Supernova bound on keV-mass sterile neutrinos

Shun Zhou

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), 80805 München, Germany

DOI: http://dx.doi.org/10.3204/DESY-PROC-2011-03/zhou

In this talk, I first explain why the keV-mass sterile neutrinos, slightly mixing with ordinary neutrinos, are interesting in particle astrophysics. Then the production and oscillation of such sterile neutrinos in the supernova core are discussed. Assuming the ν_τ-ν_s mixing and implementing the standard energy-loss argument, I finally draw the supernova bound on the active-sterile mixing angle for a given sterile neutrino mass.

1 Motivation

It has been well established that the matter content of our Universe is dominated by the non-baryonic dark matter. A lot of attention has been so far focused on the cold dark matter (CDM), which has a negligible velocity dispersion and damps structures below the Earth mass scales [1]. The candidates for CDM arise from the well-motivated theories of elementary particle physics [2], such as the lightest supersymmetric particle and the axion. However, the CDM scenario suffers from several unsolved problems in the galaxy and small-scale structure formation, e.g., the overprediction of the observed satellites in the galaxy-scale halos [3] and the high concentration of dark matter in galaxies [4]. In the scenario of warm dark matter (WDM), a light-mass particle with a large velocity dispersion can suppress the structure formation up to the galaxy scales and thus solve the potential small-scale structure problems.

Sterile neutrinos of keV masses are a promising candidate for the WDM [5]. Dodelson and Widrow have proposed that sterile neutrinos with masses $m_s \sim$ keV can be produced via neutrino oscillations in the early Universe and account for all the dark matter [6], if they mix with the ordinary neutrinos via a small vacuum mixing angle $\theta \sim 10^{-(4\cdots5)}$. Due to such a tiny mixing angle, the sterile neutrinos have never been in thermal equilibrium. In the presence of a primordial lepton asymmetry, Shi and Fuller have observed that the production rate of sterile neutrinos could be enhanced by the Mikheyev-Smirnov-Wolfenstein (MSW) effect [7] and the correct relic abundance can be reproduced even for much smaller mixing angles [8]. One possible way to detect sterile-neutrino WDM is to look for the X-rays from their radiative decays [9]. Conversely, the non-observation of an X-ray line from the local group dwarf galaxies has placed restrictive limits on the mass and mixing angle of sterile neutrinos. Other limits can be obtained from the Lyman-alpha forest and Supernova (SN) 1987A [5]. Put all together, the window for the Dodelson-Widrow mechanism of non-resonant production is closed, while the Shi-Fuller mechanism of resonant production is still viable [10]. Roughly speaking, sterile neutrinos with $m_s = 1 \sim 10$ keV and $\theta = 10^{-(4\cdots6)}$ could be WDM. However, it should be noted that the observational constraints depend crucially on the production mechanisms of sterile neutrinos, so they can be evaded in various models [11].

Moreover, the WDM sterile neutrinos could play an important role in generating the supernova asymmetries and the pulsar kicks [12], and perhaps in the supernova explosions [13]. Hence it is interesting to reexamine the SN bound on the keV-mass sterile neutrinos.

2 Sterile neutrinos in SN cores

Sterile neutrinos with masses in the keV range can be copiously produced in the SN core. For $m_s \gtrsim 100$ keV, the vacuum mixing angle of sterile neutrinos is stringently constrained $\sin^2 2\theta \lesssim 10^{-9}$ in order to avoid excessive energy loss [14]. For smaller masses, however, the MSW effect on active-sterile neutrino mixing becomes very important and the SN bound on vacuum mixing angle is not that obvious. Note that the bounds on mixing angles depend on which neutrino species the sterile neutrino mixes with. We concentrate on the SN bound in ν_τ-ν_s-mixing case for simplicity, because ν_τ and $\overline{\nu}_\tau$ only have neutral-current interactions and essentially stay in thermal equilibrium with the ambient matter.

The matter density in the SN core is so high that the incoherent scattering of active neutrinos on matter particles may even dominate over flavor oscillations as the production mechanism for keV-mass sterile neutrinos. An elegant formalism to deal with both incoherent scattering and flavor oscillations has been developed in Ref. [15], where the evolution equations for the occupation numbers of different neutrino species have been derived. In the weak-damping limit, which is always valid for supernova neutrinos mixing with keV-mass sterile neutrinos, the evolution of ν_τ number density is determined by [16]

$$\dot{N}_{\nu_\tau} = -\frac{1}{4}\sum_a \int \frac{E^2 \mathrm{d}E}{2\pi^2} s^2_{2\theta_\nu} \int \frac{E'^2 \mathrm{d}E'}{2\pi^2} W^a_{E'E} f^\tau_{E'} \ , \tag{1}$$

where $s_{2\theta_\nu} \equiv \sin 2\theta_\nu$ with θ_ν being the neutrino mixing angle in matter, f^τ_E the occupation number of ν_τ, and $W^a_{E'E}$ the transition probability for $\nu(E') + a \to \nu(E) + a$ with a being background particles in the SN core. In a similar way, we can derive the evolution equation of the $\bar{\nu}_\tau$ number density, involving the mixing angle $\theta_{\bar{\nu}}$, the occupation number $f^{\bar{\tau}}_E$ and the transition probability $\bar{W}^a_{E'E}$. Due to the MSW effect, the mixing angle of neutrinos in matter is different from that of antineutrinos, i.e.,

$$\sin^2 2\theta_{\nu,\bar{\nu}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta \pm E/E_\mathrm{r})^2} \ , \tag{2}$$

where θ denotes the vacuum mixing angle, and the upper sign refers to ν and the lower to $\bar{\nu}$. The resonant energy $E_\mathrm{r} \equiv \Delta m^2/2|V_{\nu_\tau}|$ can be written as

$$E_\mathrm{r} = 3.25\ \mathrm{MeV} \left(\frac{m_s}{10\ \mathrm{keV}}\right)^2 \rho_{14}^{-1} \left|Y_0 - Y_{\nu_\tau}\right|^{-1} \ , \tag{3}$$

where ρ_{14} is the matter density ρ in units of 10^{14} g cm^{-3} and $Y_0 \equiv (1 - Y_e - 2Y_{\nu_e})/4$. Note that $Y_x \equiv (N_x - N_{\bar{x}})/N_\mathrm{B}$ with N_B being the baryon number density, N_x and $N_{\bar{x}}$ being the number densities of particle x and its antiparticle $\bar{x}$. For tau neutrinos, the matter potential $V_{\nu_\tau} = -(G_\mathrm{F}/\sqrt{2})N_\mathrm{B}\,(1 - Y_e - 2Y_{\nu_e} - 4Y_{\nu_\tau})$ is negative if the typical values of $Y_e = 0.3$, $Y_{\nu_e} = 0.07$ and $Y_{\nu_\tau} = 0$ for a SN core are taken. Therefore, the mixing angle for $\bar{\nu}_\tau$ is enhanced by matter effects, and the emission rate for $\bar{\nu}_\tau$ exceeds that for ν_τ, indicating that a ν_τ-$\bar{\nu}_\tau$ asymmetry (i.e., $Y_{\nu_\tau} \neq 0$) will be established. An interesting feedback effect emerges: (i) The chemical

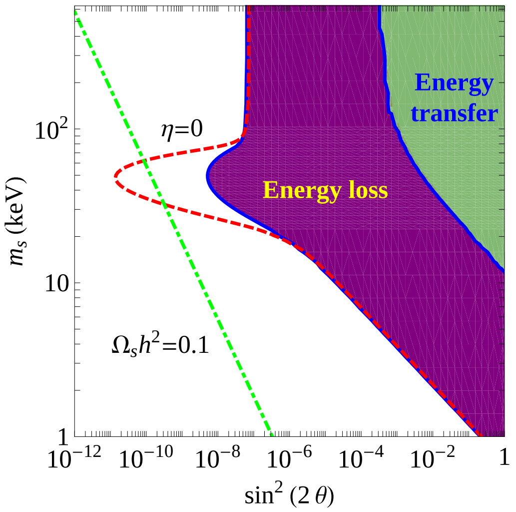

Figure 1: (color online) Supernova bound on sterile neutrino masses m_s and mixing angles θ, where the purple region is excluded by the energy-loss argument while the green one by the energy-transfer argument [16]. The excluded region will be extended to the dashed (red) line if the build-up of degeneracy parameter is ignored, i.e., $\eta(t) = 0$. The dot-dashed (green) line represents the sterile neutrinos as dark matter with the correct relic abundance $\Omega_s h^2 = 0.1$.

potential for tau neutrinos develops and thus changes the occupation numbers of ν_τ and $\bar{\nu}_\tau$; (ii) The ν_τ-$\bar{\nu}_\tau$ asymmetry shifts the resonant energy $E_{\rm r}$, and thus modifies the mixing angles θ_ν and $\theta_{\bar{\nu}}$; (iii) Both effects in (i) and (ii) will feed back on the emission rates. Hence a stationary state of this active-sterile neutrino system will be achieved if the emission rates for neutrinos and antineutrinos become equal to each other [16].

3 SN bound on sterile neutrinos

Given the sterile neutrino mass m_s and vacuum mixing angle θ, the energy loss rate $\mathcal{E}(t)$ due to sterile neutrino emission can be calculated by following the evolution of ν_τ-$\bar{\nu}_\tau$ asymmetry $Y_{\nu_\tau}(t)$. It has been found that the stationary state can be reached within one second and the feedback effect is very important for 20 keV $\lesssim m_s \lesssim$ 80 keV and $10^{-9} \lesssim \sin^2 2\theta \lesssim 10^{-4}$. To avoid excessive energy losses, we require that the average energy-loss rate $\langle \mathcal{E} \rangle \equiv \int_0^{\tau_{\rm d}} \mathcal{E}(t)\ {\rm d}t$ with $\tau_{\rm d} = 1$ s should be $\langle \mathcal{E} \rangle \lesssim 3.0 \times 10^{33}$ erg cm^{-3} s^{-1}. Otherwise, the duration of neutrino burst from SN 1987A would have been significantly reduced. In Fig. 1, we show the contours of energy-loss rates in the $(\sin^2 2\theta, m_s)$-plane, where we have assumed a homogeneous and isotropic core with matter density $\rho = 3.0 \times 10^{14}$ g cm^{-3} and temperature $T = 30$ MeV. Based on the energy-loss argument, the purple region has been excluded. The most stringent bound $\sin^2 2\theta \lesssim 10^{-8}$ arises for $m_s = 50$ keV. For the large-mixing angle region, the energy-loss rate is actually small, because sterile neutrinos have been trapped in the core and cannot carry away energies. However, the mean free path of sterile neutrinos is comparable to or even larger than that of ordinary neutrinos, indicating that they may transfer energies in a more efficient way. As a consequence, the duration of neutrino burst will be shortened by emitting neutrinos more rapidly. In this sense, the excessive energy transfer should be as dangerous as the excessive energy loss. Hence the large-mixing angle region is excluded when the energy-transfer argument is applied. The green line in Fig. 1 indicates the relic abundance of dark matter $\Omega_s h^2 = 0.1$, where keV-mass sterile neutrinos are warm dark matter and the non-resonant production mechanism is assumed. If we ignore the feedback effect (i.e., a vanishing chemical potential for tau neutrinos $\eta = \mu_{\nu_\tau}/T = 0$), the excluded region will extend to the red line, which overlaps the relic-abundance line. However, the mixing angles are essentially unconstrained in the favored warm-dark-matter mass range 1 keV $\lesssim m_s \lesssim$ 10 keV.

As for the ν_μ-ν_s-mixing case, our discussions about the feedback effects are essentially applicable. However, the charged-current interactions of ν_μ and $\bar{\nu}_\mu$ should be taken into account, and the change of ν_μ-$\bar{\nu}_\mu$ asymmetry will be redistributed between muon neutrinos and charged muons. The ν_e-ν_s mixing in SN cores is more involved because of the large trapped electron number and high ν_e degeneracy. Besides energy loss, deleptonization by sterile neutrino emission is an effect to be taken into account.

Acknowledgements

The author would like to thank the organizers for such a wonderful workshop on supernova neutrinos, and Georg Raffelt for collaboration. This work was supported by the Alexander von Humboldt Foundation.

References

[1] S. Hofmann, D.J. Schwarz and H. Stoecker, Phys. Rev. D **64**, 083507 (2001).

[2] F.D. Steffen, Eur. Phys. J. C. **59**, 557 (2009).

[3] G. Kauffmann, S.D.M. White and B. Guiderdoni, Mon. Not. R. Astron. Soc. **264**, 201 (1993).

[4] P.J.E. Peebles, arXiv:astro-ph/0101127.

[5] A. Kusenko, Phys. Rept. **481**, 1 (2009).

[6] S. Dodelson and L.M. Widrow, Phys. Rev. Lett. **72**, 17 (1994).

[7] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978);
S.P. Mikheyev and A.Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985).

[8] X.D. Shi and G.M. Fuller, Phys. Rev. Lett. **82**, 2832 (1999).

[9] K.N. Abazajian, arXiv:0903.2040 [astro-ph.CO].

[10] A. Boyarsky *et al.*, Phys. Rev. Lett. **102**, 201304 (2009).

[11] A. Kusenko, Phys. Rev. Lett **97**, 241301 (2006);
F. Bezrukov, H. Hettmansperger and M. Lindner, Phys. Rev. D **81**, 085032 (2010).

[12] A. Kusenko and G. Segre, Phys. Lett. B **396**, 197 (1997).

[13] J. Hidaka and G.M. Fuller, Phys. Rev. D **74**, 125015 (2006);
J. Hidaka and G.M. Fuller, Phys. Rev. D **76**, 083516 (2007).

[14] K. Kainulainen, J. Maalampi and J.T. Peltoniemi, Nucl. Phys. B **358**, 435 (1991);
G. Raffelt and G. Sigl, Astropart. Phys. **1**, 165 (1993);
X. Shi and G. Sigl, Phys. Lett. B **323**, 360 (1994);
K. Abazajian, G.M. Fuller and M. Patel, Phys. Rev. D **64**, 023501 (2001).

[15] G. Sigl and G. Raffelt, Nucl. Phys. B **406**, 423 (1993).

[16] G.G. Raffelt and S. Zhou, Phys. Rev. D **83**, 093014 (2011).