Sterile Neutrinos in extra dimensions as Warm Dark Matter candidates

Juliana Stachurska

MPIK Heidelberg

Schule für Astroteilchenphysik 2014
Obertrubach-Bärnfels, October 8 - 16, 2014,

Max-Planck-Institut für Kernphysik

$m_\nu = m_L - m_D^T M_R^{-1} m_D$

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Sterile-active neutrino mixing

- in Standard Model, neutrinos only left-handed $\rightarrow$ massless
- Right-handed neutrinos are sterile under weak interaction $\Rightarrow$ sterile under all Standard Model interactions
- only way to interact: mixing

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

  where $i = \{1, 2, 3, s1, s2, s3, ...\}$
- usually only one active-sterile mixing $U_{\alpha s}$ with vacuum mixing angle $\theta_{\alpha s} = \theta$ "large" assumed

Sterile Neutrinos in Extra Dimensions

- one effective compactified extra dimension of radius R
  $\Rightarrow$ decomposition into Kaluza-Klein tower of particles
  $\psi(x, y) = \frac{1}{\sqrt{2\pi R}} \left[\psi^0 + \sum_{k=0}^{\infty} \left(\psi_+^k(x) \cos \frac{ky}{R} + \psi_-^k(x) \sin \frac{ky}{R}\right)\right]$

Sterile Neutrinos in Extra Dimensions

- one effective compactified extra dimension of radius R
  $\Rightarrow$ decomposition into Kaluza-Klein tower of particles
  $\psi(x,y) = \frac{1}{\sqrt{2\pi R}} \left[\psi^0 + \sum_{k=0}^{\infty} \left(\psi_+^k(x) \cos \frac{ky}{R} + \psi_-^k(x) \sin \frac{ky}{R} \right) \right]$
  zero mode ψ^0, even mode ψ_+^k, odd mode ψ_-^k

Sterile Neutrinos in Extra Dimensions

- one effective compactified extra dimension of radius R
  $\Rightarrow$ decomposition into Kaluza-Klein tower of particles
  $\psi(x, y) = \frac{1}{\sqrt{2\pi R}} \left[\psi^0 + \sum_{k=0}^{\infty} \left(\psi_+^k(x) \cos \frac{ky}{R} + \psi_-^k(x) \sin \frac{ky}{R}\right)\right]$
  zero mode ψ^0, even mode ψ_+^k, odd mode ψ_-^k
- mass of the modes depends on R as $m_{s,k} \approx k/R$
- mixing then is

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

  where $i = \{1, 2, 3, s1, s2, s3, ...\}$and $\theta_{\alpha s_k} \propto \frac{m_\alpha}{m_{s_k}}$

Generation of Sterile Neutrino Warm Dark Matter

- with a mass in the keV range, sterile neutrinos are a good Warm Dark Matter candidate
- could solve "missing satellite problem" of CDM
- various proposed production mechanisms:
    - oscillation (Dodelson-Widrow mechanism)
    - resonant enhancement of oscillation (Shi-Fuller mechanism)
    - decay of a more massive scalar
    - ...

Shi-Fuller mechanism

- to produce significant amount of sterile neutrinos to account for Dark Matter in the universe: need resonant enhancement of oscillation
- resonant enhancement of oscillations in early universe via matter effect on oscillation parameters (**M**ikheyev **S**mirnov **W**olfenstein effect) if:

Shi-Fuller mechanism

- to produce significant amount of sterile neutrinos to account for Dark Matter in the universe: need resonant enhancement of oscillation
- resonant enhancement of oscillations in early universe via matter effect on oscillation parameters (**M**ikheyev **S**mirnov **W**olfenstein effect) if:
    - matter mixing angle $\sin^2 2\theta_m$ different from vacuum mixing angle $\sin^2 2\theta_0$
    - asymmetry between neutrinos and antineutrinos enhances the matter mixing angle and can make it maximal
    - the resulting resonance is adiabatic = very effective conversion of active to sterile states $\Rightarrow$ essentially all ν_α in the resonant region get transformed into ν_s

Lepton Asymmetry

- an additional oscillation potential can change the effective oscillation potential between the active and sterile state significantly
- additional potential comes from neutrinos interacting with the bath
  - one-loop contributions to neutrino self-energy
  - depends on different amounts of particle and antiparticle
    $\Rightarrow$ sign of contribution different for neutrino and antineutrino
    $\Rightarrow$ if neutrino oscillation is enhanced for one flavor, it is suppressed for the corresponding antineutrino

Oscillation Potential

- effective oscillation potential is $\mathbf{V} = (V_x, V_y, V_z)$ where $V_x = \frac{\delta m^2}{2E} \sin 2\theta$ is the transformation rate, $V_y = 0$

Oscillation Potential

- effective oscillation potential is $\mathbf{V} = (V_x, V_y, V_z)$ where $V_x = \frac{\delta m^2}{2E}\sin 2\theta$ is the transformation rate, $V_y = 0$

$$V_z \approx -\frac{\delta m^2}{2E}\cos 2\theta \qquad +0.35\, G_F\, T^3 (L_0 + \mathcal{L})$$

$$\begin{array}{rr} \uparrow & \uparrow \\ \text{vacuum osc.} & \text{contribution from} \\ \text{potential} & \text{asymmetric plasma} \end{array}$$

Oscillation Potential

- effective oscillation potential is $\mathbf{V} = (V_x, V_y, V_z)$ where $V_x = \frac{\delta m^2}{2E} \sin 2\theta$ is the transformation rate, $V_y = 0$

$$V_z \approx -\frac{\delta m^2}{2E} \cos 2\theta + 0.35\, G_F T^3 (L_0 + \mathcal{L})$$

$$\uparrow \qquad\qquad\qquad \uparrow$$

vacuum osc. potential — contribution from asymmetric plasma

$\mathcal{L} = 2L_{\nu_\alpha} + \sum_{\beta \neq \alpha} L_{\nu_\beta}$ is the effective lepton asymmetry, $L_{\nu_\alpha} = (n_{\nu_\alpha} - n_{\overline{\nu}_\alpha})/n_\gamma$ is the lepton asymmetry in the oscillating neutrino flavor

Active-to-sterile conversion

- resonance condition is $V_z = 0 \Leftrightarrow$ active-sterile level crossing
- if resonance is adiabatic $\Rightarrow$ all $\nu_\alpha \to \nu_s$
- spectral parameter $\epsilon = E/T$
- resonance temperature:

$$\frac{T_{\rm res}}{\rm MeV} \approx 90 \left(\frac{m_{s_k}}{\rm keV}\right)^{1/2} \left(\frac{\mathcal{L}}{10^{-3}}\right)^{-1/4} \epsilon_{\rm res}^{-1/4}$$

Active-to-sterile conversion

- resonance condition is $V_z = 0 \Leftrightarrow$ active-sterile level crossing
- if resonance is adiabatic $\Rightarrow$ all $\nu_\alpha \to \nu_s$
- spectral parameter $\epsilon = E/T$
- resonance temperature:

$$\frac{T_{\rm res}}{\rm MeV} \approx 90 \left(\frac{m_{s_k}}{\rm keV}\right)^{1/2} \left(\frac{\mathcal{L}}{10^{-3}}\right)^{-1/4} \epsilon_{\rm res}^{-1/4}$$

- higher-mass modes hit resonance first
- lower-energy part of neutrino spectrum converted first

Shi-Fuller mechanism - abundance

- adiabaticity condition:

$$V_x^2 \left| \frac{\mathrm{d}\epsilon_{\mathrm{res}}}{\mathrm{d}\, V_z} \right| \left| \frac{\mathrm{d}\epsilon_{\mathrm{res}}}{\mathrm{d}t} \right|^{-1} > 1$$

Shi-Fuller mechanism - abundance

- adiabaticity condition:

$$V_x^2 \left| \frac{\mathrm{d}\epsilon_{\mathrm{res}}}{\mathrm{d}\,V_z} \right| \left| \frac{\mathrm{d}\epsilon_{\mathrm{res}}}{\mathrm{d}t} \right|^{-1} > 1$$

$$4{\cdot}10^8 \left(\frac{m_{s_k}}{\mathrm{keV}}\right)^{1/2} \left(\frac{\mathcal{L}}{10^{-3}}\right)^{3/4} \epsilon_{\mathrm{res}}^{-1/4} \sin^2 2\theta_{\alpha s_k} \left(1 - \frac{\mathrm{d}\mathcal{L}/\mathrm{d}t}{4H\mathcal{L}}\right)^{-1} \overset{!}{>} 1$$

Shi-Fuller mechanism - abundance

- adiabaticity condition:

$$V_x^2 \left|\frac{\mathrm{d}\epsilon_{\mathrm{res}}}{\mathrm{d}V_z}\right| \left|\frac{\mathrm{d}\epsilon_{\mathrm{res}}}{\mathrm{d}t}\right|^{-1} > 1$$

$$4{\cdot}10^8 \left(\frac{m_{s_k}}{\mathrm{keV}}\right)^{1/2} \left(\frac{\mathcal{L}}{10^{-3}}\right)^{3/4} \epsilon_{\mathrm{res}}^{-1/4} \sin^2 2\theta_{\alpha s_k} \left(1 - \frac{\mathrm{d}\mathcal{L}/\mathrm{d}t}{4H\mathcal{L}}\right)^{-1} \overset{!}{>} 1$$

- assume all active neutrinos get converted in adiabatic, resonant region
  $\Rightarrow$ abundance today:

$$\Omega_{\nu_s}^{SF} h^2 = \frac{4}{3} \Delta L_{\nu_\alpha} \left(\frac{m_{\nu_s}}{91.5\mathrm{eV}}\right)$$

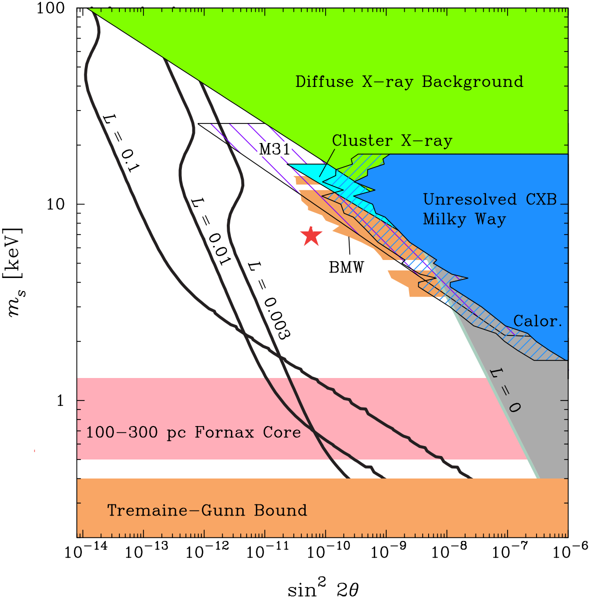
Signatures of sterile neutrinos I

- sterile neutrinos can decay into an active neutrino and a photon of $E_\gamma = m_s/2$ with the rate

$$\Gamma(\nu_s \to \nu_\alpha \gamma) = 1.38 \cdot 10^{-29}\ s^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1\mathrm{keV}}\right)^5$$

- recently found 3.55 keV line consistent with the decay of a sterile neutrino with a mass of 7.1 keV and a mixing angle of $\sin^2 2\theta \approx 7 \cdot 10^{-11}$
(Bulbul et al. arXiv:1402.2301; Boyarsky et al. arXiv: 1402.4119)

Signatures of sterile neutrinos I

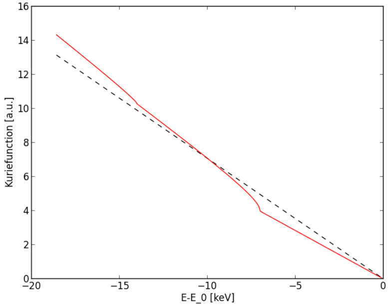


Signatures of sterile neutrinos II

- presence of a sterile neutrino changes the energy distribution of electrons from β-decay as

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \cos^2\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_{eff}^2) + \sin^2\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_s)$$

$\Rightarrow$ kinks in the Kurie spectrum $K(E) = \sqrt{\frac{\mathrm{d}\Gamma/\mathrm{d}E}{F(E,Z)}}$



KK tower shown here has
$m_1 = 7$ keV, $\sin\theta_1 = 0.5$;
$m_k = m_1/k$, $\sin\theta_k = \sin\theta_1/k$;
$k = (1, 2, 3, 4)$

Summary

- sterile neutrinos are a good Warm Dark Matter candidate (1-10keV masses)
- small mixing angles with active neutrinos required $\Rightarrow$ possible production through resonant enhancement of oscillations in Early Universe
- in extra dimension setting, get tower of states with clearly defined sequence of masses $\Rightarrow$ clear signatures e.g. in beta spectrum
- unidentified 3.55 keV line might be from a sterile neutrino