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How do sterile neutrinos affect heavy-element formation in supernovae?

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Outline

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

This seminar is based on a project developed in collaboration with G.G. Raffelt, L. Huedepohl and H.-T. Janka [arXiv: 1110.2104, JCAP in press].

Experimental hints for light sterile neutrinos

Observations at odds with standard 3-neutrino interpretation of global oscillation data:

- ★ LSND anomaly [A. Aguilar et al., PRD 64, 112007 (2001)]
- ★ MiniBooNE antineutrino results [A.A.Aguilar-Arevalo et al., PRL 102, 101802 (2009)]
- ★ Short-baseline disappearance experiments (Bugey, ROVNO, ILL)
- ★ Recent re-evaluation of reactor fluxes
[Mention et al. PRD 83, 073006 (2011), Huber, PRC 84, 024617 (2011)]

Light sterile neutrinos explain quite well these anomalies.

Cosmological hints for light sterile neutrinos

★ Precision cosmology and BBN mildly favor extra-radiation in the universe beyond photons and neutrinos ($N_{\rm eff} > 3$).

★ Low-mass sterile neutrinos are one natural possibility (even if not the only one). Cosmological data allow one sub-eV mass sterile family, introduced also to explain the LSND/MiniBooNE.*

★ eV-sterile neutrinos adopted to explain reactor anomalies are difficult to accommodate in the minimal cosmological scenario.**

* J. Hamman, S. Hannestad, G.G. Raffelt, I. Tamborra and Y.Y.Y. Wong, PRL 105 (2010) 181301.

** J. Hamman, S. Hannestad, G.G. Raffelt and Y.Y.Y. Wong, JCAP 1109 (2011) 034.

eV-mass sterile neutrinos in supernovae

★ Reactor $\bar{\nu}_e$ spectra are interpreted assuming the existence of 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.

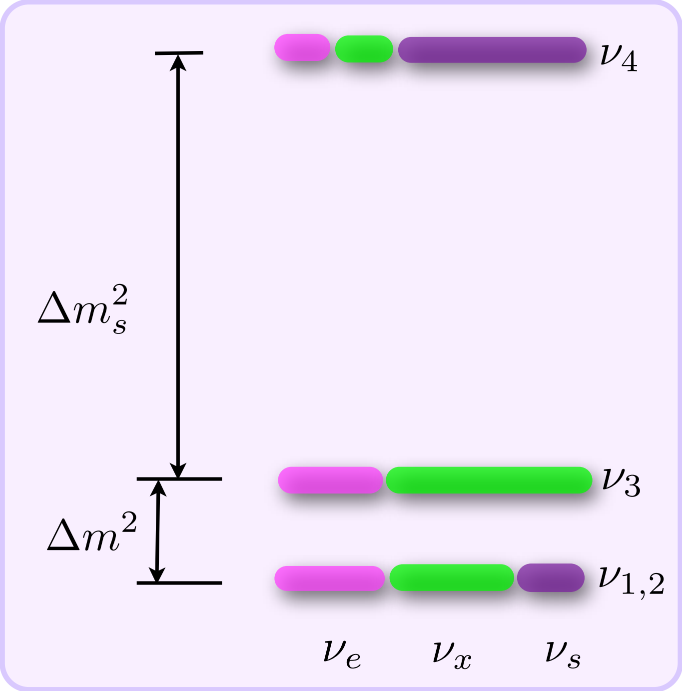
** See Fetter et al., Astrop. Phys. 18 (2003) 433, PRC 59 (1999) 2873 and references therein.

(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 →



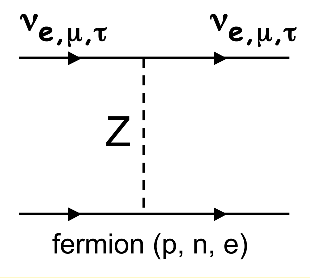
$$\delta m^2_{\rm atm} = 2 \times 10^{-3}\ {\rm eV}^2 \qquad \sin^2 2\theta_{14} = 0.165$$

$$\delta m^2_{\rm ste} = 2.35\ {\rm eV}^2 \qquad \sin^2\theta_{13} = 10^{-4}$$

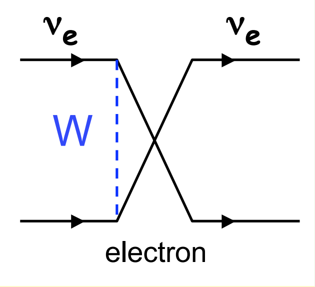
Mass and mixing parameters

Neutrino interactions

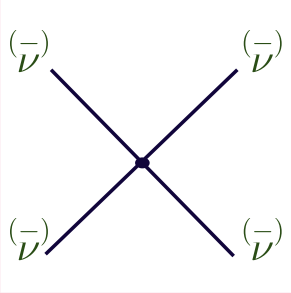
Active neutrinos interact with matter and among themselves...



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

$$\boxed{\begin{aligned} i\dot{\boldsymbol{\rho}}_E &= [\mathbf{H}_E, \boldsymbol{\rho}_E] \\ i\dot{\overline{\boldsymbol{\rho}}}_E &= [\overline{\mathbf{H}}_E, \overline{\boldsymbol{\rho}}_E] \end{aligned}}$$

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

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

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

Electron fraction

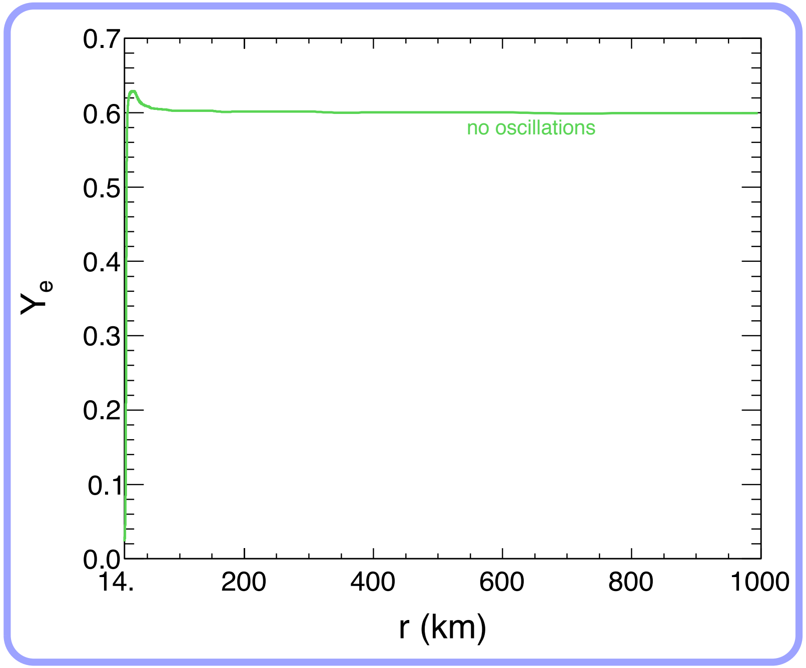
A hot problem in astrophysics is the location of the r-process nucleosynthesis.

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:

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

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



$Y_e < 0.5 \Longleftrightarrow$ more n than $p \Rightarrow$ 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 following neutrino and antineutrino capture rates on free nucleons

$$\boxed{\begin{array}{l} \nu_e + n \to p + e^- \\ \bar{\nu}_e + p \to n + e^+ \end{array}}$$

and the associated reversed processes.

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

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

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.

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*

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

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

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

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

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

neutrino contribution

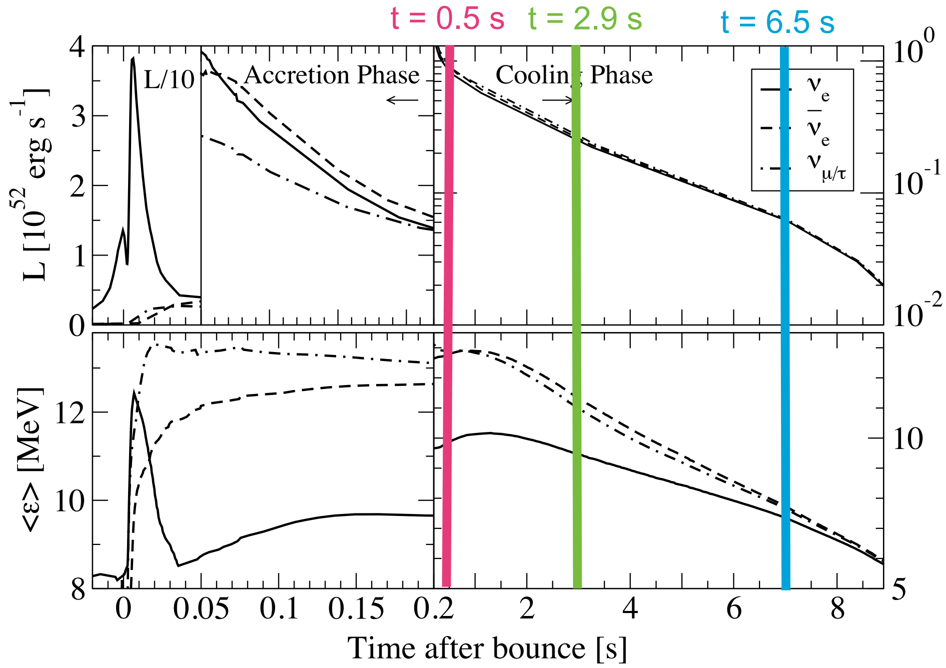
NC+CC matter contribution

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 study* three representative times of the cooling phase extracted by an exploding 1D electron-capture supernova simulation as examples.**



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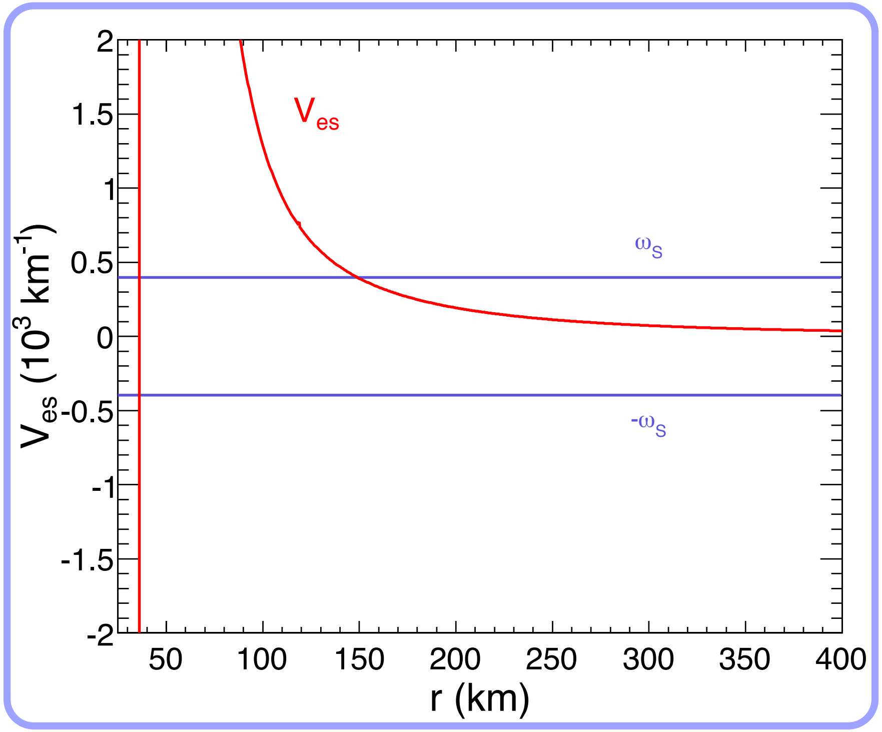
* For details see: I. Tamborra, G.G. Raffelt, L. Huedepohl, H.-T. Janka, arXiv: 1110.2104 [astro-ph.SR]

** Huedepohl et al., arXiv: 0912.0260.

Our results: t = 0.5 s

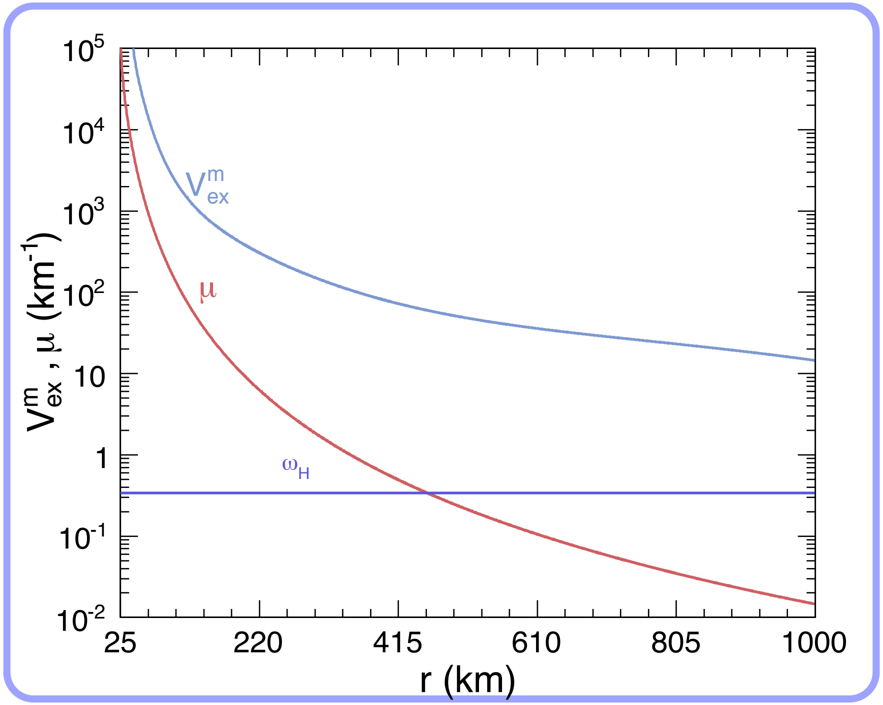


Dynamical $\nu_e - \nu_s$ energy difference

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.

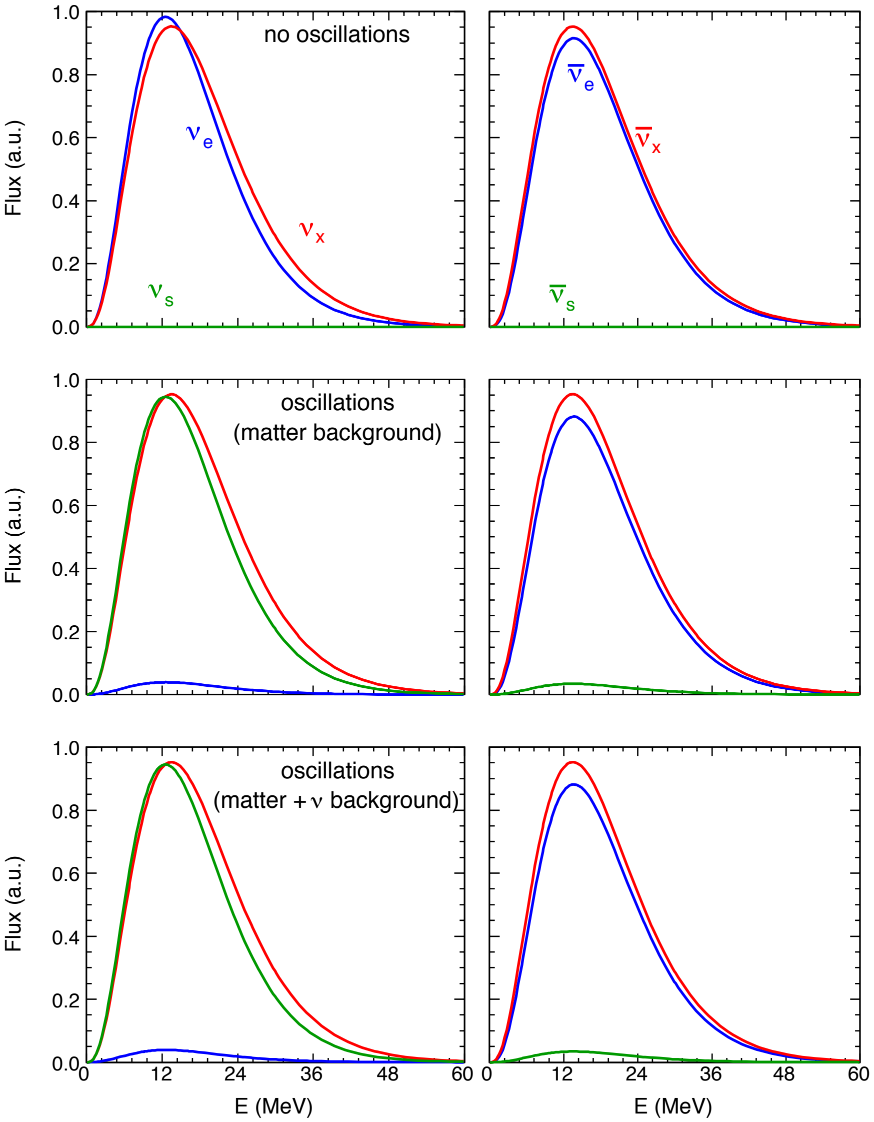
Dynamical $\nu_e - \nu_x$ energy difference

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



Our results: t = 0.5 s

Energy spectra



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.

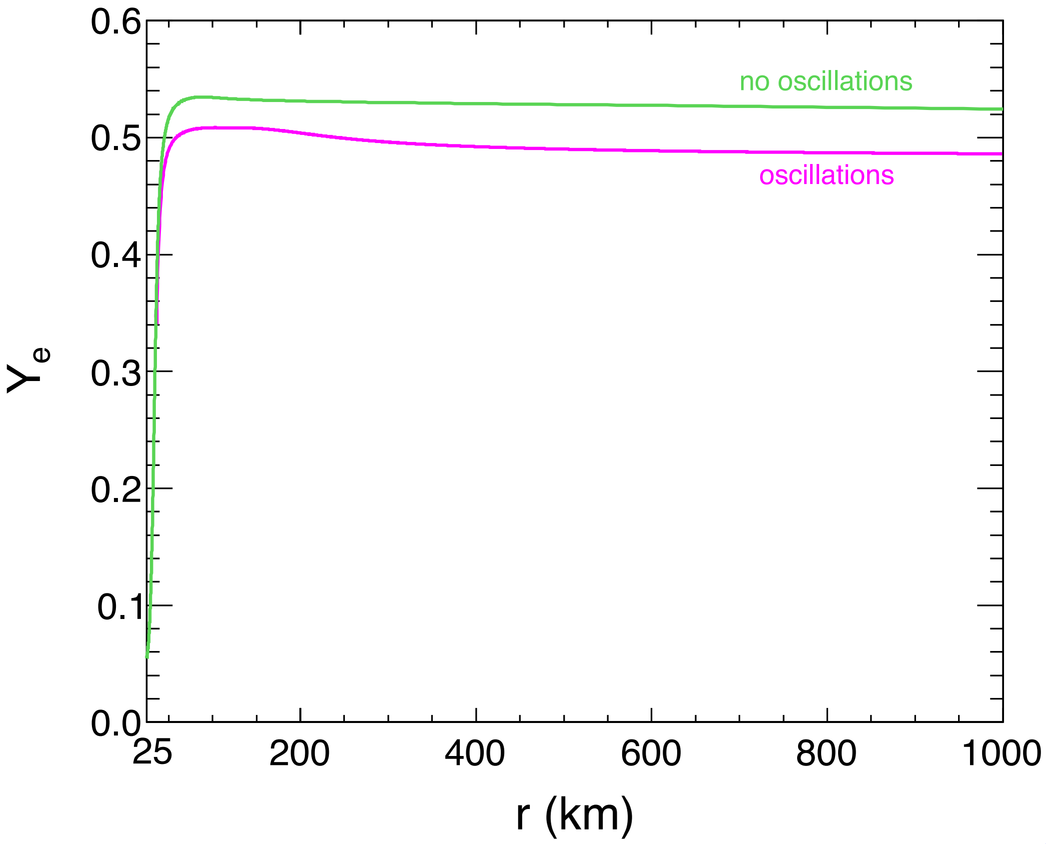
oscillations (matter+neutrino background)

The strong asymmetry between neutrinos and antineutrinos inhibits any further flavor conversion.

Our results: t = 0.5 s

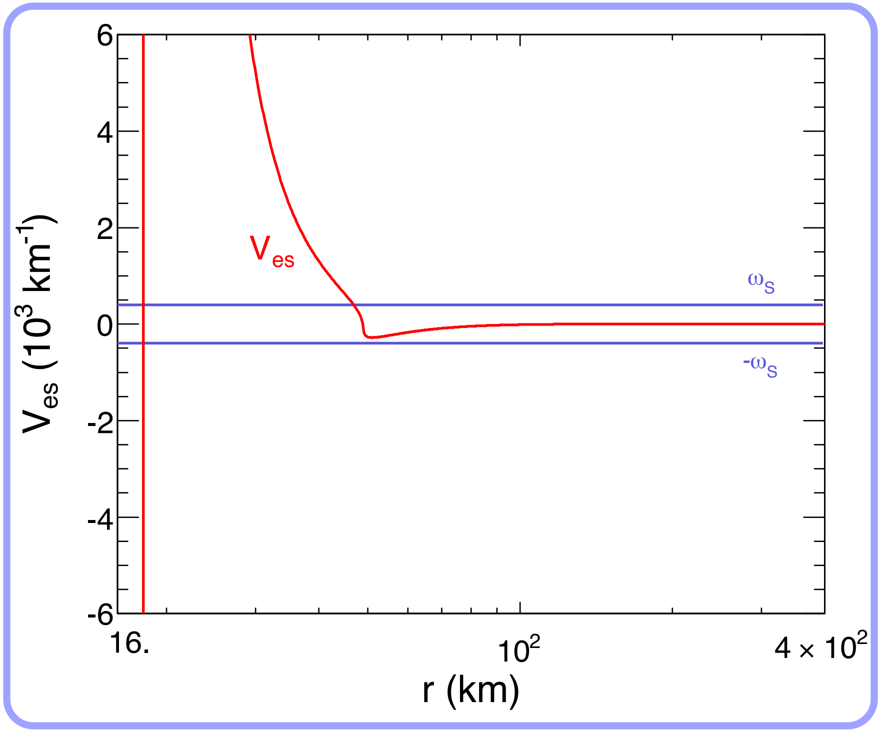
less ν_e ⇨ more n ⇨ Y_e decreases

Electron abundance



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: t = 2.9 s

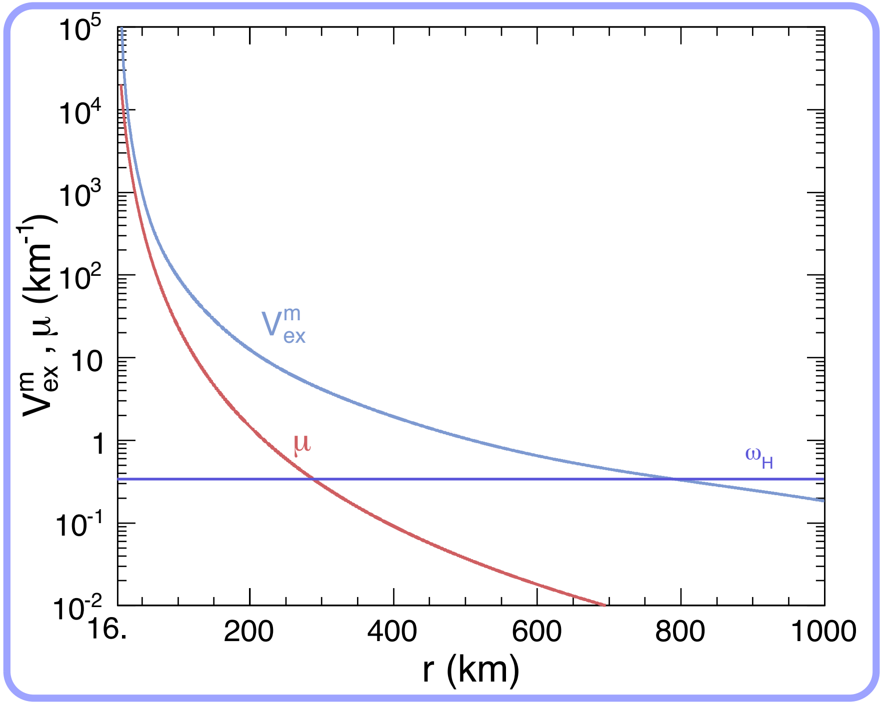


Dynamical $\nu_e - \nu_s$ energy difference

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 experience a resonance.

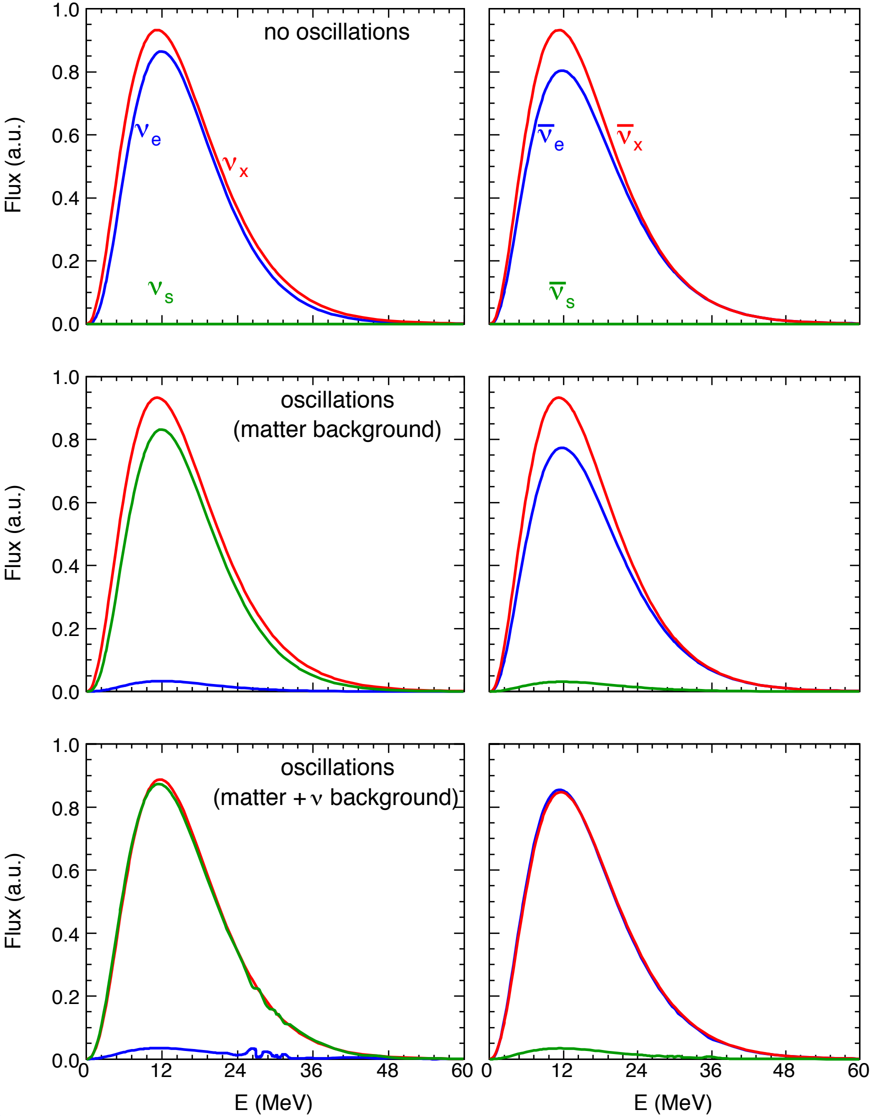
Dynamical $\nu_e - \nu_x$ energy difference

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



Our results: t = 2.9 s

Energy spectra



no oscillations

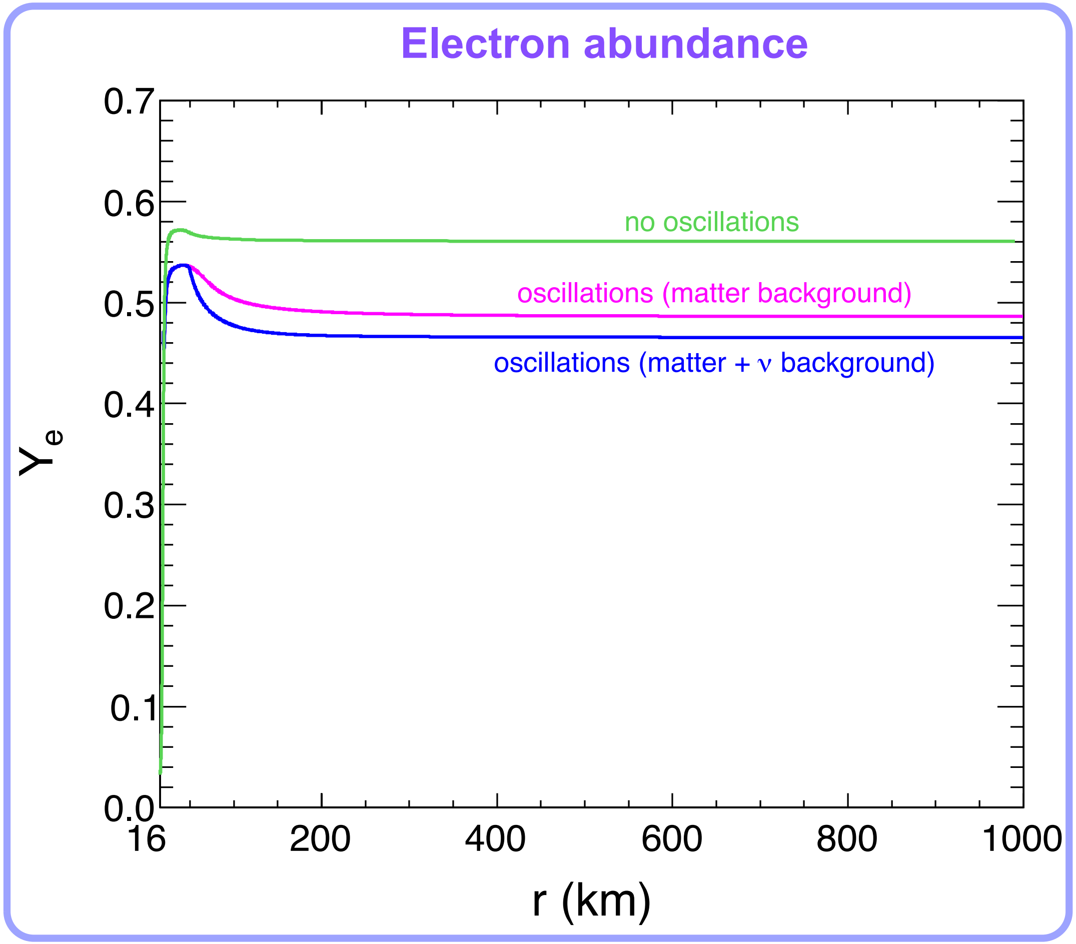
oscillations (matter background)

The MSW flavor conversion is responsible for the disappearance of ν_e in favor of ν_s .
$\bar{\nu}$ and ν_x fluxes are almost unchanged.

oscillations (matter+neutrino background)

The neutrino background is not negligible. $\bar{\nu}_e$ are more abundant than in the case with matter only.

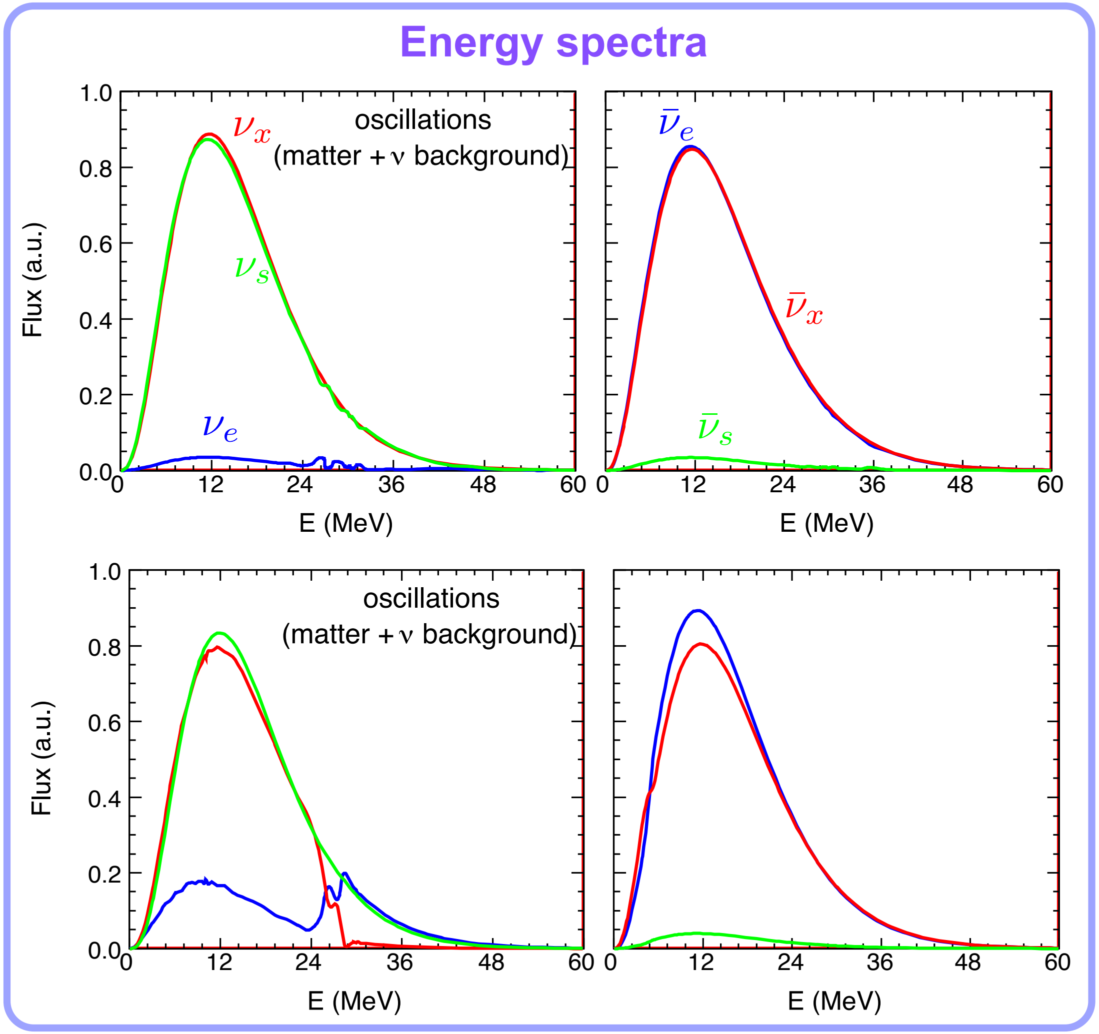
Our results: t = 2.9 s



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

Collective effects are responsible for increasing the $\bar{\nu}_e$ abundance with respect to the case without ν background. Therefore the electron abundance decreases. **Sterile neutrinos can affect the r-process and, in general, the nuclei formation.**

Our results: different mixing parameters

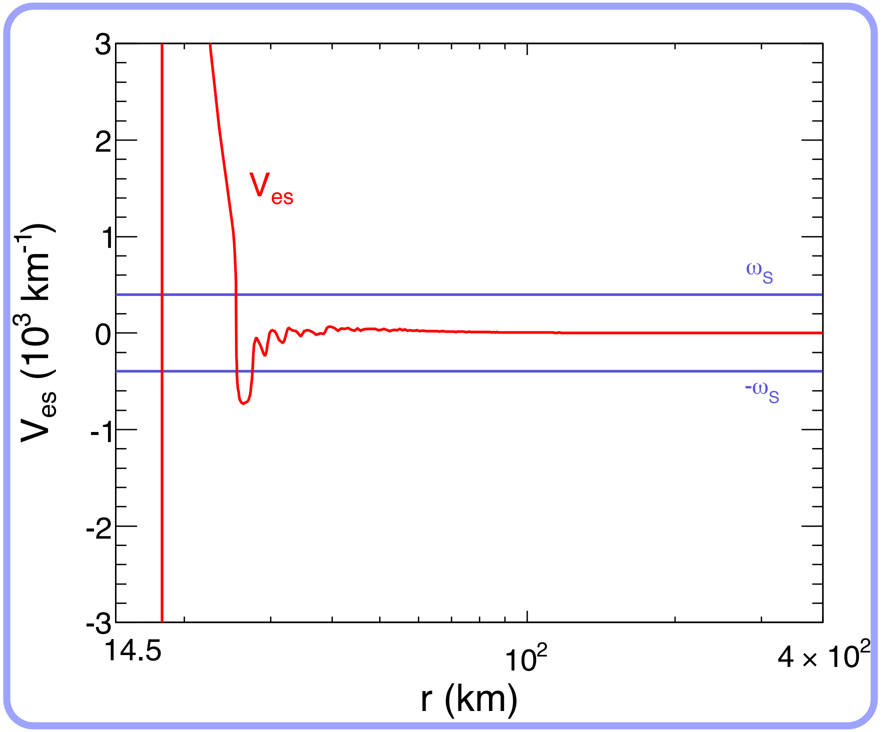


small θ_{13}

large θ_{13}

★ Y_e is slightly sensitive to the mass-mixing parameters but it does not decrease so much as required to trigger r-process for the allowed regions.

Our results: t = 6.5 s

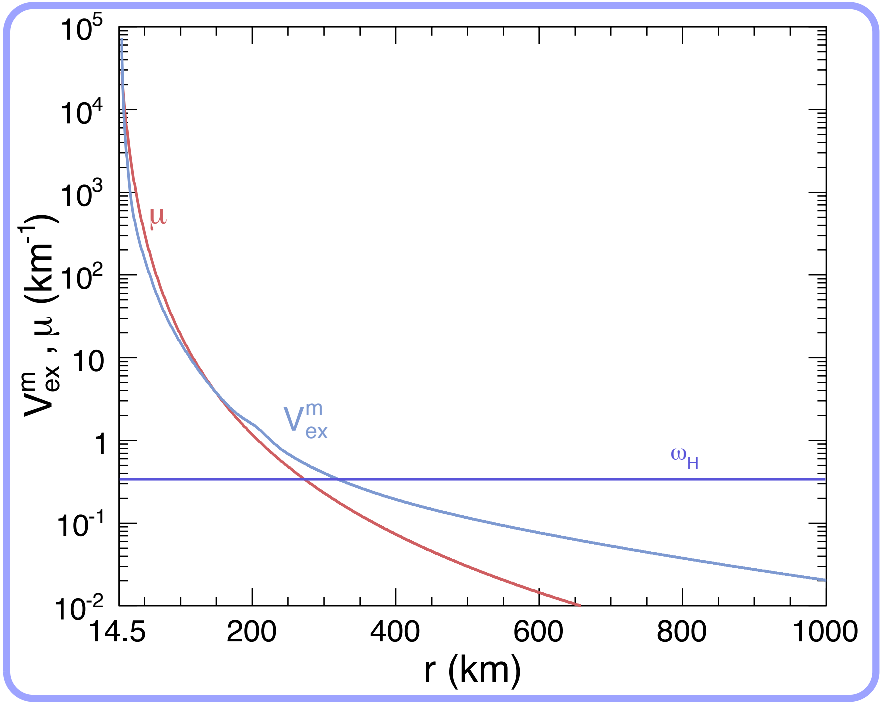


Dynamical $\nu_e - \nu_s$ energy difference

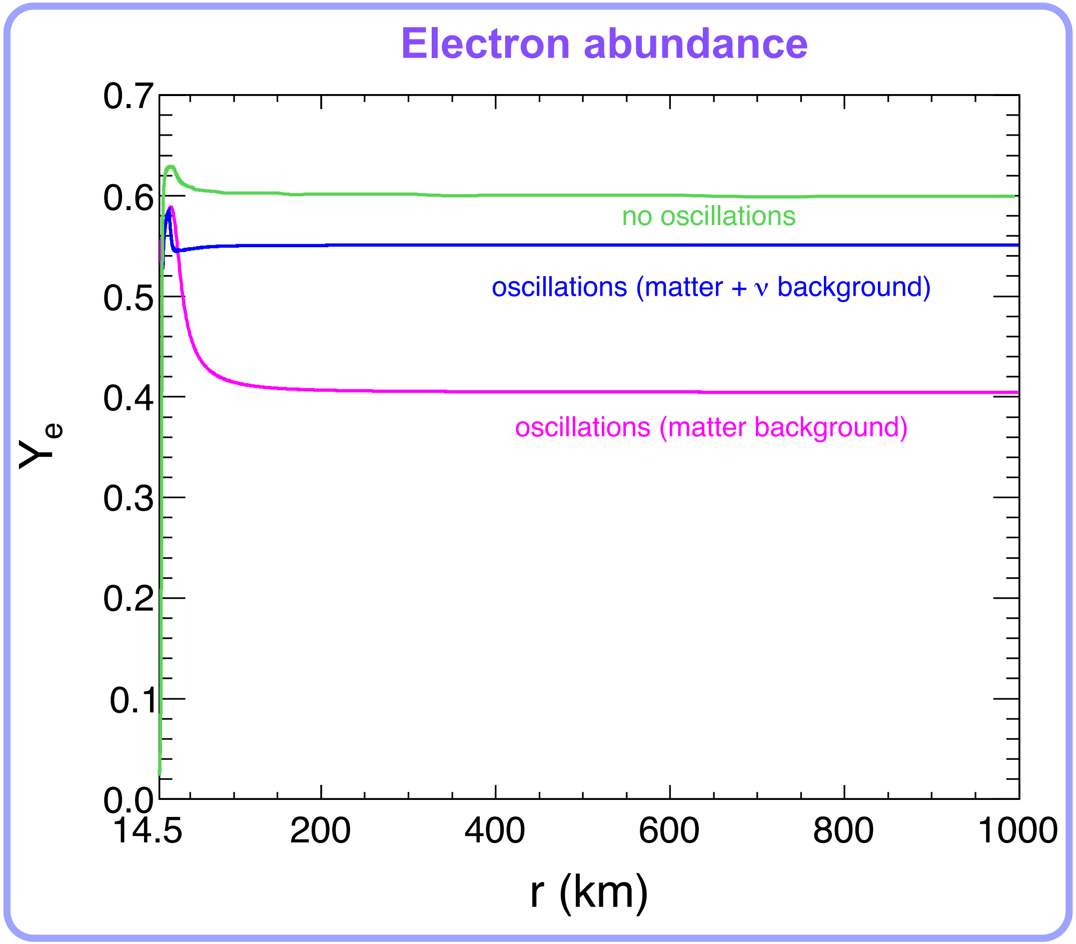
A non-adiabatic MSW resonance for both neutrinos and antineutrinos is occurring close to the neutrino-sphere. At large radii, neutrinos go towards a second adiabatic resonance and only few antineutrino energy modes experience a resonance.

Dynamical $\nu_e - \nu_x$ energy difference

The matter potential is of the same order of the $\nu - \nu$ potential.



Our results: t = 6.5 s



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

Collective effects are responsible for increasing the $\bar{\nu}_e$ abundance with respect to the case without ν background. Therefore the electron abundance decreases. **Sterile neutrinos can affect the r-process and, in general, the nuclei formation.**

Conclusions

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

★ 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.

★ 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 it might not enable the r-process. Sterile neutrinos could also affect other aspects of element formation.

Thank you for your attention!