Direct Detection of Hot Dark Matter
(Active + Sterile Neutrinos)

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Cosmic neutrino + antineutrino background is predicted by the standard cosmology: it was hot but is almost dark

If it isn't Dark, it doesn't Matter

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CνB Must Be There

Today's matter & energy densities in the Universe (Dunkley et al 09; Komatsu et al 09; Nakamura et al 10): 5-year WMAP + ΛCDM model

Parameter	Value
Hubble parameter h	0.72 ± 0.03
Total matter density $\Omega_{\rm m}$	$\Omega_{\rm m} h^2 = 0.133 \pm 0.006$
Baryon density $\Omega_{\rm B}$	$\Omega_{\rm B} h^2 = 0.0227 \pm 0.0006$
Vacuum energy density $\Omega_{\rm v}$	$\Omega_{\rm v} = 0.74 \pm 0.03$
Radiation density $\Omega_{\rm r}$	$\Omega_{\rm r} h^2 = 2.47 \times 10^{-5}$
Neutrino density Ω_ν	$\Omega_\nu h^2 = \sum m_i / (94 \text{ eV})$
Cold dark matter density $\Omega_{\rm CDM}$	$\Omega_{\rm CDM} h^2 = 0.110 \pm 0.006$

The CMB (t ~ 380 000 years) is already measured today

Is it likely to detect the CνB (t ~ 1 s) in the foreseeable future? ---- important to test the standard cosmology.

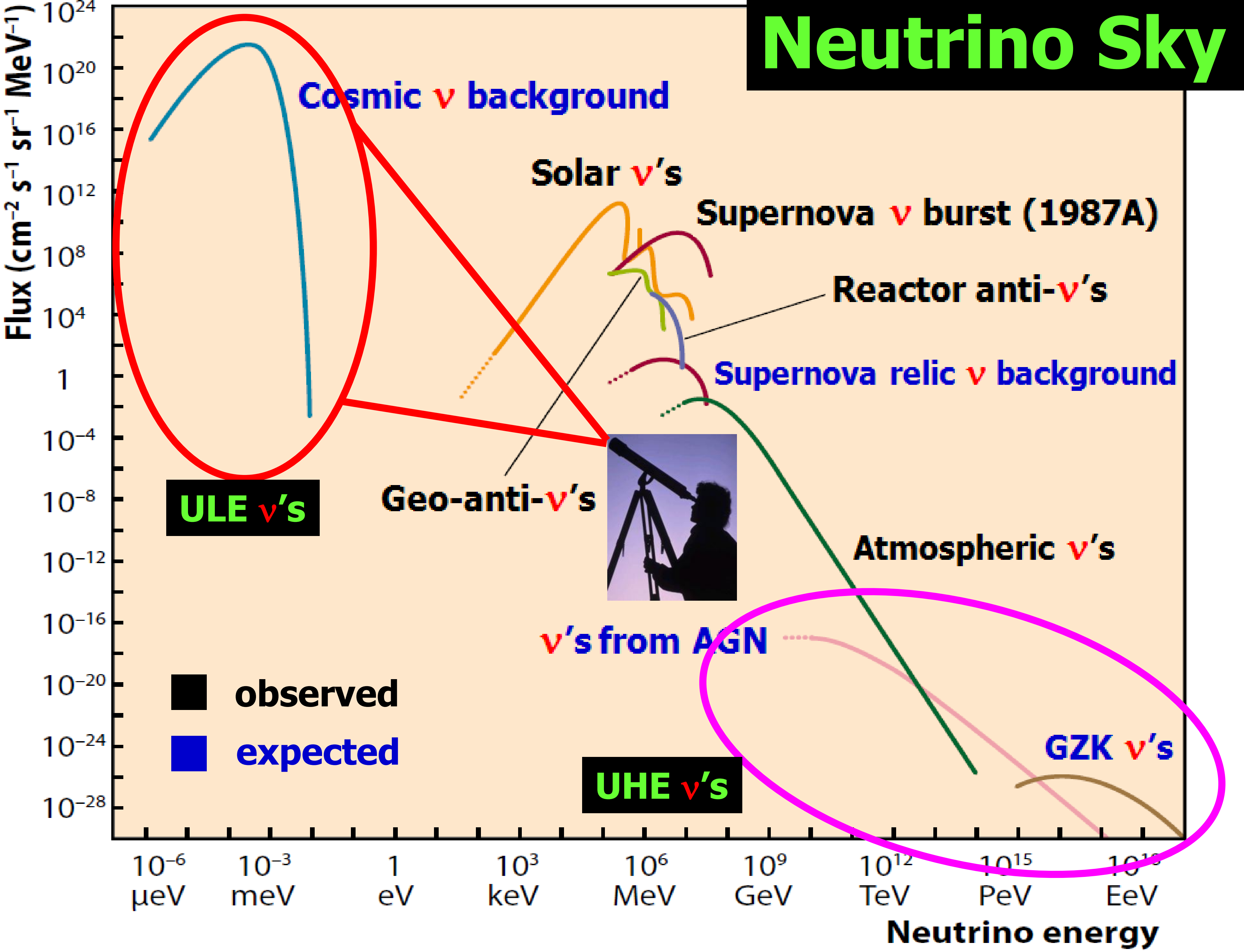
A Naïve (Why Not) Picture

Hot dark matter: CνB is guaranteed but not significant.

Cold dark matter: most likely? At present most popular.

Warm dark matter: suppress the small-scale structures.

Neutrino Sky



Formation of CνB

As $T \sim$ a few MeV in the Universe, the survival relativistic particles were photons, electrons, positrons, neutrinos and antineutrinos.

Electroweak reactions:

$$\gamma + \gamma \rightleftharpoons e^+ + e^- \rightleftharpoons \nu_\alpha + \overline{\nu}_\alpha \quad (\text{for } \alpha = e, \mu, \tau)$$

$$\nu_e + n \rightleftharpoons e^- + p, \overline{\nu}_e + p \rightleftharpoons e^+ + n \qquad \overline{\nu}_e + e^- + p \rightleftharpoons n$$

Neutrinos decoupled from matter:

Weak interactions $\quad \Gamma \sim G_{\rm F}^2 T^5$

Hubble expansion $\quad H \sim \dfrac{\sqrt{g_*} T^2}{M_{\rm Pl}}$

Number density of 6 relic ν's:

$$n_\nu = \frac{9}{11} n_\gamma \approx 336 \left(\frac{T_\gamma}{2.725\ {\rm K}}\right)^3 {\rm cm}^{-3}$$

$\Gamma > H$ $\qquad$ $\Gamma \sim H$ $\qquad$ $\Gamma < H$

ν's in thermal contact with cosmic plasma | ν's not in thermal contact with matter

arrow of time

$T < m_e$ $\qquad$ $e^+ + e^- \to \gamma + \gamma$

neutrino and photon temperatures (blue)

neutrino decoupling

$$T_\nu = T_\gamma$$

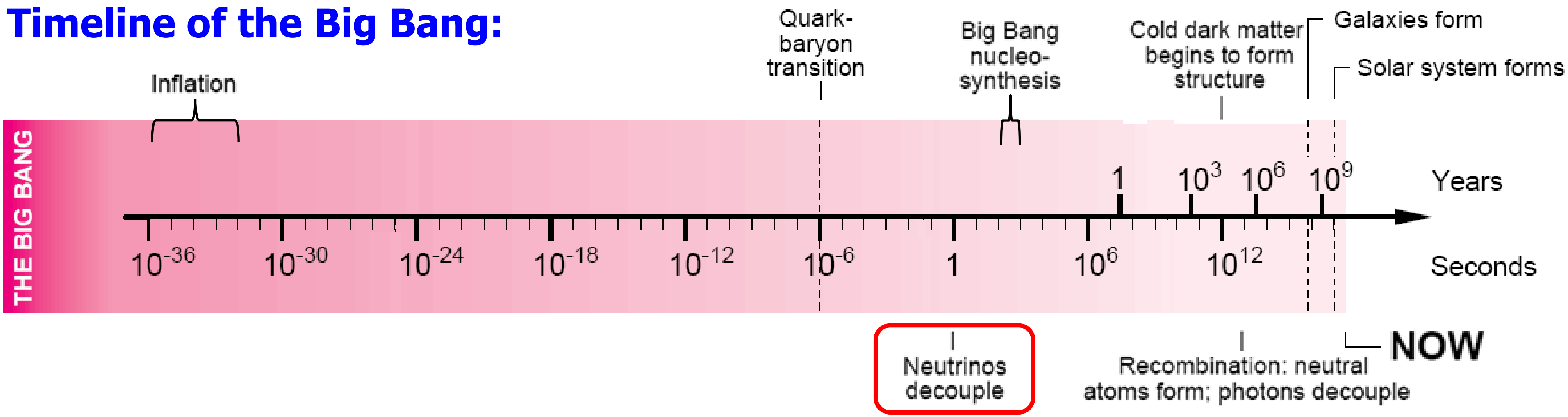
$$T_{\rm fr} \sim \left(\frac{\sqrt{g_*}}{G_{\rm F}^2 M_{\rm Pl}}\right)^{1/3} \sim 1\ {\rm MeV}$$

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

Witness / Participant

CMB and LSS: the existence of relic neutrinos had an impact on the epoch of matter-radiation equality, their species and masses could affect the CMB anisotropies and large scale structures (Wong's talk)

Timeline of the Big Bang:



At the time of recombination (t ~ 380 000 yrs):

$$\rho_\gamma + \rho_\nu = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_\nu^{\mathrm{CMB}} \right]$$

The CνB contribution to the total energy density of the Universe today

relativistic

$$\Omega_\nu = \frac{21}{8} \left(\frac{4}{11} \right)^{4/3} \Omega_\gamma \approx 1.68 \times 10^{-5} h^{-2}$$

non-relativistic

$$\Omega_\nu = \frac{8\pi G_{\mathrm{N}}}{3H^2} \sum_i m_i \left(n_{\nu_i} + n_{\overline{\nu}_i} \right) \approx \frac{1}{94\ h^2\ \mathrm{eV}} \sum_i m_i$$

Detection of CνB

Way 1: CνB-induced mechanical effects on Cavendish-type torsion balance;

Way 2: Capture of relic ν's on radioactive β-decaying nuclei (Weinberg 62);

Way 3: *Z*-resonance annihilation of UHE cosmic ν's and relic ν's (Weiler 82).

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

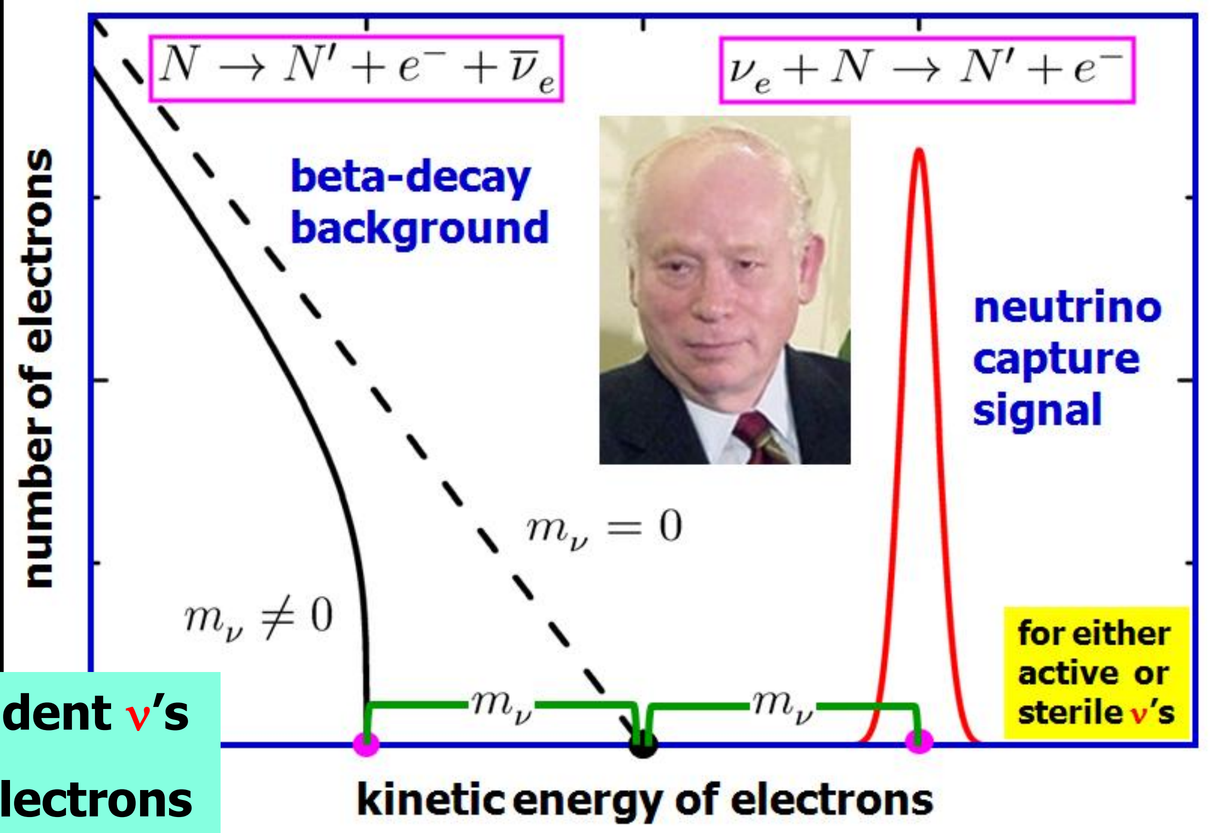
$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4}\ \mathrm{eV}$$

At least 2 ν's cold today

How to detect ULE ν's ?

(Irvine & Humphreys, 83)

Relic neutrino capture on β-decaying nuclei



- no energy threshold on incident ν's
- mono-energetic outgoing electrons

Example

Salient feature: the cross section of a capture reaction scales with $\frac{c}{v_\nu}$ so that the number of events converges to a constant for $v_\nu \to 0$:

$$\sigma(\nu_e N) \cdot \left.\frac{v_\nu}{c}\right|_{v_\nu \to 0} = \text{const.}$$

e.g. $$\sigma(\nu_e {}^3\mathrm{H}) \cdot \left.\frac{v_\nu}{c}\right|_{v_\nu \to 0} \simeq (7.84 \pm 0.03) \times 10^{-45} \mathrm{cm}^2$$

(Cocco et al 07, Lazauskas et al 08).

$$\boxed{\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-}$$

Capture rate: (1 MCi = 100 g = $N_\mathrm{T} \approx 2.1 \times 10^{25}$ tritium atoms)

$$\frac{\mathrm{d}\mathcal{N}_{\mathrm{C}\nu\mathrm{B}}}{\mathrm{d}T_e} \approx 6.5 \sum_i |V_{ei}|^2 \frac{n_{\nu_i}}{\langle n_{\nu_i} \rangle} \cdot \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e^i)^2}{2\sigma^2}\right] \mathrm{yr}^{-1}\,\mathrm{MCi}^{-1}$$

$$T_e^i = Q_\beta + E_{\nu_i}$$

Background: (the tritium β-decay)

$$E_e = T_e' + m_e \qquad \langle n_{\nu_i} \rangle \approx \langle n_{\bar{\nu}_i} \rangle \approx 56\ \mathrm{cm}^{-3}$$

$$\frac{\mathrm{d}\mathcal{N}_\beta}{\mathrm{d}T_e} \approx 5.55 \int_0^{Q_\beta - \min(m_i)} \mathrm{d}T_e' \left\{ N_\mathrm{T} \frac{G_\mathrm{F}^2 \cos^2\theta_\mathrm{C}}{2\pi^3} F(Z,\, E_e) \sqrt{E_e^2 - m_e^2}\, E_e (Q_\beta - T_e') \right.$$
$$\left. \times \sum_i \left[|V_{ei}|^2 \sqrt{\left(Q_\beta - T_e'\right)^2 - m_i^2}\, \Theta(Q_\beta - T_e' - m_i) \right] \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e')^2}{2\sigma^2}\right] \right\}$$

Energy resolution (Gaussian function) :

$$\Delta = 2\sqrt{2\ln 2}\,\sigma \approx 2.35482\,\sigma$$

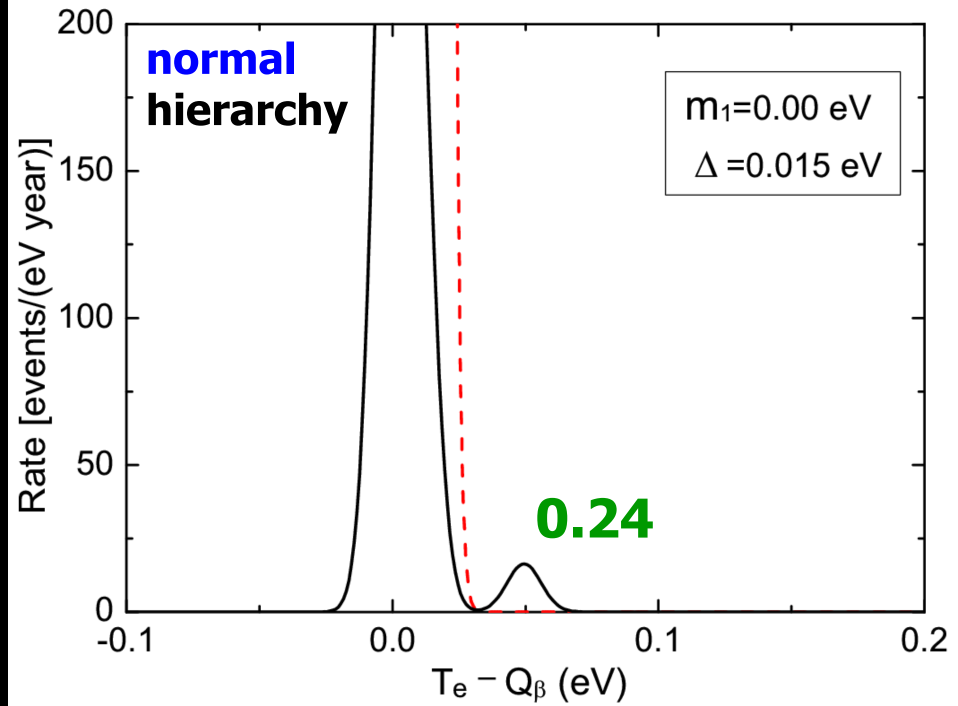
Illustration

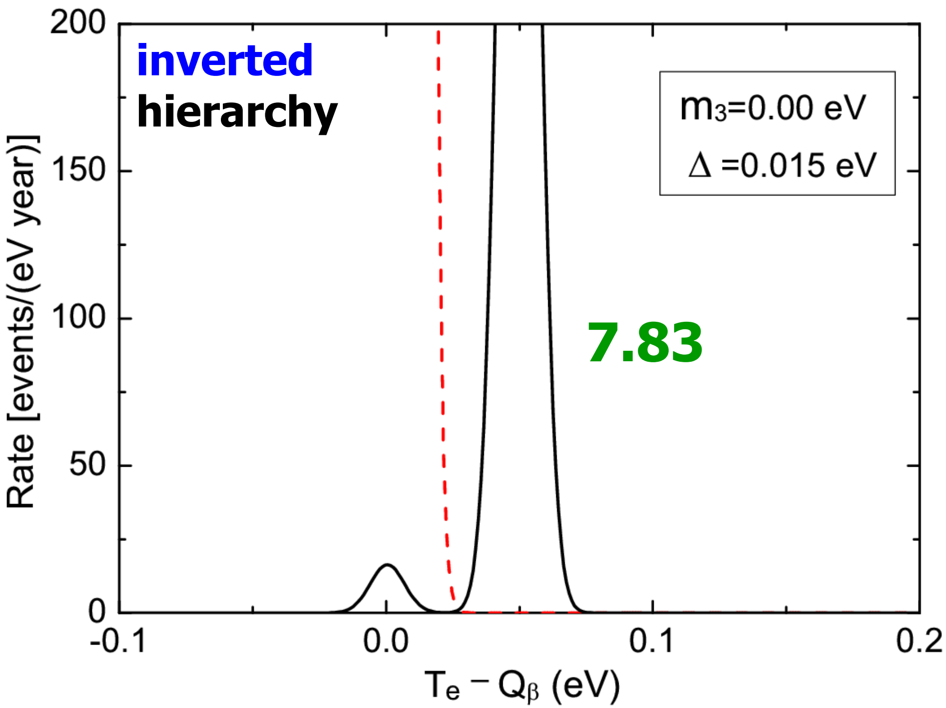
Target mass: 100 g tritium atoms

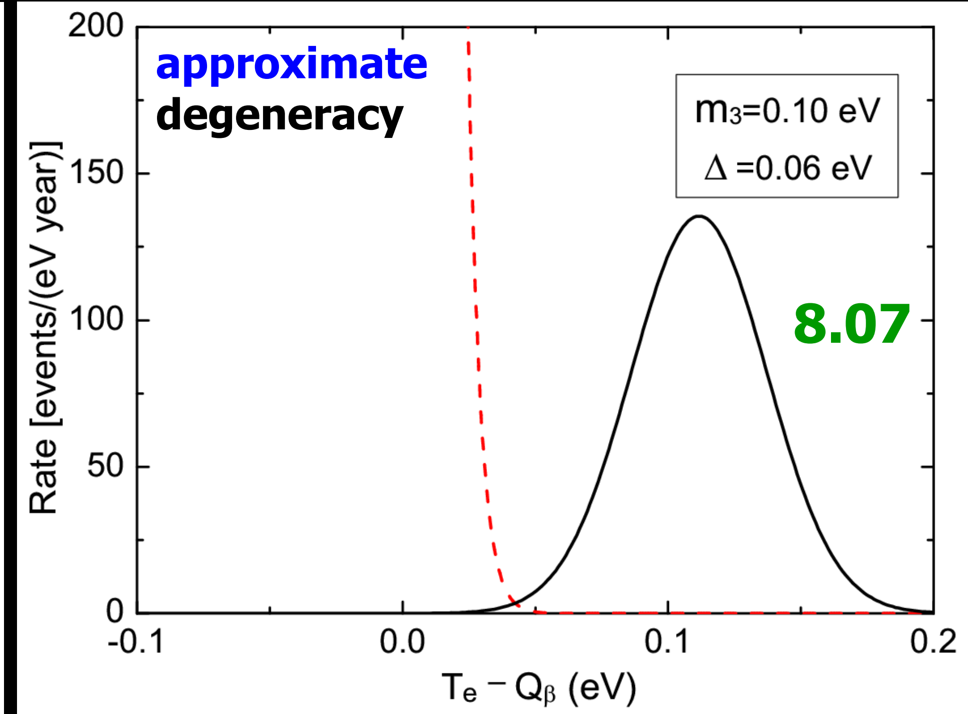
Input θ(13) : 10 degrees

Number of events per year: ~ 8

Flavor effects are quite important (Blennow 08; Li, Xing 10, 11)





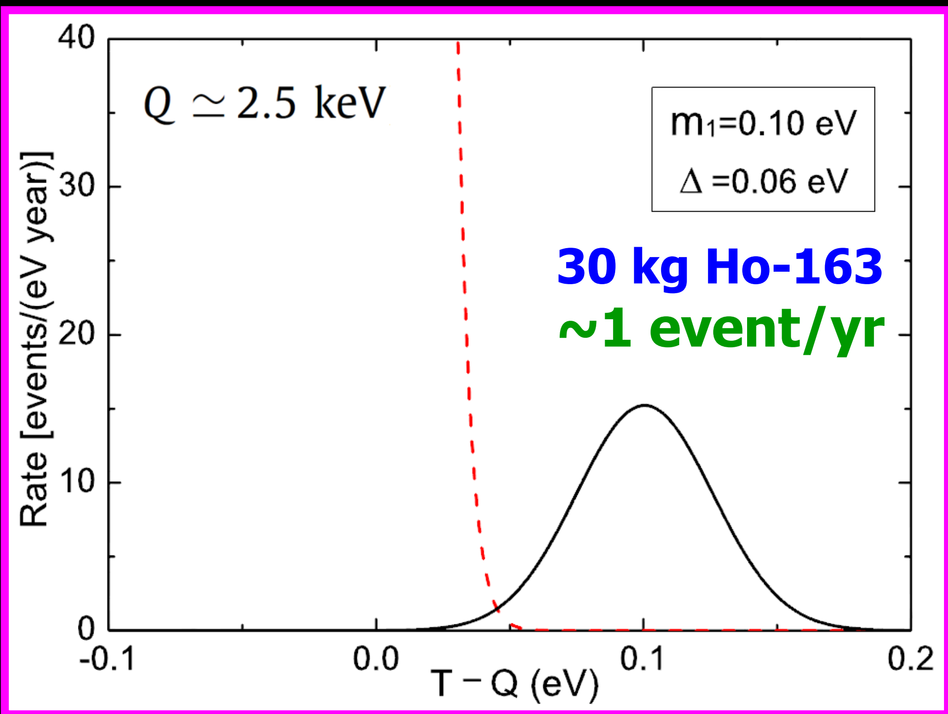


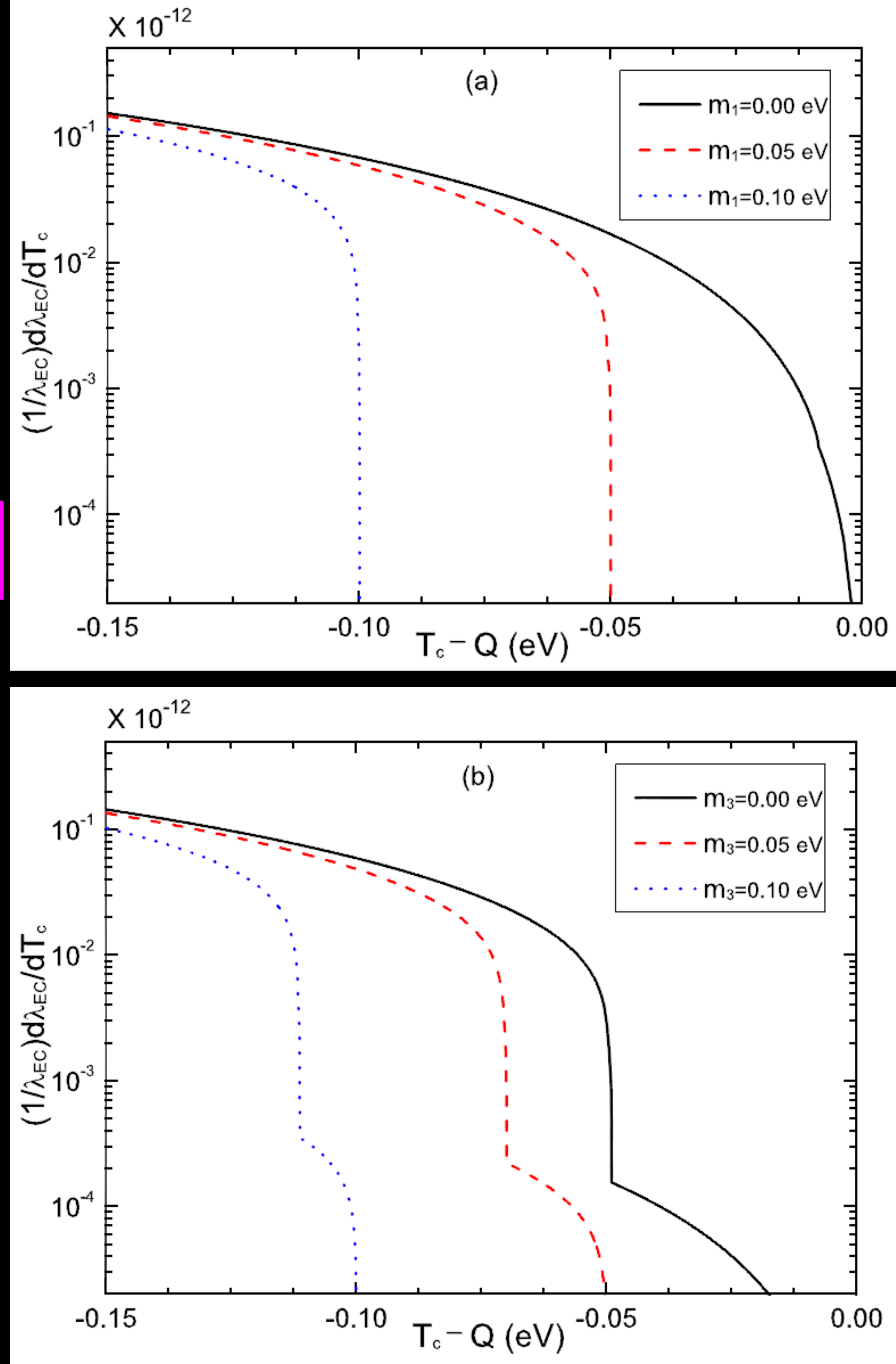
Cosmic anti-ν Background?

Relic antineutrino capture on EC-decaying Ho-163 nuclei.

$$\overline{\nu}_e + {}^{163}\mathrm{Ho} + e^-_{i(\mathrm{shell})} \rightarrow {}^{163}\mathrm{Dy}^*_i \rightarrow {}^{163}\mathrm{Dy} + E_i$$

(Lusignoli, Vignati 11; Li, Xing 11)

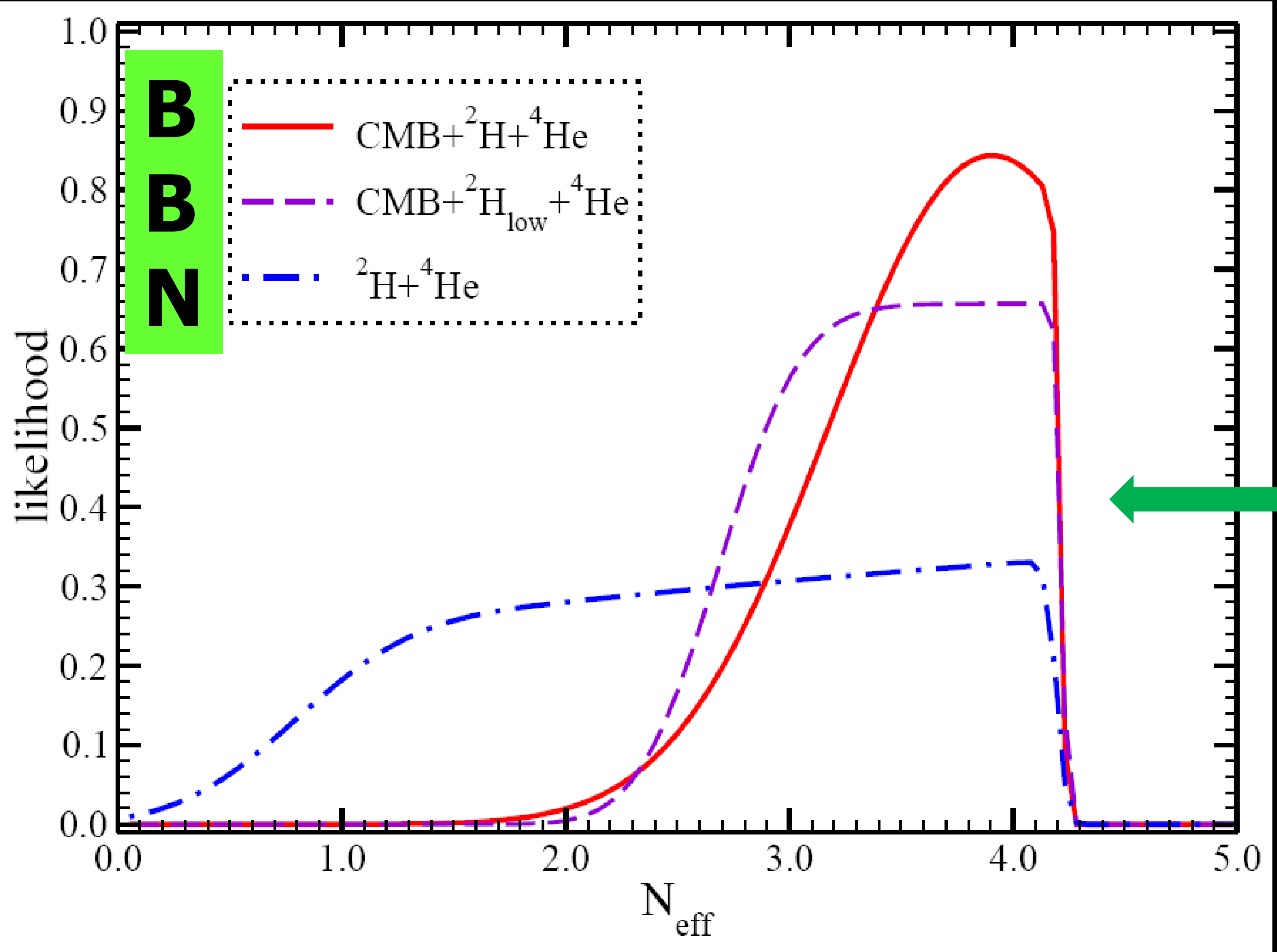




Sub-eV Sterile ν's?

BBN: current data only allow **one** sub-eV **sterile** neutrino;

CMB: current data can allow **two** sub-eV **sterile** neutrinos.



G. Mangano,
P. Serpico,
arXiv:1103.1261

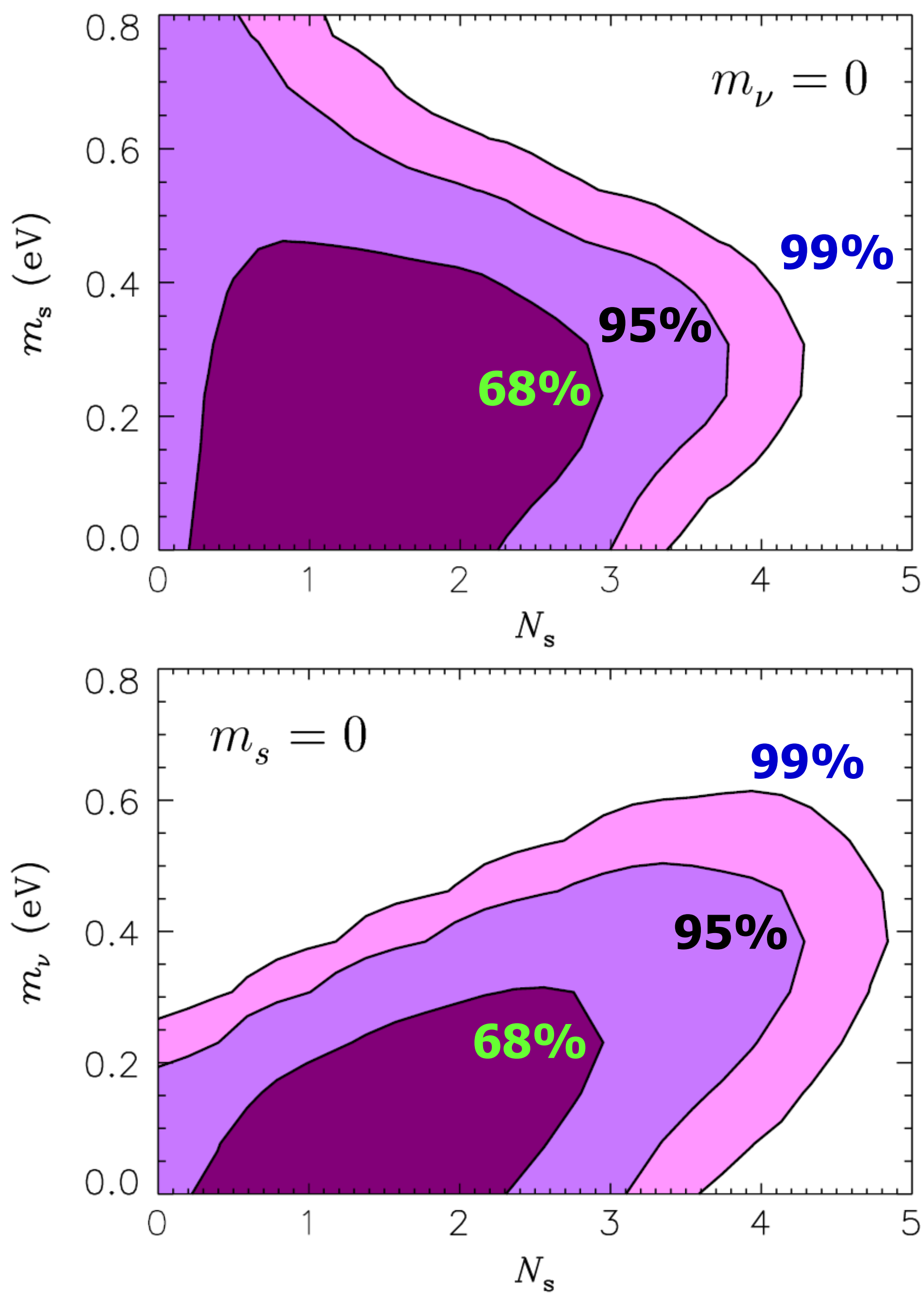
$N_{\rm eff} < 4.2$

(95% C.L.)

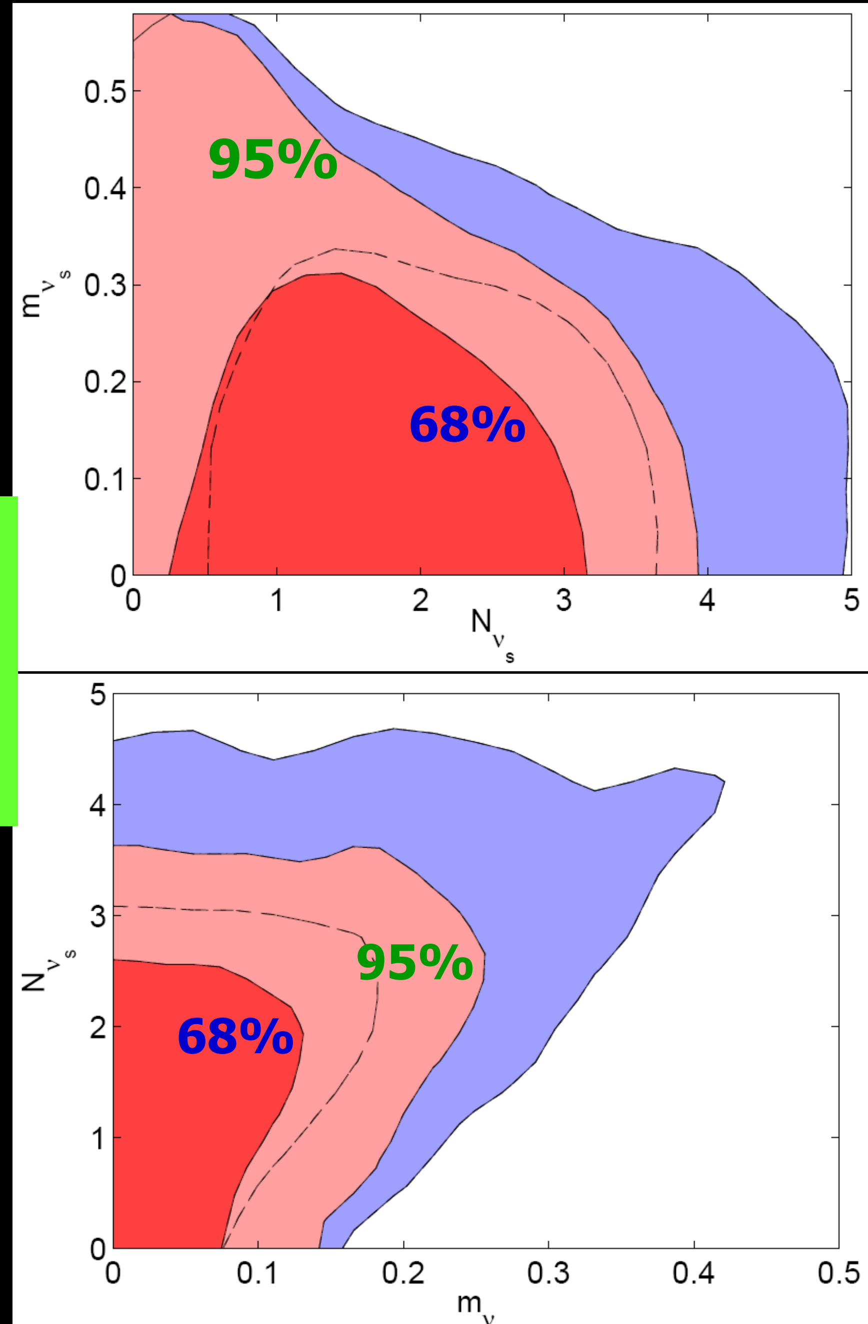
The sharp cut-off is due to a He-4 abundance upper bound (<0.2631).

$N_{\rm eff}^{\rm SM} = 3.046$

Hamann et al, arXiv:1006.5276; 1108.4136 **Giusarma et al, arXiv:1102.4774**



CMB

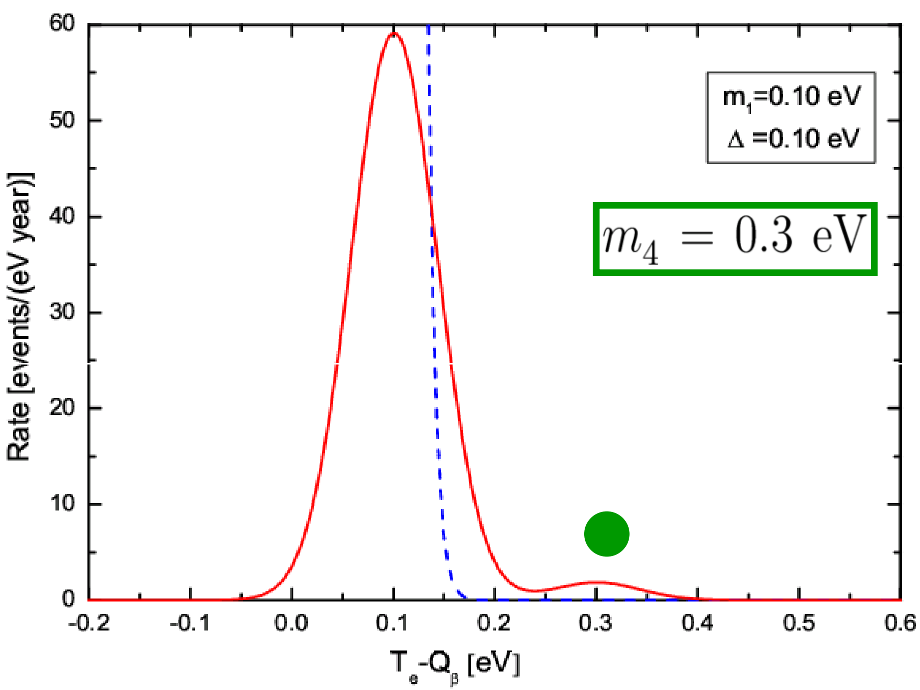


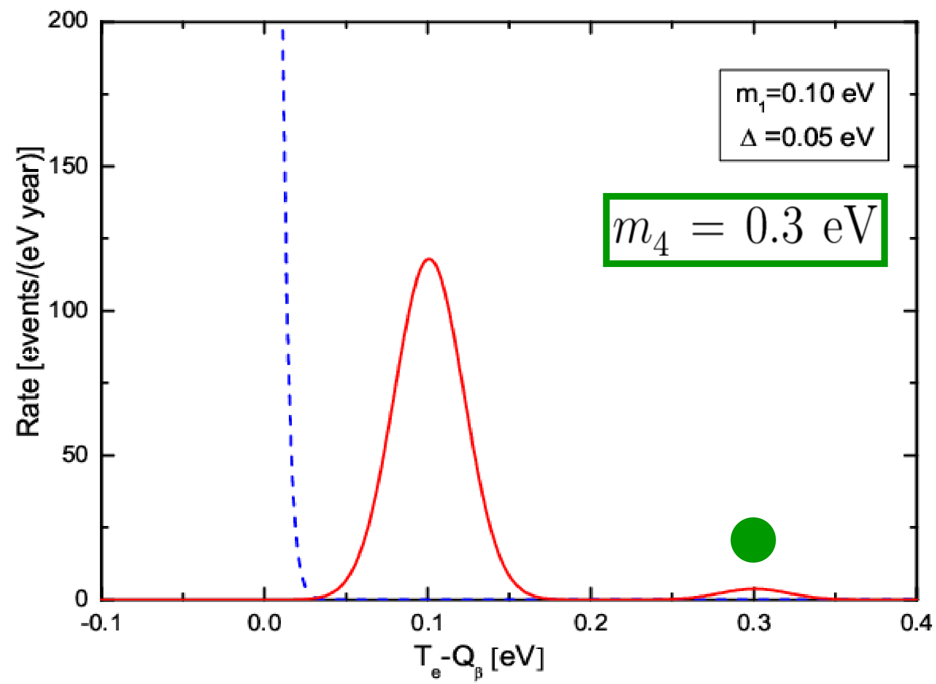
(3+1) Scheme

Besides the CMB + BBN hints, the LSND + MiniBOONE anomalies and the reactor antineutrino anomaly also hint at 1 or 2 sub-eV sterile ν's.

They could be thermally excited in the early Universe via oscillations or collisions with active ν's; they are now non-relativistic; and their number density per species is expected to equal that of active ν's.

Input: $|V_{e1}| \approx 0.804\ , \ \ |V_{e2}| \approx 0.542\ , |V_{e3}| \approx 0.171\ , |V_{e4}| \approx 0.174$ (Li, Xing, Luo 10)





Overdensity

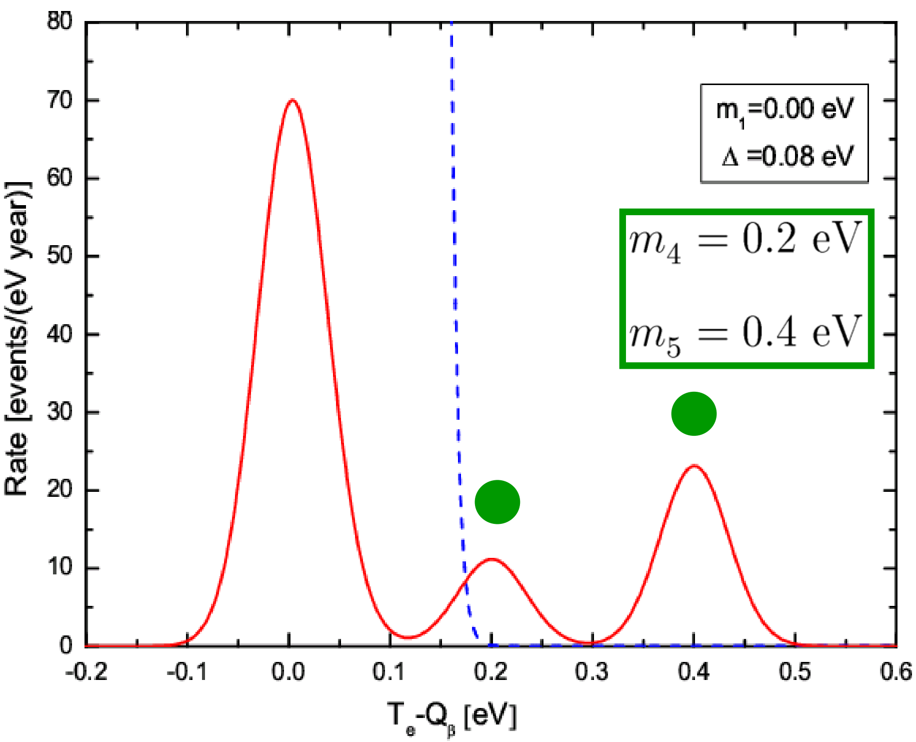
Gravitational clustering: Those cosmic ν's with velocities smaller than the escape velocity of a given structure can be bound to it. So larger GC effects for heavier ν's around the Earth (Ringwald, Wong 04).

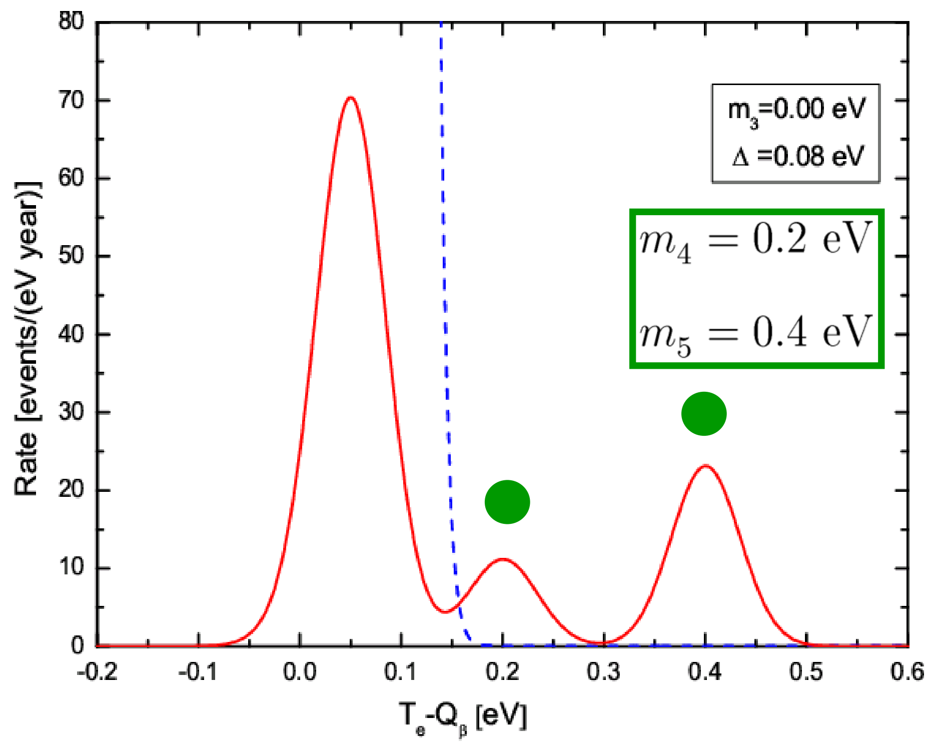
The (3+2) scheme:

$$\frac{n_{\nu_1}}{\langle n_{\nu_i}\rangle} \approx \frac{n_{\nu_2}}{\langle n_{\nu_i}\rangle} \approx \frac{n_{\nu_3}}{\langle n_{\nu_i}\rangle} \approx 1 \,, \qquad \frac{n_{\nu_5}}{\langle n_{\nu_i}\rangle} \approx 2\frac{n_{\nu_4}}{\langle n_{\nu_i}\rangle} \approx 10$$

Input:

$$|V_{e1}| \approx 0.792 \,, \ |V_{e2}| \approx 0.534 \,, |V_{e3}| \approx 0.168 \,, |V_{e4}| \approx 0.171 \,, |V_{e5}| \approx 0.174$$





Summary

----- CνB: a test of cosmology as early as t ~ 1 s after the Big Bang, but a direct measurement is extremely difficult.

----- Weinberg's idea works in principle, but in practice it suffers from small target mass, low ν number density, ...

e.g., KATRIN's tritium mass $\leq$ 0.1 mg, toooooo small

----- Sterile ν's as hot dark matter (sub-eV) might not be impossible, and they could be detected in the same way.

----- Cosmic anti-ν background could also be detected by using the same idea and EC-decaying nuclei as the target.

In practice, this seems more difficult (Vignati's talk)

The dream to detect hot DM is so remote that a good idea is needed.

L. Pauling: the best way to have a good idea is to have a lot of ideas.