On the detection of low energy neutrino background in the universe

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理论物理前沿研讨会，2011年12月26日－28日

Content

Content:

- **keV scale Dark Matter vs GeV scale Dark Matter**
- **keV scale spin** $1/2$ **dark matter, sterile neutrino**
- **capture of sterile neutrino DM by radioactive nuclei**
- keV scale spin 0 dark matter, pseudo-Goldstone boson(axion-like particle)
- capture of axion-like particle by intense crystalline field
- **cosmic background neutrinos in the universe**
- **detection of CBN in a target of periodic structure**
- **summary**

keV scale DM vs GeV scale DM

keV scale WDM vs. GeV scale CDM

CDM has problem in explaining small structures in galaxies

- Initial halos of WIMP-like CDM, $\sim 1 - 10$ Earth mass, emerge to form large halos, the galactic halo etc.
- Numerical simulation: around 1000 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
- However, Lyman-α observations disfavor WDM

WDM and CDM both have problems and are open for exploration.

We consider keV scale dark matter, not limited to WDM

keV scale DM vs GeV scale DM

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

keV scale sterile neutrino dark matter

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

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

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

$\Theta^2 = |R_{es}|^2 + |R_{\mu s}|^2 + |R_{\tau s}|^2$.
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 sterile neutrino dark matter

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:

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

  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

keV scale sterile neutrino dark matter

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)

keV scale sterile neutrino dark matter

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 $\nu_{R1} \to \nu + \gamma$
- structure formation($M_1 \gtrsim 1$ keV)
- Lyman-α forest constraints

keV scale sterile neutrino dark matter

If thermal history of the early universe has a reheating at temperature around multi-MeV range

- decay of some non-relativistic particles produce entropy release $S \gg 1$
- ν_{R1} density over-produced by mixing $|R_{l1}|^2 > 10^{-8}$ can be diluted by large entropy production
- velocity dispersion re-scaled by $S^{-1/3}$, Lyman-α constraint weaken
- ν_{R1} mixing can reach the X-ray observation bound

$$\Theta^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1\ \mathrm{keV}}{M_1} \right)^5$$

Significant entropy release can be produced by the decay of one of the degenerate $\nu_{R2,3}$. (Liao, 2010)

ν_s capture by radioactive nuclei

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

ν_s capture by radioactive nuclei

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 2010

ν_s capture by radioactive nuclei

ν_s number density is enhanced by its small mass

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

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

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.

ν_s capture by radioactive nuclei

Capture of ν_s on radioactive nuclei produce mono-energetic electron well beyond the end point of beta decay spectrum

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

Signal is clear, easy to detect

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

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

solar neutrino background are negligible

ν_s capture by radioactive nuclei

The solar system may stay in a sub-halo in which local dark matter density can be much larger than the galactic average value.

Astronomical constraint (J.-M. Frere et.al., 2008):

$$\rho_{dm} \lesssim 10^5 \ \mathrm{GeV\ cm^{-3}}$$

It means $n_{\nu_s} \lesssim 10^{11}$ cm^{-3} for keV scale ν_s

Better radioactive nuclei(beta or anti-beta decay) may exist. Conditions:

- enough life time;
  large enough capture cross section
- significant production in reactor or available in nature
- better to have large decay energy to avoid pollution of other radioactive sources

cosmic background neutrino

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

$$n_\nu = 57\ \mathrm{cm}^{-3}$$

- Relic CBNs, if relatisvistic, should have

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

cosmic background neutrino

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

$$\sin^2\theta_{12} \approx 0.30,\ \ \sin^2\theta_{23} \approx 0.50,\ \ \sin^2\theta_{13} \lesssim 0.15.$$

cosmic background neutrino

- constraint from β decay experiment

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

- constraint from CMB measurement

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

It's easy to figure out that

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

cosmic background neutrino

We can conclude that

- These massive neutrinos should all be non-relativistic today
- They should be clustered in galaxy
- They should have lost coherence and exist as mass eigenstates 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

detection of CBNs

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

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

In the mass base this interaction is

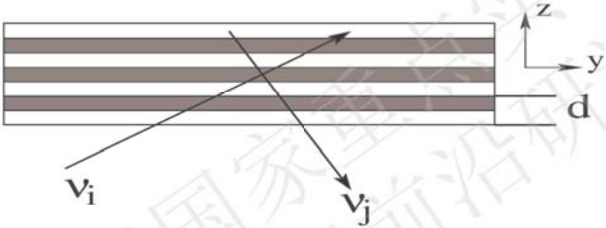
$$\Delta\mathcal{L} \quad = -V_e \; U^*_{ej} U_{ei} \; \bar{\nu}_j \gamma^0 \nu_i,$$

$V_e = \sqrt{2} G_F N_e$

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

detection of CBNs

Consider a target with periodic matter structure



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

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

detection of CBNs

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.

detection of CBNs

The condition of resonant conversion is

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

k_j^z is solved

$$|k_j^z| = \sqrt{m_i^2 - m_j^2 + (k_i^z)^2} \tag{1}$$

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

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

detection of CBNs

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

$$P = P_{+1} - P_{-1} \tag{2}$$

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

$$|\Delta_{+1} L_z| < 1 < |\Delta_{-1} L_z| \tag{3}$$

or

$$|\Delta_{-1} L_z| < 1 < |\Delta_{+1} L_z| \tag{4}$$

detection of CBNs

- 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 $\sqrt{\Delta m^2_{ij}}$ should be achieved to better than 1%.
- present knowledge on Δm^2_{ij} is not enough
- careful matching can be achieved by using a large number of sample detectors

detection of CBNs

Previous works ($\sim$ 30 years ago) have shown that

- momentum transfer from CBNs(relativistic) is $\sim 10^{-4}$eV
- the probability is proportional to $(V/E_\nu)^2(L/\lambda_\nu) \approx (V_e/E_\nu)(VL)$.

In this new approach making use of the massive nature of neutrinos

- conversion of neutrinos in mass bases is considered and the momentum transfer is of order $\sqrt{\Delta m_{ij}} \sim 10^{-2}$ eV
- The probability of resonant conversion is proportional to $(VL)^2$
- Both of these two quantities can be enhanced by orders of magnitude in comparison with previous results

Summary

- keV scale dark matter is interesting
- keV scale ν_s is a good spin 1/2 DM candidate. $|R_{ls}|^2$ can reach 10^{-6}(for $\sim$ 2 keV), the bound from X-ray observation; Other astrophysical constraints satisfied
- 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

Summary

- Detection of CBNs is an un-solved fundamental problem in cosmology
- A new scheme to detect CBNs making use of the massive nature of neutrinos is proposed.
- The momentum transfer and reaction rate can all be enhanced by orders of magnitude compared to old results
- Net momentum can be achieved by carefully adjusting the periodic structure of target detector
- This might be a valuable step towards the final solution to the problem of detecting CBNs

Thank you