Phenomenological approach to dense hyperon mixed matter EOS

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Dynamics and Correlations in Exotic Nuclei (DCEN2011)
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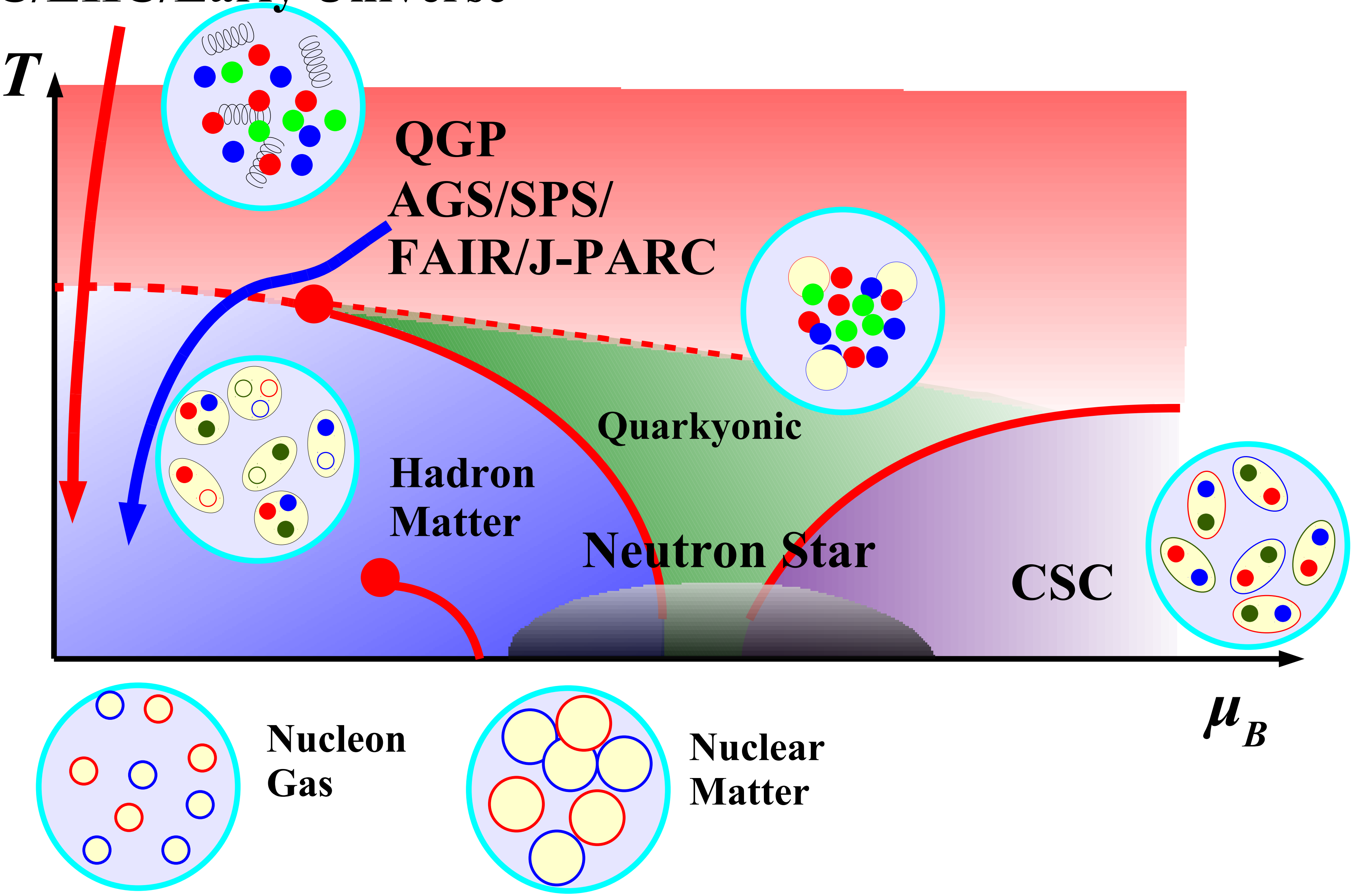
Yukawa Institute for Theoretical Physics, Kyoto, Japan

- **Introduction**
- **Relativistic Mean Field for Hypernuclei and Hyperonic Matter**
- **Do hyperons survive in 1.97 $M_\odot$ neutron star ?**
- **Summary**

QCD Phase Diagram



RHIC/LHC/Early Universe

T

QGP

AGS/SPS/
FAIR/J-PARC

Quarkyonic

Hadron
Matter

Neutron Star

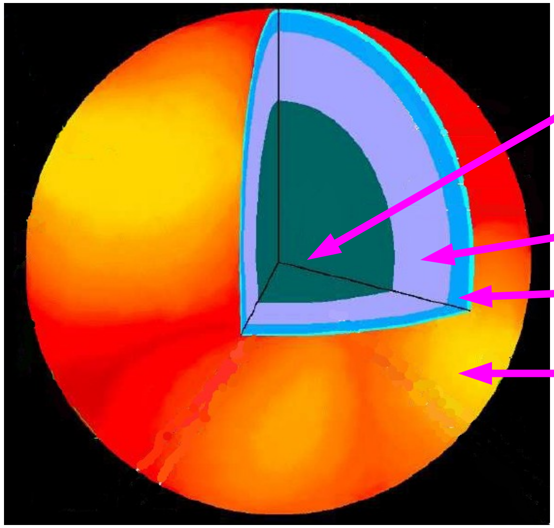
CSC

Nucleon
Gas

Nuclear
Matter

μ_B

Neutron Star Composition

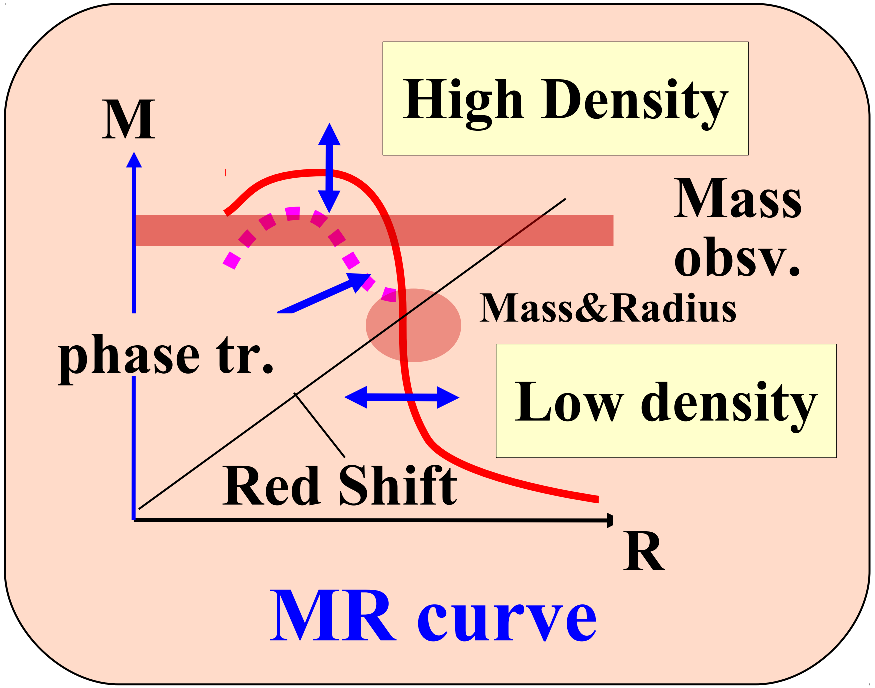


Hyperons, mesons, quarks

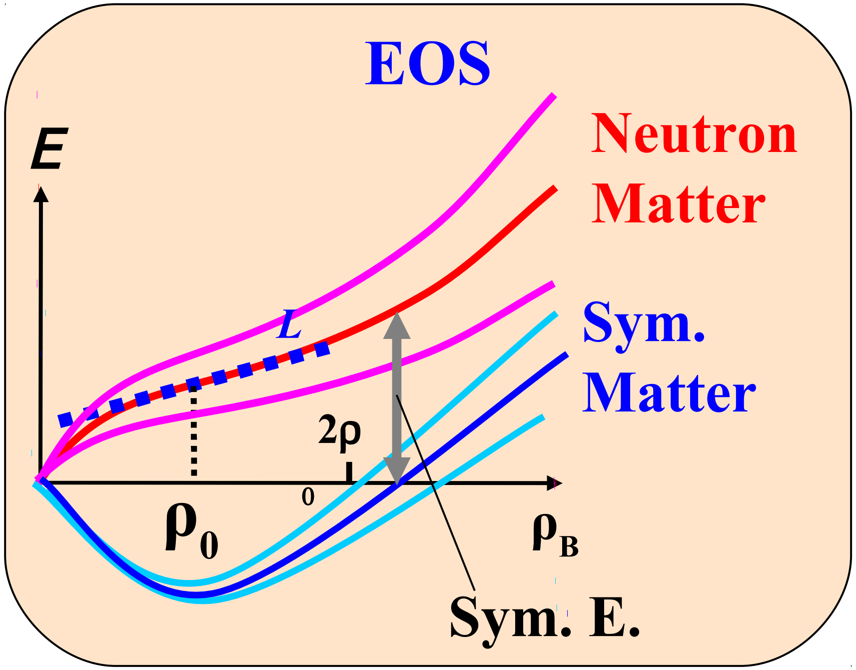
Asym. nuclear matter+elec.+μ

Nuclei+neutron gas+elec.

Nuclei + elec.

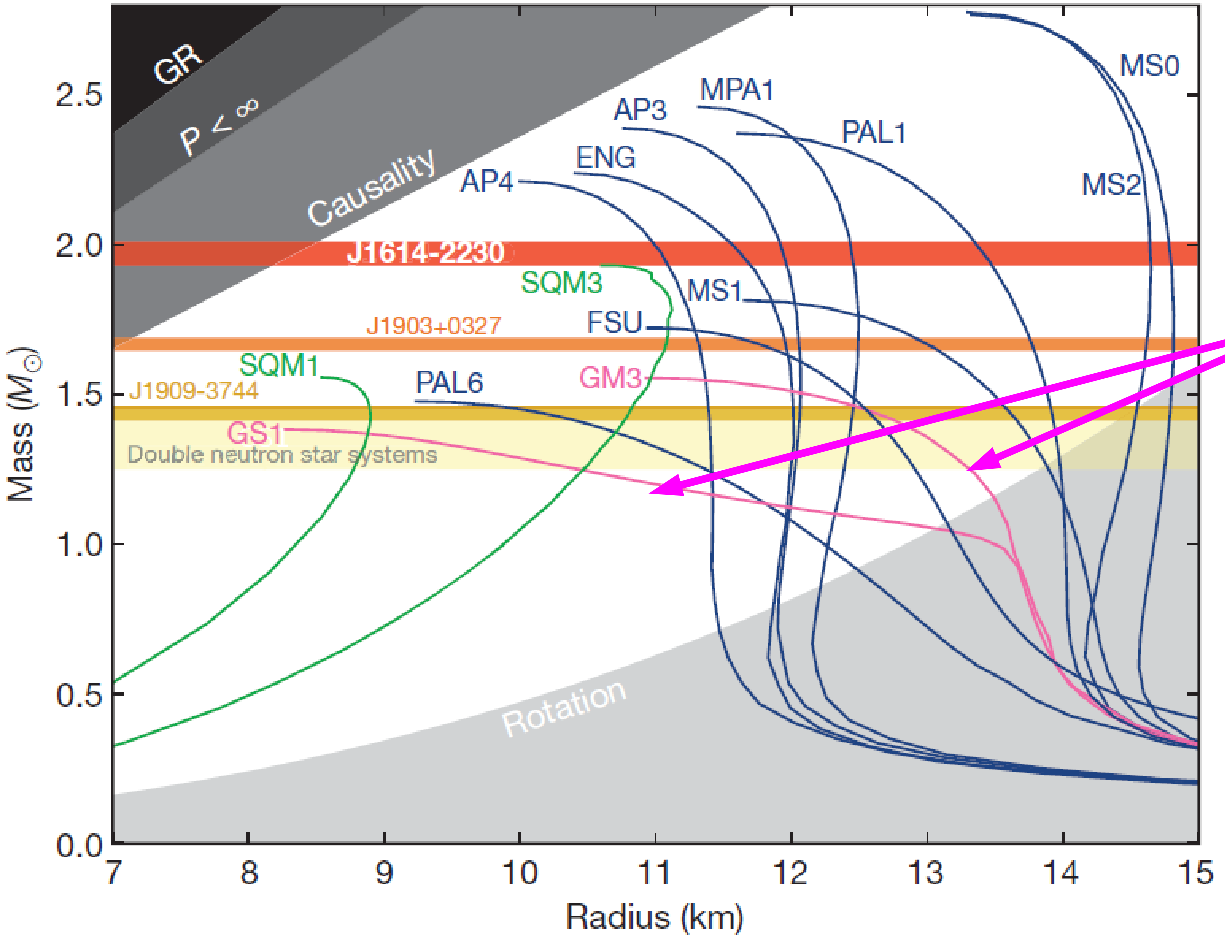


TOV eq.

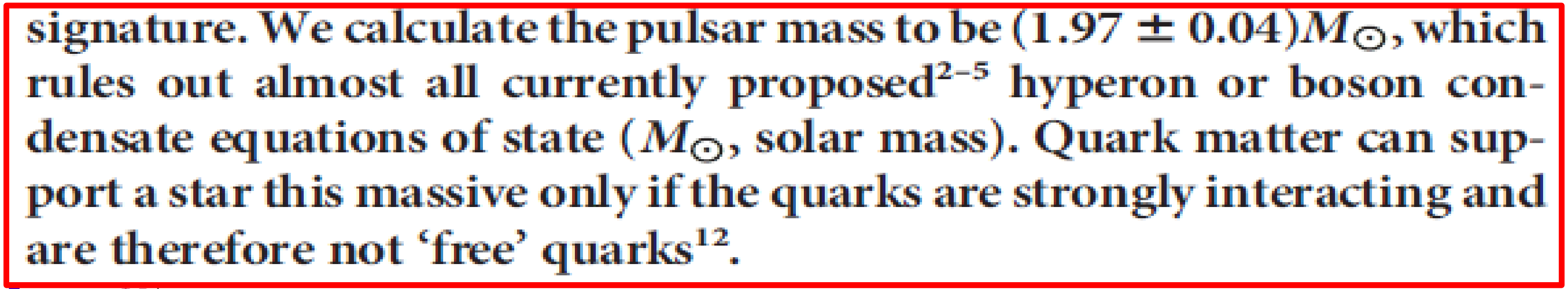


1.97 ± 0.04 $M_\odot$ Neutron Star

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



EOS with Strange Hadrons


signature. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_\odot$, which rules out almost all currently proposed$^{2-5}$ hyperon or boson condensate equations of state ($M_\odot$, solar mass). Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not 'free' quarks^{12}.

Hyperons in Dense Matter

- **Hyperons are HOT now !**
  - **What makes NS matter core ? Nucleons ? Quarks ? Hyperons ?**
  - **How can we suppress hyperon appearance in NS ?**
    or How can hyperonic matter be so stiff ?
    or Which inter-quark interaction supports 1.97 $M_\odot$ NS ?

We stick to hyperonic matter (rather than quark matter),
and discuss possible mechanism
to stiffen the EOS at high density.

Dense Nuclear Matter EOS with Hyperon Admixture

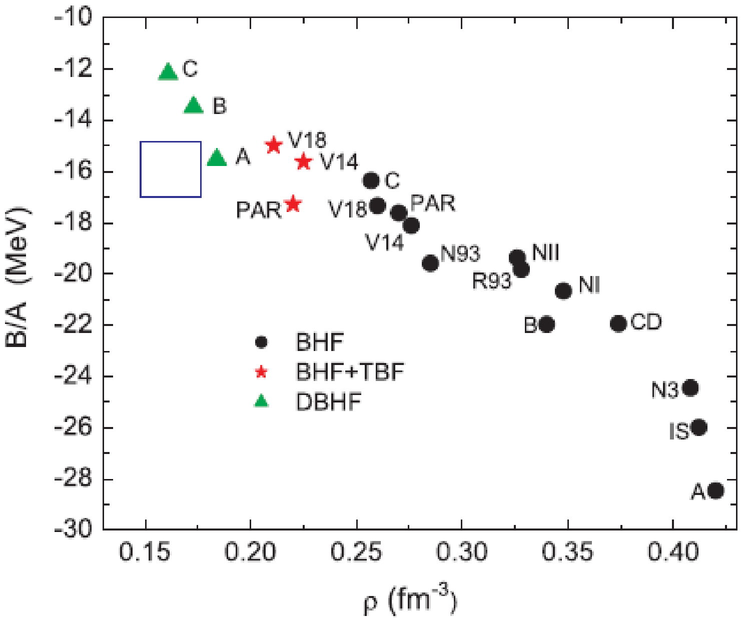
Theories/Models for Nuclear Matter EOS

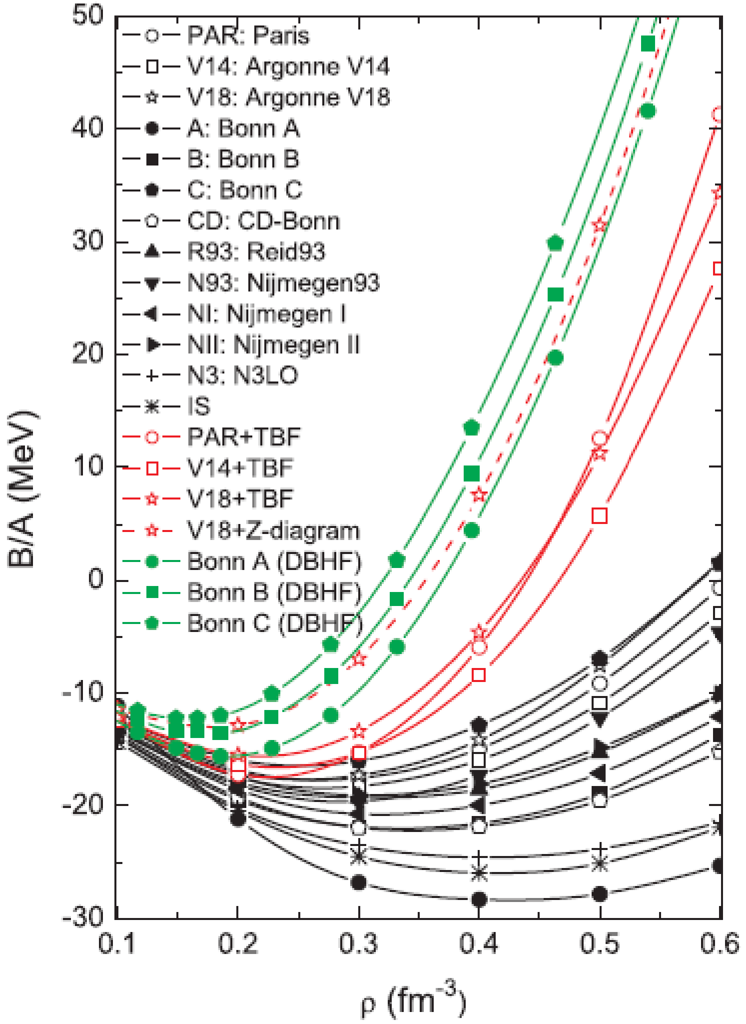
- **Ab initio Approaches to Nuclear Matter**
  → LQCD, Variatonal, GFMC, BHF(G-Matrix), DBHF, ...
  - **LQCD-MC: Not (yet) applicable to cold dense matter, A ≤ 4**
    SC-LQCD: Nuclear matter does not bound
  - **Variatioal, BHF: Need phen. 3-body repulsion to reproduce saturation point.**
  - **GFMC: Limited to be A ≤ 12.**
  - **DBHF: Good, but E/A is not enough. Not yet extensively investigated.**

  → Not easy to handle, Not yet satisfactory for phen. purposes
- **Mean Field Models (~ Nuclear Density Fuctional approach)**
  - **Skyrme Hartree-Fock(-Bogoliubov)**
    - **Nuclear Mass is very well explained (HFB, 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)**

Bruckner-Hartree-Fock

- **Self-consistent treatment of**
  Effective interaction (G-matrix) in the Bruckner Theory
  and Single particle energy from G-matrix
  - **Need 3-body force to reproduce saturation point.**
    → FY type 2 π exchange
    + phen. or Z-diagram

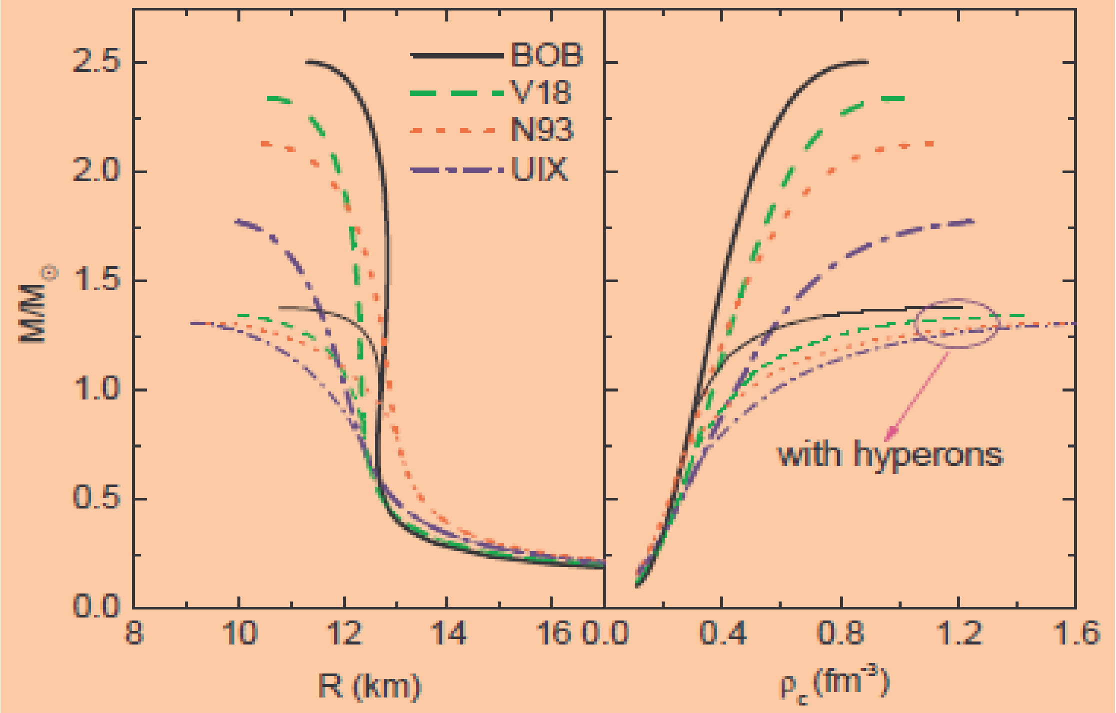




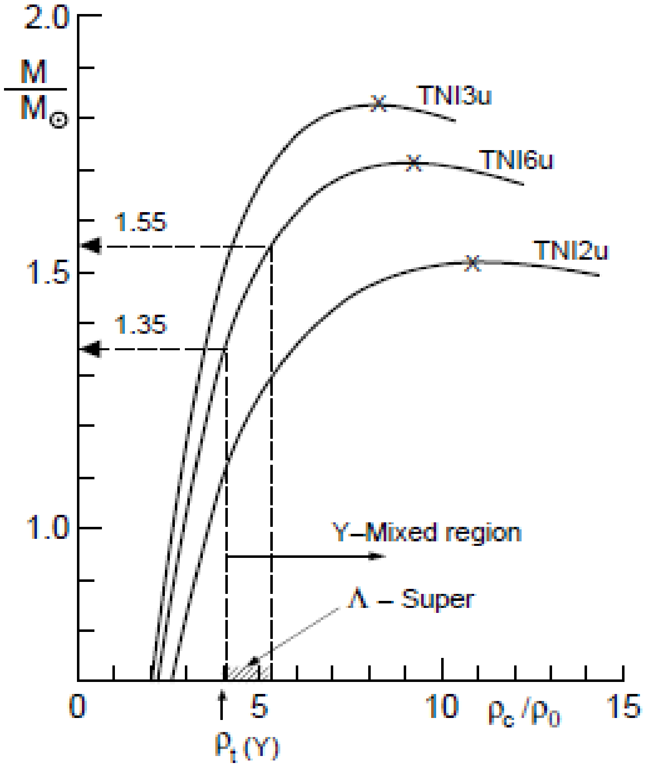
Z.H.Li, U. Lombardo, H.-J. Schulze, W. Zuo, L. W. Chen, H. R. Ma, PRC74('06)047304.

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.

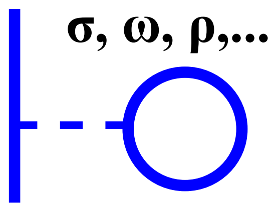


S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

Relativistic Mean Field

- **Effective Lagrangian of Baryons and Mesons + Mean Field App.**

  B.D.Serot, J.D.Walecka, Adv.Nucl.Phys.16 ('86), 1



$$L = L_B^{\text{free}} + L_M^{\text{free}} + L_{BM} + L_M^{\text{Int}}$$

$$L_M^{\text{Int}} = -U_\sigma(\sigma) + \frac{1}{4} c_\omega (\omega_\mu \omega^\mu)^2 + \cdots$$

$$L_{BM} = -\sum_{B,S} g_{BS} \bar{\psi}_B \varphi_S \psi_B - \sum_{B,V} g_{BV} \bar{\psi}_B \gamma^\mu V_\mu \psi_B$$

$$L_B^{\text{free}} = \bar{\psi}_B (i\gamma^\mu \partial_\mu - M_B) \psi_B \ , \quad L_M^{\text{free}} = \sum_S \left[\frac{1}{2} \partial^\mu \varphi_S \partial_\mu \varphi_S - \frac{1}{2} m_S^2 \varphi_S^2\right] + \sum_V \left[-\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} V_\mu V^\mu\right]$$

- **Baryons and Mesons: B=N, Λ, Σ, Ξ, ..., S= σ, ς, ..., V= ω, ρ, φ, …**
- **Based on Dirac phenomenology & Dirac Bruckner-Hatree-Fock**

  E.D. Cooper, S. Hama, B.C. Clark, R.L. Mercer, PRC47('93),297
  R. Brockmann, R. Machleidt, PRC42('90),1965

- **Large scalar (att.) and vector (repl.) → Large spin-orbit pot.**
  Relativistic Kinematics → Effective 3-body repulsion
- **Non-linear terms of mesons → Bare 3-body and 4-body force**

  Boguta, Bodmer ('77), NL1:Reinhardt, Rufa, Maruhn, Greiner, Friedrich ('86), NL3: Lalazissis, Konig, Ring ('97),TM1 and TM2: Sugahara, Toki ('94), Brockmann, Toki ('92)

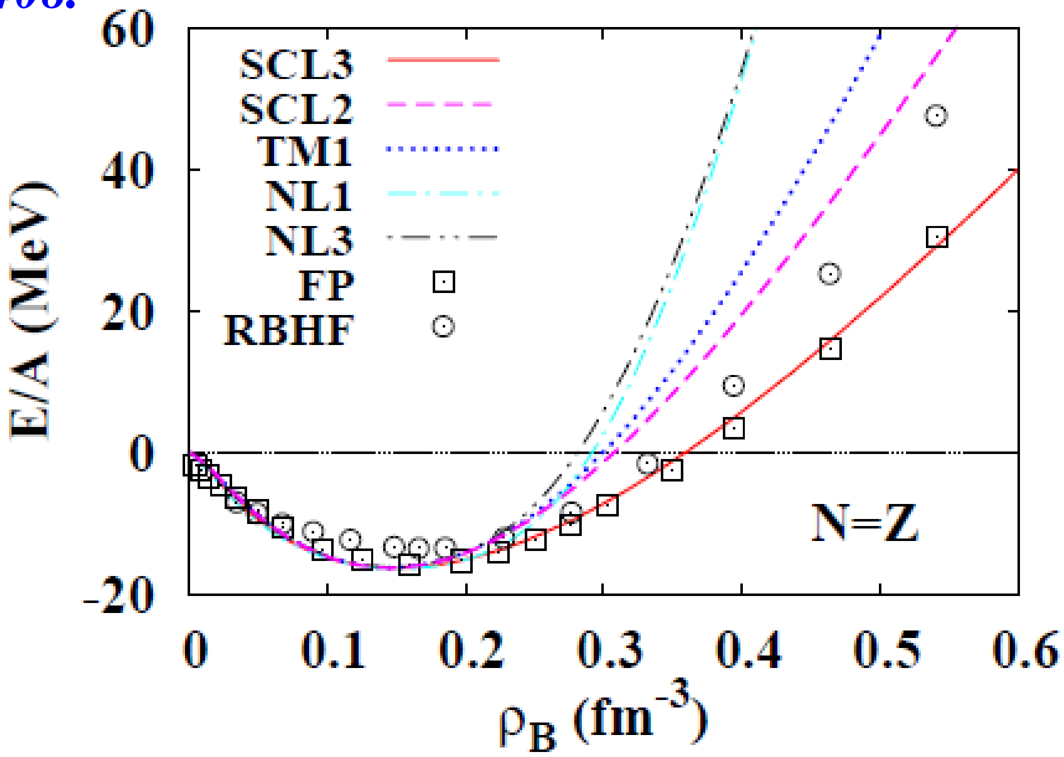
RMF is a phenomenological MODEL !

- **Baryon one-loop approximation (Hartree approximation) makes RMF a phenomenological model.**
  → We need DATA and AB INITIO results.
  - **Saturation point (ρ_0 and $E/A(\rho_0)$) from mass formula**
  - **Nuclear binding energies**
  - **U_v and U_s from DBHF results**
  - **$P(\rho_B)$ from heavy-ion data**
  - **Λ separation energy from single Λ hypernuclear data**
  - **ΛΛ bond energy from double Λ hypernuclear data**
  - **Σ atomic shift**
  - **Σ and Ξ potential depth from quasi-free production data**
  - ***Pure neutron matter EOS from ab initio calculations (not used here)***

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.**
    TM1&2: 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.

Choice of $U_\sigma(\sigma)$

- **Logarithmic σ potential**

  K.Tsubakihara, AO, PTP 117 (2007) 903.
  K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10) 065206.

$$U_\sigma = -\frac{a_\sigma}{2}\log\det\left(M M^+\right) + \frac{b_\sigma}{2}\mathrm{tr}\left(M M^+\right)$$

$$-d_\sigma\left(\det M + \det M^+\right) - \frac{c_\sigma}{4}\mathrm{tr}\left(M + M^+\right)$$

$$M = \text{Meson matrix} = \left[\lambda^a\left(\sigma^a + i\pi^a\right)\right]/\sqrt{2}$$

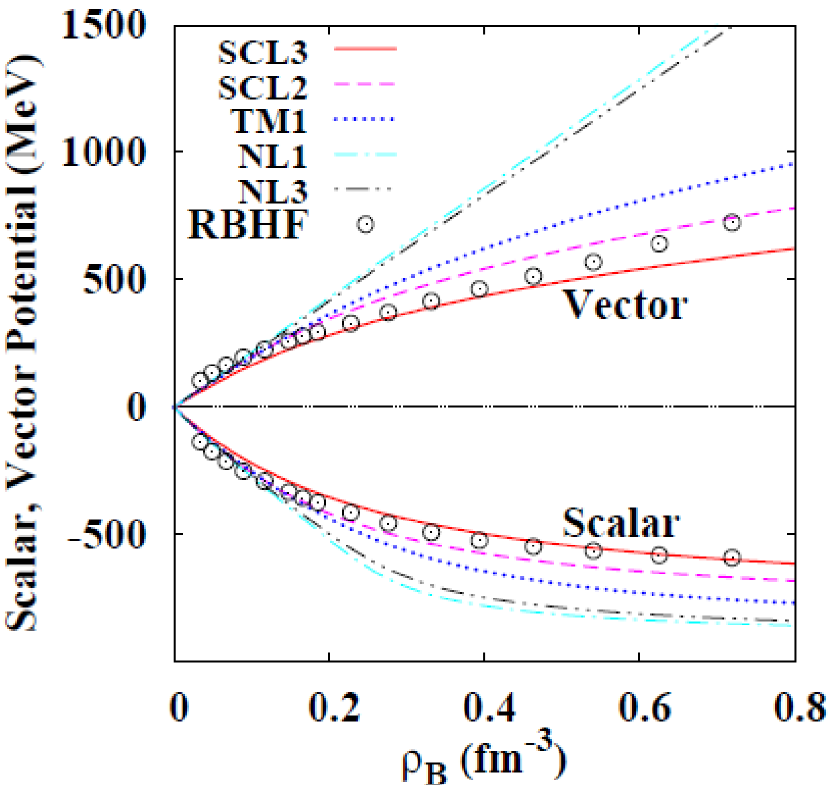
- **No chiral collapse, No instability at large σ**
- **Log σ term appears from coupling to dilaton (scale anomaly)**
  E. K. Heide, S. Rudaz, and P. J. Ellis, NPA571('94)713
  or from strong coupling limit of lattice QCD
  N.Kawamoto, J.Smit, NPB 190 ('81)100.
- **det σ term (KMT interaction) represents $U(1)_A$ anomaly**
  M.Kobayashi, T.Maskawa, PTP44('70)1422; M.Kobayashi, H.Kondo, T. Maskawa, PTP 45('71)1955; G. 't Hooft, PRD 14 ('76)3432.

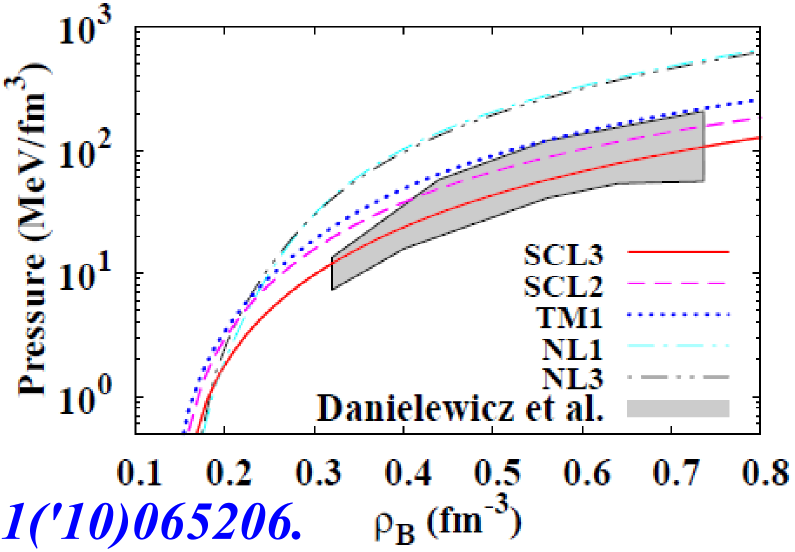
Vector potential in RMF

- **Vector potential from ω dominates at high density !**

$$U_v(\rho_B) = g_\omega \omega \sim \frac{g_\omega^2}{m_\omega^2} \rho_B$$

  - **Dirac-Bruckner-Hartree-Fock shows suppessed vector potential at high ρ_B.**
    R. Brockmann, R. Machleidt, PRC42('90)1965.
  - **Collective flow in heavy-ion collisions suggests pressure at high ρ_B.**
    P. Danielewicz, R. Lacey, W. G. Lynch, Science298('02)1592.
  - **Self-interaction of ω ~ $c_\omega(\omega_\mu\omega^\mu)^2$**
    → DBHF results & Heavy-ion data





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

RMF with Hyperons (Single Λ hypernuclei)

- **RMF for Λ hypernuclei**

x ~ 1/3: R. Brockmann, W. Weise, PLB69('77)167; J. Boguta and S. Bohrmann, PLB102('81)93.
x ~ 2/3: N. K. Glendenning, PRC23('81)2757, PLB114('82)392;
Tensor: Y. Sugahara, H. Toki, PTP92('94)803; H. Shen, F. Yang, H. Toki, PTP115('06)325;
J. Mares, B. K. Jennings, PRC49('94)2472.
ρ-dep. coupling: H. Lenske, Lect. Notes Phys. 641('04)147; C. M. Keil, F. Hofmann, H. Lenske, PRC 61('00)064309.
SU(3) or SU(6) (ς, φ): J. Schaffner, C. B. Dover, A. Gal, C. Greiner, H. Stoecker,PRL71('93)1328;
Schaffner et al., Ann.Phys.235('94)35; J. Schaffner, I. N. Mishustin, PRC 53('96)1416.
Chiral SU(3) RMF: K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

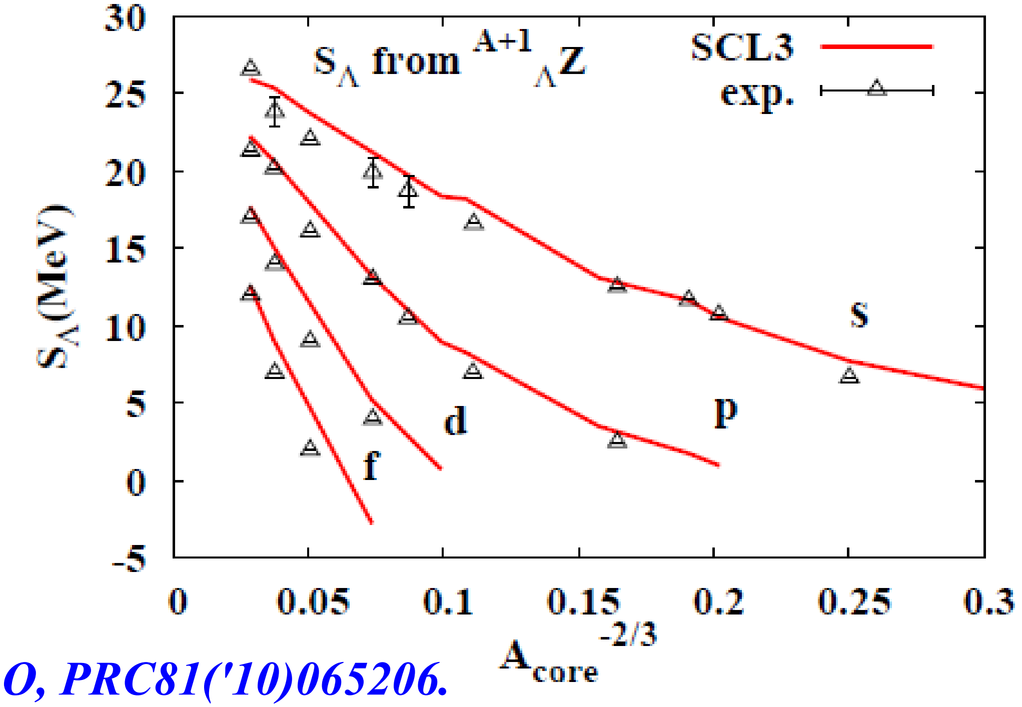
- **Sep. E. of Λ is well fitted by $U_\Lambda \sim -30$ MeV $\sim 2/3\ U_N$**
- **Coupling with mesons**

  $x_M = g_{M\Lambda}/g_{MN}$

  quark counting: $x_\sigma \sim 2/3$

  π exchanges: $x_\sigma \sim 1/3$

  → Which is true ?



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

RMF with Hyperons (Double Λ hypernuclei)

- **Nagara event $\Delta B_{\Lambda\Lambda}$ ~ 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_ω=2/3 (no ς, φ)

    Model 2: $R_\varsigma = g_{\varsigma\Lambda} / g_{\sigma N}$=0.56-0.57, $R_\varphi = g_{\varphi\Lambda} / g_{\omega N} = -\sqrt{2}/3$

  - **Chiral SU(3) RMF**

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

    SU(3)f for vector coupling

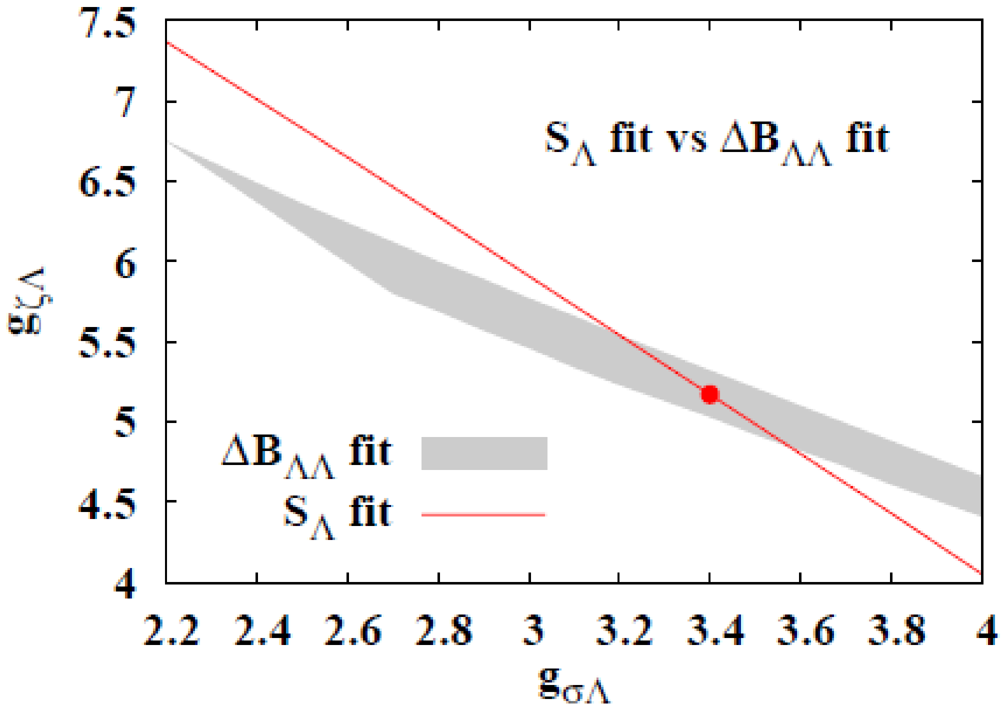
    x_ω=0.64, R_φ=0.504

    Det. (KMT) int. mixes σ and ς

    M. Kobayashi, T. Maskawa, PTP44('70)1422;

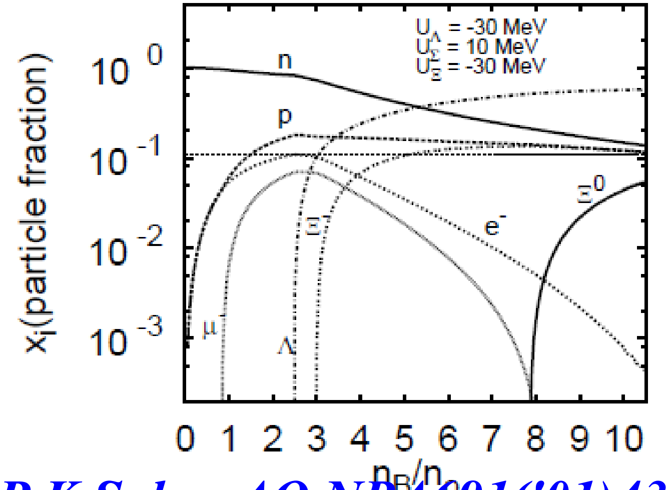
    G. 't Hooft, PRD14('76)3432.

    → x_σ=0.335, R_ς=0.509

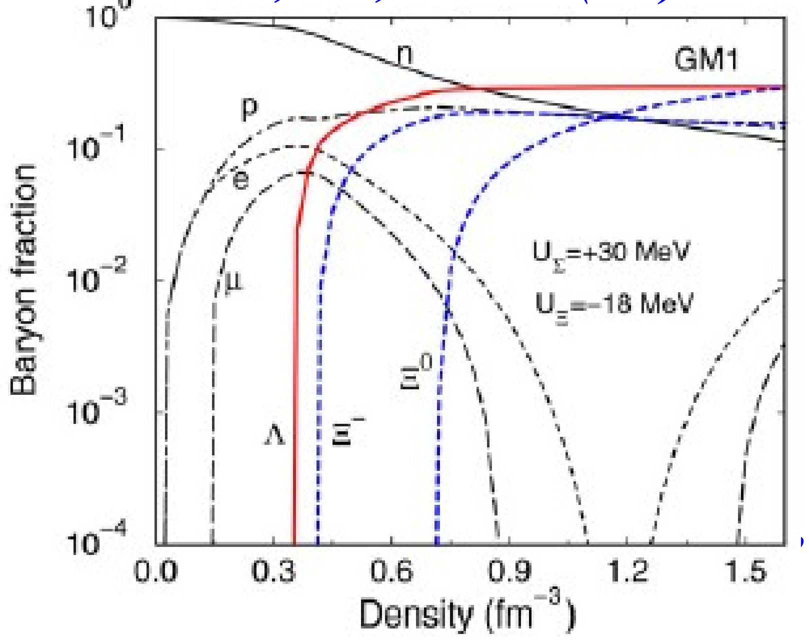


Hyperon Composition in Dense Matter

- **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.
    S. Balberg, A. Gal, NPA625('97)435;
    H. Noumi et al., PRL89('02)072301;
    T. Harada, Y. Hirabayashi, NPA759('05)143;
    M. Kohno et al. PRC74('06)064613.



P.K.Sahu, AO,NPA691('01)439c

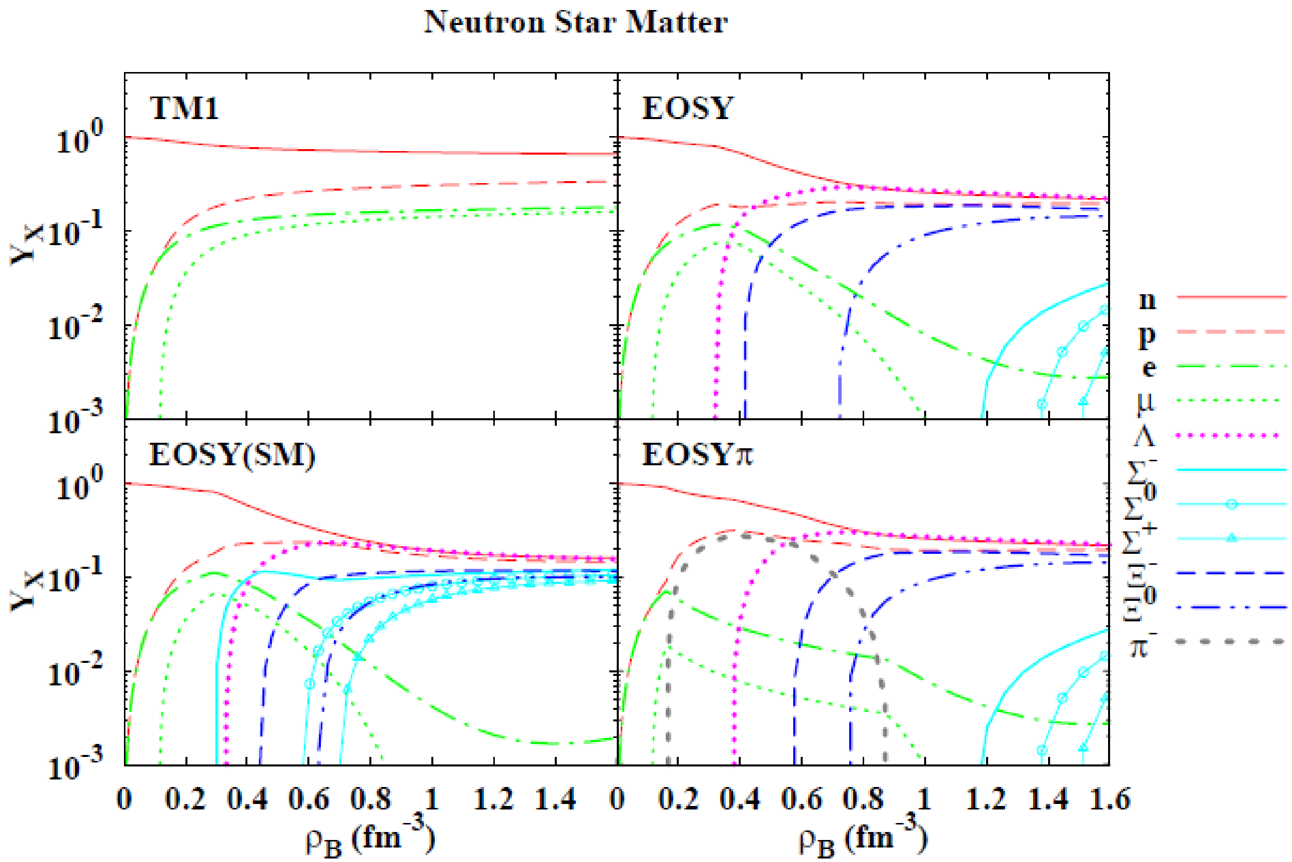


J. Schaffner-Bielich, NPA804('08)309.

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 ?



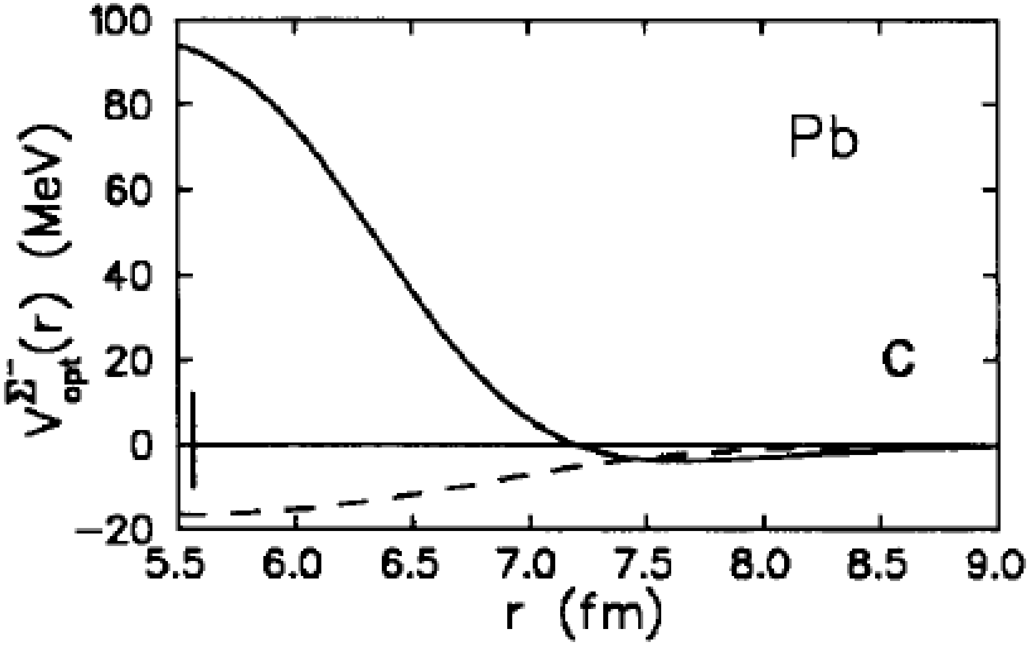
Σ^- atom data

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

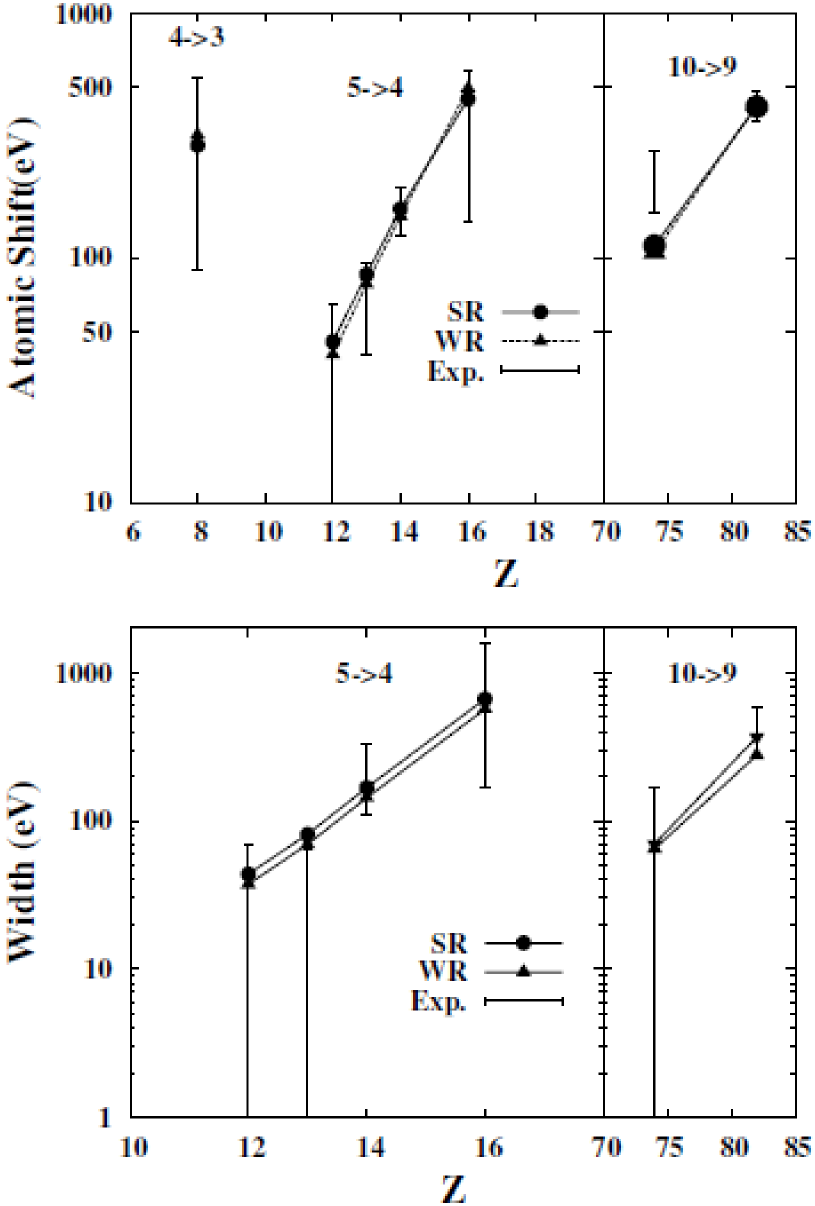
  C.J.Batty, E.Friedman, A.Gal, PLB335('94)273

  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

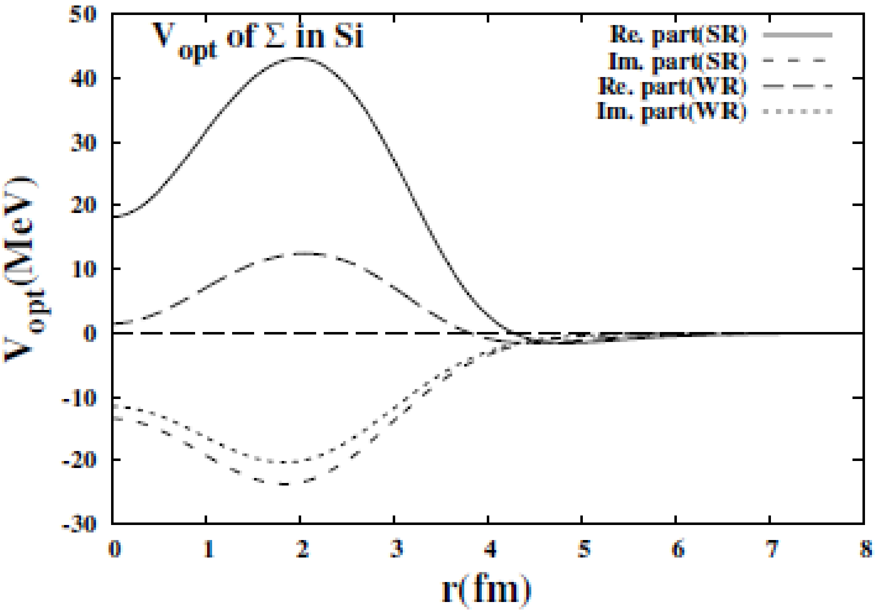
- **RMF fit of Si and Pb Σ^- atom**

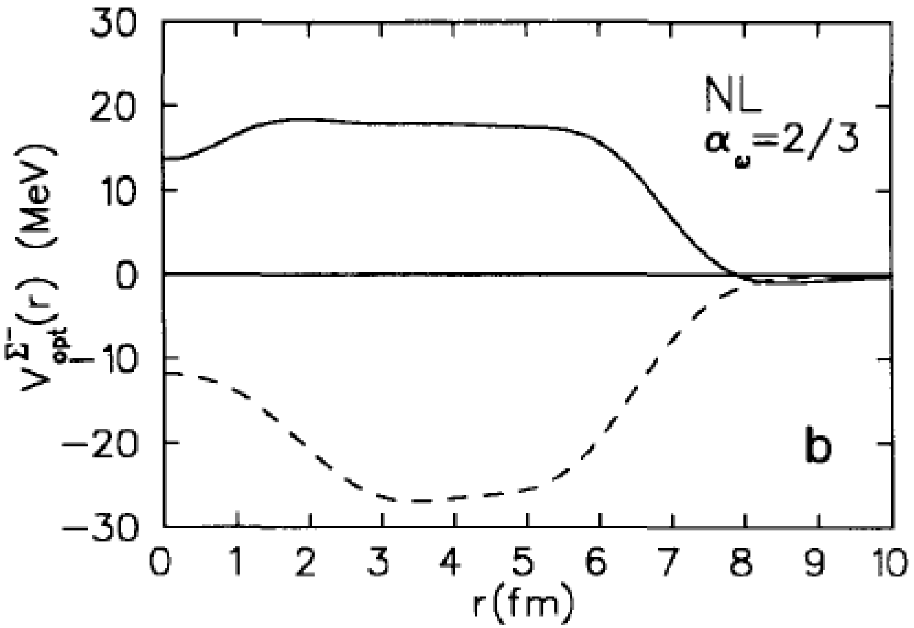
  $\alpha_\omega = g_{\omega\Sigma} / g_{\omega N} \sim 2/3$(M), 0.69 (T)

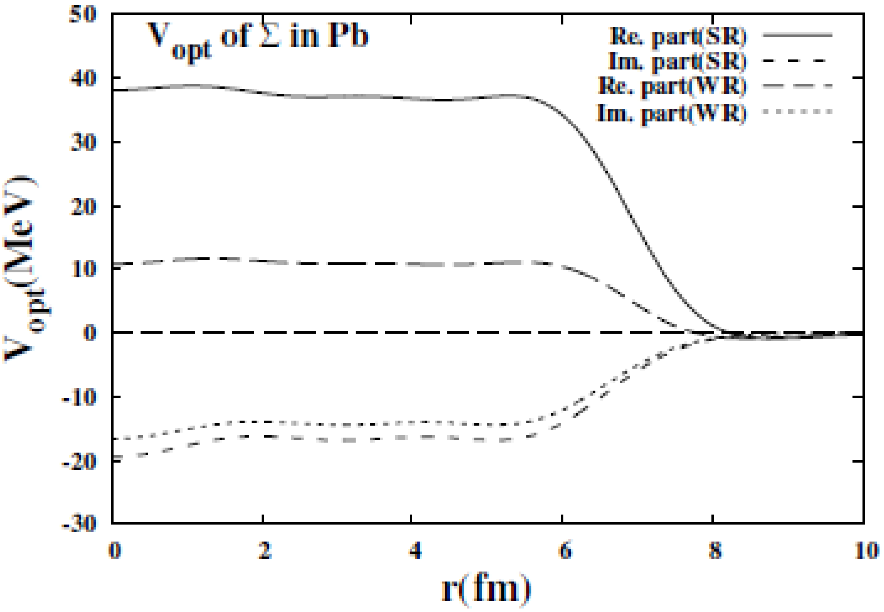
  $\alpha_\rho = g_{\rho\Sigma} / g_{\rho N} \sim 2/3$(M), 0.434(T)

  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.**



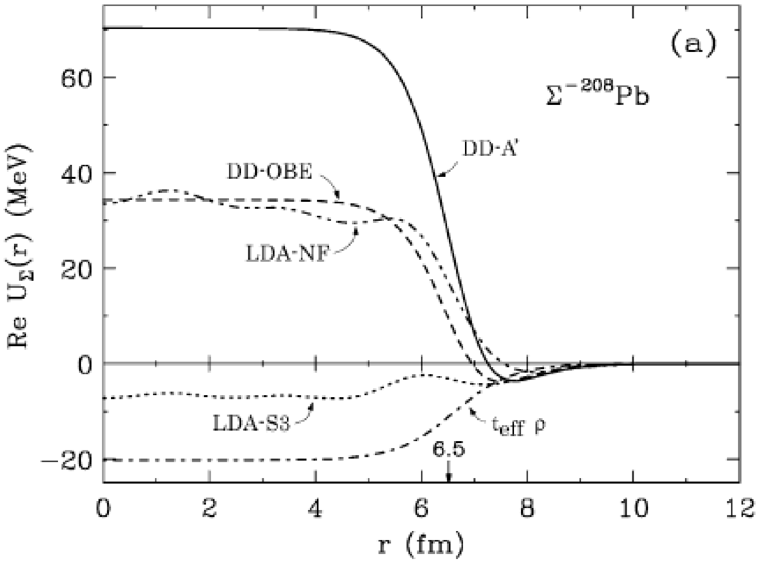




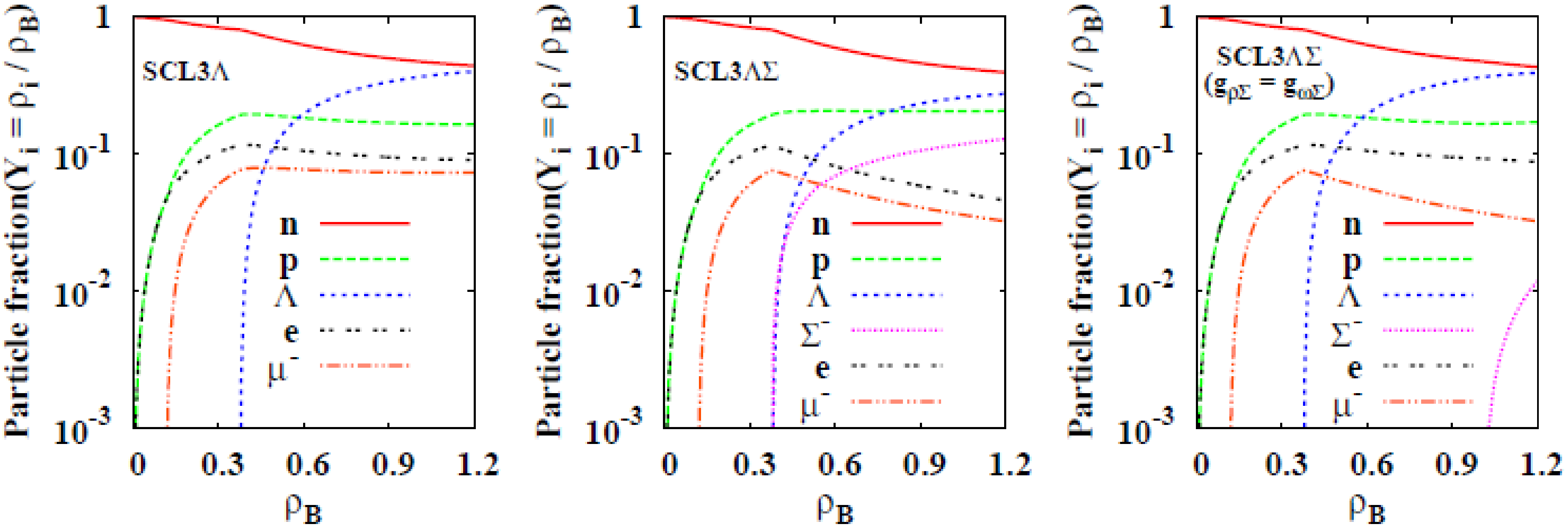
Σ atom and Neutron Star

- **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.



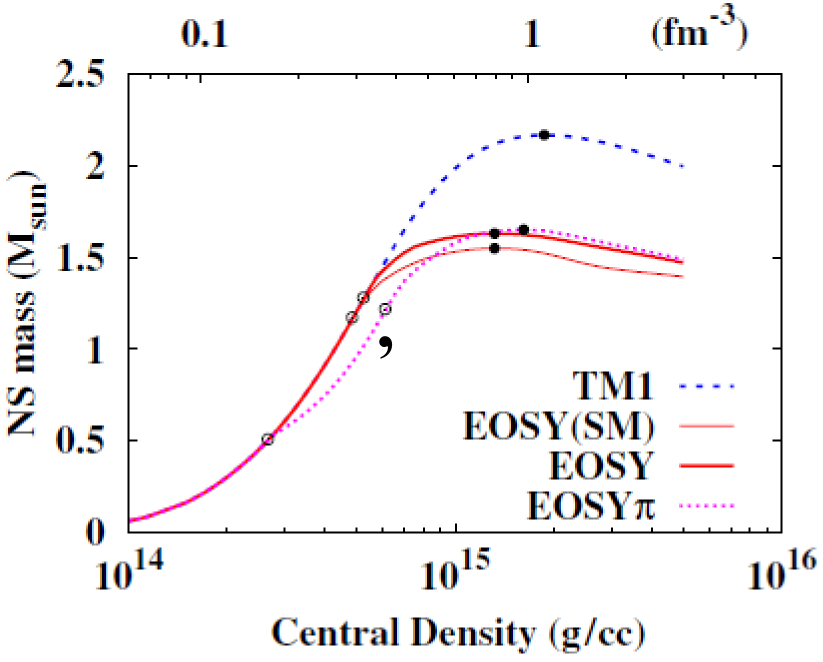
T. Harada, Y. Hirabayashi, NPA767('06)206

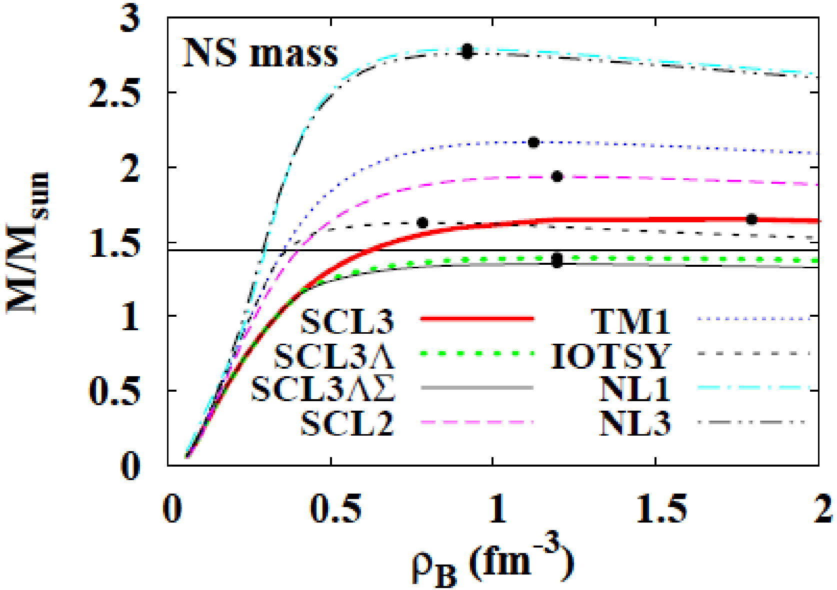


K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

Neutron Star Mass

- **Large fraction of hyperons softenes EOS at ρ_B > (0.3-0.4) 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.

RMF is a phenomenological MODEL !

- **Baryon one-loop approximation (Hartree approximation) makes RMF a phenomenological model.**
  → We need DATA and AB INITIO results.

- O **Saturation point (ρ_0 and $E/A(\rho_0)$) from mass formula**
- O **Nuclear binding energies**
- O **U_v and U_s from DBHF results**
- O **$P(\rho_B)$ from heavy-ion data**
- O **Λ separation energy from single Λ hypernuclear data**
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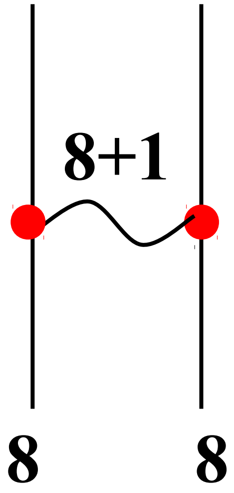
- O **Σ atomic shift**
- O **Σ and Ξ potential depth from quasi-free production data**
- ***Pure neutron matter EOS from ab initio calculations (not used here)***
- Δ **Neutron Star Max. Mass ~ 1.40 $M_\odot$, a little smaller 1.44 $M_\odot$.**

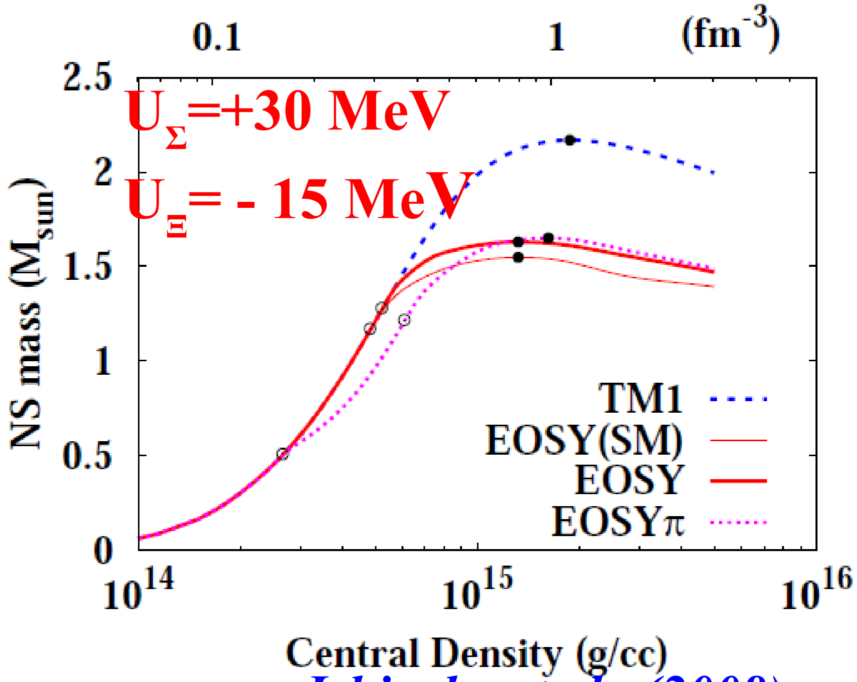
The Judgement Day, Oct. 28, 2010.

Can hyperon survive in 1.97 $M_\odot$ neutron star ?

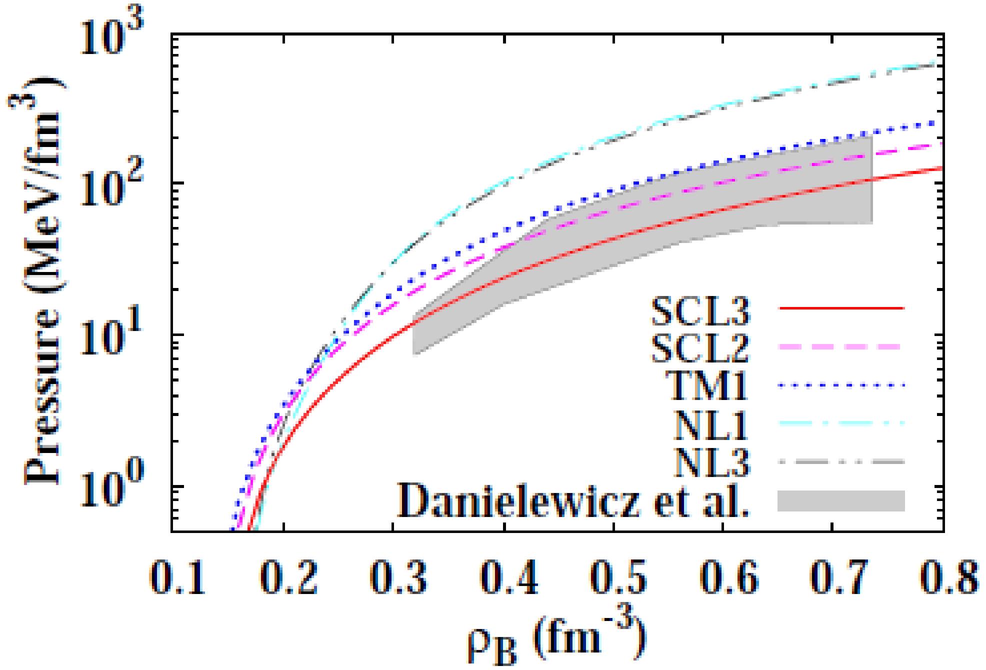
Which type of EOSs are rejected ?

- **Rejected Hyperonic Matter EOS**
  - **Relativistic Mean Field model**
    GM3: Glendenning & Moszkowski (1991)(npY)
    GS1: Glendenning & Schaffner-Bielich (1999)(npK)
  - **Coupling ~ Quark Counting ($g_{\omega Y}/g_{\omega N}$ ~ 2/3)**
  - **Even with rel. effects, we cannot support $1.97M_\odot$ as long as we respect hypernuclear & HIC data.**





Ishizuka et al., (2008)



Tsubakihara et al., (2010)

Glendenning & Moszkowski (1991)

- **RMF with hyperons**
  - **n, p, Y, σ, ω, ρ / σ^3, σ^4**
  - **Give $x_\sigma = g_{\sigma Y}/g_{\sigma N}$ and fix $x_\omega = g_{\omega Y}/g_{\omega N}$ to fit Λ separation energy.**
  - **$x_\sigma = 0.6 \rightarrow m^*/m = 0.7$, $x_\omega = 0.653$ (similar to quark number counting result, $x=2/3$) $\rightarrow M_{\max} \sim 1.6\, M_\odot$**

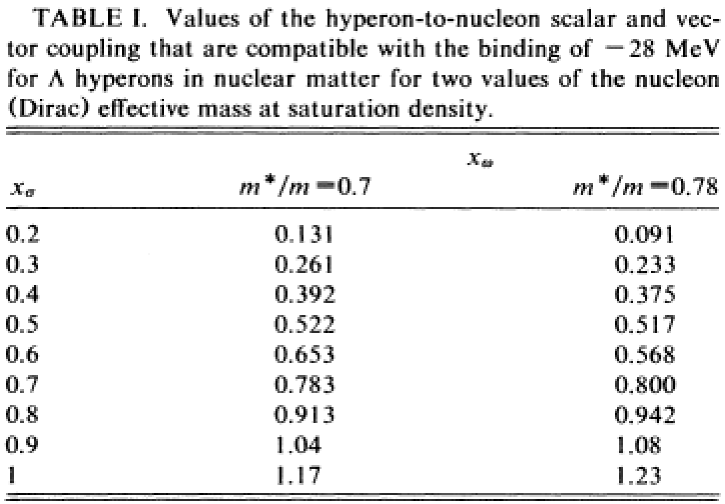
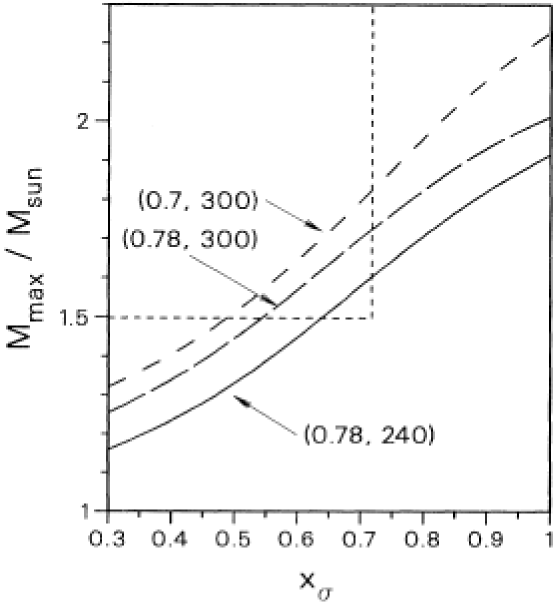
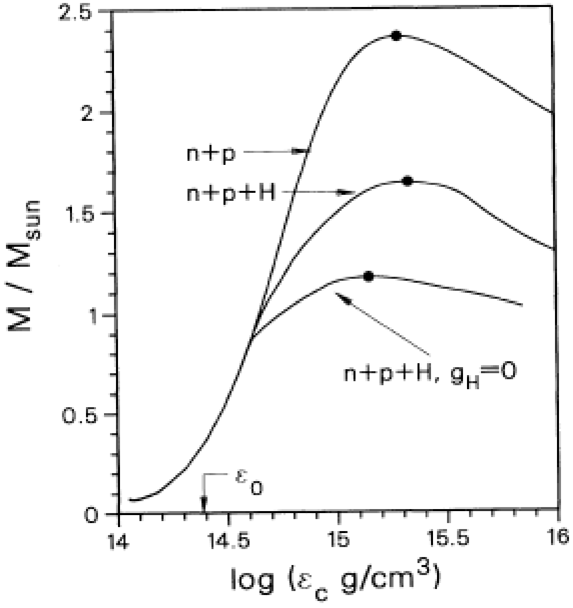
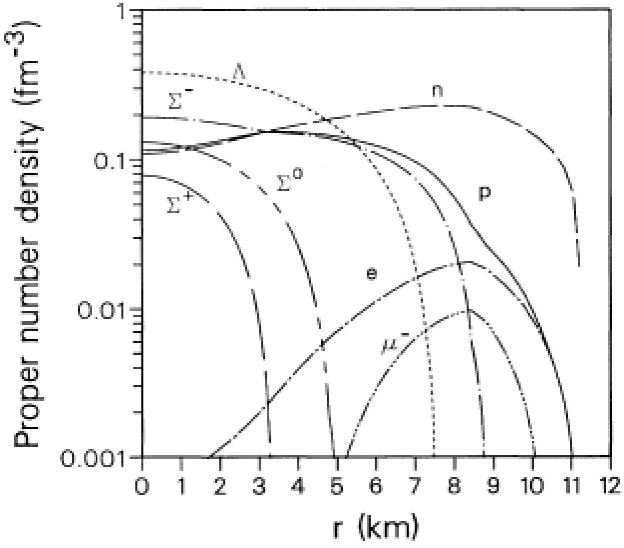


TABLE I. Values of the hyperon-to-nucleon scalar and vector coupling that are compatible with the binding of −28 MeV for Λ hyperons in nuclear matter for two values of the nucleon (Dirac) effective mass at saturation density.

	x_ω	
x_σ	$m^*/m=0.7$	$m^*/m=0.78$
0.2	0.131	0.091
0.3	0.261	0.233
0.4	0.392	0.375
0.5	0.522	0.517
0.6	0.653	0.568
0.7	0.783	0.800
0.8	0.913	0.942
0.9	1.04	1.08
1	1.17	1.23



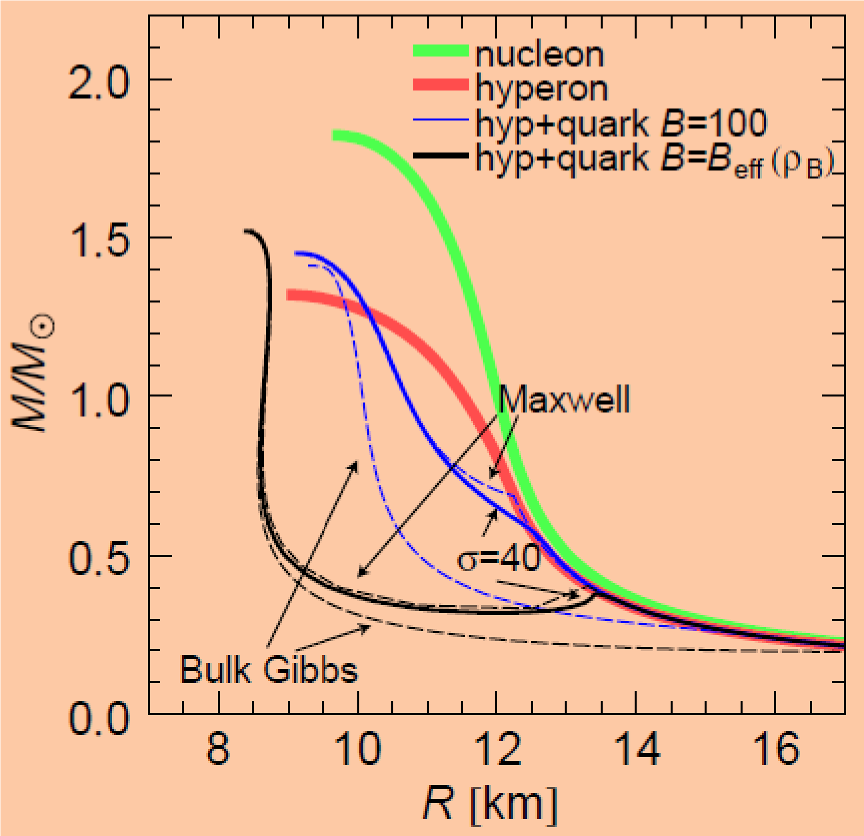




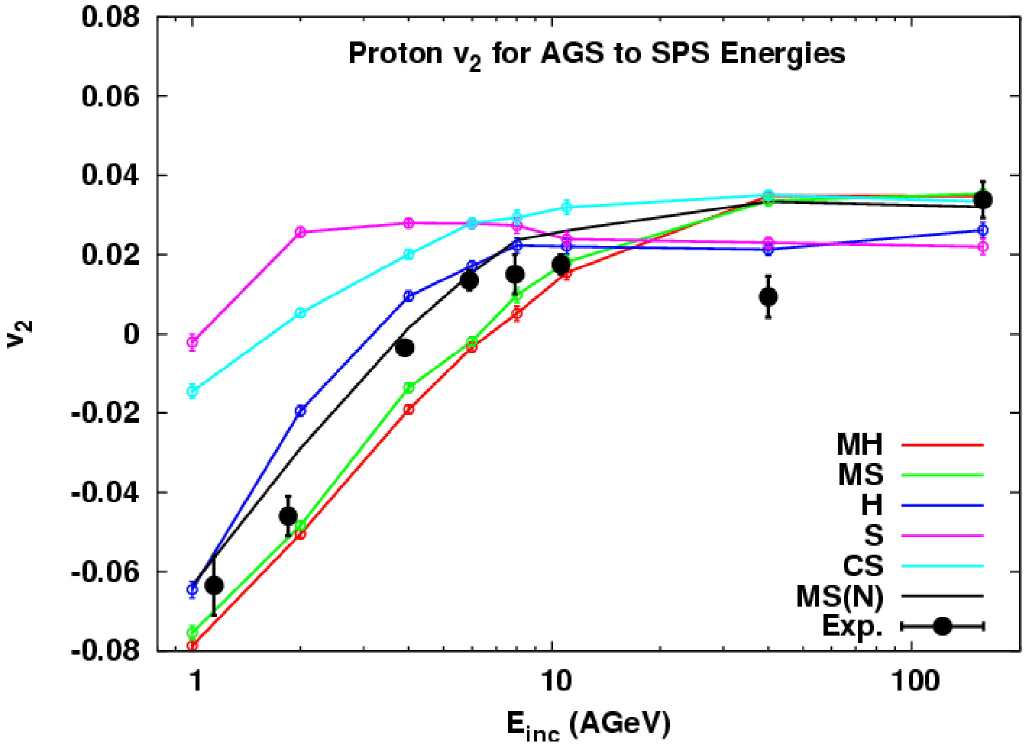
N.K.Glendenning, S.A.Moszkowski, PRL67('91)2414

How can we solve it ?

- **No Hyperons, No Kaons**
  → How can it be consistent with YN interaction ?
- **Stiff nuclear matter EOS + transition to quark matter at small ρ_B**
  → How can it be consistent with HIC data at AGS-SPS energies ?
- **Three-body force for baryons, quarks, ...**



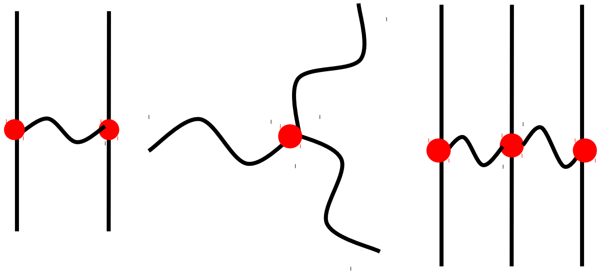
H.-J. Schulze, NFQCD10



M.Isse, AO, N.Otuka, P. K.Sahu, Y.Nara, PRC72 ('05)064908

RMF with 3BF

- **Three-baryon coupling term**



$$L = L_B^{\mathrm{free}} + L_M^{\mathrm{free}} + L_{BM} + L_M^{\mathrm{Int}} + \delta L$$

$$\delta L = -U_\sigma(\sigma) - \frac{1}{2} c_{\sigma\omega} \underline{\sigma \omega_\mu \omega^\mu} - \frac{1}{4} c_{\omega\omega} (\omega_\mu \omega^\mu)^2$$

$$- \sum_B \underline{\bar{\psi}_B \left[g_{\sigma\sigma B} \sigma^2 + g_{\sigma\omega B} \sigma \omega_\mu \gamma^\mu + g_{\omega\omega B} \omega_\mu \omega^\mu \right] \psi_B}$$

ν = 3 terms

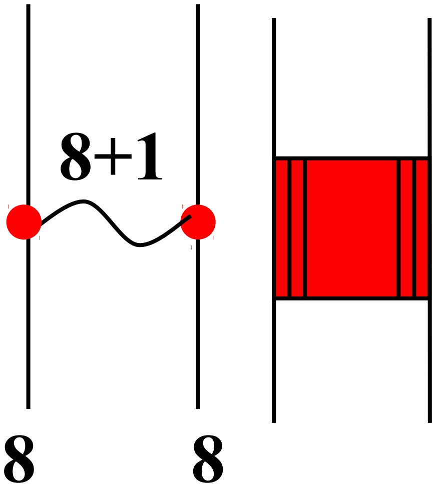
- **BBMM terms are ignored in standard RMF.**
  (They can be absorbed in other terms by field re-definitions.)
  R.D.Furnstahl, B.D.Serot, H.-B. Tang, NPA615 ('97)441

- **But field re-definition modifies the order of NDA.**
  Naïve dimensional analysis (NDA)
  ν = B/2 + M + d
  (B, M, d=# of baryon and non-NG boson field, derivatives to NG fields)

- **Higher ν terms are found to be suppressed at ρ ~ ρ0, but they will contribute more at high densities.**

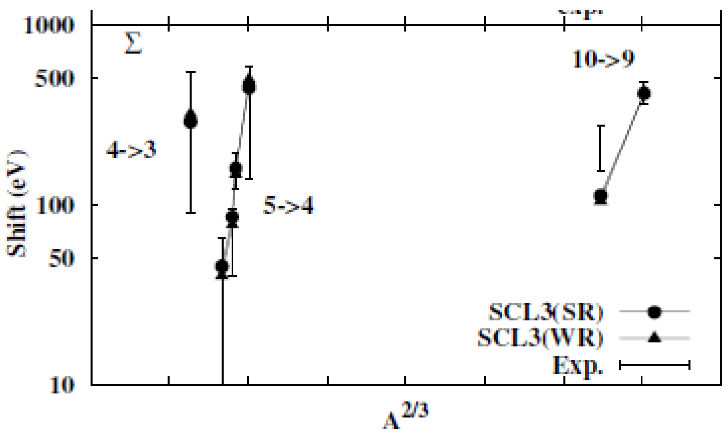
$SU(3)_f$ *“violating” coupling*

- **Naïve RMF assumption = BM coupling follows $SU(3)_f$.**
- **Short range BB interaction comes from quark Pauli blocking + one-gluon exch.**
  Oka, Yazaki; Faessler et al.; Fujiwara et al.; HAL QCD collab.
- **Short-range BB repulsion is sensitive to (S,T) in the s-channel. When we include those interactions in the bosonized form, BM coupling violates $SU(3)_f$.**



$$V=\sum_{\alpha,\beta}(\bar\psi\,\bar\psi)_\alpha\Gamma_{\alpha\beta}(\psi\,\psi)_\beta\to-\frac{1}{2}\sum_\alpha m_\alpha^2\omega_\alpha^2+\sum_\alpha g_\alpha\omega_\alpha(\psi\,\Gamma\,\psi)_\alpha$$

E.g., Σ atomic shift
→ $g_{\sigma\Sigma}$ ~ $g_{\sigma\Sigma}$ (SU(3)) x (0.2-0.3)

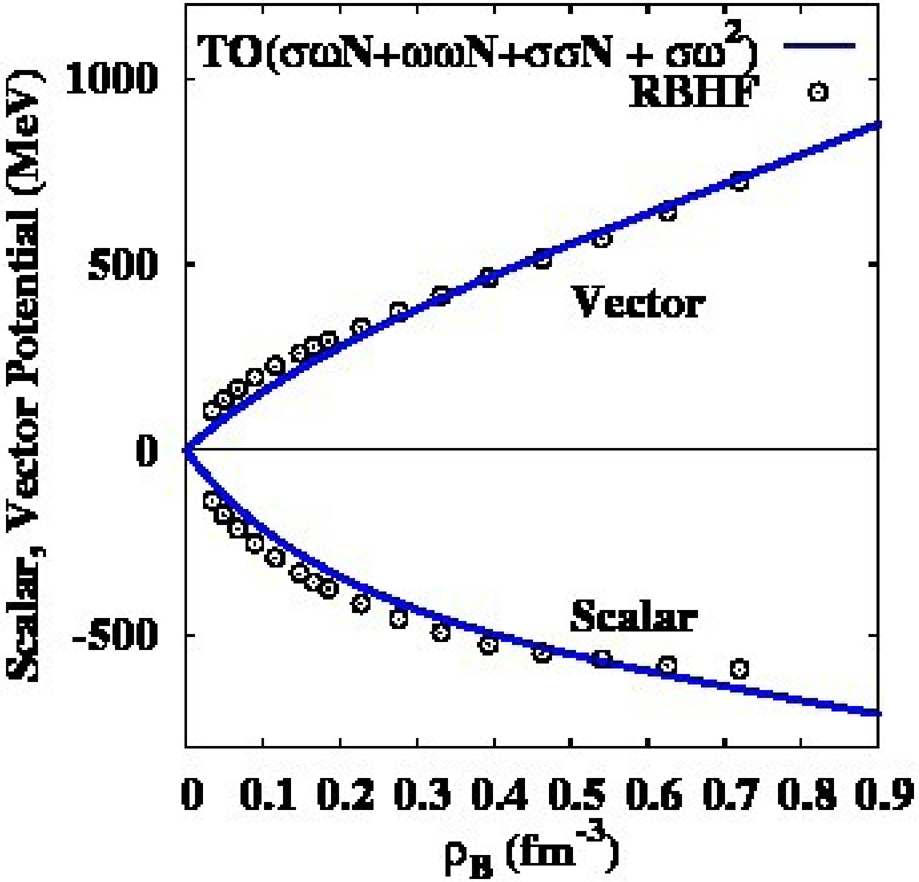


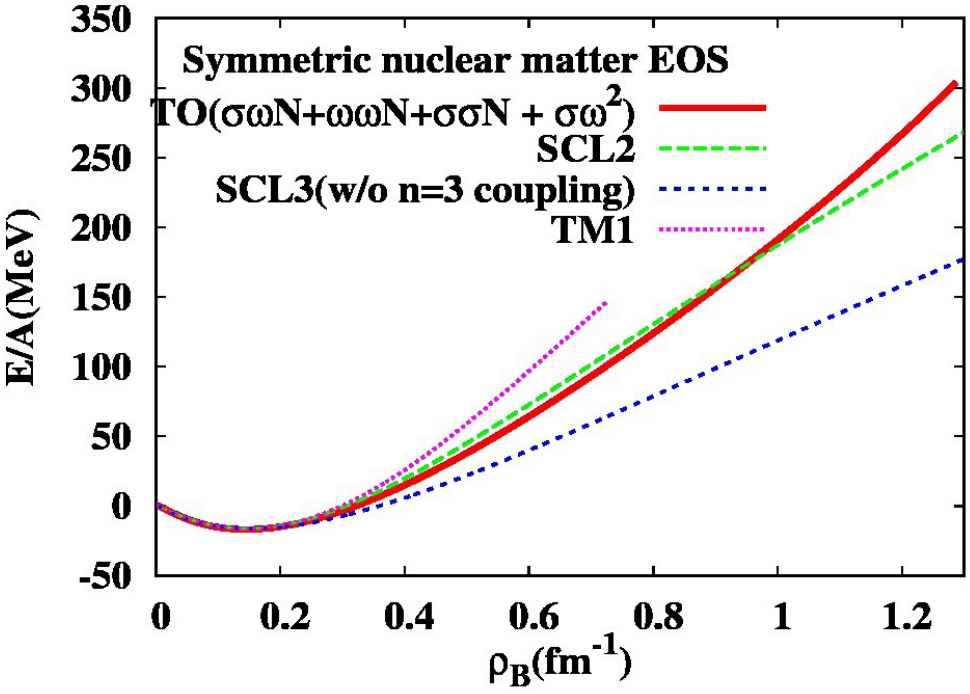
Tsubakihara et al., (2010)

RMF with 3BF

Tsubakihara, AO, in prep.

- **Nucleon vector potential $U_v(\rho)$ in DBHF: Non-linear behavior in ρ_B.**
  → EOS becomes gradually stiffer at high density !



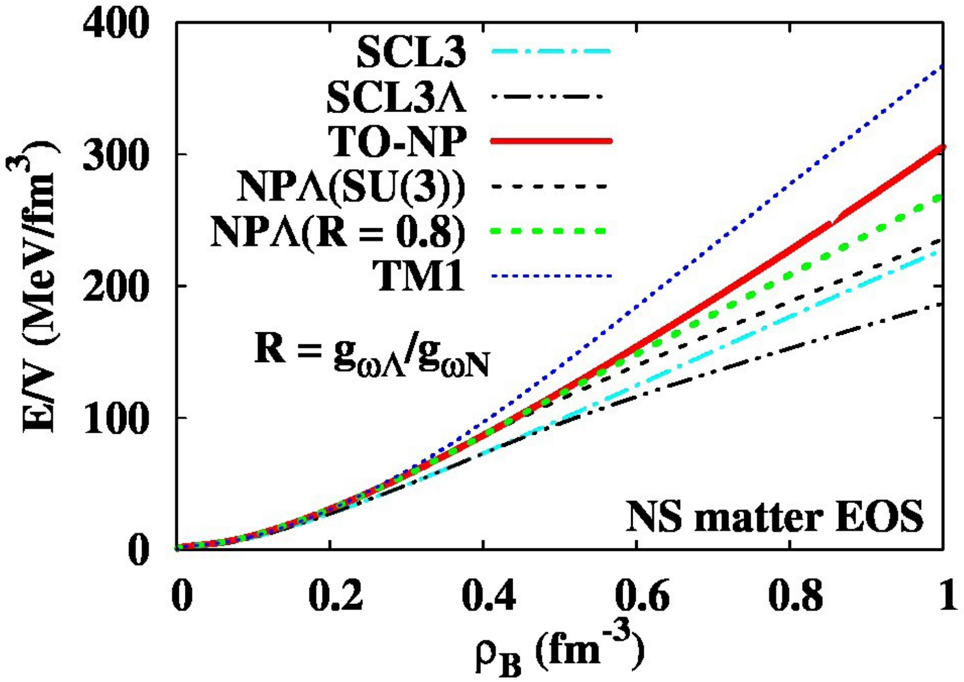


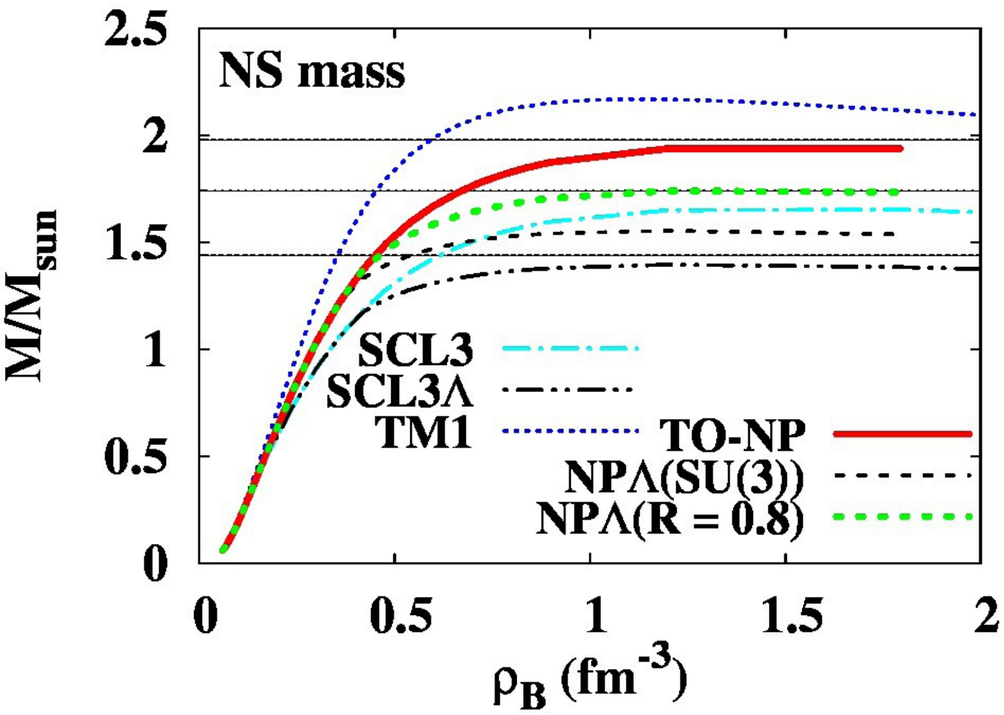
RMF with 3BF + SU(3)$_f$ "violation"

Tsubakihara, AO, in prep.

- Two types of modification
  - 3-baryon repulsion → EOS becomes stiff gradually at high density. (Fitting meson mass (E325) and Uv in RBHF)
  - $R = g_{\omega\Lambda} / g_{\omega N} \sim 0.8$ ($\sim 2/3$ (SU(3)))

→ $M_{max} \sim 1.7\, M_{\odot}$ with hyperons ($\sim 1.4\, M_{\odot}$ w/o 3BF, violation)



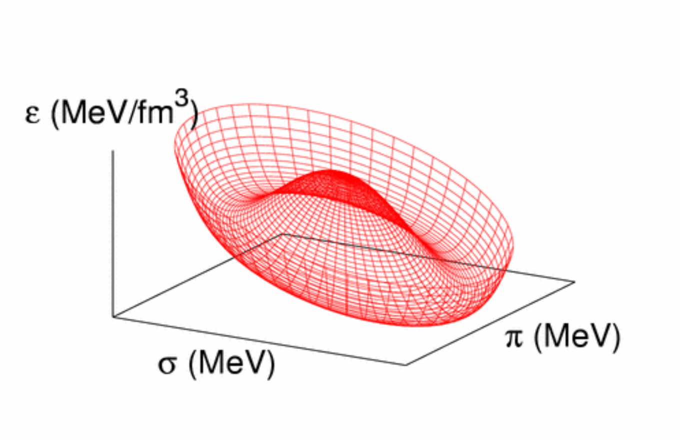


Summary

- Hyperons in dense matter is still an important problem.
- Standard RMF with hyperons cannot support 1.97 $M_\odot$ neutron star.
  - Various data / DBHF results can be fitted in RMF.
  - Vector Coupling ~ $SU(3)_f$, linear BM coupling ($\bar{B}MB$)
- RMF with 3BF + $SU(3)_f$ "violation" may help to support the heavy NS.
  - Atomic shift data of Σ atom suggests the violation" of $SU(3)_f$.
    Similar trend is seen in previous RMF with hyperons.
    R.Brockmann, W.Weise, PLB69('77)167; J.Boguta, S.Bohrmann, PLB102('81)93.
  - Ab initio calculations with induced/bare 3B force are helpful for phen. approaches to fix parameters.
  - Discussions during DCEN 2011 were encouraging.
    (Importance of 3BF, large effects of 3BF at ρ_0)
- Can we support 1.97 $M_\odot$ neutron star with hyperons ?
  → Open problem.

Thank you for your attention !

Chiral Symmetry



- **Fundamental symmetry of massless QCD, and its spontaneous breaking generates hadron masses.**

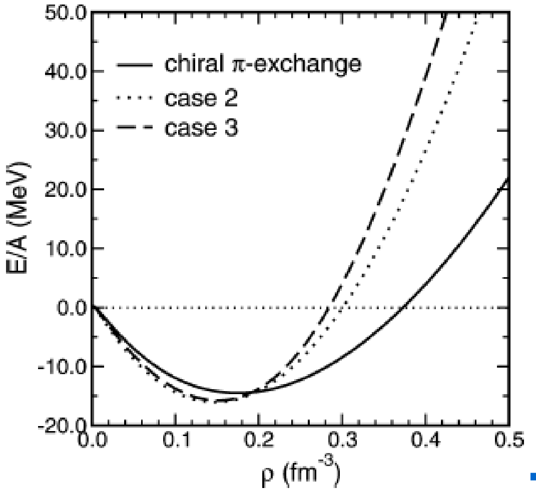
  Nambu, Jona-Lasinio ('61)

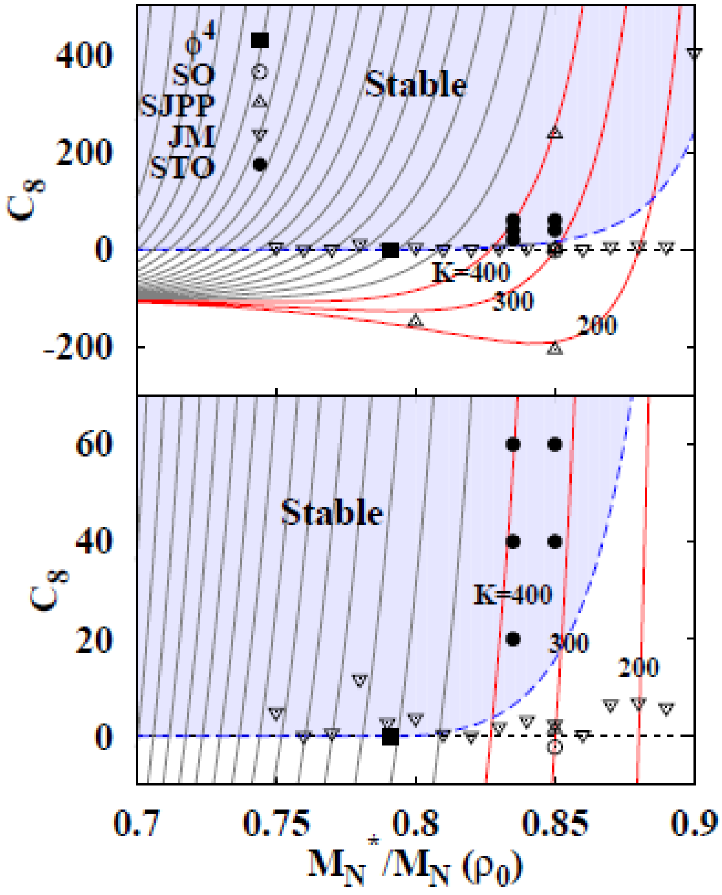
- **Many of the linear σ models are unstable against finite density (chiral collapse).**
  → Log type chiral potential

  Sahu, Tsubakihara, AO('10), Tsubakihara, AO('07)

- **Non-linear representation (chiral pert.) leads to density dependent coupling from pion loops.**

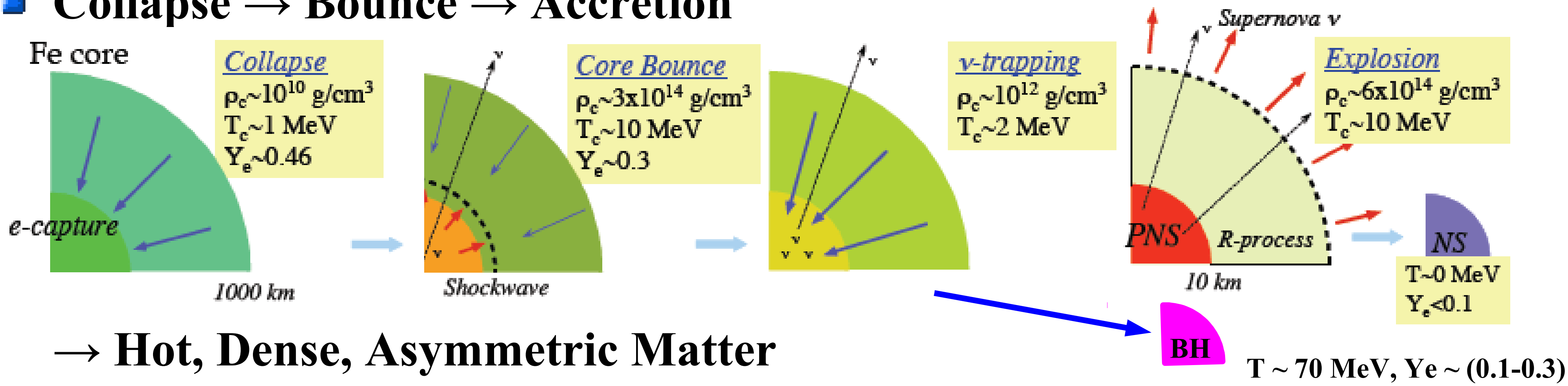
  Kaiser, Fritsch, Weise ('02),
  Finelli, Kaiser, Vretener
  Weise ('04)





Dynamical Black Hole Formation

- **Collapse → Bounce → Accretion**



Collapse
ρ_c~10^{10} g/cm^3
T_c~1 MeV
Y_e~0.46

Core Bounce
ρ_c~3x10^{14} g/cm^3
T_c~10 MeV
Y_e~0.3

ν-trapping
ρ_c~10^{12} g/cm^3
T_c~2 MeV

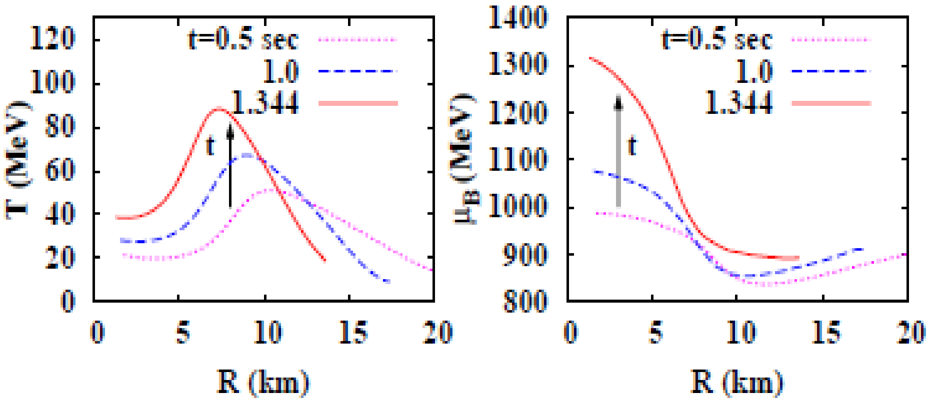
Explosion
ρ_c~6x10^{14} g/cm^3
T_c~10 MeV

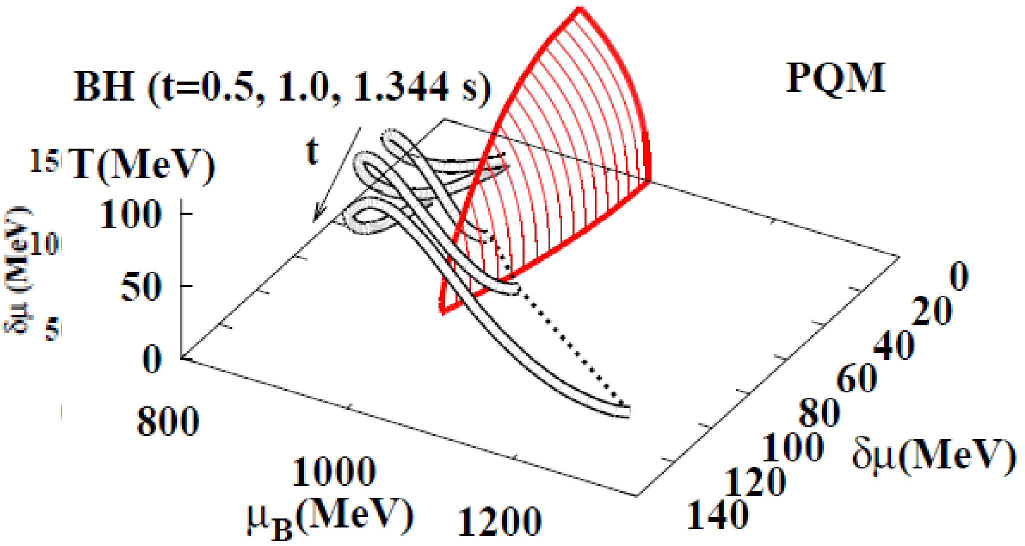
T~0 MeV
Y_e<0.1

T ~ 70 MeV, Ye ~ (0.1-0.3)

→ Hot, Dense, Asymmetric Matter
T ~ 70 MeV, μ_B ~ 1300 MeV, $\delta\mu=\mu_e/2$ ~ 130 MeV

→ CP may be reachable





K. Sumiyoshi, et al.,('06); K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki ('09)
AO, H.Ueda, T.Z.Nakano, M. Ruggieri, K. Sumiyoshi, PLB in press.