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TOWARDS THE DETECTION OF COSMOLOGICAL RELIC NEUTRINOS WITH NEUTRINO CAPTURE ON BETA DECAYING NUCLEI

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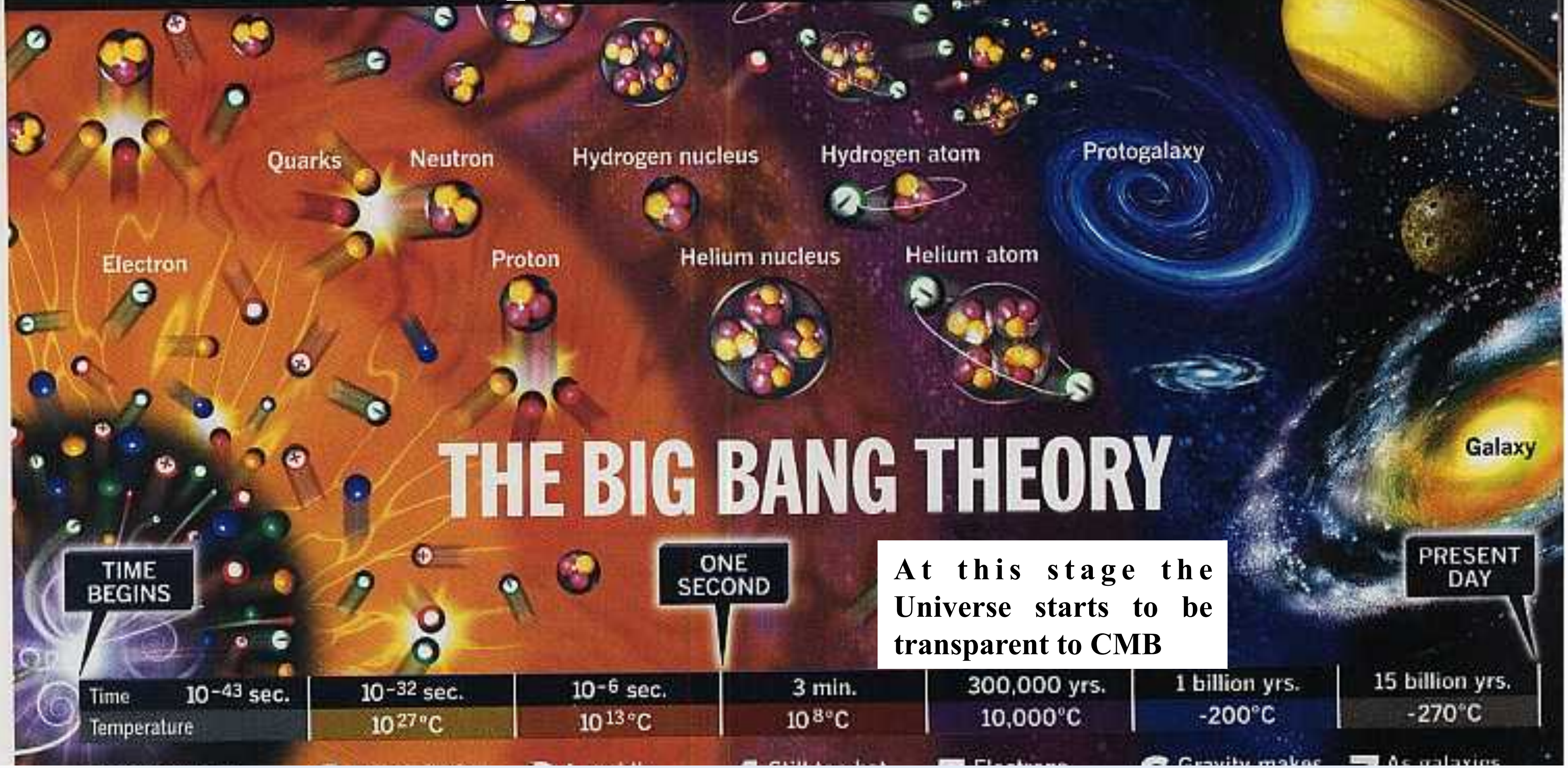
Outline

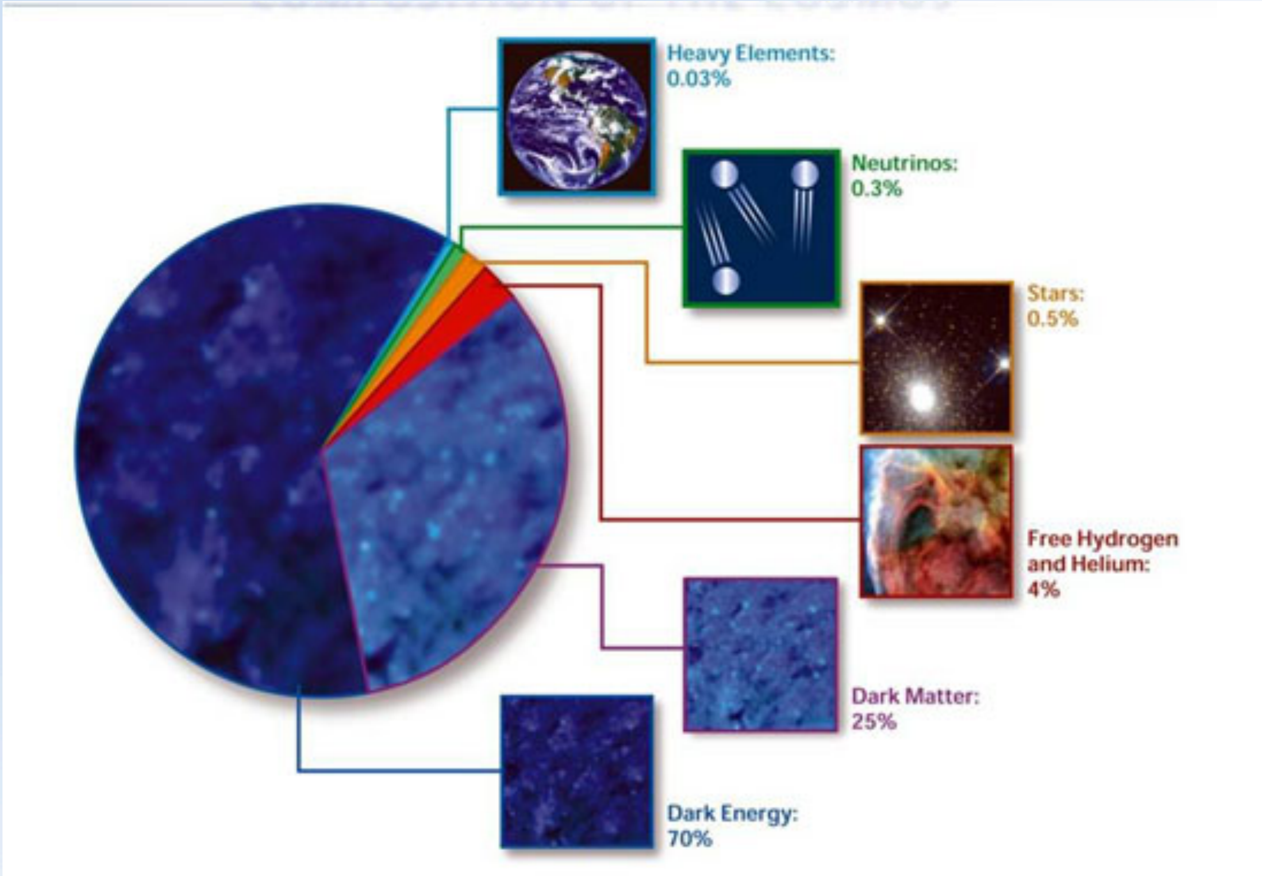
- State of Art
- The expected rate of the relic neutrinos on beta instable elements
- Gravitational clustering effect enhancing the interaction rate
- Possible experimental approach for the detection of relic neutrinos
- Conclusions

The expansion of the Universe



The relic neutrinos are produced with a $T_n \sim 10^{10}$ K (1 MeV).

Why relic neutrinos are so important



Even if relic neutrinos are among the most abundant components of the Universe they have not been discovered yet.

The Cosmological Relic Neutrinos

We know that Cosmological Relic Neutrinos (CRN) are weakly-clustered

$$\sim 1\sec > BigBang$$

Date of birth

$$\bar{n}_{\nu_i 0} = \bar{n}_{\bar{\nu}_i 0} = \frac{3}{22}\bar{n}_{\gamma 0} = 53cm^{-3}$$

density per flavour

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma 0} = 1.95K$$

temperature

$$\bar{p}_{\nu_i 0} = \bar{p}_{\bar{\nu}_i 0} = 3T_{\nu,0} = 5 \times 10^{-4} eV$$

mean kinetic energy

$$\lambda = \frac{1}{\bar{p}_{\nu_i}} = \frac{0.12cm}{\left\langle p/T_{\nu,0\bar{p}_{\nu_i 0}}\right\rangle}$$

Wave function extension

The detection methods proposed so far!

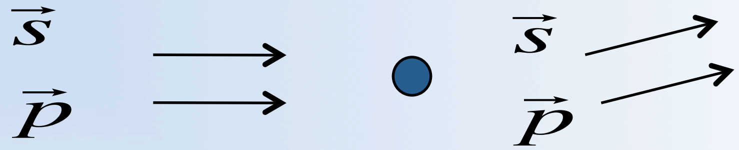
The longstanding question (I)

Is it possible to measure the CRN?

Method 1

The first method proposed for the detection of CRN was based on the fact that given the null mass of the neutrinos (today we know it is small) any variation of ν momentum (Δp) implies a variation of the ν spin (ΔJ) (R. R. Lewis Phy. Rev. D**21** 663, 1980):

$$\Delta J = \mp \hat{\lambda} \cdot \Delta \vec{p}$$

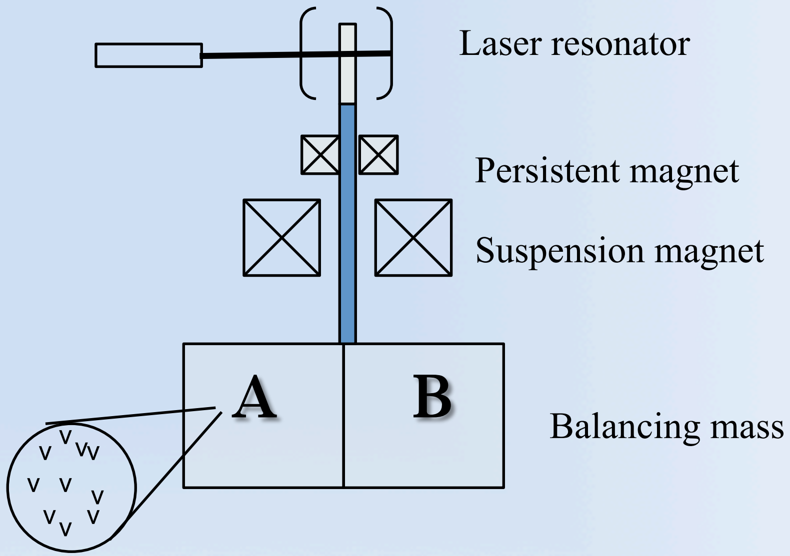


<u>Neutrino and anti-neutrino with the same momentum they transfer opposite sign Δp and the same ΔJ</u>. This is due to the fact the opposite sign of the scattering amplitude reflects in a different refraction index for ν (n>1) and anti-ν (n<1) and so a different scattering angle.

The longstanding question (II)

Is it possible to measure the CRN?

Method 1



Unfortunately the effect vanish at first order in Fermi constant G_F (Phys. Lett. **B114** 115,1982).

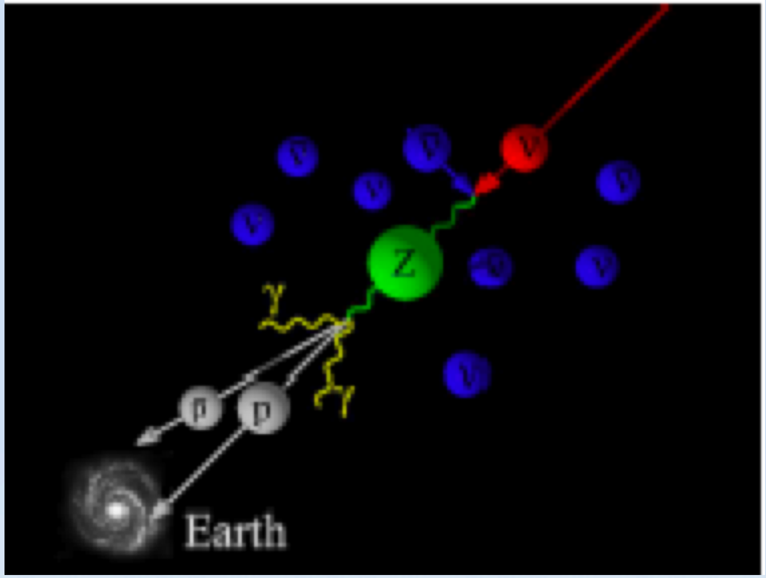
$$a_{G_F} \approx 10^{-27} \frac{cm}{s^2}$$

The value of acceleration expected is almost 15 order of magnitude far from the current sensitivity of any accelerometers used today in "Cavendish" experiments.

The longstanding question

Is it possible to measure the CRN ?

Method 2



The second method proposed was based on the a resonant annihilation of EECν off CRN into a Z-boson.
The annihilation occurs at energy:

$$E_{\nu_i}^{res} = \frac{m_Z^2}{2m_{\nu_i}} \approx 4x10^{21}\left(\frac{eV}{m_{\nu_i}}\right)eV$$

The signature would be a deep in the neutrino flux around 10^{22} eV or an excess of events with primary photons or protons beyond the GKZ deep (where the photons of CMB are absorbed by protons). Such energetic neutrino sources are unknown so far and not even hypothised.

The longstanding question

Is it possible to measure the CRN ?

Method 3

The third method was based on the observation of interactions of extremely high energy protons from terrestrial accelerator with the relic neutrinos.

In this case even with an accelerator ring (VLHC) of $\sim 4\text{x}10^4$ km length (Earth circumference) with $E_{beam} \sim 10^7$ TeV the interaction rate would be negligible.

The detection methods proposed so far!

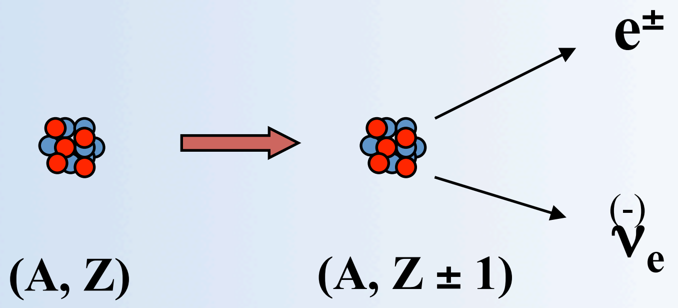
All those methods require unrealistic experimental apparatus or astronomical neutrino sources not yet observed and not even hypothesized.

For recent reviews on this subject see:
A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini G. B. Gemini Phys.Scripta T121:131-136,2005

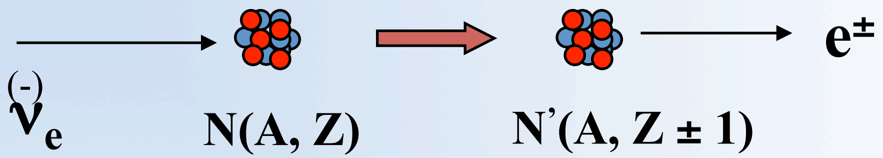
How to detect relic neutrinos

A process without energy threshold

Beta decay



Neutrino Capture on a
Beta decaying nucleus



Since $M(N)-M(N')=Q_\beta>0$ the ν interaction on beta instable nuclei is always energetically allowed no matter the value of the incoming ν energy.

In this case the phase space does not put any energetic constraint to the neutrino interaction on a beta instable nucleus (NCB).

NCB Cross Section (I)

NCB

$$\sigma_{NCB} \cdot v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z,E_e) C(E_e,p_\nu)_\nu$$

$$E_e = E_\nu + Q_\beta + m_e = E_\nu + m_\nu + W_0$$

Where $F(Z,E_e)$ is the Fermi function and $C(E_e,p_\nu)_\nu$ is the nuclear shape factor which is an angular momentum weighted average of the nuclear state transition amplitudes.

It is more convenient to focalize our attention on the interaction rate:

$$\lambda_\nu = \frac{G_\beta^2}{2\pi^3} \int_{W_0+2m_\nu}^{\infty} p_e E_e F(Z,E_e) \cdot C(E_e,p_\nu)_\nu \cdot E_\nu \, p_\nu f(p_\nu) dE_e$$

NCB Cross Section (II)

The most difficult part of the rate estimation is the nuclear shape factor calculation:

$$C(E_e,p_\nu)_\beta = \sum_{k_e,k_\nu,K} \lambda_{k_e}\left[M_K^2(k_e,k_\nu) + m_K^2(k_e,k_\nu) - \frac{2\mu_{k_e} m_e \gamma_{k_e}}{k_e E_e} M_K^2(k_e,k_\nu) m_K^2(k_e,k_\nu)\right]$$

On the other hand, the NCB (see previous slide) and the corresponding beta decay rates

$$\lambda_\beta = \frac{G_\beta^2}{2\pi^3}\int_{m_e}^{W_0} p_e E_e F(Z,E_e)\cdot C(E_e,p_\nu)_\beta \cdot E_\nu p_\nu dE_e$$

are related thanks to the following formula:

$$C(E_e,p_\nu)_\nu = C(E_e,-p_\nu)_\beta$$

NCB Cross Section (III)

The beta decay rate provides a relation that allows to express the mean shape factor:

$$\overline{C}_\beta = \frac{1}{f}\int_{m_e}^{W_0} p_e E_e F(Z,E_e)\cdot C(E_e,p_\nu)_\beta E_\nu p_\nu dE_e \qquad f = \int_{m_e}^{W_0} p_e^{'} E_e^{'} E_\nu^{'}, p_\nu^{'} F(Z,E_e^{'}) dE_e^{'}$$

in terms of observable quantities:

$$ft_{1/2} = \frac{2\pi^3 \ln 2}{G_\beta^2 \overline{C}_\beta}$$

then if we derive G_β in terms of $\overline{C}_\beta$ and of $ft_{1/2}$ and replace it in the expression of the NCB cross section we obtain:

$$\sigma_{NCB} v_\nu = 2\pi^2 \ln 2 \cdot p_e E_e F(Z,E_e)\frac{C(E_e,p_e)_\nu}{ft_{1/2}\overline{C}_\beta} = \frac{2\pi^2 \ln 2}{t_{1/2}} \frac{p_e E_e F(Z,E_e)\cdot C(E_e,p_\nu)_\nu}{\int_{m_e}^{W_0} p_e^{'} E_e^{'} F(Z,E_e^{'})\cdot C(E_e^{'},p_\nu^{'})_\beta dE_e^{'}} = \frac{2\pi^2 \ln 2}{A\cdot ft_{1/2}}$$

NCB cross section (IV)

Super-allowed transitions: $$\sigma_{NCB} v_{\nu} = 2\pi^2 \ln 2 \frac{p_e E_e F(Z,E_e)}{ft_{1/2}}$$ $0^+ \to 0^+$

This expression of the cross section is a very good approximation also for allowed transitions (Tritium case) since: $$\frac{C(E_e,p_\nu)_\beta}{C(E_e,p_\nu)_\nu} \approx 1$$ $J \to J$

- *K-th* unique forbidden

(Leptonic contribution)

$$u_1(p_e,p_\nu) = p_\nu^2 + \lambda_2 p_e^2$$

$$u_2(p_e,p_\nu) = p_\nu^4 + \frac{10}{3}\lambda_2 p_\nu^2 p_e^2 + \lambda_3 p_e^4$$

$$u_3(p_e,p_\nu) = p_\nu^6 + 7\lambda_2 p_\nu^4 p_e^2 + 7\lambda_3 p_\nu^2 p_e^4 + \lambda_4 p_e^6$$

$J \to J + K$

$$C(E_e,p_\nu)_\beta^i = \left[\frac{R^i}{(2i+1)!!}\right]^2 \left|{}^A F^{(0)}_{(i+1)i1}\right| u_i(p_e,p_\nu)$$

(Nuclear contribution)

$$A_i = \int_{m_e}^{W_0} \frac{u_i\left(p_e',p_\nu'\right)p_e' E_e' F\left(Z,E_e'\right)}{u_i\left(p_e,p_\nu\right)p_e E_e F\left(Z,E_e\right)} E_\nu' p_\nu' dE_e'$$

NCB Cross Section Evaluation

The case of Tritium

Using the expression

$$\sigma_{NCB} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z,E_e) C(E_e,p_\nu)_\nu$$

we obtain

$$\sigma_{NCB}(^3H)\frac{v_\nu}{c} = (7.7 \pm 0.2) \times 10^{-45}\, cm^2$$

where the uncertainty mainly due to lack of knowledge of $C(E_e,p_\nu)$

Using shape factors ratio

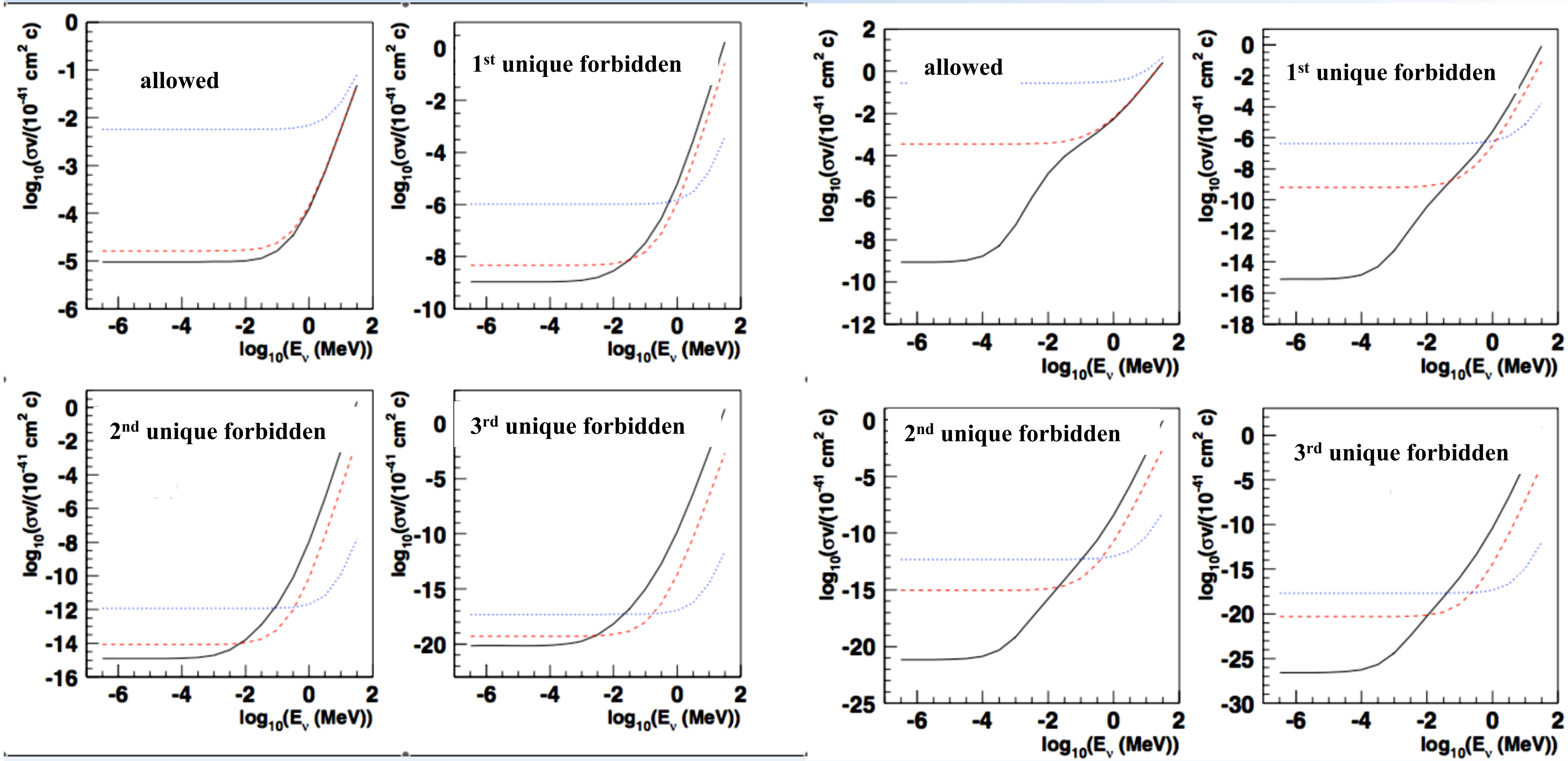
$$\sigma_{NCB} v_\nu = \frac{2\pi^2 \ln 2}{A \cdot ft_{1/2}}$$

$$\sigma_{NCB}(^3H)\frac{v_\nu}{c} = (7.84 \pm 0.03) \times 10^{-45}\, cm^2$$

where the uncertainty is only due to the uncertainties on Q_β and $t_{1/2}$

NCB Cross Section

as a function of E_ν, for several Q_β and nuclear transition multipolarity values



Q_β = 1 keV
Q_β = 100 keV
Q_β = 10 MeV

NCB Cross Section Evaluation

specific cases

Isotope	Q_β (keV)	Half-life (s)	$\sigma_{NCB}(v_\nu/c)$ $(10^{-41}\ \mathrm{cm}^2)$
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.350 2	3.54×10^{-2}
^{34}Cl	4469.78	1.528 0	5.90×10^{-2}
^{38m}K	5022.4	0.925 12	7.03×10^{-2}
^{42}Sc	5403.63	0.681 43	7.76×10^{-2}
^{46}V	6028.71	0.422 99	9.17×10^{-2}
^{50}Mn	6610.43	0.283 71	1.05×10^{-1}
^{54}Co	7220.6	0.193 50	1.20×10^{-1}

Super-allowed $0^+ \rightarrow 0^+$

Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{NCB}(v_\nu/c)$ $(10^{-41}\ \mathrm{cm}^2)$
^{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}
^{11}C	β^+	960.2	1.226×10^{3}	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^{2}	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^{2}	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^{3}	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^{4}	3.87×10^{-4}

Nuclei having the highest product $\boldsymbol{\sigma_{NCB}}\ \boldsymbol{t_{1/2}}$

NCB Cross Section

what we said so far

- **Exist a process (NCB) that allows in principle the detection of neutrino of vanishing energy!**

- **The cross section (times the neutrino velocity) does not vanish when the neutrino energy becomes negligible!**

- **Thousands of cross sections for neutrino interactions on beta unstable nuclei have been evaluated!**

The detection of the relic neutrinos has been downscaled from a principle problem to a technological challenge.

Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei JCAP 0706:015,2007,
Low Energy Antineutrino Detection Using Neutrino Capture on EC Decaying Nuclei: Phys. Rev. D 79, 053009 (2009)

Relic Neutrino Detection

signal to background ratio

The ratio between capture (λ_ν) and beta decay rate (λ_β) is obtained using the previous expressions:

$$\frac{\lambda_\nu}{\lambda_\beta} = \frac{2\pi^2 n_\nu}{A}$$

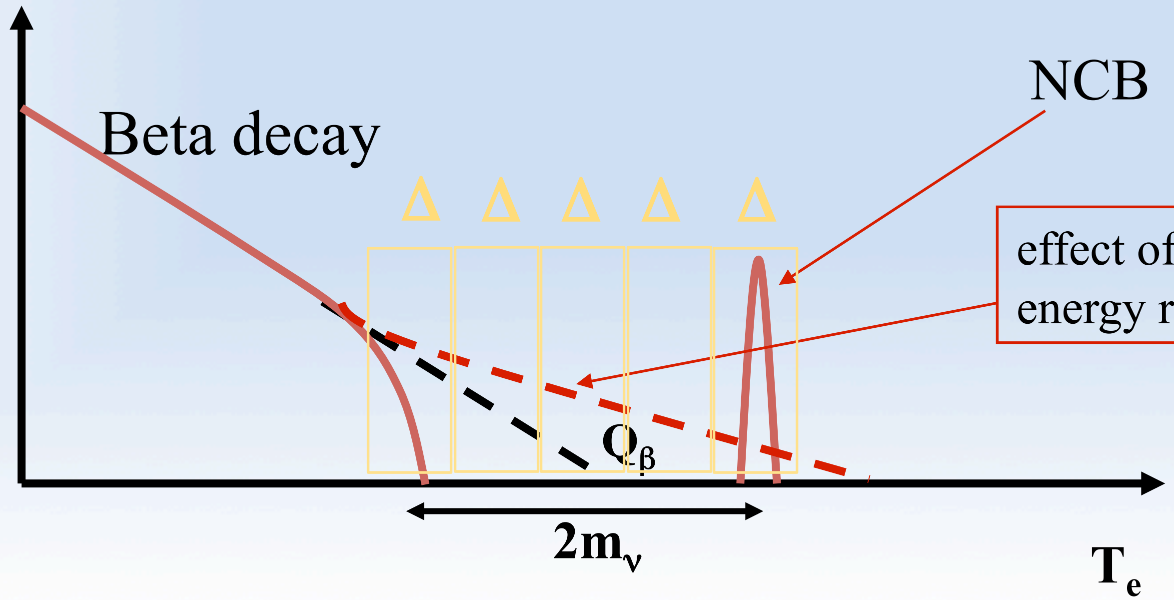
Then, if we evaluate $\lambda_\nu/\lambda_\beta$ for ^3H in the full energy range of the β decay spectrum, with the assumption that $m_\nu=0$, $n_\nu \sim 53/cm^3$ we get a value to small to be considered in an experimental framework ($0.66\ 10^{-23}$).

Relic Neutrino Detection (III)
signal to background ratio

As a general result for a given experimental resolution Δ the signal (λ_ν) to background (λ_β) ratio is given by:

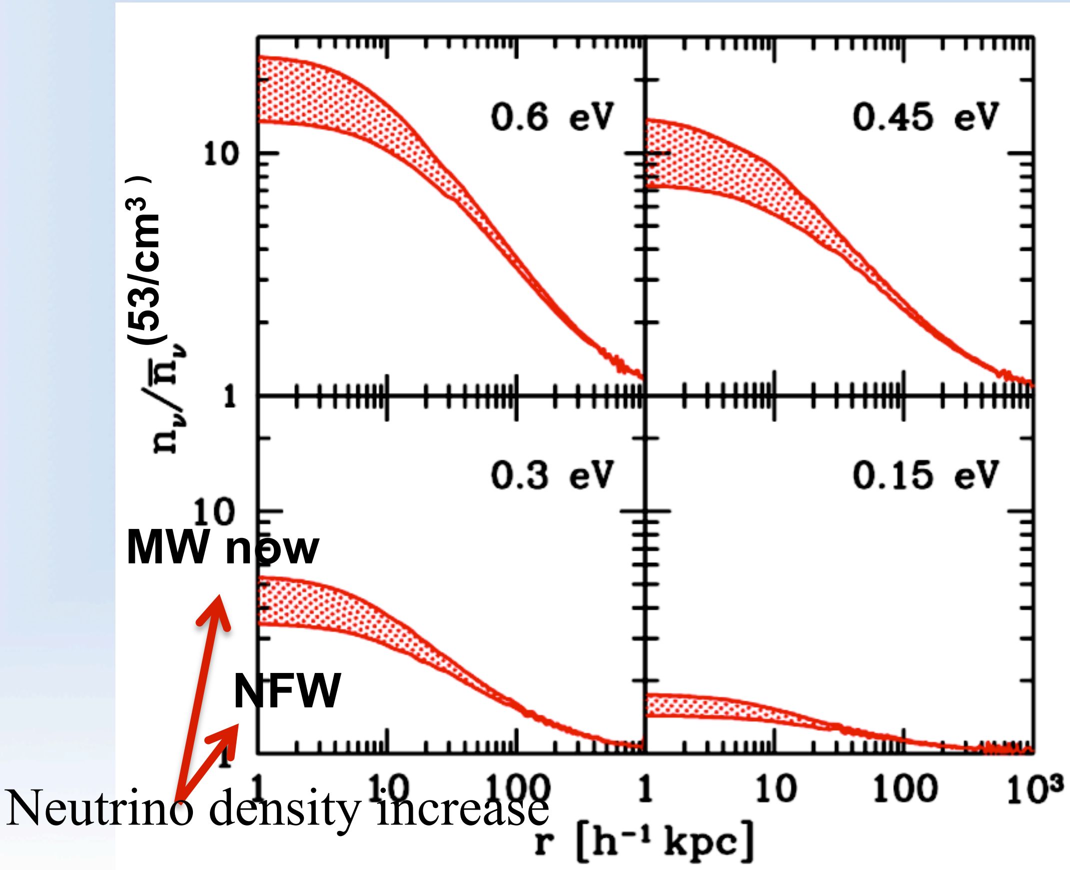
$$\frac{S}{B}=\frac{9}{2}\varsigma(3)\left(\frac{T_\nu}{\Delta}\right)^3\frac{1}{\left(1+2m_\nu/\Delta\right)^{3/2}}\left[\frac{1}{\sqrt{2\pi}}\int_{2m_\nu-\frac{1}{2}}^{2m_\nu+\frac{1}{2}}e^{-x^2/2}dx\right]^{-1}$$

where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the $2m_\nu$ gap.



Possible effects enhancing the NCB (I)

A.Ringwald and Y.Y.Wong (JCAP12(2004)005) made predictions about the CRN density by using an N-body simulation under two main assumptions. In one they considered the clustering of the CRN under the gravitational potential given by the Milk Way matter density as it is today. The second prediction was made considering a gravitational potential evolving during the Universe expansion (Navarro, Franck and White). In both cases the neutrinos were considered as spectators and not participating to the potential generation.



Possible effects enhancing the
NCB (II)

In table the number of events per year are reported if we assume the target mass of 100 g of Tritium

m_ν(eV)	FD (events/yr)	NFW (events/yr)	MW (events/yr)
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

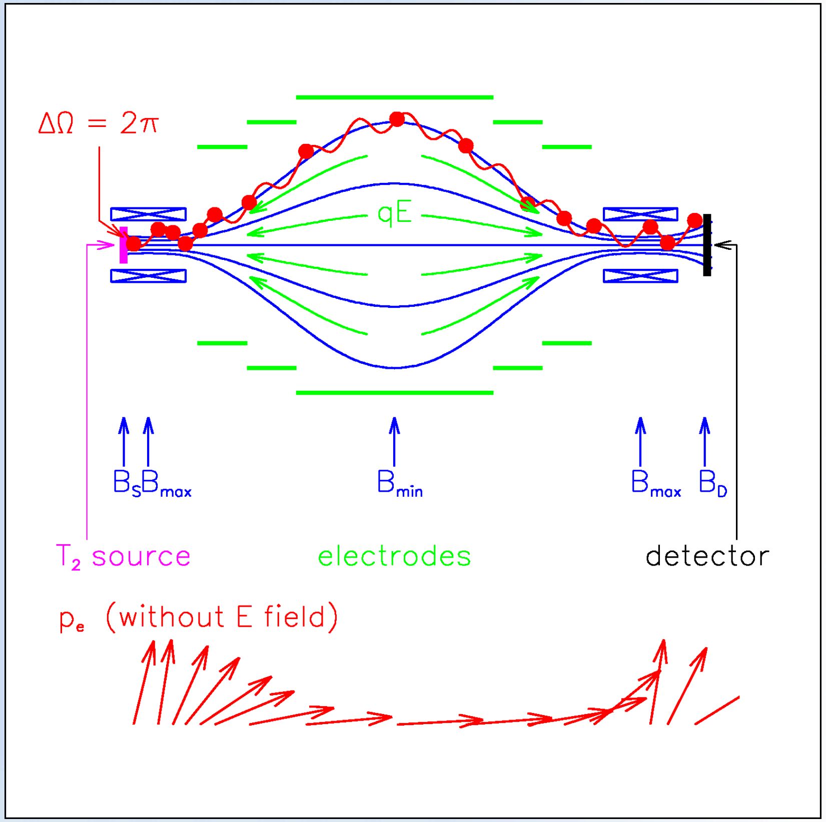
No background has been considered so far!

Possible experimental solutions

One possible experimental approach (I)

KATRIN detector, the ultimate direct neutrino experiment,
aiming at direct neutrino mass measurement through the study of the ^{3}H end-point
(Q_β =18.59 keV, $t_{1/2}$ =12.32 y)

The beta electrons, isotropicaly emitted at the source, are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. This parallel beam of electrons is running against an electrostatic potential formed by a system of cylindrical electrodes. All electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected.

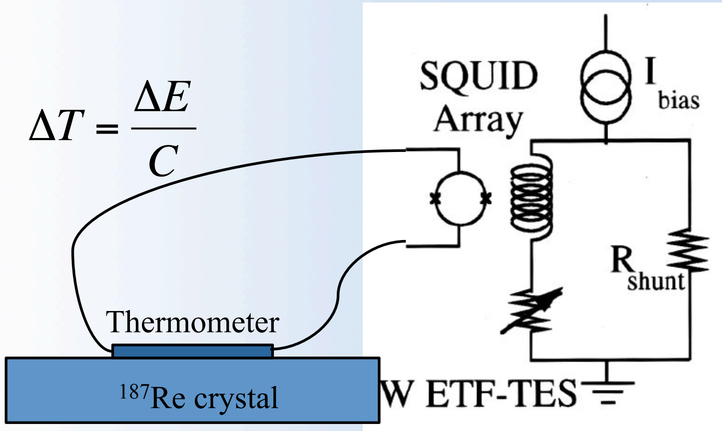


$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

Another experimental solution to detect the CRN

MARE detector

$$\Delta T = \frac{\Delta E}{C}$$



The key issue of the read-out system are the very low noise SQUID amplifier

$$\Delta V = V_{bias} \cdot A \cdot \frac{\Delta T}{T} = \frac{V_{bias} A}{C \cdot T} \Delta E$$

MARE collaboration claims that can achieve a resolution of part of eV. This would match our request but much larger mass with respect to the case of Tritium is needed since the cross section of NCB on ^{187}Re is lower. The MARE collaboration foresees to have in ~2011 100000 micro calorimeters of 1-5 mg mass each. This is still 4-6 order of magnitude far from the mass we need but in principle this detector technology can be scaled up easily.

Why KATRIN and MARE experiments can not work

- **The KATRIN technology meets the detector performance we request but can not run enough target mass. If we try to fit 10 g of T in the KATRIN experiment the energy resolution will be spoiled out. The only possibility to run with 10 g of T and obtain the resolution we aim at is to make KATRIN as large as the Everest mountain.**

- **The MARE detector also meet the desired performance but in order to have the desired luminosity we would need ~ 10^{10} bolometers (channels).**

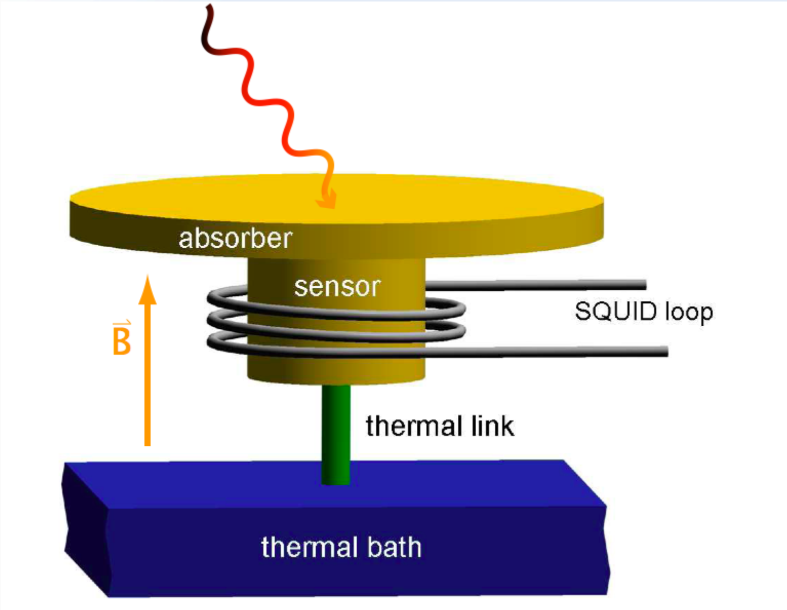
What we need to be able to detect relic neutrinos.

- **Highest cross section: Tritium**

- **The best energy resolution**

- **The capability to select only interesting events.**

Magnetic Micro Calorimeter (I)



❖ Operation at low temperatures (T<100mK)

small heat capacity

large temperature change

small thermal noise

❖ Main differences to resistive calorimeters

no dissipation in the sensor

no galvanic contact to the sensor

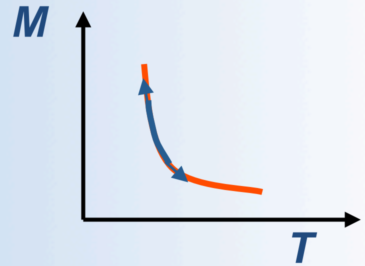
Temperature rise upon absorption:

$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

a rise time as short as 90 ns

$$\tau = \frac{C_{\mathrm{tot}}}{G}$$

paramagnetic sensor: Au:Er

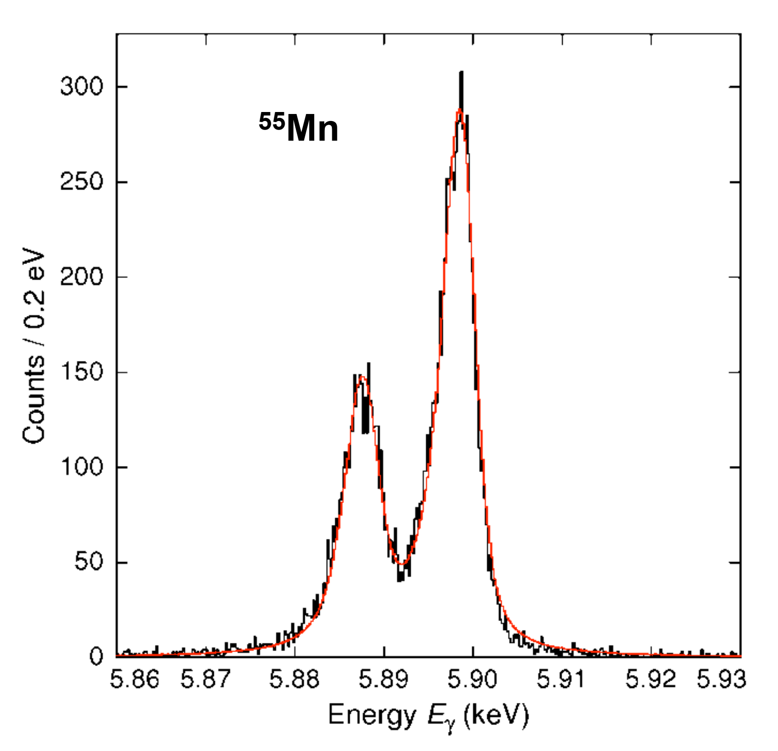


$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

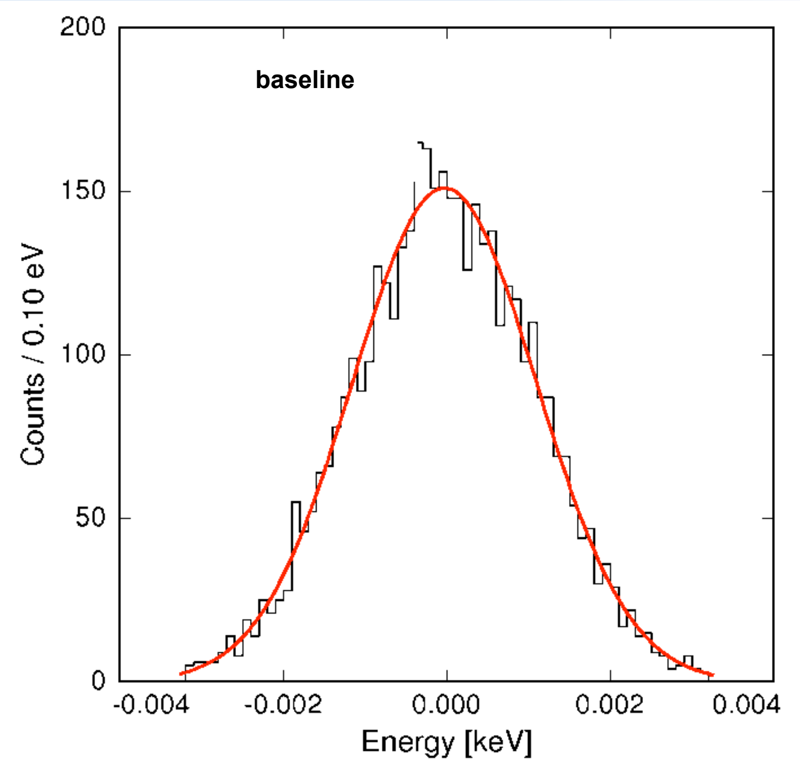
MARE proposal

Metallic Magnetic Calorimeter (II)

ΔE_{FWHM} = 2.8 eV @ 6 keV



ΔE_{FWHM}= 2.65 eV @ 0 keV



→ Expected energy resolution for next detectors <1. eV

MARE proposal

Next steps

• Decide which is the technology more appropriate: we need support for an R&D

• Realize the first test with 1-10 μg of T where we mainly investigate the capability of selecting events in the desired energy interval.

• Design and possibly realize the experiment with a T mass on the scale of gram. The following steps will be physics results oriented.

Conclusions

- The fact that neutrino has a nonzero mass has renewed the interest on Neutrino Capture on Beta decaying nuclei as a <u>unique tool to detect very low energy neutrino.</u>
- The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a near future if:
  - neutrino mass is in the eV range
  - an electron energy resolution of 0.1 – 0.2 eV is achieved

- Different technological approaches are under study and one out of those is particularly interesting:
  - ✓Magnetic Micro Calorimeter.