New Constraints on Neutrino Physics from Cosmology

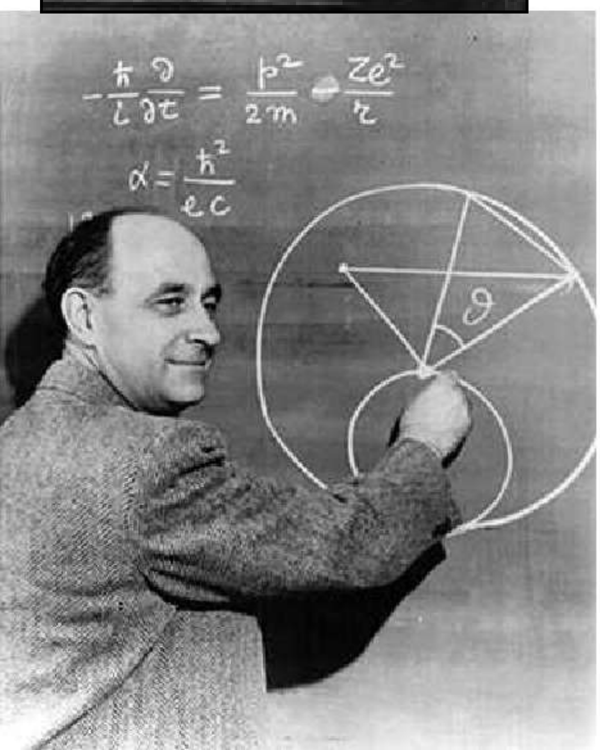
Paris, 10 December, 2004

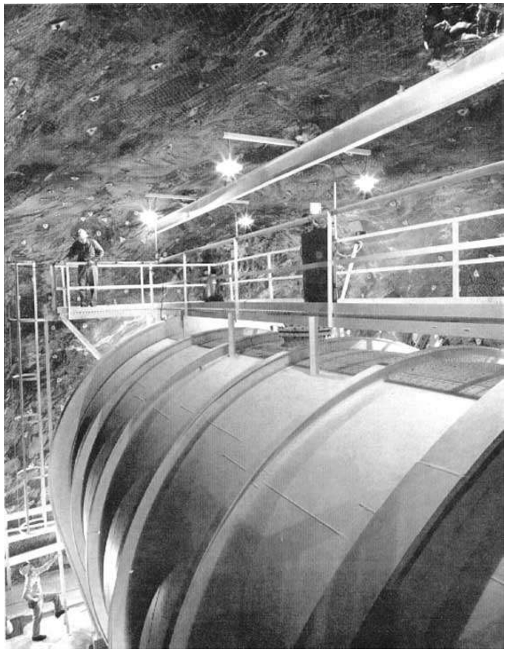
Alessandro Melchiorri

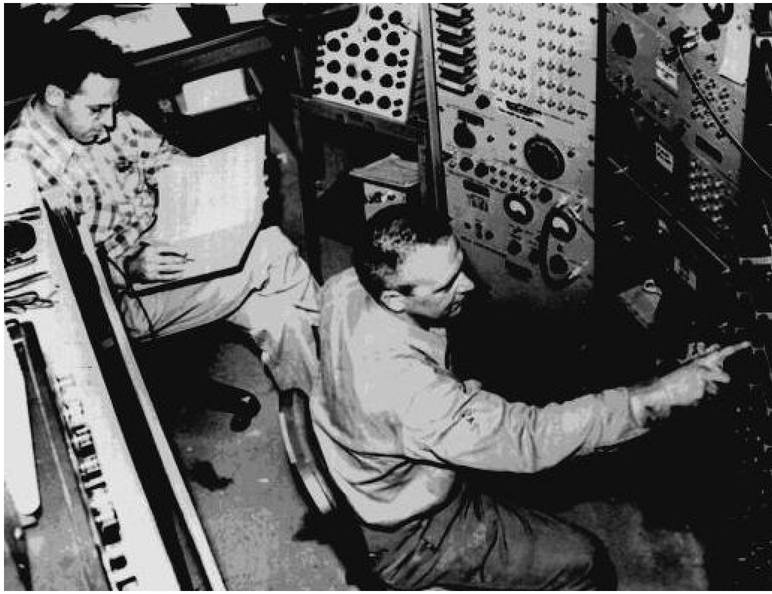
Universita' di Roma, "La Sapienza"

INFN, Roma-1

A brief history of neutrino mistery

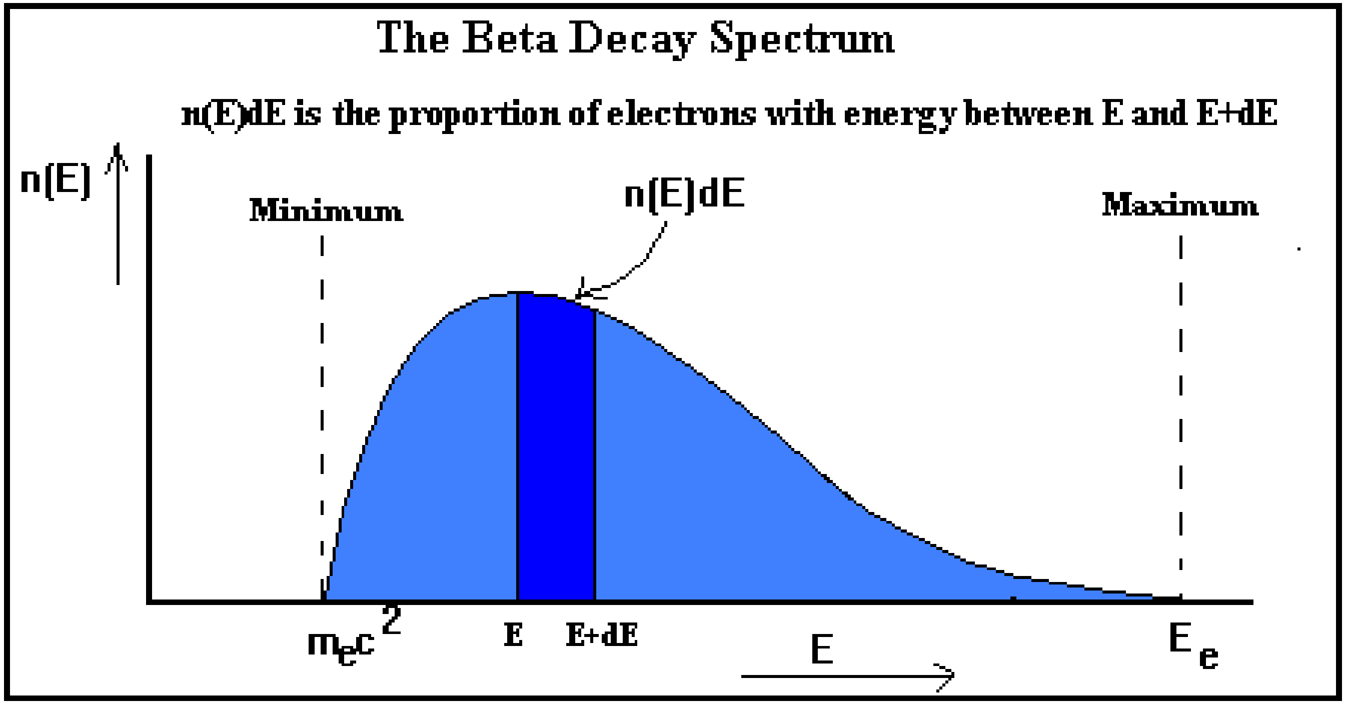






The Beta Decay

Heavy atom decays to lighter atom, emitting electron.



Why is the spectrum continuous? Why is electron energy not equal to difference between two atomic energies?

A brief history of the Neutrino mistery

1930. Wolfgang Pauli proposed a "desperate remedy" to save the law of energy conservation in nuclear beta decay by introducing a new neutral particle with spin ½ dubbed the "neutron".

1932. James Chadwick discovered what we now call the neutron, but it was clear that this particle was too heavy to be the "neutron".

1933. Enrico Fermi formulated the first theory of nuclear beta decay and invented a new name: the neutrino (a little neutral one in italian).

1956. Clyde Cowan and Fred Reines first detected antineutrinos emitted from a nuclear reactor at Savannah River in South Carolina.

1957. Goldhaber, Grodzins and Sunyar measured the "handedness" of neutrinos in a ingenious experiment at the Brookhaven National Lab. Neutrino are always left-handed and therefore particle physicist concluded that they had to be massless.

There are 3 types of massless neutrinos (1958)

- Corresponding to 3 families of electrons
- Electron, muon, and tau neutrinos
- They are massless because we see only left-handed neutrinos.
- If not they are not necessarily mass eigenstates: one species can "oscillate" into another

$$\langle \nu_\mu | e^{iHt} | \nu_e \rangle \neq 0$$

Only if masses are non-zero

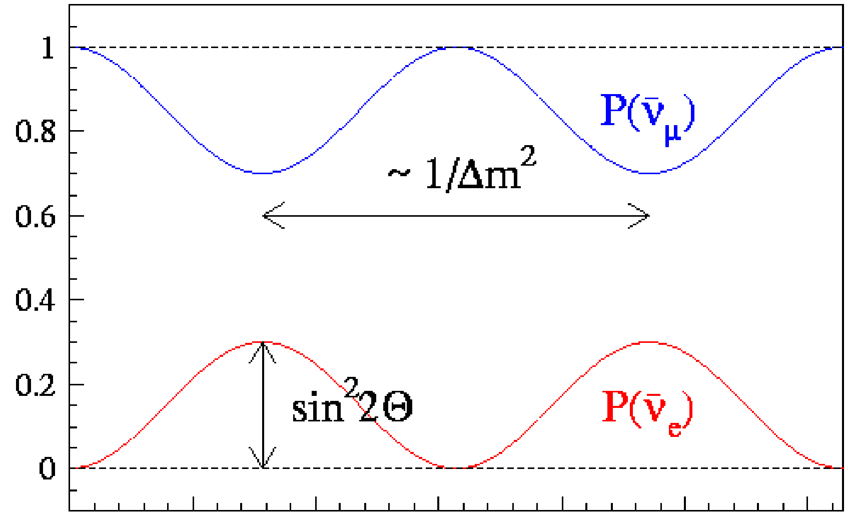
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\Theta)\sin^2(1.27 \text{ x } \Delta m^2 \text{ x } L/E_\nu)$$

$\Delta m^2 = |m_1^2 - m_2^2|$ [eV^2]

L = Distance to Source [m]

E_ν = Neutrino Energy [MeV]



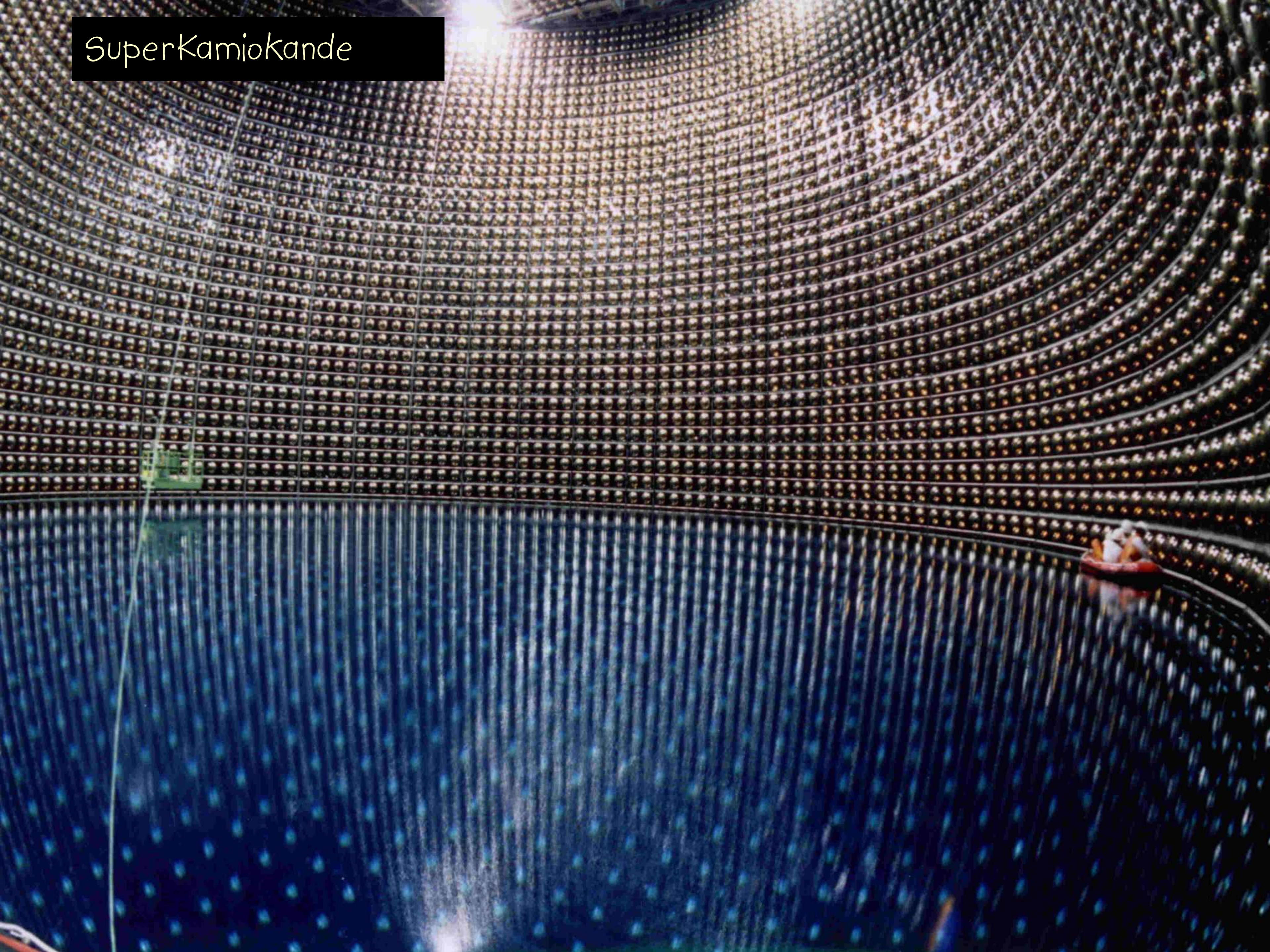
A brief history of the Neutrino mistery part deux

1968. Ray Davis and colleagues get first radiochemical solar neutrino results using cleaning fluid in the Homestake Mine in North Dakota, leading to the observed deficit known as the "solar neutrino problem".

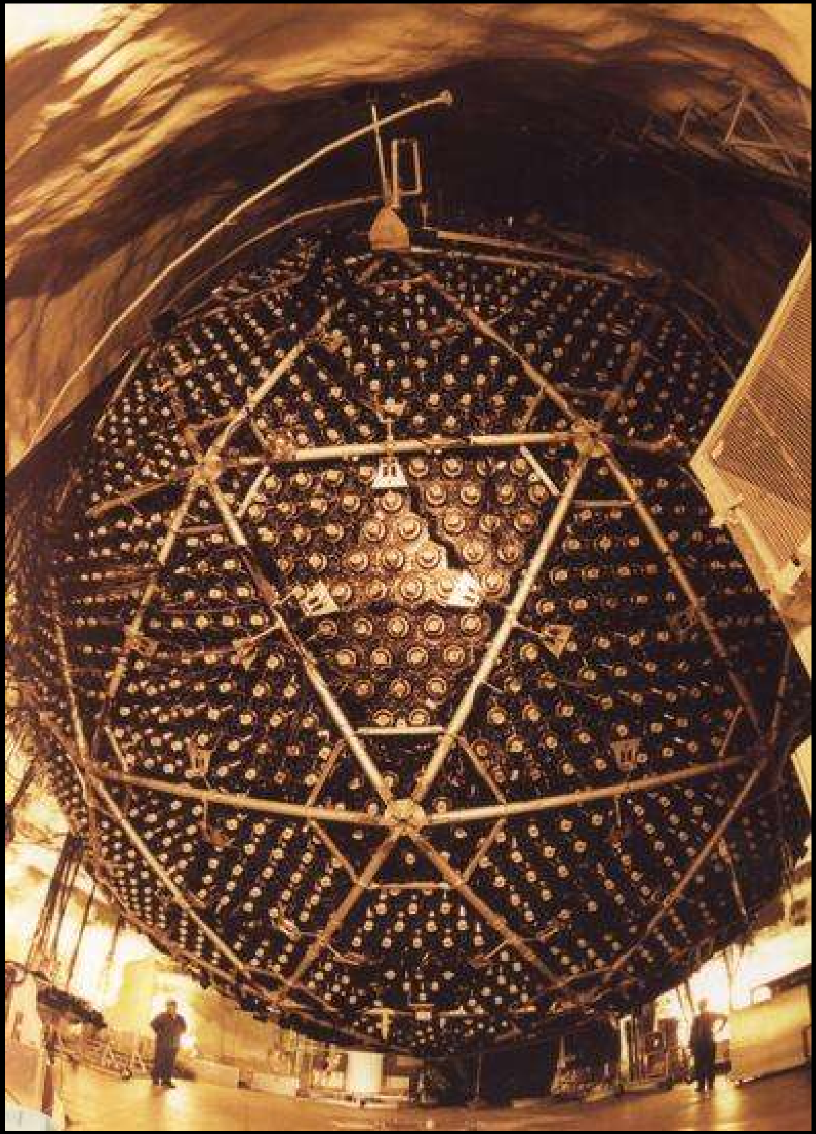
1985. The "atmospheric neutrino anomaly" is observed at IMB and Kamiokande.

1998. The Super-Kamiokande experiment reports finding oscillations and, thus, mass muon neutrinos.

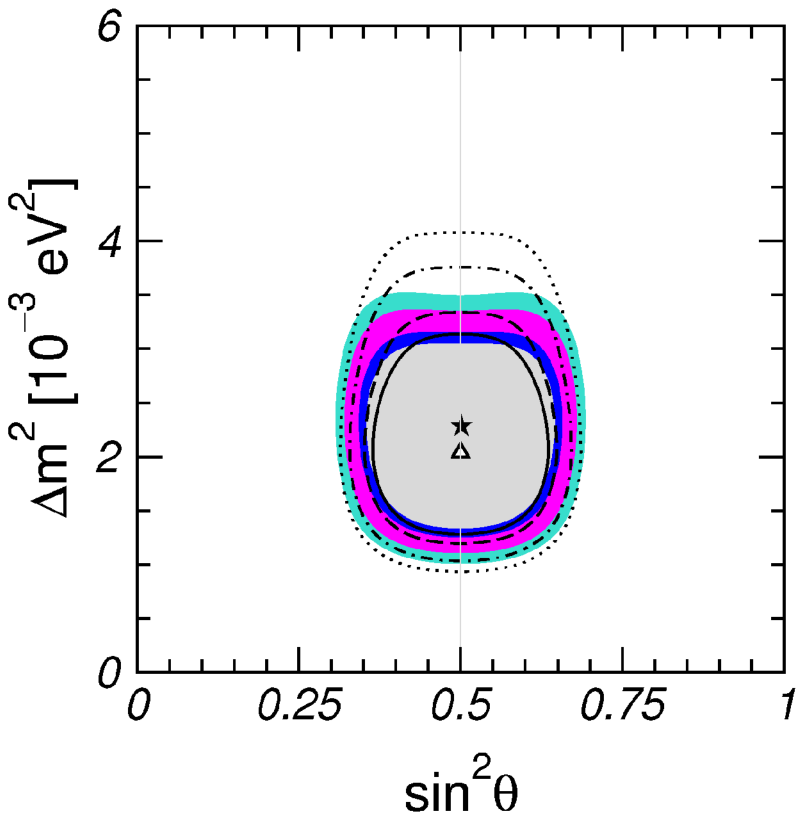
2001. SNO announces observations of neutral currents from solar neutrinos providing convincing evidence that neutrino oscillations are the cause of the solar neutrino problem. By combining with SuperKamiokande the SNO collaboration determined how many muon neutrinos or tau neutrinos were incident at the Japanese detector.


SuperKamioKande

SNO

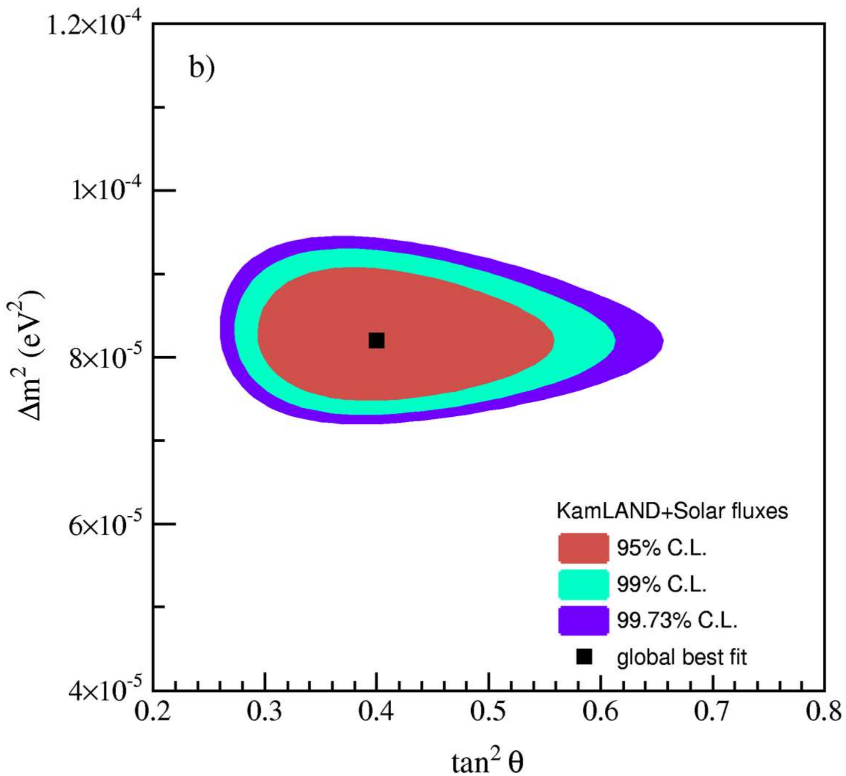


STATUS OF 2-3 MIXING
(ATMOSPHERIC + K2K)



Maltoni et al. hep-ph/0405172

STATUS OF 1-2 MIXING
(SOLAR + KAMLAND)



Araki et al. hep-ex/0406035

__The__ Neutrino mistery

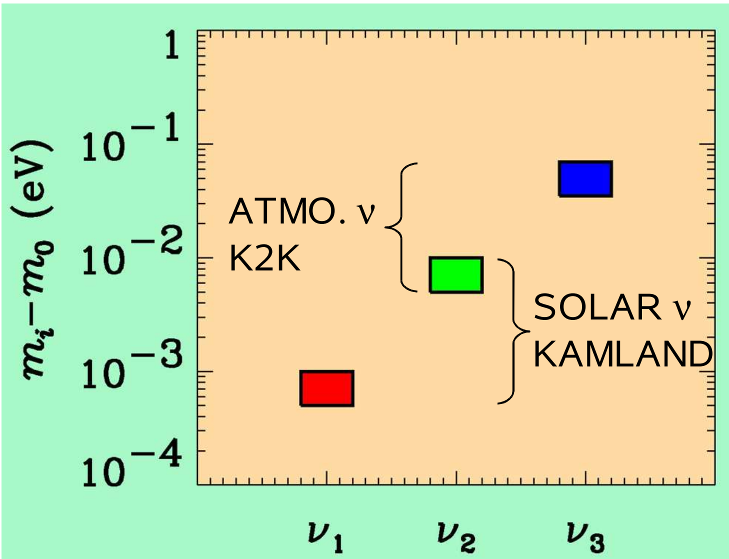
If neutrinos have mass, we have to solve 2 problems:

1- We have to overcome the contradiction between left-handedness and mass.
2- Why the neutrino mass is so small compared with other mass particles (electrons are at least 500000 times more massive than neutrinos) ?

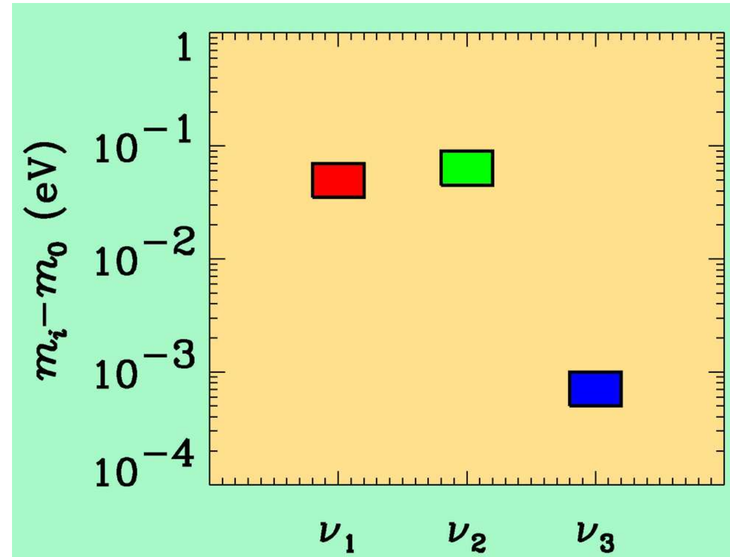
Dirac neutrinos: the reason why the right-handed neutrinos have escaped detection so far is that their interaction are at least 26 orders of magnitude weaker than ordinary neutrinos. Neutrino masses are generated via the Higgs mechanism. Neutrino interactions with the Higgs boson at least 12 orders of magnitude weaker than that of the top quark !

Majorana neutrinos:We give up with fundamental distinction between matter and antimatter. Neutrinos and antineutrinos are the same particle. Left-handed collides with Higgs boson, acquires a mass, and then it transforms to an heavier right-handed for short time given by Heisenberg uncertainty (seesaw mechanism).

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy



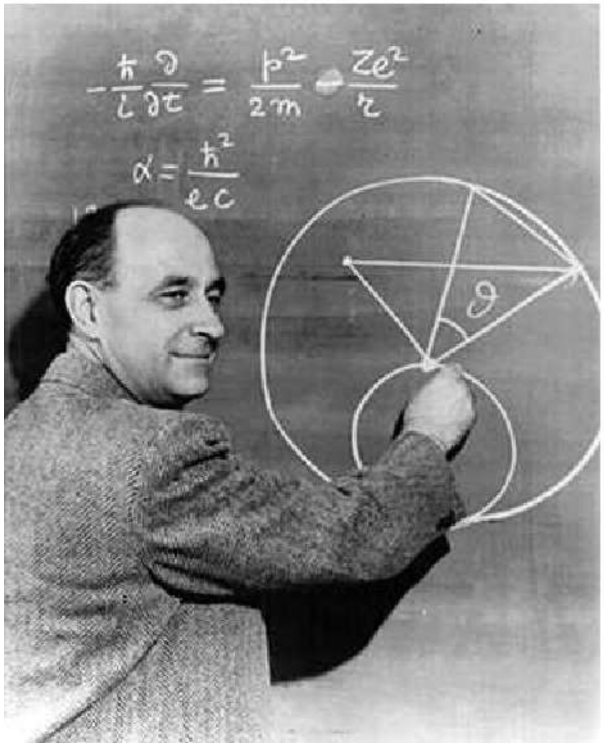
Inverted hierarchy

$$m_3 > m_2 > m_1$$

$$m_2 > m_1 > m_3$$

Moreover neutrino masses can also be degenerate

[redacted]




USA Enrico
33 Fermi

Laboratory bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale :

Tritium beta decay:

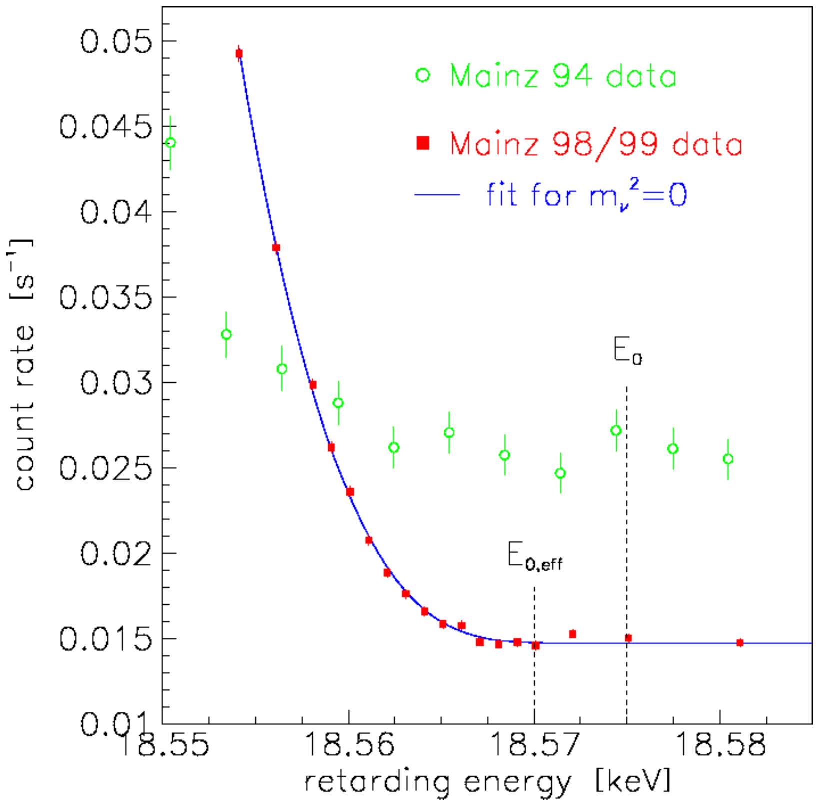
$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2}$$

$$m_\beta^2 = -1.2 \pm 3.0 \quad eV^2 \text{ (Mainz)}$$

$$m_\beta^2 = -2.3 \pm 3.2 \quad eV^2 \text{ (Troitsk)}$$

$$\boxed{m_\beta < 1.8 \quad eV \qquad (2\sigma)}$$

Best fit gives a negative mass !!!



Bounds on neutrino mass

Experiments sensitive to *absolute neutrino mass scale* :

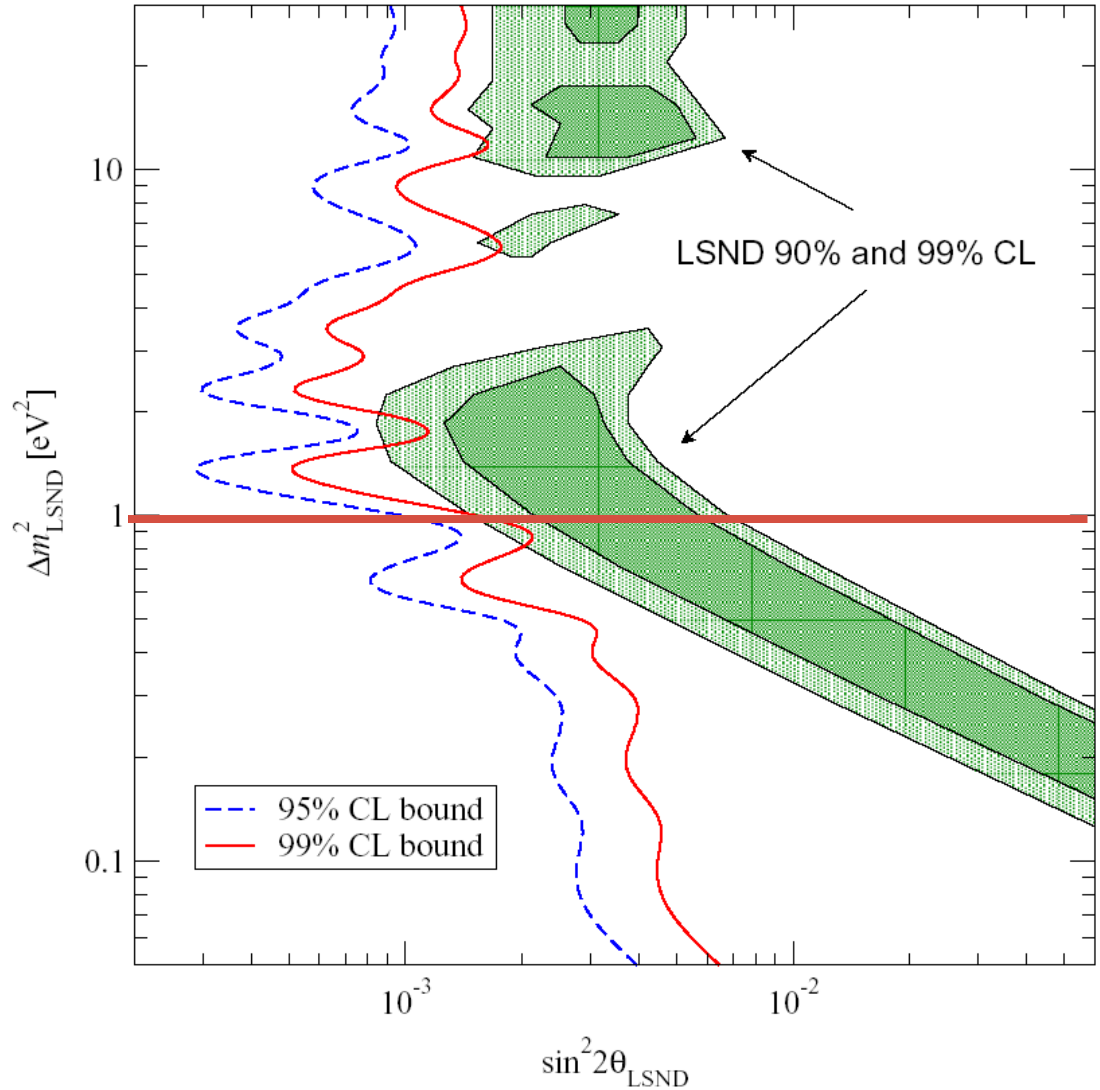
Neutrinoless double beta decay (only if neutrino are majorana particles!):

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

Neutrinoless doule beta decay processes have been searched in many experiments with different isotopes, yielding negative results.
Recently, members of the Heidelberg-Moscow experiment have claimed the detection of a $0\nu 2\beta$ signal from the ^{76}Ge isotope.
If the claimed signal is entirely due to a light Majorana neutrino masses then we have the constraint:

$$0.17 \; eV < m_{\beta\beta} < 2.0 \; eV \quad (3\sigma)$$

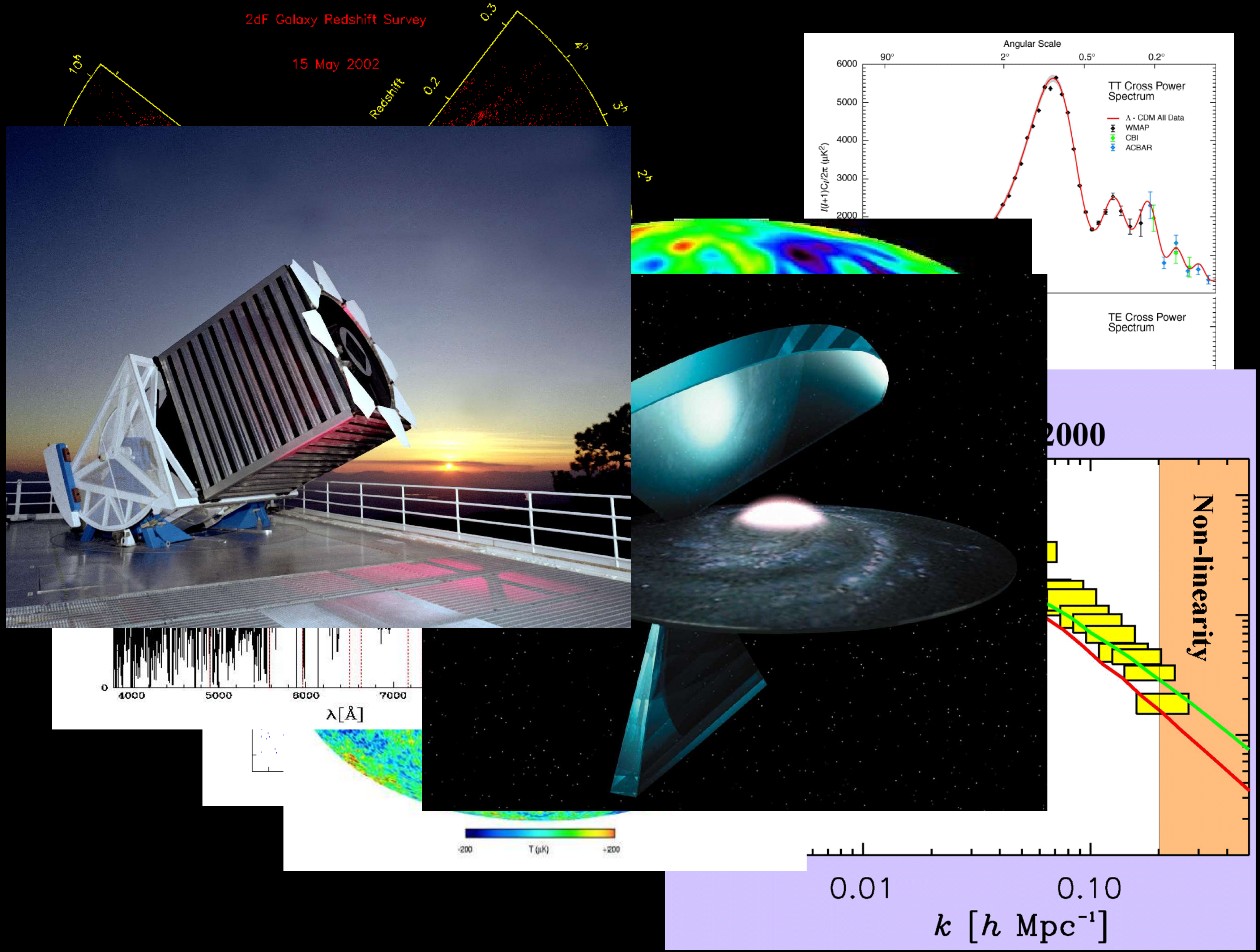
$$N_\nu = 4???$$



Moreover, controversial results from LSND seems to suggest a 4th sterile neutrino (not favoured by oscillation experiments.

NO ALLOWED REGIONS EXIST FOR LOW Δm^2.

(Pierce & Murayama, hep-ph/0302131; Giunti hep-ph/0302173)


2dF Galaxy Redshift Survey
15 May 2002
Redshift
Angular Scale
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
TE Cross Power Spectrum
2000
Non-linearity
λ[Å]
T (μK)
0.01
0.10
k [h Mpc^{-1}]

Successfull Cosmologists


9 pm
TV LAND
tvland.com
Olivier Dore's new car (Soon)
wmap2

Cosmological Neutrinos

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

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

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:

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

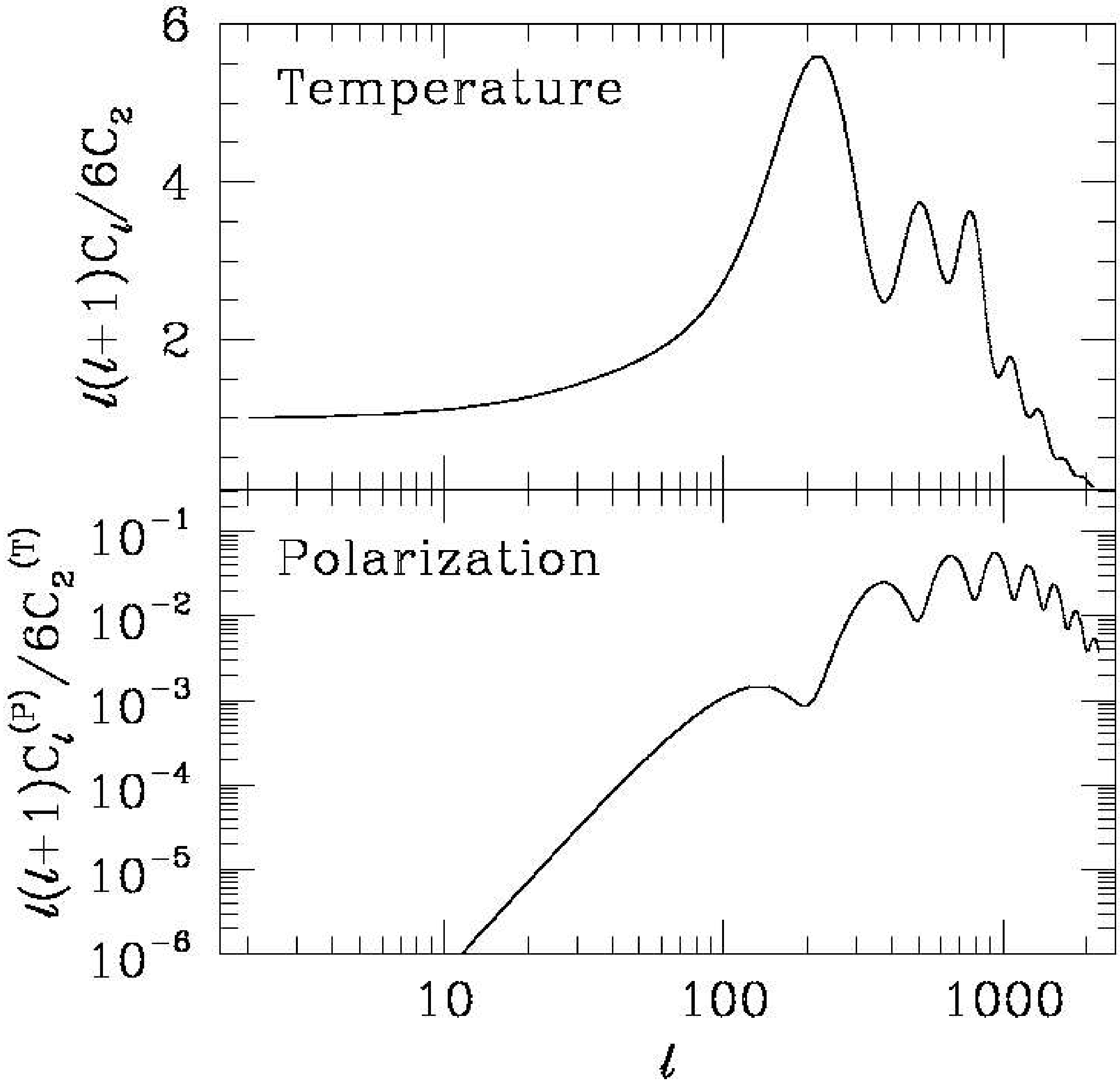
That, for a massive neutrino translates in:

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

Cosmological Neutrinos

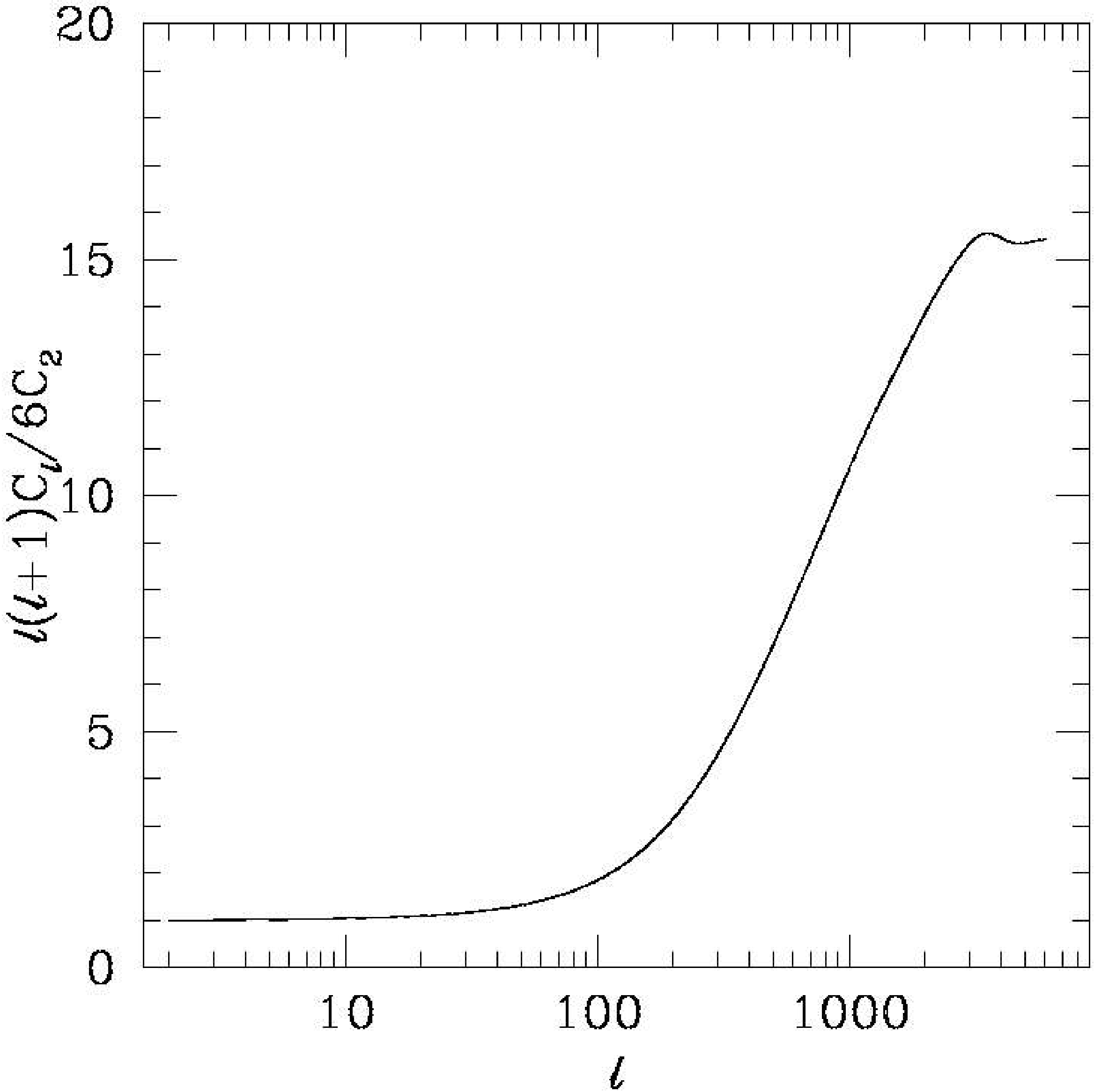
Unfortunately, despite their high density, we can't detect cosmological
neutrinos directly (see Hagmann astro-ph/9905258 for a discussion
about future im-possibilities).
However, neutrinos have great impact on

Cosmological Structure Formation.



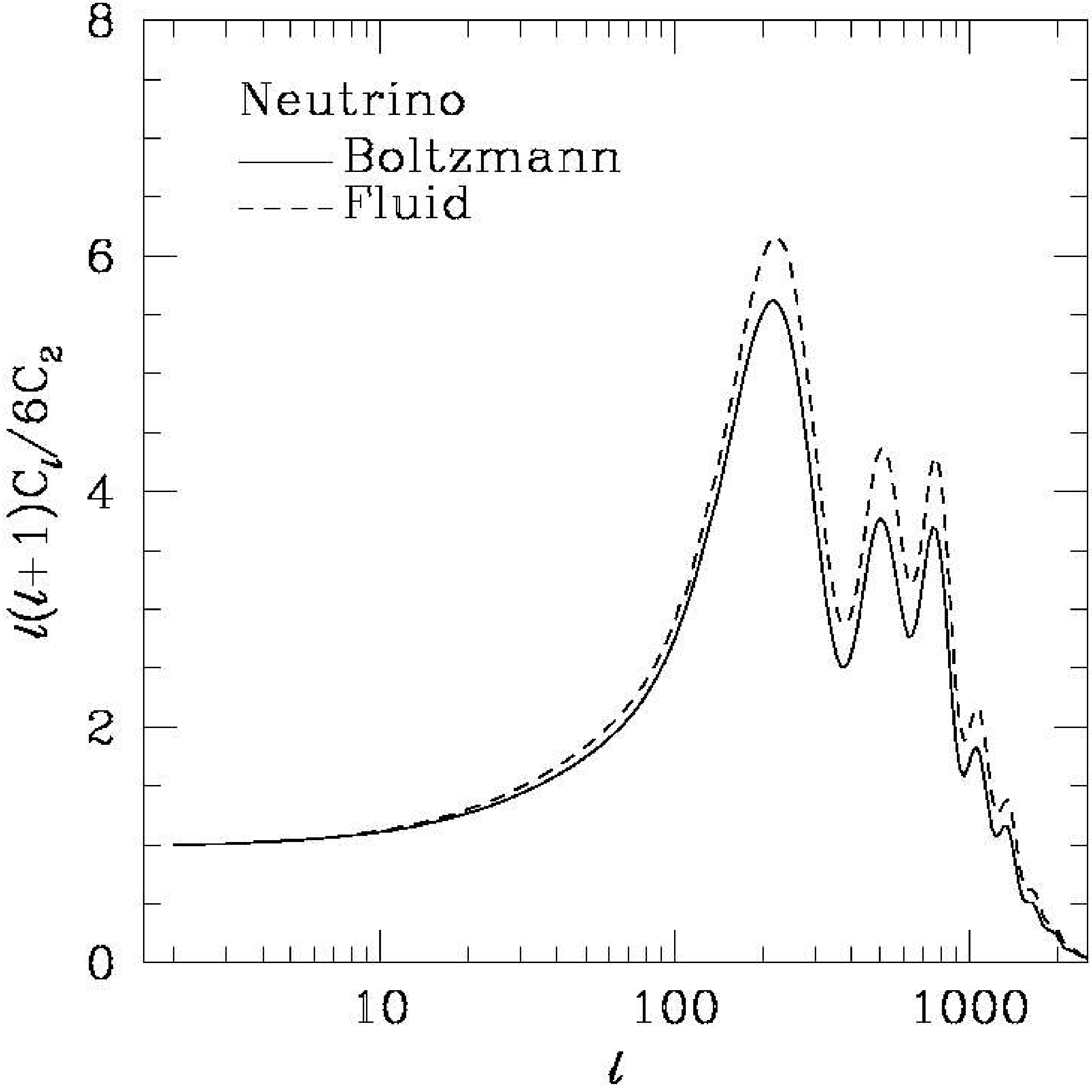
Temperature
Polarization
6
4
2
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
100
1000
l
$l(l+1)C_l/6C_2$
$l(l+1)C_l^{(P)}/6C_2^{(T)}$

Also the neutrino background has anisotropies.
Can we see them ?



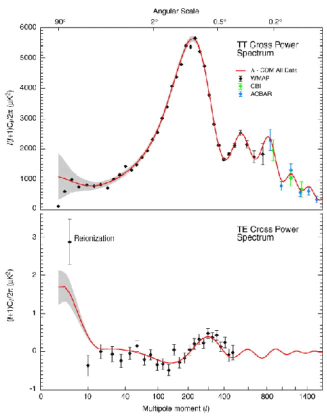
Hu et al., astro-ph/9505043

Not directly!
But we can see the effects on the CMB angular spectrum !
CMB photons see the NB anisotropies through gravity.

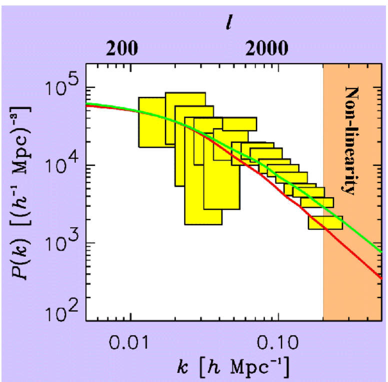


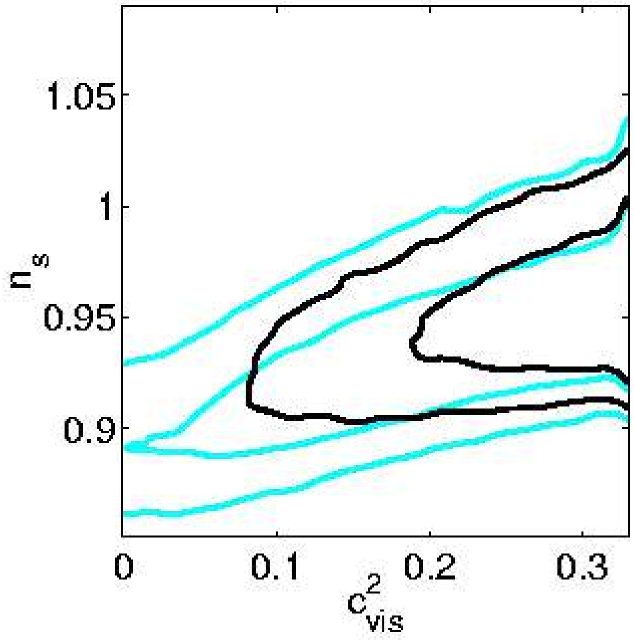
Current CMB+SLOAN
data provide evidence
at 2.4 σ for anisotropies
in the Neutrino
Background.
Standard Model o.k.

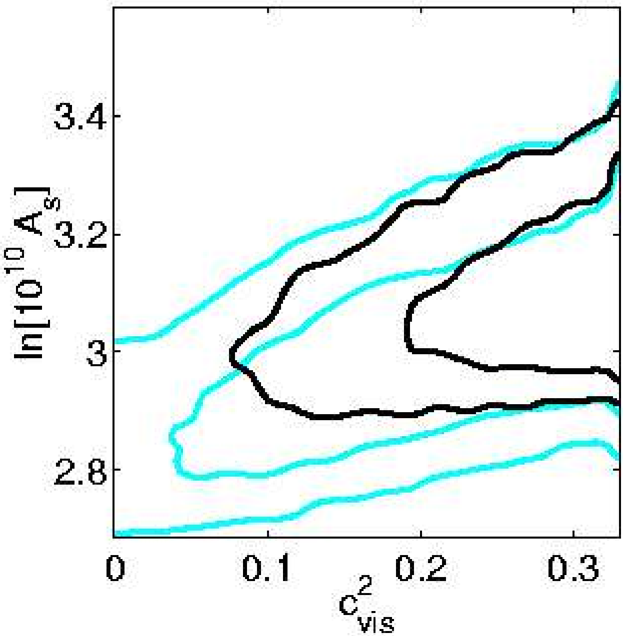
(see R. Trotta and AM
few days ago on the web!).



+







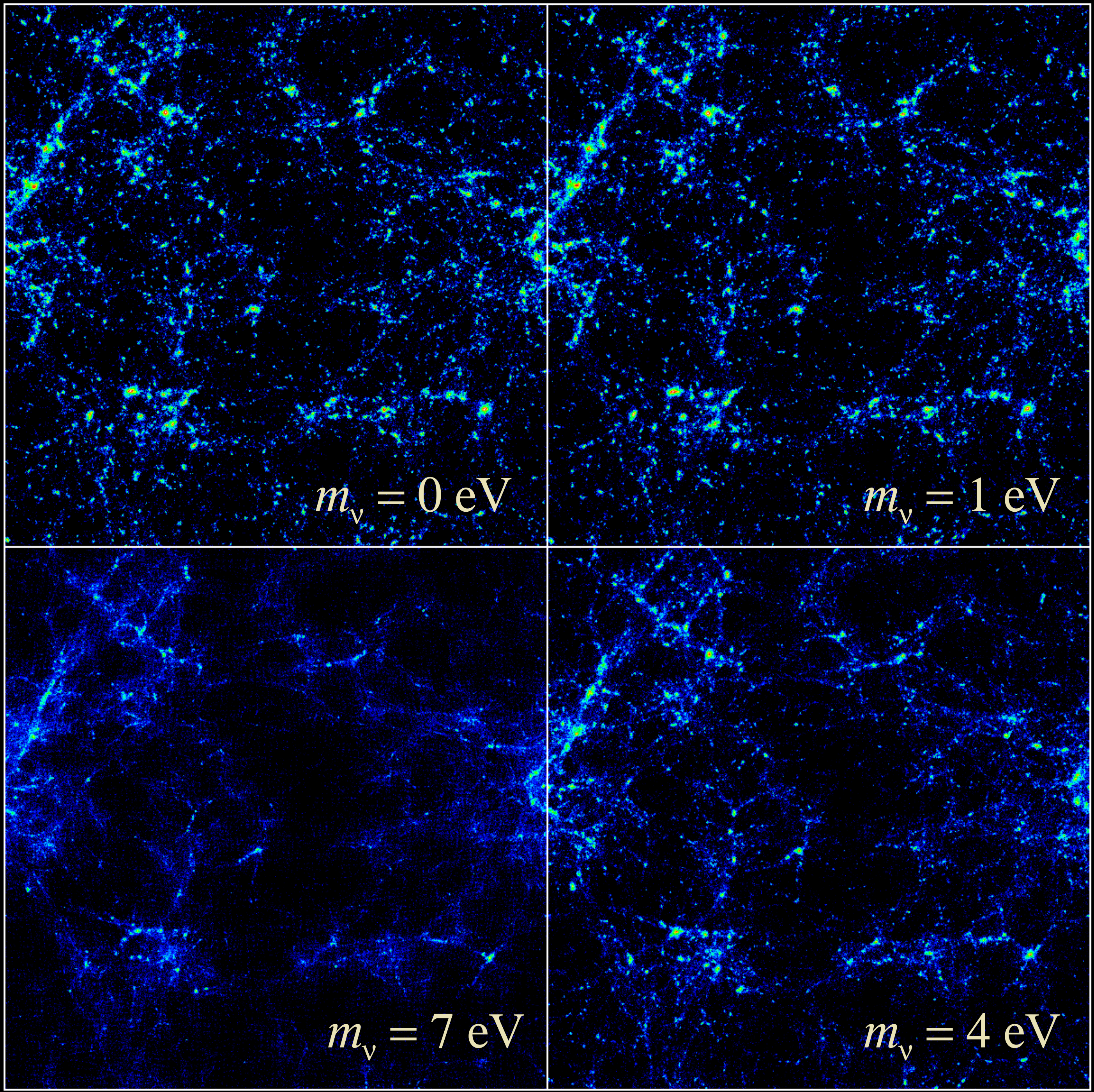
Massive Neutrinos affect large scale structure !

- We can relate the neutrino abundance in the universe to the total mass:

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{92.5 eV}$$

- Neutrinos stream out of overdense regions when KT ~ 1 eV.

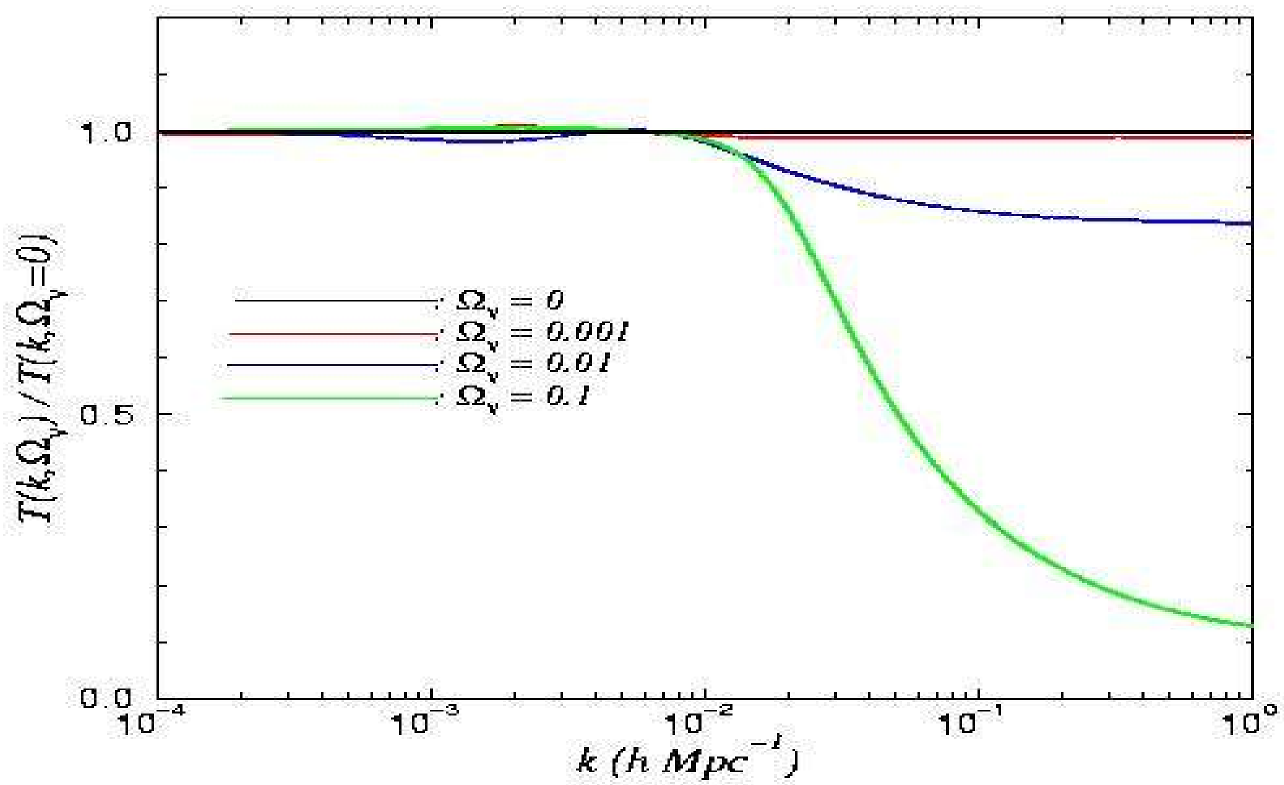
- Less clustering in universe with massive neutrinos.



Ma ’96

In practice, neutrinos affect the Power Spectrum of the 2-point density correlation function.

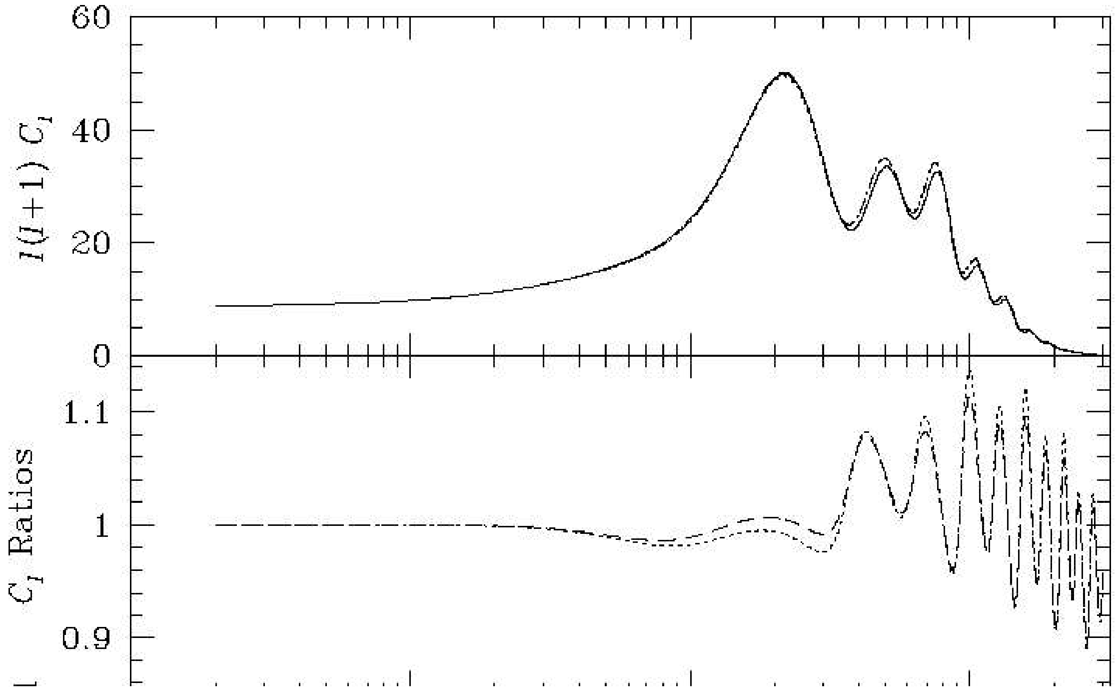
$$P(k)=A\, k^{n}\, T^{2}(k)$$



Neutrino Free Streaming

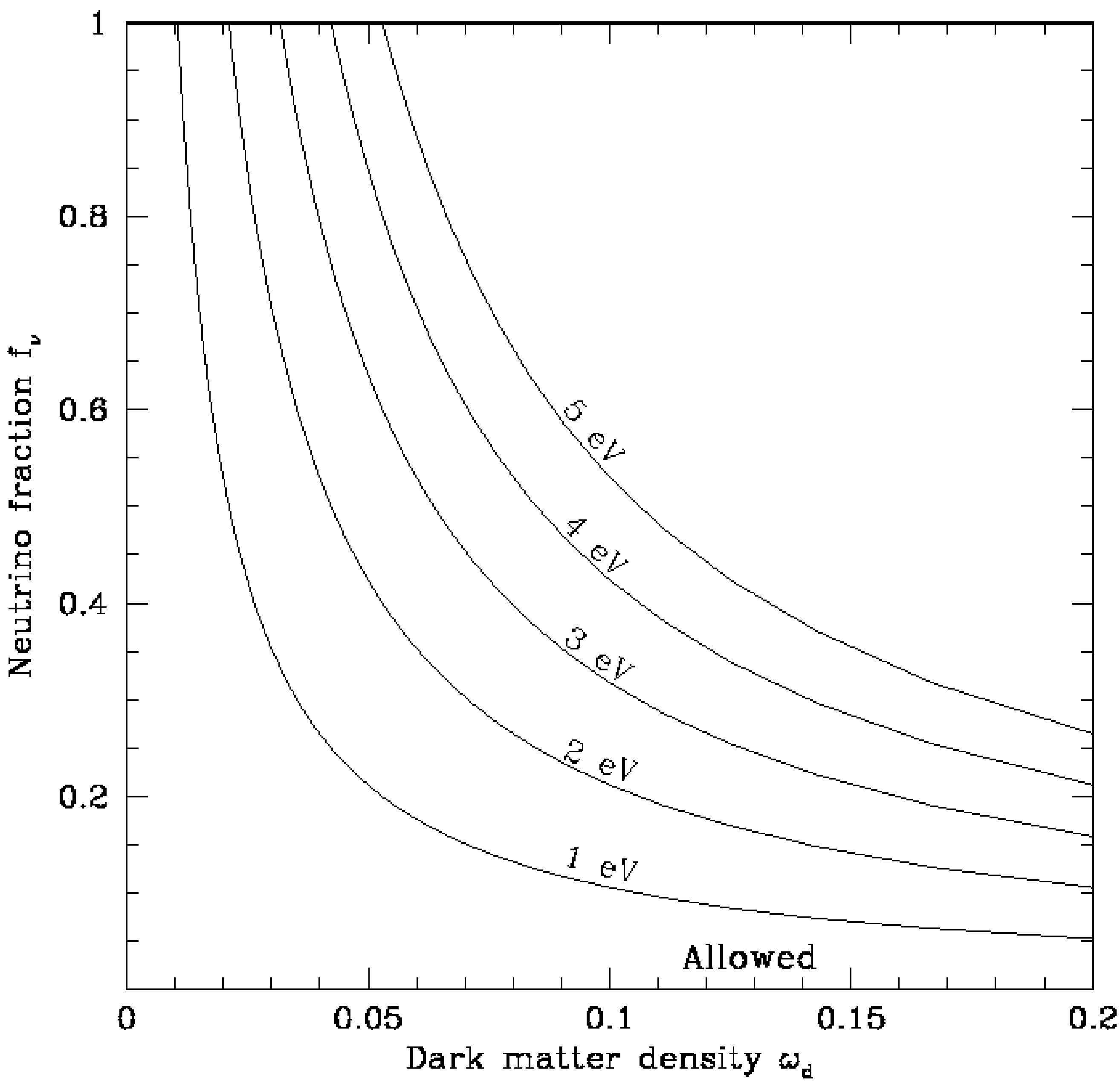
$\Delta P(k)/P(k) = -8\ \Omega_\nu/\Omega_m$ (Hu et al. 1998)

CMB anisotropies

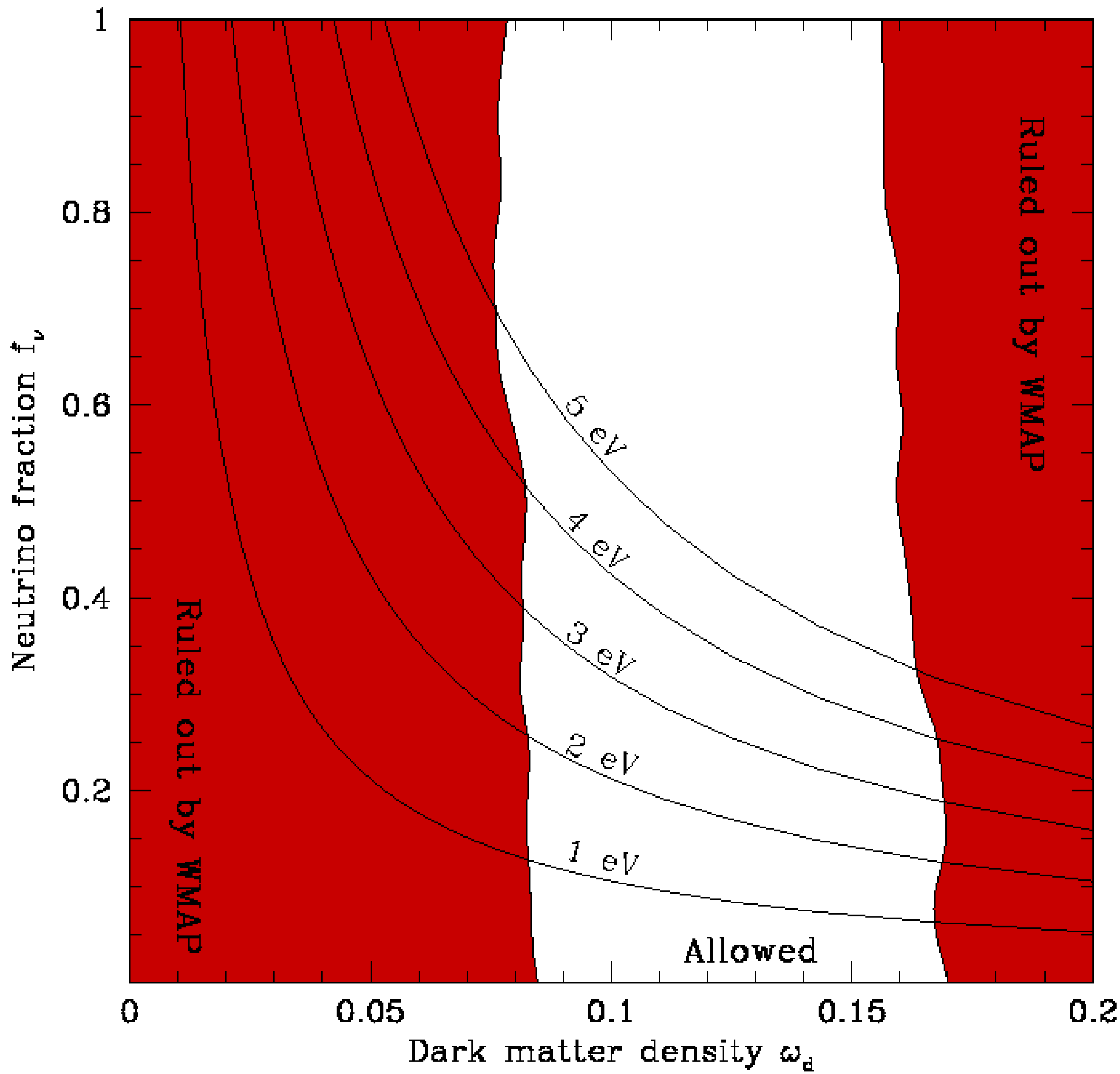


CMB Anisotropies are weakly affected by massive neutrinos. However they constrain very well the matter density and other parameters and, when combined with LSS data can break several degeneracies.

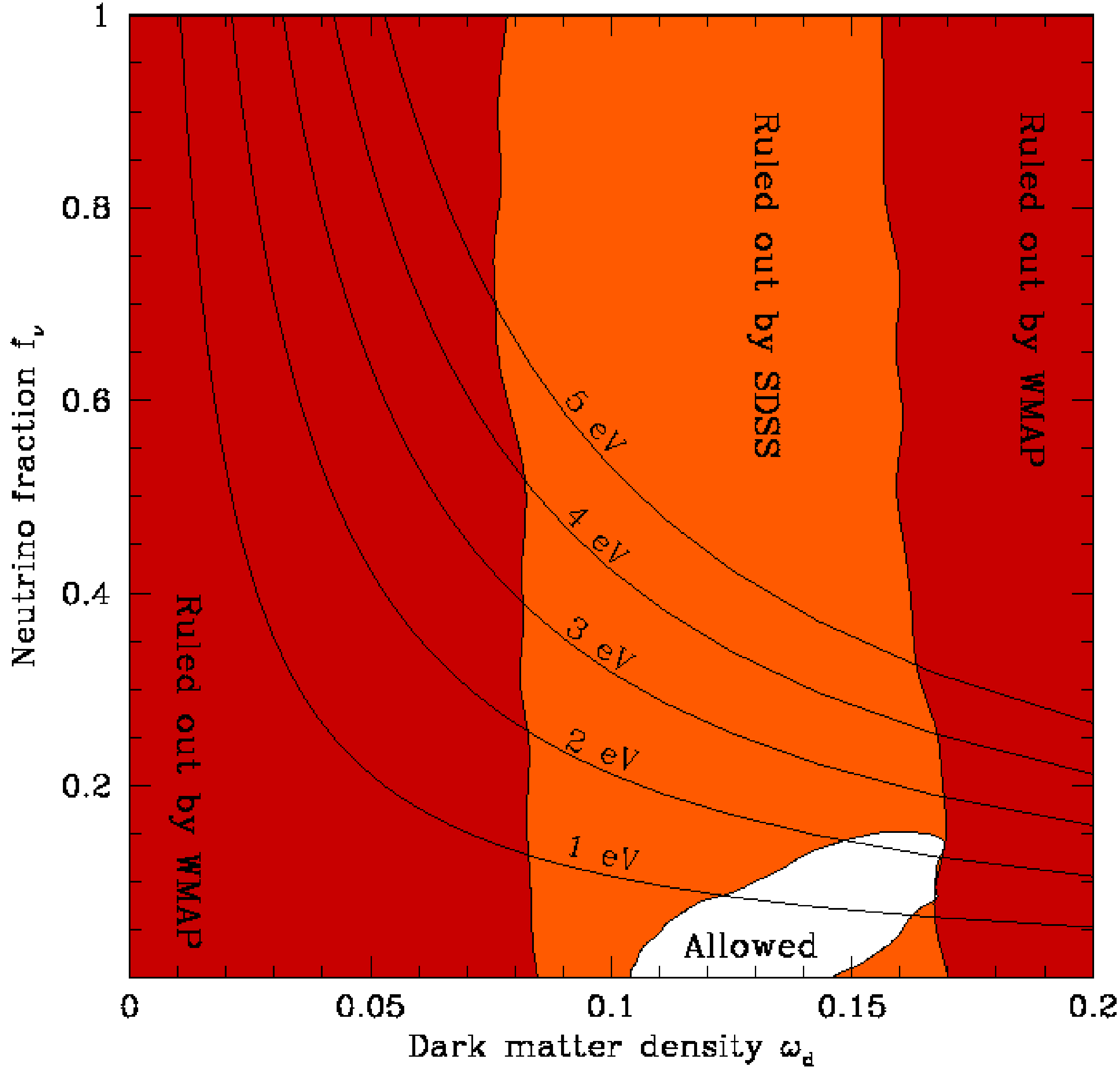
Tegmark



1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2
Neutrino fraction f_ν
Dark matter density ω_d
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed



Ruled out by WMAP
Ruled out by WMAP
Allowed
5 eV
4 eV
3 eV
2 eV
1 eV
Neutrino fraction f_ν
Dark matter density ω_d
0
0.05
0.1
0.15
0.2
0.2
0.4
0.6
0.8
1



Ruled out by WMAP
Ruled out by SDSS
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed
Neutrino fraction f_ν
Dark matter density ω_d
0
0.05
0.1
0.15
0.2
0.2
0.4
0.6
0.8
1

Neutrino mass from Cosmology

Data	Authors	Σm_i
2dFGRS	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+...	Spergel et al. 03	< 0.7 eV
WMAP+2dF	Hannestad 03	< 1.0 eV
SDSS+WMAP	Tegmark et al. 04	< 1.7 eV
WMAP+2dF+ SDSS	Crotty et al. 04	< 1.0 eV
WMAP+SDSS Lya	Seljak et al. 04	< 0.43 eV
Clusters +WMAP	Allen et al. 04	$0.56^{+0.30}_{-0.26}$ eV

All upper limits 95% CL, but different assumed priors !

Our Analysis

Fogli, Lisi, Marrone,Melchiorri, Palazzo,Serra,Silk
hep-ph/0408045, PRD in press.

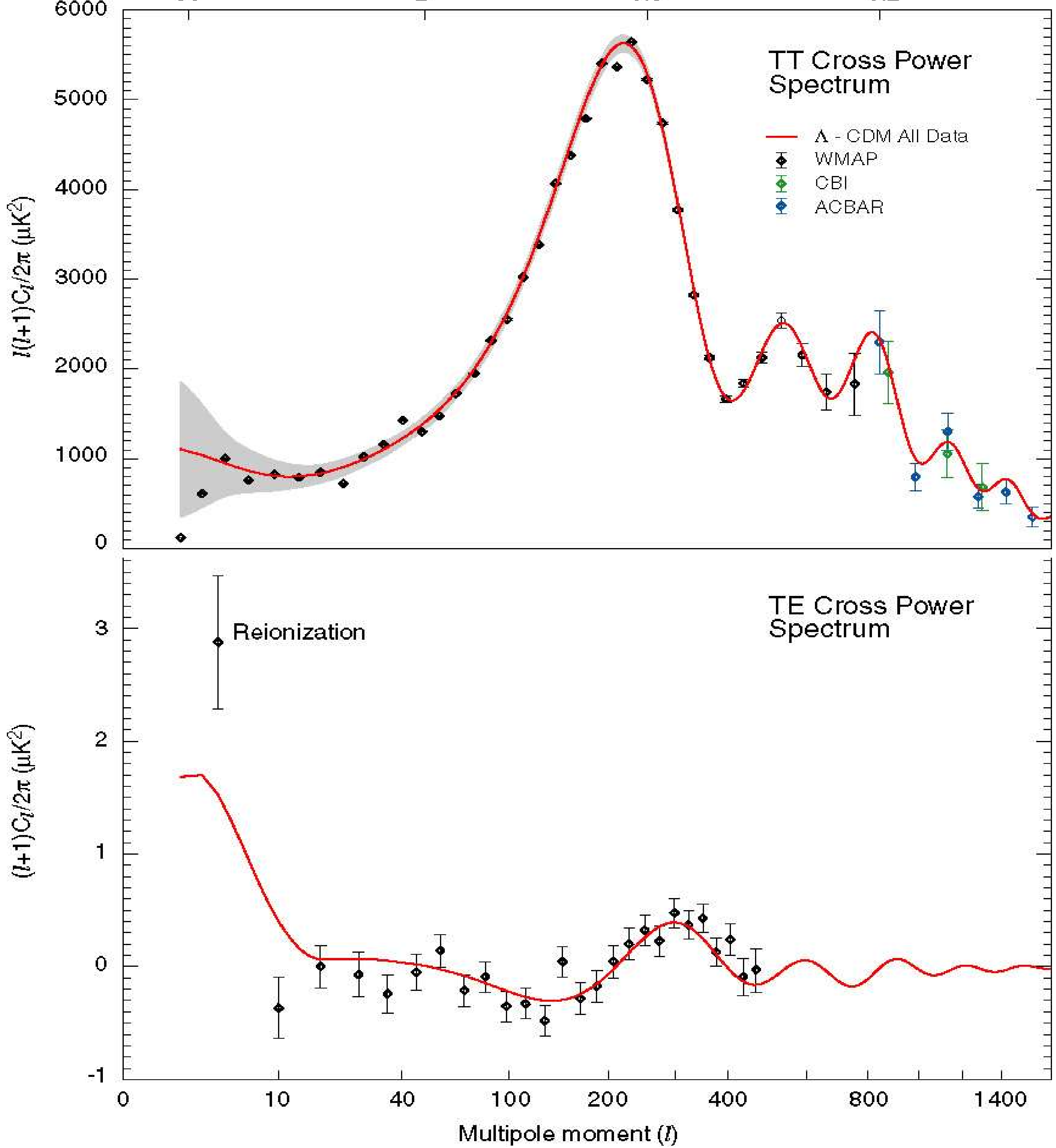
We Analyzed the latest CMB, Galaxy Clusters, Ly-alpha (SDSS), SNI-IA data in order to constrain the sum of neutrino masses in cosmology.

We restricted the analysis to three-flavour neutrino mixing.

We assume the Λ-CDM model with primordial adiabatic and scalar invariant inflationary perturbations.

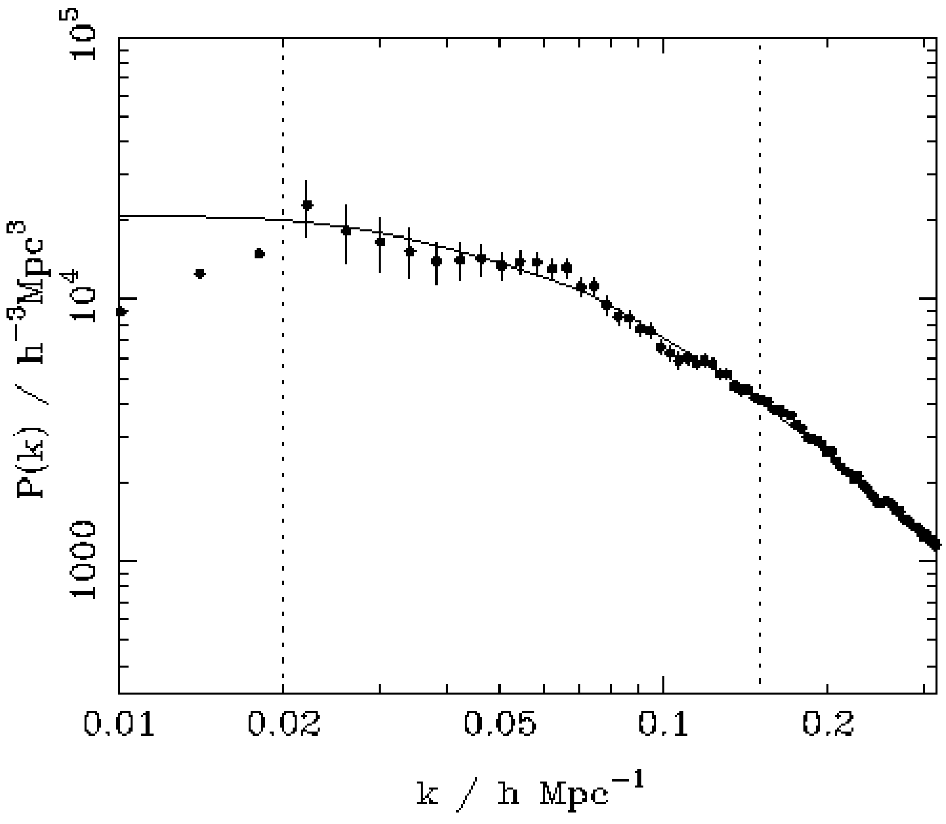
Datasets fusion is a difficult and dangerous task !!!

WMAP



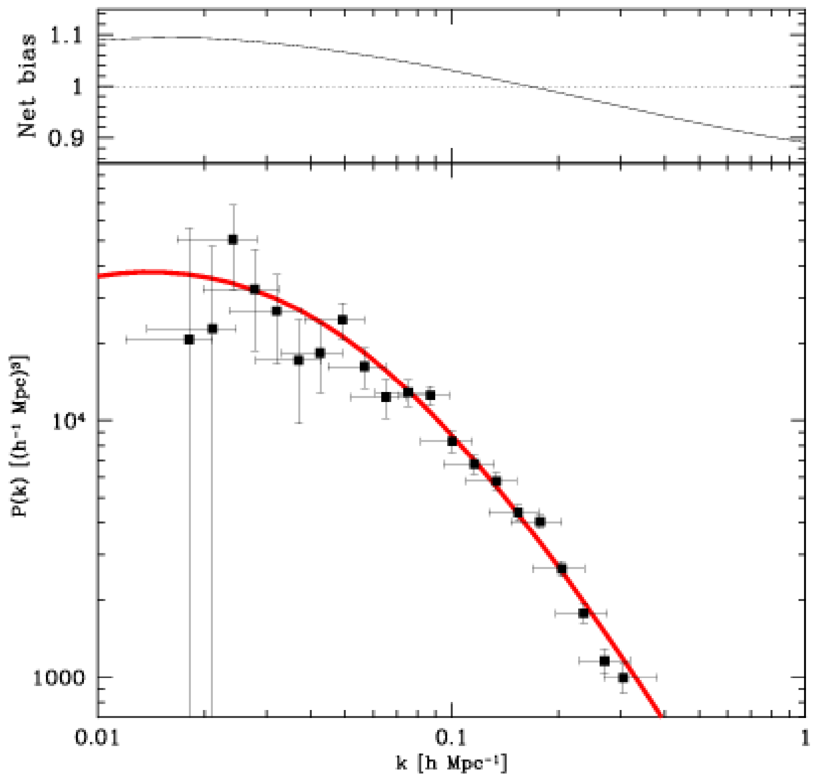
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi\ (\mu K^2)$
6000
5000
4000
3000
2000
1000
0
TE Cross Power Spectrum
Reionization
$(l+1)C_l/2\pi\ (\mu K^2)$
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)

The 2dFGRS Power Spectrum



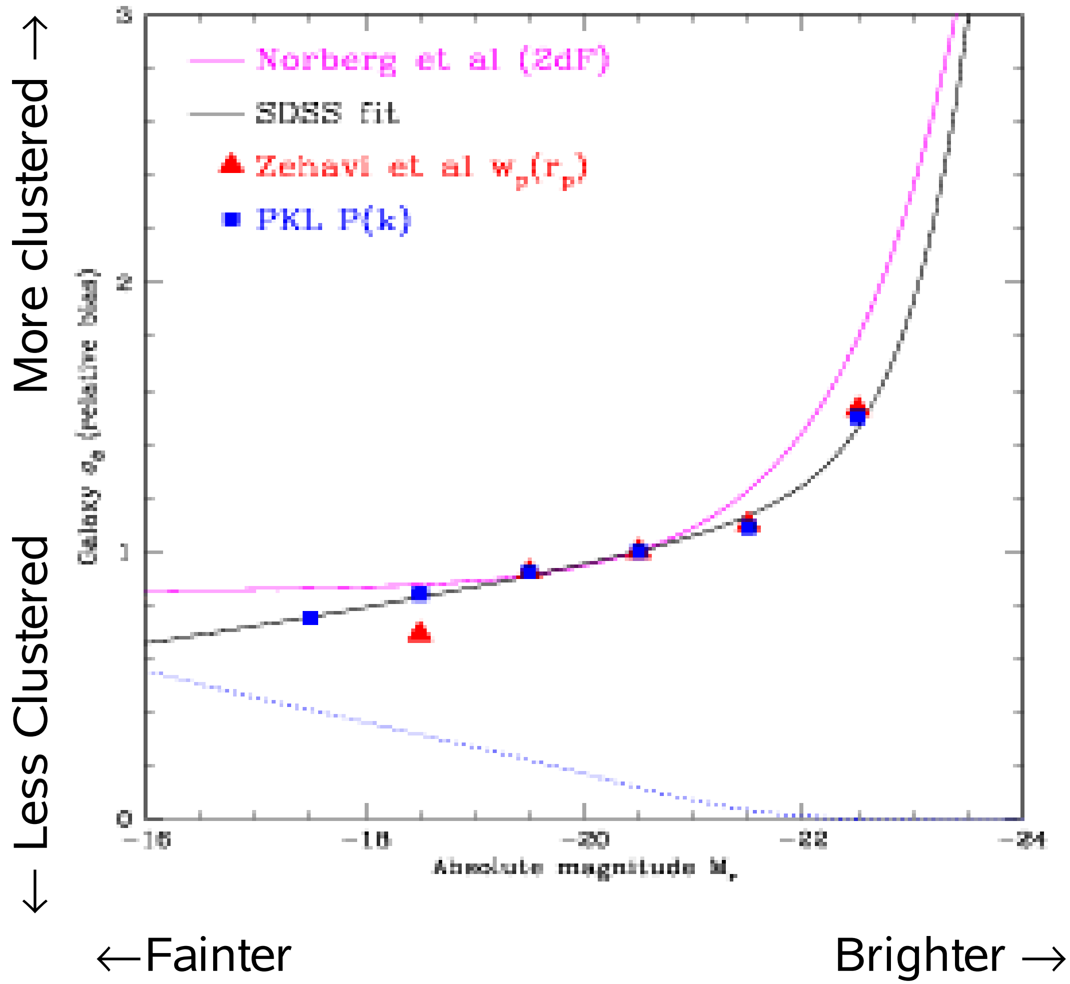
SDSS Survey

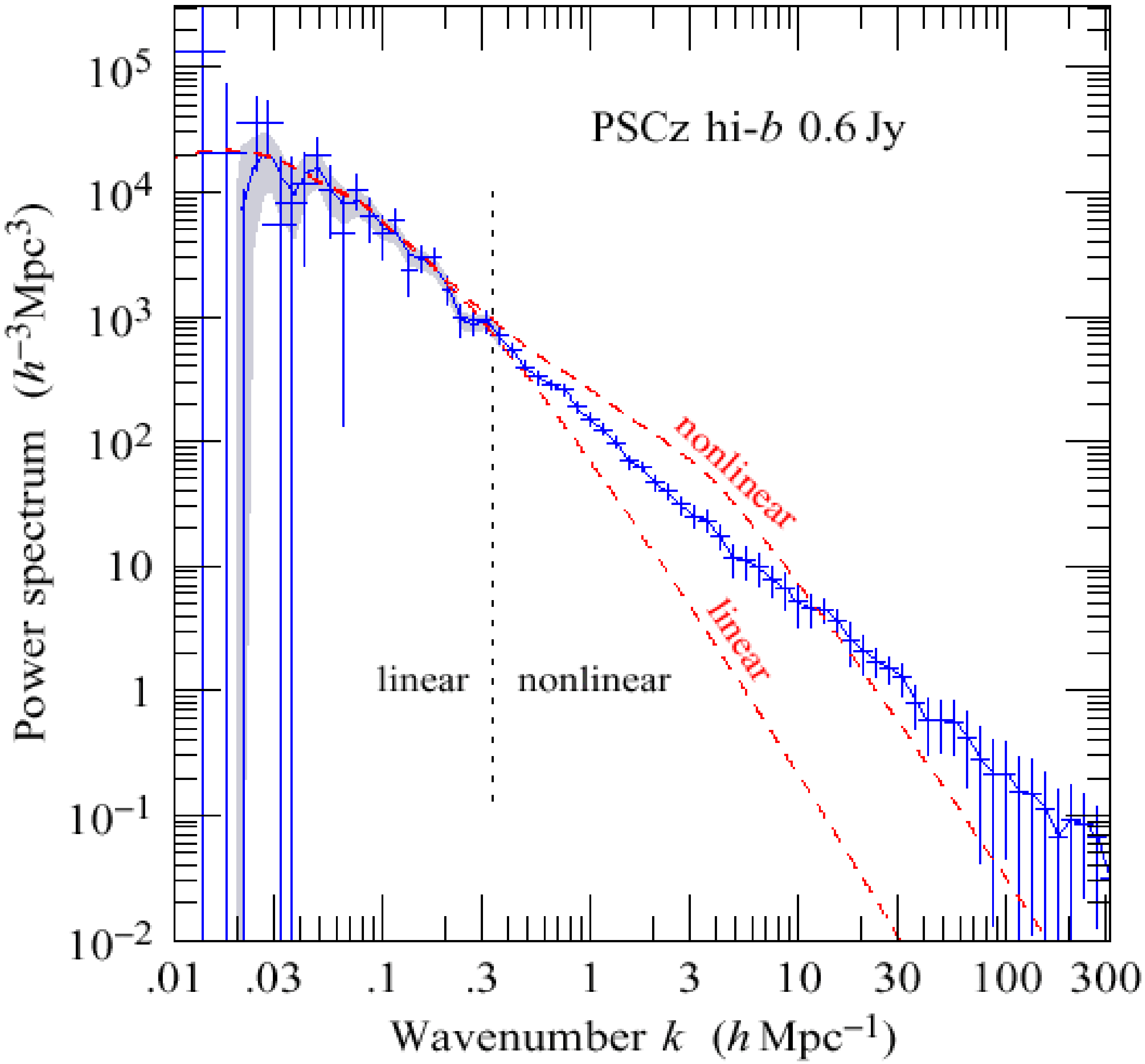
- 150K galaxies measured. Sloan Digital Sky Survey will eventually get redshifts of close to a million galaxies.
- Photometry and spectroscopy done in same survey: helps with systematics



Tegmark et al. 2003

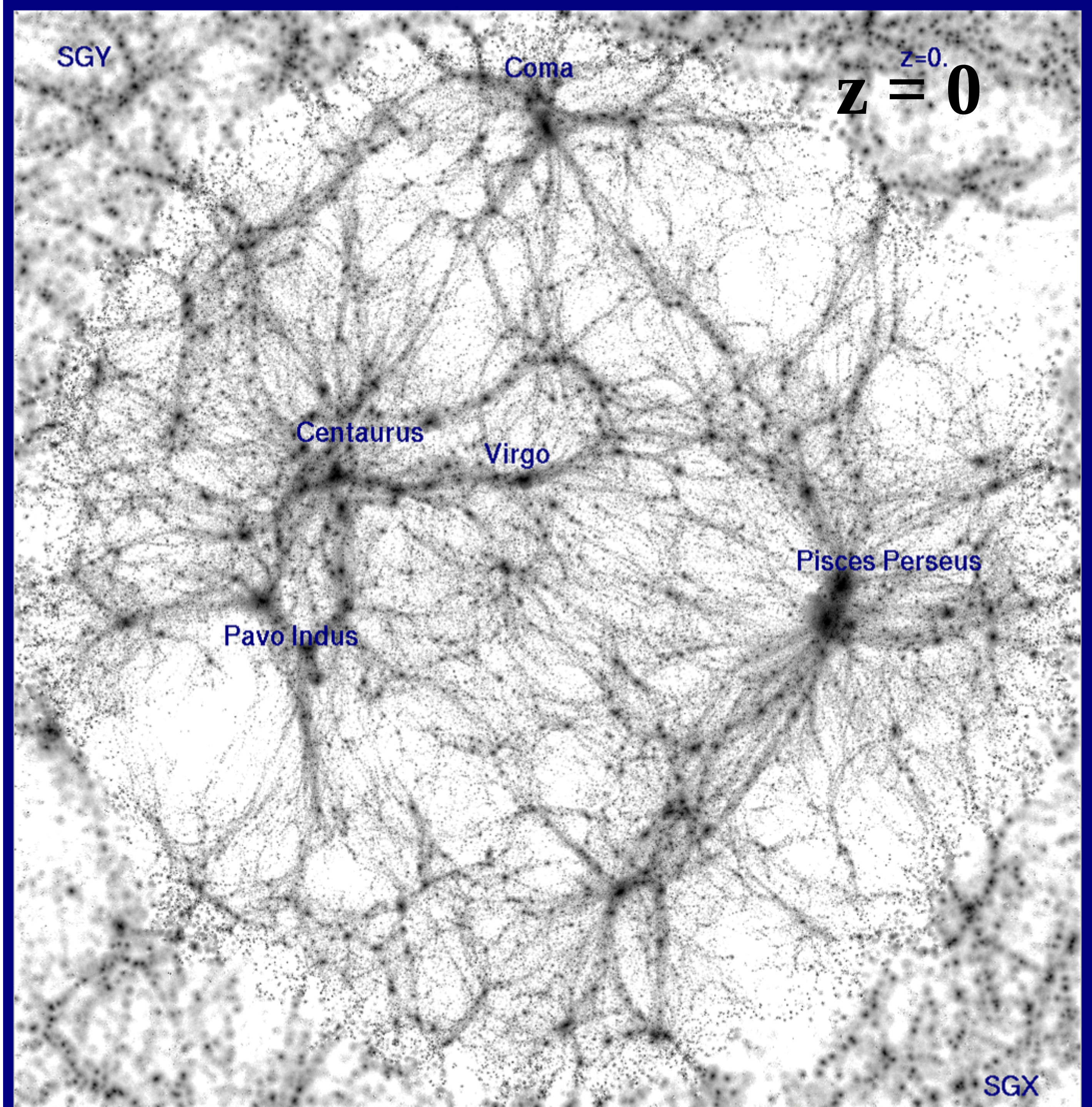
Systematic: luminosity bias: Intrinsically brighter galaxies are seen at large distances (cause faint ones can't be seen). These determine large scale power spectrum. Since these are more clustered, large scale spectrum is biased high! Conversely, small scale spectrum is biased low!

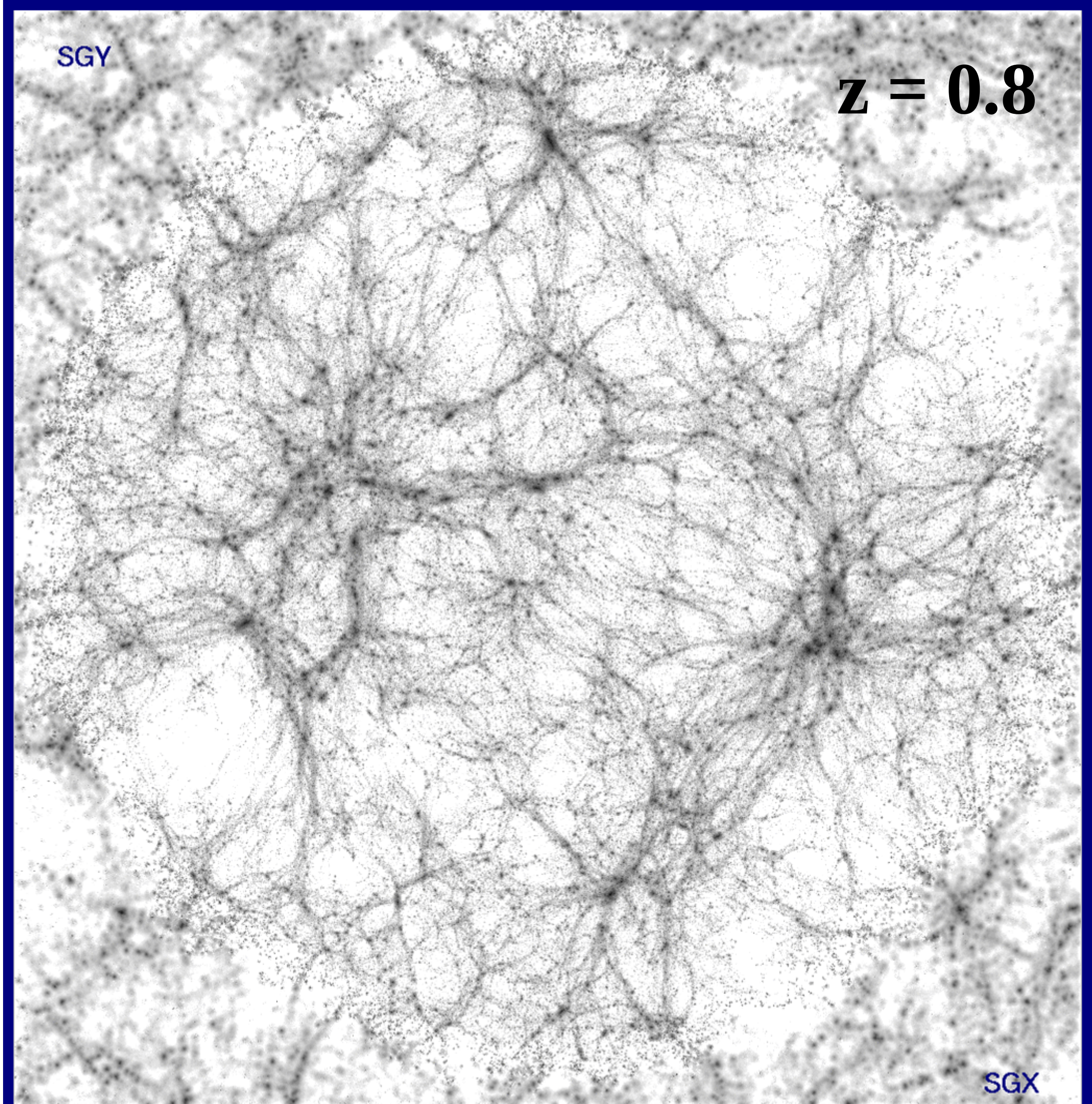


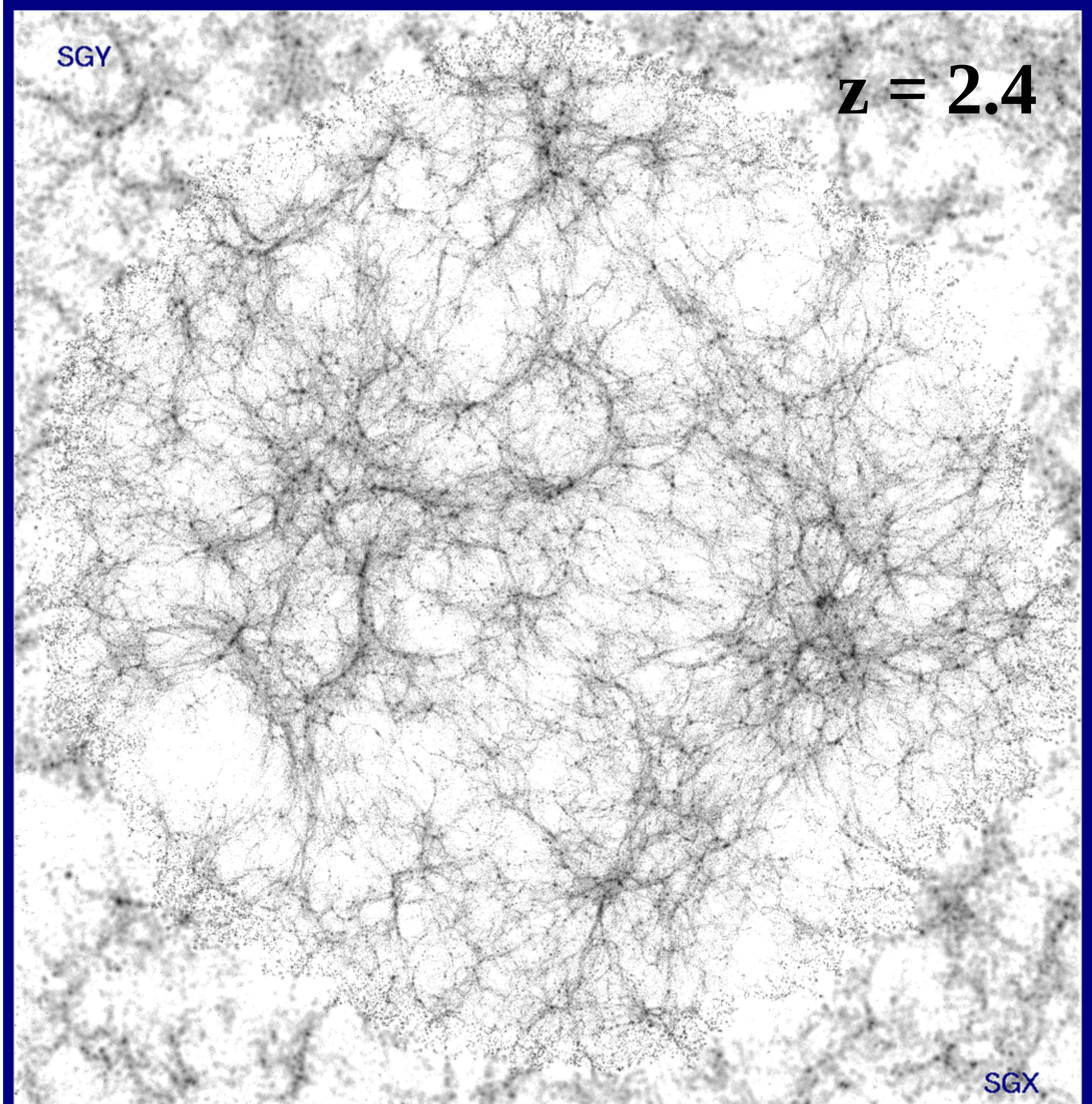


We want to go to smaller scales!!! (and be linear)

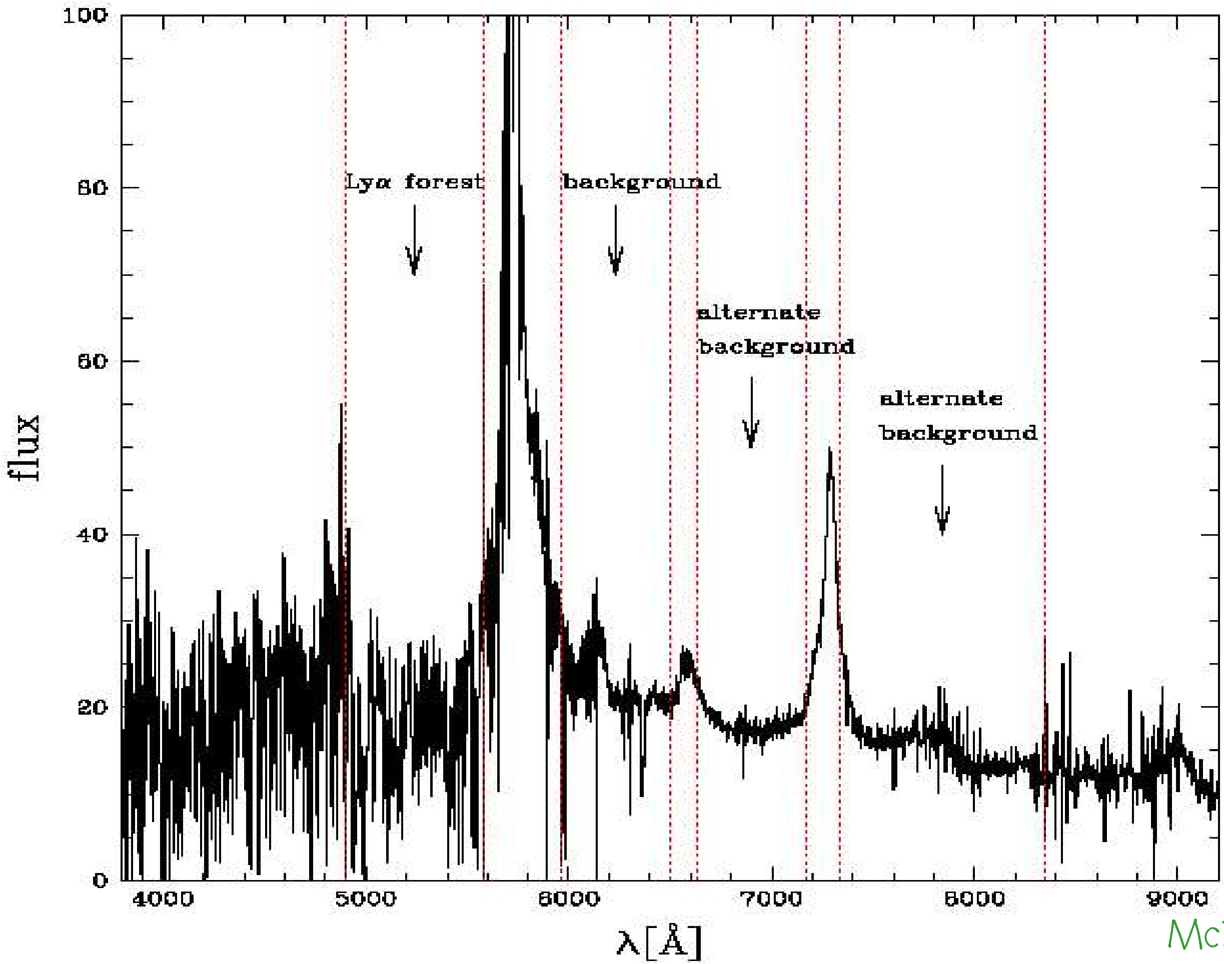
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001




SGY
z = 0.8
SGX


SGY
z = 2.4
SGX

Lyman alpha forest



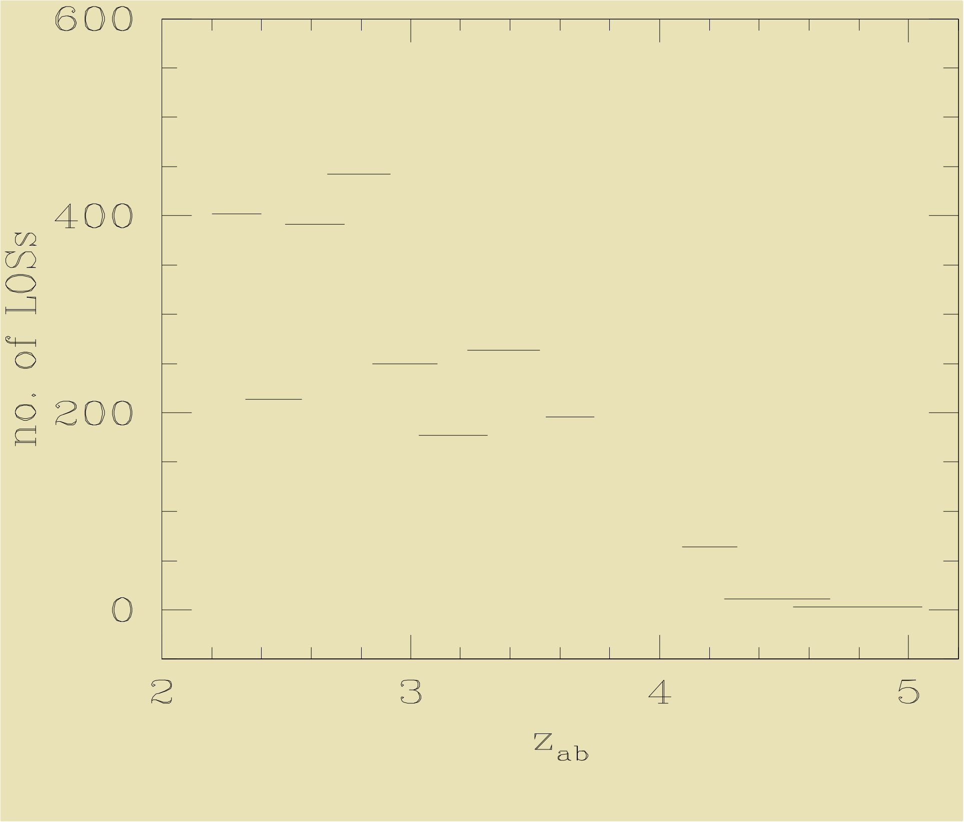
McDonald et al. 02

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.

SDSS: Lyman Alpha Forest

3000 QSOs
with absorption
lines from z 2 to
4.2

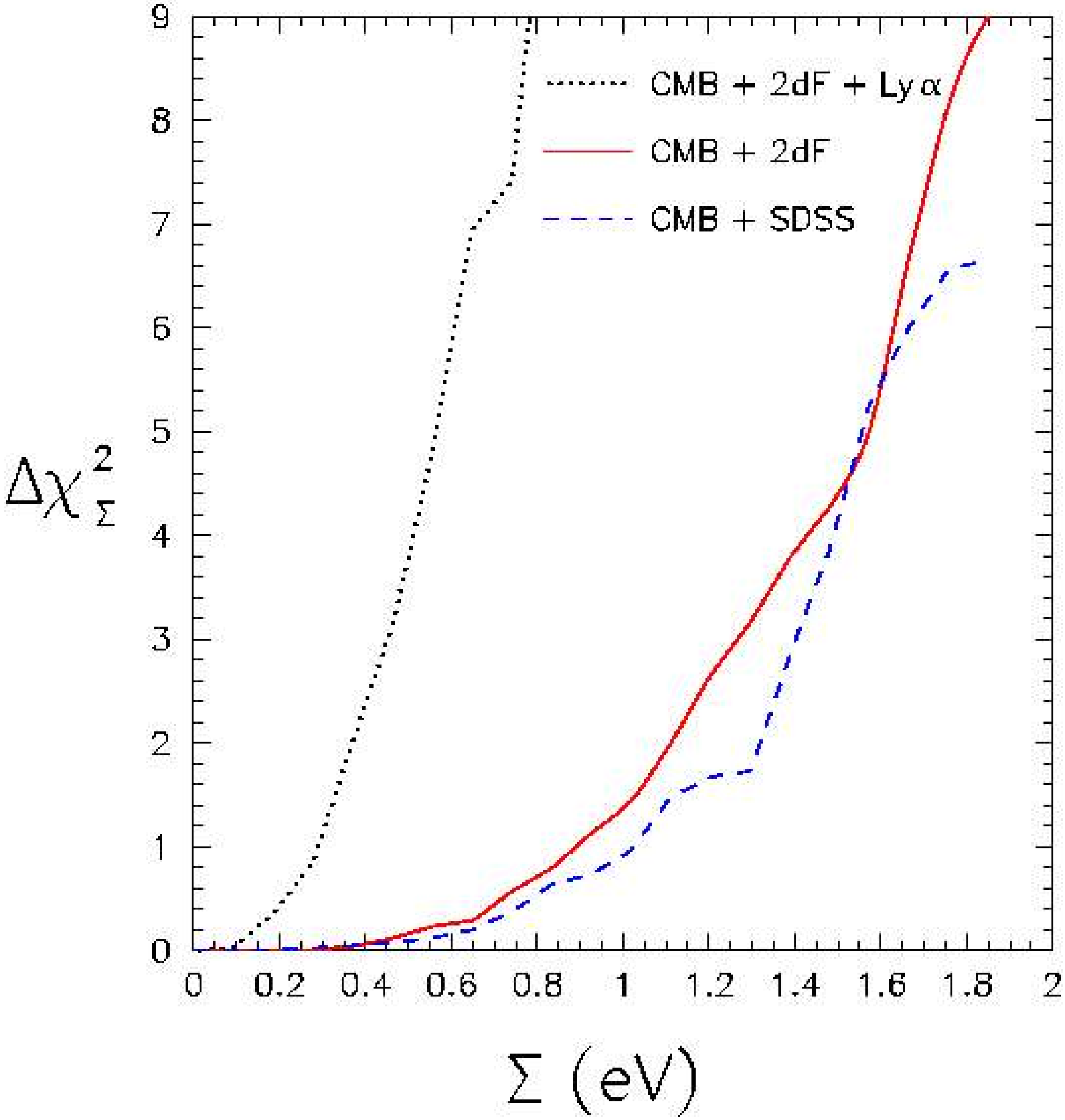


- Each spectrum is a 1D probe of ~400 Mpc/h through the IGM (with full wavelength coverage)
- Fluctuations in absorption trace the underlying mass distribution

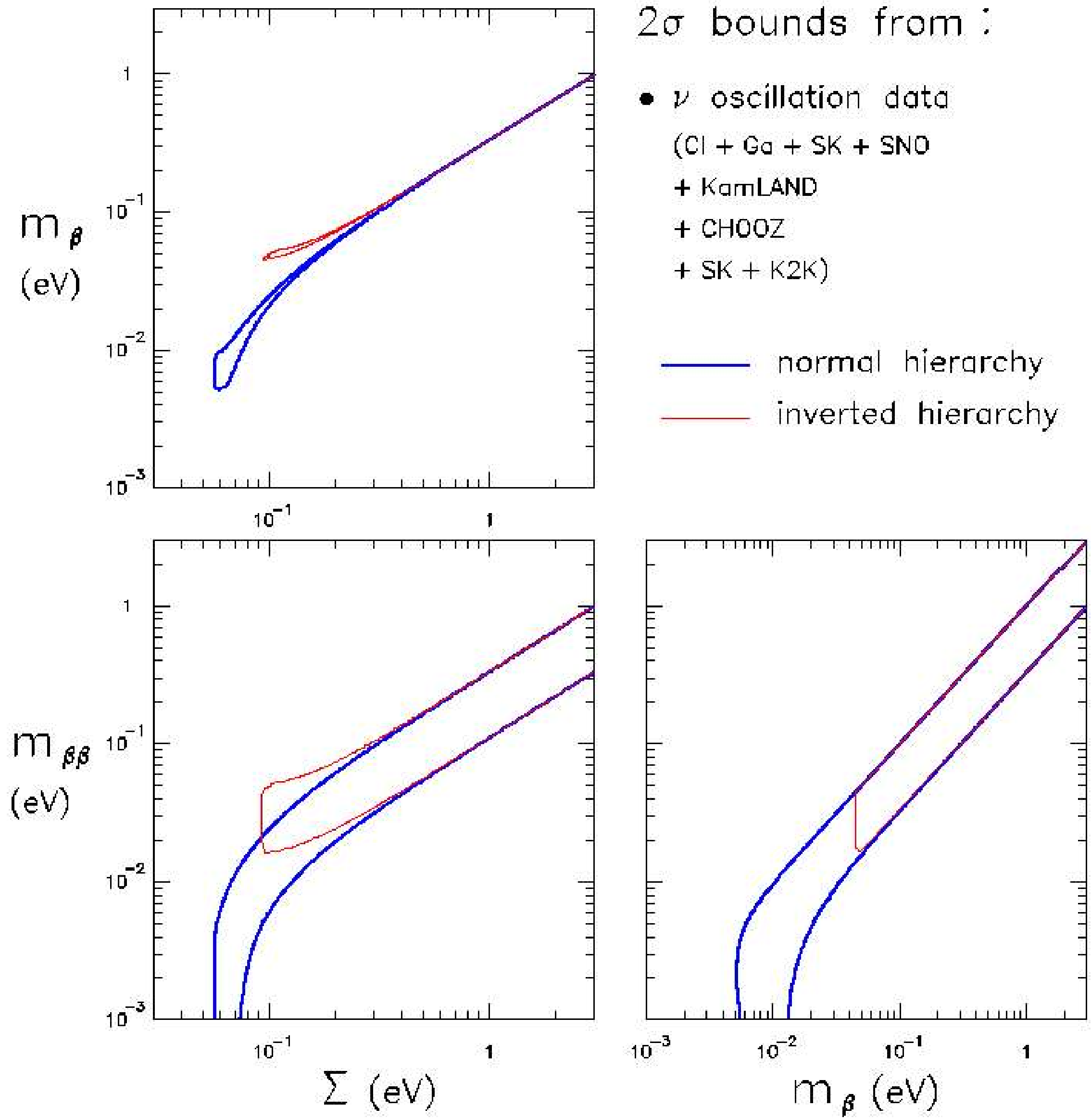
Hui et al., 2003
Seljak et al., 2003

Convert 1D Flux Spectrum to 3D Linear Matter Power Spectrum

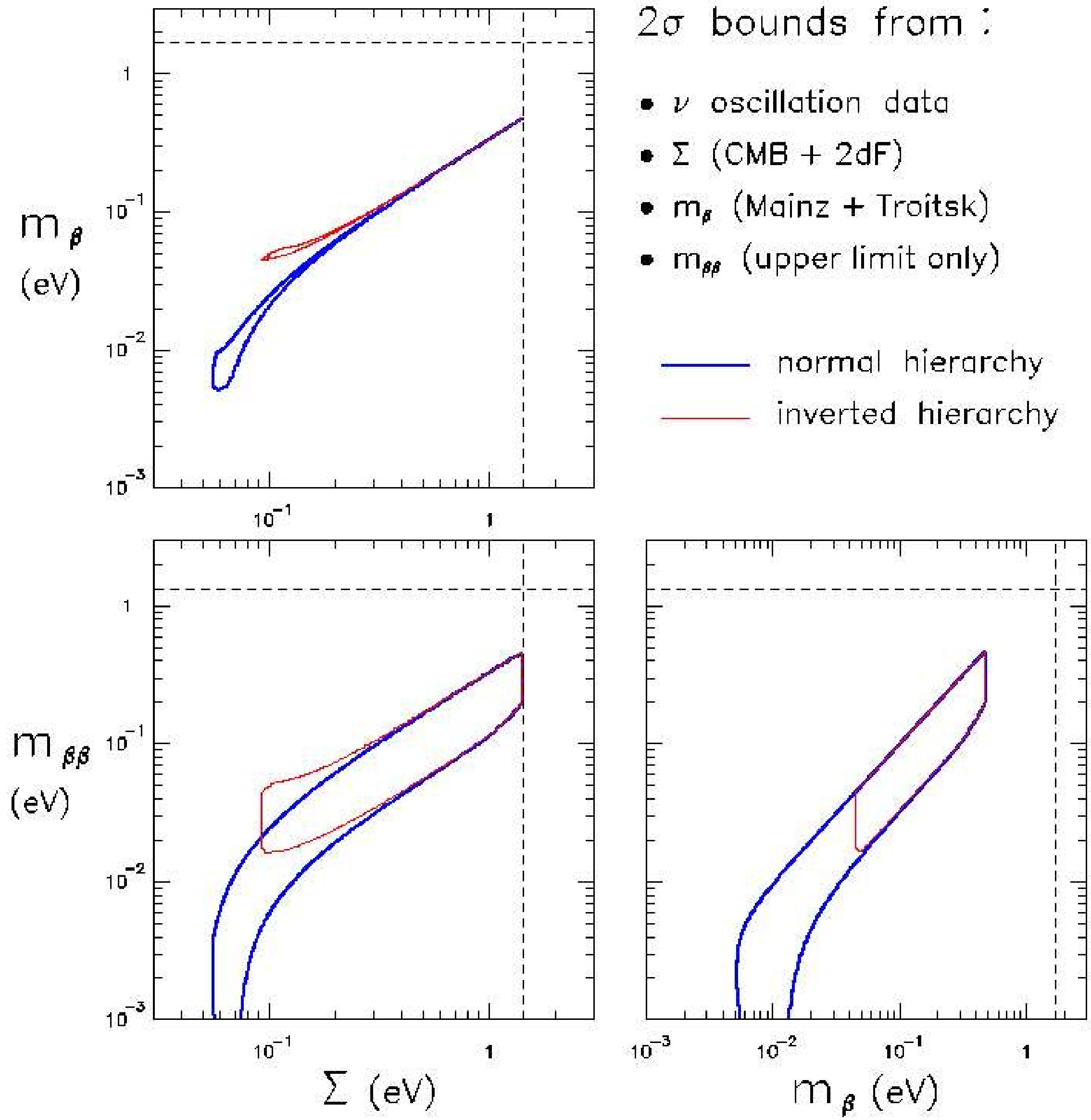
- Run many simulations with CDM-like spectra
- Extract Flux power spectra from each simulation
- Fit amplitude and slope of power at 1 Mpc
- Nonlinear (need large simulations)
- Astrophysics effects could lead to systematics (winds, fluctuations in UV/T, QSO continuum)
- Degeneracies between Lyalpha parameters.



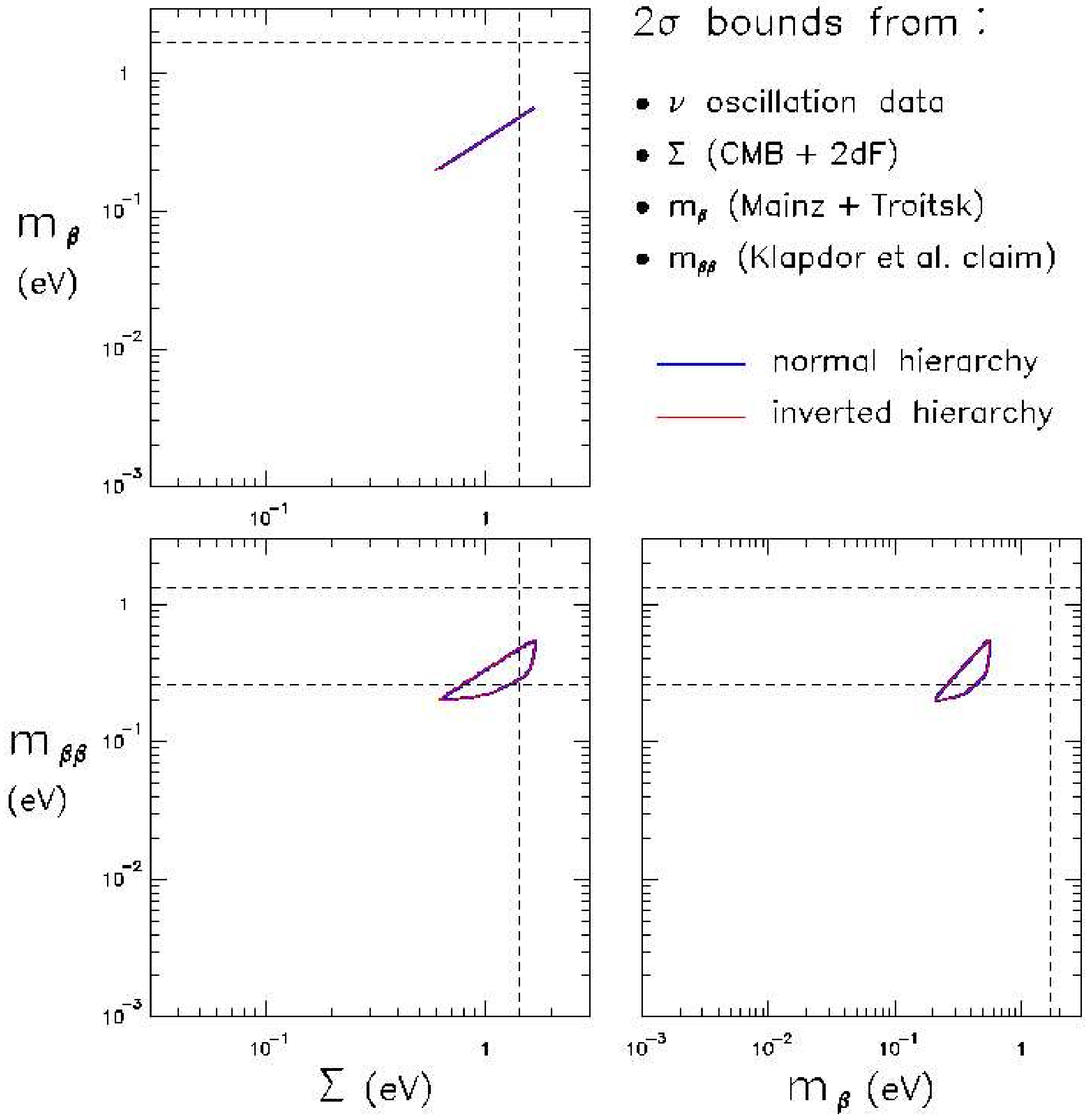
Fogli, Lisi, Marrone,Melchiorri, Palazzo,Serra,Silk
hep-ph/0408045



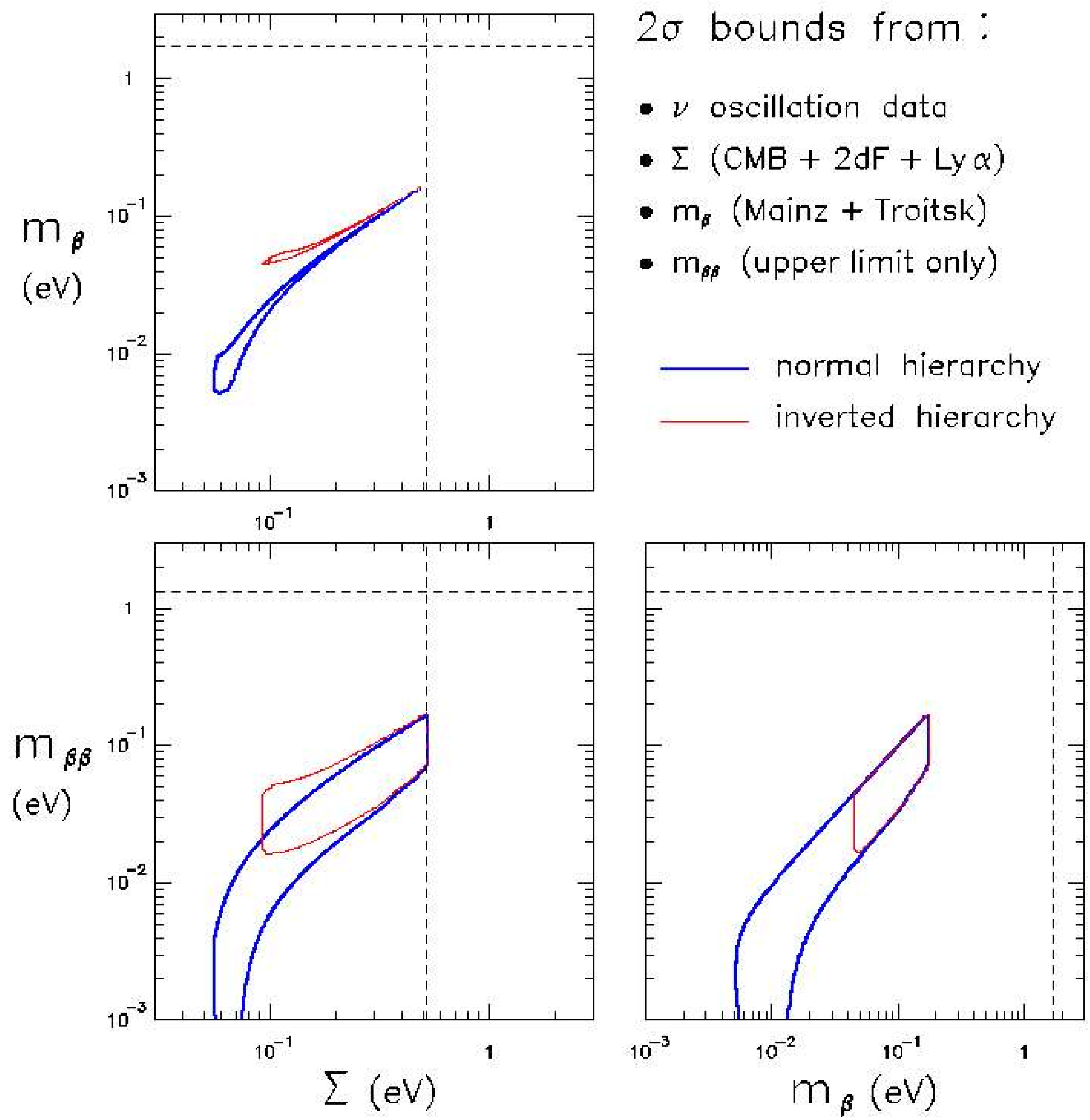
Fogli, Lisi, Marrone,Melchiorri, Palazzo,Serra,Silk
hep-ph/0408045



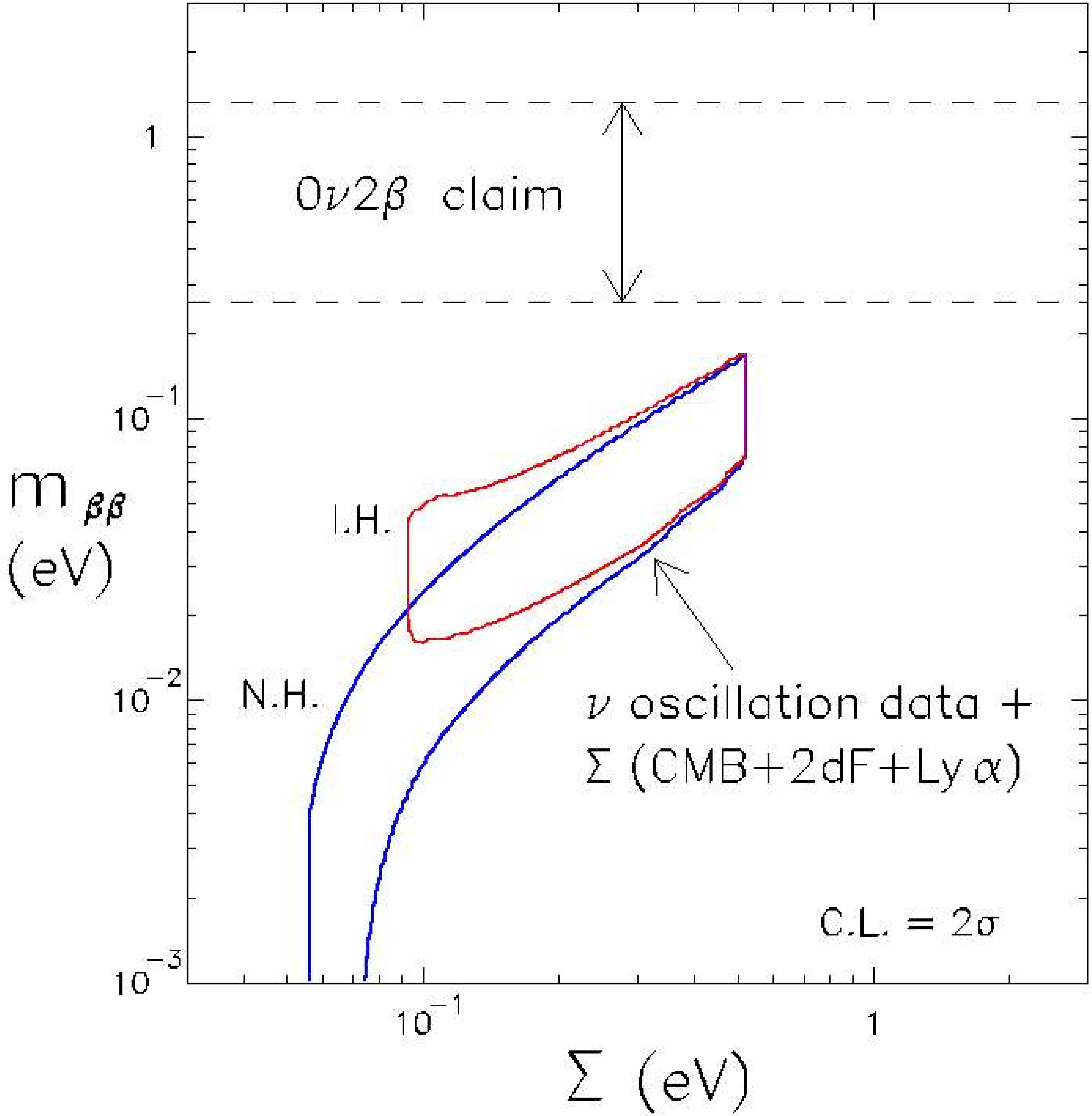
Fogli, Lisi, Marrone,Melchiorri, Palazzo,Serra,Silk
hep-ph/0408045



Fogli, Lisi, Marrone,Melchiorri, Palazzo,Serra,Silk
hep-ph/0408045



Fogli, Lisi, Marrone,Melchiorri, Palazzo,Serra,Silk
hep-ph/0408045



$0\nu 2\beta$ claim
1
10^{-1}
10^{-2}
10^{-3}
$m_{\beta\beta}$ (eV)
I.H.
N.H.
ν oscillation data +
Σ (CMB+2dF+Ly α)
C.L. = 2σ
10^{-1}
1
Σ (eV)

Prospects on neutrino mass bounds

Summary of 1σ expected errors on $M=\Sigma m_\nu$ (eV)

	none	SDSS	shear survey
none	-	1.3	0.21
Planck	0.31	0.13	0.05
Planck (lens. extr.)	0.15	0.10	0.05
CMBpol	0.07	0.07	0.03
CMBpol (lens. extr.)	0.04	0.03	0.02
Cos. var.	0.05	0.05	0.03
Cos. var. (lens. extr.)	0.02	0.02	0.01

Abazajian & Dodelson 03, Song & Knox 03, Kaplinghat et al. 03, ...

What about $N\nu$?

Interesting possibilities for $N_\nu>3$:

Presence of EXTRA RELATIVISTIC RELICS like sterile n's (thermalized or not), axion, light gravitinos, majoron, extra-D...

Non-Standard NEUTRINO DECOUPLING

- standard model (non-instantaneous) :
  - e^-e^+ annihilation heats ν's
  - finite T° QED corrections $N_\nu = 3.0395$
- exotic models (out of thermal equilibrium)
  - $N_\nu \neq 3.04$ e.g. low-scale (TeV) reheating

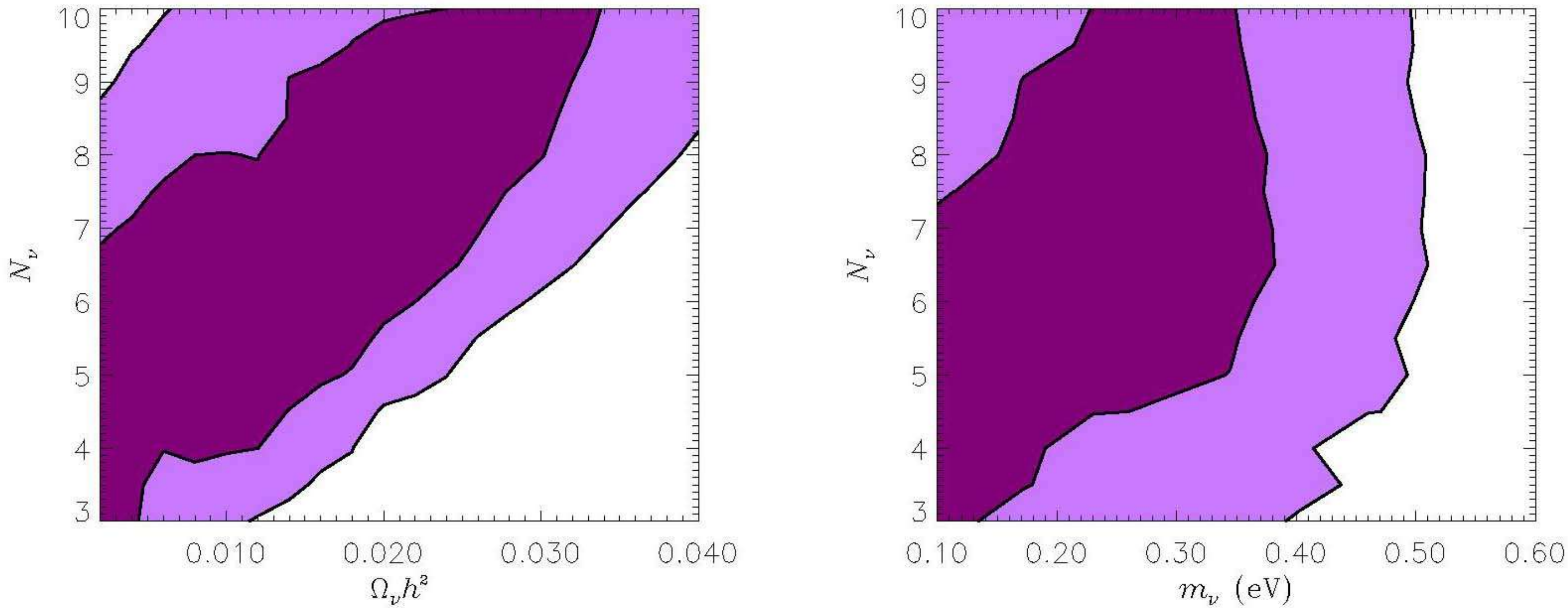
Non-Standard Big Bang Nucleosynthesis

sBBN : 2 free parameters $\{\Omega_b h^2, N_n\}$

- $\Omega_b h^2 = 0.022 \pm 0.004$ (2σ)
- $N_\nu = 2.5 \pm 1.1$ (2σ)

test $\nu - \nu$ asymmetry, i.e. $\boxed{\Delta N_\nu = \frac{15}{7}\left[2\left(\frac{\xi_\nu}{\pi}\right)^2 + \left(\frac{\xi_\nu}{\pi}\right)^4\right]}$

Degeneracy between Σm_ν and N_ν



HANNESTAD AND RAFFELT (JCAP 0404, 008 (2004))
CROTTY, LESGOURGUES & PASTOR HEP-PH/0402049

Future prospects :

Planck [+ SDSS] : $\sigma(N_\nu) \sim 0.3$

see Bowen et al. 02

Bashinsky & Seljak 03

CMBpol : $\sigma(N_\nu) \sim 0.05$ to 0.1

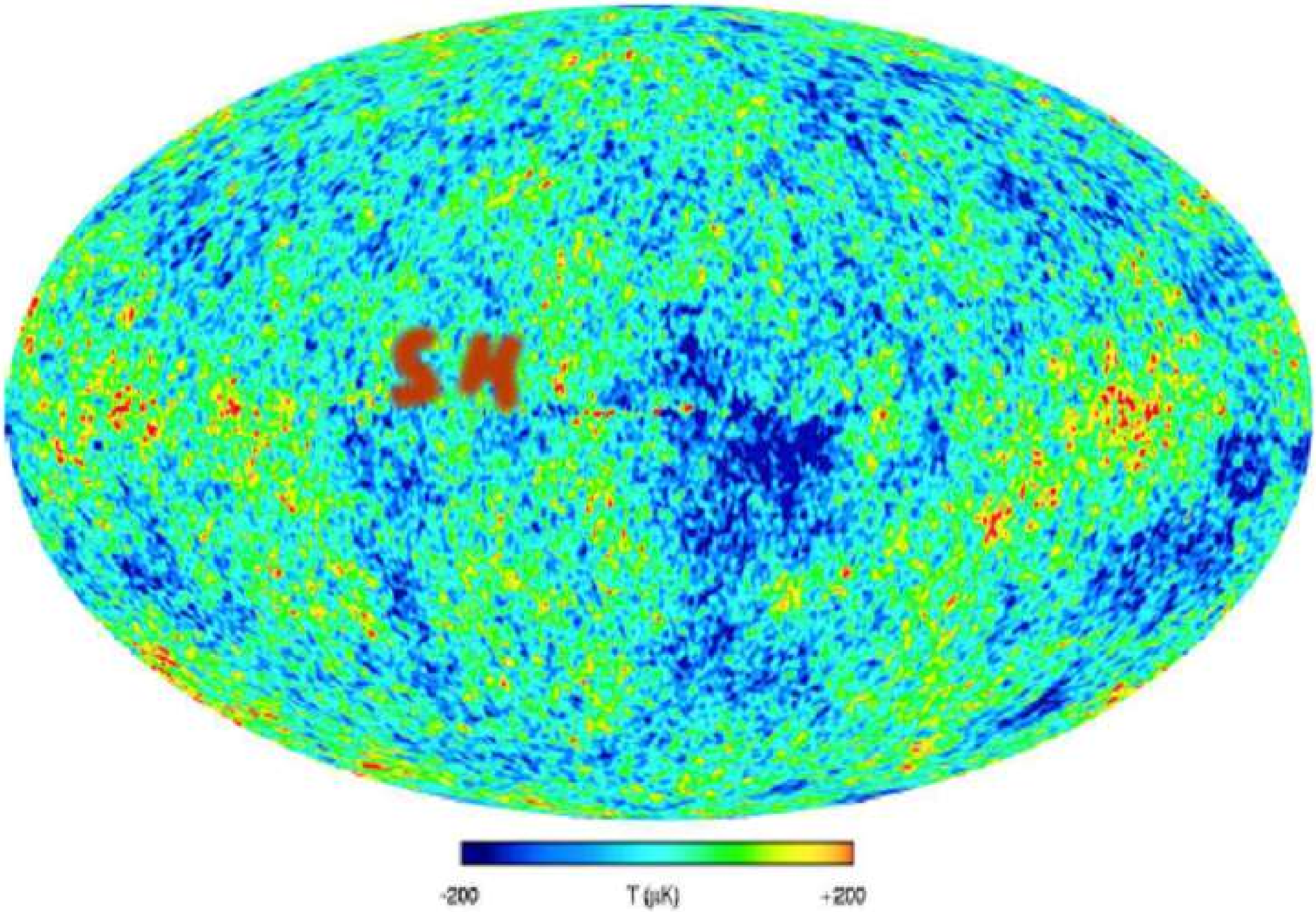
Conclusions

- 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. Neutrino anisotropies are there and neutrino physics at decoupling can be further tested.

- Cosmological constraints on neutrino mass are rapidly improving. If one includes bias information and Ly-alpha then Σ<0.5 eV. Tension with the $0\nu\beta\beta$ results.Sensitivity to Σ=0.1 eV is possible in the very near future.

- Wide variety of techniques/experiments needed to eliminate systematics. The constraints are model dependent.

- Particle physicists must all become familiar with: Big Bang cosmology, large scale structure, dark energy, inflation, cosmic microwave background, ...


SH
-200
T (μK)
+200

WMAP 2nd year ??