Stellar Core Collapse and Exotic Matter

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Outline

1. Introduction

   Equation of state（EOS）of hot and dense matter and stellar core collapse

2. Hyperon appearance

   Ishizuka+ 2008, Nakazato+ 2012

3. QCD transition

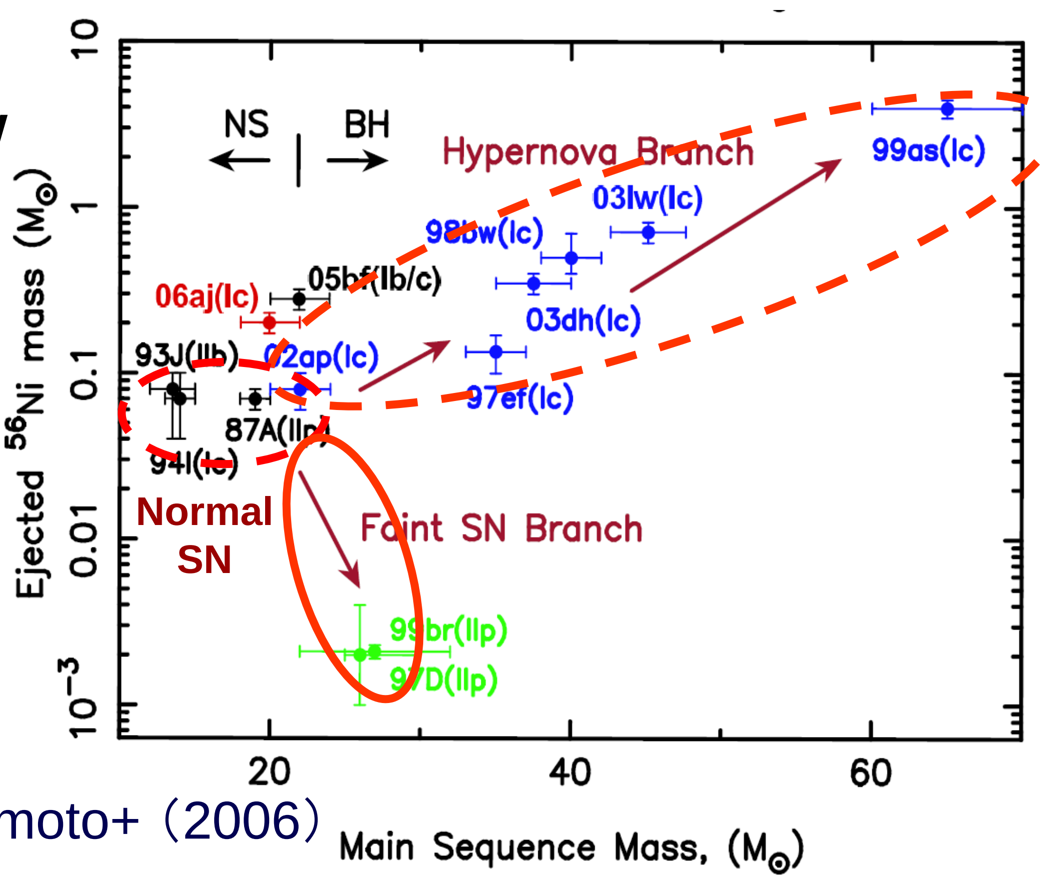
   Nakazato+ 2008, 2010, in prep.

4. Conclusion

1. Introduction

Fates of massive stars

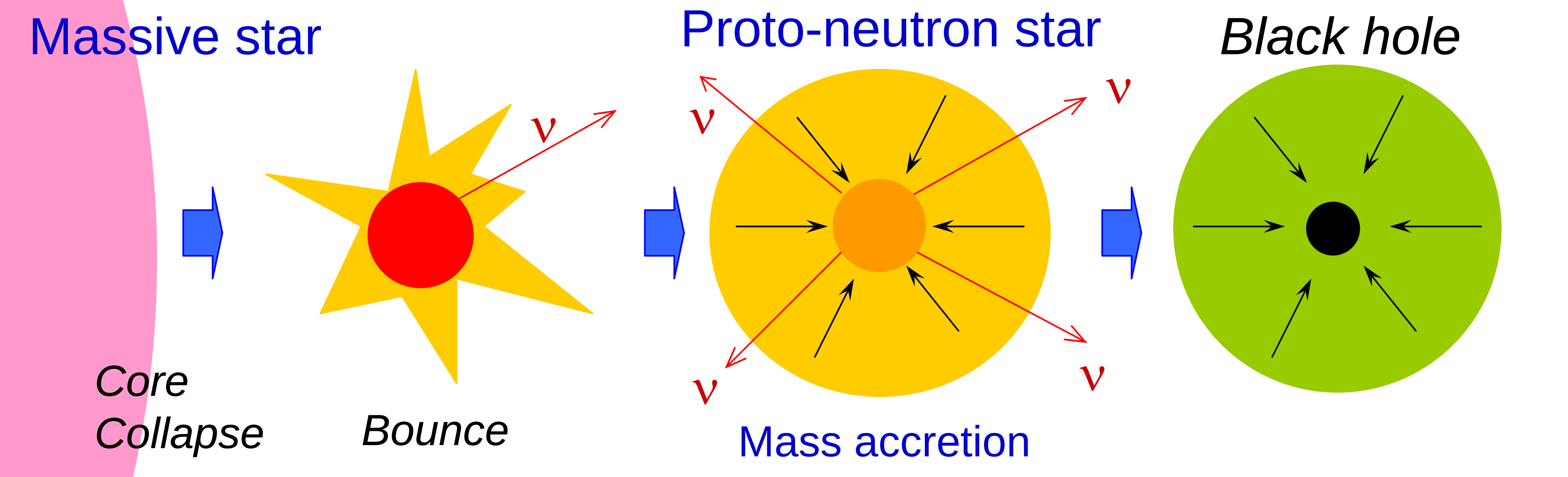
- Stars with > $10M_{solar}$ make a gravitational collapse and, possibly, a supernova explosion.
- Stars with > $25M_{solar}$ are thought to form a black hole（BH）.
- Observations show 2 branches.
  - Hypernovae（Rapid rotation）
  - Faint or Failed Supernovae（Weak rotation）



Nomoto+（2006）

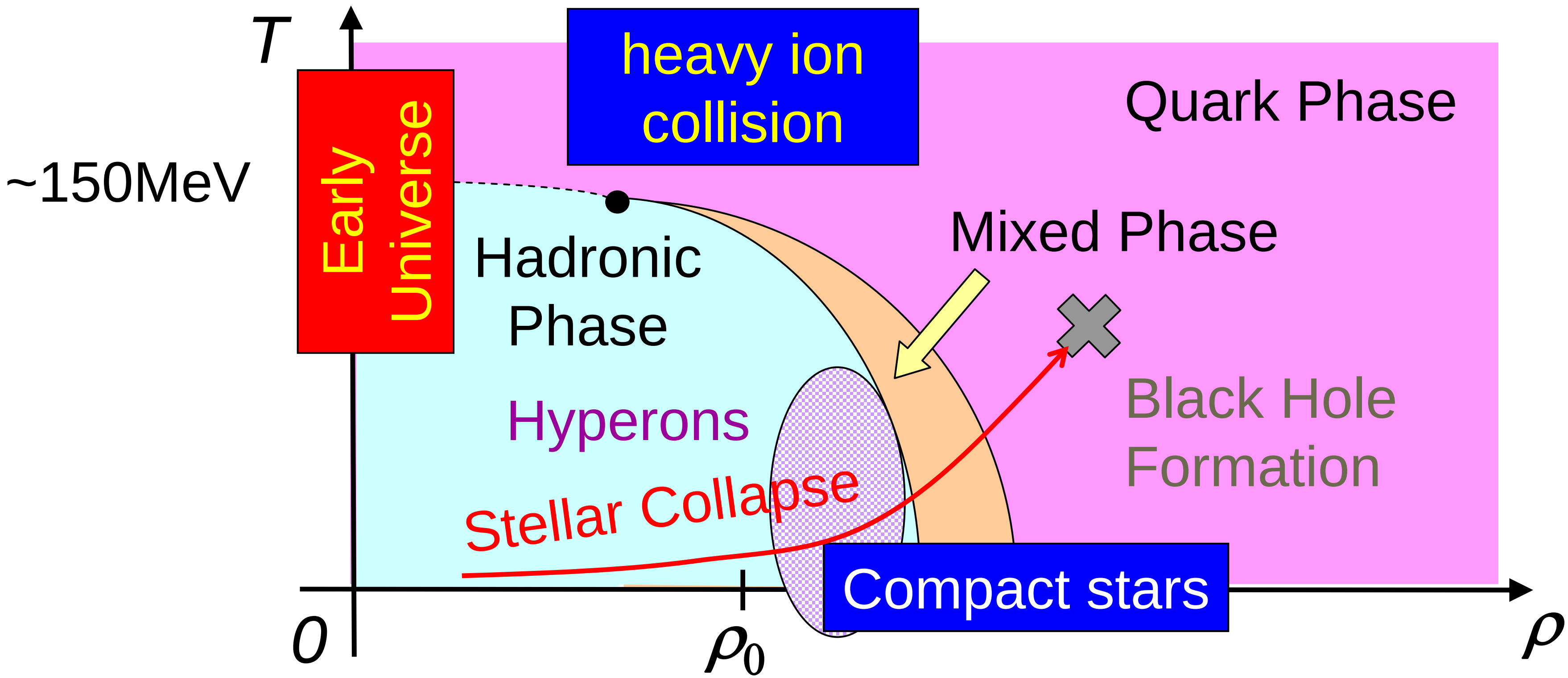
Failed supernova neutrinos

- Failed supernova progenitor makes bounce once and recollapse to the black hole.
- In this process, temperature and density of central region gets a few times 10 MeV and a few times ρ_0 (saturation density of nuclear matter), and a lot of neutrinos are emitted.



Motivation

- Collapsing core would be enough hot and dense to undergo exotic states, such as hyperon appearance and QCD transition.



Aims of this study

- We compute the dynamics and ν emission for the black hole formation of $40M_{solar}$ non-rotating progenitor（failed supernovae） involving equation of state（EOS） with hyperon appearance and QCD transition.
  - General relativistic ν radiation hydrodynamics in spherical symmetry（Sumiyoshi+ 2005）.
  - Hyperon（Ishizuka+ 2008, Nakazato+ 2012）
  - QCD transition（Nakazato+ 2008, 2010, in prep.）
- We investigate the impacts on the dynamics and ν signal.

Hydrodynamics & Neutrinos

Yamada, Astrophys. J. 475 (1997), 720
Yamada et al., Astron. Astrophys. 344 (1999), 533
Sumiyoshi et al., Astrophys. J. 629 (2005), 922

Spherical, Fully GR Hydrodynamics

metric: Misner-Sharp (1964)   mesh: 255 non uniform zones

+

Neutrino Transport (Boltzmann eq.)

Species : ν_e , $\bar{\nu}_e$, ν_μ (= ν_τ) , $\bar{\nu}_\mu$ (= $\bar{\nu}_\tau$)

Energy mesh : 14 zones (0.9 – 350 MeV)

Reactions : $e^- + p \leftrightarrow n + \nu_e$, $e^+ + n \leftrightarrow p + \bar{\nu}_e$, $\nu + N \leftrightarrow \nu + N$,
$\nu + e \leftrightarrow \nu + e$, $\nu_e + A \leftrightarrow A' + e^-$, $\nu + A \leftrightarrow \nu + A$,
$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$, $\gamma^* \leftrightarrow \nu + \bar{\nu}$, $N + N' \leftrightarrow N + N' + \nu + \bar{\nu}$

List of equations of state

- Current status
  - Lattimer-Swesty (LS) EOS
    - Liquid drop model with Skyrme interactions（1991）
  - Shen EOS
    - Relativistic Mean Field theory（H. Shen et al. 1998）
  - Hyperon + pion EOS
    - Shen-EOS with hyperons（Ishizuka et al. 2008）
  - Quark + pion EOS
    - Shen-EOS with MIT Bag model（Nakazato et al. 2008a）

- Notes
  - Kanzawa et al.（2009）, Hemple & Schaffner-Bielich（2010, NSE）, G. Shen et al.（2011）, Furusawa et al.（2011, NSE）, Steiner et al.（2012）, Togashi's talk in this symposium ...

2. Hyperon appearance

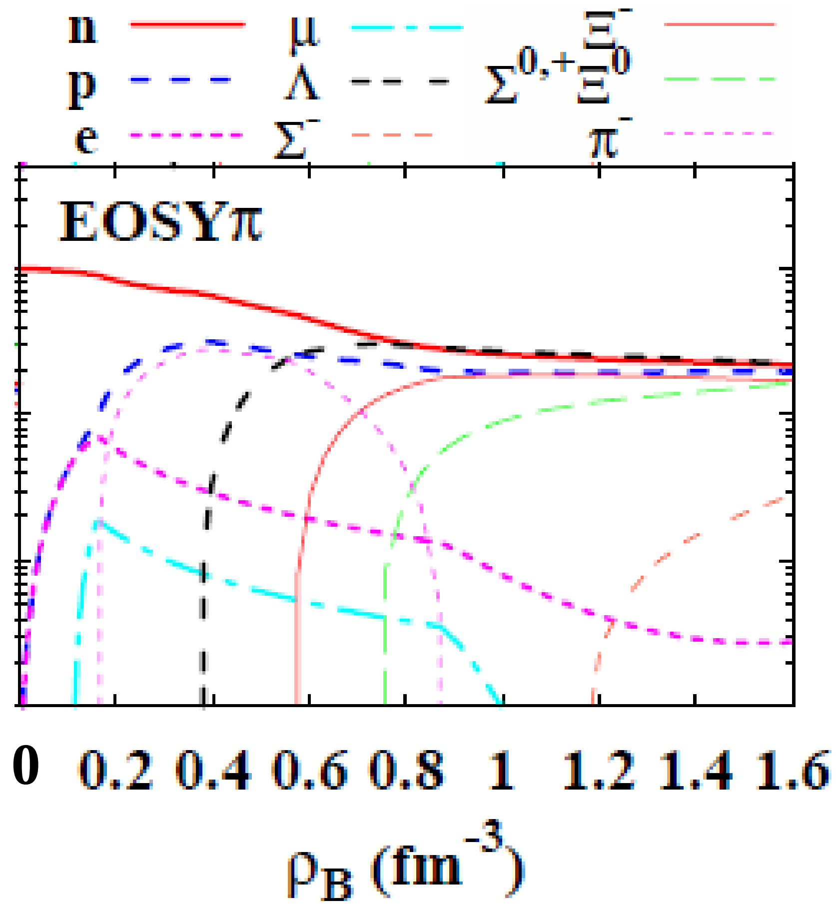
Heperonic Equation of State

Ishizuka et al. J. Phys. G **35** (2008) 085201

- Relativistic Mean Field Theory
  - extension of Shen EOS to the baryon octet
- Potentials
  - $U_\Lambda = -30$ MeV
  - $U_\Sigma = 30$ MeV (repulsive)

    or

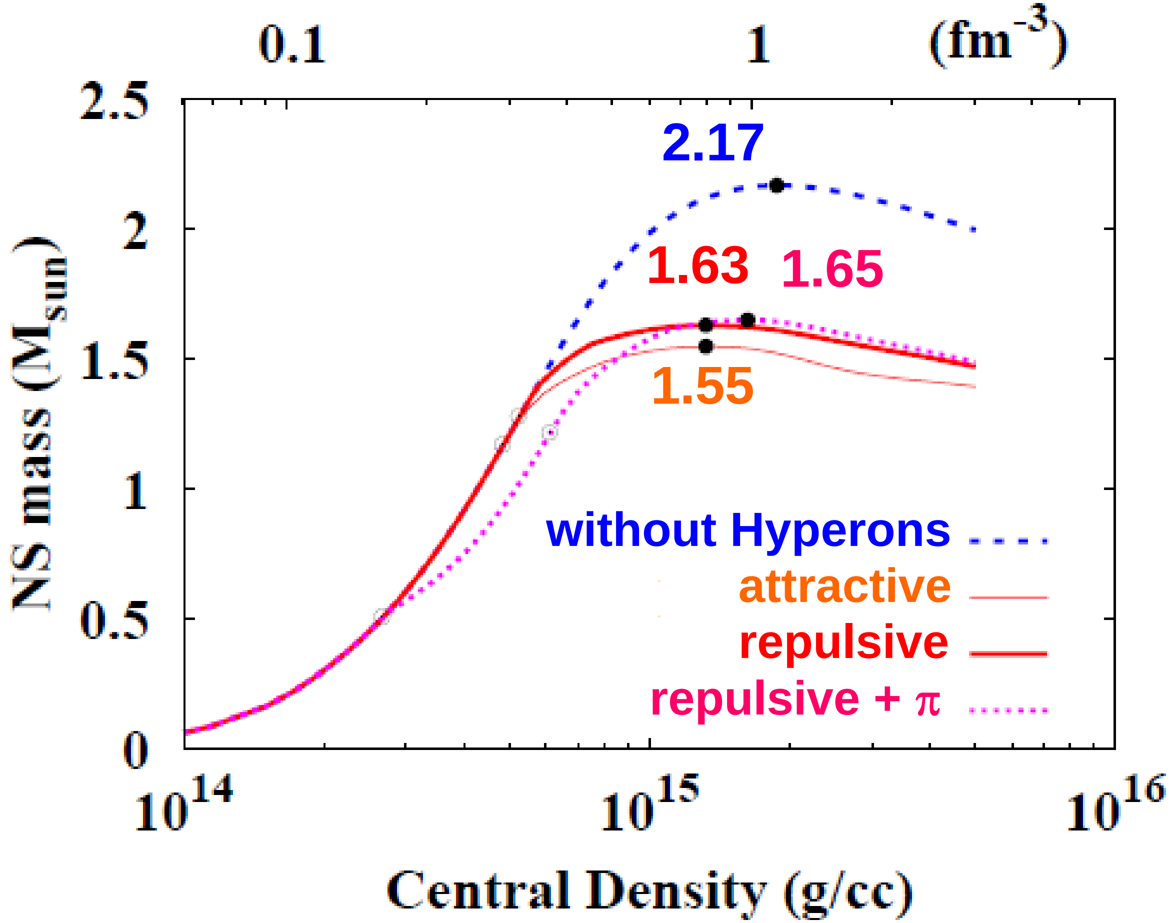
    -30 MeV (attractive)
  - $U_\Xi = -15$ MeV
- Data with thermal pions is also prepared.



Max. Mass of Neutron Stars

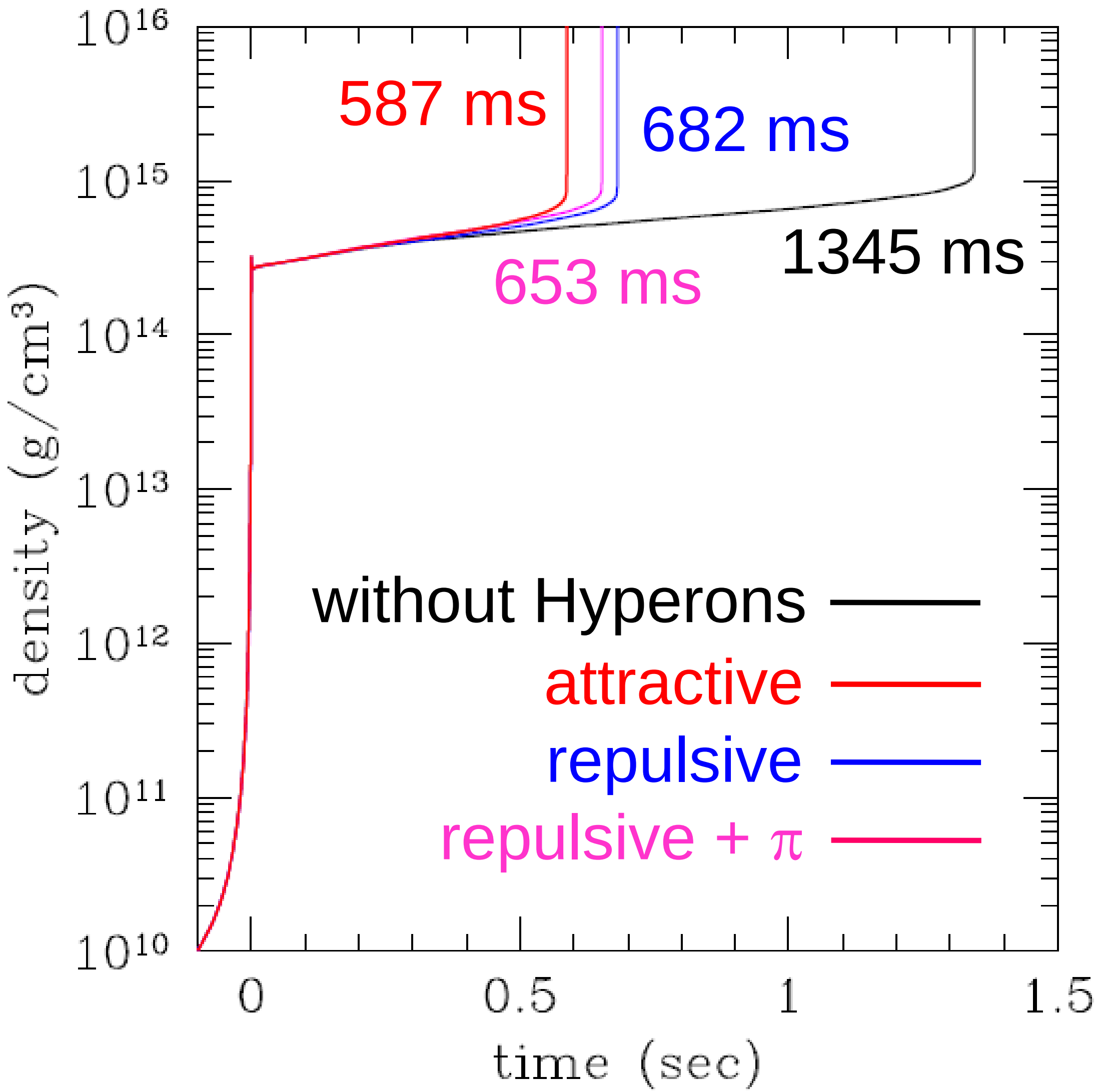
- Maximum mass of neutron stars gets lower due to softening by hyperons.
- Difference between repulsive and attractive is ~5%.
- Pions makes subtle change.
- Hyperonic EOS cannot account for $2M_{solar}$.

Ishizuka et al. (2008)

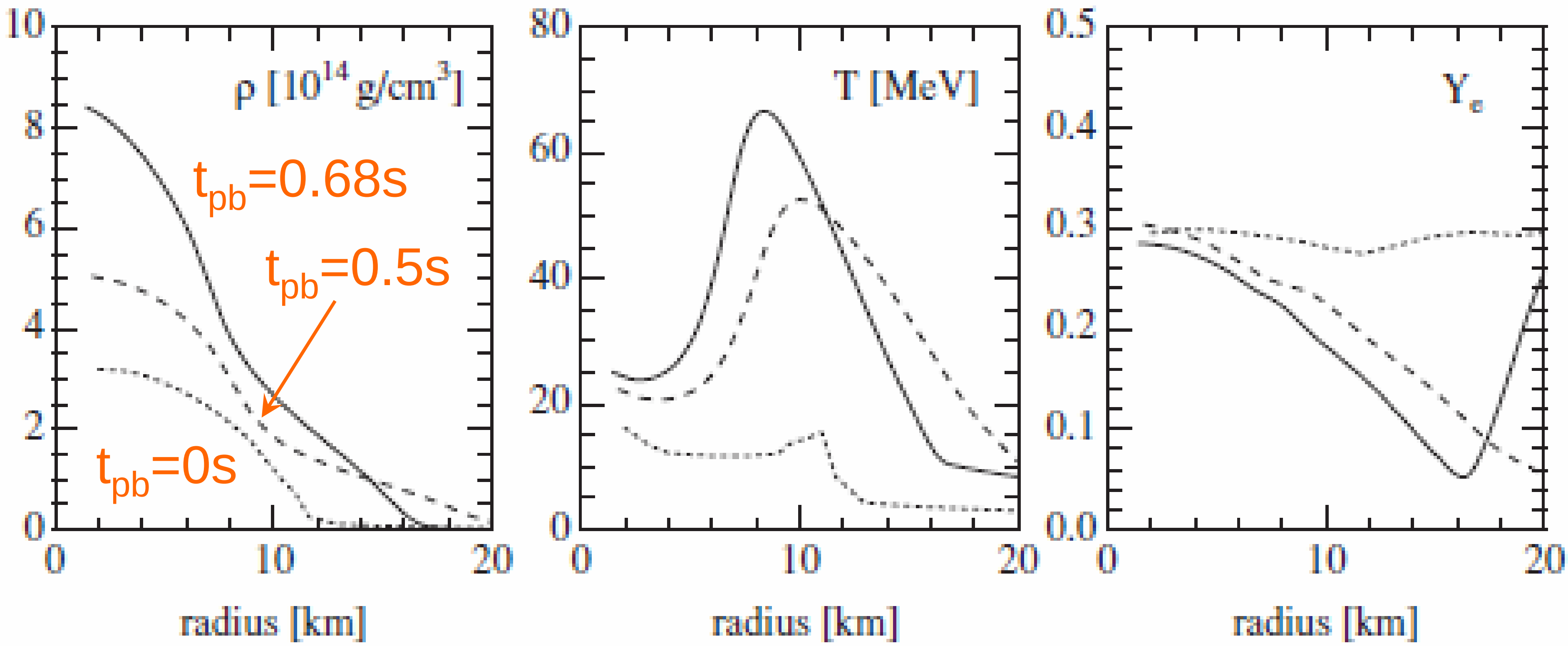


Evolutions of Central density

- Hyperons accelerate the collapse.
- Interval between the bounce and BH formation gets shorter.
- The repulsive case is ~15% longer than the attractive case.
- Impact of pions is tiny.



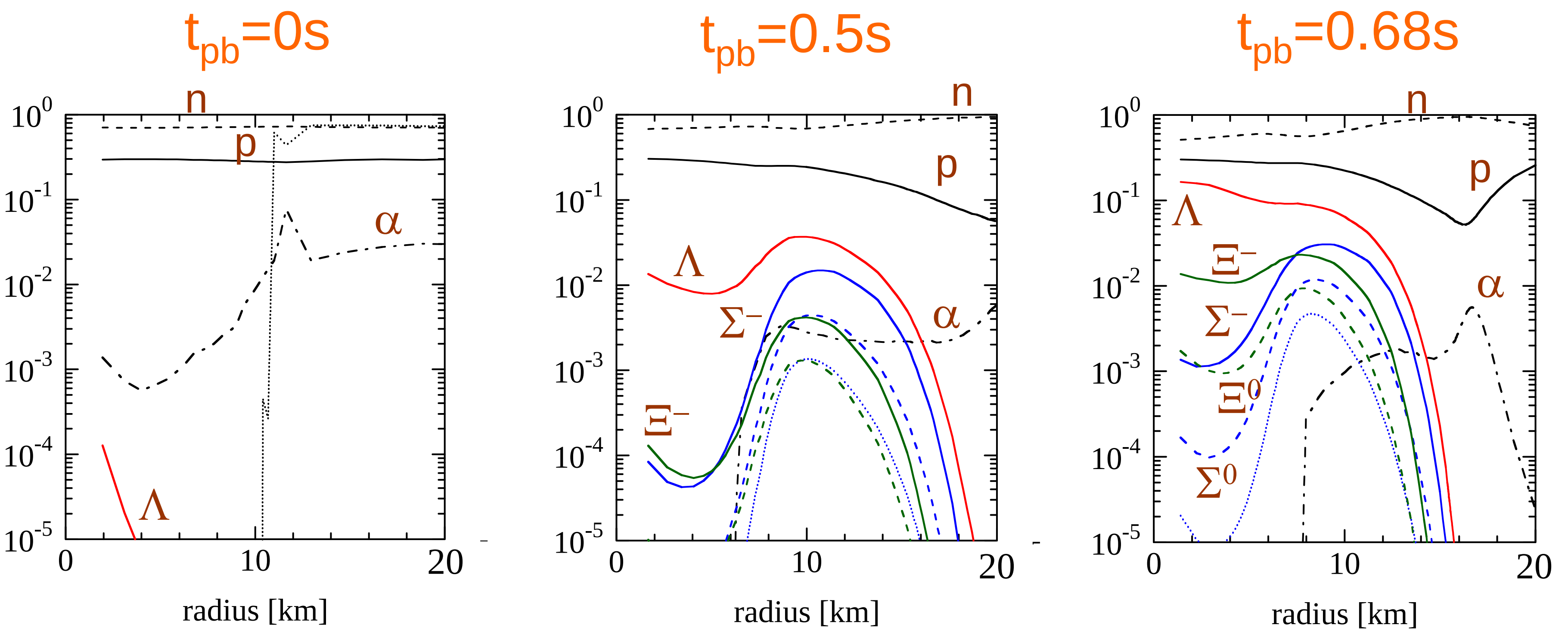
Key parameters (repulsive case)



- Roughly speaking, high ρ and low T at the center and low ρ and high T at r = 10 km.

→ Entropy is higher at r = 10 km due to shock heating.

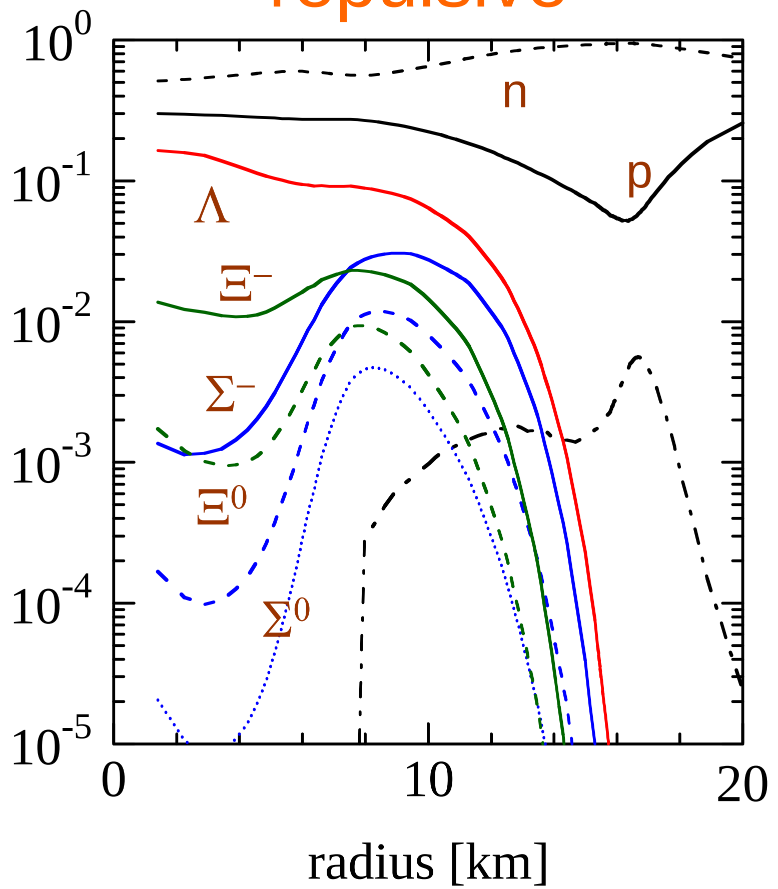
Compositions (repulsive case)



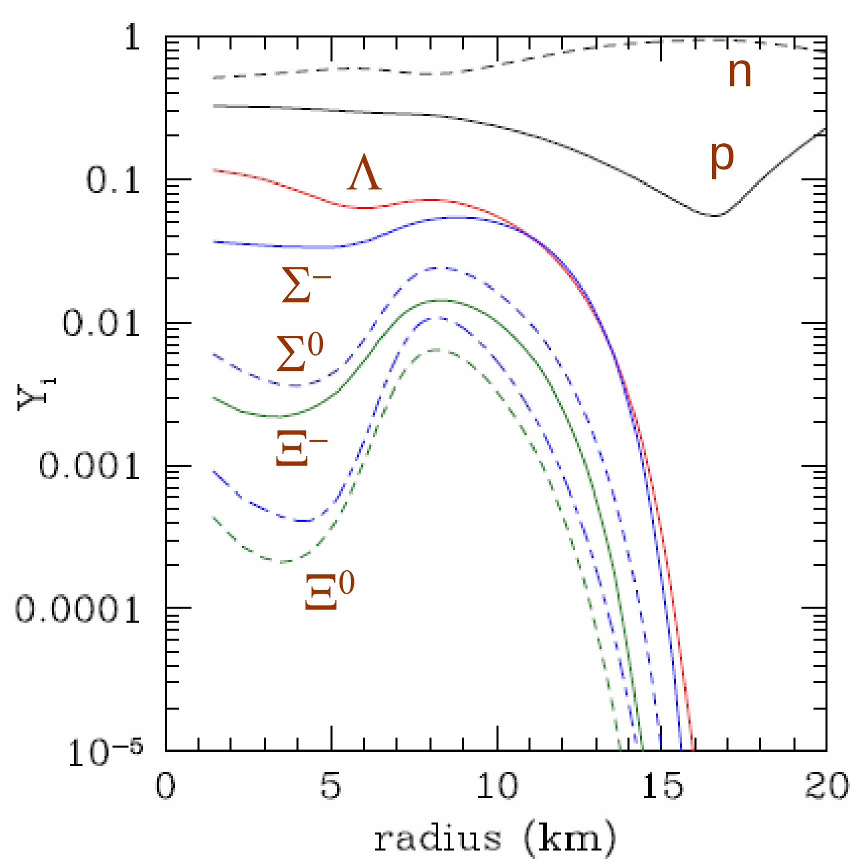
- Hyperon fraction is tiny at the bounce.
- Hyperons appear for the late phase.
  - Σ^- is suppressed for dense region (center)
  - Σ^- populates thermally for hot region (r = 10 km)

Compositions ($t_{pb} = t_{BH} - 2$ ms)

repulsive



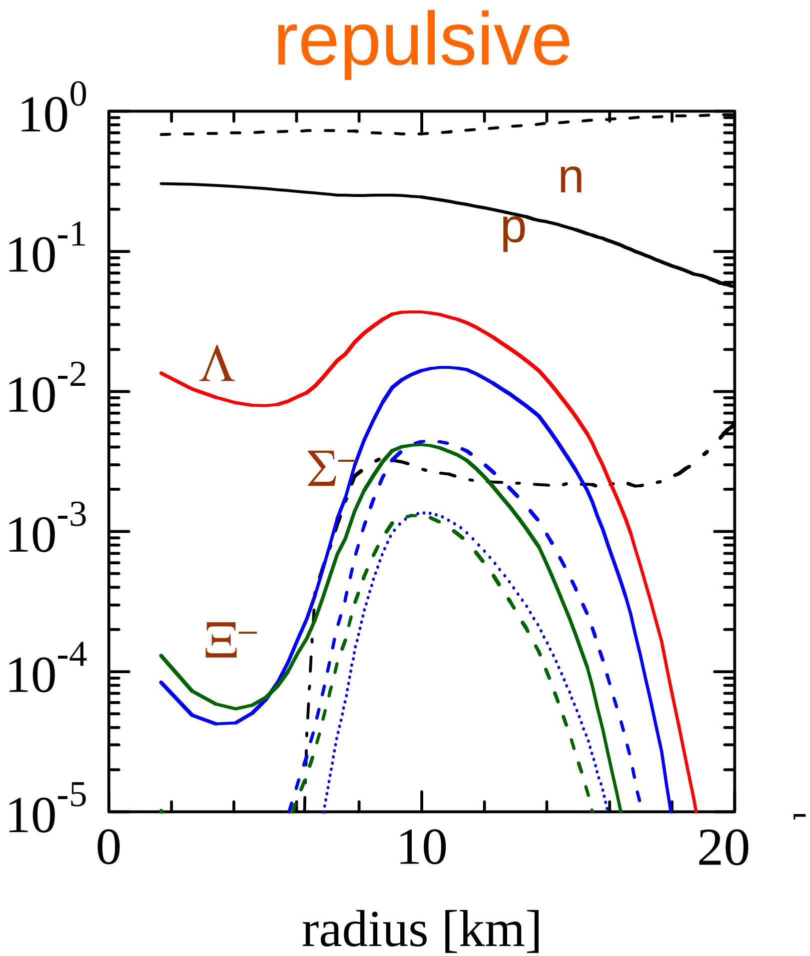
attractive

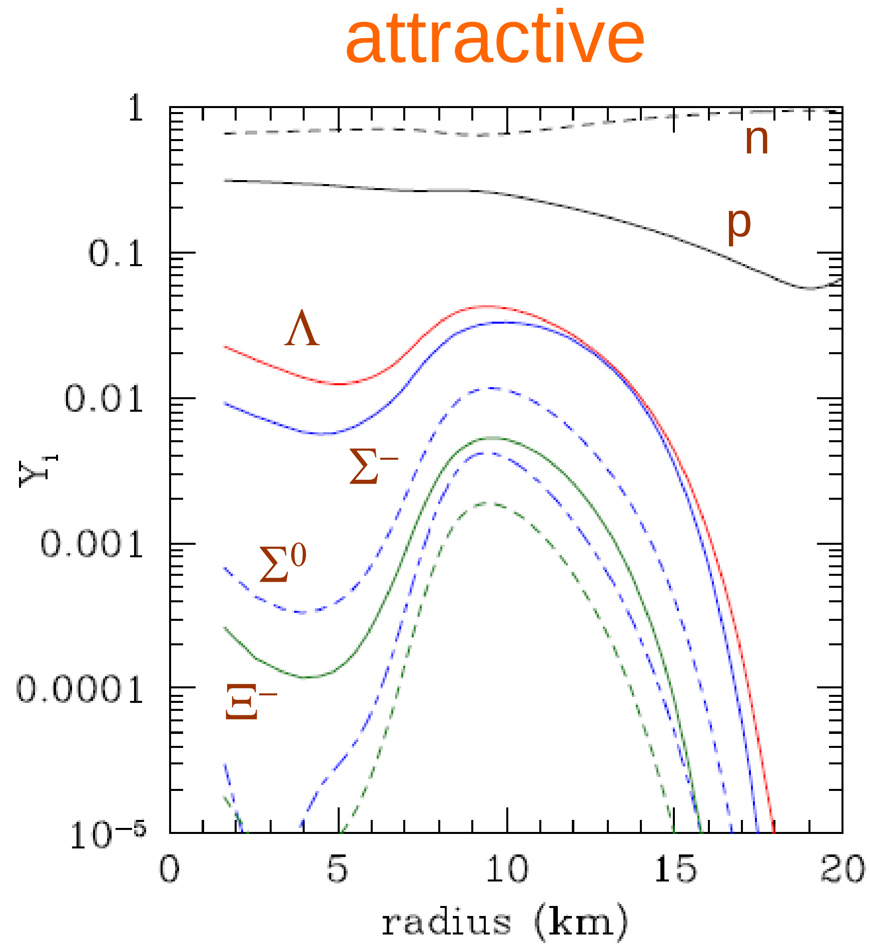


- More Σ^{-} for the center of the attractive case.

→ Collapse is more promoted due to EOS softening.

Compositions (t_{pb} = 0.5 s)





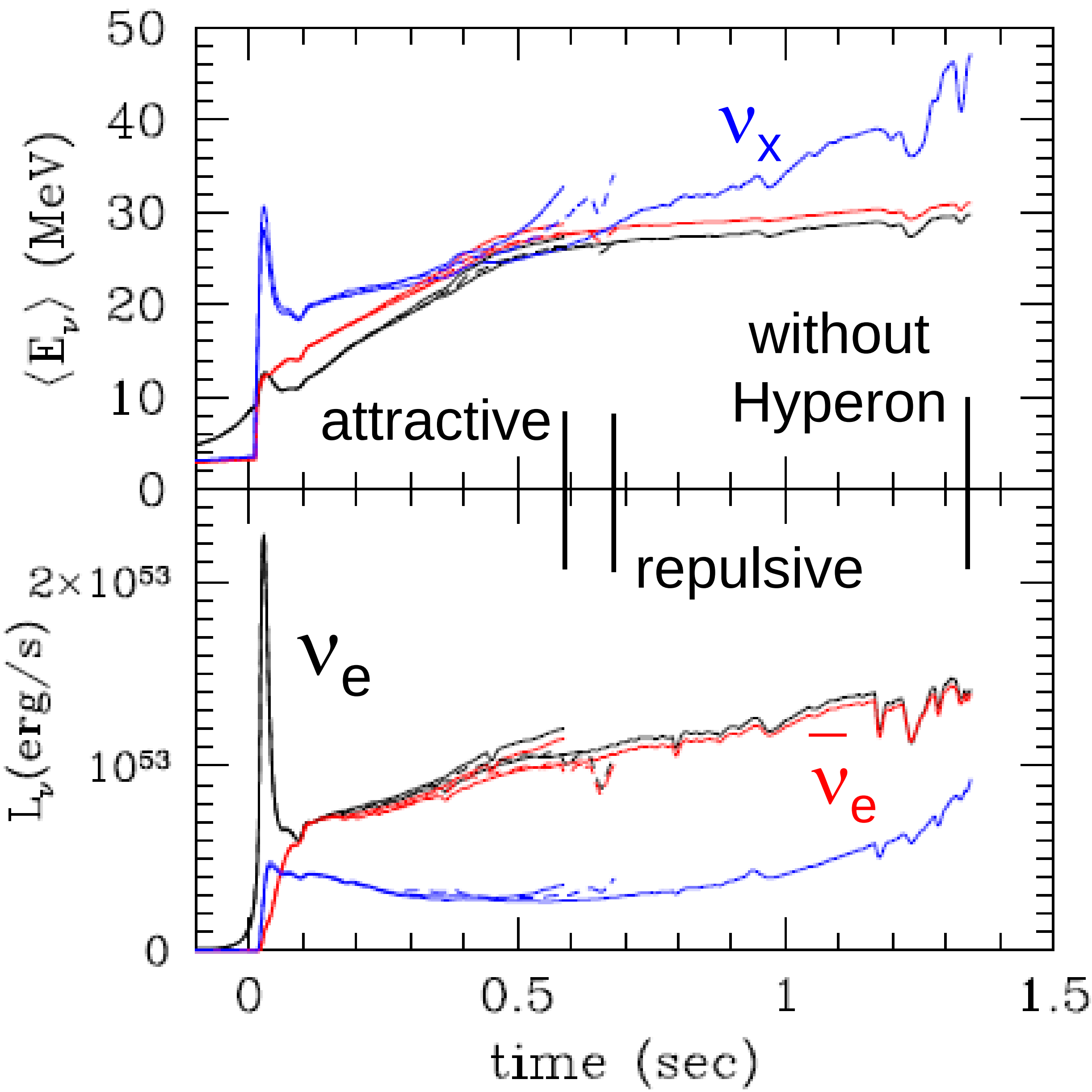
- For the attractive case, Σ^- appears earlier.

  → The influence is seen in the neutrino signal.

Neutrino Signal

- Neutrinos are mainly emitted till the black hole formation.
- Difference due to hyperons is seen earlier for attractive case.

→ Key for astro-physical probe



3. QCD transition

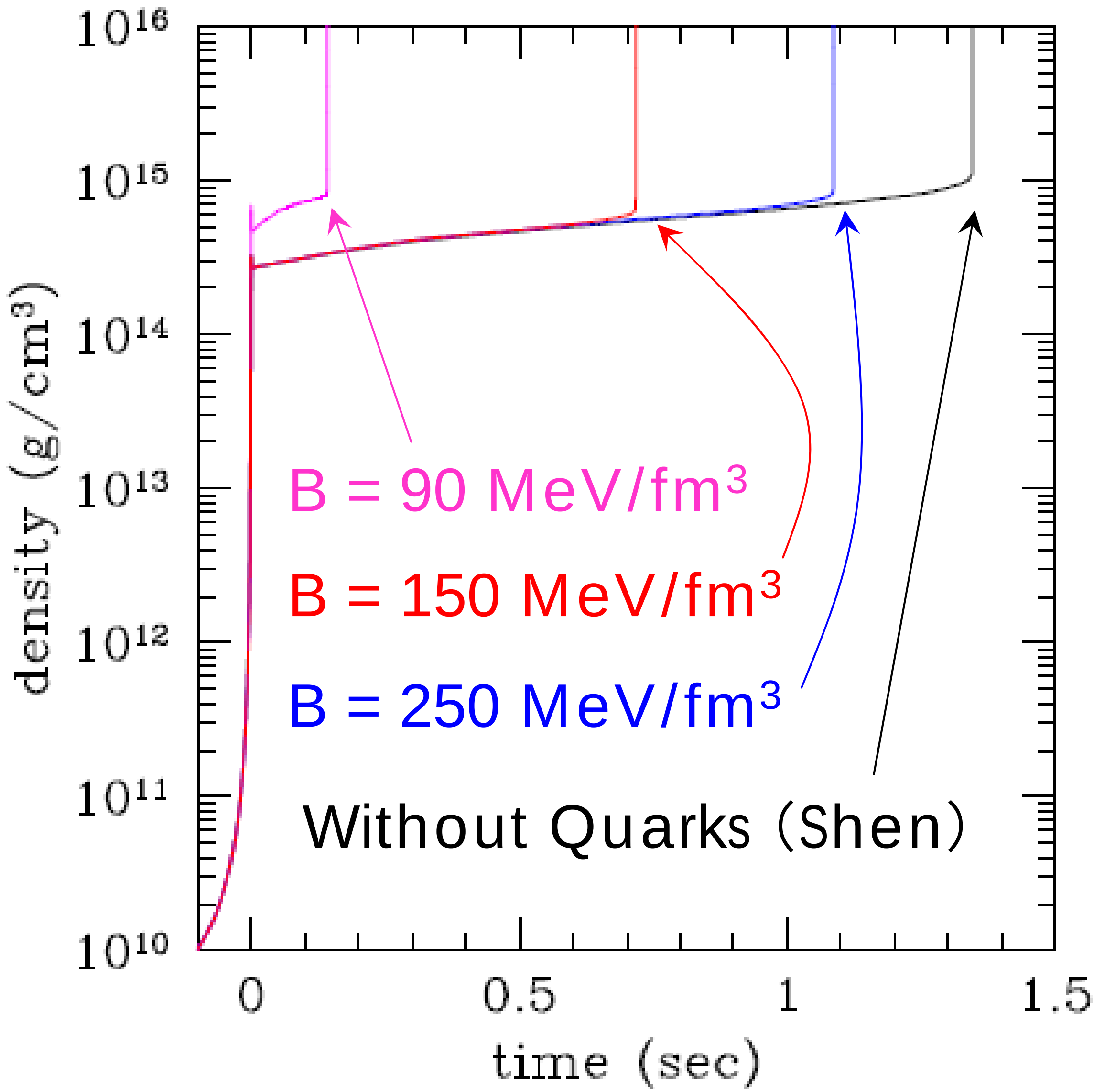
Hadron-quark mixed EOS

Nakazato et al., PRD 77（2008）, 103006

- Shen EOS with pions for Hadronic phase
- MIT Bag model（Chodos et al. 1974）for Quark phase
  - Bag constant: B = 90, 150 and 250 MeV/fm^3
- Gibbs conditions are satisfied in Mixed phase.
  - $\mu_n = \mu_u + 2\mu_d$, $\mu_p = 2\mu_u + \mu_d$
  - $P_H = P_Q$
- β equilibrium（ν trapping）is assumed in Mixed and Quark phase.
  - $\mu_d = \mu_s$, $\mu_p + \mu_e = \mu_n + \mu_\nu$

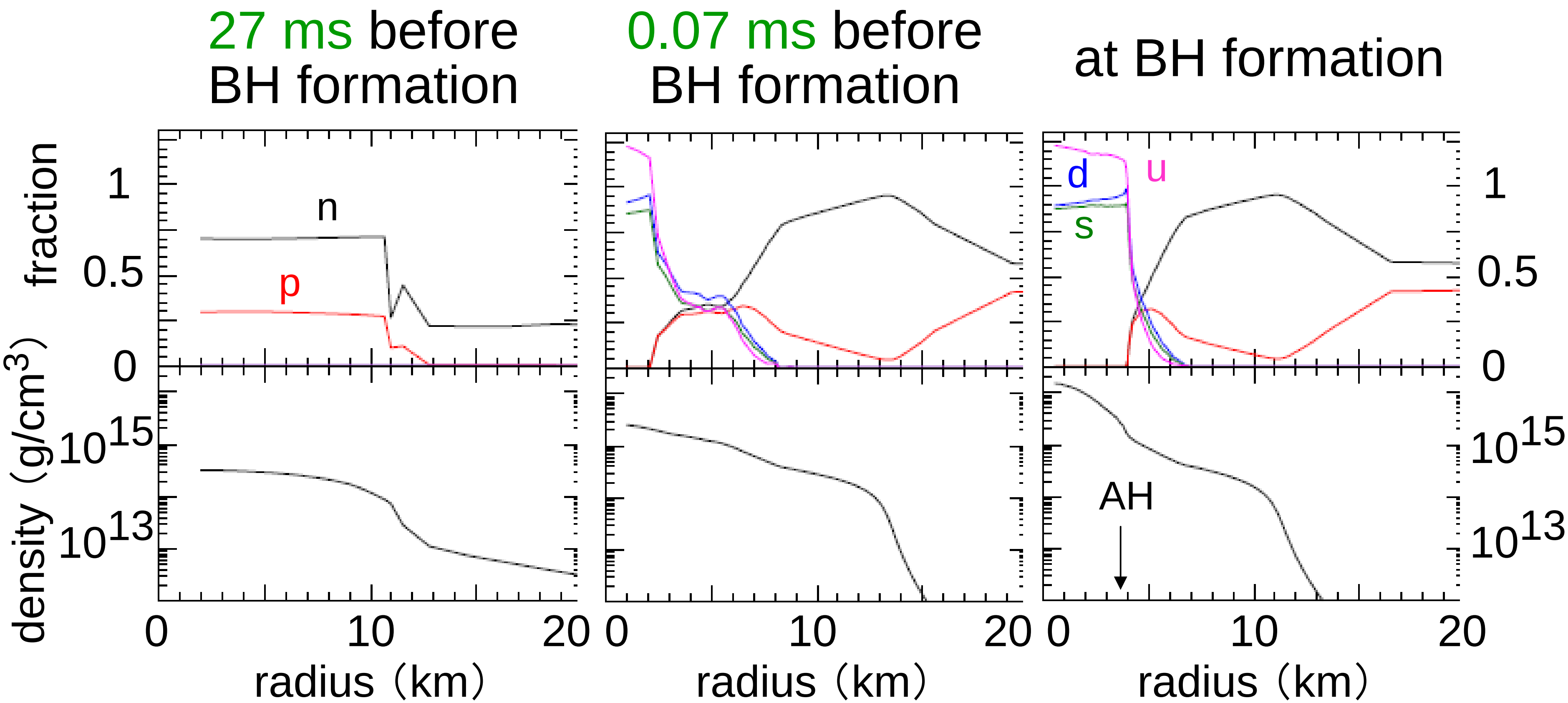
Evolutions of Central density

- QCD transition also accelerates the collapse.
- The case with B = 90 MeV/fm^3 has high density already at the bounce.
- Others are similar just until BH formations.



Compositions (B = 250 MeV/fm^3)

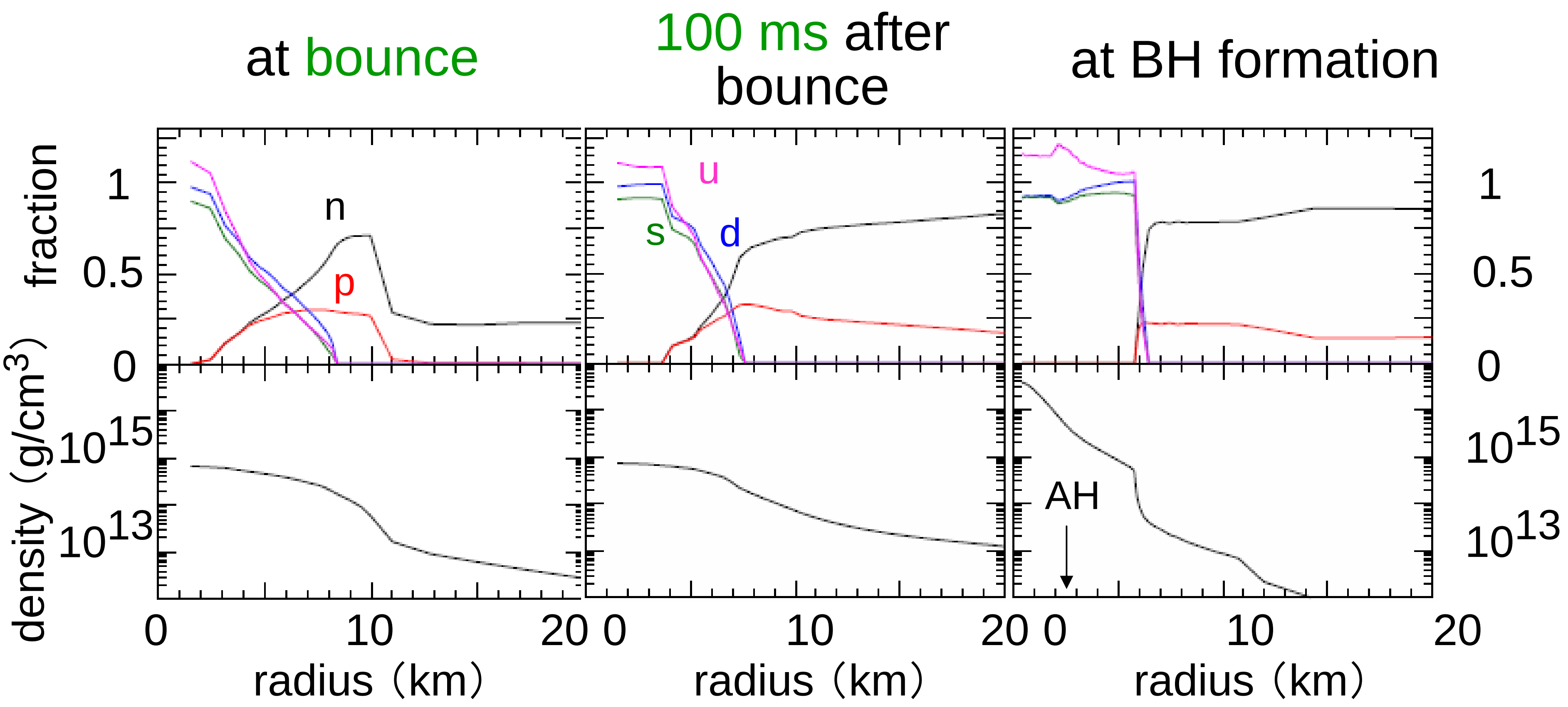
Nakazato et al., Astrophys. J. 721 (2010), 1284



- Quark transition occurs at the very late phase and trigger the black hole formation.

Compositions (B = 90 MeV/fm³)

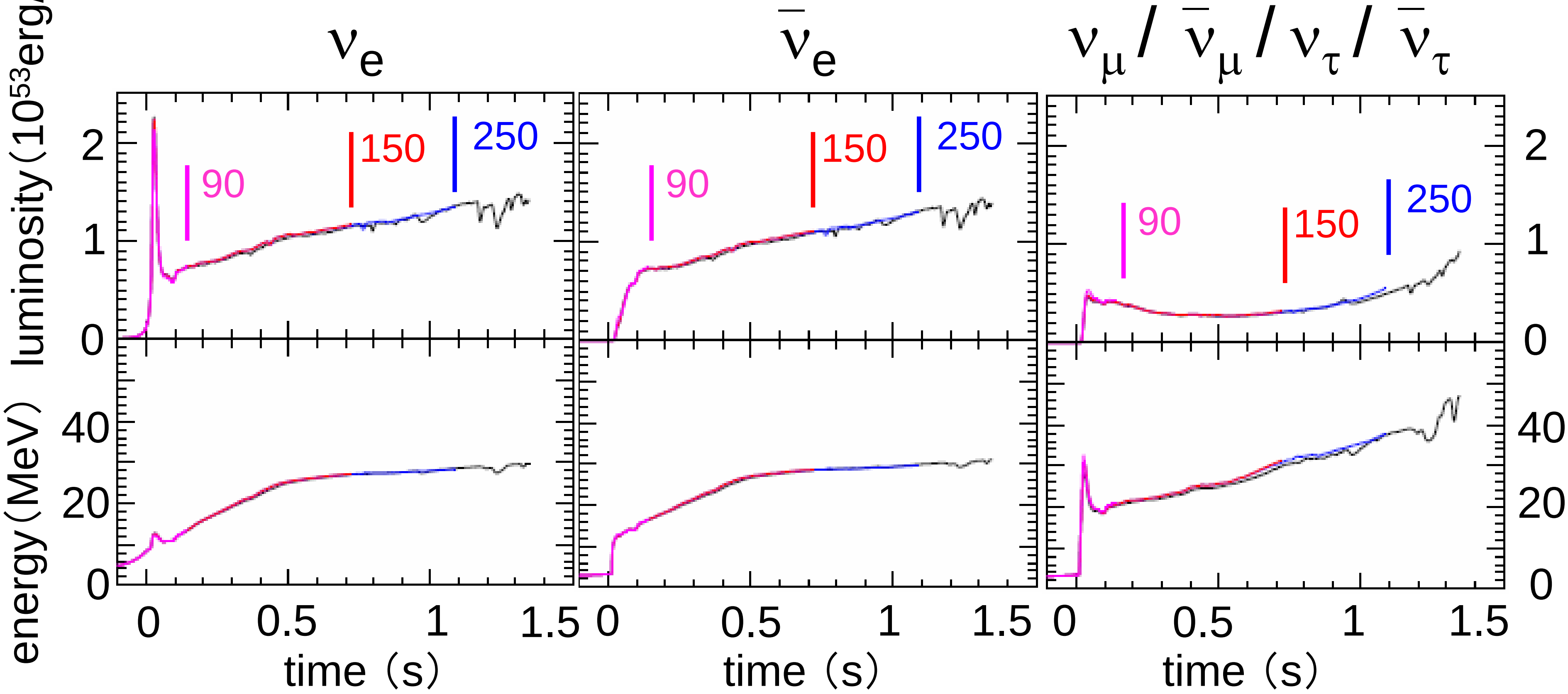
Nakazato et al., in prep.



- Quarks appear already at bounce.

→ the central density gets higher.

Neutrino Signal



- Apart from end points, there is no difference even for the model with B = 90 MeV/fm^3.
- Neutrinos emitted from the outer region.

4. Conclusion

Summary

- We have performed a series of black-hole-forming core collapse simulations for non-rotating $40M_{solar}$ star with various EOS's.
- We have found that EOS affects the emission duration and luminosity of ν.
- For hyperons, impact is larger for attractive Σ potential case because Σ^- appears earlier especially for the central region.
- For quarks, impact is larger for low bag const. case because the transition is earlier and it is drastic if the transition occurs at bounce.