Collective neutrino oscillations and matter effects in core-collapse supernovae

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Outlines

- Introduction
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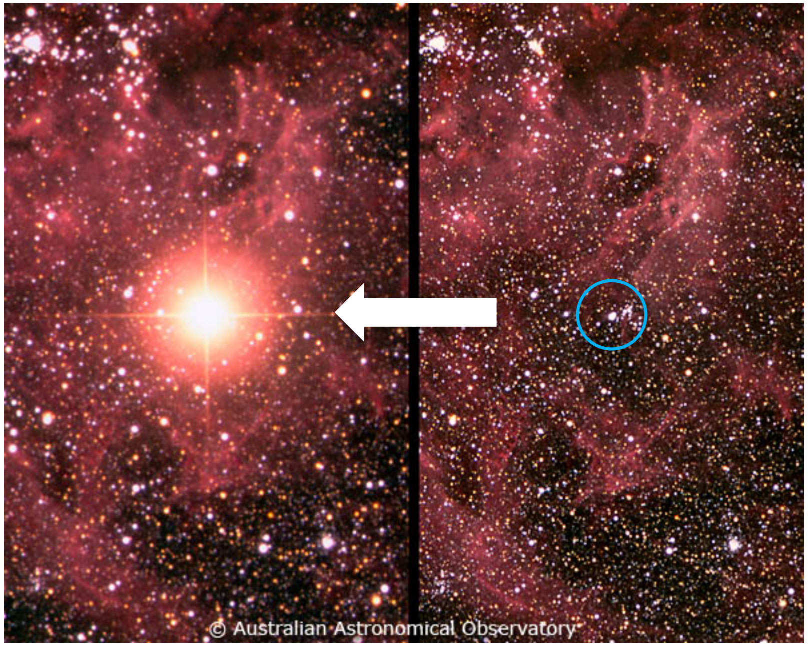
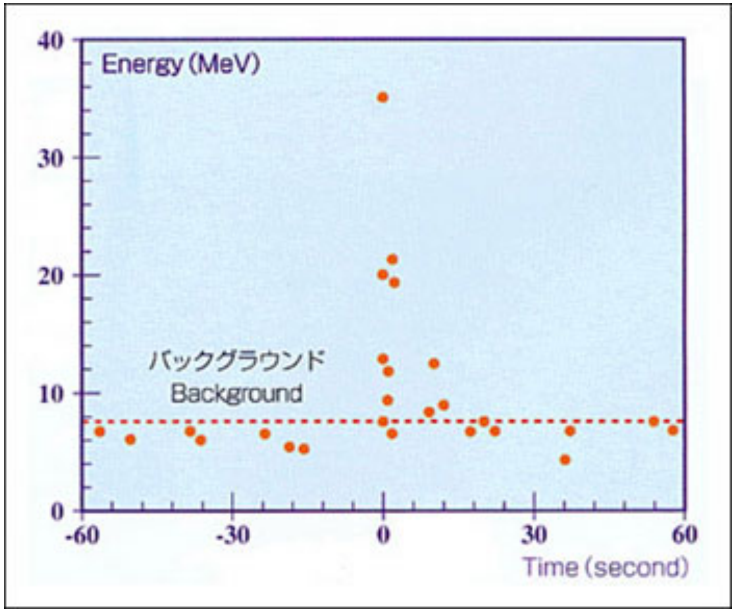
  - Collective neutrino oscillation
  - Matter effects against collective effects
- Calculation using two models
  - High mass progenitor
  - Low mass progenitor
- Summarize & Future works

Introduction





Kamiokande II detected 11 anti-neutrino events from SN1987A in LMC.

This event taught us much neutrino information.
average energy, luminosity, emission duration.

Introduction

In the next supernova, we expect to get the time evolution of event rate and neutrino spectra by Super-Kamiokande and other detectors.

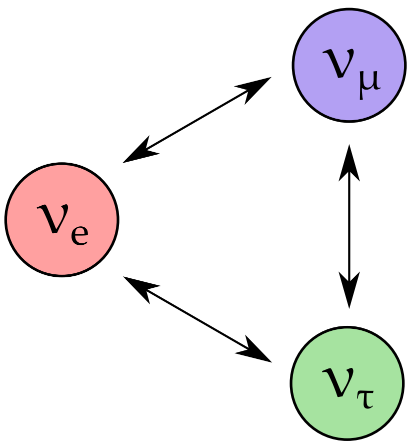
Neutrino spectra and the time evolution possess information on the PNS cooling rate and equation of state.

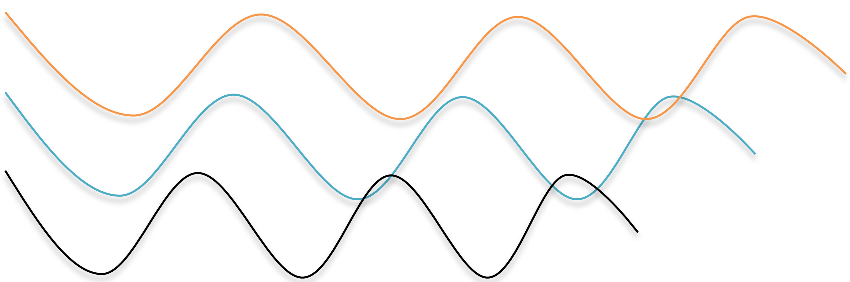
Neutrino oscillation causes mixing among neutrino flavors, and enable us not to understand detected events easily.

Big problems in neutrino physics.

Neutrino oscillation

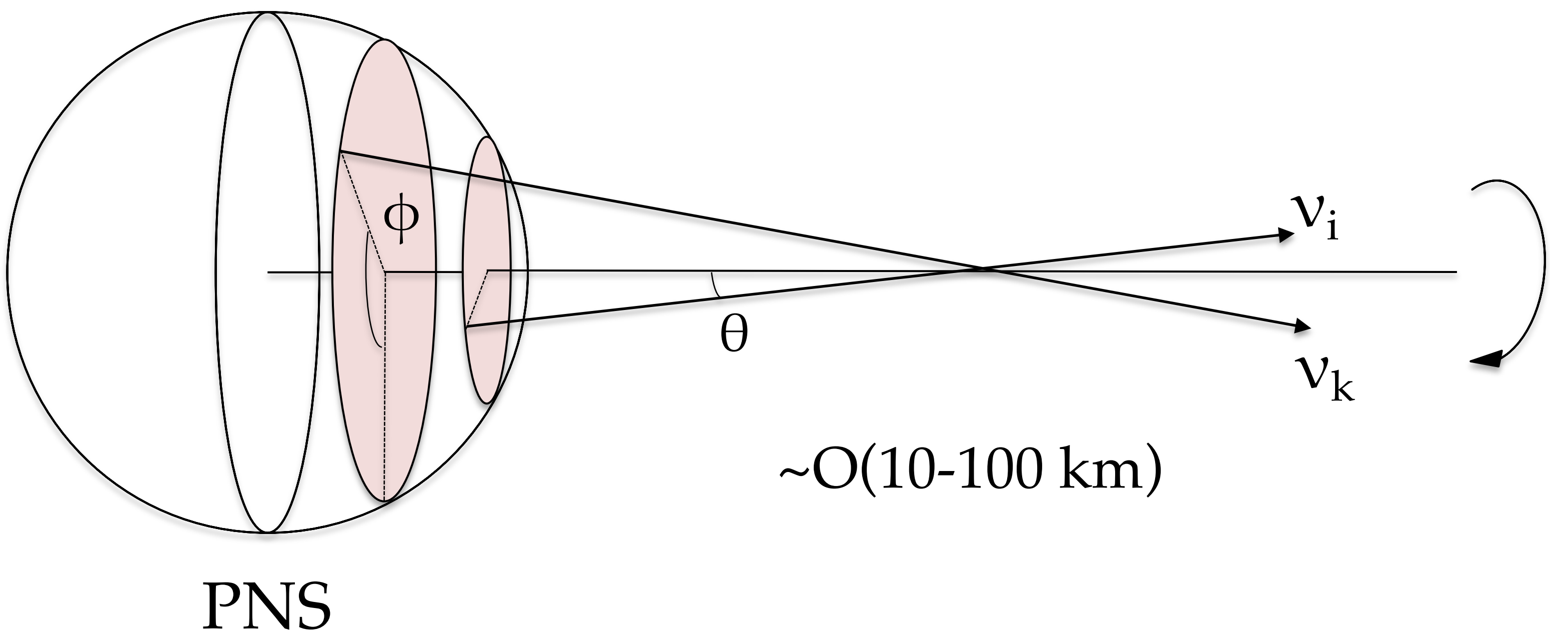
- Neutrinos changes from one flavor to another during propagation in vacuum due to the mass differences.
- If electron is in background, effective mass changes and neutrinos experience resonance in a particular density.
- These phenomena are well understood by experiments





Adopt these phenomena into supernova neutrinos.
But
It is not so simple. Very complicated.

Collective neutrino oscillation



~10^{58} neutrinos are emitted from a SN in ~10 seconds.

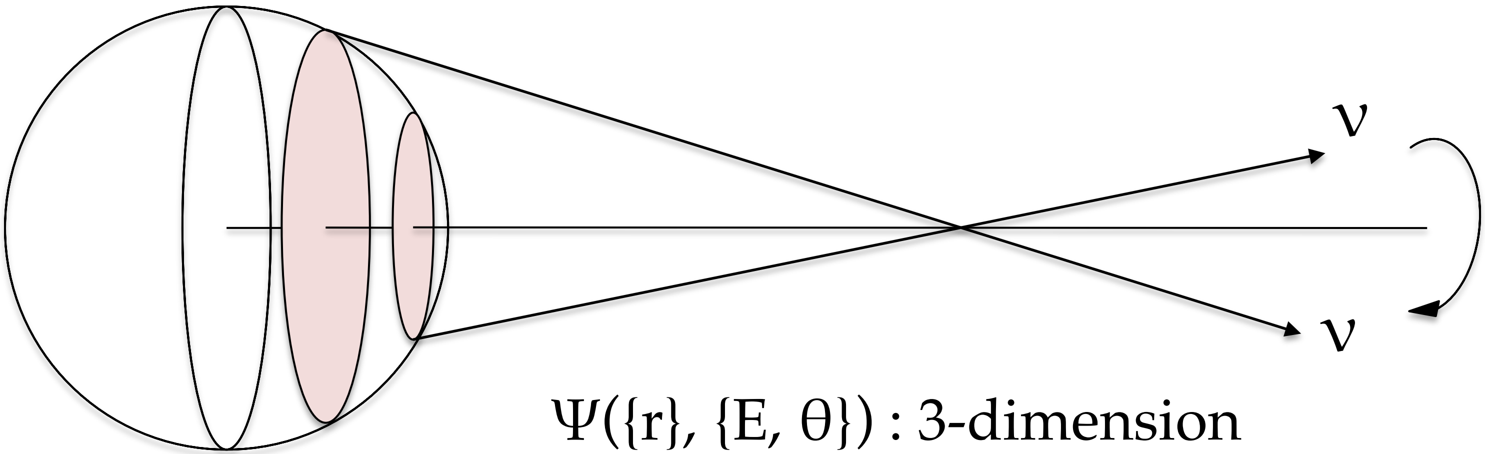
Dense neutrino gas causes neutrino-neutrino interaction near the proto-neutrino star.

Neutrino self-interaction induces collective flavor conversions.

This phenomenon has a possibility to help supernova explosion.

$$\Psi(t; \{r, \Theta, \Phi\}, \{E, \theta, \phi\}) : \text{7-dimension}$$

Collective neutrino oscillation



$\Psi(\{r\}, \{E, \theta\})$: 3-dimension

N_flavor × N_E × N_θ = O(10^7) ODE systems

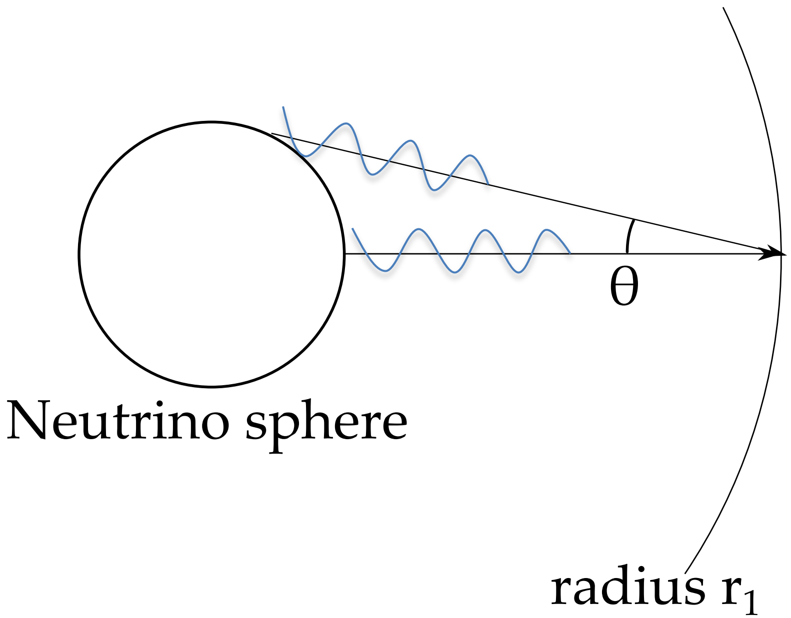
Usually, we adopt **BULB model** to simplify the neutrino self-interaction.

- Neutrinos are emitted only from the neutrino sphere.
- Uniform, Isotropic, Stationary emission
- Axial-symmetry
- 1-dimensional SN model

These assumptions enable us to calculate numerically.

(Duan+ 2006, Dasgupta+2008)

Collective effects vs. Matter effects



(Esteban-Pretel+ 2008, Chakraborty+ 2011)

Neutrino self-interaction synchronizes oscillation phases along different neutrino trajectories and neutrinos collectively have the same phase.

On the other hand,

Different neutrino trajectories give the different effective potential from background electrons.
This causes phase dispersion.

- Matter effects > neutrino self-interaction
  → Collective neutrino oscillation can be suppressed.
- Matter effects < neutrino self-interaction
  → Collective flavor transformation occurs.

Equation of motion

$$i\partial_t \rho_i = \left[+U \frac{M^2}{2E_\nu} U^\dagger + \sqrt{2} G_F N_e + \sqrt{2} G_F \int d\Gamma' \left(1 - \cos\theta_{ik}\right) \left(\rho'_{\nu_k} - \bar{\rho}'_{\nu_k}\right) ,\ \rho_i \right]$$

Vacuum oscillation
Information on Mass difference

Matter oscillation
Information on Density profile

Collective oscillation
Information on Neutrino trajectory
& Neutrino spectra

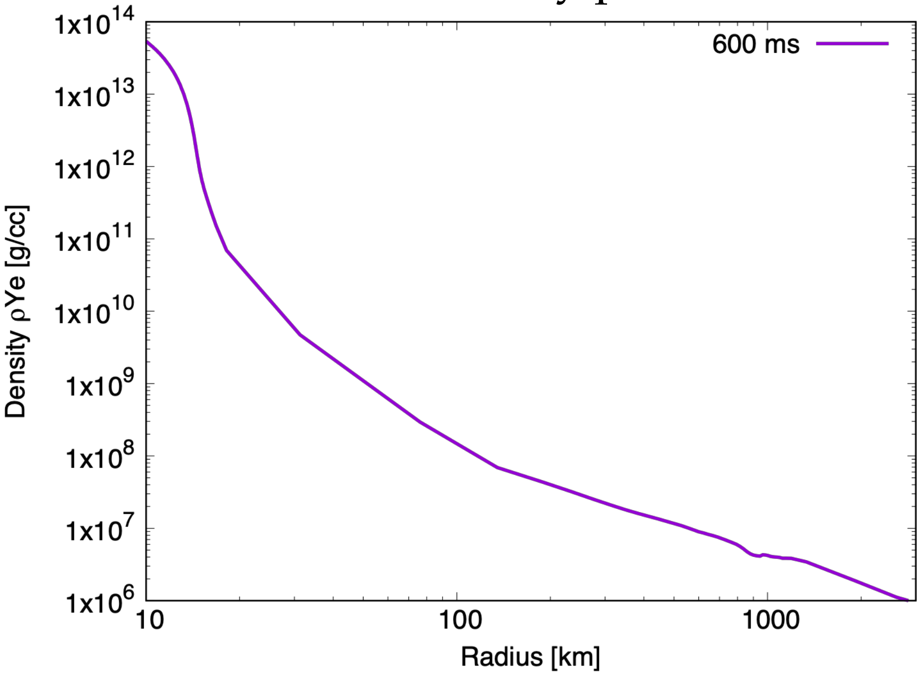
Phase dispersion
vs.
Phase synchronization

Numerical results

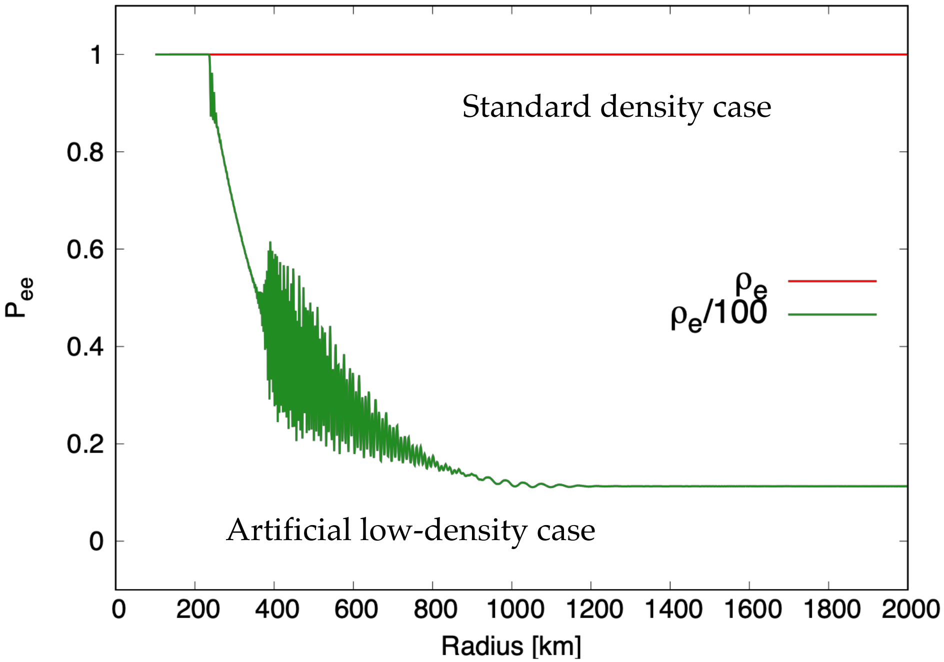
- High-mass progenitor model
- Low-mass progenitor model

High-mass model

Electron density profile



Survival probability $P_{e \to e}$



CCSN model with 40 $M_{\odot}$ progenitor by Sumiyoshi.
This is a failed SN and shock wave can't revive.

(Nakazato+2010)

Collective oscillation is completely suppressed due to high electron density.

High-mass model

Very massive progenitors suppress collective neutrino oscillation completely.

This means that neutrinos experience simple flavor conversions only.

→ MSW resonance & Vacuum oscillation

We can easily understand the observational results.

Zaizen et al., PRD **98** 103020 (2018)

Inverted mass ordering

detection | mixing

30% : 70%

$$\nu_e \longleftarrow \nu_e + \nu_{\mu/\tau}$$

100%

$$\bar{\nu}_e \longleftarrow \bar{\nu}_{\mu/\tau}$$

Normal mass ordering

detection | mixing

100%

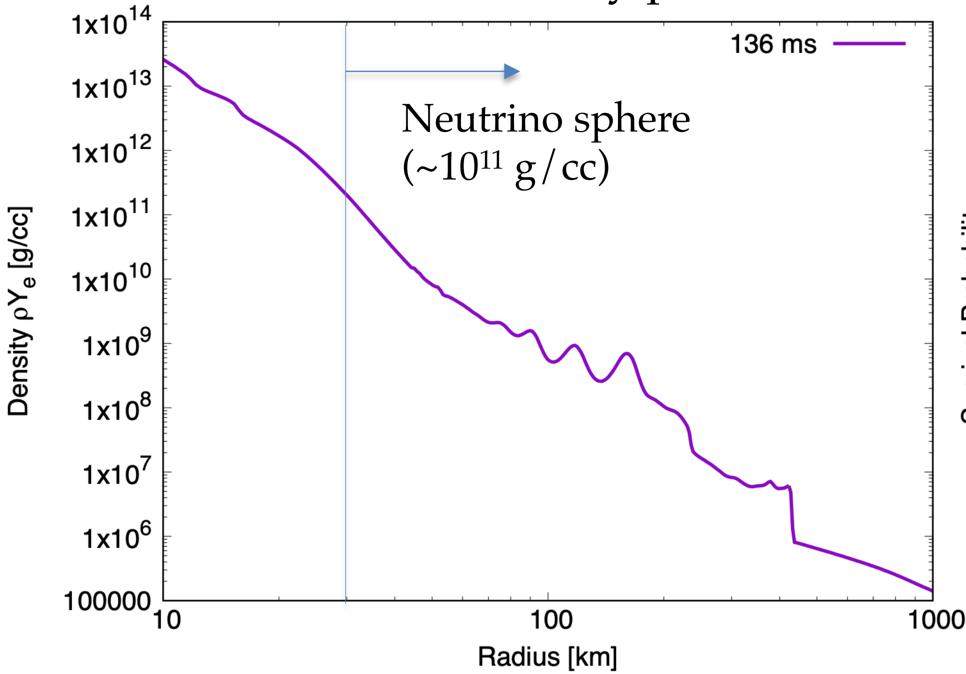
$$\nu_e \longleftarrow \nu_{\mu/\tau}$$

70% : 30%

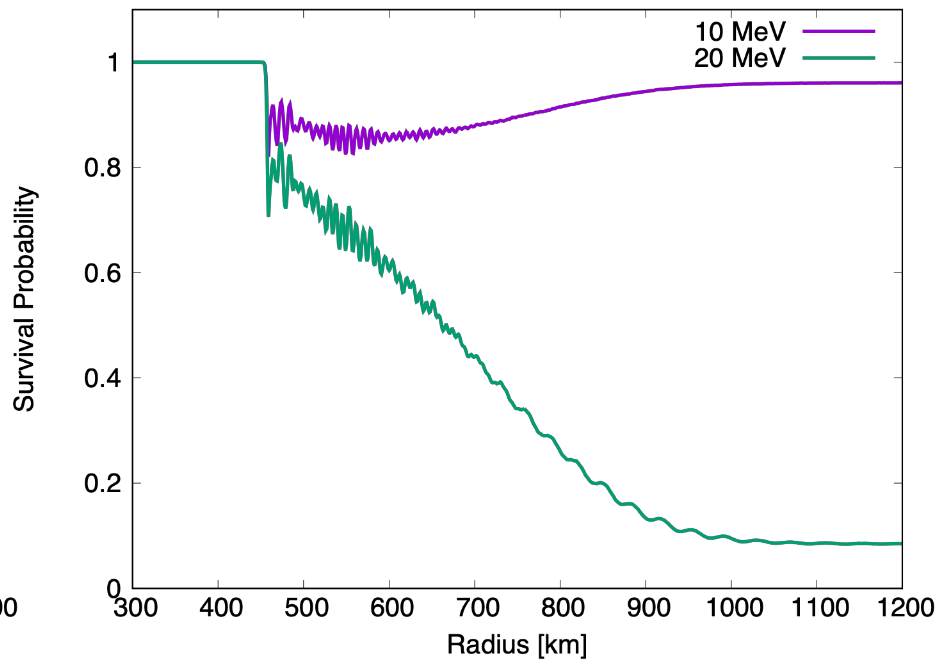
$$\bar{\nu}_e \longleftarrow \bar{\nu}_e + \bar{\nu}_{\mu/\tau}$$

Low-mass model

Electron density profile



Survival probability $P_{e \to e}$

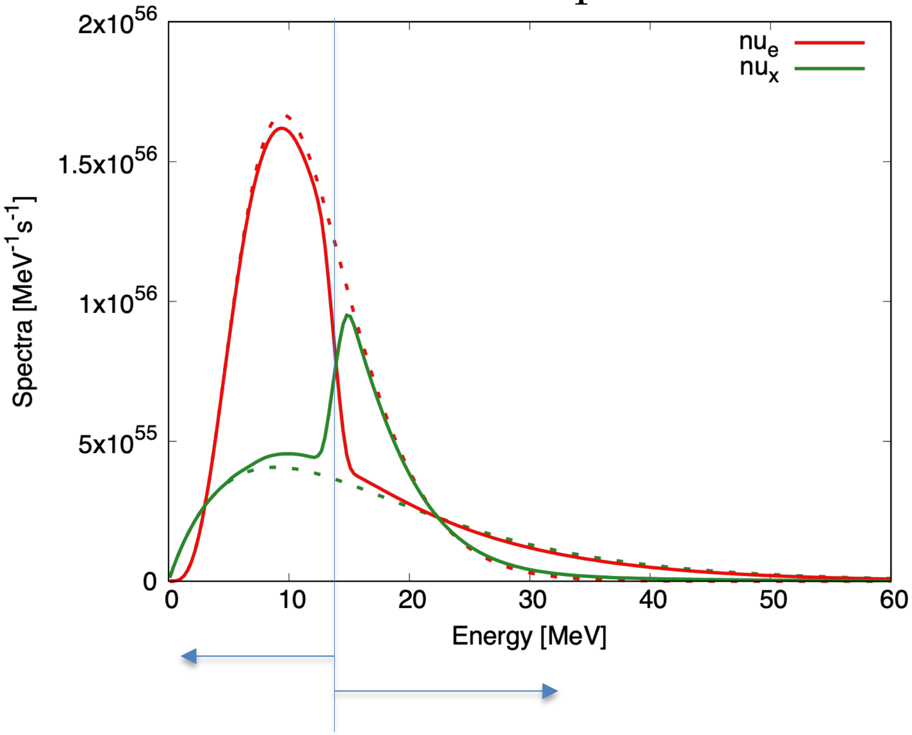


CCSN model with 9.6 $M_\odot$ progenitor by Takiwaki.
The shock wave is located around ~400 km and the density drops sharply.
The onset radius of oscillation is same as the location of the shock wave.

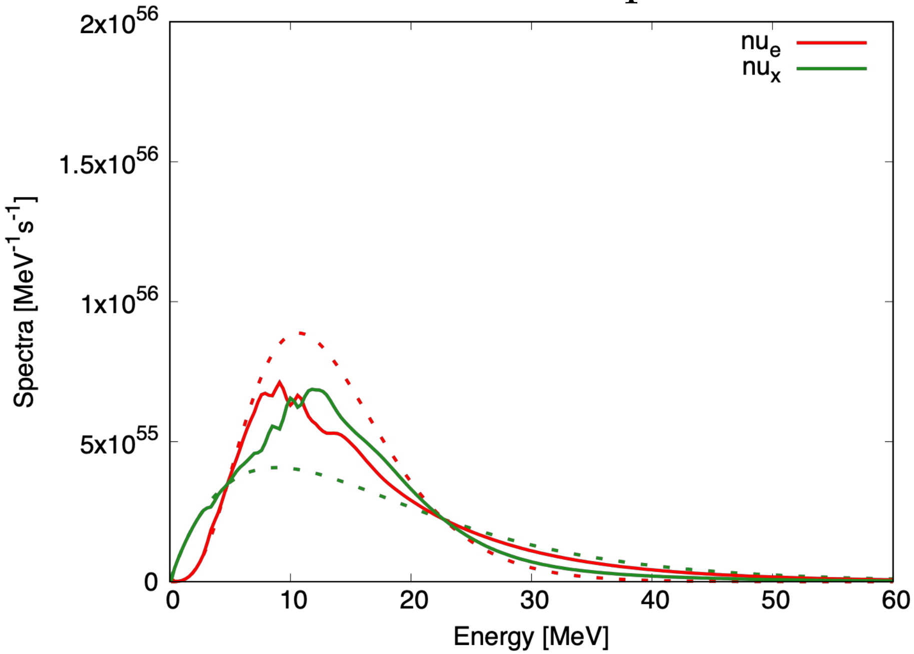
Survival probabilities split into 0 and 1, called spectral splits.

Low-mass model

Neutrino spectra



Anti-neutrino spectra



Spectral splits emerge above the critical energy, especially in neutrino spectra.

These features can be detected by electron neutrino detectors, DUNE.

(More detailed works are in prep.)

Collective vs. Matter

Low density is required in order to lead to collective neutrino oscillation.

In the low-mass case, the shock wave produces the density drop and neutrinos get free from matter suppression.

This means that the collective flavor transformation can't occur inside the shock wave at early phase.

Collective oscillation with BULB model doesn't affect explosion mechanism.

But these results include many assumptions. We must tackle Beyond BULB model.

Summary & Future works

- Recently linear analysis studies have suggested
  - Beyond BULB model can overcome matter suppression and the flavor conversion can occur inside the shock wave.
  - Require the Multi-dimensionality
  - ex.) Axial-symmetry breaking (Azimuthal-angle instability)
    Nontrivial angular distribution (Fast Flavor Conversion).

- We calculate the flavor conversion with BULB model.
  - This model simplify the neutrino self-interaction.
- Collective neutrino oscillation largely depends on the density profile.
  - Especially progenitor mass and the location of the shock wave