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Collective neutrino flavor oscillations and application to supernova nucleosynthesis

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Neutrino oscillations

Transition from a flavor state to another flavor state

$$\nu_\alpha \longleftrightarrow \nu_\beta \qquad \alpha, \beta = e, \mu, \tau$$

Flavor eigenstates are mixing of energy eigenstates in vacuum

=Mass eigenstates

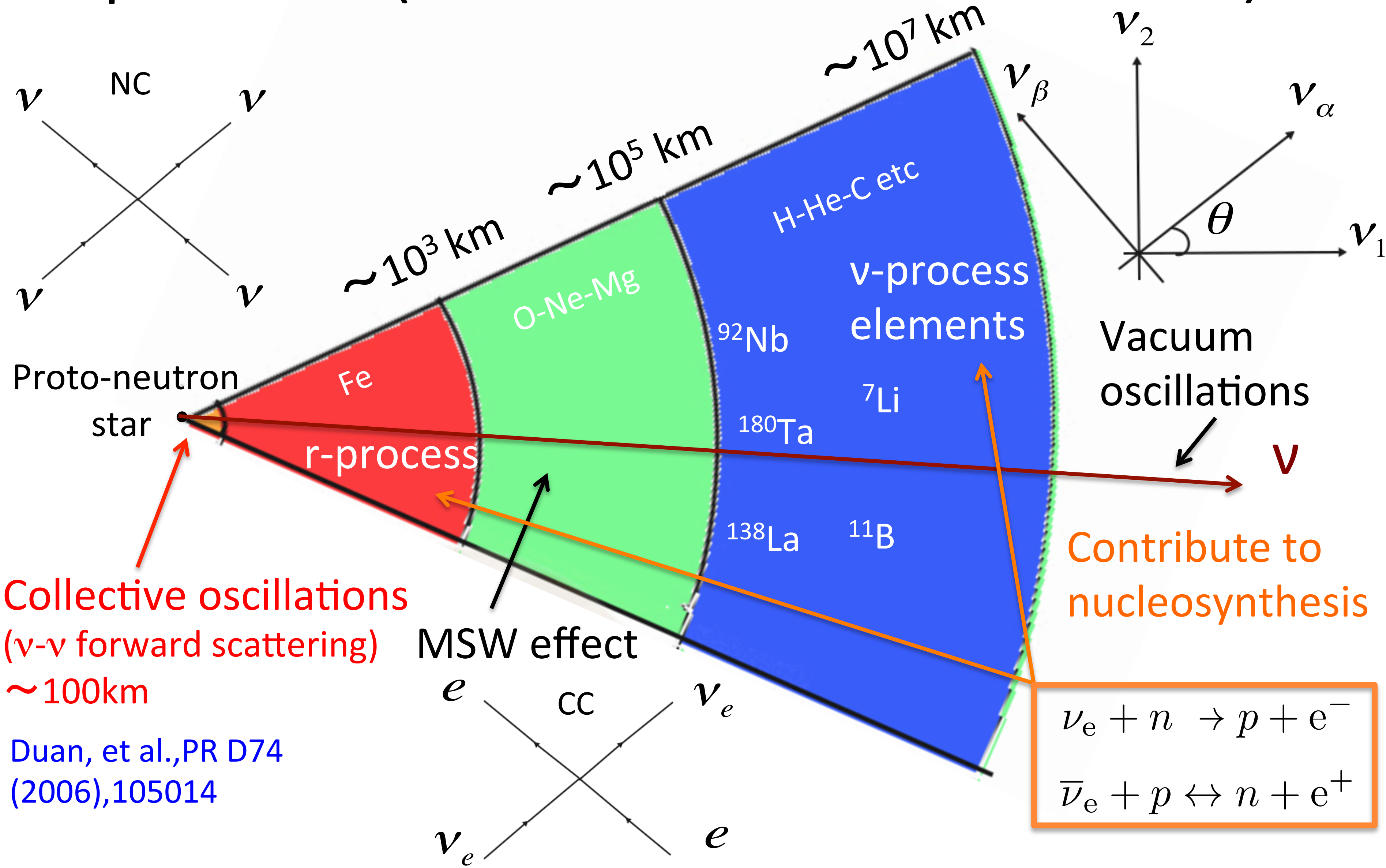
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\text{flavor}} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\text{mass}}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\mathrm{e}^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\mathrm{e}^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

This matrix causes neutrino oscillations

PMNS matrix

Neutrino oscillations in core collapse supernovae (several seconds after bounce)



Purpose of our Research

Collective oscillations will play significant roles in supernova nucleosynthesis

→ Study collective oscillations and their effects on nucleosynthesis

What we did

→ Calcultate 3 flavor collective oscillations and apply these results to network calculation in both mass hierarchy

$$\Delta m_{32}^2 = m_3^2 - m_2^2$$

$\Delta m_{32}^2 > 0$ .... Normal mass hierarchy

$\Delta m_{32}^2 < 0$ .... Inverted mass hierarchy

Model & Assumption

Our Model

- 15 $M_\odot$ progenitor (model "s15s7b2"), 1.2 s after bounce

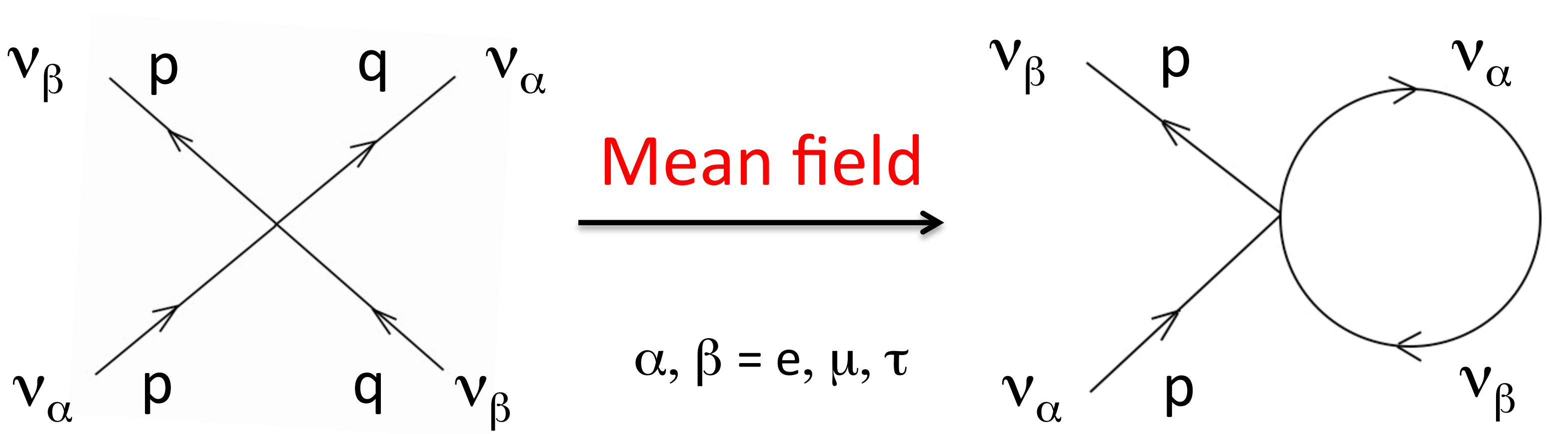
S.E. Woosley and T.A.Weaver,1995,ApJS,101,181

- Spherical symmetric and steady state
- Neutrino sphere: R = 20 km

Assumption

- Mixing parameters (θ_{ij}, Δm_{ij}^2) from PDG
- Mean field ν-ν forward scattering term $H_{\nu\nu}$

G. Sigl and G. Rafflet,1993,NP B406,423



Formalism

G. Sigl and G. Rafflet,1993,Nucl. Phys. B 406,423

We calculate the evolution of 3 x 3 density matrix

$$\rho(t, \mathbf{r}, \mathbf{p}) \quad \overline{\rho}(t, \mathbf{r}, \mathbf{p})$$

$$\langle a_j^\dagger(\mathbf{p}) a_i(\mathbf{p}')\rangle = (2\pi)^3 \delta^{(3)}(\mathbf{p}-\mathbf{p}')(\rho_\mathbf{p})_{ij}$$

$a_i(\mathbf{p}')$ .... annihilation operator of ν_i

$$\langle b_i^\dagger(\mathbf{p}) b_j(\mathbf{p}')\rangle = (2\pi)^3 \delta^{(3)}(\mathbf{p}-\mathbf{p}')(\overline{\rho_\mathbf{p}})_{ij}$$

$b_j(\mathbf{p}')$ .... annihilation operator of $\bar{\nu}_j$

Ensemble average of Heisenberg equation of $a_j^\dagger(\mathbf{p}) a_i(\mathbf{p}')$ $b_i^\dagger(\mathbf{p}) b_j(\mathbf{p}')$

↓

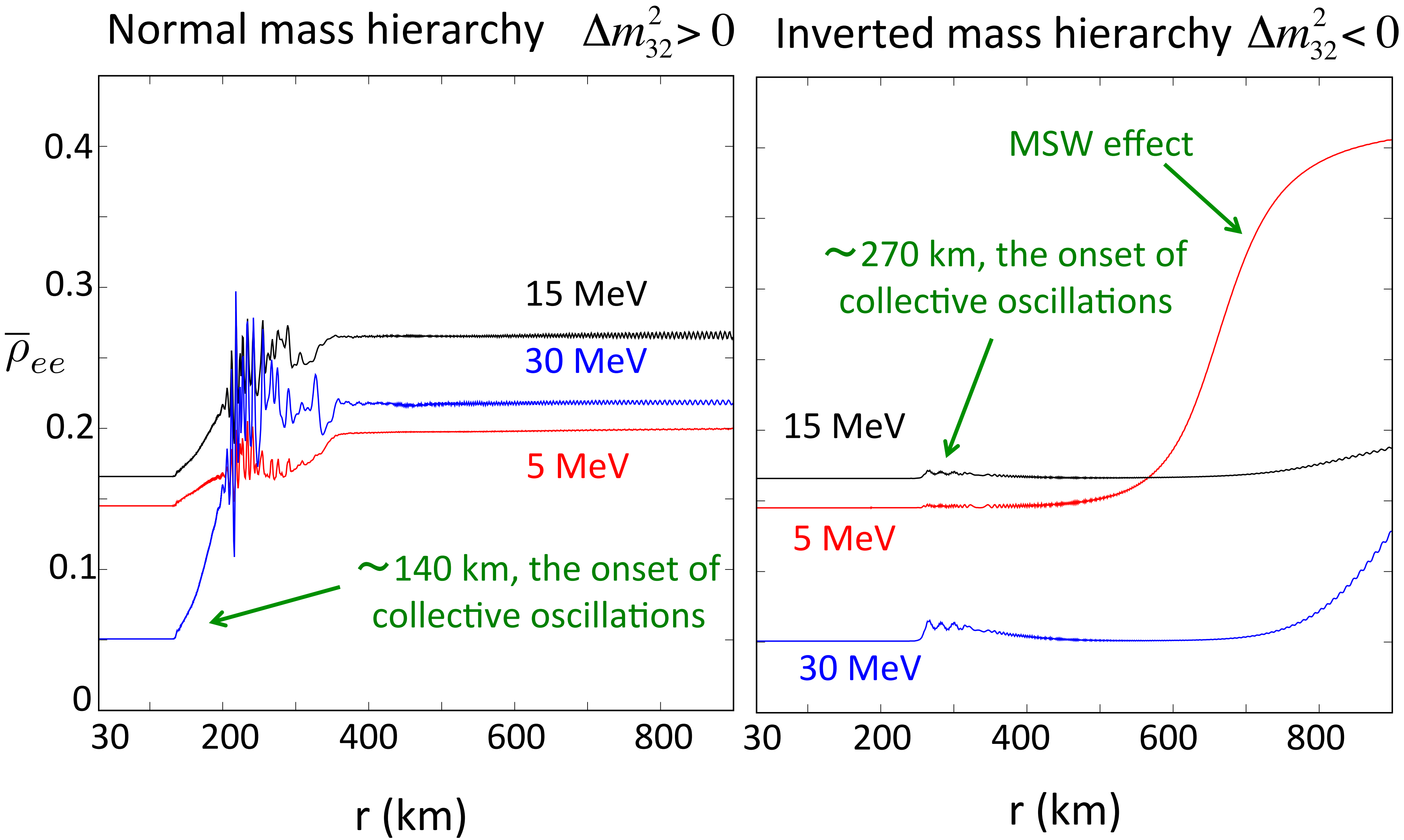
$$\dot{\rho} = -i\,[H, \rho] \quad \dot{\overline{\rho}} = -i\,[H, \overline{\rho}]$$

We solve these equations !!

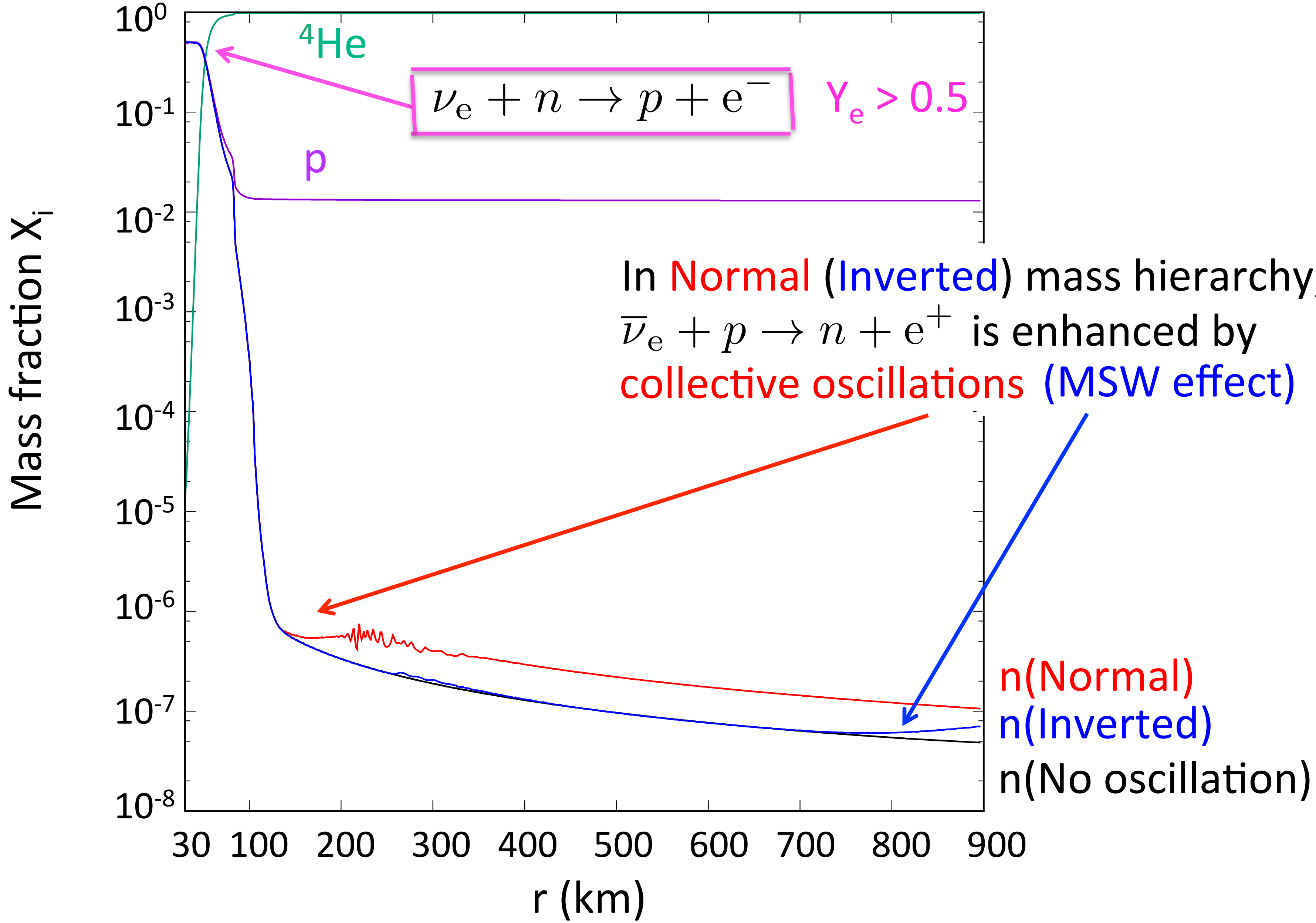
$$H = H_{\mathrm{Vacuum}} + H_{\mathrm{MSW}} + H_{\nu\nu}$$ .... Hamiltonian in flavor space

Mean field ν-ν forward scattering term

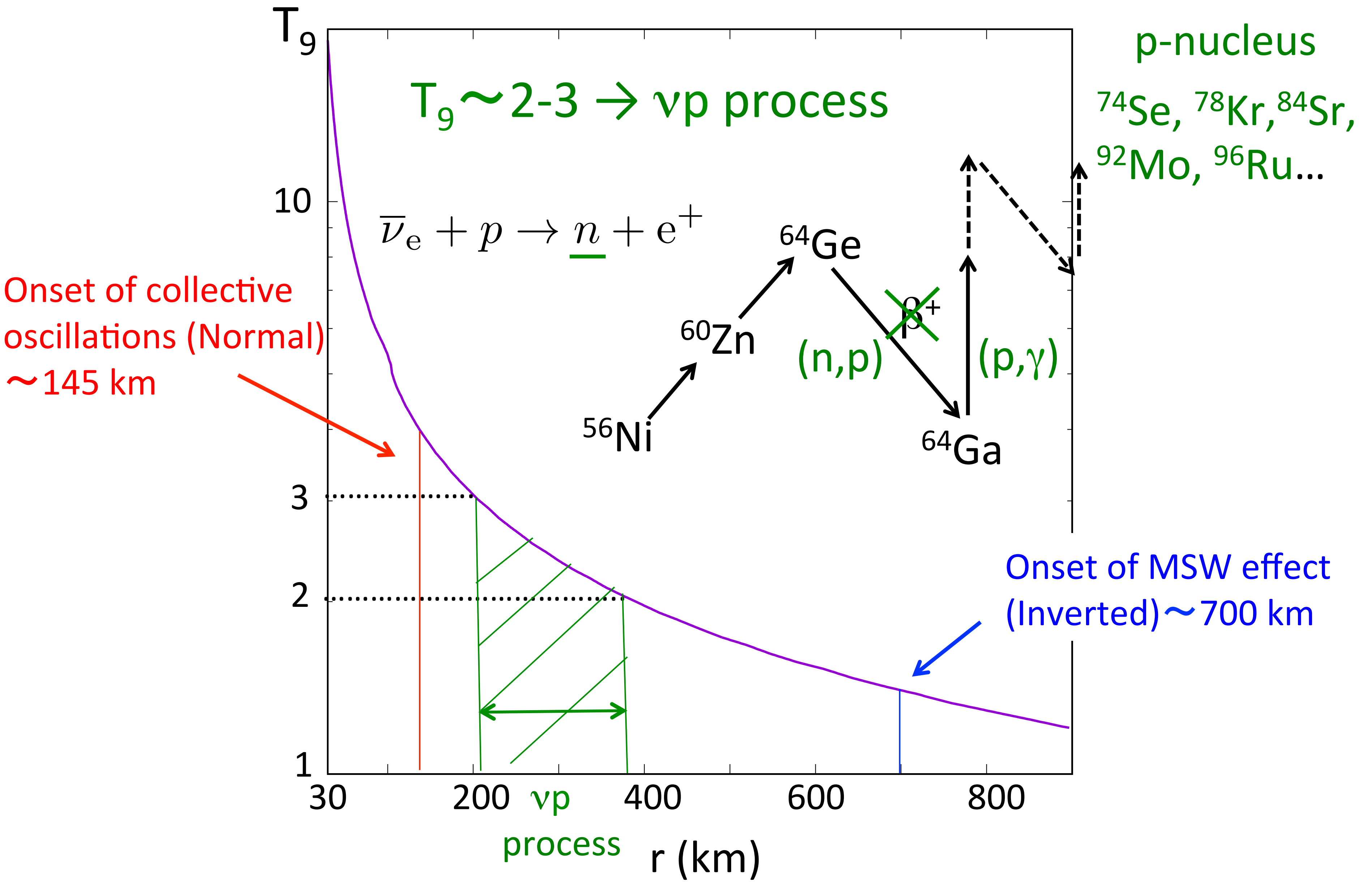
Evolution of $\overline{\rho}_{ee}$ ($\overline{\nu}_e$ probability)



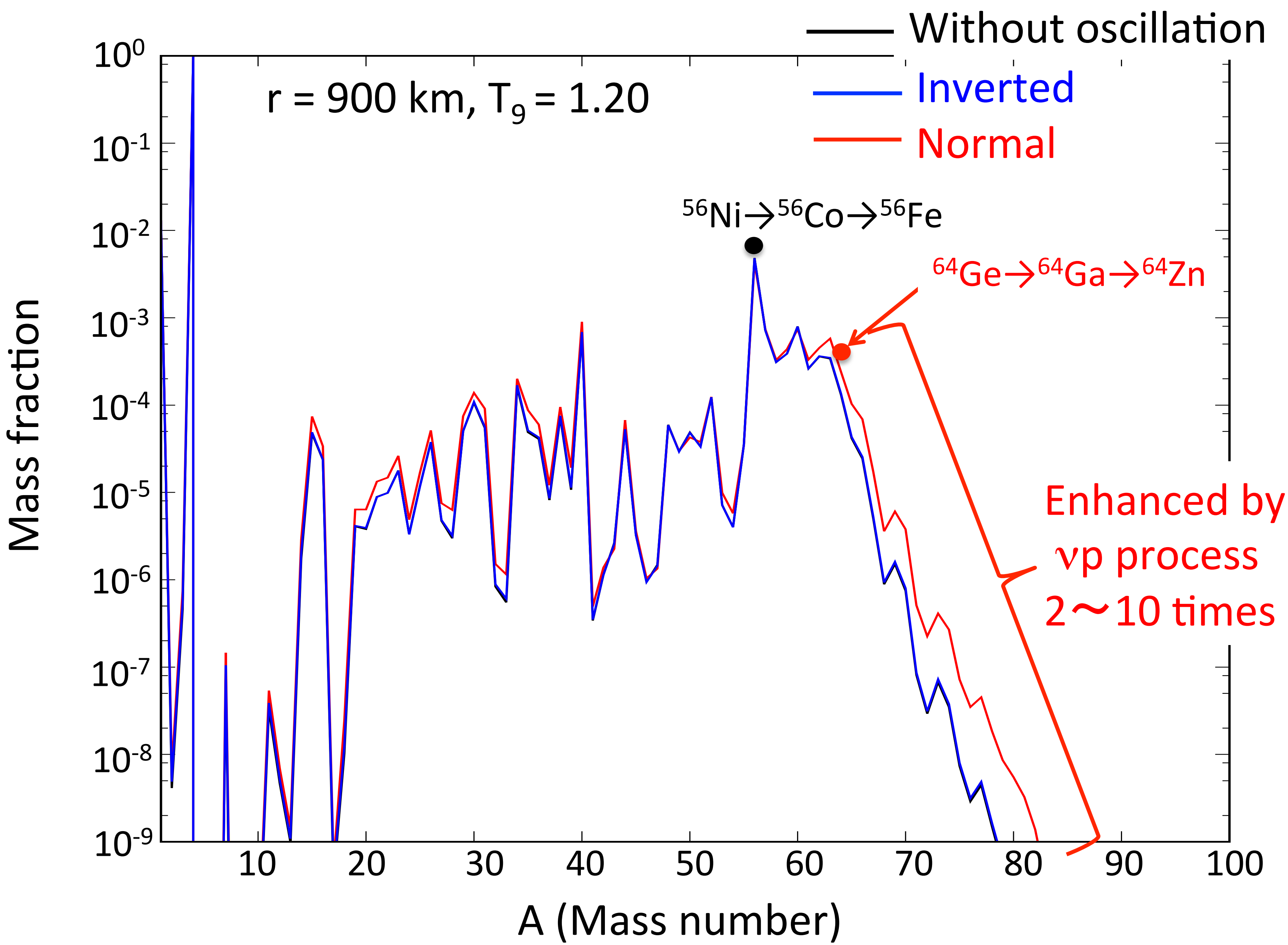
Mass fraction of nucleus



νp process and onset of oscillations



Final mass fraction



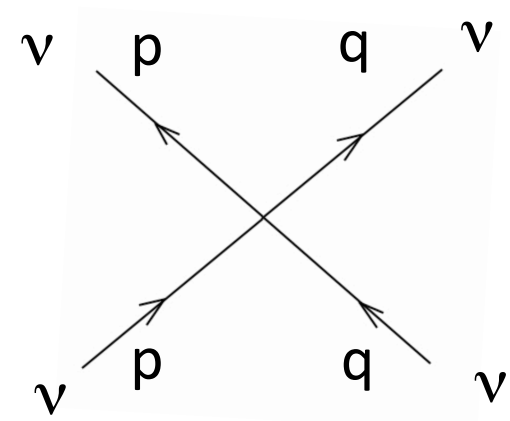
Future prospects

- Choose other trajectories and study oscillation effects on νp process elements

- Interpret oscillation phenomena analytically

- Beyond mean field

  Y. Pehlivan, et al., Phys. Rev. D, **84**, 065008, 2011



Summary

It seems that neutrino oscillations especially collective oscillations will play significant roles towards nucleosynthesis in core collapse supernovae

3 flavor collective oscillations were calculated and applied to the explosive nucleosynthesis.

In normal hierarchy, much free neutrons are created by collective oscillations before νp process, so abundance of p-nucleus are enhanced.

In inverted hierarchy, free neutrons are created by MSW effects but after νp process, so the effect of oscillations are negligible.