Revealing the history of the universe with underground particle and nuclear research 2019
@Tohoku University

CNO: Collective Neutrino Oscillation

Signature of CNO in 8.8M_s star

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Expectation of a Next Supernova

○ sn1987A:

Only about 20 neutrinos were detected.

However that opened field of neutrino astronomy.
We confirmed the standard scenario of CC-SNe.

○Next Galactic or nearby supernova:

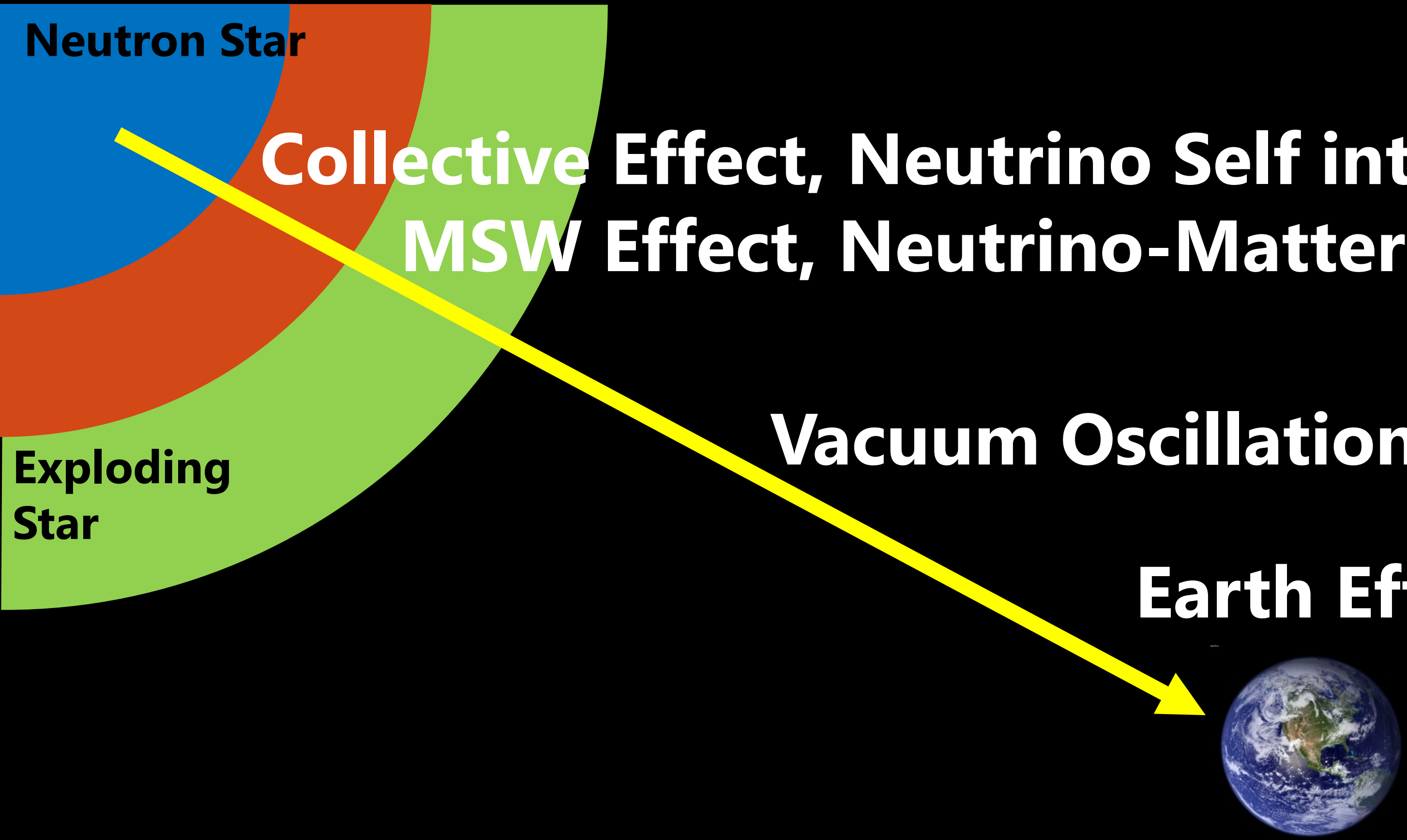
Now the volume of the detectors become 100 times larger.

More than 1000 of events are expected.

Q: What is the task for the theorists?

(1) Make a good model of Core-collapse supernovae
(2) Predict neutrino spectra taking neutrino oscillations into account

Kinds of Neutrino Oscillations



Neutron Star

Collective Effect, Neutrino Self interaction

MSW Effect, Neutrino-Matter interaction

Vacuum Oscillation

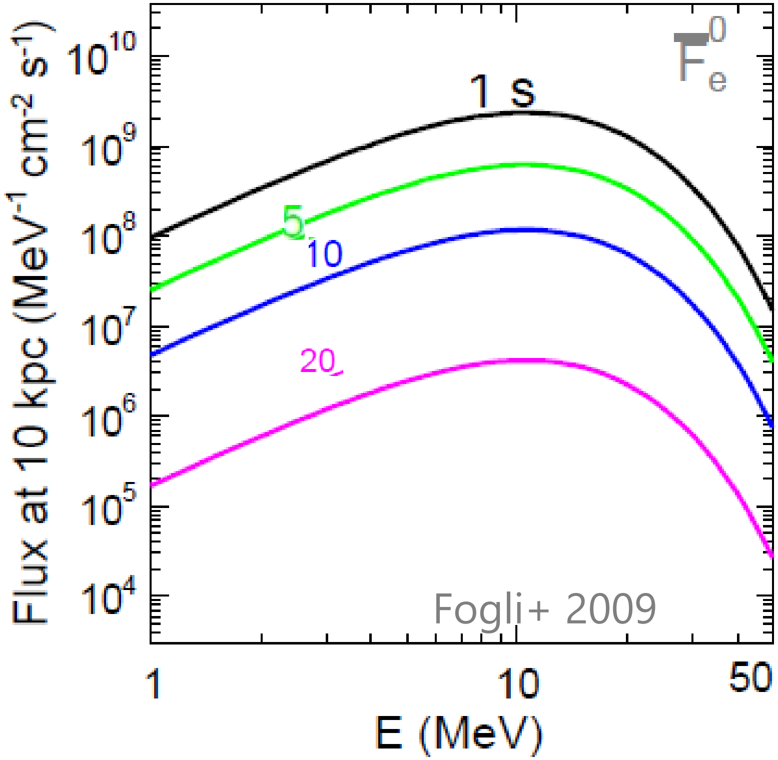
Exploding Star

Earth Effect

Among them, Collective Neutrino Oscillation (CNO) is the most complicated and not understood well.

A demonstration of CNO

Original Spectrum

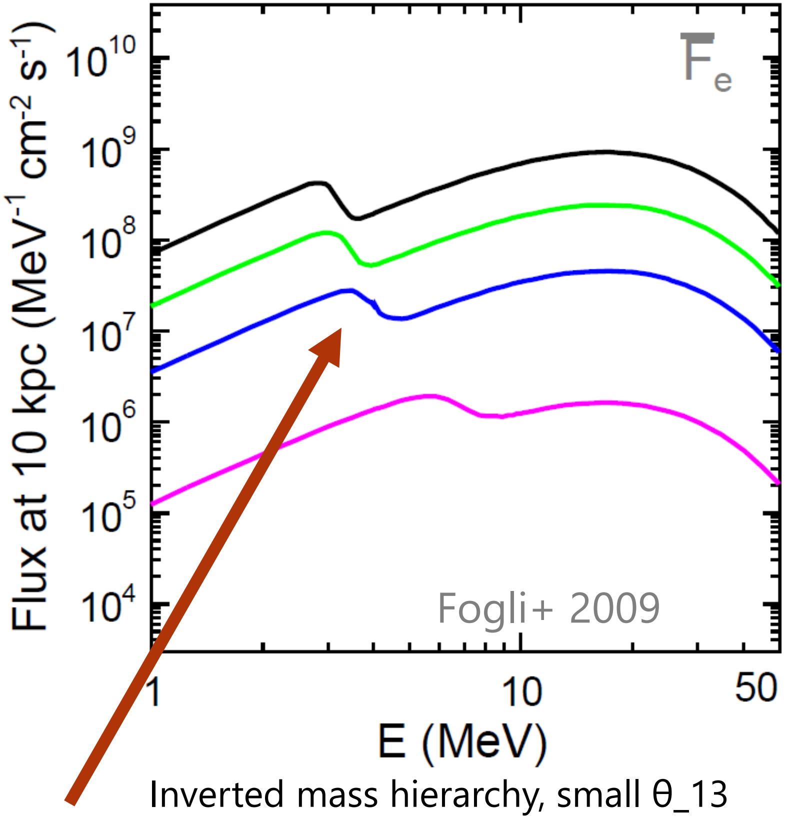


Fogli+ 2009

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

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

After CNO



Fogli+ 2009

Inverted mass hierarchy, small θ_13

Spectral split at 3MeV?
Can KamLAND detect it?

Problem of the studies on CNO

Caveat: The results strongly depends on

(1) numerical method

(2) neutrino luminosities,

(3) energies,

(4) angular distributions and

(5) matter density profiles.

The situation is not clear for non-expert.
In this study, we want to present rough sketch of the effect with standard numerical method and discuss its detectability.

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Summary of Numerical Methods

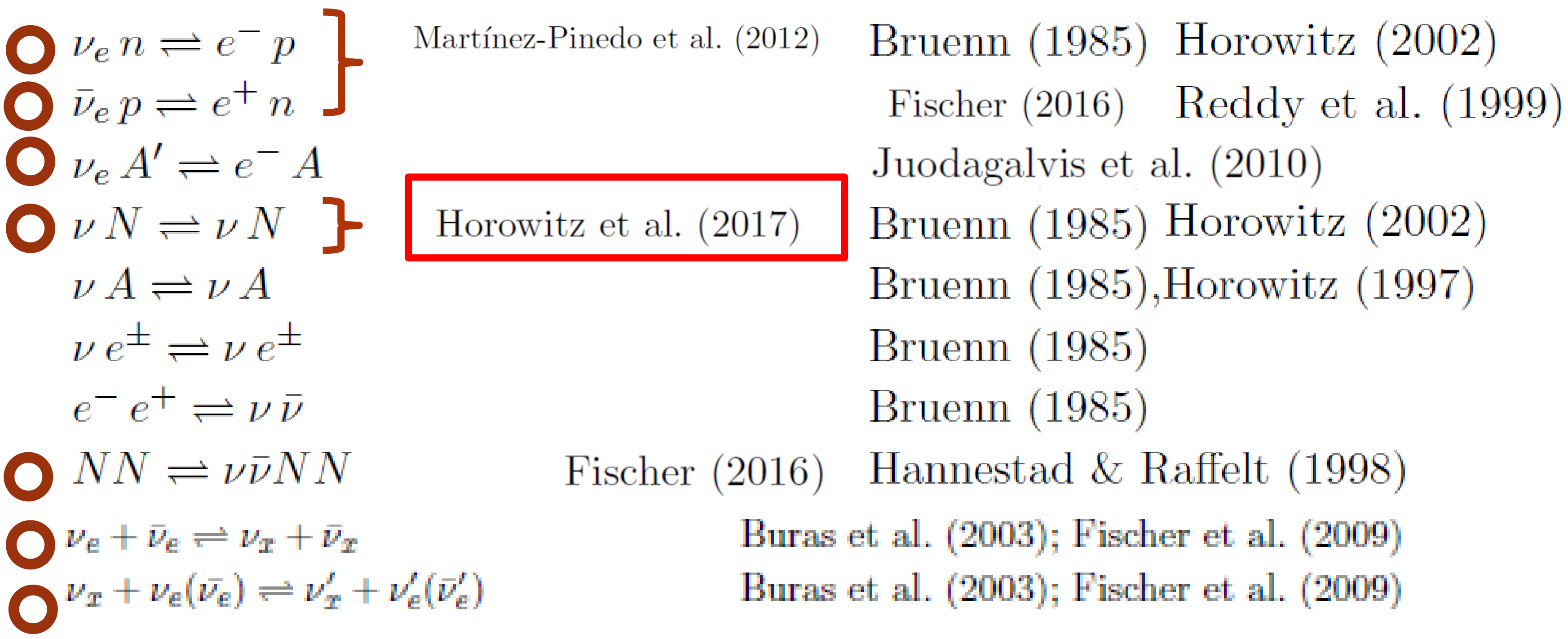
- Hydro Simulation
  3DnSNe
  Spherical coordinate 1D, 2nd order PLM (Mignone 2014)
  HLLC (Toro 2003), van Lear Limiter
  Phenomenological General Relativity (Marek+ 2006)

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

- Neutrino oscillation (post process)
  Multi angle approximation (Sasaki et al. 2017)
  The 3D simulation of r(or t), E, θ.

New Reaction Sets

Kotake et al. 2018

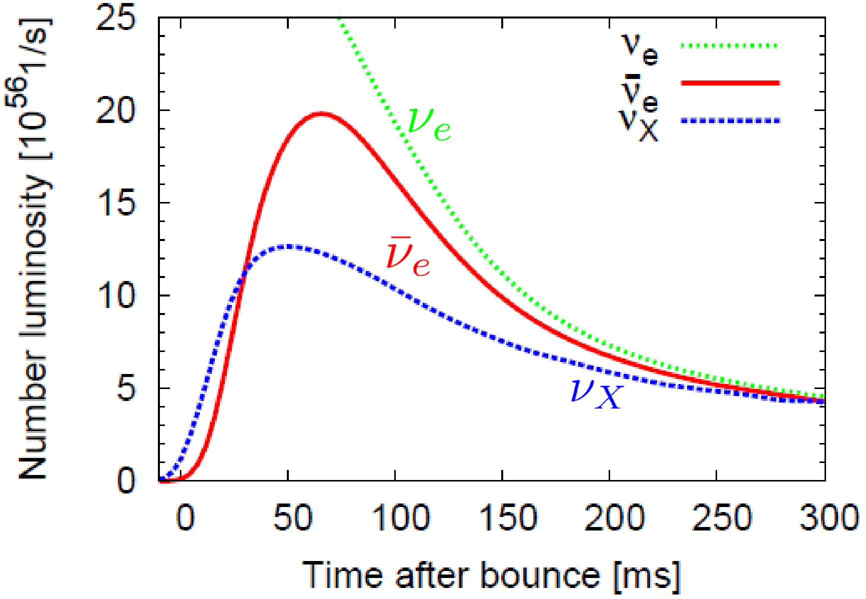


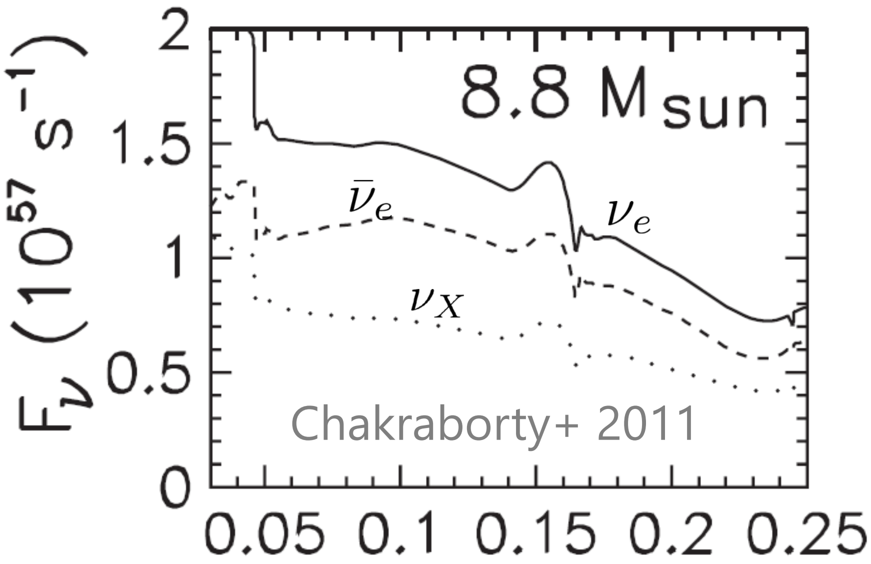
○	$\nu_e\, n \rightleftharpoons e^-\, p$	Martínez-Pinedo et al. (2012)	Bruenn (1985) Horowitz (2002)
○	$\bar{\nu}_e\, p \rightleftharpoons e^+\, n$		Fischer (2016) Reddy et al. (1999)
○	$\nu_e\, A' \rightleftharpoons e^-\, A$		Juodagalvis et al. (2010)
○	$\nu\, N \rightleftharpoons \nu\, N$	Horowitz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

Horowitz+2017, Many body effects (RPA&Virial)

=> Decrease the cross section of nucleon scattering.
More neutrino can escape from the neutron star.

Neutrino Luminosities.





Chakraborty+ 2011

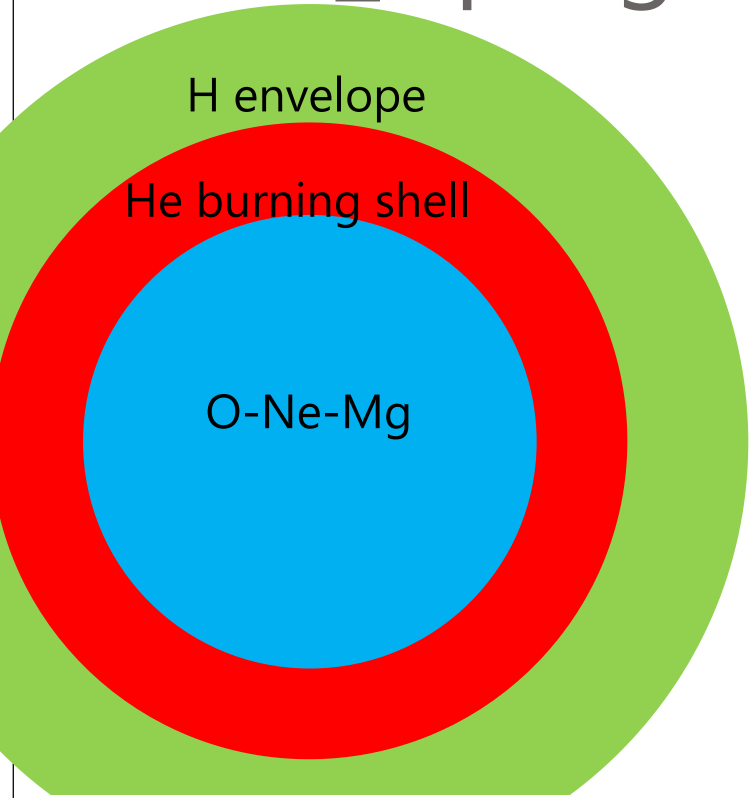
The hierarchy of the flux is similar to the previous work of accretion phase before 200ms. $\nu_e > \bar{\nu}_e > \nu_X$

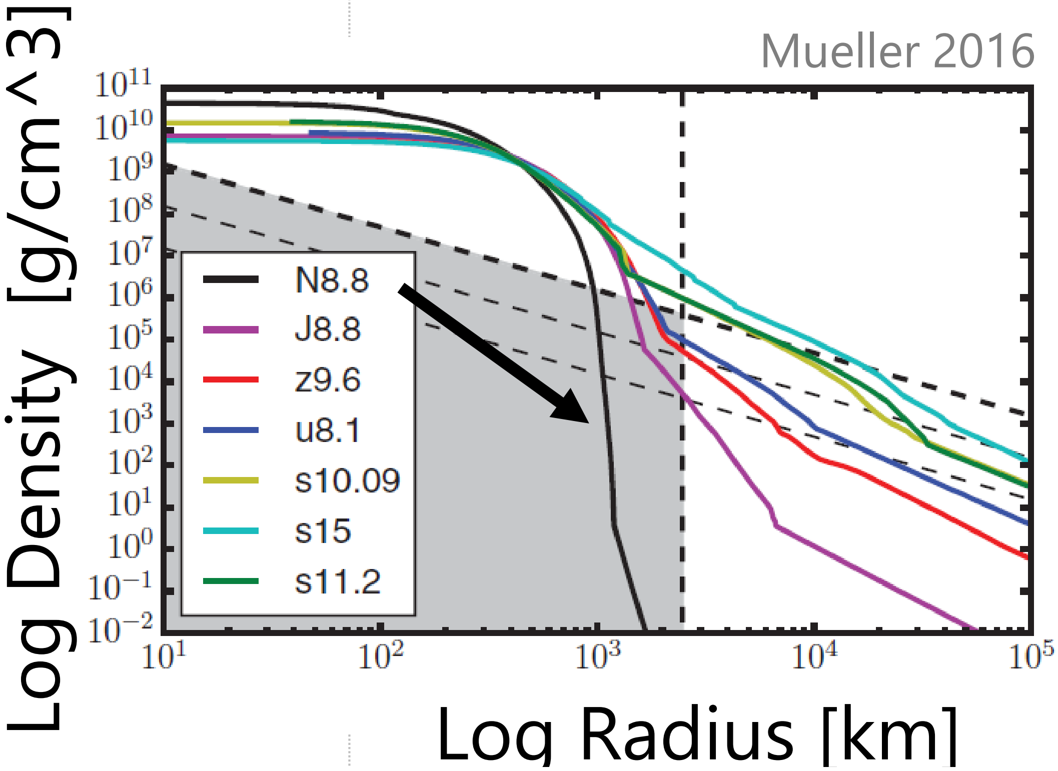
After that, my model shows more typical feature of cooling phase. $\nu_e \sim \bar{\nu}_e \sim \nu_X$

Note that hierarchy of mean energy is standard one.

$\nu_e < \bar{\nu}_e < \nu_X$

8.8 M_s progenitor




Mueller 2016

The envelop of the progenitor is really dilute.
That is preferable condition to see the effect of CNO.
In other progenitors, the effect of CNO is not prominent due to matter suppression (in early phase).

Matter Suppression –preparation-

Suppose Schrödinger equation

$$i\hbar\frac{\mathrm{d}\psi_\nu}{\mathrm{d}t} = \mathcal{H}\psi_\nu, \ \ \nu = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$$

Hamiltonian can be decomposed in three terms

$$\mathcal{H} = \mathcal{H}_{\text{vac}} + \mathcal{H}_e + \mathcal{H}_\nu$$

CNO OSC.

MSW resonance

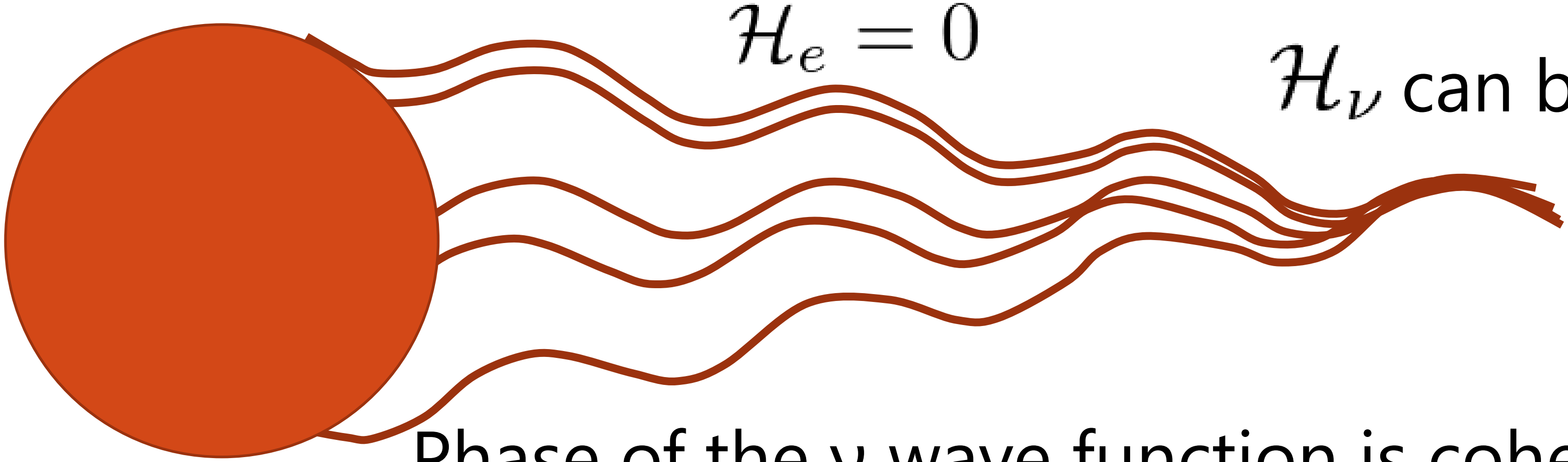
Transition from a state to the other state causes a large flavor conversion.

Matter Suppression: $\mathcal{H}_e \geq \mathcal{H}_\nu$

Effect of CNO is suppressed compared to $\mathcal{H}_e = 0$

Matter Suppression

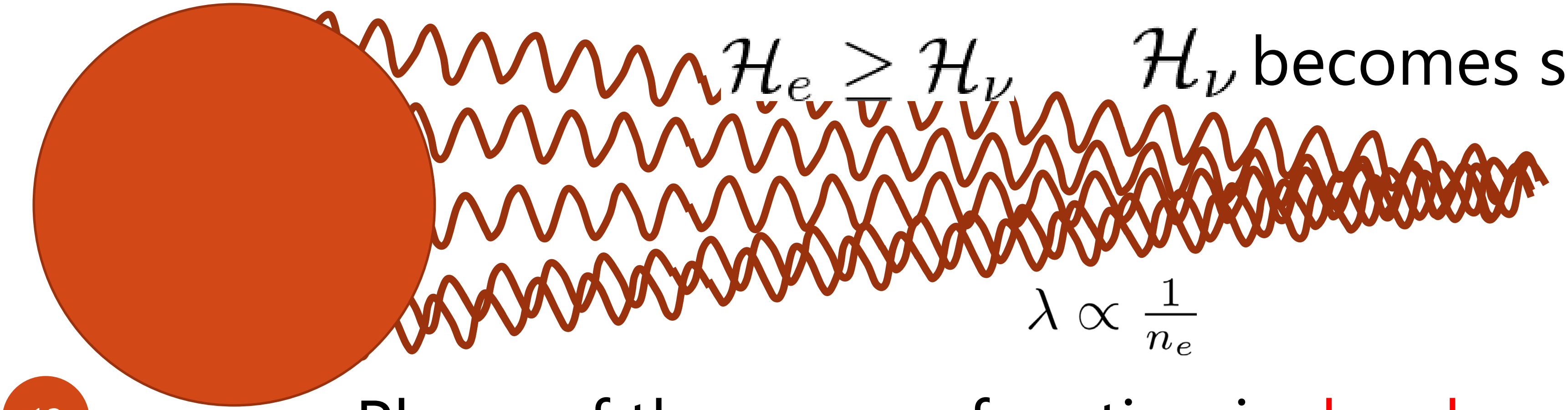
Matter suppression = Matter induced decoherence



$\mathcal{H}_e = 0$

$\mathcal{H}_\nu$ can be large

Phase of the ν wave function is coherent.



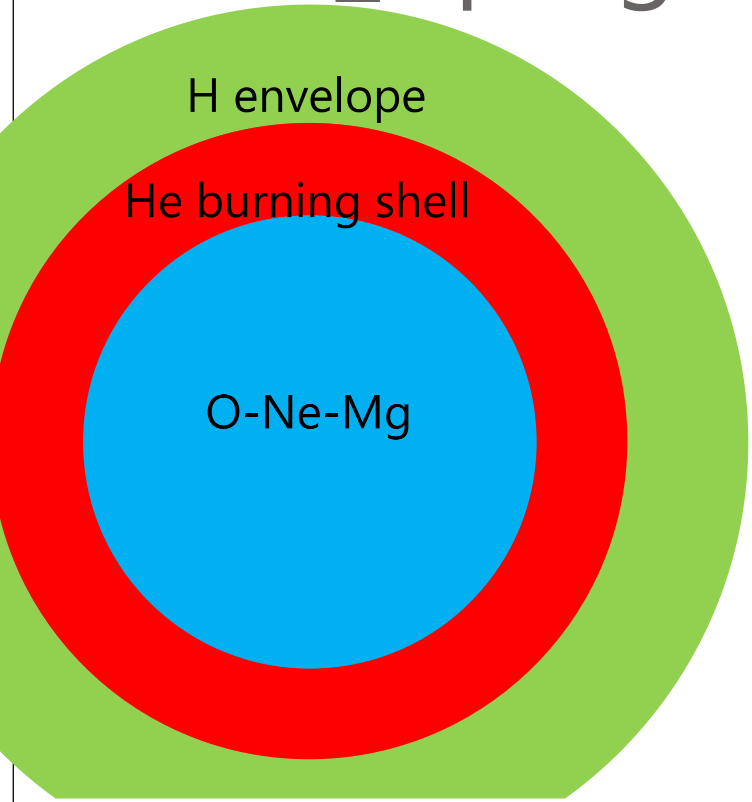
$\mathcal{H}_e \geq \mathcal{H}_\nu$

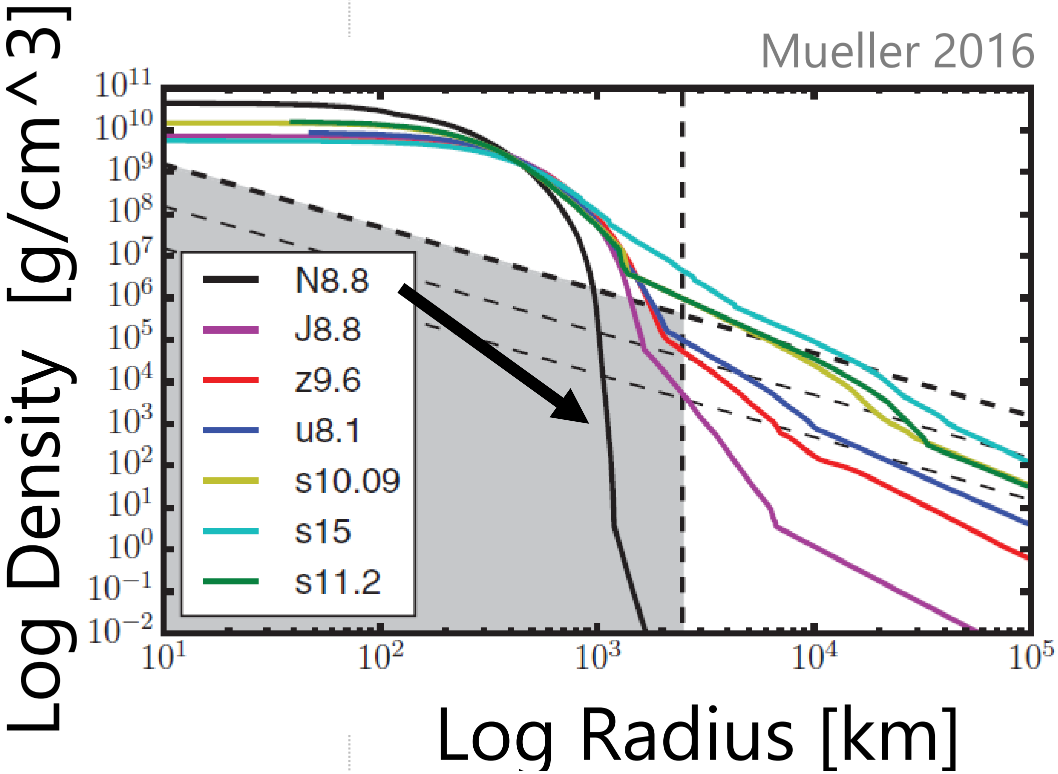
$\mathcal{H}_\nu$ becomes small

$\lambda \propto \frac{1}{n_e}$

Phase of the ν wave function is decoherent.

8.8 M_s progenitor





Mueller 2016

To investigate the effect of CNO, light progenitors with dilute envelop are preferable.

8.8M_s progenitor is the best.

In other progenitors, CNO will occur later.

Or CNO will be completely suppressed.

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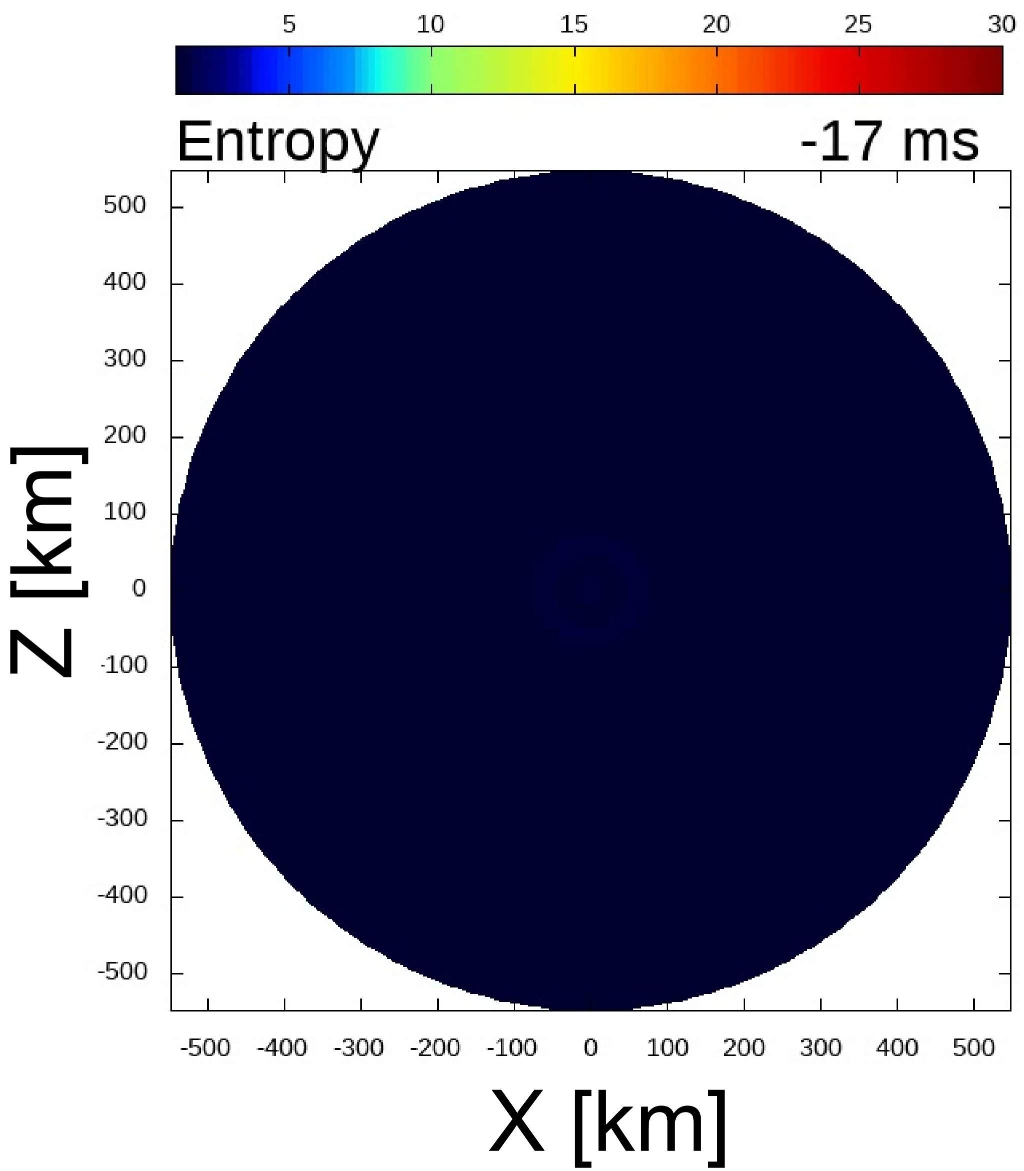
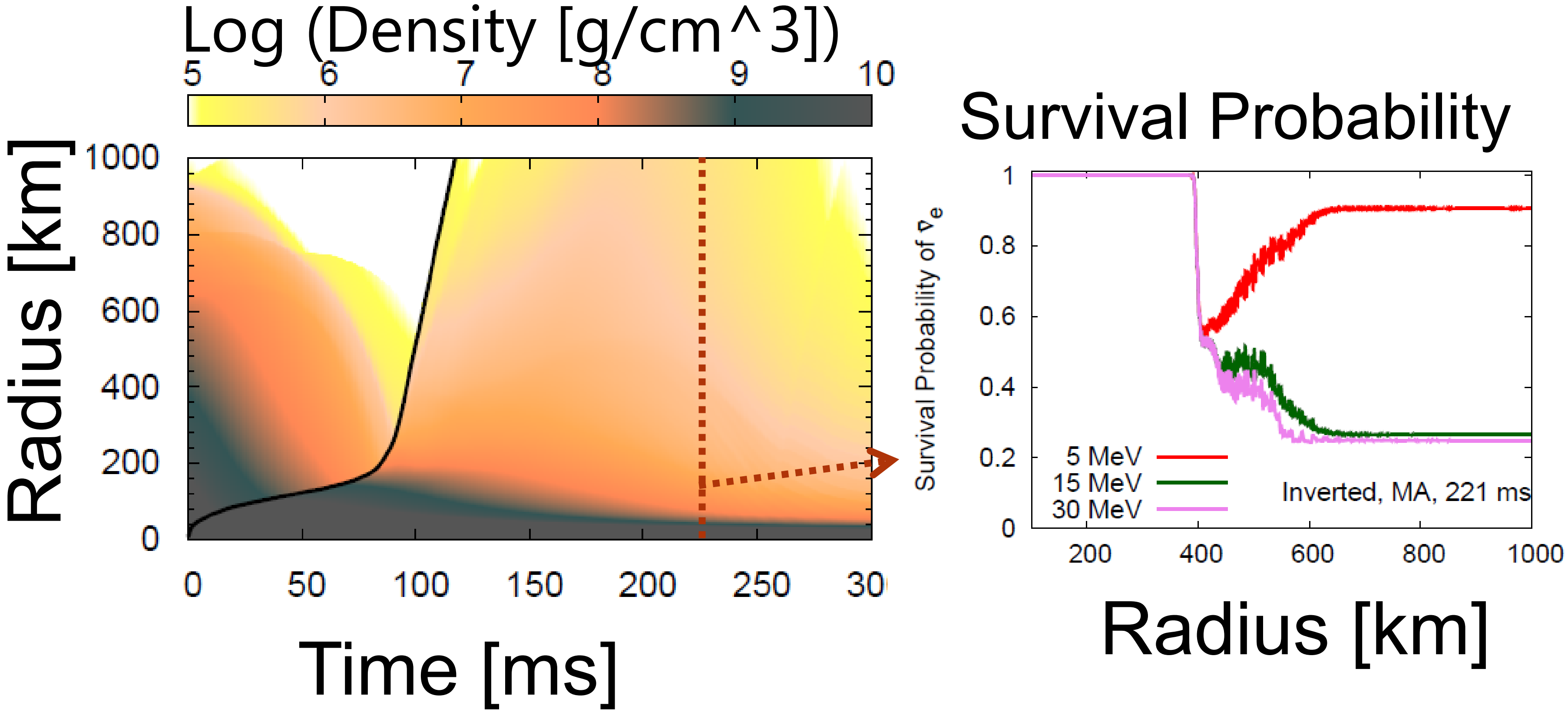
Explosion Model



Entropy per baryon
= T^3/ ρ
is a good probe to show the exploding region.

Beginning of CNO

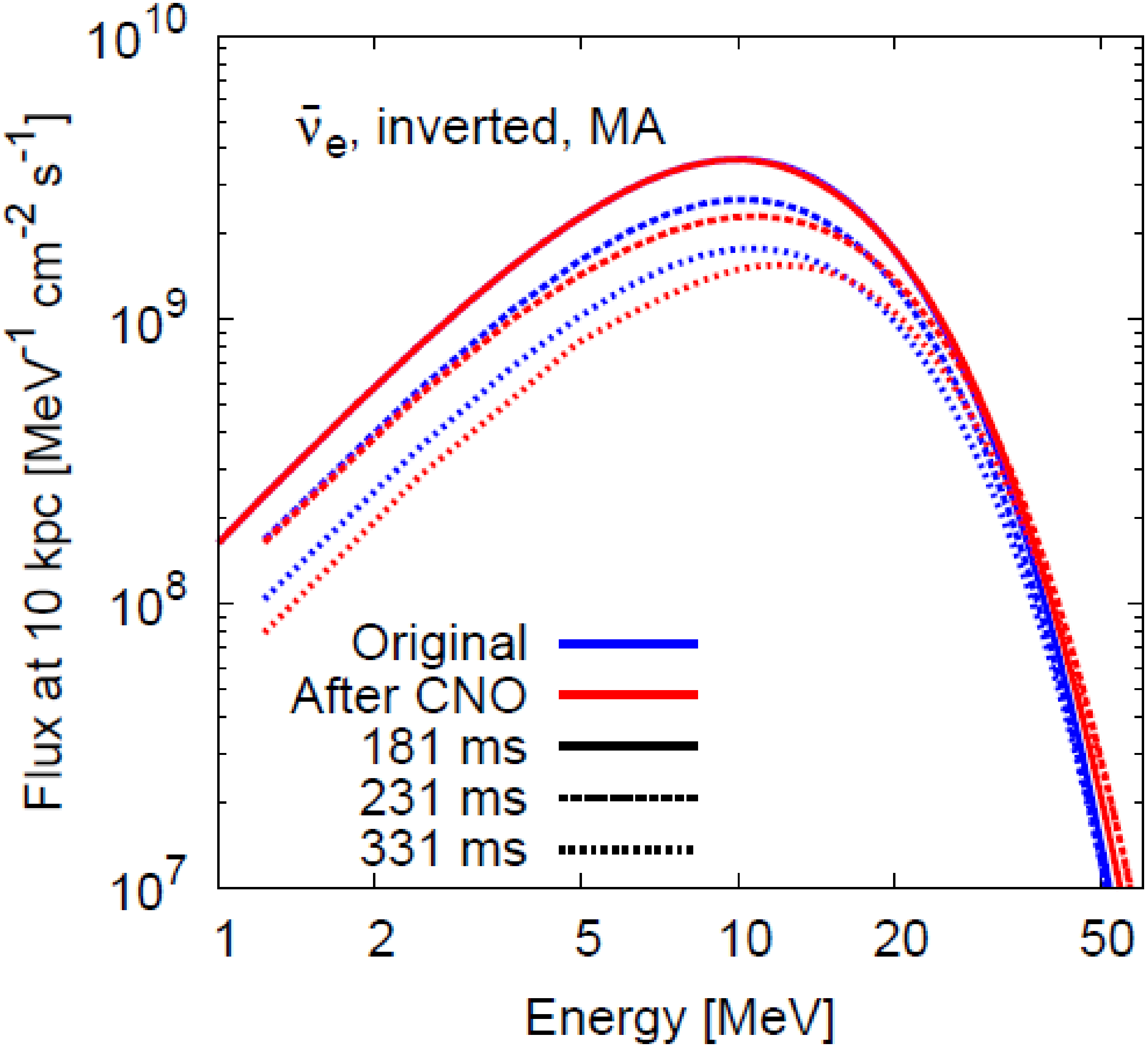


Log (Density [g/cm^3])

Survival Probability

This progenitor explodes even in 1D since the envelope is light. After 200ms, CNO starts to emerge since the density becomes significantly low at about 400km.

Time evolution of Spectrum



181ms:

No CNO

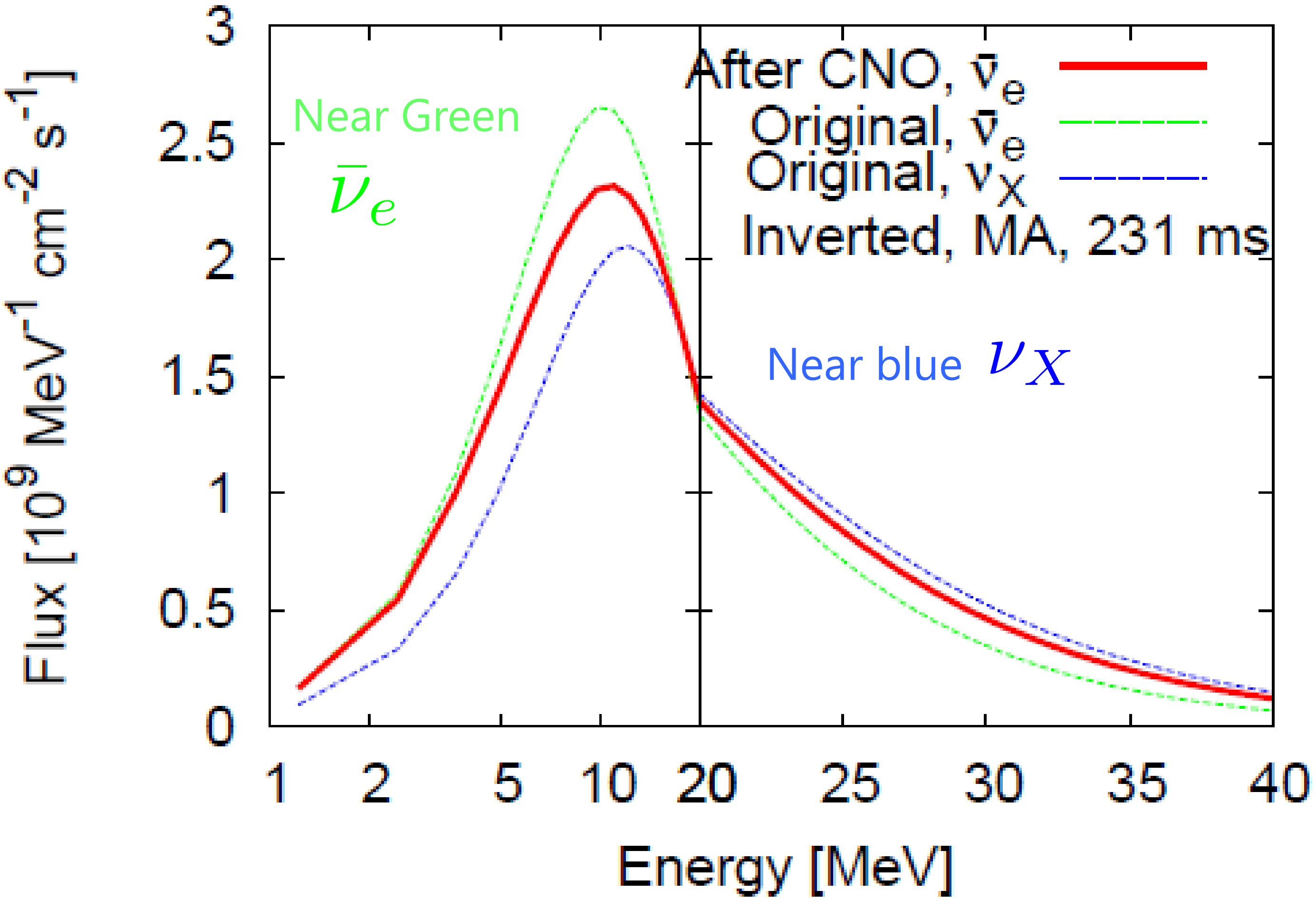
231ms:

CNO occurs at high energy side

331ms:

CNO occurs in all energy.

Detail of Spectrum



Near Green

$\bar{\nu}_e$

Near blue ν_X

The partial swap is seen at 231ms,

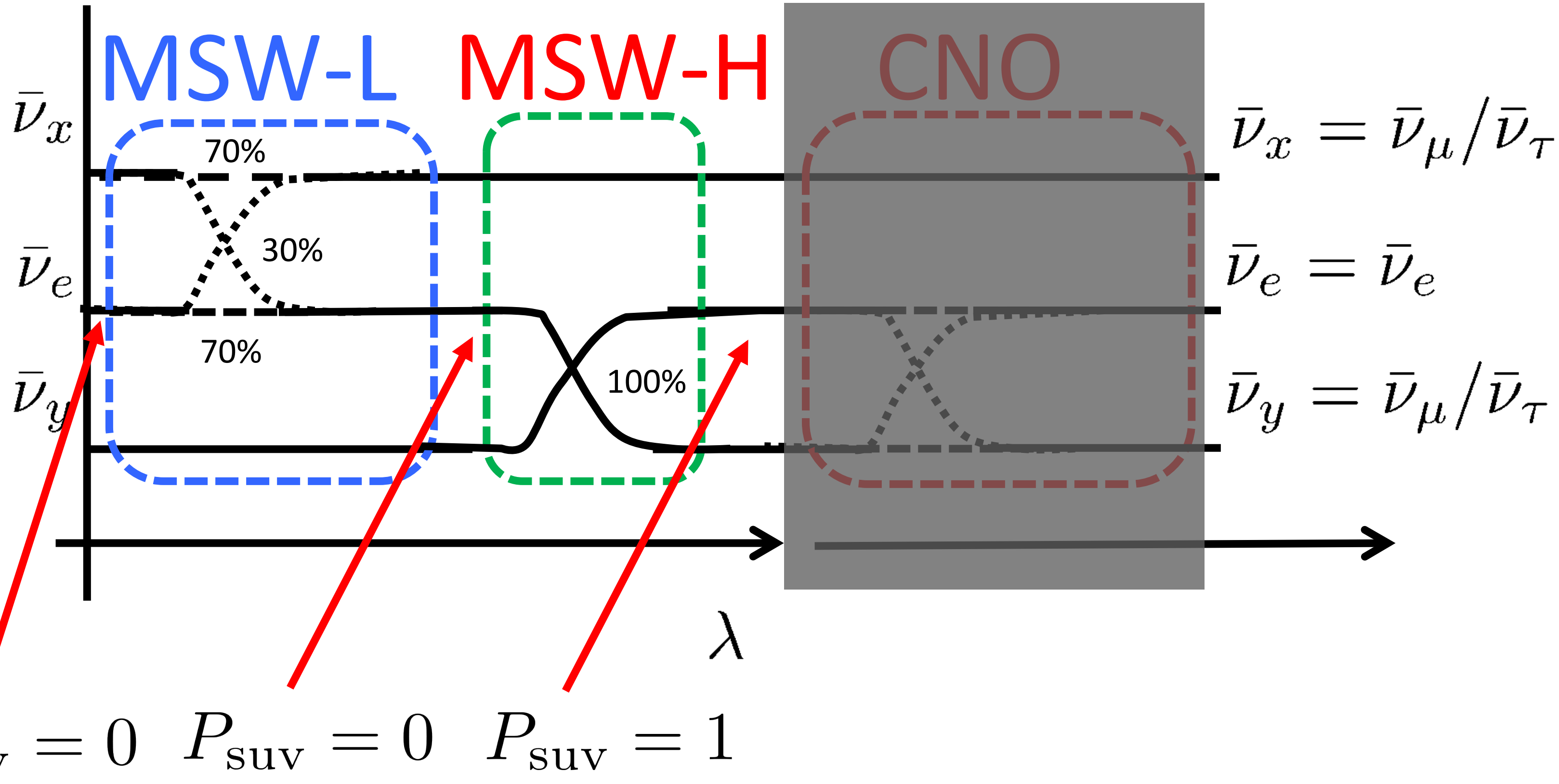
100ms later, neutrino swapped in all energy.

Detectability?

Can we see the impact of CNO by observations?

Neutrino spectrum at Earth

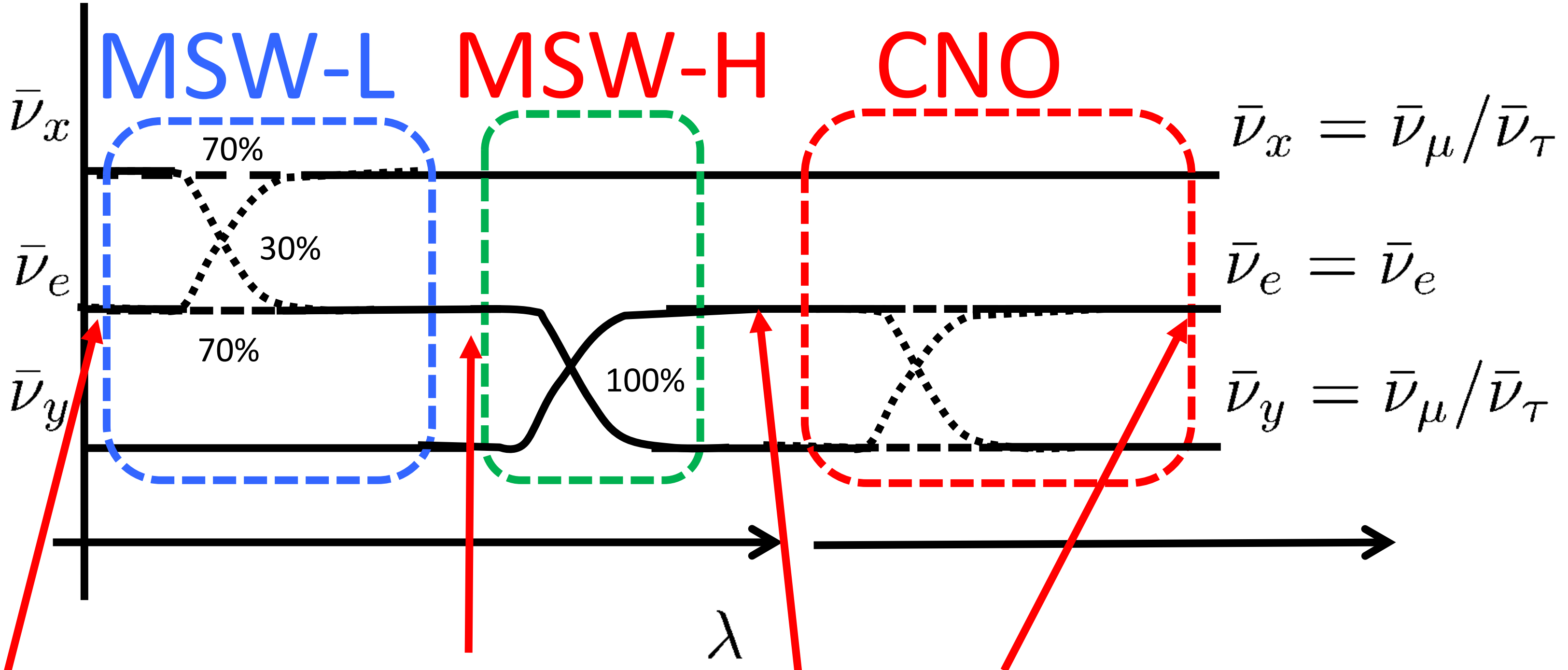
Inverted mass hierarchy. w/o CNO



w/o CNO $P_{\rm suv} = 0$

Neutrino spectrum at Earth

Inverted mass hierarchy. w/ CNO



$$P_{\text{suv}} = 1 - \epsilon$$

$$P_{\text{suv}} = 1$$

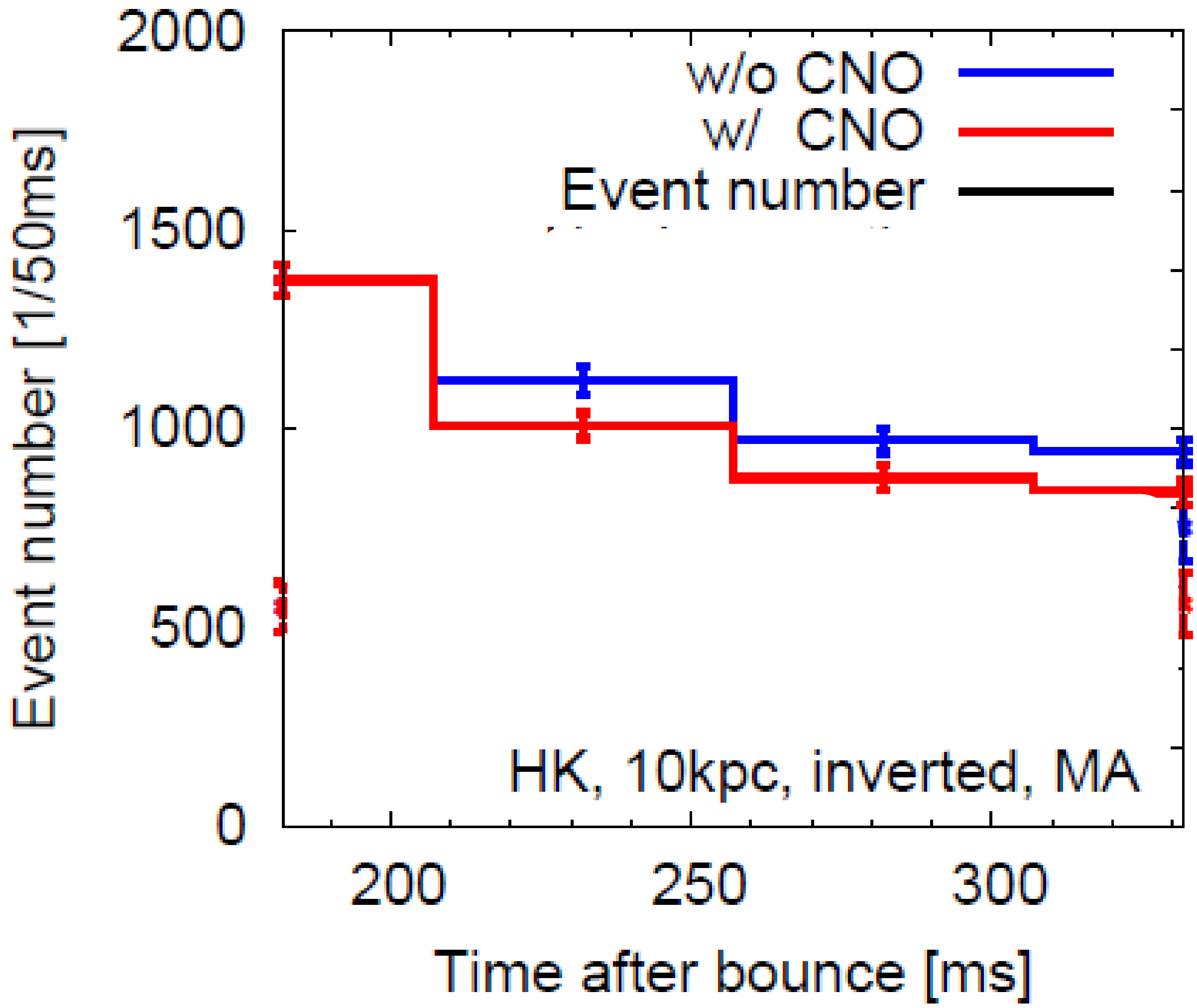
$$P_{\text{suv}} = 0.7\,(1 - \epsilon)$$

$$P_{\text{suv}} = \epsilon$$

w/ CNO $P_{\text{suv}} = 0.7\,(1 - \epsilon)$

Significant fraction of anti-electron neutrino survives in the spectrum at earth.

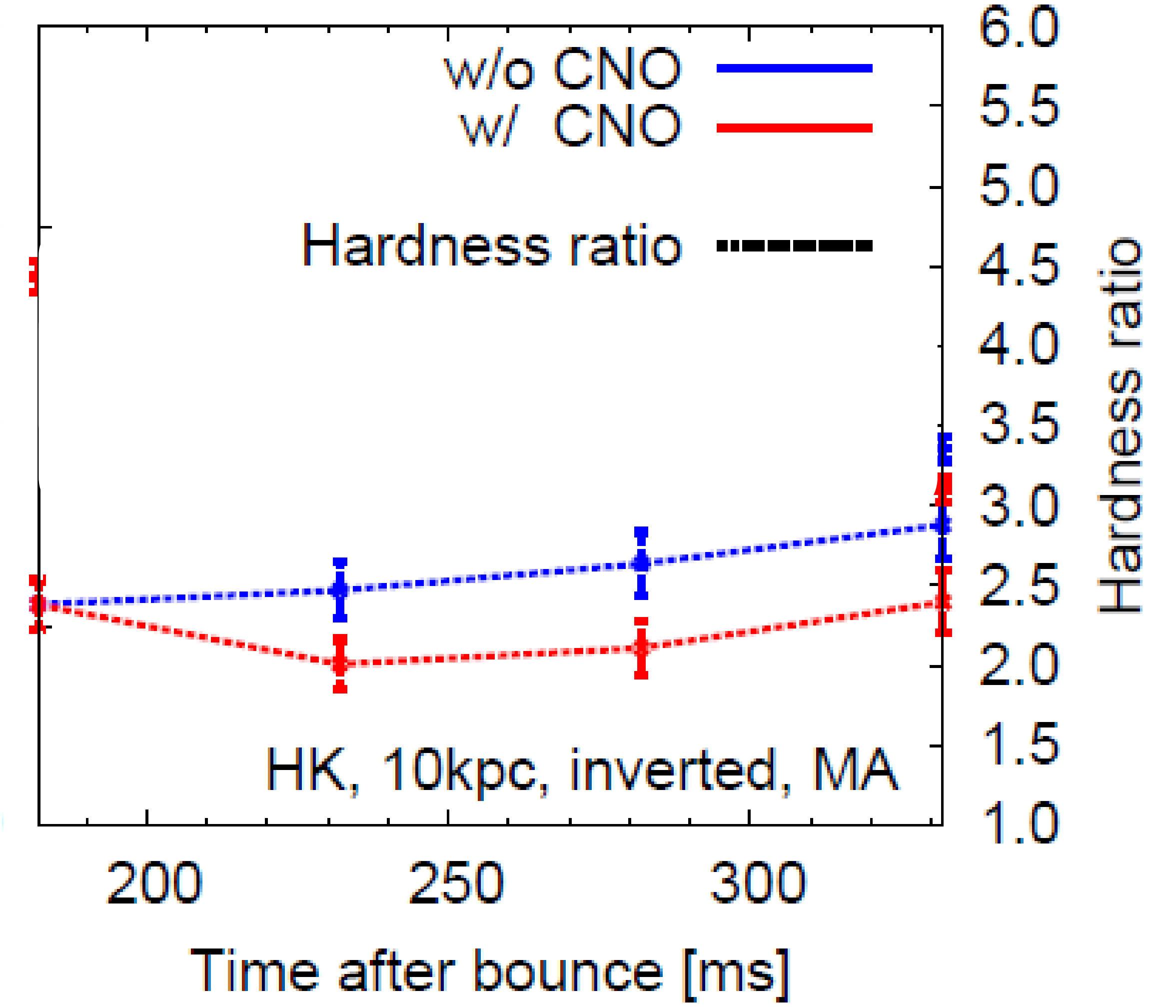
Observation with HK



In HK,
1000 of anti-e ν
is detected in
every 50ms.

CNO make
spectrum soft.
Eventually, the
event number
decreases.

Observation with HK



Hardness ratio:

$$R_{\rm H/L} = \frac{N_{20<E}}{N_{E<20}}$$

Is not affected by uncertainty of flux.

w/o CNO, P_suv=0

$\Rightarrow$ Original $\bar{\nu}_X$

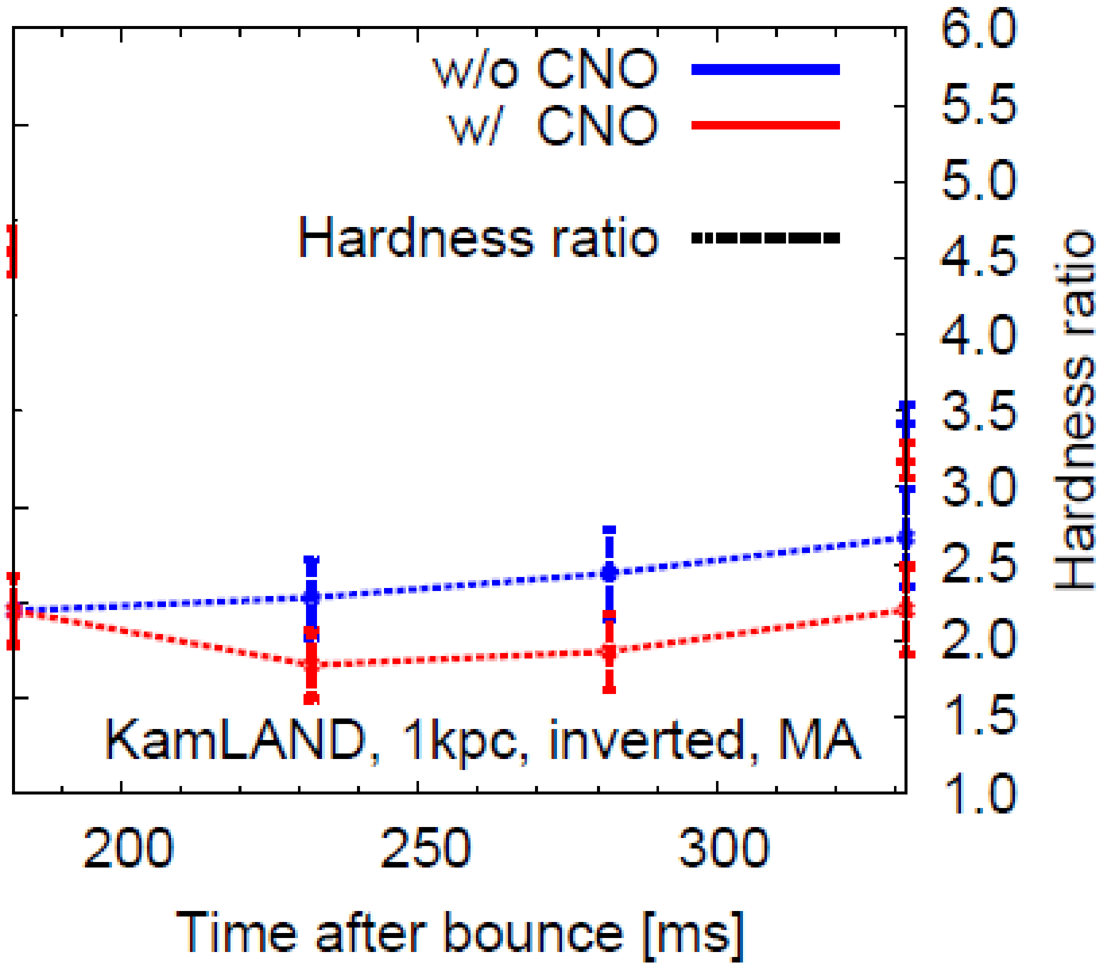
$\Rightarrow$ Hard

w/ CNO, P=0.7(1-ε)

$\Rightarrow$ Original $\bar{\nu}_e$

$\Rightarrow$ Soft

Observation with KamLAND

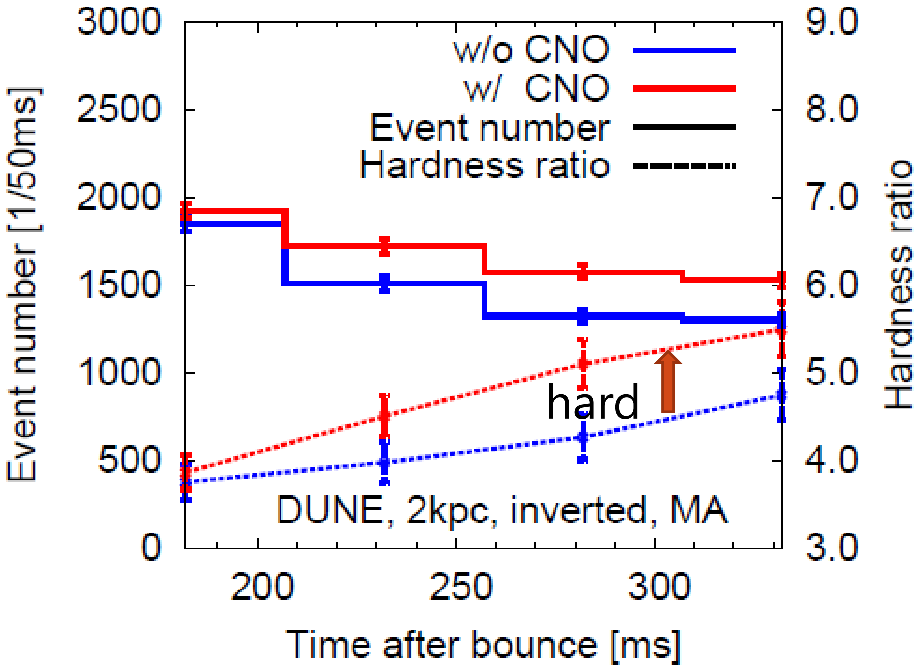


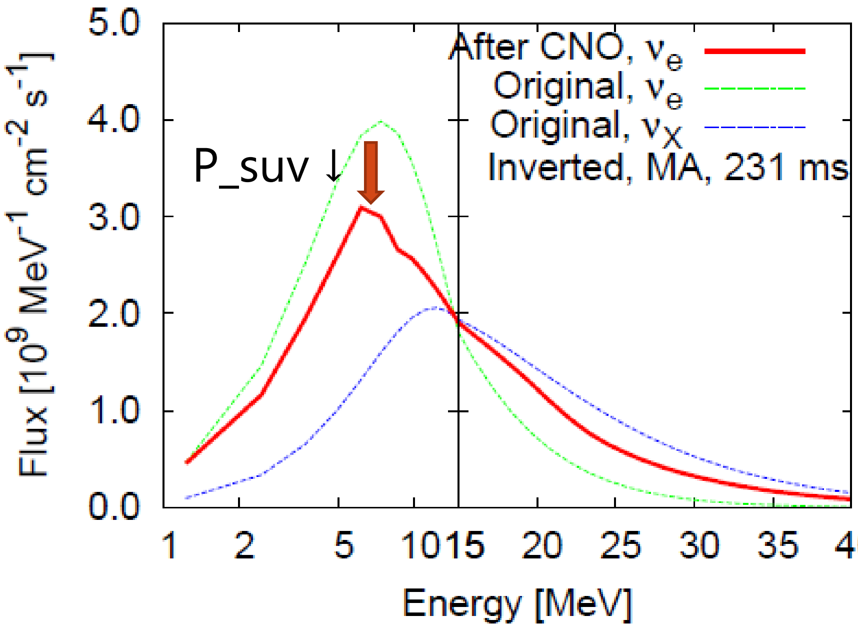
R depends on the detector due to E_th.

	HK	KamLAND
E_th[MeV]	7	1.5
w/ CNO	2.5	2.2
w/o CNO	3.0	2.7

To distinguish the effect of CNO, the source distance should be less than 1kpc.

Observation with DUNE (40kton)



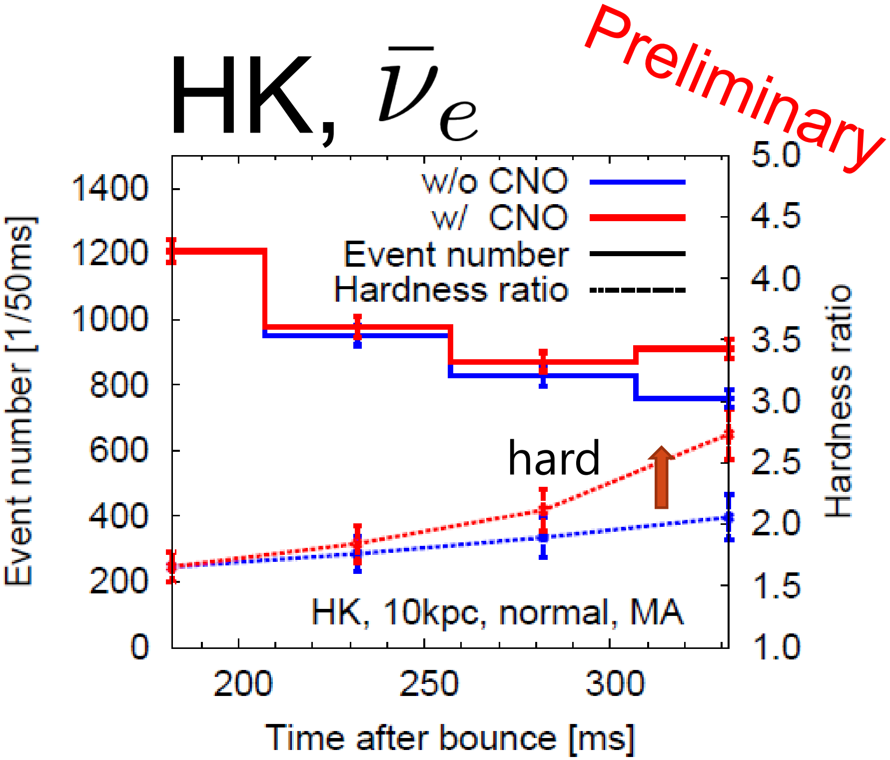


By, CNO P_suv ↓, The spectrum become hard.

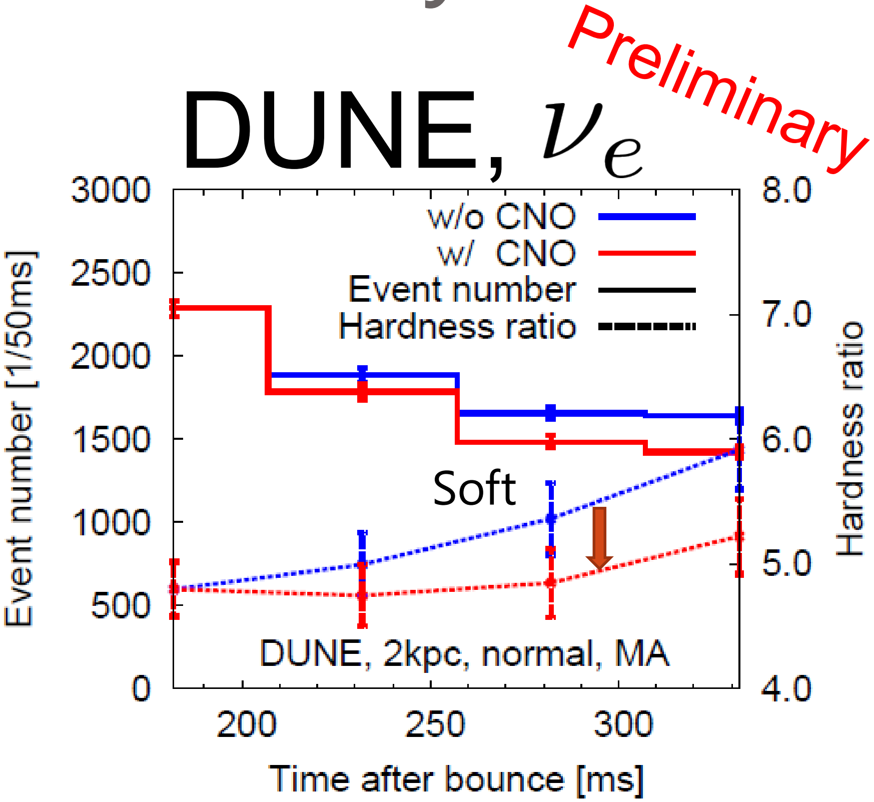
If the source is within 2kpc, the Poisson error is smaller than the model difference. However, the hardness ratio also rise as time goes. It is difficult to distinguish the effect.

The case for Normal Hierarchy

HK, $\bar{\nu}_e$



DUNE, ν_e



In normal mass hierarchy, the tendency is inverse of that of the inverted mass hierarchy.

In HK, CNO increases the hardness ratio.

In DUNE, CNO decease the hardness ratio.

Summary of the scenario

Hierarchy	Inverted	Inverted	Normal	Normal
CNO	Off	On	Off	On
$\bar{\nu}_e$ HK	Hard MSW−H(0)	Soft ~~CNO,MSW−H~~ MSW−L (0.7(1−ε))	Soft MSW−L(0.7)	Hard CNO, MSW−L (0.3+0.4 ε)
ν_e DUNE	Soft MSW−L(0.3)	Hard CNO(**ε**) MSW−L(0.3 ε)	Hard MSW−H(0)	Soft CNO,MSW−L (0.7(1− ε))

ε : P_suv after CNO, ε =1 for w/o CNO

Summary of the scenario

Hierarchy	Inverted	Inverted	Normal	Normal
CNO	Off	On	Off	On
$\bar{\nu}_e$	Hard MSW–H(0)	→ Soft ~~CNO,MSW–H~~ MSW–L (0.7(1– ε))	Soft MSW–L(0.7)	Hard CNO, MSW–L (0.3+0.4 ε)
ν_e	Soft MSW–L(0.3)	Hard CNO(ε) MSW–L(0.3 ε)	Hard MSW–H(0)	→ Soft CNO,MSW–L (0.7(1– ε))

In this phase, spectrum naturally becomes hard.
So the softening of the spectra is easy to distinguish.

Summary of the scenario

Hierarchy	Inverted	Inverted	Normal	Normal
CNO	Off	On	Off	On
$\bar{\nu}_e$ HK	Hard MSW-H(0)	Soft ~~CNO,MSW-H~~ M L (0.7(ε))	Soft MSW-L(0.7)	Hard CNO, MSW-L (0.3 ε)
ν_e DUNE	Soft MSW-L(0.3)	Hard CNO(ε) MSW-L(0.3 ε)	Hard MSW-H(0)	Soft CNO,MSW-L 0.7(1− ε)

When Anti-e sector becomes soft, e-sector becomes hard.
The collaboration of HK and DUNE make the detection robust.

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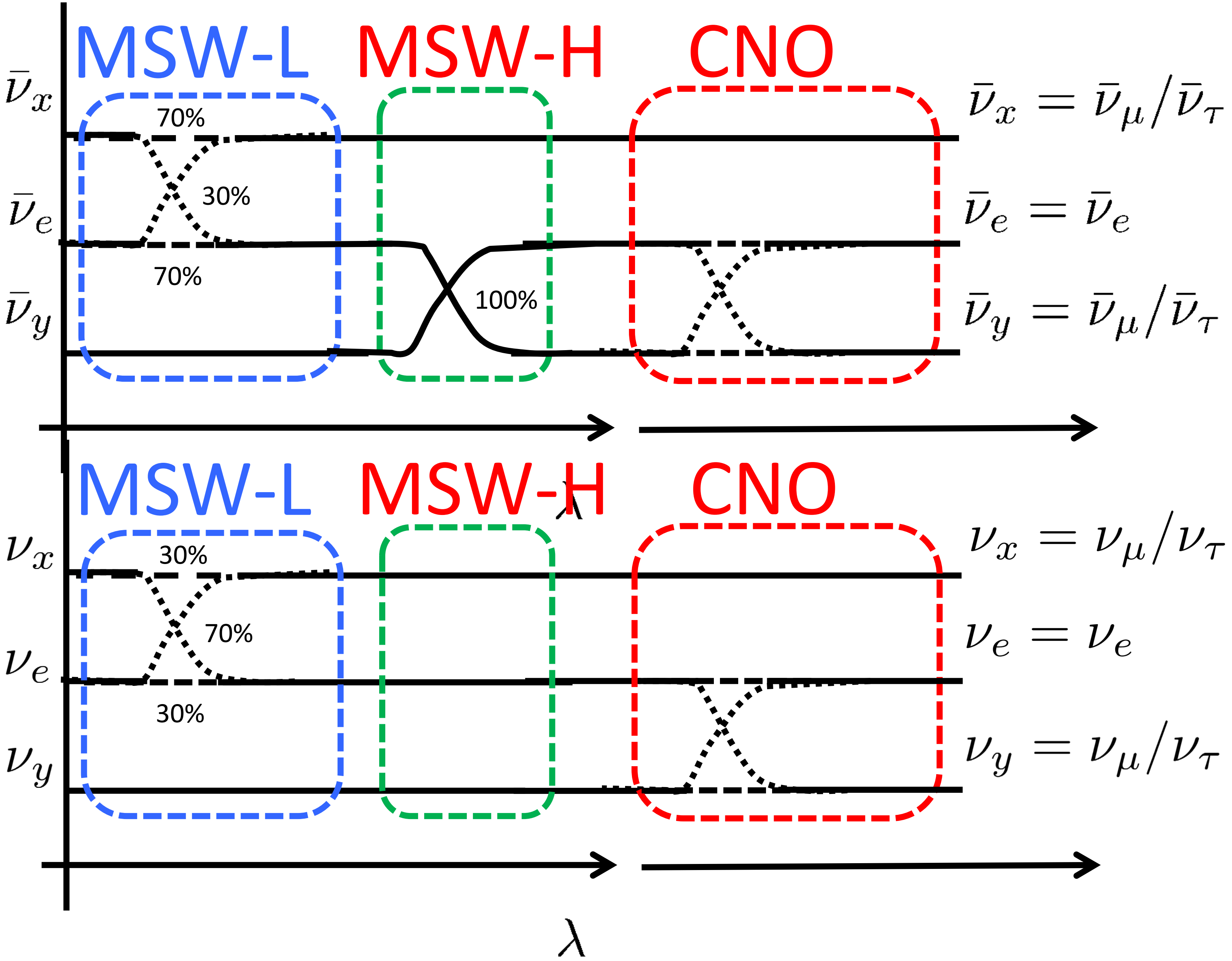
Summary

We performed **multi-angle CNO** simulation with 8.8M_s model both case of inverted (IH) and normal (NH) hierarchy.

- After 200ms post bounce, we **found a signature of CNO**.
- We defined the hardness ratio, R, of spectrum and the evolution of that depends on flavor and mass hierarchy.
- In HK, $\bar{\nu}_e$, CNO decreases R in IH and
  in DUNE, ν_e, CNO increases R in IH.
  In HK, $\bar{\nu}_e$, CNO increases R in NH and
  in DUNE, ν_e, CNO decreases R in NH.
- In this phase, R is naturally increases w/o CNO, so the decreasing trend would be easy to detect.
- A **synergetic observation of HK and DUNE** will draw a robust conclusion.

backup

Inverted mass hierarchy.



Normal mass hierarchy.