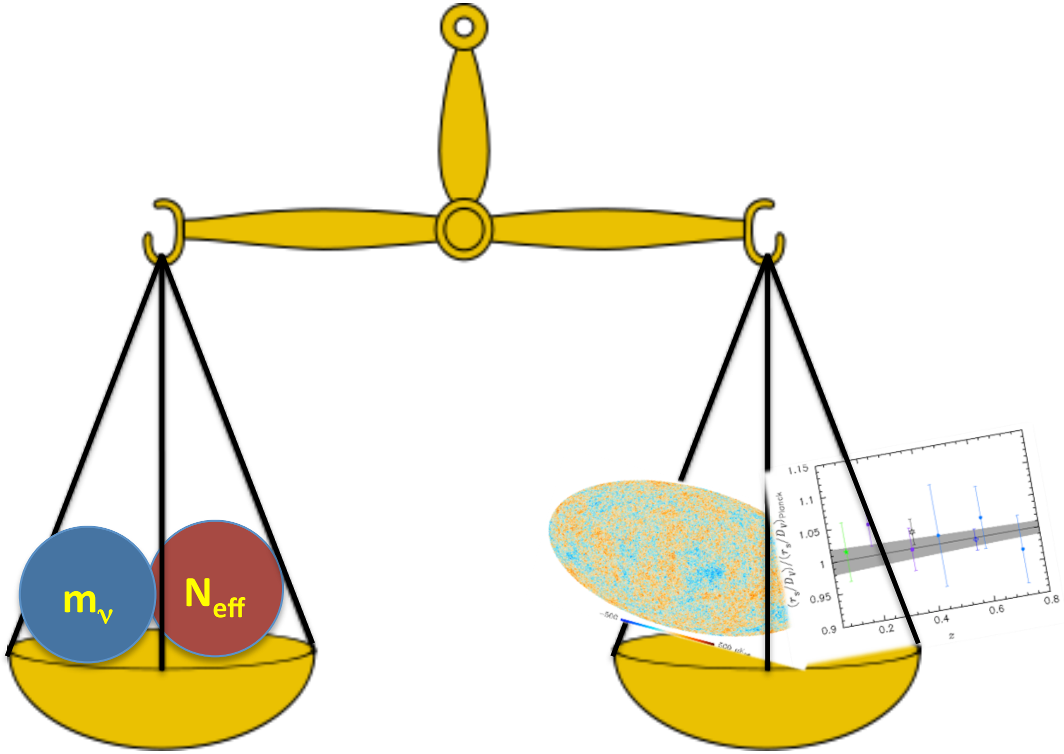
Neutrino properties from cosmological observables after Planck



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22 October 2015

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Outline

Introduction: the Cosmic Neutrino Background

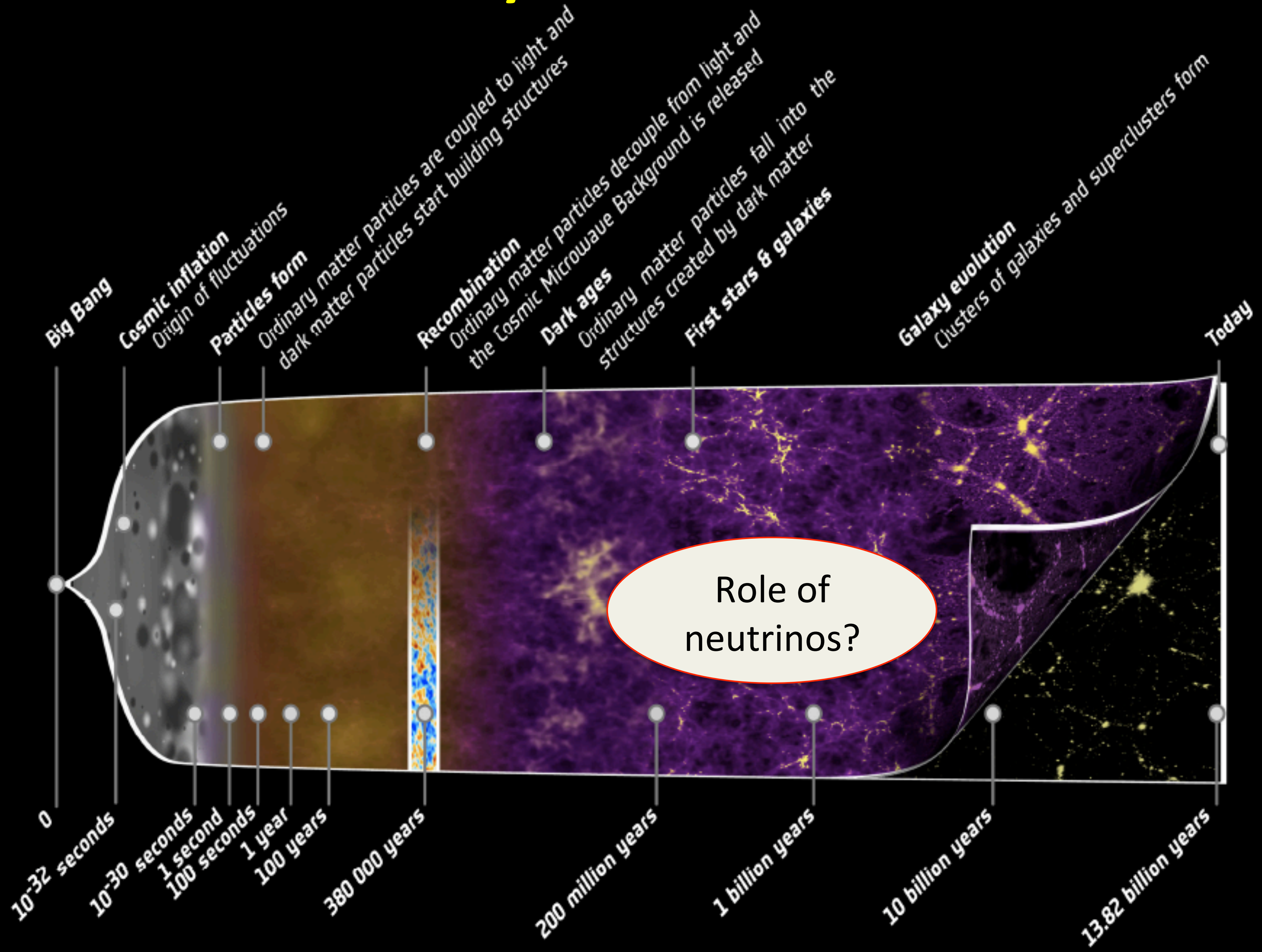
Neutrinos as Dark Matter

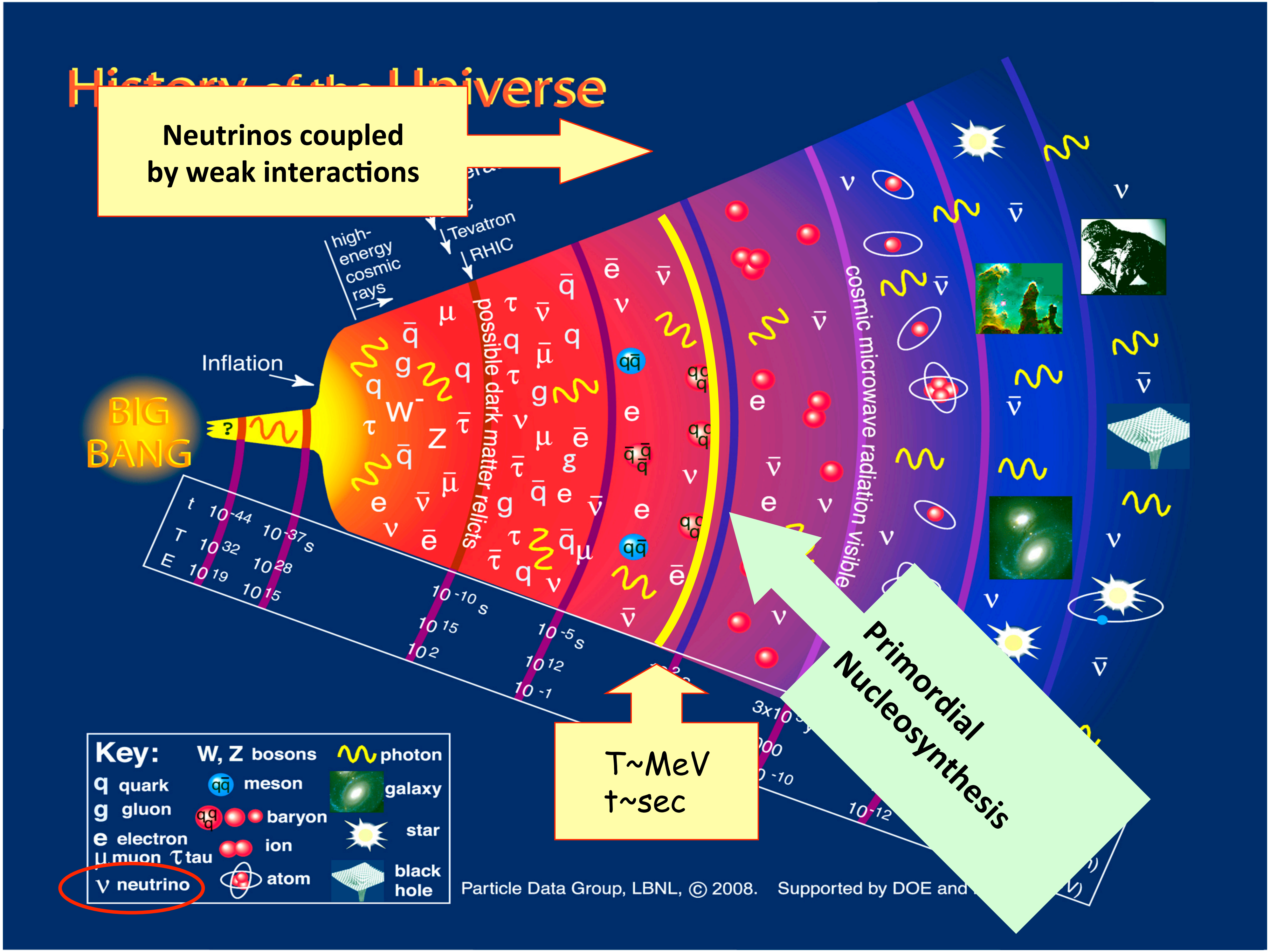
The radiation content of the Universe (N_{eff})

Bounds on neutrino properties from Planck (& other cosmo data)

Introduction: the Cosmic Neutrino Background

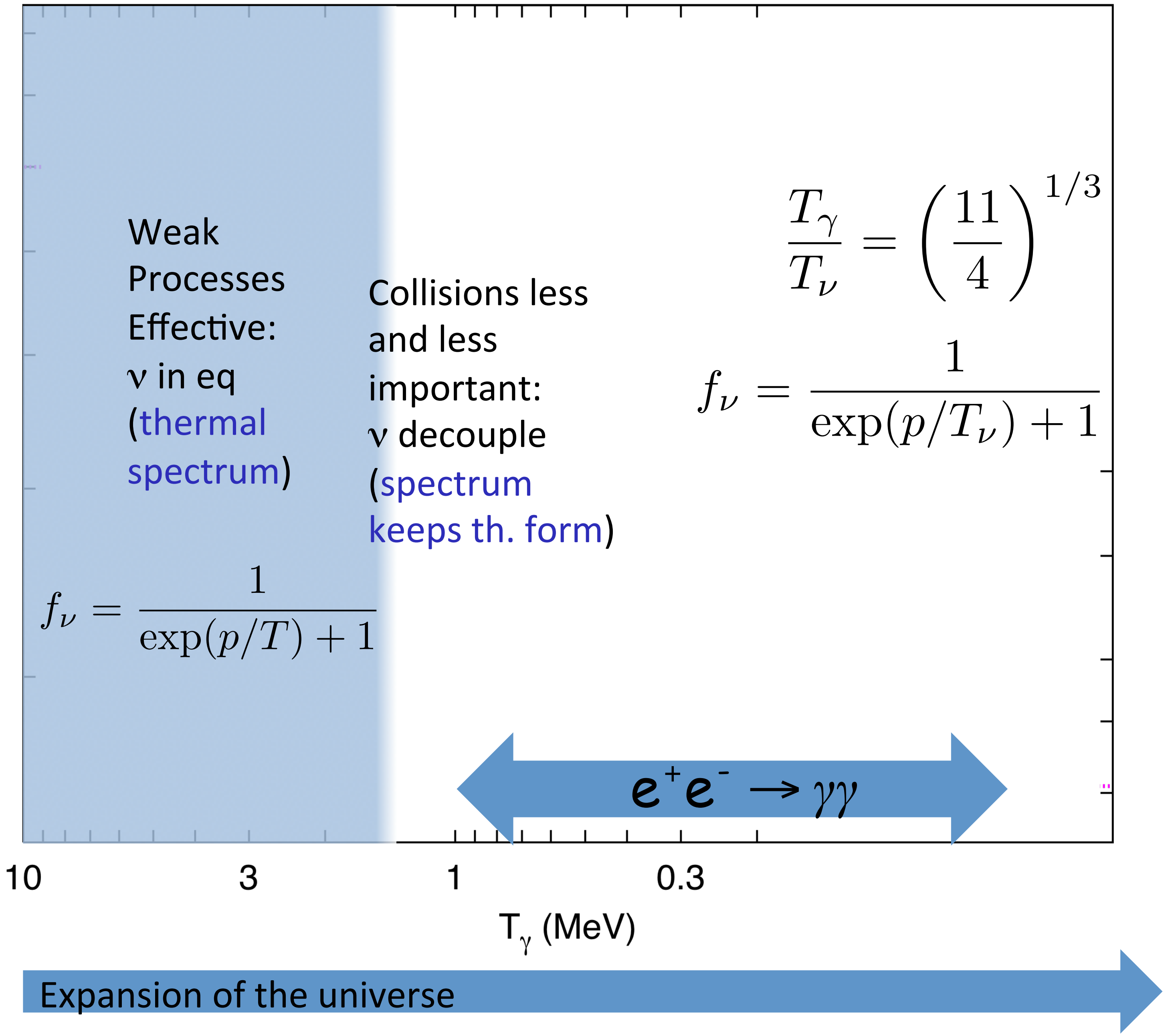
History of the Universe





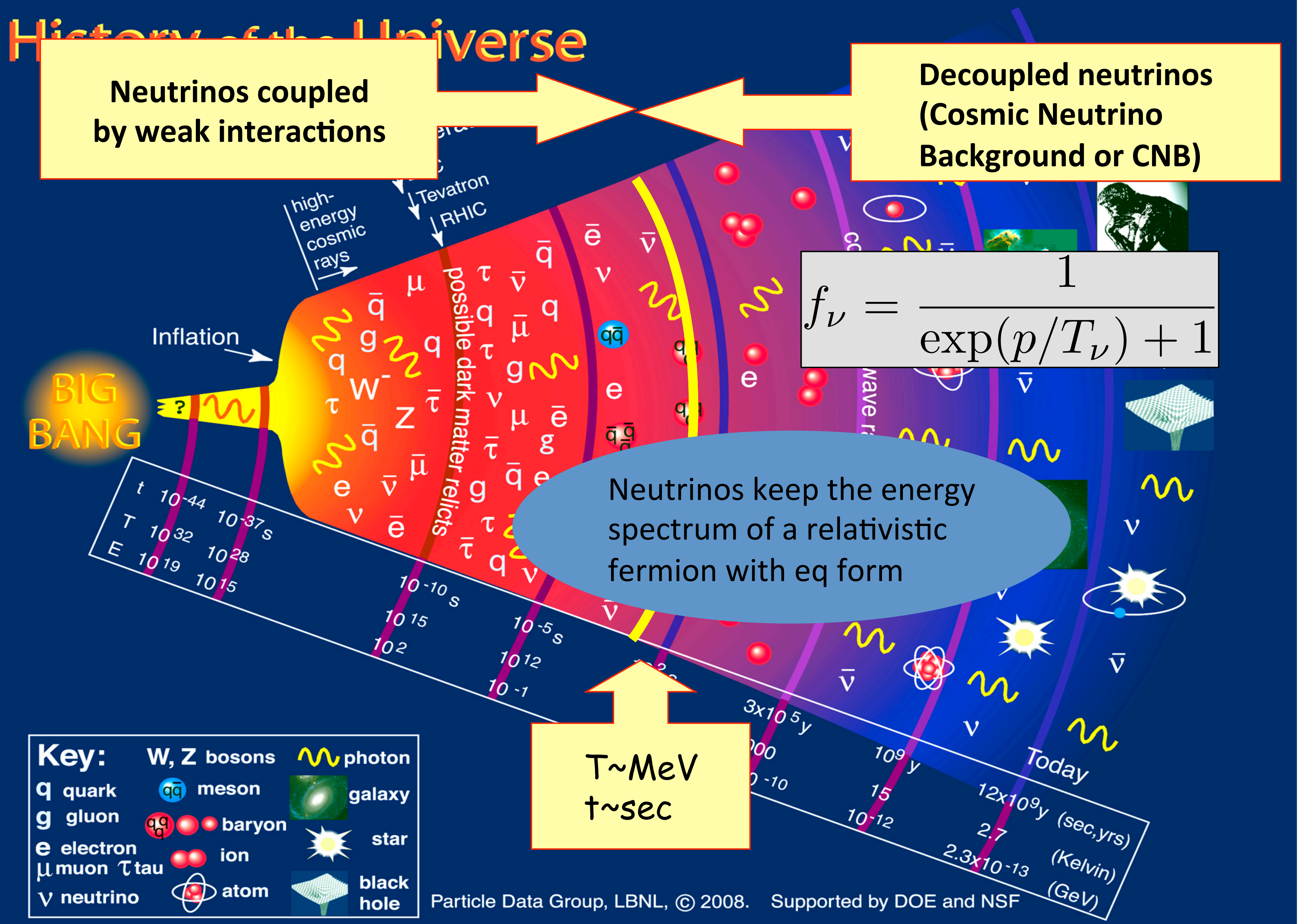
Neutrinos coupled
by weak interactions
high-energy cosmic rays
Tevatron
RHIC
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and

ν Decoupling and e± annihilations



Neutrinos coupled by weak interactions

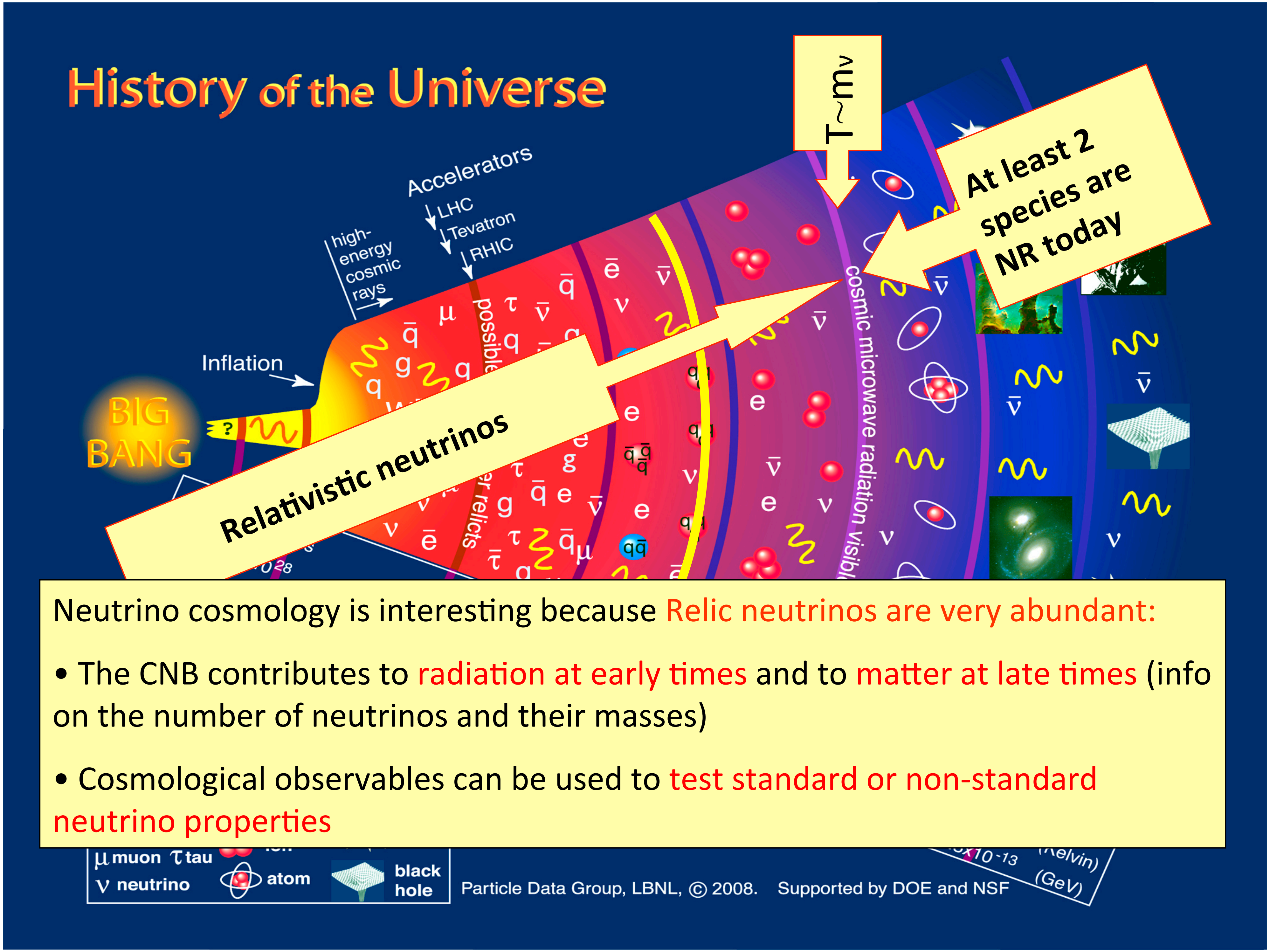
Decoupled neutrinos (Cosmic Neutrino Background or CNB)



$$f_\nu = \frac{1}{\exp(p/T_\nu)+1}$$

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

T~MeV
t~sec



Neutrino cosmology is interesting because Relic neutrinos are very abundant:

- The CNB contributes to radiation at early times and to matter at late times (info on the number of neutrinos and their masses)

- Cosmological observables can be used to test standard or non-standard neutrino properties

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

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

- Energy density

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

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

The Cosmic Neutrino Background

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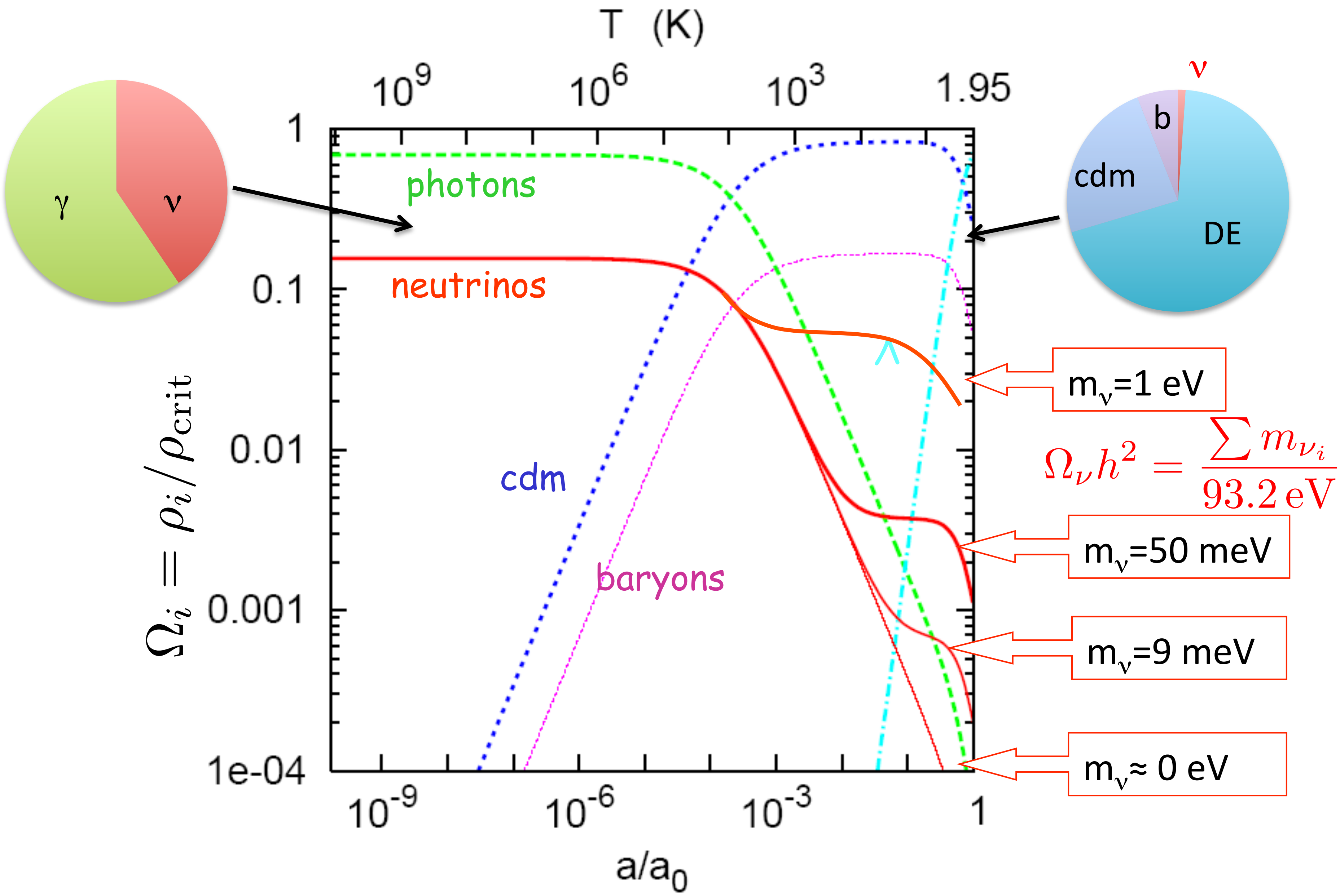
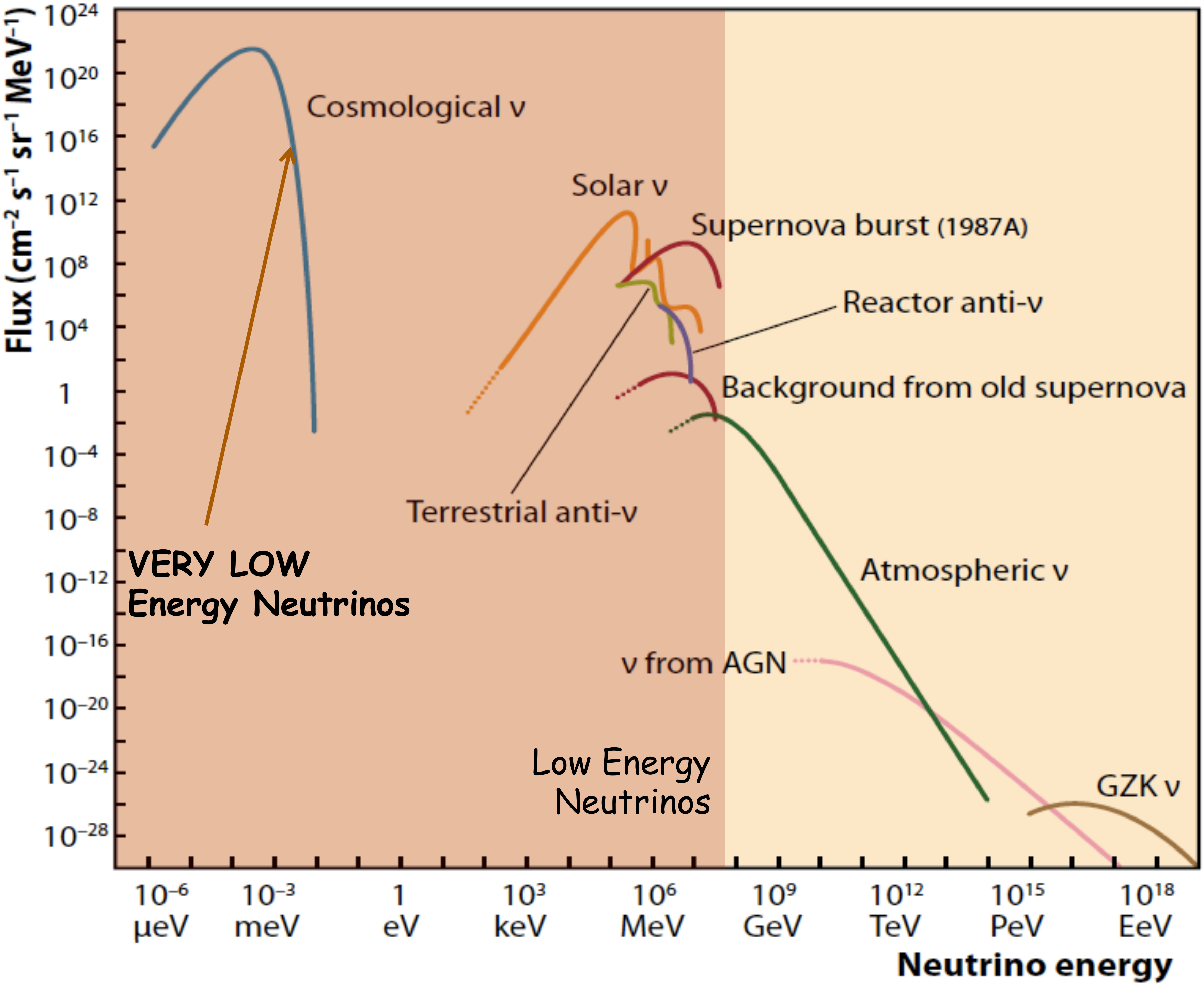
$$\Omega_\nu h^2 \simeq 1.7 \times 10^{-5}$$ Massless

$$\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93.2\ \mathrm{eV}}$$ Massive

$m_\nu \gg T$

Background densities: 1 MeV → now

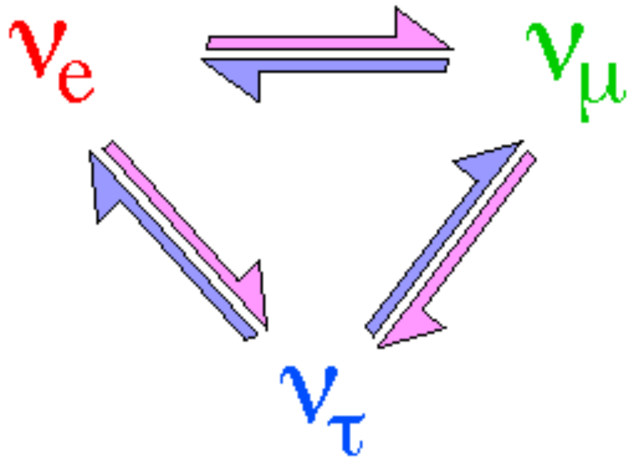



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
VERY LOW
Energy Neutrinos
Low Energy
Neutrinos
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy

Neutrinos as Dark Matter

We know that flavour neutrino oscillations exist

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

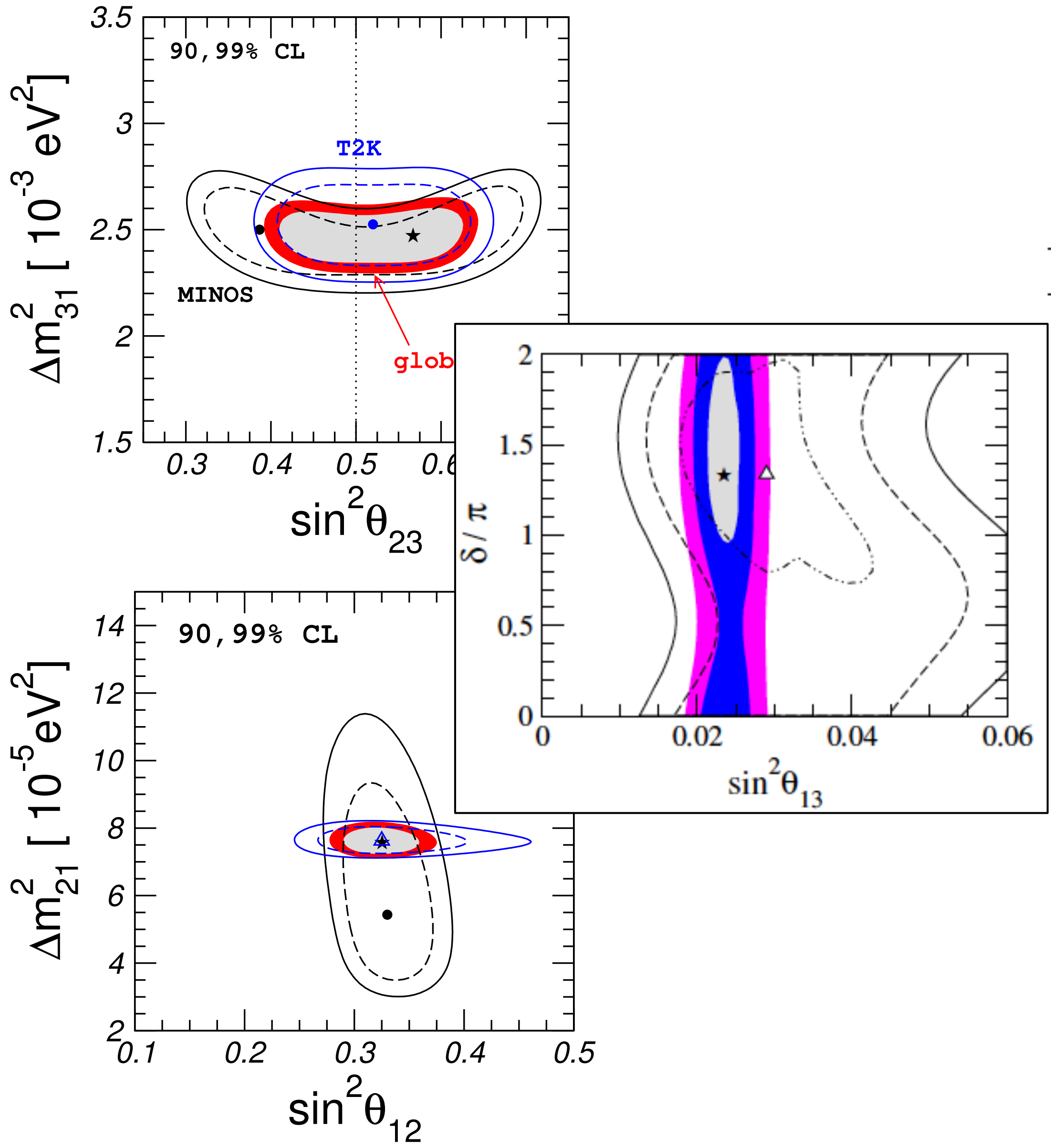


$$(e, \mu, \tau) \leftrightarrow (\nu_1, \nu_2, \nu_3)$$

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

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

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

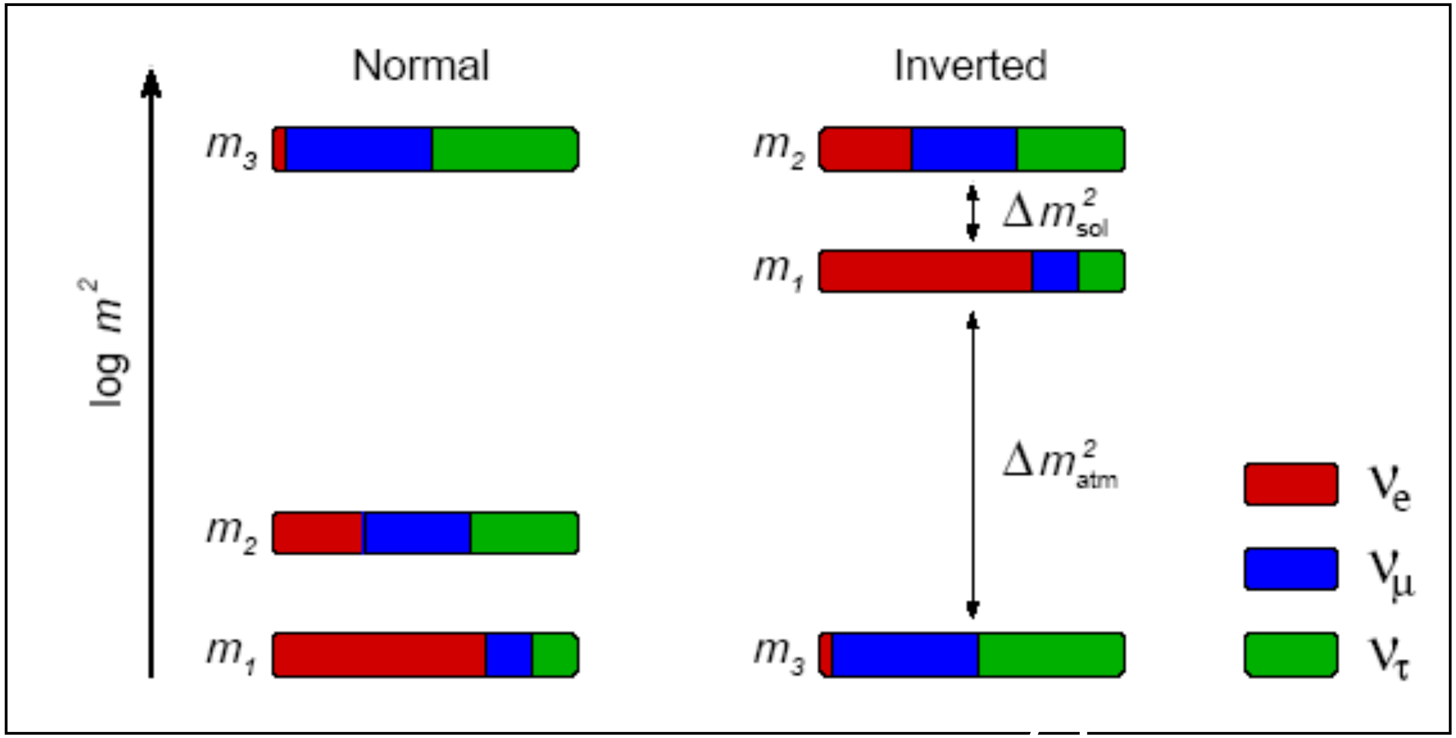


Forero, Tórtola & Valle,
PRD 90 (2014) 093006

parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.60^{+0.19}_{-0.18}$	7.26–7.99	7.11–8.18
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NH)	$2.48^{+0.05}_{-0.07}$	2.35–2.59	2.30–2.65
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IH)	$2.38^{+0.05}_{-0.06}$	2.26–2.48	2.20-2.54
$\sin^2\theta_{12}/10^{-1}$	3.23±0.16	2.92–3.57	2.78–3.75
$\theta_{12}/°$	34.6±1.0	32.7–36.7	31.8–37.8
$\sin^2\theta_{23}/10^{-1}$ (NH)	$5.67^{+0.32}_{-1.24}$ [a]	4.14–6.23	3.93–6.43
$\theta_{23}/°$	$48.9^{+1.8}_{-7.2}$	40.0–52.1	38.8–53.3
$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.73^{+0.25}_{-0.39}$	4.35–6.21	4.03–6.40
$\theta_{23}/°$	$49.2^{+1.5}_{-2.3}$	41.3–52.0	39.4–53.1
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.26±0.12	2.02–2.50	1.90–2.62
$\theta_{13}/°$	$8.6^{+0.3}_{-0.2}$	8.2–9.1	7.9–9.3
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.29±0.12	2.05–2.52	1.93–2.65
$\theta_{13}/°$	8.7± 0.2	8.2–9.1	8.0–9.4
δ/π (NH)	$1.41^{+0.55}_{-0.40}$	0.00–2.0	0.0–2.0
$\delta/°$	254^{+99}_{-72}	0–360	0–360
δ/π (IH)	1.48±0.31	0.00–0.09 & 0.86–2.0	0.0–2.0
$\delta/°$	266±56	0—16 & 155–360	0–360

see also Fogli et al, PRD 89 (2014) 093018; González-García et al, JHEP 1411 (2014) 052

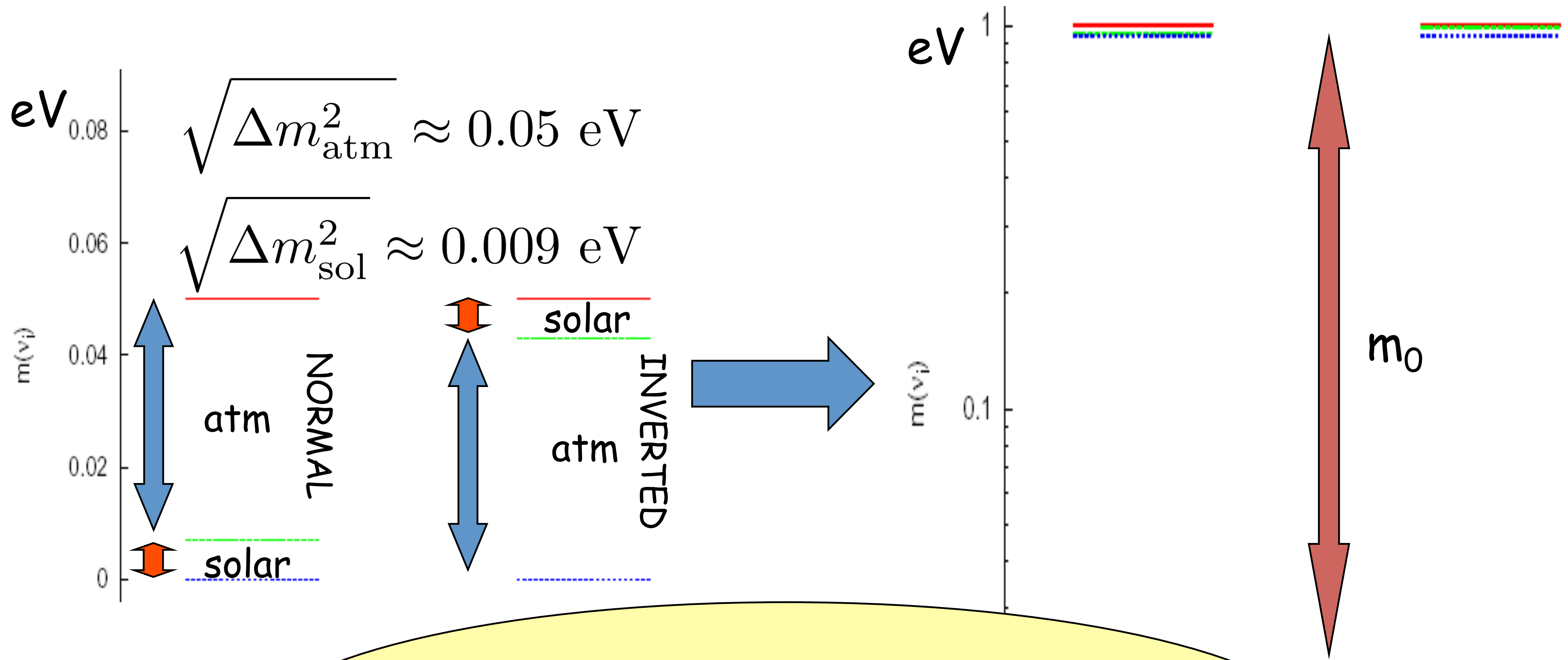
Neutrino masses



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

Neutrino masses

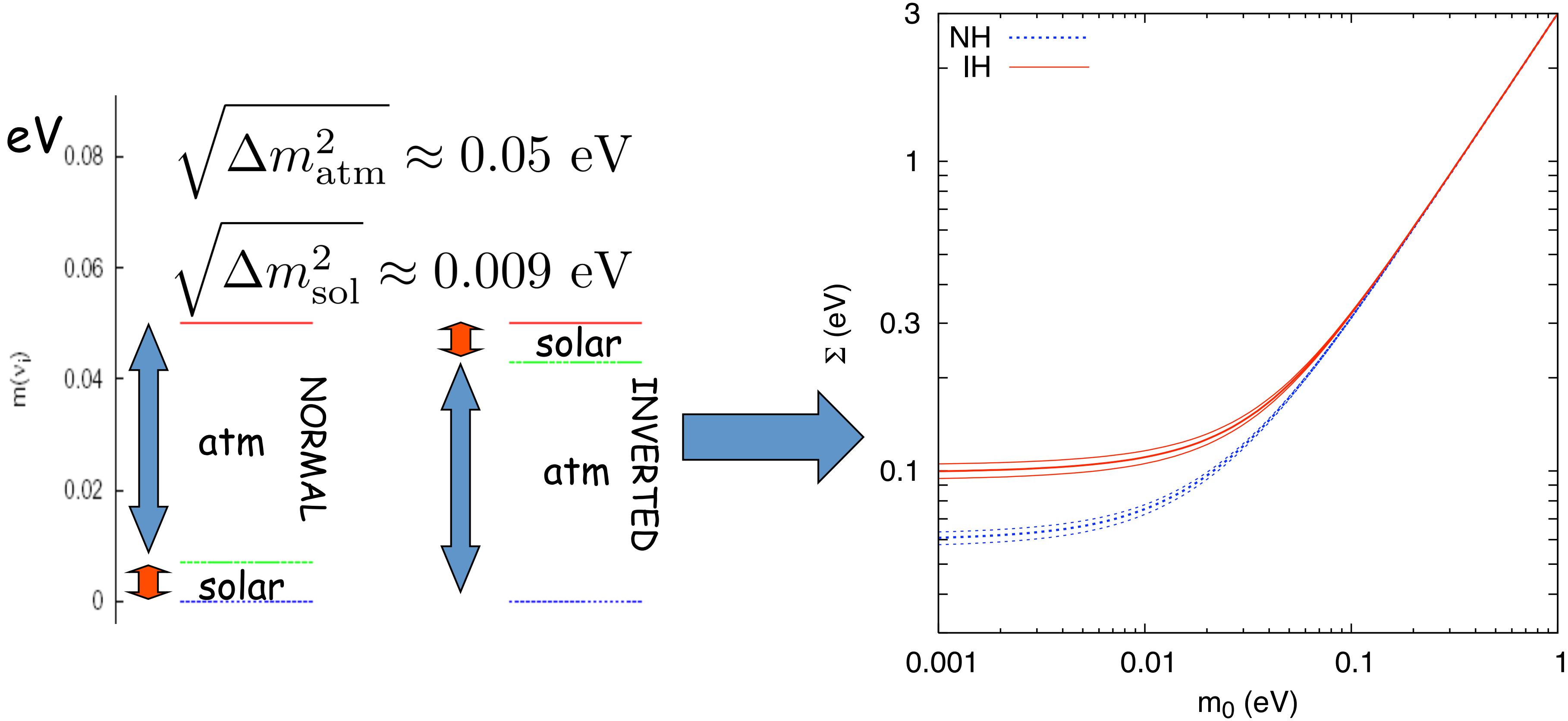
Data on flavour oscillations do not fix the absolute scale of neutrino masses



What is the value of m_0 ?

Neutrino masses

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



$$0.06(0.1)\,\mathrm{eV} \lesssim \sum_i m_i \lesssim 6\,\mathrm{eV}$$

The Cosmic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

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- Number density

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

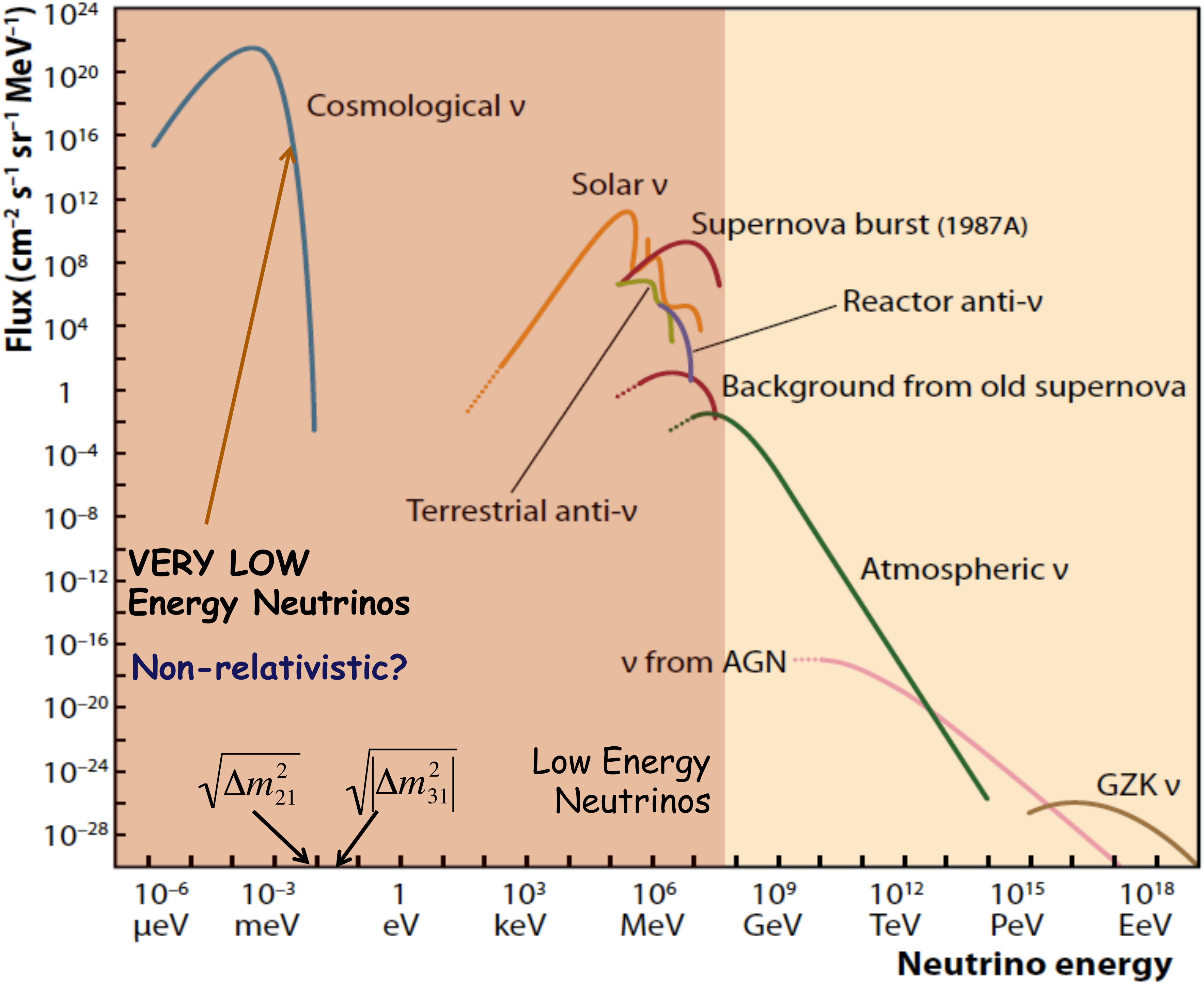
- Energy density

Contribution to the energy density of the Universe

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

$$\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93.2\ \mathrm{eV}}$$ Massive

$m_\nu >> T$



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
VERY LOW
Energy Neutrinos
Non-relativistic?
$\sqrt{\Delta m^2_{21}}$
$\sqrt{|\Delta m^2_{31}|}$
Low Energy
Neutrinos
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ \text{eV}} \qquad \Omega_\nu < 1 \rightarrow \sum_i m_i \lesssim 46\ \text{eV}$$

$$\Omega_\nu < \Omega_m \simeq 0.3 \rightarrow \sum_i m_i \lesssim 15\ \text{eV}$$

- They stream freely until non-relativistic (collisionless phase mixing) ➡
Neutrinos are HOT Dark Matter (large thermal motion)

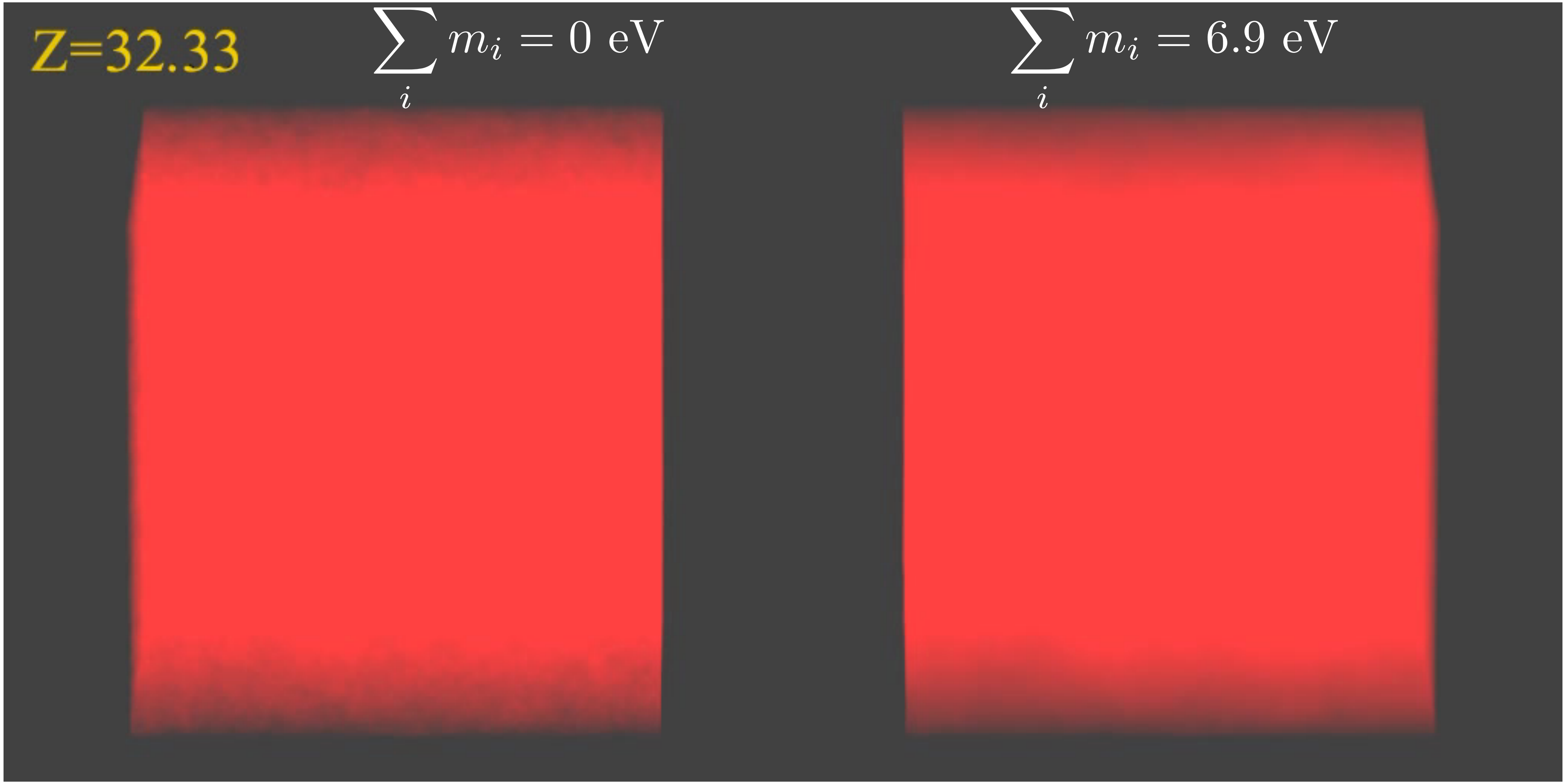
- First structures to be formed when Universe became matter –dominated are very large

- Ruled out by structure formation ➡ CDM

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

Neutrinos as Hot Dark Matter

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



S. Hannestad, Cosmology Group, Univ. Aarhus

The radiation content of the Universe (N_{eff})

Relativistic particles in the Universe

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

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

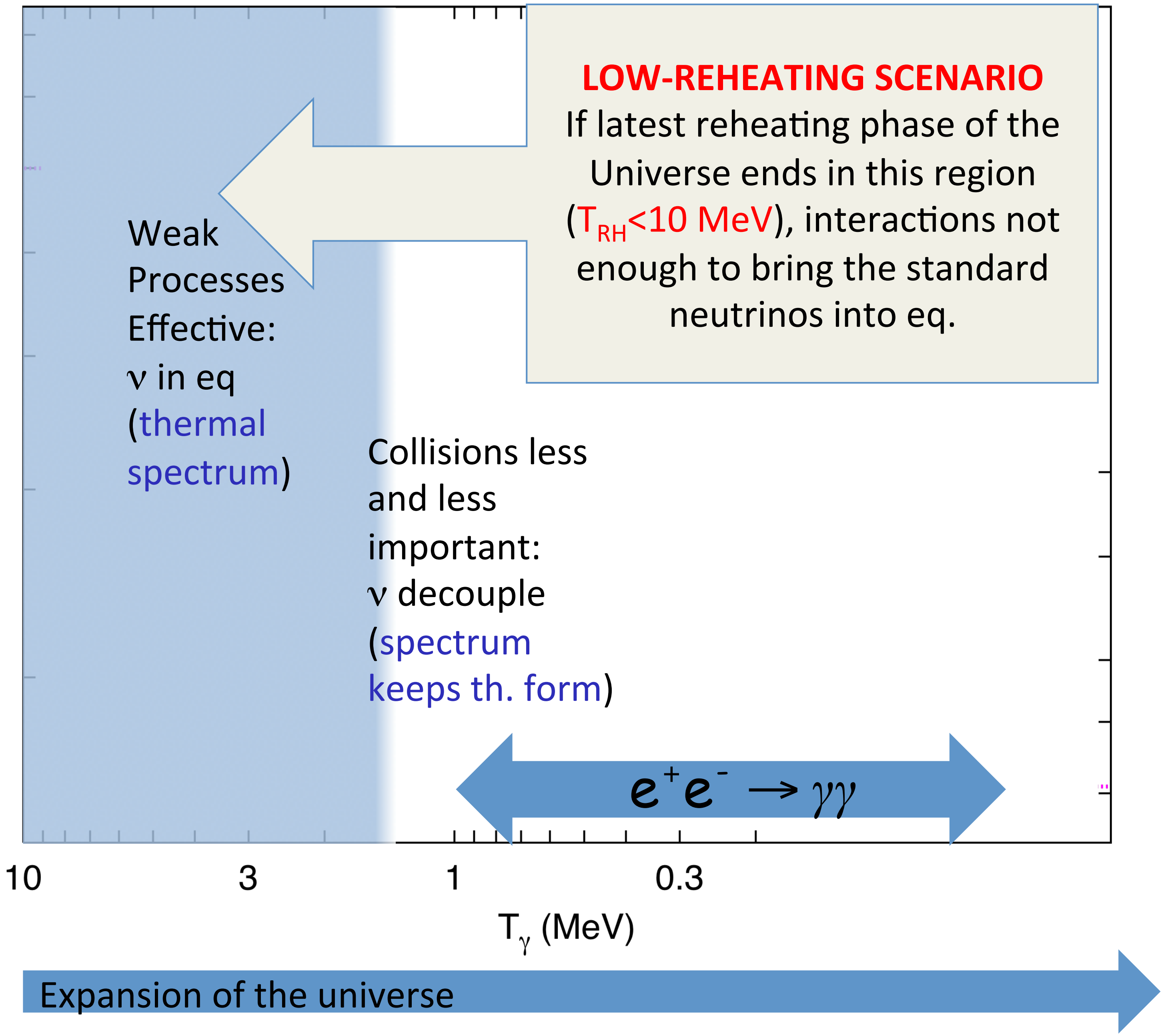
Effective number of relativistic neutrino species

Traditional parametrization of ρ stored in relativistic particles

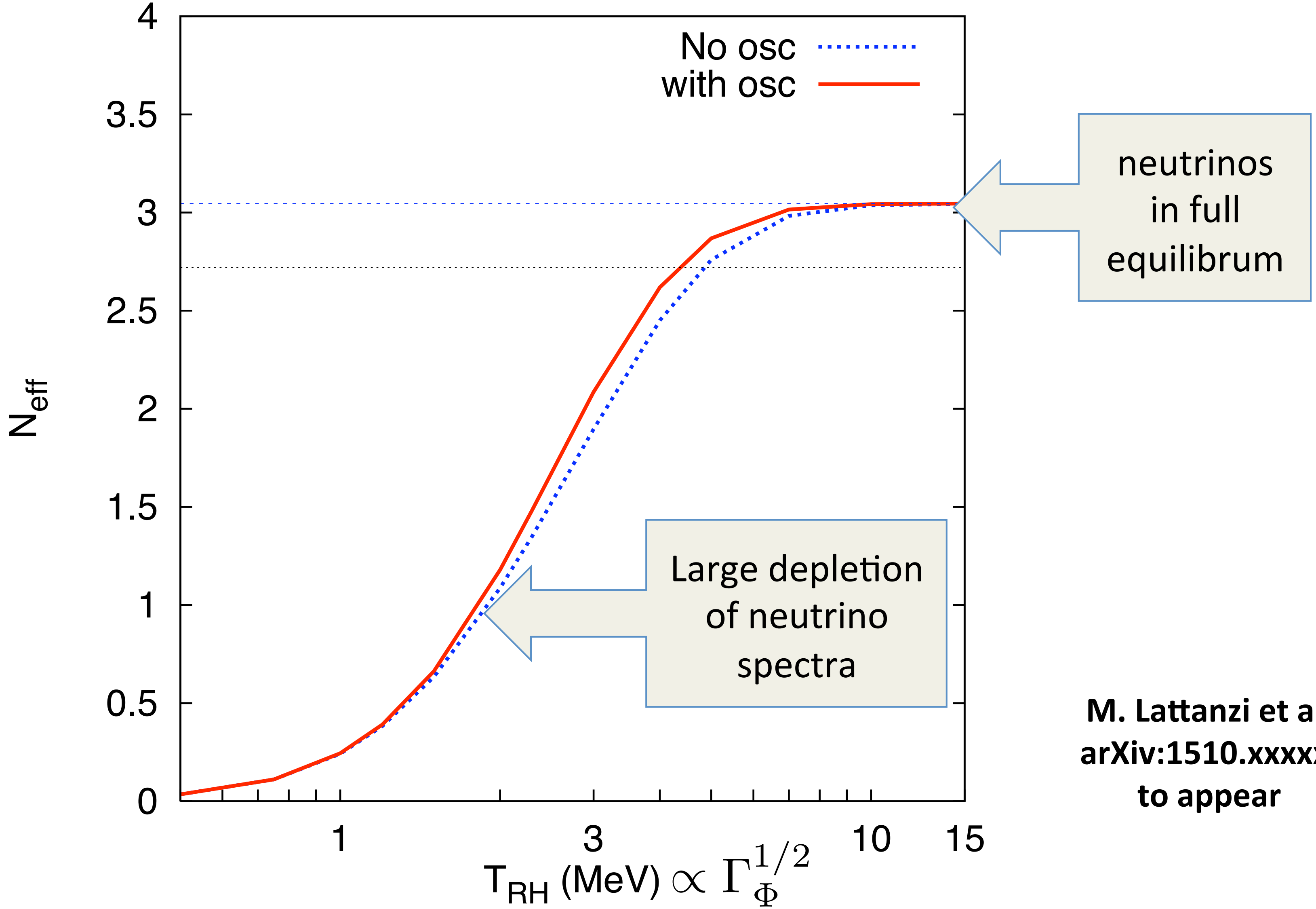
N_{eff} is a way to measure the ratio $\dfrac{\rho_\nu + \rho_x}{\rho_\gamma}$

- standard neutrinos only: $N_{eff} \simeq 3$ (3.046)

$N_{eff} < 3$?

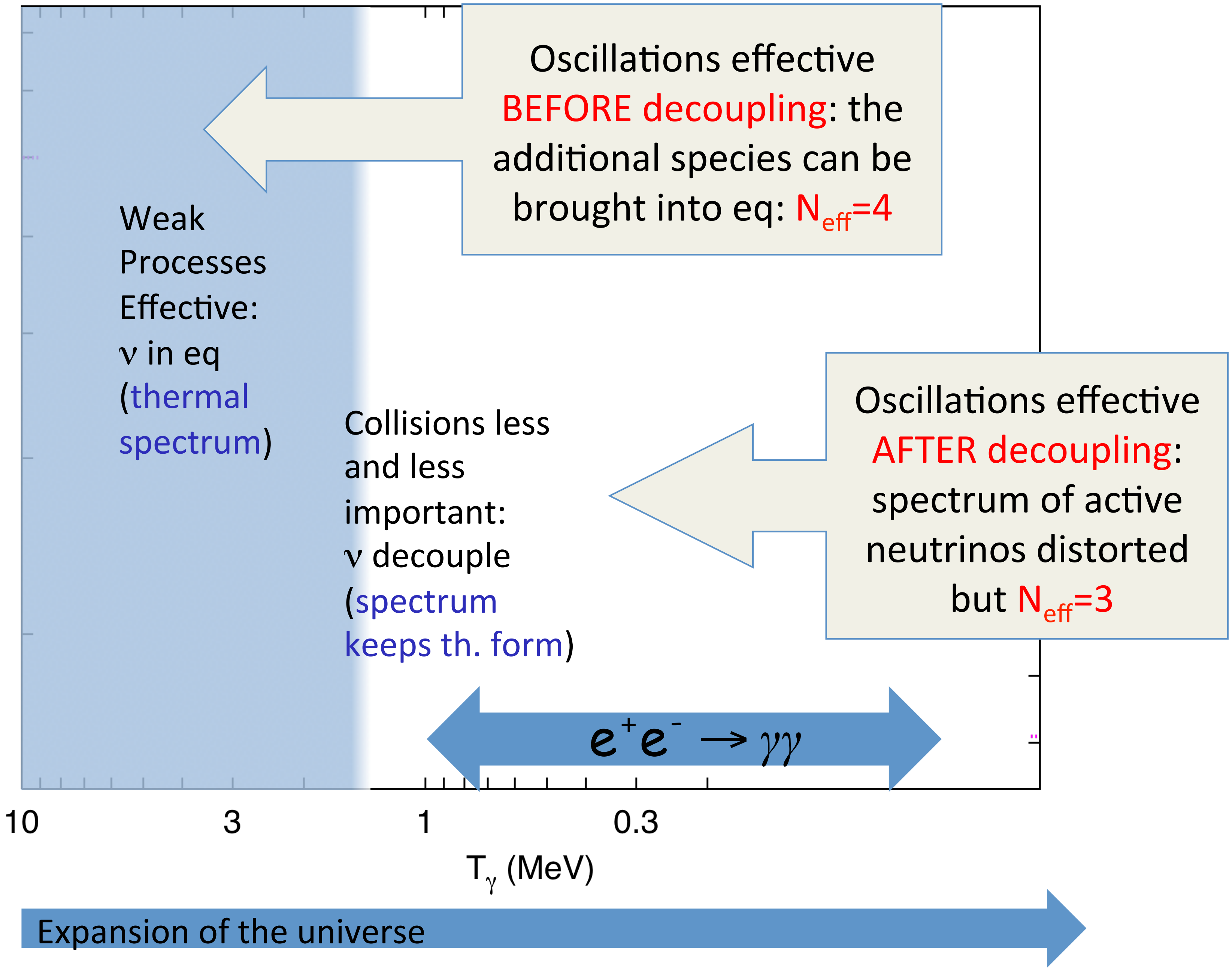

LOW-REHEATING SCENARIO
If latest reheating phase of the Universe ends in this region (T_{RH}<10 MeV), interactions not enough to bring the standard neutrinos into eq.
Weak Processes Effective: ν in eq (thermal spectrum)
Collisions less and less important: ν decouple (spectrum keeps th. form)
$e^+e^- \rightarrow \gamma\gamma$
10
3
1
0.3
T_γ (MeV)
Expansion of the universe

$N_{eff} < 3$?

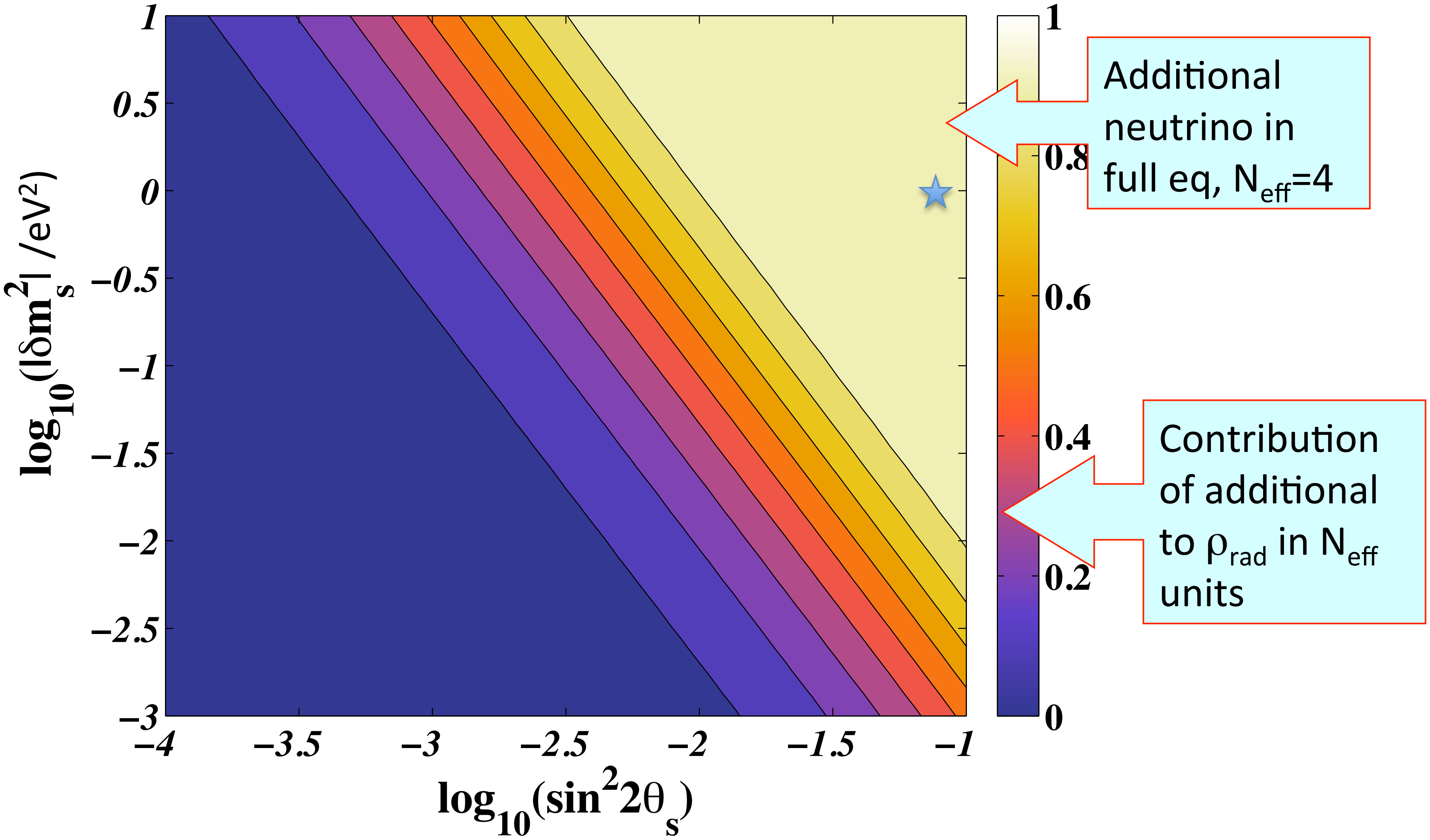


M. Lattanzi et al, arXiv:1510.xxxxx, to appear

N_{eff} & Active-sterile neutrino oscillations



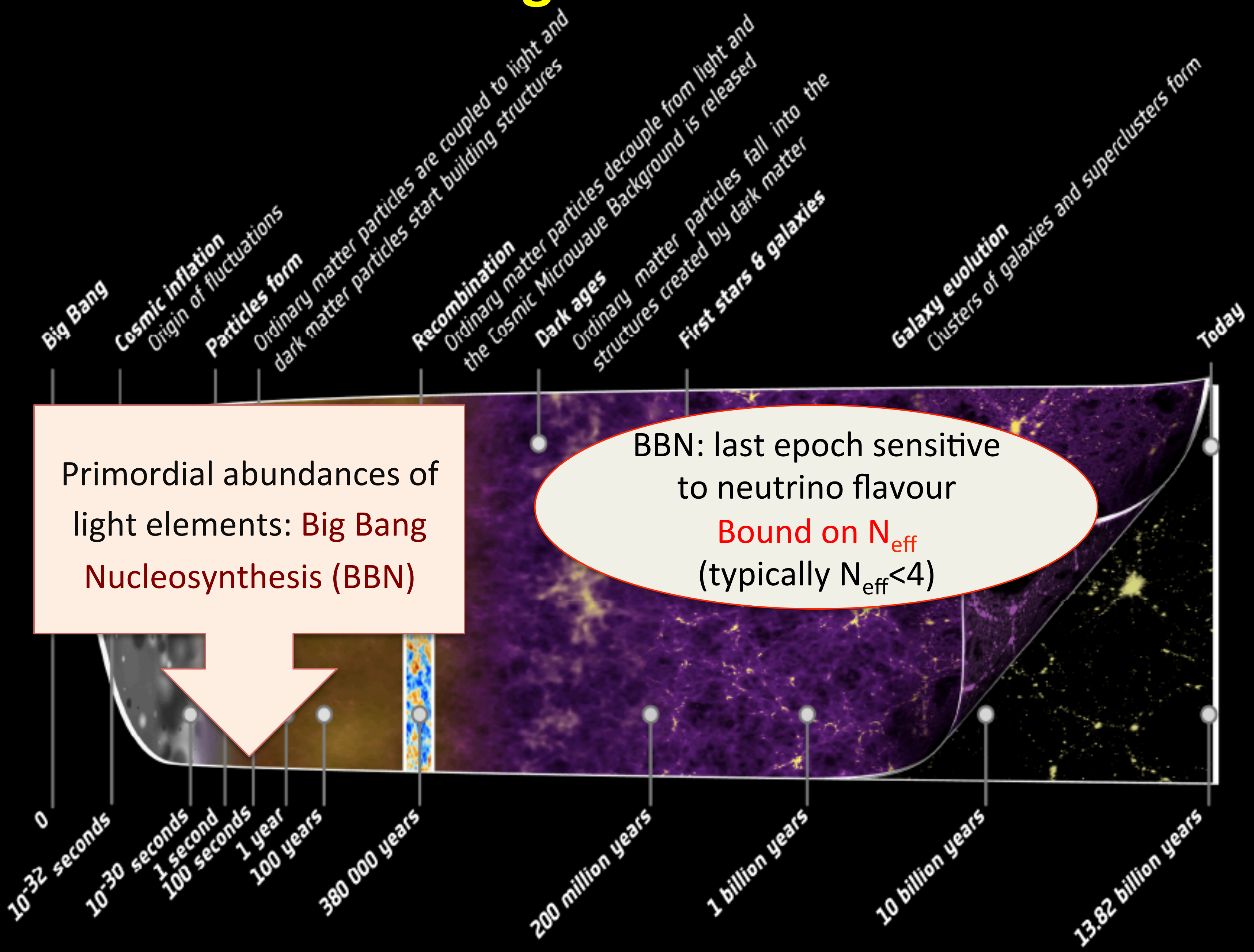
N_{eff} & Active-sterile neutrino oscillations



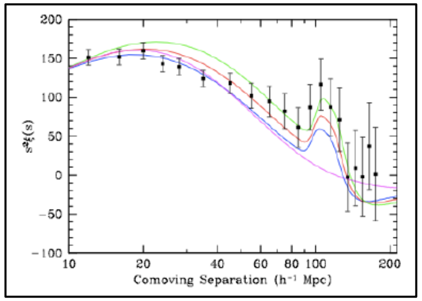
Hannestad, Tamborra & Tram, JCAP 07 (2012) 025

Cosmological Observables

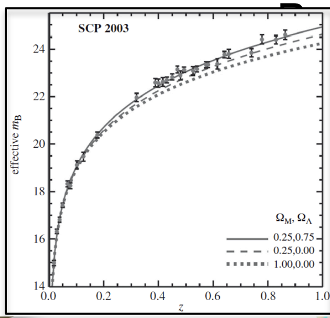
Cosmological Observables



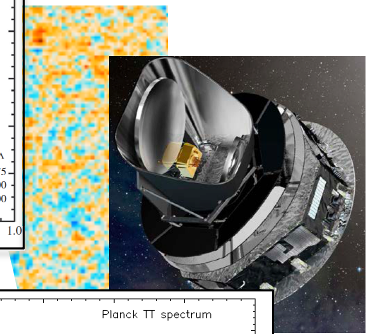
Cosmological Observables

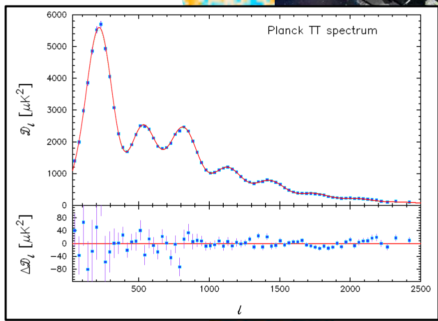


Hubble constant H_0 & cosmic distances measurements: SN Ia and Baryon Acoustic Oscillations (BAO)

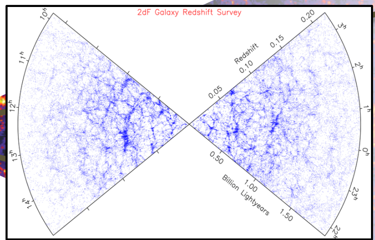


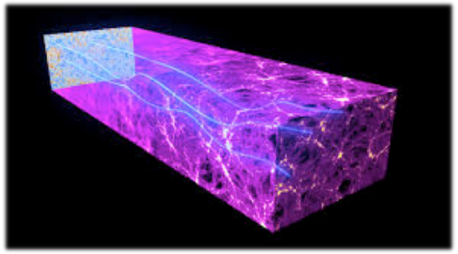
Recombination





Today





matter density fluctuations

LSS [galaxy / cosmic shear / Lyα] spectrum

Photon momentum after decoupling

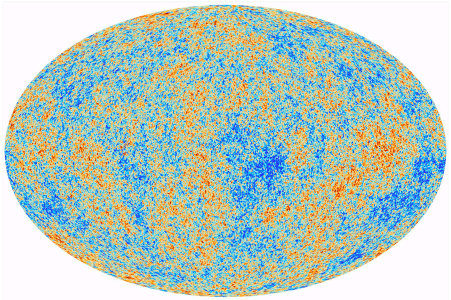
CMB secondary anisotropy spectrum

Photon density fluctuations before decoupling

CMB primary anisotropy spectrum (temp+pol)

from J. Lesgourgues

CMB data from Planck



Map of CMBR temperature Fluctuations

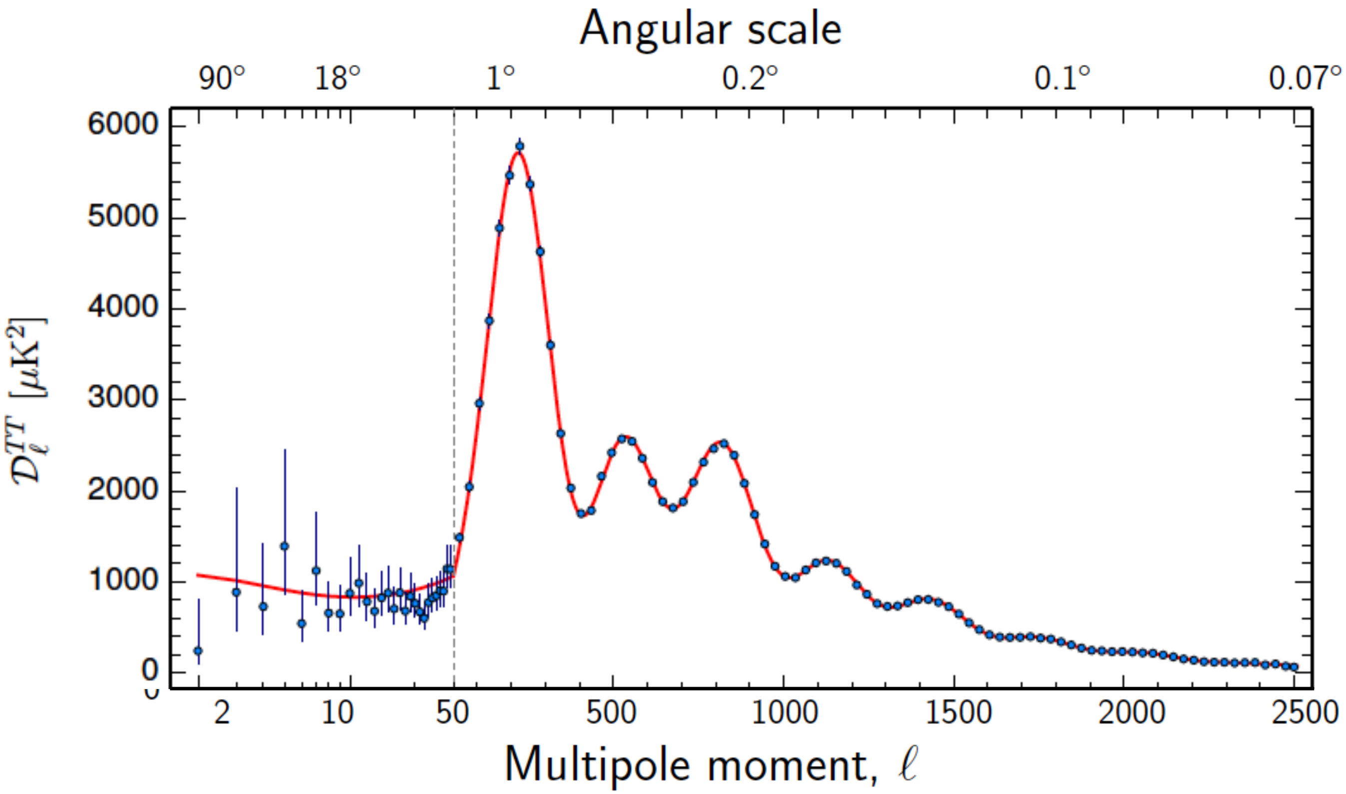
$$\Delta(\theta,\varphi)=\frac{T(\theta,\varphi)-\langle T\rangle}{\langle T\rangle}$$

Multipole Expansion

$$\Delta(\theta,\varphi)=\sum_{\lambda=0}^{\infty}\sum_{m=-\lambda}^{\lambda}a_{\lambda m}Y_{\lambda m}(\theta,\varphi)$$

Angular Power Spectrum

$$C_l=\langle a_{lm}^{*}a_{lm}\rangle=\frac{1}{2l+1}\sum_{m=-l}^{l}a_{lm}^{*}a_{lm}$$

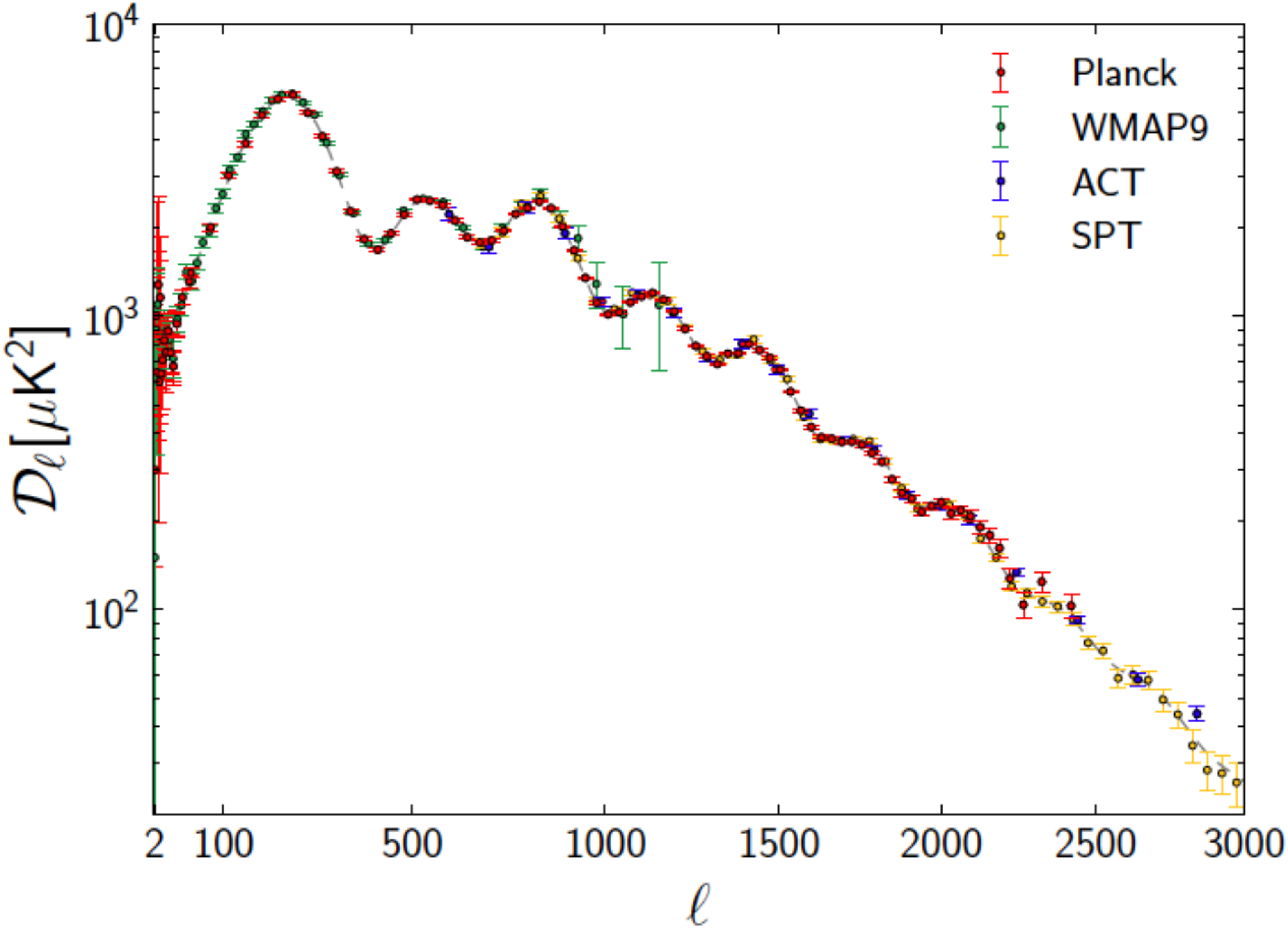


PLANCK 2015: full-mission Planck observations of temperature and polarization anisotropies

P.A.R. Ade et al, arXiv:1502.01589

Present CMB data

Planck vs other experiments



Bounds on neutrino properties from Planck (& other cosmo data)

The minimal ΛCDM model fits very well Planck data

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072

Parameter	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062

1-parameter extensions of the ΛCDM model

Parameter	TT	TT+lensing	TT+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$

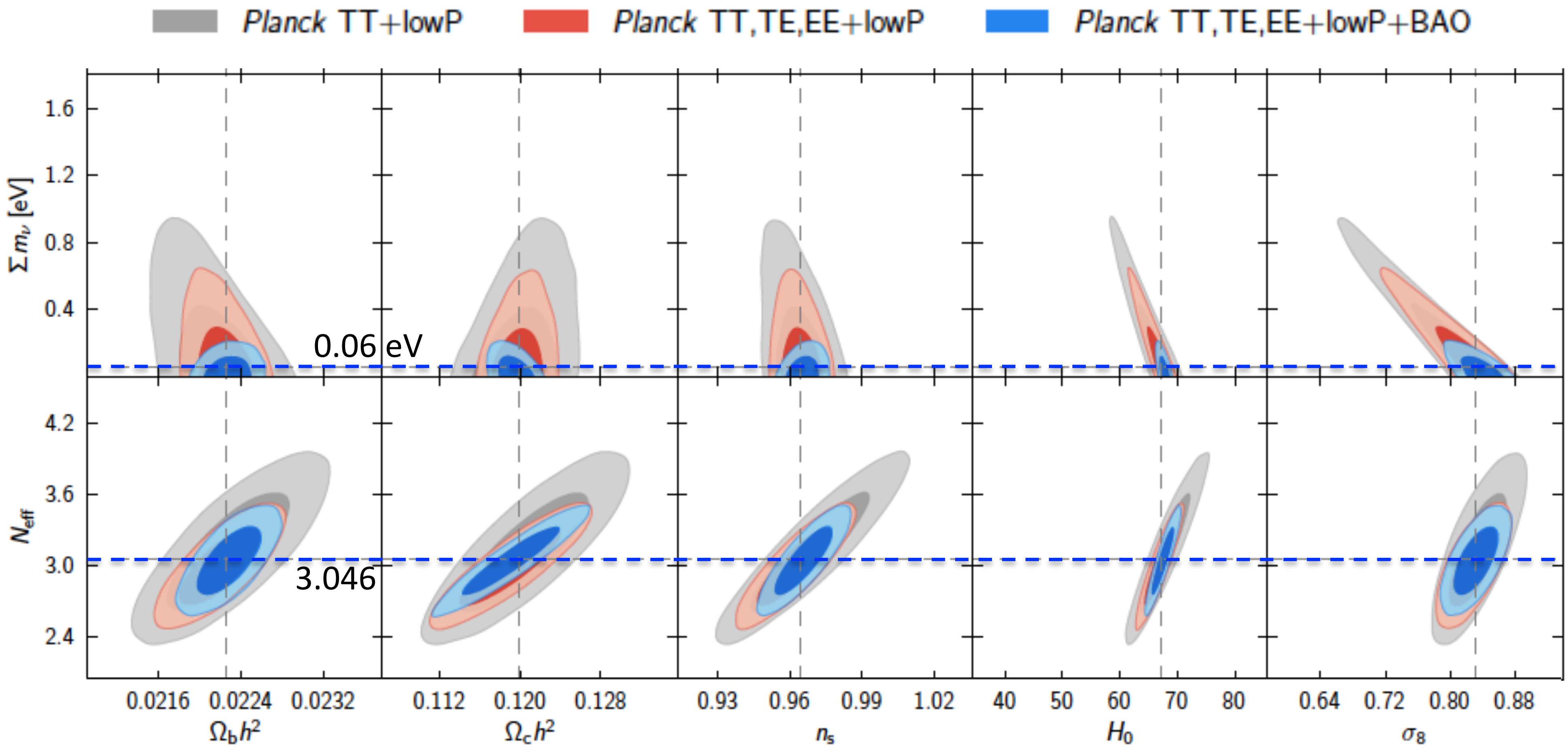
95% CL limits

Parameter	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.492	< 0.589	< 0.194
$N_{\rm eff}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.0987	< 0.112	< 0.113
w	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

Ext =BAO + JLA + H_0

Planck collaboration, arXiv:1502.01589

1-parameter extensions of the ΛCDM model

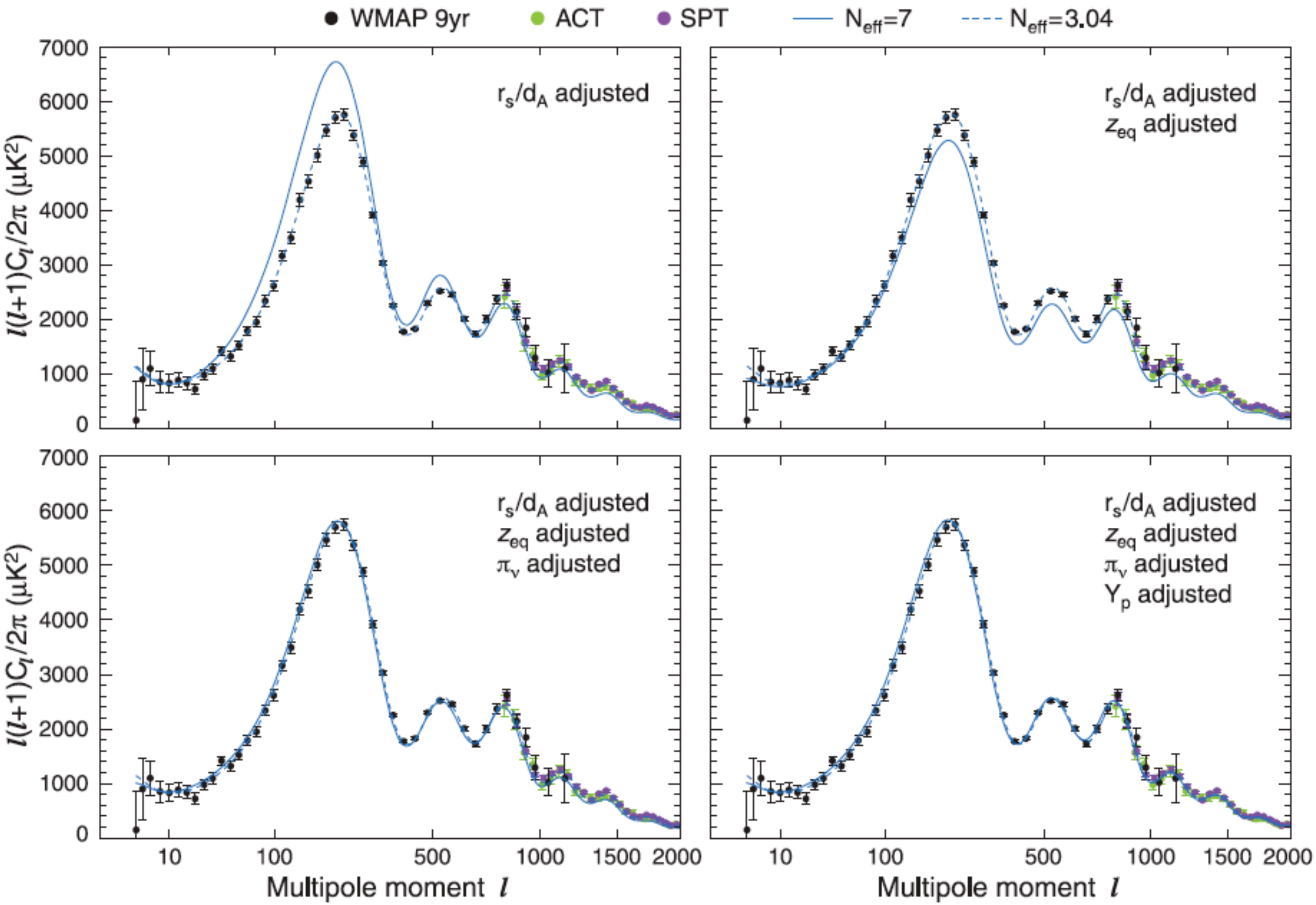


68+95%
Conf regions

Measuring N_{eff}

- N_{eff} is a parameter for the relativistic density in general
- "background effects" (change in expansion history) versus "perturbation effects" (gravitational interactions between photons and relativistic species)
- "effect of N_{eff}" depends on what is kept fixed.
- Fixing quantities best probed by CMB (angular peak scale, redshift of equality, …):
  - possible with simultaneous enhancement of radiation, matter, Λ densities, with fixed photon and baryon densities
  - then increase in N_{eff} goes with increase in H_0: positive correlation between the two

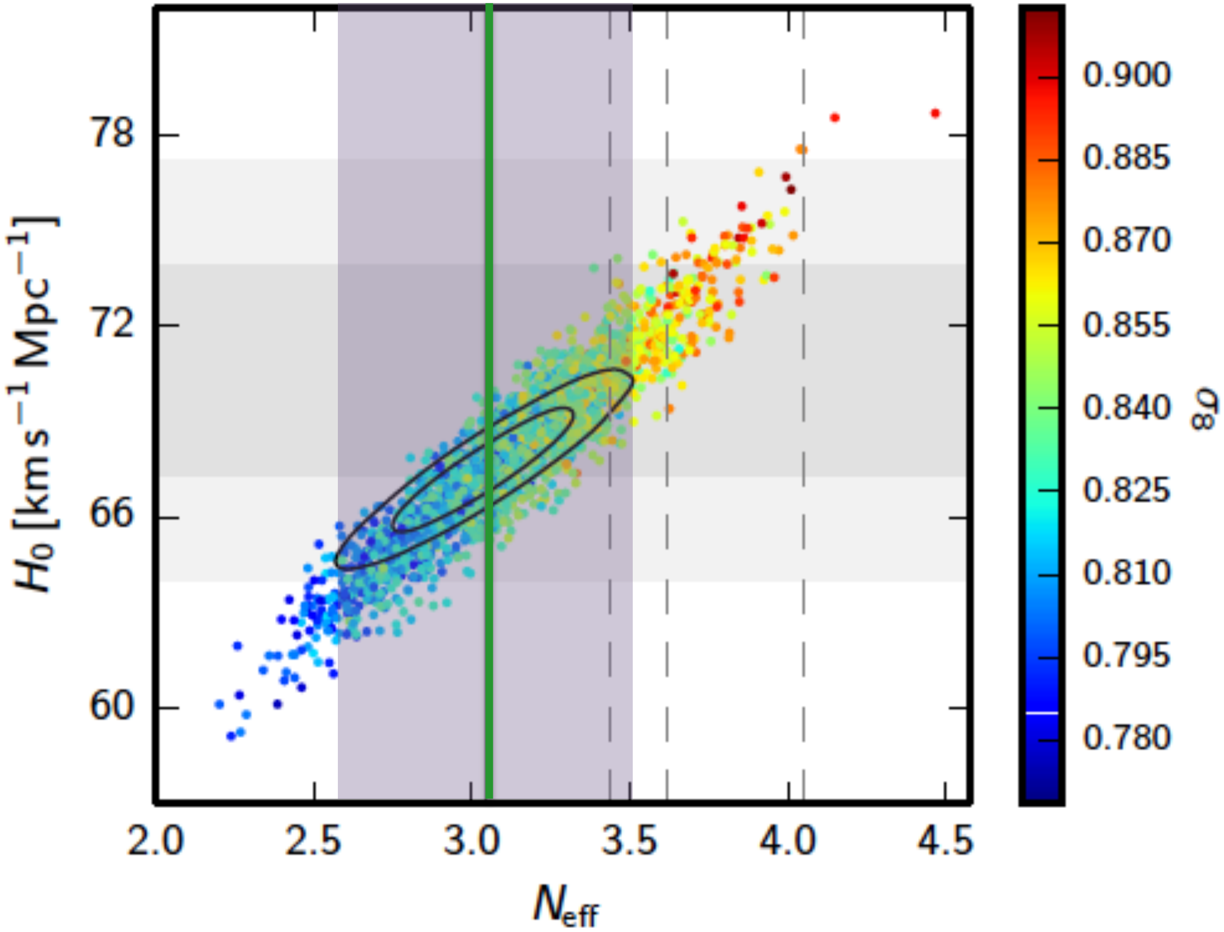
Measuring N_{eff}



Hinshaw et al, arXiv:1212.5226

Measuring N_{eff}

Indirect detection of CNB at 10-17σ



$$N_{eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP};$$

$$N_{eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO};$$

$$N_{eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP};$$

$$N_{eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}BAO}.$$

All 68%CL

Probing neutrino masses with cosmo data

Indirect probe of HDM fraction
Massive neutrinos matter today but radiation at eq.

- **Primary CMB spectrum**
- **Galaxy P(k) / BAO**
- **CMB / galaxy lensing**
- **Clusters**
- **Lyman-α**
- **H_0 , SNe-Ia**

Direct probe of free-streaming
(via scale-dependent growth factor)

Not probing directly neutrino masses
but removing parameter degeneracies

Measuring m_ν with the CMB

- Neutrinos contribute to radiation at early times and non-relativistic matter at late times
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at photon decoupling. In principle the primary CMB TT spectrum sensitive to $\Sigma m_\nu > 1.5$ eV
- "effect of m_ν" depends on what is kept fixed
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:
  - Possible by fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ
  - then increase in m_ν goes with decrease in H_0: negative correlation between the two
  - "base model" in Planck has (0.06, 0, 0) eV masses: shifts best-fitting H_0 by -0.6 h/km/Mpc with respect to massless case

Measuring m_ν with Planck

CMB alone (Planck TT+lowP):

$\Sigma m_\nu < 0.72$ eV

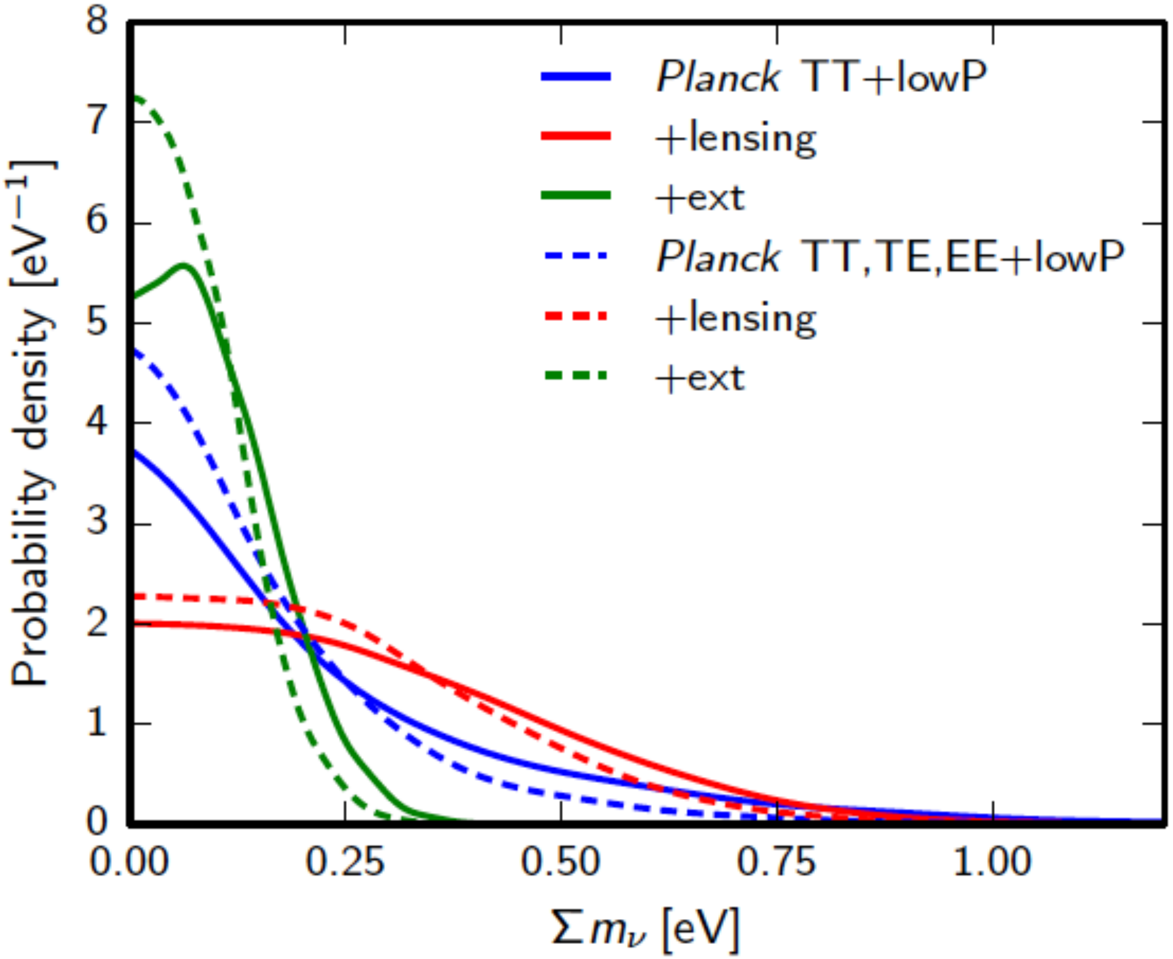
+ TE,EE+ lensing:

$\Sigma m_\nu < 0.59$ eV

Planck TT+lowP+lensing+ext:

$\Sigma m_\nu < 0.23$ eV

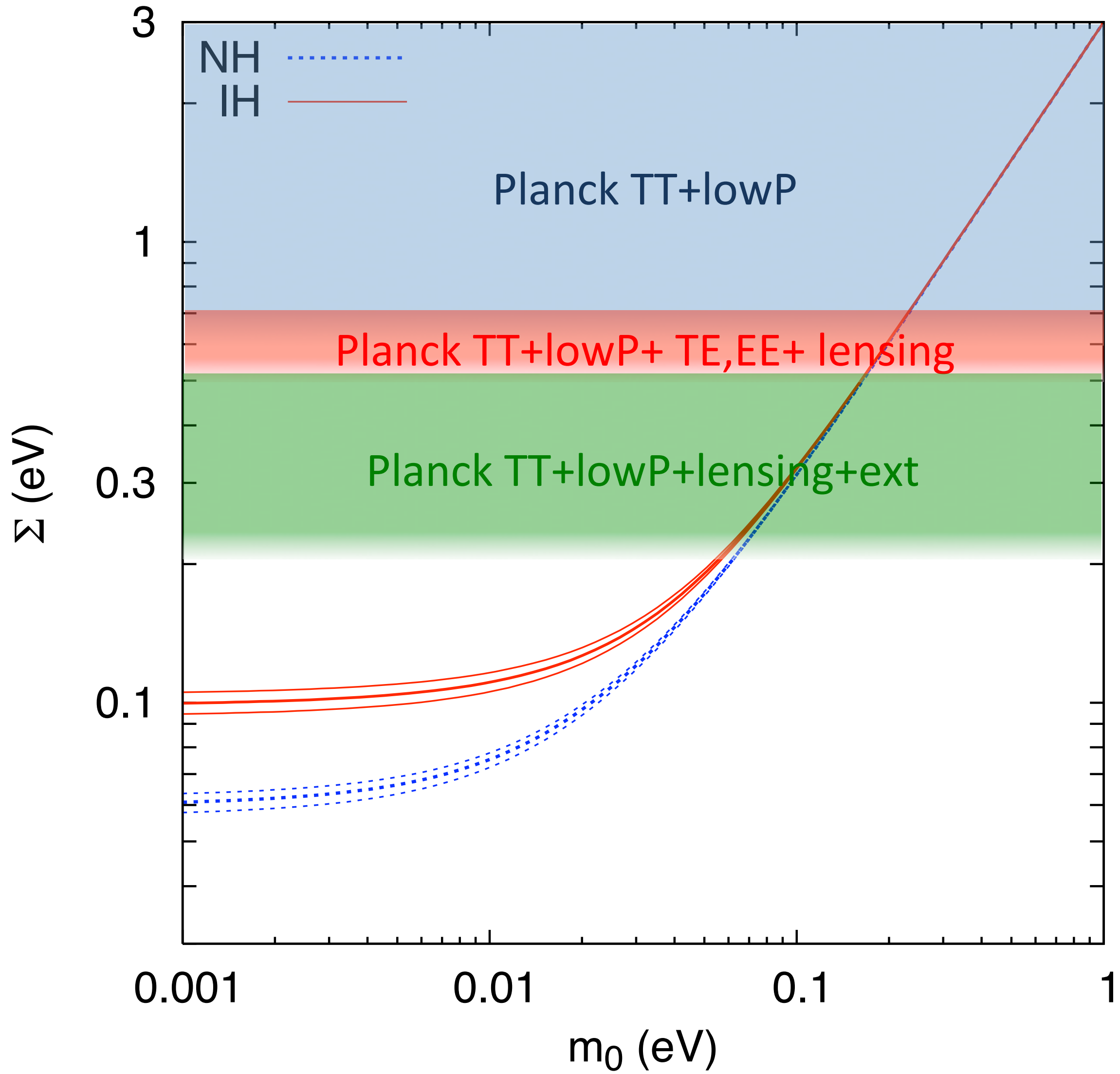
All 95% CL.



Planck collaboration, arXiv:1502.01589

Measuring m_ν with Planck

Cosmological upper limits on the sum of neutrino masses



Some combination of data leads to $m_\nu>0$

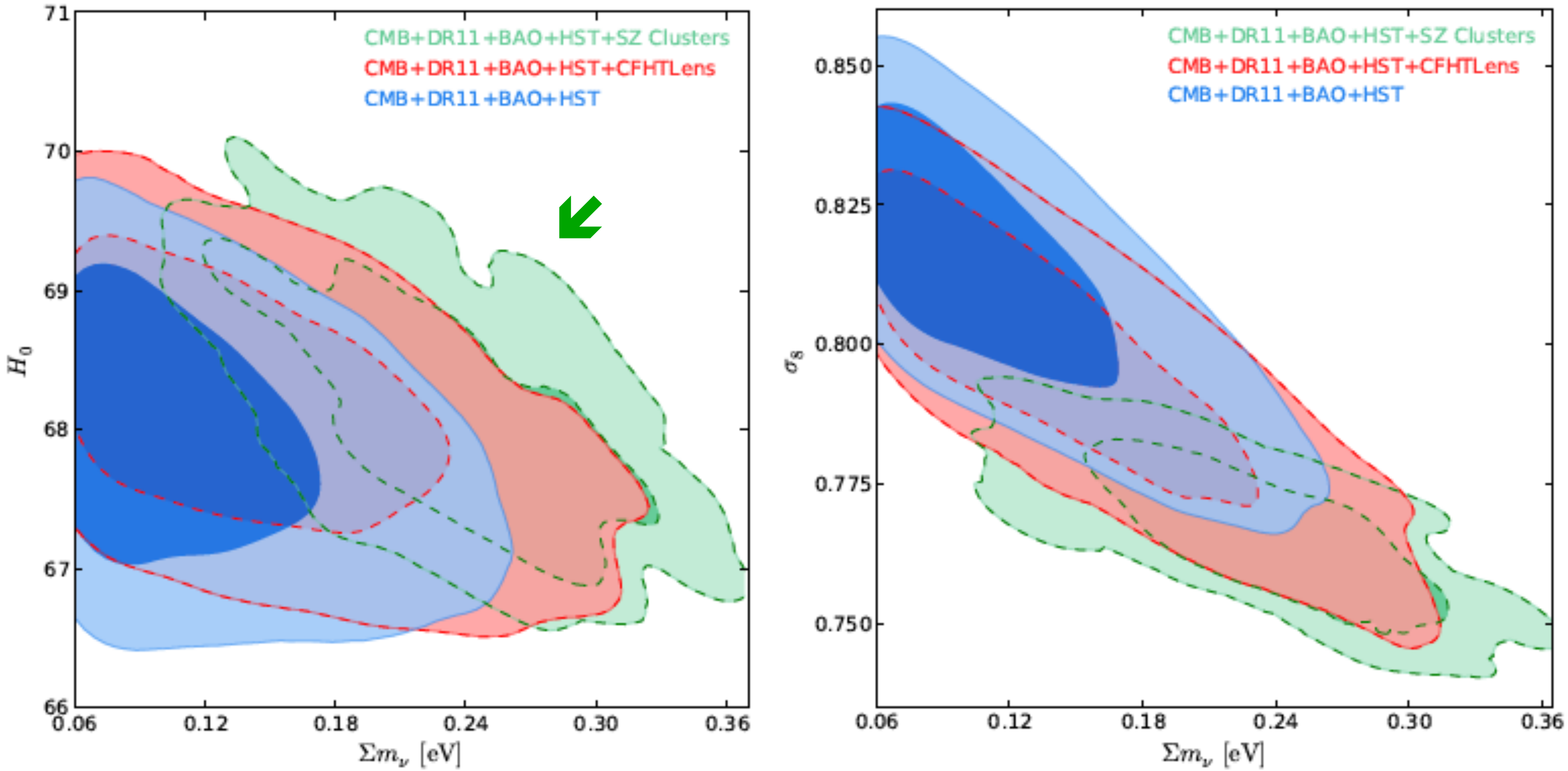


FIG. 1: Left panel: the blue contours show the 68% and 95% CL allowed regions from the combination of CMB data, BOSS DR11 BAO measurements, additional BAO measurements and a prior on the Hubble constant from HST in the ($\sum m_\nu$ (eV), H_0) plane. The red (green) contours depict the results when the $\sigma_8 - \Omega_m$ weak lensing (galaxy number counts) constraint is added in the analysis. Right panel: as in the left panel but in the ($\sum m_\nu$ (eV), σ_8) plane.

Giusarma et al, PRD 90 (2014) 043507 [arXiv:1403.4852]

Probing the absolute neutrino mass scale

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

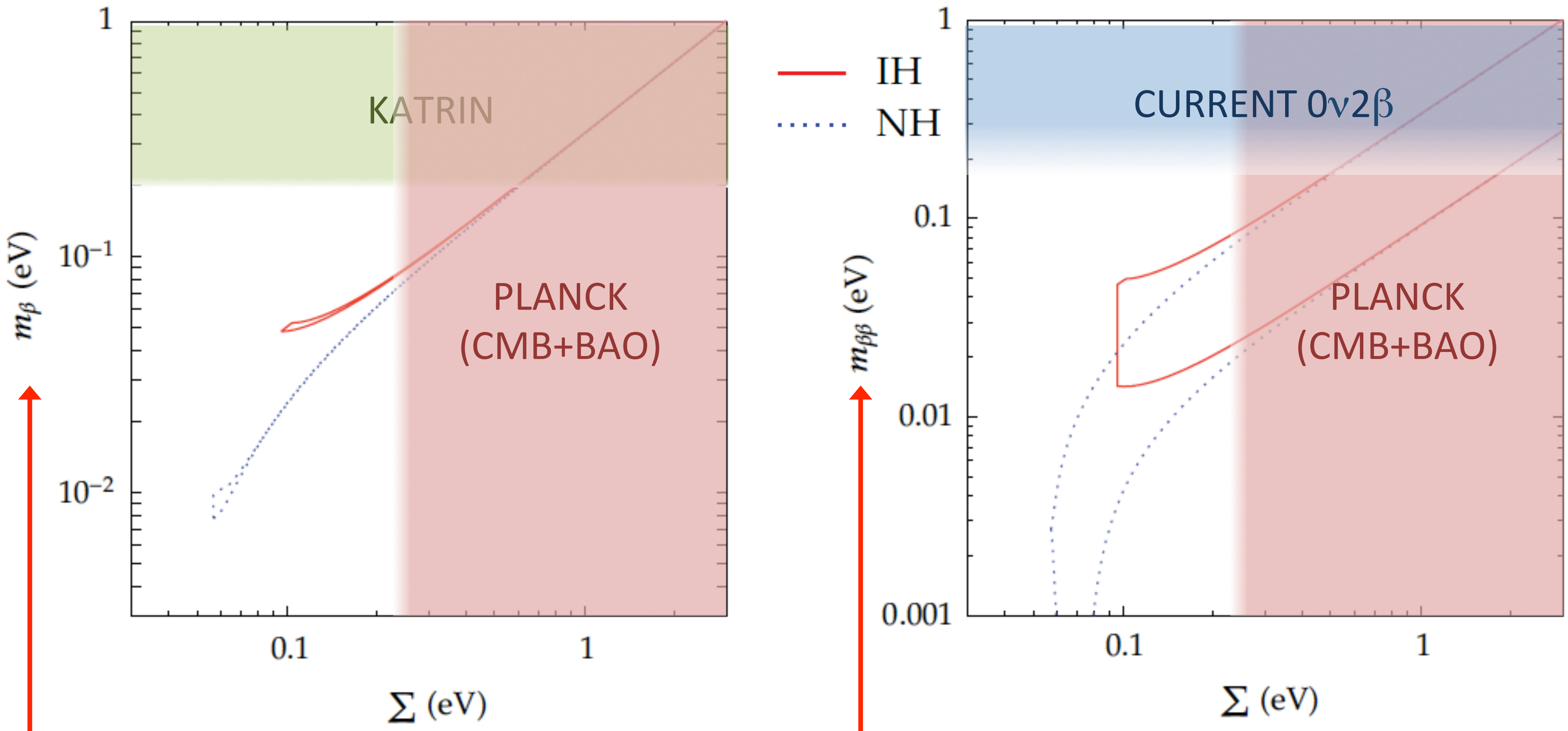
$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

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

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

Cosmology	$\sim \sum_i m_i$	< 0.23-0.7 eV

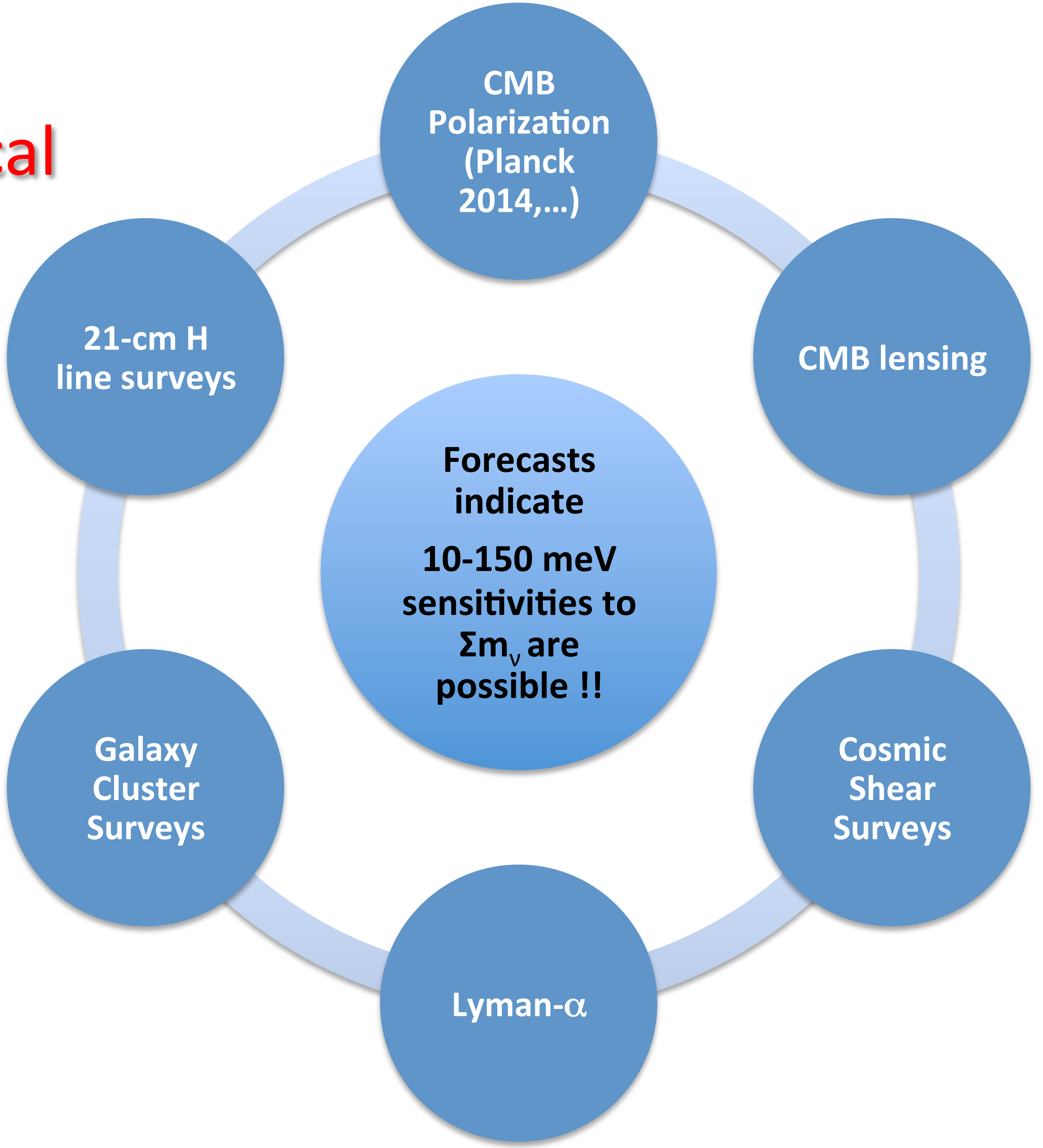
Tritium β decay, 0ν2β and Cosmology



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

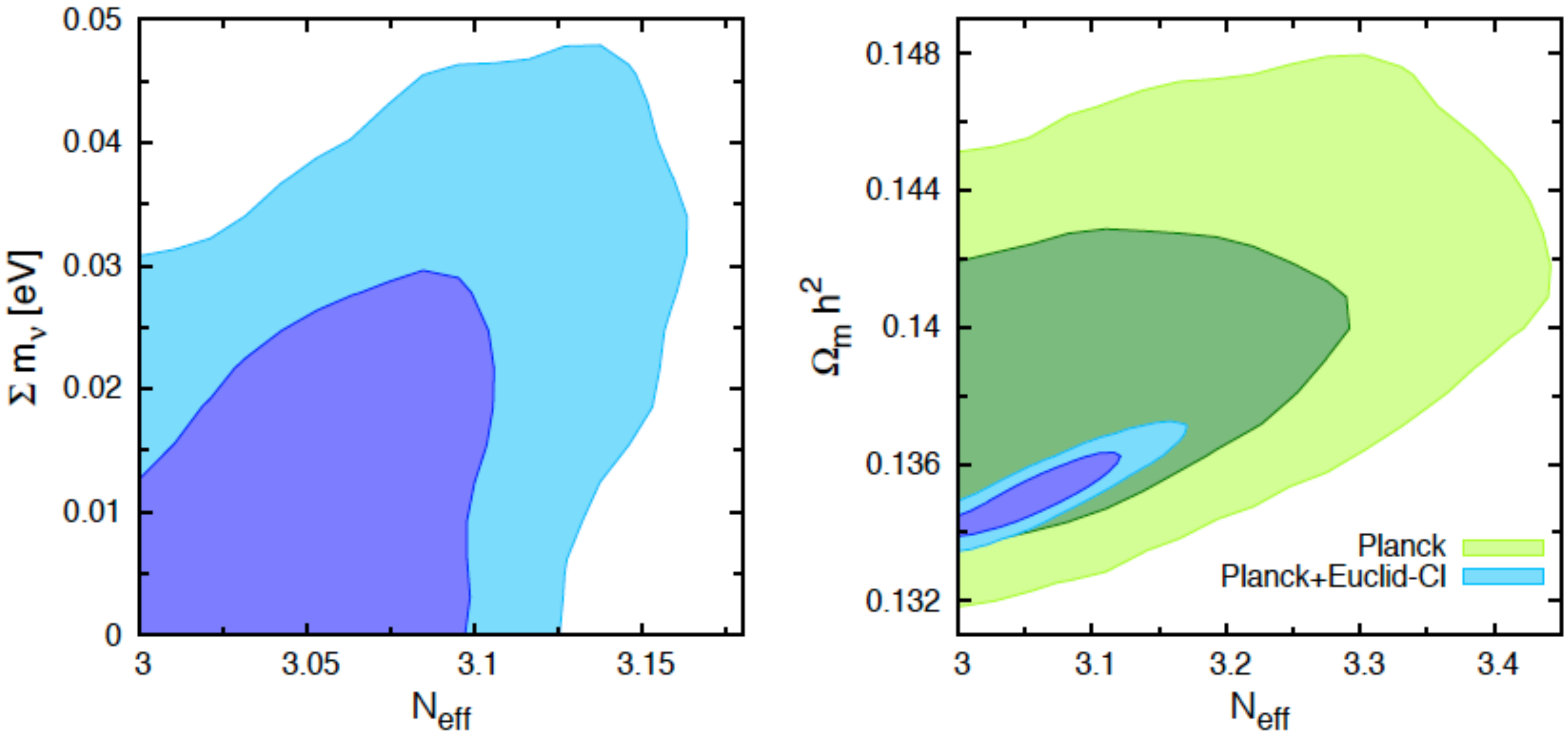
$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

Future cosmological data



Future sensitivities to N_{eff} and Σm_ν

Example of forecast: PLANCK + Euclid-like photometric galaxy cluster survey



Data		Planck+Euclid-Cl	
Model		wCDM+m_ν+$N_{\rm eff}$	ΛCDM+m_ν+$N_{\rm eff}$+$\Omega_{\rm k}$
$\sum m_\nu$ [eV]	68% CL	< 0.024	< 0.024
	95% CL	< 0.046	< 0.046
$N_{\rm eff}$	95% CL	< 3.16	< 3.17

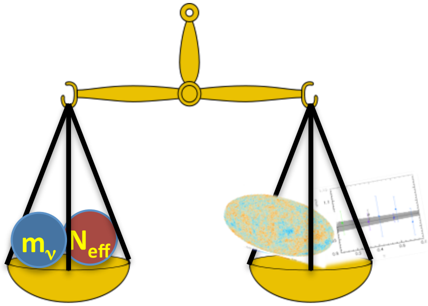
M.C.A. Cerbolini et al, JCAP 06 (2013) 020 [arXiv:1303.4550]

Future sensitivities on neutrino masses

Probe	Potential sensitivity (short term) 5-7 years	Potential sensitivity (long term) 7-15 years
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

✓ With Planck data, including CMB lensing, we can measure combinations of cosmological parameters with high precision. Still ΛCDM fits very well the data

✓ No evidence yet for nonzero neutrino masses or an enhanced radiation density (N_{eff}). Bounds **$\Sigma m_\nu < 0.2\text{-}0.7$ eV** (95% CL) and **$N_{eff} = 3.15 \pm 0.23$** (68% CL), depending on data

✓ Improved sensitivities from a variety of future cosmological data to reach $\Sigma m_\nu < 0.1$ eV

For more details...