Direct Detection of the Cosmic Neutrino Background

Yu-Feng LI

(Institute of High Energy Physics, Beijing)

2015.09.10@Torino

XIV International Conference on Topics in Astroparticle and Underground Physics

Outline

(1) Introduction and Motivation

(2) Detection of CNB using beta decaying nuclei

(3) Topics related to flavor effects

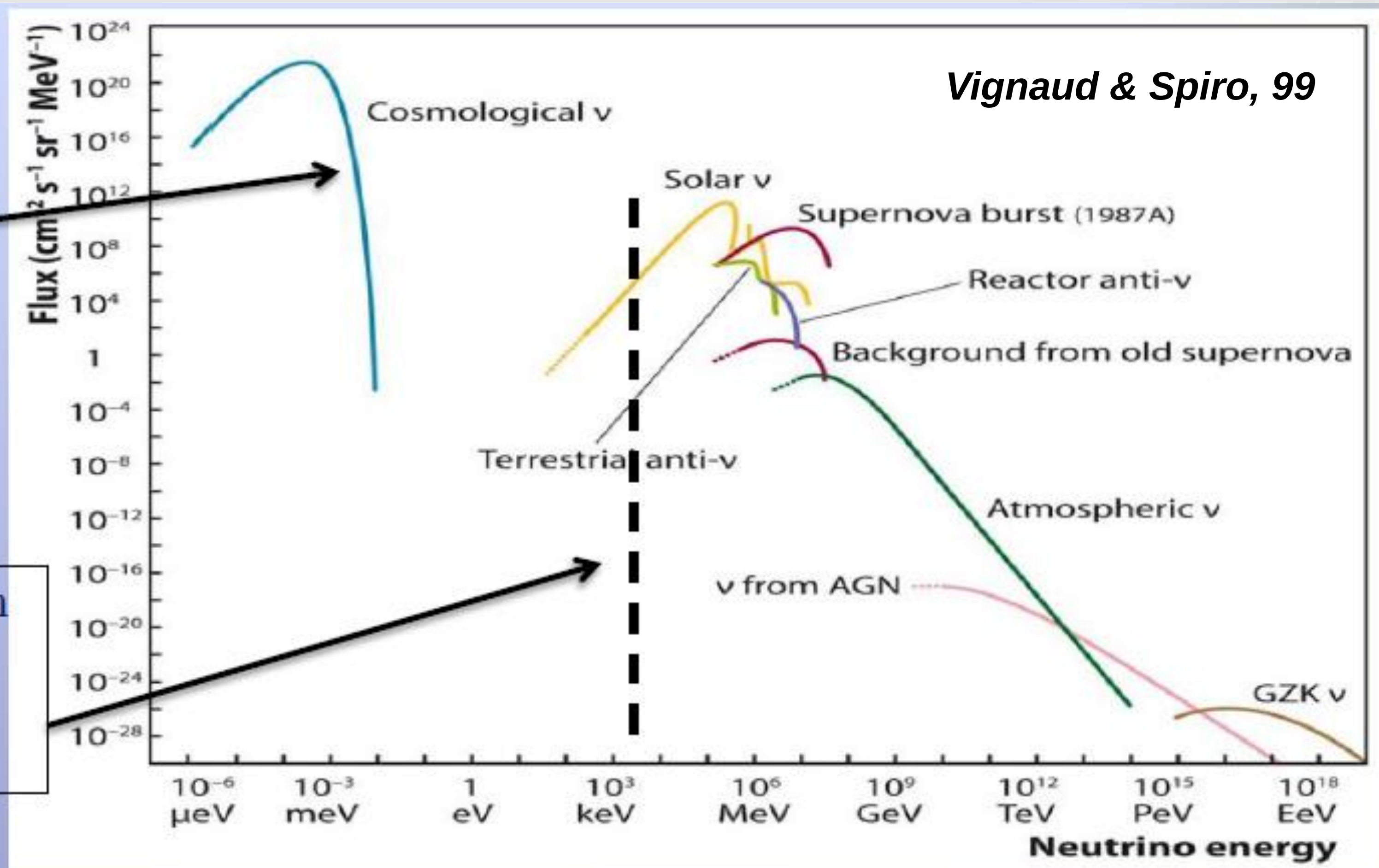
(4) Go beyond beta-decaying nuclei?

(5) Summary

Sources of neutrinos

Abundant but challenging detection

Below detection threshold of current experiments



- Flux of neutrinos on Earth from different sources as a function of energy

Hot Big Bang Cosmology

(1) Concordance model of cosmology that can explains almost everything we know about the evolution of the Universe with remarkable accuracy.

(2) Standard predictions of the Big Bang:

Neutrinos decouple at t ~ 1 sec, T ~ 1 MeV, forming the cosmic neutrino background (CNB)→

112 neutrinos / cm^3 of each flavor (56 nus + 56 anti-nus)

T_ν = 1.94 K = 1.67 x 10^{-4} eV

(3) From the Big-Bang Nucleosynthesis (first few minutes) and Cosmic Microwave Background (~400 ky), we have

N_ν = 3.15 +- 0.45   [Planck 2015 + BBN (He4)], *arXiv: 1502.01589*

(4) One would test the theory at t ~ 1 sec, T ~ 1 MeV, with direct detection of the cosmic neutrino background.

Direct Detection Methods

Possible detection methods:

a) Neutrino captures on radioactive decaying nuclei

(Weinberg, 62, Irvine & Humphs, 83,)

b) Mechanical force through coherent scattering

c) Z-resonance annihilation of ultra high energy neutrinos with CNB *(Weiler 82)*

d) Method using the atomic de-excitation

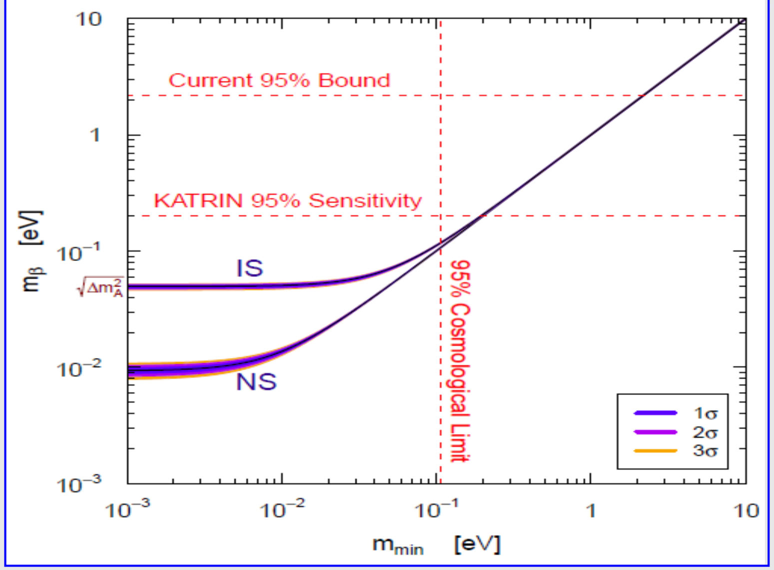
(Yoshimura et. al. 1409.3648)

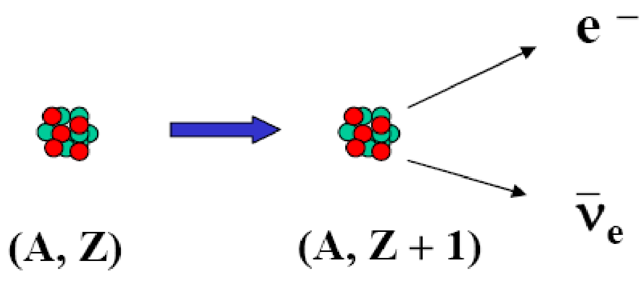
Beta-decaying Nuclei

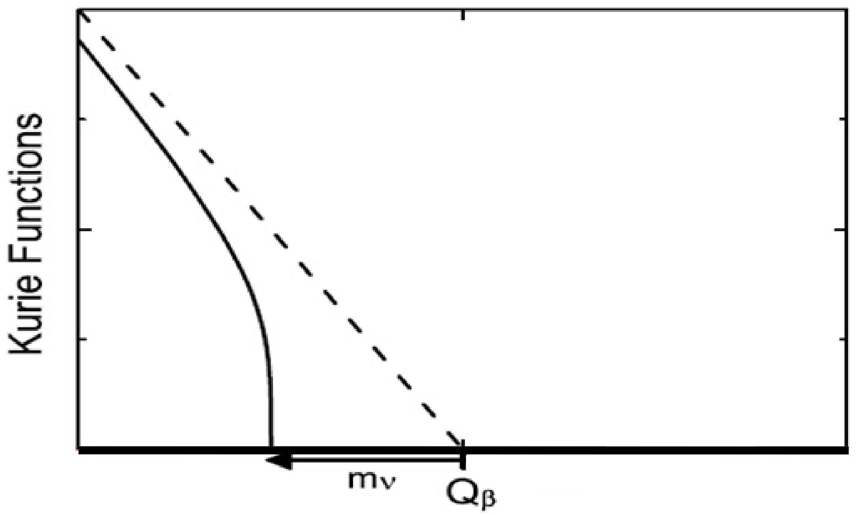
The endpoint of beta decay is a kinetic measurement of the absolute neutrino mass.

$$m_\beta = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$$

Current: Mainz/Troitsk ~ 2.0 eV
Future: KATRIN ~ 0.2 eV







Neutrino Captures

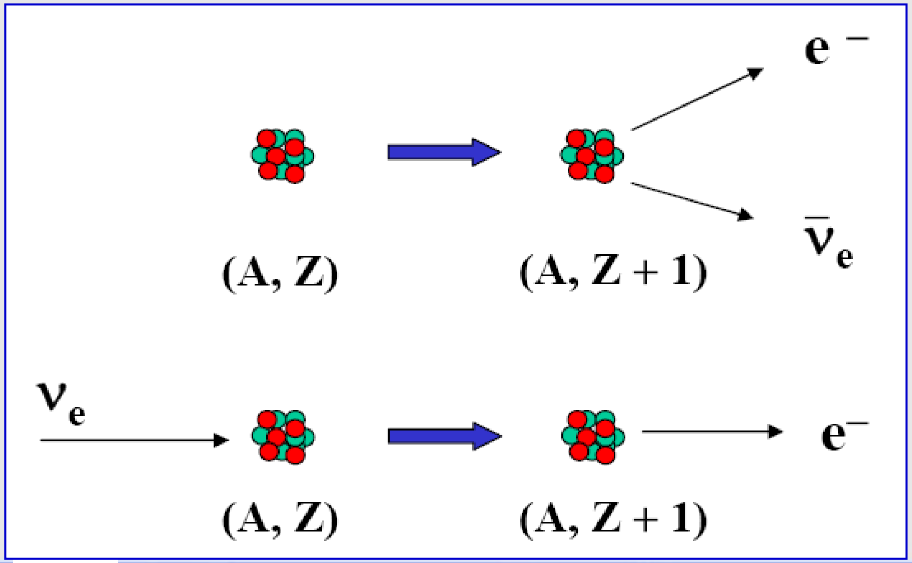
Beta-decaying nuclei: targets of low energy neutrinos

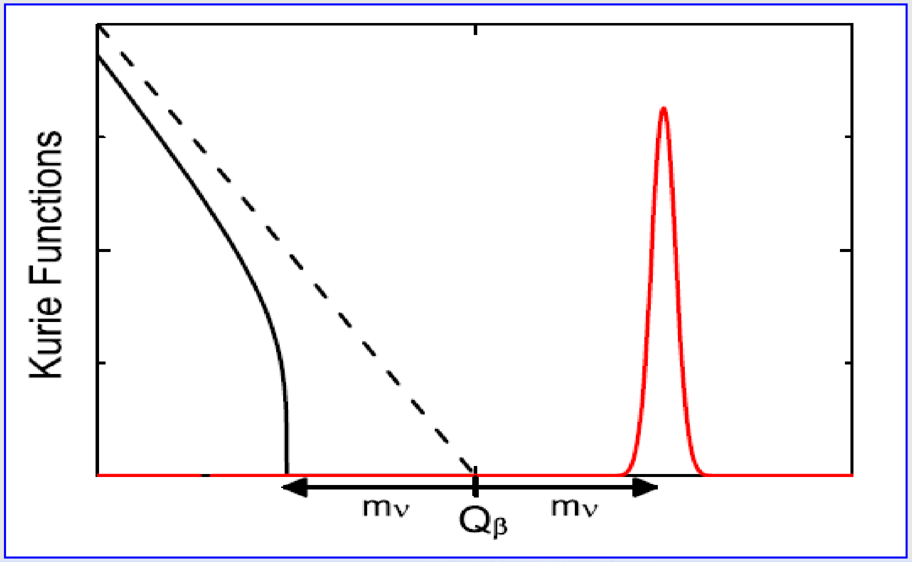
(*Weinberg, 62, Irvine & Humphs, 83, Cocco et al, 07, Lazauskas et al, 07, etc.)*

(1) no energy threshold on incident neutrinos

(2) proper cross section with vanishing velocities

(3) mono-energetic outgoing electrons





Key factors of the detection

(1) Signal: the capture rate is

$$R = [\sigma_\nu \times v_\nu] \times n_\nu \times N_T$$

$$\sigma_\nu \times v_\nu = \frac{2\pi^2}{A} \times \frac{\ln 2}{t_{1/2}}$$

$$n_\nu = \frac{n_\nu}{\langle n_\nu \rangle} \times \langle n_\nu \rangle$$

$$N_T = \frac{N(0)}{t} \times \frac{t_{1/2}}{\ln 2} \times \left(1 - e^{-t\frac{\ln 2}{t_{1/2}}}\right)$$

A:nuclear factors (Q, Z), t_1/2: the half life

Possible enhancement from the **overdensity**

Averaged target number during running time t

(2) Background:

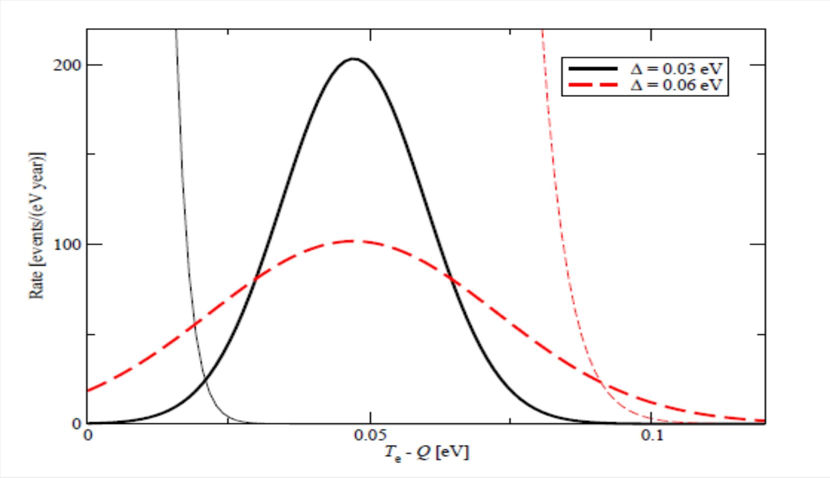
intrinsic background from

beta decay: **the energy resolution**

Cocco et al, 07, Blennow, 08

S/N>1,distinguishable

S/N<1,indistinguishable



Cross Section

(1) The cross section now contains 1/v, which means that the rate σ*v remain finite, even in the limit of vanishing velocities. ***(Cocco et al, 07, R. Lazauskas et al, 07)***

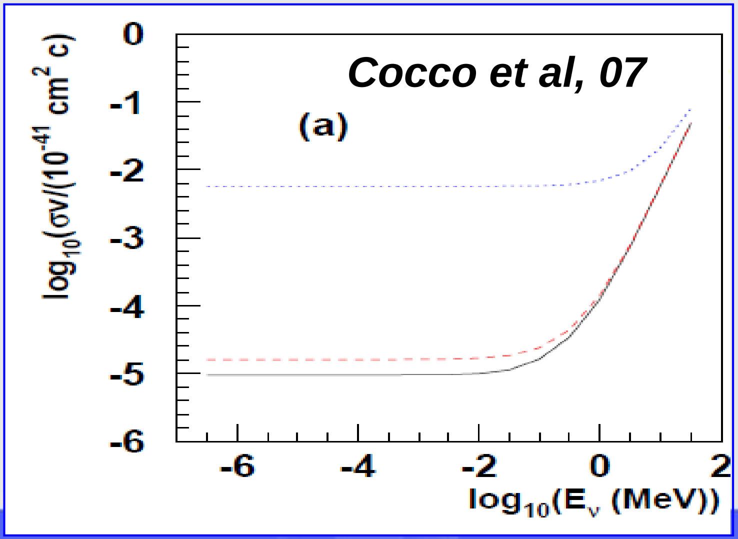
(2) The target should have half-life longer than the duration of the measurement (larger than years).

(3) The target should also have minimal possible f $t_{1/2}$, so that the cross section is as large as possible.

$$\sigma = \sigma_0 \times \langle \frac{c}{v_\nu} E_e p_e F(Z, E_e) \rangle \frac{2I' + 1}{2I + 1}$$

with

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C {m_e}^2}{\pi} |M_{nucl}|^2 = \frac{2.64 \times 10^{-41}}{f t_{1/2}}.$$



Promising Candidates: Tritium

Isotope	Decay	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ $(10^{-41}$ cm$^2)$
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}

Cocco et al, 07

(1) KATRIN: using about 50 μg of ^{3}H (spectrometer)

$$\boxed{N^\nu({\rm KATRIN}) \simeq 4.2 \times 10^{-6} \times \frac{{\rm n}_\nu}{\langle {\rm n}_\nu \rangle} \quad {\rm yr}^{-1}}$$

(2) MARE: using about 760 g of ^{187}Re (calorimeter)

$$\boxed{N^\nu({\rm MARE}) \simeq 7.6 \times 10^{-8} \times \frac{{\rm n}_\nu}{\langle {\rm n}_\nu \rangle} \quad {\rm yr}^{-1}}$$

(3) PTOLEMY (1307.4738): 100 g of ^{3}H, 2.1x10^{25} tritium atoms

$$\boxed{N^\nu(100\,{\rm g}\,^3{\rm H}) \simeq 8.0 \times \frac{n_\nu}{\langle n_\nu \rangle} \quad {\rm yr}^{-1}}$$

(assuming Majorana neutrinos)

Capture Rate: Dirac vs. Majorana, *Long et al, 2014*

$$\Gamma_{\mathrm{C\nu B}} = \sum_{j=1}^{3} |U_{ej}|^2 \, \bar{\sigma} \left[n_j(\nu_{h_R}) + n_j(\nu_{h_L}) \right] N_{\mathrm{T}} = \bar{\sigma} \left[n(\nu_{h_R}) + n(\nu_{h_L}) \right] N_{\mathrm{T}} \, ,$$

Taking 100 g of ^{3}H for illustration (PTOLEMY):

$$\Gamma_{\mathrm{M}} \approx 8 \ \mathrm{yr}^{-1} \quad (\mathrm{Majorana}) \, ; \qquad \Gamma_{\mathrm{D}} \approx 4 \ \mathrm{yr}^{-1} \quad (\mathrm{Dirac}) \, .$$

However, Scenarios for exceptions (for Dirac nus):

(1) Nonstandard production of Dirac nu_R:

J. Zhang et al, 1509.02274

(2) Non-thermal production of Dirac nu_R:

M.C. Chen et al, 1509.00481

$$A(s_\nu) \equiv 1 - 2 s_\nu v_{\nu_j} = \begin{cases} 1 - v_{\nu_j}, & s_\nu = +1/2 \quad \text{right helical} \\ 1 + v_{\nu_j}, & s_\nu = -1/2 \quad \text{left helical} \, , \end{cases}$$

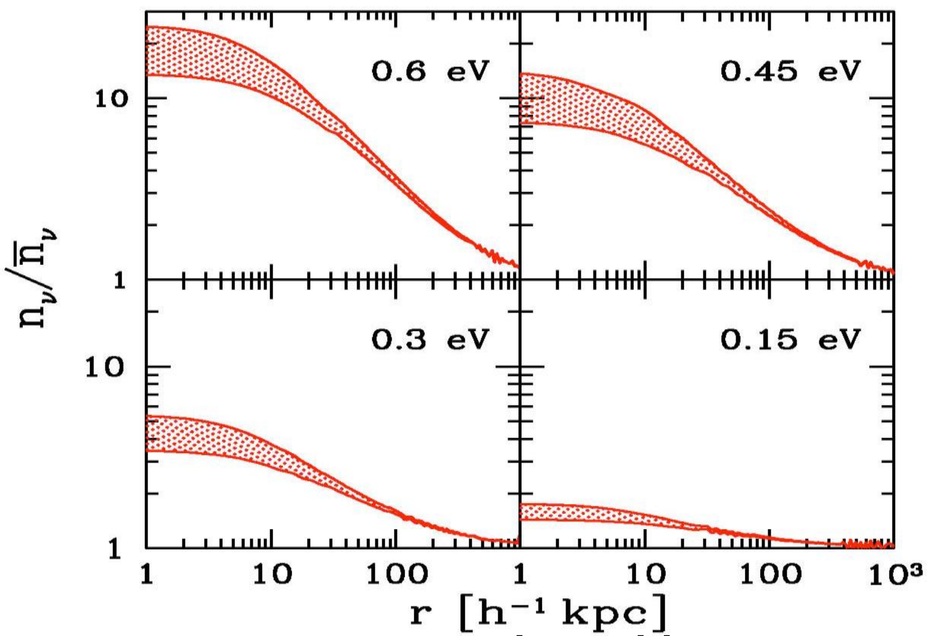
Clustering effect

(1) Non-relativistic massive neutrinos concentrate in structures of various sizes. Their densities can far exceed the averaged density.

(2)The over-density depends on the mass of cluster and the neutrino mass.

(3)Clustering evaluation for the Milky Way:

Overdensity ≈ 1−20



Ringwald & Wong, 04

m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yrs^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

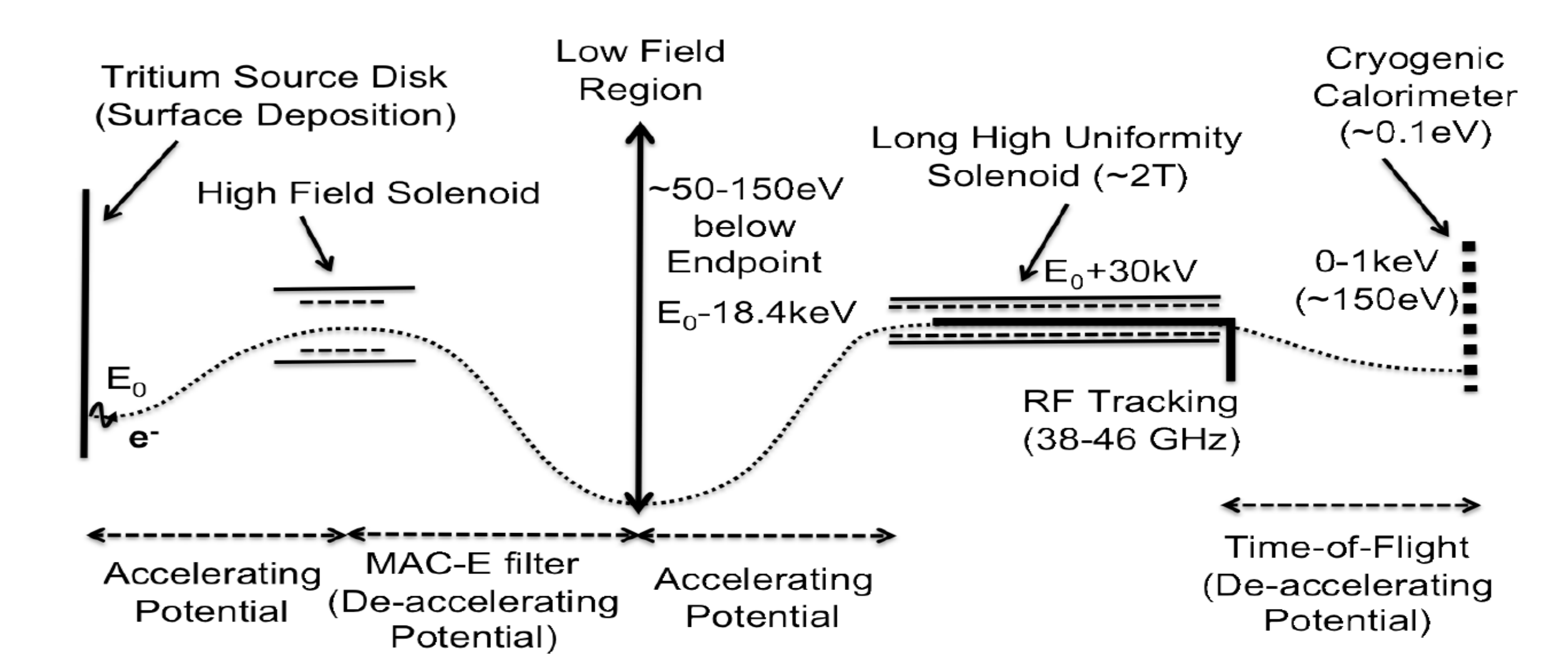
Cocco et al, 07

PTOLEMY project

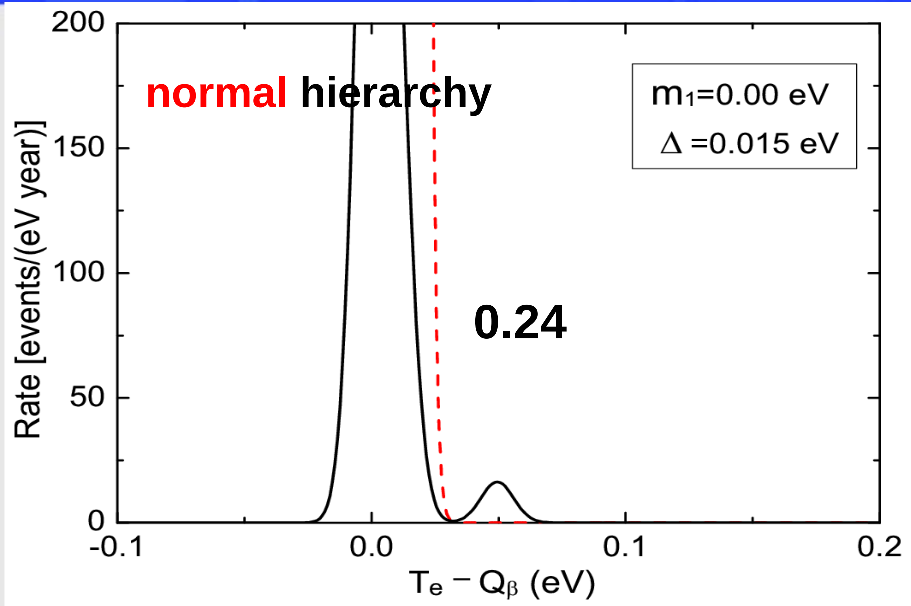
Conceptual Design (1307.4738):

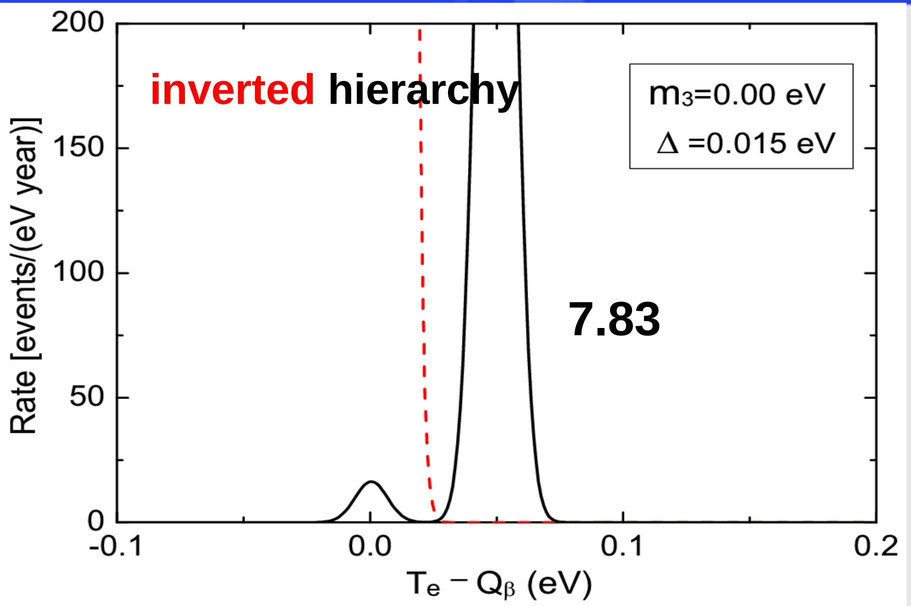
(1) Use monoatomic tritium source deposited on a graphene substrate.

(2) a combination of MAC-E filters, cryogenic calorimetry, RF tracking and time-of-flight systems.



Flavor effect(1): the mass hierarchy

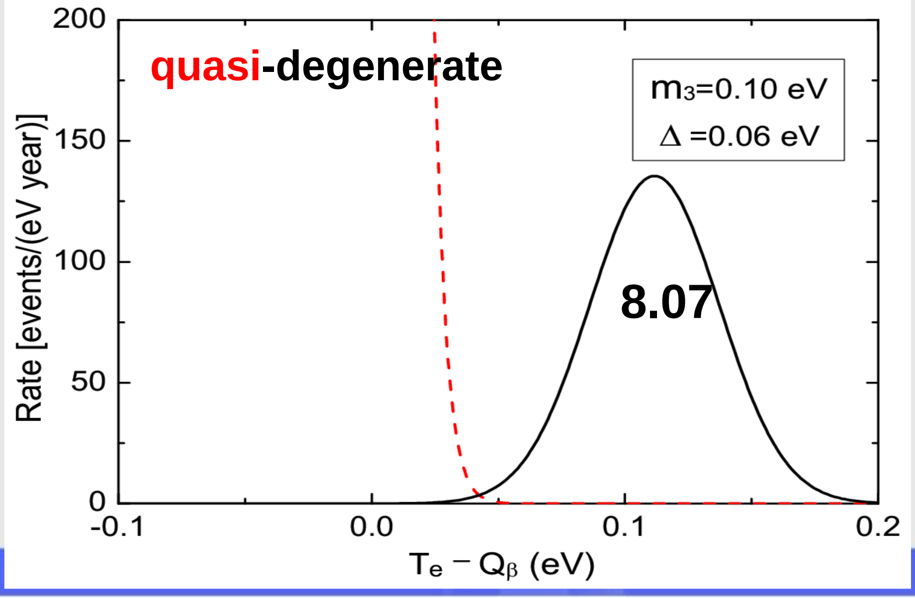




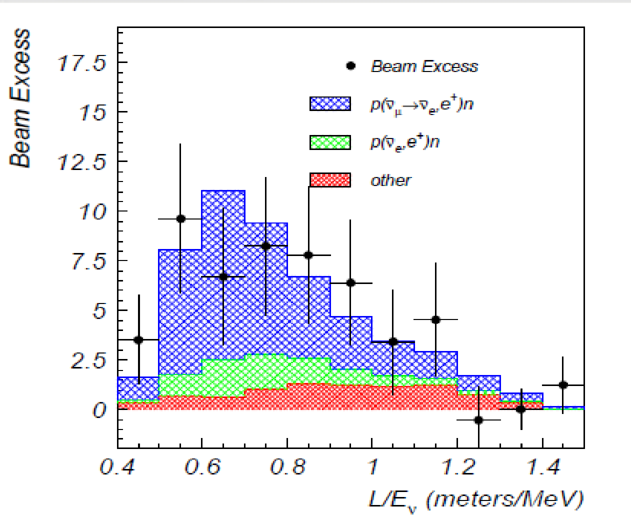
Target mass: **100 g tritium atoms**
Input theta(13): **10 degrees**
Flavor effects are important
(*Blennow 08; Li, Xing 10, 11*)

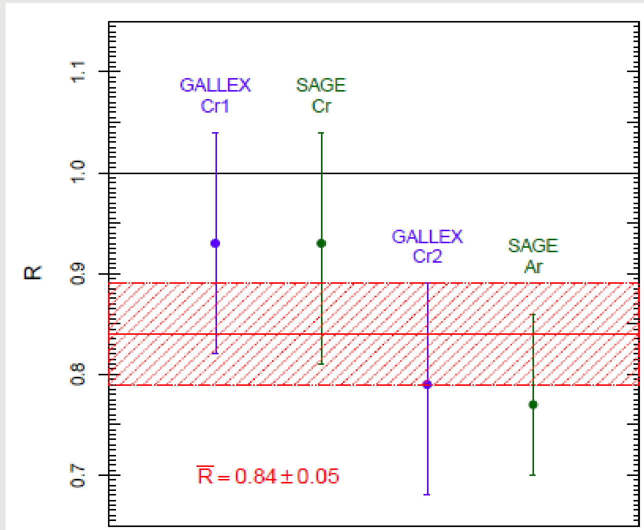
a) Observable events are different.

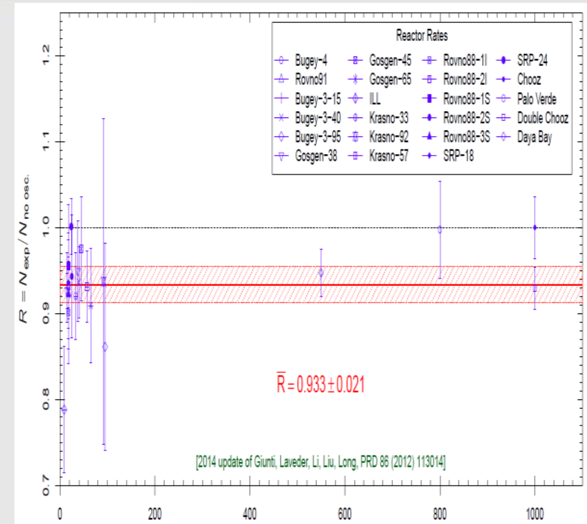
b) Requirement for the energy resolution is different.



Flavor effect(2): the sterile neutrinos







(1) Several short baseline anomalies (LSND, Gallium and Reactors): light sterile neutrinos.

(2) Cosmology has problems with (thermal) light sterile neutrinos, some ideas to resolve the tension ?

(3) The presence of sterile neutrinos with (sub-)eV masses and O(0.1)-level mixing would be helpful for the detection.

Flavor effect(2): the sterile neutrinos

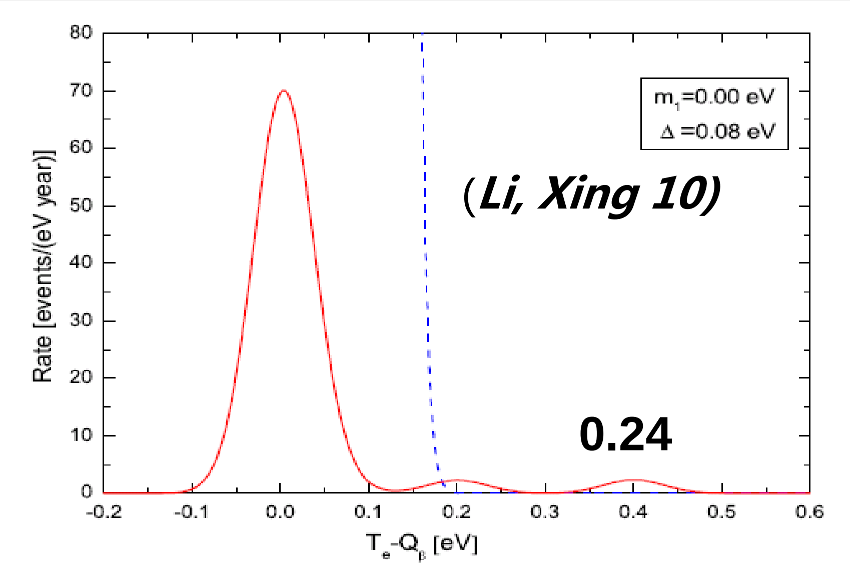
We consider the 3+2 scheme with 100 g tritium atoms

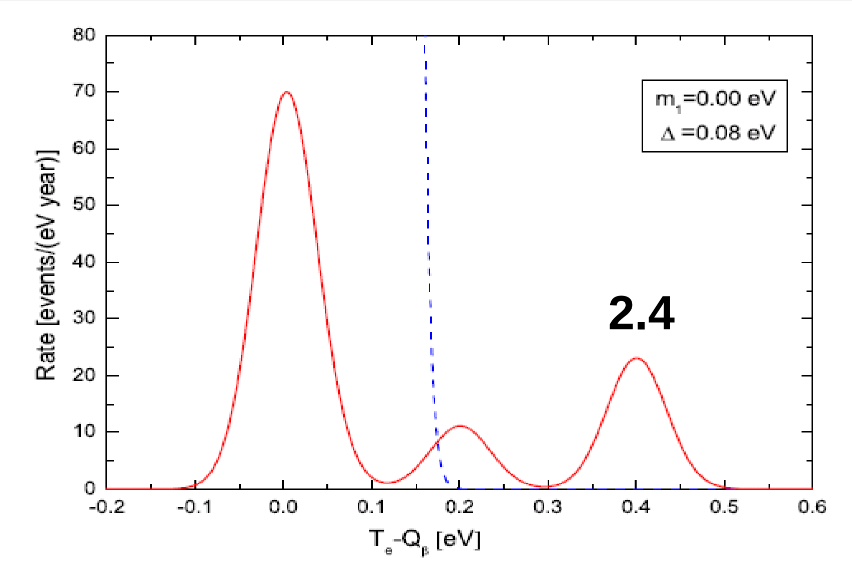
$$\frac{n_{\nu_1}}{\langle n_{\nu_i}\rangle} \approx \frac{n_{\nu_2}}{\langle n_{\nu_i}\rangle} \approx \frac{n_{\nu_3}}{\langle n_{\nu_i}\rangle} \approx 1\ , \qquad \frac{n_{\nu_5}}{\langle n_{\nu_i}\rangle} \approx 2\frac{n_{\nu_4}}{\langle n_{\nu_i}\rangle} \approx 10$$

$$|V_{e1}| \approx 0.792\ ,\ \ |V_{e2}| \approx 0.534\ , |V_{e3}| \approx 0.168\ , |V_{e4}| \approx 0.171\ , |V_{e5}| \approx 0.174$$

(1) larger neutrino mass have better S/B ratio.

(2) larger neutrino mass may have more significant clustering effect.





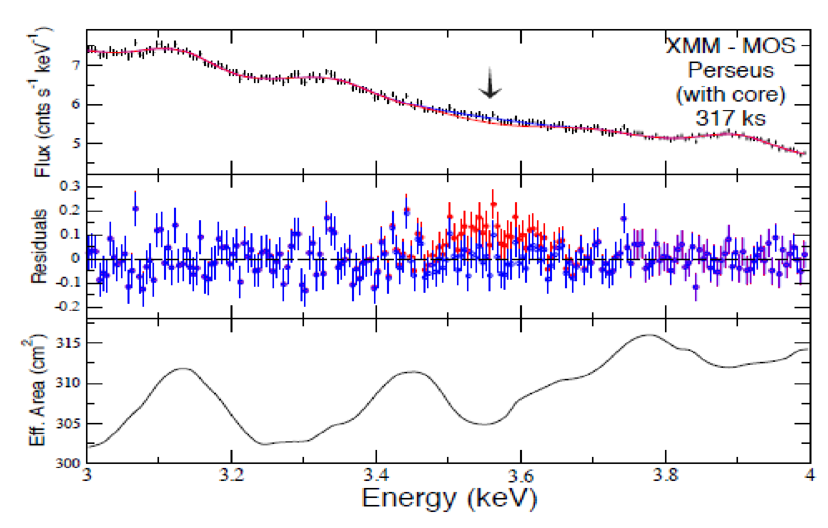
Flavor effect(3): keV sterile neutrino as WDM

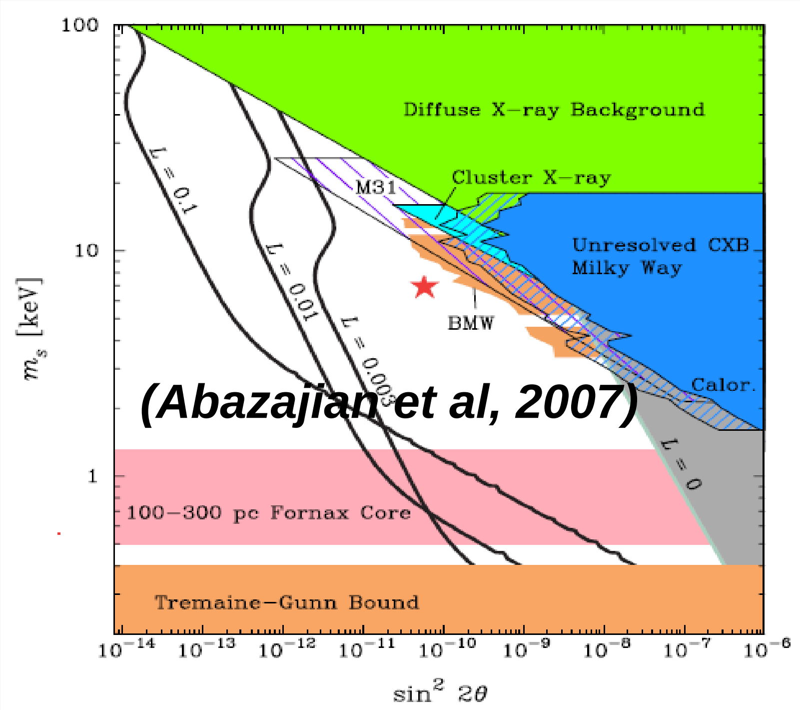
(1) Warm DM can suppress the formation of small-scale structures: with the keV sterile neutrino as an excellent candidate.

(2) Recent indications (1402.2301, 1402.4119)

XMM-Newton and Chandra observatory:

X-ray line at ~3.5 keV (m_4 ~ 7.0 keV)



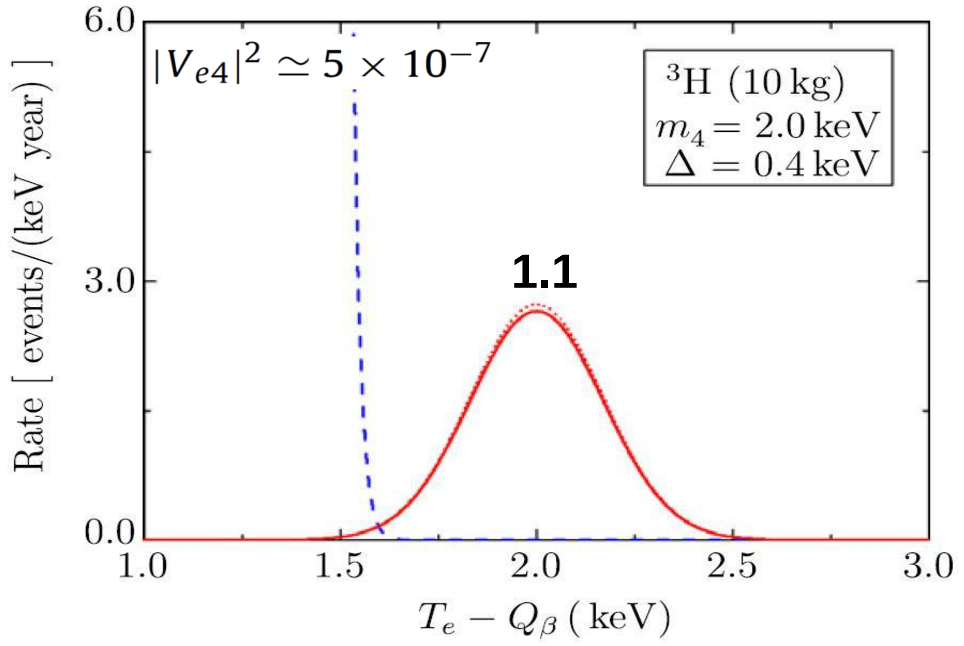


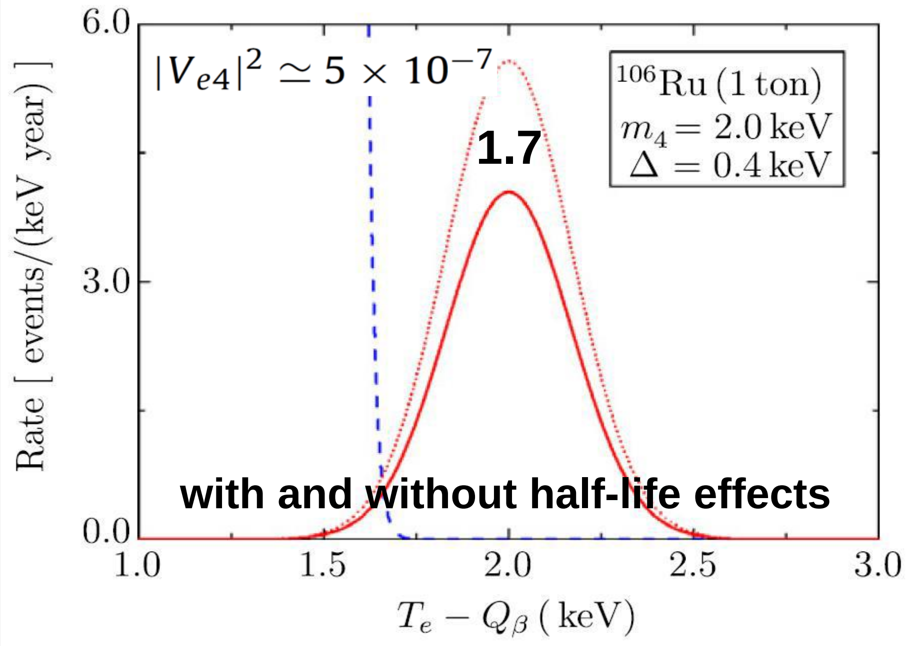
Flavor effect(3): keV sterile neutrinos as WDM

Candidate nuclei: *(Liao 10; Li & Xing 10, 11)*

$$^{3}\mathrm{H} \;:\; Q_\beta = 18.6\ \mathrm{keV}\,,\quad t_{1/2} = 3.888 \times 10^{8}\ \mathrm{s}\,,\quad \sigma_{\nu_i} v_{\nu_i}/c = 7.84 \times 10^{-45}\ \mathrm{cm}^2$$

$$^{106}\mathrm{Ru} \;:\; Q_\beta = 39.4\ \mathrm{keV}\,,\quad t_{1/2} = 3.228 \times 10^{7}\ \mathrm{s}\,,\quad \sigma_{\nu_i} v_{\nu_i}/c = 5.88 \times 10^{-45}\ \mathrm{cm}^2$$





(1)Tiny active-sterile neutrino mixing angles (main problem)

(2)background froms solar nus and ES scattering. (Liao, 13)

Go beyond the beta-decaying nuclei ?

Comic anti-neutrino background

Using the electron-capture (EC) decaying nuclei:

Relic antineutrino capture on ^{163}Ho

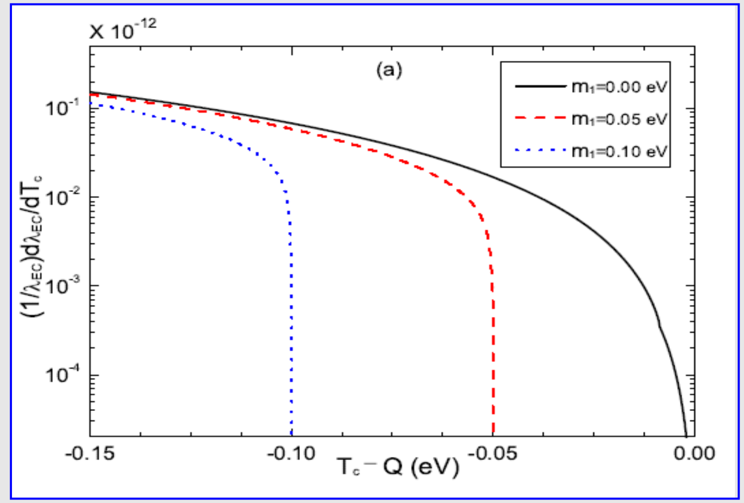
(Lusignoli, Vignati 11; Li, Xing 11)

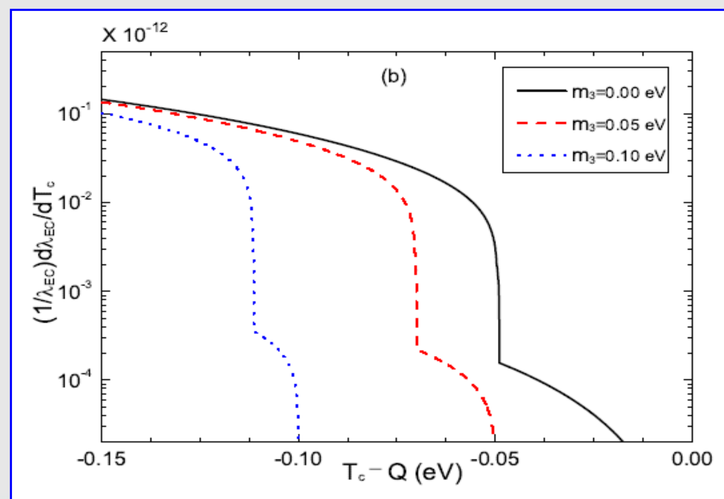
Background (Breit-Wigner distribution):

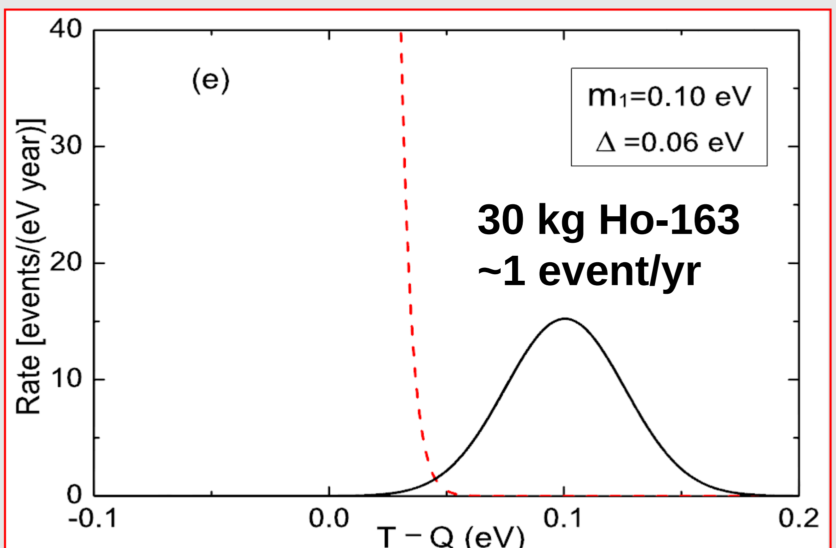
$$^{163}\mathrm{Ho} + e^-_{i(\mathrm{shell})} \rightarrow {}^{163}\mathrm{Dy}^*_i + \nu_e \rightarrow {}^{163}\mathrm{Dy} + E_i + \nu_e$$

Signal (mono-enegetic signal in calorimeter):

$$\overline{\nu}_e + {}^{163}\mathrm{Ho} + e^-_{i(\mathrm{shell})} \rightarrow {}^{163}\mathrm{Dy}^*_i \rightarrow {}^{163}\mathrm{Dy} + E_i$$







Other flavors of CNB

A flux of extremely energetic particles for scattering on relic neutrinos as target:

(1) accelerator beams ***(Muller, 87; Melissinos, 99 Weiler, 01)***

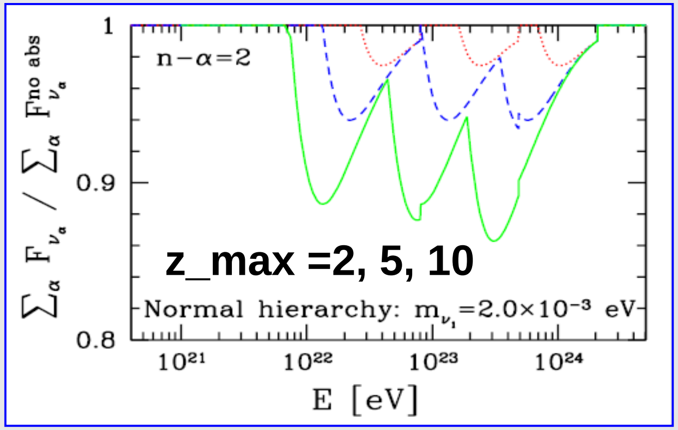
$$R_{\nu {}^{A}_{Z}N} \simeq 2\times10^{-8}\ \frac{n_\nu}{\bar{n}_\nu}\ \frac{m_\nu}{\mathrm{eV}}\ \frac{A^2}{Z}\ \frac{E_N}{10\ \mathrm{TeV}}\ \frac{L}{100\ \mathrm{km}}\ \frac{I}{0.1\ \mathrm{A}}\ \mathrm{yr}^{-1}$$

accel.	N	E_N [TeV]	L [km]	I [A]	$\frac{R_{\nu A}}{\left[\frac{n_\nu}{\bar{n}_\nu}\frac{m_\nu}{\mathrm{eV}}\right]}$ [yr^{-1}]
LHC	p	7	26.7	0.6	2×10^{-8}
	Pb	574	26.7	0.006	1×10^{-5}
VLHC	p	87.5	233	0.06	2×10^{-7}
	Pb	7280	233	0.0006	1×10^{-4}
ULHC	p	10^7	40 000	0.1	10

(2) from cosmic rays:

annihilation of UHE neutrinos with CNB ***(Weiler 82)***

$$E_\nu^{\mathrm{res}} = \frac{m_Z^2}{2m_\nu} \simeq 4\times10^{21}\ \frac{\mathrm{eV}}{m_\nu}\ \mathrm{eV}$$



Eberl et al 04

Using double beta-decaying nuclei

(1) Single capture vs. double capture (**lepton number conserving processes**) *(Hodak et al, 2010)*

Single capture	Double capture
$\nu + (A,Z) \rightarrow (A,Z+2) + 2e^- + \bar{\nu}$	$2\nu + (A,Z) \rightarrow (A,Z+2) + 2e^-$

(2)MOON experiment (Molybdenum Observatory Of Neutrinos)

(a)Measuring the effective netrino mass by neutrino-less double beta decay with sensitivity of 0.01 ~ 0.06 eV.

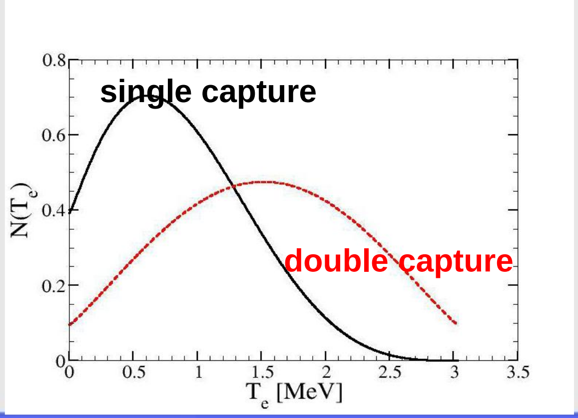
(b) Assuming 1 ton of ^{100}Mo.

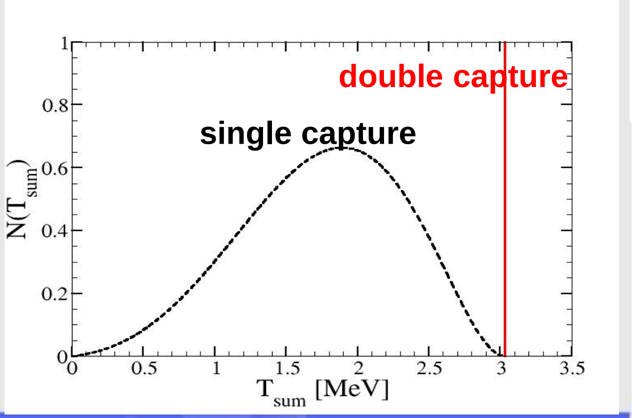
(c) Spectra of single electron (left) and double electrons (right).

(d) Not realistic

$$N^{\nu\bar{\nu}}(\mathrm{MOON}) \simeq 8.8 \times 10^{-20} \times \frac{\mathrm{n}_\nu}{\langle \mathrm{n}_\nu \rangle} \quad \mathrm{yr}^{-1}$$

$$N^{\nu\nu}(\mathrm{MOON}) \simeq 1.0 \times 10^{-48} \times \left(\frac{\mathrm{n}_\nu}{\langle \mathrm{n}_\nu \rangle}\right)^2 \quad \mathrm{yr}^{-1}$$





Conclusion

(1) Cosmic neutrino backgroud: a test of cosmology as early as t~ 1 s after the Big Bang.

(2) BBN and CMB provide presently the only evidence of CNB.

(3) Weinberg's idea using beta-decaying nuclei seems as the most promising method in the market.

100 g of ^3H is a must, PTOLEMY will be the first experimental attempt.

(4) Flavor effects are important in the view of detection prospects.

Absolute neutrino masses, Hierarchy, Sterile neutrinos.

(5) It might not be hopeless in the long term.

Thanks for your attention