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Workshop Towards Neutrino Technologies

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Towards cosmological relic neutrino detection

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Towards Cosmological Relic Neutrino Detection

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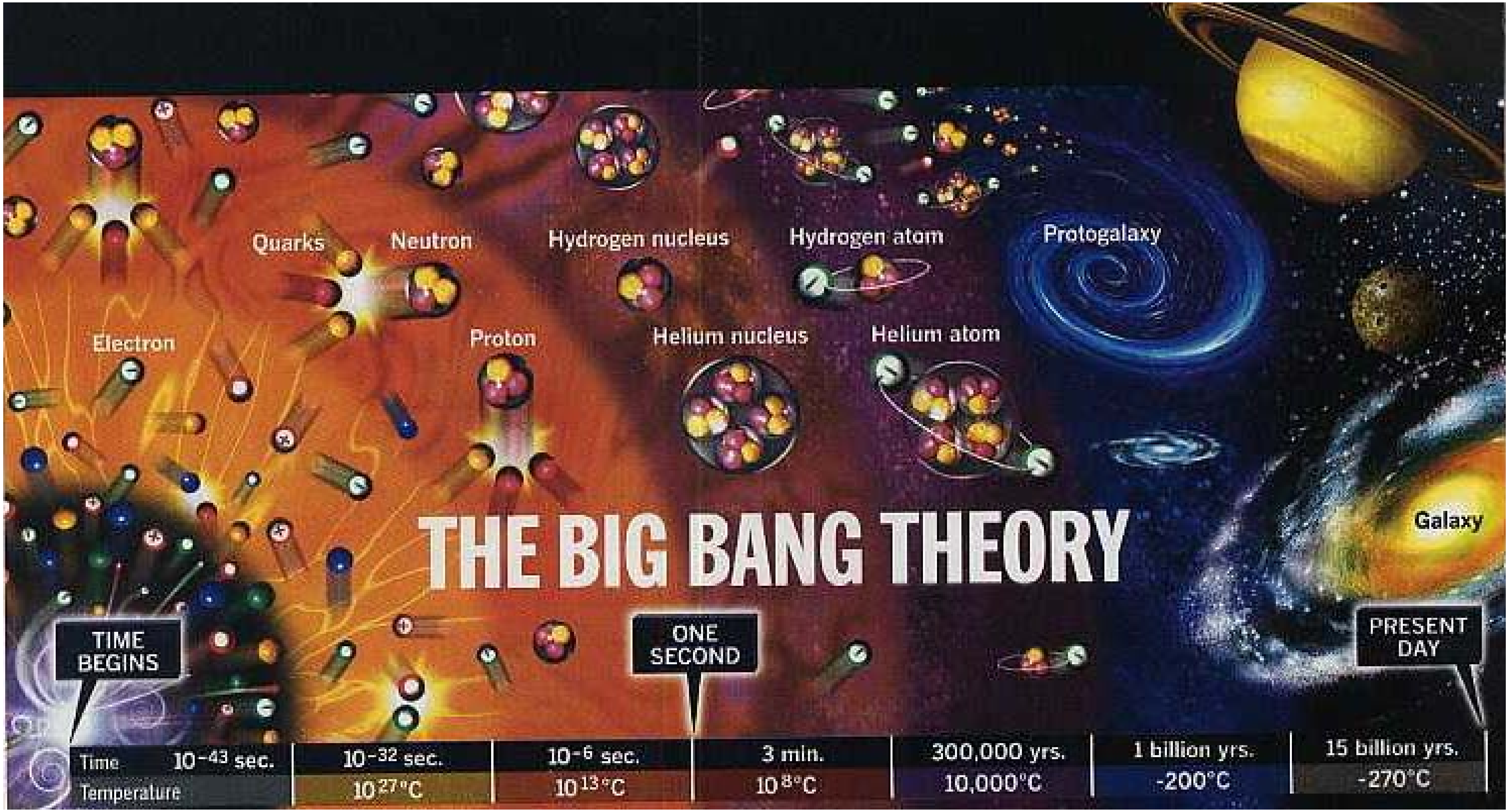


Neutrinos decouple (CνB)

Neutral atoms (CMB)

Cosmological relic neutrino Background (CνB)

In the Big-Bang scenario neutrinos decoupled when T ~ MeV

This happened about 1 s after the Universe was born

$\Rightarrow$ ν are the oldest “detectable” relics !!

“Thermal” spectrum $\quad f_\nu(p,T) = \dfrac{1}{e^{p/T_\nu}+1} \qquad p_\nu \approx 10^{-4}\ \mathrm{eV}$

Number density today

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3 \cong \left(56\ \mathrm{cm}^{3}\right)\times 6$$

Energy density today

massless $\quad \Omega_\nu h^2 = 1.7\times 10^{-5}$

massive $\quad \Omega_\nu h^2 = \dfrac{\sum_i m_i}{94.1\ \mathrm{eV}}$

Detection: G_F

Stodolsky effect: energy split of electron spin states in the ν background

requires ν chemical potential (Dirac) or net helicity (Majorana)

requires breaking of isotropy (Earth velocity)

results depend on Dirac/Majorana,relativistic/non relativistic, clustered/unclustered

Duda et al '01

$$\Delta E \approx G_F g_A \vec{s} \cdot \vec{\beta}_{\oplus} (n_\nu - \overline{n}_\nu)$$

Torque on frozen magnetized macroscopic piece of material of dimension R

$$\mathbf{a} \approx 10^{-27} \left(\frac{100}{\mathbf{A}} \right) \left(\frac{\mathbf{cm}}{\mathbf{R}} \right) \left(\frac{\beta_{\oplus}}{10^{-3}} \right) \left(\frac{\mathbf{n}_\nu - \overline{\mathbf{n}}_\nu}{100\ \mathbf{cm}^{-3}} \right) \mathbf{cm\ s}^{-2}$$

Presently Cavendish torsion balances: $\mathbf{a} \approx 10^{-12}\ \mathbf{cm\ s}^{-2}$

Detection: G_F^2

ν-Nucleus collision: net momentum transfer due to Earth peculiar motion

$$\sigma_{\nu N} = G_F^2\, E_\nu^2$$

$$a = n_\nu v_\nu \frac{N_A}{A} \sigma_{\nu N} \Delta p$$

$$\Delta p = \beta_\oplus E_\nu$$

$$\Delta p = \beta_\oplus m_\nu$$

$$\Delta p = \beta_\oplus T_\nu$$

$$\Rightarrow \quad \mathbf{a \approx (10^{-46} - 10^{-54}) \frac{A}{100}\, cm\, s^{-2}}$$

Coherence enhancement

$$\lambda_\nu \approx 1/T_\nu \quad \text{- } 1/\mathrm{m}_\nu \approx mm \qquad N_c = \frac{N_A}{A} \rho \lambda_\nu^3$$

Zeldovich and Khlopov '81

Smith and Lewin '83

The longstanding question

Is it possible to detect/measure the Cosmological Relic Neutrino background (CνB) ?

We know that neutrino of CνB are non-relativistic and weakly-clustered

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

The answer is: no !!

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

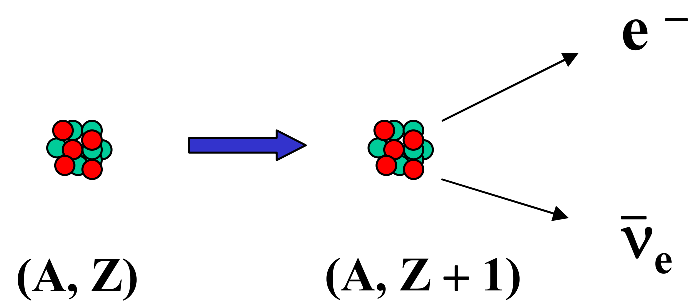
A.Ringwald “Neutrino Telescopes” 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

But…..

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

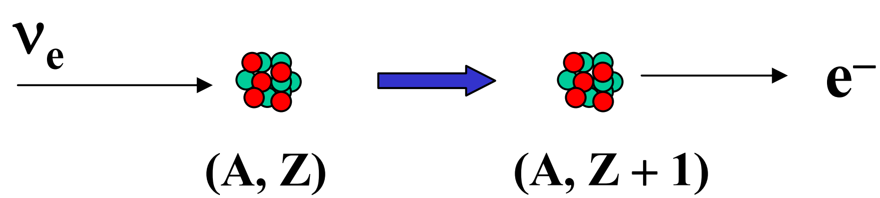
Known

Nuclear Beta decay



Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)

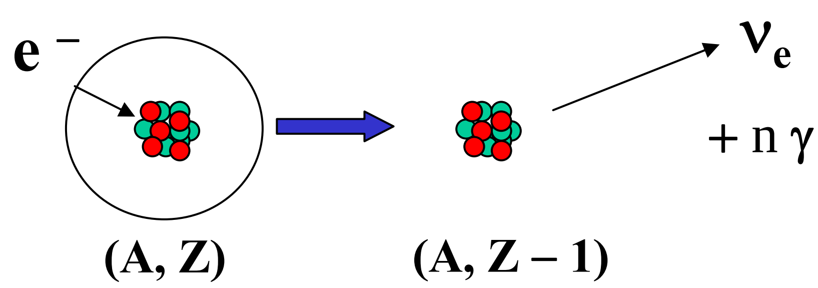


This process has no energy threshold !

Antineutrino capture on EC decaying nuclei (a)

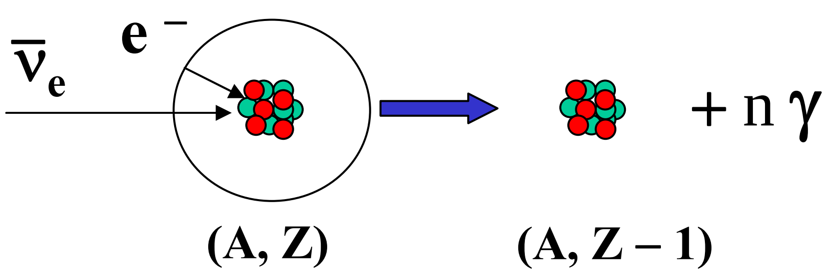
Known

Electron Capture



Possible

Simultaneous $\bar{\nu}$ and electron Capture

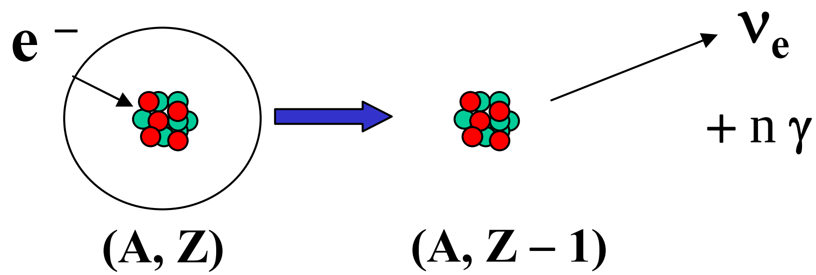


This process has no energy threshold !

Antineutrino capture on EC decaying nuclei (b)

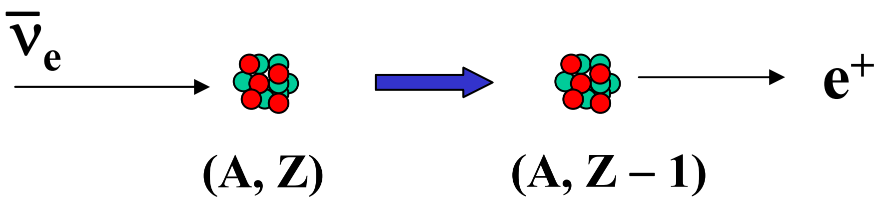
Known

Electron Capture



Possible

Antineutrino Capture



E_ν **threshold =** $2m_e$ **-** Q_{EC}

The effect of $m_\nu \neq 0$

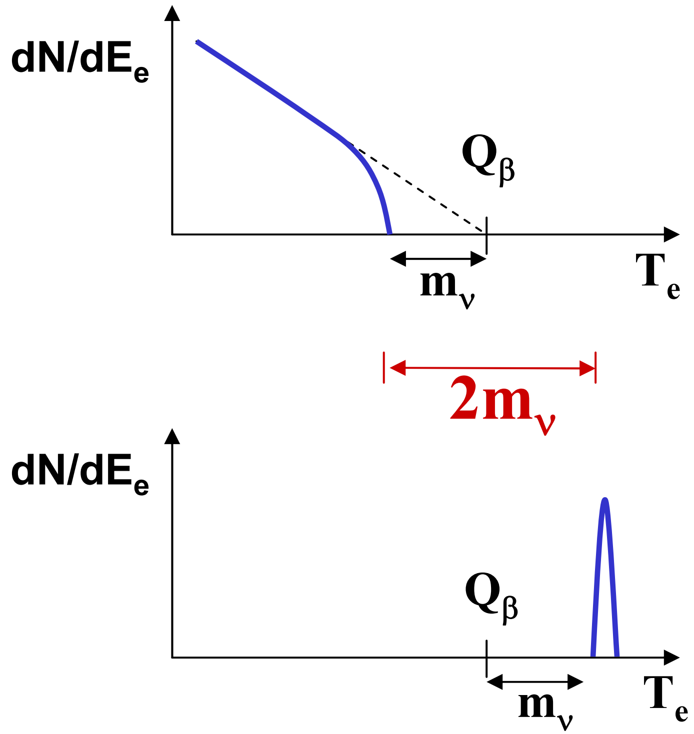
Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe

exploiting $m_\nu \neq 0$

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

Nuclear Beta decay

Neutrino Capture on a Beta Decaying Nucleus



The events induced by Neutrino Capture have a unique signature:
there is a gap of $2m_\nu$ (centered at Q_β) between “signal” and “background”

exploiting $m_\nu \neq 0$

Antineutrino capture on EC decaying nuclei reaction (a)

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)

exploiting $m_\nu \neq 0$

Antineutrino capture on EC decaying nuclei reaction (b)

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

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

$E_{thr} = 2m_e - Q_{EC}$

But, in case $2m_e - m_\nu \leq Q_{EC} < 2m_e + m_\nu$

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

The interactions exist…..

….but what about cross sections ?

If $\sigma_{NCB} \propto E_\nu$

then $\sigma_{NCB} \xrightarrow{E_\nu \to 0} 0$

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

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

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 $\beta^{\pm}$ 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

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

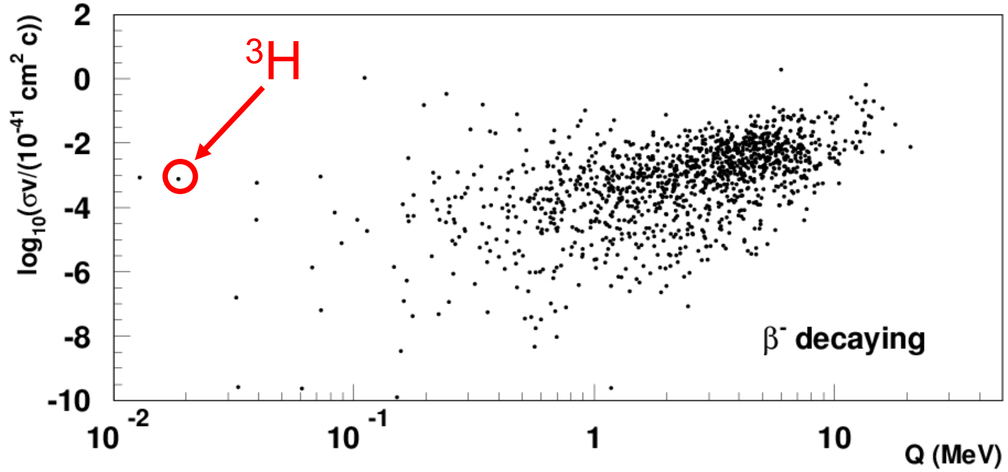
$$\sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} \underset{\lim \beta \to 0}{=} (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ {\rm cm}^2$$

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

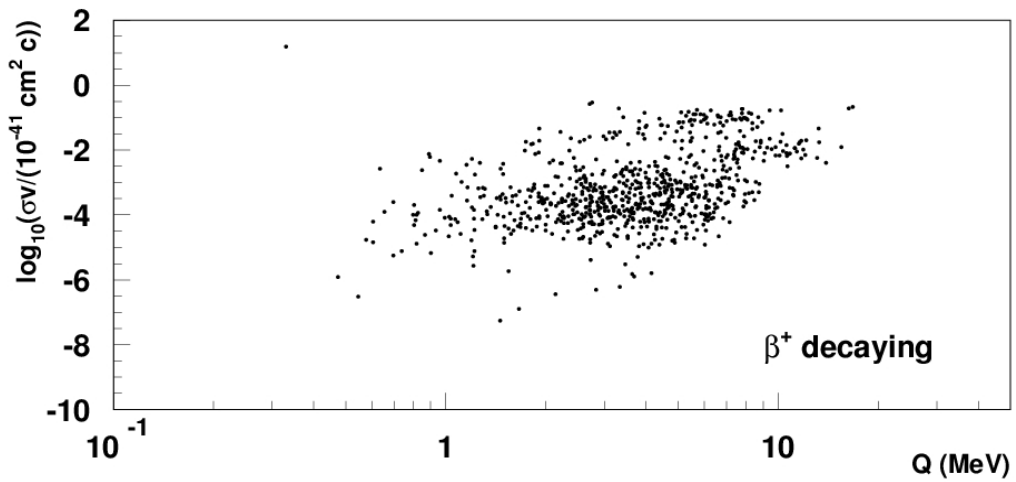
NCB Cross Section Evaluation

using measured values of Q_β and $t_{1/2}$

1272 β^- decays



799 β^+ decays



Beta decaying nuclei having BR($\beta^\pm$) > 5 %
selected from 14543 decays listed in the ENSDF database

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}

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

K capture

Nuclei having the highest product

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

Relic Antineutrino Detection

using EC decaying nuclei (a)

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

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 (b)

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

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 $\gamma_{\min} = \dfrac{E_{\rm thr}}{m_\nu}$
- Interaction rate is given by $$\lambda_{\rm NCB} = \frac{n_{\bar{\nu}}\, 2\pi^2 \ln 2}{\mathcal{A} \cdot t_{1/2}^{\rm EC}}\, \mathcal{N}$$

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

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

$$\lambda_{\rm NCB} \simeq 10^{-18}\ {\rm s}^{-1}$$

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

Question: “Is it possible to detect/measure the CνB ?”

Short answer: In the most favourable scenario (β decays)
it depends on the value of m_ν and on the
experimental energy resolution Δ

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

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

In the case of Tritium (and using n_ν=50) we found that

$$\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$$

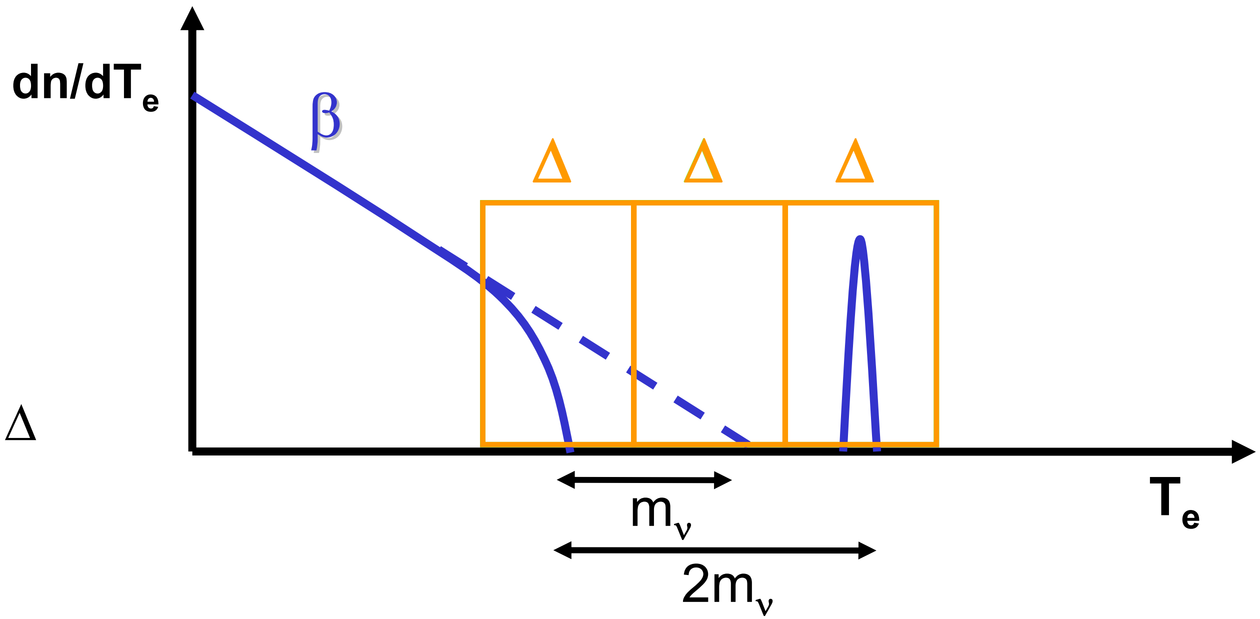
Taking into account the beta decays occurring in the last bin of width Δ at the spectum end-point we have that

$$\frac{\lambda_\nu}{\lambda_\beta(\Delta)} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}} \sim 10^{-10}$$

Relic Neutrino Detection

signal to background ratio

Observing the last energy bins of width Δ



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

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

It works for $\Delta < m_\nu$

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

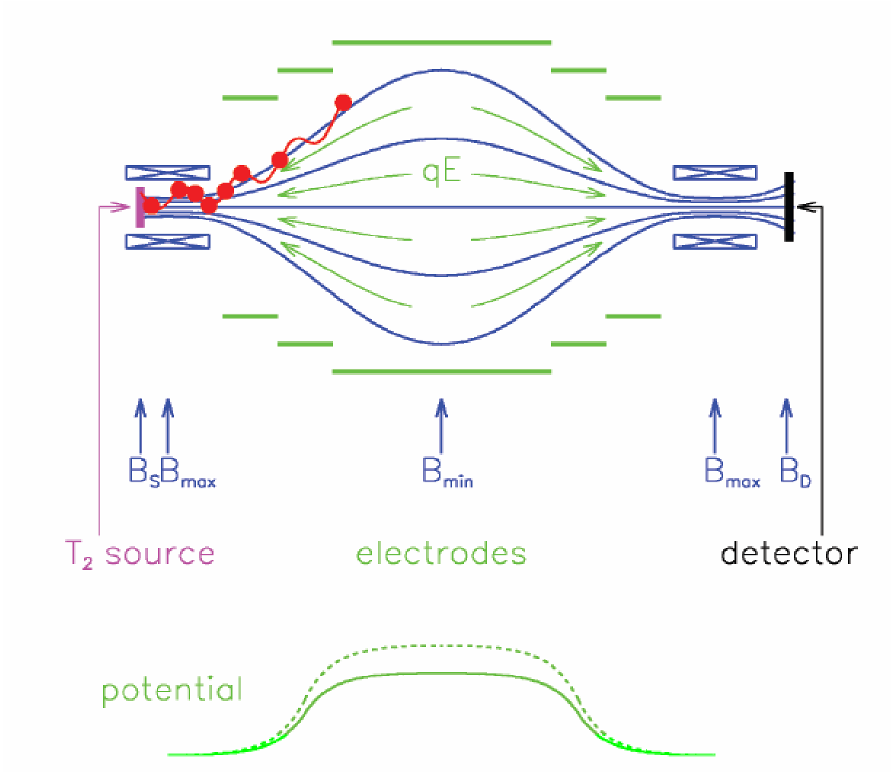
m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yr^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

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

KATRIN
Karlsruhe Tritium Neutrino Experiment

Aim at direct neutrino mass measurement through the study of the ^{3}H endpoint(Q_β =18.59 keV, $t_{1/2}$=12.32 years)

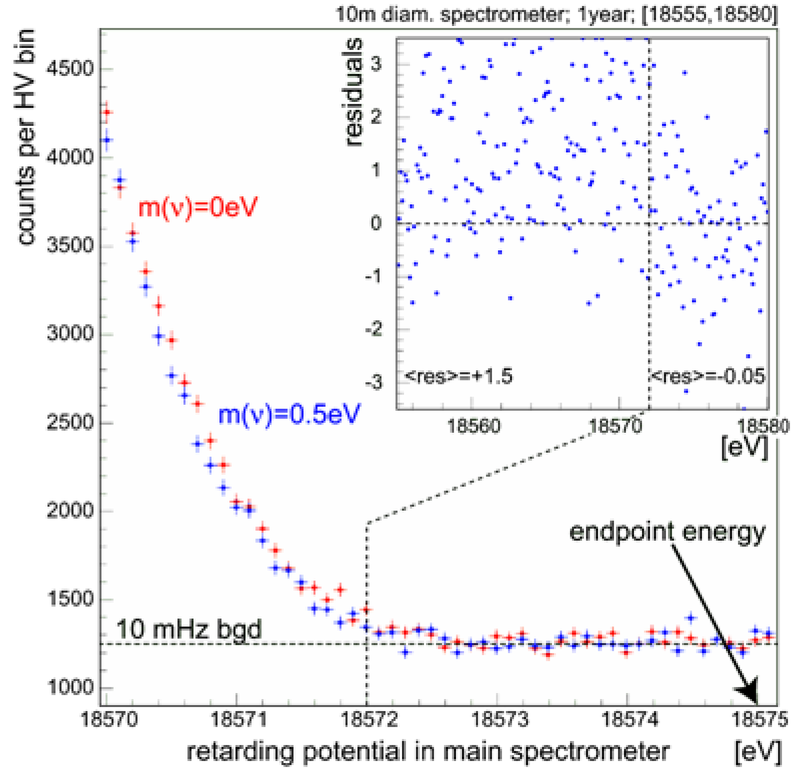
Phase I
- Energy resolution: 0.93 eV
- Tritium mass: ~ 0.1 mg
- Noise level 10 mHz
- Sensitivity to ν_e mass: 0.2 eV



Magnetic Adiabatic Collimator + Electrostatic filter

KATRIN
Karlsruhe Tritium Neutrino Experiment

MonteCarlo simulation of phase I data

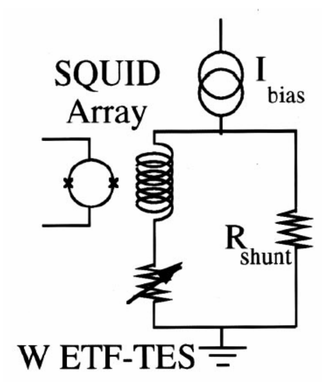


First results in 2011
End of Phase I data taking: 2015

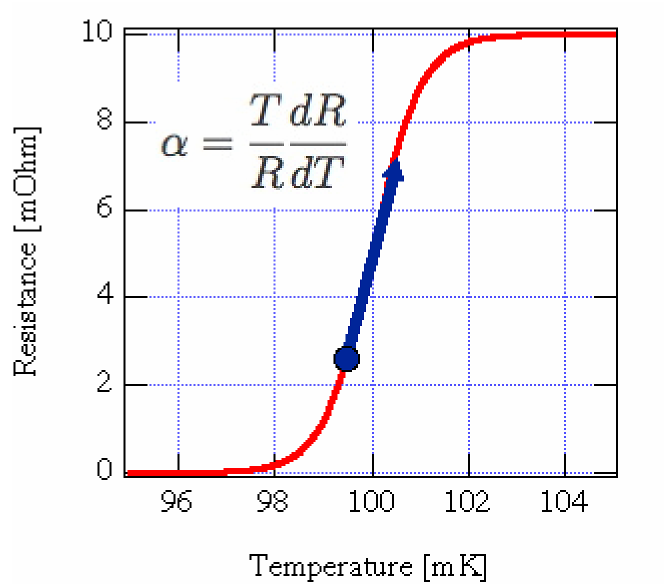
Phase II
- Energy resolution: 0.2 eV
- Noise level 1 mHz

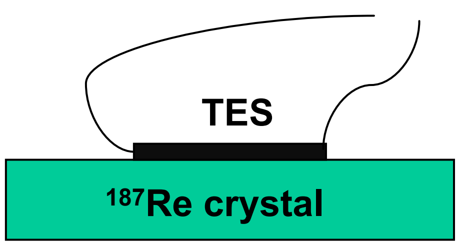
MARE

Aim at direct neutrino mass measurement through the study of the ^{187}Re endpoint (Q_β =2.66 keV, $t_{1/2}$=4.3 x 10^{10} years)
Using TES+micro-bolometers @ 10 mK temperature



$$\Delta E \simeq 2.35\sqrt{4kT^2\frac{C}{\alpha}}$$



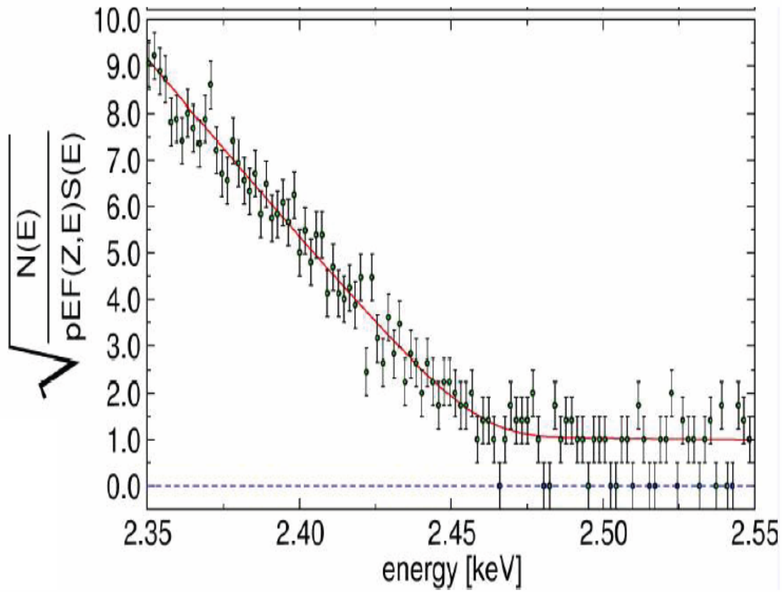


Monica Sisti on Tuesday

MARE

Energy resolution: 2÷3 eV

Total ^{187}Re mass: ~ 100 g



Phase II

Energy resolution: < 1 eV(?)

A possible path to follow…

Scale MARE technology towards:

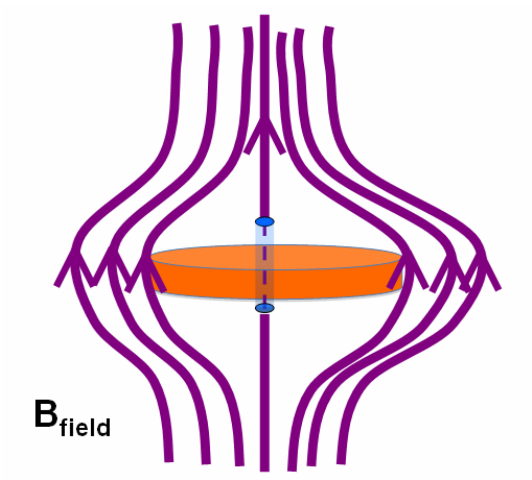
- “macroscopic” crystals (increase mass/readout channels ratio)
- faster response (avoid pile-up)

Geometrically metastable superconducting strip detectors

Beta decay induces local phase transition to non superconducting state (hole)

Magnetic field flowing into these holes can be measured by SQUIDS

$$E_{released} = \Delta h \cdot L_y S$$



I think we should approach the detection problem also using different point of views…

As an example:

Relic neutrino wave packets have a huge size:

Q: is there coherence enhancement in charged current interactions ?

A: ….

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

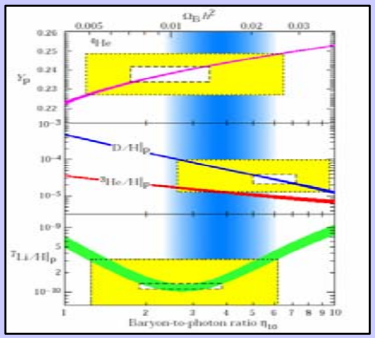
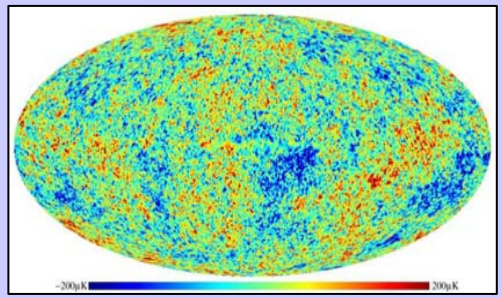
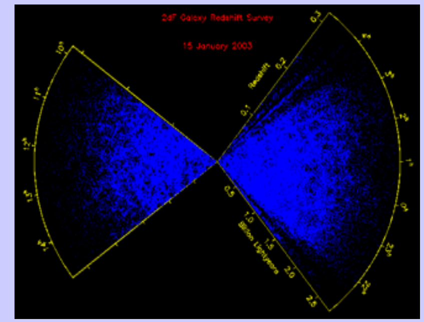
The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a few years using $\beta^{\pm}$ decaying nuclei

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…)

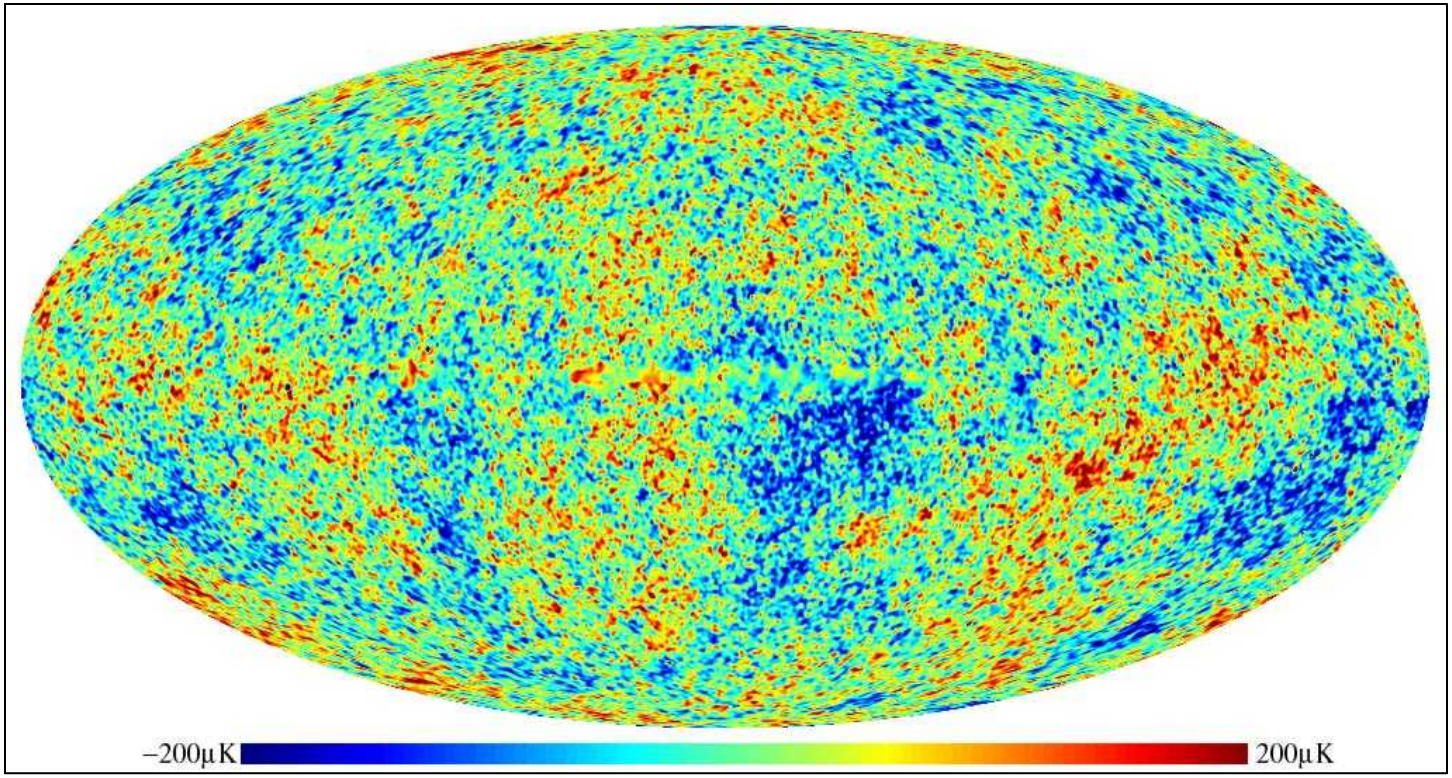
A.G.Cocco, G.Mangano and M.Messina, JCAP 06 (2007) 015
A.G.Cocco, G.Mangano and M.Messina, Phys. Rev. D 79 (2009) 053009

backup

CνB indirect evidences

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
T ~ MeV	T < eV	
flavor dependent	Flavor blind	

ν Anisotropy Probe Collaboration



CνB map in 20??