Sterile neutrino production in the supernovae explosion

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Some of papers on the sterile neutrinos in SN

- $\nu_s - \nu_e$ mixing - Phys.Lett.B323:360-366,1994 - energy loss and cooling constraints
- $\nu_s - \nu_e$ mixing - arXiv:hep-ph/9702372 - energy loss
- $\nu_{\tau/\mu} - \nu_s$ mixing - arXiv:1102.5124 - Collision production and energy loss
- $\nu_{\tau/\mu} - \nu_s$ mixing - arXiv:1605.00654v resonance conversion, energy-loss argument
SN explosion and energy loss argument

- SN emits all $\nu$ flavors
- If $\nu_s$ exist, they are also emitted
- Energy comes from gravitational binding energy of remnant

Figure: See H.T. Janka - 1702.08713
SN 1987A observations

Detection of neutrinos from SN1987A in three experiments - Kamiokande, Baskan, IMB.

- Flux of $\bar{\nu}_e$ was detected in $\bar{\nu}_e + p \rightarrow n + e^+$ reactions within $\approx (10 - 12)$ sec. interval.
- Other species weren’t detected
- $\bar{\nu}_e$ total energy flux estimated as $(5 - 8) \times 10^{52}$ erg.
- No remnant observed

Figure from "Stars as laboratories for fundamental physics" (Georg Raffelt)
Resonant conversion

Similar to solar MSW (\(\nu_e \rightarrow \bar{\nu}_x, \nu_\mu \rightarrow \nu_s\))

1. \(\bar{\nu}_x\) is produced in the SN core
2. Propagating radially outward, pass of resonance and converts to sterile
3. Difference between Sun and SN - non-adiabaticity (no full \(\bar{\nu}_x \rightarrow \nu_s\) conversion)

\[
\begin{align*}
\nu_1 &= \cos(\theta) \nu_e + \sin(\theta) \nu_\mu \\
\nu_2 &= -\sin(\theta) \nu_e + \cos(\theta) \nu_\mu
\end{align*}
\]

\[\theta \approx \frac{\pi}{2}, \quad \theta \approx \theta_{\text{vac}}\]

Figure: Eigenvalues of Hamiltonian for Sun - left panel, SN - right panel
Population change

- Rapid loss of $\bar{\nu}_x$ in the production area
- Restoration of $\bar{\nu}_x$ population with pair production
  \[ n + n \rightarrow n + n + \nu_x + \bar{\nu}_x \]
- Increase of $\nu_x$ number $\rightarrow$ Pauli blocking of pair production
- Population is not restored fully - nonzero chemical potential
Diffusion of asymmetry

- $\nu_x/\bar{\nu}_x$ population change over the SN inhomogeneously
- Diffusion of lepton number aims to redistribute $\bar{\nu}_x$ population.
- Diff. time-scale depends on radius and energy and can vary (0.1 - 10 sec)
- Back-reaction suppresses $\nu_s$ production

Figure: Chem. potential - left panel, Asymmetry parameter $\frac{N_x-N_\bar{x}}{N_b}$ - right panel
### Model of the SN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core radius</td>
<td>$R_{\text{core}} = 10 \text{ km}$</td>
</tr>
<tr>
<td>Max. Temperature</td>
<td>$T_{\text{max}} = 30 \text{ MeV}$</td>
</tr>
<tr>
<td>Min. Temperature</td>
<td>$T_{\text{min}} = 3 \text{ MeV}$</td>
</tr>
<tr>
<td>Baryon core density</td>
<td>$\rho_0 = 3 \times 10^{14} \text{ g/cm}^3$</td>
</tr>
<tr>
<td>Baryon core number density</td>
<td>$N_0 = [10^{38}] \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>Electron asymmetry</td>
<td>$Y_e = 0.3$</td>
</tr>
<tr>
<td>Electron neutrino asymmetry</td>
<td>$Y_{\nu_e} = 0.07$</td>
</tr>
</tbody>
</table>

Asymmetry parameter $Y_i = \frac{N_i - \bar{N}_i}{N_b}$

$$\rho = \rho_0 \exp \left[ \frac{r - R_{\text{core}}}{R_{\text{core}}} \right]$$

- Temperature decrease linearly from $T_{\text{max}}$ (Core) to $T_{\text{min}}$ (50 km - production is negligible here)
- Assume LTE for neutrinos
Effective potential and mixing angle

For $\nu_\tau/\bar{\nu}_\tau$ (same for $\nu_\mu$ up to $\tau \leftrightarrow \mu$):

$$V_{\text{eff}} = \pm \frac{G_f}{2} N_B (1 - Y_e - 2Y_{\nu_e} - 2Y_{\nu_\mu} - 4Y_{\nu_\tau})$$

(1)

"+" for neutrinos, "-" - for anti-neutrinos.

$$\tan 2\theta = \frac{\Gamma}{\Gamma \cos 2\theta_0 + V_{\text{eff}}}, \text{ Resonance: } \Gamma \cos 2\theta_0 + V_{\text{eff}} = 0$$

(2)

Parameter $\Gamma = \frac{m^2}{2E}$

- Resonance only for **anti-neutrinos**
Adiabatic limit

Parameter of adiabaticity

\[ \frac{\theta'(r)}{E_a(r) - E_b(r)} \]  

follows from the Hamiltonian

\[ i \frac{d}{dr} \begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} E_a(r) & i\theta'(r) \\ -i\theta'(r) & E_b(r) \end{pmatrix} \begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} \]
Probability of conversion $\nu_x \rightarrow \nu_s$ for small mixing angle:

$$P_{\nu_x \rightarrow \nu_s} = \frac{1}{2} - \frac{1}{2} \cos(2\theta_{in})\cos(2\theta_{out}), \quad \text{Adiabatic limit} \quad (5)$$

$$P_{\nu_x \rightarrow \nu_s} = \frac{1}{2} - \left(\frac{1}{2} - P_x\right)\cos(2\theta_{out})\cos(2\theta_{in}) = P_{\text{res}}, \quad \text{Non-adiabatic limit} \quad (6)$$

$$P_x = \text{Exp}\left[-\frac{2\pi \Gamma^2 \theta_0^2}{V'_\text{eff}(R_{\text{res}})}\right] \quad (7)$$

Kinetic equation:

$$\frac{dN_s}{d^3pdt} = 4\pi^2 R_{\text{res}}^2(E)f_{\nu_x}^{\text{out}}(R_{\text{res}}(E), E, t)P_{\text{res}}(E) \quad (8)$$
Asymmetry evolution equation

Asymmetry evolution given by diffusion equation with source

$$\frac{\partial \Delta f(E, r, t)}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 D(r, E) \frac{\partial \Delta f(E, r, t)}{\partial r} \right) + I(E, r, t) \tag{9}$$

$$\Delta f(E, r, t) = f_{\nu_x} - f_{\bar{\nu}_x}$$ - asymmetry and $I(E, r, t)$ - source

- Diffusion coefficient $D(r, E) = \frac{\lambda_{\text{mfp}}(r, E)}{3} = \frac{\pi}{3G_F^2 N_b(r)E^2}$

$$\frac{dn_s}{dt} = S(r, t) + \frac{1}{6\pi G_F^2 r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{N_b(r)} \frac{\partial \mu_{\nu_x}}{\partial r} \right) \tag{10}$$

$S(r, t)$ - integrated source of asymmetry

$$S(r, t) = \frac{dN_s}{d^3r dt} = \pi E_{\text{res}}^2 \phi_{\bar{\nu}_x}^{\text{out}}(r, E_{\text{res}}, t) P_{\text{res}}(E_{\text{res}}) \frac{dE_{\text{res}}(r)}{dr} \tag{11}$$
Energy emission

Energy, carried with them

\[ Q_S = \int dt \int dpp^3 \frac{dN_s}{dt d^3p} \cos \theta d\Omega \]  

We need to find energy output with active flavors in our model.
- See, if it is consistent with observations
- Compare sterile and active energy output
Energy emission of active flavor

Find a radius, from which neutrino with given energy escapes freely:

\[ R_{\nu_{\text{sph}}} = R_{\text{core}} (1 + \ln(R_{\text{core}} \sigma(E) N_0)) \]  \hspace{1cm} (13)

Inside \( R_{\nu_{\text{sph}}} \) \( \nu \)'s are trapped and free outside it.

- radiation of neutrinos from surface of sphere

So

\[ \frac{dQ}{dt} = \int 4\pi R_{\nu_{\text{sph}}}^2(E) E f_{\nu}^{\text{out}} d^3p \]  \hspace{1cm} (14)

Integration gives \( Q = 0.22 \cdot 10^{53} \) erg. - comparable with modelling results
Results

- There is a range of parameters, when sterile flavor carry as much energy as several active species.
- If sterile neutrino is the only dark-matter component we have the X-ray bounds on parameters.

**Figure:** Left panel - emitted $\nu_x$ and $\nu_s$ spectra integrated over the first second of explosion for the best-fit X-Ray parameters ($m_s = 7.1\,keV$, $\sin^2 2\theta = 5 \times 10^{-11}$). Right panel - energy, emitted via sterile neutrinos during first second.
Results

Features of the main result (on Fig. 4):

- Weak dependence of the mixing angle starting from some particular value - with $\sin 2\theta^2$ increasing, conversion becomes adiabatic.
- Rapid decrease of produced energy for small ($\sim 1$ keV) and large ($> 40$ keV) masses.
  1. For low masses - only low-energy neutrinos are converted actively ($E \sim m^2$) → total energy is small
  2. For higher masses - energies of converted neutrinos are $\gg T$, so we have lack of neutrinos to be converted

Feature of spectra

- Non-negligible high energy population (compared to active)
- Cut-off at low energies
Possible sources of bounds:

- Energy-loss argument - based on knowledge of total released energy and observed energy, their difference - hidden energy (unknown particles) - *can’t impose definite constraints due to uncertainties of those energies*

- Active species spectra (may be different for $\nu_x/\bar{\nu}_x$ in presence of $\nu_s$) - *requires high precision detection of both $\nu_x\bar{\nu}_x$ spectra to compare*

- Duration of neutrino signal (Observation gives $\approx 10$ sec) - *Reducing of neutrino signal can appear as effect of faster SN cooling - requires more detailed study*