On the detection low energy neutrino background in the Universe

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keV scale ν_s dark matter

- keV scale spin $1/2$ dark matter, sterile neutrino
- detection of sterile neutrino DM using radioactive nuclei

Cosmic background neutrinos

- cosmic background neutrinos in the universe
- detection of CBN in a target of periodic structure

Summary

CDM has problem in explaining small structures in galaxies

- Numerical simulation: $10^3 - 10^4$ dwarf galaxies in Milky Way.
  Only around 10 observed

WDM: $m_{WDM} \gtrsim 1$ keV from structure formation

- WDM has larger velocity dispersion and leads to less sub-structures in simulation
- Lyman-α observations put a good constraint on keV scale WDM

WDM or CDM? Question open for exploration.

We consider keV scale warm dark matter

Virtue of keV scale DM for theorists

GeV scale DM

- should be stable or has lifetime longer than the age of the universe
- some quantum number should guarantee its stability; extra global or discrete symmetry needed in theory.
- symmetry usually put in by hand, not natural for theorists

keV scale DM

- naturally has long lifetime since it does not have enough phase space for decay
- extra quantum number is not needed and no extra symmetry put in by hand

ν_s decay rate is suppressed by its small mass,
no extra global quantum number needed, compared to CDM

ν_s decays mainly through $\nu_s \to \nu + 2\bar{\nu}, 2\nu + \bar{\nu}$:

$$\tau_{\nu_s} = 5. \times 10^{26} s \left(\frac{1 \text{ keV}}{M_s} \right)^5 \frac{10^{-8}}{\Theta^2}$$

$\Theta^2 = |R_{es}|^2 + |R_{\mu s}|^2 + |R_{\tau s}|^2$.
τ_{ν_s} much larger than the age of the universe $\sim 10^{17}$s

ν_s is a good dark matter candidate

keV scale $\nu_{R1}(\nu_s)$ dark matter in low energy seesaw

A low energy seesaw(keV scale ν_{R1} and GeV scale $\nu_{R2,3}$, νSM) (Asaka, Blanchet and Shaposhnikov, 2005)

We found(He, Li and Liao, 2009)

- the νSM has an approximate Friedberg-Lee symmetry:

$$\nu_{R1} \rightarrow \nu_{R1} + \theta$$

  natural splitting of keV scale ν_{R1} and GeV scale $\nu_{R2,3}$
- active neutrino masses either normal or inverse hierarchy
- large mixing of $\nu_{R2,3}$ with active neutrinos can be achieved
- $0\nu\beta\beta$ constraint can be satisfied for quasi-degenerate $\nu_{R2,3}$ even if mixings are large

ν_{R1} dark matter can be produced in the early universe

- through mixing with active neutrinos: R_{l1}
- or through the decay of a singlet S: $S \to \nu_{R1}\nu_{R1}$ (Shaposhnikov and Tkachev, 2006; Kusenko, 2006)

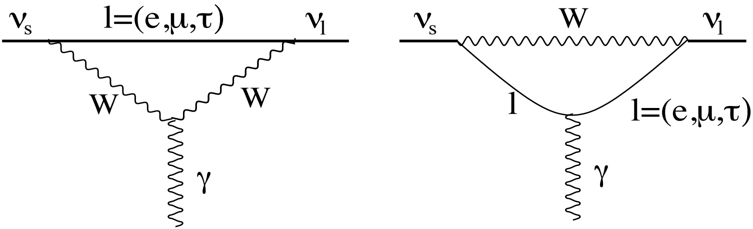
$$\Delta L = \frac{f_\alpha}{2} S \bar{\nu}_{R\alpha} \nu^c_{R\alpha} + h.c. + V(S, H)$$

$< S >$ gives mass to ν_R; S in thermal equilibrium, ν_{R1} is not

- or through decay of other particles (Lindner et. al., 2010)

Major constraints on this model of dark matter:

- Production of $\rho_{\nu_{R1}}$ in the right range of Ω_{dm}
- Satellite X-ray observation on the decay line of $\nu_{R1} \rightarrow \nu + \gamma$
- structure formation($M_1 \gtrsim 1$ keV)
- Lyman-α forest constraints



$\nu_s - \nu_l$ mixing leads to radiative decay $\nu_s \to \nu_l + \gamma$

$$\Gamma = \frac{9\alpha_{EM} G_F^2}{256\pi^4}\Theta^2 m_{\nu_s}^5, \quad \Theta^2 = R_{es}^2 + R_{\mu s}^2 + R_{\tau s}^2$$

Satellite X-ray observation gives

$$\Theta^2 \lesssim 1.8 \times 10^{-5}\left(\frac{1 \text{ keV}}{m_{\nu_s}}\right)^5$$

The X-ray constraint is independent of ν_s model.
Other constraints on mixing R_{ls} depend on model of ν_s DM.

Model independently we have

$$m_{\nu_s} \gtrsim 1 \text{ keV}$$

$$\Theta^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1 \text{ keV}}{m_{\nu_s}} \right)^5$$

For example, large entropy release at multi-MeV scale temperature can be produced in low energy seesaw model. (Liao, 2010)

When two $\nu_{R2,3}$ are degenerate, one of them can be long-lived like K_L in Kaon system and its decay can reheat the universe.

- The decay produces entropy release $S \gg 1$
- $\nu_{R1}(\nu_s)$ density over-produced by mixing $|\theta_{ls}|^2 \sim 10^{-6}$ can be diluted by large entropy production
- velocity dispersion re-scaled by $S^{-1/3}$, Lyman-α constraint weaken
- $\nu_{R1}(\nu_s) - \nu_l$ mixing can reach the X-ray observation bou nd

Constraint on ν_s DM is much weaker in this example

It's crucial to detect ν_s dark matter in the universe.

Apparently detection of ν_s dark matter is difficult:

- The energy scale is quite low $\sim$ keV
- Its small mixing to active neutrinos give a further suppression to its weak interaction
- For $\sin^2\theta_{es} = 10^{-6}$ and $m_{\nu_s} = 2$ keV the $\nu_s - e$ scattering cross section is

$$\sigma \frac{v}{c} \approx 1. \times 10^{-55}\ \mathrm{cm}^{-2}$$

But the detection of keV scale ν_s DM is still possible.

I suggest to detect keV scale ν_s DM using radioactive nuclei (W. Liao, Phys. Rev. D82, 073001, 2010).
This is a new way to detect DM in the universe.

β decay nuclei with decay energy Q_β:

$$N \to N' + e + \bar{\nu}_e$$

$E_e = Q_\beta$ at the end point of β decay spectrum.

ν_s capture by radioactive nuclei N

$$\nu_s + N \to N' + e$$

has no threshold

anti-β decay nuclei can also be considered

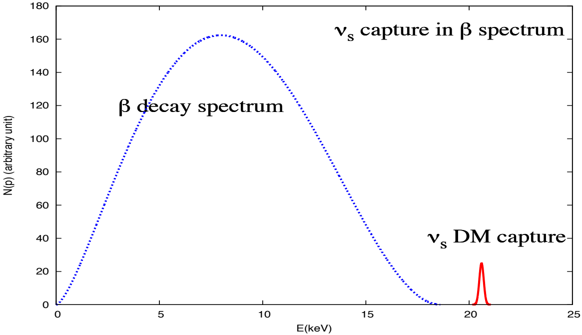
We found (Liao, 2010)
On Tritium(production rate in reactor: 0.01%)

$$N \approx 0.7 \ \mathrm{year}^{-1} \times \frac{n_{\nu_s}}{10^5 \ cm^{-3}} \frac{|R_{es}|^2}{10^{-6}} \frac{{}^3\mathrm{H}}{10 \ \mathrm{kg}}$$

On ^{106}Ru(production rate in reactor: 0.4%)

$$N \approx 16 \ \mathrm{year}^{-1} \times \frac{n_{\nu_s}}{10^5 \ cm^{-3}} \frac{|R_{es}|^2}{10^{-6}} \frac{{}^{106}\mathrm{Ru}}{10 \ \mathrm{Ton}}$$

Lifetime effect, Li and Xing 2011



Events of ν_s capture by radioactive nuclei: mono-energetic electrons well beyond the end point of beta decay spectrum

$$E_e = Q_\beta + m_{\nu_s}$$

ν_s number density is enhanced by its small mass

Taking the estimate of the galactic value of ρ_{dm} in the solar system

$$n_{\nu_s} = 10^5 \ \mathrm{cm}^{-3} \frac{\rho_{\nu_s}}{0.3 \ \mathrm{GeV} \ \mathrm{cm}^{-3}} \frac{3 \ \mathrm{keV}}{M_s}$$

Although the cross section suppressed by $|R_{es}|^2$
event rate enhanced by the large n_{ν_s} and hence the flux of ν_s.

Background caused by solar pp neutrinos with energy $\lesssim$ 10keV:

$$\sim 4.0 \times 10^{-3}\ \mathrm{year}^{-1} \quad \text{for } 10 \text{ kg } {}^3\mathrm{H}$$
$$\sim 8.5 \times 10^{-2}\ \mathrm{year}^{-1} \quad \text{for } 10 \text{ Ton } {}^{106}\mathrm{Ru}$$

solar neutrino background are negligible

According to big-bang cosmology

- neutrinos are in thermal equilibrium with photons, electrons, positrons and other particles for $T \gtrsim 1$ MeV
- The relic number density of CBN are correlated with the number density of CMB photons. n_ν per species is predicted to be

$$n_\nu = 56 \text{ cm}^{-3}$$

- Relic CBNs, if relatisvistic, should have

$$T_\nu = 1.96 \text{ K} \sim 10^{-4} \text{ eV}$$

According to neutrino oscillation experiments

- Neutrinos have masses and flavor mixing

$$\nu_l = \sum_i U_{li} \; \nu_i$$

- The mass squared differences are measured

$$\Delta m^2_{21} \approx 0.76 \times 10^{-4} \; \mathrm{eV}^2, \; |\Delta m^2_{32}| \approx 2.4 \times 10^{-3} \; \mathrm{eV}^2$$

- Mixing angles are measured as

$$\sin^2\theta_{12} \approx 0.30, \;\; \sin^2\theta_{23} \approx 0.50, \;\; \sin^2\theta_{13} \approx 0.09.$$

- constraint from β decay experiment

$$m_{\bar{\nu}_e} < 2.3 \text{ eV}$$

- constraint from CMB measurement

$$\sum_i m_i \lesssim 0.68 \text{ eV}$$

It's easy to figure out that

- at least two types of neutrinos are massive
- two massive neutrinos should have masses $\geq \sqrt{\Delta m_{21}^2}$
- if neutrinos are all massive, $m_i \lesssim 0.2 - 0.3$ eV

We can conclude that

- These massive neutrinos should all be non-relativistic today
- Relic neutrinos with low velocity should be clustered in galaxy or in cluster
- They should have lost coherence and exist in mass states today
- Solar system should stay in a halo of CBNs and there are wind of CBNs passing through us everyday.

How to detect this wind of CBNs

We remind that the non-universal effect of matter at rest to neutrinos are described by

$$\Delta\mathcal{L} \quad = -\sqrt{2} G_F N_e \bar{\nu}_e \gamma^0 \nu_e,$$

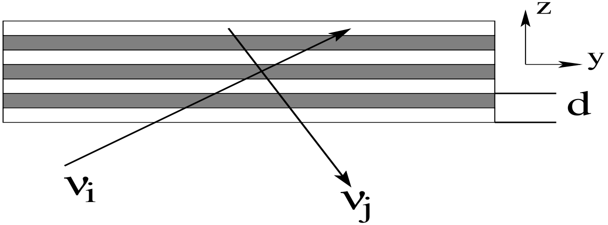
In the mass base this interaction is

$$\Delta\mathcal{L} \quad = -V_e \; U^*_{ej} U_{ei} \; \bar{\nu}_j \gamma^0 \nu_i,$$

$V_e = \sqrt{2} G_F N_e$

$\nu_i - \nu_j$ conversion can be induced by matter

Consider a target with periodic matter structure
(W. Liao, Phys. Rev. D86, 073011, 2012)



The cross section of $\nu_i - \nu_j$ conversion is

$$\sigma = \frac{1}{2E_i v_i} \int \frac{d^3 k_j}{(2\pi)^3} \frac{1}{2E_j} 2\pi\delta(E_i - E_j) \, |M|^2 \times \left| \int_\Omega d^3x \;\, V_e(x) U^*_{ei} U_{ej} \; e^{-i(\vec{k}_i - \vec{k}_j)\cdot\vec{x}} \right|^2,$$

The conversion probability is

$$p_n = \frac{|k_j^z||M|^2}{4E_i^2 v_i E_j} |V_n L_z U_{ej}^* U_{ei}|^2 \frac{4\sin^2(\Delta_n L_z)}{(\Delta_n L_z)^2},$$

L_z: the length of target in z direction, $\Delta_n = k_i^z - k_j^z - q_n$.
V_n, the Fourier component of $V_e(z)$

$$V_e(z) = \sum_n V_n \ e^{i\vec{q}_n \cdot \vec{x}},$$

$\vec{q}_n = q_n \hat{z}$, $q_n = 2\pi n/d$

- if $|\Delta_n L_z| > 1$, $p_n \propto |V_n/\Delta_n|^2$
- if $|\Delta_n L_z| < 1$, $p_n \propto |V_n L_z|^2$ and conversion is resonantly enhanced.

The condition of resonant conversion is

$$\vec{k}_i - \vec{k}_j - \vec{q}_n = 0.$$

k_j^z is solved

$$|k_j^z| = \sqrt{m_i^2 - m_j^2 + (k_i^z)^2}$$

$m_i^2 - m_j^2 > 0$ is required. Momentum transfer is $\approx \sqrt{\Delta m_{ij}^2}$

ν_j can pass through($k_j^z > 0$) or be reflected by($k_j^z < 0$) the detector

In this conversion process

- ν_i converts to ν_j and releases part of its rest energy to kinetic energy of ν_j
- momentum is balanced by the momentum transfer to electrons in target matter
- a periodic matter structure helps to balance momentum and enhance the conversion probability
- the effect of the periodic structure in the reflection case is like that in bragg scattering

Net momentum transfer from CBNs to detector is proportional to (for $|n| = 1$)

$$p = p_{+1} - p_{-1}$$

sizeable P can be achieved if the detector is arranged in such a way that

$$|\Delta_{+1} L_z| < 1 < |\Delta_{-1} L_z|$$

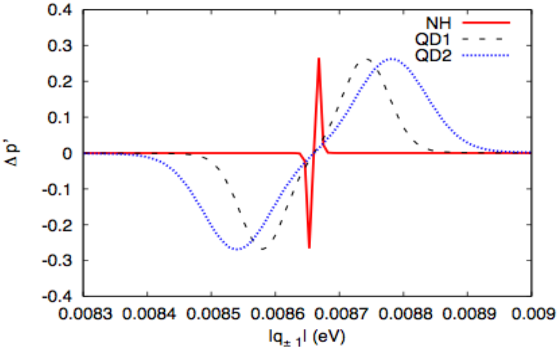
or

$$|\Delta_{-1} L_z| < 1 < |\Delta_{+1} L_z|$$

- The solar system moves with $\approx 300 km/s$ relative to the halo of Milky Way
- average $|\vec{k}| \sim 10^{-4} - 10^{-5}$ eV

To get significant transition rate and net momentum transfer matching between $2\pi/d$ and $\sqrt{\Delta m_{ij}^2}$ should be achieved to better than k_s scale.

- detail depends on the mass hierarchy
- present knowledge on Δm_{ij}^2 is not always enough
- careful matching can be achieved by using a large number of sample detectors



Asymmetry of $p'_{\pm 1}$ versus $|q_{\pm 1}|$ for $\nu_2 - \nu_1$ transition. $k_s L_z = 10$. $k_i^z = k_s = m_2|\vec{v}_s|$. NH: $m_2 = \sqrt{\Delta m_{21}^2}$; QD1: $m_2 = 2 \times \sqrt{|\Delta m_{31}^2|}$; QD2: $m_2 = 3 \times \sqrt{|\Delta m_{31}^2|}$.

Net momentum transfer per unit time from CBNs:

$$P \sim |q_{\pm 1}| \sqrt{1 - \frac{m_j^2}{m_i^2}} \frac{S}{1 \text{ m}^2} \frac{n_i}{100 \text{ cm}^{-3}} \times \left(\frac{L_z}{1 \text{ cm}} \right)^2 \frac{2.5}{k_s L_z} \text{ s}^{-1}.$$

Signal is very weak.

New idea is required to detect this momentum transfer to electrons in periodic target matter

- keV scale ν_s is an interesting DM candidate.
  $|R_{ls}|^2$ can reach 10^{-6}(for $\sim$ 2 keV), the bound from X-ray observation; Other astrophysical constraints satisfied
- I point out that it's possible to detect ν_s DM through capture by target of radioactive nuclei
- Capture of ν_s give mono-energetic electron well beyond the end point of the beta decay spectrum; signal very clear
- For $|R_{es}|^2 \sim 10^{-6}$ a few to tens events per year available for 10kg Tritium or 10 Ton ^{106}Ru

Possible to detect keV scale ν_s dark matter in β decay experiment

- Detection of CBNs is an un-solved fundamental problem in particle physics and cosmology
- A new scheme to detect CBNs making use of the massive nature of neutrinos is proposed.
- Net momentum can be achieved by carefully adjusting the periodic structure of target detector
- This might be a valuable step towards a final solution to the problem of detecting CBNs