Systematic study of neutrino spectra emitted from core-collapse supernovae: Effect of neutrino oscillation

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Shio Kawagoe (University of Tokyo)

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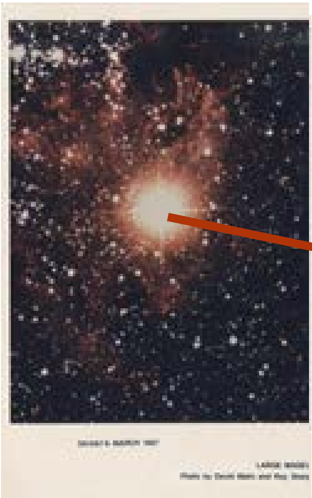
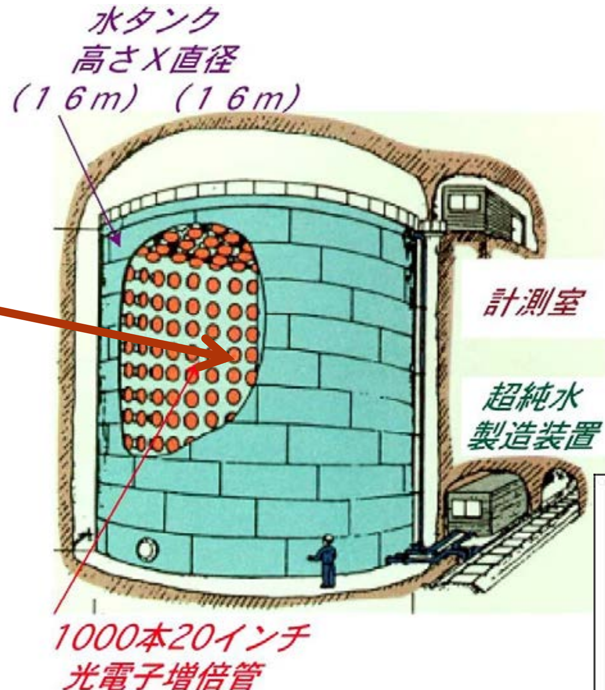
SN1987a

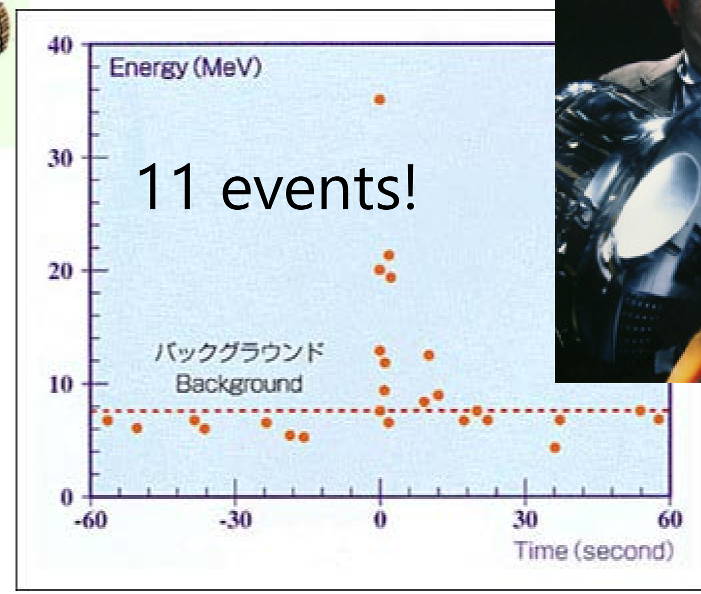


SN explosion happened in a next galaxy.



Neutrino is detected by Kamiokande.

Nobel prize in 2002 is awarded to Prof. Koshiba and Kamiokande

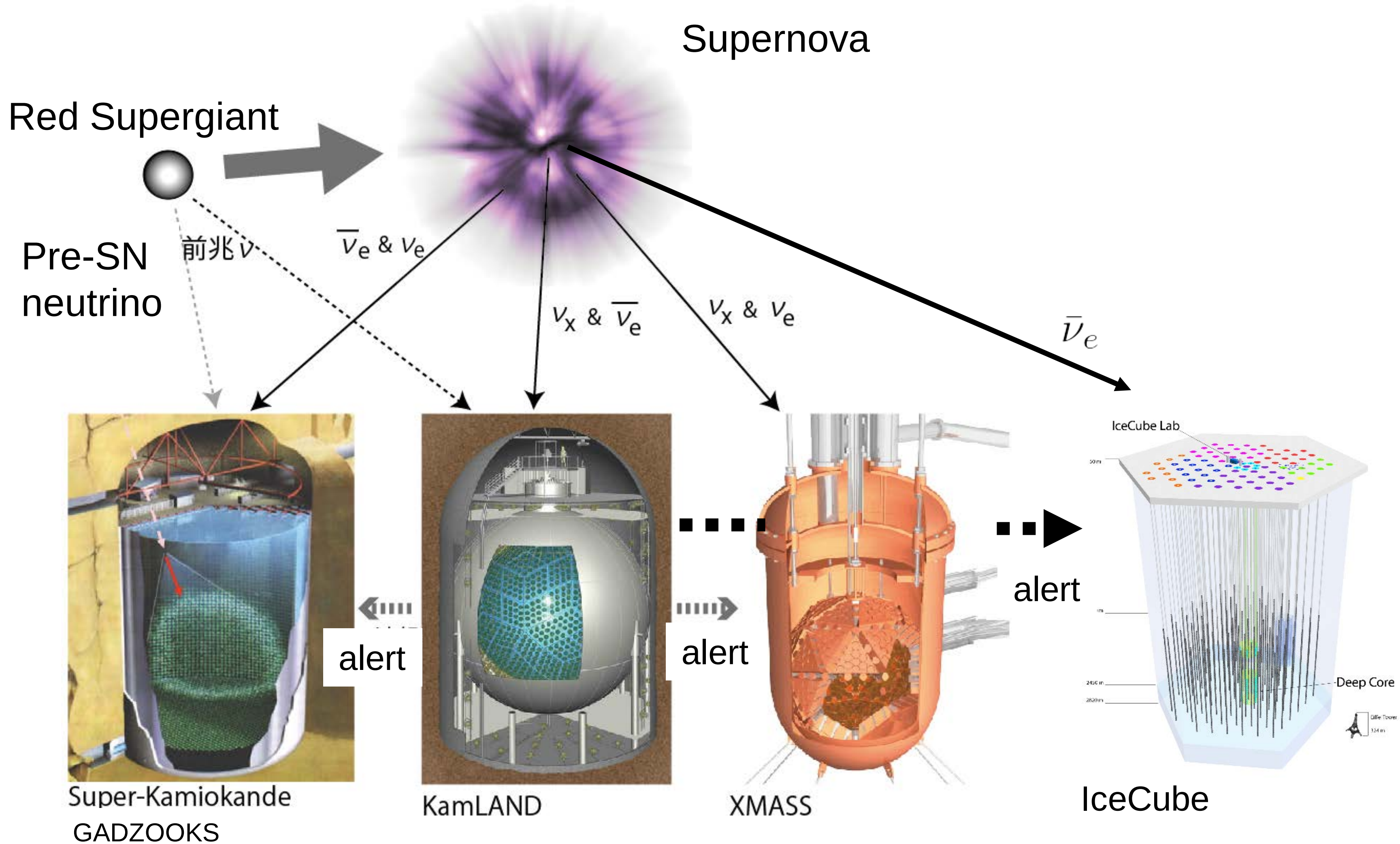


11 events!

NS birth=SN: Rough sketch has been made.

=> Detailed Study with Multi-Detectors

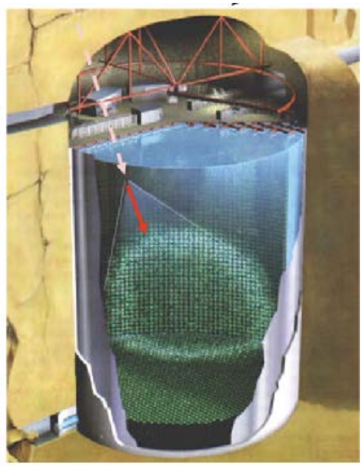
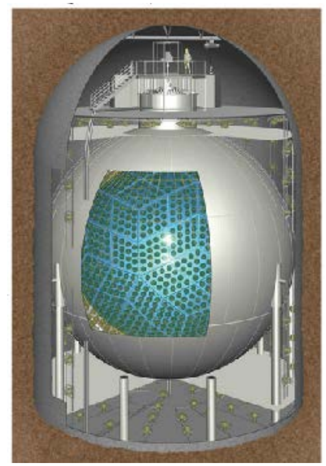
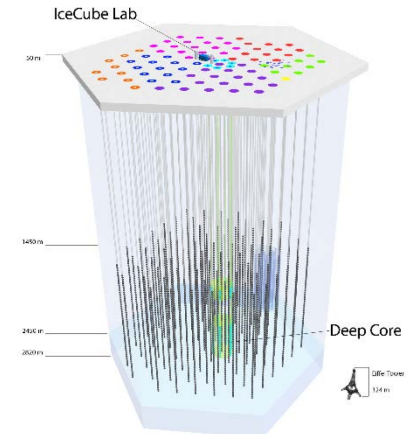
Neutrino Detection Strategy By Multi-Detectors



http://www.lowbg.org/ugnd/?page_id=53

IceCube Collaboration, Nature 484 (2012) 351-353

Comparison of Detector Capability

	 Super-Kamiokande	 KamLAND	 IceCube
Target Material	H_2O	C_nH_{2n+2}	H_2O
Volume	32 kton	1 kton	0.6 Gton
Feature	Light Curve Spectrum (>7MeV) Direction	Spectrum (>0.5MeV)	Light Curve (Time variability)

Please modify the description if I am wrong.

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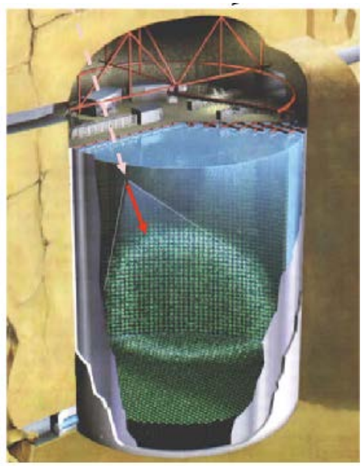
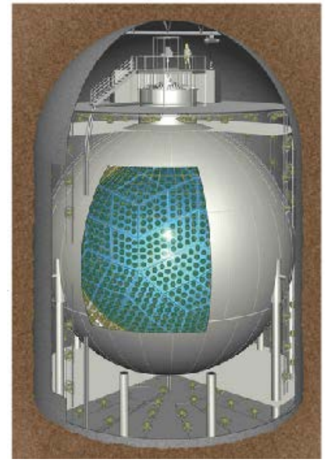
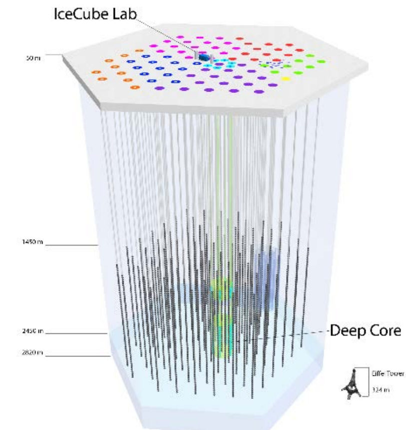
Comparison of Detector Capability

	 Super-Kamiokande	 KamLAND	 IceCube
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Volume	32 kton	1 kton	0.6 Gton
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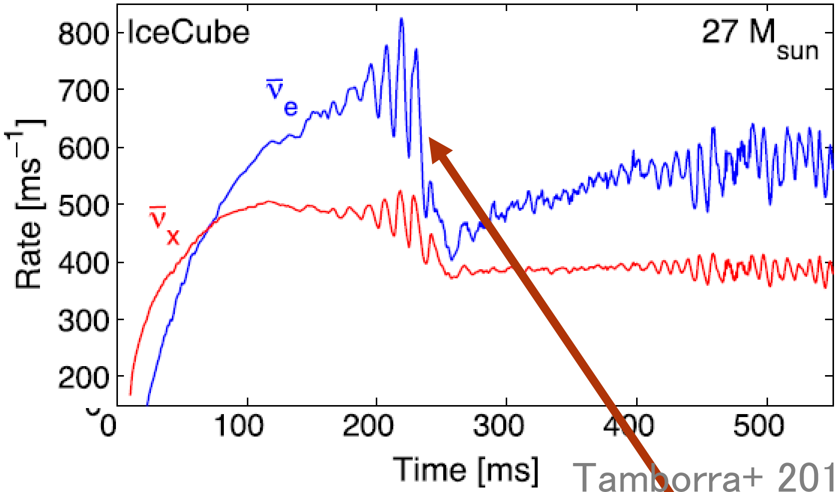
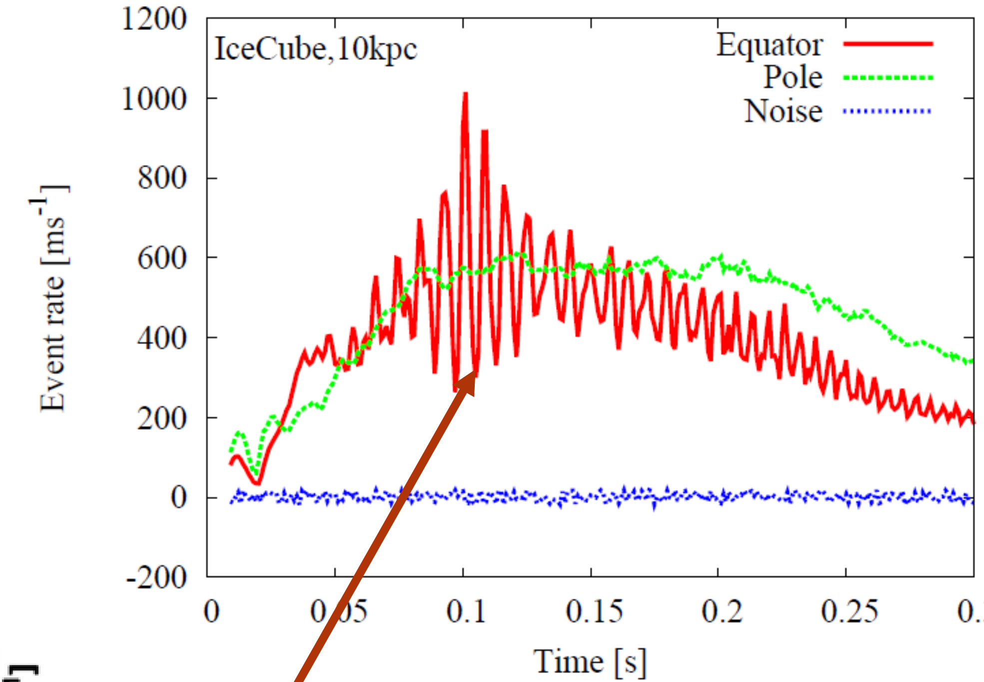
Please modify the description if I am wrong.

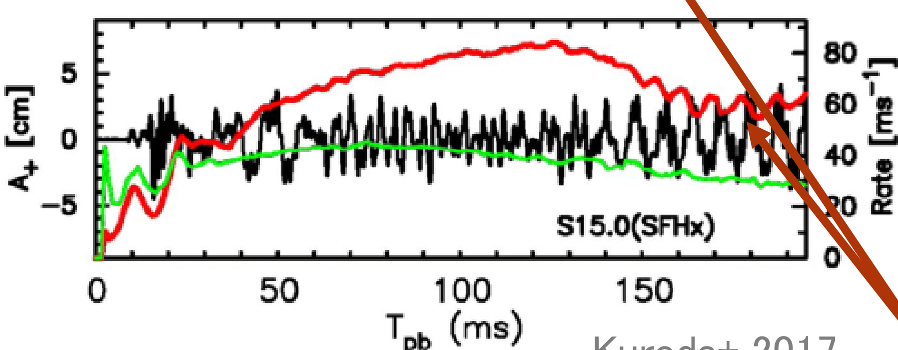
Light Curve and Time Variability



Tamborra+ 2013



Takiwaki+ 2018 (Accepted in MNRAS Letters)



Kuroda+ 2017

Low T/W instability

SASI (Standing Accretion Shock Instability)

From the time variability of detected neutrino count, we can extract information on the hydrodynamic instabilities that occur in SNe.

See Kotake_san's presentation

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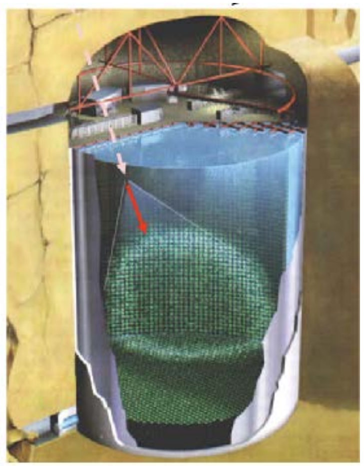
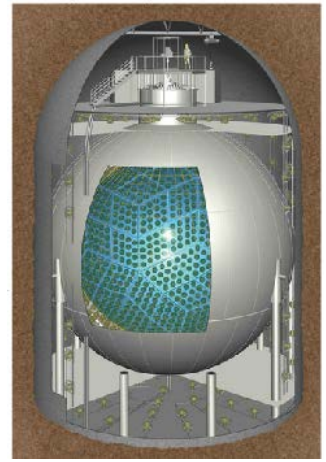
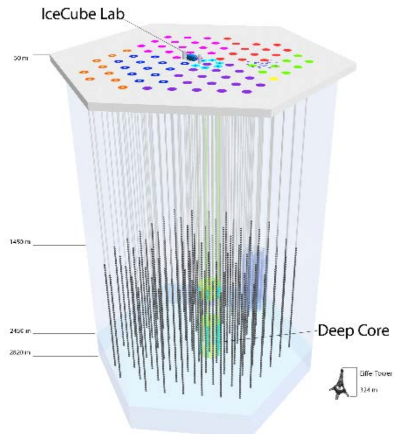
Comparison of Detector Capability





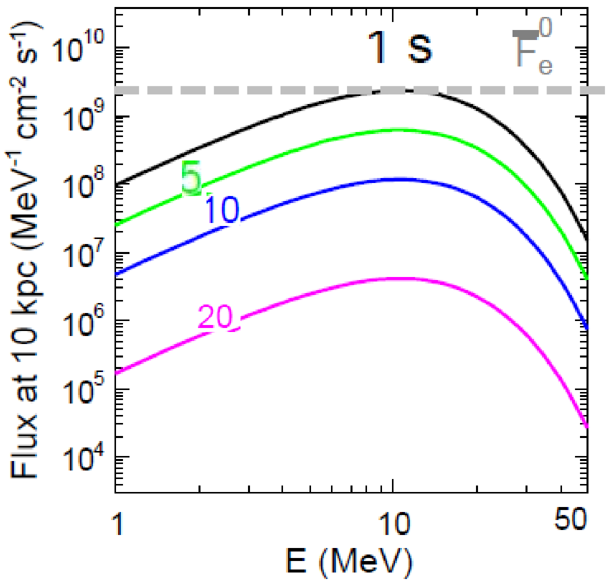


	Super-Kamiokande	KamLAND	IceCube
Target Material	H_2O	C_nH_{2n+2}	H_2O
Volume	32 kton	1 kton	0.6 Gton
Feature	Light Curve Spectrum (>7MeV) Direction	Spectrum (>0.5MeV)	Light Curve (Time variability)

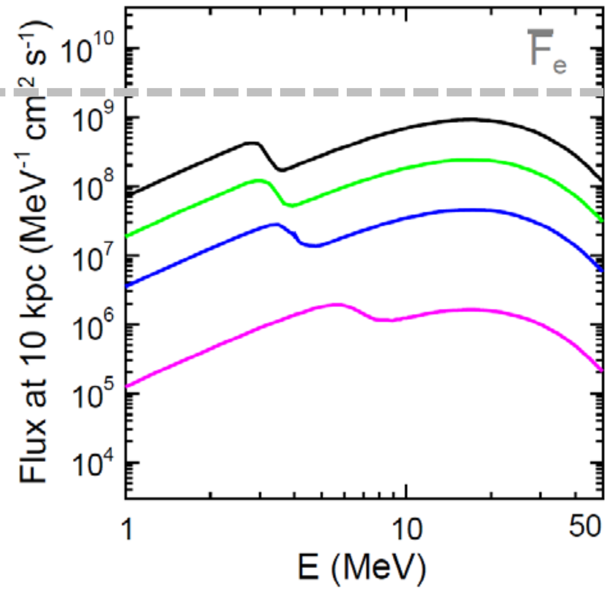
Please modify the description if I am wrong.

Neutrino Spectra and Neutrino Oscillation

Original Spectrum



After Neutrino Oscillation



$$L(t) = \frac{E_B}{6}\frac{e^{-t/\tau}}{\tau}$$

Inverted mass hierarchy, small θ_13

Fogli+ 2009

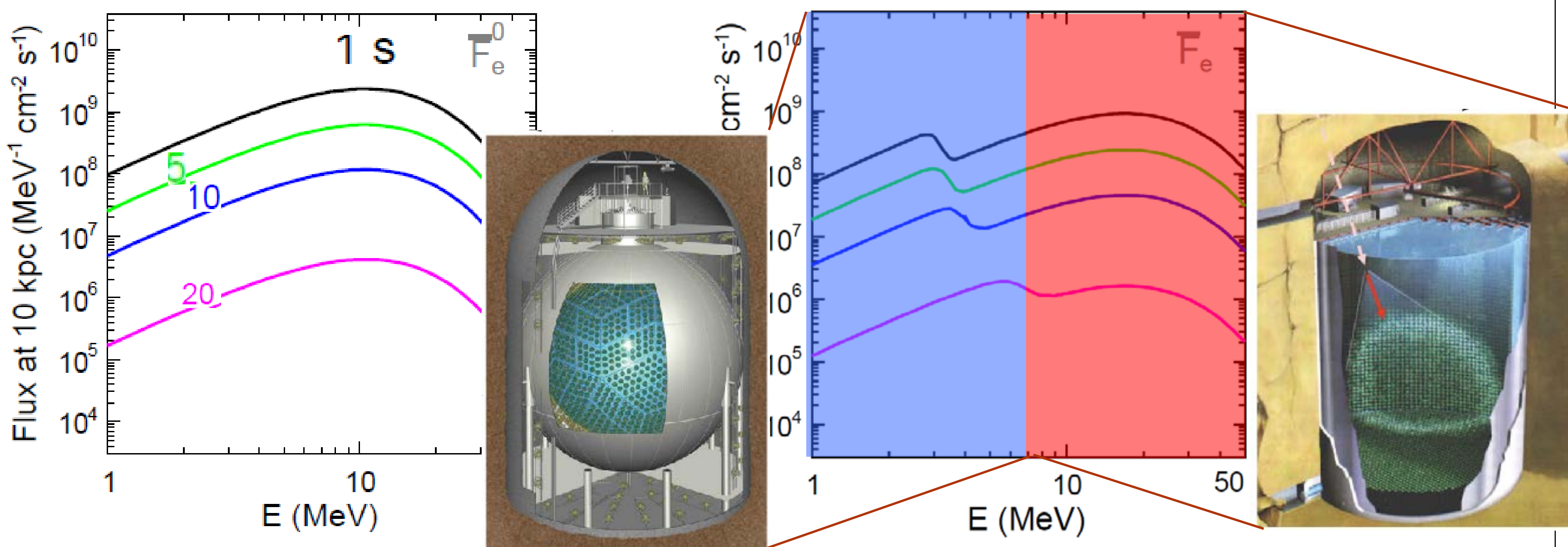
$$\langle E_e \rangle = 10 \text{ MeV}, \ \langle \overline{E}_e \rangle = 15 \text{ MeV}, \ \langle E_x \rangle = 24 \text{ MeV},$$

The effect of neutrino oscillation could be prominent in low energy region!

Neutrino Spectra and Neutrino Oscillation

Original Spectrum

After Neutrino Oscillation



Fogli+ 2009

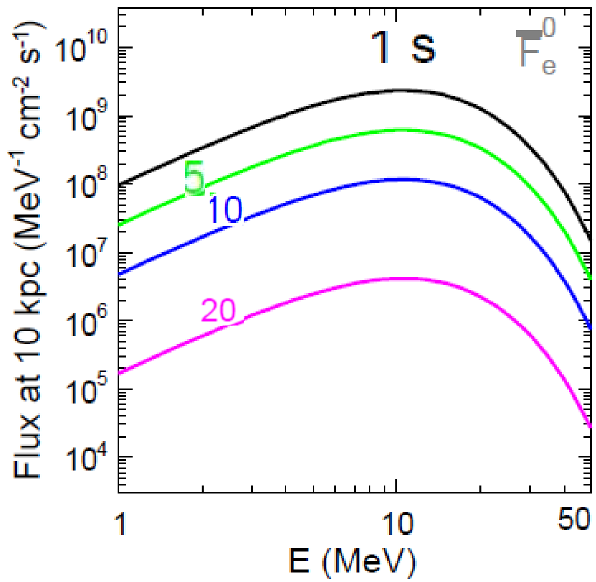
Above 7 MeV, SK can correctly determine its spectrum.

Below 7 MeV, KamLAND can determine the spectrum.

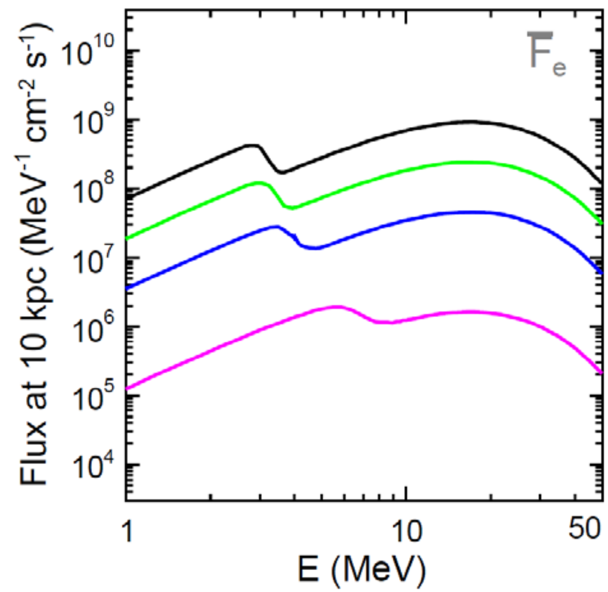
The cooperation of the two detectors is important!

Motivation of our study

Original Spectrum



After Neutrino Oscillation



Fogli+ 2009

How does the spectrum bump robustly appears in the realistic situation?

What can we learn from it?

Contents

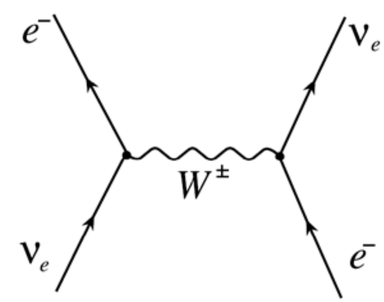
Basics of Neutrino Oscillation

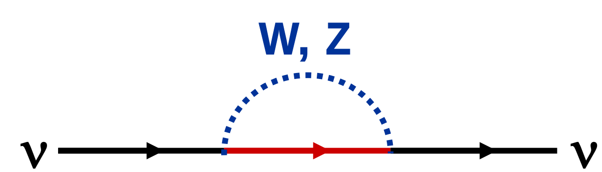
Beginning from Schrödinger equation.

$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix}$$

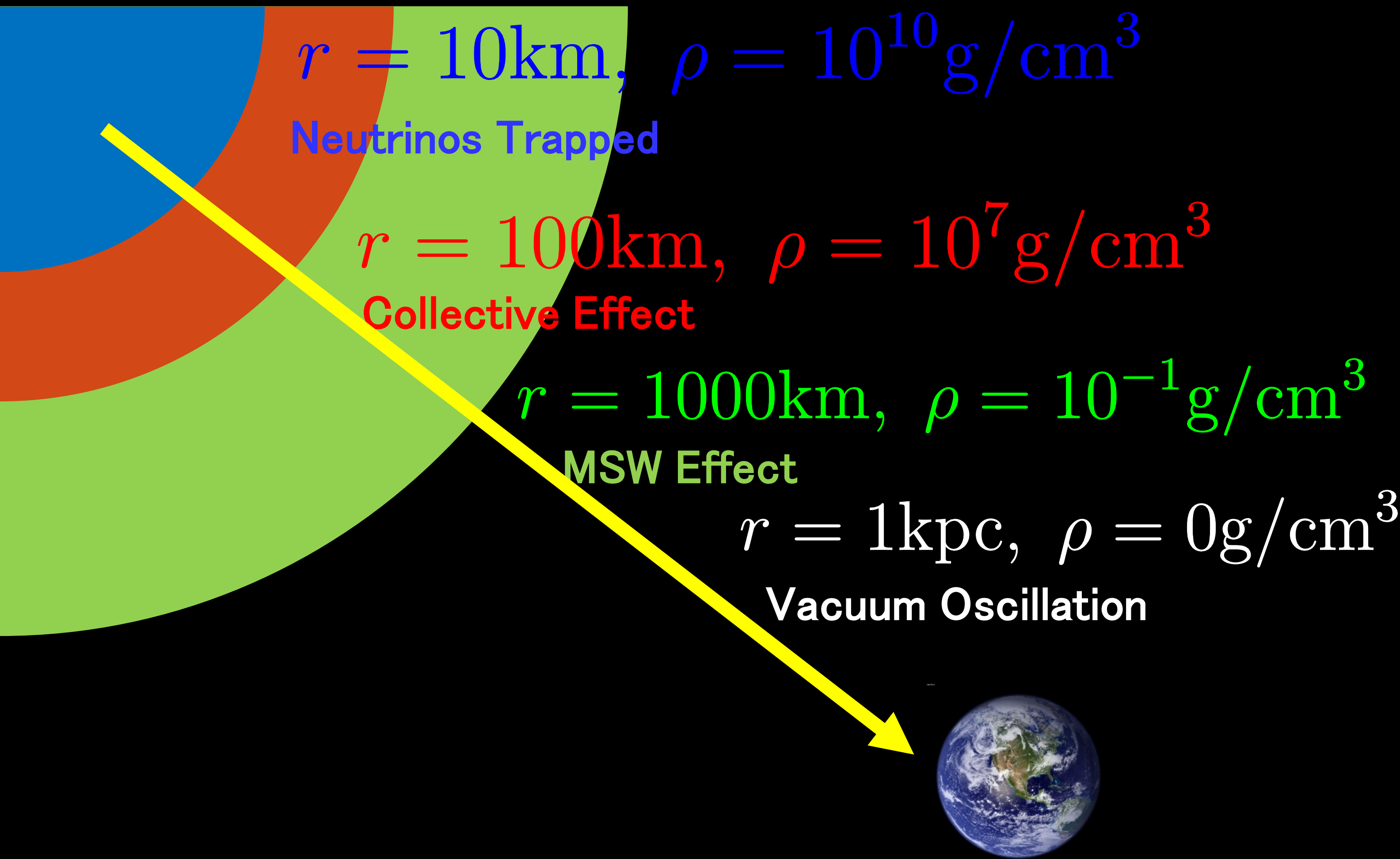
Hamiltonian is not diagonal and affected by matter and neutrino itself.

$$\begin{aligned} H \;=\; & \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2/2E \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \\ & + \sqrt{2} G_F \begin{pmatrix} n_e & 0 \\ 0 & 0 \end{pmatrix} \\ & + \sqrt{2} G_F \begin{pmatrix} n_{\nu_e} & n_{<\nu_e|\nu_X>} \\ n_{<\nu_X|\nu_e>} & n_{\nu_X} \end{pmatrix} \end{aligned}$$





Various Neutrino Oscillations



Though the travel to the Earth, neutrino flavor changes by many effects.

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Summary of Numerical Methods

- Hydro Simulation
  3DnSNe
  Spherical coordinate 1D, PLM (Mignone 2014)
  HLLC (Toro 2003), van Lear Limiter
  Phenomenological General Relativity (Marek+ 2006)

- Neutrino Radiation Simulation
  3flavor IDSA
  Updated Reaction Set (next page)

- Neutrino oscillation (post process)
  Single angle approximation (should be updated!)
  3 flavor (Dasgupta 2010)

New Reaction Sets

	Reaction		Reference
O	$\nu_e\, n \rightleftharpoons e^-\, p$	Martínez-Pinedo et al. (2012)	Bruenn (1985) Horowitz (2002)
O	$\bar{\nu}_e\, p \rightleftharpoons e^+\, n$		Fischer (2016) Reddy et al. (1999)
O	$\nu_e\, A' \rightleftharpoons e^-\, A$		Juodagalvis et al. (2010)
O	$\nu\, N \rightleftharpoons \nu\, N$	Horowitz et al. (2017)	Bruenn (1985) Horowitz (2002)
	$\nu\, A \rightleftharpoons \nu\, A$		Bruenn (1985),Horowitz (1997)
	$\nu\, e^{\pm} \rightleftharpoons \nu\, e^{\pm}$		Bruenn (1985)
	$e^-\, e^+ \rightleftharpoons \nu\, \bar{\nu}$		Bruenn (1985)
O	$N N \rightleftharpoons \nu\bar{\nu} N N$	Fischer (2016)	Hannestad & Raffelt (1998)
O	$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_x + \bar{\nu}_x$		Buras et al. (2003); Fischer et al. (2009)
O	$\nu_x + \nu_e(\bar{\nu}_e) \rightleftharpoons \nu_x' + \nu_e'(\bar{\nu}_e')$		Buras et al. (2003); Fischer et al. (2009)

Kotake et al. in prep

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Typical Spectrum

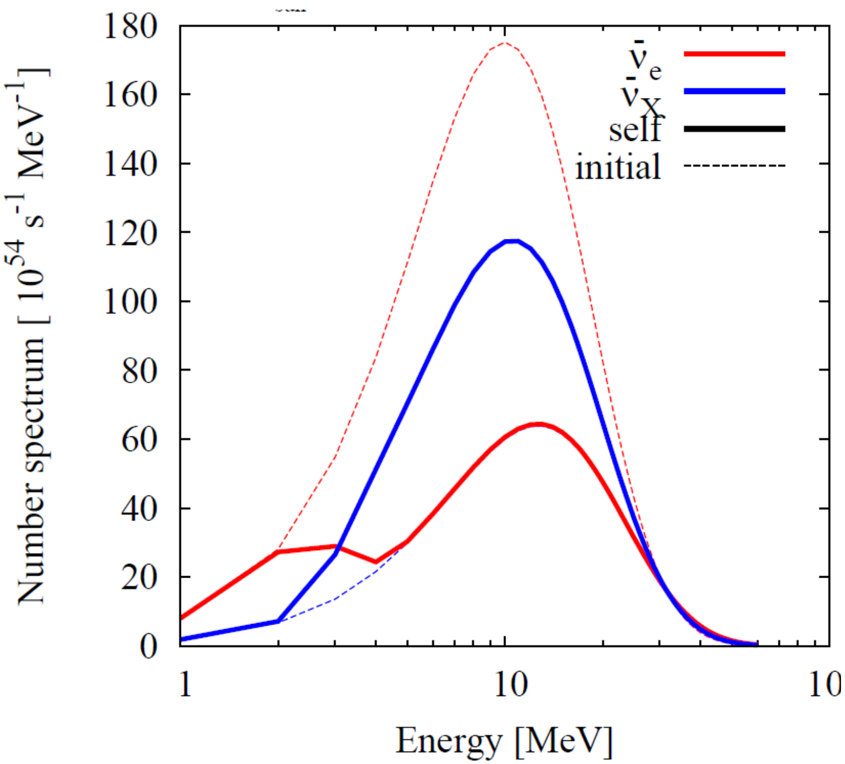
15M_s(WH07 model) progenitor 112ms after bounce.

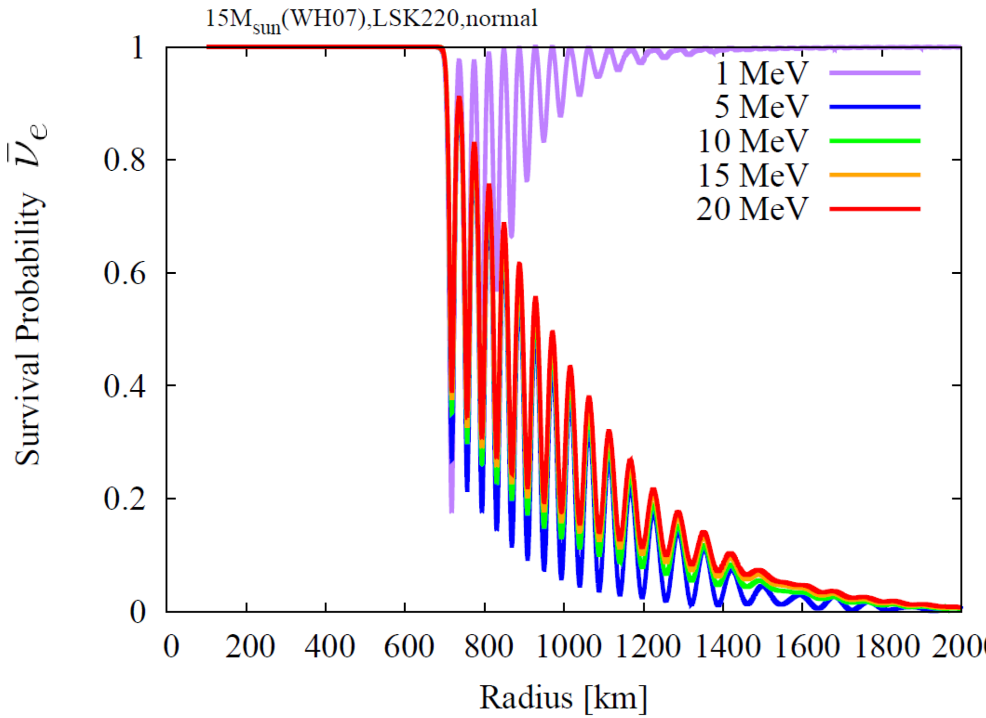
Normal mass hierarchy.

$$L_{\nu_e,\bar{\nu}_e,\nu_X}[10^{52}\mathrm{erg/s}] = 6.3, 6.6, 3.8$$

$$< E_{\nu_e,\bar{\nu}_e,\nu_X} > [\mathrm{MeV}] = 10.8, 13.9, 17.7$$

Spectrum at 2000km





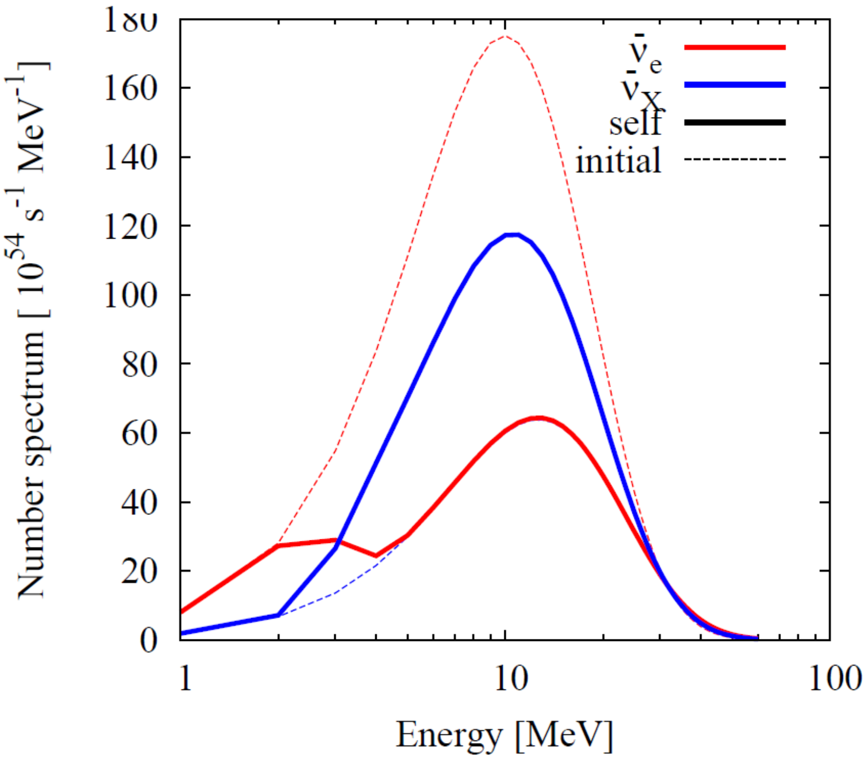
Spectral swap only happens at high energy (>4MeV).

Typical Spectrum

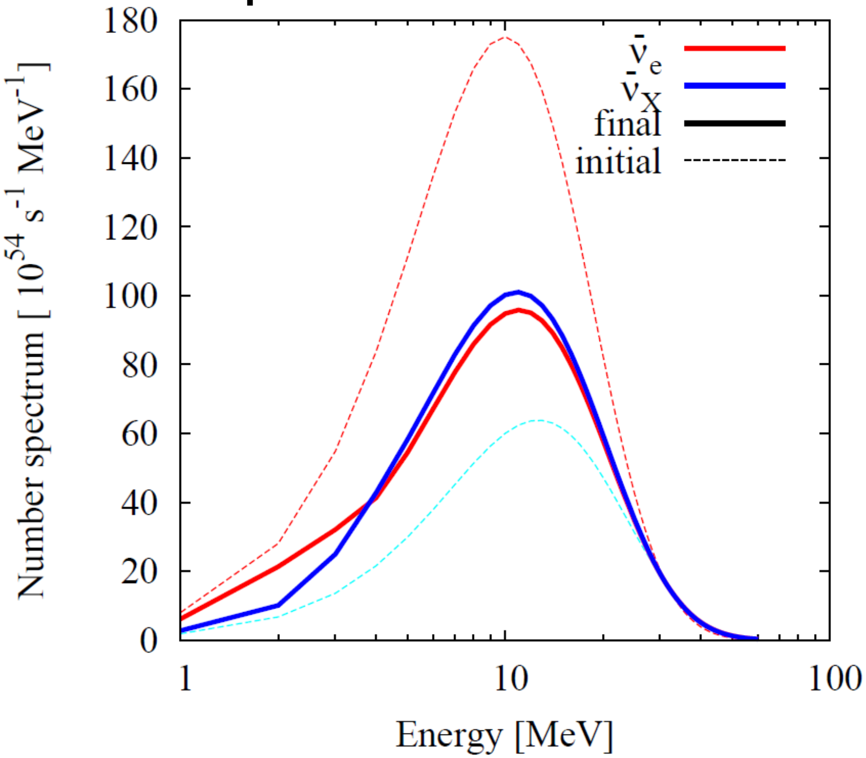
15M_s(WH07 model) progenitor 112ms after bounce.

Normal mass hierarchy.

Effect of ν self-interaction

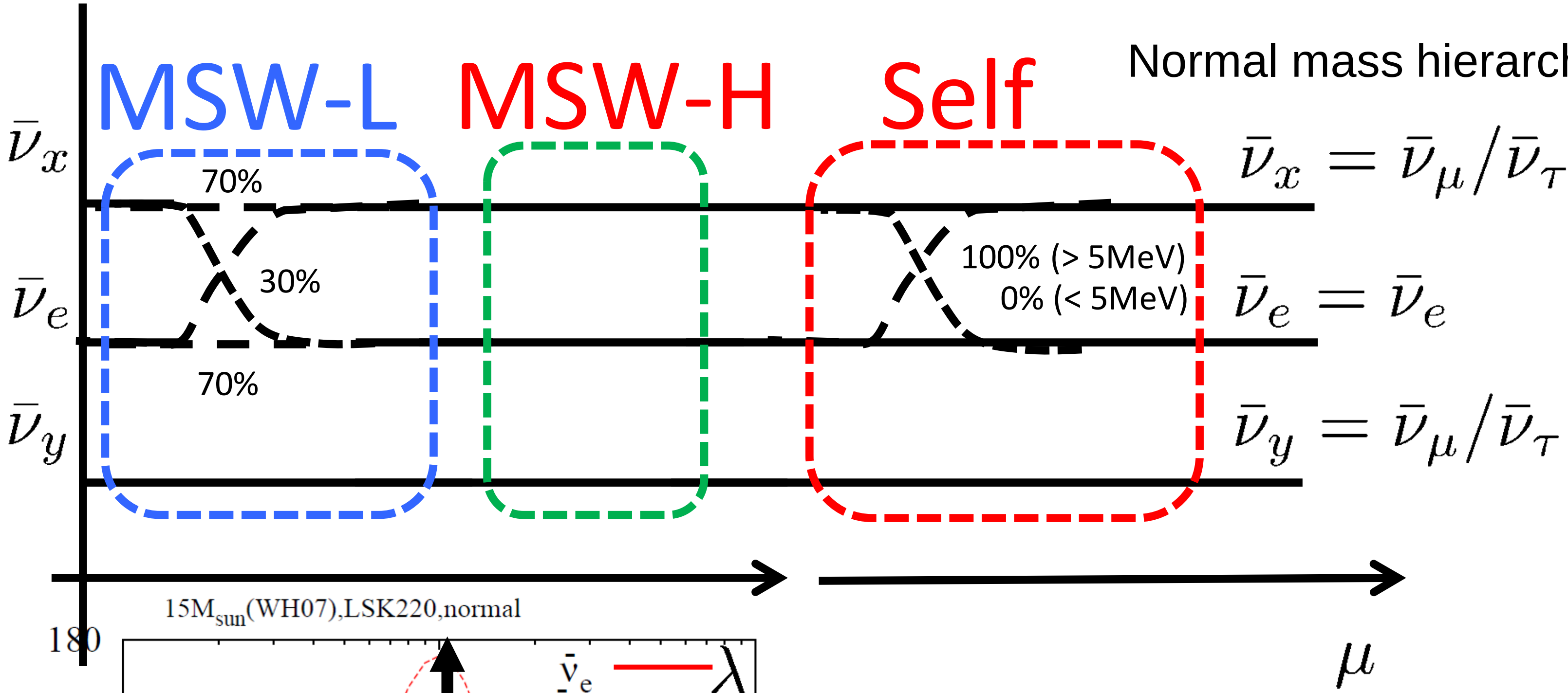


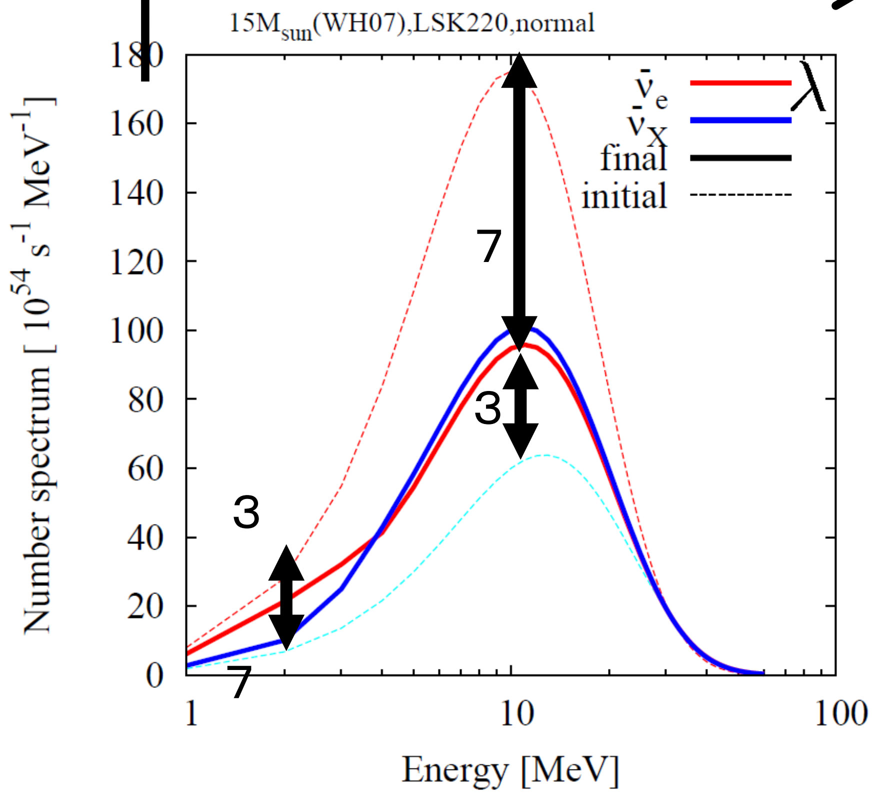
Spectrum at Earth



Self interaction makes a prominent spectral swap in low energy region.
However, MSW effects hide the swap and it become less obvious.
We should check the feasibility to detect the effect including errors.

Normal mass hierarchy.



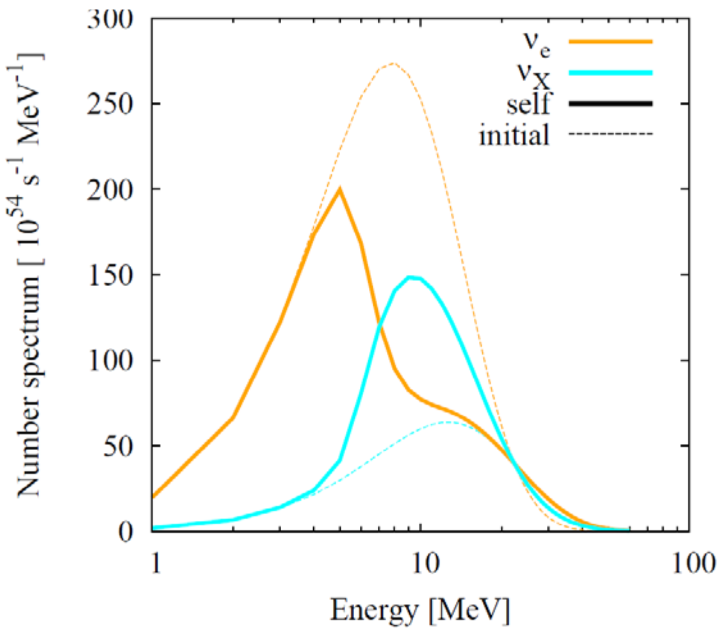


High Energy part:
100% go to x and 30% returns.

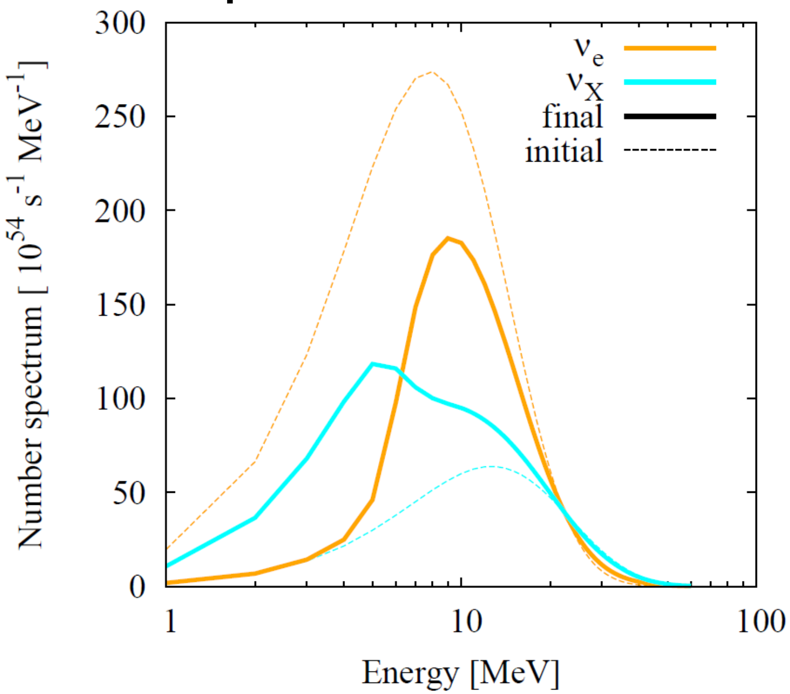
Low Energy part:
100% remains and then 30% goto x.

Spectrum for electron type neutrino

Effect of ν self-interaction



Spectrum at Earth

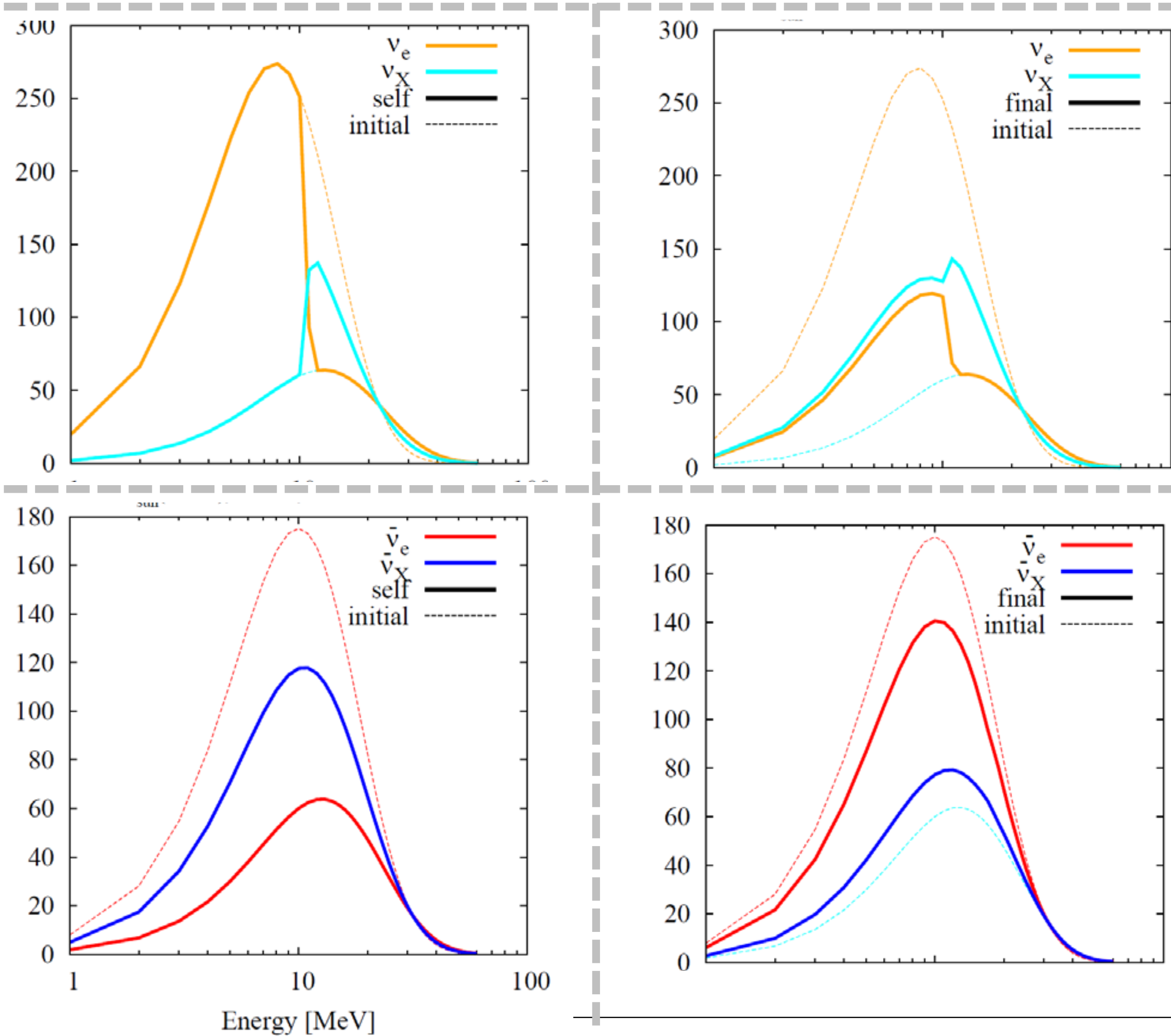


The spectrum of ν_e is also interesting!

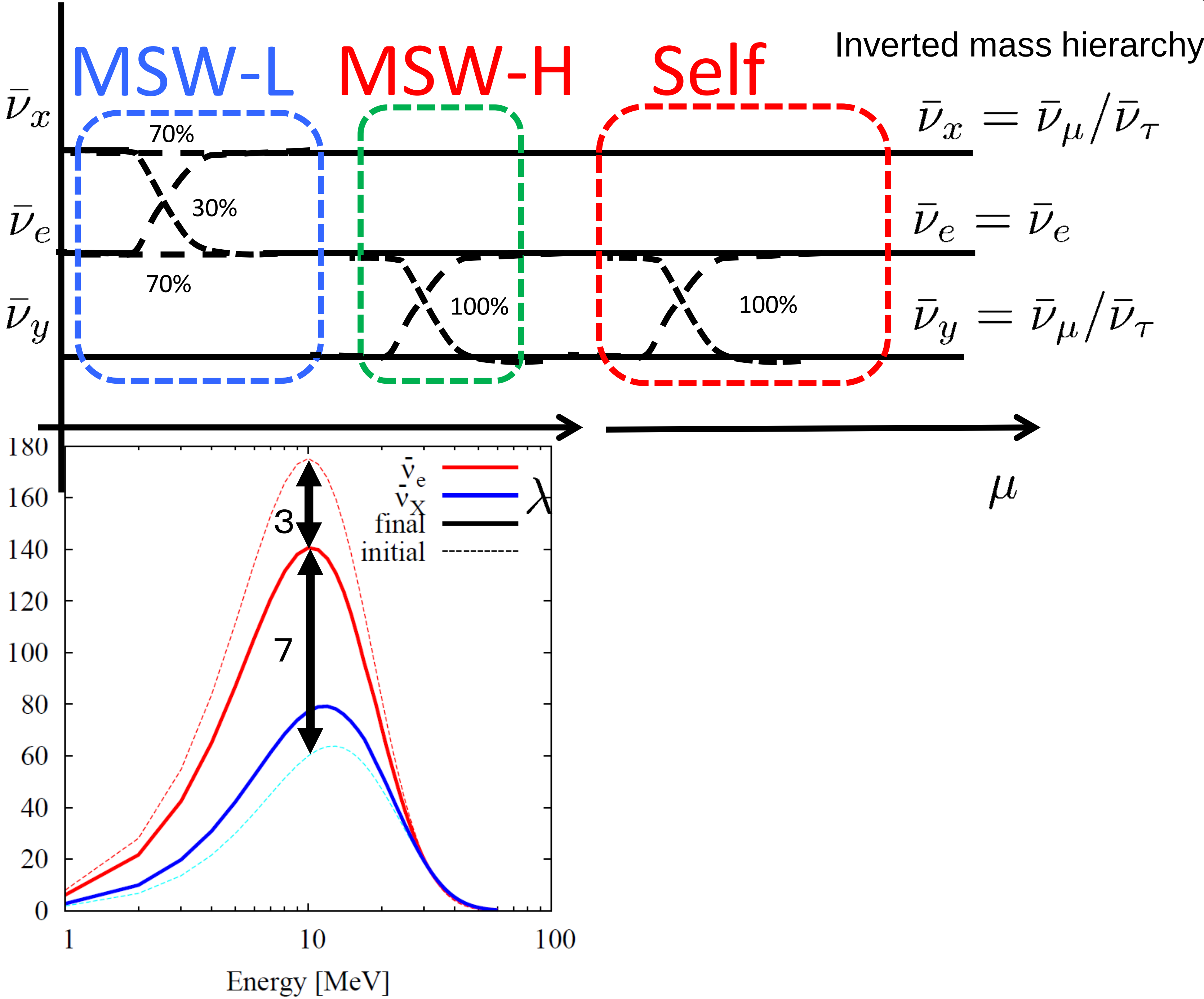
Detector for ν_e is necessary! Dune?

Case for Inverted Mass hierarchy

	self-interaction	Spectrum at Earth
ν_e		
$\bar{\nu}_e$		



Strong feature does not appear in $\bar{\nu}_e$.


Inverted mass hierarchy.
MSW-L
MSW-H
Self
$\bar{\nu}_x$
$\bar{\nu}_e$
$\bar{\nu}_y$
70%
30%
70%
100%
100%
$\bar{\nu}_x = \bar{\nu}_\mu/\bar{\nu}_\tau$
$\bar{\nu}_e = \bar{\nu}_e$
$\bar{\nu}_y = \bar{\nu}_\mu/\bar{\nu}_\tau$
λ
μ
$\bar{\nu}_e$
$\bar{\nu}_X$
final
initial
3
7
Energy [MeV]

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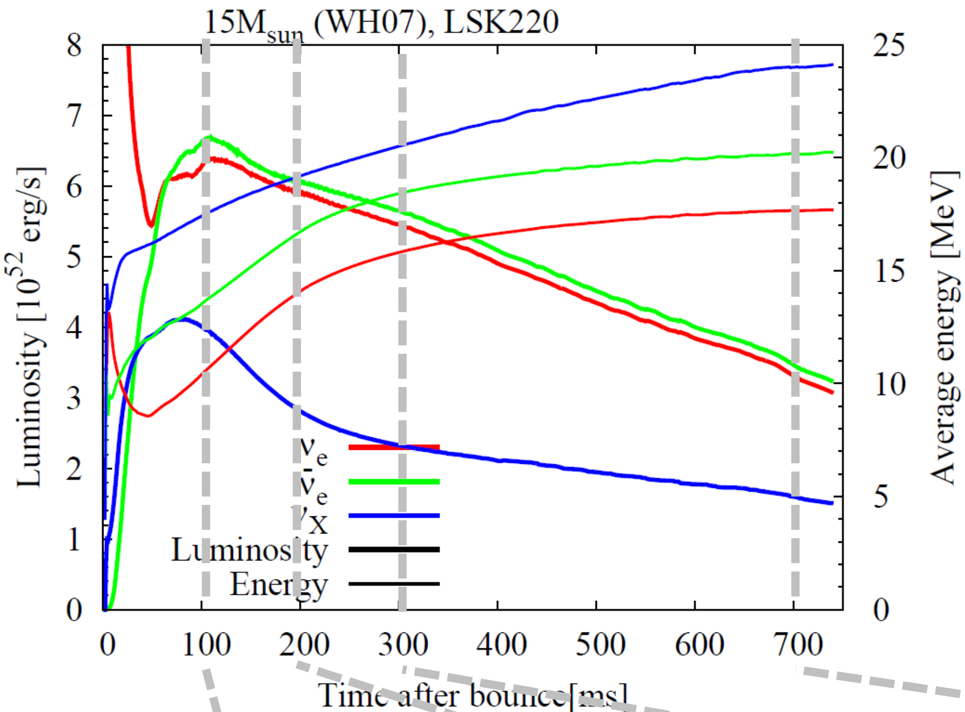
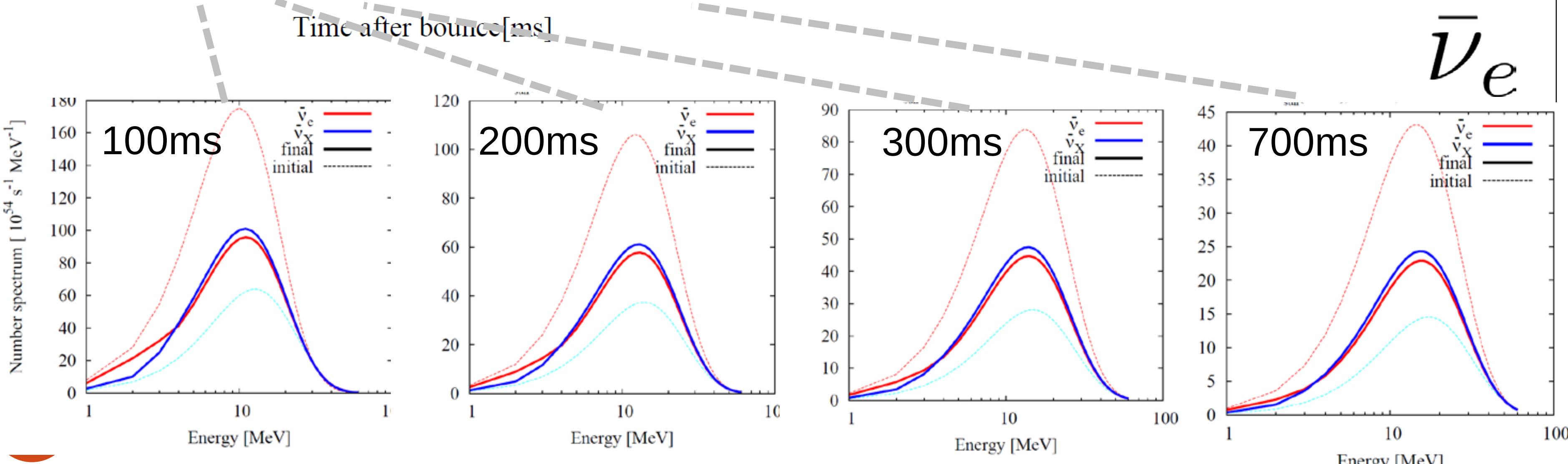
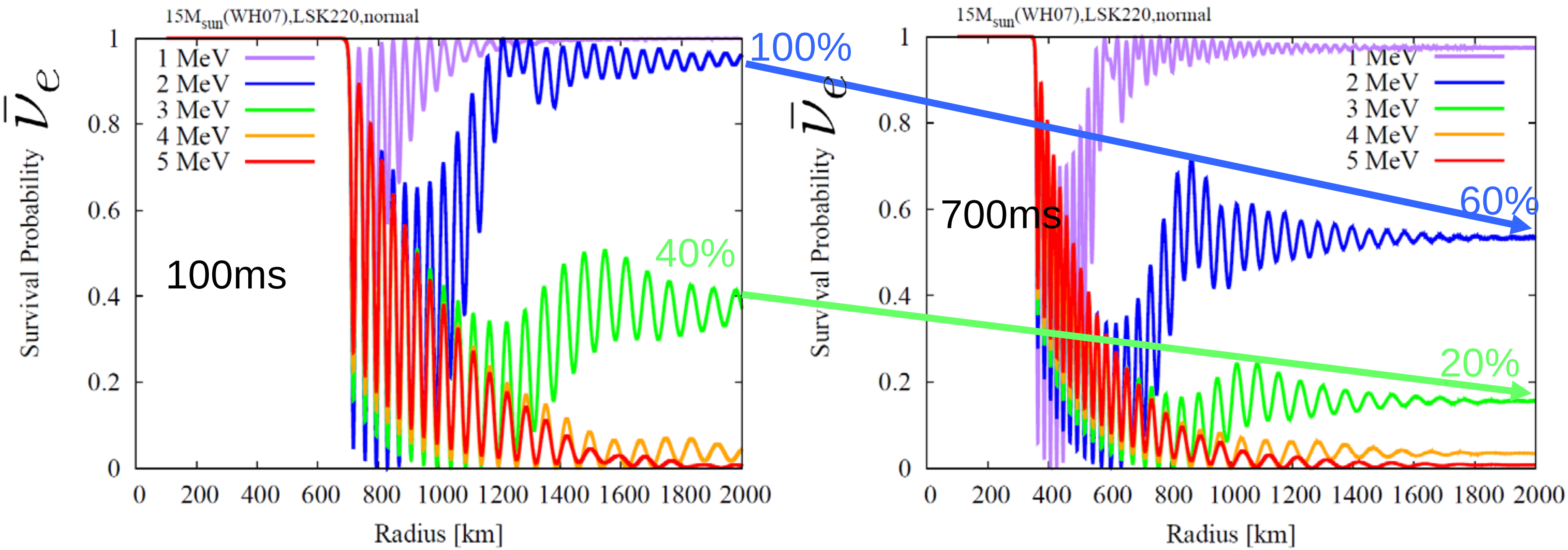
Time dependence

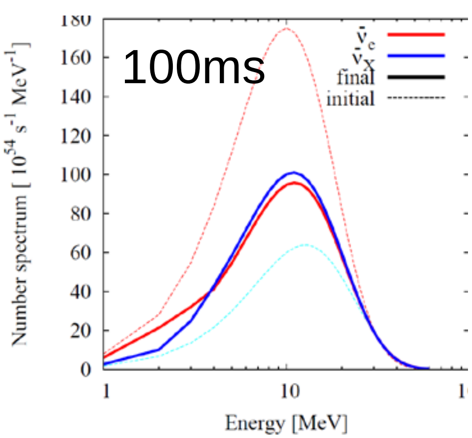


Deviation from thermal spectrum gradually disappears.
After 300ms, it is hard to see it.

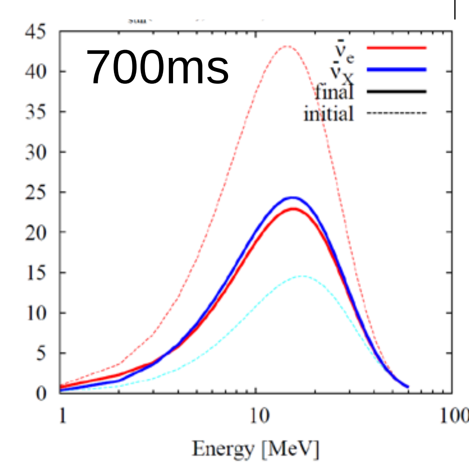


Time dependence





Survival probability of low energy neutrino decrease as time proceeds.



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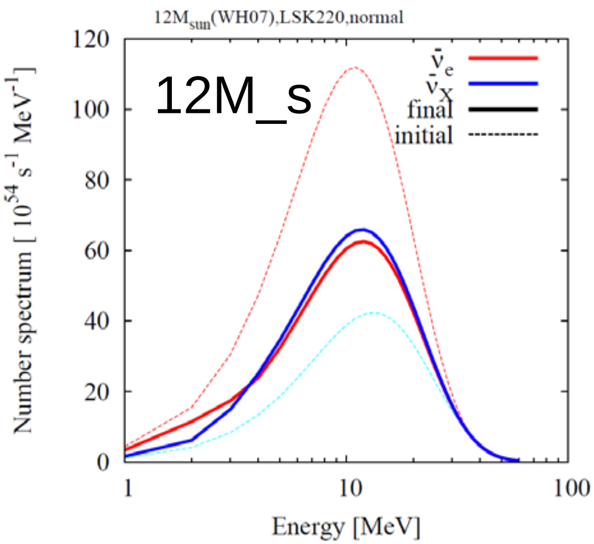
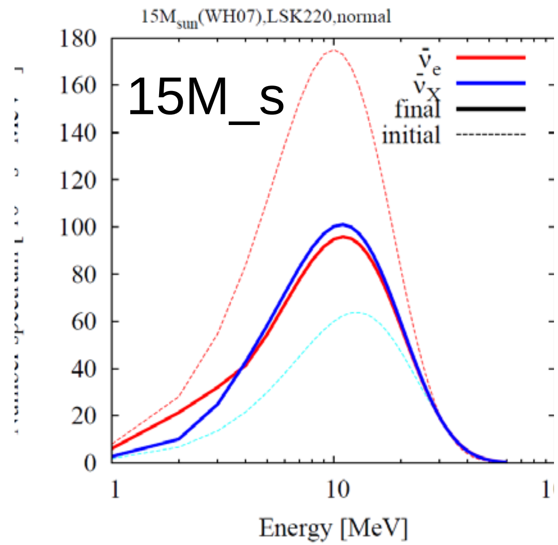
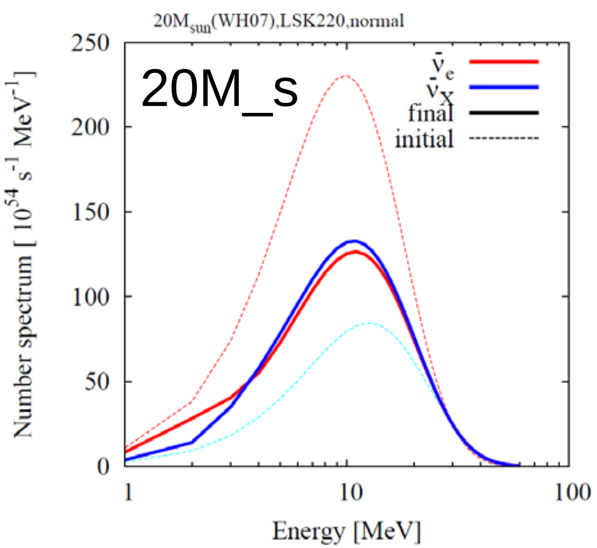
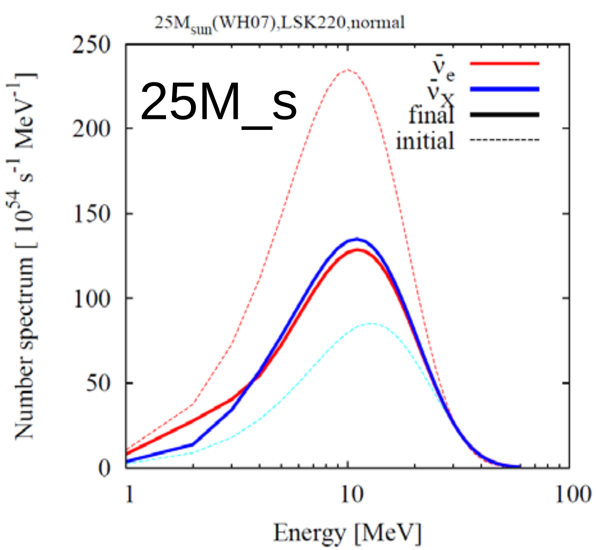
Progenitor Dependence

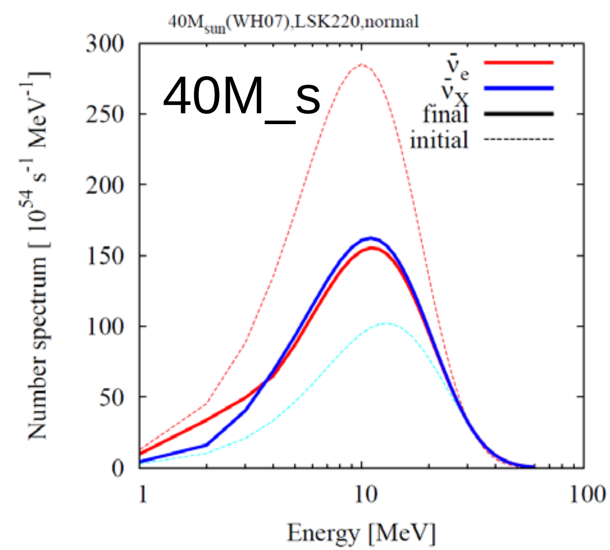




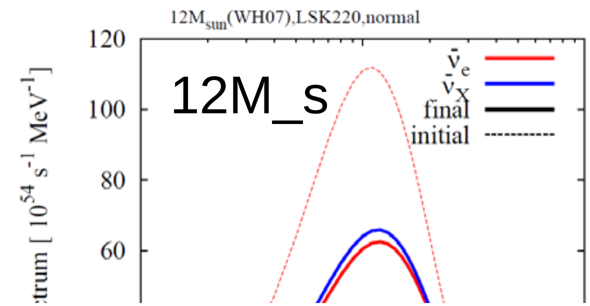
The early spectra (~100ms) shape are similar.
(But the luminosities are different.)

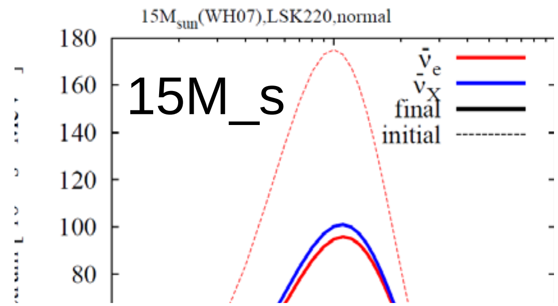






Progenitor Dependence

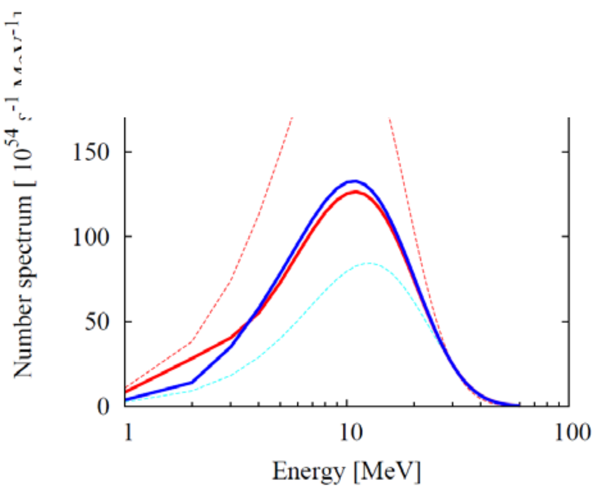


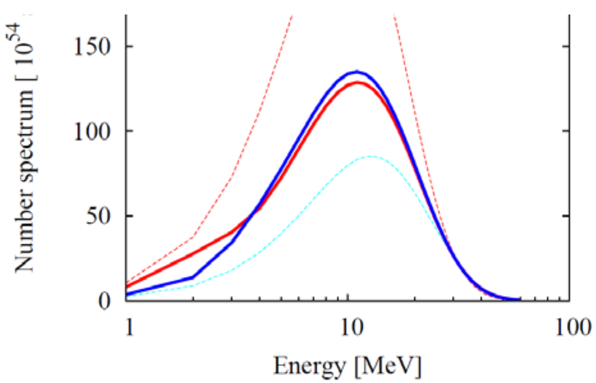


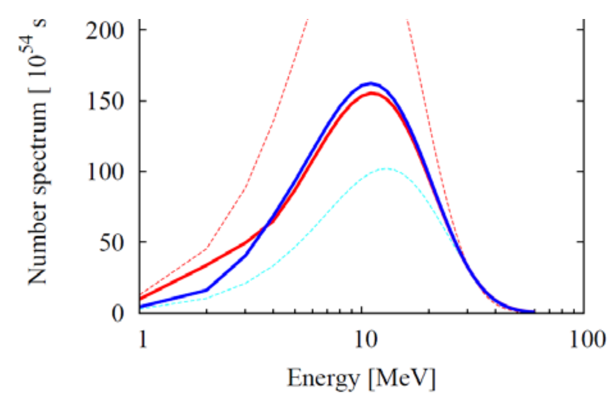
The early spectra (~100ms) shape are similar.

We are preparing late phase spectra.

Stay tuned!







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Summary

Systematic study on neutrino oscillation is performed.

Single angle approximation is used and hydrodynamics is limited to 1D.

- In normal mass hierarchy, we found a spectral deviation from thermal one for all progenitors (12–40M_s, WH07).
- The feature will continues about 200ms after bounce.
- The effect of ν –self interaction is prominent. However, MSW effect smears that out. An analysis with error should be necessary to clarify the feasibility to detect such a effect (your helps is highly appreciated).
- Sophistication of the method for neutrino oscillation is required to draw a robust conclusion.