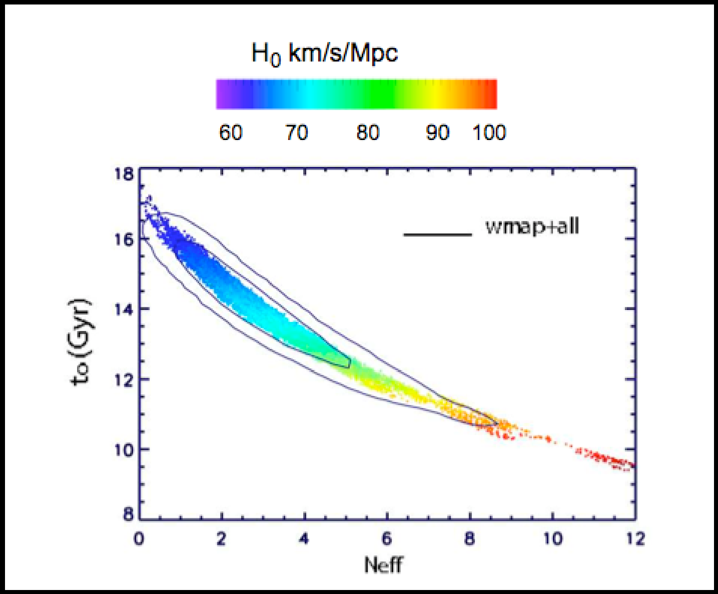
Neutrino properties from Cosmology



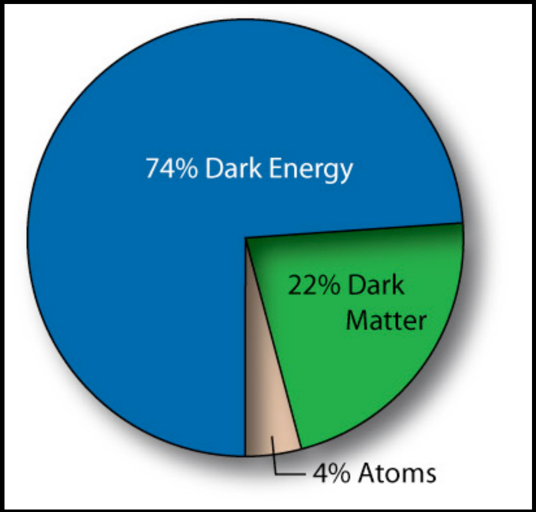
Disclaimer:
this talk will be by no means a complete and unbiased review of the literature!

Licia Verde
ICE (IEEC-CSIC)

www.ice.csic.es/personal/verde

The standard cosmological model (LCDM)

Cosmic Pie



Only 6 parameters, fits observations of the Universe from z=1100 to today.

Spatially flat, made of baryonic matter, cold dark matter, cosmological constant, radiation-unimportant today-,

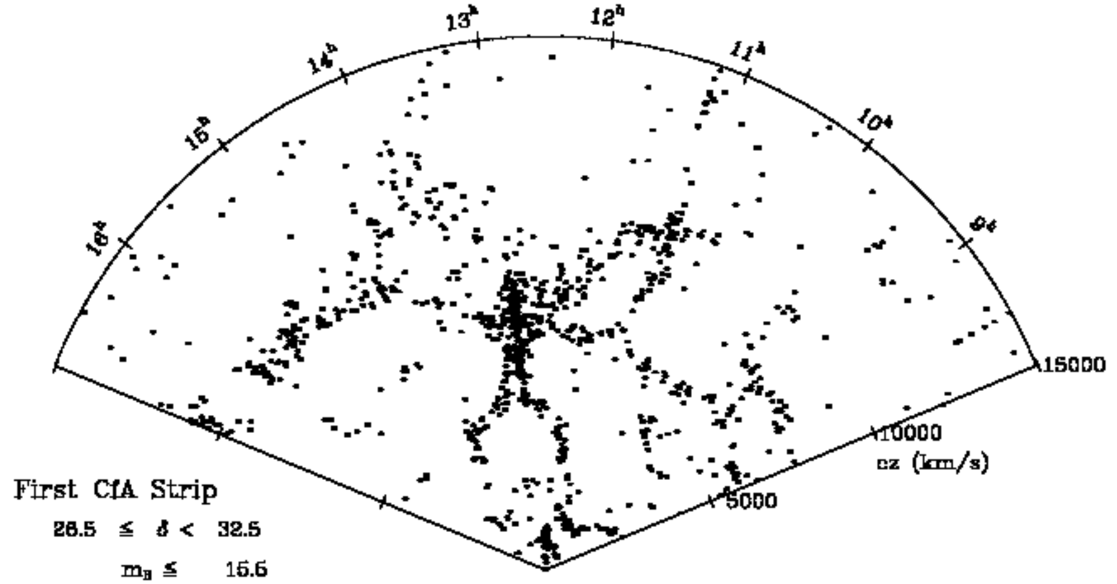
inflationary scenario generated perturbations: amplitude and slope of the power spectrum of primordial perturbations

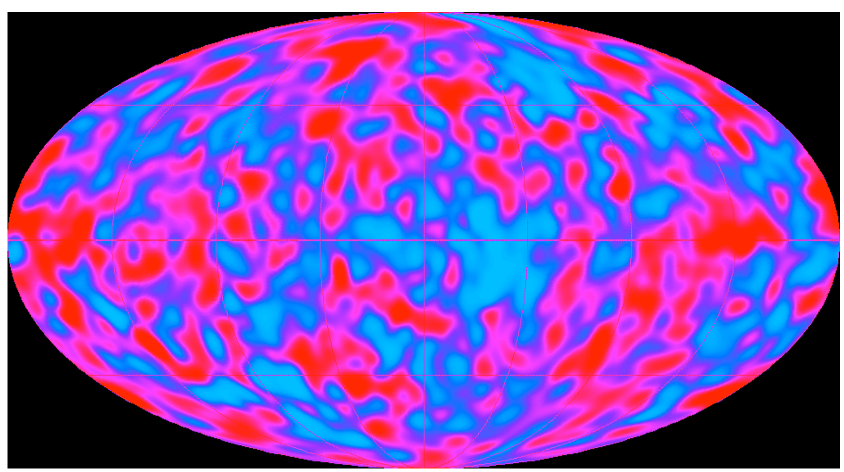
Optical depth (reionization)

present-day expansion rate

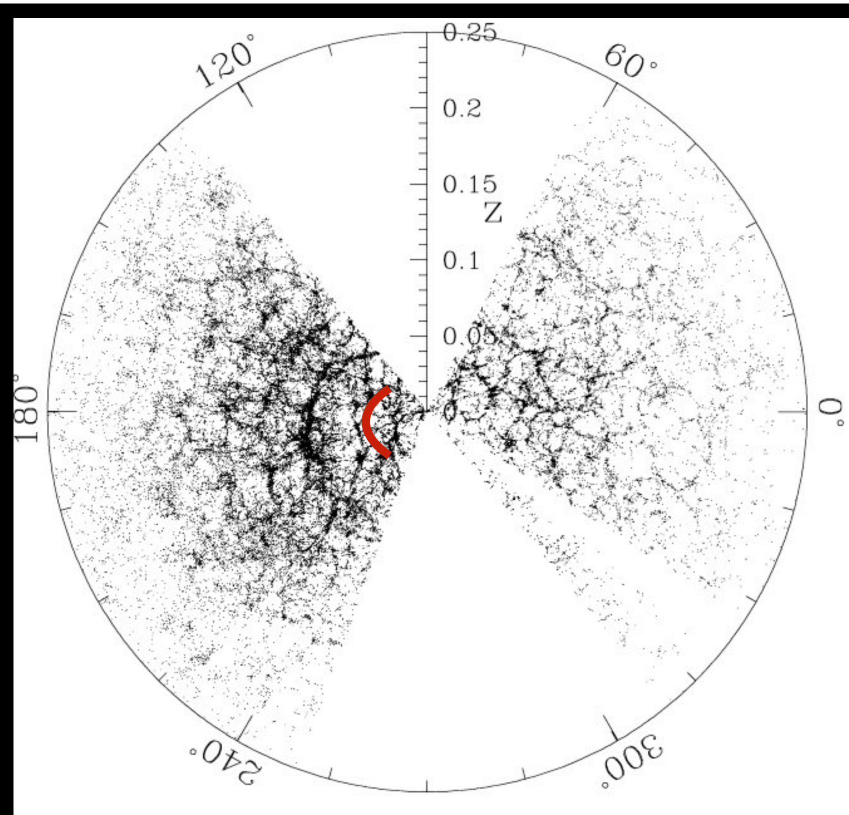
Extremely successful model

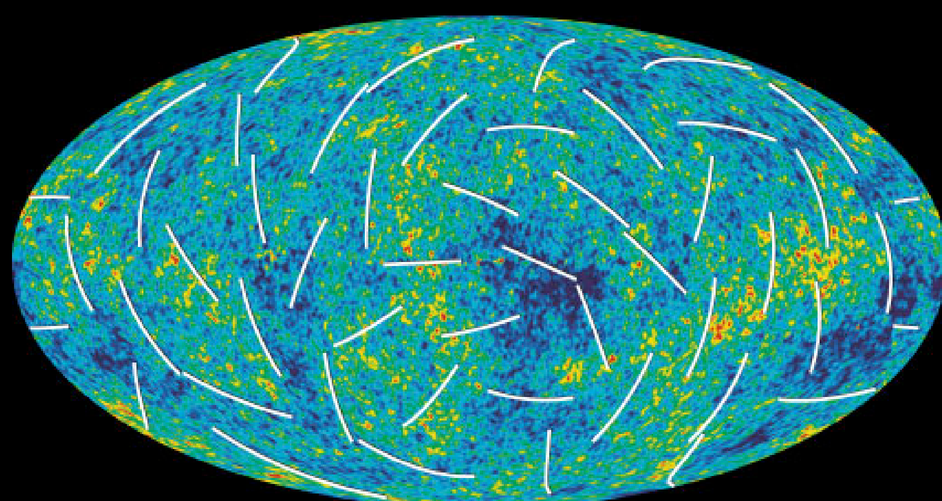
State of the art of data then…





State of the art of data now…

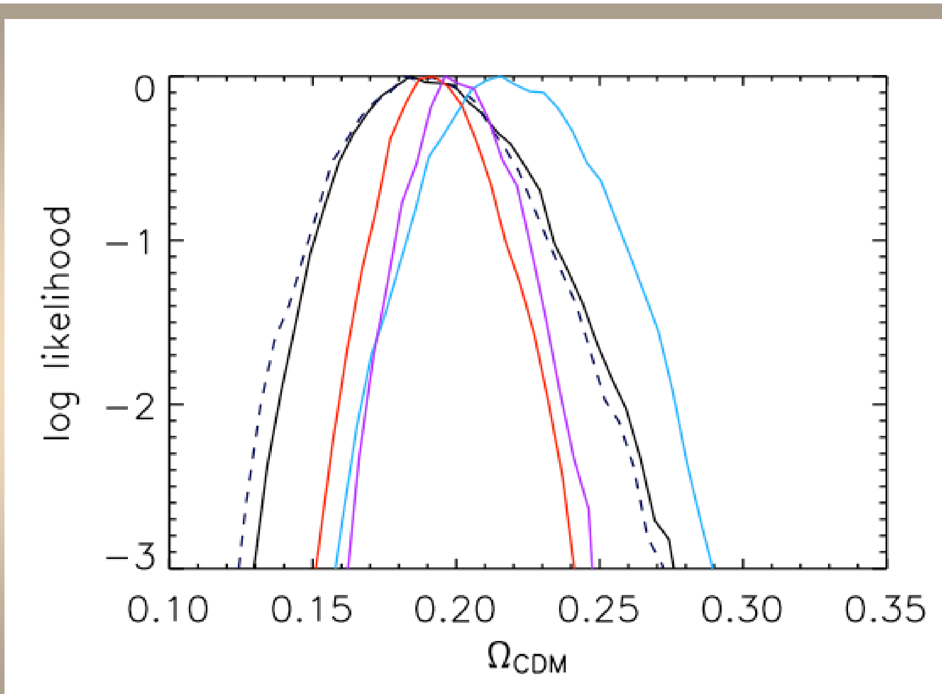




LCDM model survives!

Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.212^{+0.066}_{-0.084}$	$2.231^{+0.070}_{-0.088}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0072}_{-0.0095}$	$0.1233^{+0.0070}_{-0.0086}$	$0.1259^{+0.0077}_{-0.0095}$	$0.1262^{+0.0045}_{-0.0062}$
h	$0.734^{+0.028}_{-0.038}$	$0.743^{+0.027}_{-0.037}$	$0.739^{+0.028}_{-0.038}$	$0.732^{+0.018}_{-0.025}$
A	$0.801^{+0.043}_{-0.054}$	$0.796^{+0.042}_{-0.052}$	$0.798^{+0.046}_{-0.054}$	$0.799^{+0.042}_{-0.051}$
τ	$0.088^{+0.028}_{-0.034}$	$0.088^{+0.027}_{-0.033}$	$0.088^{+0.030}_{-0.033}$	$0.083^{+0.027}_{-0.031}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.951^{+0.015}_{-0.020}$	$0.948^{+0.014}_{-0.018}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.043}_{-0.053}$	$0.739^{+0.047}_{-0.059}$	$0.737^{+0.033}_{-0.045}$
Ω_m	$0.238^{+0.030}_{-0.041}$	$0.226^{+0.026}_{-0.036}$	$0.233^{+0.029}_{-0.041}$	$0.236^{+0.016}_{-0.024}$

Parameter	WMAP+ SDSS	WMAP+ LRG	WMAP+ SNLS	WMAP + SN Gold	WMAP+ CFHTLS
$100\Omega_b h^2$	$2.233^{+0.062}_{-0.086}$	$2.242^{+0.062}_{-0.084}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$	$2.255^{+0.062}_{-0.083}$
$\Omega_m h^2$	$0.1329^{+0.0056}_{-0.0075}$	$0.1337^{+0.0044}_{-0.0061}$	$0.1295^{+0.0056}_{-0.0072}$	$0.1349^{+0.0056}_{-0.0071}$	$0.1408^{+0.0034}_{-0.0050}$
h	$0.709^{+0.024}_{-0.032}$	$0.709^{+0.016}_{-0.023}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$	$0.687^{+0.016}_{-0.024}$
A	$0.813^{+0.042}_{-0.052}$	$0.816^{+0.042}_{-0.049}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$	$0.846^{+0.037}_{-0.047}$
τ	$0.079^{+0.029}_{-0.032}$	$0.082^{+0.028}_{-0.033}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$	$0.088^{+0.026}_{-0.032}$
n_s	$0.948^{+0.015}_{-0.018}$	$0.951^{+0.014}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$	$0.953^{+0.015}_{-0.019}$
σ_8	$0.772^{+0.036}_{-0.048}$	$0.781^{+0.032}_{-0.045}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$	$0.826^{+0.022}_{-0.035}$
Ω_m	$0.266^{+0.026}_{-0.036}$	$0.267^{+0.018}_{-0.025}$	$0.249^{+0.024}_{-0.031}$	$0.276^{+0.023}_{-0.031}$	$0.299^{+0.019}_{-0.025}$



CDM density

WMAP II

WMAP+high l experiments

SDSS main

2dFGRS

LRG SDSS

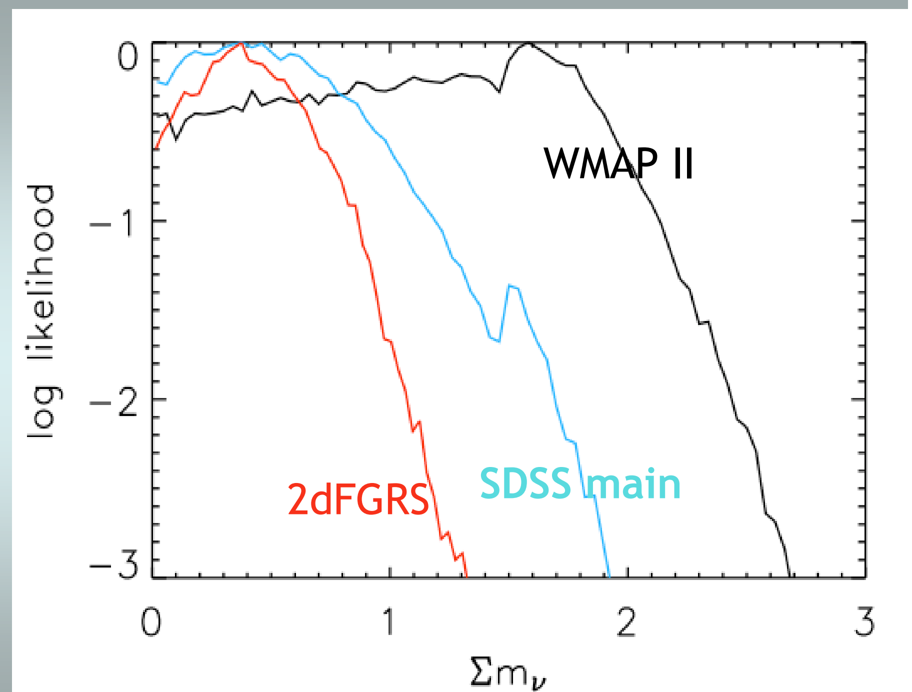
Neutrino mass

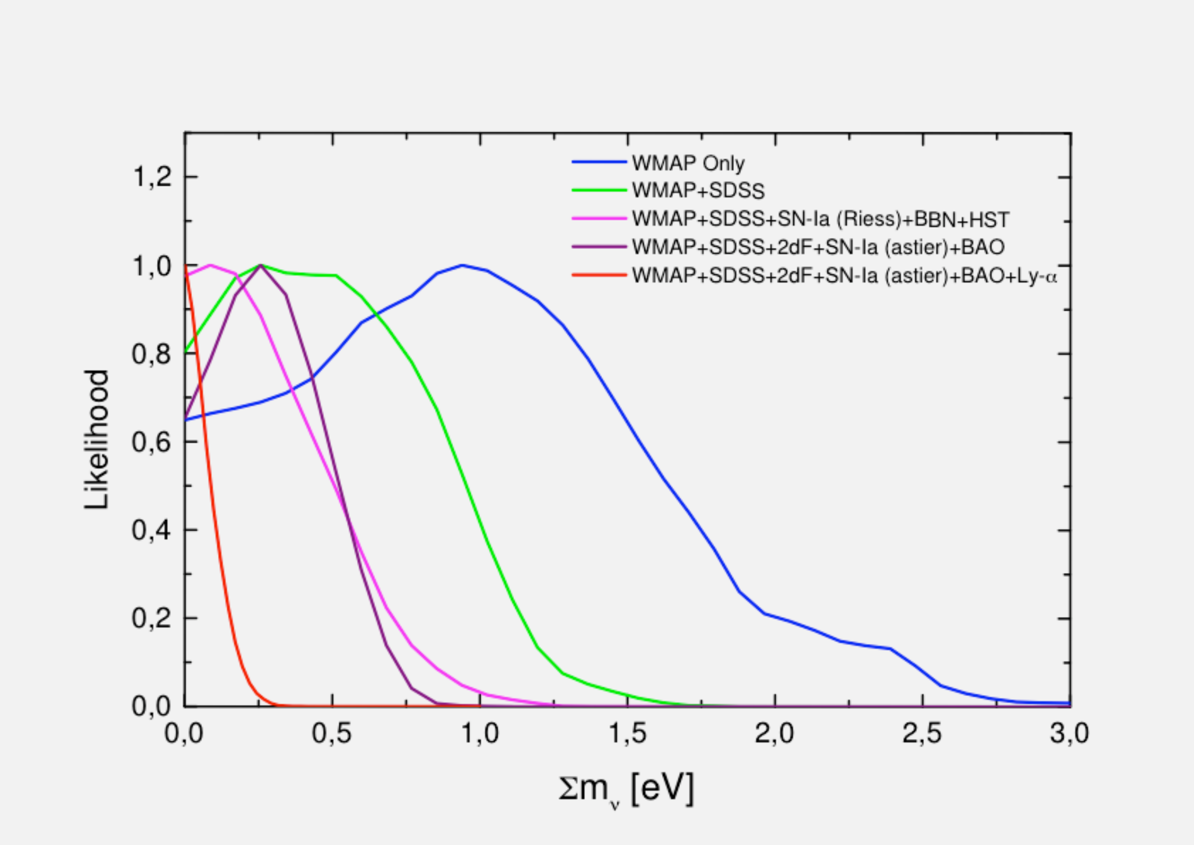
Spergel et al '07

Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.04$)	N_ν
WMAP	1.8 eV (95% CL)	–
WMAP + SDSS	1.3 eV (95% CL)	$7.1^{+4.1}_{-3.5}$
WMAP + 2dFGRS	0.88 eV (95% CL)	2.7 ± 1.4
CMB + LSS +SN	0.66 eV (95% CL)	3.3 ± 1.7

CMB+SDSS LRG 0.9eV (95% CL)

Tegmark et al '07





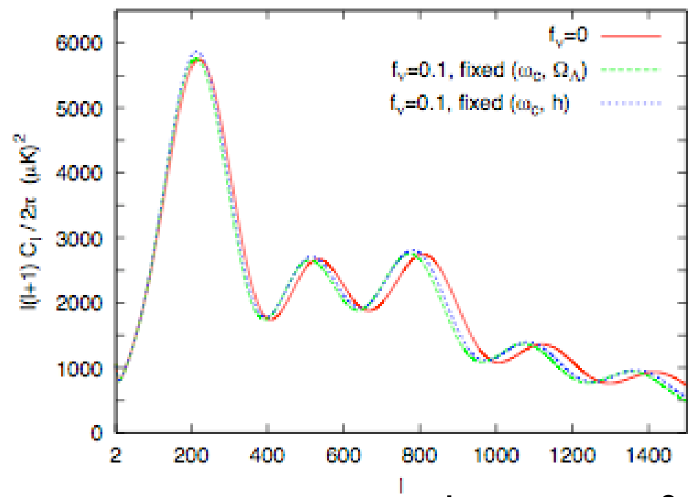
(assuming 3 Active Neutrino model)

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + $\mathrm{SN}_{\mathrm{Riess}}$ + HST + BBN	< 0.78 eV
4	CMB + LSS + $\mathrm{SN}_{\mathrm{Astier}}$	< 0.75 eV
5	CMB + LSS + $\mathrm{SN}_{\mathrm{Astier}}$ + BAO	< 0.58 eV
6	CMB + LSS + $\mathrm{SN}_{\mathrm{Astier}}$ + Ly-α	< 0.21 eV
7	CMB + LSS + $\mathrm{SN}_{\mathrm{Astier}}$ + BAO + Ly-α	< 0.17 eV

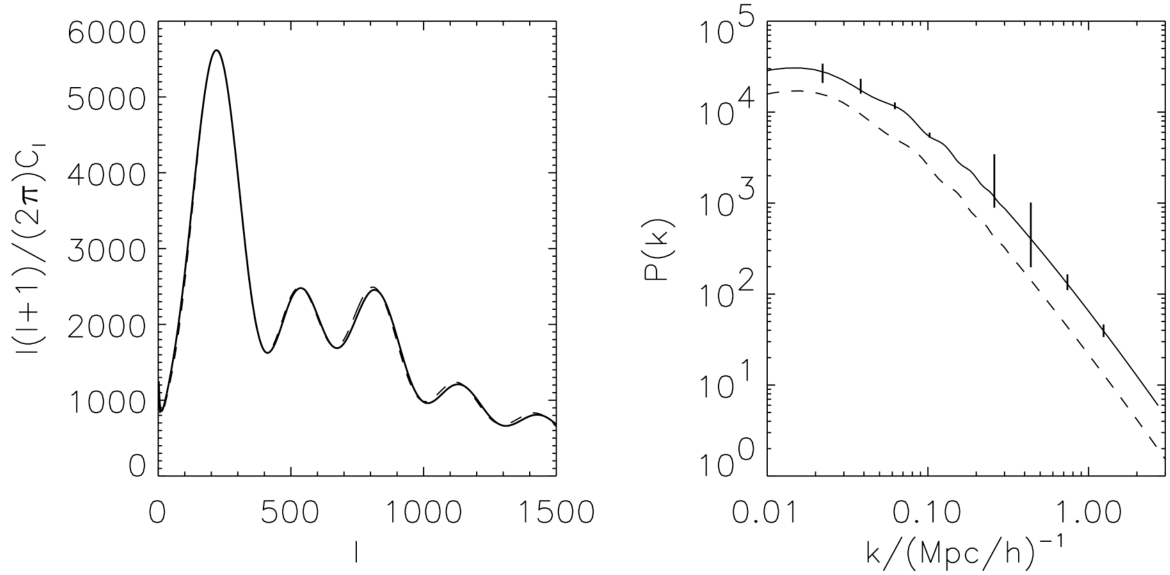
Fogli et al., Phys. Rev. D 75, 053001 (2007)

Why CMB?

$$1+z_{eq} = \frac{4.05\times10^4\,\Omega_m h^2}{1+0.6905(N_\nu/3.04)}$$



Lesgorges & Pastor 06



Verde et al 03

Why large scale structure?

$$\Omega_\nu h^2 = \frac{m_{\nu,\mathrm{tot}}}{94\ \mathrm{eV}},$$

Neutrino effect on Structure:

hot dark matter *suppression*

$$k_{\mathrm{nr}} \approx 0.026 \left(\frac{m_\nu}{1\,\mathrm{eV}}\right)^{1/2} \Omega_m^{1/2} h\,\mathrm{Mpc}^{-1}.$$

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right).$$

The effect is z dependent!

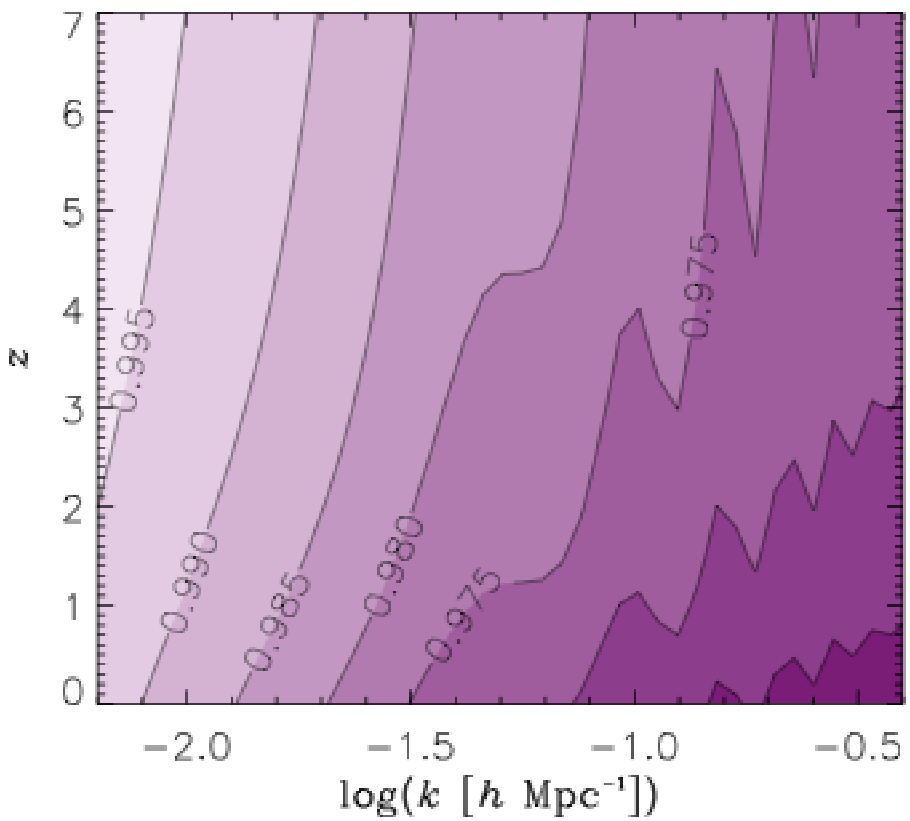
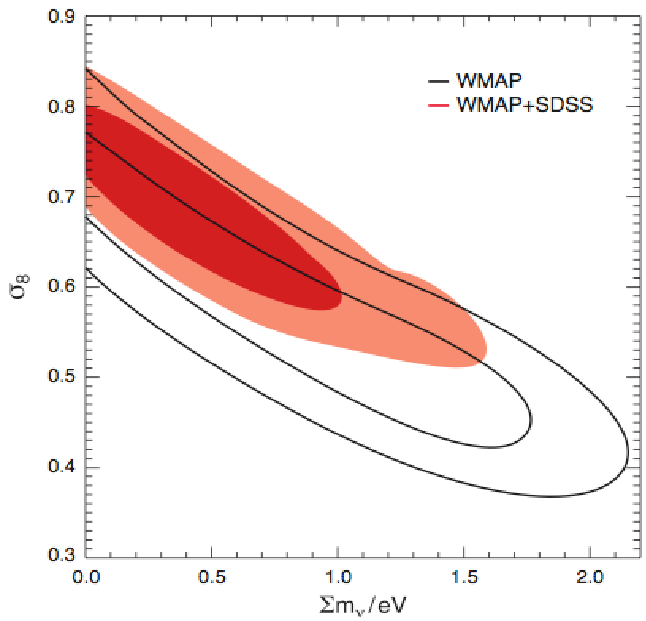
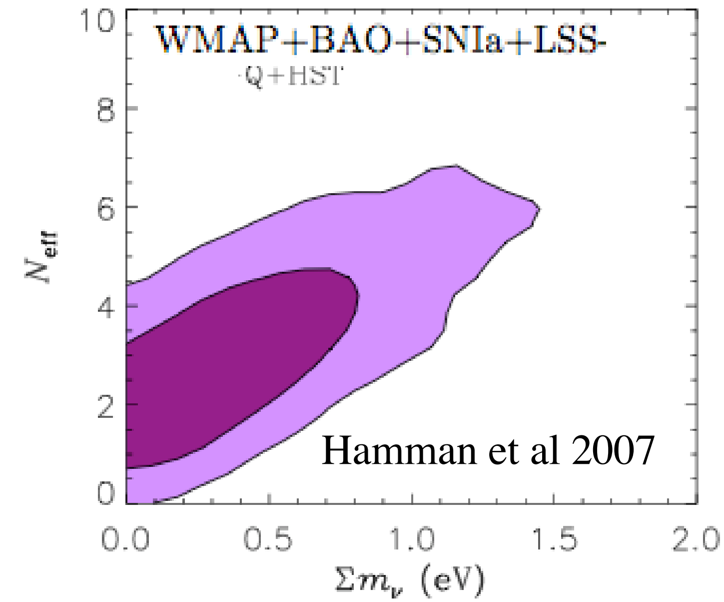


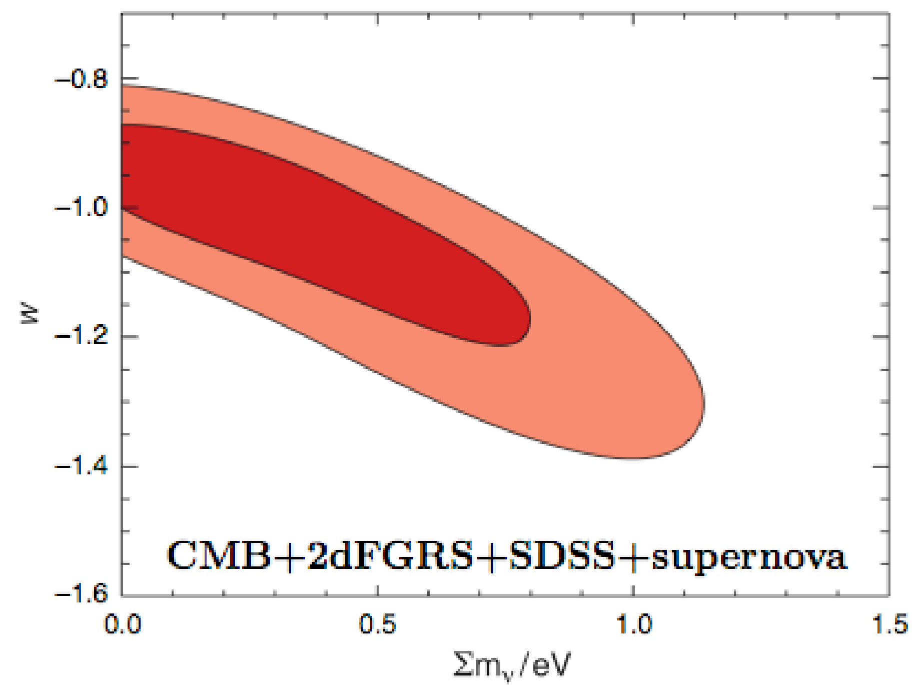
Figure 1. The power spectrum suppression factor $P(k,z)/P_{m_\nu=0}(k,z)$ as a functio of wavenumber k and redshift z for a neutrino mass of $\sum m_\nu = 0.08$ eV. The shading are from 0.96 (darkest) to 1.00 (lightest) in steps of 0.005.

Hannestad &Wong 07

Beware of degeneracies….





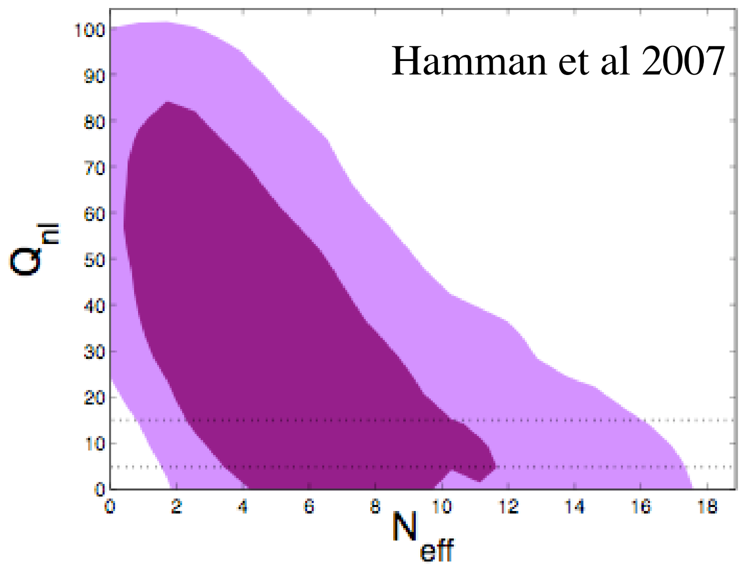


And more importantly beware of systematics… example….

$$P_{NL} = b^2 \frac{1+Qk^2}{1+Ak} P_{Lin}(k)$$

$A = 1.4$

$Q = 4.6$



See also Sanchez & Cole 2007

Spergel et al '07

Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.04$)	N_ν
WMAP	1.8 eV (95% CL)	–
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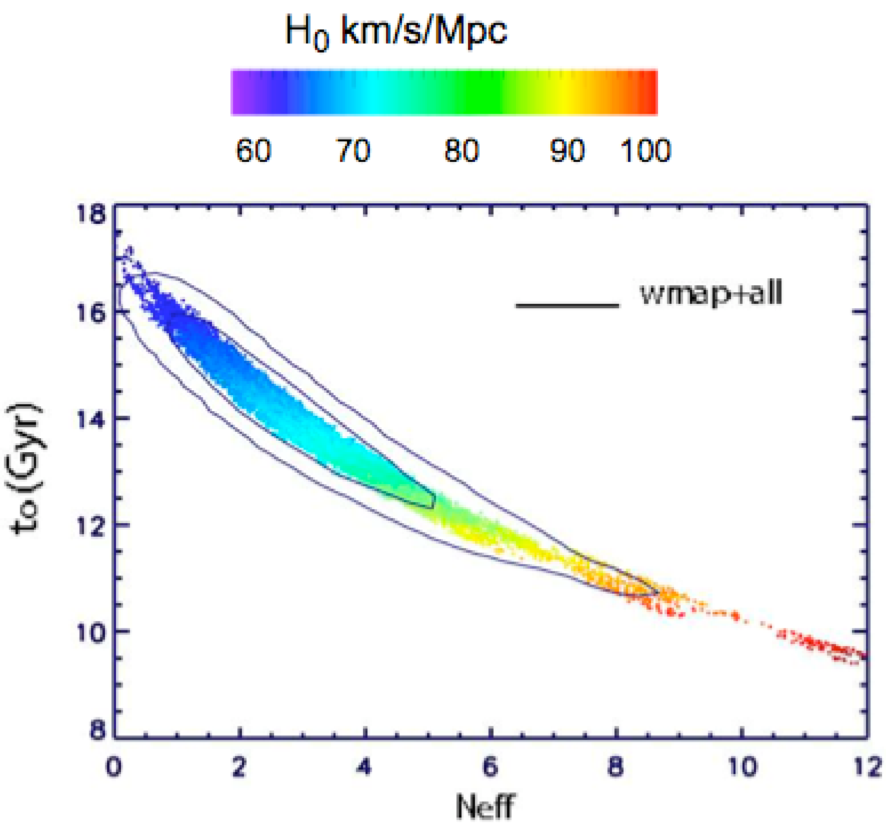
CMB+SDSS LRG	0.9eV (95% CL)
Tegmark et al '07	

Recommended:
Use a Combination
of approaches

Neutrinos and H(z)

F. de Bernardis, A. Melchiorri, L. Verde, R. Jimenez

arXiv:0707.4170



$$\omega_{\rm rel} = \omega_\gamma + N_{\rm eff} \cdot \omega_\nu$$

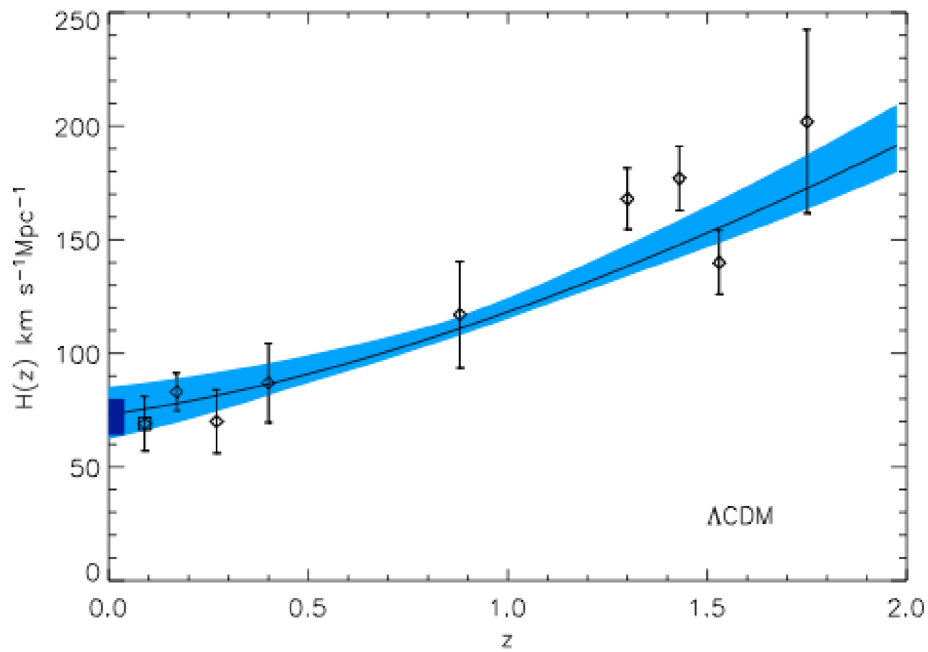
Not only neutrinos…

$$N_{\rm eff}^{\rm BBN} = 3.1^{-1.2}_{+1.4}$$

Age of the Universe

CMB data are able to tightly constrain the age of the Universe (and expansion history) **for a LCDM model** 13.83 ± 0.3 Gyrs

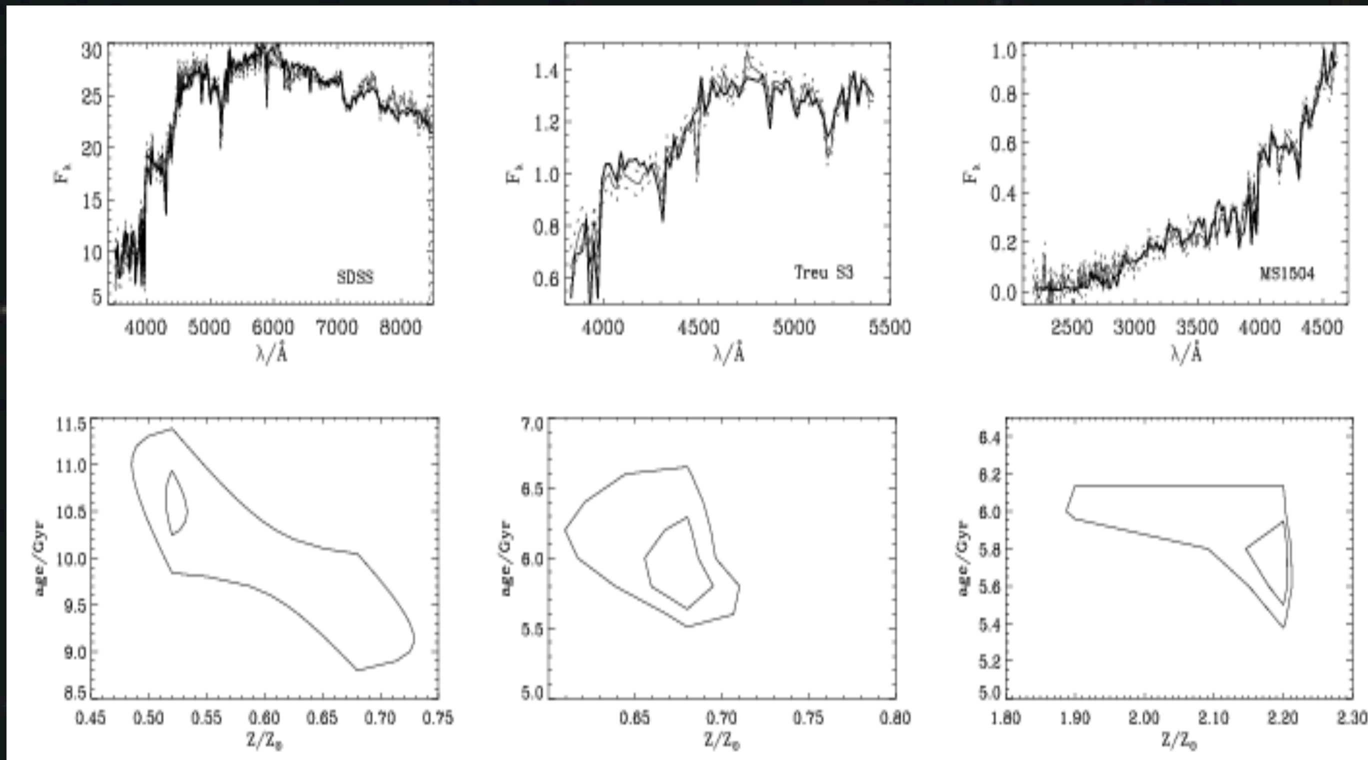
Direct
and "model
independent"
age estimates
have much
larger
error bars !



…however the WMAP constrain is model dependent.
Key parameter: energy density in relativistic particles.

$$\omega_{rel} = \omega_\gamma + N_\nu^{eff}\omega_\nu \longrightarrow t_0 = 13.8^{+2.3}_{-3.2} \text{ Gyrs}$$

Dating galaxies



If galaxies are standard clocks then we should see a red envelop: i.e. an age- redshift relation
(-> expansion history, dark energy etc.)

(Simon Verde Jimenez 2005
Jimenez, Verde, Treu, Stern 2003)

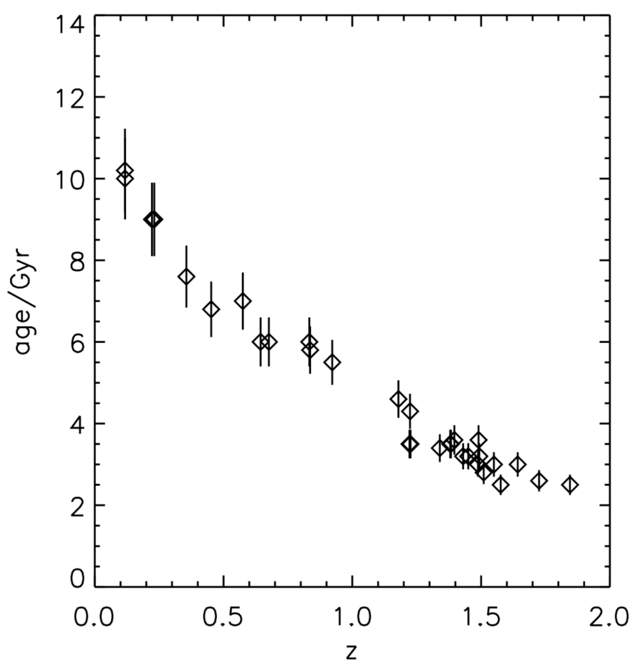
GDDS +high z radiogalaxies + Treu et al. 2000 sample

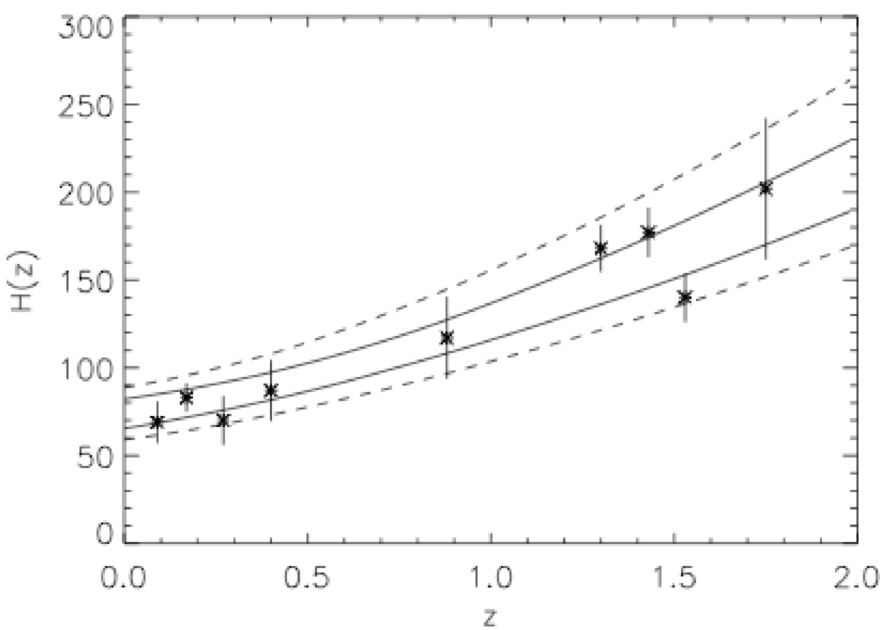
McCarthy et al 2004

$$\frac{\dot{a}(t)}{a(t)} = H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$

$$H^2 = H^2{}_0[\rho(z)/\rho(0)]$$

(the red envelope)

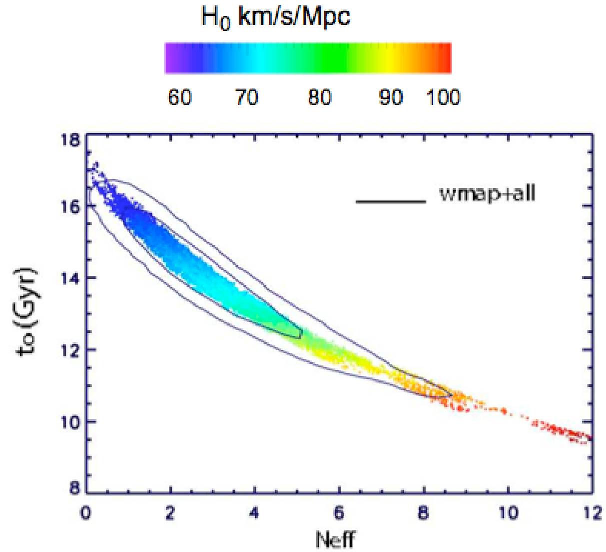




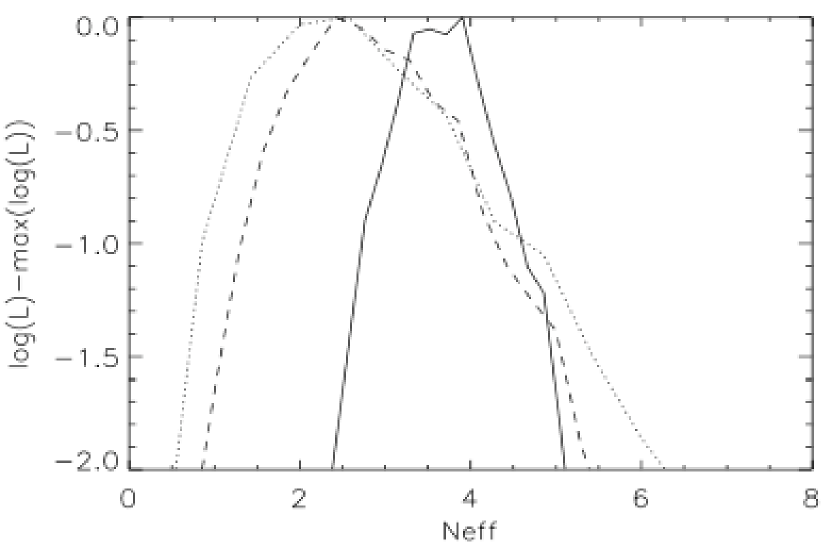
And break this degeneracy….

$$N_\nu^{eff} = 3.7 \pm 1.1$$

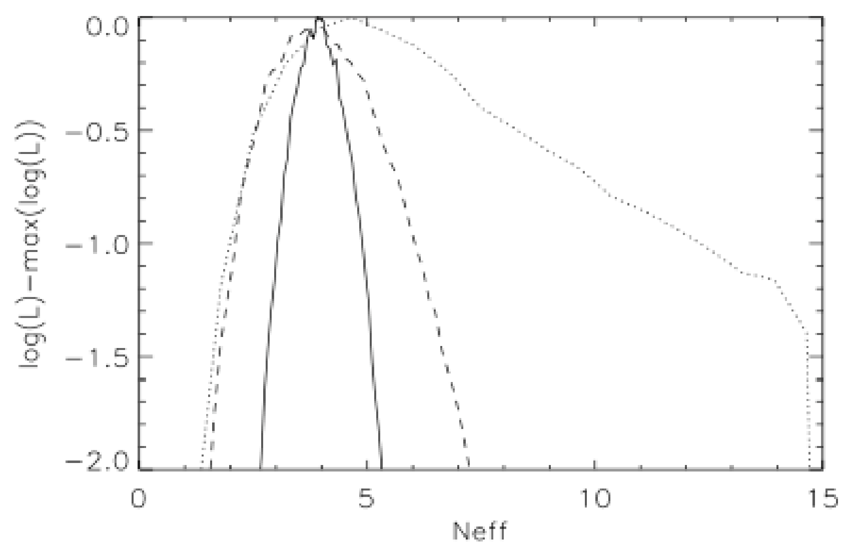
$N_{\mathrm{eff}} > 1.8$ at better than 99%CL



WMAP+ALL+HST+SVJ



WMAP+SDSS+HST+SVJ



95% c.l.

Parameter	WMAP+ALL $N_{\rm eff}=3.04$	WMAP+ALL	WMAP+ALL +HST	WMAP+ALL +SVJ	WMAP+ALL +HST+SVJ
$N_{\rm eff}$	–	$3.3^{+4.0}_{-2.3}$	$3.03^{+2.2}_{-1.7}$	$3.8^{+1.2}_{-1.15}$	$3.71^{+1.17}_{-1.08}$
H_0	$70.8^{+3.3}_{-3.1}$	71^{+21}_{-12}	$70.5^{+10.}_{-9.5}$	$73.8^{+6.6}_{-6.5}$	$73.5^{+6.1}_{-5.9}$
ω_c	$0.1087^{+0.0088}_{-0.0078}$	$0.113^{+0.086}_{-0.037}$	$0.109^{+0.045}_{0.029}$	$0.121^{+0.024}_{-0.021}$	$0.120^{+0.023}_{-0.020}$
Ω_m	$0.262^{+0.036}_{-0.032}$	$0.265^{+0.038}_{-0.039}$	$0.264^{+0.035}_{-0.036}$	$0.262^{+0.36}_{-0.040}$	$0.263^{+0.035}_{-0.036}$
age(Gyr)	$13.84^{+0.28}_{-0.28}$	$13.8^{+2.3}_{-3.2}$	$13.9^{+1.8}_{-2.0}$	$13.27^{+1.1}_{-0.97}$	$13.31^{+1.0}_{-0.91}$

Parameter	WMAP+SDSS $N_{\rm eff}=3.04$	WMAP+SDSS	WMAP+SDSS +HST	WMAP+SDSS +SVJ	WMAP+SDSS +HST+SVJ
$N_{\rm eff}$	–	$7.1^{+7.1}_{-5.1}$	$4.3^{+2.8}_{-1.6}$	$4.0^{+1.2}_{-1.1}$	$4.0^{+1.1}_{-1.1}$
H_0	$70.9^{+5.3}_{-4.7}$	86^{+24}_{-21}	75^{+13}_{-21}	$74.5^{+7.7}_{-7.3}$	$74.0^{+6.9}_{-6.6}$
ω_c	$0.110^{+0.013}_{-0.013}$	$0.18^{+0.13}_{-0.086}$	$0.132^{+0.068}_{-0.042}$	$0.128^{+0.027}_{-0.024}$	$0.127^{+0.027}_{-0.024}$
Ω_m	$0.265^{+0.062}_{-0.056}$	$0.265^{+0.077}_{-0.065}$	$0.270^{+0.069}_{-0.060}$	$0.271^{+0.065}_{-0.057}$	$0.274^{+0.062}_{-0.055}$
age(Gyr)	$13.77^{+0.29}_{-0.30}$	$11.5^{+3.3}_{-2.7}$	$13.0^{+2.0}_{-2.0}$	$13.0^{+1.0}_{-0.92}$	$13.1^{+0.96}_{-0.87}$

$$N_{\rm eff} = 3.7^{+1.2}_{-1.1}\ (95\%\ \text{cl.})$$

Degeneracies?

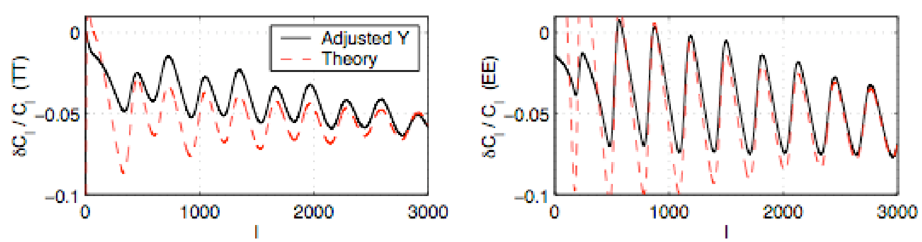
Parameter	WMAP+2dF +SN-Ia	WMAP+2dF +SN-Ia+SVJ
$N_{\rm eff}$	$3.5^{+3.8}_{-3.5}$	$3.8^{+1.1}_{-1.1}$
w	$-0.96^{+0.14}_{-0.15}$	$-0.95^{+0.14}_{-0.16}$
H_0	$72.7^{-13.2}_{+18.7}$	$74.2^{+6.8}_{-7.2}$
ω_c	$0.11^{+0.07}_{-0.04}$	$0.116^{+0.027}_{-0.023}$
Ω_m	$0.25^{+0.04}_{-0.04}$	$0.251^{+0.042}_{-0.039}$
age(Gyr)	$13.7^{+2.5}_{-2.9}$	$13.2^{+1.1}_{-1.0}$

What about the future?

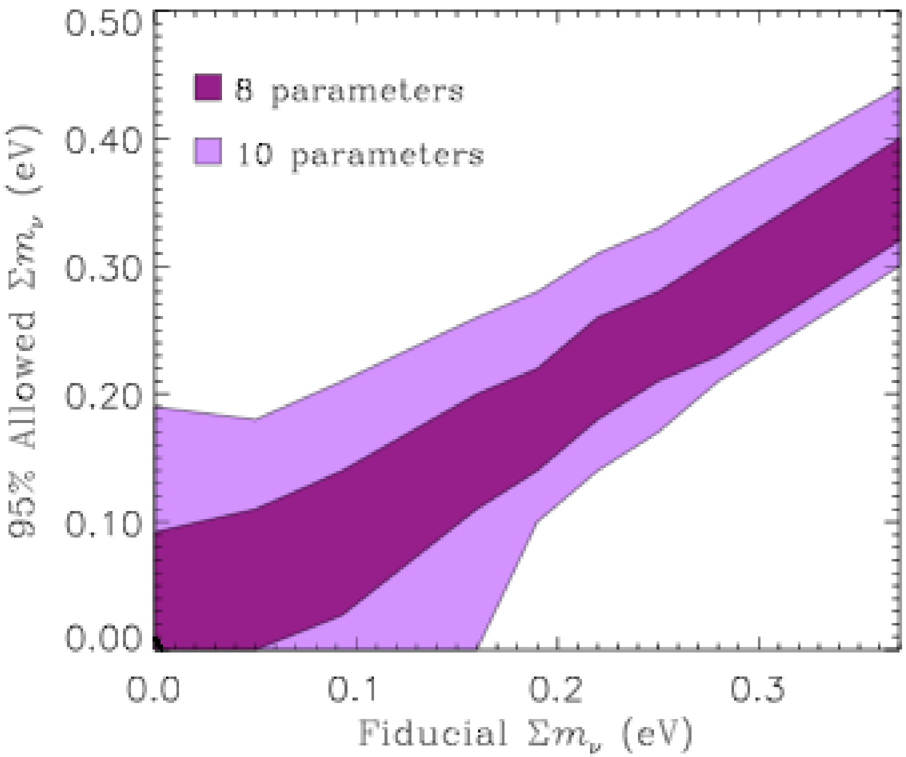
CMB:
lensing

On large scale structure:
Any experiment for BAO will do
ν very well….

Small scales CMB and polarization



Relative changes for Nnu 2.5 to 3.5



- G1: $0.5 < z < 2$, ground-based, $\Omega_{\rm sky} = 1500\ \mathrm{deg}^2$
- G2 : $2 < z < 4$, ground-based, $\Omega_{\rm sky} = 300\ \mathrm{deg}^2$, a
- SG : $4 < z < 6$, space-based, $\Omega_{\rm sky} = 300\ \mathrm{deg}^2$,

Figure 4. The projected 1D marginalised 95 % confidence range for $\sum m_\nu$ as a function of the fiducial $\sum m_\nu$ for Planck+G1+G2+SG with BAO extraction. The light shaded band denotes the 10-parameter model, while the dark band corresponds to the 8-parameter model.

Hannestad &Wong 07

Conclusions:

The statistical power of cosmological data means that cosmology can now constrain neutrino properties.

Example: Dodelson et al 2006 $m_s < 0.23$ eV at 95% c.l.

4th sterile neutrino

Butts on the line

"The implications were staggering," says Scott Dodelson at Fermilab. "Cosmologically, we decided there should not be a sterile neutrino, so to some extent, our butts were on the line."

New Scientist, April 2007, (immediately after MiniBOONE press release)

Beware of systematic effects!

The future is bright….