Light neutrinos in Cosmology (II)

Picture from Hubble ST

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IV Int. Pontecorvo Neutrino Physics School
Alushta, October 2010

AHEP Astroparticle and High Energy Physics Group

CSIC Consejo Superior de Investigaciones Científicas

Vniversitat de València

Light neutrinos in Cosmology

2nd lecture

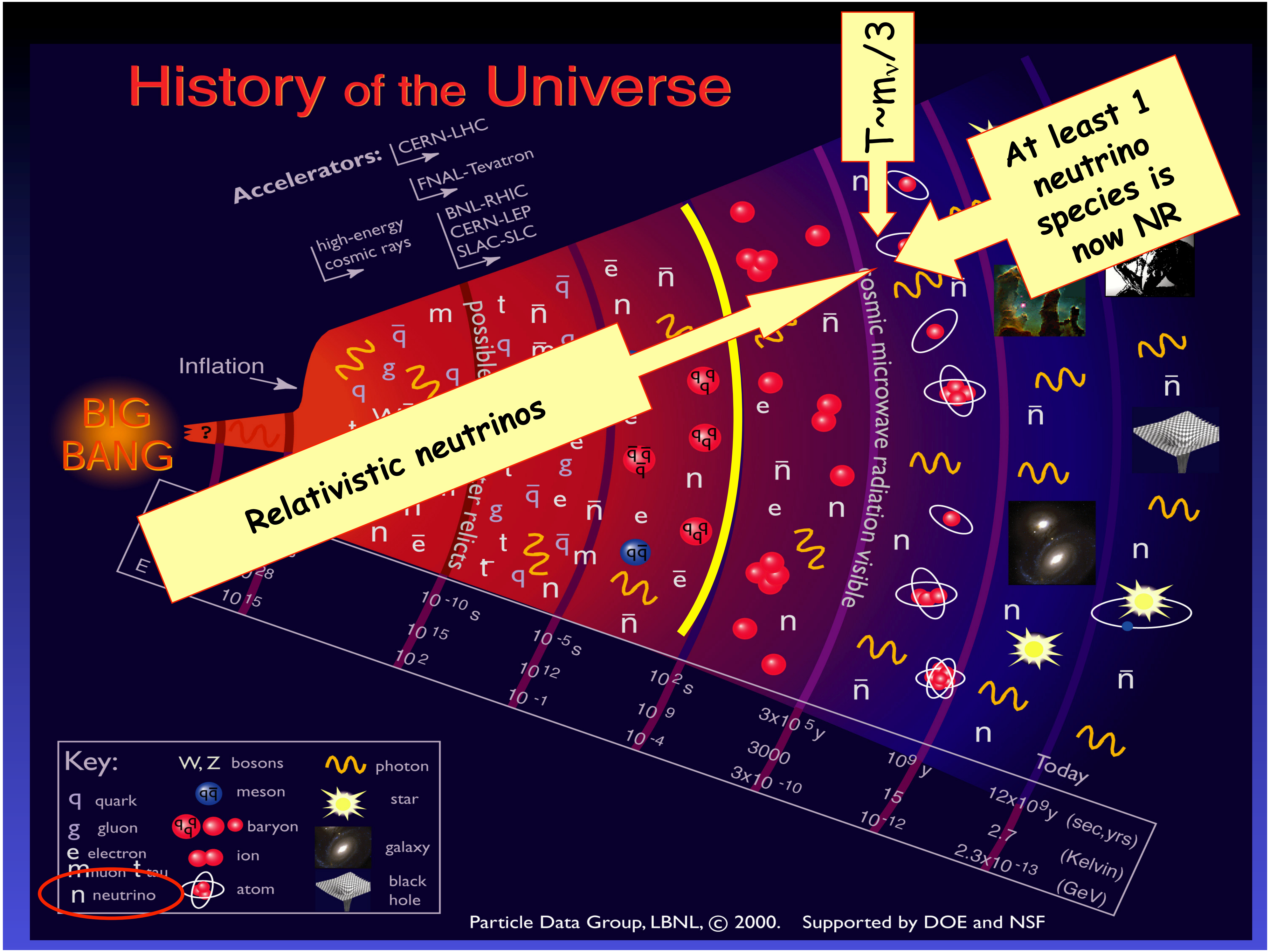
Massive neutrinos as Dark Matter

Effects of neutrino masses on cosmological observables

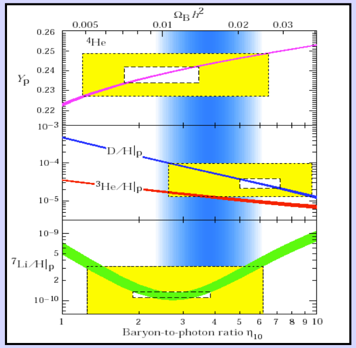
Bounds on m_ν from CMB, LSS and other data

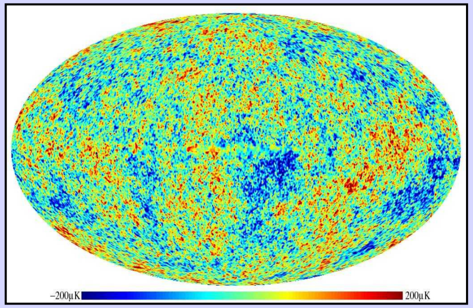
Future sensitivities on m_ν and N_{eff} from cosmology

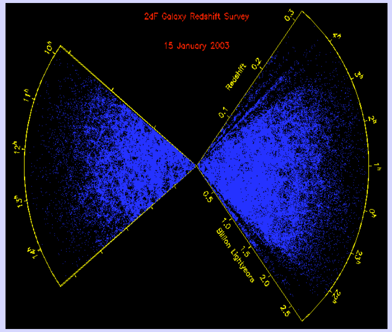
Neutrinos as Dark Matter


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

Relic neutrinos influence several cosmological epochs



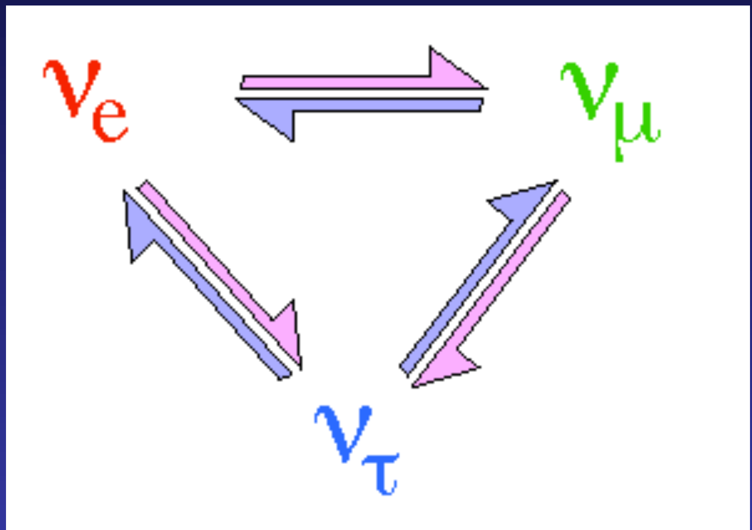




Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
T ~ MeV	T < eV	
ν_e vs $\nu_{\mu,\tau}$ N_{eff}	No flavour sensitivity N_{eff} & m_ν	

We know that flavour neutrino oscillations exist

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



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

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Evidence for Particle Physics beyond the Standard Model !

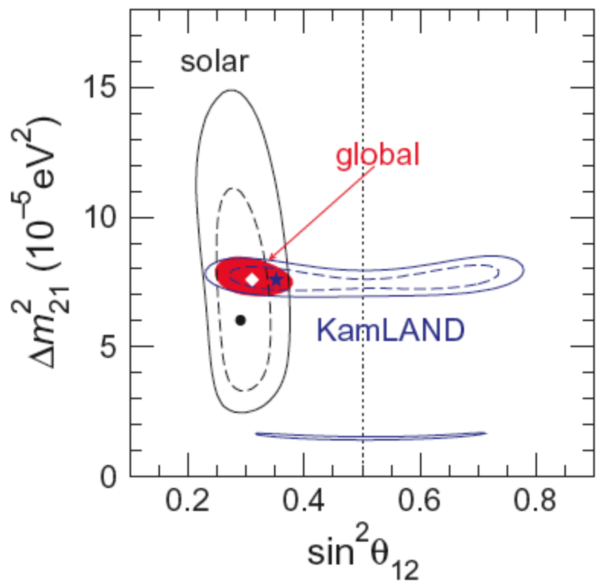
Mixing Parameters...

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

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

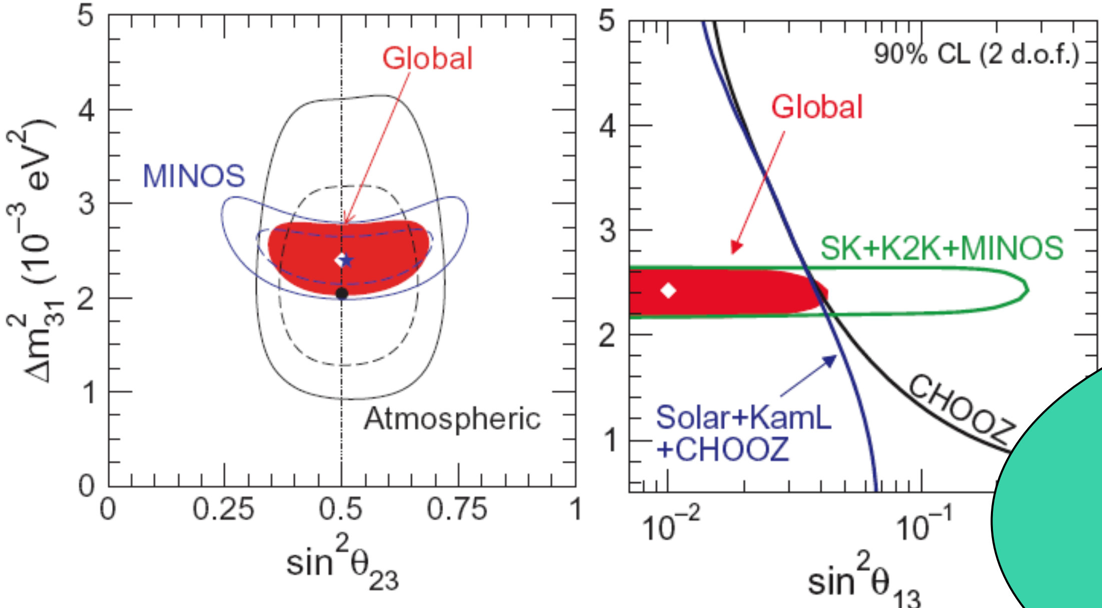
$$\times\ \mathrm{diag}(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1)\ .$$

Mixing Parameters...



Parameter	Best fit	2σ	3σ
Δm^2_{21} (10^{-5} eV^2)	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\|\Delta m^2_{31}\|$(10^{-3} eV^2)	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	$\leqslant 0.040$	$\leqslant 0.056$

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

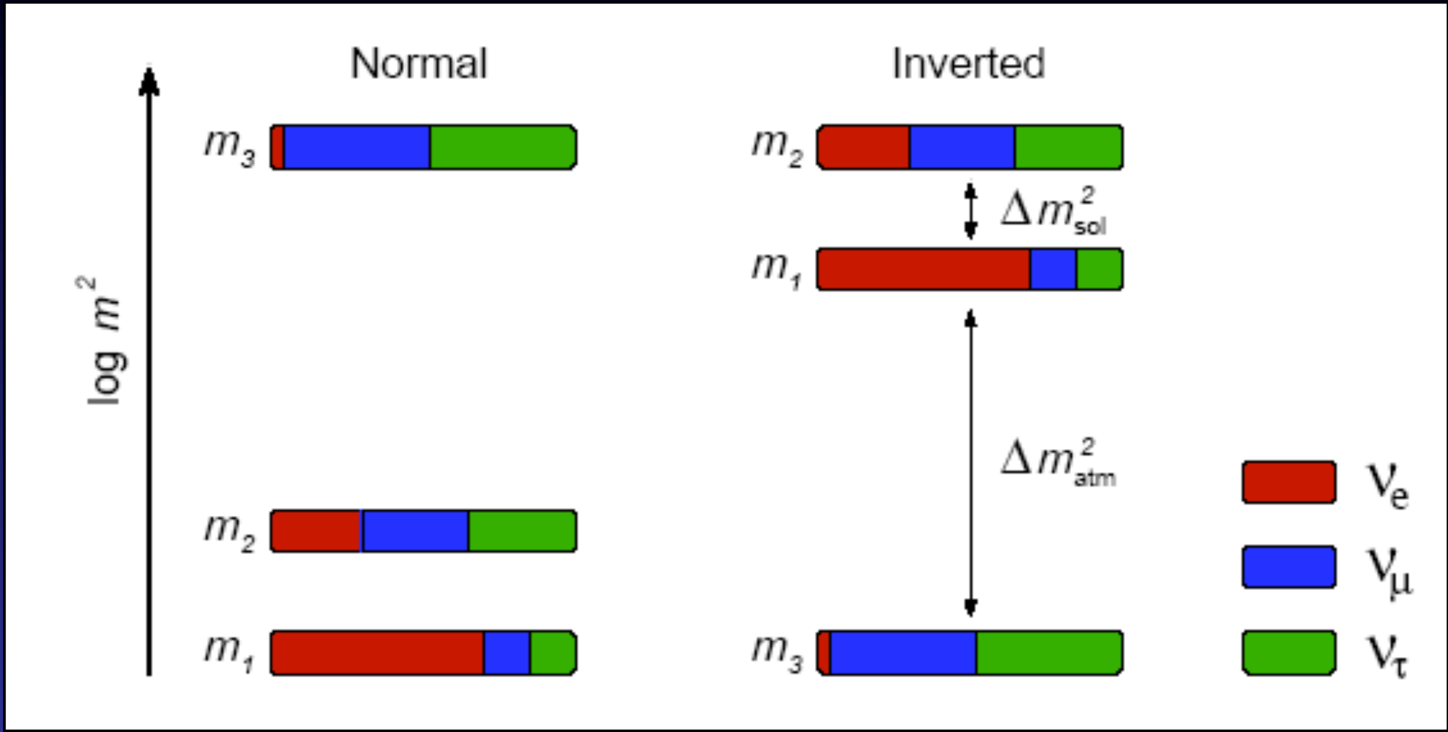


Schwetz, Tórtola & Valle, New J Phys **10** (2008) 113011

[González-García & Maltoni , Phys Rep **460** (2008) 1,
Fogli et al, Phys Rev Lett **101** (2008) 141801, and others]

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

... and neutrino masses



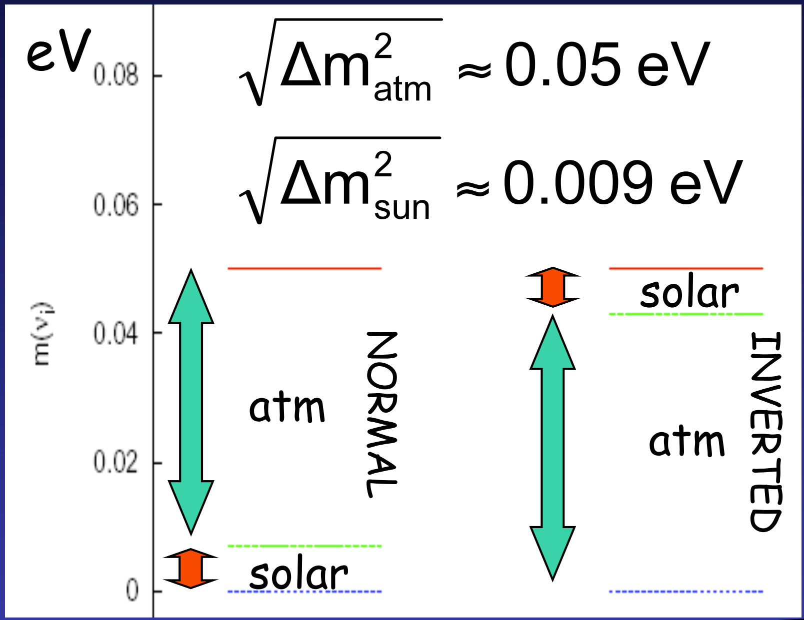
Possible neutrino mass hierarchy patterns

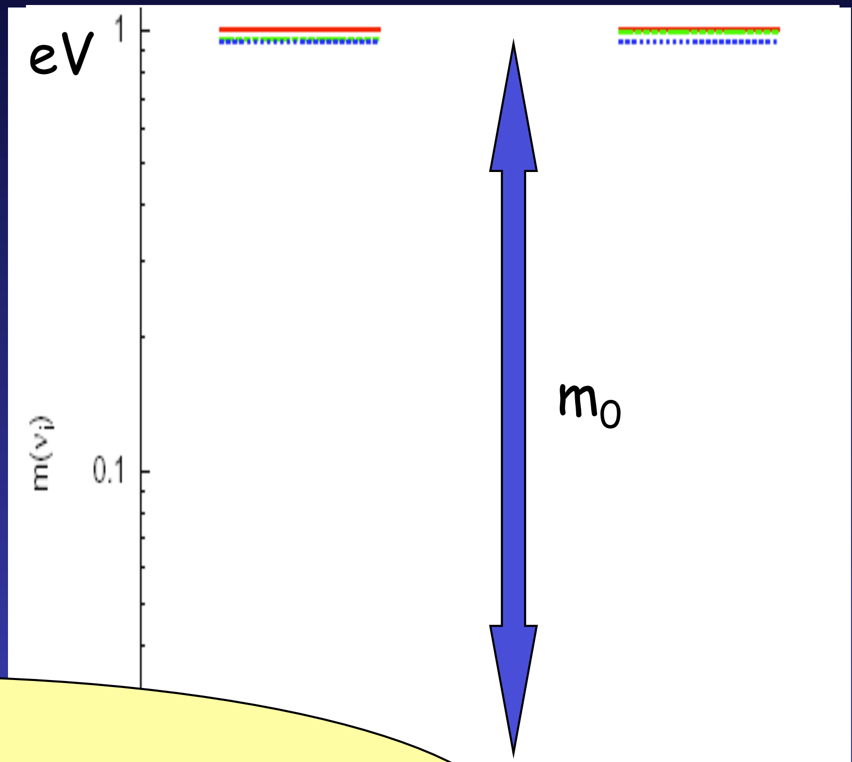
$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{iL}, \quad (\alpha = e, \mu, \tau)$$

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

... and neutrino masses

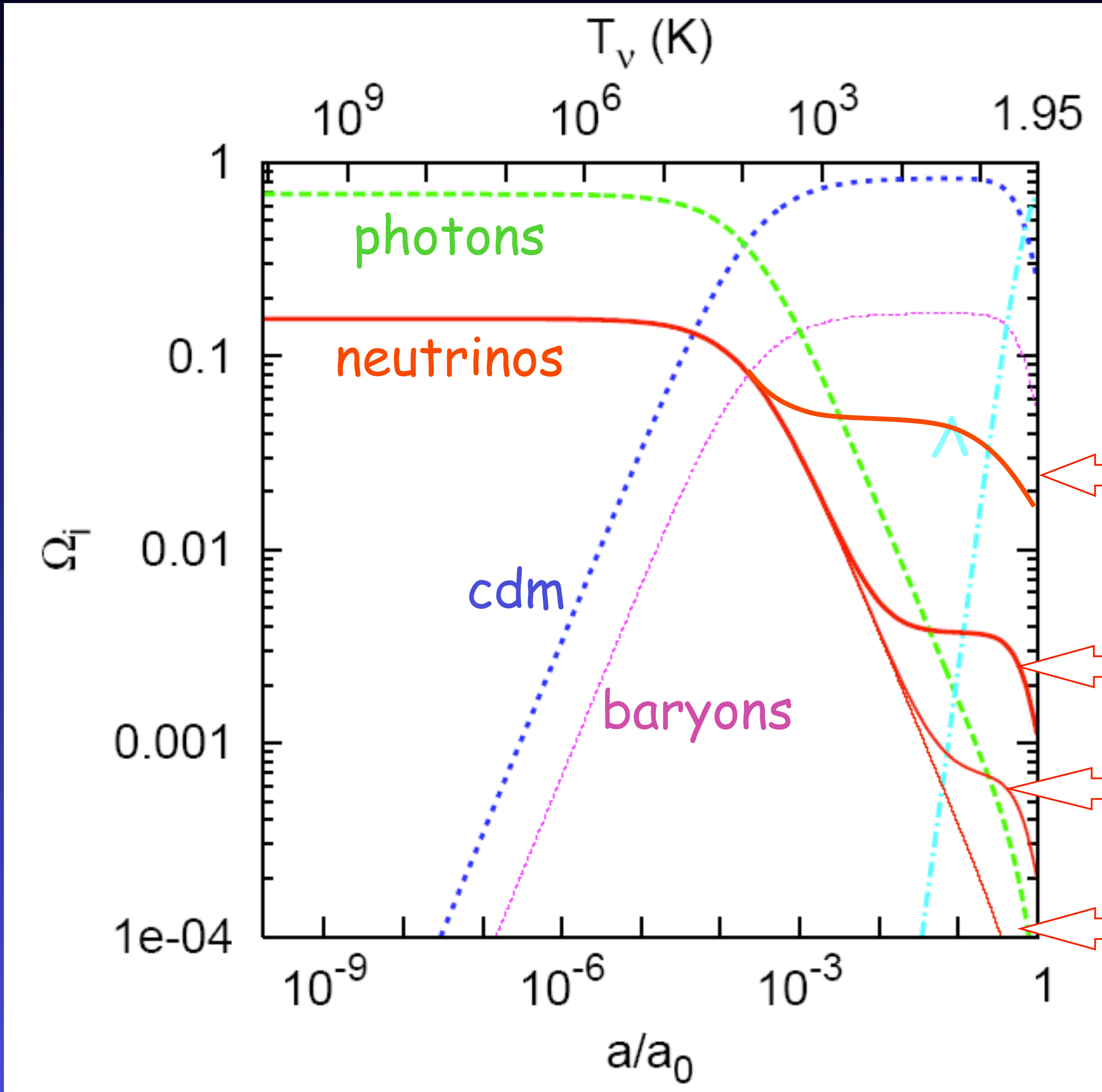
Data on flavour oscillations do not fix the absolute scale of neutrino masses





What is the value of m_0 ?

Evolution of the background densities: 1 MeV → now



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

m_ν=1 eV

m_ν=0.05 eV

m_ν=0.009 eV

$m_\nu \approx$ 0 eV

The Cosmic Neutrino Background

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

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

- Number density

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

- Energy density

Contribution to the energy density of the Universe

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

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

$m_\nu \gg T$

Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

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

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

- They stream freely until non-relativistic (collisionless phase mixing) ⟹ Neutrinos are HOT Dark Matter

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

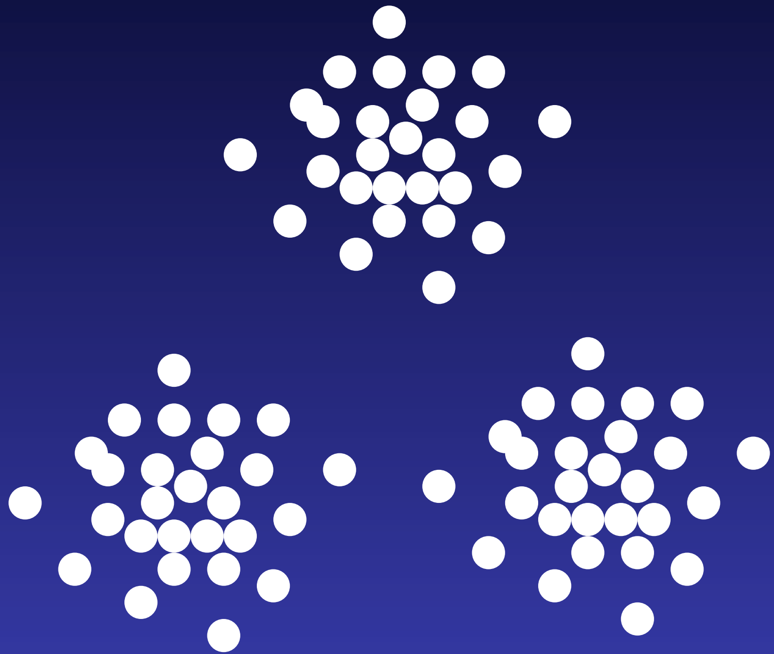
- Ruled out by structure formation ⟹ CDM

Neutrinos as Hot Dark Matter

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

Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



Structure formation after equality

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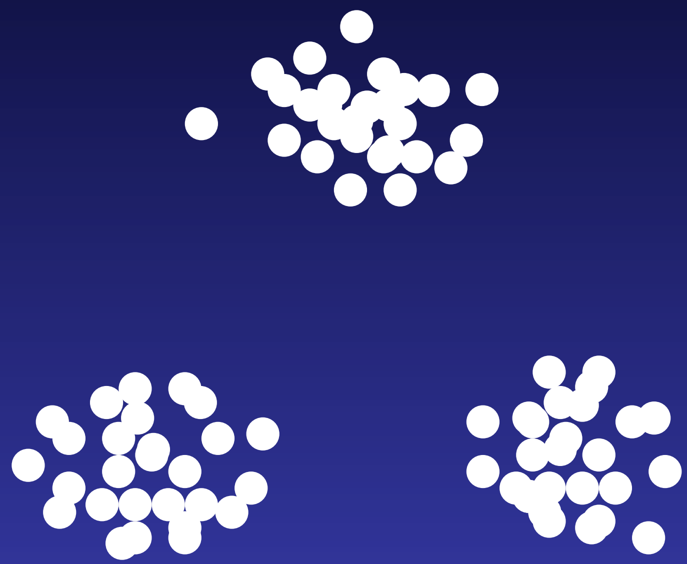

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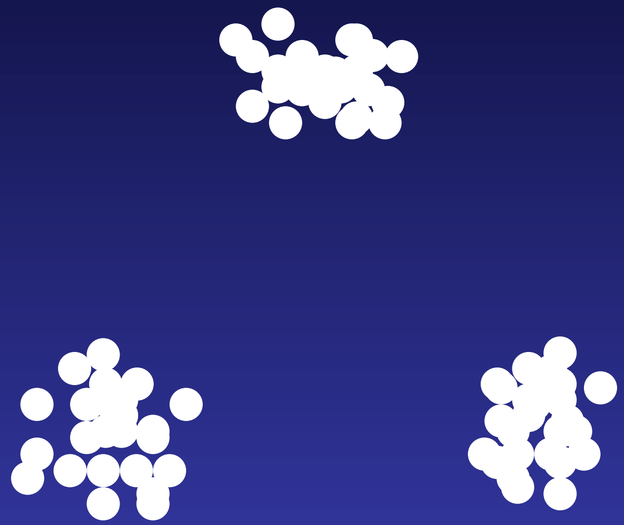

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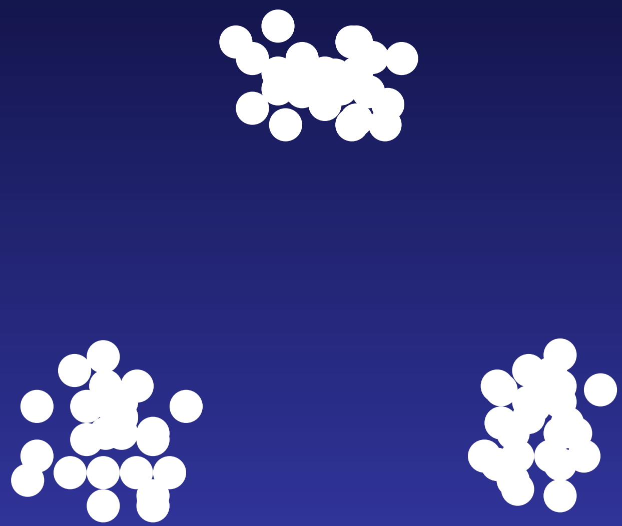


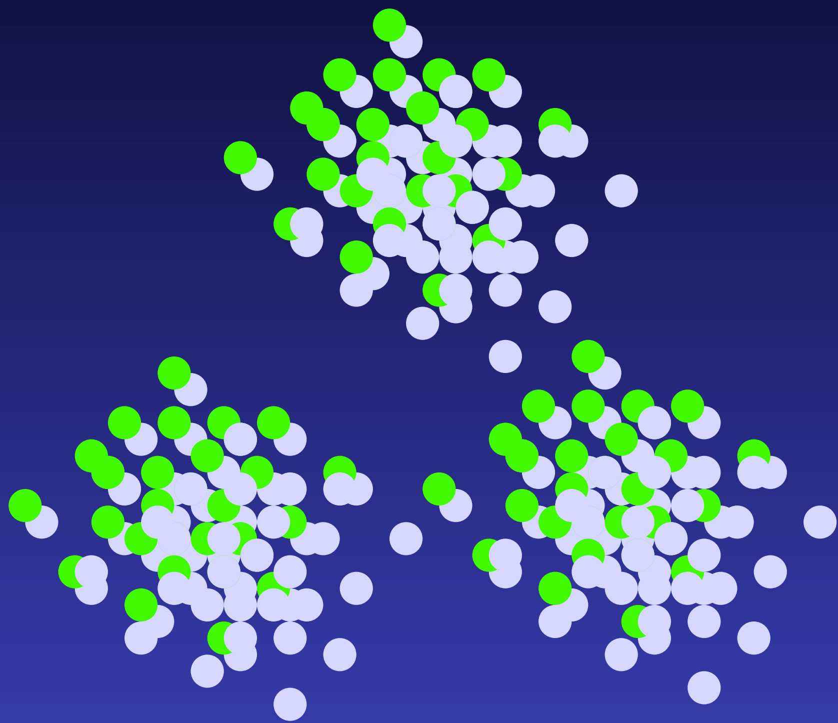
growth of $\delta\rho/\rho$ (k,t) fixed by

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 <p>/m

Structure formation after equality

baryons and
CDM (matter)
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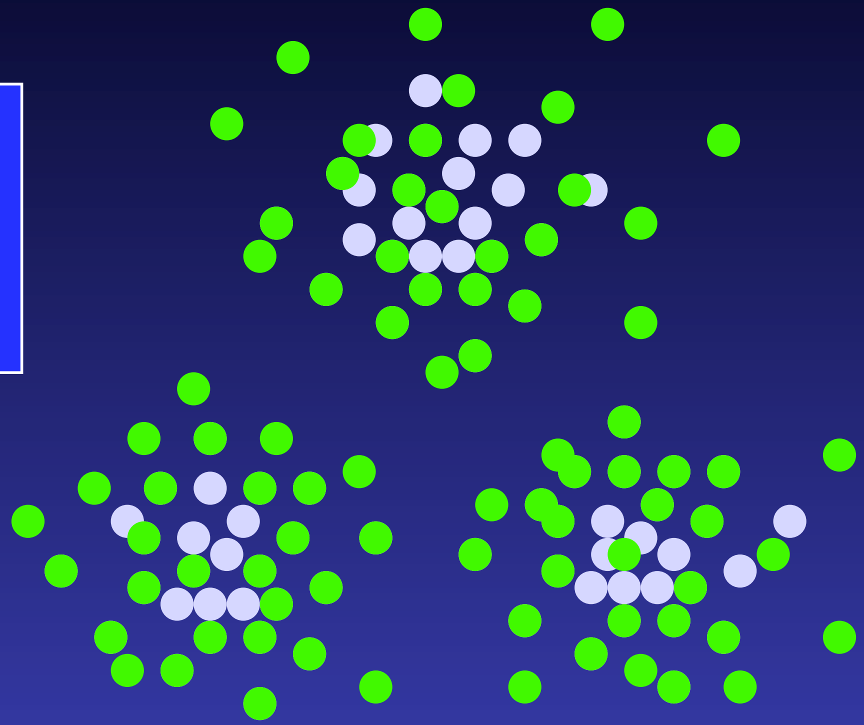

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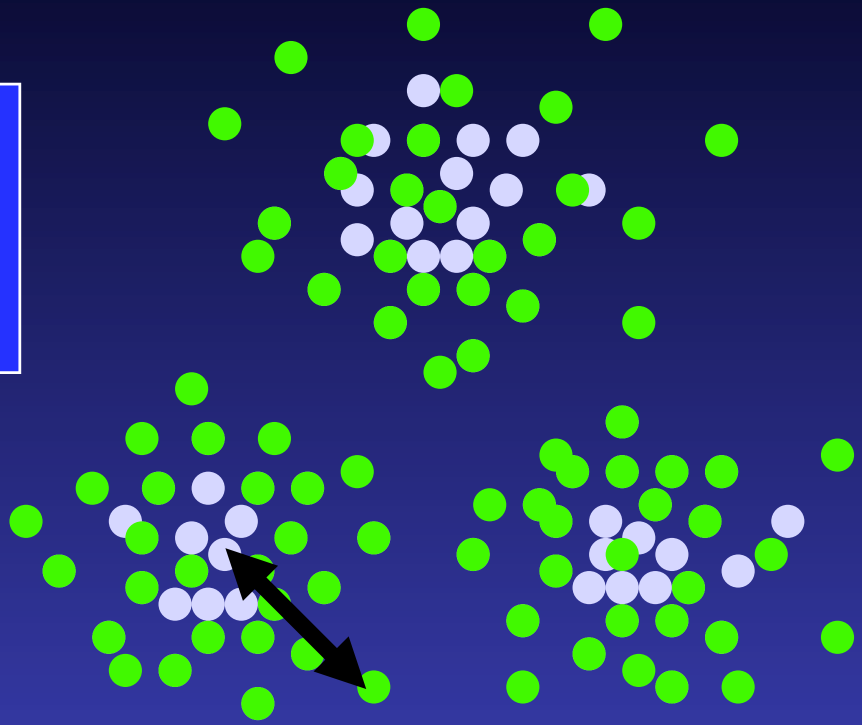


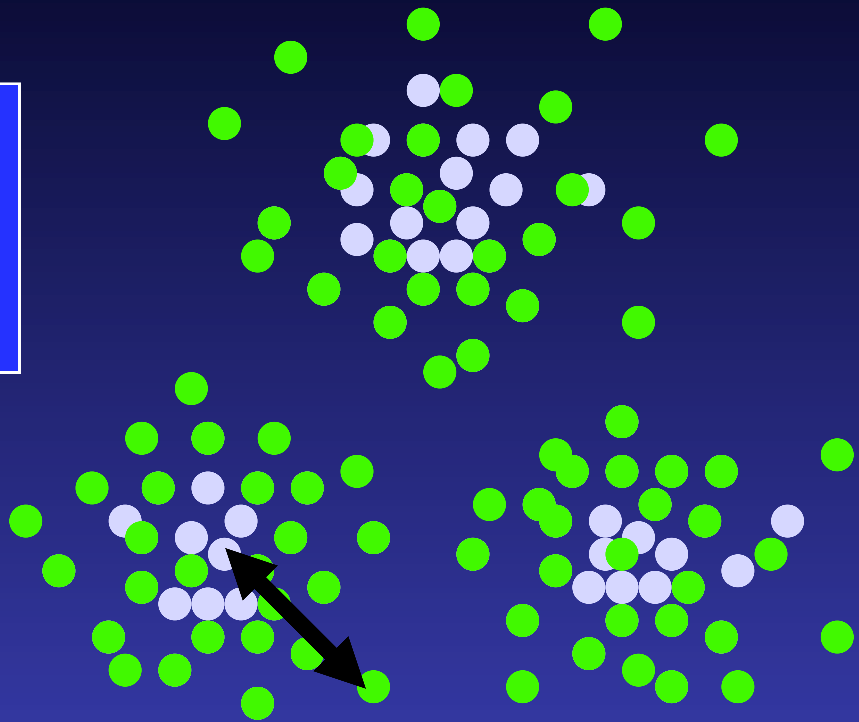
neutrinos experience free-streaming with $v = c \text{ or } \langle p \rangle / m$

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 $\langle p \rangle / m$

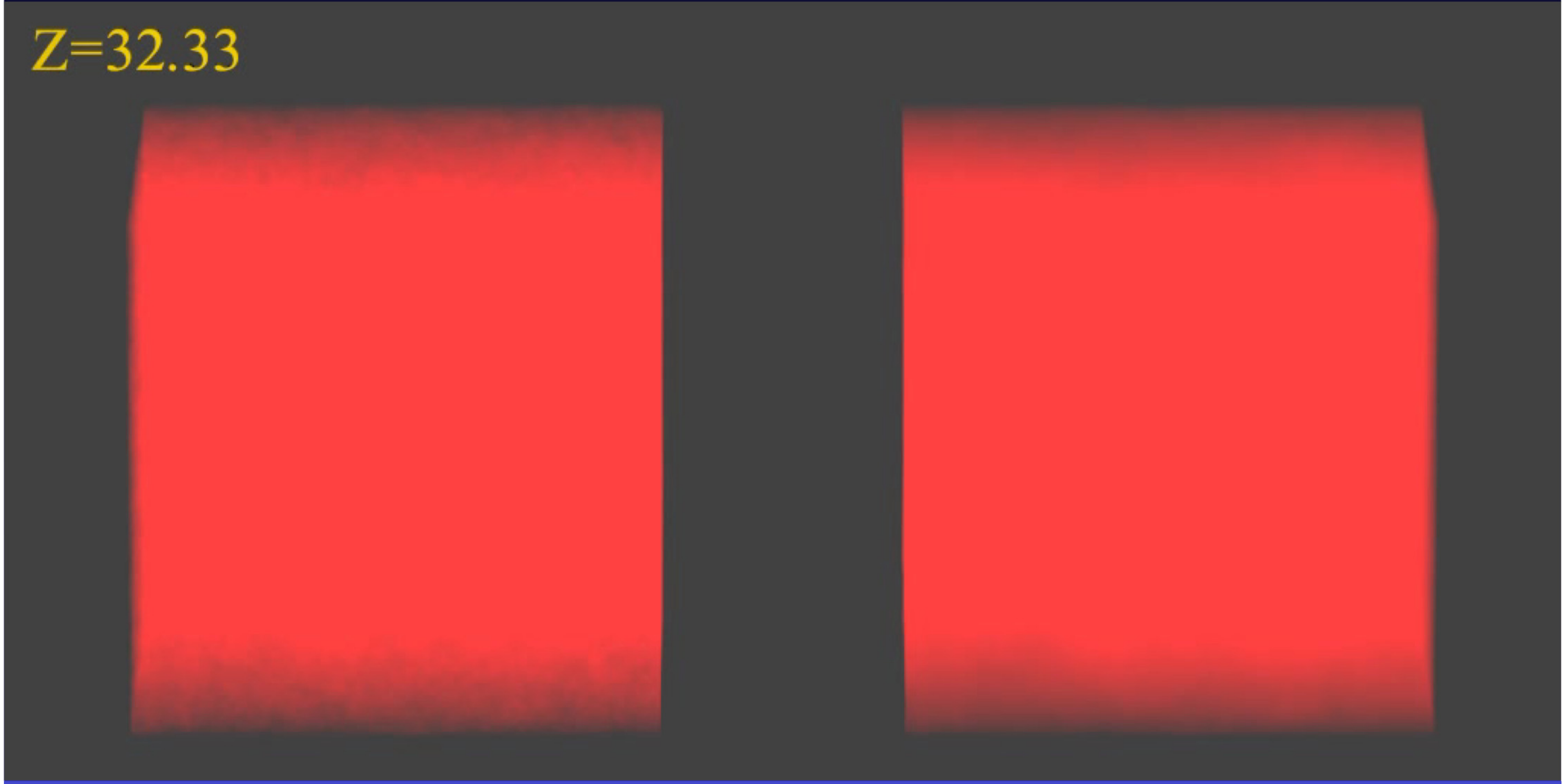
for $(2\pi/k) < \lambda$,

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)



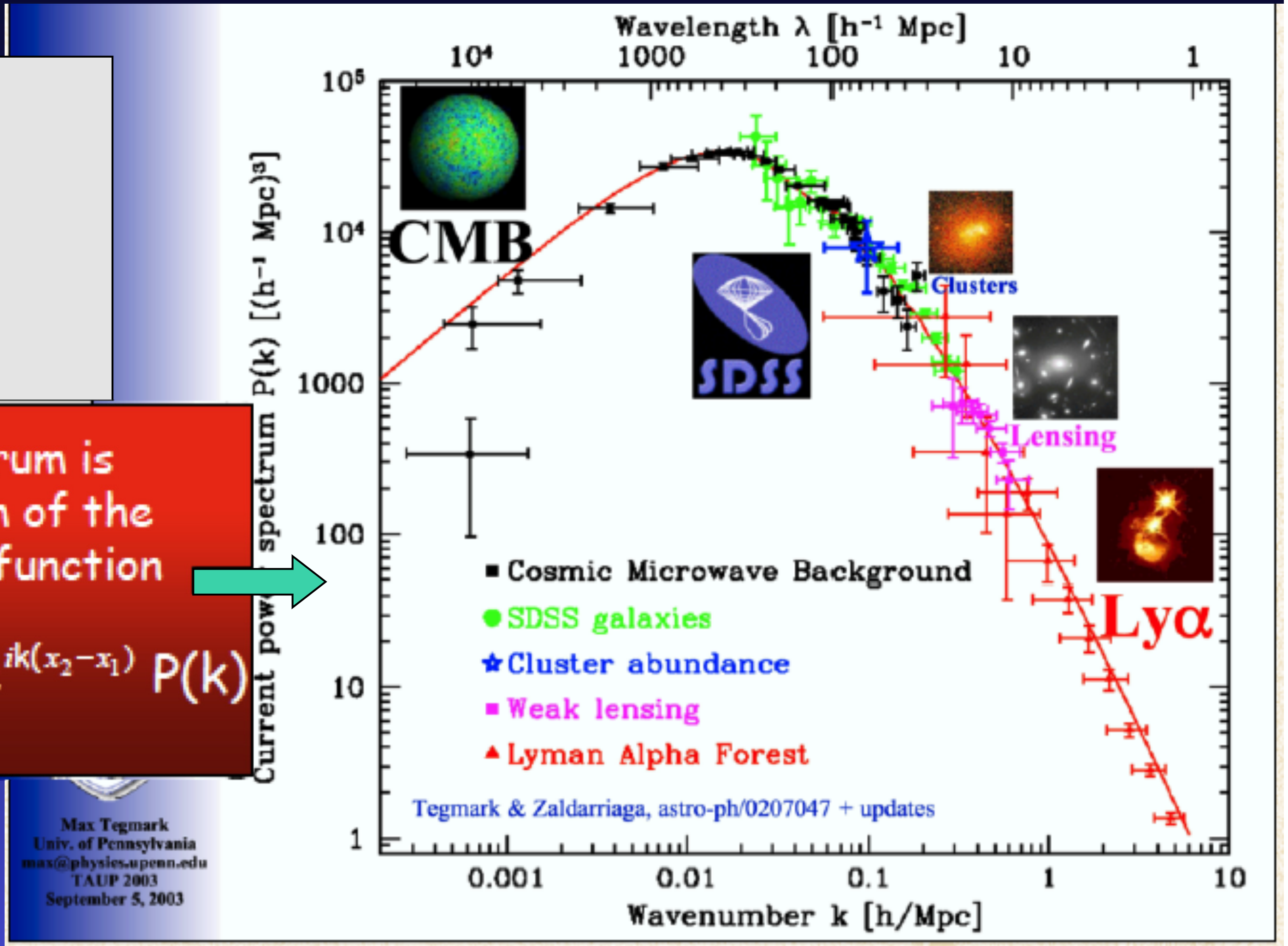
Power Spectrum of density fluctuations

Field of density Fluctuations

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

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

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



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

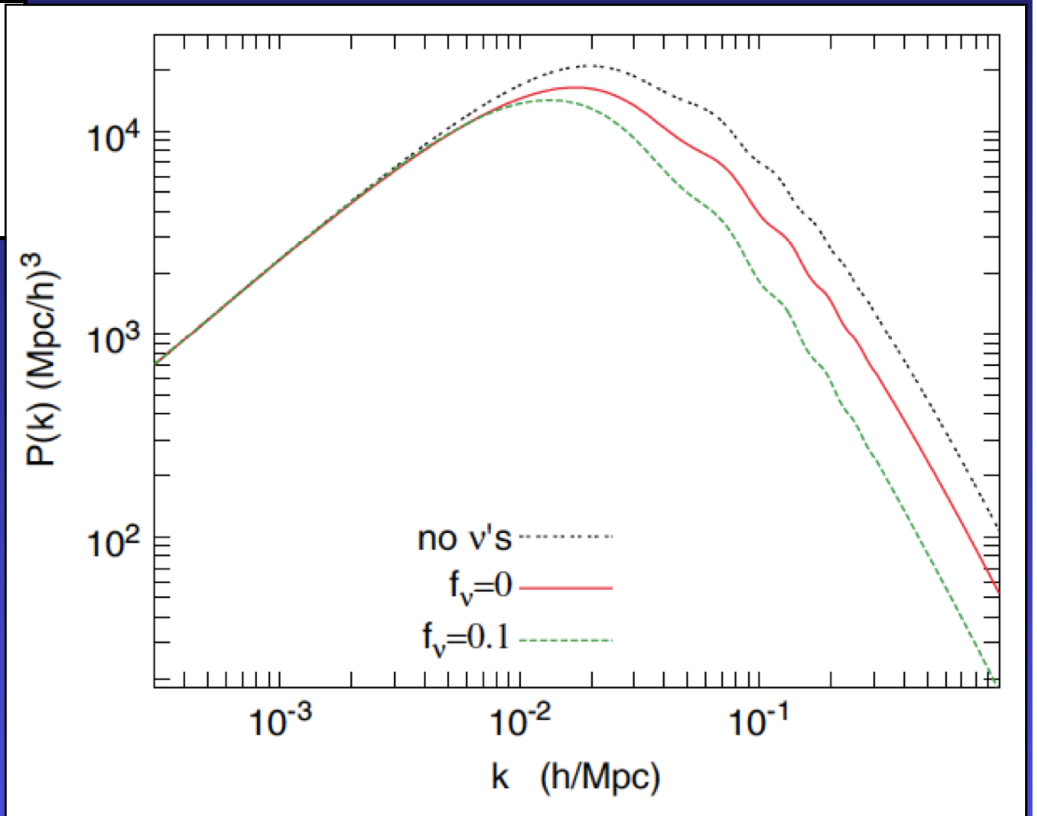
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

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

The small-scale suppression is given by

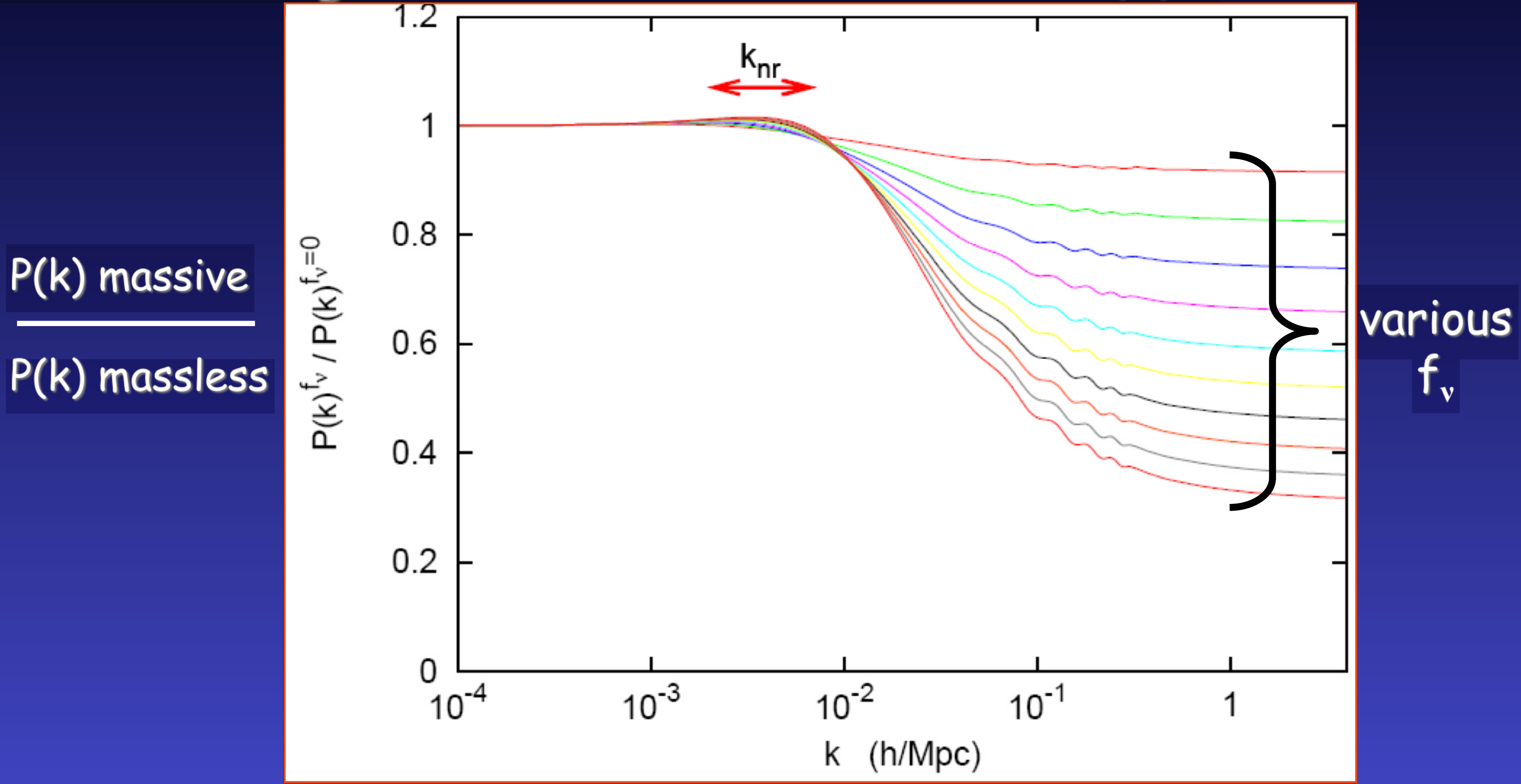
$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

f_ν



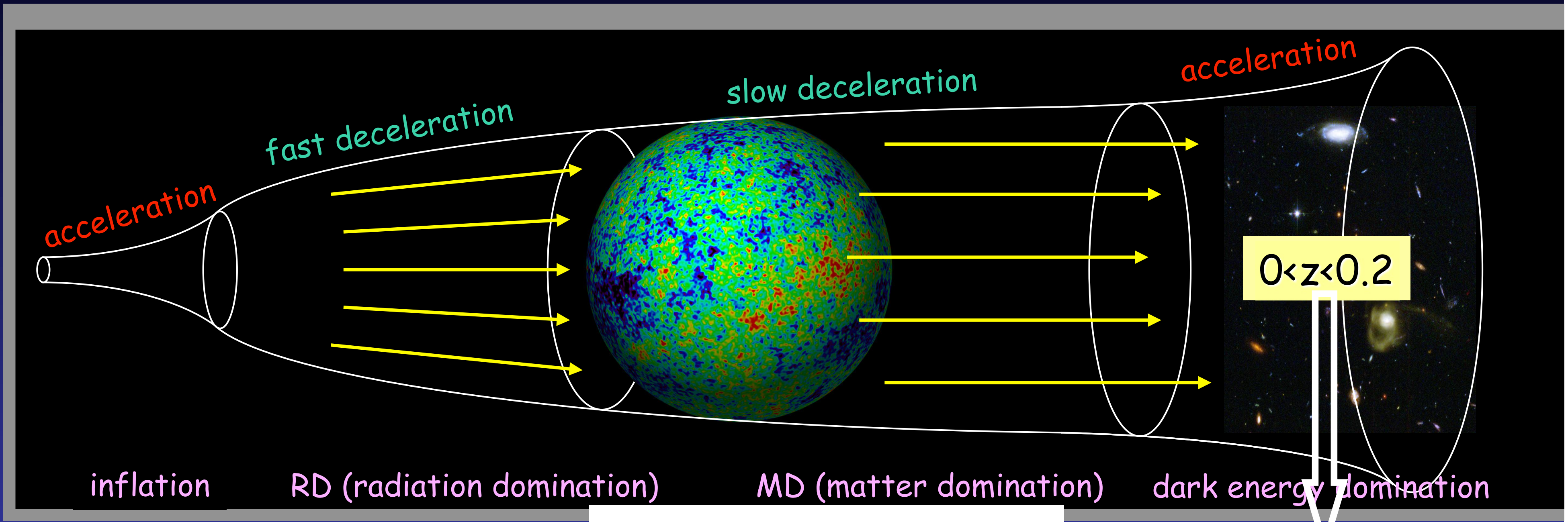
Effect of massive neutrinos on P(k)

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

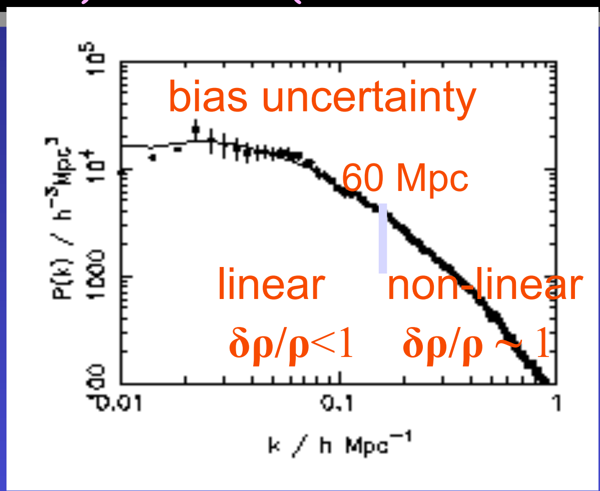


Lesgourgues & SP, Phys. Rep. 429 (2006) 307

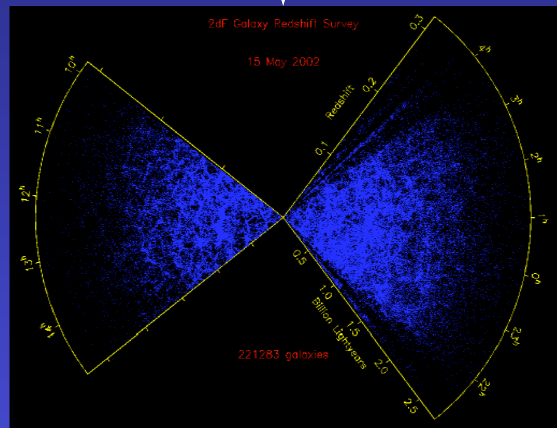
Cosmological observables: LSS



Distribution
of large-scale
structures at low z

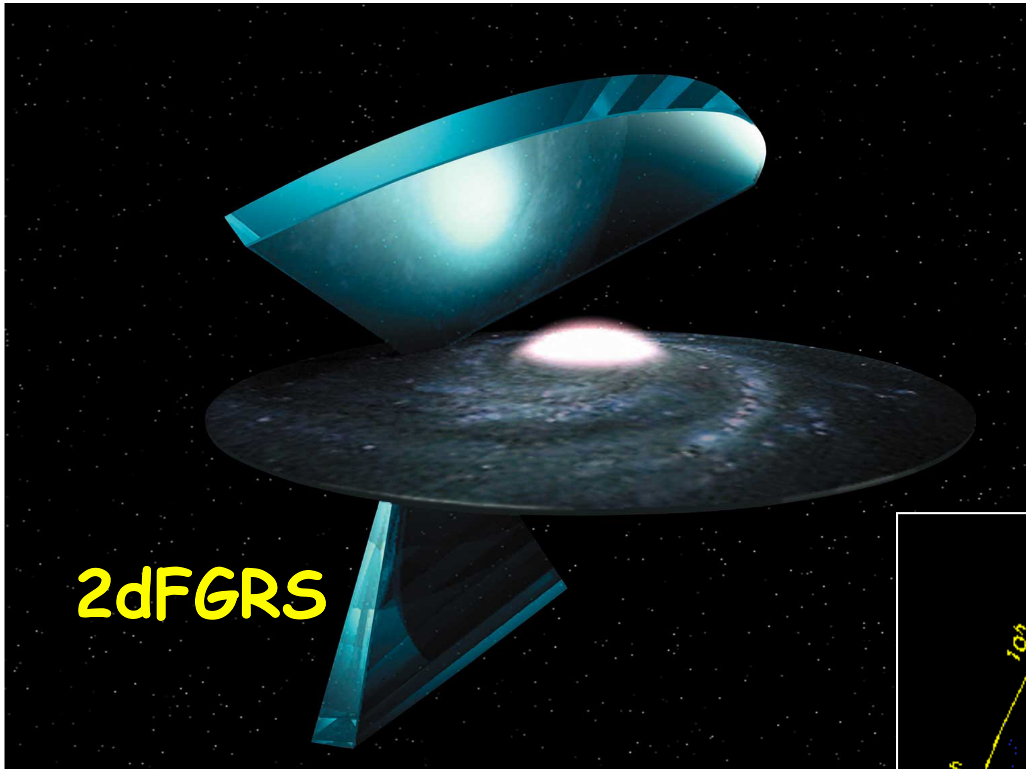


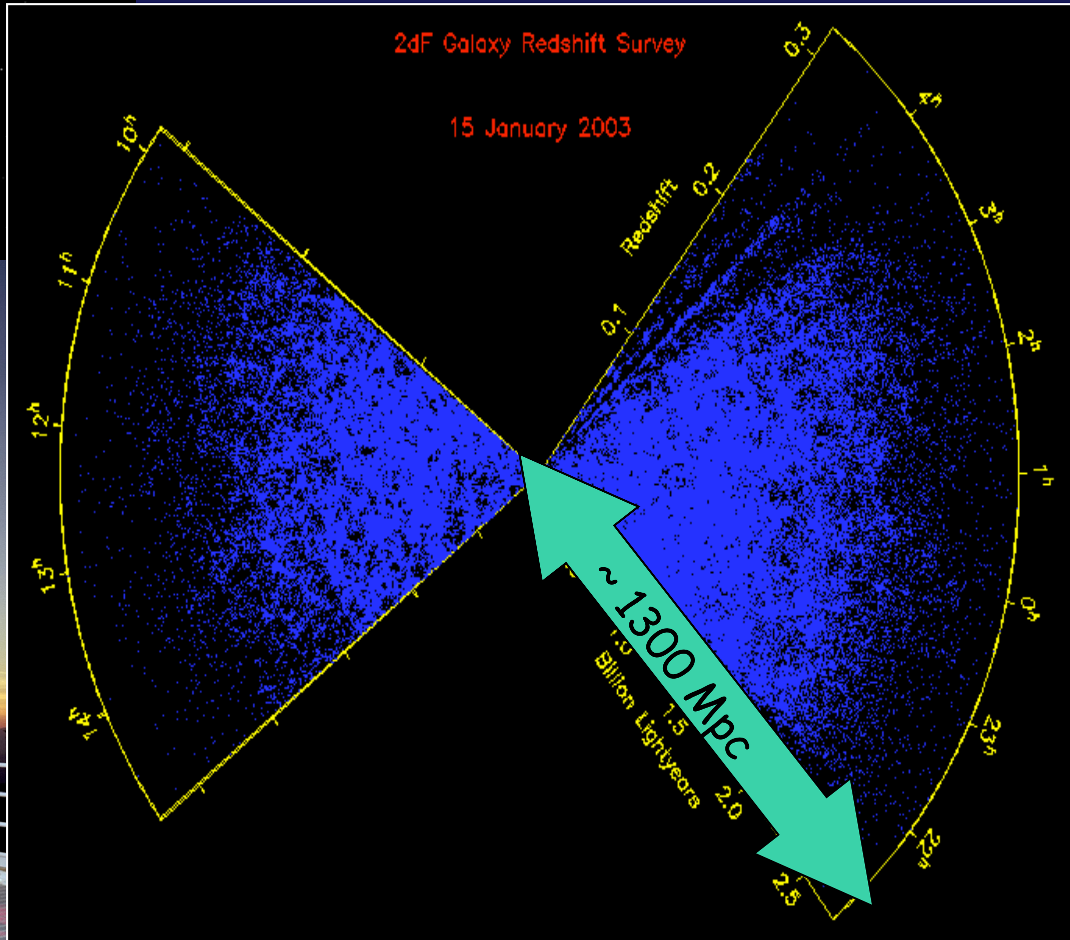
matter power spectrum P(k)



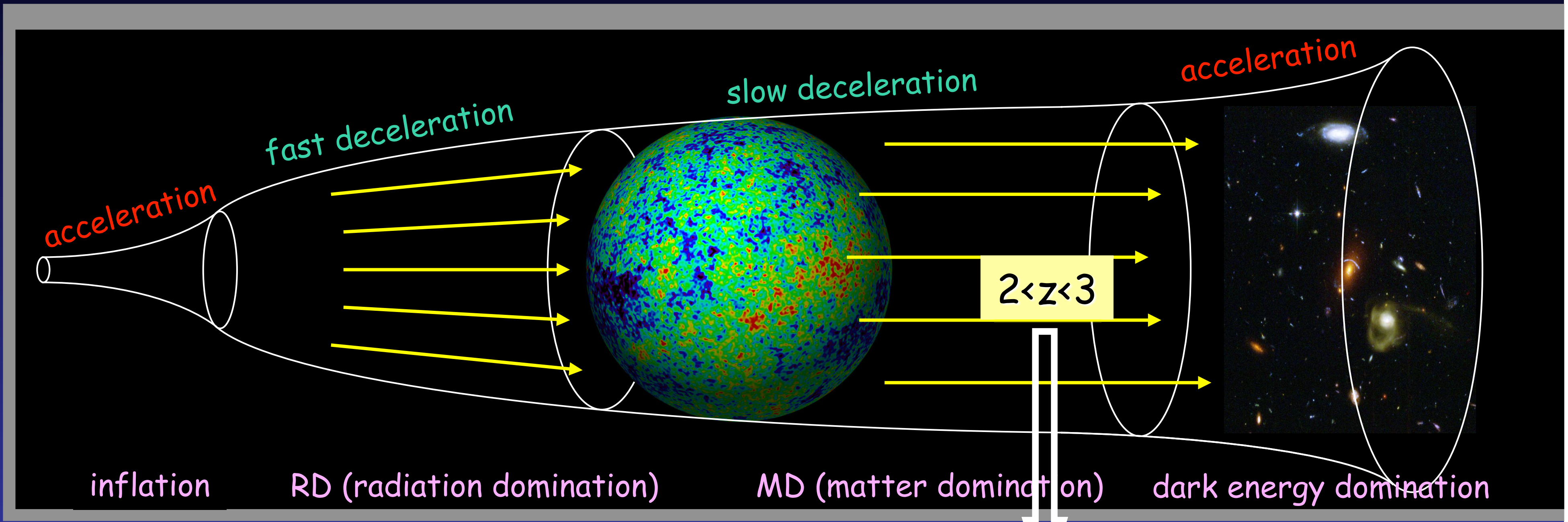
galaxy redshift surveys

Galaxy Redshift Surveys

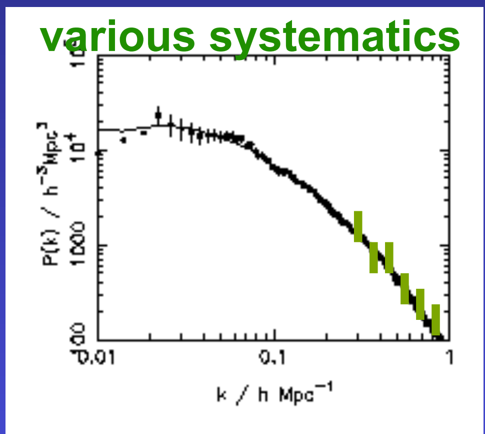




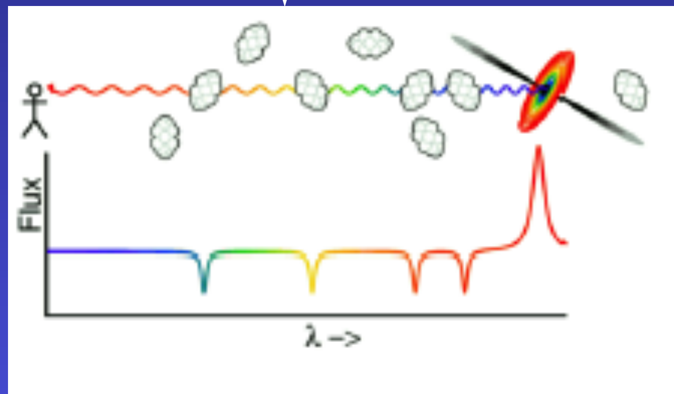
Cosmological observables : LSS



Distribution of large-scale structures at medium z

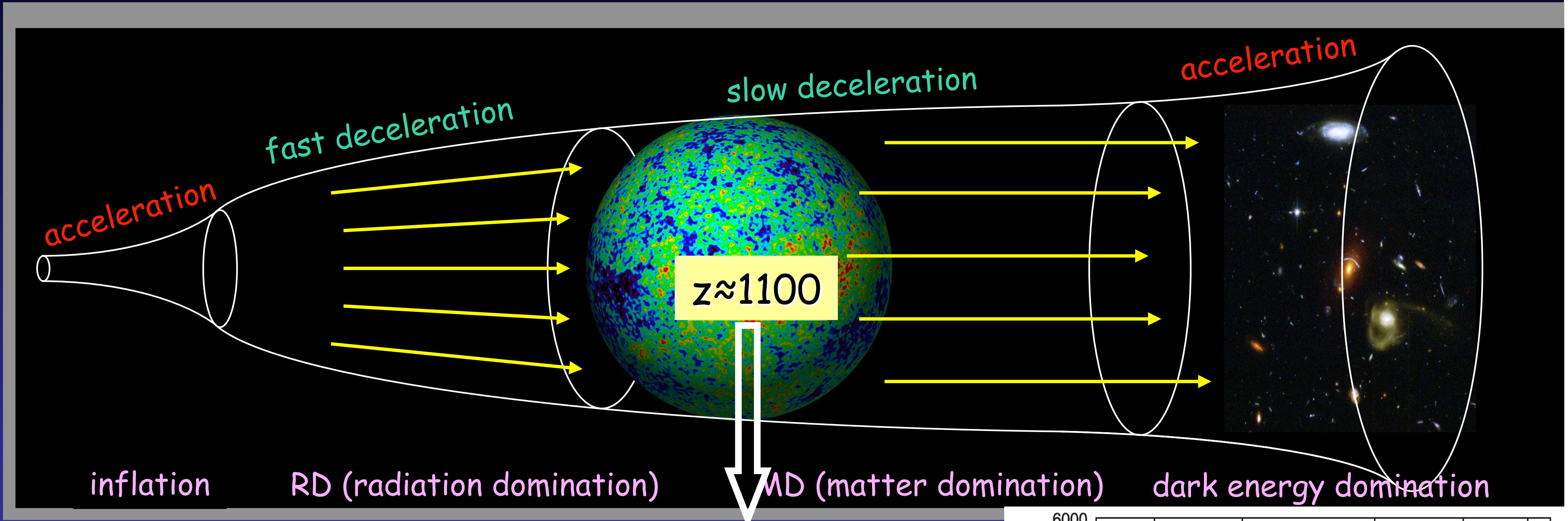


matter power spectrum P(k)

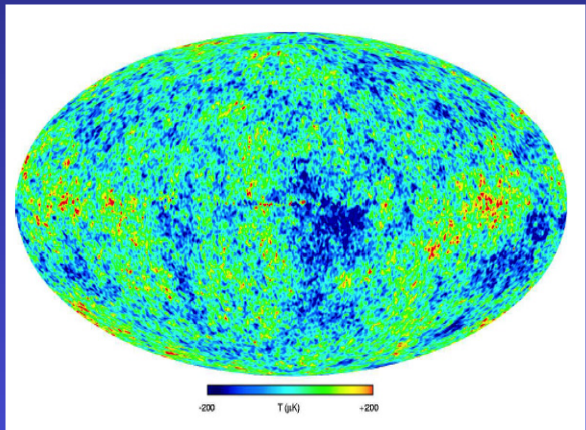


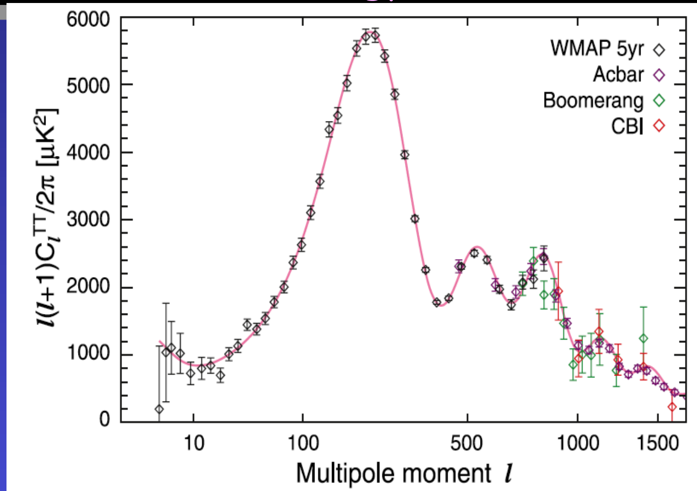
Lyman-α forests in quasar spectra

Cosmological observables: CMB



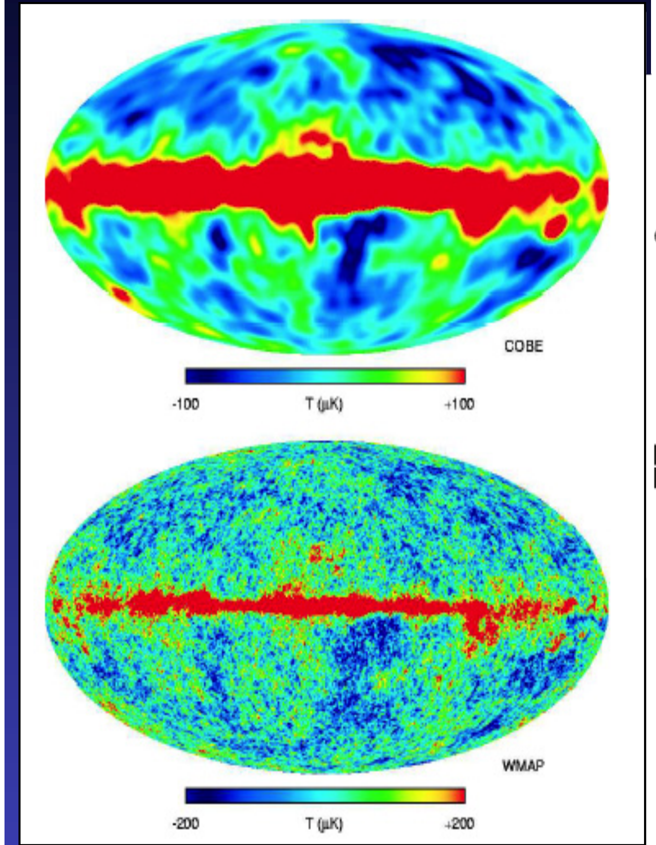
Anisotropies of the Cosmic Microwave Background



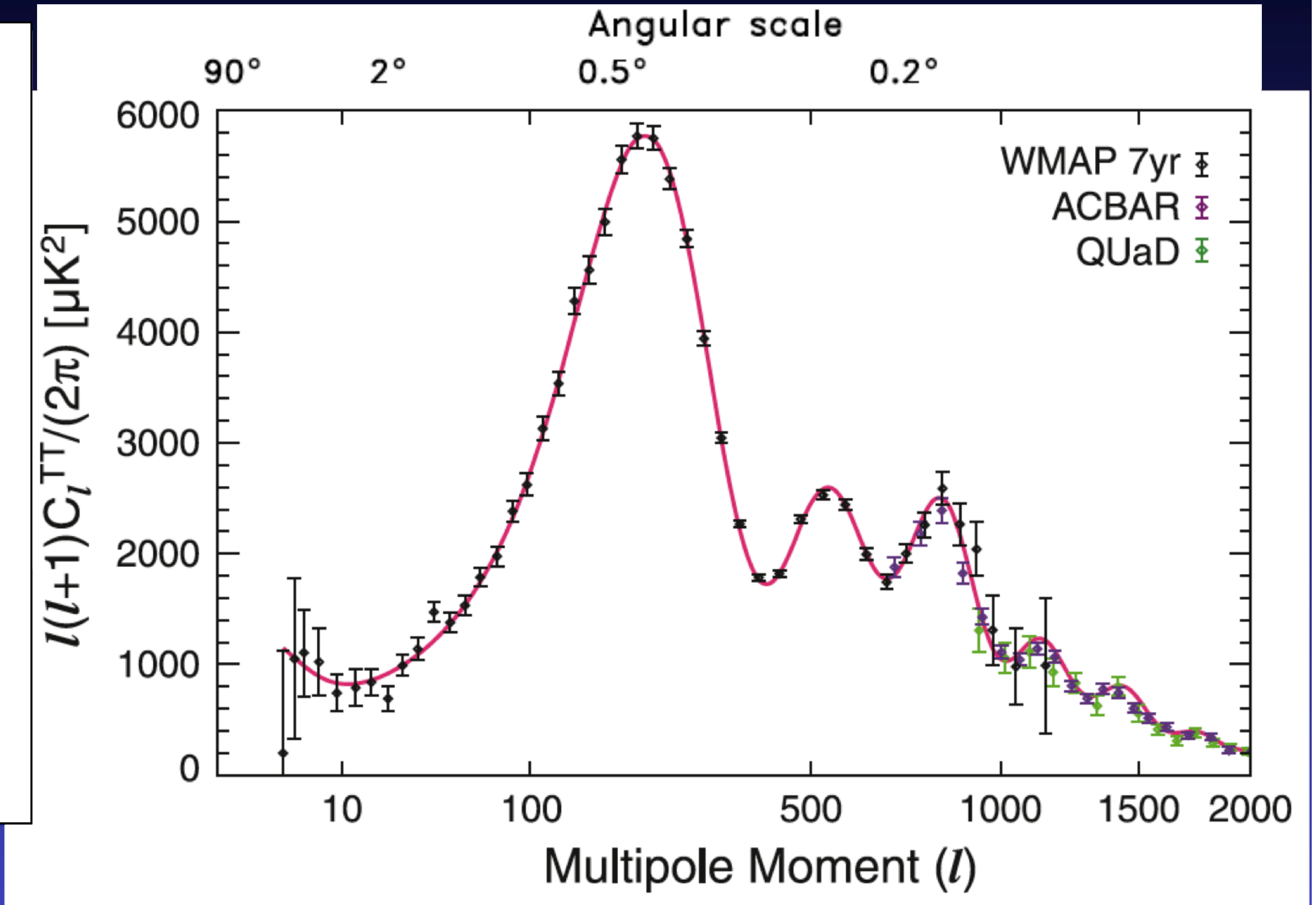


CMB temperature/polarization anisotropies ⇒ photon power spectra

CMB TT DATA



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



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

Effect of massive neutrinos on the CMB spectra

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

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

Neutrinos become NR BEFORE recombination if:

$$\omega_\nu \gtrsim 0.017 \quad \Longrightarrow \quad \sum_i m_{\nu_i} \gtrsim 1.6 \text{ eV}$$

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

Effect of massive neutrinos on the CMB spectra

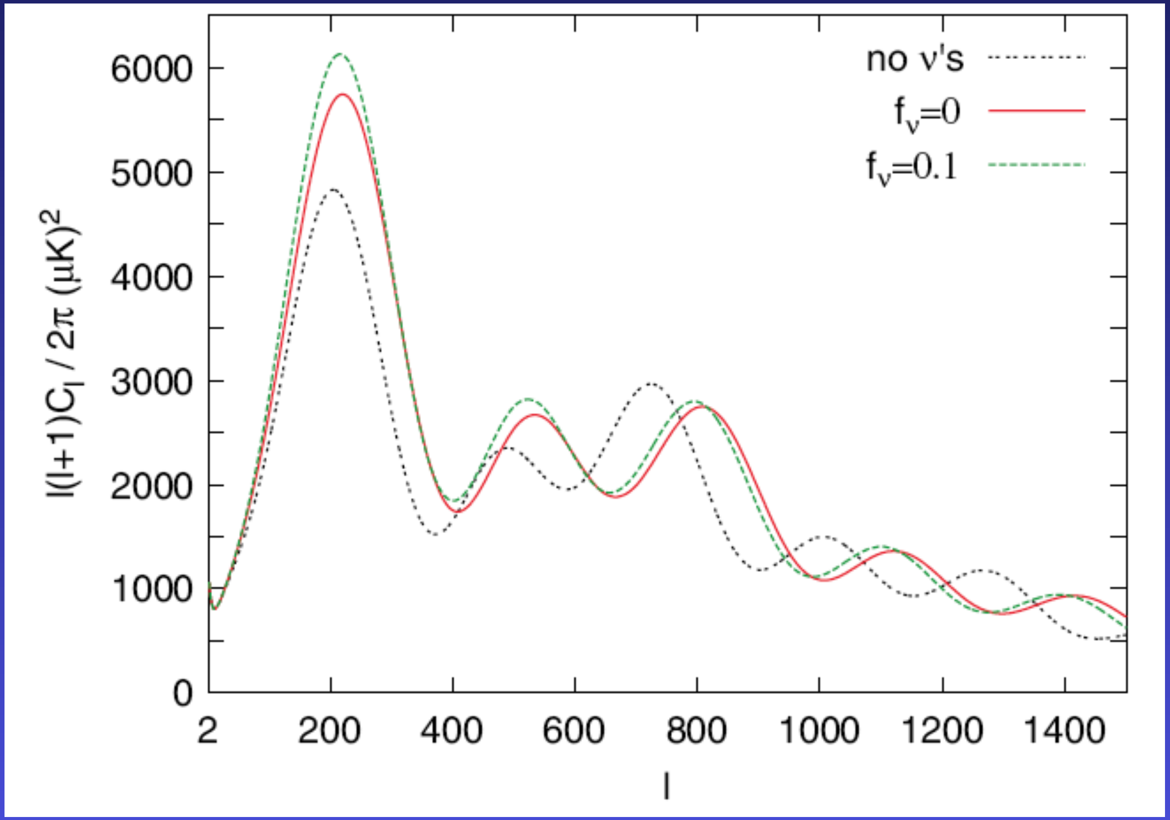
1) CMB spectrum essentially unchanged if neutrinos become NR AFTER photon decoupling.

2) Impact on CMB spectra is indirect: non-zero Ω_ν modifies the background evolution (change in equality time)

Ex: in a flat universe,

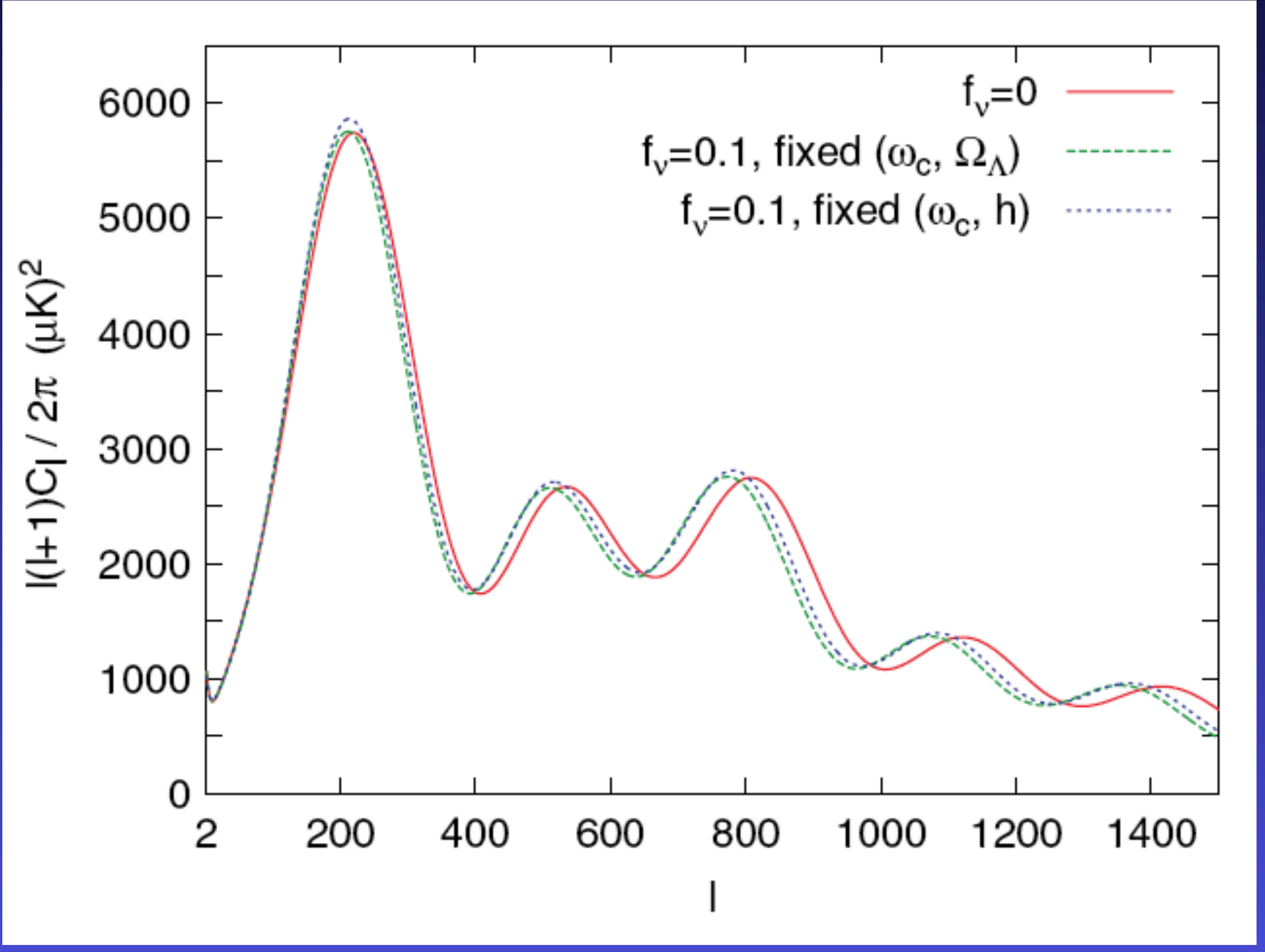
keep $\Omega_\Lambda+\Omega_{cdm}+\Omega_b+\Omega_\nu=1$

constant



Effect of massive neutrinos on the CMB spectra

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



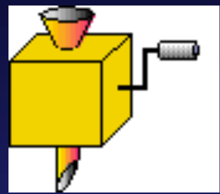
Bounds on m_ν from CMB, LSS and other data

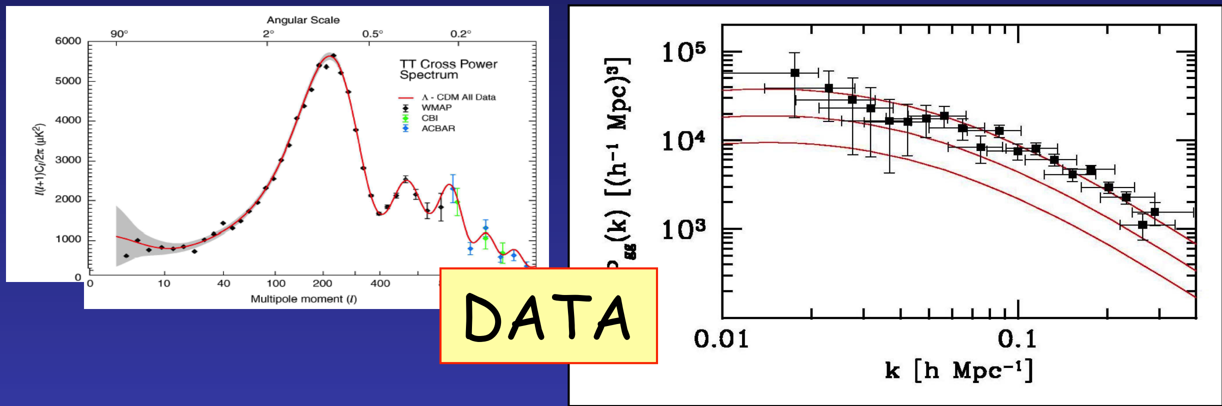
Neutrinos as Hot Dark Matter

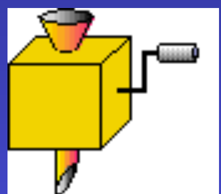
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

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

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







PARAMETER ESTIMATES

Cosmological Data

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

• CMB Polarization: WMAP,…

• Large Scale Structure:

* Galaxy Clustering (2dF,SDSS)

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

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

* Baryon acoustic oscillations (SDSS)

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

Cosmological Parameters: example

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

SDSS Coll, PRD 69 (2004) 103501

Cosmological bounds on neutrino mass(es)

A unique cosmological bound on m_ν DOES NOT exist !

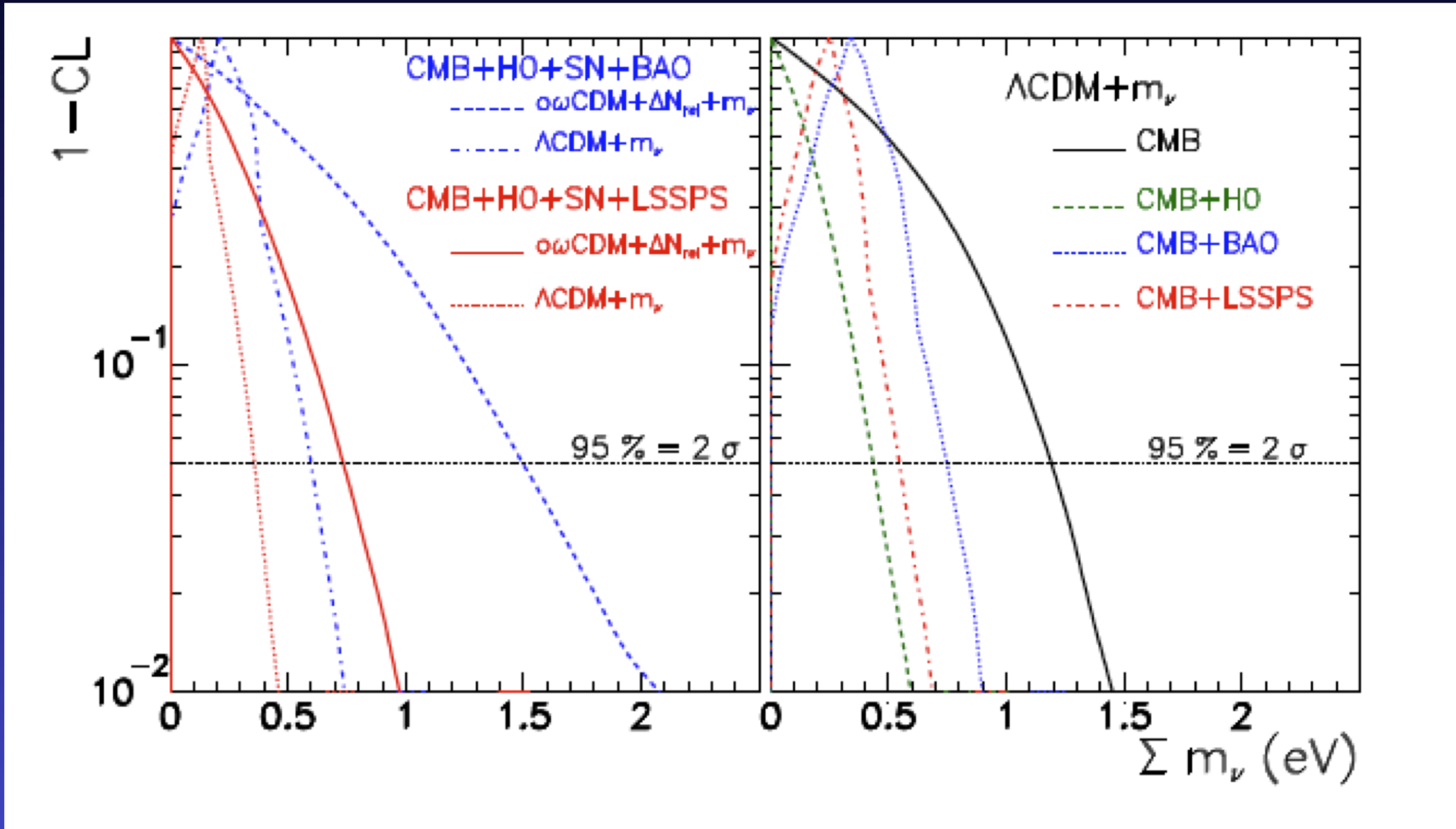
Cosmological bounds on neutrino mass(es)

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

Current cosmological bounds on neutrino masses



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

Current cosmological bounds on neutrino masses

	CMB+HO+SN+BAO			CMB+HO+SN+LSS-PS		
	best	1σ	95% CL	best	1σ	95% CL
H_0 km/s/Mpc	76.2	$^{+3.0}_{-2.8}$	$^{+5.7}_{-5.6}$	74.4	$^{+2.8}_{-2.9}$	$^{+5.6}_{-5.6}$
$\Omega_b h^2 \times 100$	2.205	$^{+0.057}_{-0.050}$	$^{+0.103}_{-0.105}$	2.239	$^{+0.059}_{-0.046}$	$^{+0.095}_{-0.108}$
$\Omega_c h^2$	0.131	$^{+0.018}_{-0.013}$	$^{+0.036}_{-0.023}$	0.128	$^{+0.024}_{-0.009}$	$^{+0.042}_{-0.018}$
n_S	0.961	$^{+0.021}_{-0.015}$	$^{+0.040}_{-0.030}$	0.971	$^{+0.019}_{-0.017}$	$^{+0.037}_{-0.033}$
τ	0.086	$^{+0.011}_{-0.015}$	$^{+0.026}_{-0.028}$	0.083	$^{+0.016}_{-0.011}$	$^{+0.030}_{-0.023}$
σ_8	0.787	$^{+0.091}_{-0.073}$	$^{+0.135}_{-0.179}$	0.824	$^{+0.051}_{-0.048}$	$^{+0.097}_{-0.105}$
Ω_k	-0.006	$^{+0.010}_{-0.009}$	$-0.022 \leq \Omega_k \leq 0.016$	-0.011	$^{+0.008}_{-0.009}$	$-0.028 \leq \Omega_k \leq 0.007$
ω	-1.17	$^{+0.19}_{-0.21}$	$-0.62 \leq \omega + 1 \leq 0.18$	-1.12	$^{+0.21}_{-0.20}$	$-0.57 \leq \omega + 1 \leq 0.26$
$\Delta N_{\rm rel}$	1.2	$^{+1.1}_{-0.61}$	$0.08 \leq \Delta N_{\rm rel} \leq 3.2$	1.3	$^{+1.4}_{-0.54}$	$0.21 \leq \Delta N_{\rm rel} \leq 3.6$
$\sum m_\nu$ (eV)		≤ 0.77	≤ 1.5		≤ 0.37	≤ 0.76

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

Cosmological bounds on neutrino masses using WMAP

Dependence on the data set used:

With WMAP3

Cosmological data set	Σ bound (2σ)
WMAP	< 2.3 eV
WMAP + SDSS	< 1.2 eV
WMAP + SDSS + $SN_{\rm Riess}$ + HST + BBN	< 0.78 eV
CMB + LSS + $SN_{\rm Astier}$	< 0.75 eV
CMB + LSS + $SN_{\rm Astier}$ + BAO	< 0.58 eV
CMB + LSS + $SN_{\rm Astier}$ + Ly-α	< 0.21 eV
CMB + LSS + $SN_{\rm Astier}$ + BAO + Ly-α	< 0.17 eV

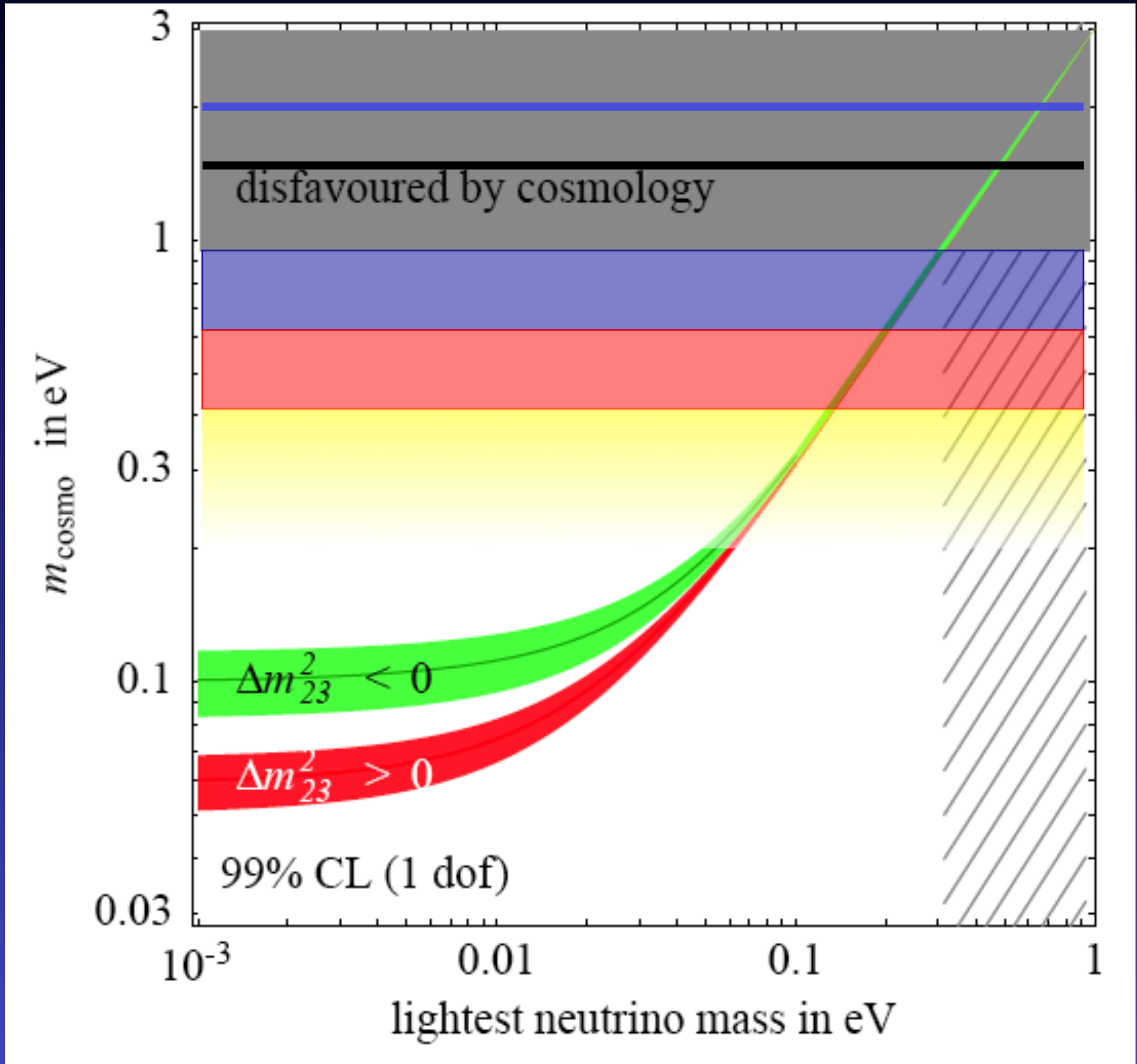
Fogli et al., PRD 75 (2007) 053001

With WMAP5

Cosmological data set	Σ (at 2σ)
CMB	< 1.19 eV
CMB + HST + SN-Ia	< 0.75 eV
CMB + HST + SN-Ia + BAO	< 0.60 eV
CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

Fogli et al., PRD 78 (2008) 033010

Neutrino masses in 3-neutrino schemes



CMB

CMB + galaxy clustering

+ HST, SNI-a…

+ **BAO** and/or bias

+ including Ly-α

Strumia & Vissani, hep-ph/0606054

Current cosmological bounds on neutrino masses

Dependence on the data set AND the cosmological model used.

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

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

Absolute mass scale searches

Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$	2.2 eV
Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	< 0.2-0.8 eV
Cosmology	$\sim \sum_i m_i$	< 0.2-2.0 eV

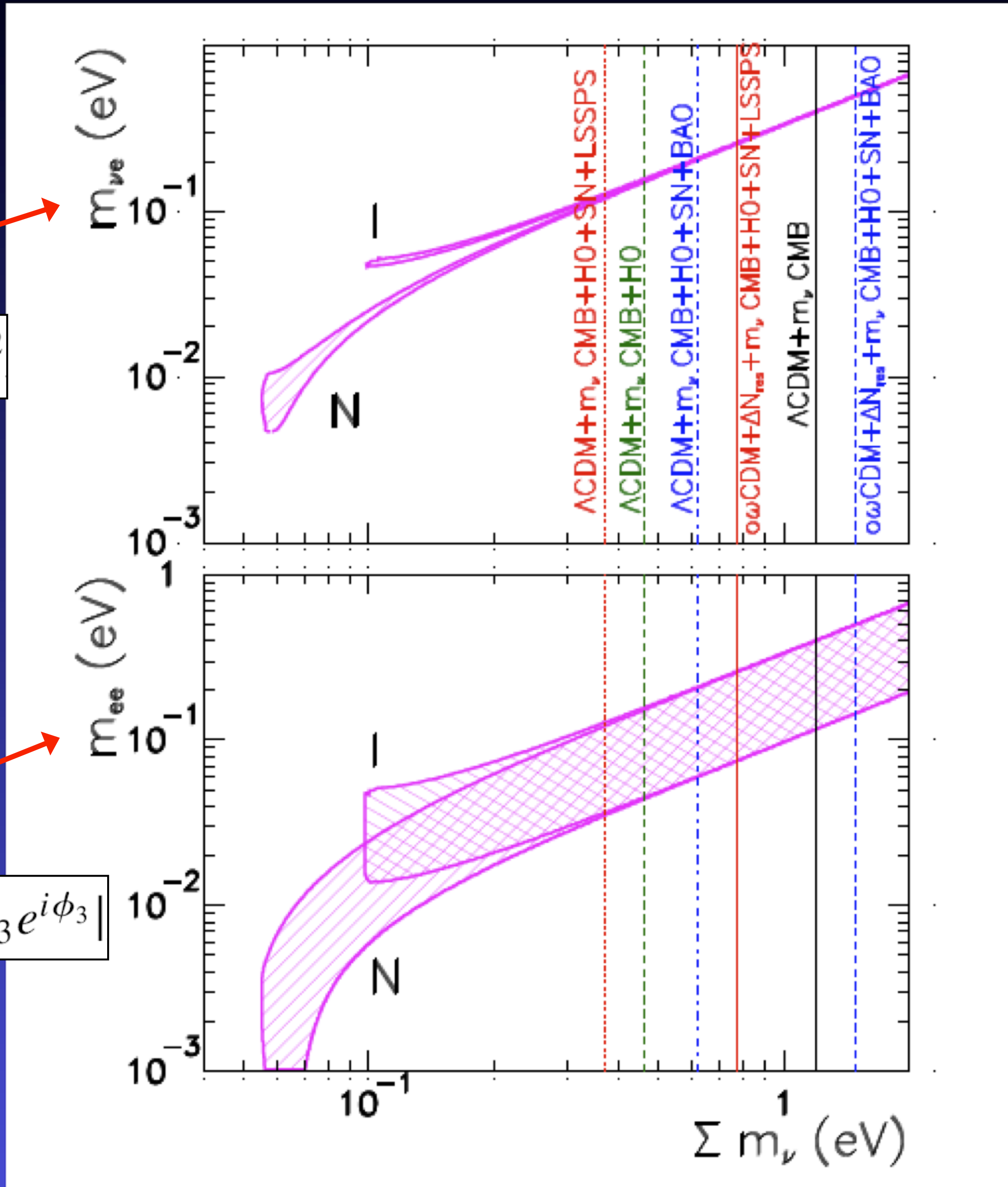
$$m_{\nu_e} \rightarrow [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

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

Tritium β decay, 0ν2β and Cosmology

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

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



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

Non-standard relic neutrinos

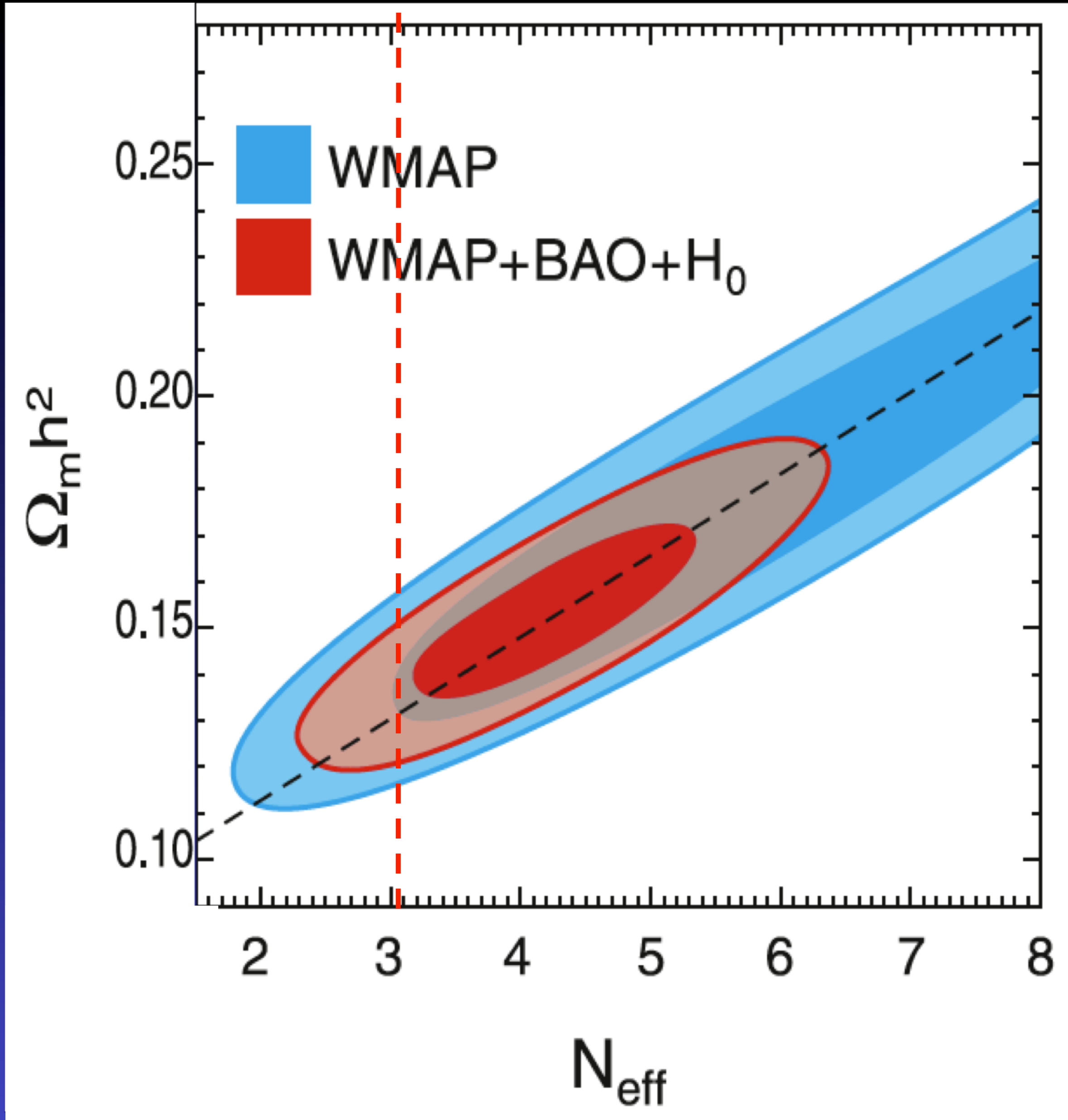
The cosmological bounds on neutrino masses are modified if relic neutrinos have non-standard properties (or for non-standard models)

Two examples where the cosmological bounds do not apply

- **Massive neutrinos strongly coupled to a light scalar field**: they could annihilate when becoming NR
- **Neutrinos coupled to the dark energy**: the DE density is a function of the neutrino mass (mass-varying neutrinos)

Future sensitivities on m_ν and N_{eff} from cosmology

allowed range for N_{eff}



WMAP [7-year], arXiv:1001.4538

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

Future bounds on N_{eff}

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

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

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

ERROR FORECASTS

Experiment	f_{sky}	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Example of future CMB satellite

Bashinsky & Seljak, PRD 69 (2004) 083002

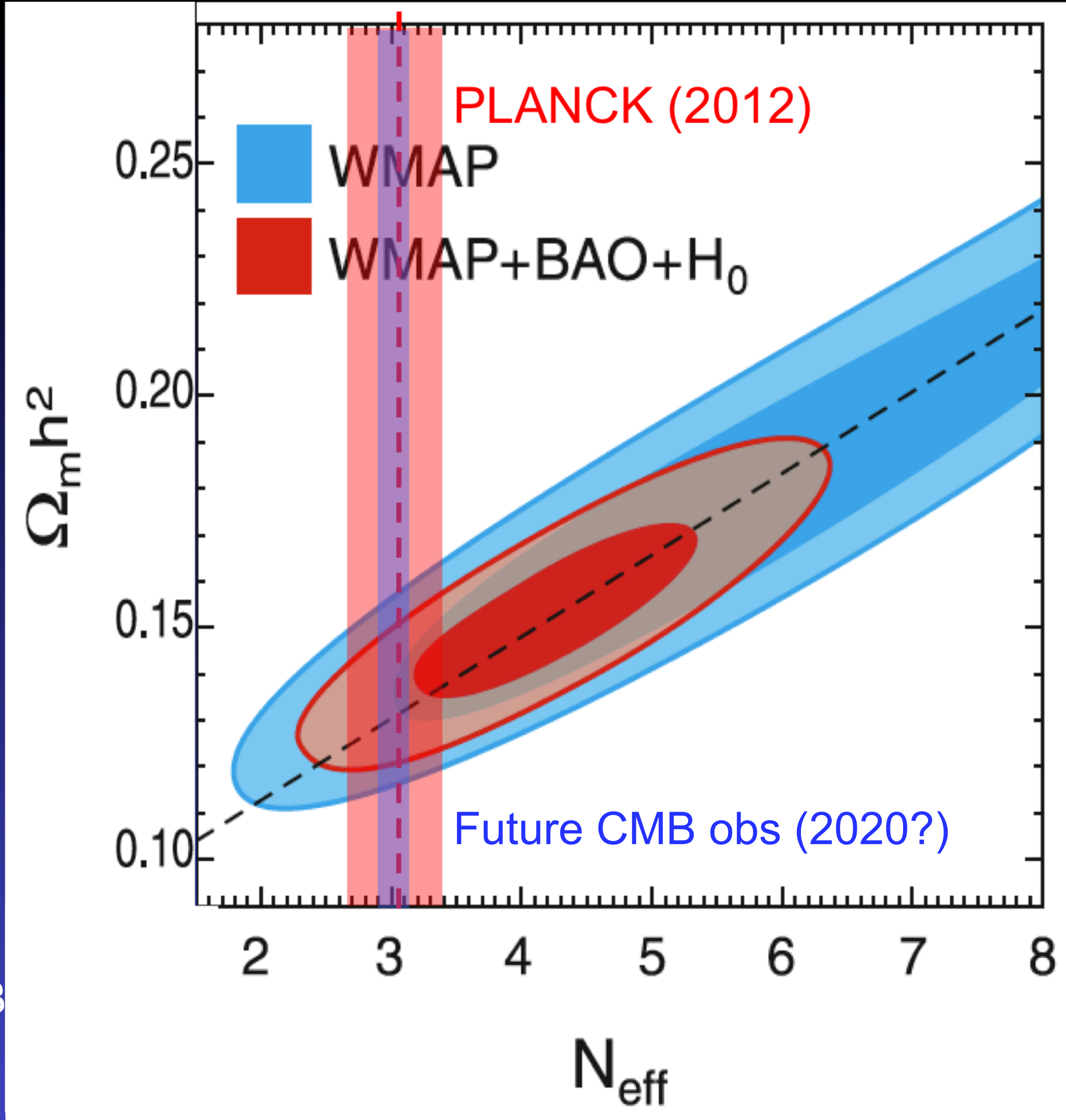
Future bounds on N_{eff}

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

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

Hamann et al, JCAP 07 (2010) 022

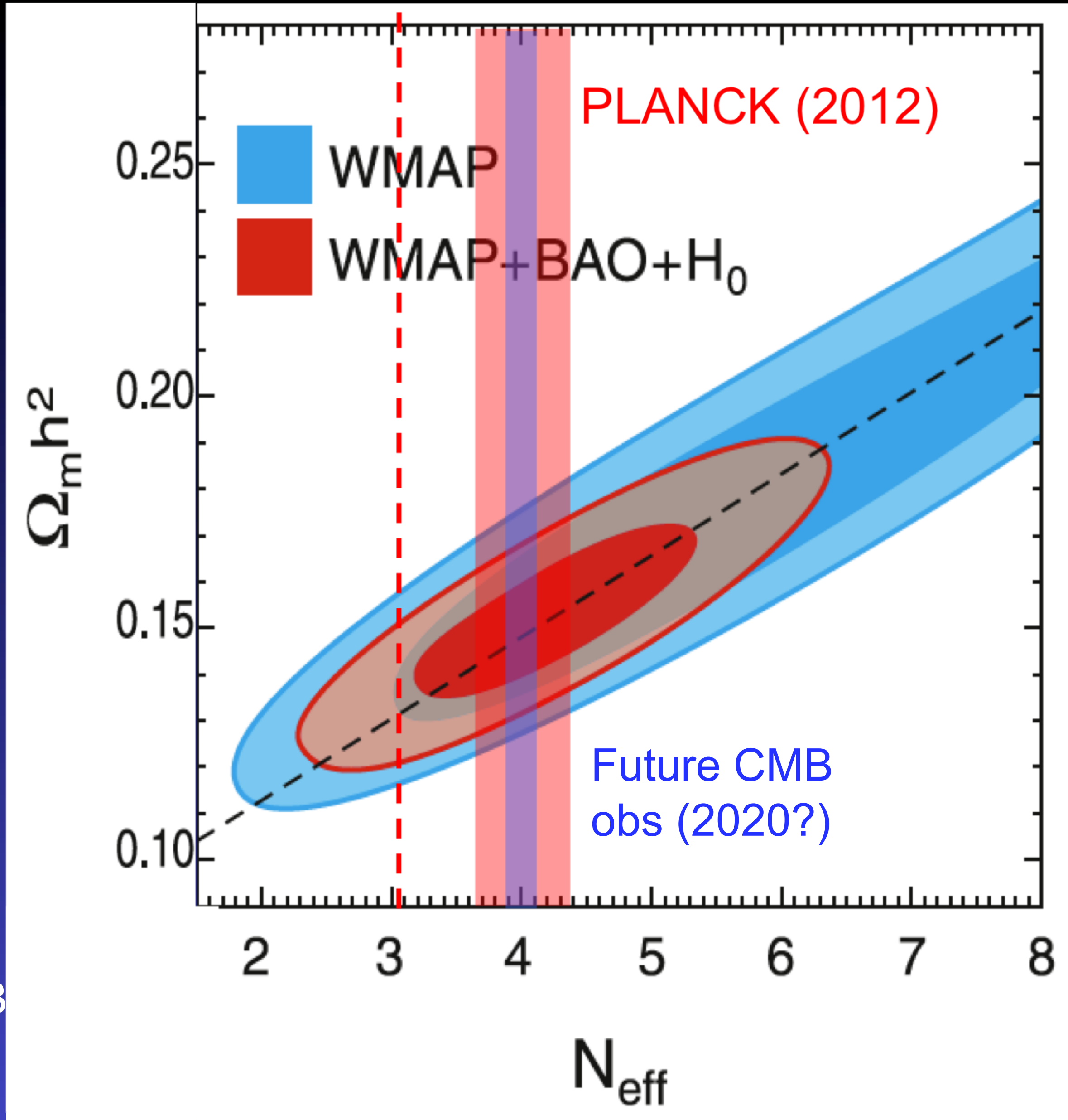
allowed range for N_{eff}



WMAP [7-year], arXiv:1001.4538

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

allowed range for N_{eff}



WMAP [7-year], arXiv:1001.4538

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

Future sensitivities to Σm_ν

Future cosmological data will be available from

- CMB (Temperature & Polarization anis.)
- High-z Galaxy redshift surveys

  Hannestad & Wong, JCAP 07 (2007) 004

  Takada et al, PRD 73 (2006) 083520
- Galaxy cluster surveys

  Wang et al, PRL 95 (2005) 011302
- Weak lensing surveys (tomography)

  Hannestad et al, JCAP 06 (2006) 025

  Song & Knox, PRD 70 (2004) 063510
- CMB lensing

  Perotto et al, JCAP 10 (2006) 013

  Lesgourgues et al, PRD 73 (2006) 045021
- Fluctuations in the 21 cm H line

  Loeb & Wyithe, PRL 100 (2008) 161301

  Pritchard & Pierpaoli, PRD 78 (2008) 065009

Forecasts indicate 0.01-0.15 eV sensitivities to Σm_ν are possible !!

PLANCK+SDSS

- Fisher matrix analysis: expected sensitivities assuming a fiducial cosmological model, for future experiments with known specifications

Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau, \Sigma m_\nu) =$
$(0.0245 , 0.148 , 0.70 , 0.98 , 0.12, \Sigma m_\nu)$

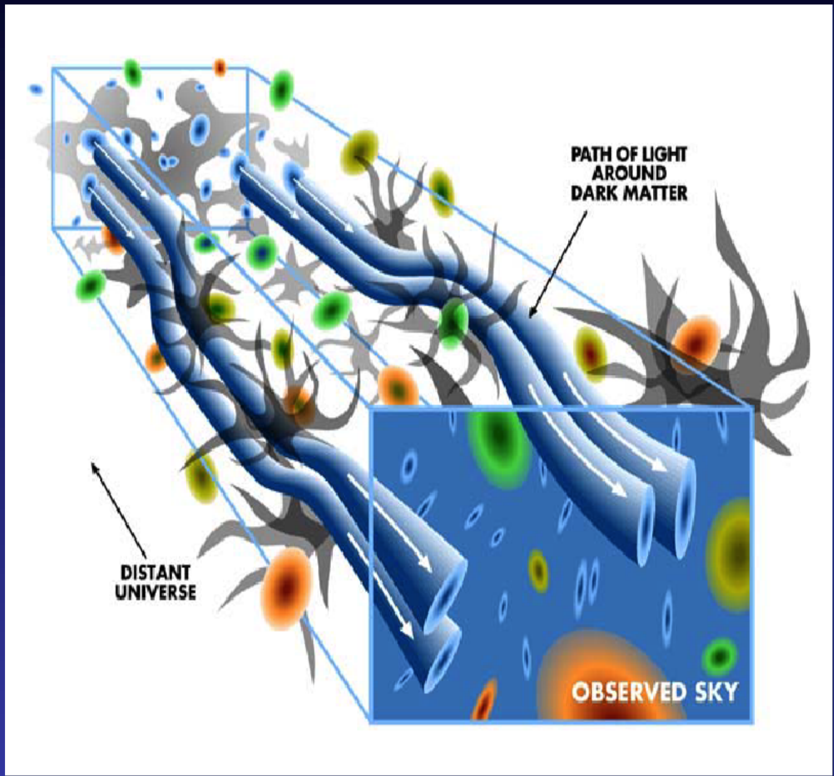
Σm detectable at 2σ if larger than

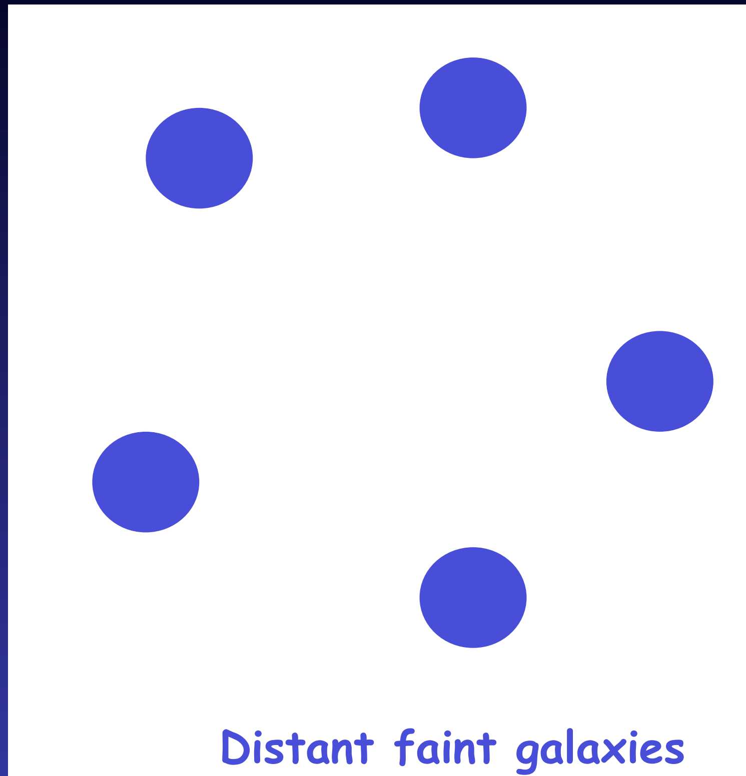
0.21 eV (PLANCK+SDSS)

0.13 eV (CMBpol+SDSS)

Lesgourgues, SP & Perotto, PRD 70 (2004) 045016

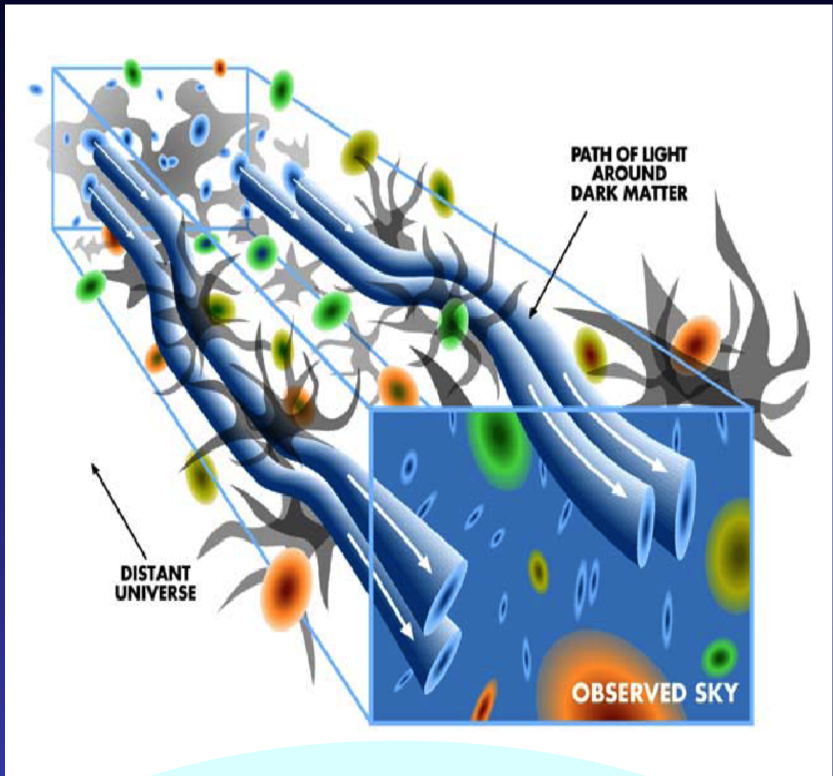
Future sensitivities to Σm_ν: weak gravitational lensing

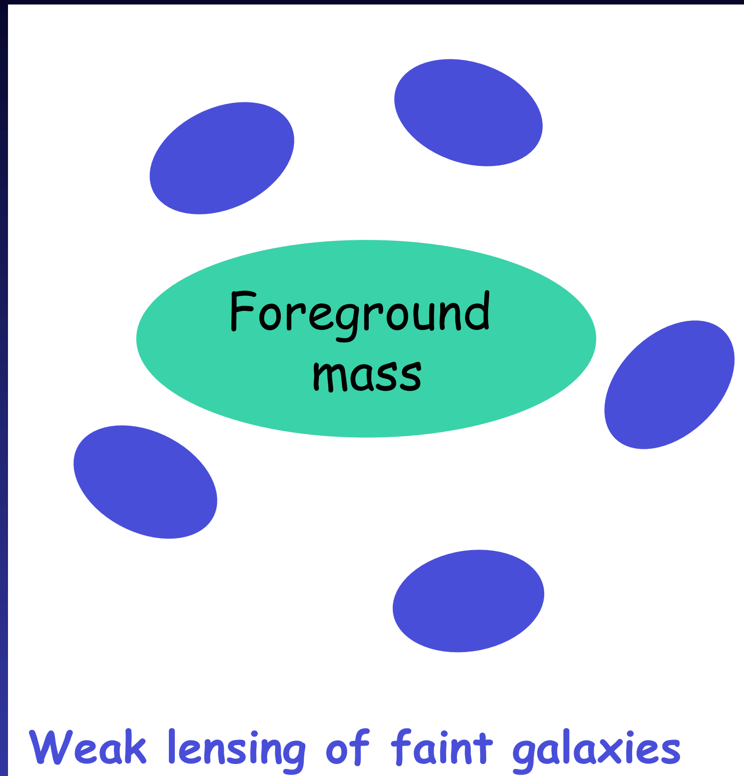




Frieman, Dodelson

Future sensitivities to Σm_ν: weak gravitational lensing



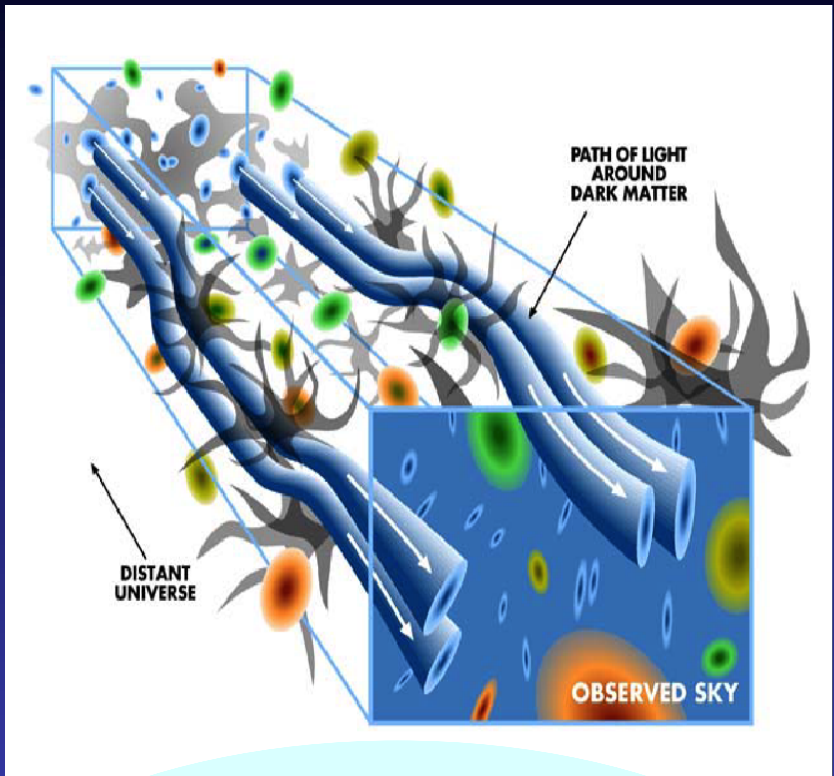


Frieman, Dodelson

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



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

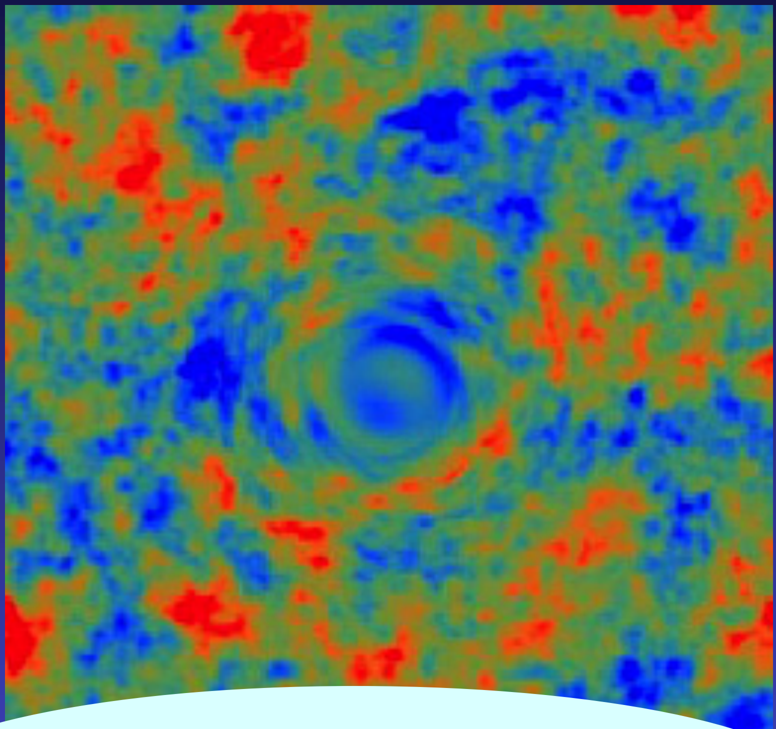
sensitivity of future weak lensing survey $(4000°)^2$ to m_ν

$\sigma(m_\nu) \sim 0.1$ eV

Abazajian & Dodelson
PRL 91 (2003) 041301

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 eV (Planck)

$\sigma(m_\nu)$ = 0.044 eV (CMBpol)

Kaplinghat, Knox & Song
PRL 91 (2003) 241301

CMB lensing: recent forecast analysis

$\sigma(M_\nu)$ in eV for future CMB experiments alone :

Lesgourgues et al, PRD 73 (2006) 045021

Free parameters:	8 parameters of minimal ΛMDM			
Lensing extraction:	no	no	yes	yes
Foreground cleaning:	perfect	none	perfect	none
QUaD+BICEP	1.3	1.6	0.31	0.36
BRAIN+ClOVER	1.5	1.8	0.34	0.43
PLANCK	0.45	0.49	0.13	0.14
SAMPAN	0.34	0.40	0.10	0.17
PLANCK+SAMPAN	0.32	0.36	0.08	0.10
Inflation Probe	0.14	0.16	0.032	0.036

Free parameters:	same + $\{\alpha,\ w,\ N_{\rm eff}\}$			
Lensing extraction:	no	no	yes	yes
Foreground cleaning:	perfect	none	perfect	none
QUaD+BICEP	1.5	1.9	0.36	0.40
BRAIN+ClOVER	1.7	2.0	0.42	0.51
PLANCK	0.51	0.56	0.15	0.15
SAMPAN	0.37	0.44	0.12	0.18
PLANCK+SAMPAN	0.34	0.40	0.10	0.12
Inflation Probe	0.25	0.26	0.035	0.039

"Measuring" even m_ν=0.05 eV ?

New cosmological observable as a potential probe of fluctuations at intermediate redshifts (6<z<20) ⇒ **study of fluctuations in the 21cm line emitted by neutral H**

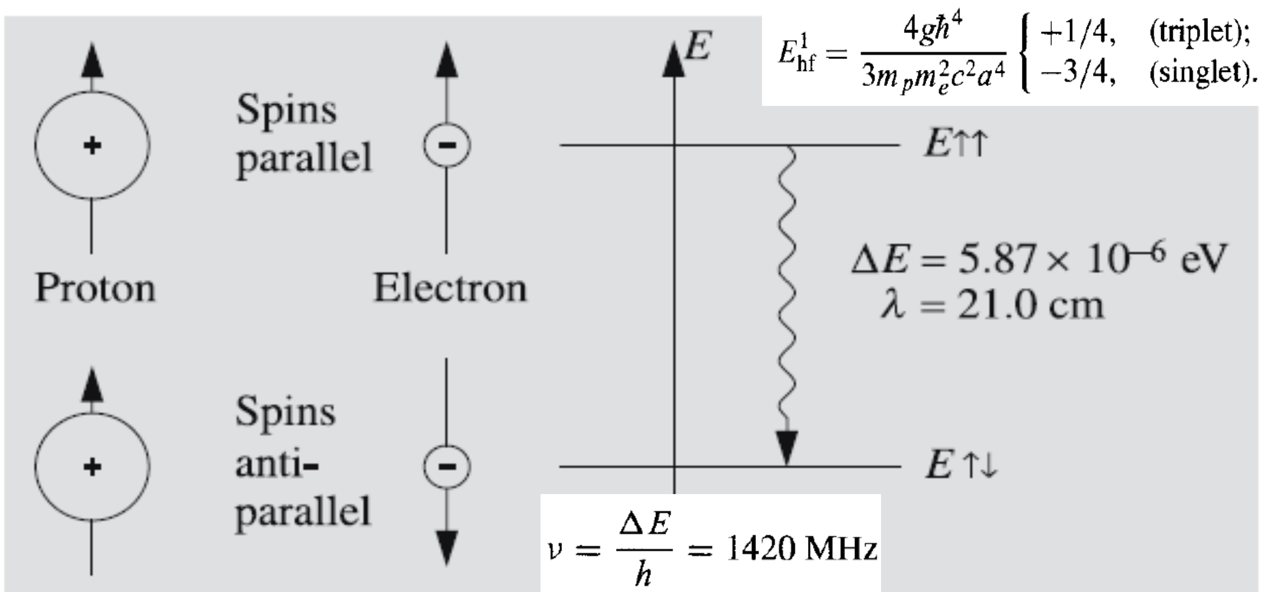
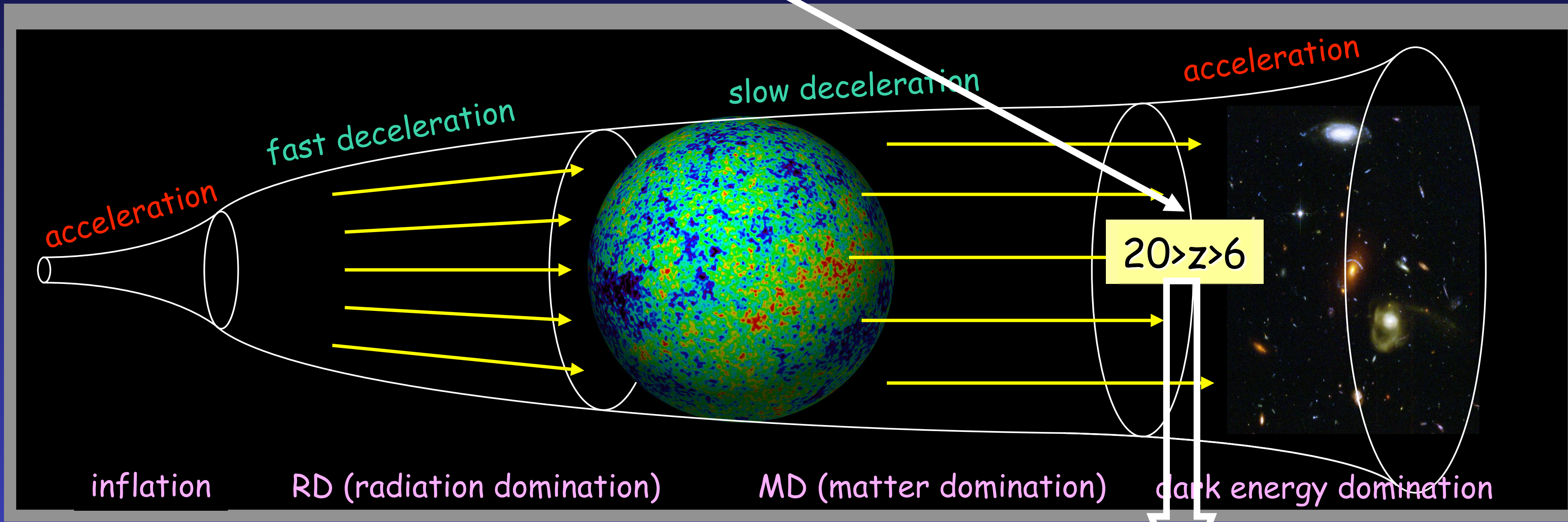


Fig. 5.8. The origin of the hydrogen 21 cm line. The spins of the electron and the proton may be either parallel or opposite. The energy of the former state is slightly larger. The wavelength of a photon corresponding to a transition between these states is 21 cm

Karttunen *et al. 2007*

"Measuring" even m_ν=0.05 eV ?

New cosmological observable as a potential probe of fluctuations at intermediate redshifts (6<z<20) ⇒ study of fluctuations in the 21cm line emitted by neutral H



Redshifted line:
2.1 m at
redshift 10

$$\left\langle \tilde{\delta}_{21}(\mathbf{k}_1)\, \tilde{\delta}_{21}(\mathbf{k}_2) \right\rangle \equiv (2\pi)^3 \delta_D(\mathbf{k}_1 + \mathbf{k}_2) P_{21}(\mathbf{k}_1)$$

power spectrum of 21 cm brightness fluctuations P_{21}(k)

Future sensitivities on Σm_ν from 21cm observ.

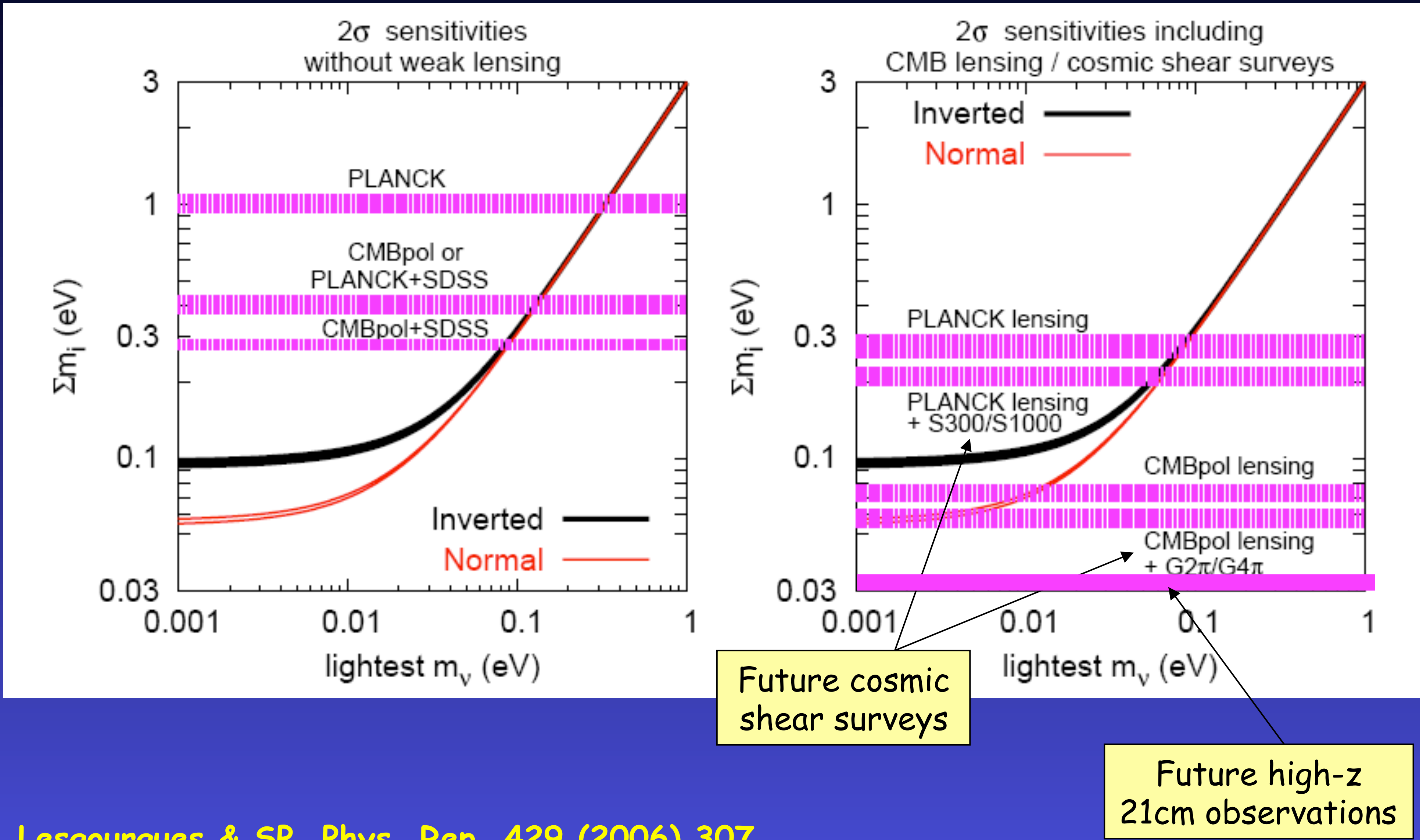
	$\Omega_m h^2$	$\Omega_b h^2$	Ω_Λ	w	n_s	A_s^2	τ	Y_{He}	M_ν
Fiducial	0.147	0.023	0.7	-1	0.95	26.6	0.1	0.24	0.3
SDSS	0.456	0.083	0.117	1.21	0.503	∞	-	-	6.16
G1	0.119	0.0207	0.0358	0.574	0.174	∞	-	-	1.28
G2	0.0354	0.00593	0.295	1.22	0.0482	∞	-	-	1.01
G3	0.0252	0.00438	0.0076	0.122	0.037	∞	-	-	0.272
MWA	0.0317	0.00761	0.972	3.13	0.0487	∞	-	-	0.749
SKA	0.00191	0.00056	0.234	0.747	0.0054	∞	-	-	0.175
FFTT	4.94e-05	4.77e-05	0.0045	0.014	0.0002	∞	-	-	0.009
Planck	0.0045	0.00024	0.068	0.18	0.0074	0.26	0.0048	0.011	0.38
+SDSS	0.0033	0.00024	0.023	0.11	0.0074	0.254	0.0046	0.0103	0.272
+G1	0.0016	0.00021	0.013	0.081	0.0068	0.245	0.0044	0.01	0.136
+G2	0.00089	0.00022	0.037	0.149	0.0067	0.243	0.0044	0.0099	0.104
+G3	0.00051	0.00016	0.003	0.021	0.0051	0.24	0.0043	0.0081	0.052
+MWA	0.00146	0.00021	0.053	0.17	0.0066	0.242	0.0044	0.0101	0.144
+SKA	0.00029	0.00014	0.020	0.065	0.003	0.236	0.0043	0.0044	0.080
+FFTT	4.23e-05	3.97e-05	0.004	0.011	0.0002	0.23	0.0043	0.0030	0.0075
CosmicVar	0.00244	4.16e-05	0.030	0.033	0.0024	0.124	0.0023	0.0028	0.222
+FFTT	3.3e-05	2.58e-05	0.0024	0.0076	0.0002	0.111	0.0021	0.0011	0.0068

Future Low-ν radio telescopes

Pritchard & Pierpaoli, PRD 78 (2008) 065009

[also Loeb & Wyithe, PRL 100 (2008) 161301; Mao et al, PRD 78 (2008) 023529]

Summary of future sensitivities



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

Summary of future sensitivities

Probe	Potential sensitivity (short term)	Potential sensitivity (long term)
CMB	0.4-0.6	0.4
CMB with lensing	0.1-0.15	0.04
CMB + Galaxy Distribution	0.2	0.05-0.1
CMB + Lensing of Galaxies	0.1	0.03-0.04
CMB + Lyman-α	0.1-0.2	Unknown
CMB + Galaxy Clusters	-	0.05
CMB + 21 cm	-	0.0003-0.1

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

Hannestad, arXiv:1007.0658

End of 2nd lecture

Conclusions

Cosmological observables can be used to bound (or measure) neutrino properties, in particular the sum of neutrino masses (info complementary to laboratory results)

The radiation content of the Universe (N_{eff}) will be very constrained in the near future (Planck)

Current bounds on the sum of neutrino masses from cosmological data (best $\Sigma m_\nu < 0.4-0.6$ eV, conservative $\Sigma m_\nu < 1$ eV)

Different cosmological observations in the next future → Sub-eV sensitivity (0.1-0.2 eV and better) → Test degenerate mass region and eventually the mimimum total mass for IH case