Hunting for Cosmological Neutrino Background ($C\nu B$)

Alfredo Cocco
&
Gianpiero Mangano

INFN, Sezione di Napoli, Italy

CνB standard features

Neutrinos decoupled at T~MeV, keeping a "thermal" spectrum

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

Number density today

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3$$

Energy density today

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

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

CνB details

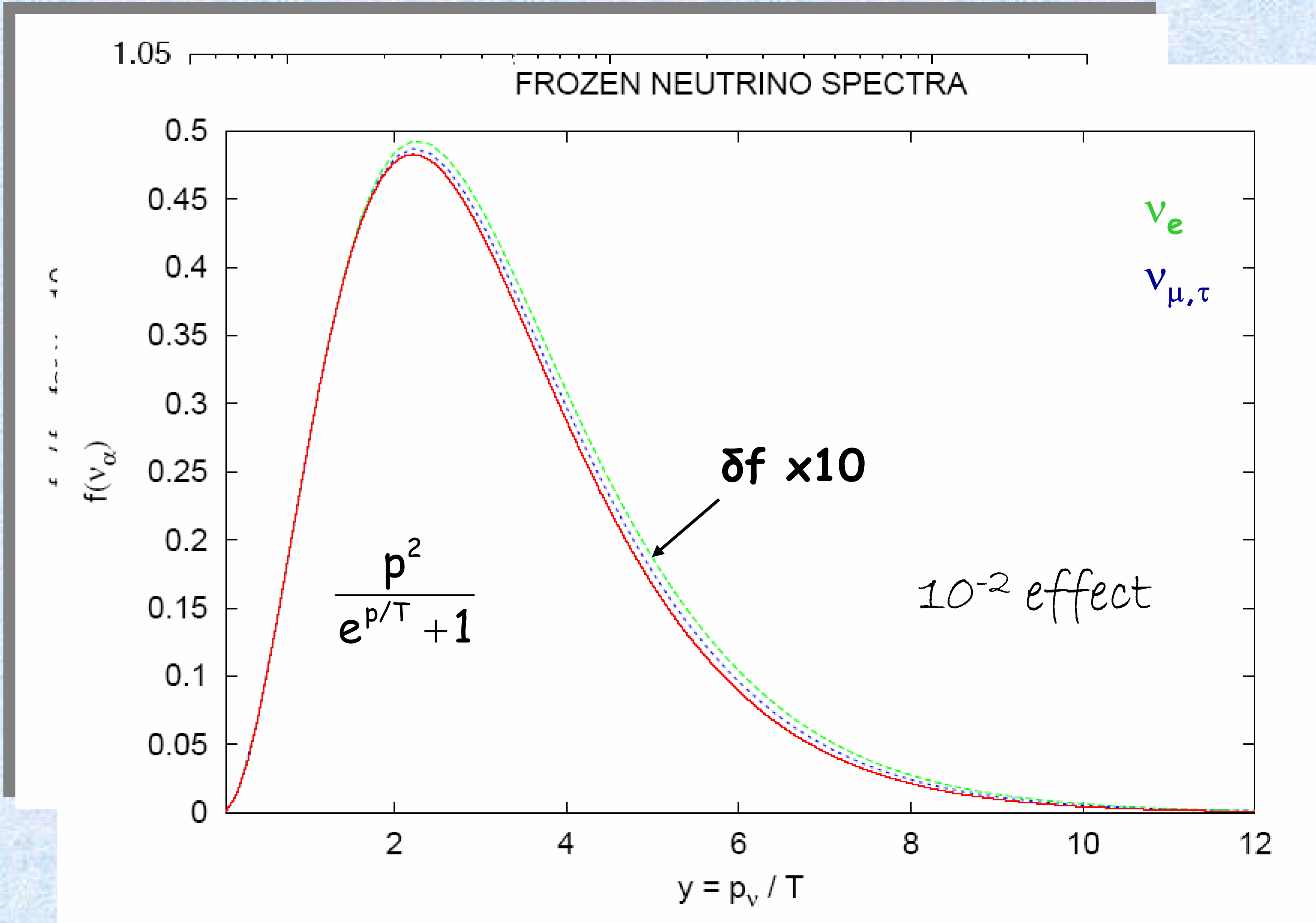
At $T \sim m_e$, e^+e^- pairs annihilate heating photons

$$e^+e^- \to \gamma\gamma$$

… and neutrinos. Non thermal features in ν distribution (small effect). Oscillations slightly modify the result

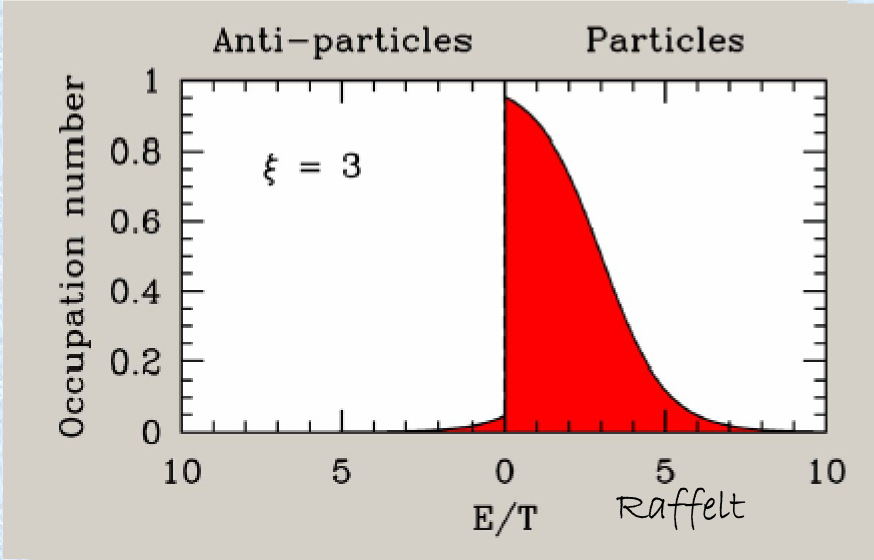
$$f_\nu = f_{FD}(p, T_\nu)\,[1 + \delta f(p)]$$

$$\left(i\partial_t - Hp\partial_p\right)\rho = \left[\frac{M^2}{p} - \frac{8\sqrt{2}G_F}{m_W^2}E, \rho\right] + C(\rho)$$


1.05
FROZEN NEUTRINO SPECTRA
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
4
6
8
10
12
$f(\nu_\alpha)$
$y = p_\nu / T$
ν_e
$\nu_{\mu,\tau}$
δf ×10
$\frac{p^2}{e^{p/T}+1}$
10^{-2} effect

CνB details

Fermi-Dirac spectrum with temperature T and chemical potential $\mu_\nu = \xi_\nu T_\nu$



$$n_\nu \neq n_{\bar{\nu}}$$

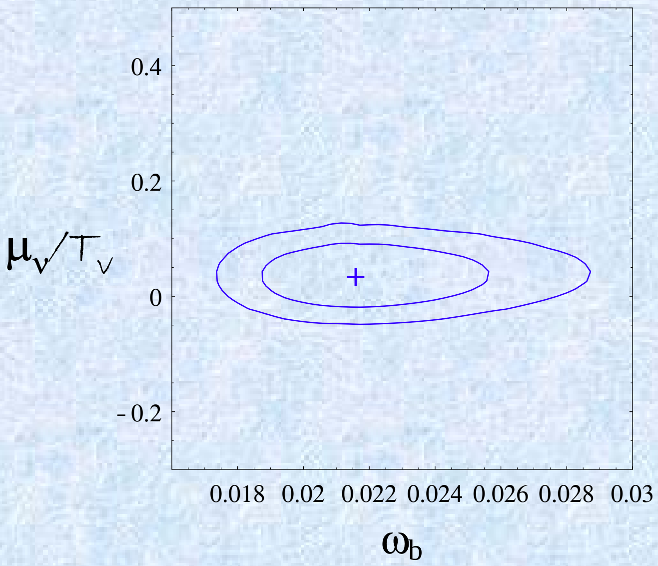
$$L_\nu = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma} = \frac{1}{12\zeta(3)}\left(\frac{T_\nu}{T_\gamma}\right)^3 \left[\pi^2 \xi_\nu + \xi_\nu^3\right]$$

$$\Delta\rho_\nu = \frac{15}{7}\left[2\left(\frac{\xi_\nu}{\pi}\right)^2 + \left(\frac{\xi_\nu}{\pi}\right)^4\right]$$

More radiation

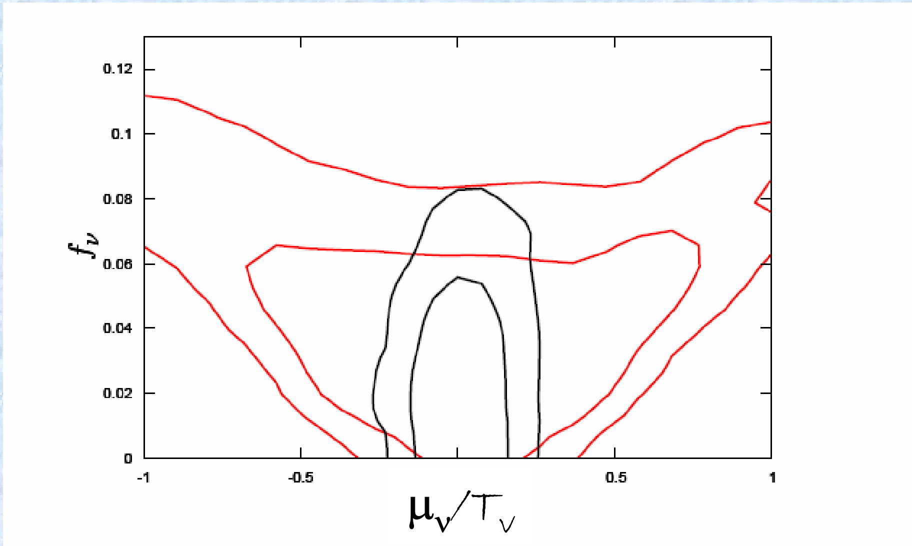
μ_ν/T_ν very small (bad for detection!)

BBN, CMB (LSS) + oscillations



Cuoco et al 04

PLANCK



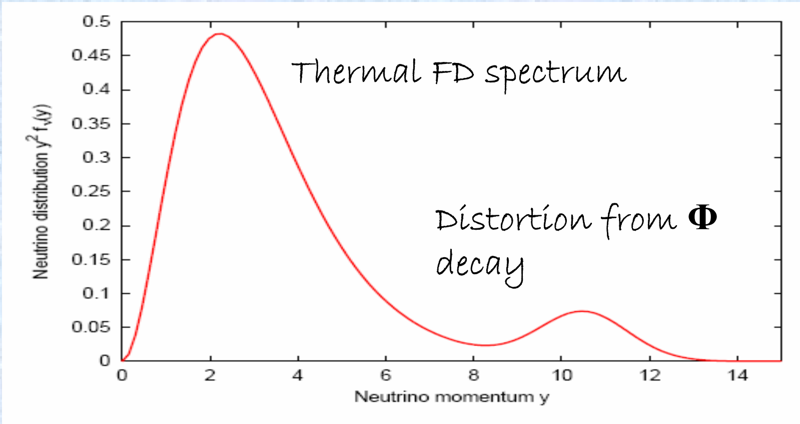
Hamann, Lesgourgues and GM 08

CνB for optimists

ν produced by decays at some cosmological epoch

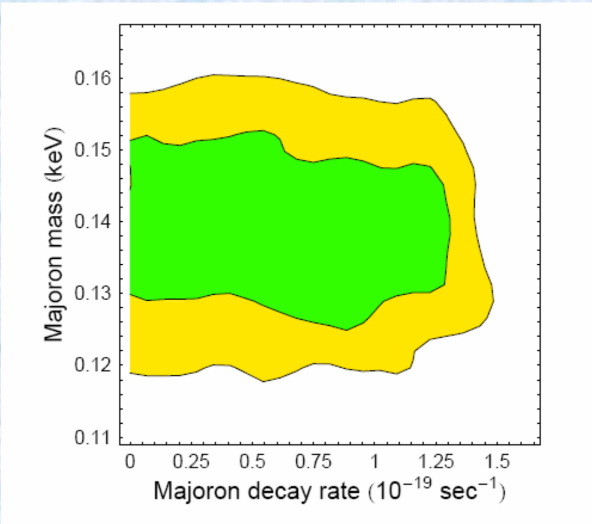
Early on:

($T_{BBN} > T > T_{CMB}$)



$$\Phi \to \nu\bar{\nu}$$

Cuoco, Lesgourgues, GM and Pastor '05



Late ($T << T_{CMB}$):

Unstable DM (e.g. Majoron)

$$\Omega_\nu < \frac{\Gamma}{H_0}\Omega_{dm} \qquad \frac{\Gamma}{H_0} < 0.1$$

Lattanzi and Valle '07

Lattanzi, Lesgourgues, GM and Valle (in progress)

CνB indirect evidences

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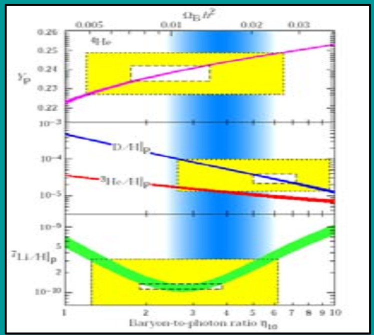
<td>
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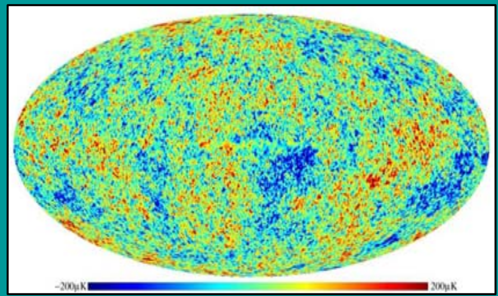
<td>
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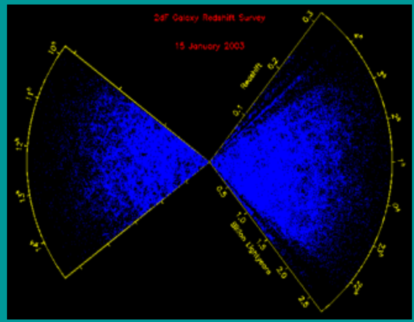
<td></td>
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<td>Primordial Nucleosynthesis
BBN</td>
<td>Cosmic Microwave Background
CMB</td>
<td>Formation of Large Scale Structures
LSS</td>
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<tr>
<td>T ~ MeV</td>
<td colspan="2">T < eV</td>
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<tr>
<td>flavor dependent</td>
<td colspan="2">Flavor blind</td>
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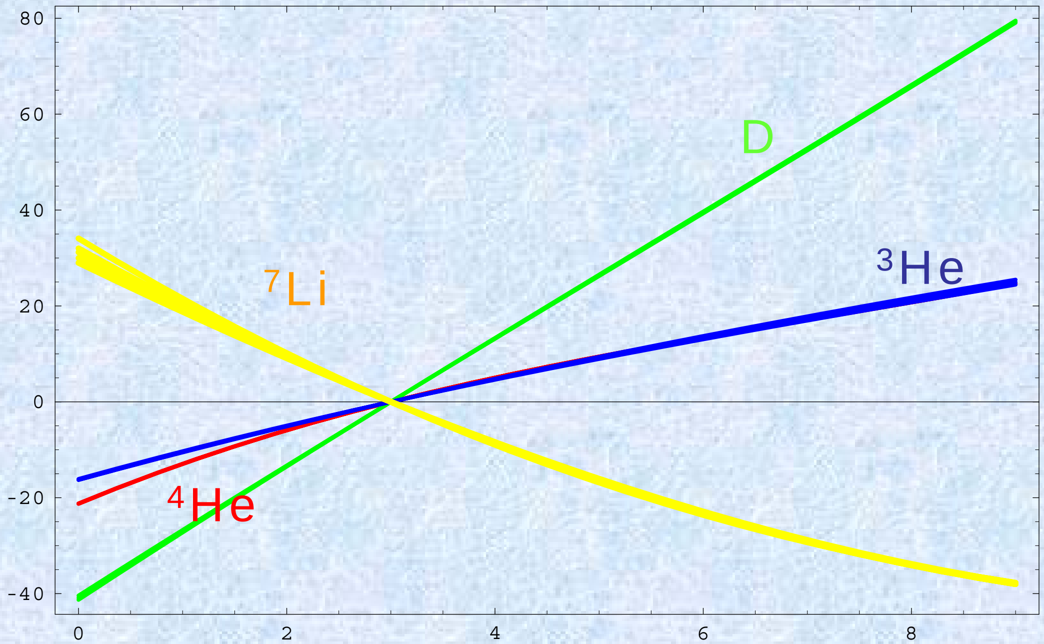
</table>

Effect of neutrinos on BBN

1. N_{eff} fixes the expansion rate during BBN

$$H = \sqrt{\frac{8\pi\pi\rho}{3}}$$

$$\rho_R = \rho_\gamma + \rho_\nu + \rho_x = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N^{eff}{}_\nu\right)\rho_\gamma$$

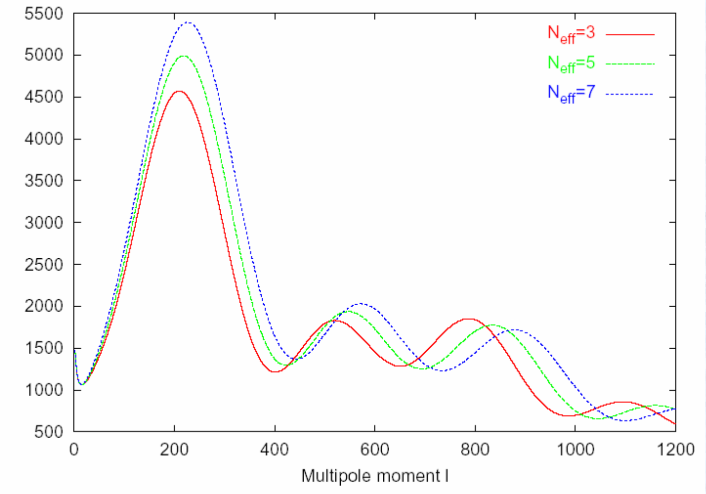


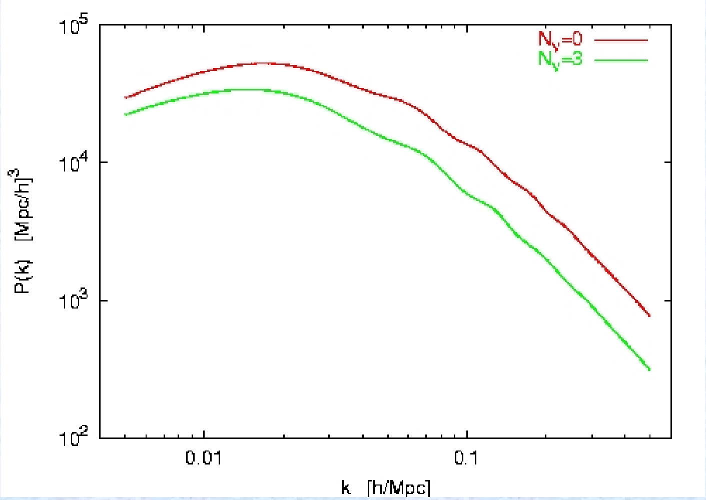
2. Direct effect of electron neutrinos and antineutrinos on the n-p reactions

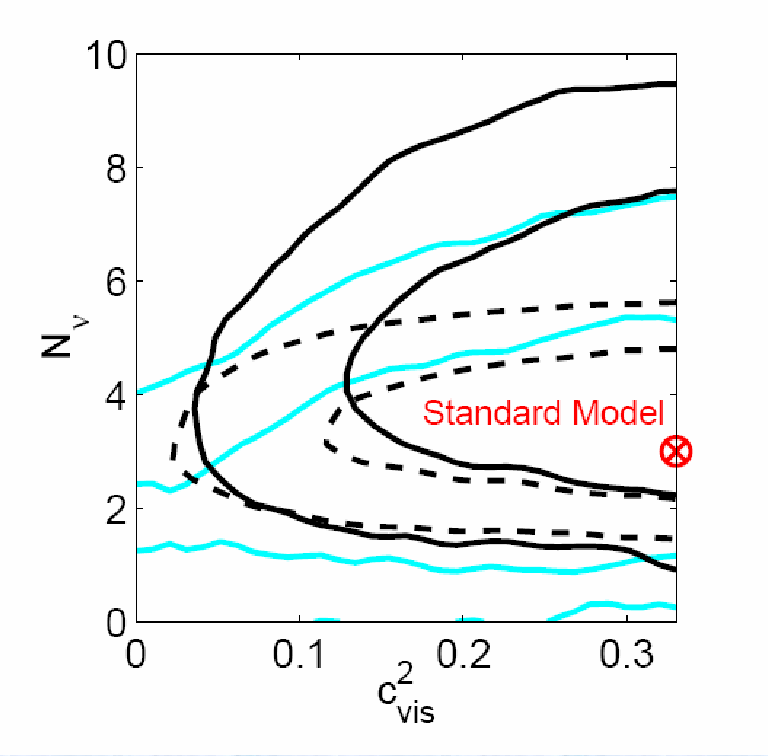
$$\nu_e + n \longleftrightarrow p + e^- \quad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

Effect of CνB on CMB and LSS

Mean effect (Sachs-Wolfe, M-R equality) + perturbations







Melchiorri and Trotta '04

CνB locally: a closer look

Neutrinos cluster if massive (eV) on large cluster scale

Escape velocity: Milky Way 600 Km/s

clusters 10^3 Km/s

$$v_\nu \approx c\sqrt{T_\nu / m_\nu} \approx 6 \cdot 10^3\, Km/s\,(m_\nu / eV)$$

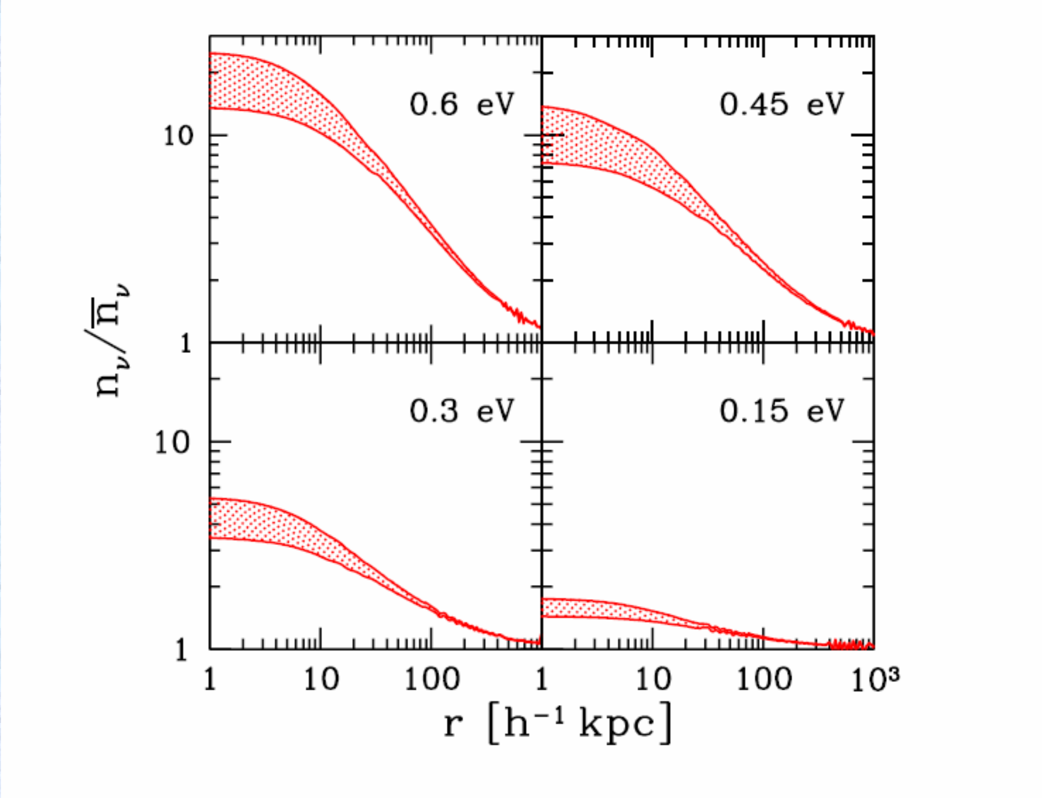
How to deal with: Boltzmann eq. + Poisson

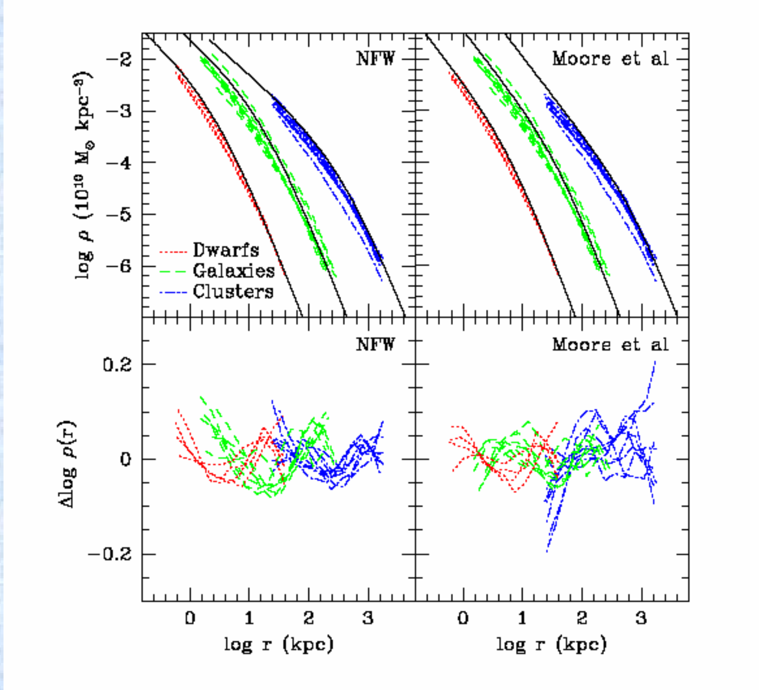
$$\dot{f}_\nu + \dot{x}\,\partial_x f_\nu - a m_\nu \nabla\phi = 0$$

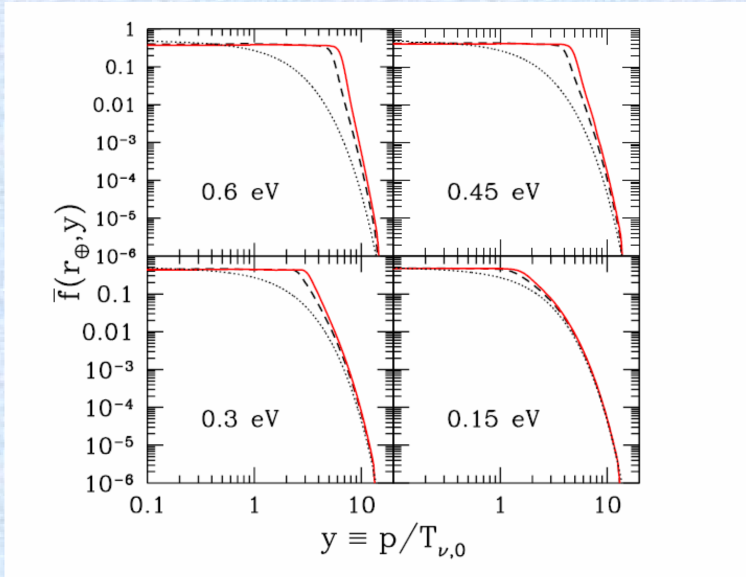
$$\Delta\phi = 4\pi G a^2 \delta\rho$$

Sing and Ma '02

Ringwald and Wong '04







Milky Way
($10^{12}\ M_\odot$)

Ringwald and Wong '04

@ Earth

Detection I: 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 or Majorana,
relativistic/non relativistic, clustered/unclustered

Duda et al '01

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

Torque on frozen magnetized macroscopic piece of material of dimension R

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

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

The only well established linear effect in G_F
Coherent interaction of large De Broglie wavelength

$$F = G_F \int d^3x\ \rho(x) \nabla n_{\nu}(x)$$

Cabibbo and Maiani '82

Langacker et al '83

Energy transfer at order G_F^2

Detection II: G_F^2

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

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

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

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

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

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

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

Coherence enhances

$\lambda_\nu \approx 1/T_\nu$ - $1/m_\nu \approx mm$

$$N_c = \frac{N_A}{A} \rho \lambda_\nu^3$$

Zeldovich and Khlopov '81

Smith and Lewin '83

Backgrounds: solar ν + WIMPS

Detection III

Accelerator: νN scattering hopeless $\quad R \approx 10^{-8}\,yr^{-1}$

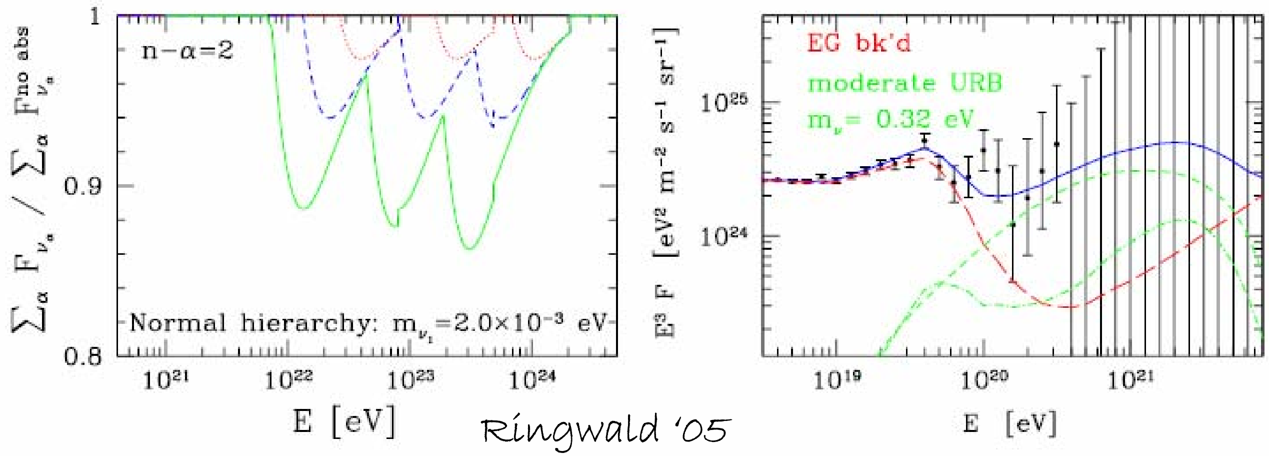
LHC

Cosmic Rays (indirect): resonant ν annihilation at m_Z

$$E = \frac{m_Z^2}{2m_\nu} \approx 4\;10^{21}\left(\frac{eV}{m_\nu}\right)eV$$

Absorption dip (sensitive to high z)

Emission: Z burst above GZK (sensitive to GZK volume, (50 Mpc)³)



Ringwald '05

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

Answer: NO !

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

Reviews on this subject: A.Ringwald hep-ph/0505024
G.Gelmini hep-ph/0412305

A '62 paper by S. Weinberg and ν chemical potential

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

In the original idea a large neutrino chemical potential distorts the electron (positron) spectrum near the endpoint energy

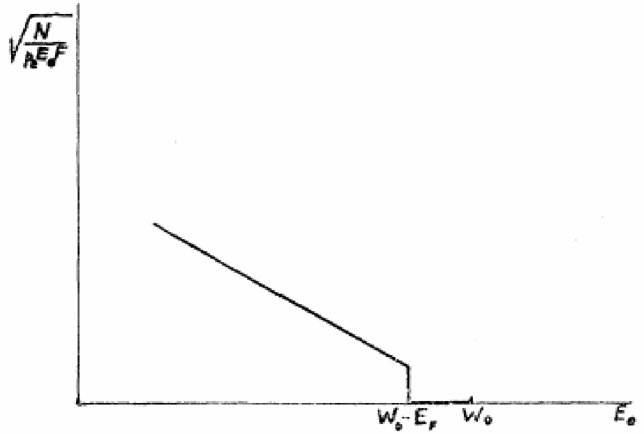


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

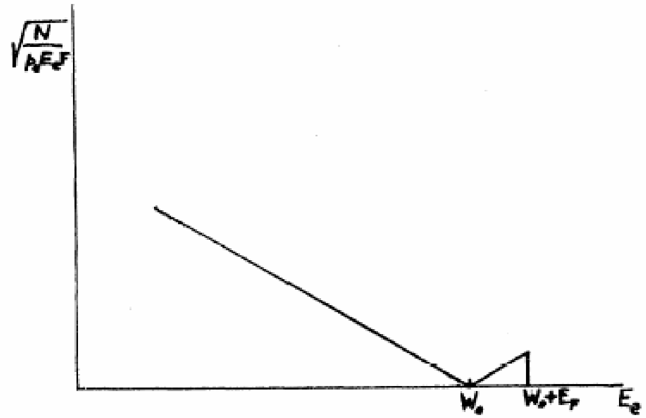
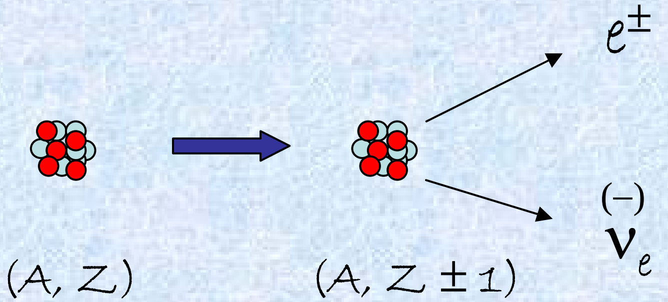


FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

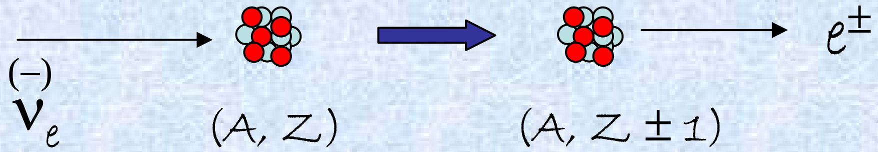
Massive neutrinos and neutrino capture on beta decaying nuclei

A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

Beta decay



Neutrino Capture on a Beta Decaying Nucleus

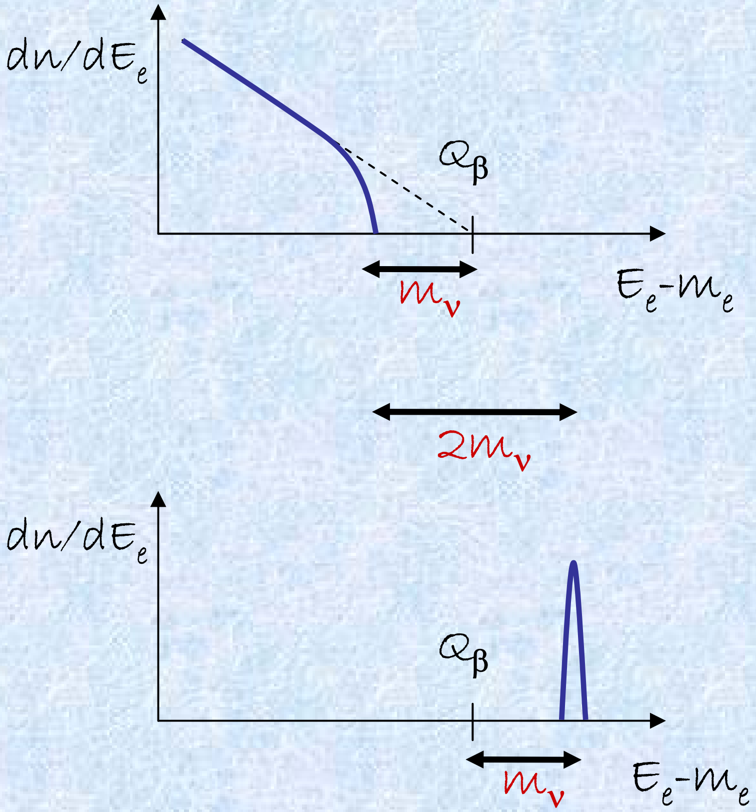


This process has no energy threshold !

Today we know that ν are NOT degenerate but are massive !!

Beta decay

Neutrino Capture on a Beta Decaying Nucleus



A 2 m_ν gap in the electron spectrum centered around Q_β

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

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

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

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

NCB Cross Section

on different types of decay transitions

- Superallowed transitions

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

- 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

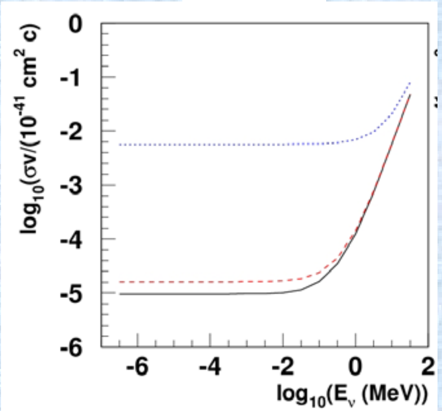
$$\sigma_{\rm NCB} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z,E_e)}{f t_{1/2}}$$

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

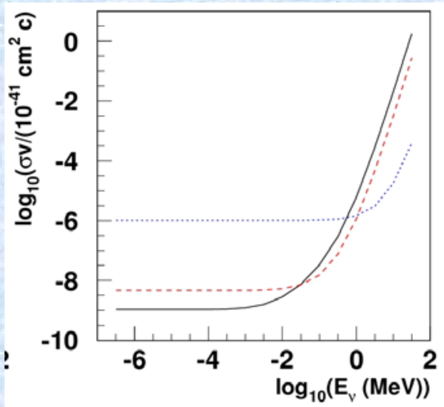
where the error is due only to uncertainties on Q_β and $t_{1/2}$

NCB Cross Section Evaluation

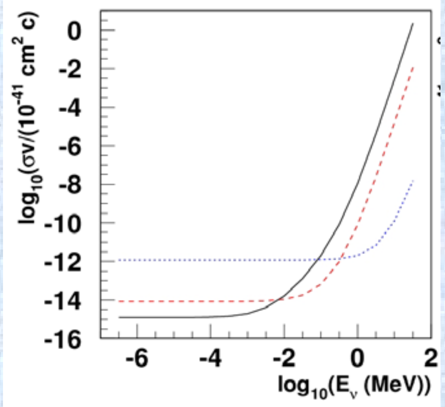
allowed



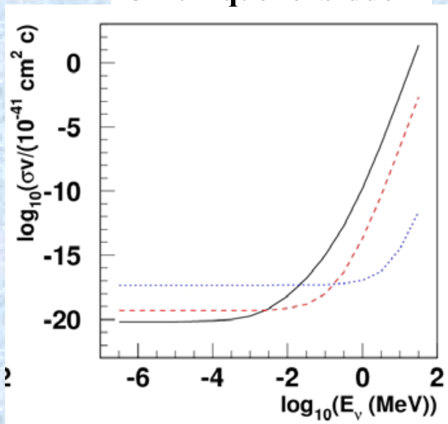
1st unique forbidden



2nd unique forbidden



3rd unique forbidden

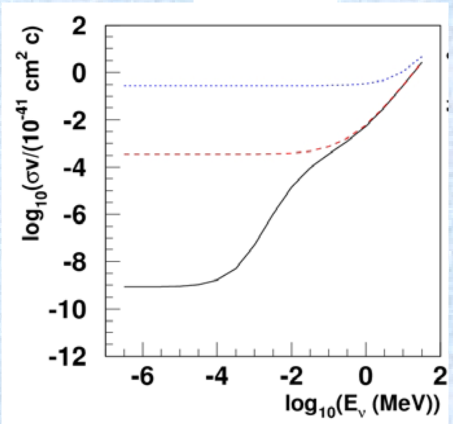


β^- (top)

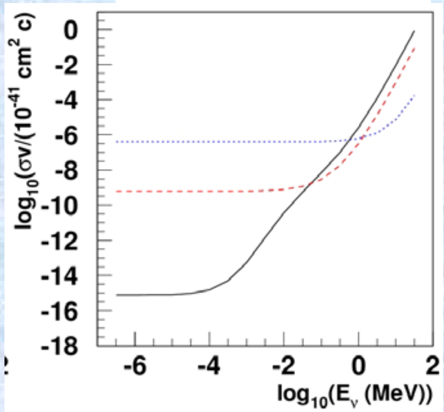
β^+ (bottom)

solid (black)	Q_β = 1 keV
dashed (red)	Q_β = 100 keV
dotted (blue)	Q_β = 10 MeV

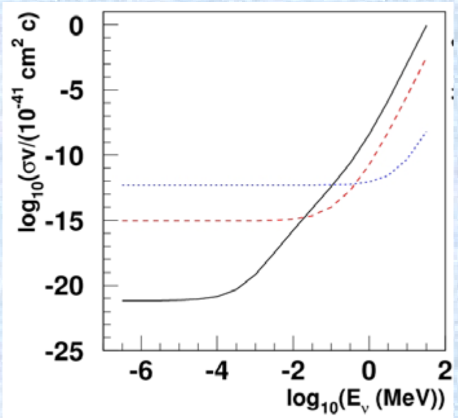
allowed



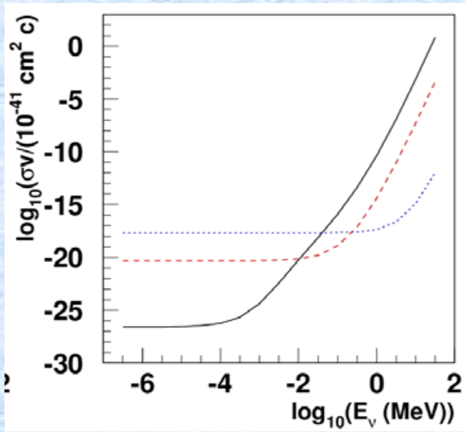
1st unique forbidden



2nd unique forbidden



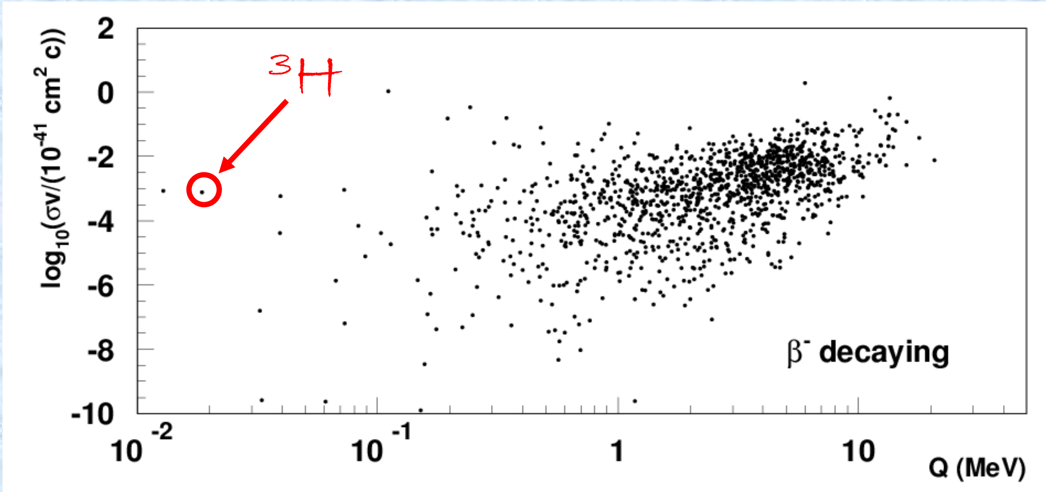
3rd unique forbidden



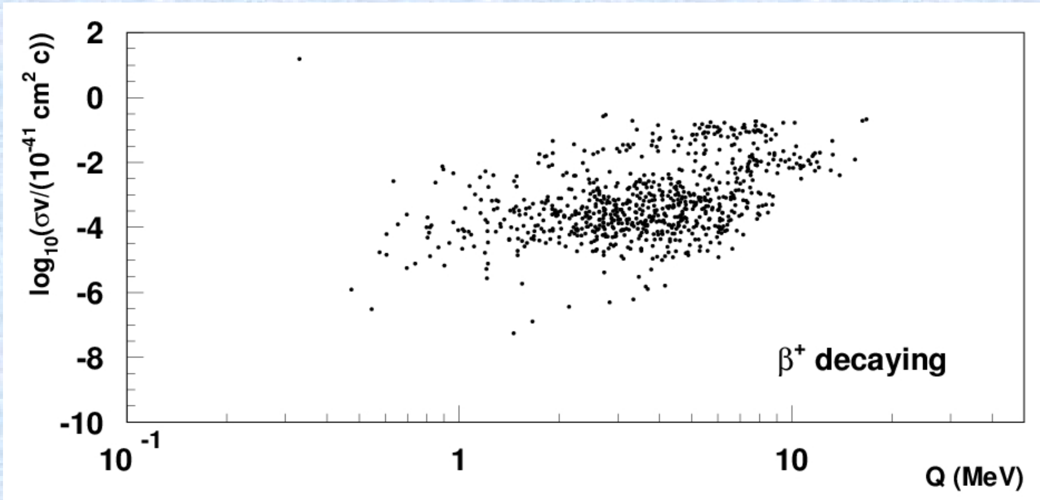
NCB Cross Section Evaluation

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

Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ (10^{-41} 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	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	0.42299	9.17×10^{-2}
^{50}Mn	6610.43	0.28371	1.05×10^{-1}
^{54}Co	7220.6	0.19350	1.20×10^{-1}

Superallowed $0^+ \longrightarrow 0^+$ decays used for CVC hypotesis testing (very precise measure of Q_β and $t_{1/2}$)

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ (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}

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

Relic Neutrino Detection

The cosmological relic neutrino capture rate is given by

$$\lambda_\nu = \int \sigma_{\rm NCB} v_\nu \frac{1}{\exp(p_\nu/T_\nu)+1} \frac{d^3 p_\nu}{(2\pi)^3}$$

$$T_\nu = 1.7 \cdot 10^{-4}\ \mathrm{eV}$$

after the integration over neutrino momentum and inserting numerical values we obtain

$$2.85 \cdot 10^{-2} \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} \mathrm{cm}^2}\ \ \mathrm{yr}^{-1}\ \mathrm{mol}^{-1}$$

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

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

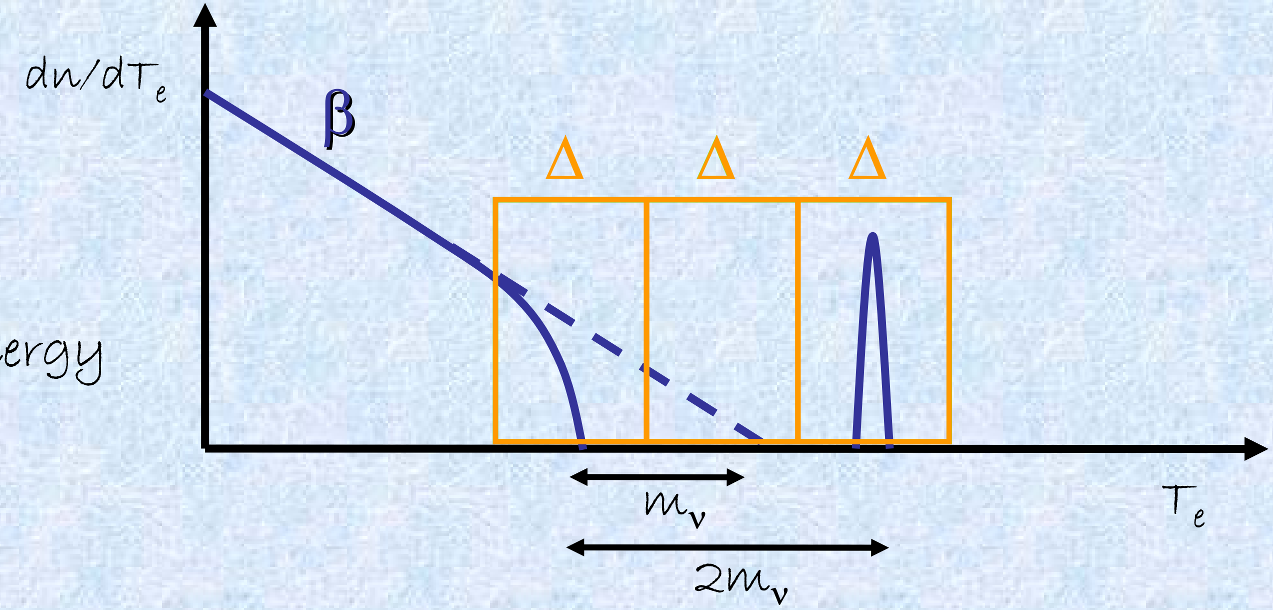
$$\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$$

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

discovery potential

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of 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 5**σ** effect

In case of neutrino 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)

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

Answer: Maybe….it depends on S/B ratio !

The relevance of this statement can be pictured as

$$\frac{\neq 0}{0} = \infty$$

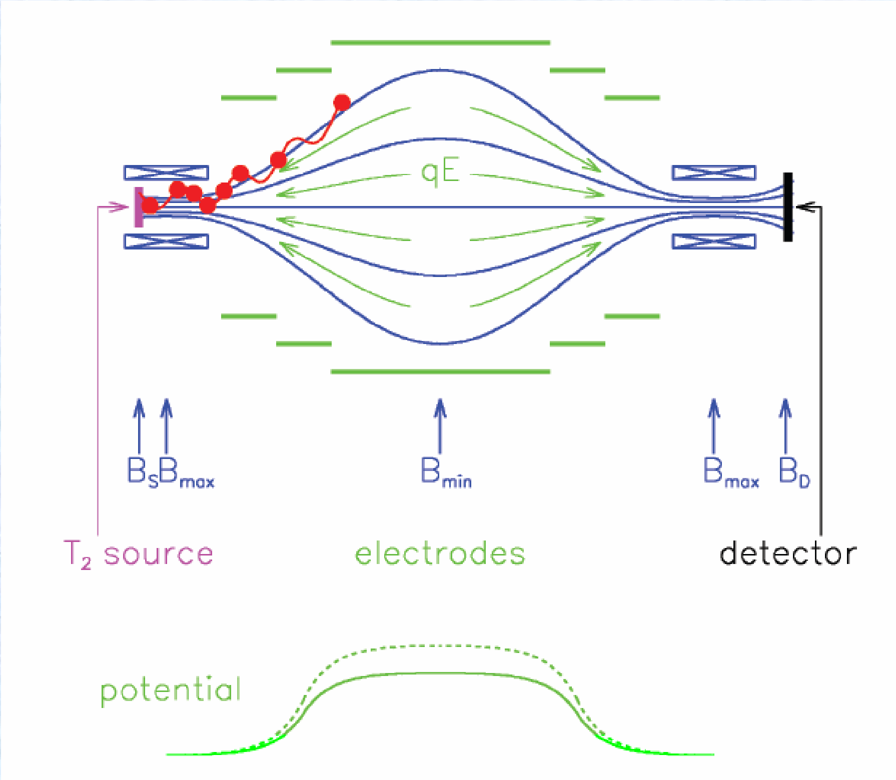
KATRIN

Karlsruhe Tritium Neutrino Experiment

Aim at direct neutrino mass measurement through the study of the ^3H 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

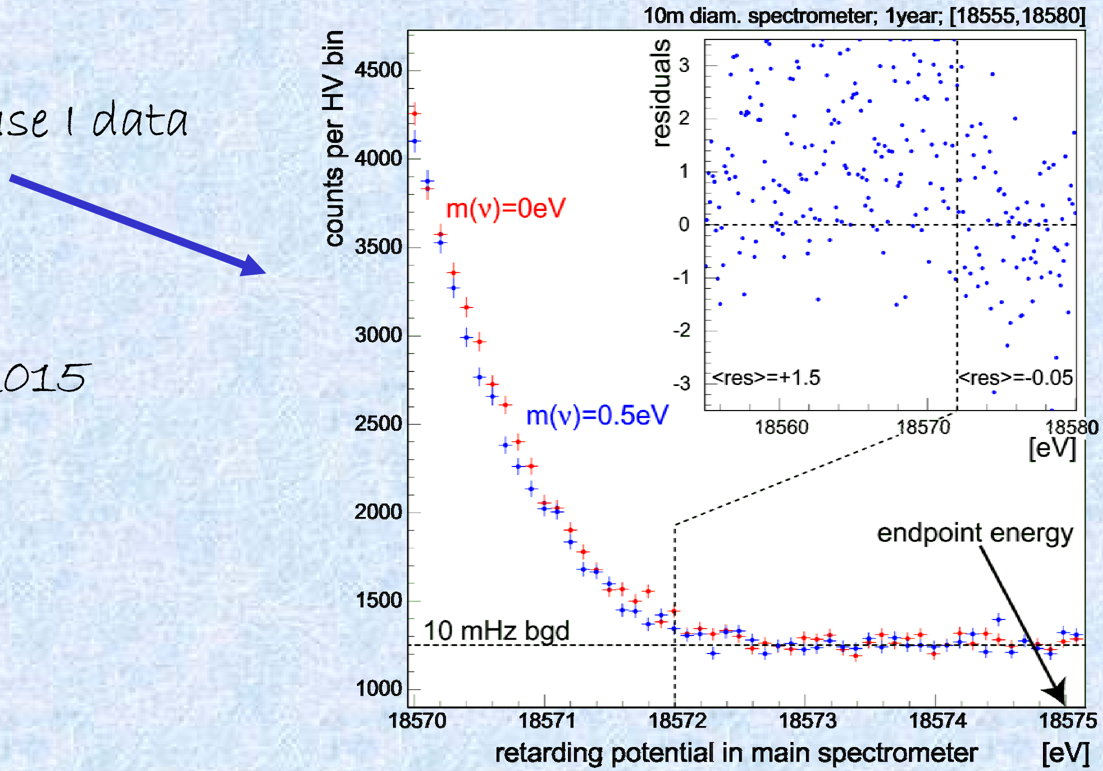
MonteCarlo simulation of phase I data

First results in 2011

End of Phase I data taking: 2015

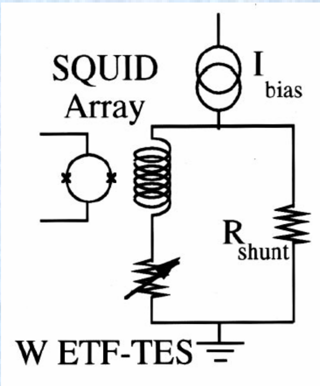
Phase II:

- Energy resolution: 0.2 eV
- Noise level 1 mHz

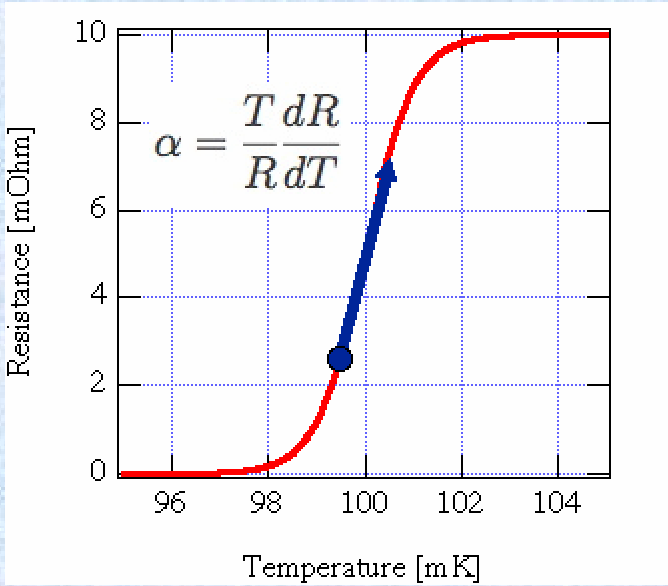


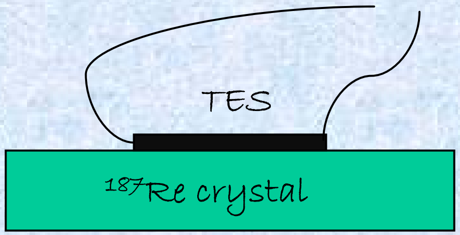
MARE

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



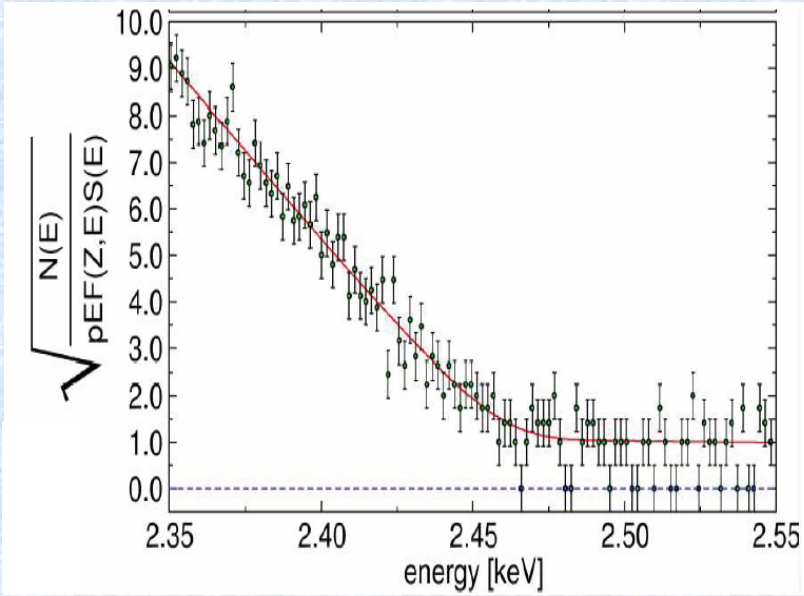
$$\Delta E \simeq 2.35\sqrt{4kT^2\frac{C}{\alpha}}$$





MARE

Energy resolution: 2÷3 eV
Total ^{187}Re mass: ~ 100 g



Phase II:

Energy resolution: < 1 eV

Neutrino masses

Courtesy of A.Marrone

Terrestrial bounds

ν_e <2 eV (^{3}H decay)

ν_μ <0.19 MeV (pion decays)

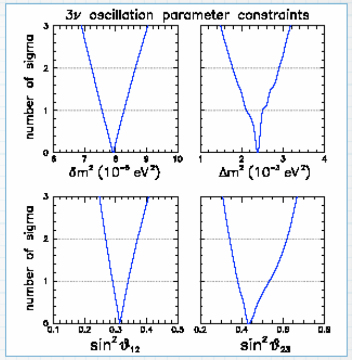
ν_τ <18.2 MeV (τ decays)

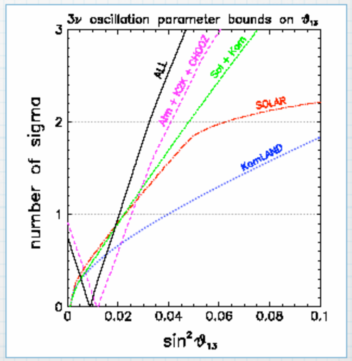
Oscillation Parameters

$$\delta m^2 = 7.92(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.15})$$

$$\Delta m^2 = 2.6(1^{+0.14}_{-0.15}) \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.45(1^{+0.35}_{-0.20})$$

$$\sin^2\theta_{13} = 0.8(1^{+2.3}_{-0.8}) \times 10^{-2}$$





Cosmology

Bounds on $\Sigma_i\, m_i$

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + $\mathrm{SN_{Riess}}$ + HST + BBN	< 0.78 eV
4	CMB + LSS + $\mathrm{SN_{Astier}}$	< 0.75 eV
5	CMB + LSS + $\mathrm{SN_{Astier}}$ + BAO	< 0.58 eV
6	CMB + LSS + $\mathrm{SN_{Astier}}$ + Ly-α	< 0.21 eV
7	CMB + LSS + $\mathrm{SN_{Astier}}$ + BAO + Ly-α	< 0.17 eV

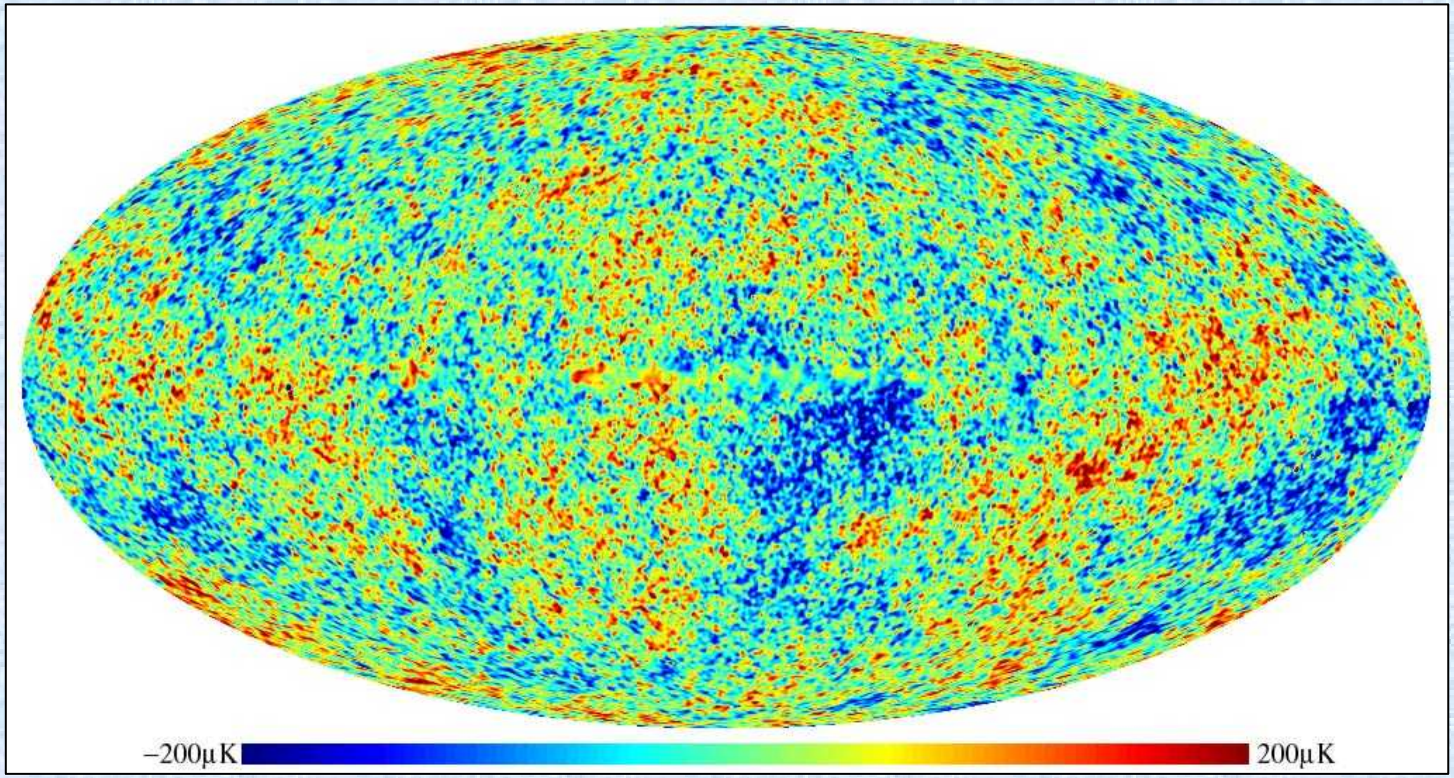
G. Fogli et al. 2007

Conclusions

The fact that neutrino has a nonzero mass has renewed
the interest on Netrino Capture on Beta 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 uncertainty
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



VAP Collaboration

CνB map 20??

Variation on the theme:

Beta-beams

Electron-capture nuclei (fighting with energy threshold!)

Best nucleus candidate?

Already there ? (Troisk anomaly) Unlikely large flux!!

Waiting for Katrin