Relativistic EOS of Supernova Matter with Hyperons

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in collaboration with
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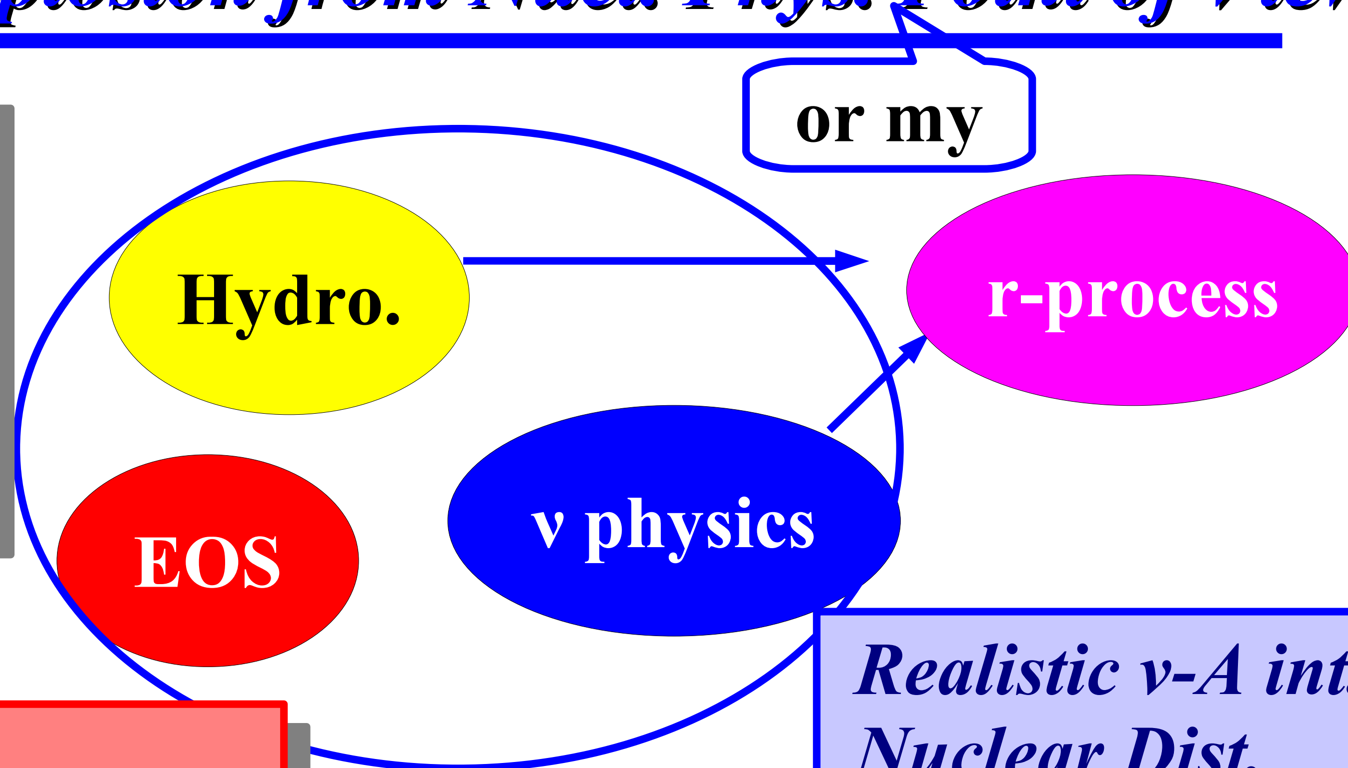
K. Sumiyoshi (Numazu CT), S. Yamada (Waseda U.)

- **Introduction**
- **Hyperon potential in nuclear matter**
  Maekawa, Tsubakihara, AO, EPJA 33 (2007), 269 [arXiv:nucl-th/0701066]
  Maekawa, Tsubakihara, Matsumiaya, AO, arXiv:0704.3929 (Ξ); in preparation (Σ)
- **Relativistic EOS of Supernova Matter with Hyperons**
  Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, to be submitted
  http://nucl.sci.hokudai.ac.jp/~chikako/EOS/
- **Summary**

Supernova Explosion from Nucl. Phys. Point of View



Multi Dim.
Instability
Magnetic Field
Acoustic Revival
....

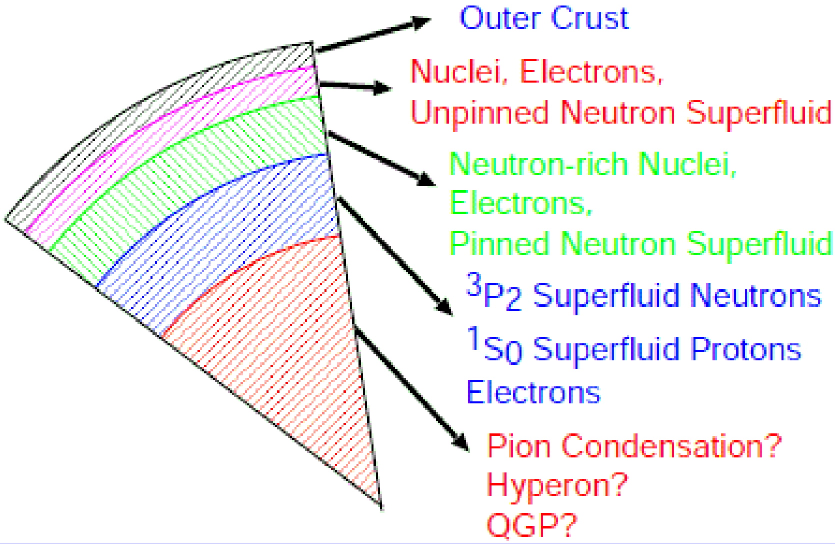
EOS tables
Lattimer-Swesty (1981)
Rel. (Shen) EOS (1998)
→ *How to extend ?*

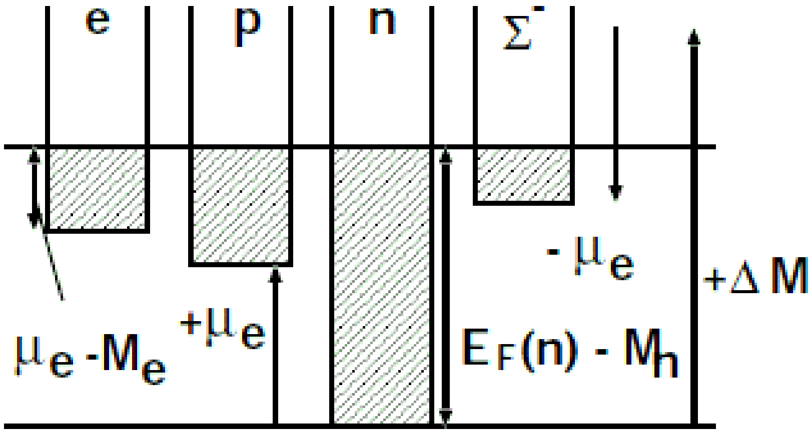
Realistic ν-A int.
Nuclear Dist.
Exact ν transfer
.....

- **Supernovae DO NOT EXPLODE in theor. calculation at present with realistic microphysics inputs. → How can we succeed ?**
  - **Multi-Dim. Hydro (Instability)+*Additional Energy Release* (10 %-factor 10)**

Hyperons in Dense Matter

- What appears at high density ?
  - Nucleon superfluid ($^3S_1$, $^3P_2$)
  - Pion condensation, Kaon condensation, Baryon Rich QGP
  - Hyperons
    Tsuruta, Cameron (66); Langer, Rosen (70); Pandharipande (71); Itoh(75); Glendenning; Weber, Weigel; Sugahara, Toki; Schaffner, Mishustin; Balberg, Gal; Baldo et al.; Vidana et al.; Nishizaki,Yamamoto, Takatsuka; Kohno,Fujiwara et al.; Sahu,Ohnishi; Ishizuka, Ohnishi, Sumiyoshi, Yamada; ...





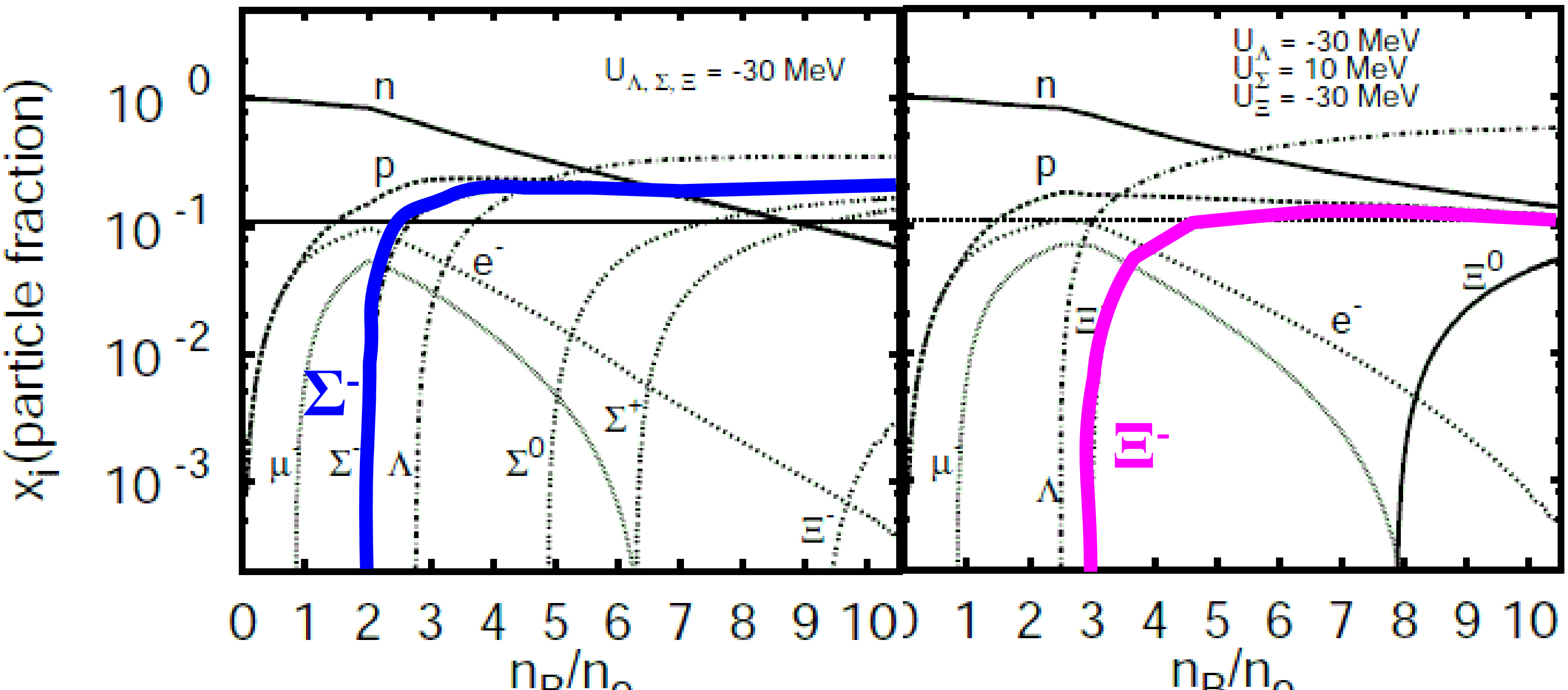
Nobody says "Hyperons do not appear in neutron star core" !

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

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

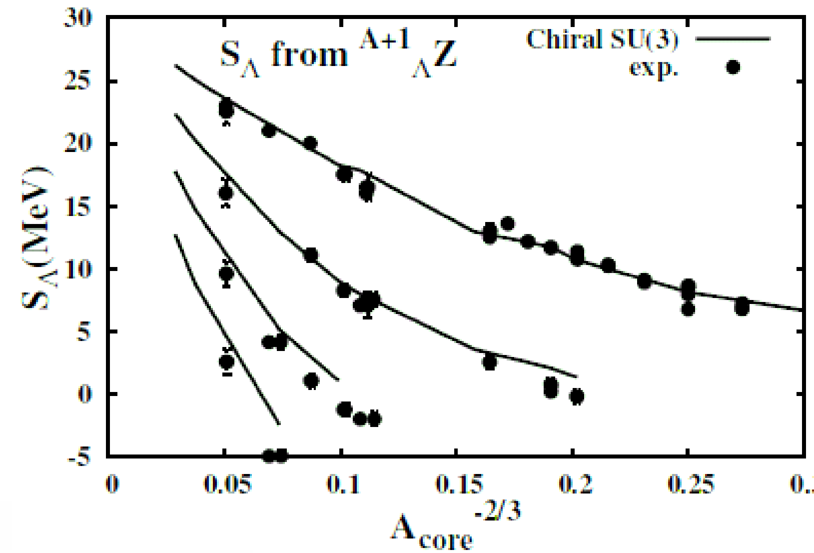
We include recent hyperon info. in supernova matter EOS

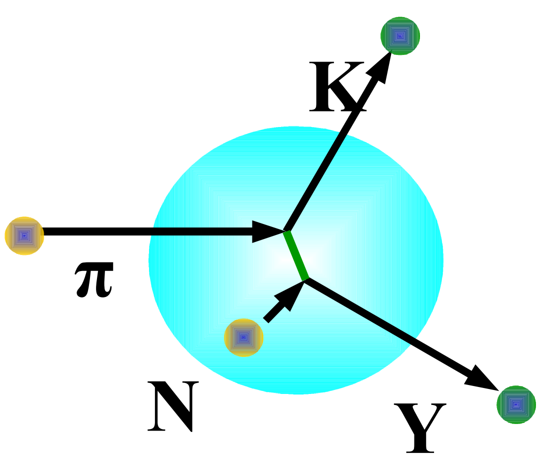
Hyperon Potential in Nuclear Matter

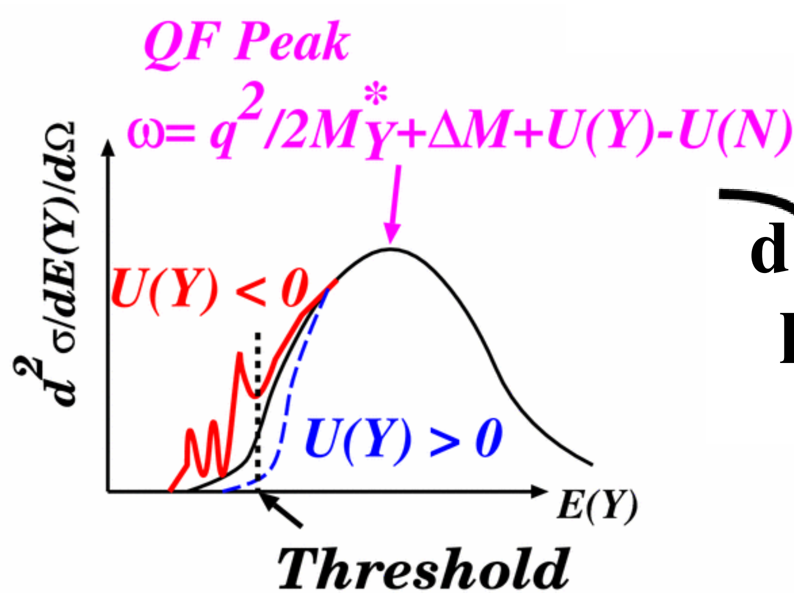
Σ Potential in Nuclear Matter

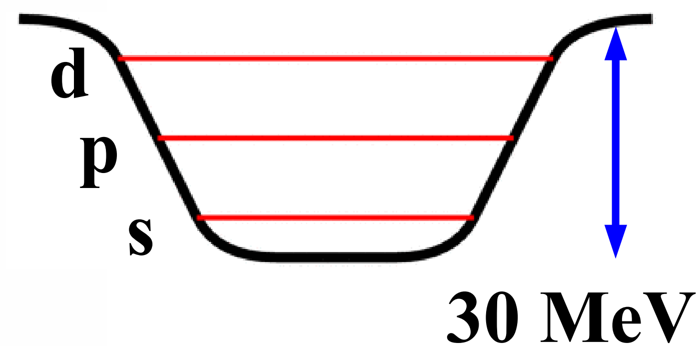
- $U_\Lambda(\rho_0) \sim -30$ MeV: Well known from single particle energies
- Naïve expectation
  = Quark Number (ud number) Scaling
  $U_\Lambda \sim 2/3\, U_N \rightarrow U_\Sigma \sim 2/3\, U_N \sim -30$ MeV
- Problems with Σ
  - Only one bound state ${}^4_\Sigma$He (Too light !)
  - → Continuum (Quasi-Free) Spectroscopy is necessary

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









Σ Potential in Nuclear Matter

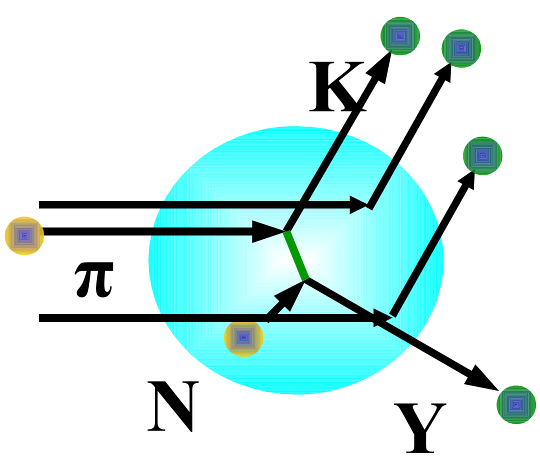
- **Cont. Spec. Theory = Distorted Wave Impulse Approx. (DWIA)**

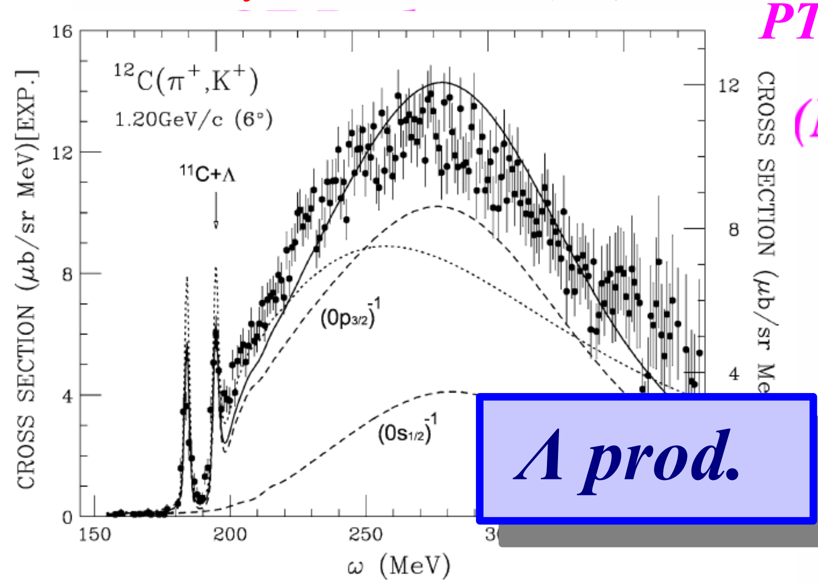
$$\frac{d^2\sigma}{dE_K\, d\Omega_K} = \boxed{\beta}\ \boxed{\left(\frac{d\sigma}{d\Omega}\right)^{Elem.}_{N\pi\to KY}}\ \boxed{S(E,\boldsymbol{q})}$$

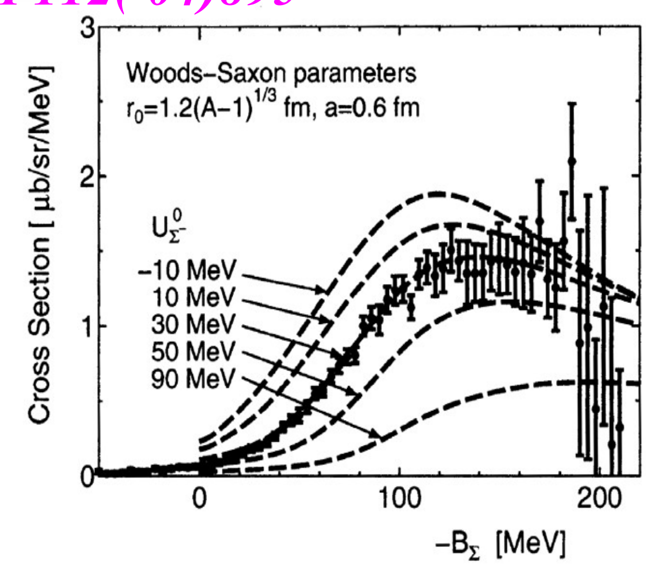
Kinematical Factor (β) — **Elem. Cross Sec.** — **Strength Func.** ($S(E,\boldsymbol{q})$)

- **Large (ω, q) range → Important to respect On-Shell Kinematics**
- **Kinematics depends on Reaction Point with Hyperon Potential**

Harada, Hirabayashi, NPA744('04),323. *Kohno, Fujiwara, Kawai, et al. PTP112('04)895*







Σ Potential in Nuclear Matter

Maekawa, Tsubakihara, AO, EPJA 33(2007),269.
Maekawa, Tsubakihara, Matsumiya, AO, in preparation.

- **DWIA with Local Optimal Fermi Averaging t-matrix (DWIA-LOFAt)**
  - **Green's Func. Method + Reaction Point Deps. of t-matrix**

$$\frac{d^2\sigma}{dE_K\,d\Omega_K} = \frac{p_K E_K}{(2\pi)^2 v_{\rm inc}} R_Y(E_Y) \qquad R_Y(E_Y) = -\frac{1}{\pi}\,{\rm Im}\left\langle \bar{t}(\boldsymbol{r})^{+} \frac{1}{E_Y - H_Y + i\varepsilon} \bar{t}(\boldsymbol{r}')\right\rangle$$

Response Func. **Local t-mat.** **Green's Func.**

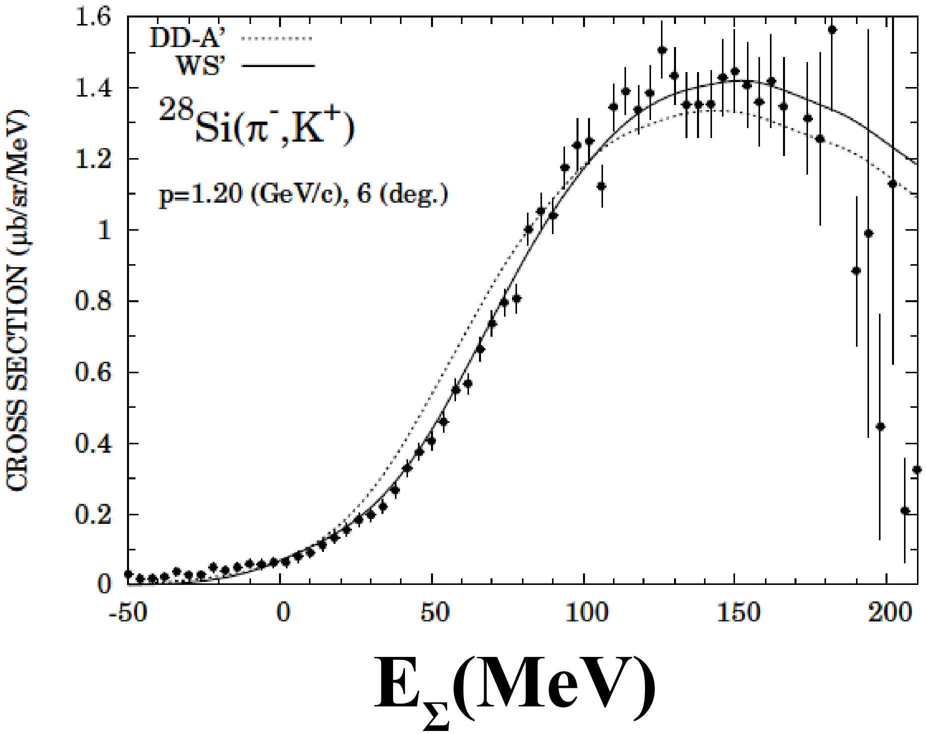
$$\bar{t}(\boldsymbol{r},\omega,\boldsymbol{q}) = \frac{\int d\,\boldsymbol{p}_N\;\; t(s,t)\rho(p_N)\delta^{(4)}(p_1(\boldsymbol{r})+p_2(\boldsymbol{r})-p_3(\boldsymbol{r})-p(\boldsymbol{r}))}{\int d\,\boldsymbol{p}_N\;\; \rho(p_N)\delta^{(4)}(p_1(\boldsymbol{r})+p_2(\boldsymbol{r})-p_3(\boldsymbol{r})-p(\boldsymbol{r}))} \qquad E_i = \sqrt{p_i^2 + m_i^*(r)^2} \simeq m_i + \frac{p_i^2}{2{\rm m}_i} + V_i\,,\quad m_i(r)^2 = m_i^2 + 2m_i V_i(r)$$

  - **After careful treatment of**
    K+ potential, Elementary cross section, Angular distribution, ...
    we analyze the recently measured Σ^- production spectrum
    (Saha, Noumi et al. (KEK-E438), PRC70('04)044613)

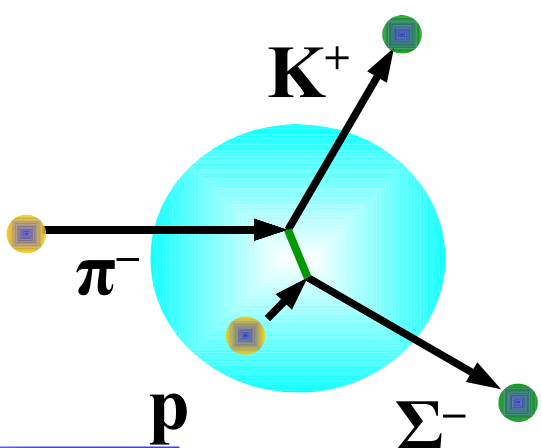
Σ Potential in Nuclear Matter

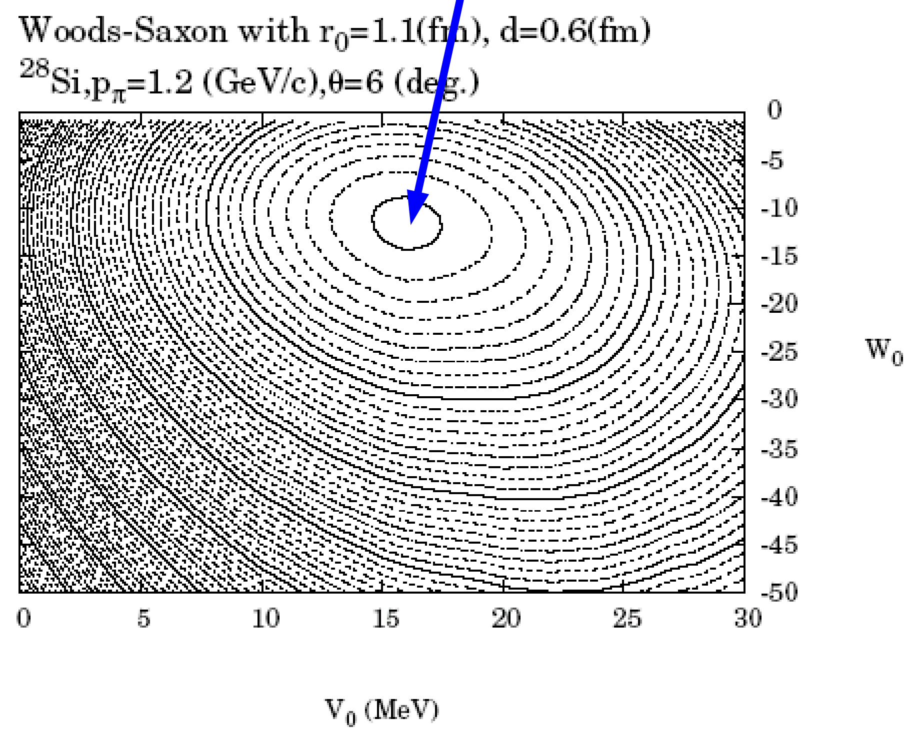
$$\frac{d^2\sigma}{dE_K\, d\Omega_K}$$

Maekawa, Tsubakihara, AO, EPJA 33(2007),269.
Maekawa, Tsubakihara, Matsumiya, AO, in preparation.



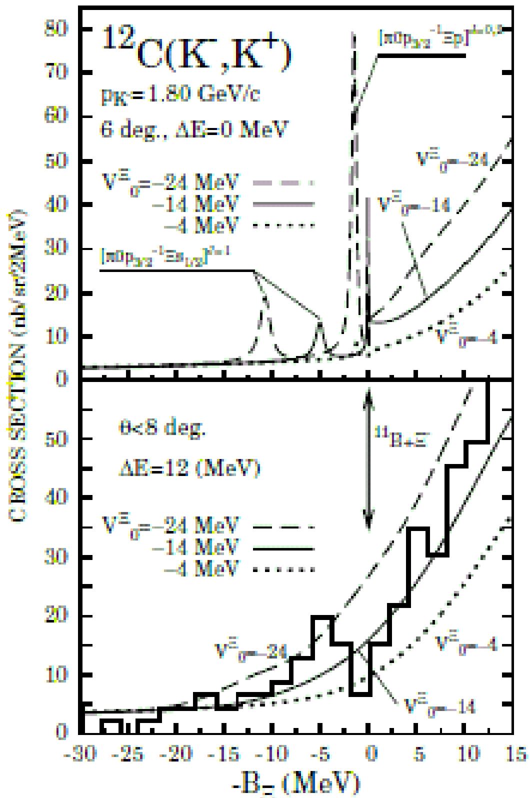
$U_\Sigma(\rho_0) \sim +15$ MeV $-i$ 10 MeV with Woods-Saxon potential, no Atomic shift fit

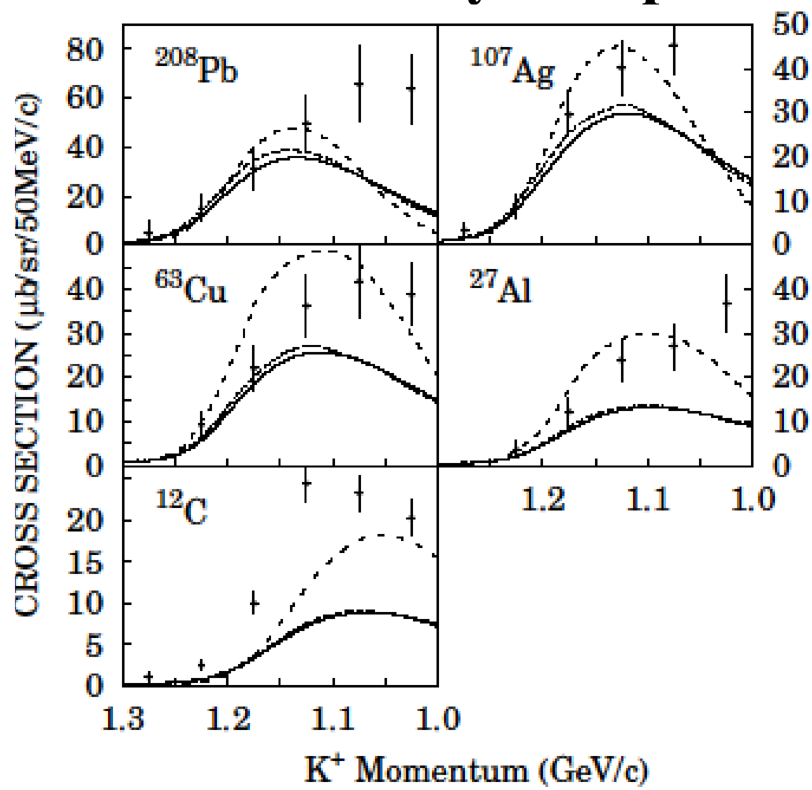




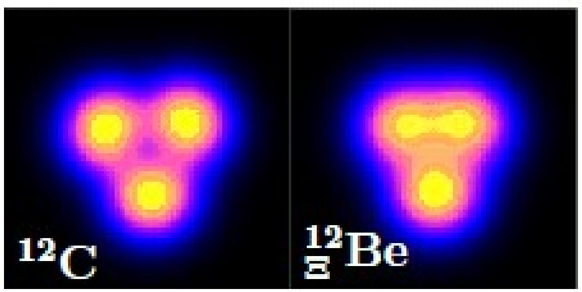
Ξ Potential in Nuclear Matter

- Currently accepted value: $U_\Xi \sim -14$ MeV
  Twin hypernuclear form., Spectrum shape in the bound state region
  (Aoki et al. PLB355('95),45; Fukuda et al. PRC58('98),1306; Khaustov et al. PRC61('00), 054603)
- Absolute values of $^{12}C(K^-,K^+)$ spectra → Still Difficult to Understand
- Nuclear Deformation would modify the spectrum.





Maekawa, Tsubakihara, Matsumiya, AO, arXiv:0704.3929.



Matsumiya, et al. (Coupled Channel AMD)

Let's wait for J-PARC results

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

Relativistic EOS of Supernova Matter with Hyperons

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, Ohnishi, Tsubakihara, Sumiyoshi, Yamada, in preparation)
  - **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

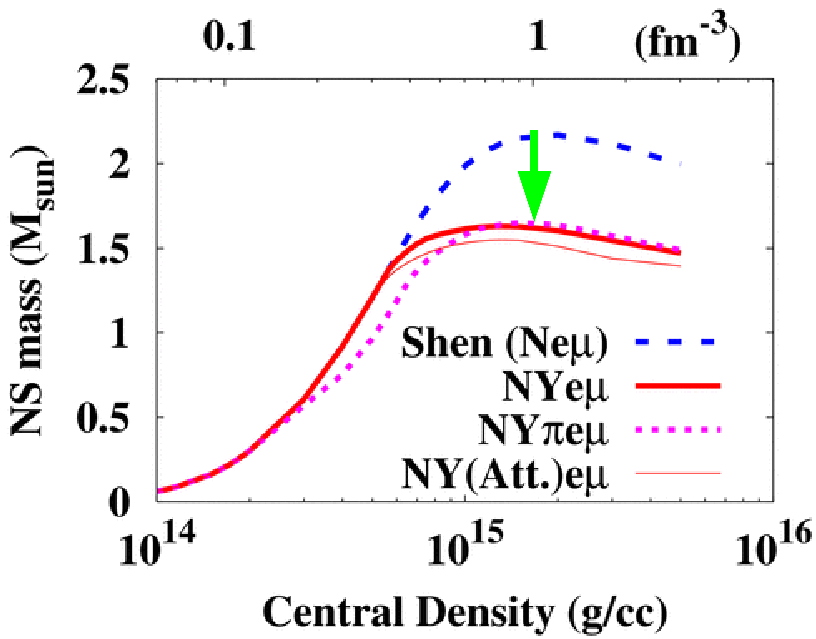
	g_{MB}	σ		ζ	ω	ρ	ϕ
	N	10.0289		0	12.6139	4.6783	0
	Λ	6.21		6.67	8.41	0	−5.95
SM	Σ	4.36	(6.21)	6.67	8.41	$2g_{\rho N}$	−5.95
IOTSY	Ξ	3.11	(3.49)	12.35	4.20	4.63	−11.89

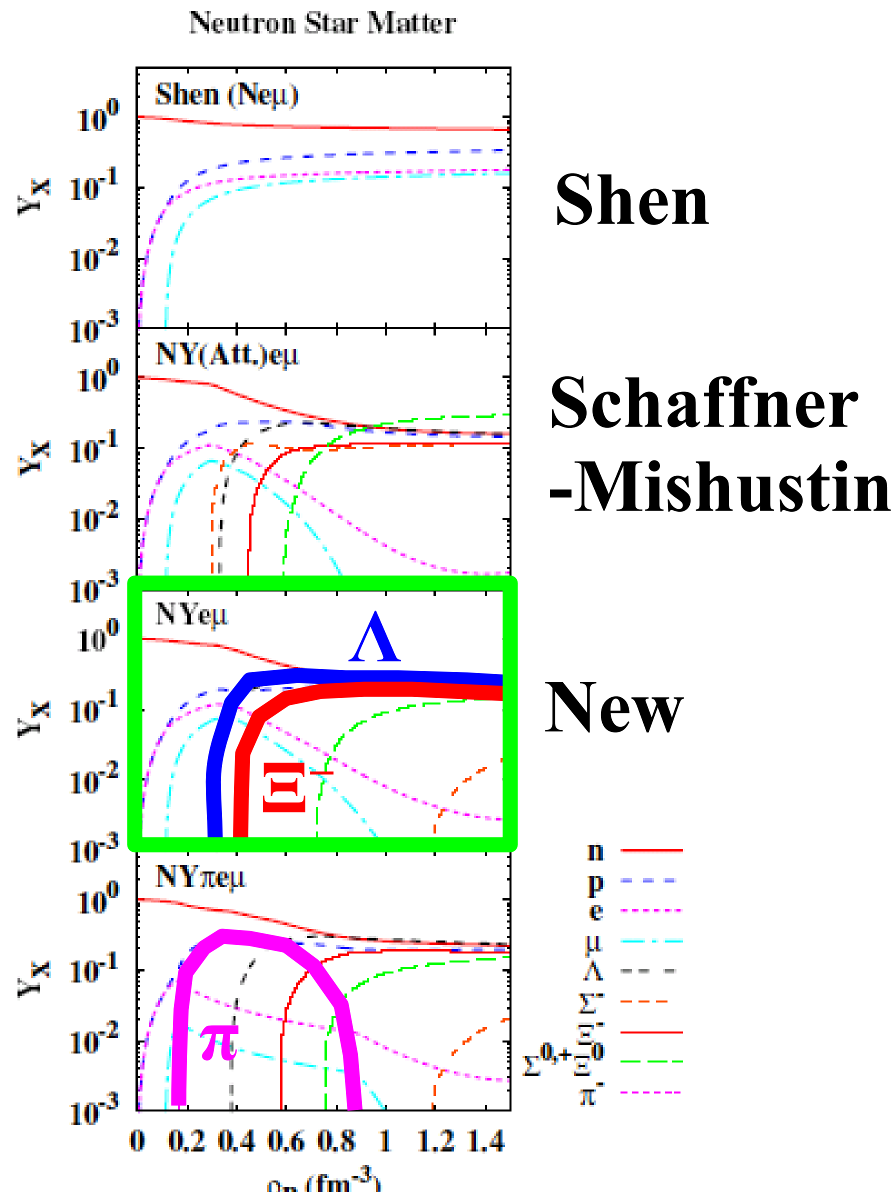
- ***$g_{\sigma Y}$ is tuned to fit Hyperon Potential in Nuclear Matter***
  $U_\Lambda = -30$ MeV, $U_\Sigma = +30$ MeV, $U_\Xi = -15$ MeV
- ***Nuclear Formation is included using Shen EOS table***

Neutron Star

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, in preparation

- **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 $\rho > 1.5\ \rho_0$**

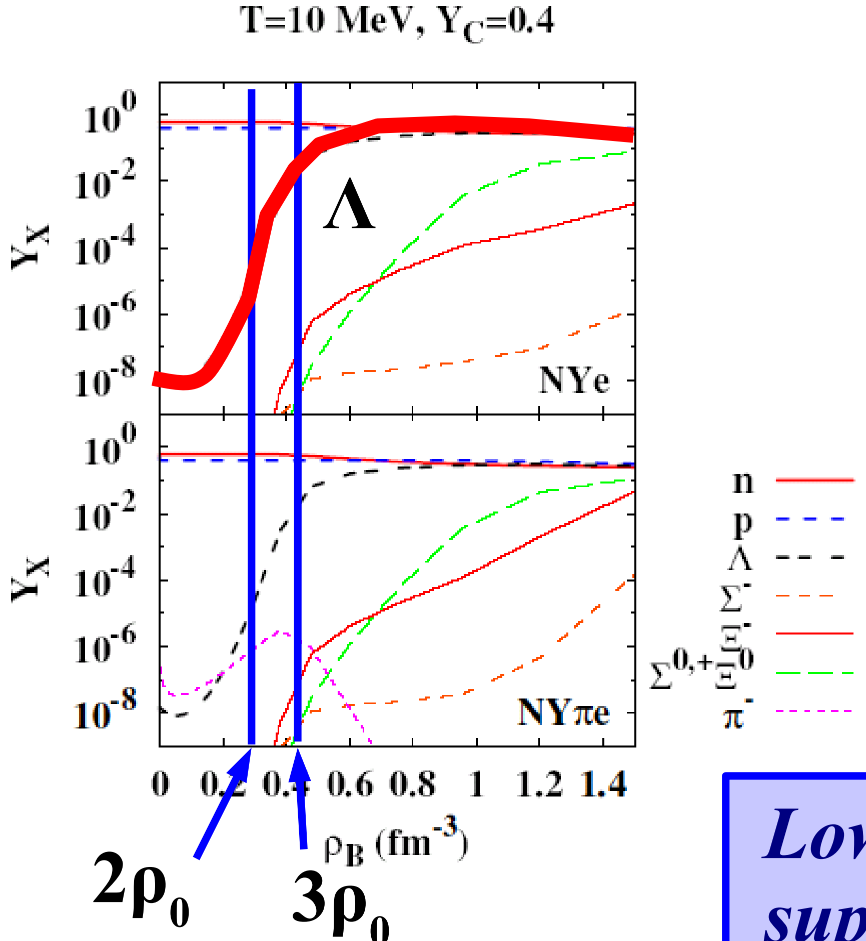




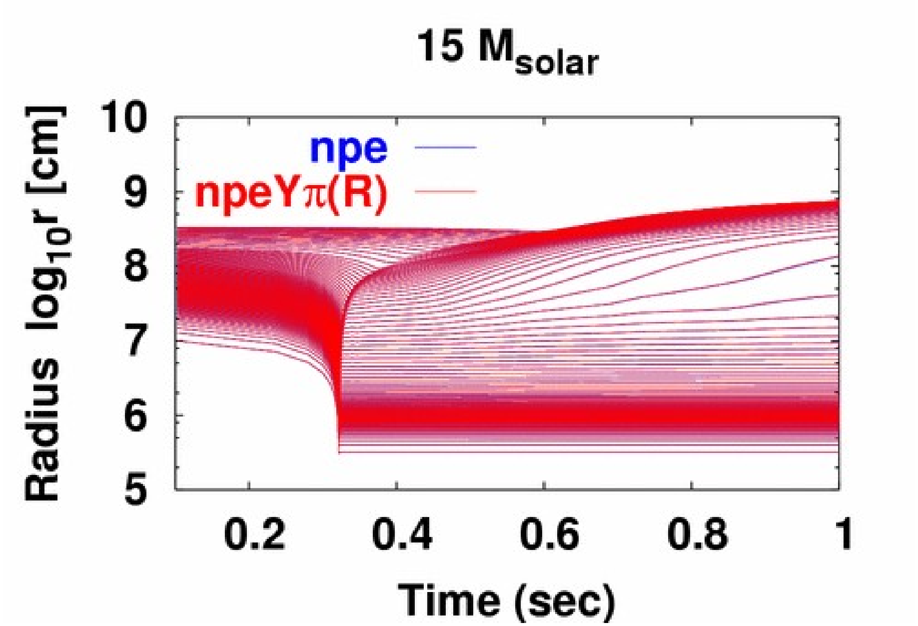
Finite Temperature and Supernova

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, in preparation

- **Example: T=10 MeV, Ye = 0.4**
  - **Λ starts to increase at $\rho \sim 2\rho_0$, becomes significant at $\rho \sim 3\rho_0$.**



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



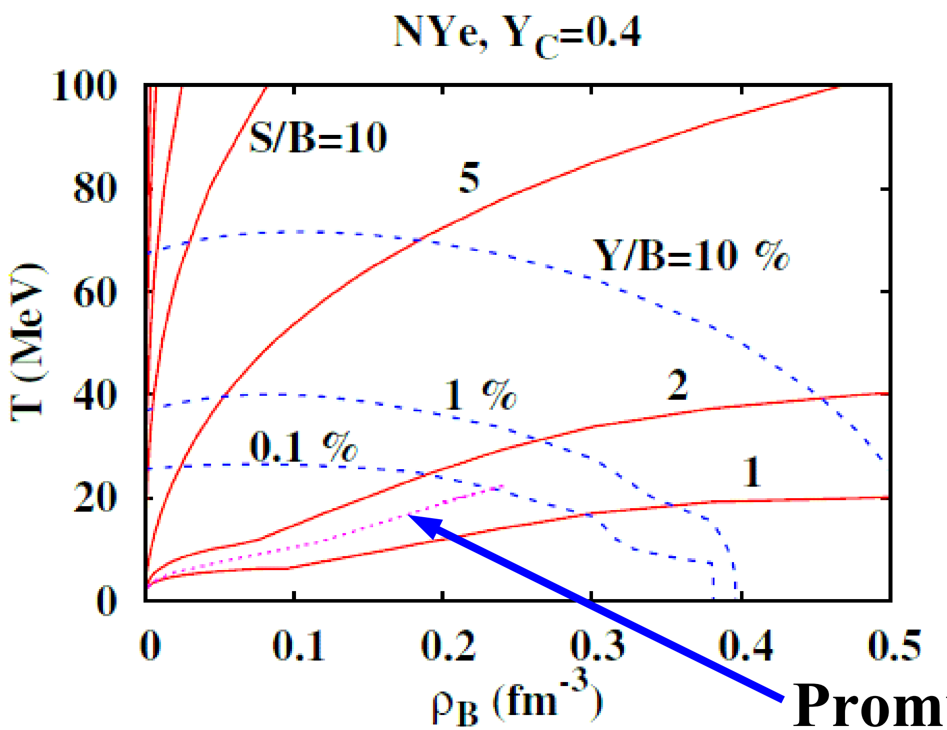
WW95 + 1 Dim. Hydro.(Sumiyoshi, Yamada)

Low density and High Ye suppresses Hyperons in the Early Stage

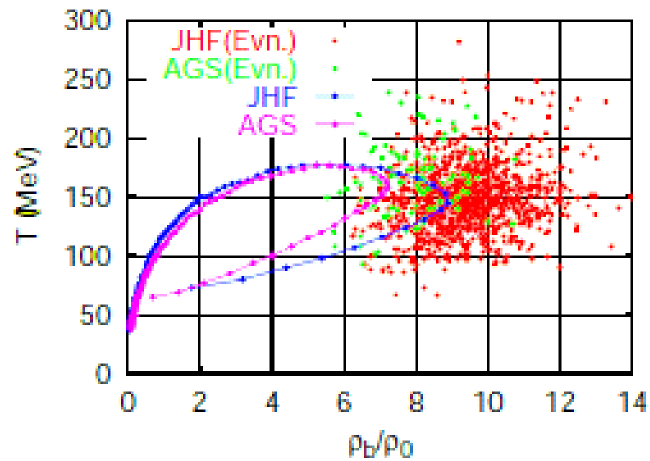
Where Do We See Hyperons ?

- **Hyperon Fraction is sensitive to Ye, T, and ρ_B.**
  - **Yν ~ 0 (Neutron Star) → $\rho_B > 2\ \rho_0$**
  - **Ye ~ 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)



Heavy-Ion Collision Simulation by using JAM (Nara et al.)

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

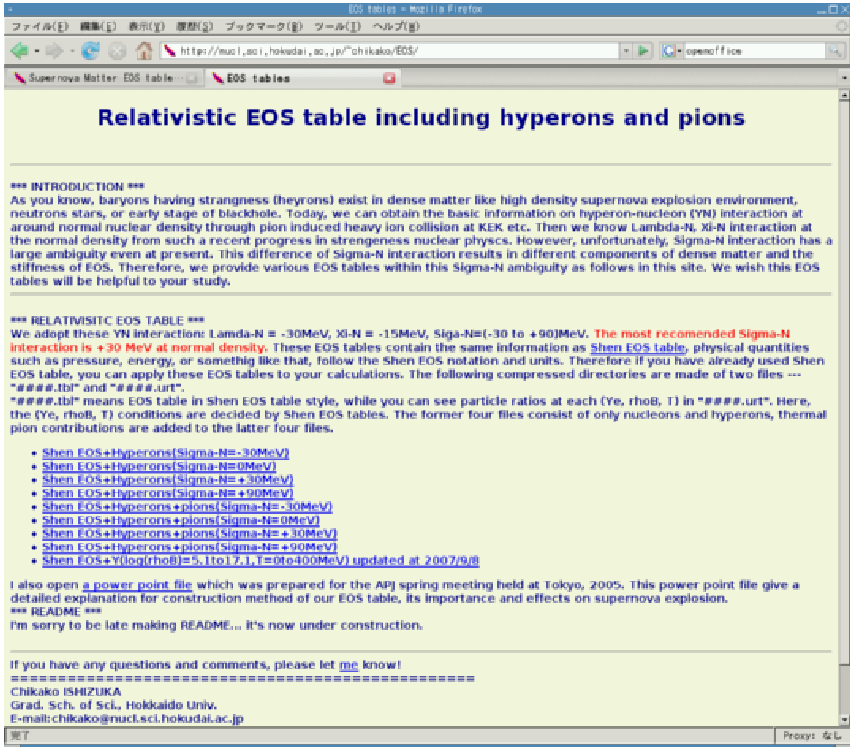
  ρ =10(5.1-15.4) g/cc, T=0-100 MeV, Ye=0-0.56**

  (Ishizuka,AO,Tsubakihara, Sumiyoshi,Yamada, to be subm. soon.)

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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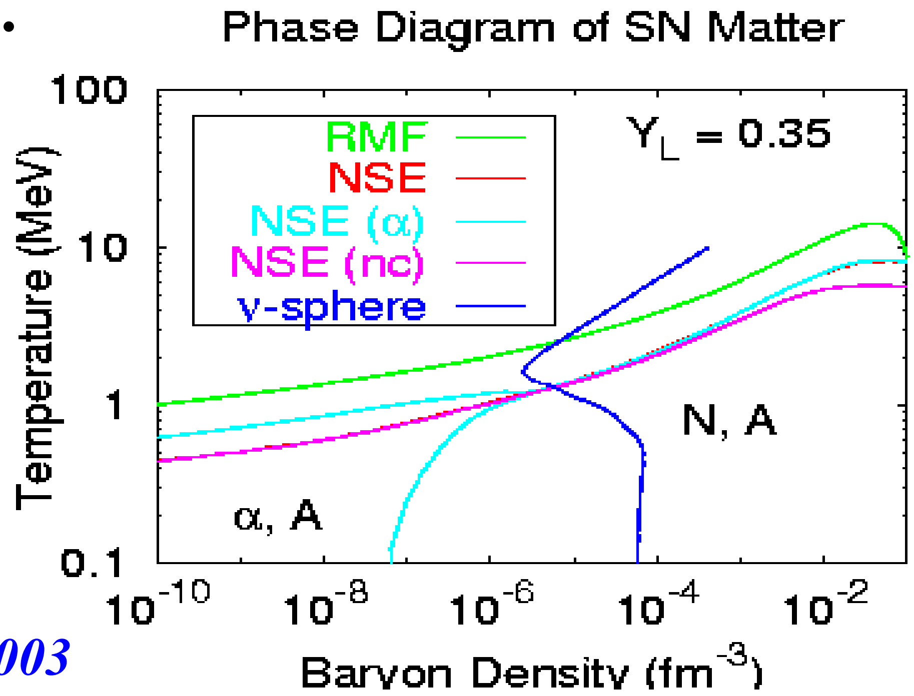
To do

- Relation to QCD
- Chiral Symmetry (important at high ρ)
- Atomic Shift of Exotic Atom (Σ^-, Ξ^-)

Tsubakihara's Talk

- Hyperon potentials at higher densities
- Kaon and pion potential in nuclear matter
- Mmax = 2.1 Msun ?
  → How to "Harden" EOS at high ρ.
- Distribution of nuclei at low ρ.
- Nuclear Pasta at low ρ.
- ....



Ishizuka,AO,Sumiyoshi, 2003

Announce

Thank you for your attention (as a speaker),
and coming to Sapporo (as one of the organizers) !