Exploring Hadron Physics in Black Hole Formation: a New Promising Target of Neutrino Astronomy

Ken’ichiro Nakazato

（Department of Astronomy, Kyoto University）

in collaboration with K. Sumiyoshi（Numazu CT）,
H. Suzuki（Tokyo U of Sci.）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. Core collapse simulation

   Impact of EOS and neutrino signal

3. Neutrino detection

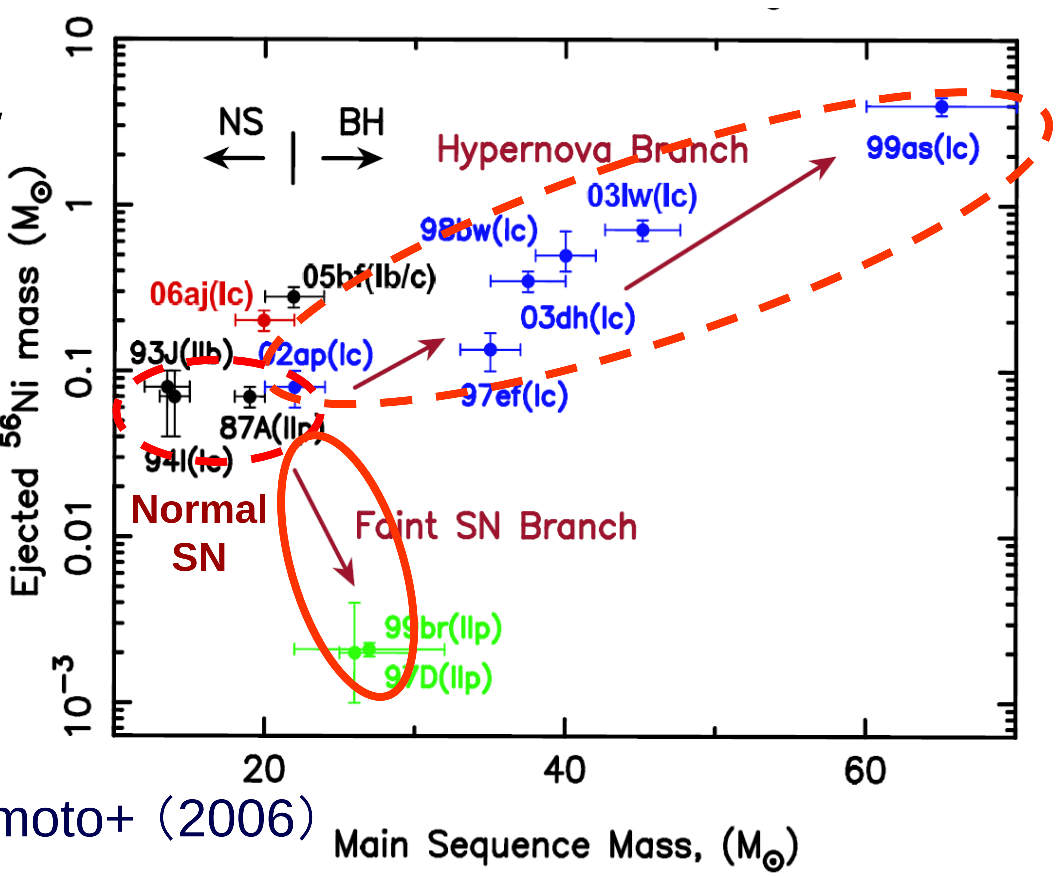
   Statistical analyses

4. Conclusion

1. Introduction

Fates of massive stars

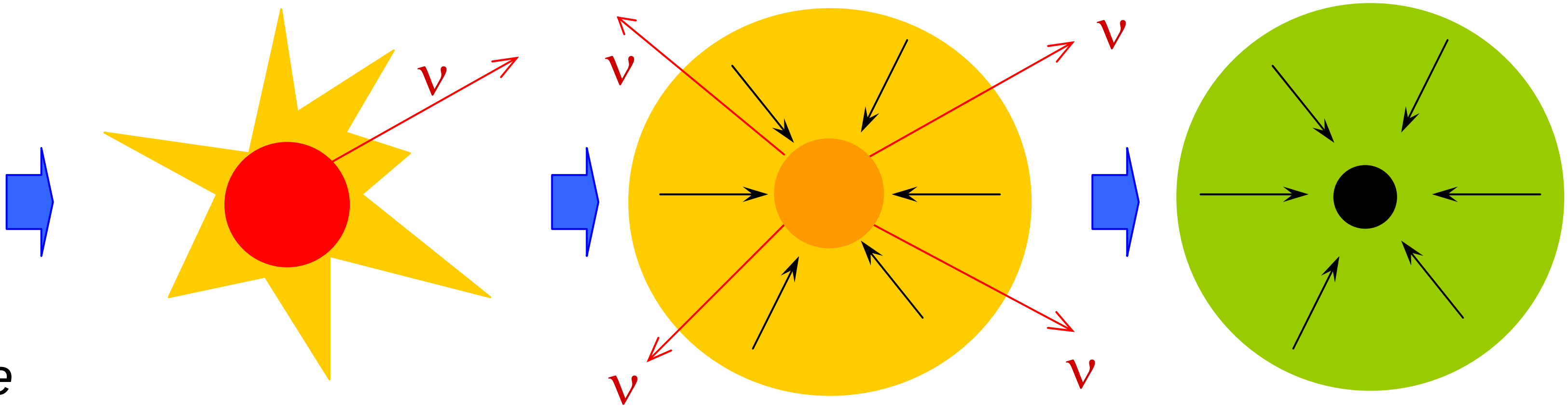
- Stars with > $10M_{solar}$ make a gravitational collapse and, possibly, a supernova explosion.
- Stars with > $25M_{solar}$ are thought to form a black hole（BH）.
- Observations show 2 branches.
  - Hypernovae（Rapid rotation）
  - Faint or Failed Supernovae（Weak rotation）



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.



Massive star

Proto-neutron star

Black hole

Core Collapse

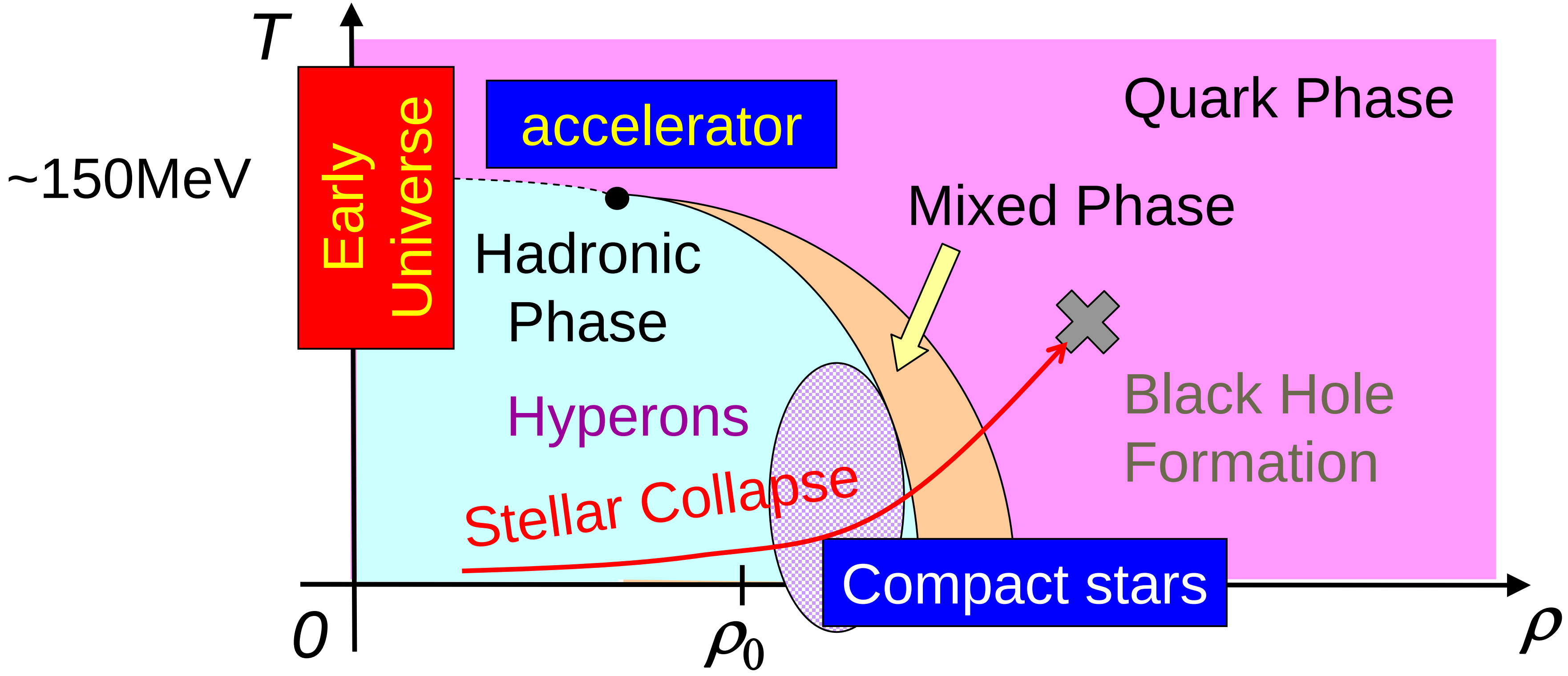
Bounce

Mass accretion

Motivation

- Can we probe into physics of hot and dense matter (including hyperons and quarks) by the black hole formation?

→ observable: Neutrinos!



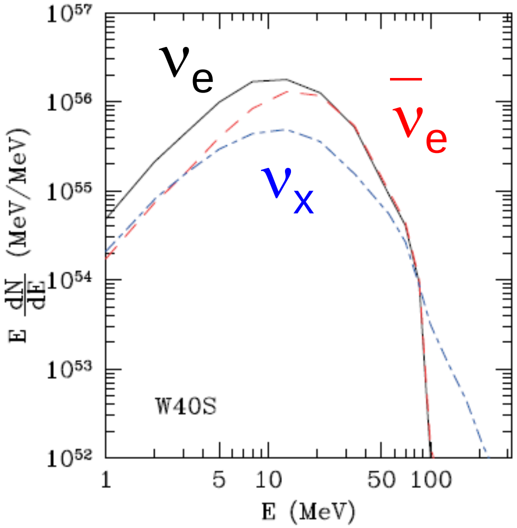
Aims of this study

- Thus, property of hot and dense matter is also a target of neutrino astronomy.
  - Equation of State（EOS）of nuclear matter
  - Hyperon（Ishizuka+ 2008, Sumiyoshi+ 2009）
  - QCD transition（Nakazato+ 2008a, in prep.）
- Evaluate the ν event number from failed supernovae with $40M_{solar}$ non-rotating progenitor.
- Investigate the EOS dependences of ν signal.

Brief sketch of our study

- Numerical simulations of black hole formation

- Spectra of emitted neutrinos



Nakazato et al. (2008b)

- Event numbers on the detector

  （SuperKamiokande）→ Discussion

Brief sketch of our study

- Numerical simulations of black hole formation

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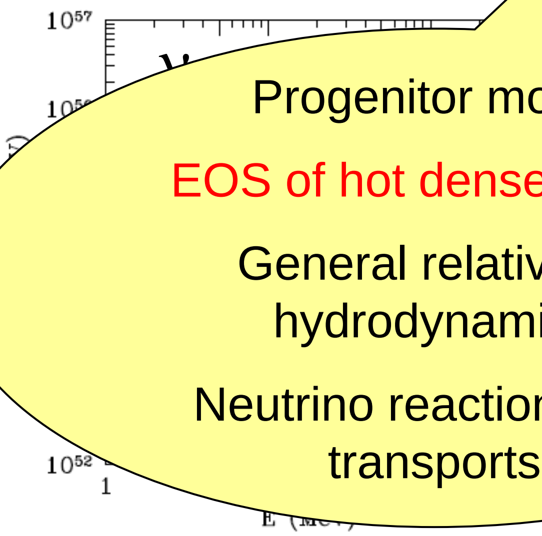

Progenitor model

EOS of hot dense matter

General relativistic hydrodynamics

Neutrino reactions and transports

Neutrino Oscillation

Neutrino reaction in the detector

Detectability（e.g. energy resolution）

- Event numbers on the detector（SuperKamiokande）→ Discussion

2. Core collapse simulation

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）
    - 3 choices of incompressibility: K = 180, 220, 375 MeV
  - Shen EOS
    - Relativistic Mean Field theory（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）
- Future work
  - Quark + hyperon + pion EOS

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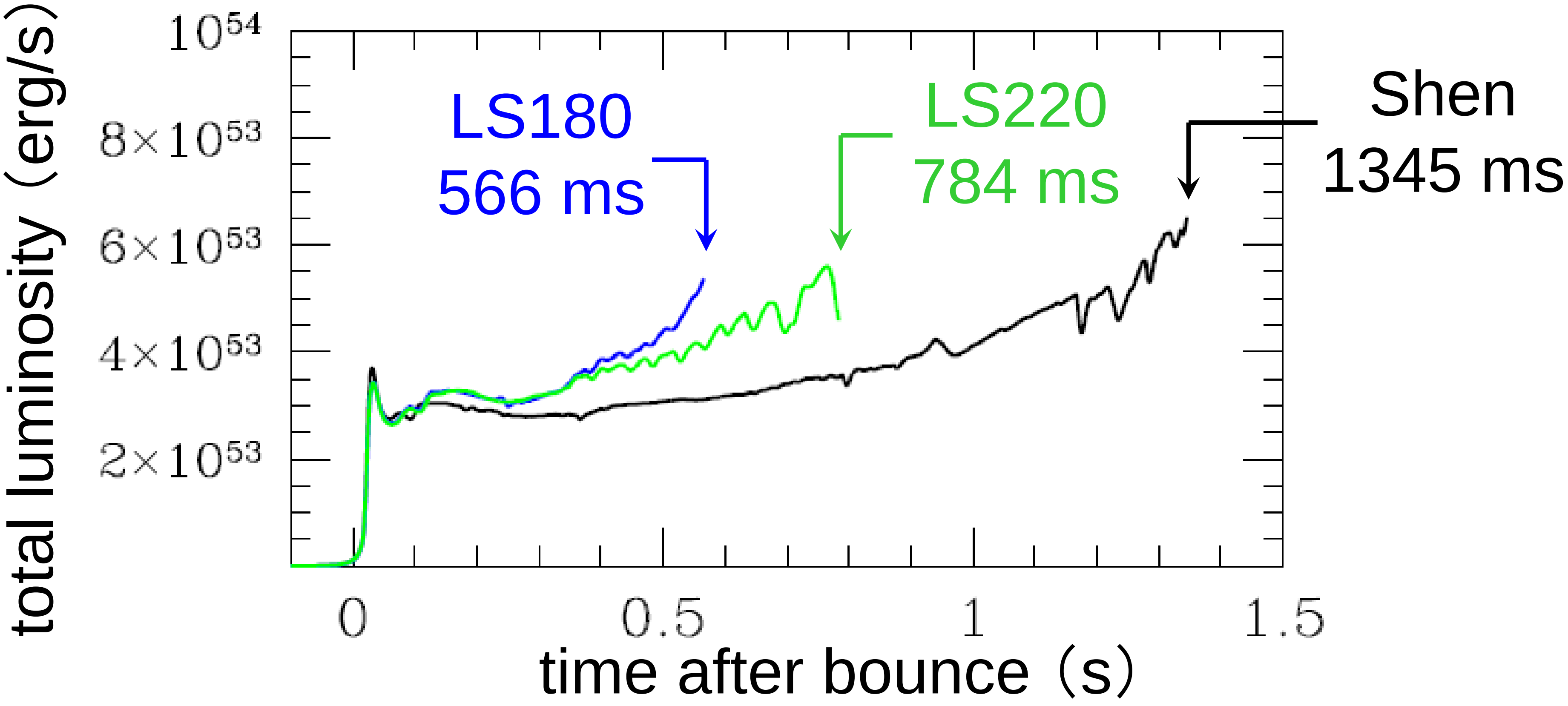
Already utilized in our numerical simulations.

Results for “nucleonic” EOS’s



LS180
566 ms

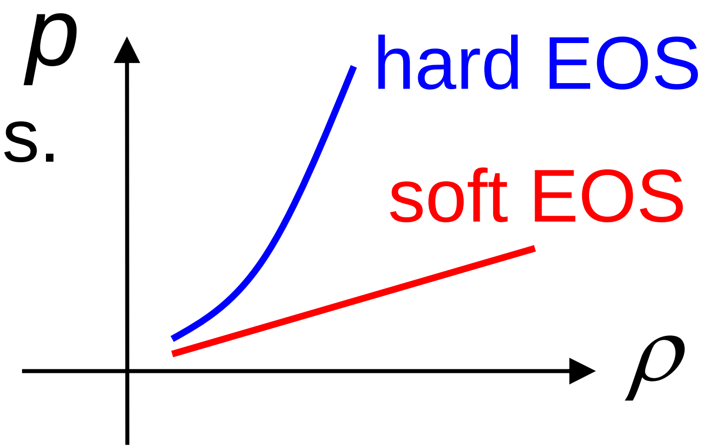
LS220
784 ms

Shen
1345 ms

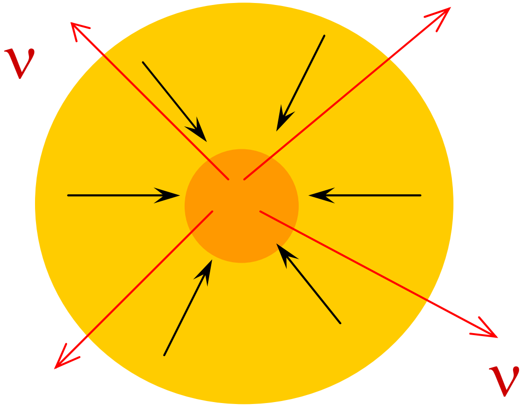
- Shen EOS is hardest (K = 281 MeV).
- Harder EOS has longer ν emission.
- Softer EOS has high ν luminosity.

Role of matter property

- Determining hardness of Equation of State (EOS).
  - Soft EOS is easy to compress.
  - Maximum mass of compact star is lower for soft EOS.



Mass accretion
(ram pressure)



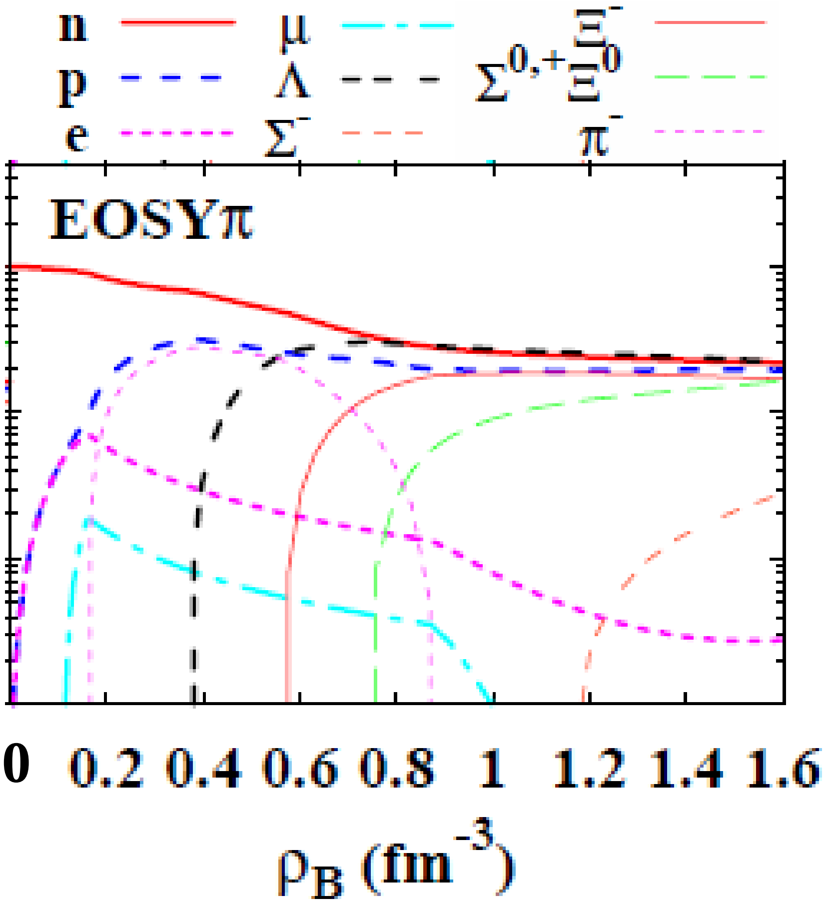
Proto-neutron star

- Inside the failed supernovae…
  - For soft EOS, more compressed, T ↗, ν energy and luminosity ↗.
  - For soft EOS, BH formation is fasten due to low maximum mass.

Hyperon EOS

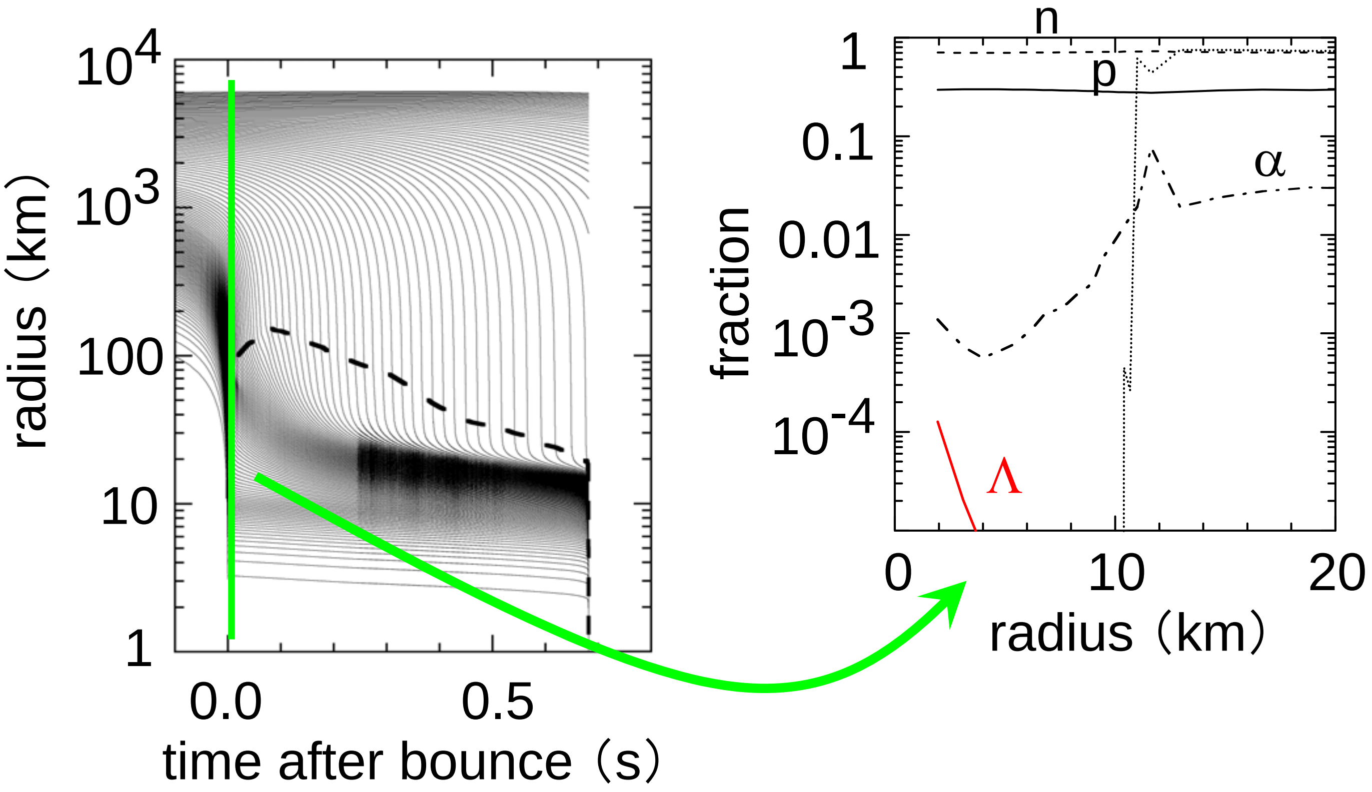
Ishizuka et al., J. Phys. G 35,（2008）, 085201

- Relativistic Mean Field Theory
  - extension of Shen EOS to the baryon octet
- Latest experimental results for potentials are taken into account.
  - $U_\Lambda = -30$ MeV
  - $U_\Sigma = 30$ MeV（repulsive）
  - $U_\Xi = -15$ MeV
- Data with thermal pions is also prepared.



Collapse with hyperon EOS

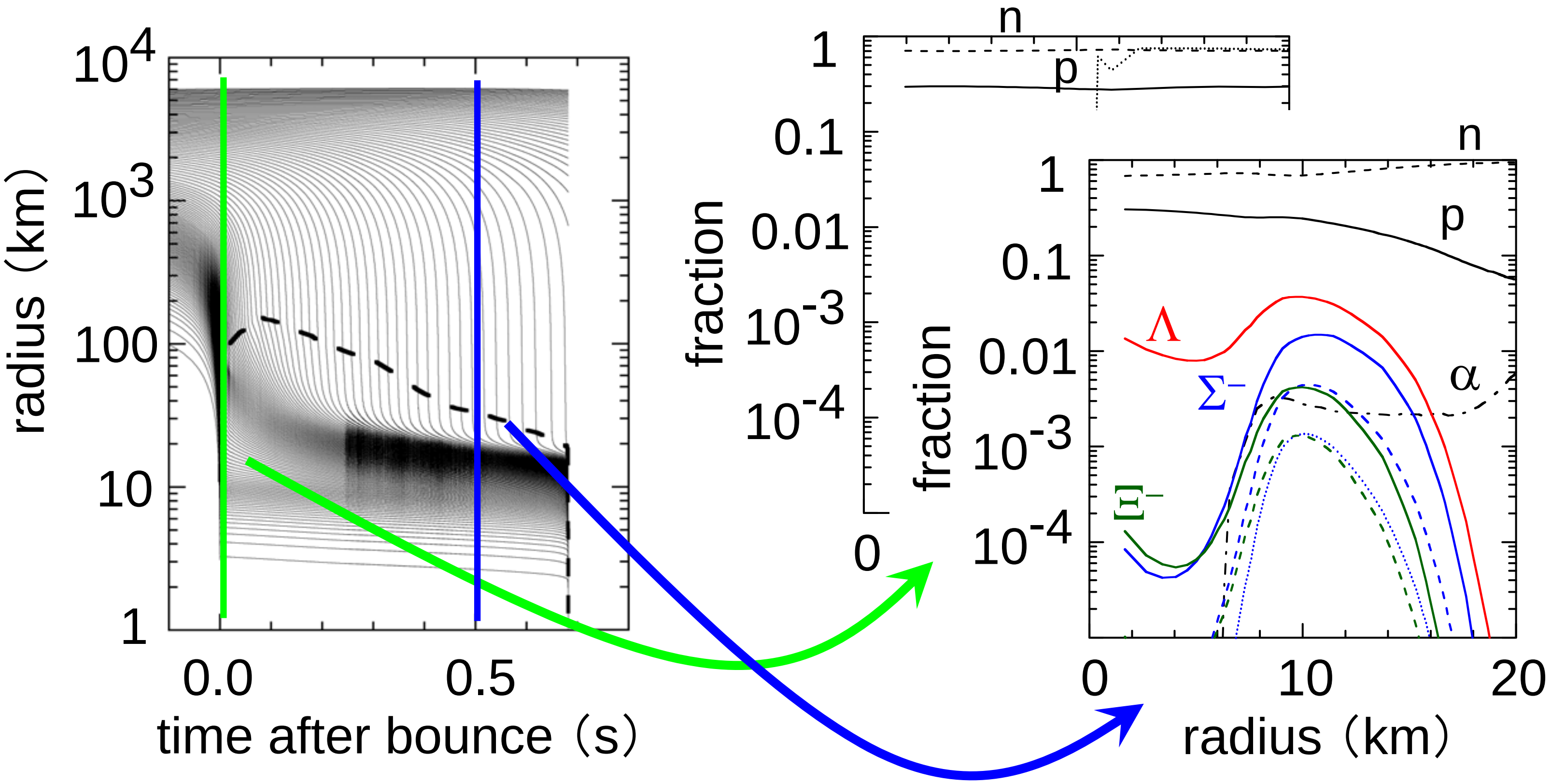
Sumiyoshi et al., Astrophys. J. Lett. 690（2009）, 43



- Hyperons appear for the late phase.

Collapse with hyperon EOS

Sumiyoshi et al., Astrophys. J. Lett. 690（2009）, 43



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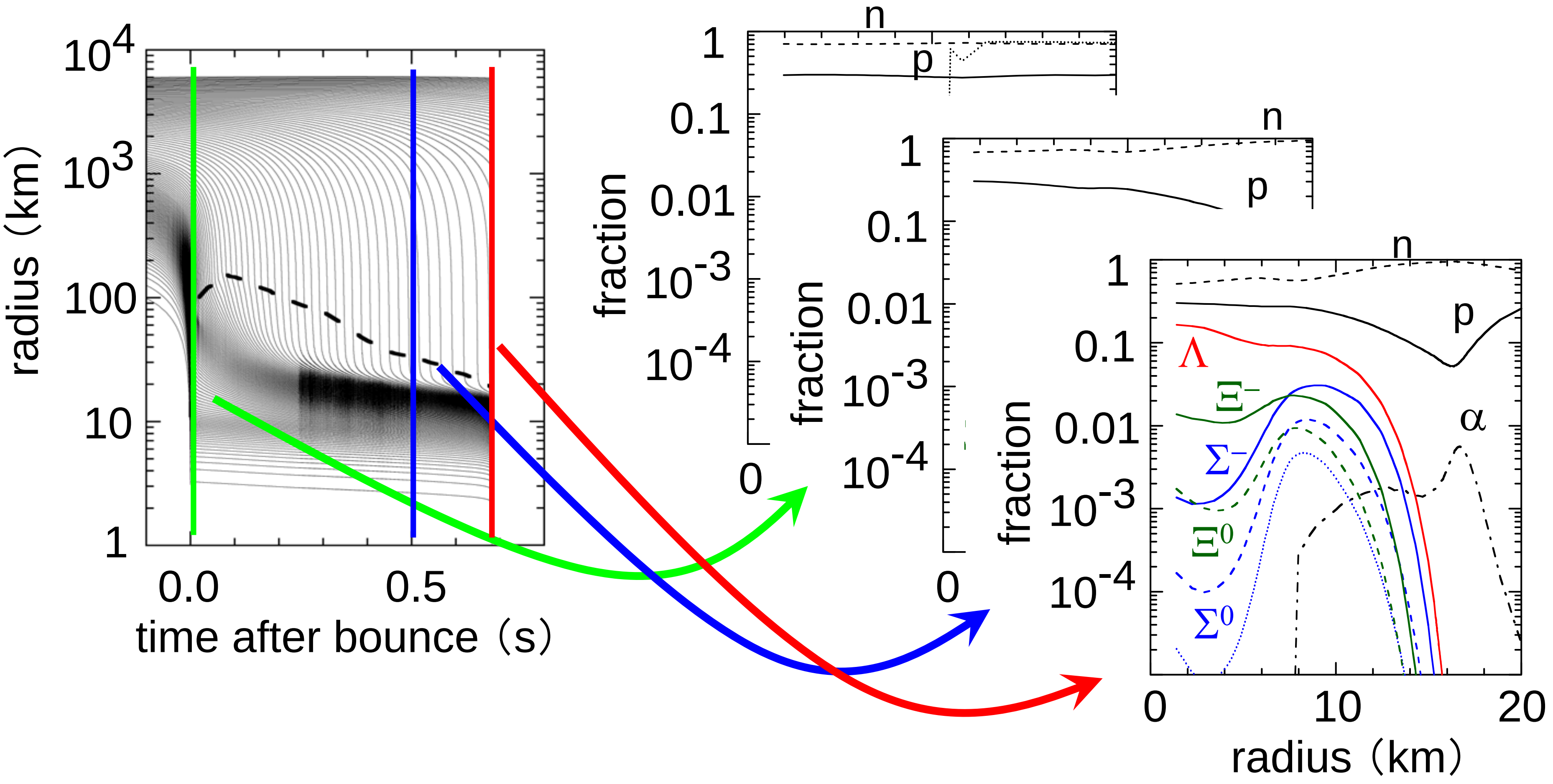


- Hyperons appear for the late phase.

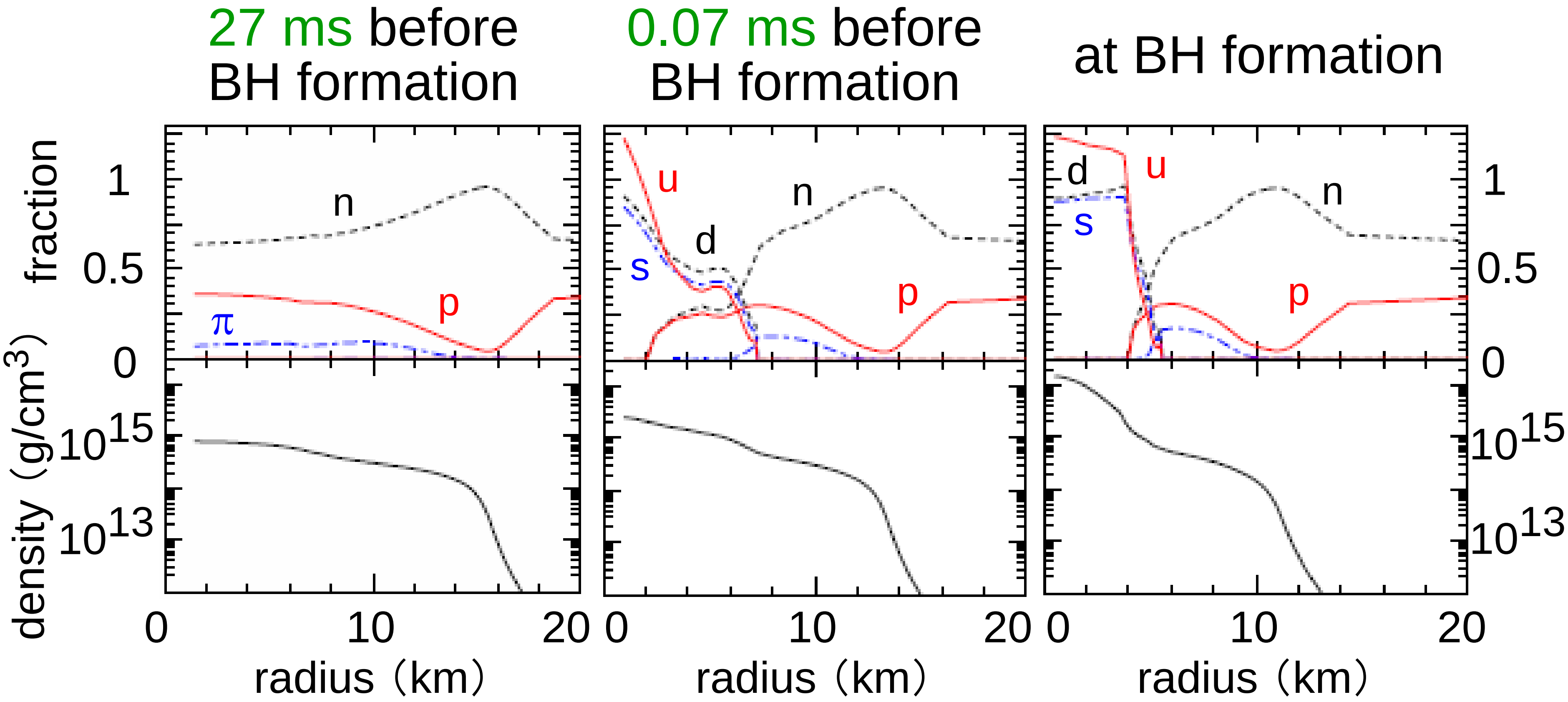
Hadron-quark mixed EOS

Nakazato et al., PRD 77（2008a）, 103006

- Shen EOS with pions for Hadronic phase
- MIT Bag model（Chodos et al. 1974）for Quark phase
  - Bag constant: $B = 250\ \mathrm{MeV/fm^3}$
- 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.
  - $\mu_d = \mu_s$, $\mu_p + \mu_e = \mu_n + \mu_\nu$

Collapse with quark EOS

Nakazato, Ph. D thesis（2008）& Nakazato et al., in prep.



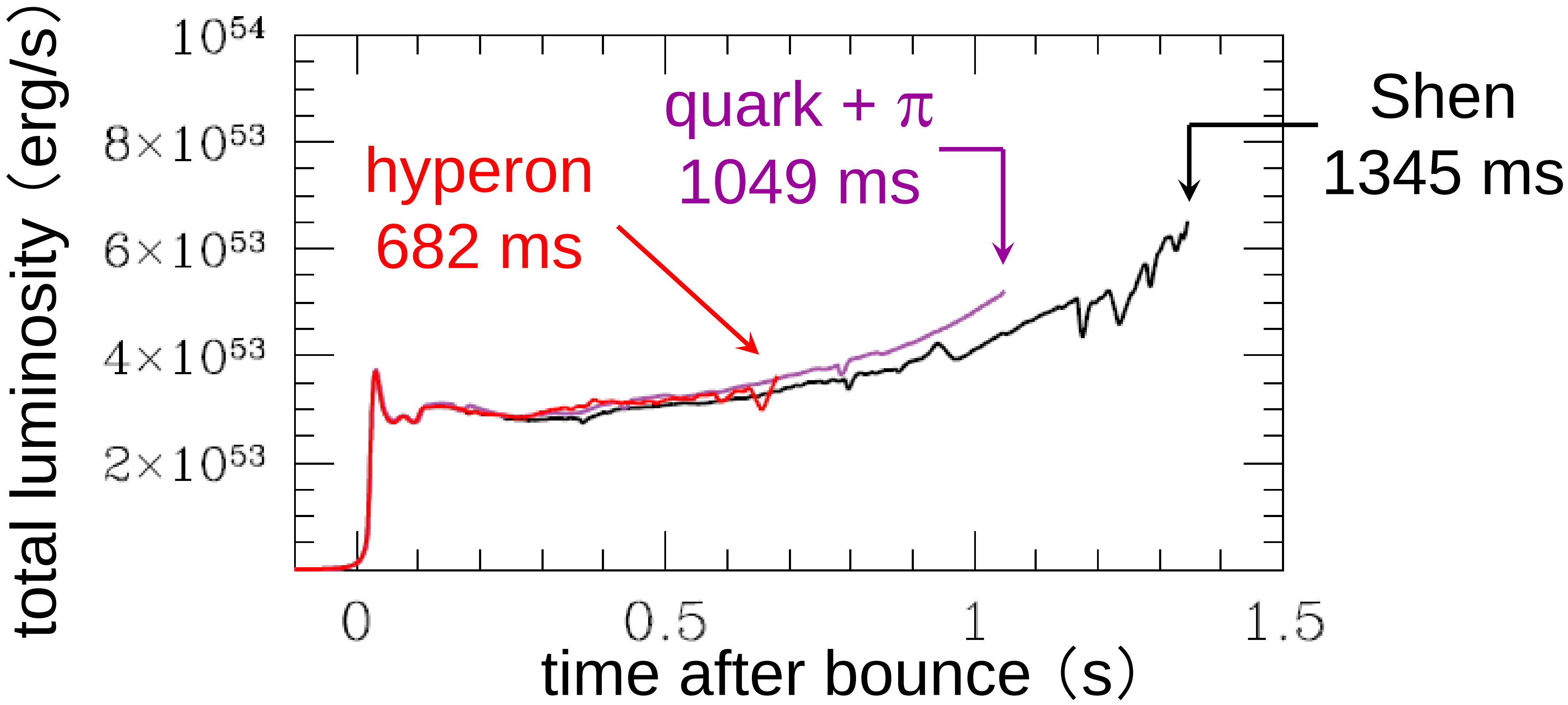
27 ms before BH formation

0.07 ms before BH formation

at BH formation

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

Results for “exotic” EOS’s



hyperon
682 ms

quark + π
1049 ms

Shen
1345 ms

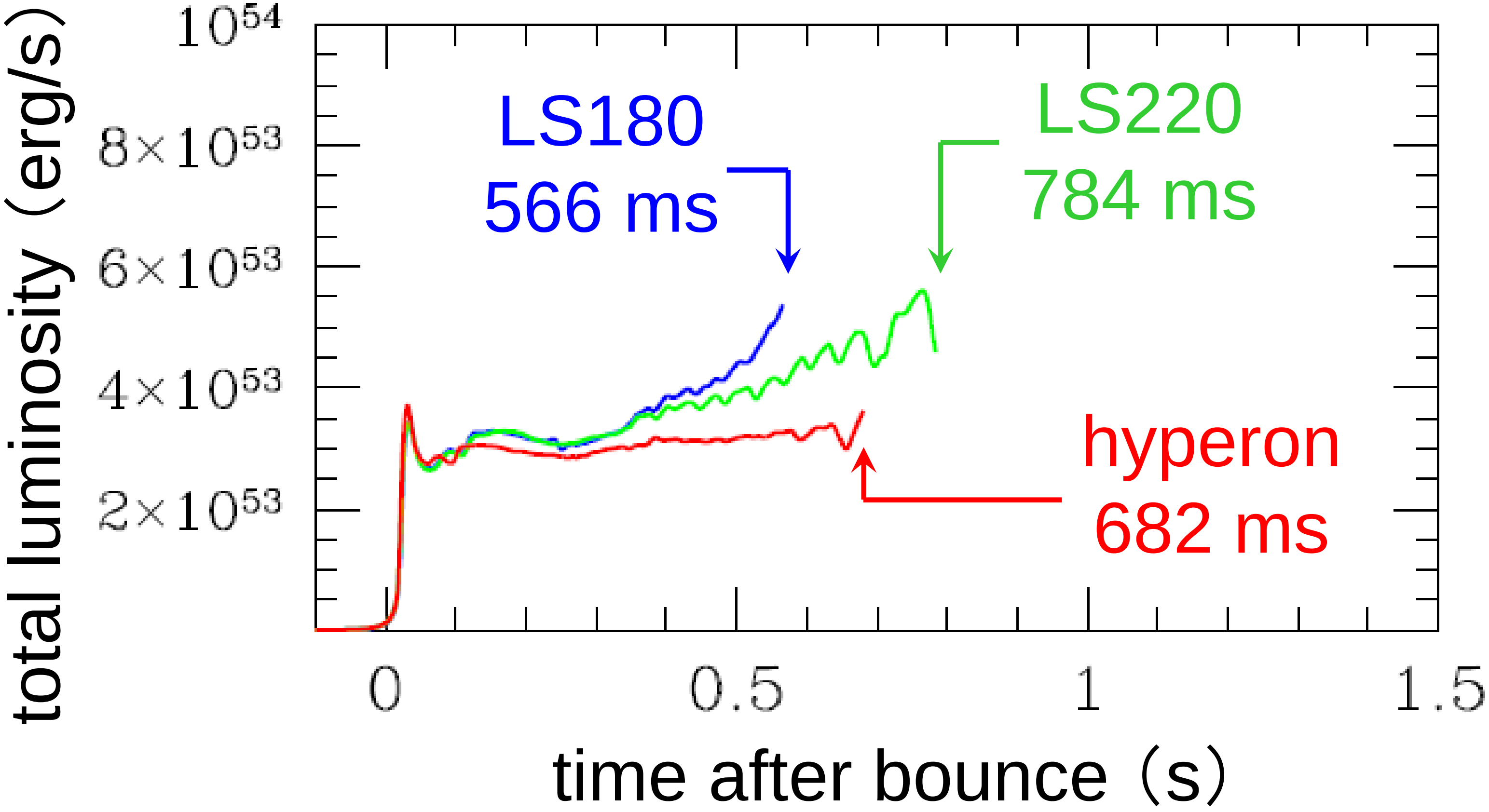
- Hyperons and quarks (with pions) shorten the duration of ν emission.
- But, not affect the ν luminosity very much.

Short summary

- For nucleonic model, soft EOS has short duration and high luminosity ν emission.
- Hyperons and quarks shorten the duration but not affect ν luminosity very much.

- However, there is a question.

Short summary



- Can we distinguish hyperonic model from soft nucleonic models?

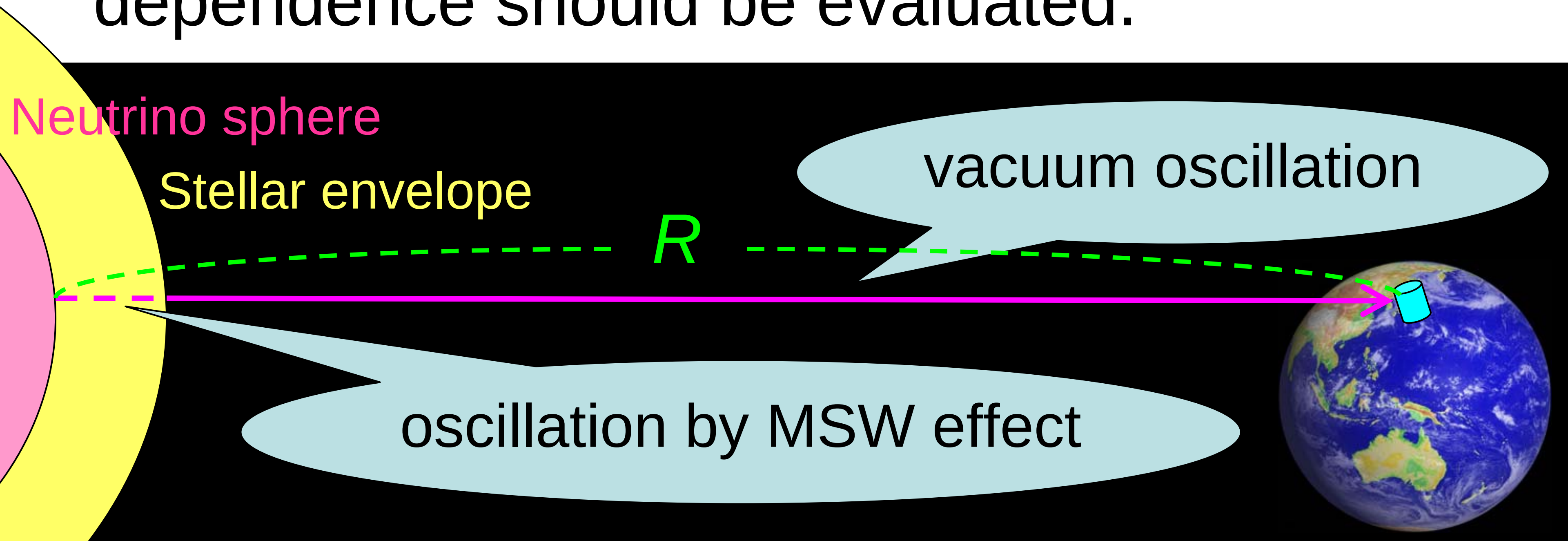
3. Neutrino detection

Oscillation of failed supernova ν

Nakazato et al., PRD 78（2008b）, 083014

- Neutrino oscillation occurs before detection.
- But there are undetermined parameters, namely $\sin^2\theta_{13} < 0.02$ and mass hierarchy.

→ Neutrino oscillation and its parameter dependence should be evaluated.



Neutrino event number

- Neutrino flux is scaled as $\propto 1 / R^2$
- Event number is comparable to that of ordinary SN ν (~ 10000 for events in our Galaxy).
- Event number depends also on the mixing parameters.

EOS	Normal & $\sin^2\theta_{13}=10^{-8}$	Inverted & $\sin^2\theta_{13}=10^{-2}$
Hyperon	16,490	9,952
LS180	16,086	12,136
LS220	25,978	23,656

Event numbers for R = 10 kpc, but R may be undetermined from obs…

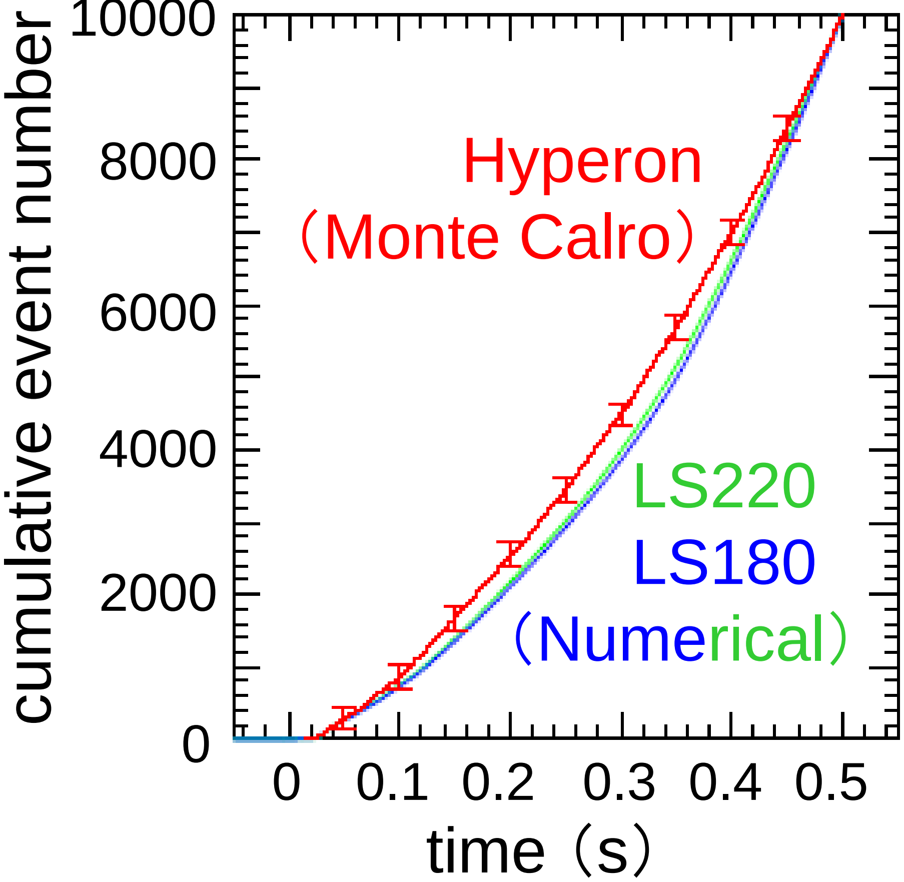
Statistical analyses

Nakazato et al., submitted.

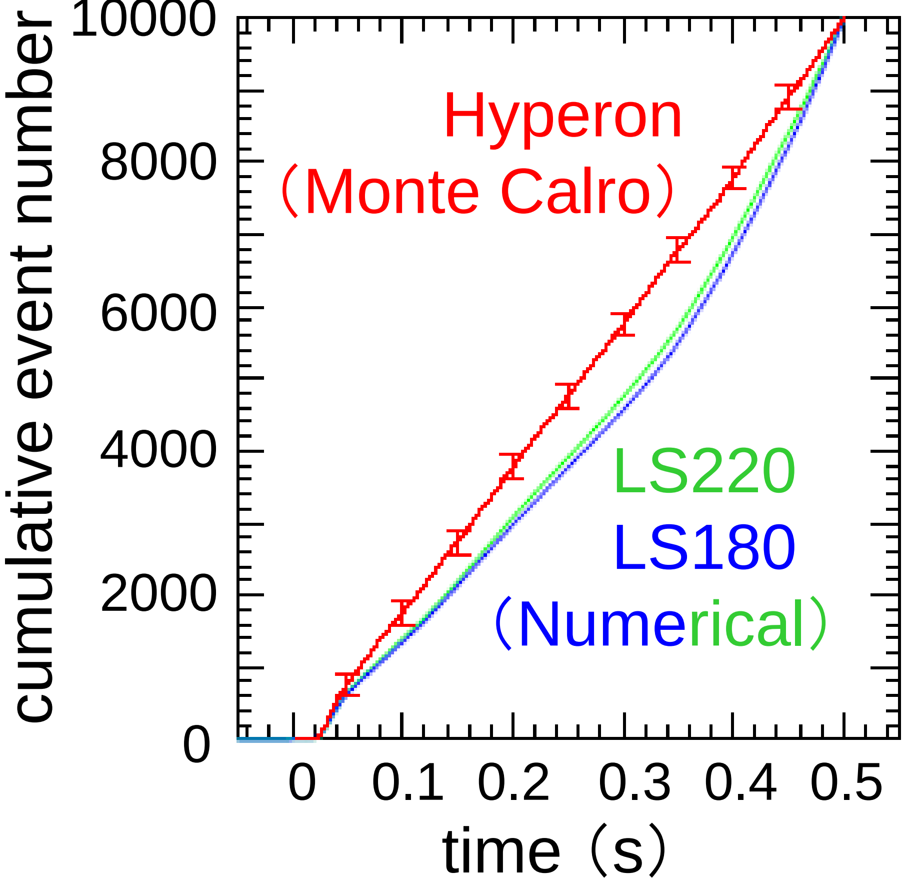
- Normalize cumulative event numbers by total event number till 0.5s after bounce, $N_{0.5s}$, and assume $N_{0.5s}$ = 10000（event in our Galaxy）.
- Perform Monte Carlo simulation for detection based on numerical data of Hyperon case, and compare it to numerical data of LS cases.
- Judge these cases are distinguished or not by Kolmogorov-Smirnov test.
- Merit of this method;
  - We do not have to take care of the distance to the source and ν emission after BH formation.

Result of the fitting（$N_{0.5s}$= 10000）

Normal & $\sin^2\theta_{13}=10^{-8}$

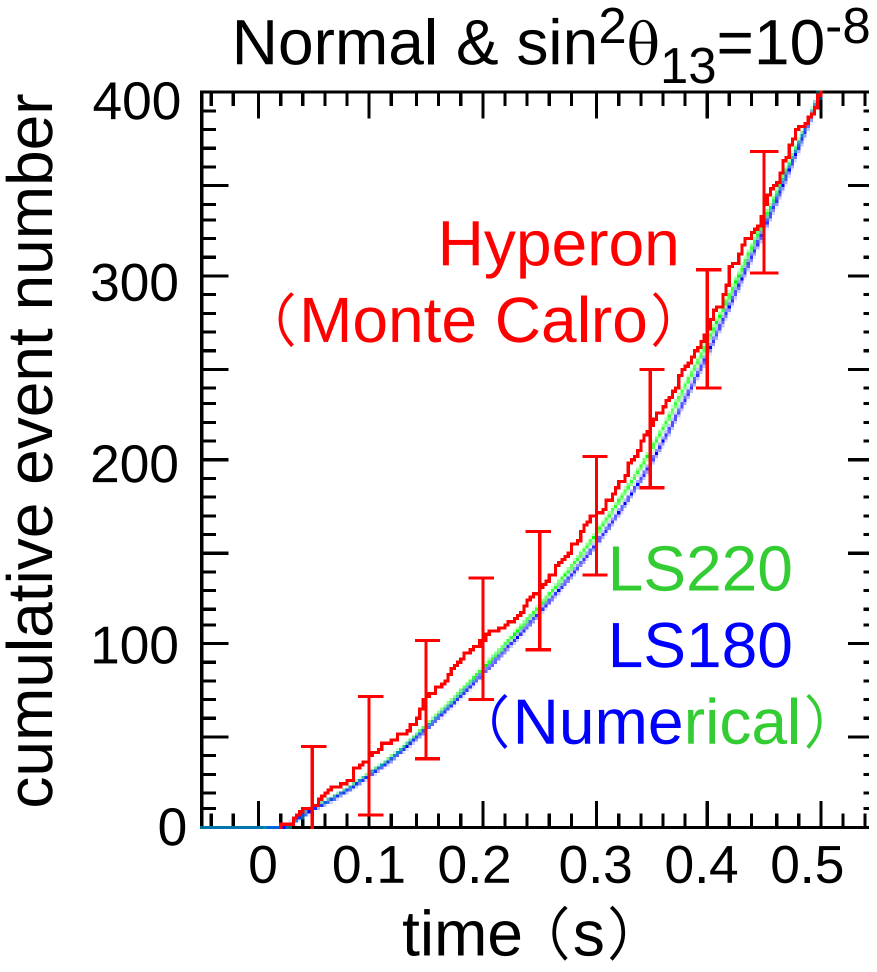


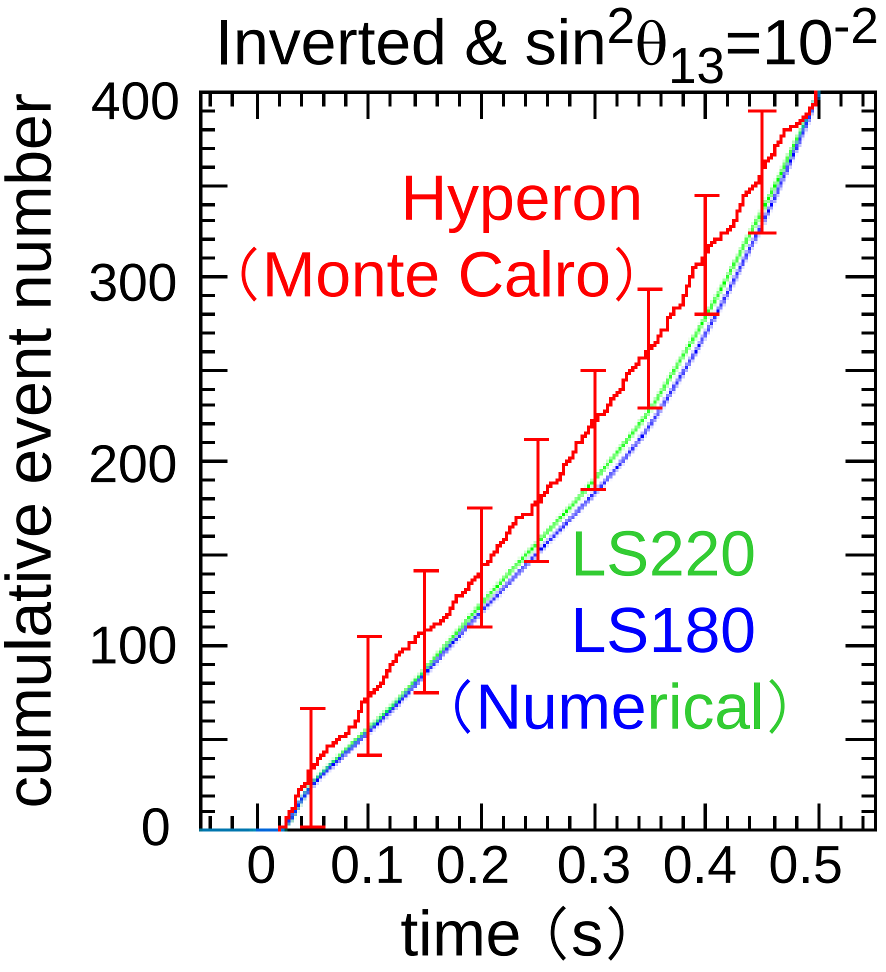
Inverted & $\sin^2\theta_{13}=10^{-2}$



- They are distinguishable with 99% C.L. for both mixing parameter sets.

Result of the fitting（$N_{0.5s}$= 400）


Normal & $\sin^2\theta_{13}=10^{-8}$


Inverted & $\sin^2\theta_{13}=10^{-2}$

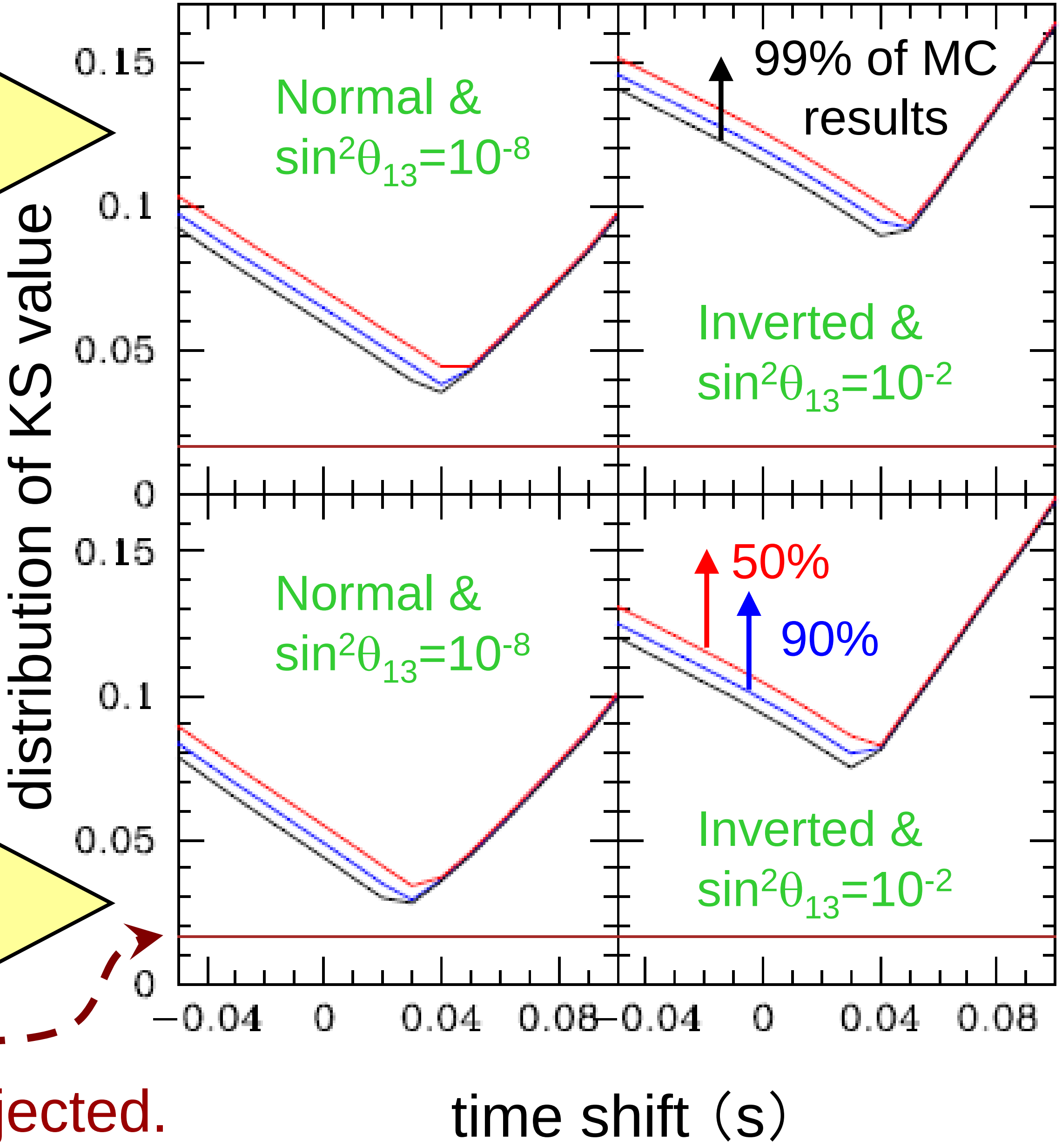
- The distinction is difficult for left case but feasible for right case（90% of MC simulations）.

Analyses with time-shift（$N_{0.5s}$= 10000）

Hyperon vs. LS180

- Start point of burst is vague.
- If start point is shifted, they are distinguishable for any cases.

Hyperon vs. LS220



MC sim. with KS value larger than this line is rejected.

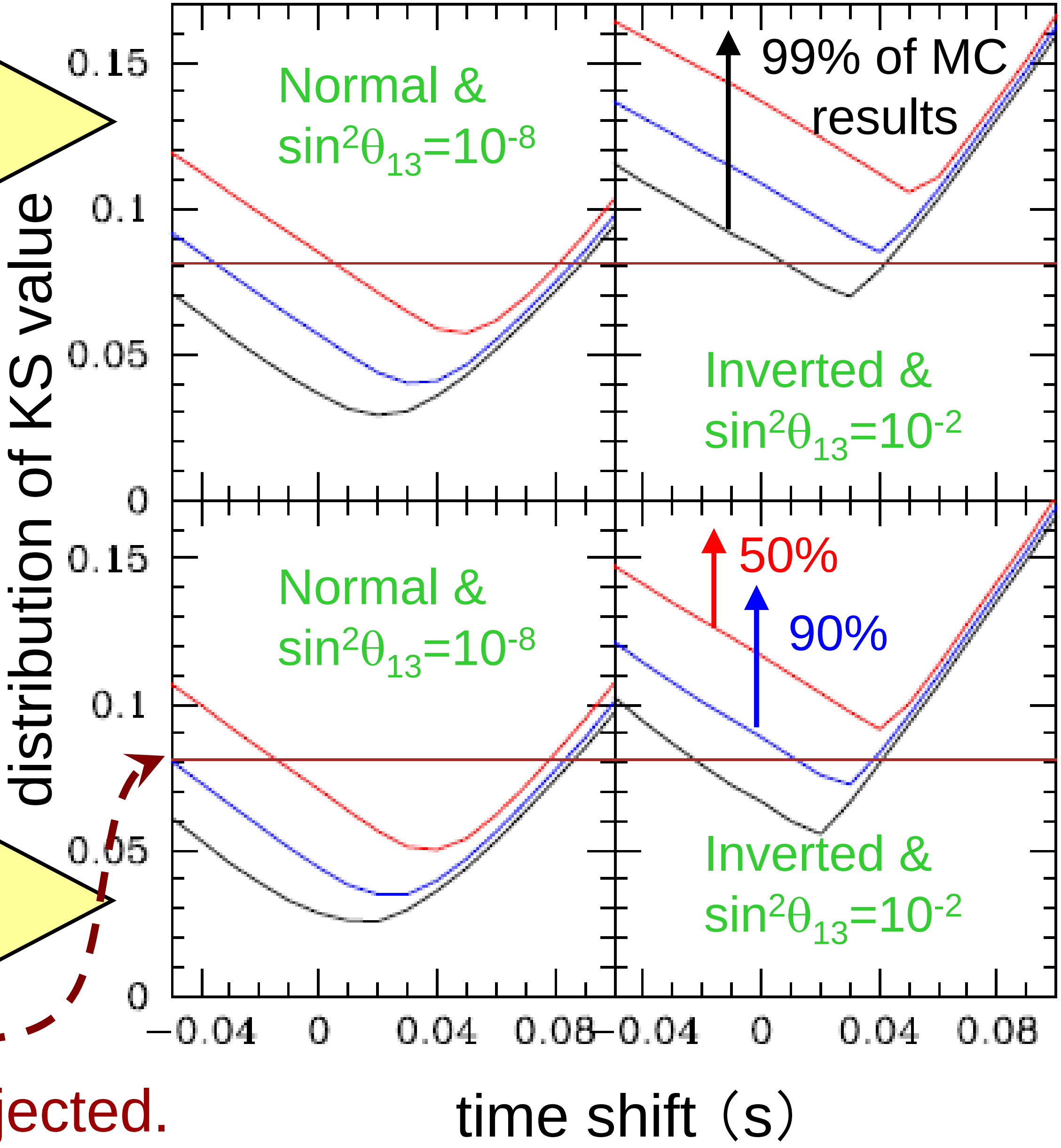
Analyses with time-shift（$N_{0.5s}$= 400）

Hyperon vs. LS180

- The distinction is difficult for normal & $\sin^2\theta_{13} = 10^{-8}$, but feasible for inverted & $\sin^2\theta_{13} = 10^{-2}$.

Hyperon vs. LS220

MC sim. with KS value larger than this line is rejected.



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.
- Differences in ν light curve is statistically distinguishable by SuperKamiokande for the progenitors in our Galaxy.

→ *These results implies possibilities to probe the properties of hot and dense nuclear matter from neutrino astronomy.*

Future work

- More EOS’s.
  - EOS with quarks, hyperons and pions.
  - EOS by other frameworks（e.g., many body theory etc.）
- More initial models.
  - Mass loss and convection may affect the density profile of outer layer.
- More detailed treatments for ν detection.
  - Earth effect
  - Oscillation by self interaction

→ *This is the beginning!!*