

Stellar Core Collapse and Exotic Matter

Ken'ichiro Nakazato

(Tokyo University of Science)



東京理科大学

TOKYO UNIVERSITY OF SCIENCE

in collaboration with **K. Sumiyoshi** (Numazu CT),
C. Ishizuka, **H. Suzuki** (Tokyo U of Sci.), **A. Ohnishi** (Kyoto U),
S. Furusawa and **S. Yamada** (Waseda U)

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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

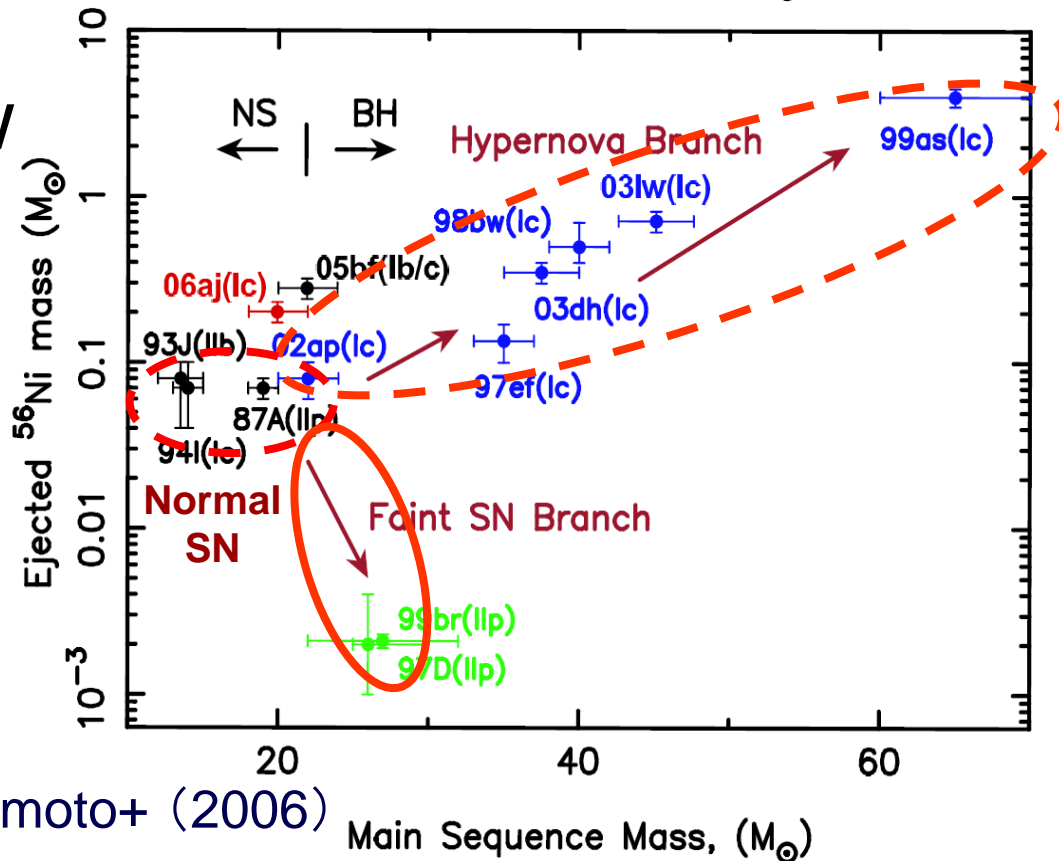
Nakazato+ 2008, 2010, in prep.

4. Conclusion

1. Introduction

Fates of massive stars

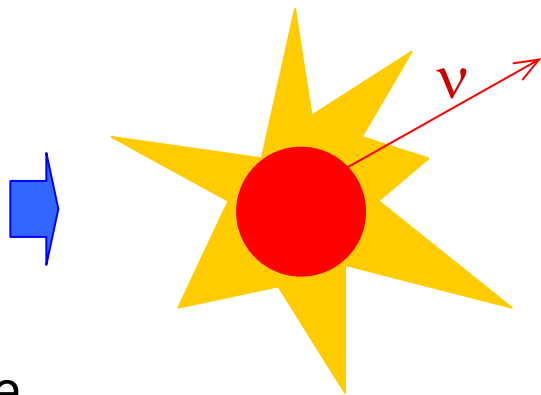
- Stars with $> 10M_{\text{solar}}$ make a gravitational collapse and, possibly, a **supernova explosion**.
- Stars with $> 25M_{\text{solar}}$ are thought to form a **black hole (BH)**.
- Observations show 2 branches.
 - Hypernovae (Rapid rotation)
 - Faint or Failed Supernovae (Weak rotation)



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.

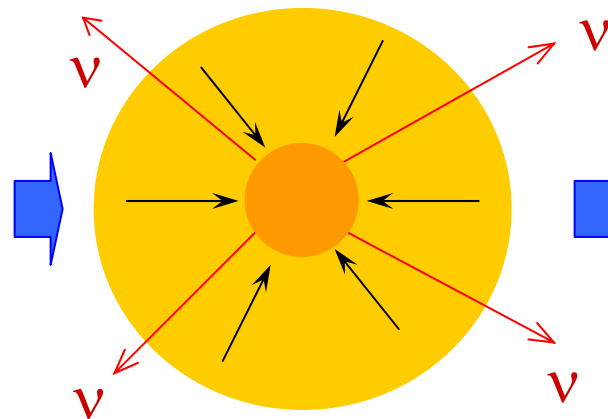
Massive star



Core
Collapse

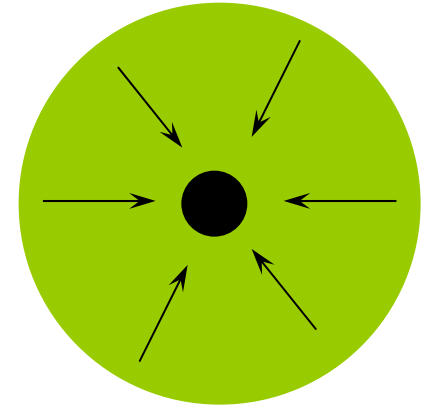
Bounce

Proto-neutron star



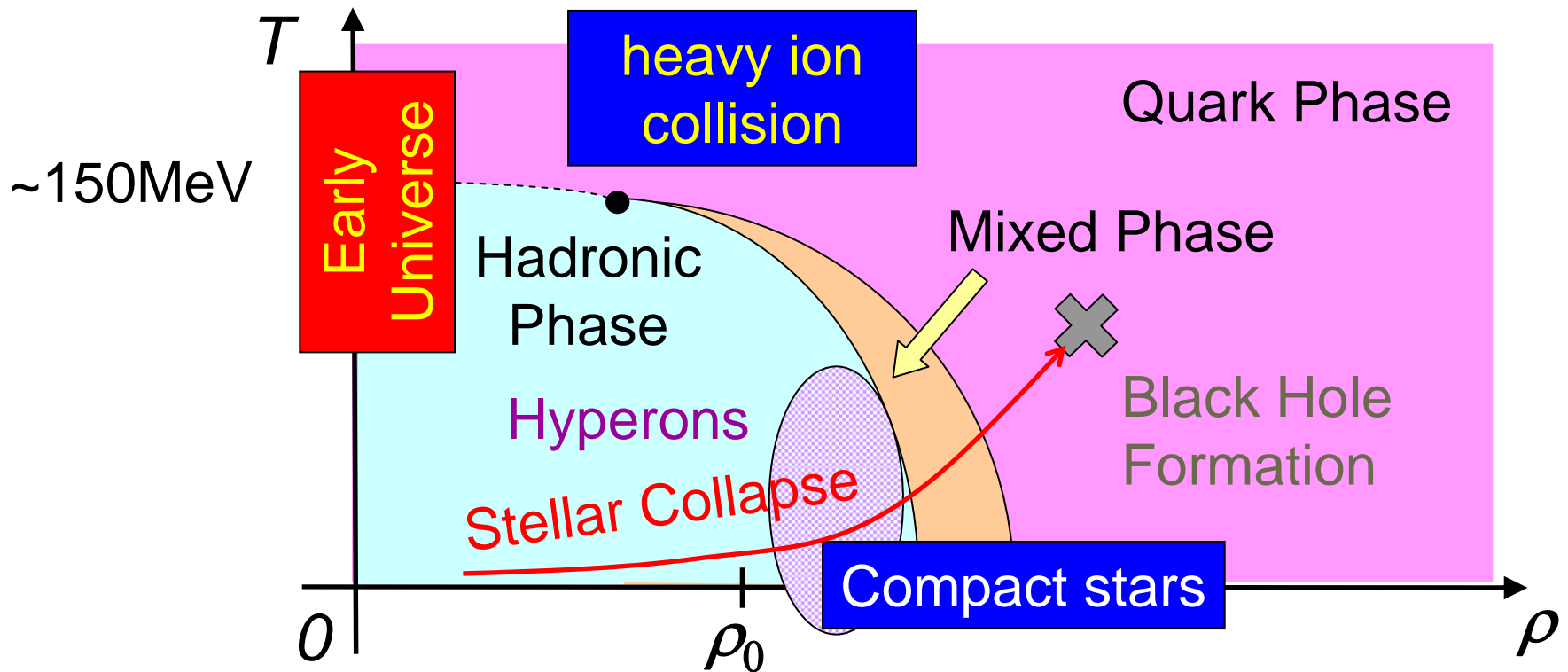
Mass accretion

Black hole



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 $40M_{\text{solar}}$** 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), Hempel & 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

Hyperonic 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

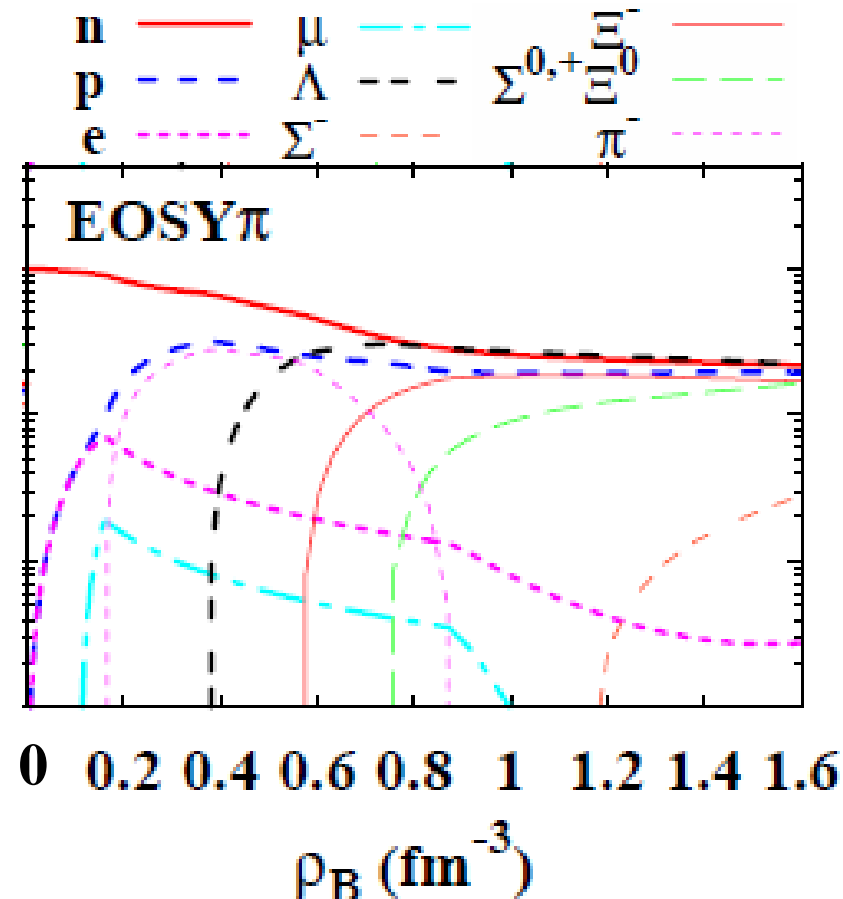
- $U_{\Sigma} = 30$ MeV (repulsive)

or

- -30 MeV (attractive)

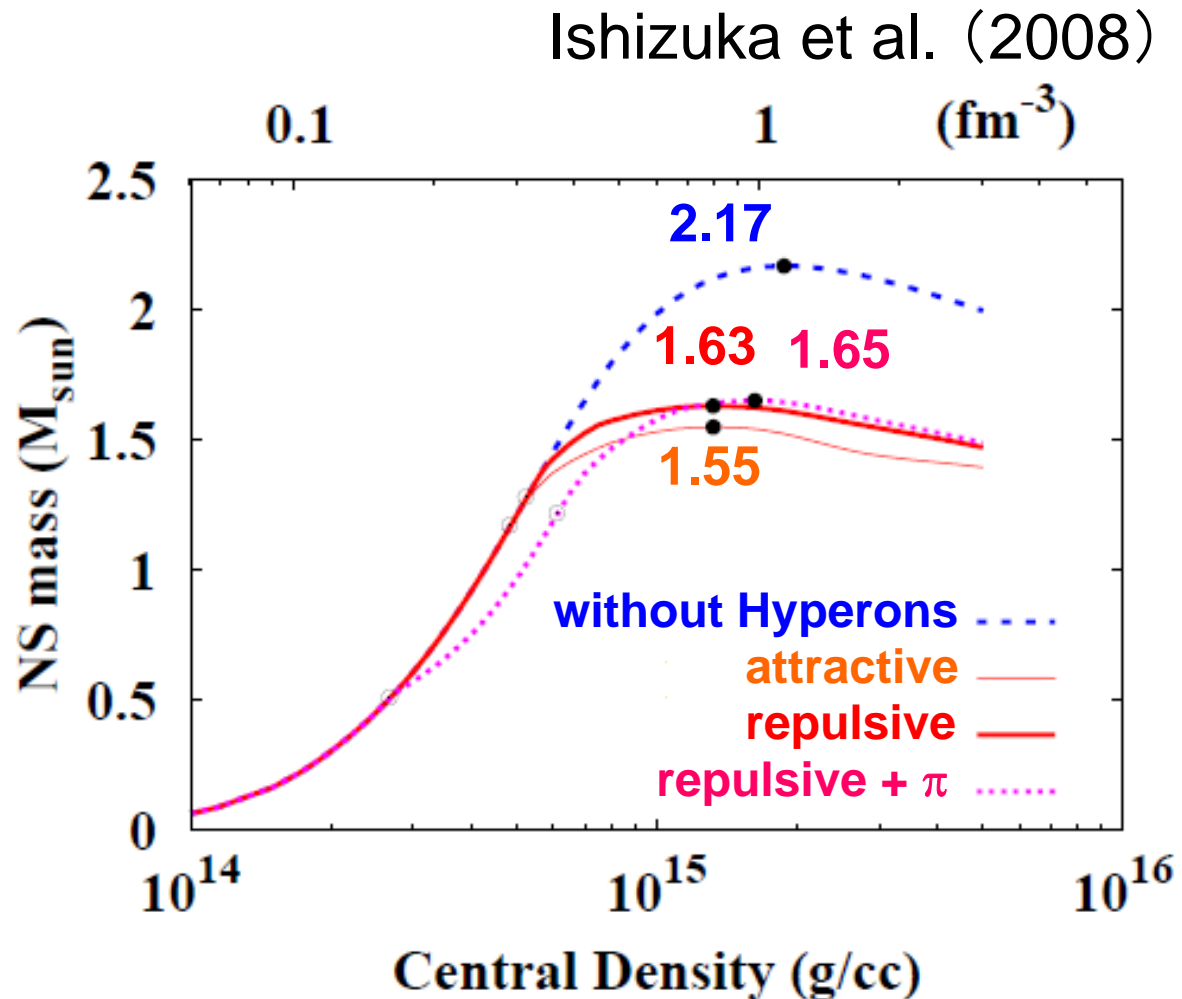
- $U_{\Xi} = -15$ MeV

- Data with thermal pions is also prepared.



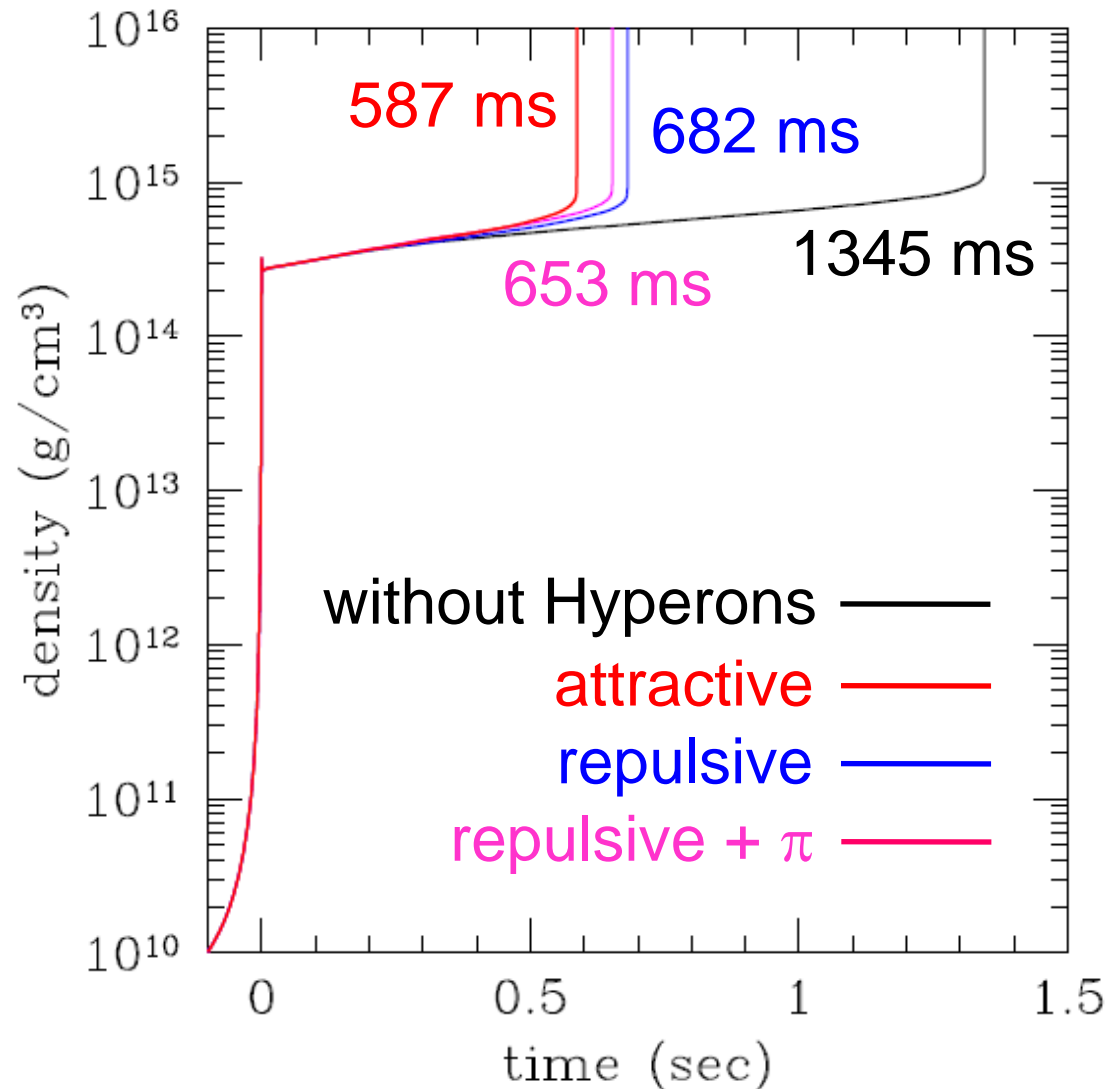
Max. Mass of Neutron Stars

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

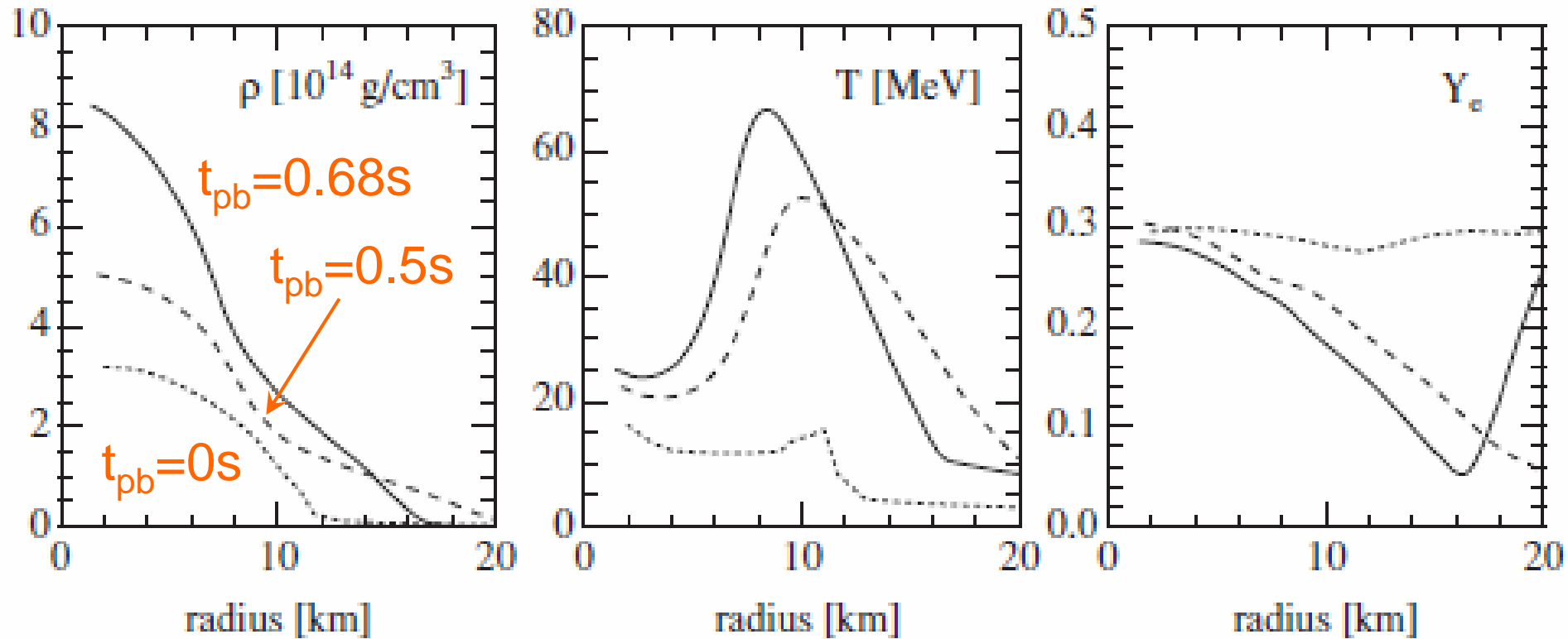


Evolution of Central density

- 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.

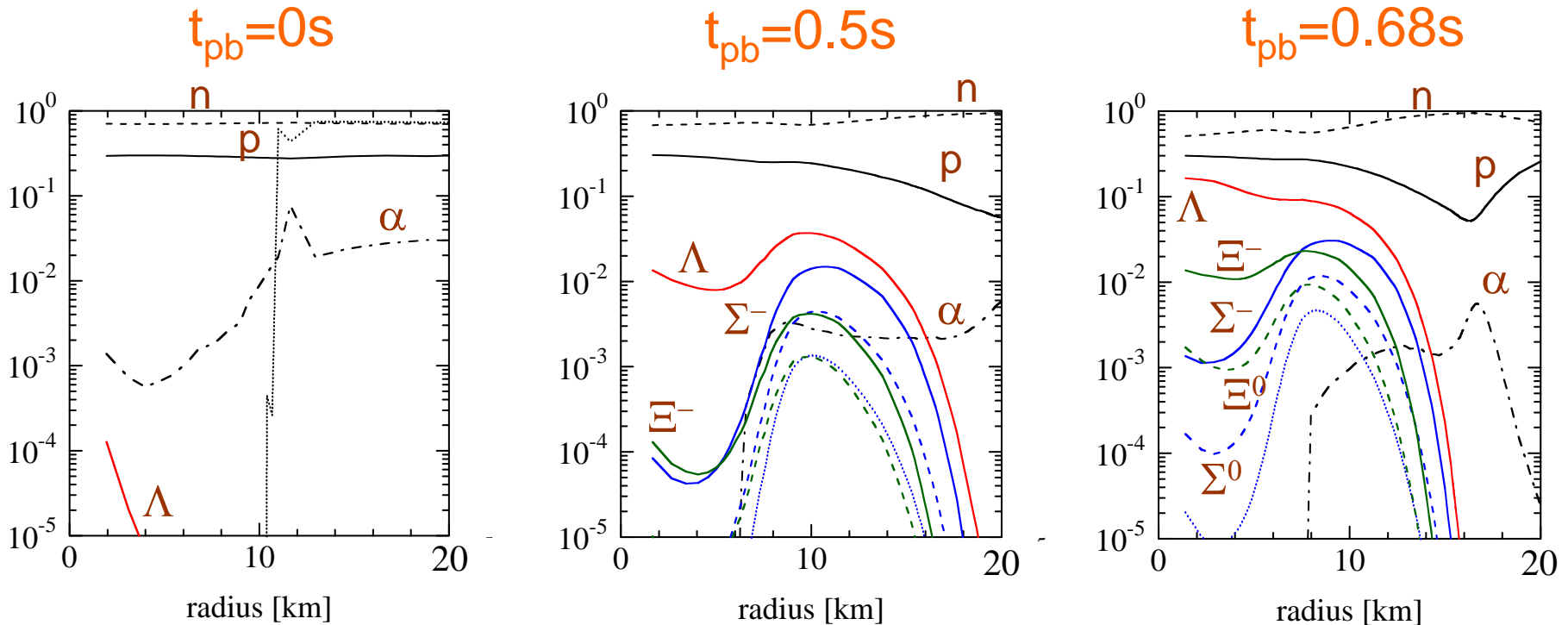


Key parameters (repulsive case)



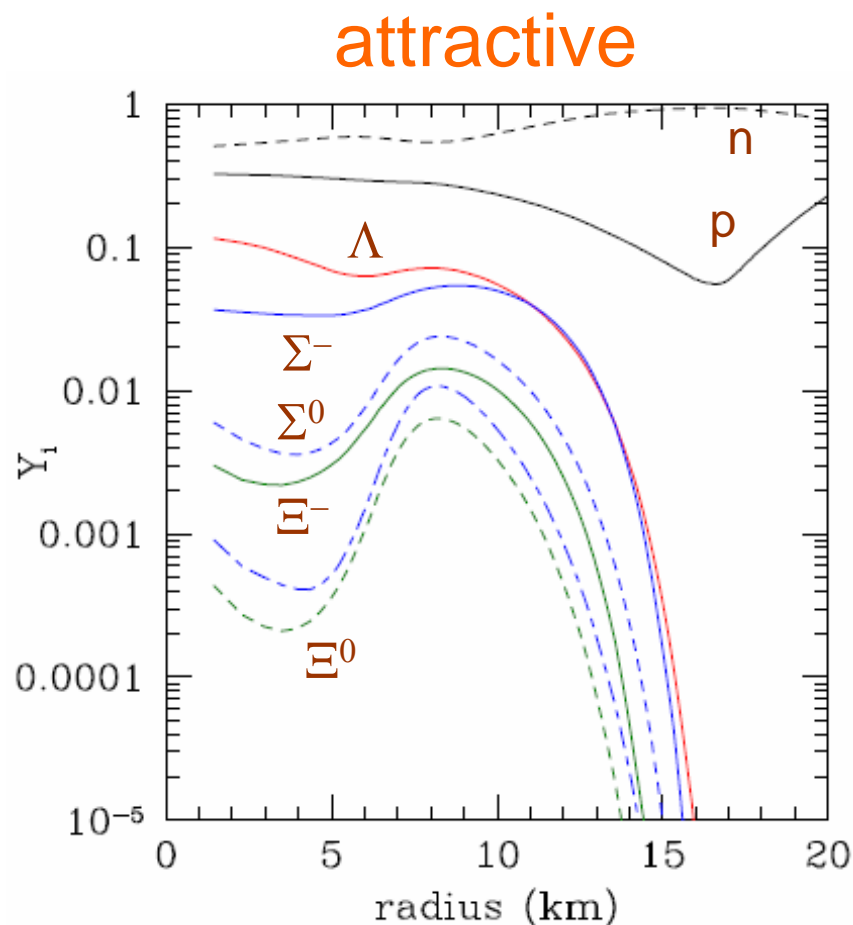
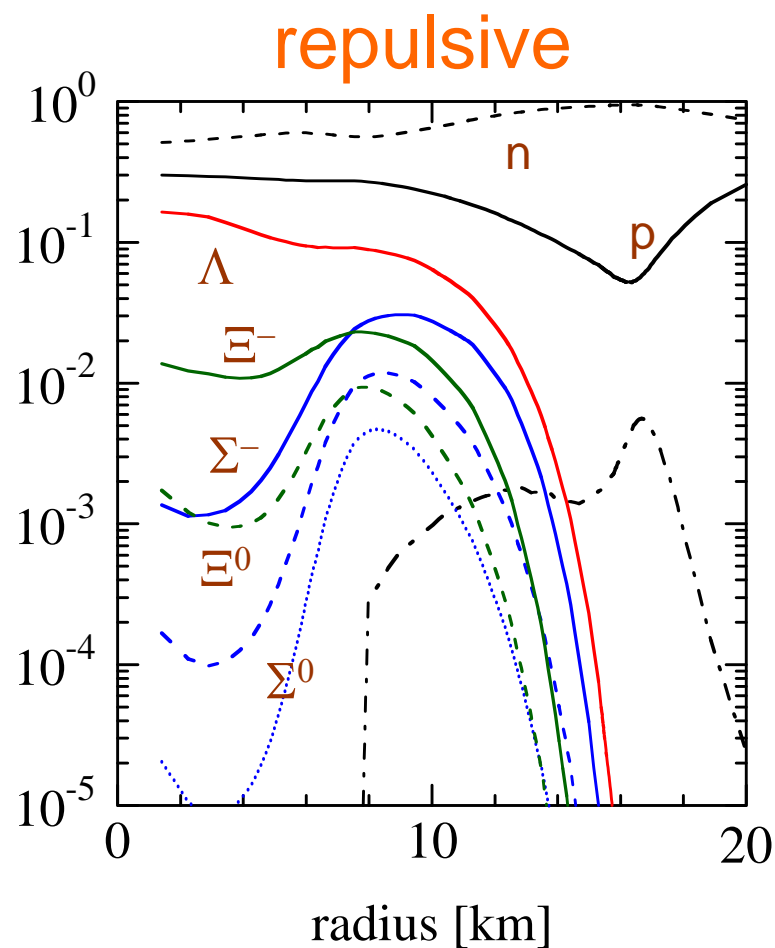
- Roughly speaking, **high ρ** and **low T** at the center and **low ρ** and **high T** at $r = 10$ km.
→ Entropy is higher at $r = 10$ km due to shock heating.

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)

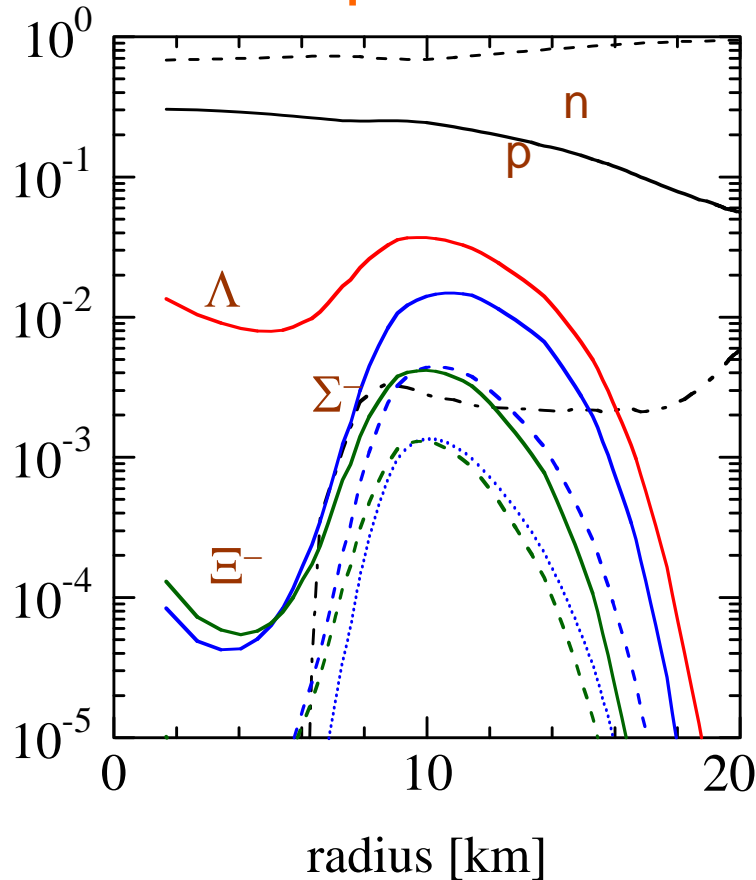
Compositions ($t_{\text{pb}} = t_{\text{BH}} - 2 \text{ ms}$)



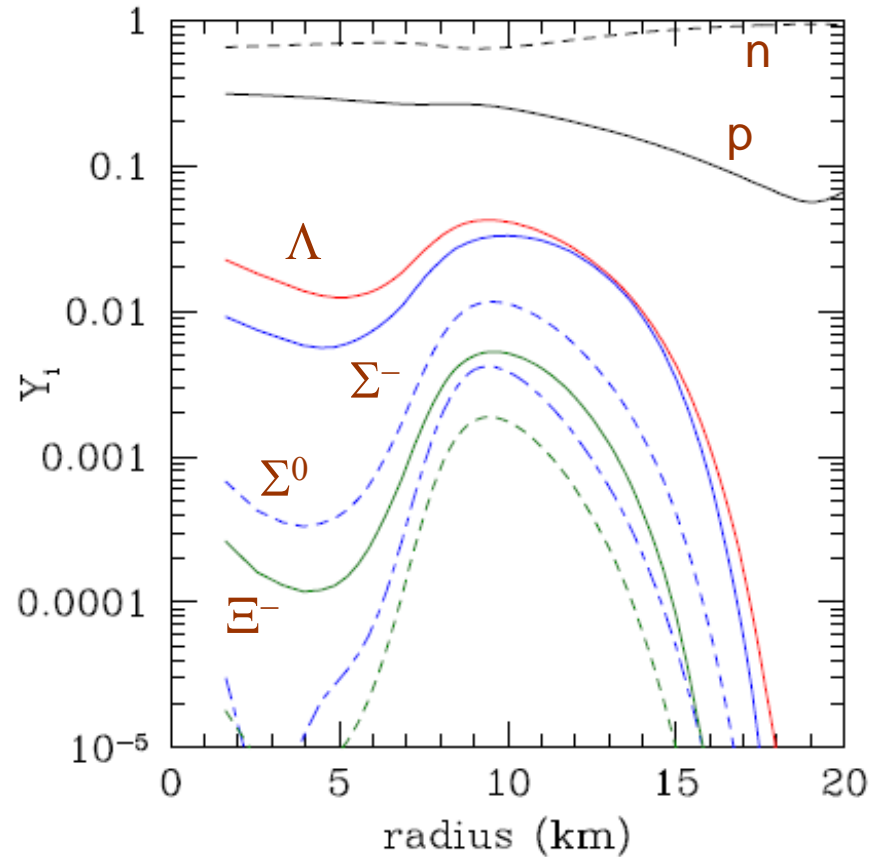
- More Σ^- for the center of the attractive case.
→ Collapse is more promoted due to EOS softening.

Compositions ($t_{\text{pb}} = 0.5 \text{ s}$)

repulsive



attractive

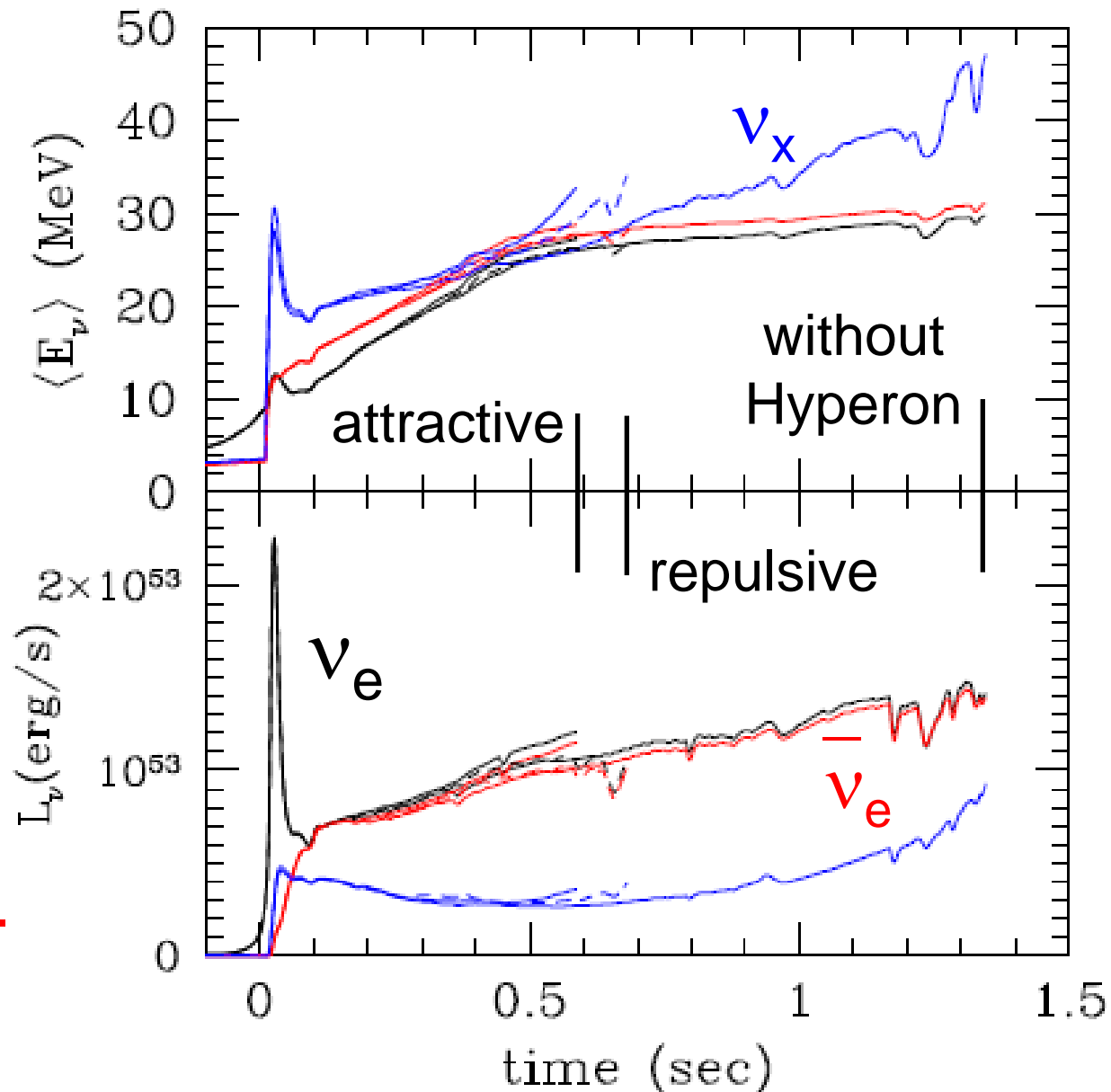


- For the attractive case, Σ^- appears earlier.
→ The influence is seen in the neutrino signal.

Neutrino Signal

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

→ Key for astrophysical probe



3. QCD transition

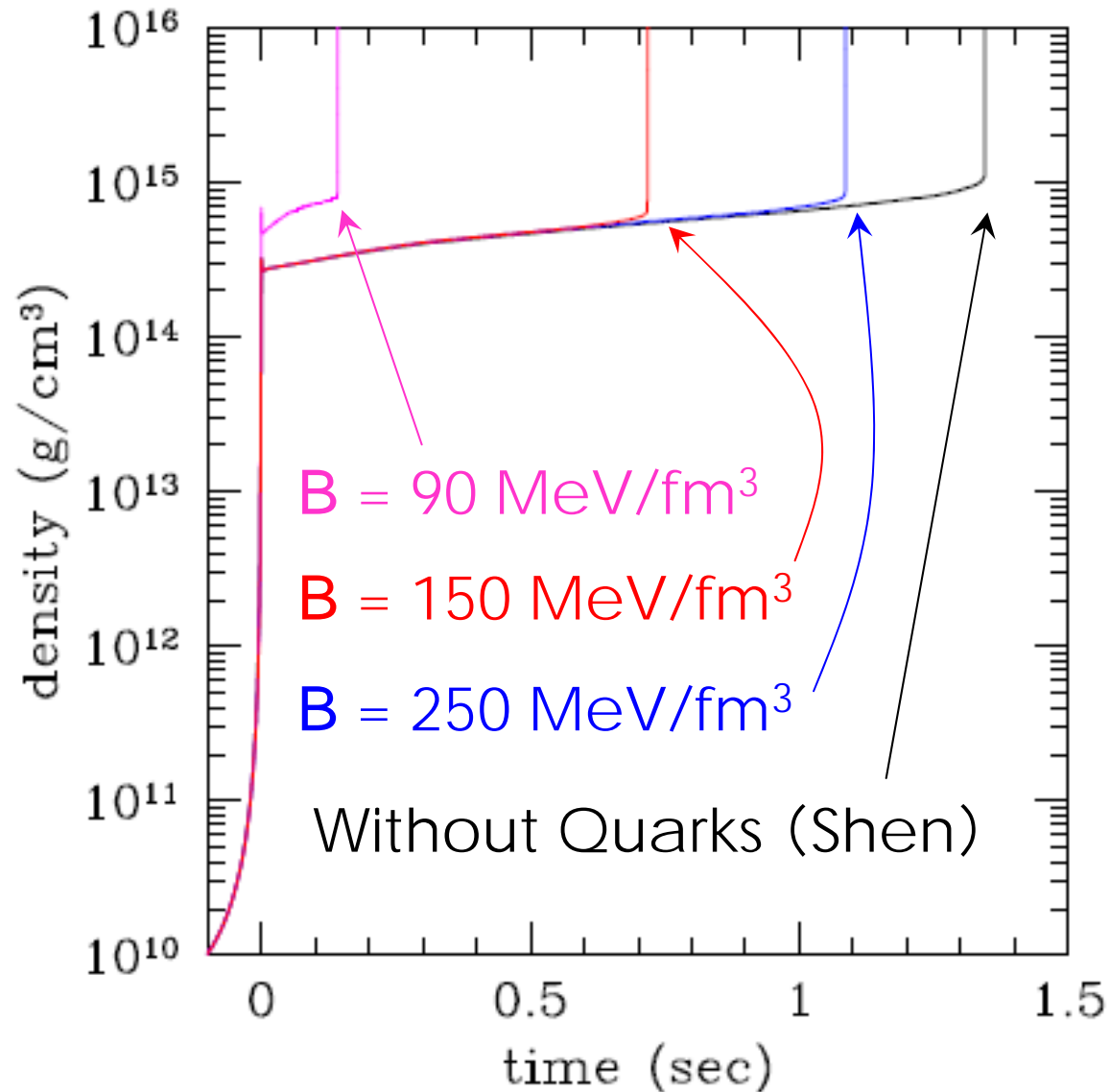
Hadron-quark mixed EOS

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.
 - $\mu_n = \mu_u + 2\mu_d, \quad \mu_p = 2\mu_u + \mu_d$
 - $P_H = P_Q$
- β equilibrium (ν trapping) is assumed in **Mixed** and **Quark** phase.
 - $\mu_d = \mu_s, \quad \mu_p + \mu_e = \mu_n + \mu_\nu$

Evolution of Central density

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



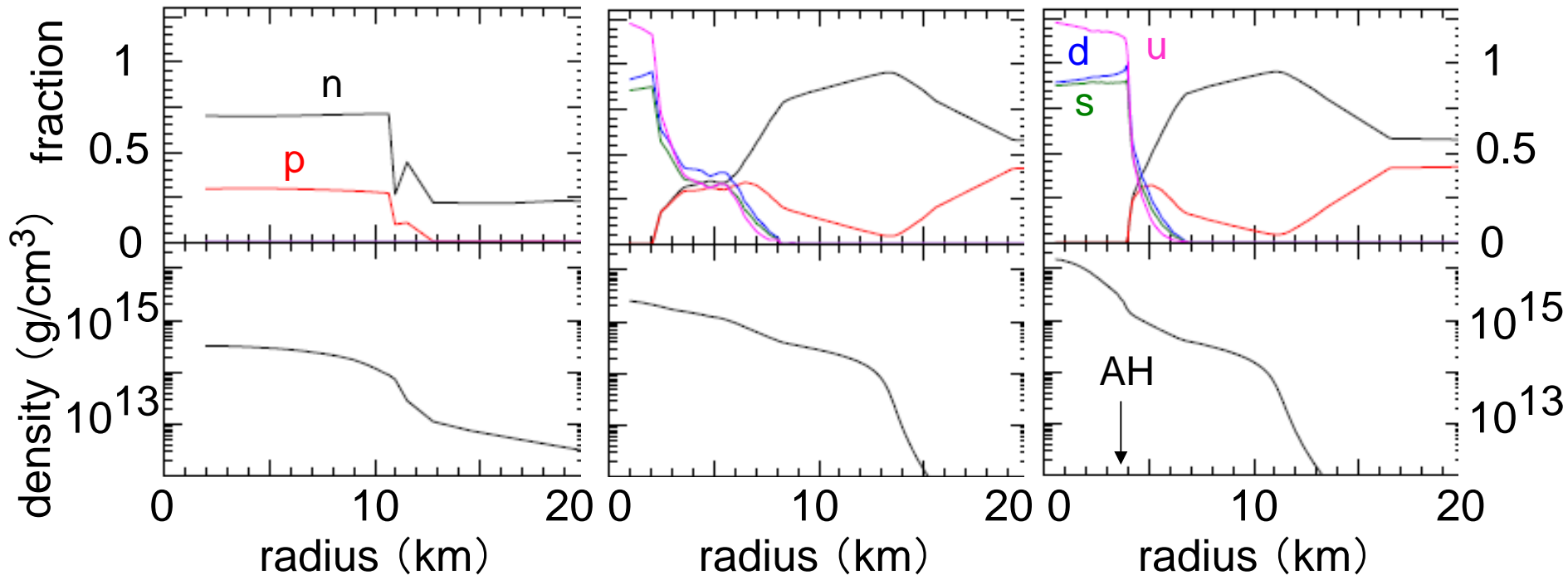
Compositions ($B = 250 \text{ MeV}/\text{fm}^3$)

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

27 ms before
BH formation

0.07 ms before
BH formation

at BH formation



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

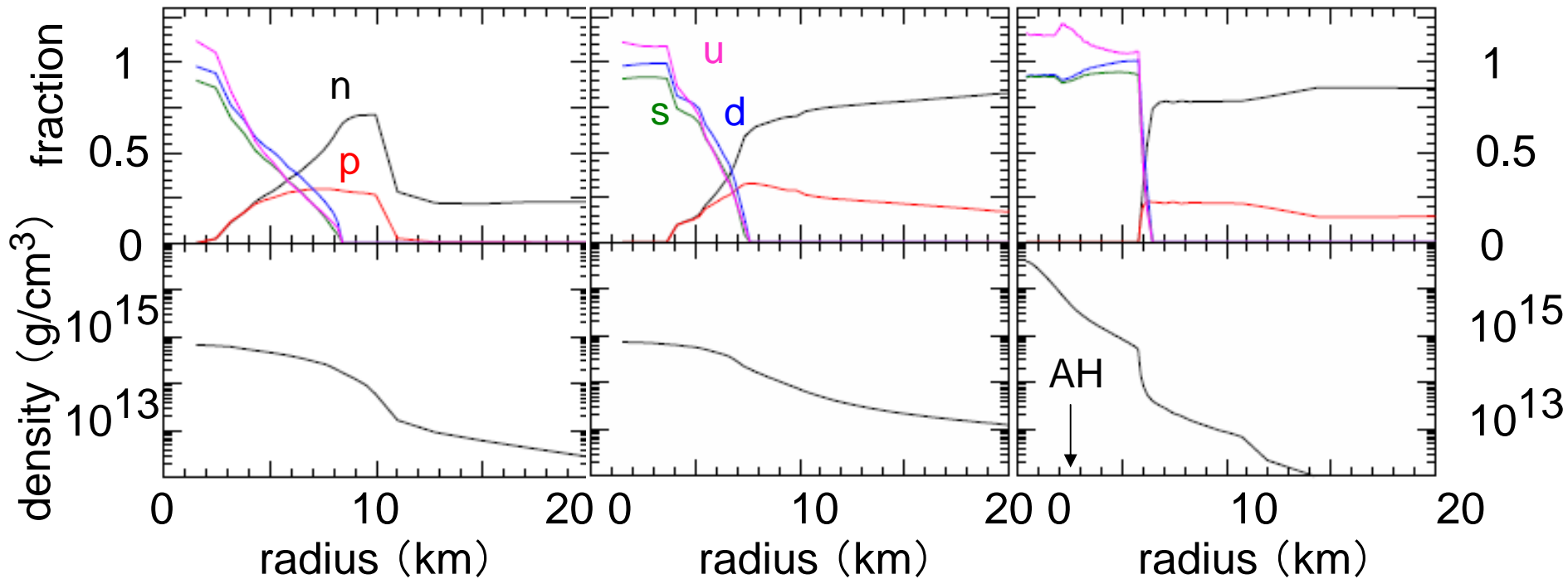
Compositions ($B = 90 \text{ MeV}/\text{fm}^3$)

Nakazato et al., in prep.

at bounce

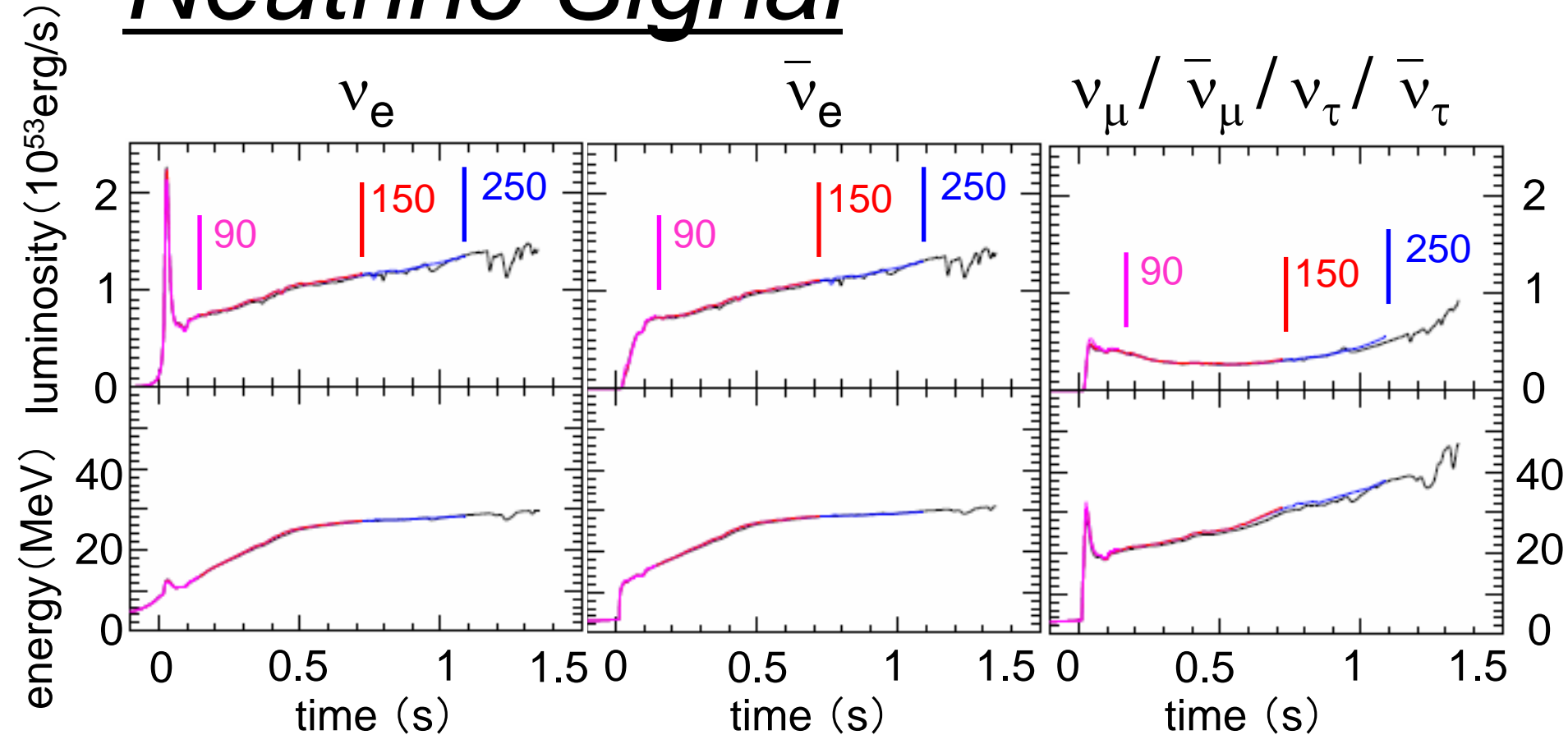
100 ms after bounce

at BH formation



- 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 $B = 90 \text{ MeV}/\text{fm}^3$.
- Neutrinos emitted from the outer region.

4. Conclusion

Summary

- We have performed a series of black-hole-forming core collapse simulations for non-rotating $40M_{\text{solar}}$ 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.