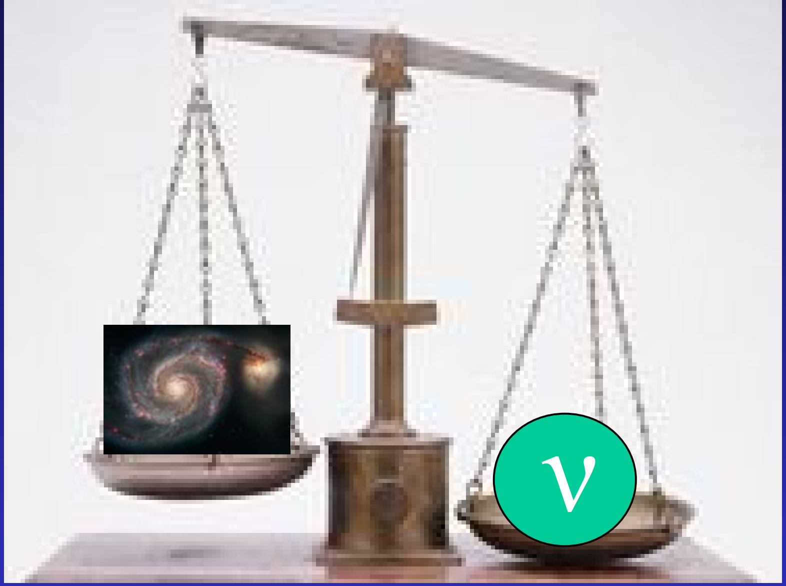
Neutrino masses and cosmology



AHEP
Astroparticle and High Energy Physics Group

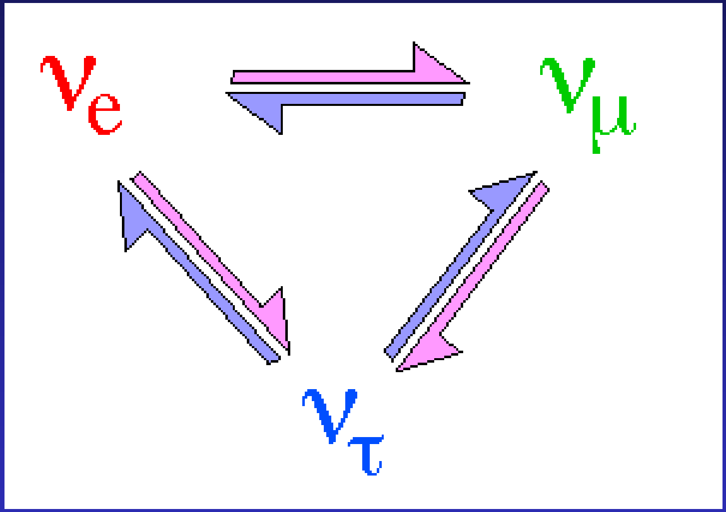
Sergio Pastor (IFIC)

HEP2005, Lisboa, July 2005

CSIC

We know that flavour neutrino oscillations exist

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



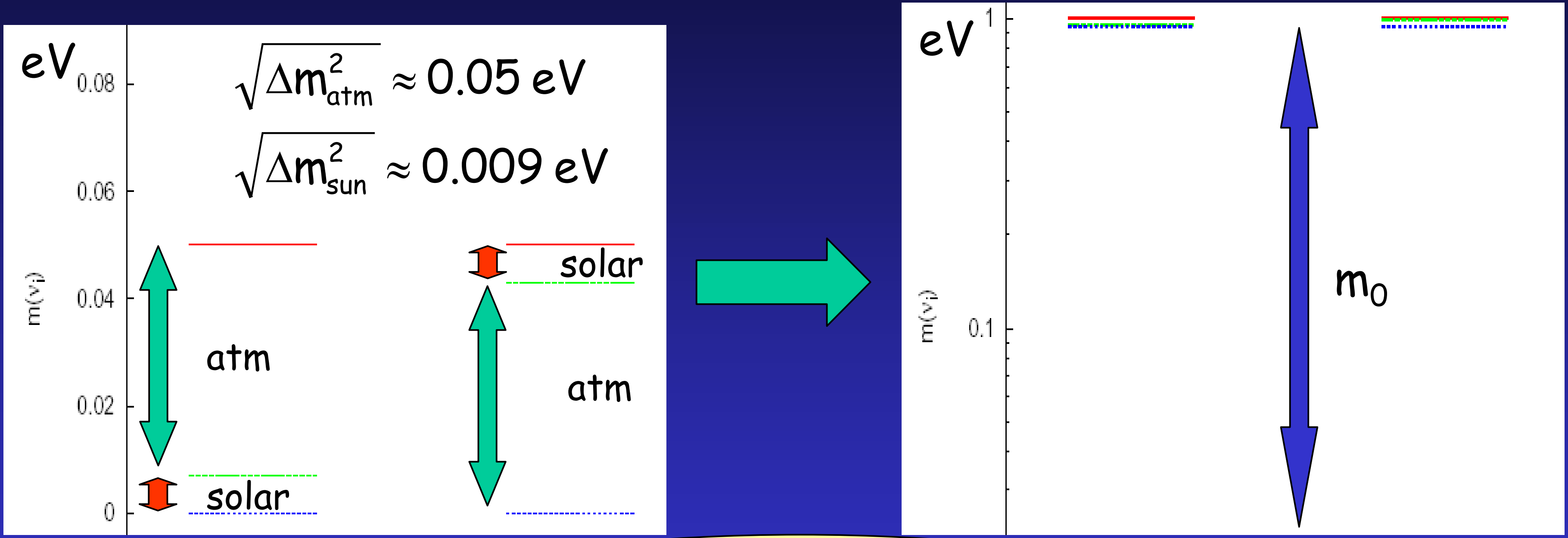
$$\boxed{(e,\mu,\tau) \leftrightarrow (\nu_1,\nu_2,\nu_3)}$$

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

First evidence of physics beyond the Standard Model !

Neutrino masses

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



What is the value of m_0 ?

Absolute mass scale searches

Tritium β decay

$$m_{\nu_e} = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2}$$

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

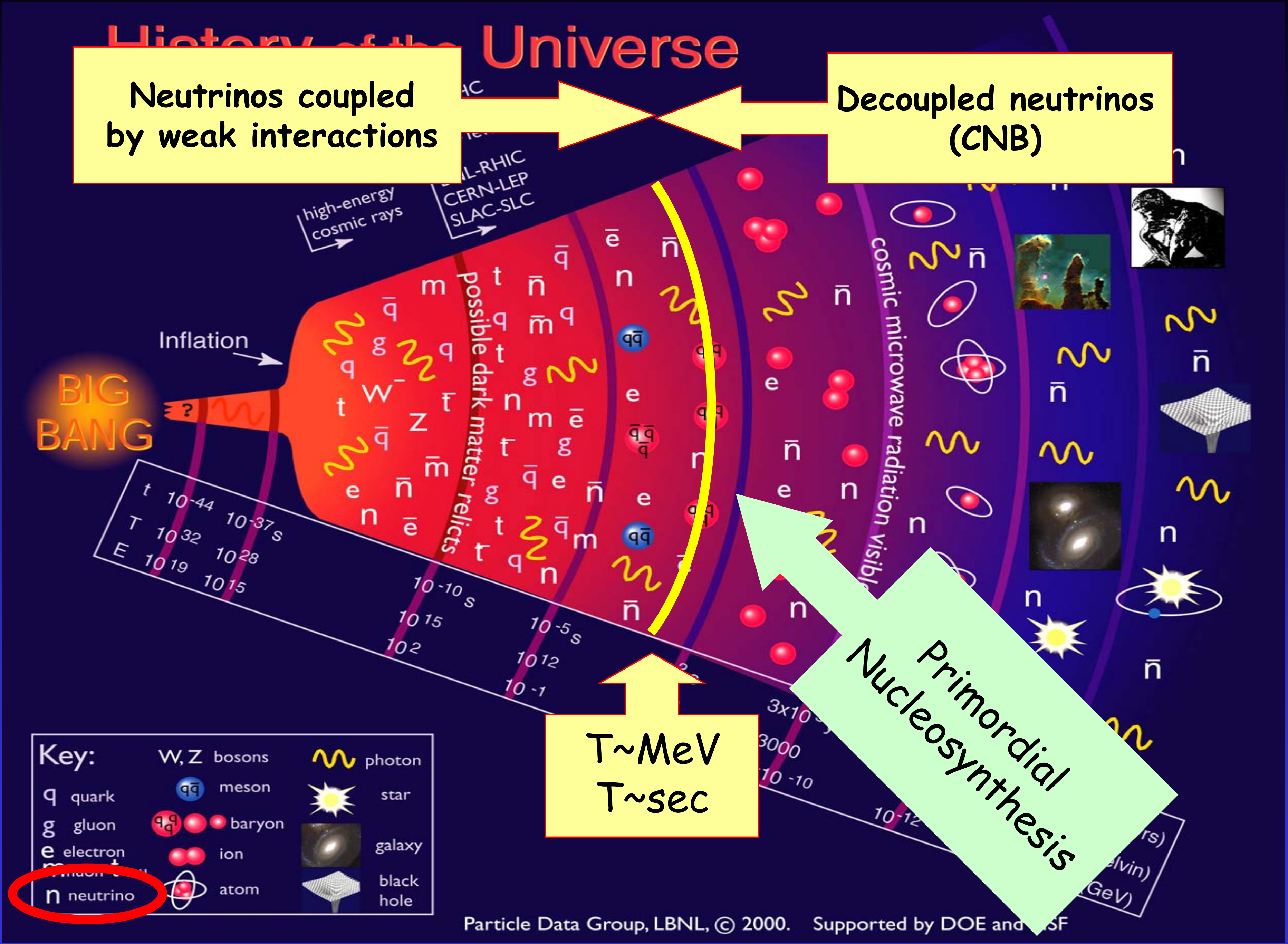
Neutrinoless double beta decay

$$m_{ee} = \left| \sum_i U_{ei}^2 m_i \right|$$

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

Cosmology

$$\sim \sum_i m_i$$



Neutrinos coupled by weak interactions

Decoupled neutrinos (CNB)

T~MeV
T~sec

Primordial Nucleosynthesis

The Cosmic Neutrino Background

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

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

- Number density

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

- Energy density

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 = 1.7\times10^{-5}$$

Massless

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\,\mathrm{eV}}$$

Massive

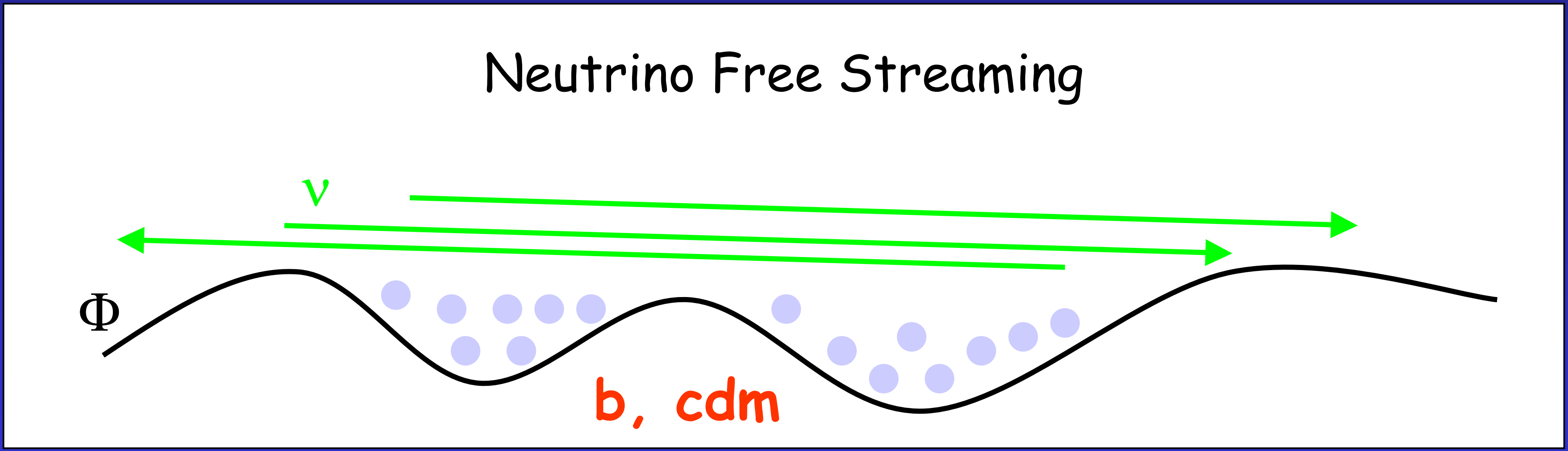
$m_\nu \gg T$

Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

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

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



Neutrinos as Dark Matter

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- First structures to be formed when Universe became matter -dominated

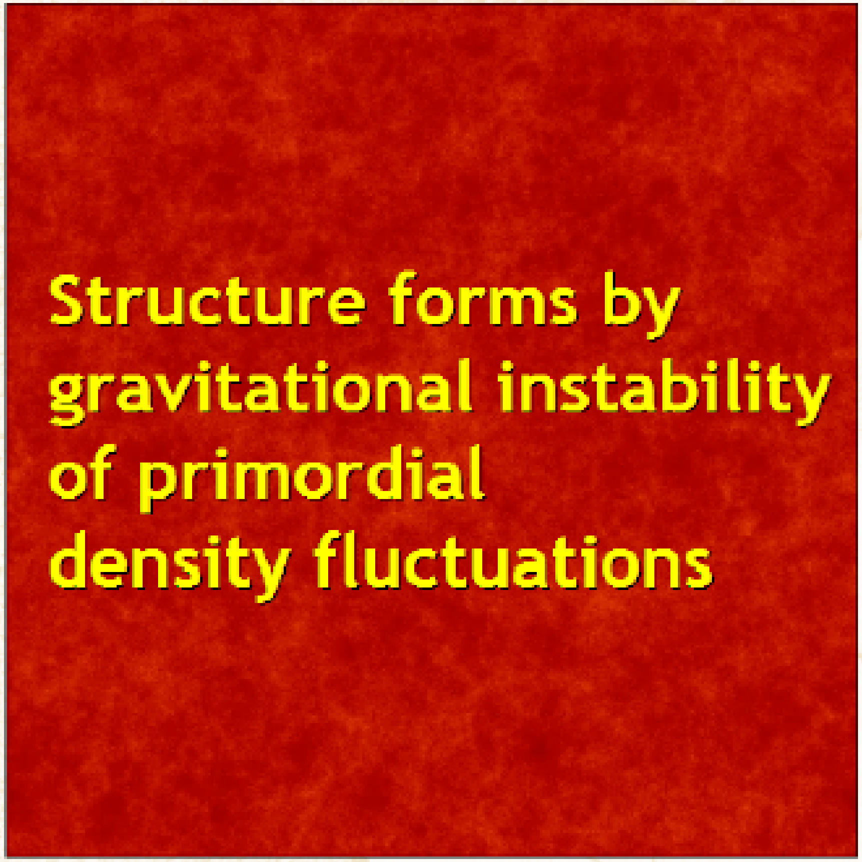
$$41\left(\frac{m_\nu}{30\ \mathrm{eV}}\right)^{-1} \mathrm{Mpc}$$

- HDM ruled out by structure formation → CDM

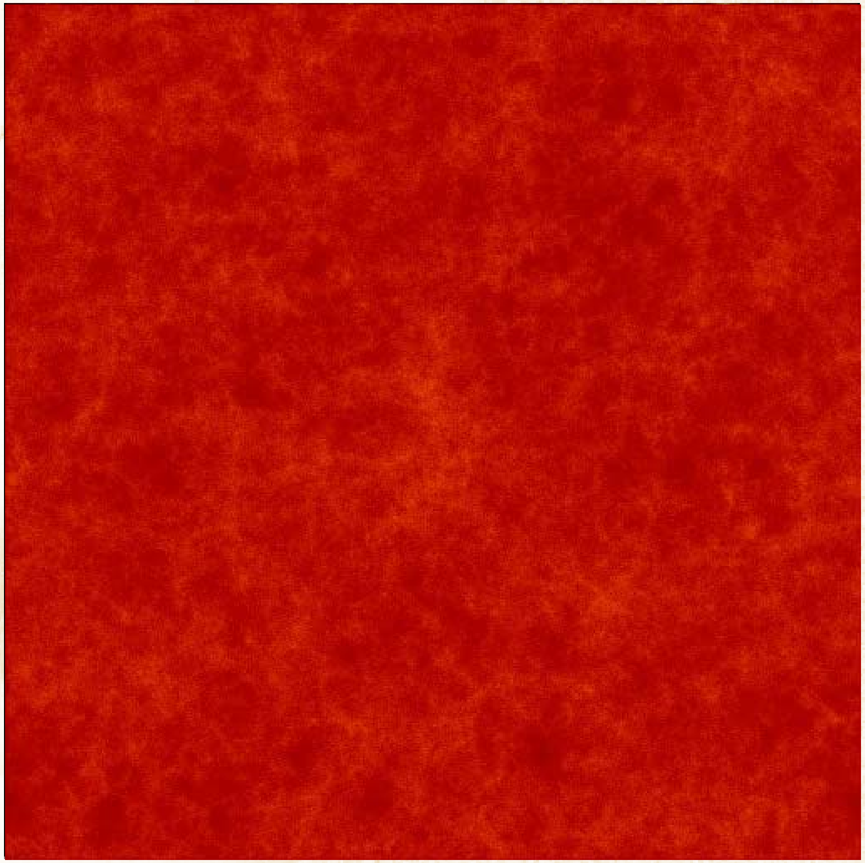
Neutrinos as Hot Dark Matter

Effect of Massive Neutrinos: suppression of Power at small scales

Smooth → **Structured**

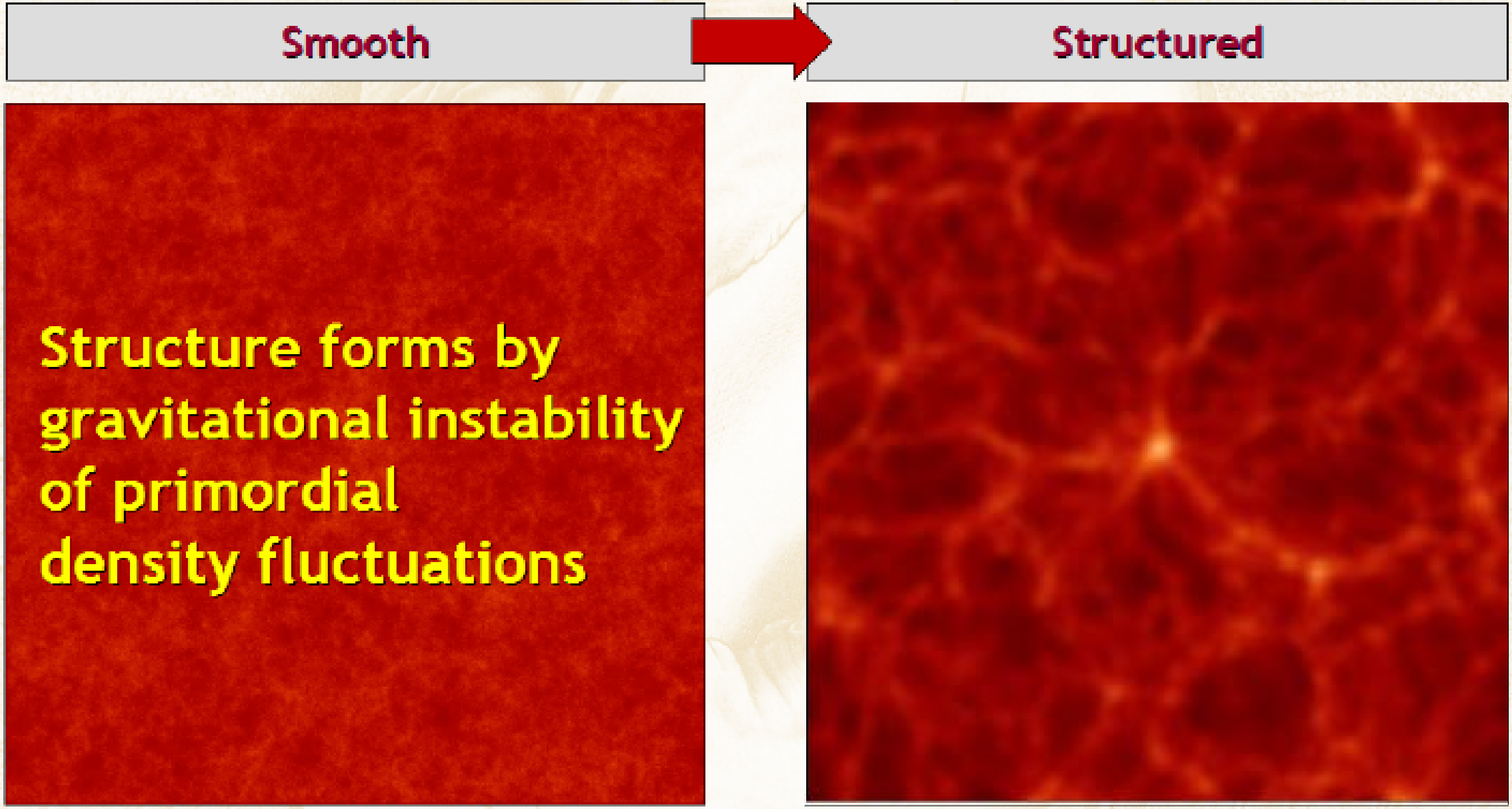


Structure forms by gravitational instability of primordial density fluctuations



Neutrinos as Hot Dark Matter

Effect of Massive Neutrinos: suppression of Power at small scales



Smooth

Structured

Structure forms by gravitational instability of primordial density fluctuations

RAFFELT

Neutrinos as Hot Dark Matter

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

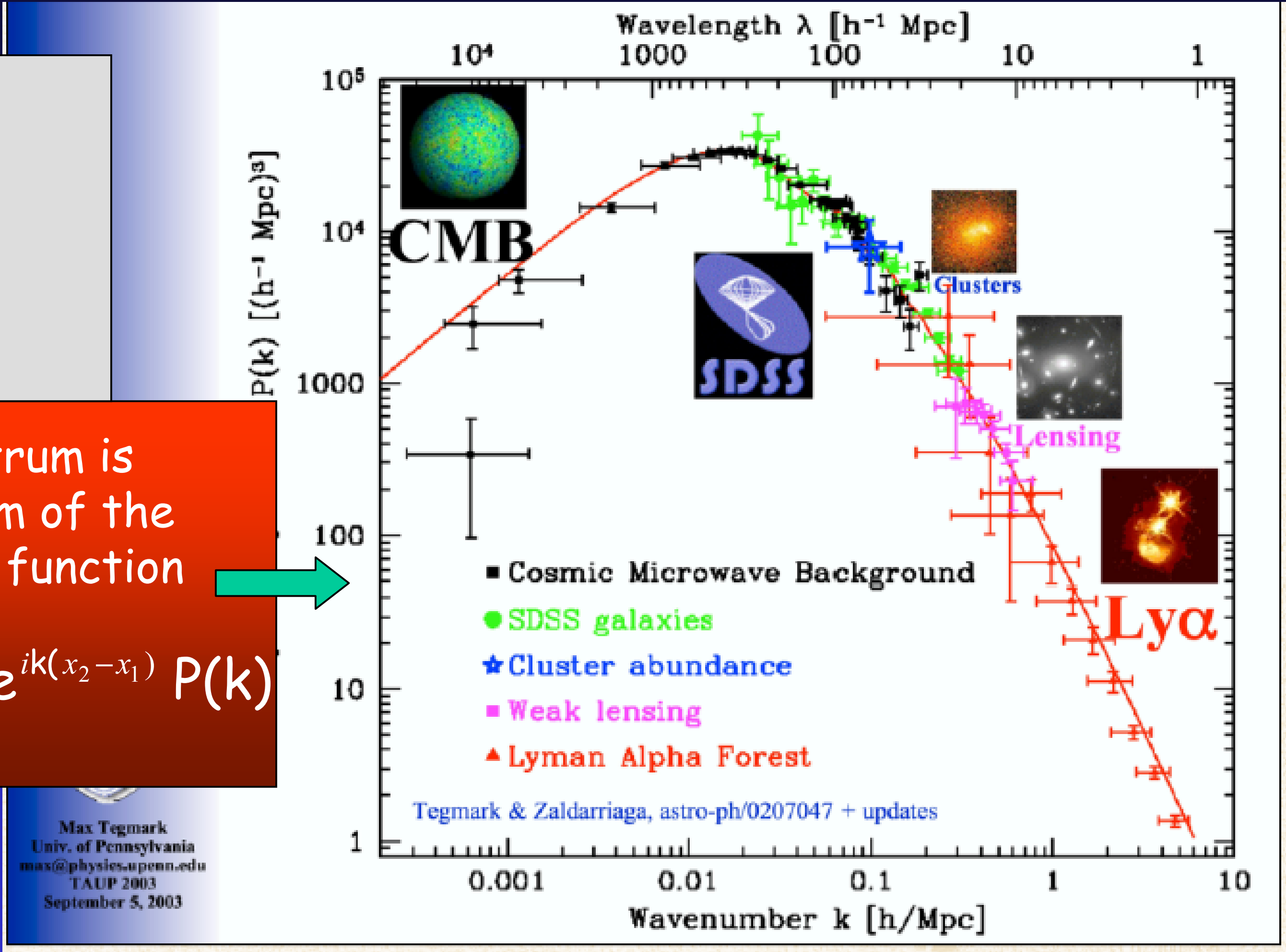
Power Spectrum of density fluctuations

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

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



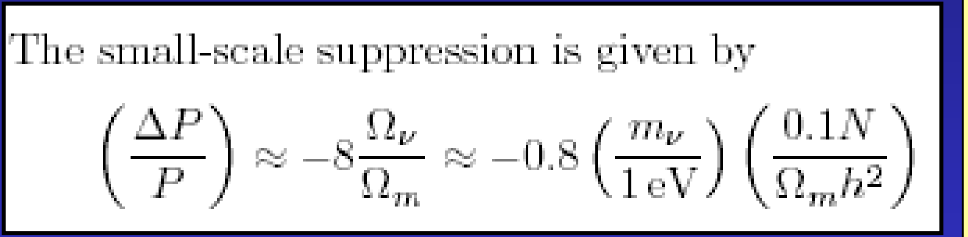
Tegmark & Zaldarriaga, astro-ph/0207047 + updates

Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

Neutrinos as Hot Dark Matter

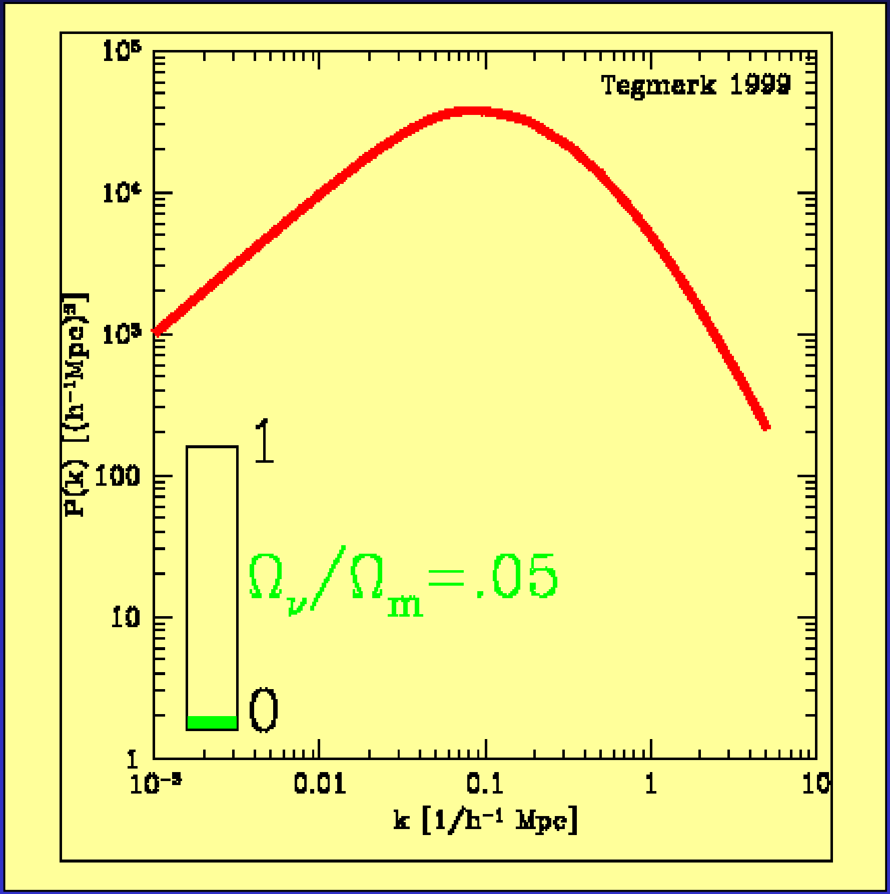
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

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

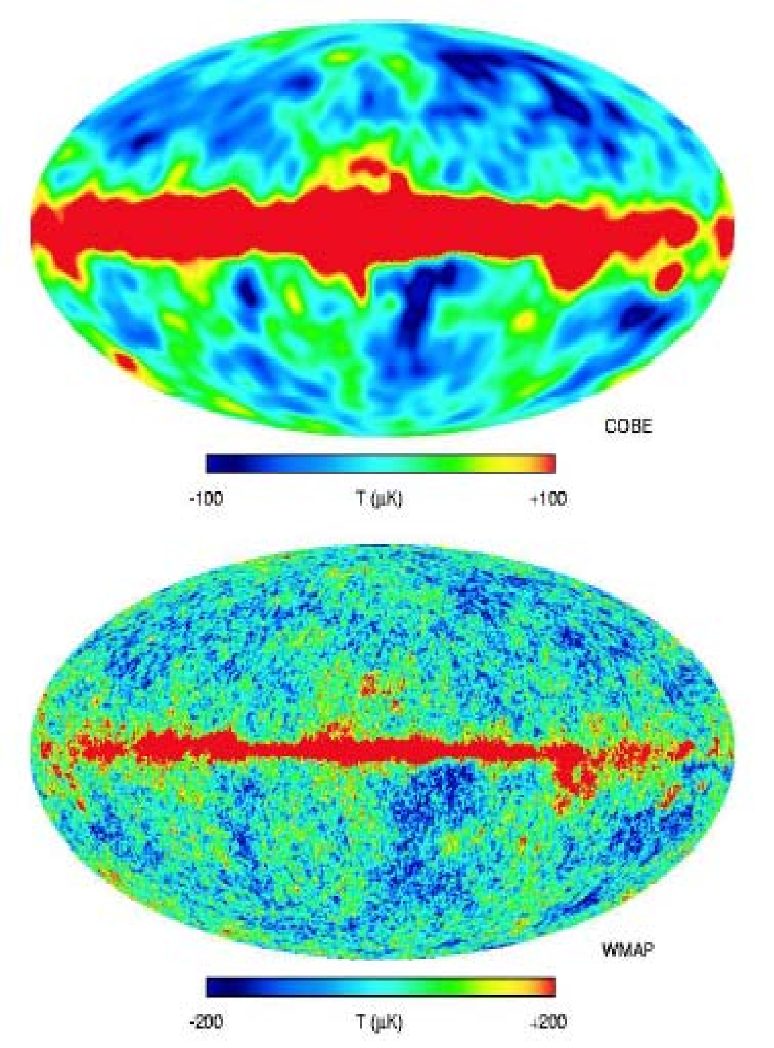


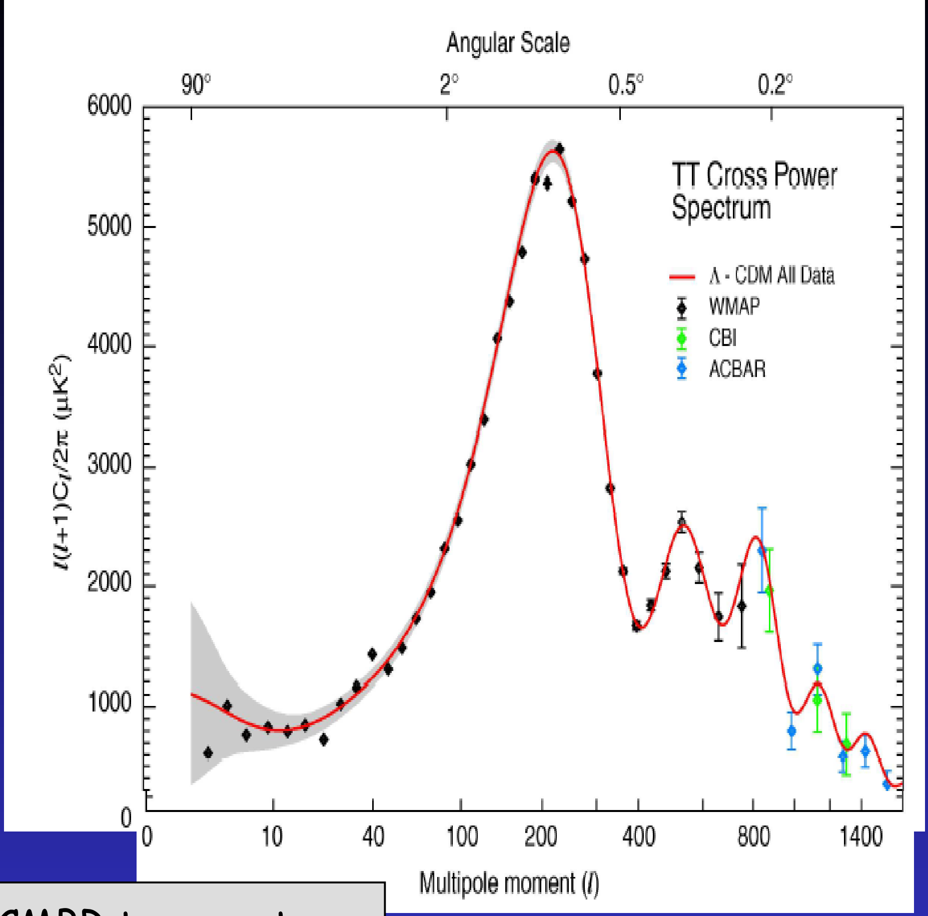
The small-scale suppression is given by

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



CMB DATA: INCREASING PRECISION





Map of CMBR temperature Fluctuations

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

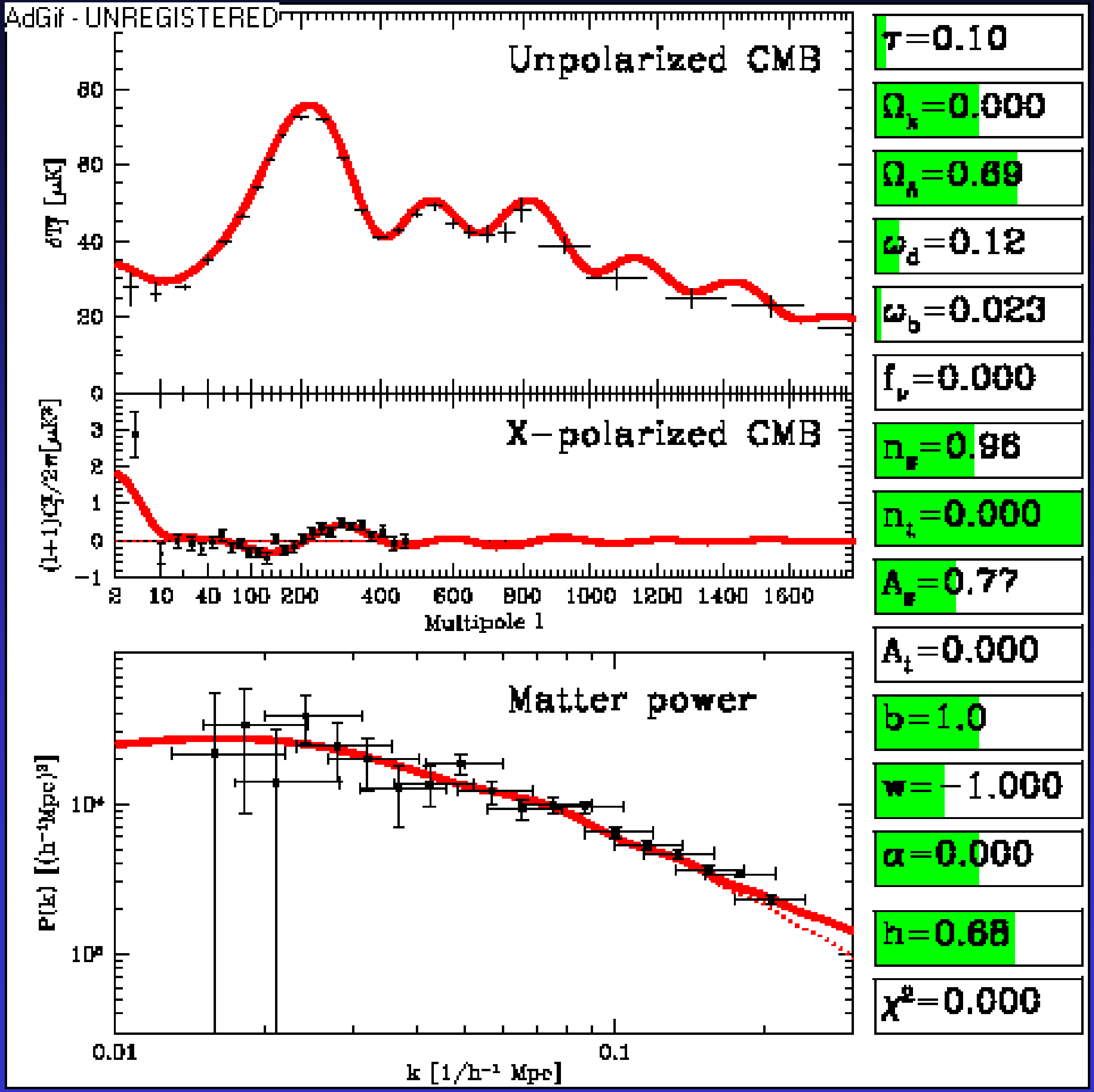
Multipole Expansion

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

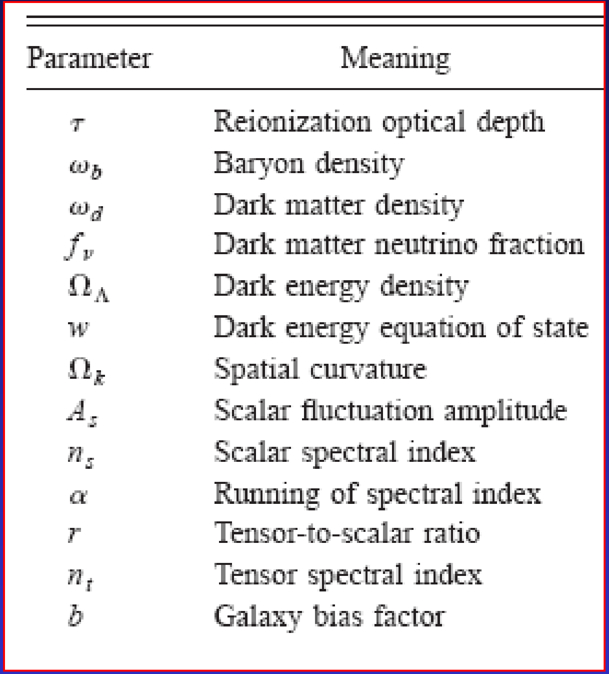
Angular Power Spectrum

$$C_\ell = \langle a^*_{\ell m} a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^*_{\ell m} a_{\ell m}$$

Effect of massive neutrinos on the CMB and Matter Power Spectra



$\tau=0.10$
$\Omega_k=0.000$
$\Omega_\Lambda=0.69$
$\omega_d=0.12$
$\omega_b=0.023$
$f_\nu=0.000$
$n_s=0.96$
$n_t=0.000$
$A_s=0.77$
$A_t=0.000$
$b=1.0$
$w=-1.000$
$\alpha=0.000$
$h=0.68$
$\chi^2=0.000$



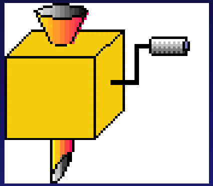
Parameter	Meaning
τ	Reionization optical depth
ω_b	Baryon density
ω_d	Dark matter density
f_ν	Dark matter neutrino fraction
Ω_Λ	Dark energy density
w	Dark energy equation of state
Ω_k	Spatial curvature
A_s	Scalar fluctuation amplitude
n_s	Scalar spectral index
α	Running of spectral index
r	Tensor-to-scalar ratio
n_t	Tensor spectral index
b	Galaxy bias factor

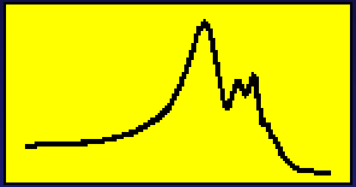
Max Tegmark

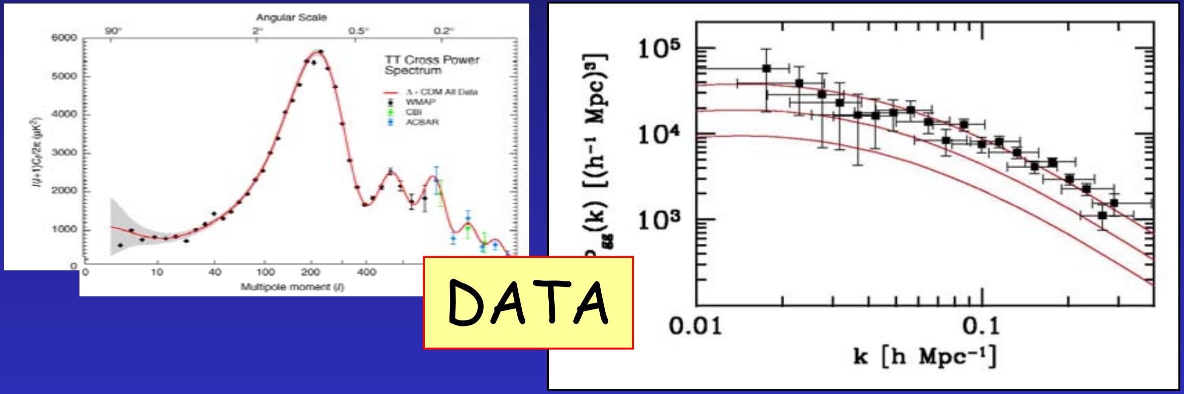
www.hep.upenn.edu/~max/

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

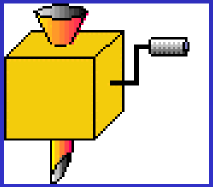
Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau, \Sigma m_\nu)$







DATA



PARAMETER ESTIMATES

Cosmological 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 in the semi-linear regime
- Bounds on parameters from other data: SNIa (Ω_m), HST (h), …

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 !

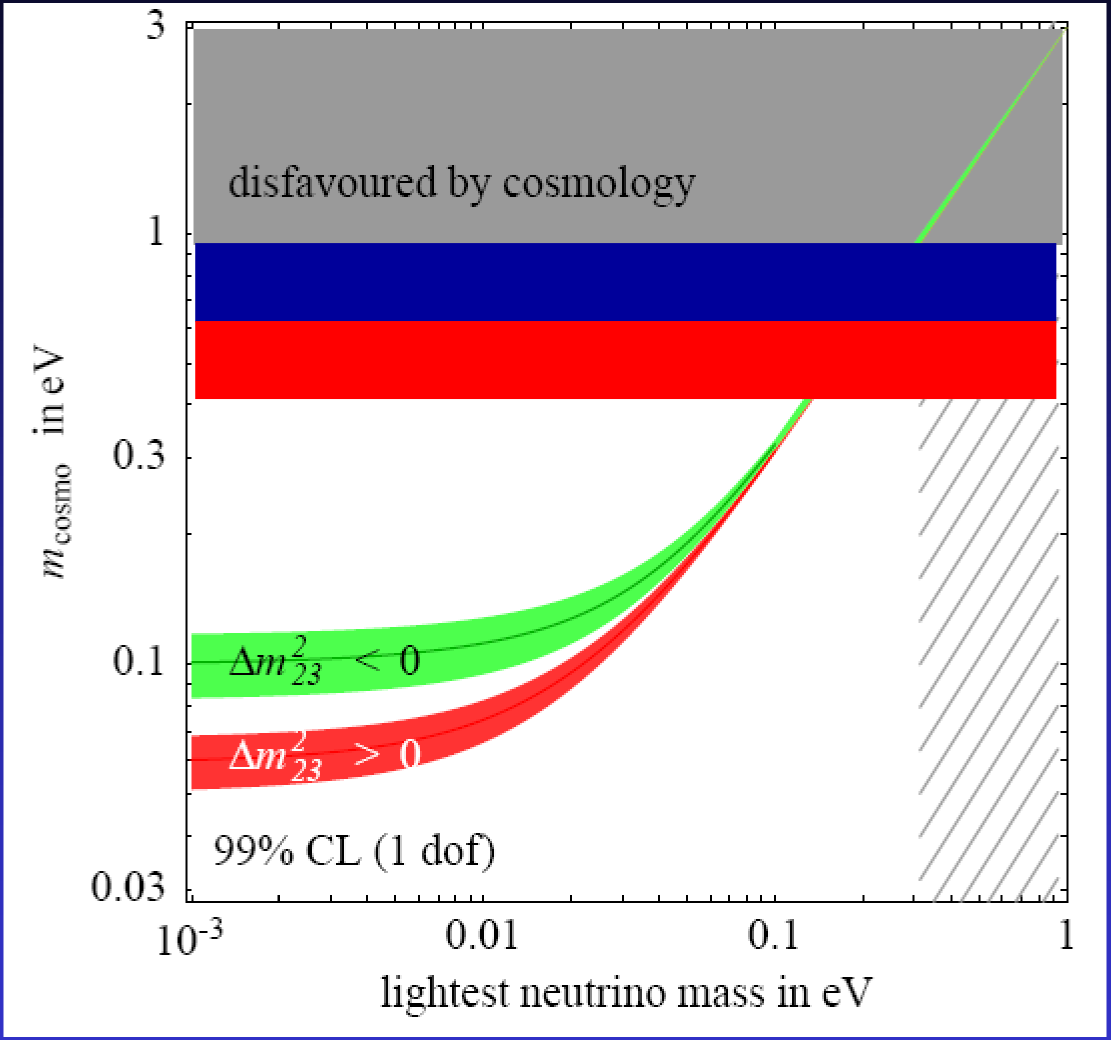
Different analyses have found upper bounds on neutrino masses, since they depend on

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

Cosmological bounds on neutrino mass since 2003

	Bound on Σm_ν (eV) at 95% CL	Data used
Ichikawa, Fukugita & Kawasaki PRD 71 (2005) 043001	2.0	WMAP
SDSS Coll. PRD 69 (2004) 103501	1.7	WMAP, SDSS
Hannestad JCAP 0305 (2003) 004	1.01	WMAP, other CMB, 2dF, HST
Crotty, Lesgourgues & SP PRD 69 (2004) 123007	1.0 [0.6]	WMAP, other CMB, 2dF, SDSS [HST,SN]
Barger, Marfatia & Tregre PLB 595 (2004) 55	0.75	WMAP, other CMB, 2dF, SDSS, HST
WMAP Coll. ApJ Suppl 148 (2003) 175	0.7	WMAP, other CMB,2dF (bias,galaxy clustering), Ly-α, HST
Fogli et al. PRD 70 (2004) 113003	0.47	WMAP, other CMB, 2dF, SDSS (Ly-α),HST
Seljak et al. PRD 71 (2005) 103515	0.42	WMAP, SDSS (bias, galaxy clustering, Ly-α)

Neutrino masses in 3-neutrino schemes



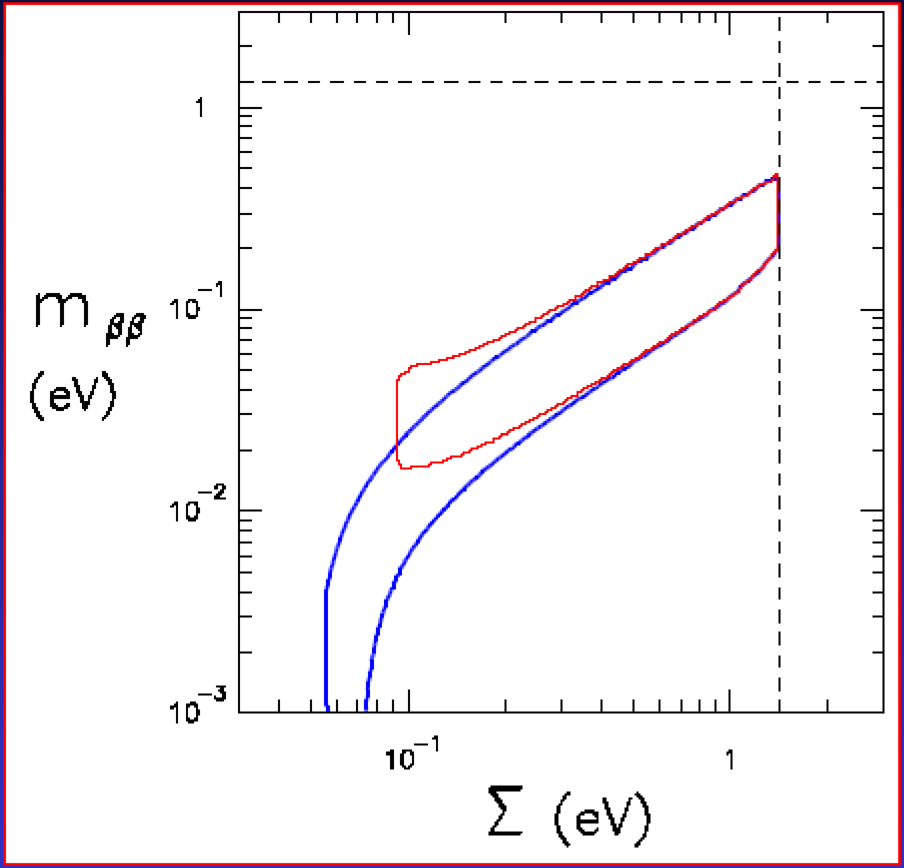
CMB + galaxy clustering

+ HST, SNI-a [σ_8]

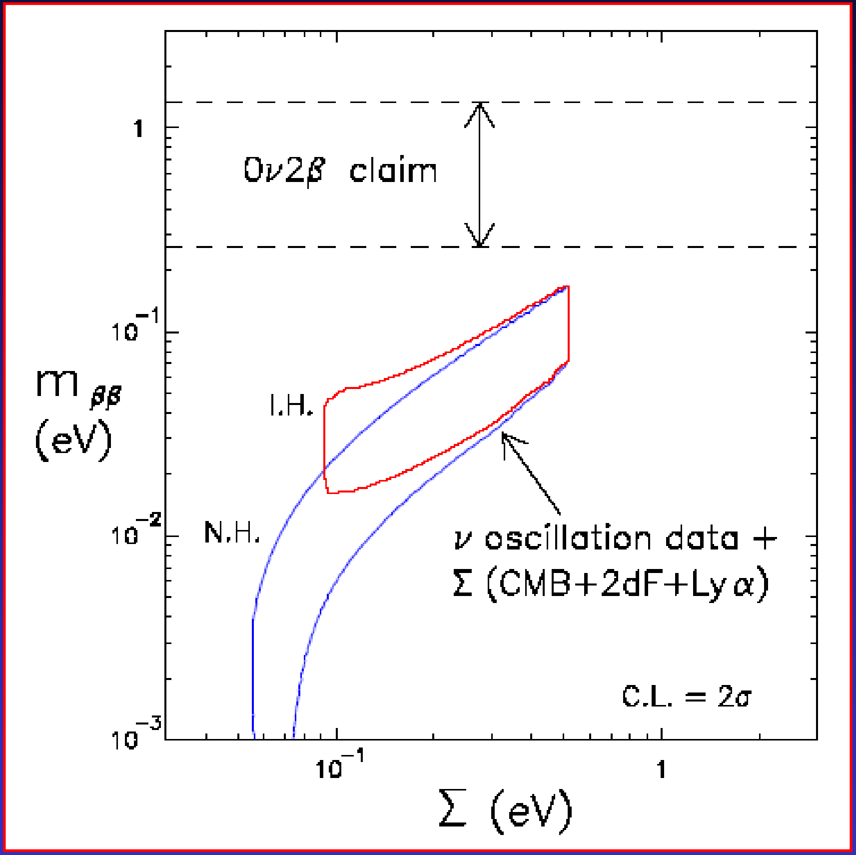
+ **Ly-α** [bias]

Fig from Strumia & Vissani, hep-ph/0503246

Global analysis: ν oscillations + tritium β decay + $0\nu2\beta$ + Cosmology



CMB + 2dF



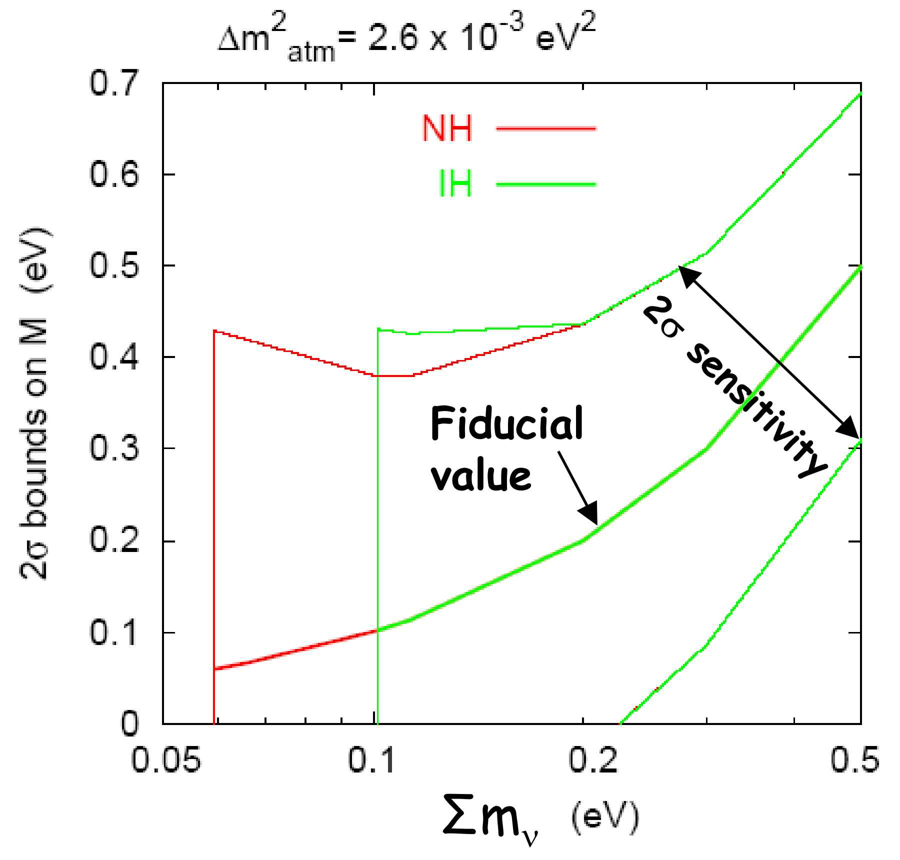
Fogli et al., PRD 70 (2004) 113003

Future sensitivities to Σm_ν

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

1. CMB (T+P) + galaxy redshift surveys
2. CMB (T+P) and CMB lensing
3. Weak lensing surveys
4. Weak lensing surveys + CMB lensing

PLANCK+SDSS



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

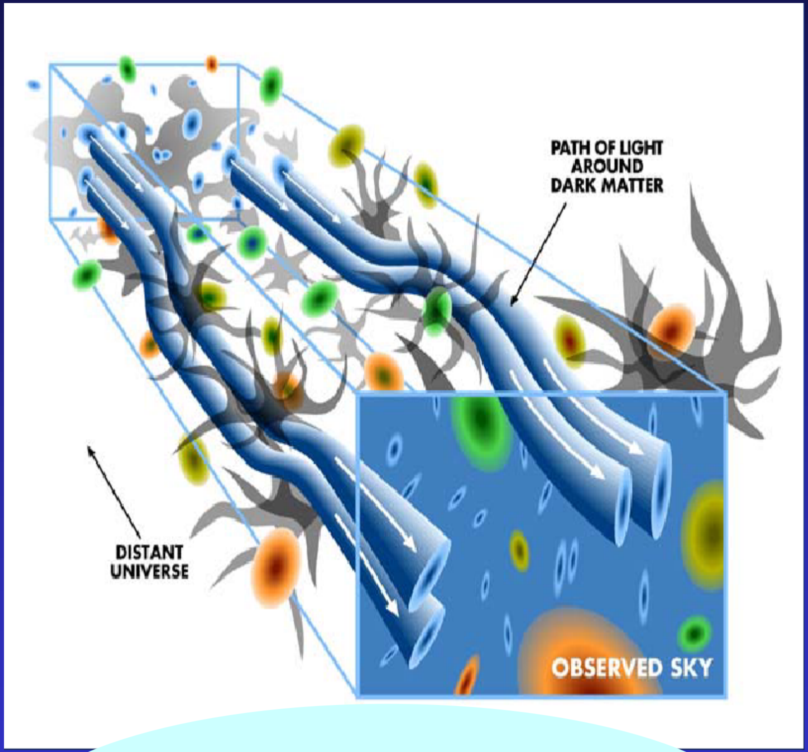
0.21 eV (PLANCK+SDSS)

0.13 eV (CMBpol+SDSS)

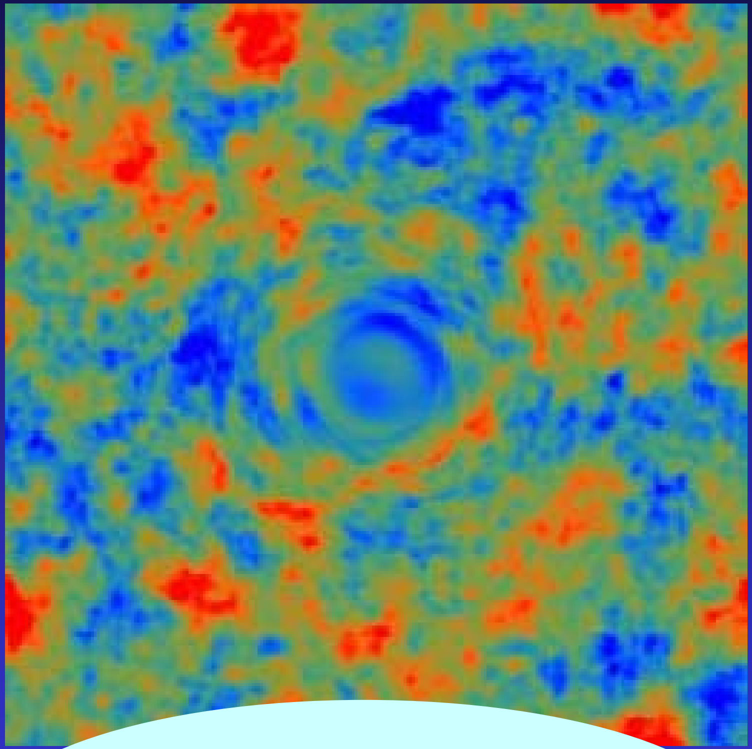
Lesgourgues, SP & Perotto,
PRD 70 (2004) 045016

Future sensitivities to Σm_ν: new ideas

weak gravitational lensing and CMB lensing



no bias uncertainty
small scales in linear regime



makes CMB sensitive to
much smaller masses

Future sensitivities to Σm_ν:

weak gravitational lensing and CMB lensing

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

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

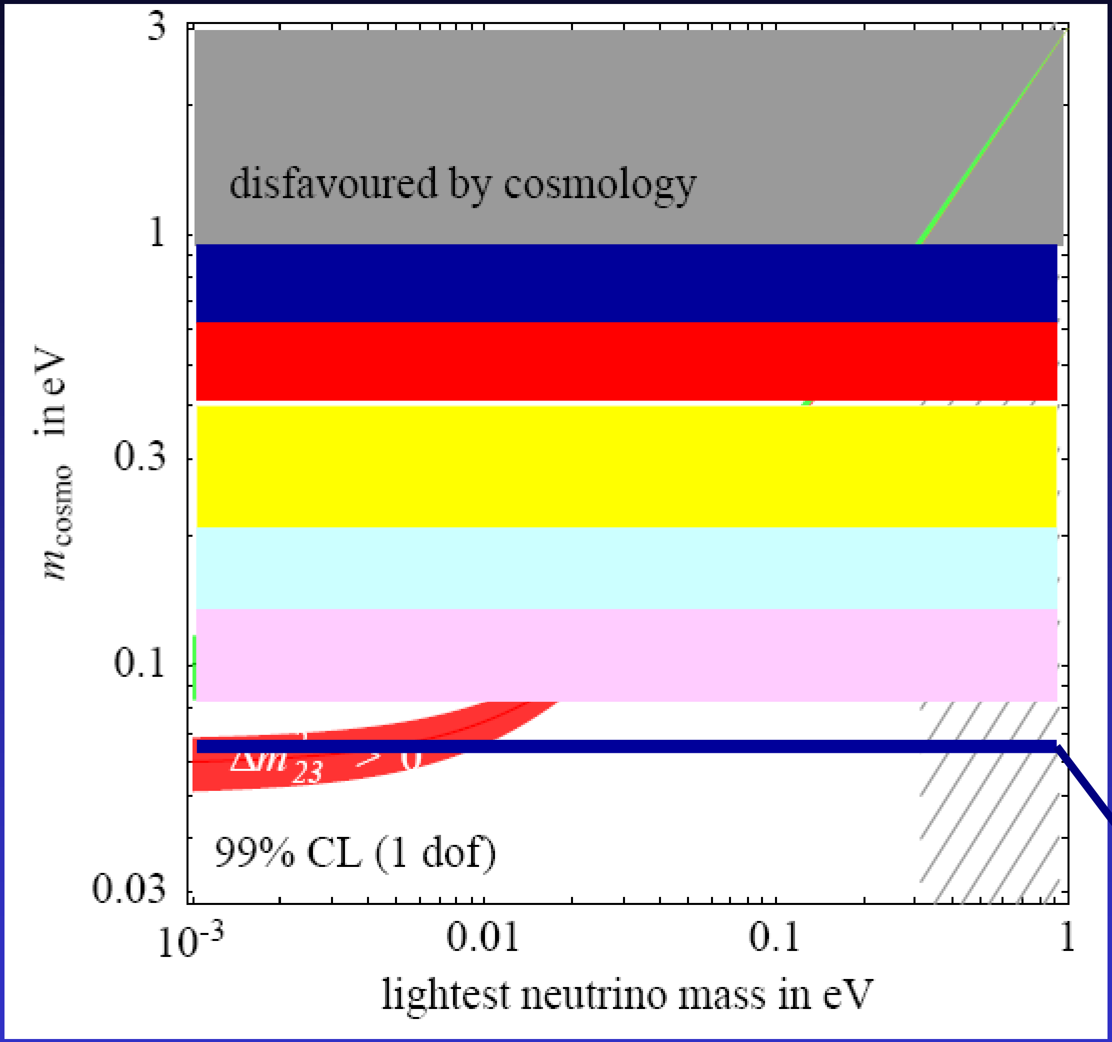
Abazajian & Dodelson
PRL 91 (2003) 041301

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

Neutrino masses in 3-neutrino schemes



CMB + galaxy clustering

+ HST, SNI-a [σ_8]

+ **Ly-α** [bias]

PLANCK + SDSS

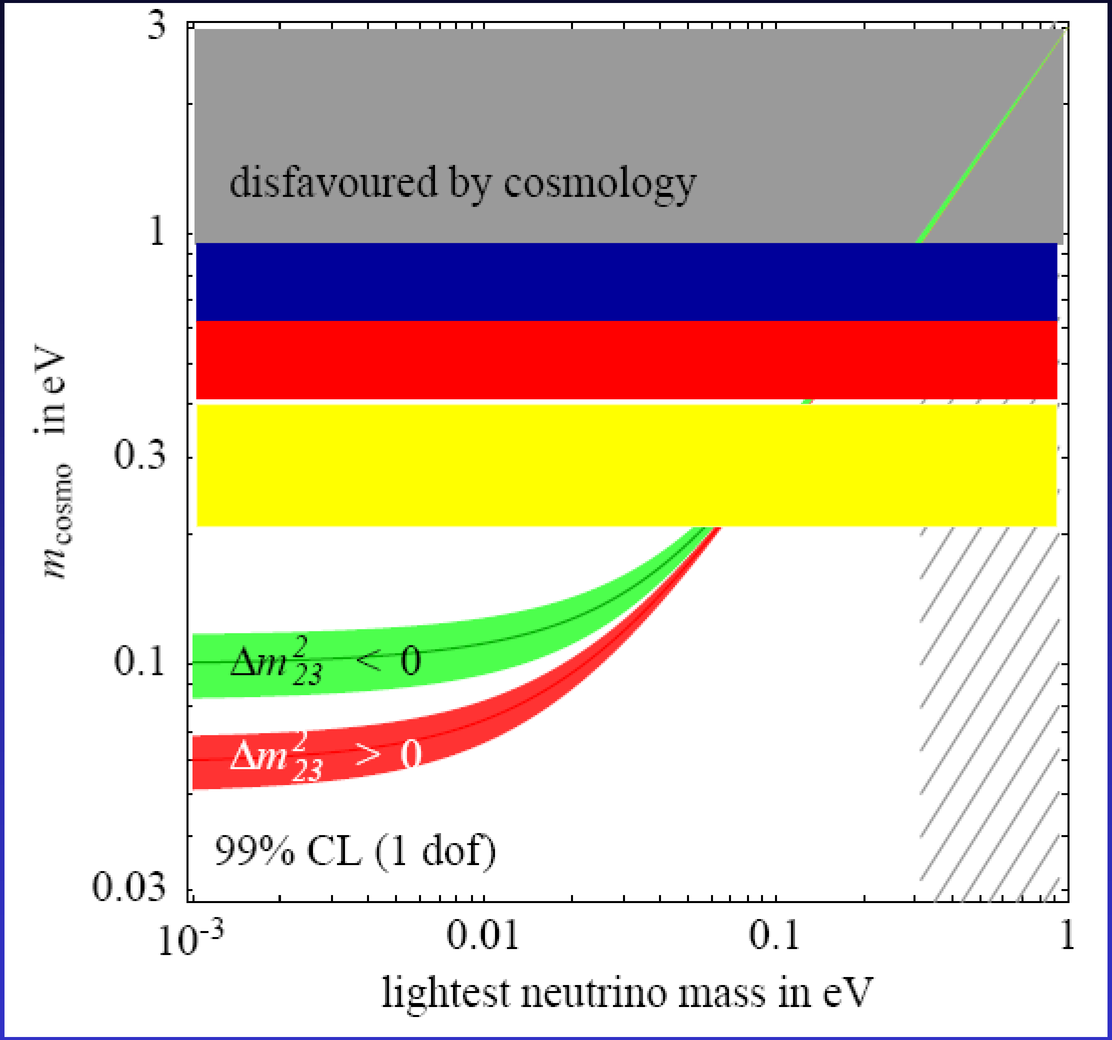
CMBpol + SDSS

CMBpol (including CMB lensing)

All-sky weak lensing survey + CMB lensing (CMBpol)

Fig from Strumia & Vissani, hep-ph/0503246

Neutrino masses in 3-neutrino schemes



CMB + galaxy clustering

+ HST, SNI-a [σ_8]

+ Ly-α [bias]

PLANCK + SDSS

≈ 2010

Fig from Strumia & Vissani, hep-ph/0503246

Conclusions

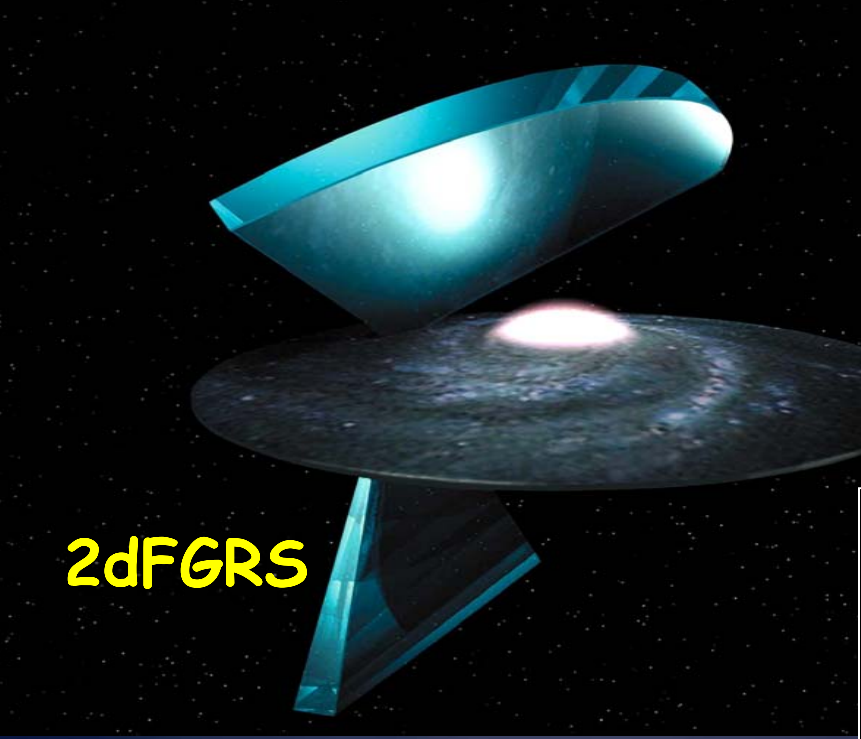
ν

Cosmological observables can be used to limit (or measure) the absolute scale of neutrino masses

Current bounds on the sum of neutrino masses from cosmological data (best $\Sigma m_\nu < 0.42$ eV, conservative $\Sigma m_\nu < 1$ eV)

Sub-eV sensitivity in the next future (0.1-0.2 eV and better) → Test degenerate mass region and eventually the IH case

Galaxy Redshift Surveys



2dFGRS

SDSS