Pion and Muon Effects on Supernova Explosion Energy

Chikako Ishizuka (Hokkaido Univ.)
Akira Ohnishi (Hokkaido Univ.)
Kousuke Sumiyoshi (Numazu C.T.)
Shoichi Yamada (Waseda Univ.)

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How do supernovae explode ?

- Successful explosion: Long standing problem
  - Pure Hydrodynamics can lead successful explosion
  - With dynamical neutrino transport is taken into acco unt, explosion fails in 1-dim.
- What is the KEY ?
  - Equation of State:
    - ➔ Soft EOS is believed to give larger Expl. E
  - Neutrino-Nucleus interaction
    - ➔ Larger Neutrino-Nucleus Int. transfers energy mo re effectively.
  - Non-Spherical Effect
    - ➔ Concentration of energy to a certain direction ma y make Explosion easier (2-dim. Hydrodynamics)

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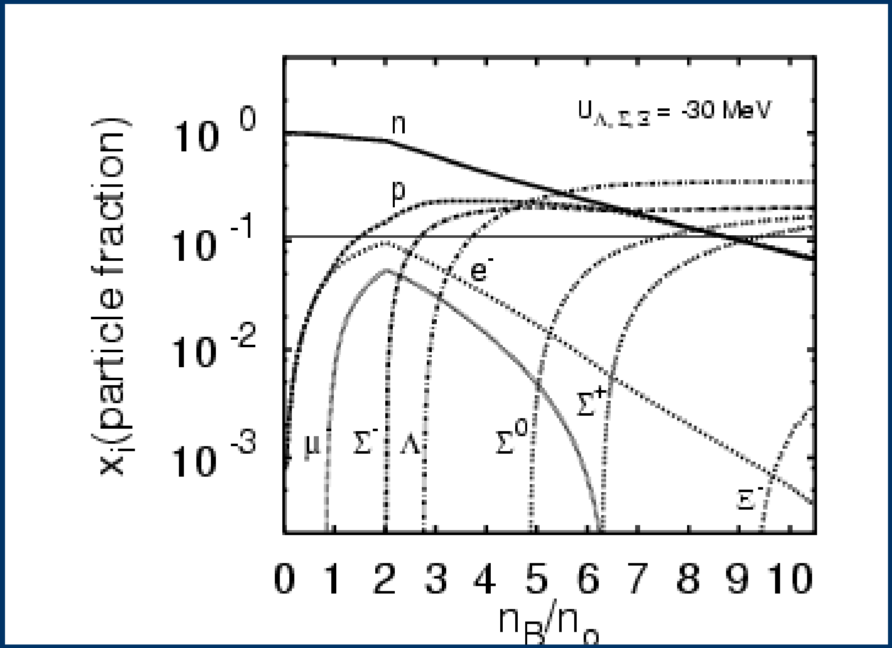
How can we make EOS softer ?

- Base Model: RMF-TF model by Shen et al.
  - Shen, Oyamatsu, Sumiyoshi, Toki, NPA
  - Mean Field: RMF-TM1 + Thomas-Fermi Appr.
  - Covers wide range:
    - ➔ $\rho=10^{5.1}$ g/cc-$10^{15.4}$ g/cc, T=0-100 MeV
  - Constituents: n, p, e, alpha, heavy-nuclei
  - Successful Hydrodynamical Explosion (Sumiyoshi et al., NPA2004)
- Problems
  - No Heavy Fermions
    - ➔ Hyperons and Muons are important in N. S.
  - No Pions
    - ➔ Pions will dominate at High T and Small ρ_B
  - No Neutrinos
    - ➔ Neutrinos should be dynamically included
  - Thomas-Fermi Approx.:
    - ➔ No Distribution of Nuclei

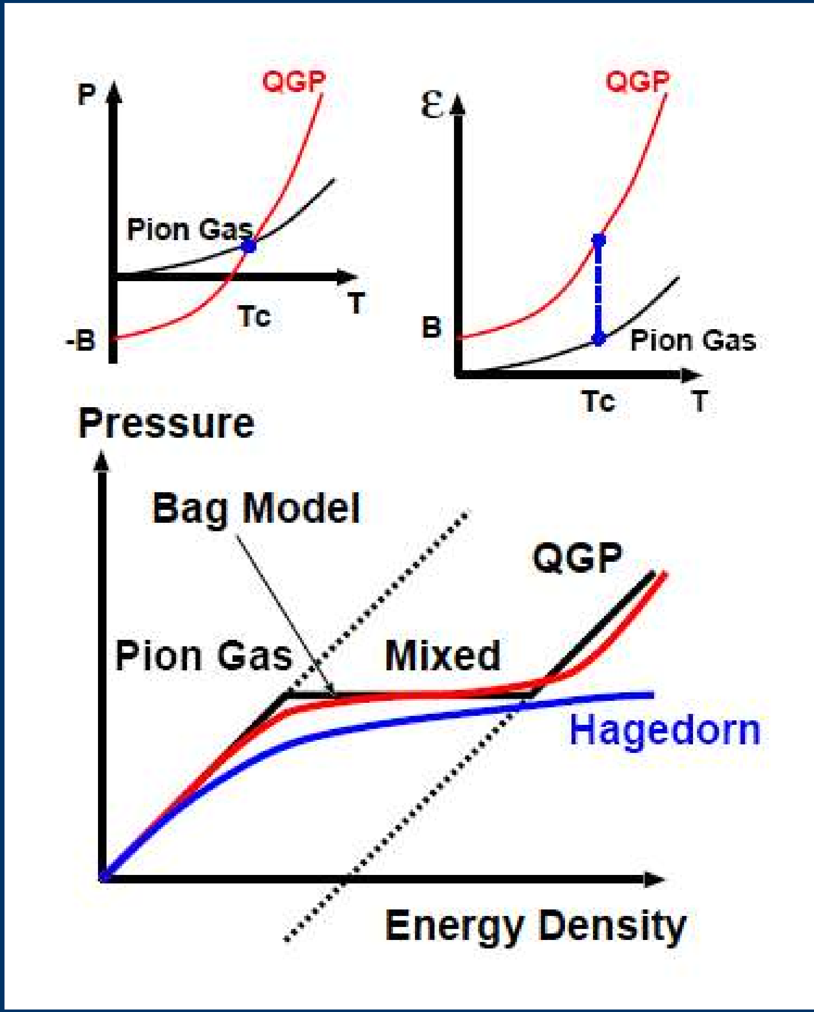
Hyperon, Muon and Pion Effects

- Hyperons and Muons



(RMF: Sahu, Ohnishi,
Nucl. Phys. A691 (2001), 439.)

- Pion Role at High T

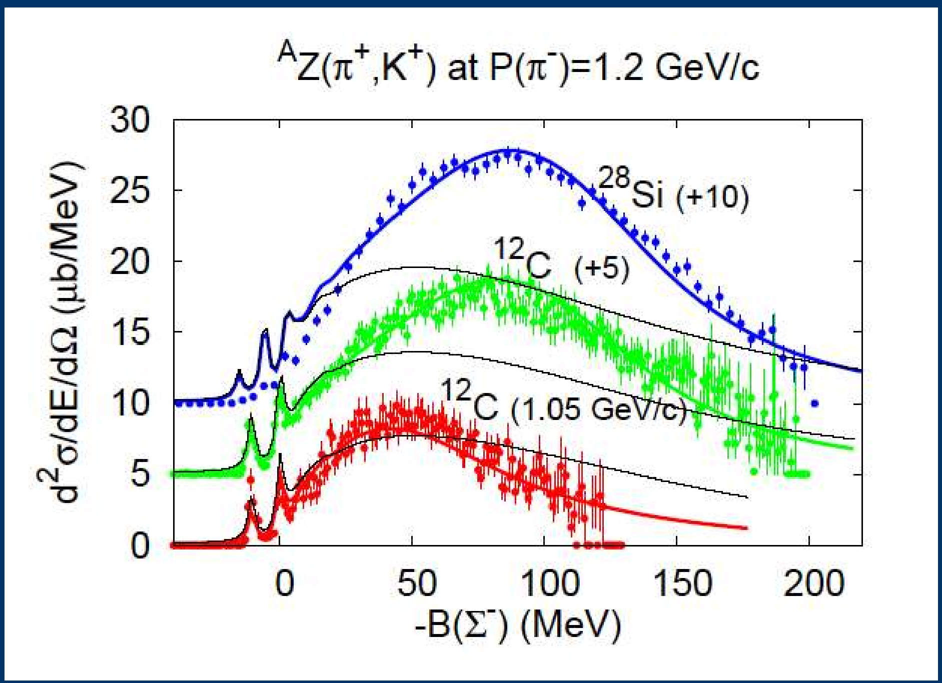


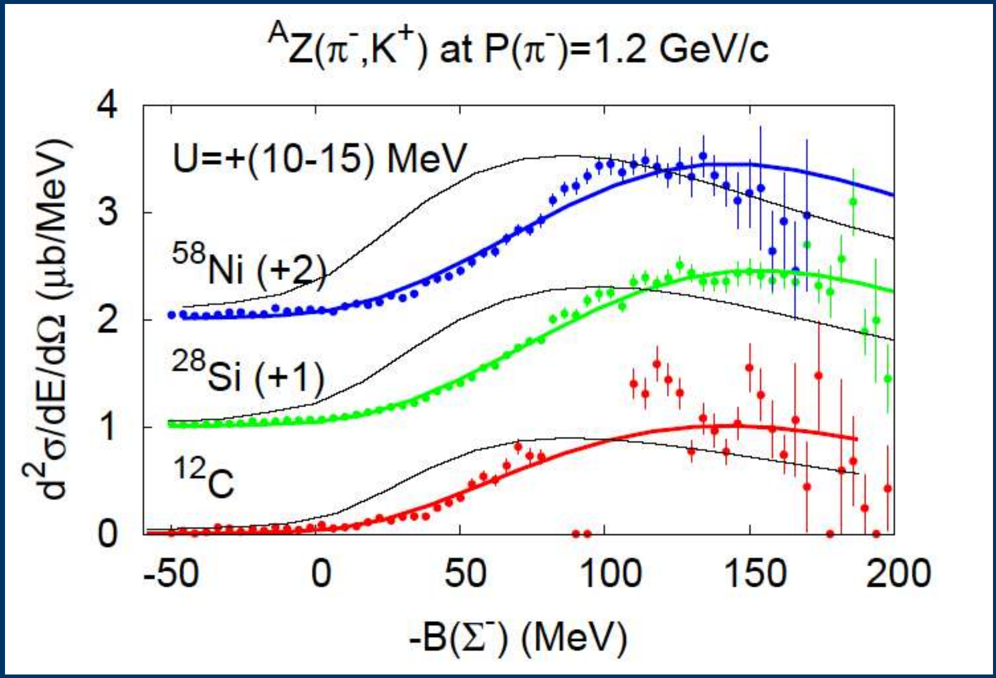
Hyperon Potentials (I)

- **SU(3) Extention of RMF-TM1**
  - Schaffner-Mishustin,
  - Based on Old Conjectures
    - → U(Λ)≈ U(Σ)≈-30 MeV, U(Ξ)≈-24 MeV
    - → Strong Λ-Λ attraction, $B_{\Lambda\Lambda} \approx 5$ MeV
- **Recent Experimental Suggestions**
  - Λ potential at around $\rho_0 \approx -30$ MeV
    - → Bound state and Continuum (QF) spectroscopy
  - Ξ potential at around $\rho_0 \approx -(12\text{-}16)$ MeV
    - → Yield of Cross Sections in Bound State region
  - Σ-Nucleus potential ; Unknown Yet
    - → Only One bound state is found ($^4_\Sigma$He)
    - → Continuum Spectroscopy → U(Σ)≈+(10-150) MeV
  - Λ-Λ Potential; Weakly Attractive
    - → Nagara Event, $B_{\Lambda\Lambda} \approx 1$ MeV

Hyperon Potentials (II)

- **Recent (π, K+) and (K-,K+) Experiments**





cf. Harada/ Maekawa and Ohnishi / Kohno et al.

Hyperons, Pions and Muons in this work

- Purpose: To Investigate the role of New Constituents (Hyperons, Pions, Muons) in Supernova Explosion
- Based on the Relativistic Mean Field (RMF) treatment with Thomas-Fermi Approx. for Heavy Nuclei.
  - $EOS(new)=EOS(Shen)+EOS_{RMF}(npY\pi\mu)-EOS_{RMF}(np)$
- Treatment of New Constituents
  - Hyperons: $U(\Xi)$ = -15 MeV, $U(\Sigma)$=+30 MeV at $\rho=\rho_0$
    - ➔ Rather than Vector, Scalar Meson Coupling is adj usted
  - Pions: Included WITHOUT interaction
  - Muons: Weak Equilibrium or Net Free

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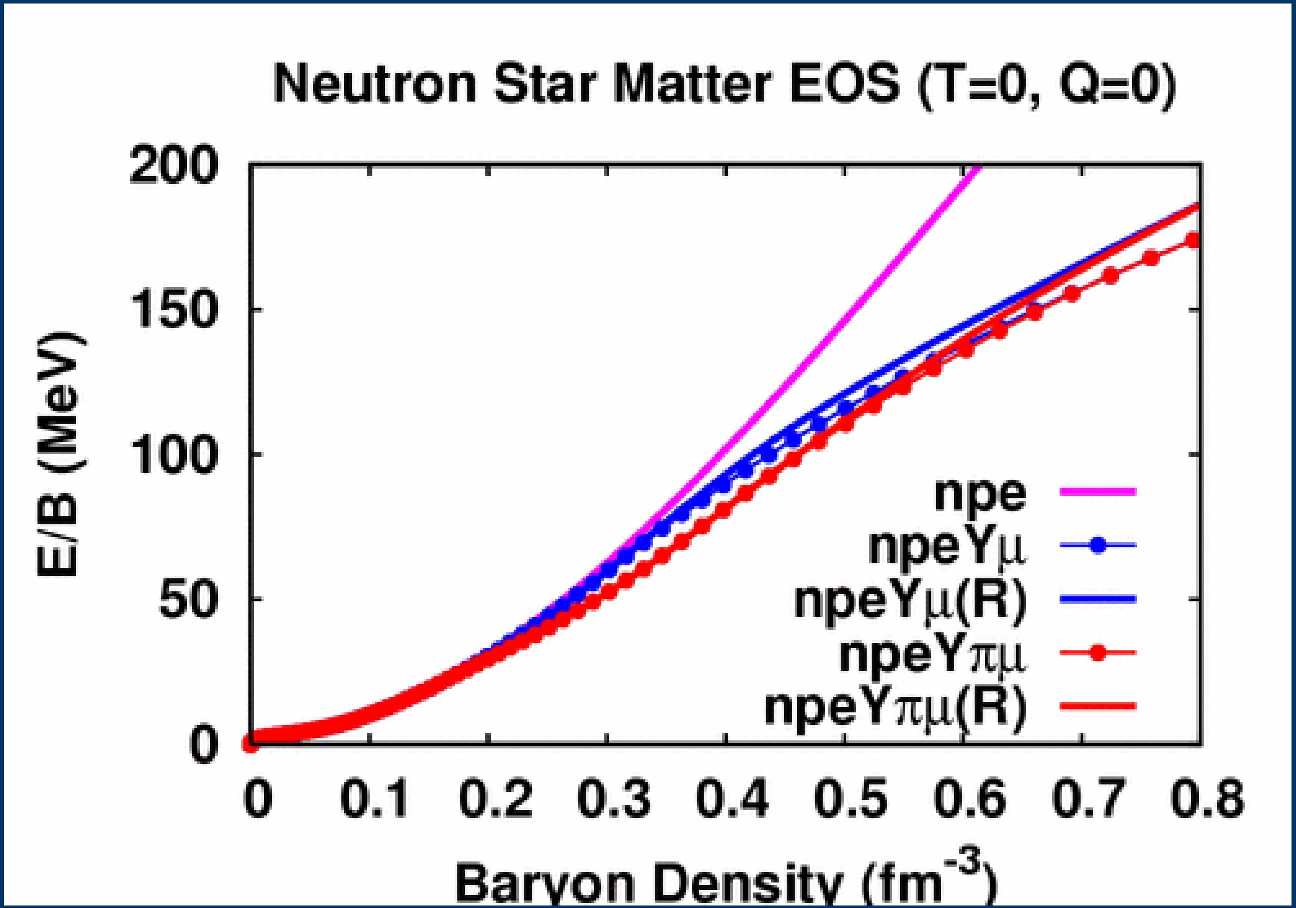
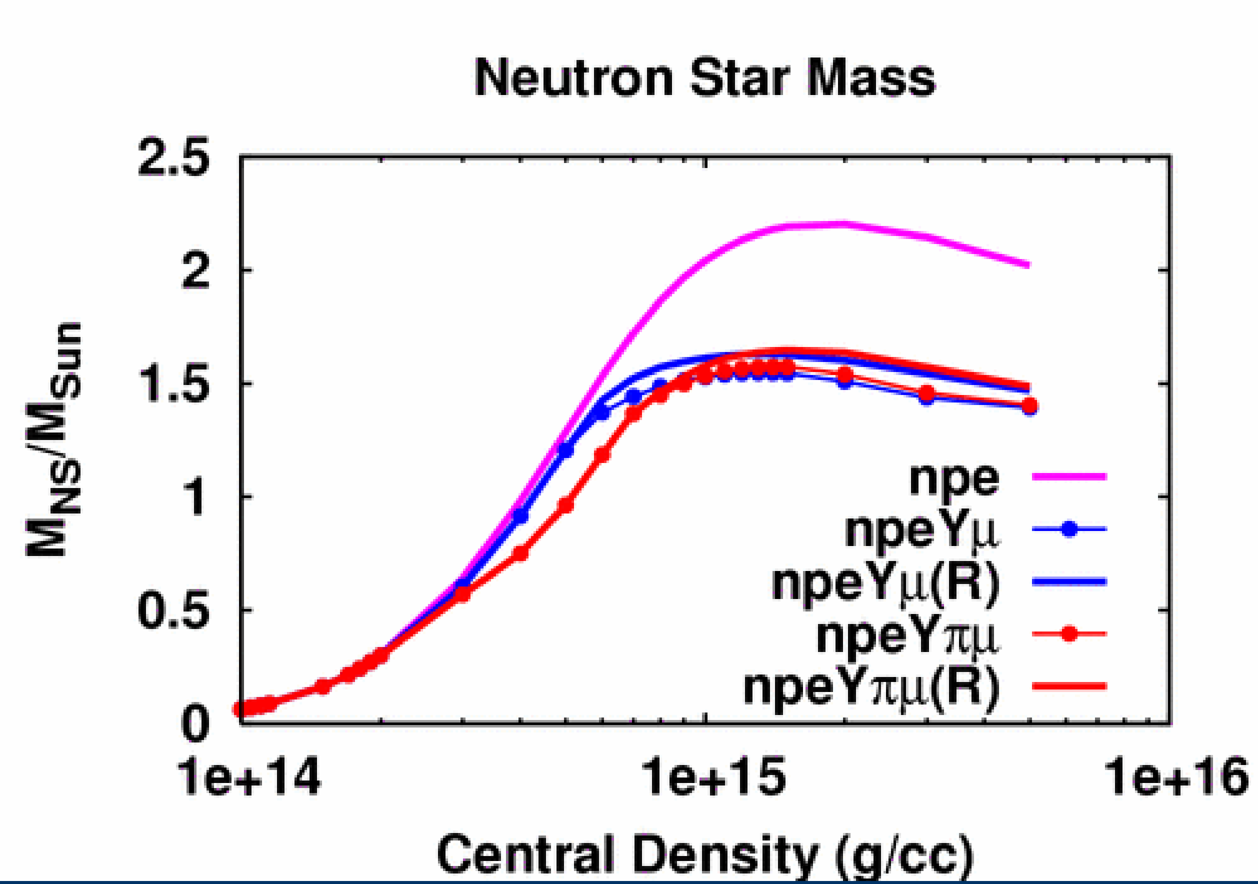
Application to Neutron Star (I)

- **Effects on Equation of States**
  - **Hyperons and Pions soften EOS at ρ ≥ 0.2fm^{-3}.**
  - **Repul. U(Σ) and Less Attr. U(Ξ) harden EOS at ρ ≥ 0.35 (0.5) fm^{-3} without (with) pions.**



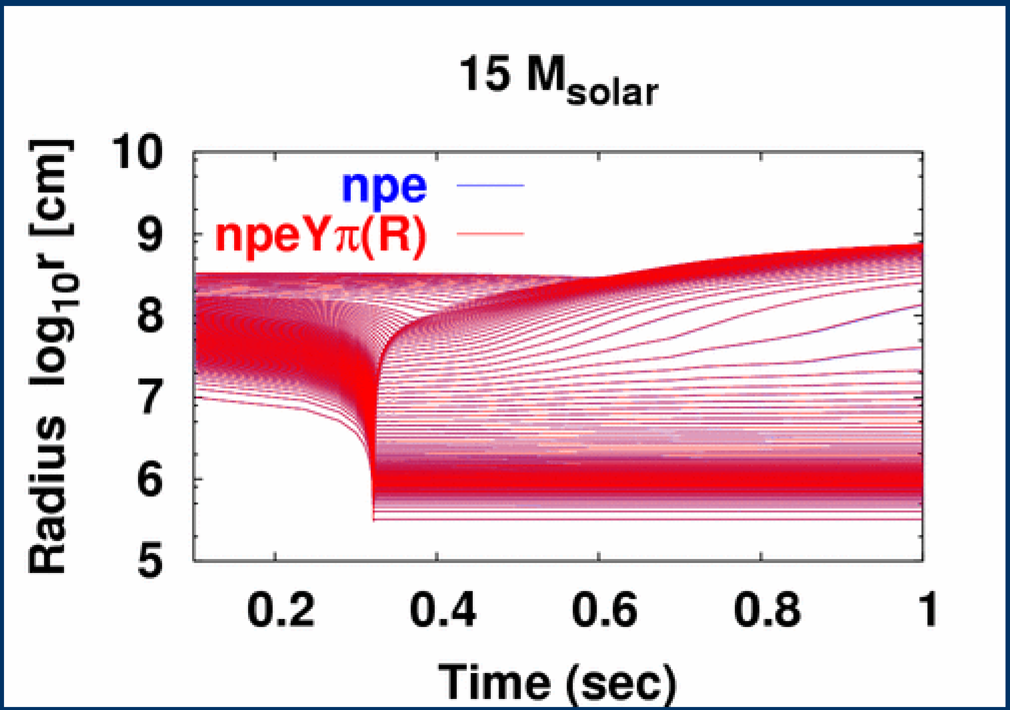
Application to Neutron Star (II)

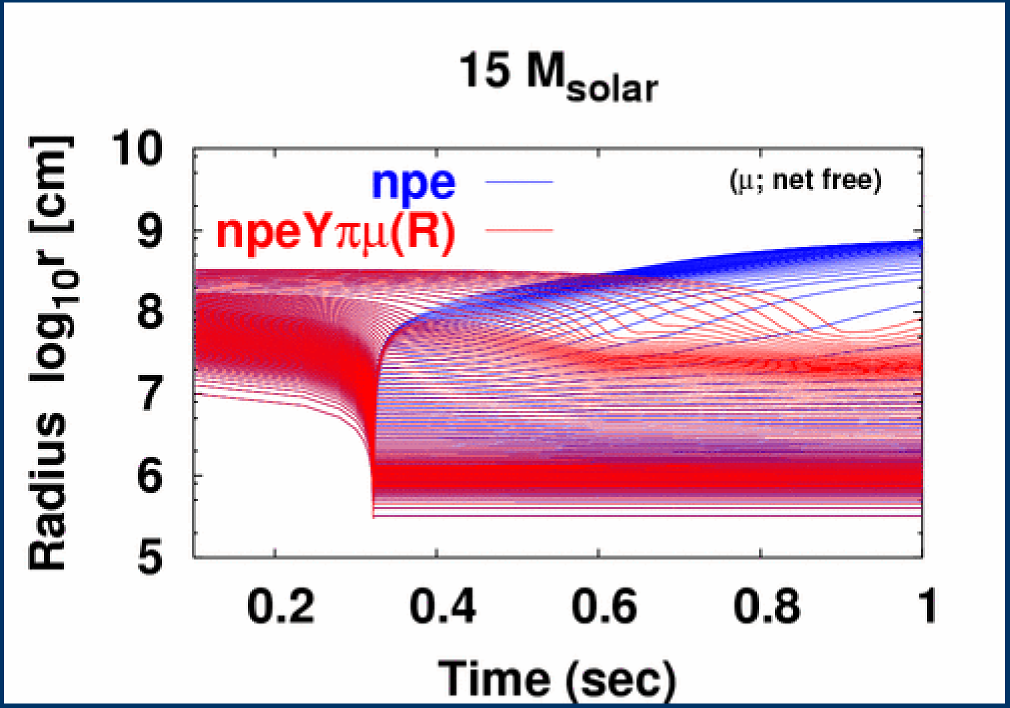
- **Maximum Mass of Neutron Star**
  - Must be larger than 1.44 M_{sun}.
  - Hyperons: Reduce Max. Mass of N.S. by 0.5-1.0 M_{sun}
  - Free Pions: Shift the Highest Density by 20-30 %



Application to Supernova

- **Hydrodynamical Explosion Model**
  - Sumiyoshi et al., 2004
  - EOS by Shen et al.
- **Effects of New Constituents**
  - Hyperons and Pions: No Qualitative Effects
  - Muons: Suppresses Explosion





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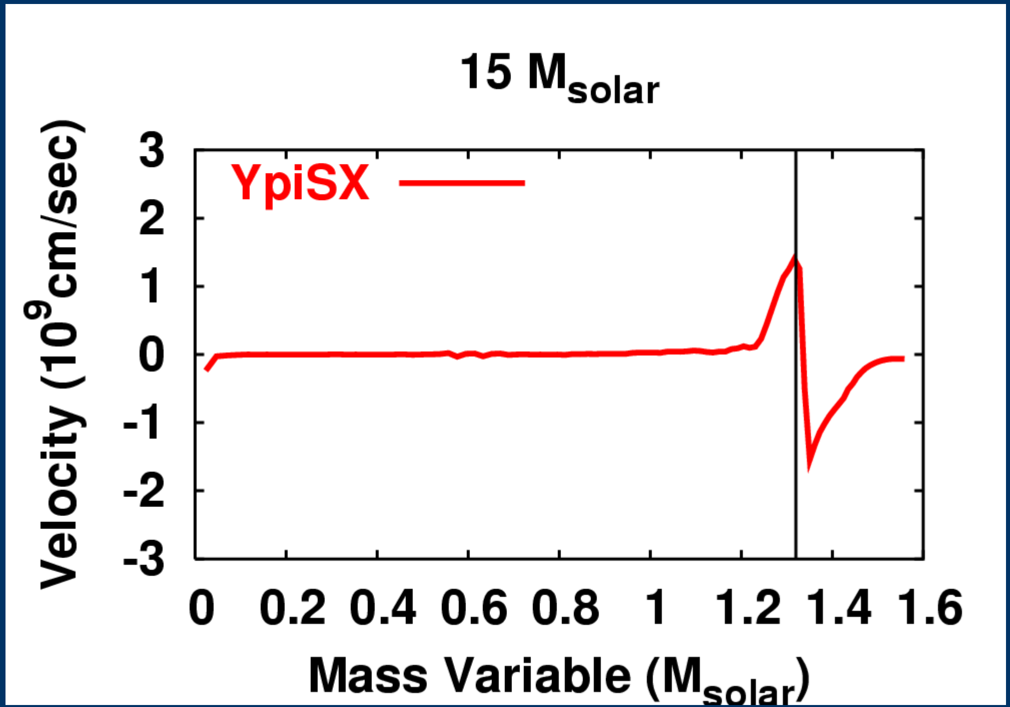
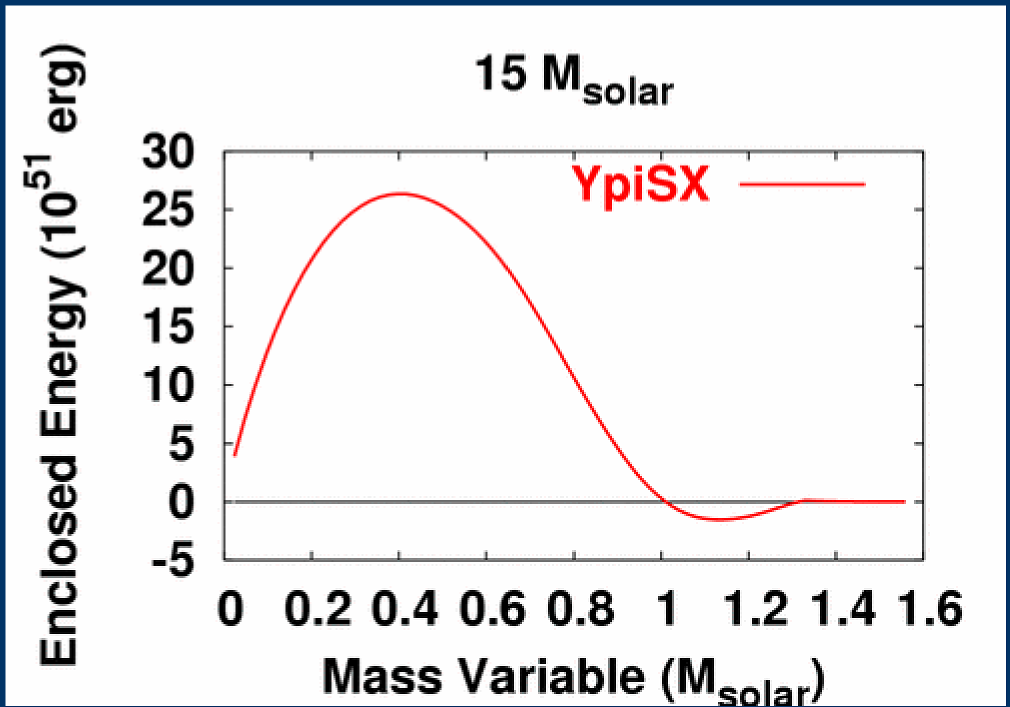
Explosion Energy (I)

- Definition of E_{expl}:
  - Ref: Sumiyoshi et al. 2004
  - Enclosed Energy: $E_{encl} = M_{Baryon} - M_{grav}$
  - t_{expl} = time when the shock pass iron core surface
  - E_{expl} = Max. of E_{encl} ($t = t_{expl}$)





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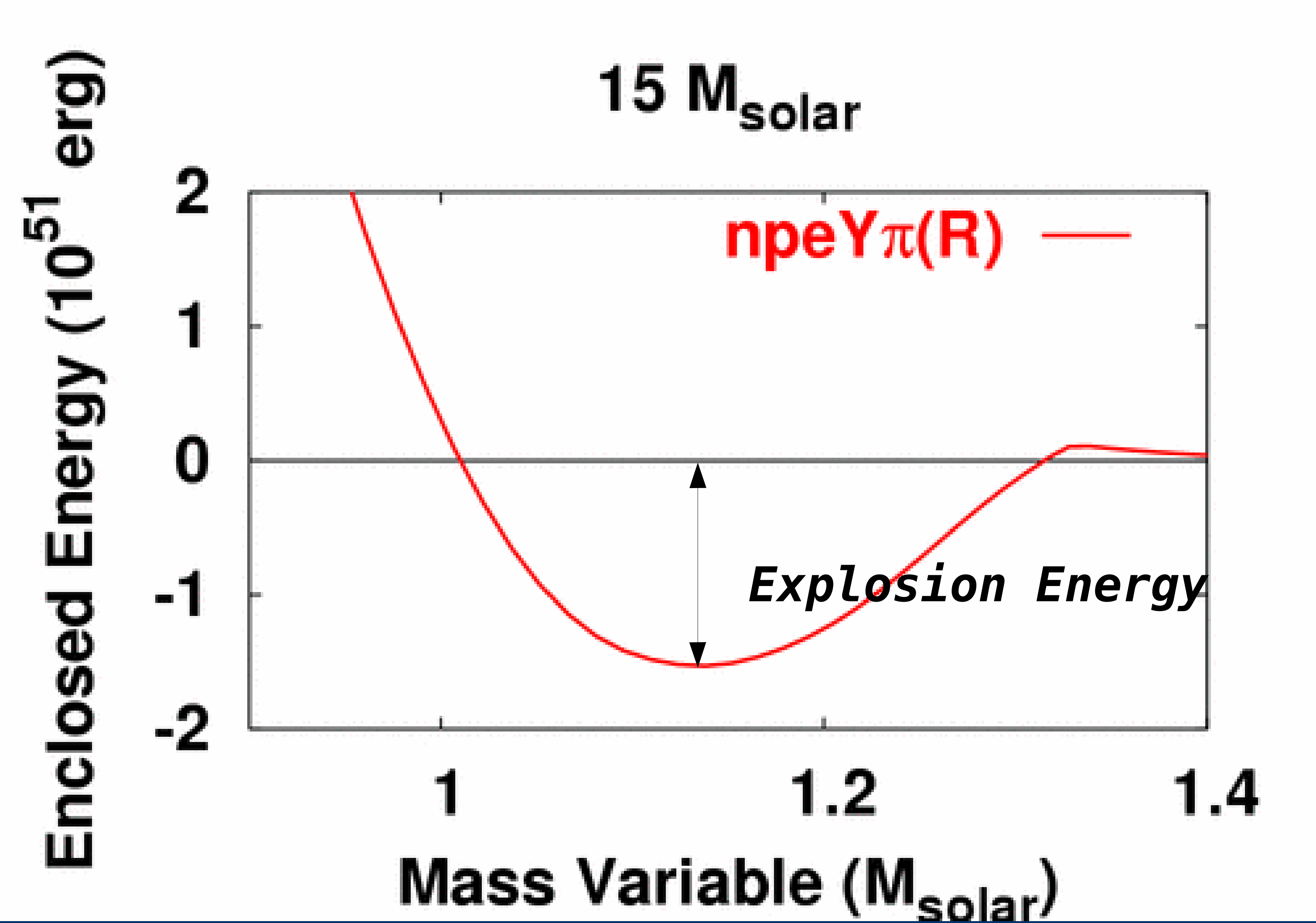
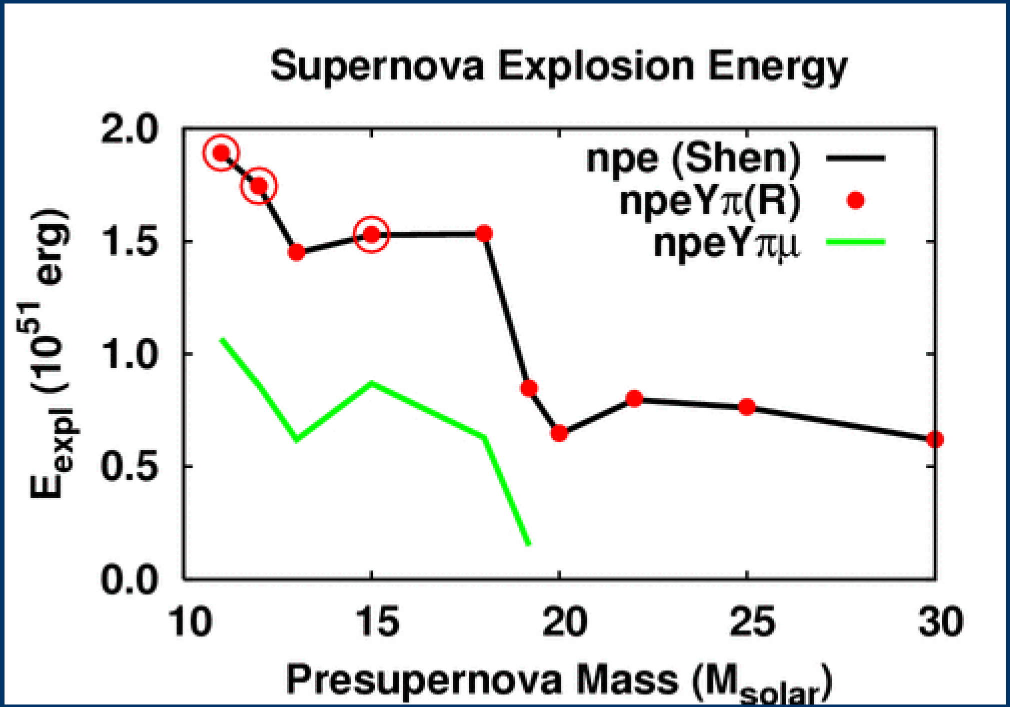
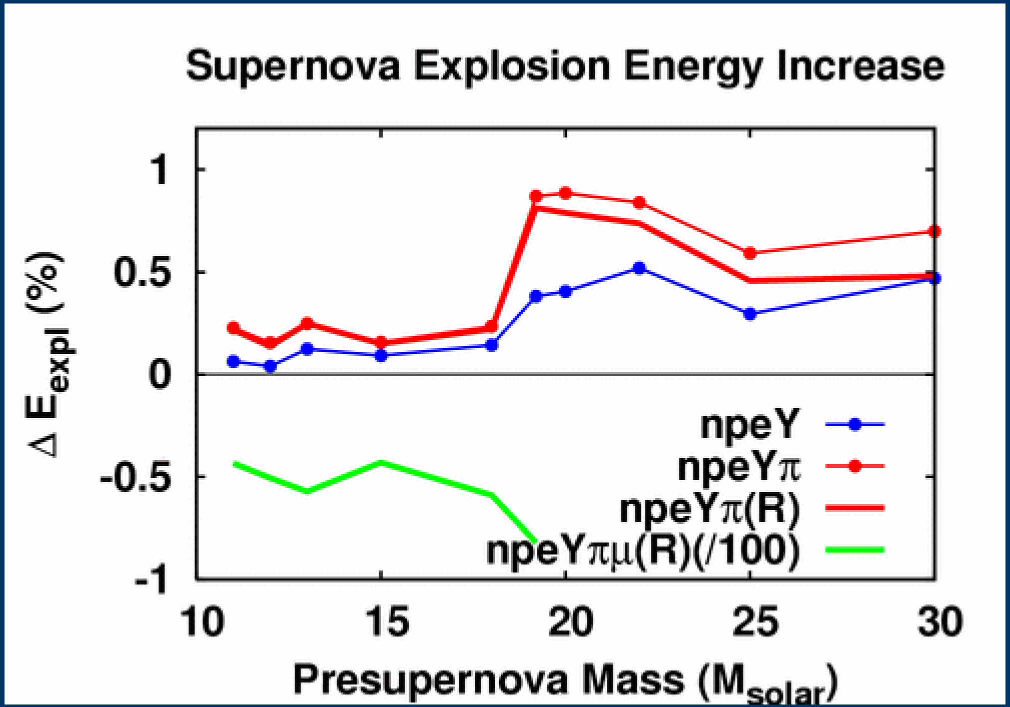

15 M_{solar}
Enclosed Energy (10^{51} erg)
2
1
0
-1
-2
npeYπ(R)
Explosion Energy
1
1.2
1.4
Mass Variable (M_{solar})

Explosion Energy (II): EOS Deps.

- No Large Effects of “New” Hadrons
  - Hyperons increase Eexpl by (0.1-0.5) %
  - Pions increase Eexpl by (0.1-0.5) %





Summary

- We have extended the Relativistic EOS table by Shen et al. by introducing new constituent s of Hyperons, Pions, and Muons.
  - Hyperons and Pions: Soften the EOS at High Densiti es
  - Pions would dominate at High T and Low ρ_B.
- EOS deps. of Neutron Star Mass
  - Hyperons reduce the Max. Mass of N.S. by (0.5-1) S olar Mass. When we use repulsive Σ and Ξ potential s, Max. mass is not very different.
  - Pions reduce the N.S. mass for a given ρcent, but th e Max. mass is kept.
- EOS deps. of Supernova Explosion Energy
  - Hyperons and Pions increase the explosion energy by (0.1-0.5) %, respectively.
  - Muons suppresses explosion.

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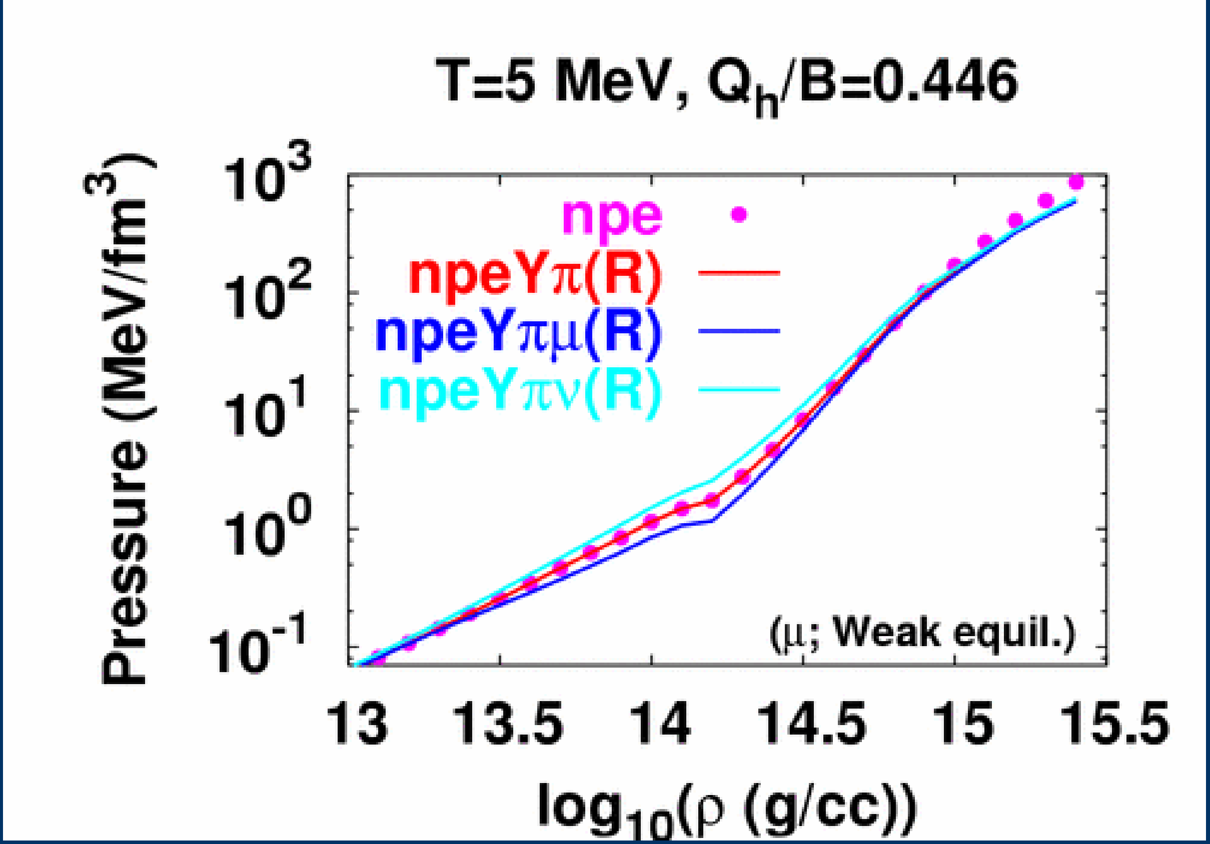
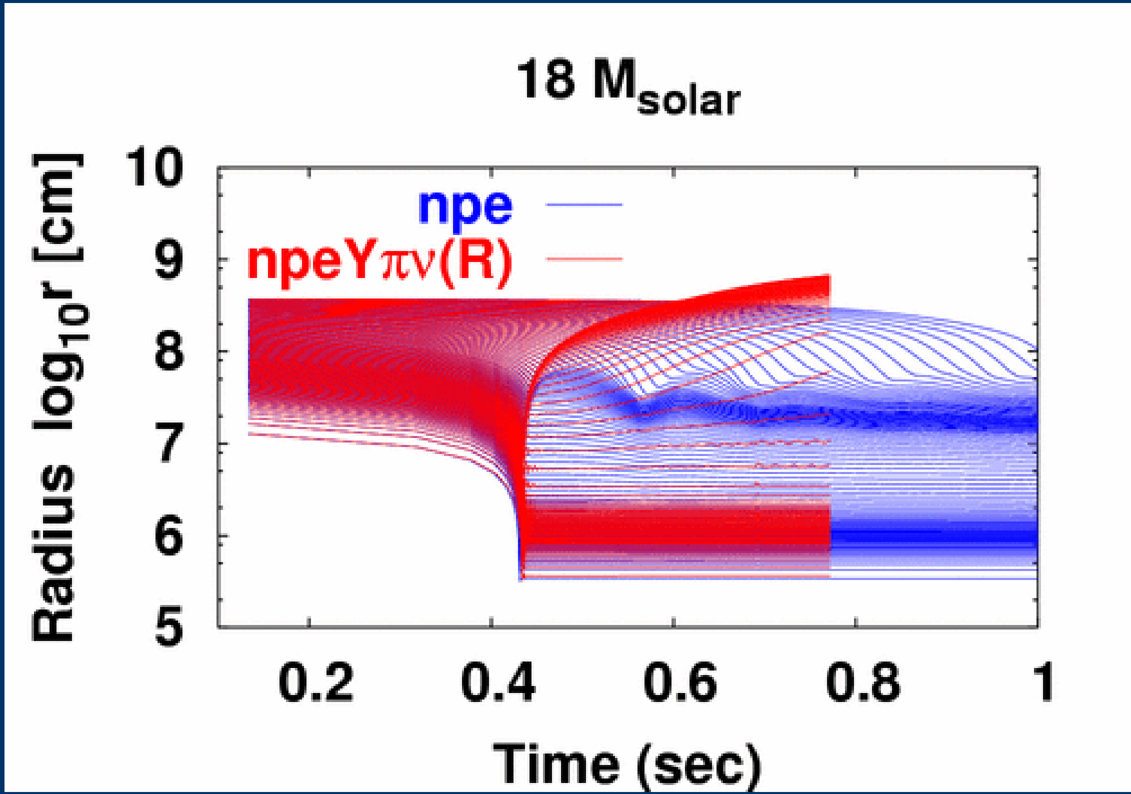
Discussion (I)

- Softer EOS at Higher Density ($\rho_B > \rho_0$) does no t necessarily lead to successful explosion.
  - ρ and T are not high enough for Y and π
- We have pressure valley at around $\rho_B = 0.7\ \rho_0$ in Shen EOS, and μ further reduces pressure th ere.



Discussion (II)

- Neutrino Effects ?
  - Filling pressure valley at around ρ_B = 0.7 ρ_0 make explosion stronger. (Inconsistent Calculation)
- Neutrino ? Fragment ? Symmetry Energy ?
  - → to be discussed further



$$P_\nu = P_\nu^{(0)} / (1 + \exp(\log \rho_B - \log \rho_c)/\Delta) \quad \rho_c = 10^{14} g/cc, \ \Delta = 0.5$$