Sterile neutrino production in the supernovae explosion

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ICNFP, 2018

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

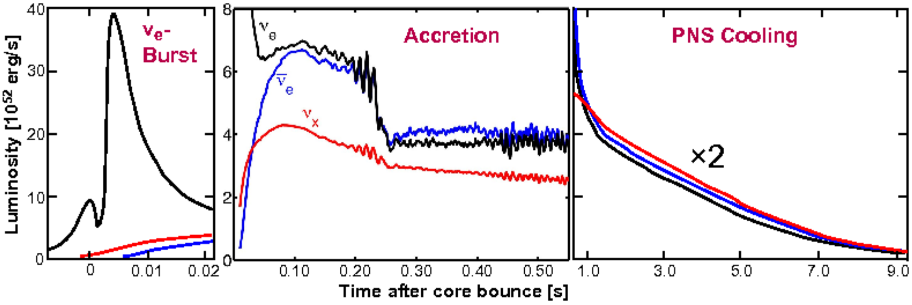


Figure: See H.T. Janka - 1702.08713

- SN emits all ν flavors
- If ν_s exist, they are also emitted
- Energy comes from gravitational binding energy of remnant

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

- Flux of $\bar{\nu}_{\rm e}$ 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

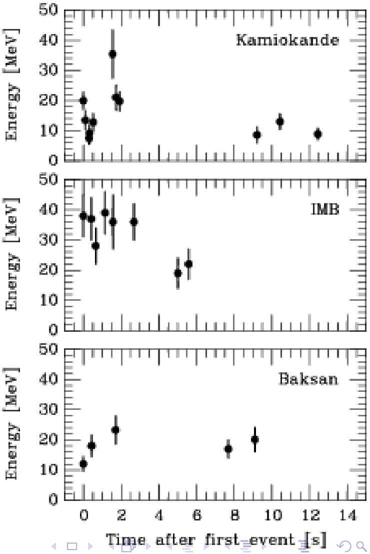
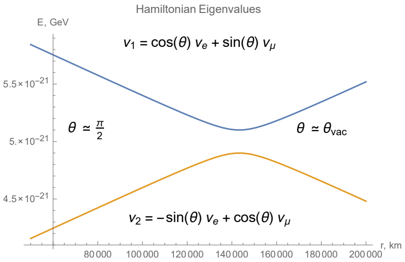


Figure from "Stars as laboratories for fundamental physics" (Georg Raffelt)

Resonant conversion

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

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 $\bar{\nu}_x \to \nu_s$ conversion)



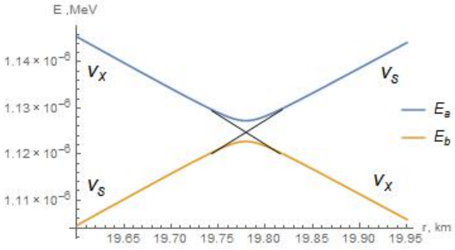


Figure: Eigenvalues of Hamiltonian for Sun - left panel, SN - right panel

Population change

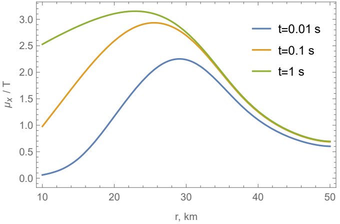
- Rapid loss of $\bar{\nu}_x$ in the production area
- Restoration of $\bar{\nu}_x$ population with pair production

$$n + n \rightarrow n + n + \nu_x + \bar{\nu}_x$$

- Increase of ν_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 ν_s production



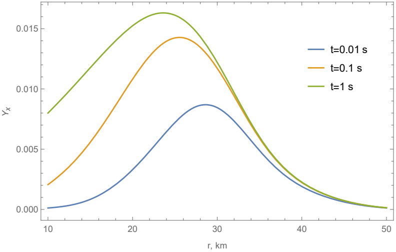


Figure: Chem. potential - left panel, Asymmetry parameter $\frac{N_x - N_{\bar{x}}}{N_b}$ - right panel

Model of the SN

Core radius	$R_{\mathrm{core}} = 10\ km$
Max. Temperature	$T_{\mathrm{max}} = 30\ MeV$
Min. Temperature	$T_{\mathrm{min}} = 3\ MeV$
Baryon core density	$\rho_0 = 3 \times 10^{14} \frac{\mathrm{g}}{\mathrm{cm}^3}$
Baryon core number density	$N_0 = [10^{38}] cm^{-3}$
Electron asymmetry	$Y_e = 0.3$
Electron neutrino asymmetry	$Y_{\nu_e} = 0.07$

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

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

- Temperature decrease linearly from T_{max} (Core) to T_{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 $\tau \leftrightarrow \mu$):

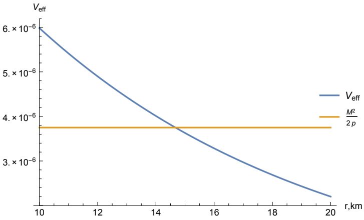
$$V_{eff} = \pm\frac{G_f}{2}N_B(1 - Y_e - 2Y_{\nu_e} - 2Y_{\nu_\mu} - 4Y_{\nu_\tau}) \qquad (1)$$

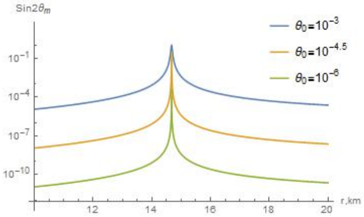
"+" for neutrinos, "-" - for anti-neutrinos.

$$\tan 2\theta = sin2\theta_0\frac{\Gamma}{\Gamma cos2\theta_0 + V_{\rm eff}}, \quad \text{Resonance:} \quad \Gamma cos2\theta_0 + V_{eff} = 0 \qquad (2)$$

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

- Resonance only for **anti-neutrinos**





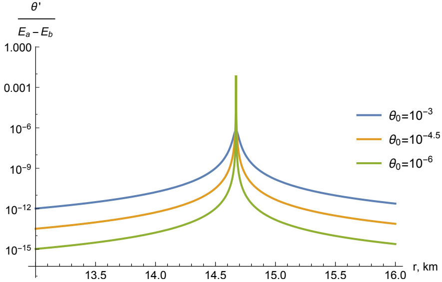
Adiabatic limit

Parameter of adiabaticity

$$\frac{\theta'(r)}{E_a(r) - E_b(r)} \tag{3}$$

follows from the Hamiltonian

$$i\frac{d}{dr}\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} E_a(r) & i\theta'(r) \\ -i\theta'(r) & E_b(r) \end{pmatrix}\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} \tag{4}$$



- Probability of conversion $\nu_x \to \nu_s$ for small mixing angle:

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

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

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

Kinetic equation:

$$\frac{dN_s}{d^3pdt} = 4\pi^2 R_{\rm res}^2(E) f_{\bar{\nu}_x}^{out}(R_{\rm res}(E), E, t) P_{\rm res}(E) \tag{8}$$

Asymmetry evolution equation

Asymmetry evolution given by diffusion equation with source

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

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

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

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

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

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

Energy emission

Energy, carried with them

$$Q_S = \int dt \int dpp^3 \frac{dN_s}{dtd^3p} cos\theta d\Omega \tag{12}$$

- 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:

$$R_{\nu sph} = R_{core}(1 + Ln(R_{core}\sigma(E)N_0)) \tag{13}$$

Inside $R_{\nu sph}$ ν's are trapped and free outside it.

- radiation of neutrinos from surface of sphere

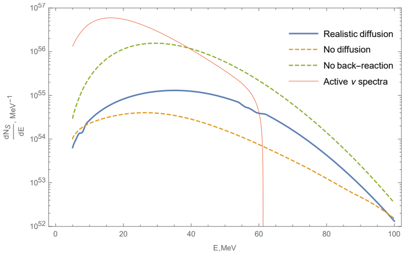
So

$$\frac{dQ}{dt} = \int 4\pi R^2_{\nu sph}(E) E f^{out}_{\overline{\nu}} d^3p \tag{14}$$

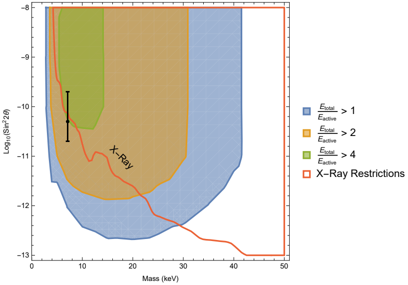
Integration gives $Q = 0.22 \cdot 10^{53}$ erg. - comparable with modelling results

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.



a)



b)

Figure: Left panel - emitted ν_x and ν_s spectra integrated over the first second of explosion for the best-fit X-Ray parameters $\left(m_s = 7.1keV, \sin^2 2\theta = 5 \times 10^{-11}\right)$. 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 (~ 1 keV) and large (> 40 keV) masses.
  1. For low masses - only low-energy neutrinos are converted actively ($E \sim m^2$) $\to$ 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

Conclusions

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 ν_s) - *requires high precision detection of both* $\nu_x\bar{\nu}_x$ *spectra to compare*
- Duration of neutrino signal (Observation gives $\approx 10sec$) -*Reducing of neutrino signal can appear as effect of faster SN cooling - requires more detailed study*