NEUTRINOS IN COSMOLOGY & ASTROPHYSICS

The Role in Cosmology

* Baryon number generation via leptogenesis (possible)

Nucleosynthesis: n/p ratio or ^{4}He abundance

* Large scale structure; CMB multipoles (negative roles)

The Role in Astrophysics

Core-collapse supernovae (crucial element)

Neuron star / White dwarf cooling

Carbon burning time scale

Critical mass for Helium ignition (Flash)

Observable Neutrinos

Type II supernovae: Burst and relic

* Solar neutrinos

Nitrogen flash (only academic interest?)

COSMOLOGICAL PARADIGM

Evolution of the Universe understood!

$H_0 = 71 \pm 5$ km s^{-1}Mpc^{-1}

$\Omega_m = 0.28 \pm 0.03, \qquad \Omega_\Lambda = 0.72 \pm 0.03$

$\Omega_m + \Omega_\Lambda = 1.01 \pm 0.01$ (flat universe)

$\Omega_b = 0.045$

6% stars; 2% neutral/H_2 gas

3% hot gas (X ray emitting)

90% warm/cool gas (invisible!)

Evolution of Large Scale Structure understood!

Measure: Power spectrum $P(k) = \int d^3x \langle \underbrace{\delta(x)\delta(0)}_{\xi(x)} \rangle e^{ikx}$

Matter = Non-baryonic = Cold Dark Matter

Fluctuation: Adiabatic, scale invariant spectrum

$$P(k) = |k|^n \text{ with } n = 1 \pm 0.02$$

Consistent with Inflation

Growth by Gravitational instability

We Need:

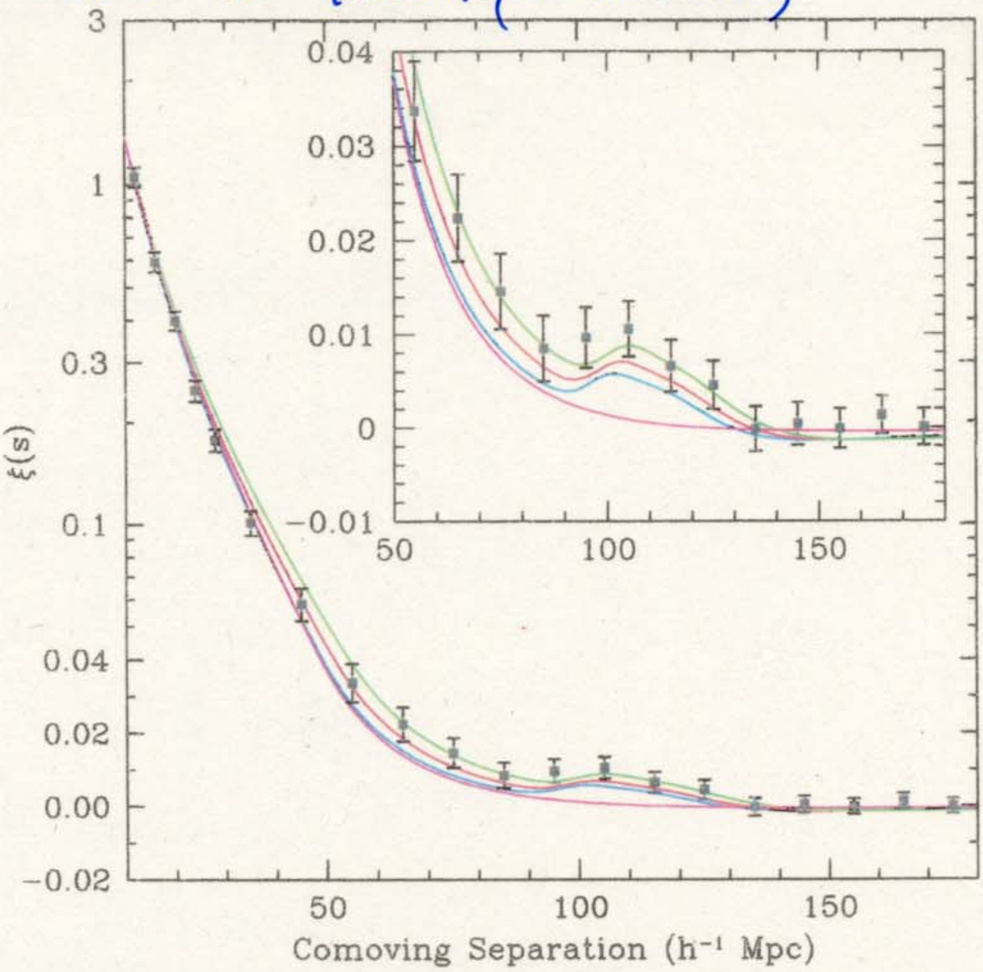
Cold dark matter

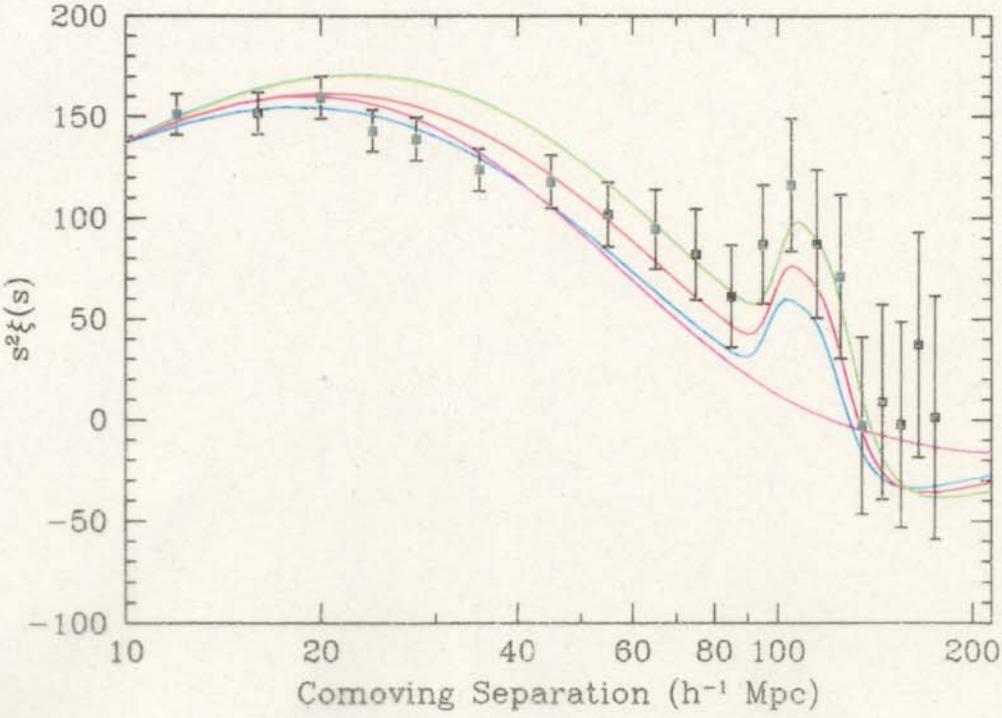
Vacuum (-like) energy

Inflation / inflaton

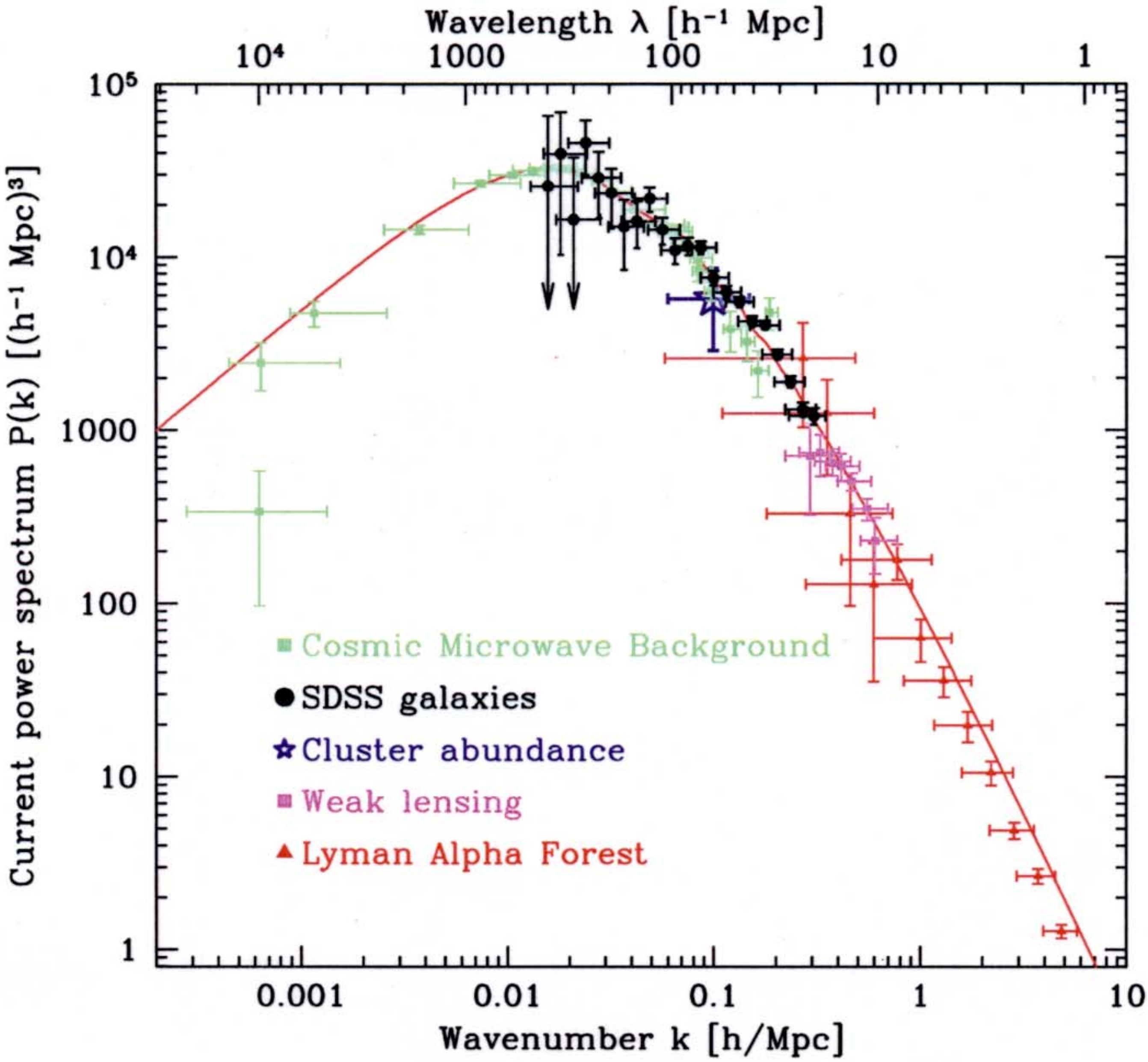
SDSS: Eisenstein et al. 2005

Acoustic Peak in Galaxy Clustering





SDSS : Tegmark et al 2003



CMB ⟷

galaxy clustering ⟷

Lensing ⟷

Ly α ⟷

Role of Neutrinos in Structure Formation

(1) Free-streaming (when hot) damps fluctuations

Suppress small scale structure

$$M \lesssim 10^{18} M_{\odot} (m_{\nu}/1eV)^2$$

Empirical $P(k)$ gives a constraint on Ω_{ν}

At large scale: CMB multipoles (WMAP)

At small scale:

(a) Galaxy clustering $\xi(x) = \langle \delta(x)\delta(0) \rangle$

SDSS+WMAP (Tegmark et al. 2003)

$\sum m_{\nu} < 1.7$ eV (95%) $\lesssim 1$ eV 2dF

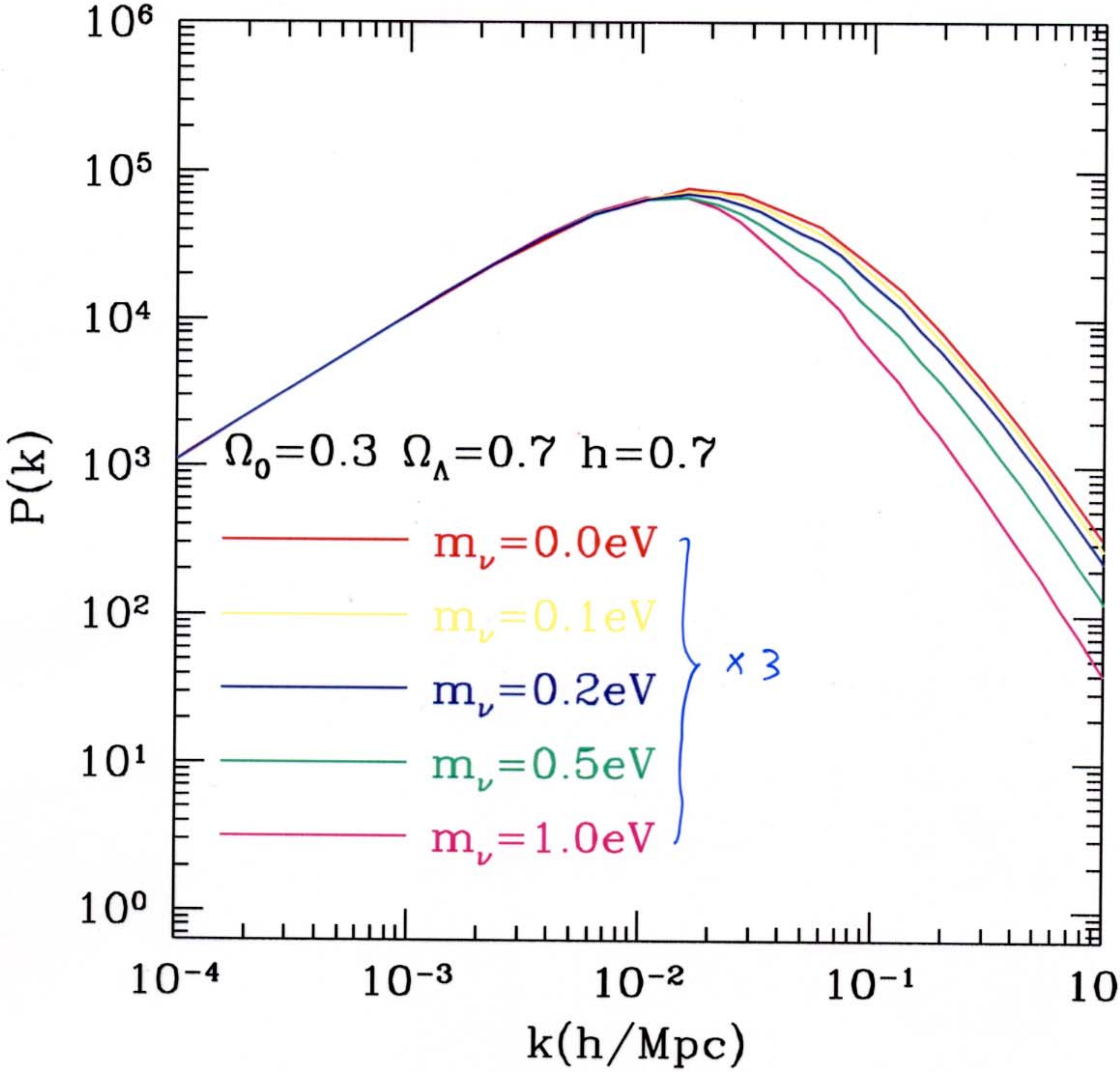
(b) Cluster abundance

(c) Lyman α clouds (low-density hydrogen clouds)

SDSS(galaxy+Lyα)+WMAP (Seljak et al.)

$\sum m_{\nu} < 0.42$ eV (95%)

(d) Gravitational lensing - cosmic shear



10^6
10^5
10^4
10^3
10^2
10^1
10^0
P(k)
Ω_0=0.3 Ω_Λ=0.7 h=0.7
m_ν=0.0eV
m_ν=0.1eV
m_ν=0.2eV
m_ν=0.5eV
m_ν=1.0eV
× 3
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
k(h/Mpc)

Table 1. Neutrino Mass Limits from Cosmology

authors	CMB	LSS	other input	$\sum m_\nu$
Croft et al. 1999	COBE	Lyα	$\sigma_8 - \Omega_m$ reln	16.5 eV
Fukugita et al. 2000	COBE	σ_8	$n = 1$, $\Omega_m < 0.4$	2.7 eV
Wang et al. 2002	Pre-WMAP	PSCz, Lyα		4.2 eV
Elgaroey et al. 2002	none	2dFGRS	n=1.0 ***	2.2 eV
Hannestad 2002	Pre-WMAP	2dFGRS		2.5 eV
Lewis & Bridle 2002	Pre-WMAP	2dFGRS	***	0.9 eV
Spergel et al 2002	WMAPext	2dFGRS		0.71 eV
Hannestad 2003	WMAPext	2dFGRS	***	1.01 eV
Allen et al. 2003	WMAPext	2dFGRS	***	$0.56^{+0.30}_{-0.26}$ eV
Tegmark et al. 2003	WMAP	SDSS		1.7 eV
Barger et al. 2003	WMAP	SDSS+2dFGRS		0.75 eV
Crotty et al. 2004	WMAP	SDSS+2dFGRS		1.0 eV
Seljak et al. 2004	WMAP	SDSS	theor bias	0.54 eV
Ichikawa et al. 2004	WMAP	none		2.0 eV
Seljak et al. 2004	WMAP	SDSS+Lyα		0.42 eV

Compilation by Elgarøy & Lahav, but modified by MF

Caveat

(a) Galaxy clustering

galaxy distribution vs. mass distribution (biasing)

✓ $$\xi_g(x) = b^2 \xi_m(x) \quad (?)$$

✓ biasing is galaxy population dependent

systematic difference in P(k) between SDSS and 2dFGRS at large k

(b) Cluster abundance

uncertainty in cluster mass estimates

(c) Lyman α clouds

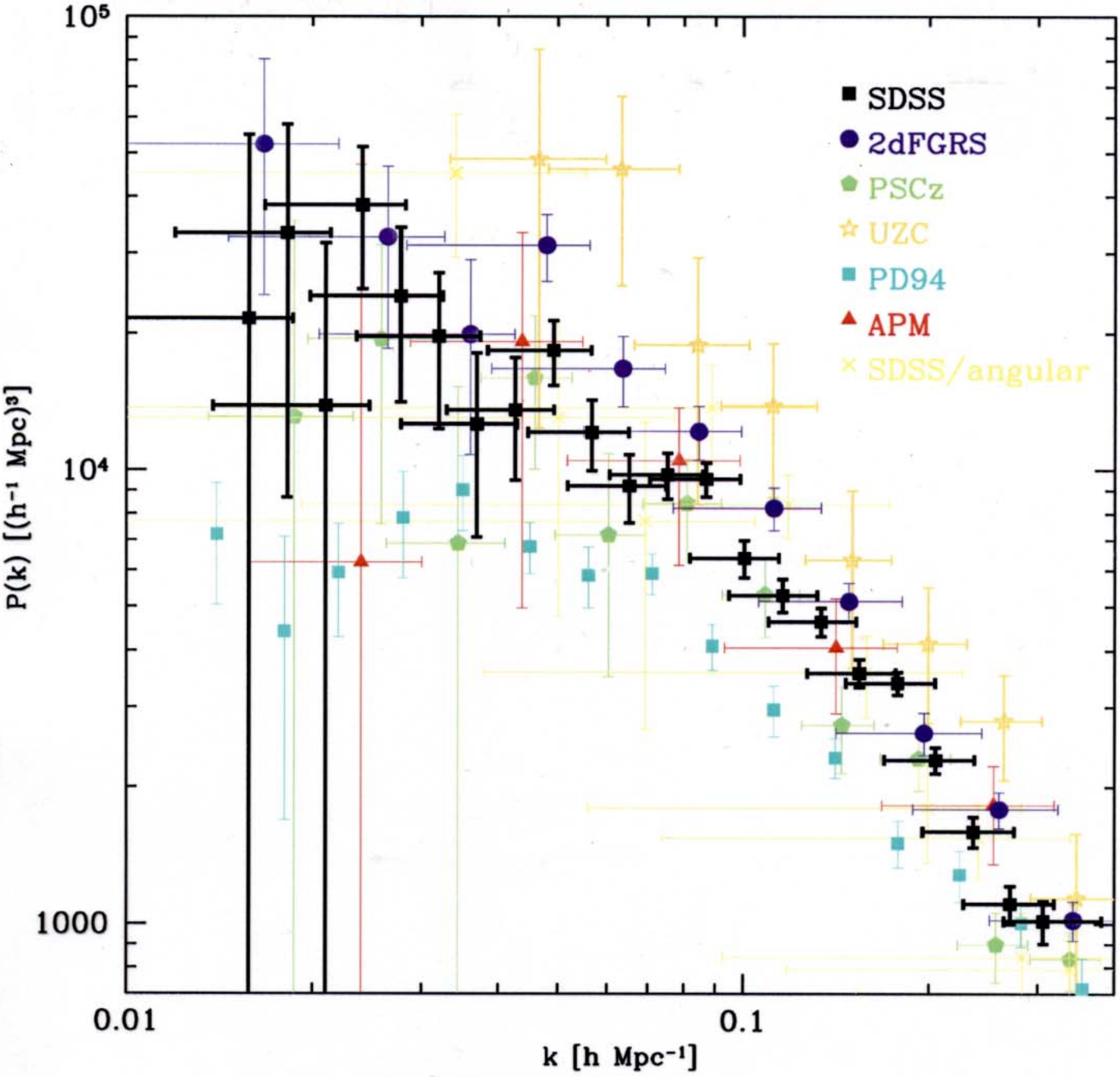
need simulations to derive P(k)

(d) Cosmic shear

in principle bias free,

but small amplitudes, instrumental systematics

There is a correlation between m_ν and n



SDSS
2dFGRS
PSCz
UZC
PD94
APM
SDSS/angular
10^5
10^4
1000
0.01
0.1
P(k) [(h⁻¹ Mpc)³]
k [h Mpc⁻¹]

Can We Get Limits from CMB Alone?

No: Tegmark et al. (2003), Lahav & Elgarøy (2003)

"Exists" hot+cold dark matter-like solution (LE) no Λ

Yes: Ichikawa-MF-Kawasaki (2004)

If ν's are relativistic at recombination epoch, effects are absorbed into other parameters

If ν's are already non-relativistic at recombination epoch, effects cannot be absorbed.

Effect (2): Gravitational potential decreases by NR neutrinos, causing larger forced oscillation in CMB multipoles

ν NR at z $\quad m_\nu \simeq z/2000(\text{eV})$

$z_{\text{rec}} = 1089$

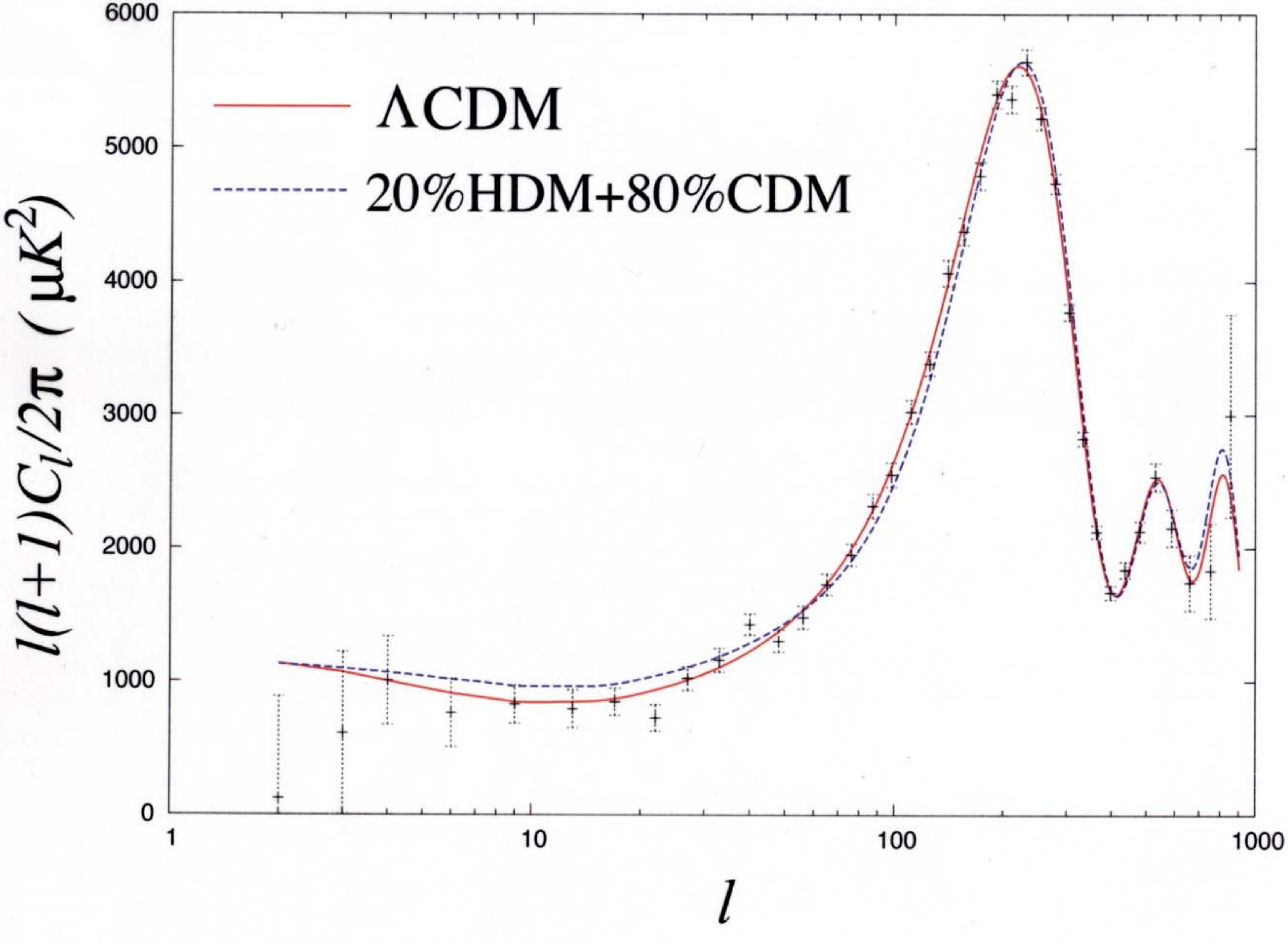
means $\sum m_\nu \sim 1.5$ eV (degenerate ν)

Results from WMAP alone: $\sum m_\nu \leq 2.0$ eV (95%)

Higher accuracy in CMB data does not improve this limit much, however

Anticorrelation between m_ν and n

No hot+cold dark matter-like solution: $\Delta\chi^2 > 50$



ΛCDM
20%HDM+80%CDM
6000
5000
4000
3000
2000
1000
0
1
10
100
1000
l(l+1)C_l/2π (μK^2)
l

Ichikawa MF Kawasaki
04

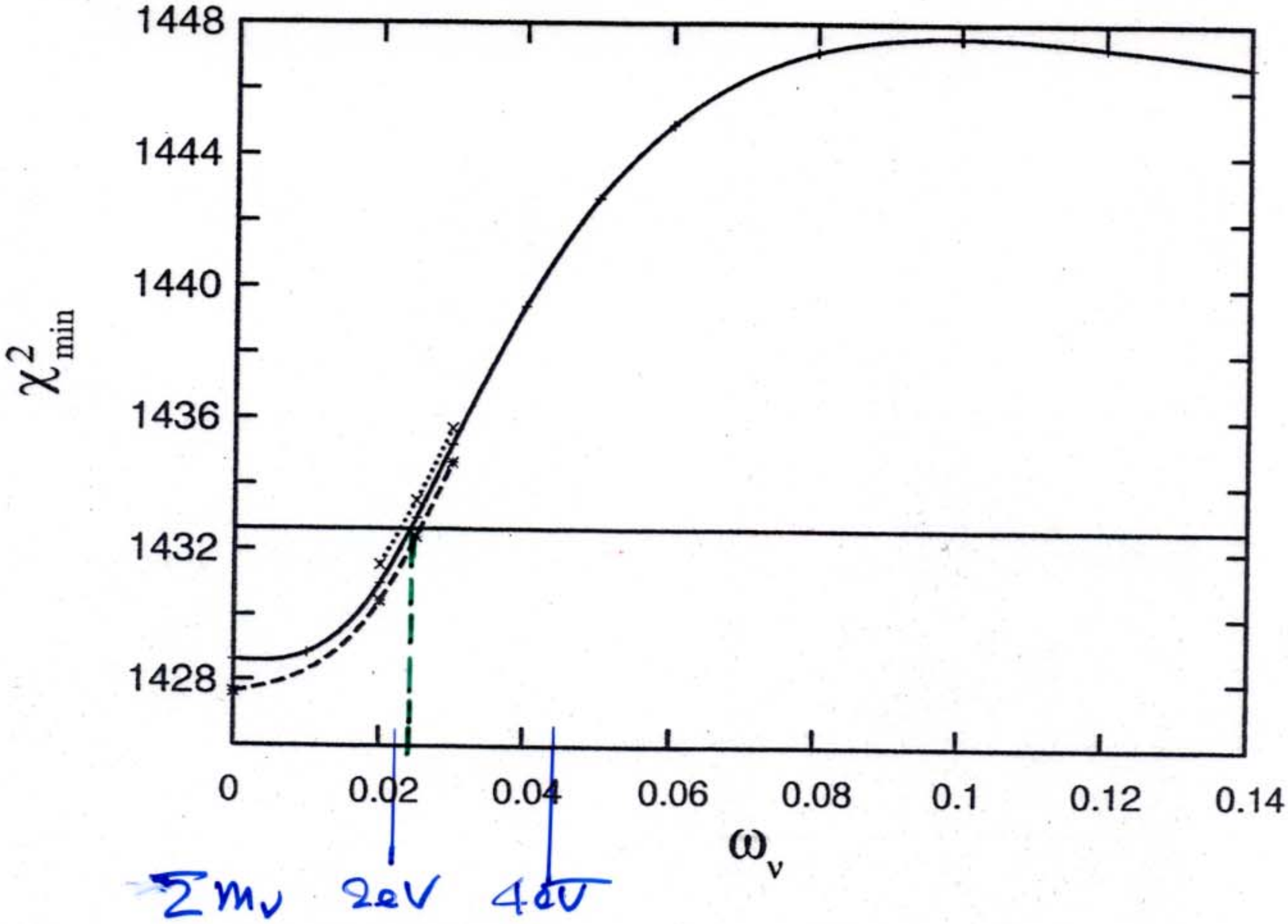
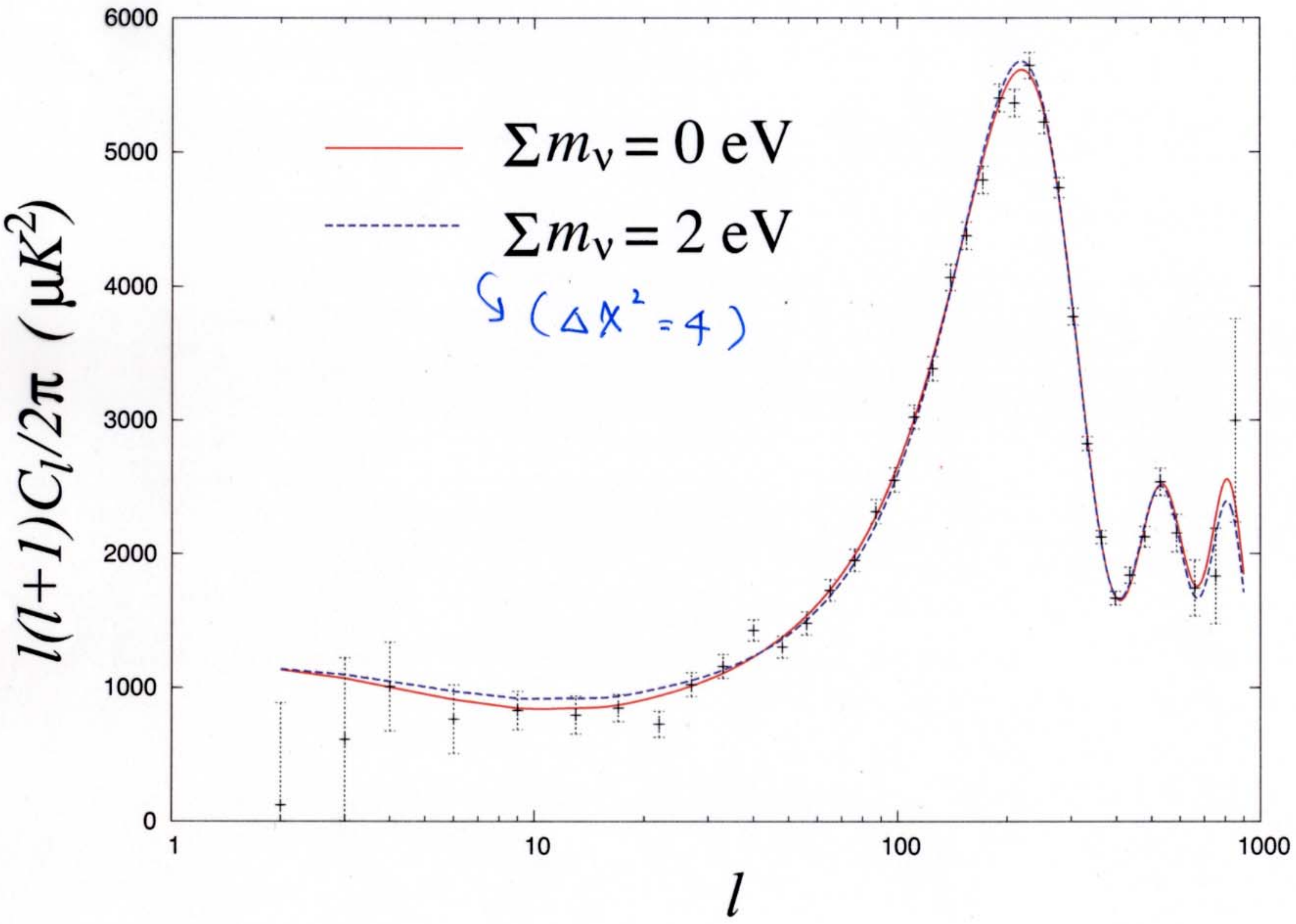


FIG. 1. Minimum χ^2 as a function of the neutrino energy density ω_ν. The solid curve is for the flat universe. The dotted and the dashed curves show the cases for a negative and a positive curvature universe, respectively.



6000
5000
4000
3000
2000
1000
0
1
10
100
1000
$l(l+1)C_l/2\pi$ (μK^2)
l
$\Sigma m_\nu = 0$ eV
$\Sigma m_\nu = 2$ eV
($\Delta\chi^2 = 4$)

Conclusions

- Two mechanisms that give constraints on m_ν
  - (a) Damping of power spectrum at small scales
  - (b) Gravitational potential decay
- WMAP alone $\sum m_\nu < 2$ eV from (b)
  Need (a) to get tighter limits → difference in P(k) SDSS vs 2dF
- Current limit $\sum m_\nu < 1 - 1.7$ eV from galaxy clustering
  One gets $\sum m_\nu < 0.42$ eV, if Ly α data are used
  But must be worried with systematics more and more
- All arguments assume ΛCDM model and power-law spectrum (or only small departures)

Proposed improvements

We want to go to $\sum m_\nu < 0.05$ eV

- Use of gravitational lensing signal in CMB polarisation
  Forecast: 0.15 eV (with Planck); 0.04 eV (with CMBpol)
  (Kaplinghat, Knox, Song 2003)
- Use of large cluster surveys
  Forecast: 0.03 eV (with Planck+LSST)
  (Wang, Haiman et al. 2005)
- In any case we need accurate simulations

SOLAR NEUTRINOS

SNO verified the Standard Solar Model!

$$\frac{\phi_{^8\mathrm{B}}(\mathrm{BS04})}{\phi_{^8\mathrm{B}}(\mathrm{SNO})} = 1.09 \pm 0.18$$

Another verification: helioseismology

$R_{\mathrm{CZ}} = 0.714 \pm 0.01 R_\odot$ vs. $0.713 \pm 0.001 R_\odot$ (obs)

and also c_s (sound velocity) to 0.3%

Recent Development

1. New determination of heavy element abundance of the sun by non-LTE 3D code   Asplund et al 03 +

   C 1/1.9; O 1/1.4; ⋯ Fe 1/1.12

   This disturbed the solar model

   $R_{\mathrm{CZ}} = 0.728$, also c_s

   ^{8}B flux decreased by 20%

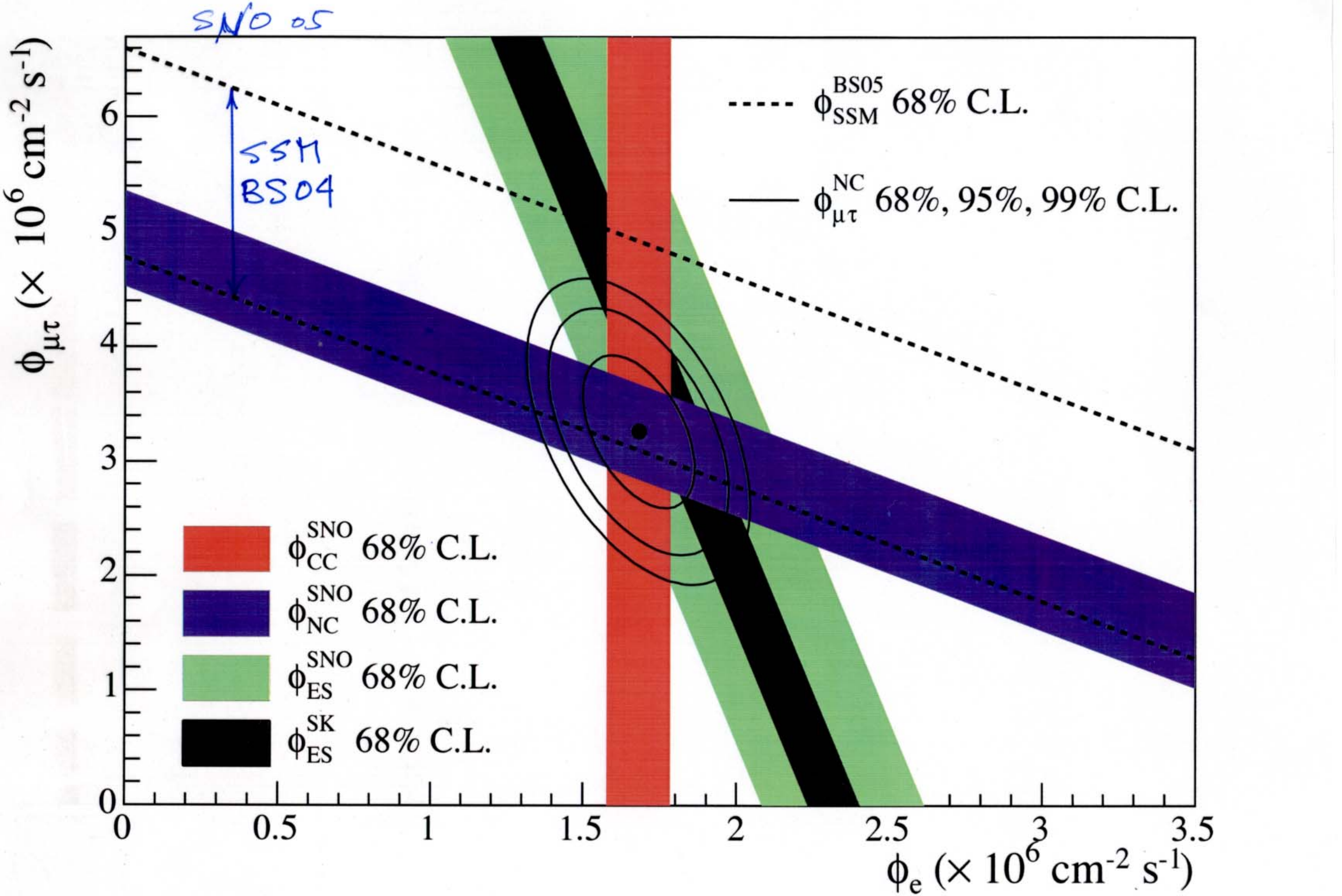
$$\frac{\phi_{^8\mathrm{B}}(\mathrm{BS05})}{\phi_{^8\mathrm{B}}(\mathrm{SNO})} = 0.87$$

2. Change from BP04/BS04 to BS05

   $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction rate $1/2\times$

   decreases the CNO neutrino flux by 1/2

   $\epsilon_{CNO}/\epsilon_{pp}$ $1/2\times$


SNO 05
SSM
BS04
ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ϕ_{CC}^{SNO} 68% C.L.
ϕ_{NC}^{SNO} 68% C.L.
ϕ_{ES}^{SNO} 68% C.L.
ϕ_{ES}^{SK} 68% C.L.
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})

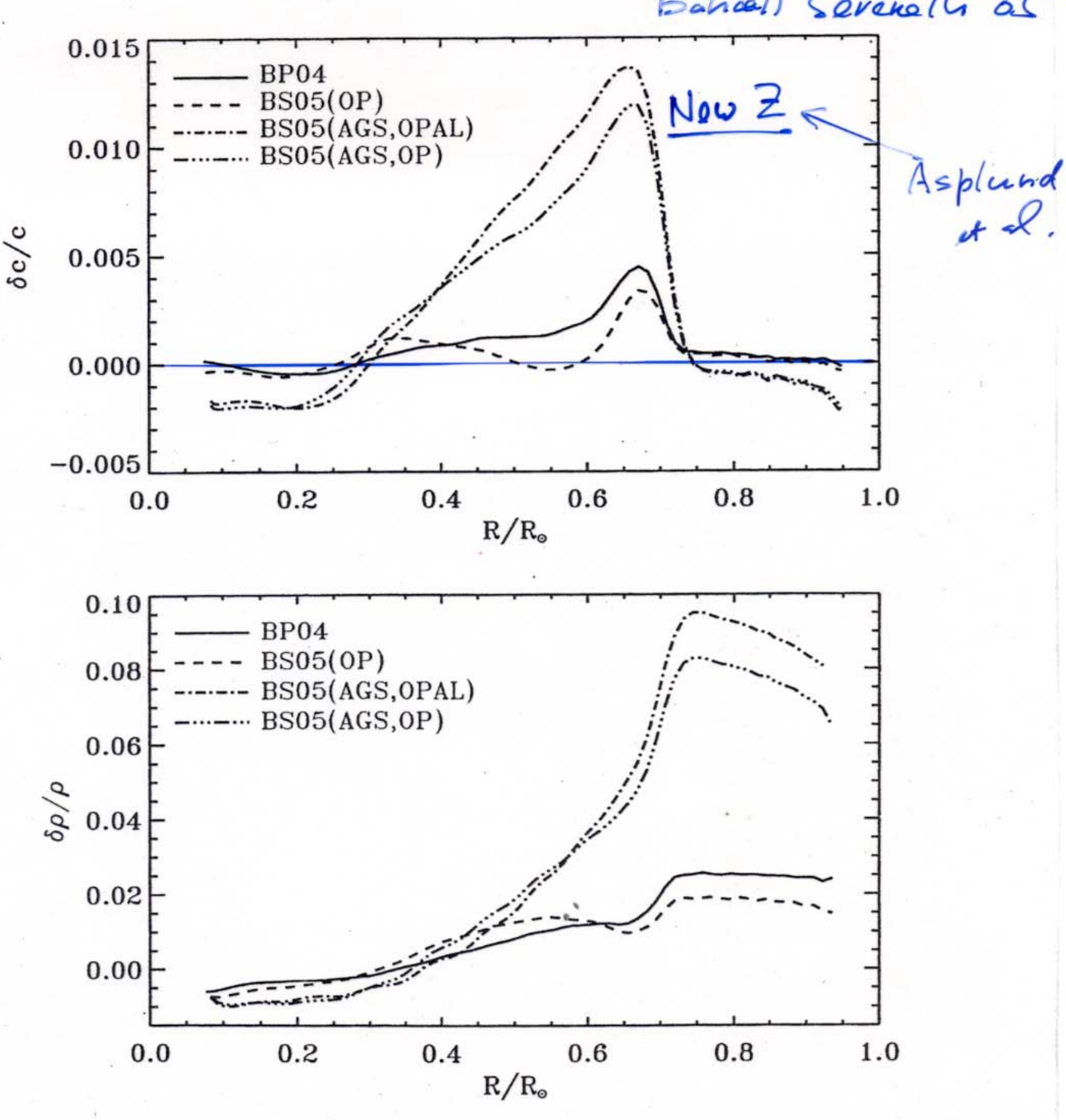


FIG. 1.—Relative sound speed differences, $\delta c/c = (c_{\odot} - c_{\rm model})/c_{\rm model}$, and relative densities, $\delta\rho/\rho$, between solar models and helioseismological results from Michelson Doppler Imager data.

TABLE IV. Cross-section factor $S(0)$ for the reaction $^{14}N(p,\gamma)^{15}O$. The proton energies E_p at which measurements were made are indicated.

$S(0)$ keV b	E_p MeV	Reference
3.20 ± 0.54	0.2–3.6	Schröder *et al.* (1987)
3.32 ± 0.12		Bahcall *et al.* (1982)
3.32		Fowler, Caughlan, and Zimmerman (1975)[a]
2.75	0.2–1.1	Hebbard and Bailey (1963)
3.12		Caughlan and Fowler (1962)[a]
2.70	0.100–0.135	Lamb and Hester (1957)
$3.5^{+0.4}_{-1.6}$		Present recommended value

[a]Compilation and evaluation: no original experimental data.

New

1.8 ± 0.2	Angulo & Descouvemont 2001
1.7 ± 0.2	Mukhamedzhanov et al. 2003
1.7 ± 0.2	Formicola et al. 2004

BURST FROM NITROGEN FLASH

Sarcinelli + M.F 05

^{14}N is accumulated by the time of He flash

At the He Flash, $^{14}N+\alpha \rightarrow ^{18}F+\gamma$ proceeds

and destructs all ^{14} N in the outer region in 1 year.

$^{18}F \rightarrow ^{18}O + \nu + e^+$ follows

(Only neutrino producing process in helium burning)

$L_\nu \sim 10^8 L_\odot$ for several days

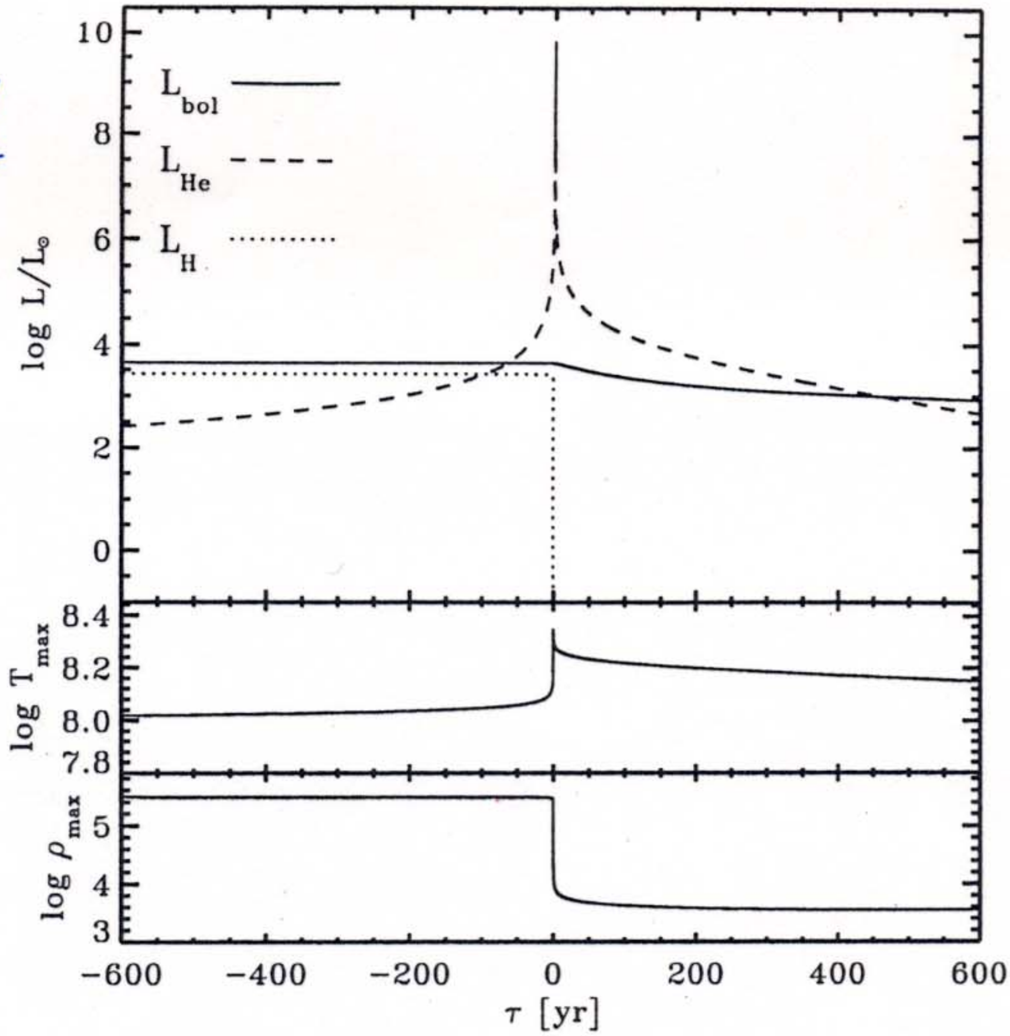
$\phi_\nu = 5 \times 10^7 (d/10\text{pc})^{-2}\ \text{cm}^{-2}\text{s}^{-1}$

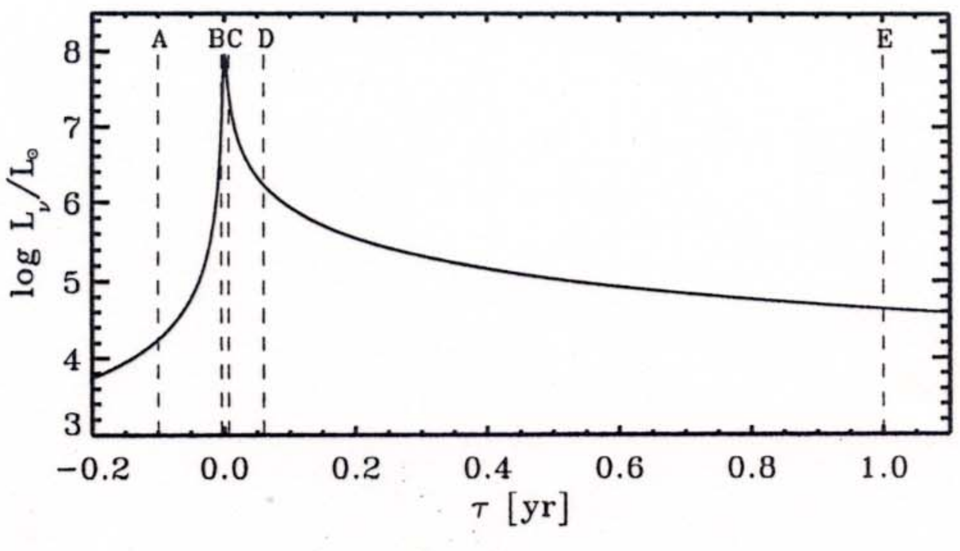
In 1000 ton CH_2 scintillator
with the $0.42 < E < 0.63$ MeV window

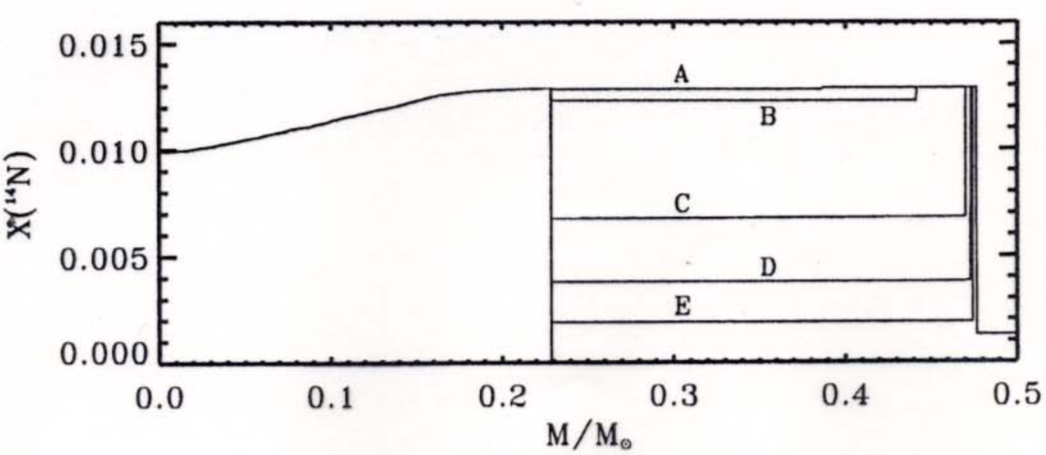
10 events for 3 days for He/N flash at 10 pc

cf. solar CNO 40 events

Seranelli +MF05







LEPTOGENESIS

Thermal leptogenesis requirements:

$$10^{-3}\text{eV} \lesssim m_{\nu_i} \lesssim 0.1\text{eV}$$

Buchmüller et al 04

What are needed to make the scenario convincing?

- Majorana nature of neutrinos
- Evidence for high energy scale unification
- CP violation (this is most likely)

CONCLUSION

- Neutrino mass limit from cosmology

  Current limit $\sum m_\nu < 2 \quad \rightarrow \quad 0.4$ eV

  Planck alone does not improve the limit too much

  To achieve $\sum m_\nu < 0.05$ eV,

  Precision small-scale P(k) data are needed

  Large-scale galaxy/cluster/lensing survey +

  study of systematics

- Not everything is fine with the Standard Solar Model

  New low heavy element abundances

  Interest in observing CNO neutrinos: $\epsilon_{\rm CNO}/\epsilon_{pp}$

- Thermal leptogenesis: 0.001 eV$\lesssim m_i \lesssim 0.1$ eV

- Nitrogen flash neutrino (academic interest?)

- Cosmology with relic core-collapse neutrinos

NEUTRINO SEA IN THE UNIVERSE

Cosmic Energy Inventory MF + Peebles (2004+)

CMB	$\Omega = 10^{-4.2}$
He B.E.	$10^{-4.1}$
Gravit. B.E.	
galaxy and larger	$10^{-6.1}$
star	$10^{-4.9}$
nuclear B.E.	$10^{-5.2}$
photon radiation	$10^{-5.7}$
nuclear burning neutrino	$10^{-6.8}$
white dwarf neutrino	$10^{-7.7}$
core collapse neutrino	$10^{-5.5}$
gravitational wave	$10^{-7.5\pm0.5}$

7%

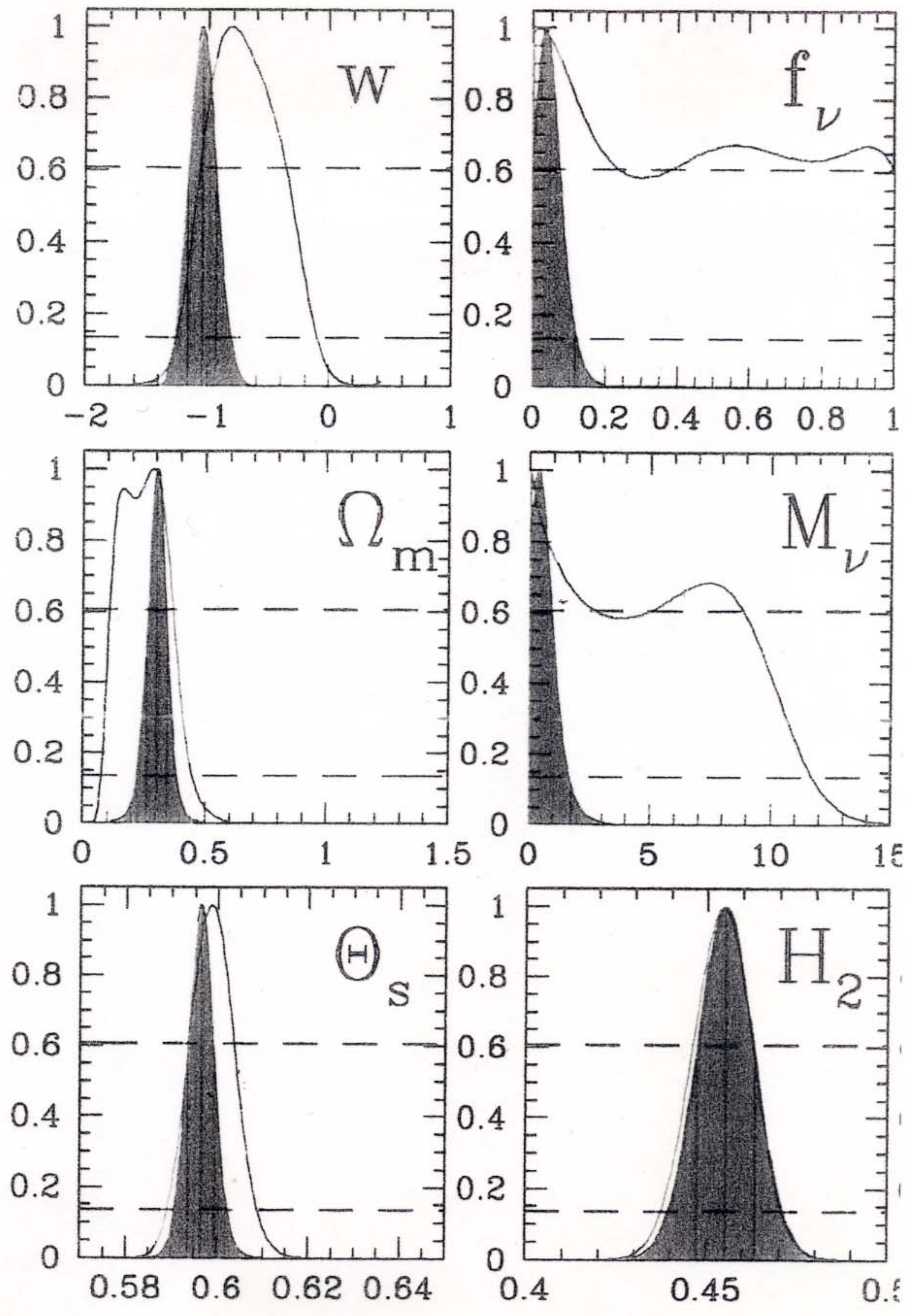
Relic Core Collapse Neutrinos

SK limit $\approx 1 - 3\times$ expected from Hα survey

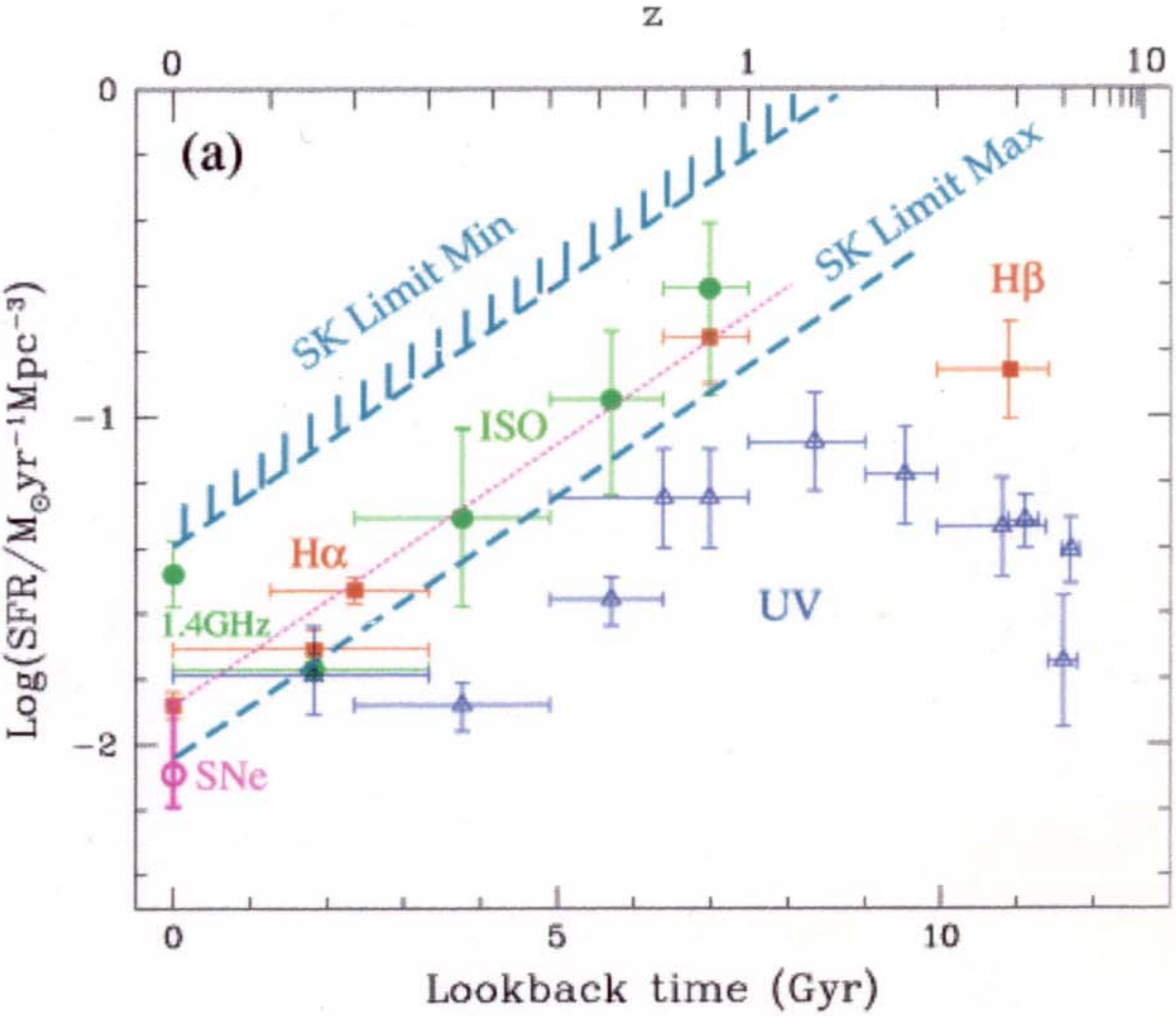
The most important uncertainty:

Core collapse neutrino spectrum

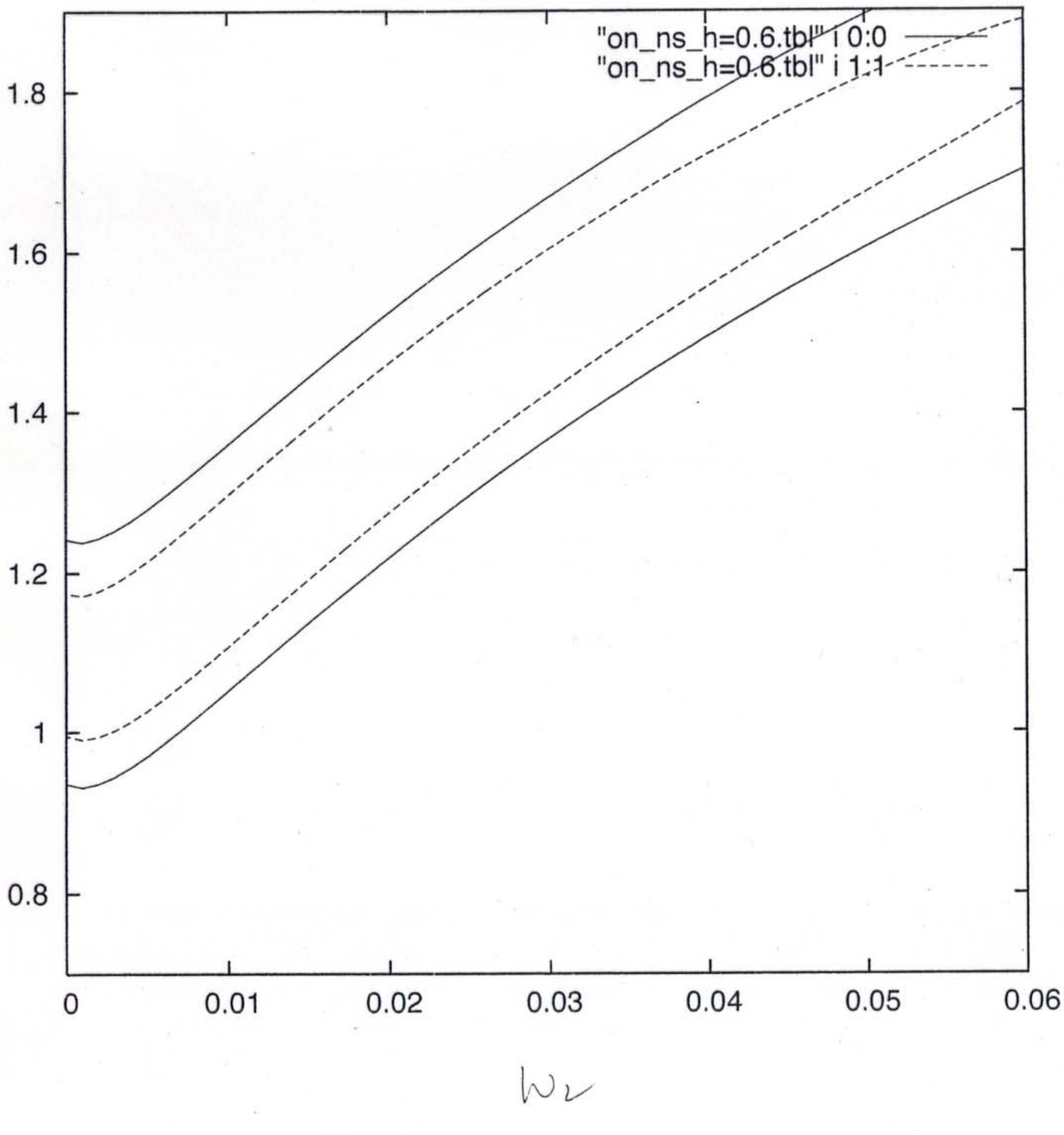
It is *not* $\mu = 0$ Fermi distribution


w
f_ν
Ω_m
M_ν
Θ_s
H_2

MF + Kawasaki



z
0
1
10
0
-1
-2
(a)
SK Limit Min
SK Limit Max
Hβ
ISO
Hα
1.4GHz
UV
SNe
0
5
10
Lookback time (Gyr)
Log(SFR/M⊙yr⁻¹Mpc⁻³)



$h = 0.6$

$\chi^2_{min} = 15.396$

$\omega_\nu = 0.013$

$n_s = 1.25$