Detecting Relic Neutrinos with β-decaying nuclei

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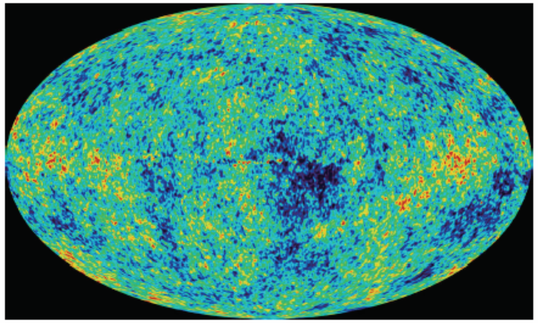
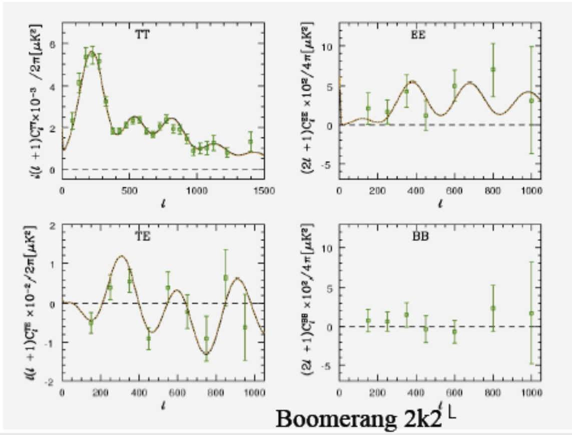
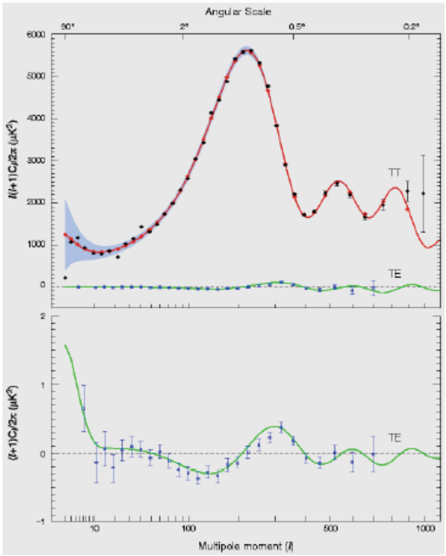
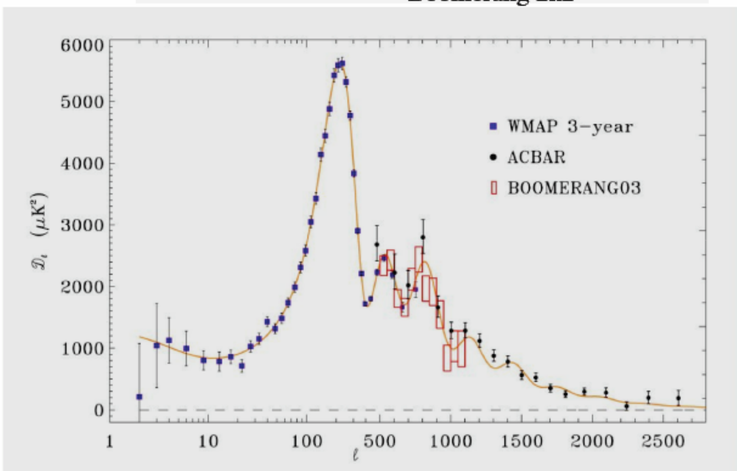
Sezione di Napoli

The issue: Cosmic Neutrino Background (CvB)









Summary:

- CνB as we suppose to know it
- A ’62 paper by S. Weinberg and ν chemical potential
- Massive neutrinos and neutrino capture on beta decaying nuclei
- Clustering and ν local density
- The case of ^3H
- Outlooks

Based on a work in collaboration with A. Cocco and M. Messina, JCAP 0706, 015 (2007), hep-ph/0703075

CvB as we suppose to know it

As photons but much earlier, neutrinos decouple from the comoving thermal bath during the expansion

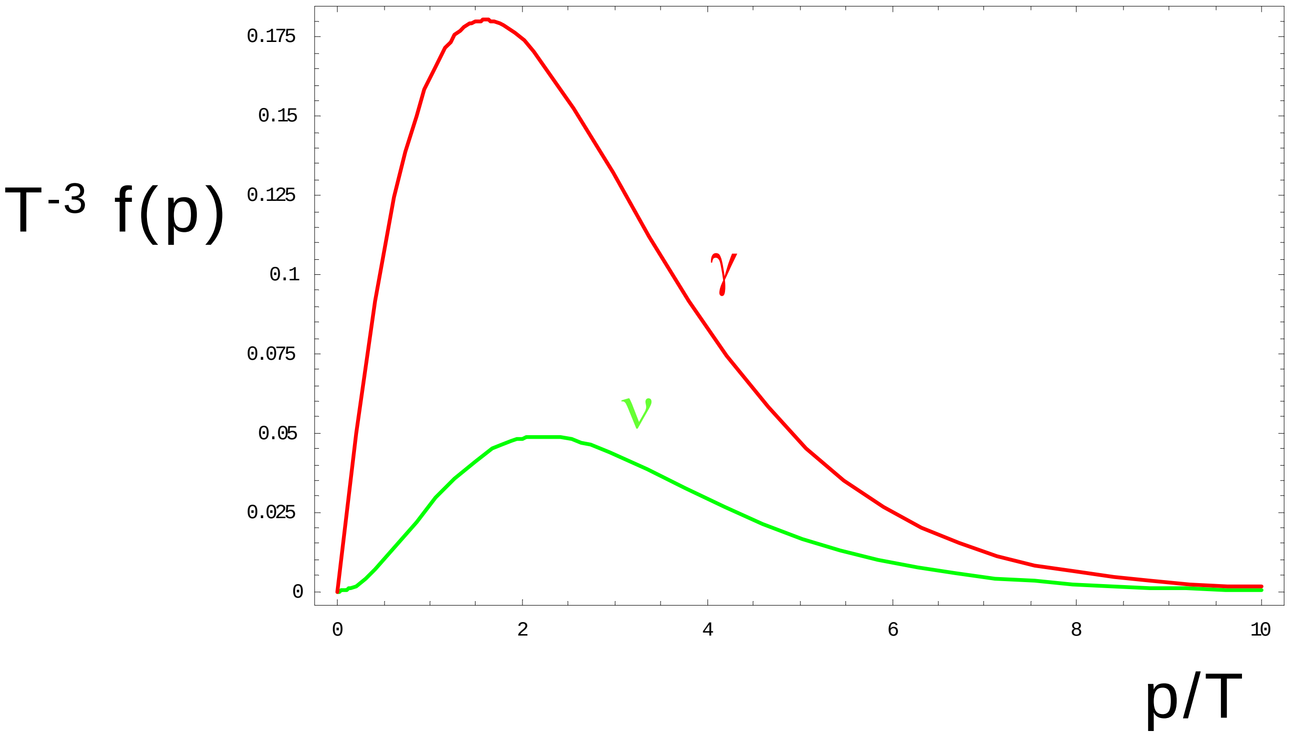
neutrino decoupling: weak interactions become too weak at T ~ MeV

$$f_{\nu_i}(p) = \frac{1}{2\pi^2}\frac{p^2}{e^{p/T_\nu}+1}$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945\ {}^{\mathrm{o}}K \rightarrow \mathrm{k_B} T_\nu \approx 1.68 \cdot 10^{-4} eV$$

$$n_f = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{93.2eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_k m_k}{93.2eV}$$

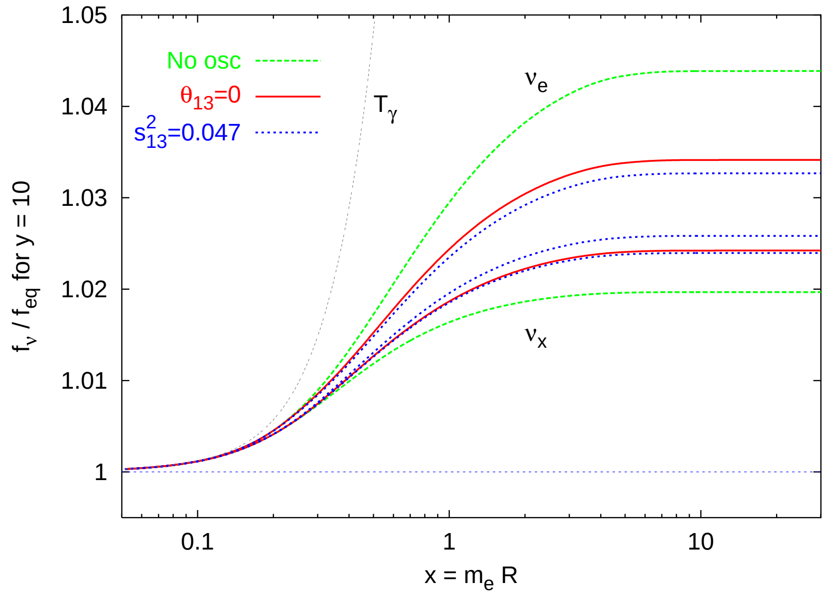


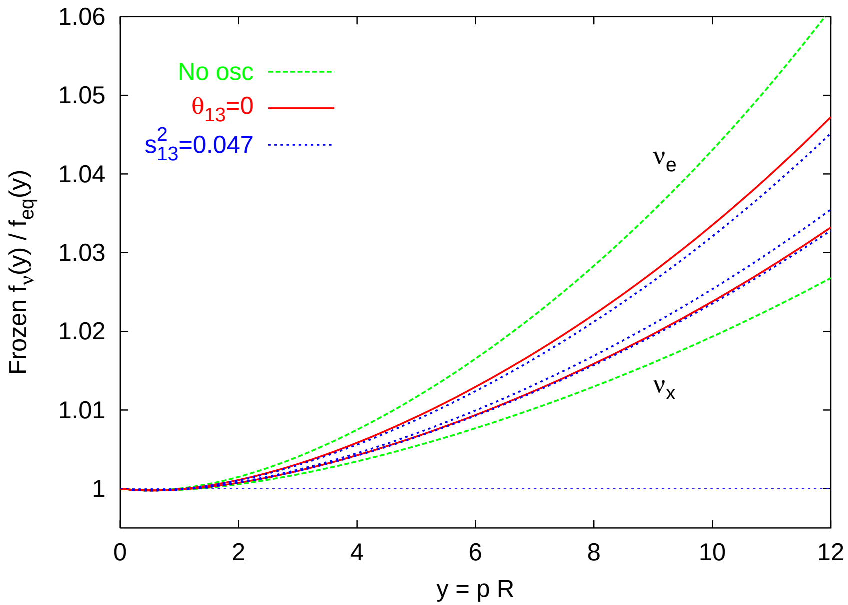
detailed neutrino decoupling:

small entropy release to ν's from e^+-e^- annihilation

- momentum dependent distortion in ν distribution
- smaller photon temperature

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





G. M. et al 2005

z=T a	$\delta\rho_e$	$\delta\rho_x$	N_ν^{eff}
1.4	0.73%	0.52%	3.05

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

Exotics

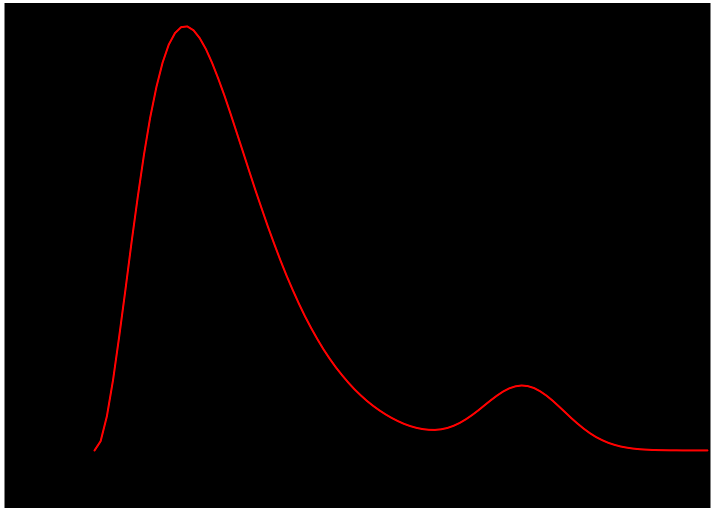
Effects seen in CMB and LSS

Extra neutrinos from out of equilibrium decay of scalars after neutrino decoupling

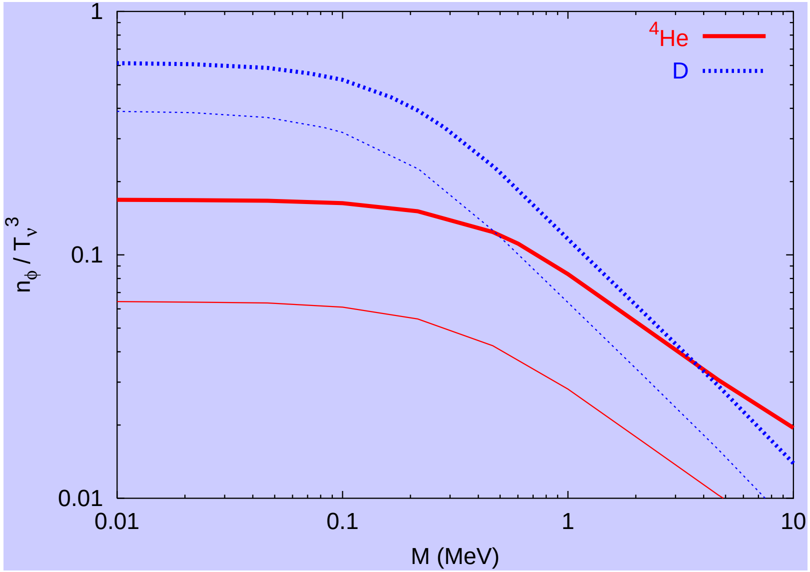
Neutrinos decays into scalar particles (neutrinoless Universe)

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

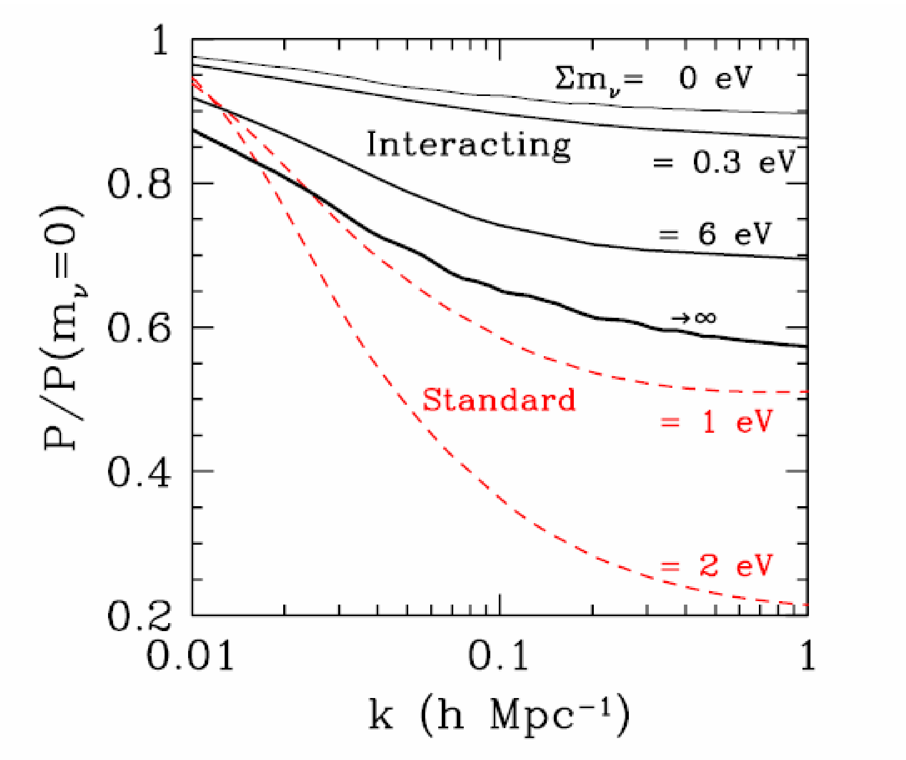
$$f_a(y) = y^2 \frac{1}{e^y + 1} + \pi^2 \frac{A}{\sqrt{2\pi\sigma^2}} e^{-(y-y_*)^2/2\sigma^2}$$



Bounds from BBN
Φ particles (decoupled) should not contribute too much to the expansion rate H



Cuoco, Lesgourgues, G.M. and Pastor 2005



Beacom, Bell and Dodelson 2004
Bell, Pierpaoli and Sigurdson 2005
Hannestad 2005

Neutrino decay: bounds from LSS...

CνB: very low energy, difficult to measure directly by ν-scattering

1. Large De Broglie wavelength λ~0.1 cm

   Coherent scattering over macroscopic domain

   Wind force on a test body, acceleration ~ 10^{-28} cm^2 s^{-1}

   Today: Cavendish torsion balances can test acceleration as small as 10^{-13} cm^2 s^{-1} !!

2. Accelerators:

$$\sigma(\nu p) = G_F^2 s / \pi = 10^{-44} (m_\nu / eV)(E / TeV) cm^2$$

   Too small even at LHC or beyond !

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)

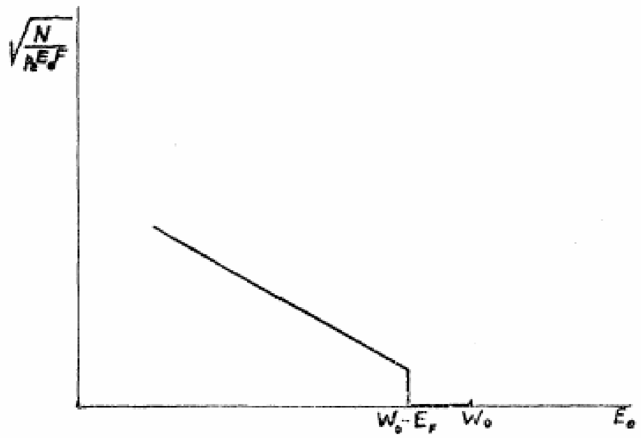


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

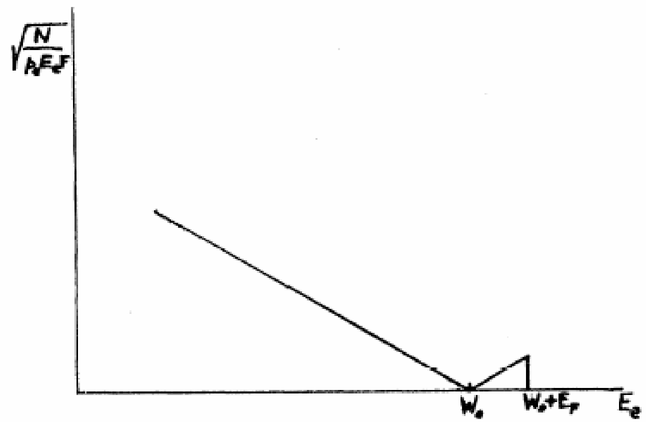


FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

Neutrino-antineutrino asymmetry ($\xi=\mu/T_\nu$, $E_F(\xi)$) strongly constrained by Big Bang Nucleosynthesis

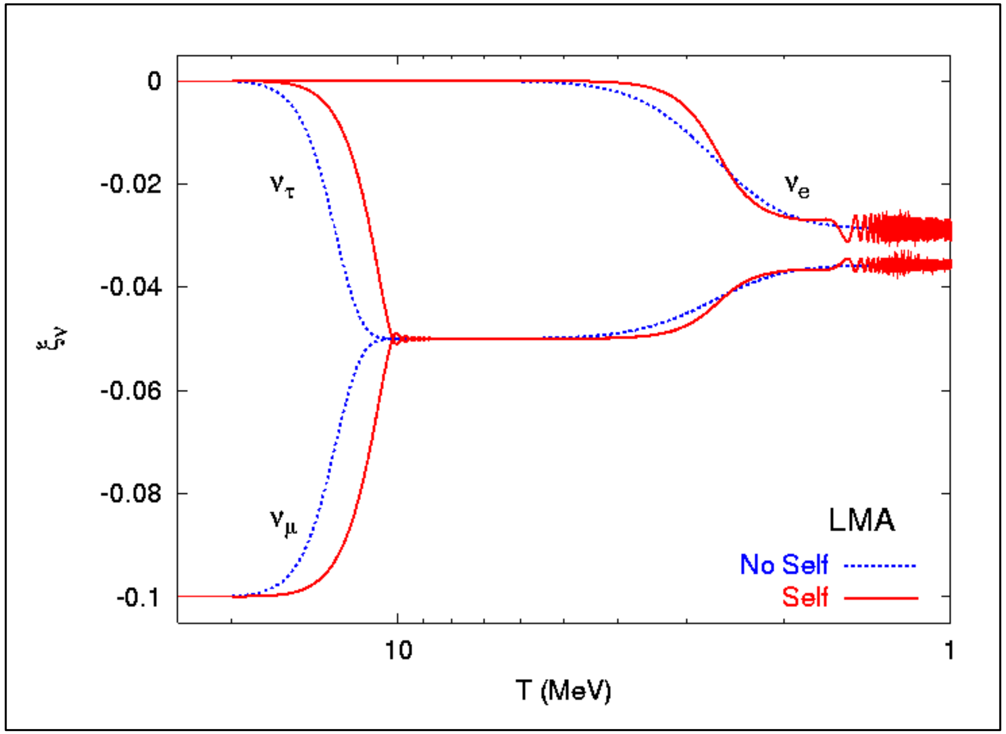
1) chemical potentials contribute to neutrino energy density

$$\rho_\nu = \frac{7\pi^2}{120}\left(3+\sum_i\left(\frac{30\xi_i^2}{7\pi^2}+\frac{15\xi_i^4}{7\pi^4}\right)+....\right)T_\nu^4$$

2) a positive electron neutrino chemical potential (more neutrinos than antineutrinos) favour n ➔ p processes with respect to p ➔n processes.

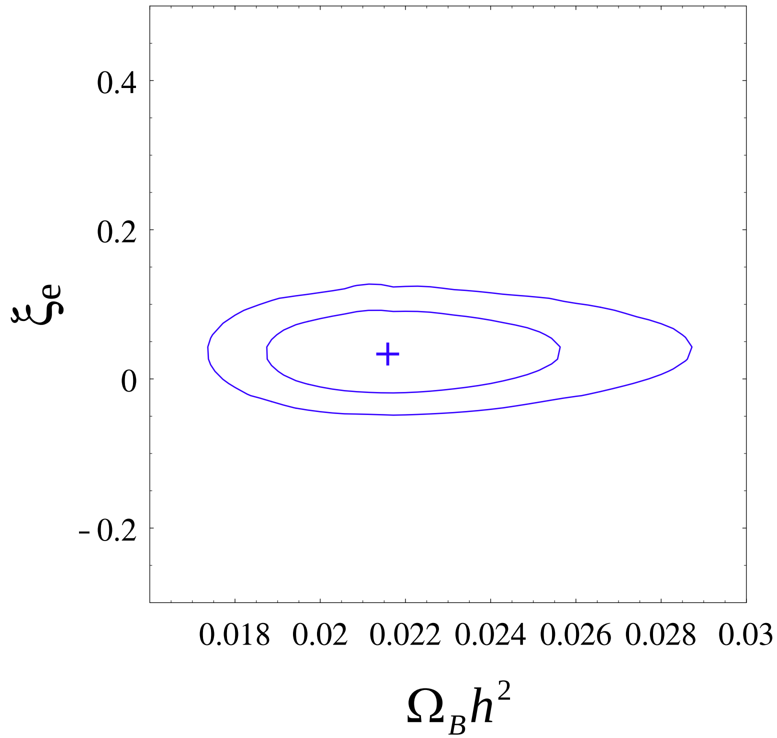
Change the ^{4}He abundance!

Though different neutrino flavor may have different chemical potentials, they however mix under oscillations



A. Dolgov et al 2002

Likelihood contours 68 & 95 c.l.



A. Cuoco et al 2004

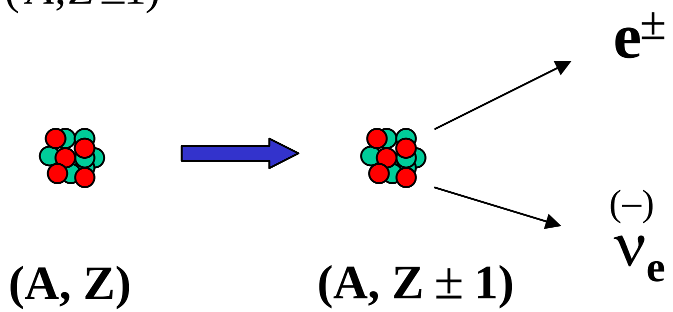
ξ very small!

Massive neutrinos and neutrino capture on beta decaying nuclei (NCβ)

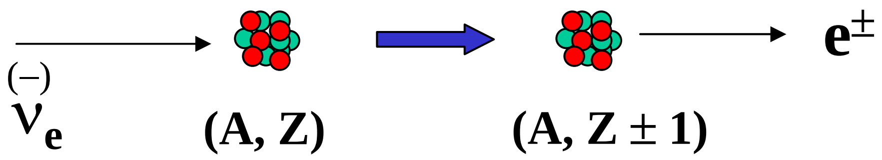
$$N_{(A,Z)} \to N'_{(A,Z\pm1)}\, e^{\pm} \overset{(-)}{\nu}_e$$

$$\overset{(-)}{\nu}_e\, N_{(A,Z)} \to N'_{(A,Z\pm1)}\, e^{\pm}$$

Beta decay

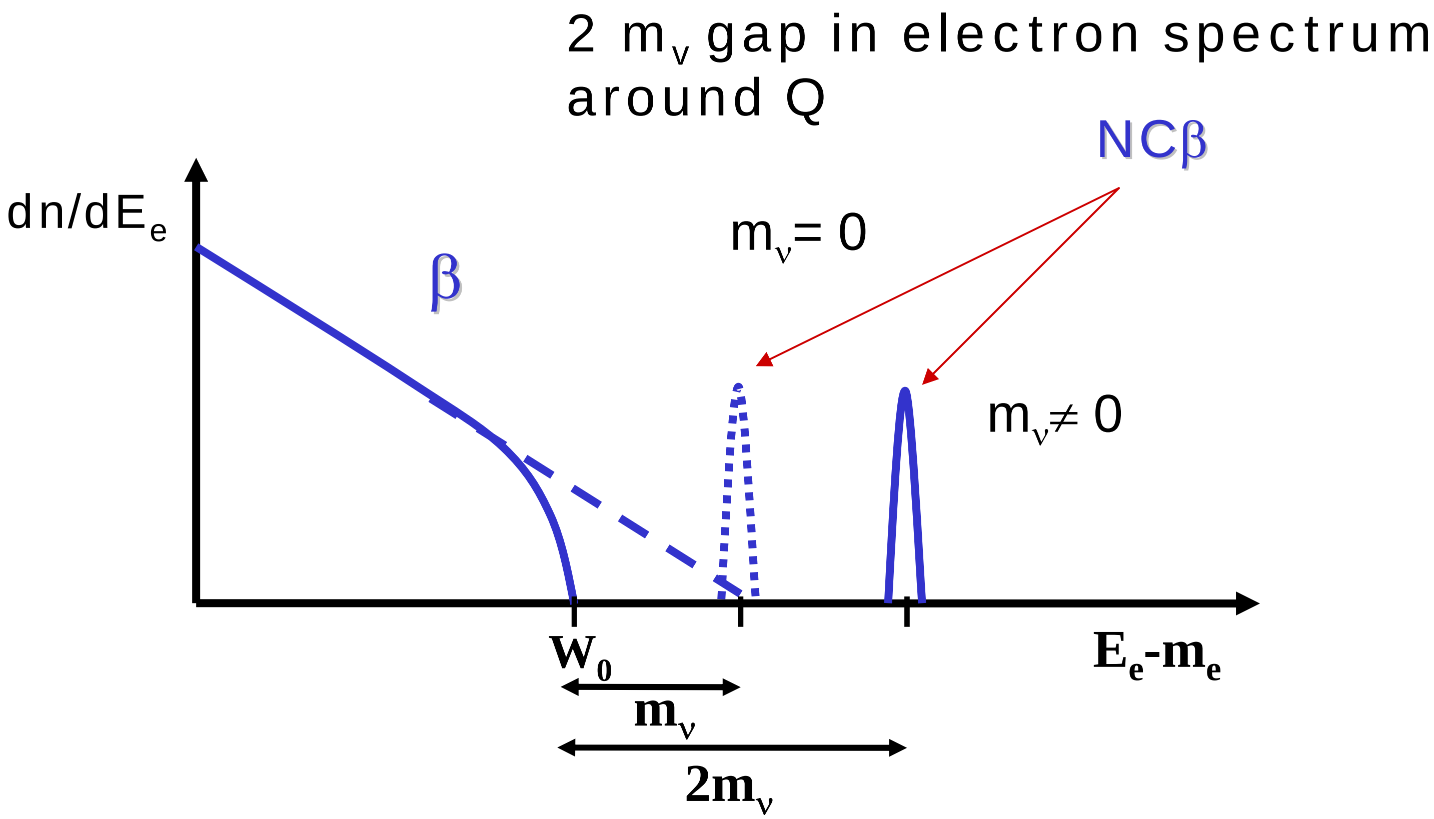


Neutrino Capture on a Beta Decaying Nucleus (NCβ)



Weinberg: if neutrinos are degenerate we could observe structures around the beta decaying nuclei endpoint Q

ν's are NOT degenerate but are massive!



Neutrino masses

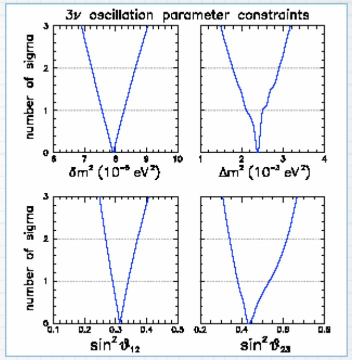
A.Marrone, IFAE 2007

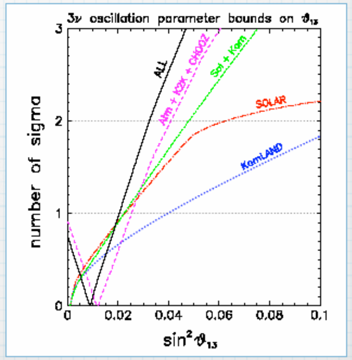
Oscillation Parameters

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

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

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





Terrestrial bounds

ν_e <2 eV (^{3}H decay)

ν_μ <0.19 MeV (pion decays)

ν_τ <18.2 MeV (τ decays)

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 + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + $\text{SN}_{\text{Astier}}$	< 0.75 eV
5	CMB + LSS + $\text{SN}_{\text{Astier}}$ + BAO	< 0.58 eV
6	CMB + LSS + $\text{SN}_{\text{Astier}}$ + Ly-α	< 0.21 eV
7	CMB + LSS + $\text{SN}_{\text{Astier}}$ + BAO + Ly-α	< 0.17 eV

G. Fogli et al. 2007

Issues:

1. Rates

$$\lambda_\nu = \int \sigma_{\rm NCB} v_\nu \, f(p_\nu) \, \frac{d^3 p_\nu}{(2\pi)^3} \, , \quad = \frac{G_\beta^2}{2\pi^3} \int_{W_o + 2m_\nu}^{\infty} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu \cdot E_\nu p_\nu \, f(p_\nu) \, dE_e \, ,$$

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

Nuclear form factors (shape factors) uncertainties: use beta observables

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

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

- Super-allowed 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

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

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

Cross sections times v_ν as high as 10^{-41} cm^2 c

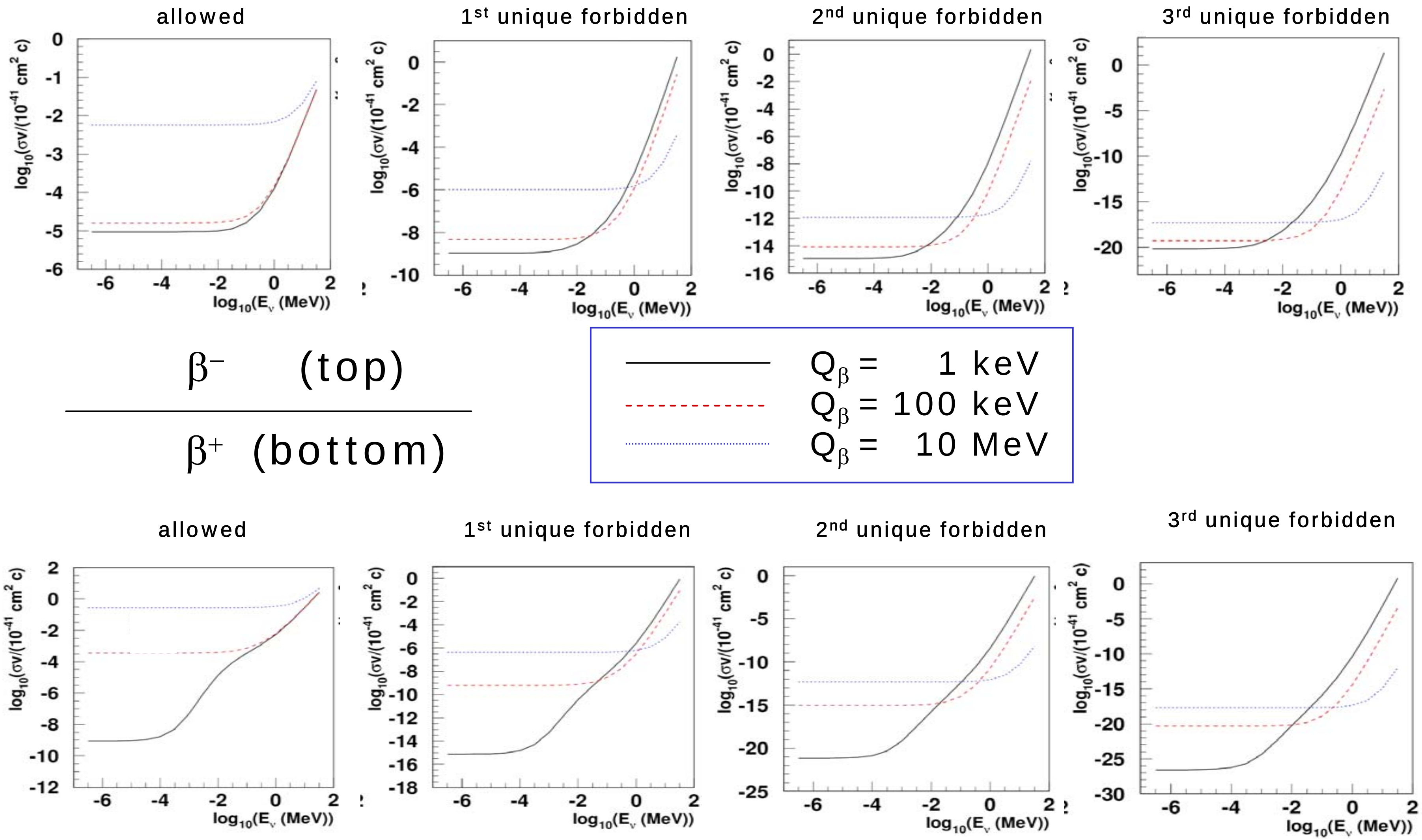
Table 1. The product $\sigma_{\rm NCB}(v_\nu/c)$ for the best known superallowed $0^+ \to 0^+$ transitions. Numerical values for Q_β and partial half-lifes are taken from [33]. The value of f is calculated adopting the parametrization of the Fermi function of [28].

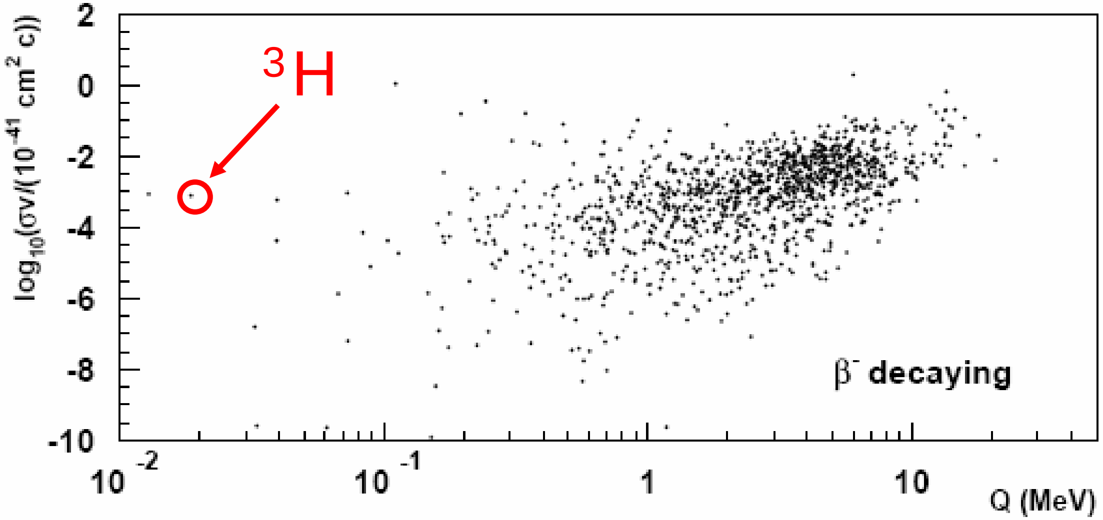
Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	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}

Table 2. Beta decaying nuclei that present the largest product of $\sigma_{\rm NCB}(v_\nu/c) \cdot t_{1/2}$ for low neutrino momentum and have a $\beta^\pm$ decay branching fraction larger than 80%.

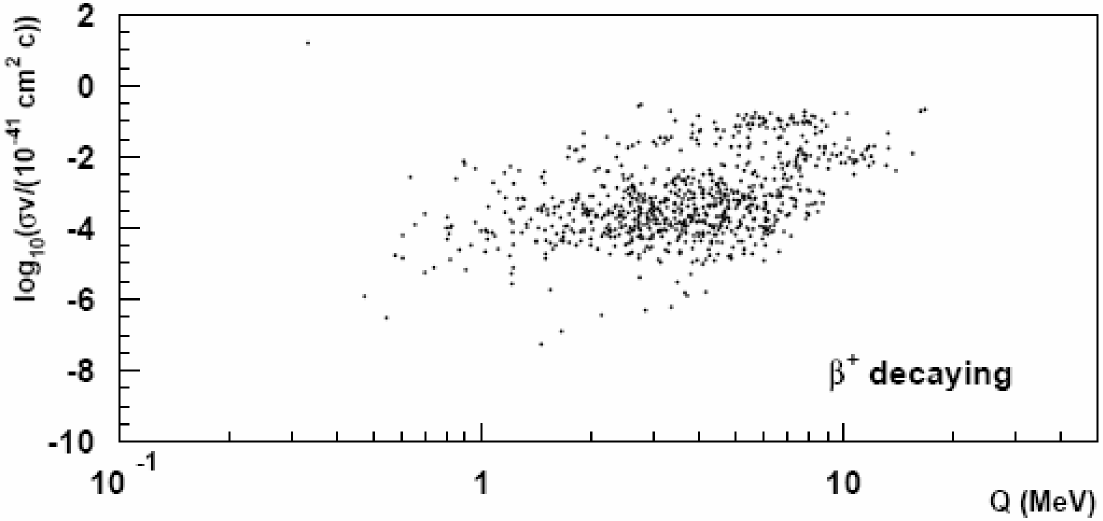
Isotope	Decay	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^{8}	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^{9}	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^{7}	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}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

A. Cocco, G.M. and M. Messina 2007


allowed
1st unique forbidden
2nd unique forbidden
3rd unique forbidden
β⁻ (top)
β⁺ (bottom)
Qβ = 1 keV
Qβ = 100 keV
Qβ = 10 MeV
log10(σv/(10^-41 cm^2 c))
log10(Eν (MeV))



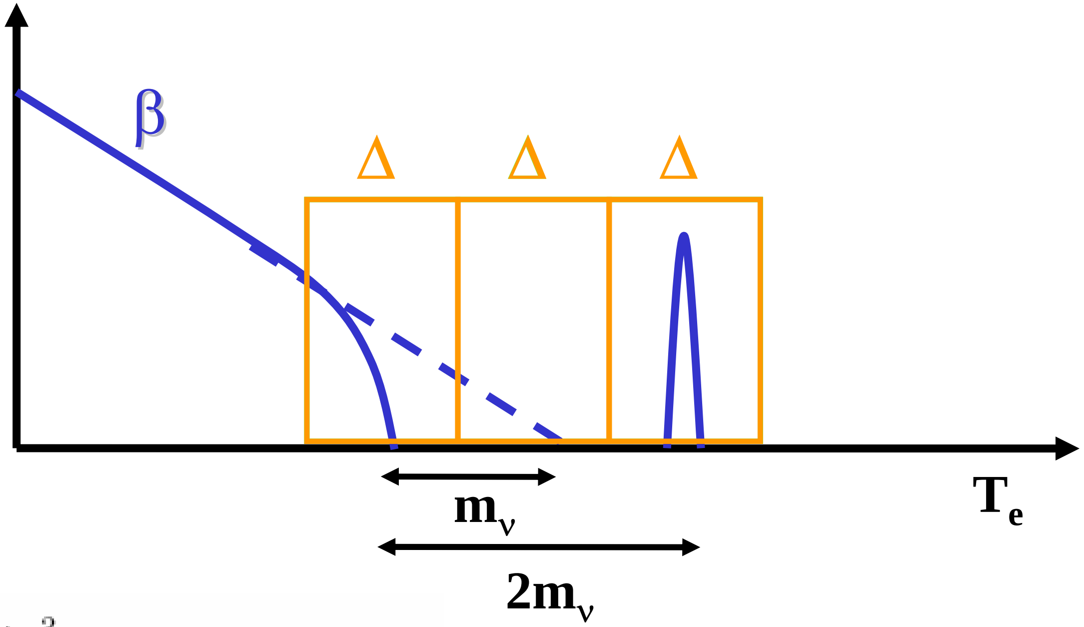
1272 β^- nuclei



799 β^+ nuclei

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

2. Background



Observing the last energy bins of width Δ

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

signal/background >1

$$\frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}\rho} \geq 1 \,,$$

$$\rho = \frac{1}{\sqrt{2\pi}}\int_{2m_\nu/\Delta-1/2}^{2m_\nu/\Delta+1/2} e^{-x^2/2}dx \,.$$

It works for $\Delta < m_\nu$

•Clustering and ν local density

Massive neutrinos cluster on CDM and baryonic structures. The local density at Earth (8 kpc away from the galactic center) is expected to be larger than 56 cm^{-3}

$$\frac{\partial f_i}{\partial \tau} + \frac{\boldsymbol{p}}{a m_i} \cdot \frac{\partial f_i}{\partial \boldsymbol{x}} - a m_i \nabla \phi \cdot \frac{\partial f_i}{\partial \boldsymbol{p}} = 0,$$

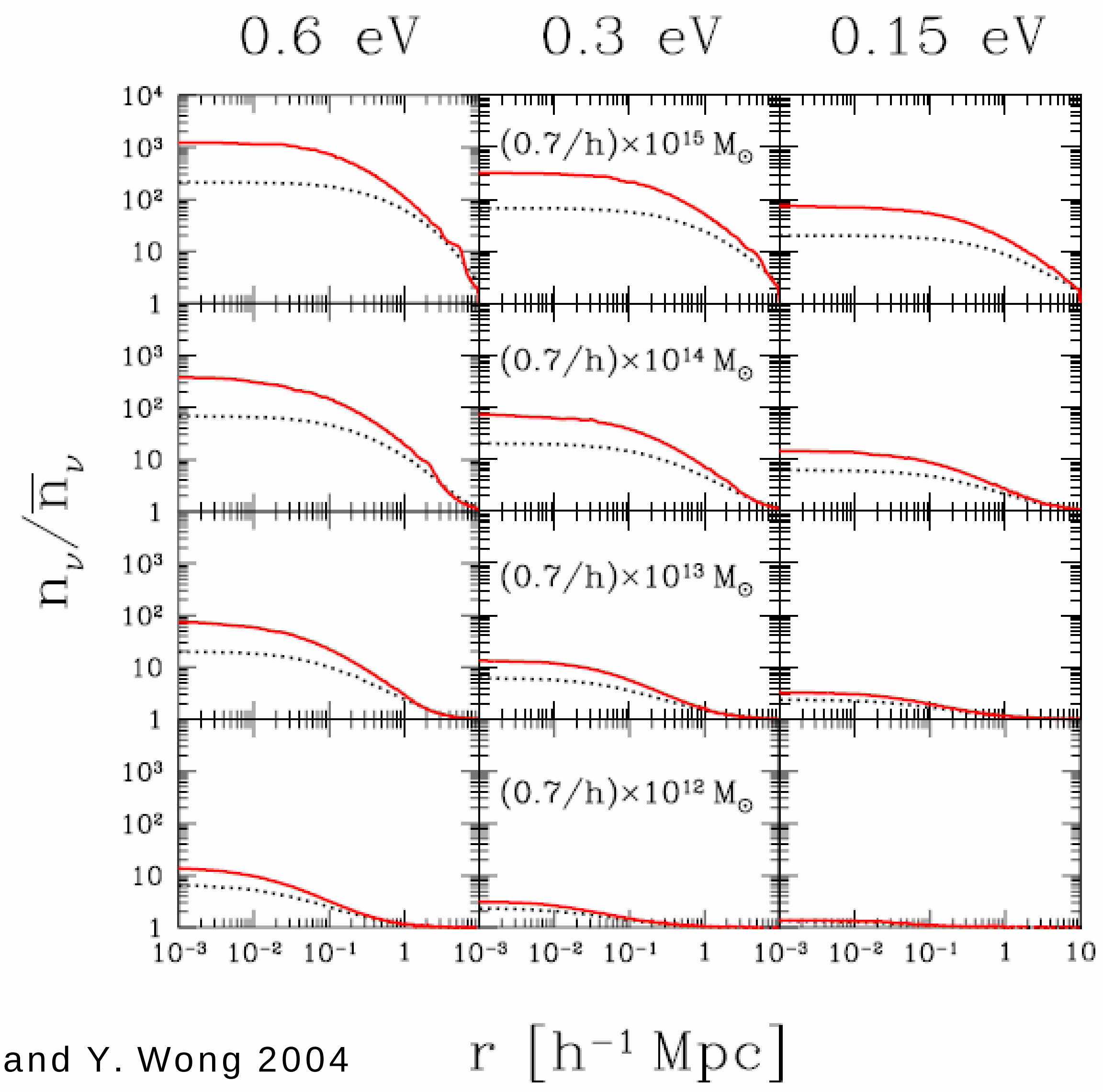
$$\nabla^2 \phi = 4\pi G a^2 \sum_i \overline{\rho}_i(\tau) \delta_i(\boldsymbol{x}, \tau),$$

$$\delta_i(\boldsymbol{x}, \tau) \equiv \frac{\rho_i(\boldsymbol{x}, \tau)}{\overline{\rho}_i(\tau)} - 1, \qquad \rho_i(\boldsymbol{x}, \tau) = \frac{m_i}{a^3} \int d^3p \; f_i(\boldsymbol{x}, \boldsymbol{p}, \tau),$$

Neutrinos accrete when their velocity becomes comparable with protocluster velocity dispersion (z<2)

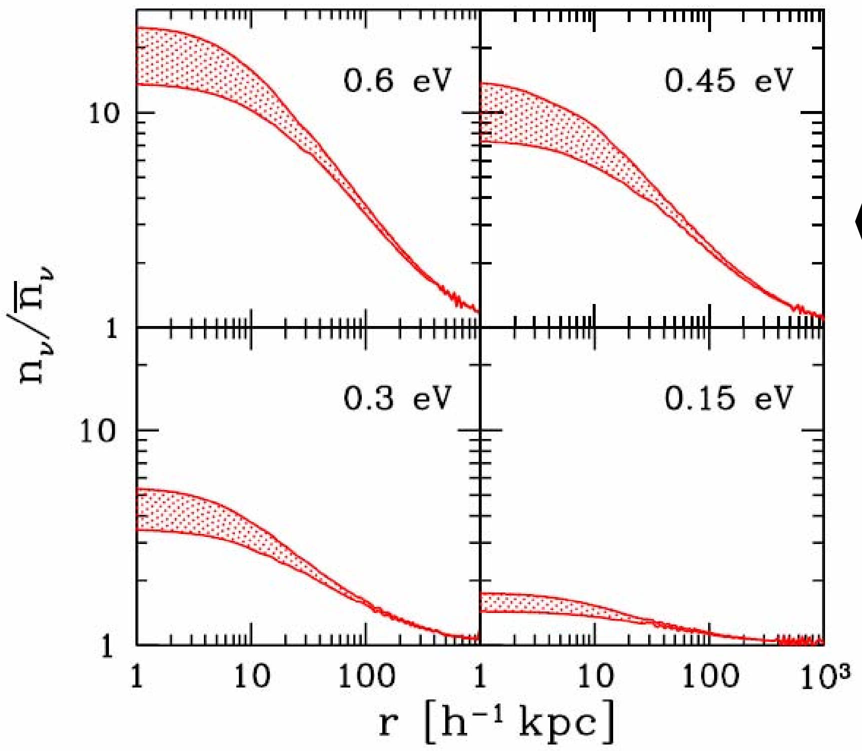
Usual assumption: Halo profile governed by CDM only

NFW universal profile $$\rho_{\rm halo}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2},$$



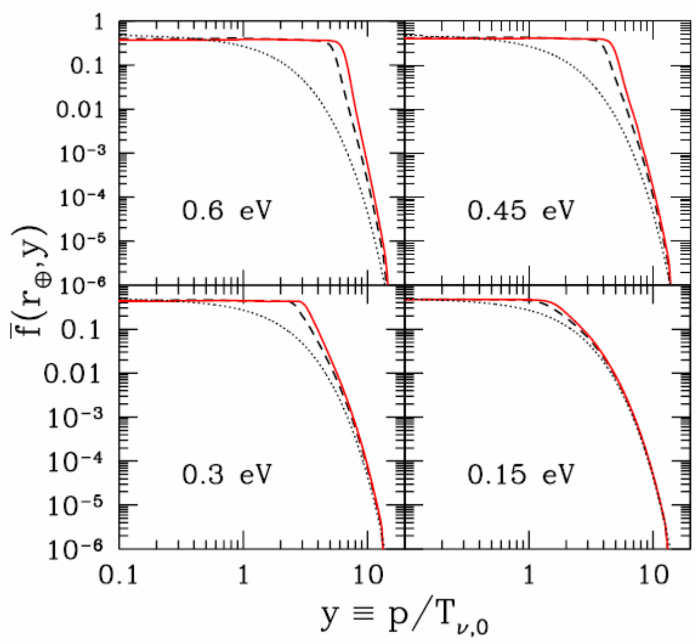
A. Ringwald and Y. Wong 2004

N-1-body simulations



Milky Way

Top curve: NFW
Bottom curve: static present MW matter profile



A. Ringwald and Y. Wong 2004

N-1-body simulations

The case of ^{3}H

$$\lambda_\beta = 2.85 \cdot 10^{-2} \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} {\rm cm}^2} {\rm yr}^{-1} \ {\rm mol}^{-1} . \quad \sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} = (\ 7.84 \pm 0.03 \ ) \times 10^{-45} \ {\rm cm}^2 ,$$

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

The number of NCB events per year for 100 g of ^{3}H

8 events yr^{-1} per 100g of ^{3}H (no clustering)

up to 10^2 events yr^{-1} per 100 g of ^{3}H due to clustering effect

signal/background = 3 for Δ=0.2 eV if m_ν=0.7 eV

Δ=0.1 eV if m_ν=0.3 eV

Outlooks

Relic neutrinos and NCβ

- neutrino mass scale?
- NCβ: high rates, but detection only for quasi degenerate mass scale (m_ν> 0.1 - 0.2 eV);
- other background rejection methods? More careful analysis of kinematics (daughter nucleus recoil, polarized nuclei which de-excite via gamma emission,...);
- look for the best nucleus; other processes?
- other low energy neutrino fluxes: thermal ν's from the Sun, diffused flux, old stars (POP III),...