The Relic Neutrino Background: Theoretical Understanding and Experimental Perspectives

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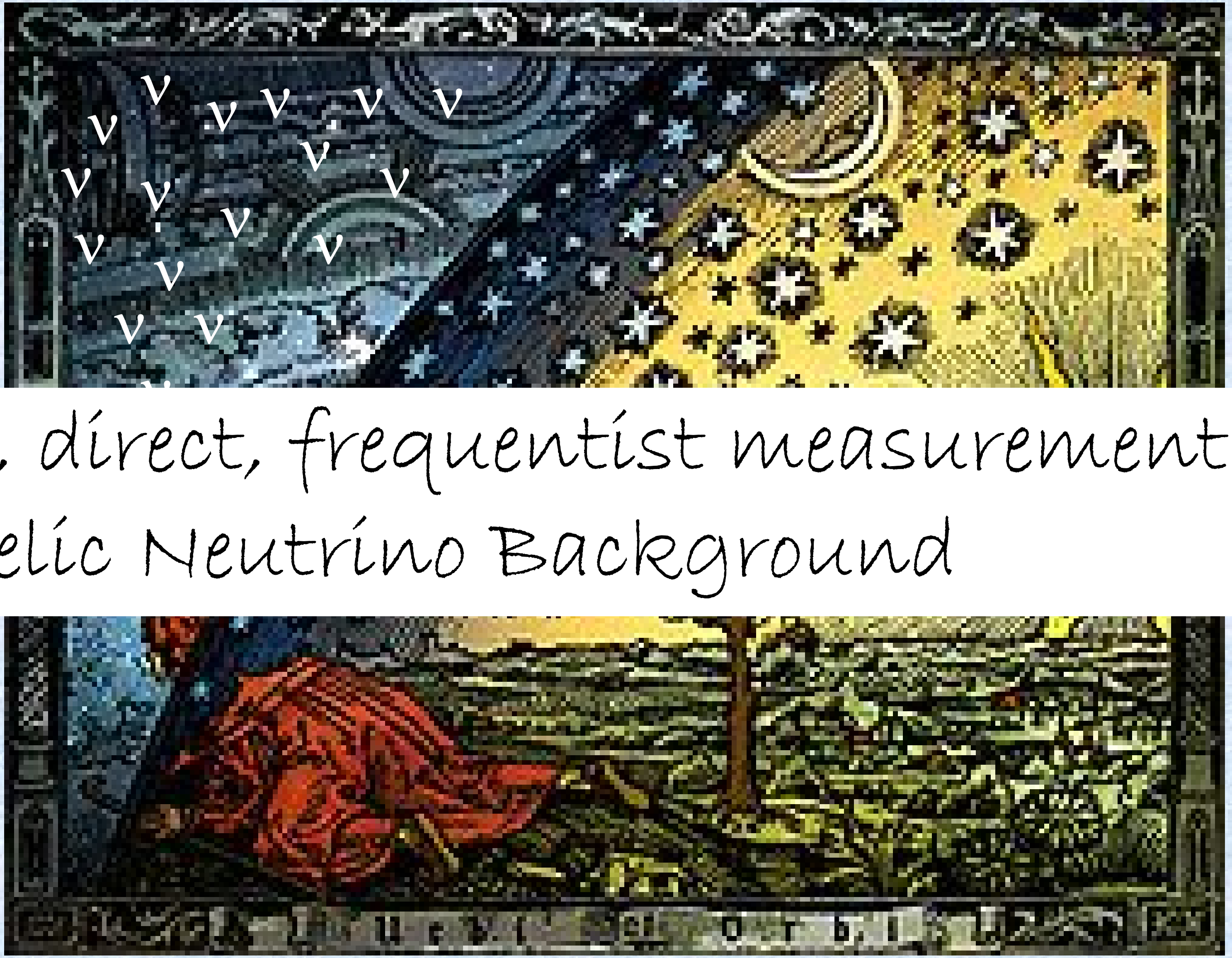


A lab, direct, frequentist measurement of the Relic Neutrino Background

Nec plus ultra?

WHAT WE SUPPOSE TO KNOW

Relic neutrino production and decoupling

$1\ \mathrm{MeV} \leq T \leq m_\mu$

$T_\nu = T_e = T_\gamma$

$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$

$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$

$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$

$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$

$$\mathcal{L}_{\mathrm{SM}} = -2\sqrt{2}G_F\left\{(\bar{\nu}_e\gamma^\mu L\nu_e)(\bar{e}\gamma_\mu L e) + \sum_{P,\alpha} g_P(\bar{\nu}_\alpha\gamma^\mu L\nu_\alpha)(\bar{e}\gamma_\mu P e)\right\}$$

$P = L,\ R = (1 \mp \gamma_5)/2$

$g_L = -\frac{1}{2} + \sin^2\theta_W$ and $g_R = \sin^2\theta_W$

Neutrino decoupling

As the Universe expands, particle densities are diluted and temperatures fall. Weak interactions become ineffective to keep neutrinos in good thermal contact with the e.m. plasma

Rough, but quite accurate estimate of the decoupling temperature

Rate of weak processes ~ Hubble expansion rate

$$\Gamma_w \approx \sigma_w |\mathrm{v}| n\,,\ H^2 = \frac{8\pi\rho_R}{3M_p^2} \rightarrow\ G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_R}{3M_p^2}} \ \rightarrow\ T_{dec}^{\nu} \approx 1\ MeV$$

Since ν_e have both CC and NC interactions with $e^\pm$

$T_{dec}(\nu_e)$ ~ 2 MeV

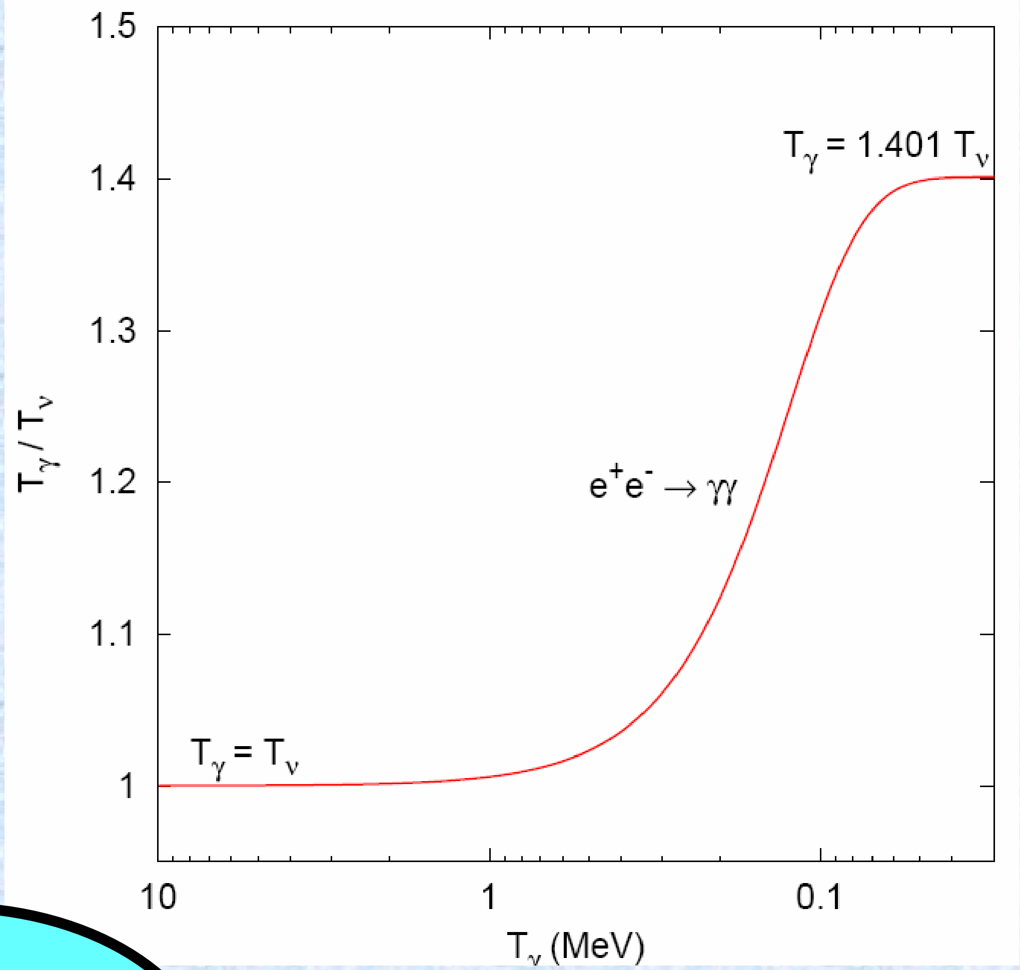
$T_{dec}(\nu_{\mu,\tau})$ ~ 3 MeV

Neutrino and Photon (CMB) temperatures

At $T \sim m_e$, electron-positron pairs annihilate

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

heating photons but not the decoupled neutrinos



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

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

Neutrino and Photon (CMB) temperatures

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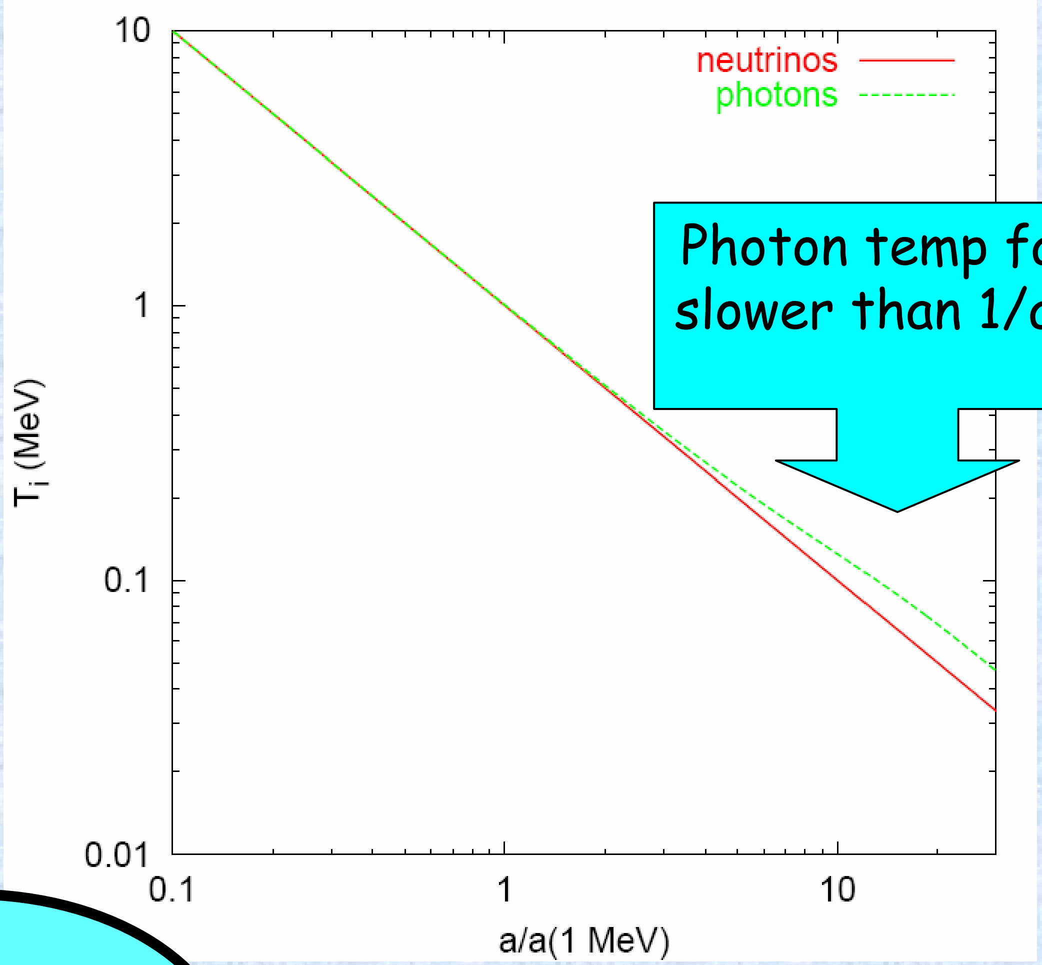


Photon temp falls slower than 1/a(t)

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

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

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species $f_\nu(p,T)=\frac{1}{e^{p/T_\nu}+1}$

- Number density

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

- Energy density

$$\rho_{\nu_i}=\int\sqrt{p^2+m_{\nu_i}^2}\,\frac{d^3p}{(2\pi)^3}f_\nu(p,T_\nu)\rightarrow\begin{cases}\frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3}T_{CMB}^4 & \text{Massless}\\ m_{\nu_i}n_\nu & \text{Massive } m_\nu \gg T\end{cases}$$

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species $f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$

- Number density

At present 112 $(\nu + \bar{\nu})$ cm^{-3} per flavour

- Energy density

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 = 1.7\times10^{-5}$$

Massless

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

Massive

$m_\nu \gg T$

CνB details

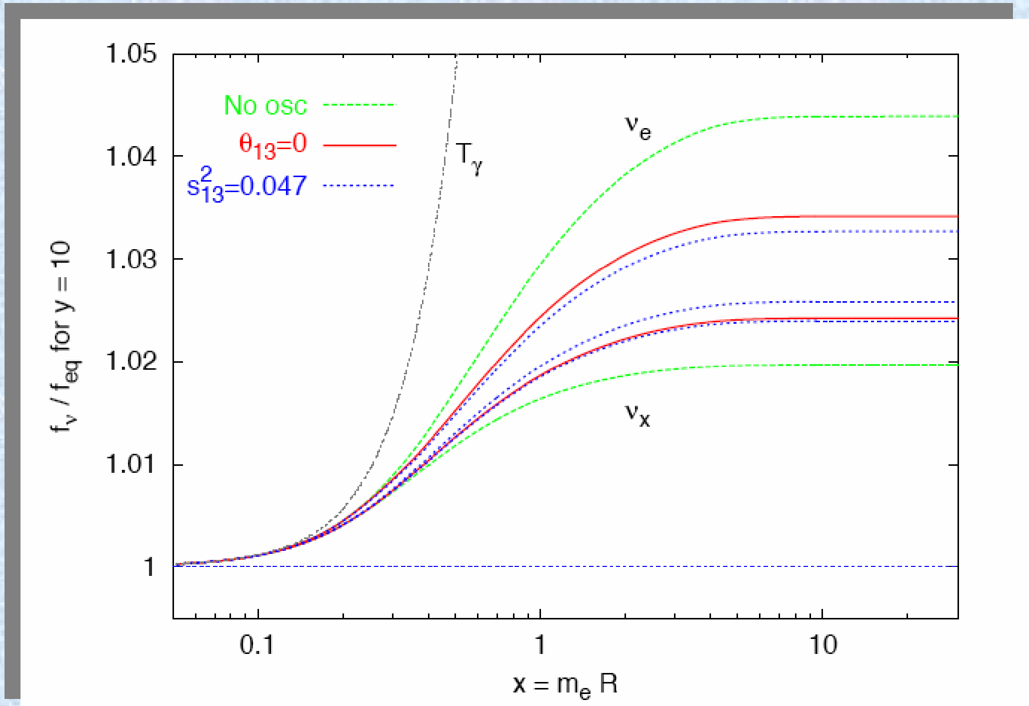
At T~m_e, e^+e^- pairs annihilate heating photons

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

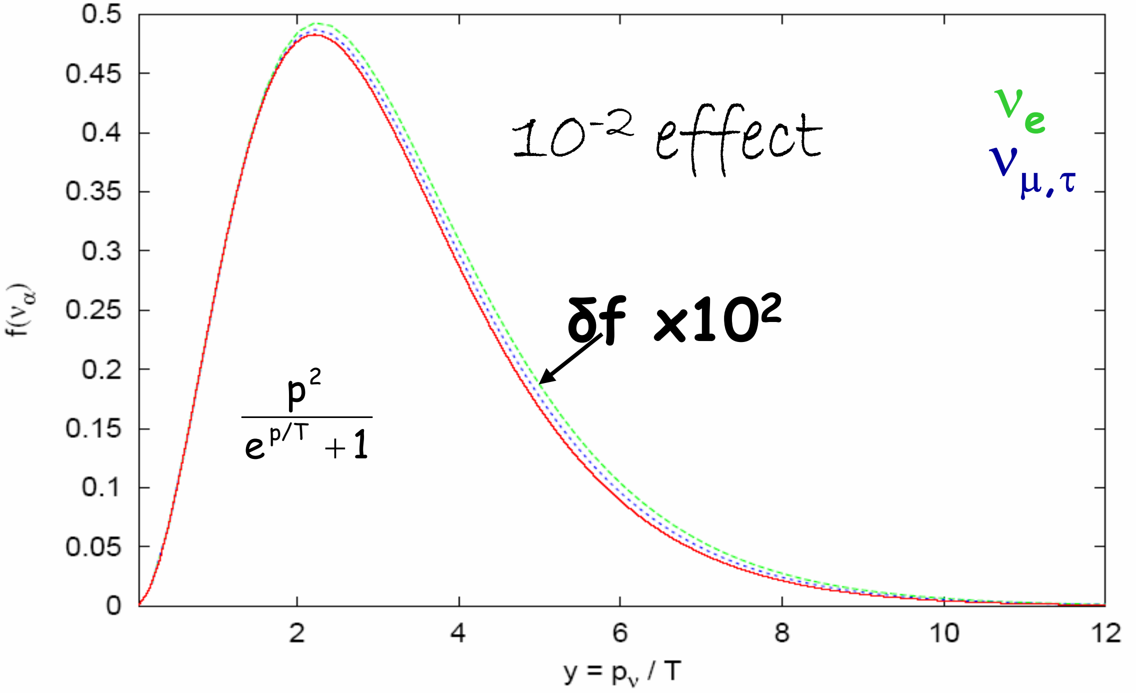
… and neutrinos. Non thermal features in ν distribution (small effect). Oscillations slightly modify the result

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

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



FROZEN NEUTRINO SPECTRA



10^{-2} effect

$\delta f \times 10^2$

$$\frac{p^2}{e^{p/T}+1}$$

Results

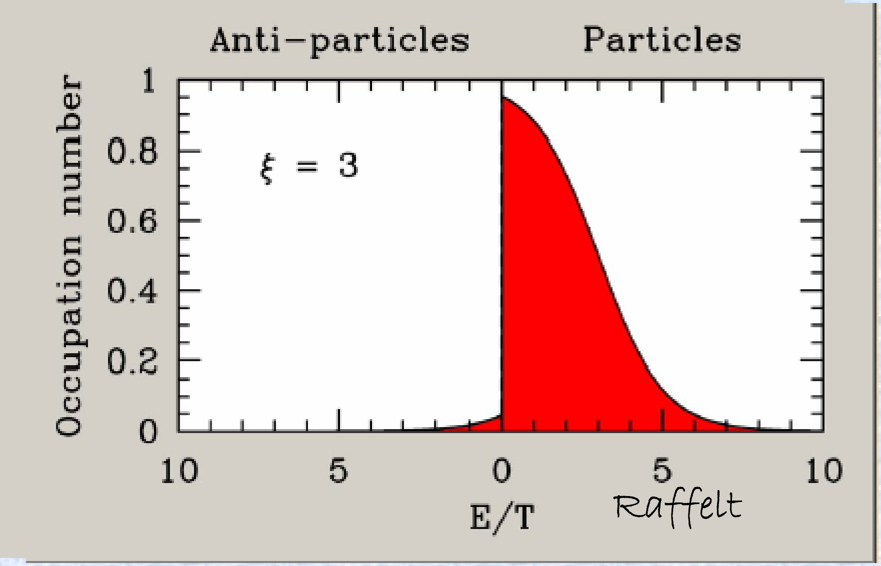
	$T^{\gamma}_{fin} / T^{\gamma}_{0}$	$\delta\rho_{\nu e}$(%)	$\delta\rho_{\nu\mu}$(%)	$\delta\rho_{\nu\tau}$(%)	N_{eff}
Instantaneous decoupling	1.40102	0	0	0	3
SM	1.3978	0.94	0.43	0.43	3.046
+3ν mixing (θ_{13}=0)	1.3978	0.73	0.52	0.52	3.046
+3ν mixing ($\sin^2\theta_{13}$=0.047)	1.3978	0.70	0.56	0.52	3.046

Dolgov, Hansen & Semikoz, NPB 503 (1997) 426
G.M. et al, PLB 534 (2002) 8

G.M. et al, NPB 729 (2005) 221

CνB details

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



Raffelt

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

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

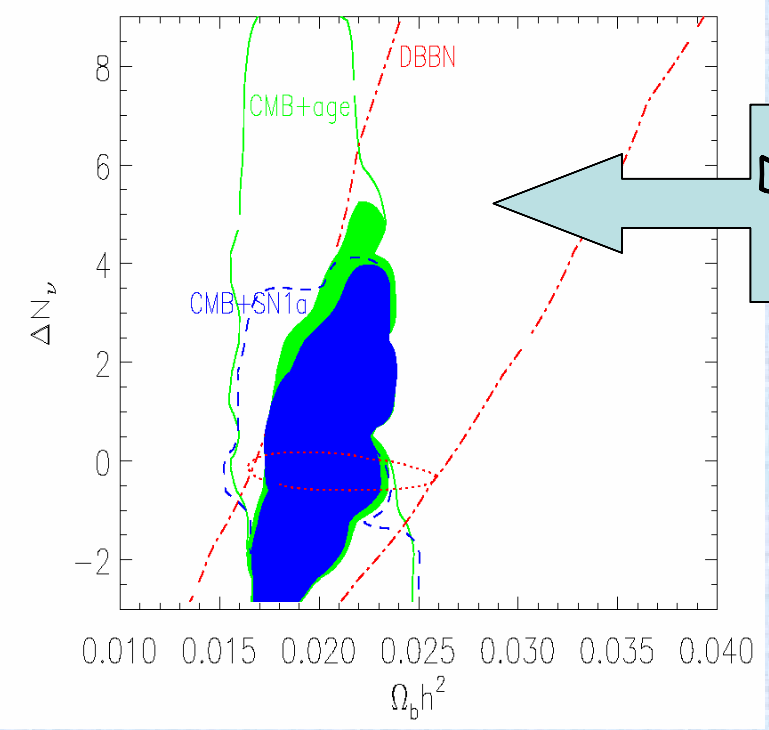
$$\Delta\rho_\nu = \frac{15}{7}\left[2\left(\frac{\xi_\nu}{\pi}\right)^2 + \left(\frac{\xi_\nu}{\pi}\right)^4\right]$$

More radiation

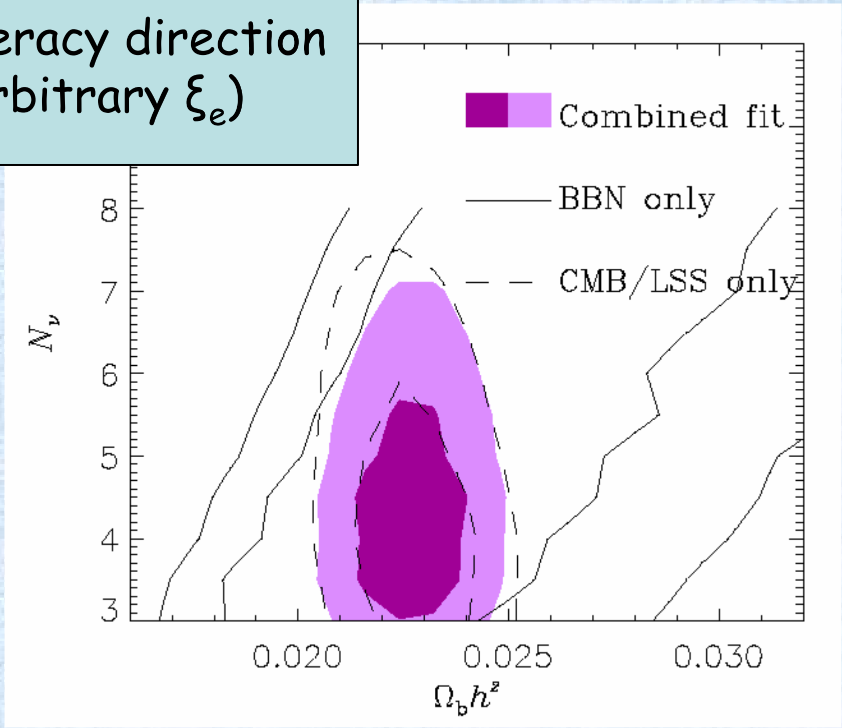
Combined bounds BBN & CMB-LSS

Kang & Steigman '92

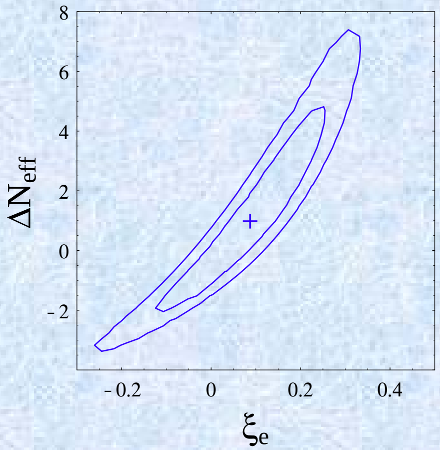
Degeneracy direction (arbitrary ξ_e)



Hansen et al 2001



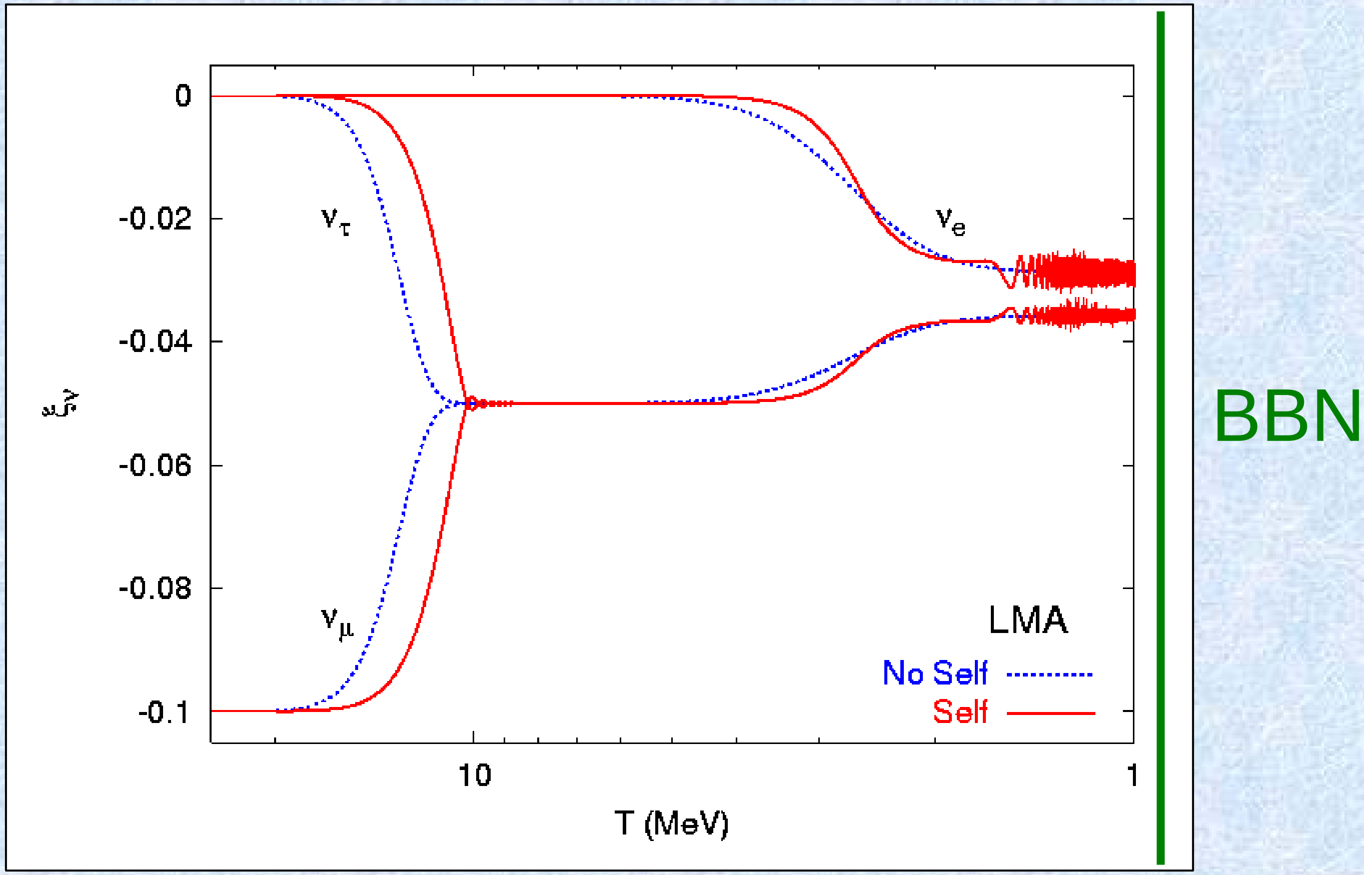
Hannestad 2003



$$-0.01 \le \xi_e \le 0.22 \qquad \left|\xi_{\mu,\tau}\right| \le 2.4$$

In the presence of flavor oscillations ?

Evolution of neutrino asymmetries



Effective flavor equilibrium (almost) established →

$$\boxed{|\xi_\nu| \leq 0.07}$$

Dolgov et al 2002
Wong 2002
Abazajian et al 2002

$$\boxed{-0.05 \leq \xi \leq 0.07}$$

Serpico & Raffelt 2005

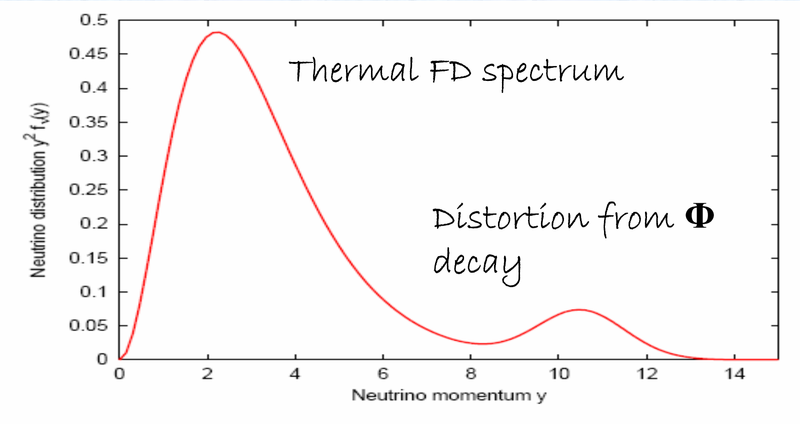
WHAT MIGHT UNEXPECTEDLY BE THE CASE

CνB for optimists

ν produced by decays at some cosmological epoch

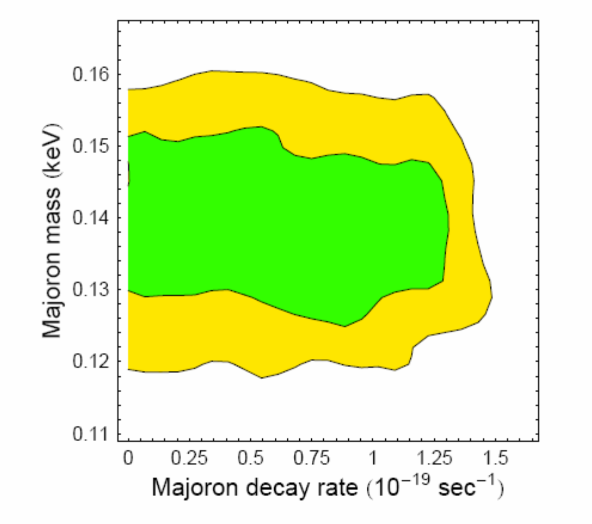
Early on:

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



$$\boxed{\Phi \rightarrow \nu\bar{\nu}}$$

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

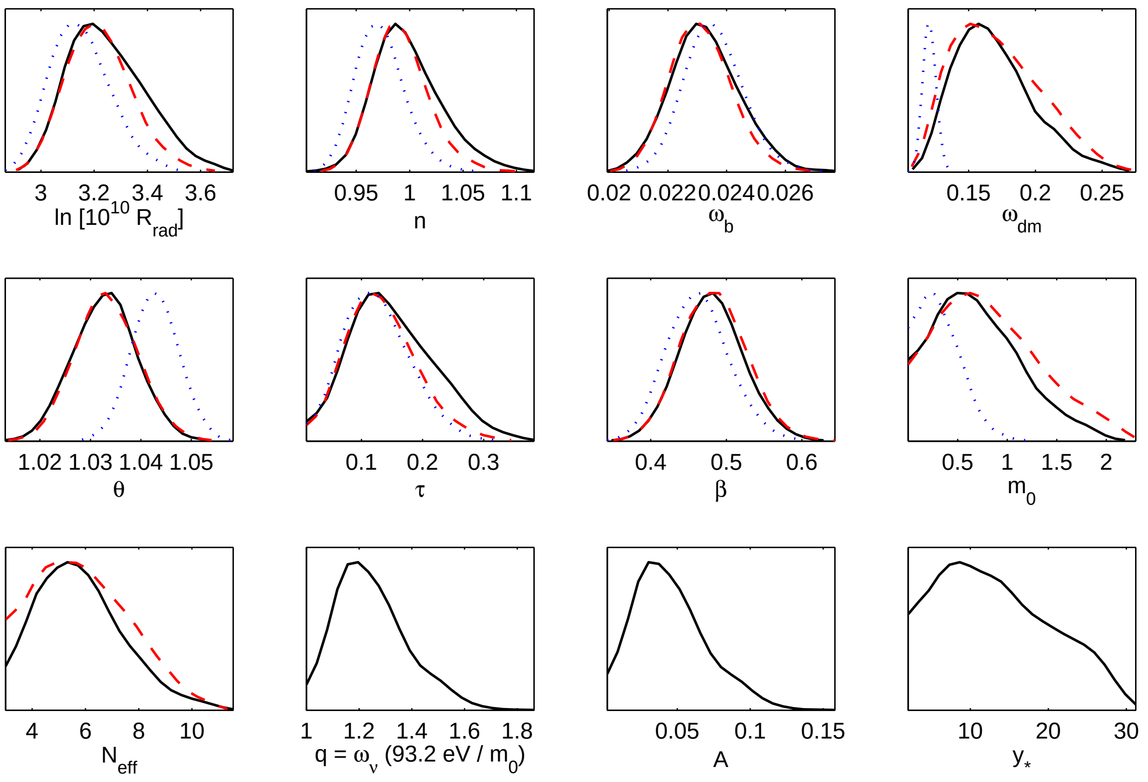
Lattanzi, Lesgourgues, GM and Valle, in preparation

Present constraints from CMB (WMAP+ACBAR+VSA+CBI) and LSS (2dFGRS+SDSS) + SNIa data (Riess et al.)

Model: standard ΛCDM + nonthermal v’s

C_l and P(k) computed using CAMB code (Lewis and Challinor 2002)

Likelihoods (using COSMOMC Lewis and Bridle 2002))



	ΛCDM	ΛCDM+R	ΛCDM+NT
$\chi^2_{\rm min}$	1688.2	1688.0	1688.0
$\ln[10^{10}\mathcal{R}_{\rm rad}]$	3.2±0.1	3.2±0.1	3.2±0.1
n_s	0.97±0.02	0.99±0.03	1.00±0.03
ω_b	0.0235±0.0010	0.0231±0.0010	0.0233±0.0011
$\omega_{\rm dm}$	0.121±0.005	0.17±0.03	0.17±0.03
θ	1.043±0.005	1.033±0.006	1.033±0.006
τ	0.13±0.05	0.13±0.06	0.15±0.07
β	0.46±0.04	0.48±0.04	0.48±0.04
m_0 (eV)	0.3±0.2	0.8±0.5	0.7±0.4
$N_{\rm eff}$	3.04	6±2	6±2
q	1	1	1.25±0.13
h	0.67±0.02	0.76±0.06	0.76±0.05
Age (Gyr)	13.8±0.2	12.1±0.9	12.1±0.8
Ω_Λ	0.68±0.03	0.67±0.03	0.67±0.03
z_{re}	14±4	16±5	18±6
σ_8	0.76±0.06	0.77±0.07	0.77±0.07

TABLE I: Minimum value of the effective χ^2 (defined as $-2\ln\mathcal{L}$, where $\mathcal{L}$ is the likelihood function) and 1σ confidence limits for the parameters of the three models under consideration. The first ten lines correspond to our basis of independent parameters, while the last five refer to related parameters.

CνB for pessimists

A neutrinoless Universe?

Beacom, Bell and Dodelson 2004

Models where ν's interact with light (pseudo)scalar particles

$$L = h_{ij}\bar{\nu}_i \nu_j \phi + h.c.$$

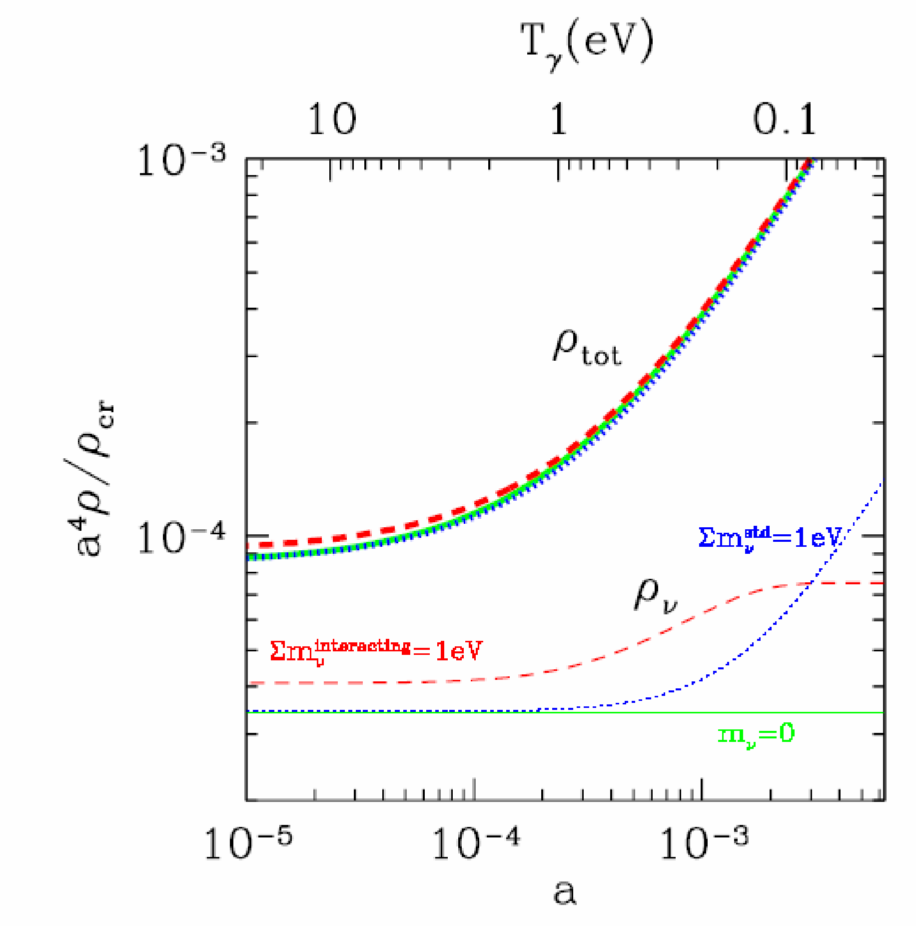
$$\nu\bar{\nu} \leftrightarrow \phi\phi$$

couplings < 10^{-5} from several data (meson decay, 0ββ, SN)

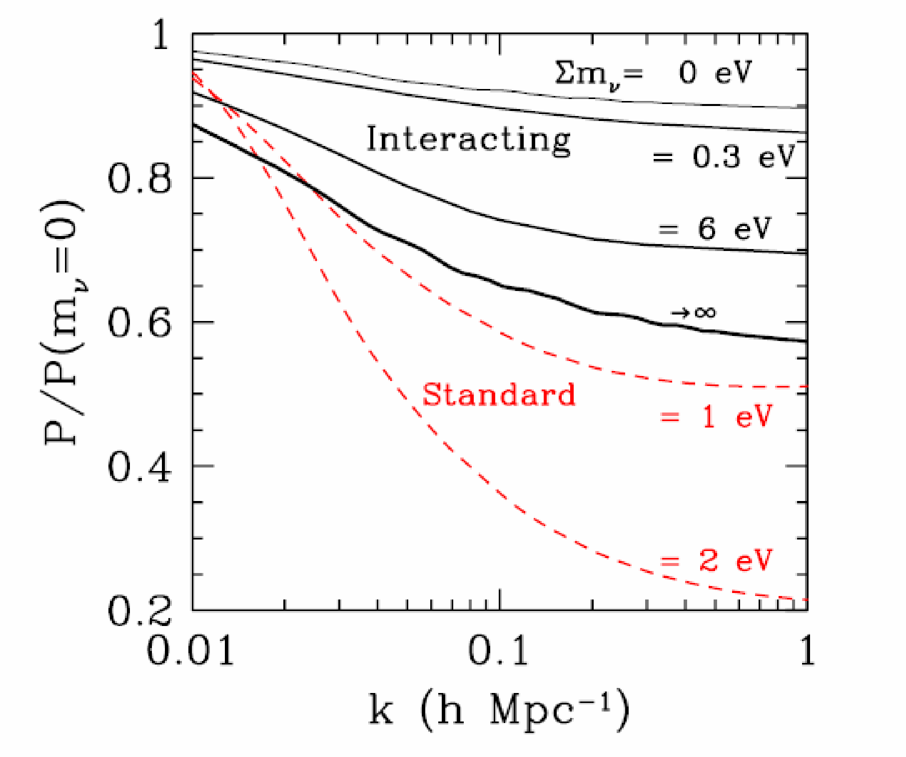
For the tightly coupled regime

ν density strongly reduced, ν's play no role in LSS

Delay in matter domination epoch, different content in relativistic species after ν decays (N_{eff}=6.6 after decays)



Beacom, Bell and Dodelson 2004



Bell, Pierpaoli and Sigurdson 2005

Hannestad 2005

Including CMB in the analysis:

- No free streaming (no anisotropic stress) leads to

    smaller effects on LSS (for massive ν's)

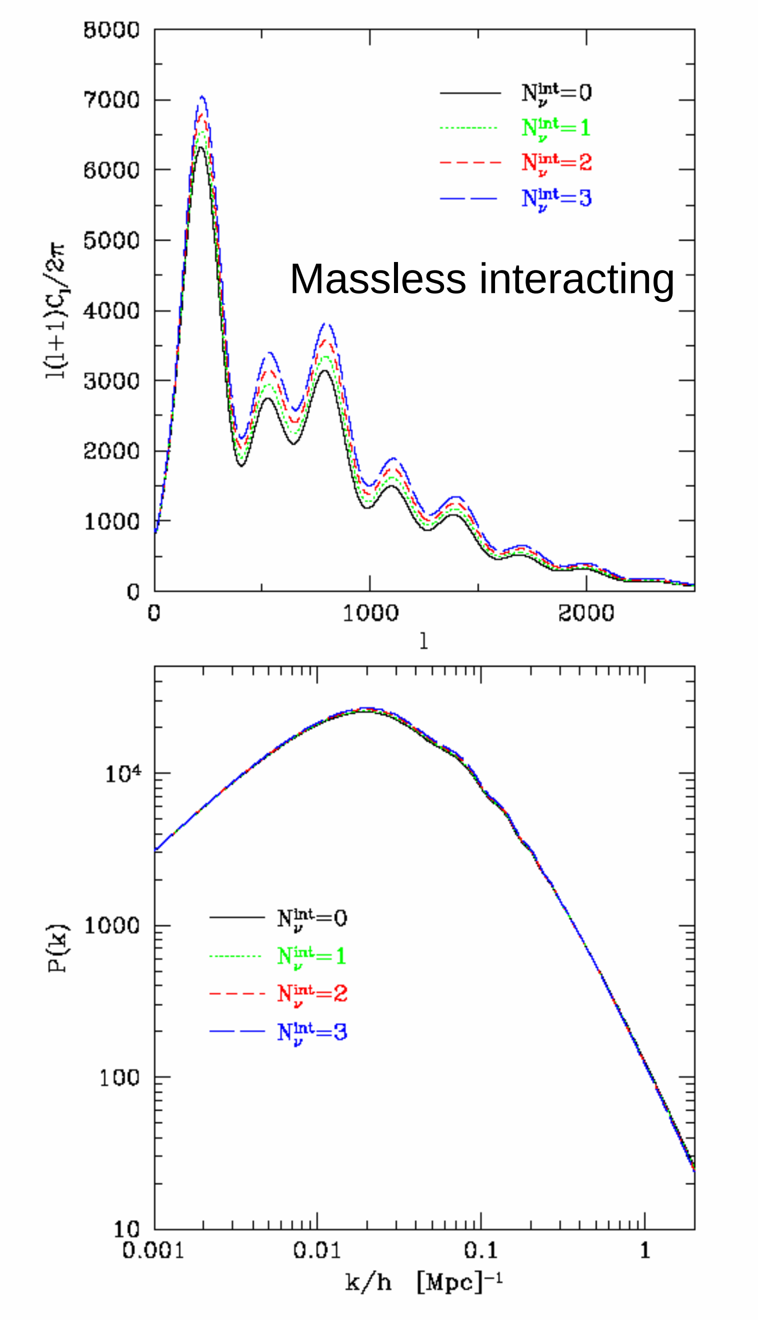
    change of sub-horizon perturbations at CMB epoch

- Change of sound speed and equation of state of the the titghly coupled ν - φ fluid

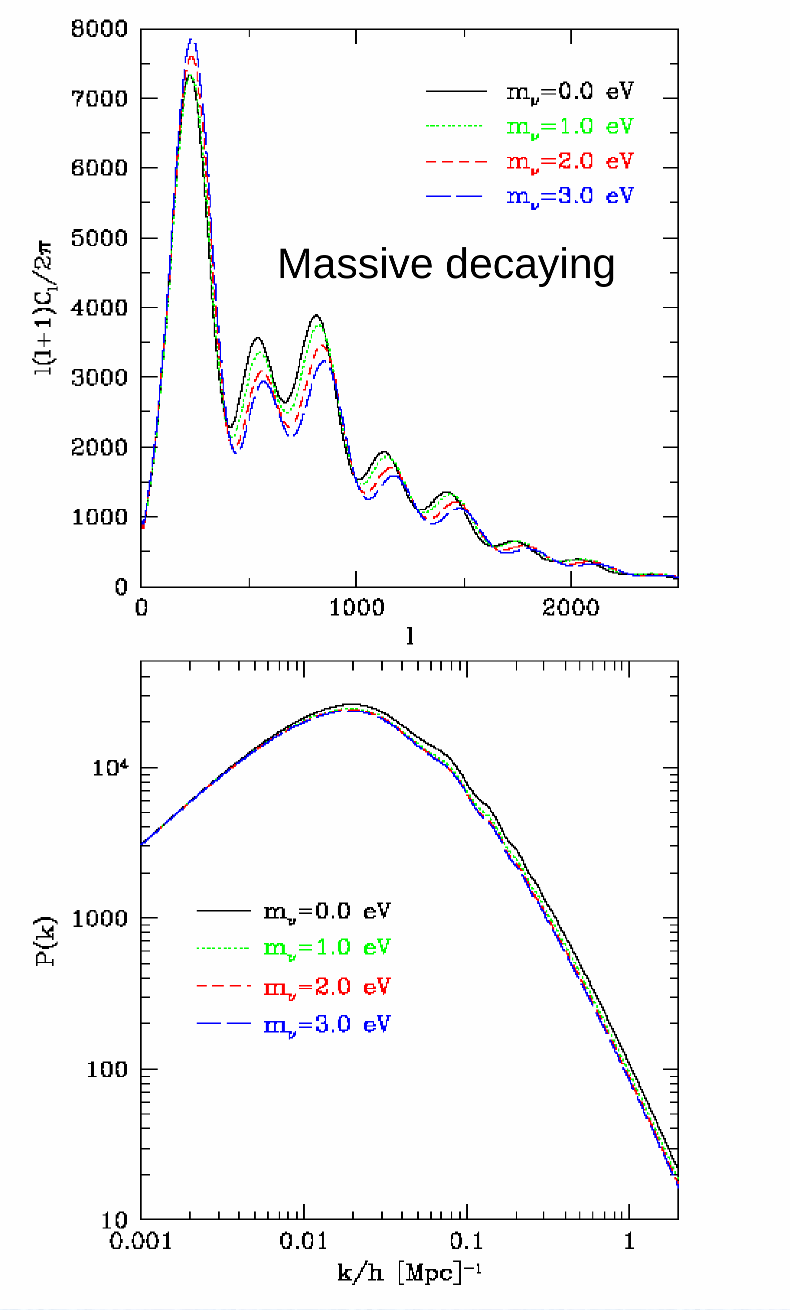
- ν decays

    larger N_{eff} i.e. larger ISW effect for CMB

    smaller effects on LSS (no ν left at LSS formation epoch



Massless interacting



Massive decaying

Interacting ν-DM

Usual picture of Dark Matter: cold collisionless massive particles which decoupled around the weak scale for freeze-out of annihilation processes

Ex: neutralino in MSSM with mass of O(100 GeV)

Difficulties:

Excess of small scale structures

Far more satellite galaxies in the Milky Way than observed (from numerical simulation)

DM in the MeV range: SPI spectrometer on the INTEGRAL satellite observed a bright 511 KeV gamma line from the galactic bulge

$$\psi\psi \to e^{+}e^{-} \qquad\qquad \psi\boldsymbol{\nu} \to \psi\boldsymbol{\nu}$$

Boehm, Fayet and Silk 2003

HOW CAN EXOTIC MODELS CAN BE CONSTRAINED

CνB indirect evidences

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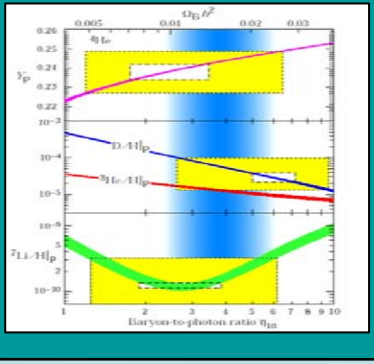
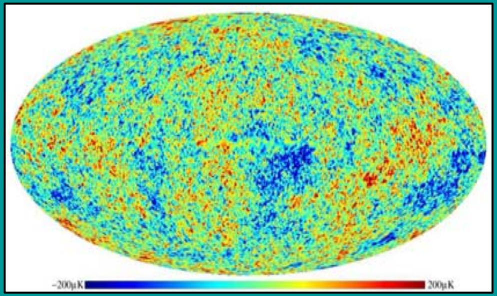
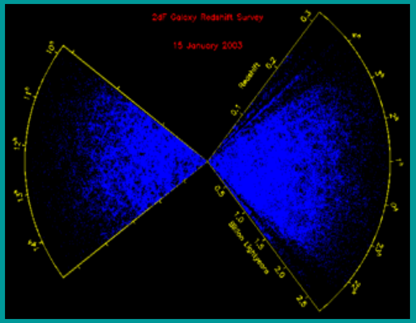
<td> </td>
<td> </td>
<td> </td>
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<tr>
<td>Primordial Nucleosynthesis
BBN</td>
<td>Cosmic Microwave Background
CMB</td>
<td>Formation of Large Scale Structures
LSS</td>
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<td>T ~ MeV</td>
<td colspan="2">T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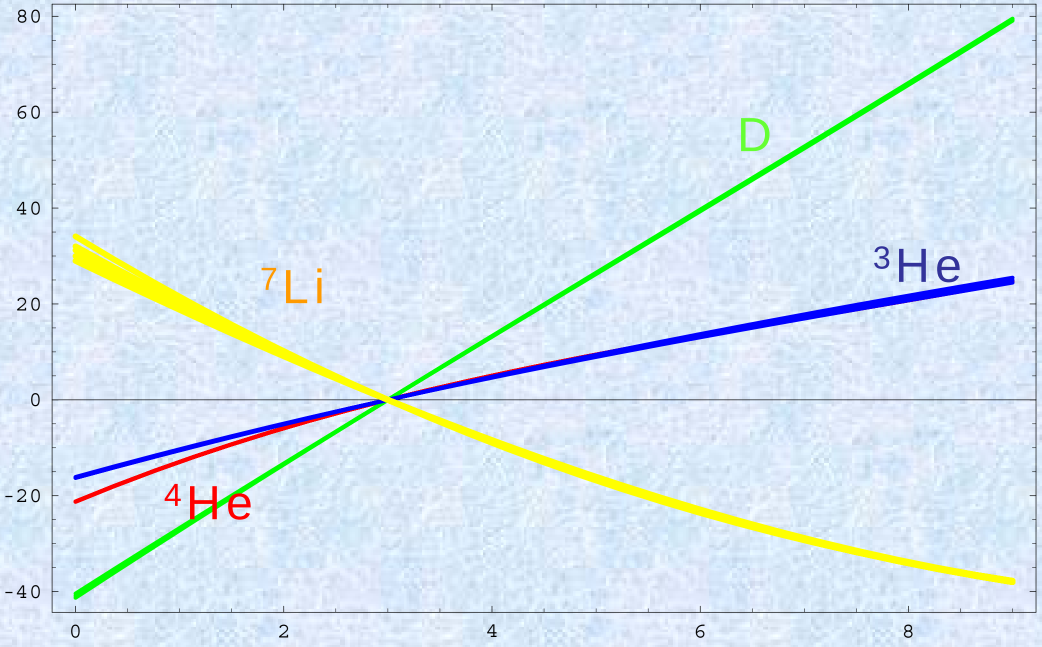
Effect of neutrinos on BBN

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

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

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

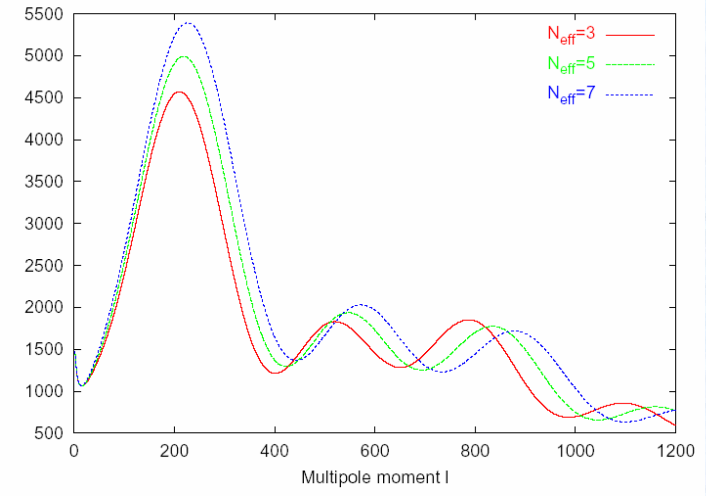


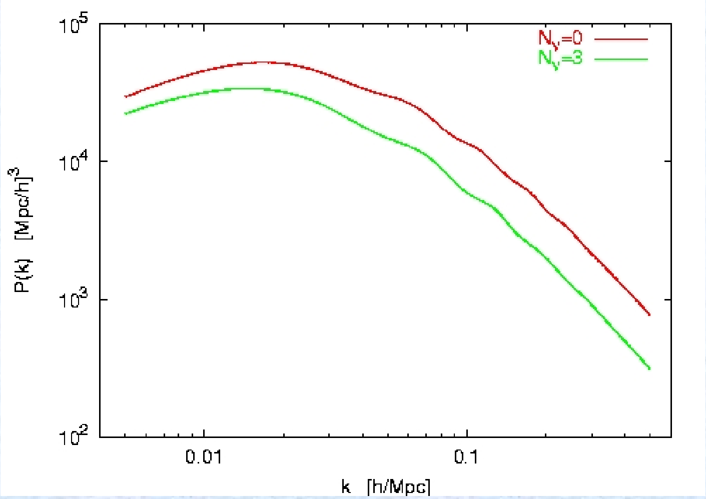
2. Direct effect of electron neutrinos and antineutrinos on the n-p reactions

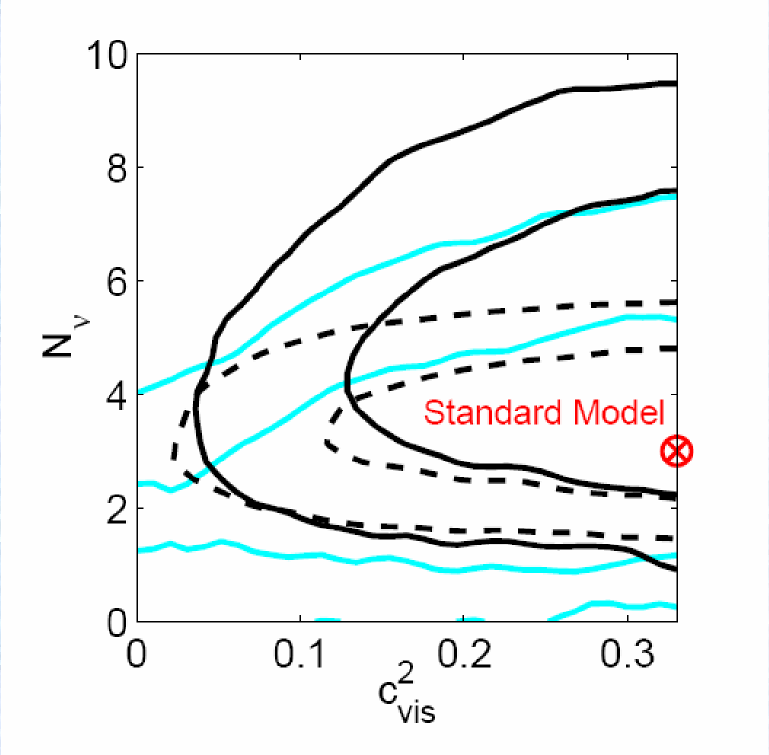
$$\nu_e + n \longleftrightarrow p + e^- \qquad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

Effect of CνB on CMB and LSS

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







Melchiorri and Trotta '04

CMB+LSS: allowed ranges for N_{eff}

- Set of parameters: ($\Omega_b h^2$, $\Omega_{cdm} h^2$, h , n_s , A , b , N_{eff})
- DATA: WMAP + other CMB + LSS + HST (+ SN-Ia)
- Flat Models

$$N_{eff} = 3.5^{+3.3}_{-2.1}$$

95% CL

$$N_{eff} = 4.0^{+3.0}_{-2.1}$$

Crotty, Lesgourgues & Pastor, PRD 67 (2003) Hannestad, JCAP 0305 (2003)

Non-flat Models

$$N_{eff} = 4.1^{+2.0}_{-1.9}$$

95% CL

Pierpaoli, MNRAS 342 (2003)

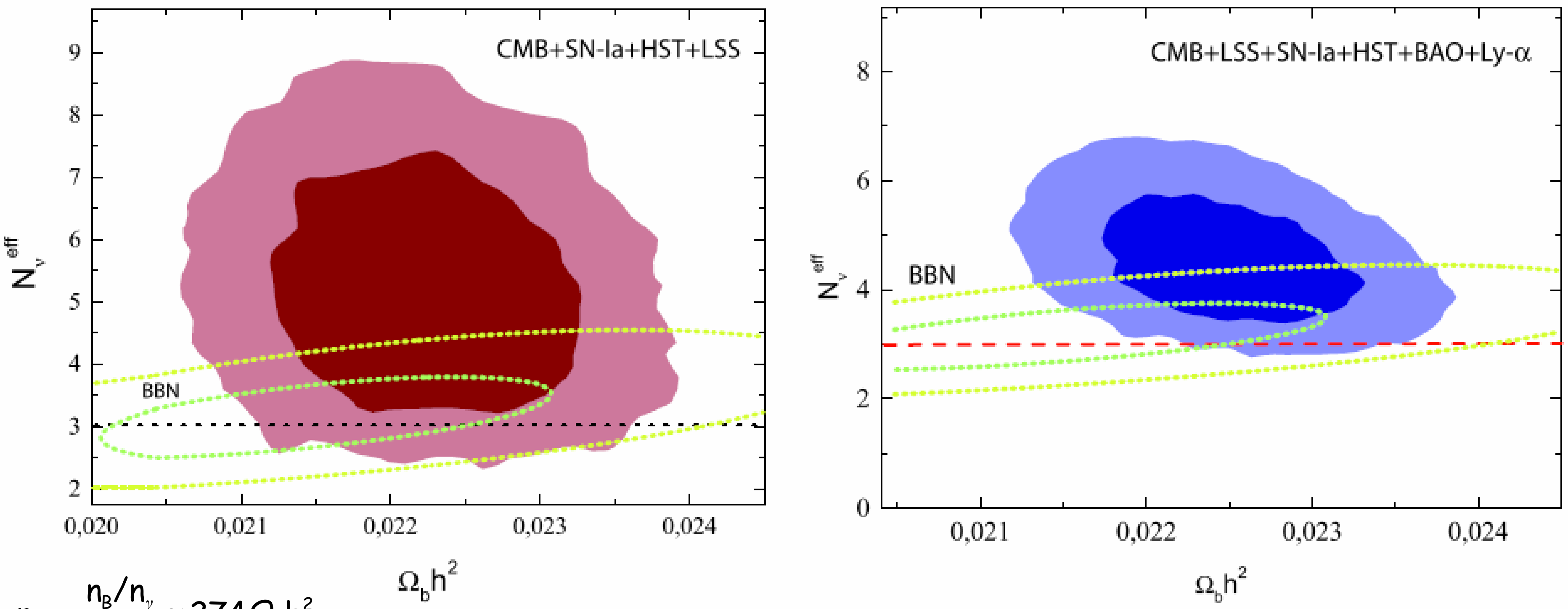
- Recent result

$$2.7 < N_{eff} < 4.6$$

95% CL

Hannestad & Raffelt, astro-ph/0607101

Allowed ranges for N_{eff}



$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \cong 274\,\Omega_B h^2$$

Figure 1. Analysis from the first (more conservative) set of cosmological data (Left Panel) and including Lyman-α and BAO data (Right Panel). We show the marginalized contours at 68% and 95% c.l. on the ω_b-N_ν^{eff} plane along with the analogous contours from BBN using D and ^{4}He experimental results (dotted lines).

Using cosmological data (95% CL)

$3.0 < N_{eff} < 7.9$ (CMB + LSS data)

$3.1 < N_{eff} < 6.2$ (+BAO and Ly - α)

G.M et al, JCAP 2006

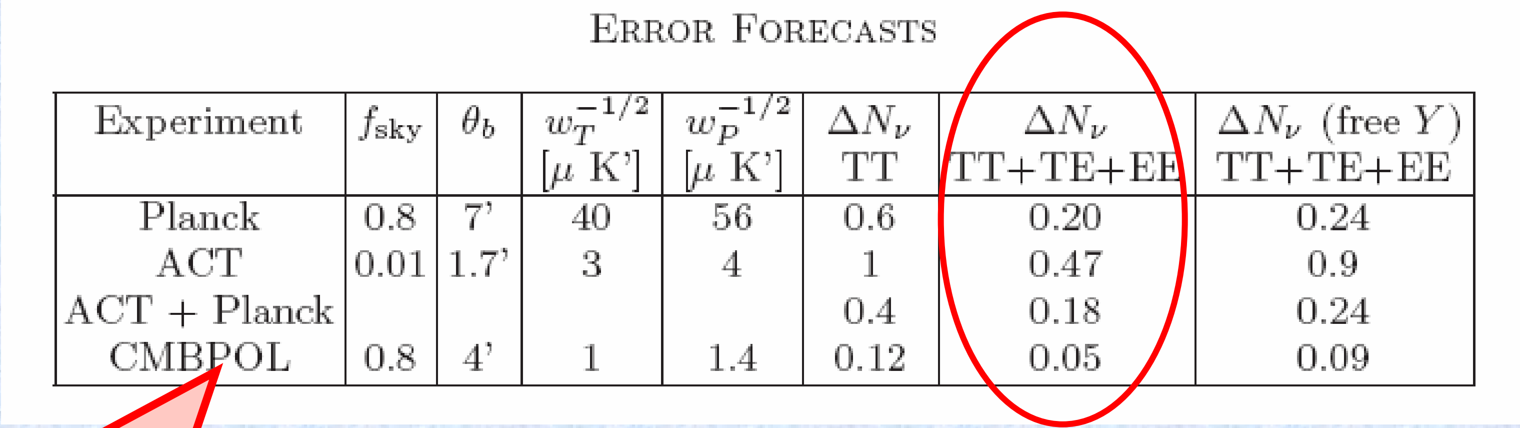
…but maybe in the near future ?

Forecast analysis:
CMB data

Bowen et al MNRAS 2002

ΔN_{eff} ~ 3 (WMAP)

ΔN_{eff} ~ 0.2 (Planck)



Error Forecasts

Experiment	$f_{\rm sky}$	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Example of future
CMB satellite

Bashinsky & Seljak PRD 69 (2004) 083002

Direct detection?

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

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

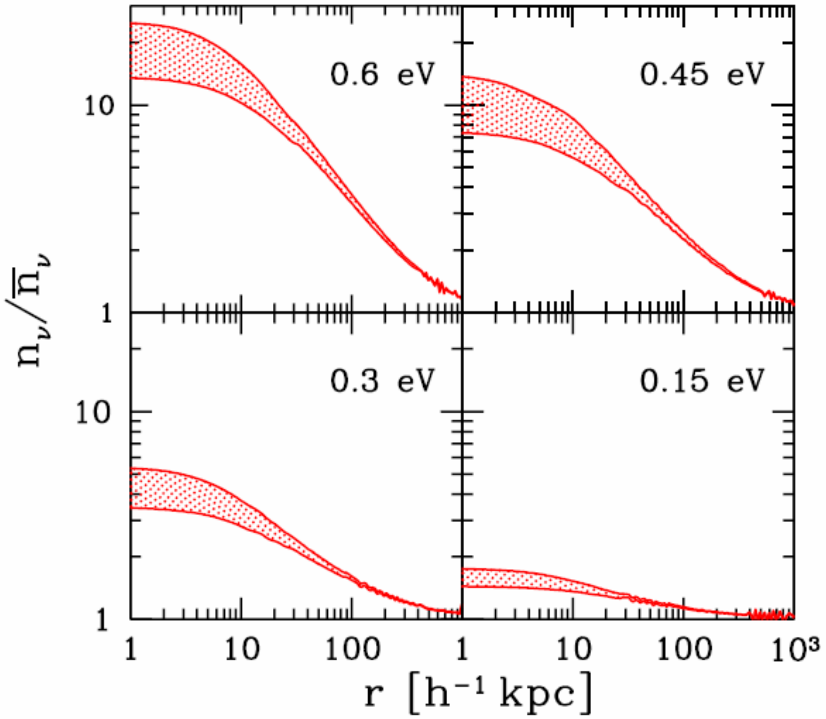
How to deal with: Boltzmann eq. + Poisson

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

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

Sing and Ma '02

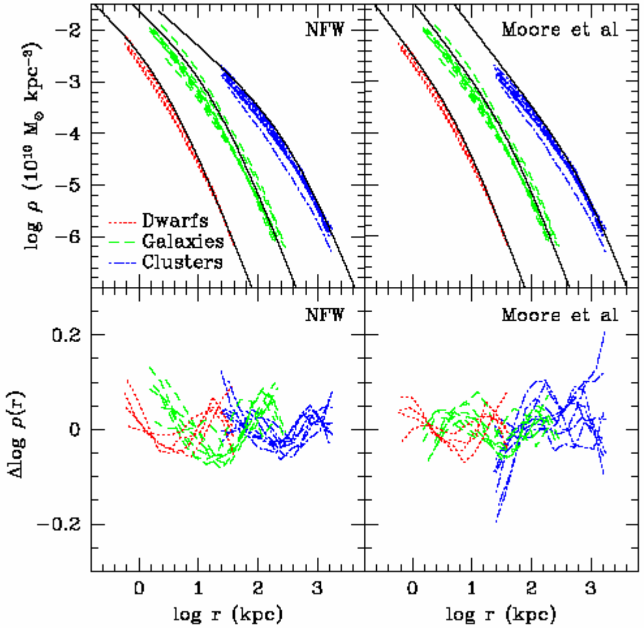
Ringwald and Wong '04

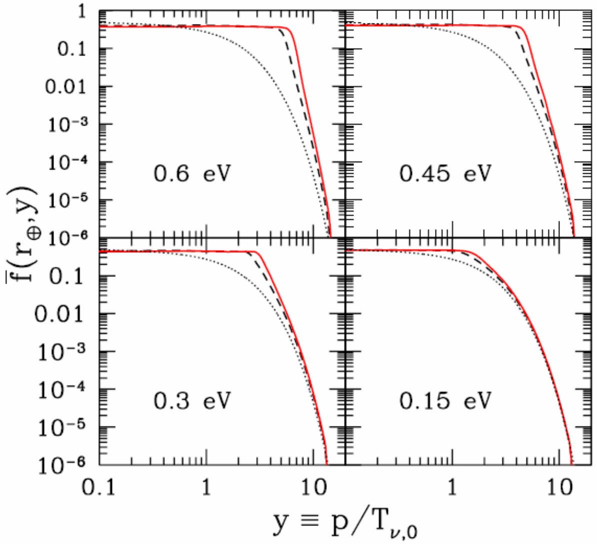


Milky Way
(10^{12} $M_\odot$)

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

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

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

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

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

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

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

Coherence enhances

$$\lambda_\nu \approx 1/T_\nu \;\; \text{-} \;\; 1/m_\nu \approx mm$$

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

Zeldovich and Khlopov '81

Smith and Lewin '83

Backgrounds: solar ν + WIMPS

Detection III

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

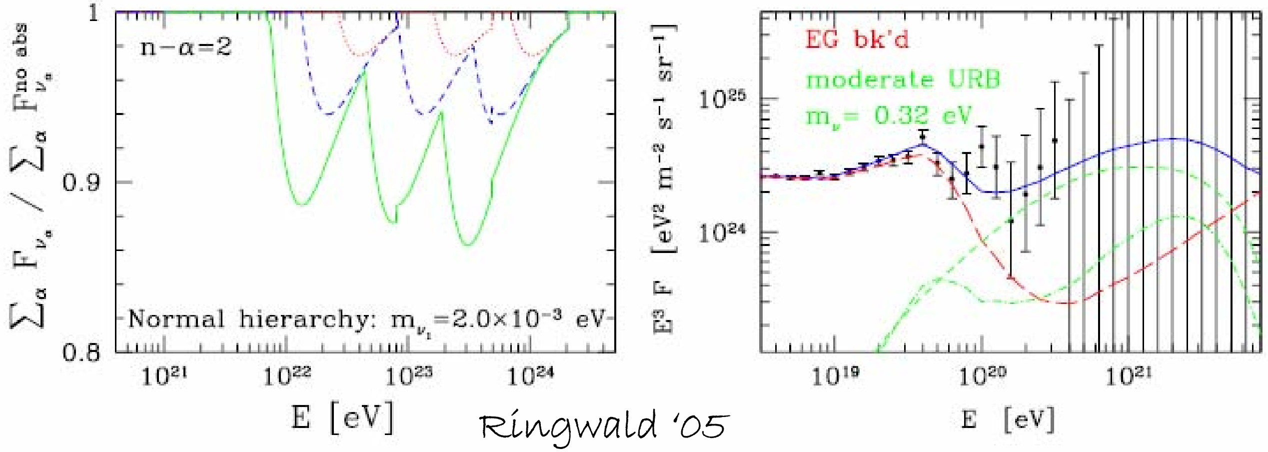
LHC

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

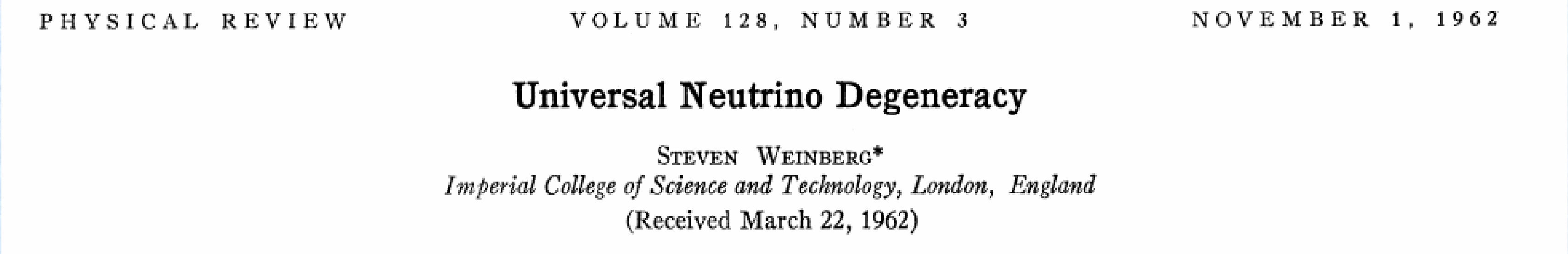
Question: “Is it possible to detect/measure the CνB ?”

Answer: ….

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

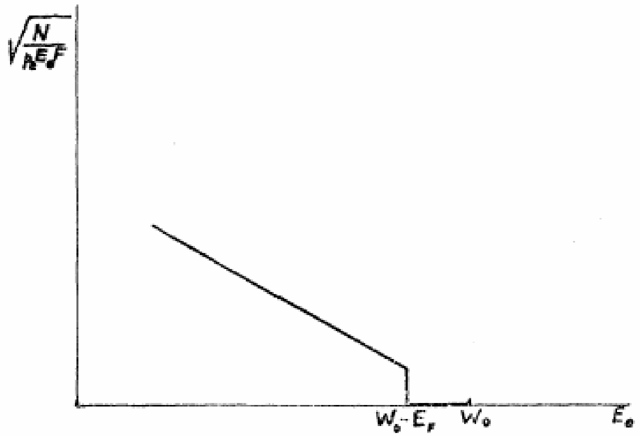


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

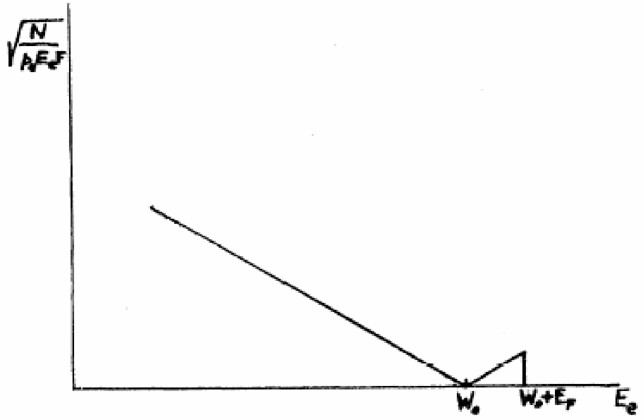
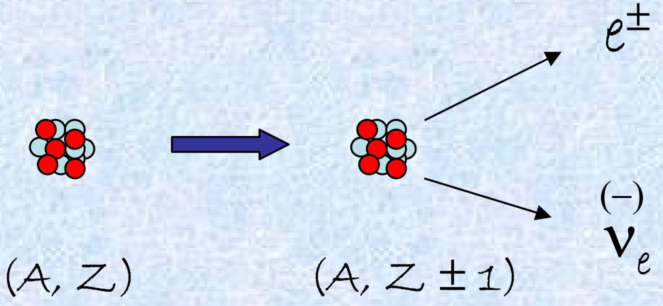


FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

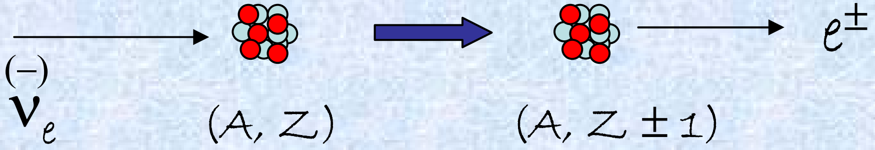
Massive neutrinos and neutrino capture on beta decaying nuclei

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

Beta decay



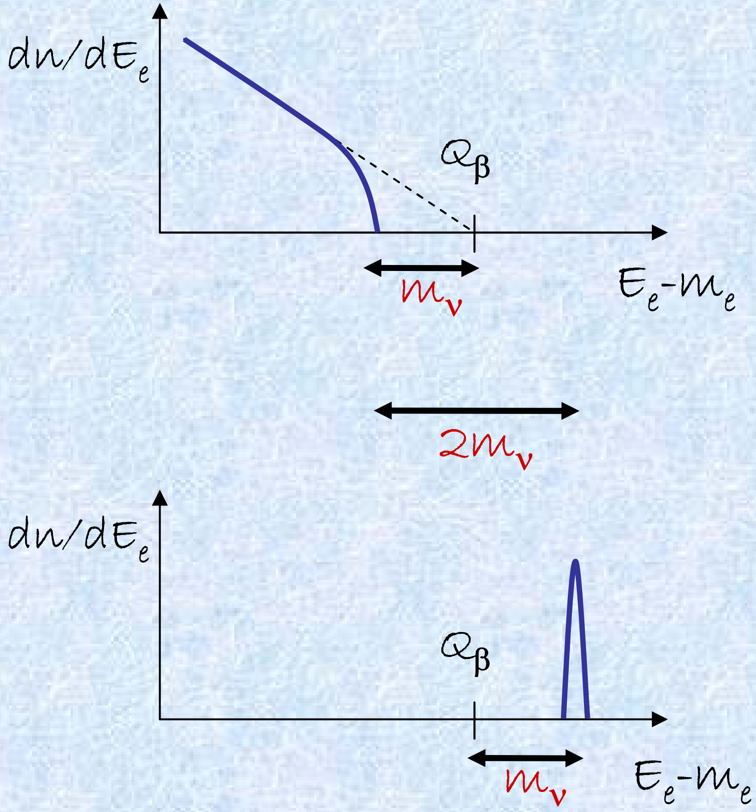
Neutrino Capture on a Beta Decaying Nucleus



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

Two issues:

Rate

Background

NCB Cross Section

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

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

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

It is convenient to define

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

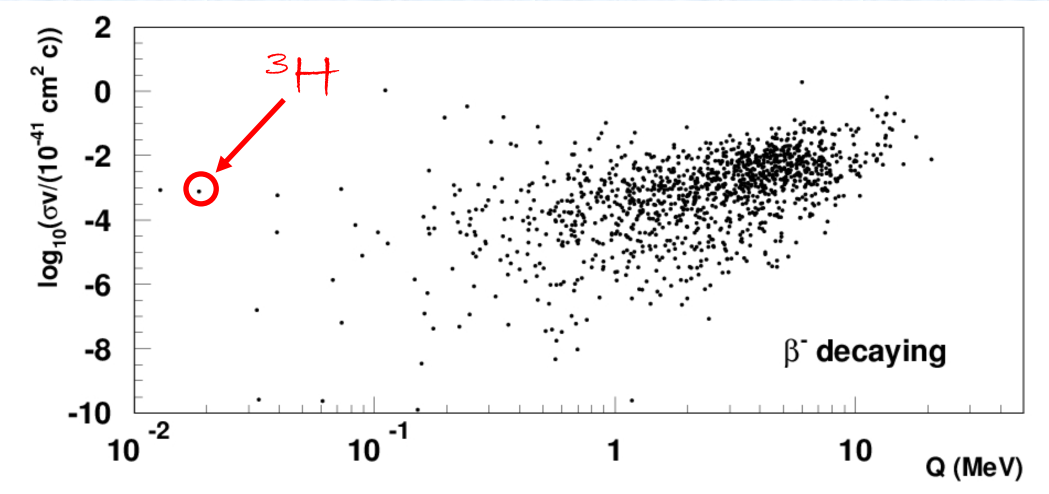
$$\boxed{\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}}$$

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)

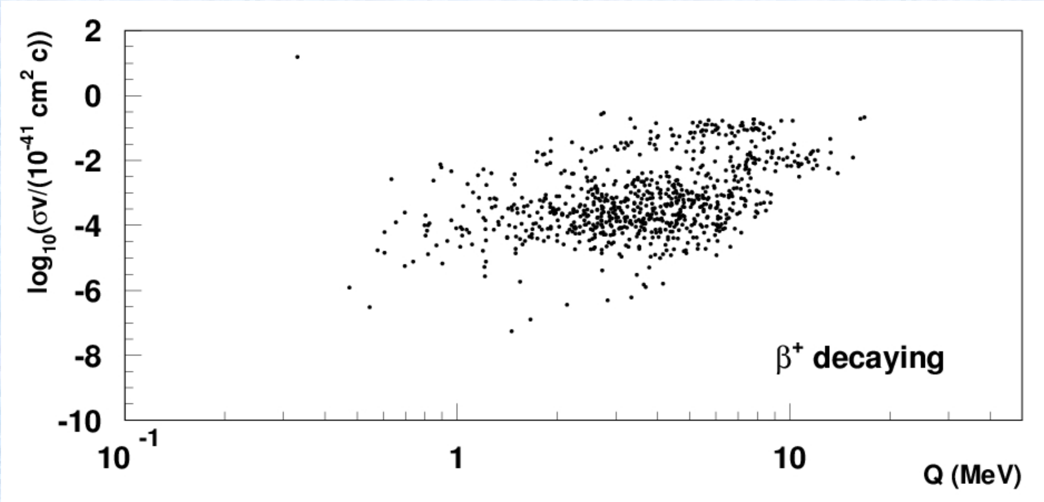
NCB Cross Section Evaluation

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

The case of Tritium

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

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

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

---

Using shape factors ratio

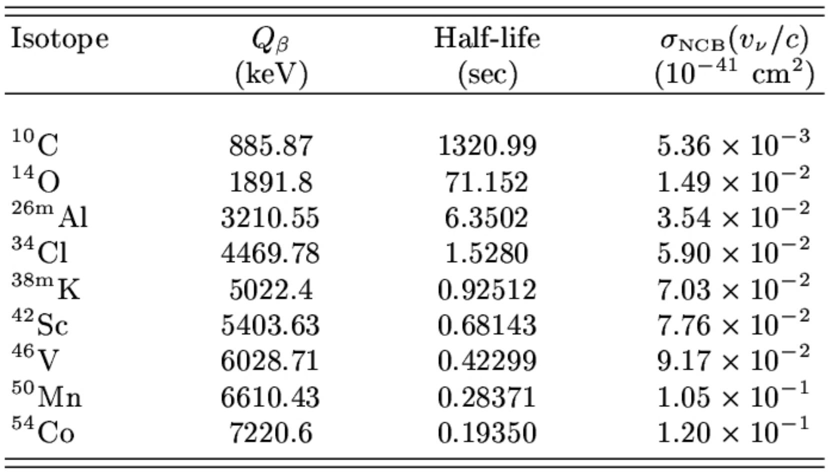
$$\boxed{\sigma_{\rm NCB}\, v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}}$$

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

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

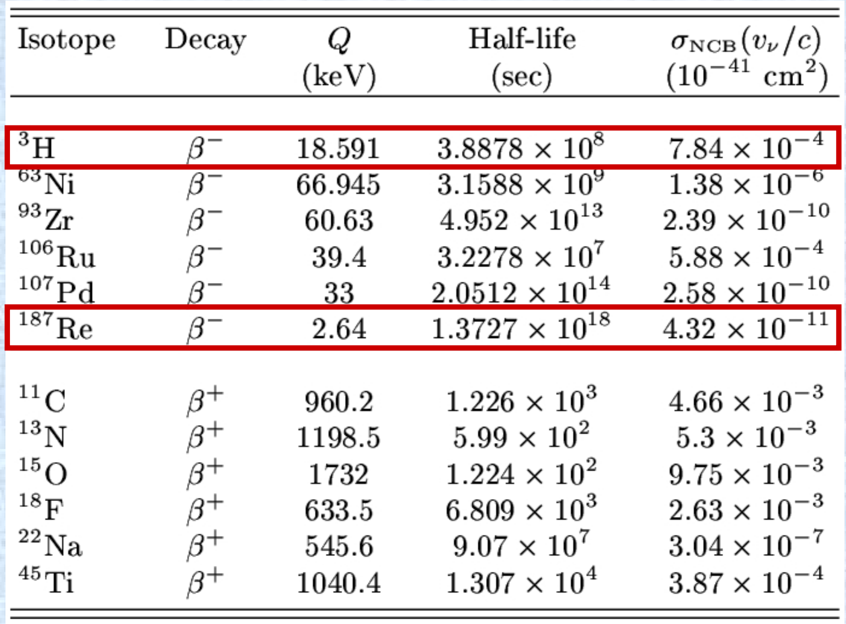
NCB Cross Section Evaluation

specific cases



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}

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)	$\sigma_{\rm NCB}(v_\nu/c)$ (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}

Nuclei having the highest product

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

Relic Neutrino Detection

The cosmological relic neutrino capture rate is given by

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

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

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

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

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

In the case of Tritium:

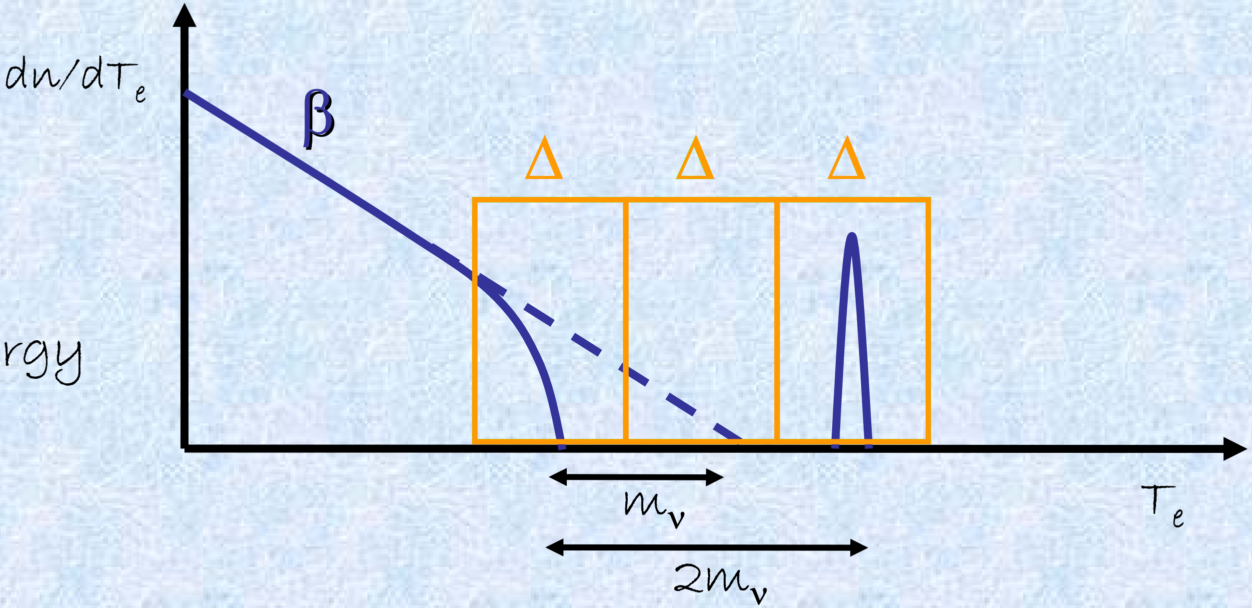
$$\boxed{\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})}$$

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

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

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 $\Delta < m_\nu$

Direct laboratory bounds on m_ν

Searching for non-zero neutrino mass in laboratory experiments

- Tritium beta decay: measurements of endpoint energy

$$^3H \to {}^3He + e^- + \bar{\nu}_e$$

$m(\nu_e) < 2.2$ eV (95% CL) Mainz

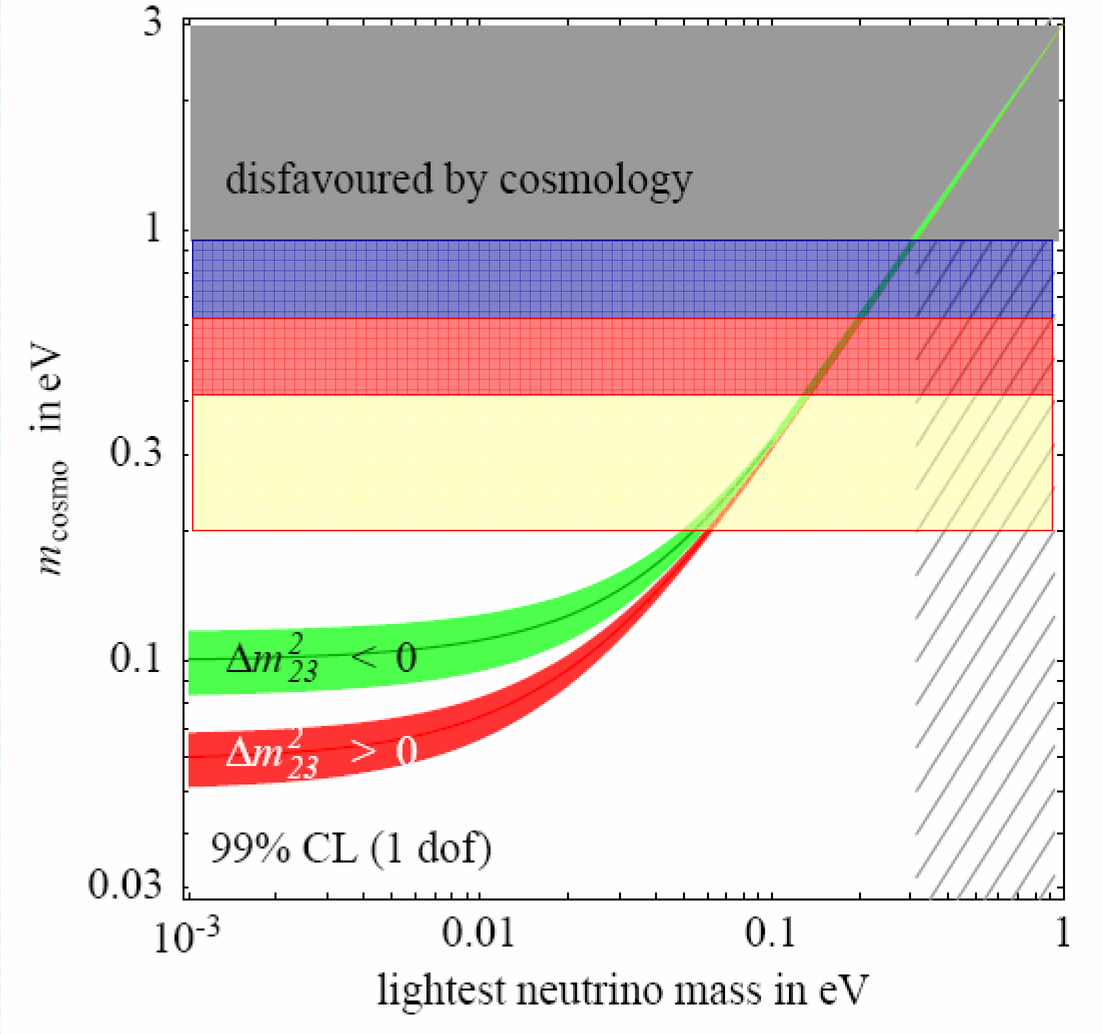
Future experiments (KATRIN) $m(\nu_e) \sim 0.2\text{-}0.3$ eV

- Neutrinoless double beta decay: if Majorana neutrinos

$$(A,Z) \to (A,Z+2) + 2e^-$$

experiments with ^{76}Ge and other isotopes: $|m_{ee}| < 0.4 h_N$ eV

Neutrino masses in 3-neutrino schemes



CMB + galaxy clustering

+ HST, SNI-a…

+ **BAO** and/or bias

+ including Ly-α

J.Lesgourgues & S.Pastor, Phys. Rep. 429 (2006) 307

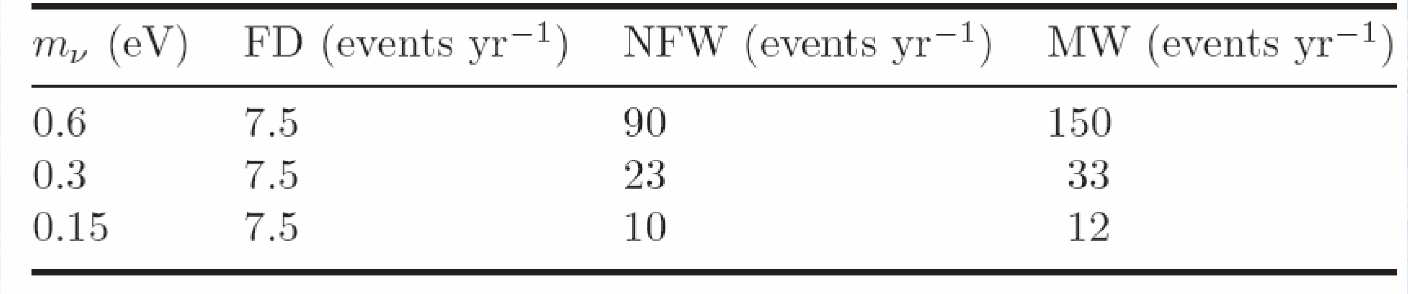
Relic Neutrino Detection

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 5σ 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

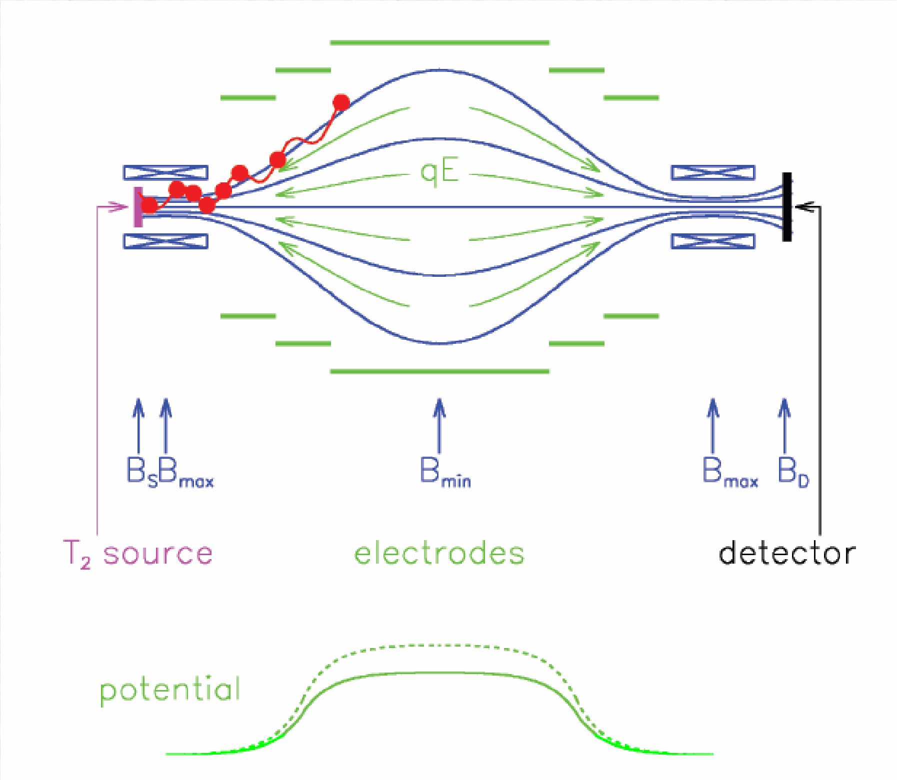
FD = Fermi-Dirac NFW= Navarro,Frenk and White
MW=Milky Way (Ringwald, Wong)

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

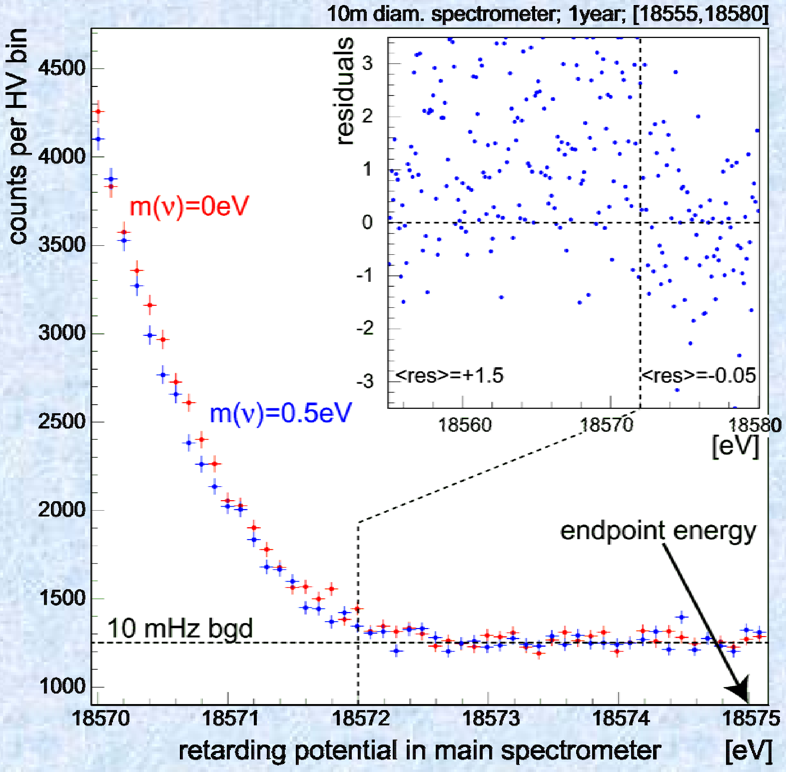


Magnetic Adiabatic Collimator + Electrostatic filter

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

Energy resolution: 2÷3 eV

Total ^{187}Re mass: ~ 100 g

Phase II:

Energy resolution: < 1 eV