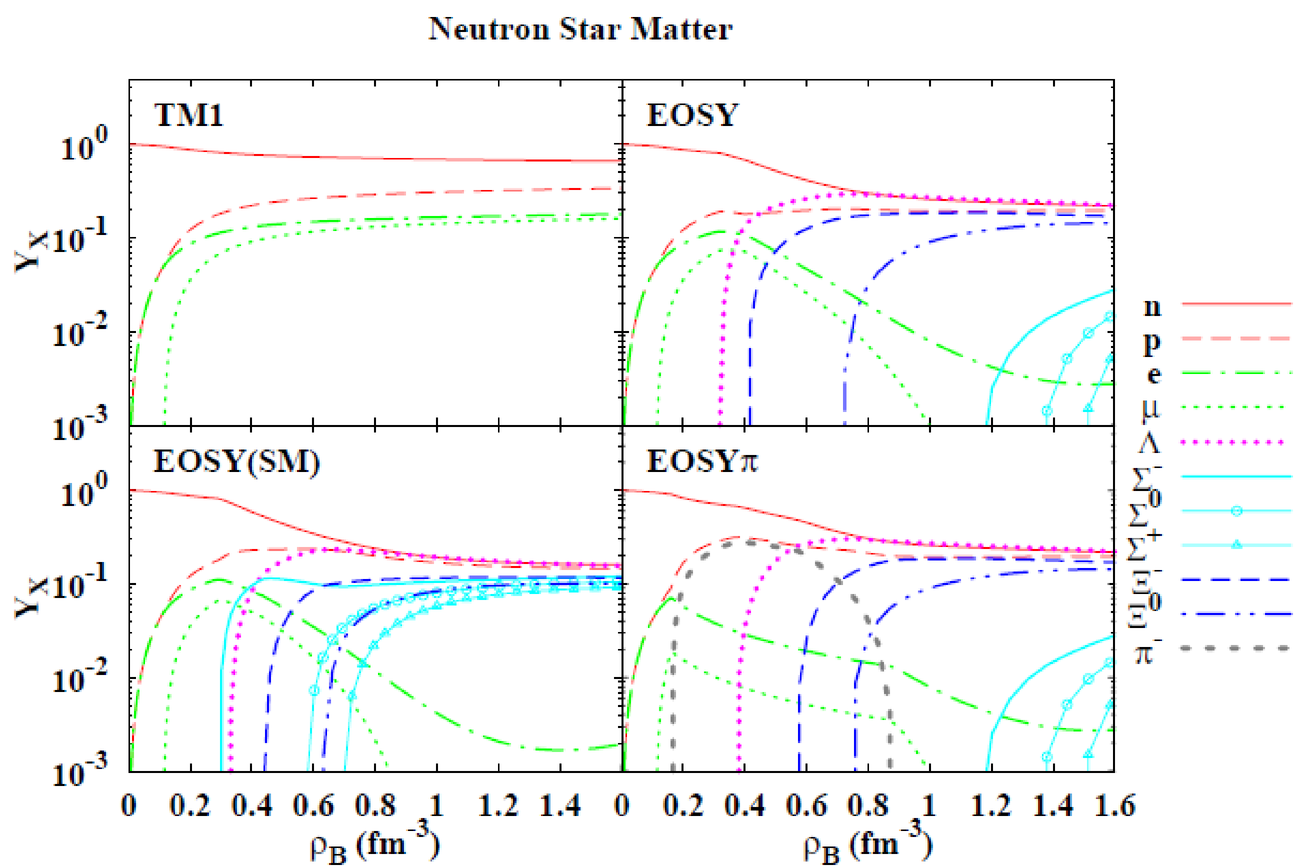


J. Schaffner-Bielich, NPA804('08)309.

Hyperon Composition in Dense Matter

- **Comparison of Hyperon Composition**
  - **U_Σ=-30 MeV, U_Ξ = -28 MeV → SU(3) sym. matter at $\rho_B \sim 10\ \rho_0$**
    Schaffner, Mishustin ('94)
  - **U_Σ=+30 MeV, U_Ξ = -15 MeV→ Σ baryons are strongly suppressed.**
    C.Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada, JPG35('08)085201.

→ Does Σ play no role in NS ?



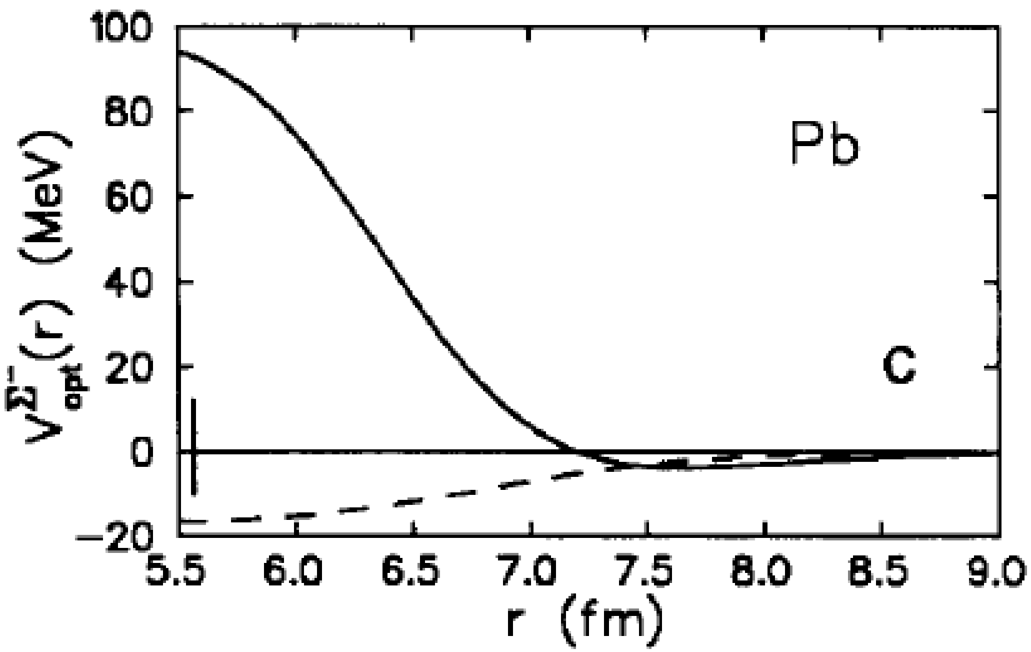
Σ^- atom data

- Σ^- atom data suggested repulsion in the interior of nuclei !

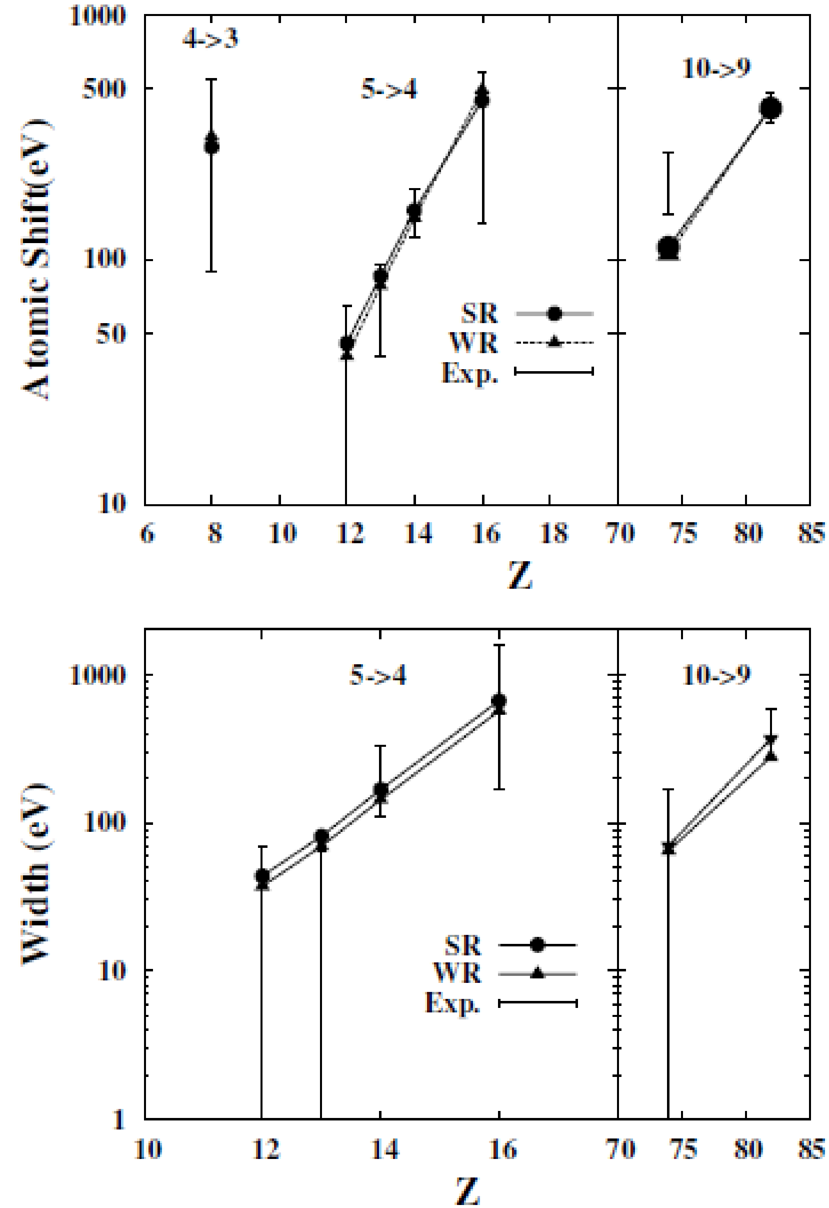
  C.J.Batty, E.Friedman, A.Gal, PLB335('94)273

  Batty's DD potential is very repulsive inside nuclei.

  → No Σ baryon in dense matter.



J.Mares, E.Friedman, A.Gal, B.K.Jennings, NPA594('95)311.



K.Tsubakihara, H.Maekawa, AO, EPJA33('07)295.

Σ^- atom in RMF

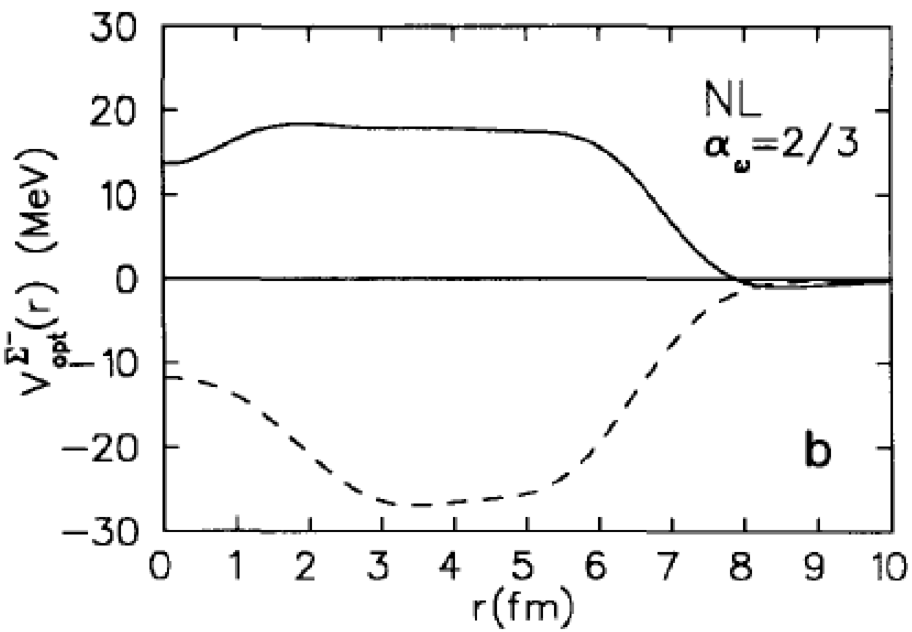
- **RMF fit of Si and Pb Σ^- atom**

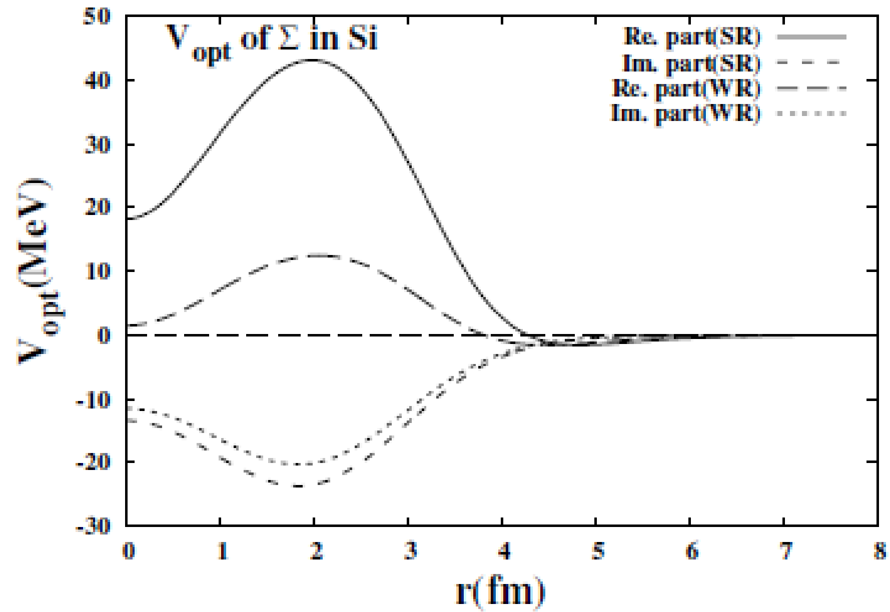
  $\alpha_\omega = g_{\omega\Sigma} / g_{\omega N} \sim 2/3(\mathrm{M}), 0.69\ (\mathrm{T})$

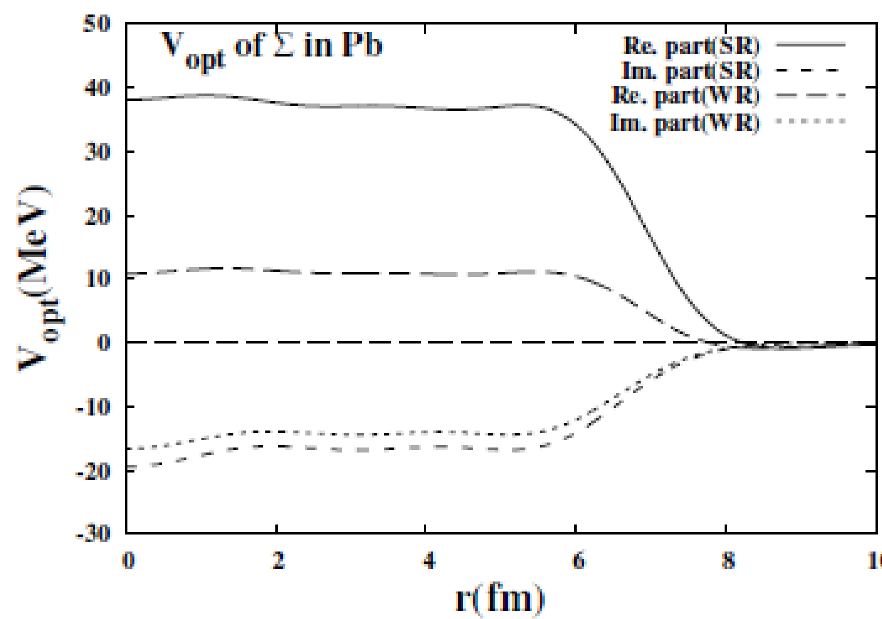
  $\alpha_\rho = g_{\rho\Sigma} / g_{\rho N} \sim 2/3(\mathrm{M}), 0.434(\mathrm{T})$

  J.Mares, E.Friedman, A.Gal, B.K.Jennings, NPA594('95)311; Tsubakihara et al.('10)

  - **Much smaller $g_{\rho\Sigma}$ than naïve SU(3) ($g_{\rho\Sigma} / g_{\rho N}$ =2), which has been applied in some of previous works.**



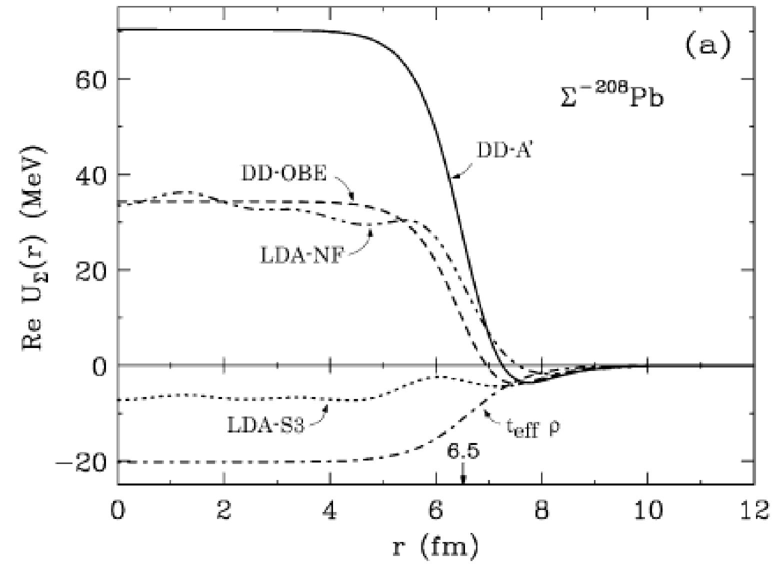




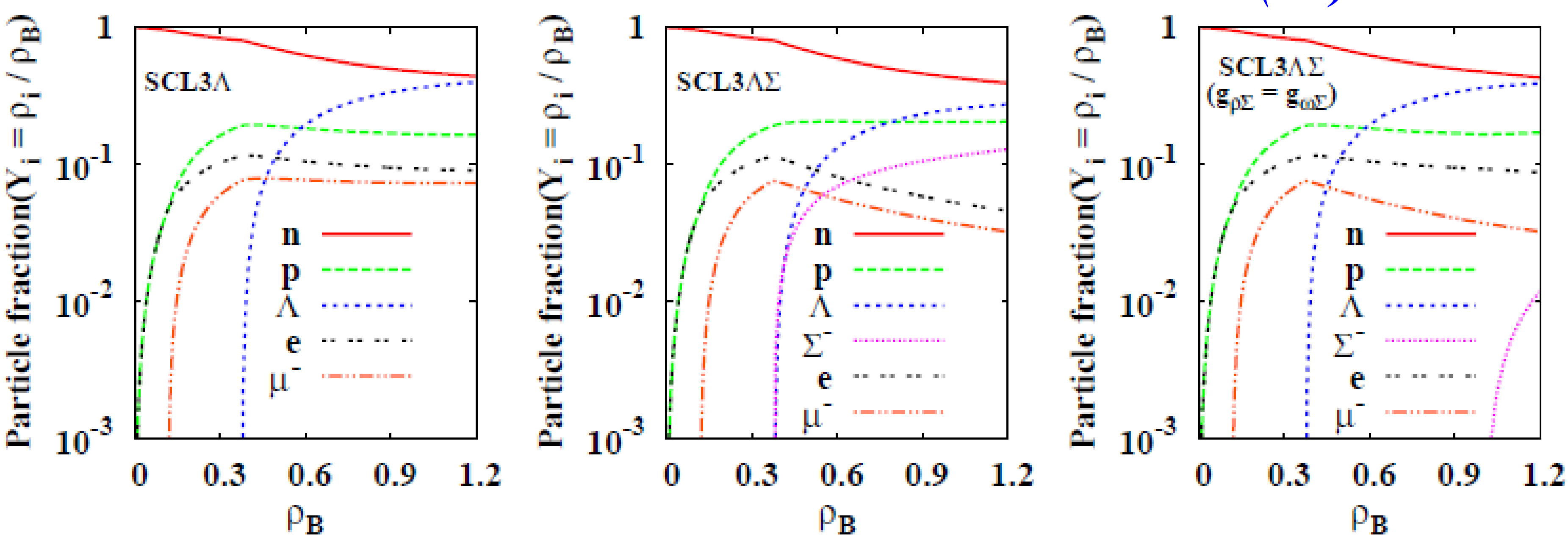
Σ atom and Neutron Star

- **Σ may not feel *very* repulsive potential in neutron star....**
  - **ρ^{γ}-type fit → very repulsive**
  - **RMF fit → small isovector potential**

→ QF prod. may support the latter.
Σ^- would appear in NS.



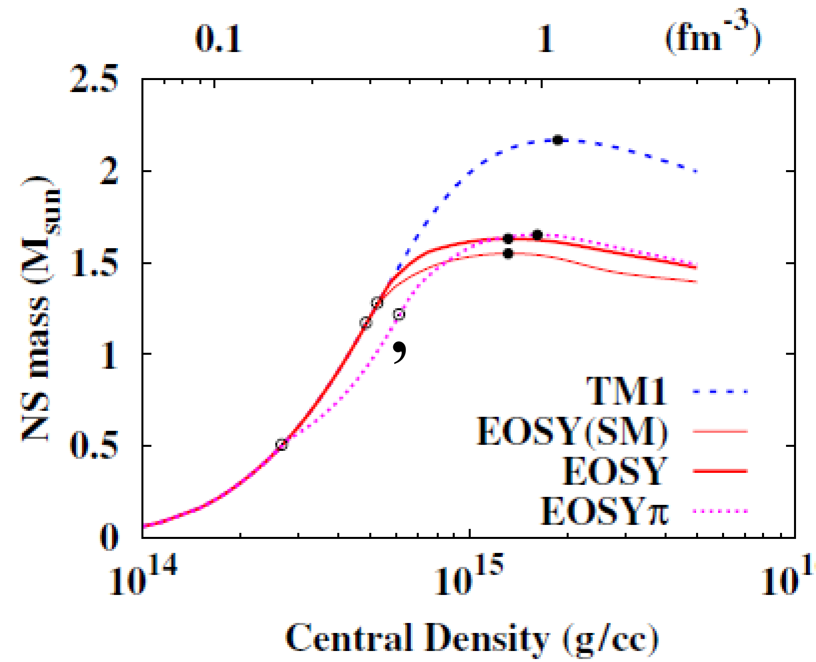
T. Harada, Y. Hirabayashi, NPA767('06)206

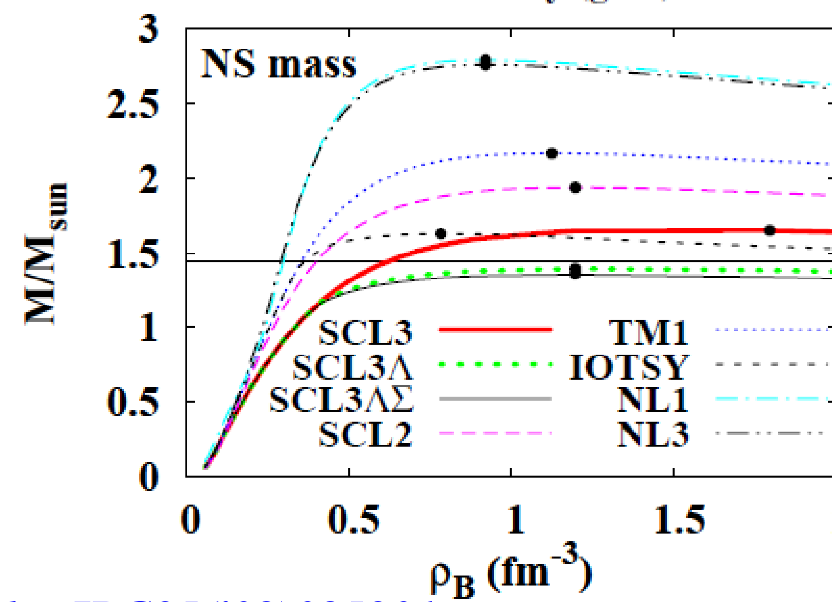


K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

Neutron Star Mass

- Large fraction of hyperons softenes EOS at $\rho_B > (0.3\text{-}0.4)\ \mathrm{fm}^{-3}$
  - NS star max. mass red. ~ 1 M_{sun}.
  - RMF generally predicts stiff EOS at high density.
    (Scalar attraction saturation,
    or Z-graph in NR view.)
  - Some of RMF with Y do not support 1.44 M_{sun}.
- Additional Repulsion at high ρ ?
  - Vector mass mod.
    → stronger repulsion at high ρ.
    M. Naruki et al., PRL96('06)092301.
  - Another term such as NNωσ.

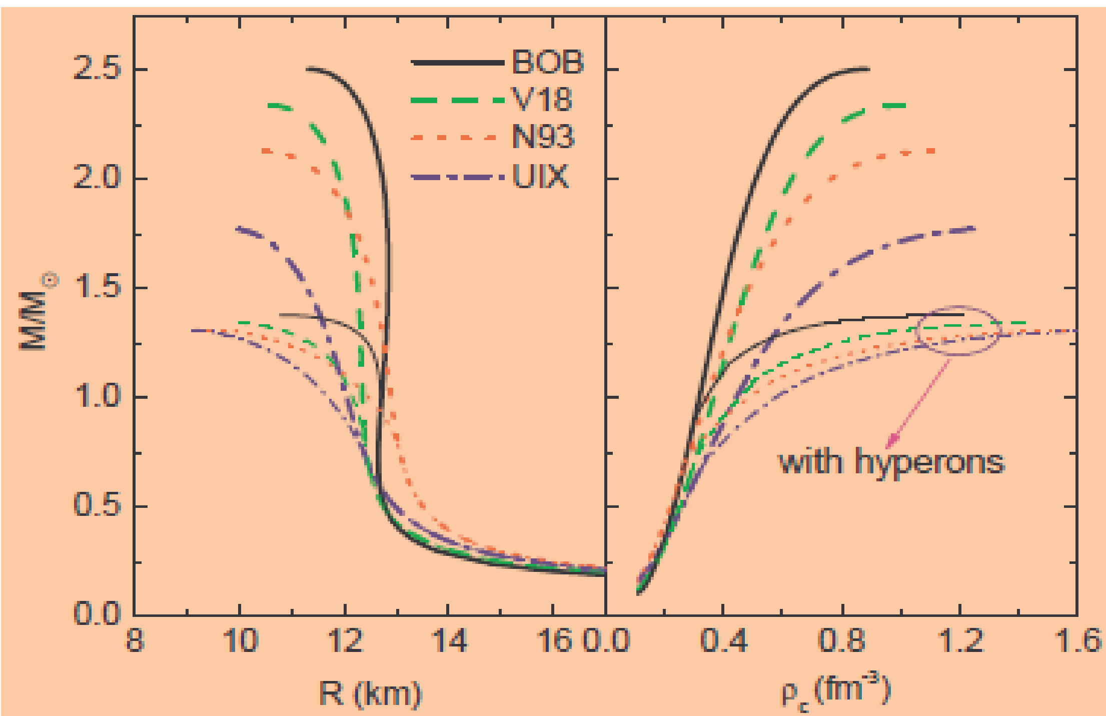




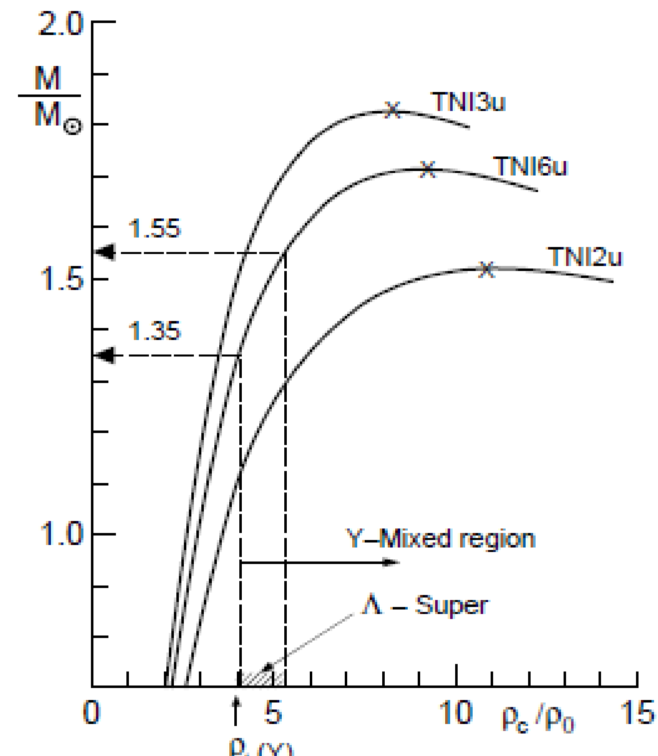
C. Ishizuka, AO, K. Tsubakihara, K. Sumiyoshi, S. Yamada, JPG35('08)085201.
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

Bruckner-Hartree-Fock theory with Hyperons

- **Microscopic G-matrix calculation with realistic NN, YN potential and microscopic (or phen.) 3N force (or 3B force).**
  - **Interaction dep. (V18, N93, ...) is large → Need finite nuclear info.**
    E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / M.Tamura et al.
  - **NS collapses with hyperons w/o 3BF.**



H.J.Schulze, A.Polls, A.Ramos, I.Vidana, PRC73('06),058801.



S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

Summary

- **Nuclear Matter EOS is important in various aspects of Nuclear Physics**
- **Relativistic Mean Field may be a good starting point to describe hadronic (baryon and meson) systems.**
  - **Relativistic → Saturation, Causality**
  - **Based on successes of Dirac Phenomenology and DBHF**
  - **Covariant Density Functional**
    → It is desirable to obtain E/V (energy density) in fundamental theories.
    (Renormalizability is not required.)
  - **We can re-write RMF equations in Schroedinger-like eqs. We may consider it as a method to parameterize DF in a transparent manner.**
  - **Higher order terms / Density dependence of the coupling constants (not mentioned) → Necessary for precise description of nuclei, but need foundations of extension.**