Light Sterile Neutrinos in Supernovae

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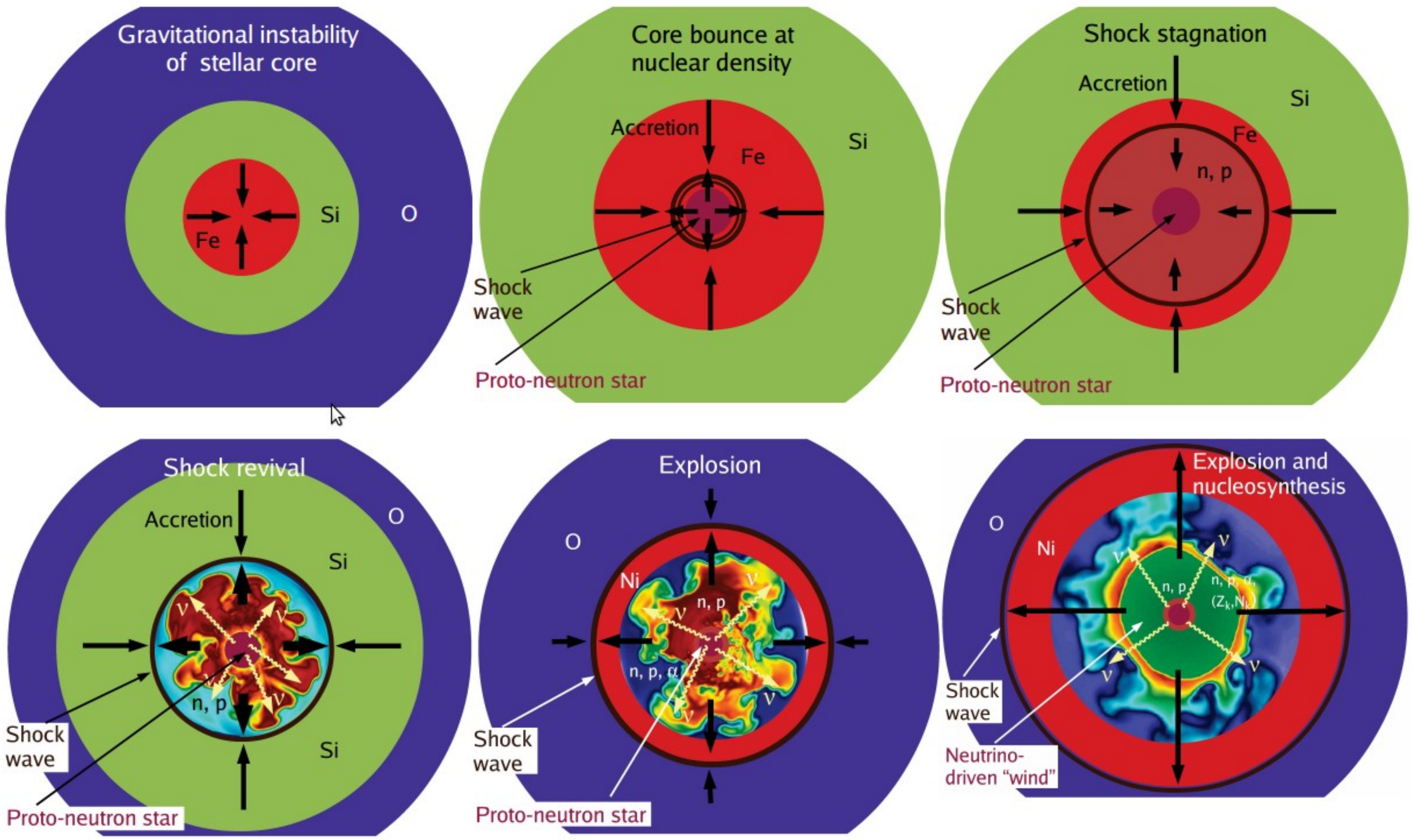
Core-collapse supernovae

(H.-Th. Janka, et al, PTEP 01A309 (2012))

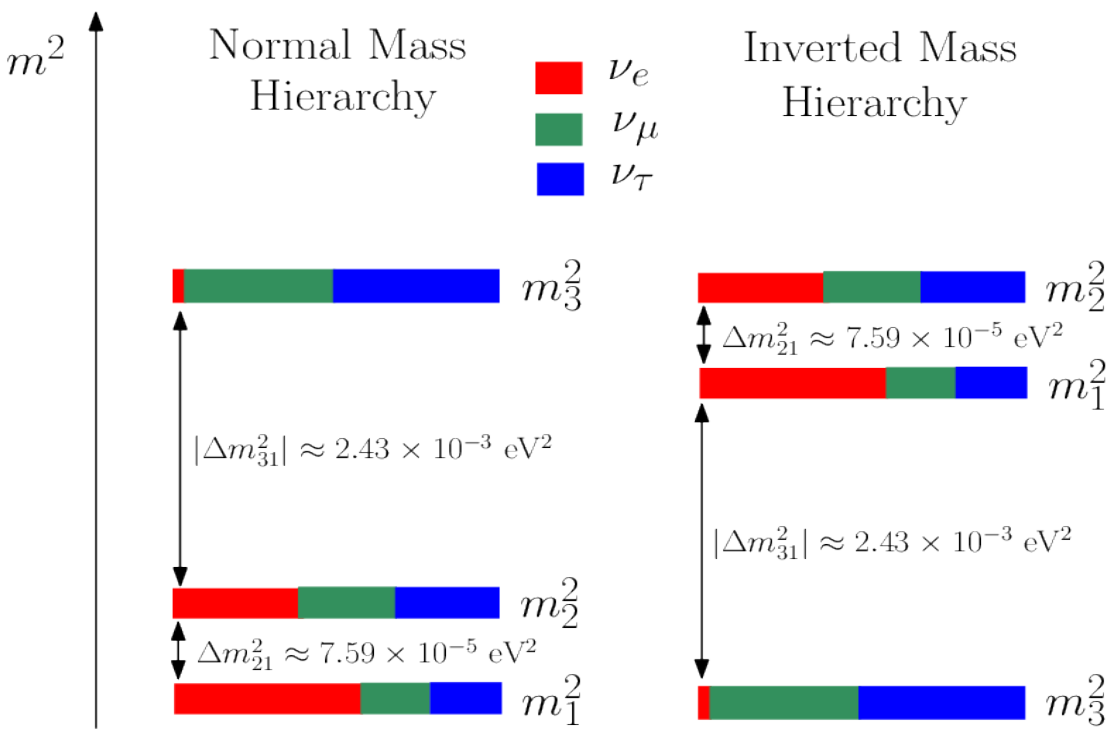


About ~10^{53} erg of the gravitational binding energy is carried away by ~10^{58} neutrinos on a time scale of 10 seconds with average energy ~ 10 MeV.

→ Delayed neutrino-heating mechanism for SN explosion
→ Neutrino-driven wind as a site of heavy element formation
→ Neutrino-induced nucleosynthesis in supernova envelopes
→ Neutrino signals as probes for physics of supernovae and properties of neutrinos

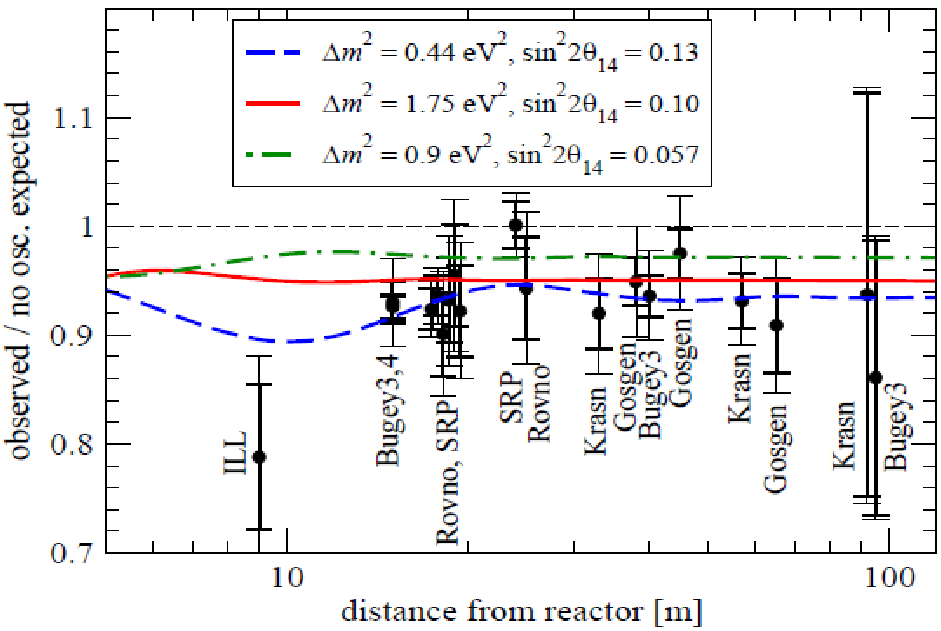
Neutrino mixing among active flavors

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}|\nu_1\rangle \\ e^{i\alpha_2/2}|\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

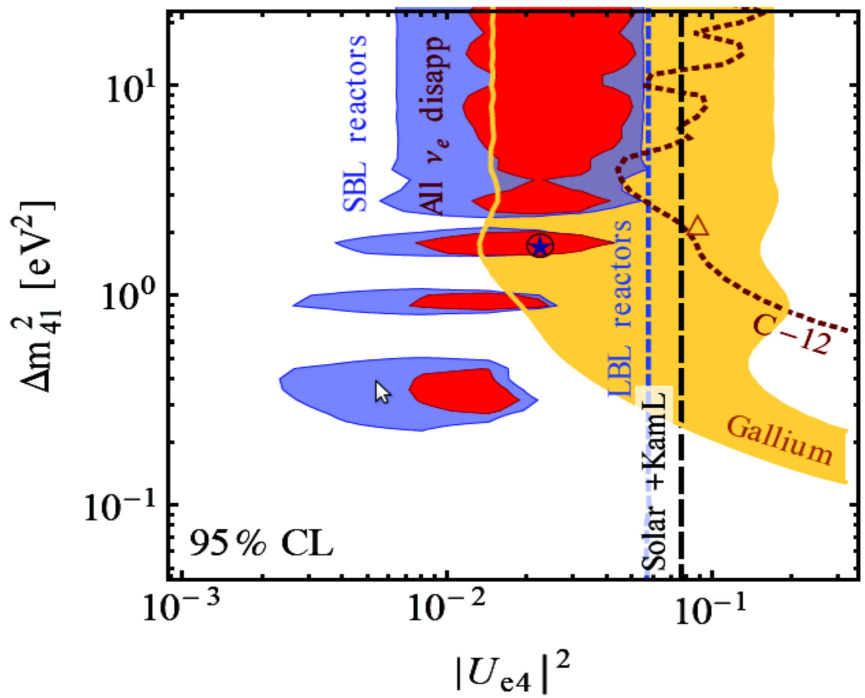


Collevtive neutrino oscillations in SN among active flavors are extremely complicated due to the non-linear and anisotropic nature.

eV sterile neutrinos?



(Kopp, Machado, Maltoni, Schwertz, JHEP05 (2013) 050)



The anomaly of electron antineutrino disappearance experiments from short-baseline reactors & Gallium solar neutrino experiments may be accounted for by introducing eV scale sterile neutrinos.

In 3+1 scheme : $P_{ee}^{\mathrm{SBL},3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m^2_{41}L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m^2_{41}L}{4E}$

$$\delta m^2_{14} \sim O(\mathrm{eV}^2), \quad \sin^2 2\theta_{14} = \sin^2 2\theta_{ee} \sim 0.1$$

Hints from different experiments/observations

- LSND, MiniBooNE

- Long-base line accelerator experiments

- Cosmology/BBN

- Solar Neutrinos

Role of eV sterile neutrinos in supernovae?

First pointed out in [Nunokawa, Peltoniemi, Rossi & Valle, PRD 56, 1704(1997)] that eV sterile neutrinos might have effects on shock-revival and electron fraction In the ejecta.

However, supernova models evolve substantially and the feedback on the electron f

Neutrino oscillations in medium

With two-flavor approximation and in the free-streaming regime, the neutrino flavor evolution is governed by the vacuum Hamiltonian + matter-induced Hamiltonian :

$$H_{\rm vac} = \frac{\delta m_{14}^2}{4E_\nu}\begin{bmatrix} -\cos 2\theta_{14} & \sin 2\theta_{14} \\ \sin 2\theta_{14} & \cos 2\theta_{14} \end{bmatrix}$$

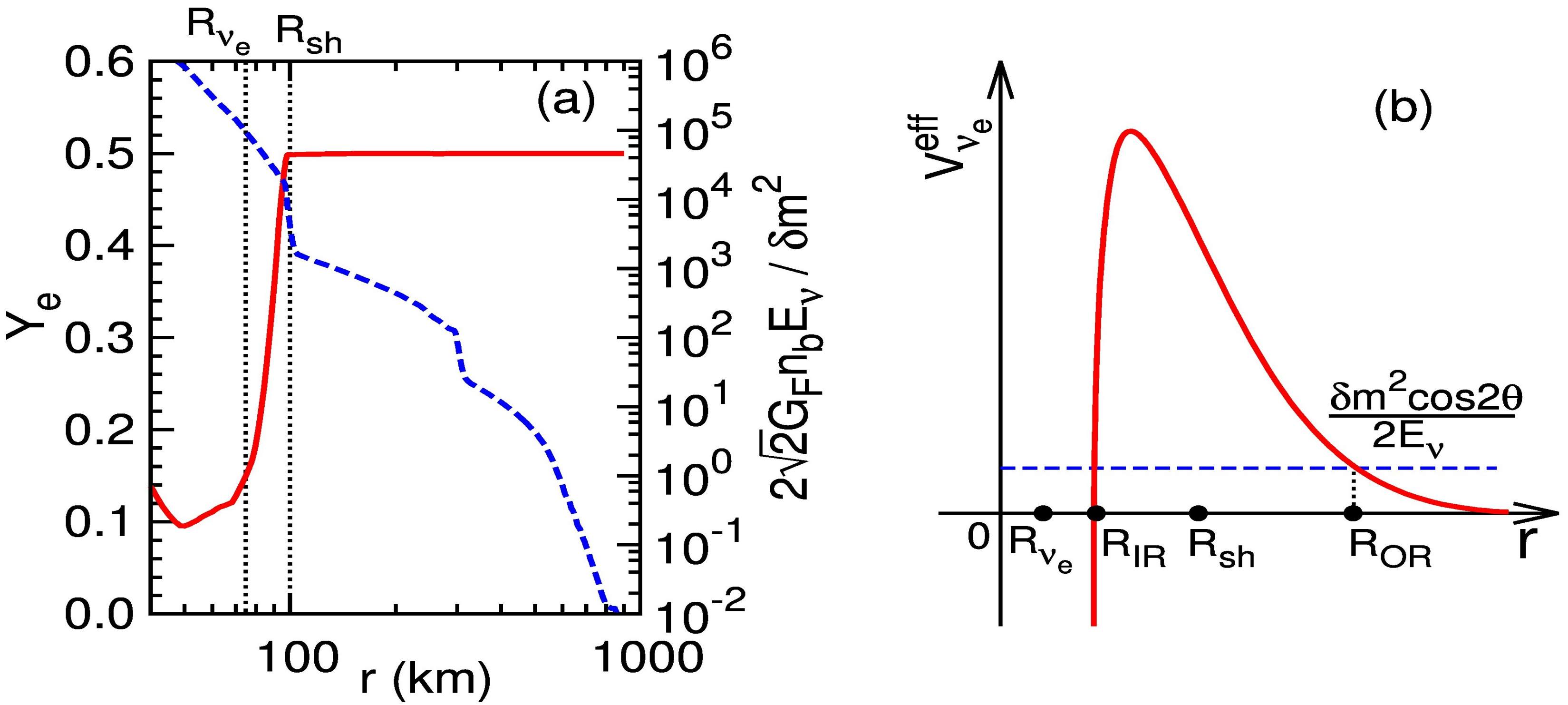
$$H_{\rm m} = \pm\frac{\sqrt{2}}{2}G_F n_b \left(Y_e - \frac{Y_n}{2}\right)\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$= \pm\frac{3\sqrt{2}}{4}G_F n_b \left(Y_e - \frac{1}{3}\right)\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

different from the MSW potential that for active flavors because of the neutral-current

=> MSW resonance : $\frac{\delta m_{14}^2}{4E_\nu}\cos 2\theta_{14} = \pm\frac{3\sqrt{2}}{4}G_F n_b \left(Y_e - \frac{1}{3}\right)$

Supernova Profiles



- Because of the deleptoniztion that occurs during the collapse and the shock break-out, the electron fraction Ye ~ 0.1 around the neutrinosphere such that active-sterile MSW resonance could occur between the neutrinosphere and the shock.

- Collective neutrino oscillations are suppressed because at IR, $\rho \sim 10^9 - 10^{11} \mathrm{g/cm}^3$ and $Y_e \gg Y_{\nu_e}$

MSW flavor transformation at the inner resonance

For neutrinos :

$$Y_e < \frac{1}{3}^+, \nu_L = \nu_e,\ \nu_H = \nu_s, \qquad Y_e > \frac{1}{3}^+, \nu_L = \nu_s,\ \nu_H = \nu_e$$

For antineutrinos :

$$Y_e < \frac{1}{3}^-, \bar{\nu}_L = \bar{\nu}_s,\ \bar{\nu}_H = \bar{\nu}_e, \qquad Y_e > \frac{1}{3}^-, \bar{\nu}_L = \bar{\nu}_e,\ \bar{\nu}_H = \bar{\nu}_s,$$

Electron (anti)neutrinos may be transformed to sterile (anti)neutrinos when they cross Ye~1/3.

MSW flavor transformation at the inner resonance

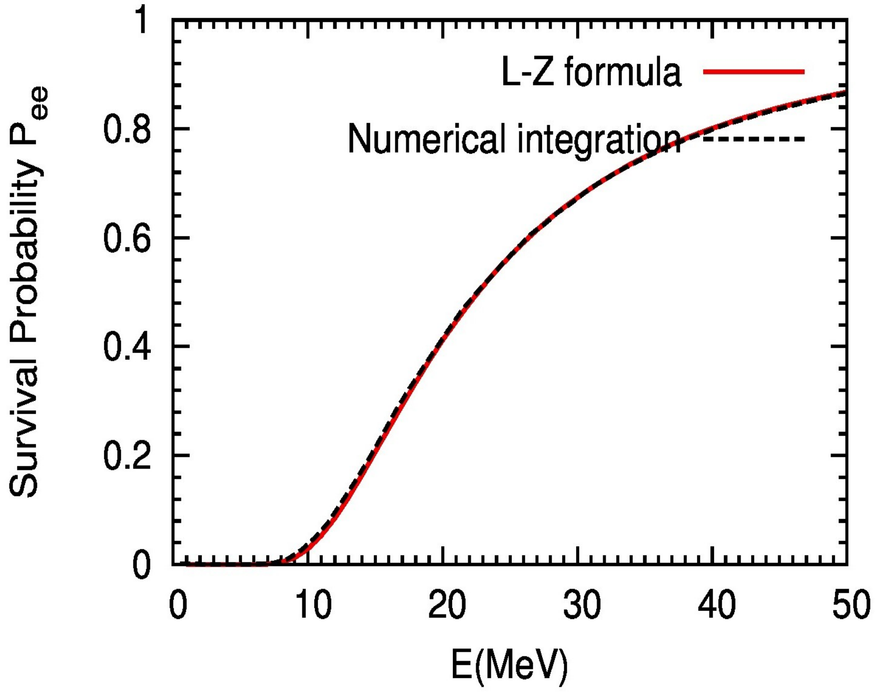
Landau-Zener survival probability :

$$P_{ee} = \exp\left(-\frac{\pi^2}{4}\frac{\Delta r}{L_{\rm osc}}\right),$$

The oscillation length at resonance :

$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m_s^2 \sin 2\theta_{14}},$$

$$\approx 45 \text{ m} \left(\frac{E_\nu}{10\text{MeV}}\right)\left(\frac{1.75\text{eV}^2}{\delta m_s^2}\right)\left(\frac{0.1^{1/2}}{\sin 2\theta}\right)$$



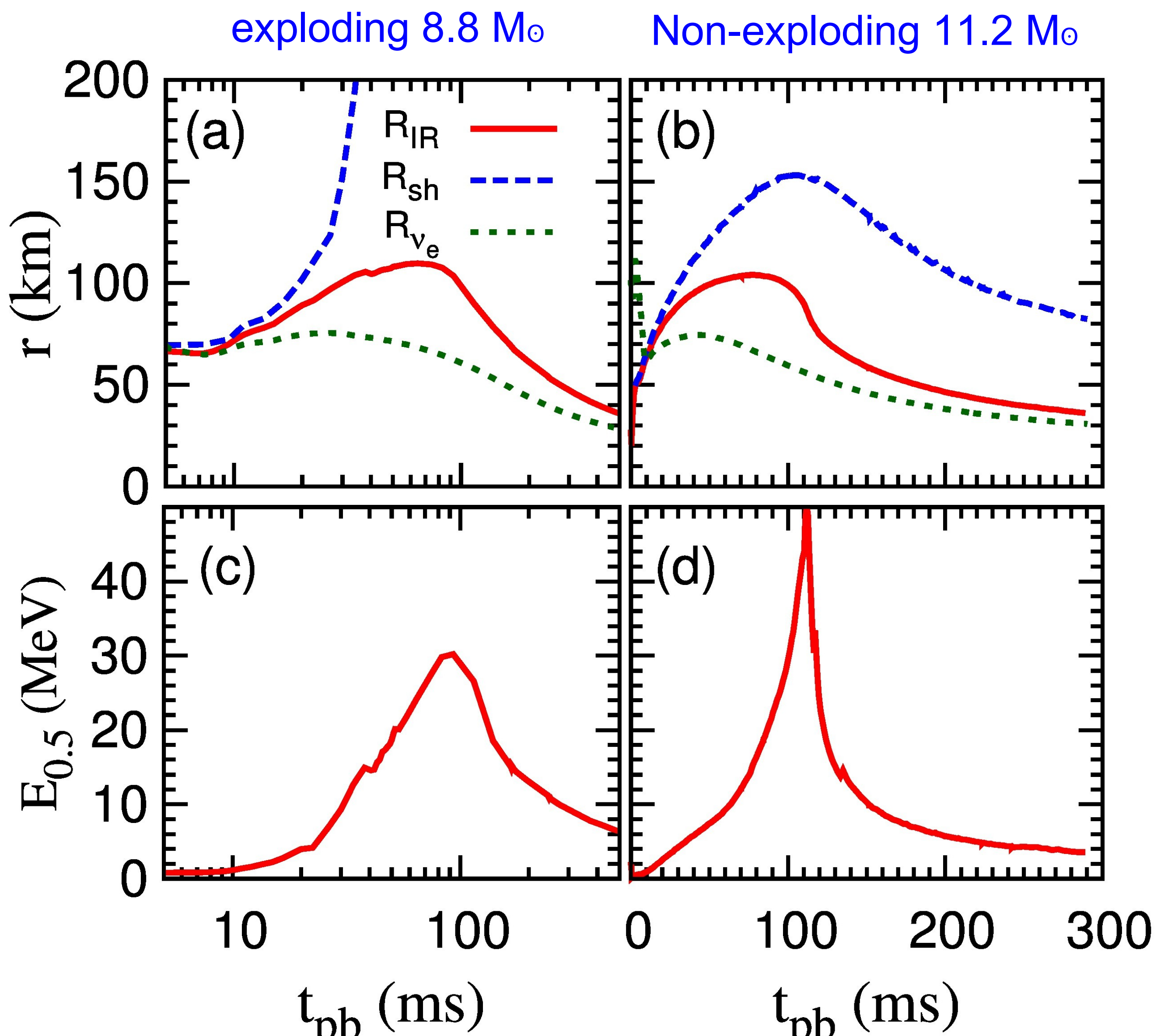
The resonant width :

$$\Delta r \approx 2\tan 2\theta_{14}\left|\frac{Y_e - 1/3}{dY_e/dr}\right|_{\rm res}$$

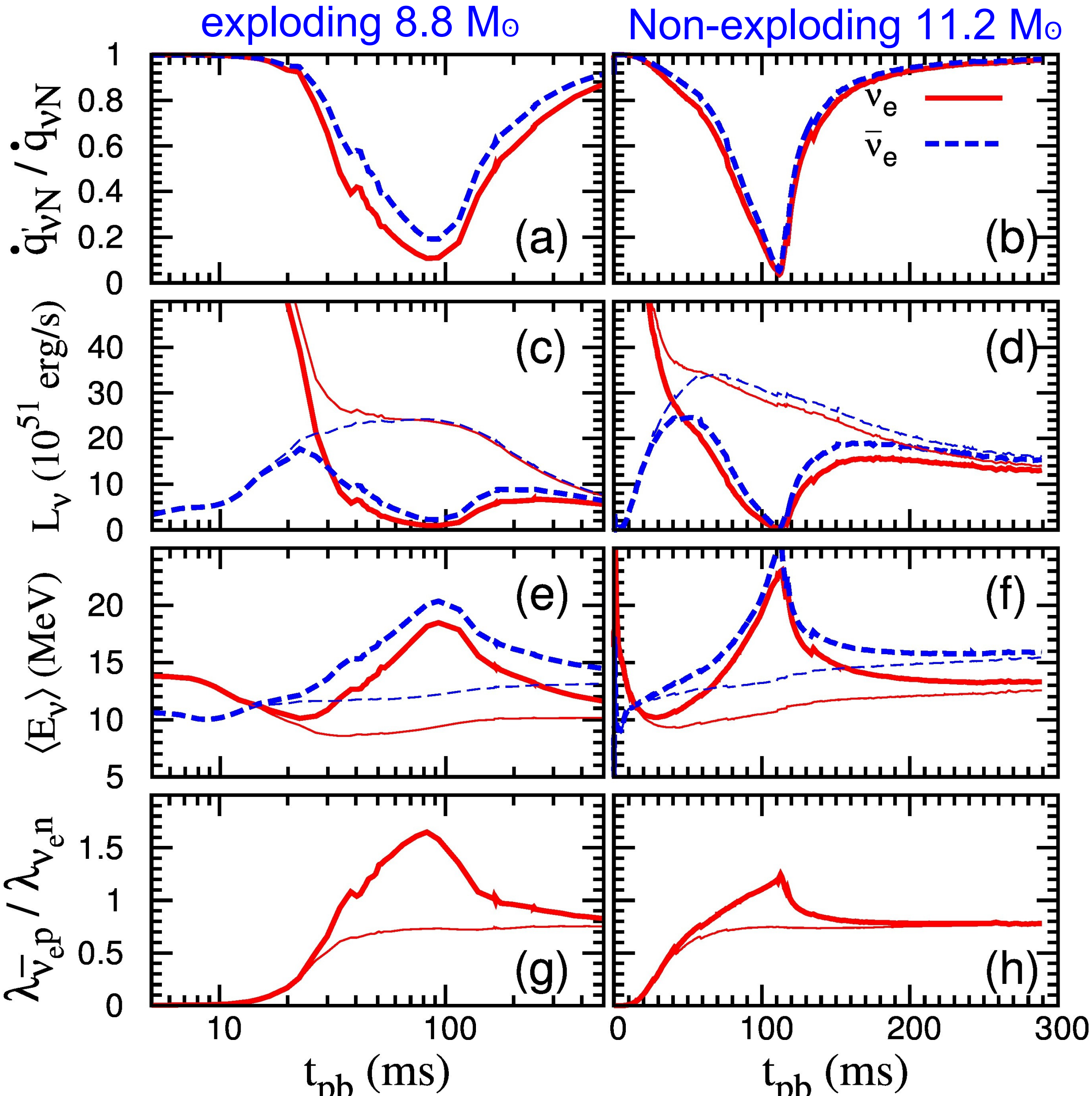
$$\approx 50 \text{ m}\left(\frac{0.1/10\text{km}}{dY_e/dr}\right)\left(\frac{10^9 g/cm^3}{\rho}\right)\left(\frac{10\text{MeV}}{E_\nu}\right)\left(\frac{\delta m_{14}^2}{1.75\text{eV}^2}\right)\left(\frac{\sin 2\theta_{14}}{0.1^{1/2}}\right)$$

Time evolution of R_{IR} and $E_{0.5}$

(MRW, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382)



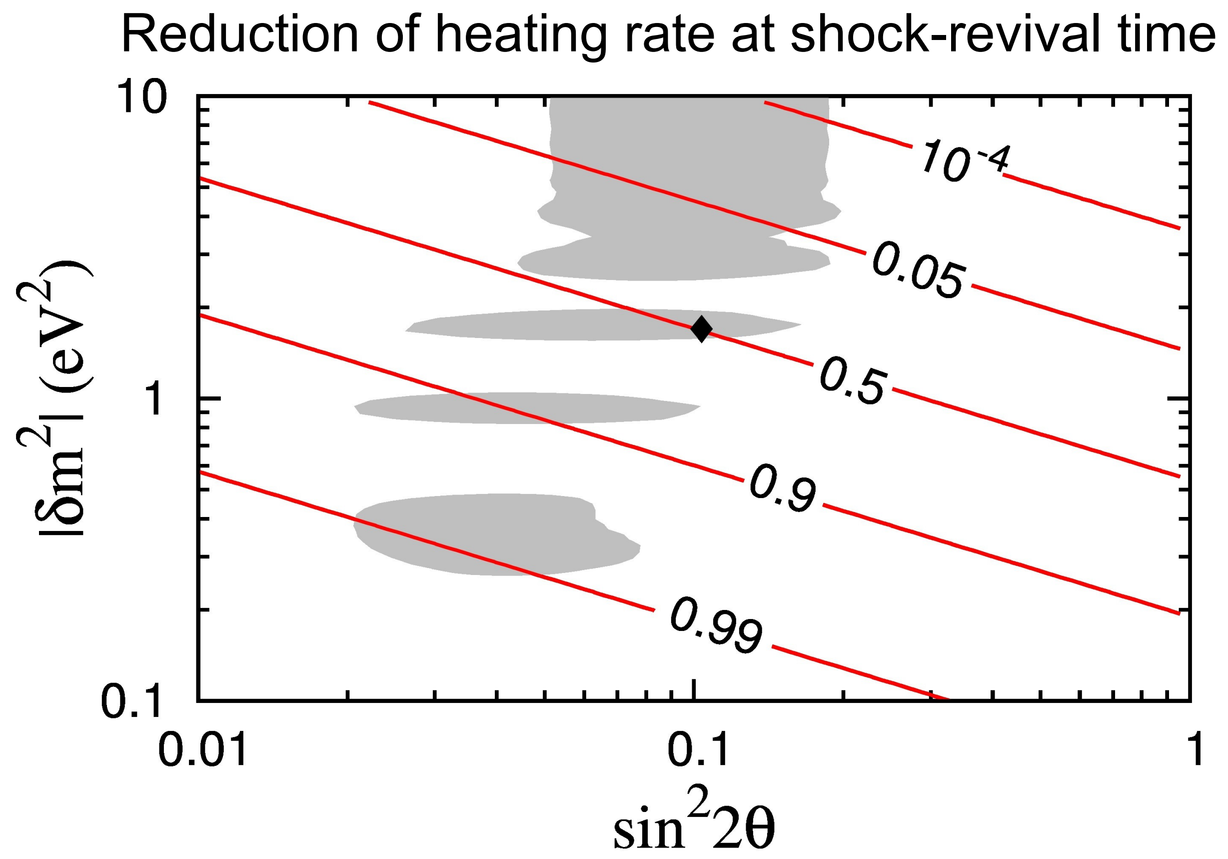
Physical consequences



(MRW, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382)

Dependence on Mixing parameters

(MRW, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382)



May supernova help constrainting the parameter space?

Feedback on Ye profile?

Since (1) Ye is determined by the competition of rates of electron/positron and electron (anti)neutrino captures :

$$\nu_e + n \rightleftharpoons p + e^-$$

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

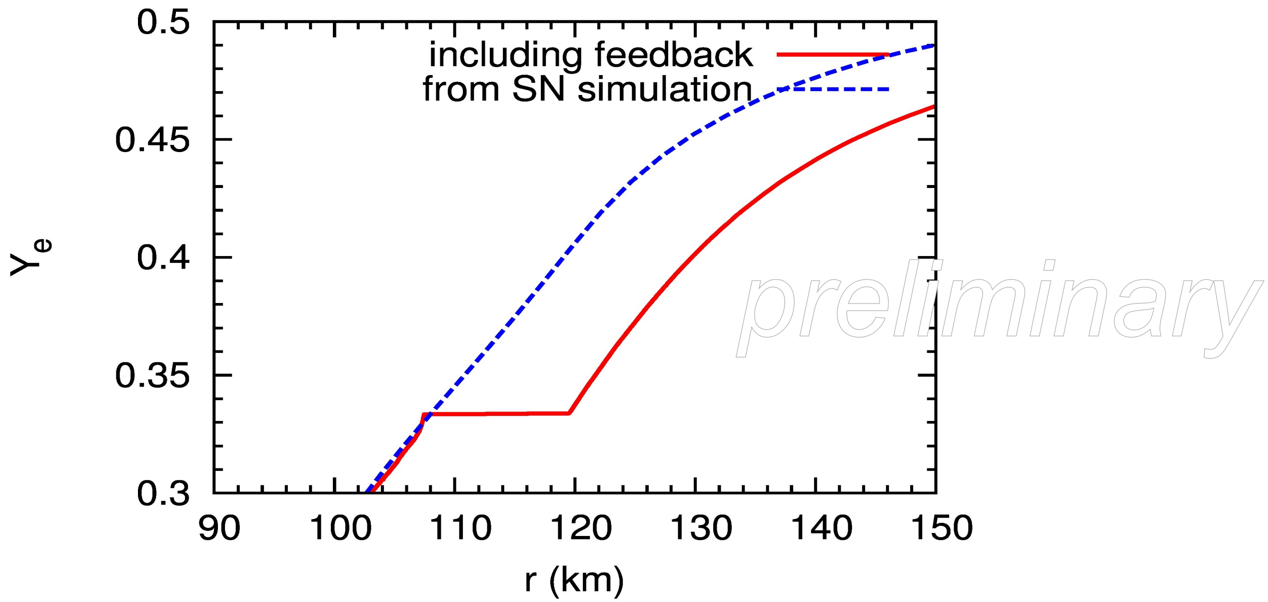
(2) electron (anti)neutrino capture rates are affected by the flavor oscillations which depends on Ye profiles

→ Need to evolve the Ye along with the active-sterile flavor transformation!

Feedback on Ye profile:

We follow the evolution of Ye for relevant mass shells, but assuming the hydrodynamics does not change.

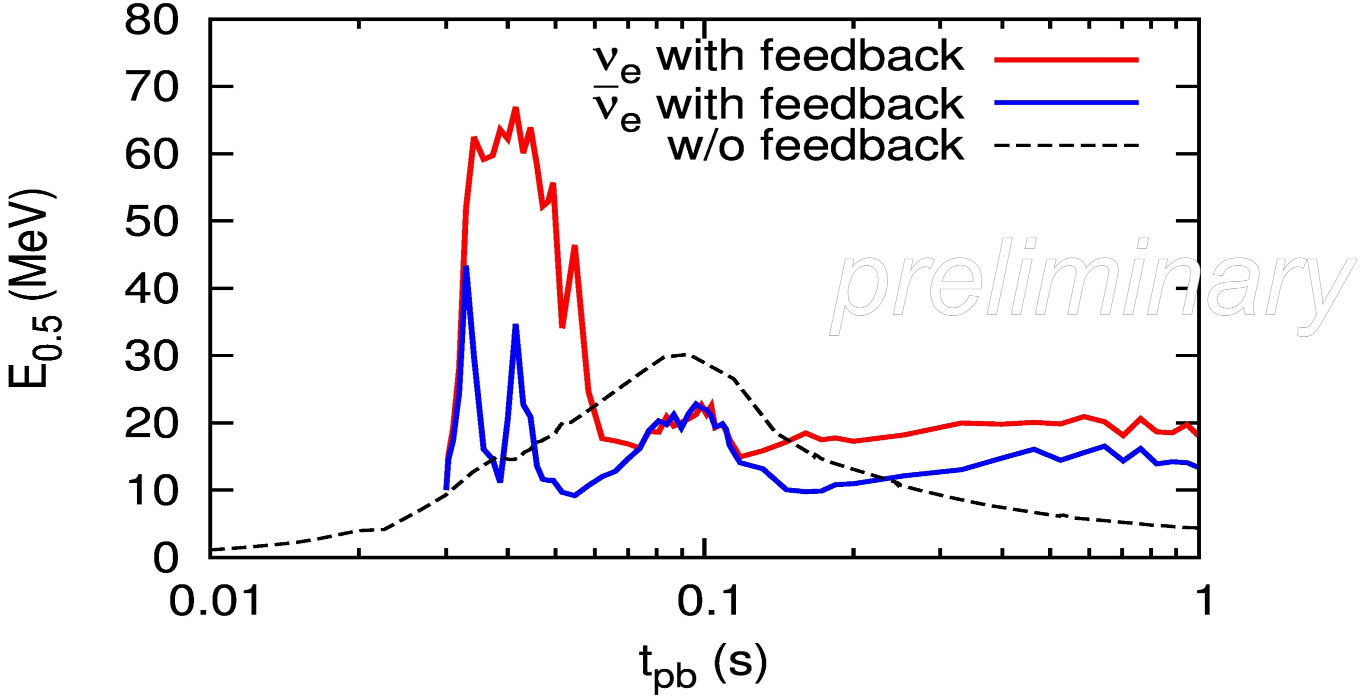
$$\frac{dY_e}{dt} = (\lambda_{\nu_e n} + \lambda_{e^+ n})Y_n - (\lambda_{\bar{\nu}_e p} + \lambda_{e^- p})Y_p$$



$$(-\dot{Y}_e)|_{r<r_{\rm IR}(\bar{\nu}_e)} < (-\dot{Y}_e)|_{r_{\rm IR}(\bar{\nu}_e)<r<r_{\rm IR}(\nu_e)} < (-\dot{Y}_e)|_{r_{\rm IR}(\nu_e)<r}$$

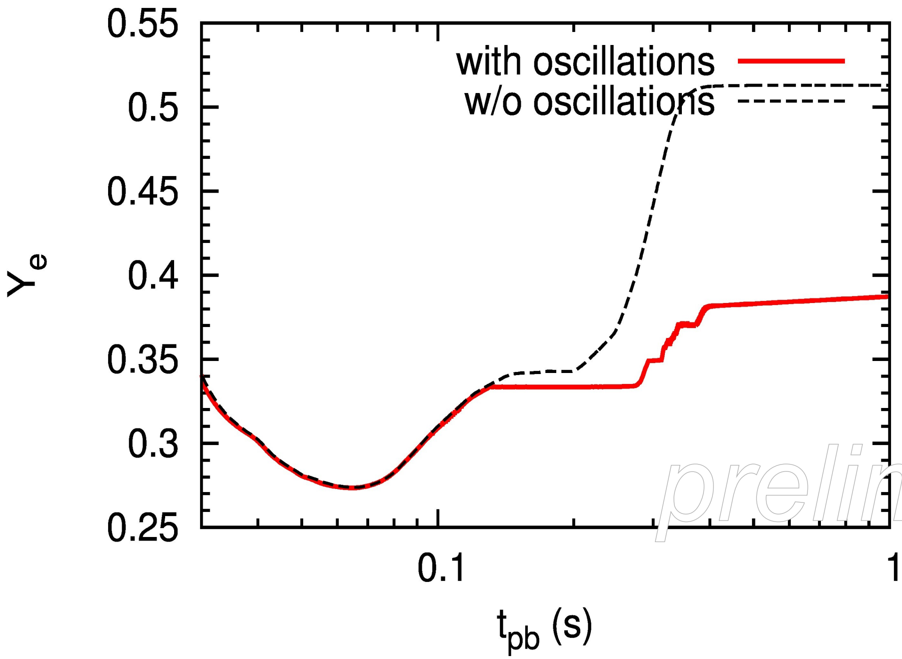
Effect on the oscillations

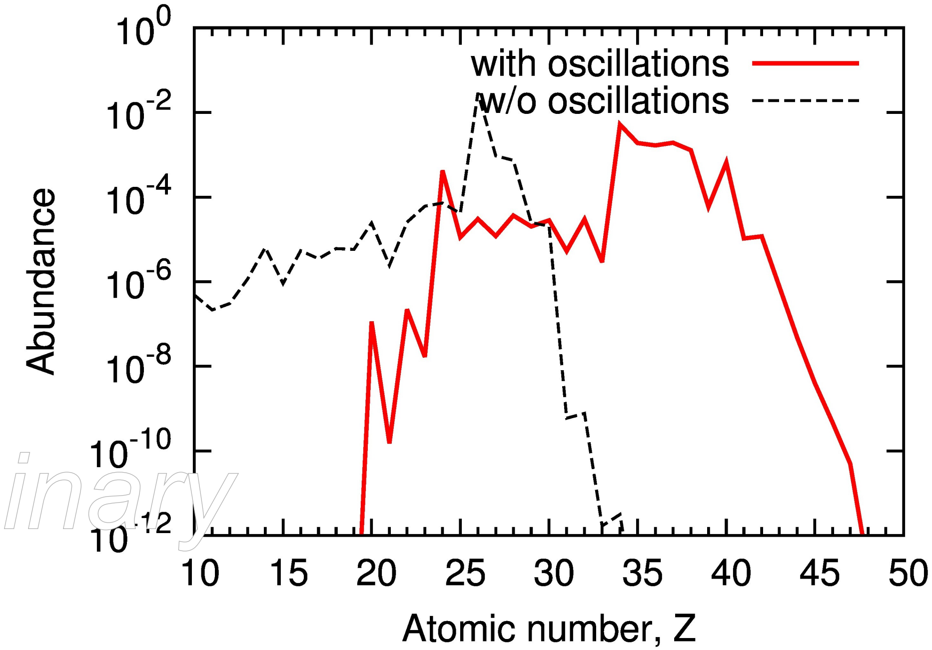
The formation of the Ye plateau breaks the degeneracy between neutrinos and antineutrinos and induces more flavor transformation in the shock expansion phase.



- Reduce the capture rates of electron neutrinos more than that of electron antineutrinos.
- Reduce the heating rates even more.

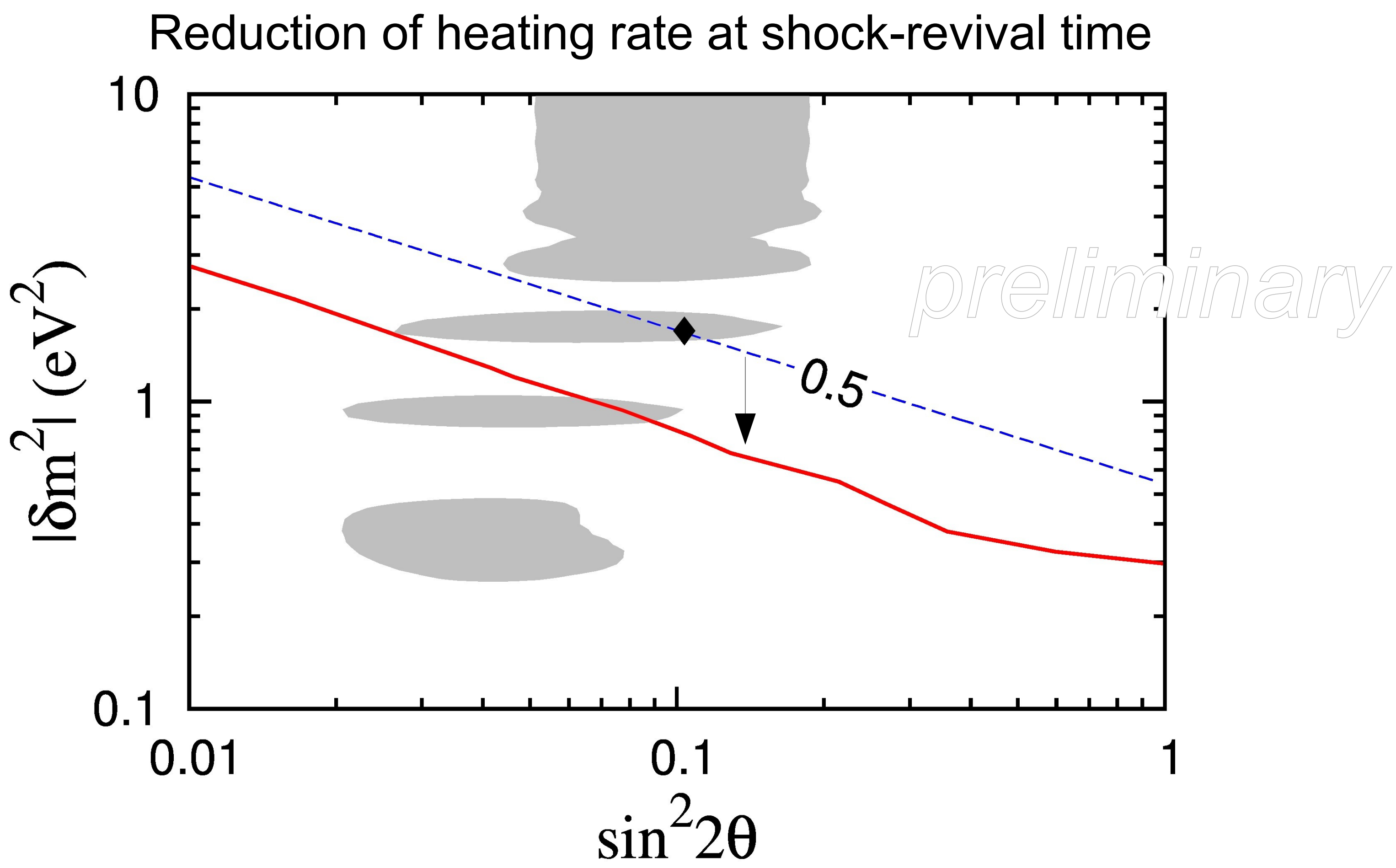
Effect on nucleosynthesis





- Ye in the ejecta is reduced from ~0.5 to ~0.4 !
- For the 8.8M⊙ O-Ne-Mg model, the main products of nucleosynthesis shift from the iron peak to Ba-Zr.

Effect on heating rates



Summary

- If light eV sterile neutrinos exist, active-sterile MSW flavor conversion in supernovae might happen between the neutrinosphere and the shock.

- The flavor conversion reduces the neutrino heating rates (dynamics) substantially and change the ratio of electron neutrino capture and electron antineutrino capture rates (nucleosynthesis).

- Including the feedback on Ye creates a plateau around Ye~1/3 and furthers enhance the effects.

- It would be interesting to include it in a supernova simulation to see if it could provide firm constraints on the parameter space of sterile neutrinos and study the signature in neutrino signals.