Supernovae and sterile neutrinos

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Motivated by the recent hints for sterile neutrinos from reactor anomalies, we discuss active-sterile conversions in an electron-capture supernova using a (2 active + 1 sterile) scenario. By including the feedback effect on the electron abundance due to neutrino oscillations, we study the impact of sterile neutrinos on both the oscillated neutrino fluxes and on Y_e.

1 Introduction

Sterile neutrinos are hypothetical gauge-singlet fermions that mix with one or more of the active states and thus show up in active-sterile flavor oscillations. Our study is motivated by the most recent indication for the possible existence of eV-mass sterile neutrinos coming from a new analysis of reactor $\bar{\nu}_e$ spectra [1, 2]. The data suggest a ν_e-ν_s mixing of $\sin^2 2\theta \sim 0.14$ with mass splitting of $\Delta m^2 \gtrsim 1.5$ eV^2.

Assuming that the sterile state is heavier than the active ones because of cosmological mass limits, in supernovae (SN) such parameters imply $\nu_e - \nu_s$ MSW conversions close to the SN core. Therefore, the ν_e flux arriving at Earth from the next SN explosion would be significantly modified by the presence of sterile neutrinos.

We here focus on a different aspect of ν_e-ν_s oscillations that could have an interesting impact during the SN cooling phase. The neutrino-driven matter outflow is a candidate site for r-process nucleosynthesis (it requires a neutron-rich environment, i.e. $Y_e < 0.5$, large entropy to favor lighter nuclei at high temperatures and fast timescales to lower the efficacy of converting alpha particles to heavier nuclei). We discuss whether sterile neutrinos might trigger the r-process or somehow affect the nuclei formation.

2 Neutrino and Y_e evolutions in electron-capture supernovae

We use long-term simulations for an electron-capture supernova of a representative progenitor with mass 8.8 $M_\odot$ [3] and we discuss here two representative cooling times ($t = 0.5, 2.9$ s). In Table 1, for each flavor ν_β, the neutrino-sphere radius, the luminosity L_{ν_β}, the average energies $\langle E_{\nu_\beta} \rangle$ are reported.

We consider a $2+1$ flavor scenario (ν_e, ν_x, ν_s) with mass differences $\delta m^2_{\rm S} = 2.35$ eV$^2 > 0$, $\delta m^2_{\rm atm} = -2 \times 10^{-3}$ eV$^2 < 0$. The mixing is driven by $\sin^2 \Theta_{13} = 10^{-4}$ and $\sin^2 2\Theta_S = 0.165$ assuming negligible the other mixing angles.

t	R_ν	L_{ν_e}	$L_{\overline{\nu}_e}$	L_{ν_x}	$\langle E_{\nu_e}\rangle$	$\langle E_{\overline{\nu}_e}\rangle$	$\langle E_{\nu_x}\rangle$	Y_e
0.5	25	9.5	10.06	10.8	16.8	18.14	18.3	5.47×10^{-2}
2.9	16	3.28	3.4	3.74	15.8	16.3	15.8	3.23×10^{-2}

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

The flavor evolution is described by matrices of densities for each energy mode E for ν and $\bar{\nu}$, being the diagonal entries the usual occupation numbers. The evolution of ρ_E is governed by the Liouville equations

$$i\partial_r \rho_E = [\mathsf{H}_E, \rho_E] \quad \text{and} \quad i\partial_r \bar{\rho}_E = [\bar{\mathsf{H}}_E, \bar{\rho}_E]\,, \tag{1}$$

where the overbar refers to antineutrinos and sans-serif letters denote 3×3 matrices in flavor space with initial conditions $\rho_E = \mathrm{diag}(n_{\nu_e}, n_{\nu_x}, 0)$ and $\bar{\rho}_E = \mathrm{diag}(n_{\bar{\nu}_e}, n_{\bar{\nu}_x}, 0)$. The Hamiltonian matrix contains vacuum, matter, and neutrino–neutrino terms $\mathsf{H}_E = \mathsf{H}_E^{\mathrm{vac}} + \mathsf{H}_E^{\mathrm{m}} + \mathsf{H}_E^{\nu\nu}$. Because of the presence of sterile neutrinos, the matter term includes both the charge current (CC) and the neutral current (NC) contributions: $\mathsf{H}_E^{\mathrm{m}} = \sqrt{2}G_{\mathrm{F}}\ \mathrm{diag}(N_e - N_n/2, -N_n/2, 0)$, with N_e the electron number density and N_n the neutron one in the medium. Note that being $Y_e = N_e(r)/(N_e(r) + N_n(r))$, H^{m} is a function of Y_e and it changes as Y_e changes. While $\mathsf{H}_E^{\nu\nu}$ has all the terms involving sterile neutrinos identically equal to zero, as proved in [4].

The electron fraction, on the other hand, is altered by the charged current weak interactions by converting neutrons into protons and viceversa. Assuming β-equilibrium is reached, the electron abundance is set by the competition between $\nu_e + n \to p + e^-$ and $\bar{\nu}_e + p \to n + e^+$ and the associated reversed processes. The rate of change of Y_e on an outflowing mass element may be written as [5]

$$\frac{dY_e}{dt} = v(r)\frac{dY_e}{dr} \simeq (\lambda_{\nu_e} + \lambda_{e^+})Y_n^f - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p^f\ , \tag{2}$$

where $v(r)$ is the velocity of the outflowing mass element, t is the time parameter, λ_{ν_e} ($\lambda_{\bar{\nu}_e}$) is the forward rate of (anti-)neutrinos and λ_{e^-} (λ_{e^+}) the electron (positron) capture rate on free nucleons [5]. Since Y_e is a function of the neutrino-capture rates, it depends on the neutrino flavor evolution. Therefore, we have to consider the double feedback effect due to both these effects.

3 Results: early-cooling phase

Figure 1 shows the spectra without (with) oscillations on the top (bottom) for $\Delta m_{\mathrm{atm}} < 0$. Neutrino refractive contribution on the ν_e–ν_s conversion is minimal. After the ν_e–ν_s MSW conversion, the e–x difference spectrum is very asymmetric between neutrinos and antineutrinos, essentially suppressing collective conversions.

Figure 2 shows Y_e as a function of the radius for the cases without and with neutrino oscillations. The MSW flavor conversions lower the electron abundance.

4 Results: intermediate-cooling phase

Figure 3 shows the energy fluxes for $\Delta m^2_{\rm atm} < 0$. The ν_e–ν_x refractive energy difference caused by matter is now much smaller, allowing for MSW conversions between the two active flavors, in the neutrino sector for the chosen hierarchy. The neutrino background is responsible for increasing the $\bar{\nu}_e$ flux with respect to the case with only matter and averaging out the $\bar{\nu}_x$ and $\bar{\nu}_e$ fluxes.

In Fig. 4 the electron abundance is plotted as a function of the radius. The oscillations are responsible for an asymptotic value of Y_e lower than in the case without oscillations, and in particular collective effects make it even lower. The smaller value of Y_e due to sterile neutrinos could sensitively affect the nucleosynthesis in supernovae.

5 Conclusions

Motivated by the recent hints on sterile neutrinos, we assume the existence of one sterile family with the reactor anomaly mixing parameters and discuss for the first time the impact of ν_s on two active flavor evolution and on nucleosynthesis.

The sterile neutrino production is triggered by the MSW resonance between the active and the sterile sector. However for $t = 0.5$ s, no further flavor conversion is determined by ν–ν interactions because collective oscillations are suppressed. For $t = 2.9$ s, the ν–ν interactions do trigger further flavor conversions. For both the time slices discussed, Y_e is lower than in the case without oscillations and it could affect the nuclei formation.

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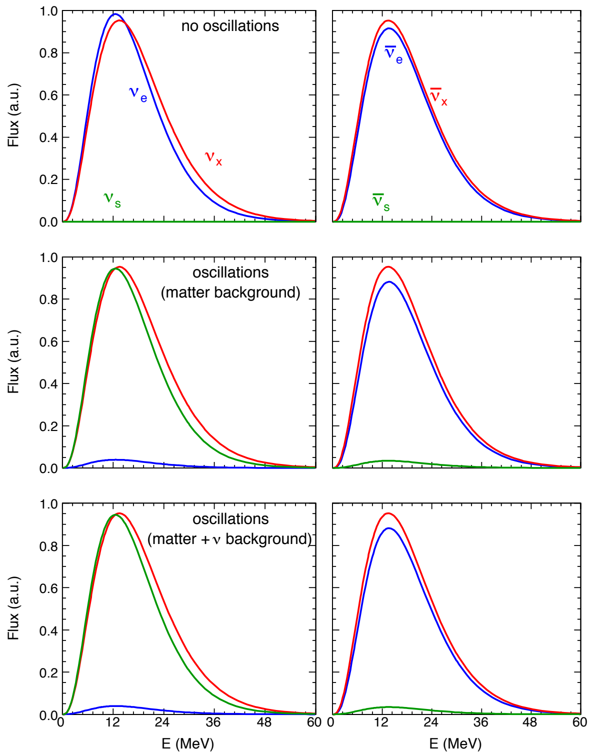

Figure 1: (color online) Spectra for neutrinos (left) and antineutrinos (right) in arbitrary unites (a.u.) for the 0.5 s model. Top: No oscillations (spectra at neutrino sphere). Middle: Oscillated spectra, including only the matter effect. Bottom: ν–ν interactions are also included, but cause no visible difference.

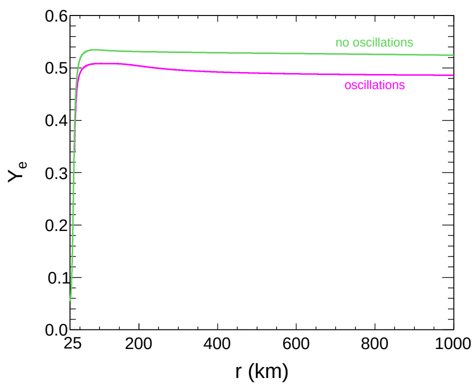

Figure 2: (color online) Electron abundance as a function of the radius at $t = 0.5$ s for the case with and without oscillations.

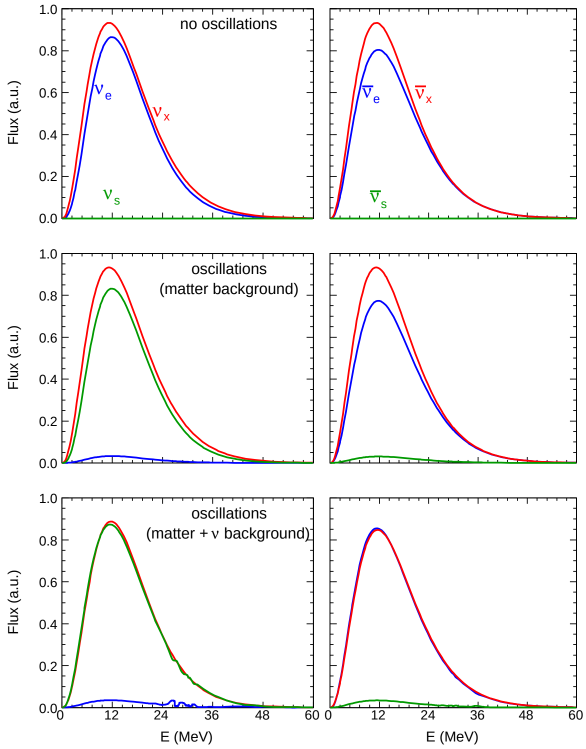

Figure 3: (color online) Energy spectra for $t = 2.9$ s, as in Fig. 1.

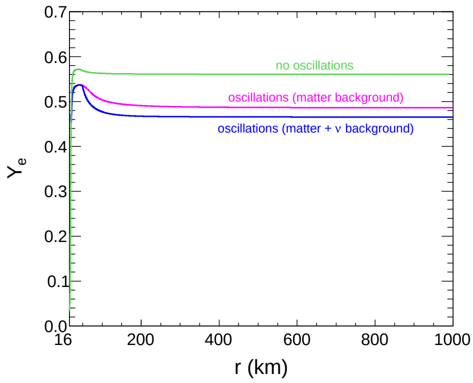

Figure 4: (color online) Electron abundance for $t = 2.9$ s, as in Fig. 2.