Neutrino oscillation in Failed Supernovae

Masamichi Zaizen[1] (master's 1st in Umeda lab.)

Takashi Yoshida[1], Kohsuke Sumiyoshi[2], Hideyuki Umeda[1]

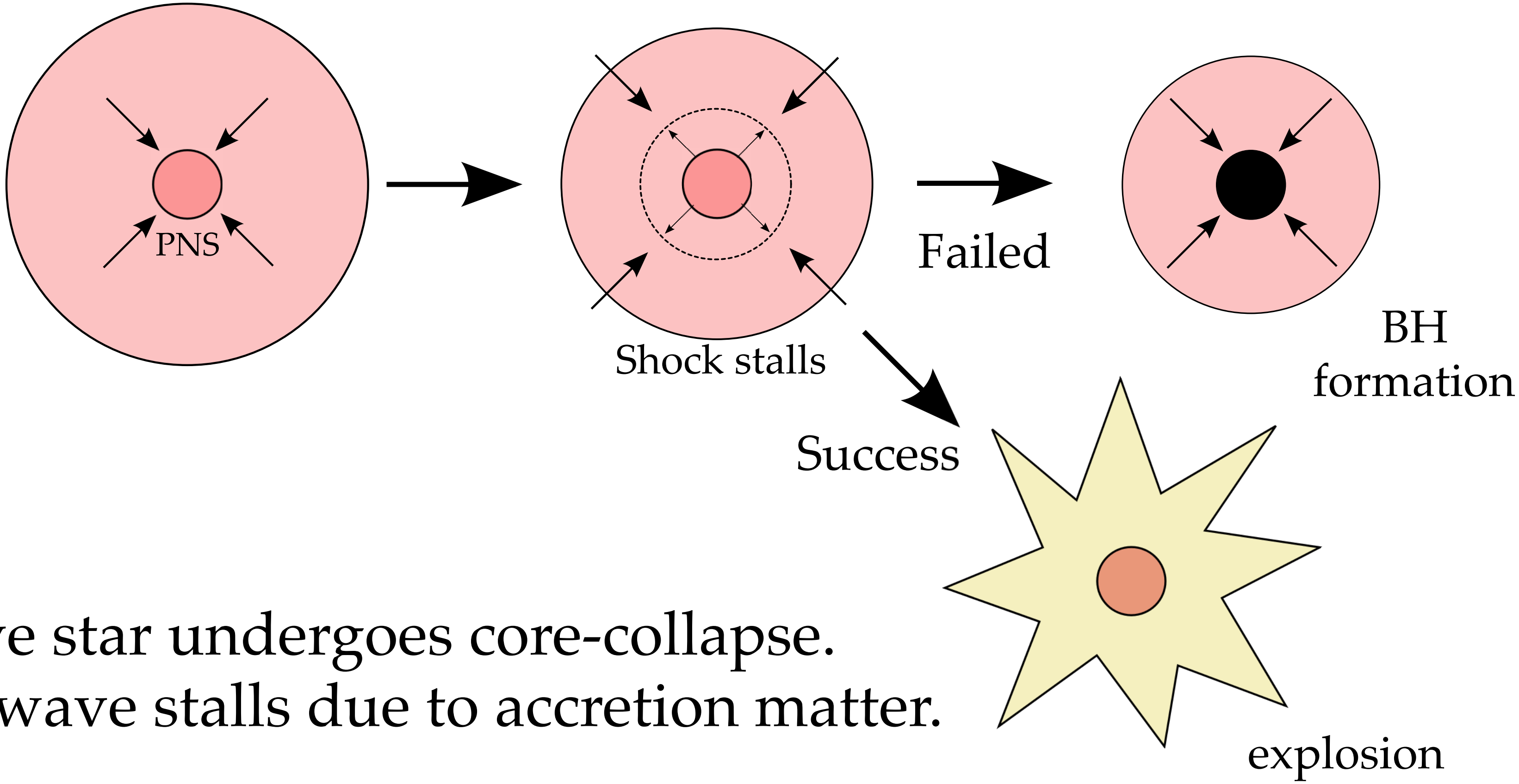
1:University of Tokyo, 2:Numazu College of Tech.

新学術「地下素核研究」第４回超新星ニュートリノ研究会
2018/1/8 @四季の湯強羅静雲荘

Outline

- Failed supernova
- Neutrino oscillation
  - (Vacuum oscillation)
  - MSW effect
  - Collective oscillation
- Methods
- Results
- Summary
- Future work

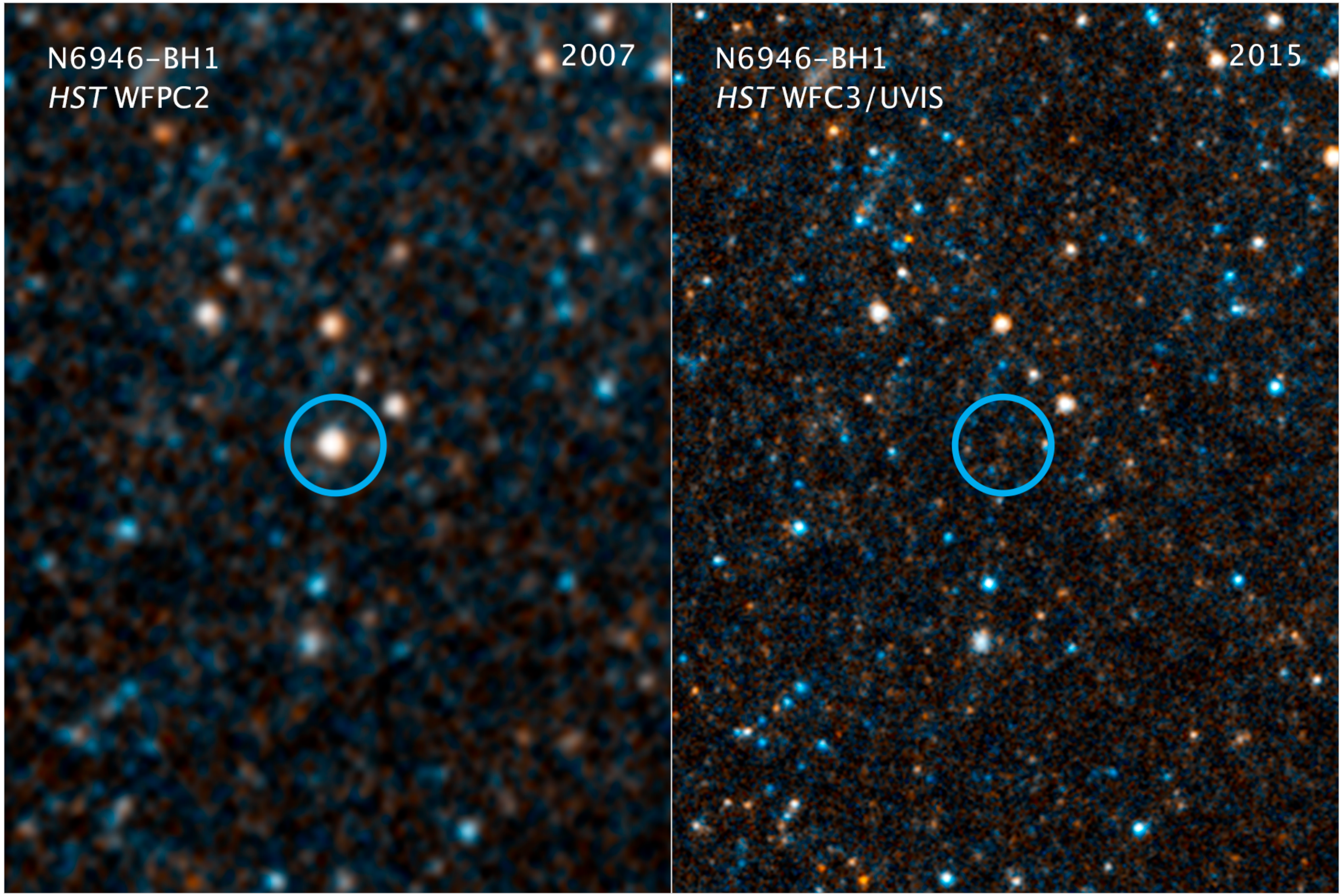
What is Failed Supernova ?



Massive star undergoes core-collapse.
Shock wave stalls due to accretion matter.

In failed SNe, the shock wave can not revive due to heavy infall of outer layer.
The proto-neutron star evolves into a black hole.

Example for a failed SN ?



N6946-BH1 (c) NASA

$25M_{\odot}$, Red super giant, 6Mpc, Cygnus & Cepheus

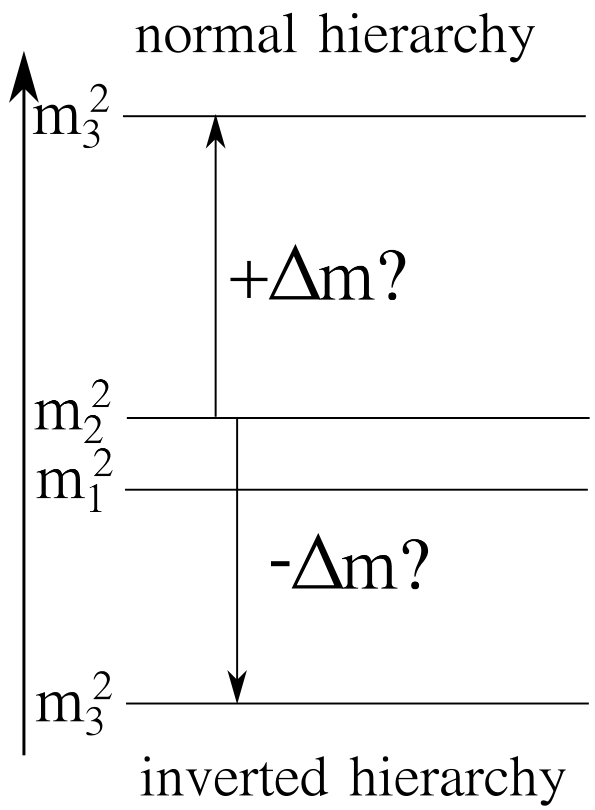
Gerke et al. 2015, Adams et al. 2017

Failed SNe and Neutrinos

- Failed SN is faint in EM, but bright in neutrino.
- Surrounding matter continues to accrete onto the PNS.
- Neutrino emission stops when covering neutrino sphere with BH event horizon formed in the center.

- Neutrino spectra depend on EoS of high temperature and high density, so the observation enables us to understand it.
- Neutrinos are the important tool to get information on failed SNe.
- How many neutrinos do we observe on the Earth?

2. Neutrino oscillation



Mass hierarchy is not yet known.
(We're looking forward to this solution.)
We assume two hierarchy cases in this work.

And we choose the modified flavor basis:

$$\nu_x = \cos\theta_{23}\nu_\mu - \sin\theta_{23}\nu_\tau$$

$$\nu_y = \sin\theta_{23}\nu_\mu + \cos\theta_{23}\nu_\tau$$

Dighe et al. 2000, Dasgupta et al. 2008

Then ν_x doesn't include ν_3 and θ_{13}.
Thereby ν_x isn't affected by the oscillation associated with θ_{13}, Δm_{13}.
ex.) H resonance, 2 flavor collective…

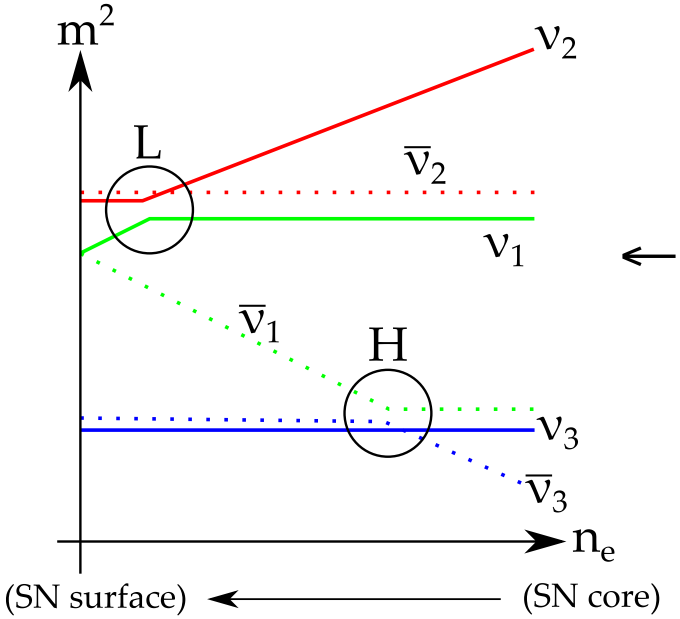
$$\nu_e \leftrightarrow \nu_y$$

$$\nu_e \leftrightarrow \nu_x$$

1-to-1 oscillation sets

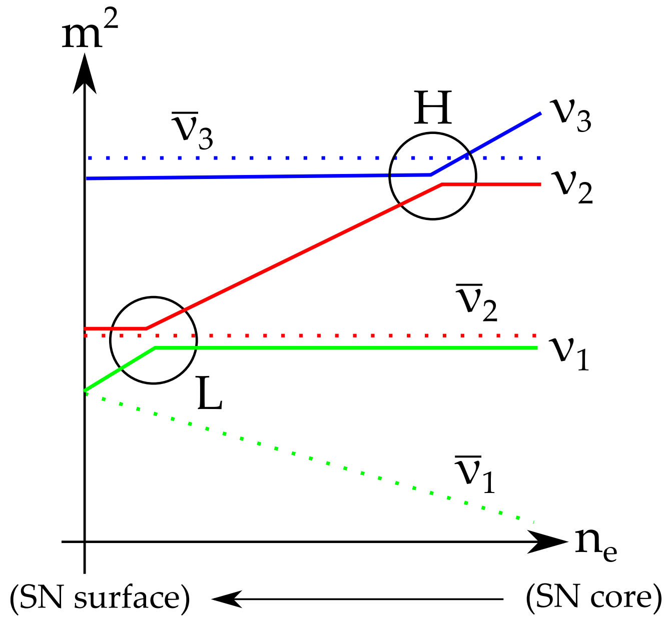
2. Neutrino oscillation

- MSW effect (the matter oscillation)



← inverted case

normal case →



Survival probability of electron neutrino after undergoing **adiabatic** MSW H and L resonances.
Shock wave effects don't exist in failed SNe, unlike success SNe.

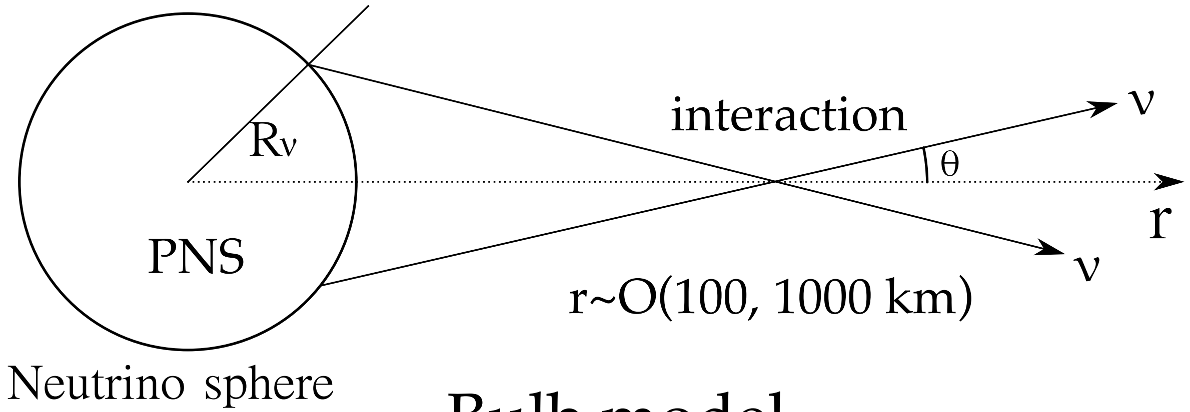
	P	$\overline{P}$
NH	$\sin^2\theta_{13}\sin^2\theta_{12}$	$\cos^2\theta_{13}\cos^2\theta_{12}$
IH	$\cos^2\theta_{13}\sin^2\theta_{12}$	$\sin^2\theta_{13}\cos^2\theta_{12}$

$$\cos^2\theta_{13}\sim 1$$

$$\cos^2\theta_{12}\sim 0.7$$

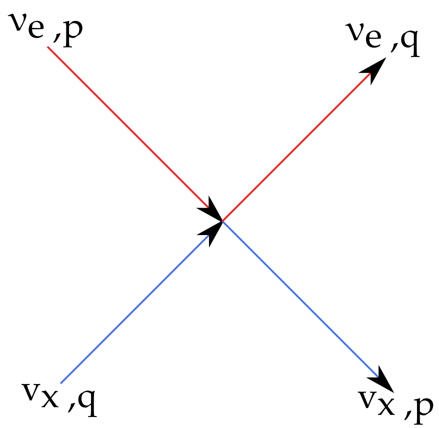
2. Neutrino oscillation

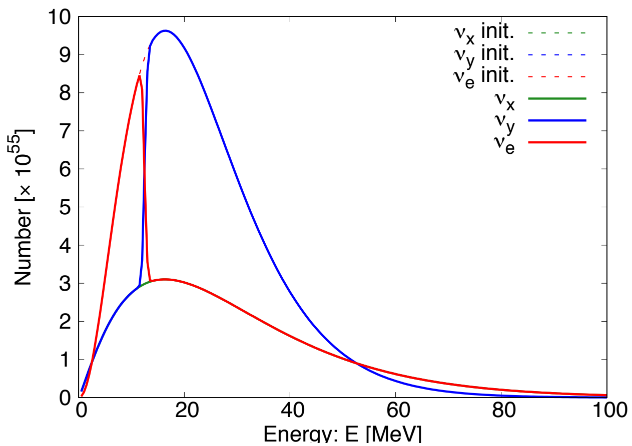
- Collective oscillation（Self-interaction effect）



Bulb model

The collective oscillation is due to ν-ν inteaction and causes the spectral splits.
This effect is important near the supernova core.





3. Method

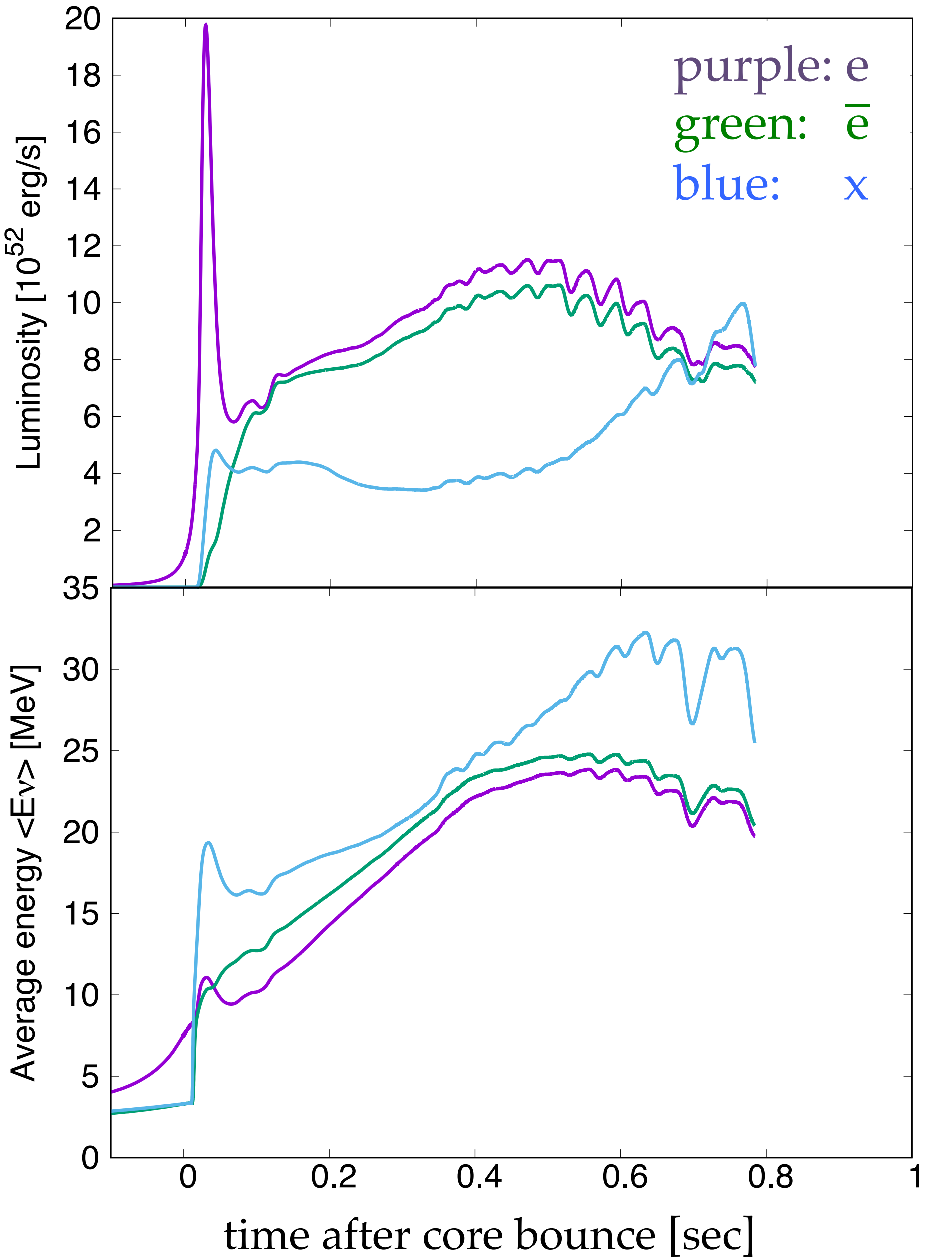
We obtain the flavor evolutions by solving the following equation of motion for the density matrix;

$$i\partial_t \rho_{\boldsymbol{p}} = \left[\underbrace{+U\frac{M^2}{2p}U^\dagger}_{\text{VO}} + \underbrace{\sqrt{2}G_F L}_{\text{MSW}} + \underbrace{\sqrt{2}G_F \int \frac{\mathrm{d}^3 q}{(2\pi)^3} (1-\cos\theta_{\boldsymbol{pq}}) \left\{ n_\nu(\boldsymbol{q})\rho_{\boldsymbol{q}} - \overline{n}_\nu(\boldsymbol{q})\overline{\rho}_{\boldsymbol{q}} \right\}}_{\text{Collective (non-linear term)}}, \rho_{\boldsymbol{p}} \right]$$

In this work, we assume the single-angle approximation. This approximation is that wave functions don't depend on the angle of incidence.

The multi-angle simulation is … under construction.
I face several difficulties and the results are incomplete.

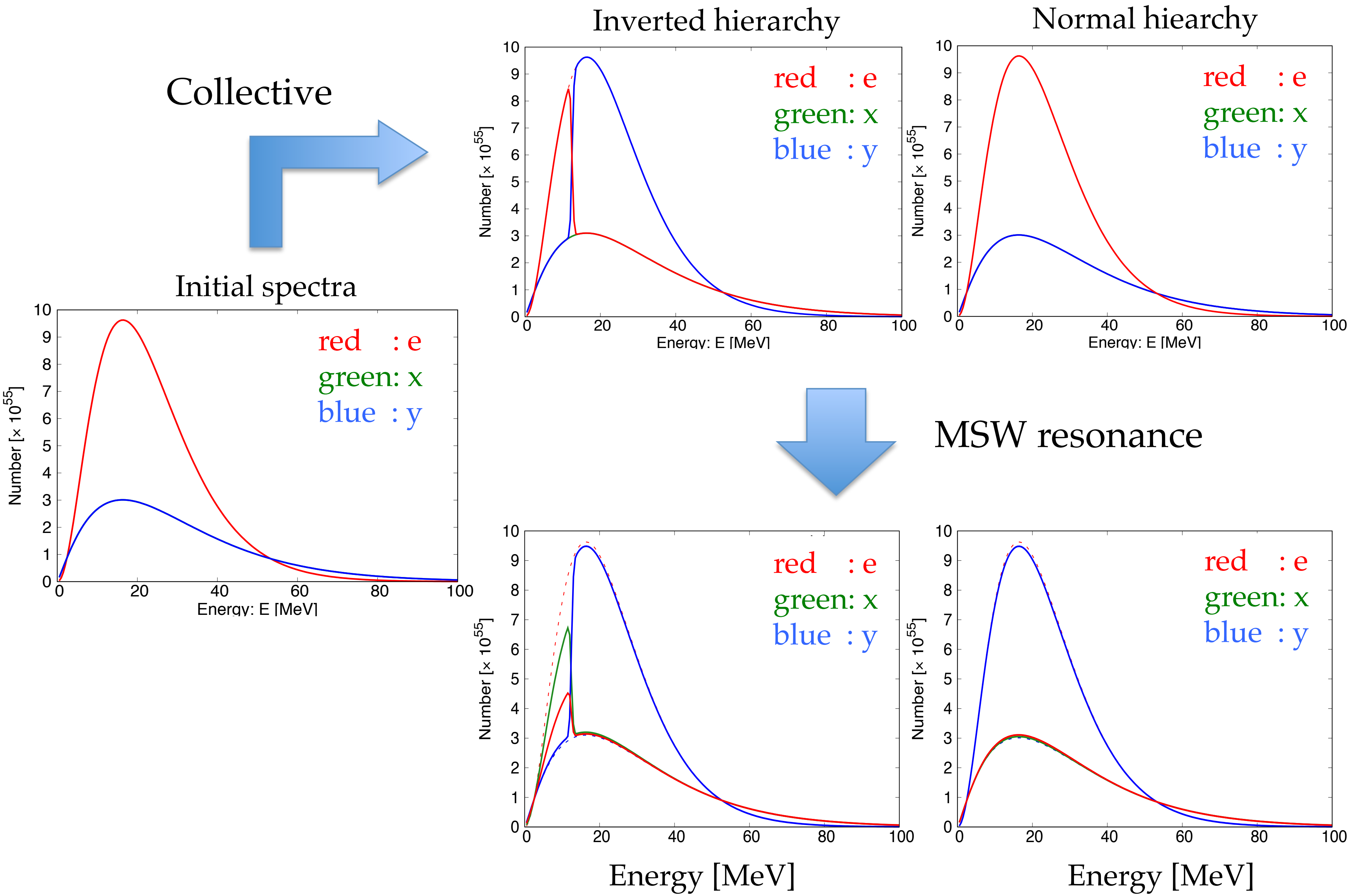
Using model



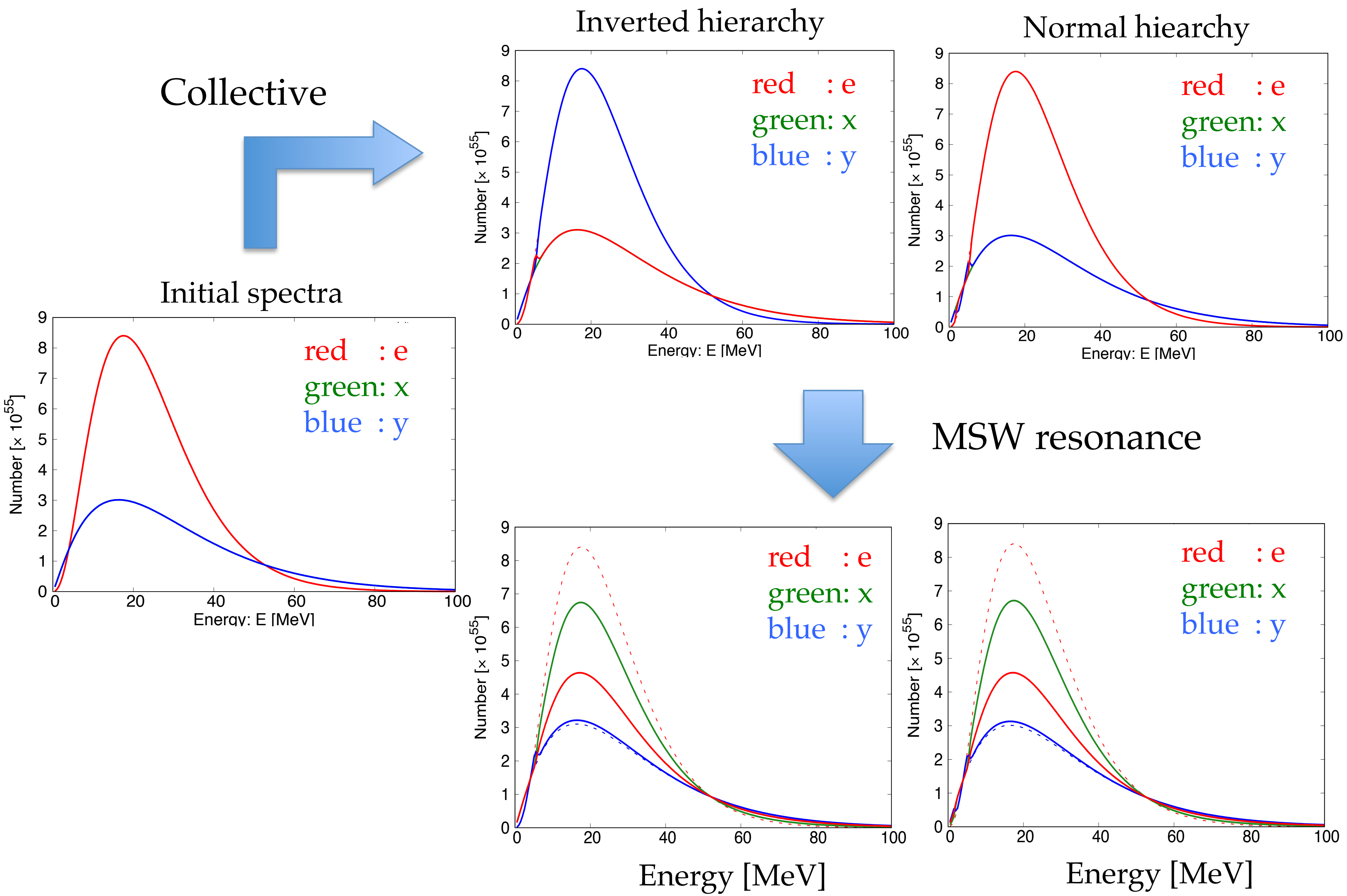
- Calculation by Sumiyoshi
- $40M_{\odot}$、EoS:LS220、1D model
  - Sumiyoshi et al. 2007, 2008
- Top left figure shows neutrino luminosity.
- Bottom left figure shows neutrino averaged energy.
- These values continue to increase after core bounce.

- At several time steps, we carry post-process calculation in the normal and inverted hierarchy.
- t = 30, 100, 200, 300, 400, 500, 600, 750 ms

Result ex.: 600ms, Neutrino, IH & NH



Result ex.: 600ms, Antineutrino, IH & NH



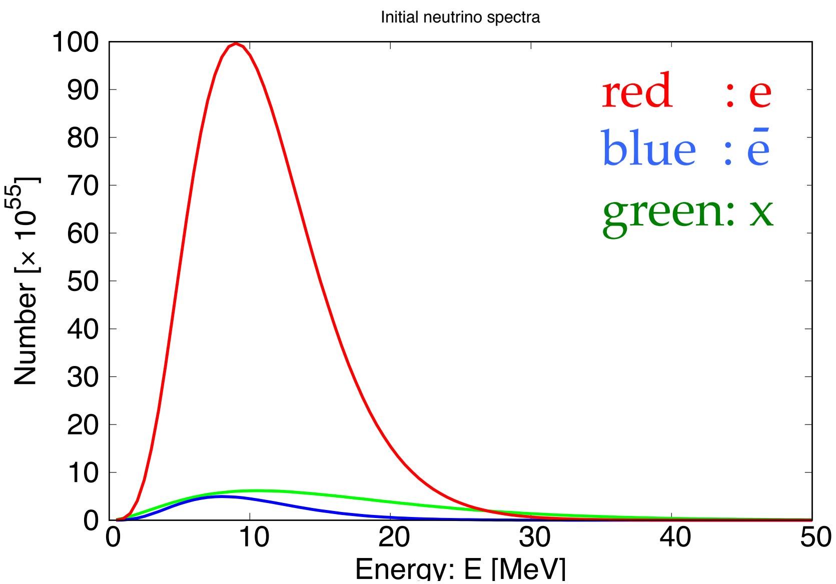
Results at other time steps.

- Oscillation effects are qualitatively same at the time except for the neutronization burst at t = 30 ms.

- At the neutronization burst, collective effects are suppressed.
  - Due to the excess of electron neutrinos.
  - Therefore the differences occur between two hierarchies by MSW.

$$\nu_e \overline{\nu}_e \leftrightarrow \nu_x \overline{\nu}_x$$

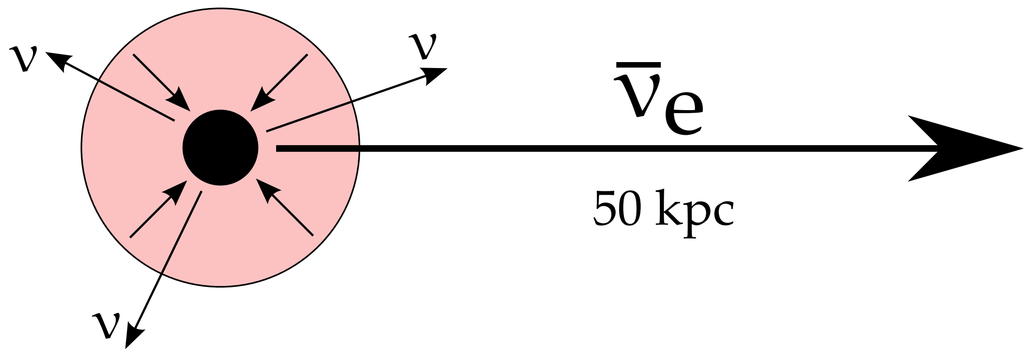
Pair conversion -> no collective

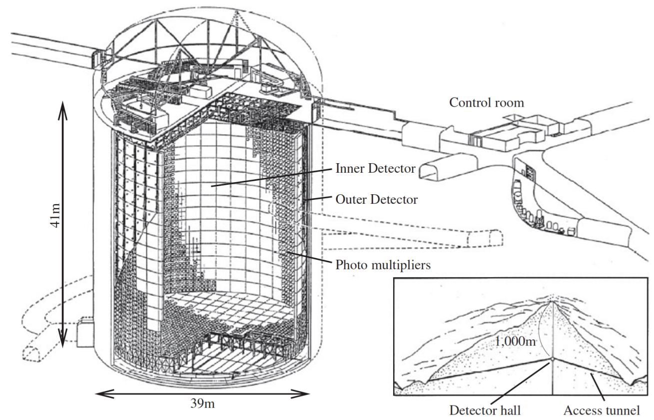


Detectionability at Super-Kamiokande

- Neutrinos arrive at the Earth.
- How many electron antineutrinos are detected by Super-Kamiokande?
- Super-Kamiokande have a high sensitivity to inverse beta decay with water Cherenkov detector.

$$\bar{\nu}_e + p \rightarrow n + e^+$$





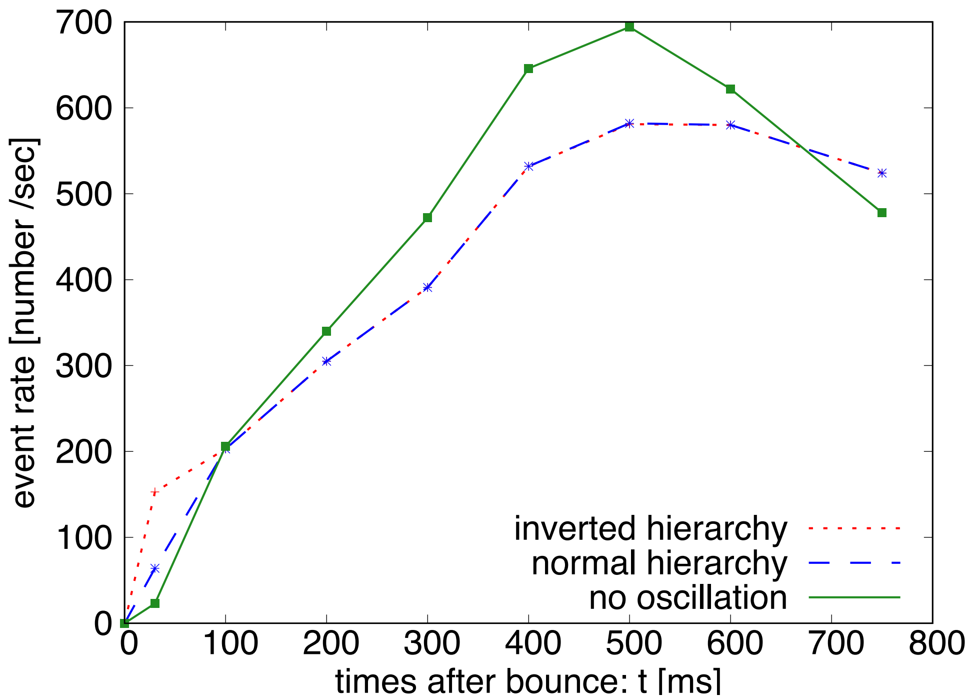
Abe et al. 2011

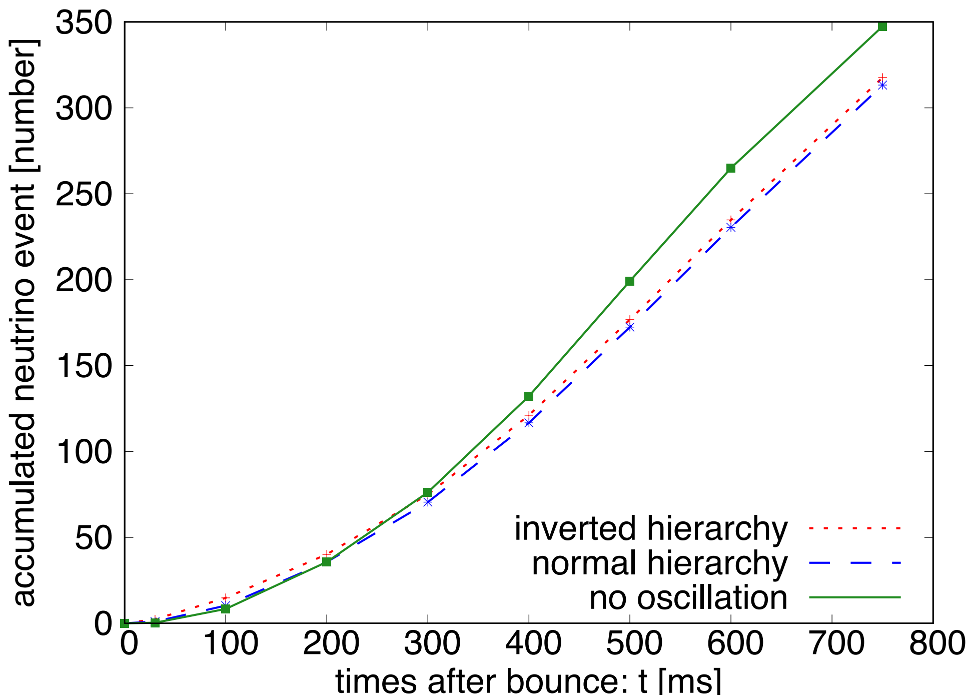
Detectionability at Super-Kamiokande

- Event rate of antineutrinos by Super-Kamiokande
  - N_p : proton number
    = fiducial volume 22.5 kton
  - d : distance to Failed SN (LMC, assume 50 kpc)
  - E_{th} : threshold energy
    = 4.79 MeV (3.5 MeV for recoil electrons)
  - $\phi(E)$: spectrum at the detector
  - $\sigma(E)$: cross section of IBD (Strumia et al. 2003)

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t} = \frac{N_p}{4\pi d^2}\int_{E_{\mathrm{th}}}^{\infty} \phi(E)\sigma(E)\mathrm{d}E$$

Event rate at Super-Kamiokande





Hundreds of neutrinos are detected without EM counterpart.

Event number rate is same in normal and inverted hierarchy.

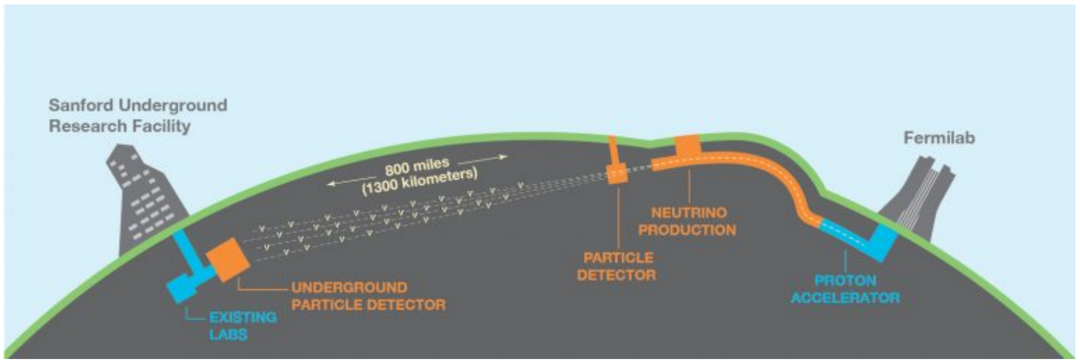
- collective effect and H resonance cancel each other in inverted hierarchy.

Detectionability at DUNE

- Deep Underground Neutrino Experiment
- A next generation detector in the United States.
- Finish all construction by 2028.
- DUNE have a high sensitivity to Charged-Current reaction with liquid argon.

$$^{40}\mathrm{Ar} + \nu_e \rightarrow ^{40}\mathrm{K}^* + e^-$$

- How many electron neutrinos are detected by DUNE ?

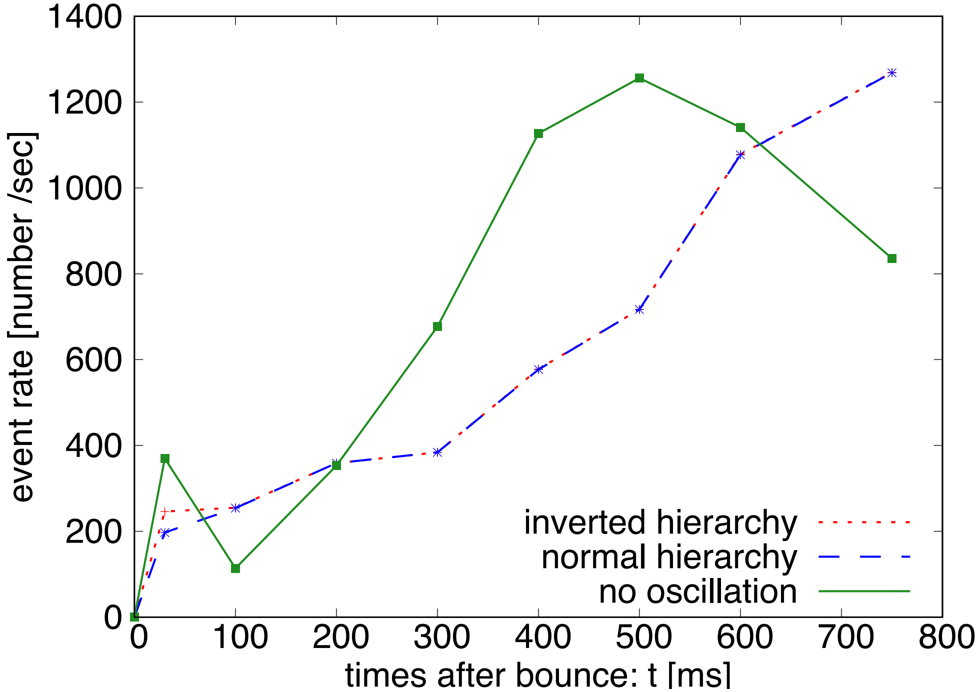


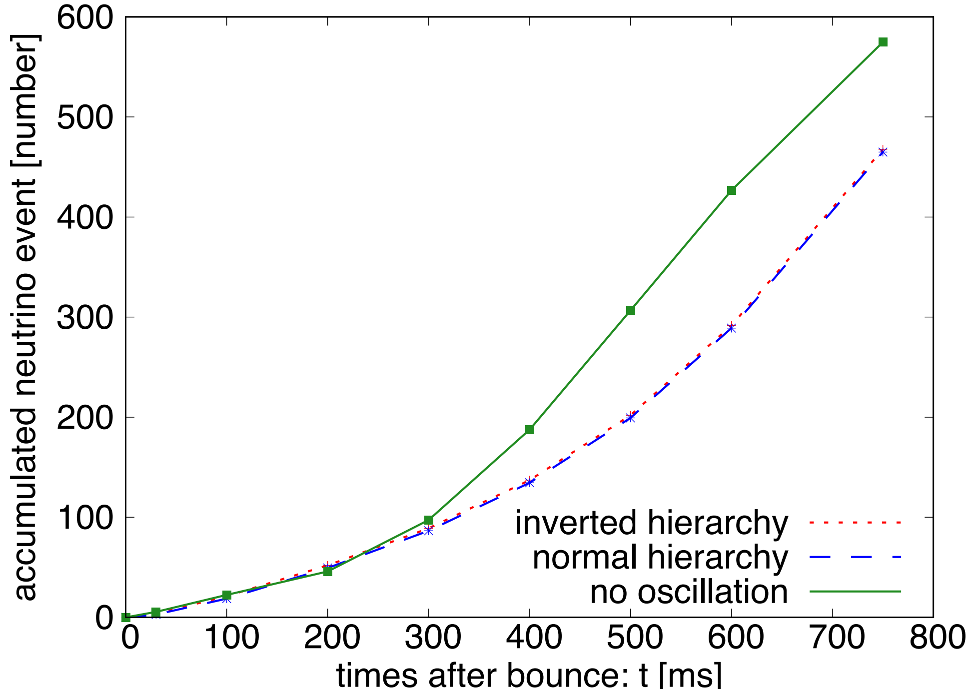
Detectionability at DUNE

- Event rate of neutrinos by DUNE
  - N_{Ar} : Argon number
    = fiducial volume 4×10 kton
  - d : distance to Failed SN (LMC, assume 50 kpc)
  - E_{th} : threshold energy
    = 8.28 MeV (5 MeV electron cut-off)
  - $\phi(E)$: spectrum at the detector
  - $\sigma(E)$: cross section of CC (Suzuki et al. 2013)

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t} = \frac{N_{\mathrm{Ar}}}{4\pi d^2}\int_{E_{\mathrm{th}}}^{\infty}\phi(E)\sigma(E)\mathrm{d}E$$

Event rate at DUNE

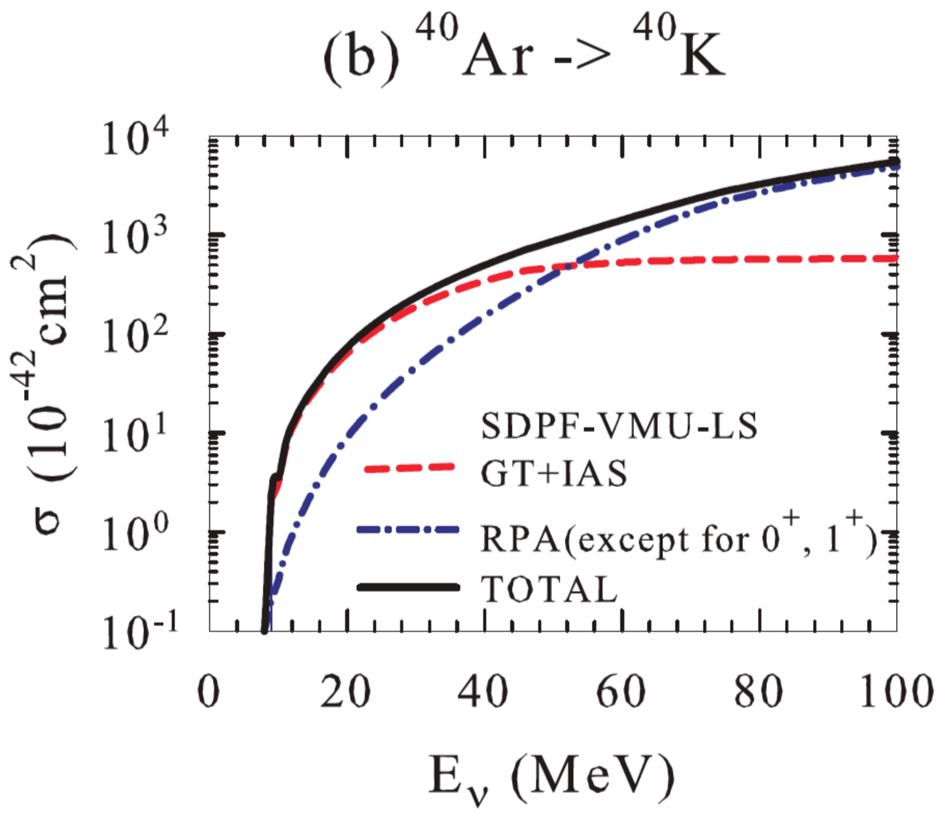




- Event number is same in normal and inverted hierarchy.
  - Spectra are different between two hierarchies.
  - Why?

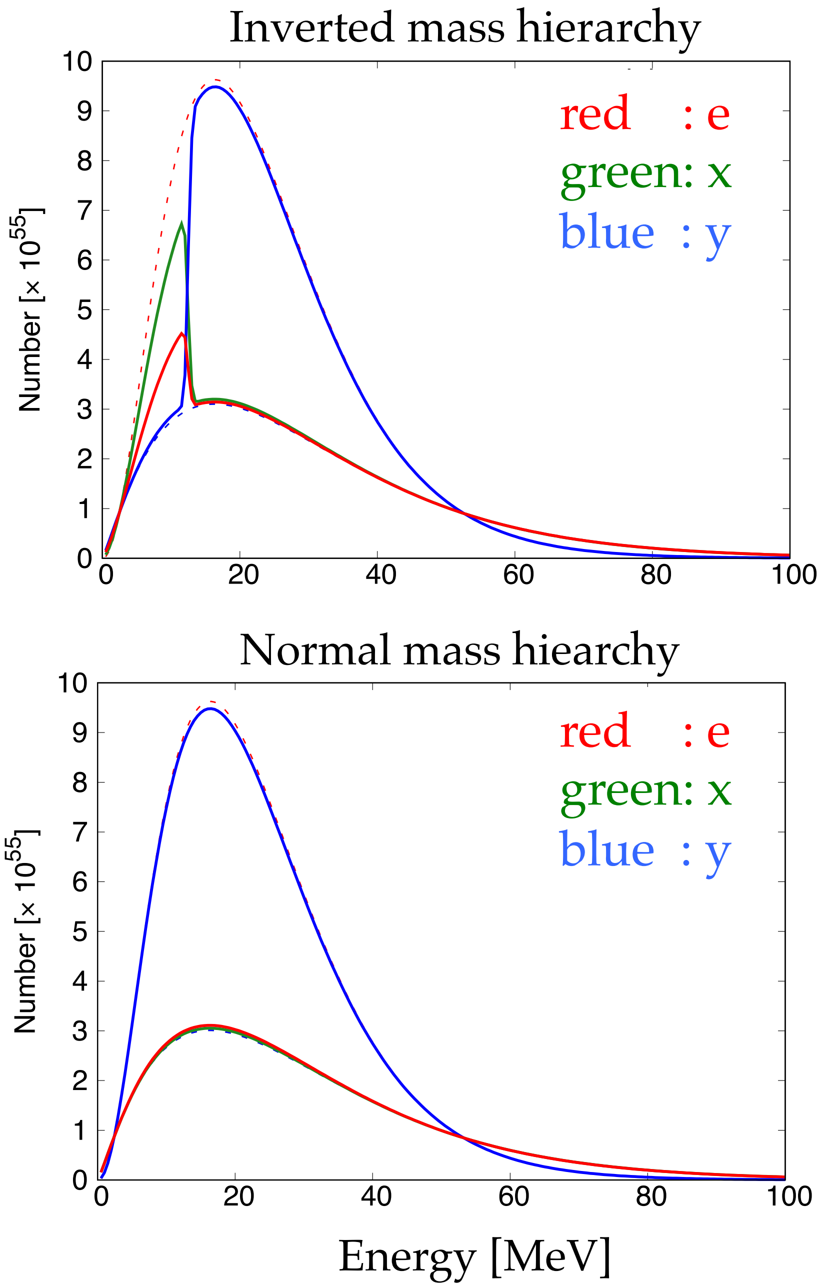
Cross section of CC reaction

Cross section in DUNE case
(CC reaction)



Suzuki et al. 2013

Cross section increases in the order with energy.



Future work

The multi-angle approximation?

Future work

- verify the multi-angle matter suppression

$$i\partial_t \rho_{\boldsymbol{p}} = \left[+U\frac{M^2}{2p}U^\dagger + \sqrt{2}G_F L + \sqrt{2}G_F \int \frac{\mathrm{d}^3 q}{(2\pi)^3}(1-\cos\theta_{\boldsymbol{pq}})\left\{n_\nu(\boldsymbol{q})\rho_{\boldsymbol{q}} - \overline{n}_\nu(\boldsymbol{q})\overline{\rho}_{\boldsymbol{q}}\right\}, \rho_{\boldsymbol{p}}\right]$$

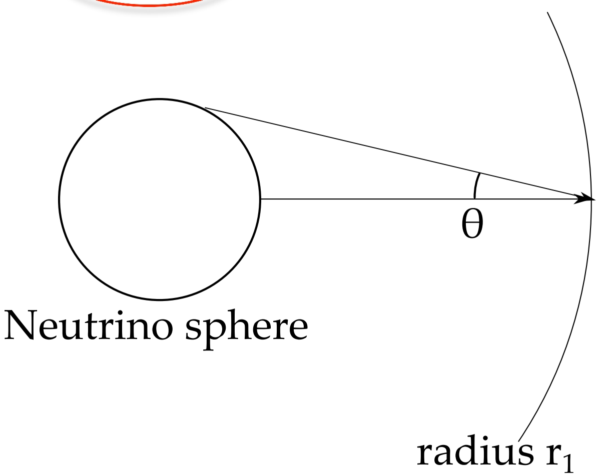
VO MSW Collective (non-linear term)

multi-angle approximation

polarization vector

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{P} = \left[\frac{+\omega\boldsymbol{B} + \lambda\boldsymbol{D}}{v_{r,u}} + \frac{\sqrt{2}G_F}{2\pi R_\nu^2}\frac{R_\nu^2}{2r^2}\int \mathrm{d}E'\mathrm{d}u'\left(\frac{1}{v_{r,u}v_{r,u'}} - 1\right)(n_\nu\boldsymbol{P} - \overline{n}_\nu\overline{\boldsymbol{P}})\right] \times \boldsymbol{P}$$

$$v_{r,u} = \cos\theta = \sqrt{1 - \sin^2\theta_R \frac{R_\nu^2}{r^2}}$$

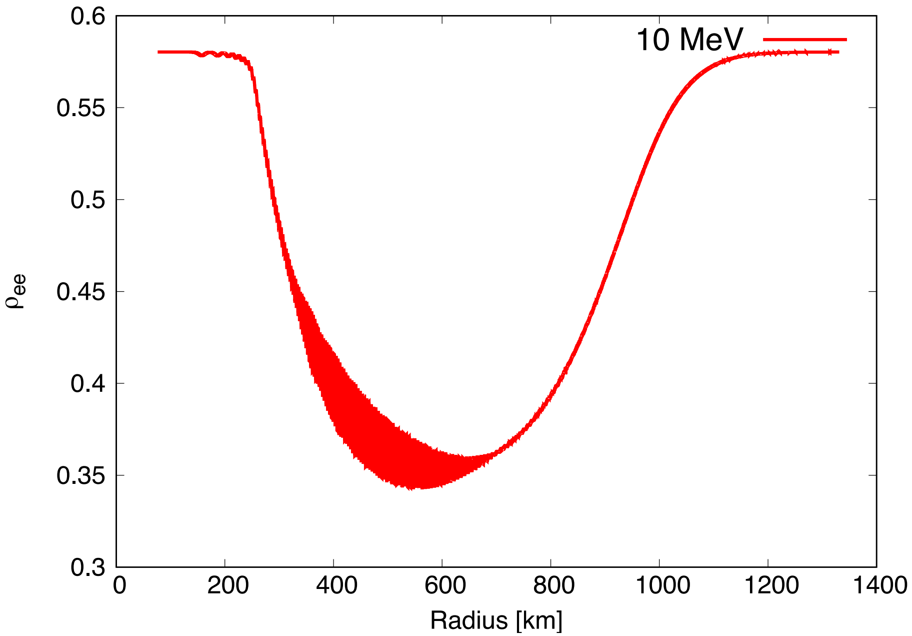


longer path to the same radius r_1

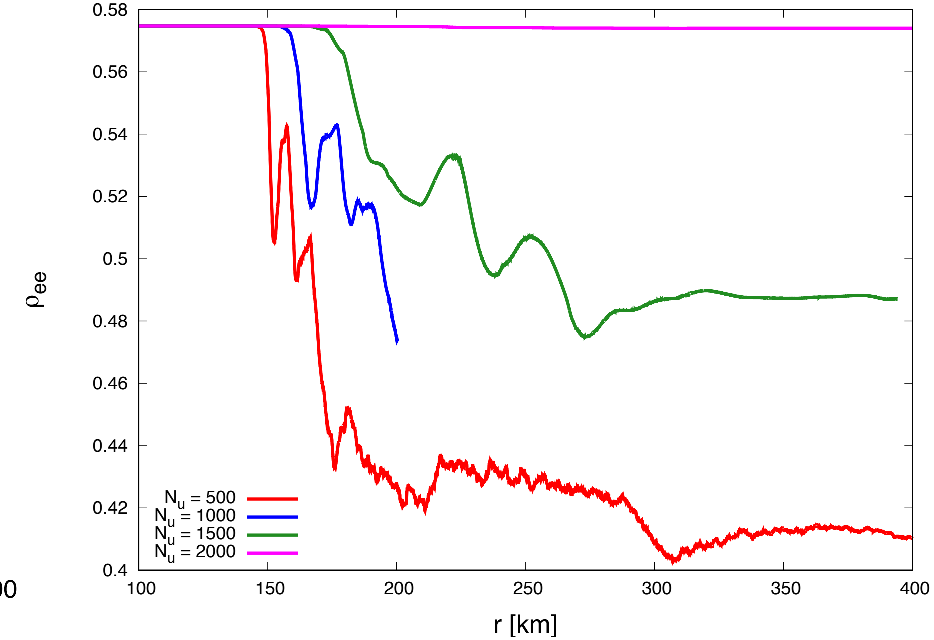
→ experience larger matter effect.

Future work

single-angle



multi-angle



- How large do we use the angle bin?
  - a lack of angle samplings causes the artificial collective oscillations.
  - good resolution :$N_\theta \sim O(10^3)$. 1000 ?, 2000 ?, …5000 ?

1D × 2D calculation. $$8 \times N_E \times N_\theta \times 2 \lesssim 1,000,000$$

Summary

- We calculate 3-flavor neutrino oscillation for 1-D failed supernova model.
- Hundreds of neutrinos and antineutrinos are detected from a failed SN located in LMC (50 kpc).
- The event numbers of neutrino and antineutrino are identical in both hierarchy cases.
  - High energy components are dominant at DUNE.
- We tackle the multi-angle approximation.