Detection of keV scale warm dark matter

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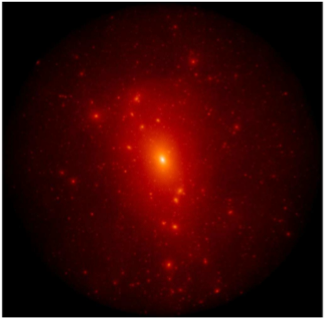
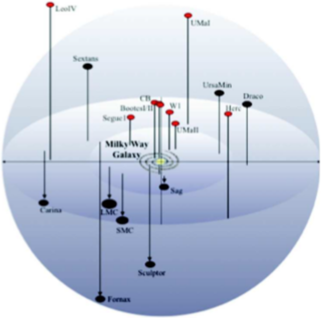
- keV scale Warm Dark Matter vs GeV scale Cold Dark Matter
- keV scale spin 1/2 dark matter, sterile neutrino
- detection of sterile neutrino DM by radioactive nuclei
- summary

CDM produces too many small substructures



45×10^3 substructures (Aquarius simulation)



$\sim$ 30 observed substructures within our Galaxy. M. Geha 2010

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 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

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

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

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

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 point out (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

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.

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:

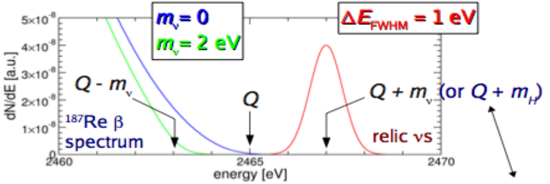
$$\sim 4.0 \times 10^{-3}\ \mathrm{year}^{-1}\ \ \mathrm{for\ 10\ kg}\ {}^3\mathrm{H}$$
$$\sim 8.5 \times 10^{-2}\ \mathrm{year}^{-1}\ \ \mathrm{for\ 10\ Ton}\ {}^{106}\mathrm{Ru}$$

solar neutrino background are negligible

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

MARE and KATRIN are considering to detect keV scale WDM in their their upgrade

Light and heavy relic neutrino detection in MARE?



Interaction rates in **KATRIN** and **MARE**	relic ν_e (CνB)	isotope mass	rate	sterile ν_H $m_H = 1$ keV
$\nu + {}^3H \rightarrow {}^3He + e^-$	$0.1\ y^{-1}\ g^{-1}$ (1)	100 μg	$10^{-5}\ y^{-1}$	$100 \sin^2\theta\ y^{-1}\ g^{-1}$ (4)
$\nu + {}^{187}Re \rightarrow {}^{187}Os + e^-$	$10^{-10}\ y^{-1}\ g^{-1}$ (2)	1000 g	$10^{-7}\ y^{-1}$	$10^{-7} \sin^2\theta\ y^{-1}\ g^{-1}$
$\bar{\nu} + e^- + {}^{163}Ho \rightarrow {}^{163}Dy^*$	$10^{-5}\ y^{-1}\ g^{-1}$ (3)	100 μg	$10^{-9}\ y^{-1}$	$10^{-3} \sin^2\theta\ y^{-1}\ g^{-1}$ (5)

ν densities

CνB: $n_\nu \approx 55\ \nu_e/cm^3$

WDM: $n_\nu \approx 3\times10^5\ \nu_H/cm^3$

$Q_{EC} = 2.5$ keV

(1) R.Lazauskas et al., J. Phys. G: Part. Phys. 35, 025001 (2008)
(2) A.G.Cocco et al., J. Cosmol. Astropart. Phys. 06, 15 (2007)
R.Hodak et al., Progr. in Part. and Nucl. Phys. 66, 452 (2011)
(3) M.Lusignoli, M.Vignati, Phys. Lett., B697, 11 (2011) (arXiv:1012.0760 [hep-ph])
(4) W.Liao, Phys. Rev., D82, 73001 (2010)
Y.F.Li, Z.Z.Xing, Phys. Lett. B695, 205 (2011)
(5) Y.F.Li, Z.Z.Xing, arXiv:1104-4000 [astro-ph]

- 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
- We first 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

谢谢