Upper limits on neutrino masses from cosmology

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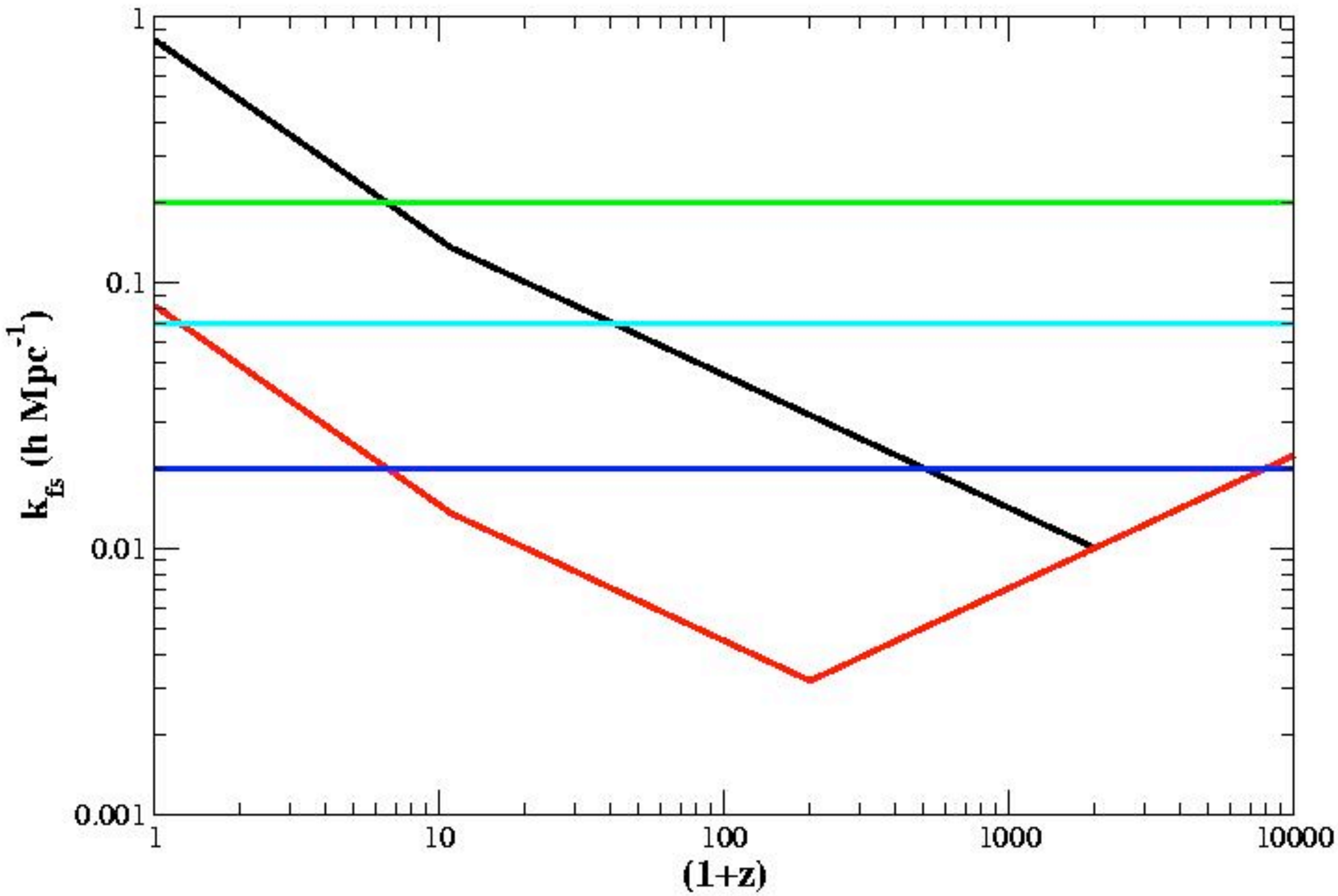
Bottom line

- We have only one Universe
- There are few model-independent observations in cosmology
- So cosmological neutrino mass bounds are only as certain as the assumptions that go into deriving them
- Most bounds assume standard neutrino physics and the ΛCDM model.

Neutrino masses and LSS

- Neutrinos become non-relativistic at
  $1+z_{nr} \sim 2.1 \times 10^3\ m_\nu / 1\ \mathrm{eV}$
- While relativistic, the free-streaming scale is set by the horizon
- When non-relativistic, the free-streaming scale is
  $k_{fs} \sim 0.82\ (H(z) / H_0(1+z)^2)(m_\nu / 1\ \mathrm{eV})\ \ h\ \mathrm{Mpc}^{-1}$

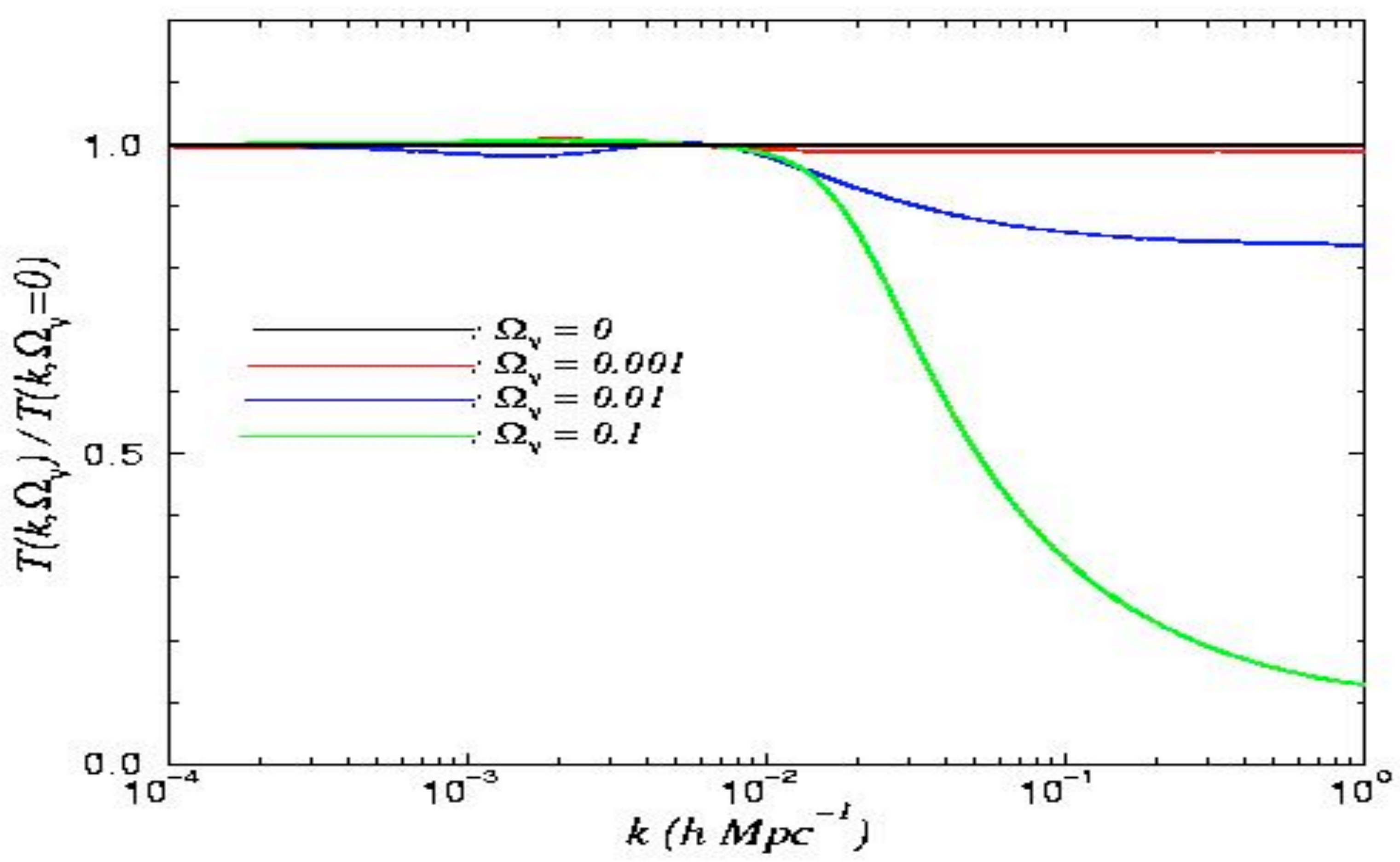


1
0.1
0.01
0.001
k_{fs} (h Mpc^{-1})
1
10
100
1000
10000
(1+z)

Neutrino masses and LSS

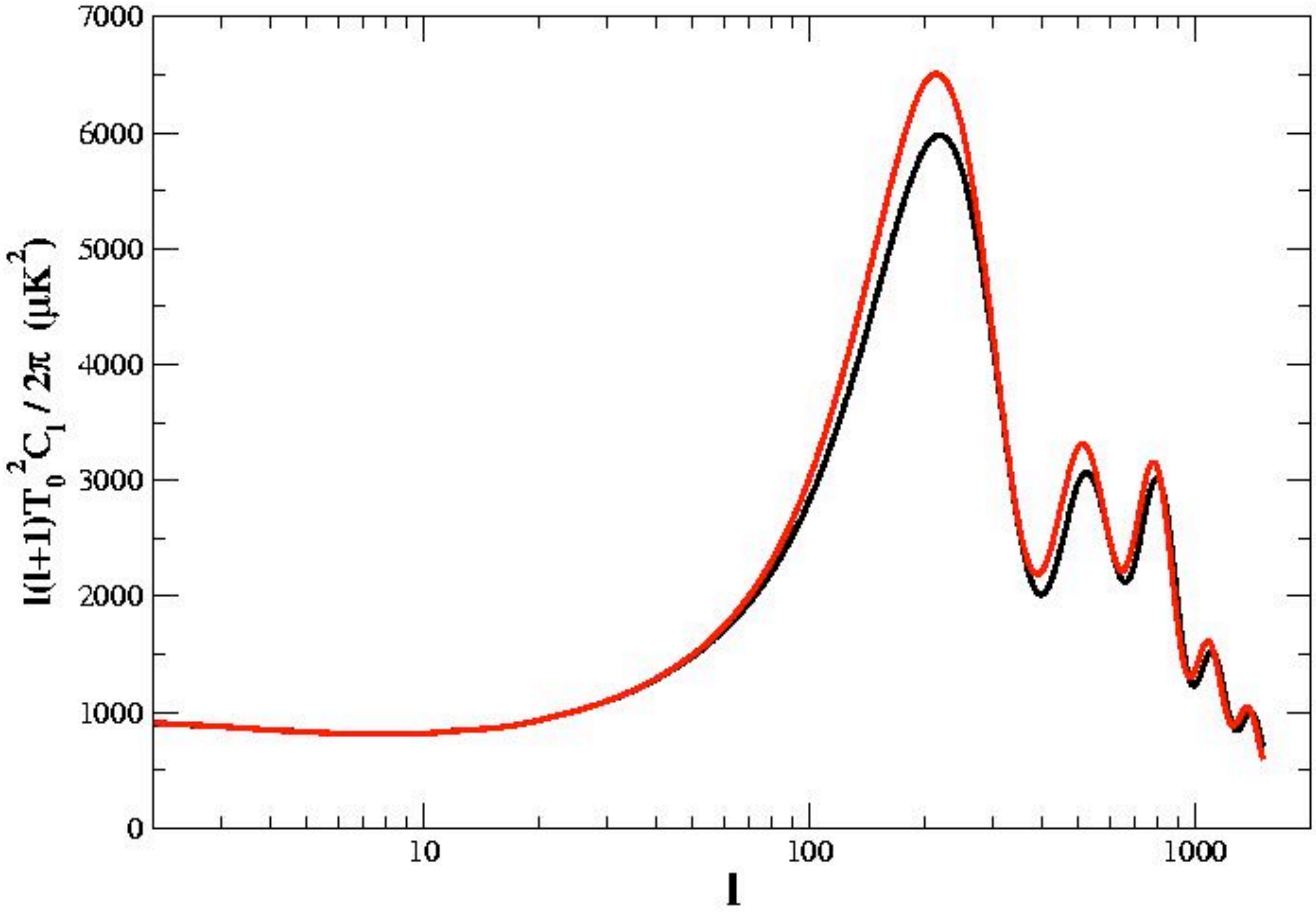
- On scales below the free-streaming scale, the effect is basically to reduce the source term in the growth equation
- Note: depends on
  $f_\nu = \Omega_\nu / \Omega_m$

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4\pi G\rho_0(1 - f_\nu)\delta$$

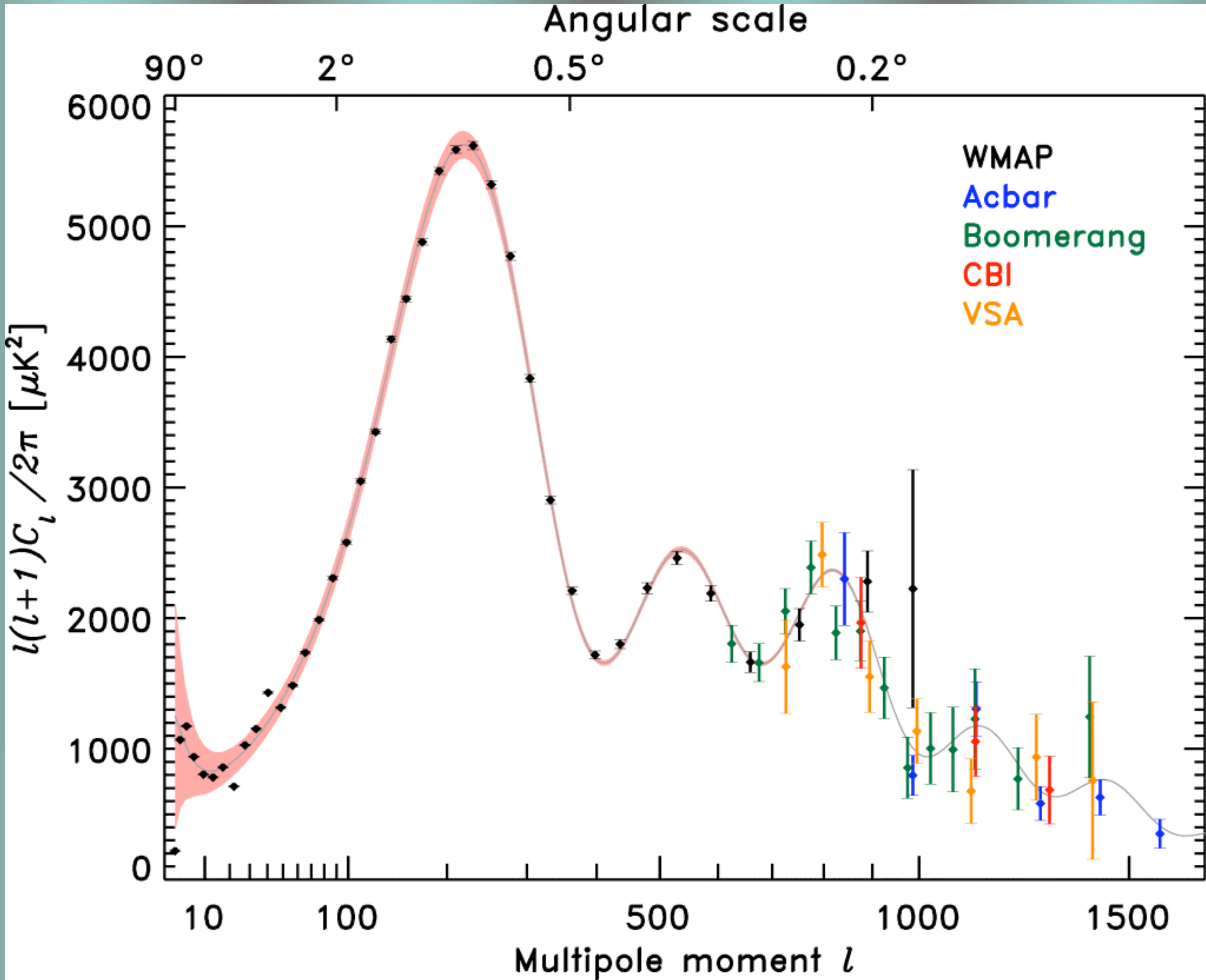

$T(k,\Omega_\nu) / T(k,\Omega_\nu=0)$
$k\ (h\ Mpc^{-1})$
: $\Omega_\nu = 0$
: $\Omega_\nu = 0.001$
: $\Omega_\nu = 0.01$
: $\Omega_\nu = 0.1$
1.0
0.5
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

Neutrinos and the CMB

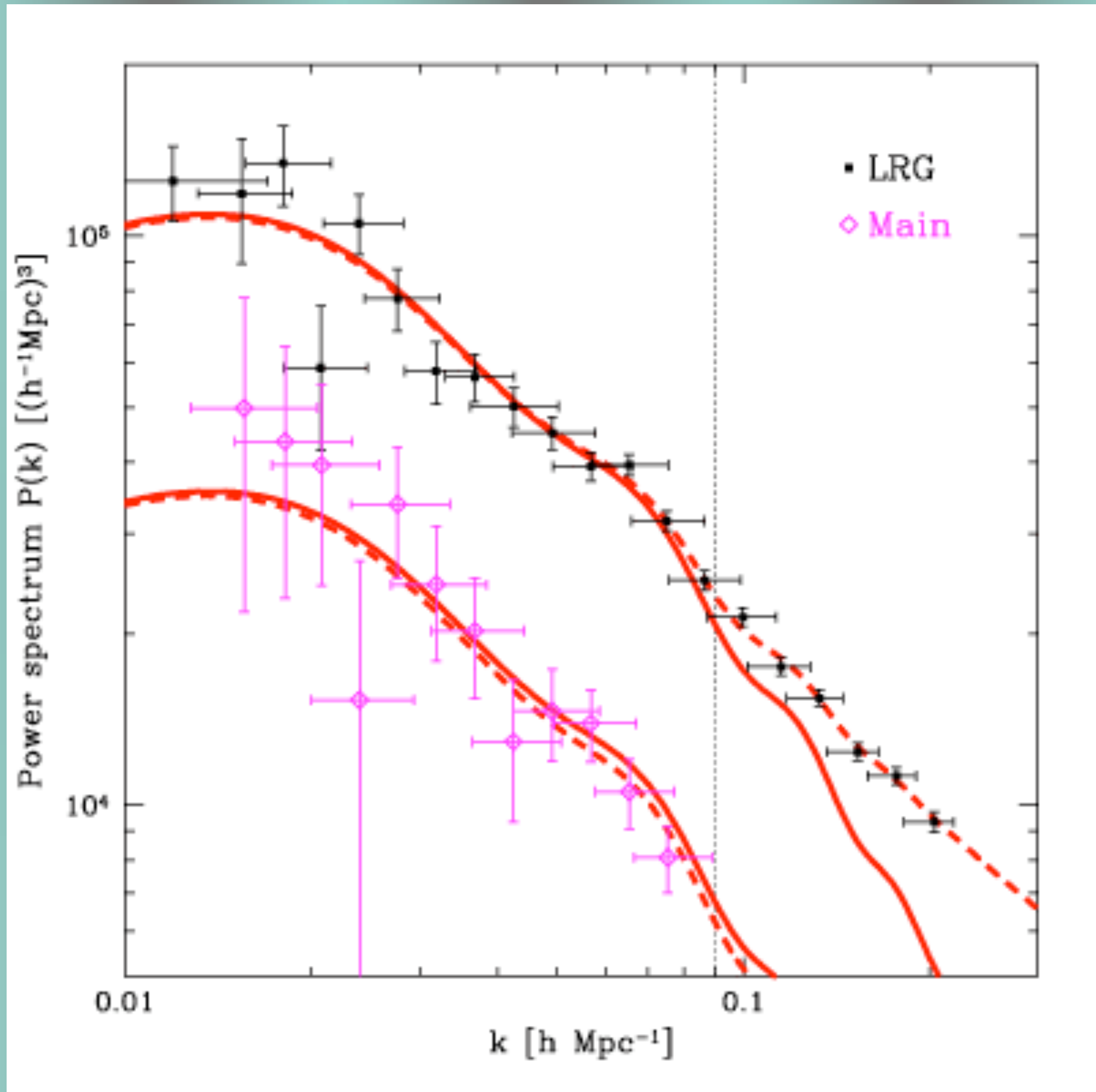
- Neutrinos became non-relativistic before recombination if M_ν > 1.6 eV
- Postpone matter-radiation equality, smooth out gravitational potentials and enhance baryon oscillations -> shift peaks and enhance temperature fluctuations for l > 300
- If they became non-relativistic after recombination, the CMB was produced before neutrino masses could influence the temperature fluctuations.



7000
6000
5000
4000
3000
2000
1000
0
10
100
1000
l(l+1)T0 2C l / 2π (μK 2)
l

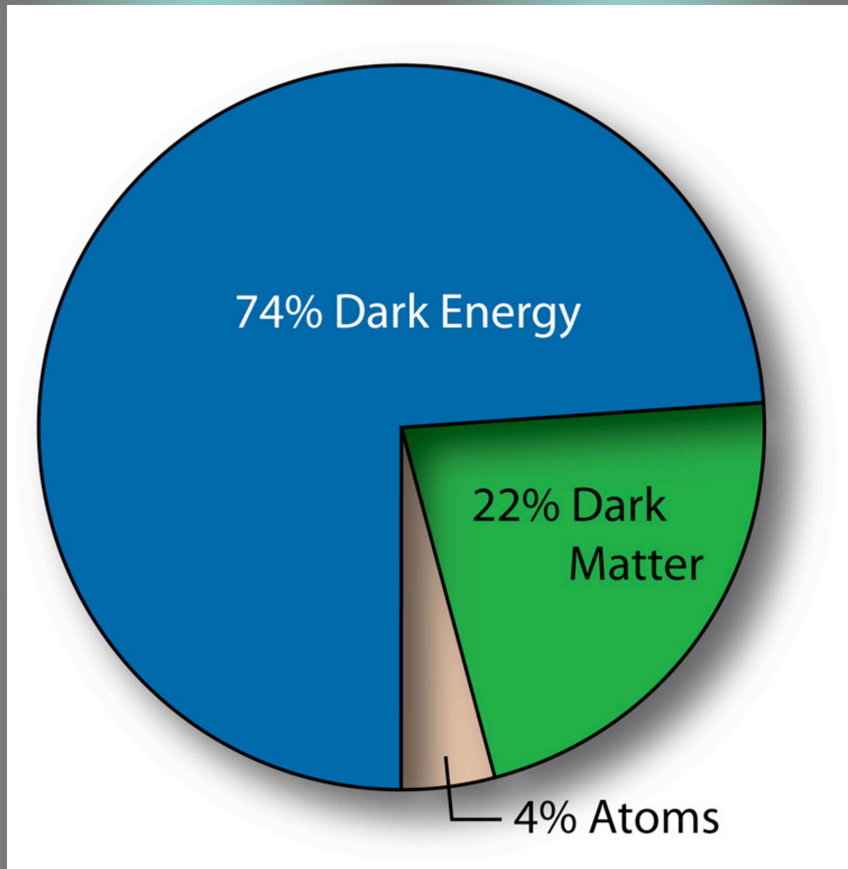


NASA/WMAP Science Team



Tegmark et al., astro-ph/0608632

Room for neutrinos?

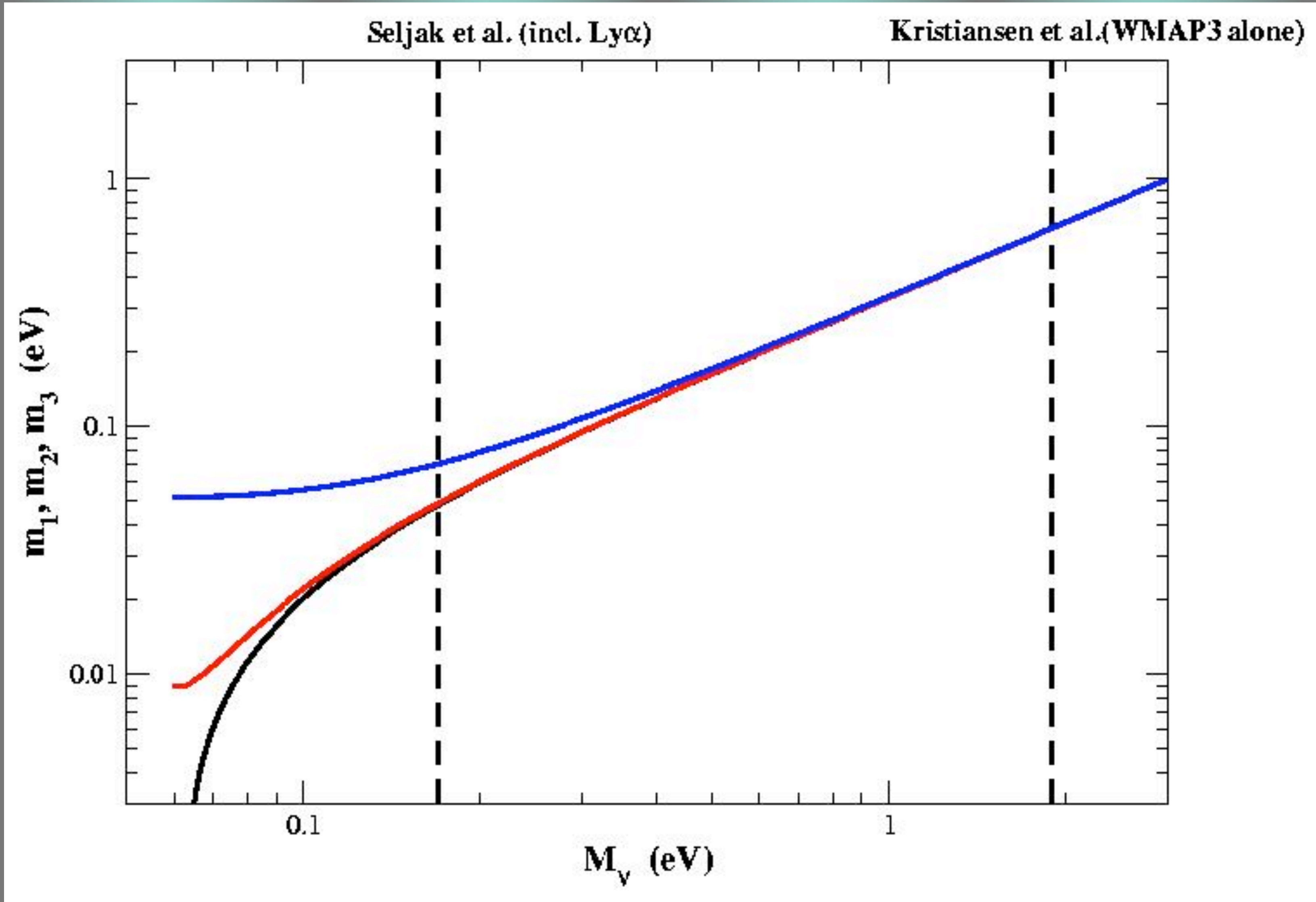


NASA/WMAP Science Team

Neutrino mass from Cosmology

Data	Authors	$M_\nu = \Sigma m_i$
2dF (P01)	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+…	Spergel et al. 03	< 0.7 eV
SDSS LRG+WMAP3	Tegmark et al. 06	< 0.9 eV
BAO+CMB+LSS+SNIa	Goobar et al. 06	< 0.5 eV
Ly-α + SDSS+ WMAP3	Seljak et al. 06	< 0.17eV
WMAP3 alone	Kristiansen et al. 06	< 1.6 eV

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



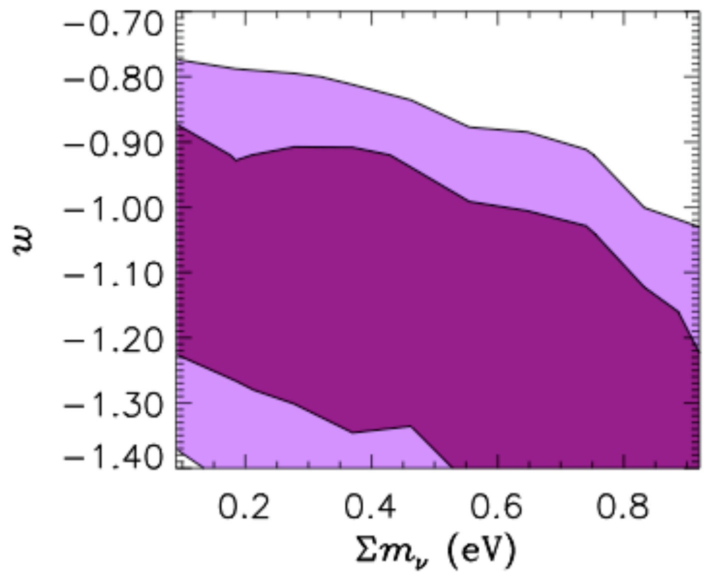
Seljak et al. (incl. Lyα)
Kristiansen et al.(WMAP3 alone)
1
0.1
0.01
m1, m2, m3 (eV)
0.1
1
Mν (eV)

Example of “model” systematics: Dark energy

- Most cosmological neutrino mass limits have assumed that the dark energy is a cosmological constant
- There are (too!) many alternatives
- Common parameterization:

$$p = w\rho$$

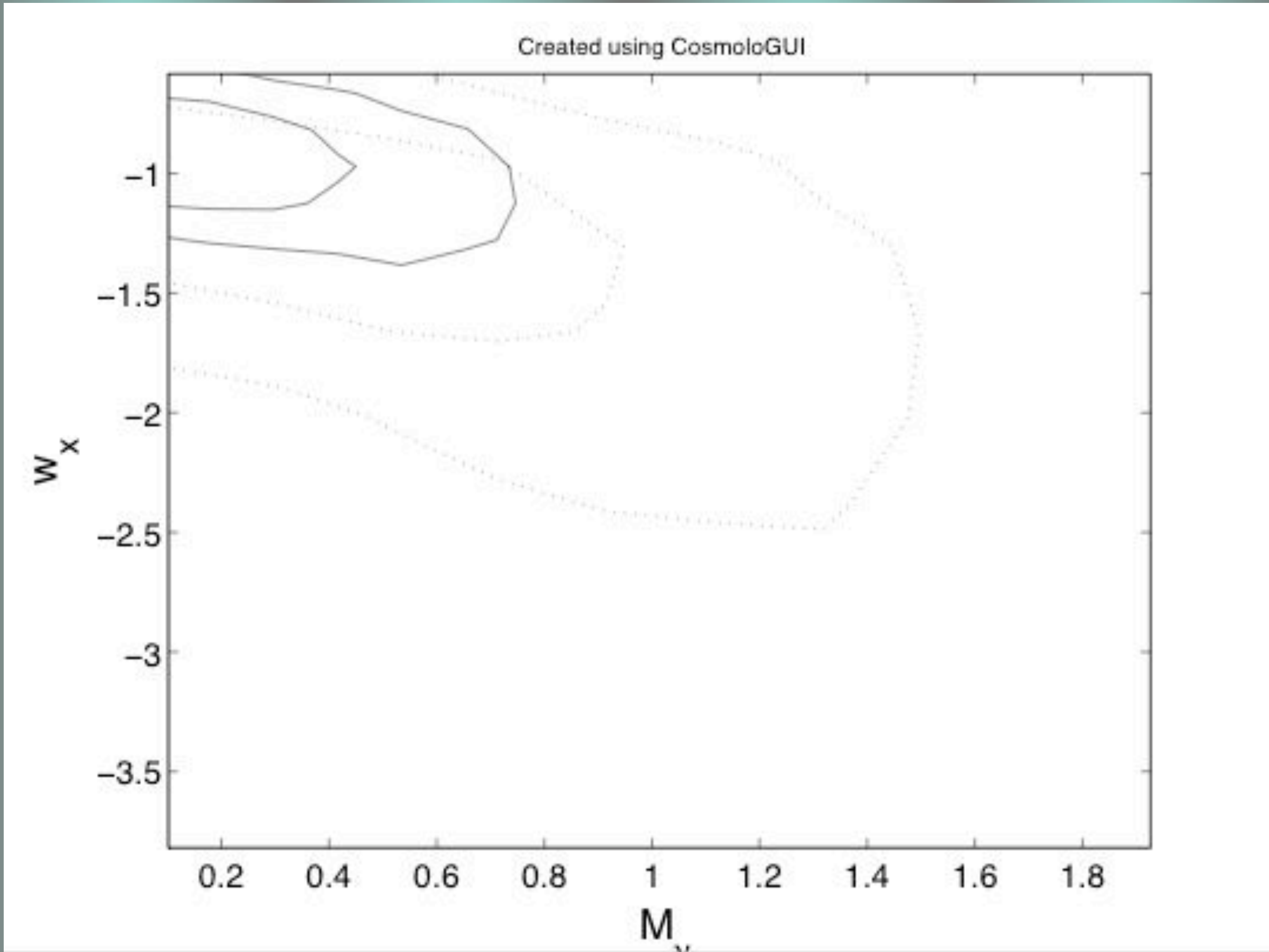
where w is a constant (can be < -1)



Hannestad, PRL95 (2005) 221301

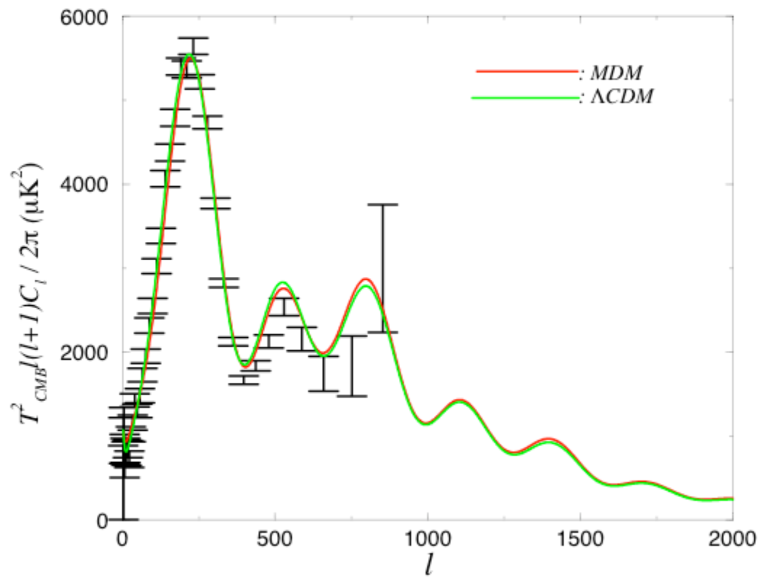
Why this degeneracy?

- P(k) sensitive to the combination $f_\nu=\Omega_\nu/\Omega_m$
- But $m_\nu=93.14\Omega_\nu h^2$ eV
- If one allows for w <-1, SNIa data allow large values of Ω_m
- The degeneracy is indirect, the effect of varying w on P(k) corresponds roughly to varying the amplitude
- Can be broken by e.g. BAO

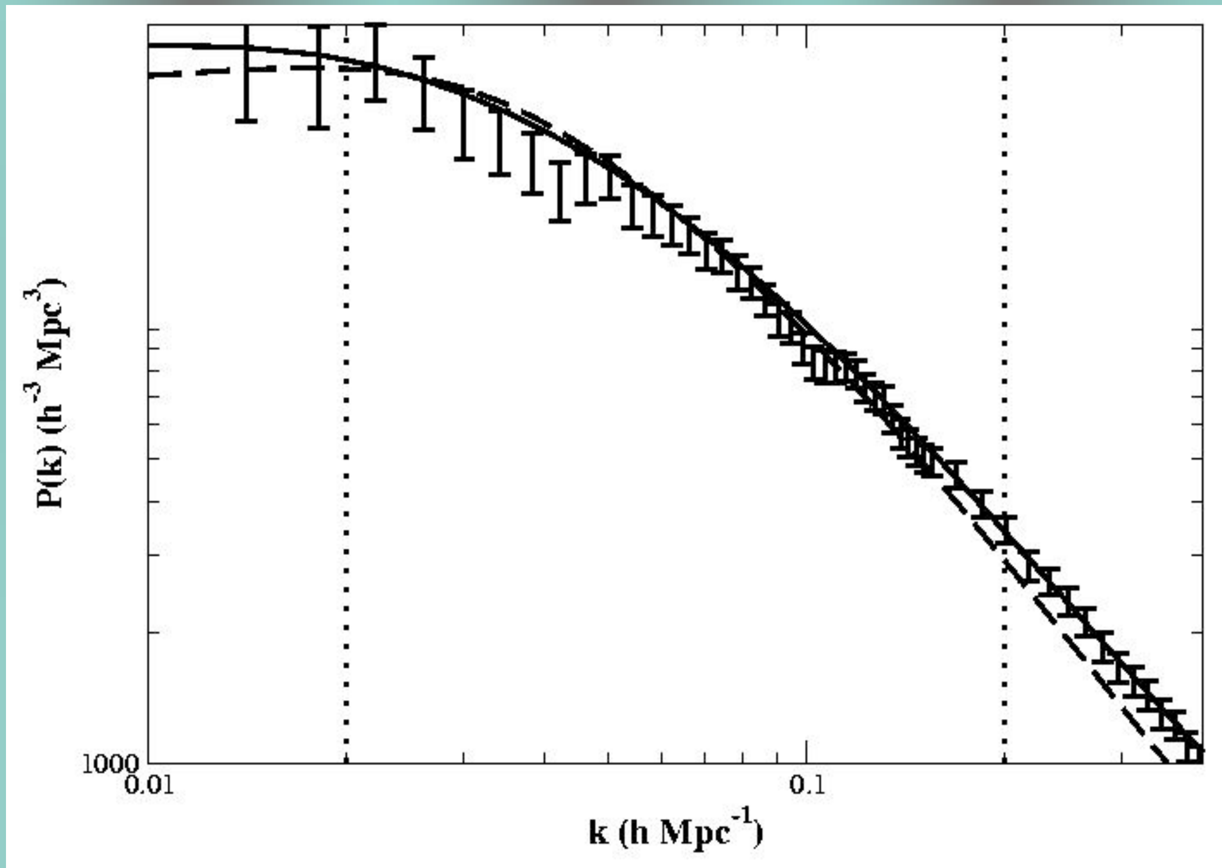


J. R. Kristiansen, master thesis

CMB alone: still room for M_ν



Galaxies alone: room for M_ν



Bias

- Current approaches assume that the relation between the distributions of luminous and dark matter is simple (“constant bias”)
- Recent results suggests that the situation is more complicated, see Percival et al., astro-ph/0608636
- Better modelling is needed, or rely on CMB+weak lensing

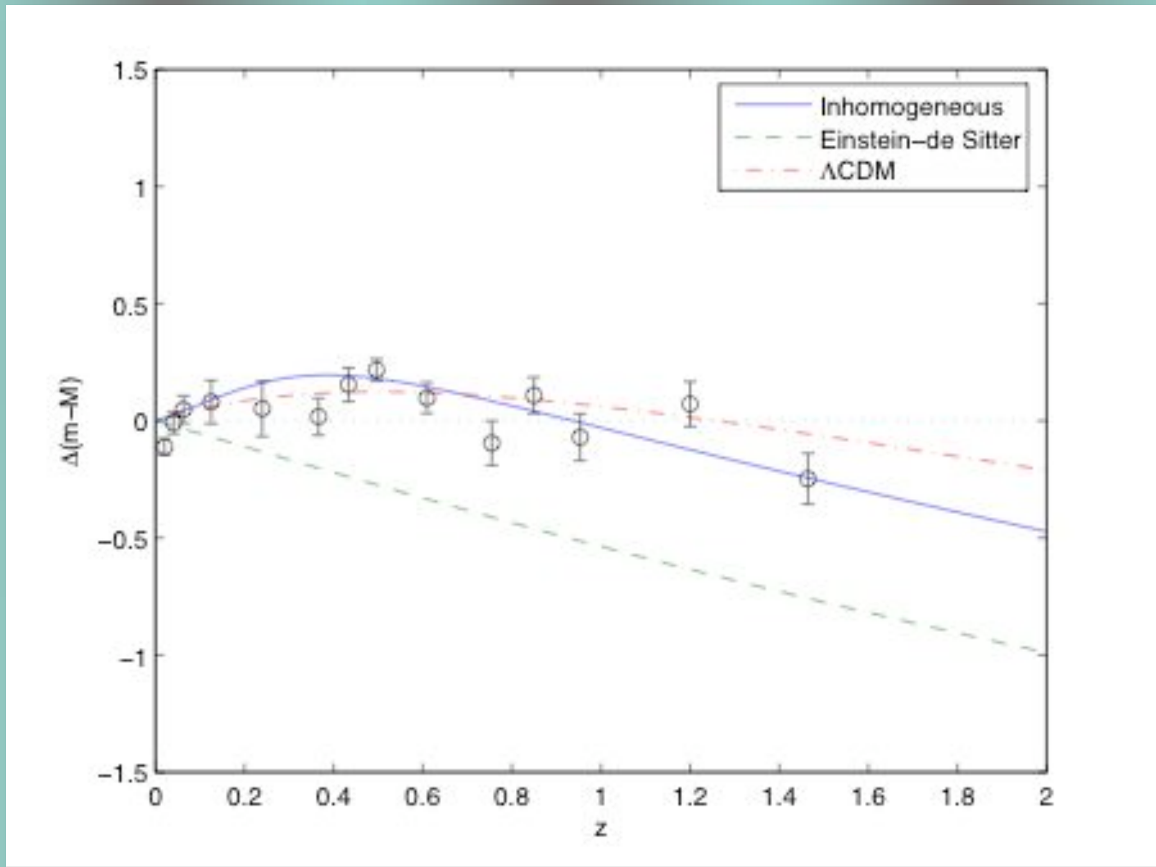
Emerging fashion

- Turn the question around: what can neutrino experiments tell us about cosmology?
- La Macorra et al., astro-ph/0608351: HM-result rules out a cosmological constant at more than 2σ
- Dodelson et al., PRL97 (2006) 04301: If LSND result is confirmed, the “concordance model” is in trouble

Bullet Cluster: DM confirmed?

Clowe et al., astro-ph/0608407, see also
Angus et al., astro-ph/0609125: MOND saved by 2 eV neutrinos

Challenging basic assumptions: an inhomogeneous universe



Alnes, Amarzguioui and Grøn, PRD 73 083519

Summary

- Cosmological neutrino mass limits start to probe the sub-eV range
- Need to focus on systematics
- No data set can do the job alone if one wants tight constraints or rule out funny models
- Bias looks to be a real concern, need better modelling or direct probes of the DM
- A non-cosmological measurement of neutrino masses could rule out funny models or spell trouble for ΛCDM.
- Reviews:

Lesgourgues & Pastor, Phys. Rep. 429 (2006) 307, astro-ph/0603494

ØE & Ofer Lahav, NJP 7 (2005) 61, astro-ph/0412075