天体物理と状態方程式
Nuclear matter EOS for compact astrophysical phenomena

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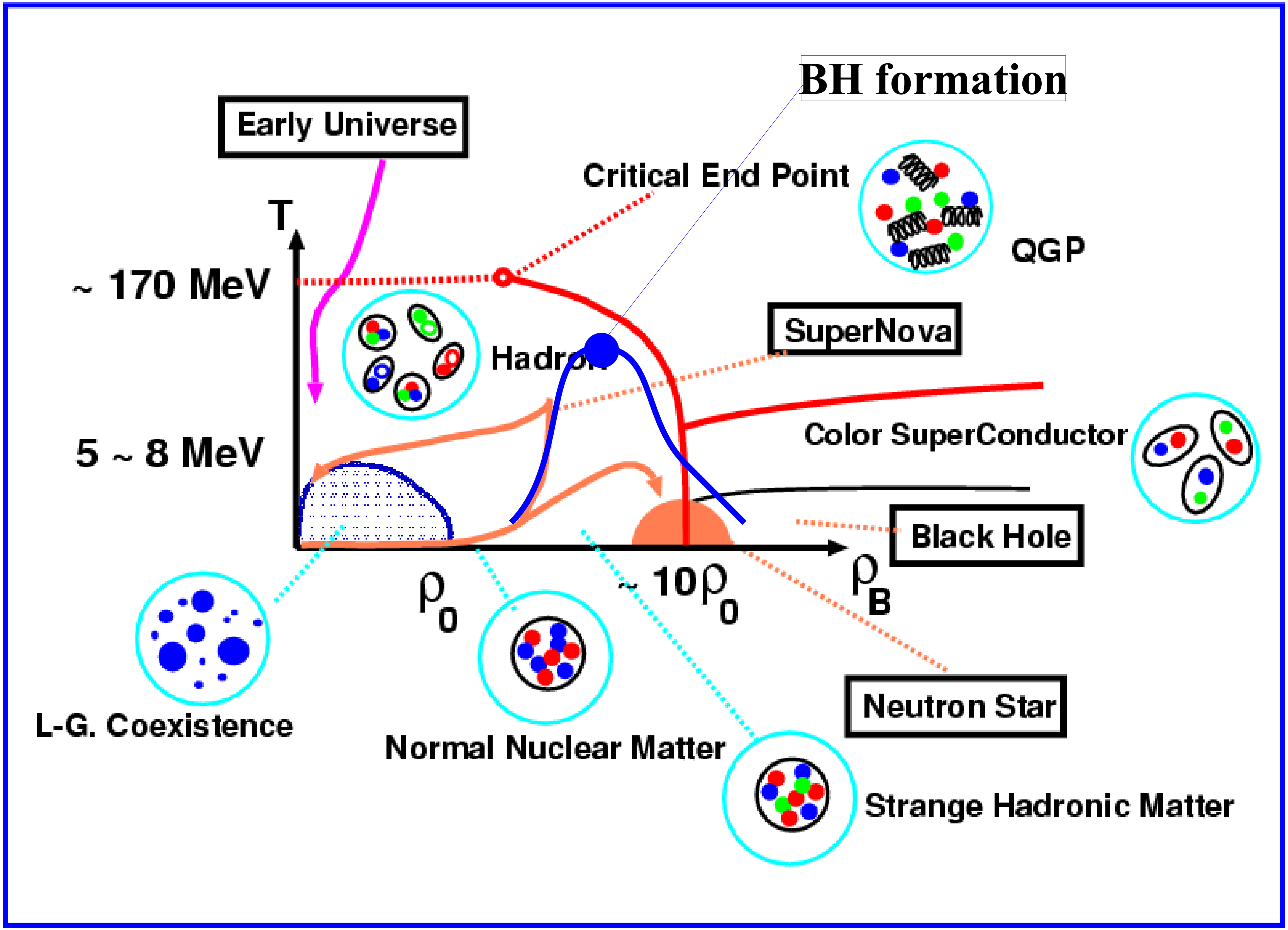
- Introduction
- Hyperon potential and 1st order phase transition at high density
- Constituents of nuclear matter at low densities
- Summary

Compact Astrophysical Phenomena

- **Neutron Stars**
  - **Cold, dense (~ 5 ρ0), static, ν-less**
  - **Many new forms of matter have been proposed !**
- **Supernovae**
  - **Warm (T ~ 20 MeV), dense (~ 1.6 ρ0), dynamical, non-eq. ν**
  - **Important site of nucleosynthesis**
- **Black hole formation**
  - **Hot (T ~ 70 MeV), dense (~ 5 ρ0), dynamical, non-eq. ν**
- **BH-BH, NS-BH, NS-NS merger → Numerical Relativity**

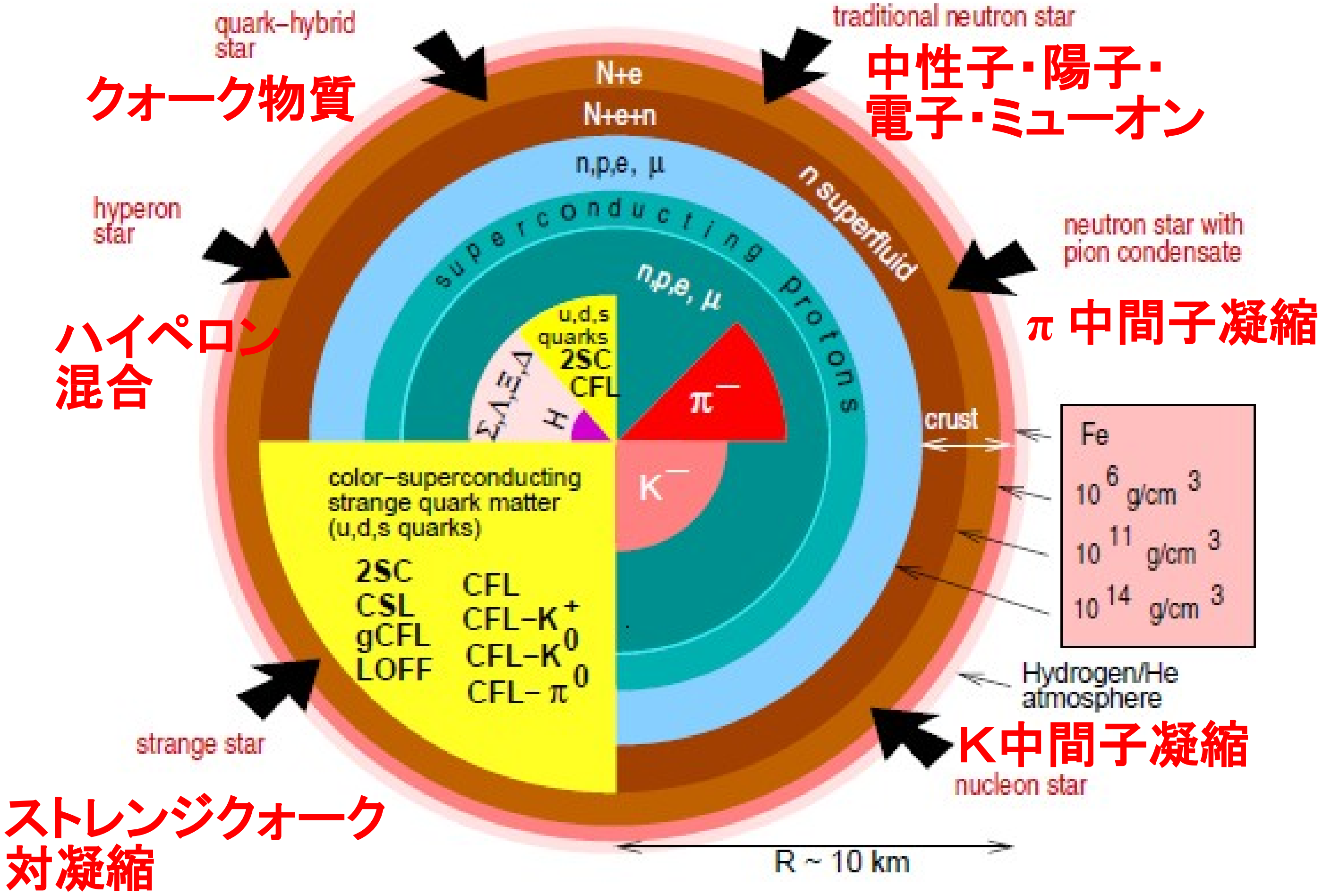
Nuclear matter at various densities and temperatures is realized in nature !

Nuclear Matter Phase Diagram



Neutron Stars

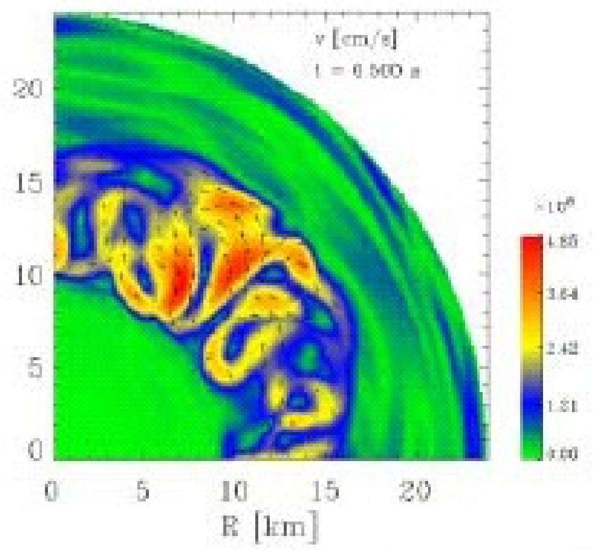
- **What are “neutron” stars made of ?**
  → neutron, proton, electron, muon, hyperon, meson, quark, diquark, ..
  → How do we know ?

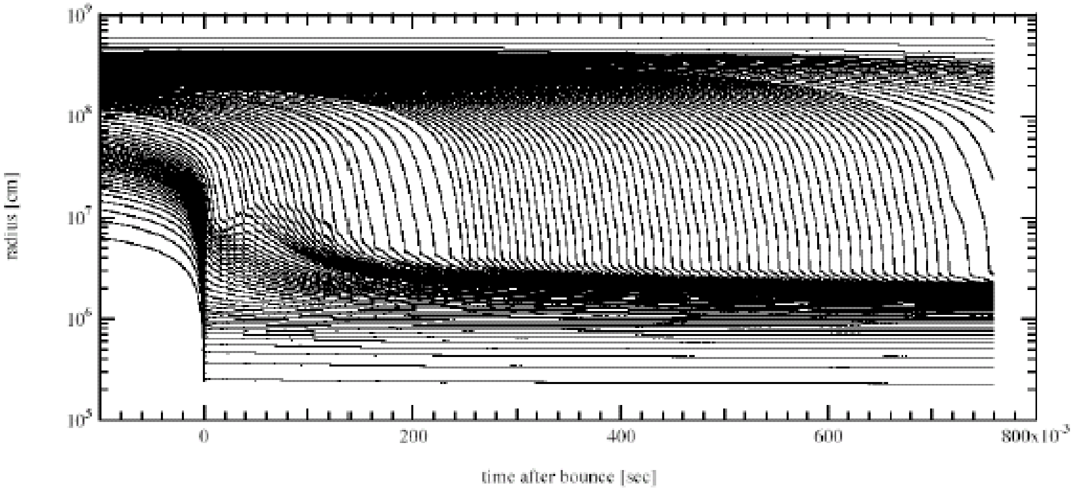


F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193

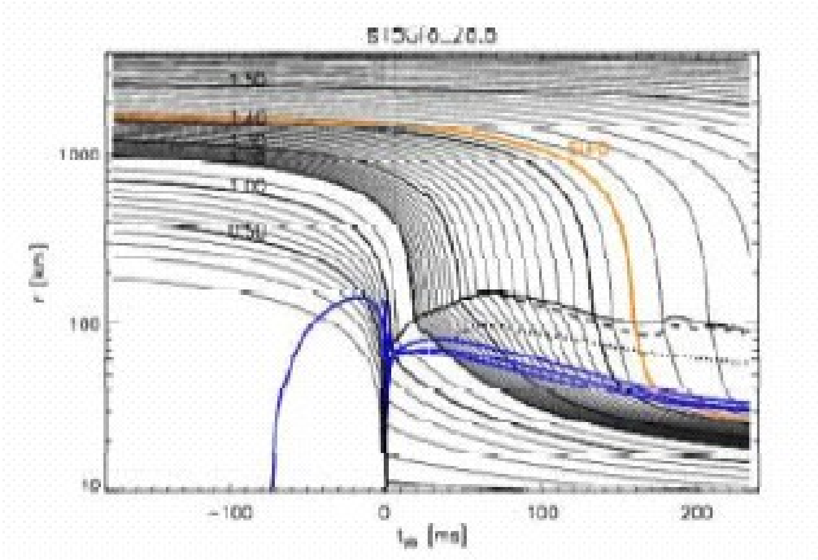
Numerical Simulation of Supernova Explosion

- ν radiation hydrodynamics
  - Baryons, Electons, Photons (Hydro)
    + neutrinos (Boltzmann)
  - 1-dim. (Spherical Sym.)
    → Exact ν transport leads
    to failed supernova explosion failure.
    (Sumiyoshi et al., 2005)
  - 2-dim. Hydrodynamics → merginal
    (Janka et al., 2002)





Sumiyoshi et al., 2005



(Janka et al., 2002)

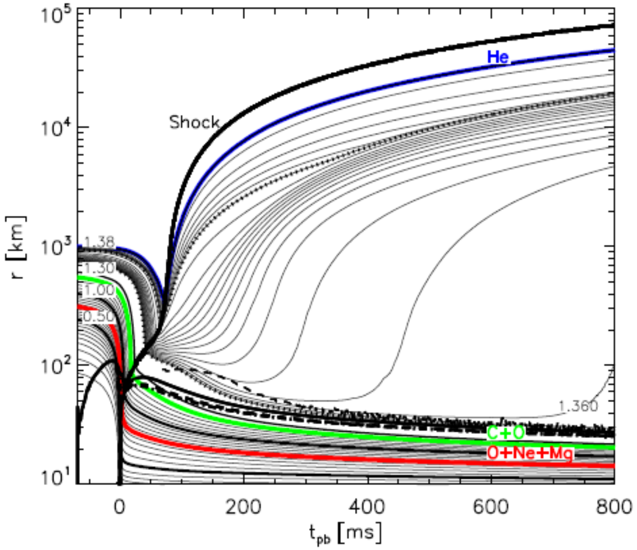
Numerical Simulation of Supernova Explosion

- **Recent developments (approximate ν transport)**
  - **Light progenitor (8-10 Msun)**

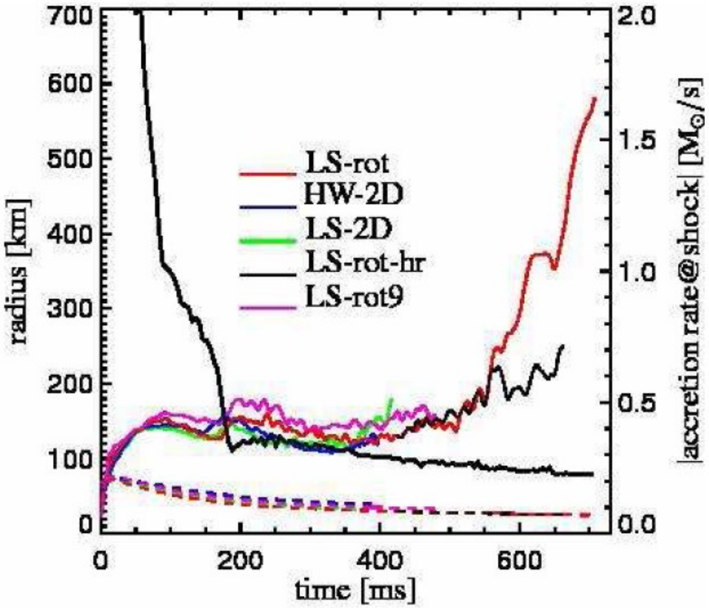
    → Successful explosion with simultaneous calc. of nucleosynthesis
  - **Heavy progenitor (15 Msun)**

    → Standing accretion shock instability (SASI) causes late expl.

There are some successful examples, but not conclusive yet.



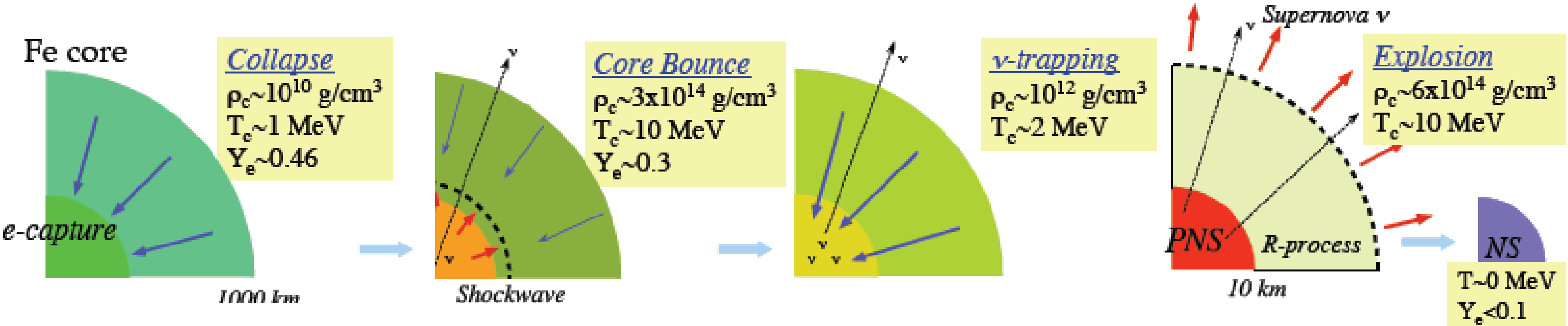
Kitaura, Janka, Hillebrandt, 2006

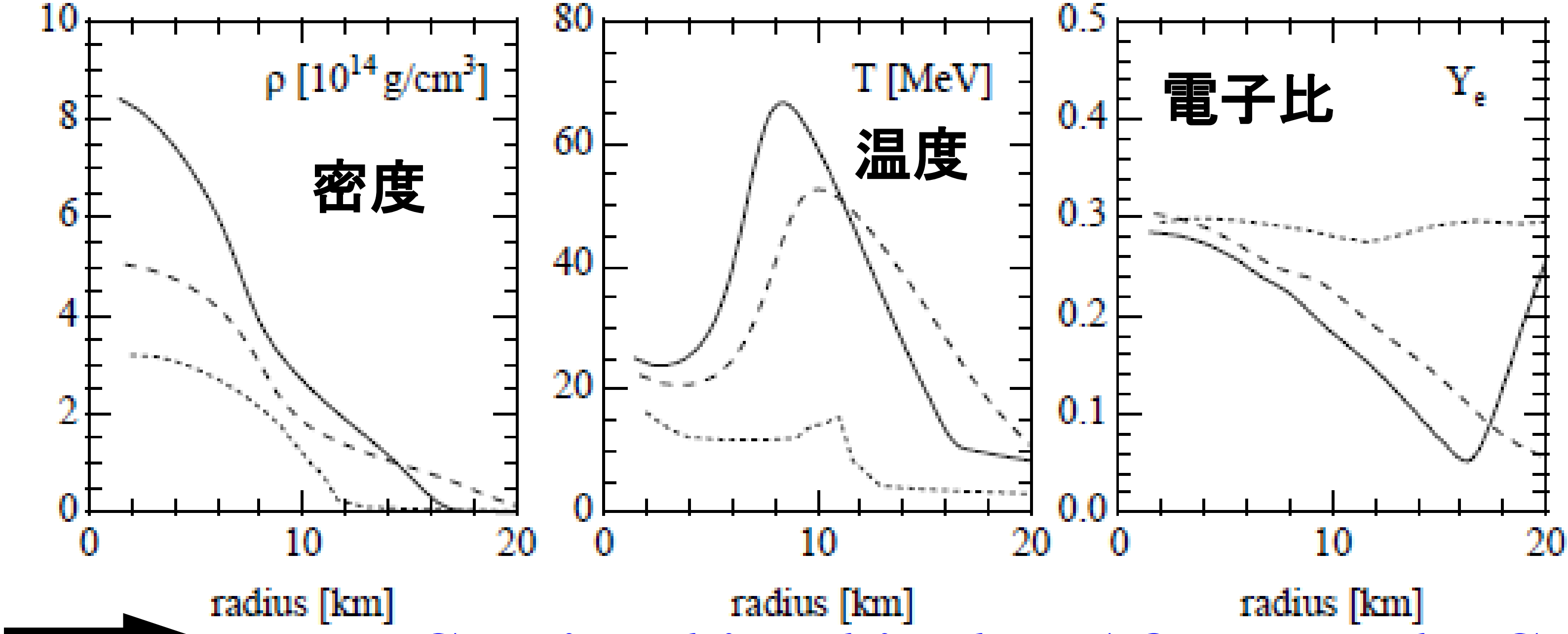


Marek, Janka, 2008

Black Hole Formation (Failed Supernova)

- **“Hot” rather than “Dense” in BH formation process !**
  T ~ 70 MeV (~ 1/3 of QCD phase transition T.)





バウンス直後
500 ms
680 ms
(BH 生成直前)

半径

Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009

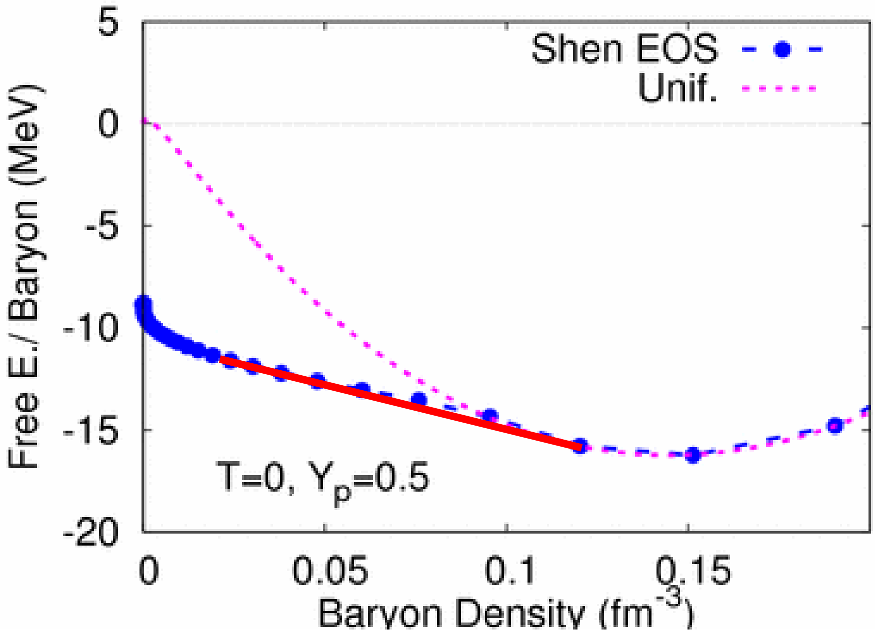
Nuclear EOS table for Core-Collapse Processes

- **Numerical Simulation of Supernova Explosion**
  - **Time-scale ~ a few 100 msec**
    = Long enough for EM, not enough for all ν to escape
    → ν radiation hydrodynamics
    - **Hydro: Baryons, electrons, photons → Nuclear EOS**
    - **Boltzmann: neutrinos → e capture, ν-nucleus reaction rate**
- **Frequently Used EOS Table**
  → Including Finite T info. + (practically) opened to public
  - **Lattimer-Swesty (LS) EOS: Compressible Liquid-Drop**
    - **Skyrme type density dep. int. (K=180-350 MeV)+Liquid Drop**
    - **Provided as subroutines**
  - **Relativistic EOS (Shen-Toki-Sumiyoshi-Oyamatsu)**
    - **RMF-TM1(K~280 MeV)+Thomas-Fermi Approx. +α**
    - **Provided in the numerical table**

Problems and Interests in EOS table

- Why is EOS (for core-collapse processes) interesting from a Nuclear Physicist point of view ?
  - Extreme conditions (HighT and ρ) → phase transition may be detected !

    E.g. Density: 10^5 g/cc ~ 10^{15} g/cc (ρ_0 ~ 2.5 x 10^{14} g/cc)
  - Nuclei + Hadrons (+ Quarks): What composes matter ?
- Problems
  - High Density
    - Potentials of hyperons, pions, … ?
    - Can we detect (1st order) phase transition to quark matter ?
  - Low Density
    - Constituents of matter at sub-saturation density ? Fermi gas ? Nuclei ? Pasta ?
    - Pressure is discontinuous in Shen EOS. Why ? Maxwell construction (LS) ? or Other mech. to make it continuous ?

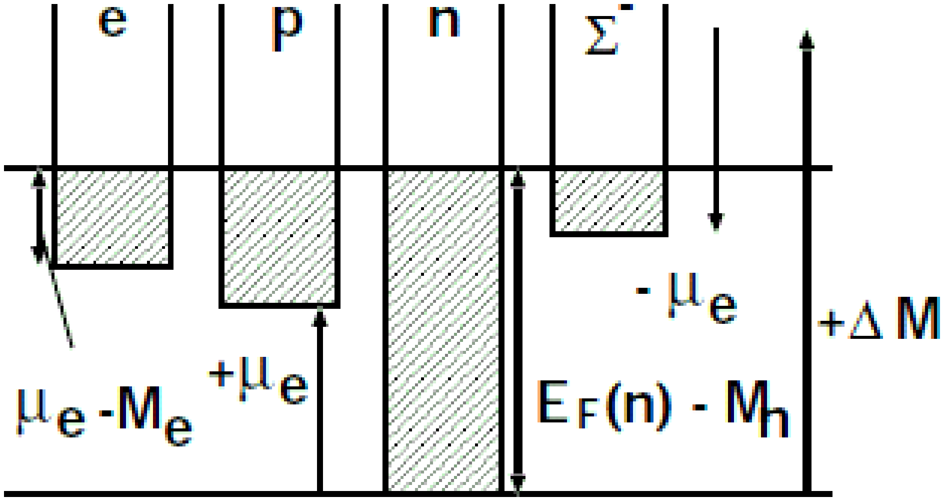


Hyperon Potentials and 1st order phase transition at high ρ

What happens (appears) at high ρ ?

- **High density → Larger Fermi Energy**
  → Admixture of other hadrons than nucleons
  (Hyperons, mesons, ...)

- **Example: Chem. Equilibrium in NS**
  → "Strangeness" is not conserved !
  (Weak equilibrium)
  - **Conserved Quantity**
    = baryon number and charge



$$E_F(n)+U(n)=\mu_n$$
$$E_F(p)+U(p)=\mu_n-\mu_e$$
$$E_F(\Lambda)+U(\Lambda)=\mu_n-(M_\Lambda-M_N)$$
$$E_F(\Sigma^-)+U(\Sigma^-)=\mu_n-(M_\Sigma-M_N)+\mu_e$$

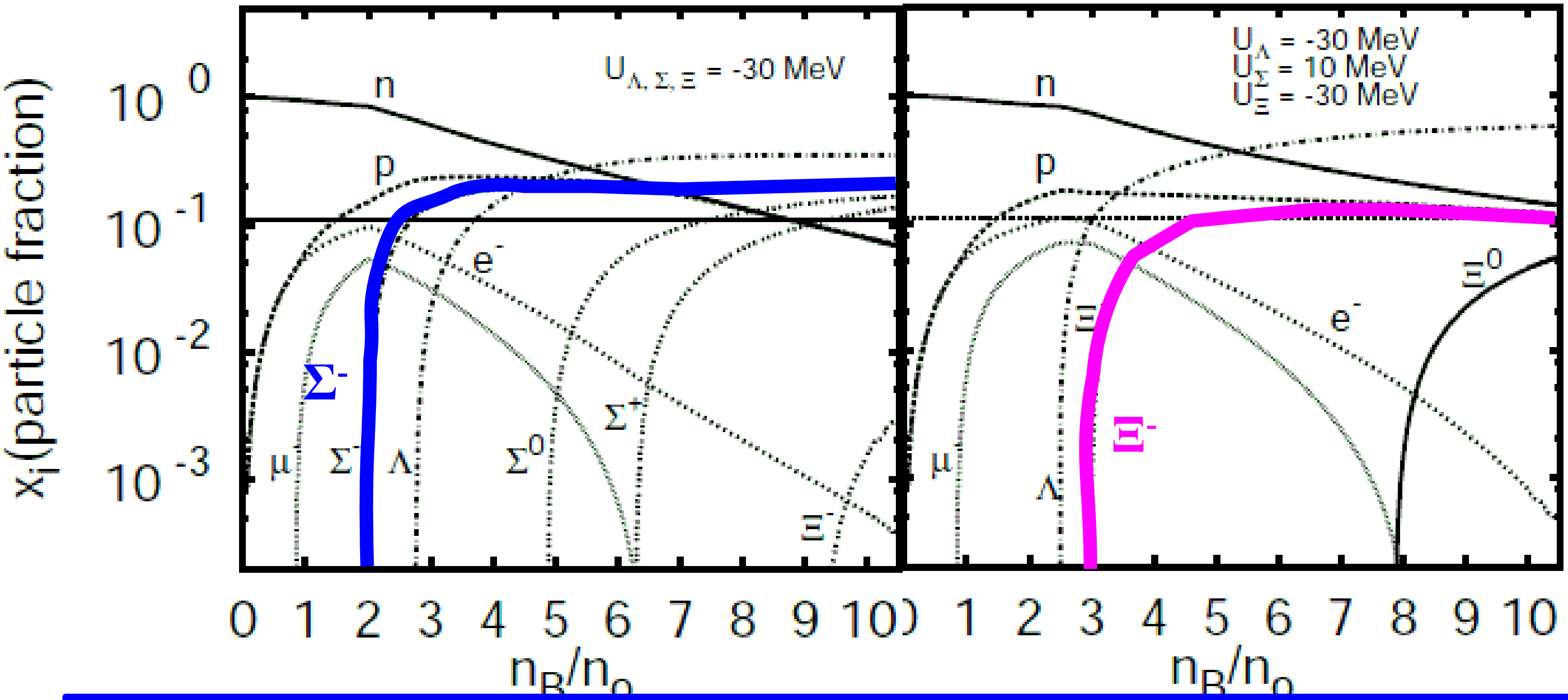
Hyperons are the strongest non-nucleon candidates !

$$\mu_B=E_F(n)+U(n)\ \geq\ M(Y)+U(Y)+Q_Y\mu_e$$

Hyperons in Supernova Matter

- **Problems to include hyperons in Supernova Matter EOS**
  - **Uncertainties of hyperon potentials $U_Y(\rho)$** → ***Recent Hypernuclear Phys.*** **(e.g. Balberg, Gal, 1997)**
  - **Density may not be very high in supernova** → ***Needed in cooling stage***

Attractive U_Σ **Repulsive U_Σ**



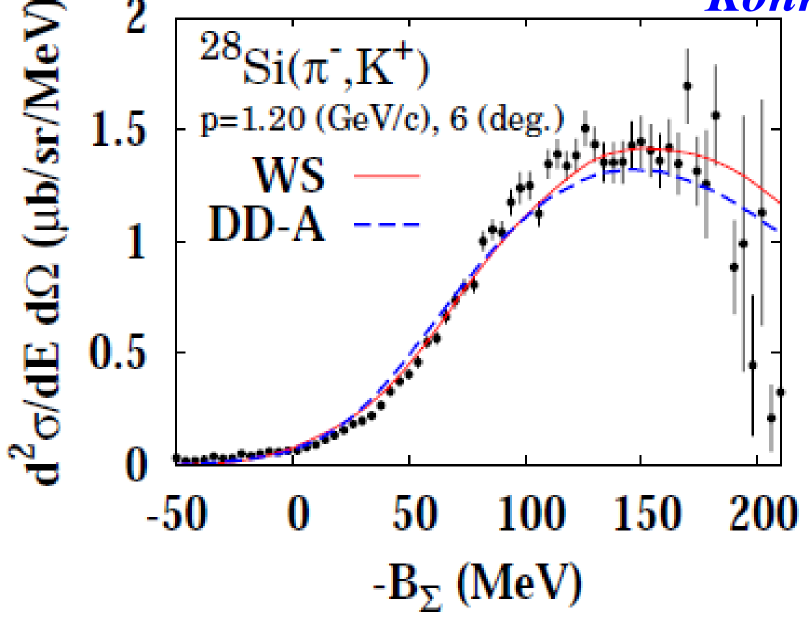
Sahu, AO, 2003

We include recent hyperon info. in supernova matter EOS

Σ Potential in Nuclear Matter

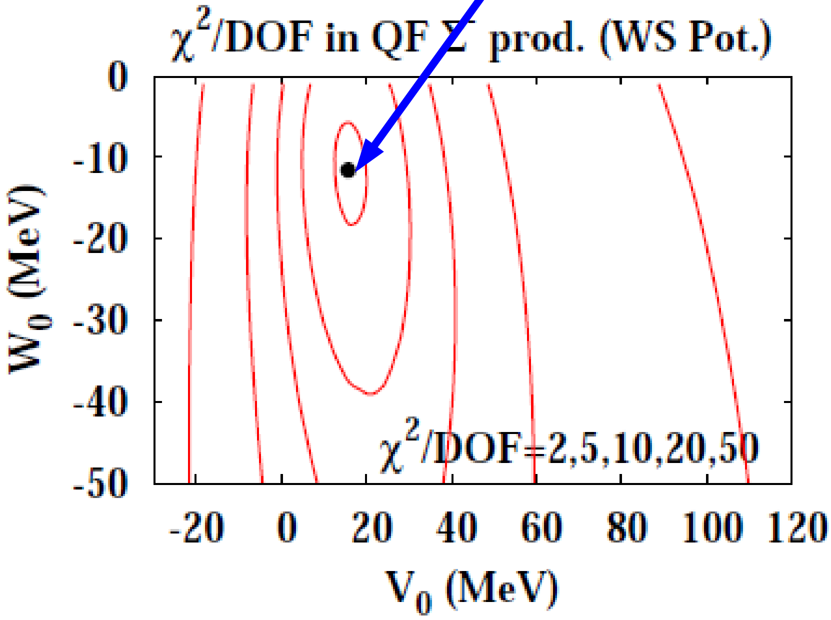
$$\frac{d^2\sigma}{d E_K \, d\Omega_K}$$

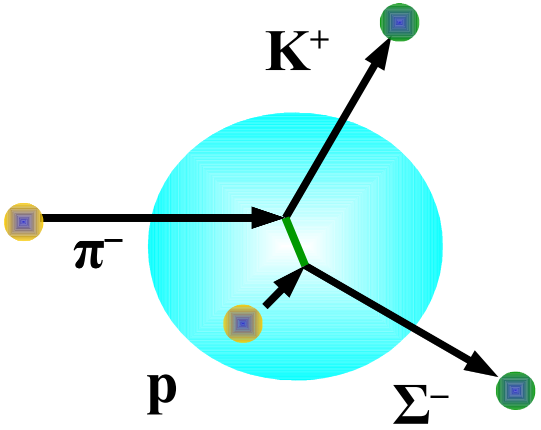
Maekawa, Tsubakihara, AO, EPJA 33(2007),269.
Harada, Hirabayashi, NPA744('04),323.
Kohno, Fujiwara, Kawai, et al. PTP112('04)895



$U_\Sigma(\rho_0) \sim +15$ MeV –i 10 MeV
with Woods-Saxon potential,
no Atomic shift fit

E$_\Sigma$(MeV)





Σ feels repulsive potential in nuclei

Relativistic Mean Field

- **RMF Lagrangian**

$$
\begin{aligned}
\mathcal{L} = & \sum_B \bar{\Psi}_B \left(i\not{\partial} - M_B\right)\Psi_B + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - U_\sigma(\sigma) \\
& - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{R}^\mu\cdot\vec{R}_\mu \\
& - \sum_B \bar{\Psi}_B \left(g_{\sigma B}\sigma + g_{\omega B}\not{\omega} + g_{\rho B}\not{\vec{R}}\cdot\vec{t}_B\right)\Psi_B + \frac{1}{4}c_\omega(\omega^\mu\omega_\mu)^2 + \mathcal{L}^{YY}
\end{aligned}
$$

- **Schroedinger Equvalent Potential**
  - **Schroedinger Eq. for upper components of Dirac spinor → Sch. Eq. Potential**

$$
\begin{aligned}
U_B(\rho, E(\mathrm{p})) &= U_s(\rho) + \frac{E(\mathrm{p})}{M_B}U_v(\rho) \\
&= g_{\sigma B}\sigma + g_{\zeta B}\zeta + \frac{E}{M}\left(g_{\omega B}\omega + g_{\rho B}R + g_{\phi B}\phi\right)
\end{aligned}
$$

SEP=U$_Y$ → RMF coupling → EOS

Relativistic EOS of Supernova Matter with Hyperons

- **Extention of the Relativistic (Shen) EOS to SU$_f$(3) with updated Hyperon Potentials in Nuclear Matter**
  (Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada,J. Phys. G35(08),085201)
  - **Relativistic (Shen) EOS** *(Shen, Toki, Oyamatsu, Sumiyoshi, PTP 100('98), 1013)*
    Rel. Mean Field (RMF) + Local Density Approx.(Nuclear Formation)
  - **SU$_f$(3) Extention of RMF** *(Schaffner, Mishustin, PRC53 (1996), 1416)*
    Coupling ~ Quark Number Counting

SM

IOTSY

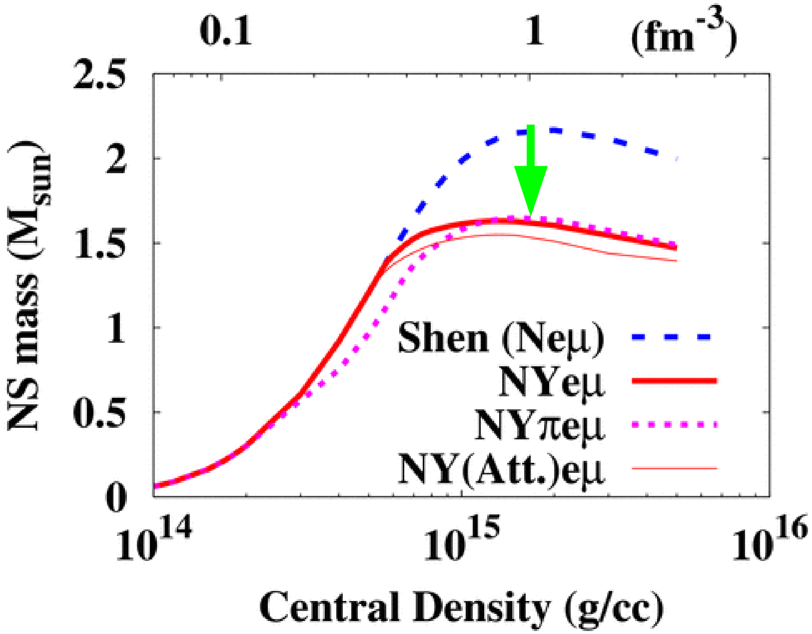
g_{MB}	σ	ζ	ω	ρ	ϕ
N	10.0289	0	12.6139	4.6783	0
Λ	6.21	6.67	8.41	0	-5.95
Σ	4.36 (6.21)	6.67	8.41	$2g_{\rho N}$	-5.95
Ξ	3.11 (3.49)	12.35	4.20	4.63	-11.89

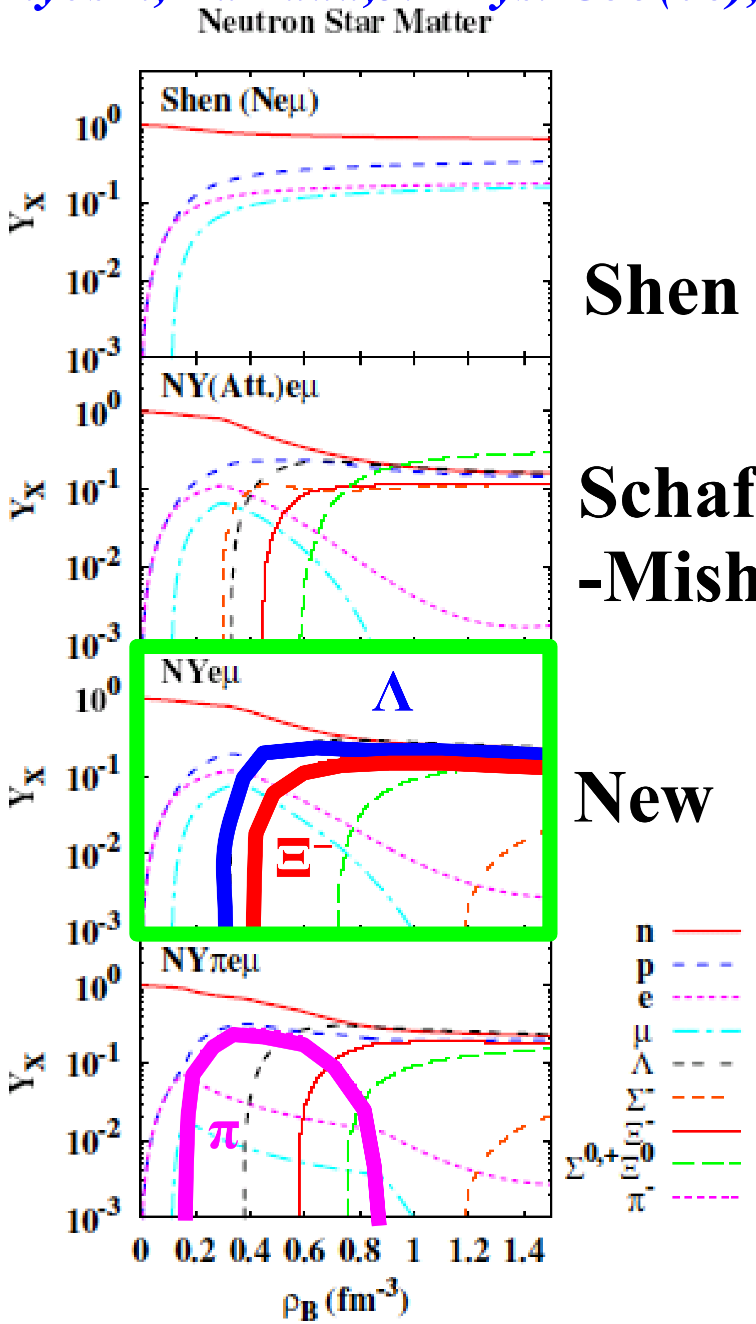
- ***$g_{\sigma Y}$ is tuned to fit Hyperon Potential in Nuclear Matter***
  $U_\Lambda = -30$ MeV, $U_\Sigma = +30$ MeV, $U_\Xi = -15$ MeV
- ***Nuclear Formation is included using Shen EOS table***

Neutron Star

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada,J. Phys. G35(08),085201

- **Hyperon Effect is DRASTIC**
  - **Mmax=2.1 Msun → 1.56 Msun**
  - **Composition $Y_\Lambda \sim Y_n$**
  - **Large fraction of Ξ**
- **Thermal (free) pions can admix at $\rho > 1.5\,\rho_0$**





Shen

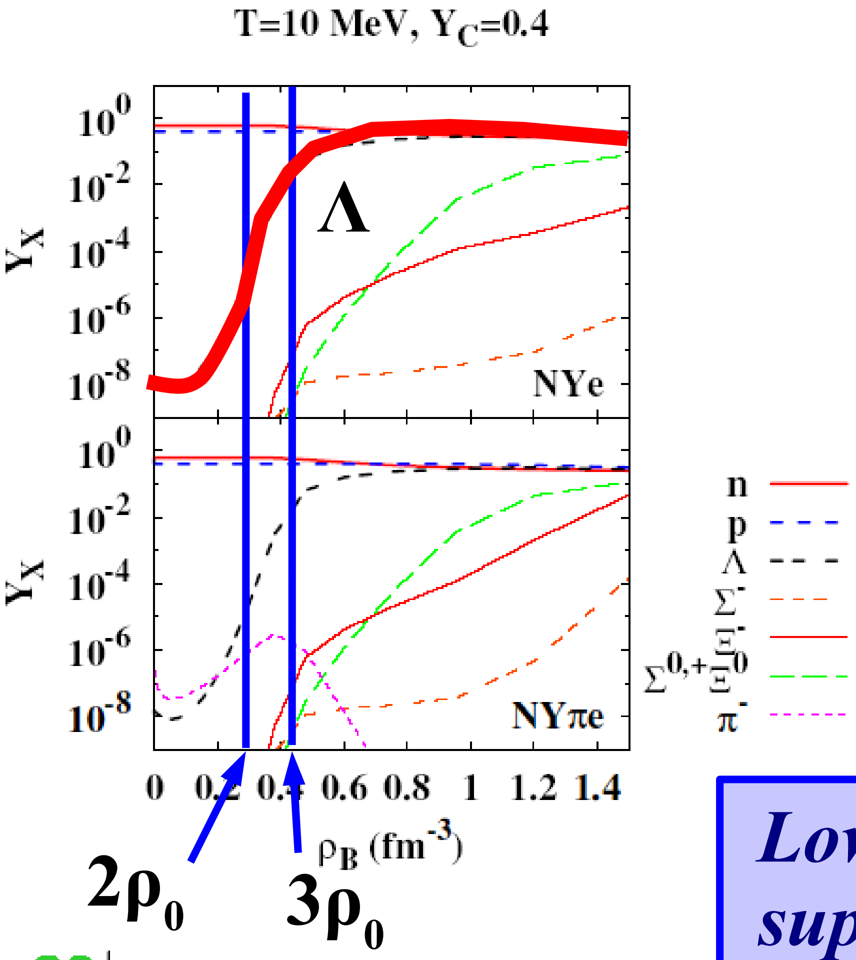
Schaffner -Mishustin

New

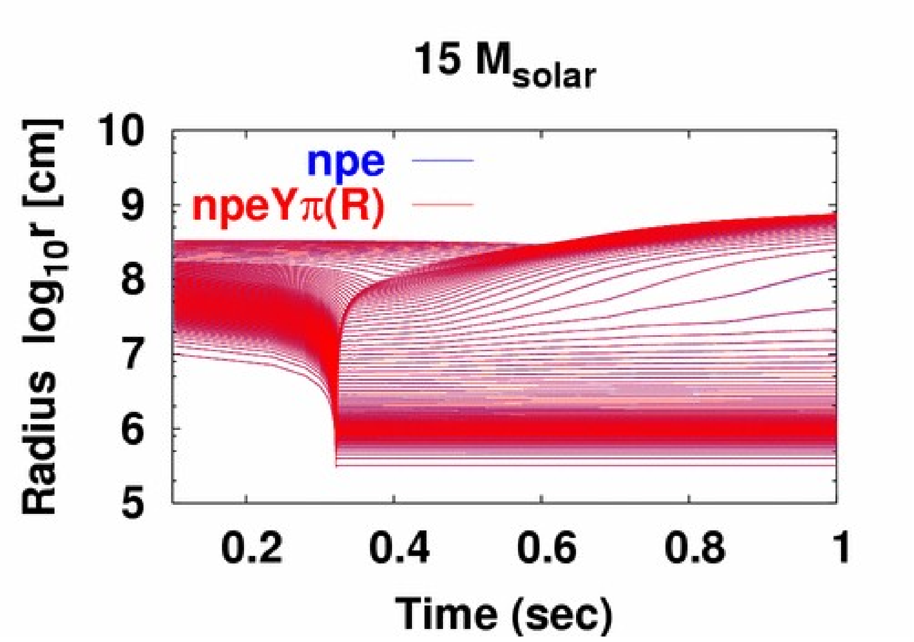
Finite Temperature and Supernova

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada,J. Phys. G35(08),085201

- **Example: T=10 MeV, Ye = 0.4**
  - **Λ starts to increase at ρ ~ 2 ρ_0 , becomes significant at ρ ~ 3ρ_0 .**



- **Prompt explosion (without ν transport)**
  → Almost no change
  (Expl. E. increase ~ (0.1-0.5 %))



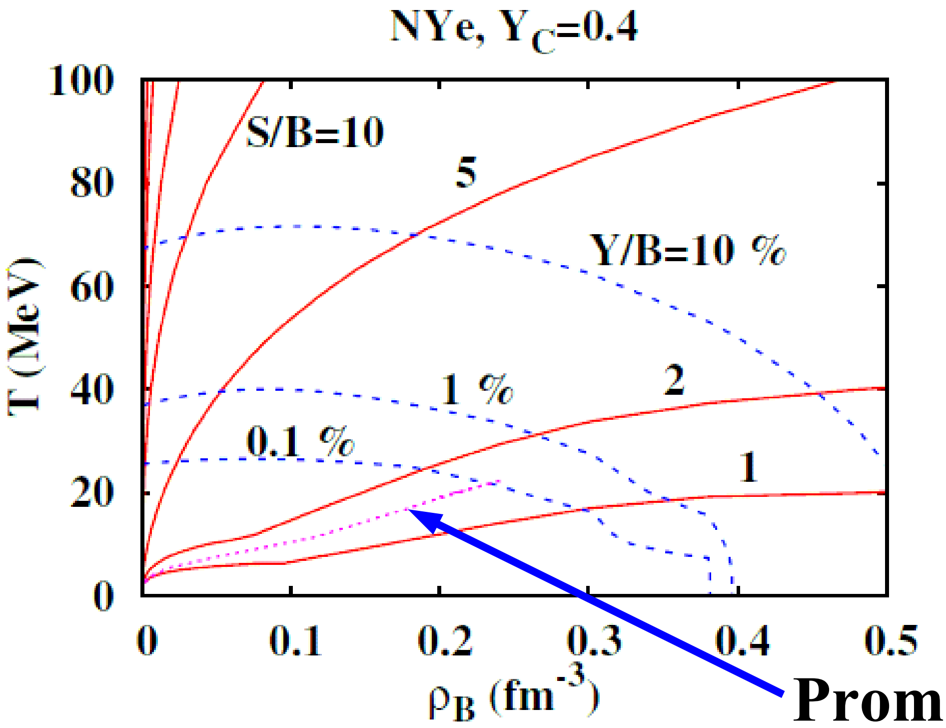
WW95 + 1 Dim. Hydro.(Sumiyoshi, Yamada)

Low density and High Ye suppresses Hyperons in the Early Stage

Where do we see Hyperons ?

- **Hyperon Fraction is sensitive to Ye, T, and ρ_B.**
  - **$Y\nu \sim 0$ (Neutron Star) → $\rho_B > 2\ \rho_0$**
  - **$Ye \sim 0.4$ (Supernova, early stage) → $T > 40$ MeV or $\rho_B > 3\ \rho_0$**

Hyperons would be important in Late Stage(Nstar cooling), BH formation, and Heavy-Ion Collisions

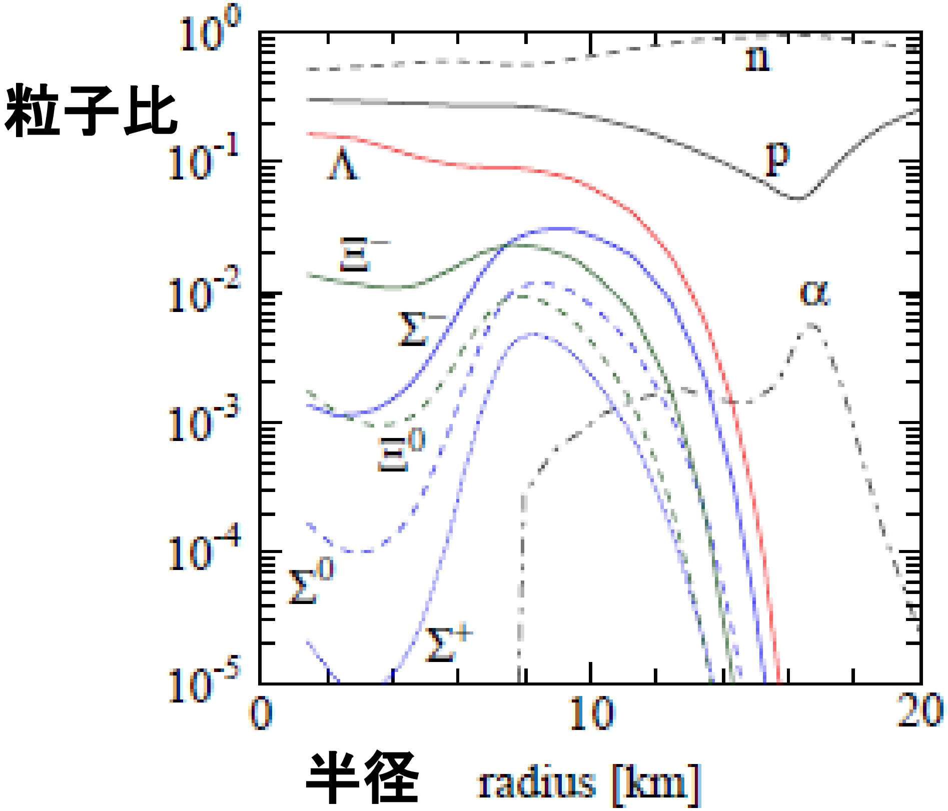


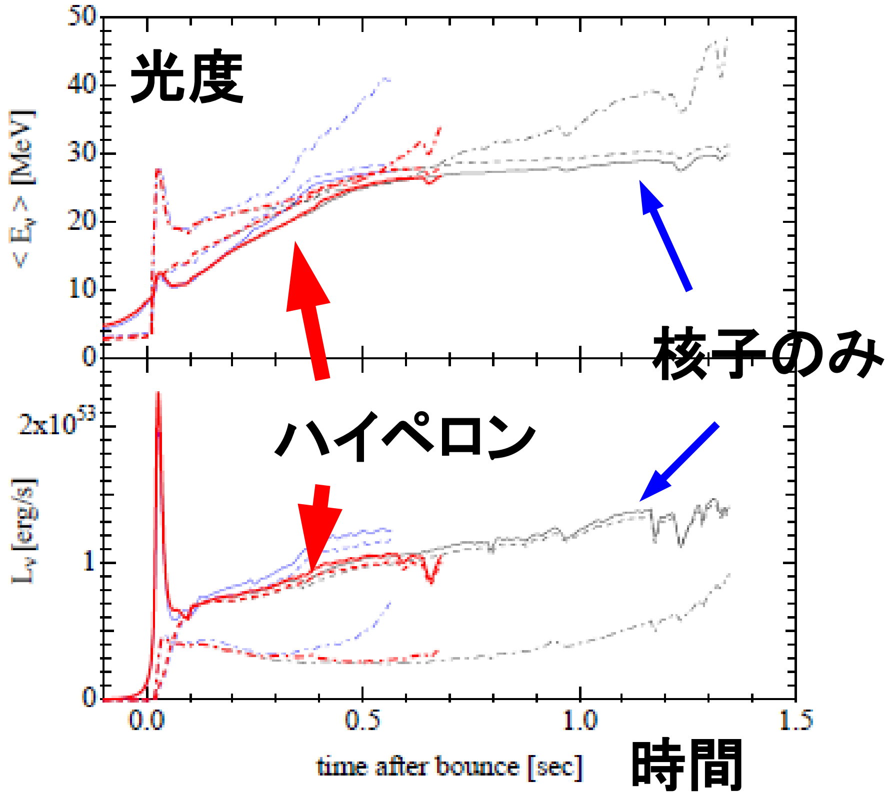
Prompt Expl. (15 Msun)

Black Hole Formation (Failed Supernova)

- **High T during BH formation**
  → Abundant hyperons → Soft EOS → Earlier Collapse to BH

Short ν emission may be the signal of Hyperon Admixture at high density and/or temperature



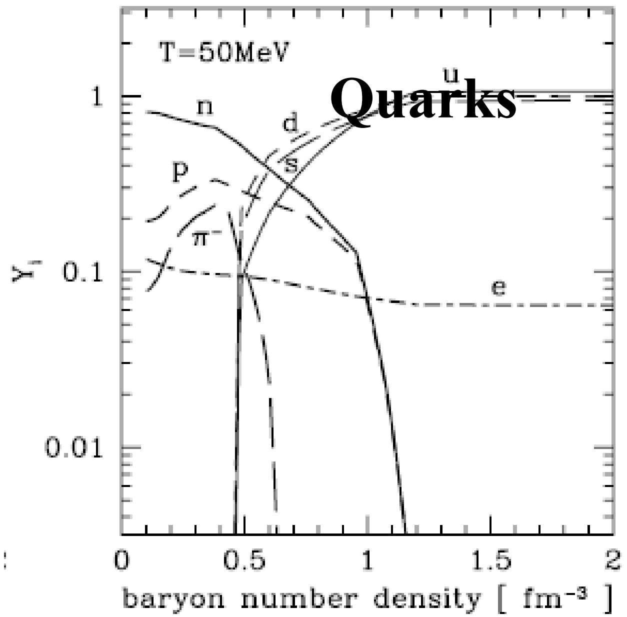


Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009

Can we detect Quark Matter ?

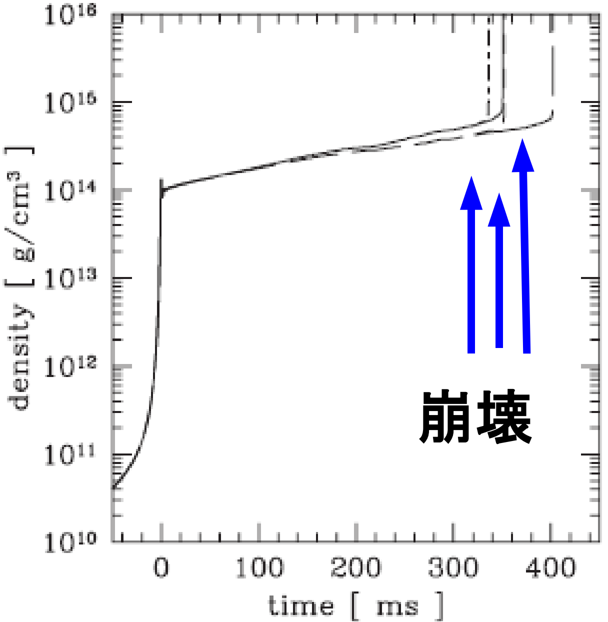
- **Supernova EOS with Quark-Hadron Coexistence**
  - **Quark matter=Bag model, Hadronic matter= RMF with free pions**
    → Earlier Collapse to Black Hole *(Nakazato, Sumiyoshi, Yamada, 2008)*
  - **Transition to Strange Quark Star → Second Shock** *(Sagert et al., 2009)*

粒子比



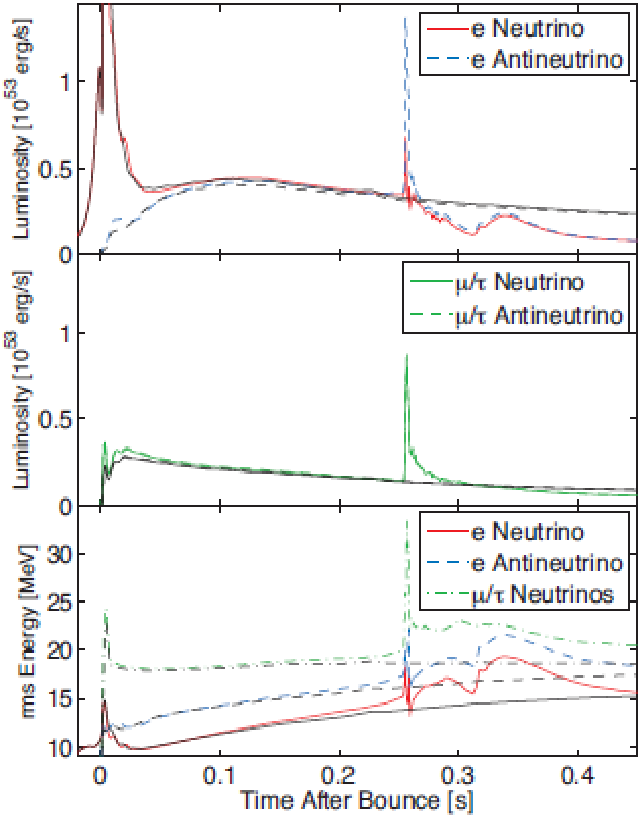
密度

密度



時間

Nakazato, Sumiyoshi, Yamada



Sagert et al., 2009

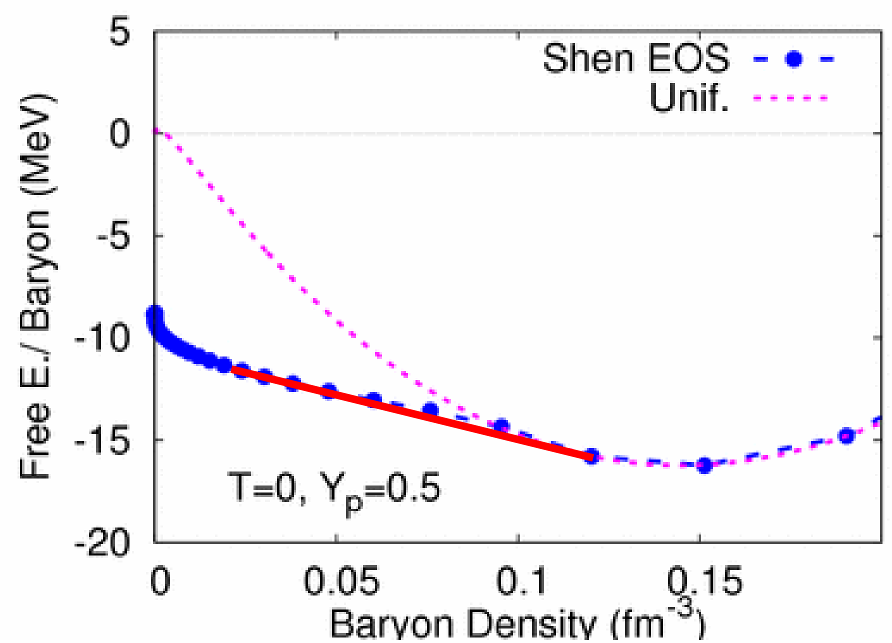
Composition of Nuclear Matter at Low Densities

Problems in Low Density Region

- **Supernova does not explode in ν radiation hydro.**
  → What is necessary to obtain "a little more" energy ?
  - **Multi-dim. Hydro. → Convection, Rotation, Magnetic Field, ...**
  - **Neutrino transport property → νA cross section, e-capture rate, ...**
  - **Nuclear EOS at low densities → Pressure discontinuity**
- **What composes nuclear matter at sub-saturation densities ?**
  - **Nuclei in LS EOS and Shen EOS**
    → One Representative Nucleus
  - **Nuclear Statistical Equilibrium (NSE)**
    → Stat. Dist. of Nuclei

    (Explosion is promoted by the energy from nucleosynthesis. Sagert et al.)

Does NSE solve the pressure gap problem ?



Nuclear Statistical Equilibrium

- **Grand partition function of nuclear fragments**

$$\Omega = -PV = -VT\sum_i \rho_f - P_\ell V - P_\gamma V \ ,$$

$$\rho_f = \zeta_f(T)\left(\frac{M_f T}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{B_f+\mu_f}{T}\right) \ ,$$

$$\mu_f = Z_f(\mu_p - m_N) + N_f(\mu_n - m_N) \ ,$$

  - **Assumption:**
    Interaction btw fragments are negligible except for Coulomb
  - **Coulomb E. Mod. in medium**

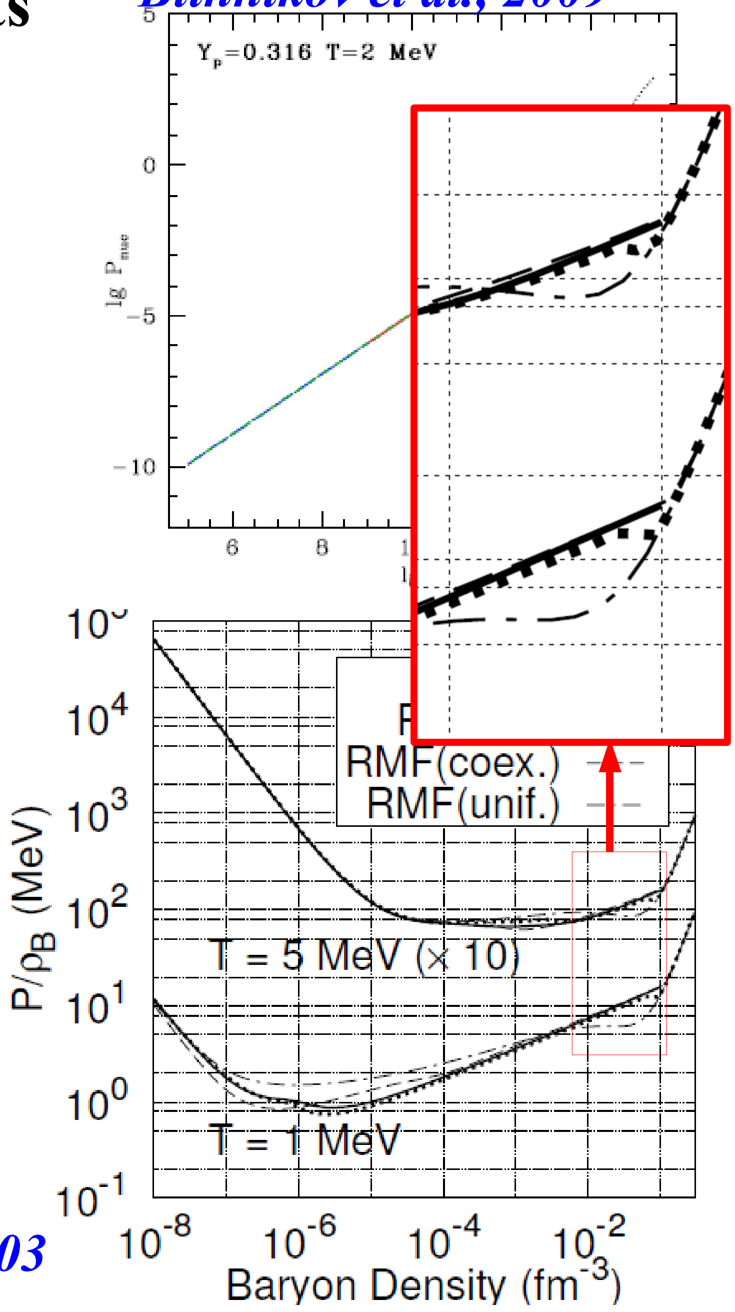
$$B_f(\rho_e) = B_f(0) - \Delta V_f^{Coul}(\rho_e) \ ,$$

$$\Delta V_f^{Coul} = -\frac{3}{5}\frac{Z_f^2 e^2}{R_0}\left(\frac{3}{2}\eta_f - \frac{1}{2}\eta_f^3\right) \ ,$$

$$\eta_f \equiv \frac{R_{0f}}{R_{ef}} = \left(\frac{\rho_e}{Z_f \rho_0 / A_f}\right)^{1/3}$$

→ Pressure has a gap at around ρ_0 !

Blinnikov et al., 2009

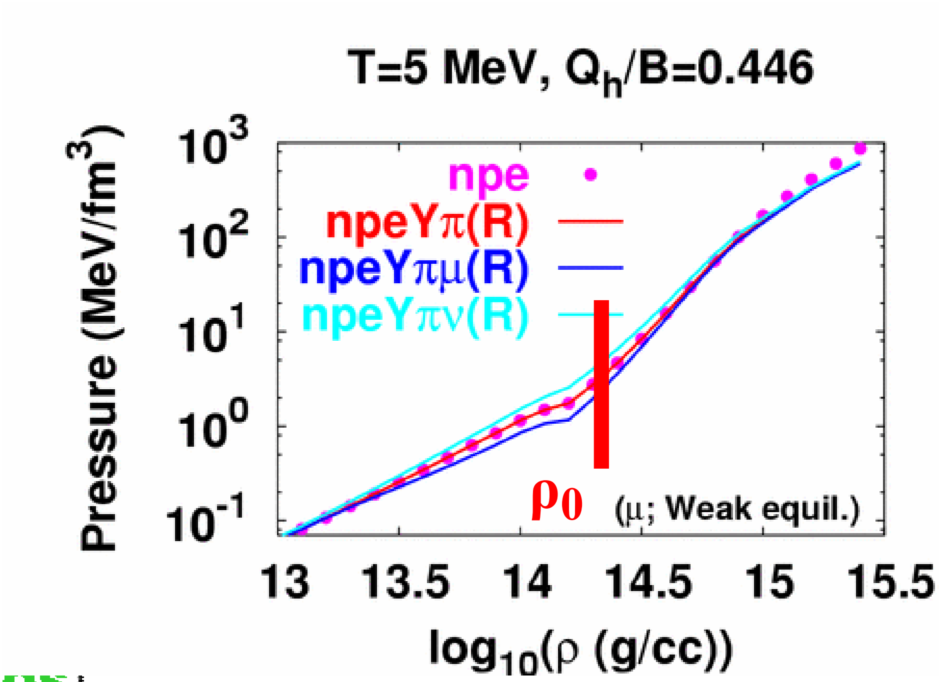


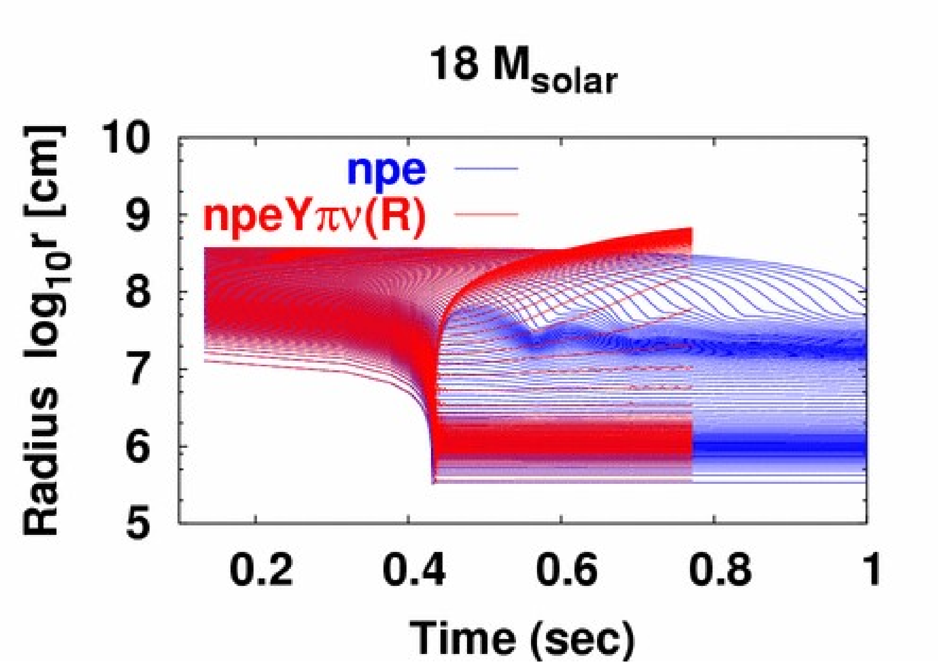
Ishizuka, AO, Sumiyoshi, 2003

Why do I care such a “small” difference ?

- **Pressure gap comes from the diff. of**
  Surface + Coulomb potential
  in spherical nuclei (droplet) and in uniform matter.
- **“Artificial” smoothing of EOS around 0.7 ρ_0 enhances explosion E ! (Ishizuka, Thesis)**

Smooth EOS may help for SN to explode !





Nuclear Pasta

- **Nuclei with exotic shapes may exist in neutron star crust below the saturation density !**

  Sphere → Rod → Plate → Hole → Bubble

$$F = (1-X)\,F(\rho_{BL}, Y_{pL}) + X\,F(\rho_{BG}, Y_{pG}) + V_{SC}(\Delta\rho_c, u)$$

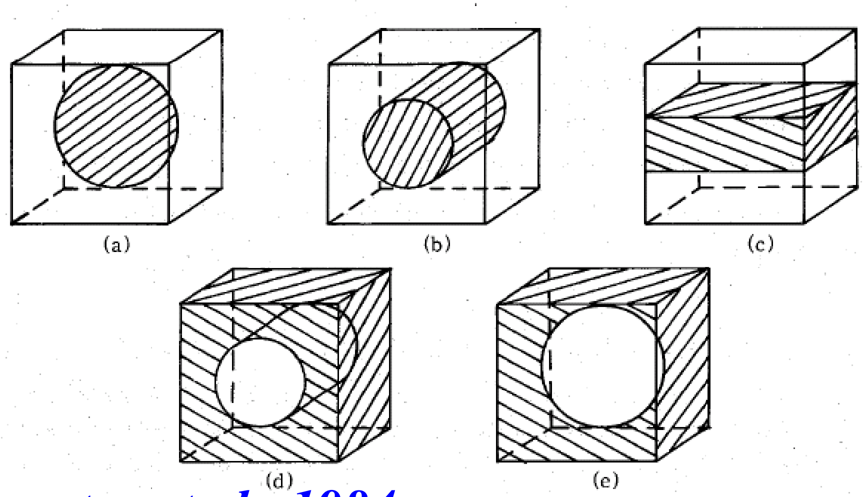
F : **Free energy per nucleon**

X : **Gas nucleon occupation fraction**

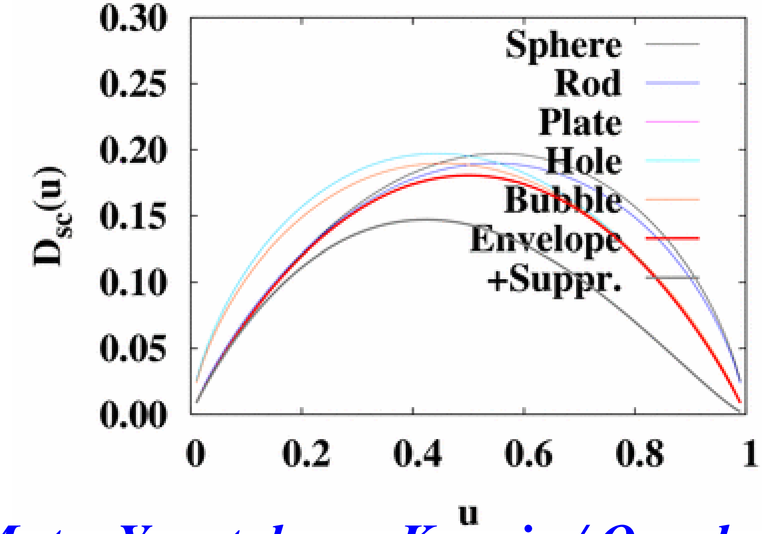
u : **Volume occupation fraction of liquid**

V_{SC} : **Surface + Coulomb E per nucleon**

$$V_{sc} = \frac{a_{surf}}{R} + \beta_{Coulomb} R^2 = C(\Delta\rho_c)^{2/3} D_{sc}(u)/\rho_B$$



Oyamatsu et al., 1984



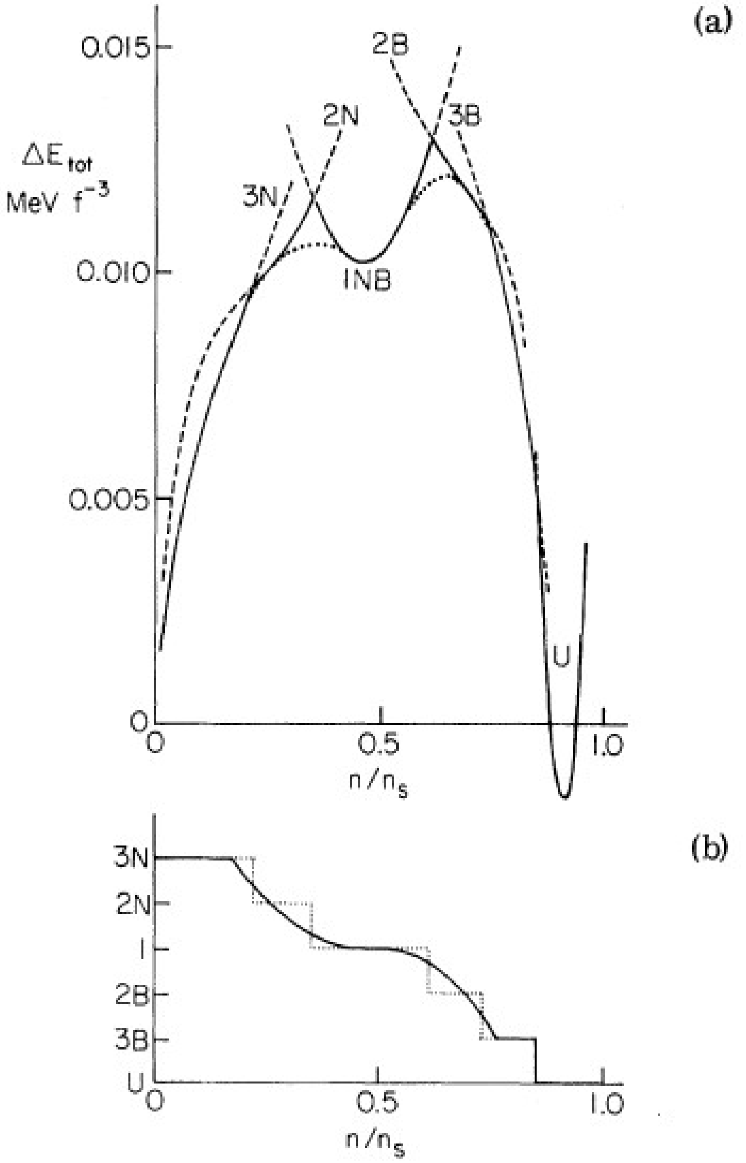
Tatsumi, Maruyama, Muto, Yasutake .... Kaonic / Quark pasta

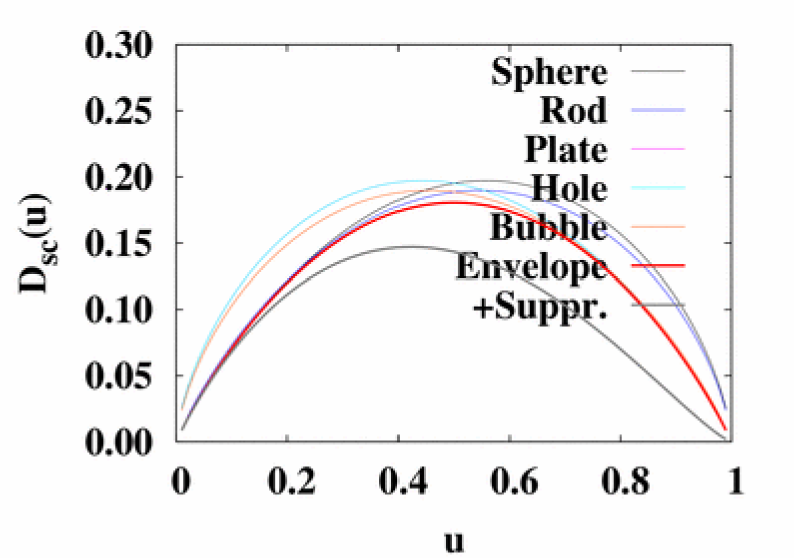
Nuclear Pasta

- **Pasta with continuous dimension**
  → Energy is connected more smoothly,
  but the pressure is not yet smooth.

We have introduced phenomenological Surface+Coulomb suppression factor,

$V_{sc} \rightarrow V_{sc} \times (1-u)^{\alpha}$

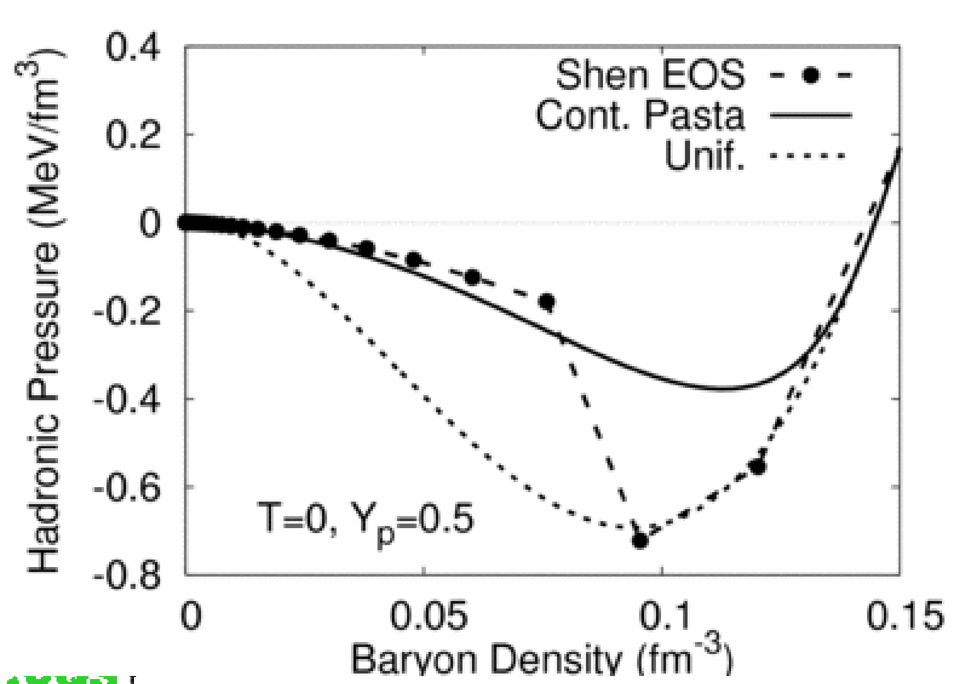


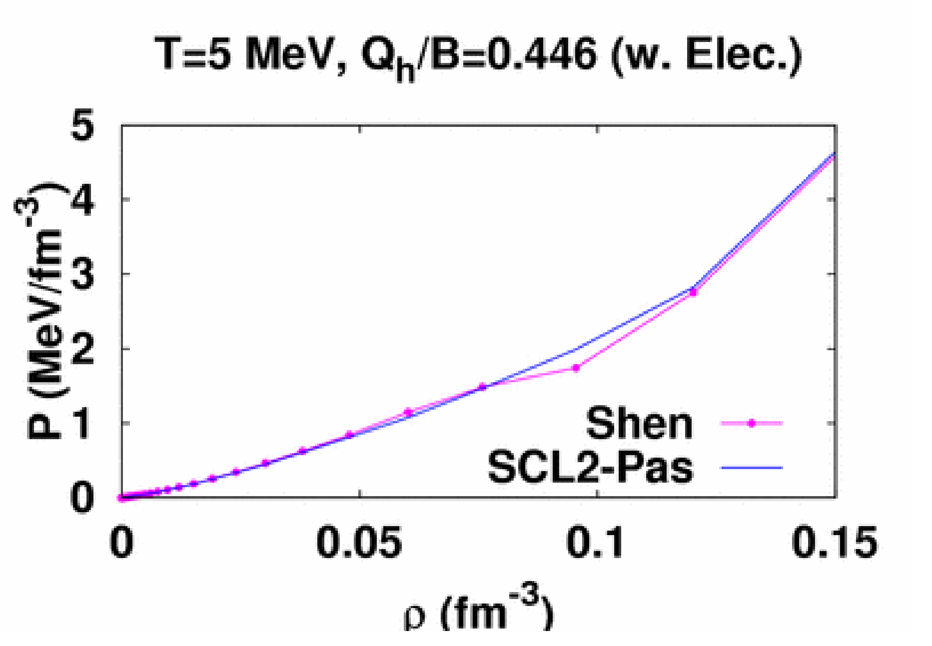


Ravenhall, Pethic, Wilson, PRL50(83),2066

Some preliminary results: Pasta + Unif.

- **Pasta + Uniform matter**
  - **Continuum pasta (with $(1-u)^\alpha$ suppr.) + uniform matter → pressure is continuous in symmetric nuclei (Y_p=0.5) around ρ_0**
  - **We still have problems**
    - **Uniform → Pasta is not continuous at low densities.**
    - **Pasta (small u, sph.) → Pasta (large u, hall) jump is discontinuous in asymmetric nuclear matter.**

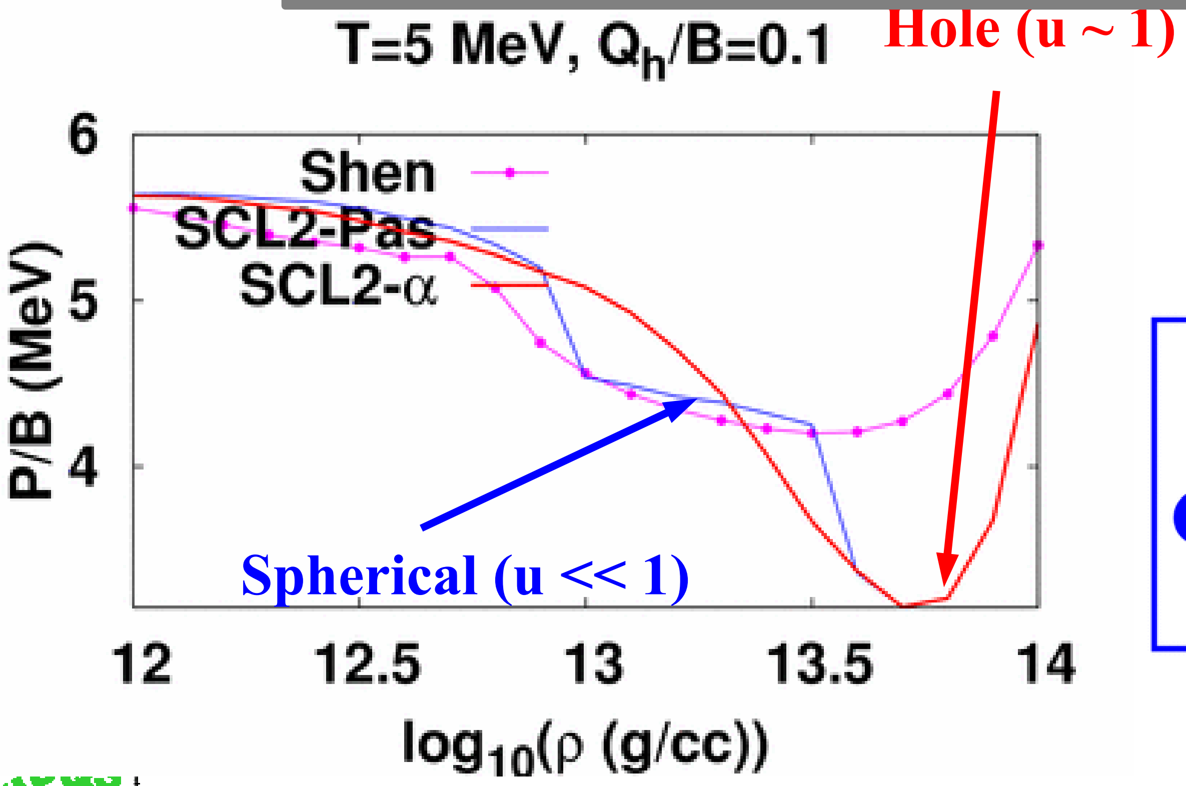




Some preliminary results: Pasta + NSE

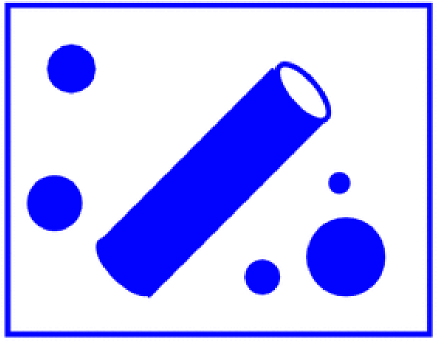
- **Pressure gap means we should have further coexistence !**
  - **Low density gap**
    (Unif. →) Mixture of small nuclei → Pasta → Unif.
  - **High density gap in asym. matter**
    Spherical / Cylindrical nuclei → ? → Hole

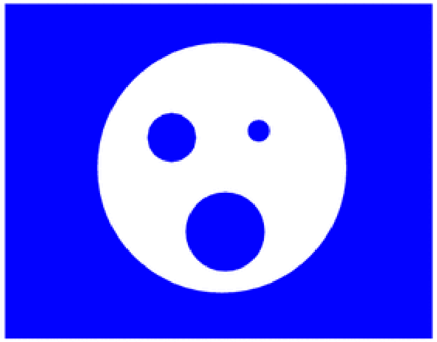
It would be necessary to incorporate Pasta + NSE



Hole (u ~ 1)

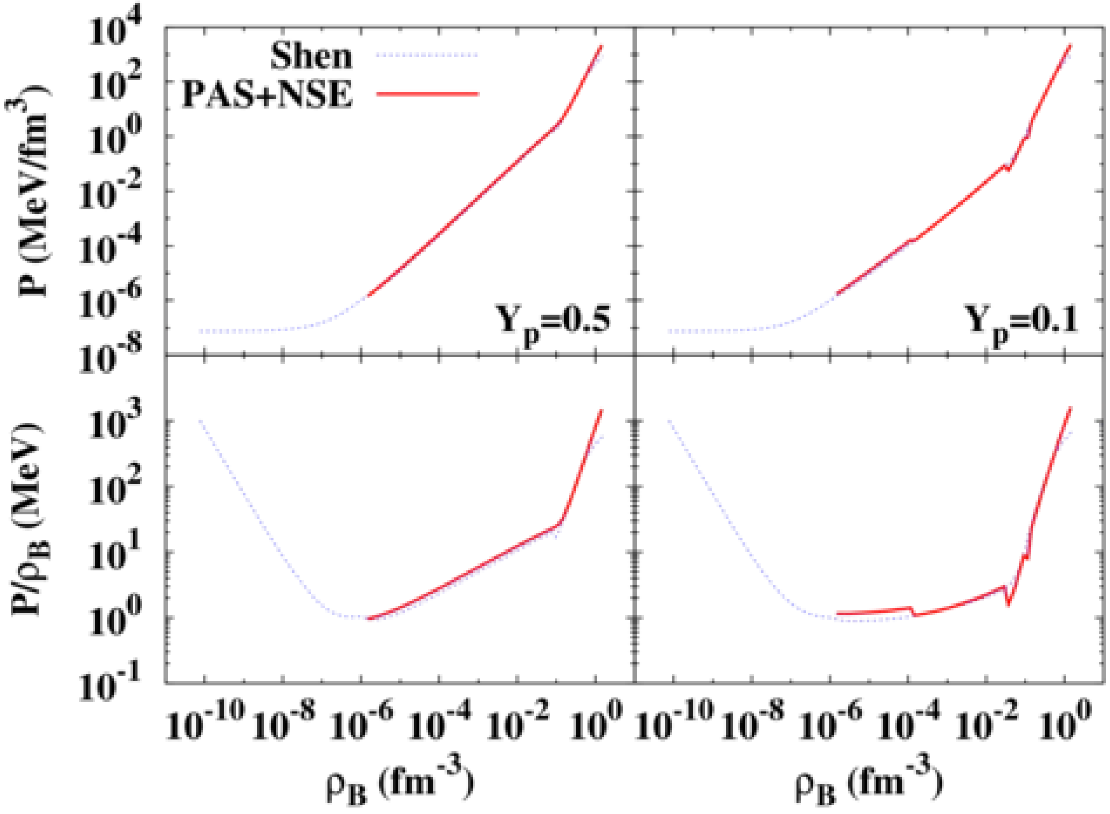
Spherical (u << 1)





Some preliminary results: Pasta + NSE

- **Coexisting Calc. of Pasta + Fragments**
  - **Pasta: Continuous dimension, $(1\text{-}u)^{\alpha}$ suppr.**
  - **NSE: Excluded volume effects are taken into account**
  - **Discontinuity in asymmetric matter**
    Physics ? or Numerical problem ?



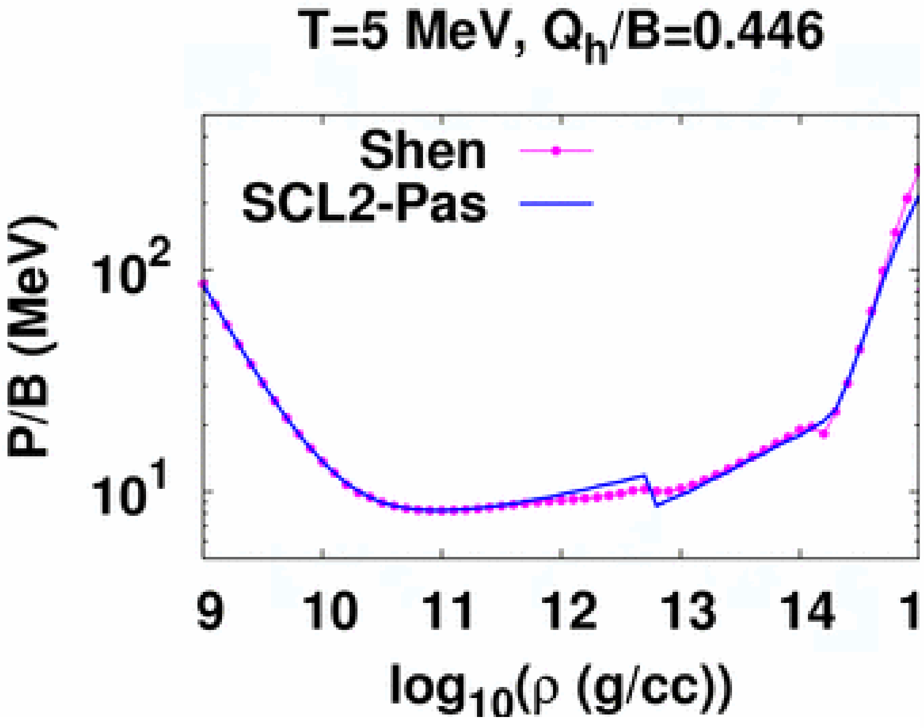
Summary

- Core-Collapse processes and their remnants (neutron / quark star) are interesting objects to investigate also from nuclear physics side !
  - High density matter is formed in equilibrium (in strong int. time scale)
  - High temperature region may be also probed during black hole formation.
- High density EOS may be detected in observations, and it is closely related to quark-hadron physics.
  - Neutron star → Mass, Radius, Cooling, Glitch, ..
  - Black hole → ν emission duration, energy spectra, …
- Low density (sub-saturation) nuclear matter is NOT uniform, and would have various structures.
  - NSE (stat. dist. of nuclei) should be dominant at very low densities.
  - Pasta may appear between spherical nuclear dominant region and uniform matter.

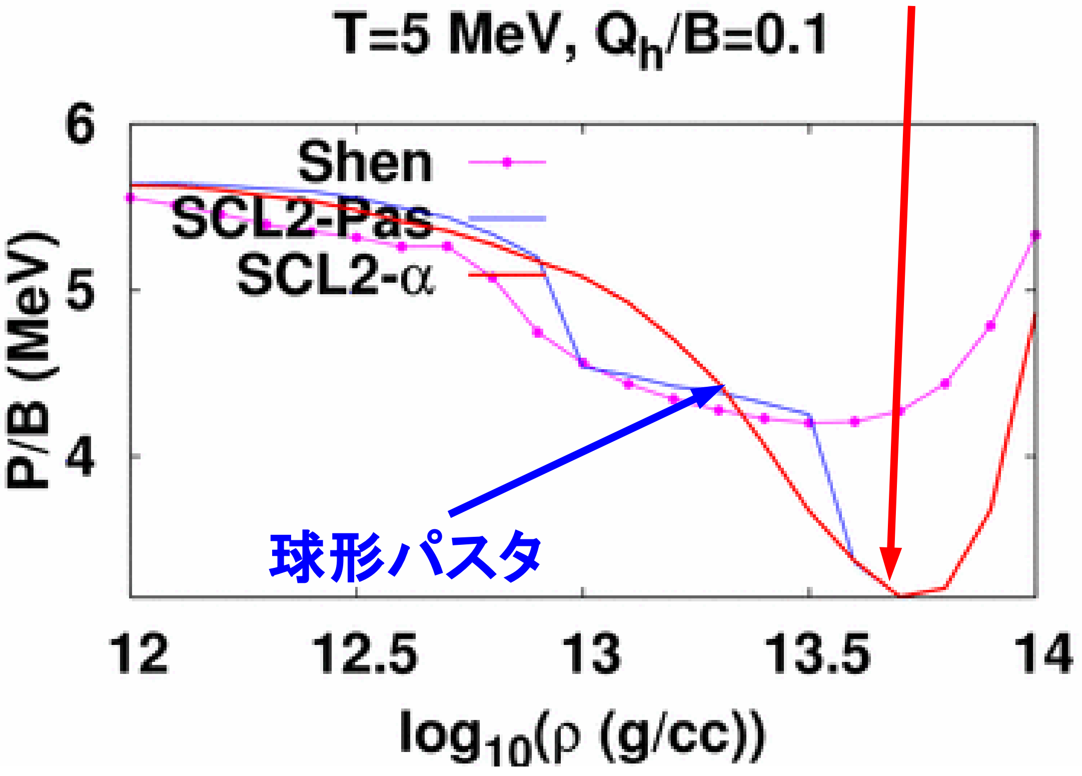
Thank You for Your Attention !

Some preliminary results: Pasta + Unif.

- **問題点**
  - 低密度: gas から Pasta への変化が連続的でない
    → α の影響
  - 非対称物質 : 球形パスタ(u<<1) と非球形パスタ (u~1) が競合
    → u<<1 から u~1 へ非連続に移行



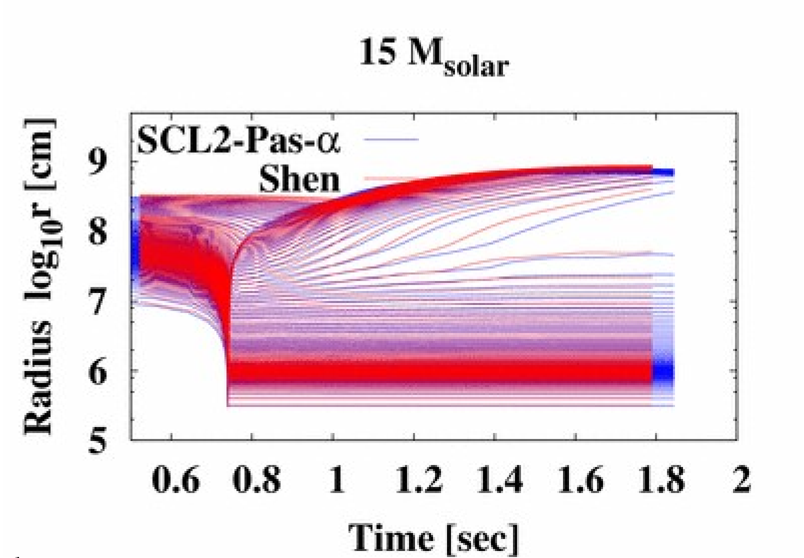
非球形パスタ (u ~ 1)

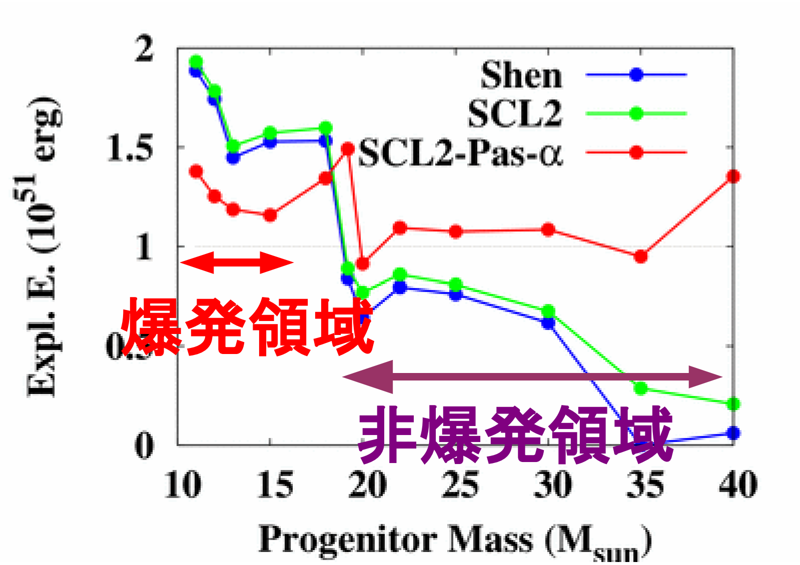


球形パスタ

超新星爆発エネルギー

- 超新星爆発模型 : 1 次元流体模型　(Sumiyoshi et al., 2002)
  - ニュートリノ輸送は考慮せず、Ye は一定 → prompt Expl.
- 「 Chiral RMF+ 連続パスタ」→ 爆発は起こらず
- 「 Chiral RMF+ 連続パスタ +α 」(preliminary) を非常に低密度の領域で Shen EOS と連続に結合
  - 爆発の成否は Shen EOS と同じ
  - 爆発エネルギーは 10-20 % の減少



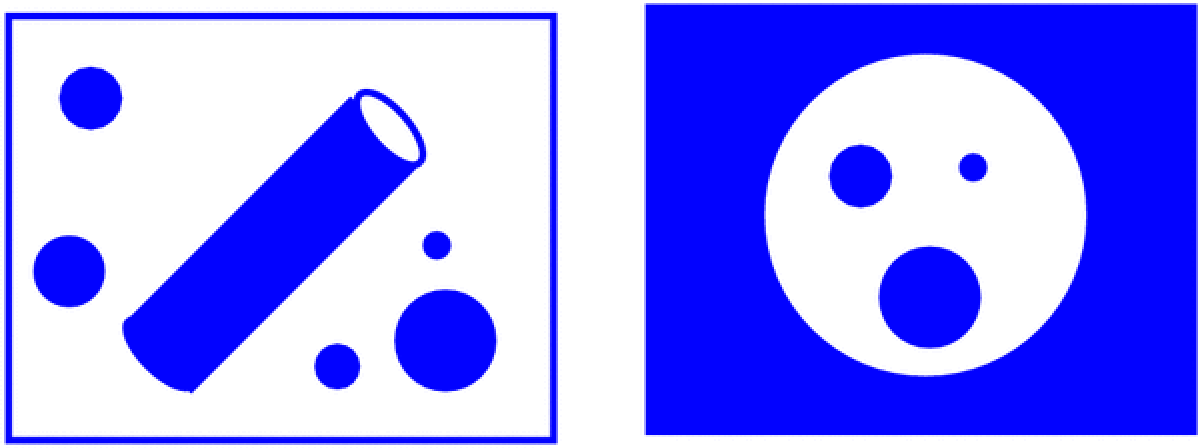


まとめ

- 「Chiral RMF+ 連続パスタ」による超新星物質 EOS 構築の模索
  - Chiral RMF: 強結合格子 QCD に基づき、比較的柔らかい EOS
→ Shen EOS より程度爆発エネルギーが 1-5% 増加 (前回、椿原)
  - 連続パスタ : 対称核物質で体積占有率の高いパスタから一様物質への転移を滑らかにする。
- 「核子ガス + パスタ」のみでは、低密度領域、あるいは非対称物質において圧力は連続に変化しない。
  - 低密度側 : α などの「有限原子核」の影響
  - 高密度側 ($\sim\rho_0$): 球形パスタ (~ 原子核) と非球形パスタの競合
- 低密度側の EOS は超新星爆発エネルギーに大きな影響を与える
  - ρ_0 より少し低い密度での十分な圧力が重要と考えられる。

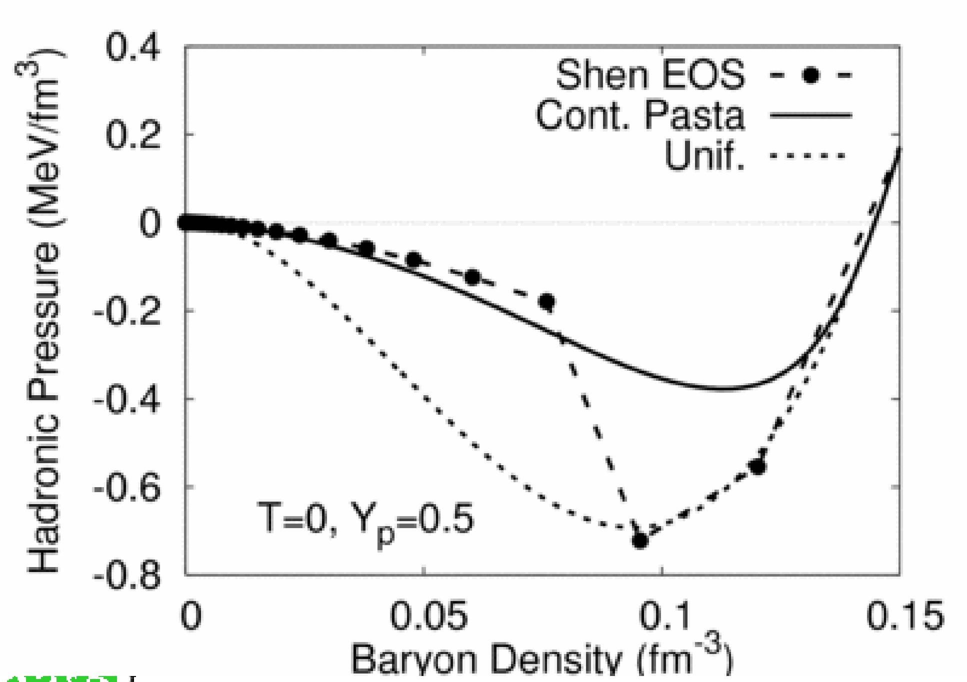
今後の課題

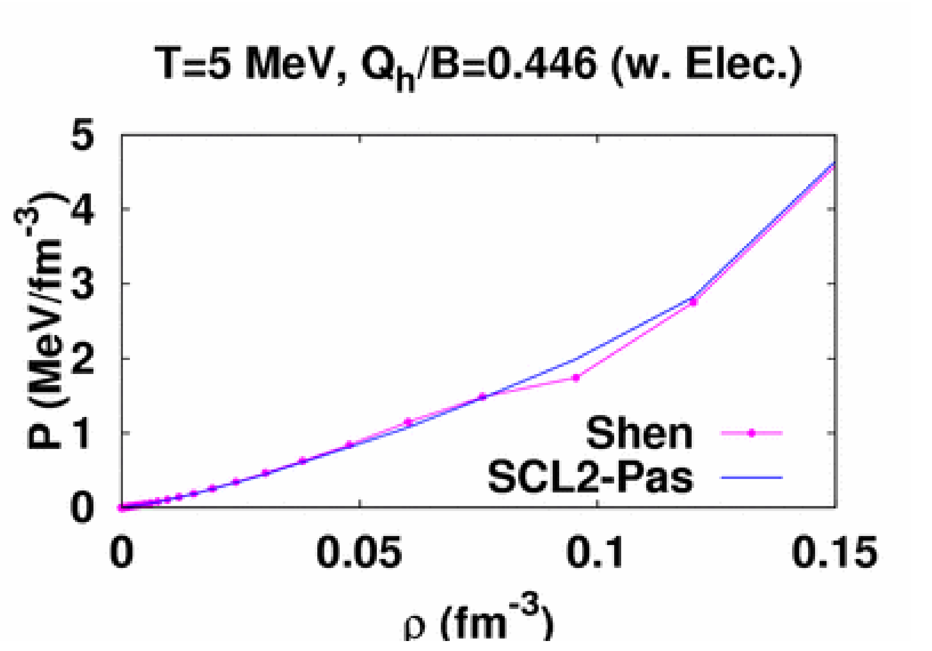
- 一様物質の EOS
  - SU(2) Chiral RMF → SU(3) Chiral RMF (椿原)
    - Single, Double Λ 核、Σ 原子の束縛エネルギーを再現可
    - Hidden Strange meson (ζ、あるいは f_0) と σ の結合により、K ~ 220 MeV 程度へ軟化
- 異なるパスタ配位が同様の自由エネルギーを与える
  - 様々な球形パスタ (~ 原子核) と非球形パスタの共存
→パスタと NSE(Nucl. Stat. Equil.) の組み合わせ



Chiral RMF+ 連続パスタ:状態方程式の変化 (1)

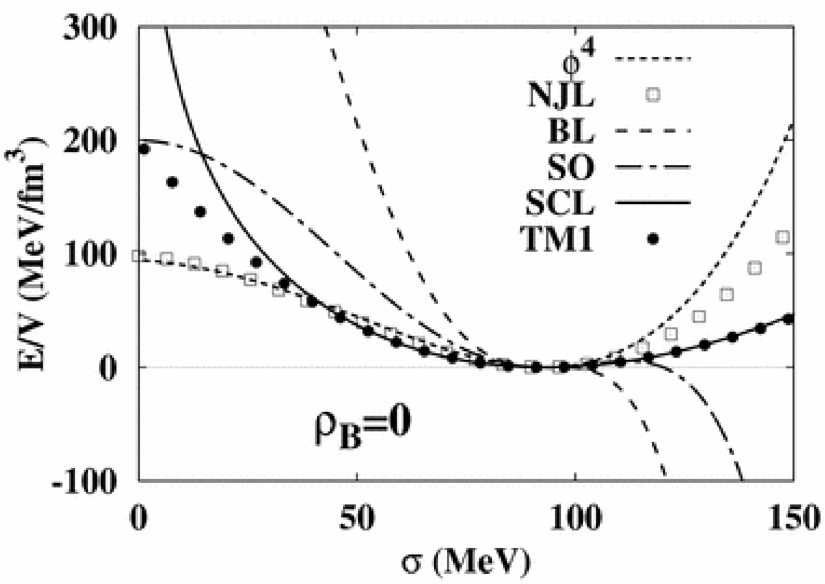
- **T=0: 真空 + パスタ→ 体積占有率が増加し、一様物質へ転移**
- **T>0: 一様核子ガス→ 核子ガス + パスタ→ 一様核物質**

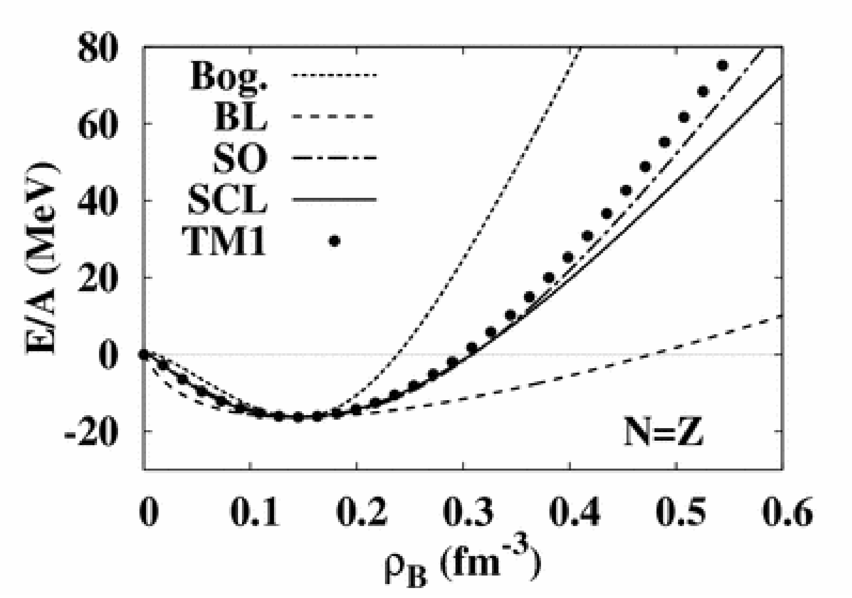


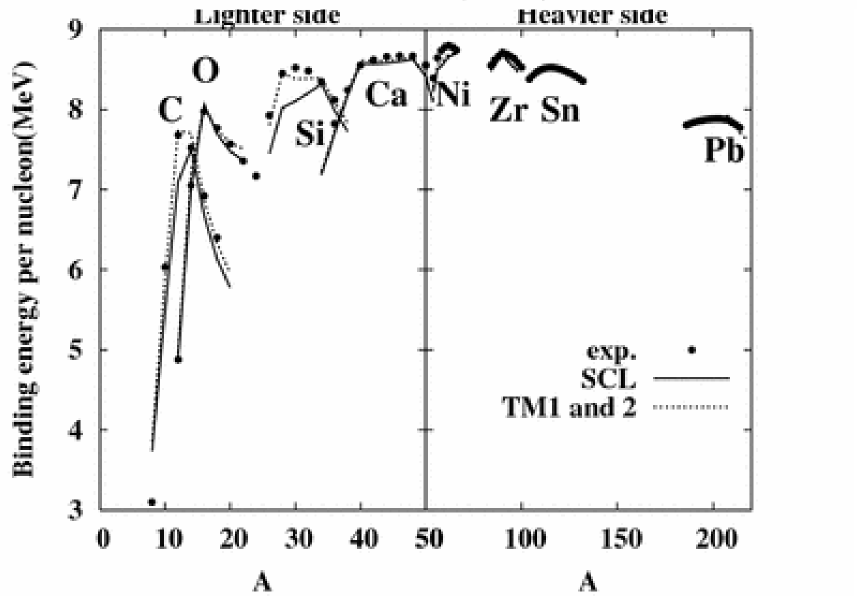


Chiral RMF

- **強結合格子 QCD の成果に基づく対数型の Chiral potential を導入**
  → 真空の安定性
- **十分に柔らかい状態方程式**
- **広い質量数領域において、原子核の束縛エネルギーと荷電半径を再現**





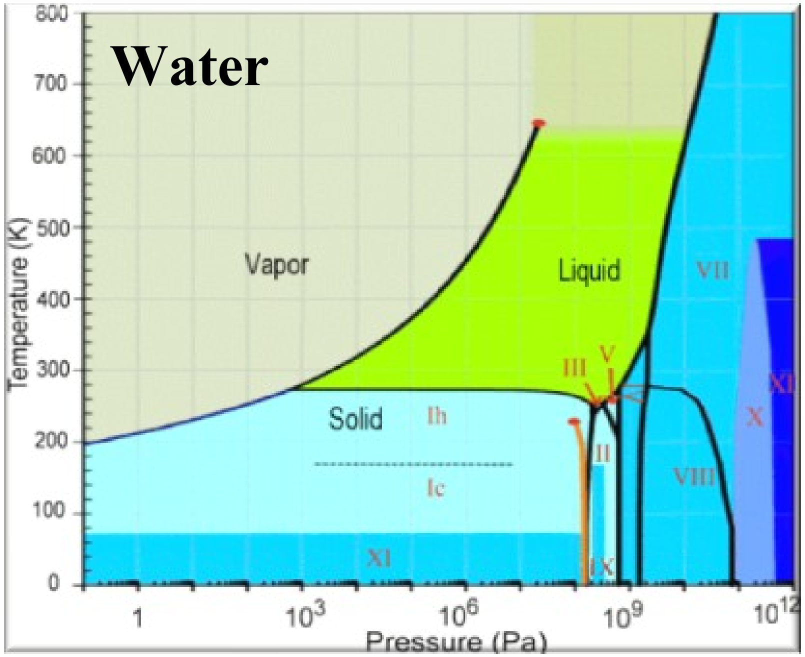


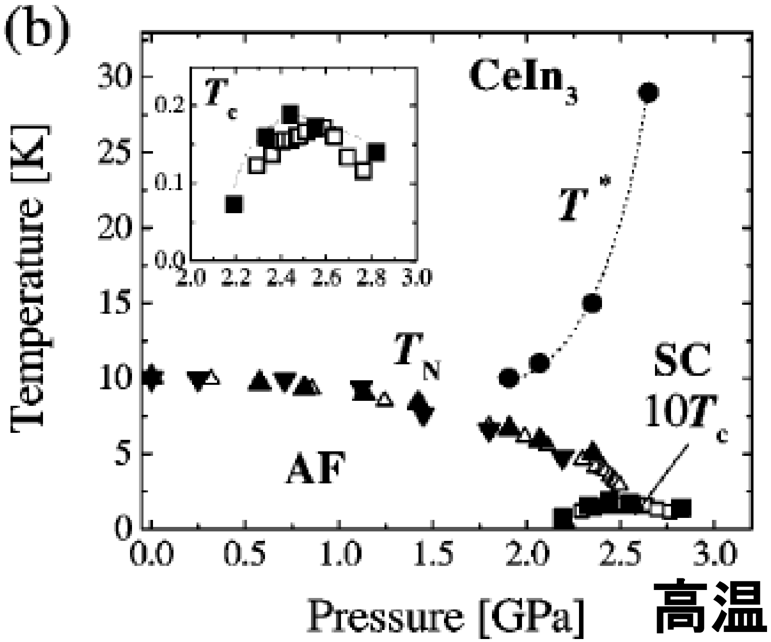
(Tsubakihara,AO, 2006)

- **Supernova explosion from light progenitor**
  NSE and nucleosynthesis is solved simultaneously with ν radiation hydro.

  F. S. Kitaura, H.-T. Janka, and W. Hillebrandt Astron. Astrophys. 450 (2006) 345–350,arXiv:astro-ph/0512065.
- **SASI**
  A. Marek and H. T. Janka arXiv:0708.3372 [astro-ph].

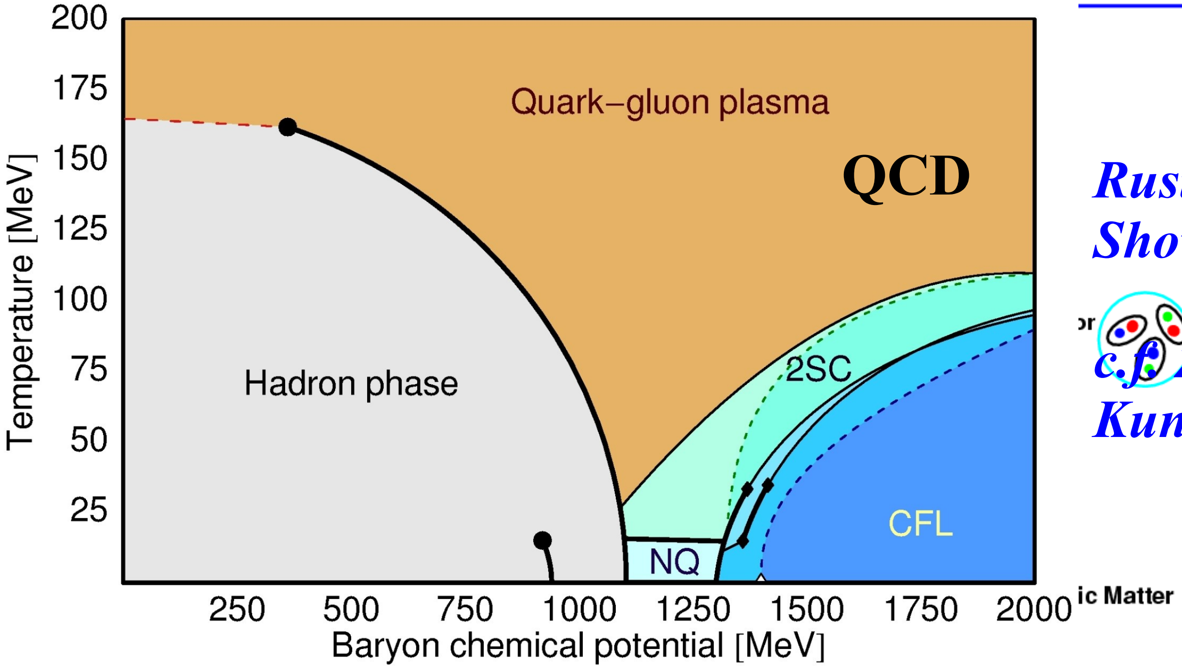
物質の相図





高温超伝導体

Kawasaki et al, 2001



Ruster, Verth, Buballa, Shovkovey, Rischke, 2005

c.f. Zhang, Fukushima, Kunihiro, 2008

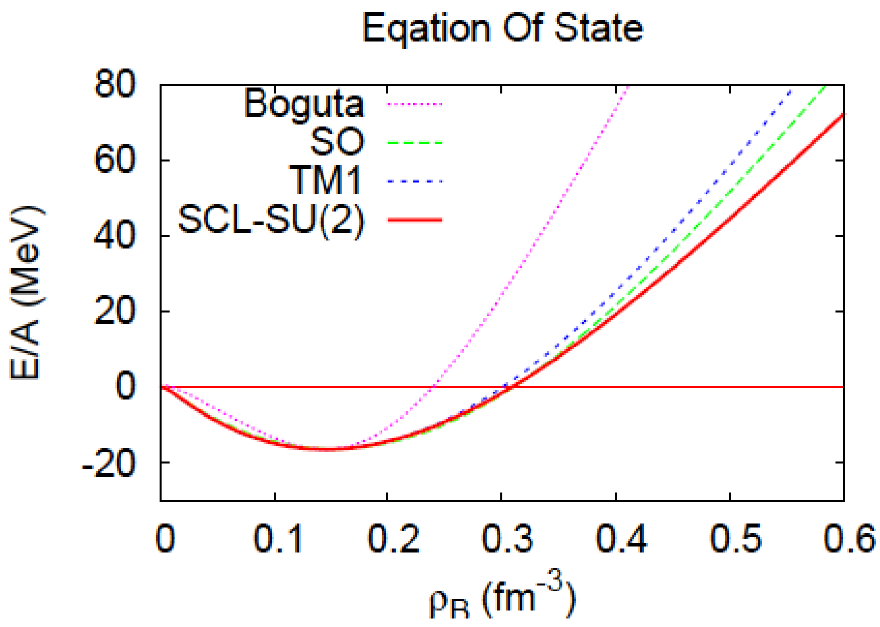
Chiral RMF based on SCL-LQCD

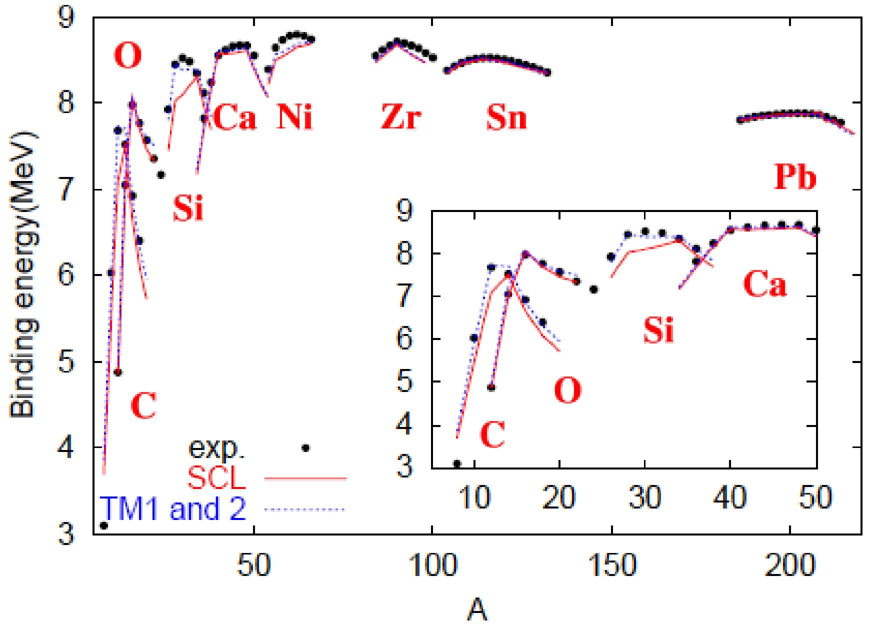
Tsubakihara, AO, PTP 117('07)903 [nucl-th/0607046]

- **強結合格子 QCD に基づく Chiral RMF 模型**

$$U_{\text{Linear}\sigma\text{model}}(\sigma)=-\frac{\mu^{٢}}{٢}\sigma^{٢}+\frac{\lambda}{٤}\sigma^{٤}\ \rightarrow\ U_{\text{SCL}}(\sigma)=\frac{١}{٢}b_\sigma\sigma^{٢}-a_\sigma\log\sigma$$

  - **QCD に基づき、カイラル対称性をもち、不安定性はない。**
  - **少ない数のパラメータで、核物質・原子核のバルクな性質をよく説明**





QCD から原子核の「密度汎関数」を与える第一歩！

Summary (1), A la Michelin

- **$U_\Lambda(\rho_0) \sim -30$ MeV** ✿✿✿
  - ***Bound State Spectroscopy** + **Continuum Spectroscopy***
- **$U_\Sigma(\rho_0) > +15$ MeV** ✿✿
  - **Continuum (Quasi-Free) spectroscopy with *Local Optimal Fermi Averaging t-matrix* (LOFAt)**
  - **Atomic shift data (attractive at surface) should be respected.**
- **$U_\Xi(\rho_0) \sim -14$ MeV** ✿
  - **No confirmed bound state, No atomic data, High mom. transf., ... → Small Potential Deps.**
  - **Continuum low-res. spectrum shape → – 14 MeV**
  - **Spin-Isospin deps. (π exch.) → Deformation → Spectrum shape may be modified.**

There is no
"No Star"
Restaurant
in Michelin Tokyo

Summary (2)

- **Hyperons are included in the Relativisitic (Shen) EOS with recently accepted Hyperon Potentials in Nuclear Matter,**

  $U_\Lambda = -30$ MeV, $U_\Sigma = +30$ MeV , $U_\Xi = -15$ MeV

  http://nucl.sci.hokudai.ac.jp/~chikako/EOS

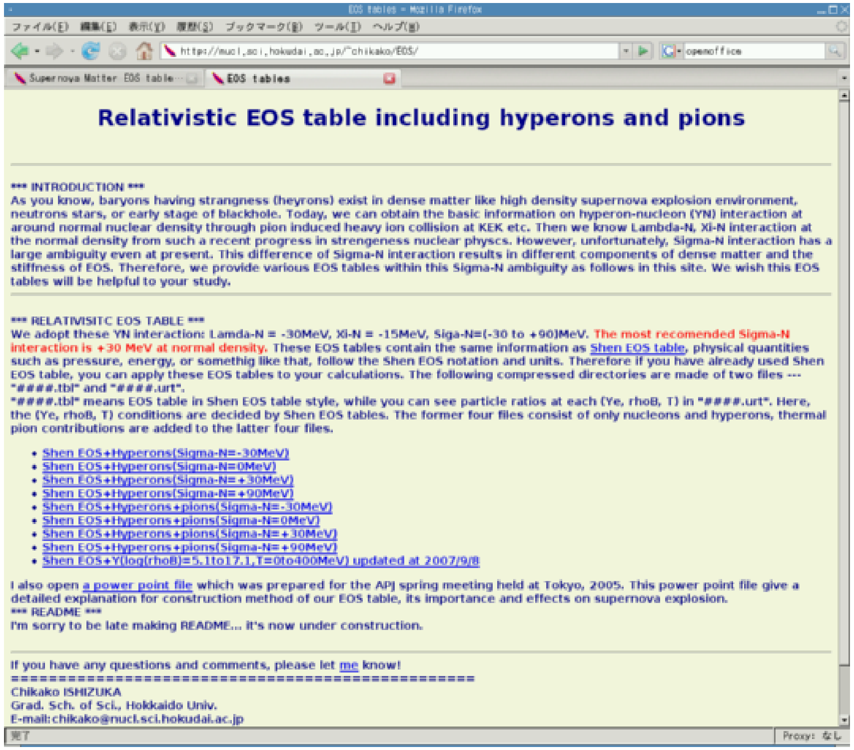
  ρ =10(5.1-15.4) g/cc, T=0-100 MeV, Ye=0-0.56**

  (Ishizuka,AO,Tsubakihara, Sumiyoshi,Yamada, arXiv:0802.2318)

EOSY by IOTSY

- **Hyperon effects:**
  Decisive in Nstar
  Small in SNe (early)
  Significant in BH formation.
  (Sumiyoshi's Talk !)

- **Japan Proton Accelerator Research Complex (J-PARC) data will come soon.**
  Stay Tuned !



Relativistic EOS table including hyperons and pions

*** INTRODUCTION ***
As you know, baryons having strangness (heyrons) exist in dense matter like high density supernova explosion environment, neutrons stars, or early stage of blackhole. Today, we can obtain the basic information on hyperon-nucleon (YN) interaction at around normal nuclear density through pion induced heavy ion collision at KEK etc. Then we know Lambda-N, Xi-N interaction at the normal density from such a recent progress in strengeness nuclear physcs. However, unfortunately, Sigma-N interaction has a large ambiguity even at present. This difference of Sigma-N interaction results in different components of dense matter and the stiffness of EOS. Therefore, we provide various EOS tables within this Sigma-N ambiguity as follows in this site. We wish this EOS tables will be helpful to your study.

*** RELATIVISITC EOS TABLE ***
We adopt these YN interaction: Lamda-N = -30MeV, Xi-N = -15MeV, Siga-N=(-30 to +90)MeV. The most recomended Sigma-N interaction is +30 MeV at normal density. These EOS tables contain the same information as Shen EOS table, physical quantities such as pressure, energy, or somethig like that, follow the Shen EOS notation and units. Therefore if you have already used Shen EOS table, you can apply these EOS tables to your calculations. The following compressed directories are made of two files --- "####.tbl" and "####.urt".
"####.tbl" means EOS table in Shen EOS table style, while you can see particle ratios at each (Ye, rhoB, T) in "####.urt". Here, the (Ye, rhoB, T) conditions are decided by Shen EOS tables. The former four files consist of only nucleons and hyperons, thermal pion contributions are added to the latter four files.

- Shen EOS+Hyperons(Sigma-N=-30MeV)
- Shen EOS+Hyperons(Sigma-N=0MeV)
- Shen EOS+Hyperons(Sigma-N=+30MeV)
- Shen EOS+Hyperons(Sigma-N=+90MeV)
- Shen EOS+Hyperons+pions(Sigma-N=-30MeV)
- Shen EOS+Hyperons+pions(Sigma-N=0MeV)
- Shen EOS+Hyperons+pions(Sigma-N=+30MeV)
- Shen EOS+Hyperons+pions(Sigma-N=+90MeV)
- Shen EOS+Y(log(rhoB)=5.1to17.1,T=0to400MeV) updated at 2007/9/8

I also open a power point file which was prepared for the APJ spring meeting held at Tokyo, 2005. This power point file give a detailed explanation for construction method of our EOS table, its importance and effects on supernova explosion.
*** README ***
I'm sorry to be late making README... it's now under construction.

If you have any questions and comments, please let me know!
==
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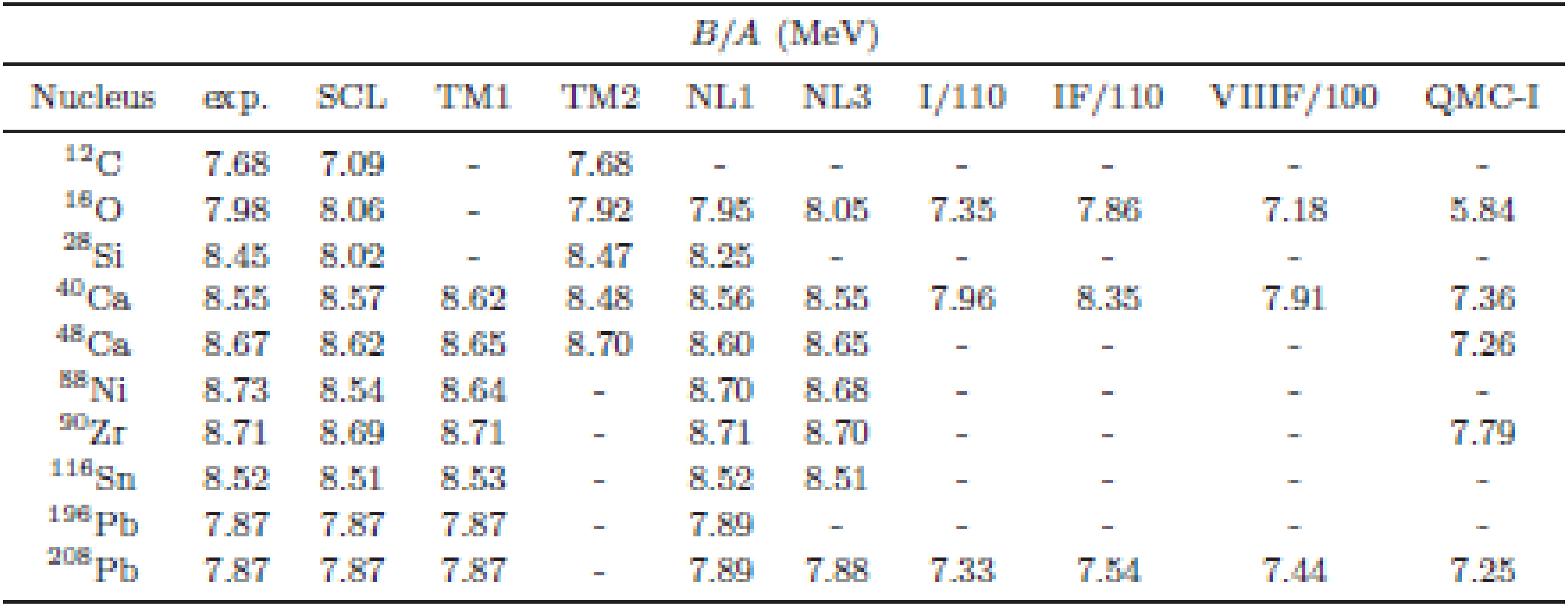
E-mail:chikako@nucl.sci.hokudai.ac.jp

Binding Energies in Chiral and Non-Chiral RMF

- **Non-Chiral High Precision RMF: TM1 & 2, NL1, NL3**
  (Sugahara, Toki, 1994; Reinhard et al., 1986; Lalazissis, Koenig, Ring, 1997)
- **Log term from Scale Anomaly: I/110, IF/110, VIIIF/100**
  (Heide, Rudas, Ellis, 1994)
- **Quark Meson Coupling model**
  (Saito, Tsushima, Thomas, 1997)



					B/A (MeV)					
Nucleus	exp.	SCL	TM1	TM2	NL1	NL3	I/110	IF/110	VIIIF/100	QMC-I
^{12}C	7.68	7.09	-	7.68	-	-	-	-	-	-
^{16}O	7.98	8.06	-	7.92	7.95	8.05	7.35	7.86	7.18	5.84
^{28}Si	8.45	8.02	-	8.47	8.25	-	-	-	-	-
^{40}Ca	8.55	8.57	8.62	8.48	8.56	8.55	7.96	8.35	7.91	7.36
^{48}Ca	8.67	8.62	8.65	8.70	8.60	8.65	-	-	-	7.26
^{58}Ni	8.73	8.54	8.64	-	8.70	8.68	-	-	-	-
^{90}Zr	8.71	8.69	8.71	-	8.71	8.70	-	-	-	7.79
^{116}Sn	8.52	8.51	8.53	-	8.52	8.51	-	-	-	-
^{196}Pb	7.87	7.87	7.87	-	7.89	-	-	-	-	-
^{208}Pb	7.87	7.87	7.87	-	7.89	7.88	7.33	7.54	7.44	7.25

Chiral $SU_f(3)$ RMF

Tsubakihara, Maekawa, AO, EPJA33('07)295 [nucl-th/0702008]

- **Extention to Flavor SU(3)**
  → Chiral Potential from SCL-LQCD
  + Determinant Int. ($U_A(1)$ anomaly)
  + Explicit breaking term

$$U_{\sigma\zeta} = -\,a\,\log(\det MM^\dagger) + b\,\mathrm{tr}(MM^\dagger) + c_\sigma\sigma + c_\zeta\zeta + d\,(\det M + \det M^\dagger).$$

- **Normal, Single & Double Λ, Σ atom, EOS (~ FP), ...**