Massive Neutrinos and Structure Formation in the Universe

Masataka Fukugita
ICR Univ. Tokyo / Inst. Adv. Study, Princeton

Effect on the structure formation

Neutrinos are hot dark matter

1. Thermal equilibrium: free streaming

$$\ell \sim ct_{\{T \sim m_\nu\}}$$

damps fluctuations to this scale

Modify the power spectrum P(k) at smaller scales

2. Gravitational potential decays plasma

Modify geometry & Integrated Sachs Wolfe effect

Modify the CMB harmonic pattern

constraints from ‘CMB alone’

Power spectrum :

$$P(k) = \int d^3x \xi(x) \exp(ikx)$$

$$\xi(|x - x'|) = \langle \delta\rho(x) \delta\rho(x') \rangle \ \bar{\rho}^{-2}$$

NB: They are the mass correlation

Effect from nu free streaming: perturbations damps

$$\lambda < 110 \ \mathrm{Mpc}(m_\nu/1\mathrm{eV})^{-1} \qquad k > 0.03 \ \mathrm{Mpc}^{-1}$$

At smaller scales (larger k) damping is controlled by

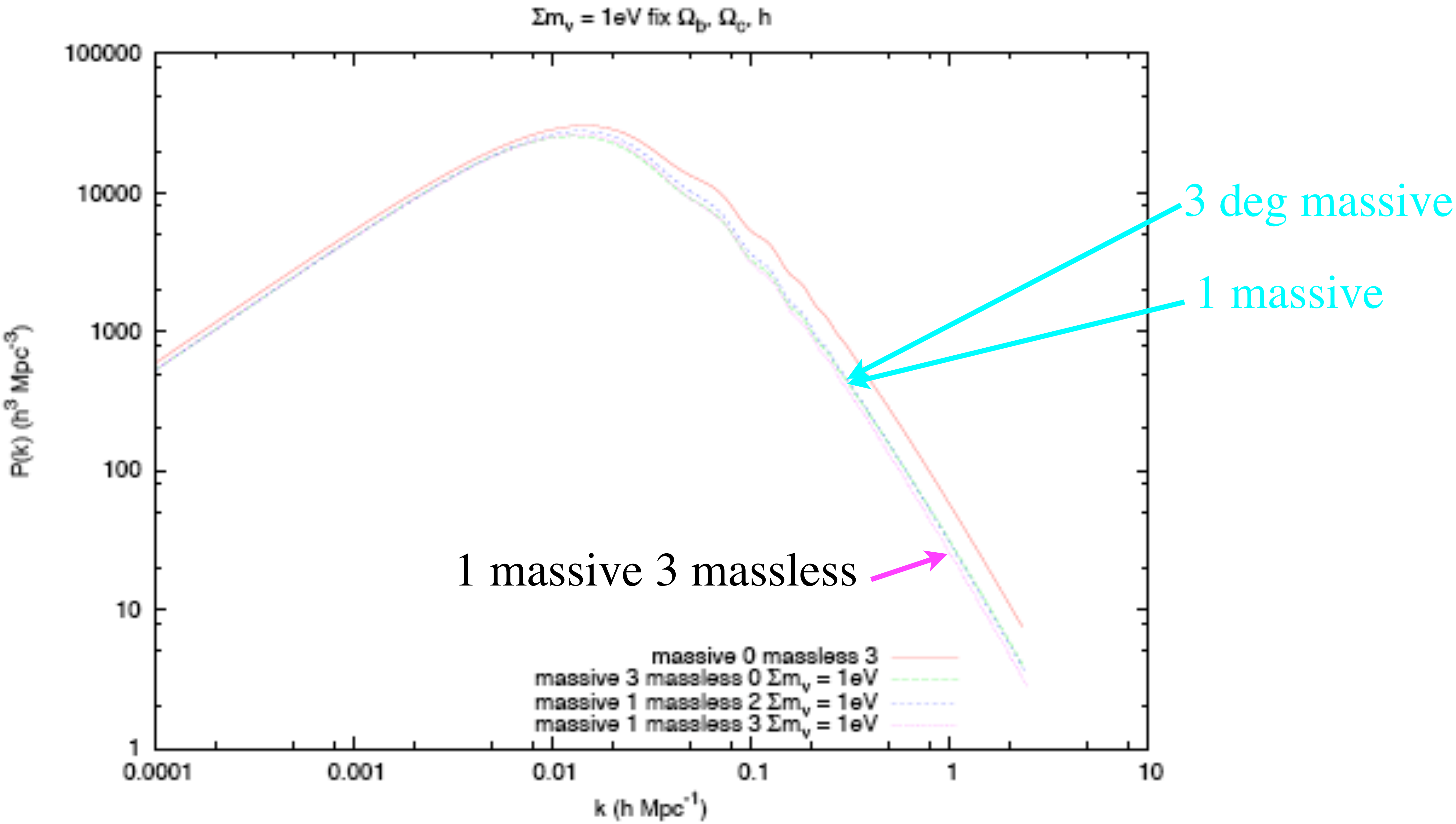
$$\Omega_\nu \qquad (i.e. \sum m_\nu)$$

Either use

CMB as the pivot, or P(k) in wide range of k: 0.01-0.2

power spectrum P(k)

$$\sum m_\nu = 1\mathrm{eV}$$



Sloan Digital Sky Survey: 2000-2008+

Mapping the Universe in the North
where not obscured by our Galaxy (1/2 of N. sky)

Design+instrumentation 1992-2000

Unique, yet most difficult feature:
wide field of view: 50x ordinary

First Light 1999 (photom)+2000 (spectro)

Output just as designed from the 1st night

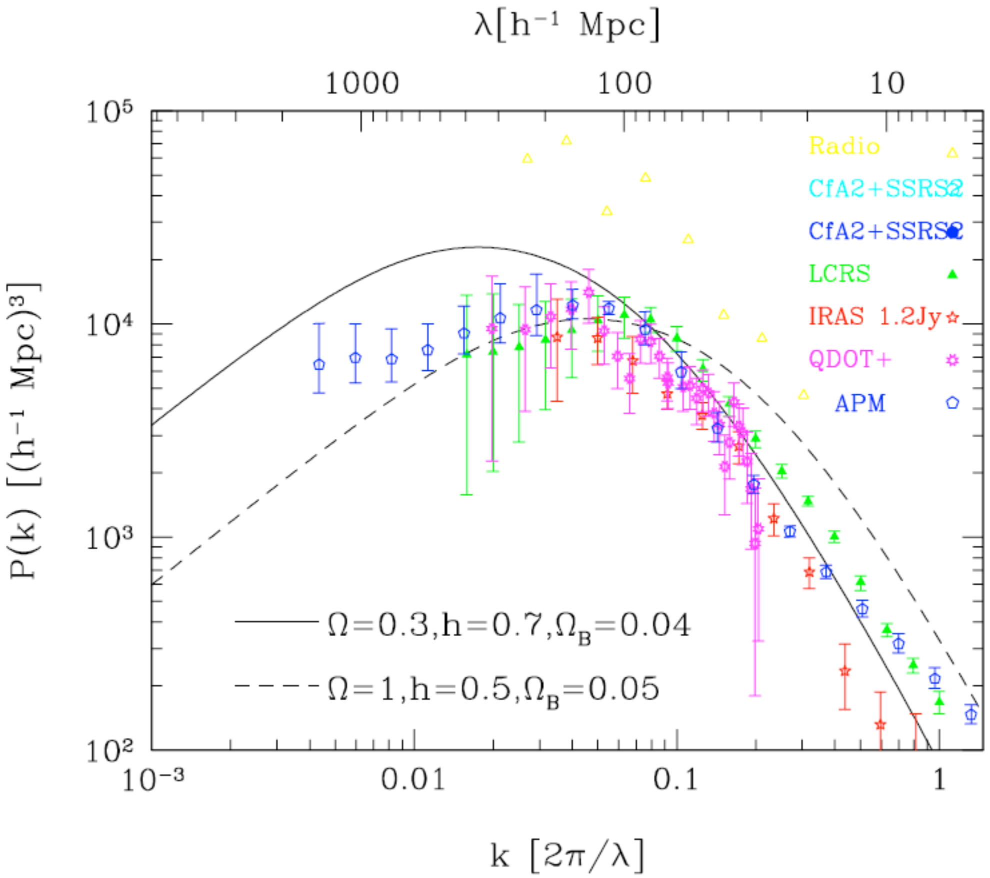
Survey operation 2000-2005

95% of time observing throughout 5 yr

Survey extended (SDSS-II) 2005-2008 Ended!

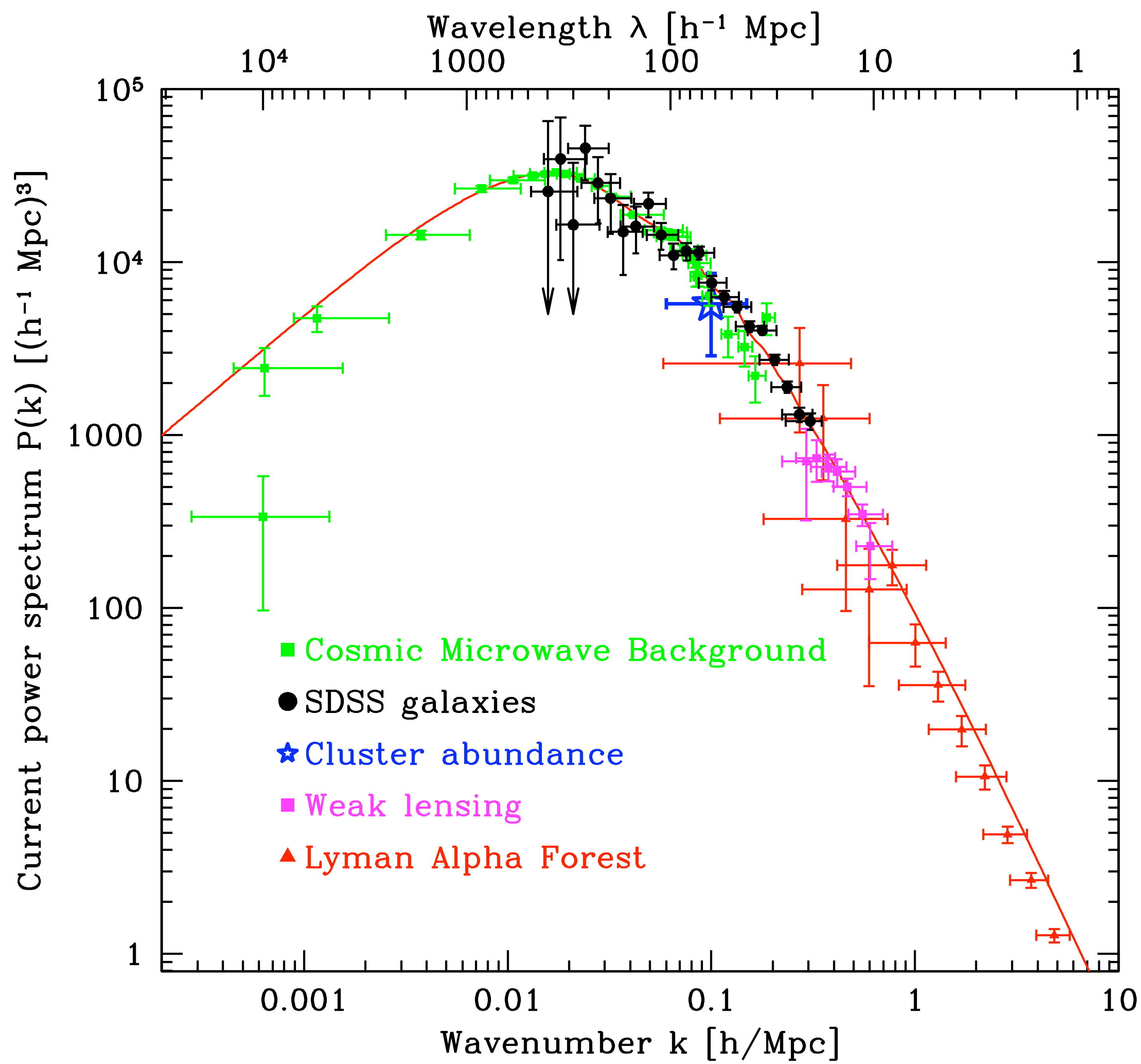
photometry 250M objects (galaxies+stars)
spectroscopy (redshift) 1M galaxies+quasars
cf. CfA survey (approx 10years -1985) 2401 galaxies
z to 0.2 (ordinary galaxies) 0.4 (LRG)
5.4 (quasars)
produced omnipurpose data base

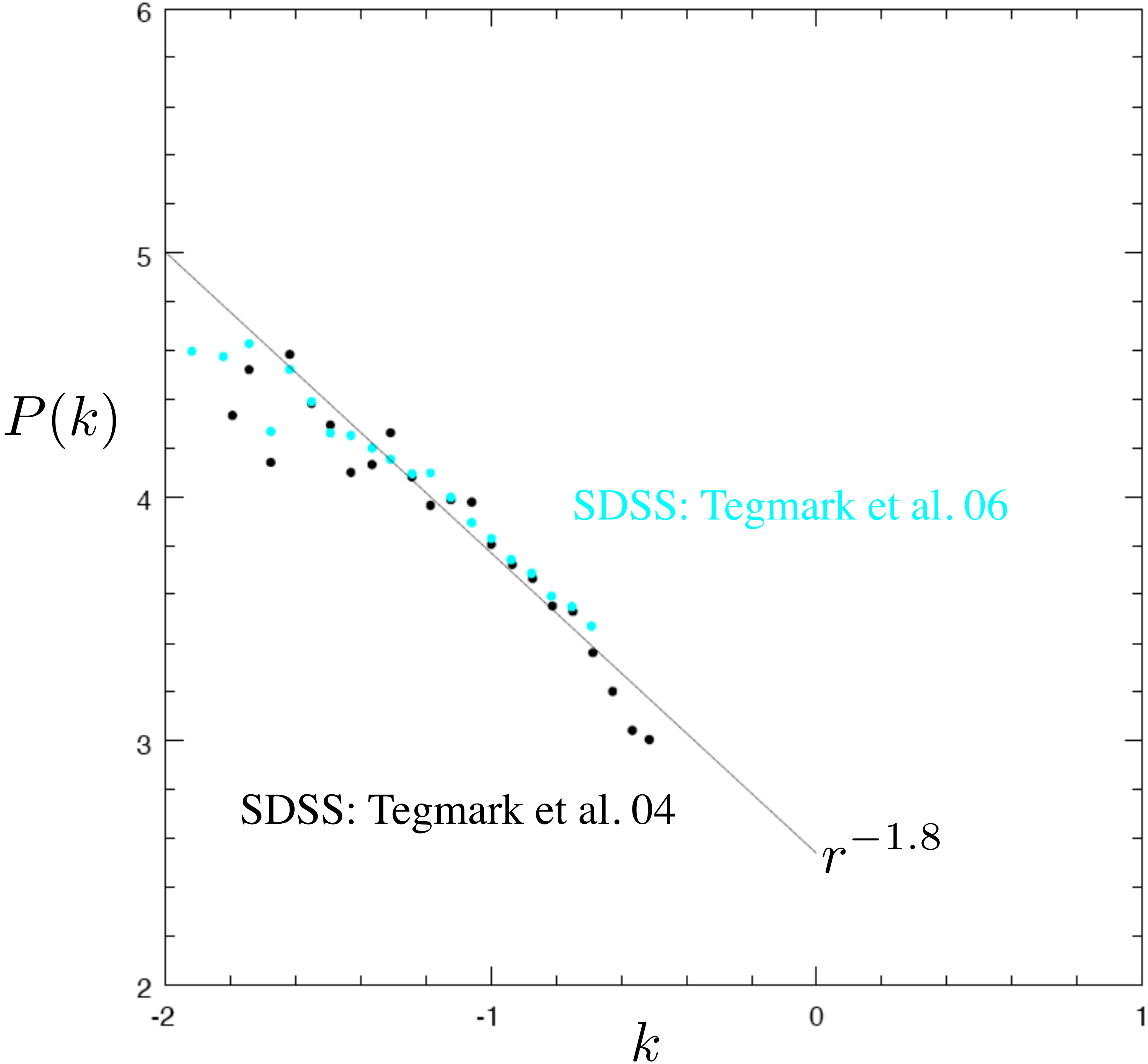
Example of the use (originally aimed)
Two point correlation function of galaxies
z=0 fiducial of the universe
large-scale clustering (e.g., dark matter property)
cosmological parameters
if they match with CMB at z=1100



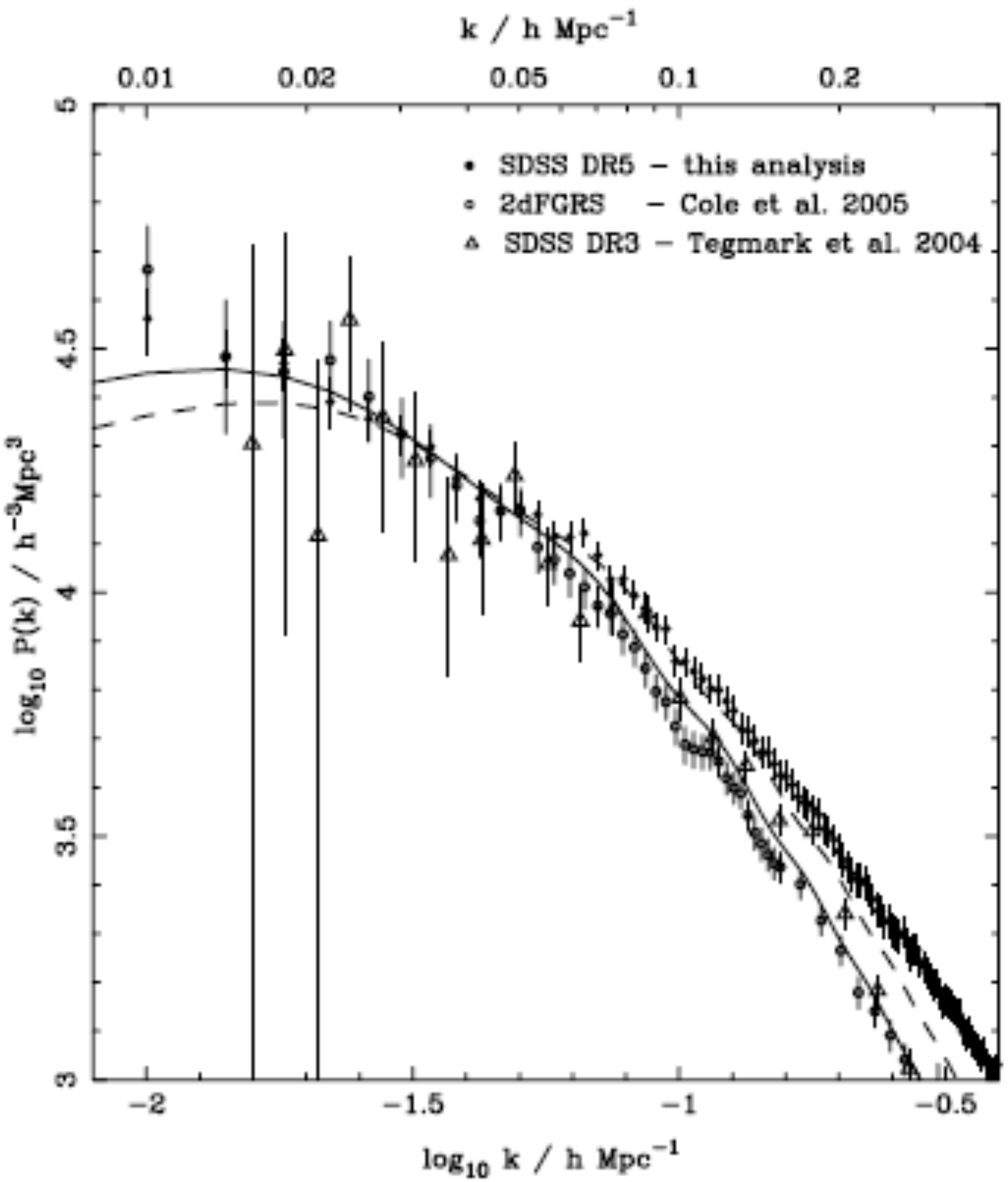
pre SDSS/2dFGRS

SDSS:
Tegmark et al. 2004





6
5
4
3
2
-2
-1
0
1
$P(k)$
k
SDSS: Tegmark et al. 06
SDSS: Tegmark et al. 04
$r^{-1.8}$



SDSS: Percival et al. 07

"Biasing"

Type of galaxies: morphologies

Some 'practical problems' in estimating P(k) at a large k

problem of the algorism: shouldn't be difficult

Attempts to estimate the halo abundance

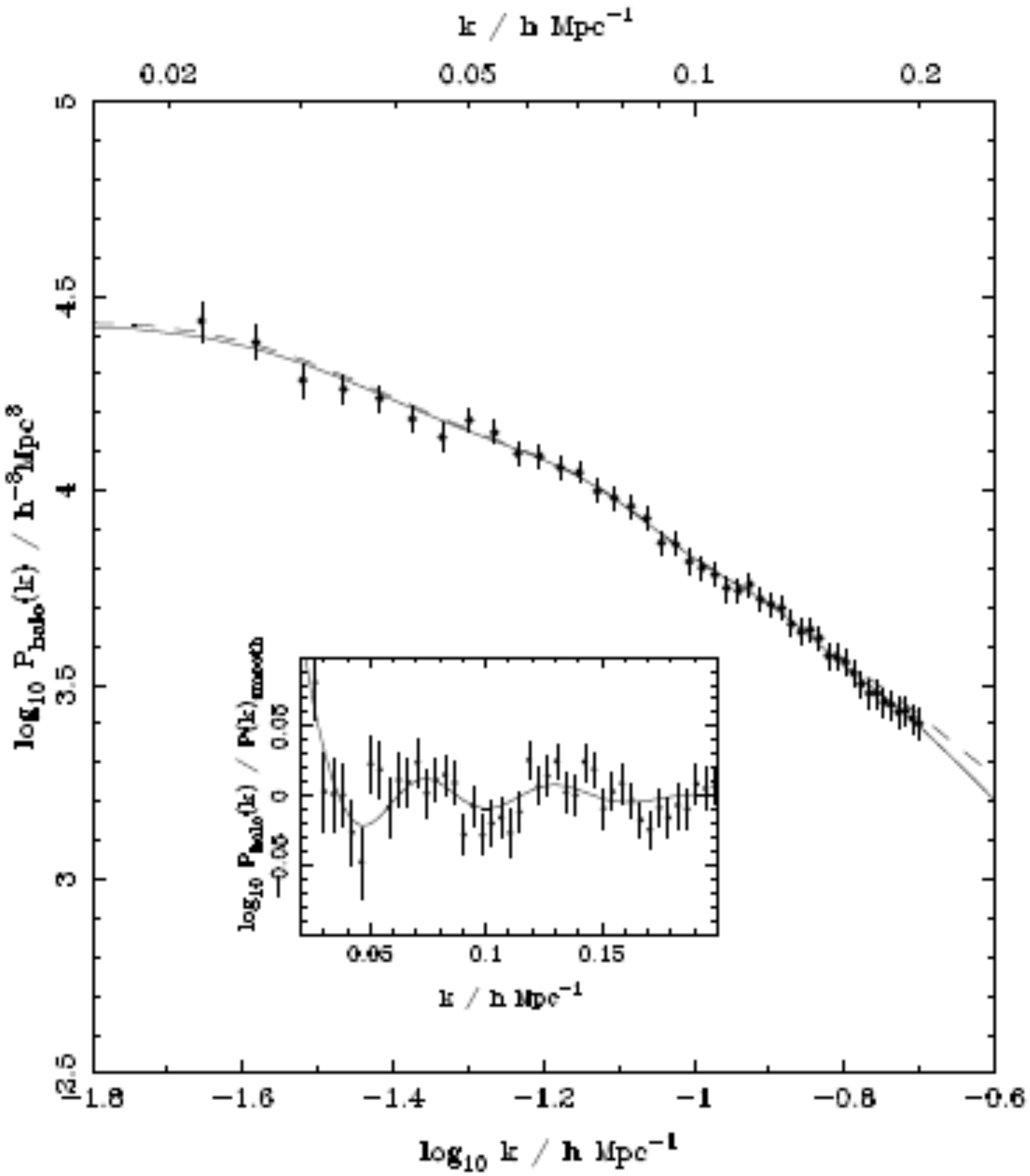
SDSS collaboration: Reid et al. 09

$$\sum m_\nu < 0.62\mathrm{eV} \quad (95\% CL)$$

Use of Lyman alpha clouds: small scales

Can go to smaller scales, but severer model dependences

Difficult to unfold P(k) : problematic



halo power spectrum

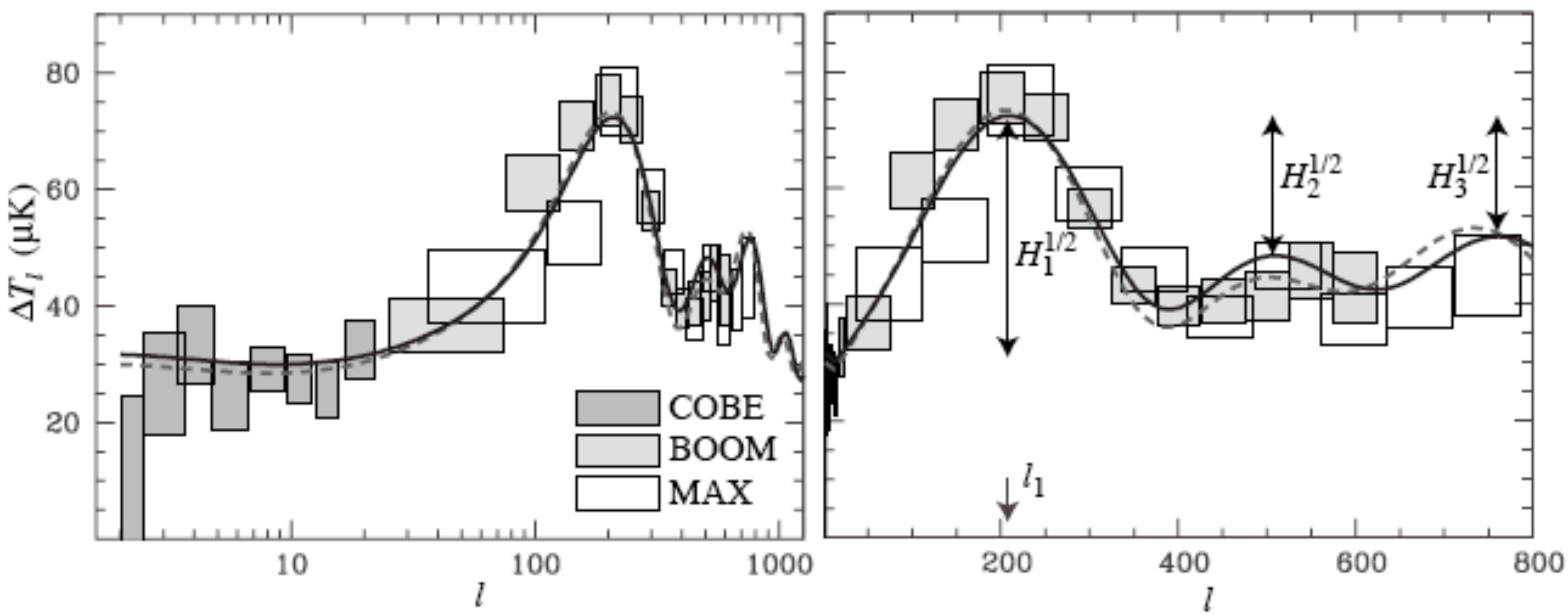
SDSS: Reid et al. 09

$$\sum m_\nu < 0.62 \text{ eV} \quad \text{at } 95\%\text{C.L.}$$

SDSS: Reid et al. 2009
usng SDSS full data

CMB harmonics

Parameters: $\Omega_m, \Omega_b, H_0, n_s, \tau, \sigma_8$



"Reduced CMB Observables"

ell_1: age

H_1

H_2: Omega_b

H_3: Omega_m

CMB: traces mass more faithfully, physics is simple

CMB indicators   Hu, MF, Zaldarriaga, Tegmark 2001

	WMAP5 errors	
ℓ_1	+/- 1	(0.5%)
$H_1 = (\Delta T_{\ell_1}/\Delta T_{10})^2$	+/- 0.35	(7%)
$H_2 = (\Delta T_{\ell_2}/\Delta T_{\ell_1})^2$	+/- 0.005	(1%)
$H_3 = (\Delta T_{\ell_3}/\Delta T_{\ell_1})^2$	+/- 0.01	(2%)

Decay of gravitational potential $r < r_{\text{free stream}}$

enhances C_ℓ at $\ell > \ell_{\text{nr}}$

Integrated Sachs Wolfe effect modified

$$l_m = l_A(m - \phi_m)$$

Ichikawa, MF, Kawasaki 05
Shiraishi, MF + 09

Do we understand physics of massive neutrino well?

Can find a 'mock' massless neutrino theory

Classify the effects and

Replace $\omega_m = \omega_m + \omega_{\nu(NR)}$

N_ν

h (to account for Λ change)

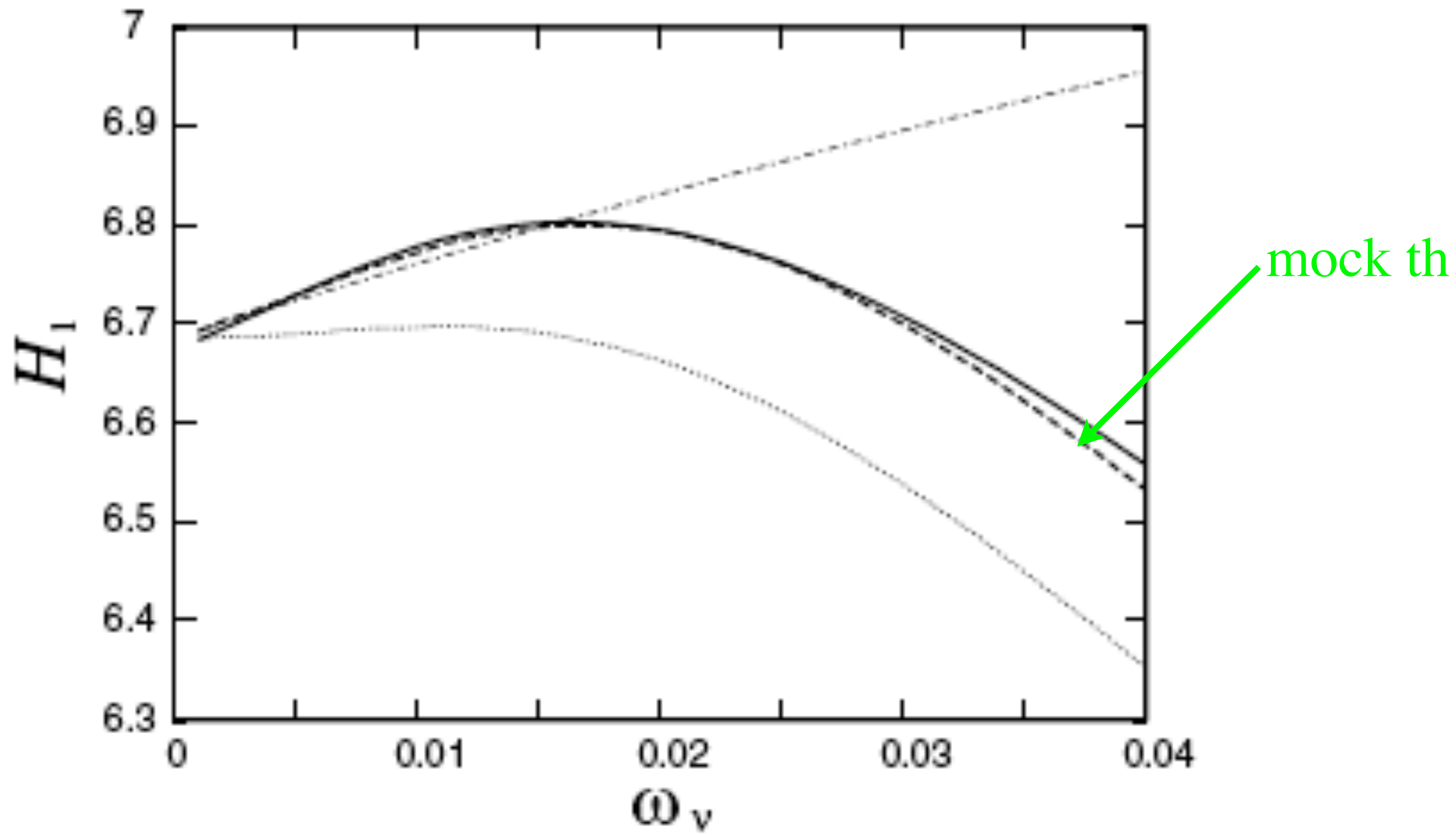
Find the response to m_ν WMAP-5 WMAP

$\sum m_\nu \leq 1.2\text{eV}$ 1.5eV

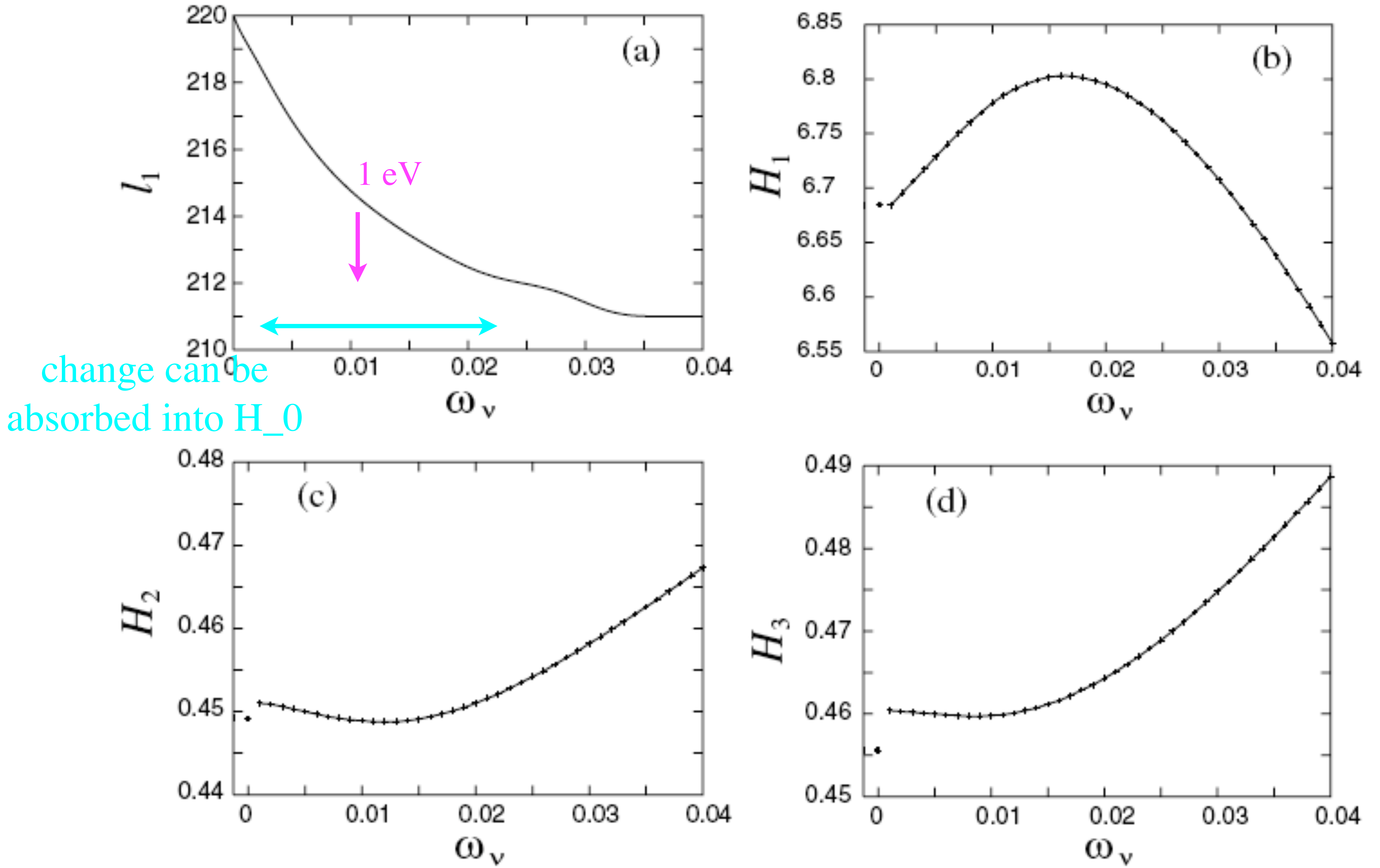
Ichikawa, MF, Kawasaki 05

Shiraishi, MF + 09

ICHIKAWA, FUKUGITA, AND KAWASAKI

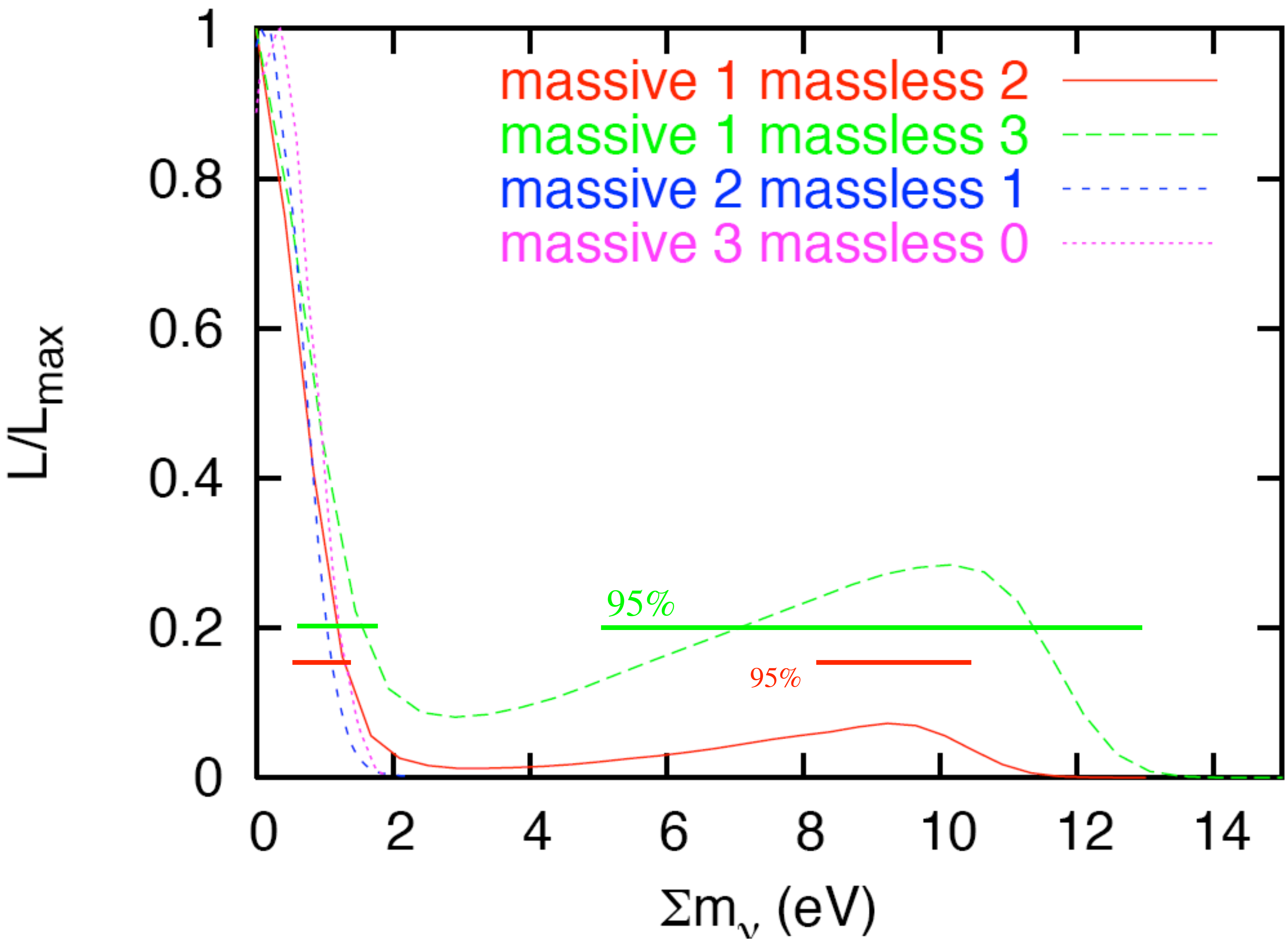


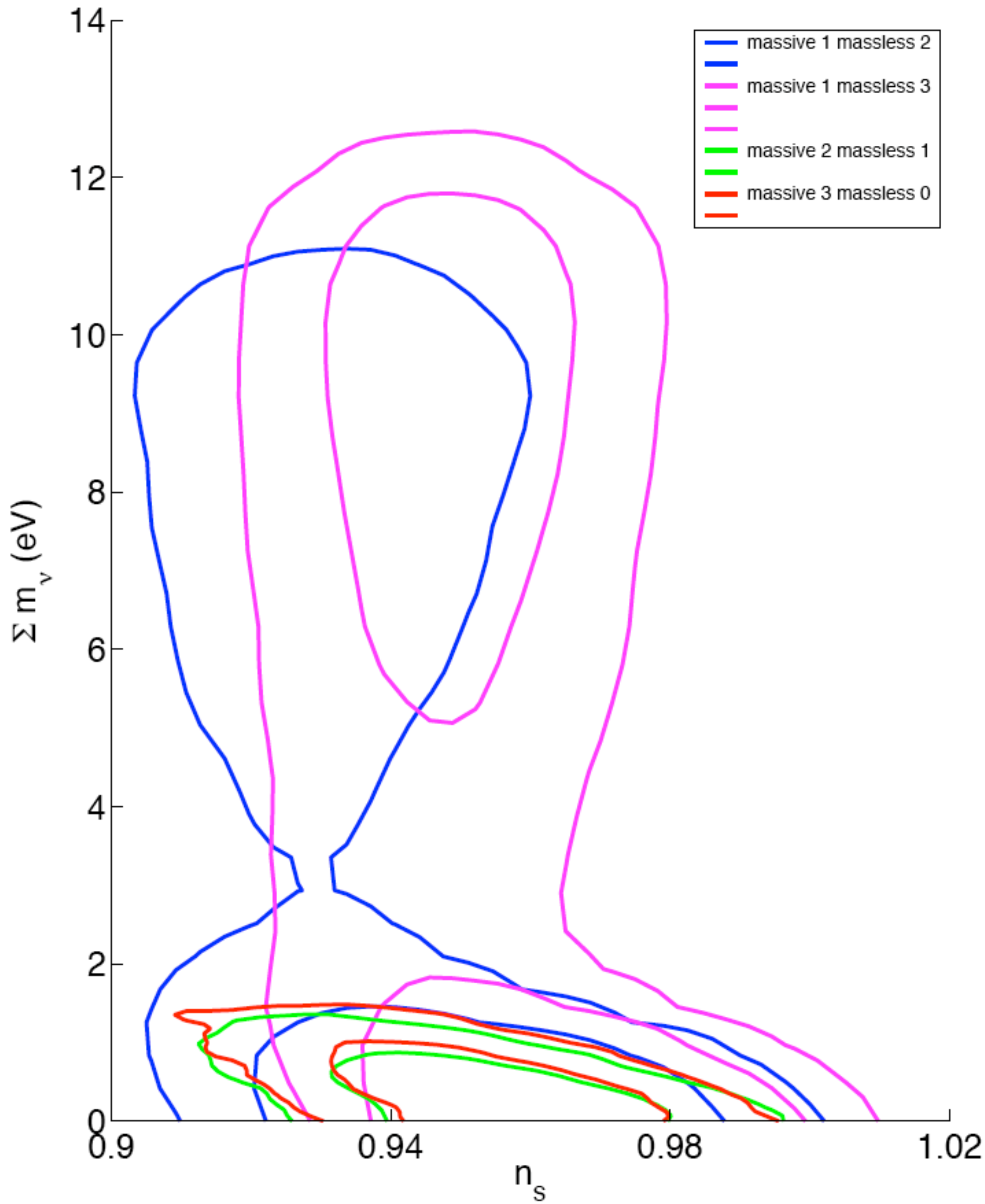
ICHIKAWA, FUKUGITA, AND KAWASAKI PHYSICAL REVIEW D 71, 043001 (2005)

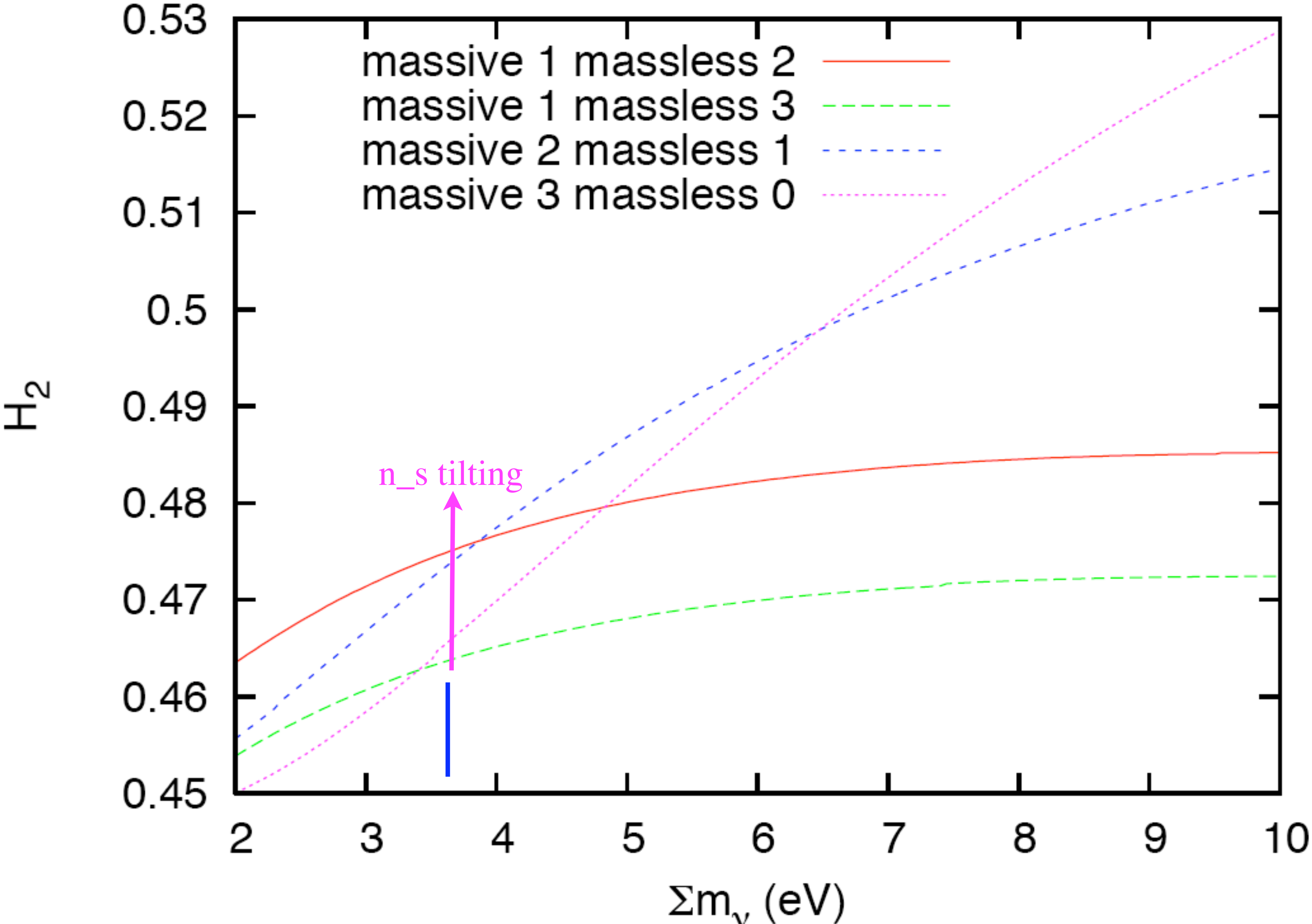


Shiraishi, MF 09

m_ν limits: CMB harmonics alone

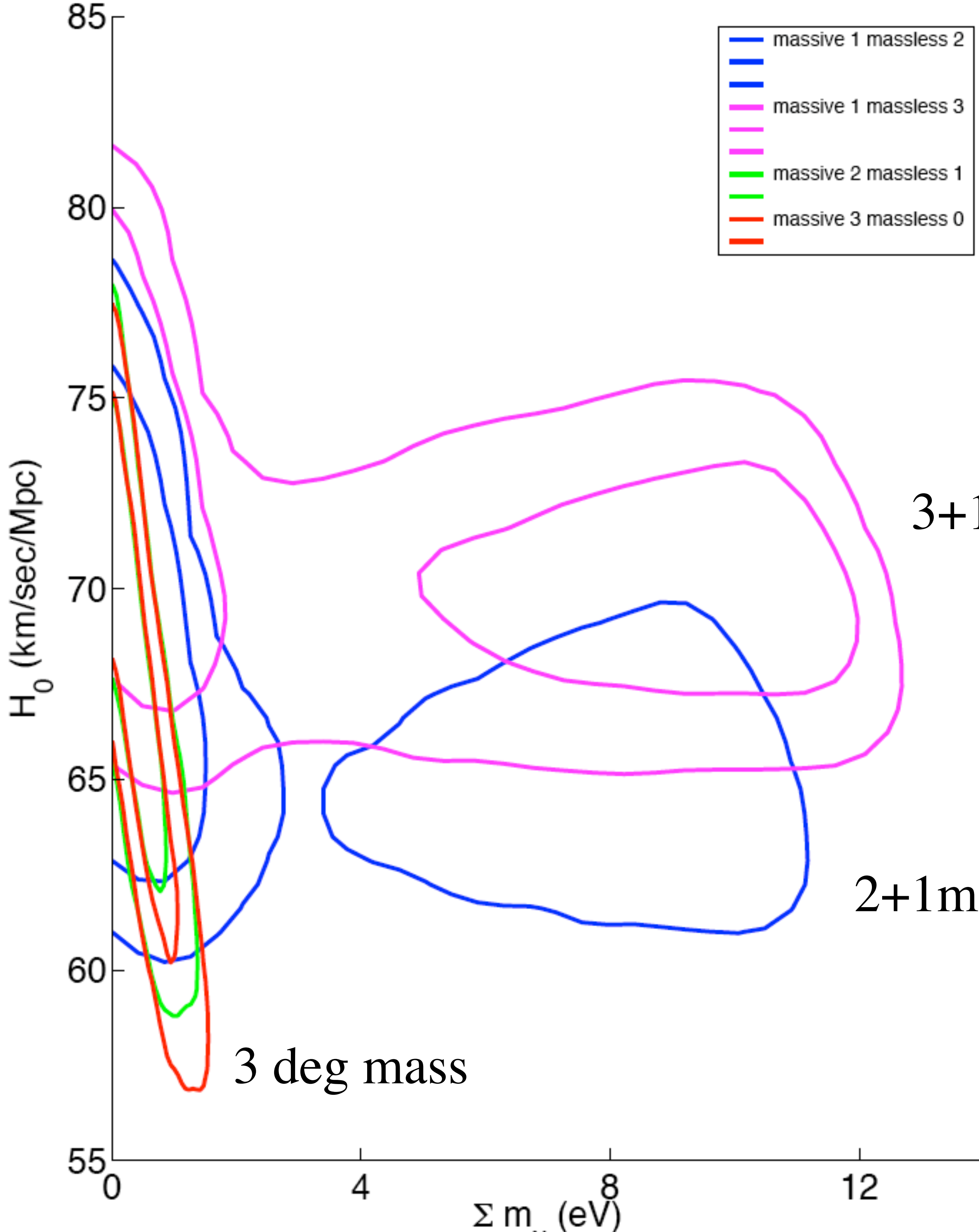



massive 1 massless 2
massive 1 massless 3
massive 2 massless 1
massive 3 massless 0
14
12
10
8
6
4
2
0
Σm_ν (eV)
0.9
0.94
0.98
1.02
n_s

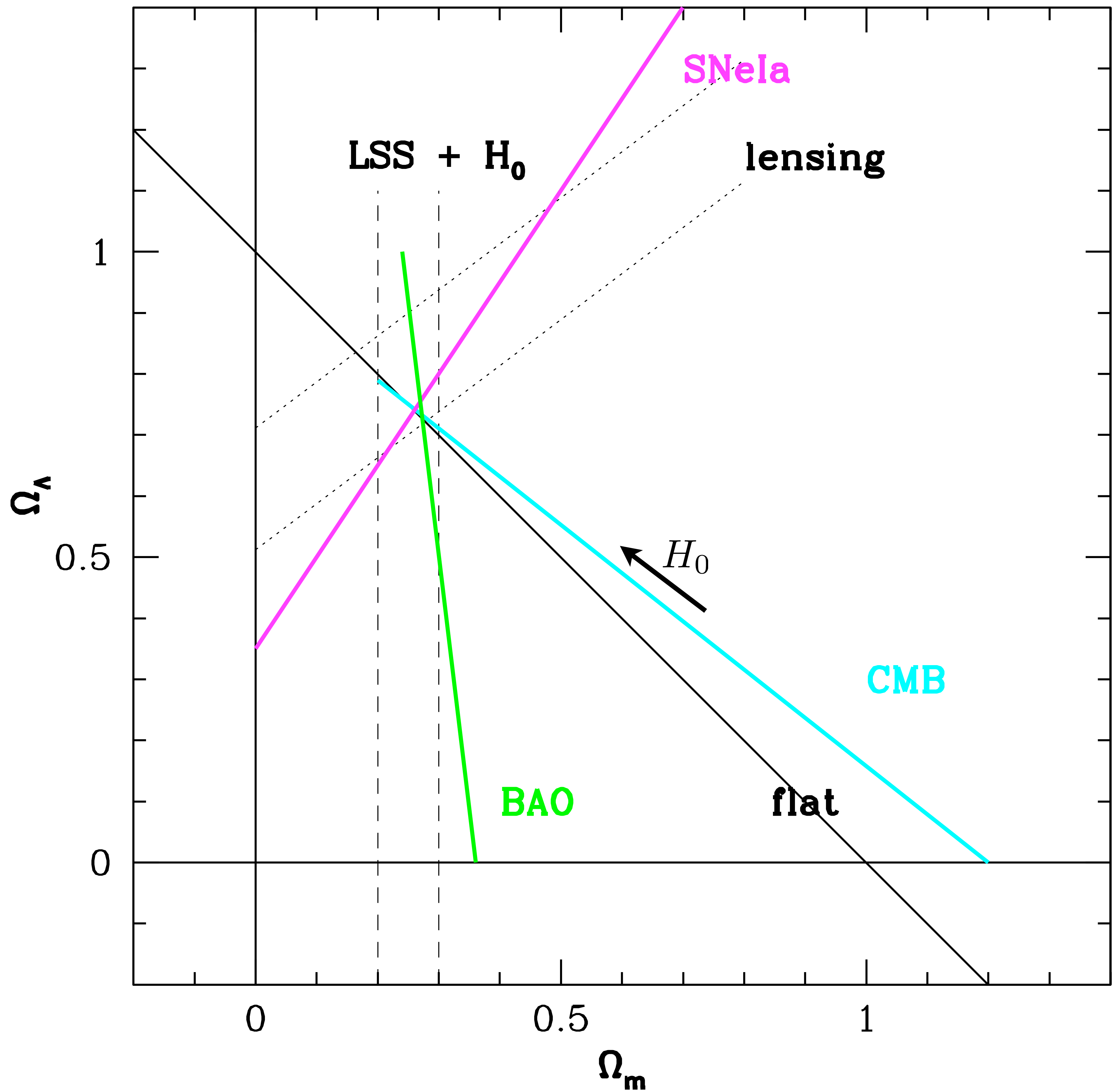


massive 1 massless 2
massive 1 massless 3
massive 2 massless 1
massive 3 massless 0
n_s tilting
H2
Σmν (eV)
0.53
0.52
0.51
0.5
0.49
0.48
0.47
0.46
0.45
2
3
4
5
6
7
8
9
10

CMB harmonics only



NB: ‘singular soln’s are excluded if P(k) is used

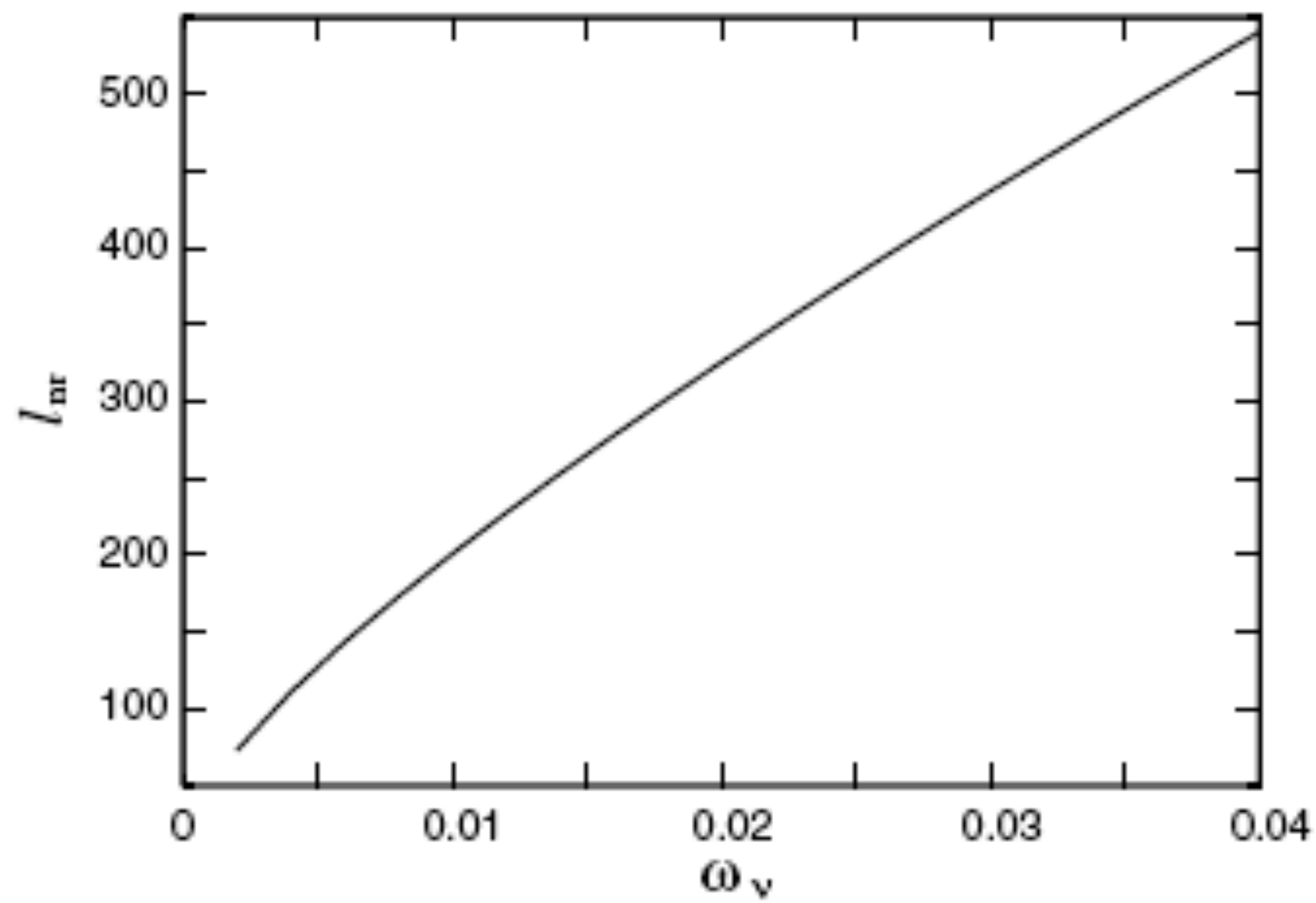


SNeIa
LSS + H0
lensing
1
0.5
0
Ωʌ
H0
CMB
BAO
flat
0
0.5
1
Ωm

Conclusions:

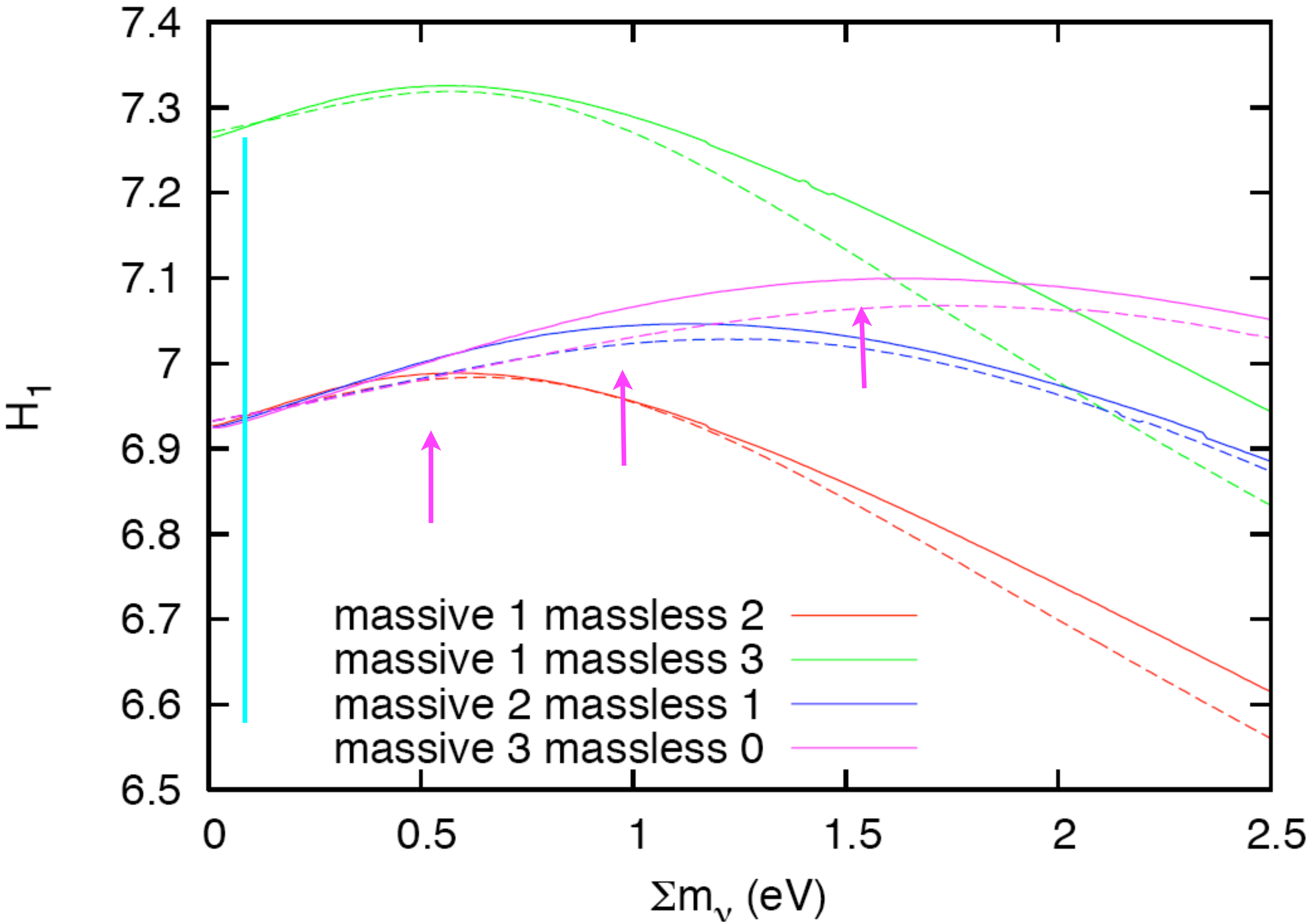
- Constraints on the mass of neutrinos
  - Use of the power spectrum
    - Attempt: halo distribution $\sum m_\nu < 0.62\text{eV} \quad (95\% CL)$
  - Use of CMB alone $\sum m_\nu < 1.2\text{eV} \quad (95\% CL)$
  - Lower Hubble constant: $H_0 = 70 - 72 \;\; \rightarrow 62 - 72$
    - + Ext. data to constrain H_0 → $\sum m_\nu < 0.7\text{eV}$
- Special case: 3 massless + 1 massive neutrinos (Angus 09)
  - massive neutrino behaves as quasi-CDM: OK with CMB,
    - but excluded by P(k) unless gravity largely modified
- Future:
  - Verification of the halo model
  - Weak lensing for B mode polarisation (Kaplinghat et al. 03)
  - Too reach $\sum m_{\nu_i} \sim 0.05\text{eV}$ would not be too unrealistic

A



500
400
300
200
100
l_{nr}
0
0.01
0.02
0.03
0.04
ω_ν

H_1 takes a peak at $m_\nu = 0.5\mathrm{eV}$ per nu



WMAP-3: Spergel et al. 2006