Light neutrinos in Cosmology: a short review

Picture from Hubble ST

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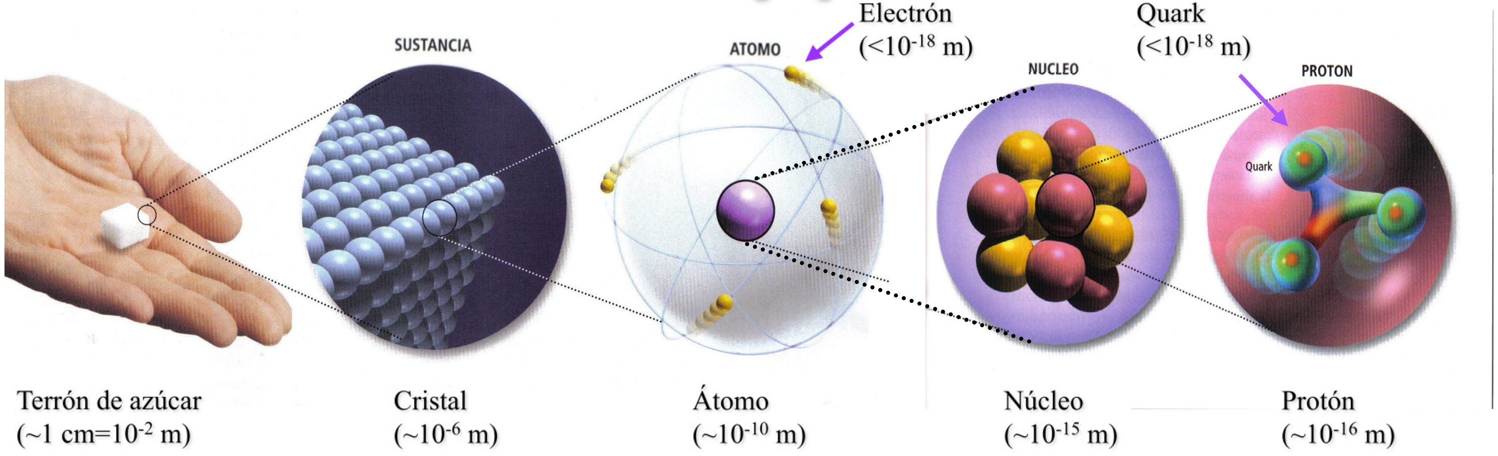
AHEP
Astroparticle and High Energy Physics Group

CSIC
Consejo Superior de Investigaciones Científicas

Vniversitat de València

Elementary particles



	Quarks		Leptons	
	Charge +2/3	Charge −1/3	Charge −1	Charge 0
1st Family	Up u	Down d	Electron e	Neutrino-e ν_e
2nd Family	Charm c	Strange s	Muon μ	Neutrino-μ ν_μ
3rd Family	Top t	Bottom b	Tau τ	Neutrino-τ ν_τ

Gravitation

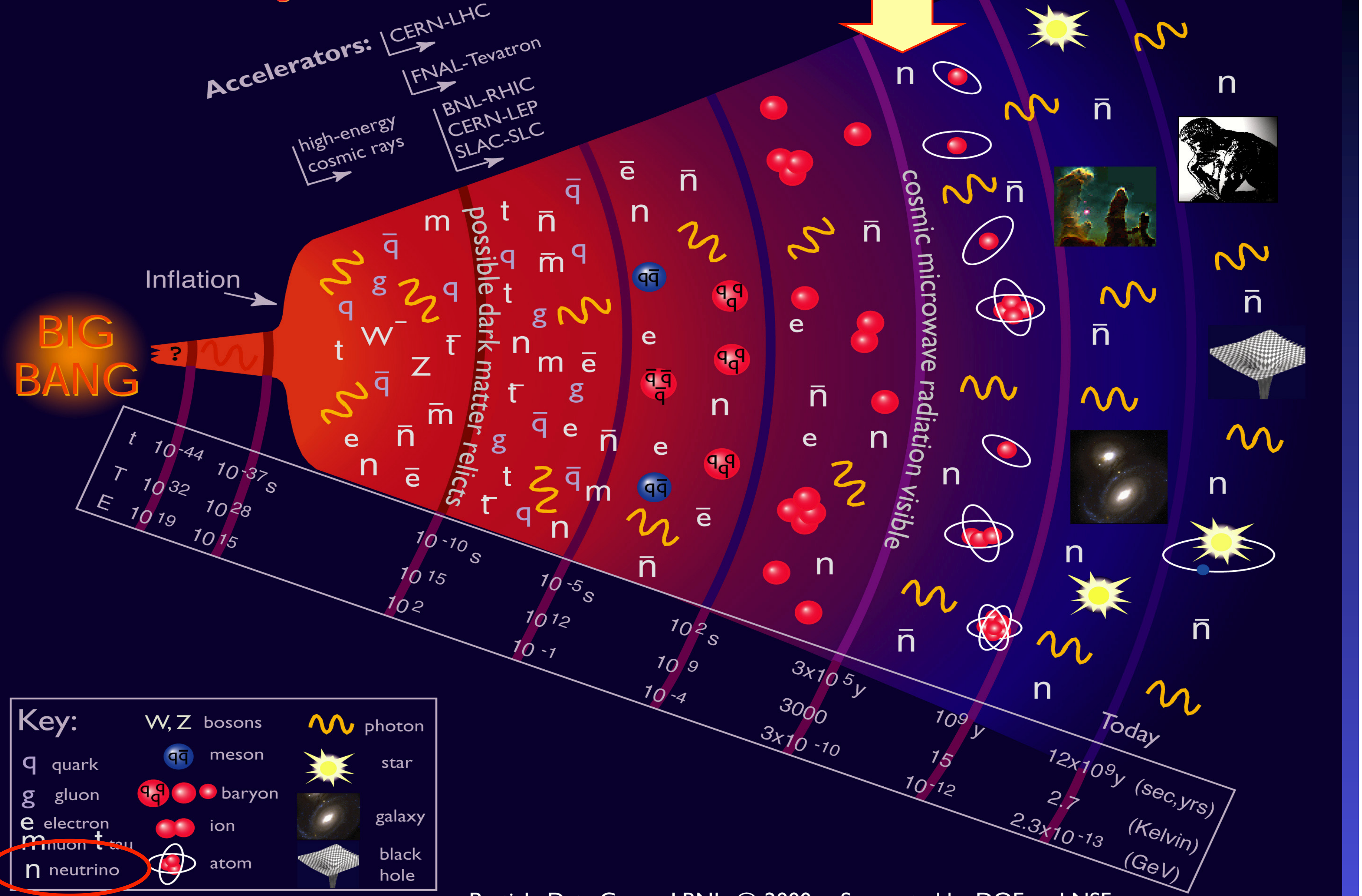
W, Z Weak nuclear

Forces: γ Electromagnetism

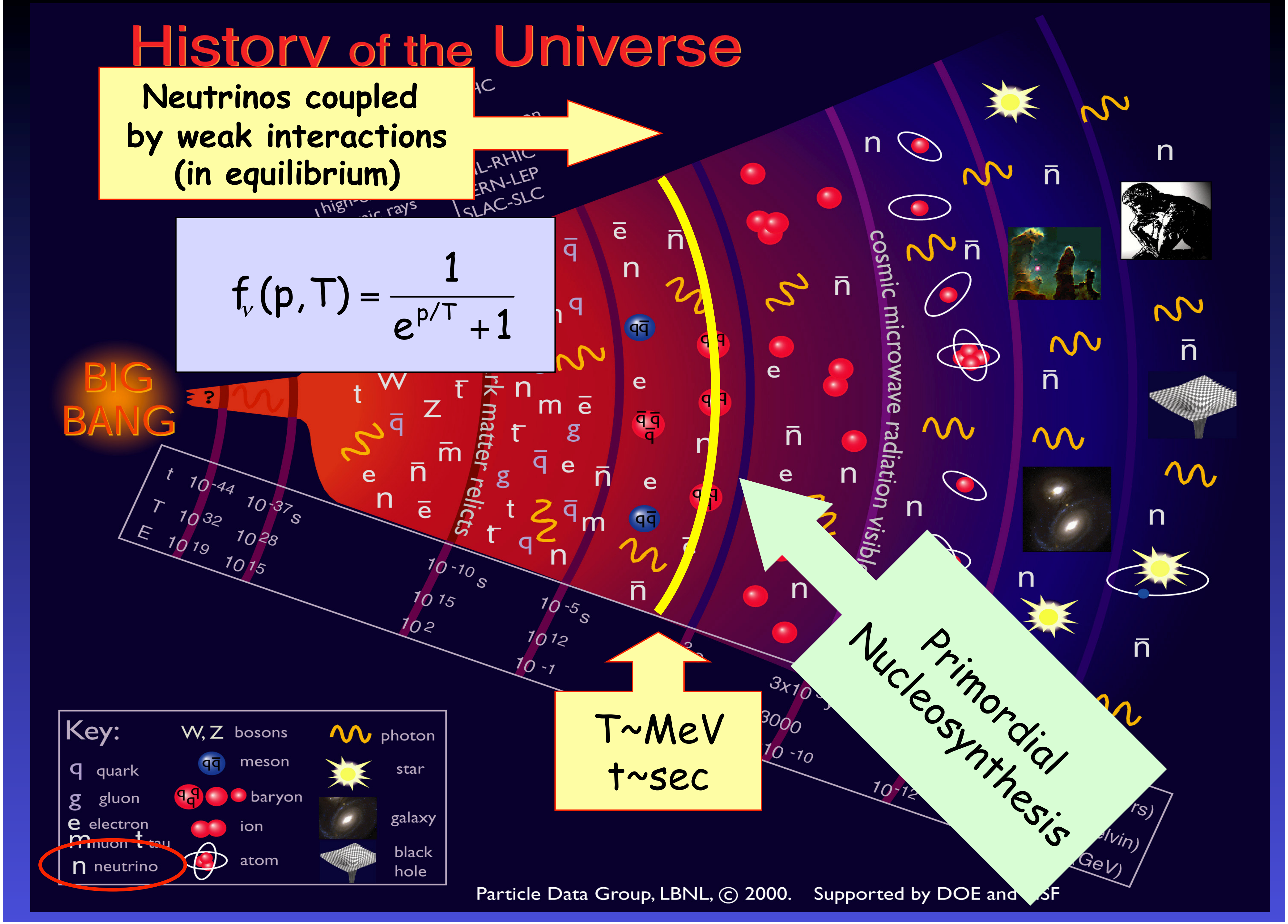
g Strong nuclear

History of the Universe

This is a neutrino!



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



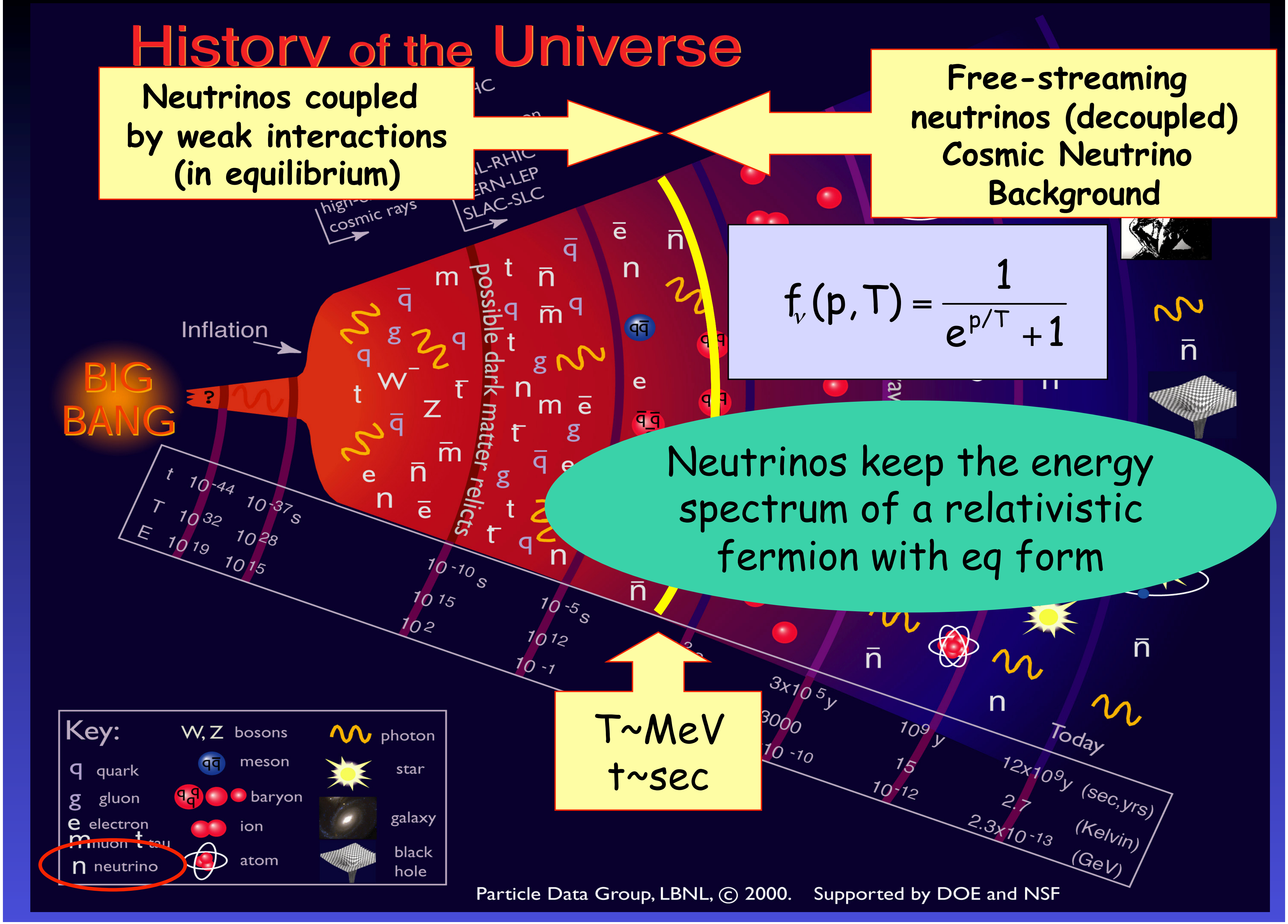
Neutrinos coupled
by weak interactions
(in equilibrium)

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

T~MeV
t~sec

Primordial
Nucleosynthesis

History of the Universe



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Neutrinos coupled by weak interactions (in equilibrium)

Free-streaming neutrinos (decoupled) Cosmic Neutrino Background

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

Neutrinos keep the energy spectrum of a relativistic fermion with eq form

T~MeV
t~sec

The Cosmic Neutrino Background

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

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

- Energy density

$$\rho_{\nu_i} = \int \sqrt{p^2 + m^2_{\nu_i}} \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) \rightarrow \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T^4_{CMB}$$ Massless

The Cosmic Neutrino Background

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

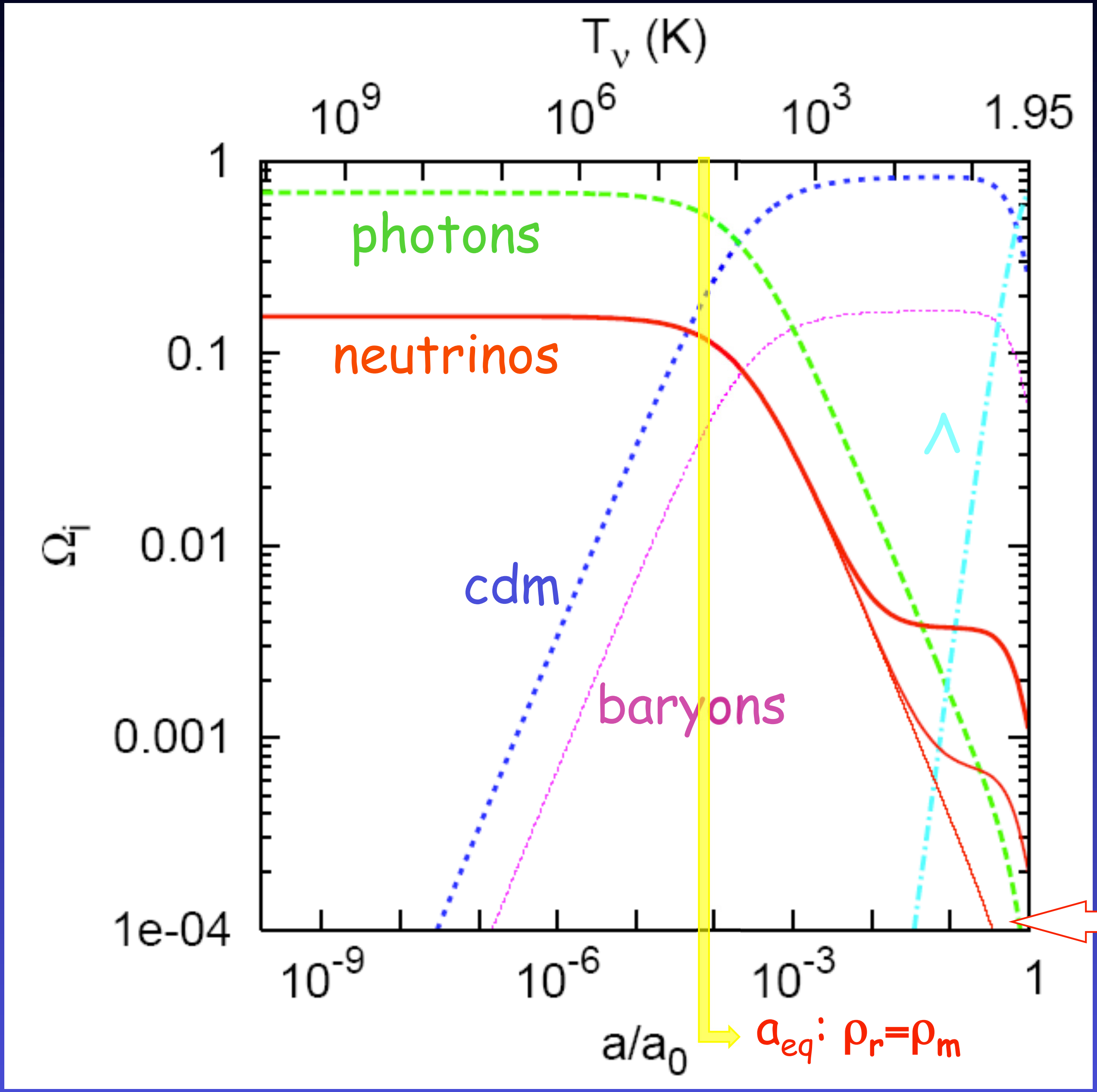
At present 112 $(\nu + \bar{\nu})$ cm^{-3} per flavour

- Energy density

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 \simeq 1.7 \times 10^{-5}$$ Massless

Evolution of the background densities: 1 MeV → now



$\Omega_i = \rho_i/\rho_{crit}$

m≈ 0 eV

Relativistic particles in the Universe

At $T<m_e$, the radiation content of the Universe is

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

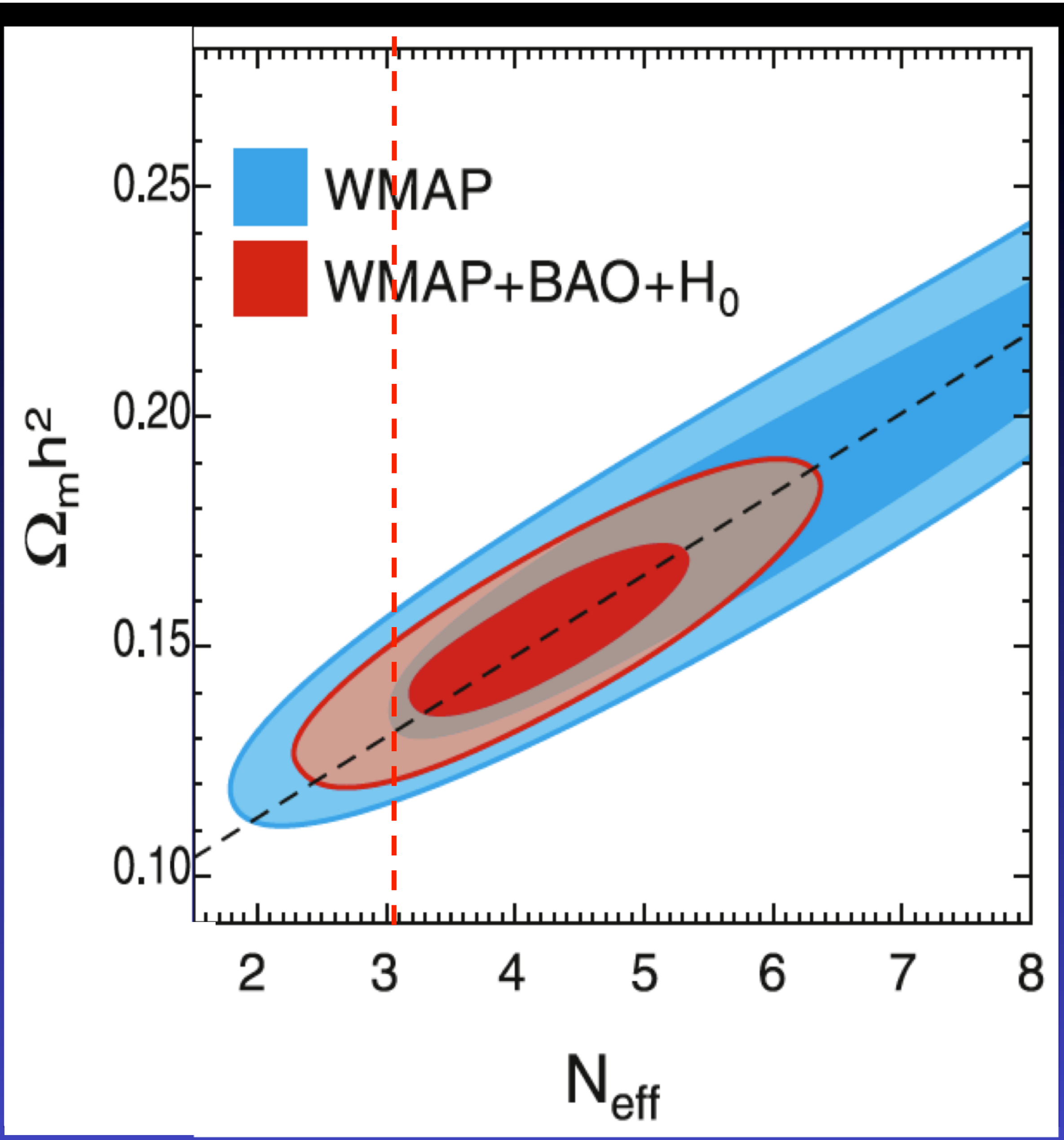
Effective number of relativistic neutrino species

Traditional parametrization of ρ stored in relativistic particles

N_{eff} is a way to measure the ratio $\dfrac{\rho_\nu + \rho_x}{\rho_\gamma}$

- standard neutrinos only: $N_{eff} \simeq 3$ (3.04)

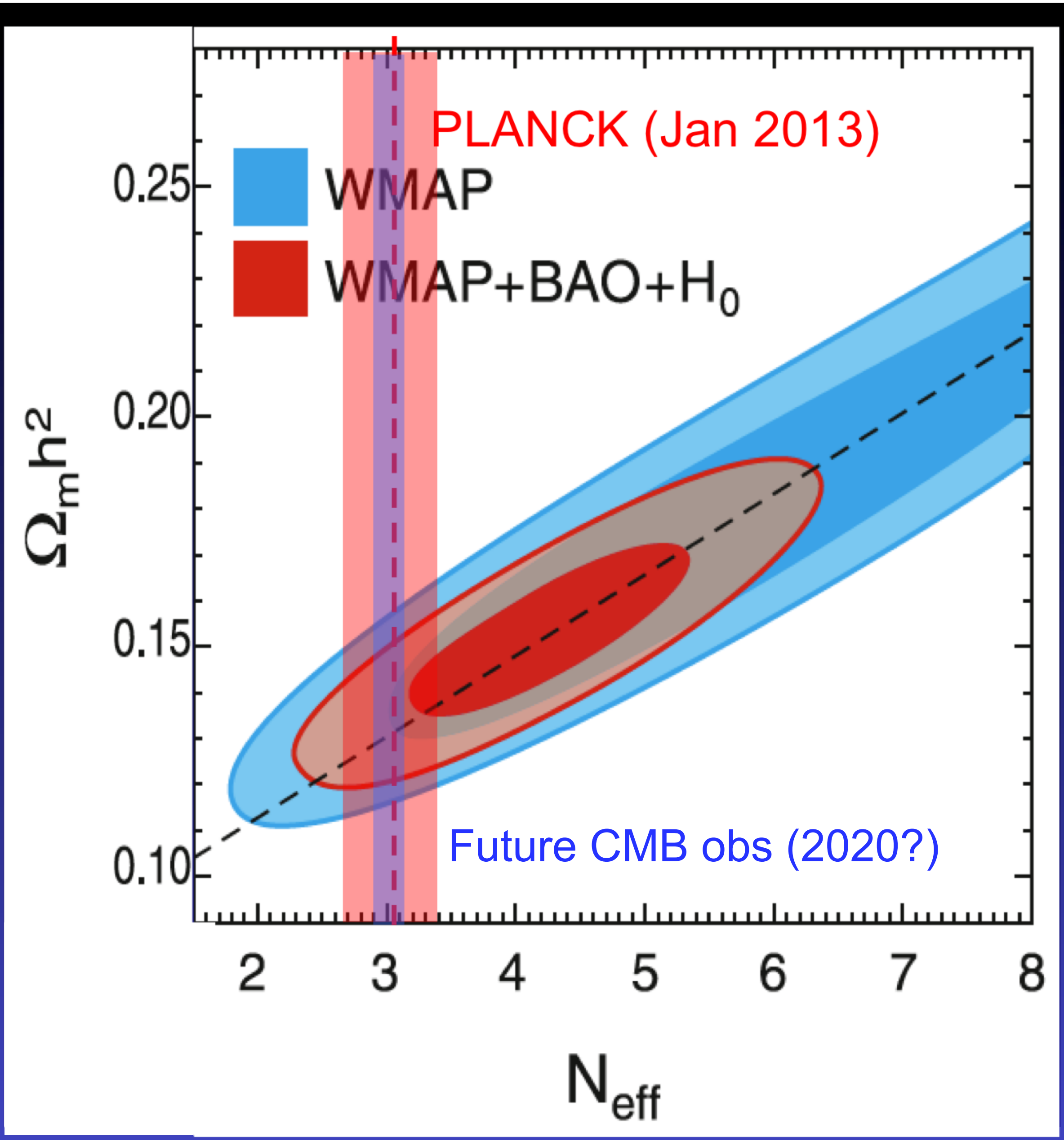
allowed range for N_{eff}



WMAP [7-year], arXiv:1001.4538

$2.7 < N_{eff} < 6.2$ (WMAP+BAO+H_0, 95%CL)

allowed range for N_{eff}



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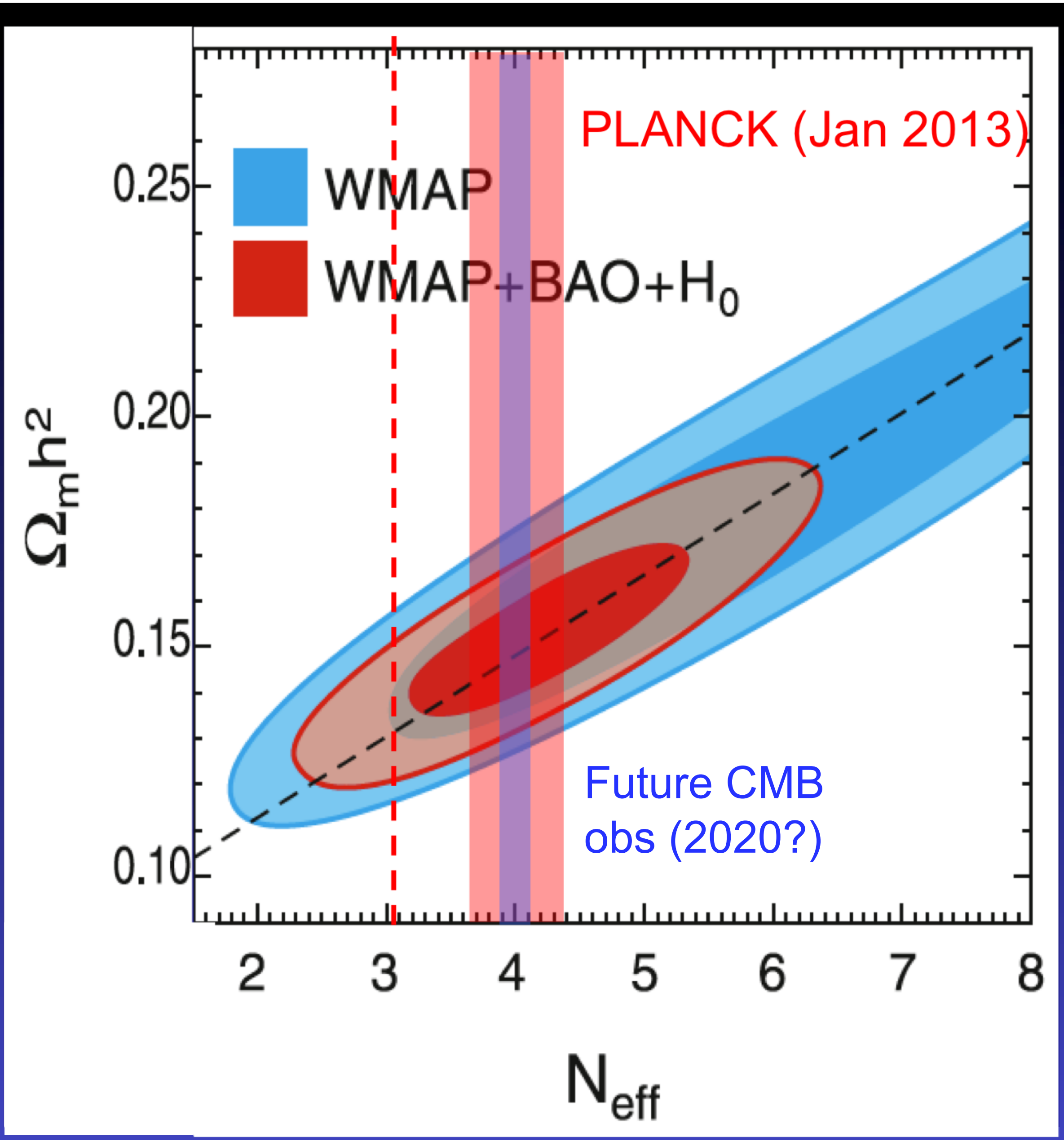
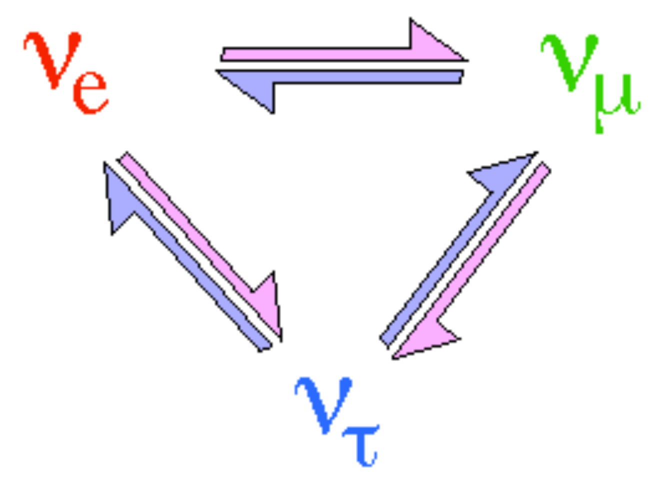


WMAP [7-year], arXiv:1001.4538

$2.7 < N_{eff} < 6.2$ (WMAP+BAO+H_0, 95%CL)

We know that flavour neutrino oscillations exist

From present evidences of oscillations from experiments measuring atmospheric, solar, reactor and accelerator neutrinos



$$(e,\mu,\tau) \leftrightarrow (\nu_1,\nu_2,\nu_3)$$

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL}, \quad (\alpha = e,\mu,\tau)$$

Evidence for Particle Physics beyond the Standard Model !

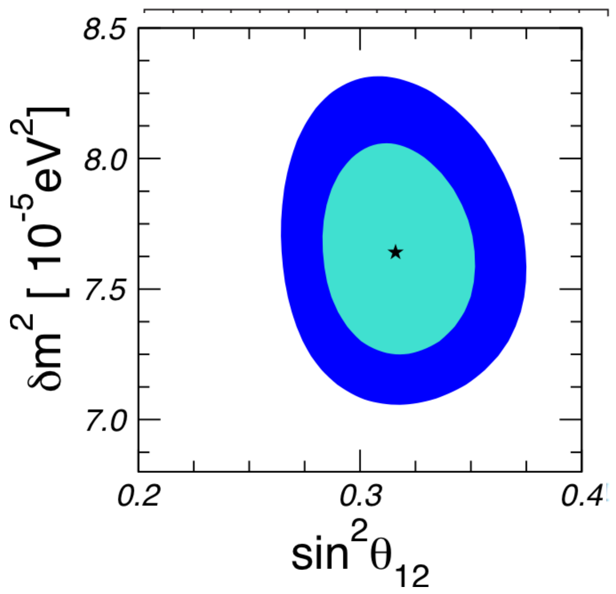
Mixing Parameters...

From present evidences of oscillations from experiments measuring atmospheric, solar, reactor and accelerator neutrinos

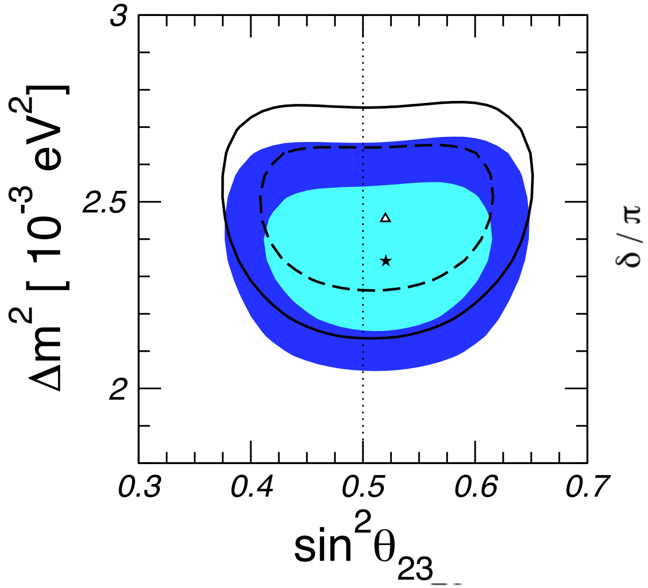
$$\begin{array}{c|ccc|} & \nu_1 & \nu_2 & \nu_3 \\ \nu_e & c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \nu_\mu & -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ \nu_\tau & s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array}$$

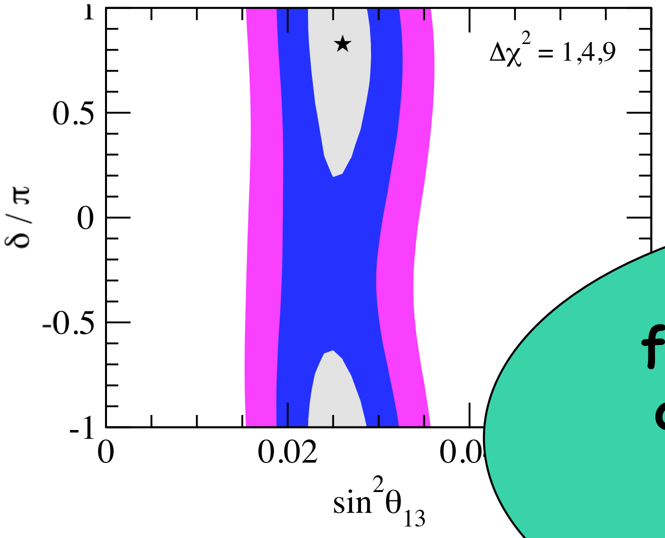
$$\times\ \mathrm{diag}(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1)\ .$$

Mixing Parameters...



parameter	best fit $\pm1\sigma$	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	7.62 ± 0.19	7.27–8.01	7.12–8.20
Δm^2_{31} [10^{-3}eV^2]	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41–0.62 0.42–0.62	0.39–0.64
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	0.019–0.033 0.020–0.034	0.015–0.036 0.016–0.037
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	$0 - 2\pi$	$0 - 2\pi$



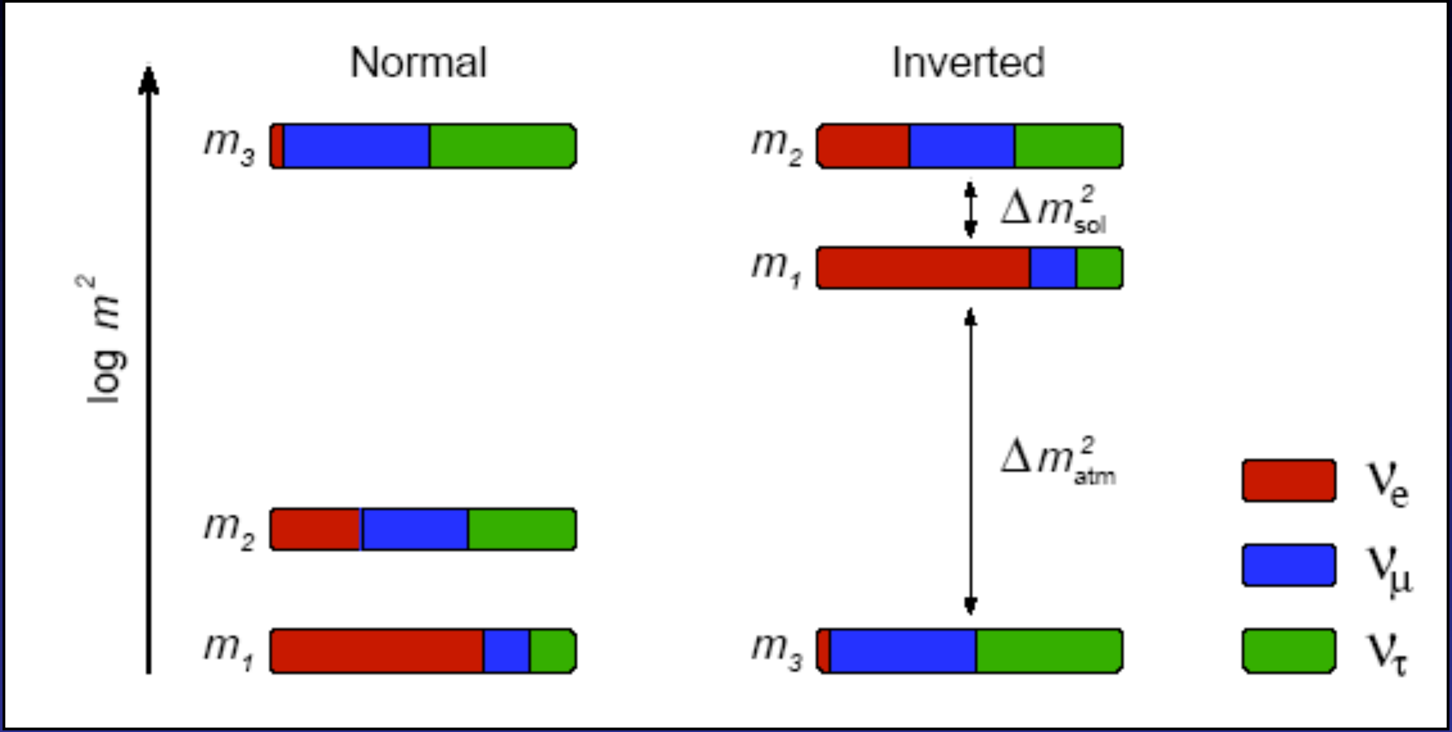


Tórtola, Vanegas & Valle, arXiv:1205.4018

[see also Fogli et al, arXiv:1205.5254, and others]

Present evidences for flavour neutrino oscillations: data on solar, atmospheric, reactor and accelerator neutrinos

... and neutrino masses



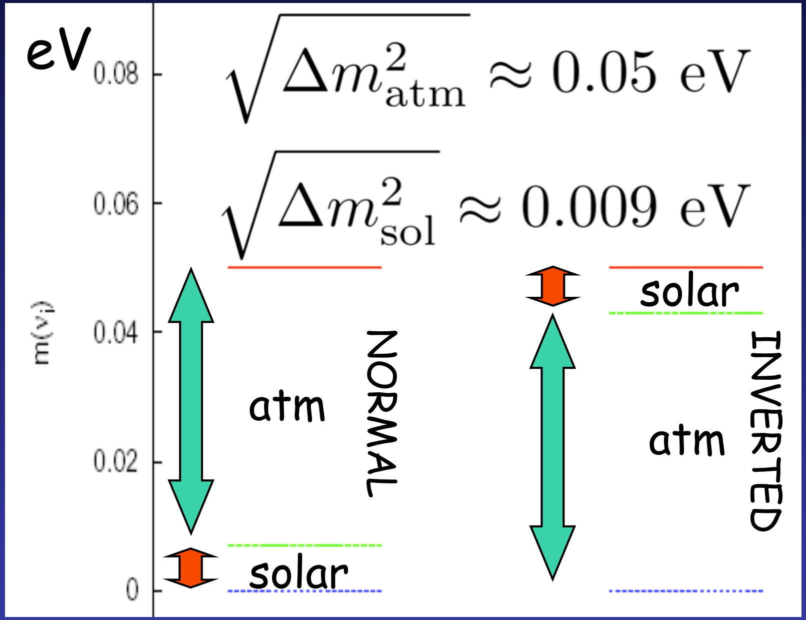
Possible neutrino mass hierarchy patterns

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{iL}, \quad (\alpha = e, \mu, \tau)$$

Present evidences for flavour neutrino oscillations: data on solar, atmospheric, reactor and accelerator neutrinos

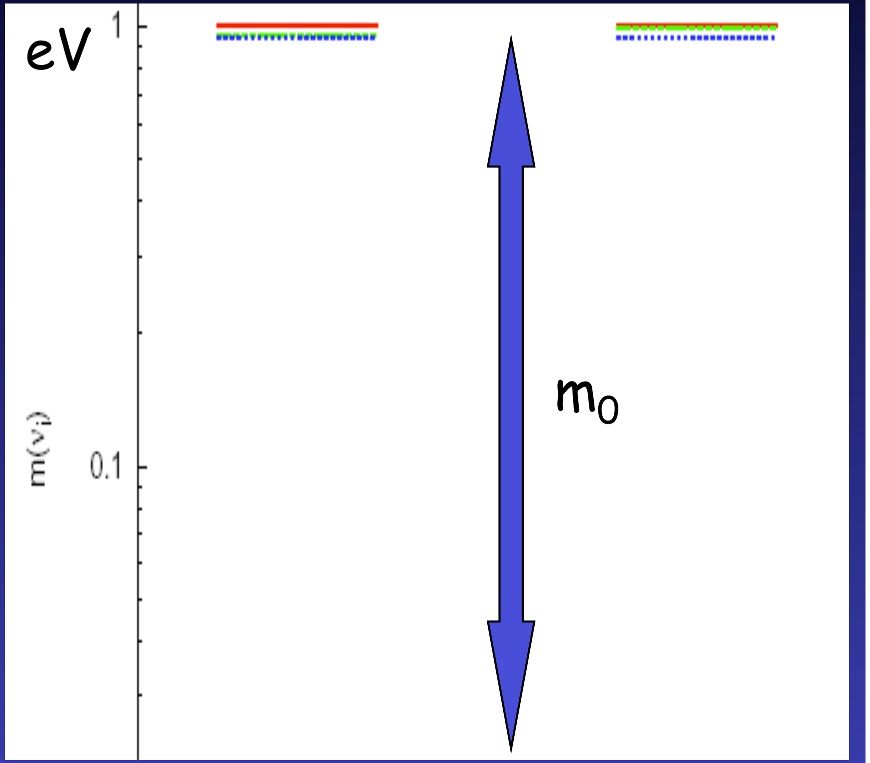
… and neutrino masses

Data on flavour oscillations do not fix the absolute scale of neutrino masses



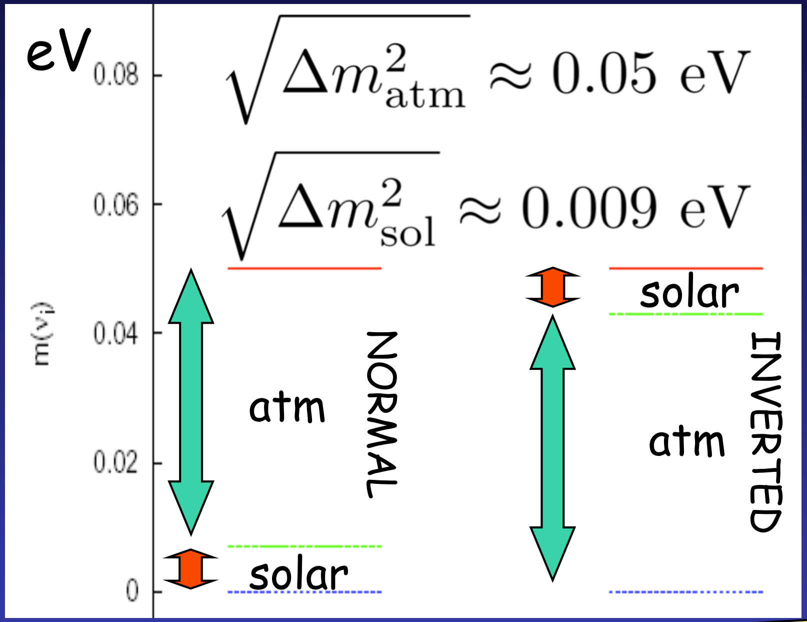
$$\sqrt{\Delta m^2_{\rm atm}} \approx 0.05\ {\rm eV}$$

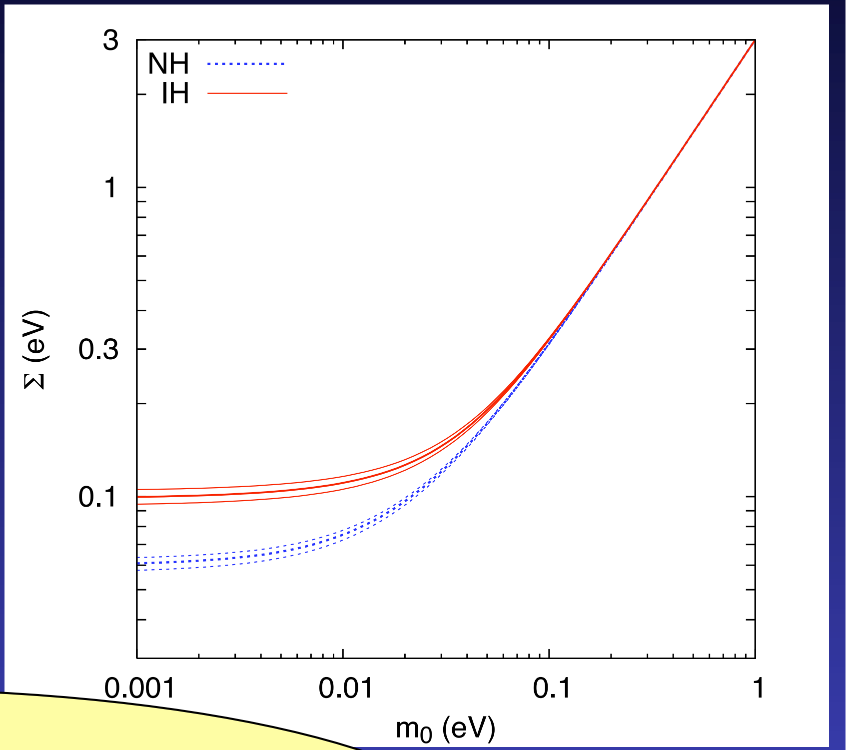
$$\sqrt{\Delta m^2_{\rm sol}} \approx 0.009\ {\rm eV}$$



... and neutrino masses

Data on flavour oscillations do not fix the absolute scale of neutrino masses





What is the value of m_0 ?

The Cosmic Neutrino Background

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

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

- Energy density

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

The Cosmic Neutrino Background

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

- Number density

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

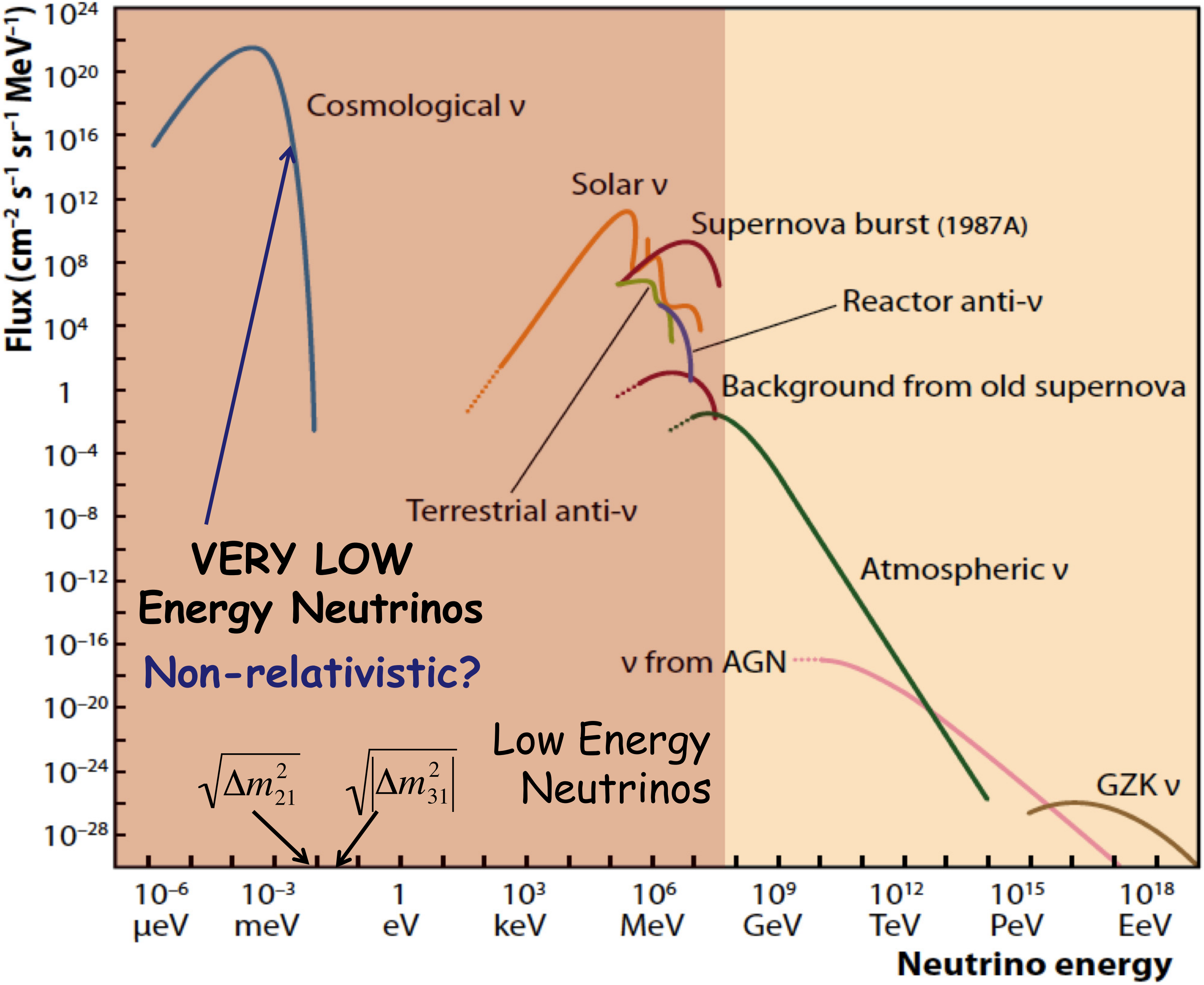
- Energy density

Contribution to the energy density of the Universe

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

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1\ \mathrm{eV}}$$ Massive

$m_\nu \gg T$



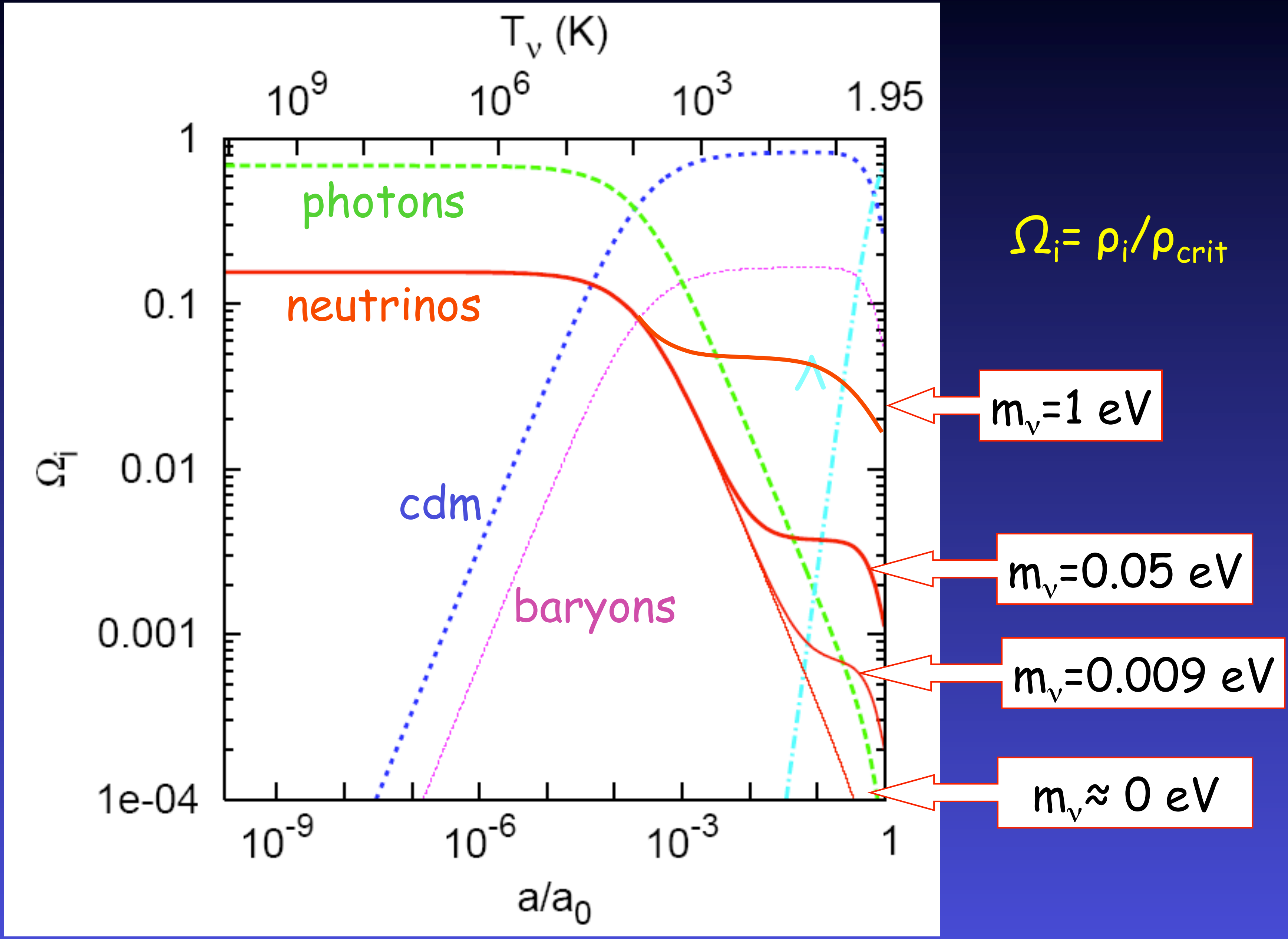
VERY LOW
Energy Neutrinos

Non-relativistic?

Low Energy
Neutrinos

$\sqrt{\Delta m^2_{21}}$ $\sqrt{|\Delta m^2_{31}|}$

Evolution of the background densities: 1 MeV → now



$\Omega_i = \rho_i / \rho_{crit}$

Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\,\mathrm{eV}} \qquad \Omega_\nu < 1 \to \sum_i m_i < 46\,\mathrm{eV}$$

$$\Omega_\nu < \Omega_m \approx 0.3 \to \sum_i m_i < 15\,\mathrm{eV}$$

- They stream freely until non-relativistic (collisionless phase mixing) → Neutrinos are HOT Dark Matter
- First structures to be formed when Universe became matter -dominated are very large
- Ruled out by structure formation → CDM

Effect of massive neutrinos on the CMB spectra

1) CMB spectrum essentially unchanged if neutrinos become NR AFTER photon decoupling (z_{rec}~1089)

$$\begin{aligned} 1 + z_{\rm nr} &= \frac{T_{\nu,\rm nr}}{T_{\nu,0}} \\ &= 1.99 \times 10^3 (m_\nu/\mathrm{eV}) \\ &= 6.24 \times 10^4 \omega_\nu , \end{aligned}$$

Neutrinos become NR BEFORE recombination if:

$$\omega_\nu \gtrsim 0.017 \quad \Longrightarrow \quad \sum_i m_{\nu_i} \gtrsim 1.6\ \mathrm{eV}$$

More details including effects of neutrino mass on "reduced CMB observables" in Ichikawa et al, PRD 71 (2005) 043001

Effect of massive neutrinos on the CMB spectra

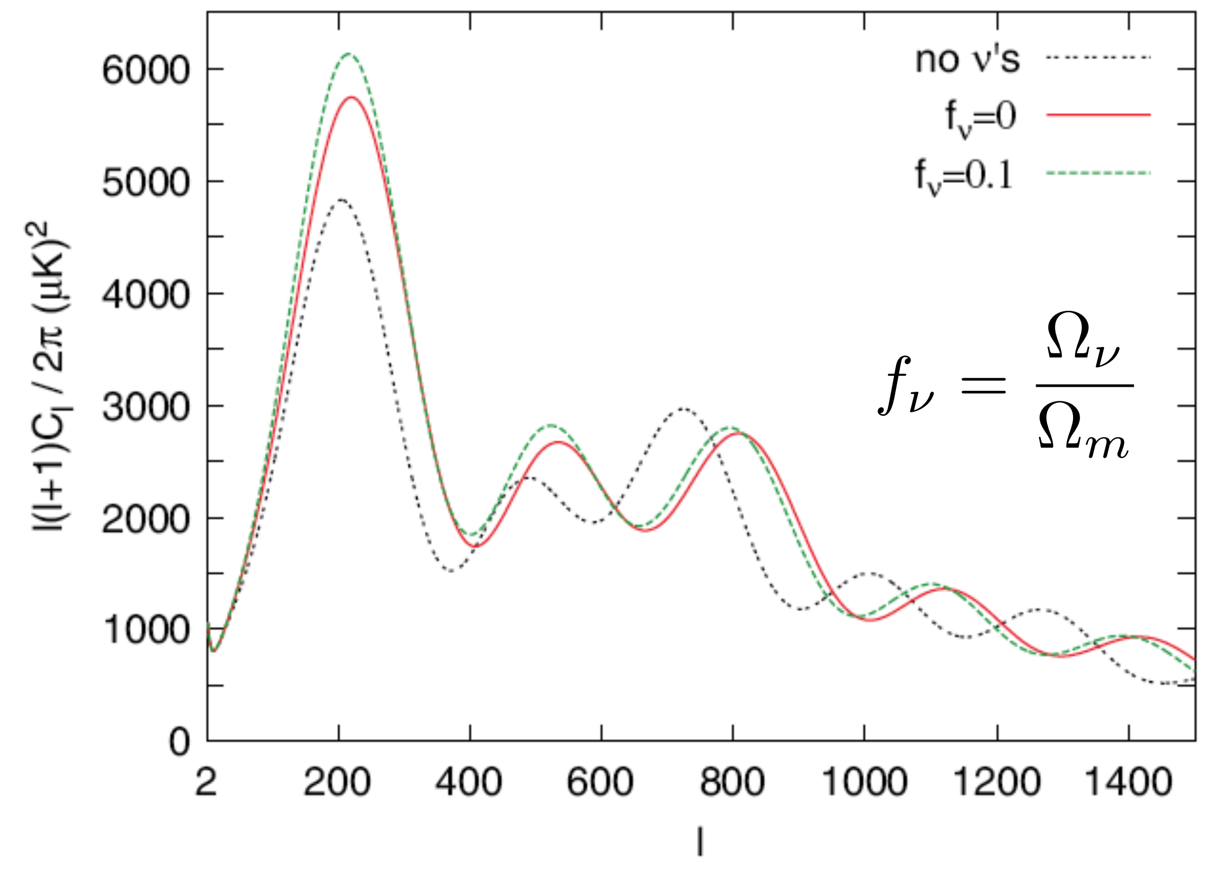
1) CMB spectrum essentially unchanged if neutrinos become NR AFTER photon decoupling.
2) Impact on CMB spectra is indirect: non-zero Ω_ν modifies the background evolution (change in equality time)

Ex: in a flat universe,

keep

$\Omega_\Lambda+\Omega_{cdm}+\Omega_b+\Omega_\nu=1$

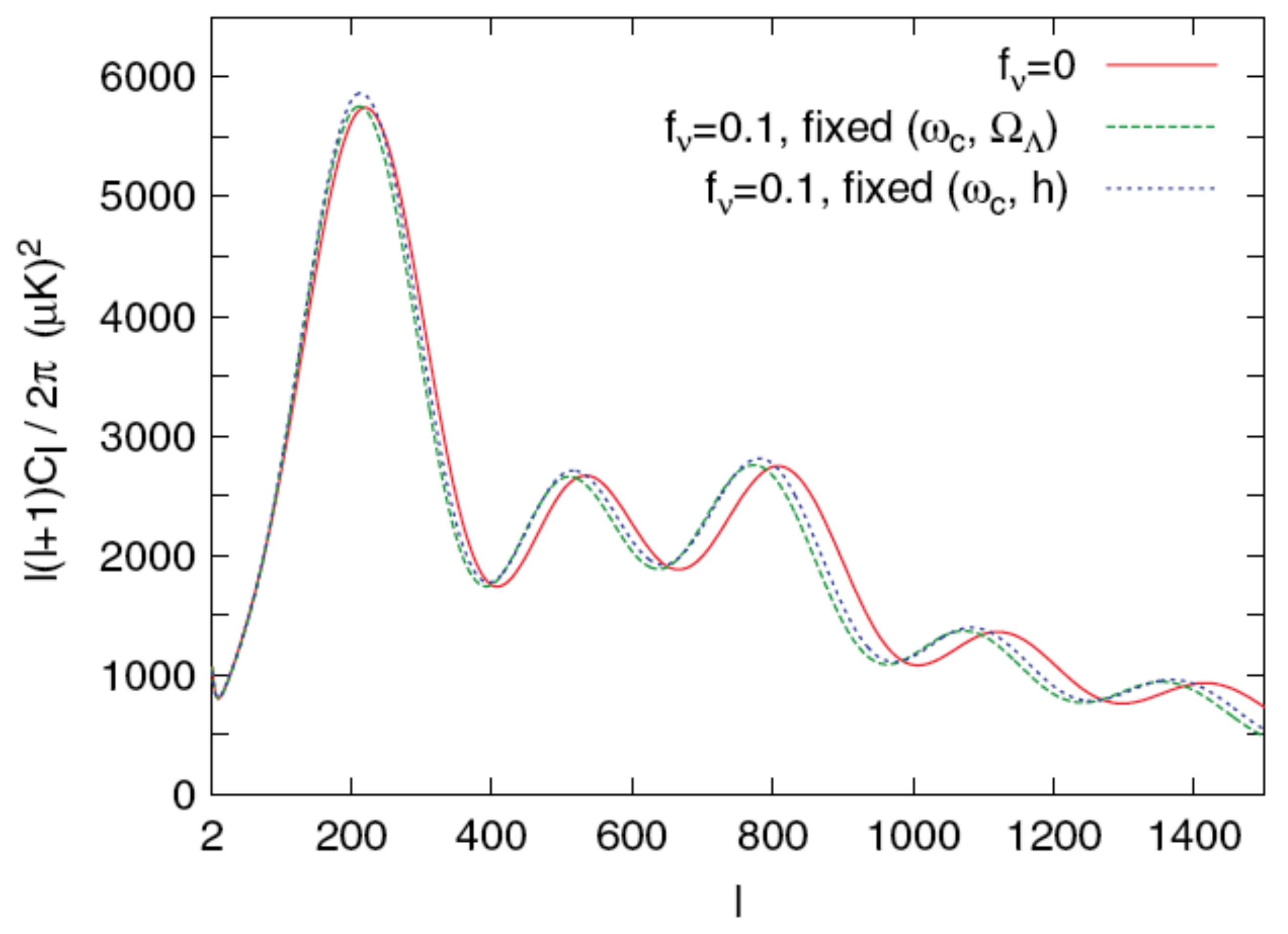
constant



$$f_\nu = \frac{\Omega_\nu}{\Omega_m}$$

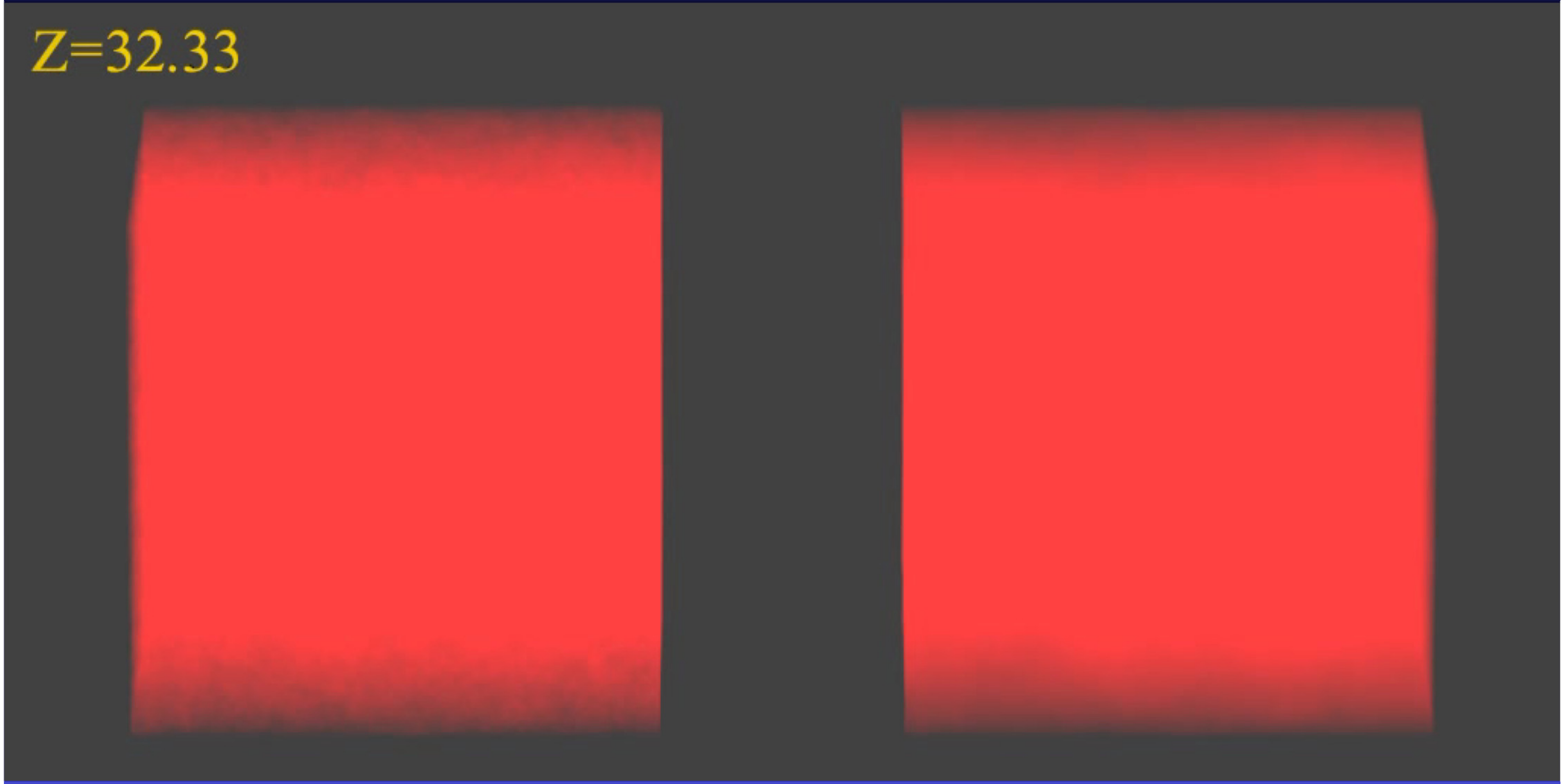
Effect of massive neutrinos on the CMB spectra

Problem with parameter degeneracies: change in other cosmological parameters can mimic the effect of nu masses



Neutrinos as Hot Dark Matter

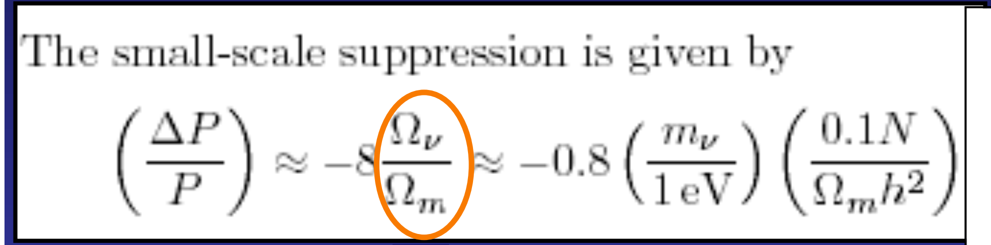
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)



Neutrinos as Hot Dark Matter: effect on P(k)

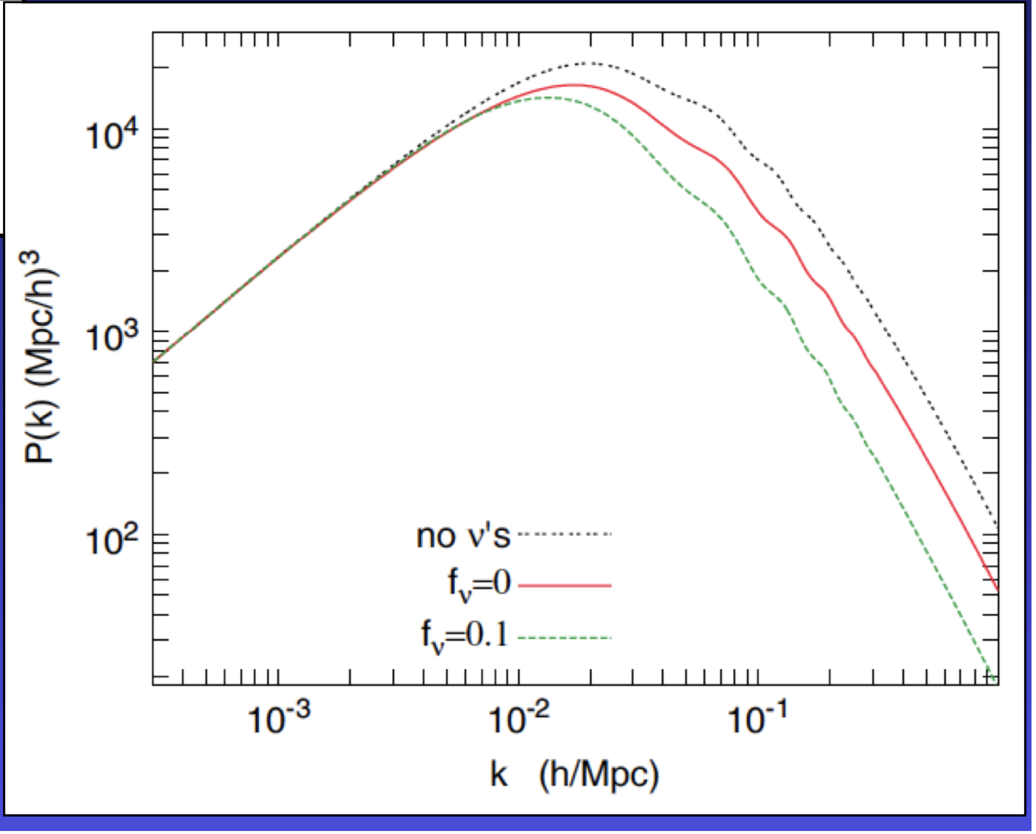
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

- Effect of Massive Neutrinos: suppression of Power at small scales



The small-scale suppression is given by

$$\left(\frac{\Delta P}{P}\right) \approx -8\underbrace{\frac{\Omega_\nu}{\Omega_m}}_{f_\nu} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$



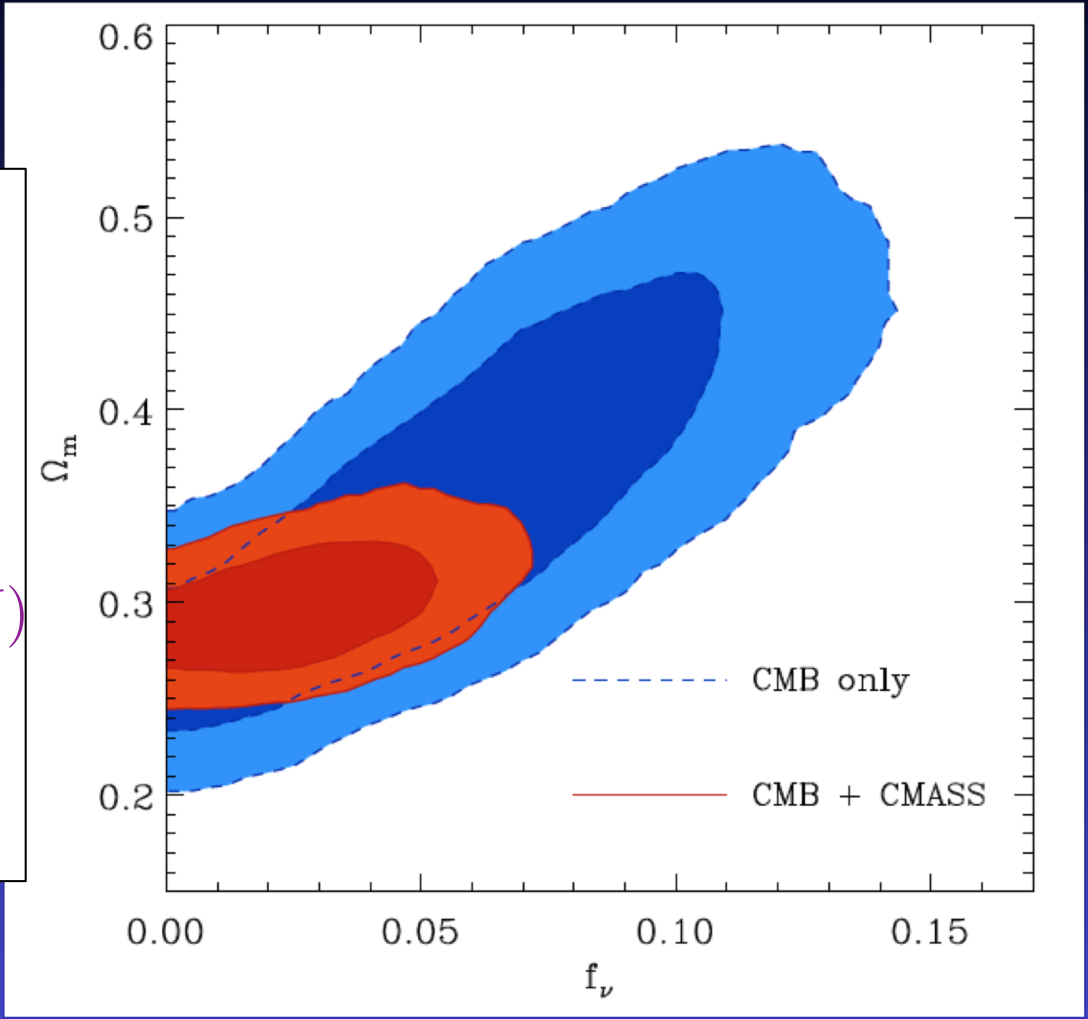
Current cosmological bounds on neutrino masses

95%CL upper limits

$\sum_i m_{\nu_i} < 1.4$ eV (CMB only)

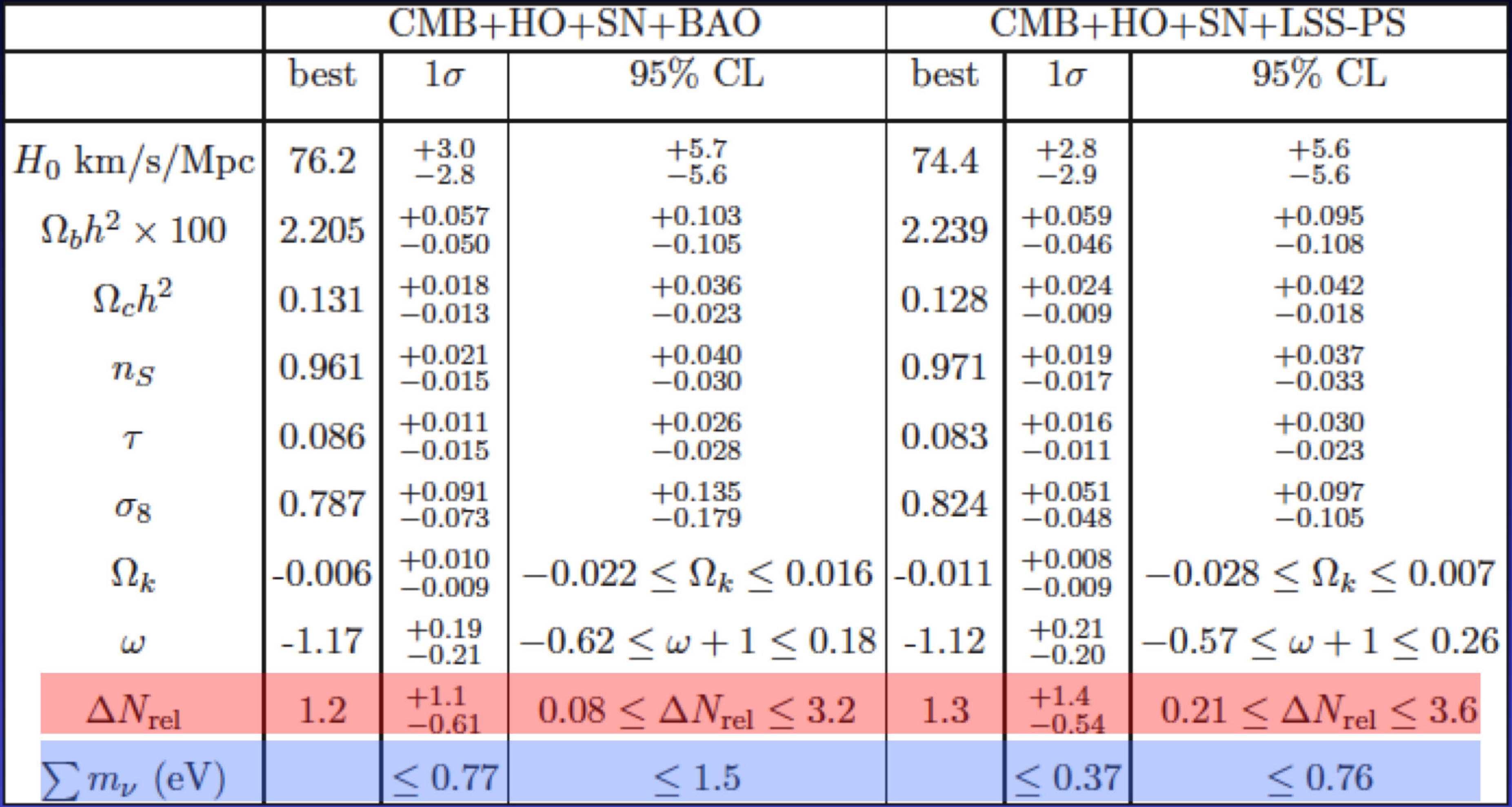
$\sum_i m_{\nu_i} < 0.61$ eV (+CMASS)

$\sum_i m_{\nu_i} < 0.51$ eV (+BAO+SN)



A.G. Sánchez et al., arXiv:1203.6616

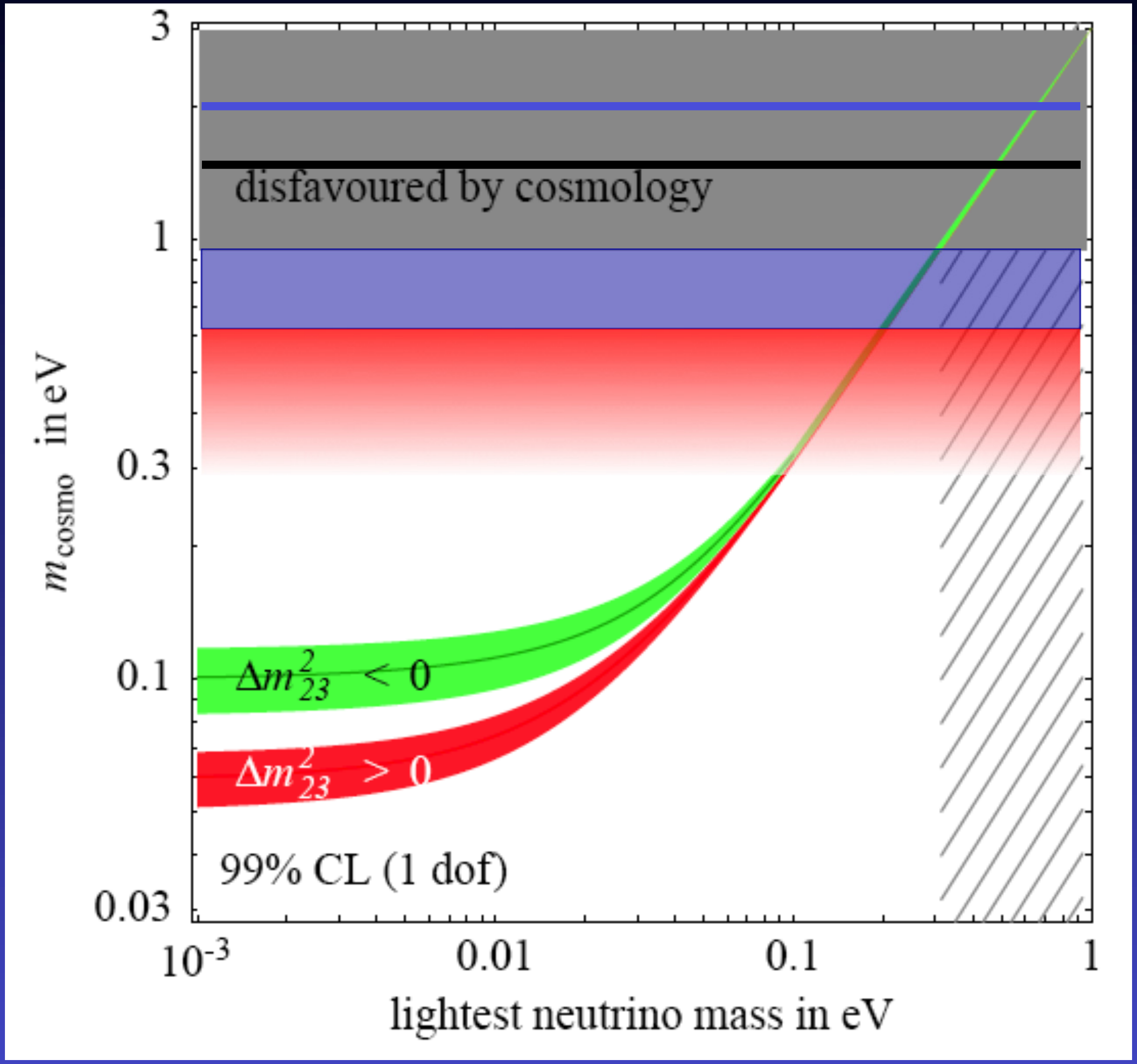
Current cosmological bounds on neutrino masses



	CMB+HO+SN+BAO			CMB+HO+SN+LSS-PS		
	best	1σ	95% CL	best	1σ	95% CL
H_0 km/s/Mpc	76.2	$^{+3.0}_{-2.8}$	$^{+5.7}_{-5.6}$	74.4	$^{+2.8}_{-2.9}$	$^{+5.6}_{-5.6}$
$\Omega_b h^2 \times 100$	2.205	$^{+0.057}_{-0.050}$	$^{+0.103}_{-0.105}$	2.239	$^{+0.059}_{-0.046}$	$^{+0.095}_{-0.108}$
$\Omega_c h^2$	0.131	$^{+0.018}_{-0.013}$	$^{+0.036}_{-0.023}$	0.128	$^{+0.024}_{-0.009}$	$^{+0.042}_{-0.018}$
n_S	0.961	$^{+0.021}_{-0.015}$	$^{+0.040}_{-0.030}$	0.971	$^{+0.019}_{-0.017}$	$^{+0.037}_{-0.033}$
τ	0.086	$^{+0.011}_{-0.015}$	$^{+0.026}_{-0.028}$	0.083	$^{+0.016}_{-0.011}$	$^{+0.030}_{-0.023}$
σ_8	0.787	$^{+0.091}_{-0.073}$	$^{+0.135}_{-0.179}$	0.824	$^{+0.051}_{-0.048}$	$^{+0.097}_{-0.105}$
Ω_k	-0.006	$^{+0.010}_{-0.009}$	$-0.022 \leq \Omega_k \leq 0.016$	-0.011	$^{+0.008}_{-0.009}$	$-0.028 \leq \Omega_k \leq 0.007$
ω	-1.17	$^{+0.19}_{-0.21}$	$-0.62 \leq \omega + 1 \leq 0.18$	-1.12	$^{+0.21}_{-0.20}$	$-0.57 \leq \omega + 1 \leq 0.26$
$\Delta N_{\rm rel}$	1.2	$^{+1.1}_{-0.61}$	$0.08 \leq \Delta N_{\rm rel} \leq 3.2$	1.3	$^{+1.4}_{-0.54}$	$0.21 \leq \Delta N_{\rm rel} \leq 3.6$
$\sum m_\nu$ (eV)		≤ 0.77	≤ 1.5		≤ 0.37	≤ 0.76

González-García et al., JCAP 08 (2010) 117

Neutrino masses in 3-neutrino schemes



CMB

CMB + galaxy clustering

+ HST, SNI-a…

+ **BAO** and/or bias

Strumia & Vissani, hep-ph/0606054

Direct laboratory bounds on m_ν

Searching for non-zero neutrino mass in laboratory experiments

- Tritium beta decay: measurements of endpoint energy

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

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

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

- Neutrinoless double beta decay: if Majorana neutrinos

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

experiments with ^{76}Ge, ^{130}Te and other isotopes:
$|m_{ee}| < 0.23\text{-}0.85$ eV , depending on NME

Absolute mass scale searches

Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$	2.2 eV

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	< 0.2-0.8 eV

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

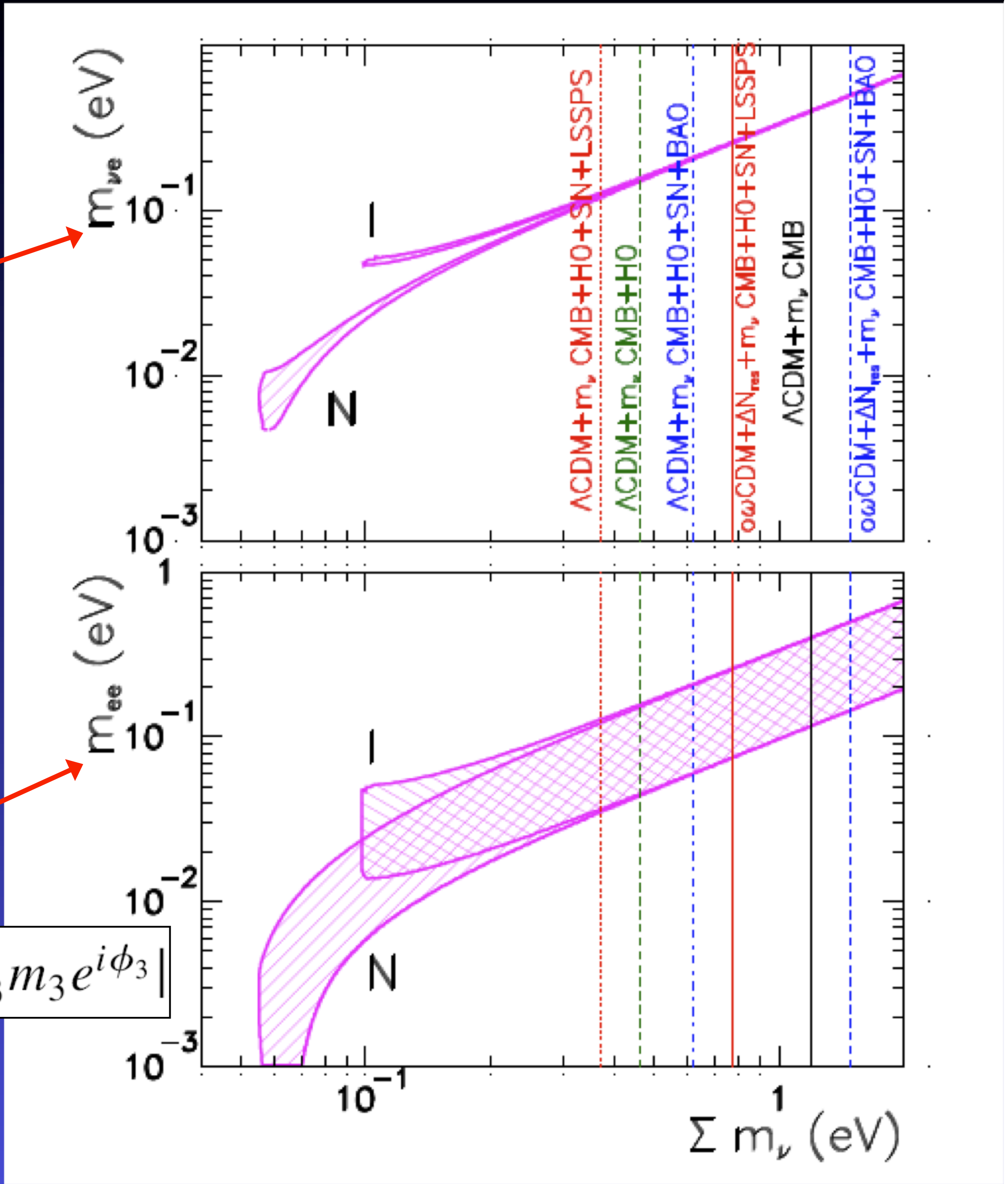
Cosmology	$\sim \sum_i m_i$	< 0.3-2.0 eV

Tritium β decay, 0ν2β and Cosmology

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

$$\left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

González-García et al.,
JCAP 08 (2010) 117



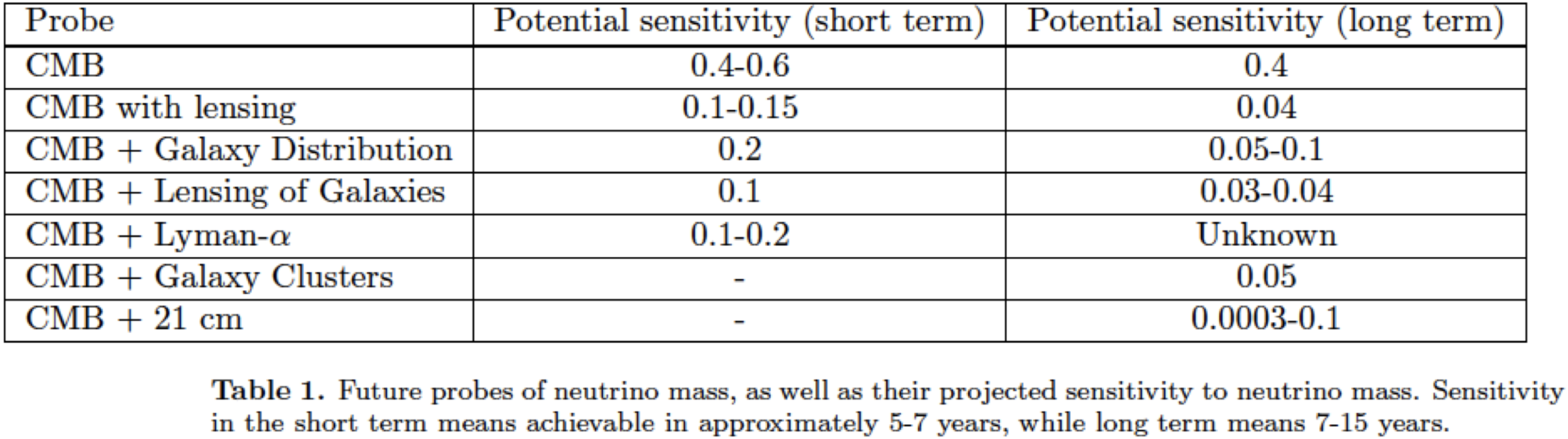
Future sensitivities to Σm_ν

Future cosmological data will be available from

- CMB (Temperature & Polarization anis.)
- High-z Galaxy redshift surveys
  Hannestad & Wong, JCAP 07 (2007) 004
  Takada et al, PRD 73 (2006) 083520
- Galaxy cluster surveys
  Wang et al, PRL 95 (2005) 011302
- Weak lensing surveys (tomography)
  Hannestad et al, JCAP 06 (2006) 025
  Song & Knox, PRD 70 (2004) 063510
- CMB lensing
  Perotto et al, JCAP 10 (2006) 013
  Lesgourgues et al, PRD 73 (2006) 045021
- Fluctuations in the 21 cm H line
  Loeb & Wyithe, PRL 100 (2008) 161301
  Pritchard & Pierpaoli, PRD 78 (2008) 065009

Forecasts indicate 10-150 meV sensitivities to Σm_ν are possible !!

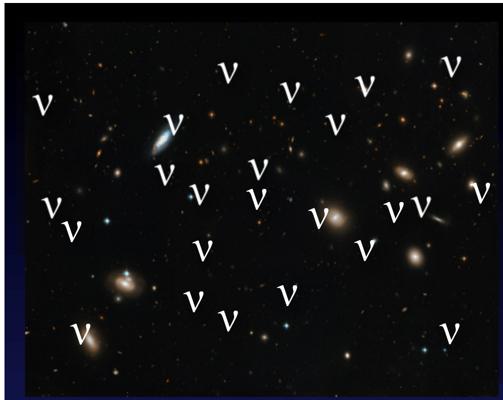
Summary of future sensitivities



Probe	Potential sensitivity (short term)	Potential sensitivity (long term)
CMB	0.4-0.6	0.4
CMB with lensing	0.1-0.15	0.04
CMB + Galaxy Distribution	0.2	0.05-0.1
CMB + Lensing of Galaxies	0.1	0.03-0.04
CMB + Lyman-α	0.1-0.2	Unknown
CMB + Galaxy Clusters	-	0.05
CMB + 21 cm	-	0.0003-0.1

Table 1. Future probes of neutrino mass, as well as their projected sensitivity to neutrino mass. Sensitivity in the short term means achievable in approximately 5-7 years, while long term means 7-15 years.

Hannestad, Progr. Part. Nucl. Phys. 65 (2010) 185



Conclusions

Cosmological observables can be used to bound (or measure) neutrino properties, in particular the sum of neutrino masses (info complementary to laboratory results)

The radiation content of the Universe (N_{eff}) will be very constrained in the near future (Planck)

Current bounds on the sum of neutrino masses from cosmological data (best Σm_ν<0.3-0.6 eV, conservative Σm_ν<1 eV)

Different cosmological observations in the next future → Sub-eV sensitivity (0.1-0.2 eV and better) → Test degenerate mass region and eventually the mimimum total mass for IH case

Active-sterile neutrino oscillations

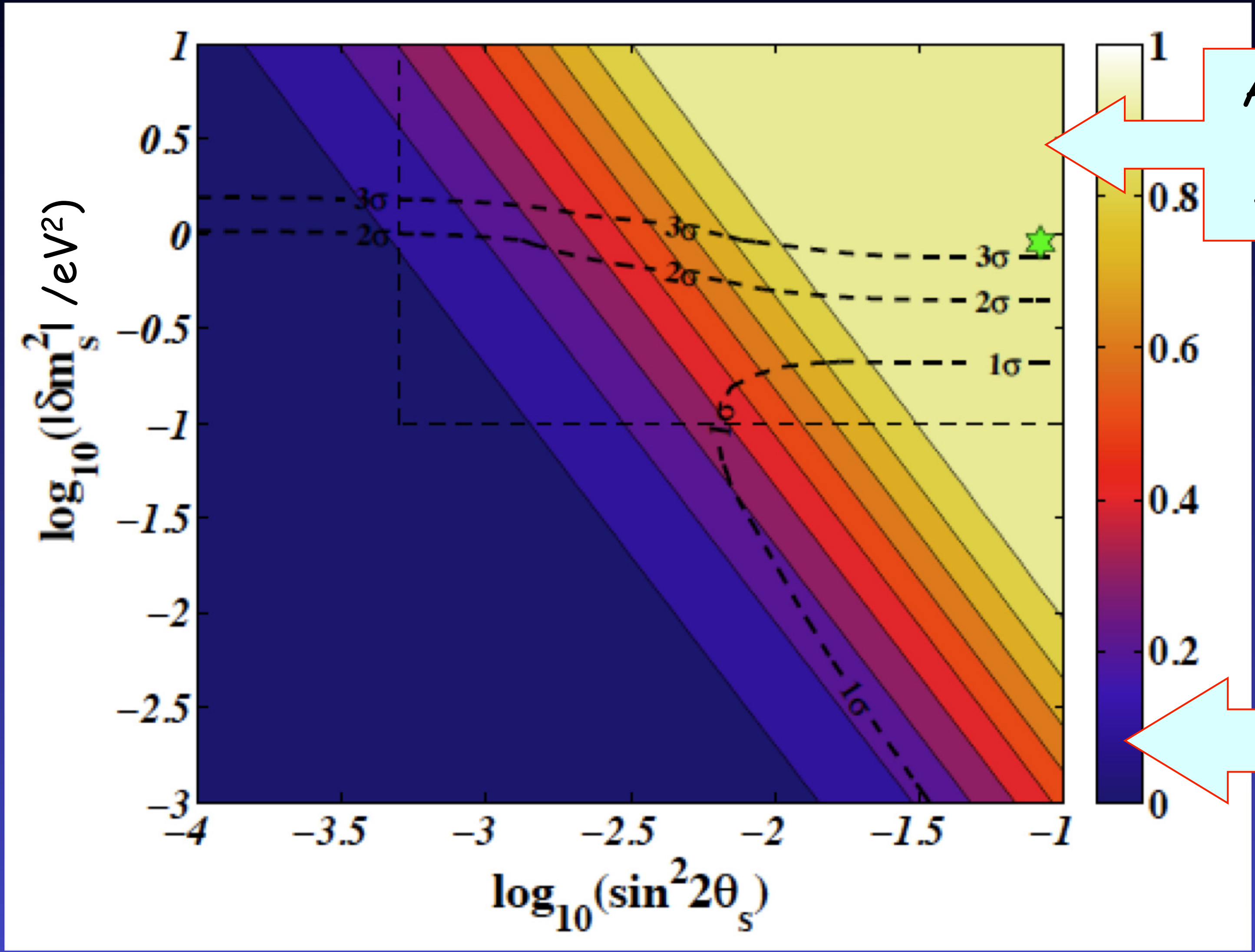
What if additional, light *sterile* neutrino species are mixed with the flavour neutrinos?

♣ If oscillations are effective before decoupling: the additional species can be brought into equilibrium: $N_{eff}=4$

♣ If oscillations are effective after decoupling: $N_{eff}=3$ but the spectrum of active neutrinos is distorted (direct effect of ν_e and anti-ν_e on BBN)

Results depend on the sign of Δm^2
(resonant vs non-resonant case)

Active-sterile neutrino oscillations



Additional neutrino fully in eq

Contribution of additional to ρ_{rad} in N_{eff} units

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