Neutrinos in Cosmology (II)

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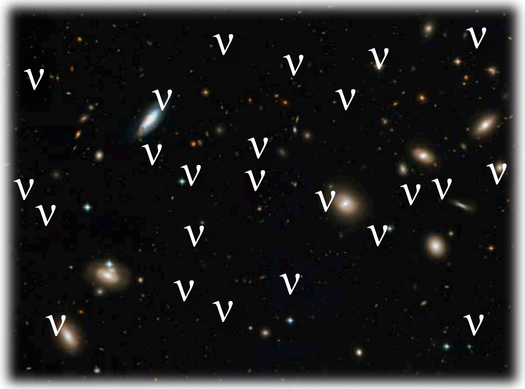
Outline



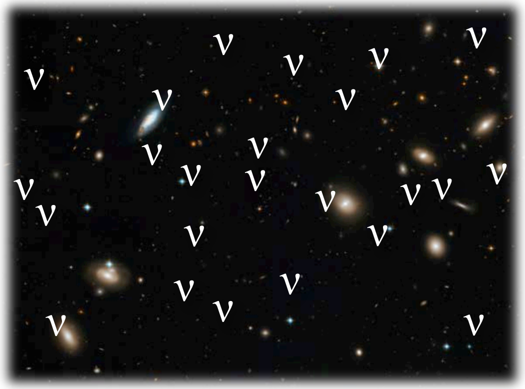
Introduction: neutrinos and the history of the Universe

Basics of Cosmology

Production and decoupling of relic neutrinos

1st

Outline



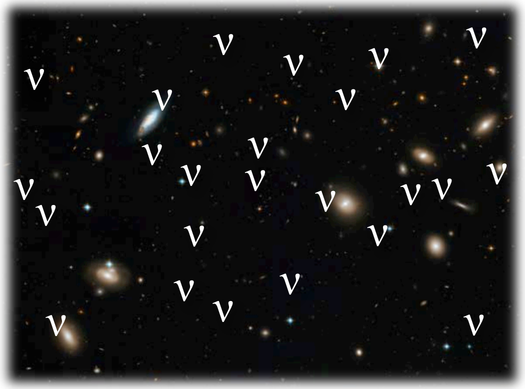
The radiation content of the Universe (N_{eff}) — 1st

Neutrinos and Primordial Nucleosynthesis

Neutrino oscillations in the Early Universe

2nd

Outline



Massive neutrinos as Dark Matter

Effects of neutrino masses on cosmological observables

Present bounds on neutrino properties from cosmology

Future sensitivities on neutrino physics from cosmology

2nd

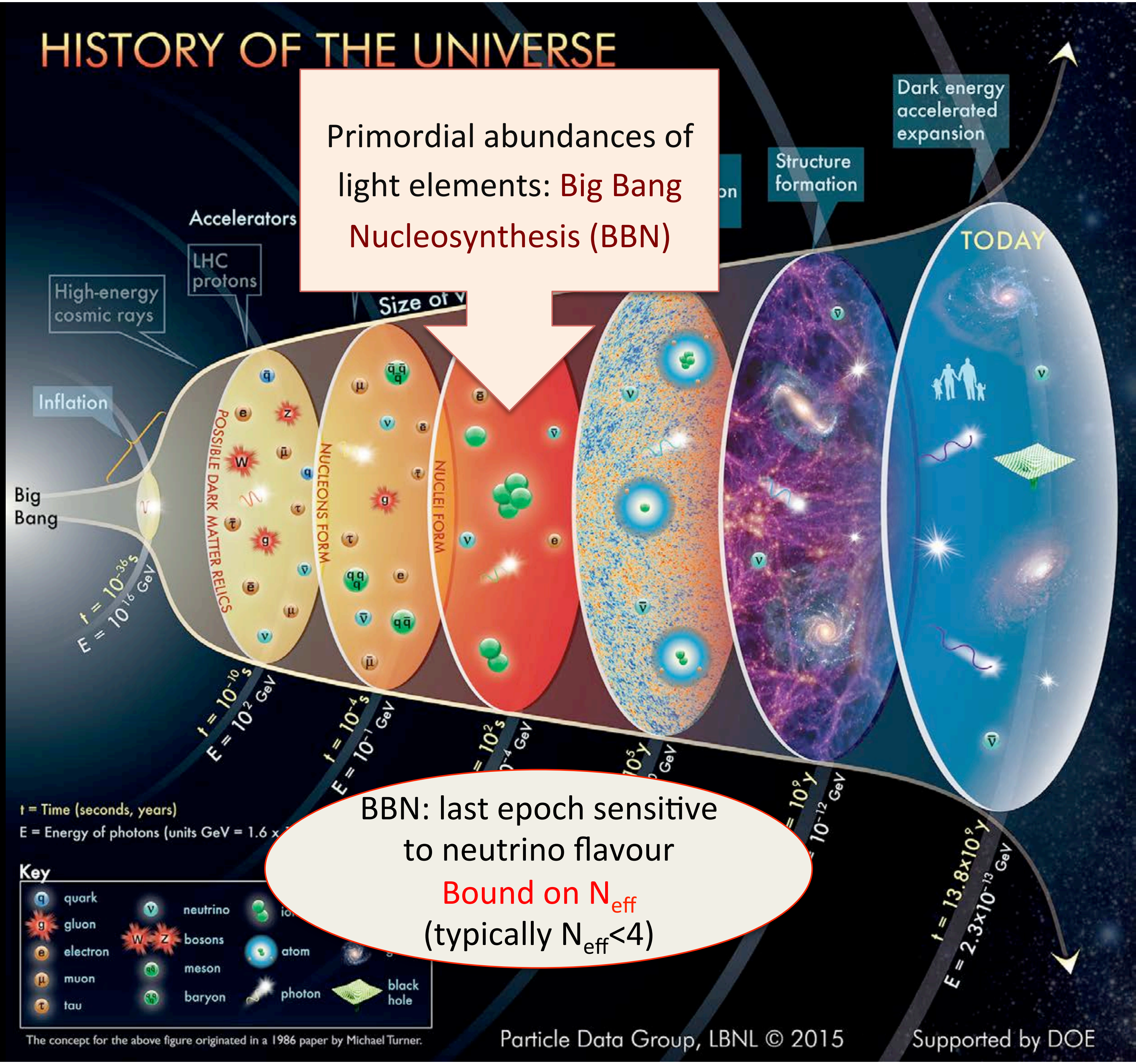
Neutrinos and Primordial Nucleosynthesis

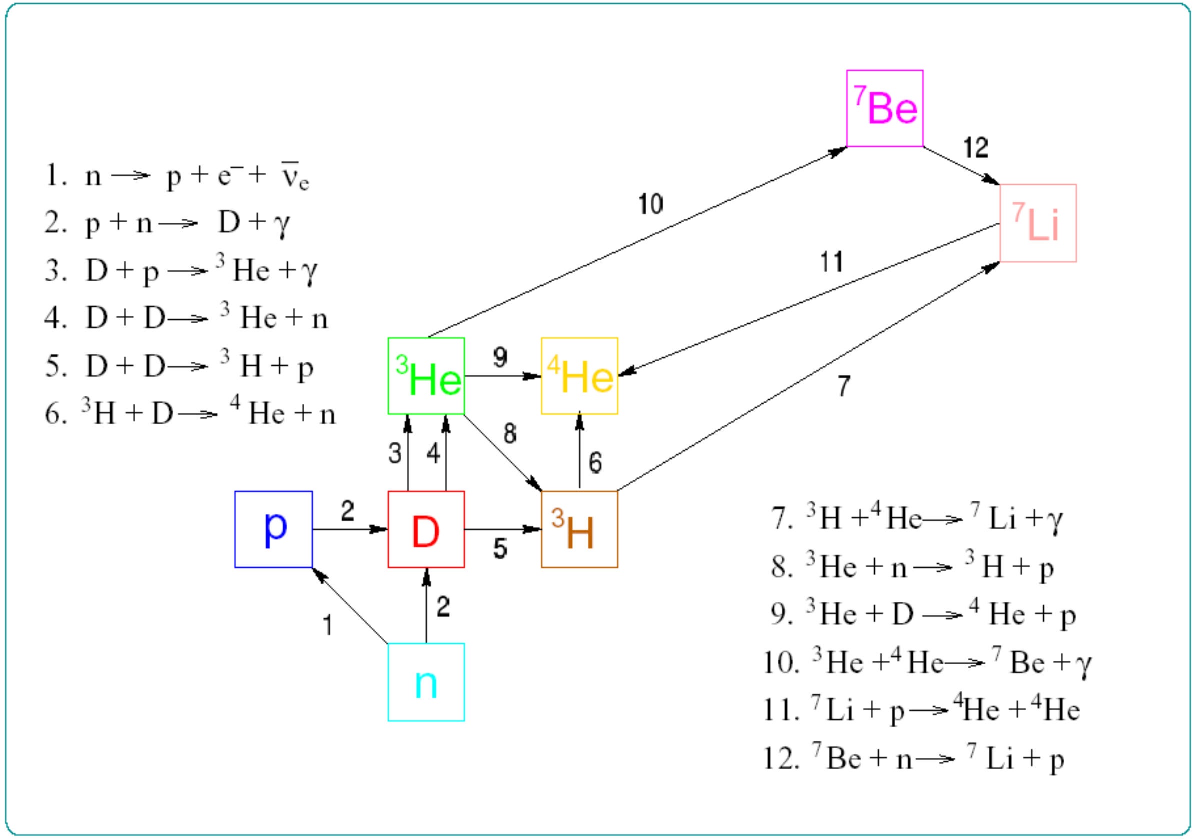
Primordial abundances of light elements: Big Bang Nucleosynthesis (BBN)

BBN: last epoch sensitive to neutrino flavour

Bound on N_{eff}

(typically $N_{eff}<4$)





BBN: Creation of light elements

Produced elements: D, ${}^3He$, ${}^4He$, ${}^7Li$ 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.

$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

BBN: Creation of light elements

Range of temperatures: from 0.8 to 0.01 MeV

$$t \simeq 0{,}74 \left(\frac{\text{MeV}}{T}\right)^2 \text{ sec}$$

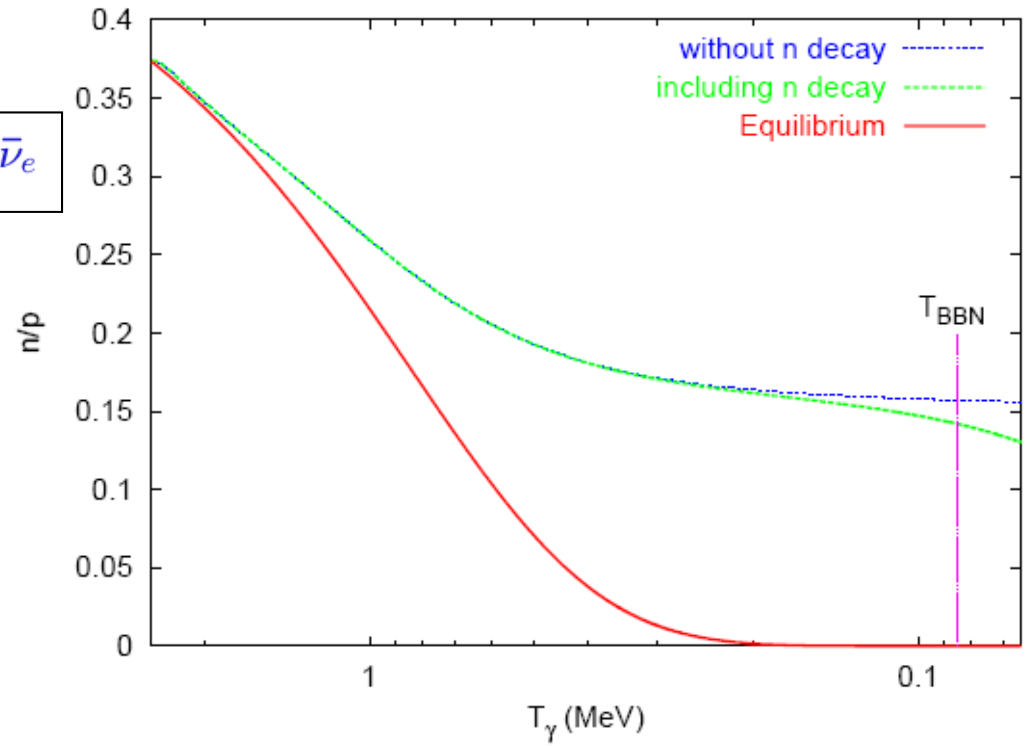
Phase I: 0.8-0.1 MeV

n-p reactions

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

n/p freezing and neutron decay

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

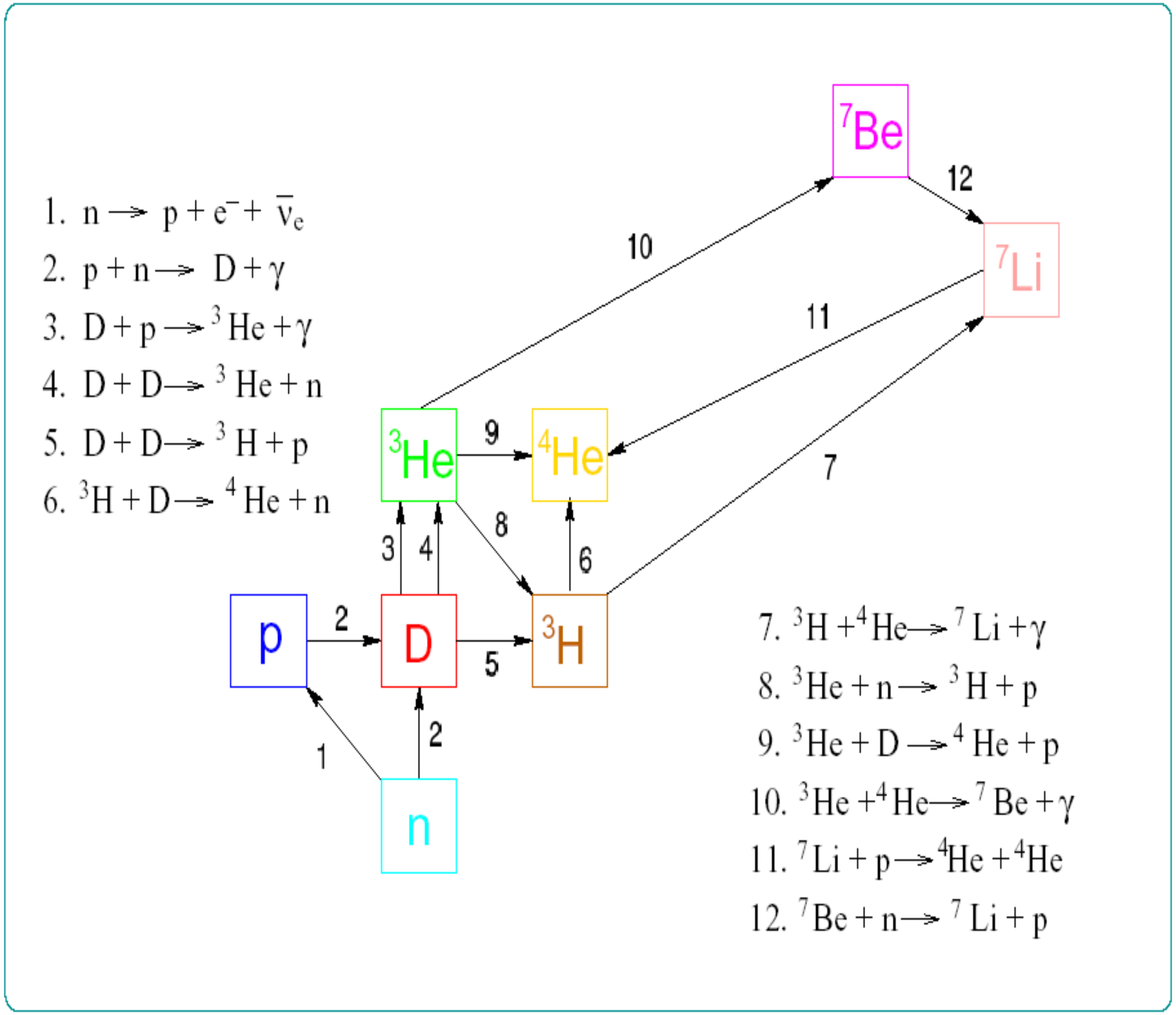


$$\left(\frac{n}{p}\right)_{eq} \simeq \exp\left(-\frac{m_n - m_p}{T_\gamma}\right) = \exp\left(-\frac{1{,}293 \text{ MeV}}{T_\gamma}\right)$$

BBN: Creation of light elements

Phase II: 0.1-0.01 MeV
Formation of light nuclei starting from D

Photodesintegration prevents earlier formation for temperatures closer to nuclear binding energies



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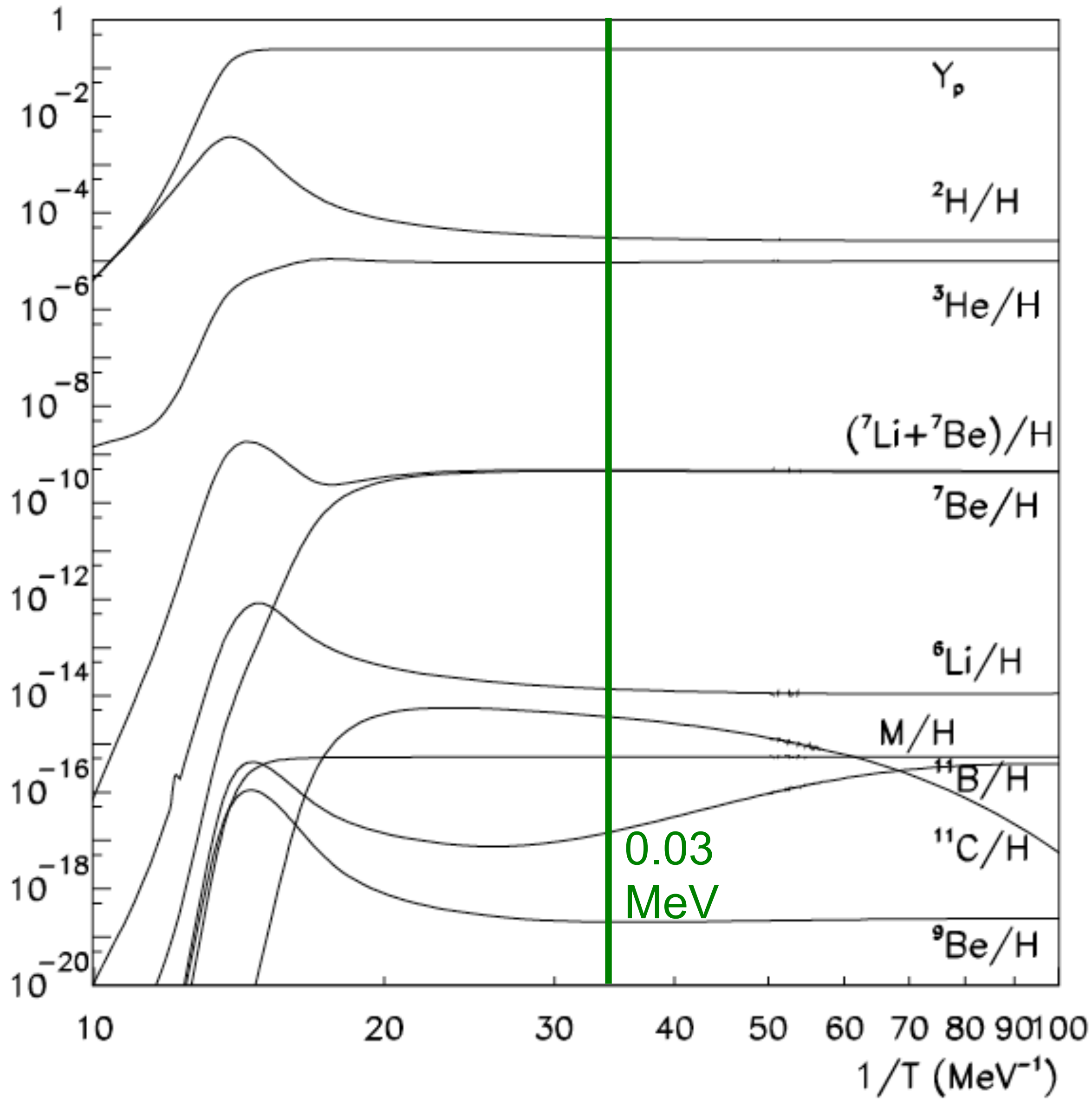

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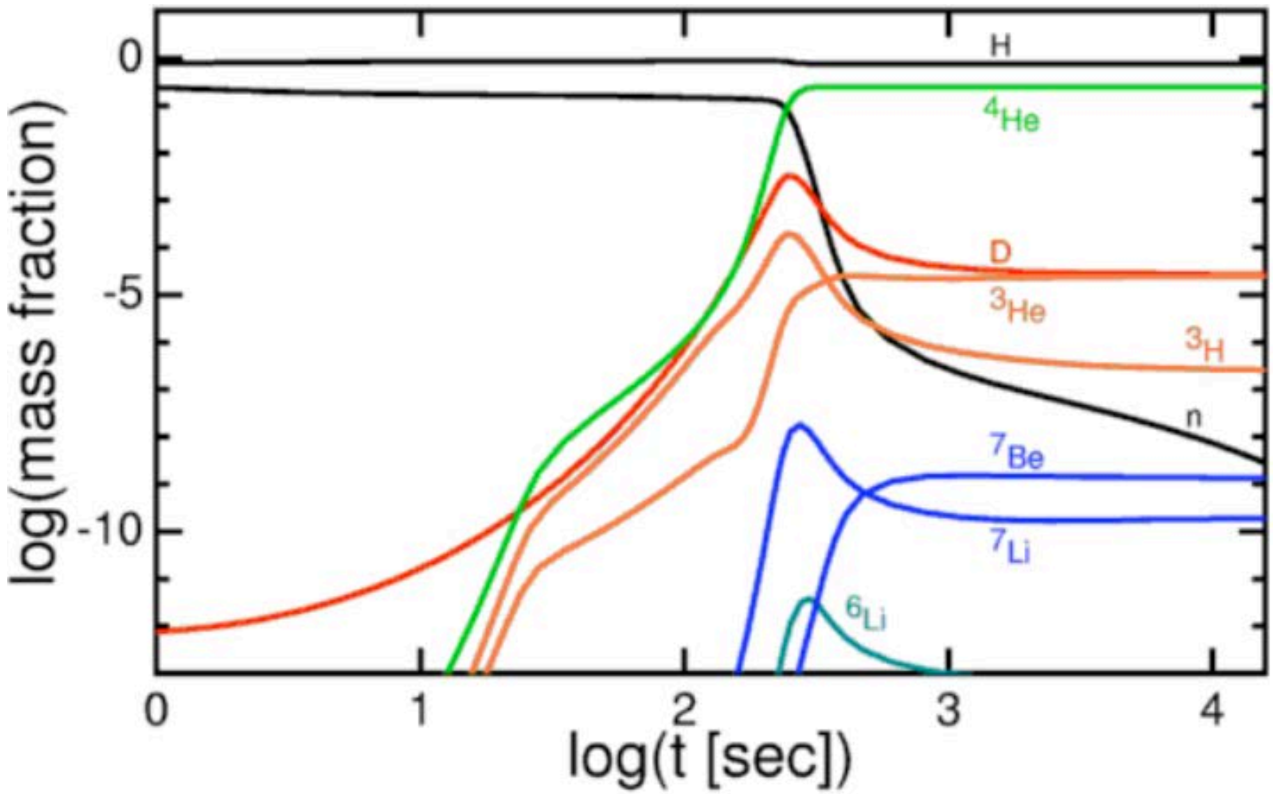


BBN: Measurement of Primordial abundances

Difficult task**: search in astrophysical systems with chemical evolution as small as possible**

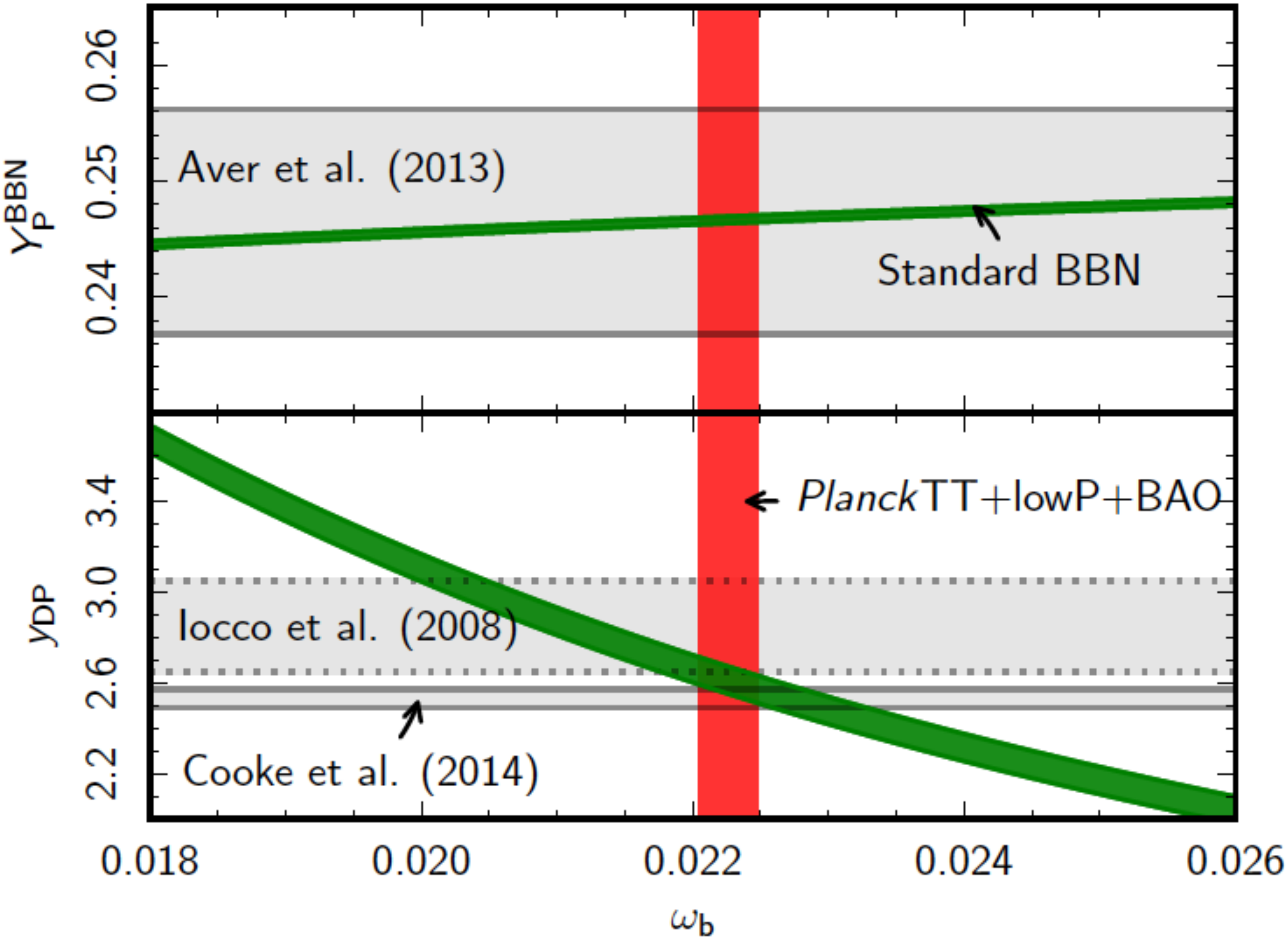
Deuterium: destroyed in stars. Any observed abundance of D is a *lower* limit to the primordial abundance. Data from high-z, low metallicity QSO absorption line systems

Helium-3: produced and destroyed in stars (complicated evolution) Data from solar system and galaxies but not used in BBN analysis

Helium-4: primordial abundance increased by H burning in stars. Data from low metallicity, extragalatic HII regions

Lithium-7: destroyed in stars, produced in cosmic ray reactions. Data from oldest, most metal-poor stars in the Galaxy

BBN: Predictions vs Observations



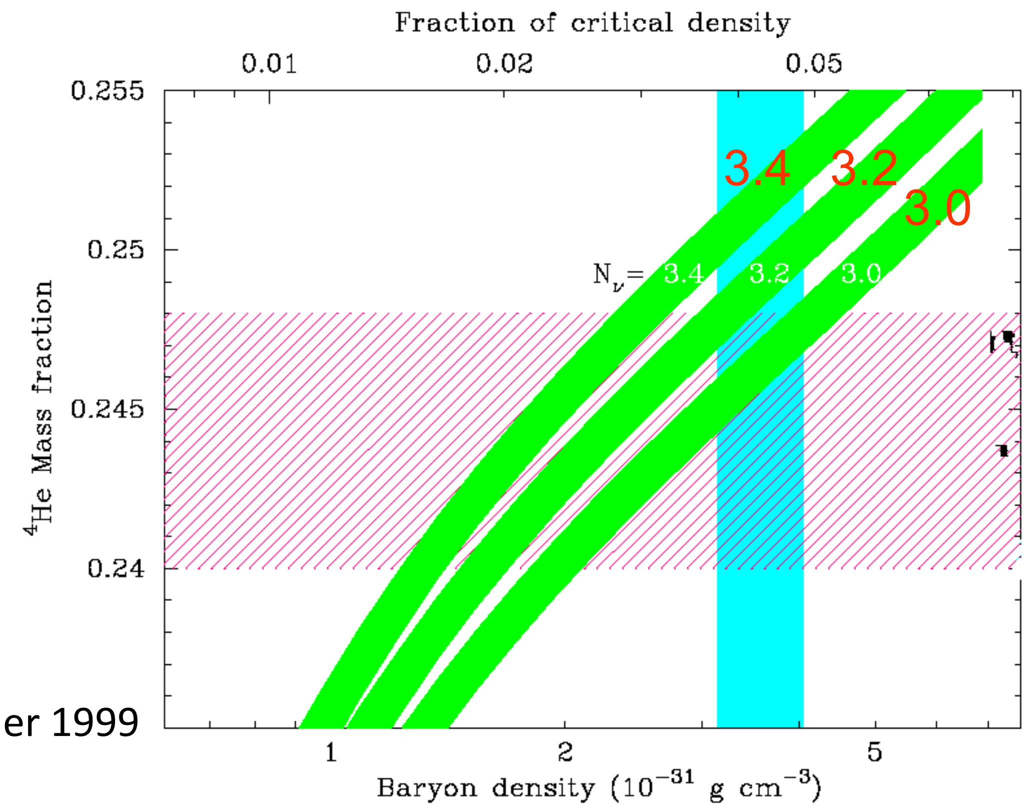
Planck 2015, arXiv:1502.01589

Effect of neutrinos on BBN

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

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

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

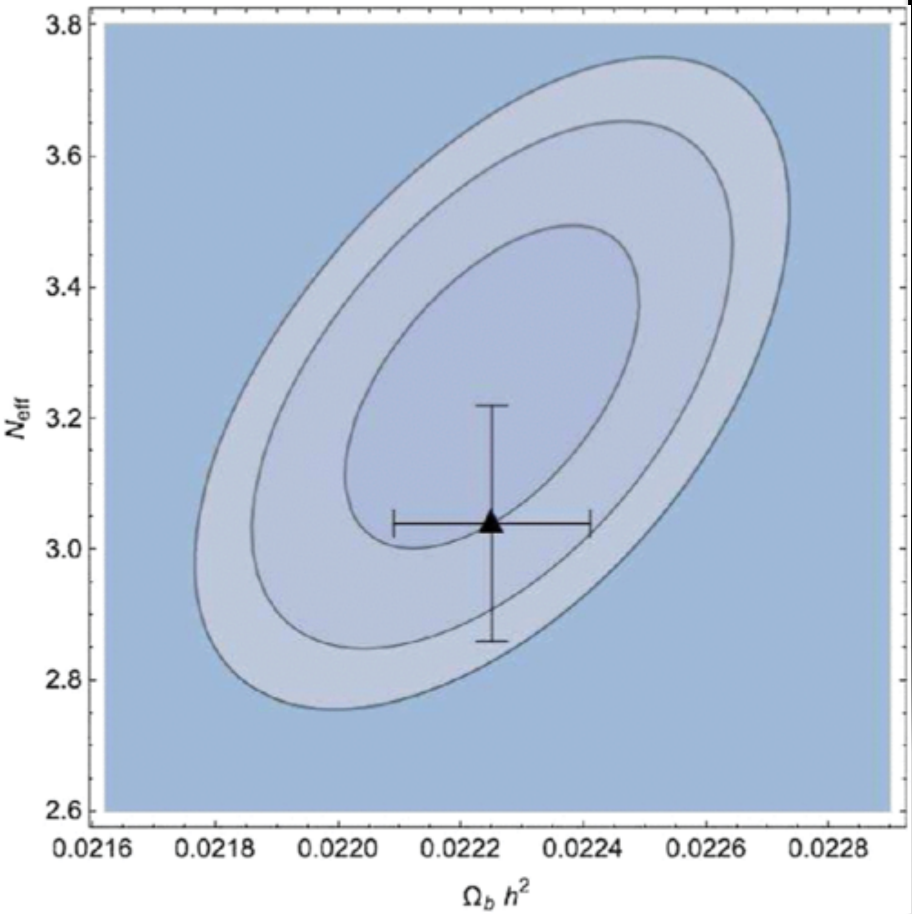


Burles, Nollett & Turner 1999

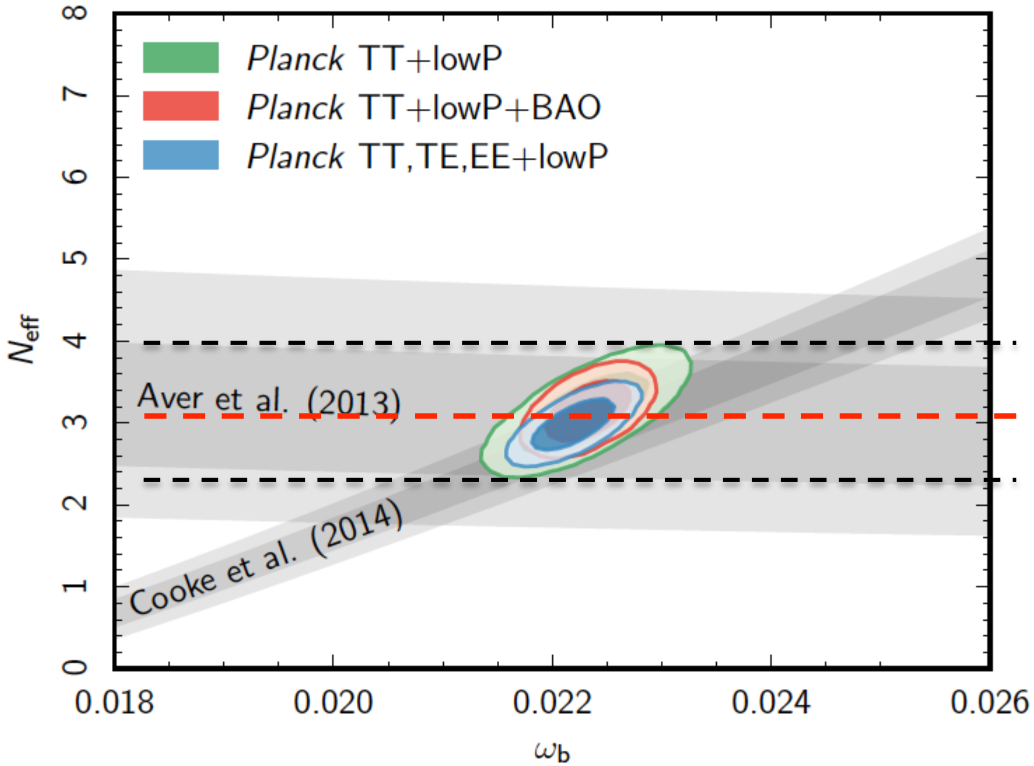
2. Direct effect of electron neutrinos and antineutrinos on the n-p reactions

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

BBN: allowed ranges for N_{eff}



Deuterium-only bounds
Marcucci et al, PRL 116 (2016) 102501
[arXiv:1510.07877]



Planck 2015, arXiv:1502.01589

Neutrino oscillations in the Early Universe

Flavour neutrino oscillations in the Early Universe

Standard case: all neutrino flavours equally populated

→ oscillations are effective below a few MeV, but have no effect (except for mixing the small distortions δf_ν)

Cosmology is insensitive to neutrino flavour after decoupling!

Non-zero neutrino asymmetries: flavour oscillations lead to (approximate) global flavour equilibrium

↓

the restrictive BBN bound on the $\nu_e \bar{\nu}_e$ asymmetry applies to all flavors, but fine-tuned initial asymmetries always allow for a large surviving neutrino excess radiation that may show up in precision cosmological data (**value depends on θ_{13}**)

Active-sterile neutrino oscillations

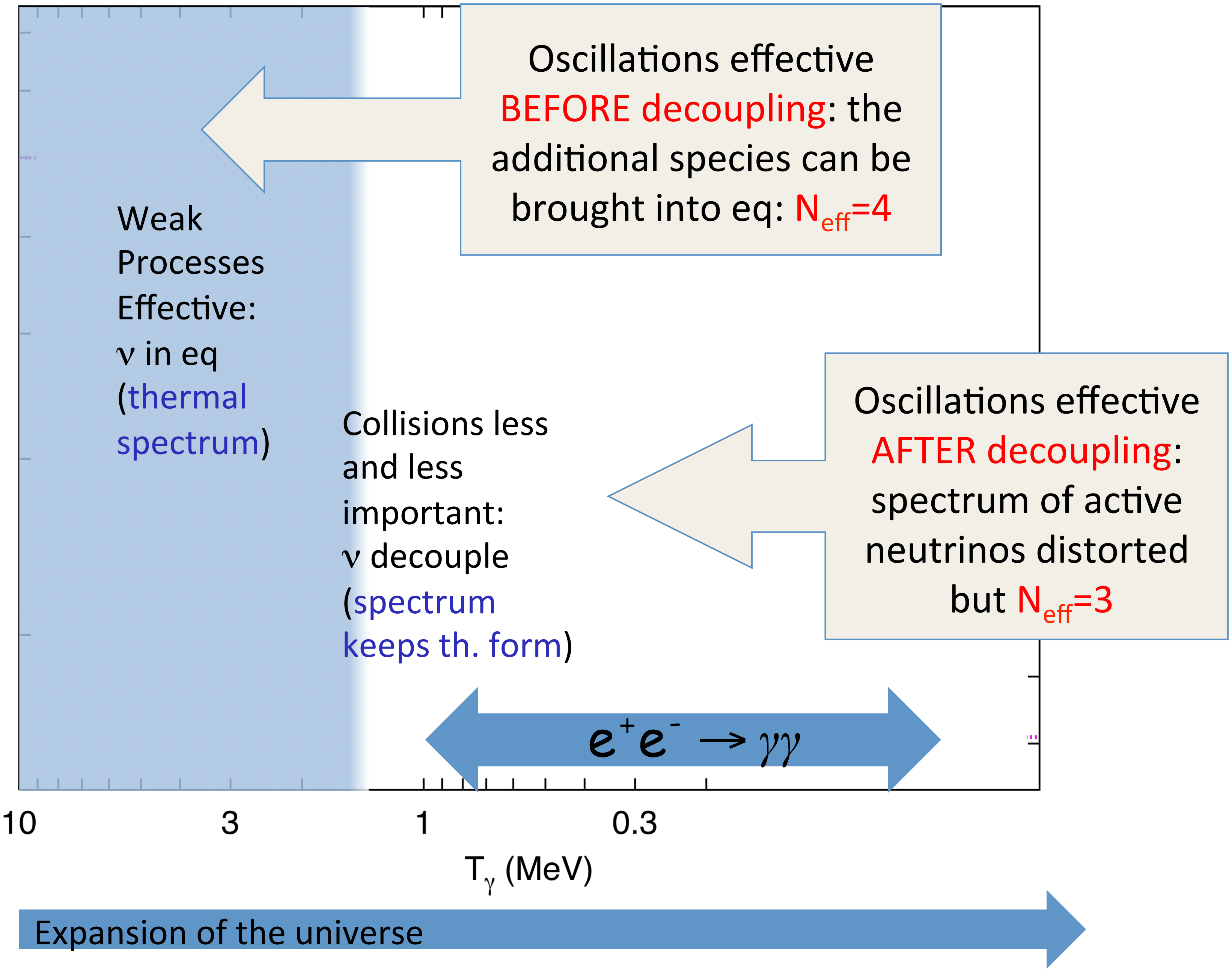
What if additional, light *sterile* neutrino species are mixed with the flavour neutrinos?

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

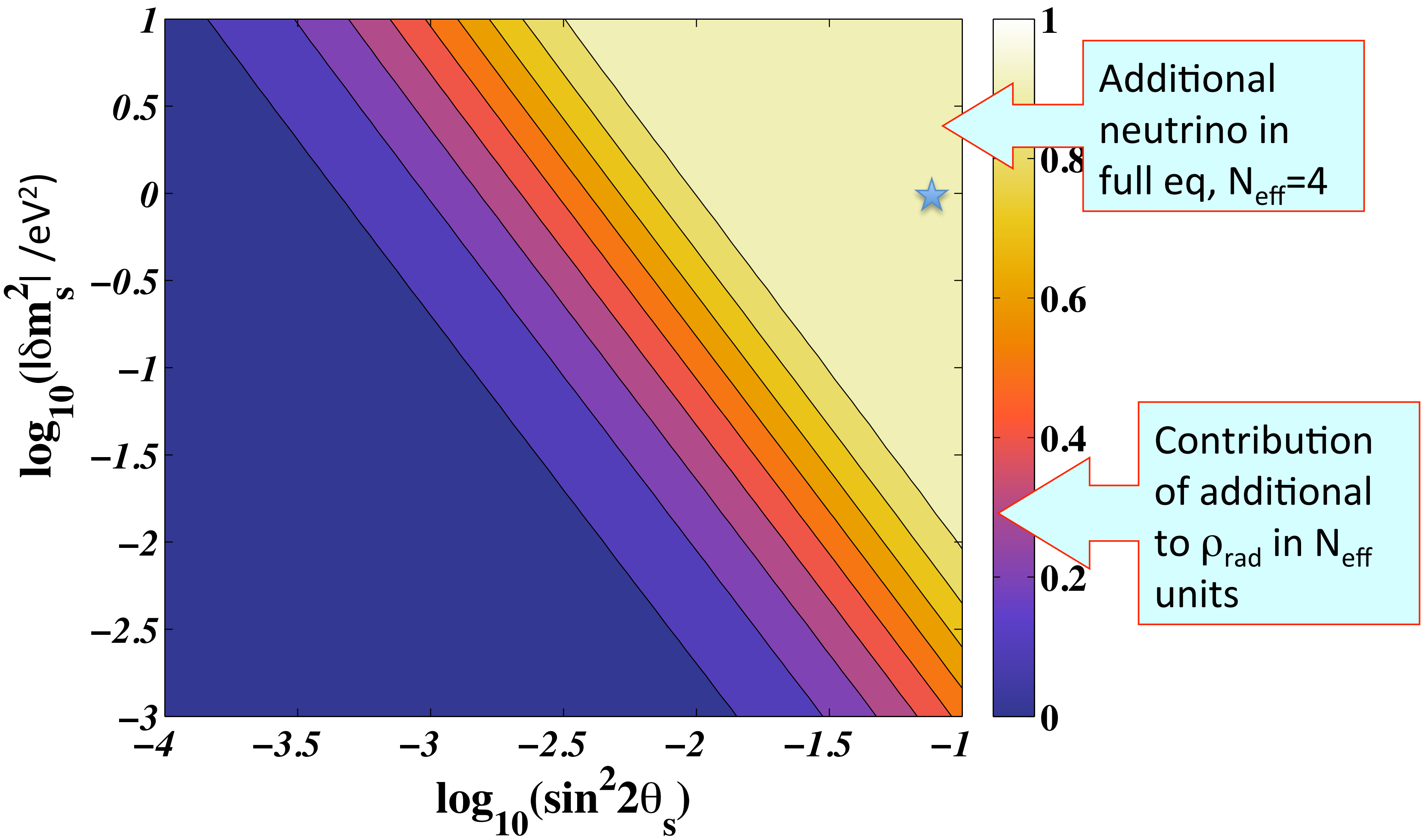
♣ If oscillations are effective after decoupling: $N_{eff}=3$ but the spectrum of active neutrinos is distorted (direct effect of ν_e and anti-ν_e on BBN)

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

N_{eff} & Active-sterile neutrino oscillations



N_{eff} & Active-sterile neutrino oscillations



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

Neutrinos as Dark Matter

The Cosmic Neutrino Background

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

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

- Number density

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

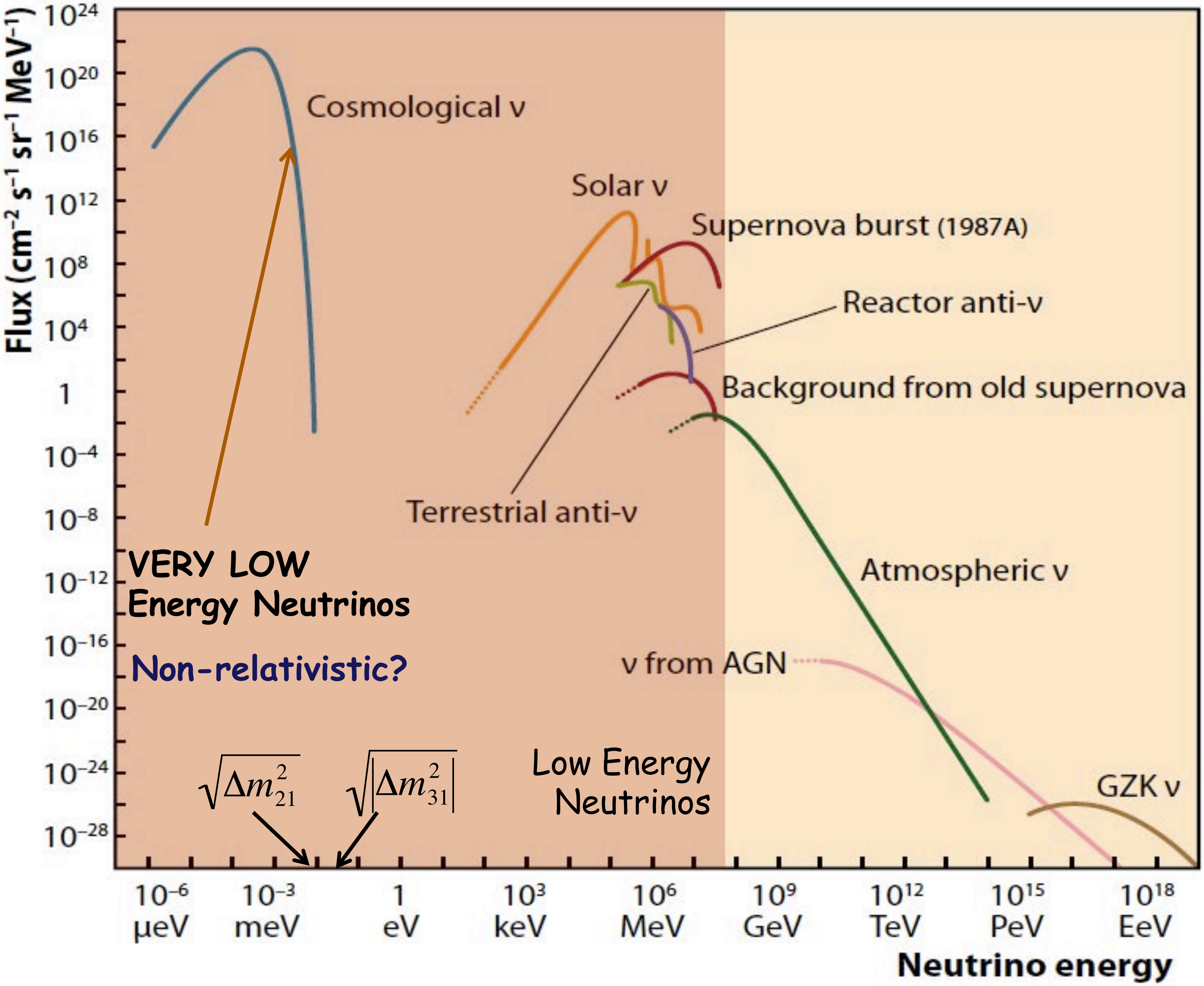
- Energy density

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

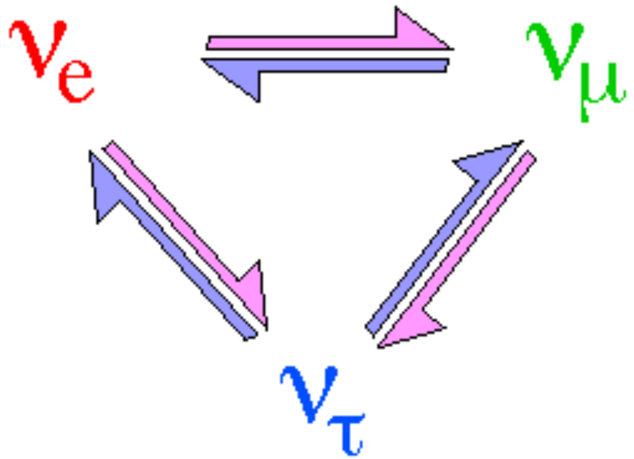
$m_\nu >> T$



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

We know that flavour neutrino oscillations exist

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



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

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

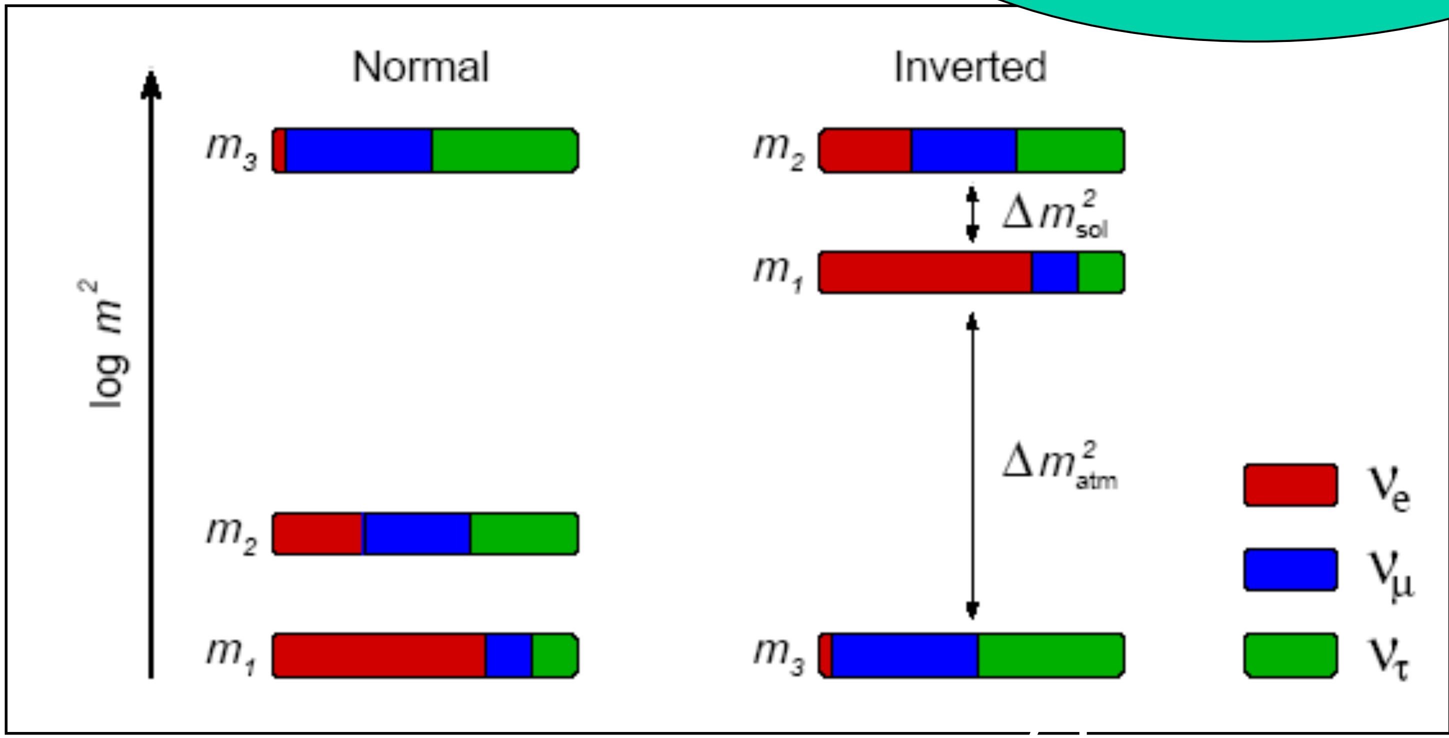
$$\begin{array}{cc} & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} & \left[\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}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

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

Neutrino masses

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

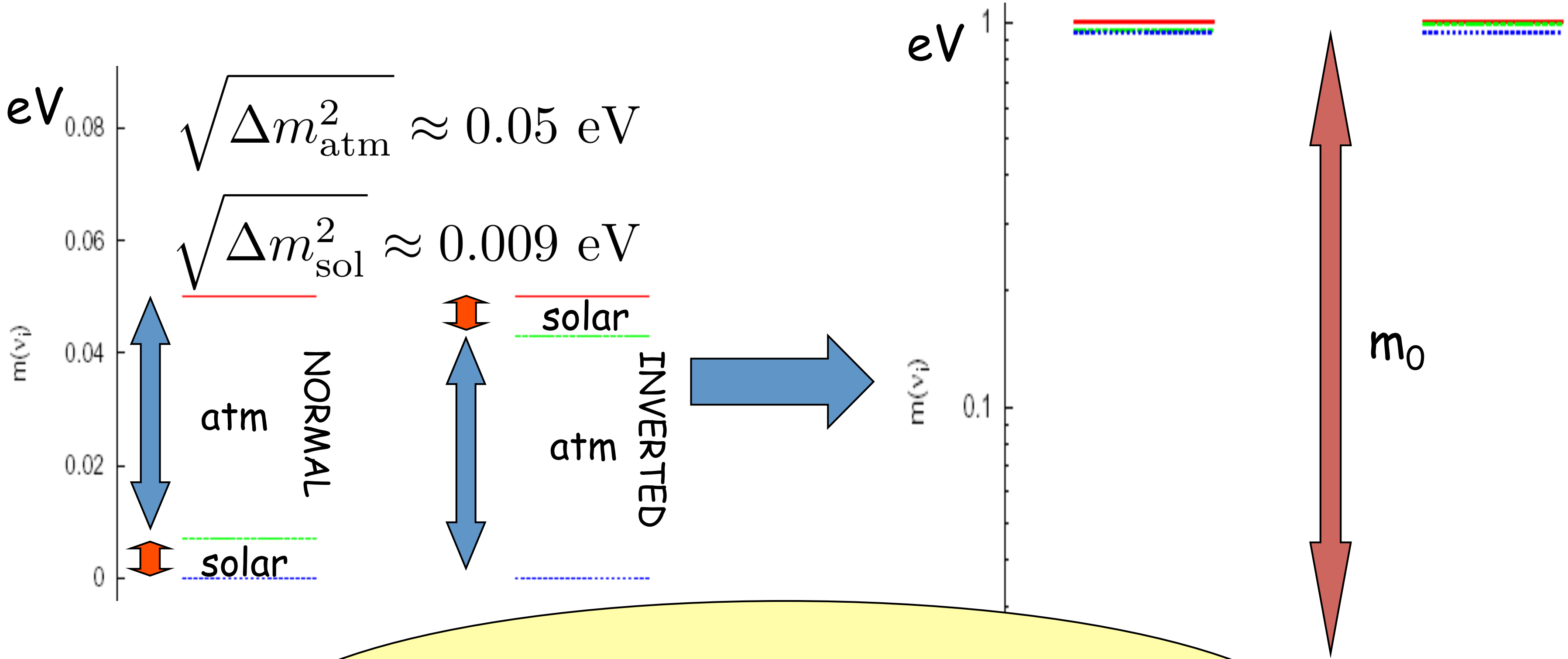
Present evidences for flavour neutrino oscillations: data on solar, atmospheric, reactor and accelerator neutrinos



Possible neutrino mass hierarchy patterns

Neutrino masses

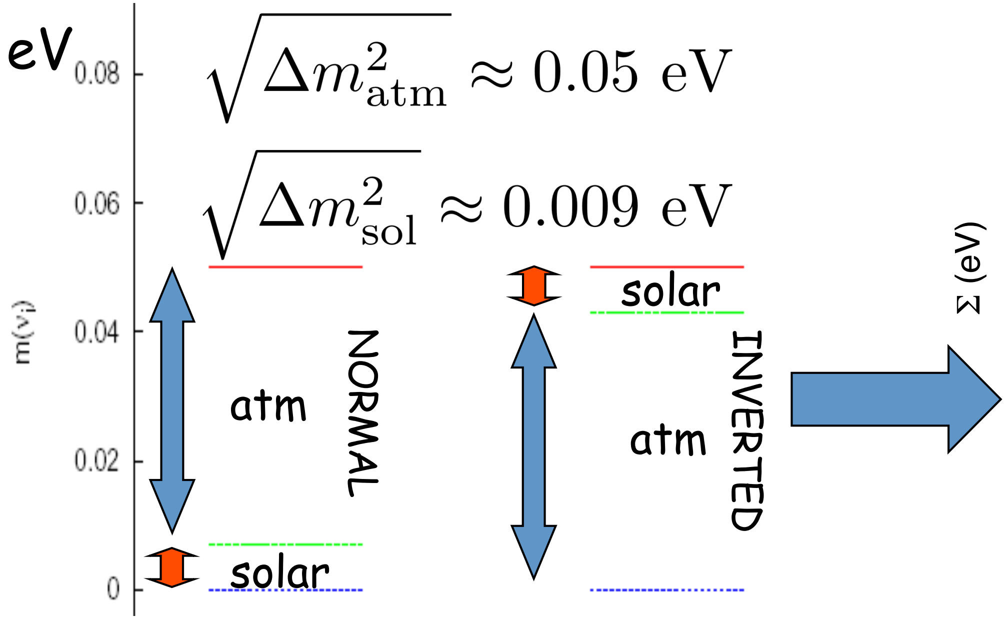
Data on flavour oscillations do not fix the absolute scale of neutrino masses

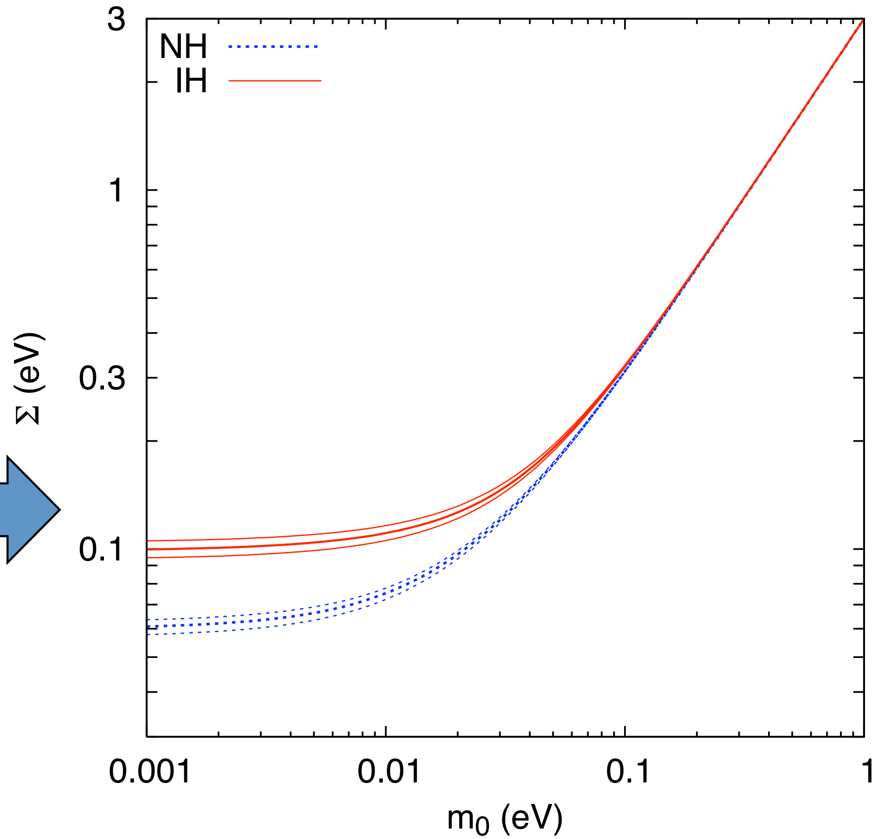


What is the value of m_0 ?

Neutrino masses

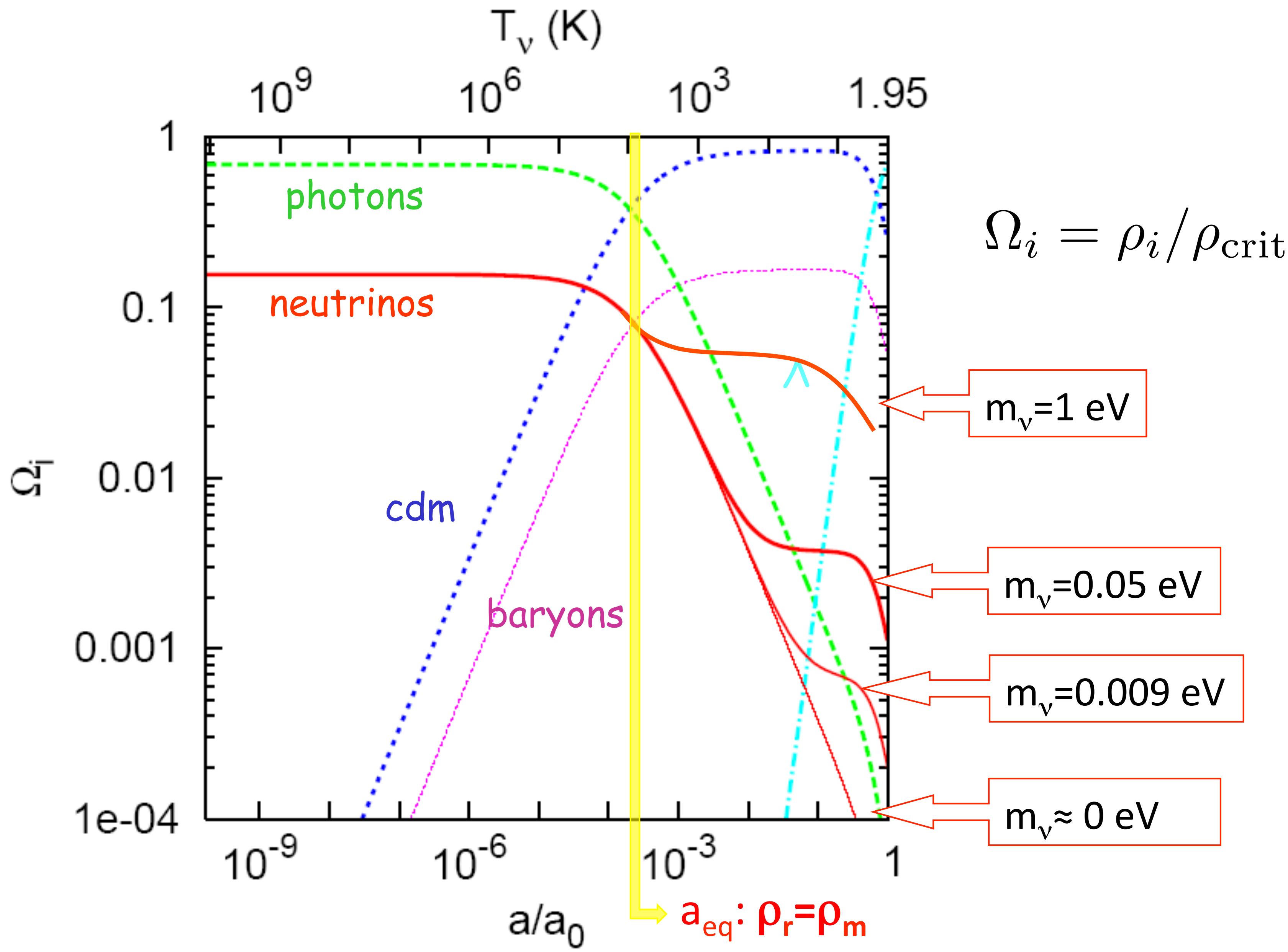
Data on flavour oscillations do not fix the absolute scale of neutrino masses





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

Evolution of the background densities: 1 MeV → now



Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

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

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

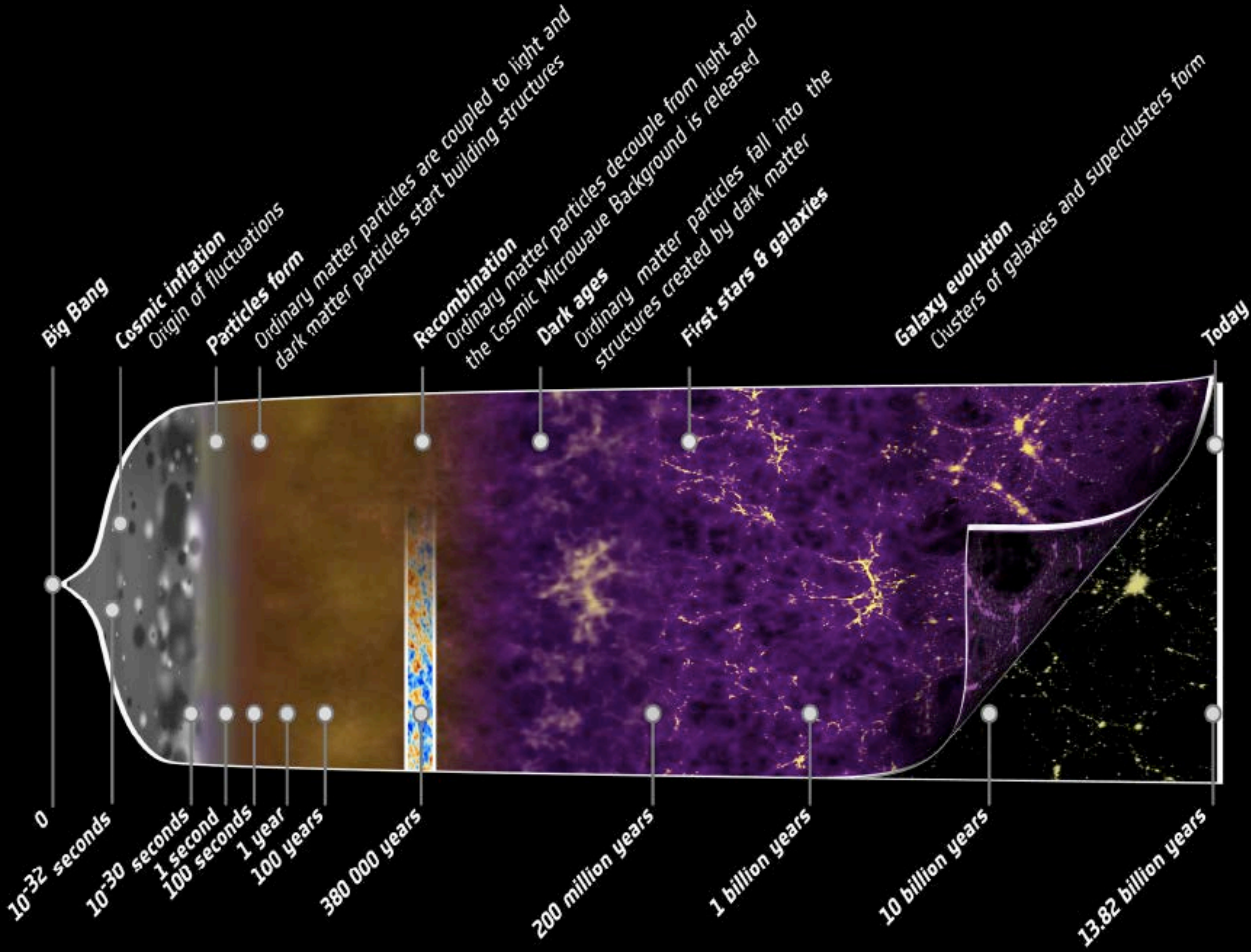
- They stream freely until non-relativistic (collisionless phase mixing) ⇒
Neutrinos are HOT Dark Matter (large thermal motion)

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

- Ruled out by structure formation ⇒ CDM

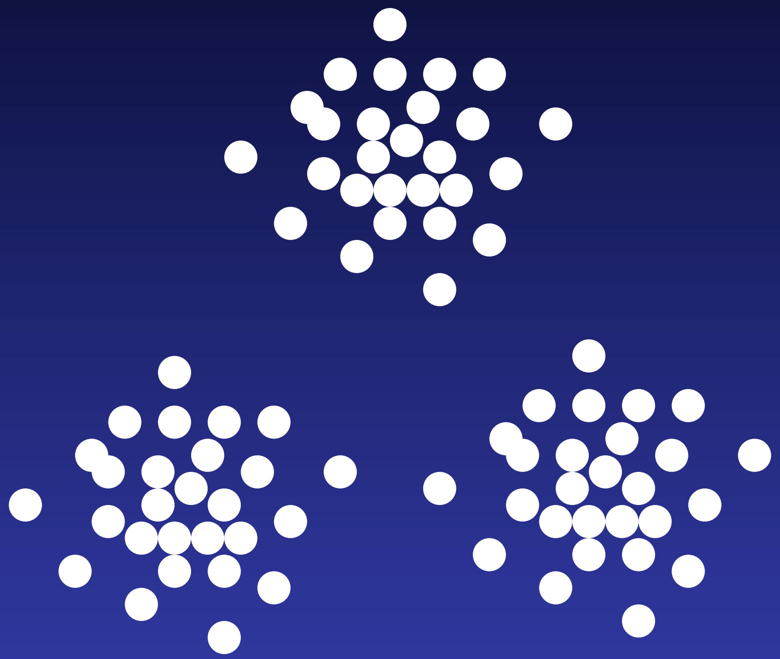
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

Evolution of the Universe



Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



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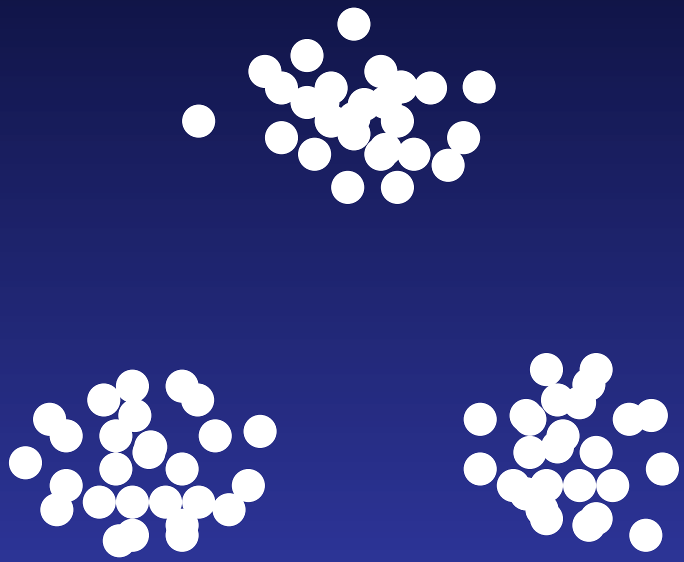

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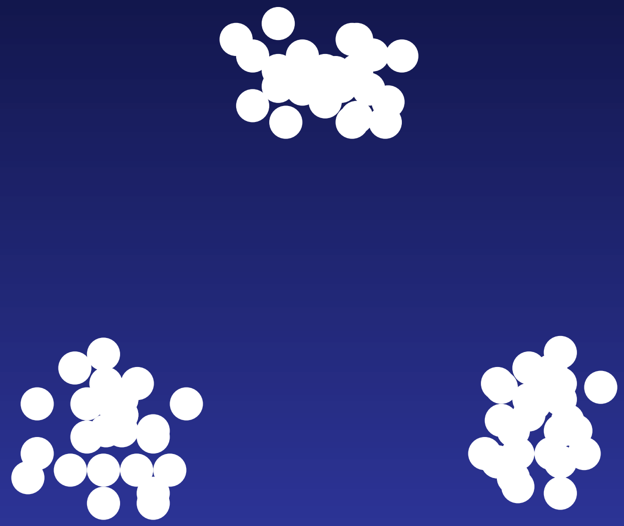

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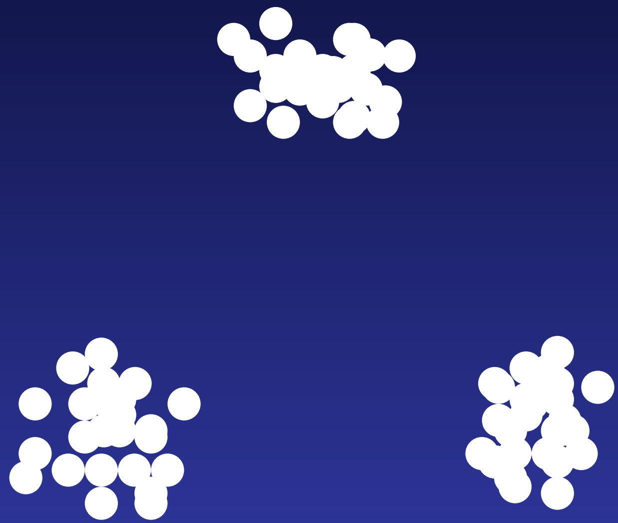


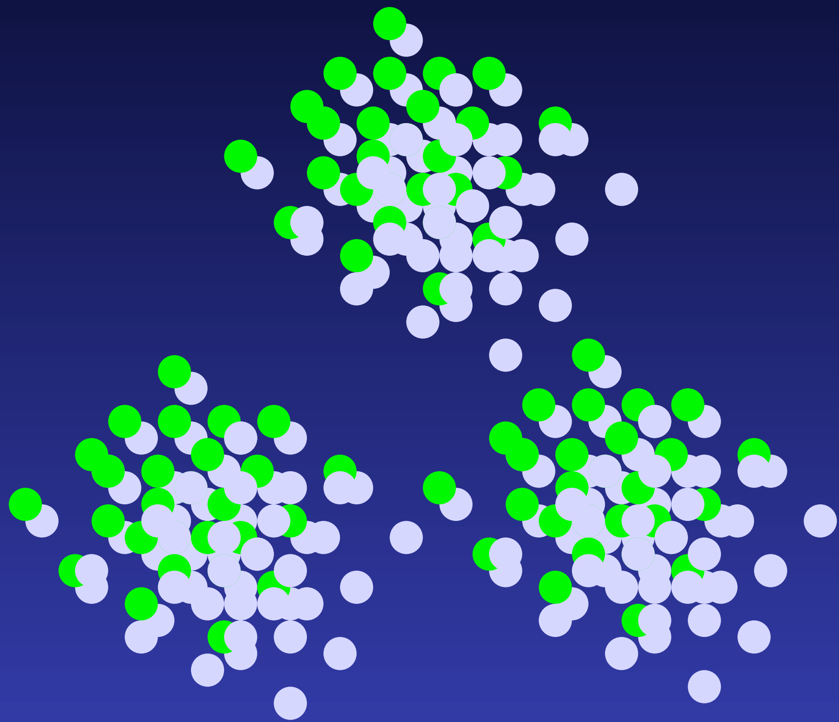
growth of $\delta\rho/\rho\ (k,t)$ fixed by

gravity vs expansion balance

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

Structure formation after equality

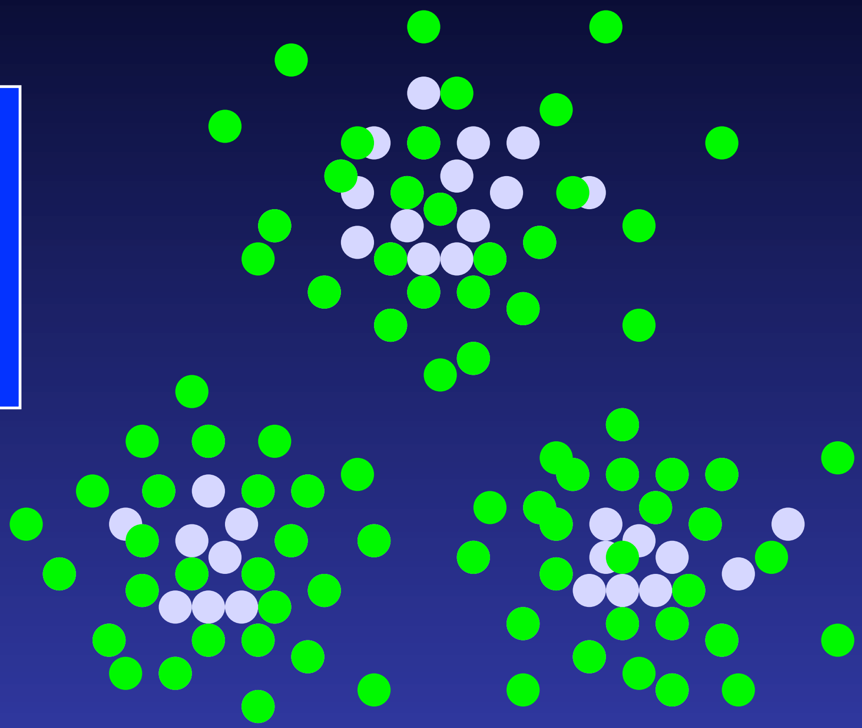
baryons and CDM (matter) experience gravitational clustering



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

Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



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

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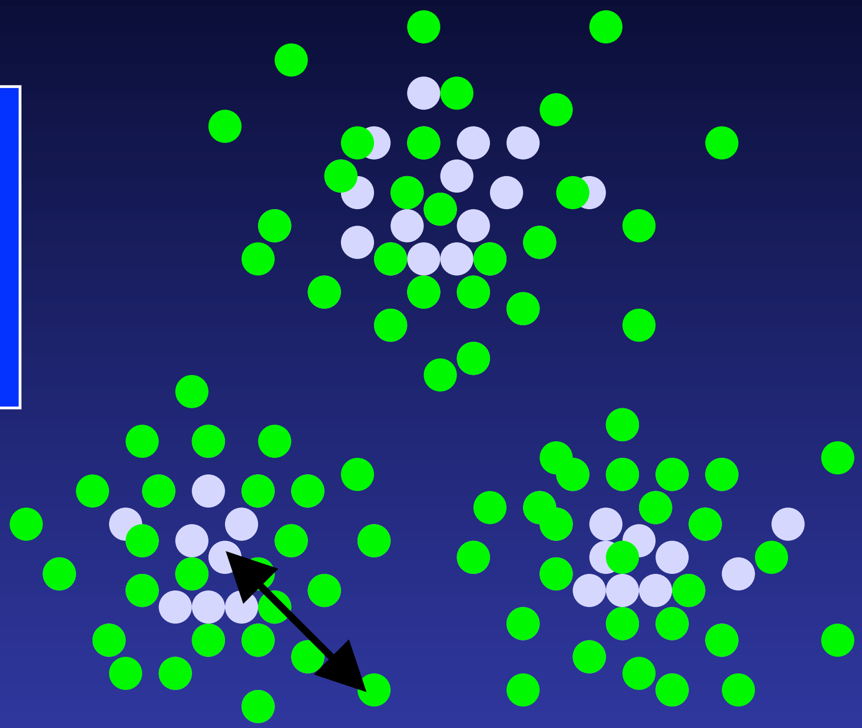


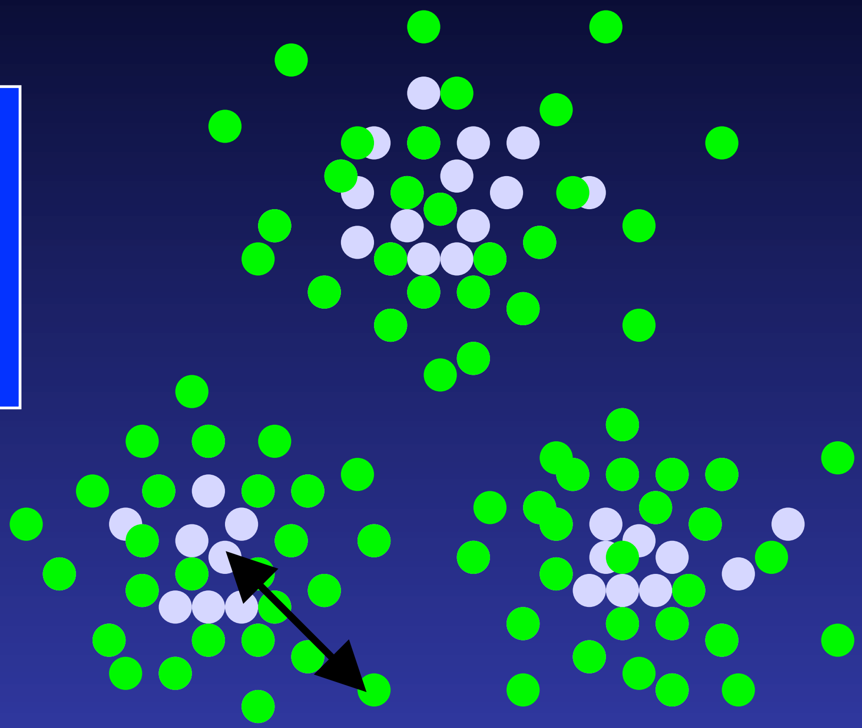
neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

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 $\langle p \rangle / m$

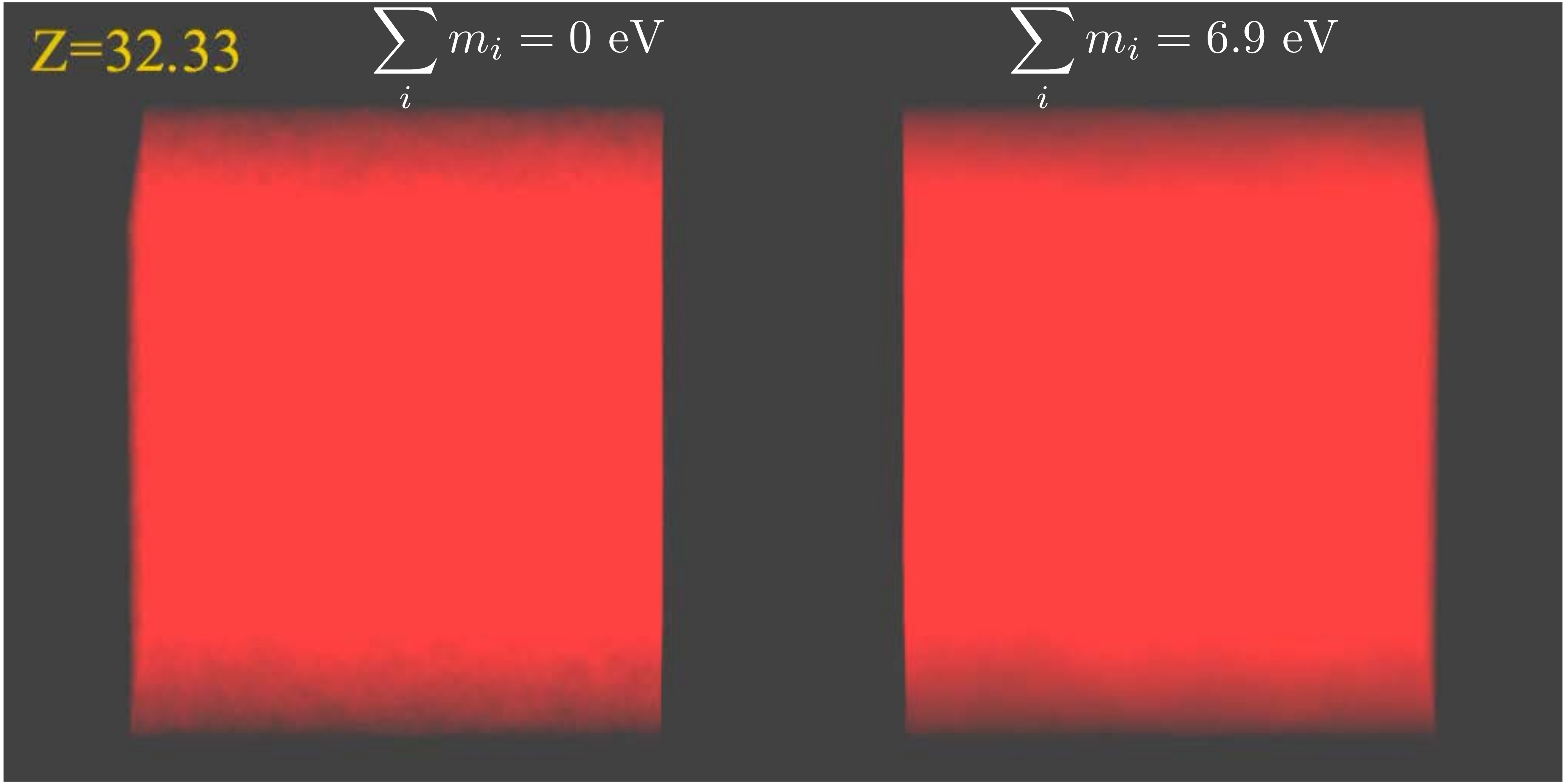
for $(2\pi/k) < \lambda$,

free-streaming supresses growth of structures during MD

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

Neutrinos as Hot Dark Matter

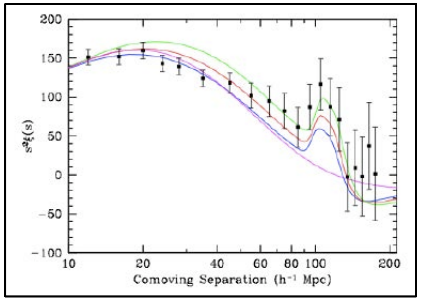
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)



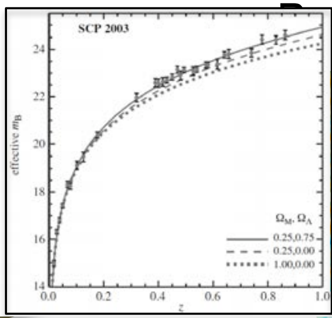
S. Hannestad, Cosmology Group, Univ. Aarhus

Effects of neutrino masses on cosmological observables

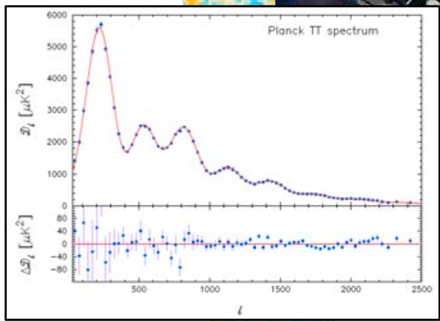
Cosmological Observables

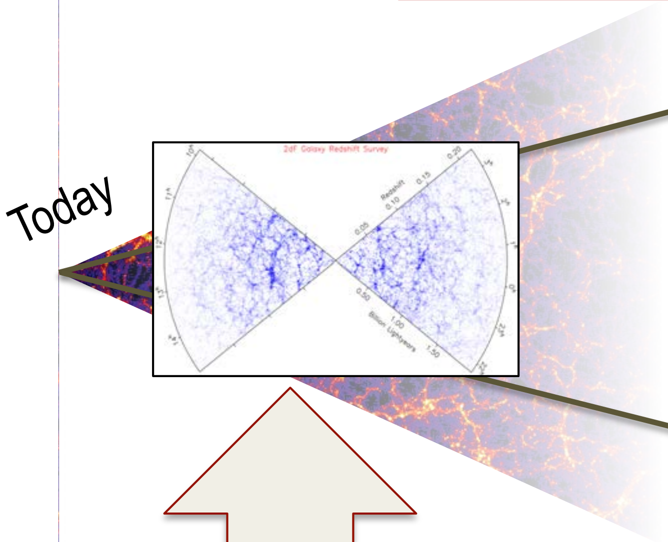


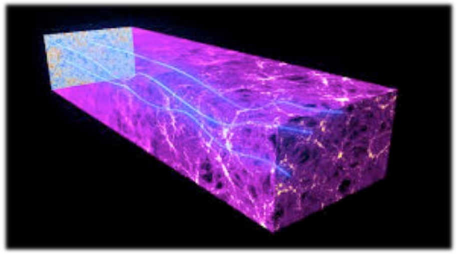
Hubble constant H_0 & cosmic distances measurements: SN Ia and Baryon Acoustic Oscillations (BAO)



combination







matter density fluctuations
Large-Scale Structures
[galaxy / cosmic shear / Lyα]
LSS spectrum

Photon momentum
after decoupling
CMB secondary anisotropy
spectrum

Photon density fluctuations
before decoupling
CMB primary anisotropy
spectrum (temp+pol)

from J. Lesgourgues

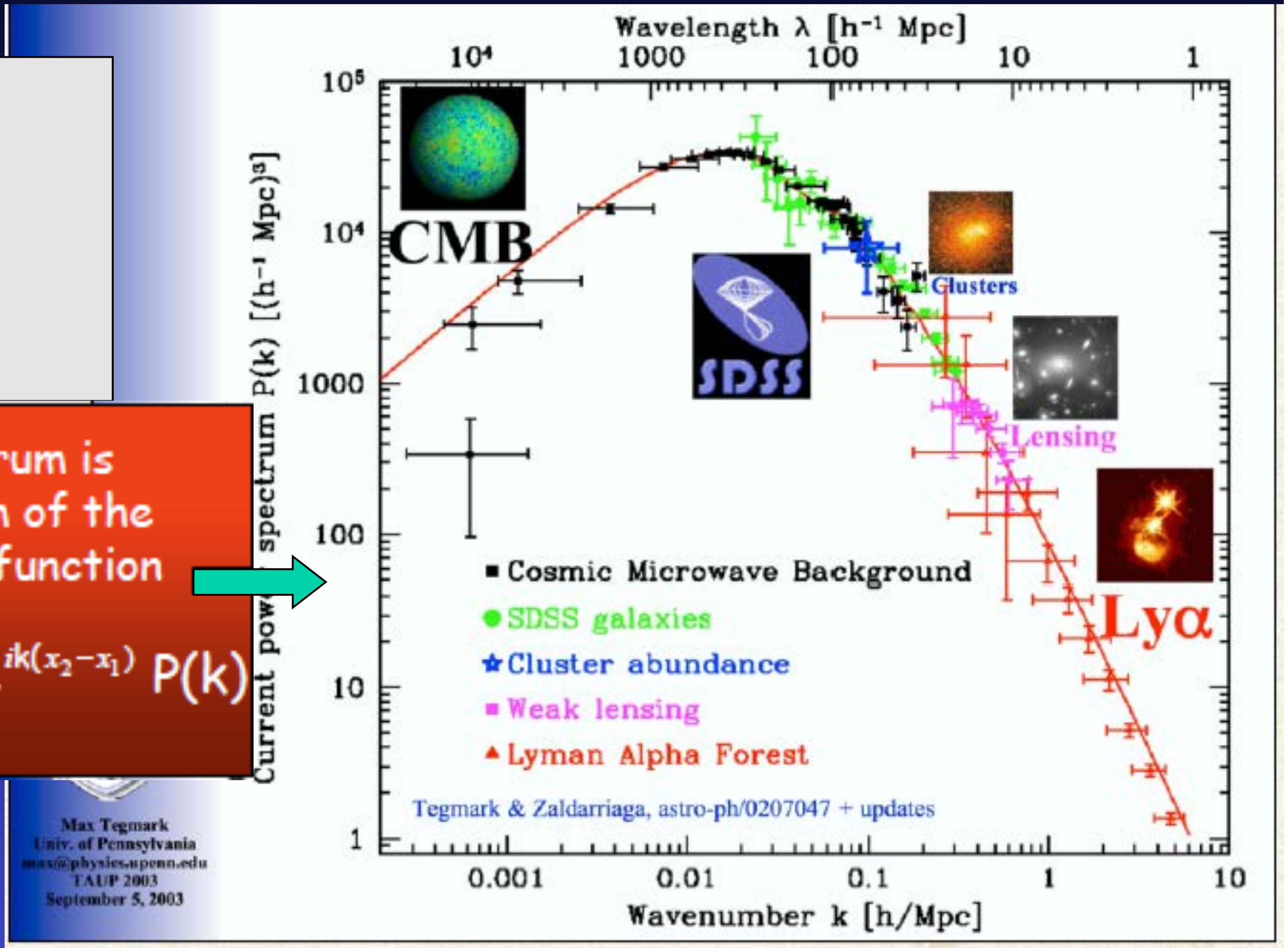
Power Spectrum of density fluctuations

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

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



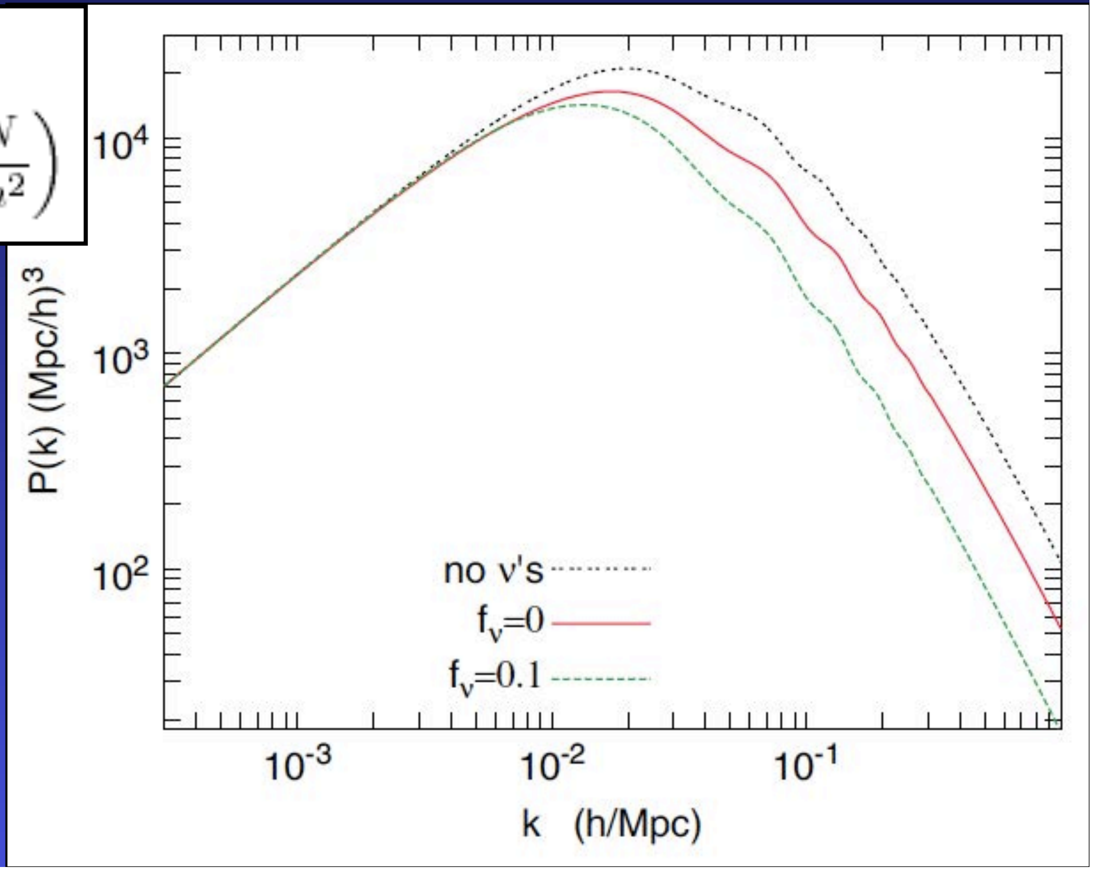
Neutrinos as Hot Dark Matter: effect on P(k)

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

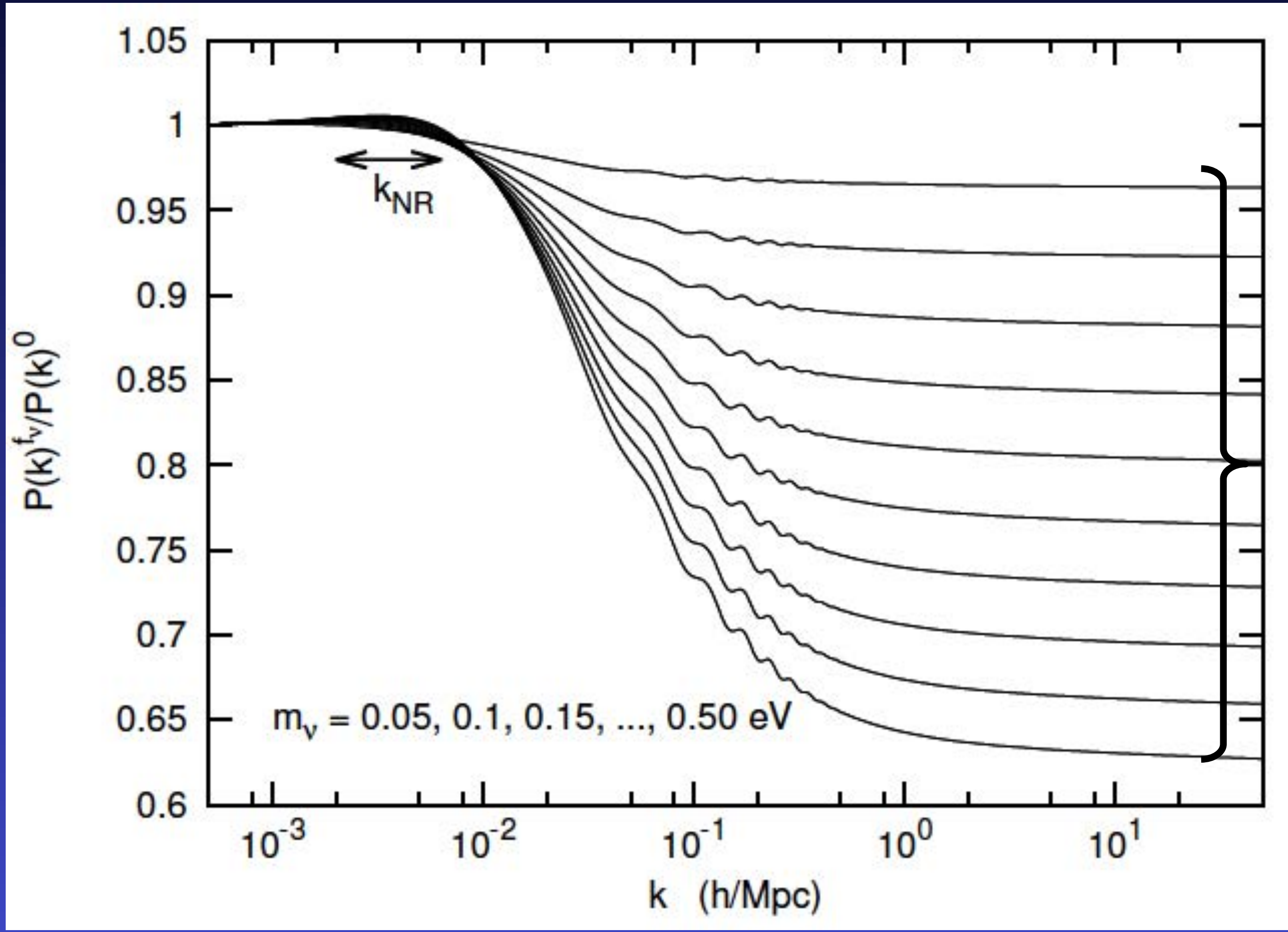
$$\left(\frac{\Delta P}{P}\right) \approx -8\underbrace{\frac{\Omega_\nu}{\Omega_m}}_{f_\nu} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$



Effect of massive neutrinos on P(k)

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

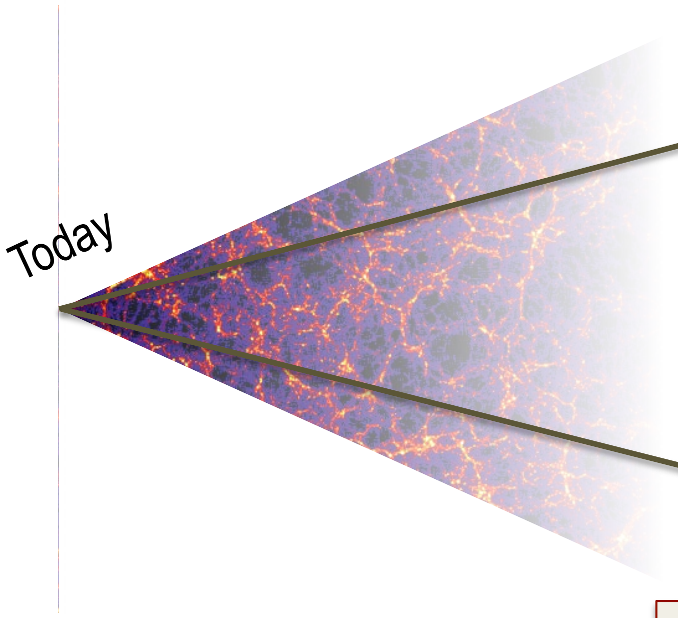
$$\frac{P(k)\ \text{massive}}{P(k)\ \text{massless}}$$

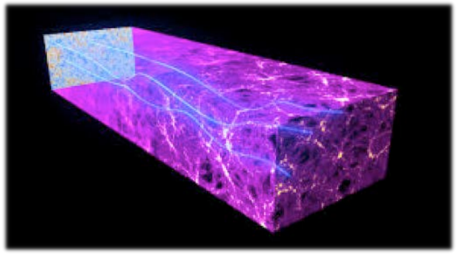


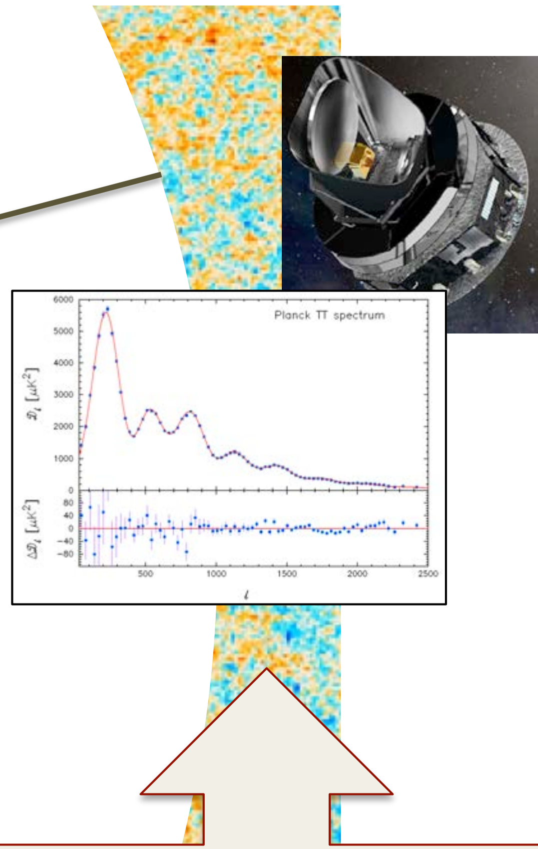
various f_ν

Cosmological Observables

Recombination





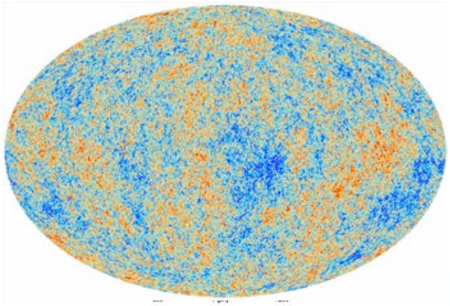


Photon momentum
after decoupling
CMB secondary anisotropy
spectrum

Photon density fluctuations
before decoupling
CMB primary anisotropy
spectrum (temp+pol)

from J. Lesgourgues

CMB data from Planck



Map of CMBR temperature Fluctuations

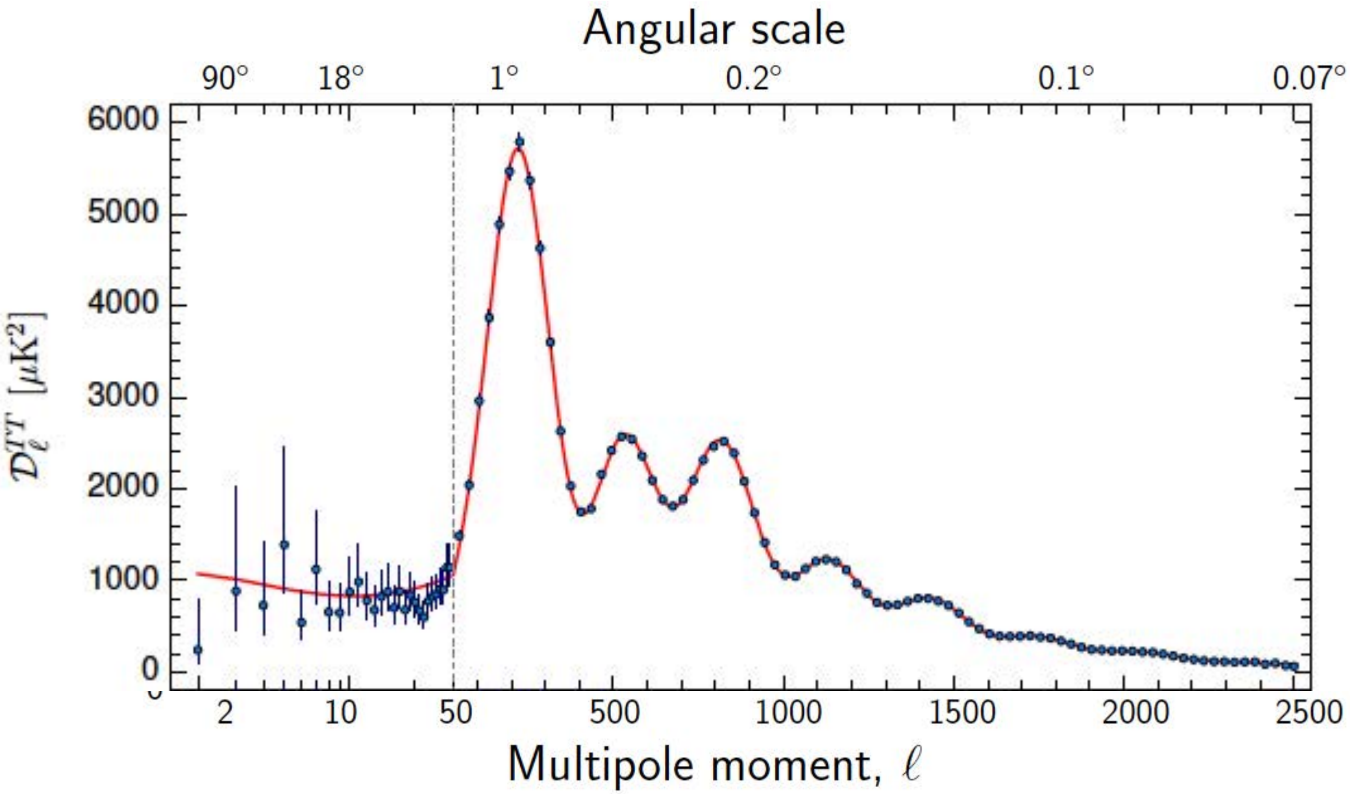
$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$

Multipole Expansion

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

Angular Power Spectrum

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

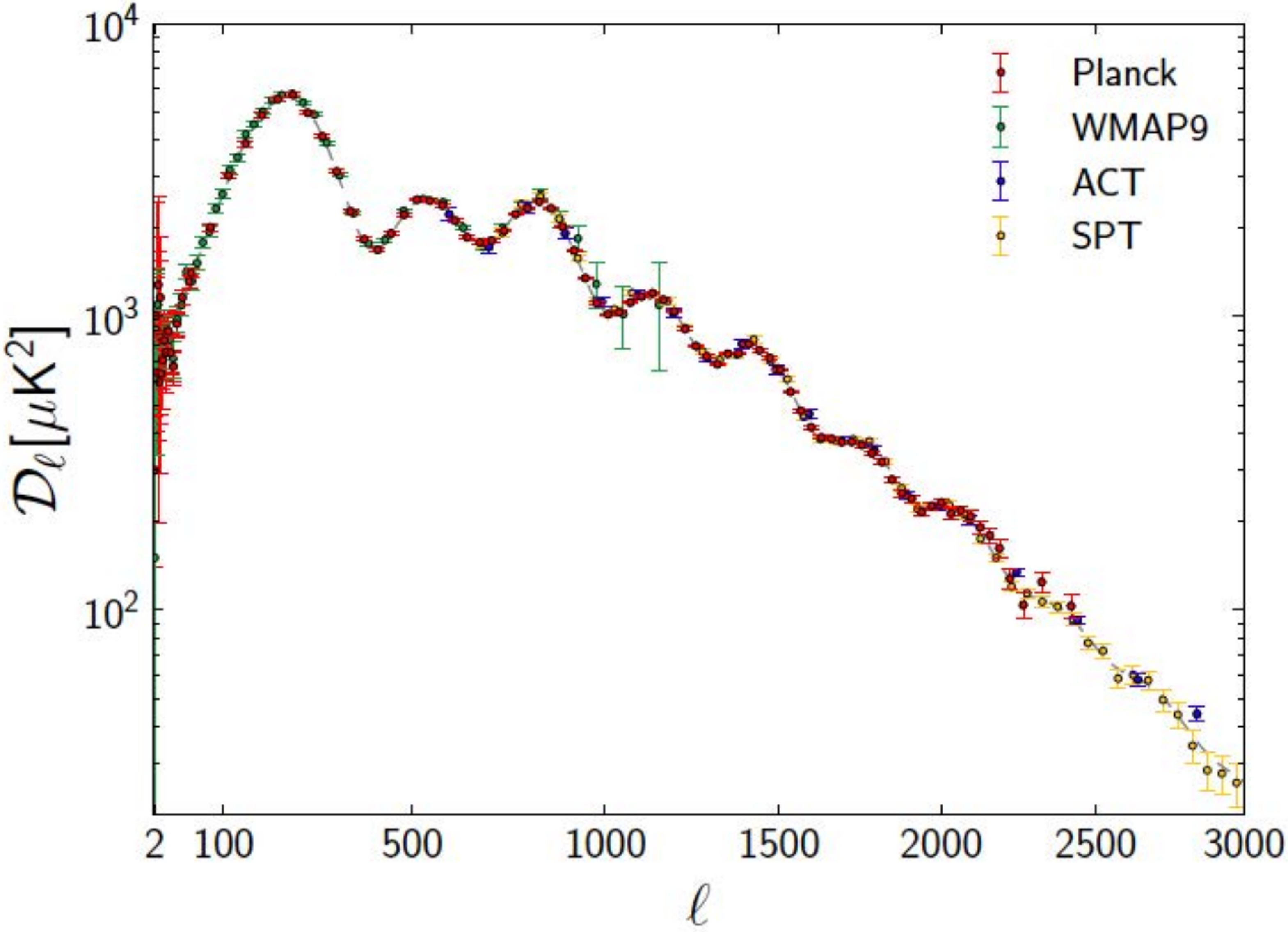


PLANCK 2015: results from 15 months, measures the TT CMB spectrum in a wide range of l's (also TE & EE)

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

Present CMB data

Planck vs other experiments



Effects of m_ν on the CMB

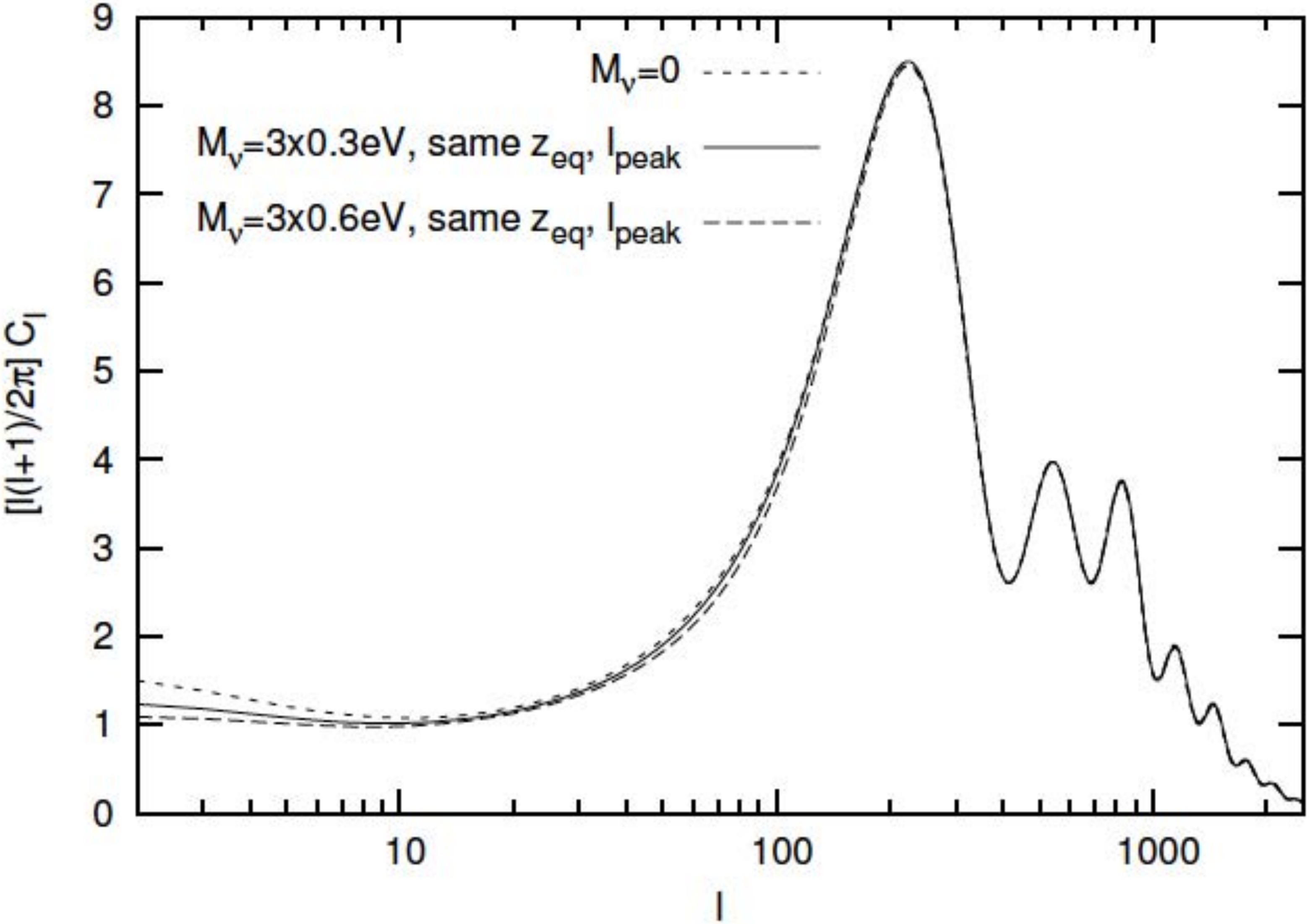
- Neutrinos contribute to radiation at early times and non-relativistic matter at late times

- 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 combination of parameters 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

Effects of m_ν on the CMB

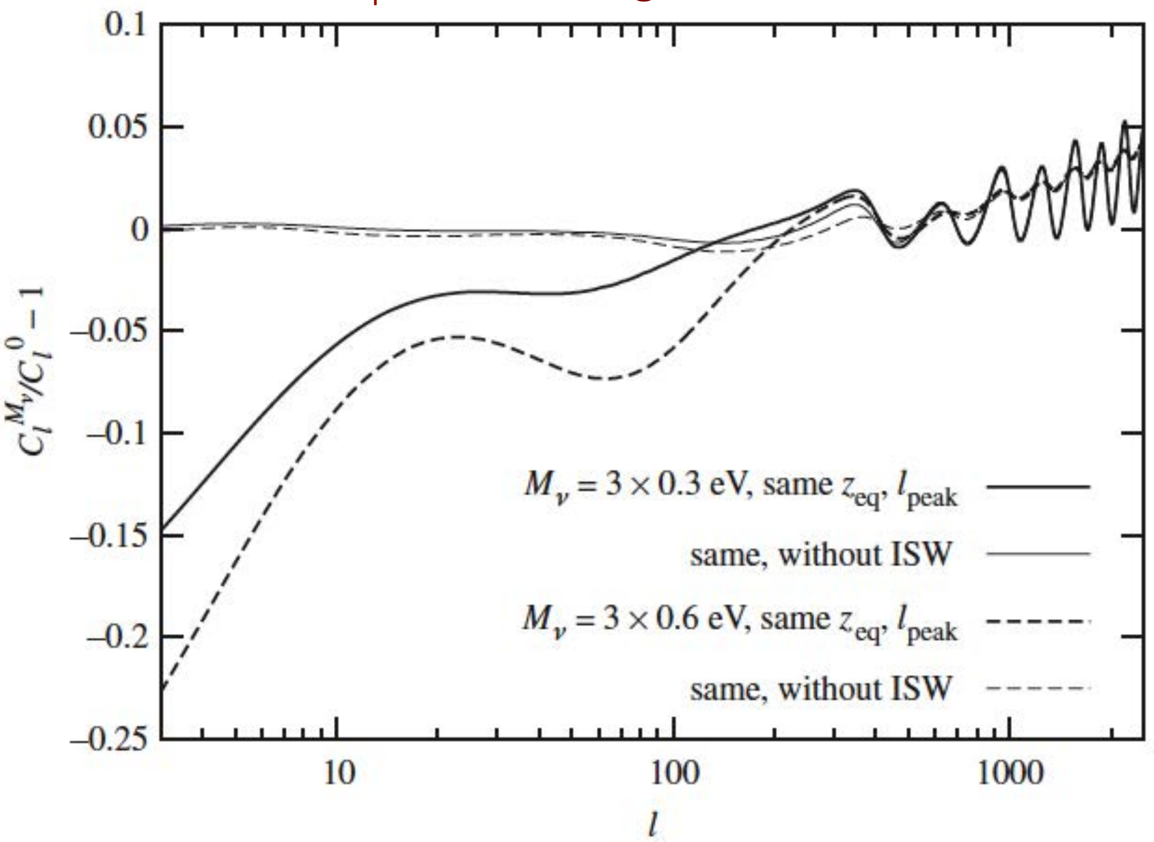


Effects of m_ν on the CMB

- 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:



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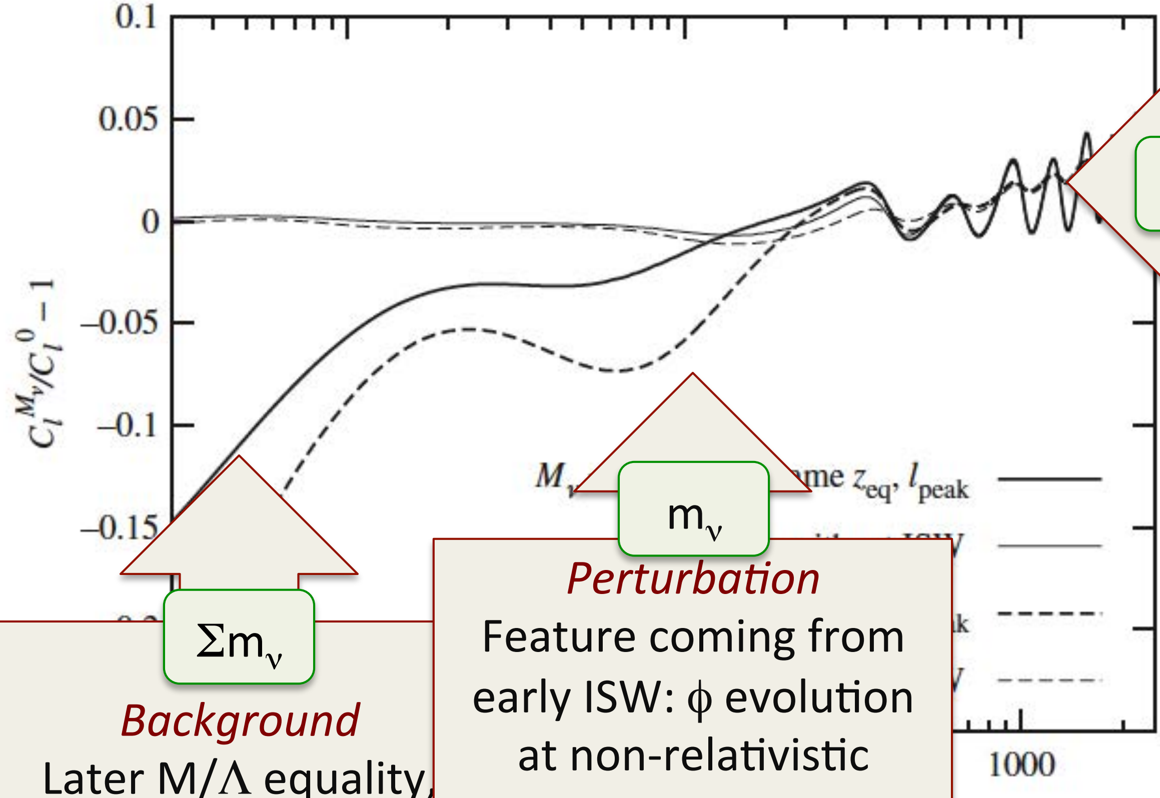


Perturbation
Not fully relativistic before decoupling: less free-streaming and shifting

m_ν

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

m_ν

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

Σm_ν

+ different lensing effect

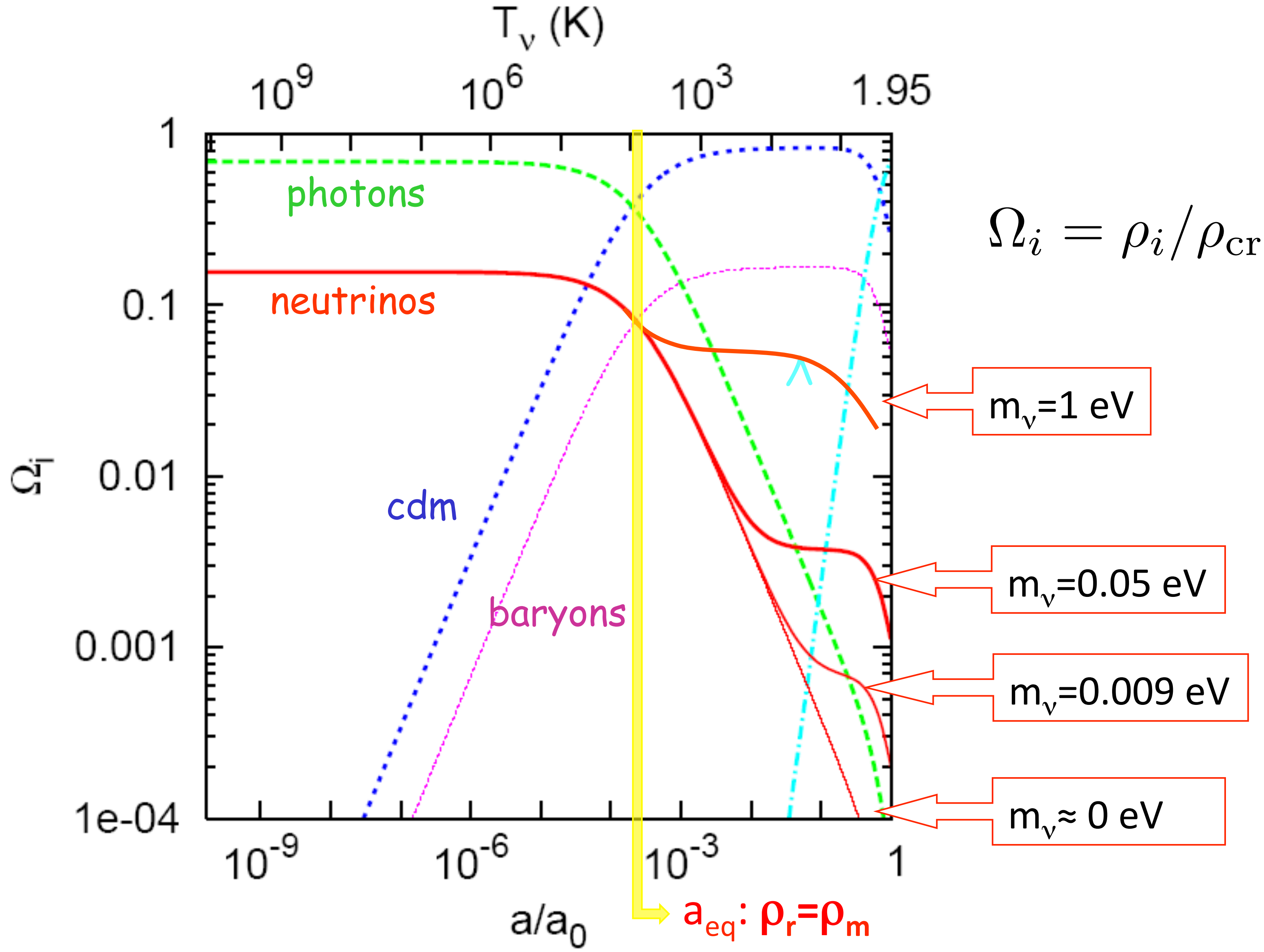
Σm_ν

Effects of N_{eff} on cosmological observables

Effects of N_{eff} on the CMB

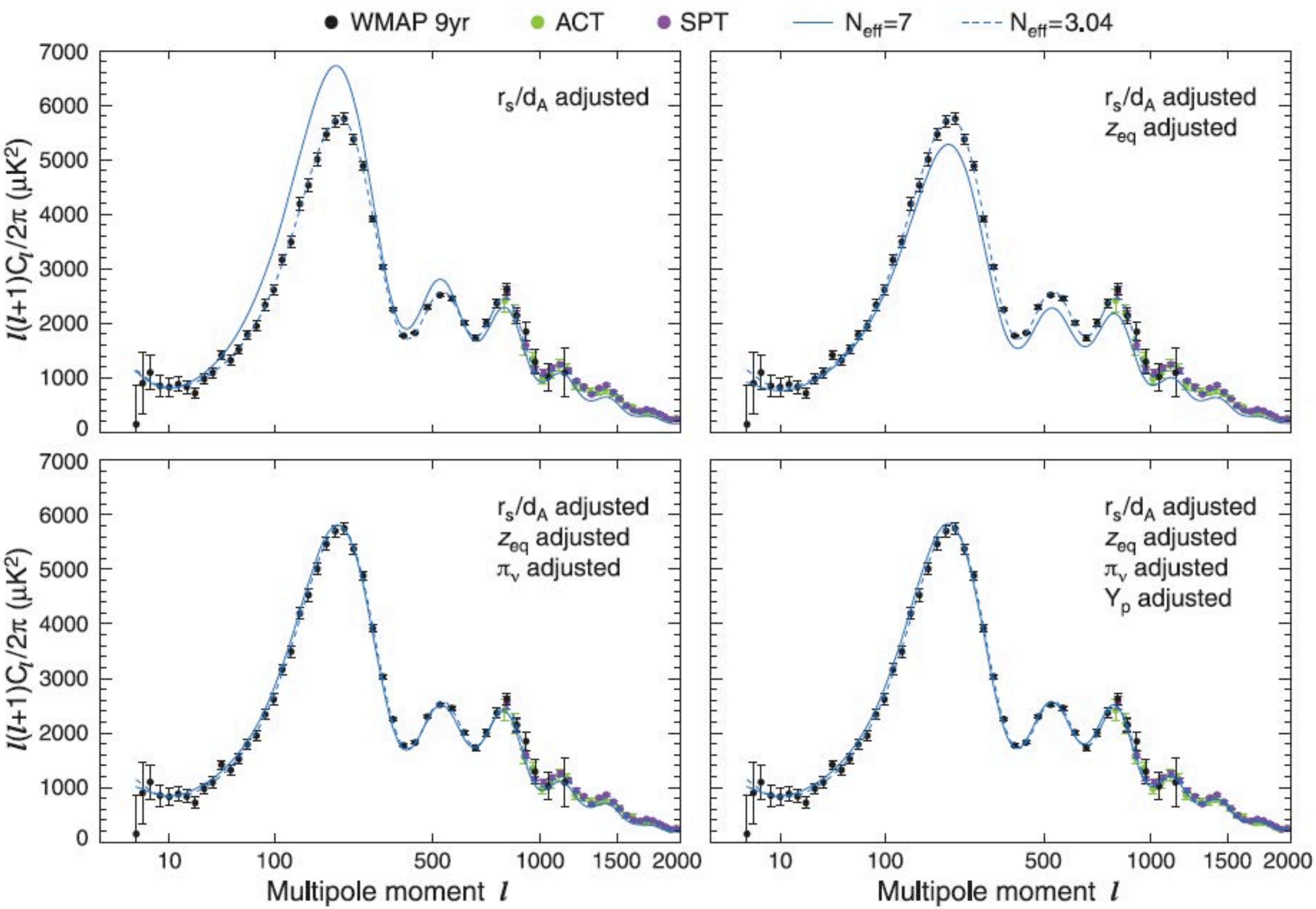
- N_{eff} is a parameter for the relativistic density in general
- "background effects" (change in expansion history) versus "perturbation effects" (gravitational interactions between photons and relativistic species)
- "effect of N_{eff}" depends on what is kept fixed.
- Fixing quantities best probed 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

Evolution of the background densities: 1 MeV → now



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

Effects of N_{eff} on the CMB



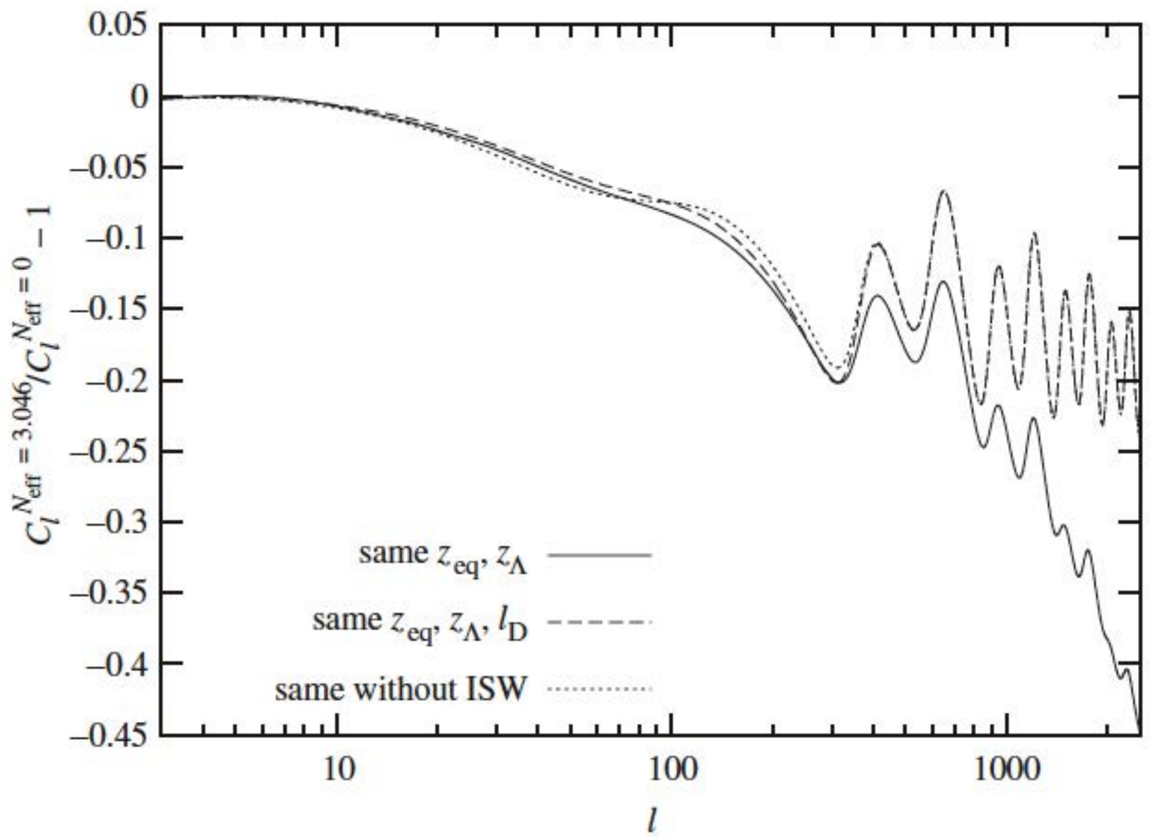
Hinshaw et al, arXiv:1212.5226

Effects of N_{eff} on the CMB

- 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 :



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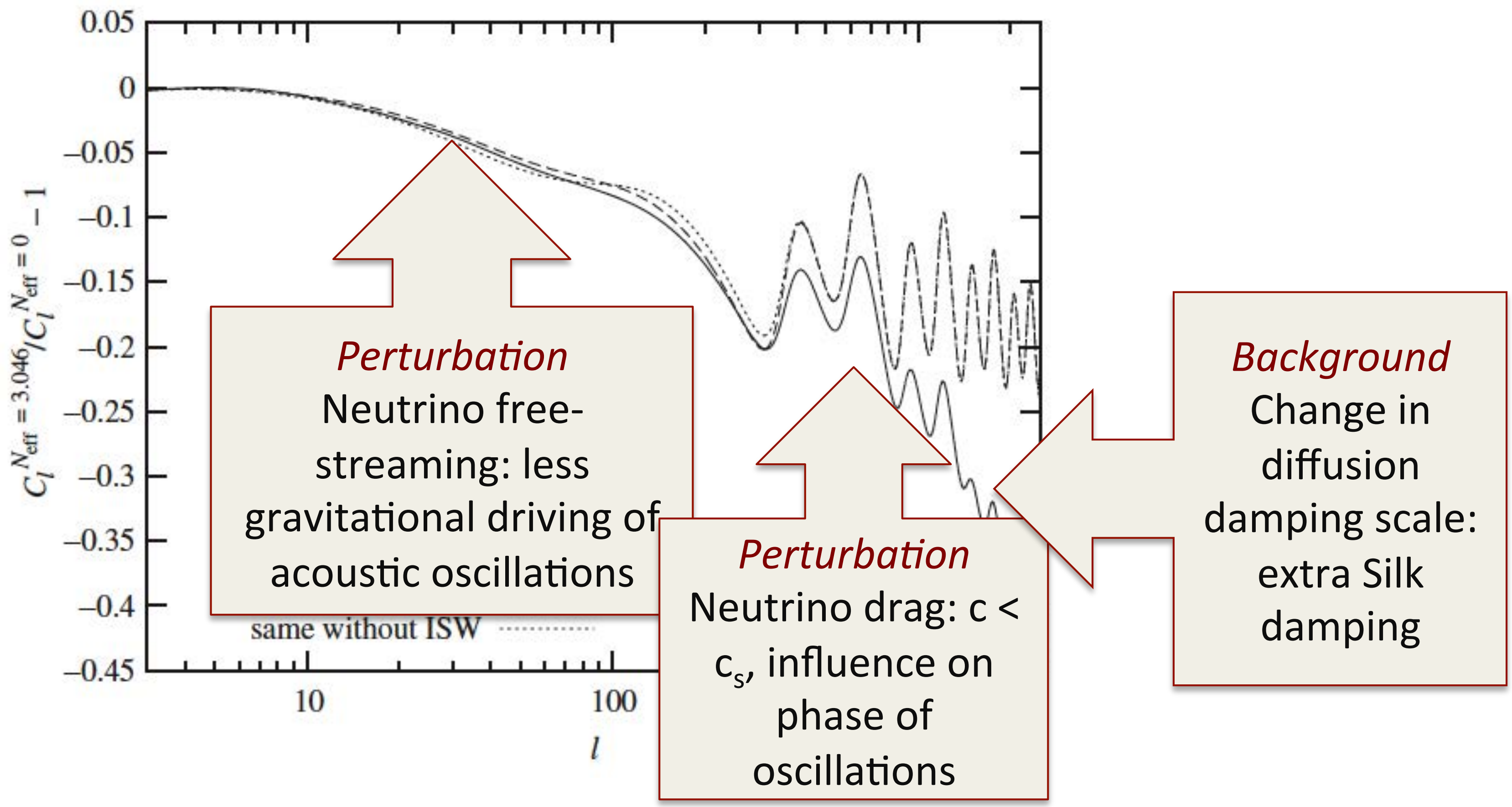
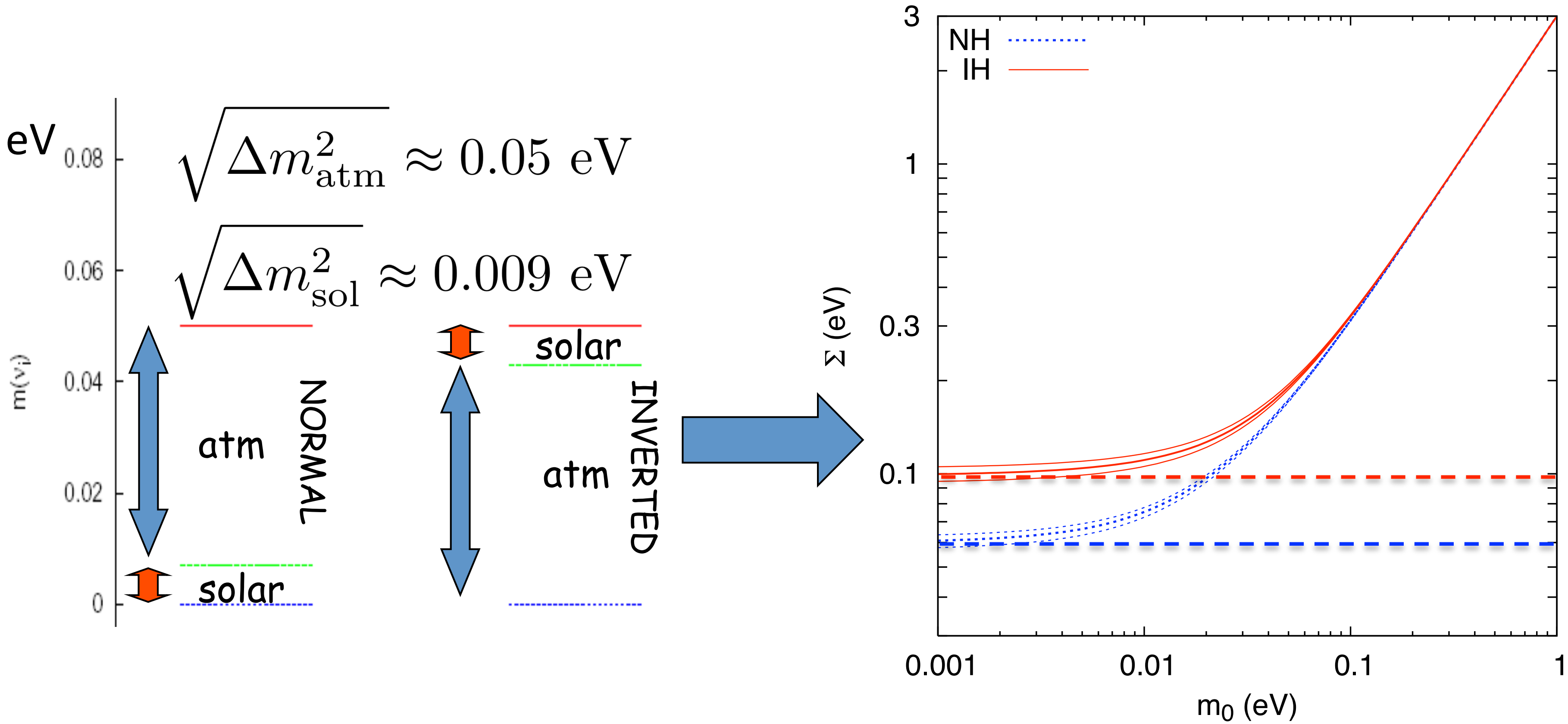


Present bounds on neutrino properties from cosmology

Neutrino masses

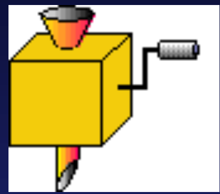
Data on flavour oscillations do not fix the absolute scale of neutrino masses

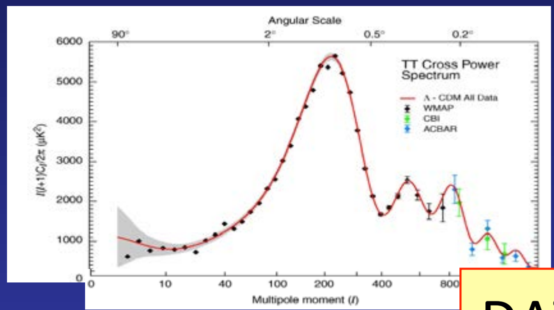


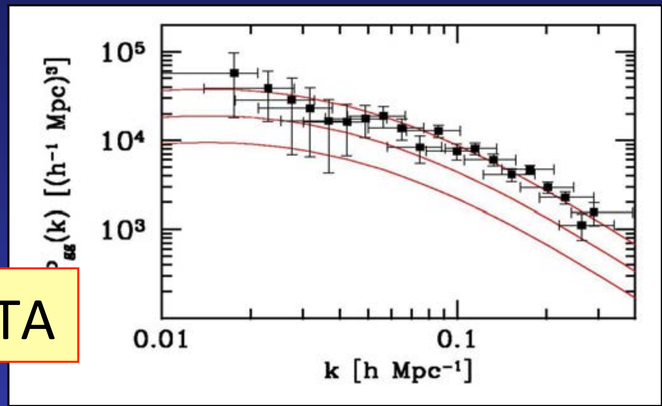
$$0.06(0.1)\,\mathrm{eV} \lesssim \sum_i m_i \lesssim 6\,\mathrm{eV}$$

How to get a bound (measurement) of neutrino masses from Cosmology

Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau, \Sigma m_\nu)$



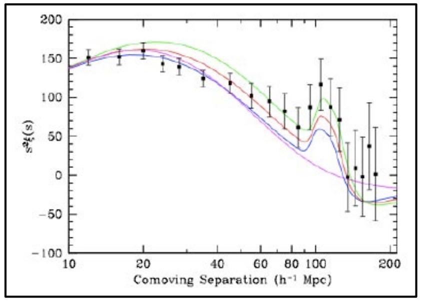




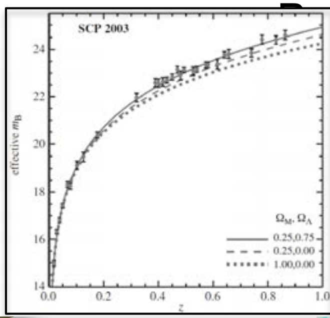
DATA

PARAMETER ESTIMATES

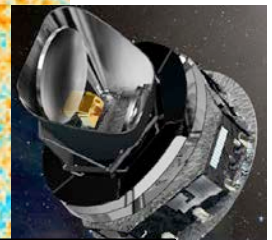
Cosmological Observables

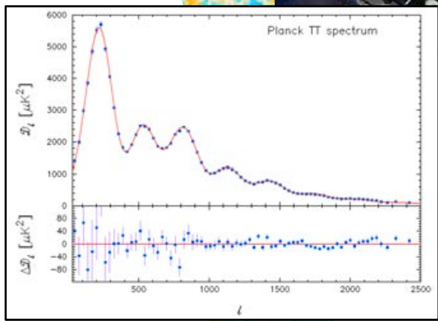


Hubble constant H_0 & cosmic distances measurements: SN Ia and Baryon Acoustic Oscillations (BAO)

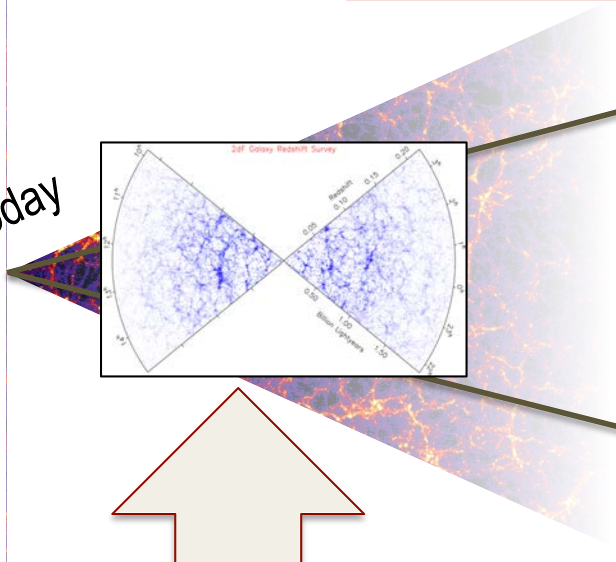


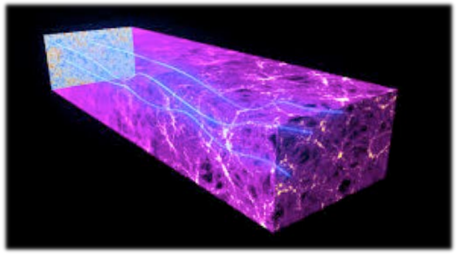
combination





Today





matter density fluctuations
Large-Scale Structures
[galaxy / cosmic shear / Lyα]
LSS spectrum

Photon momentum
after decoupling
CMB secondary anisotropy
spectrum

Photon density fluctuations
before decoupling
CMB primary anisotropy
spectrum (temp+pol)

from J. Lesgourgues

Cosmological Data

- CMB Temperature: Planck plus data from other experiments at large multipoles (ACT, SPT…)
- CMB Polarization and lensing: Planck,…
- Large Scale Structure:
    - * Galaxy Clustering
    - * Bias (Galaxy, …): Amplitude of the Matter P(k)
    - * Lyman-α forest: independent measurement of power on small scales
    - * Baryon acoustic oscillations (BAO)

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

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

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	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$

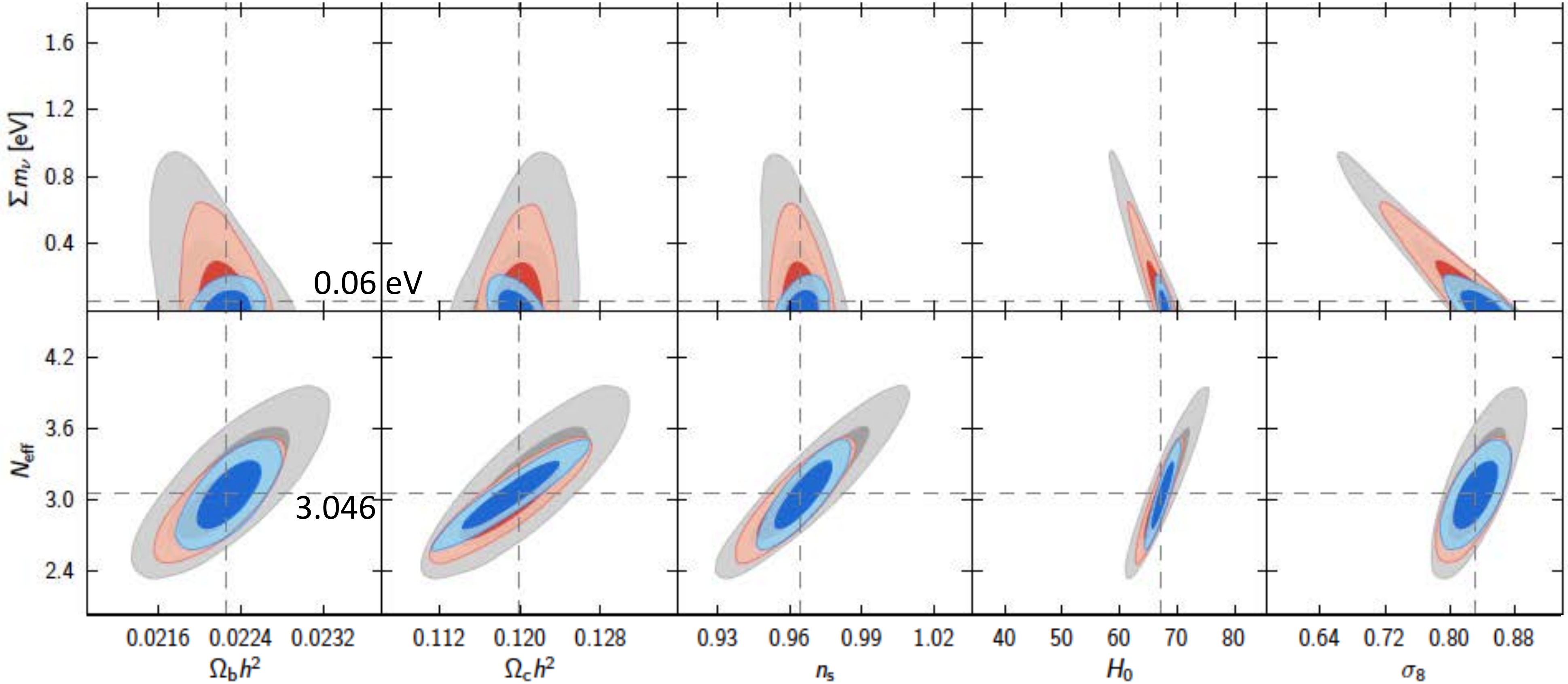
95% CL limits

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

1-parameter extensions of the ΛCDM model

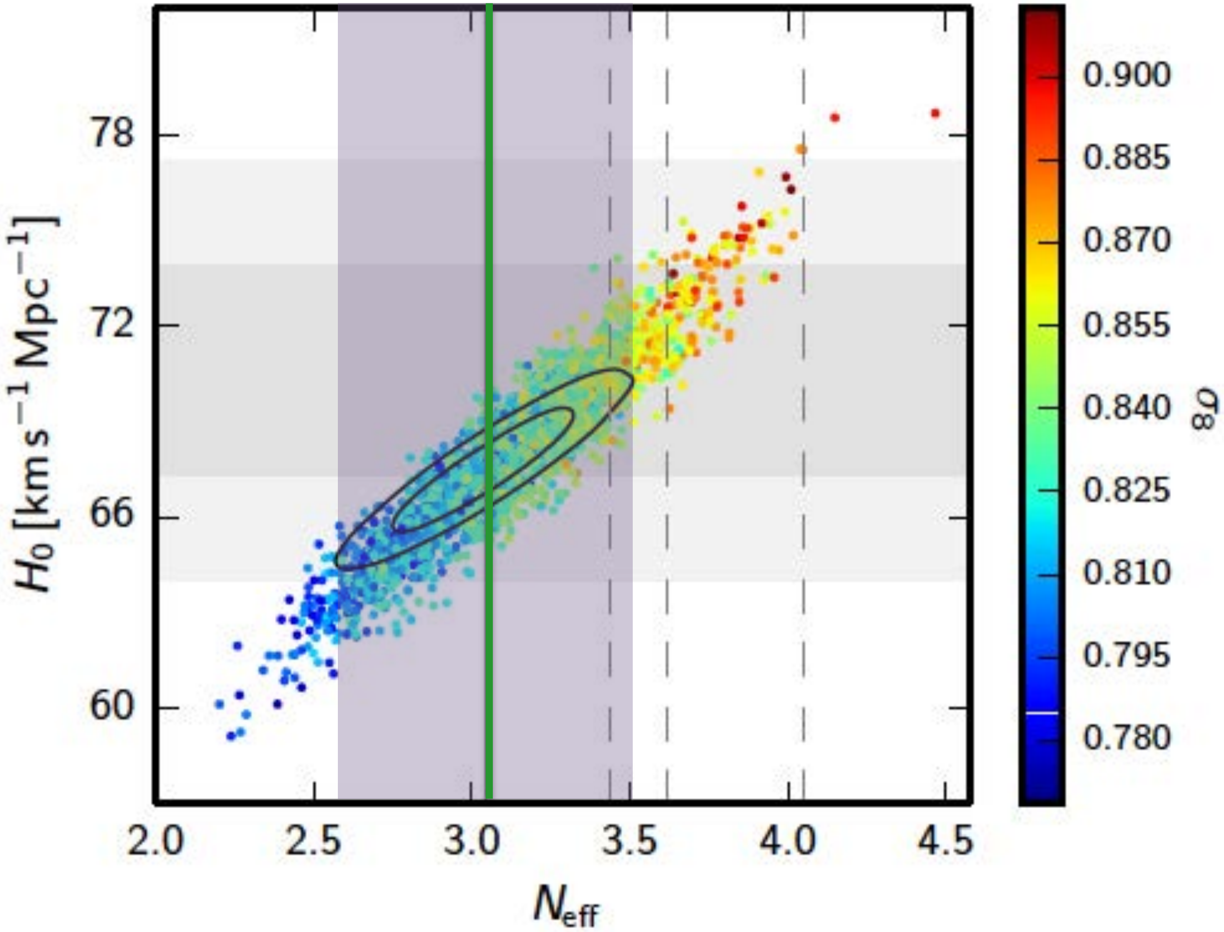
68+95%
Conf regions



Planck TT + lowP   **Planck TT,TE,EE + lowP**   **Planck TT,TE,EE + lowP + BAO**

Measuring N_{eff}

Indirect detection of CNB at 10-17σ



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

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

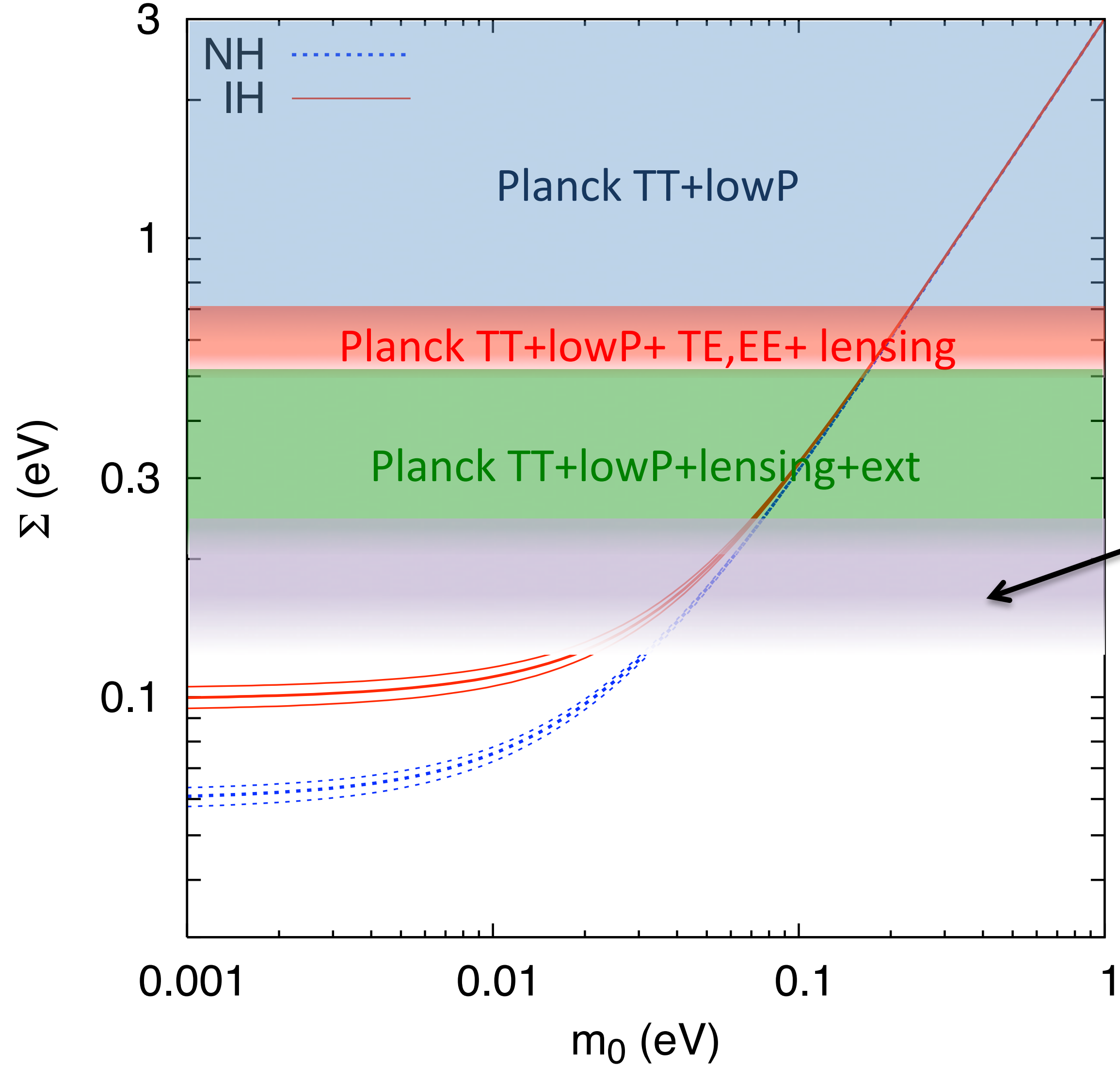
$$N_{\mathrm{eff}} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP};$$

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

All 68%CL

Measuring m_ν with Planck (+other cosmo data)

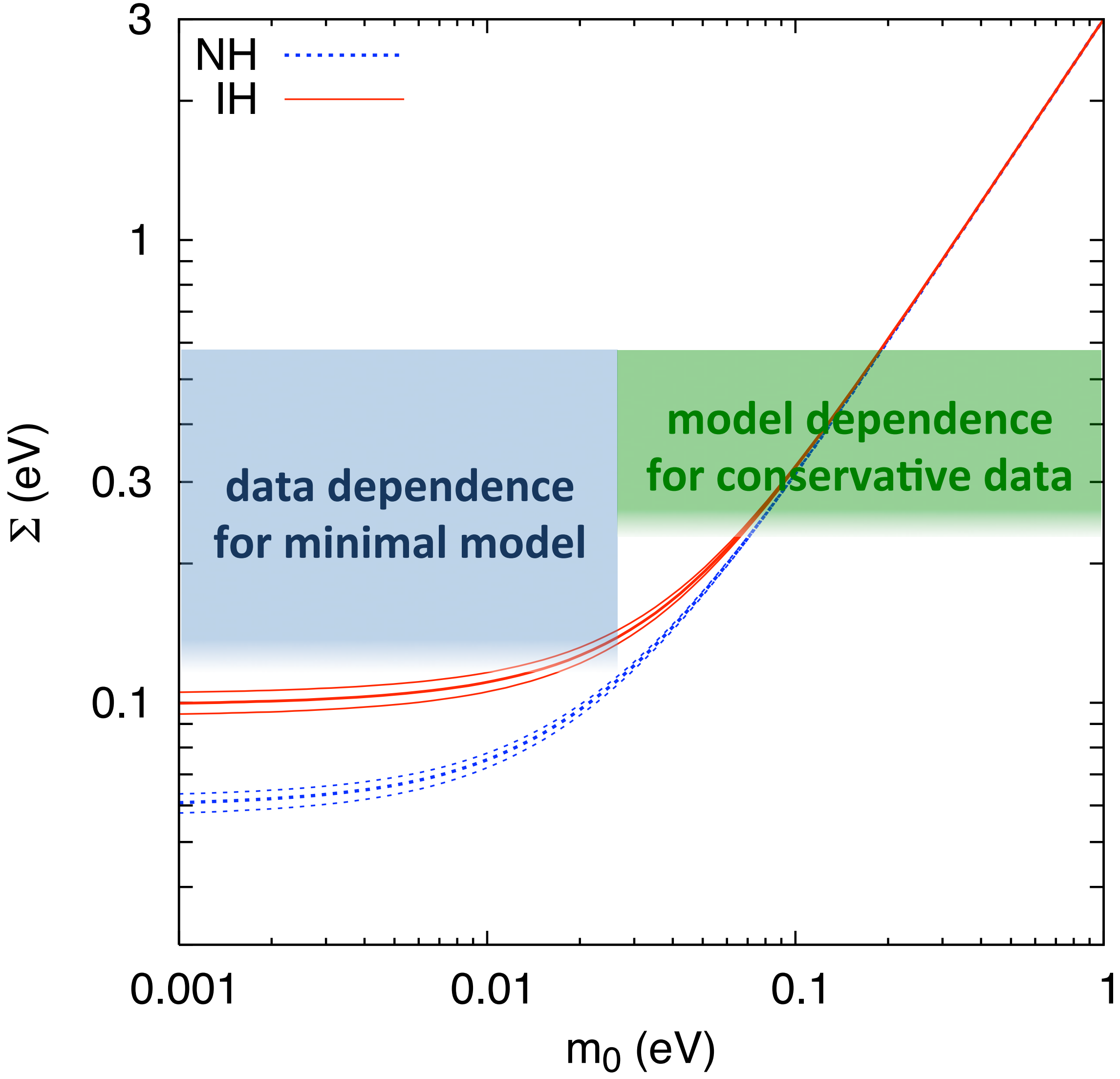
Cosmological upper limits on the sum of neutrino masses



Latest analyses
Planck 2016 +
BAO / Ly-α
see e.g.
Vagnozzi et al
PRD 96 (2017) 123503
Capozzi et al
PRD 95 (2017) 096014

Measuring m_ν with Planck (+other cosmo data)

Cosmological upper limits on the sum of neutrino masses



Probing the absolute neutrino mass scale

Searching for non-zero neutrino mass in laboratory experiments

- Tritium beta decay: measurements of endpoint energy

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

$m_\beta < 2.2$ eV (95% CL)   Mainz

Current experiment (KATRIN) $m(\nu_e) \sim 200\text{-}300$ meV

- Neutrinoless double beta decay: if Majorana neutrinos

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

experiments with ^{76}Ge, ^{130}Te, ^{136}Xe and other isotopes:
$m_{\beta\beta} < 60\text{-}800$ meV , depending on NME

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

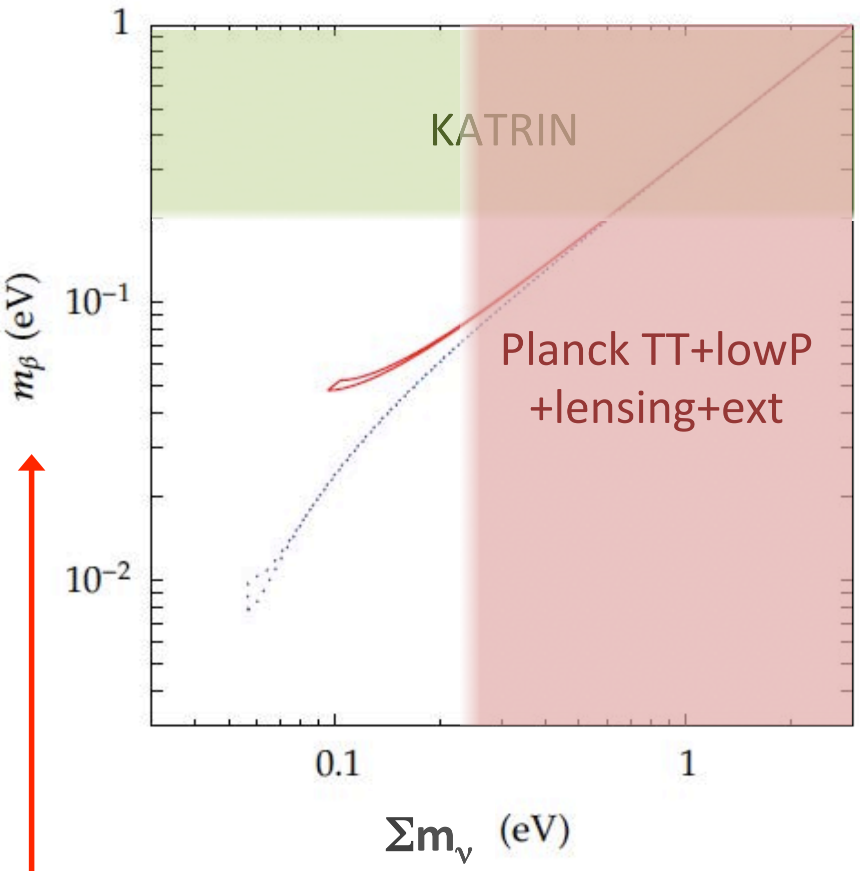
$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

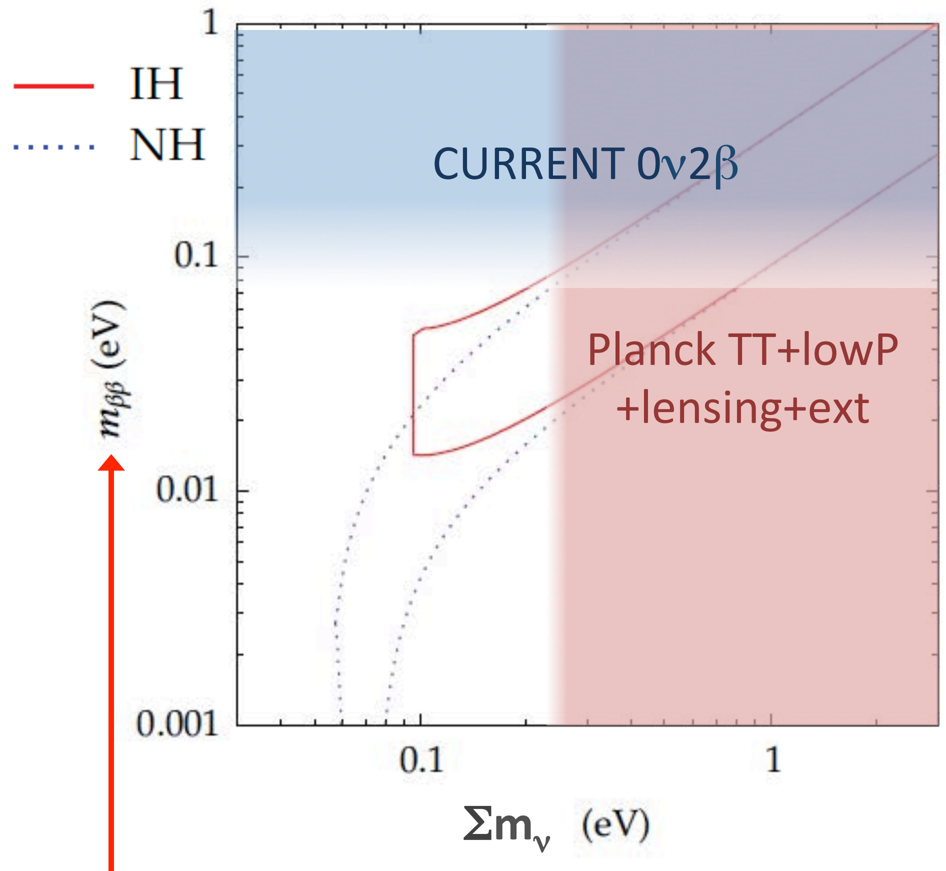
Neutrinoless double beta decay	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	$<$ 60-330 meV

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

Cosmology	$\sim \sum_i m_i$	$<$ 110-590 meV

Tritium β decay, 0ν2β and Cosmology



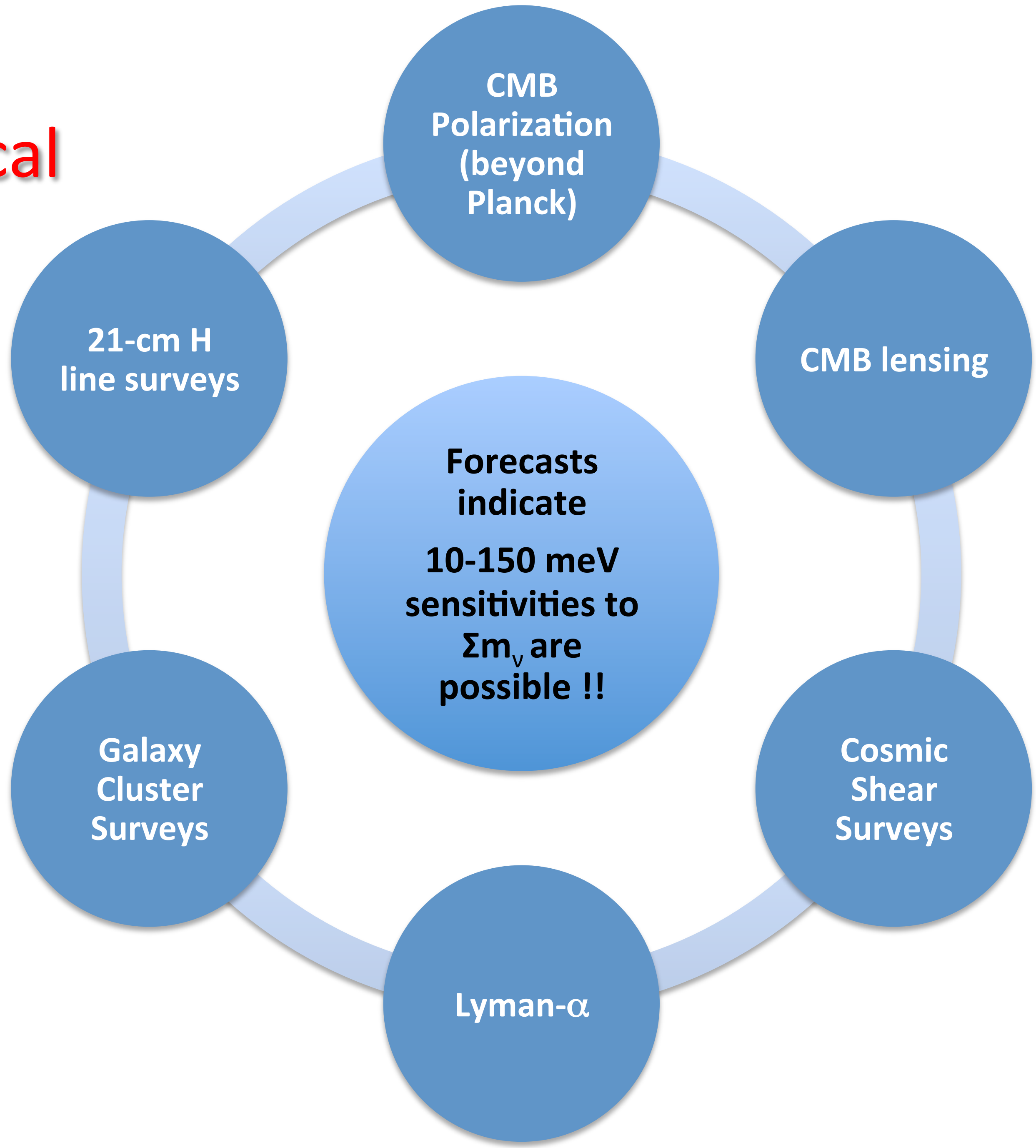


$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

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

Future sensitivities on neutrino physics from cosmology

Future cosmological data



End of 2nd lecture