Neutrinos in Cosmology

Olga Mena & Sergio Pastor
(IFIC Valencia)

Cosmology School in
the Canary Islands,
Fuerteventura, 18-22 Sep 2017

EXCELENCIA SEVERO OCHOA

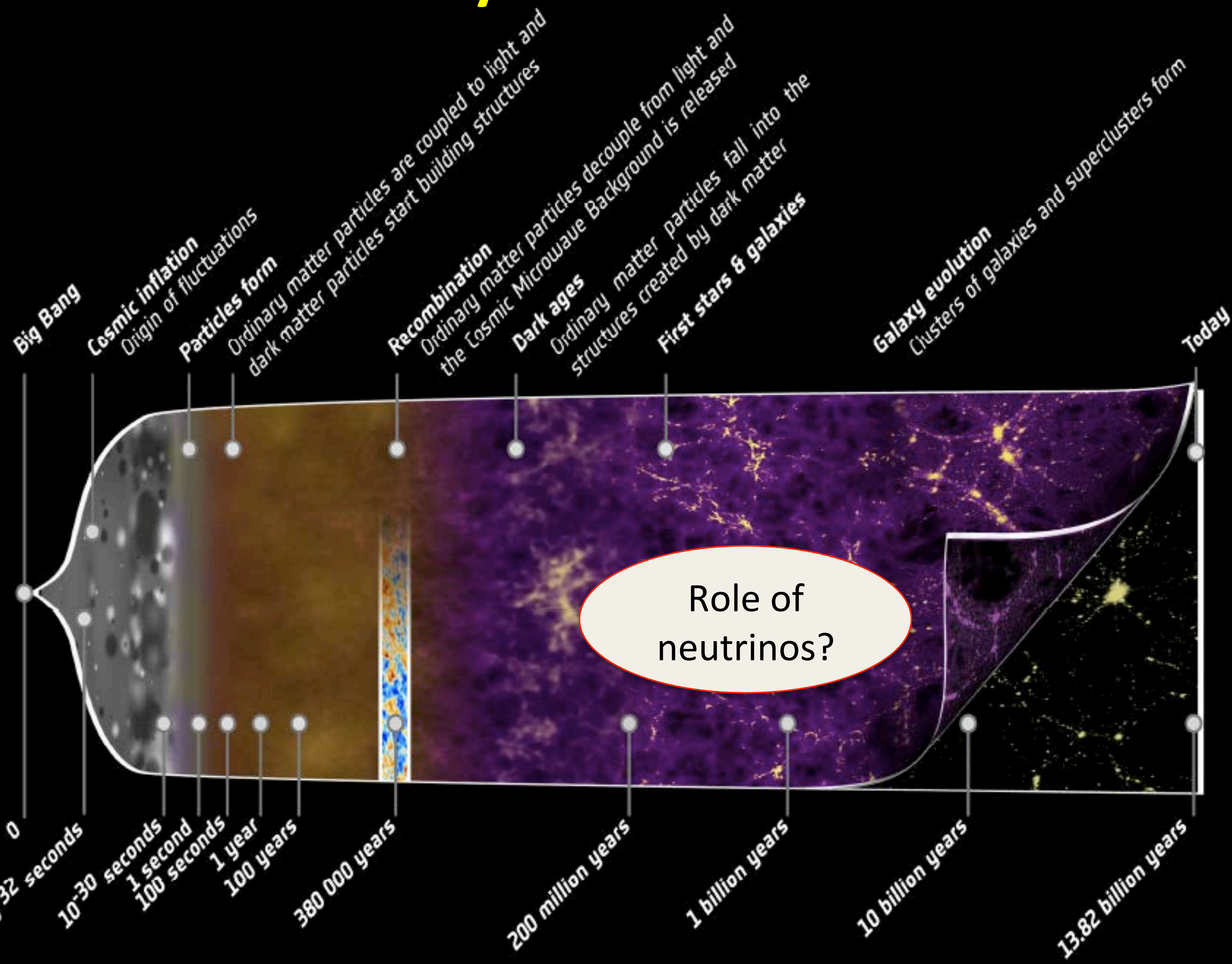
IFIC INSTITUT DE FÍSICA CORPUSCULAR

ASTROPARTICLES Astroparticles and High Energy Physics Group

VNIVERSITAT DE VALÈNCIA

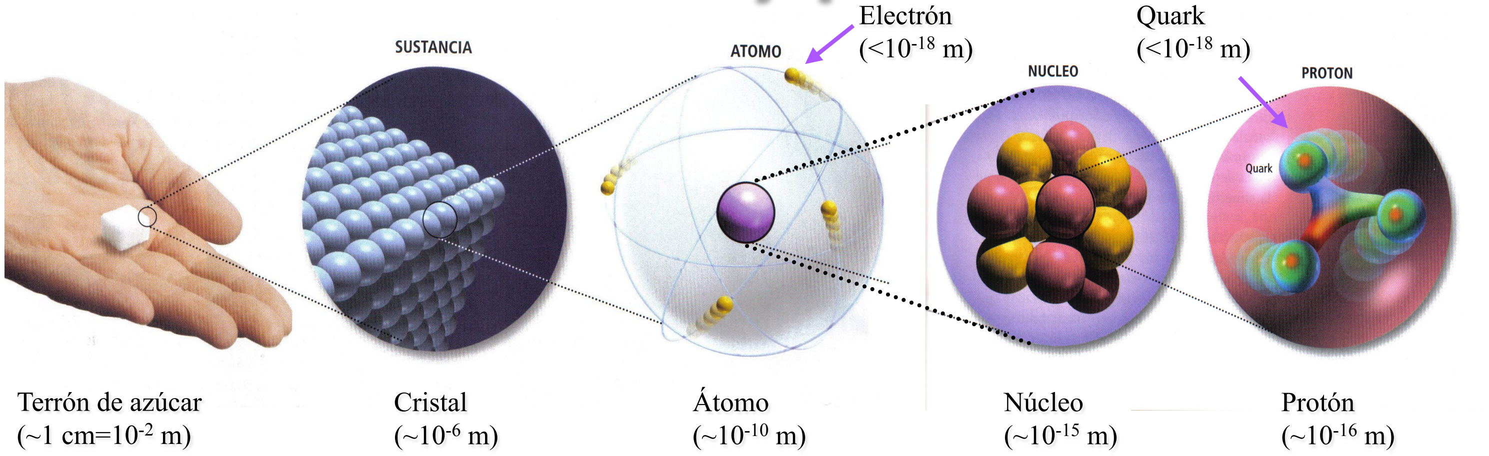
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

History of the Universe



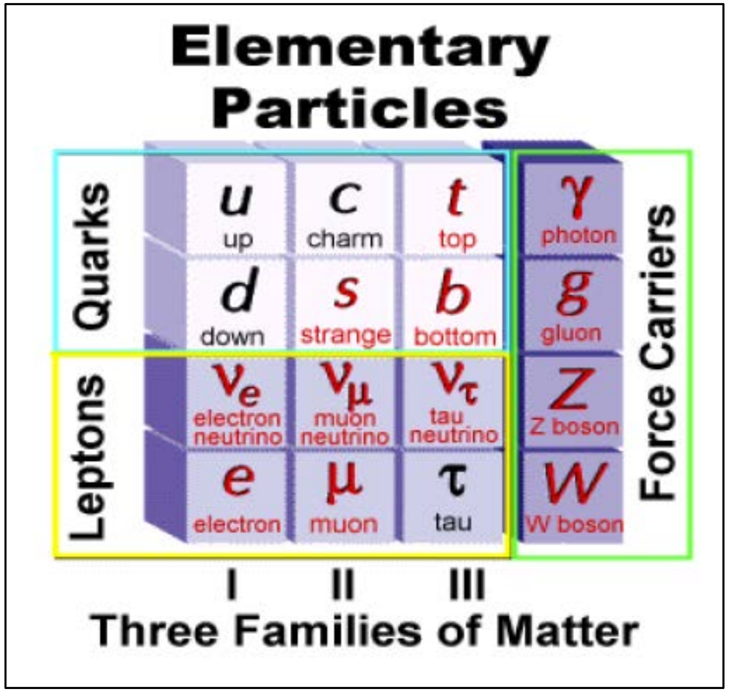
Prologue: the physics of (massive) neutrinos

Elementary particles



	Quarks		Leptons	
	Charge +2/3	Charge −1/3	Charge −1	Charge 0
1st Family	up u	down d	electron e	e-neutrino ν_e
2nd Family	charm c	strange s	muon μ	μ-neutrino ν_μ
3er Family	top t	bottom b	tau τ	τ-neutrino ν_τ
	Gravity			
	Weak interaction			
	Electromagnetism			
	Strong interaction			

Neutrinos in the Standard Model of particle physics



Each type (**flavour**) of neutrino is associated to a charged lepton

They belong to **SU(2) lepton doublets**

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

Neutrinos are only sensitive to the **weak force**

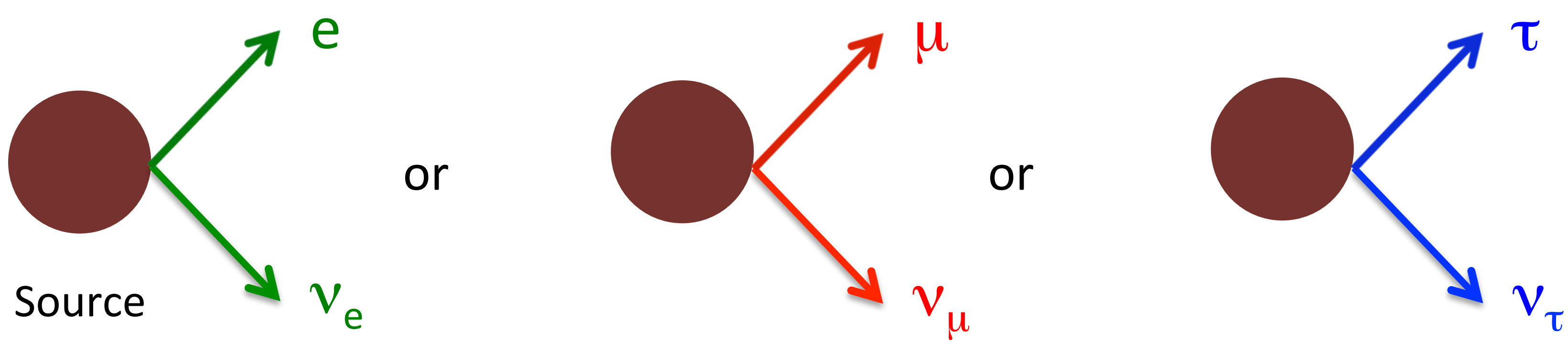
In the SM, there exist (e_R, μ_R, τ_R) but no SU(2) neutrino singlets

Neutrinos are **massless** in the SM

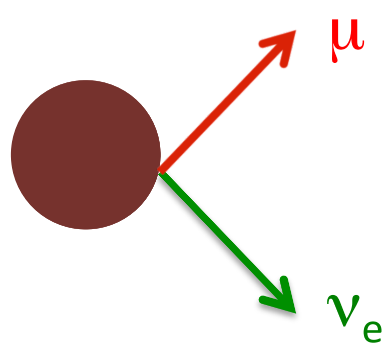
Weak interactions conserve flavour

Neutrinos are always produced together with an **associated charged lepton (e, μ, τ)**

FLAVOUR IS PRESERVED

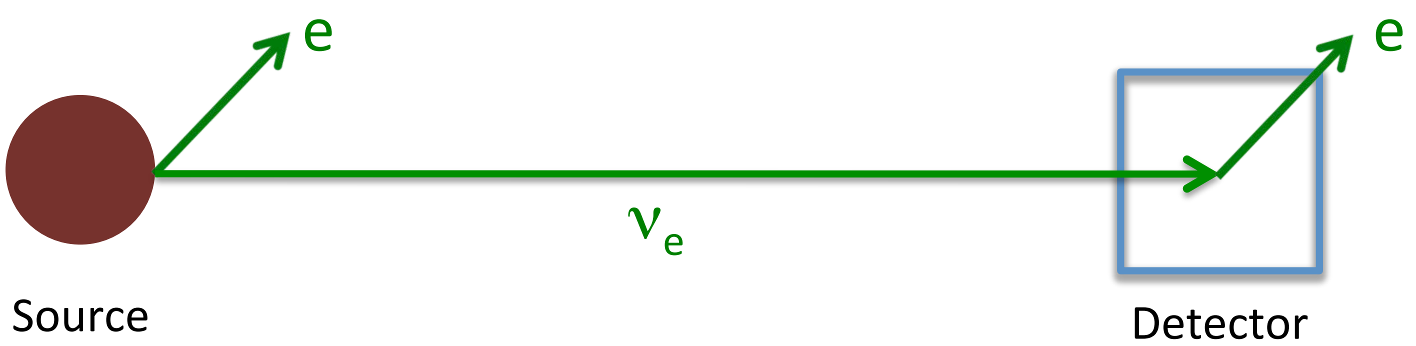


NEVER

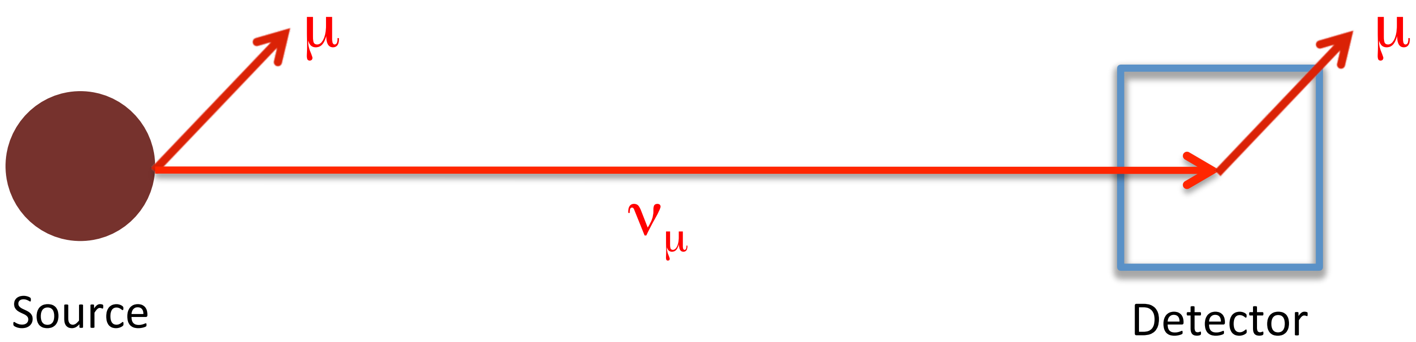


Production and detection of neutrinos

Neutrino detection at experiments is related to the corresponding **charged lepton**

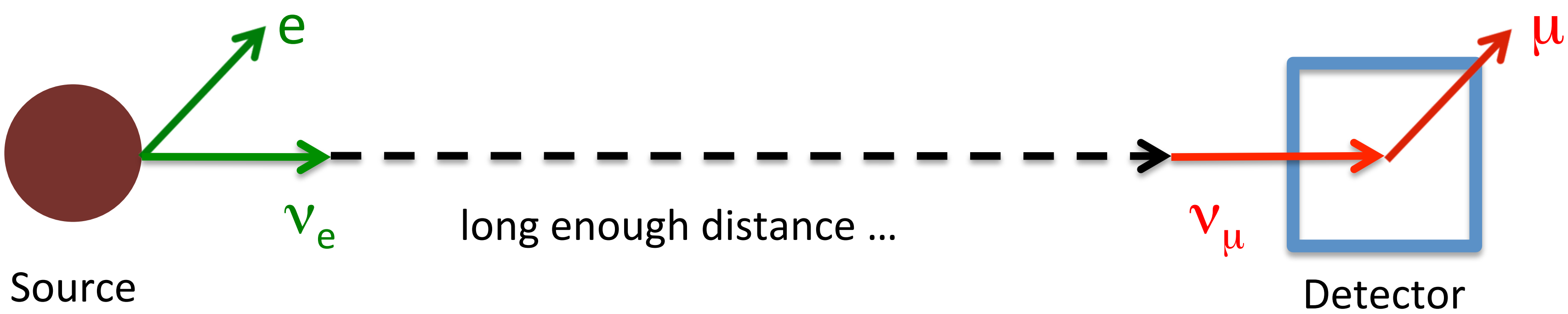


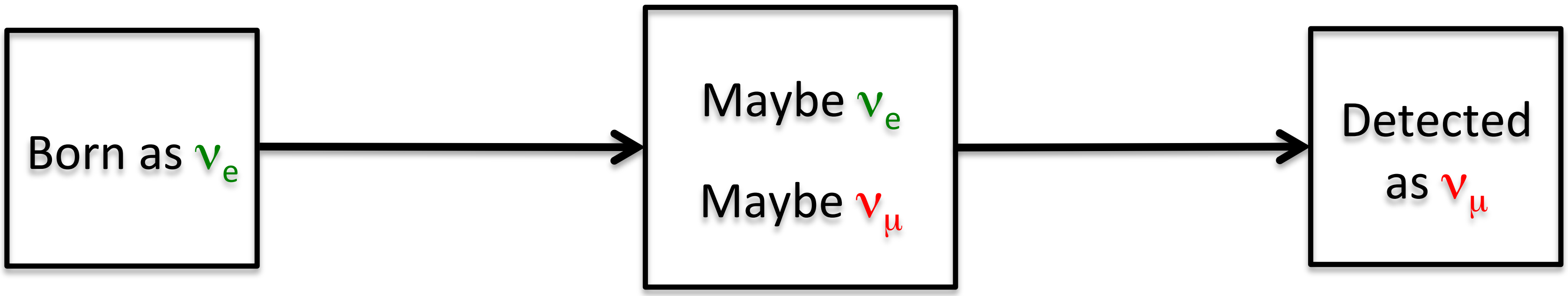
FLAVOURS DO NOT MIX



Flavour neutrino conversions?

Some experimental data can only be explained **if neutrinos change type** (flavour) during their propagation

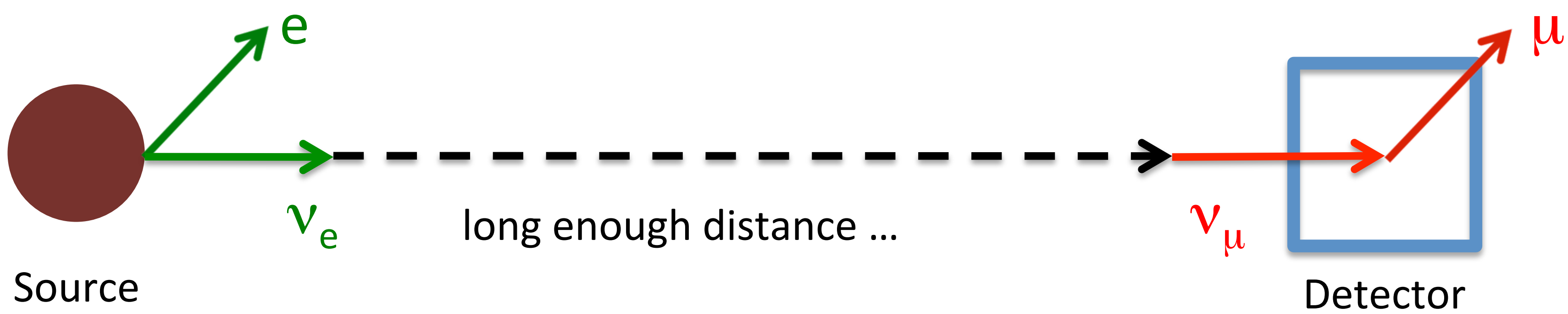


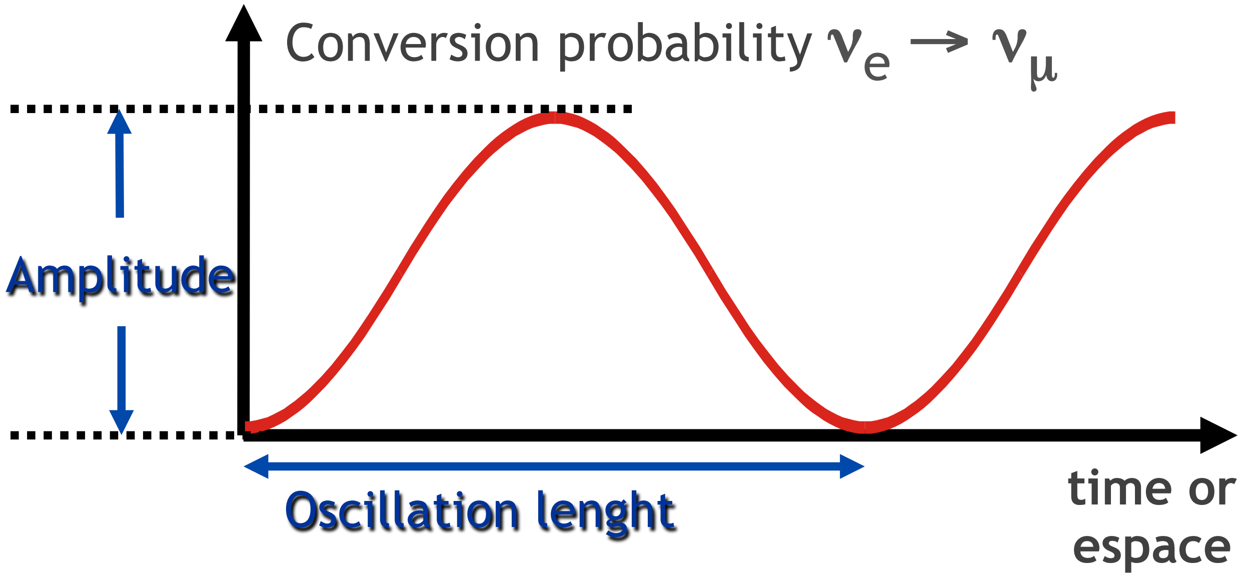


Flavour neutrinos are produced and detected, but mass eigenstates propagate (ν_1, ν_2)

Flavour neutrino conversions?

Some experimental data can only be explained **if neutrinos change type** (flavour) during their propagation

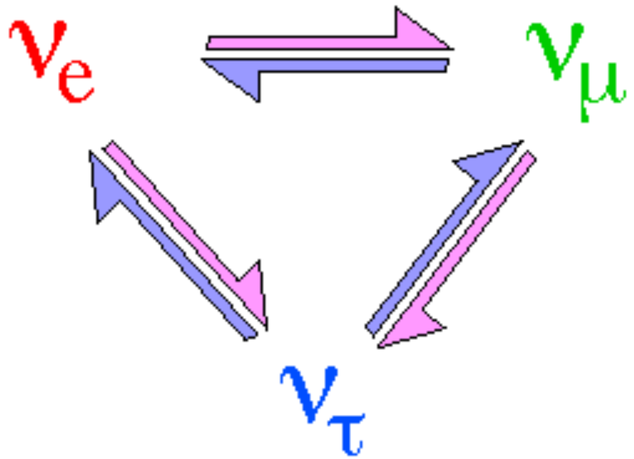




Bruno Pontecorvo (1913–1993)

We know that flavour neutrino oscillations exist

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



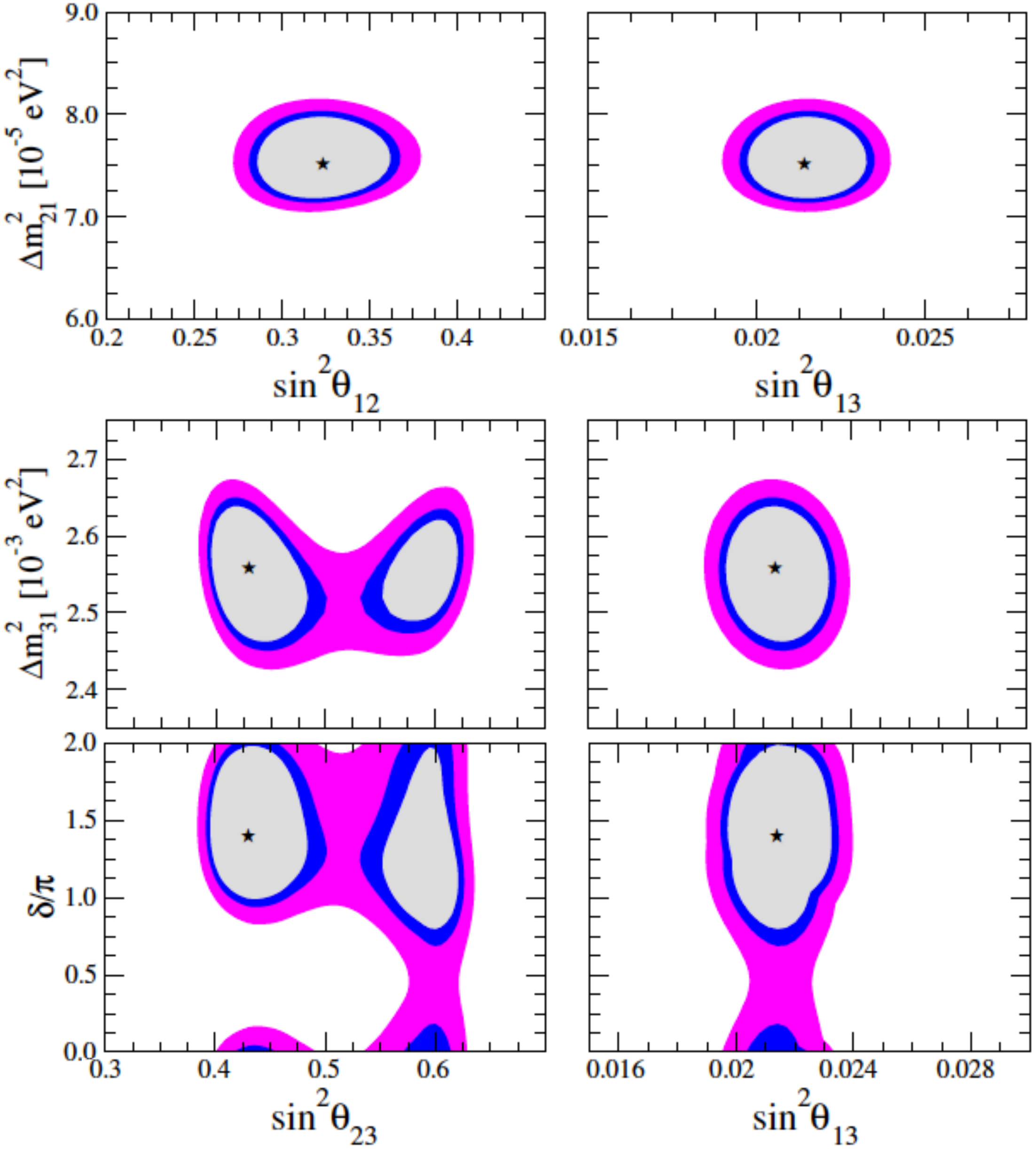
$$(e,\mu,\tau) \leftrightarrow (\nu_1,\nu_2,\nu_3)$$

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

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

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

de Salas et al, arXiv:1708.01186



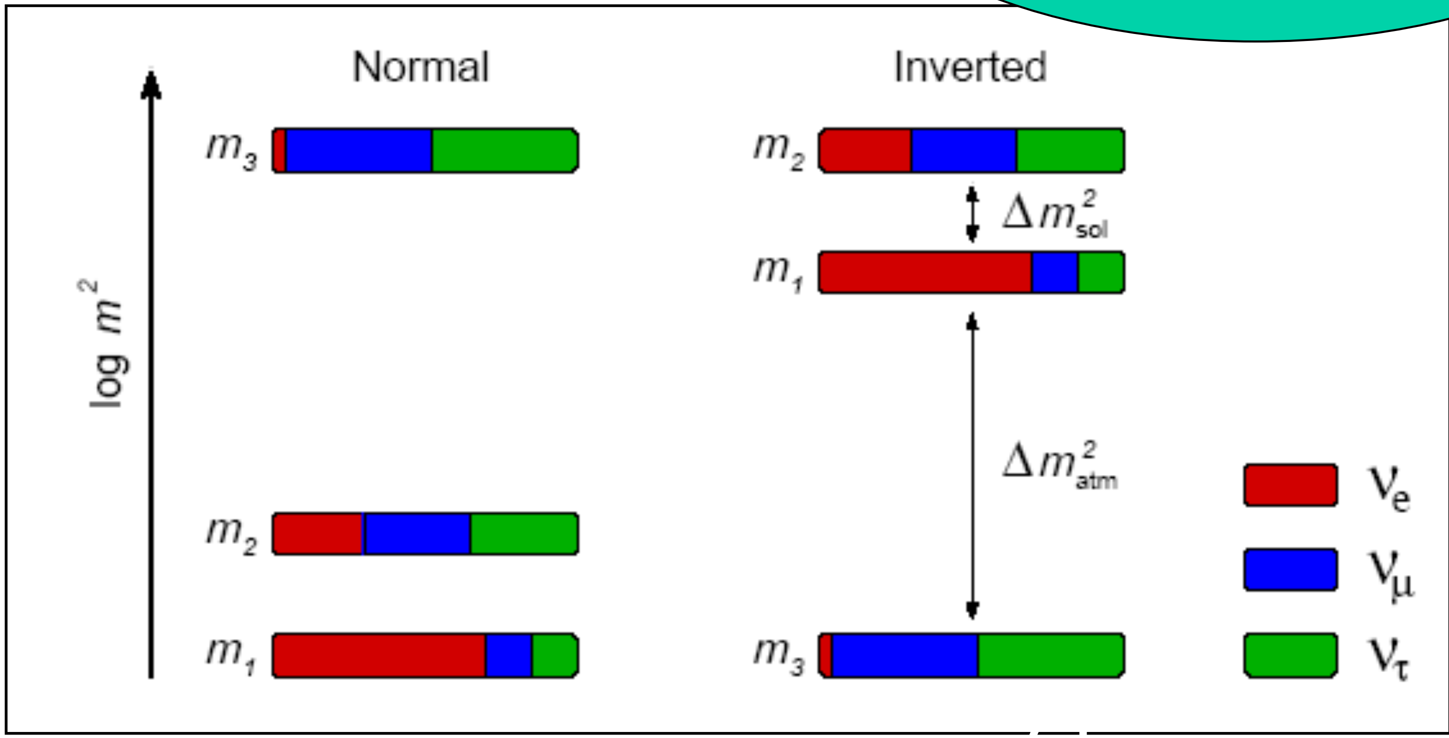
parameter	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NC	2.43–2.67
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO	2.37-2.61
$\sin^2\theta_{12}/10^{-1}$	2.73–3.79
$\theta_{12}/^\circ$	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	3.84–6.35
$\theta_{23}/^\circ$	38.3–52.8
$\sin^2\theta_{23}/10^{-1}$ (IO)	3.88–6.38
$\theta_{23}/^\circ$	38.5–53.0
$\sin^2\theta_{13}/10^{-2}$ (NO)	1.89–2.39
$\theta_{13}/^\circ$	7.9–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	1.89–2.39
$\theta_{13}/^\circ$	7.9–8.9
δ/π (NO)	0.00–2.00
$\delta/^\circ$	0–360
δ/π (IO)	0.00–0.17 & 0.79–2.00
$\delta/^\circ$	0–31 & 142–360

see also Capozzi et al, PRD 95 (2017) 096014; Esteban et al, JHEP 01 (2017) 087

Neutrino masses

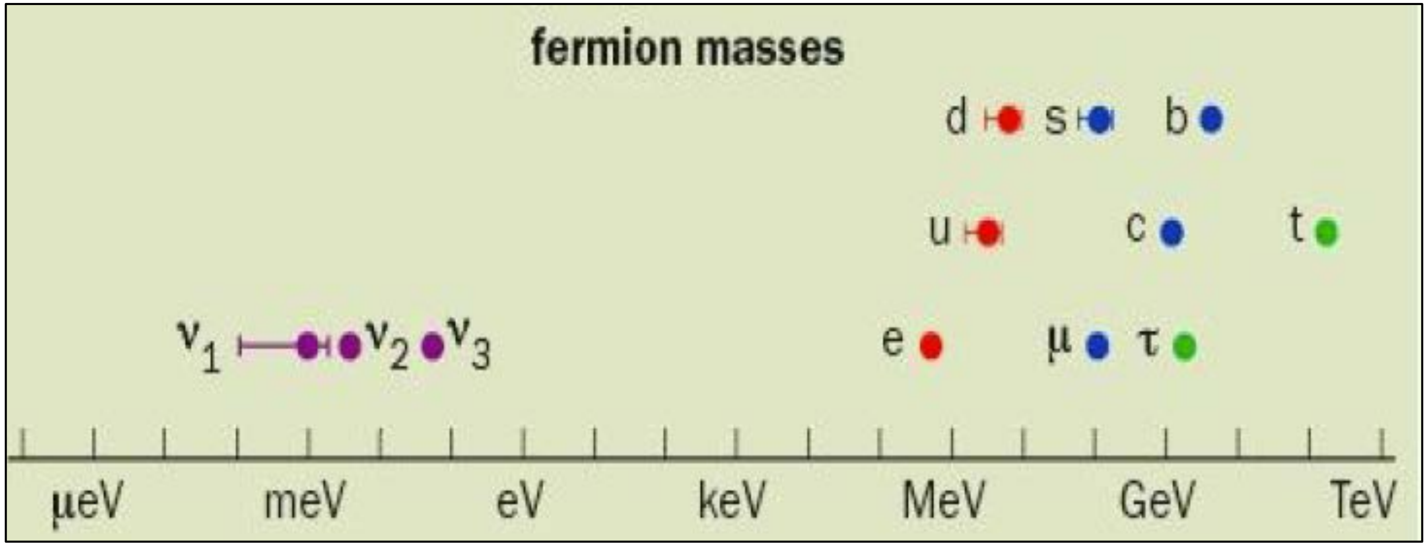
$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{iL}, \quad (\alpha = e, \mu, \tau)$$

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



Possible neutrino mass hierarchy patterns

Neutrino masses

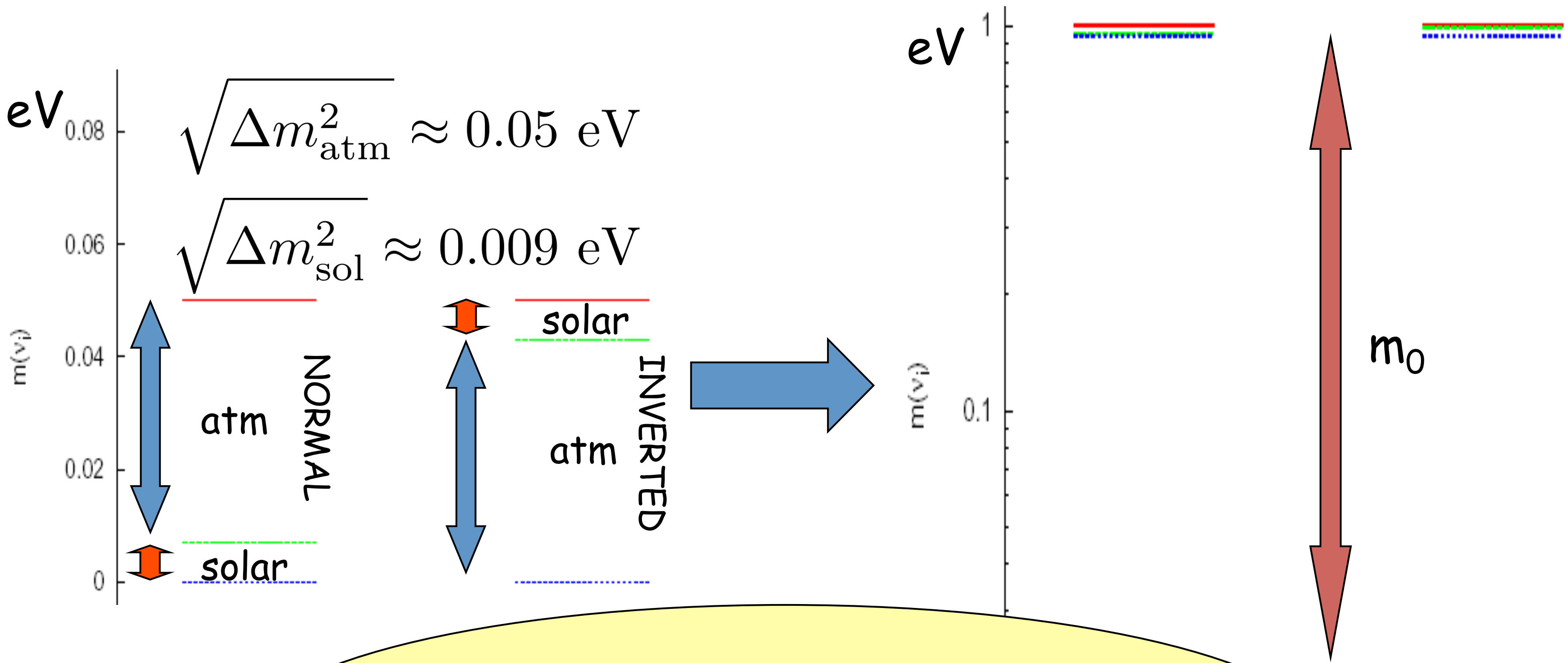


Neutrino masses (Dirac or Majorana):

$$m(\nu_i) \sim 10^{-3} - 1 \text{ eV}$$

Neutrino masses

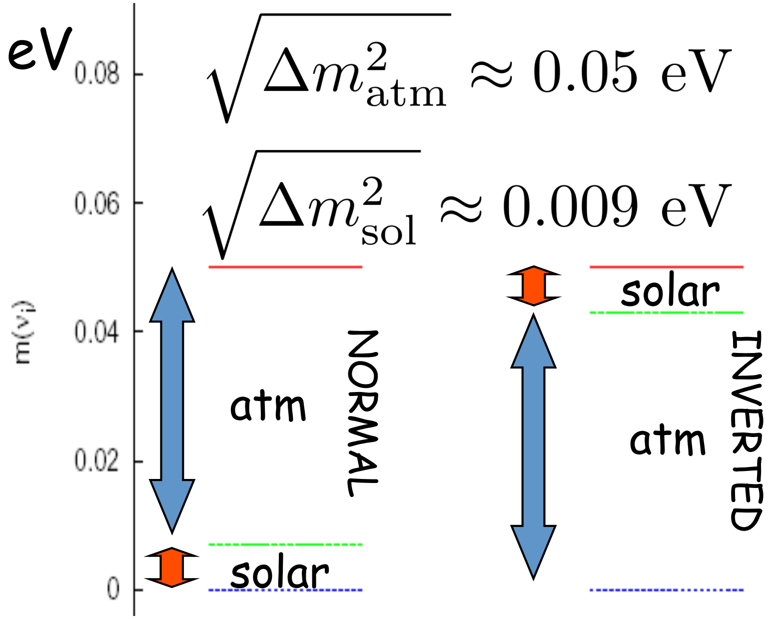
Data on flavour oscillations do not fix the absolute scale of neutrino masses

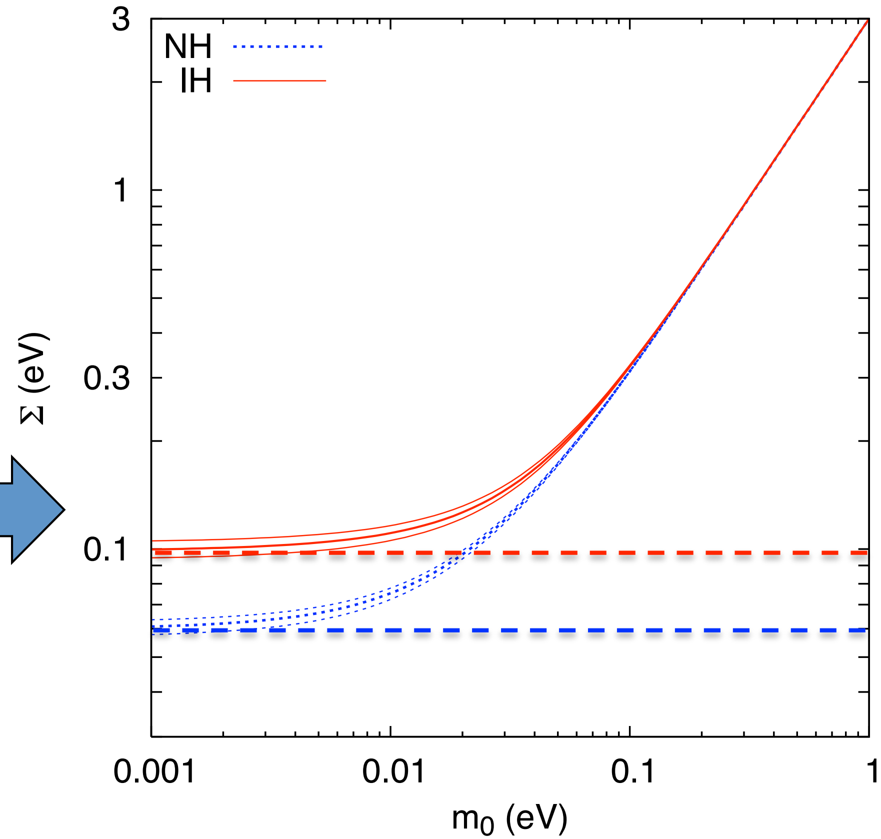


What is the value of m_0 ?

Neutrino masses

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

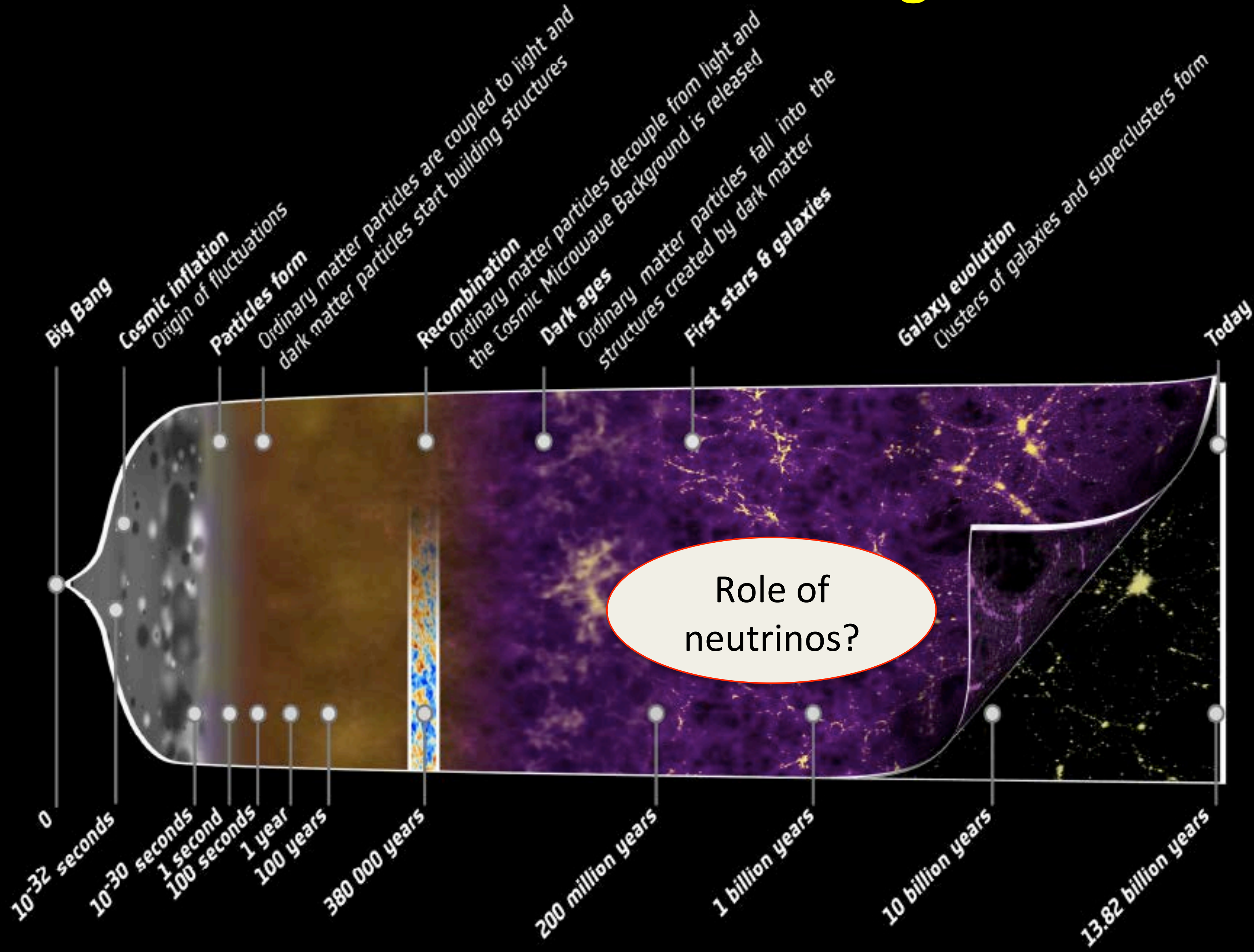




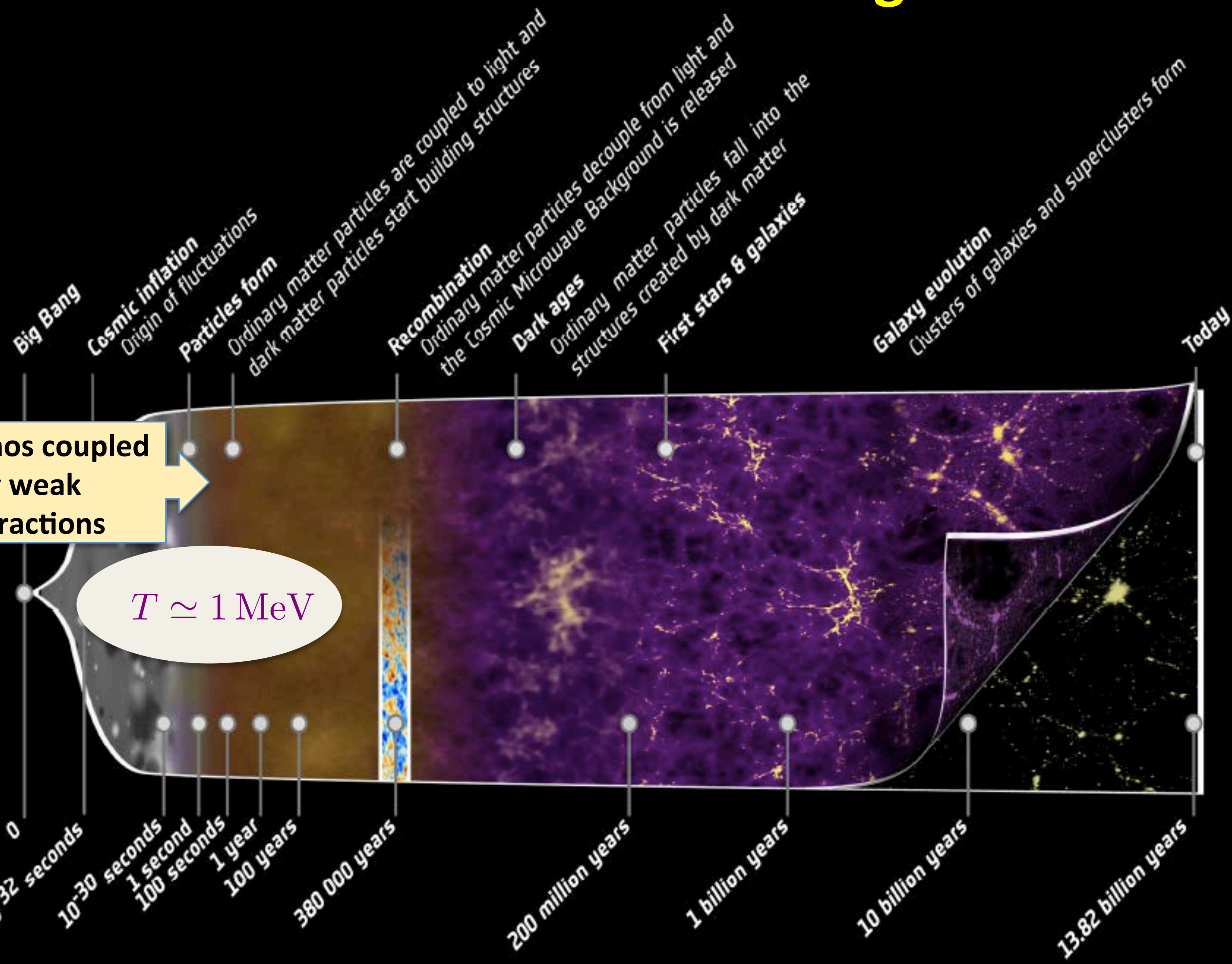
$$0.06(0.1)\,\mathrm{eV} \lesssim \sum_i m_i \lesssim 6\,\mathrm{eV}$$

Introduction: the Cosmic Neutrino Background

The Cosmic Neutrino Background



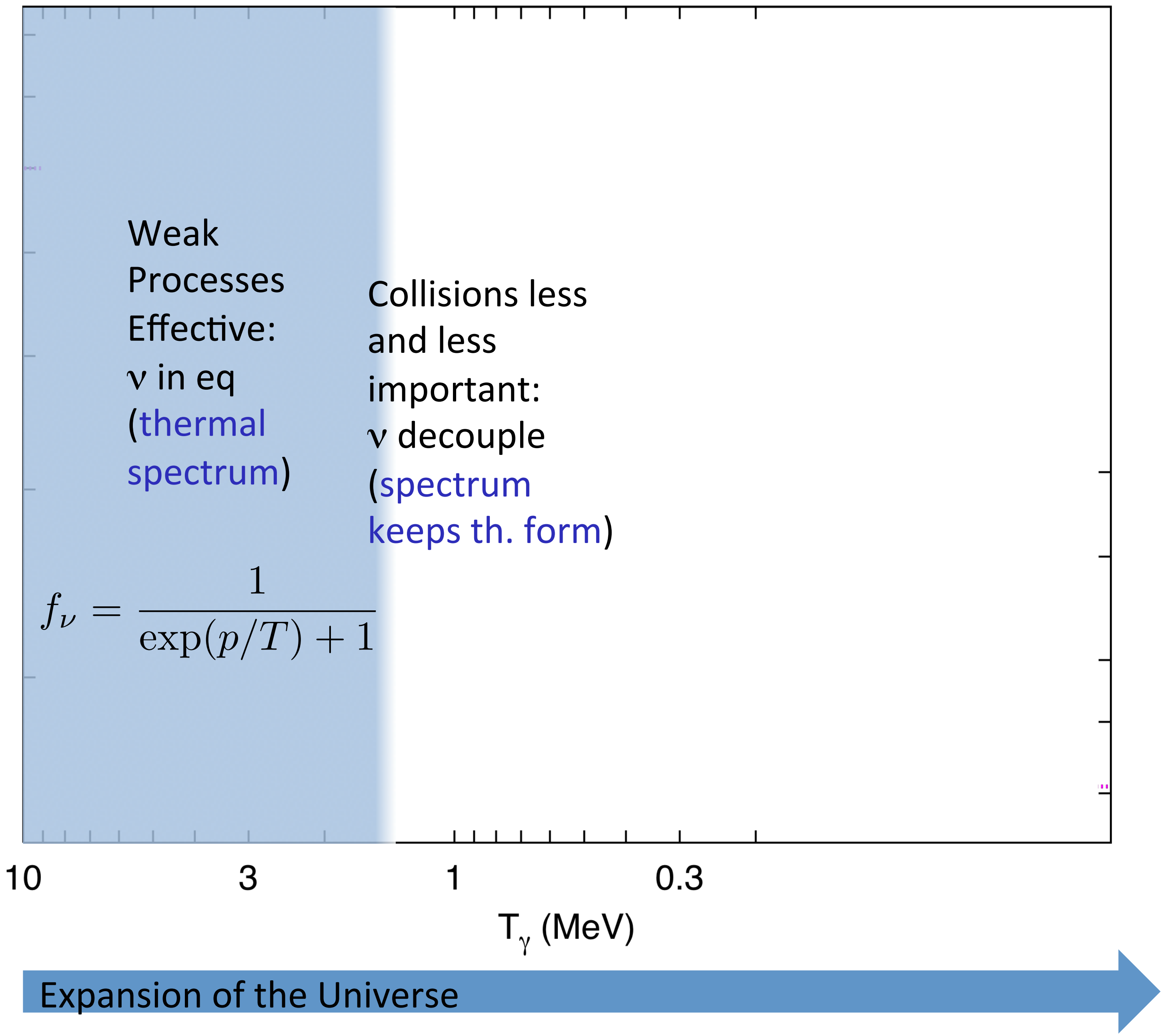
The Cosmic Neutrino Background



Neutrinos coupled by weak interactions

$T \simeq 1\,\mathrm{MeV}$

Neutrino decoupling



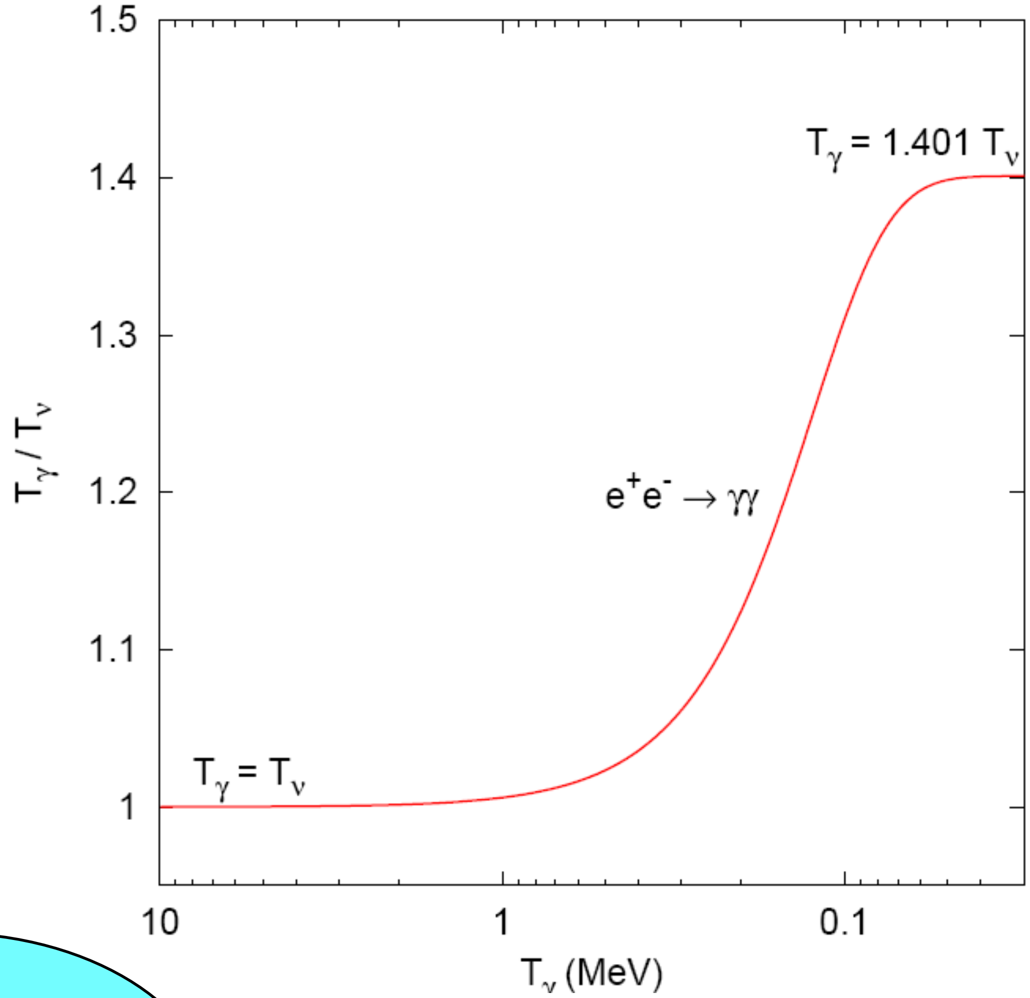
Neutrino and photon (CMB) temperatures

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

$$e^+e^- \to \gamma\gamma$$

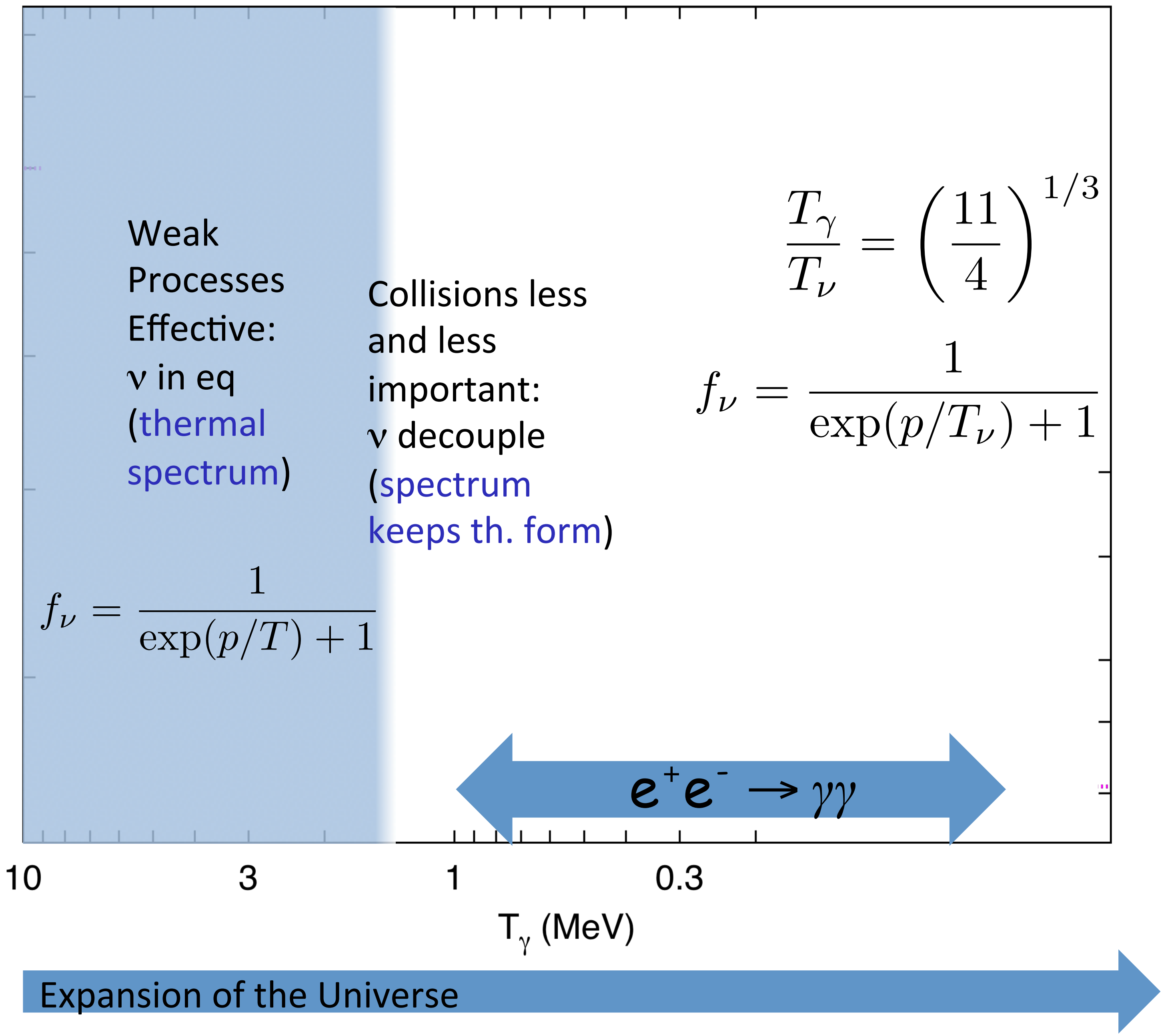
heating photons but not the decoupled neutrinos

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

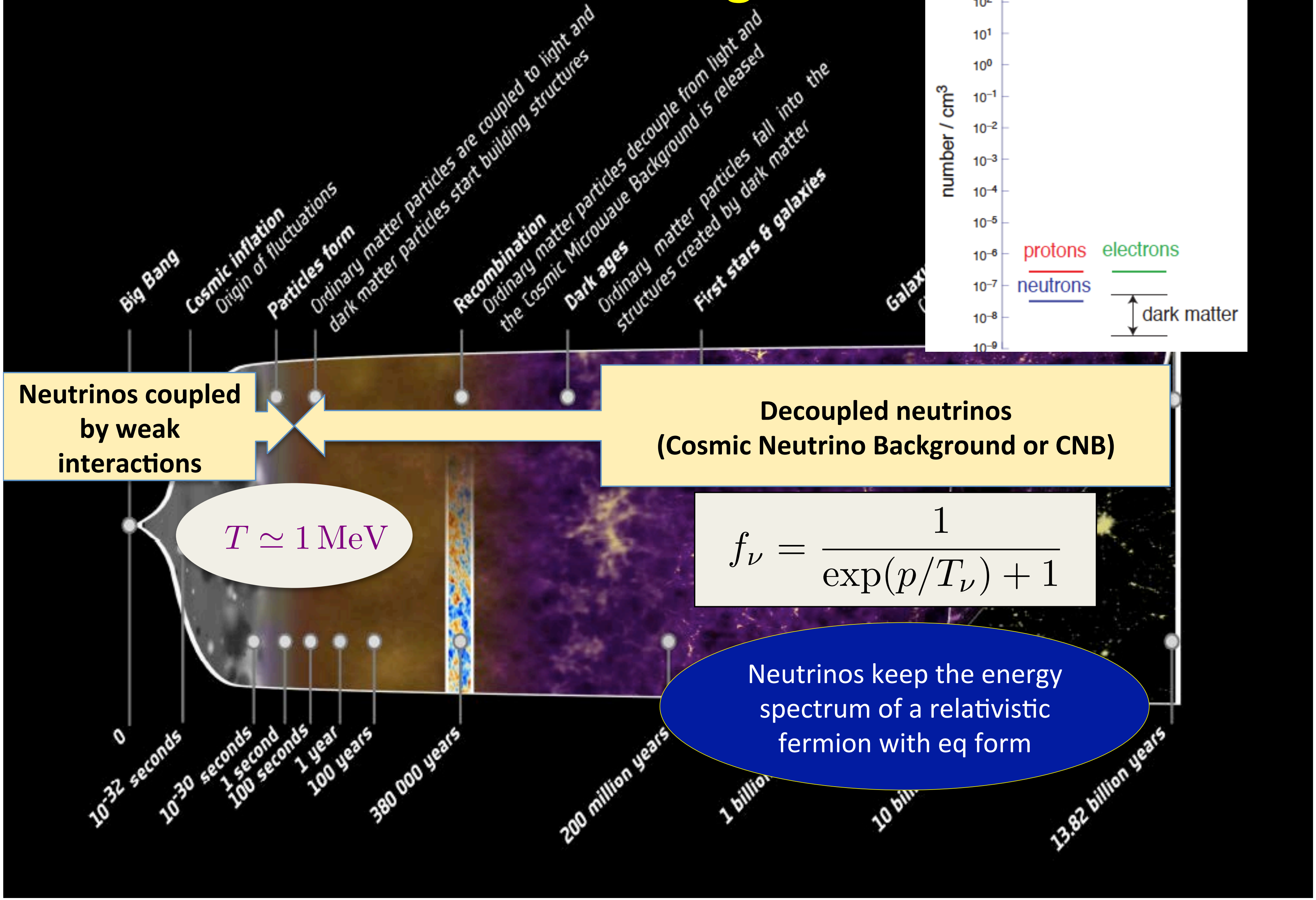


$$f_\nu(p,T) = \frac{1}{\exp(p/T_\nu)+1}$$

Neutrino decoupling and e$^{\pm}$ annihilations



The Cosmic Neutrino Background



Neutrinos coupled by weak interactions

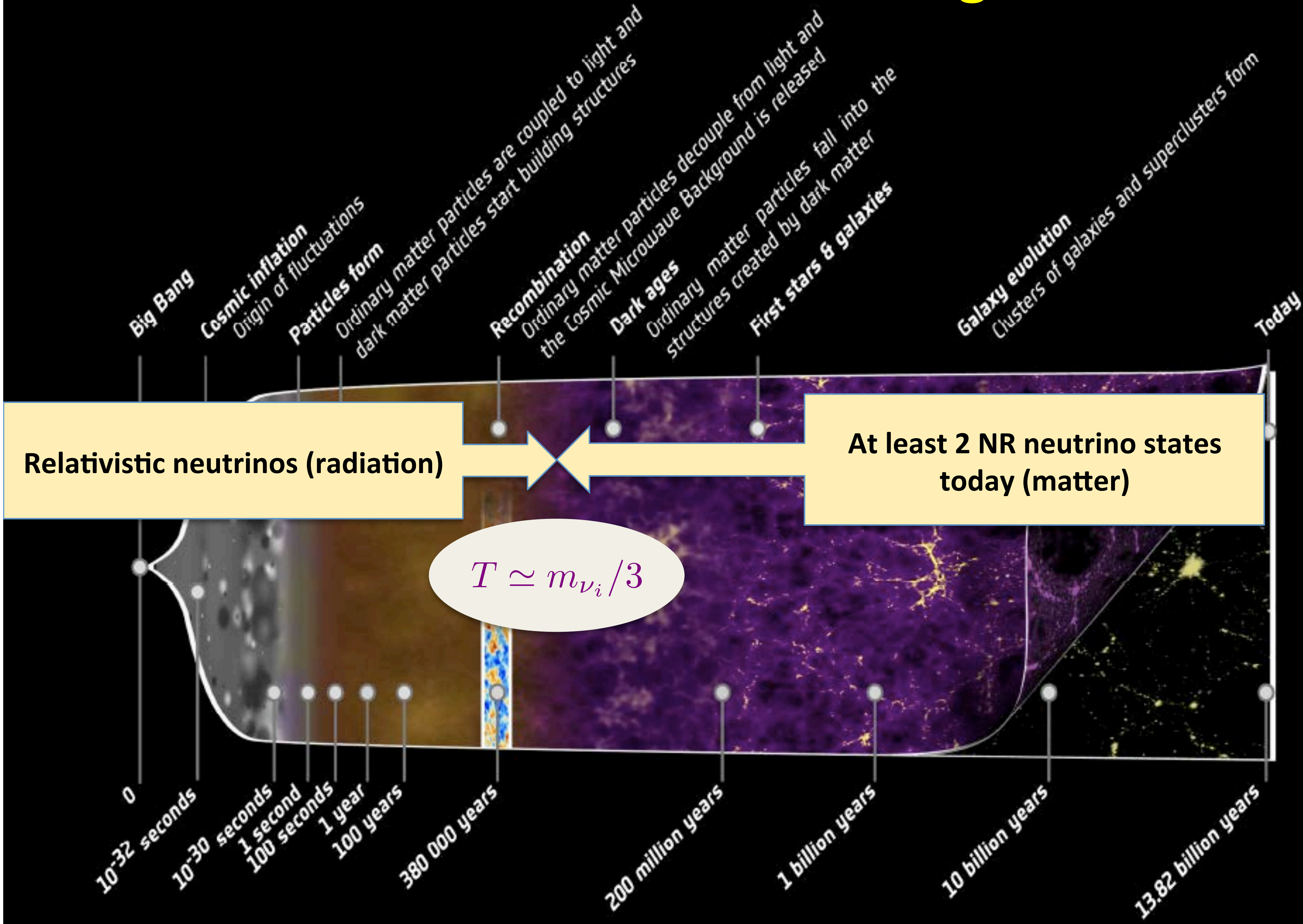
Decoupled neutrinos (Cosmic Neutrino Background or CNB)

$T \simeq 1\,\mathrm{MeV}$

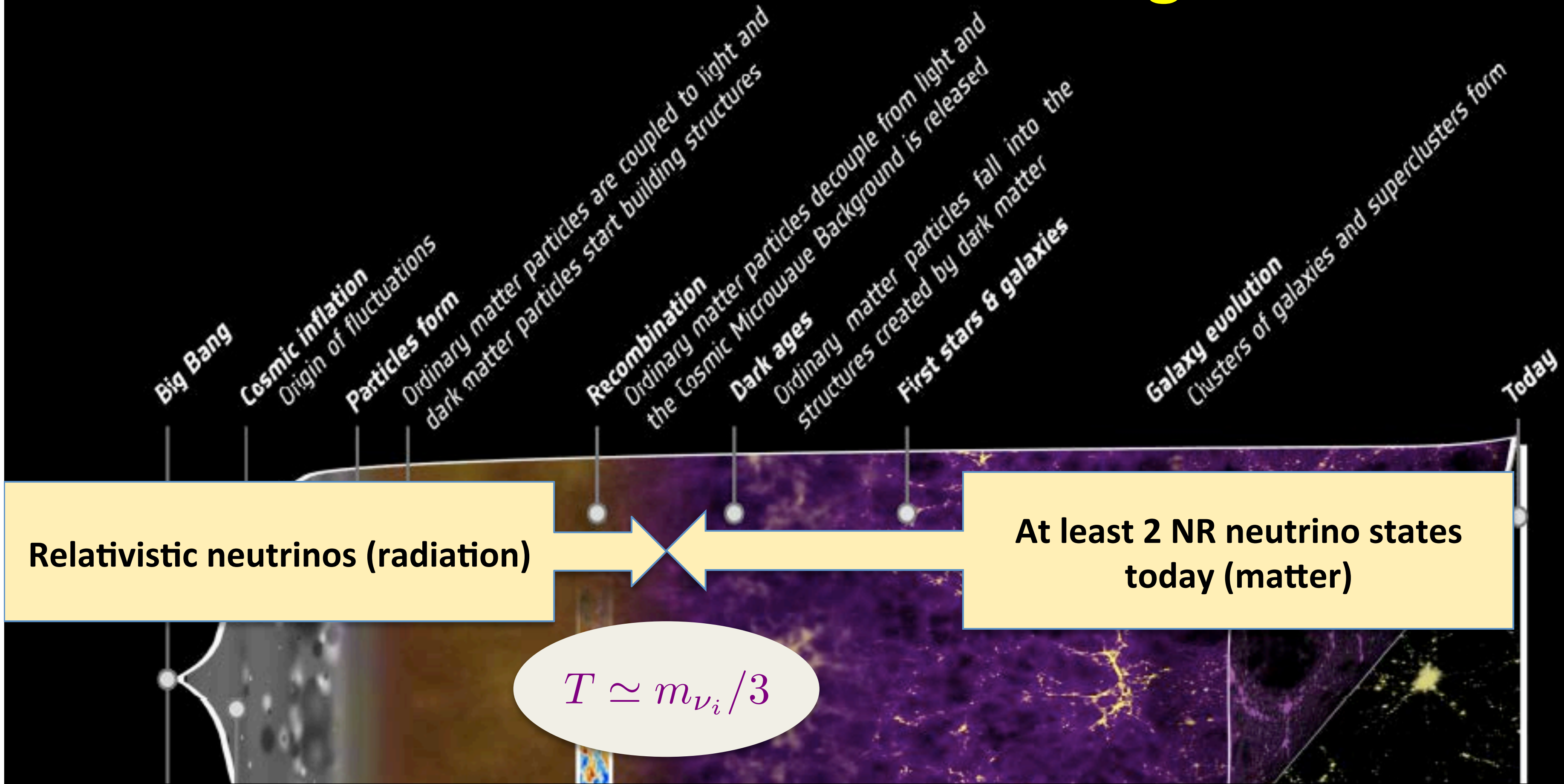
$$f_\nu = \frac{1}{\exp(p/T_\nu)+1}$$

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

The Cosmic Neutrino Background



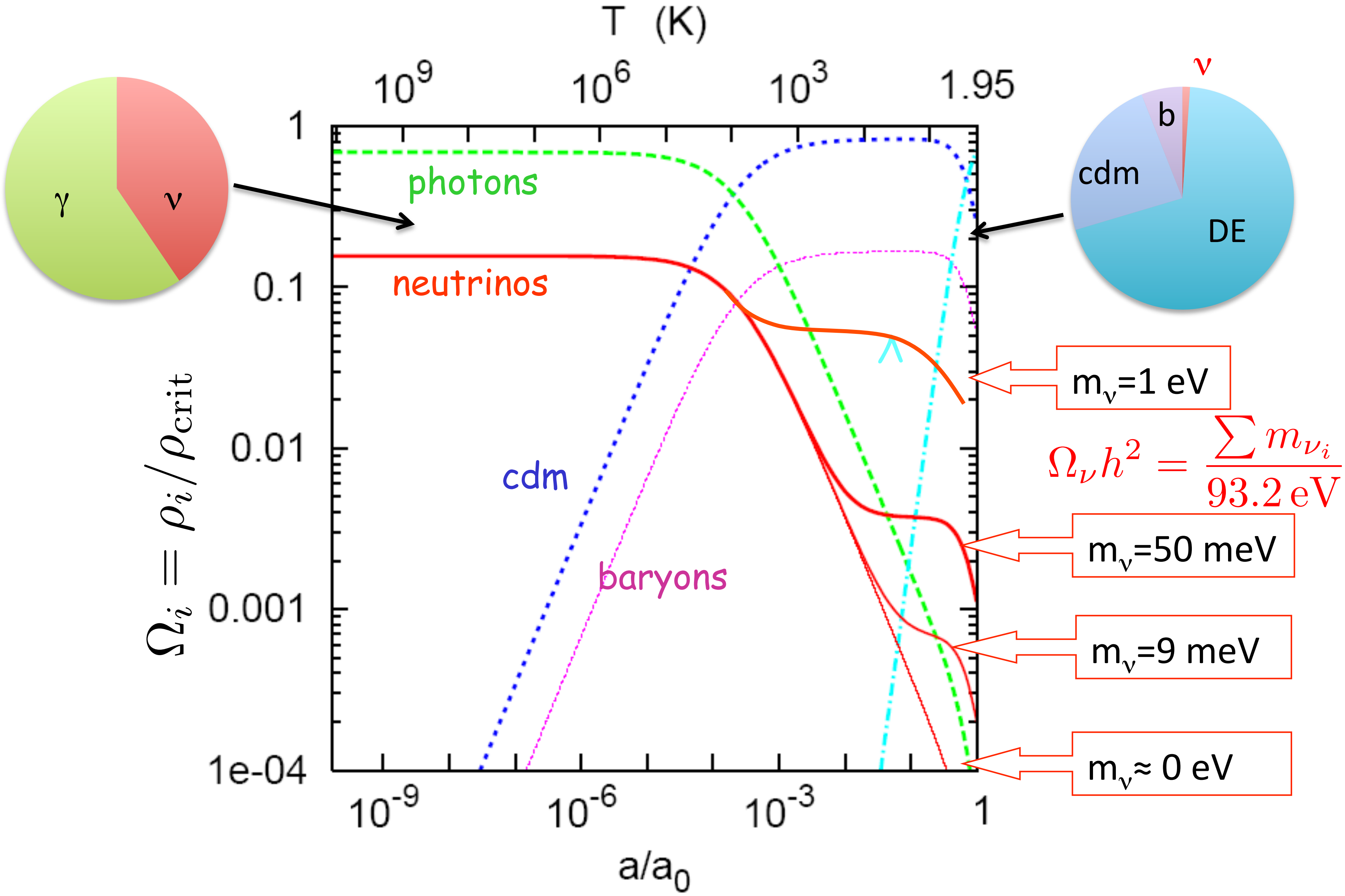
The Cosmic Neutrino Background



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

Background densities: 1 MeV → now



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

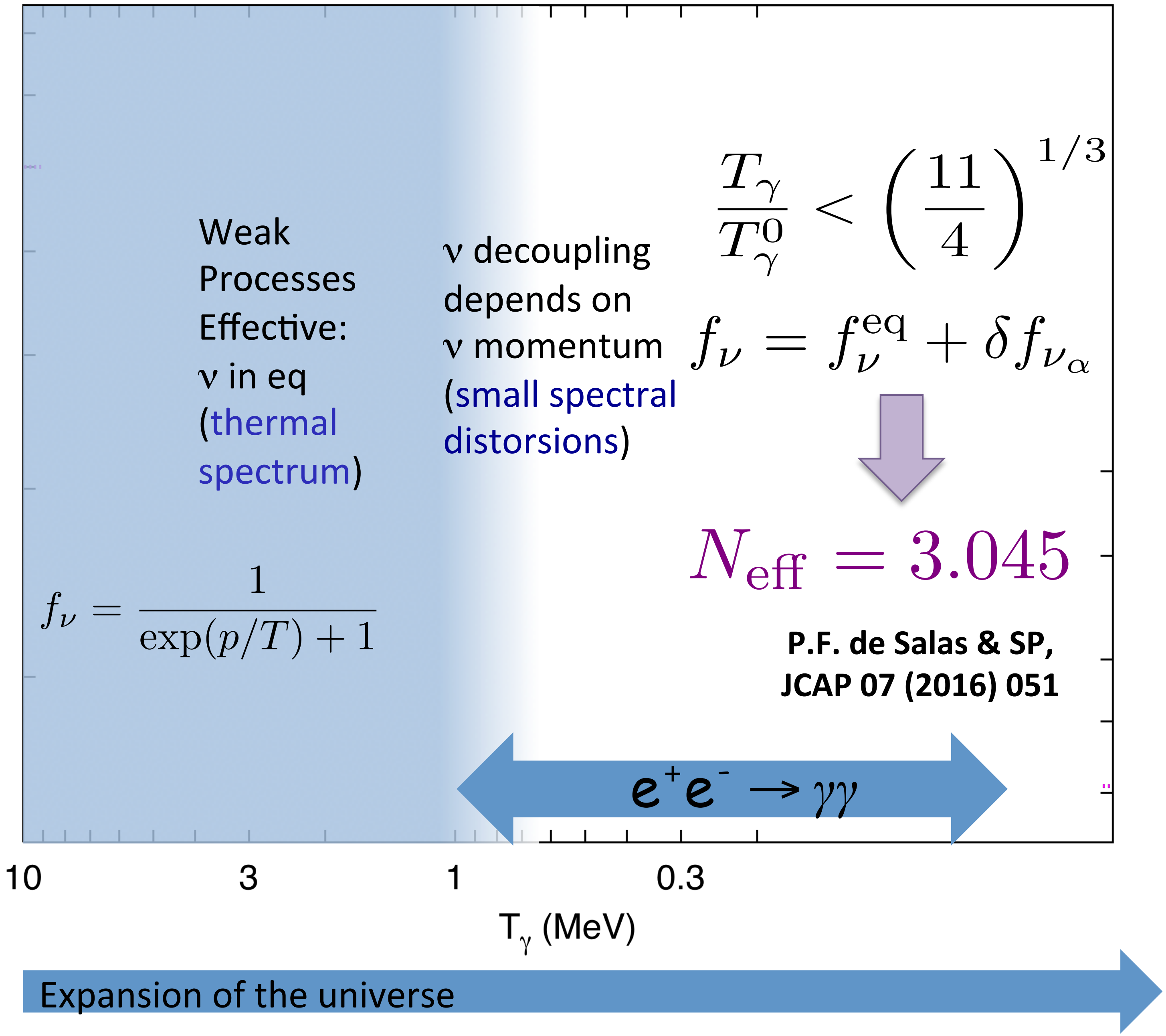
$N_{\rm eff}$ is a way to measure the ratio $\frac{\rho_\nu + \rho_x}{\rho_\gamma}$

- standard neutrinos only: $N_{\rm eff} \simeq 3$ (3.045)

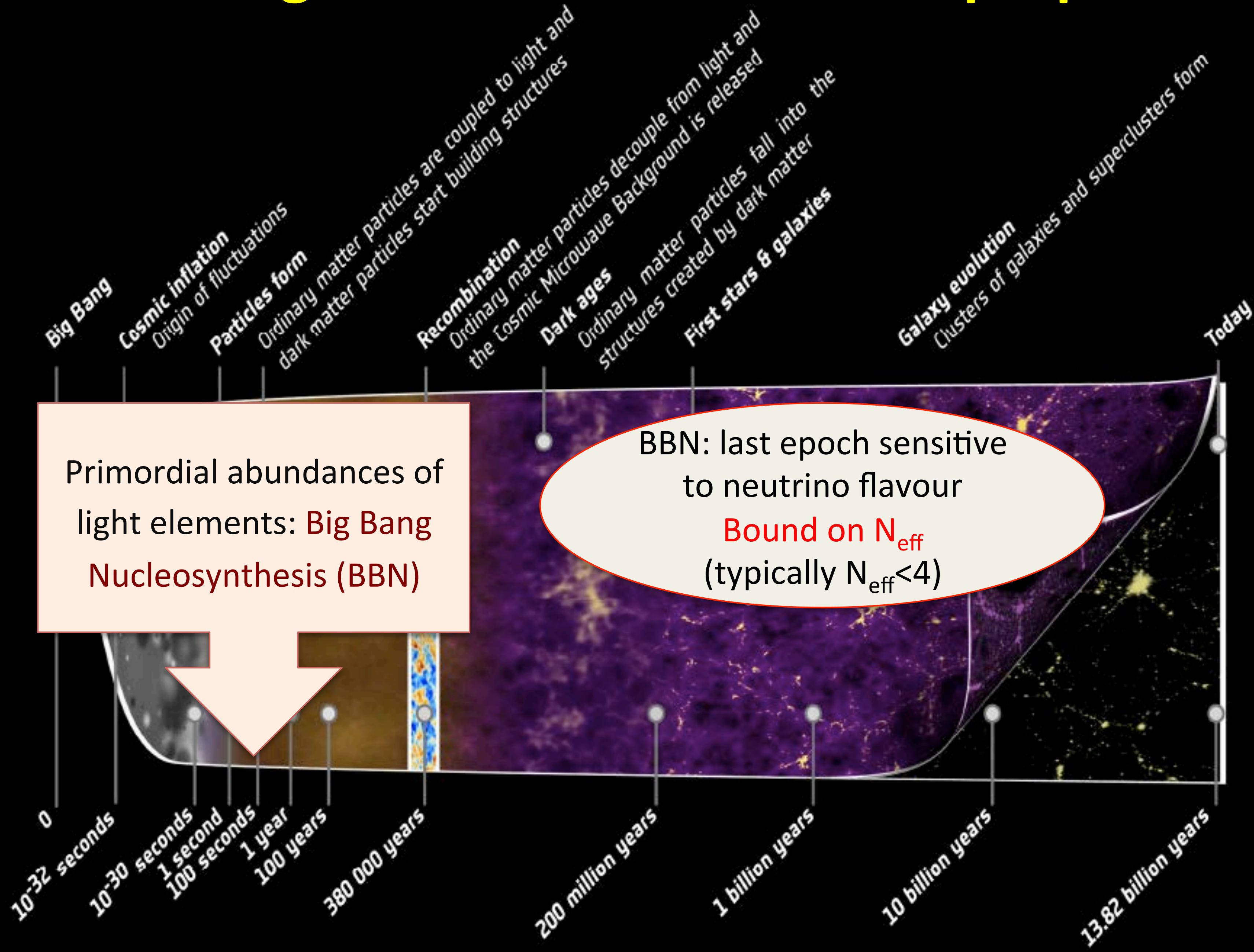
Bounds on $N_{\rm eff}$ from Primordial Nucleosynthesis and other cosmological observables (CMB+LSS)

- $N_{\rm eff} > 3$ (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,…)

$N_{eff} > 3$: small neutrino heating



Cosmological bounds on neutrino properties



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

BBN: last epoch sensitive to neutrino flavour

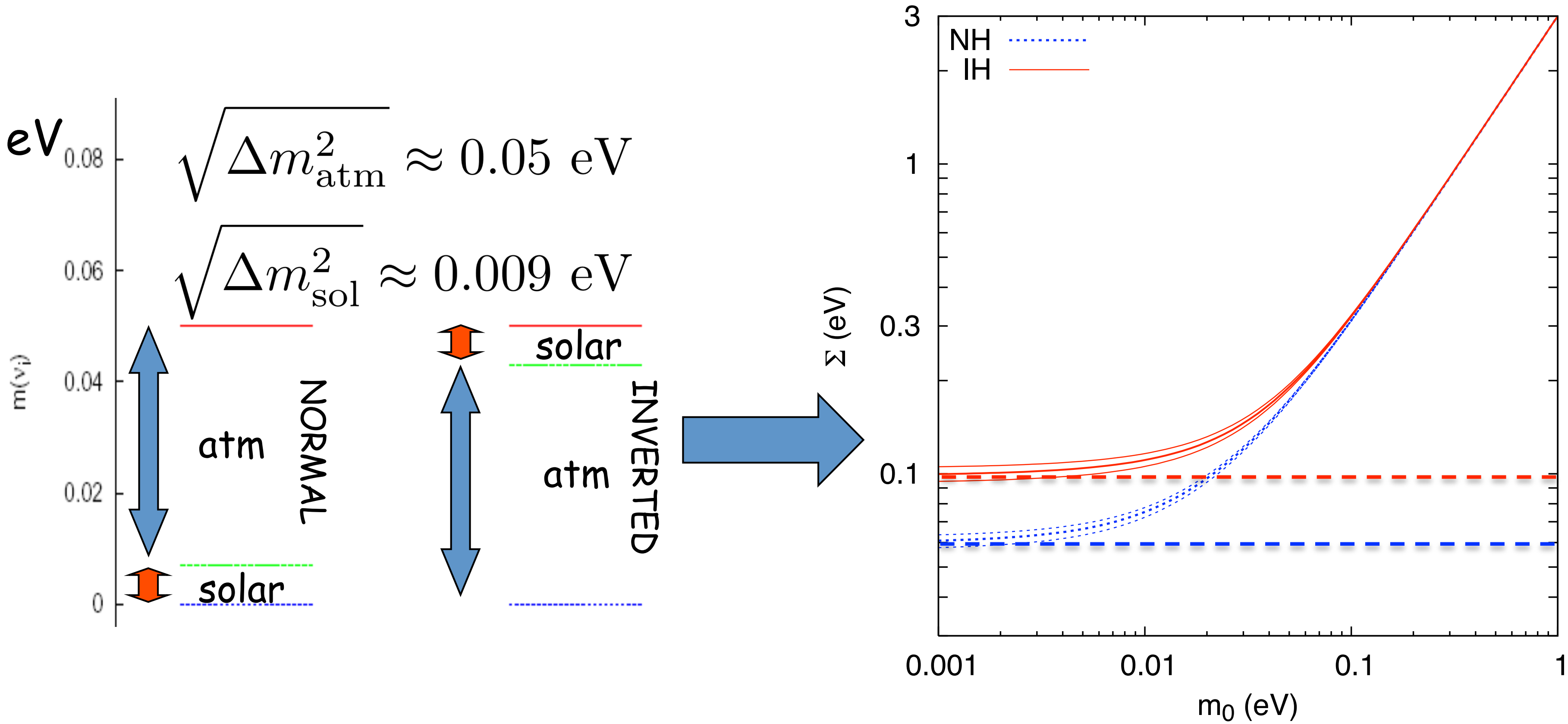
Bound on N_{eff}

(typically $N_{eff}<4$)

Neutrinos as Dark Matter

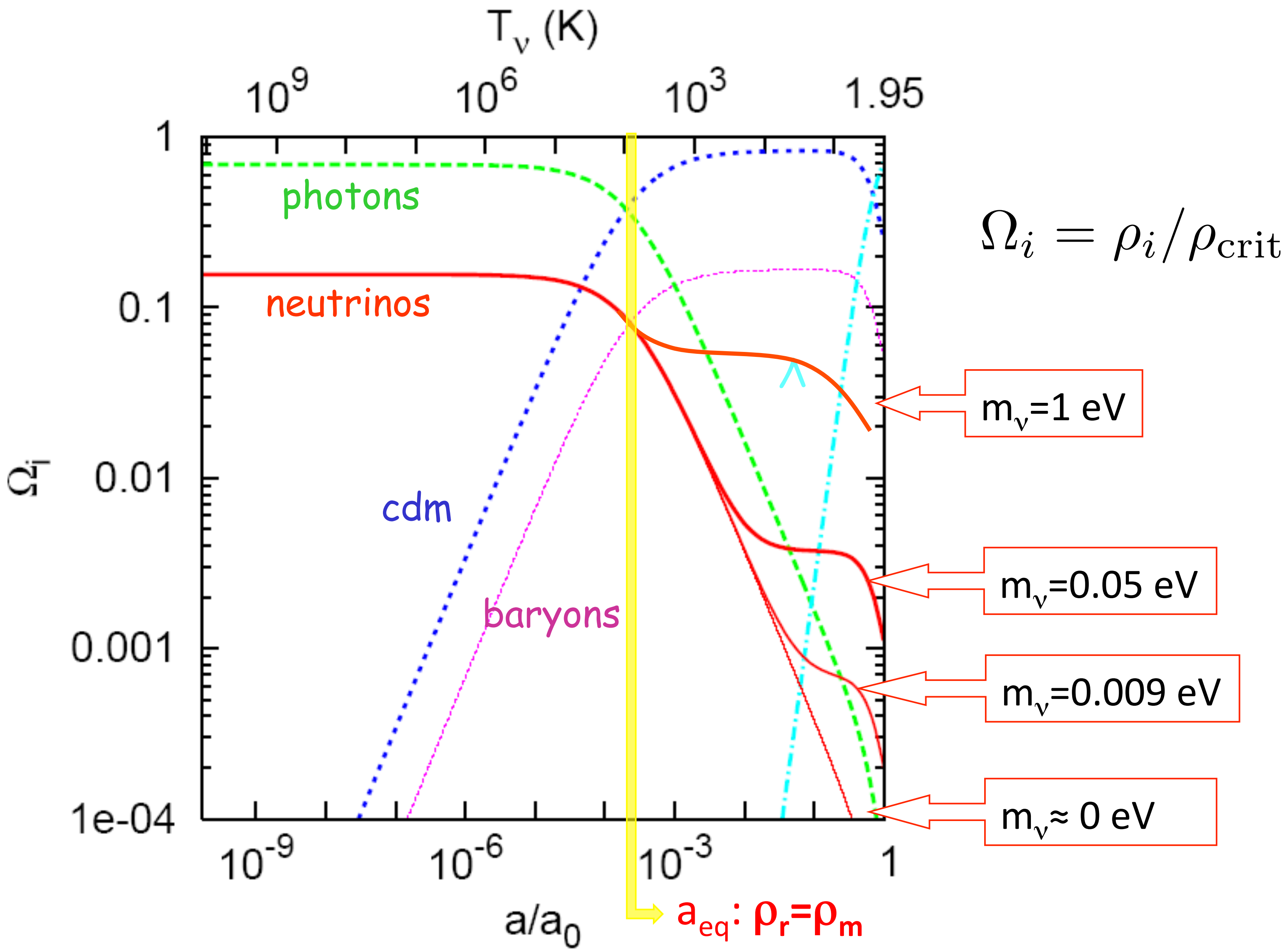
Neutrino masses

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



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

Evolution of the background densities: 1 MeV → now



Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

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

$$\Omega_\nu < \Omega_m \simeq 0.3 \to \sum_i m_i \lesssim 15\ \mathrm{eV}$$

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

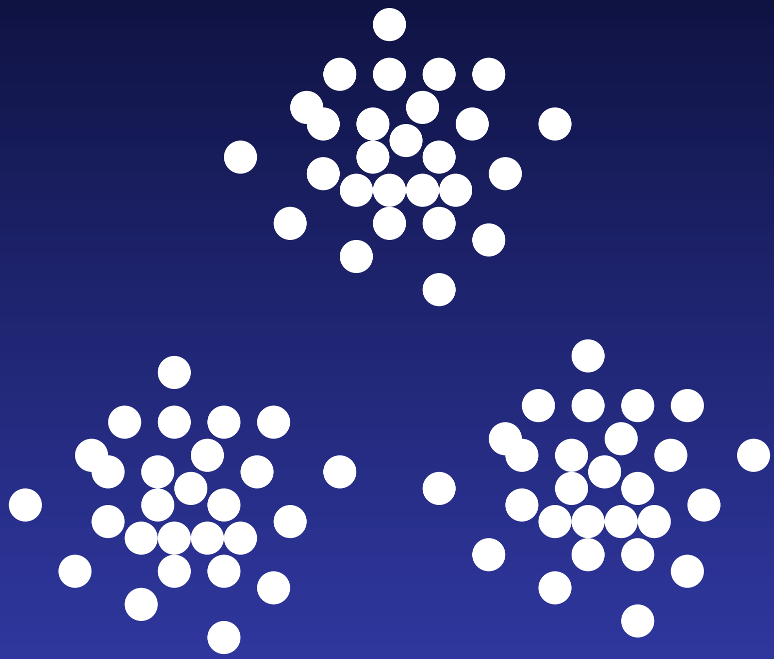
- First structures to be formed when Universe became matter –dominated are very large

- 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)

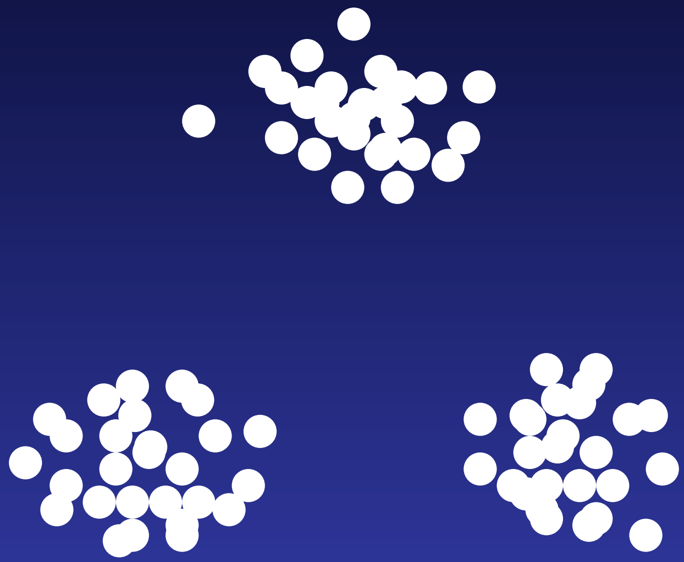
Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



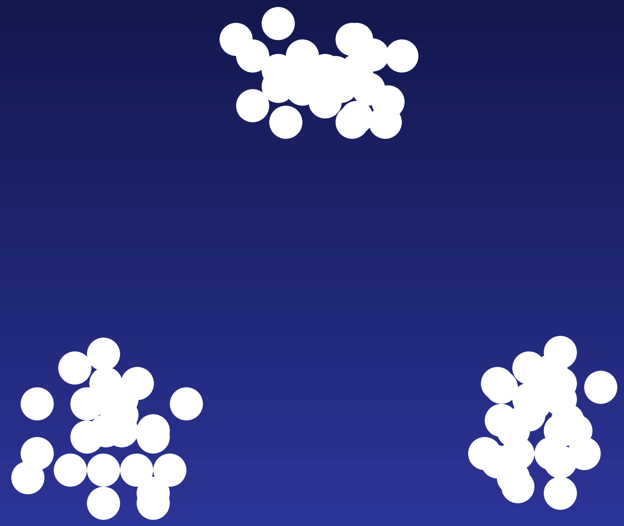
Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



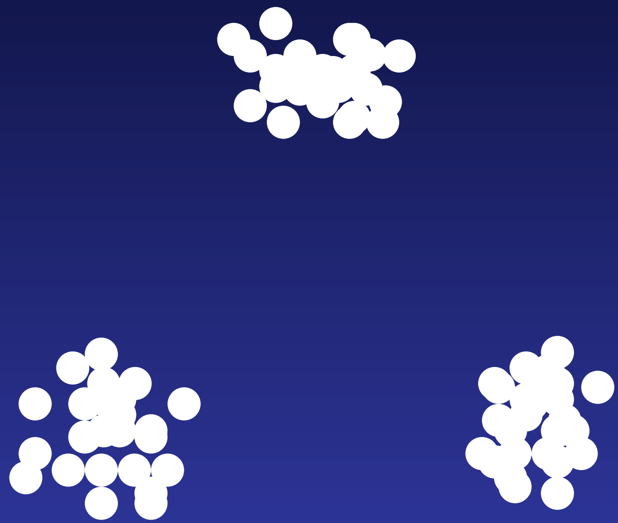
Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



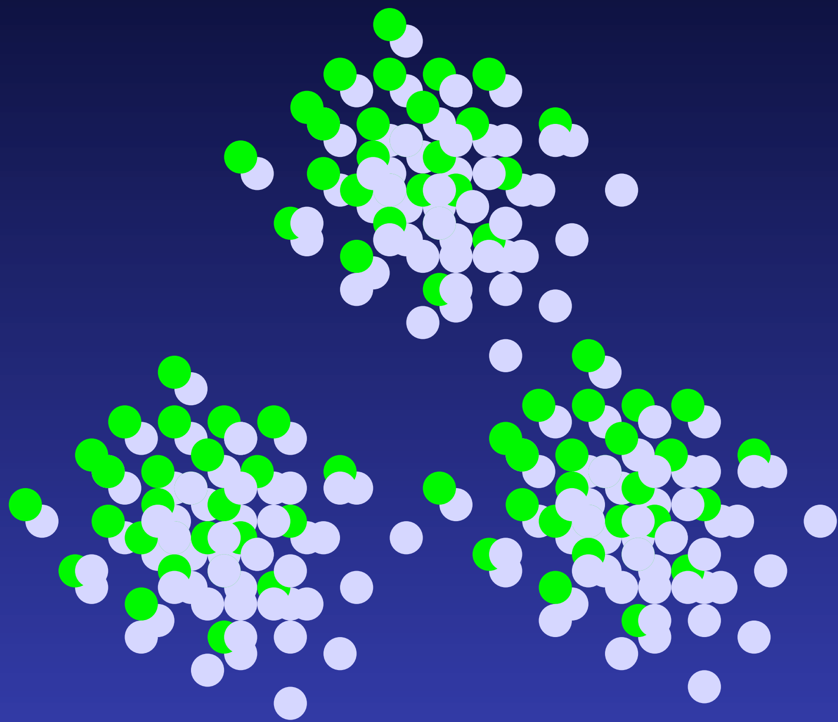
growth of $\delta\rho/\rho$ (k,t) fixed by

gravity vs expansion balance

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

Structure formation after equality

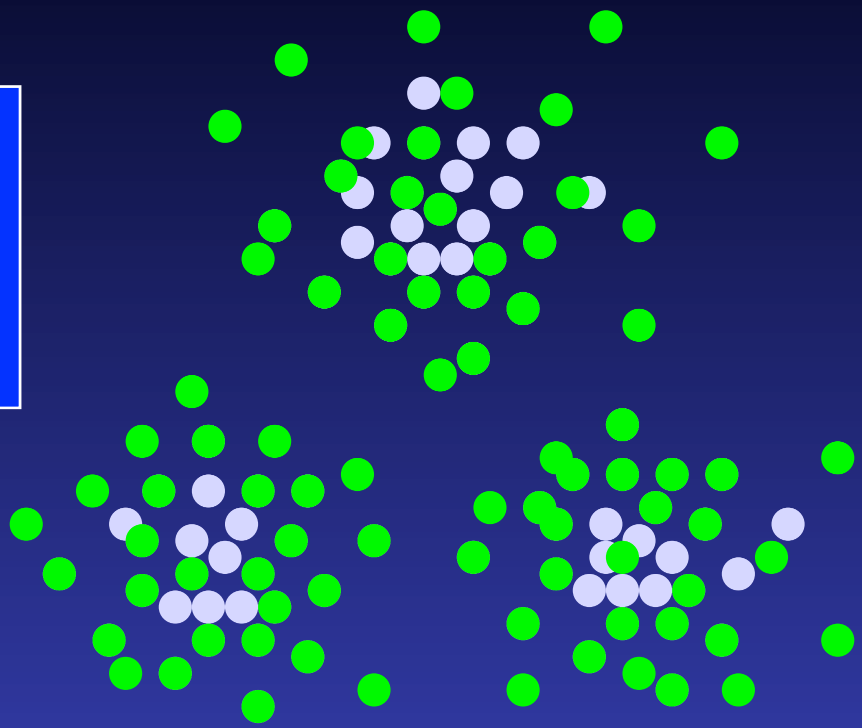
baryons and CDM (matter) experience gravitational clustering



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

Structure formation after equality

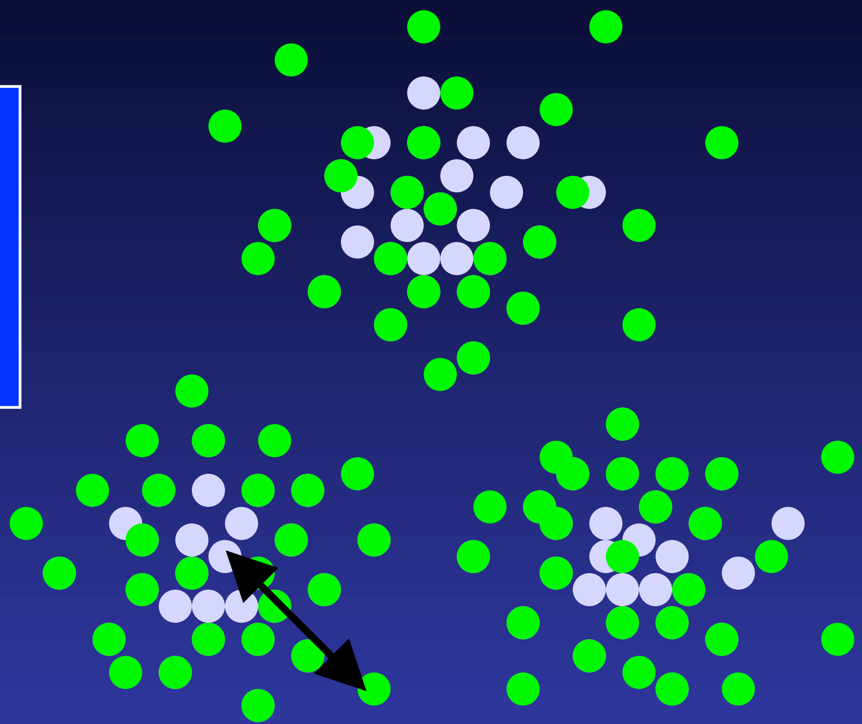
baryons and
CDM (matter)
experience
gravitational
clustering



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

Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



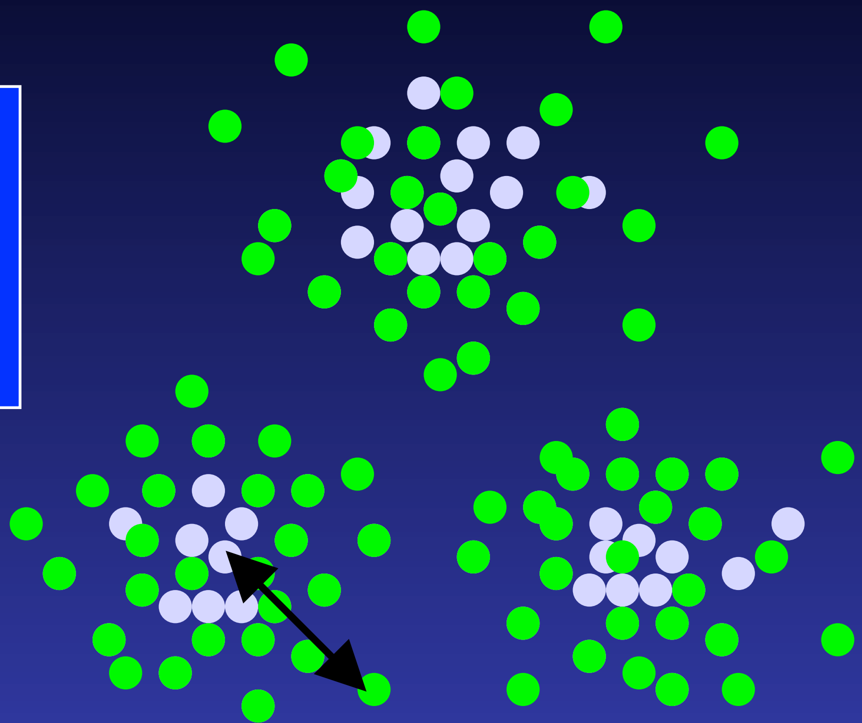
neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

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 $\langle p \rangle / m$

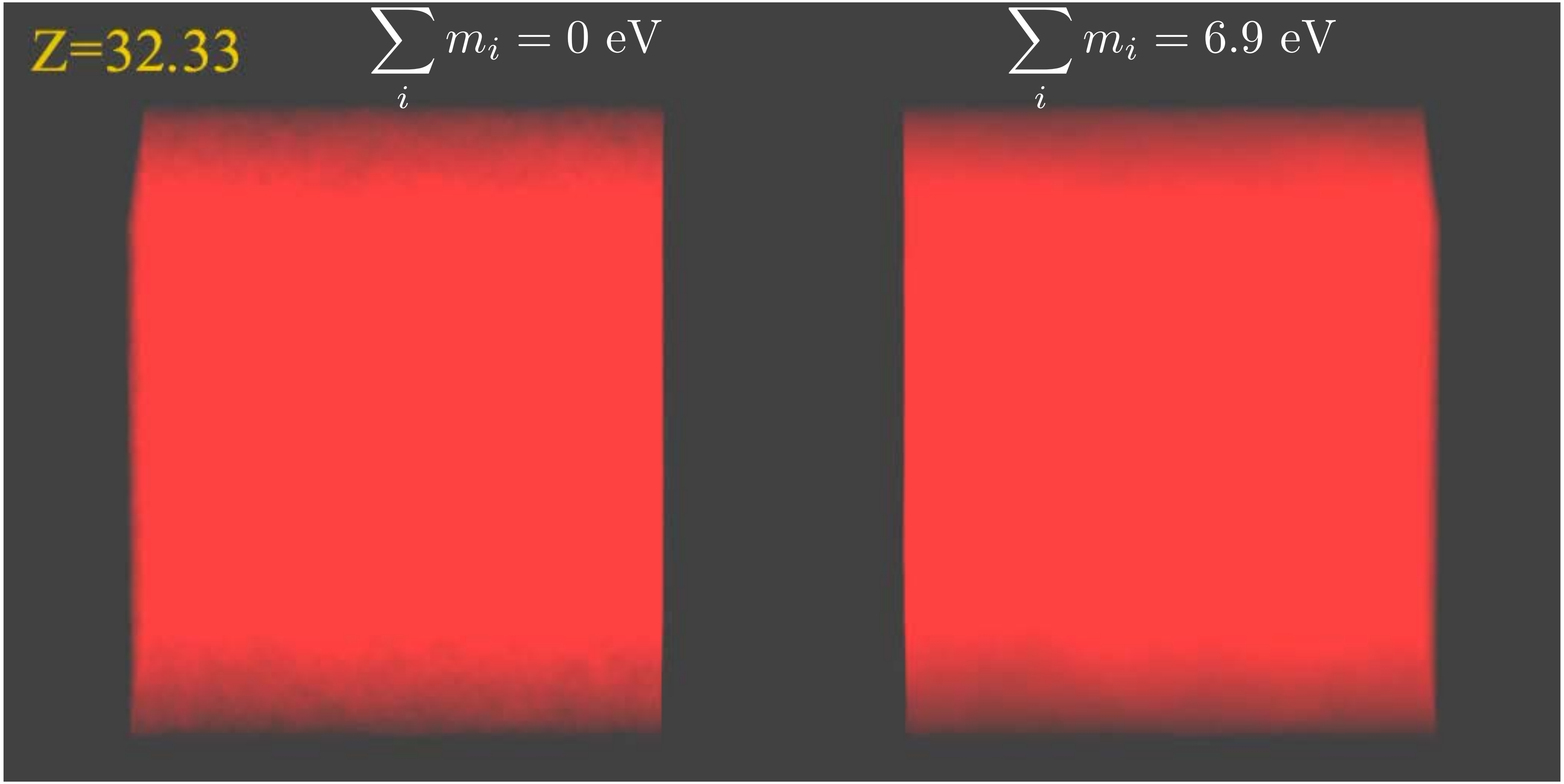
for $(2\pi/k) < \lambda$,

free-streaming supresses growth of structures during MD

⇨ $\delta\rho/\rho \propto a^{1-3/5\, f_\nu}$ 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)

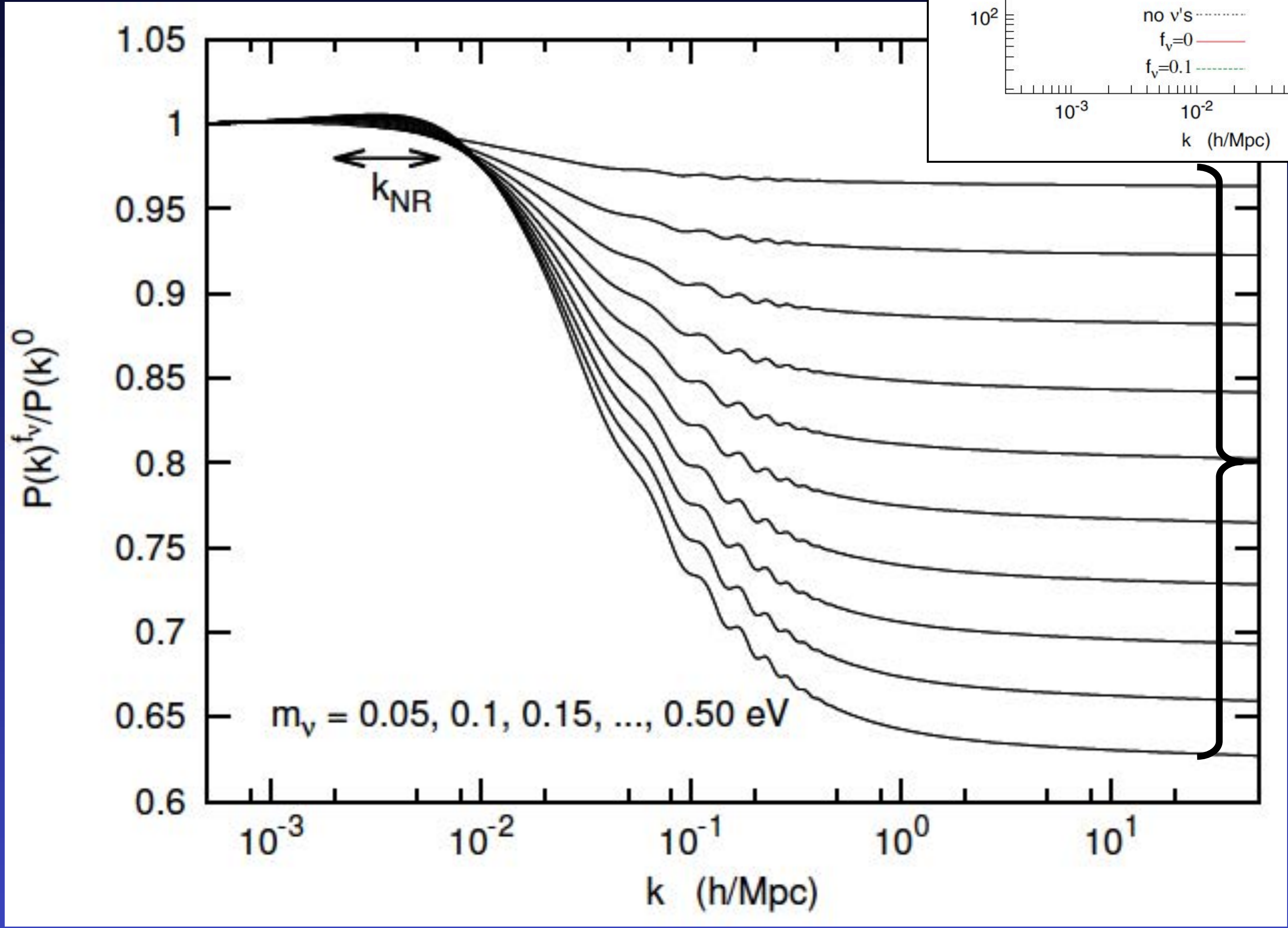


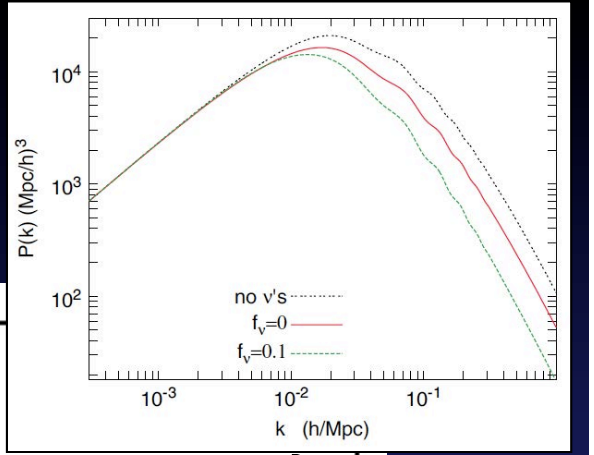
S. Hannestad, Cosmology Group, Univ. Aarhus

Effect of massive neutrinos on P(k)

Observable signature on P(k) :

P(k) massive / P(k) massless





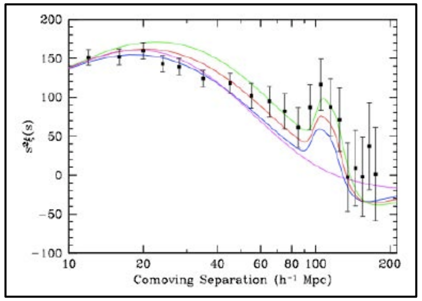
various f_ν

+ non-linear calculations: additional suppression at large k

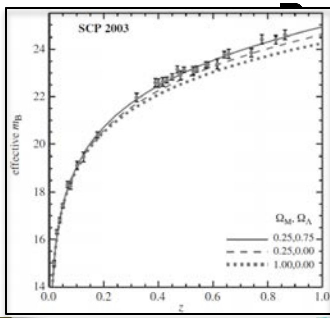
Brandbyge et al 2008, Viel et al 2010, Villaescusa-Navarro et al 2013

Effects of neutrino masses on cosmological observables

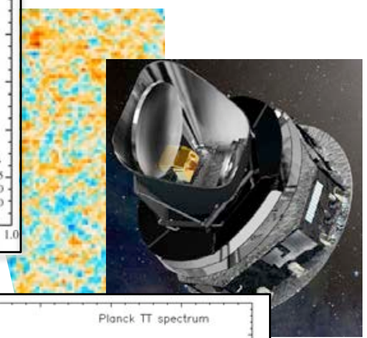
Cosmological Observables

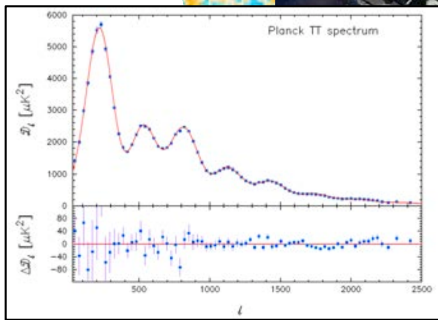


Hubble constant H_0 & cosmic distances measurements: SN Ia and Baryon Acoustic Oscillations (BAO)

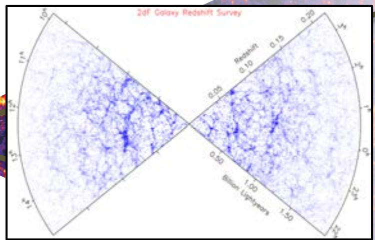


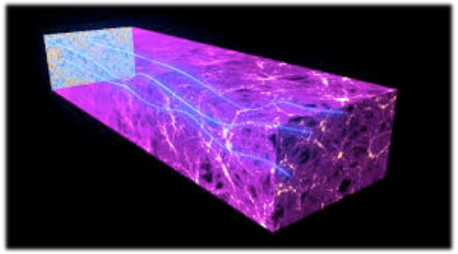
combination





Today





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

Photon momentum
after decoupling
CMB secondary anisotropy
spectrum

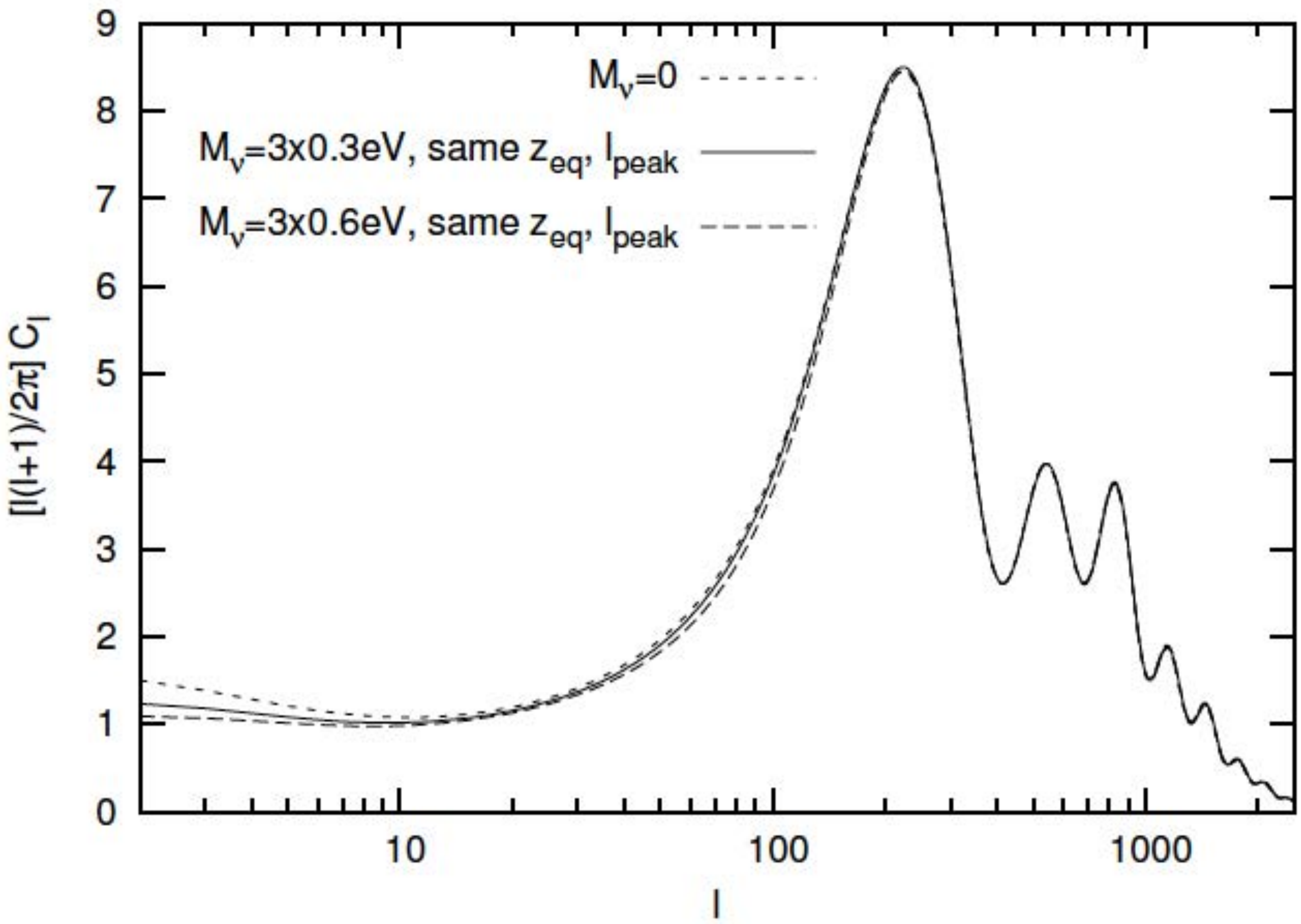
Photon density fluctuations
before decoupling
CMB primary anisotropy
spectrum (temp+pol)

from J. Lesgourgues

Effects of m_ν on the CMB

- Neutrinos contribute to radiation at early times and non-relativistic matter at late times
- If m_ν < 0.6 eV, neutrinos are relativistic at photon decoupling. In principle the primary CMB TT spectrum sensitive only 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

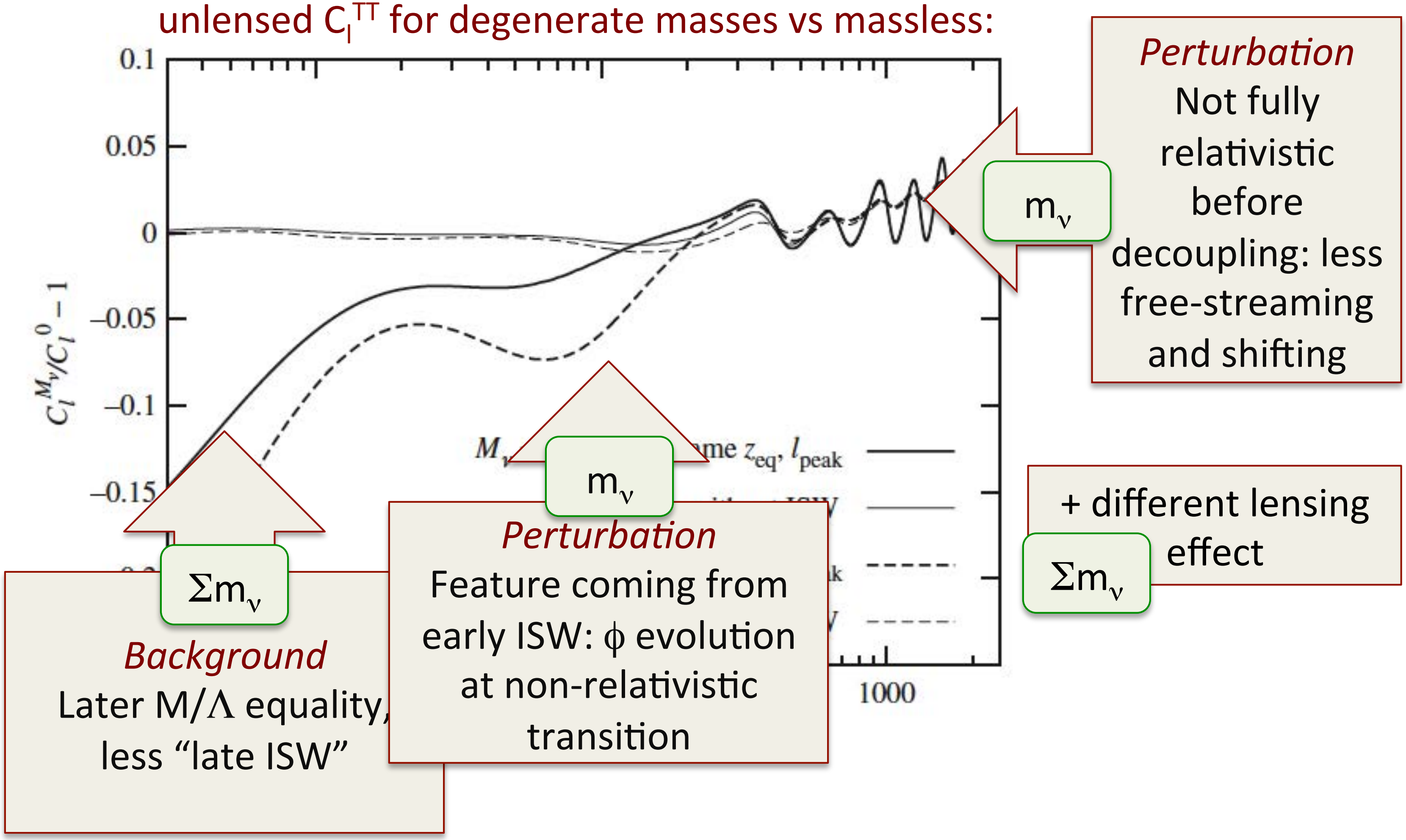


Effects of m_ν on the CMB

- 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 degenerate masses vs massless:

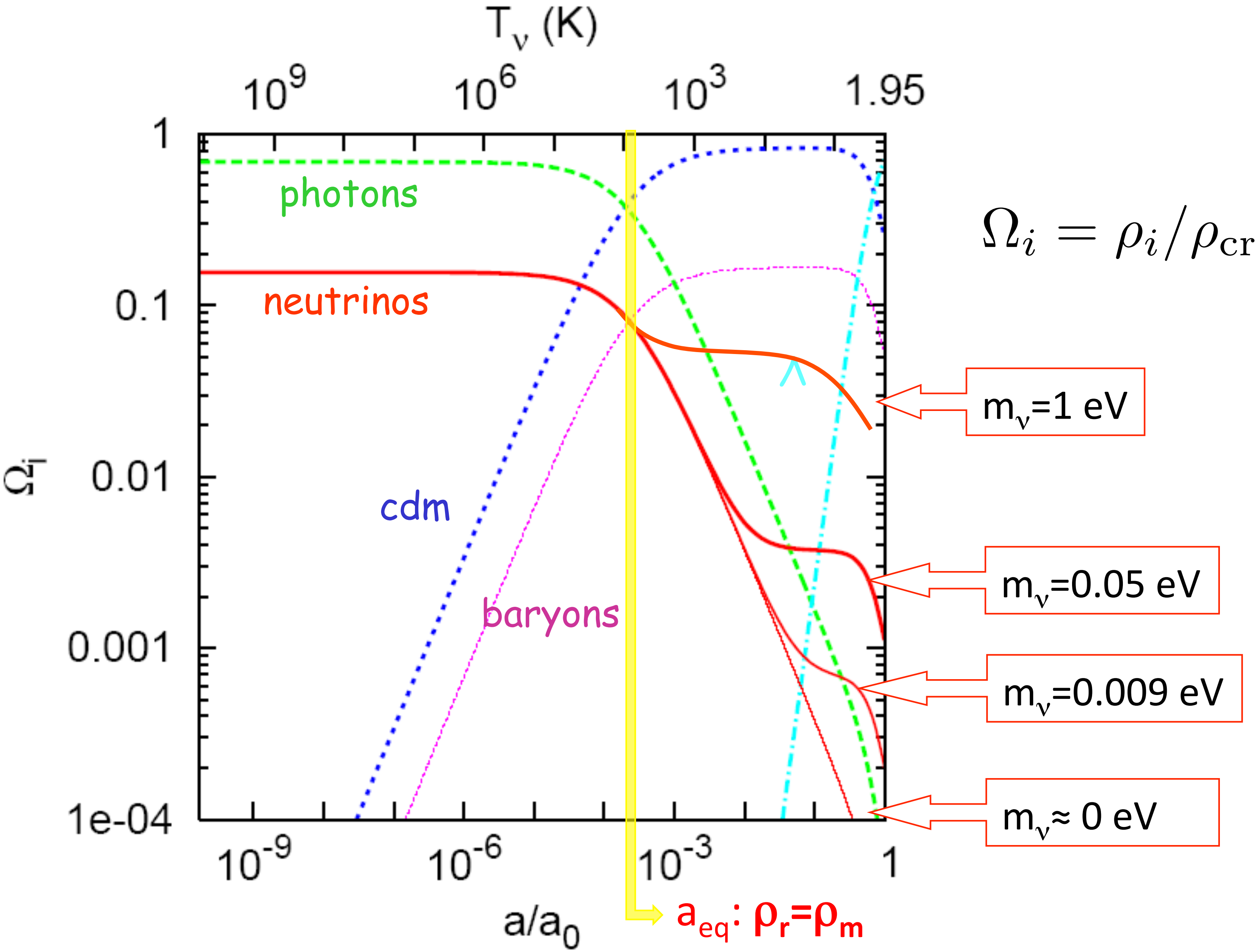


Effects of N_{eff} on cosmological observables

Effects of N_{eff} on the CMB

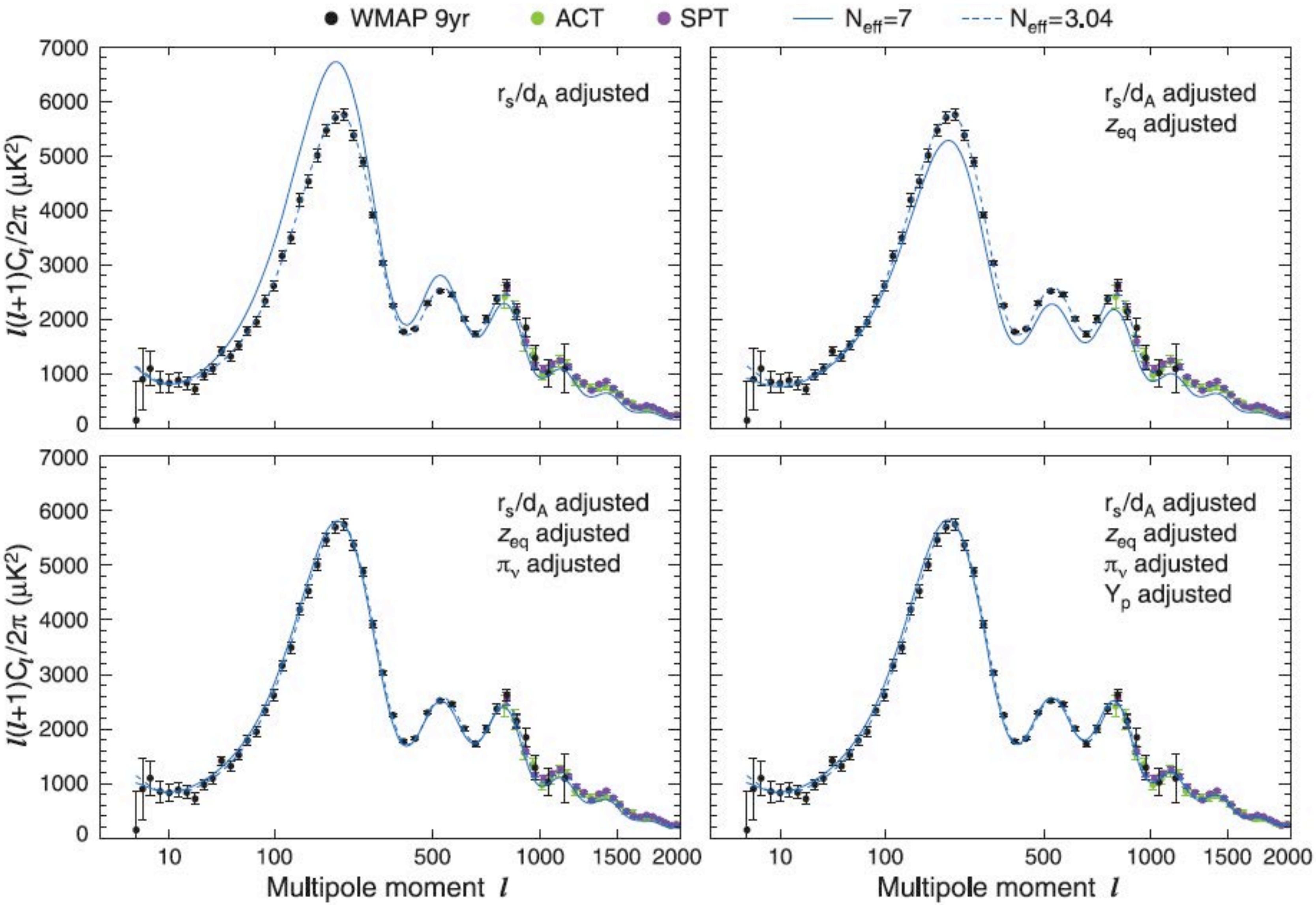
- N_{eff} is a parameter for the relativistic density in general
- "background effects" (change in expansion history) versus "perturbation effects" (gravitational interactions between photons and relativistic species)
- "effect of N_{eff}" depends on what is kept fixed.
- Fixing quantities best probed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



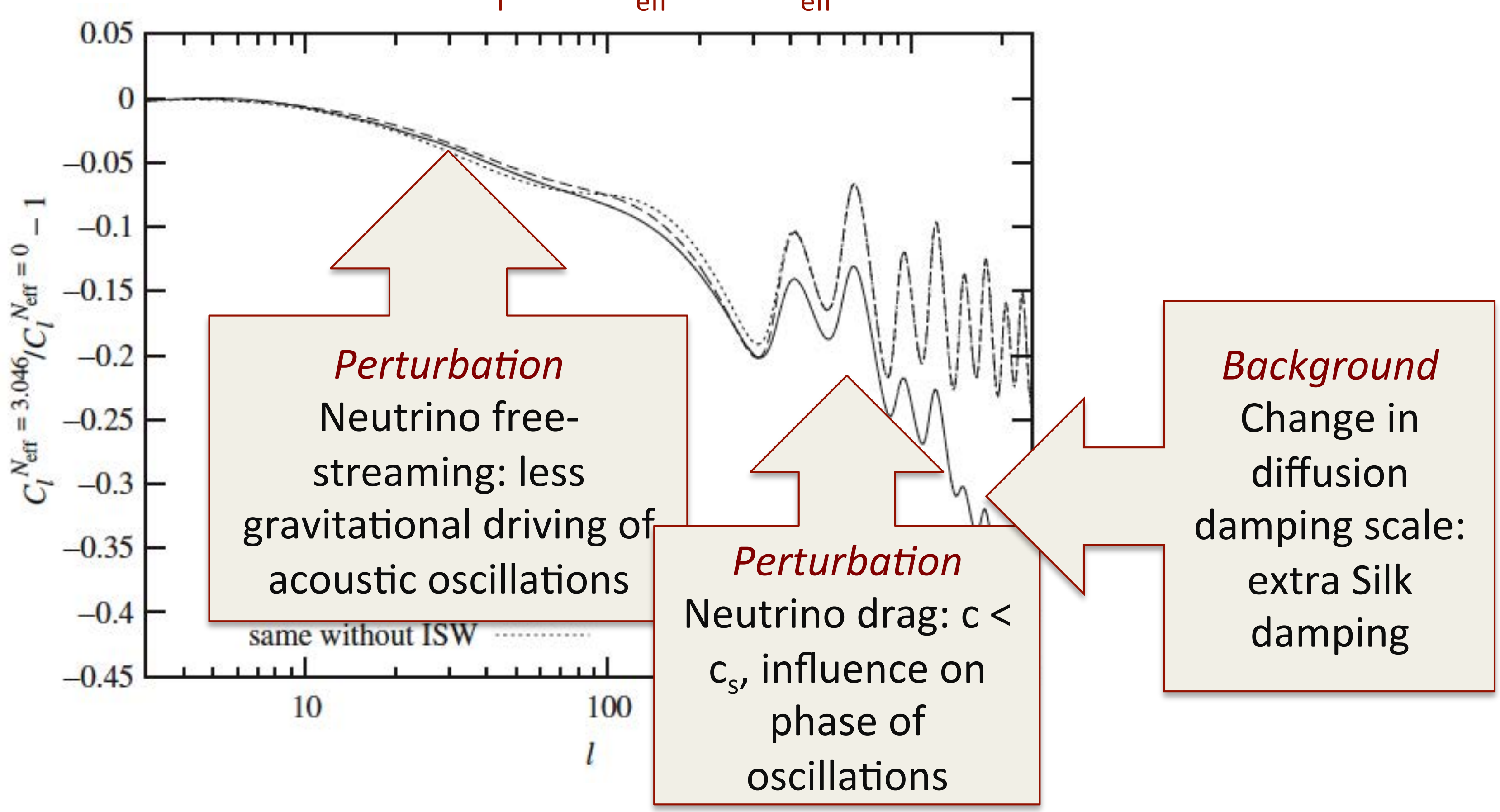
Hinshaw et al, arXiv:1212.5226

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 :



Present bounds on neutrino properties from cosmology

Probing neutrino masses with cosmo data

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

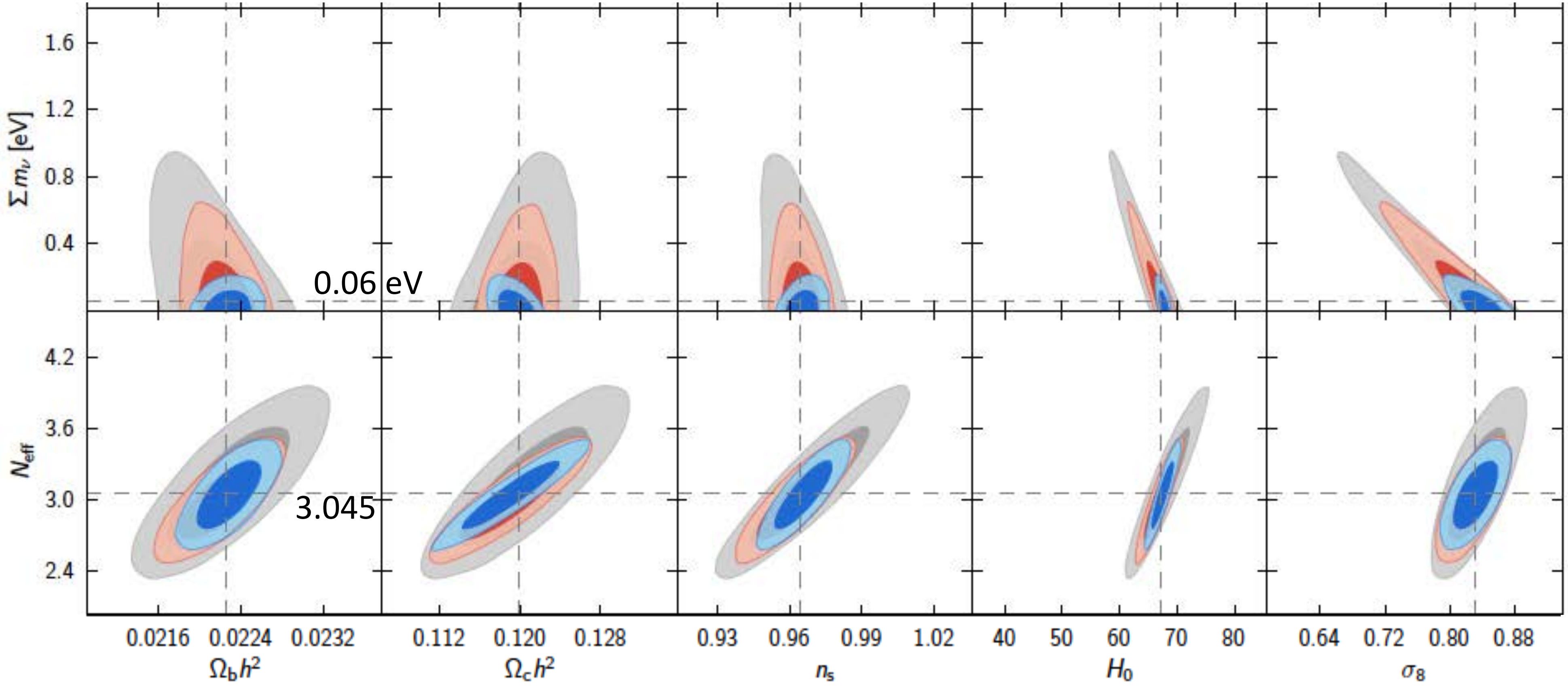
- **Primary CMB spectrum**
- **Galaxy P(k) / BAO**
- **CMB / galaxy lensing**
- **Clusters**
- **Lyman-α**
- **H_0 , SNe-Ia**

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

Not probing directly neutrino masses
but removing parameter degeneracies

1-parameter extensions of the ΛCDM model

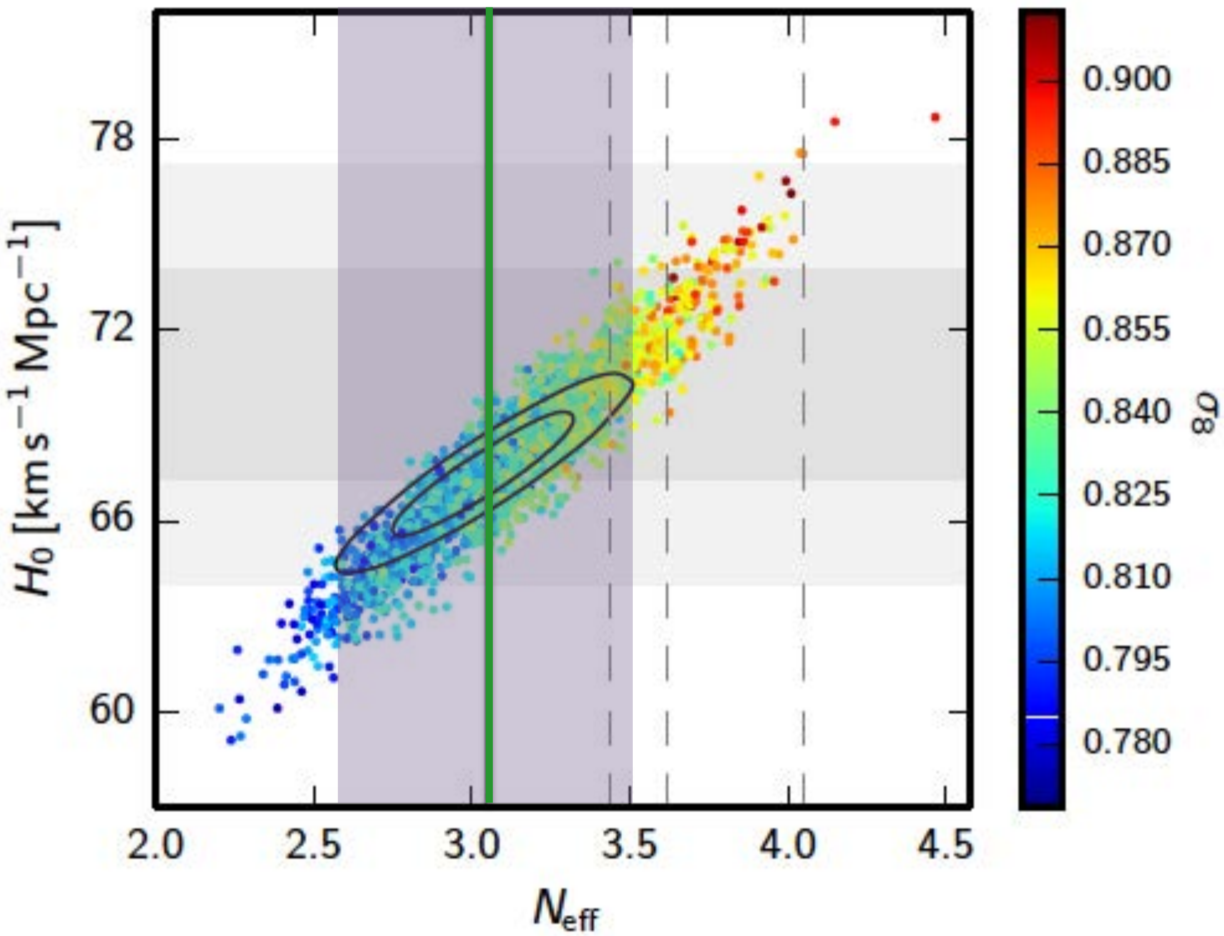
68+95%
Conf regions



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

Measuring N_{eff}

Indirect detection of CNB at 10-17σ



$N_{eff} = 3.13 \pm 0.32$ *Planck* TT+lowP;

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

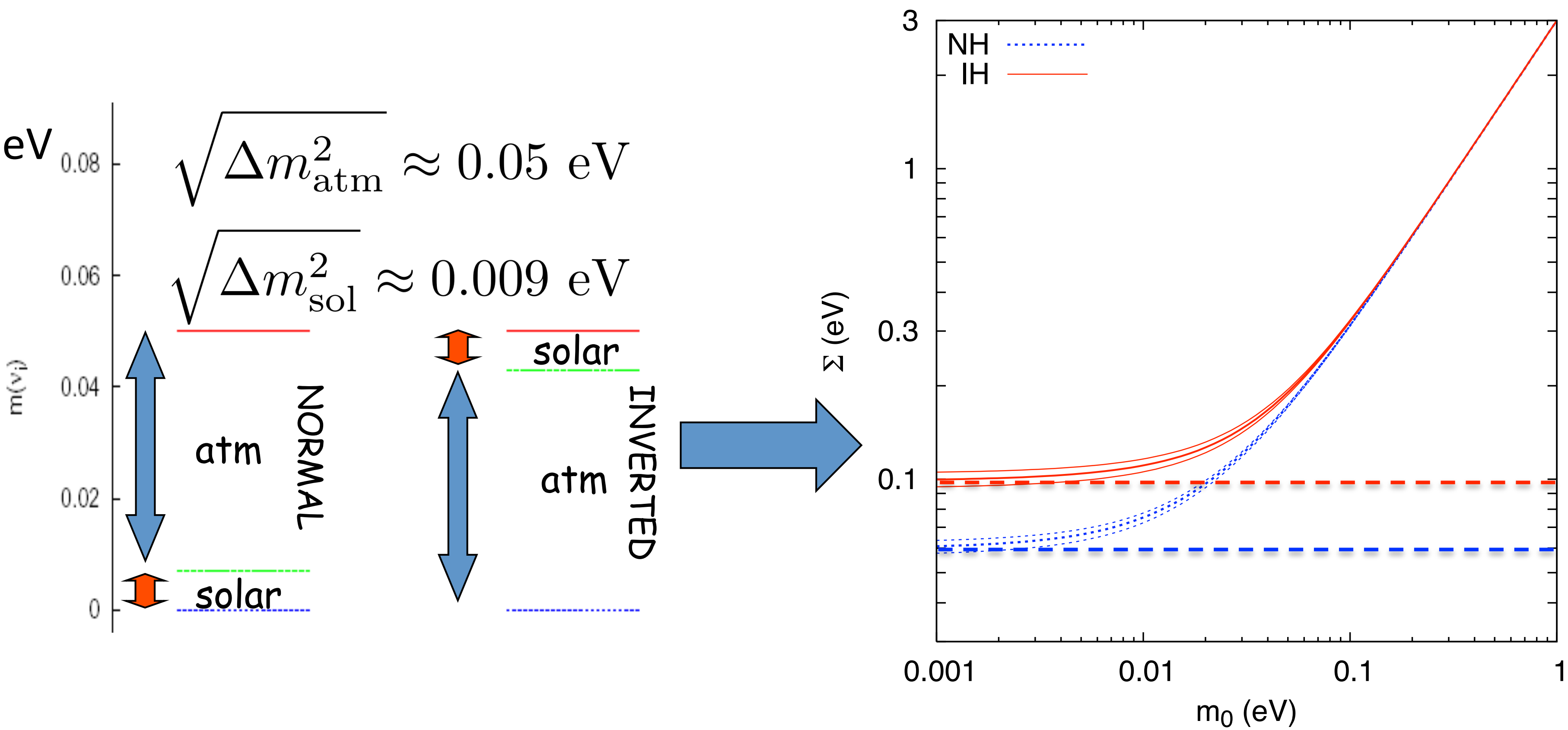
$N_{eff} = 2.99 \pm 0.20$ *Planck* TT, TE, EE+lowP;

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

All 68%CL

Neutrino masses

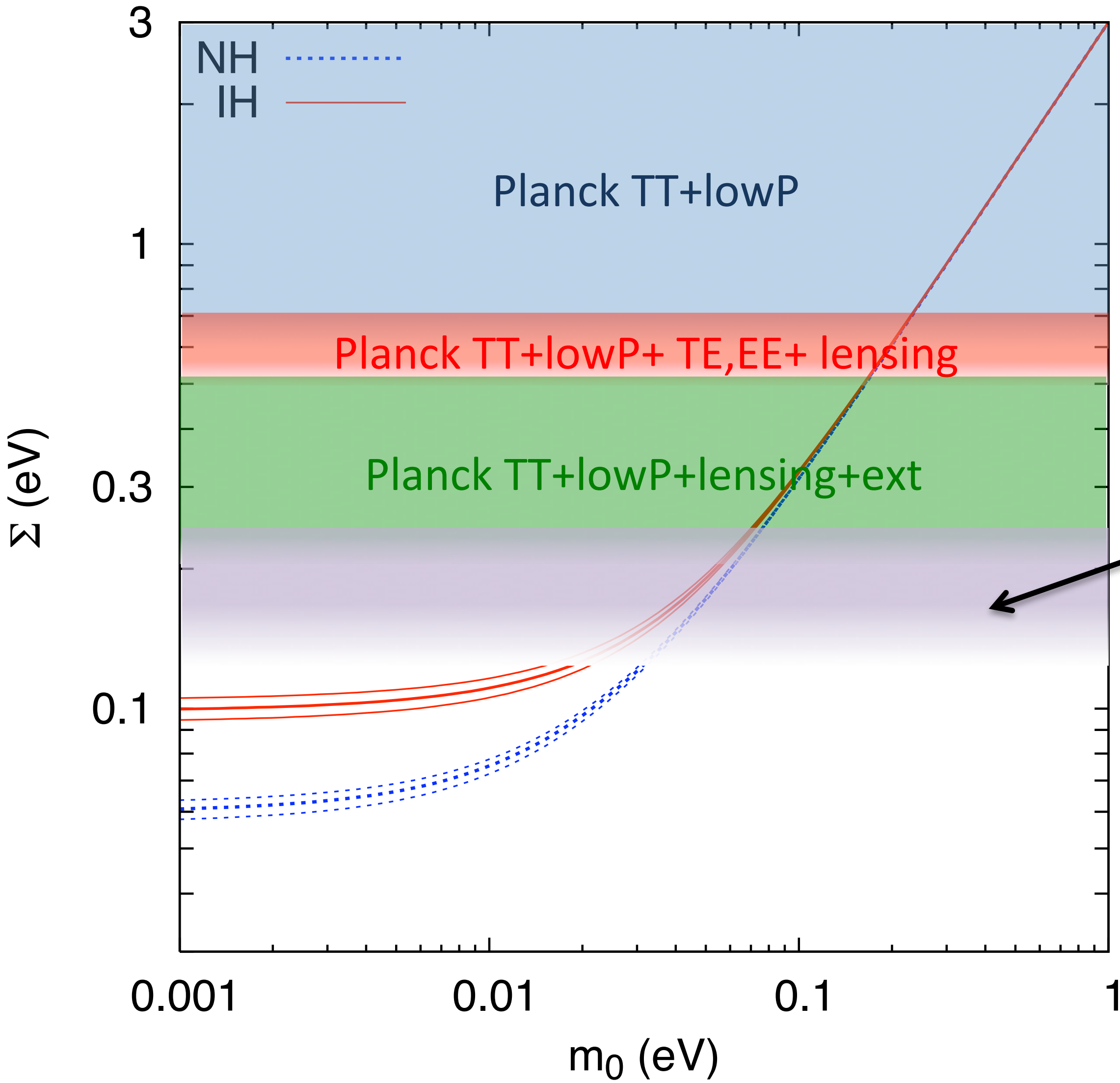
Data on flavour oscillations do not fix the absolute scale of neutrino masses



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

Measuring m_ν with Planck (+other cosmo data)

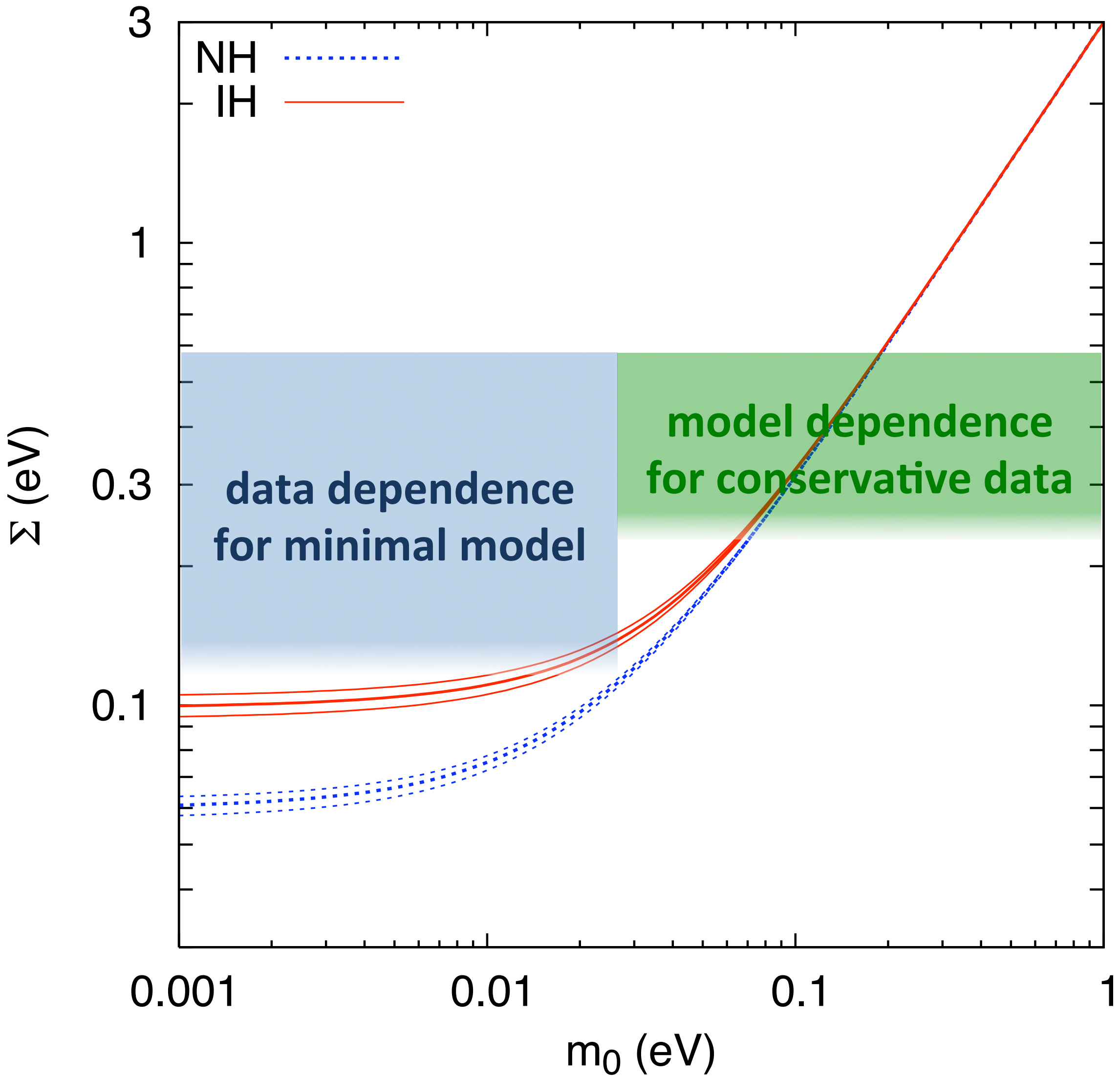
Cosmological upper limits on the sum of neutrino masses



Latest analyses Planck 2016 + BAO / Ly-α
see e.g.
Vagnozzi et al
1701.08172
Capozzi et al
1703.04471

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

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

m_β < 2.2 eV (95% CL) Mainz

Current experiment (KATRIN) $m(\nu_e)$ ~ 200-300 meV

- Neutrinoless double beta decay: if Majorana neutrinos

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

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

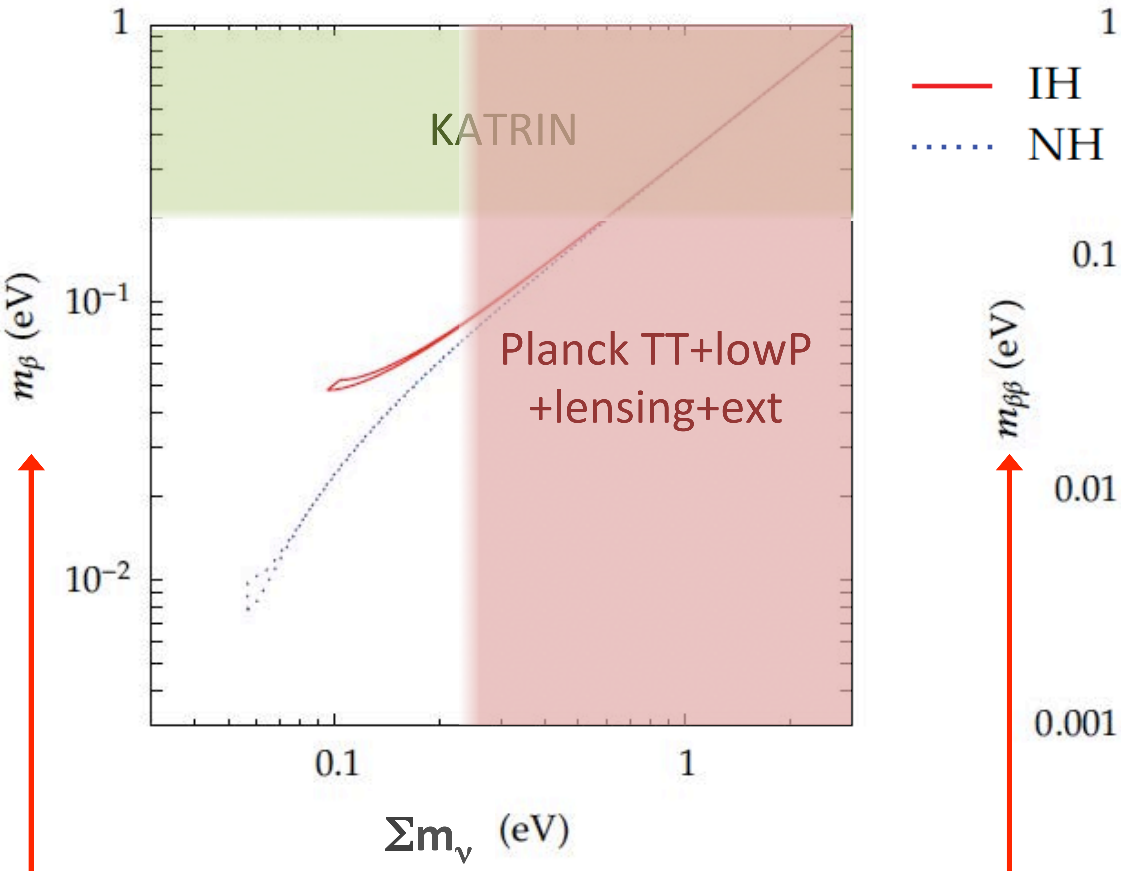
$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

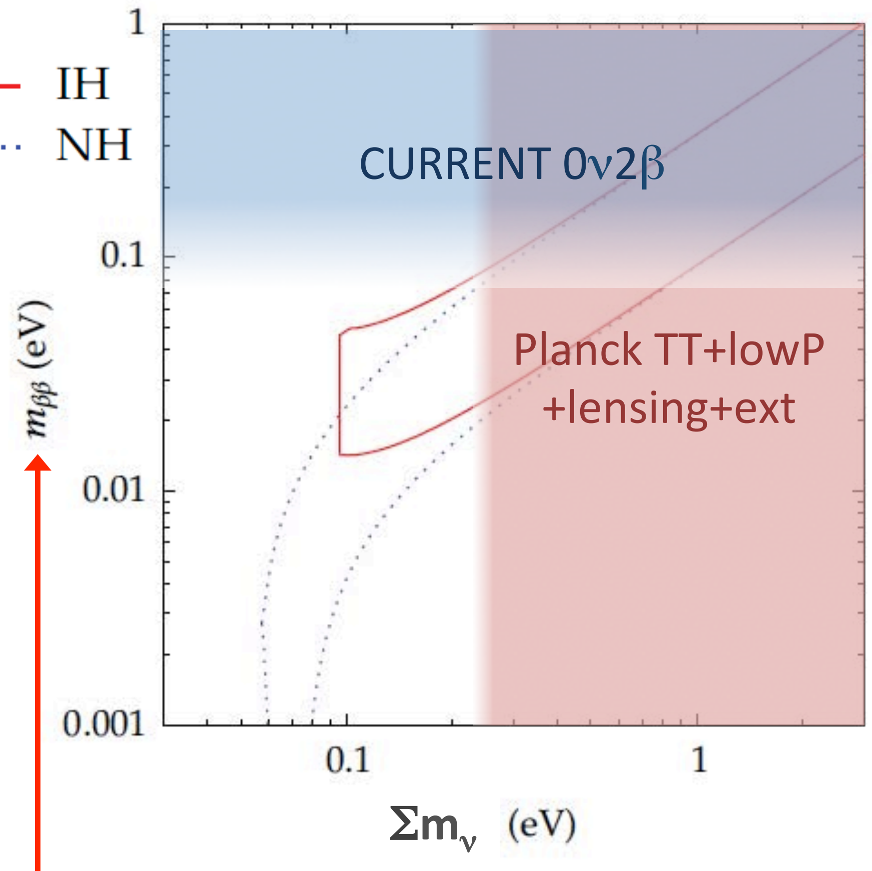
Neutrinoless double beta decay	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	$<$ 60-800 meV

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

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

Tritium β decay, 0ν2β and Cosmology



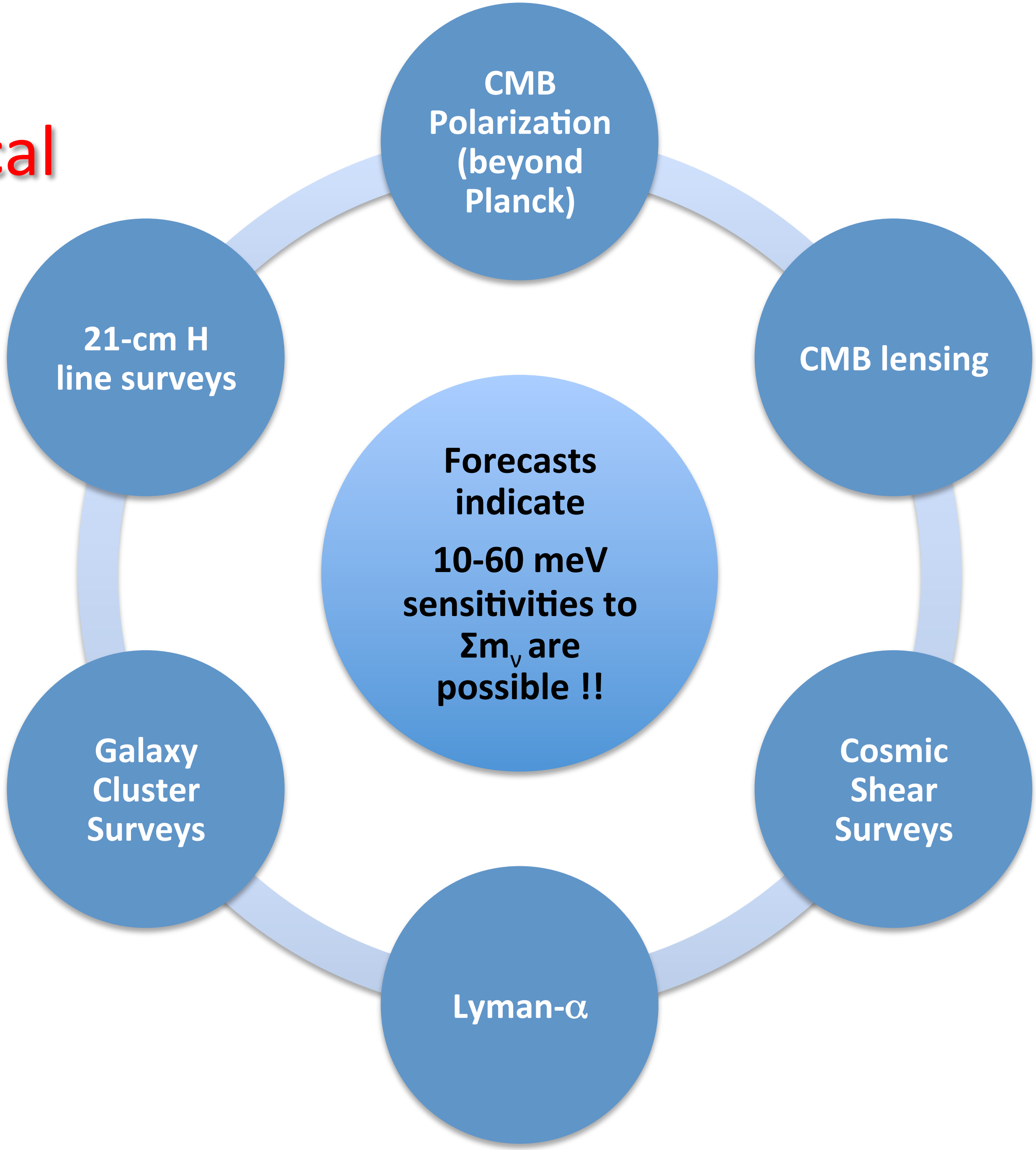


$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

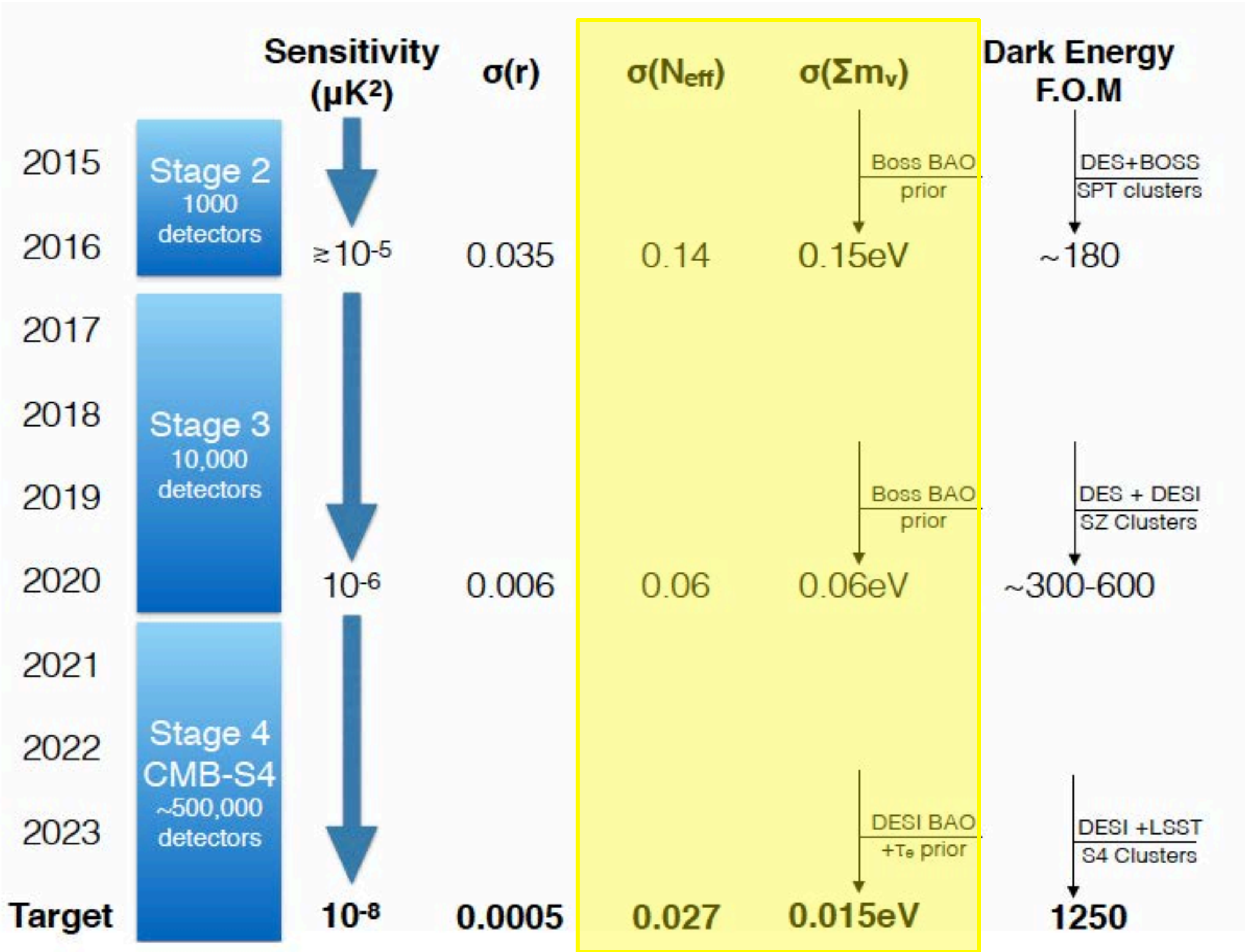
$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

Future sensitivities on neutrino physics from cosmology

Future cosmological data



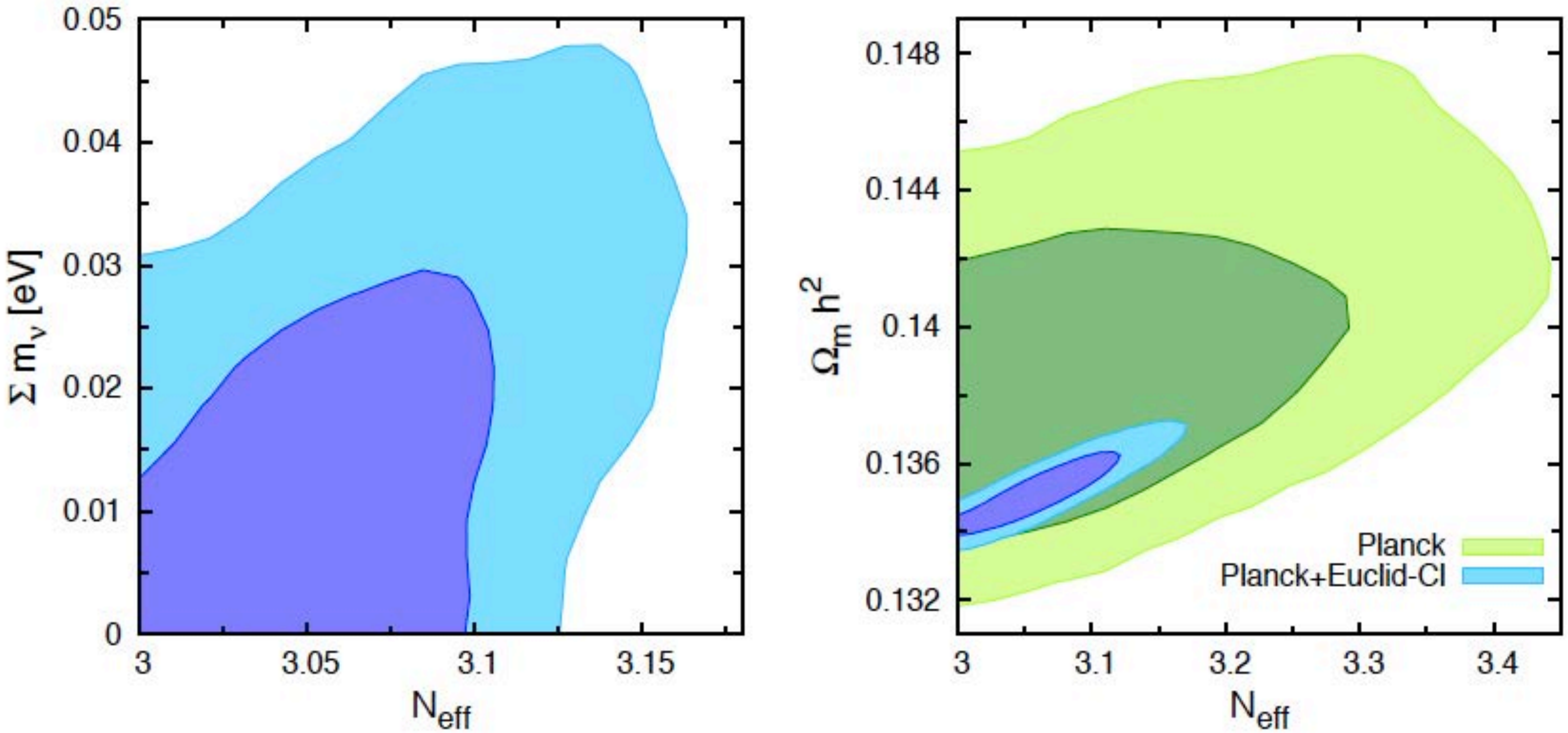
Future sensitivities on N_{eff} and neutrino masses



CMB-S4 Science Book, 1610.02743

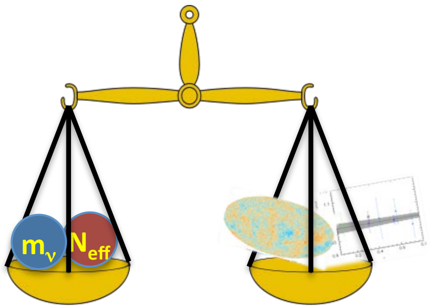
Future sensitivities to N_{eff} and Σm_ν

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

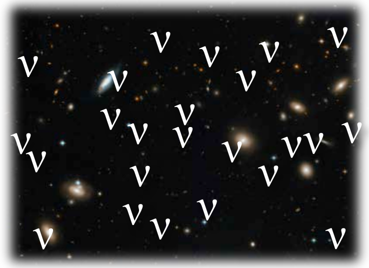


Data		Planck+Euclid-Cl	
Model		wCDM+m_ν+$N_{\rm eff}$	ΛCDM+m_ν+$N_{\rm eff}$+$\Omega_{\rm k}$
$\sum m_\nu$ [eV]	68% CL	< 0.024	< 0.024
	95% CL	< 0.046	< 0.046
$N_{\rm eff}$	95% CL	< 3.16	< 3.17

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



Conclusions

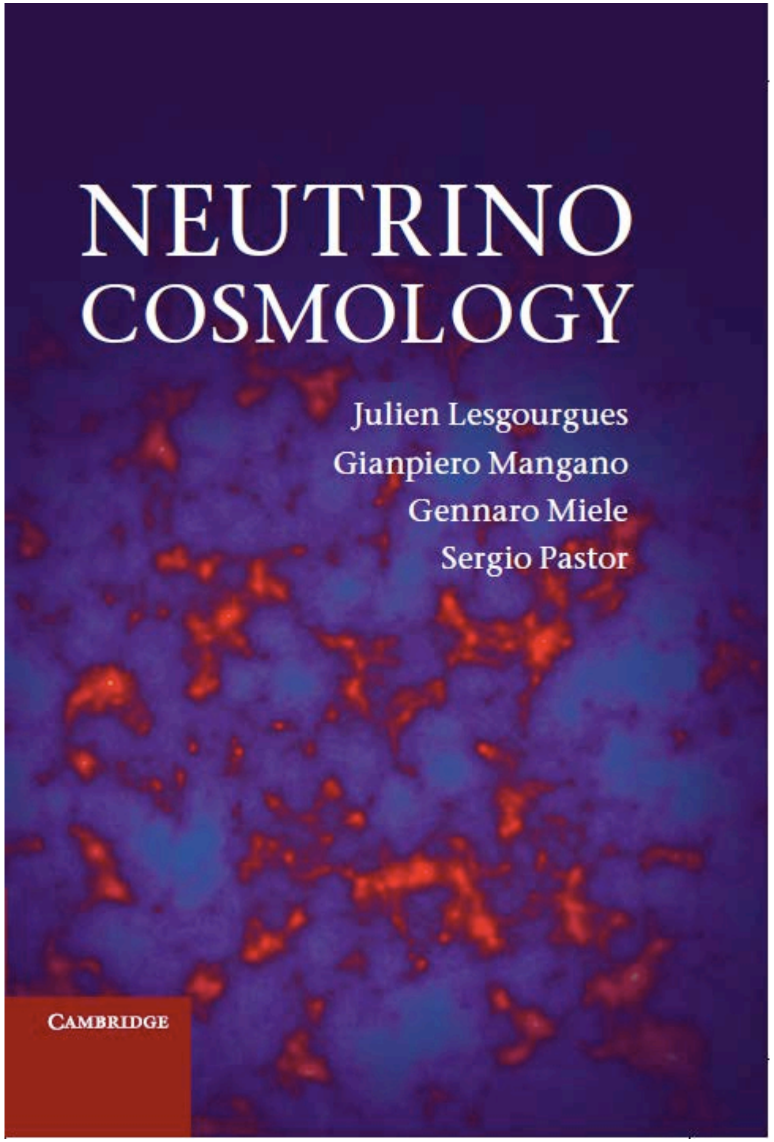


✓ With Planck, including CMB lensing, and LSS data, we can measure combinations of cosmological parameters with high precision. Still ΛCDM fits very well the data

✓ No evidence yet for nonzero neutrino masses or an enhanced radiation density (**N_{eff}**). Bounds **$\Sigma m_\nu < 0.12\text{-}0.7$ eV** (95% CL) and **$N_{eff} = 3.15 \pm 0.23$** (68% CL), depending on data

✓ Improved sensitivities from a variety of future cosmological data to reach the minimal values $\Sigma m_\nu =$ 60 or 100 meV

For more details…



Exercises: try to calculate…

- The present number density of massive/massless neutrinos n_ν^0 in cm^{-3}
- The present energy density of massive/massless neutrinos Ω_ν^0 and find the limits on the total neutrino mass from $\Omega_\nu^0<1$ and $\Omega_\nu^0 < \Omega_m^0$
- The final ratio T_γ/T_ν using the conservation of entropy density before/after $e^\pm$ annihilations
- The decoupling temperature of relic neutrinos using $\Gamma_W \approx H$

- The evolution of $\Omega(\nu,\gamma,b,cdm)$ with the expansion for neutrino masses (3,0,0), (1,1,1) and (0.05,0.009,0) [masses in eV]
- The photon temperature / redshift of the matter-radiation equality for $m_\nu = 1$ eV

The end, thanks!