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

Ken'ichiro Nakazato （Kyoto U）

Kohsuke Sumiyoshi （Numazu CT）

Hideyuki Suzuki （Tokyo U of Sci.）

Shoichi Yamada （Waseda U）

Ref: Sumiyoshi et al. (2009), Nakazato et al., submitted.

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EOS affects the dynamics of astro-physical phenomena. It's OK. But, can we investigate it observationally?

Ref: omitted.

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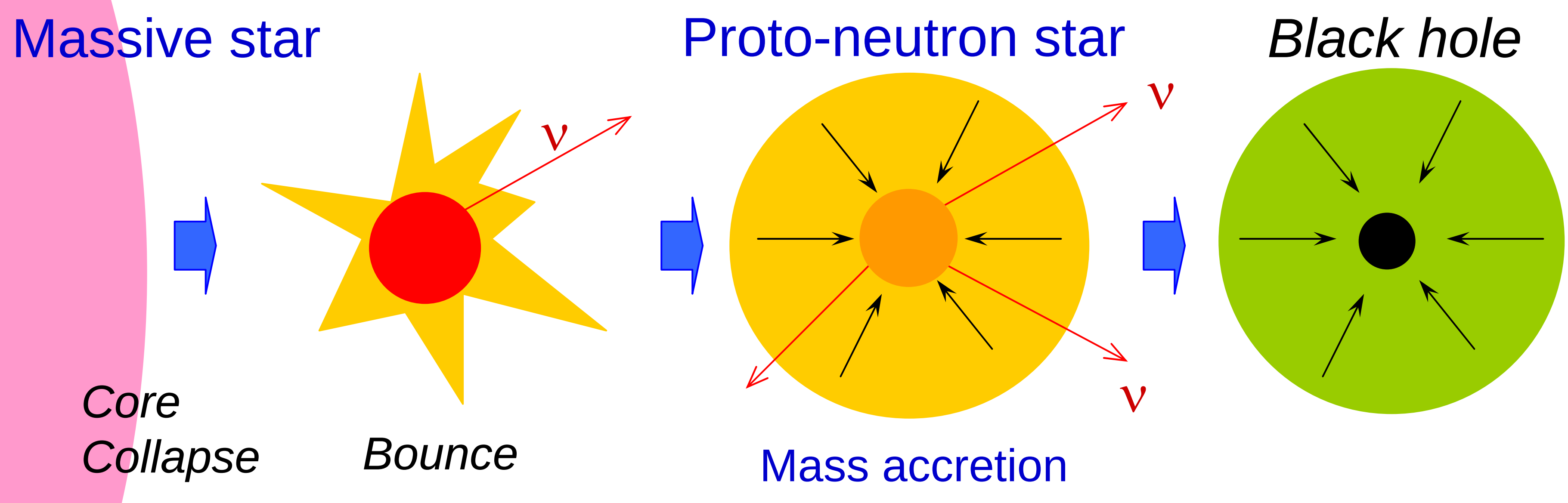
Failed supernova neutrinos

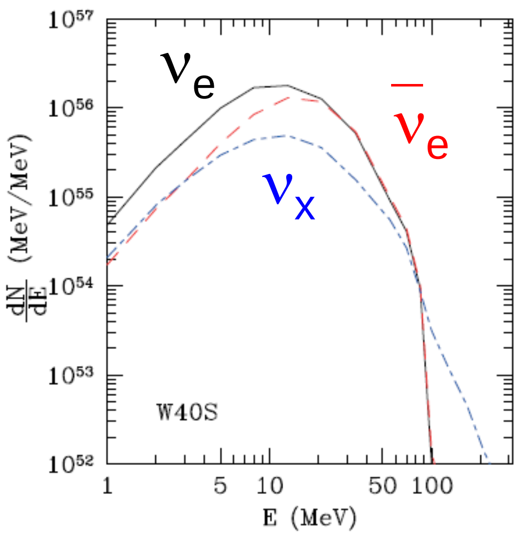
- Failed supernova progenitor makes bounce once and recollapse to the black hole.
- In this process, temperature and density of central region gets a few times 10 MeV and a few times ρ_0 (saturation density of nuclear matter), and a lot of neutrinos are emitted.



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

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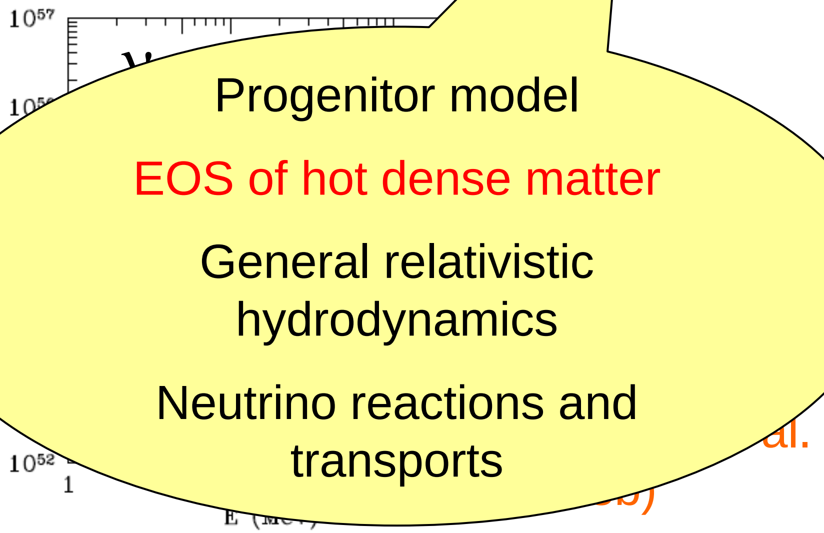


Progenitor model

EOS of hot dense matter

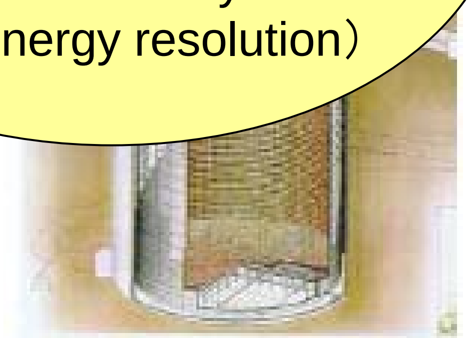
General relativistic hydrodynamics

Neutrino reactions and transports

Neutrino Oscillation

Neutrino reaction In the detector

Detectability （e.g. energy resolution）



- Event numbers on the detector （SuperKamiokande）→ Discussion

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, Sagert+ 2009）

- Evaluate the ν event number from failed supernovae with $40M_{solar}$ non-rotating progenitor based on the previous study.

- Investigate whether the EOS dependences of ν signal are distinguishable or not.

Hydrodynamics & Neutrinos

Spherical, Fully GR Hydrodynamics

（Yamada 1997）

metric：Misner-Sharp（1964）　mesh：127 non uniform zones

\+

Neutrino Transport（Boltzmann eq.）

（Yamada et al. 1999 ; Sumiyoshi et al. 2005）

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 : $e^- + p \leftrightarrow n + \nu_e$, $e^+ + n \leftrightarrow p + \bar{\nu}_e$, $\nu + N \leftrightarrow \nu + N$,

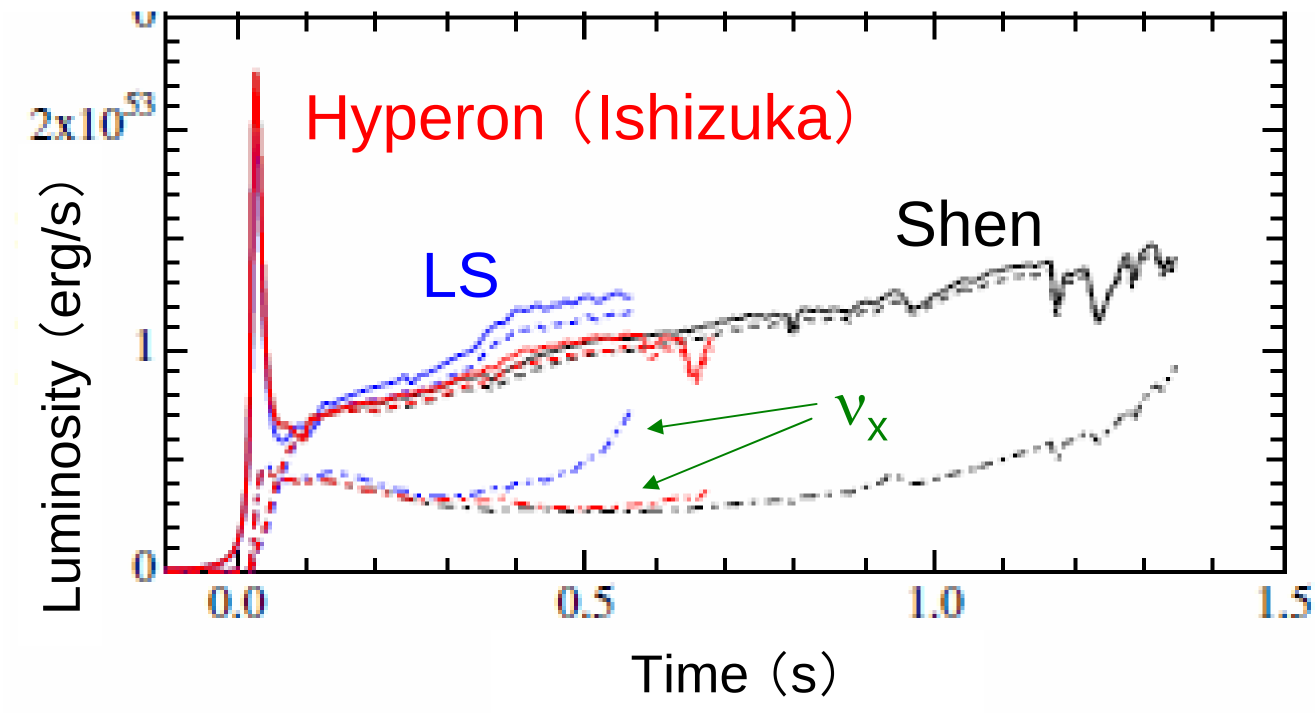
$\nu + e \leftrightarrow \nu + e$, $\nu_e + A \leftrightarrow A' + e^-$, $\nu + A \leftrightarrow \nu + A$,

$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$, $\gamma^* \leftrightarrow \nu + \bar{\nu}$, $N + N' \leftrightarrow N + N' + \nu + \bar{\nu}$

Current status of available EOS

- Crucial for maximum mass of proto-NS.
- EOS's used for our simulations.
  - Lattimer-Swesty EOS (LS), K = 180 MeV
  - 〃 , K = 220 MeV
    - Liquid drop model with Skyrme interactions （1991）
  - Shen EOS
    - Relativistic Mean Field theory （Shen et al. 1998）
  - Hyperon EOS
    - Shen-EOS with hyperons （Ishizuka et al. 2008）
  - Quark EOS
    - Shen-EOS with MIT Bag model （Nakazato et al. 2008a）

Time evolution of ν luminosity



- "Shen" is different in the duration time.
- "LS" is different for μ, τ-type ν.

→ We chose soft case (K = 180) of LS EOS.

→ More compressed and get hotter.

Total event numbers (*R* = *10kpc*)

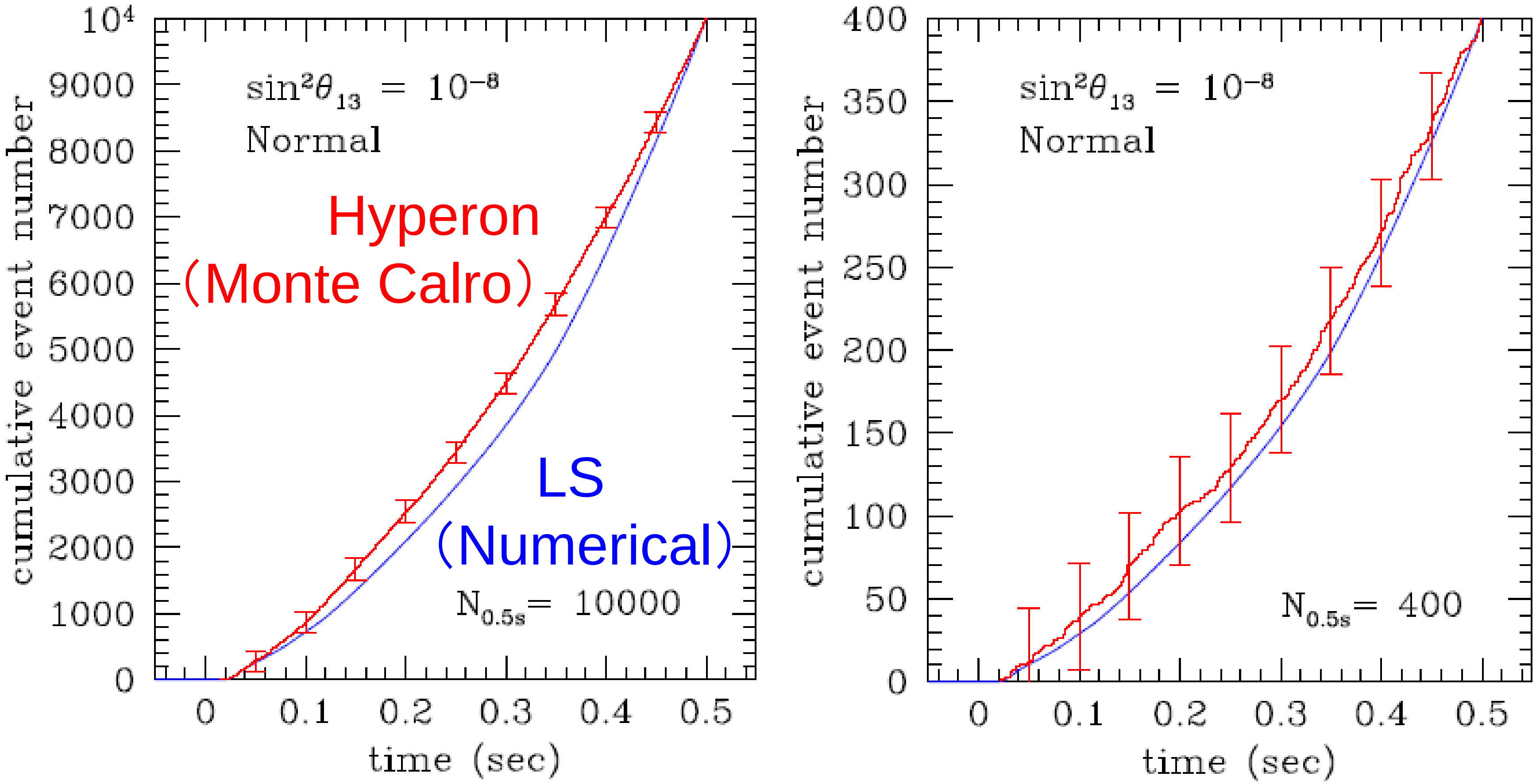
EOS	Normal & $\sin^2\theta_{13}=10^{-8}$	Inverted & $\sin^2\theta_{13}=10^{-2}$
Shen	46,601 - 49,514	29,391 - 31,041
LS	15,487 - 16,093	11,336 - 12,143
Hyperon	15,651 - 16,490	9,706 - 9,990

- Event number is larger than or comparable to that of ordinary SN ν (~ 10000).
- Earth effect (range in the sheet) is not crucial.
- For the case with “Inverted hierarchy and large $\sin^2\theta_{13}$,” event number becomes small.

Analyses

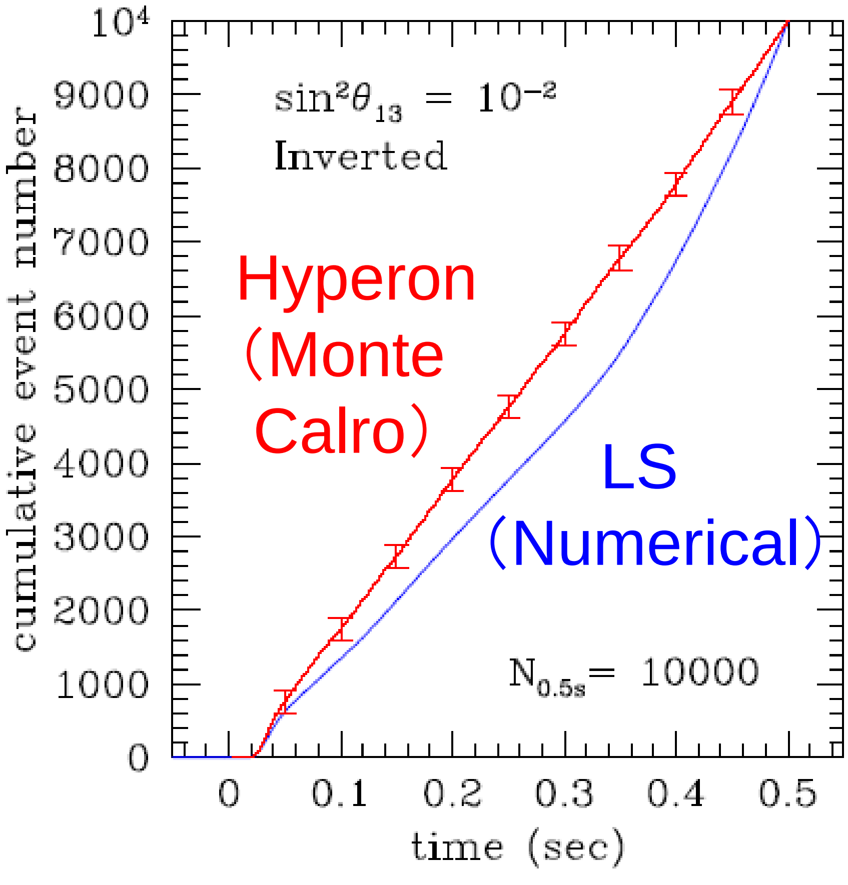
- Normalize cumulative event numbers by total event number till 0.5s after bounce, $N_{0.5s}$, and assume $N_{0.5s}$ = 10000 or 400.
- Perform Monte Carlo simulation for detection based on numerical data of Hyperon case, and compare it to numerical data of LS case.
- Judge these two cases are distinguished by Kolmogorov-Smirnov test.
- Merit of this method;
  - We do not have to take care of the ν emission after BH formation and the distance to the source.

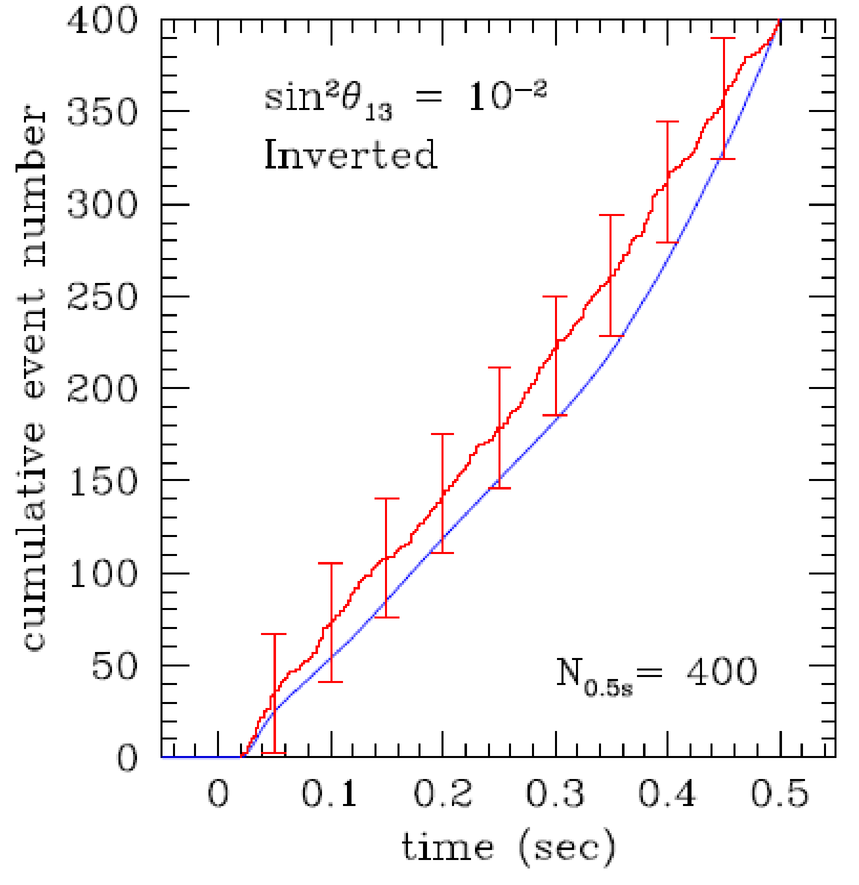
Case of "Normal & $\sin^2\theta_{13} = 10^{-8}$"



- They are distinguishable with 99% C.L. for $N_{0.5s} = 10{,}000$, but the distinction is difficult for $N_{0.5s} = 400$.

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

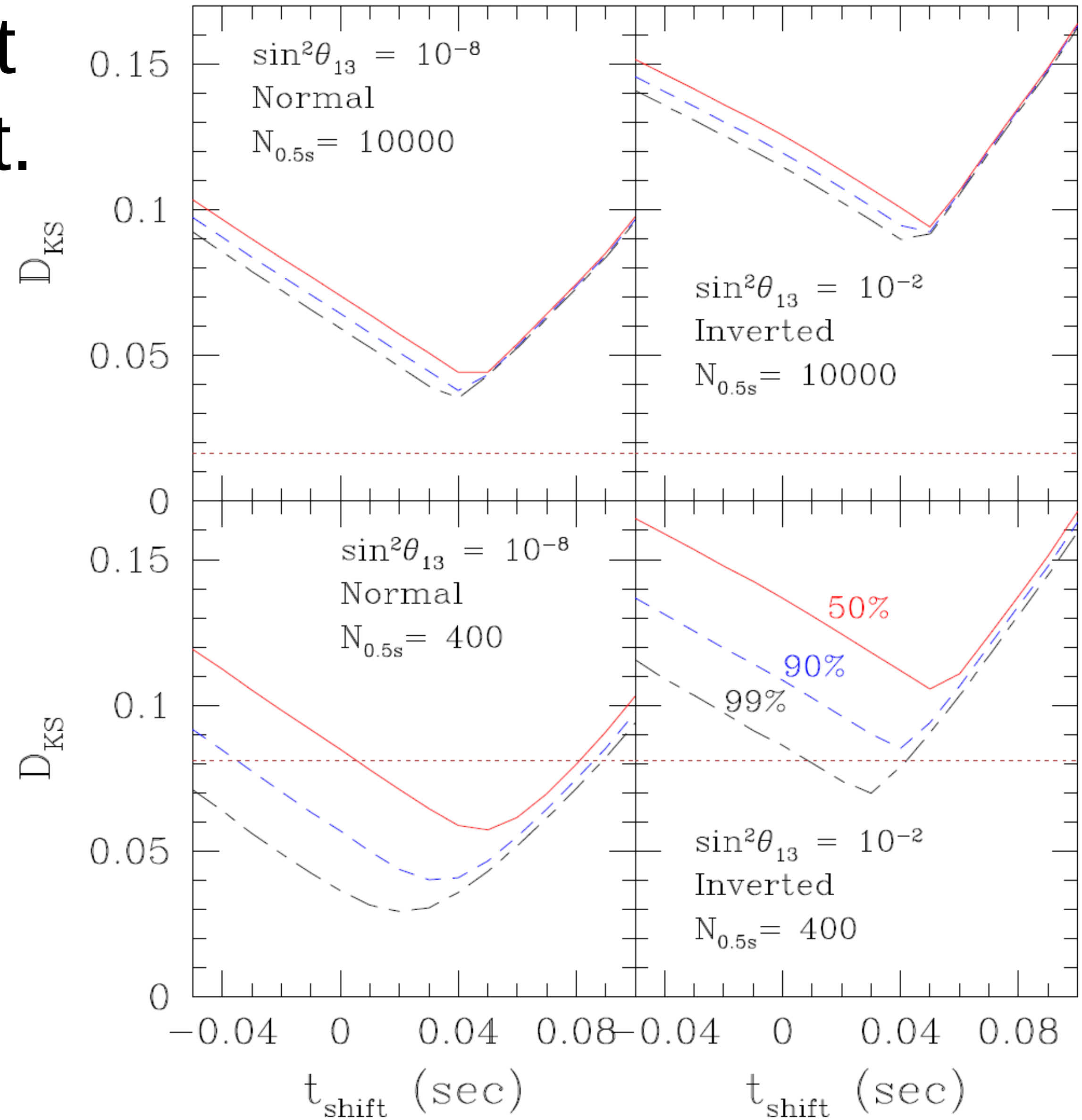




- In this case, difference is larger and we can distinguish 2 models at 99% C.L. even for $N_{0.5s} = 400$ (99483 times / 100000 MC sim.).

Analyses with time-shift

- Ambiguities exist on the start point.
- If N_{500} = 10,000, distinguishable for any cases.
- If N_{500} = 400, distinction is feasible for the case of inverted mass hierarchy with $\theta_{13} = 10^{-2}$.



Summary

- We have evaluated the event number of neutrinos emitted from stellar collapse forming black holes for SuperKamiokande.
- We have found that the event number is larger than or comparable to that of ordinary SN ν and EOS dependence of ν signal is statistically distinguishable for the progenitors in our Galaxy.

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