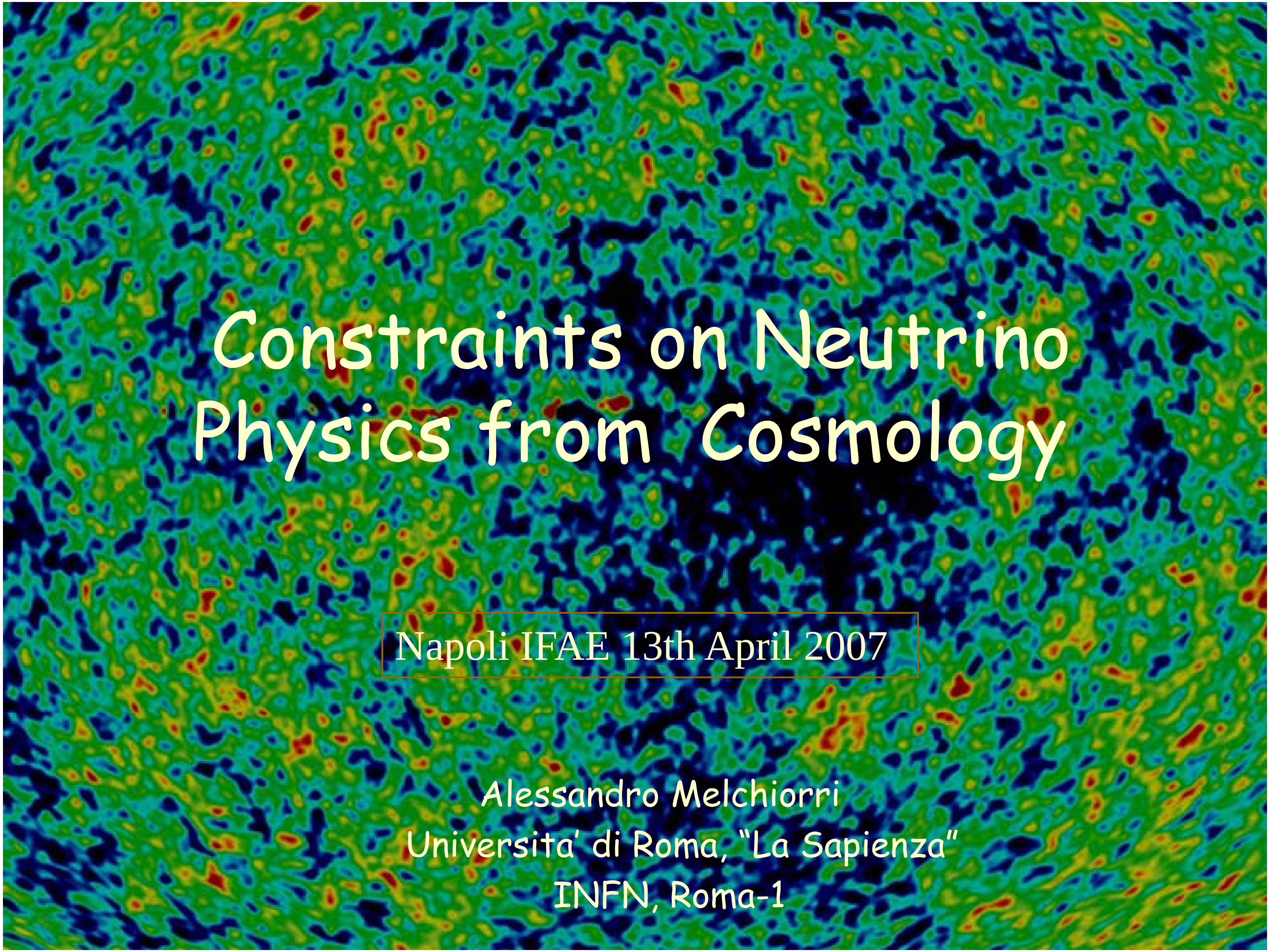


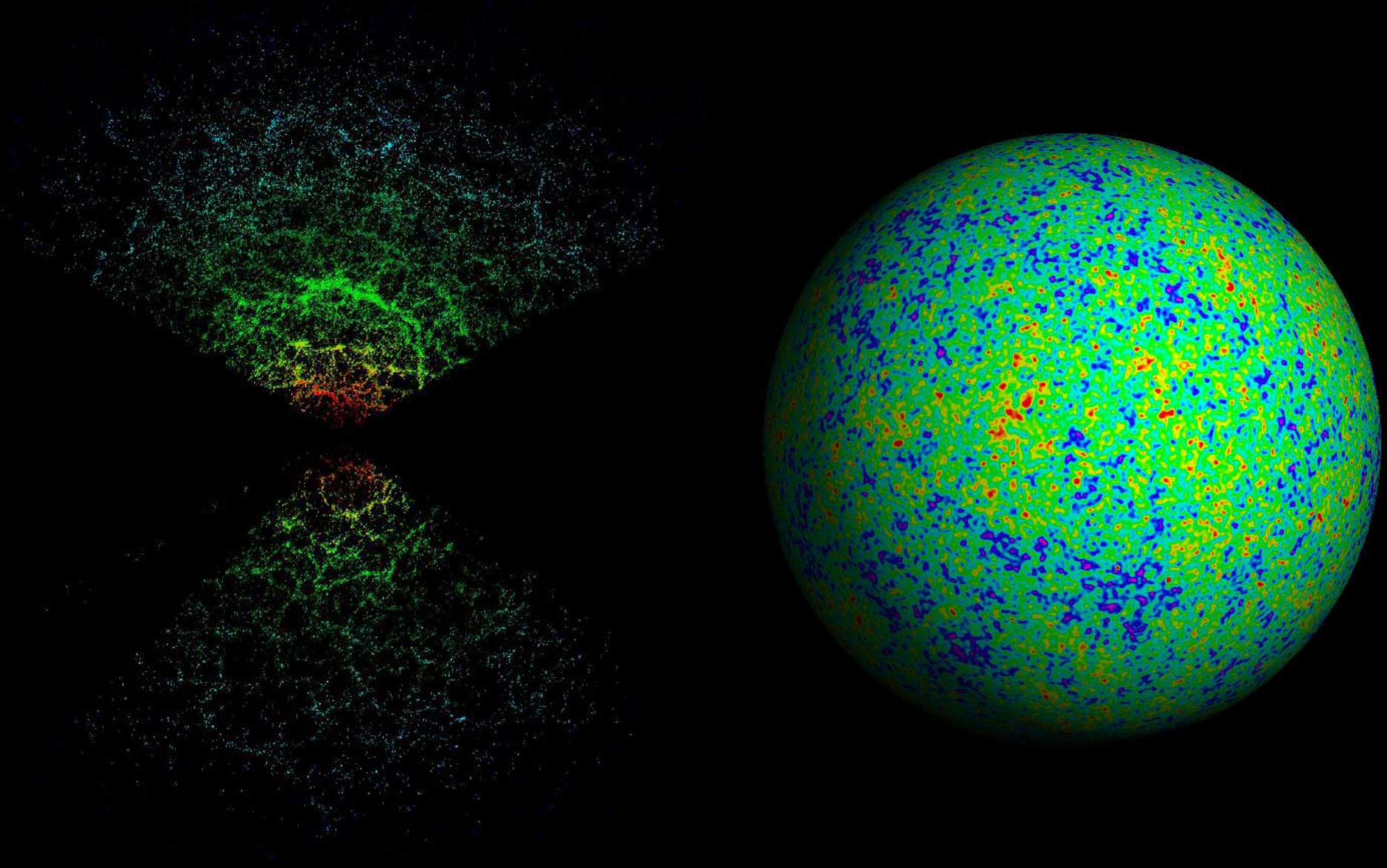
Constraints on Neutrino Physics from Cosmology

Napoli IFAE 13th April 2007

Alessandro Melchiorri
Universita' di Roma, "La Sapienza"
INFN, Roma-1


CHARTA COSMOGRAPHICA. CVM VENTORVM PROPRIA NATVRA ET OPERATIONE.
Circius, Noordt noordtweſt. SEPTEN Septentrionalis, Noordt. TRIO Aquilo, Noordt noordt ooſt.
Argeſtis. Weſt noordtweſt.
OCCI Zephyrus DENS. Weſt.
Libs Weſt zuydtweſt.
Helleſpontius Ooſt noordtooſt.
ORI Subſolanus ENS. Ooſt.
Vulturnus. Ooſt zuydtooſt.
Zona frigida
Zona temperata
Indis Orientalis pars
Tropicus æſtiuus
Æquinoctialis
Tropicus Hybernus
Baccalearum
EVROPA
TAR TA RIA
Scythia
ASIA
Scythia ultra Imaum
Seres
India trans Gangem
Perſe
Arabia felix
India
Taprobana
Oceanus Indicus Meridionalis
MARE ATLANTICVM
Barbaria
Getulia
Nigritæ
AFRICA
PERV
AMERICA
Canibales
Promontorium bone Spei
Strictum Magellanicum
Climata Australia
Climata Septen.
I
II
III
IIII
V
VI
REGIONVM LONGITVDO AD ORTVM.
Auſtroafricus. Zuydt zuydtweſt. MERI Auſter, Zuydt DIES. Euroaſter, Zuydt zuydtooſt.
I

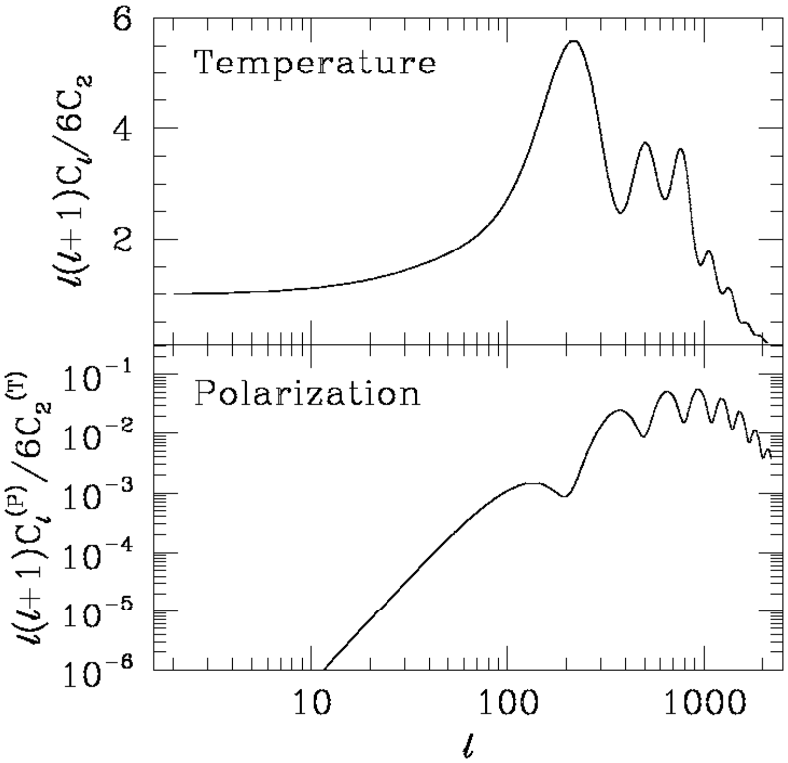
A.D. 1544

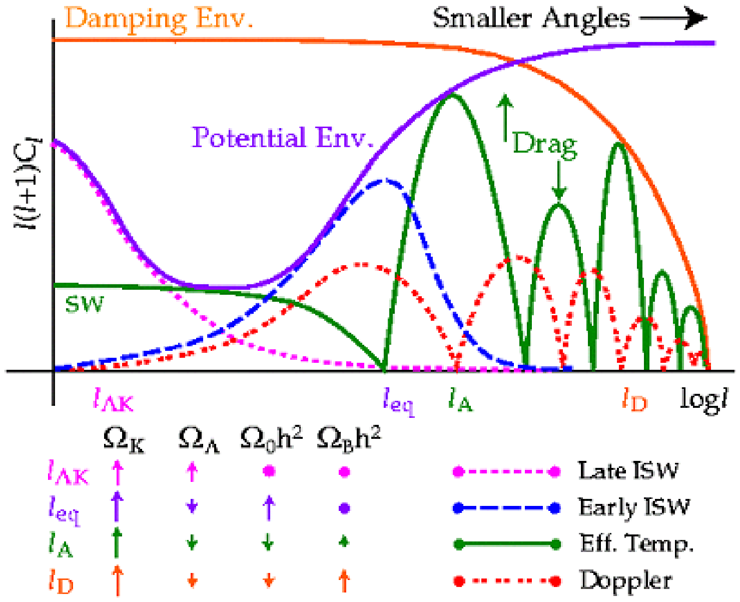


A.D. 2007

CMB: Theory

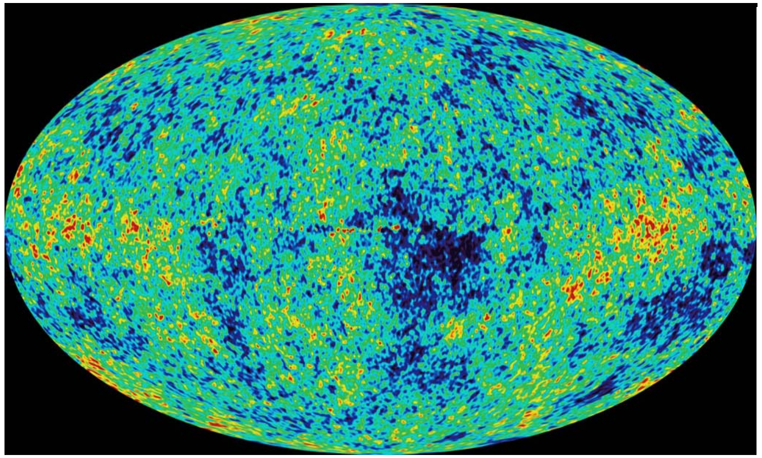
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

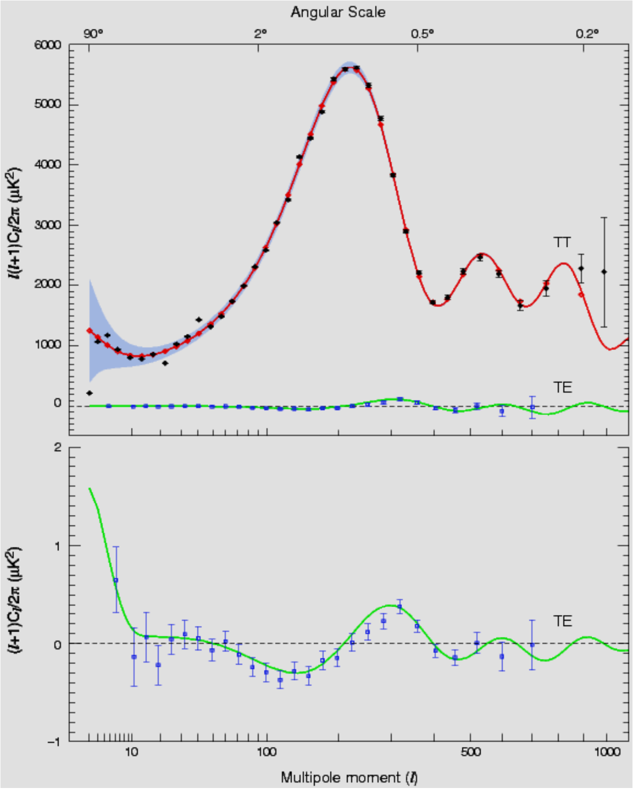


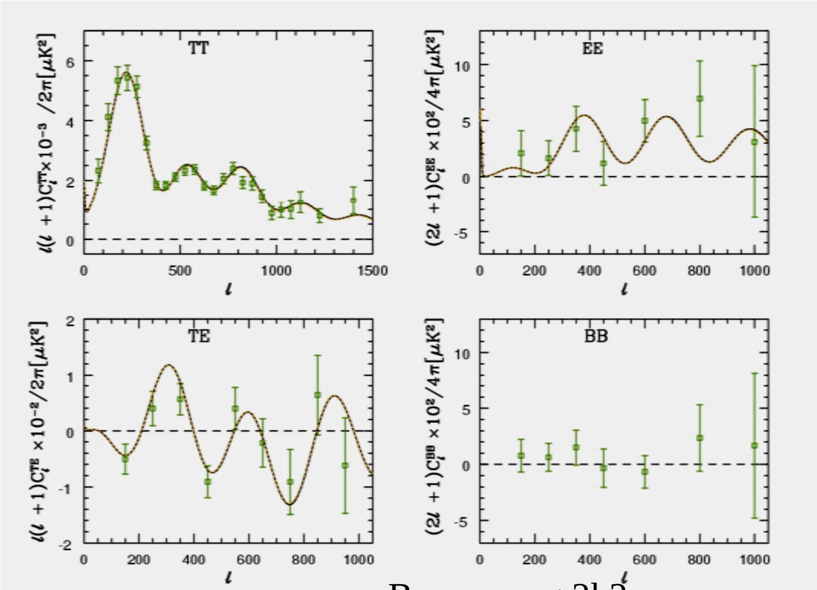


1/(Angular Scale)

CMB: Data







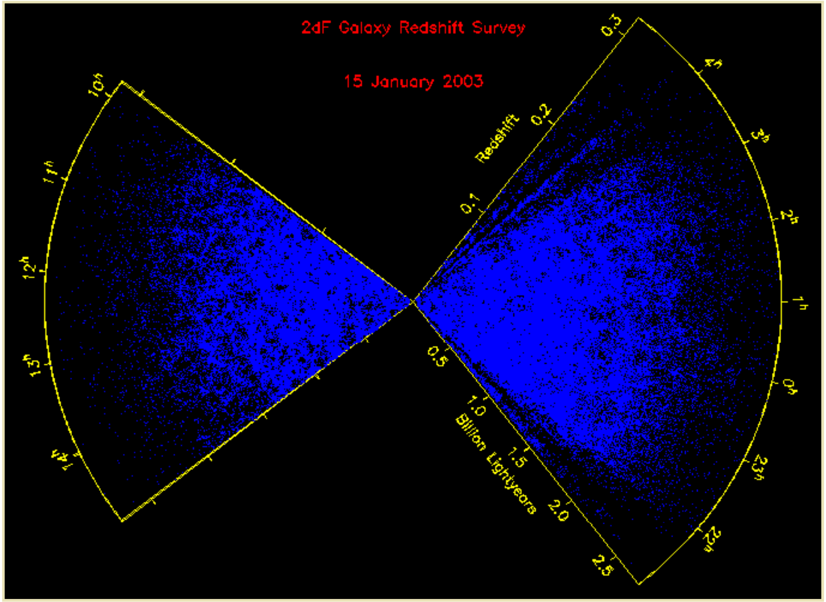
Boomerang 2k2

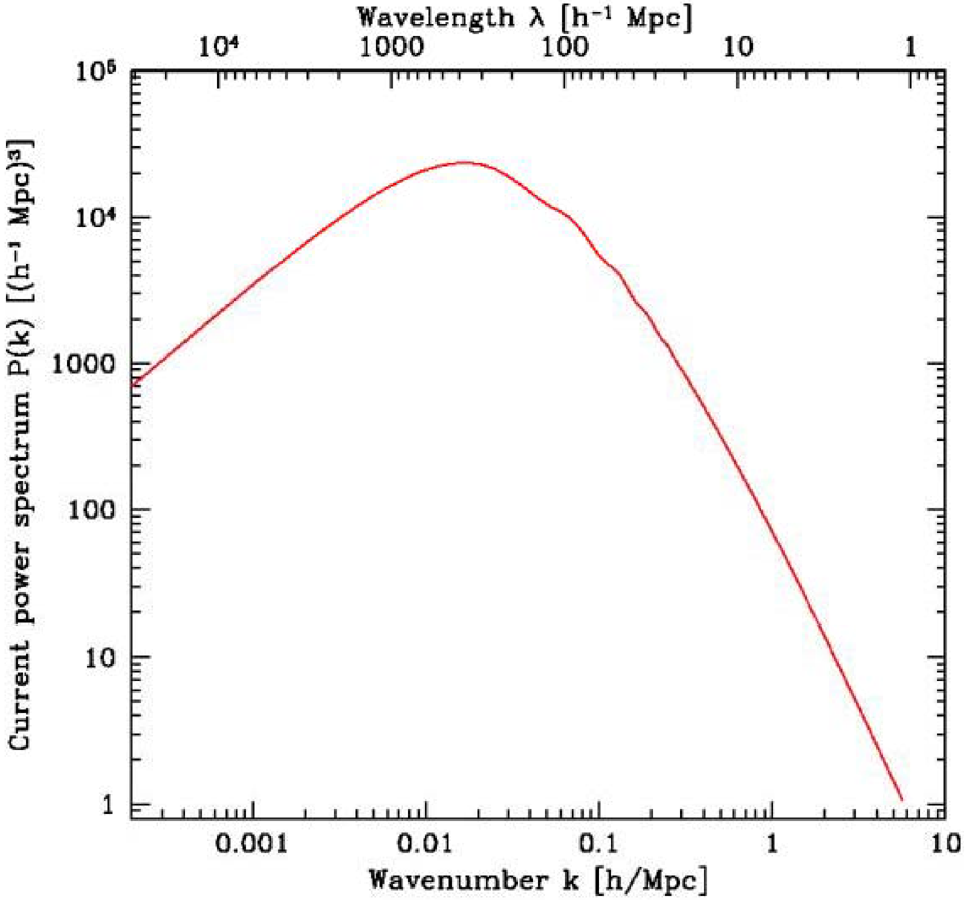
Galaxy Clustering: Theory

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

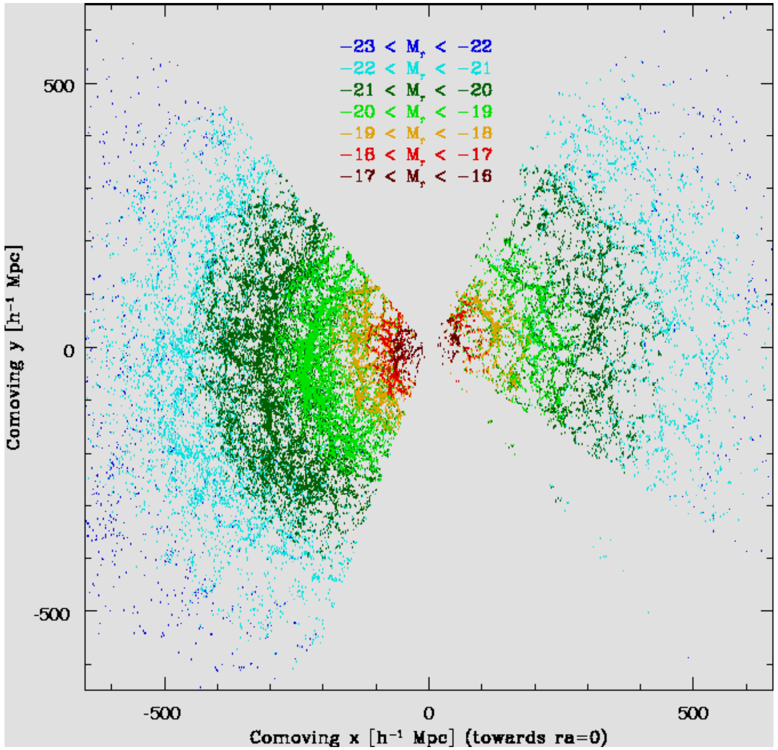
$$\xi_{galaxies}(r,t) = b^2 \xi(r,t)$$

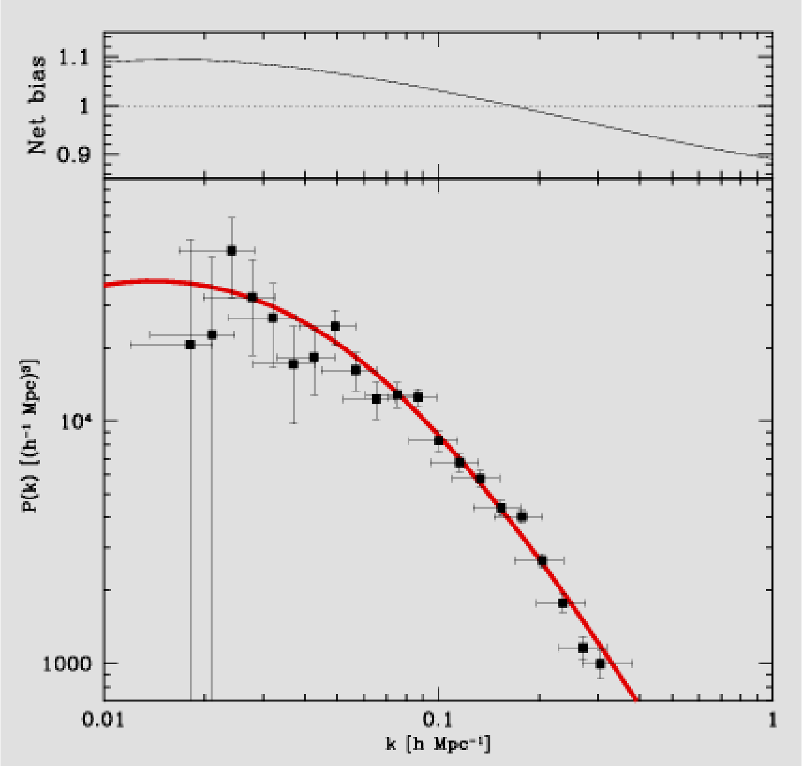
$$P(k,t) = \int d^3 r\, \xi(r,t)\, e^{i\vec{k}\cdot\vec{r}}$$





Galaxy Clustering: Data





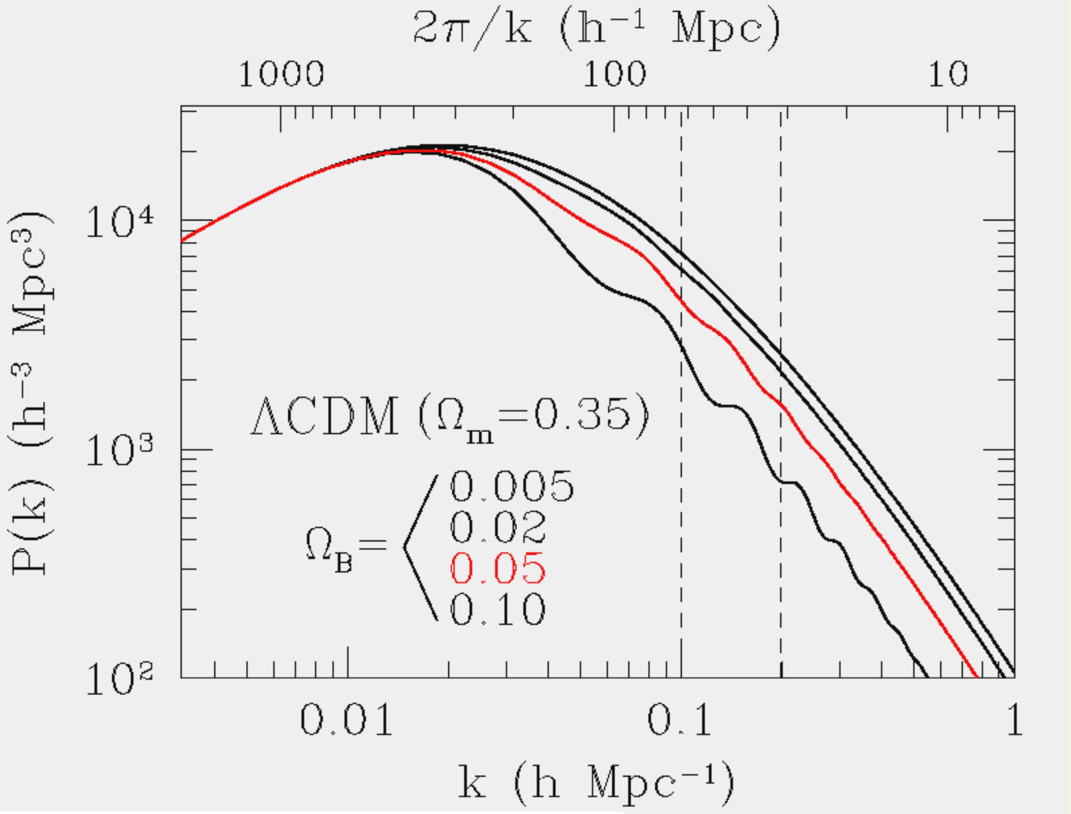
Again, perfect agreement with (low density) L-CDM model…

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:

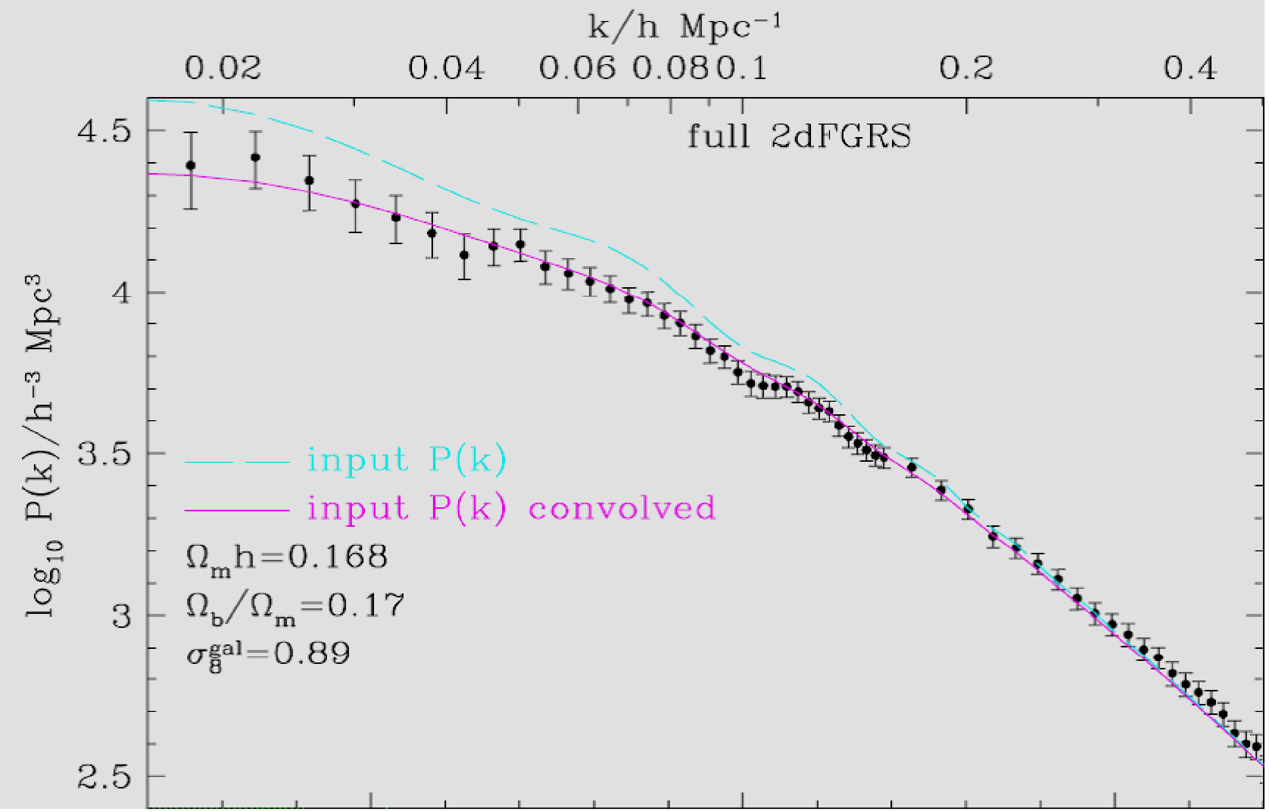
Potentially measure $d_A(z)$ at many redshifts!

Recent detections of the baryonic signature

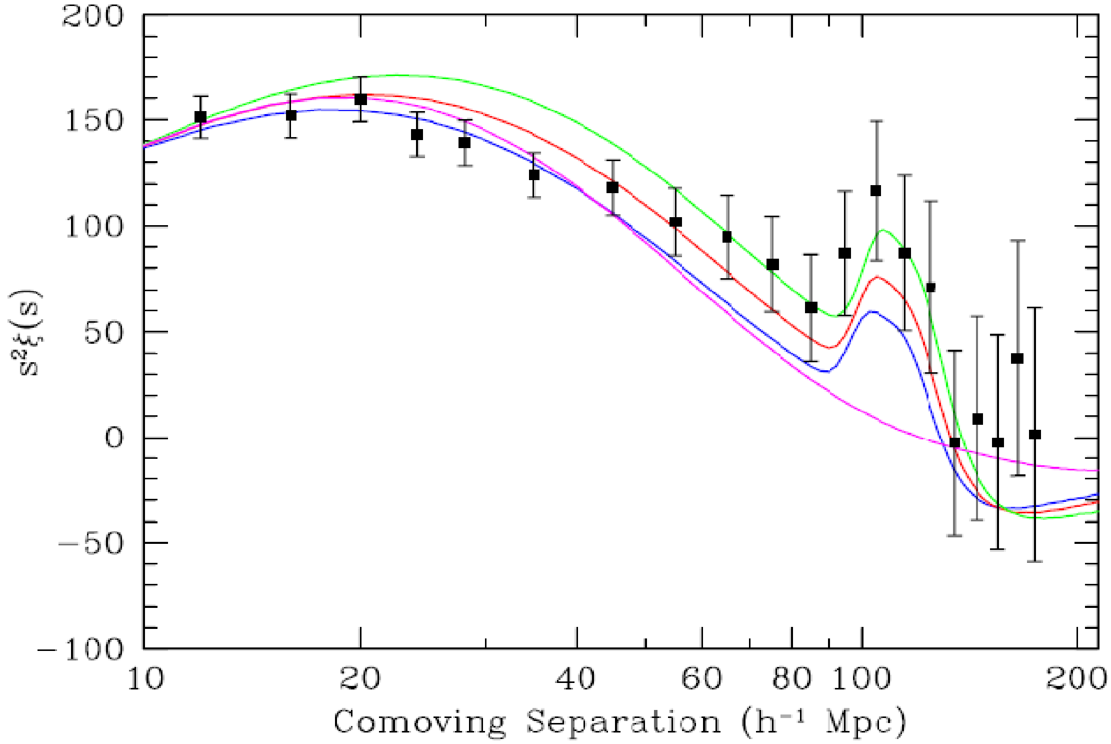
- Cole et al
  - 221,414 galaxies, $b_J < 19.45$
  - (final 2dFGRS catalogue)

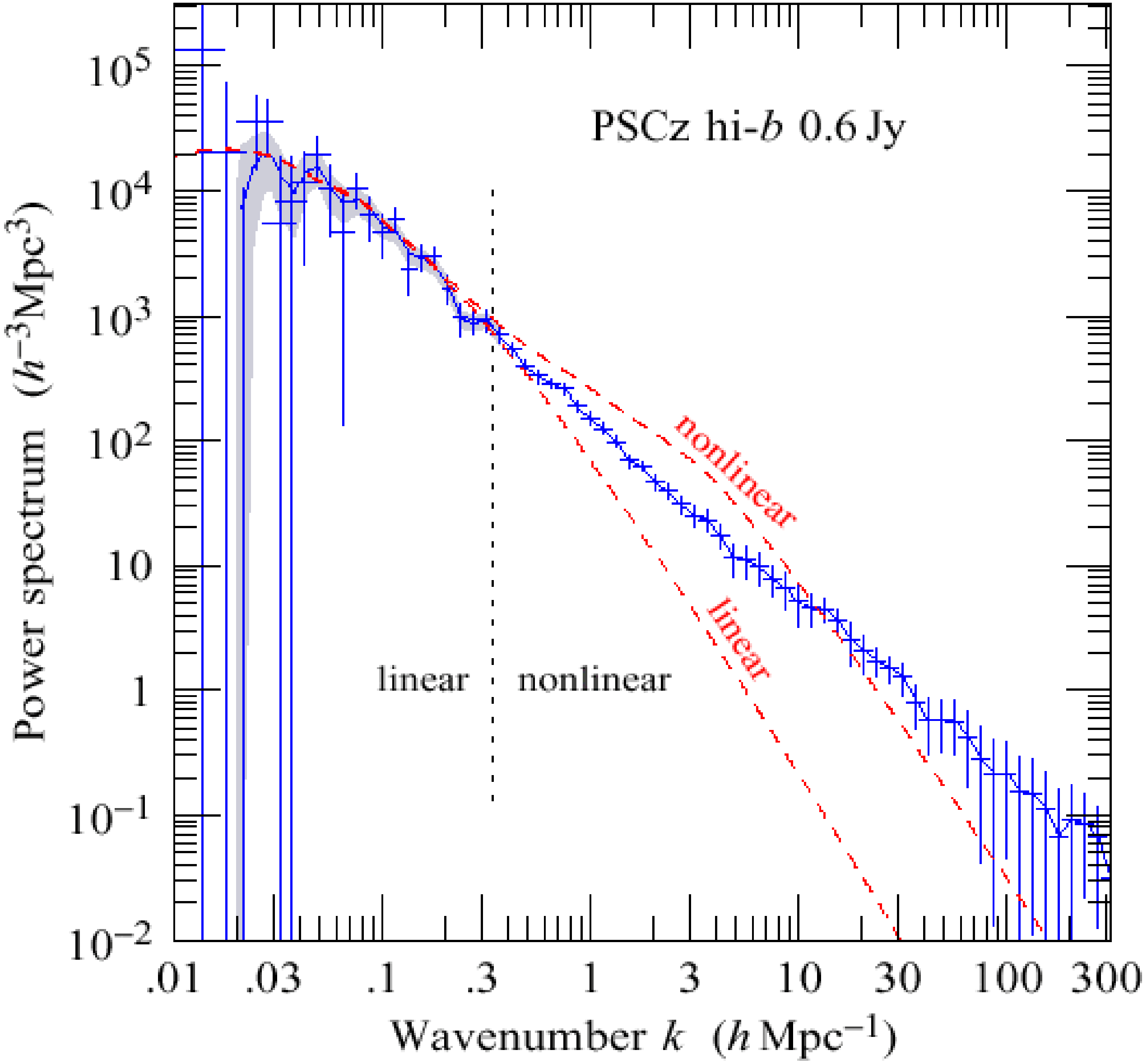
- Eisenstein et al
  - 46,748 luminous red galaxies (LRGs)
  - (from the Sloan Digital Sky Survey)

The 2dFGRS power spectrum



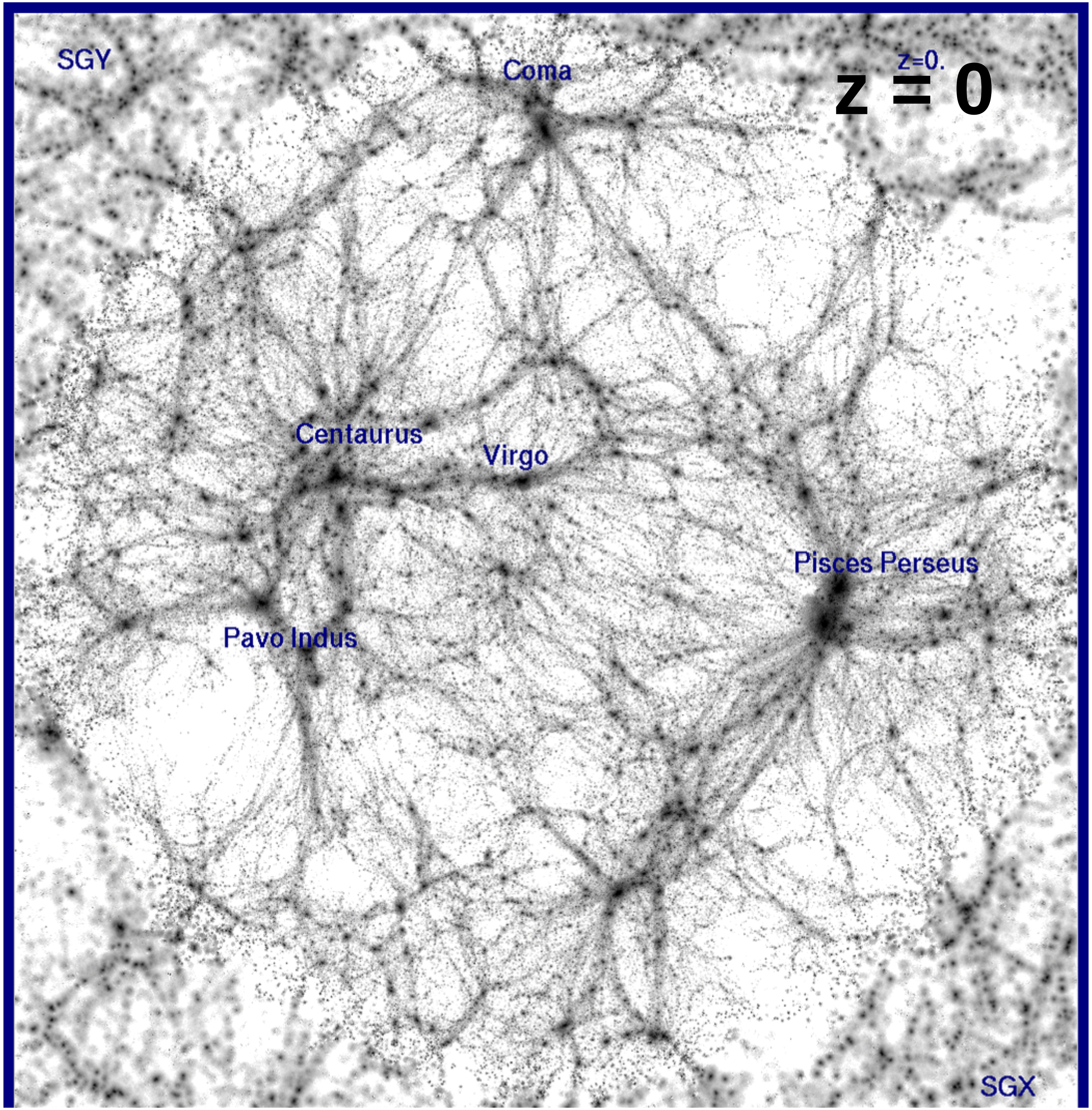
The SDSS LRG correlation function



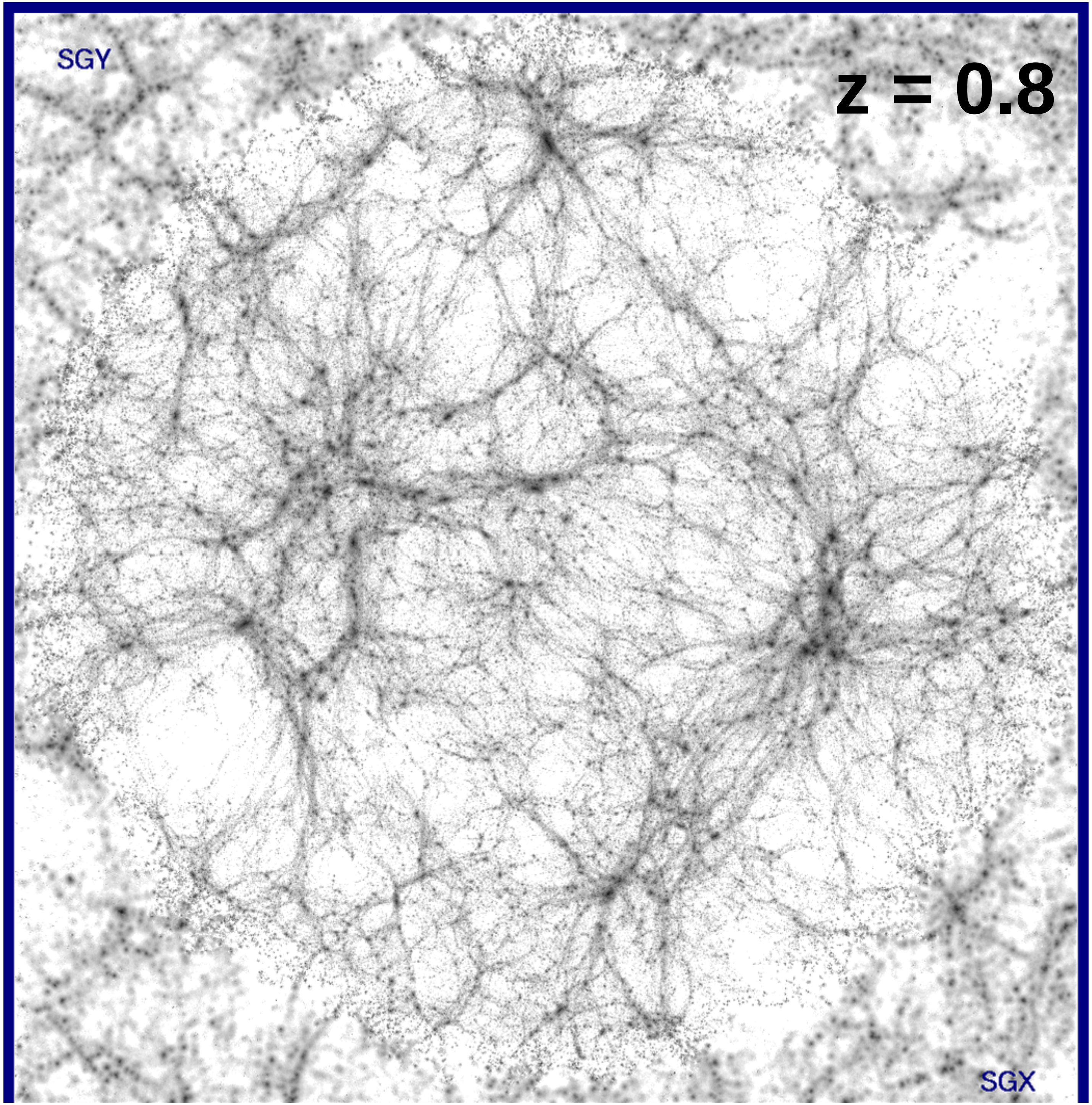


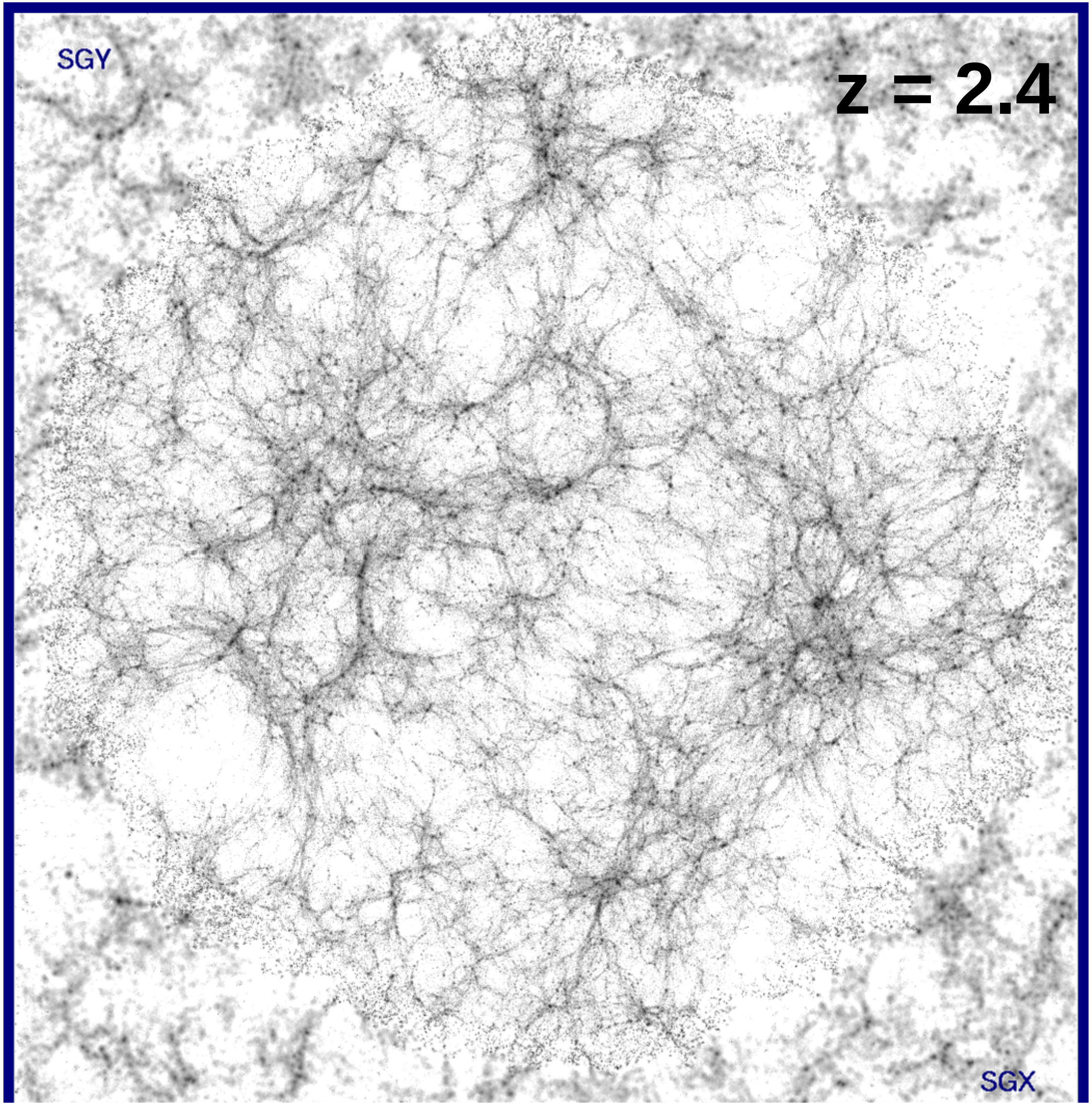
We want to go to smaller scales!!!
(and be linear)

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



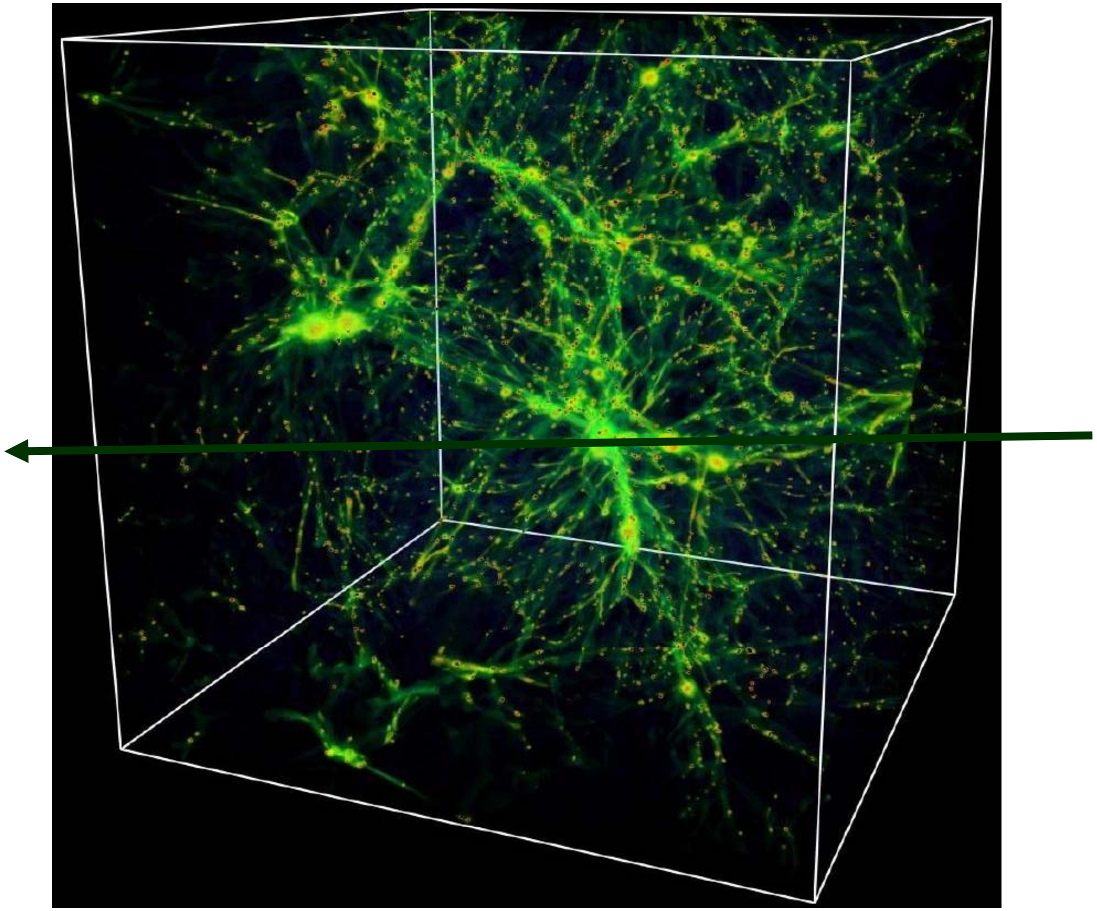
z = 0


SGY
z = 0.8
SGX


SGY
z = 2.4
SGX

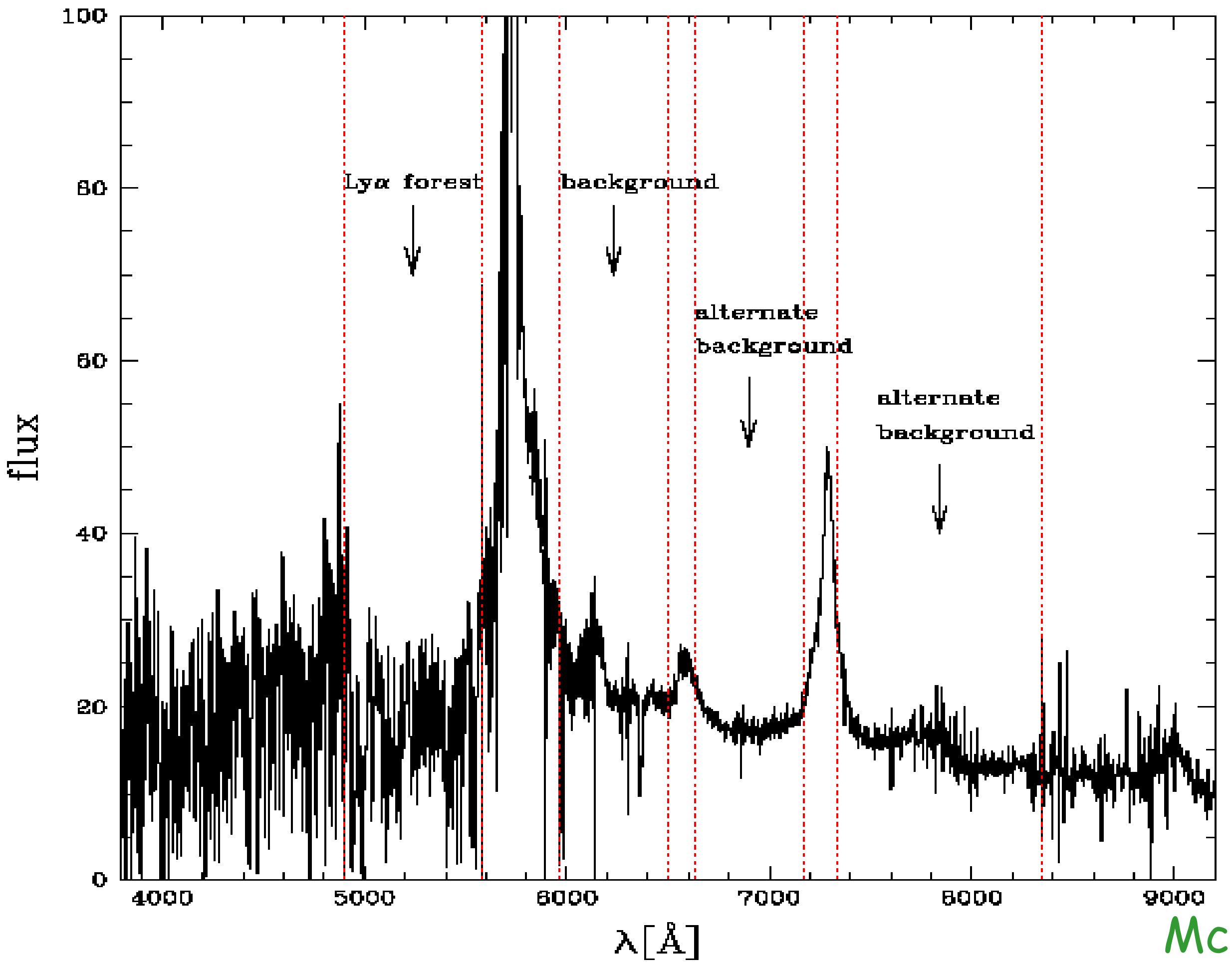
Lyman Alpha Forest Simulation: Cen et al 2001

You



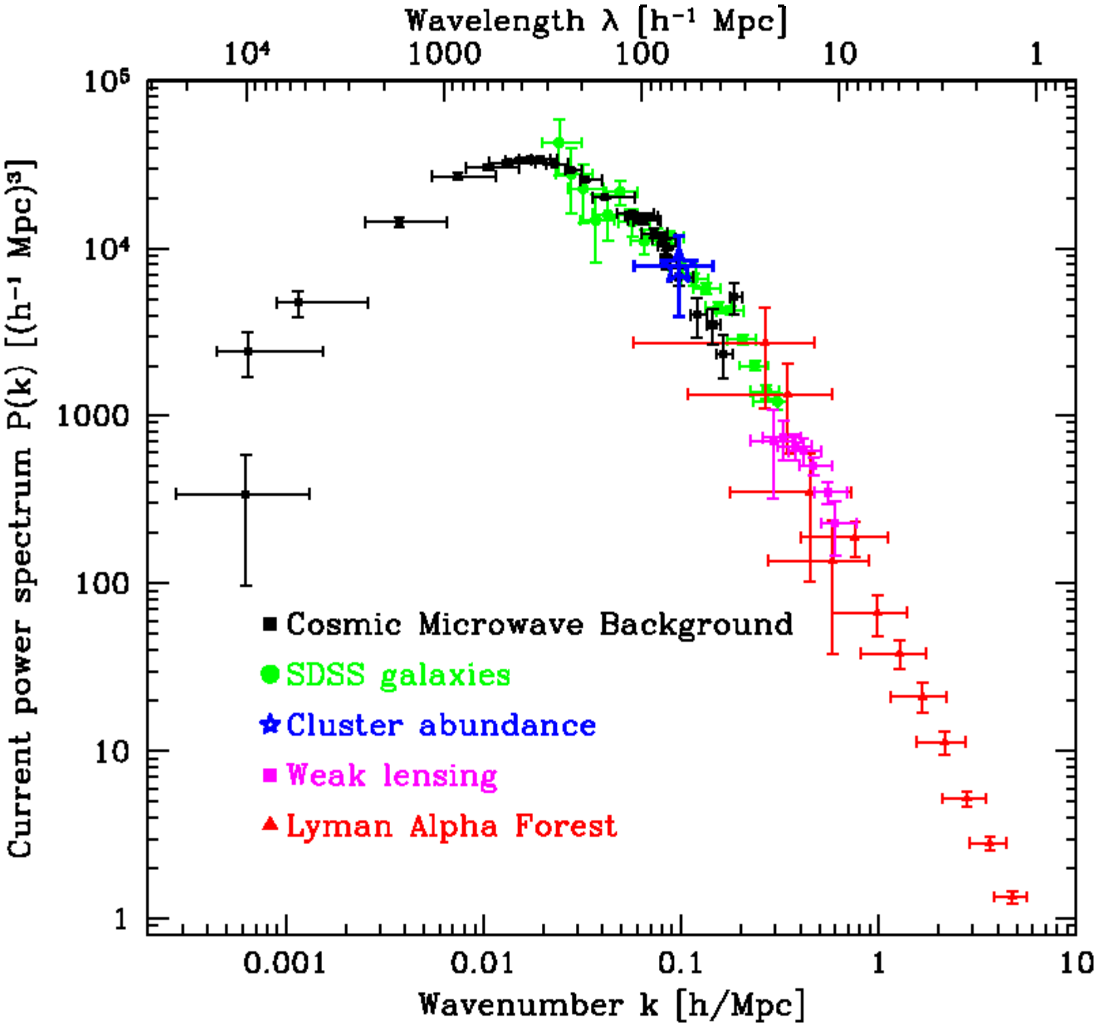
Quasar

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
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
■ 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:

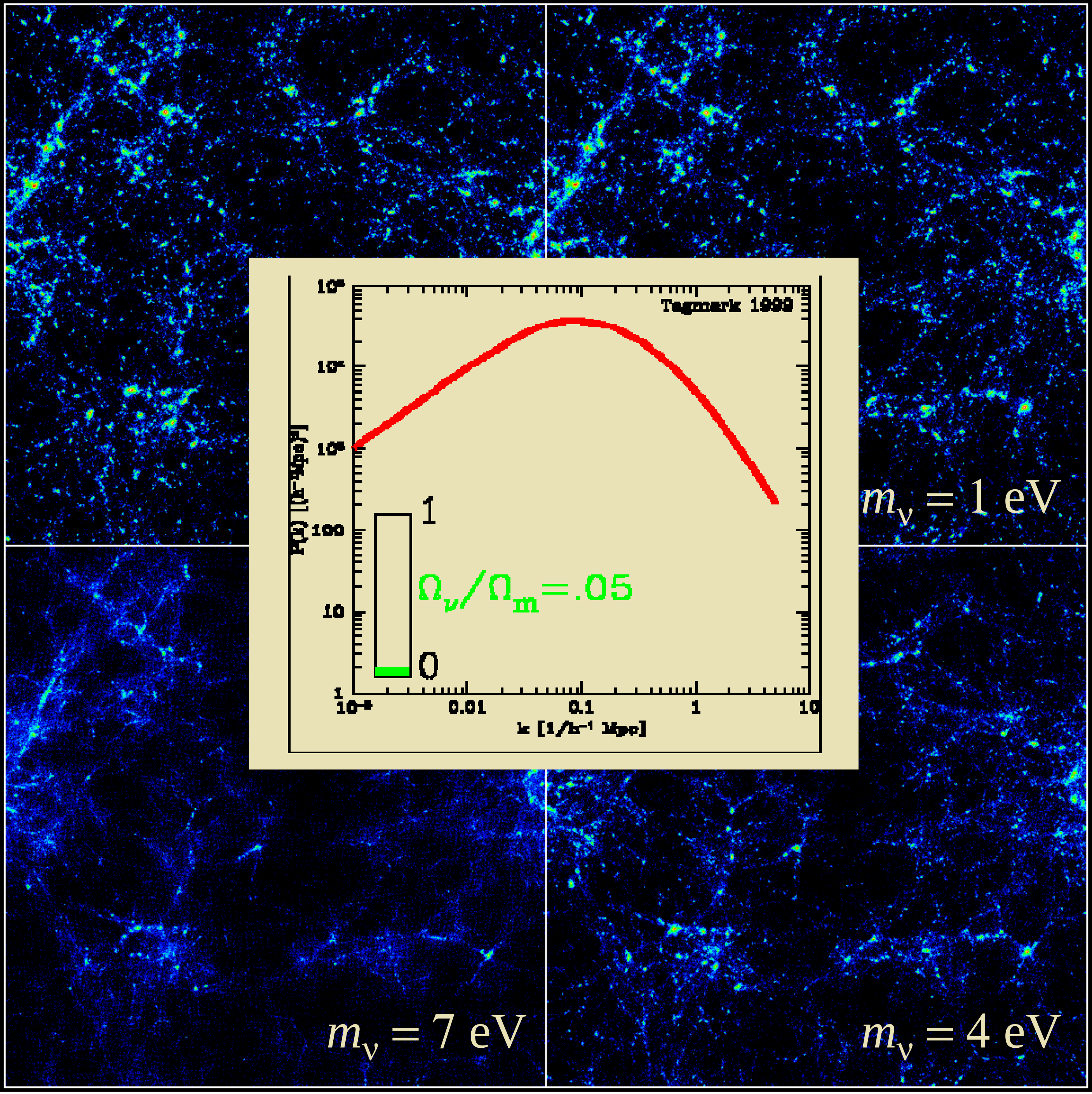
$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

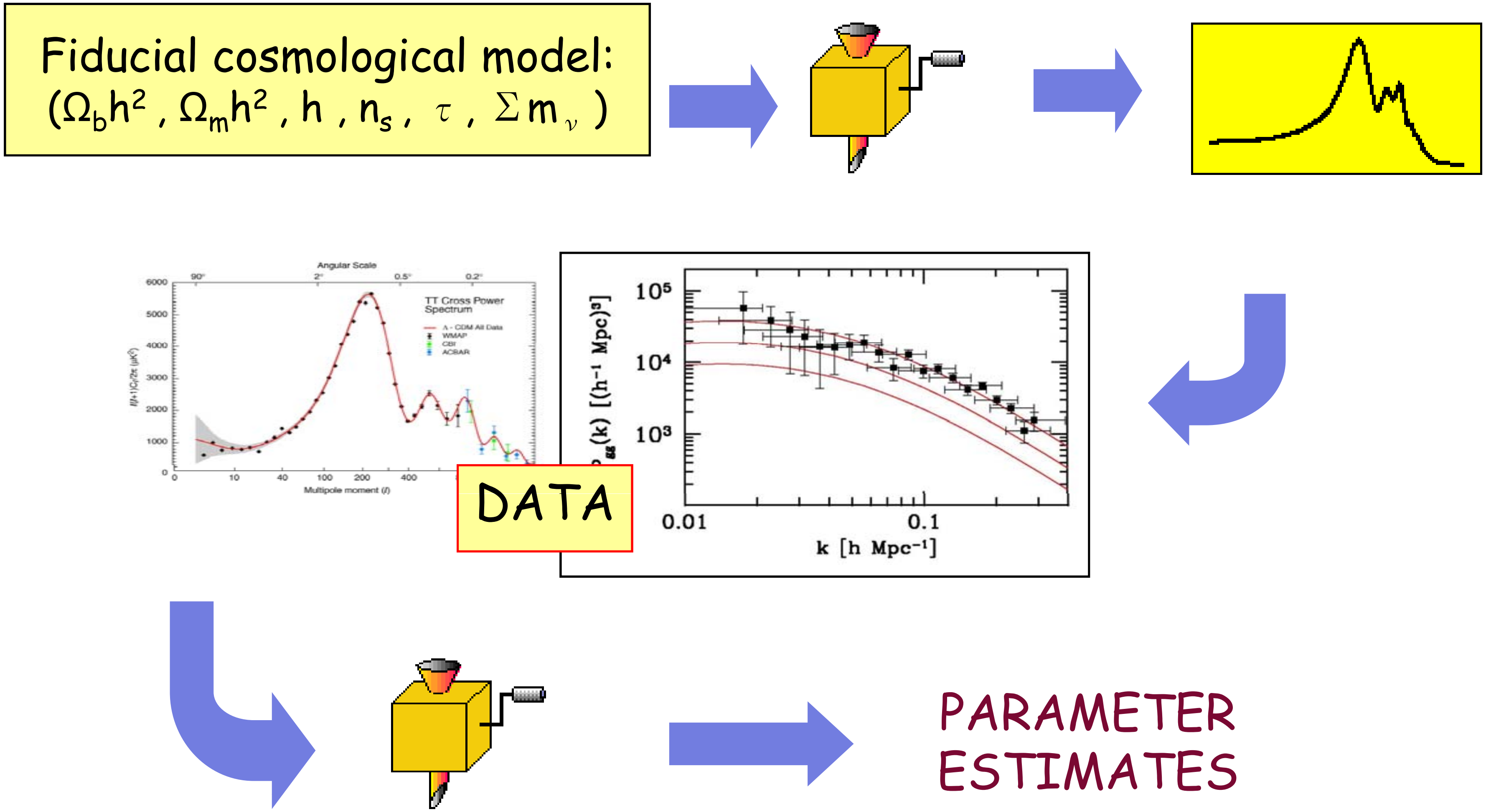
$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

That, for a massive neutrino translates in:

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


$m_\nu = 1$ eV
$m_\nu = 7$ eV
$m_\nu = 4$ eV
Tegmark 1999
$P(k)$ [$(h^{-1}$ Mpc$)^3$]
10^5
10^4
1000
100
10
1
10^{-3}
0.01
0.1
1
10
k [$1/h^{-1}$ Mpc]
1
0
Ω_ν/Ω_m=.05

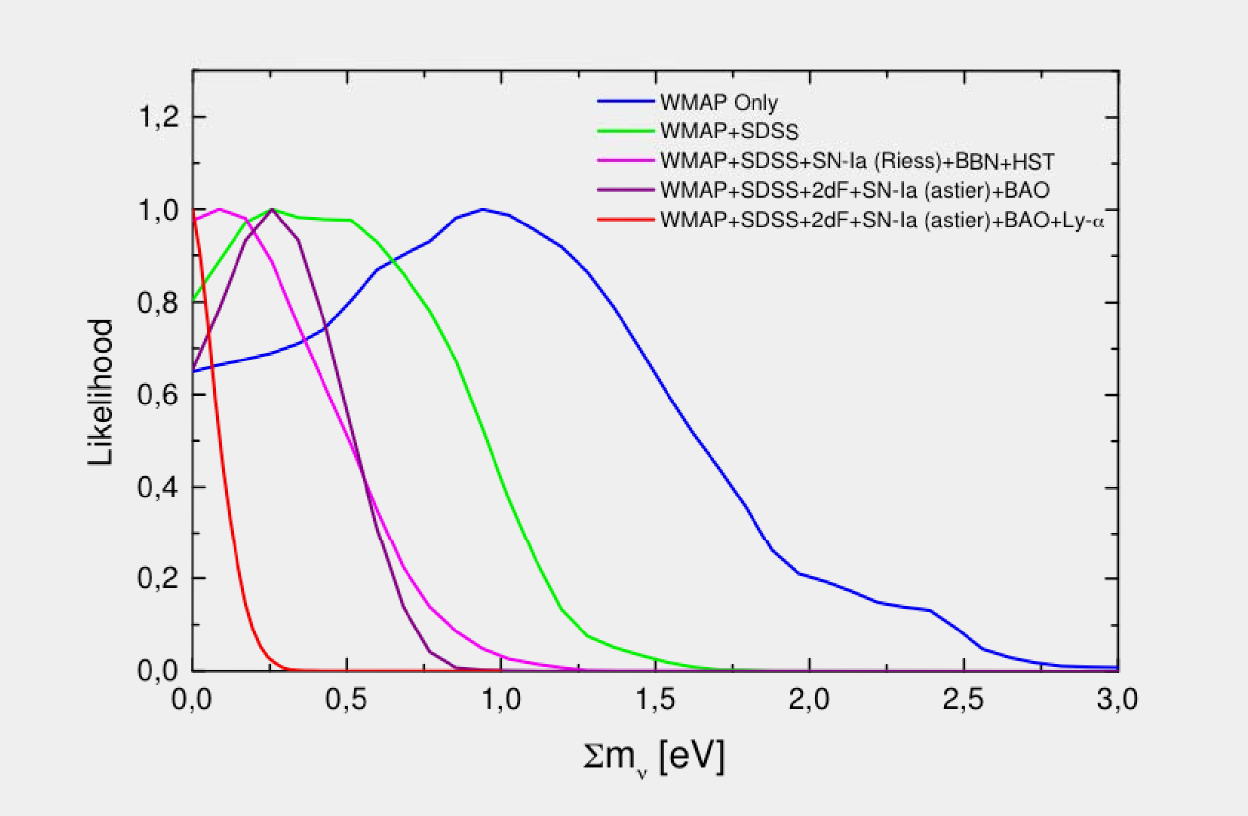
How to get a bound (measurement) of neutrino masses from Cosmology



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

DATA

PARAMETER
ESTIMATES



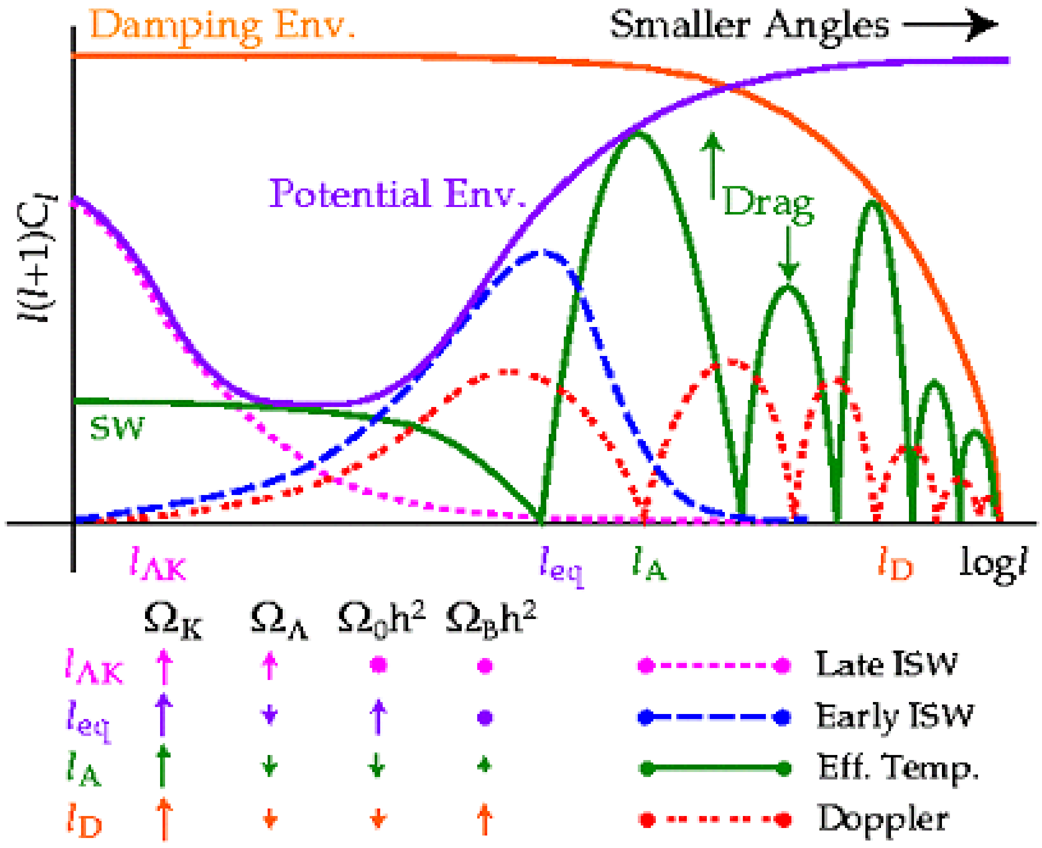
Bounds on Σ for increasingly rich data sets (assuming 3 Active Neutrino model):

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

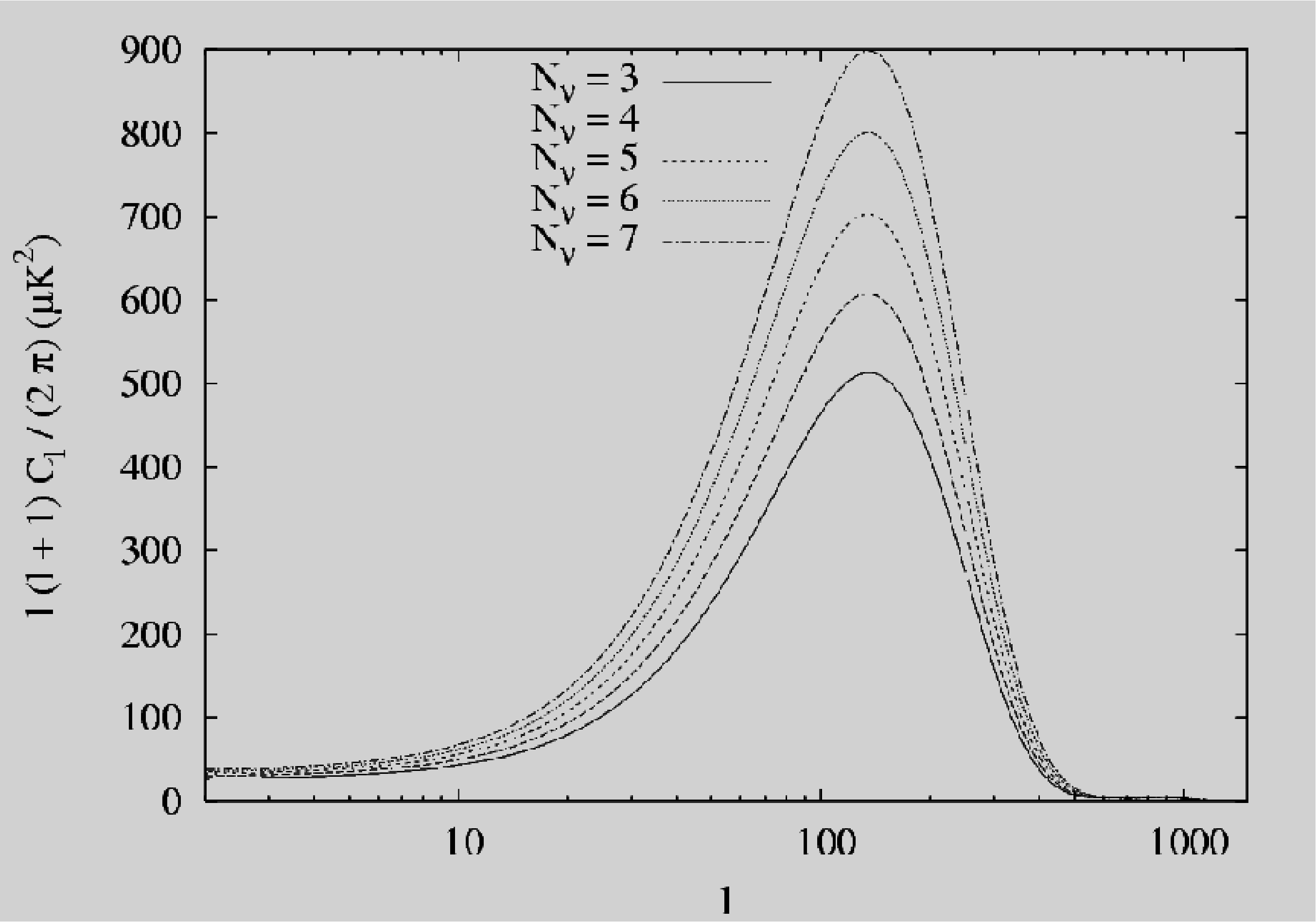
$$\nabla^2 \Phi = 4\pi G a^2 \overline{\rho} \, \delta$$

Poisson's equation

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

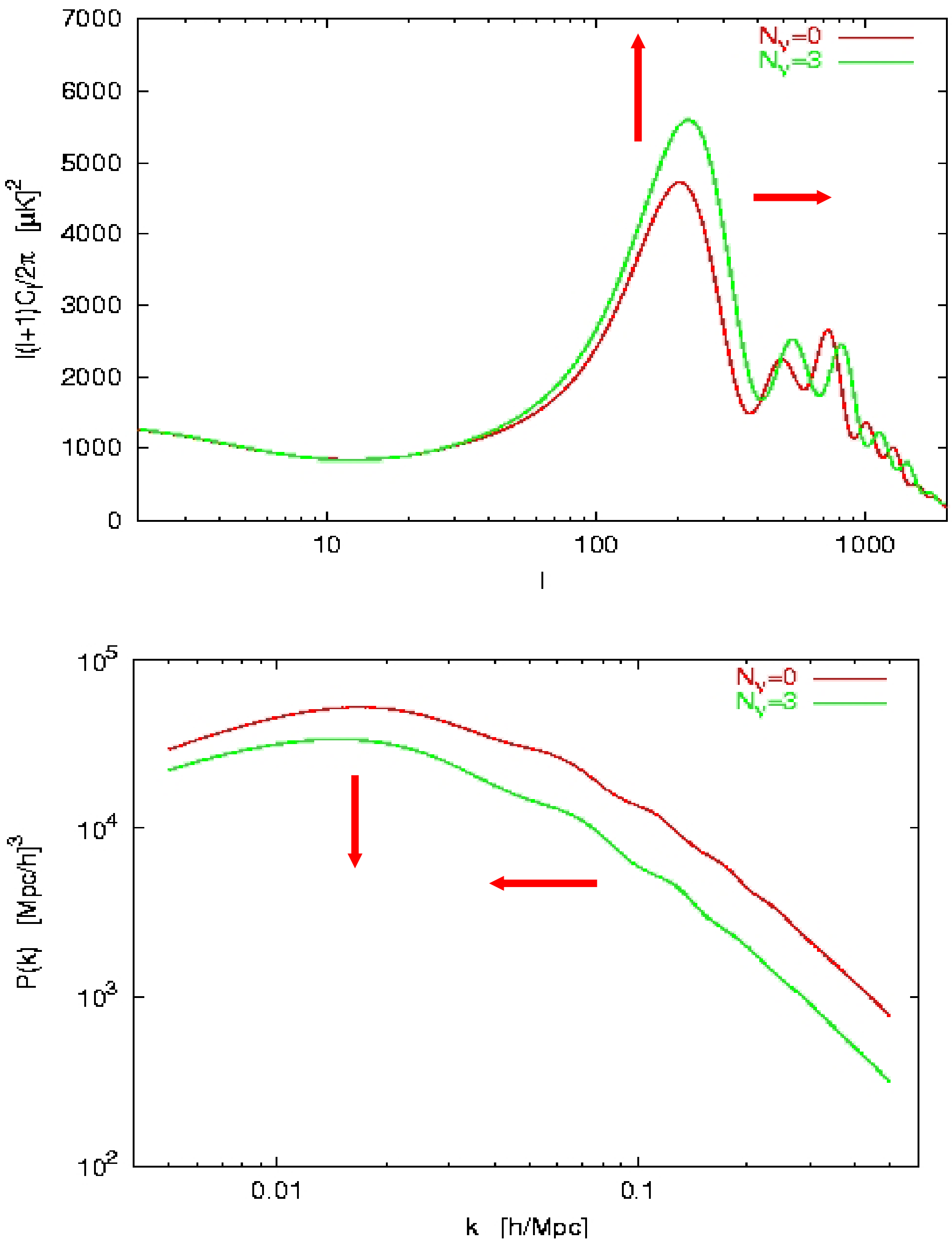
Effect of Neutrinos in the CMB: ISW

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

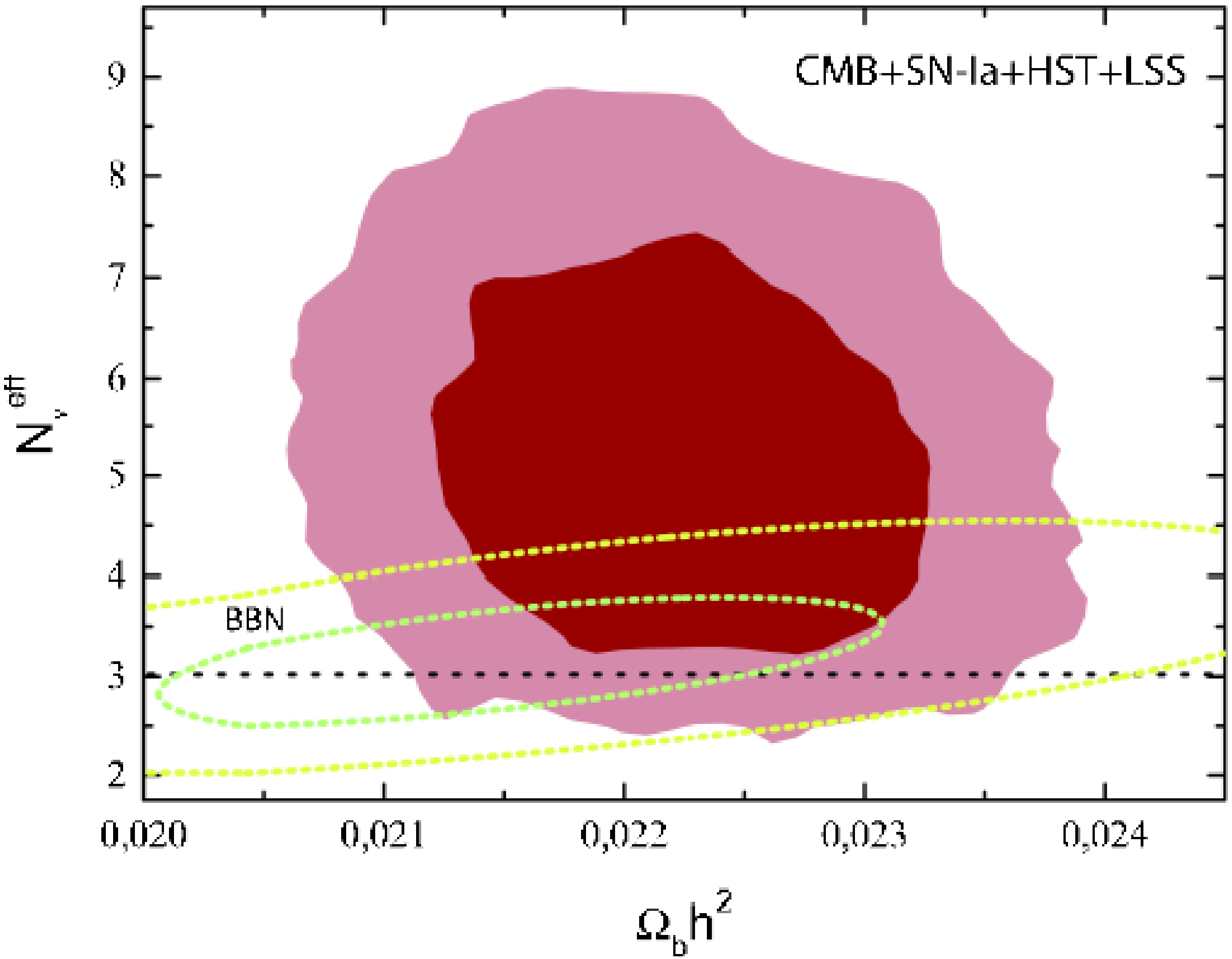


Increasing the Neutrino Massless number postpone the equivalence (while keeping constant the time of decoupling).

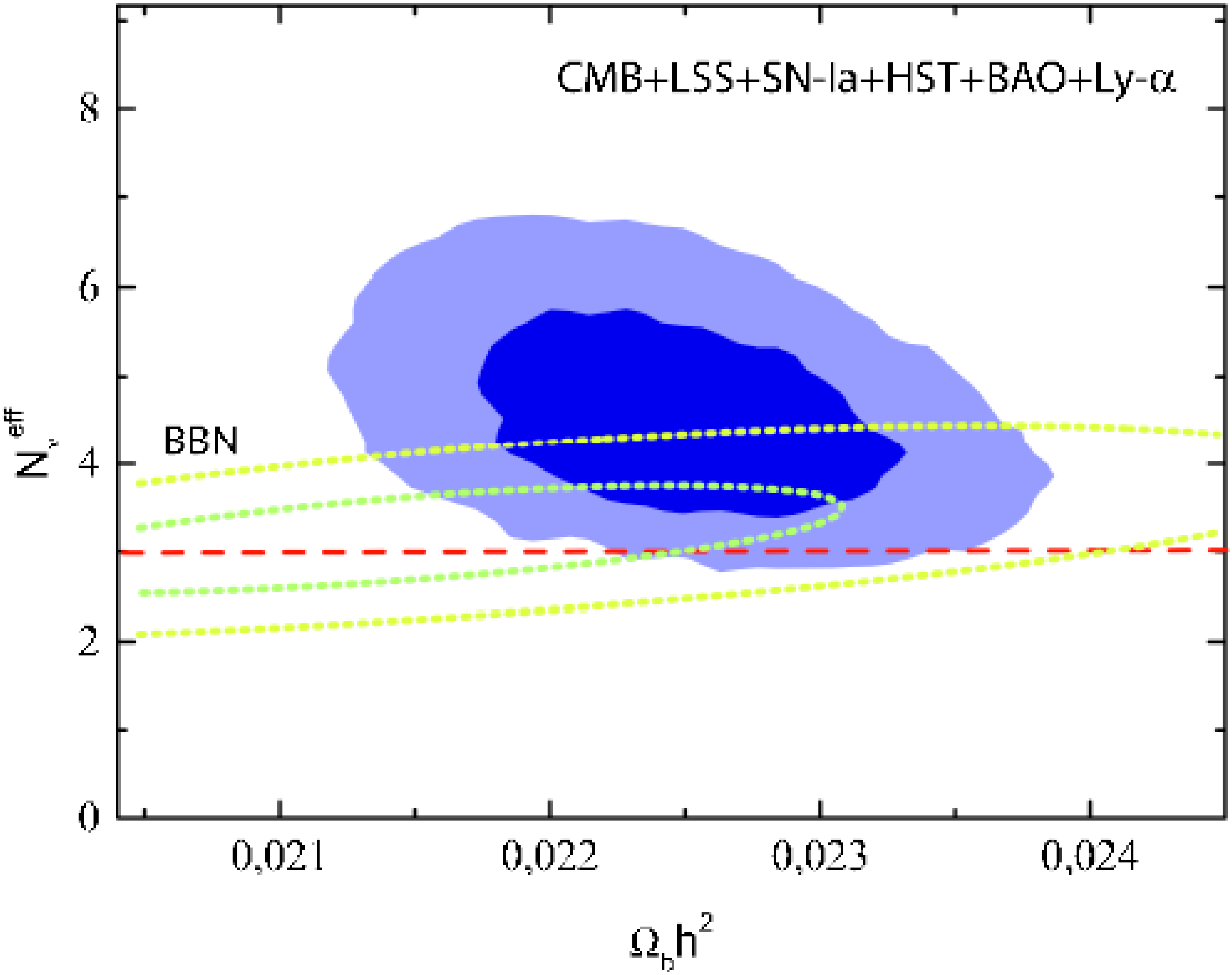
This produces a shift in the CMB power spectra since changes the sound horizon at decoupling. The height of the first peak is also increased thanks to the Early Integrated Sachs-Wolfe. The LSS matter power spectrum is also shifted since the size of the horizon at equivalence is now larger. There is less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



Latest Analysis: Indication for N>3 from Cosmology ?

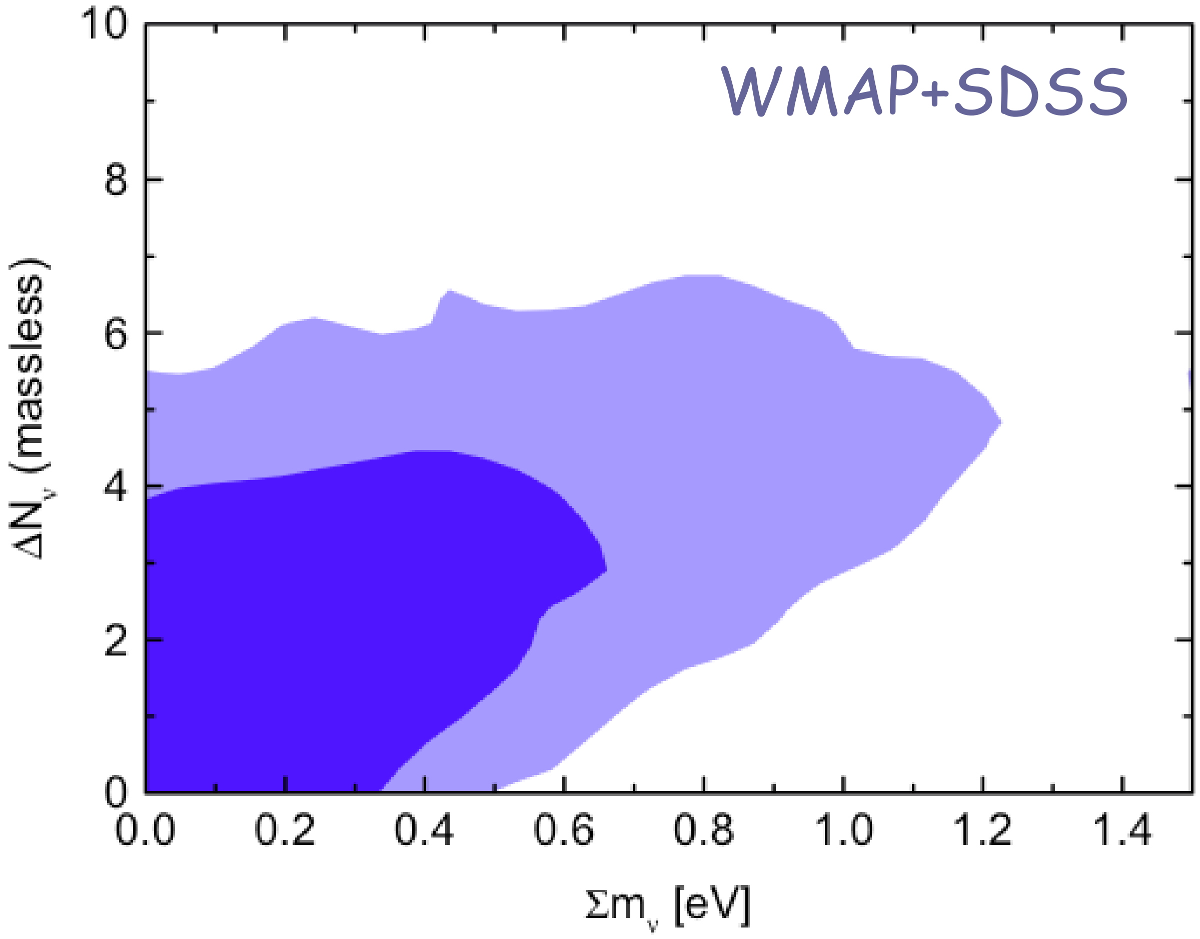


Mangano, Melchiorri, Mena, Miele, Slosar JCAP03(2007)006



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-α

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

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

$m_s < 0.23$ 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:

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

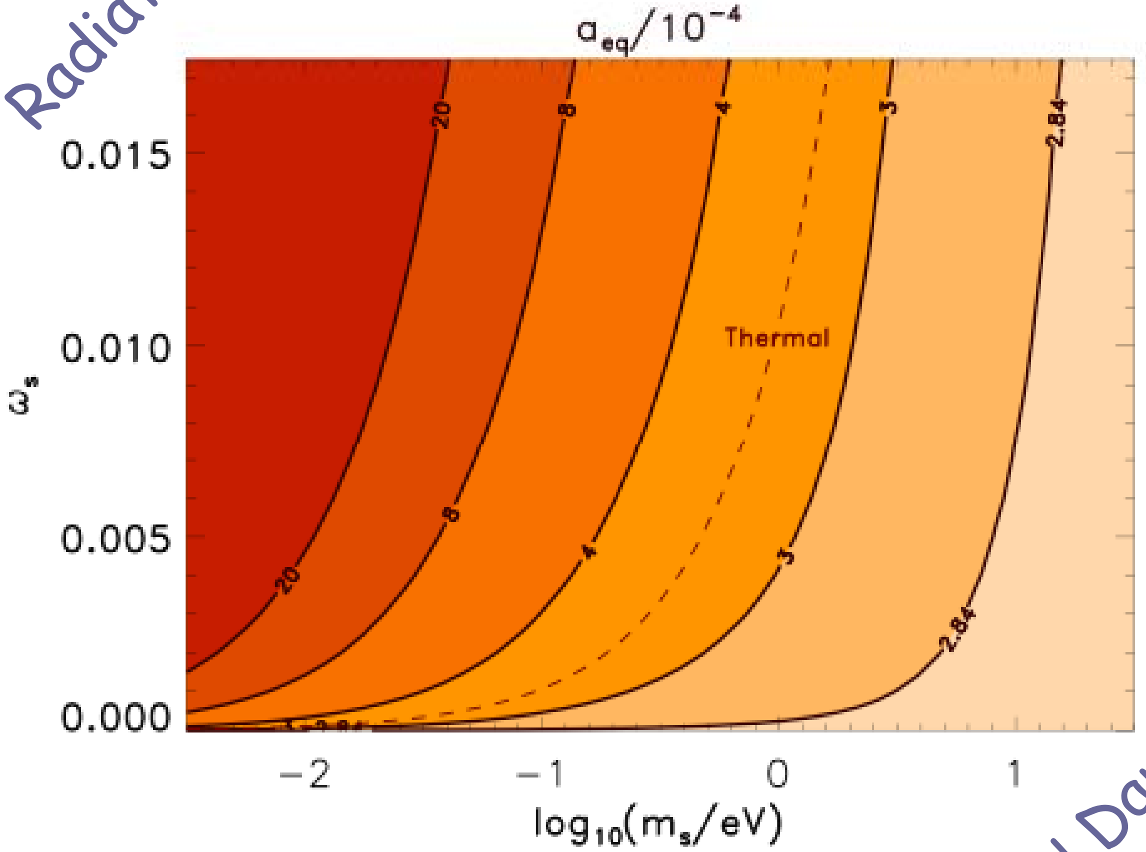
In the simplest models with one sterile neutrino this Condition is satisfied bu there are many ways of evading thermalization (see e.g. Abazajian, 2003).
In practice:

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

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

Effects on the scale of equality:

Radiation



Cold Dark Matter

Dodelson, Melchiorri, Slosar, PRL 2006

Constraints on non-thermalized sterile neutrino

Thermal

Energy density
Can be higher
For smaller masse

You may have larg
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_ν 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 $\Sigma<0.17$ eV. Tension with the $0\nu\beta\beta$ results.Fourth sterile massive neutrino if thermal is constrained to be $m_s<0.25$eV. Cosmology not compatible with LSND and $0\nu\beta\beta$(Klapdor). Compatible with latest MINIBOONE :-)

- Cosmological constraints model dependent (but that is 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."