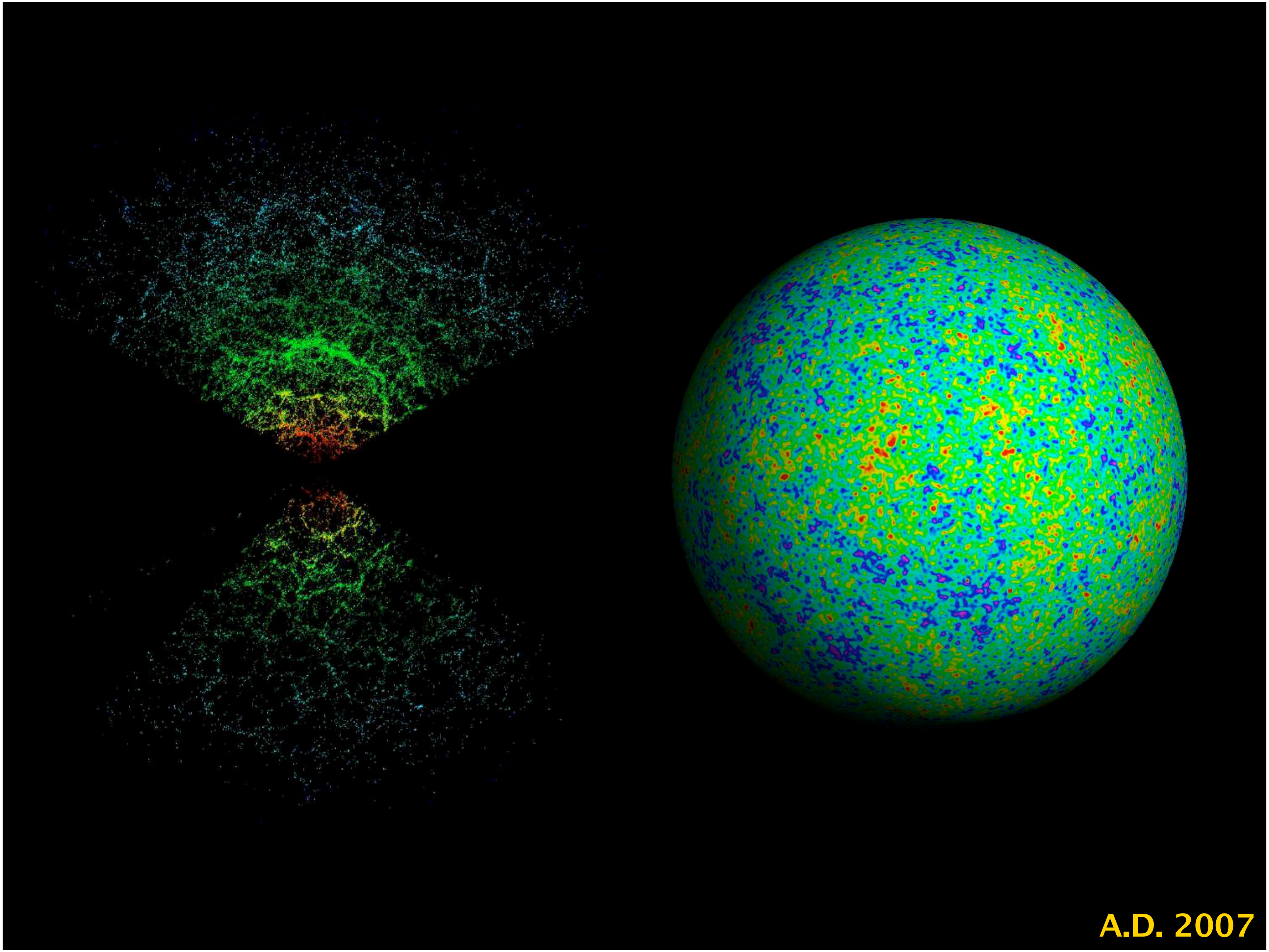
Is cosmology compatible with Sterile (light) neutrinos ?

Alessandro Melchiorri, Universita' di Roma, "La Sapienza"

Venezia, 8th March, 2007

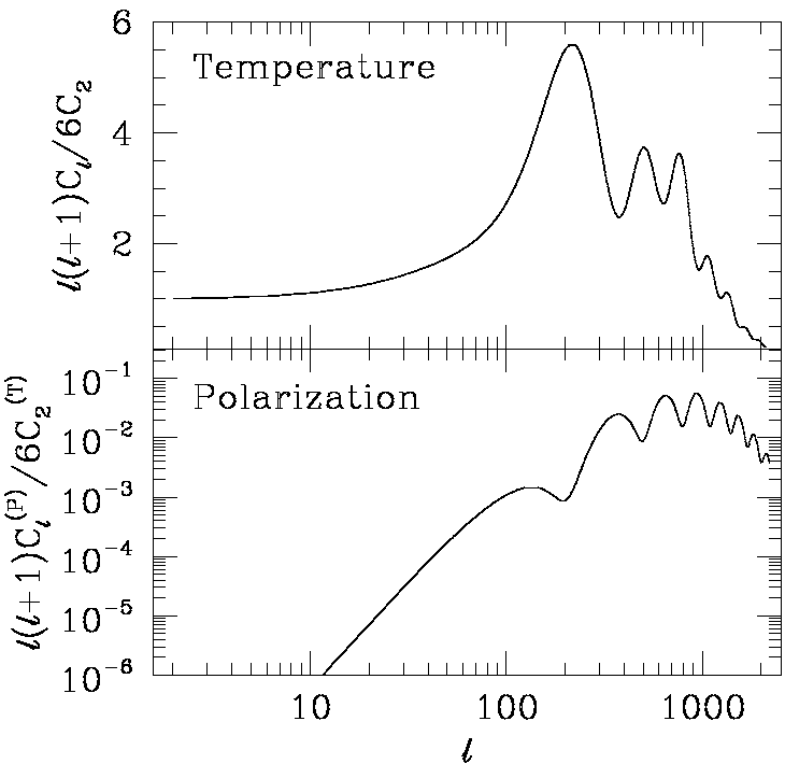

CHARTA COSMOGRAPHICA, CVM VENTORVM PROPRIA NATVRA ET OPERATIONE.
Circius, Noordt noordtwest. SEPTEN Septentrionalis, Noordt. TRIO Aquilo, Noordtnoordt oost.
Argestis. West noordtwest.
OCCI Zephyrus DENS. West.
Libs West zuydtwest.
Hellespontius Oost noordtoost.
ORI Subsolanus ENS. Oost.
Vulturnus. Oost zuydtoost.
Austroafricus. Zuydt zuydtwest. MERI Auster, Zuydt DIES. Euroaster, Zuydt zuydtoost.
I
Zona temperata
Zona frigida
Indie Orientalis pars
Tropicus æstiuus
Æquinoctialis
Tropicus Hybernus
Baccalearum
EVROPA
ASIA
Scythia
Scythia ultra Seres Imaum
India trans Gangem
Perse
Arabia fœlix
India
Seylan
Java
MARE ATLANTICVM
Hispaniola
Cuba
AFRICA
Nigritæ
Getulia
Barbaria
Nilus
Montes lune
PERV
Canibales
AMERICA
Paria
Strictum Magellanicum
Promontoriu bone Spei
Oceanus Indicus Meridianalis
Climata Septentrio
Climata Australia
REGIONVM LONGITVDO AD ORTVM.

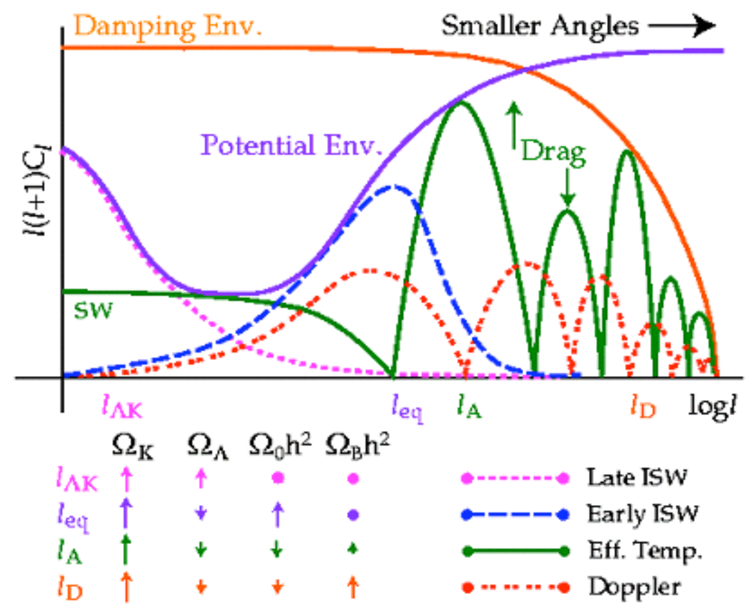
A.D. 1544


A.D. 2007

CMB: Theory

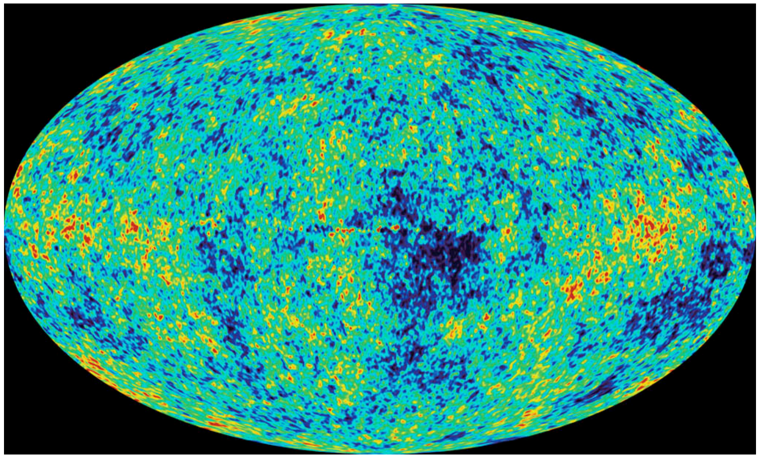
$$\left\langle \frac{\delta T}{T}(\hat{n}_1)\frac{\delta T}{T}(\hat{n}_2) \right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\hat{n}_1\cdot\hat{n}_2)$$

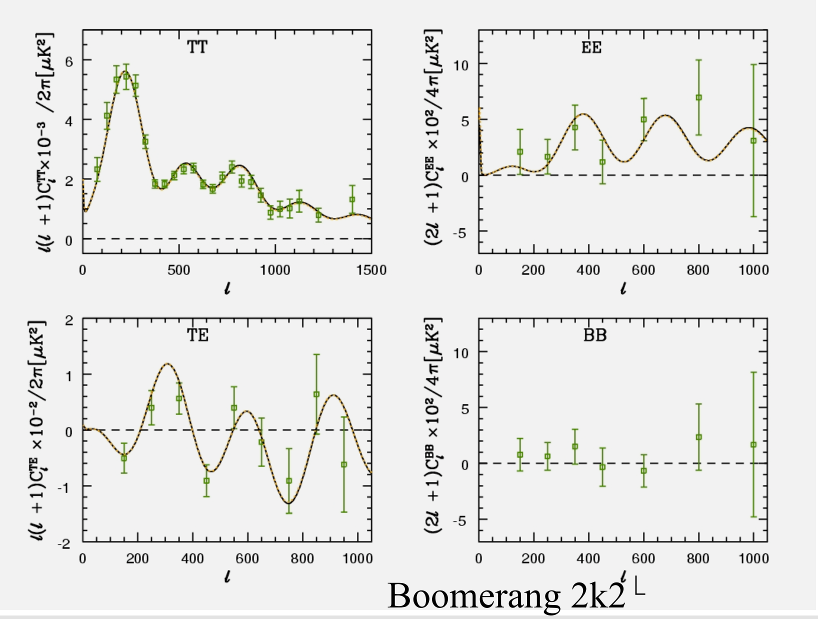


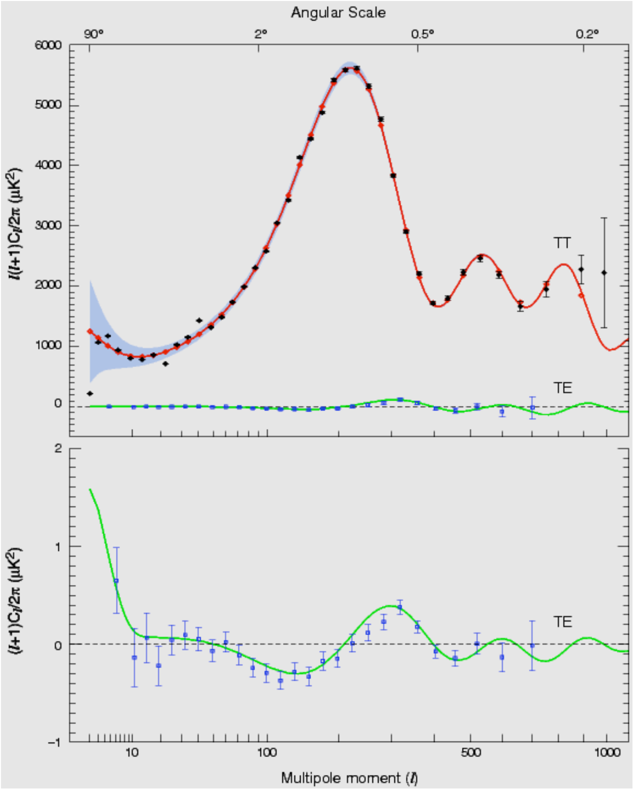


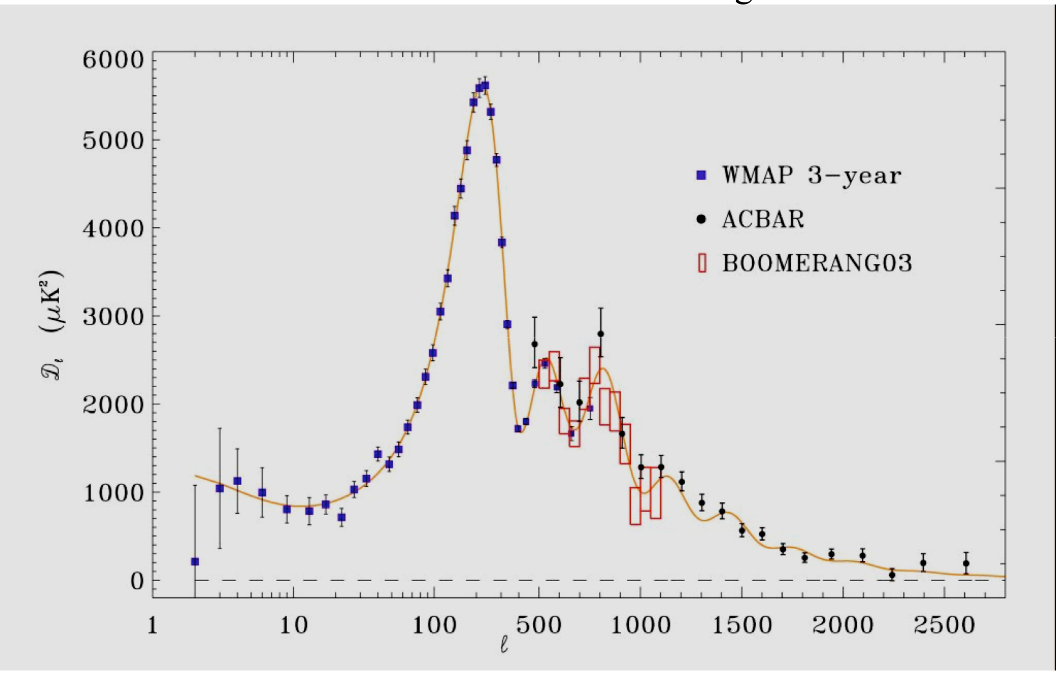
1/(Angular Scale)

CMB: Data




TT
EE
TE
BB
Boomerang 2k2


Angular Scale
90°
2°
0.5°
0.2°
TT
TE
Multipole moment (l)

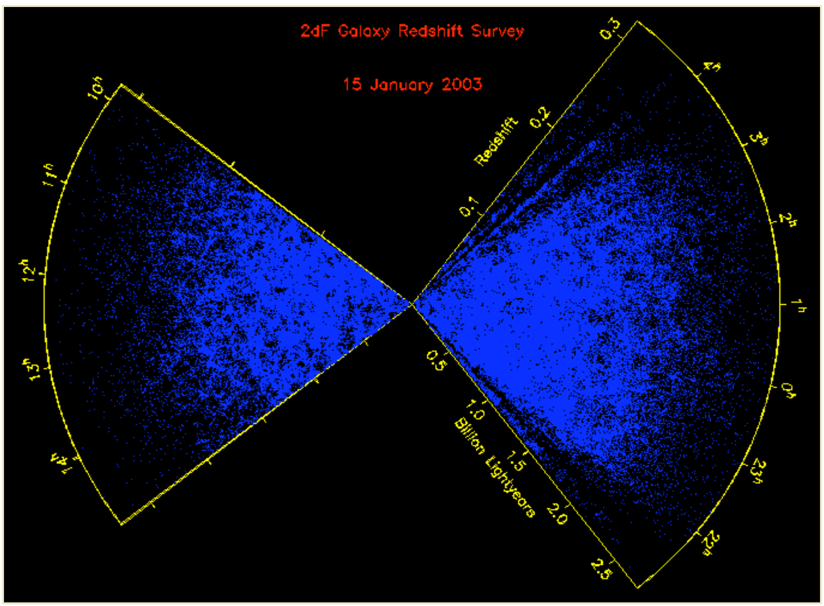

WMAP 3-year
ACBAR
BOOMERANG03

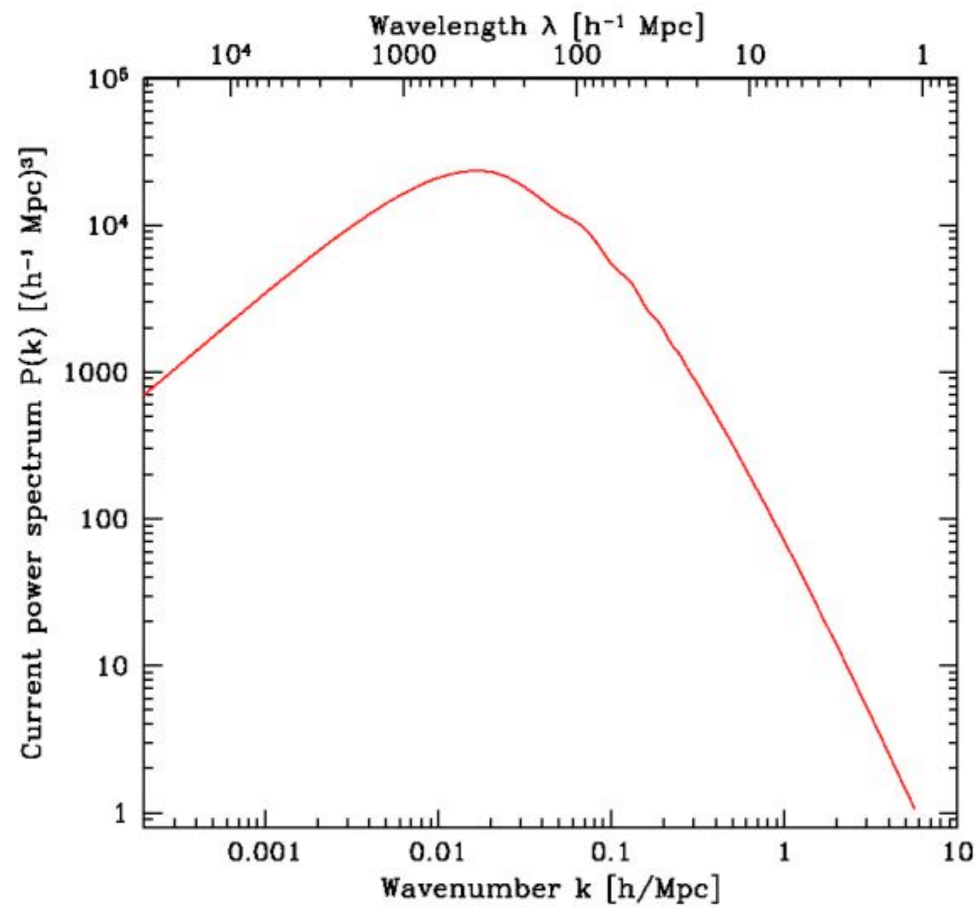
Galaxy Clustering: Theory

$$\xi(r,t) = \langle \delta(\vec{x},t)\,\delta(\vec{x}+\vec{r},t) \rangle$$

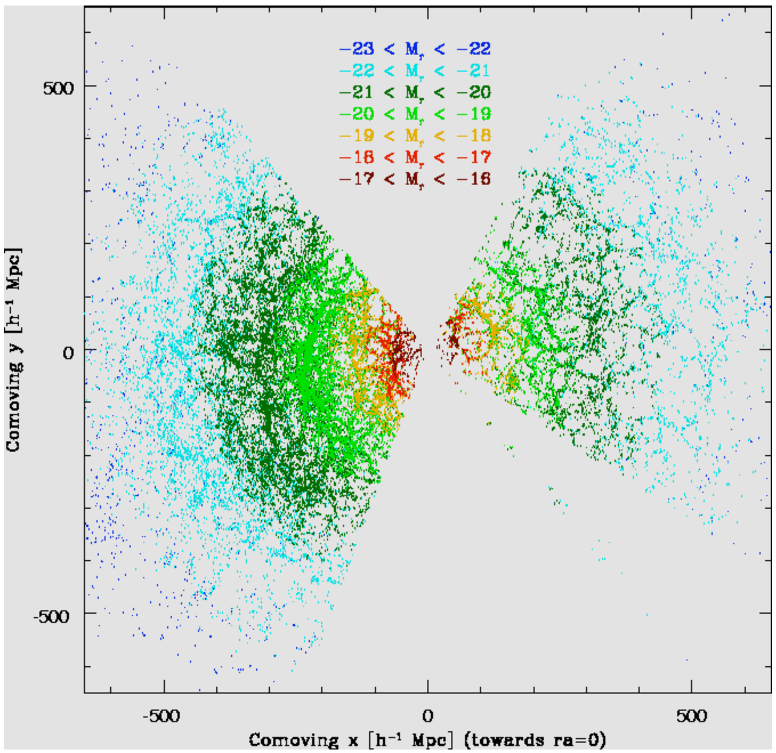
$$\xi_{galaxies}(r,t) = b^2 \xi(r,t)$$

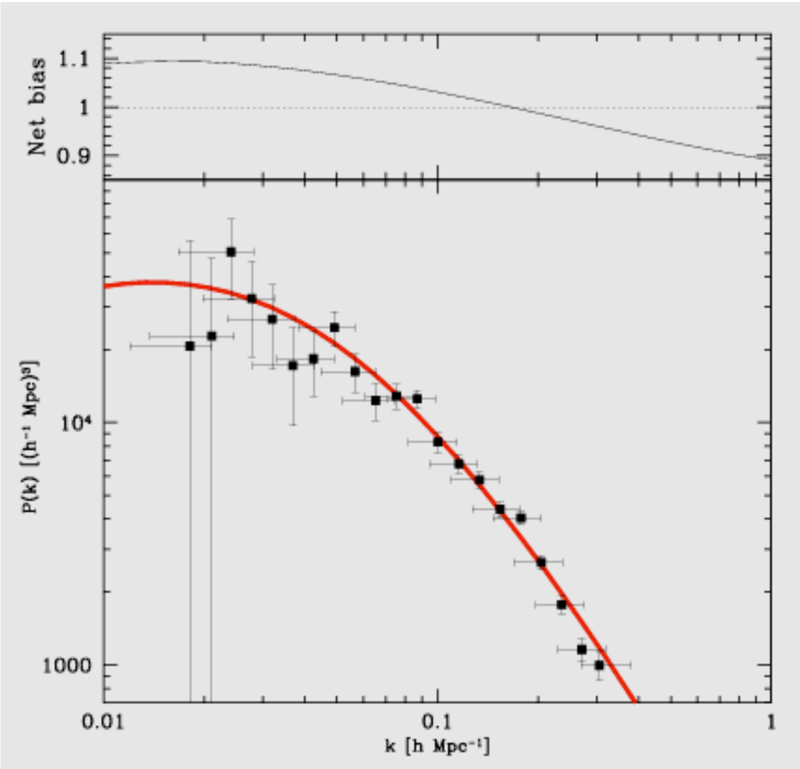
$$P(k,t) = \int d^3r\, \xi(r,t)\, e^{i\vec{k}\cdot\vec{r}}$$





Galaxy Clustering: Data





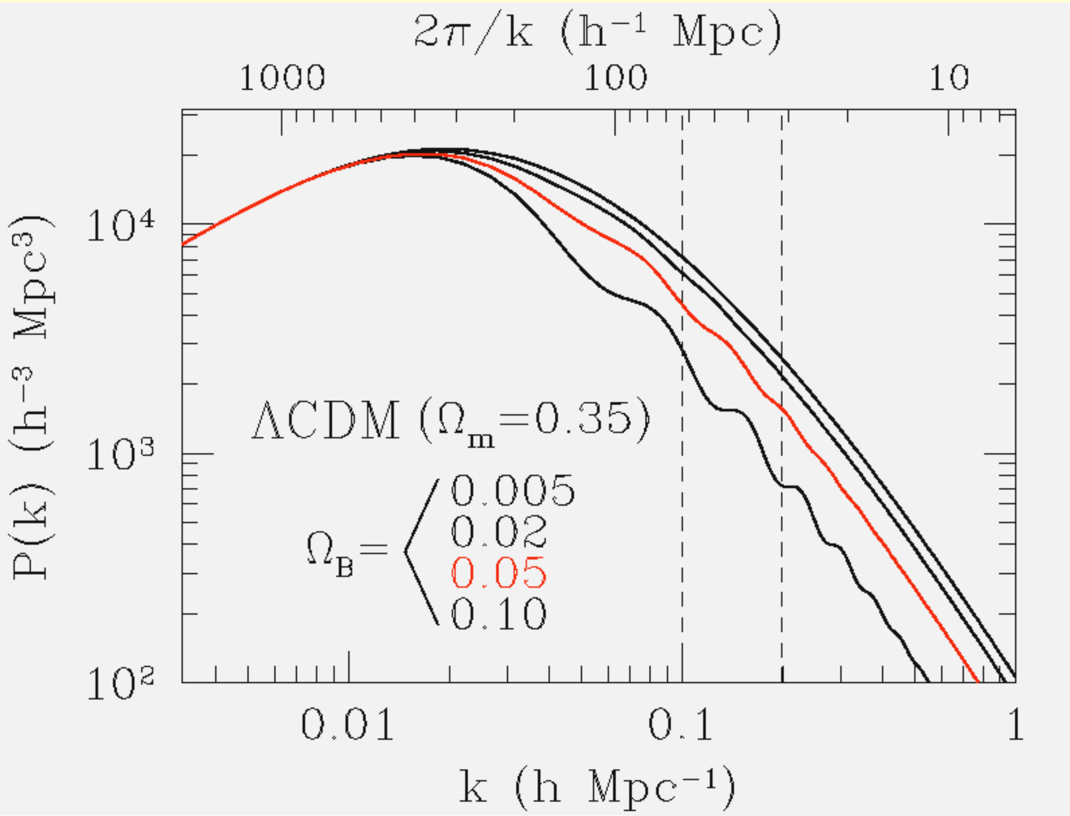
Again, perfect agreement with (low density) L-CDM model…

LSS as a cosmic yardstick

Imprint of oscillations less clear in LSS spectrum unless high baryon density

Detection much more difficult:

- Survey geometry
- Non-linear effects
- Biasing



Big pay-off:

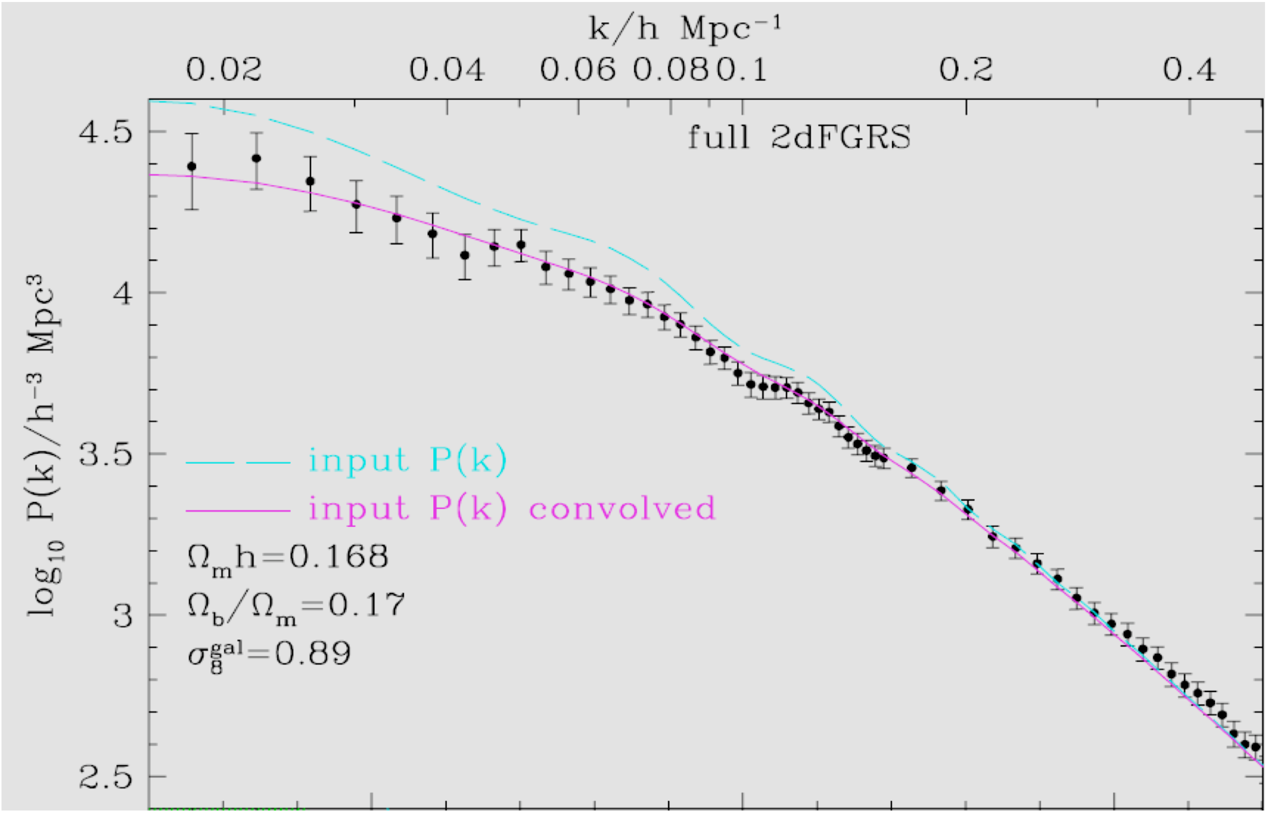
Potentially measure $d_A(z)$ at many redshifts!

Recent detections of the baryonic signature

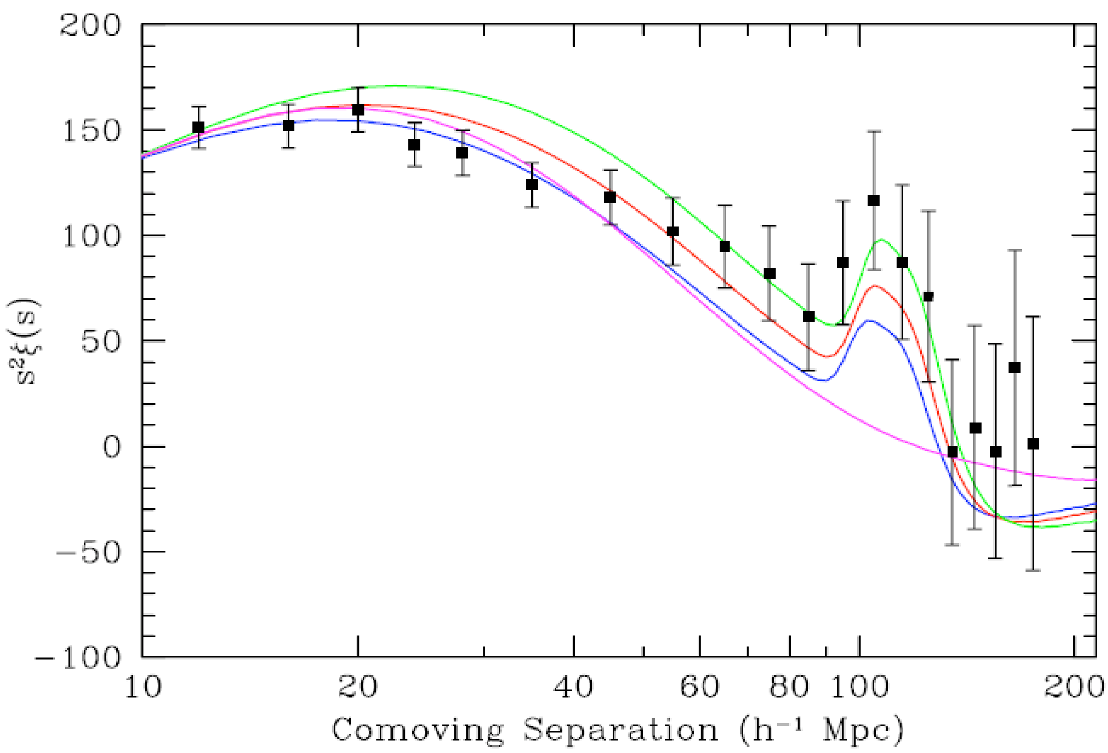
- Cole et al
  - 221,414 galaxies, $b_J < 19.45$
  - (final 2dFGRS catalogue)

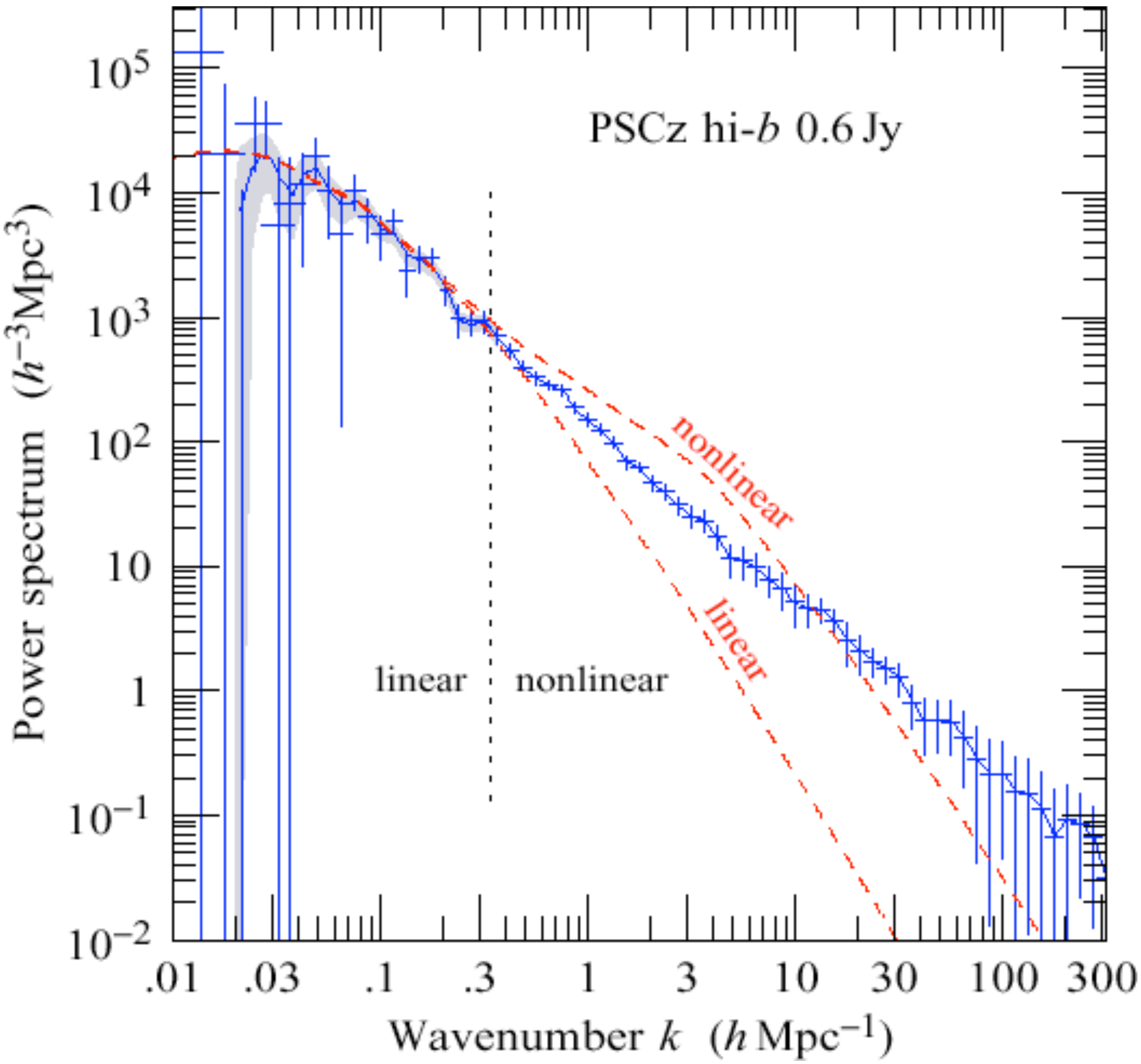
- Eisenstein et al
  - 46,748 luminous red galaxies (LRGs)
  - (from the Sloan Digital Sky Survey)

The 2dFGRS power spectrum



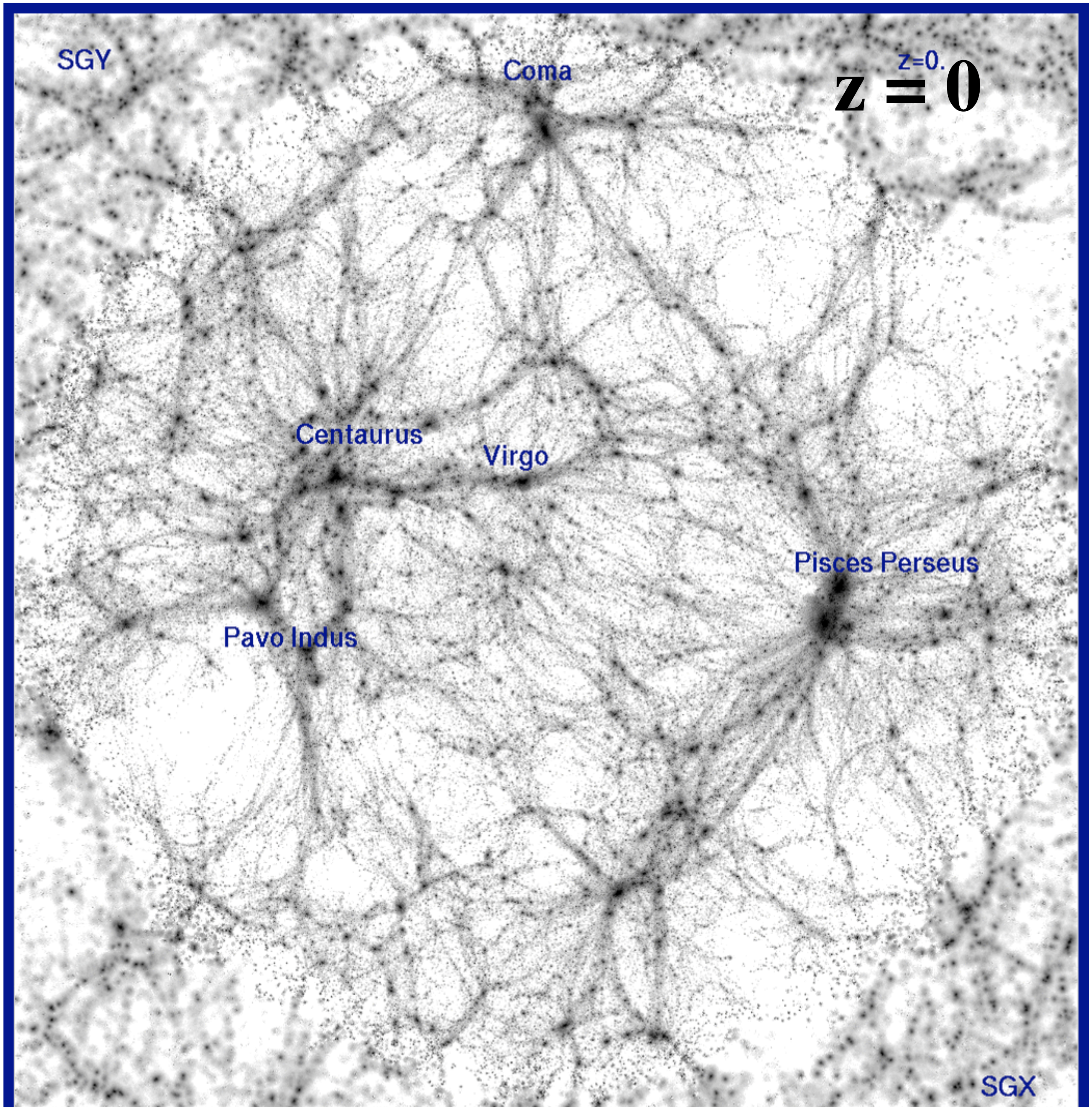
The SDSS LRG correlation function

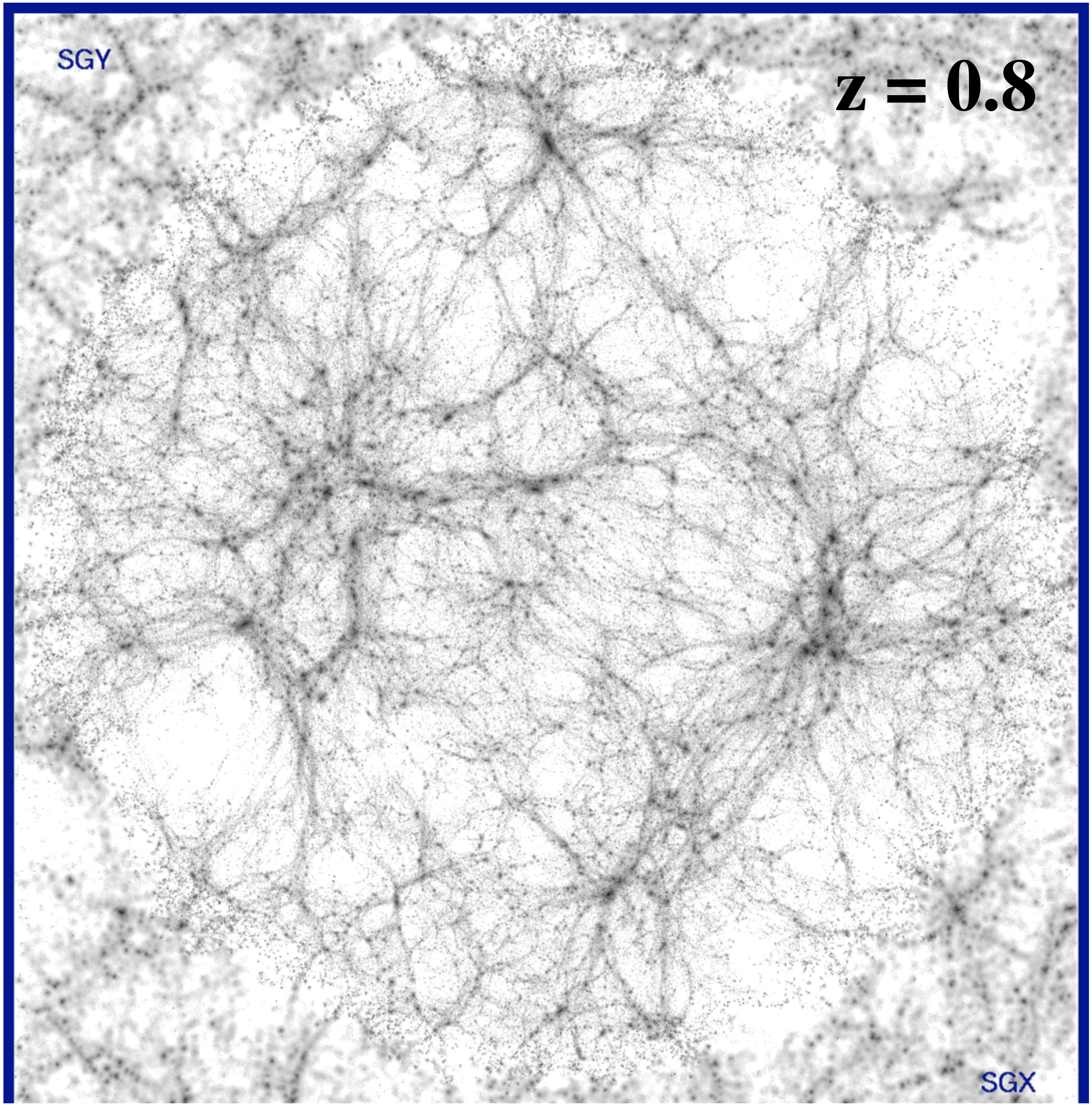


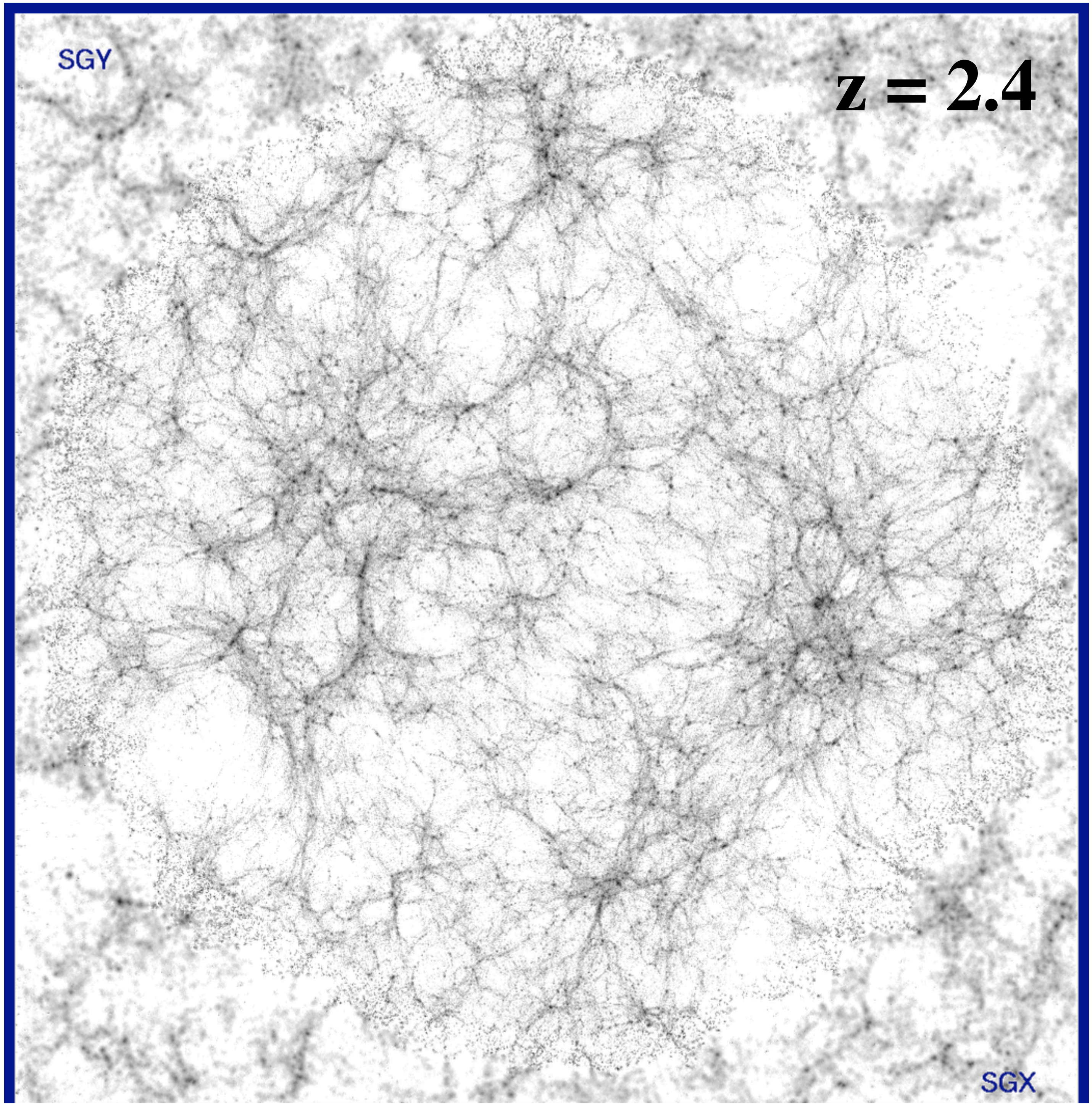


We want to go to smaller scales!!!! (and be linear)

Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001

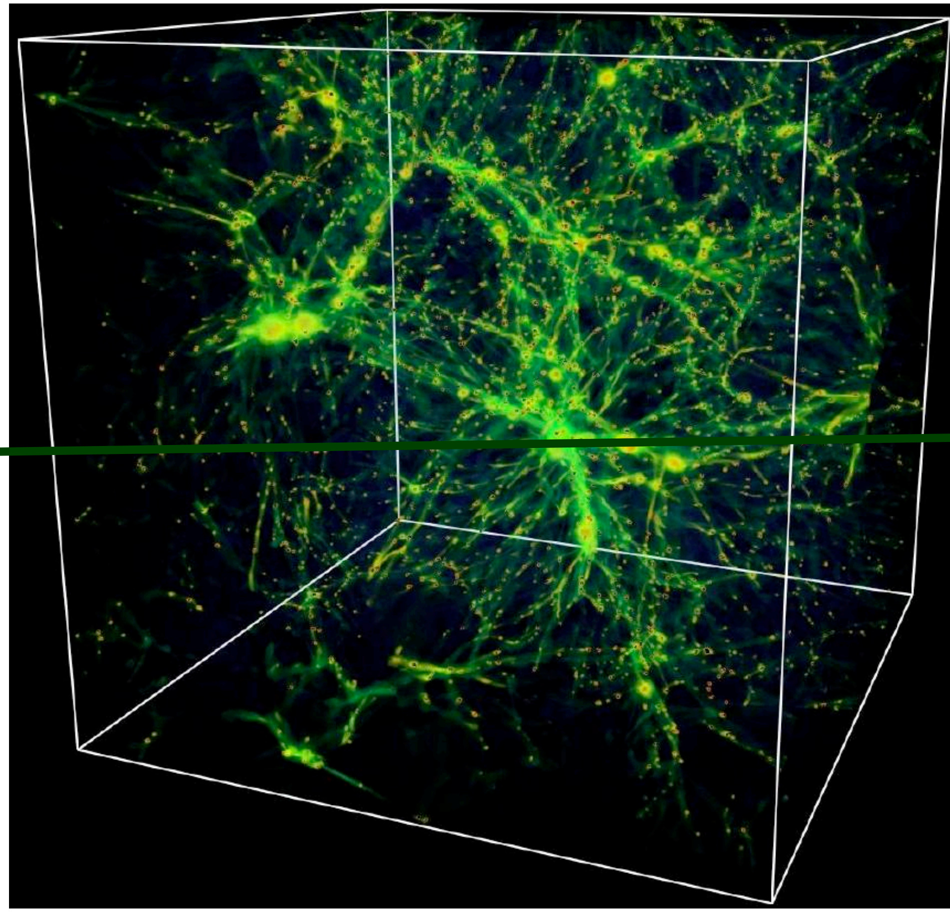


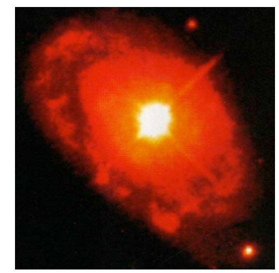

SGY
z = 0.8
SGX


SGY
z = 2.4
SGX

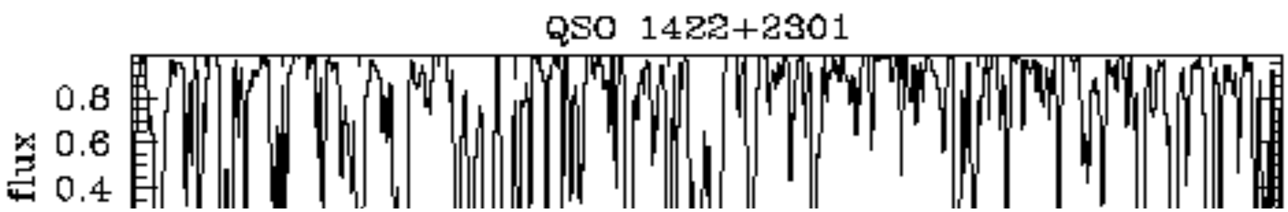
Lyman Alpha Forest Simulation: Cen et al 2001

You

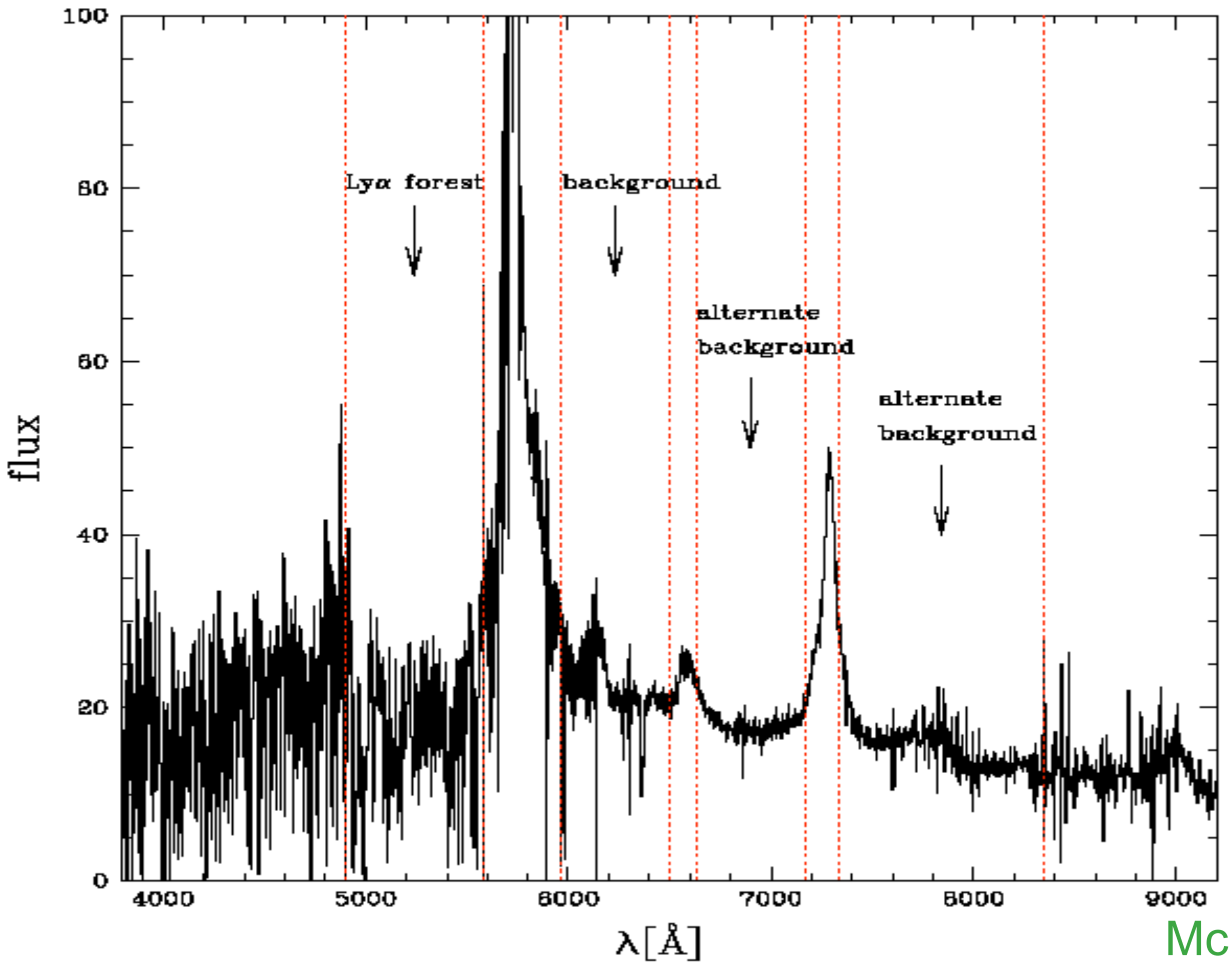




Quasar

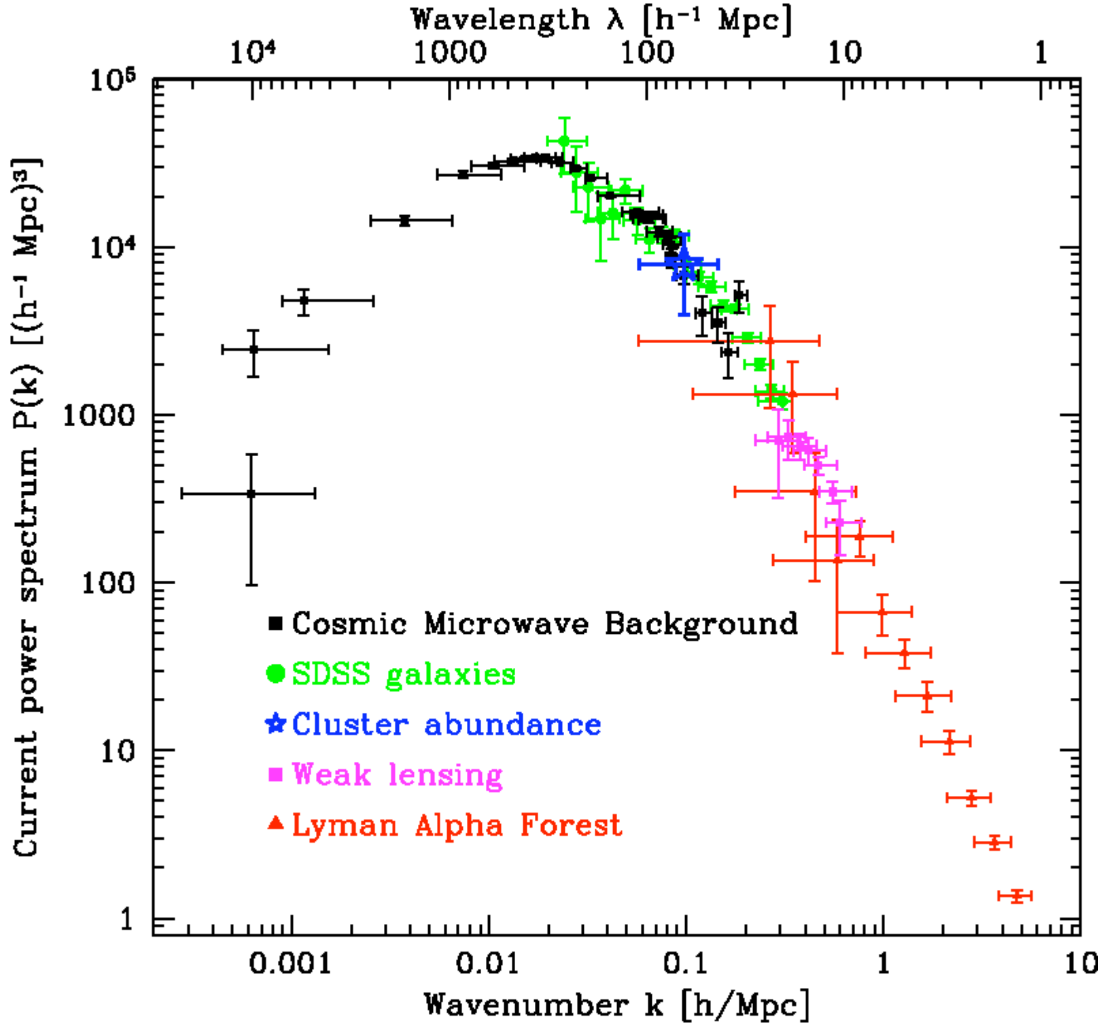


Lyman alpha forest



McDonald et al. 02

Photons with energy > (n=1 to n=2 transition energy) get absorbed along the line of sight as they lose energy due to cosmic redshift. Every absorption line corresponds to *cloud* of neutral hydrogen.



Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Cosmological (Active) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

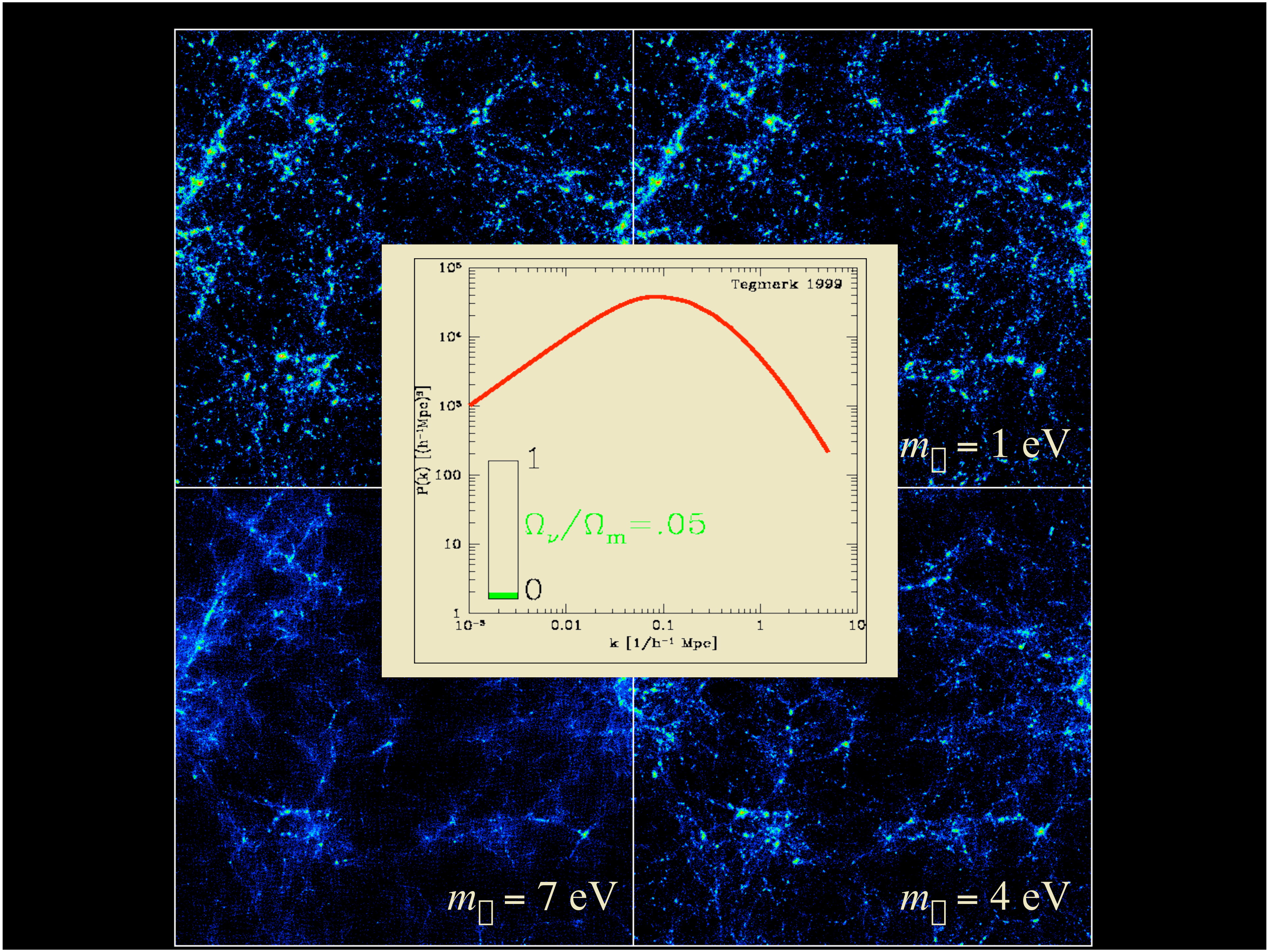
$$T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma} \approx 1.945 K \;\Rightarrow\; kT_{\nu} \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_f T_f^3 \;\Rightarrow\; n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_{\nu}^3 \approx 112 cm^{-3}$$

That, for a massive neutrino translates in:

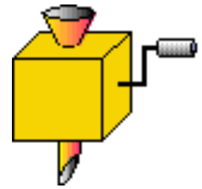
$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{92.5eV} \;\Rightarrow\; \Omega_{\nu} h^2 = \frac{\sum_k m_k}{92.5eV}$$

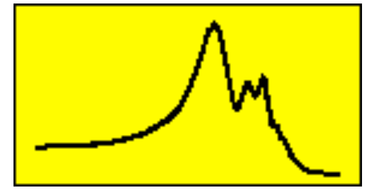


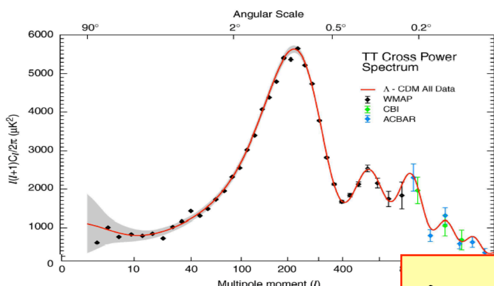
Tegmark 1999
P(k) [(h^{-1}Mpc)^3]
k [1/h^{-1} Mpc]
$\Omega_\nu/\Omega_m = .05$
1
0
m_ν = 1 eV
m_ν = 7 eV
m_ν = 4 eV

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

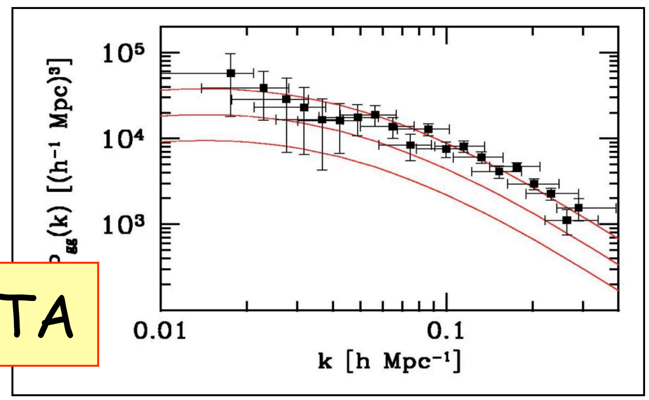
Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau, \Sigma m_\nu)$

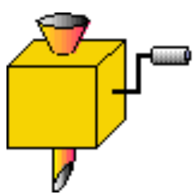




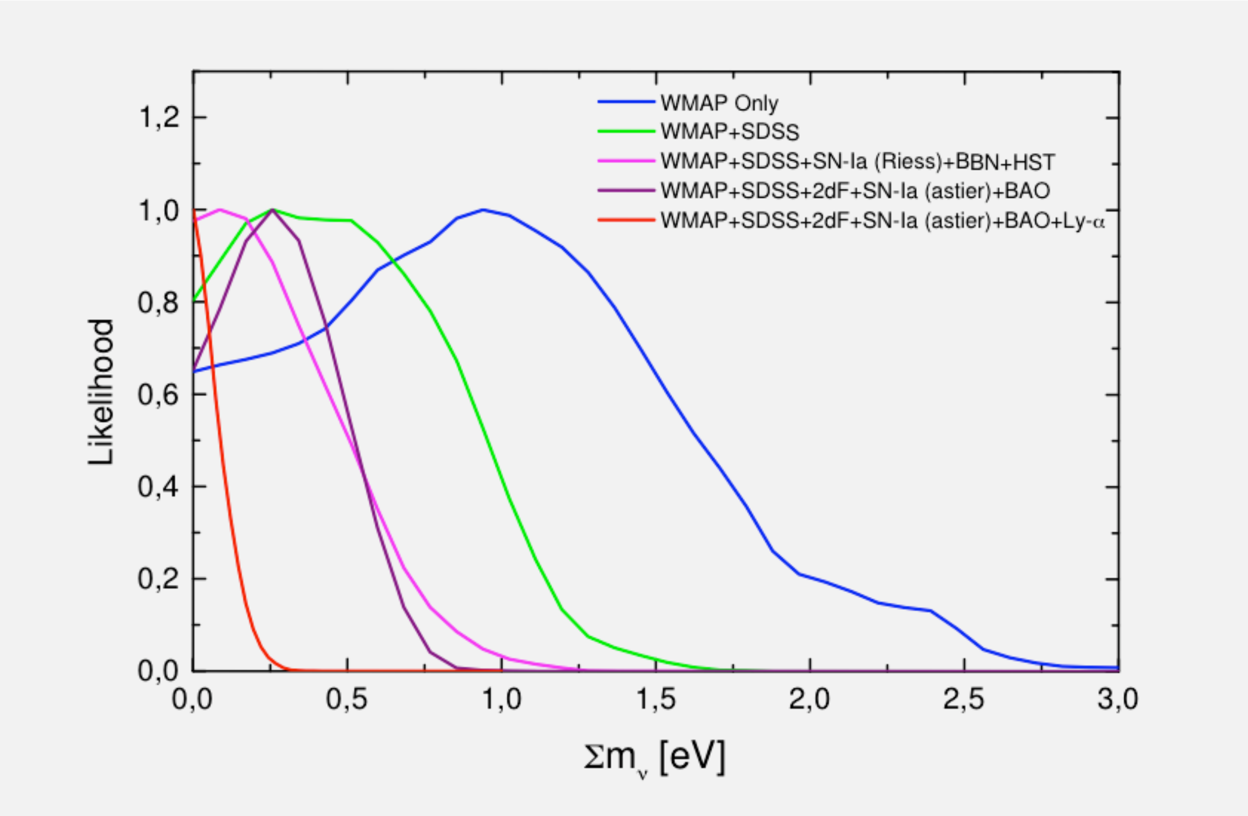


DATA





PARAMETER ESTIMATES



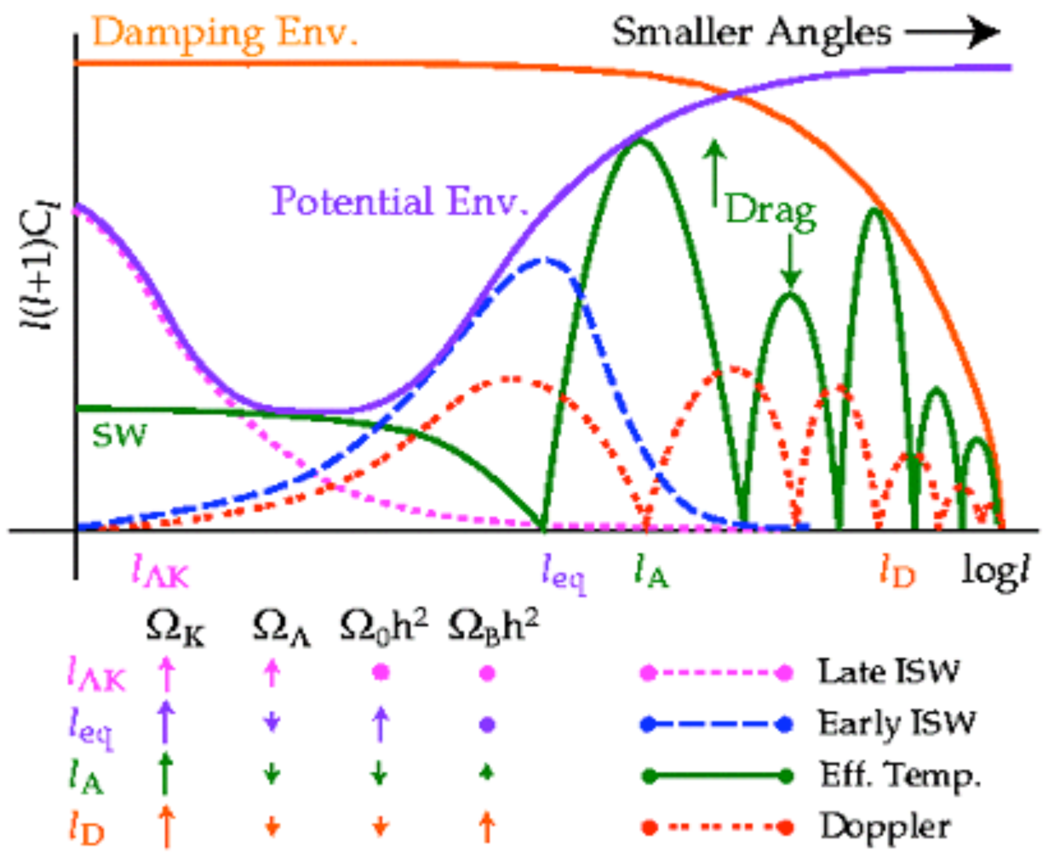
Bounds on for increasingly rich data sets (assuming 3 Active Neutrino model):

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

Fogli et al., Phys. Rev. D 75, 053001 (2007)

What about $N>3$?

Extra neutrino light component: effects on the CMB



Hu, Sugiyama, Silk, Nature 1997, astro-ph/9604166

Integrated Sachs-Wolfe effect

while most cmb anisotropies arise on the last scattering surface, some may be induced by passing through a time varying gravitational potential:

$$\frac{\delta T}{T} = -2\int d\tau\, \dot{\Phi}(\tau)$$

linear regime – integrated Sachs-Wolfe (ISW)

non-linear regime – Rees-Sciama effect

when does the linear potential change?

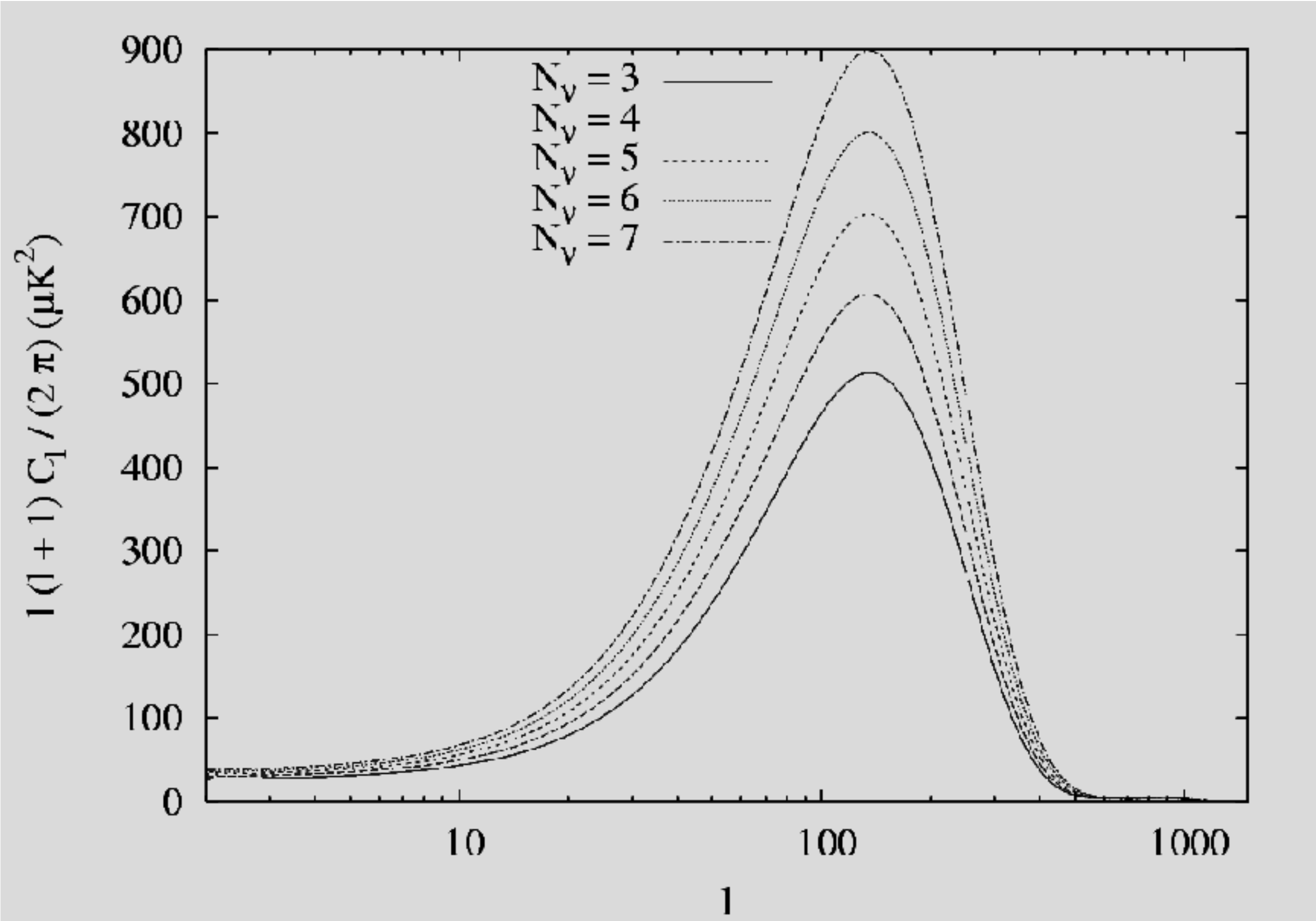
$$\nabla^2 \Phi = 4\pi G a^2 \overline{\rho}\, \delta$$

Poisson's equation

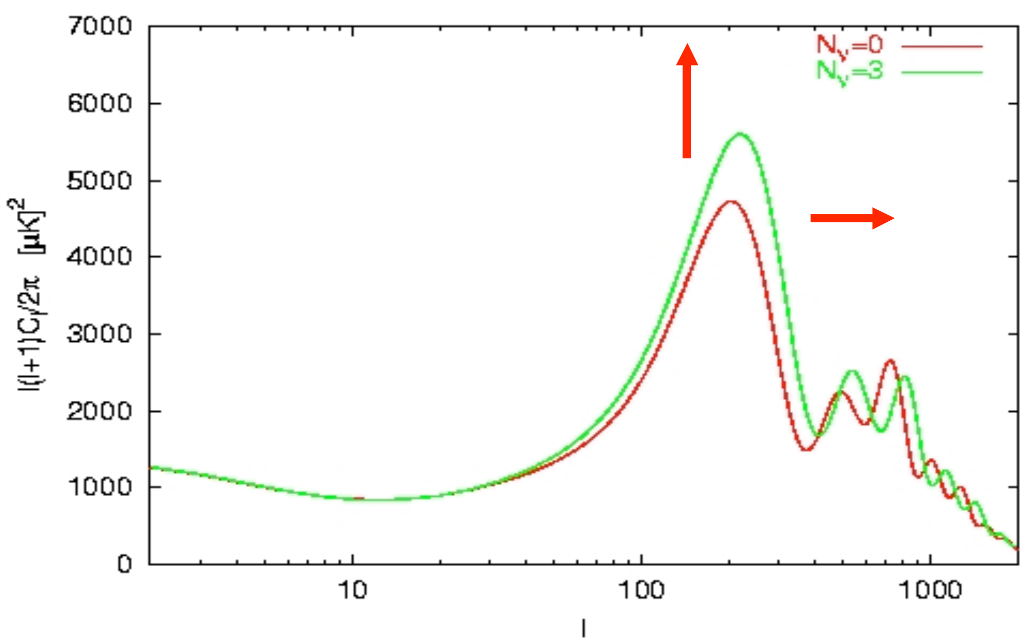
- changes during radiation domination
- decays after curvature or dark energy come to dominate (z~1)

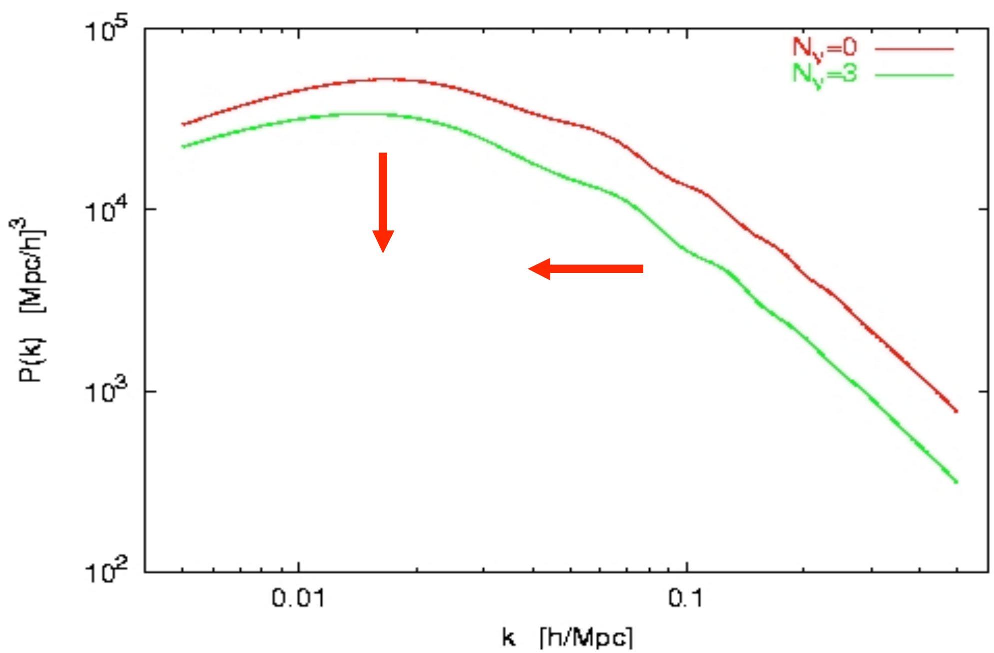
Effect of Neutrinos in the CMB: ISW

Changing the number of neutrinos (assuming them as massless) shifts the epoch of equivalence, affecting the ISW:

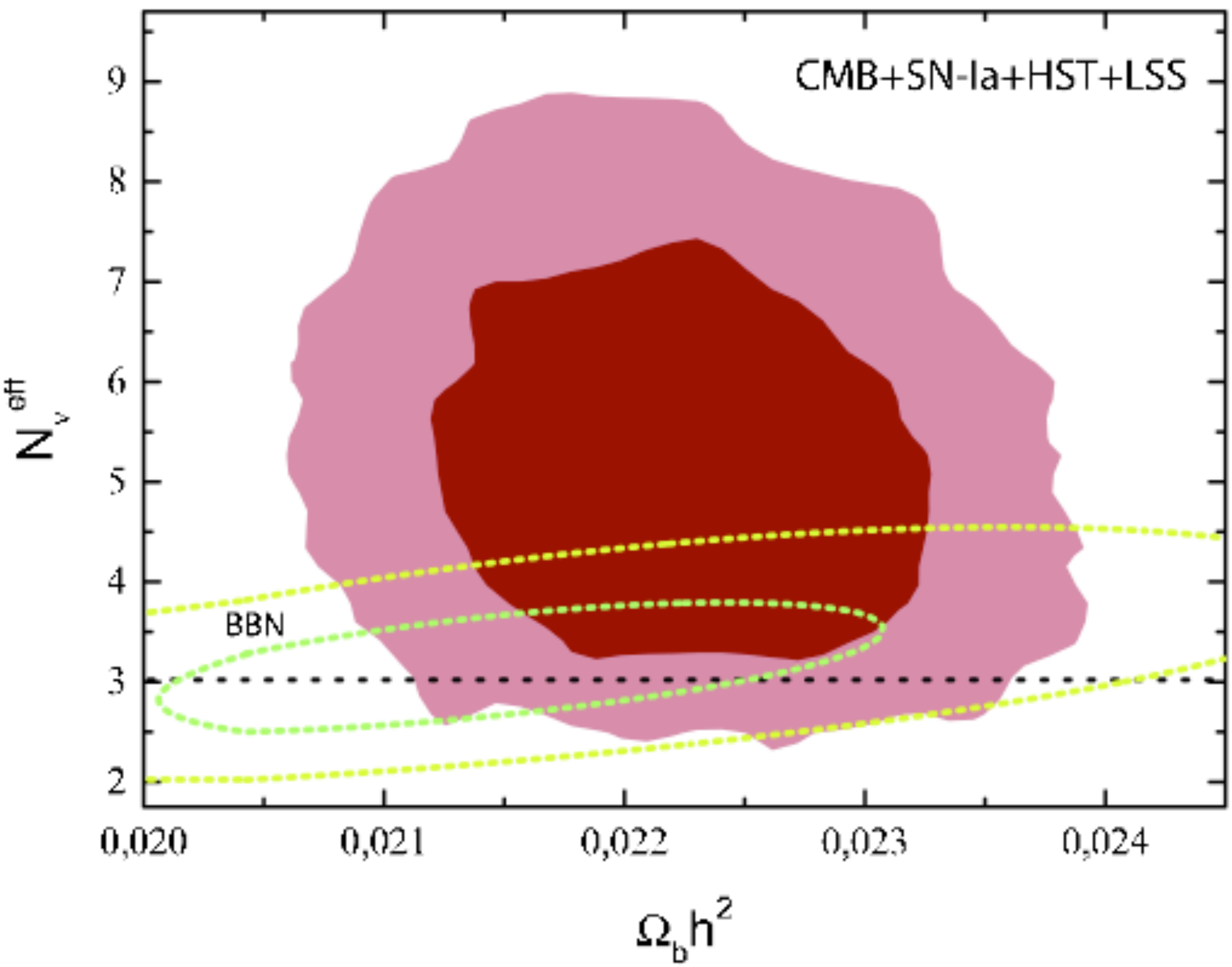


Increasing the Neutrino Massless number postpone the equivalence (while keeping constant the time of decoupling).
This produces a shift in the CMB power spectra since changes the sound horizon at decoupling. The height of the first peak is also increased thanks to the Early Integrated Sachs-Wolfe. The LSS matter power spectrum is also shifted since the size of the horizon at equivalence is now larger. There is less growth of perturbations in the MD regime.

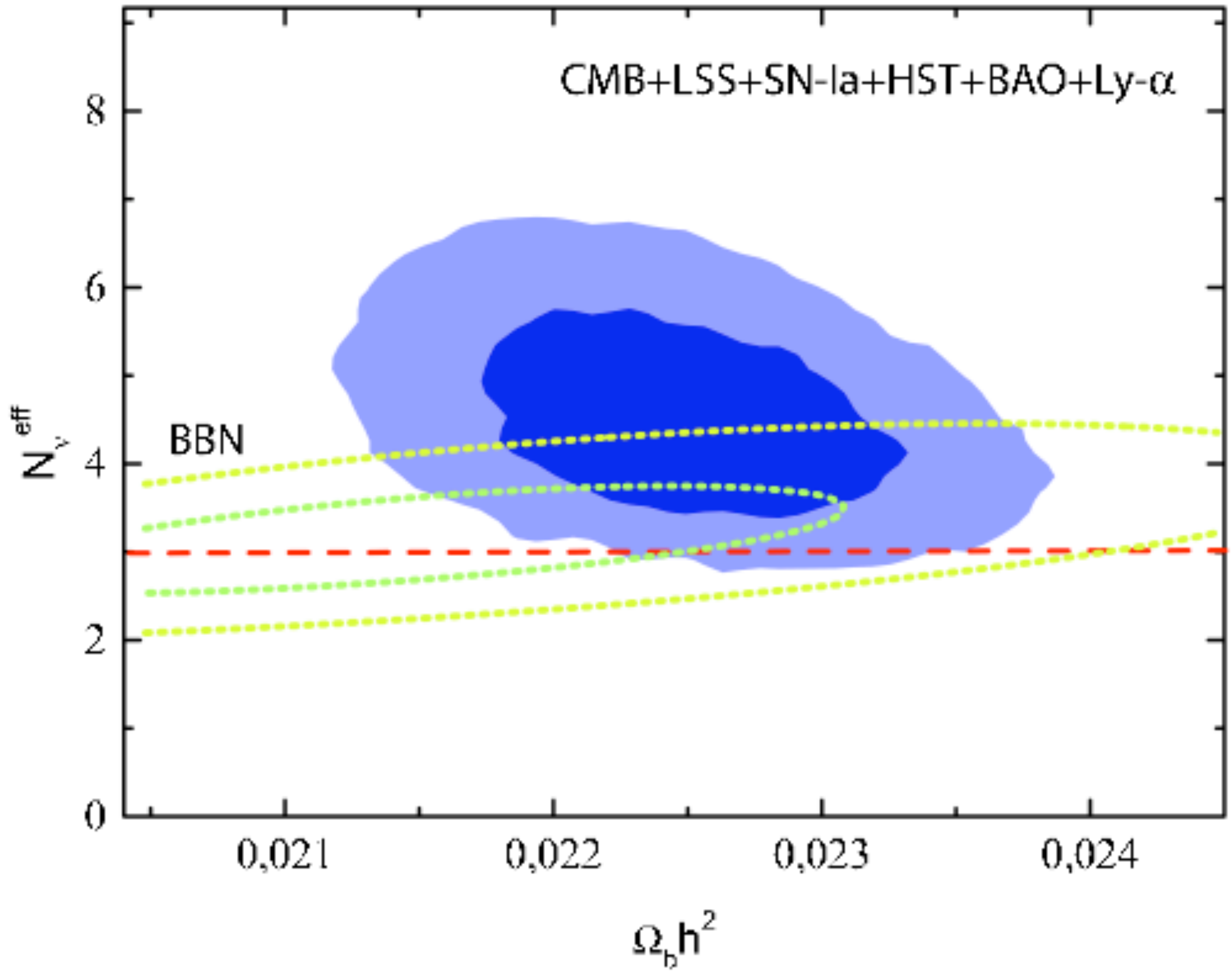




Latest Analysis: Indication for N>3 from Cosmology ?

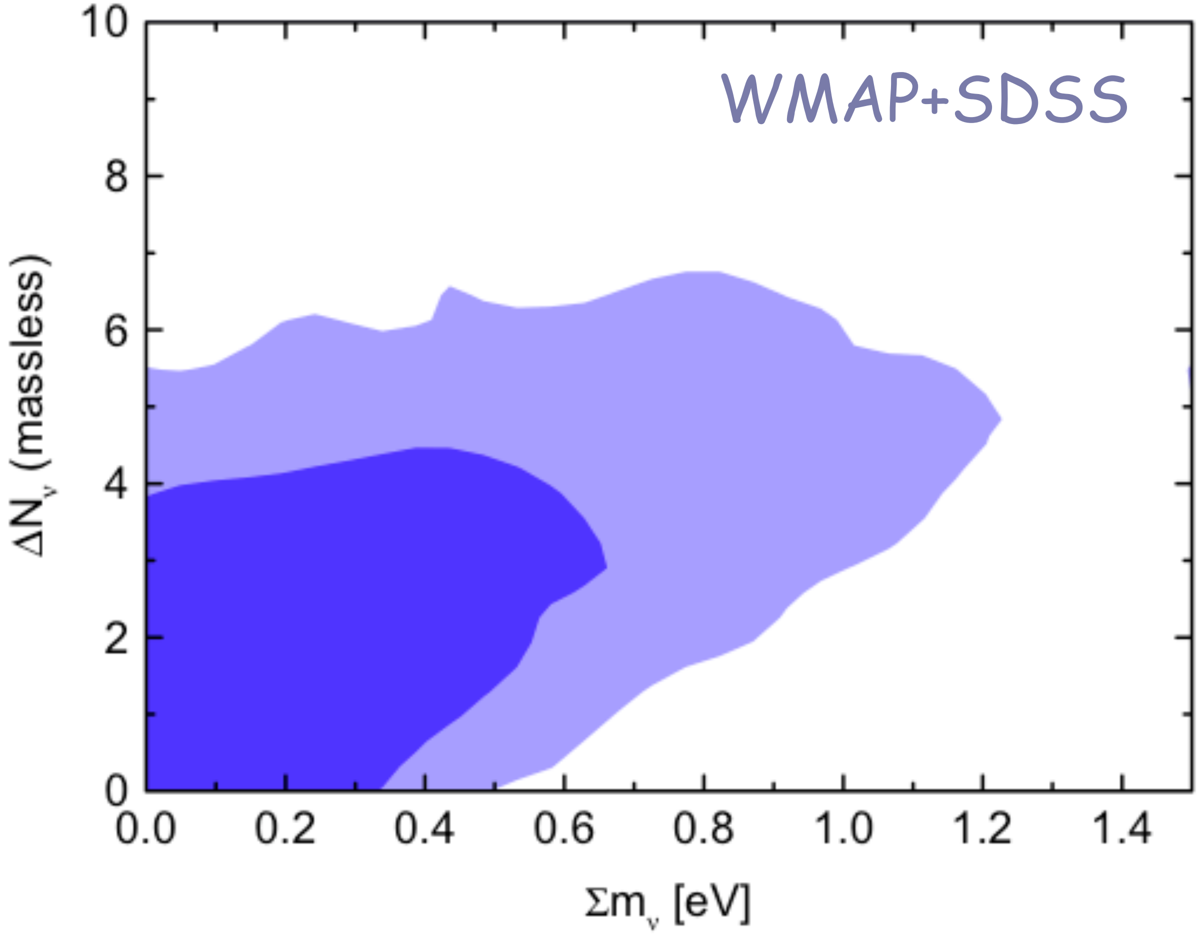


Mangano, Melchiorri, Mena, Miele, Slosar JCAP03(2007)006



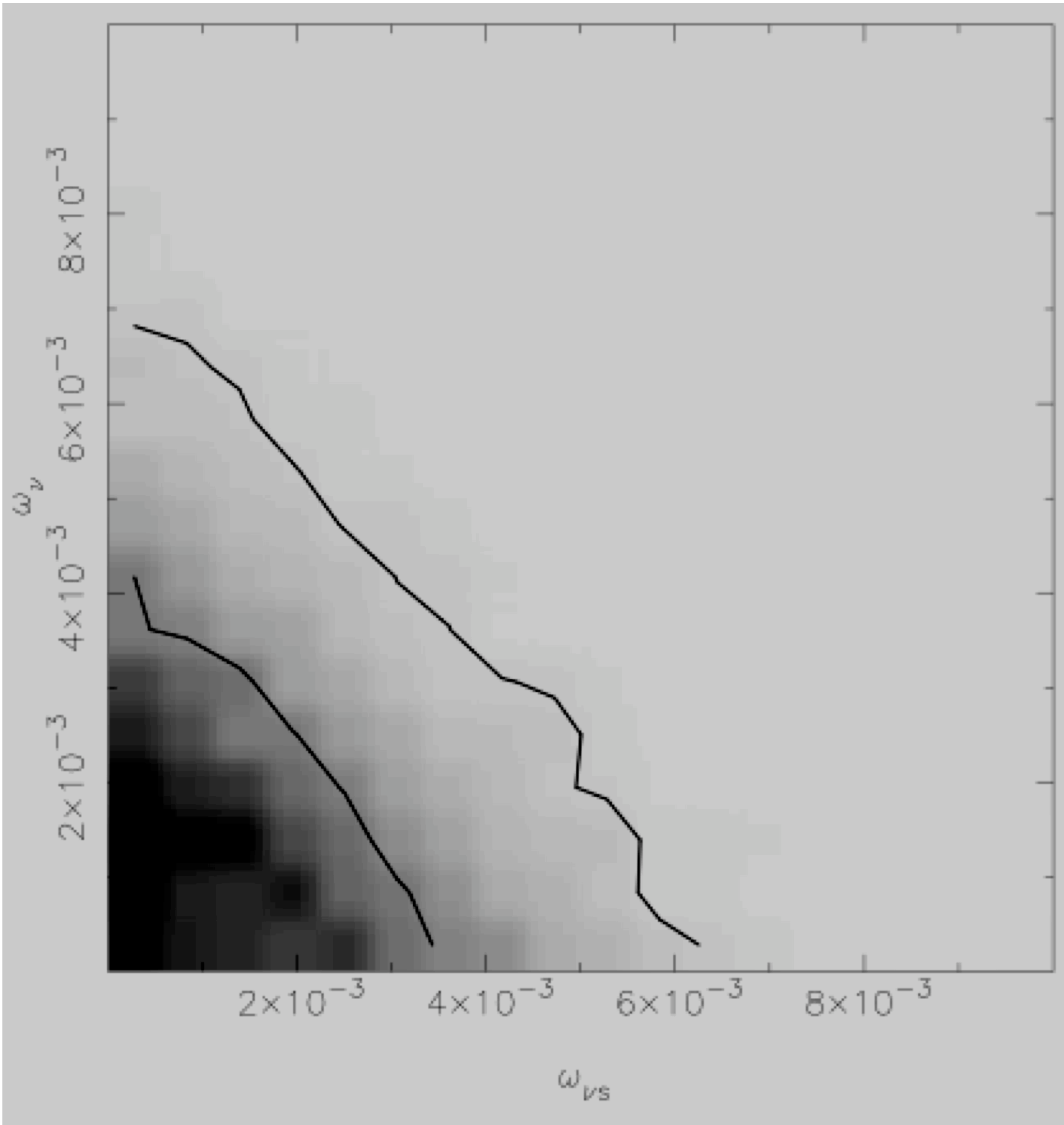
Mangano, Melchiorri, Mena, Miele, Slosar JCAP03(2007)006

Massless Neutrino Number vs Active Neutrino Masses



Adding an extra relativistic component change the bound by 10-20% par specie (See e.g. Melchiorri, Serra PRD 2006)

What about a fourth massive sterile neutrino ?



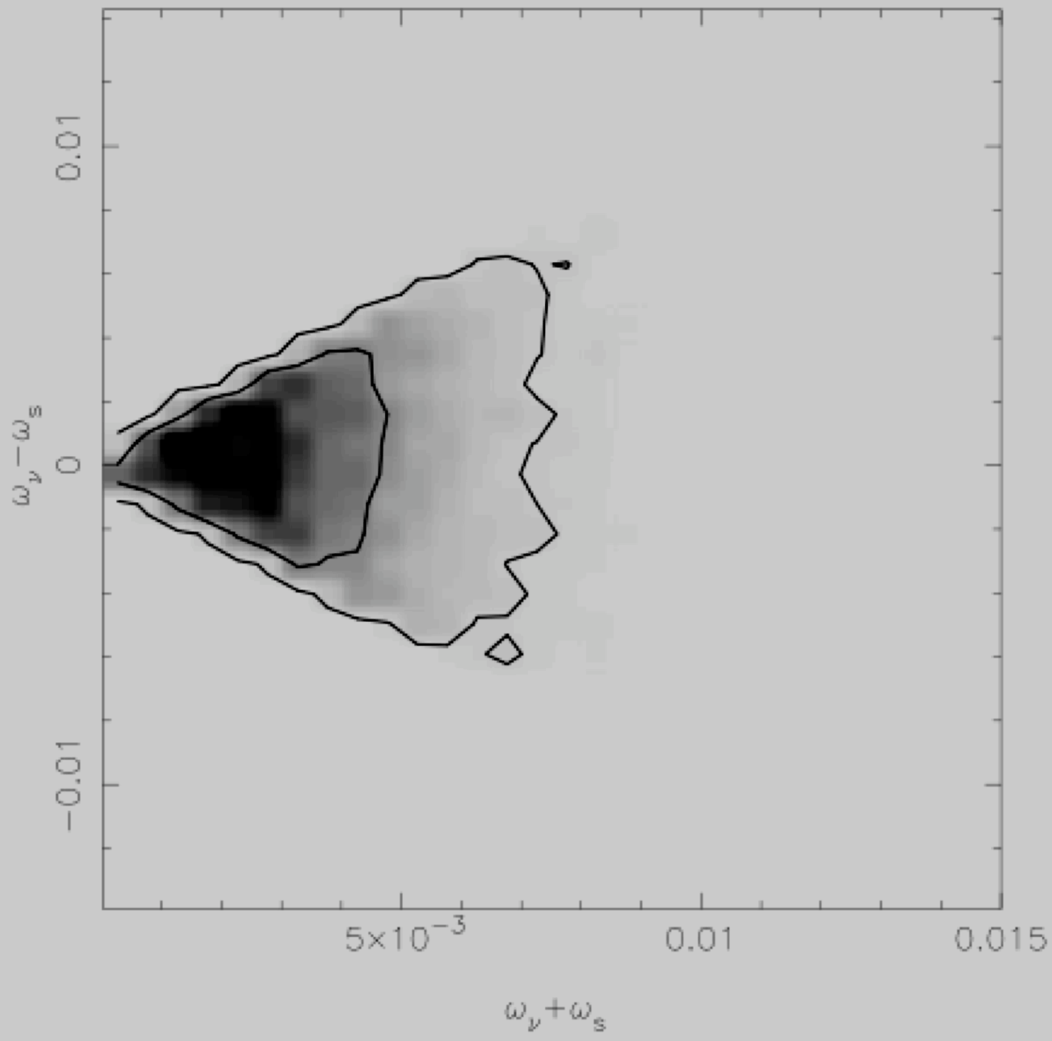
CMB+2df+
Sloan+Ly-

$$\omega_s = 0.0106 \frac{m_s}{eV}$$

$$\omega_\nu = 0.0106 \frac{3m_\nu}{eV}$$

m_s<0.23 eV at
95% c.l.

Dodelson,
Melchiorri,
Slosar,
Phys.Rev.Lett.
97 (2006) 04301



Cosmology tests only the sum of the neutrino masses (see also Slosar 2006)

Hower sterile neutrino can be non-thermal.
Thermalization occurs if:

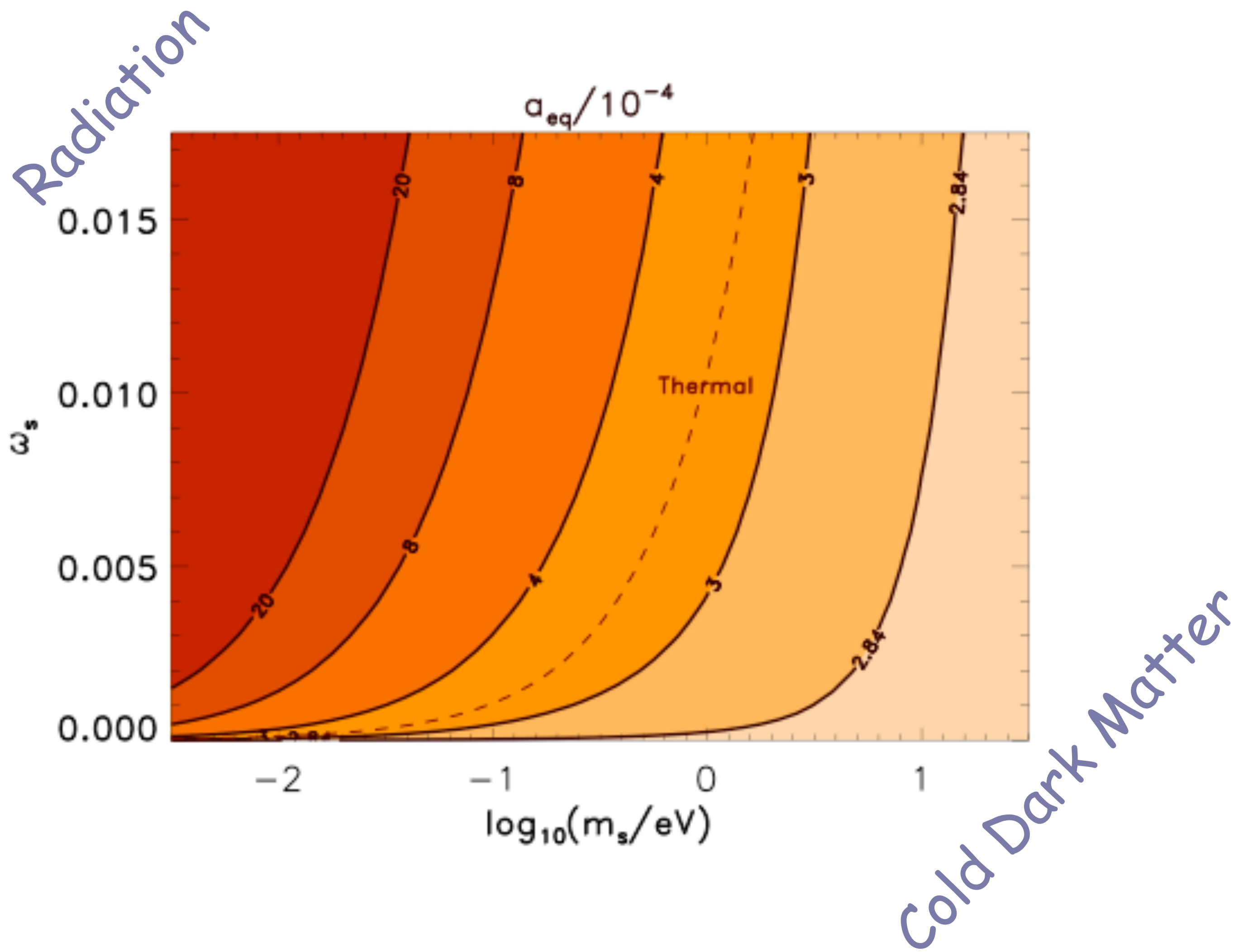
$$\Delta m^2 \sin^4 \theta > 3 \times 10^{-6} eV^2$$

In the simplest models with one sterile neutrino this Condition is satisfied bu there are many ways of evading thermalization (see e.g. Abazajian, 2003).
In practice:

$$\Omega_s \neq 0.0106 \frac{m_s}{eV}$$

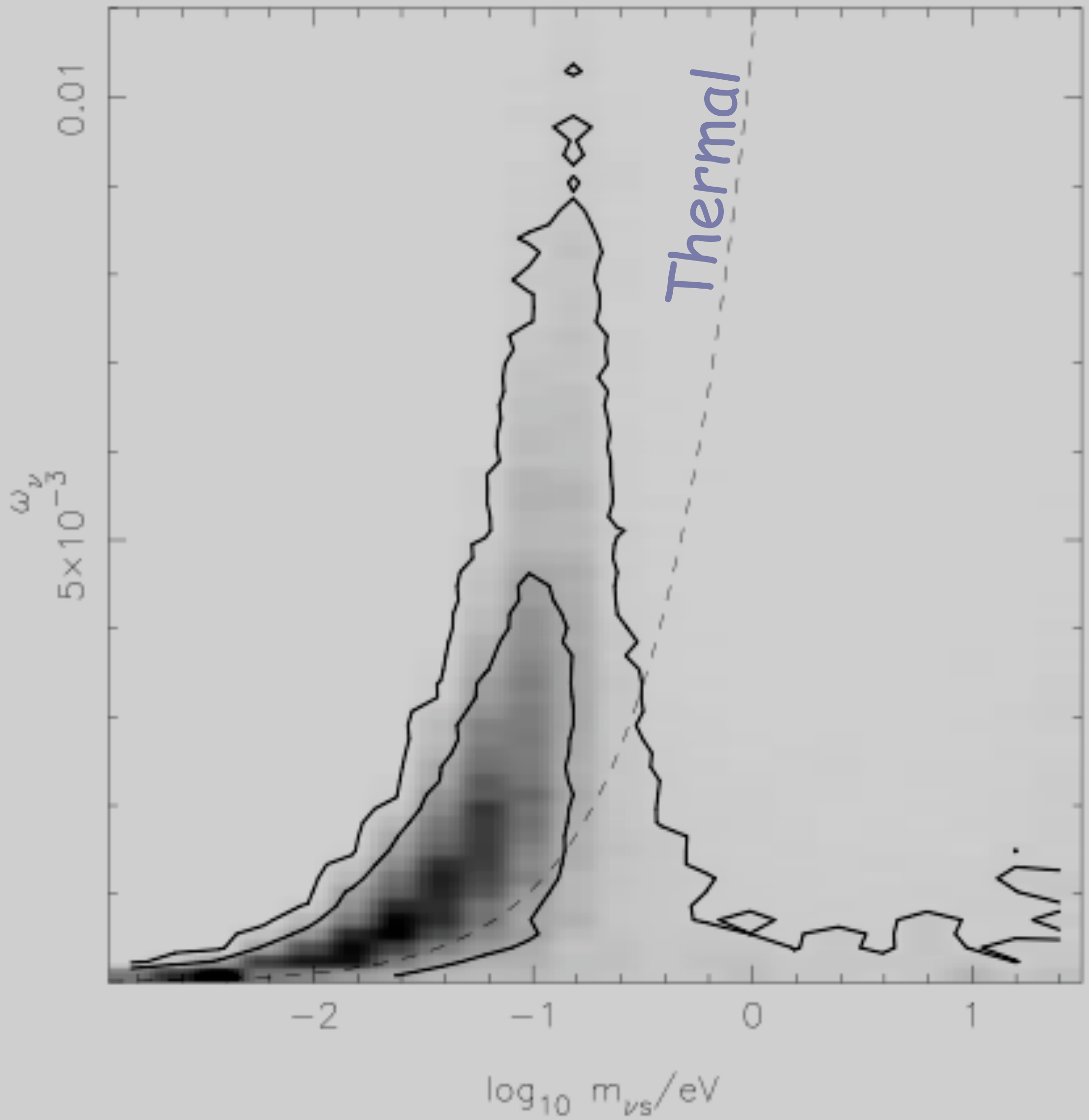
Mass and cosmological energy density should be considered as independent parameters !

Effects on the scale of equality:



Dodelson, Melchiorri, Slosar, PRL 2006

Constraints on non-thermalized sterile neutrino



Energy density
Can be higher
For smaller masses

You may have larger
masses but in this
case they are not
cosmologically
relevant.

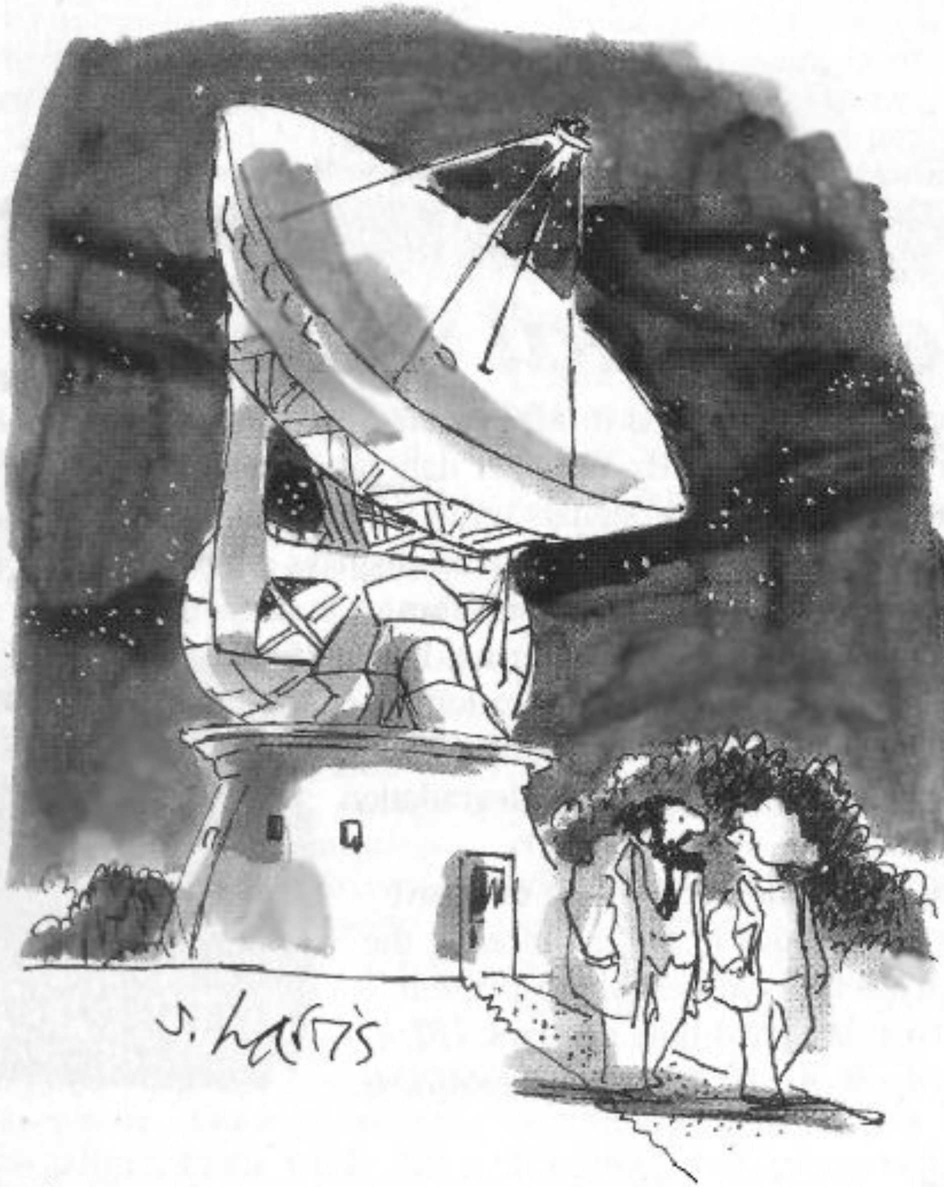
Conclusions

- Current CMB and LSS data are in very good agreement with the standard scenario. Limits on N□ are still weak, Sensitivity comparable to BBN is possible in the very near future. If Lyman-alpha are included there is some indication that N>3.

- Cosmological constraints on neutrino mass are rapidly improving.

If one includes Ly-alpha then □<0.17 eV. Tension with the 0□□□ results.Fourth sterile neutrino mass (if thermal constrained to be m_s<0.25eV). LSND, 0□□□ and cosmology all incompatible. Neutrino mass detection up to □=0.05 eV is possible in the very near future.

- The constraints are model dependent (quite common in physics…)



"I'LL BE WORKING ON THE LARGEST AND SMALLEST OBJECTS IN THE UNIVERSE—SUPERCLUSTERS AND NEUTRINOS. I'D LIKE YOU TO HANDLE EVERYTHING IN BETWEEN."