Alexander von Humboldt
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MAX-PLANCK-GESELLSCHAFT

Supernovae and sterile neutrinos

Irene Tamborra

von Humboldt Research Fellow at the MPI for Physics, Munich

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Outline

- ★ Why do we consider eV-mass sterile neutrinos in supernovae?
- ★ Neutrinos and electron fraction in electron-capture supernovae
- ★ Our results
- ★ Conclusions

This talk is based on work in progress with G.G. Raffelt and T.-H. Janka.

eV-mass sterile neutrinos

★ Reactor $\bar{\nu}_e$ spectra suggest the existence of eV-mass ν_s with mixing parameters $(\sin^2 2\theta, \Delta m_s^2) \simeq (0.14, 1.5~\mathrm{eV}^2)$.*

★ In a supernova, such parameters induce MSW $\nu_e - \nu_s$ conversions sensitively affecting the neutrino energy spectra.

★ A decrease of the ν_e flux by $\nu_e - \nu_s$ oscillations increases the neutron abundance and thus it can enable the r-nucleosynthesis (rapid neutron capture process generating elements with A >100).**

★ Using the new electron-capture supernova hydrodynamical simulations, we analyze (2 active+1 sterile) scenario with the anti-reactor mixing parameters.

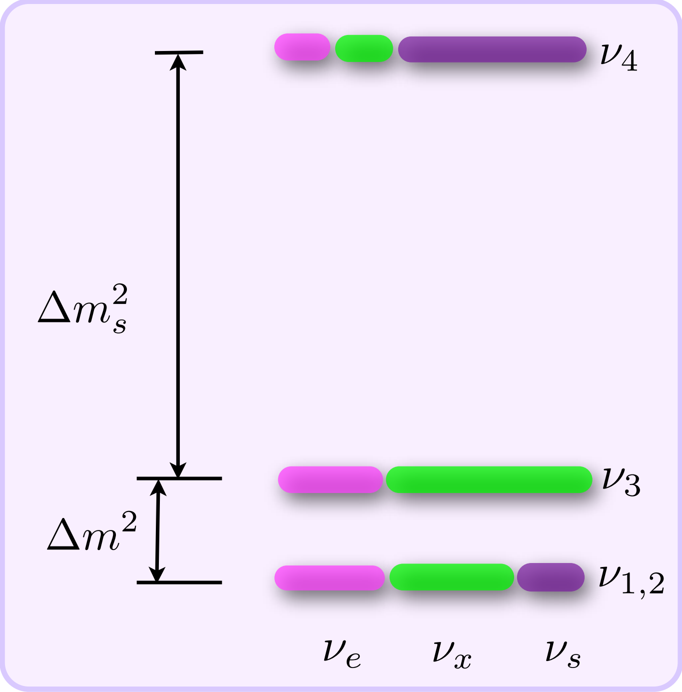
* Mention et al., arXiv: 1101.2755, Huber, arXiv: 1106.0687.
** See Fetter et al., Astrop. Phys. 18 (2003) 433, PRC 59 (1999) 2873 and references therein.

(2 active + 1 sterile) neutrino pattern

We neglect the solar mass difference with respect to the other two and we discuss the evolution of **2 active + 1 sterile families**. ν_x is the linear combination of ν_μ and ν_τ.

"sterile" mass difference →

"atmospheric" mass difference →

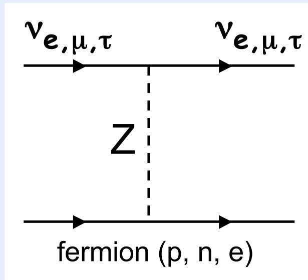


$$\delta m^2_{\rm atm} = 2 \times 10^{-3}\ {\rm eV}^2 \qquad \sin^2 2\theta_{14} = 0.165$$
$$\delta m^2_{\rm ste} = 2.35\ {\rm eV}^2 \qquad \sin^2 \theta_{13} = 10^{-2}$$

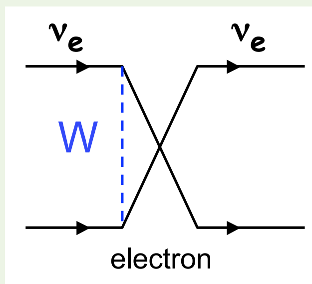
Mass and mixing parameters

Neutrino interactions

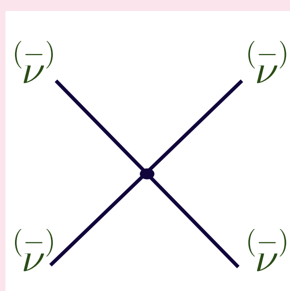
Active neutrinos interact with matter and among themselves...



Neutral current (NC) interactions with matter background



e-flavor has charged current (CC) interactions too



$\nu - \nu$ interactions

Neutrino flavor evolution

We solve the evolution equation for each energy mode E of neutrinos and antineutrinos

$$i\dot{\boldsymbol{\rho}}_E = [\mathbf{H}_E, \boldsymbol{\rho}_E]$$
$$i\dot{\overline{\boldsymbol{\rho}}}_E = [\overline{\mathbf{H}}_E, \overline{\boldsymbol{\rho}}_E]$$

with initial conditions $\boldsymbol{\rho}_E = \mathrm{diag}(n_e, n_x, 0)$ and $\overline{\boldsymbol{\rho}}_E = \mathrm{diag}(\bar{n}_e, \bar{n}_x, 0)$.

The Hamiltonian for each mode is made up by three terms

$$\mathbf{H}_E = \mathbf{H}_E^{\mathrm{vac}} + \mathbf{H}_E^{\lambda} + \mathbf{H}_E^{\nu\nu}$$

vacuum term

$$\mathbf{H}_E^{\mathrm{vac}} = U \mathrm{diag}\left(-\frac{\omega_s}{2}, +\frac{\omega_s}{2}, \omega_a\right) U^\dagger$$

collective term

$$\mathbf{H}_E^{\nu\nu} = \sqrt{2} G_F \int dE' \,(1 - \cos\theta_{EE'})\,(\boldsymbol{\rho}_{E'} - \overline{\boldsymbol{\rho}}_{E'})_{\mathrm{aa}}{}^{*}$$

matter term

$$\mathbf{H}^{\lambda} = \sqrt{2} G_{\mathrm{F}}\, \mathrm{diag}(N_e - \frac{N_n}{2}, -\frac{N_n}{2}, 0)$$

* Raffelt & Sigl, Nucl. Phys. B 406 (1993) 423.

Electron fraction

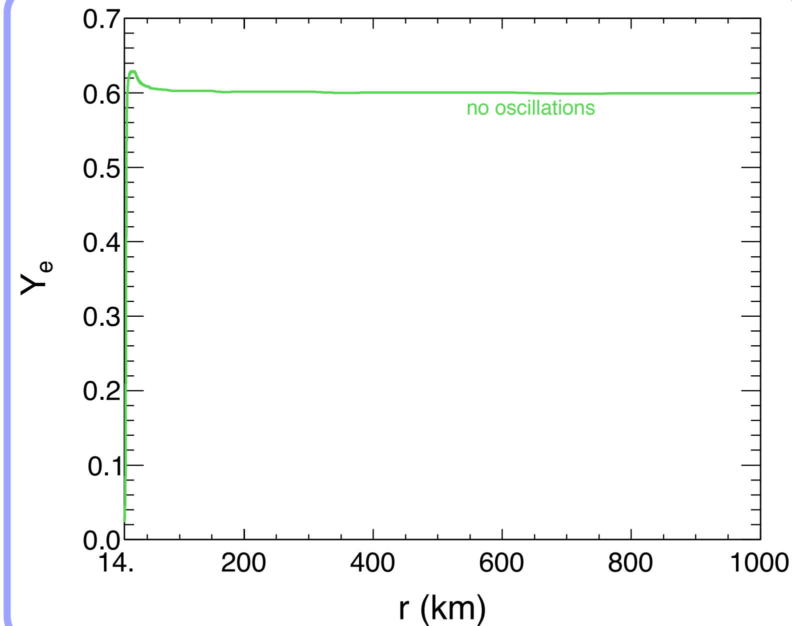
A hot problem in astrophysics is the location of the r-process nucleosynthesis.

Is the neutrino-driven matter outflow a good candidate site for the r-process nucleosynthesis in an electron-capture supernova?

To answer to this question, let's consider the evolution of the electron abundance:

$$Y_e(r) = \frac{N_e(r)}{N_e(r) + N_n(r)}$$

with $N_e(r)$ and $N_n(r)$ the effective electron and neutron densities.



$Y_e < 0.5$ ⟺ more n than p ⇒ r-process

Which is the impact of active-sterile oscillations on the electron abundance?

Electron fraction evolution

The electron abundance is set by the competition between the rates of the following neutrino and antineutrino capture on free nucleons

$$\begin{aligned} \nu_e + n \rightarrow p + e^- \\ \bar{\nu}_e + p \rightarrow n + e^+ \end{aligned}$$

and the associated reversed processes.

The electron abundance rate of change in an outflowing mass element may be written as

$$\frac{dY_e}{dt} = v(r)\frac{dY_e}{dr} \simeq (\lambda_{\nu_e} + \lambda_{e^+})Y_n^f - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p^f$$

where $v(r)$ is the velocity of the outflowing mass element, t is the time parameter, λ_α is the forward rate of each process, and $Y^f_{n\ (p)}$ is the fraction of unbounded neutrons (protons).

The neutrino scattering rates are functions of the neutrino fluxes and then flavor oscillations cannot be neglected. λ_e is a function of the electron temperature and of the electron chemical potential.

The feedback mechanism

The effective energy difference between two flavors is relevant for the oscillation of one flavor into the other one. In particular, for $\nu_e - \nu_s$ oscillations, we have to consider the NC+CC matter contribution (as a function of N_e and N_n) and the neutrino background one

$$\lambda_{\mathrm{es}} = \sqrt{2} G_F \left[n_b \left(\frac{3}{2} Y_e - \frac{1}{2} \right) + 2(N_{\nu_e} - \overline{N}_{\nu_e}) + (N_x - \overline{N}_{\nu_x}) \right]$$

NC+CC matter contribution

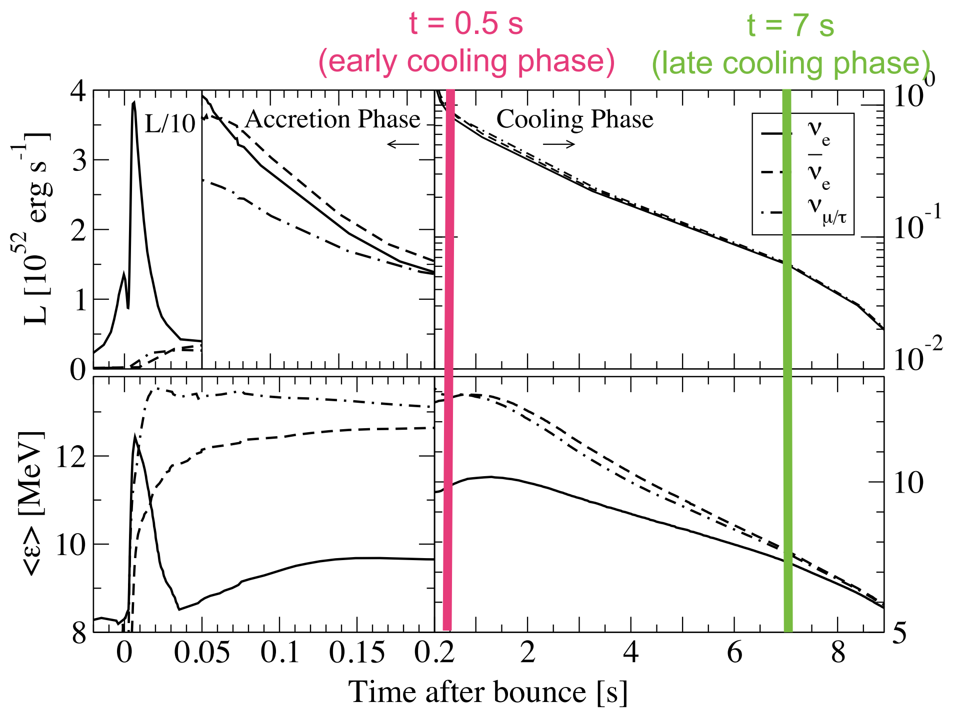
neutrino contribution

with n_b is the baryon density, N_ν is the effective neutrino density.

Neutrino oscillations are affected by Y_e and, at the same time, Y_e is affected by flavor oscillations.

Reference electron-capture supernova

We discuss two representative times of the cooling phase extracted by an exploding 1D electron-capture supernova simulation.*



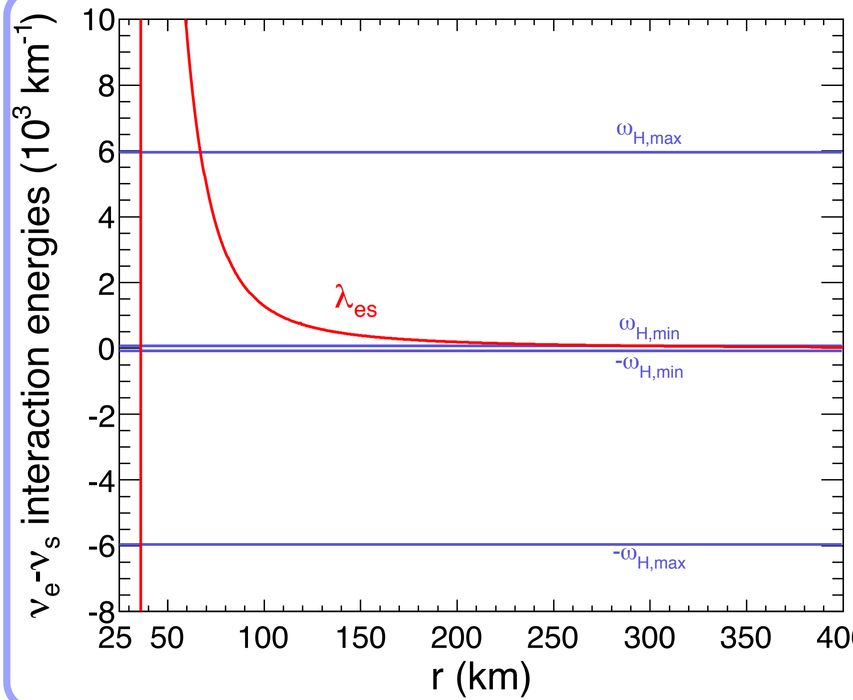
t	R_ν	L_e	$L_{\bar{e}}$	L_x	$\langle E_e\rangle$	$\langle E_{\bar{e}}\rangle$	$\langle E_x\rangle$	α_e	$\alpha_{\bar{e}}$	α_x	Y_e
0.5	25	9.5	10.06	10.8	16.8	18.14	18.3	2.9	3.	2.8	5.47×10^{-2}
7	14.5	1	0.99	1.04	12.4	11.9	11.8	2.6	2.3	2.4	2.33×10^{-2}

Table 1. Reference neutrino-sphere radii R_ν in km (assumed equal for all the different flavors for sake of simplicity), luminosities L_β (in units of 10^{51} erg/s), average energies $\langle E_\beta\rangle$ (in MeV), and the factor α_β for two different post-bounce times t (in seconds) and for each flavor ν_β (with $\beta = e, \bar{e}, x$).

Reference supernova inputs

* Huedepohl et al., PRL 104 (2010) 251101.

Our results: early cooling (t = 0.5 s)

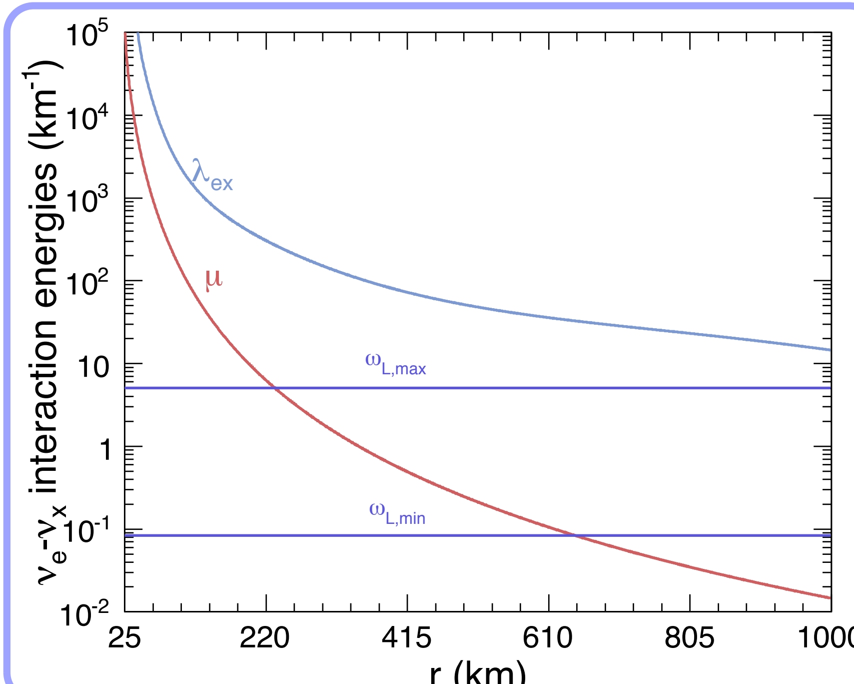


Dynamical $\nu_e - \nu_s$ energy difference

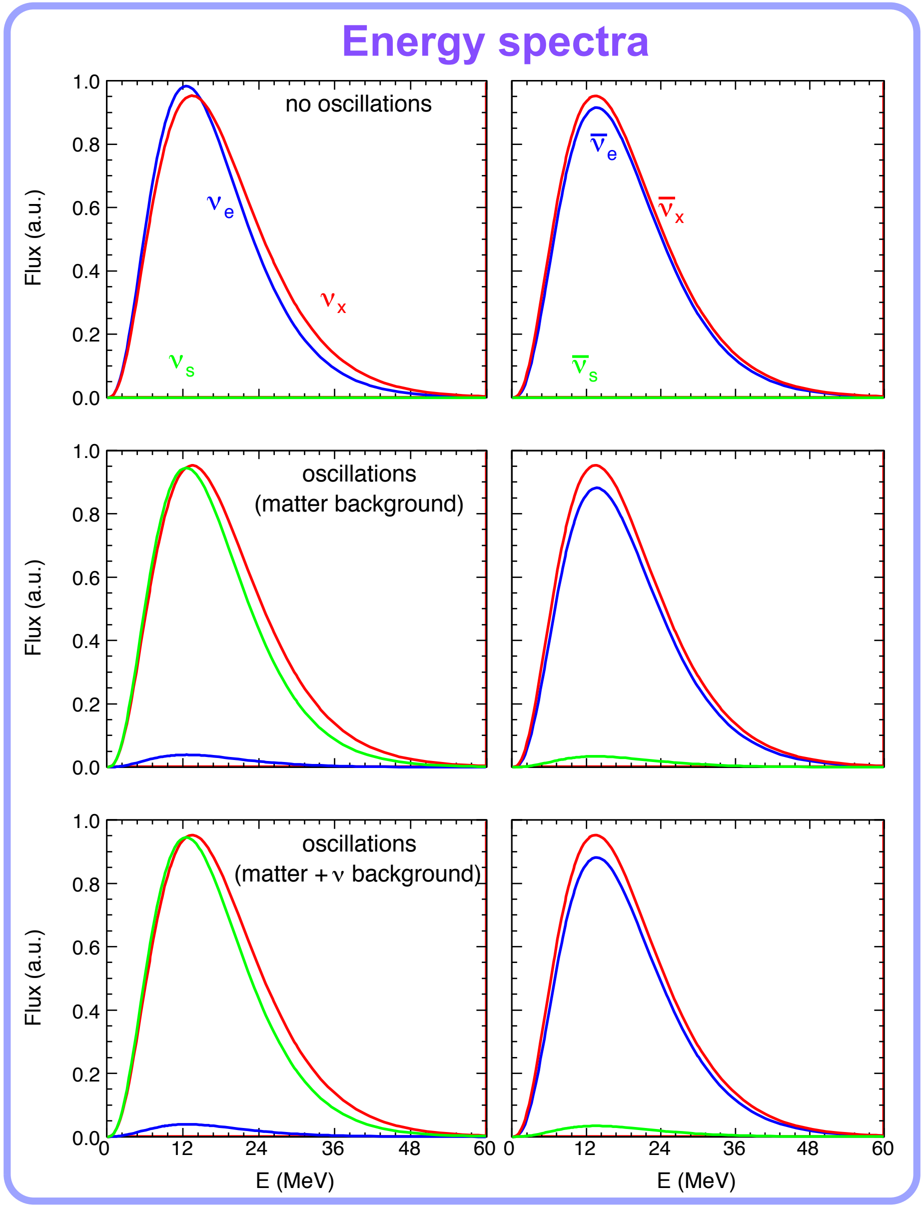
A non-adiabatic MSW resonance for both ν and $\bar{\nu}$ occurs close to the ν-sphere. At large radii, only neutrinos go towards a second adiabatic resonance.

Dynamical $\nu_e - \nu_x$ energy difference

The matter potential dominates on the $\nu - \nu$ potential. Self-interactions play a sub-leading role.



Our results: early cooling (t = 0.5 s)



no oscillations

oscillations (matter background)

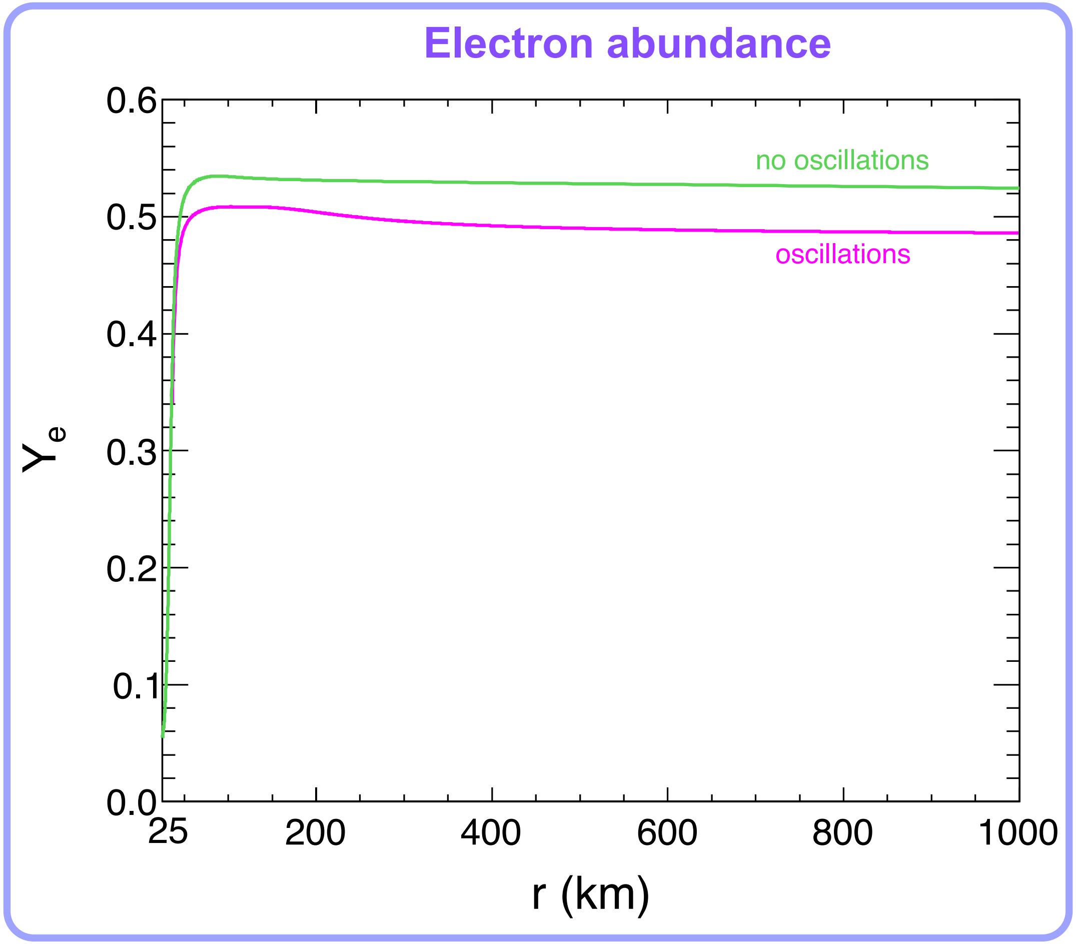
The MSW flavor conversion is responsible for the disappearance of ν_e in favor of ν_s.
Antineutrinos are almost unchanged.

oscillations (matter+neutrino background)

The neutrino background is not responsible for any further flavor conversion.

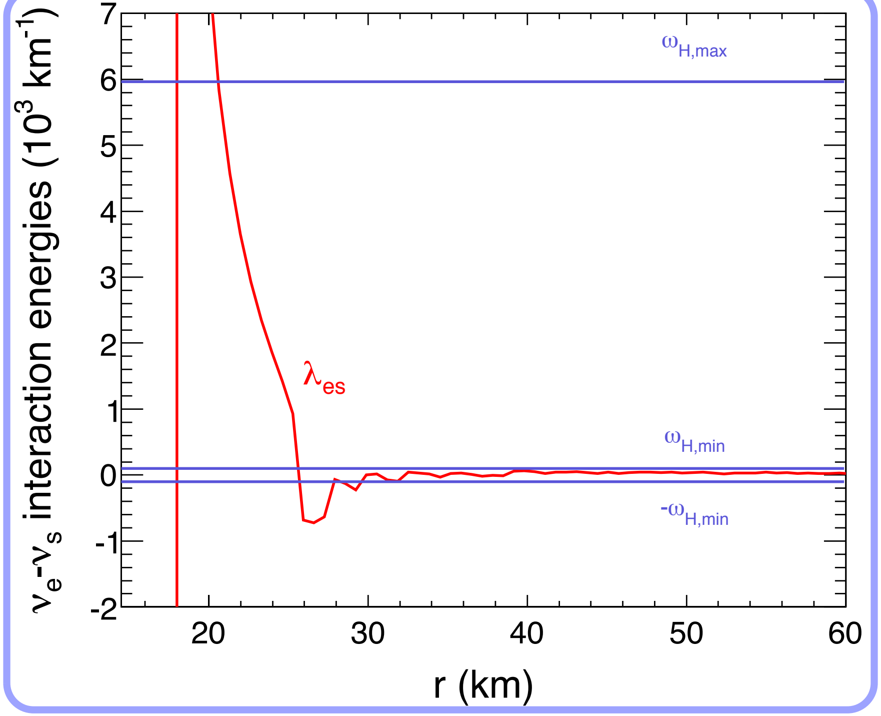
Our results: early cooling (t = 0.5 s)

less ν_e → more n → Y_e decreases



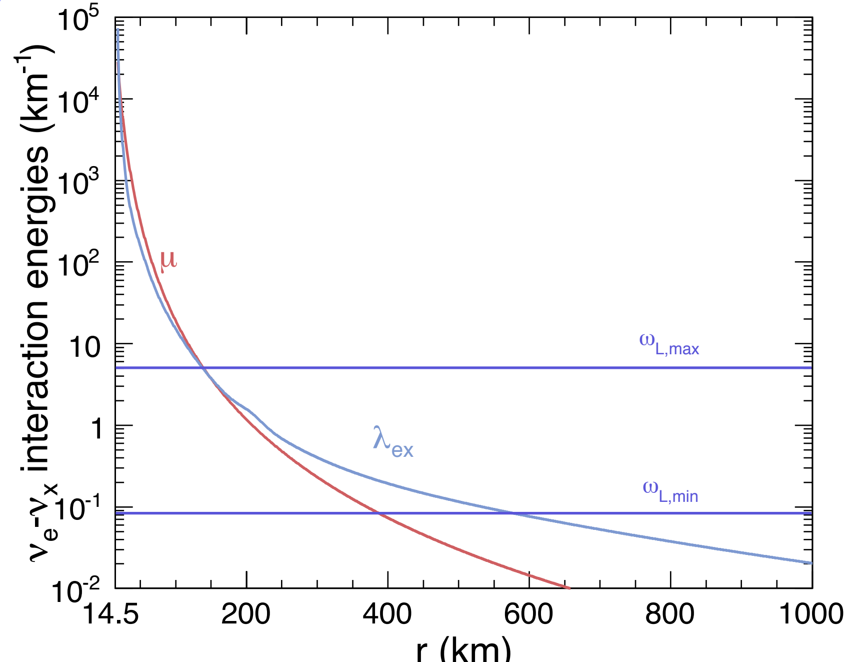
The production of sterile neutrinos determines an environment slightly rich in neutrons ($Y_e < 0.5$) with respect to the case without neutrino oscillation feedback.

Our results: late cooling (t = 7 s)



Dynamical $\nu_e - \nu_s$ energy difference

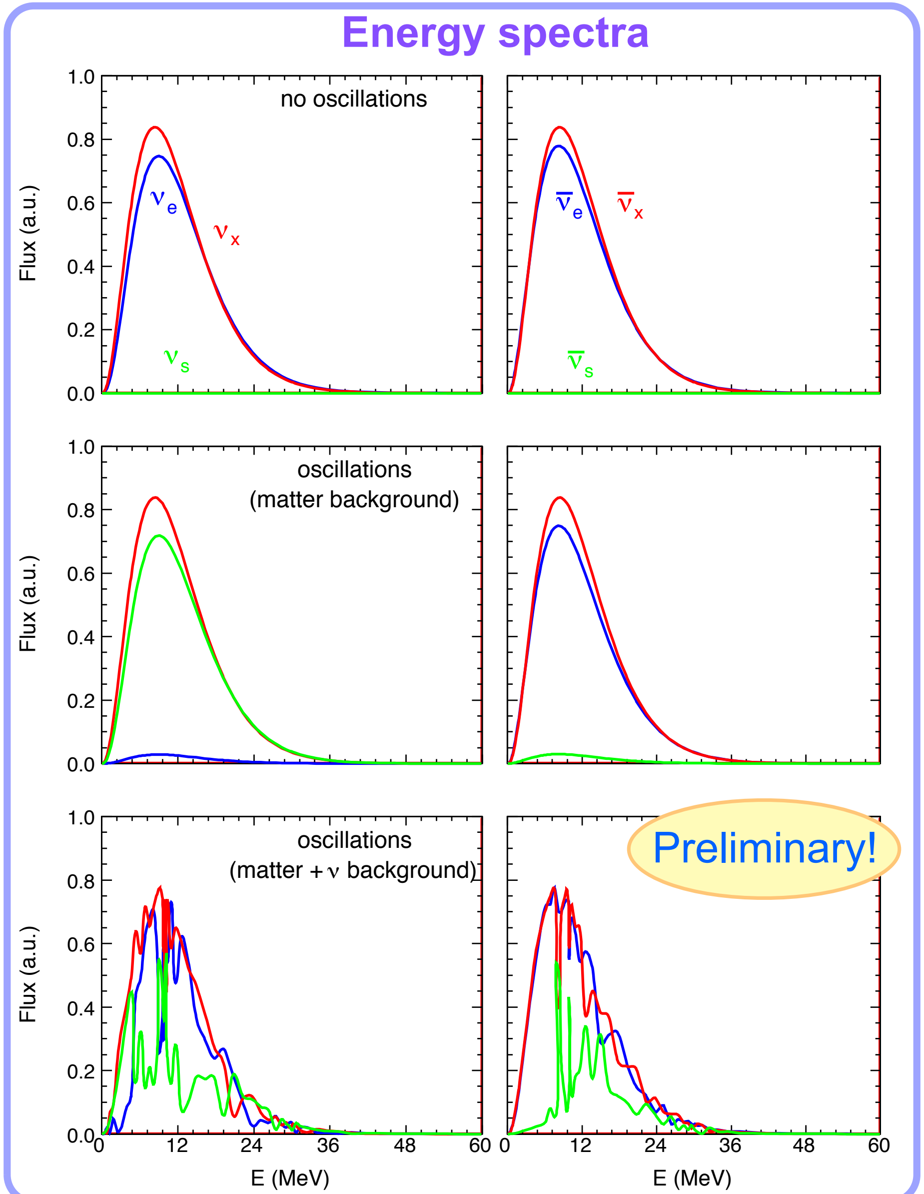
A non-adiabatic MSW resonance for both neutrinos and antineutrinos is occurring close to the neutrino-sphere. At large radii, neutrinos go towards a second adiabatic resonance and only few antineutrino energy modes.



Dynamical $\nu_e - \nu_x$ energy difference

The matter potential is of the same order of the $\nu - \nu$ potential. Therefore self-interactions play an important role.

Our results: late cooling (t = 7 s)



no oscillations

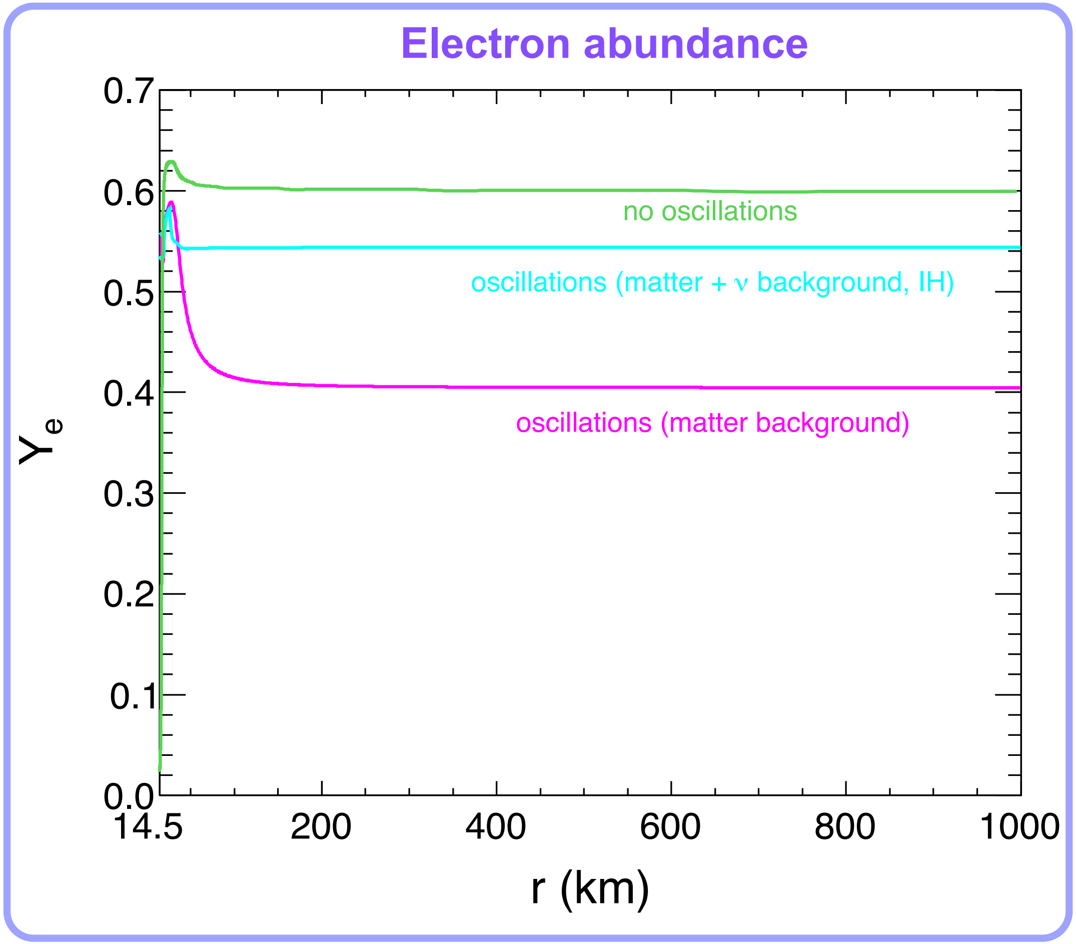
oscillations (matter background)

The MSW flavor conversion is responsible for the disappearance of ν_e in favor of ν_s.
Antineutrinos are almost unchanged.

oscillations (matter+neutrino background)

The neutrino background is responsible for repopulating the ν_e flux and averaging ν_e and ν_x fluxes.
The oscillating potential induces a parametric resonance and wiggles in the energy spectra (work in progress).

Our results: late cooling (t = 7 s)



The MSW resonance is responsible for inducing an environment rich in neutrons that might enable the r-process.

The neutrino background raises up the active neutrino abundance and it is responsible for an higher value of the electron abundance. **Sterile neutrinos cannot be responsible for enabling the r-process**.

Conclusions

★ Active-sterile conversions affect the neutrino fluxes and the electron abundance.

★ Early cooling phase: MSW conversions are responsible for the disappearance of ν_e in favor of ν_s.

★ Late cooling phase: neutrino background significantly contributes and it is responsible for a suppression of the $\nu_e - \nu_s$ MSW conversion.

★ The next supernova explosion could be a benchmark for testing the existence of sterile neutrinos.

★ The presence of sterile neutrinos lowers the value of Y_e although not enough to enable the r-process. Sterile neutrinos could also affect other aspects of nucleosynthesis physics.


Waiting for the next supernova explosion...thank you for your attention!

Back-up slides

Forward rates

Neutrino forward rates*

$$\lambda_{\nu_e} \simeq \left(\frac{L_{\nu_e}}{4\pi r^2 \langle E_{\nu_e} \rangle} \right) \langle \sigma_{\nu_e n}(r) \rangle$$

$$\lambda_{\bar{\nu}_e} \simeq \left(\frac{L_{\bar{\nu}_e}}{4\pi r^2 \langle E_{\bar{\nu}_e} \rangle} \right) \langle \sigma_{\bar{\nu}_e p}(r) \rangle$$

The neutrino scattering rates are functions of the neutrino fluxes and then flavor oscillations cannot be neglected.

Electron forward rates*

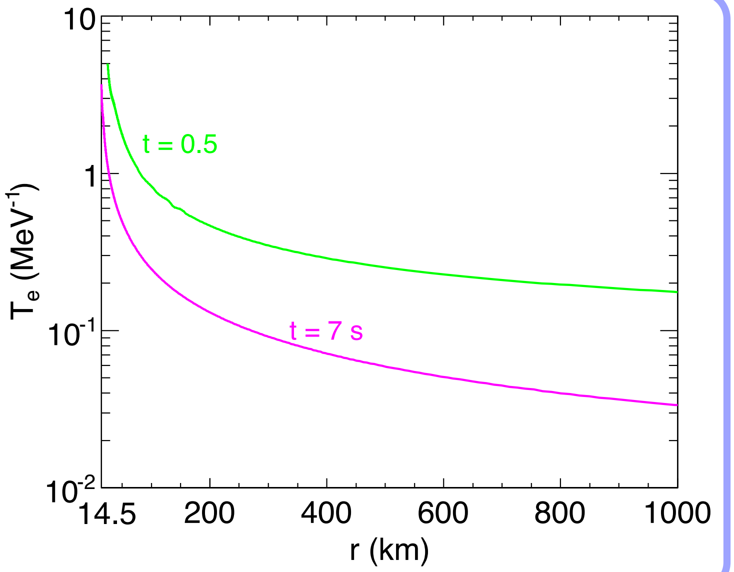
$$\lambda_{e^-} \simeq (1.578 \times 10^{-2}\ \mathrm{s}^{-1}) \left(\frac{T_e}{m_e c^2} \right)^5 e^{(-1.293+\mu_e)/T_e} \left(1 + \frac{0.646\ \mathrm{MeV}}{T_e} + \frac{0.128\ \mathrm{MeV}^2}{T_e^2} \right)$$

$$\lambda_{e^+} \simeq (1.578 \times 10^{-2}\ \mathrm{s}^{-1}) \left(\frac{T_e}{m_e c^2} \right)^5 e^{(-0.511-\mu_e)/T_e} \left(1 + \frac{1.16\ \mathrm{MeV}}{T_e} + \frac{0.601\ \mathrm{MeV}^2}{T_e^2} + \frac{0.178\ \mathrm{MeV}^3}{T_e^3} + \frac{0.035\ \mathrm{Me}}{T_e^4} \right.$$

* Mc Laughlin, Fuller, Wilson, Astrophys. J. 472 (1996) 440 (and references therein).

Forward rates

λ_e is a function of the electron temperature T_e and of the electron chemical potential.



Electron chemical potential*

$$Y_e = \frac{8\pi}{3n_b} T_e^3 \frac{\mu_e}{T_e} \left(\frac{\mu_e^2}{T_e^2} + \pi^2 \right)$$

* Bludman, Van Riper, Astrophys. J. 224 (1978) 631.