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Neutrino oscillations in MHD supernova explosions

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Outline

0. Introduction

1. Neutrino oscillations in matter

2. Numerical method

3. Result and discussions

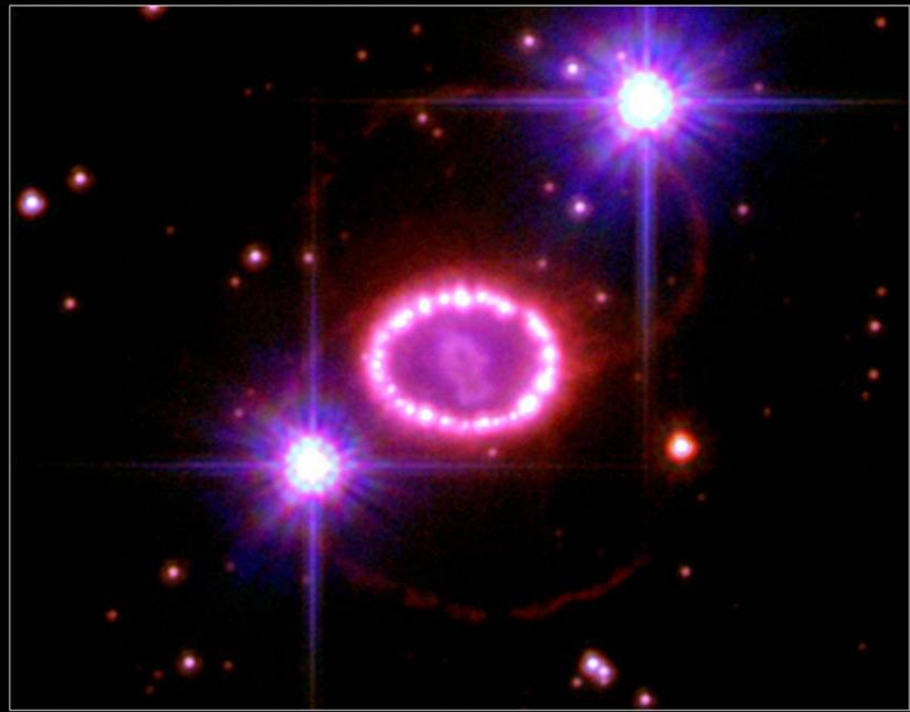
4. Summary

Introduction

SN1987A

After 20 years…

The axisymmetric structure of the supernova remnant.



Supernova 1987A • December 2006
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC07-10

Supernova Neutrinos

- The gravitational energy for the core collapse

$$\Delta E_G = -\left(\frac{GM^2_{\rm core}}{R_{\rm Fe\ core}} - \frac{GM^2_{\rm core}}{R_{\rm NS}}\right) \sim O(10^{53})\,{\rm erg}$$

- All of kinds of neutrinos are generated.

$$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$$

- T < O(100) MeV $\rightarrow n_{e^-} \gg n_\mu, n_\tau$ ➡ $\nu_x \equiv \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

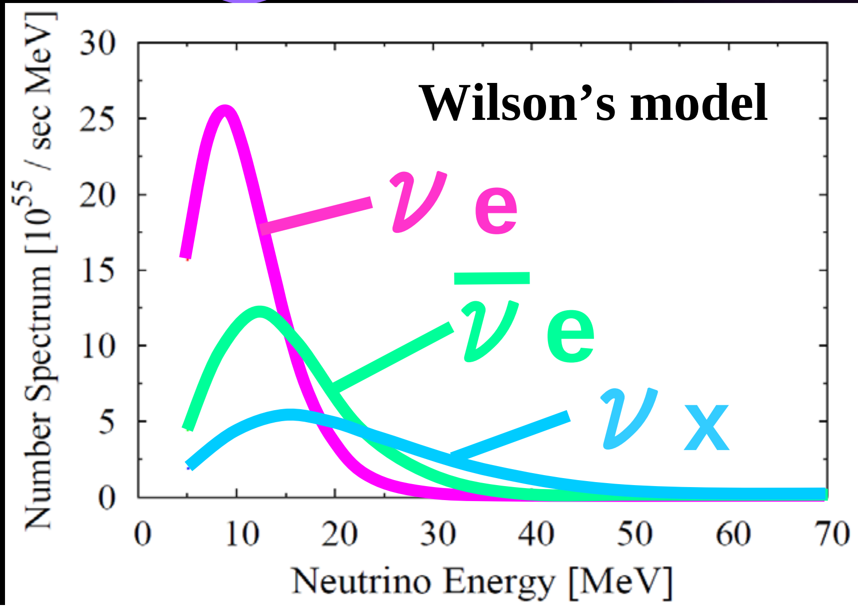
- The energy spectrum is different.

$$\sigma_{\nu_e} > \sigma_{\bar{\nu}_e} > \sigma_{\nu_x}$$

$$R_{\nu_e} > R_{\bar{\nu}_e} > R_{\nu_x}$$

$$T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$$

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$



Neutrino Oscillation Parameters

The mass squared difference

$$\Delta m^2_{12} \sim 7 \times 10^{-5} \mathrm{eV}^2$$

$$\left|\Delta m^2_{23}\right| \sim 3.2 \times 10^{-3} \mathrm{eV}^2$$

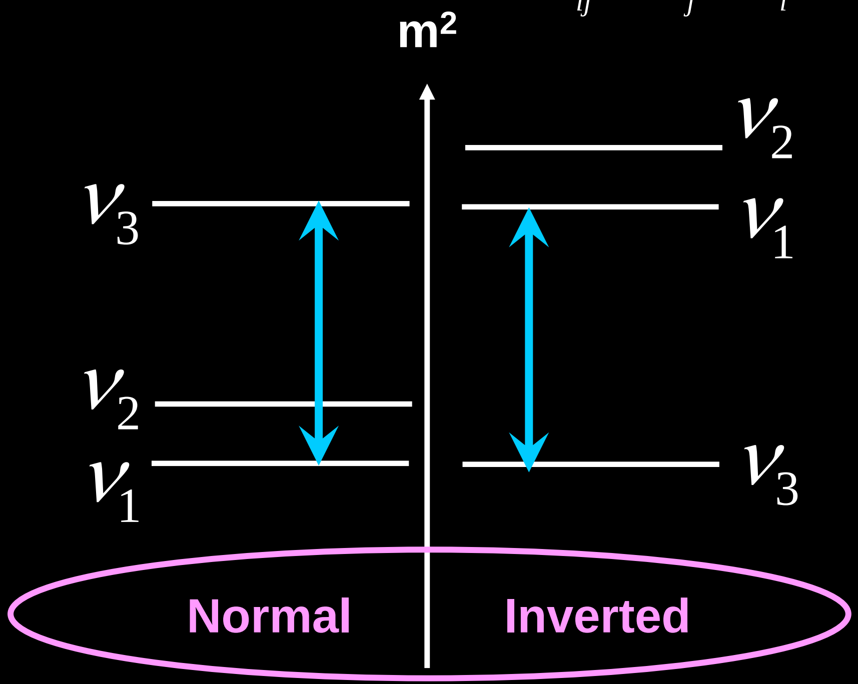
$$\Delta m^2_{ij} = m^2_j - m^2_i$$

The mixing angle

$$\sin^2 2\theta_{12} \sim 0.84$$

$$\sin^2 2\theta_{23} \sim 1.00$$

$$\sin^2 2\theta_{13} < 0.1$$



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The Matter (MSW) Effect

☆ **H-resonance** : $O\,(10^3)$ g/cm^3 ($\sin^2 2\theta_{13} \rightarrow$ unknown)

☆ **L-resonance** : $O\,(1)$ g/cm^3 ($\sin^2 2\theta_{12} \rightarrow$ large)

$\sin^2 2\theta$ is large. and $\left|\frac{dn_e}{dr}\right|$ is small. ⟶ $\gamma \gg 1$ adiabatic

shock

$\sin^2 2\theta$ is small. or $\left|\frac{dn_e}{dr}\right|$ is large. ⟶ $\gamma \ll 1$ non adiabatic

★Inverted mass hierarchy

☆ **H-resonance** → $\bar{\nu}_e$ spectrum changes.

☆ **L-resonance** → ν_e spectrum changes.

Purpose

☆The supernova neutrino spectra change according to the shock wave and $\sin^2 2\theta$

H-resonance：~O (10^3) g/cm^3

L-resonance： ~O (1) g/cm^3

⇩

We study the influence of H-resonance and L-resonance.

☆We study how non-spherically symmetrical supernova affects the neutrinos.

⇩

☆We calculated the expected event rate of the neutrinos in equatorial and polar direction and compare them.

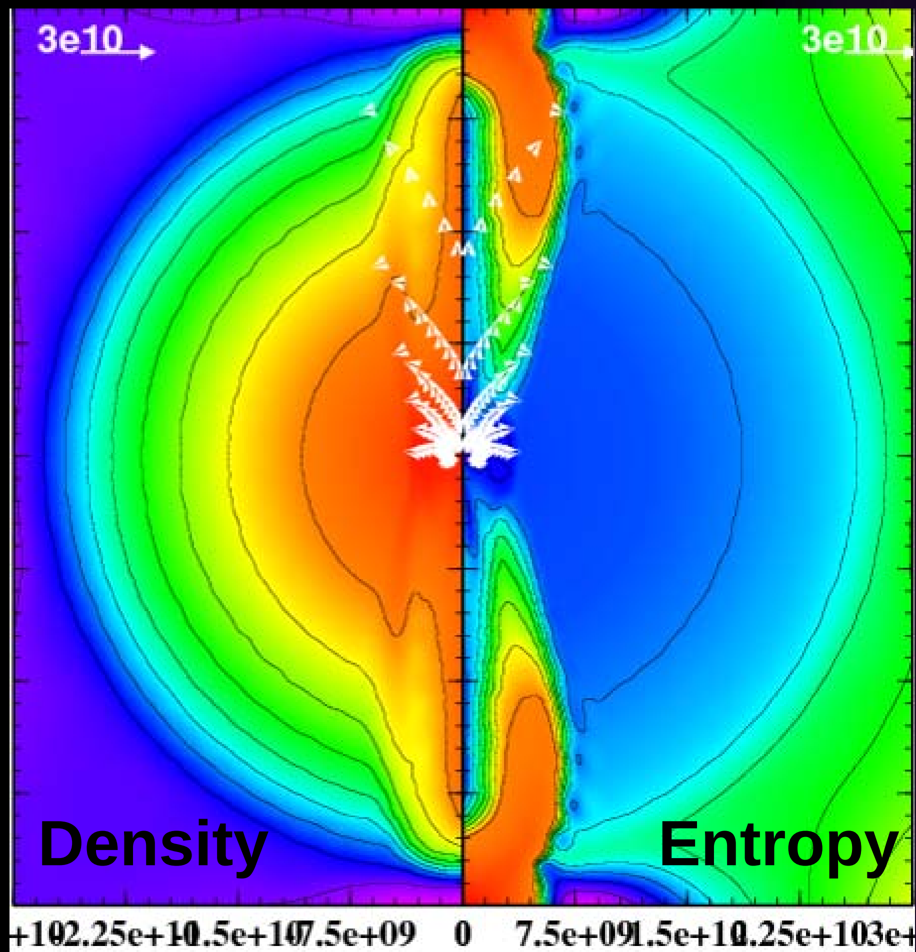
Explosion model

★Type-Ic supernova which was calculated using the 2D magnetohydrodynamical computations by Takiwaki.

★Progenitor is rotating 25M$_{solar}$ star .

Heger et al. 2000

★Initial magnetic field is 10^{12}G.



The calculation of event rate

☆Survival Probability of neutrino

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta E & 0\\ \cdots & \cdots & \cdots\end{pmatrix}U^{-1}\begin{pmatrix}\nu_e\\ \cdots\\ \cdots\end{pmatrix} + \begin{pmatrix}\sqrt{2}G_F n_e(r) & 0 & 0\\ 0 & 0 & 0\\ \cdots & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Inverted hierarchy $\sin^2 2\theta_{13} = 10^{-3}$

☆Neutrino spectra

spectra — Original spectra

$$\begin{pmatrix}\phi^{SN}_{\nu_e}(E)\\ \phi^{SN}_{\bar{\nu}_e}(E)\\ \phi^{SN}_{\nu_x}(E)\end{pmatrix} = \begin{pmatrix}P(E) & 0 & 1-P(E)\\ 0 & \overline{P}(E) & 1-\overline{P}(E)\\ 1-P(E) & 1-\overline{P}(E) & 2+P(E)+\overline{P}(E)\end{pmatrix}\begin{pmatrix}\phi^{org}_{\nu_e}(E)\\ \phi^{org}_{\bar{\nu}_e}(E)\\ \phi^{org}_{\nu_x}(E)\end{pmatrix}$$

$$\phi_{\nu_x} \equiv \frac{1}{4}(\phi_{\nu_\mu} + \phi_{\nu_\tau} + \phi_{\bar{\nu}_\mu} + \phi_{\bar{\nu}_\tau})$$

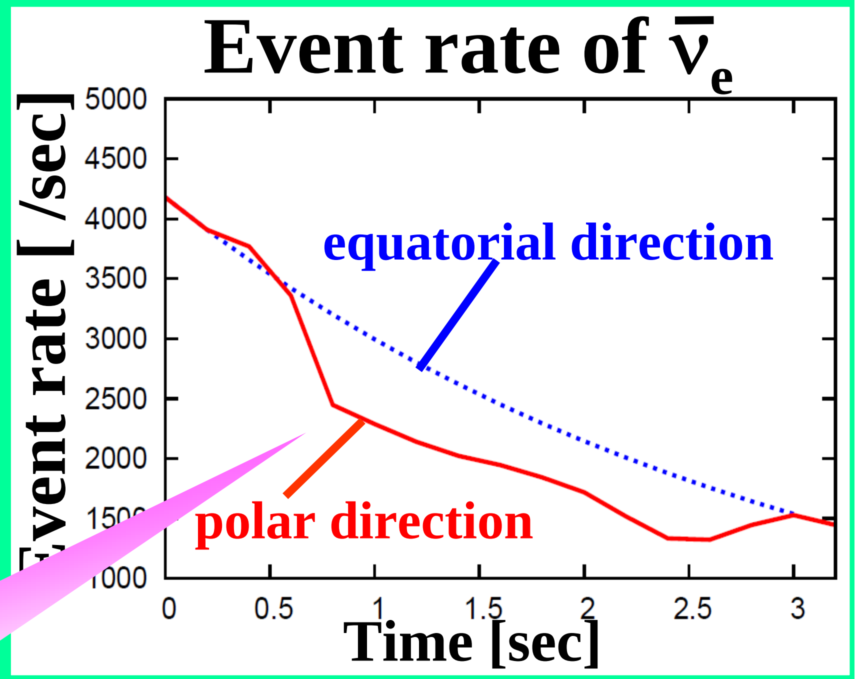
☆Event number

$$\frac{d^2N}{dE_e dt} = N_{target}\cdot\eta(E_e)\cdot\frac{1}{4\pi d^2}\cdot\frac{d^2N_\nu}{dE_\nu dt}\cdot\sigma(E_\nu)\cdot\frac{dE_\nu}{dE_e}$$

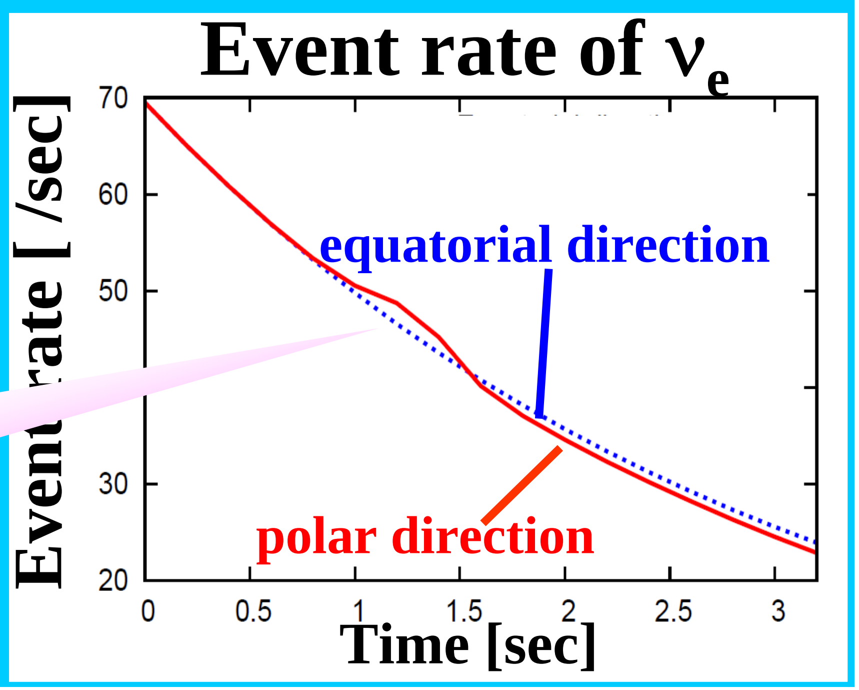
- N_{target}: Target number
- $\eta(E_e)$: efficiency
- d: Distance of supernova → 10kpc
- $\frac{d^2N_\nu}{dE_\nu dt}$: spectrum
- $\sigma(E_\nu)$: Cross section

The expected event rate

- ☆Super-Kamiokande
- ☆Inverted mass hierarchy and $\sin^2 2\theta_{13} = 10^{-3}$
- ☆The influence of H-resonance ⇒ $\bar{\nu}_e$
- ☆The influence of L-resonance ⇒ ν_e



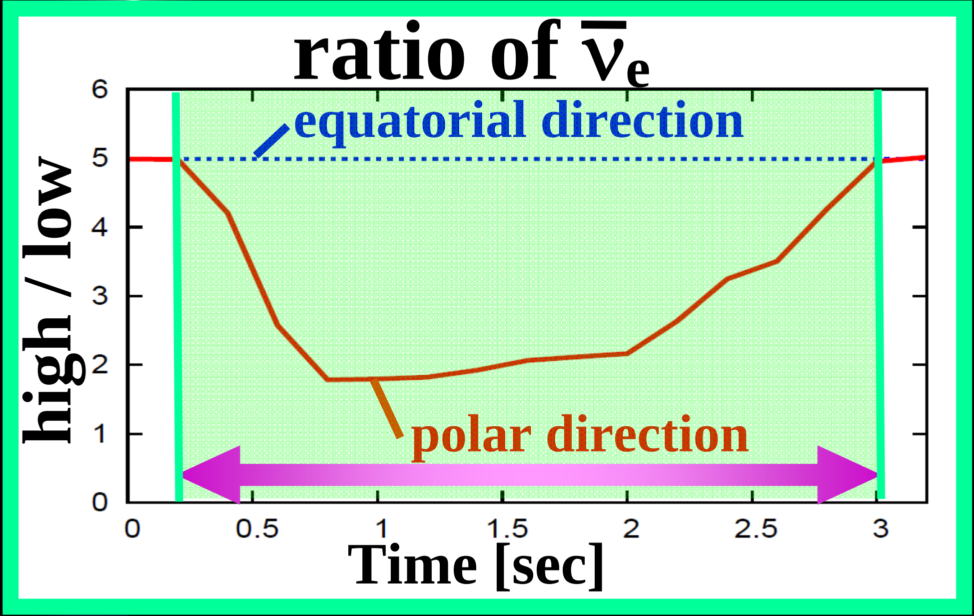
This gap is the influence of shock wave at H-resonance.

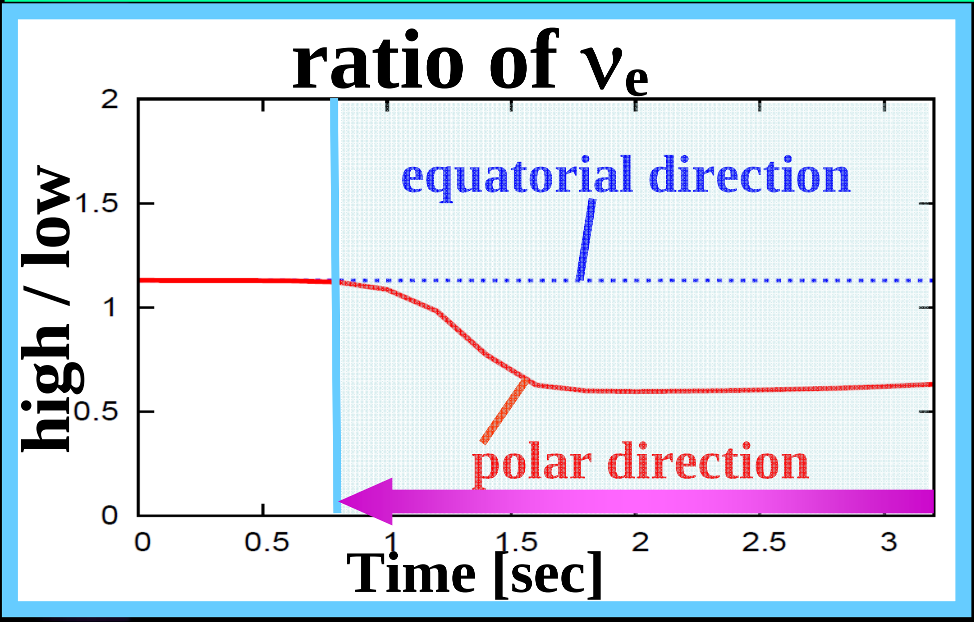


The influence at L-resonance is small.

Kawagoe et al. 2009 submitted to JCAP

The time evolution of Ratio (SK)





Ratio (SK) $= \dfrac{\text{event number of } 20 < E < 60\text{MeV}}{\text{event number of } 5 < E < 20\text{MeV}}$

☆The neutrinos become in the state of non-adiabatic, and average energy becomes low while the shock wave propagates through

- H-resonance → $\bar{\nu}_e$
- L-resonance → ν_e

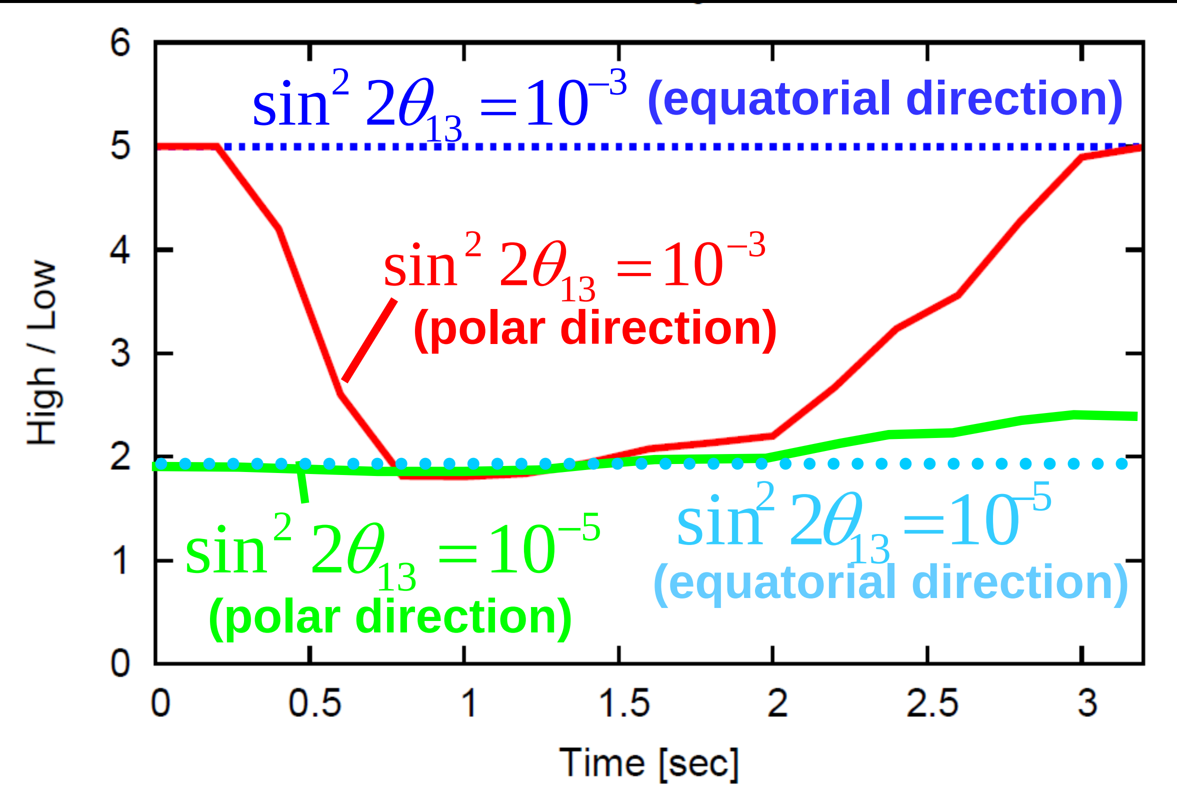
☆We can see the propagation of shock wave more clearly.

Kawagoe et al. 2009 submitted to JCAP

Dependence of θ_{13} on $\bar{\nu}_e$

$$\text{Ratio (SK)} = \frac{\text{events of } 20 < E < 60\text{MeV}}{\text{events of } 5 < E < 20\text{MeV}}$$

☆The ratio of $\bar{\nu}_e$ events (H-resonance)

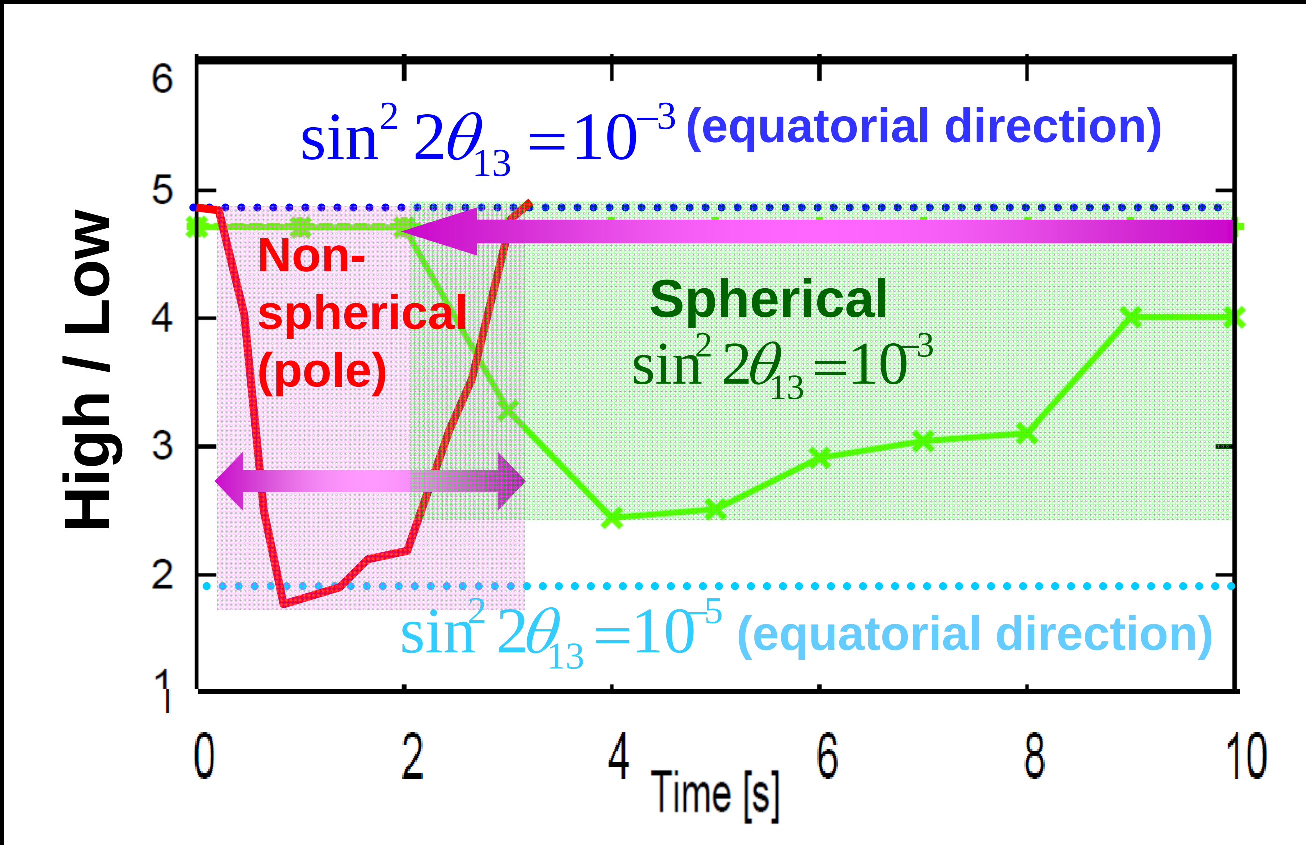


☆The ratio of 10^{-5} is smaller than that of 10^{-3}, regardless of the viewing direction.

Difference of explosion mechanism

$$\text{Ratio (SK)} = \frac{\text{events of } 20 < E < 60\text{MeV}}{\text{events of } 5 < E < 20\text{MeV}}$$

☆The ratio of $\bar{\nu}_e$ events (H-resonance)



☆The variation of the ratio is different according to the mechanism.

Summary

☆ We calculated the expected event rate of the neutrinos in equatorial and polar direction and compare them.

⇓

The event rate of the polar direction is different from the event rate of the equatorial direction.

☆ We use the high-to-low energy ratio of neutrinos.

⇓

equatorial direction : the ratio is almost constant
polar direction : the ratio change greatly

☆We discussed the difference of θ_{13} and explosion mechanism.

⇓

The ratio of small θ_{13} case is smaller than that of large case, regardless of the viewing direction.

The variation of the ratio is different according to the mechanism.


S. KAWAGOE TAUP2009@Rome, July 1-5, 2009
Thank you very much!