第32回理論懇シンポジウム 12/25-27

電子捕獲型超新星における
ニュートリノ集団振動とその観測可能性

(arXiv:1907.01002)

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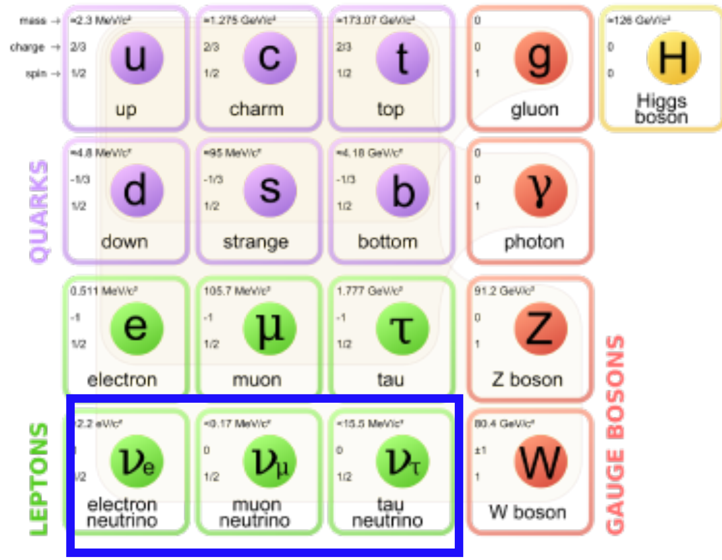
1. **Introduction**
2. **Method**
3. **Result & Discussion**
4. **Summary**

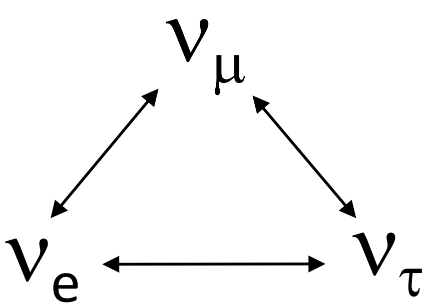
Property of Neutrino

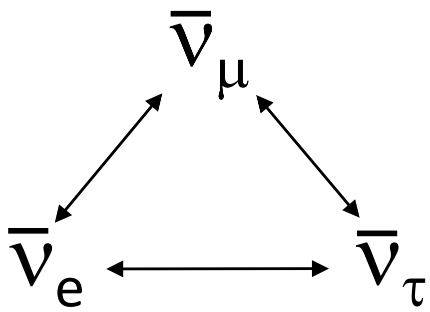
- Neutral leptons
- Weak interactions
- Small mass $\sum m_\nu < 1 \text{ eV}$
- 3 flavors and antiparticles

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

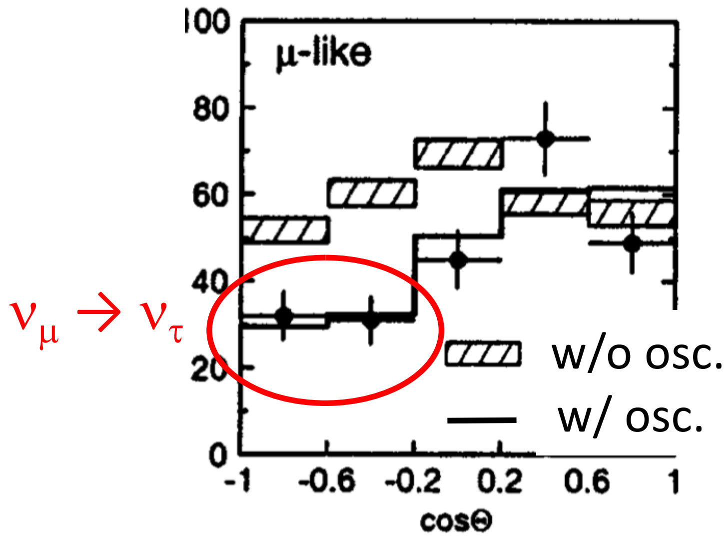
- Neutrino oscillations





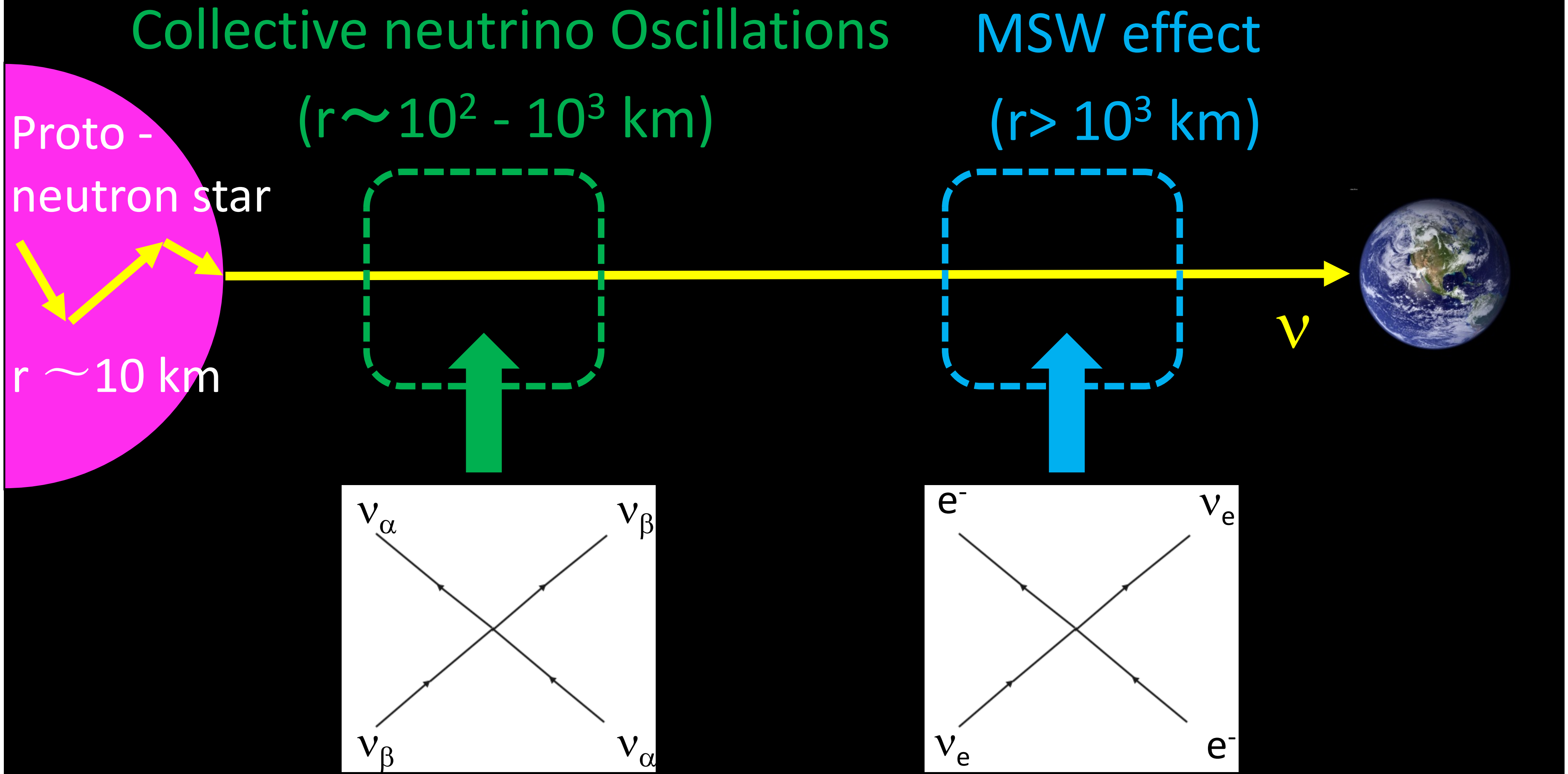


SK collaboration, 1998



Neutrino oscillations in core-collapse supernovae

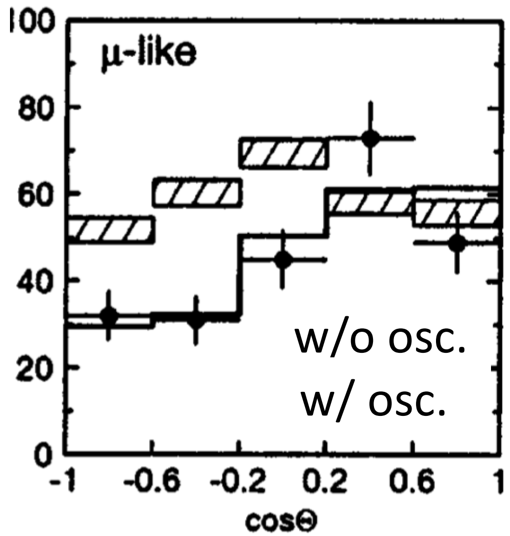
Neutrino oscillations are sensitive to coherent forward scatterings with background medium



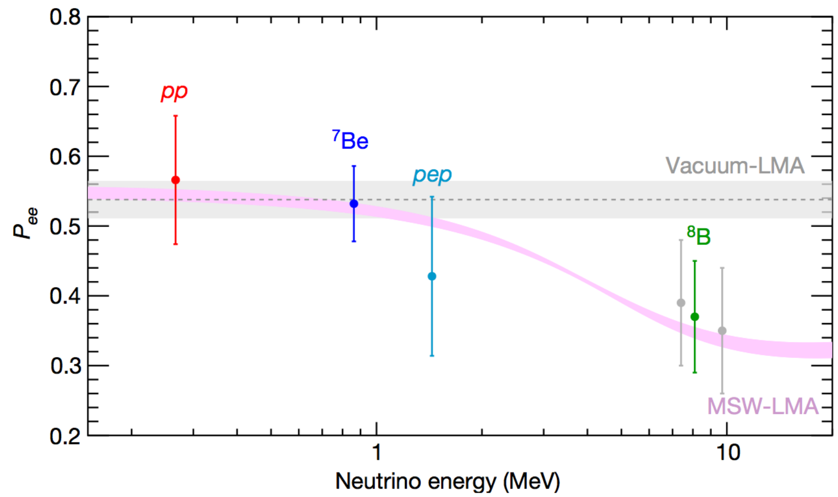
The purpose of our research

Vacuum neutrino oscillations and MSW effects are observed in neutrino experiments.

SK collaboration, 1998



Borexino collaboration, 2018



However, there is no evidence of collective neutrino oscillations (CNO)

→ We discuss detectability of collective neutrino oscillations in future neutrino detectors

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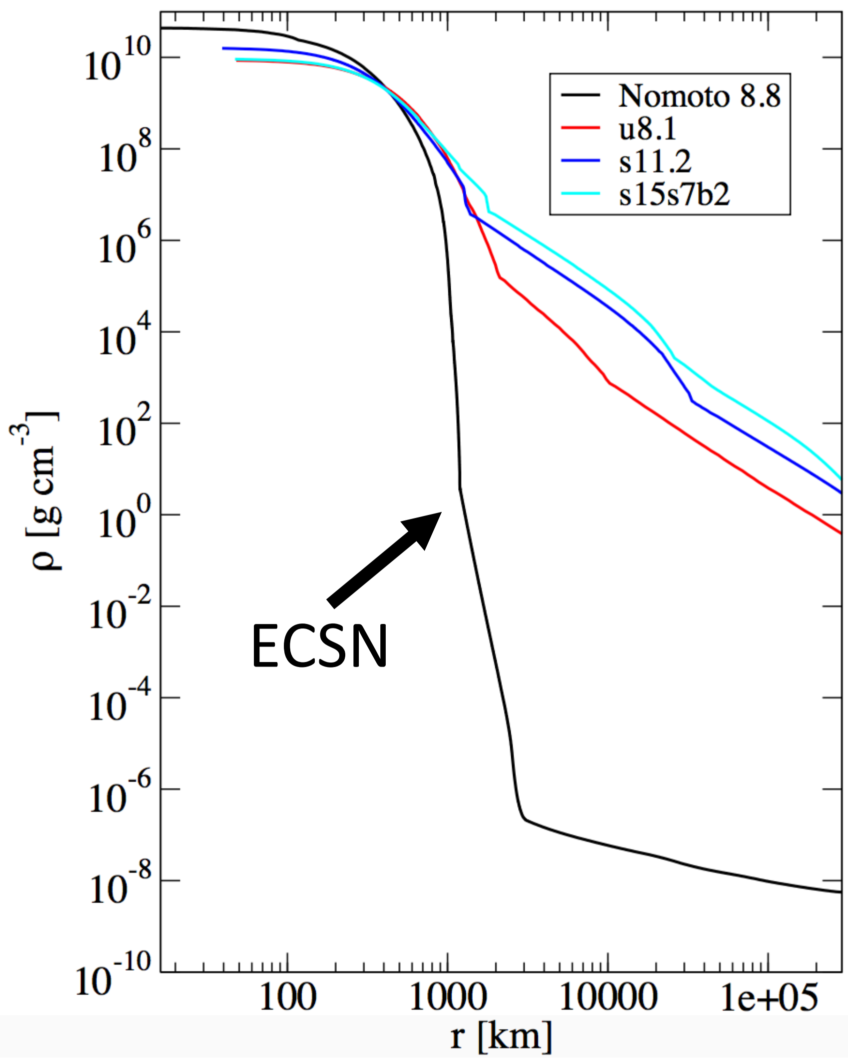
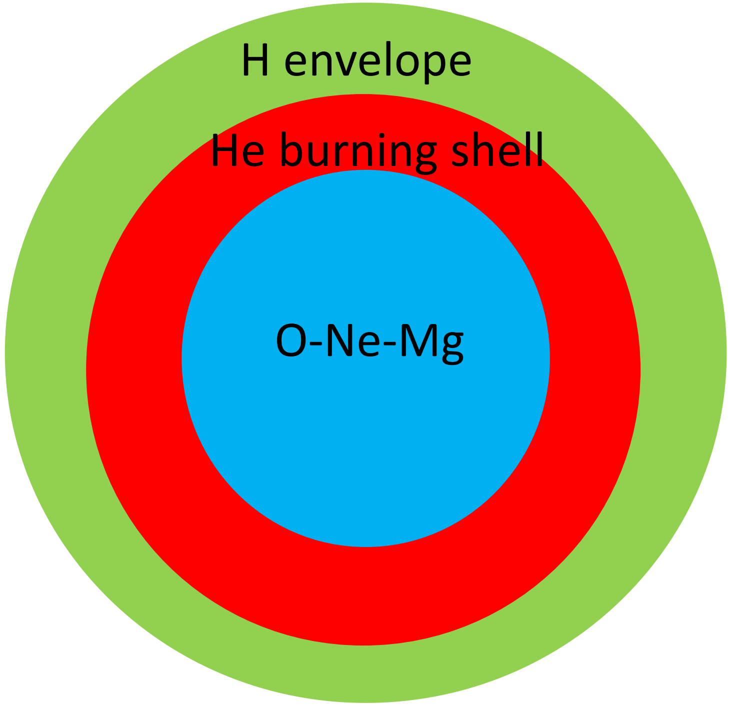
Progenitor of Electron capture supernova (ECSN)

Janka, 2012



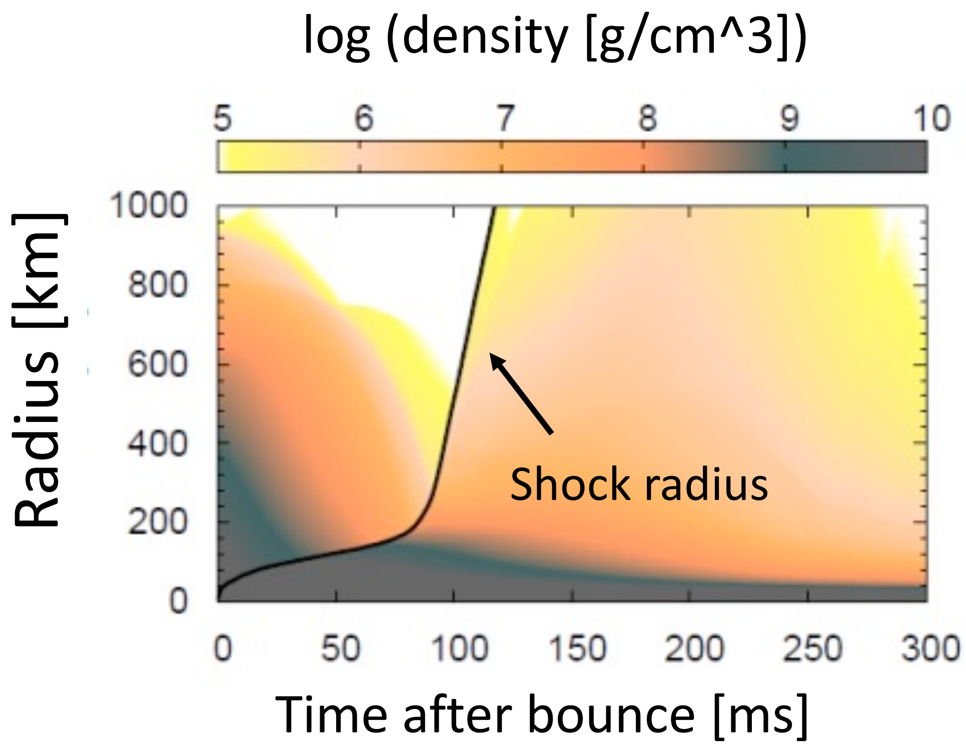


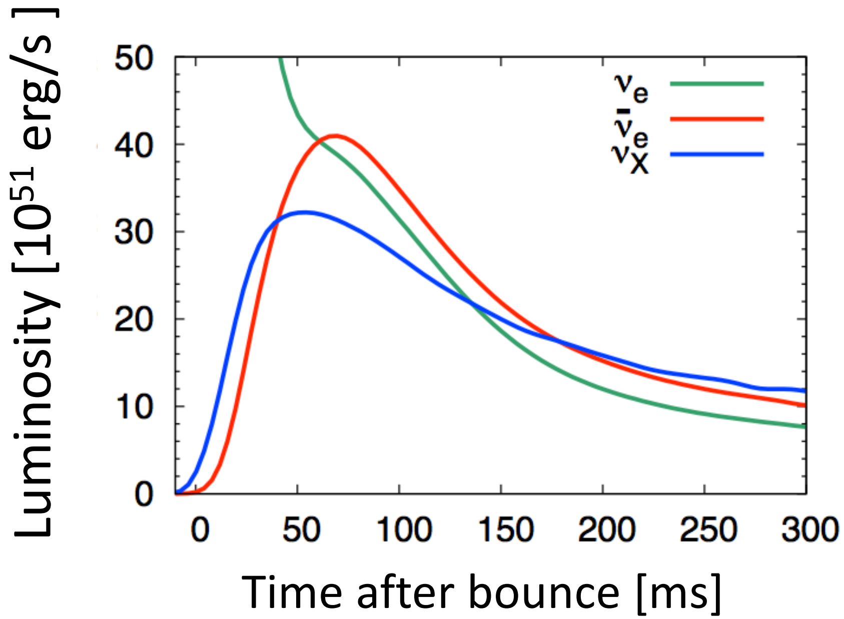
ECSN is triggered by electron capture reactions at O-Ne-Mg core

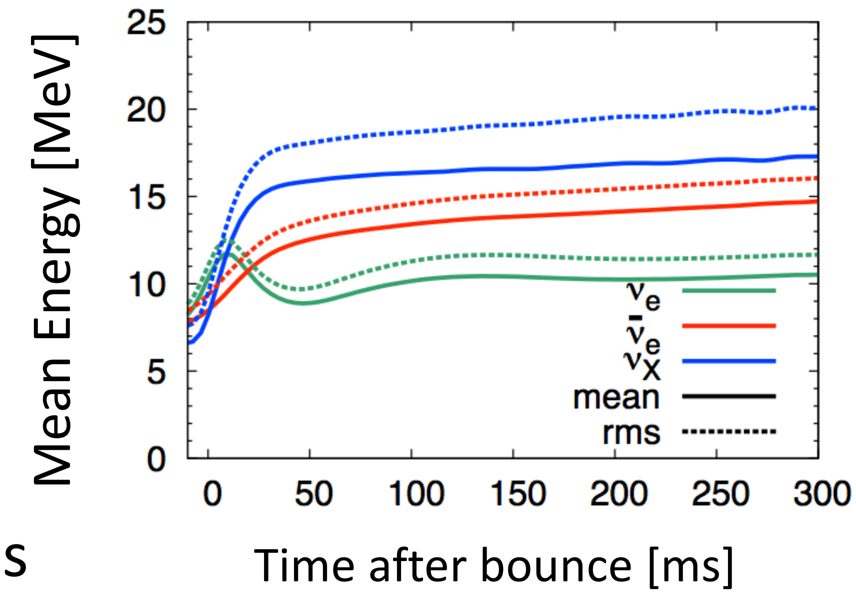
Progenitor mass is in 8-10 M_{sun}

The dilute envelop of ECSN-progenitor (8.8 M_{sun}) is suitable for collective neutrino oscillations

Hydrodynamic simulation & Neutrino radiation







This progenitor explodes even in the 1D model because of the dilute envelope

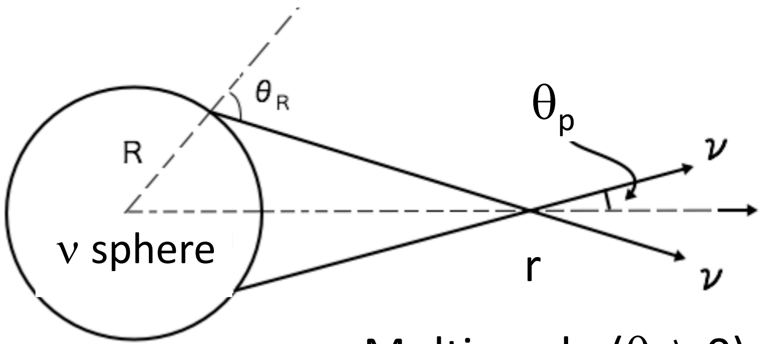
Neutrino oscillations are calculated by using time snapshot of these quantities

Neutrino oscillations in 3 flavor multiangle calculation

Liuville-von Neumann equations
of neutrino density matrices (Duan,2006):

$$\cos\theta_p \frac{\partial}{\partial r}\rho(r,E,\theta_p) = -i\left[\Omega(E) + V_{\rm MSW}(r) + V_{\rm self}(r,\theta_p),\ \rho(r,E,\theta_p)\right]$$

$$\cos\theta_p \frac{\partial}{\partial r}\bar{\rho}(r,E,\theta_p) = -i\left[-\Omega(E) + V_{\rm MSW}(r) + V_{\rm self}(r,\theta_p),\ \bar{\rho}(r,E,\theta_p)\right]$$



Multi angle ($\theta_p \neq 0$)

MSW matter potential:

$$V_{\rm MSW}(r) = \sqrt{2}G_F n_e(r)\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

Vacuum Hamiltonian:

$$\Omega(E) = \frac{\Delta m^2_{21}}{6E}U\begin{pmatrix}-2 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}U^\dagger + \frac{\Delta m^2_{32}}{6E}U\begin{pmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & 2\end{pmatrix}U^\dagger,$$

U: PMNS matrix

Mass hierarchy is unknown

$\Delta m^2_{32} > 0$: Normal hierarchy

$\Delta m^2_{32} < 0$: Inverted hierarchy

Neutrino self interactions:

$$V_{\rm self}(r,\theta_p) = \frac{\sqrt{2}G_F}{2\pi R_\nu^2}\int {\rm d}q\ {\rm d}(\cos\theta_q)\ (1-\cos\theta_p\cos\theta_q)$$
$$\times \sum_{\alpha={\rm all\ flavor}}\left\{\frac{L_{\nu_\alpha}}{\langle E_{\nu_\alpha}\rangle}f_{\nu_\alpha}(q)\rho(r,q,\theta_q) - \frac{L_{\bar\nu_\alpha}}{\langle E_{\bar\nu_\alpha}\rangle}f_{\bar\nu_\alpha}(q)\bar\rho(r,q,\theta_q)\right\}$$

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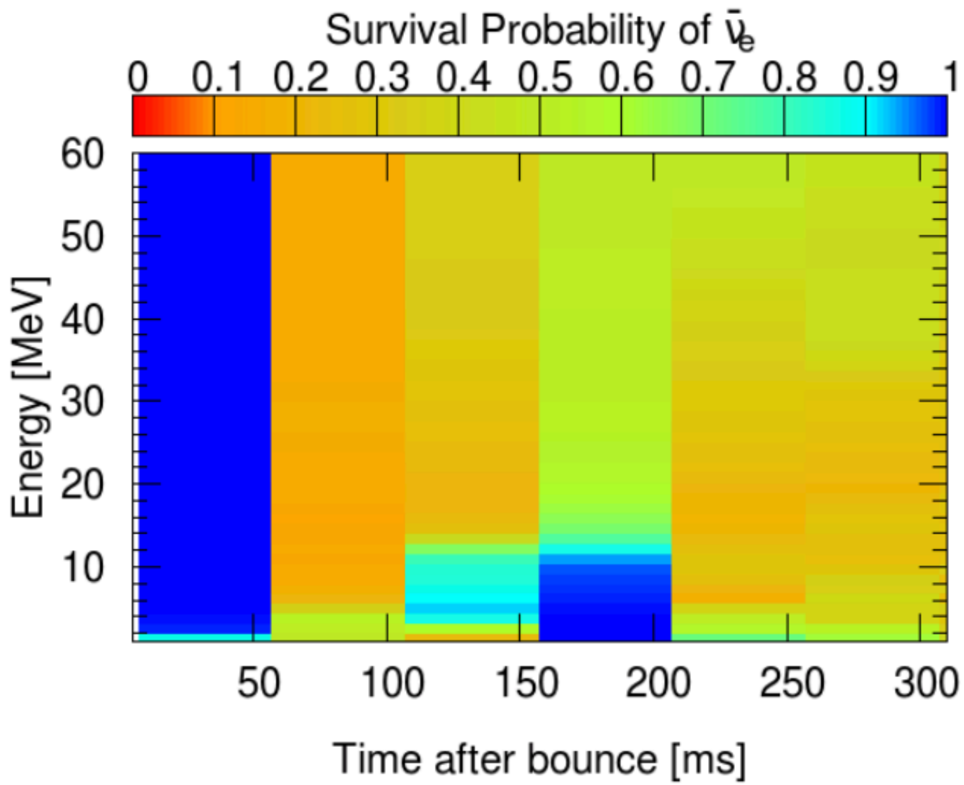
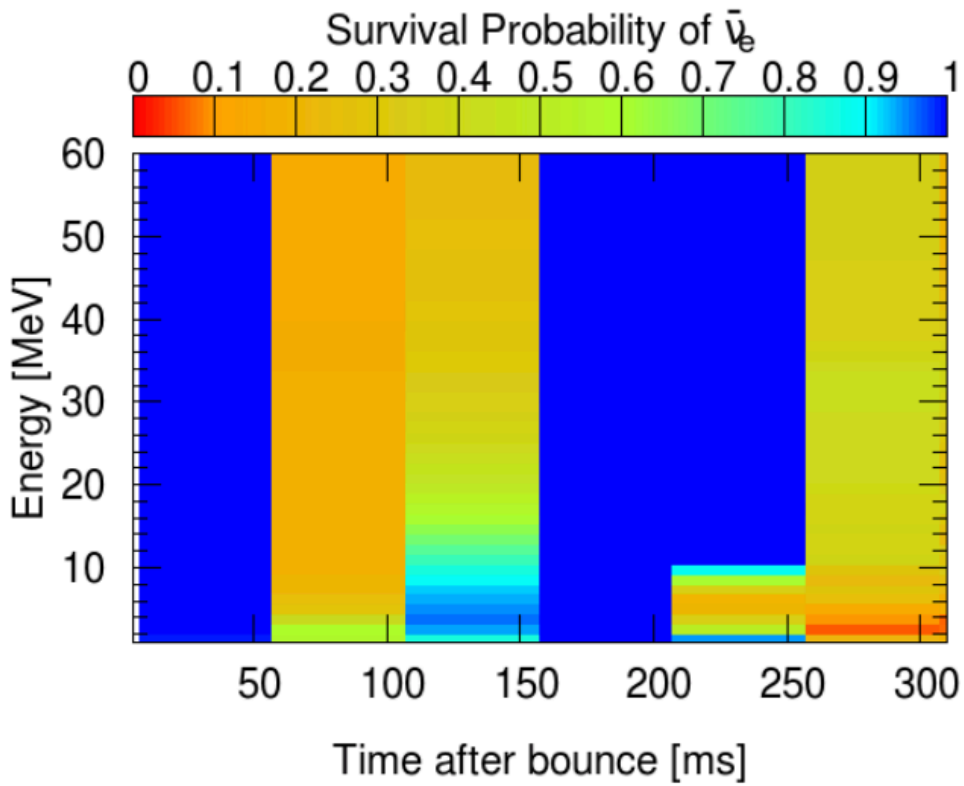
Survival probability of $\bar{\nu}_e$ at 1500 km after collective neutrino oscillations (CNO)

Inverted(Δm^2_{32} <0)



Normal(Δm^2_{32} >0)

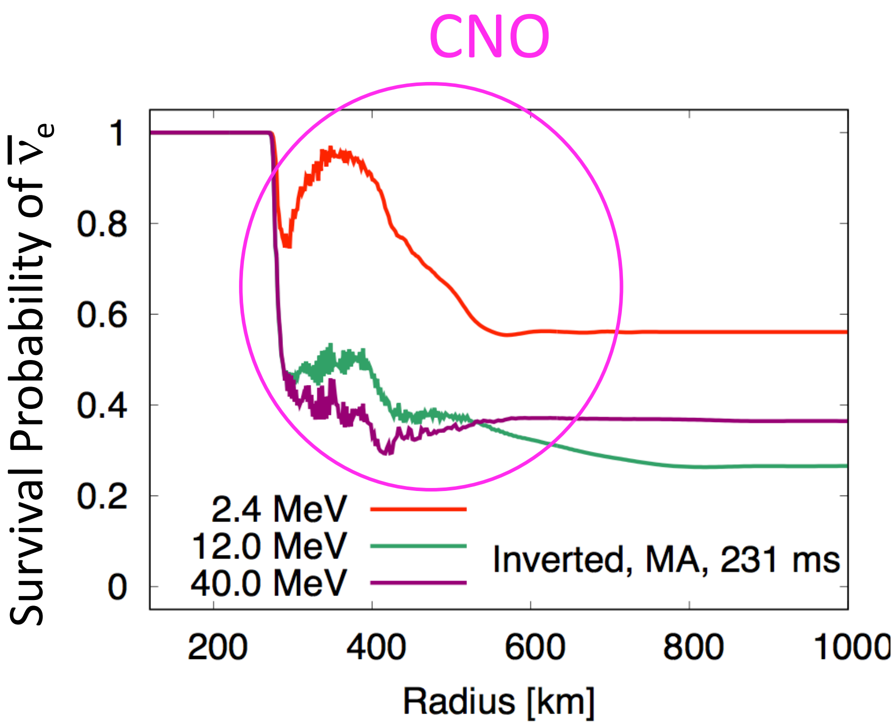


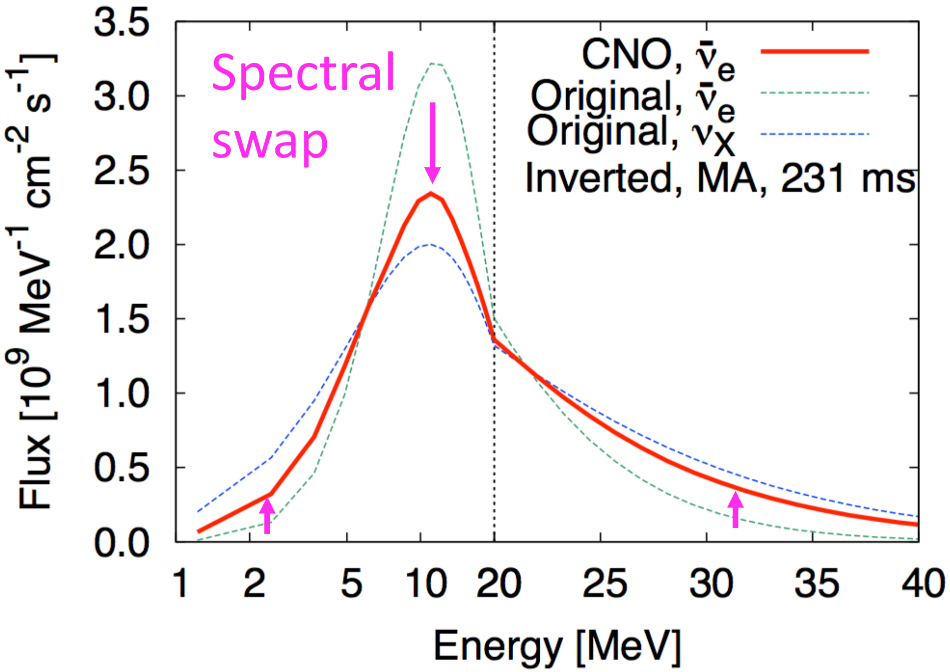
CNO appears in both mass hierarchies

CNO is suppressed in dense matter profiles

Collective neutrino oscillations (CNO) & Spectral swap

231 ms, inverted mass hierarchy



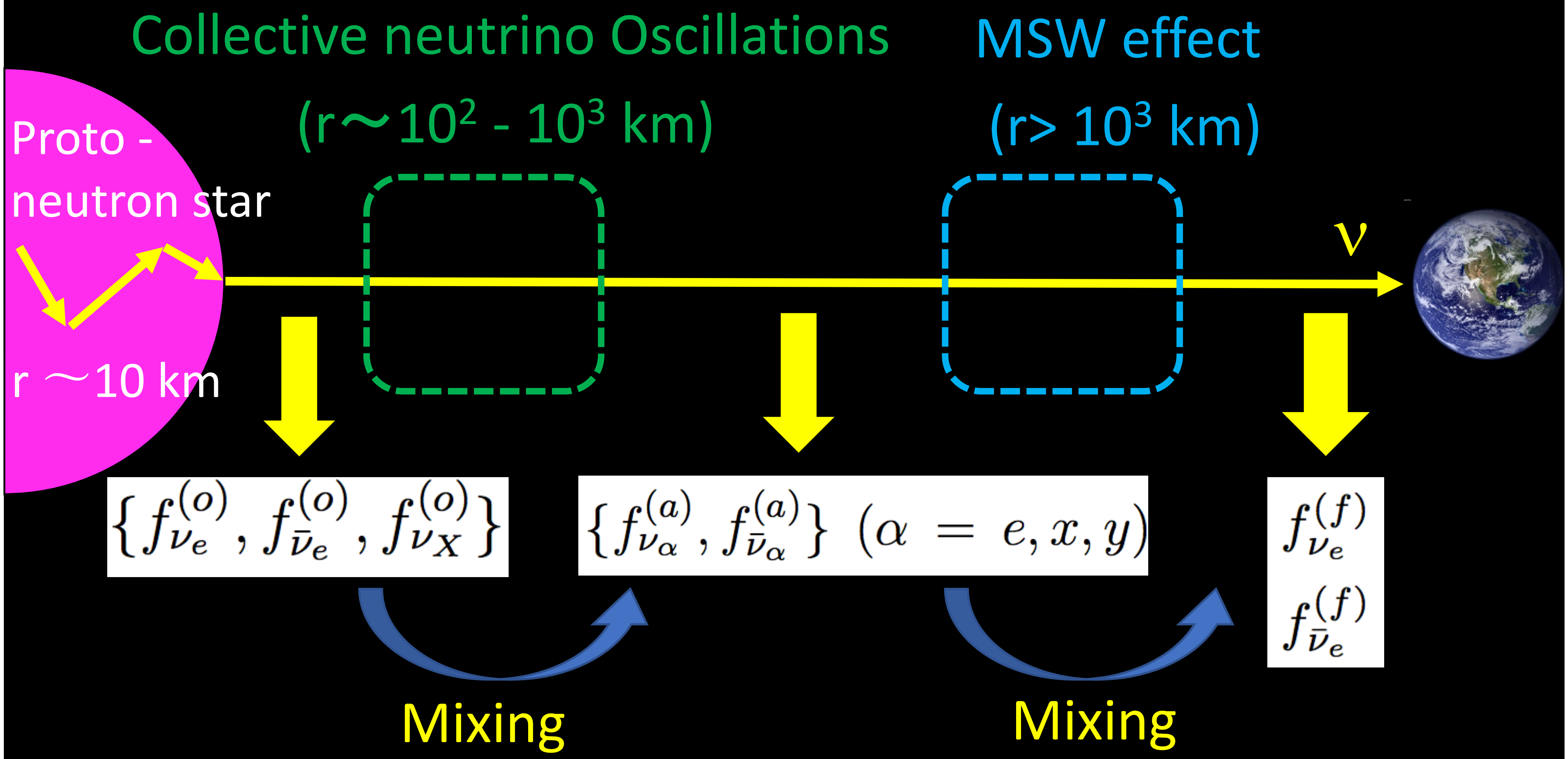


CNO occurs at 250 km where $G_F\, n_\nu \sim \langle |\Delta m^2_{32}|/2E \rangle$

n_ν : Total neutrino number density

Spectral swap (green to blue) occurs after CNO, which increases energetic $\bar{\nu}_e$

Neutrino spectra affected by oscillations



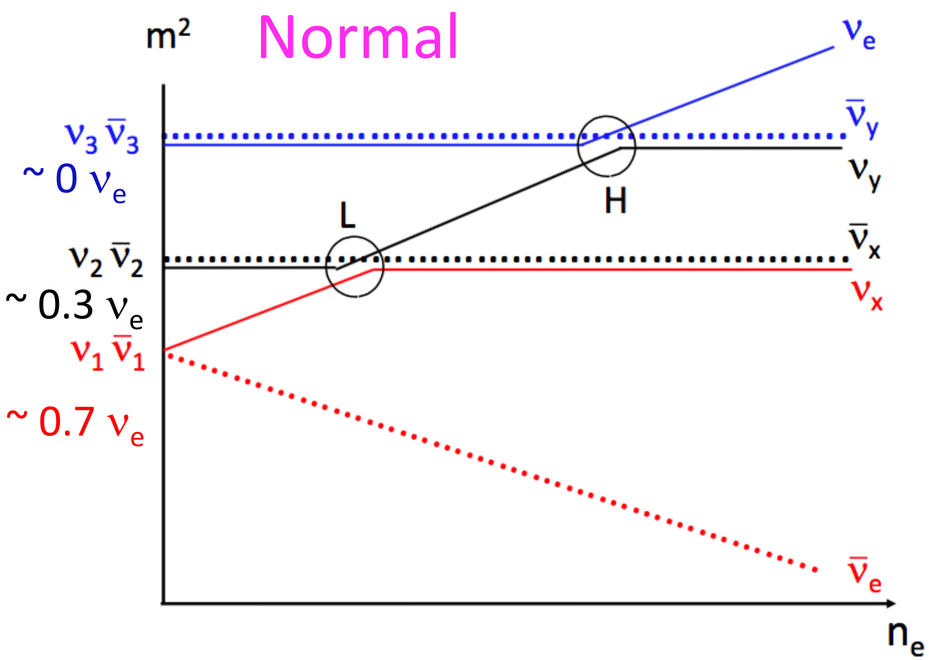
Final neutrino spectra are mixing of initial neutrino spectra

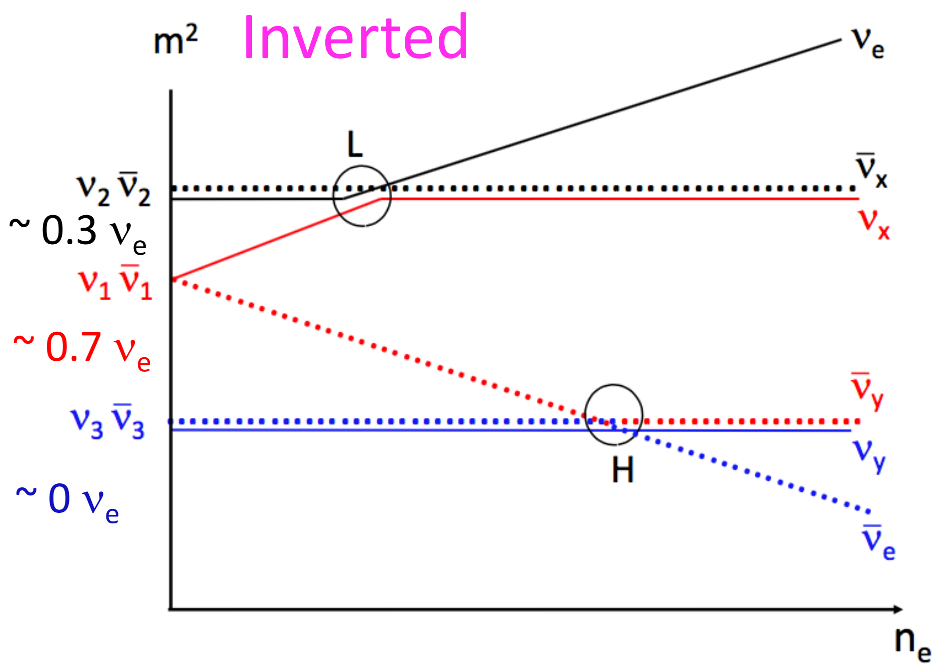
Neutrino spectra on the earth

Neutrino spectra after CNO are affected by MSW effects in outer layers

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

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





Fluxes of ν_e , $\bar{\nu}_e$ on the earth:

$$f_{\nu_e}^{(\mathrm{f})} = s_{13}^2 f_{\nu_e}^{(\mathrm{a})} + \underline{c_{12}^2 c_{13}^2} f_{\nu_x}^{(\mathrm{a})} + s_{12}^2 c_{13}^2 f_{\nu_y}^{(\mathrm{a})}$$

$$f_{\bar{\nu}_e}^{(\mathrm{f})} = c_{12}^2 c_{13}^2 f_{\bar{\nu}_e}^{(\mathrm{a})} + s_{12}^2 c_{13}^2 f_{\bar{\nu}_x}^{(\mathrm{a})} + s_{13}^2 f_{\bar{\nu}_y}^{(\mathrm{a})}$$

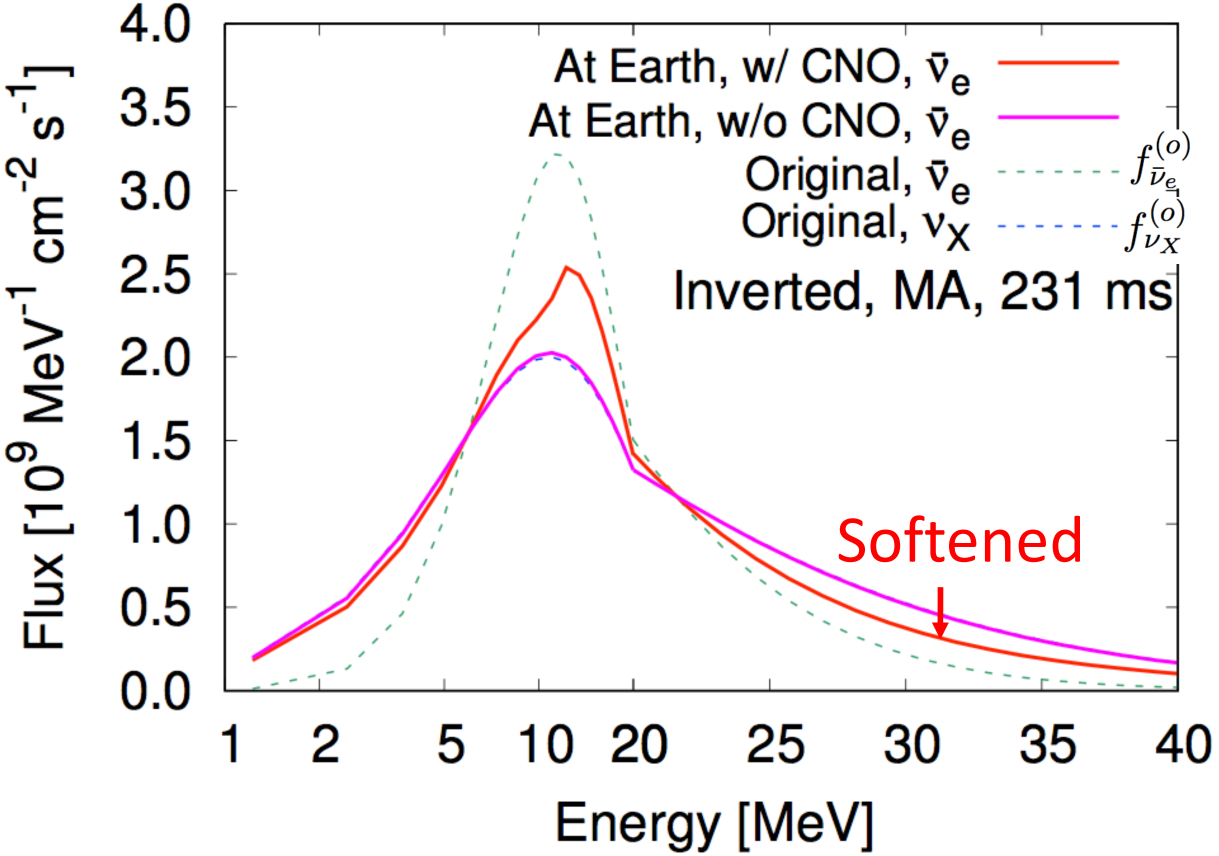
$$f_{\nu_e}^{(\mathrm{f})} = s_{12}^2 c_{13}^2 f_{\nu_e}^{(\mathrm{a})} + c_{12}^2 c_{13}^2 f_{\nu_x}^{(\mathrm{a})} + s_{13}^2 f_{\nu_y}^{(\mathrm{a})}$$

$$f_{\bar{\nu}_e}^{(\mathrm{f})} = s_{13}^2 f_{\bar{\nu}_e}^{(\mathrm{a})} + s_{12}^2 c_{13}^2 f_{\bar{\nu}_x}^{(\mathrm{a})} + \underline{c_{12}^2 c_{13}^2} f_{\bar{\nu}_y}^{(\mathrm{a})}$$

$s^2_{13} \sim 0$, $s^2_{12}\, c^2_{13} \sim 0.3$, $c^2_{12}\, c^2_{13} \sim 0.7$

$\bar{\nu}_e$ spectrum on the earth

231 ms, inverted mass hierarchy



$\bar{\nu}_e$ spectrum on the earth

$$f^{(\mathrm{f})}_{\bar{\nu}_e} \sim 0.7(1-\epsilon) f^{(\mathrm{o})}_{\bar{\nu}_e} + (0.3 + 0.7\epsilon) f^{(\mathrm{o})}_{\bar{\nu}_X}$$

ε : Survival probability of $\bar{\nu}_e$ after CNO

w/o CNO : ε=1 → Hard spectra

w/ CNO : $0<\varepsilon<1$ → Soft spectra

Future neutrino detectors

- **Hyper-Kamiokande (HK)**

  200 kton, Water Cherenkov

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

- **JUNO**

  20 kton, Liquid scintillator

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

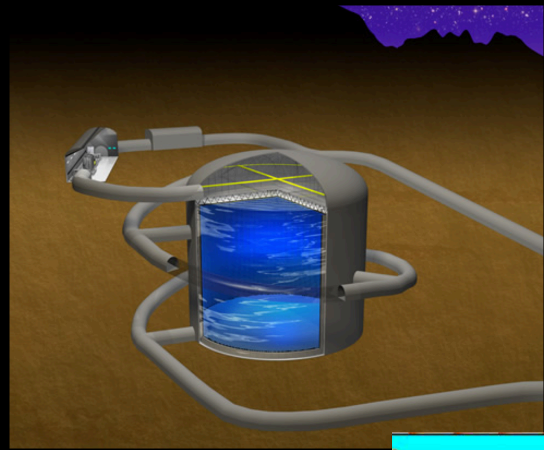
  $n + p \rightarrow d + \gamma$

- **DUNE**

  40 kton, Liquid Argon

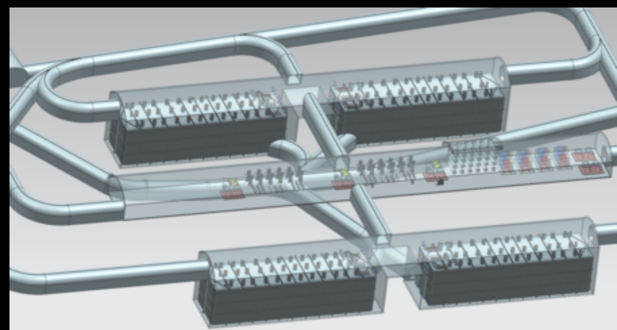
  $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}Kr^*$

HK

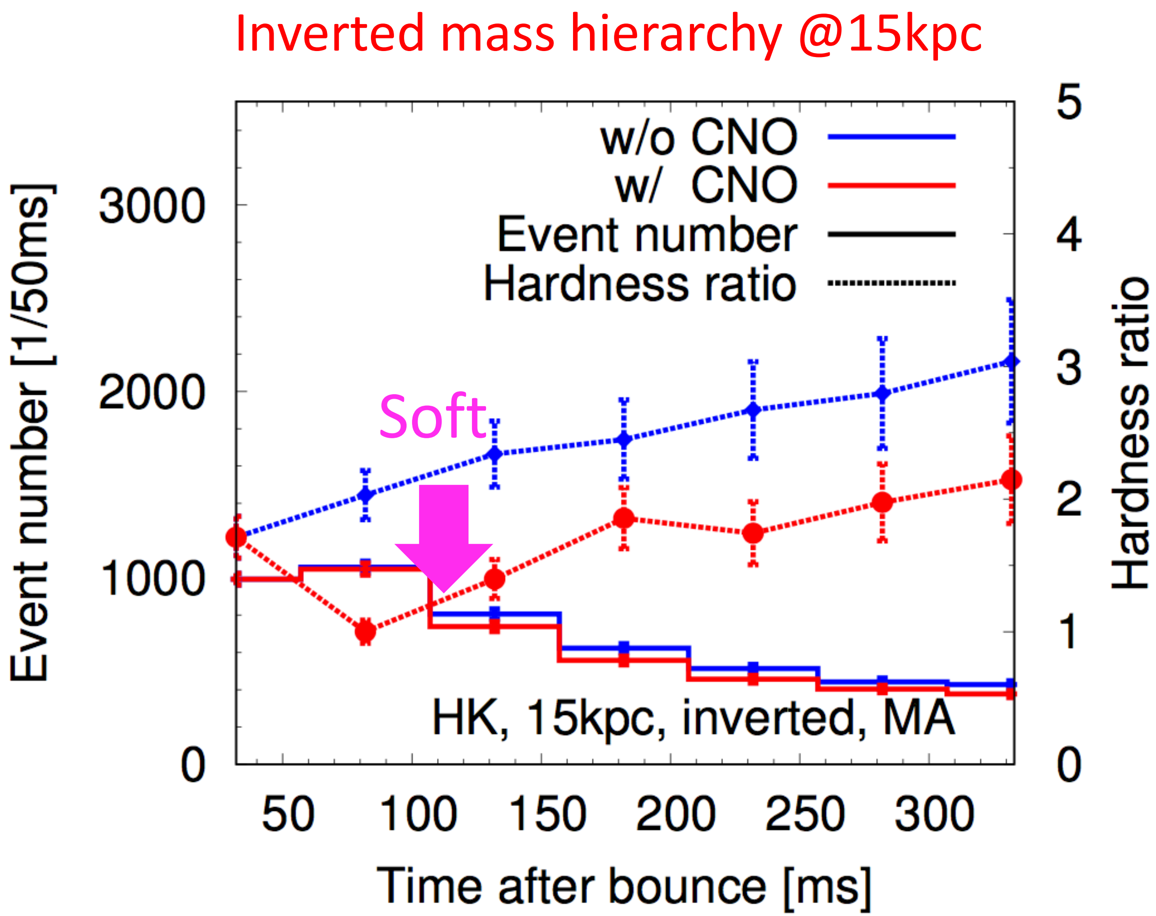


JUNO

DUNE



$\bar{\nu}_e$ detection @ Hyper-Kamiokande(HK)



Event number [1/50ms]:

$$\frac{dN}{dt} = N_{tar} \int_{E_{th}} F \sigma dE$$

N_{tar}: Number of H_2O

$f_{\bar{\nu}_e}^{(f)}$: Flux of $\bar{\nu}_e$

σ : Cross section $\propto E^2$

Hardness ratio:

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

$N_{E_c<E}$: # of E> E_c

$N_{E<E_c}$: # of E< E_c

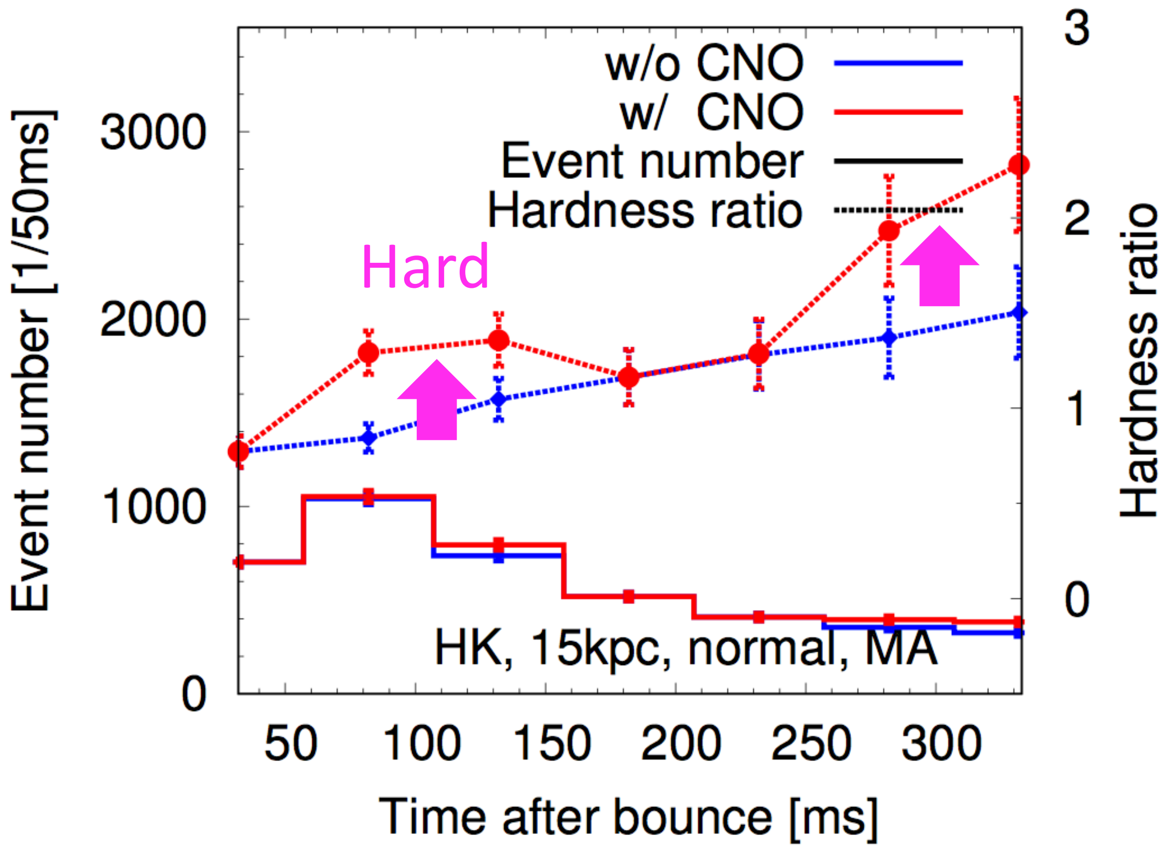
E_c =20 MeV

The both event number and hardness ratio are reduced by CNO

→ The softened $R_{H/L}$ is preferable for detection of CNO

$\bar{\nu}_e$ detection in normal mass hierarchy

Normal mass hierarchy @15kpc



CNO make energetic $\bar{\nu}_e$

→ Such $\bar{\nu}_e$ can survive on the earth

→ Event number increases $R_{H/L}$ becomes hard

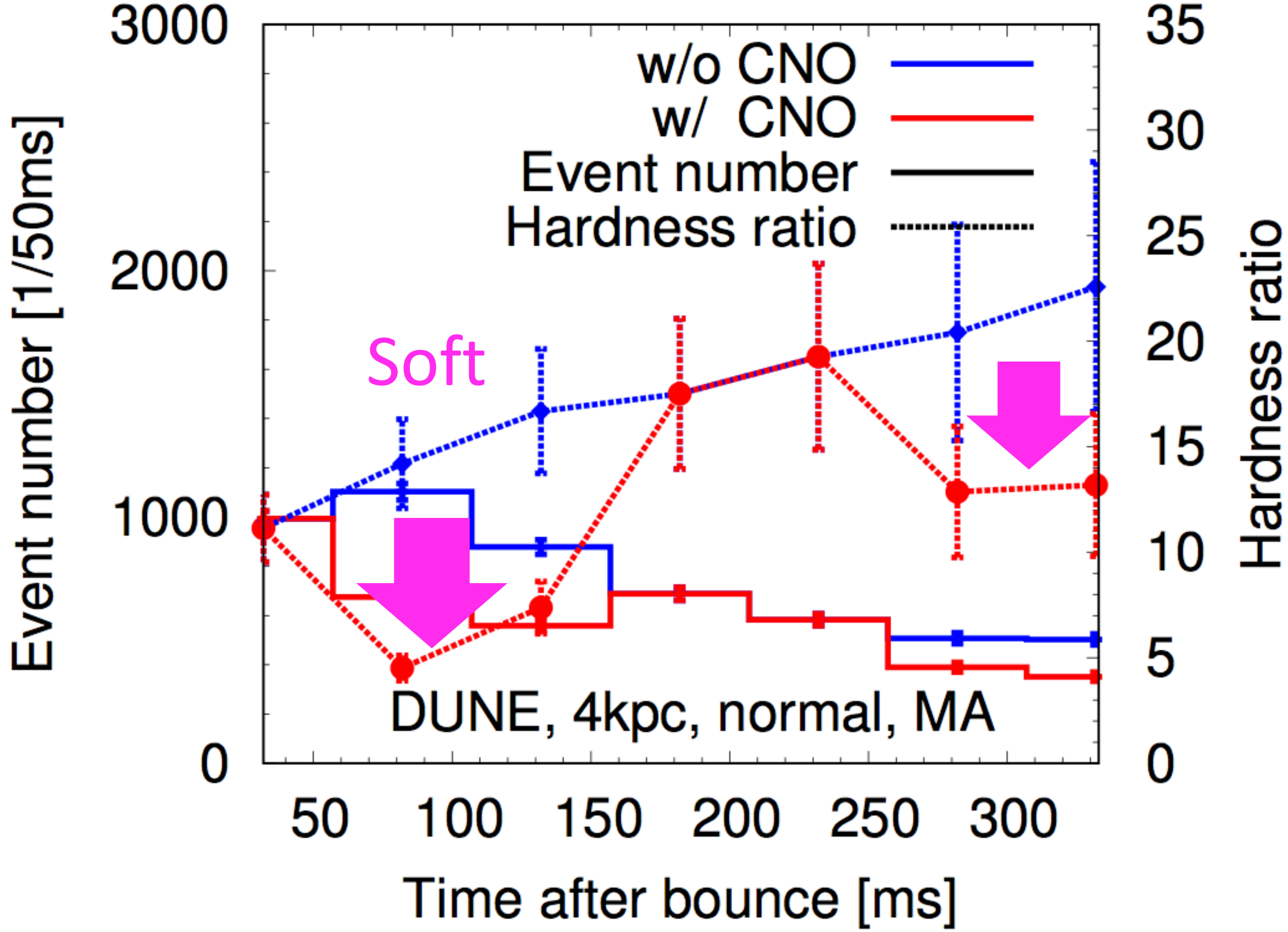
$$f_{\bar{\nu}_e}^{(\mathrm{f})} \sim (0.3+0.4\epsilon) f_{\bar{\nu}_e}^{(\mathrm{o})} + (0.7-0.4\epsilon) f_{\bar{\nu}_X}^{(\mathrm{o})}$$

w/o CNO : ε=1 → soft spectra

w/ CNO : 0<ε<1 → Hard spectra

ν_e observation in normal mass hierarchy @ DUNE

Normal mass hierarchy @4kpc



$$f_{\nu_e}^{(\mathrm{f})} \sim (0.7 - 0.7\epsilon) f_{\nu_e}^{(\mathrm{o})} + (0.3 + 0.7\epsilon) f_{\nu_X}^{(\mathrm{o})}$$

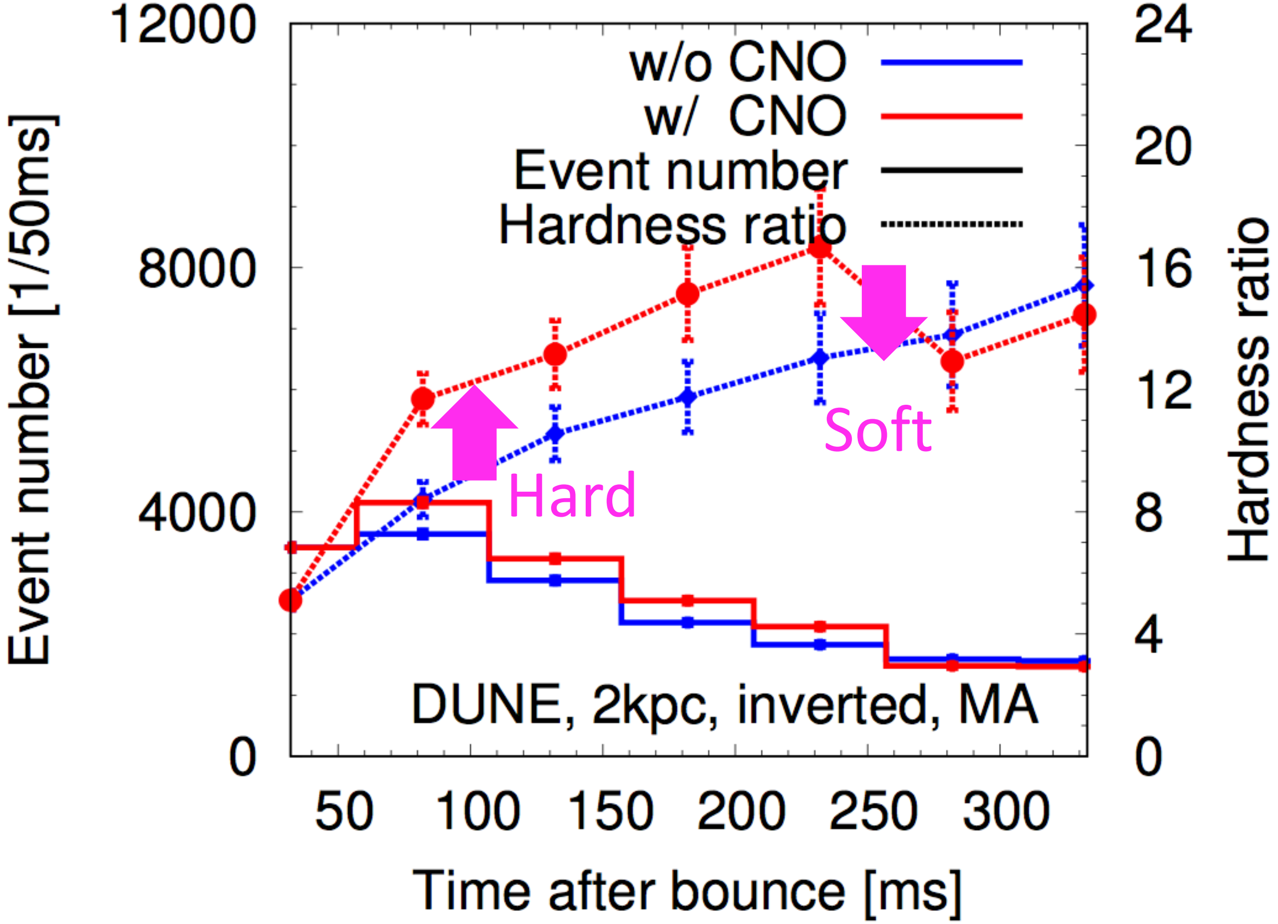
ε : Survival probability of ν_e in e-x sector

w/o CNO : ε=1 → Hard spectra

w/ CNO : $0<\varepsilon<1$ → Soft spectra

ν_e observation in inverted mass hierarchy @ DUNE

Inverted mass hierarchy @2kpc



$$f_{\nu_e}^{(\mathrm{f})} \sim [0.3\epsilon + 0.7(1-\eta)(1-\epsilon)]f_{\nu_e}^{(\mathrm{o})} + [1.0 - 0.3\epsilon - 0.7(1-\eta)(1-\epsilon)]f_{\nu_X}^{(\mathrm{o})}$$

$0<\varepsilon<1$, $\eta=1$ → Hard spectra

$0<\varepsilon<1$, $0<\eta<1$ → Soft spectra

ε : Survival probability in e-x sector, η : Survival probability in e-y sector

Summary of CNO detectability

We summarize behaviors of hardness ratio $R_{H/L}$

Spectrum \ Hierarchy	Normal	Inverted
ν_e DUNE	Soft	Hard → Soft
$\bar{\nu}_e$ HK	Hard	Soft

In the accretion phase, neutrino spectra naturally become hard
→ Softening neutrino spectrum is easy to distinguish

Combination of HK and DUNE gives us softening $R_{H/L}$ in both hierarchy

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Summary

- Neutrino self interactions certainly induce collective neutrino oscillations (CNO) in core-collapse supernovae

- However, the signature of CNO has not been found in observations

- We carry out numerical simulations of electron capture supernovae (8.8 M_sun) and discuss detectability of CNO

- The softening hardness ratio traces spectral swap caused by CNO

- In inverted mass hierarchy, HK can distinguish softening hardness ratio of $\bar{\nu}_e$ within 15 kpc

- In normal mass hierarchy, DUNE can clarify softening hardness ratio of ν_e within 4 kpc