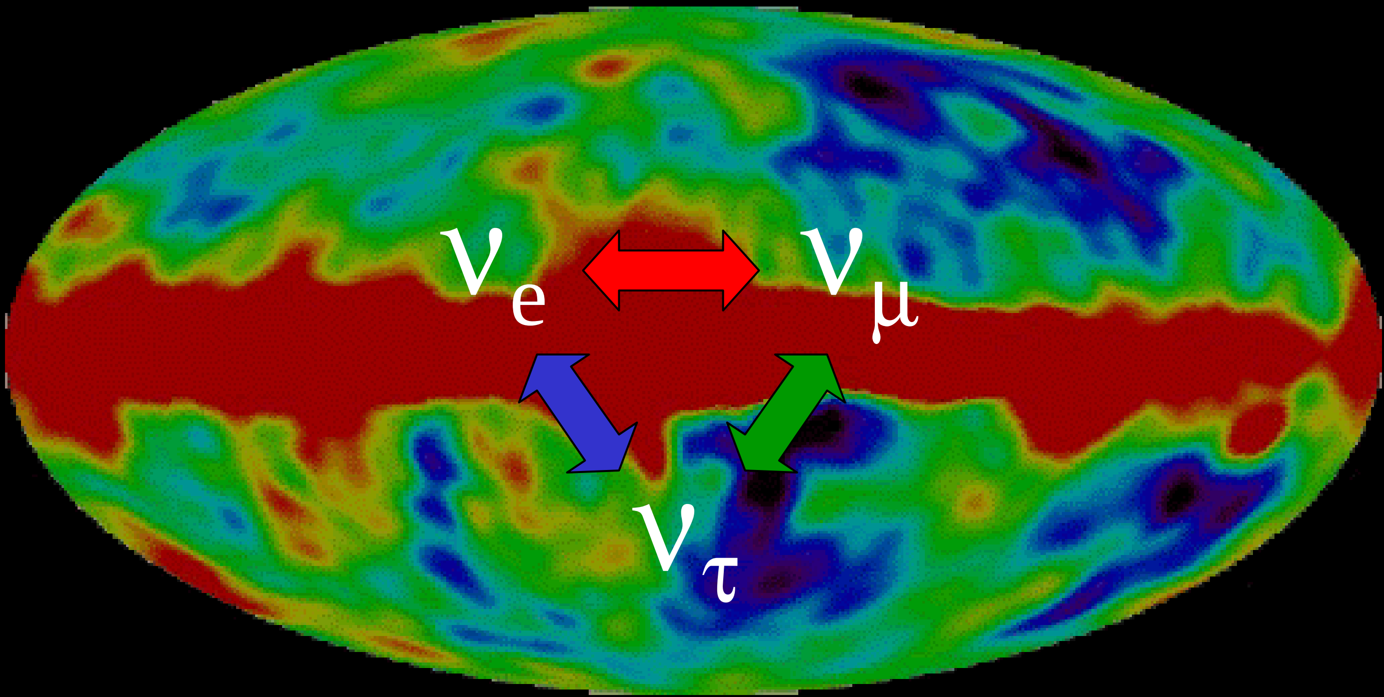
NEUTRINO PHYSICS FROM COSMOLOGICAL OBSERVATIONS



STEEN HANNESTAD, NORDITA

Nu'02, 29 MAY 2002

EXPERIMENTAL QUESTIONS FROM NEUTRINO ASTROPHYSICS

- NEUTRINO MASS HIERARCHY AND MIXING MATRIX
  - solar & atmospheric neutrinos
  - supernovae
- ABSOLUTE NEUTRINO MASSES
  - cosmology: CMB and large scale structure
  - supernovae
- COSMOLOGICAL NEUTRINO CHEMICAL POTENTIAL
  - cosmology: BBN and CMB
- STERILE NEUTRINOS (BARYOGENESIS)?
  - cosmology,supernovae

NEUTRINOS IN COSMOLOGY

NEUTRINOS INFLUENCE SEVERAL AREAS OF COSMOLOGY

- BIG BANG NUCLEOSYNTHESIS
- THE COSMIC MICROWAVE BACKGROUND
- LARGE SCALE STRUCTURE FORMATION

2000-1: First precision measurements of smaller scale CMB anisotropies

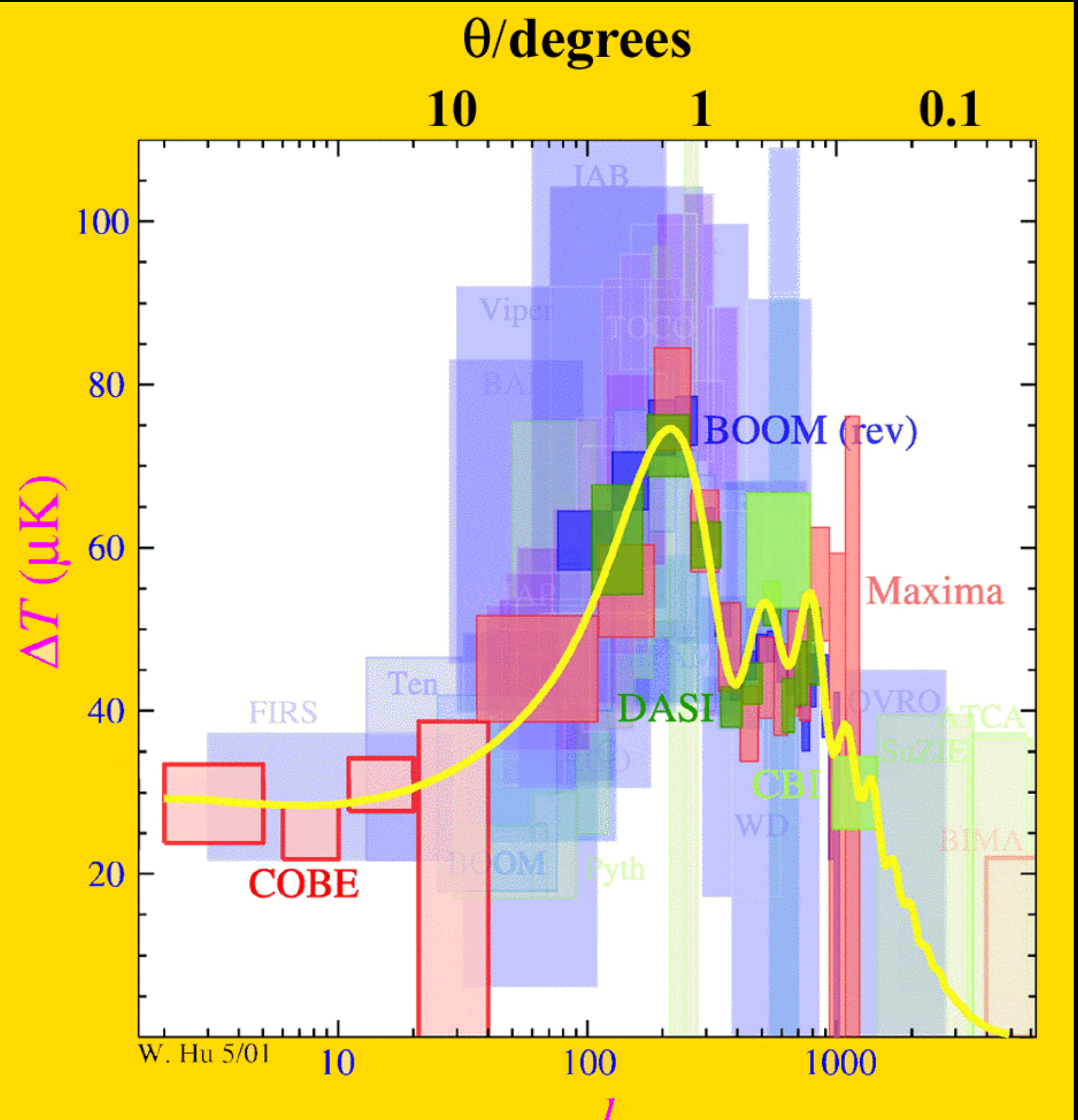
BALLOON EXPERIMENTS

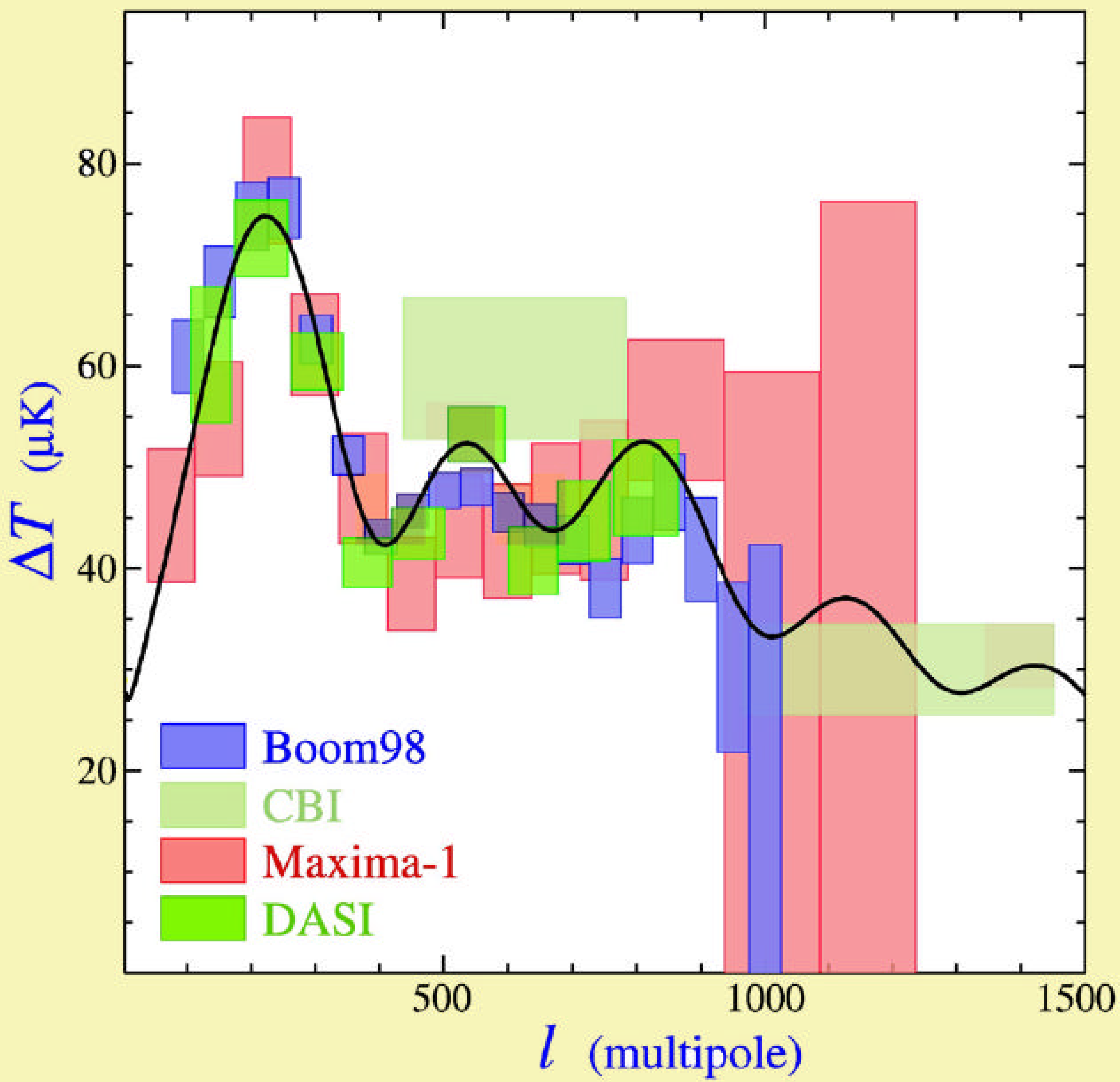
NAME	STATUS
BOOMERanG	published
MAXIMA-I	published
TopHat	data taken
Archeops	data taken

GROUND BASED INTERFEROMETERS

NAME	STATUS
CBI	published
DASI	published
VSA	published

PRESENT DATA (AS OF 1/5-2002)





80
60
40
20
ΔT (μK)
500
1000
1500
l (multipole)
Boom98
CBI
Maxima-1
DASI

Hu '02

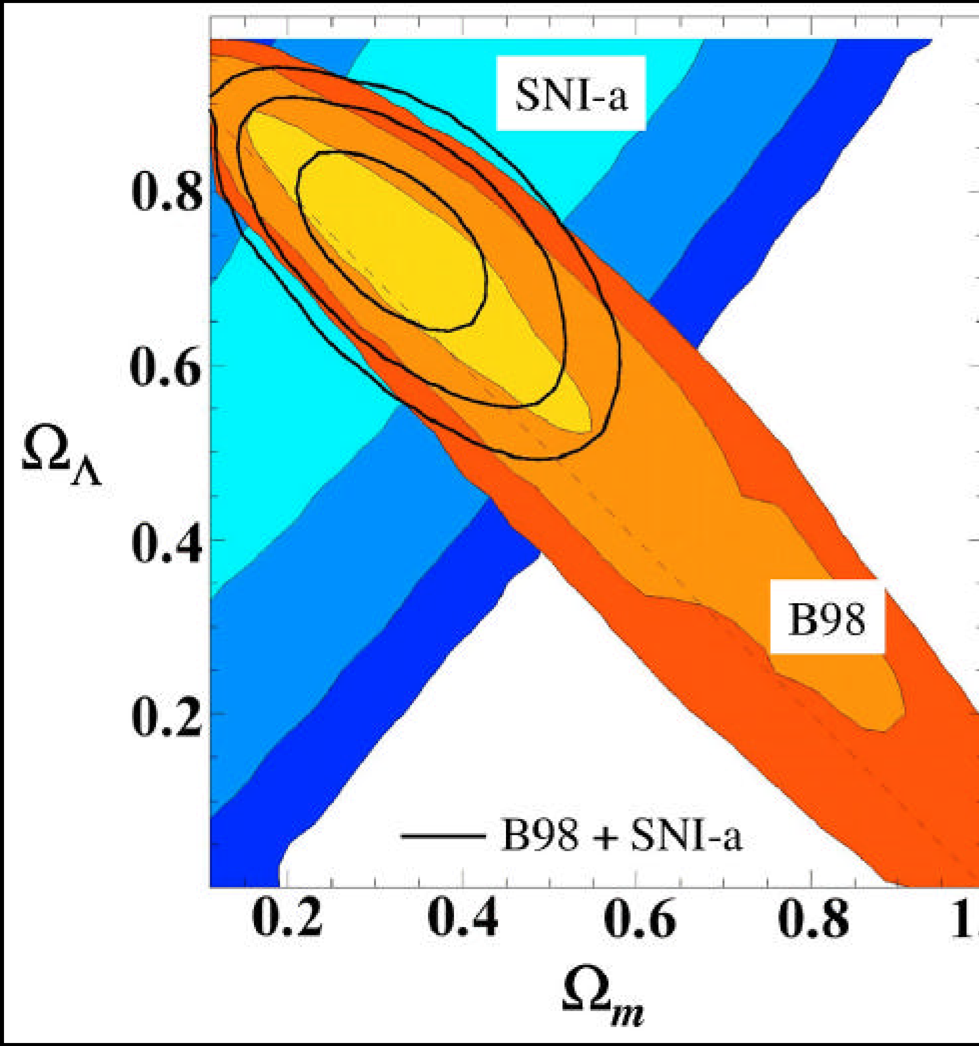
STATUS OF COSMOLOGY AFTER THESE EXPERIMENTS

Geometry very close to being flat. (as predicted by the simplest inflation models)

$$\Omega_{\mathrm{TOT}} = \Omega_m + \Omega_\Lambda = 1.02^{+0.06}_{-0.06}$$

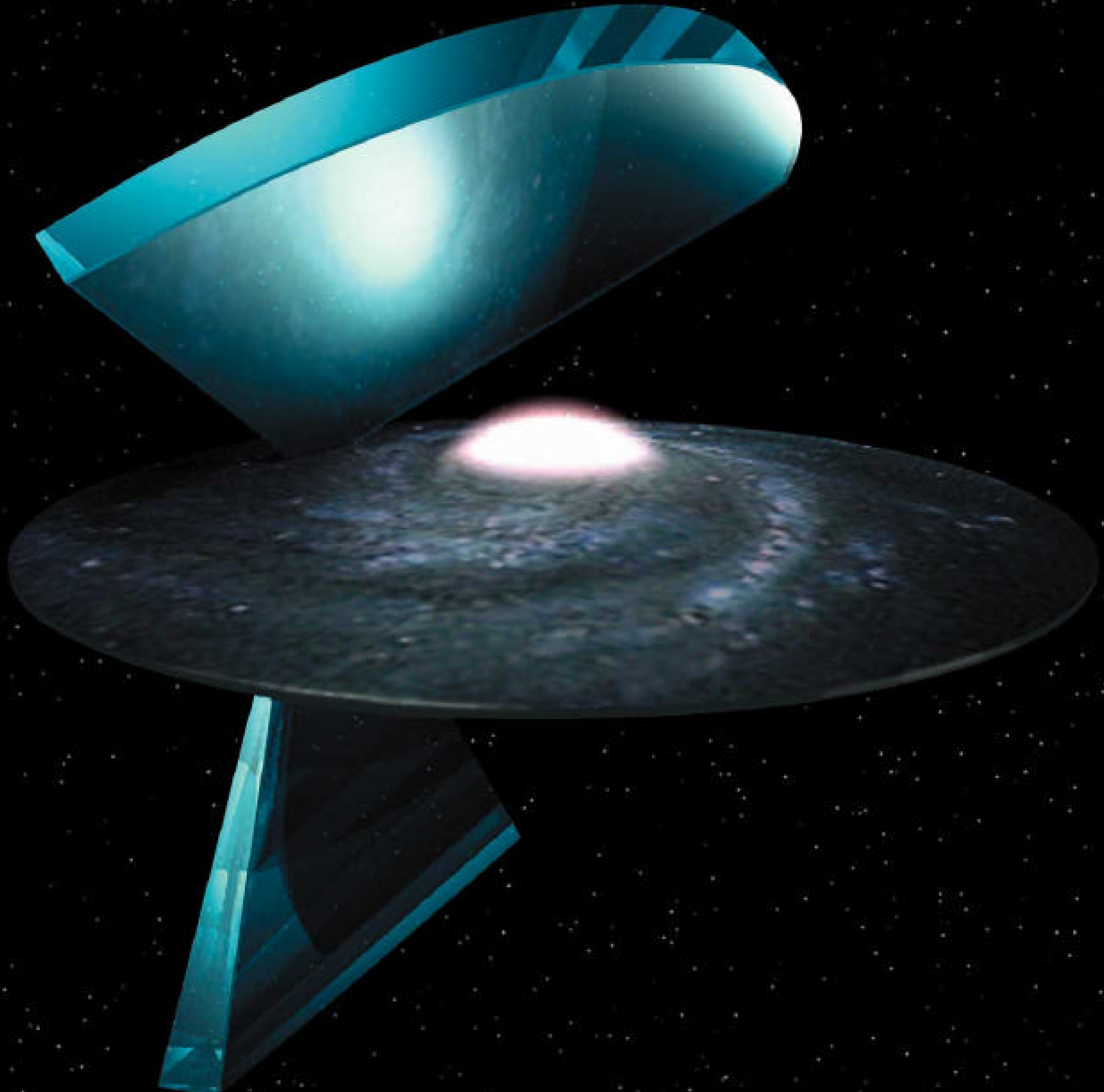
A cosmological constant detected at 2σ from CMBR alone. At 7σ if SN-Ia observations are used

$$\Omega_\Lambda = 0.51^{+0.20}_{-0.20}$$

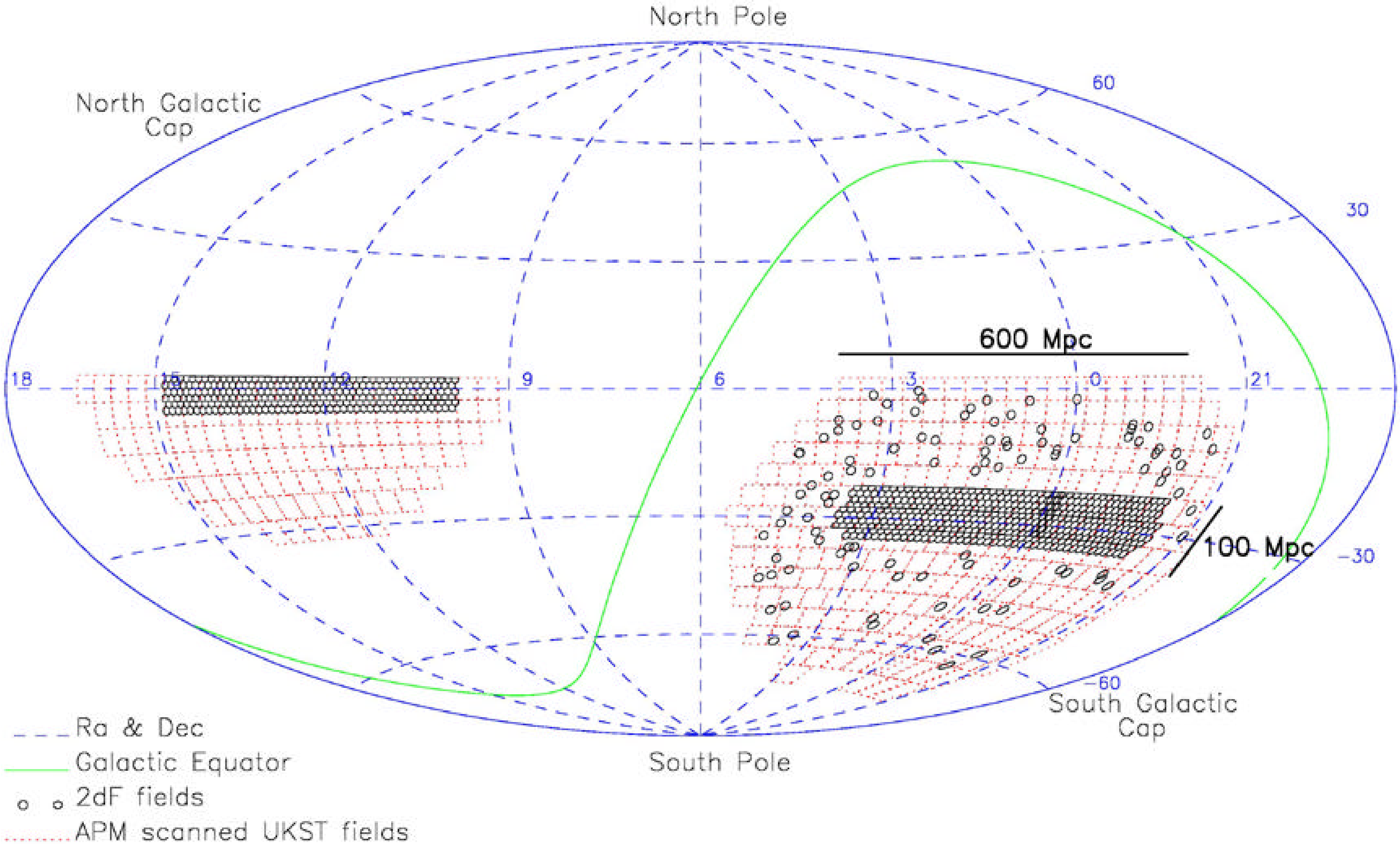


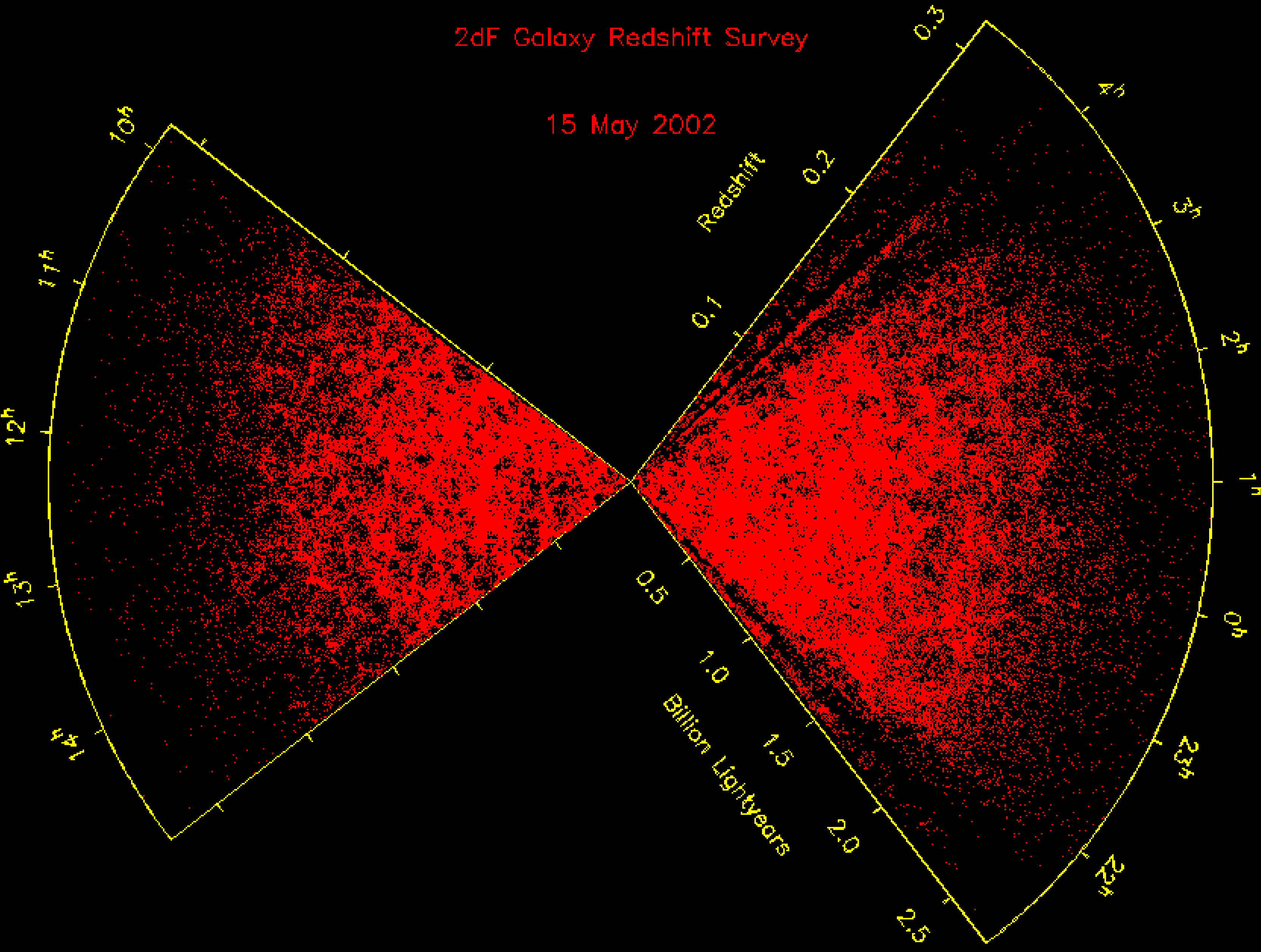
Boomerang collaboration ’01

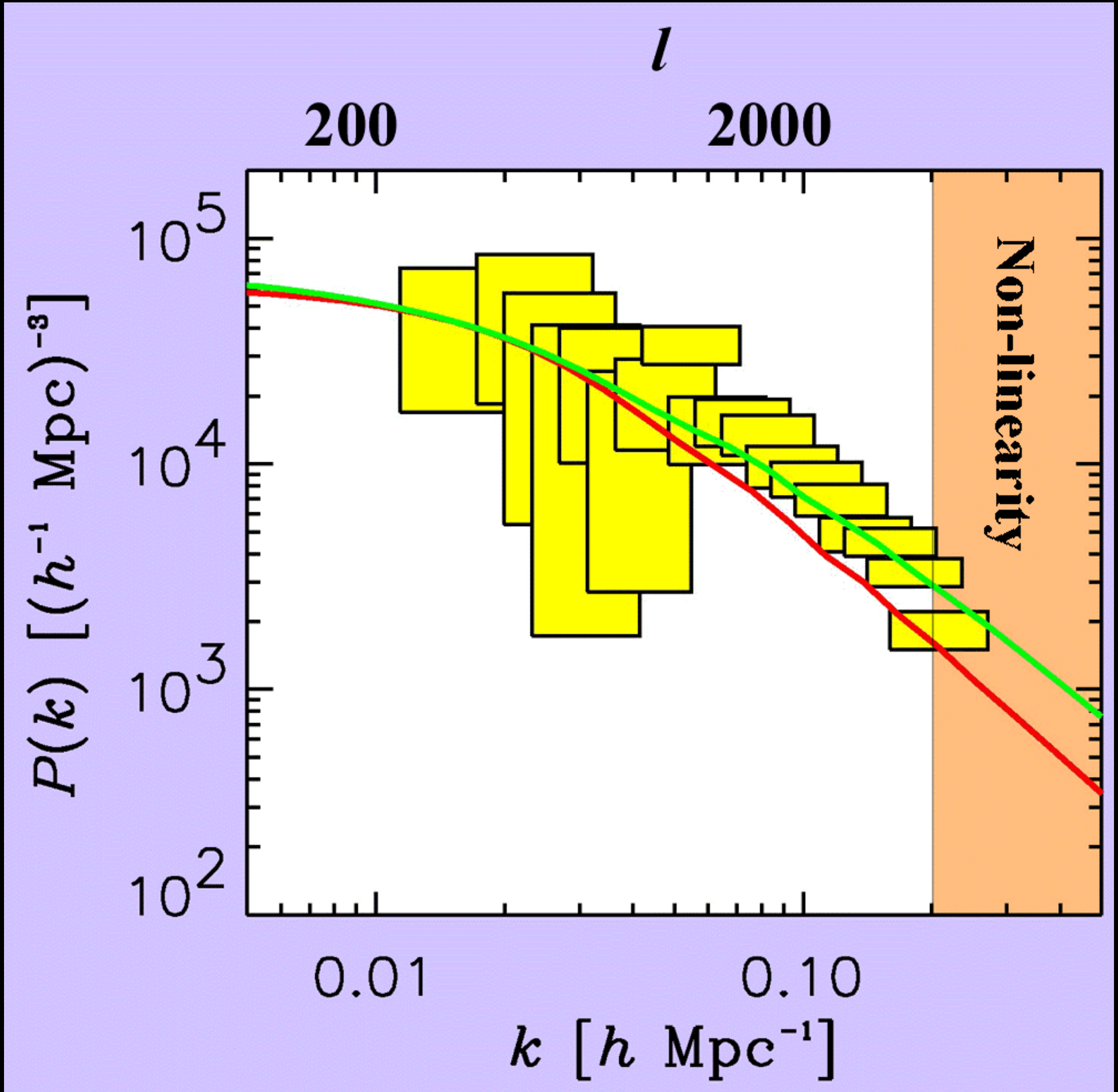
2dF SURVEY



All-sky map showing APM Survey



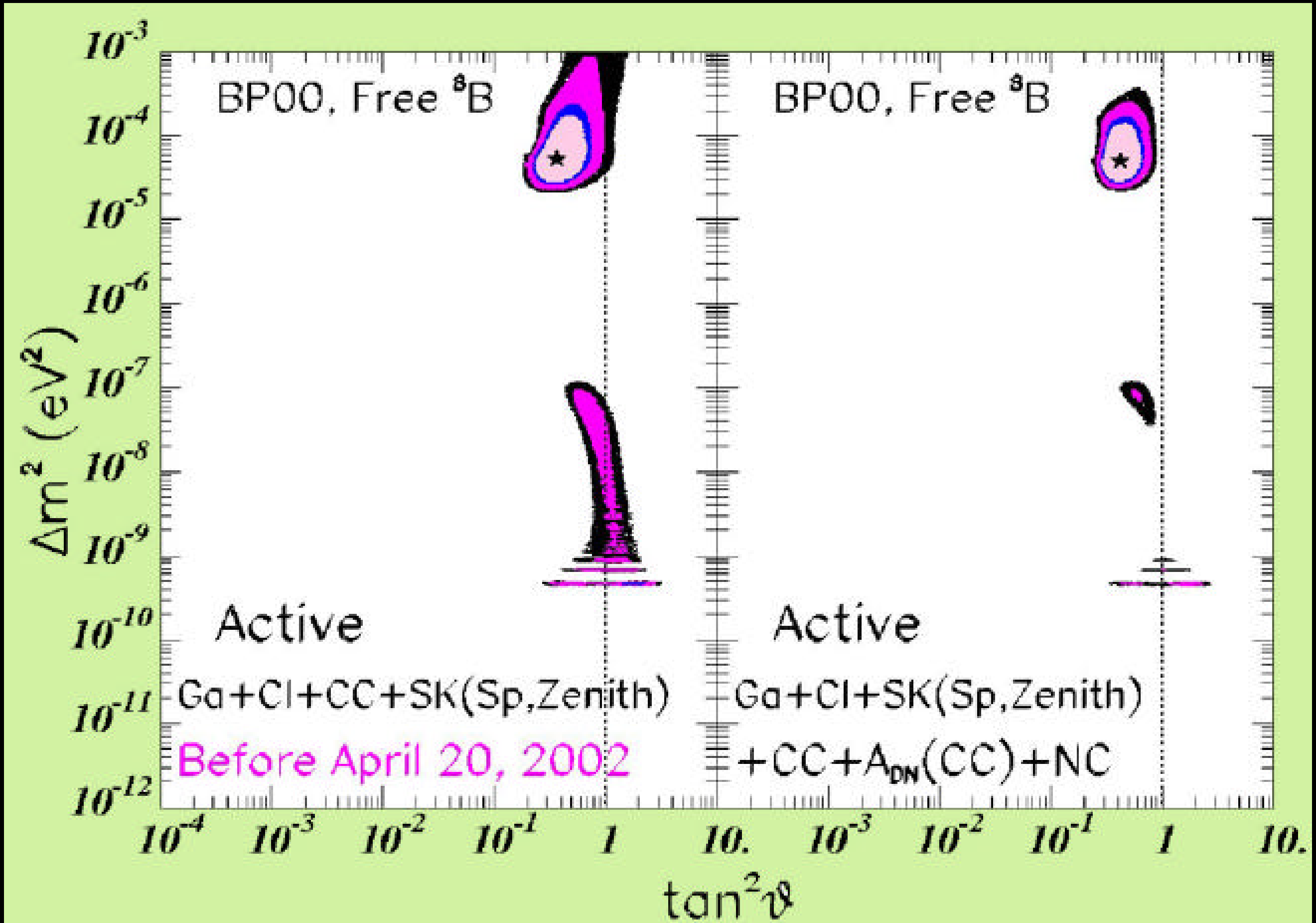

2dF Galaxy Redshift Survey
15 May 2002
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h



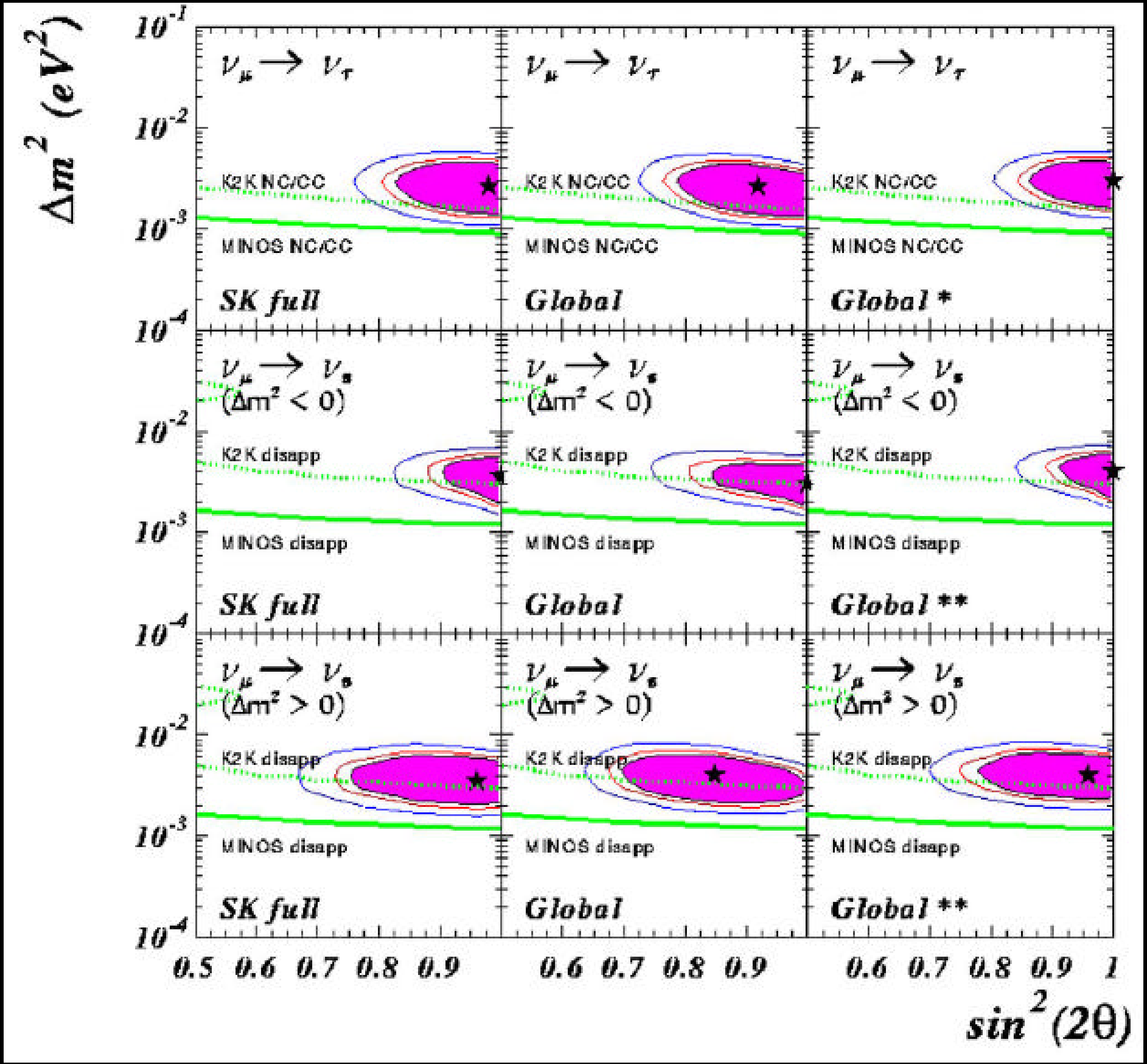
l
200
2000
10^5
10^4
10^3
10^2
$P(k)$ $[(h^{-1}$ Mpc$)^{-3}]$
Non-linearity
0.01
0.10
k $[h$ Mpc$^{-1}]$

ABSOLUTE NEUTRINO MASSES

Bahcall, Gonzalez-Garcia & Pena-Garay hep-ph/0204314
New global analysis including SNO NC and D/N data

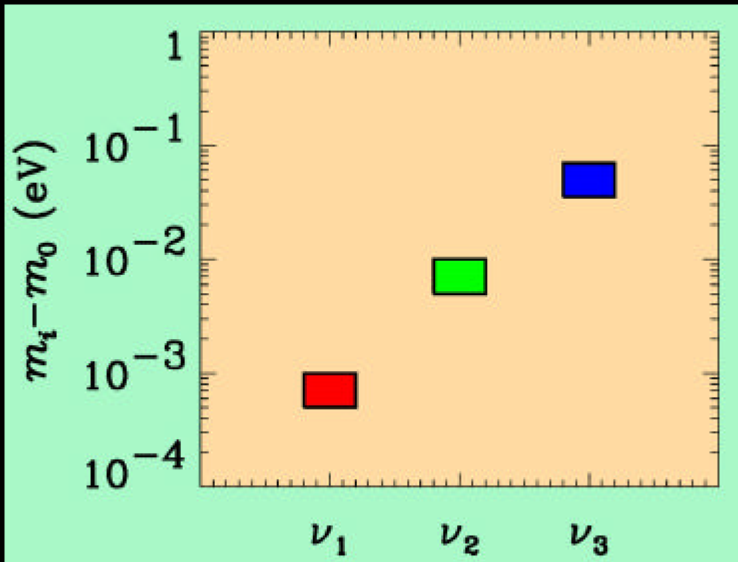


STATUS OF ATMOSPHERIC NEUTRINO PROBLEM

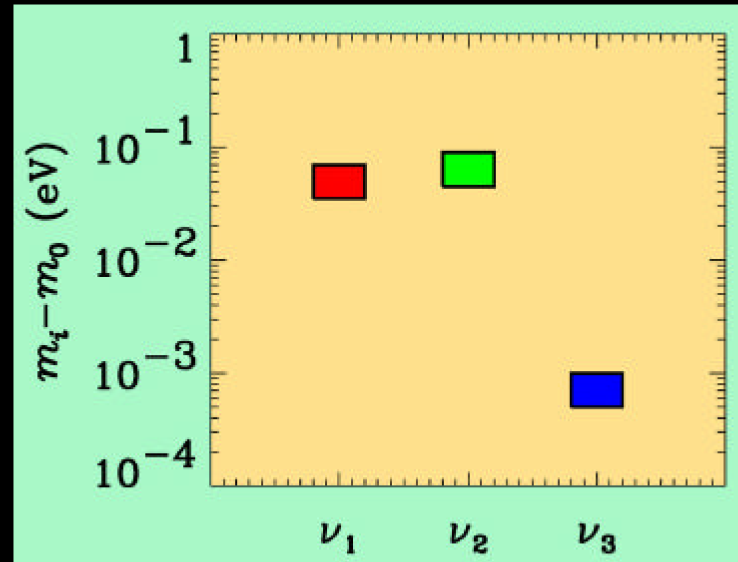


Fornengo, Gonzalez-Garcia & Valle '00

If neutrino masses are hierarchical then oscillation experiment
do give information on the absolute value of neutrino masses



Normal hierarchy



Inverted hierarchy

However, if neutrino masses are degenerate

$$m_0 >> dm_{\text{atmospheri c}}$$

no information can be gained from such experiments.

Experiments which rely on the kinematics of neutrino mass are most efficient for measuring m_0

Tritium decay endpoint measurements have reached limits on the electron neutrino mass (Weinheimer's talk)

$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2\right)^{1/2} \leq 2.2\ \text{eV} \quad (95\%)$$

Bonn et al. 2001 (Mainz experiment)

This translates into a limit on the sum of the three mass eigenstates

$$\sum m_i \leq 7\ \text{eV}$$

THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION BECAUSE THEY ARE A SOURCE OF DARK MATTER

HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

$$d_{\mathrm{FS}} \sim 1200\,\mathrm{Mpc}\; m_{\mathrm{eV}}^{-1}$$

SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO SUPPRESSION OF POWER ON SMALL SCALES

$$\frac{\Delta P}{P} \approx -8\,\frac{\Omega_n}{\Omega_m}$$

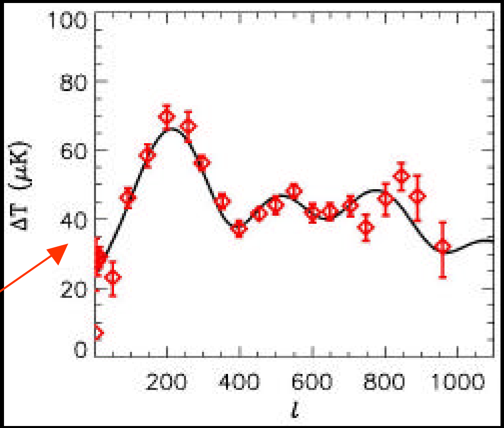
THIS ALLOWS FOR CONSTRAINTS ON m_n

THREE DIFFERENT PROBES

1) COSMIC MICROWAVE BACKGROUND
BOOMERANG,MAXIMA,CBI,DASI

PROBES VERY LARGE SCALES
d > 100-200 Mpc

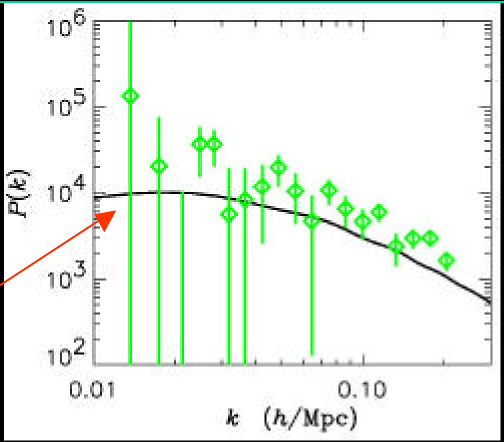
COMPILATION BY WANG ET AL.



2) LARGE SCALE STRUCTURE SURVEYS
PSCz,2df,SLOAN

PROBES INTERMEDIATE SCALES
d ~ 1-200 Mpc

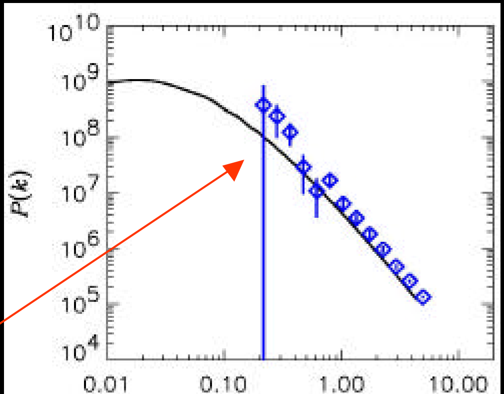
PSC-z SURVEY



3) FLUCTUATIONS IN LY-a FOREST AT HIGH Z

PROBES VERY SMALL SCALES
d ~ 0.1-10 Mpc

CROFT ET AL., DATA FROM <z>=2.72



Neutrino masses have very little influence on the CMB spectrum because CMB measures scales much larger than the free streaming length for eV neutrinos

Neutrino masses have a big influence on large scale structure because the LSS length scales are comparable to, or smaller than, the free streaming length for eV neutrinos

m_n (eV)	l_{FS}	k_{FS} (Mpc^{-1})	$\Omega_\nu h^2$	
0.1	20	0.001	0.001	COBE
0.5	100	0.005	0.005	BOOMERANG
1	200	0.01	0.02	BOOMERANG LSS
5	1000	0.05	0.05	BOOMERANG LSS
10	2000	0.1	0.1	LSS

$\Omega_0 = 1.0$

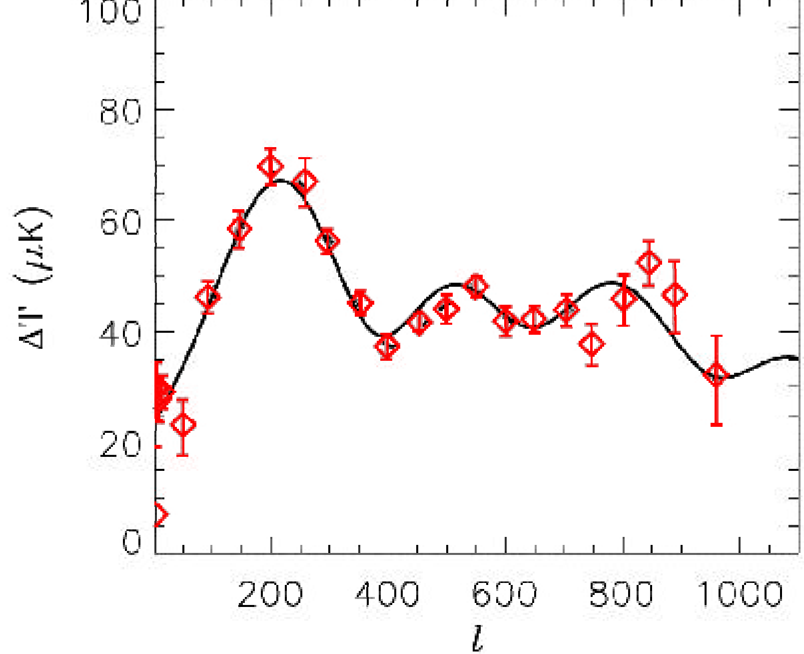
$\Omega_\Lambda = 0.66$

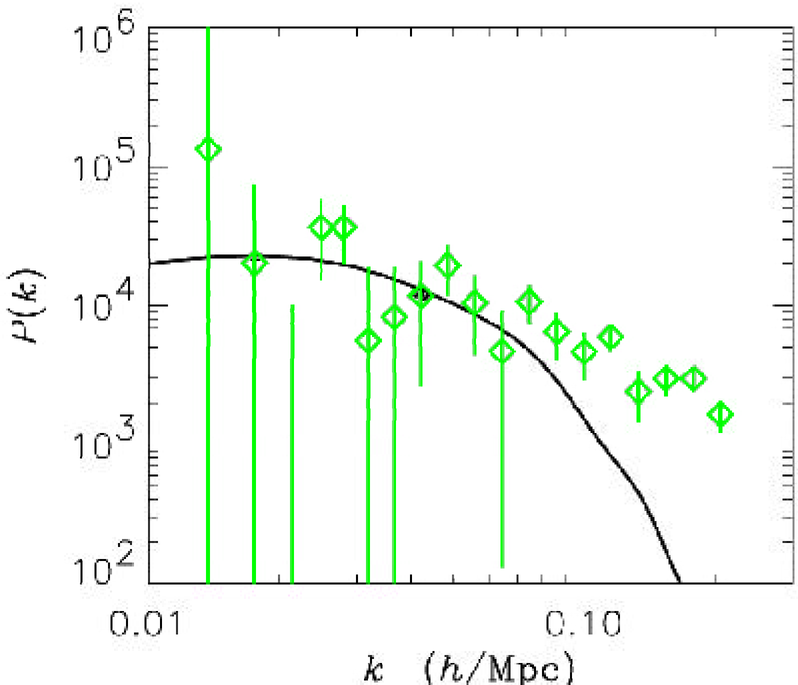
$\Omega_b = 0.04$

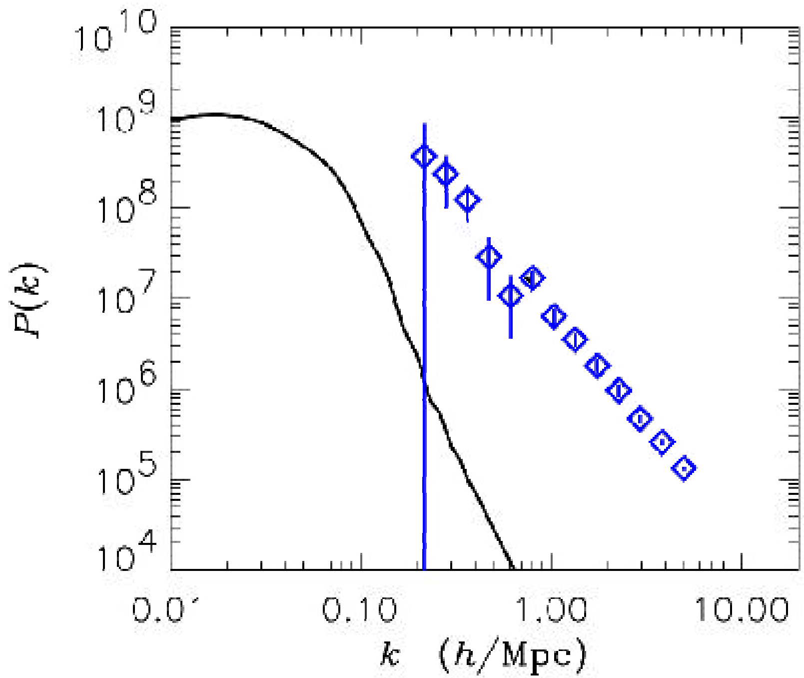
$H_0 = 72$

$n_s = 0.94$

$\Omega_\nu = 0.25$

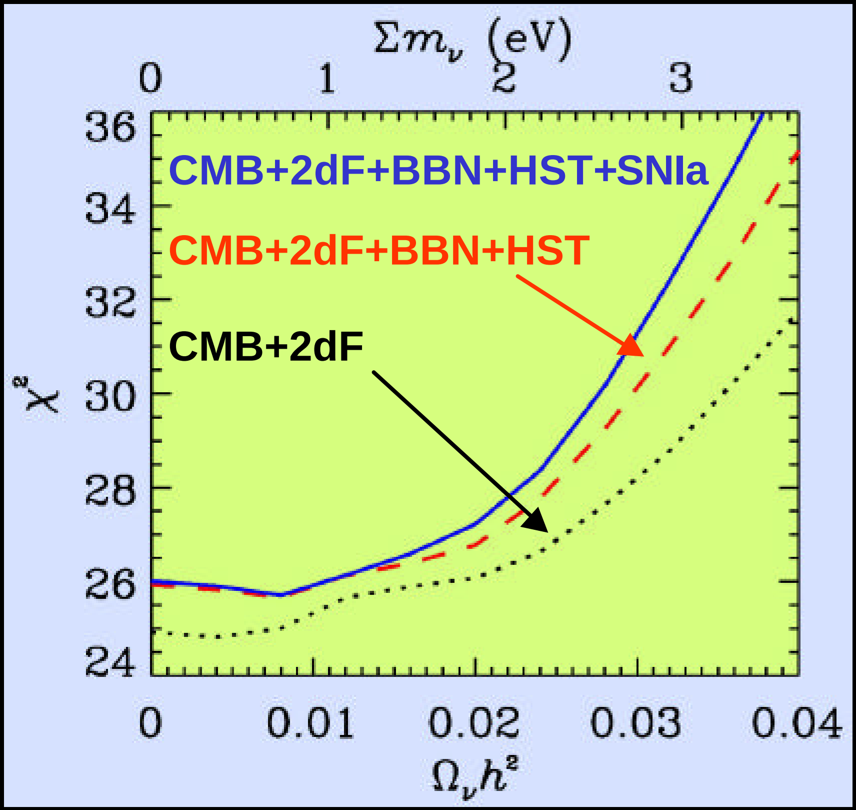






Upper limit using the best available present data

$$\sum m_n < 2.5 - 3\,\text{eV (95\%)}$$



SH, astro-ph/0205223, 2002

This limit depends on the chosen parameter space and priors on other parameters

The 2dF collaboration finds

$$\sum m_n \le 1.8 - 2.2\,\text{eV (95\%)}$$

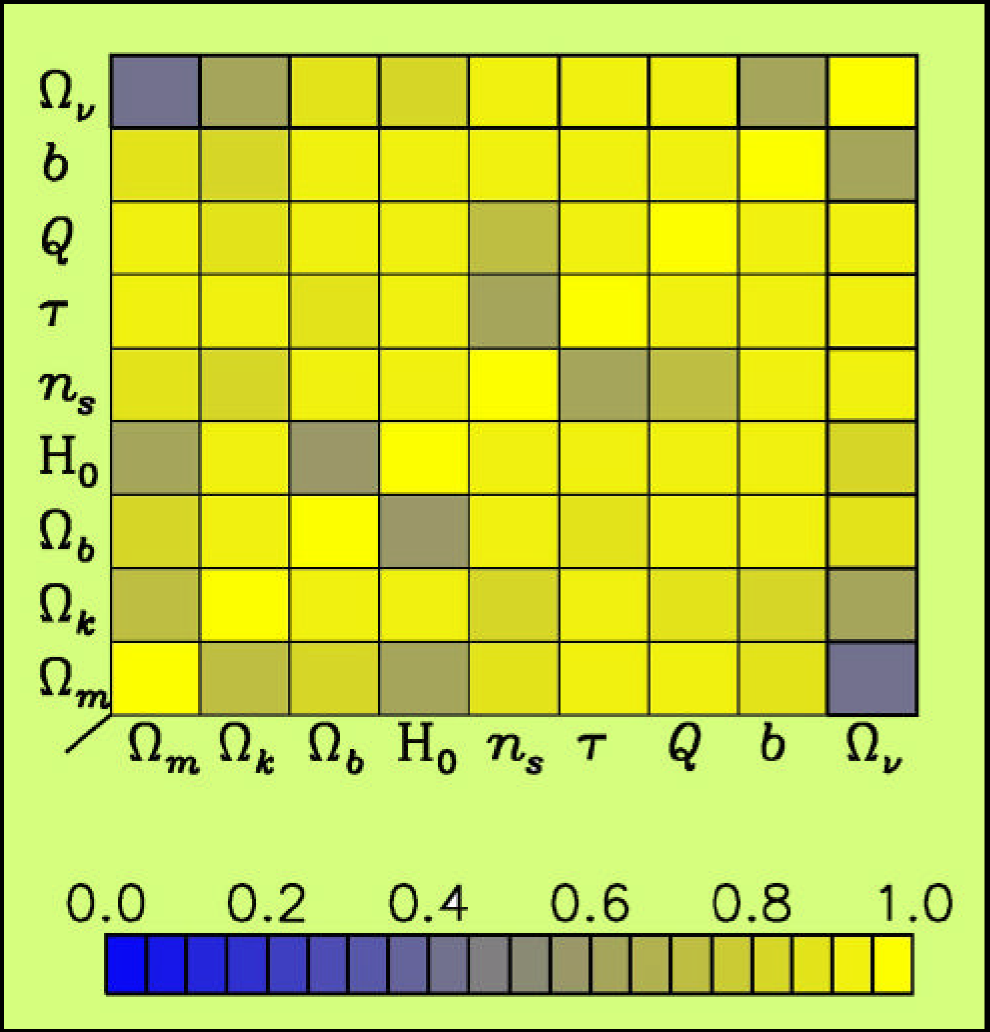
For a more restricted paramete
space
Elgaroy et al., astro-ph/020415
(Lewis & Bridle, astro-ph/0205436)

The degeneracy between neutrino mass and other cosmologica parameters can be studied using a Fisher matrix analysis

”Degeneracy parameter” r_{ij} is defined as

$$r_{ij} \equiv \frac{s_{j\,\mathrm{fixed}}(q_i)}{s_{j\,\mathrm{free}}(q_i)}$$

Main degeneracies are with Ω_m and b, the bias parameter (normalization of the large scale structure power)



$_m = 0.28\,, \Omega_\Lambda = 0.72$

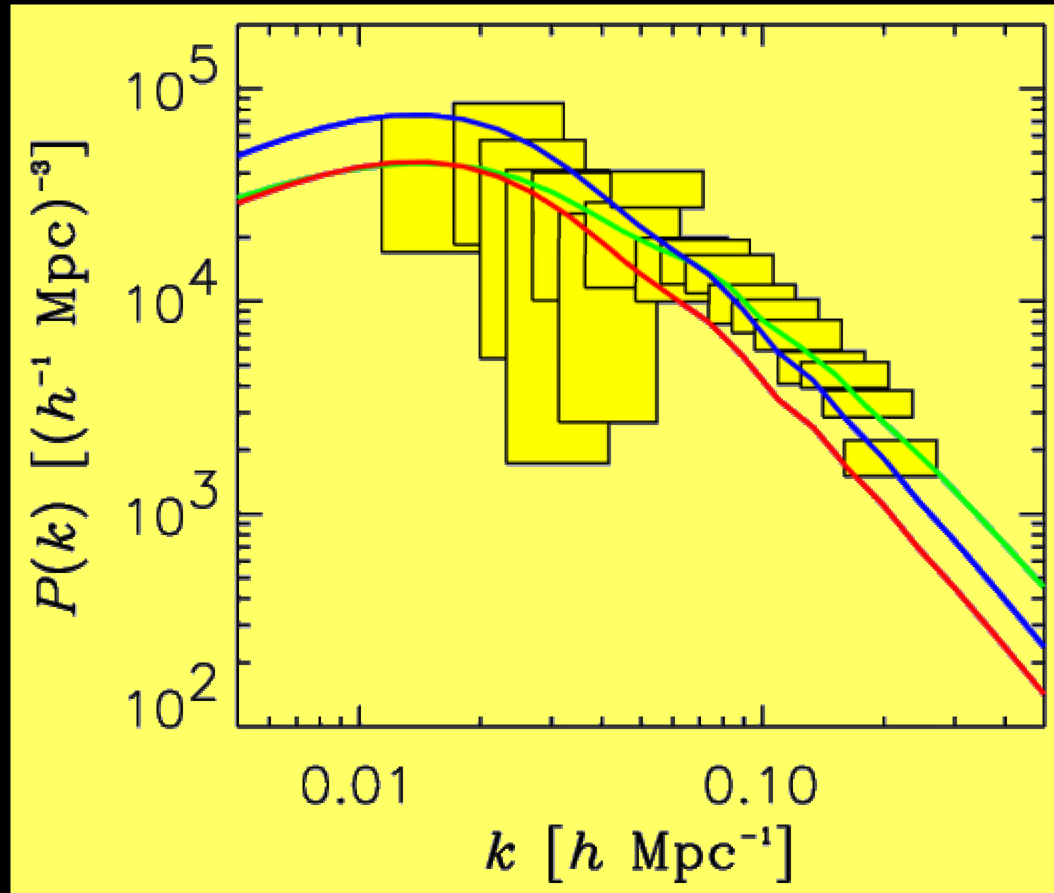
$_n = 0\,, b = 1$

$_m = 0.28\,, \Omega_\Lambda = 0.65$

$_n = 0.07\,, b = 1$

$_m = 0.28\,, \Omega_\Lambda = 0.65$

$_n = 0.07\,, b = 0.83$

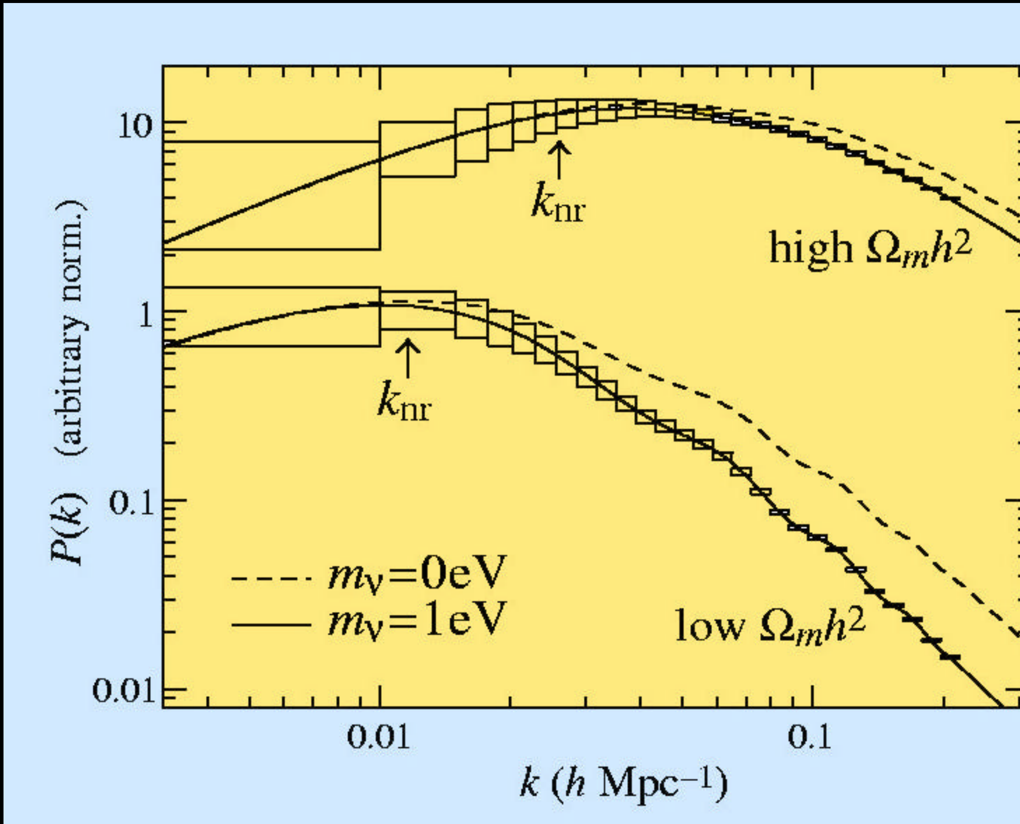


FUTURE POSSIBILITIES

Combining CMB data from MAP/Planck with SLOAN survey could give

$$\sum m_n < 0.3\,\text{eV}$$

A precision comparable to the KATRIN experiment



Hu, Eisenstein & Tegmark 1998

LIMITS ON THE NUMBER OF NEUTRINO SPECIES AND THE COSMOLOGICAL NEUTRINO LEPTON NUMBER

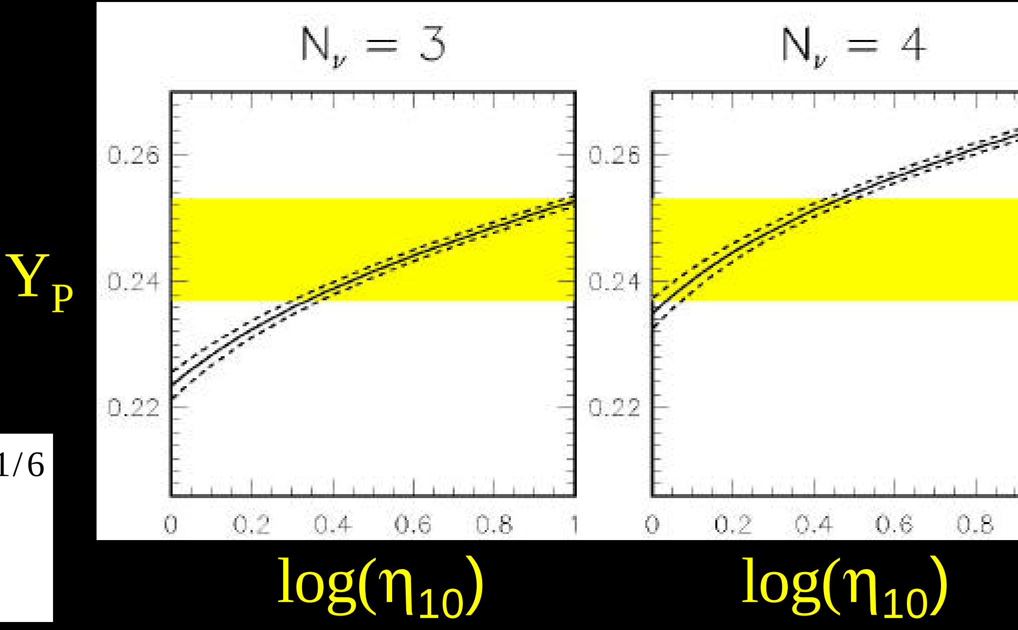
Extra energy density can be parameterized as:

$$\Delta N_n \equiv \frac{\Delta r}{r_n}$$

THE HELIUM ABUNDANCE DEPENDS ON ΔN_ν

$$\frac{^4\mathrm{He}}{\mathrm{H}} \approx \frac{2n/p}{1+n/p}\Big|_{T=0.2\,\mathrm{MeV}}$$

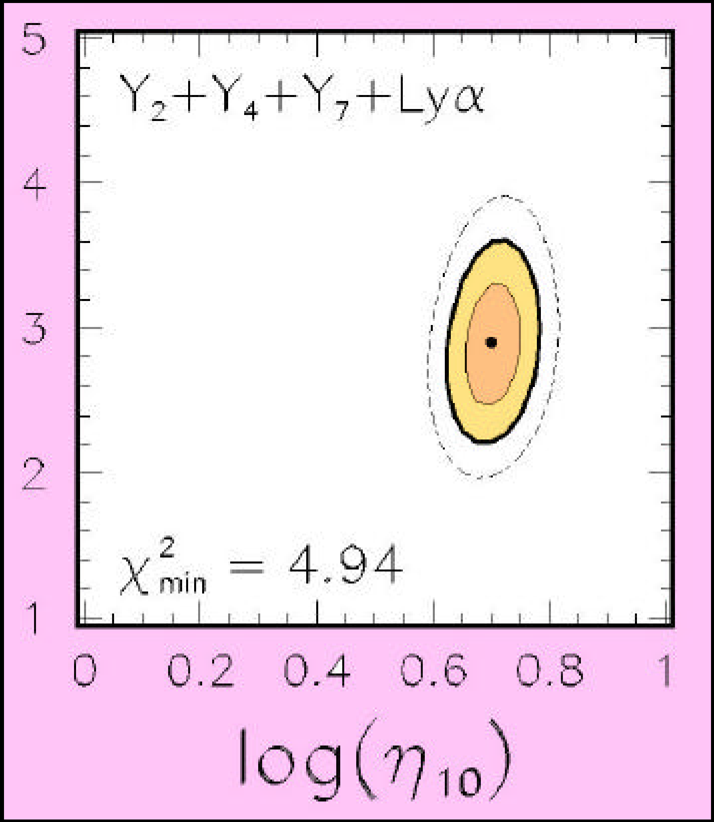
$$(n/p)_{\text{at He formation}} \propto \left(\frac{43}{4}+\frac{7}{4}\Delta N_n\right)^{1/6}$$



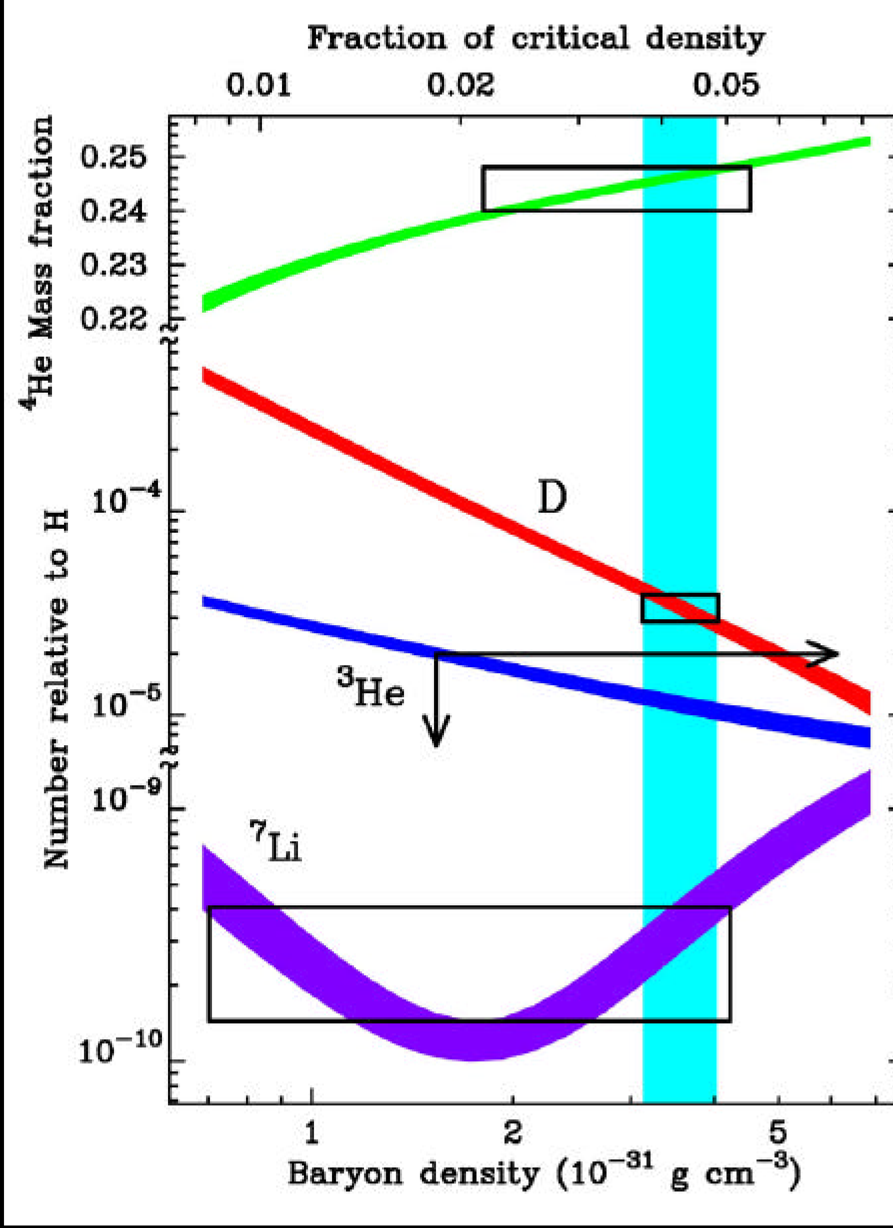
Lisi, Sarkar & Villante 1998

Present upper limit

$$N_n \leq 4$$



Lisi, Sarkar & Villante 1998



Burles, Nollett & Turner 1999

NEUTRINO CHEMICAL POTENTIAL

Previous limit assumes no chemical potential for the active species (i.e. extra energy is in other species)

$$f_n = \frac{1}{\exp\left(\frac{E_n}{T} - x_n\right) + 1} \ , \ f_{\bar{n}} = \frac{1}{\exp\left(\frac{E_{\bar{n}}}{T} + x_n\right) + 1} \ , \ x_n \equiv \frac{m_n}{T}$$

$$n_e + n \leftrightarrow e^- + p$$

$$e^+ + n \leftrightarrow \bar{n}_e + p$$

$$n \leftrightarrow e^- + p + \bar{n}_e$$

Increasing ξ_{ν_e} decreases *n/p* so that N_ν can be much higher than 4

Yahil ’76, Langacker ’82, Kang&Steigman ’92, Lesgourgues&Pastor ’99, Lesgourgues&Peloso ’00, Hannestad ’00, Orito et al. ’00, Esposito et al. ’00, Lesgourgues&Liddle ’01, Zentner & Walker ’01

BBN alone: $-0.06 \leq x_e \leq 1.1 \ , \ \left| x_{m,t} \right| \leq 6.9$

CMB IS ALSO SENSITIVE TO N_ν VIA THE EARLY INTEGRATED SACHS-WOLFE EFFECT

$$\frac{\Delta E_g}{E_g} \sim \int \dot{f}(r(t),t)\,dt$$

$$\dot{f} = 0 \text{ if } O_m = 1$$

$$\dot{f} \neq 0 \text{ if } O_\Lambda \neq 0 \qquad \text{(LATE ISW)}$$

$$\dot{f} \neq 0 \text{ if } r_R / r_M \neq 0 \qquad \text{(EARLY ISW)}$$

LARGE SCALE STRUCTURE IS SENSITIVE TO N_ν BECAUSE HUBBLE RADIUS AT MATTER-RADIATION EQUALITY INCREASES

$$k_{\rm eq} \sim 0.1\,{\rm Mpc}^{-1}(0.595 + 0.135 N_n)^{1/2}$$

Dodelson, Gyuk & Turner '94

CMB AND LARGE SCALE STRUCTURE ARE ONLY SENSITIVE TO ENERGY DENSITY, NOT FLAVOUR

THE CAVEAT IN THE BBN BOUND CAN BE AVOIDED

$\Omega_0 = 1.0$

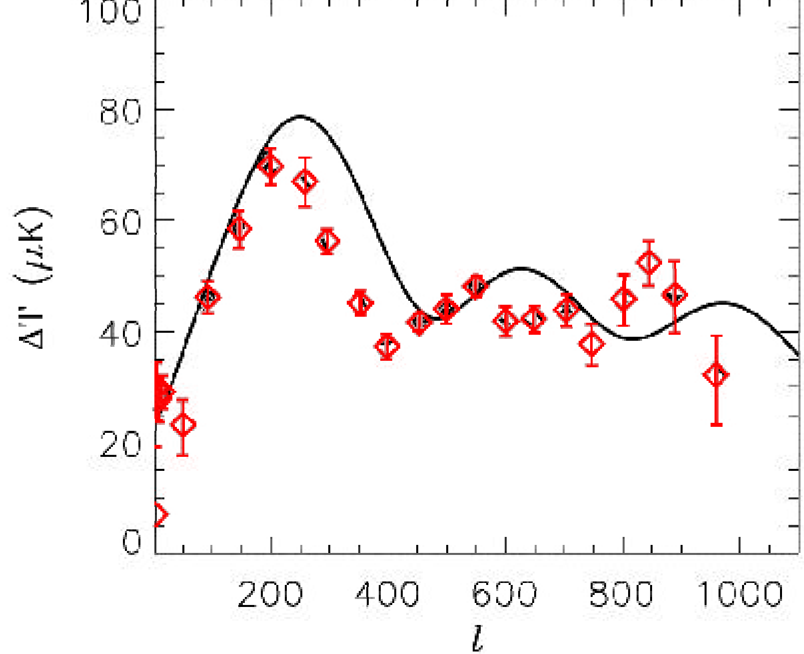
$\Omega_\Lambda = 0.66$

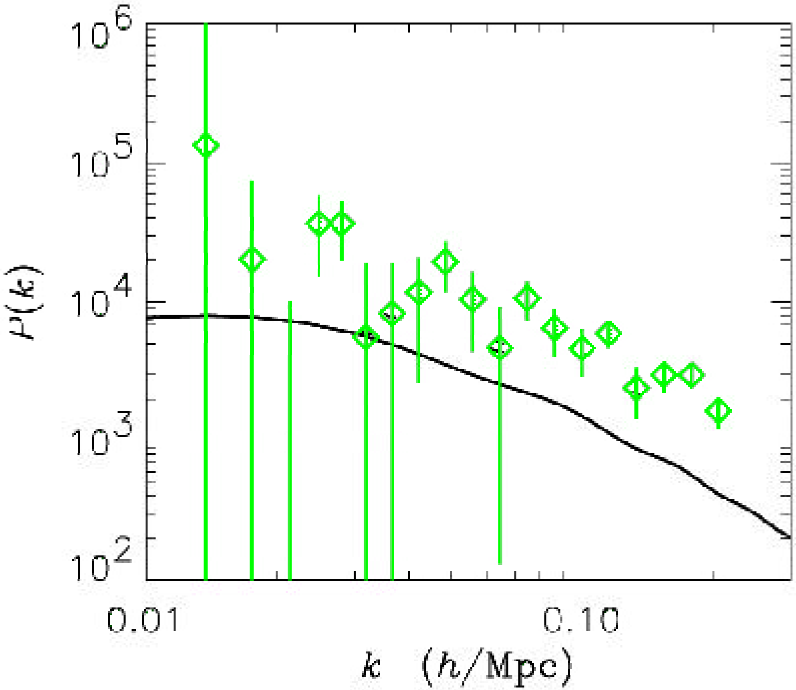
$\Omega_b = 0.04$

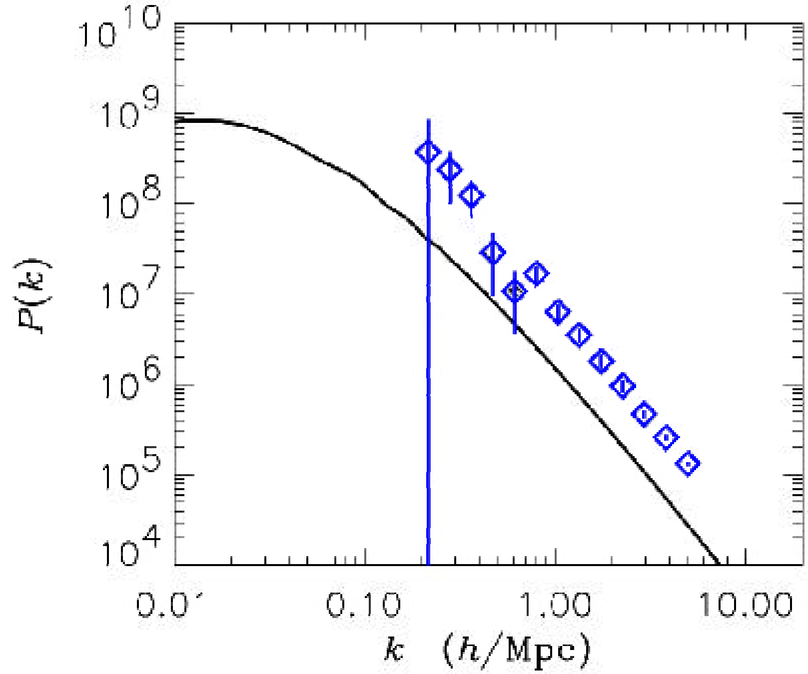
$H_0 = 72$

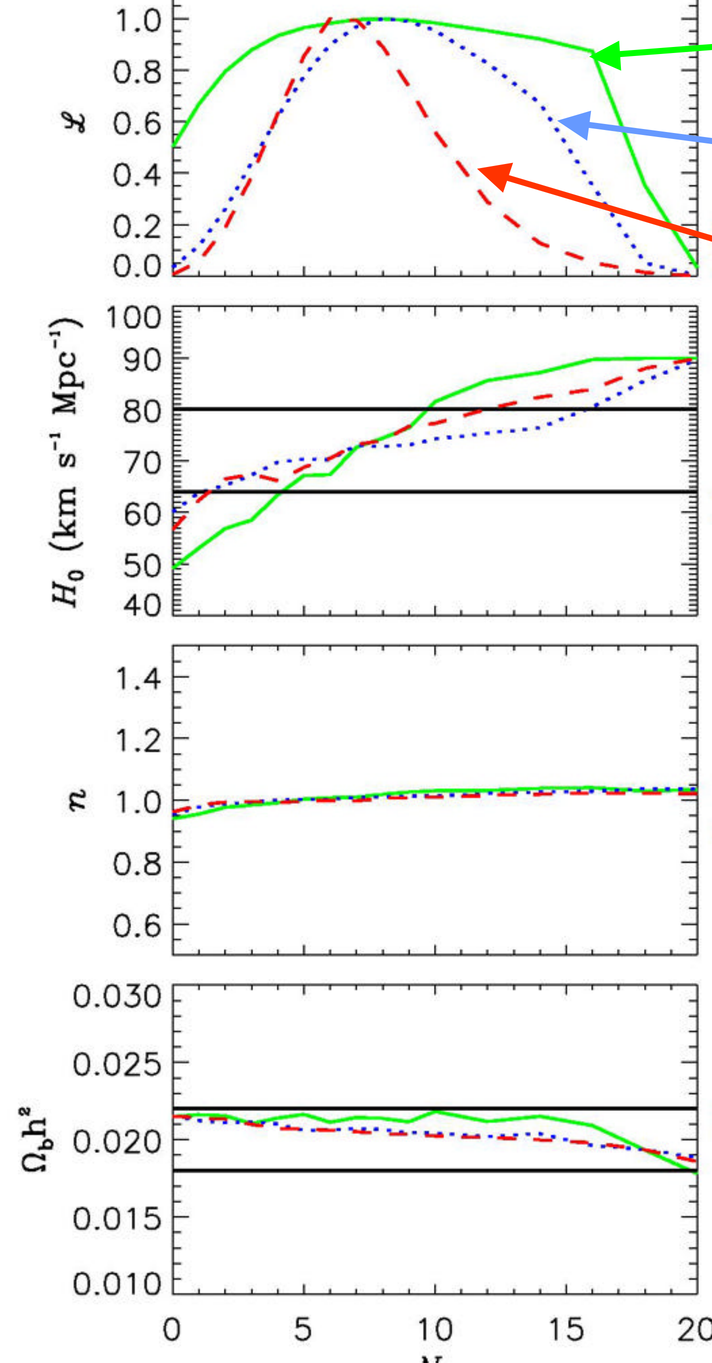
$n_s = 0.94$

$N_\nu = 13$









CMB no priors

CMB + H_0

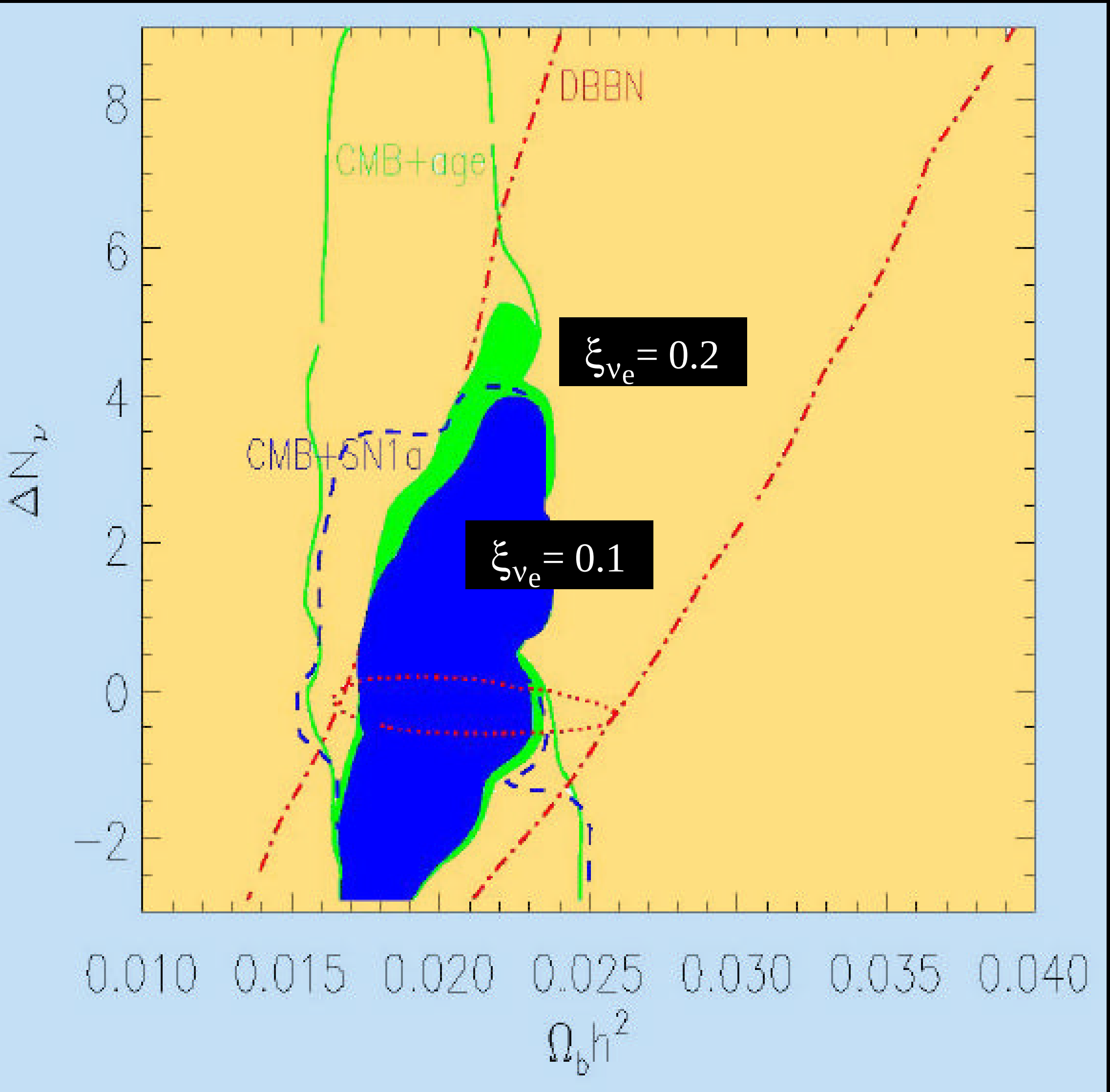
CMB + H_0 + LSS

ANALYSIS OF PRESENT DATA
GIVES A LIMIT ON N_ν OF

$$1.5 \le N_n \le 13$$

FIRST INDEPENDENT DETECTION
OF COSMIC NEUTRINO BACKGROUND

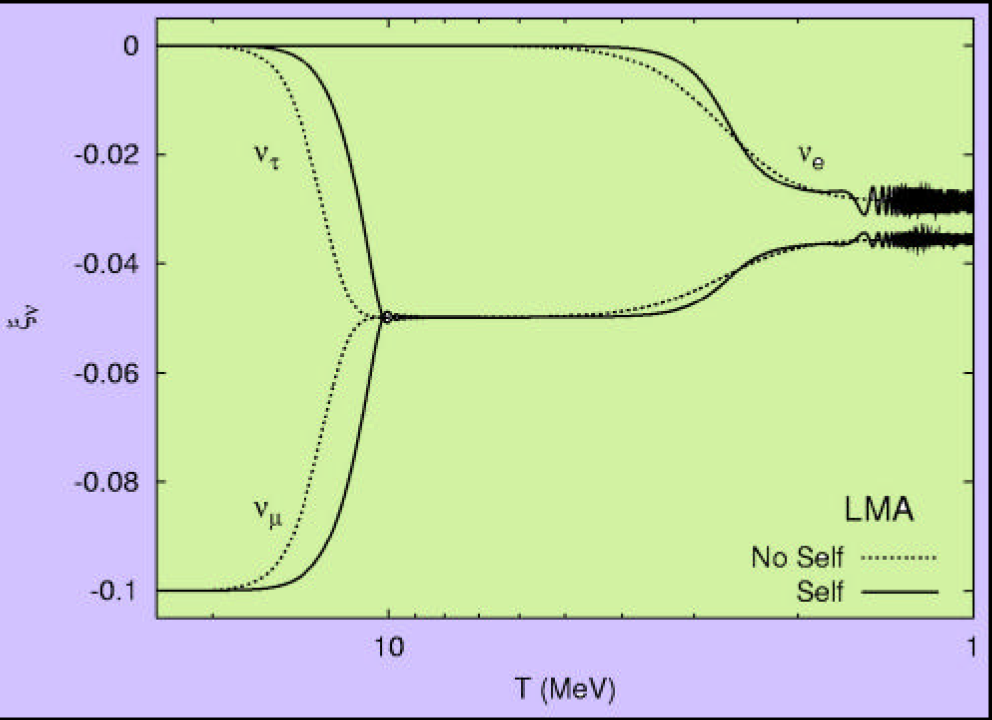
SH 2001

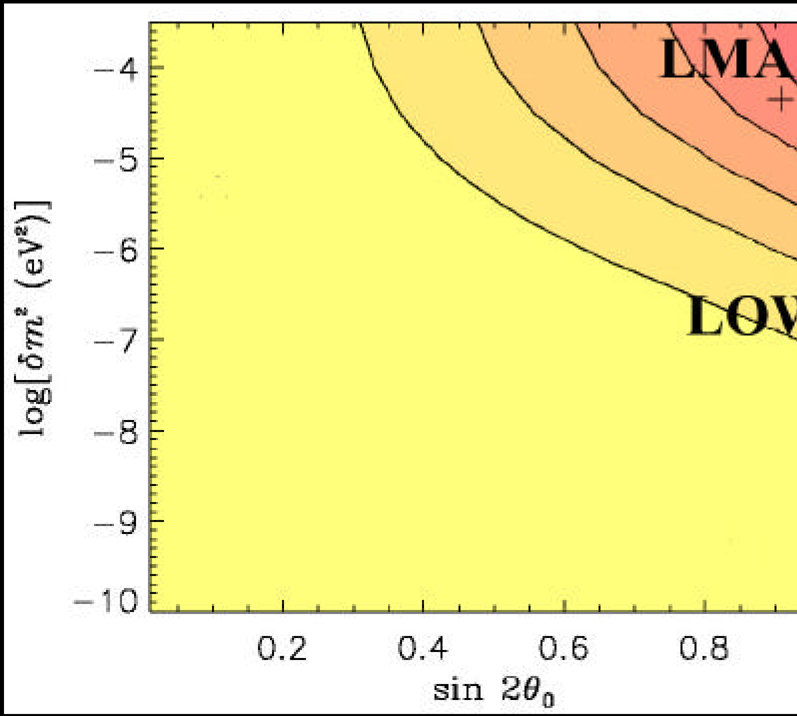


Hansen et al. 2001

Combining CMB and BBN breaks the degeneracy and allows for strong constraint on neutrino chemical potentials

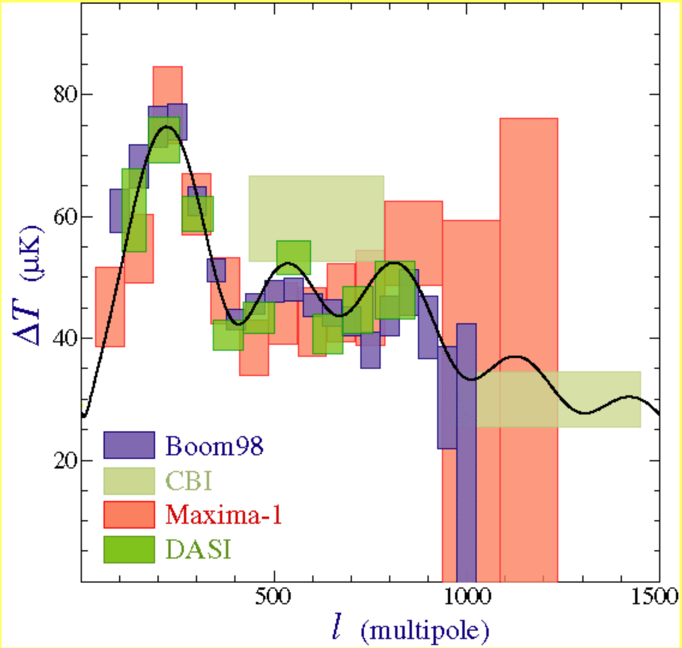
If oscillations are taken into account these bounds become much tighter from BBN alone:

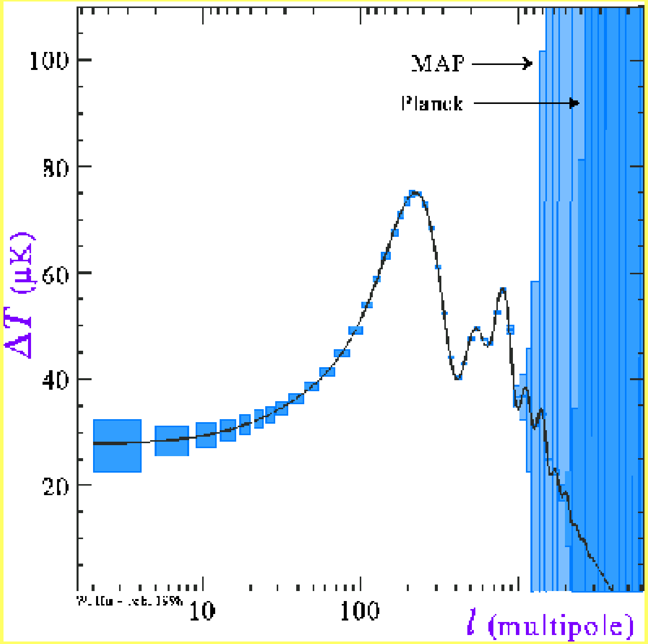


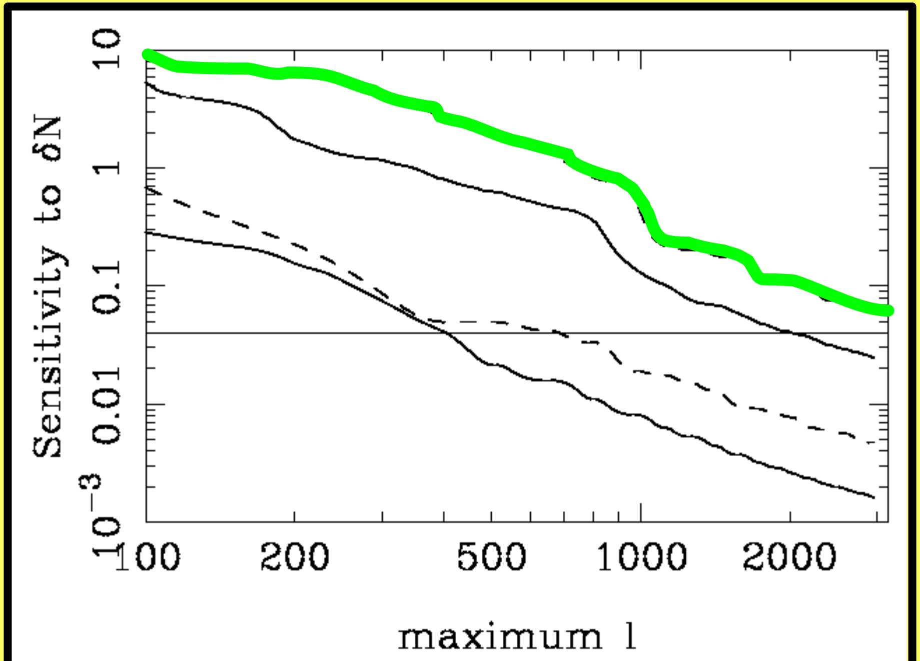


Dolgov et al., hep-ph/0201287
Abazajian, Beacom & Bell, astro-ph/0203442
Wong hep-ph/0203180

PROSPECTS FOR THE FUTURE







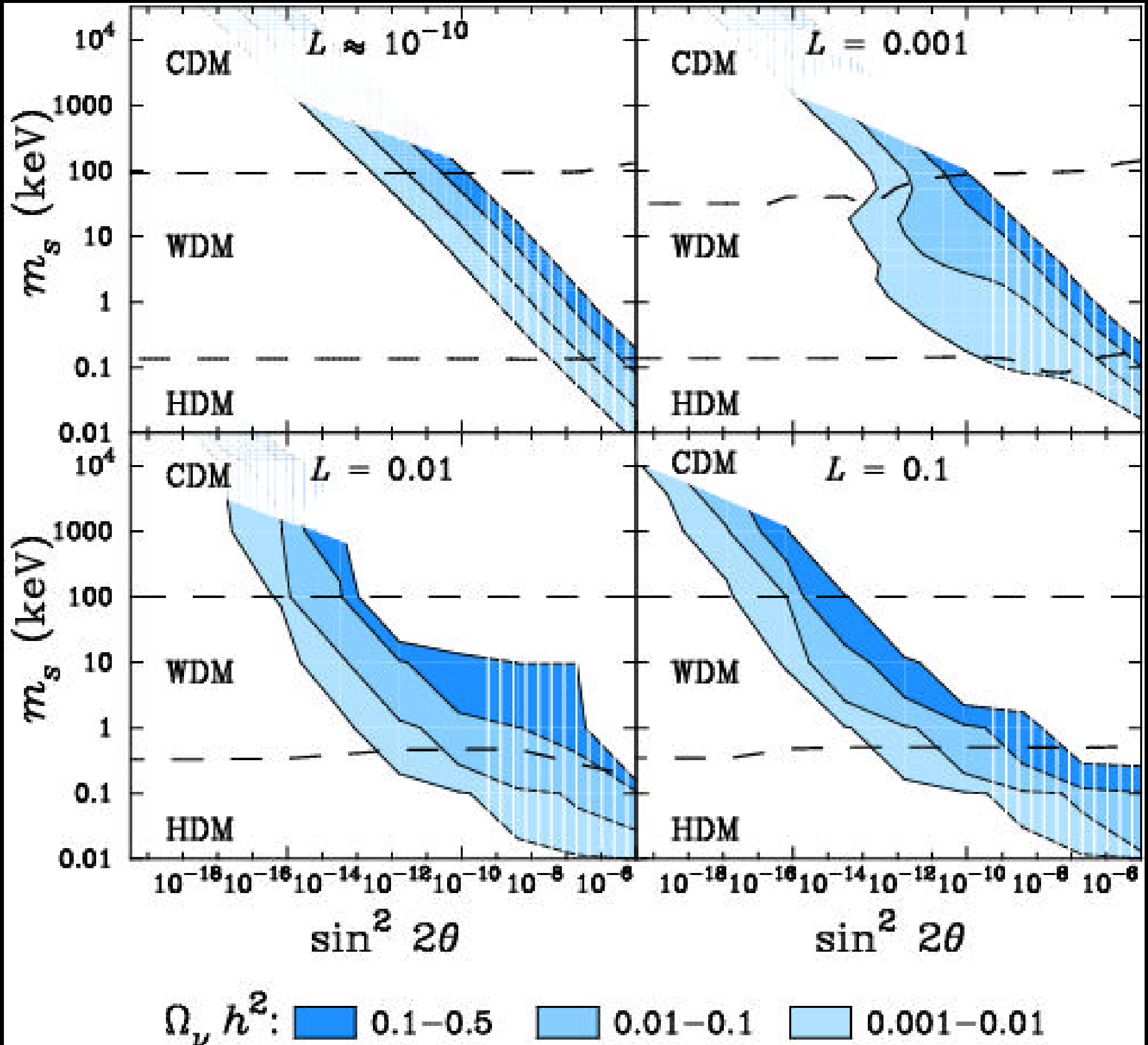
DATA FROM MAP/Planck may allow for very accurate determination of N_n

Standard model prediction N_n =3.03-3.04 due to heating and finite temperature effect could be detected

Lopez et al. 1998

Sterile neutrino dark matter

STERILE NEUTRINOS WITH keV MASSES AND VERY SMALL MIXING PROVIDE AN INTERESTING DARK MATTER CANDIDATE



Dodelson&Widrow '94,
Shi&Fuller '99,
Dolgov&Hansen '00,
Abazajian, Shi&Fuller '01

CONCLUSIONS

- COSMOLOGY HAS BECOME AN INCREASINGLY POWERFUL PROBE OF NEUTRINO PROPERTIES

- $\sum m_n \leq 2.5 - 3\,\mathrm{eV}$ $1.5 \leq N_n \leq 13$

  $x_n \leq 3\,(0.07$ if LMA is correct)

- NEUTRINO PHYSICS IS NO LONGER A "FREE PARAMETER" IN ASTROPHYSICS AND COSMOLOGY

- IN THE COMING YEARS, TERRESTRIAL EXPERIMENTS ARE LIKELY TO MEASURE SOME OF THE RELEVANT PARAMETERS VERY PRECISELY, BUT COSMOLOGY WILL REMAIN AN EXCELLENT AND COMPLEMENTARY LAB FOR NEUTRINO PHYSICS