NOW2008

Conca Specchiulla
07-09-2008

Cosmological Relic Neutrino detection using Neutrino Capture on beta decaying nuclei

Alfredo G. Cocco
Istituto Nazionale di Fisica Nucleare
(Italy)

AGC, M.Messina and G.Mangano

The longstanding question

Is it possible to detect/measure the Cosmological Relic Neutrino background ($C\nu B$) ?

We know that neutrino of $C\nu B$ are non-relativistic and weakly-clustered

- UHE cosmic rays scattering (indirect, unknown sources)
- Torsion balance (target polarization, strong ν-$\bar{\nu}$ asymmetry)

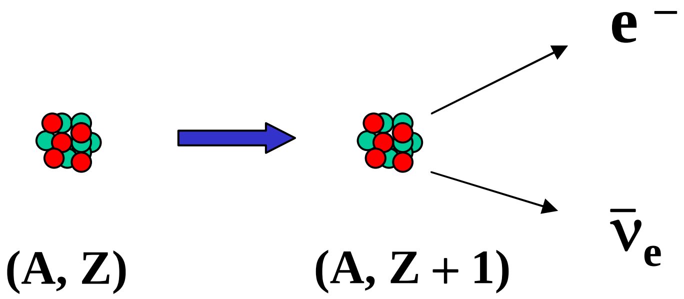
Short answer: NO !!

All the methods proposed so far require either strong theoretical assumptions or experimental apparatus having unrealistic performances

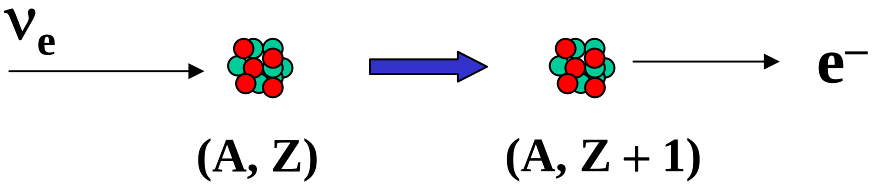
A.Ringwald “Neutrino Telescopes” 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

Neutrino capture on $\beta^{\pm}$ decaying nuclei

Beta decay



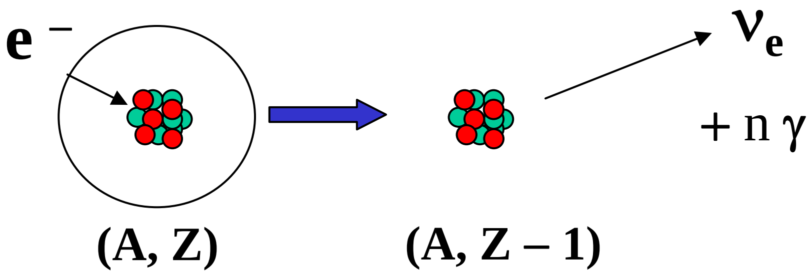
Neutrino Capture on a Beta Decaying Nucleus (NCB)



This process has no energy threshold !

Antineutrino capture on EC decaying nuclei

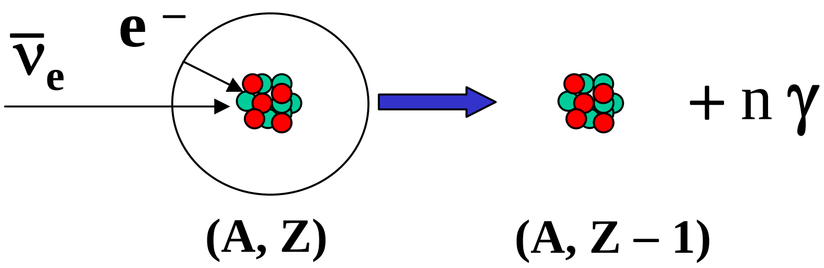
Electron Capture



e^- ν_e $+ \, n\,\gamma$

(A, Z) (A, Z – 1)

$\bar{\nu}$ and electron Capture

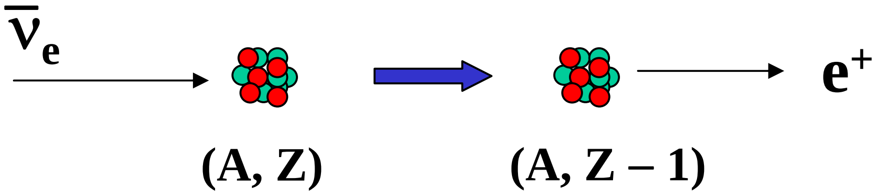


$\bar{\nu}_e$ e^- $+ \, n\,\gamma$

(A, Z) (A, Z – 1)

This process has no energy threshold !

Antineutrino Capture



$\bar{\nu}_e$ e^+

(A, Z) (A, Z – 1)

E_ν threshold = $2m_e$ - Q_{EC}

The effect of $m_\nu \neq 0$

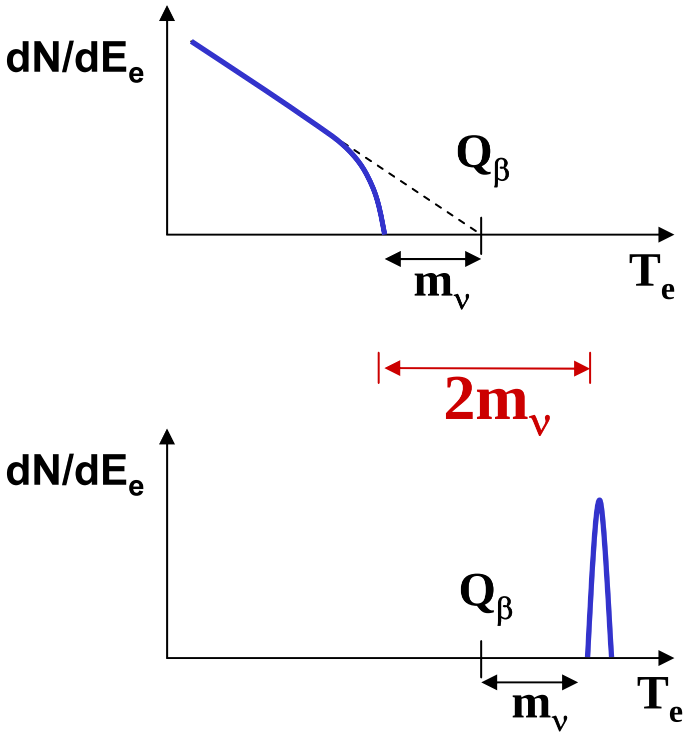
Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe

Neutrino capture on $\beta^{\pm}$ decaying nuclei

(exploiting $m_\nu \neq 0$)

Beta decay

Neutrino Capture on a Beta Decaying Nucleus



The events induced by Neutrino Capture have a unique signature provided by a gap of $2m_\nu$ centered at Q_β

Antineutrino capture on EC decaying nuclei

(exploiting $m_\nu \neq 0$)

Electron Capture

$e^- + (A,Z) \rightarrow (A,Z-1) + \nu_e + n\,\gamma$

$E_\nu = Q_{EC} - E_K$
$E_\gamma = E_K$

E_K = captured electron binding energy

$\bar{\nu}_e + e^- + (A,Z) \rightarrow (A,Z-1) + X$ Always energetically allowed

IF: $E_K - m_\nu \leq Q_{EC} < E_K + m_\nu$ (in the limit $E_\nu \rightarrow m_\nu$)

the EC decay is forbidden (no background)

$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+$ $E_{thr} = 2m_e - Q_{EC}$

IF: $2m_e - m_\nu \leq Q_{EC} < 2m_e + m_\nu$

no threshold and the β^+ decay is forbidden (no background)

NCB Cross Section

a new parametrization

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

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

The nuclear shape factors C_β and C_ν both depend on the same nuclear matrix elements

It is convenient to define $$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e$$

$$\boxed{\sigma_{\rm NCB} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}}$$

More details in: AGC, M.Messina and G.Mangano JCAP 06(2007)015

NCB Cross Section

a new parametrization

$$\sigma_{\rm NCB} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\; t_{1/2}}$$

This is valid for both $\beta^\pm$ and EC decaying nuclei

$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e$$

$\overset{(-)}{\nu}$ capture on $\beta^\pm$ nuclei

$$\mathcal{A} = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{p_e E_e F(Z, E_e) C(p_e, p_\nu)_\nu}$$

$\bar{\nu}$ capture on EC nuclei

$$\mathcal{A}' = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{\sum_x n_x C_x(E_\nu) g_x \rho_x(E_\nu)}$$

$\bar{\nu}$ + e^- capture on EC nuclei

In a large number of cases $\mathcal{A}$ can be evaluated in an exact way and NCB cross section depends only on Q_β and $t_{1/2}$ (measurable)

Example: NCB Cross Section

on β± nuclei for different types of decay transitions

- Superallowed transitions

$$\sigma_{\rm NCB} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$$

- This is a very good approximation also for allowed transitions since

$$\frac{C(E_e, p_\nu)_\beta}{C(E_e, p_\nu)_\nu} \simeq 1$$

- *i-th* unique forbidden

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

$$\mathcal{A}_i = \int_{m_e}^{W_o} \frac{u_i(p'_e, p'_\nu) p'_e E'_e F(Z, E'_e)}{u_i(p_e, p_\nu) p_e E_e F(Z, E_e)} E'_\nu p'_\nu \, \mathrm{d}E'_e$$

NCB Cross Section Evaluation

The case of Tritium

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

we obtain $\sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} \underset{\lim \beta \to 0}{=} (\ 7.7 \pm 0.2\ ) \times 10^{-45}\ {\rm cm}^2$

where the error is due to Fermi and Gamow-Teller matrix element uncertainties

---

Using shape factors ratio $\sigma_{\rm NCB} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$

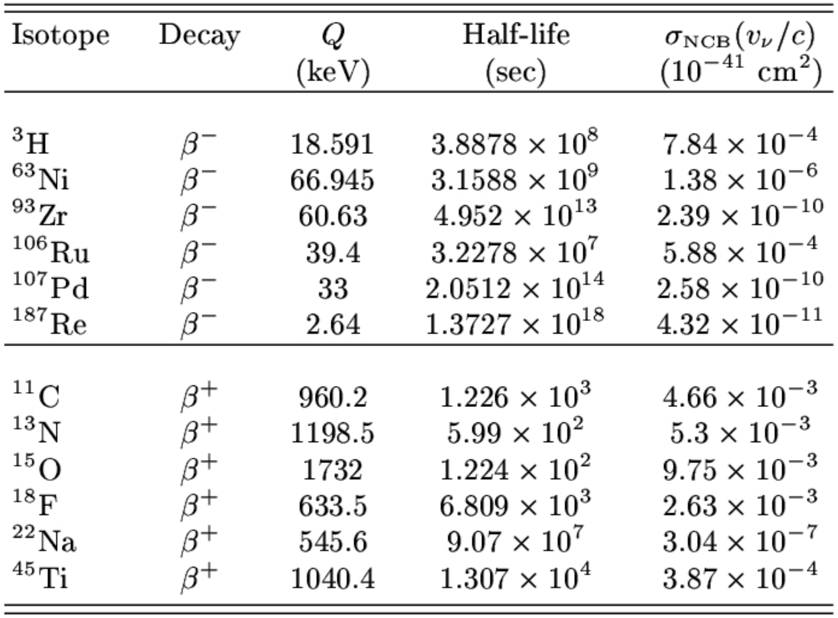
$$\sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} \underset{\lim \beta \to 0}{=} (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ {\rm cm}^2$$

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

NCB Cross Section Evaluation

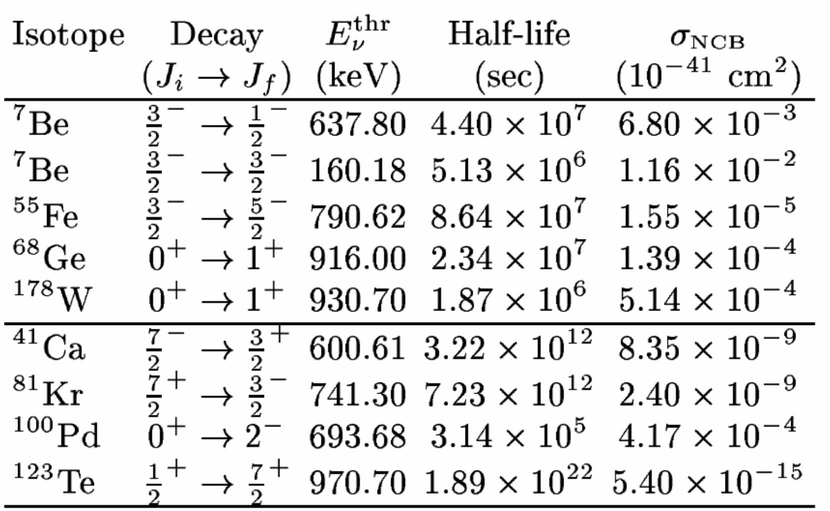
specific cases

$\beta^{\pm}$



Isotope	Decay	Q (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}
^{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}

EC



Isotope	Decay ($J_i \to J_f$)	$E_\nu^{\rm thr}$ (keV)	Half-life (sec)	$\sigma_{\rm NCB}$ (10^{-41} cm^2)
^{7}Be	$\frac{3}{2}^- \to \frac{1}{2}^-$	637.80	4.40×10^{7}	6.80×10^{-3}
^{7}Be	$\frac{3}{2}^- \to \frac{3}{2}^-$	160.18	5.13×10^{6}	1.16×10^{-2}
^{55}Fe	$\frac{3}{2}^- \to \frac{5}{2}^-$	790.62	8.64×10^{7}	1.55×10^{-5}
^{68}Ge	$0^+ \to 1^+$	916.00	2.34×10^{7}	1.39×10^{-4}
^{178}W	$0^+ \to 1^+$	930.70	1.87×10^{6}	5.14×10^{-4}
^{41}Ca	$\frac{7}{2}^- \to \frac{3}{2}^+$	600.61	3.22×10^{12}	8.35×10^{-9}
^{81}Kr	$\frac{7}{2}^+ \to \frac{3}{2}^-$	741.30	7.23×10^{12}	2.40×10^{-9}
^{100}Pd	$0^+ \to 2^-$	693.68	3.14×10^{5}	4.17×10^{-4}
^{123}Te	$\frac{1}{2}^+ \to \frac{7}{2}^+$	970.70	1.89×10^{22}	5.40×10^{-15}

$E_\nu = E_{\rm thr} + 1$ MeV

K capture

Nuclei having the highest product

$\sigma_{\rm NCB}\ t_{1/2}$

Relic Neutrino Detection

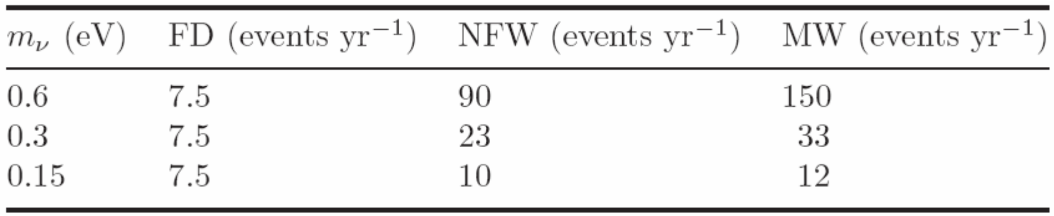
using $\beta^{\pm}$ decaying nuclei

In the case of Tritium we estimate that 7.5 neutrino capture events per year are obtained using a total mass of 100 g

Signal to background ratio depends crucially on the energy resolution (Δ) at the beta decay endpoint (It works only if $\Delta < m_\nu$)

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of Δ=0.2 eV a signal to background ratio of 3 is obtained. In the case of 100 g mass target of Tritium it would take one and a half year to observe a 5σ effect

In case of CνB gravitational clustering we expect a significant signal enhancement



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

FD = Fermi-Dirac NFW= Navarro,Frenk and White
MW=Milky Way (Ringwald, Wong)

Relic Neutrino Detection

using EC decaying nuclei

$\bar{\nu}_e + e^- + (A,Z) \rightarrow (A,Z-1) + X$

The lack of a suitable final state prevents the use of this reaction to detect CνB unless either:

1) there exist an excited level (either atomic or nuclear) with energy

$$E_o = Q_{EC} - E_K + m_\nu$$

2) the captured electron is “off-mass” shell $m_{eff} = m_e - E_o$

3) it exist a nucleus A (stable) for which $Q_{EC} = E_K - m_\nu$

Relic Antineutrino Detection

using EC decaying nuclei

$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+$

The energy threshold prevents the use of this reaction to detect CνB unless:

1) use CνB as a target for accelerated fully ionized beam
   - EC decay is inhibited (no electrons to be captured)
   - Ions should have

$$\gamma_{\min} = \frac{E_{\rm thr}^2}{2m_\nu M} + \frac{E_{\rm thr}}{m_\nu} \underset{\uparrow}{\simeq} E_{\rm thr}\,[\mathrm{eV}]$$

In case *M* ~ 1 GeV and m_ν ~ 1 eV

   - Interaction rate is given by

$$\lambda_{\rm NCB} = \frac{\gamma\, n_{\bar\nu}\, 2\pi^2 \ln 2}{\mathcal{A} \cdot t_{1/2}^{\rm EC}}\, \mathcal{N}$$

For allowed transitions and using n_ν= 56, E_{thr}=10 eV :

$$\mathcal{N} = 10^{13}$$
$$\gamma = 100$$

$$\lambda_{\rm NCB} \simeq 10^{-16}\ \mathrm{s}^{-1}$$

Too slow to be detected !

Relic Antineutrino Detection

using EC decaying nuclei

$$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+$$

2) there exist a nucleus for which

$$2m_e - m_\nu < Q_{EC} < 2m_e + m_\nu$$

In this case:

- the reaction has no energy threshold on the incoming antineutrino
- unique signature since β^+ decay is forbidden
- cross section is evaluated using EC decay observables

Conclusions

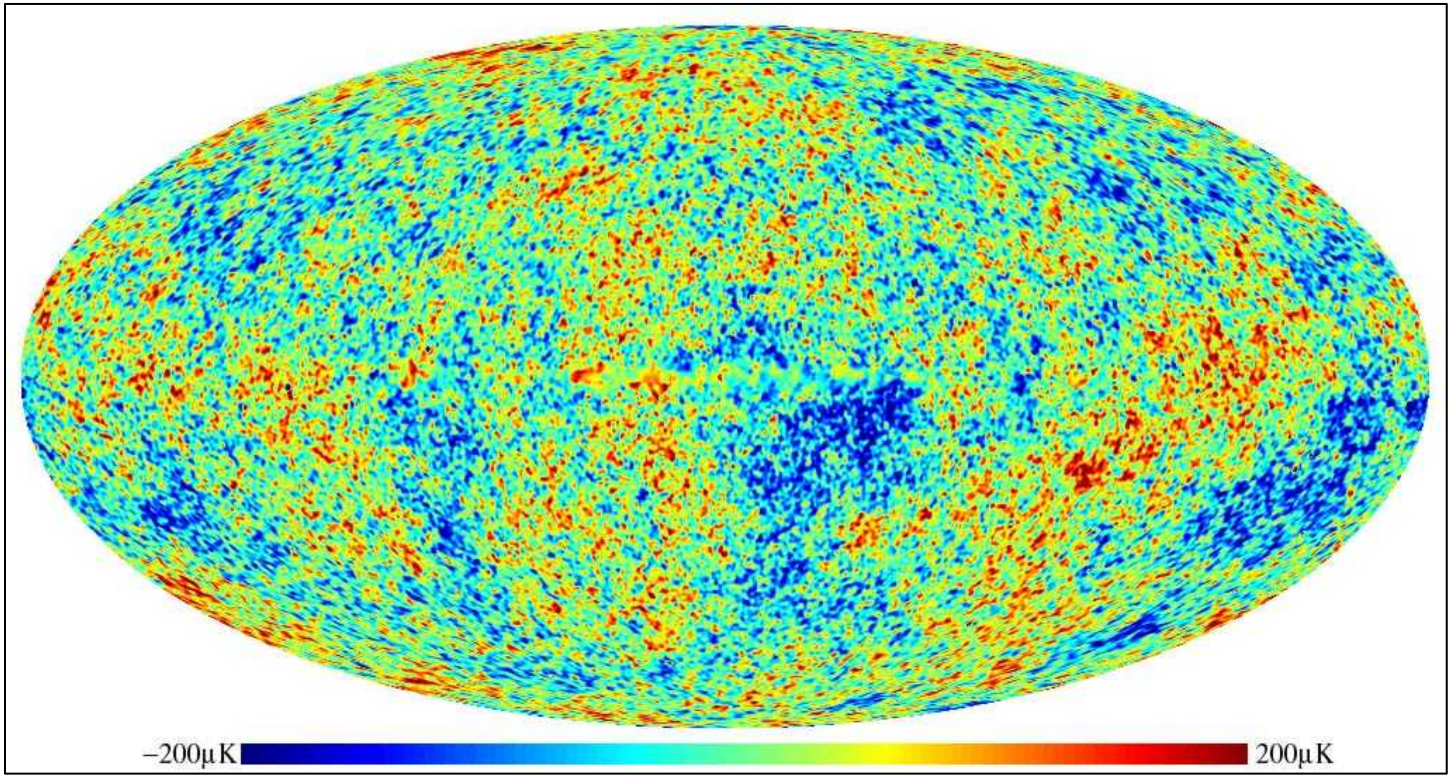
The fact that neutrino has a nonzero mass has renewed the interest on Netrino Capture on $\beta^{\pm}$ and EC decaying nuclei as a tool to measure very low energy neutrino

A detailed study of NCB cross section has been performed for a large sample of known beta decays avoiding the uncertainties due to nuclear matrix elements evaluation

The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a few years using $\beta^{\pm}$ decaying nuclei

The energy threshold in one case and the absence of a suitable final state in the other prevent the use of EC decaying nuclei unless very specific conditions are fulfilled (difficult, but worth searching further…)

ν Anisotropy Probe Collaboration



CνB map in 20??