On the detection of keV scale neutrino dark matter in β decay experiment

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Content:

- Why keV scale sterile neutrino warm dark matter
- Models and constraints of keV scale sterile neutrino DM
- Measurement of ν_s in its admixture to β decay
- Detection of ν_s DM using capture by radioactive nuclei
- Other proposals to detect ν_s DM
- Summary

Astronomical evidence suggests keV scale warm dark matter.

see numerous lectures in this workshop

Virtue of keV scale DM for particle 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, e.g. R parity put in by hand in supersymmetry

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

We consider keV scale sterile neutrino dark matter

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

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

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

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

ν_s is a good dark matter candidate

ν_s dark matter can be produced in the early universe

- through oscillation of active neutrinos to sterile neutrino
  - It is proportional to the square of the $\nu_l - \nu_s$ mixing: $\sin^2\theta_{ls}$.
  - For $\sin^2\theta_{ls} \sim 10^{-8}$, ν_s produced can account for all Ω_{dm}.
  - For $\sin^2\theta_{ls} \gtrsim 10^{-8}$, ν_s is overproduced and its density can be reduced if reheating happens after ν_s DM production.
  - It can be resonantly enhanced if some condition for matter density can be satisfied.
- or through the decay of a singlet scalar or other particles

Detailed correlation of ν_s DM density with θ_{ls} depends on the model of ν_s DM.

keV scale ν_s dark matter in low energy seesaw model (keV scale ν_{R1} and GeV scale $\nu_{R2,3}$, νSM or νMSM) (Asaka, Blanchet and Shaposhnikov, 2005)

- ν_s is identified as the keV ν_{R1} in this model
- masses and mixings of active neutrinos can be explained in this model
- active neutrino masses either normal or inverse hierarchy
- large mixing of $\nu_{R2,3}$ with active neutrinos can be achieved

This type of models of keV scale ν_s DM have been extensively discussed by many authors. Many implications and predictions have been explored.

Is it natural to have one keV scale ν_{R1} and two GeV scale $\nu_{R2,3}$ in this νSM model?

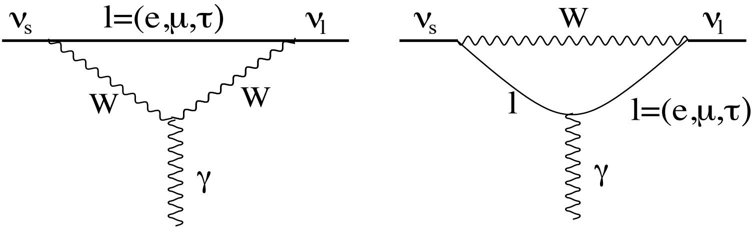
Yes, there are symmetries in the limit $m_{\nu_{R1}} \rightarrow 0$:

- The model has an approximate Friedberg-Lee symmetry(He, Li and Liao, 2009) :

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

  θ is a grassmann number
- A $U(1)$ symmetry is available if $\nu_{R2,3}$ are degenerate and $m_{\nu_{R1}} \rightarrow 0$(Shaposhnikov, 2007)

Splitting of keV scale ν_{R1} and GeV scale $\nu_{R2,3}$ is natural



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

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

Satellite X-ray observation gives

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

Lyman α forest can build an image

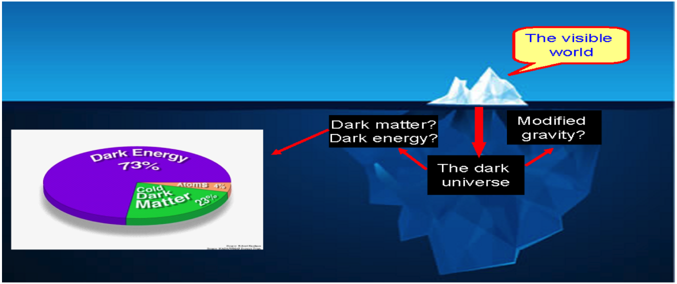
- of the hydrogen matter density
- of the power spectrum of total matter

Lyman α forest gives

$$m_{\nu_s} \gtrsim 1 - 10 \text{ keV}$$

This constraint depends on the initial ν_s velocity distribution and in some models m_{ν_s} can be as low as 1 keV

The dark universe



Ω_{ν_s} should be produced in the right range:

- $\Omega_{\nu_s} = 0.23 \pm 0.02$, if ν_s accounts for all DM
- $\Omega_{\nu_s} \lesssim 0.23$, if ν_s accounts for part of DM

This puts a constraint on Θ^2

The constraint on Θ^2 from Ω_{ν_s} depends on model of ν_s DM.

- It depends on model of ν_s production in the early universe. It is allowed to be as small as $10^{-9} - 10^{-10}$ to account for all DM in the universe.
- It depends on the thermal history of the early universe. It is allowed to reach $\sim 10^{-5} - 10^{-6}$ if reheating occurs after ν_s DM produced

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 bound

Constraint on ν_s DM is much weaker in this example

Major constraints on ν_s dark matter:

- Production of ρ_{ν_s} in the right range of Ω_{dm}, the constraint on Θ^2, depends on ν_s model
- Lyman-α forest, constraint on m_{ν_s}, depends on ν_s model
- Satellite X-ray observation on the decay line of $\nu_s \to \nu + \gamma$

Model independently we have

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

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

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.

There is a mechanism known for long to detect keV scale ν_s in β decay.

Due to the $\bar{\nu}_s - \bar{\nu}_e$ mixing, $\bar{\nu}_s$ can be produced in β decay

$$N \rightarrow N' + e + \bar{\nu}_s$$

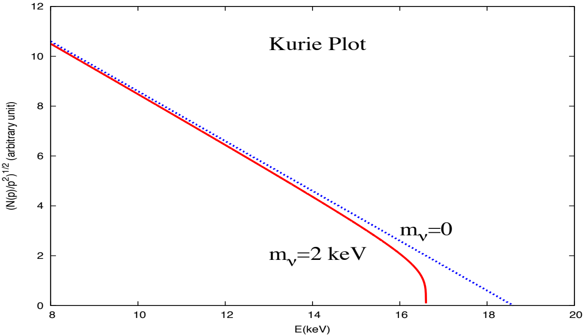
At the end point of the decay spectrum, electron energy is

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

This decay does not give electron with energy $> Q_\beta - m_{\nu_s}$.

This decay is not possible when $Q_\beta < m_{\nu_s}$

Measurement of ν_s in its admixture to β decay



Kurie Plot, $\sqrt{N(p)/p^2}$ versus E, of β decay

The total β spectrum is a mixture of both decays:

$$N \to N' + e + \bar{\nu}_e \quad \text{and} \quad N \to N' + e + \bar{\nu}_s$$

The electron count rate $N(p)$ is

$$N(p) = N_e(p, m_{\nu_e}) \cos^2 \theta_{es} + N_s(p, m_{\nu_s}) \sin^2 \theta_{es}$$

In the energy range $Q_\beta - m_{\nu_s} < E < Q_\beta$, $N_s(p, m_{\nu_s}) = 0$ and

$$N(p) = N_e(p, m_{\nu_e}) \cos^2 \theta_{es}$$

The count rate is smaller than the rate of usual β decay in this energy range.

Define

$$R = 1 - \frac{N(p)}{N_e(p,0)}$$

We can find that

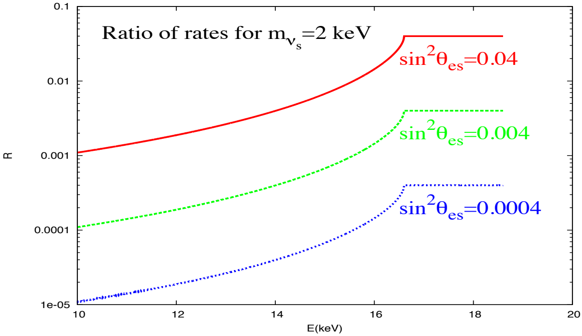
- in energy range $Q_\beta - m_{\nu_s} < E < Q_\beta$

$$R = \sin^2\theta_{es}$$

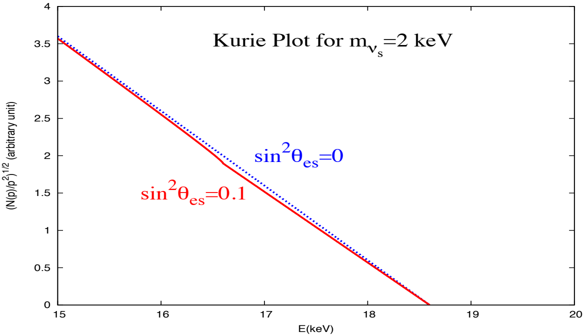
- in the energy range $E < Q_\beta - m_{\nu_s}$

$$R \to 0, \quad \text{as } E \to 0$$

R versus E



Rate only analysis in experiment can be done in a few energy intervals to measure the disappearance of β events



In Kurie plot, the slope in $[Q_\beta - m_{\nu_s}, Q_\beta]$ range is smaller

Good energy resolution is required to measure the slope

This type of measurement can also be used to look for eV scale sterile neutrino which is inspired by neutrino oscillation experiment

For keV scale ν_s the distortion to β decay spectrum is larger than for eV scale ν_s.

This type of measurement will have better sensitivity for keV scale ν_s than for eV scale ν_s.

Previous measurements(^{3}H, ^{187}Re) :
J. J. Simpson, Phys. Rev. D24,2971(1981)

K.H. Hiddenman, H. Daniel and O. Schwentker, J. Phys. G21, 639(1995)

M. Galeazzi, F. Fontanelli, F. Gatti and S. Vitale, Phys. Rev. Lett 86,1978(2001)

Most recent measurement(PRL86, 1978):

$$\sin^2\theta_{es} \lesssim 0.01, \quad \text{for } m_{\nu_s} \approx 1 \text{ keV}$$

Sensitivity to in future experiments?

Measuring the kink in β decay spectrum

- is a direct way to measure the existence of keV scale ν_s.
- is not yet a direct way to detect ν_s dark matter in the universe.

A direct laboratory detection of keV scale ν_s dark matter in the universe is needed.

Many people even believe that it's not possible to do direct laboratory search of keV scale ν_s DM(keV scale WDM in general) in the universe.

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.

Consider β decay nuclei with decay energy Q_β:

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

At the end point of the β decay spectrum, electron energy is

$$E_e = Q_\beta$$

anti-β decay nuclei can also be considered

Mixing of ν_s with ν_e makes it possible to capture ν_s DM.

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

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

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

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

Lifetime effect, Li and Xing 2011

ν_s capture by radioactive nuclei N

$$\nu_s + N \rightarrow N' + e$$

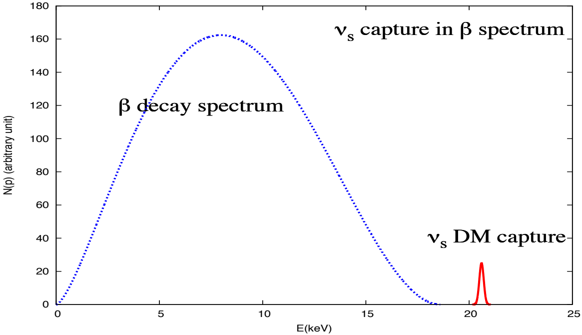
has no threshold

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

Detection of ν_s DM: capture by radioactive nuclei



ν_s capture events are well separated from β decay events and are clear.

ν_s number density is enhanced by its small mass

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

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

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

Background:
solar pp $\nu(< 10$ keV) can be captured by radioactive nuclei.

The flux of solar pp $\nu(< 10\text{keV})$ has flux $\sim 10^{-8}$ cm^{-2} s^{-1}.
Capture of solar pp ν with energy $\lesssim 10$keV:

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

This type of background can be safely neglected.

This way to detect keV scale ν_s DM looks similar to detecting cosmic relic neutrinos in the universe.

A major difference is that events of capture of keV scale ν_s are well separated from the β decay spectrum: $E = Q_\beta + m_{\nu_s}$
Detecting keV scale ν_s using β decay nuclei is possible.

On the other hand

- Cosmological constraint gives: $m_{\nu_e} \lesssim 0.2 - 0.3$ eV
- Energy resolution can not reach that high precision in modern technology
- Events of cosmic relic neutrinos can not be distinguished from β decay events

Detecting cosmic relic neutrinos in this type of measurement seems not possible in the near future.

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

Conditions of candidates for radioactive nuclei:

- 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

Or other ways to detect ν_s DM?

In JCAP 1108 (2011) 006, Li and Xing suggest to capture ν_s DM using EC-decaying nuclei

$$^{163}\mathrm{Ho} + e^- \rightarrow ^{163}\mathrm{Dy}_i^* + \nu_e \rightarrow ^{163}\mathrm{Dy} + E_i + \nu_e$$

The capture of $\bar{\nu}_s$ gives

$$\bar{\nu}_s + ^{163}\mathrm{Ho} + e^- \rightarrow ^{163}\mathrm{Dy}_i^* \rightarrow ^{163}\mathrm{Dy} + E_i$$

600 Ton ^{163}Ho is required to have one event per year for $|\theta_{es}|^2 \sim 10^{-6}$. This is very difficult.

To have a better measurement of ν_s, it was suggested to make a complete measurement of kinetic information, i.e. also to measure the recoil momenta of initial and final nuclei (F. Bezrukov and M. Shaposhnikov, 2007).

- Momenta of recoil nuclei can be measured using time-of-flight measurement
- The experimental setup should be put in low temperature environment.
- ν_s mass can be calculated on event by event basis

However it's very hard to get large amount of cold atoms and high statistics for this type of measurement

Some other ways to detect ν_s in laboratory include
detection of electron recoil(Ando and Kusenko, 2010)
detection of spin flip of nuclei(Ando and Kusenko, 2010)

They are all very difficult

Up to now capture ν_s using β decay nuclei such as ^{3}H and ^{106}Ru is the best way to do direct laboratory search of keV scale ν_s DM in the universe.

Summary

- keV scale ν_s is a well motivated dark matter candidate and is very interesting
- ν_s dark matter can be produced in the early universe through mixing with active neutrinos or through other mechanism
- $\nu_s - \nu_l$ mixing $|\theta_{ls}|^2$ can reach 10^{-6}(for ~ 2 keV), the bound from X-ray observation
- Other astronomical and cosmological constraints can be satisfied

At the moment there are two possible schemes to measure ν_s DM in β decay experiment.

1. ν_s dark matter can be measured in its mixture to the β decay, the resulting disappearance of β decay events.

This measurement of ν_s

- is a direct way to measure ν_s
- is not a direct detection of ν_s DM in the universe
- does not require large target mass of detector
- can be done using ^{3}H and ^{187}Re in current β decay experiment

2. I pointed out that direct laboratory search of ν_s dark matter can be done using capture by radioactive nuclei. This is a new way to detect DM in the universe.

- Capture of ν_s give mono-energetic electron well beyond the end point of the beta decay spectrum; signal very clear
- For $|\theta_{es}|^2 \sim 10^{-6}$ a few to tens events per year available for 10kg Tritium or 10 Ton ^{106}Ru
- It requires reasonably large target mass
- It can be done using ^{3}H and ^{106}Ru

Up to now this is the best way to do direct laboratory search of keV scale ν_s DM in the universe.

Two types of measurements can be done in one β decay experiment, or in different phases of one experiment.

β decay experiment, as a particle physics experiment in high precision frontier, can also serve for frontier research of cosmology and become a multi-purpose experiment.

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

Thank you