

Neutrinos in Cosmology (II)



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Arenzano, 22-23 June



Suggested References

Books

Modern Cosmology, S. Dodelson (Academic Press, 2003)

Kinetic theory in the expanding Universe, Bernstein (Cambridge U., 1988)

Neutrino Cosmology, Mangano, Miele, Lesgourgues & SP (Cambridge U., 2013)

Reviews

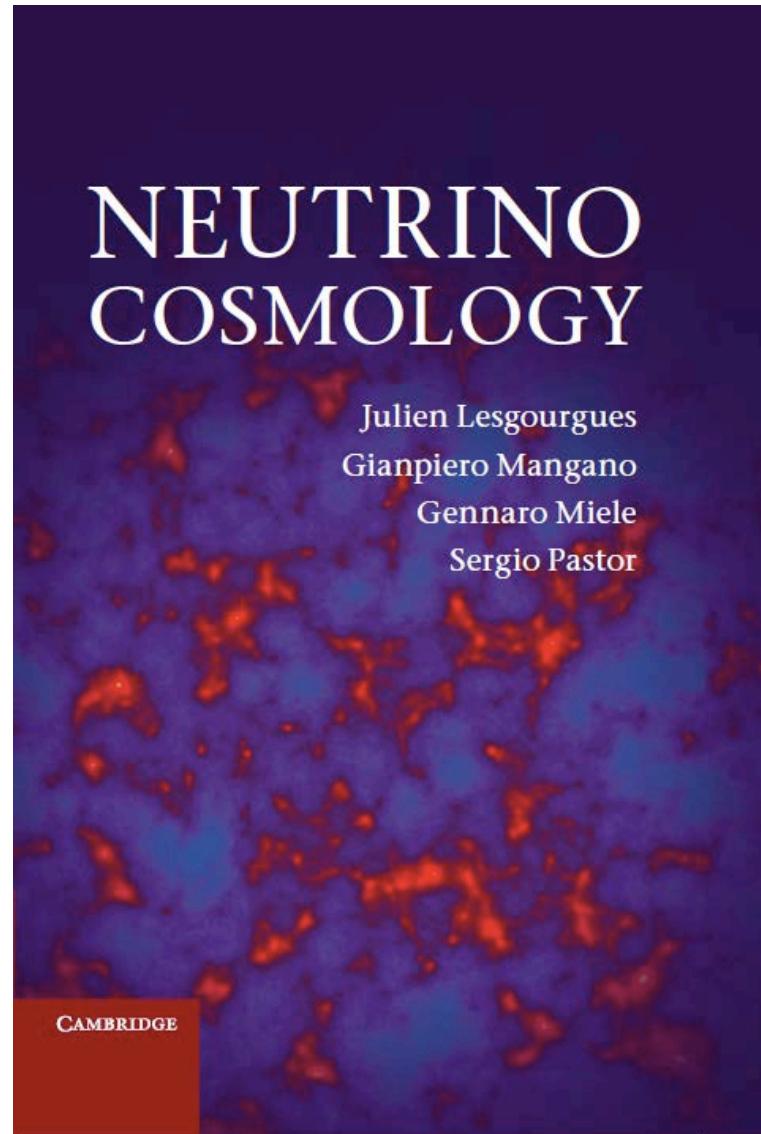
Neutrino Cosmology, A.D. Dolgov,
Phys. Rep. 370 (2002) 333-535 [[hep-ph/0202122](#)]

Massive neutrinos and cosmology, J. Lesgourgues & SP,
Phys. Rep. 429 (2006) 307-379 [[astro-ph/0603494](#)]

Primordial Nucleosynthesis: from precision cosmology to fundamental physics,
F. Iocco, G. Mangano, G. Miele, O. Pisanti & P.D. Serpico
Phys. Rep. 472 (2009) 1-76 [[arXiv:0809.0631](#)]

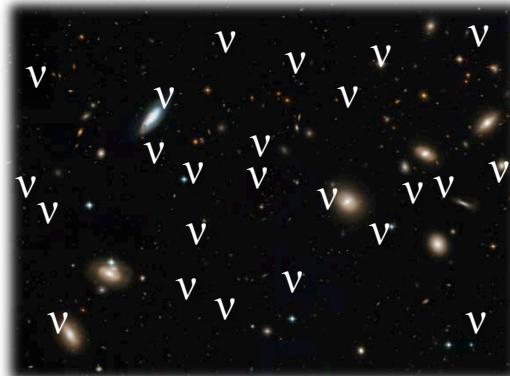
Neutrino Physics from the CMB and LSS, K.N. Abazajian, M. Kaplinghat
Ann. Rev. Nucl. Part. Sci. 66 (2016) 401-420

For more details...



Ed. Cambridge Univ. Press, 2013

Outline



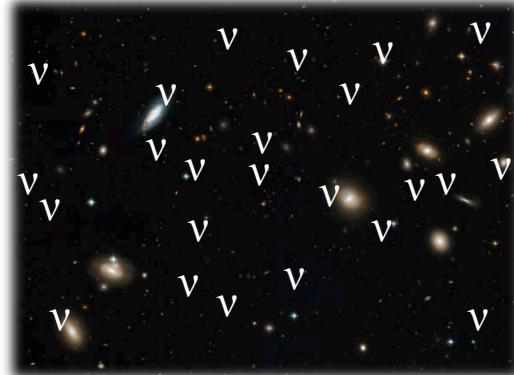
Introduction: neutrinos and the history of the Universe

Basics of Cosmology

Production and decoupling of relic neutrinos

1st

Outline



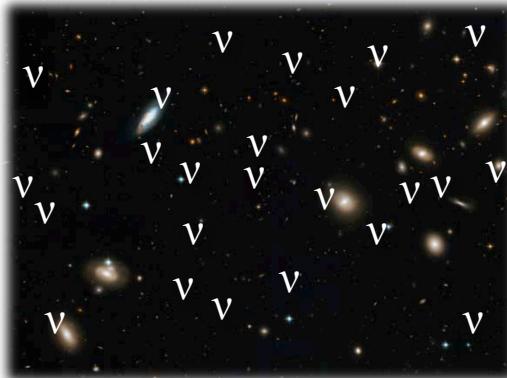
The radiation content
of the Universe (N_{eff})

Neutrinos and Primordial
Nucleosynthesis

Neutrino oscillations
in the Early Universe

1st

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 as Dark Matter

The Cosmic Neutrino Background

Neutrinos decoupled at $T \sim \text{MeV}$, keeping a spectrum as that of a relativistic species

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

- Number density

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

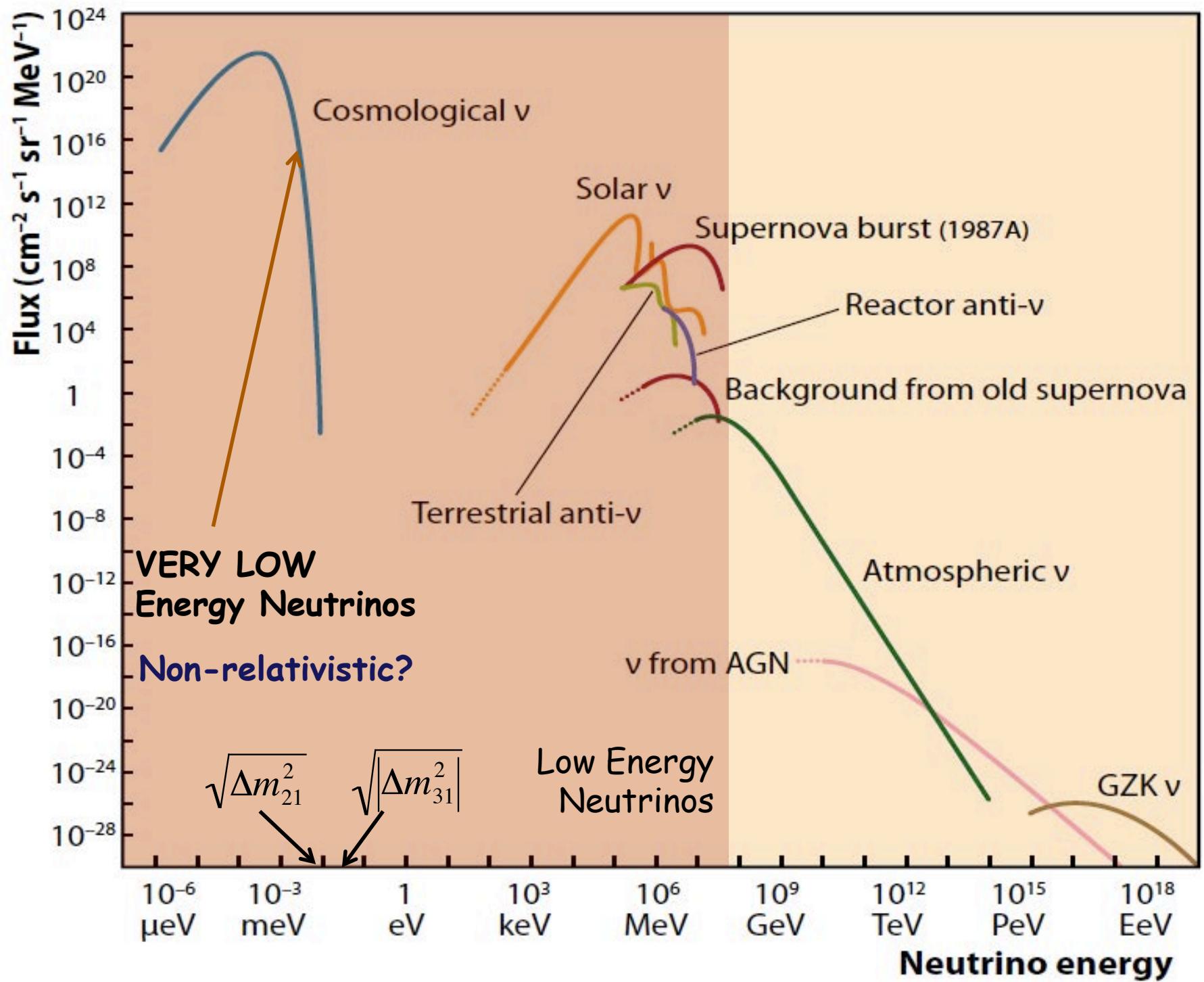
- Energy density

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

Contribution to the energy density of the Universe

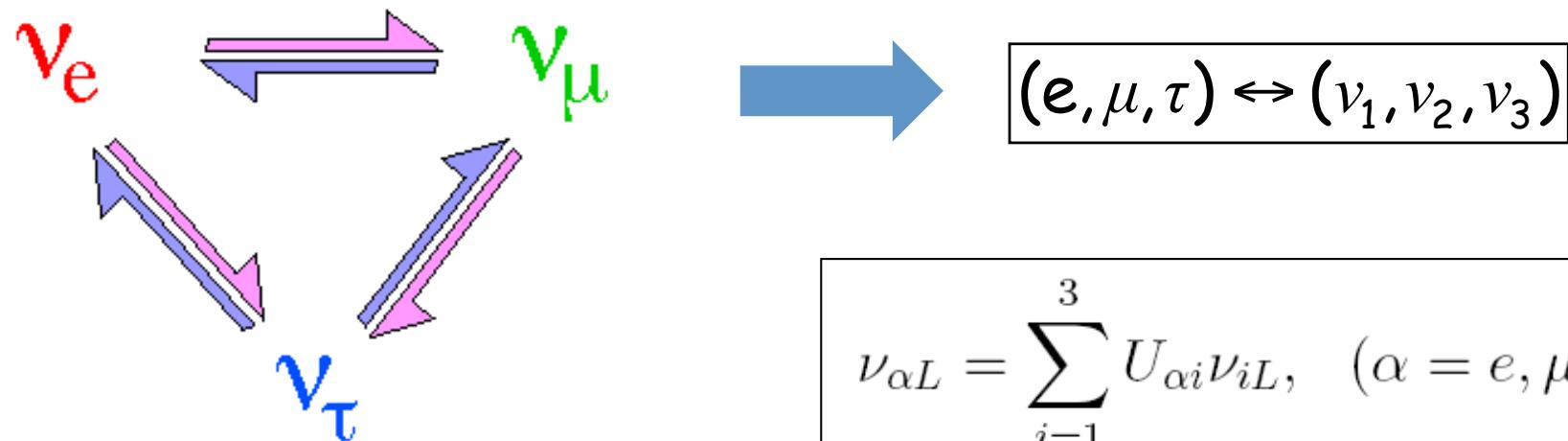
$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1 \text{ eV}}$$

Massive
 $m_\nu \gg T$



We know that flavour neutrino oscillations exist

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



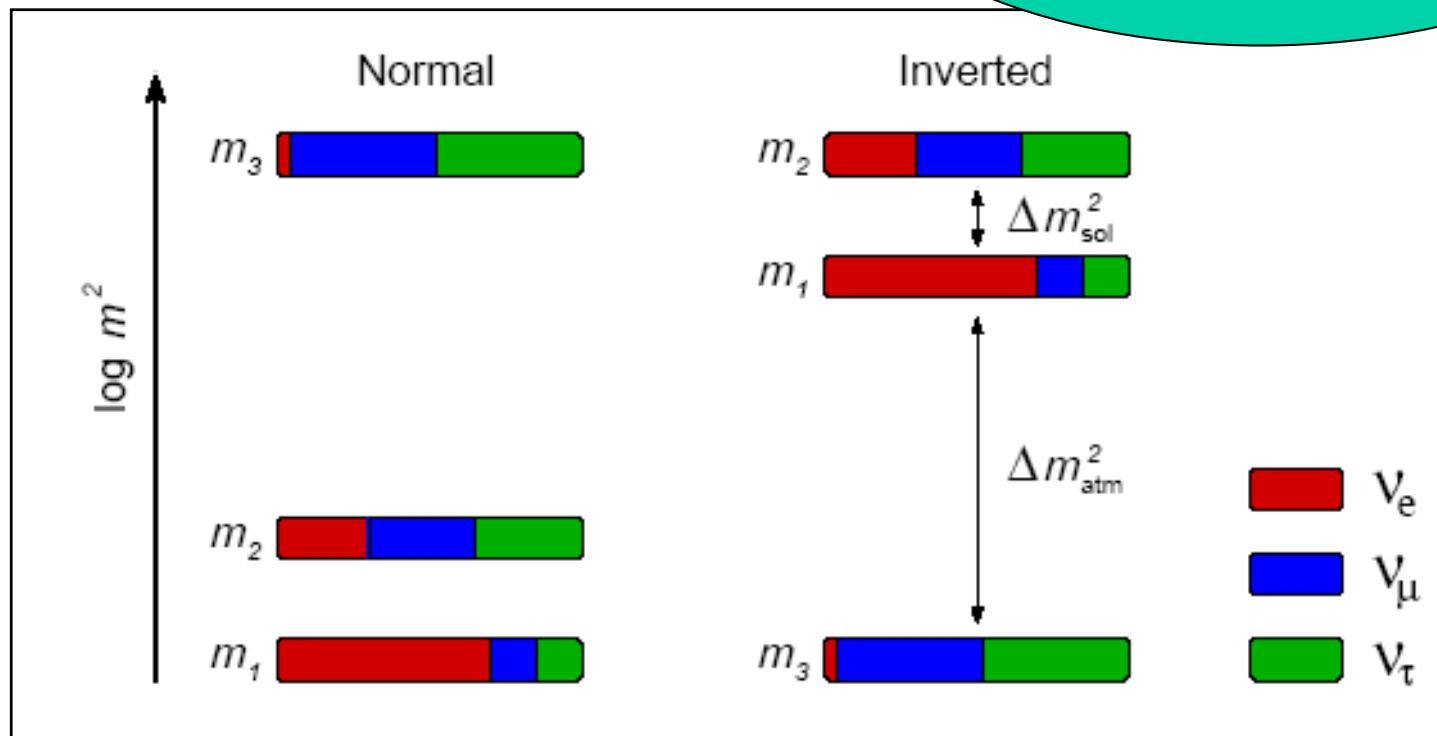
$$\nu_{\alpha L} = \sum_{i=1}^3 U_{\alpha i} \nu_{iL}, \quad (\alpha = e, \mu, \tau)$$

$$\begin{array}{ccc} & \nu_1 & \nu_2 & \nu_3 \\ \nu_e & c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \nu_\mu & -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ \nu_\tau & s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array} \times \text{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1).$$

Neutrino masses

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

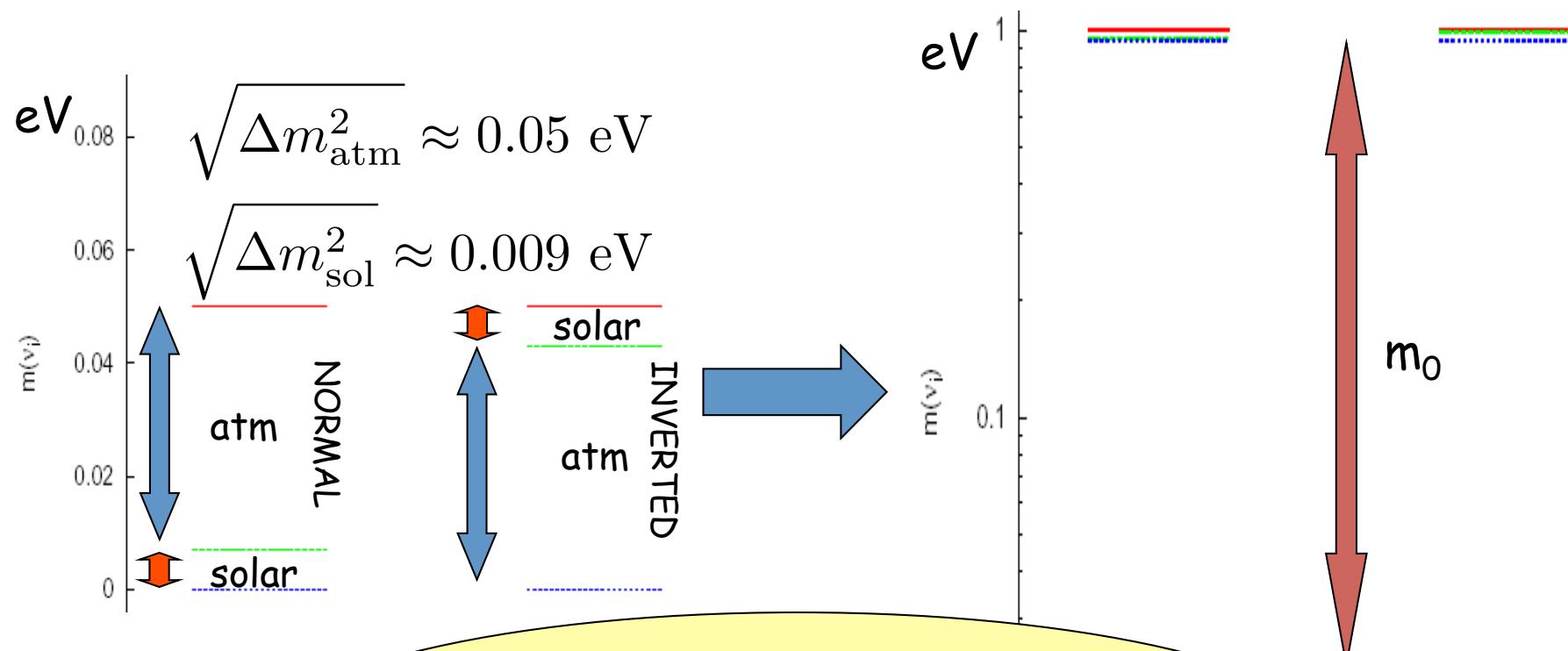
Present evidences
for flavour neutrino
oscillations: data on
solar, atmospheric,
reactor and accelerator
neutrinos



Possible neutrino mass hierarchy patterns

Neutrino masses

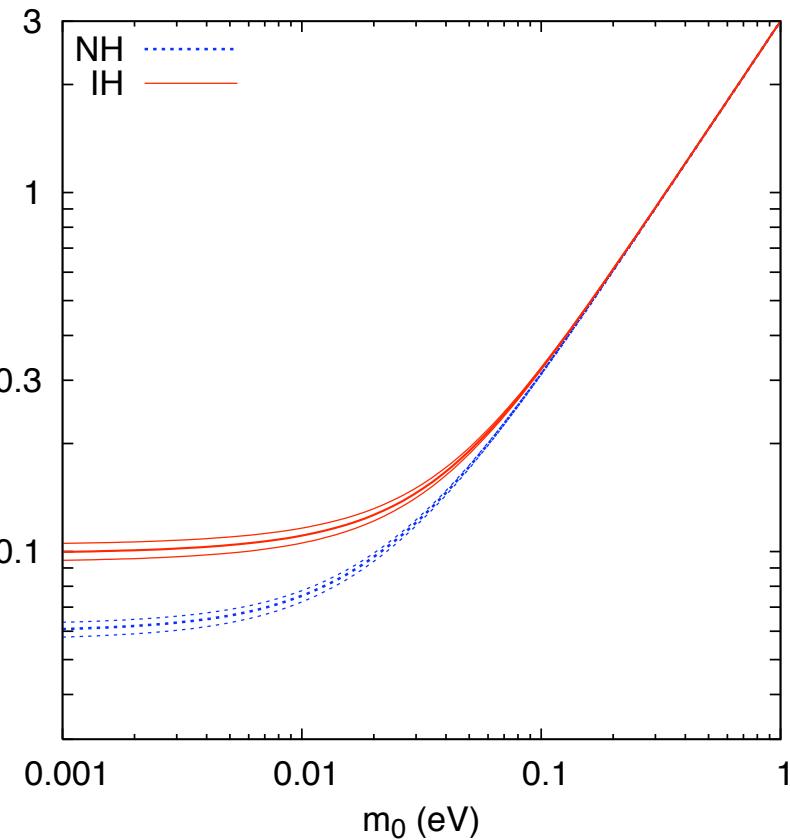
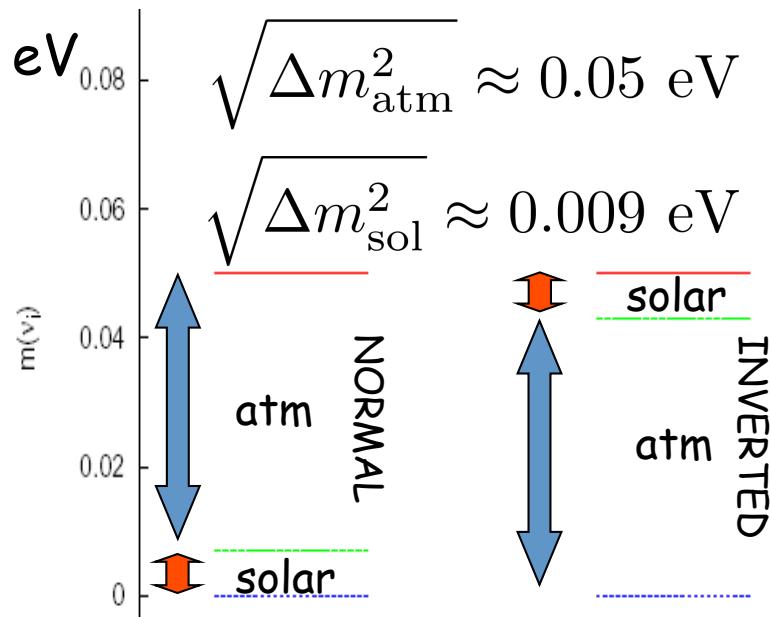
Data on flavour oscillations do not fix the absolute scale of neutrino masses



What is the value of m_0 ?

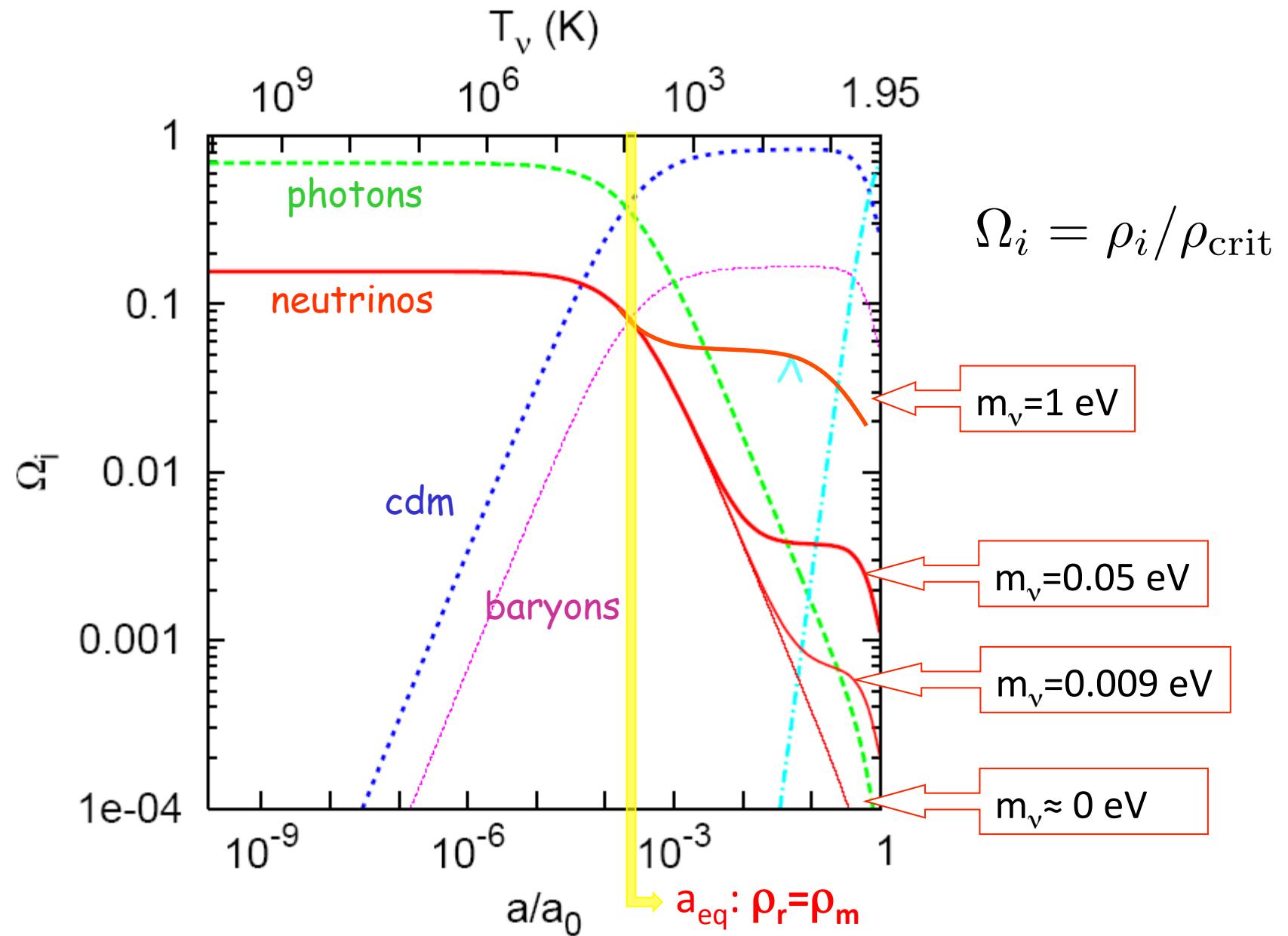
Neutrino masses

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



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

Evolution of the background densities: 1 MeV → now



Neutrinos as Dark Matter

- Neutrinos are natural **DM candidates**

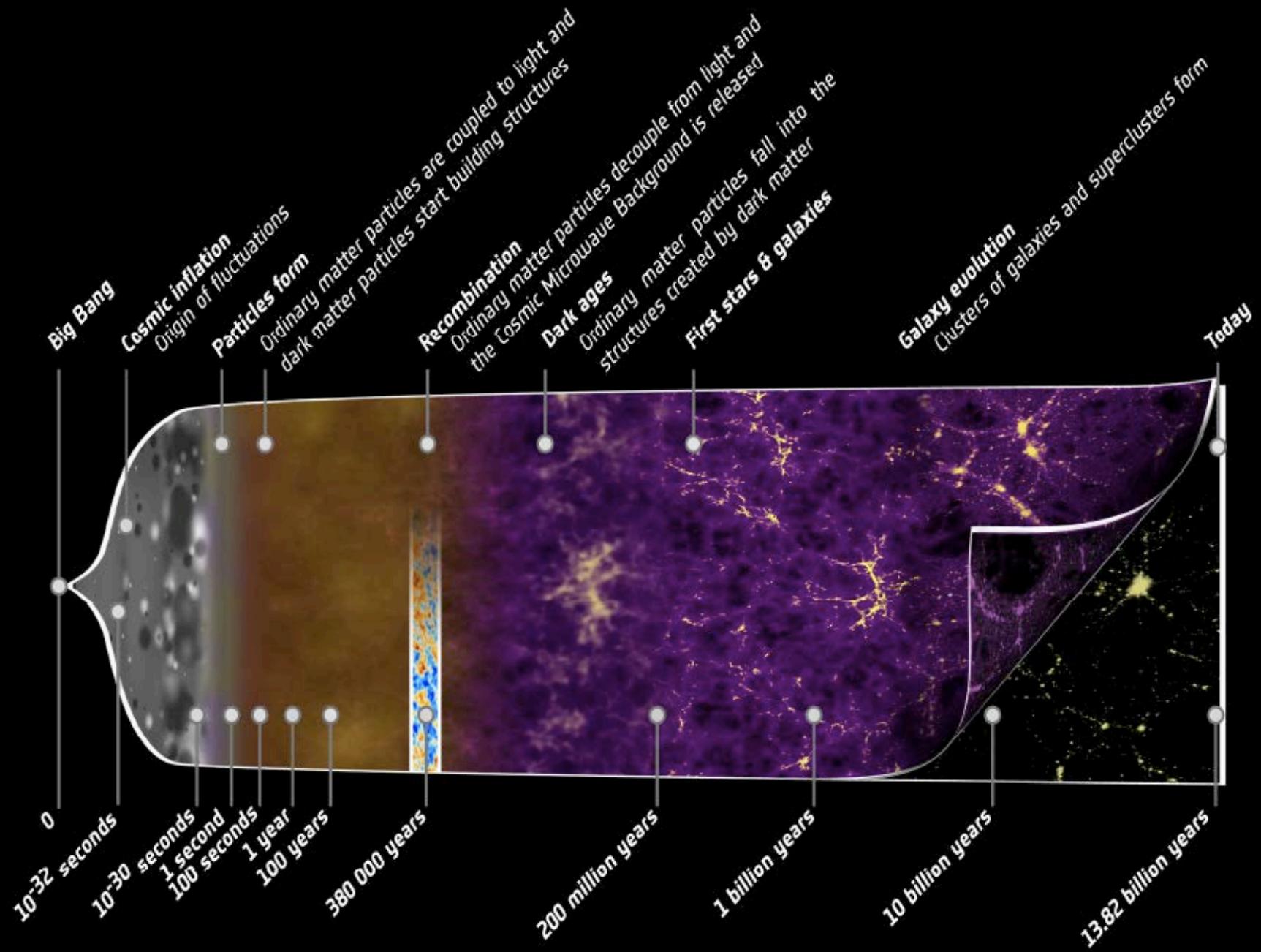
$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2 \text{ eV}} \quad \Omega_\nu < 1 \rightarrow \sum_i m_i \lesssim 46 \text{ eV}$$

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

- 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

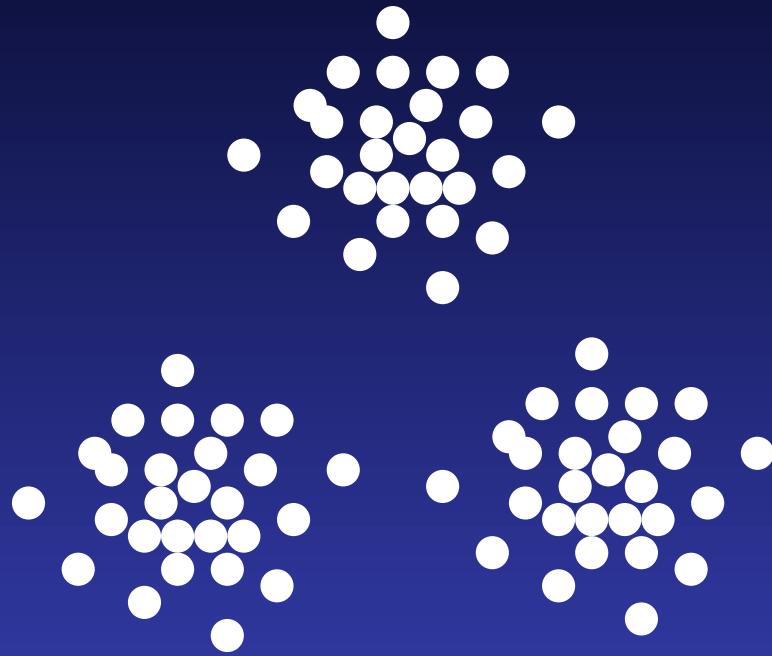
Massive Neutrinos can still be subdominant DM: **limits on m_ν from Structure Formation (combined with other cosmological data)**

Evolution of the Universe



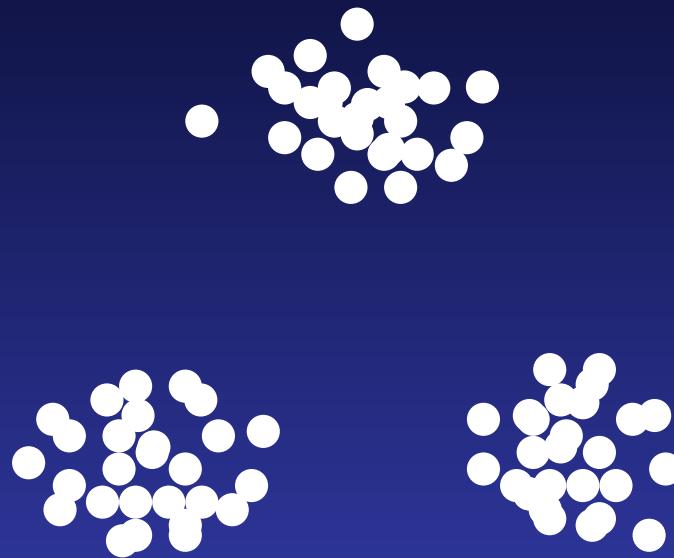
Structure formation after equality

baryons and
CDM (matter)
experience
gravitational
clustering



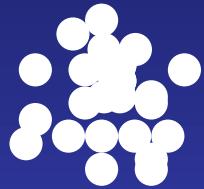
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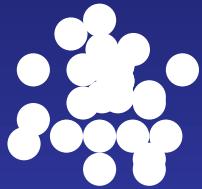
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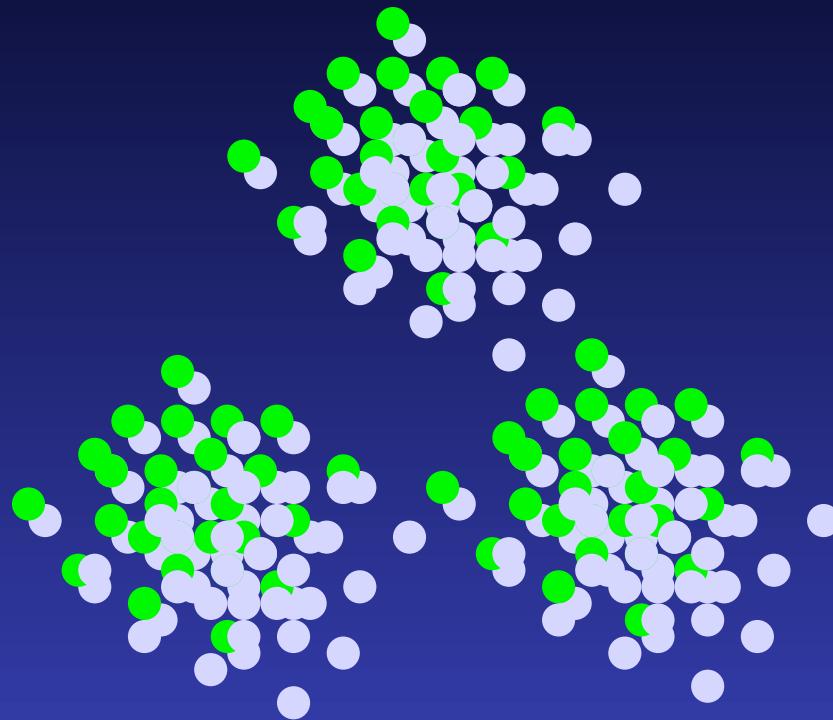


growth of $\delta\rho/\rho(k,t)$ fixed by
gravity vs expansion balance

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

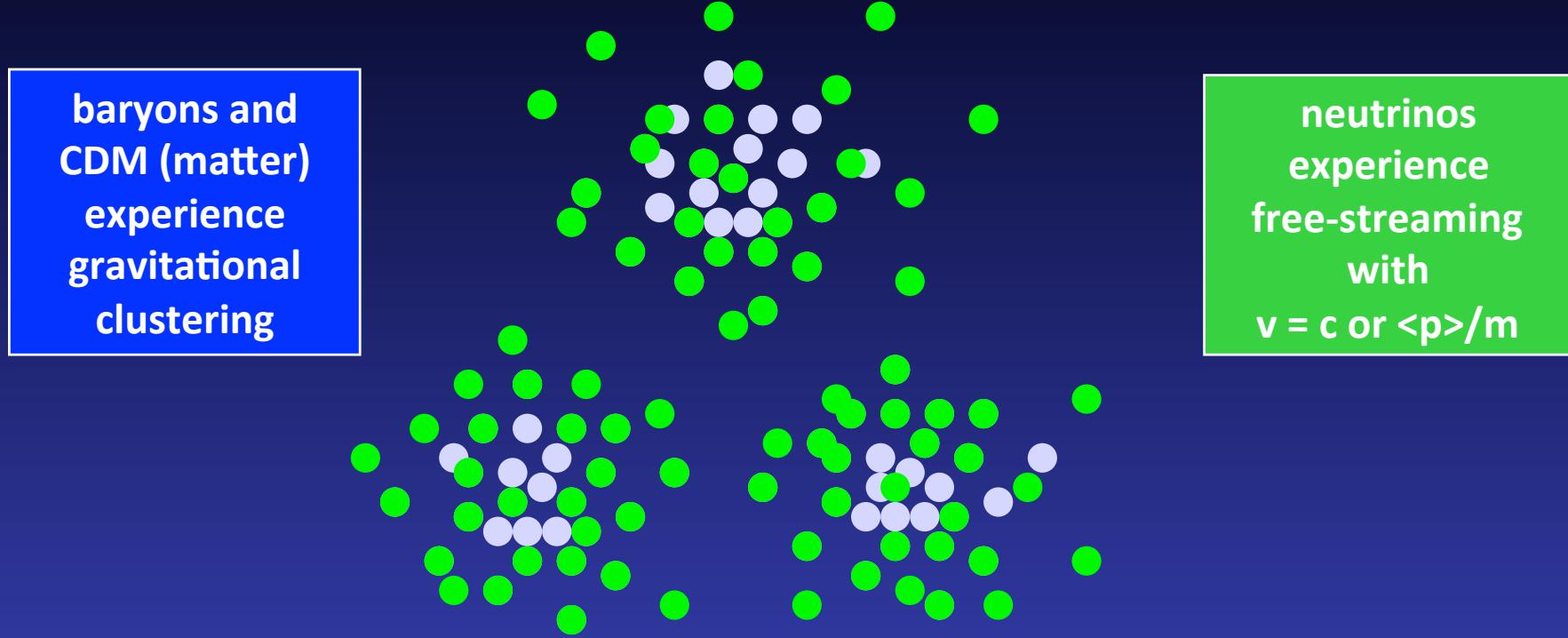
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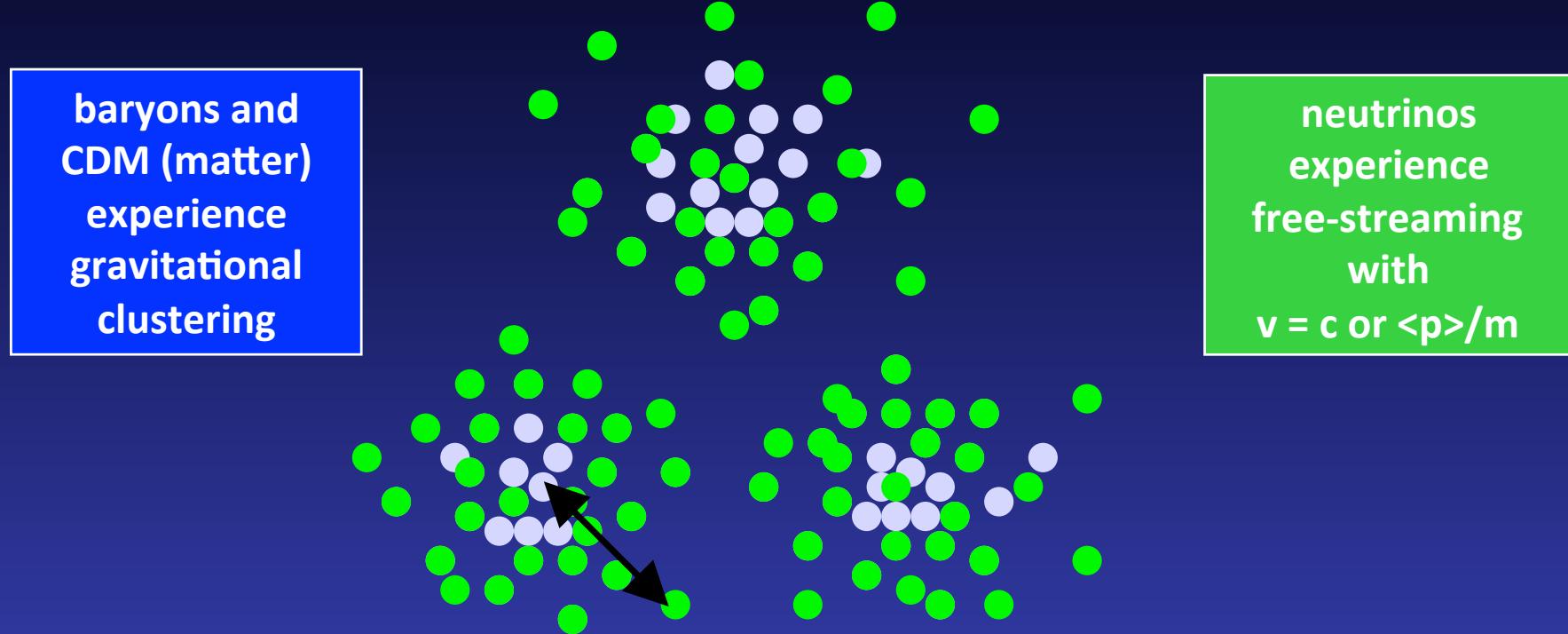


neutrinos
experience
free-streaming
with
 $v = c$ or $\langle p \rangle/m$

Structure formation after equality



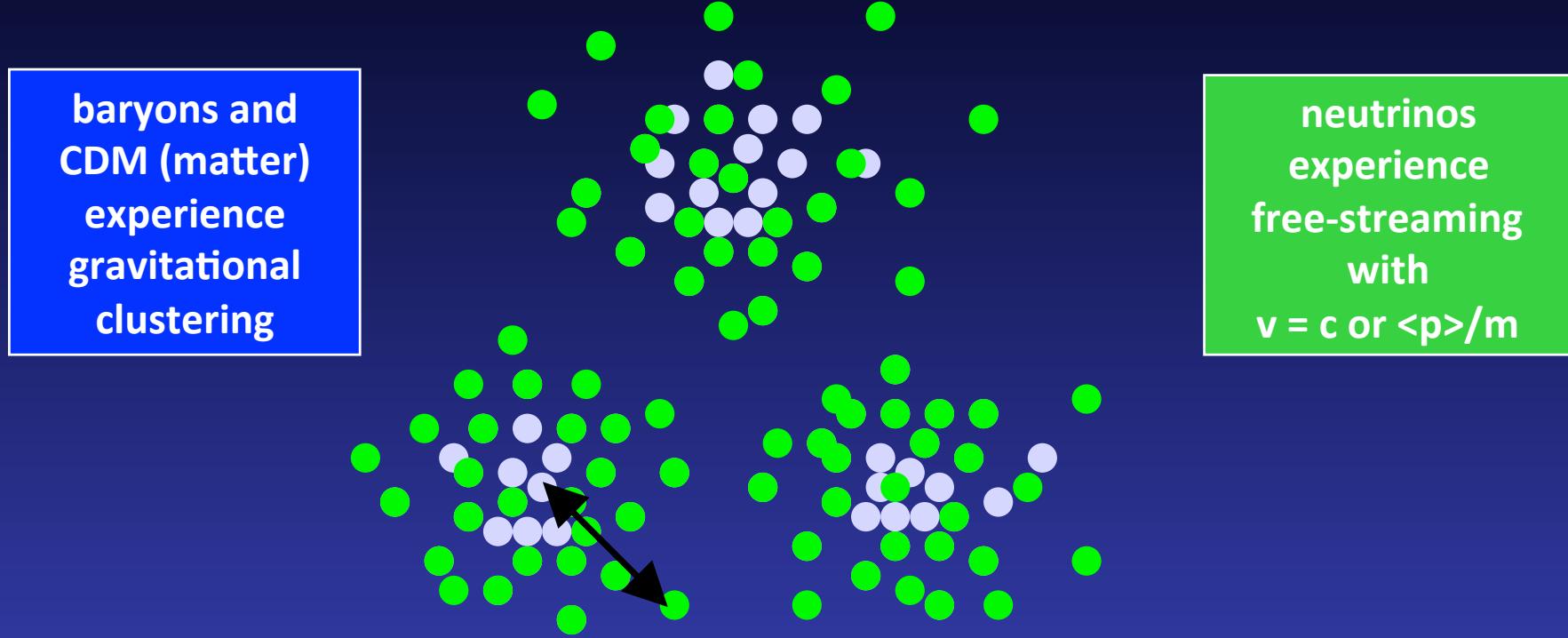
Structure formation after equality



neutrinos cannot cluster below a diffusion length

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

Structure formation after equality



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

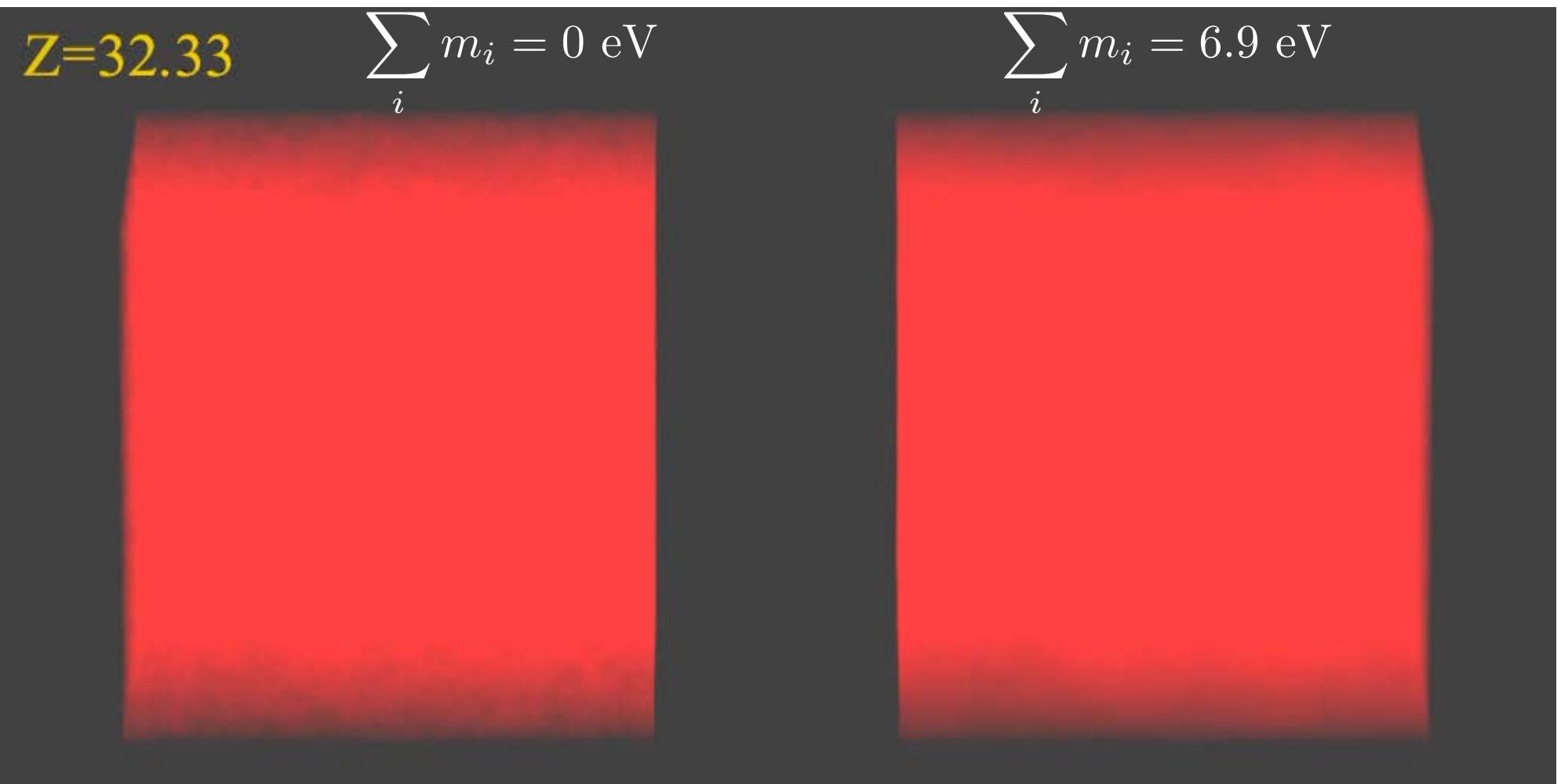
free-streaming suppresses growth of structures during MD

$$\Rightarrow \delta\rho/\rho \propto a^{1-3/5} f_v$$

$$\text{with } f_v = \rho_v / \rho_m \approx (\Sigma m_v) / (15 \text{ eV})$$

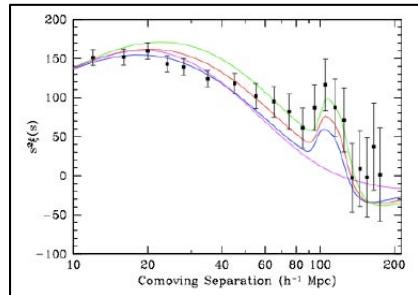
Neutrinos as Hot Dark Matter

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

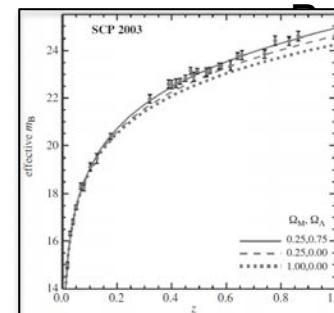


Effects of neutrino masses on cosmological observables

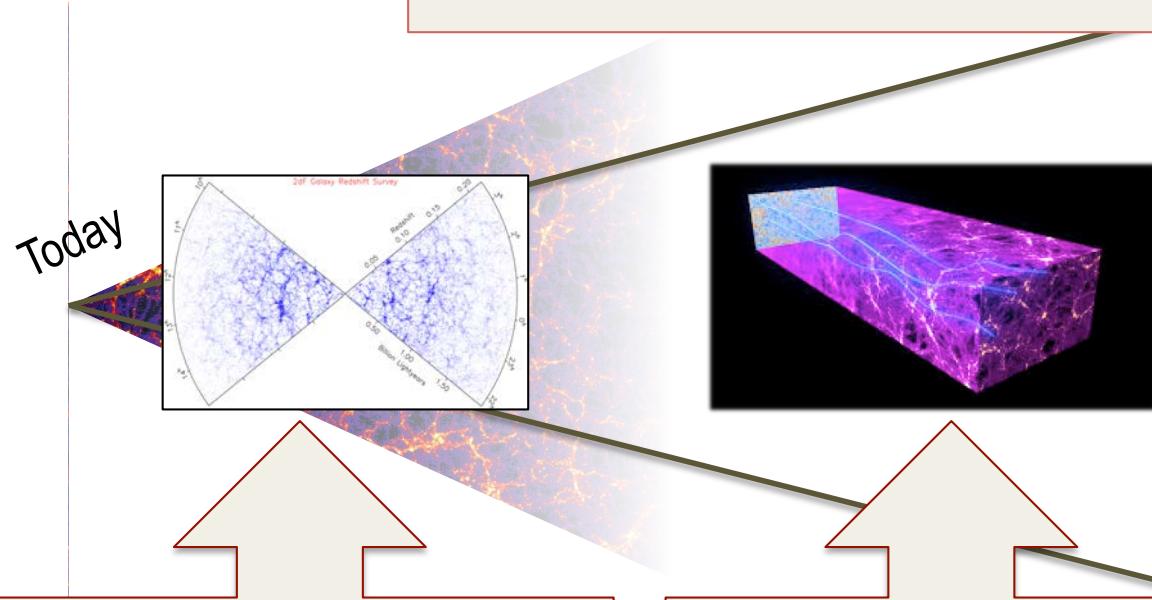
Cosmological Observables



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

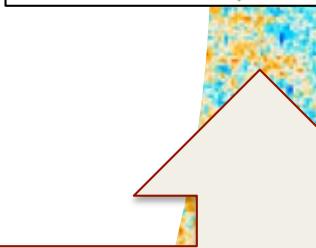
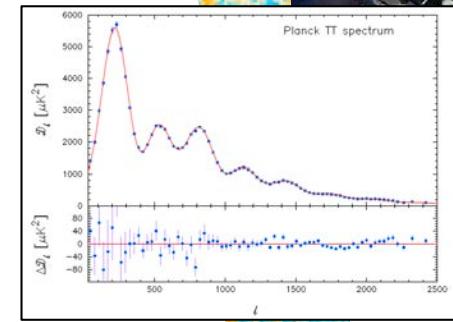


combination



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

Photon momentum
after decoupling
CMB secondary anisotropy
spectrum



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

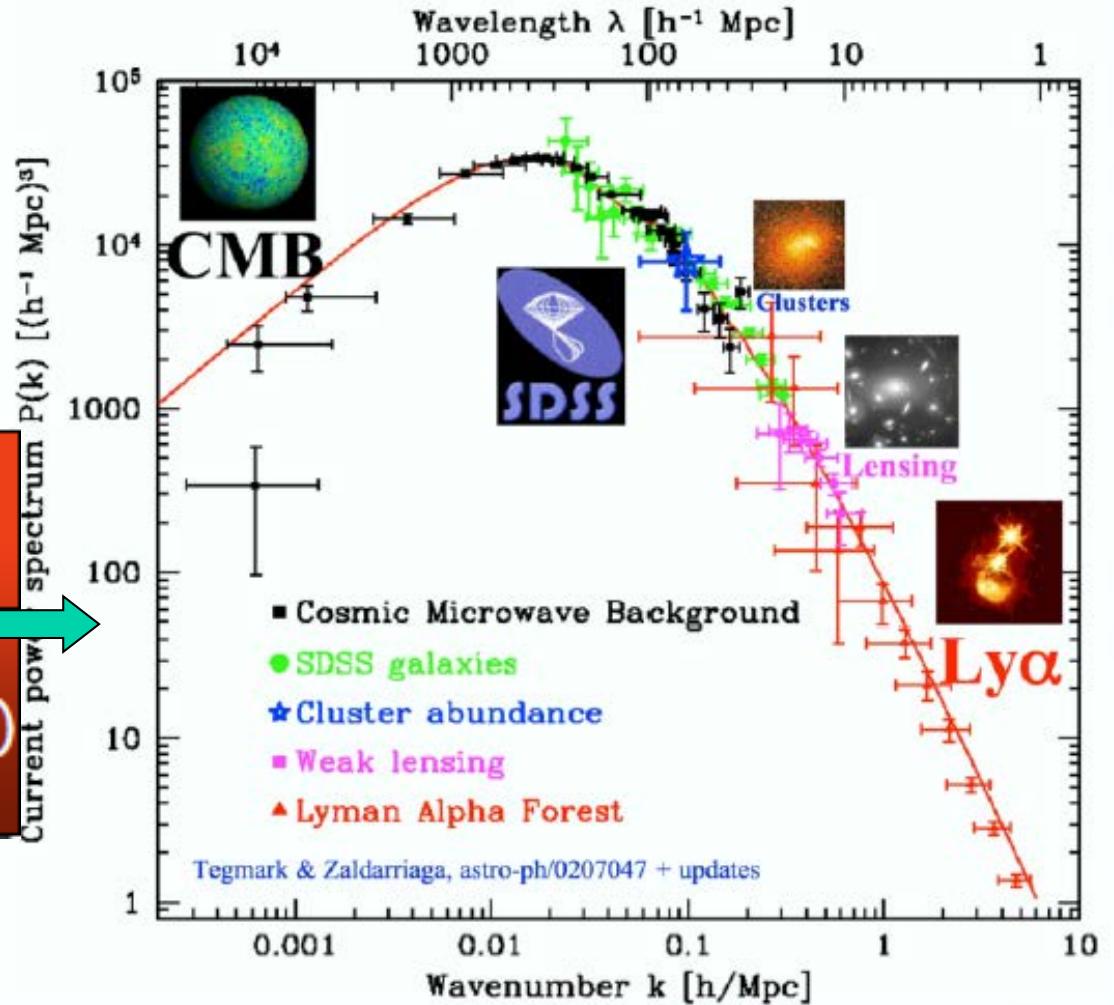
Power Spectrum of density fluctuations

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 $P(k)$

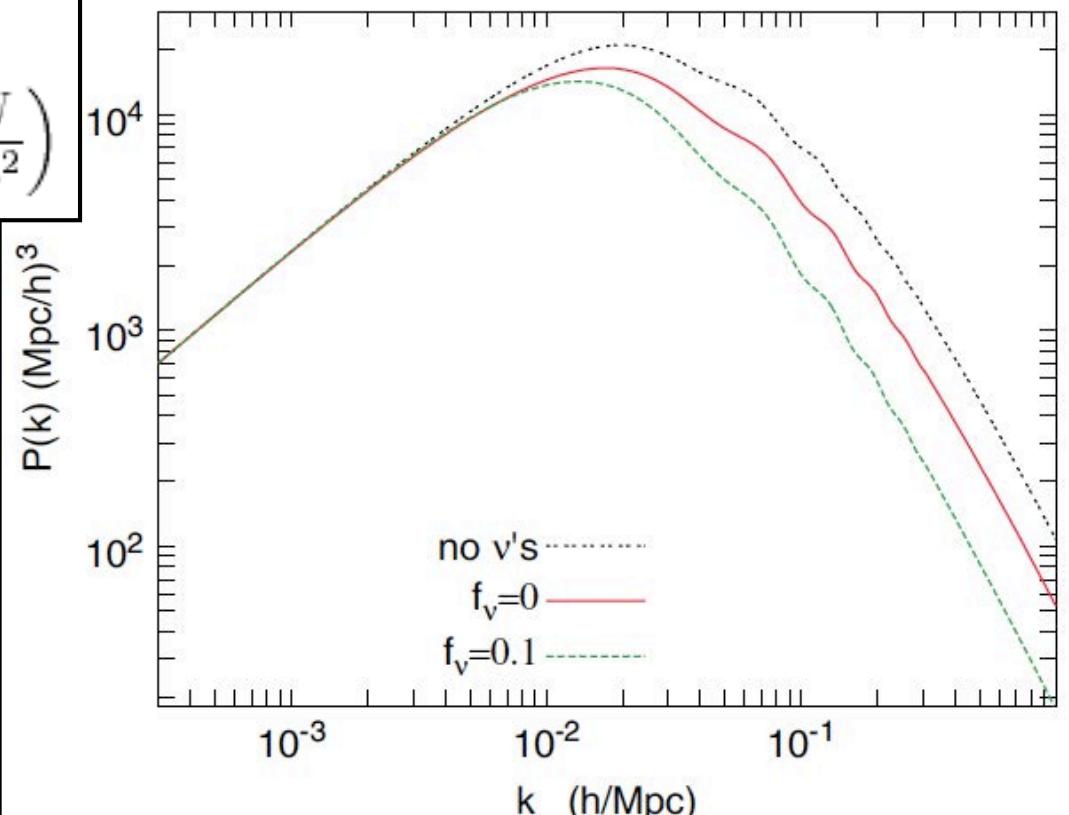
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

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

The small-scale suppression is given by

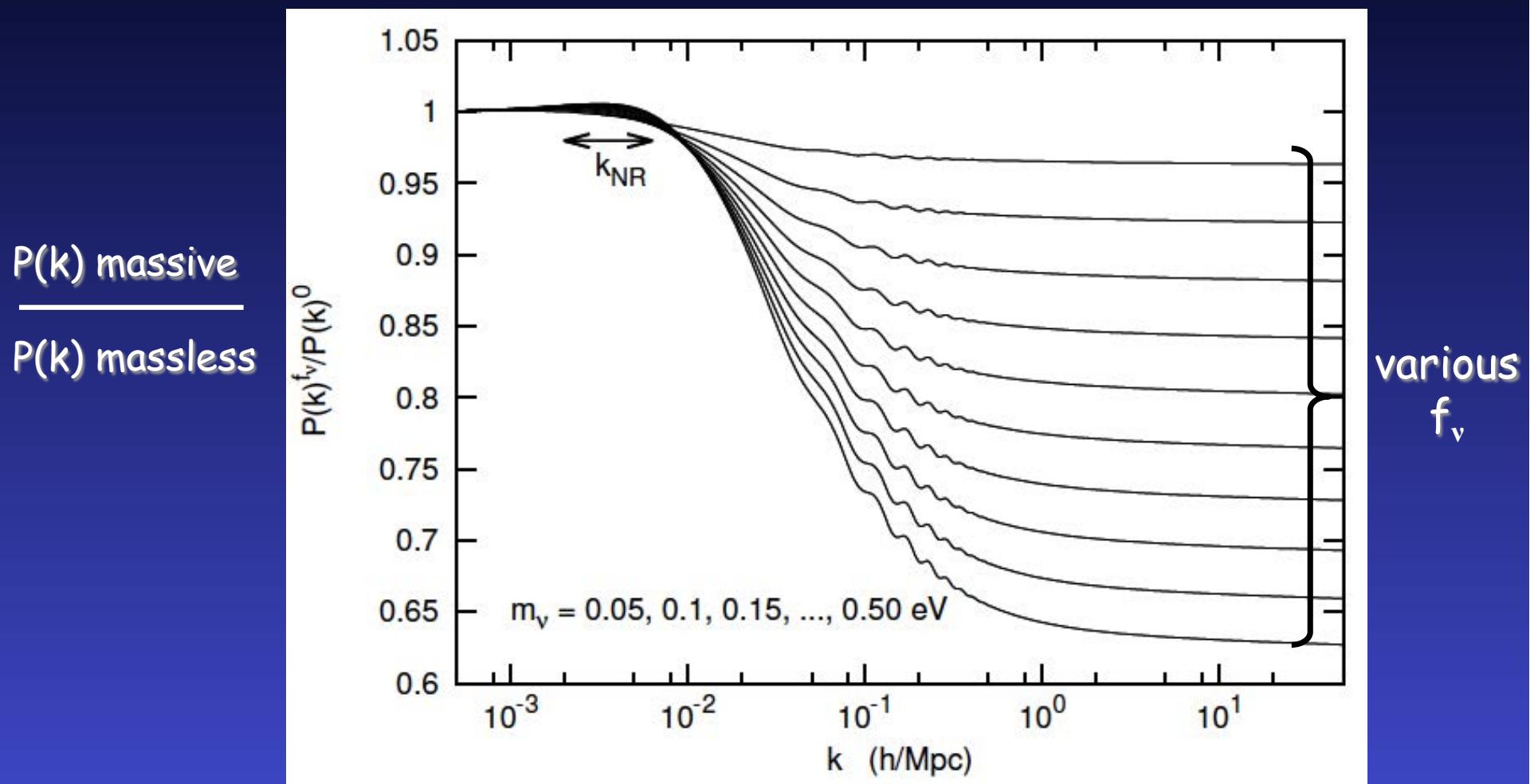
$$\left(\frac{\Delta P}{P}\right) \approx -8 \frac{\Omega_\nu}{\Omega_m} \approx -0.8 \left(\frac{m_\nu}{1 \text{ eV}}\right) \left(\frac{0.1N}{\Omega_m h^2}\right)$$

f_ν

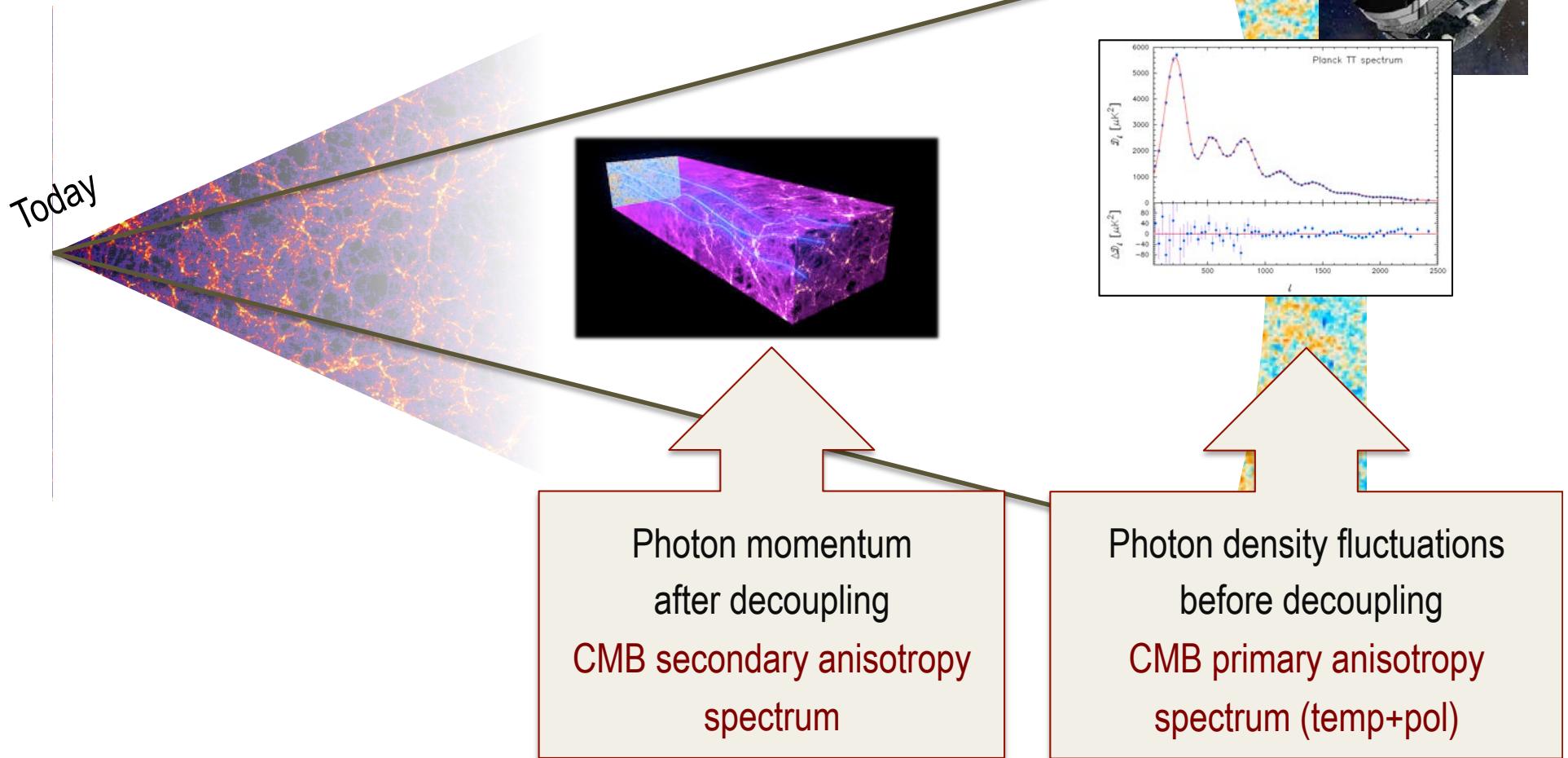


Effect of massive neutrinos on $P(k)$

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

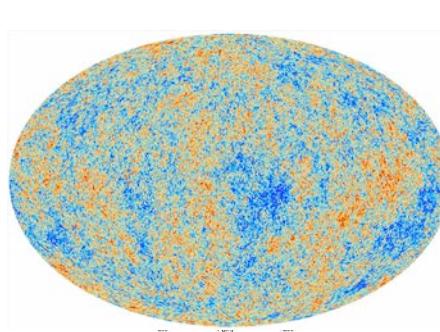


Cosmological Observables



from J. Lesgourges

CMB data from Planck



Map of CMBR temperature Fluctuations

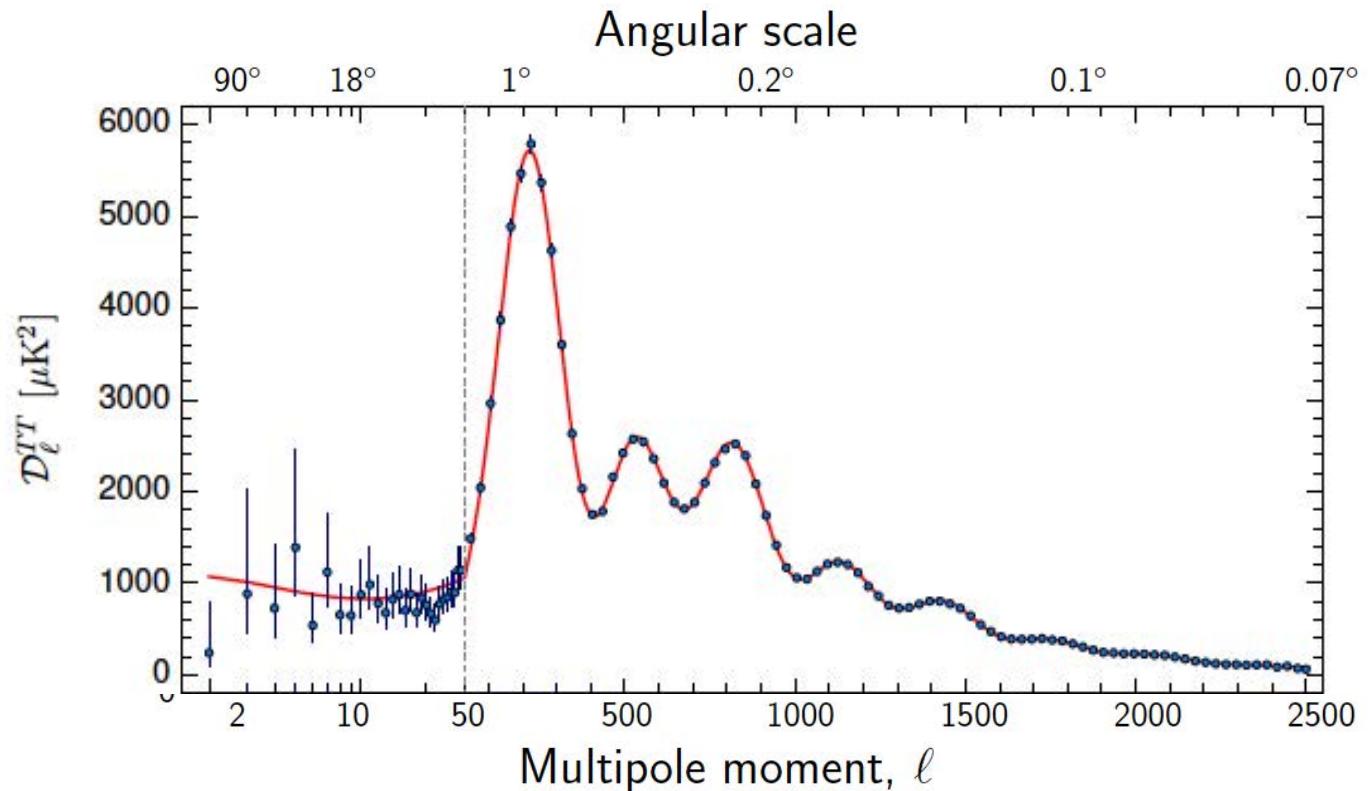
$$\Delta(\theta, \varphi) = \frac{T(\theta, \varphi) - \langle T \rangle}{\langle T \rangle}$$

Multipole Expansion

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

Angular Power Spectrum

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

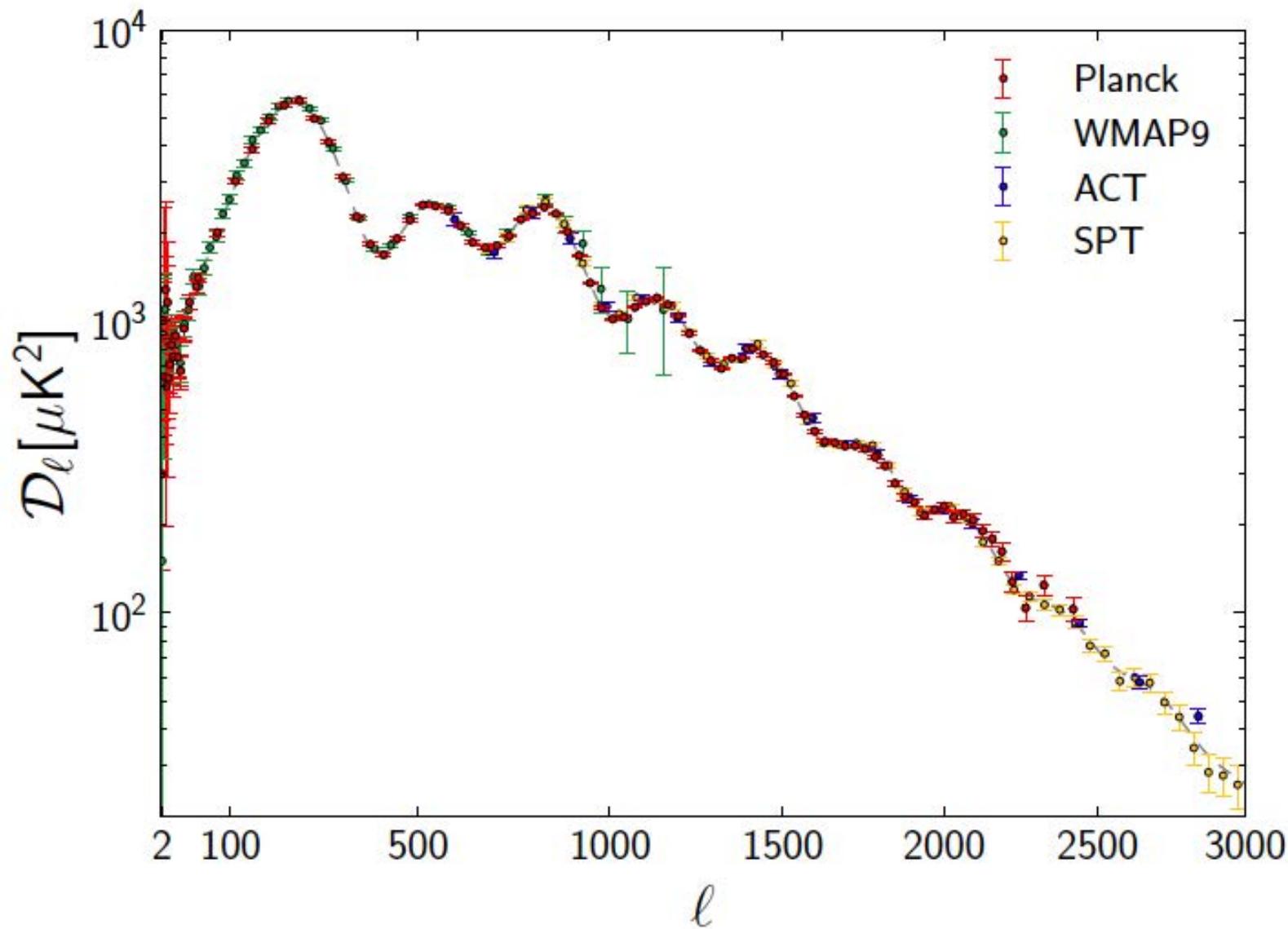


PLANCK 2015: results from 15 months, measures the TT CMB spectrum in a wide range of l's (also TE & EE)

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

Present CMB data

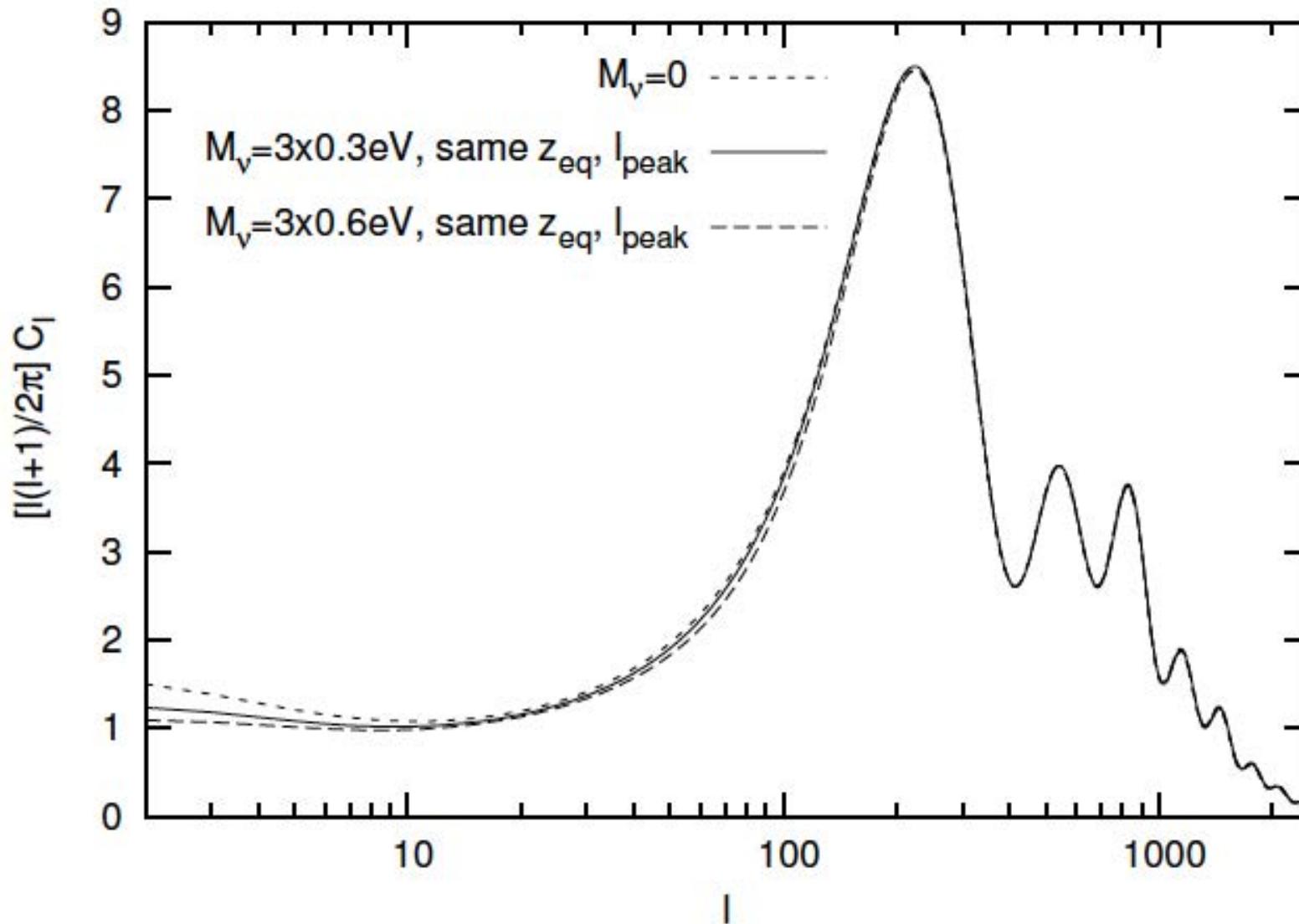
Planck vs other experiments



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 $\sum m_\nu > 1.5$ 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

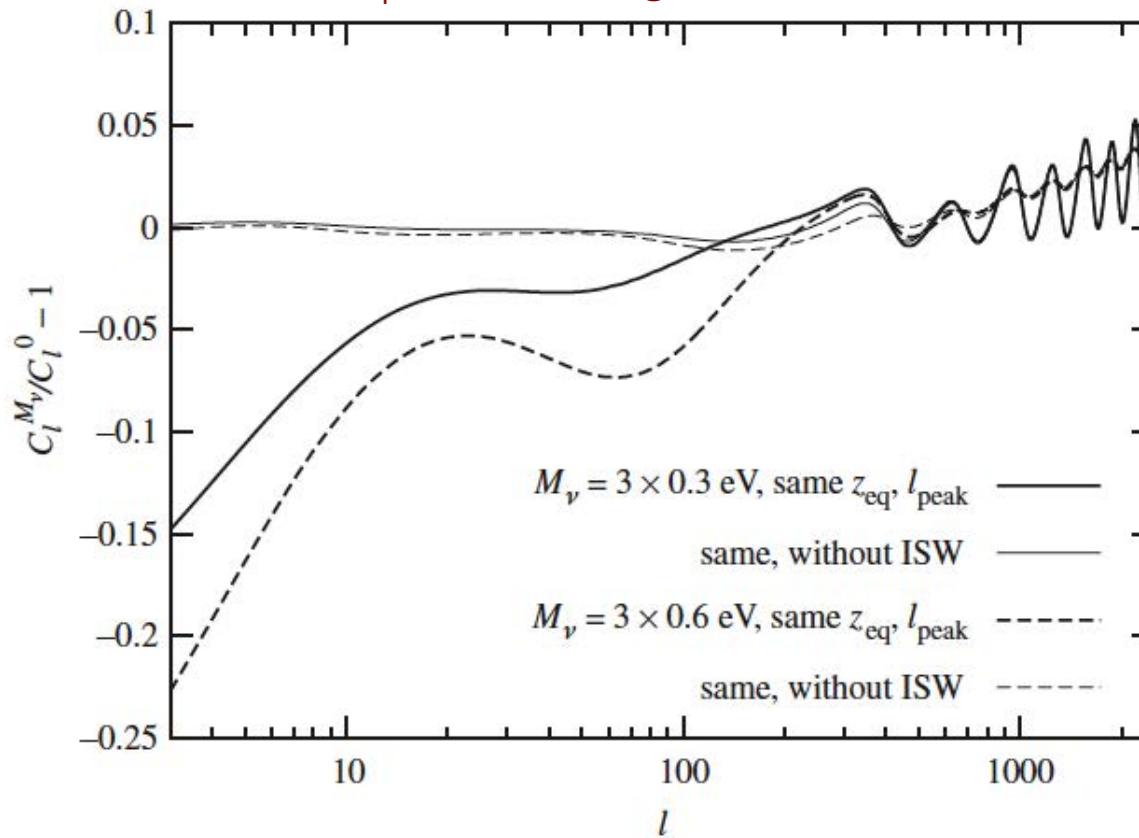


Effects of m_ν on the CMB

- 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:

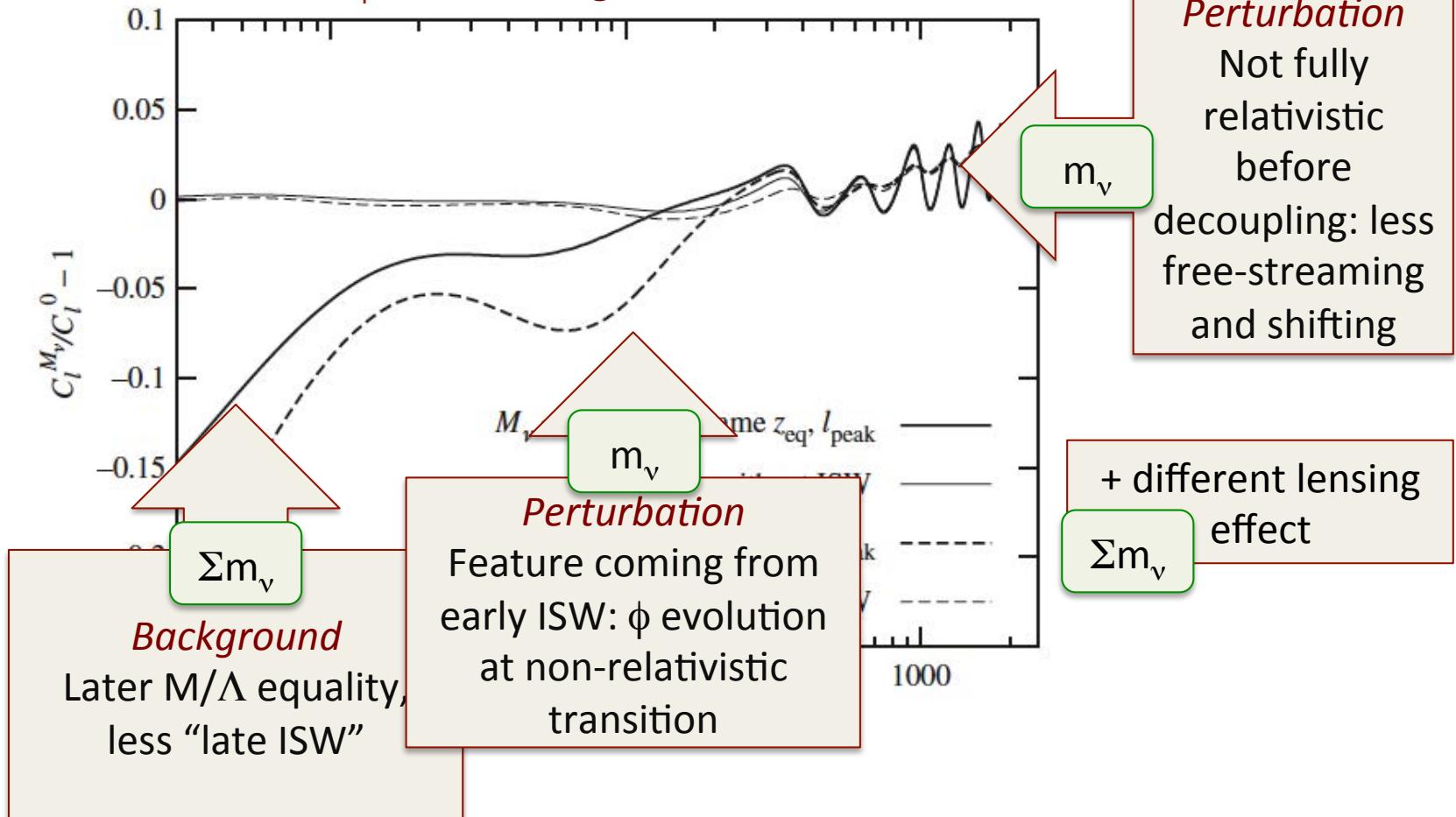


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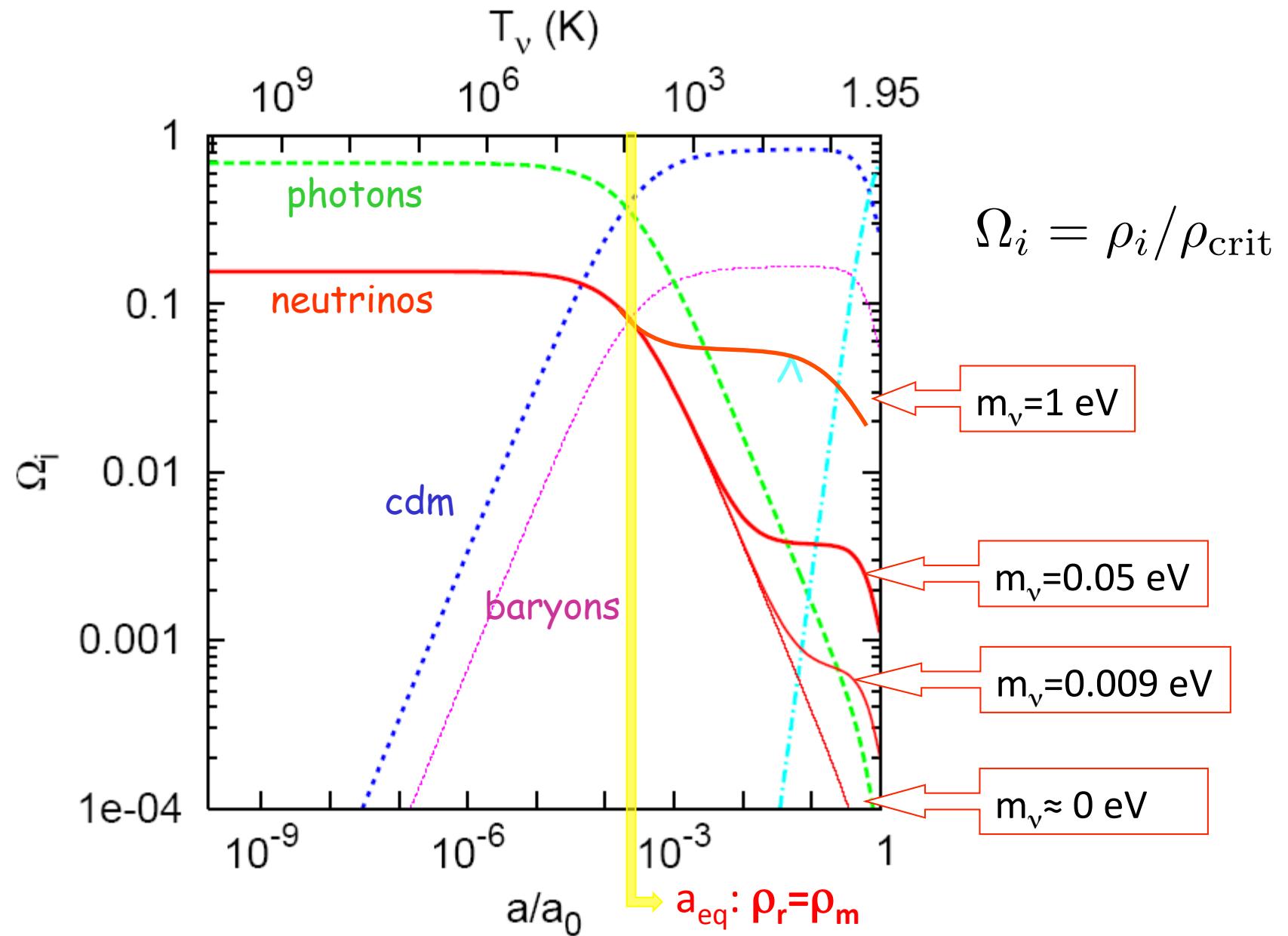


Effects of N_{eff} on cosmological observables

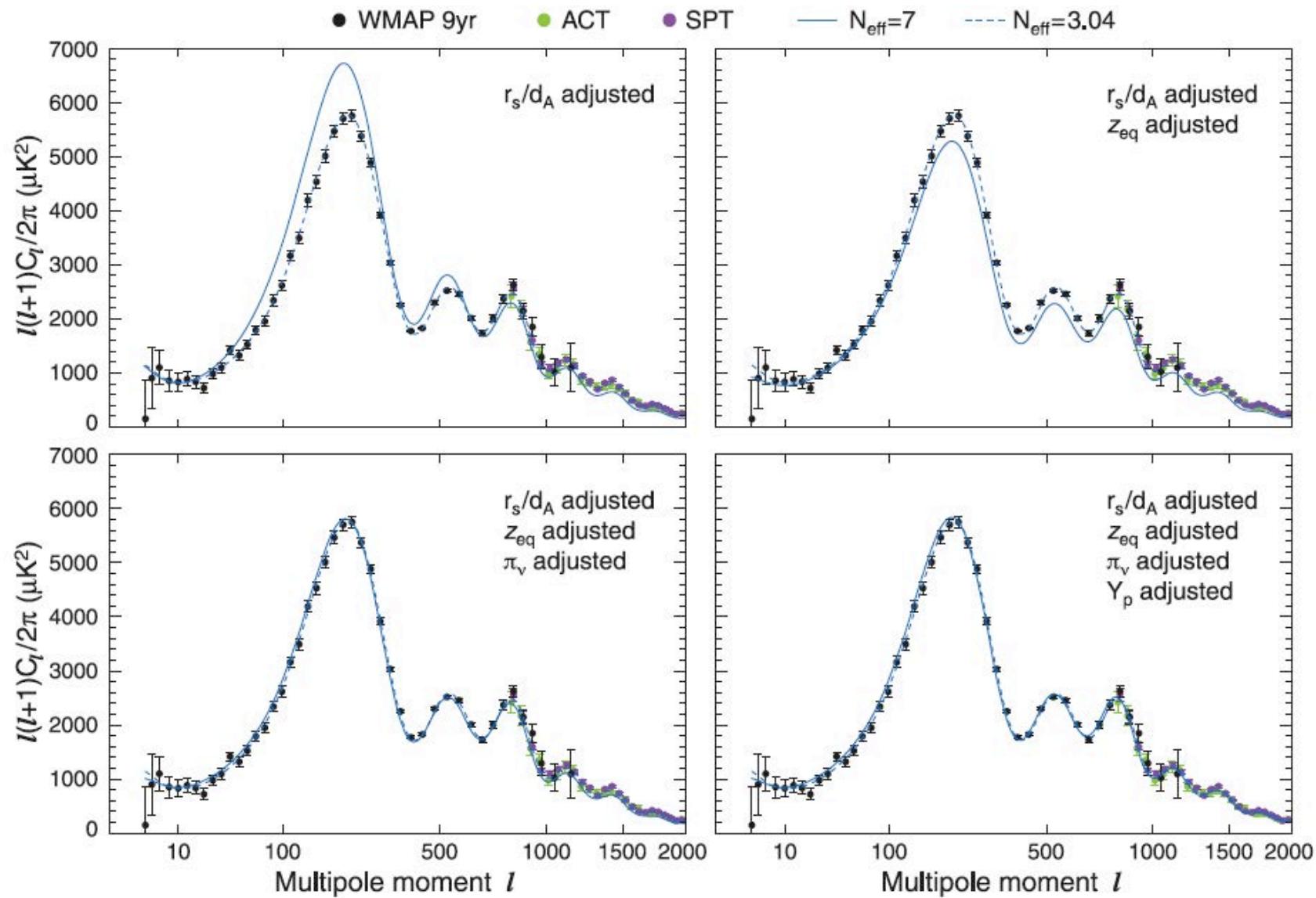
Effects of N_{eff} on the CMB

- 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



Effects of N_{eff} on the CMB

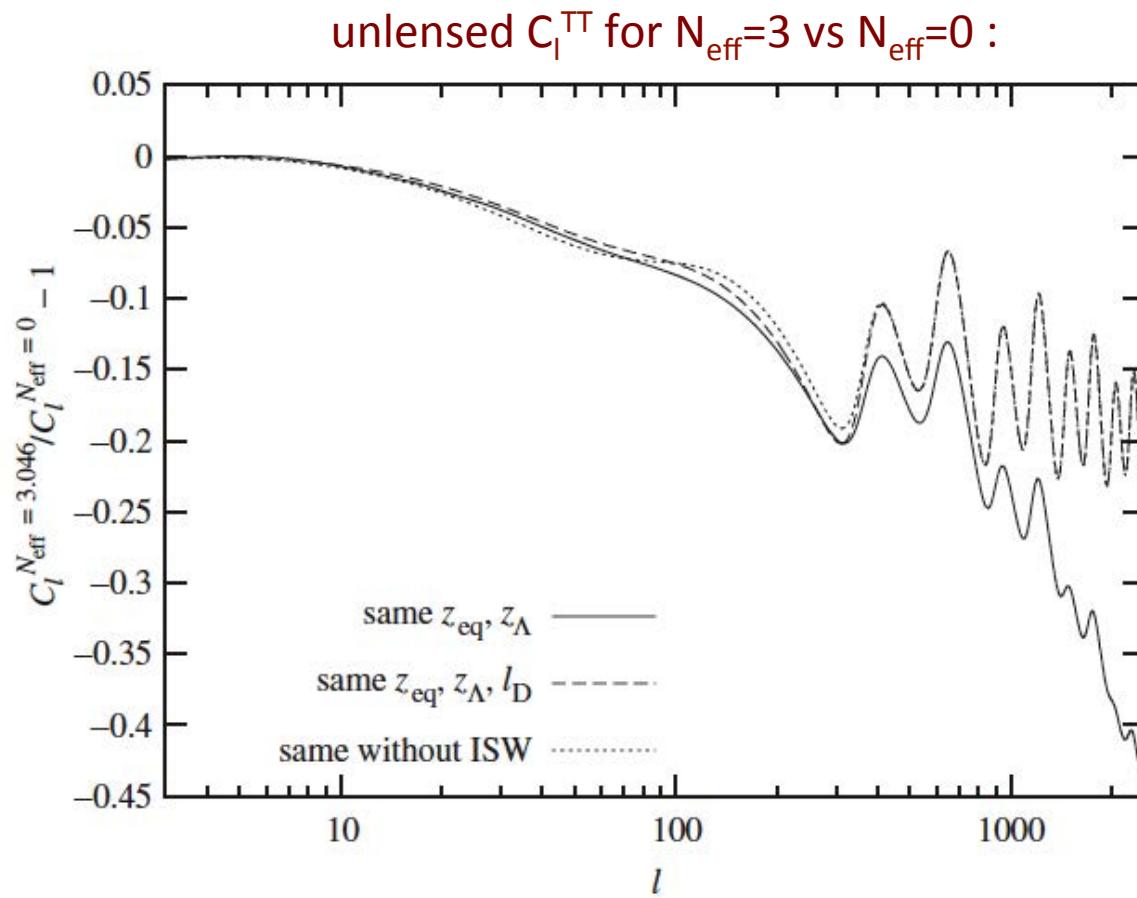


Hinshaw et al, arXiv:1212.5226

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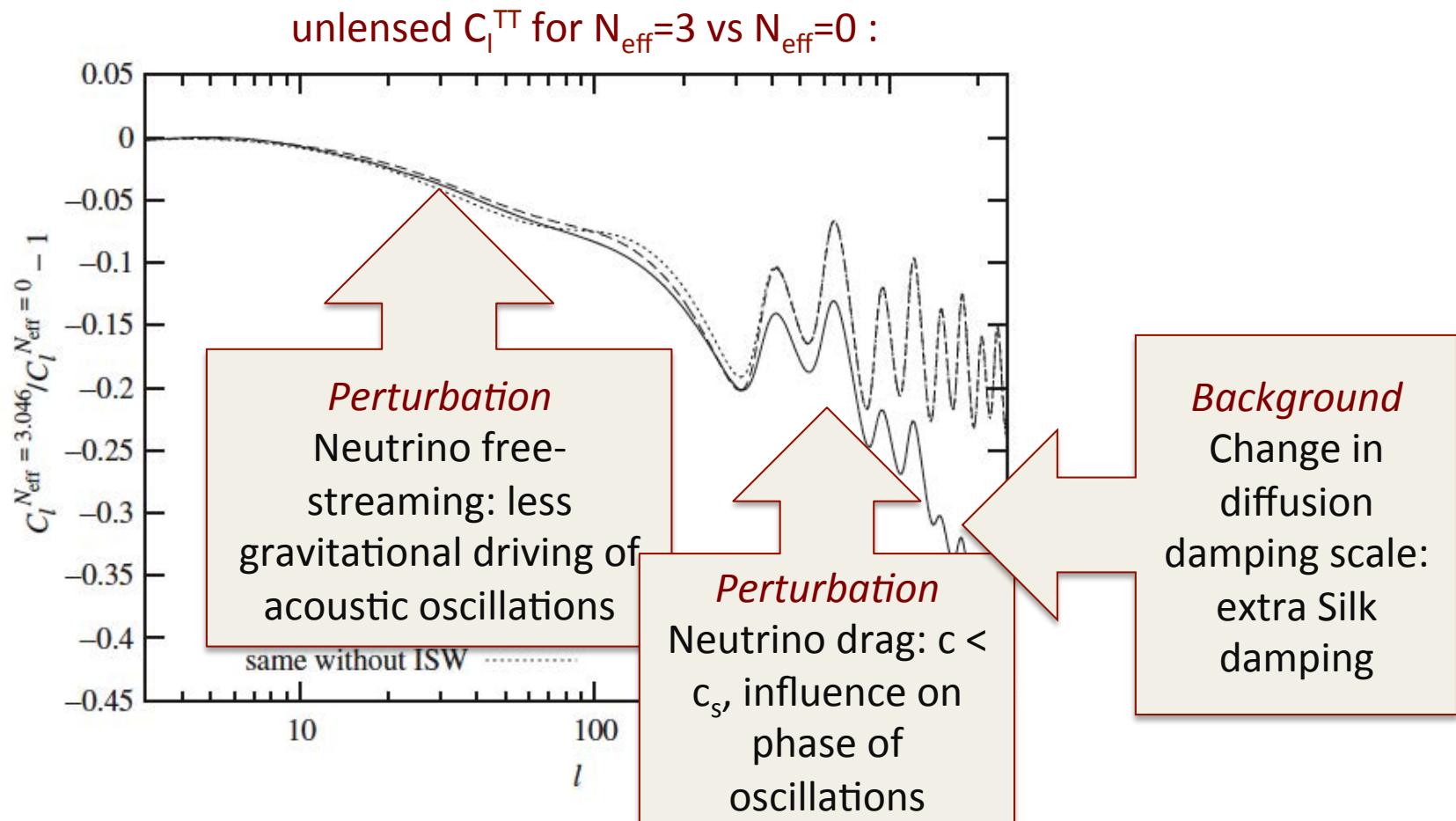
simultaneous enhancement of radiation, matter, L densities, with fixed photon and baryon densities



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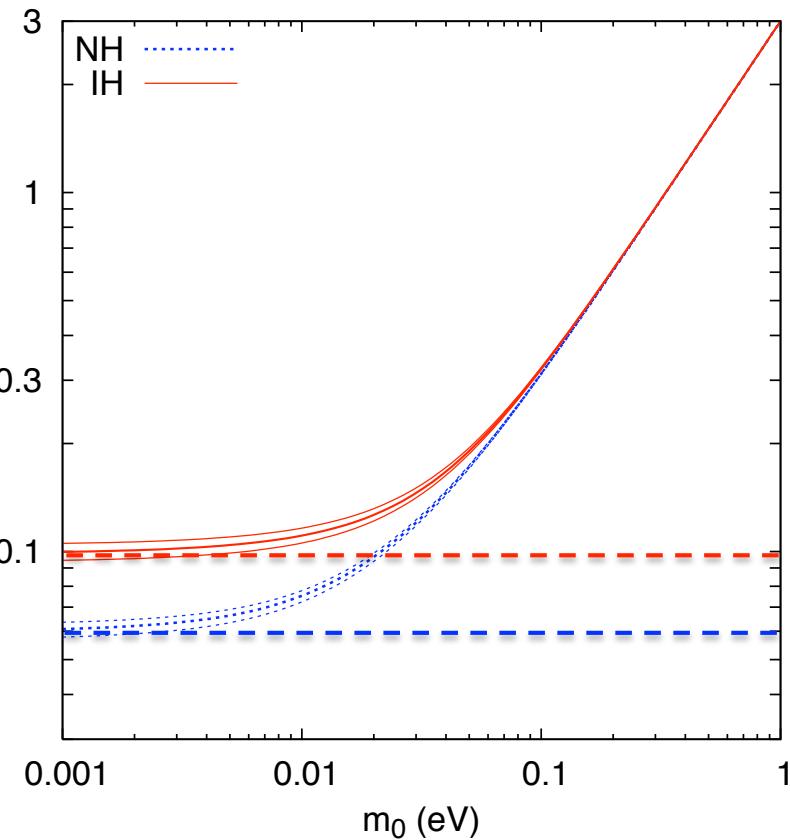
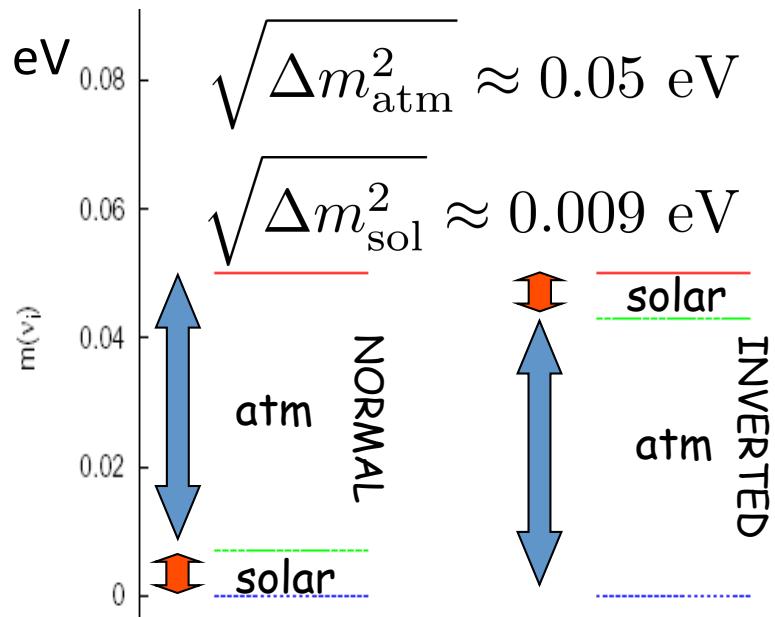
simultaneous enhancement of radiation, matter, L densities, with fixed photon and baryon densities



Present bounds on neutrino properties from cosmology

Neutrino masses

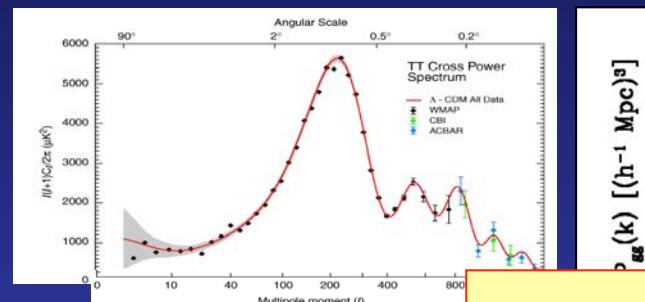
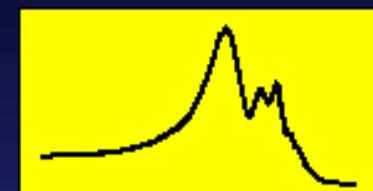
Data on flavour oscillations do not fix the absolute scale of neutrino masses



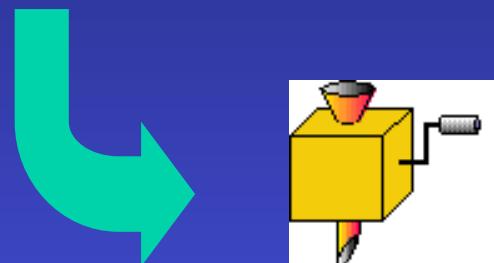
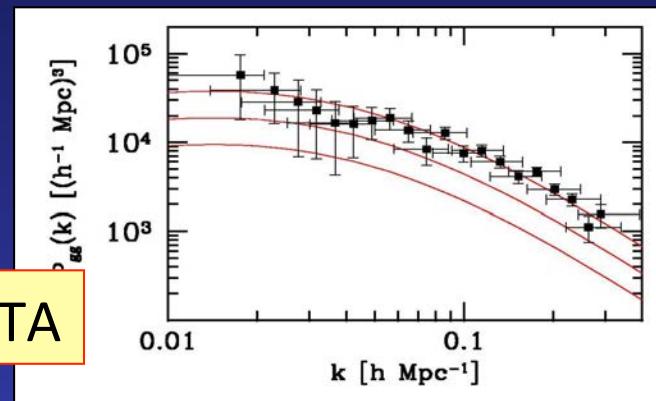
$$0.06(0.1) \text{ eV} \lesssim \sum_i m_i \lesssim 6 \text{ eV}$$

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

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

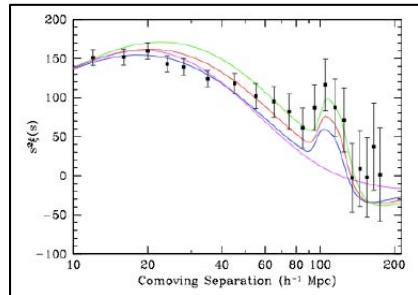


DATA

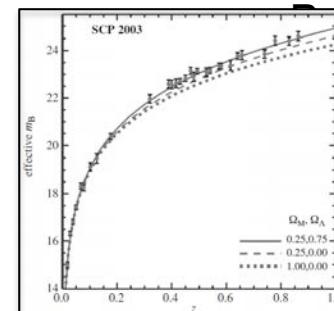


PARAMETER
ESTIMATES

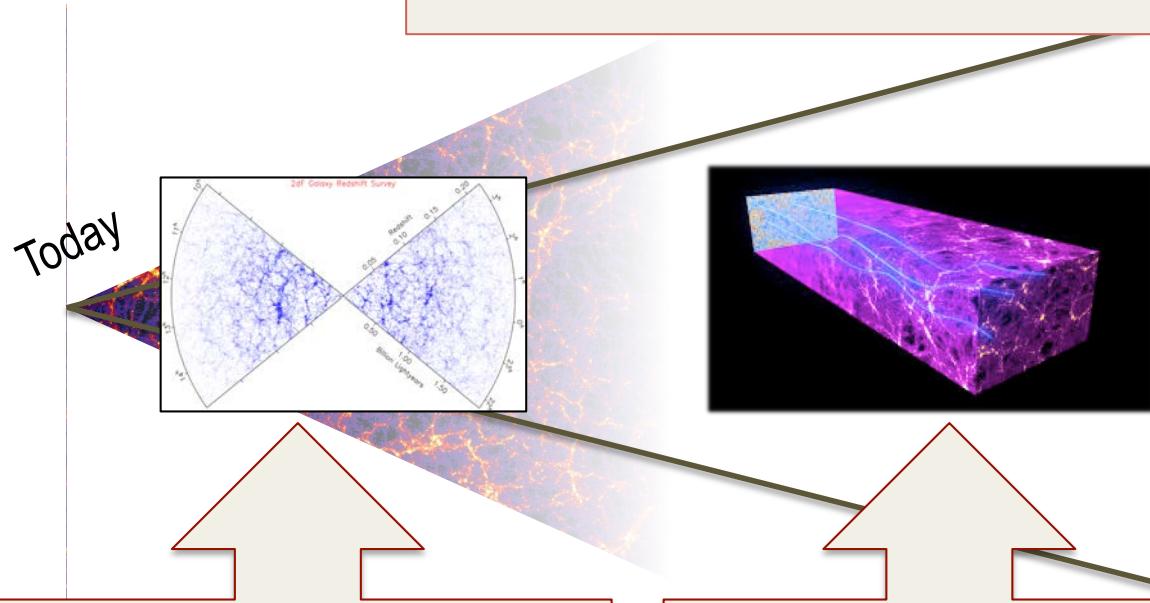
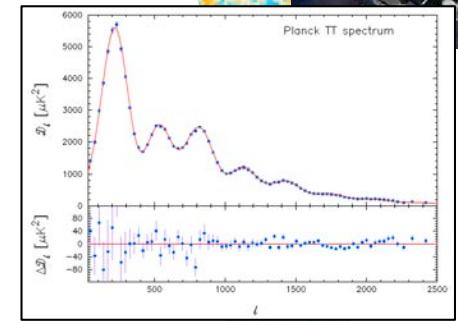
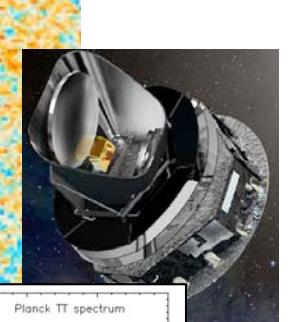
Cosmological Observables



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



combination



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

Photon momentum
after decoupling
CMB secondary anisotropy
spectrum

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

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: SN Ia (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 Λ CDM 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
$100\theta_{\text{MC}}$	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
$100\theta_{\text{MC}}$	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 Λ CDM model

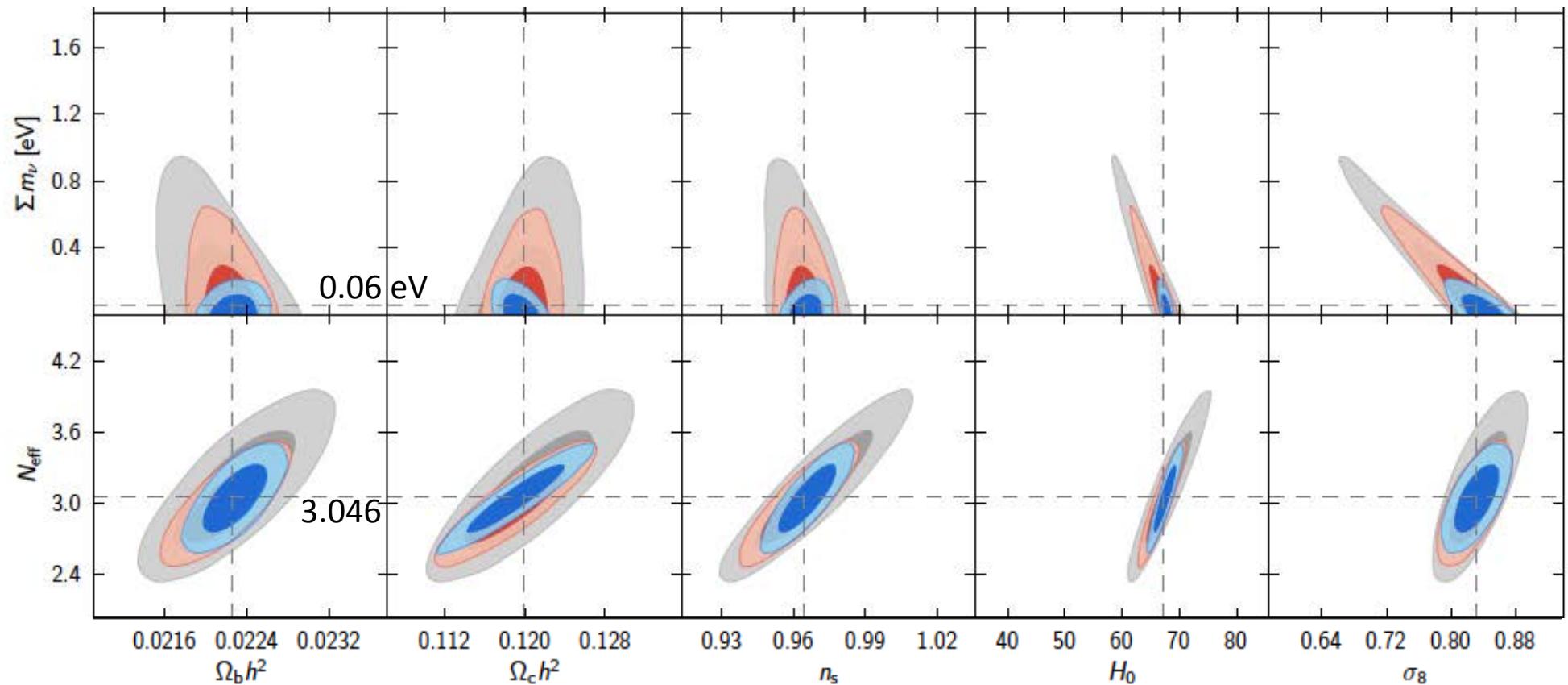
Parameter	TT	TT+lensing	TT+lensing+ext	
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	95% CL limits
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	
N_{eff}	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	
Y_P	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	
$dn_s/d \ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	
$r_{0.002}$	< 0.103	< 0.114	< 0.114	
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	

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_{eff}	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
Y_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 Λ CDM model

68+95%
Conf regions



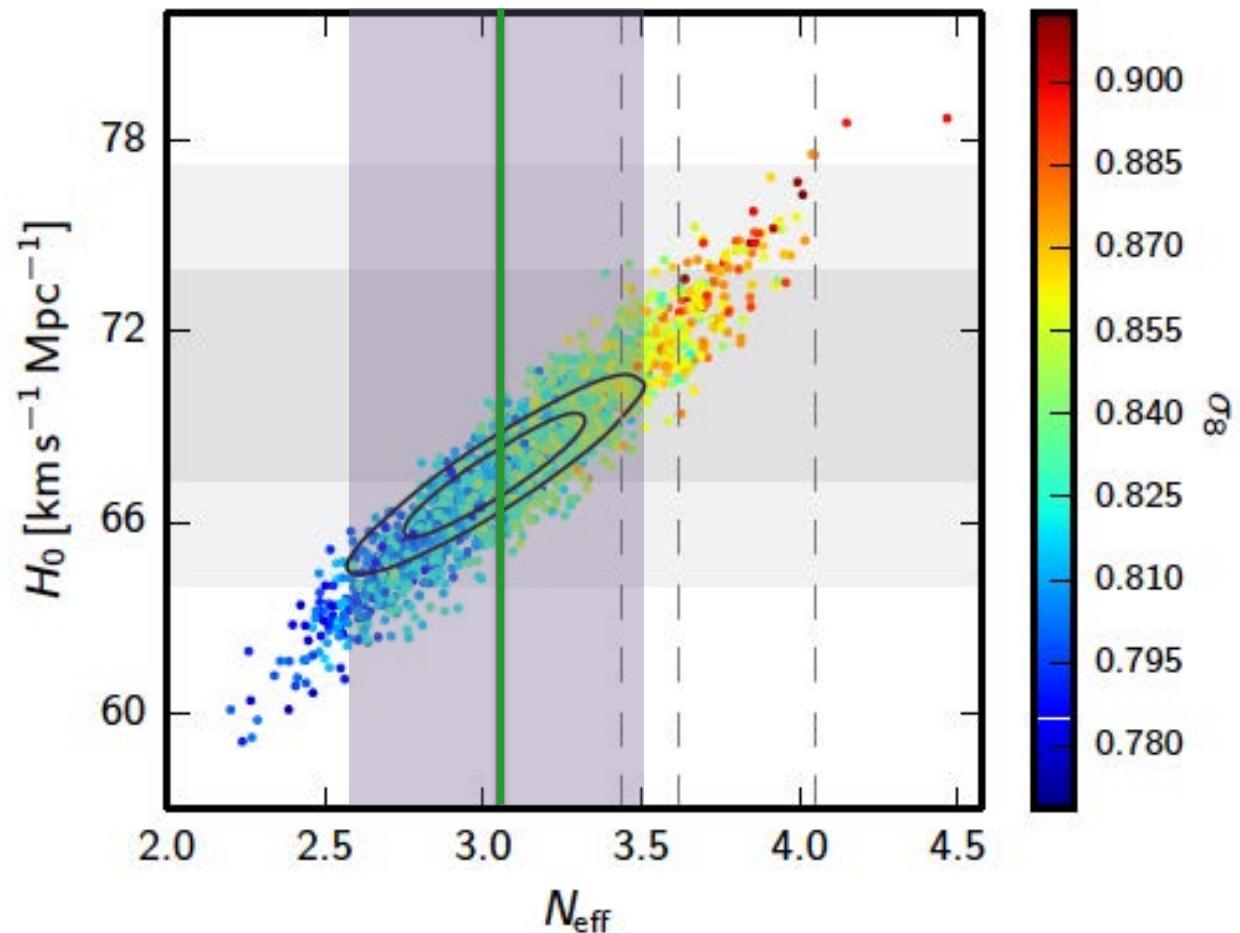
Planck TT + lowP

Planck TT,TE,EE + lowP

Planck TT,TE,EE + lowP + BAO

Measuring N_{eff}

Indirect detection of
CNB at $10\text{-}17\sigma$



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

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

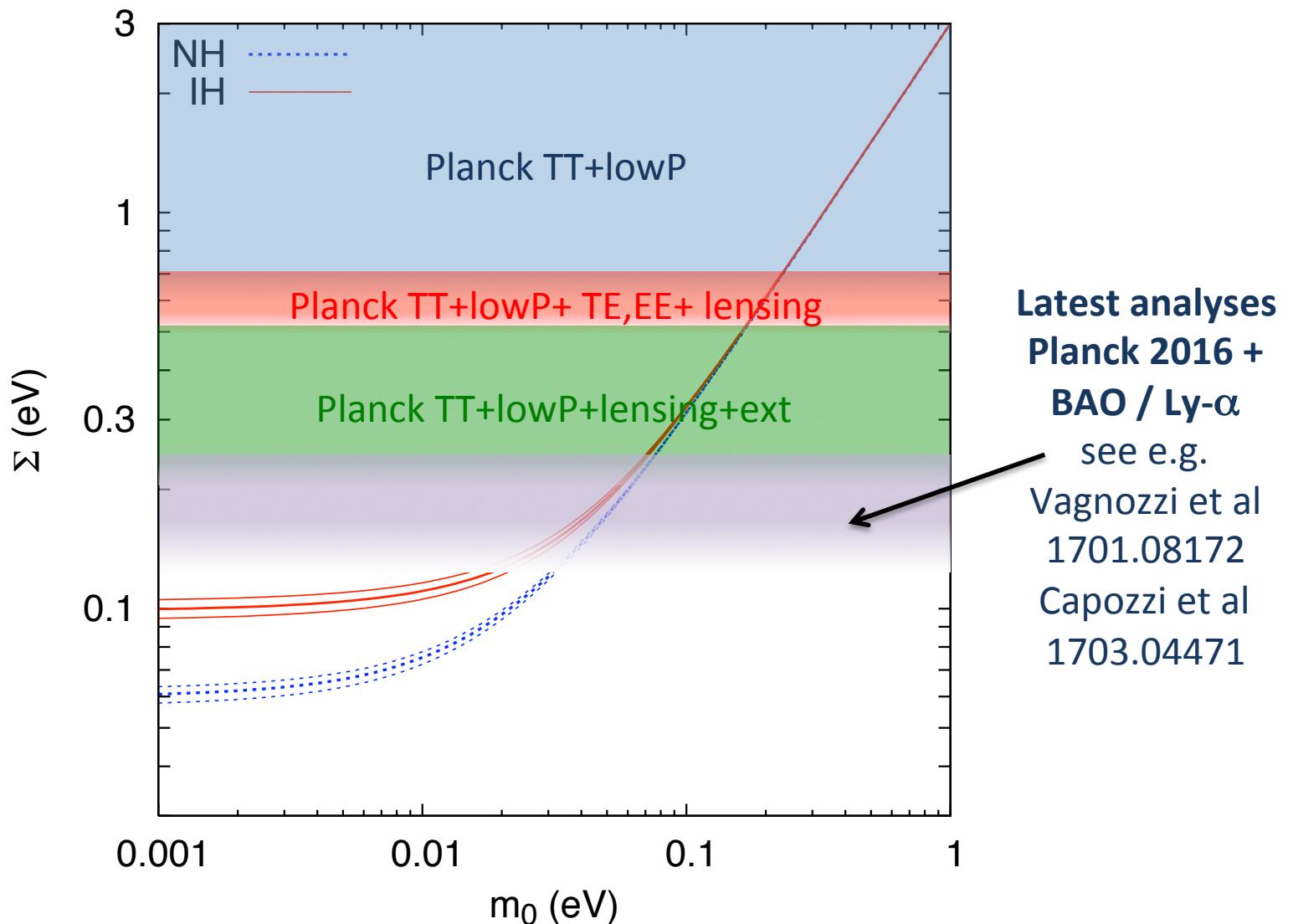
$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \text{Planck TT, TE, EE+lowP};$$

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

All 68%CL

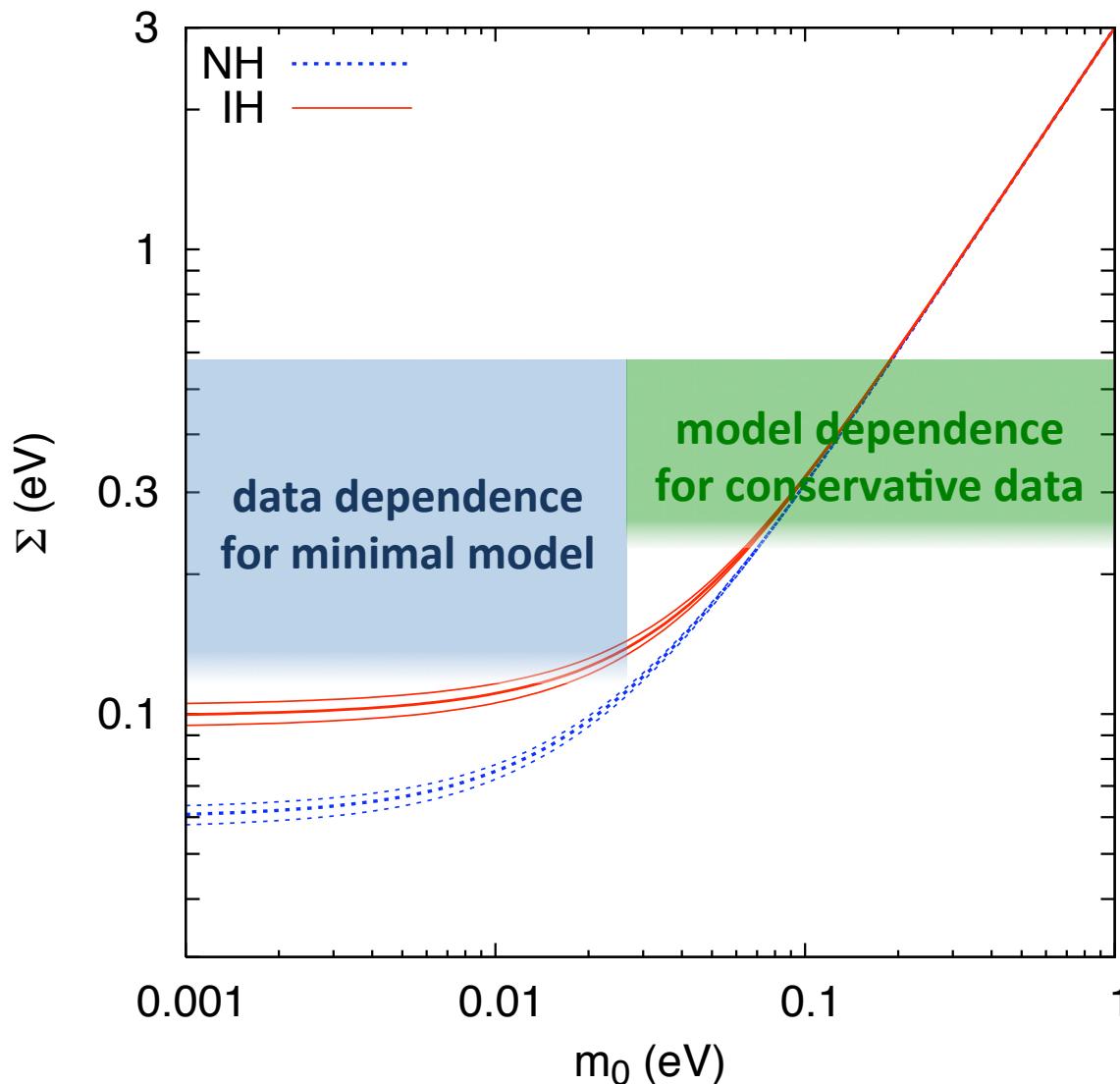
Measuring m_ν with Planck (+other cosmo data)

Cosmological upper limits on the sum of neutrino masses



Measuring m_ν with Planck (+other cosmo data)

Cosmological upper limits on the sum of neutrino masses



Measuring m_ν & N_{eff} with Planck

Results are practically unchanged (example from Planck 2013)

CMB alone (Planck+WP+HighL):

$$\Sigma m_\nu < 0.60 \text{ eV}$$

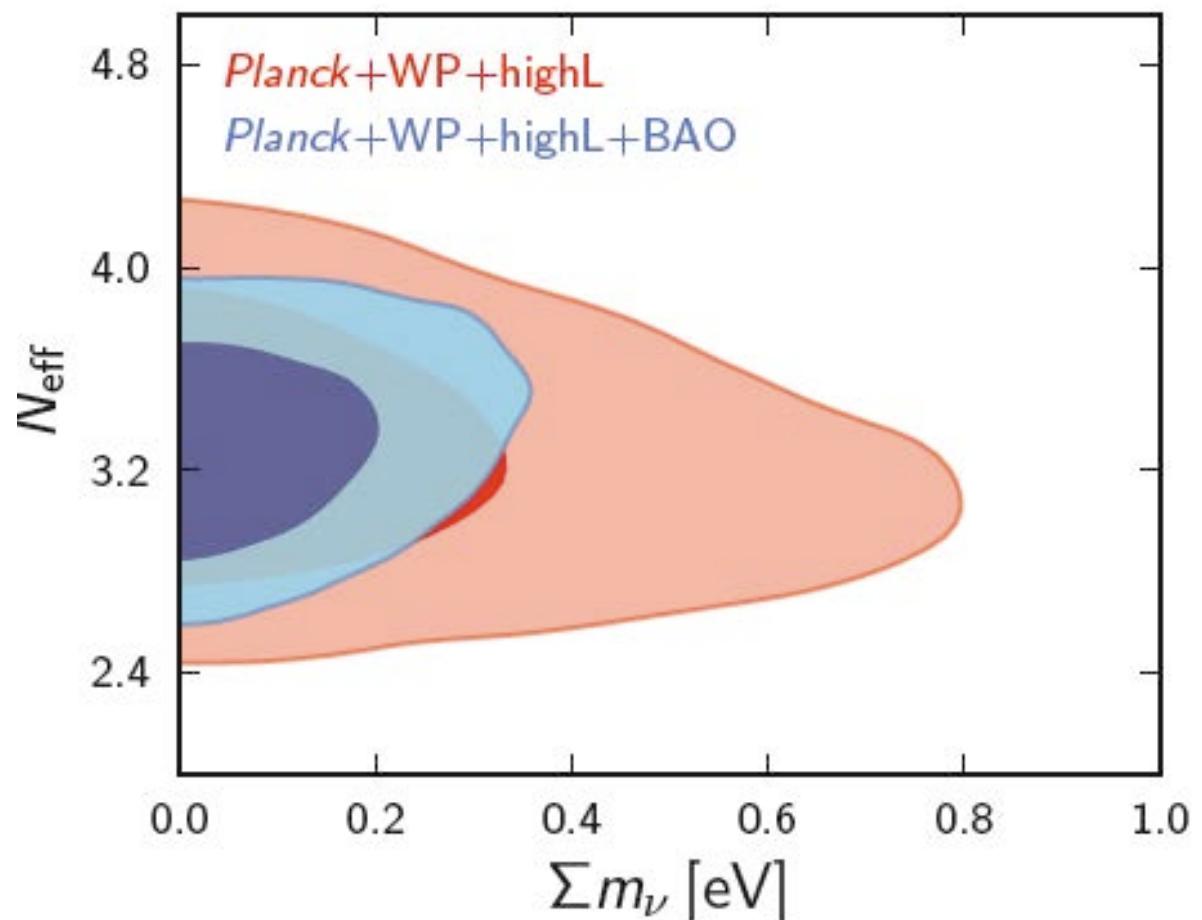
$$N_{\text{eff}} = 3.29^{+0.67}_{-0.64}$$

With BAO:

$$\Sigma m_\nu < 0.28 \text{ eV}$$

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

All 95% CL



Probing the absolute neutrino mass scale

Searching for non-zero neutrino mass in laboratory experiments

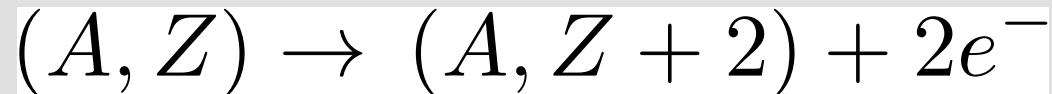
- Tritium beta decay: measurements of endpoint energy



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

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

- Neutrinoless double beta decay: if Majorana neutrinos

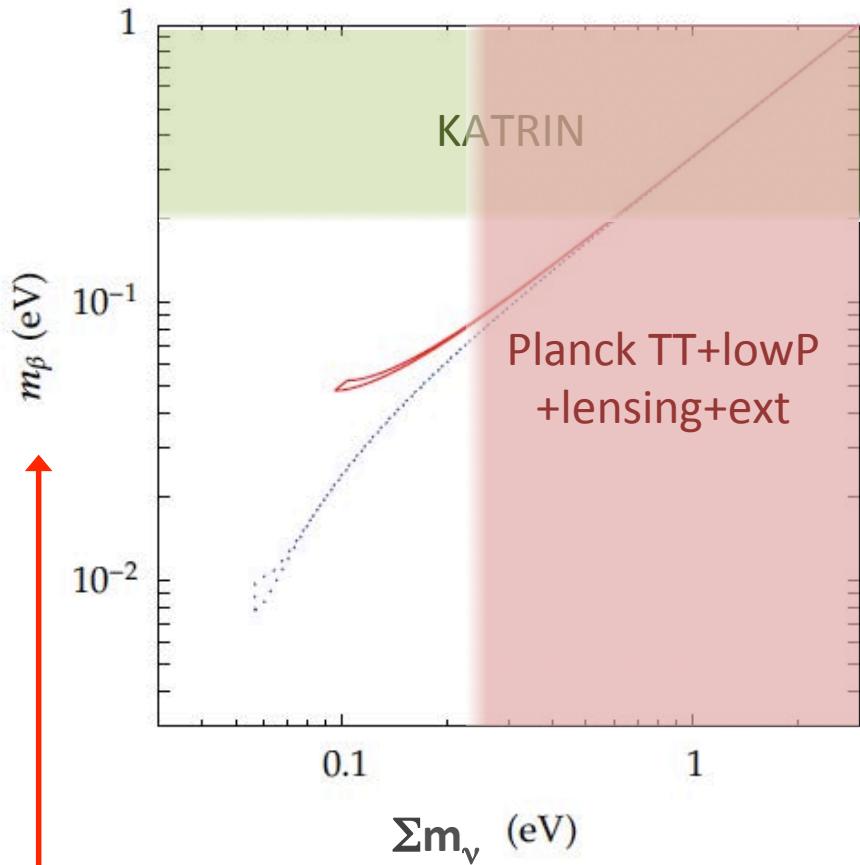


experiments with ^{76}Ge , ^{130}Te , ^{136}Xe and other isotopes:
 $m_{\beta\beta} < 60\text{-}800 \text{ meV}$, depending on NME

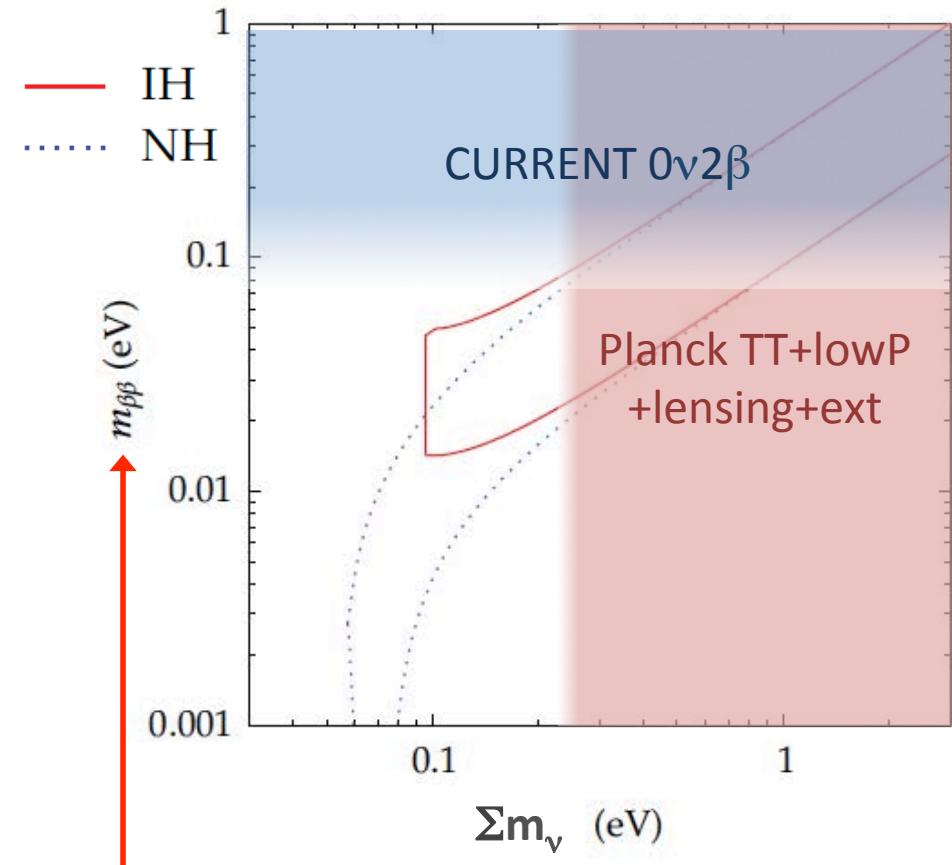
Probing the absolute neutrino mass scale

Tritium β decay	$m_\beta = \left(\sum_i U_{ei} ^2 m_i^2 \right)^{1/2}$	2.2 eV
Neutrinoless double beta decay	$m_{\beta\beta} = \left \sum_i U_{ei}^2 m_i \right $	< 60-800 meV
Cosmology	$\sim \sum_i m_i$	< 110-590 meV

Tritium β decay, $0\nu2\beta$ and Cosmology



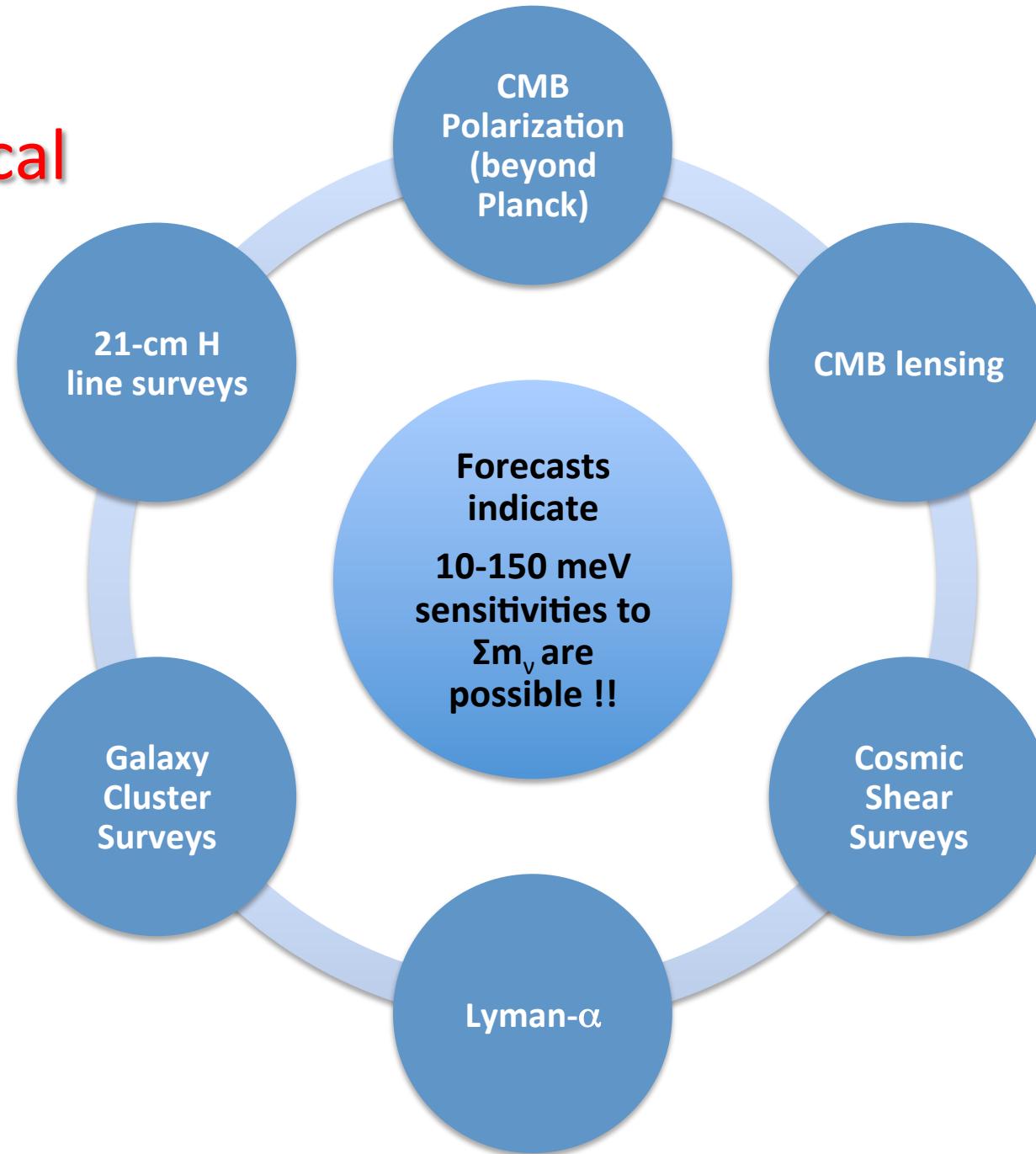
$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$



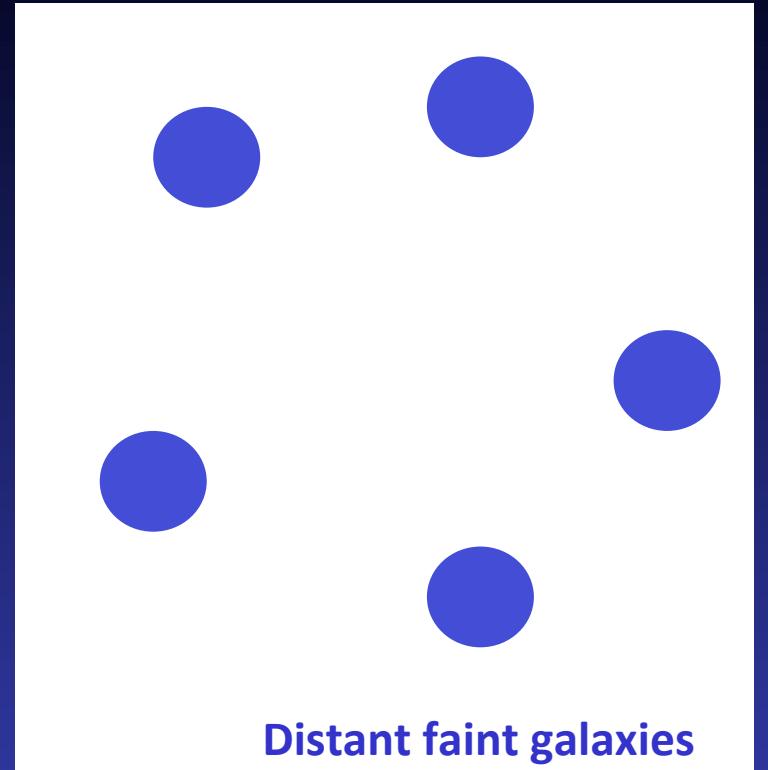
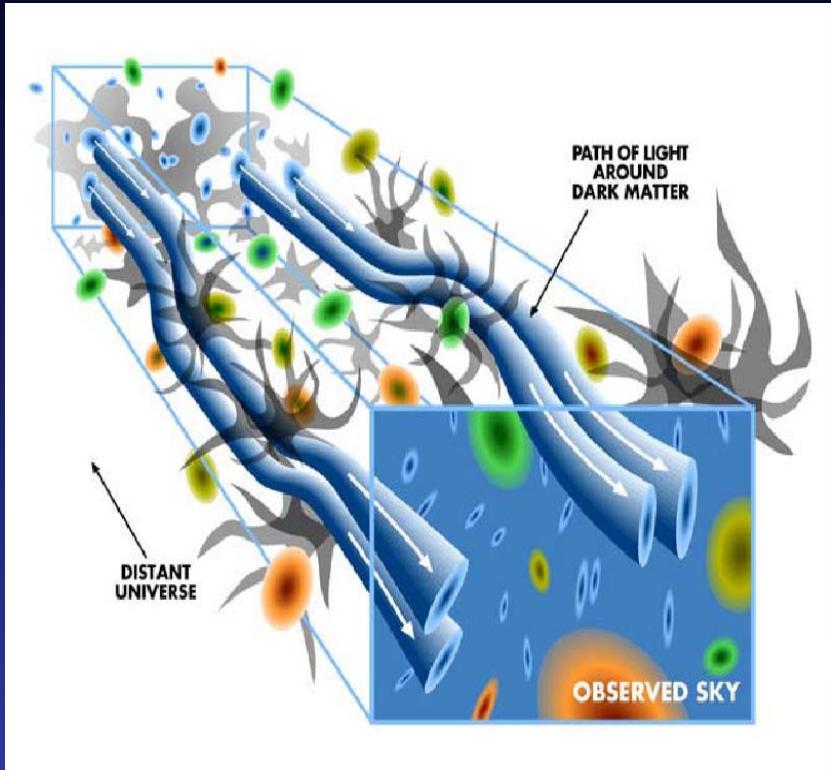
$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

Future sensitivities on neutrino physics from cosmology

Future cosmological data

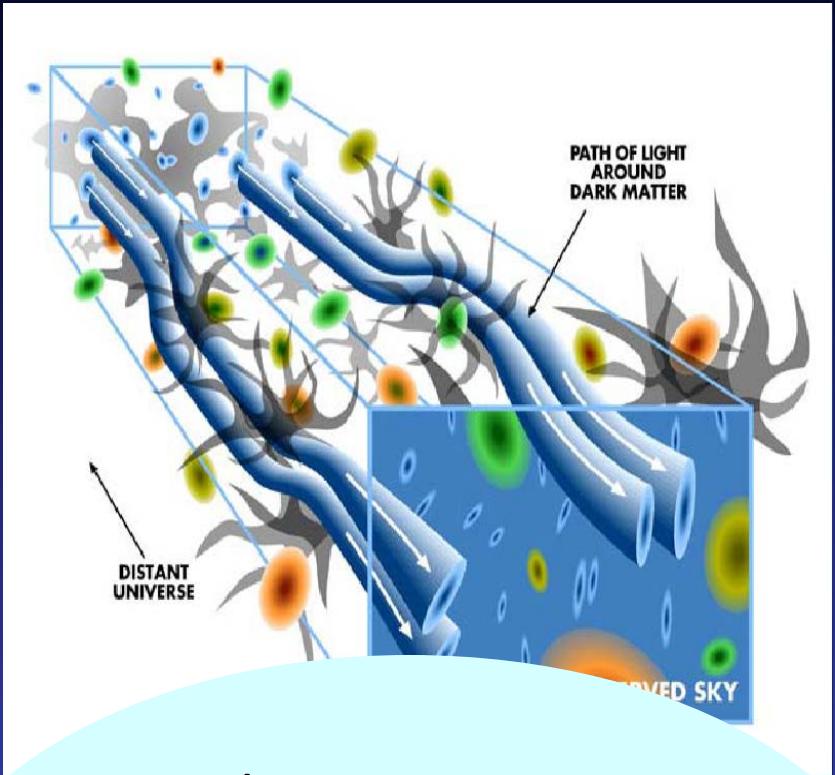


Future sensitivities to Σm_v : weak gravitational lensing

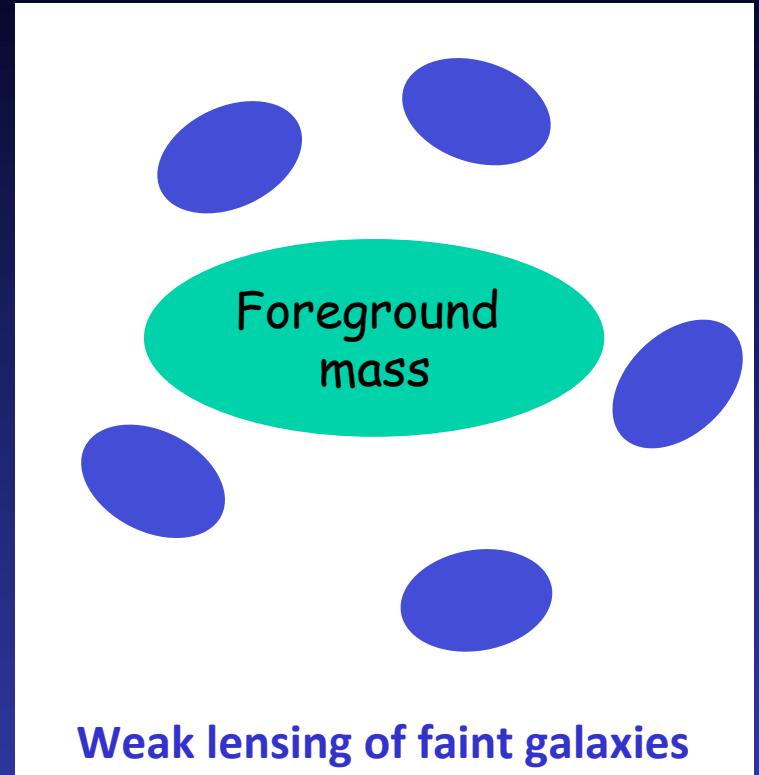


Frieman, Dodelson

Future sensitivities to Σm_v : weak gravitational lensing



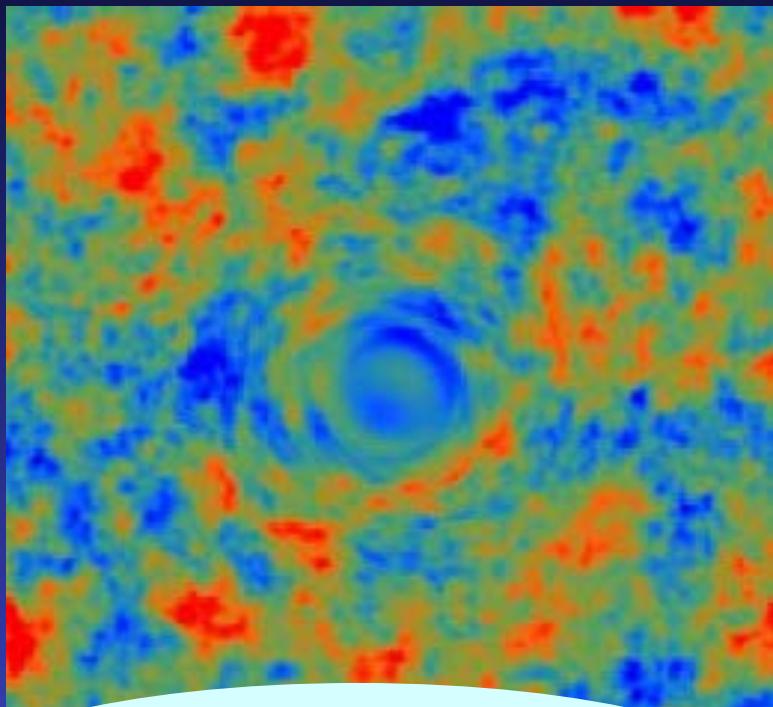
No bias uncertainty
Small scales much closer
to linear regime
Tomography:
3D reconstruction



Measure a large number
of elliptically shaped galaxies

Future sensitivities to Σm_ν : weak gravitational lensing

lensing of the CMB signal



Makes CMB sensitive to
smaller neutrino masses

sensitivity of CMB
(primary + lensing)
to m_ν

$$\sigma(m_\nu) = 0.15 \text{ eV (Planck)}$$

$$\sigma(m_\nu) = 0.044 \text{ eV (CMBpol)}$$

Kaplinghat, Knox & Song
PRL 91 (2003) 241301

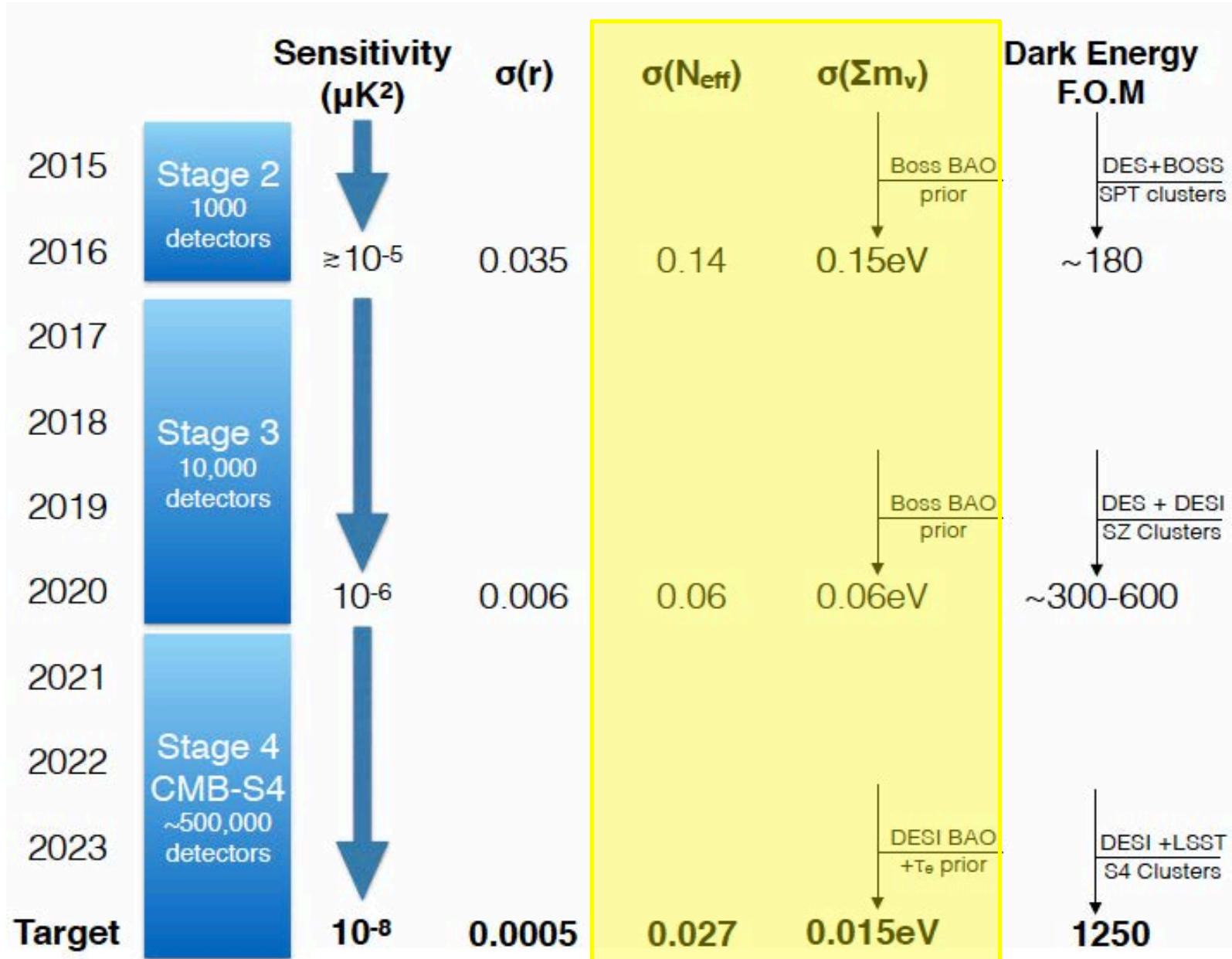
Future sensitivities on neutrino masses (eV)

Probe	5-7 years	7-15 years
CMB	0.4-0.6	0.4
CMB with lensing	0.1-0.15	0.04
CMB + Galaxy Distribution	0.2	0.05-0.1
CMB + Lensing of Galaxies	0.1	0.03-0.04
CMB + Lyman- α	0.1-0.2	Unknown
CMB + Galaxy Clusters	-	0.05
CMB + 21 cm	-	0.0003-0.1

Table 1. Future probes of neutrino mass, as well as their projected sensitivity to neutrino mass. Sensitivity in the short term means achievable in approximately 5-7 years, while long term means 7-15 years.

Hannestad, Progr. Part. Nucl. Phys. 65 (2010) 185

Future sensitivities on N_{eff} and neutrino masses



Direct detection of the CNB?

Direct detection of the CNB?

How to detect non-relativistic neutrinos?

a process without energy threshold is necessary

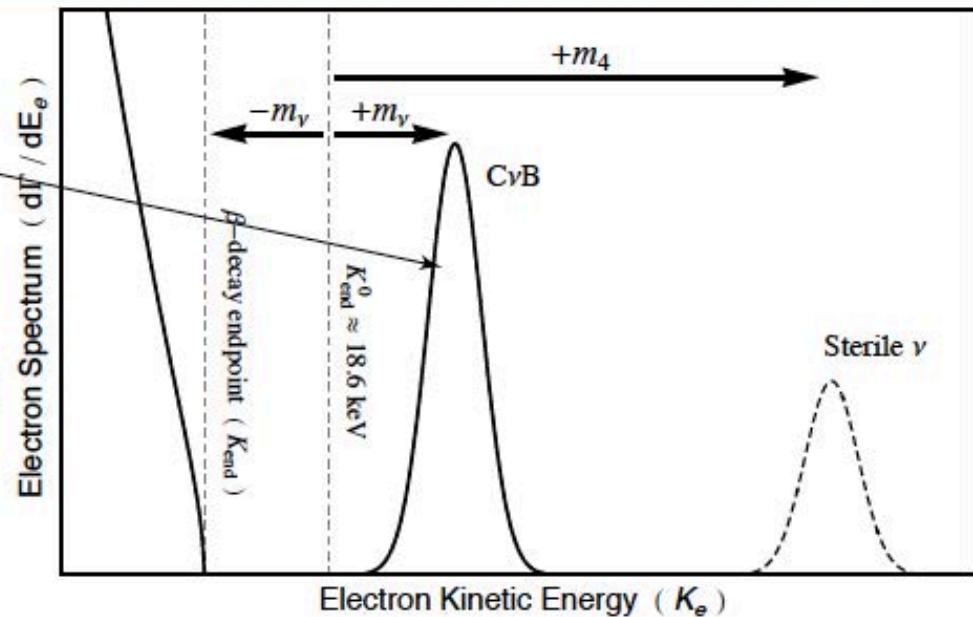
[Weinberg, 1962]: neutrino capture in β -decaying nuclei $\nu + n \rightarrow p + e^-$

signal is a peak at $2m_\nu$ above β -decay endpoint

only with a lot of material

need a very good energy resolution

Good candidate: tritium



(low Q -value) + (good availability of ${}^3\text{H}$) + (high cross section of $\nu + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$)

Direct detection of the CNB?

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq 0.1$ eV

can probe $m_\nu \simeq 1.4\Delta \simeq 0.14$ eV

built only for $C\nu B$

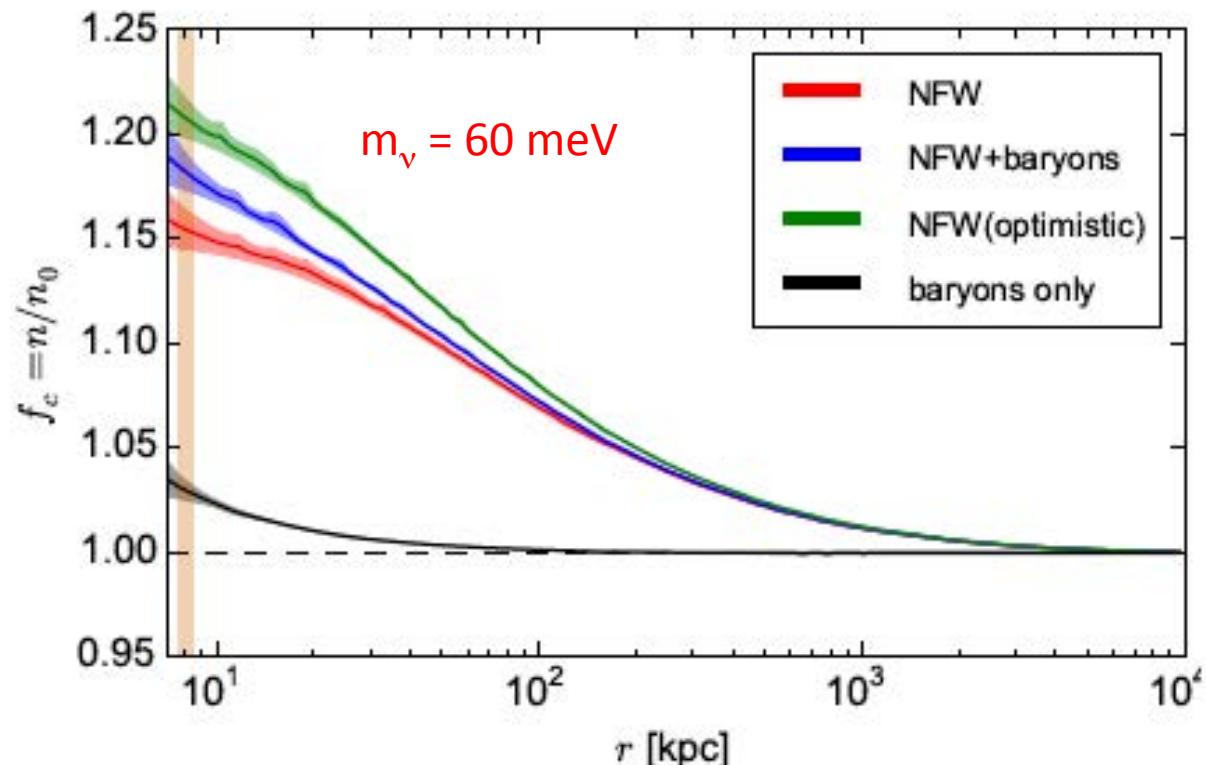
$M_T = 100$ g atomic tritium

Long et al, JCAP 08 (2014) 038

Bett et al, arXiv:1307.4738

Number of events at a PTOLEMY-like experiment depends on **local density of CNB: neutrino clustering**

P.F. de Salas et al,
to appear soon



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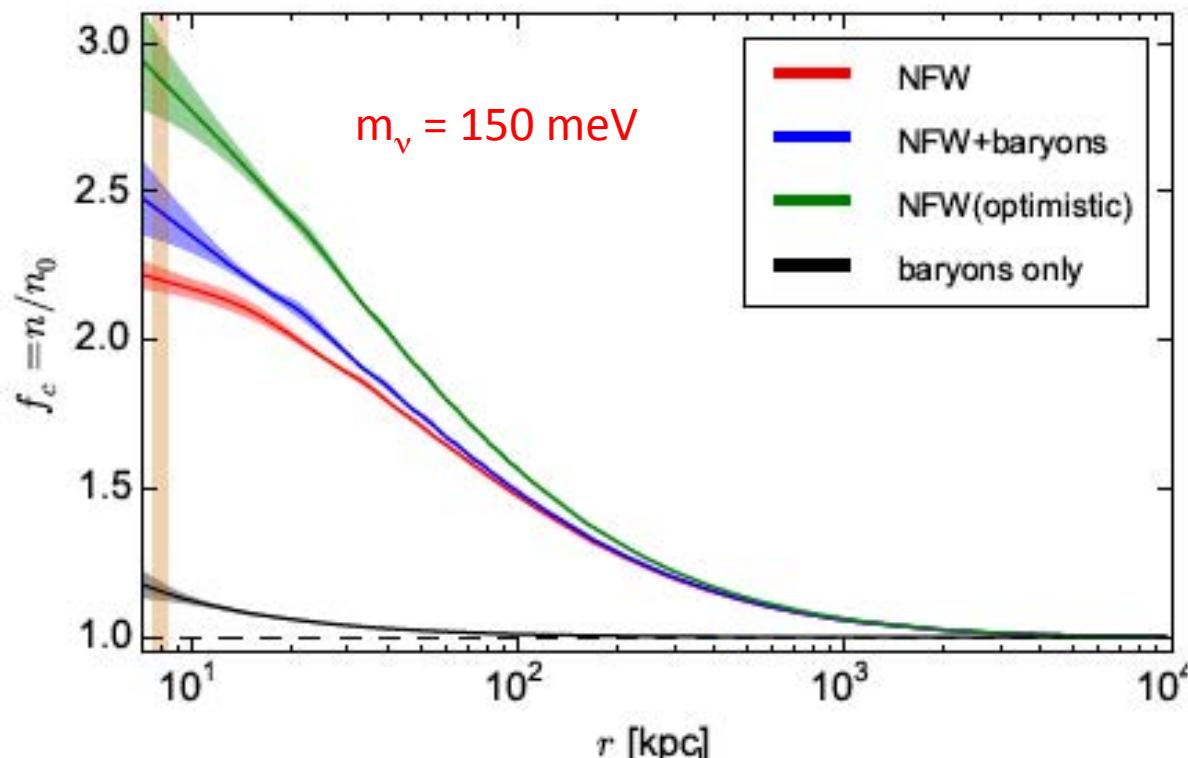
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End of 2nd lecture