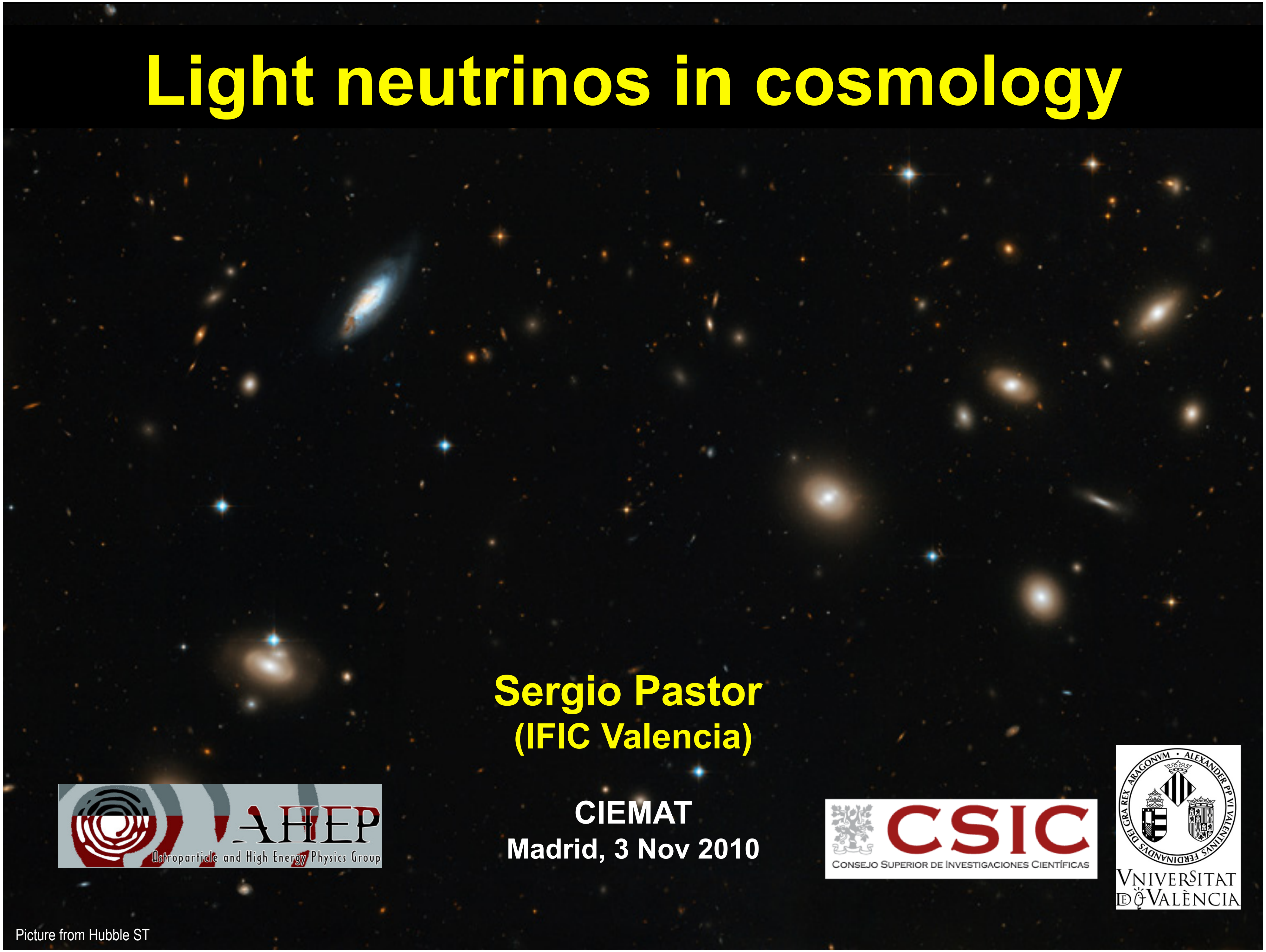
Light neutrinos in cosmology



Sergio Pastor
(IFIC Valencia)

CIEMAT
Madrid, 3 Nov 2010

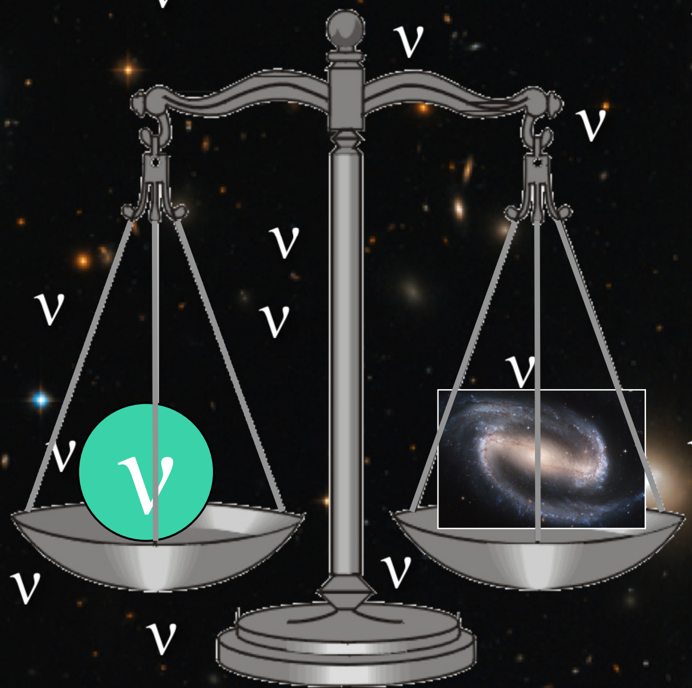
AHEP Astroparticle and High Energy Physics Group

CSIC Consejo Superior de Investigaciones Científicas

Vniversitat de València

Picture from Hubble ST

Light neutrinos in cosmology



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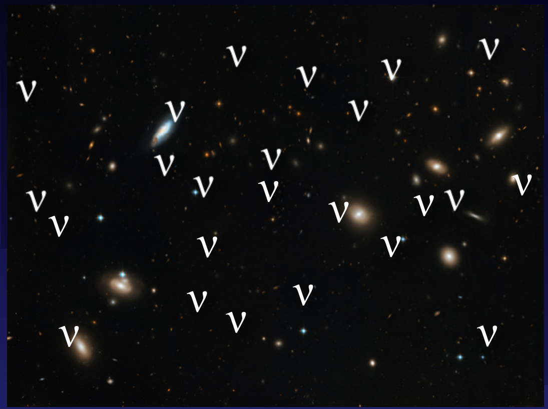


Outline

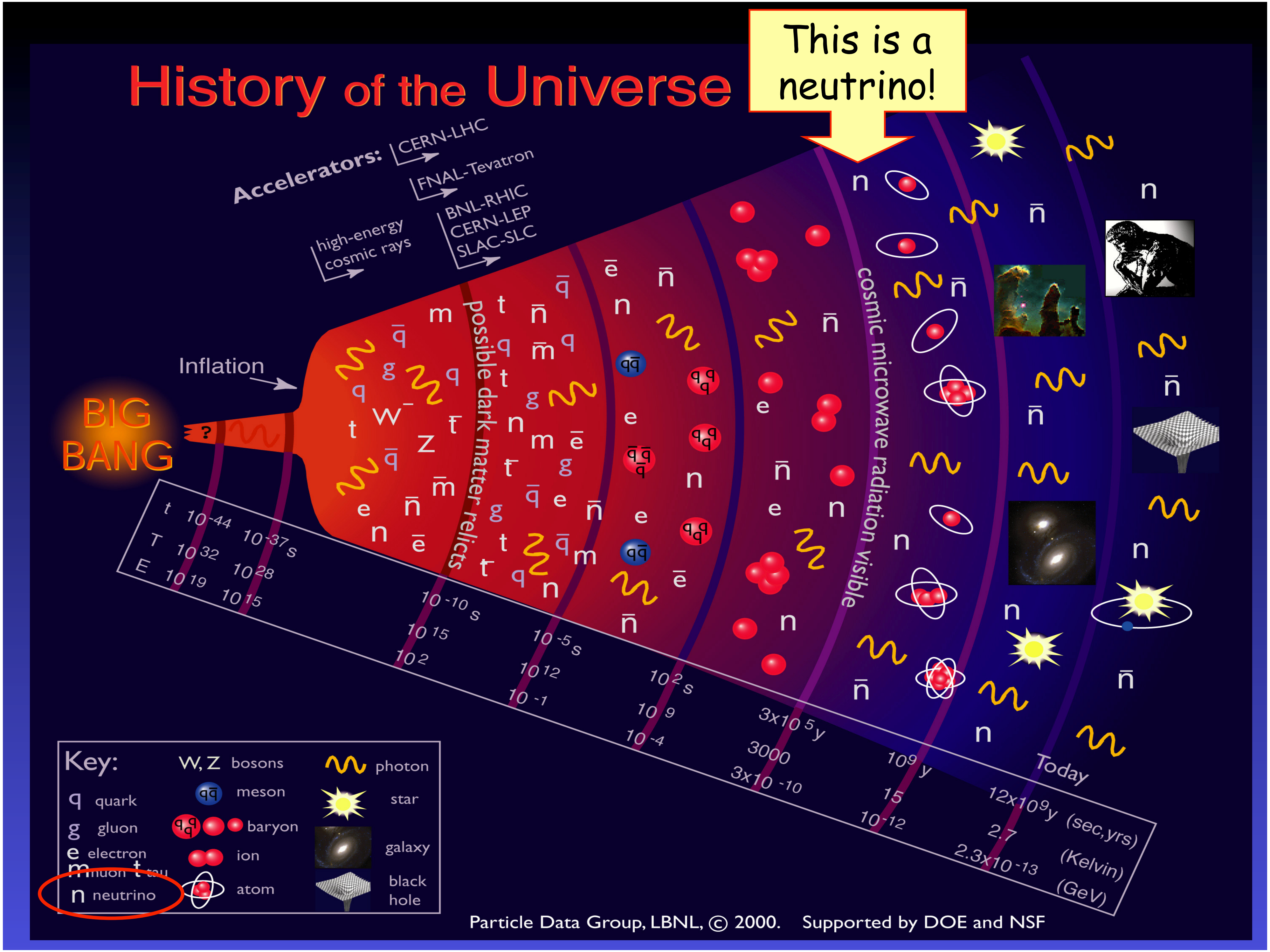
Introduction: the Cosmic Neutrino Background

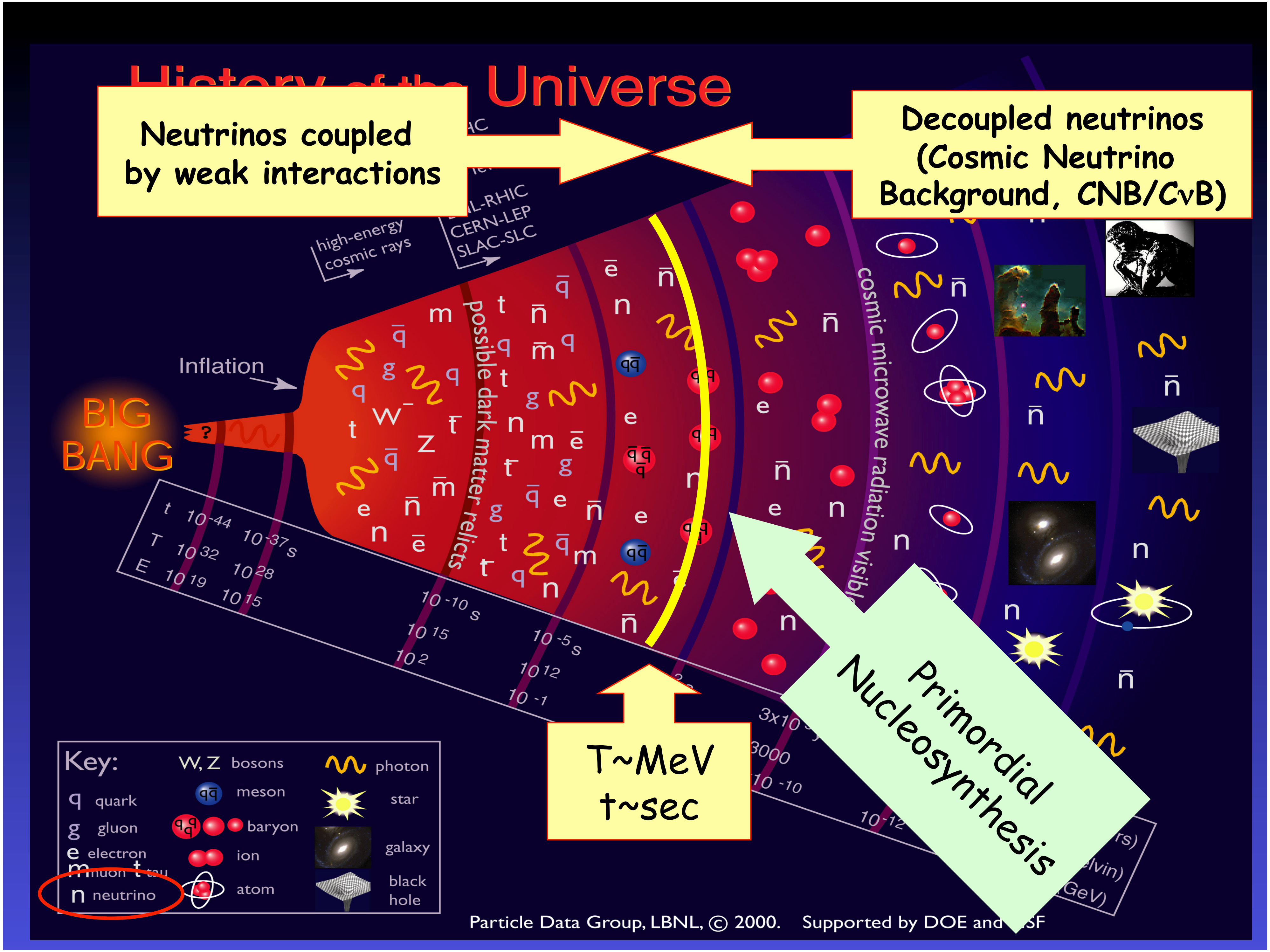
The radiation content of the Universe

Neutrinos as Dark Matter

Cosmological bounds on Σm_ν

Introduction: the Cosmic Neutrino Background


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 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
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


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

Neutrinos in Equilibrium

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

$T_\nu = T_e = T_\gamma$

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

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

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

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

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

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

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

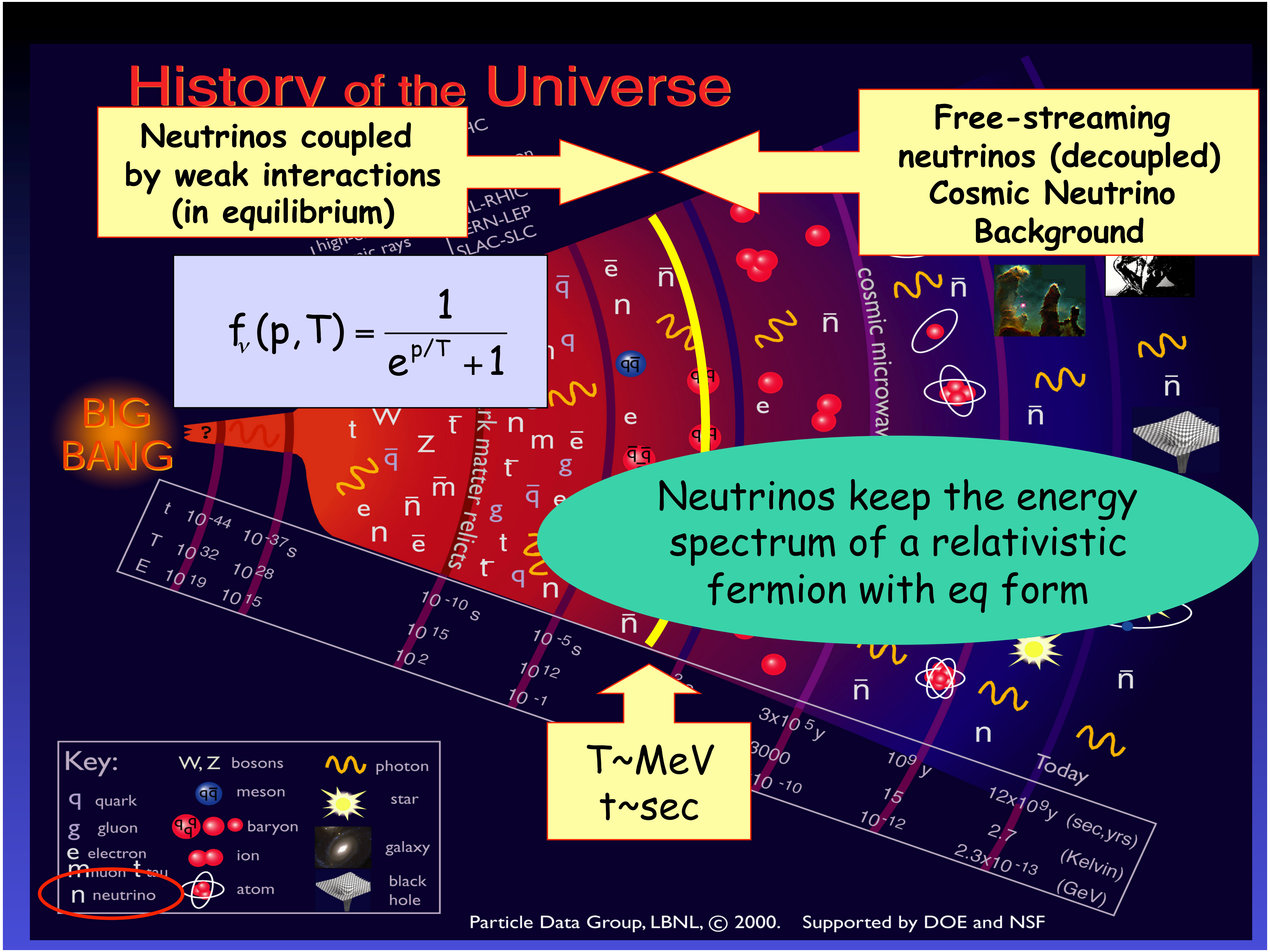
Neutrino decoupling

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

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

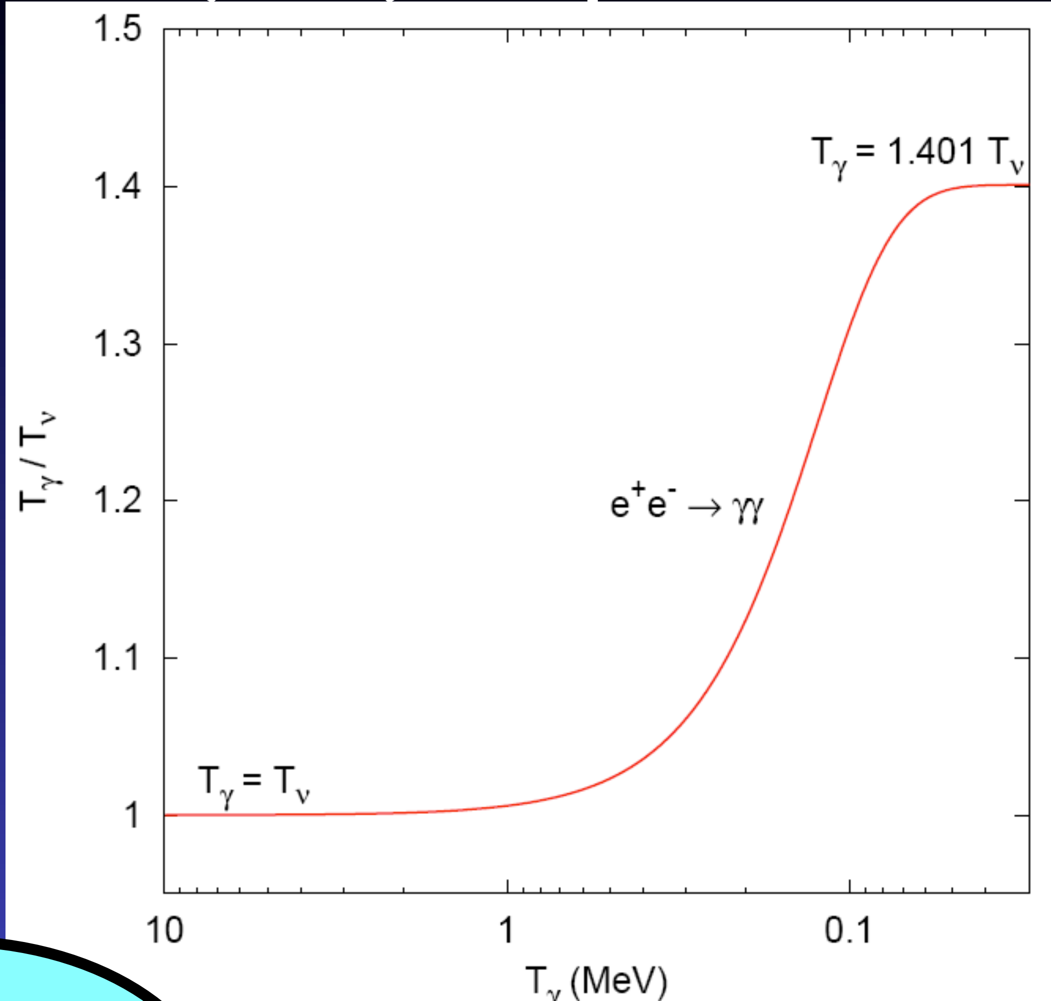

History of the Universe
Neutrinos coupled by weak interactions (in equilibrium)
Free-streaming neutrinos (decoupled) Cosmic Neutrino Background
$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$
BIG BANG
Neutrinos keep the energy spectrum of a relativistic fermion with eq form
T~MeV
t~sec
cosmic microwave
dark matter relicts
SLAC-SLC
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
3x10 5 y
3000
10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Neutrino and Photon (CMB) temperatures

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

$$e^+e^- \rightarrow \gamma\gamma$$

heating photons but not the decoupled neutrinos



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

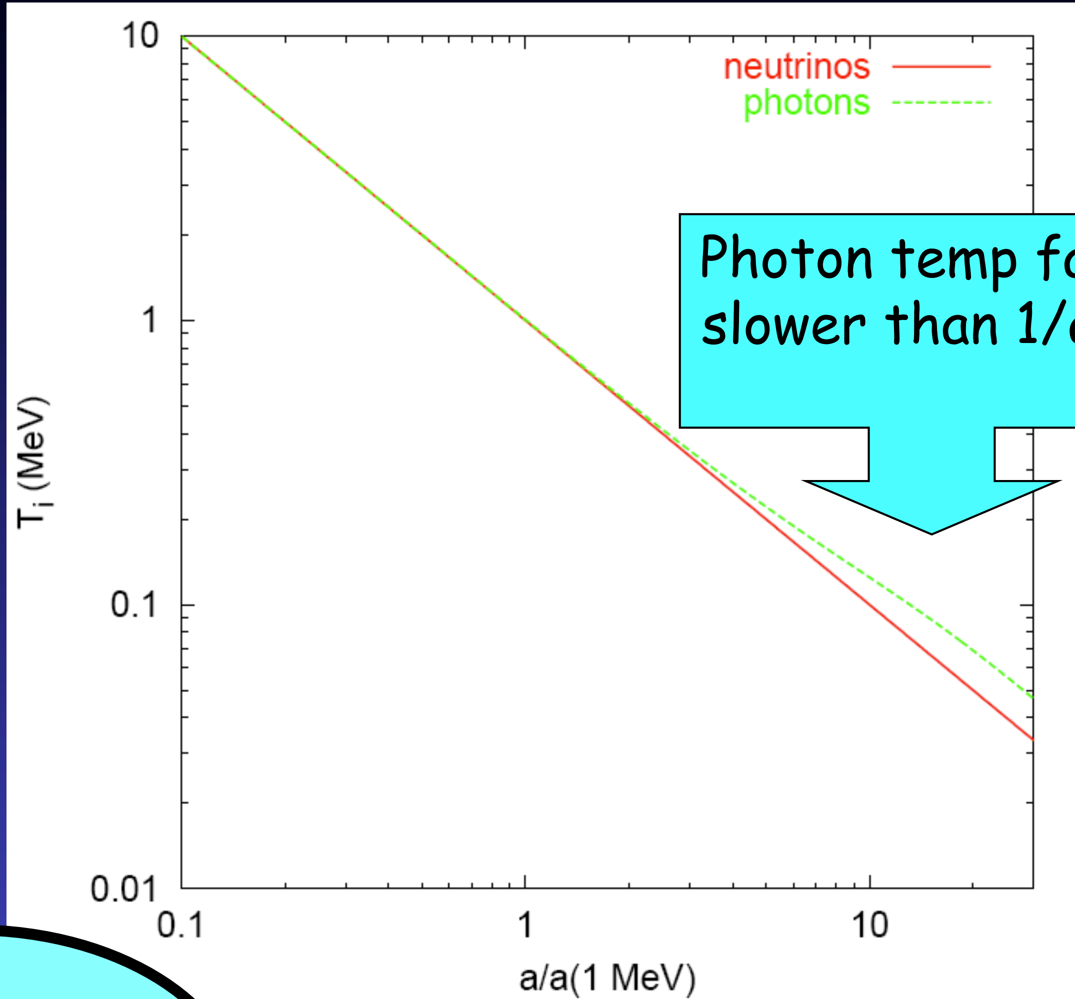
$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

Neutrino and Photon (CMB) temperatures

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

$$e^+e^- \rightarrow \gamma\gamma$$

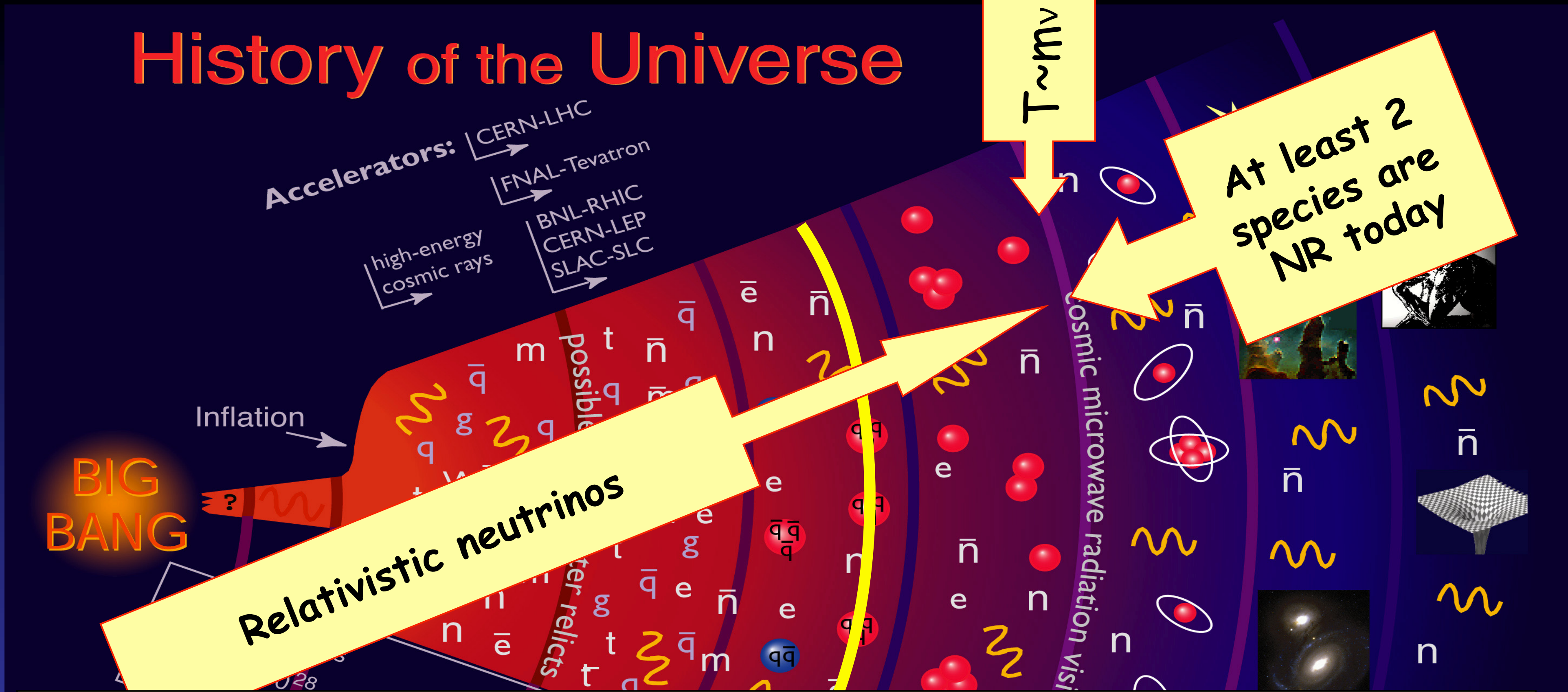
heating photons but not the decoupled neutrinos



Photon temp falls slower than 1/a(t)

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

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



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

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

- Energy density

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

The Cosmic Neutrino Background

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

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

- Number density

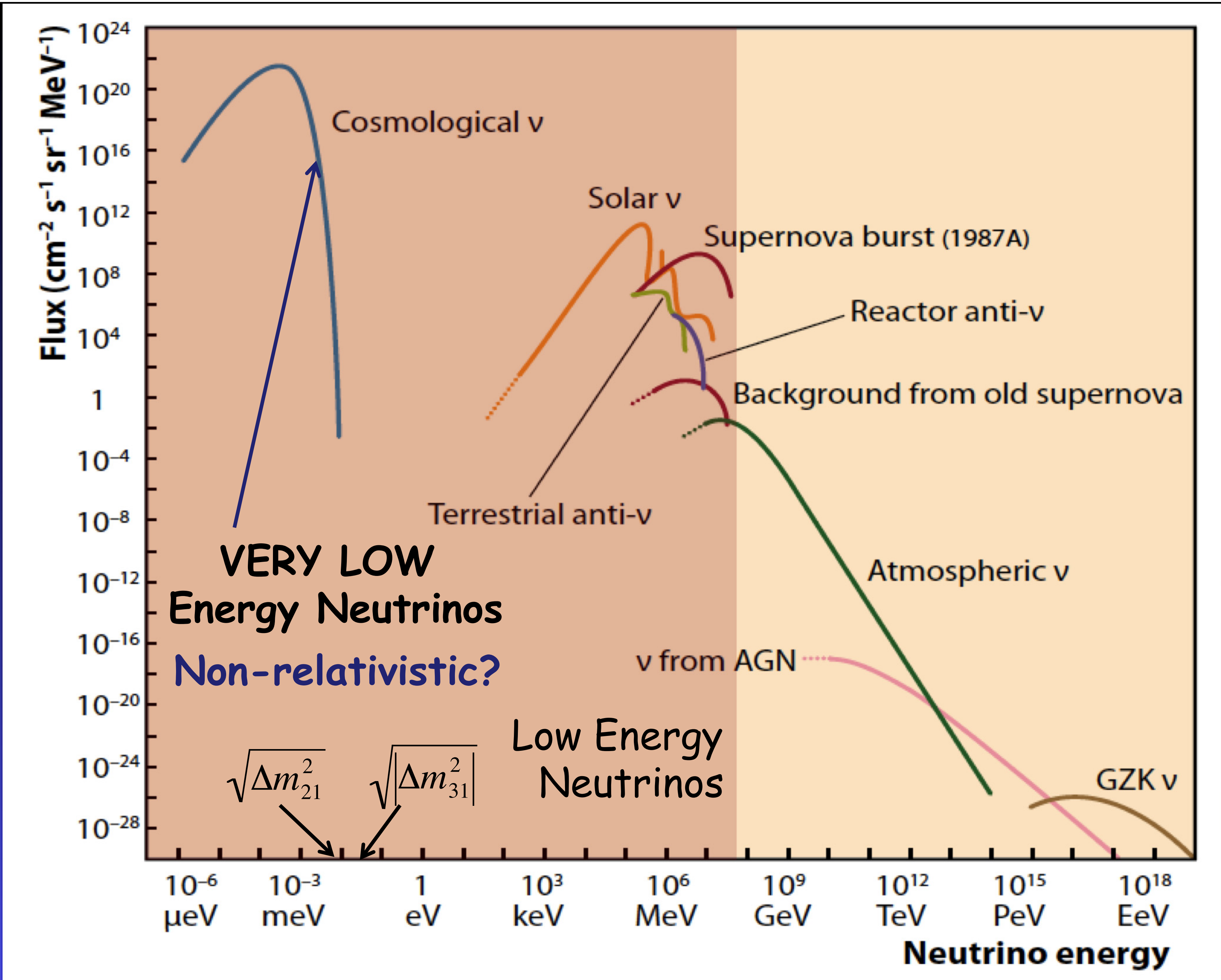
At present 112 $(\nu+\bar{\nu})$ cm^{-3} per flavour

- Energy density

Contribution to the energy density of the Universe

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

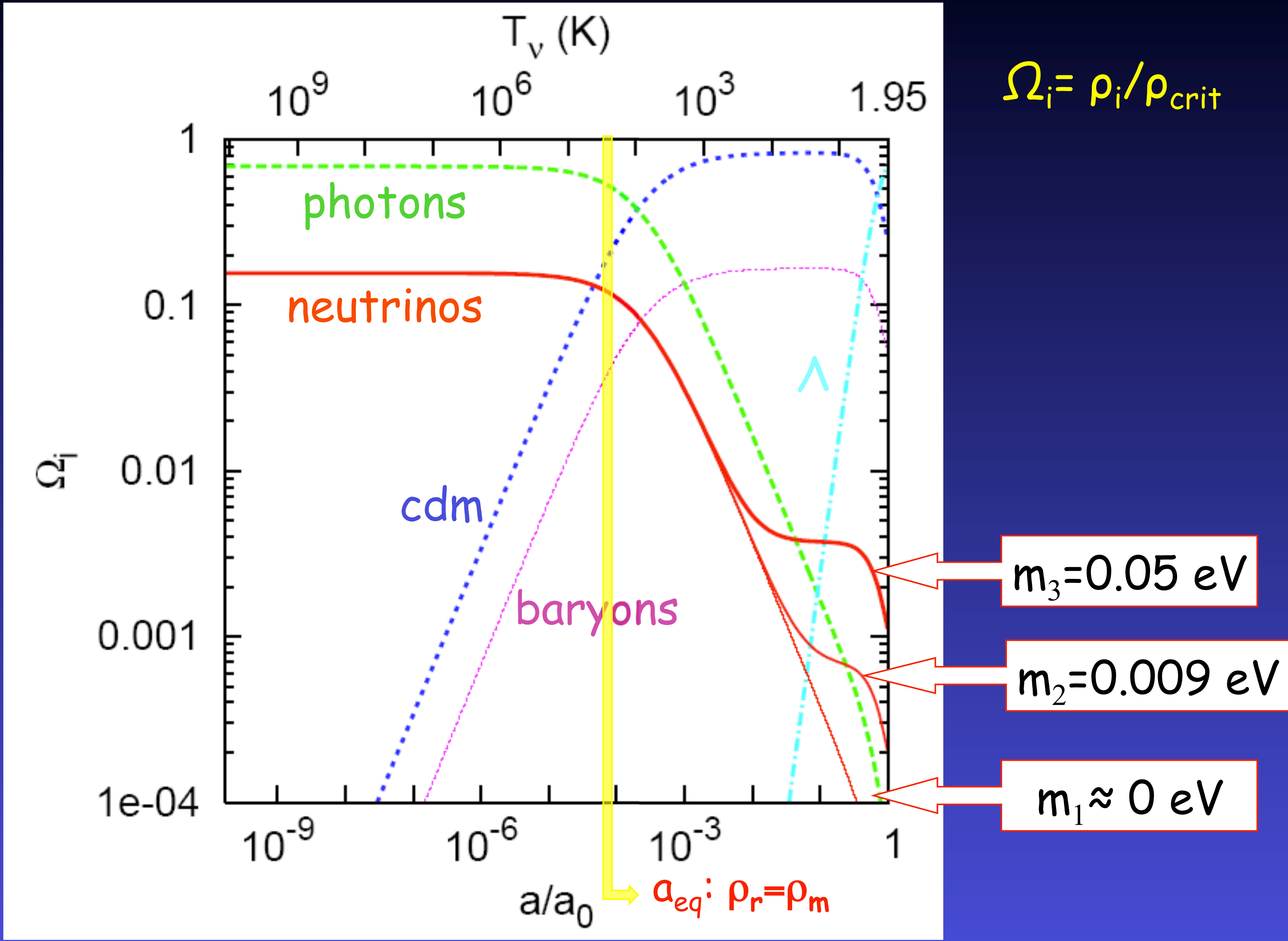
$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1 \text{ eV}}$$ Massive $m_\nu >> T$



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?
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

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



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

Relativistic particles in the Universe

At T>>m_e, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15}T^4 + 3\times\frac{7}{8}\times\frac{\pi^2}{15}T^4 = \left[1+\frac{7}{8}\times 3\right]\rho_\gamma$$

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

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15}T_\gamma^4 + 3\times\frac{7}{8}\times\frac{\pi^2}{15}T_\nu^4 = \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} 3\right]\rho_\gamma$$

$$\frac{T_\nu^4}{T_\gamma^4}$$

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

Relativistic particles in the Universe

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

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

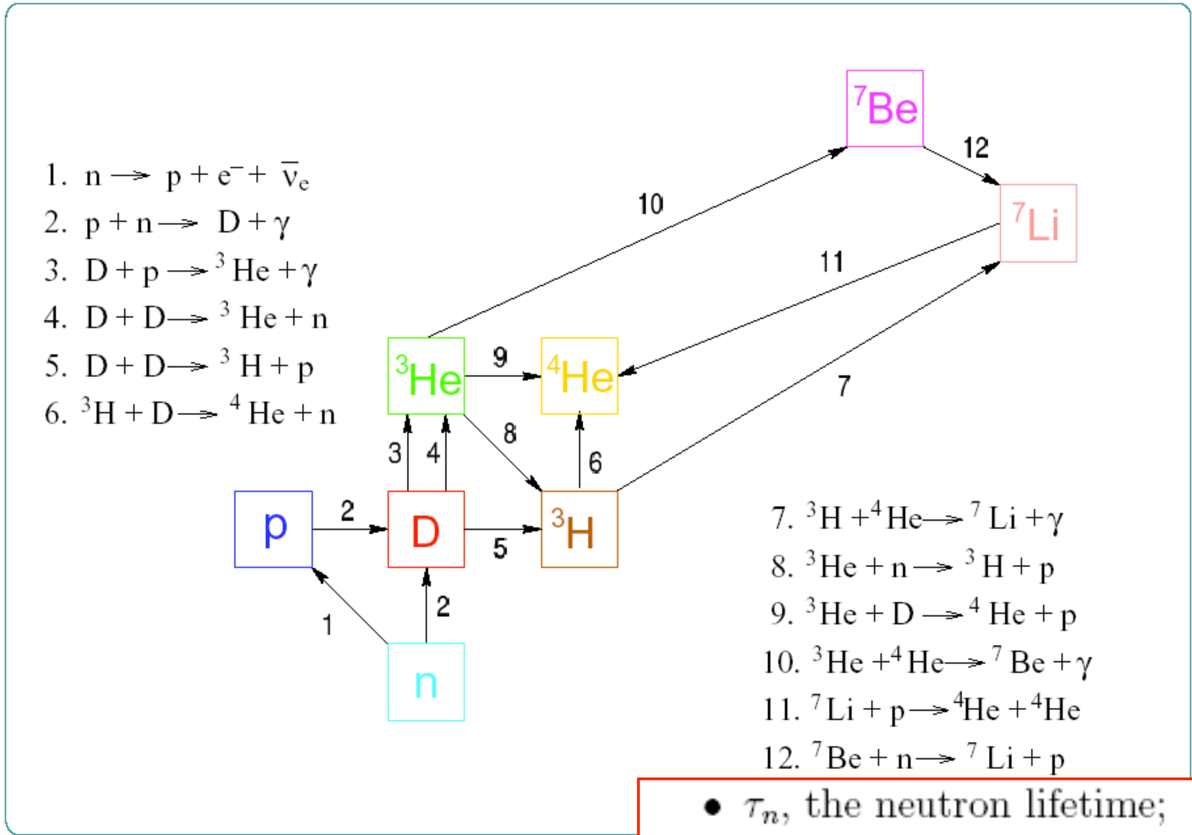
Effective number of relativistic neutrino species

Traditional parametrization of the energy density stored in relativistic particles

\# of flavour neutrinos: $N_\nu = 2.984 \pm 0.008$ (LEP data)

Constraints on N_{eff} from Primordial Nucleosynthesis and other cosmological obsevables (CMB+LSS)

BBN: Creation of light elements



Produced elements: D, ^{3}He, ^{4}He, ^{7}Li and small abundances of others

Theoretical inputs:

- τ_n, the neutron lifetime;
- G_N, the Newton gravitational constant;
- η, the baryon to photon number density ratio;
- the nuclear rates.

The first two parameters are now known with a satisfactory accuracy

$$\tau_n = 885.7 \pm 0.8\, s \quad ,$$
$$G_N = 6.7087 \pm 0.0010 \cdot 10^{-39}\, GeV^{-2} \quad .$$

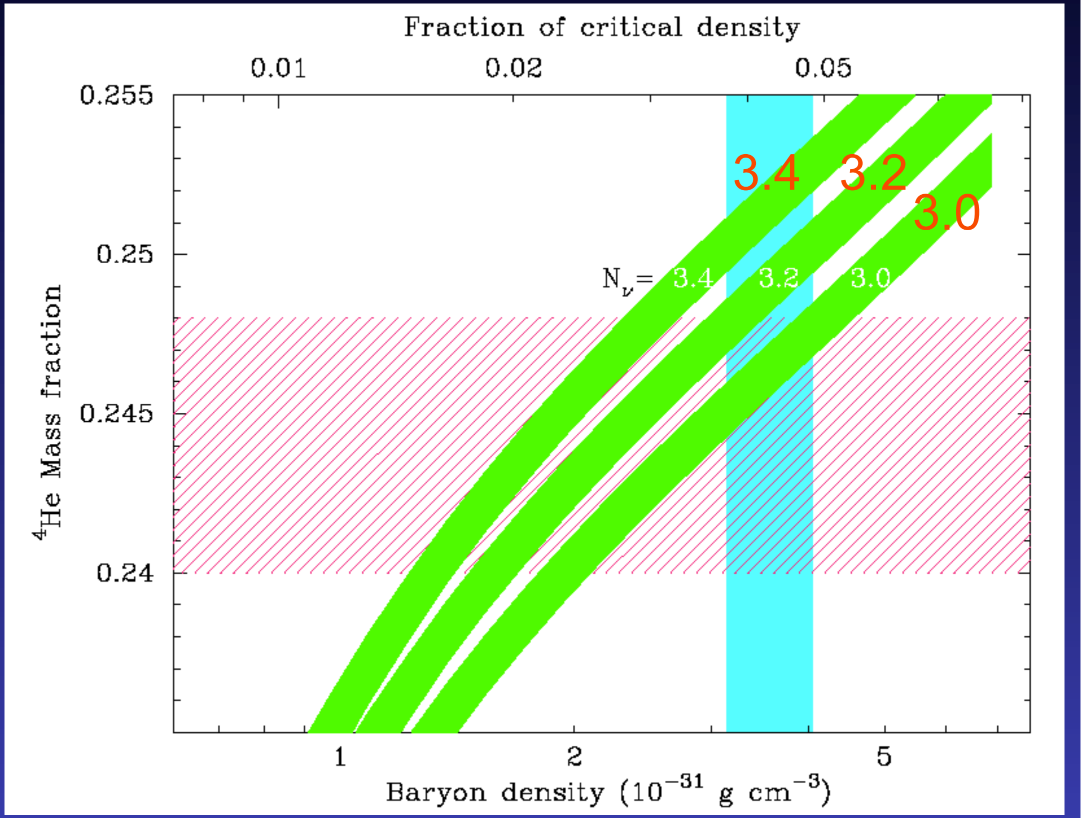
Effect of neutrinos on BBN

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

$$H = \sqrt{\frac{8\pi\rho}{3M_p^2}}$$

$\rho(N_{eff}) > \rho_0 \rightarrow \uparrow {}^4He$

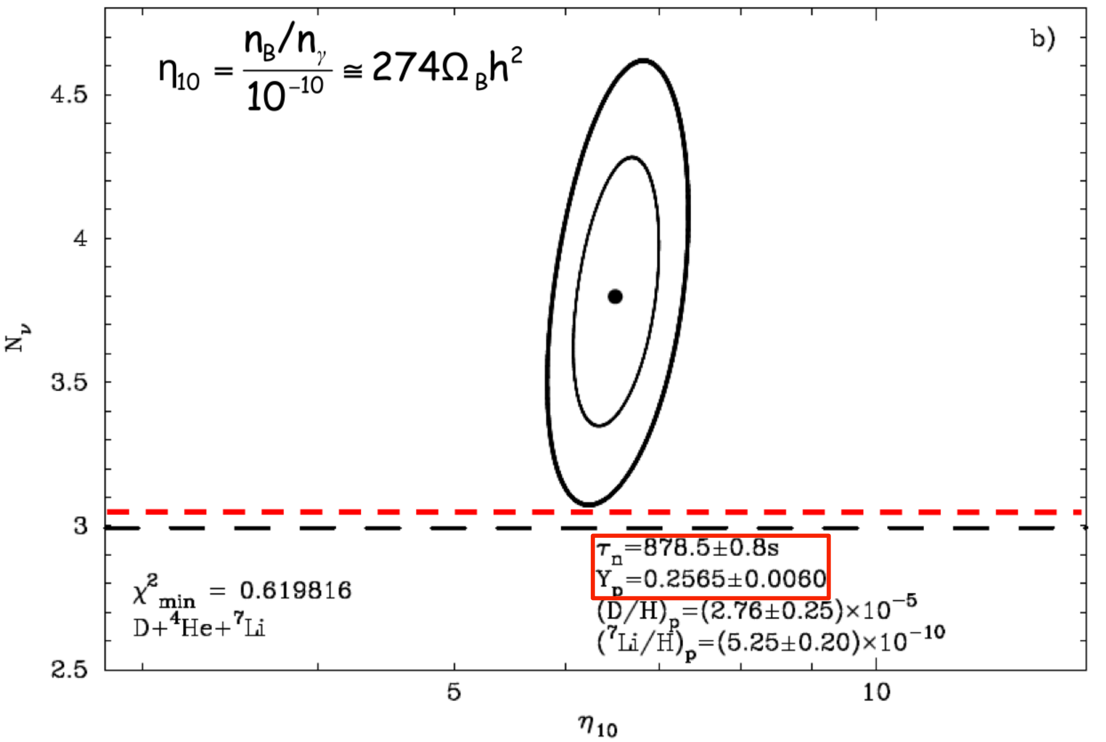
Burles, Nollett & Turner 1999

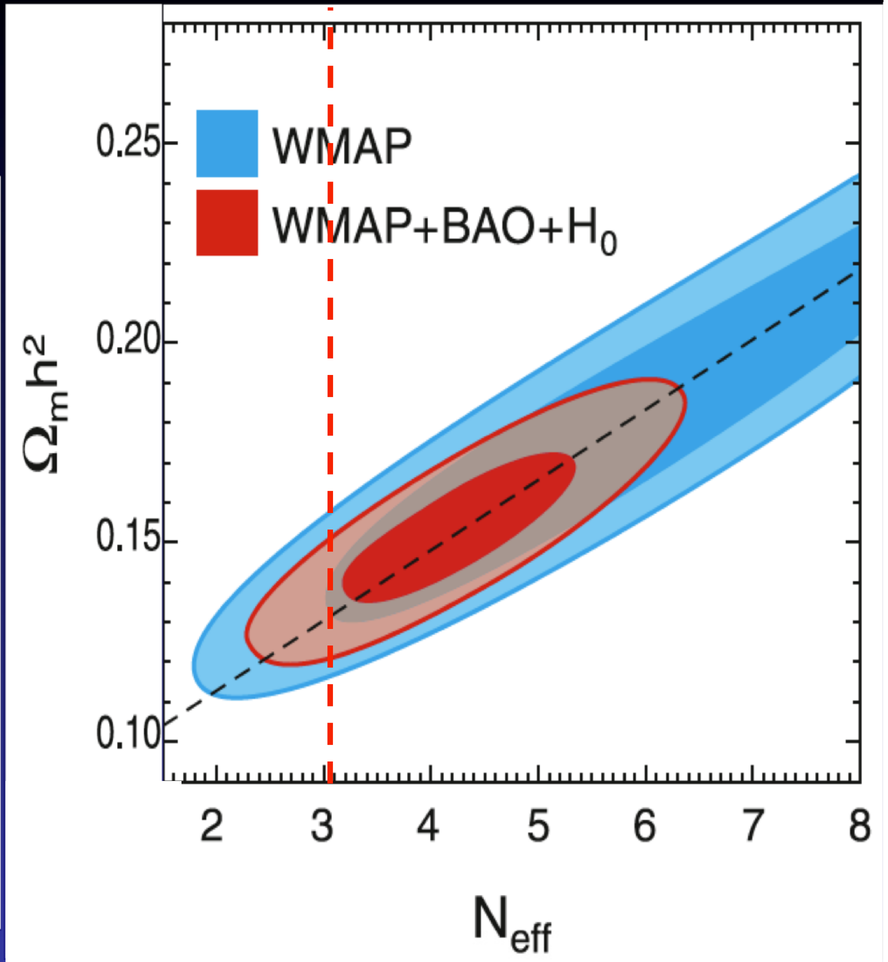


2. Direct effect of electron neutrinos and antineutrinos on the n-p reactions

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

allowed ranges for N_{eff}





Recent ^{4}He data

Izotov & Thuan, ApJ 710 (2010) L67

$$N_{eff} = 3.80^{+0.80}_{-0.70}$$

(95% CL)

from non-BBN data

WMAP [7-year], arXiv:1001.4538

$$2.7 < N_{eff} < 6.2 \text{ (WMAP+BAO+}H_0\text{)}$$

Larger errors: Aver et al, JCAP 05 (2010) 003

Extra relativistic particles

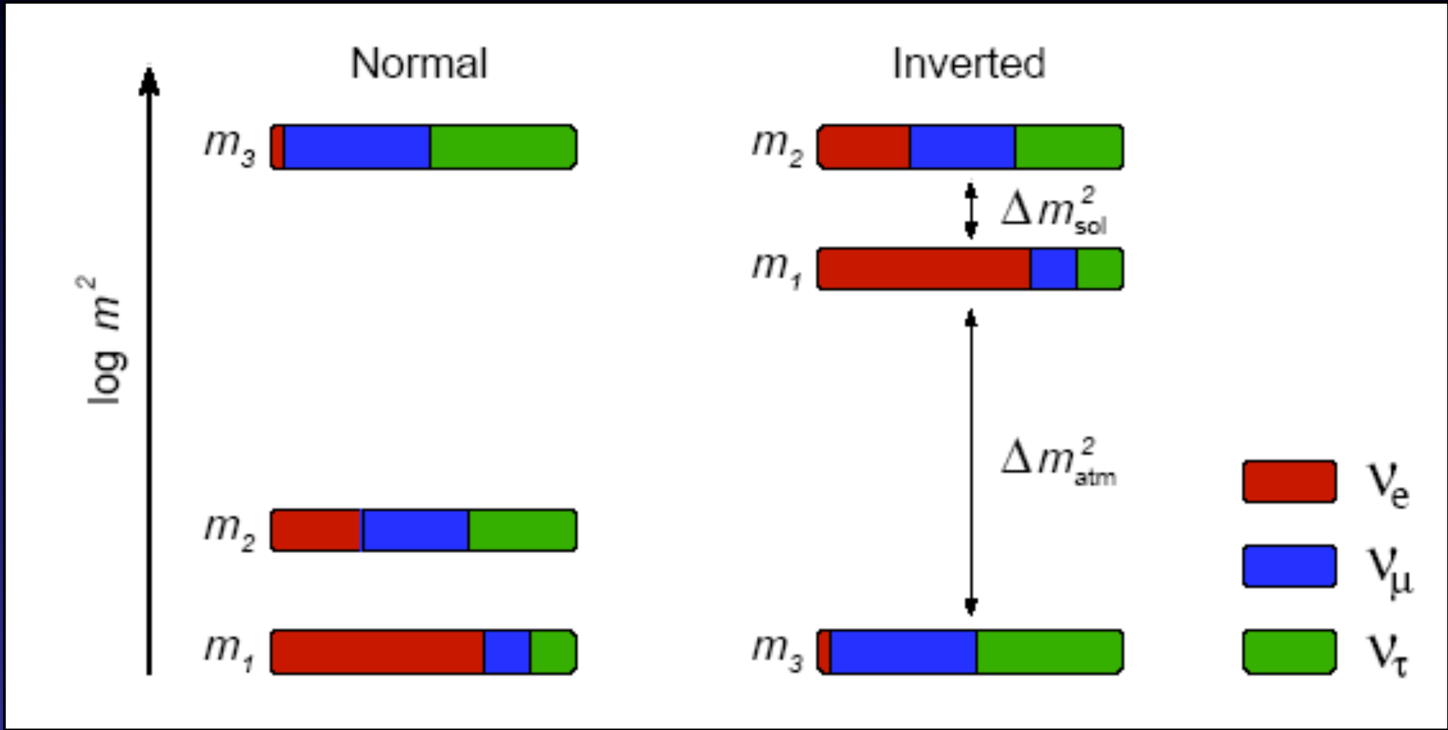
• Extra radiation: How to get N_{eff} > 3?

Neutrinos in non-standard scenarios: NS Interactions, sterile neutrinos (totally or partially thermalized), relic neutrino asymmetries

Other relativistic particles: scalars, pseudoscalars, relativistic decay products of heavy particles…

Neutrinos as Dark Matter

Neutrino masses



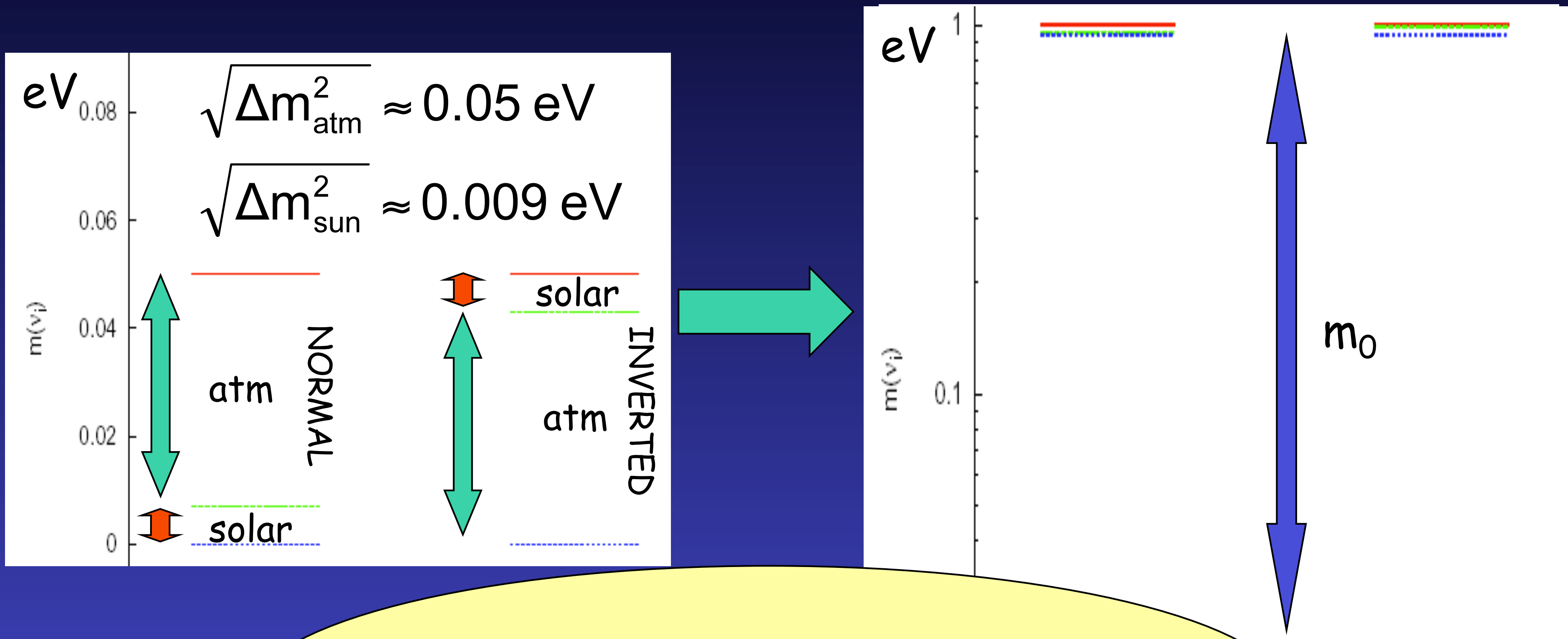
Possible neutrino mass hierarchy patterns

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

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

Neutrino masses

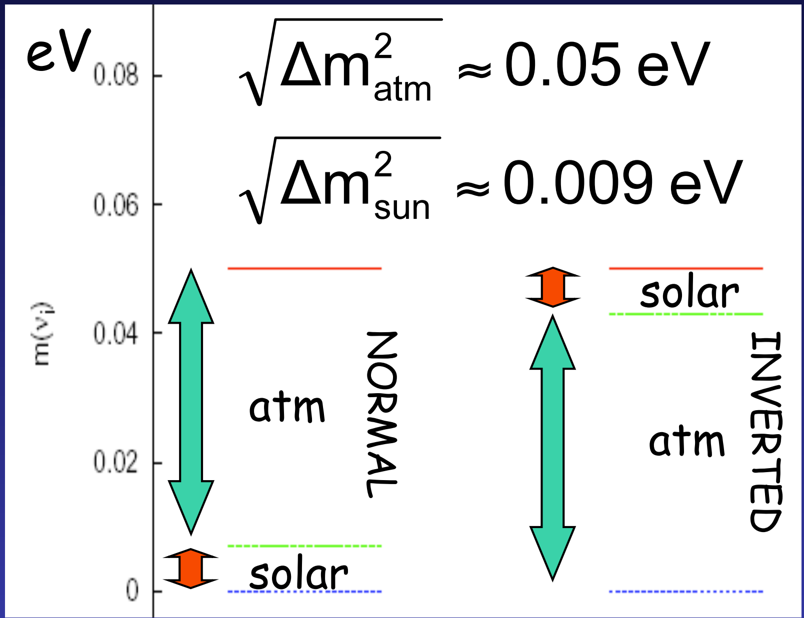
Data on flavour oscillations do not fix the absolute scale of neutrino masses

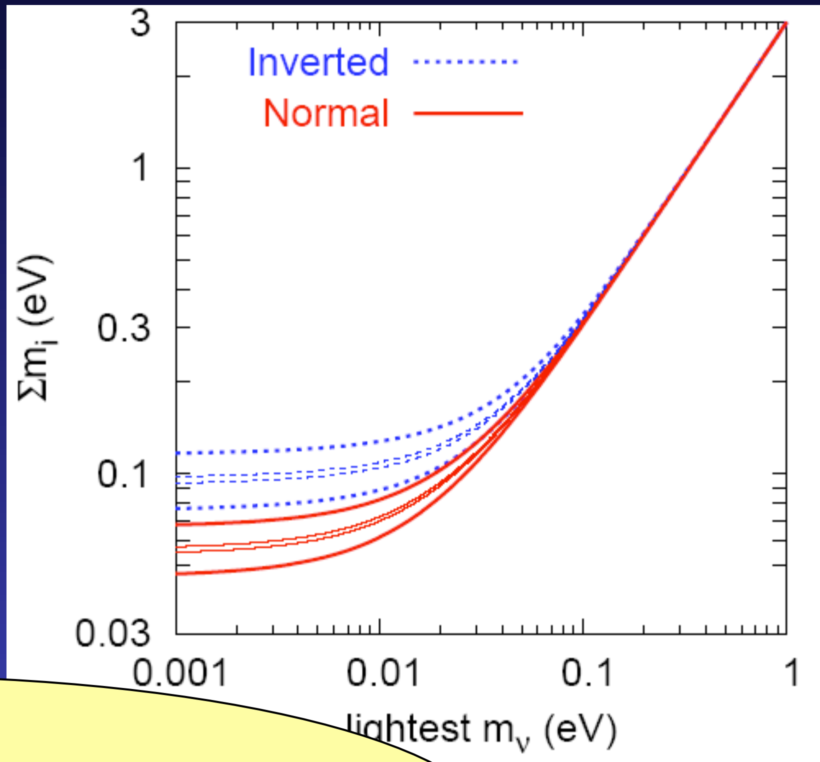


What is the value of m_0 ?

Neutrino masses

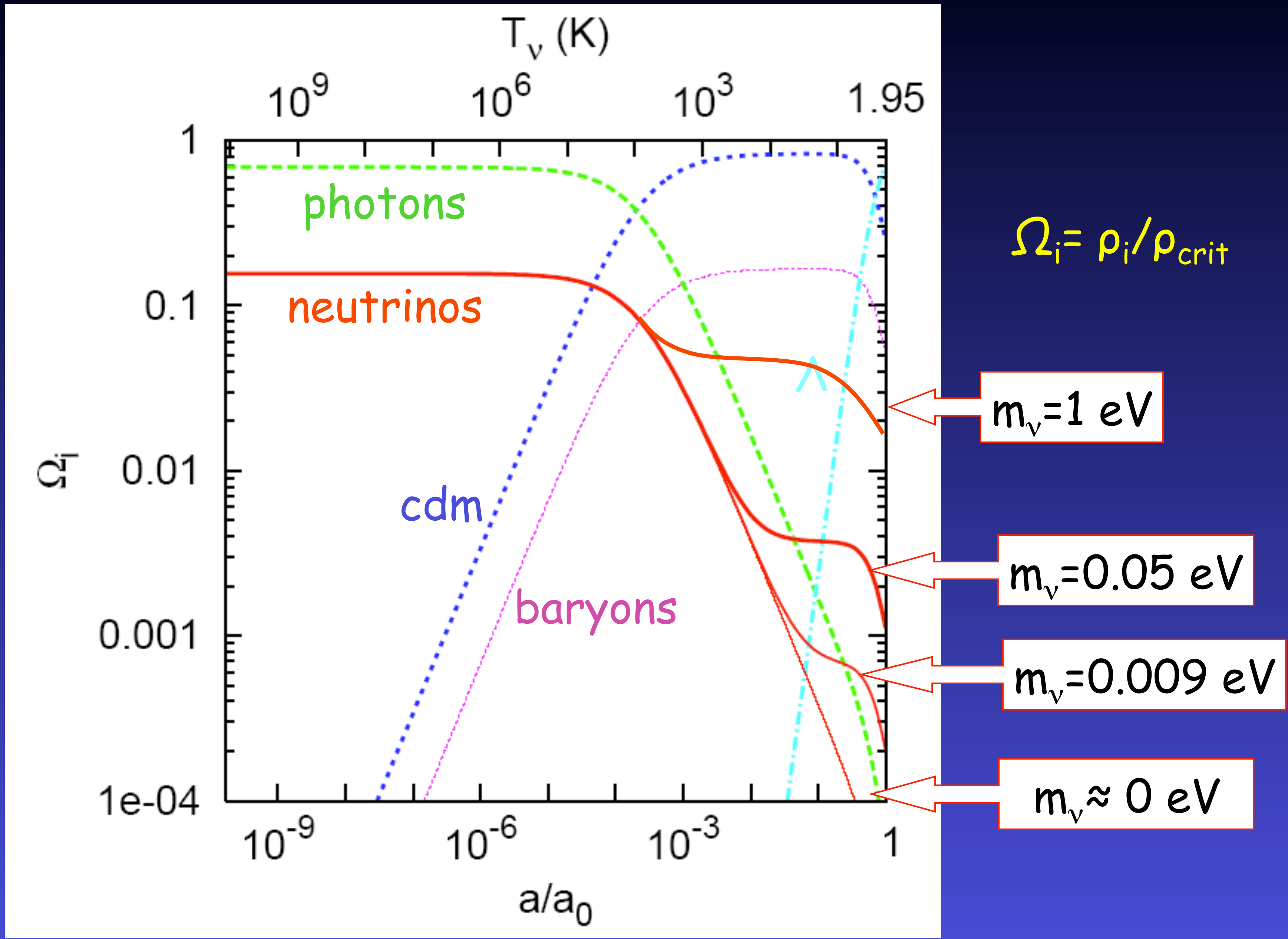
Data on flavour oscillations do not fix the absolute scale of neutrino masses





What is the value of m_0 ?

Evolution of the background densities: 1 MeV → now



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

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

Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

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

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

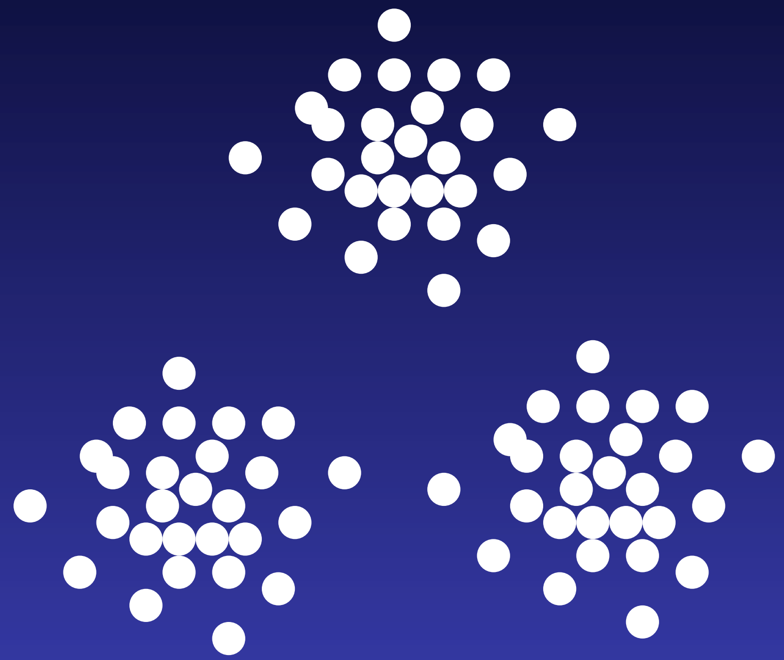
- They stream freely until non-relativistic (collisionless phase mixing) → Neutrinos are HOT Dark Matter
- First structures to be formed when Universe became matter -dominated are very large
- Ruled out by structure formation → CDM

Neutrinos as Hot Dark Matter

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

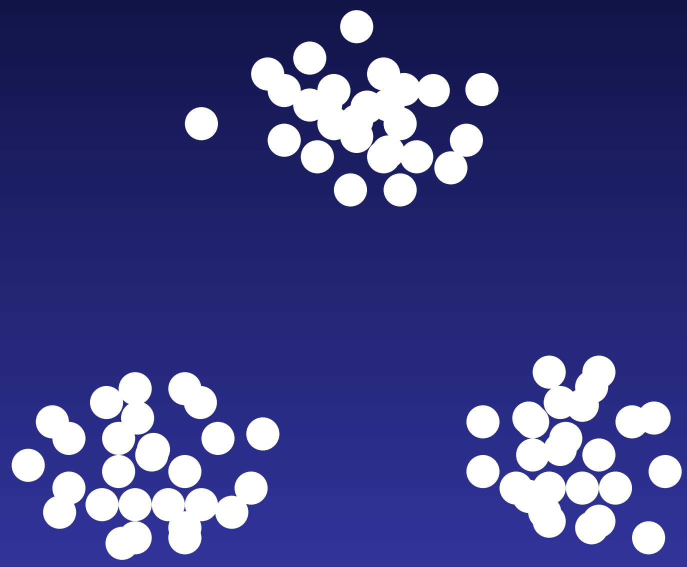
Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



Structure formation after equality

baryons and
CDM (matter)
experience
gravitational
clustering



Structure formation after equality

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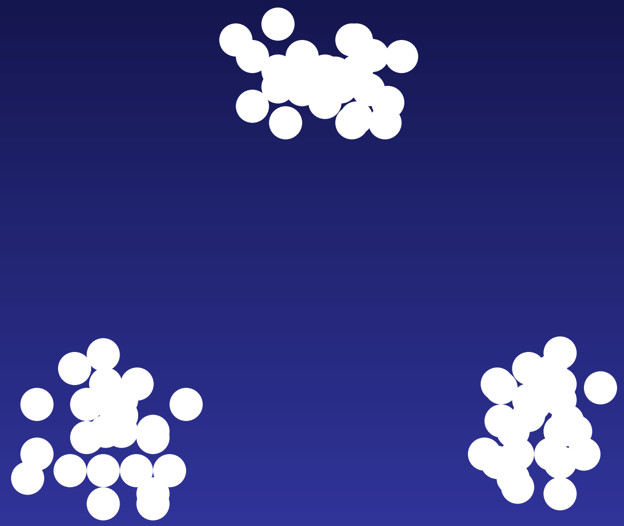
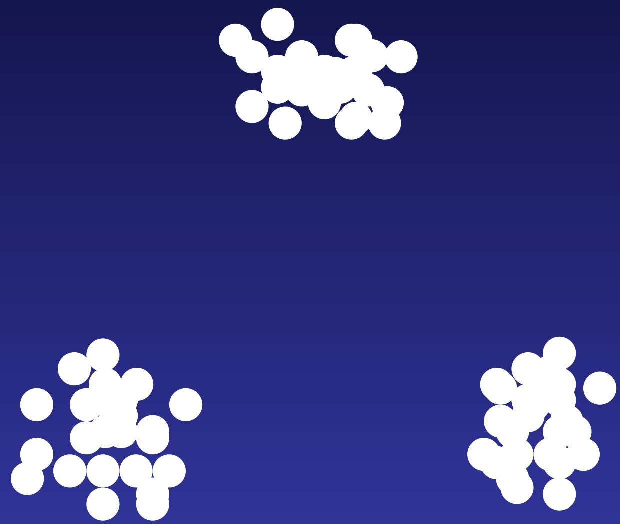


Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



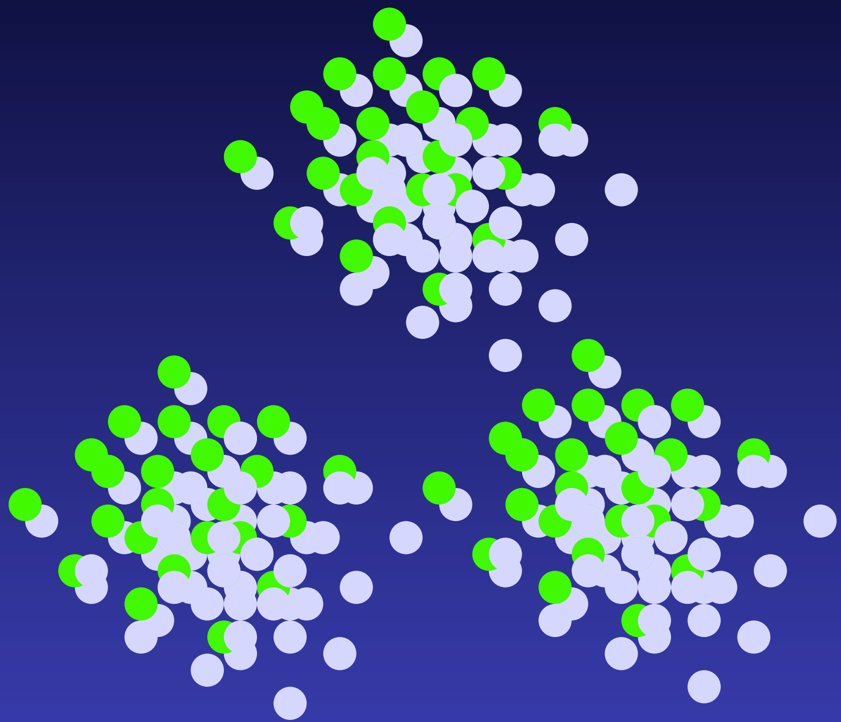
growth of $\delta\rho/\rho$ (k,t) fixed by

gravity vs expansion balance

$\Rightarrow \delta\rho/\rho \propto a$

Structure formation after equality

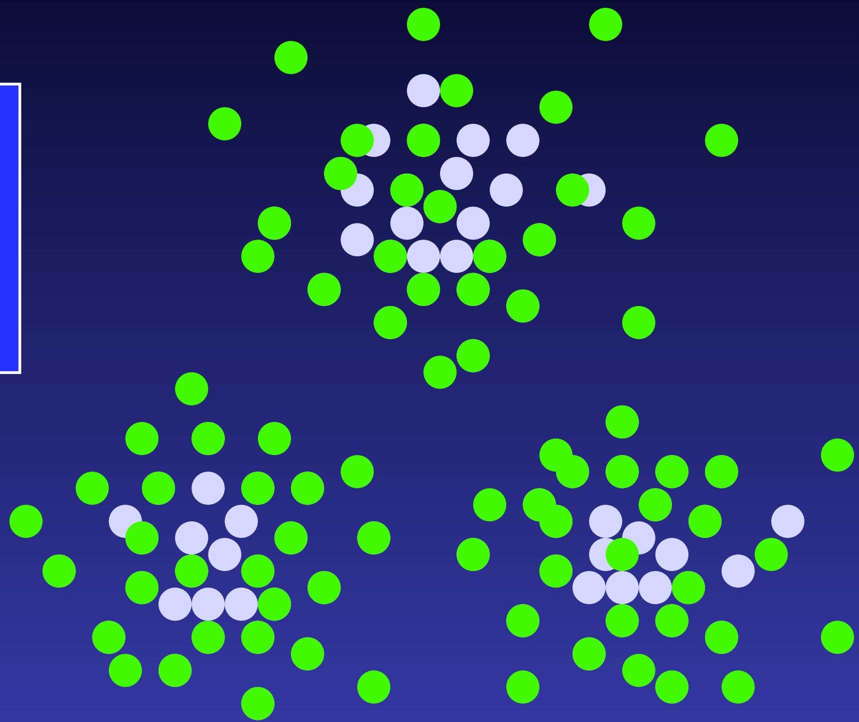
baryons and
CDM (matter)
experience
gravitational
clustering



neutrinos
experience
free-streaming
with
v = c or <p>/m

Structure formation after equality

baryons and
CDM (matter)
experience
gravitational
clustering



neutrinos
experience
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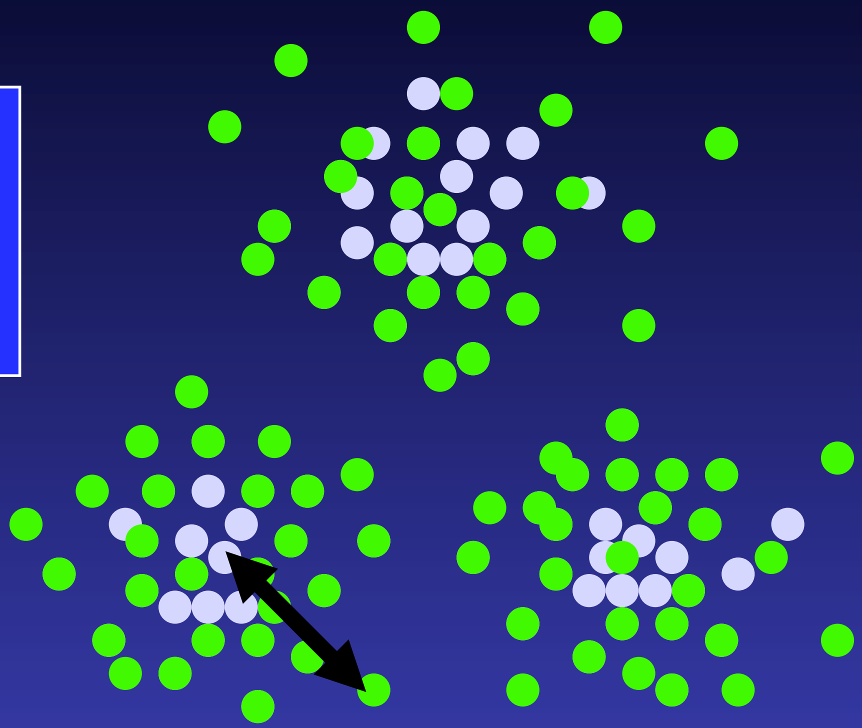
baryons and CDM (matter) experience gravitational clustering



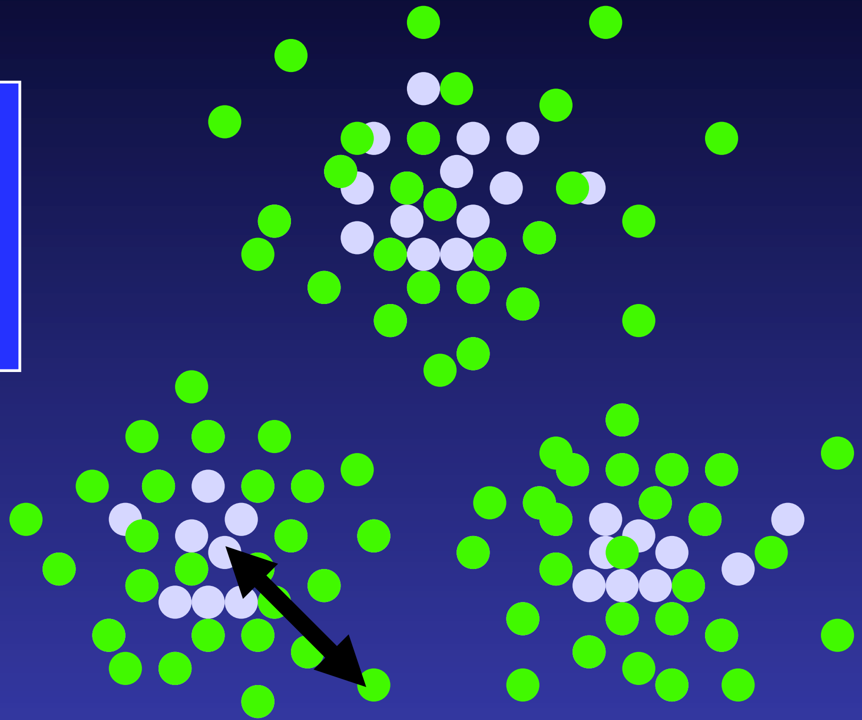
neutrinos experience free-streaming with v = c or <p>/m

neutrinos cannot cluster below a diffusion length

$$\lambda = \int v\, dt < \int c\, dt$$

Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

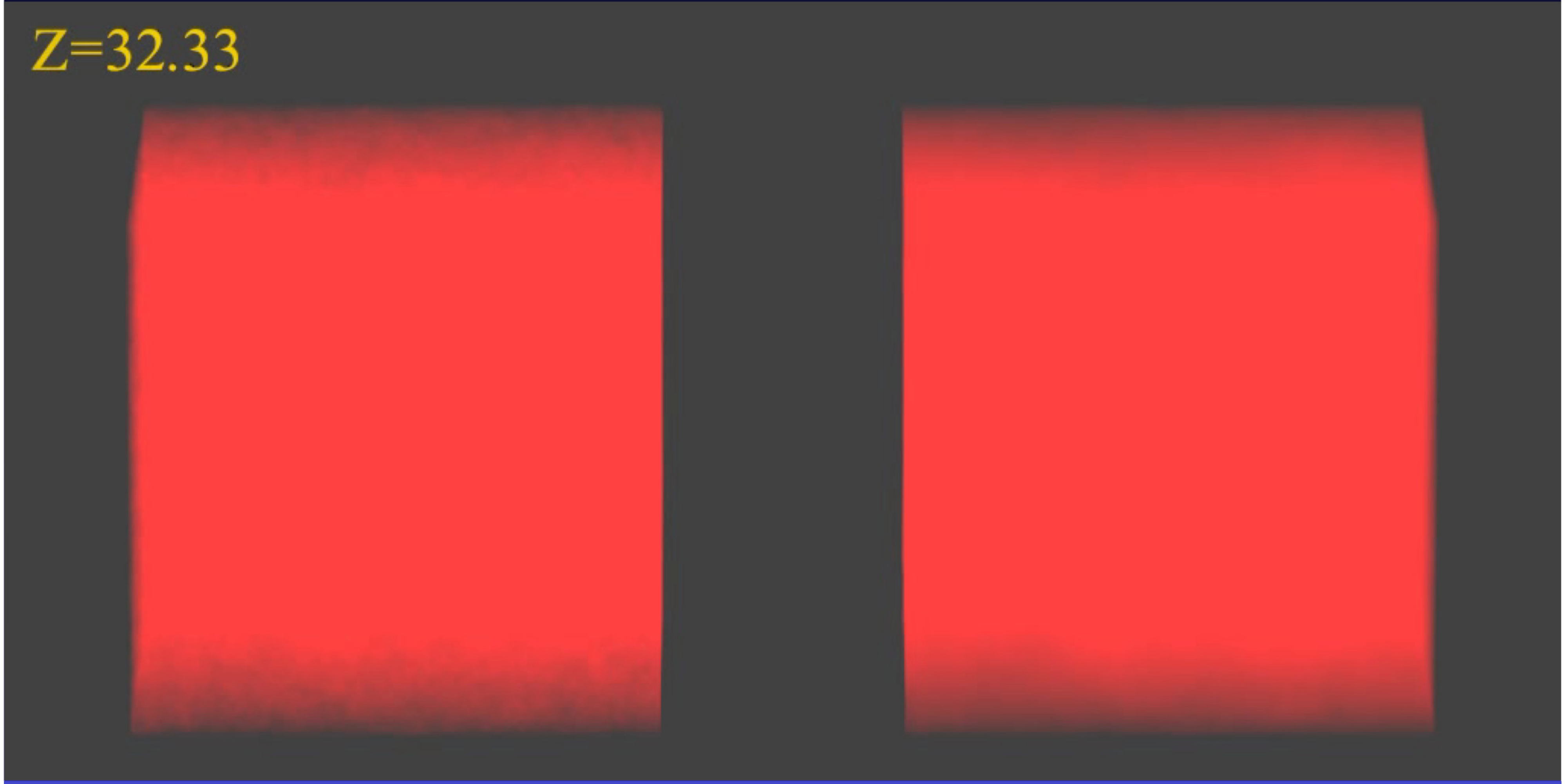
for $(2\pi/k) < \lambda$,

free-streaming supresses growth of structures during MD

⇨ $\delta\rho/\rho \propto a^{1-3/5\,f\nu}$ with $f_\nu = \rho_\nu/\rho_m \approx (\Sigma m_\nu)/(15\ \mathrm{eV})$

Neutrinos as Hot Dark Matter

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



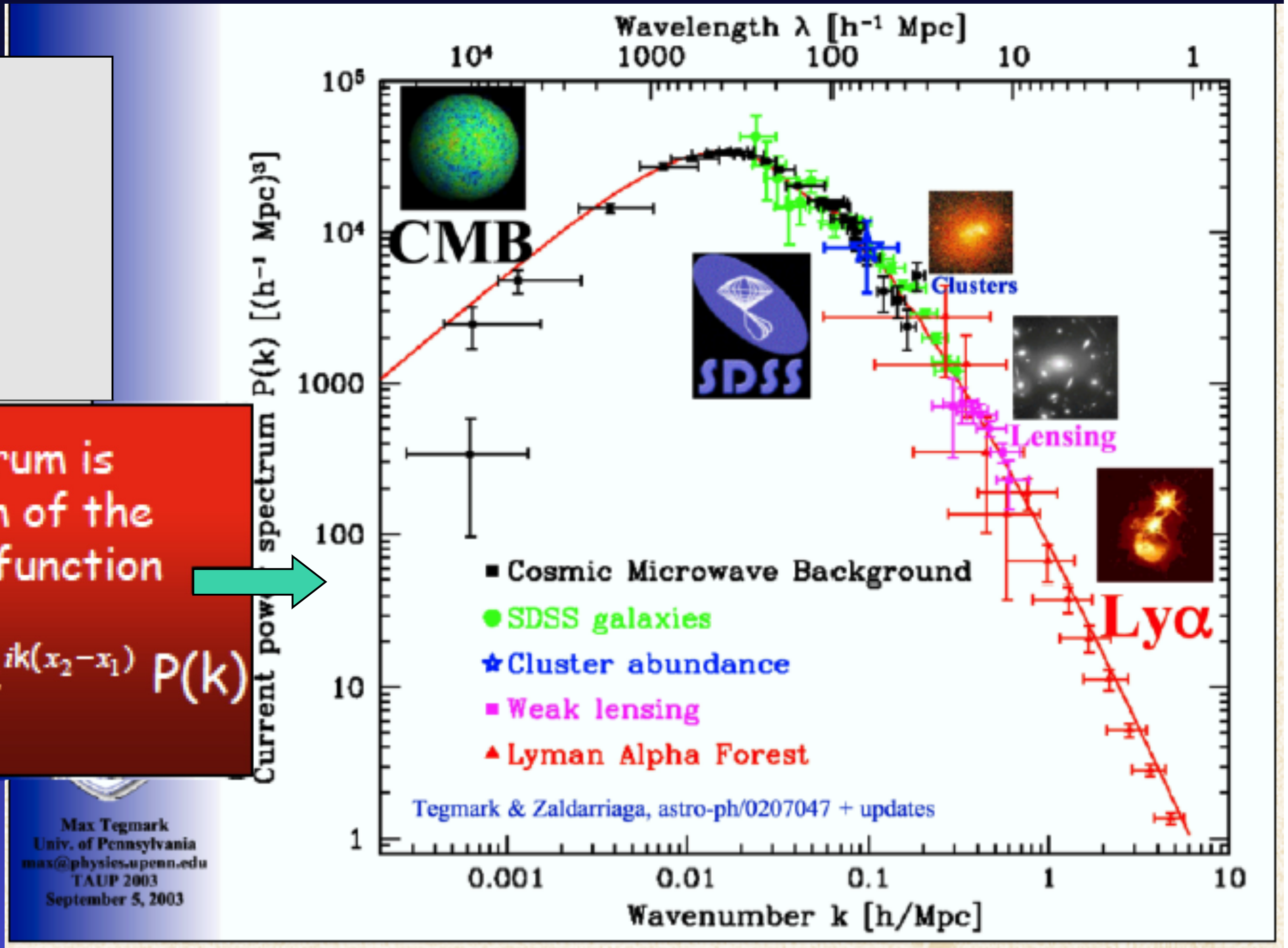
Power Spectrum of density fluctuations

Field of density Fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Matter power spectrum is the Fourier transform of the two-point correlation function

$$\langle \delta(x_1)\delta(x_2) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik(x_2 - x_1)} P(k)$$



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

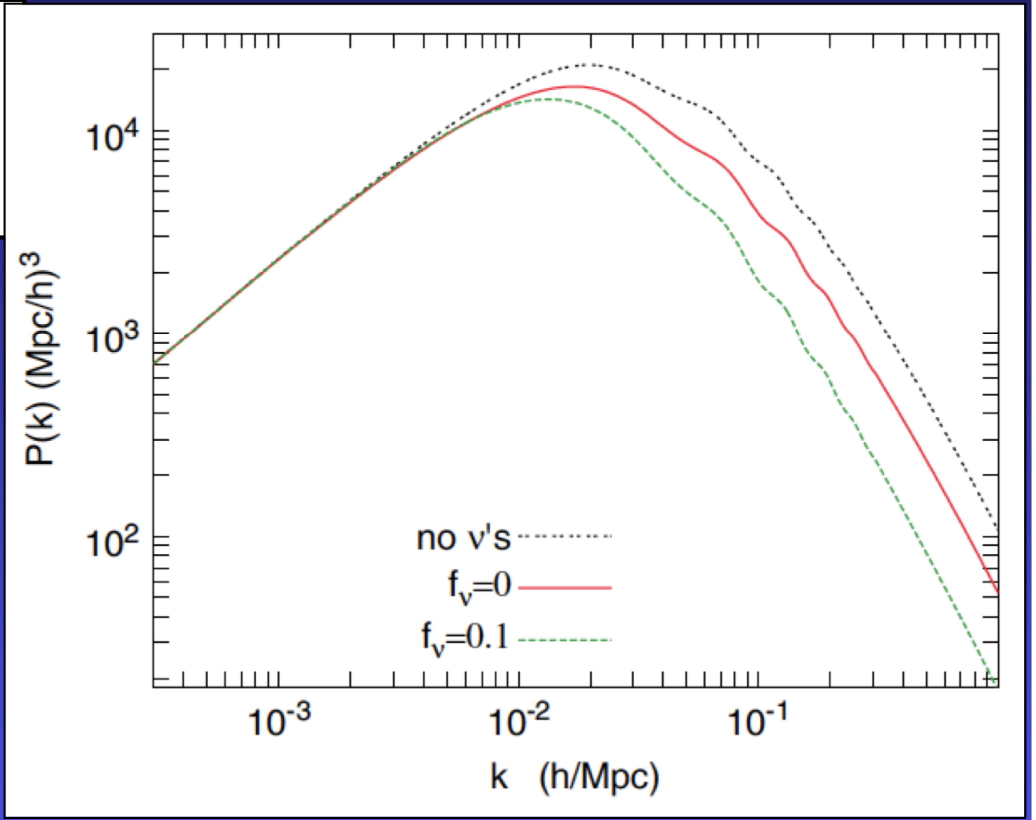
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

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

The small-scale suppression is given by

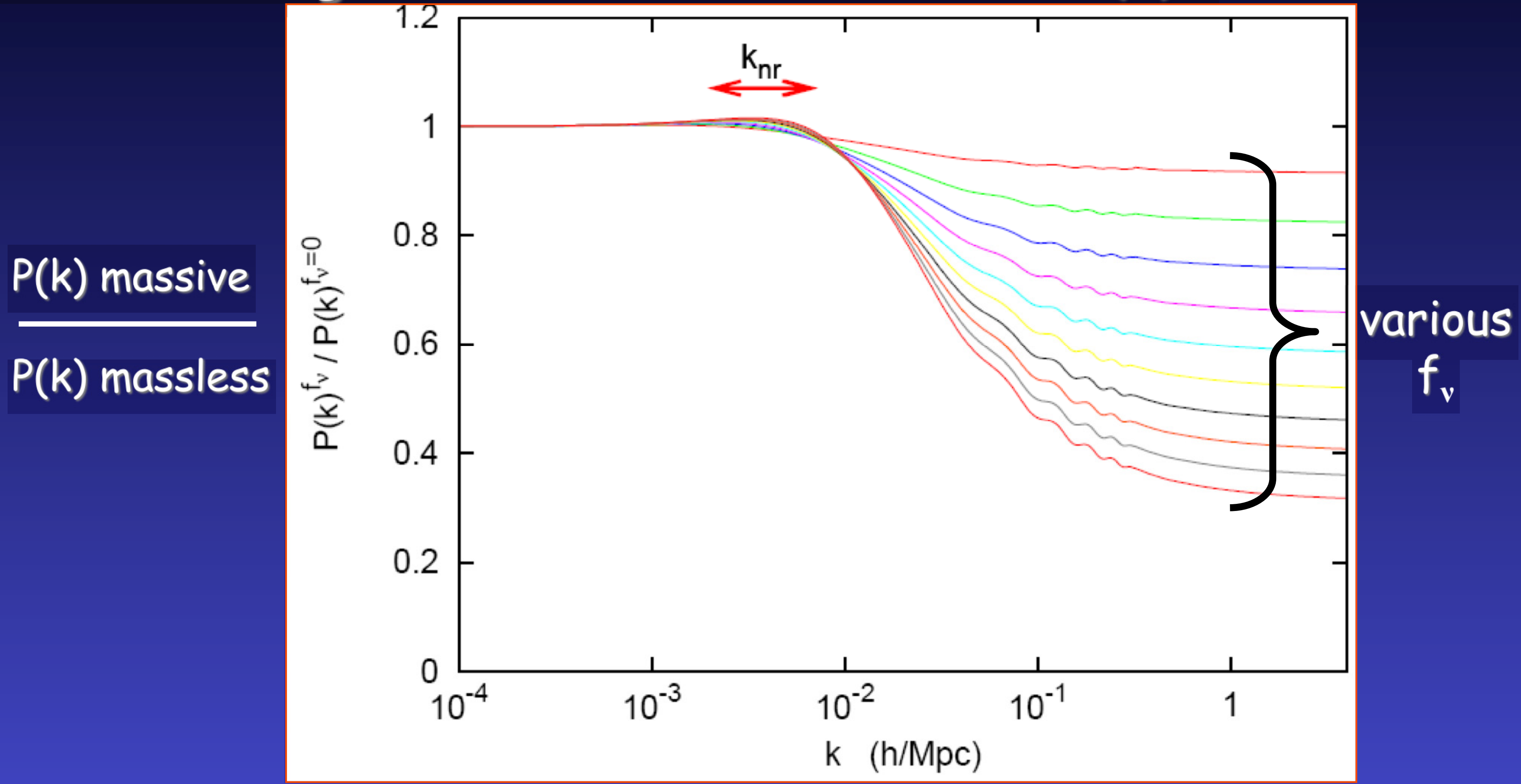
$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

f_ν



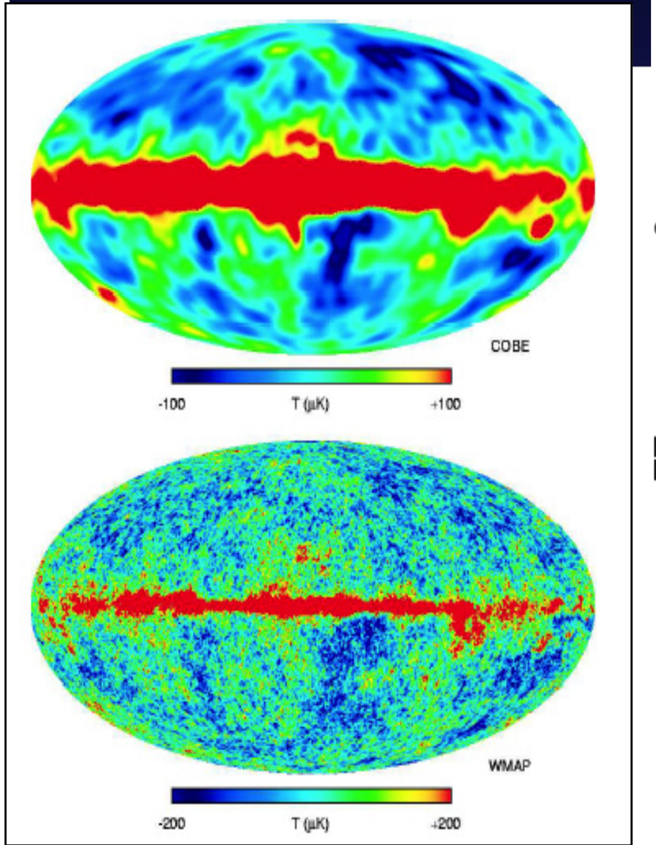
Effect of massive neutrinos on P(k)

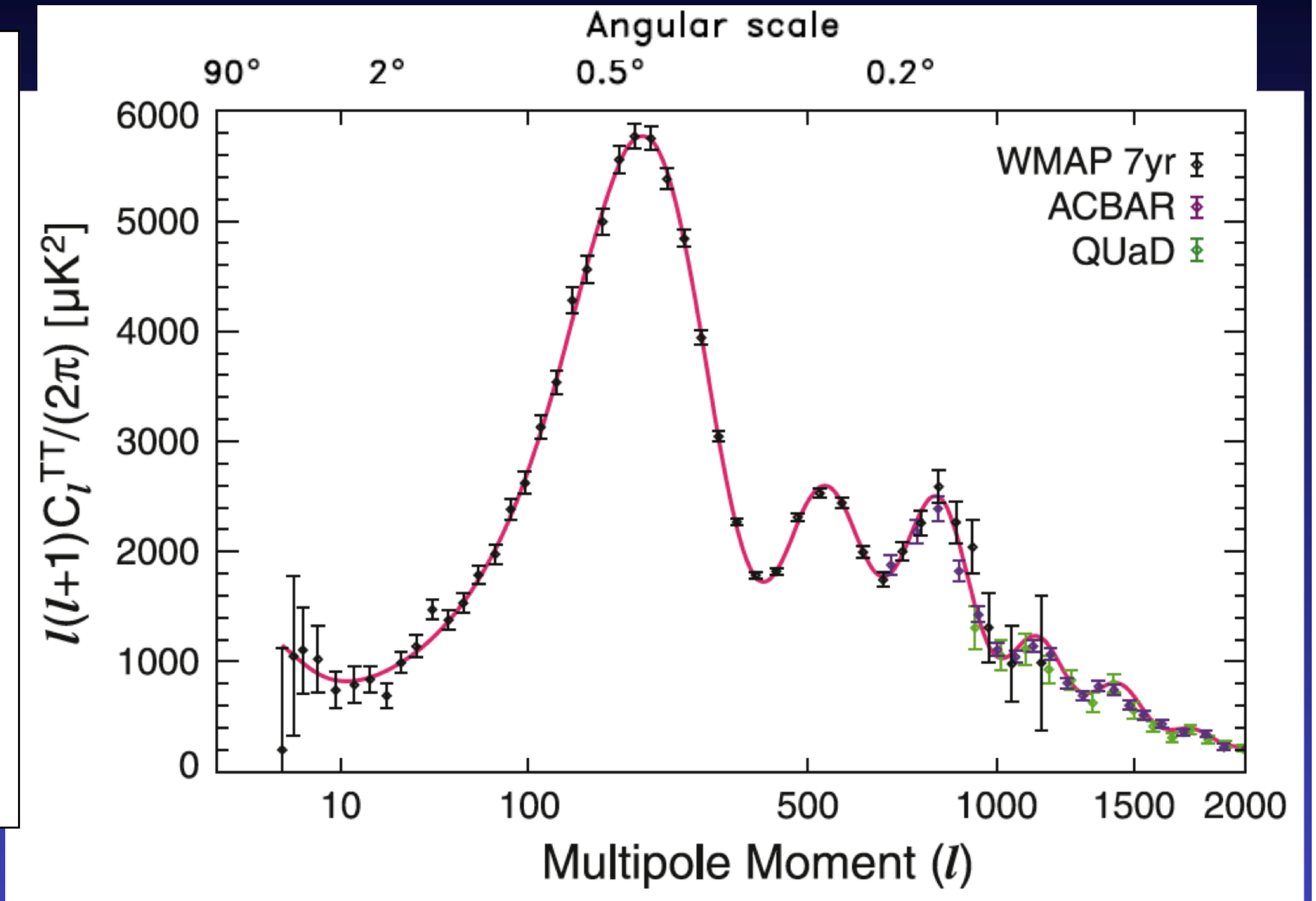
Observable signature of the total mass on P(k) :



Lesgourgues & SP, Phys. Rep. 429 (2006) 307

CMB TT DATA


COBE
-100
T (μK)
+100
WMAP
-200
T (μK)
+200


Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
WMAP 7yr
ACBAR
QUaD
10
100
500
1000
1500
2000
Multipole Moment (l)

Effect of massive neutrinos on the CMB spectra

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

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

Neutrinos become NR BEFORE recombination if:

$$\omega_\nu \geq 0.017 \quad \Rightarrow \quad \sum_i m_i \geq 1.6 \text{ eV}$$

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

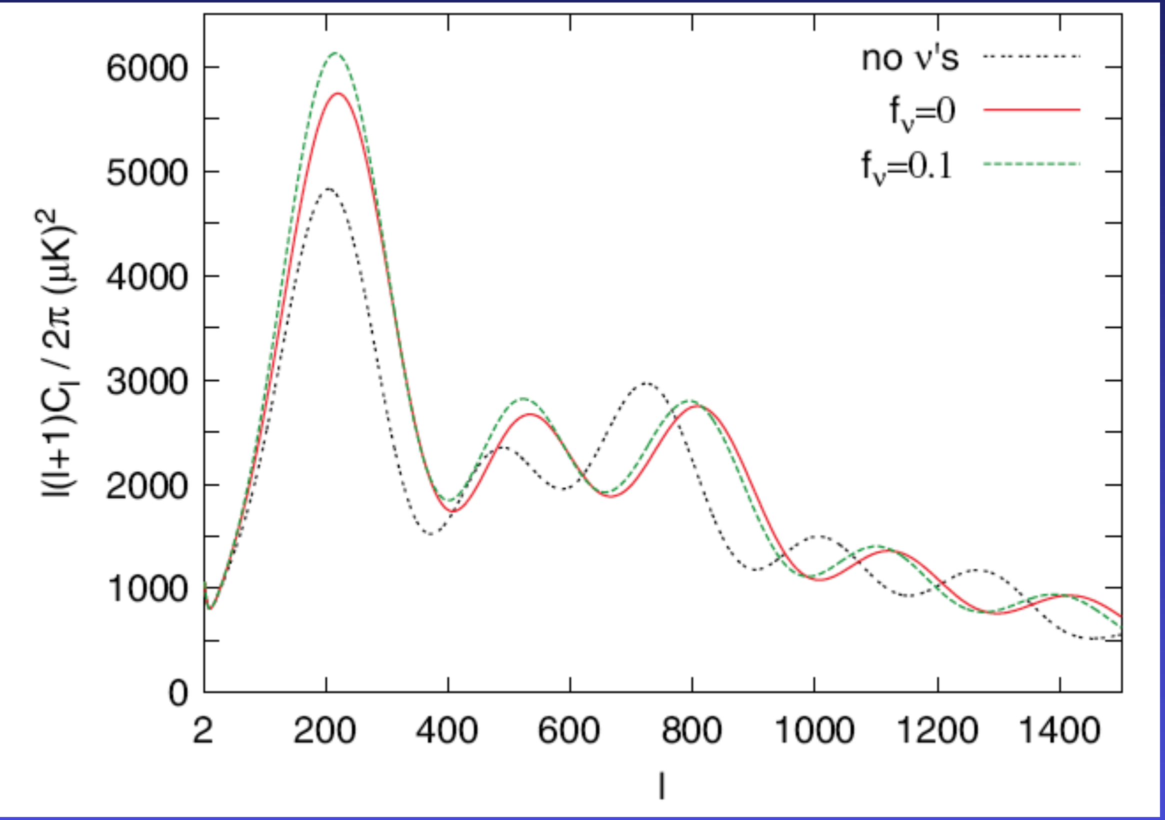
Effect of massive neutrinos on the CMB spectra

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,

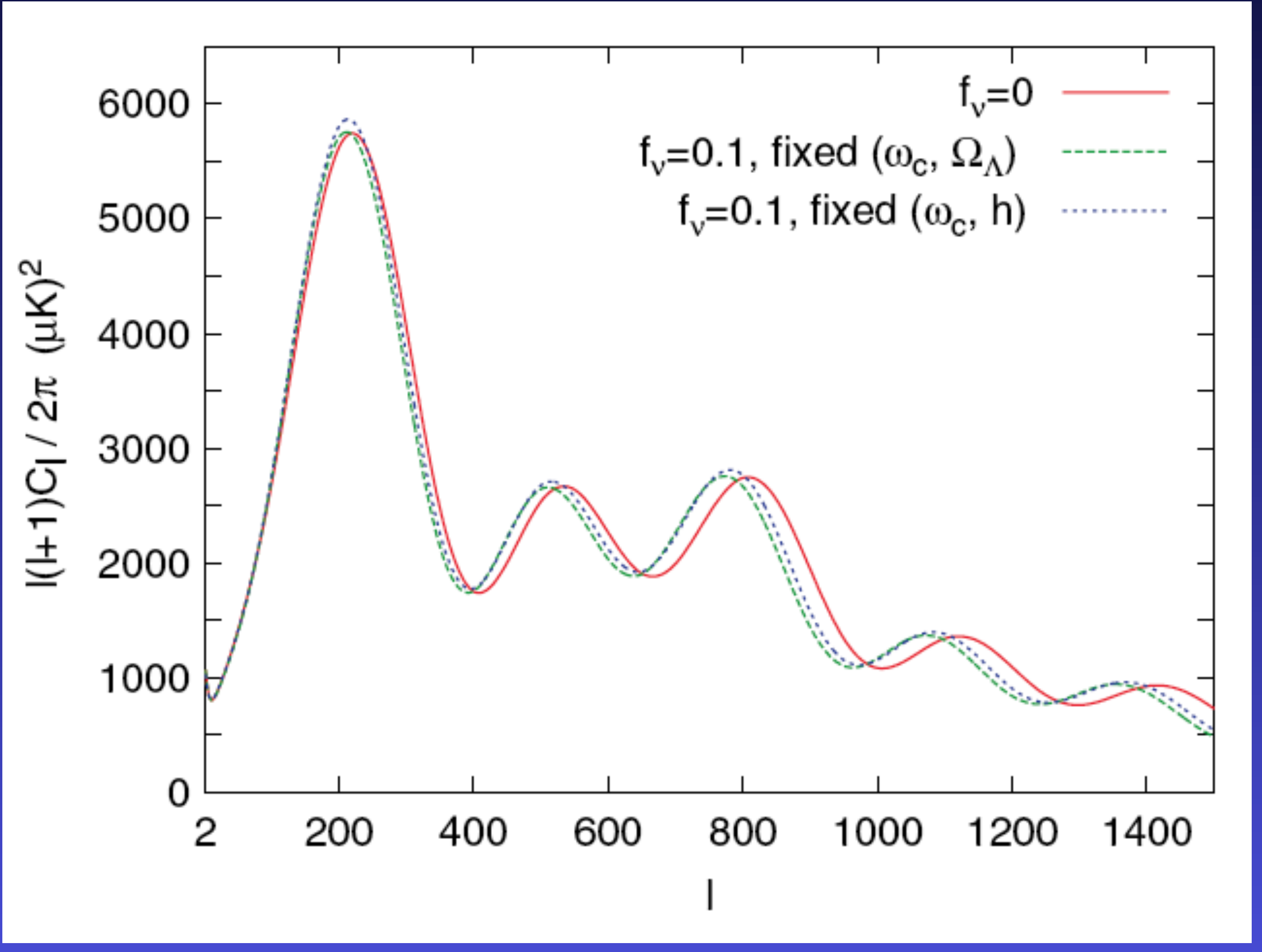
keep $\Omega_\Lambda+\Omega_{cdm}+\Omega_b+\Omega_\nu=1$

constant



Effect of massive neutrinos on the CMB spectra

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



Cosmological bounds on Σm_ν

Cosmological bounds on neutrino mass(es)

A unique cosmological bound on m_ν DOES NOT exist !

Different analyses have found upper bounds on neutrino masses, since they depend on

- The combination of cosmological data used
- The assumed cosmological model: number of parameters (problem of parameter degeneracies)
- The properties of relic neutrinos

Cosmological Data

• CMB Temperature: WMAP plus data from other experiments at large multipoles (CBI, ACBAR, VSA…)

• CMB Polarization: WMAP,…

• Large Scale Structure:

* Galaxy Clustering (2dF,SDSS)

* Bias (Galaxy, …): Amplitude of the Matter P(k) (SDSS,σ_8)

* Lyman-α forest: independent measurement of power on small scales

* Baryon acoustic oscillations (SDSS)

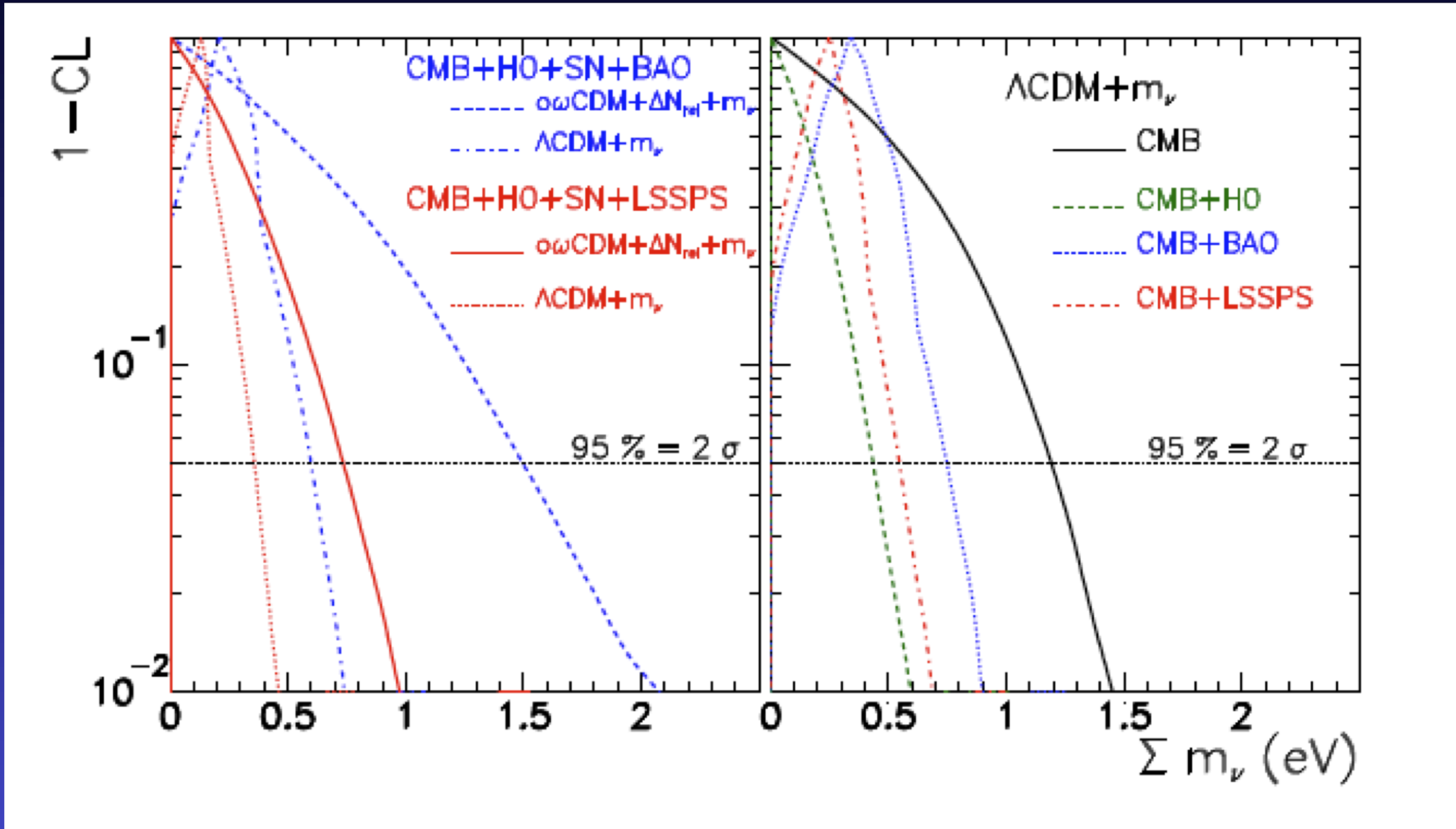
Bounds on parameters from other data: SNIa (Ω_m), HST (h), …

Cosmological Parameters: example

Parameter	Meaning	Status
τ	Reionization optical depth	Not optional
ω_b	Baryon density	Not optional
ω_d	Dark matter density	Not optional
f_ν	Dark matter neutrino fraction	Well motivated
Ω_Λ	Dark energy density	Not optional
w	Dark energy equation of state	Worth testing
Ω_k	Spatial curvature	Worth testing
A_s	Scalar fluctuation amplitude	Not optional
n_s	Scalar spectral index	Well motivated
α	Running of spectral index	Worth testing
r	Tensor-to-scalar ratio	Well motivated
n_t	Tensor spectral index	Well motivated
b	Galaxy bias factor	Not optional

SDSS Coll, PRD 69 (2004) 103501

Current cosmological bounds on neutrino masses



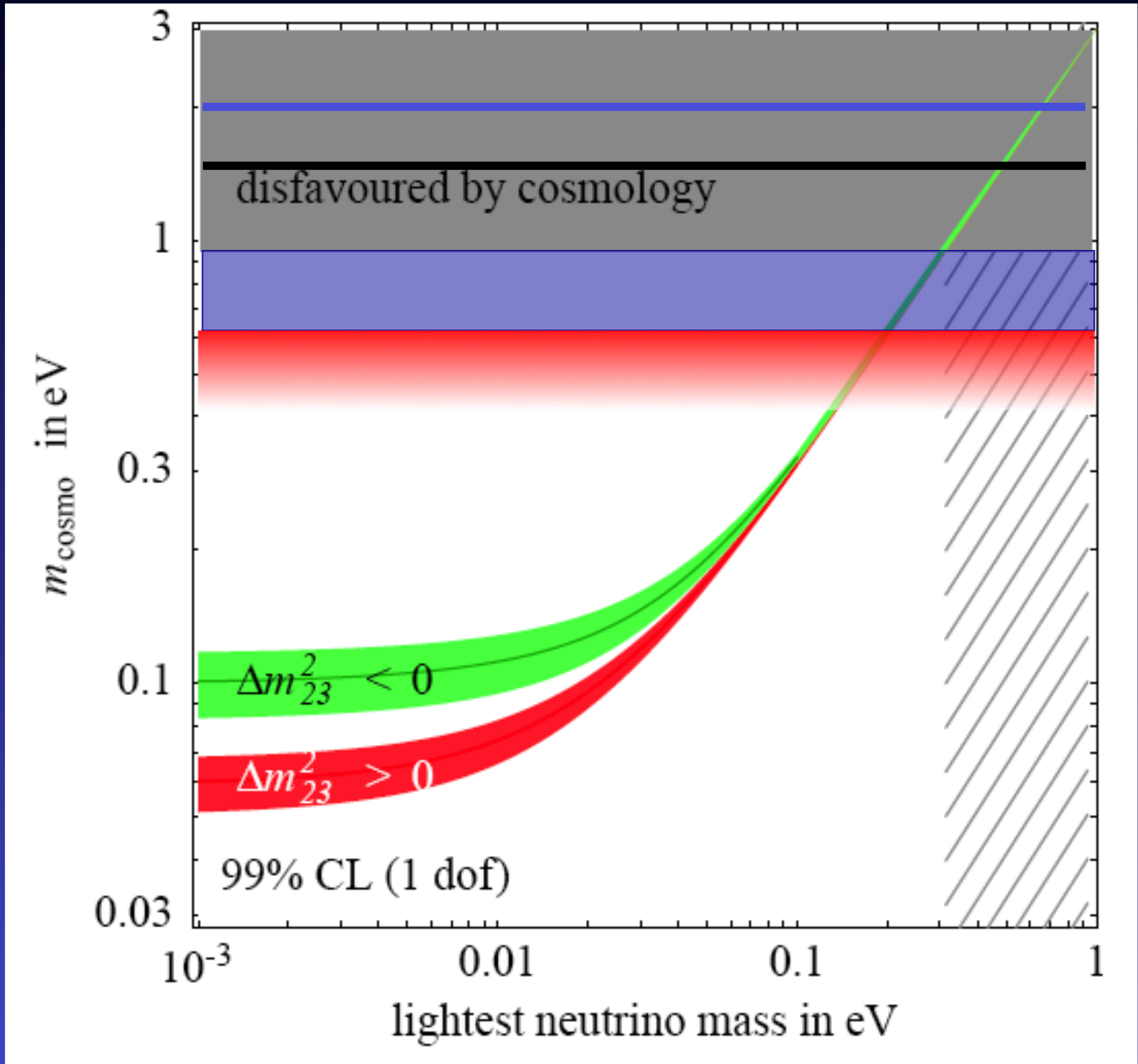
González-García et al., JCAP 08 (2010) 117

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

Current cosmological bounds on neutrino masses

Dependence on the data set AND the cosmological model used.

Model	Observables	Σm_ν (eV) 95% Bound
$o\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$o\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+BAO	≤ 0.61
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
$\Lambda\text{CDM} + m_\nu$	CMB (+SN)	≤ 1.2
$\Lambda\text{CDM} + m_\nu$	CMB+BAO	≤ 0.75
$\Lambda\text{CDM} + m_\nu$	CMB+LSSPS	≤ 0.55
$\Lambda\text{CDM} + m_\nu$	CMB+H0	≤ 0.45

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

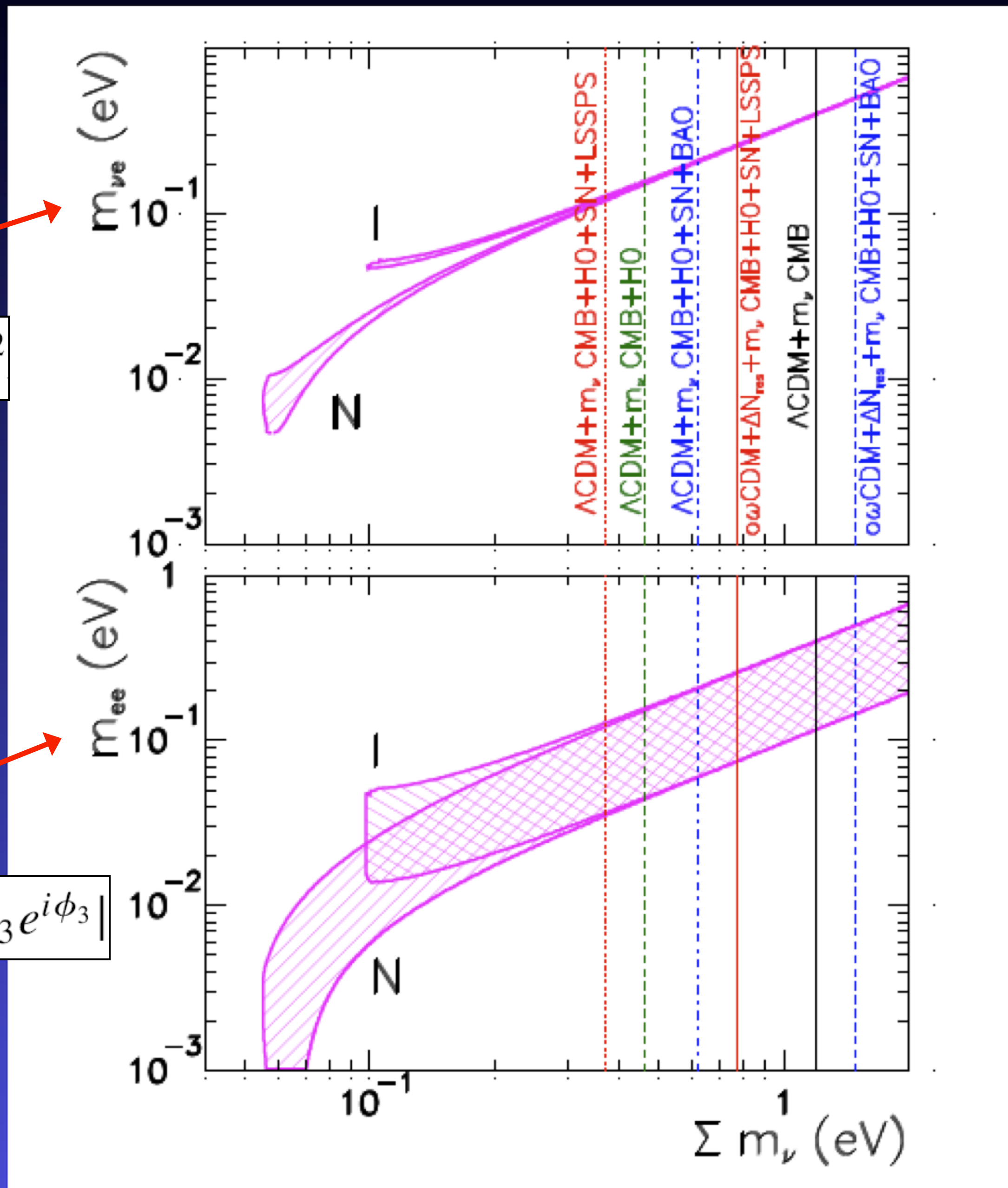
Absolute mass scale searches

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
	$\lvert c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \rvert$	
Cosmology	$\sim \sum_i m_i$	$<$ 0.2-2.0 eV

Tritium β decay, 0ν2β and Cosmology

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

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

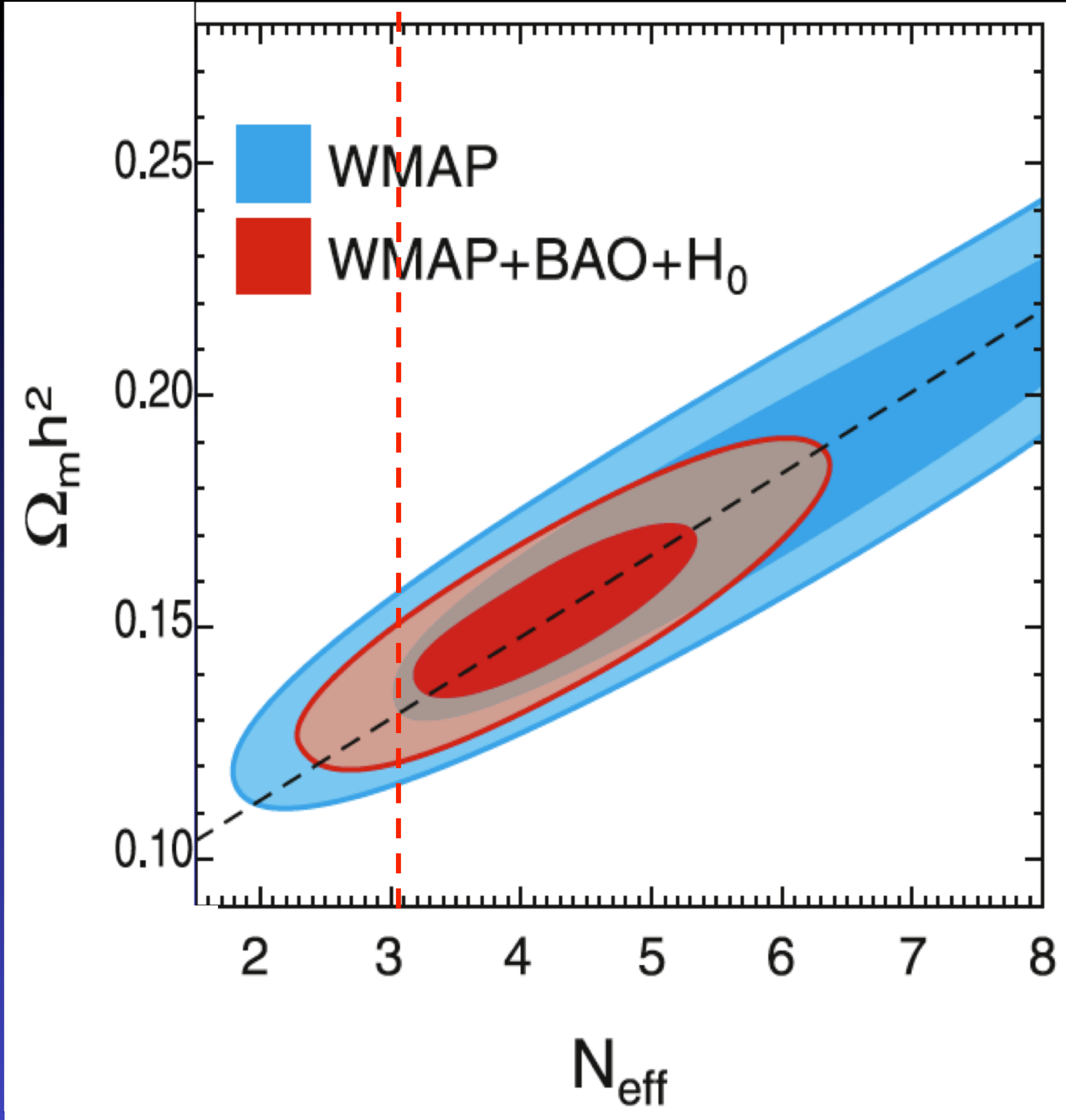


González-García et al.,
JCAP 08 (2010) 117

Future sensitivities on m_ν and N_{eff} from cosmology

allowed range for N_{eff}

WMAP [7-year], arXiv:1001.4538



$2.7 < N_{eff} < 6.2$ (WMAP+BAO+H_0)

Future bounds on N_{eff}

Forecast analysis:
Bowen et al,
MNRAS 334 (2002) 760

$\sigma[N_{eff}] \sim 3$ (WMAP)

$\sigma[N_{eff}] \sim 0.2$ (Planck)

ERROR FORECASTS

Experiment	f_{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

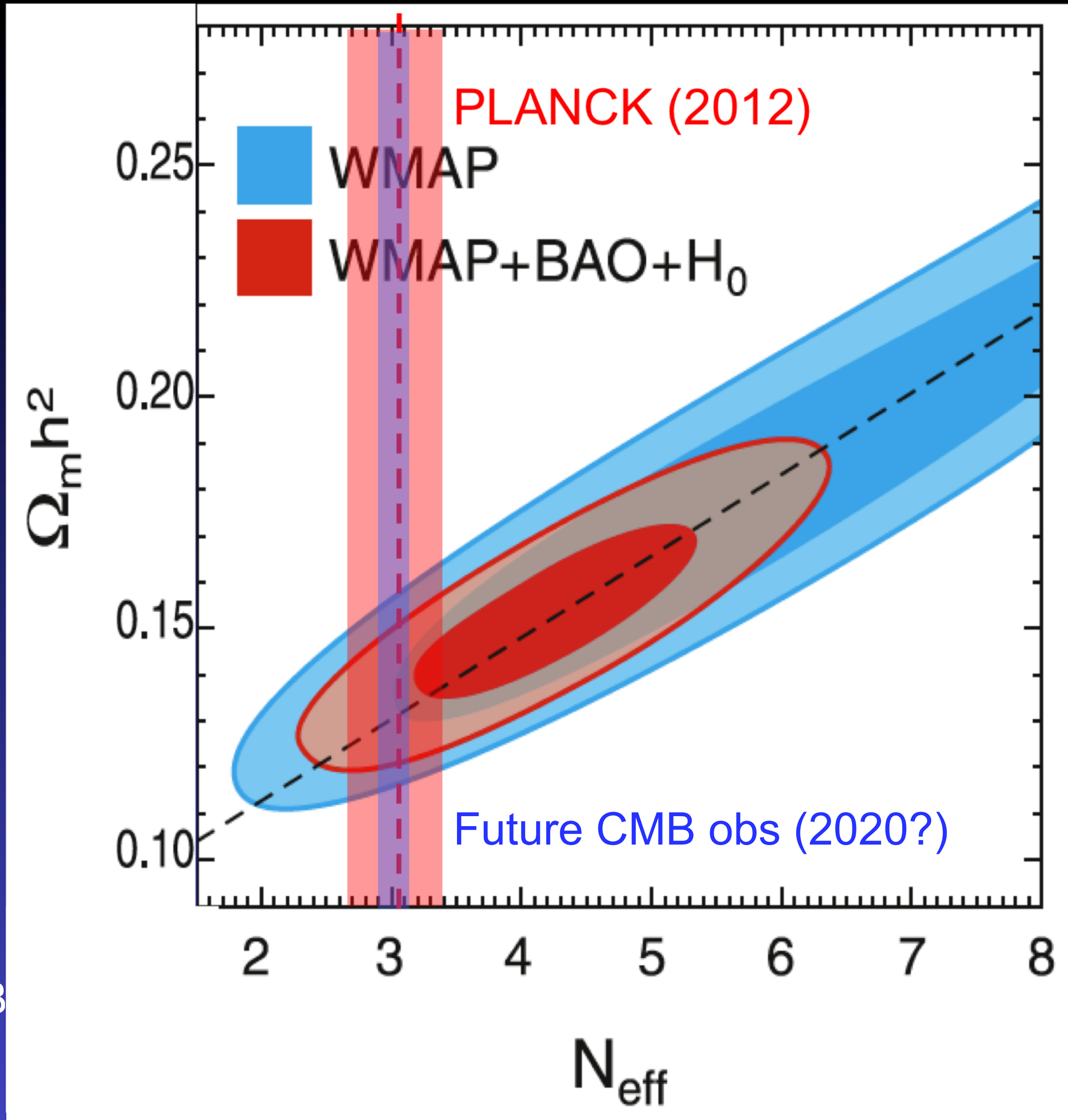
Future bounds on N_{eff}

	Planck	P+BAO	P+HPS	P+HST	P+HST+BAO	P+HST+HPS
ω_{dm}	0.22	0.24	0.20	0.21	0.21	0.19
N_{eff}	0.21	0.21	0.22	0.21	0.21	0.22
$\sum m_\nu$	0.68	0.81	0.44	0.67	0.73	0.44
w	2.14	1.16	0.72	0.74	0.76	0.55
n_S	0.46	0.48	0.49	0.46	0.48	0.48

Table 3: Projected sensitivity of Planck data (P) combined with LSS data to selected parameters of the vanilla+f_ν+N_{eff}+w model. Given are the standard deviations of the marginalised posteriors, normalised to the values obtained with current CMB+HST+HPS data. Note that just like for current CMB data, the addition of BAO data shifts the posterior towards larger neutrino masses, resulting in a two-tailed pdf with a correspondingly larger standard deviation – this does not mean that the constraining power of Planck+BAO is worse than that of Planck alone. The marginalised posteriors of all the other parameters are very close to two-tailed Gaussians, and do not suffer from this effect.

Hamann et al, JCAP 07 (2010) 022

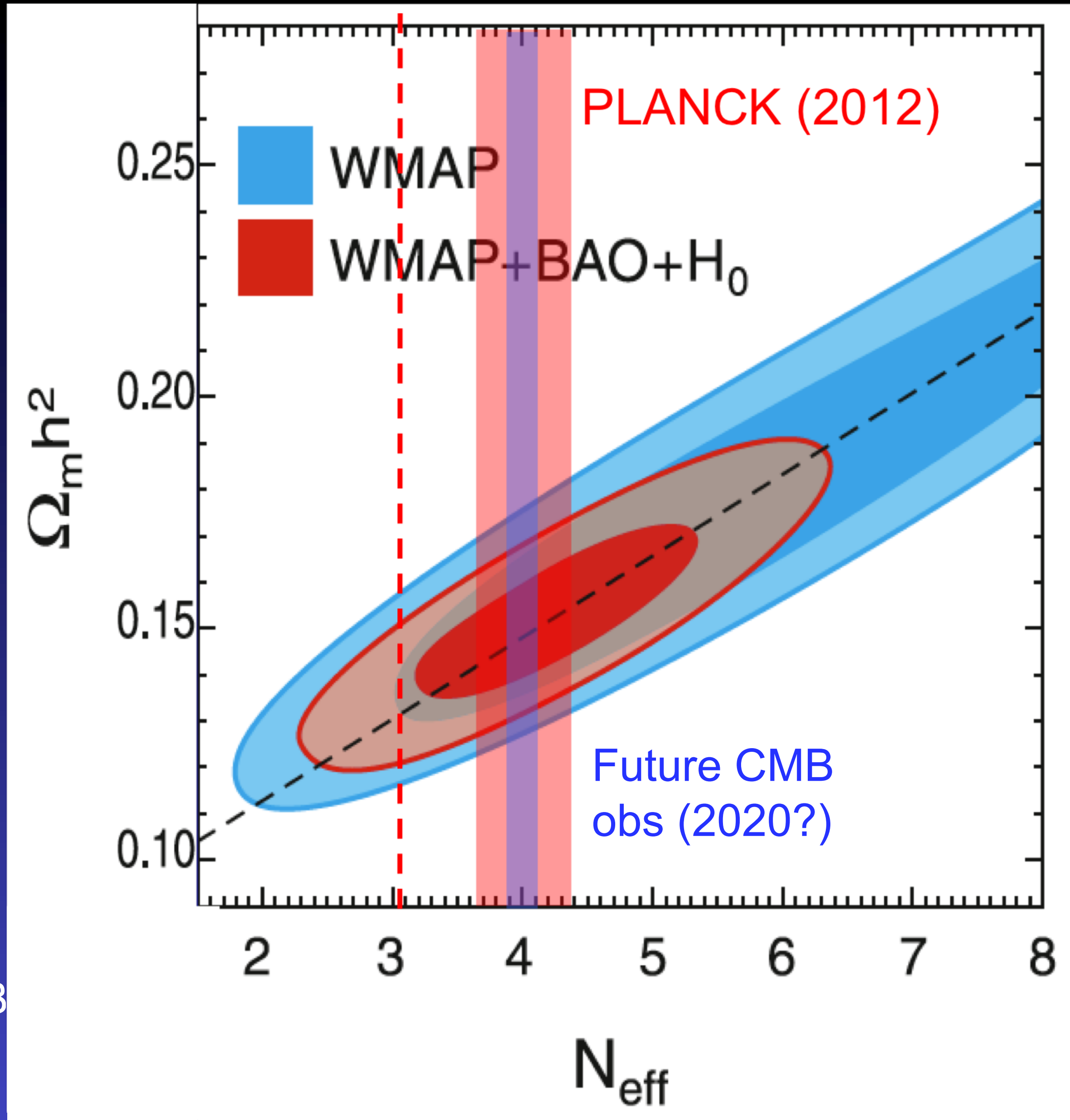
allowed range for N_{eff}



WMAP [7-year], arXiv:1001.4538

$2.7 < N_{eff} < 6.2$ (WMAP+BAO+H_0)

allowed range for N_{eff}



WMAP [7-year], arXiv:1001.4538

$2.7 < N_{eff} < 6.2$ (WMAP+BAO+H_0)

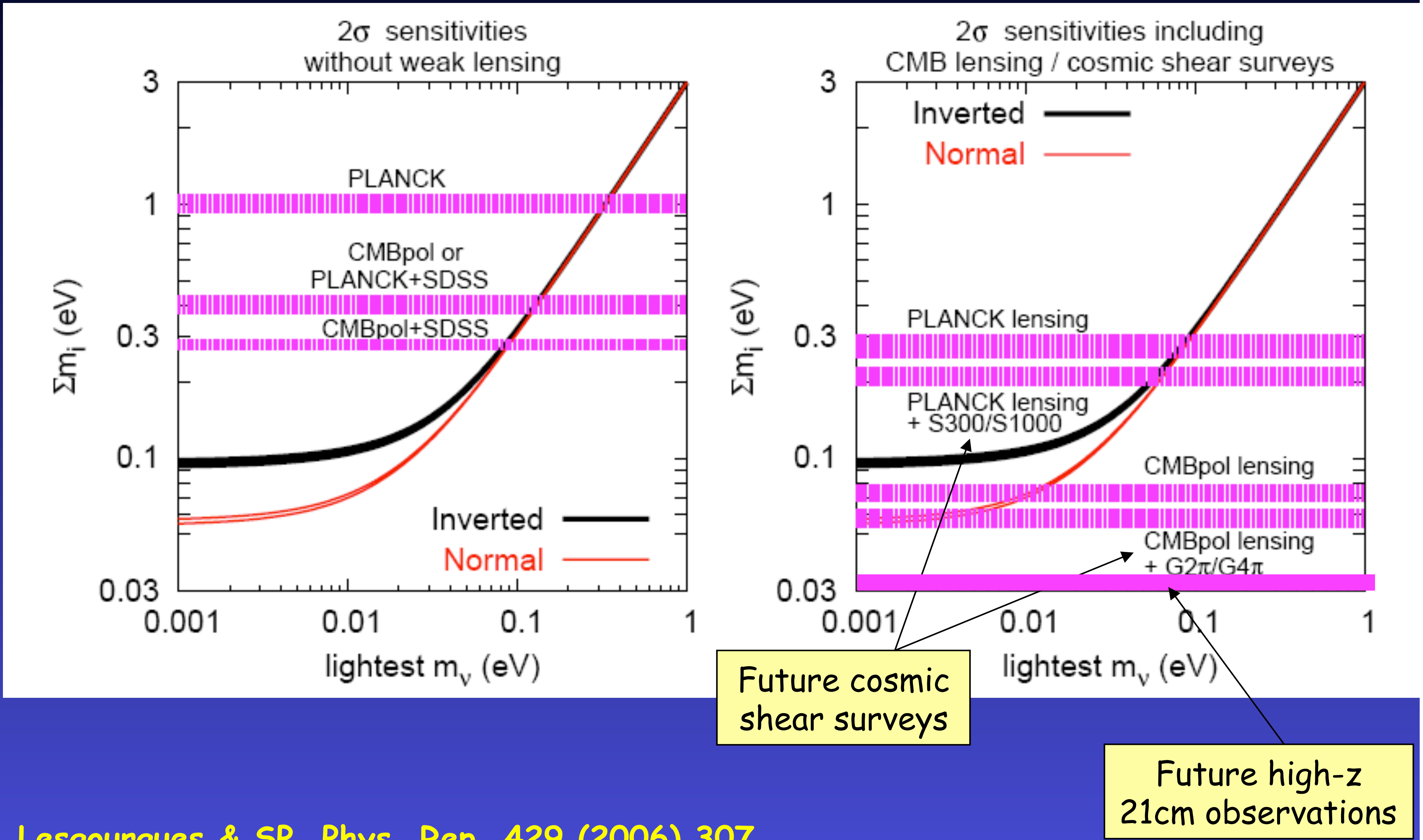
Future sensitivities on Σm_ν

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 7-100 meV sensitivities on Σm_ν are possible

Summary of future sensitivities



Lesgourgues & SP, Phys. Rep. 429 (2006) 307

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, arXiv:1007.0658

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 $\Sigma m_\nu < 0.4\text{-}0.6$ eV, conservative $\Sigma m_\nu < 1$ 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