# *EOS of hyperonic matter for core collapse supernovae*

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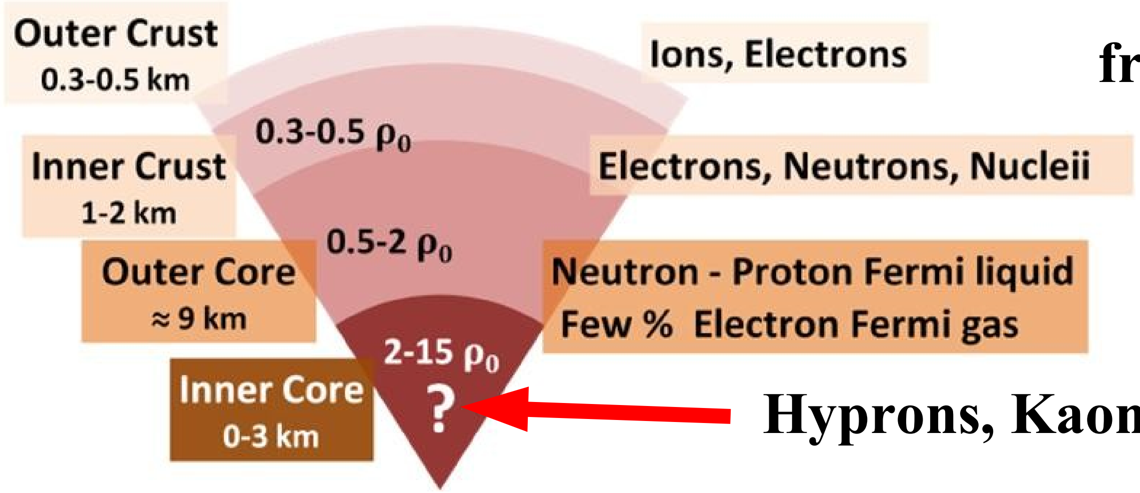
S. Yamada (Waseda U.)

- **Introduction**
- **EOS table of hyperonic matter**
  *C.Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada, JPG35(08)085201.*
- **Hyperons in Compact Stars**
  *K. Sumiyoshi, C. Ishizuka, AO, S. Yamada, H. Suzuki, ApJ690(09)L43.*
- **Summary**

# *Where do we find strangeness in the universe ?*

- **Hyperons appear in Neutron stars at $\rho_B > (2\text{-}3)\ \rho_0$ !**
  - **Cold, dense (~ 5 $\rho_0$), static, ν-less → Large $\mu_B$ and $\mu_e$**
    **(Senger, Schulze, Muto, Vidana, Hyun, Schaffner-Bielich, ....)**



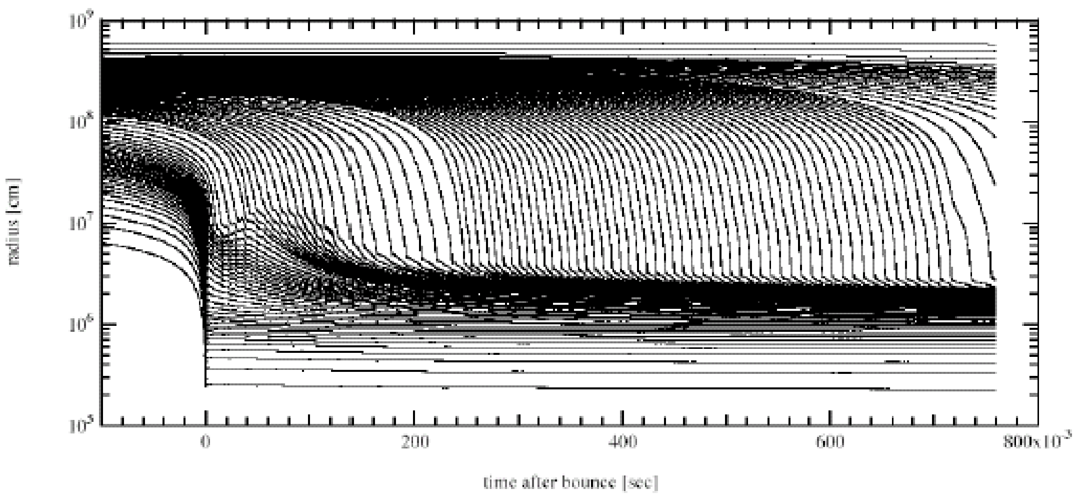

**from Wikipedia**

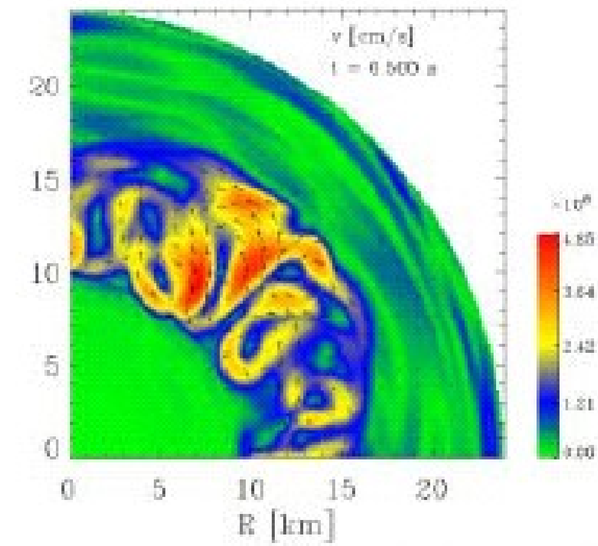
**Hyprons, Kaons, Quarks, CSC**

***How about dynamical processes ?***
- ***Supernovae: Warm (T~20 MeV) and Dense ( $\rho_B$~1.6 $\rho_0$ )***
- ***Black Hole Formation: Hot (T~70 MeV) and Dense ( $\rho_B$~4 $\rho_0$ )***
- ***NS-NS merger: Extremely Dense***

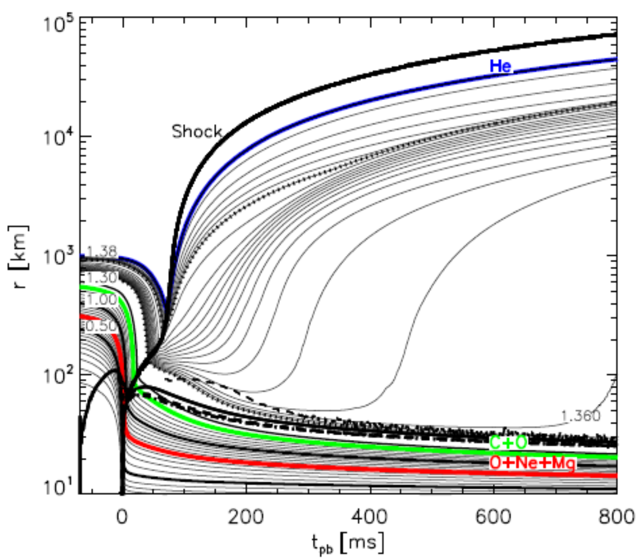
→ ***We study Hyperon Effects in "Hot Compact Star" processes***

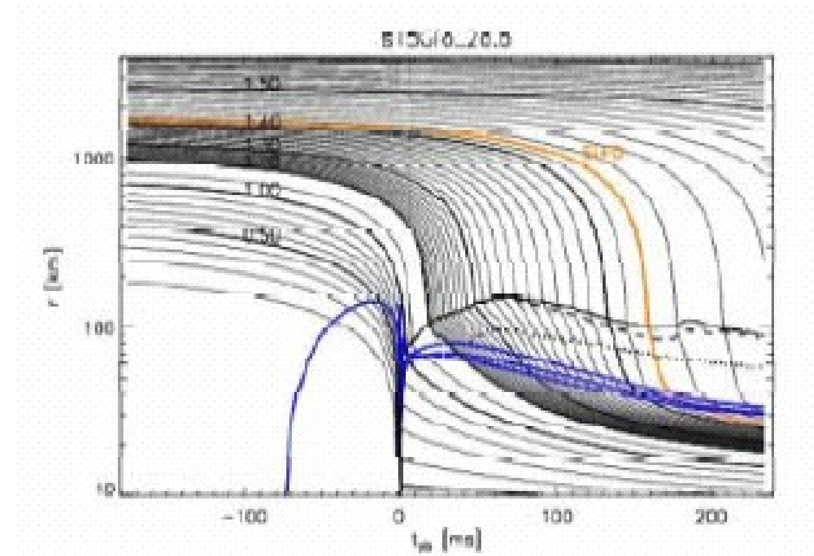
# *Numerical Simulation of Supernova Explosion*




**Sumiyoshi et al., 2005**




（**Janka et al., 2002)**

**Kitaura, Janka, Hillebrandt, 2006**

# *Nuclear EOS table for Core-Collapse Processes*

- **Numerical Simulation of Supernova Explosion**
  - **Time-scale ~ a few 100 msec → Equilibrium except for ν**
    **→Hydro (Nuclear EOS) + ν transpport.**
- **EOS for Core-Collapse Supernova**
  **→ Wide (T, $\rho_B$, $Y_e$) range must be covered.**

  **$\rho_B = (10^5 \text{ -- } 10^{15})$ g/cc ~ $(10^{-10} \text{ -- } 10)\ \rho_0$ ($\rho_0 \sim 2.5 \times 10^{14}$ g/cc)**

  **T = (0.1 -- 100) MeV, $Y_e = \rho_e / \rho_B = 0 – 0.6$**

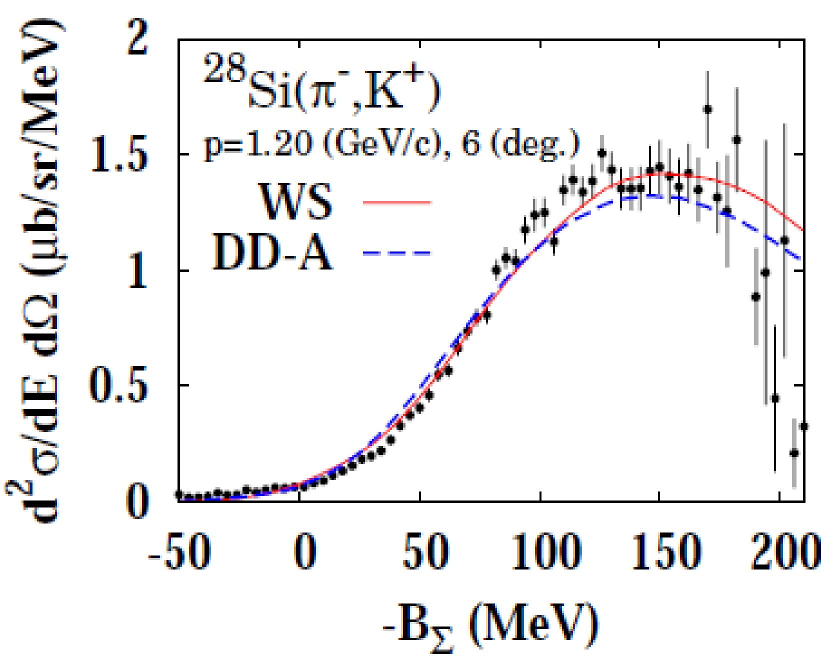
  - **Lattimer-Swesty (LS) EOS** *(J.M.Lattimer, F.D.Swesty, NPA535(91)331)*
    **Non-Rel. (Skyrme) + Liquid-Drop**
  - **Relativistic (Shen) EOS**
    *(H.Shen, H.Toki, K. Oyamatsu, K.Sumiyoshi, NPA637(98)435; PTP100(98)1013)*
    **RMF (TM1) +Thomas-Fermi Approx. +α**

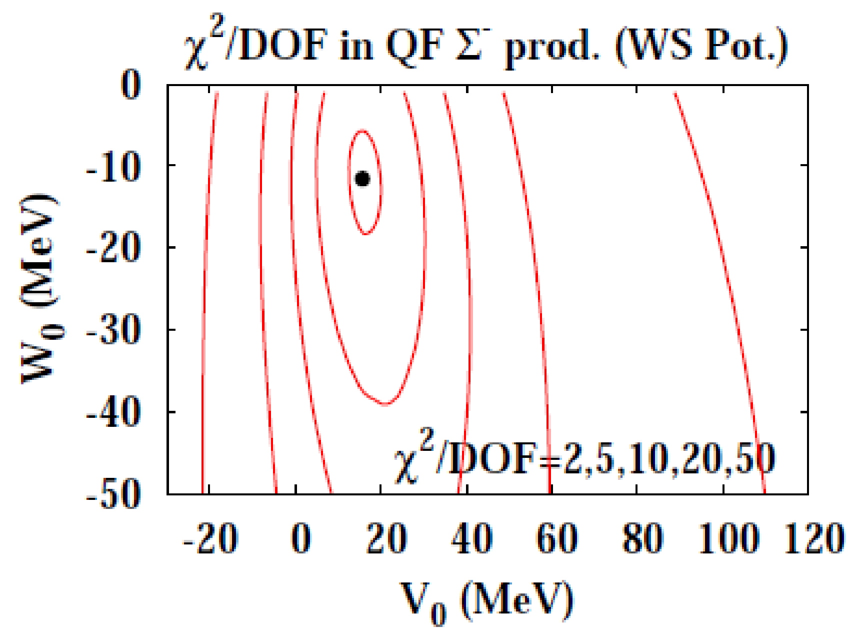
**→ Hyperons are not included in these EOS !**

***Hyperons should be included***
***in EOS for Core-Collapse Supernvae !***

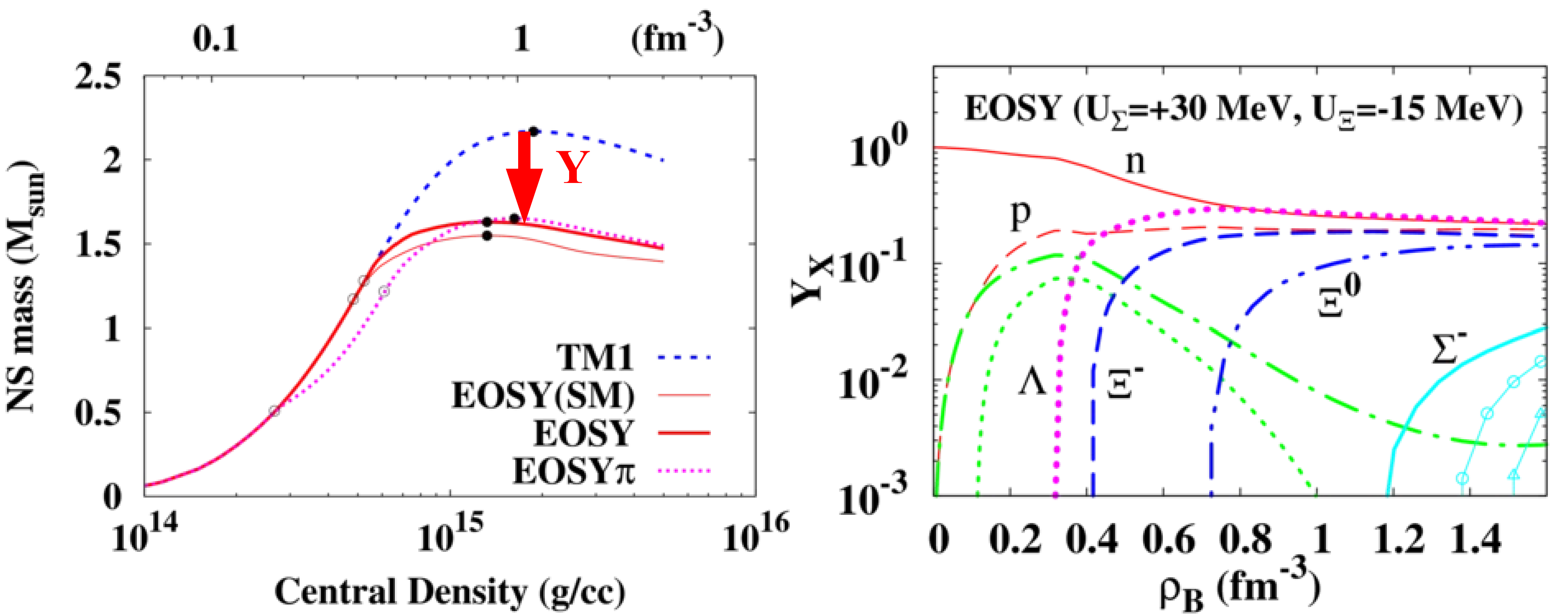
# *EOS table of Hyperonic Matter*

- **Relativistic EOS table with Hyperons for Core Collapse Supernovae**
  ***(C.Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada, JPG35(08)085201.)***
  **http://nucl.sci.hokudai.ac.jp/~chikako/EOS/index.html**
  - **Shen EOS + Hyperons**
  - **Hyperon Potential: $U_\Lambda$ = -30 MeV, $U_\Sigma$ = +30 MeV, $U_\Xi$ = -15 MeV**
    **$U_\Sigma$ = +30 MeV (Noumi et al.02, Friedmann et al. 84,Mares et al.95, Harada-Hirabayashi 06, Kohno et al. 06, Maekawa et al. 07)**
    **$U_\Xi$ ~ -15 MeV (Fukuda et al.98, Khaustov et al. 00, Maekawa et al. 07)**



- **Neutron Star: ( $\rho_B$,T,$Y_e$) ~ (5$\rho_0$, 0 MeV, 0.2) → Hyperon fraction ~ 50 %**
  - **Reduction of max. mass of NS**
  - **Repulsive Σ pot. → Ξ will be the next hyperon to Λ !**
    **(c.f. Talk by Schaffner-Bielich)**

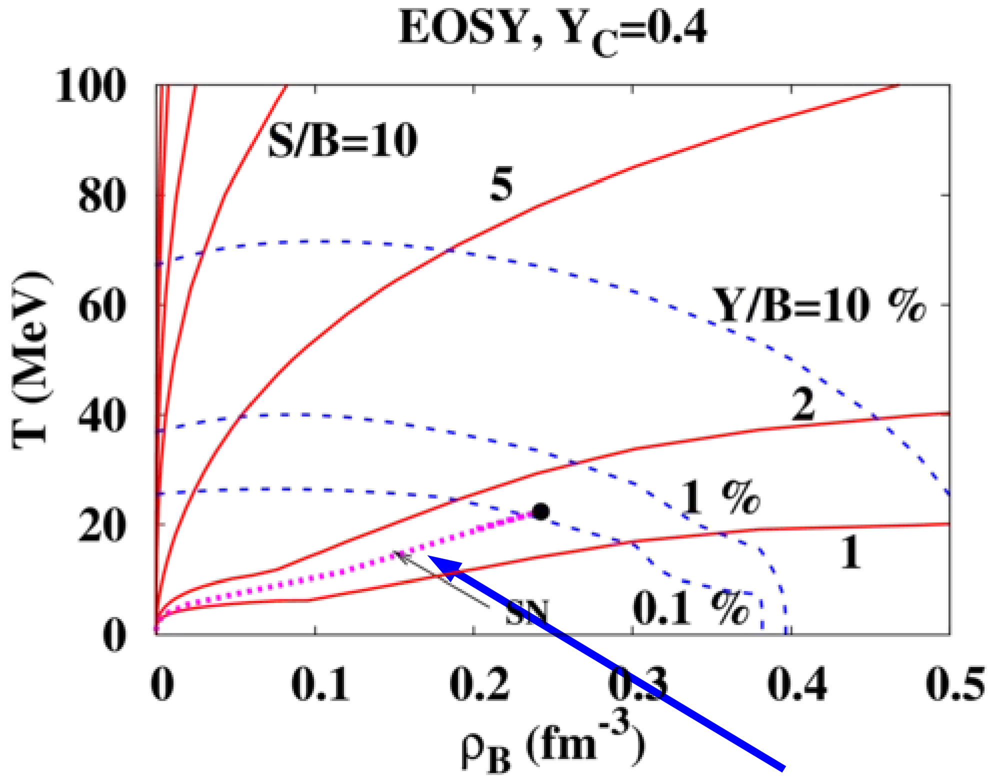



***Neutron Star can be understood as Hyperon Star !***

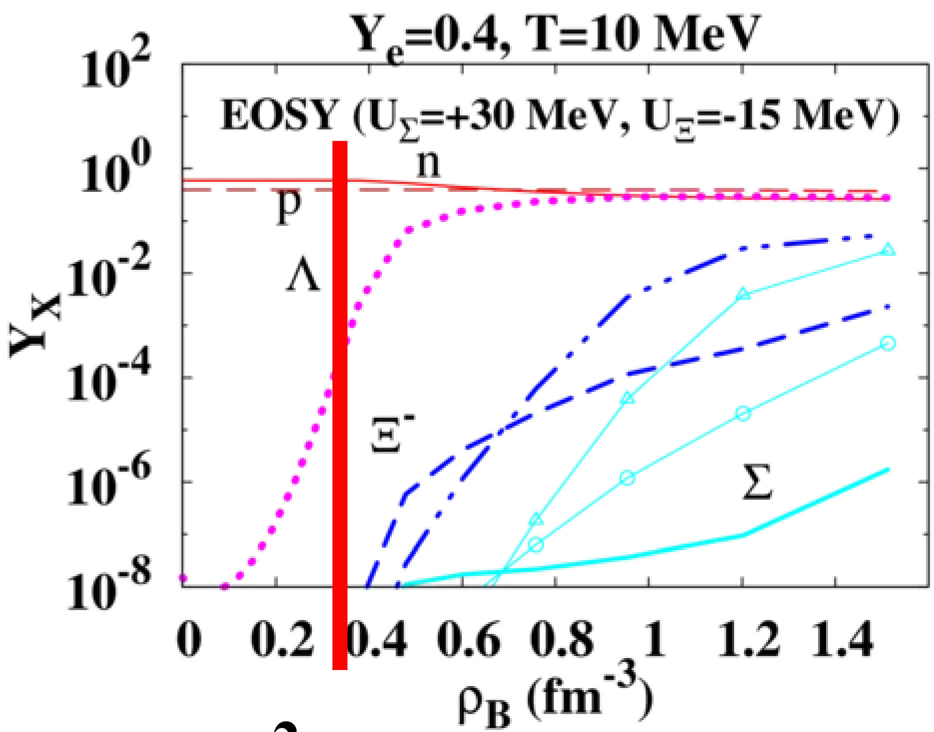
# *Supernovae*

*(C.Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada, JPG35(08)085201.)*

- **Supernova (Early stage): ( $\rho_B$, T, $Y_e$) ~ (1.6 $\rho_0$, 20 MeV, 0.4)**
  **→ Hyperon fraction ~ 0.1 %**
  **(Density and/or Temperature are not enough at $Y_e$ ~ 0.4)**




**Prompt Expl. (15 Msun)**

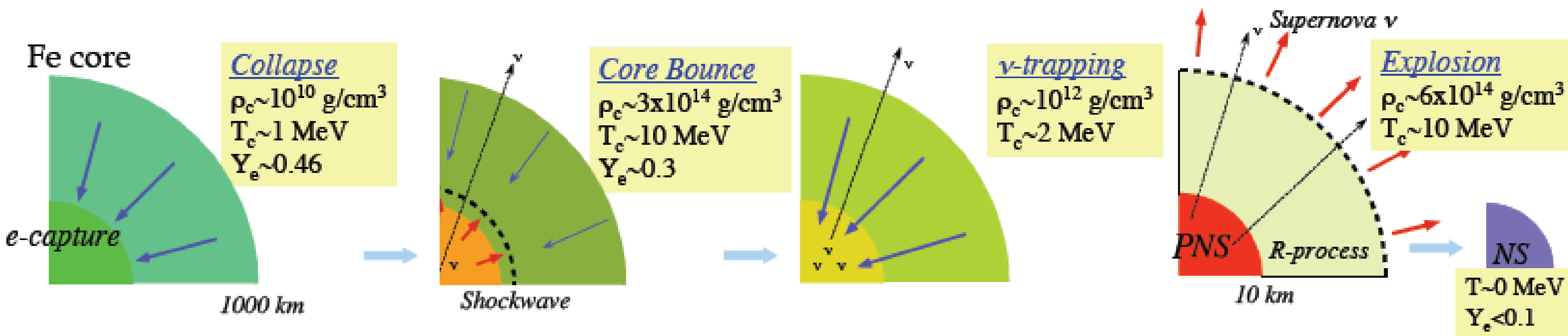



**2 $\rho_0$**

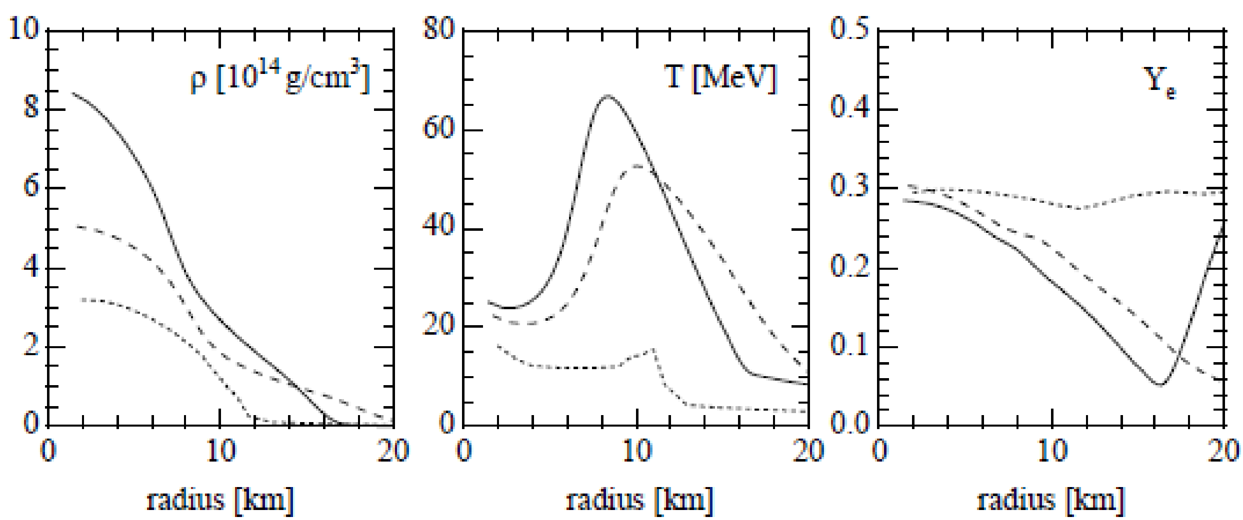
***Hyperon effects are small in supernovae in the early stage !***

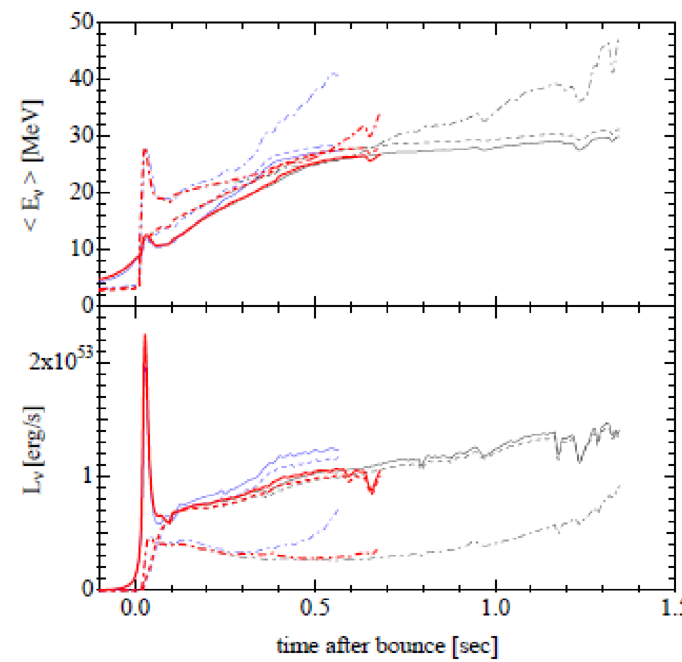
# Black Hole Formation (Failed Supernova)

## Details will be discussed in Sumiyoshi's talk on Friday.




**At bounce, 500 ms 680 ms (at BH formation)**

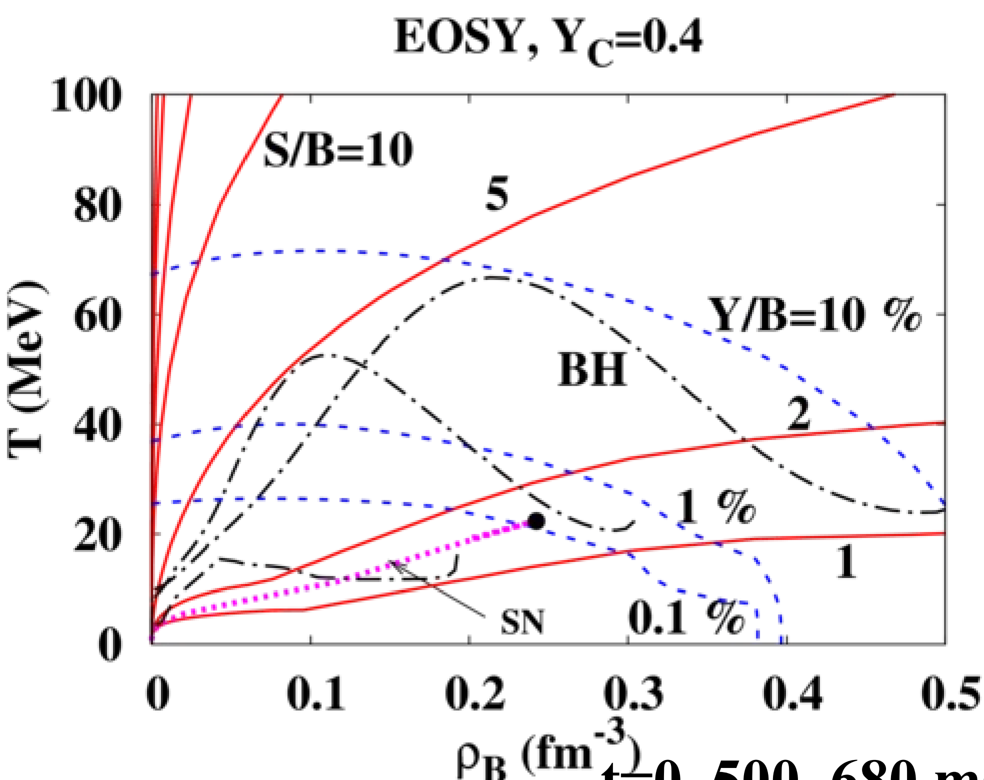


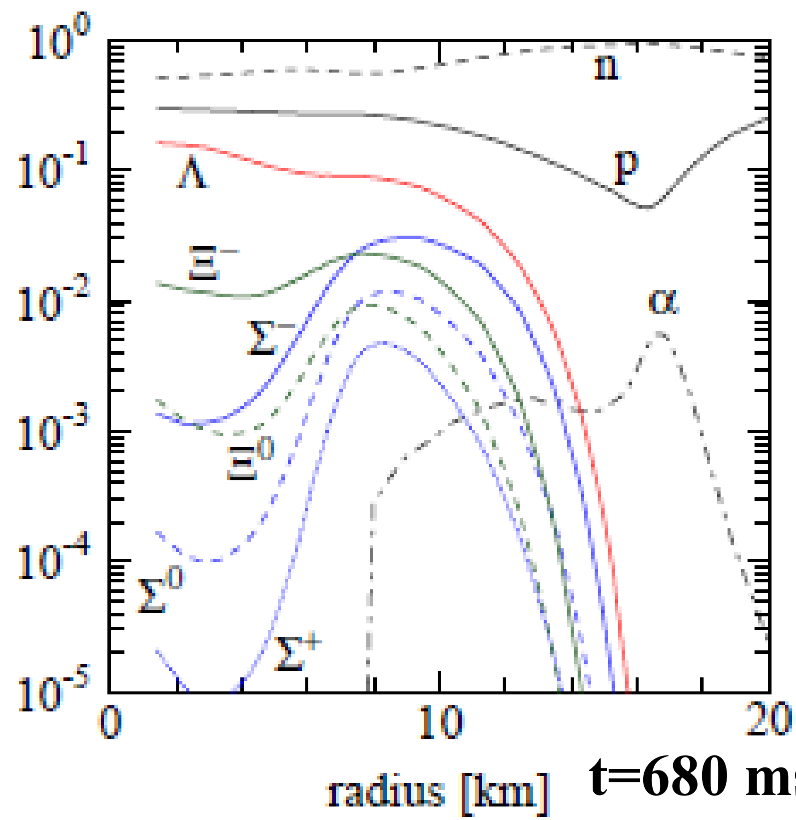

*Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009*

# *Black Hole Formation*

- **Black Hole Formation: ( $\rho_B$, T, $Y_e$) ~ (4 $\rho_0$, 70 MeV, 0.2)**
  **→ Hyperon fraction ~ 10 %**
  *(K. Sumiyoshi, C. Ishizuka, AO, S. Yamada, H. Suzuki, ApJ690(09)L43)*




**t=0, 500, 680 msec**

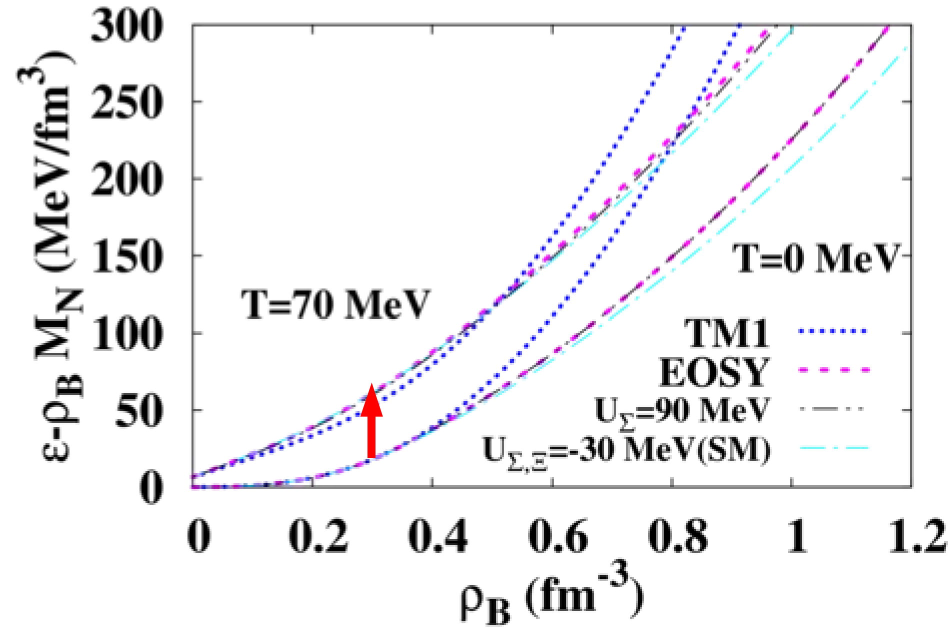


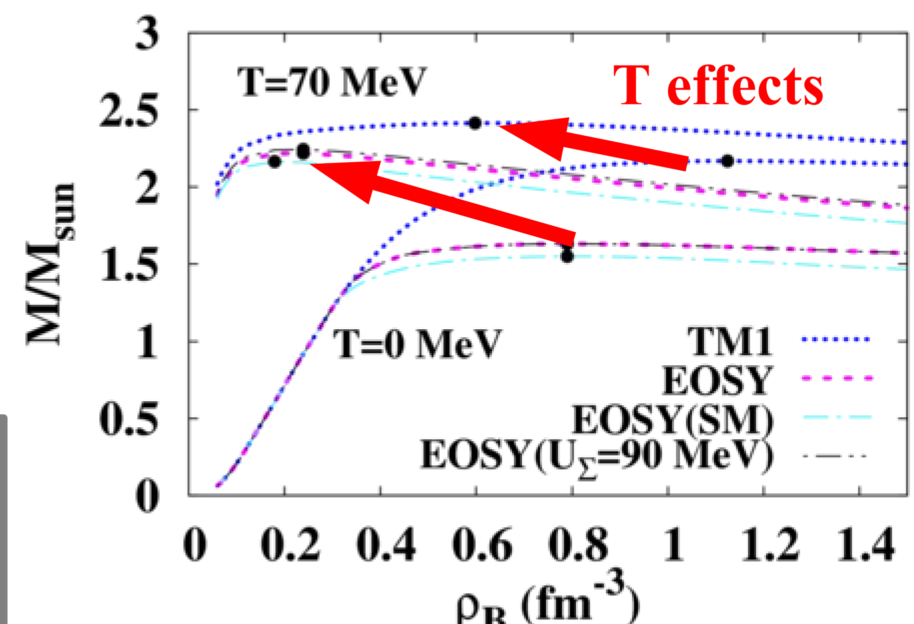

**t=680 msec**

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

# *EOS of Hot Hyperonic Matter*

- **Earlier BH formation with Y**
  **Shen: 2.4 Msun at t=1342 msec**
  **EOSY: 2.1 Msun at t=682 msec**
  **→ Larger than max. mass at T=0**
- **TOV equation at constant T**
  - **Larger pressure even at low $\rho_B$**
  - **Larger max. mass**
    **Shen: 2.17 Msun → 2.41 Msun**
    **EOSY: 1.63 Msun → 2.22 Msun**
  - **Max. mass is supported at SMALLER center density**
    **Shen: 1.12 fm$^{-3}$ → 0.60 fm$^{-3}$**
    **EOSY: 0.79 fm$^{-3}$ → 0.24 fm$^{-3}$**




***Smaller $\rho_B$ for max. mass with Y may be cause earlier formation of BH. (conjecture)***

# Summary

- EOS with hyperons for core collapse supernovae is tabulated and opened to public, as an extension of the relativistic EOS by Shen et al.
  http://nucl.sci.hokudai.ac.jp/~chikako/EOS/index.html
  Hyperon potentials are chosen to be
  $U_\Lambda$ = -30 MeV, $U_\Sigma$ = +30 MeV, $U_\Xi$ = -15 MeV
  according to recent hypernuclear physics implications.

- Hyperons are produced not only in neutron stars but also during black hole formation, where the temperature can be as high as T=70 MeV. With hyperons, BH is formed at an earlier time, which may be observable via short ν duration time in failed supernovae.
  By the temperature effects, Σ can be more abundant than Ξ.
  (c.f. Sumiyoshi's talk on Friday.)

- Earlier BH formation may be caused by the lower $\rho_B$ with hyperons, which support the max. mass of hot neutron star. Hyperon potential dependence would be smaller (a few % difference) in BH formation.

- EOS should be improved !
  Hyperon pot., Chiral Sym., Mesons, Quarks, ....

- **Collaborators**

**EOS and Astrophysical applications**

**C. Ishizuka, K. Tsubakihara (Poster on Tuesday),**
**K. Sumiyoshi (Talk on Friday), S. Yamada, H. Suzuki**

**Hypernuclear production and structure**
**H. Maekawa, H. Matsumiya (Poster on Tuesday), K. Tsubakihara,**
**M. Kimura (Talk on Tuesday), M. Isaka (Poster on Tuesday),**
**A. Dote**

**Mesons in Dense Matter**
**D. Jido (Talk on Monday), T. Sekihara (Talk on Thursday),**
**K. Tsubakihara**

***Thank You for Your Attention !***