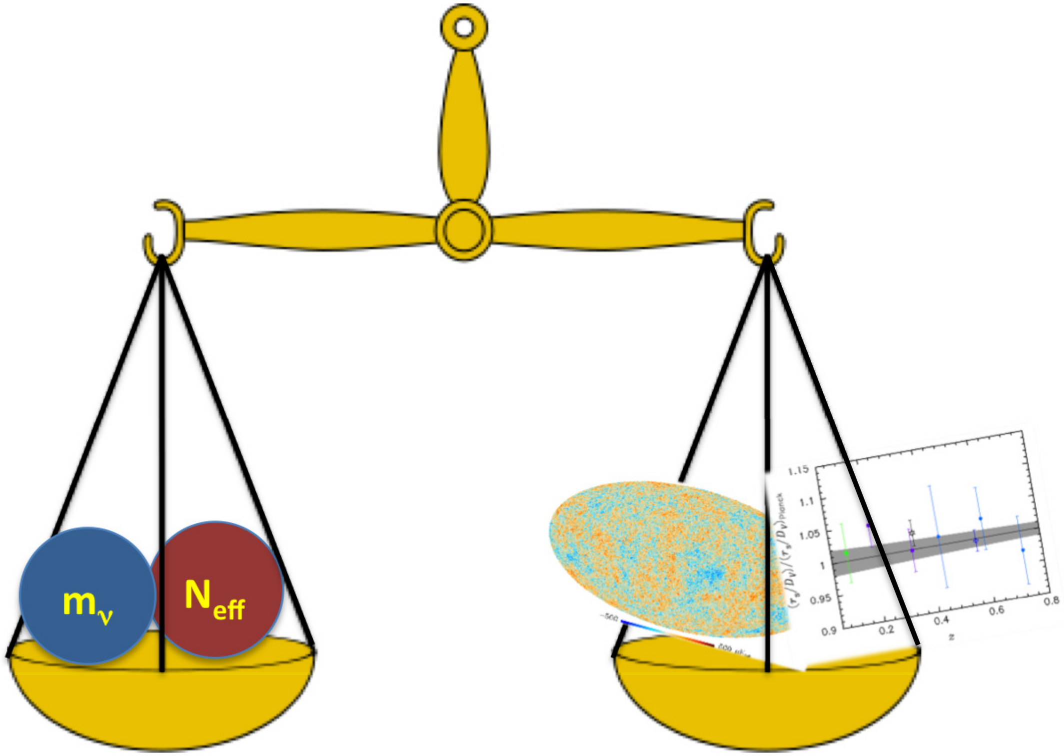
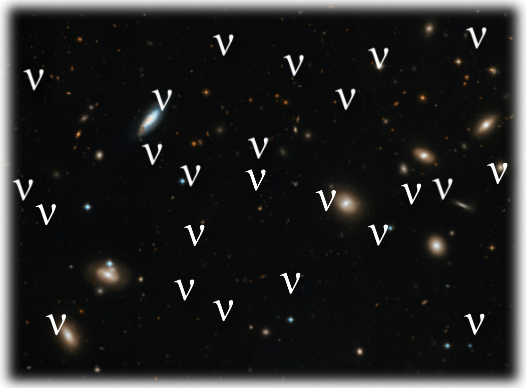
Neutrino properties from cosmological observables after Planck



Sergio Pastor
(IFIC Valencia)

Max-Planck-Institut für Kernphysik
17 June 2013

Outline



Introduction: the Cosmic Neutrino Background

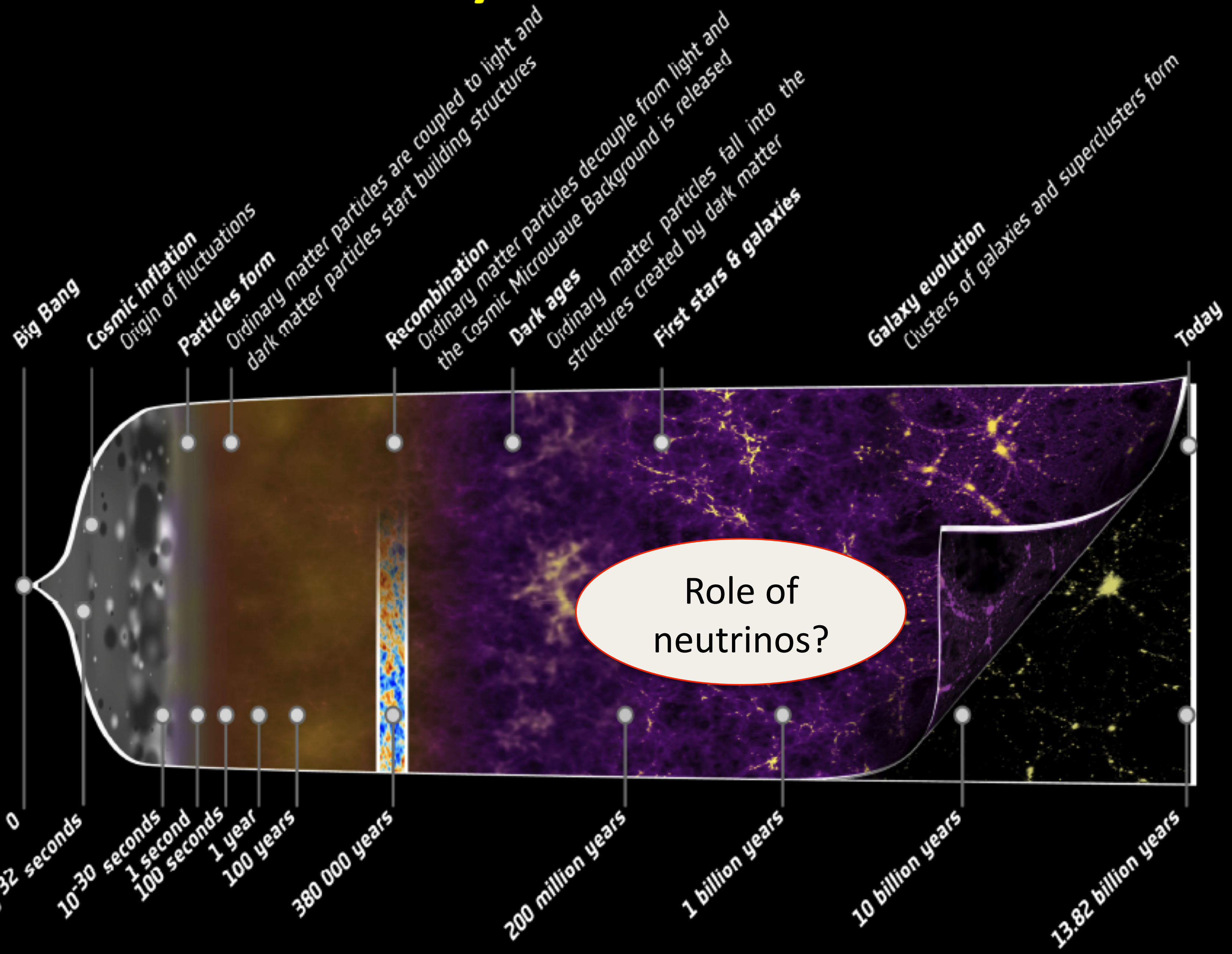
Neutrinos as Dark Matter

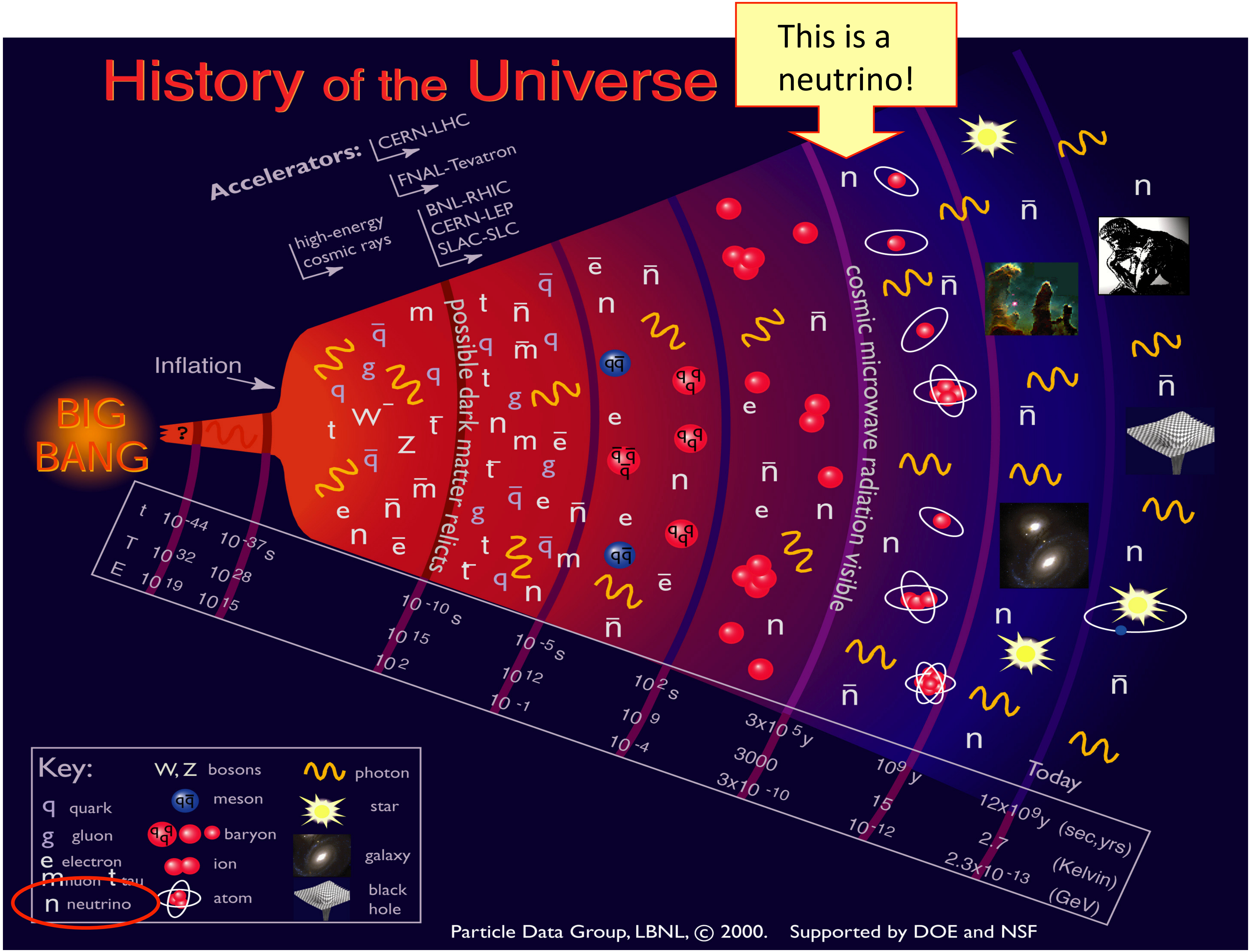
The radiation content of the Universe (N_{eff})

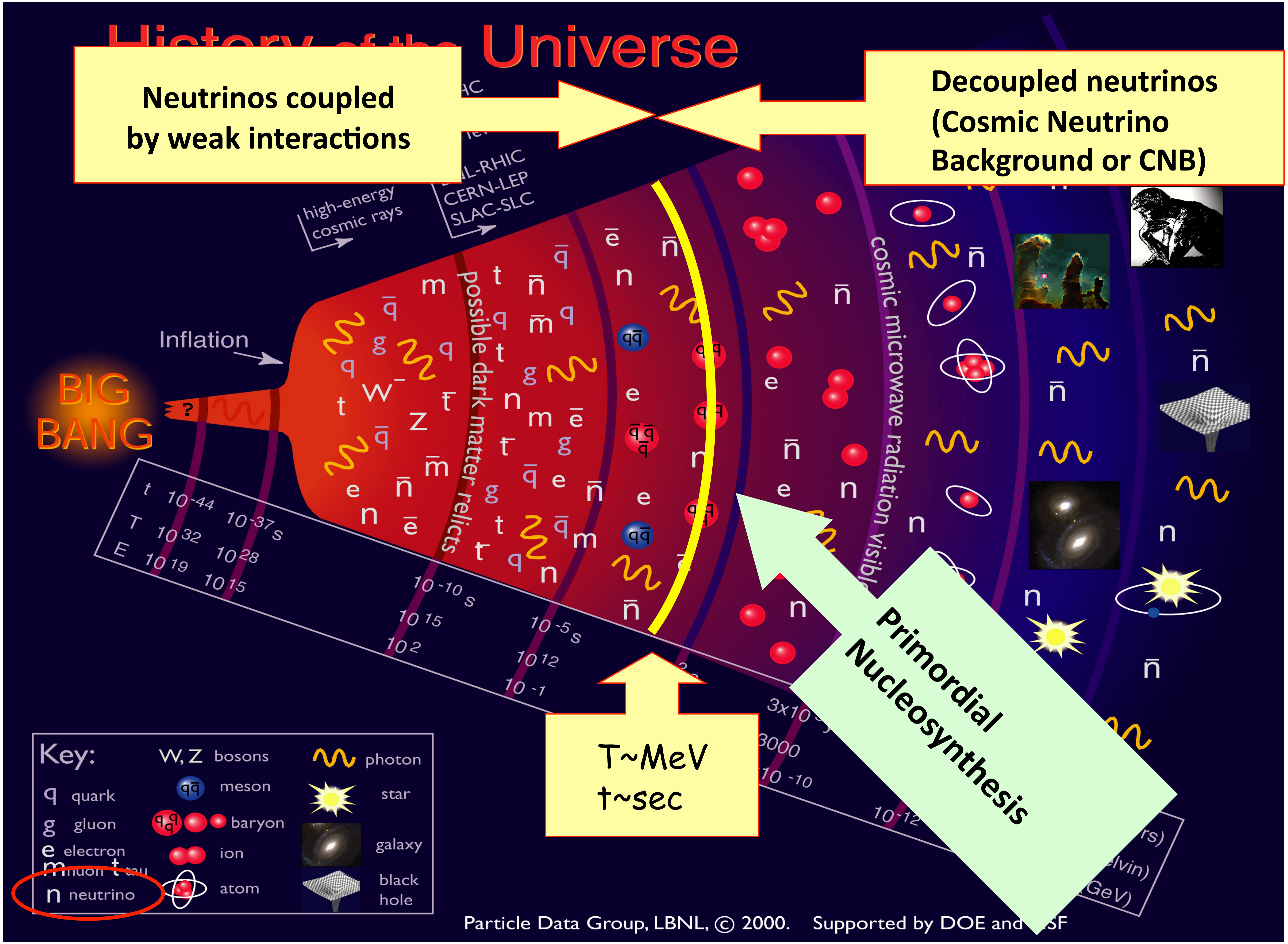
Bounds on neutrino properties from Planck (& other cosmo data)

Introduction: the Cosmic Neutrino Background

History of the Universe

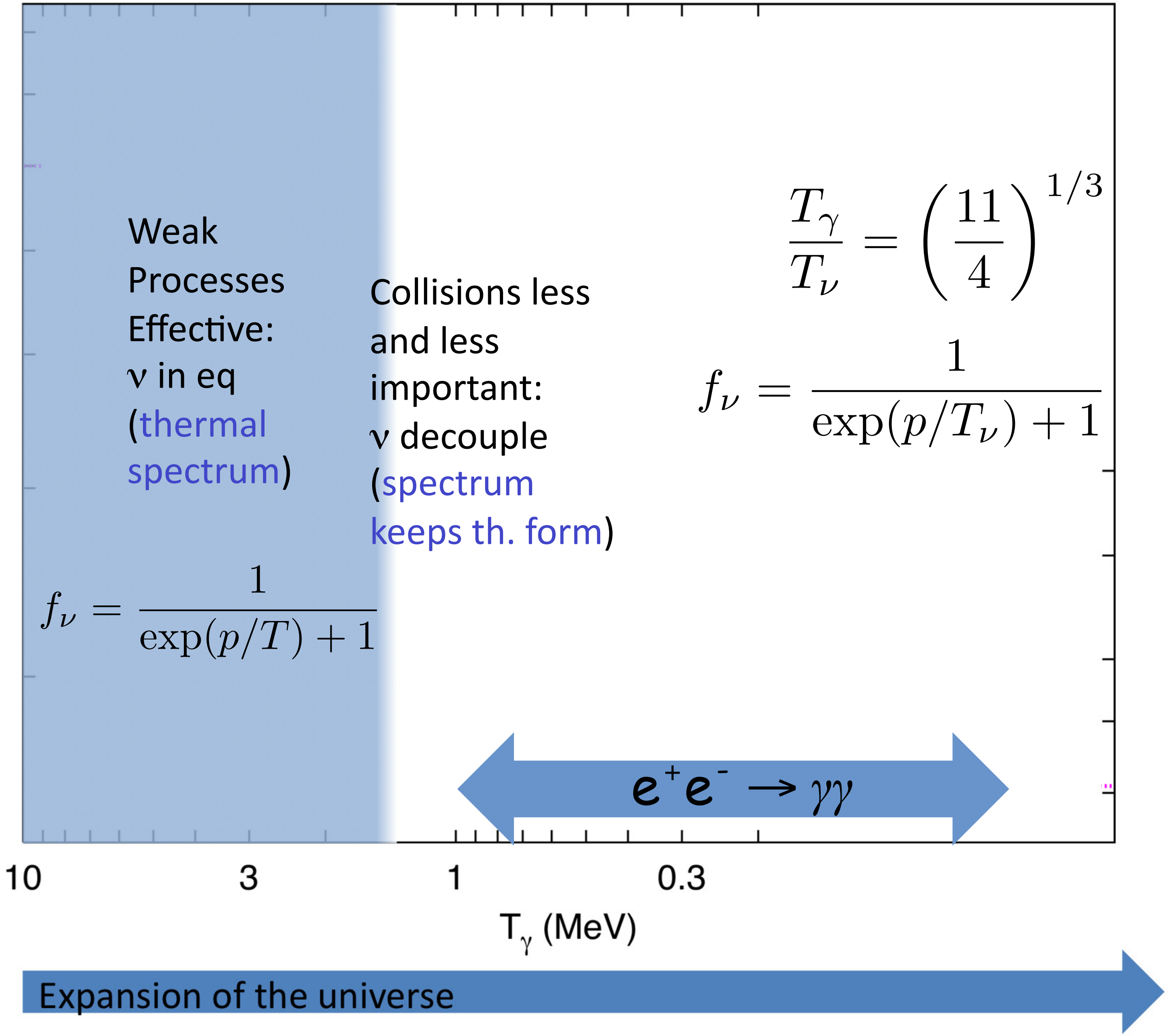


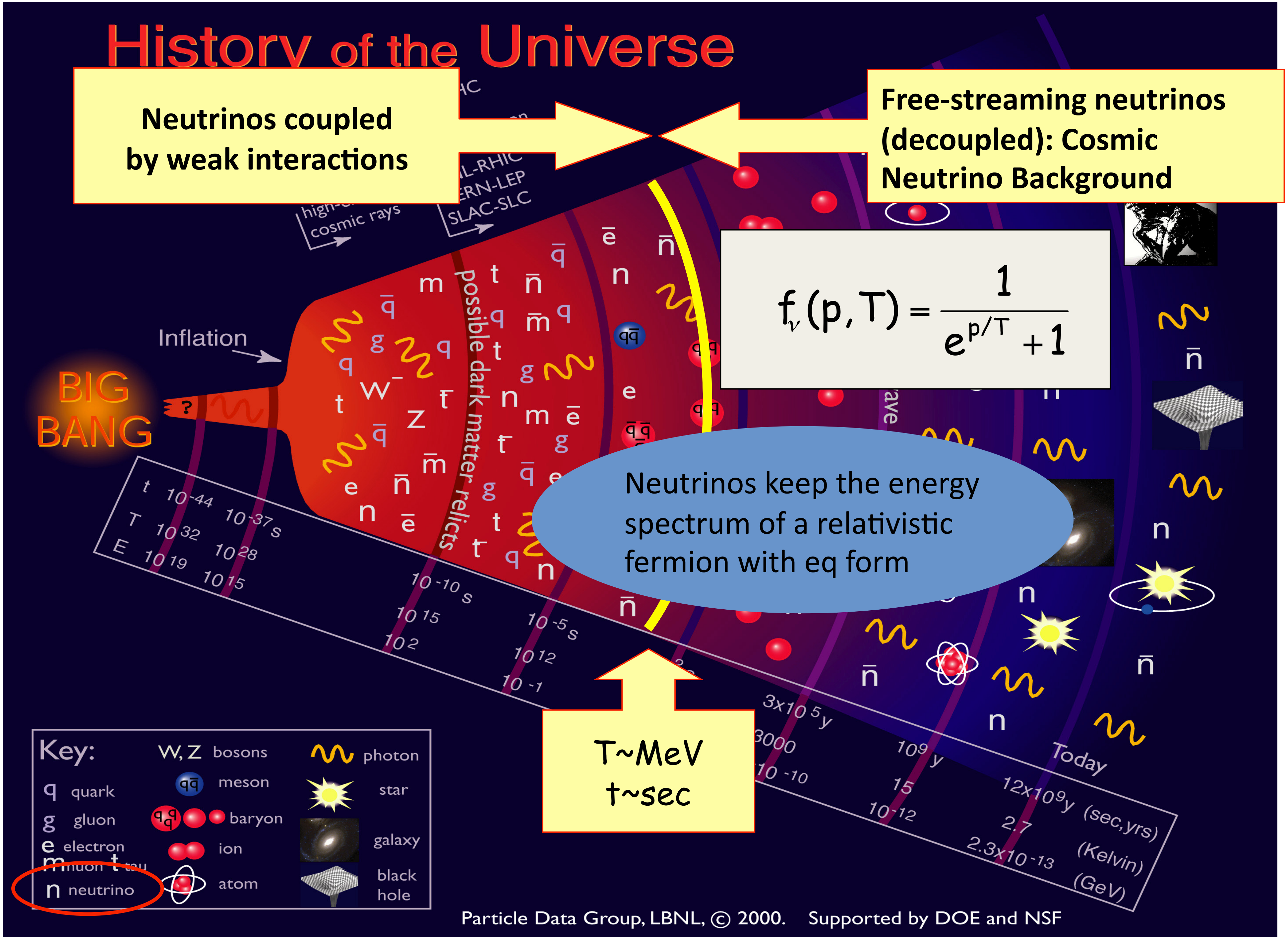

History of the Universe
This is a neutrino!
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

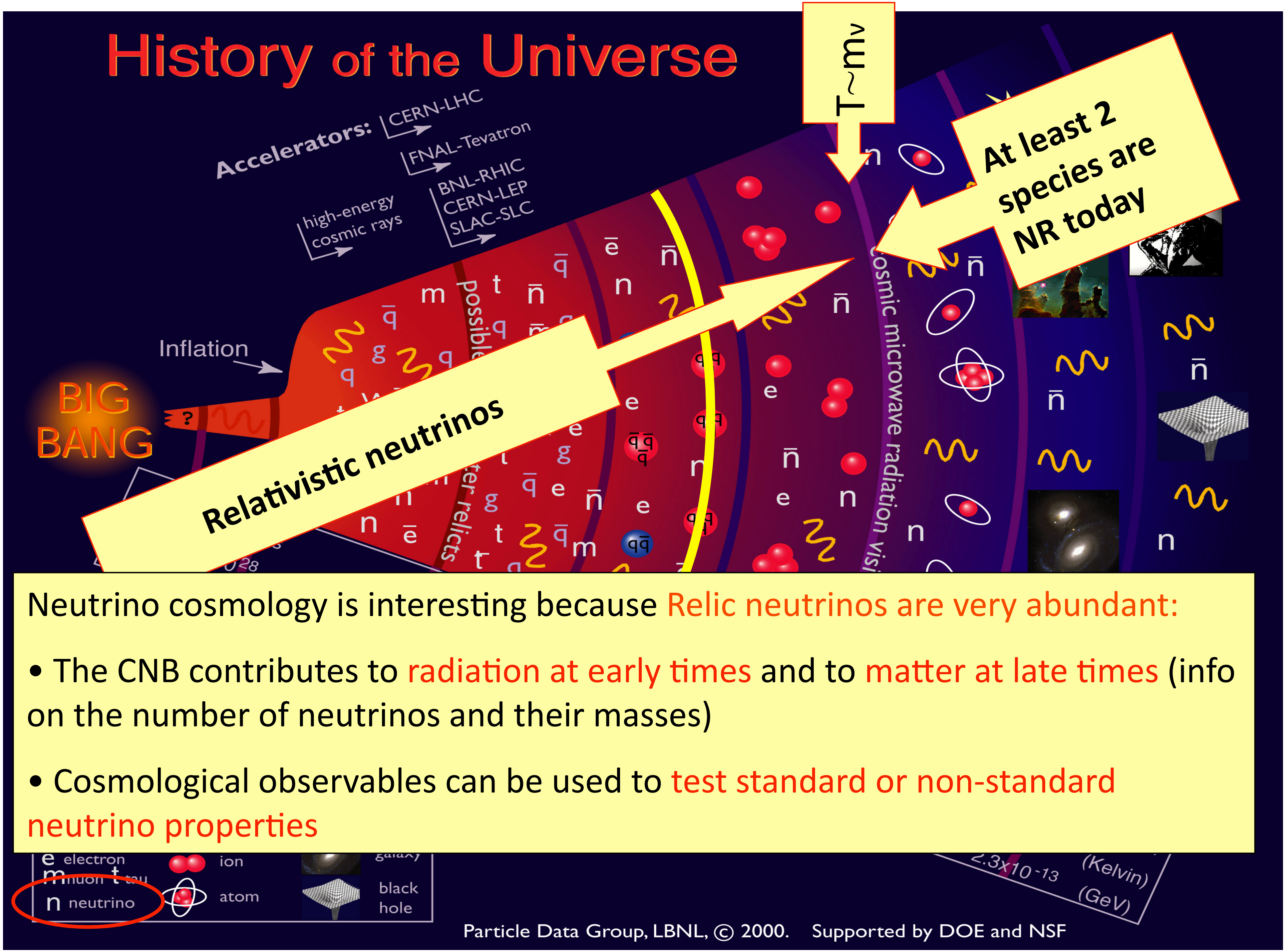


Universe
Neutrinos coupled
by weak interactions
Decoupled neutrinos
(Cosmic Neutrino
Background or CNB)
high-energy
cosmic rays
CERN-LEP
SLAC-SLC
Inflation
BIG
BANG
possible dark matter relicts
cosmic microwave radiation
T~MeV
t~sec
Primordial
Nucleosynthesis
Key:
q quark
g gluon
e electron
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black
hole
Particle Data Group, LBNL, © 2000.

ν Decoupling and e± annihilations




History of the Universe
Neutrinos coupled by weak interactions
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
BIG BANG
Inflation
possible dark matter relicts
cosmic rays
SLAC-SLC
Key:
quark
gluon
electron
muon
tau
neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Today
(sec,yrs)
(Kelvin)
(GeV)
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



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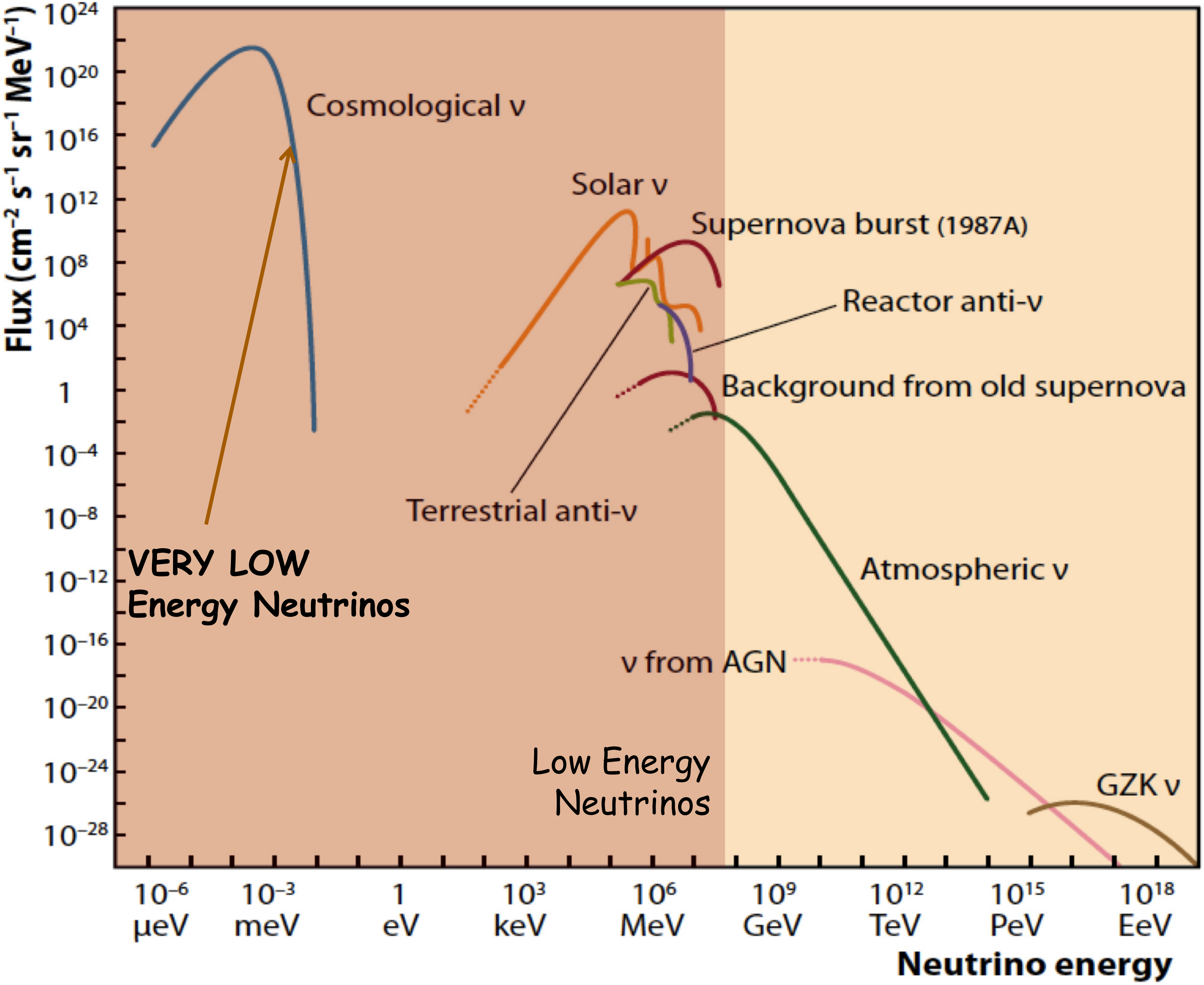
$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1\ \mathrm{eV}}$$ Massive

$m_\nu >> T$

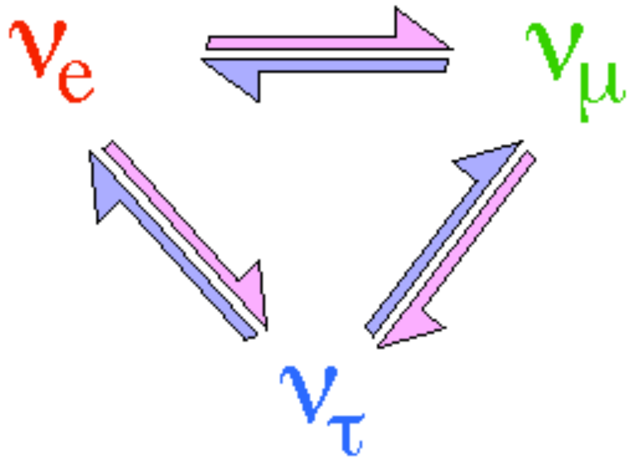


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
VERY LOW
Energy Neutrinos
Atmospheric ν
ν from AGN
Low Energy
Neutrinos
GZK ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ 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

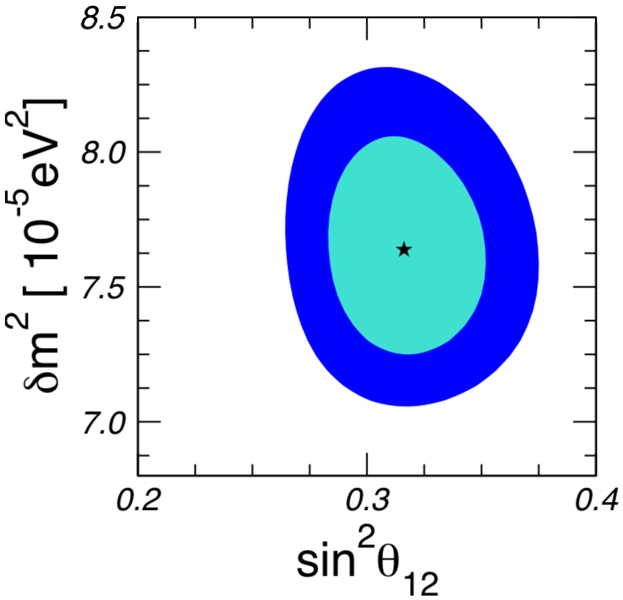


$$(e,\mu,\tau) \leftrightarrow (\nu_1,\nu_2,\nu_3)$$

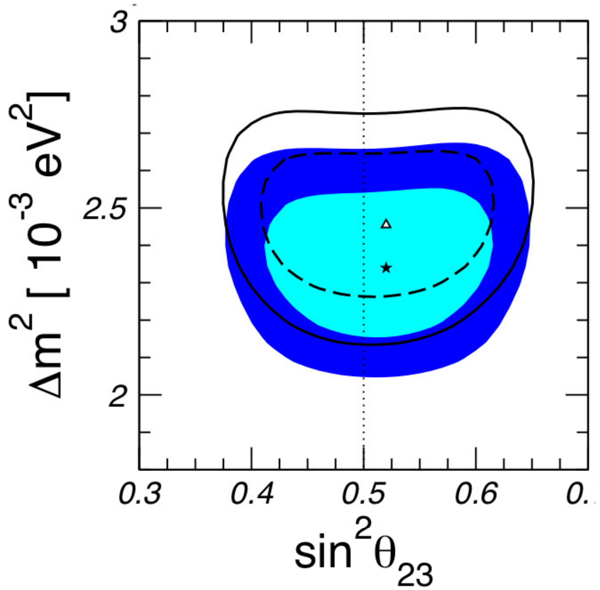
$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL}, \quad (\alpha = e,\mu,\tau)$$

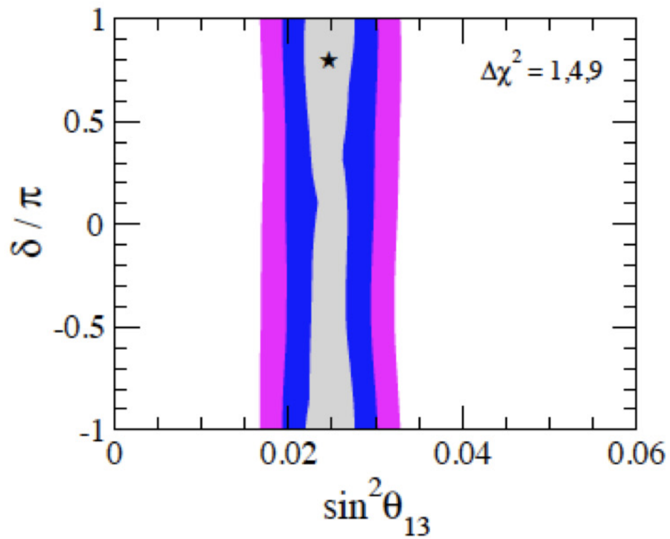
$$\begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \left[\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}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

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



parameter	best fit	1σ range	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.62	7.43–7.81	7.27–8.01	7.12–8.20
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2]	2.55 2.43	2.46 − 2.61 2.37 − 2.50	2.38 − 2.68 2.29 − 2.58	2.31 − 2.74 2.21 − 2.64
$\sin^2\theta_{12}$	0.320	0.303–0.336	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	0.613 (0.427)[a] 0.600	0.400–0.461 & 0.573–0.635 0.569–0.626	0.38–0.66 0.39–0.65	0.36–0.68 0.37–0.67
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218–0.0275 0.0223–0.0276	0.019–0.030 0.020–0.030	0.017–0.033
δ	0.80π -0.03π	$0-2\pi$	$0-2\pi$	$0-2\pi$

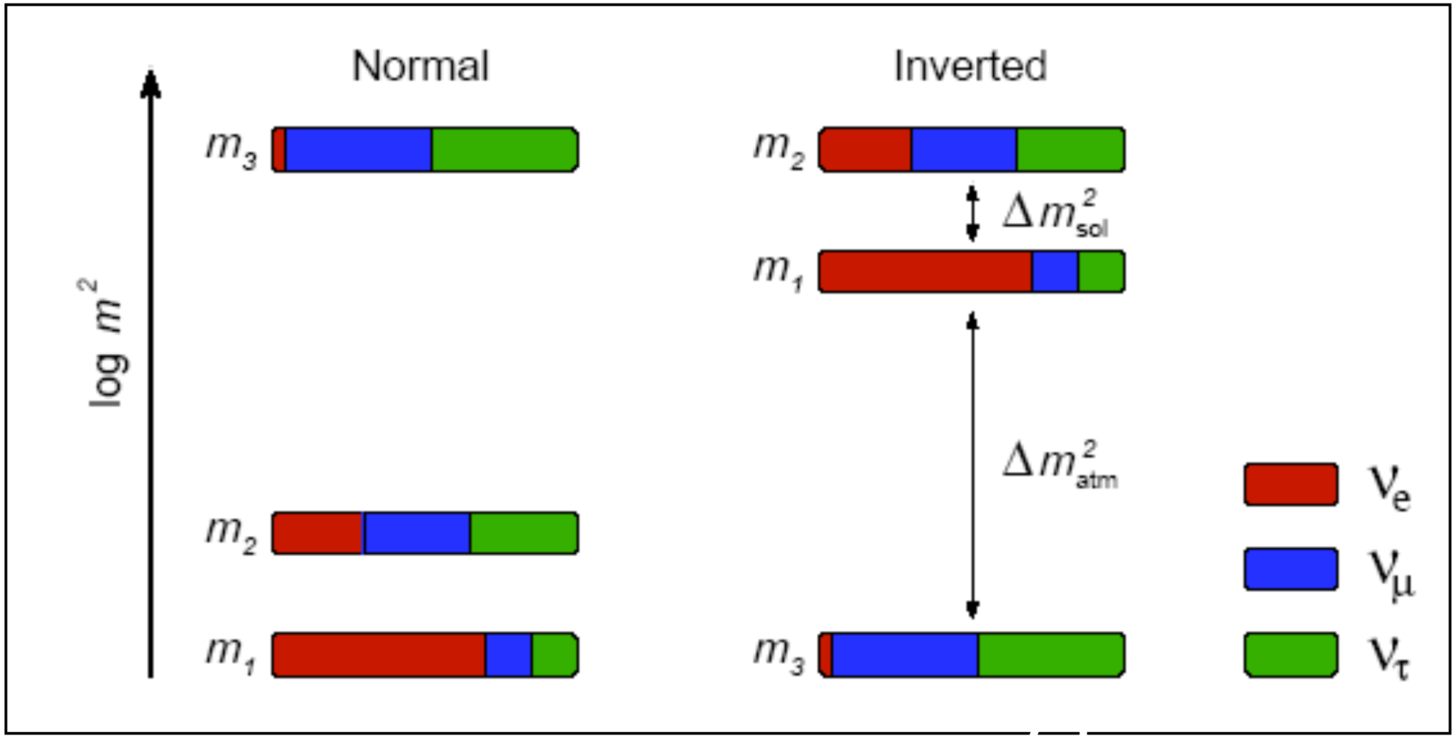




Tórtola, Vanegas & Valle, PRD 86 (2012) 073012

see also Fogli et al, 86 (2012) 073012; González-García et al, JHEP 1212 (2012) 123

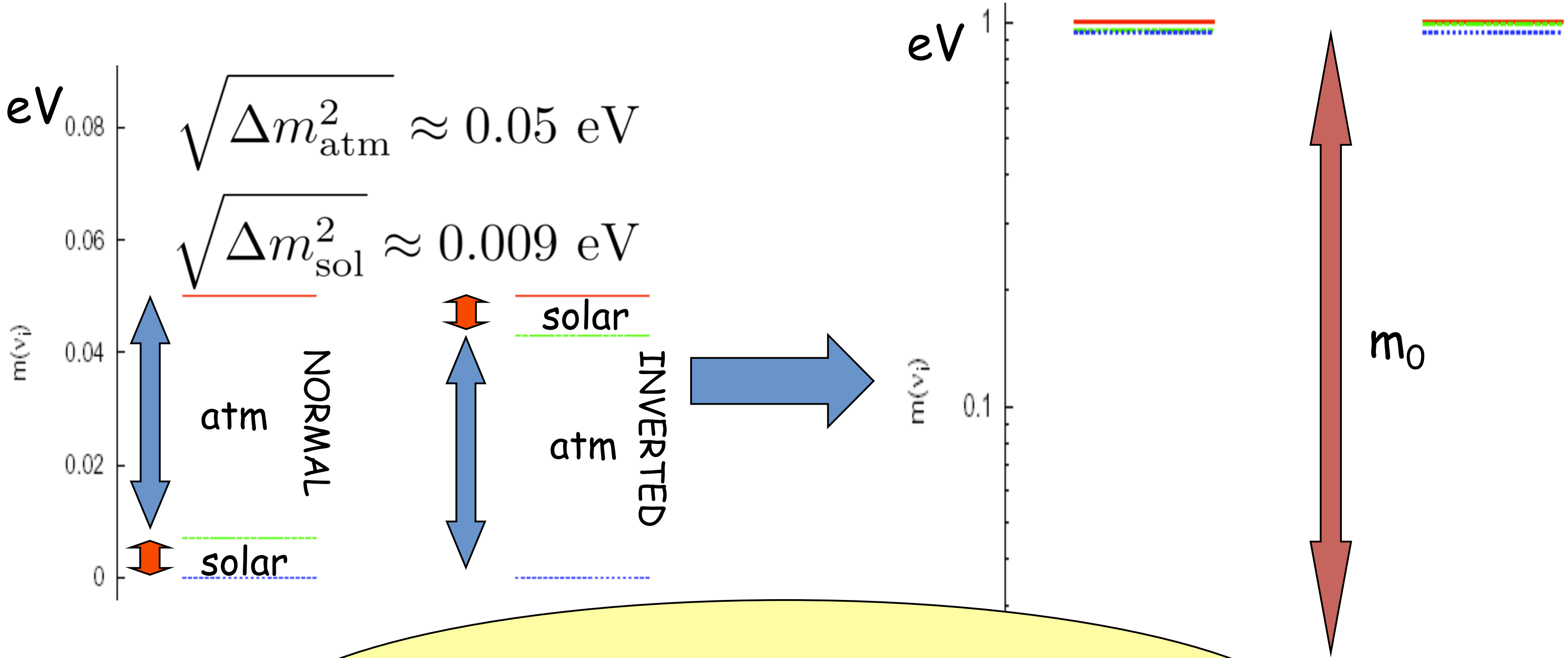
Neutrino masses



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

Neutrino masses

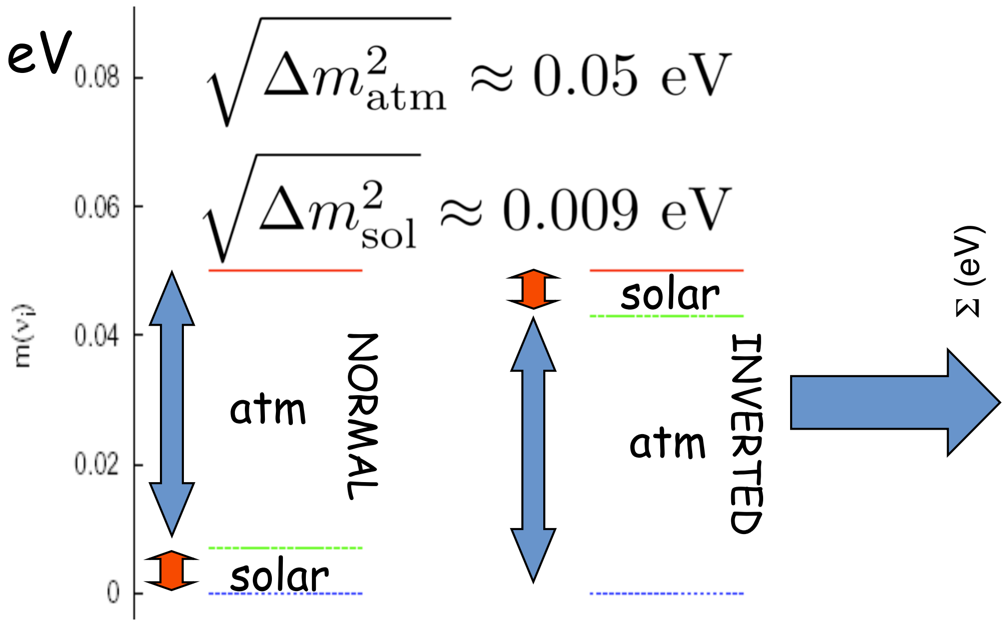
Data on flavour oscillations do not fix the absolute scale of neutrino masses

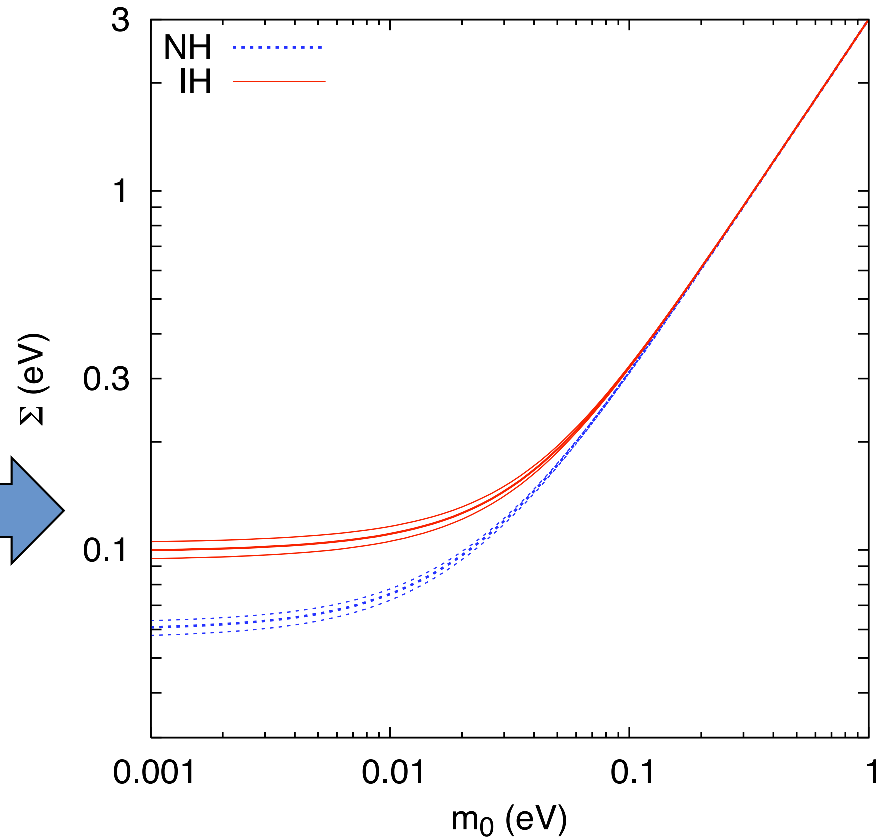


What is the value of m_0 ?

Neutrino masses

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





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

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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

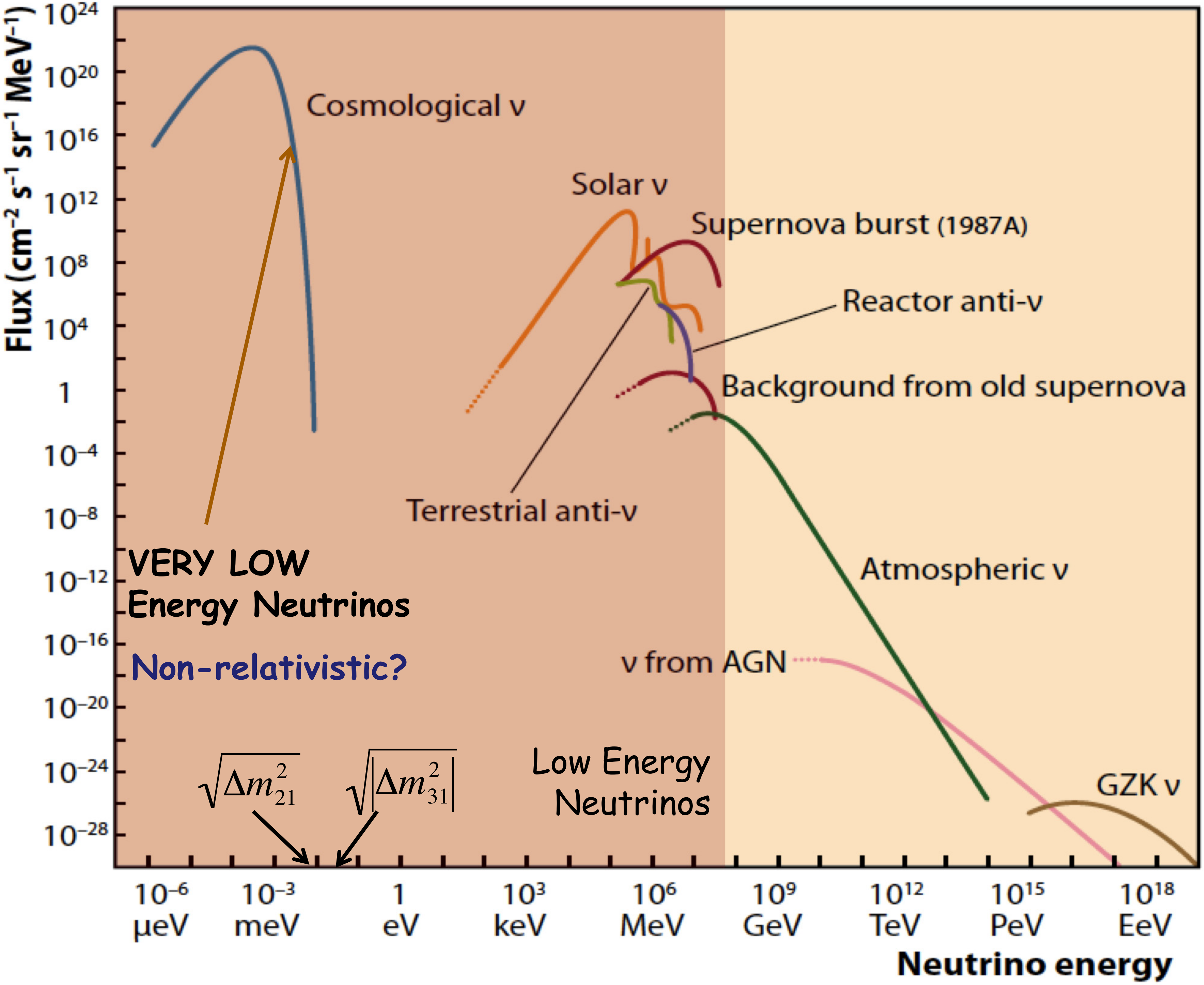
- Energy density

Contribution to the energy density of the Universe

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

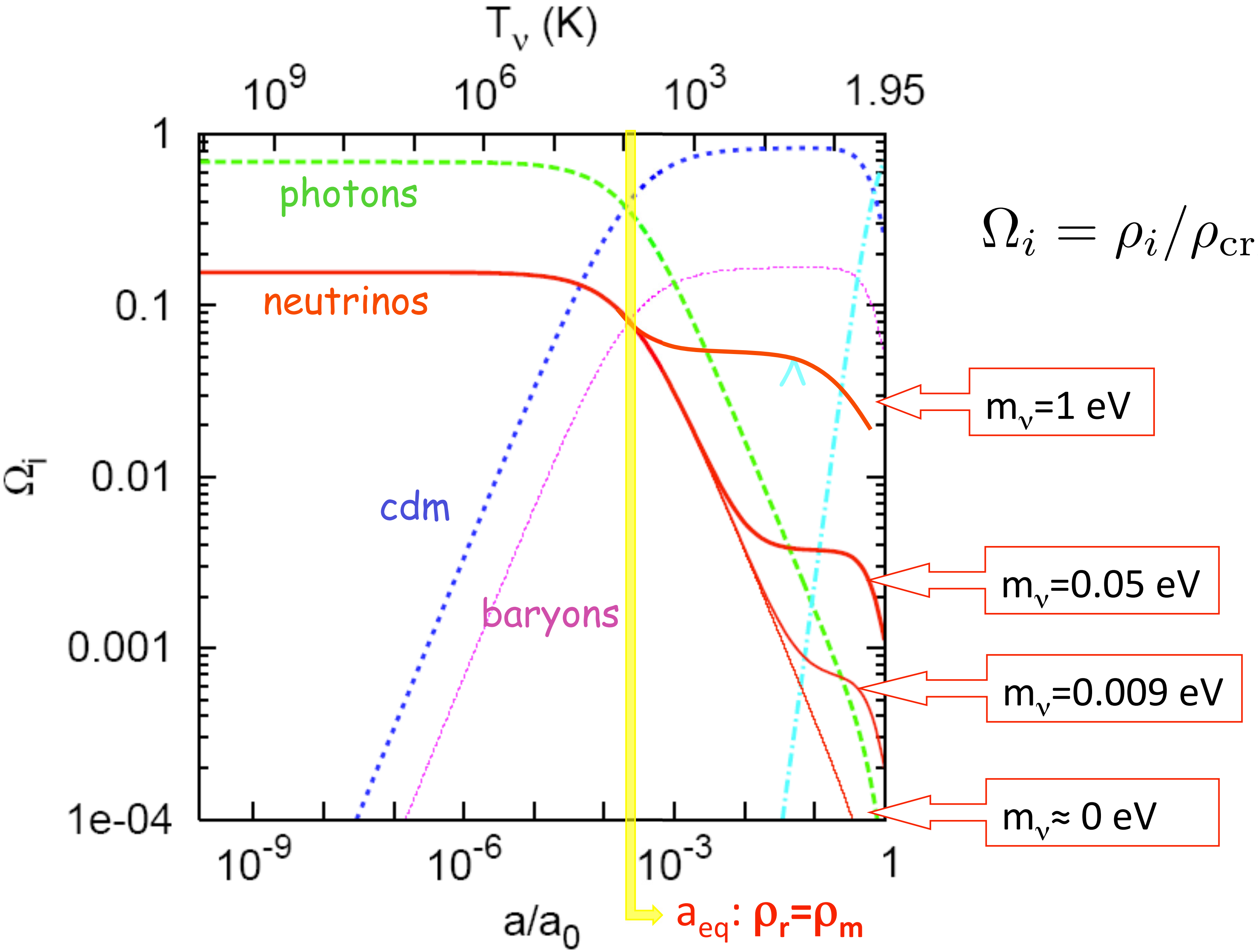
$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1 \text{ eV}}$$ Massive

$m_\nu \gg T$



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?
Low Energy
Neutrinos
$\sqrt{\Delta m^2_{21}}$
$\sqrt{|\Delta m^2_{31}|}$
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

Evolution of the background densities: 1 MeV → now



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

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

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

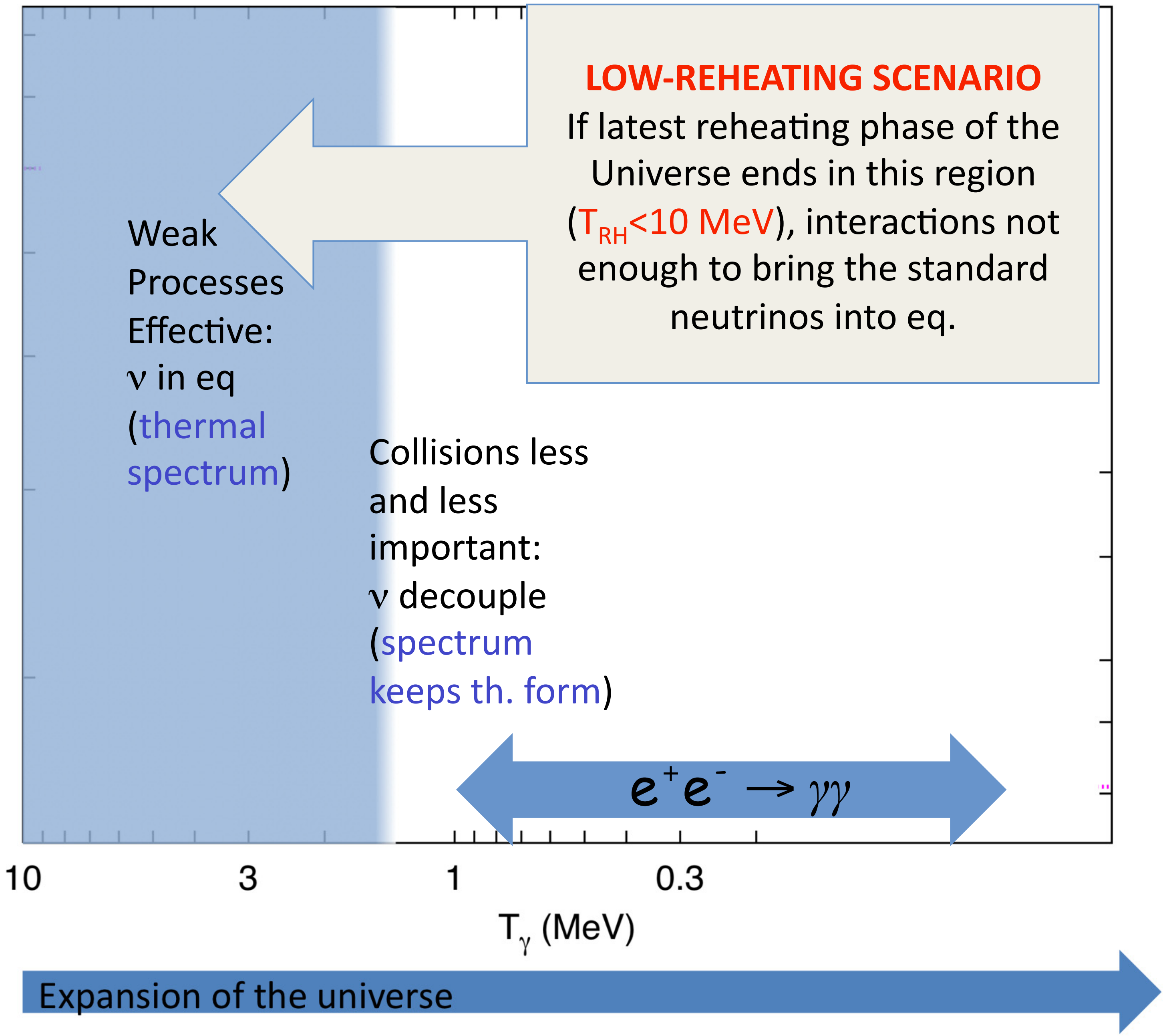
Traditional parametrization of ρ stored in relativistic particles

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

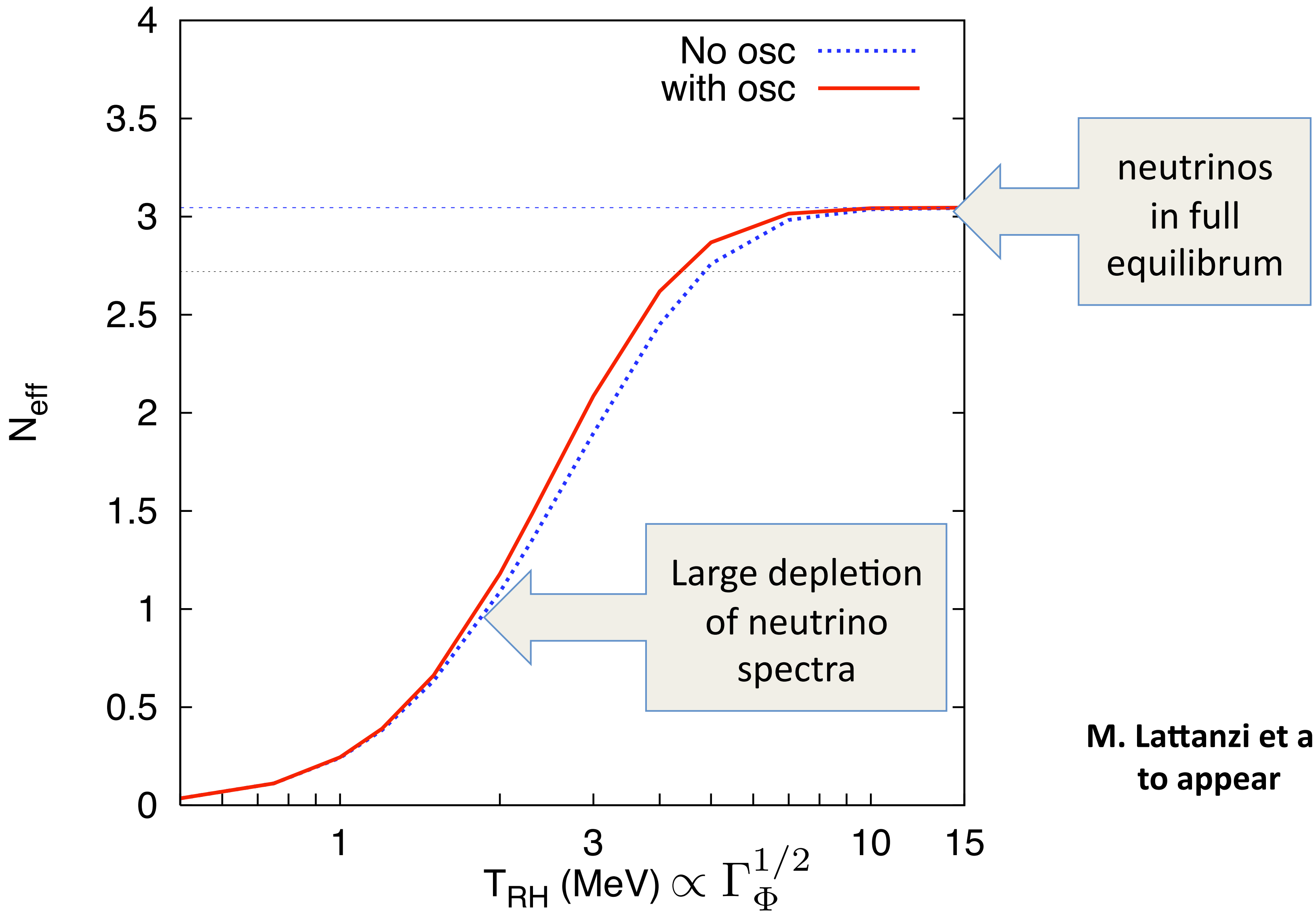
- standard neutrinos only: $N_{\rm eff} \simeq 3$ (3.046)

- $N_{\rm eff} > 3$ (delays equality time) from additional relativistic particles (scalars, pseudoscalars, decay products of heavy particles,…) or non-standard neutrino physics (primordial neutrino asymmetries, totally or partially thermalized light sterile neutrinos, non-standard interactions with electrons,…)

Neff < 3 ?

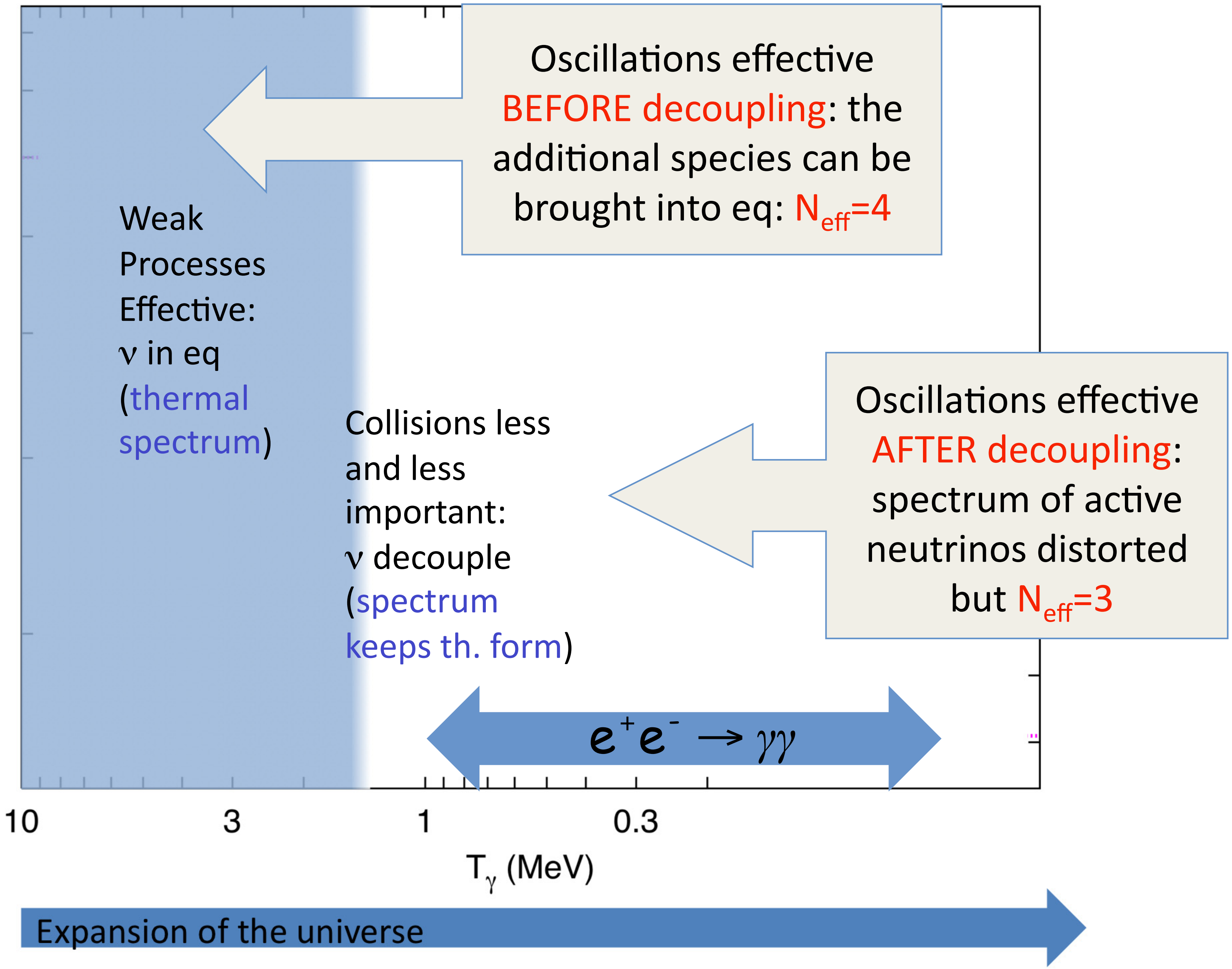

LOW-REHEATING SCENARIO
If latest reheating phase of the Universe ends in this region (T_{RH}<10 MeV), interactions not enough to bring the standard neutrinos into eq.
Weak Processes Effective: ν in eq (thermal spectrum)
Collisions less and less important: ν decouple (spectrum keeps th. form)
$e^+e^-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

Neff < 3 ?

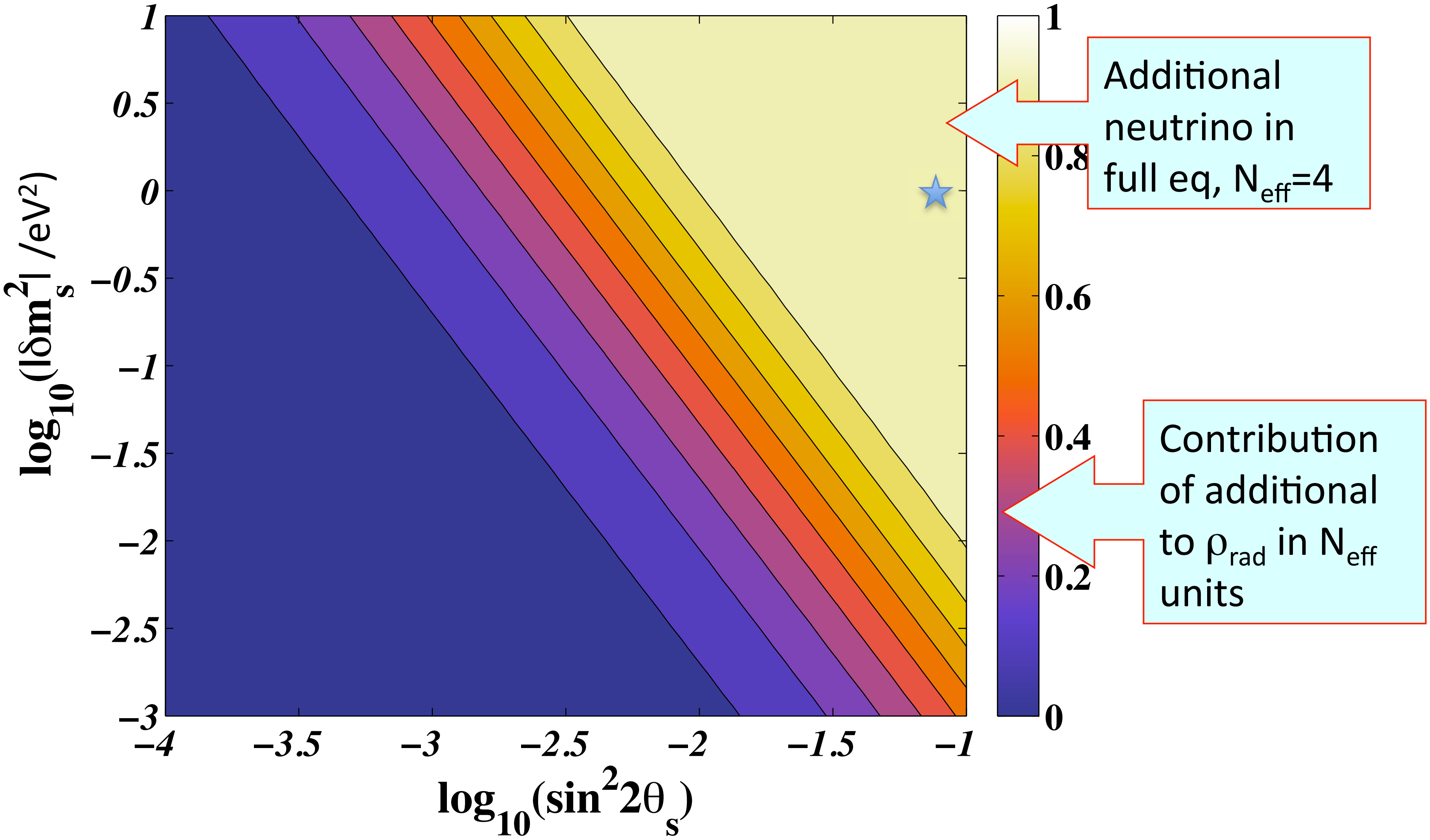


M. Lattanzi et al, to appear

Neff & Active-sterile neutrino oscillations



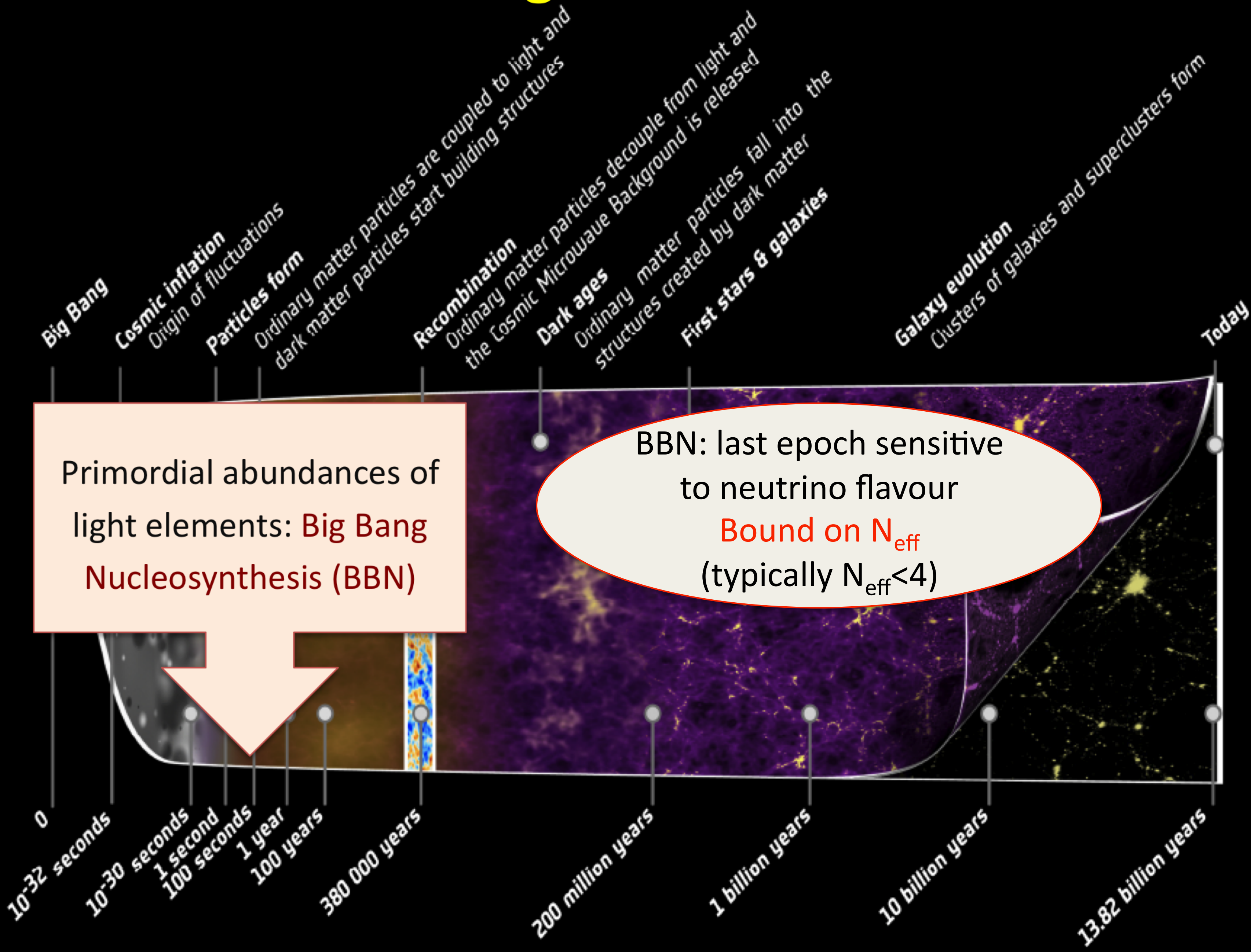
Neff & Active-sterile neutrino oscillations



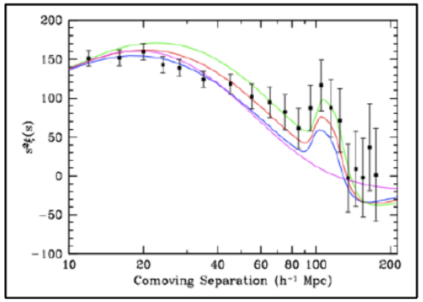
Hannestad, Tamborra & Tram, JCAP 07 (2012) 025

Cosmological Observables

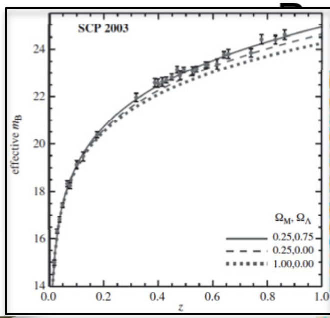
Cosmological Observables

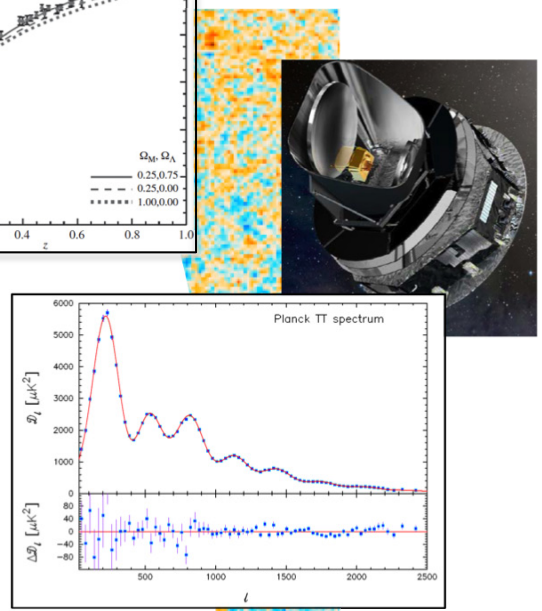


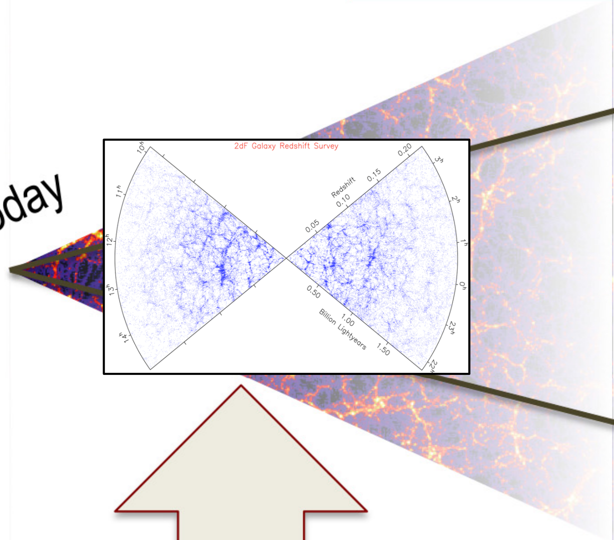
Cosmological Observables

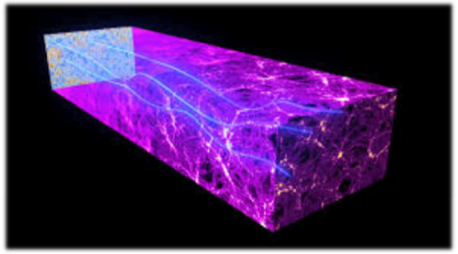


Hubble constant H_0 & cosmic distances measurements: SN Ia and Baryon Acoustic Oscillations (BAO)









matter density fluctuations

LSS [galaxy / cosmic shear / Lyα] spectrum

Photon momentum after decoupling

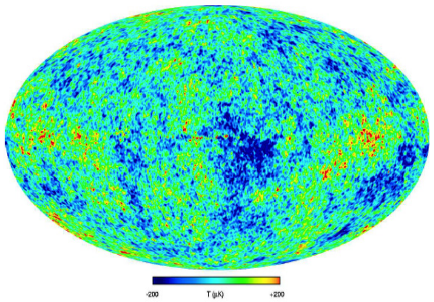
CMB secondary anisotropy spectrum

Photon density fluctuations before decoupling

CMB primary anisotropy spectrum (temp+pol)

from J. Lesgourgues

CMB data before Planck



Map of CMBR temperature Fluctuations

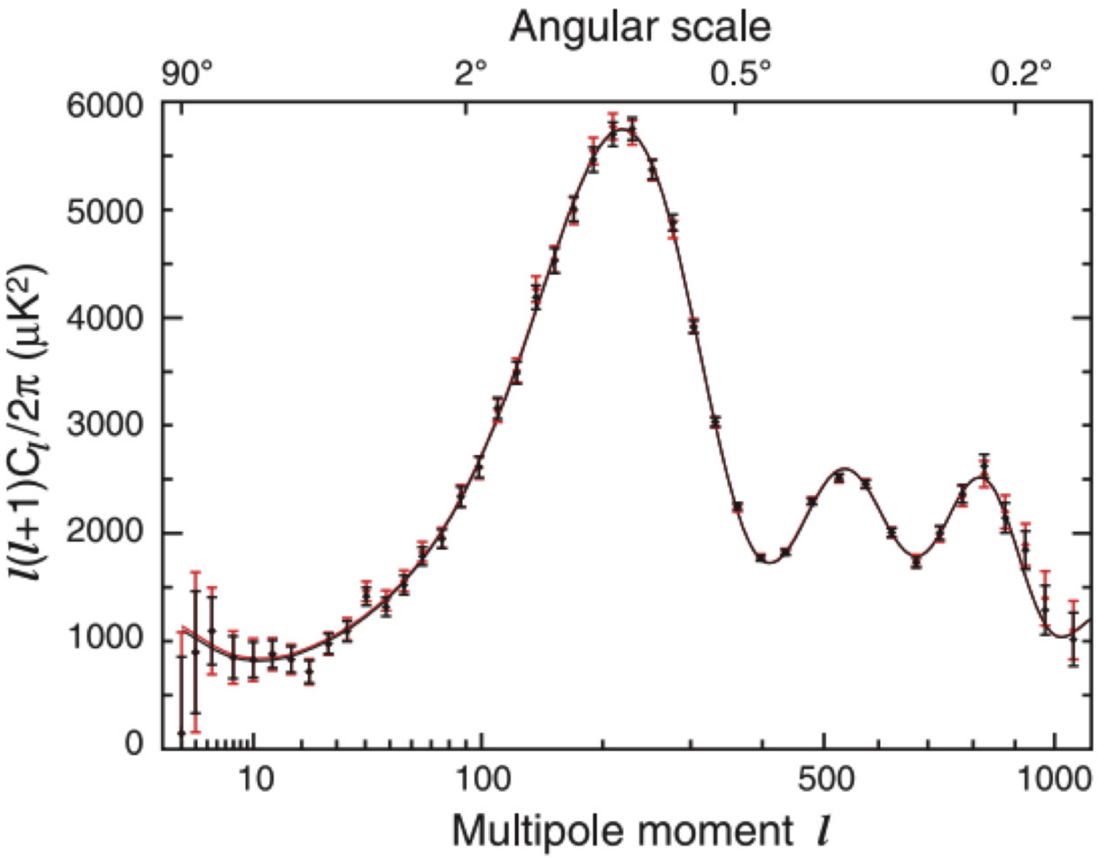
$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$

Multipole Expansion

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

Angular Power Spectrum

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



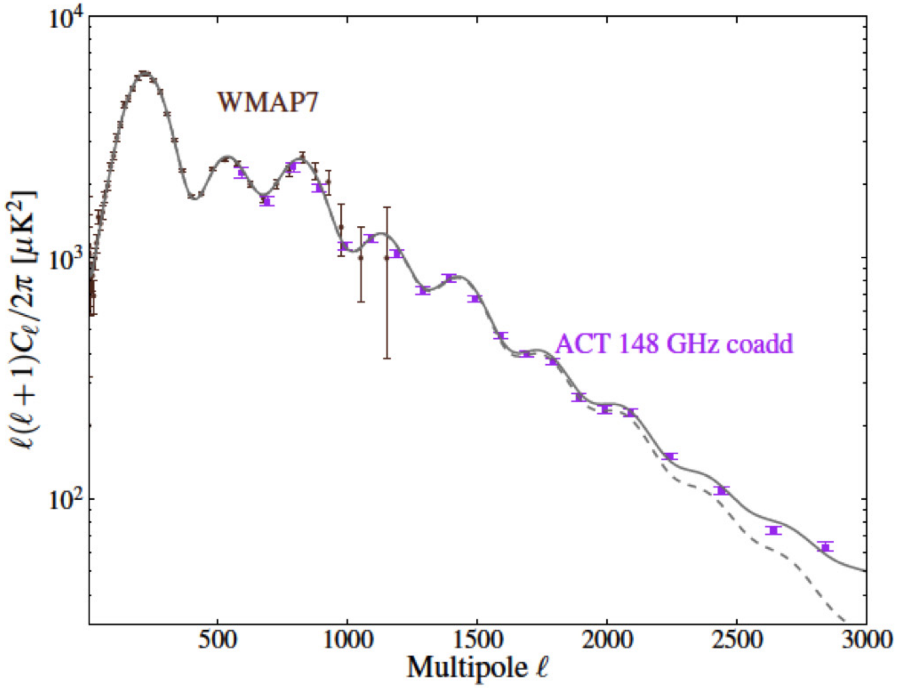
WMAP9: final results after 9 years

Data analysis refined: better treatment of the different frequency channels

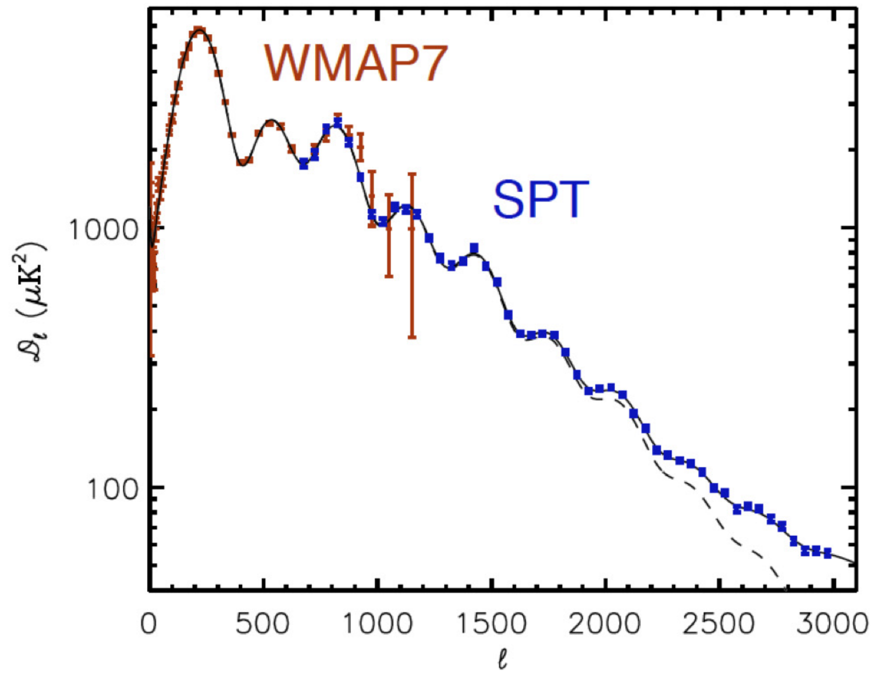
Hinshaw et al, arXiv:1212.5226

CMB data before Planck

Ground telescopes have better angular resolution: measure the CMB spectrum at high l's

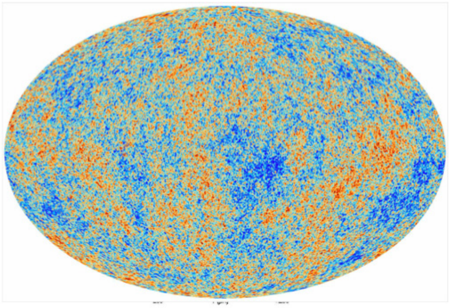


ACT, Sievers et al, arXiv:1301.0824



SPT, Story et al, arXiv:1210.7231

CMB data from Planck



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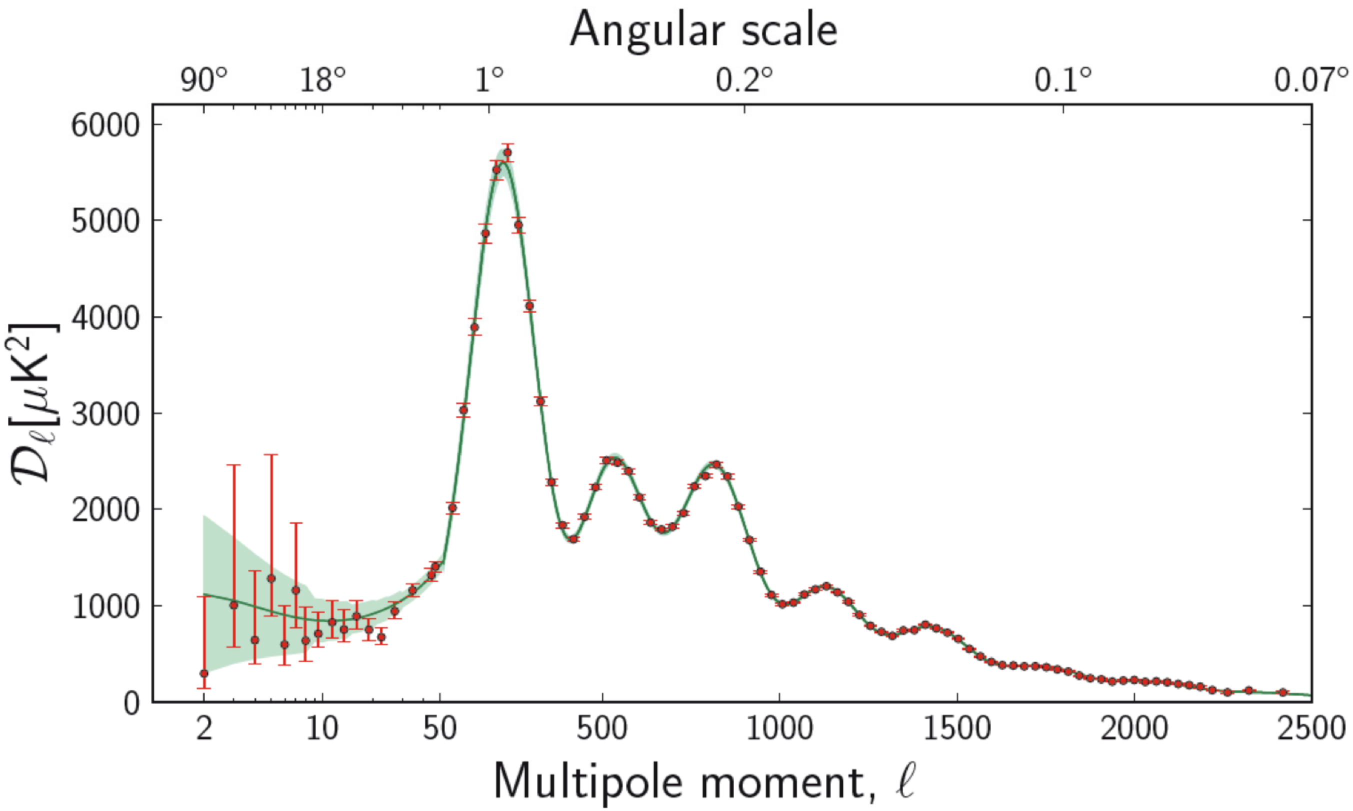


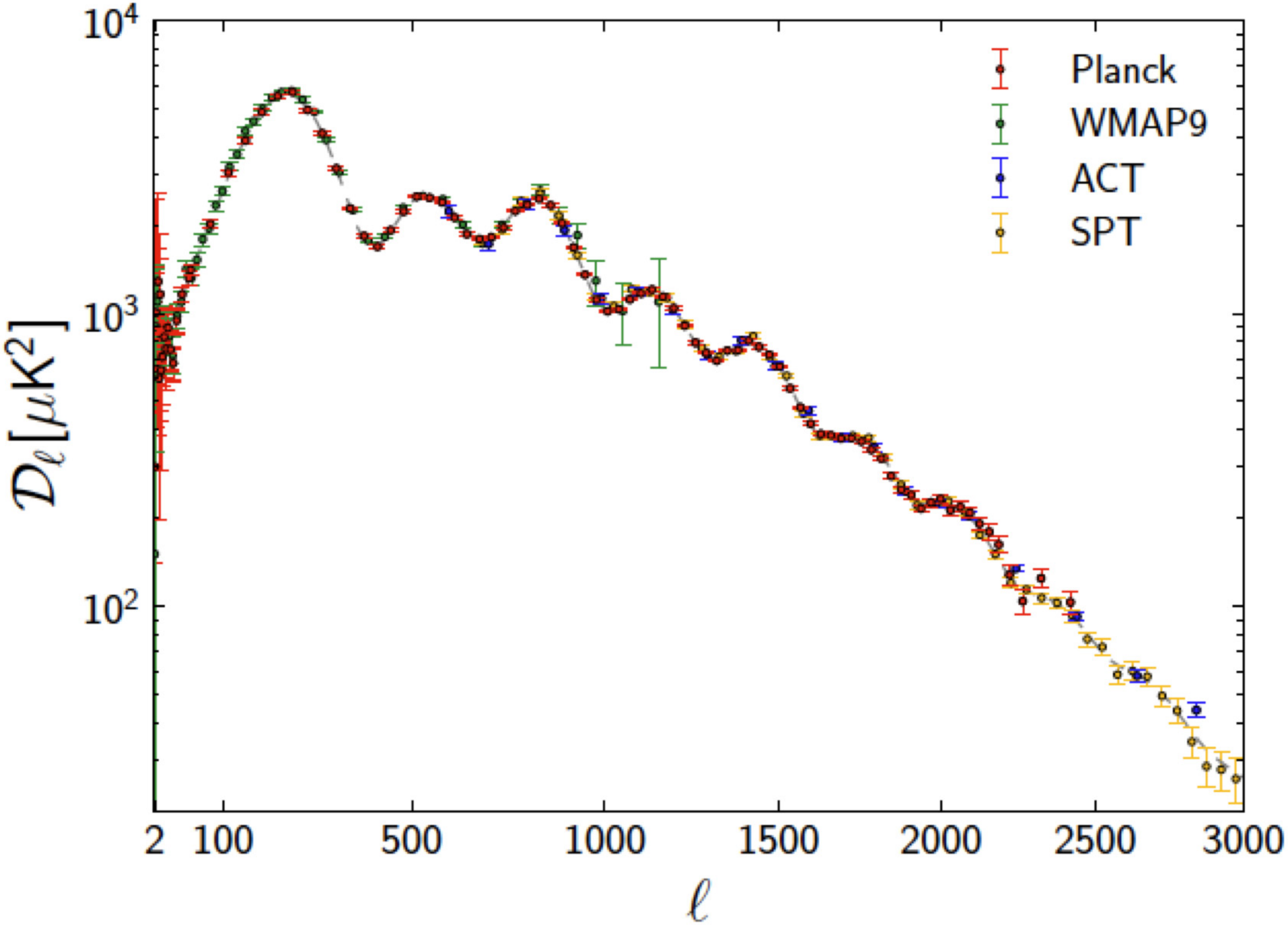
PLANCK 2013: results from 15 months, measures the CMB spectrum in a wide range of l's

Only TT spectrum with lensing extraction (projected gravitational field ~ sensitive to structures at z~1-3)

P.A.R. Ade et al, arXiv:1303.5076

Present CMB data

Planck vs other experiments



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

The minimal ΛCDM model fits very well the data

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

The minimal ΛCDM model fits very well the data

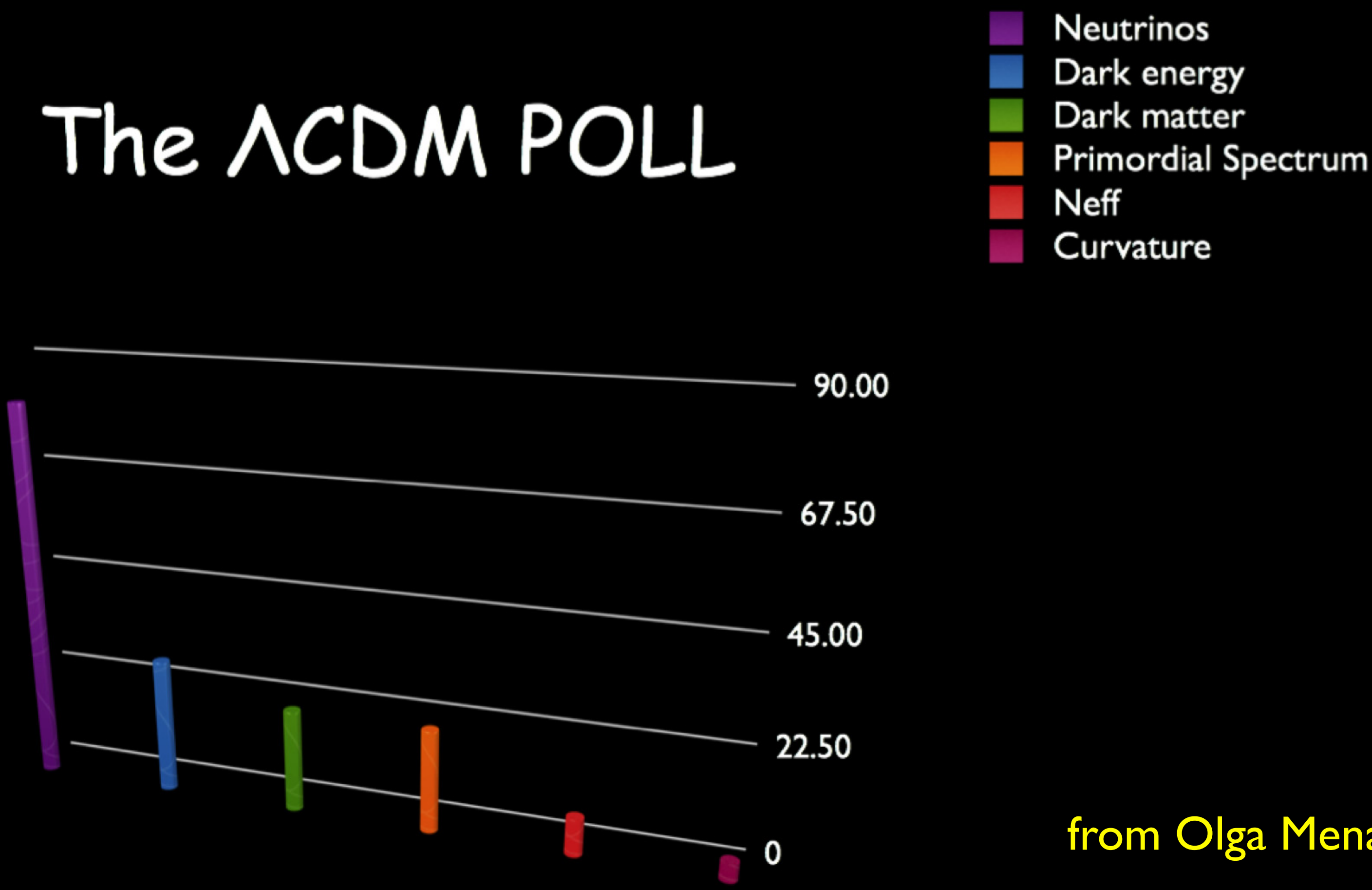
Comparison of *Planck*-only and *WMAP*-only Six-Parameter ΛCDM Fits[a]

Parameter	*Planck* ("CMB+Lens")	*WMAP* (9-year)	Difference value	Difference *WMAP* σ
$\Omega_b h^2$	0.02217 ± 0.00033	0.02264 ± 0.00050	-0.00047	0.9
$\Omega_c h^2$	0.1186 ± 0.0031	0.1138 ± 0.0045	0.0048	1.1
Ω_Λ	0.693 ± 0.019	0.721 ± 0.025	-0.028	1.1
τ	0.089 ± 0.032	0.089 ± 0.014	0	0
t_0 (Gyr)	13.796 ± 0.058	13.74 ± 0.11	56 Myr	0.5
H_0 (km $s^{-1}Mpc^{-1}$)	67.9 ± 1.5	70.0 ± 2.2	-2.1	1.0
σ_8	0.823 ± 0.018	0.821 ± 0.023	0.002	0.1
Ω_b	0.0481[b]	0.0463 ± 0.0024	0.0018	0.7
Ω_c	0.257[b]	0.233 ± 0.023	0.024	1.0

[a]The new *Planck* results strongly favor the standard six-parameter ΛCDM model with parameter values that are consistent with *WMAP* parameters, as shown in this table which compares results derived entirely from *Planck* data with those derived entirely from *WMAP* data.

[b]Parameters derived from quoted values. No error estimate is given for this data/model combination.

What ingredient, in your opinion, should be mandatory to change in the ΛCDM?



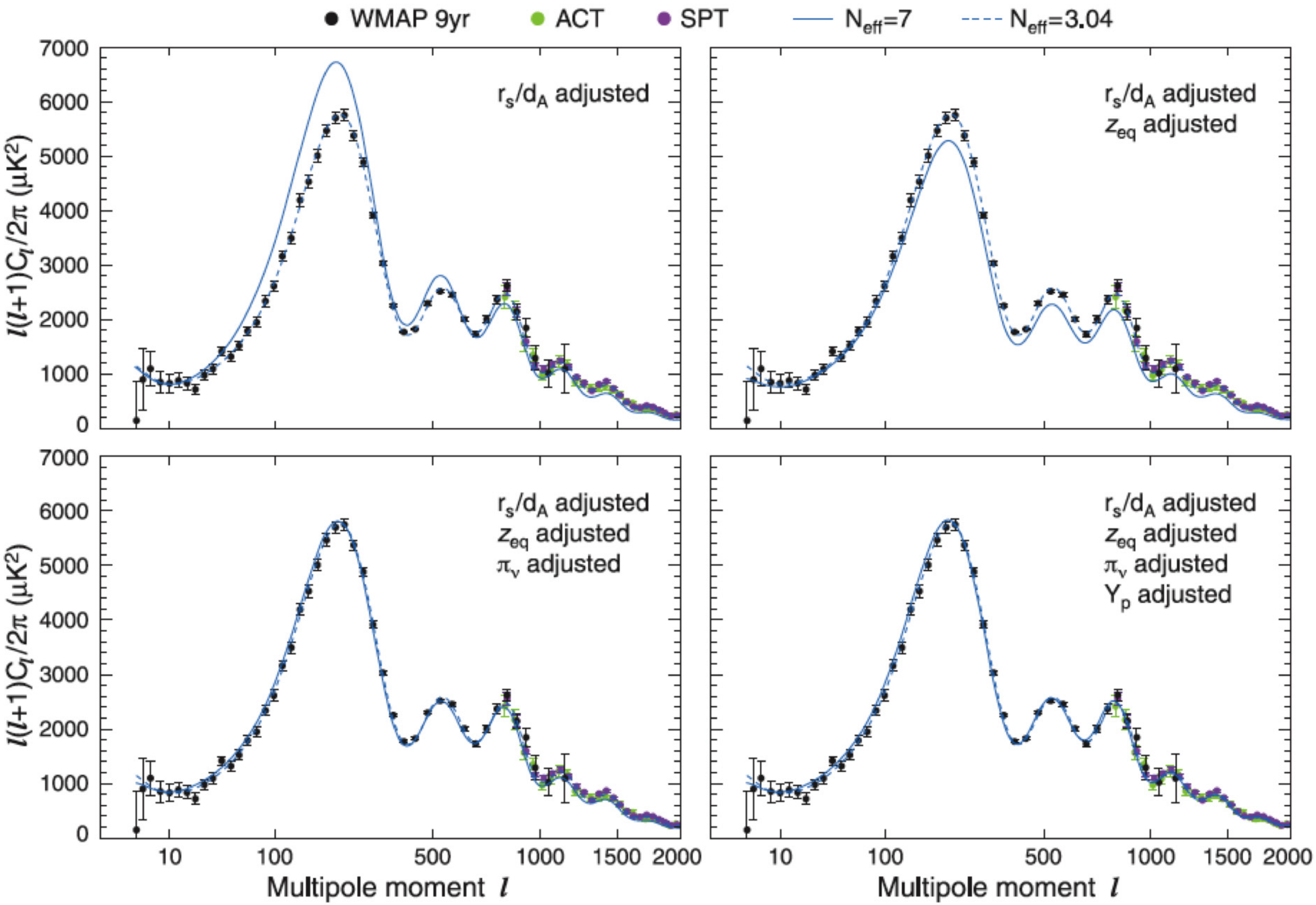
from Olga Mena

Planck collaboration has already added massive neutrinos in the vanilla-six parameter model, with $\Sigma m_{\nu,\mathrm{fiducial}} = 0.06$ eV!

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}



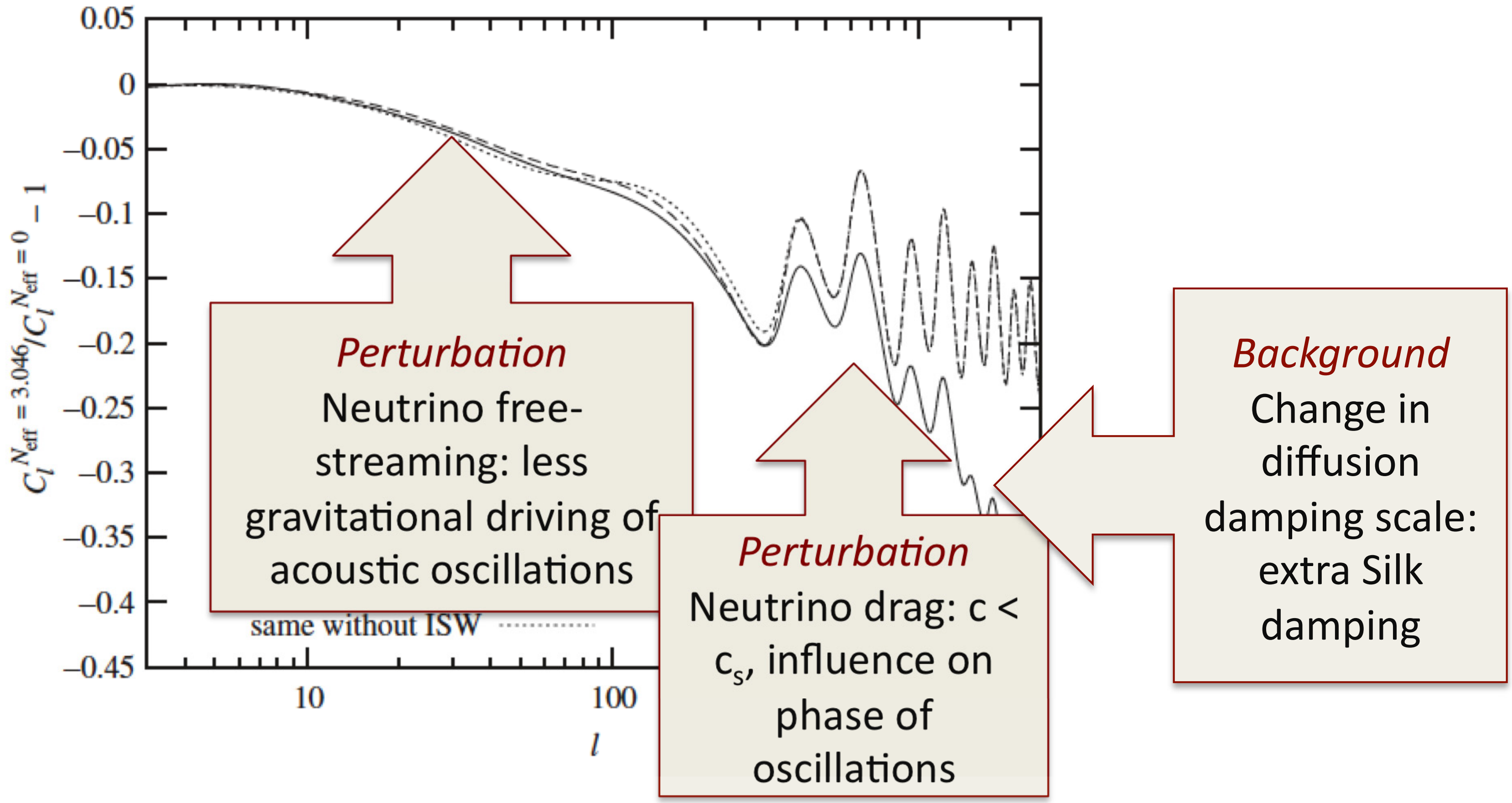
Hinshaw et al, arXiv:1212.5226

Measuring N_{eff}

- Fixing quantities best probed by CMB (angular peak scale, redshift of equality, …):

simultaneous enhancement of radiation, matter, L densities, with fixed photon and baryon densities

unlensed C_l^{TT} for N_{eff}=3 vs N_{eff}=0 :



Measuring N_{eff}

- Ultimately, constraints driven by CMB damping tail
  - WMAP+SPT see anomalously low tail: $N_{eff} > 3$ at 2 sigma
  - Planck and Planck+BAO well compatible with 3.046 at 1 sigma
  - Planck (+BAO) + HST: enforce higher H_0, hence also higher N_{eff}

- CMB alone (Planck+WP+HighL)

$$N_{eff} = 3.36^{+0.68}_{-0.64}$$

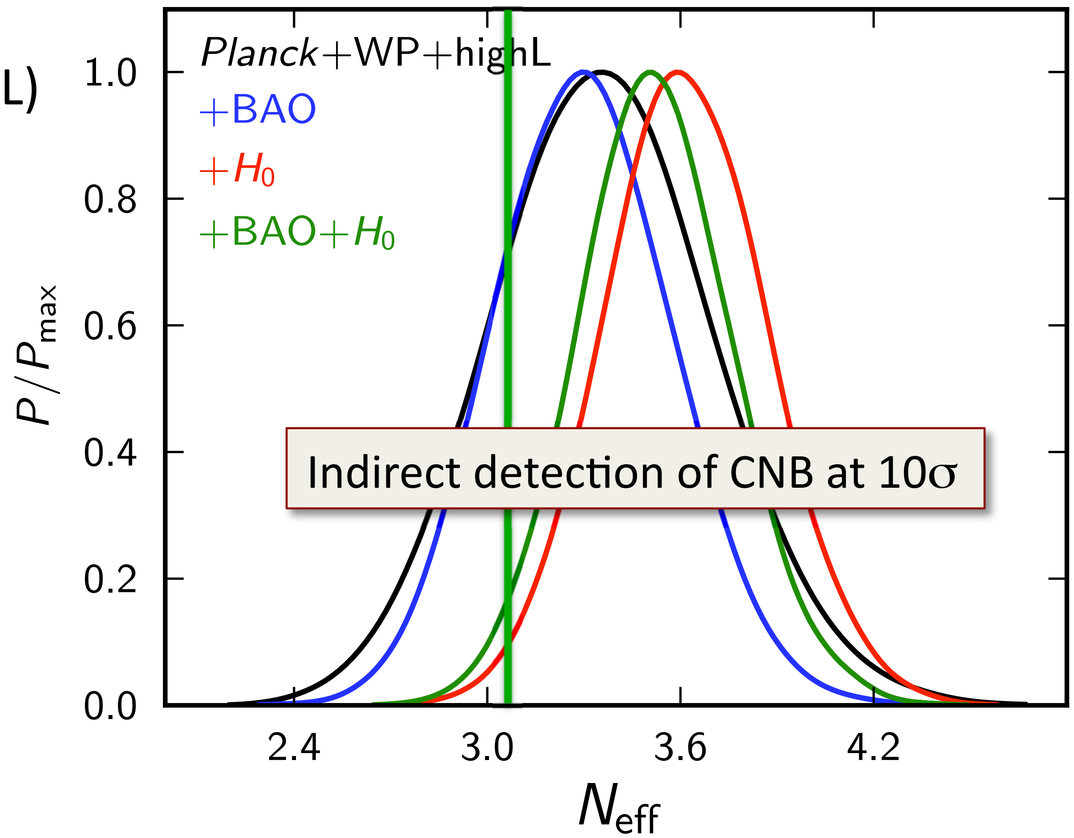
- With lensing and BAO:

$$N_{eff} = 3.30^{+0.54}_{-0.51}$$

- With H_0 and BAO:

$$N_{eff} = 3.52^{+0.48}_{-0.45}$$

all 95%CL



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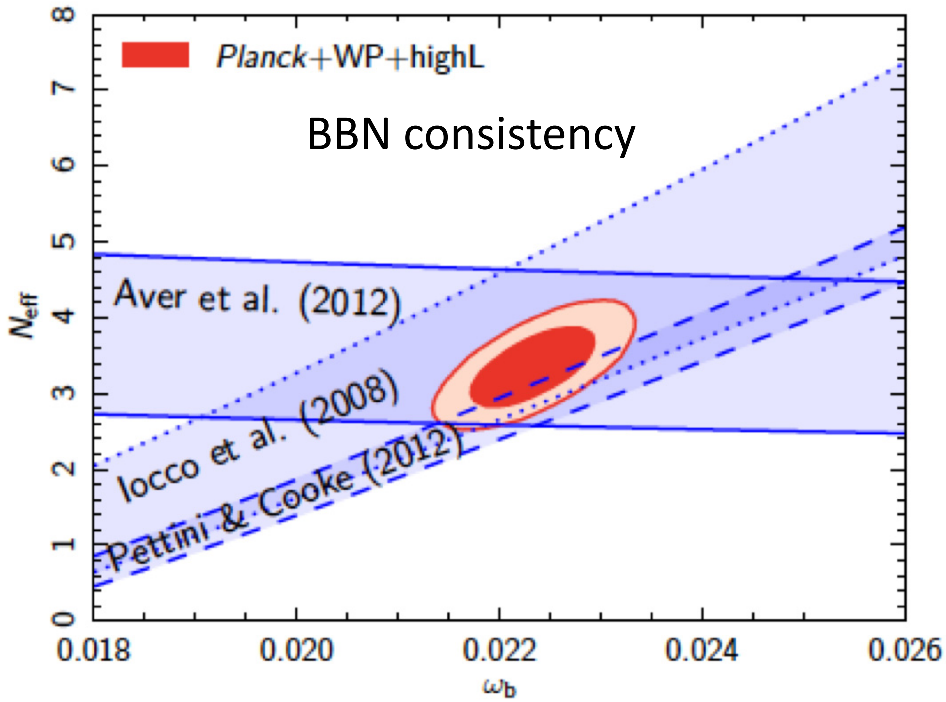


all 95%CL

Measuring m_ν with the CMB

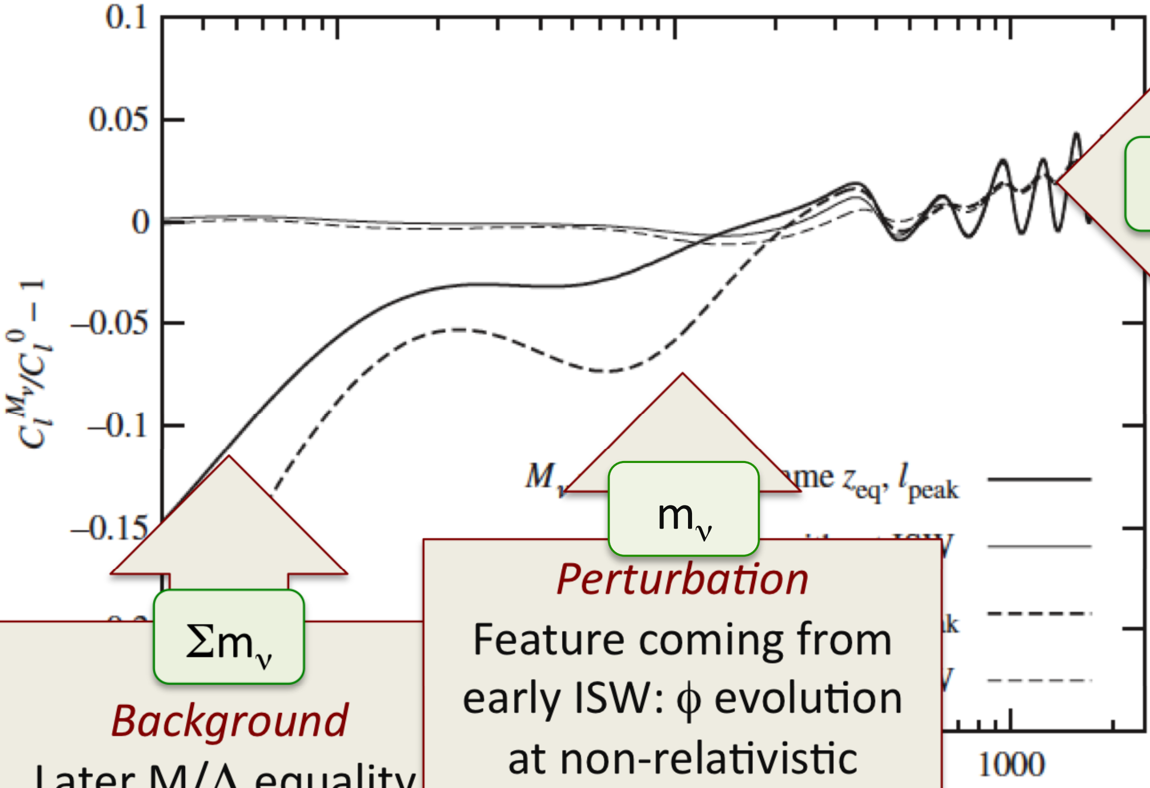
- Neutrinos contribute to radiation at early times and non-relativistic matter at late times
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at photon decoupling. In principle the primary CMB TT spectrum sensitive to $\Sigma m_\nu > 1.5$ eV
- "effect of m_ν" depends on what is kept fixed
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:
  - Possible by fixing photon, cdm and baryon densities, while tuning H_0, W_L
  - then increase in m_n 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 the CMB

- Leaving both "early cosmology" and angular diameter dist. to decoupling invariant:

fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ

unlensed C_l^{TT} for two degenerate masses vs massless:



Perturbation
m_ν
Not fully relativistic before decoupling: less free-streaming and shifting

Perturbation
m_ν
Feature coming from early ISW: ϕ evolution at non-relativistic transition

Background
Σm_ν
Later M/Λ equality, less "late ISW"

+ different lensing effect
Σm_ν

Measuring m_ν with Planck

CMB alone (Planck+WP+HighL):

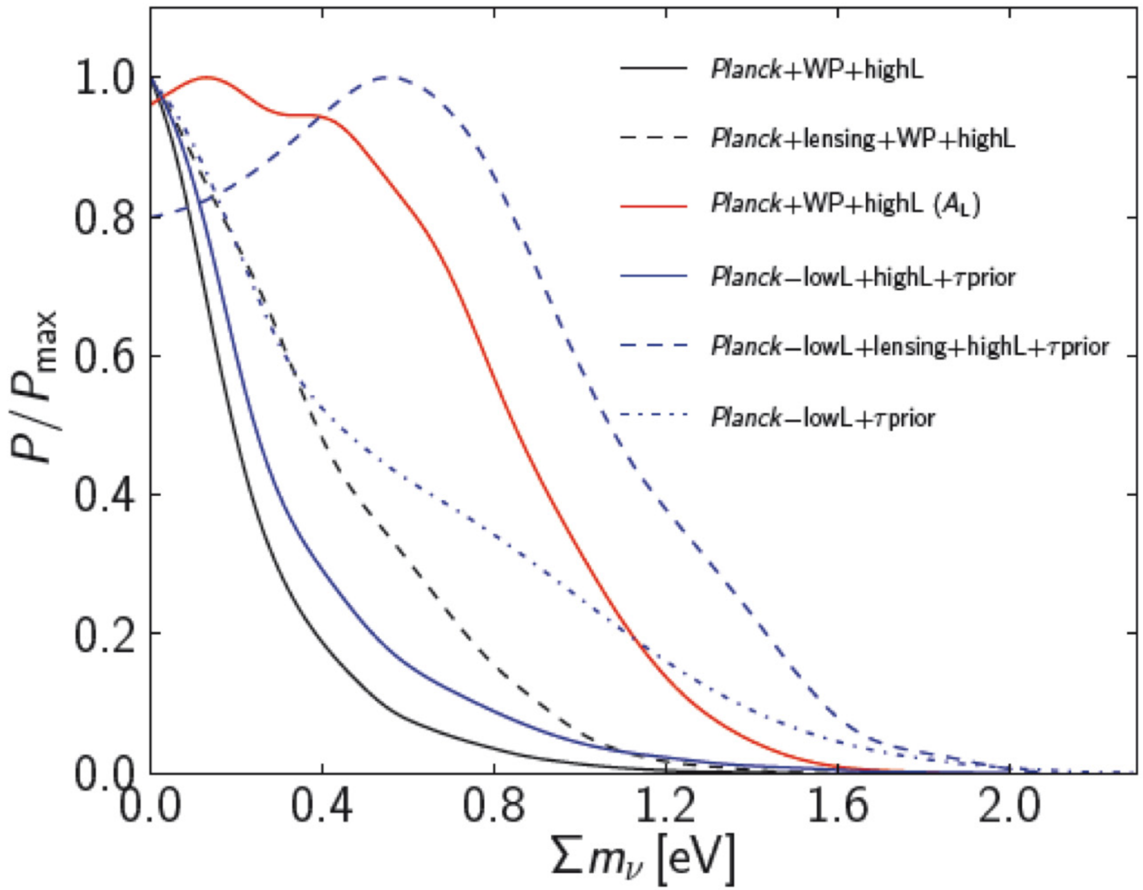
$\Sigma m_\nu < 0.66$ eV

With BAO:

$\Sigma m_\nu < 0.23$ eV

With lensing:

$\Sigma m_\nu < 0.85$ eV



All 95% CL. Robust w.r.t cosmological extensions
(except for curvature: weakens 50%)

Measuring m_ν & N_{eff} with Planck

Results are practically unchanged

CMB alone (Planck+WP+HighL):

$\Sigma m_\nu < 0.60$ eV

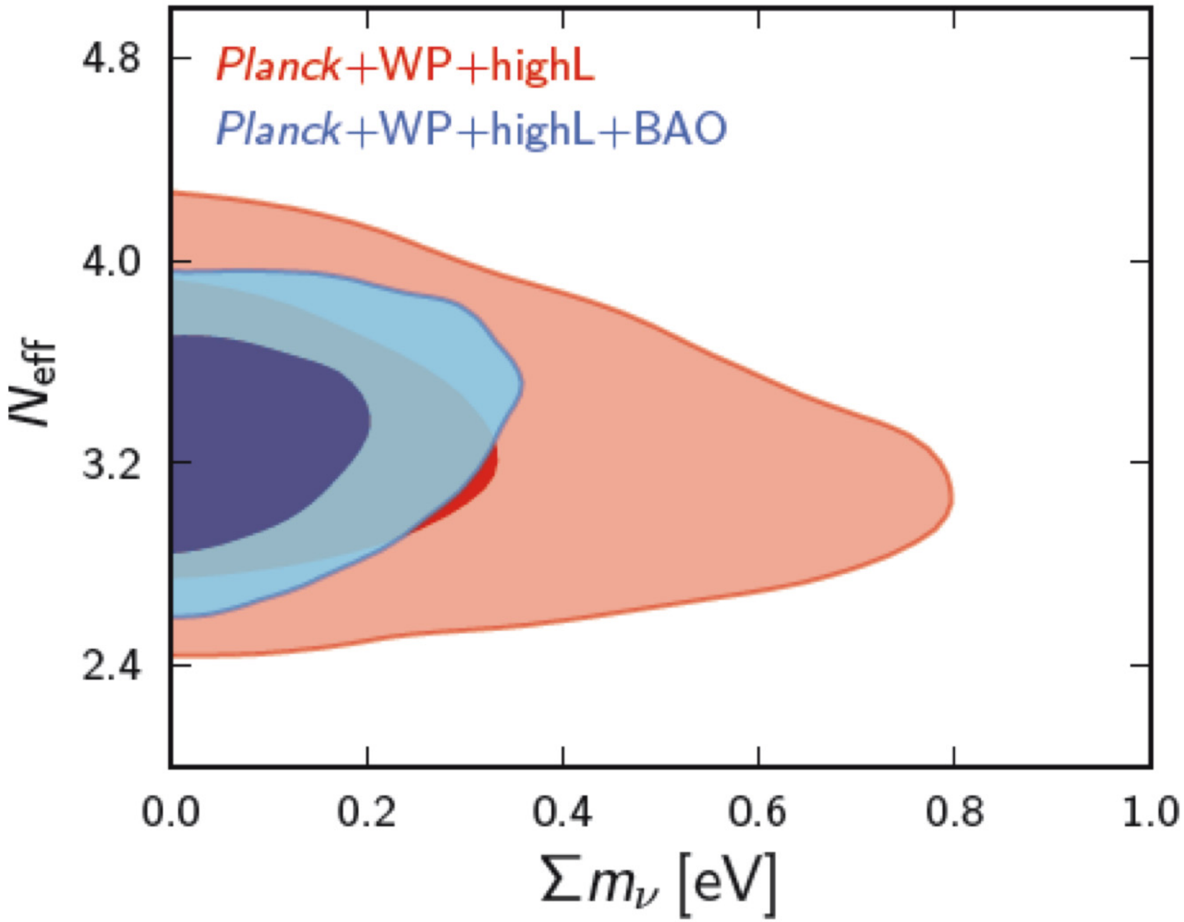
$$N_{\rm eff} = 3.29^{+0.67}_{-0.64}$$

With BAO:

$\Sigma m_\nu < 0.28$ eV

$$N_{\rm eff} = 3.32^{+0.54}_{-0.52}$$

All 95% CL



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

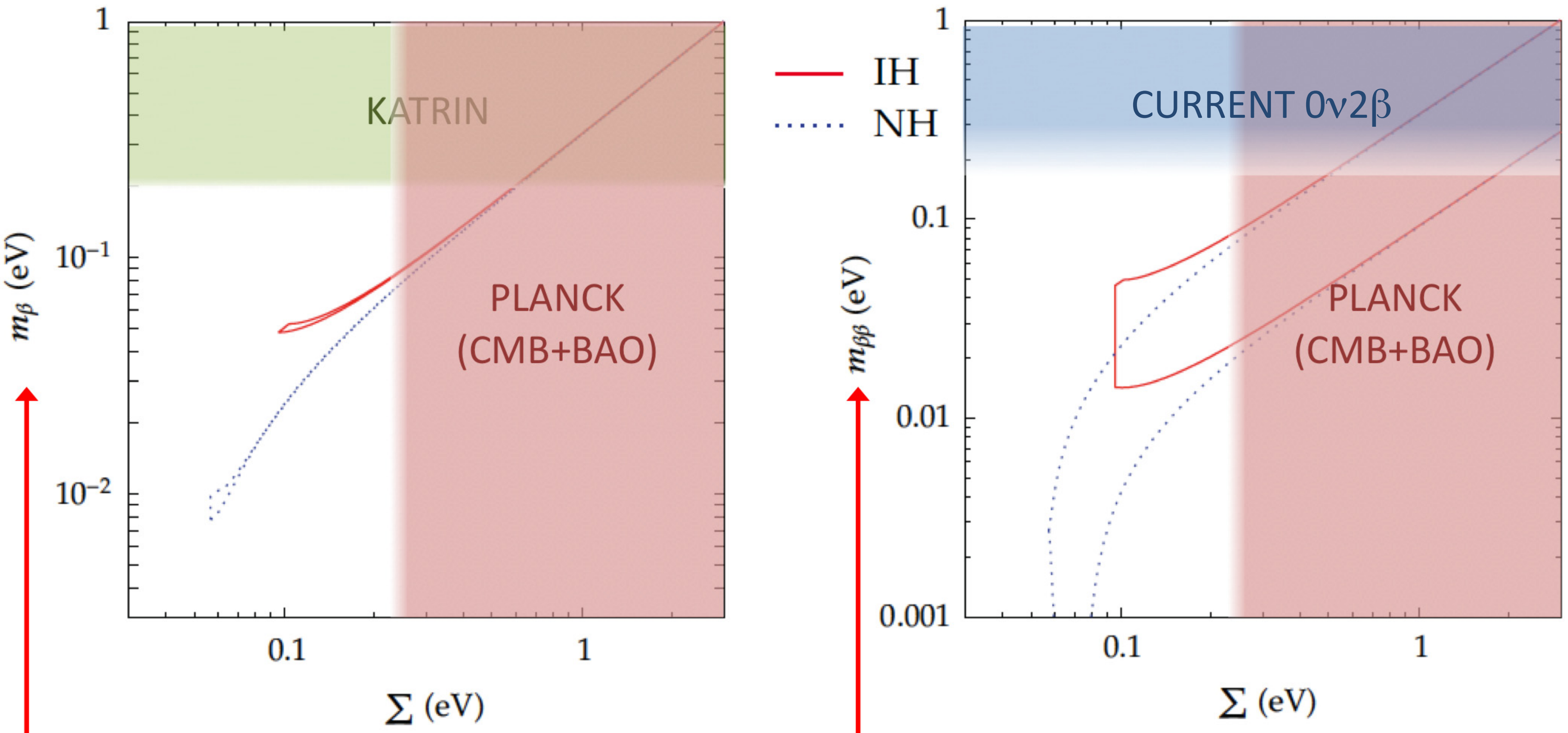
$\rightarrow [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$

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

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

Cosmology	$\sim \sum_i m_i$	$<$ 0.23-1.0 eV

Tritium β decay, 0ν2β and Cosmology



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

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

Measuring m_ν(sterile) & N_{eff} with Planck

Planck analysis of 3+1 neutrino scenarios (m_ν^{eff}). Two cases: extra state with T_s or with rescaled spectrum

for $m_{\rm sterile}^{\rm thermal} < 10\,{\rm eV}$

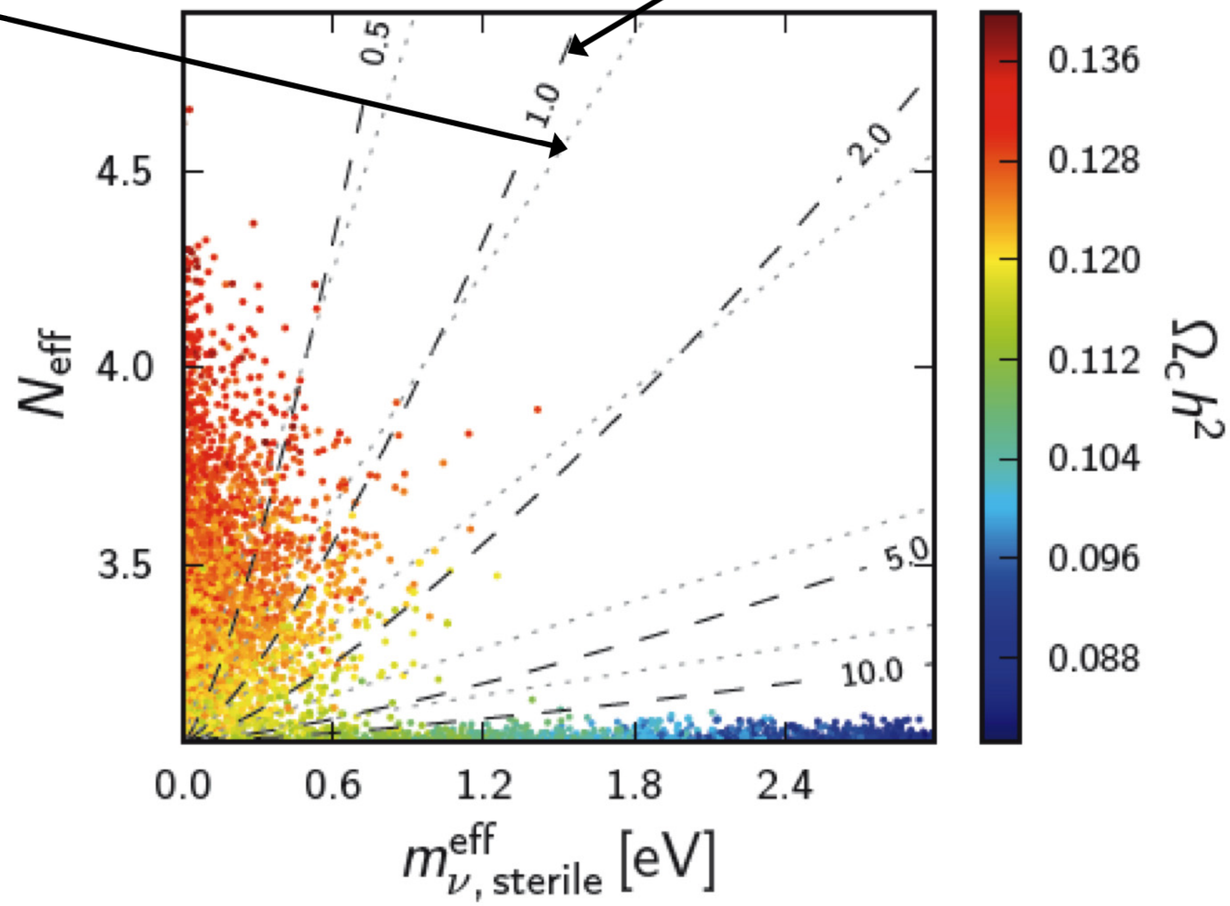
CMB alone (Planck+WP+HighL):

$$\left.\begin{array}{r} N_{\rm eff} < 3.91 \\ m_{\nu,\,\rm sterile}^{\rm eff} < 0.59\,{\rm eV} \end{array}\right\}$$

With BAO:

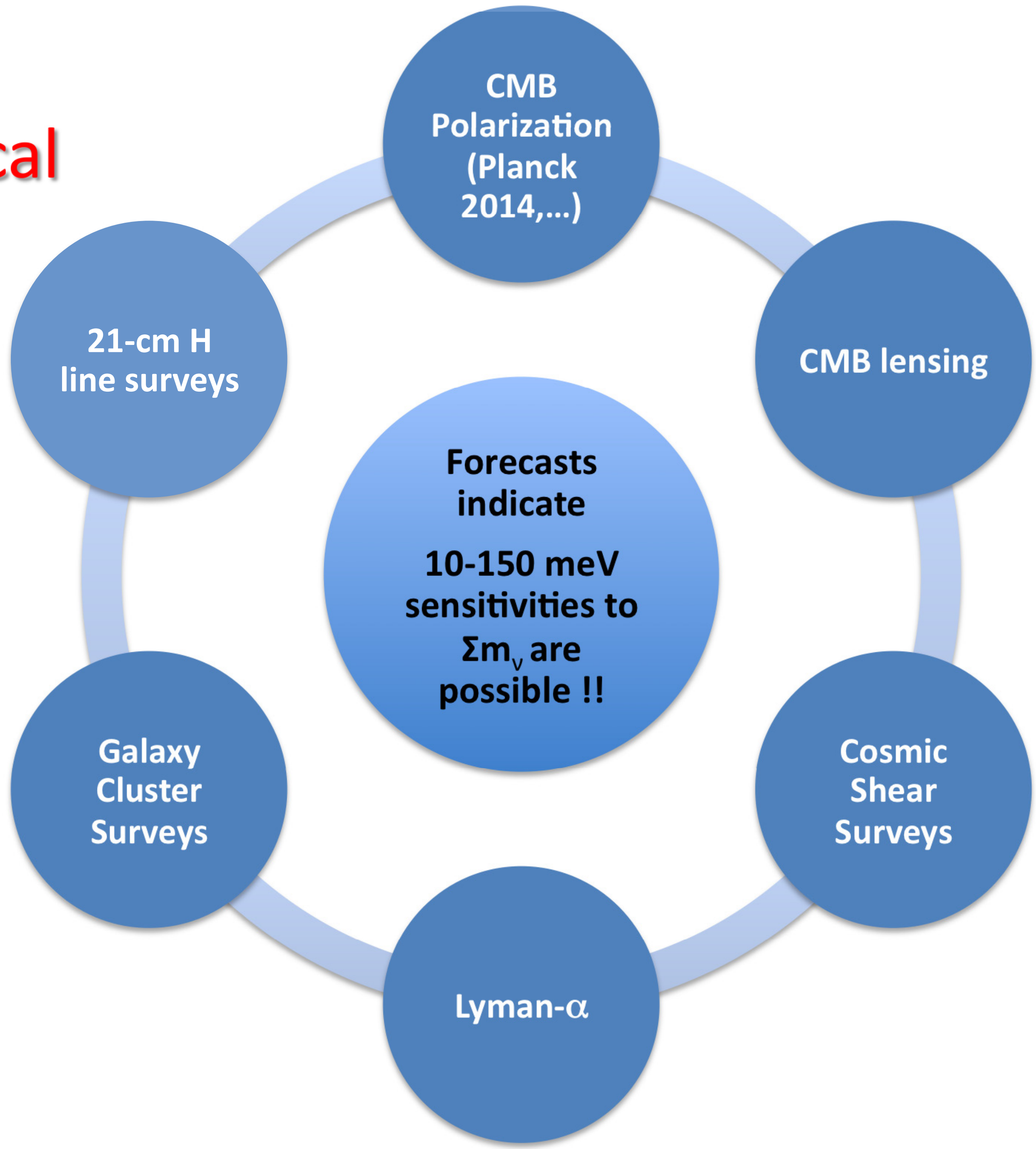
$$\left.\begin{array}{r} N_{\rm eff} < 3.80 \\ m_{\nu,\,\rm sterile}^{\rm eff} < 0.42\,{\rm eV} \end{array}\right\}$$

All 95% CL



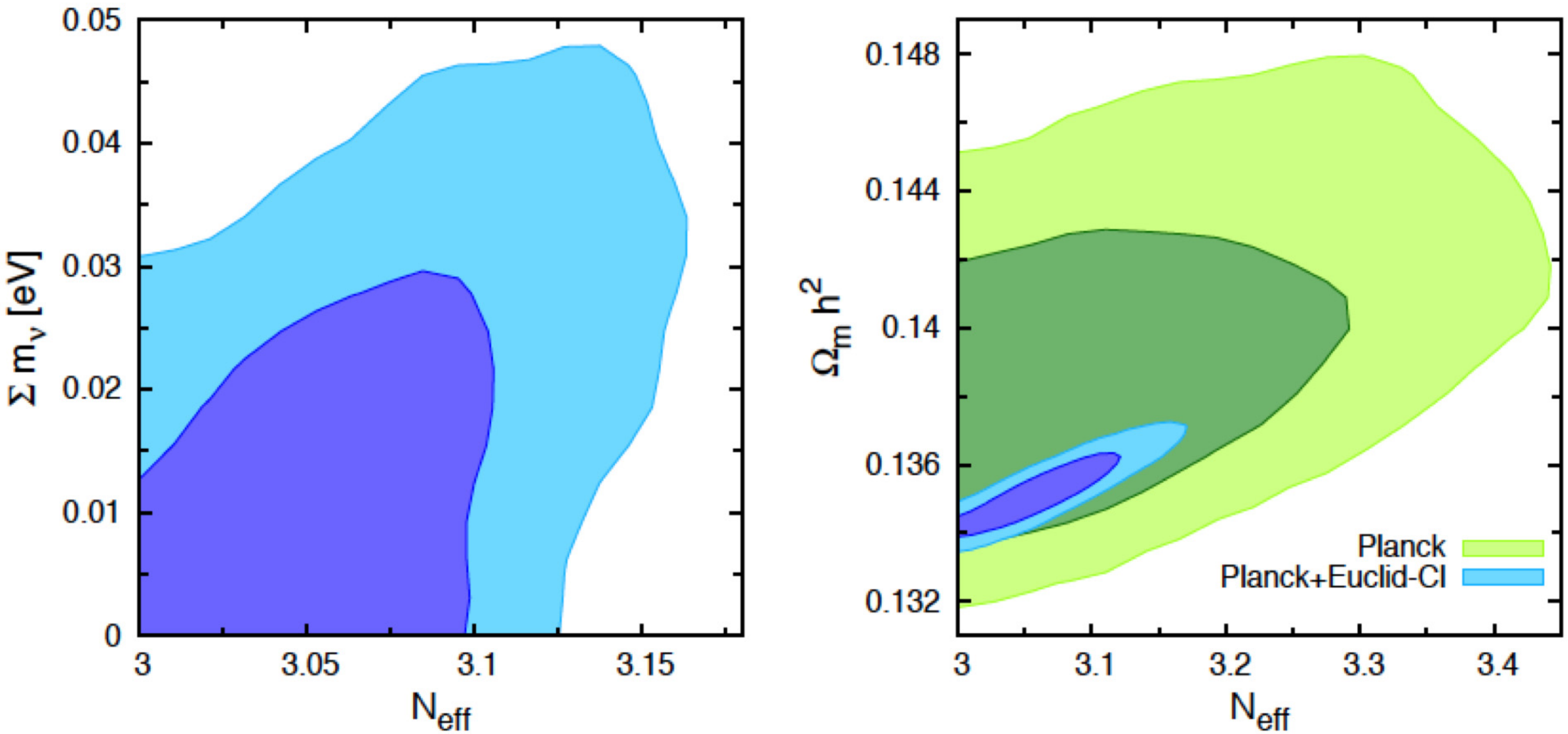
Contours of equal m_ν^{eff}

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$+m_\nu+N_{\rm eff}$	ΛCDM$+m_\nu+N_{\rm eff}+\Omega_{\rm k}$
$\sum m_\nu$ [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, arXiv:1303.4550

Future sensitivities on neutrino masses

95% C.L

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key systematics	Current surveys	Future surveys
CMB primordial	1.3	0.6	Recombination	WMAP, Planck [95]	None
CMB primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	0.2 – 0.05	NG of Secondary anisotropies	Planck, ACT [38], SPT [97]	EBEX [58], ACTPol [53], SPTPol, POLARBEAR [3], CMBPol [4]
Galaxy distribution	0.6	0.1	Nonlinearities, Bias	SDSS [59,60], BOSS [83]	DES [85], BigBOSS [82], DESpec [86], LSST [93], Subaru PFS [98], HETDEX [34]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [22], COSMOS [49]	DES [85], Hyper SuprimeCam [52], LSST [93], Euclid [89], WFIRST[101]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[82], TMT[100], GMT[90]
21 cm	∞	0.1 – 0.006	Foregrounds, Astrophysical modeling	GBT [10], LOFAR [92], PAPER [54], GMRT [87]	MWA [94], SKA [96], FFTT [48]
Galaxy clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [102] Chandra [84]	DES, eRosita [88], LSST

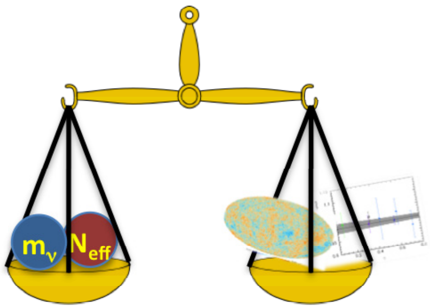
Abazajian et al, Astrop. Phys. 35 (2011) 177

Future sensitivities on neutrino masses

	5-7 years	7-15 years
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

✓ 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}). At 95% CL, bounds **Σm_ν < 0.23-0.85 eV** and **N_{eff}** between **2.79-3.84** or **3.14-4.12**, depending on data

✓ Improved sensitivities from a variety of cosmological data (Planck polarization in 2014, cosmic shear surveys…) to reach $\Sigma m_\nu < 0.1$ eV

For more details…