CMB Anisotropies and Fundamental Physics

Lecture III

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Lecture III

CMB & MORE PARAMETERS

Things we learned from lecture I&II

- The standard cosmological model is based on several assumptions: general relativity, inflation, CDM, cosmological constant.
- The minimum number of parameters needed to satisfy current CMB observations is 6: the Hubble parameter , the baryon and cold dark matter densities, the amplitude and the spectral index of primordial scalar inflationary perturbations and the optical depth τ.
- WMAP7 put strong constraints on all these parameters. However, for example, a process very complex and highly non-linear as reionization is treated in a simple way (step function) and constraints on the spectral index and other parameters may be affected by this assumption.

  CMB constraints are MODEL DEPENDENT.
- A major assumption is the cosmological constant. Already moving to a model with a constant equation of state strongly affects current CMB bounds on the Hubble parameter and the matter density.
- CMB only does'nt constrains w because of geometrical degeneracies and is weakly sensitive to DE perturbations. However if you move to more complex dark energy models where the equation of state is redshift dependent, CMB could provide important informations (for example in the case of Early Dark Energy models).

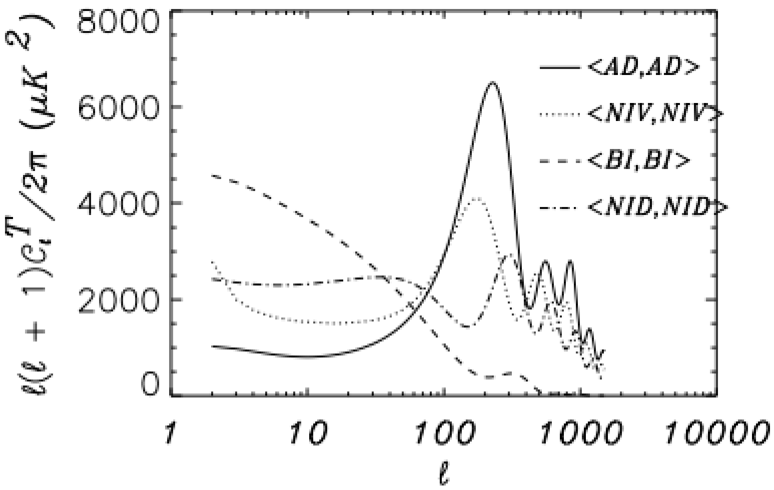
Extensions to the standard model

- Dark Energy. Adding a costant equation of state can change constraints on H_0 and the matter density. A more elaborate DE model (i.e. EDE,) can affect the constraints on all the parameters.
- Reionization. A more model-independent approach affects current constraints on the spectral index and inflation reconstruction.
- Inflation. We can include tensor modes and/or a scale-dependent spectral index n(k).
- Primordial Conditions. We can also consider a mixture of adiabatic and isocurvature modes. In some cases (curvaton, axion) this results in including just a single extra parameter. Most general parametrization should consider CDM and Baryon, neutrino density e momentum isocurvature modes.
- Neutrino background and hot dark matter component.
- Primordial Helium abundance.
- Modified recombination by for example dark matter annihilations.
- Even more exotic: variations of fundamental constants, modifications to electrodynamics, etc, etc.
- …

General Primordial Cosmic Perturbation

Perturbations to the metric may give rise to both curvature perturbations on comoving hypersurfaces, as well as entropy perturbations where the space-time curvature vanishes at early times. The former are termed adiabatic perturbations and may be quantified by the curvature perturbation, R. The latter are isocurvature modes, quantified by the entropy perturbation $S_x = \delta\rho_x/(\rho_x + p_x) - \delta\rho_\gamma/(\rho_\gamma + p_\gamma)$ in the case of density perturbations, $\delta\rho$, between photons and a fluid x, which may be CDM or baryons. There are two further isocurvature modes where the sum of the neutrino and photon densities, or momentum densities, are initially unperturbed.

See e.g. Bucher et al., Phys.Rev. D62 (2000) 083508



Since we have to consider also correlations this means that we need to add 15 (!) extra parameters. +5 if we consider different spectral indeces.

We can have enough parameters to fit an elephant surfing at the azores

General Primordial Cosmic Perturbation

Of the models with more than one isocurvature mode, those most likely to pose the greatest difficulty for distinguishing with future data are those with large fractions of both correlated CDM and neutrino density isocurvature, which provide the best fit to the data, and due to their destructive interference are highly degenerate in the CMB and galaxy power spectra. Those with neutrino velocity fluctuations are better constrained by BBN and bias measurements. With WMAP plus LSS and SN data, the baryon density and spectral tilt are found to be sensitive to the inclusion of isocurvature modes.

	AD CMB+LSS	AD+ISO CMB	AD+ISO CMB+LSS
ω_b	0.023 ± 0.001	0.043 ± 0.006	0.041 ± 0.006
ω_c	0.120 ± 0.006	0.11 ± 0.02	0.12 ± 0.01
Ω_Λ	0.71 ± 0.03	$0.79^{+0.05}_{-0.07}$	0.74 ± 0.03
n_s	0.97 ± 0.03	1.13 ± 0.07	1.10 ± 0.06
τ	$0.13^{+0.08}_{-0.06}$	$0.21^{+0.06}_{-0.08}$	0.22 ± 0.07
β	0.50 ± 0.05	$\cdots$	0.35 ± 0.05
$z_{\langle AD,AD \rangle}$	1.0	$0.55^{+0.16}_{-0.14}$	0.61 ± 0.15
$z_{\langle CI,CI \rangle}$	$\cdots$	$0.23^{+0.11}_{-0.09}$	0.23 ± 0.11
$z_{\langle NID,NID \rangle}$	$\cdots$	$0.28^{+0.12}_{-0.10}$	0.30 ± 0.12
$z_{\langle NIV,NIV \rangle}$	$\cdots$	0.34 ± 0.14	$0.28^{+0.14}_{-0.11}$
$z_{\langle AD,CI \rangle}$	$\cdots$	-0.14 ± 0.10	$-0.12^{+0.12}_{-0.10}$
$z_{\langle AD,NID \rangle}$	$\cdots$	$0.12^{+0.09}_{-0.11}$	$0.11^{+0.10}_{-0.12}$
$z_{\langle AD,NIV \rangle}$	$\cdots$	0.22 ± 0.10	0.19 ± 0.11
$z_{\langle CI,NID \rangle}$	$\cdots$	-0.15 ± 0.10	-0.18 ± 0.10
$z_{\langle CI,NIV \rangle}$	$\cdots$	$-0.10^{+0.10}_{-0.08}$	-0.09 ± 0.08
$z_{\langle NID,NIV \rangle}$	$\cdots$	0.17 ± 0.07	0.16 ± 0.08
z_{ISO}	$\cdots$	$0.84\pm^{0.08}_{0.13}$	$0.79\pm^{0.09}_{0.13}$
f_{ISO}	$\cdots$	$0.60\pm^{0.09}_{0.11}$	0.57 ± 0.09
Ω_m	0.29 ± 0.03	$0.21\pm^{0.07}_{0.05}$	0.26 ± 0.03
h	0.70 ± 0.03	$0.85\pm^{0.06}_{0.08}$	0.80 ± 0.05
b	0.95 ± 0.08	$\cdots$	1.3 ± 0.2

K. Moodley et al., Phys.Rev. D70 (2004) 103520

Dataset	h	Ω_0
CMB	> 0.2	$1.2\pm^{0.2}_{0.1}$
CMB	> 0.5	1.03 ± 0.03
CMB + LSS	> 0.2	1.04 ± 0.03
CMB + LSS	> 0.5	1.04 ± 0.02
CMB + LSS + SNIa	0.72 ± 0.08	$1.01\pm^{0.02}_{0.01}$

Dataset	h	Ω_0	$\langle f_{iso} \rangle$
CMB	> 0.2	1.6 ± 0.3	0.6
CMB	> 0.5	1.10 ± 0.05	0.6
CMB + LSS	> 0.2	1.07 ± 0.03	0.5
CMB + LSS	> 0.5	1.07 ± 0.03	0.5
CMB + LSS +SNIa	0.72 ± 0.08	1.06 ± 0.02	0.54
CMB + LSS +BBN	> 0.5	1.06 ± 0.03	0.31

J. Dunkley et al, Phys.Rev.Lett.95:261303,2005

Isocurvature: minimal models

In some cases we can restrict ourselves to a single additional isocurvature mode with the same spectral index of adiabatic .
The total angular power spectrum takes the form:

$$C_l = (1-\alpha)\, C_l^{AA} + \alpha C_l^{II} + 2\beta\sqrt{\alpha\,(1-\alpha)}C_l^{AI}$$

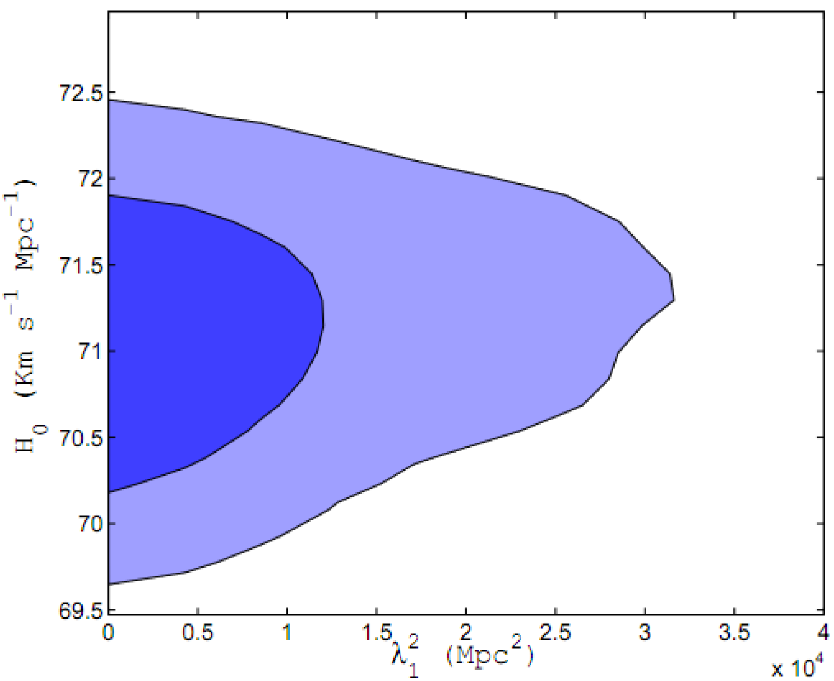
Some models on the market (using the CDM isocurvature mode):

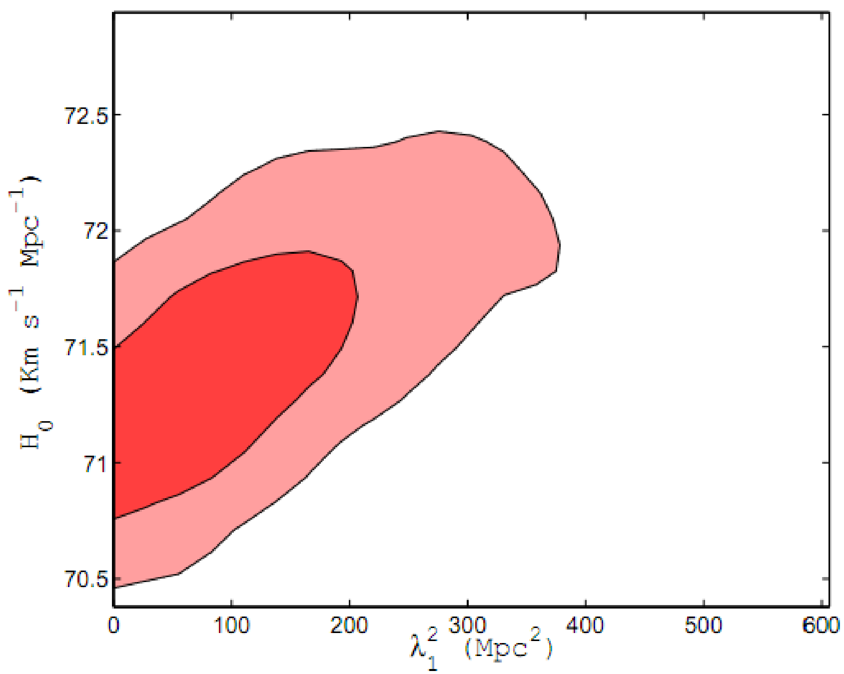
Curvaton: β=-1
Axion: β=0

Constraints from WMAP7 (Komatsu et al, 2010):

$$\alpha_{-1} < 0.011 \;\; (95\%\ \mathrm{CL})$$
$$\alpha_0 < 0.13 \;\; (95\%\ \mathrm{CL})$$

Planck, Euclid and Modified Gravity





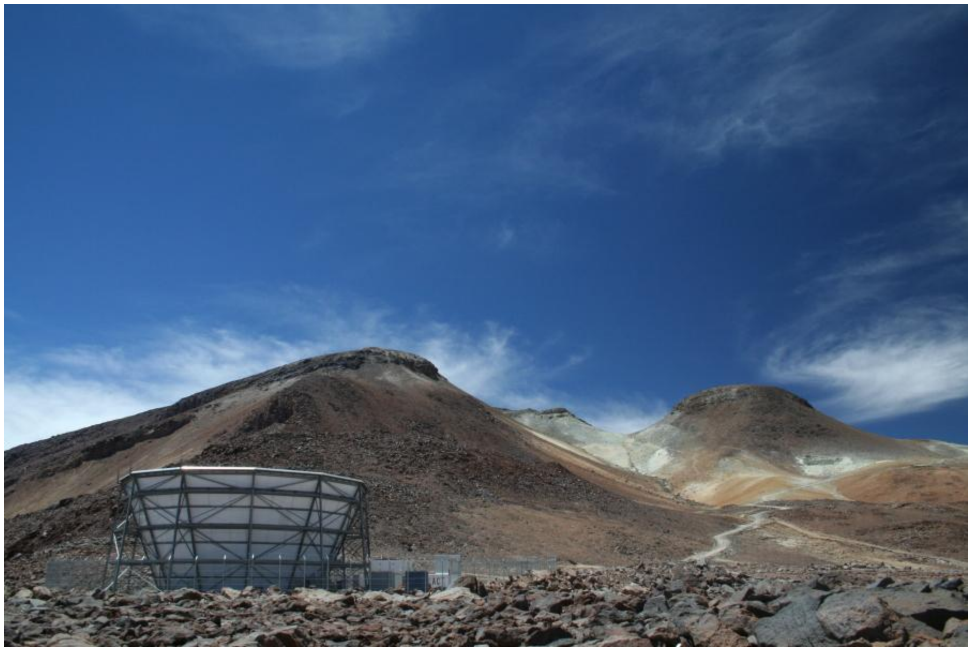
M. Martinelli et al., Phys.Rev.D83:023012,2011

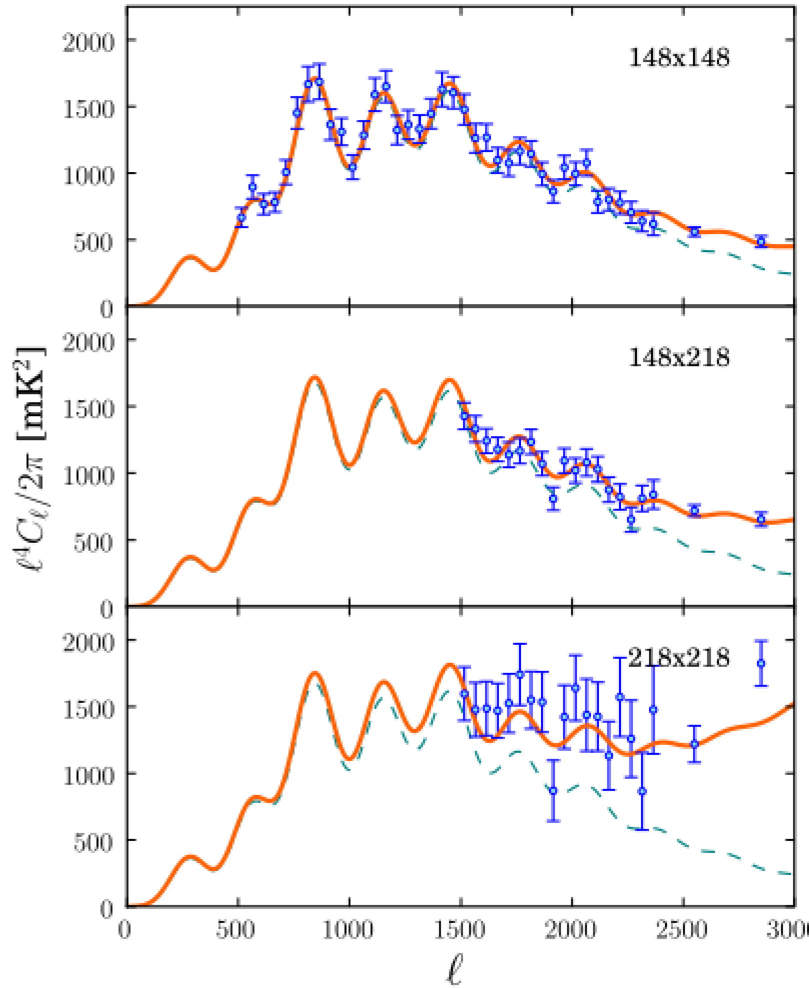
Table 3
Six-Parameter ΛCDM Fit [a]

Parameter	7-year Fit	5-year Fit
Fit parameters		
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	2.273 ± 0.062
$\Omega_c h^2$	0.1109 ± 0.0056	0.1099 ± 0.0062
Ω_Λ	0.734 ± 0.029	0.742 ± 0.030
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014	$0.963^{+0.014}_{-0.015}$
τ	0.088 ± 0.015	0.087 ± 0.017
Derived parameters		
t_0	13.75 ± 0.13 Gyr	13.69 ± 0.13 Gyr
H_0	71.0 ± 2.5 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
σ_8	0.801 ± 0.030	0.796 ± 0.036
Ω_b	0.0449 ± 0.0028	0.0441 ± 0.0030
Ω_c	0.222 ± 0.026	0.214 ± 0.027
z_{eq}	3196^{+134}_{-133}	3176^{+151}_{-150}
z_{reion}	10.5 ± 1.2	11.0 ± 1.4

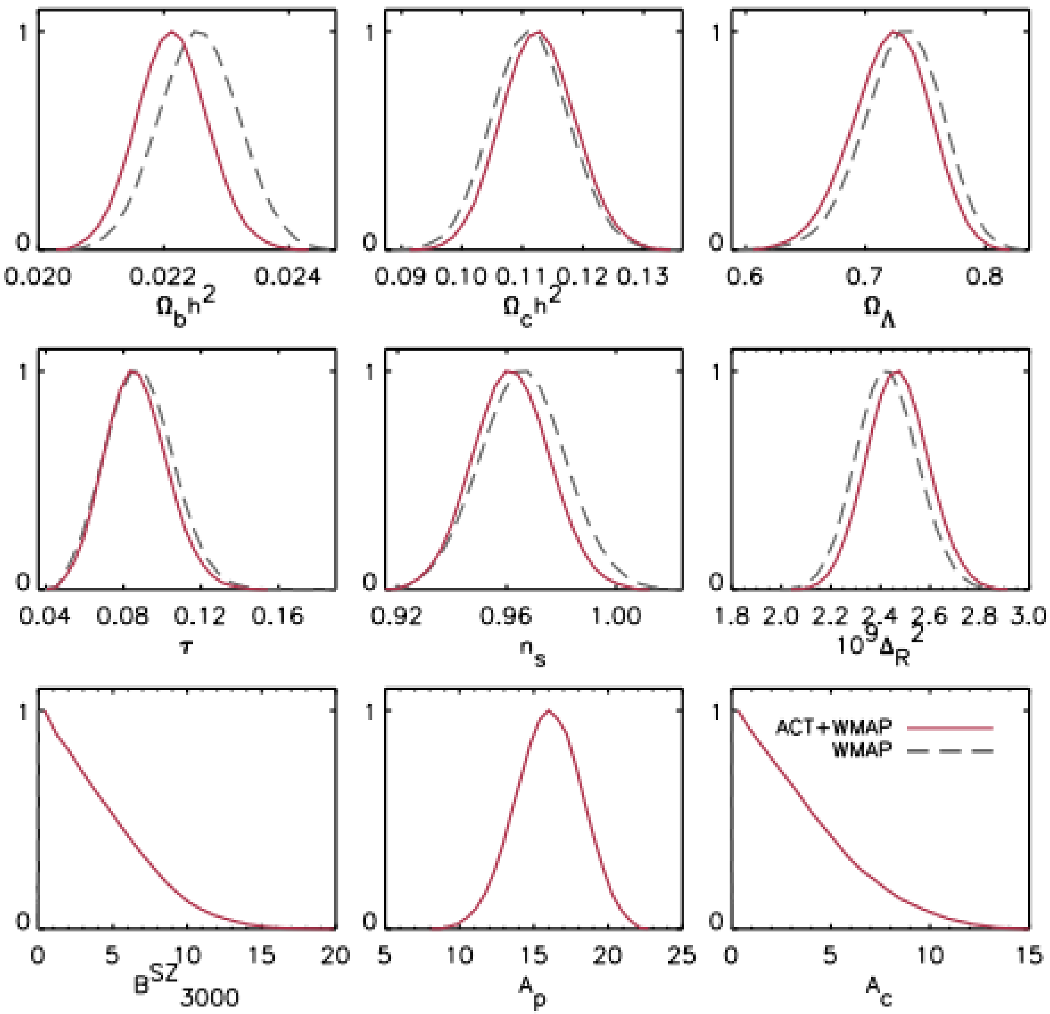
Komatsu et al, 2010, 1001.4538

ACT results





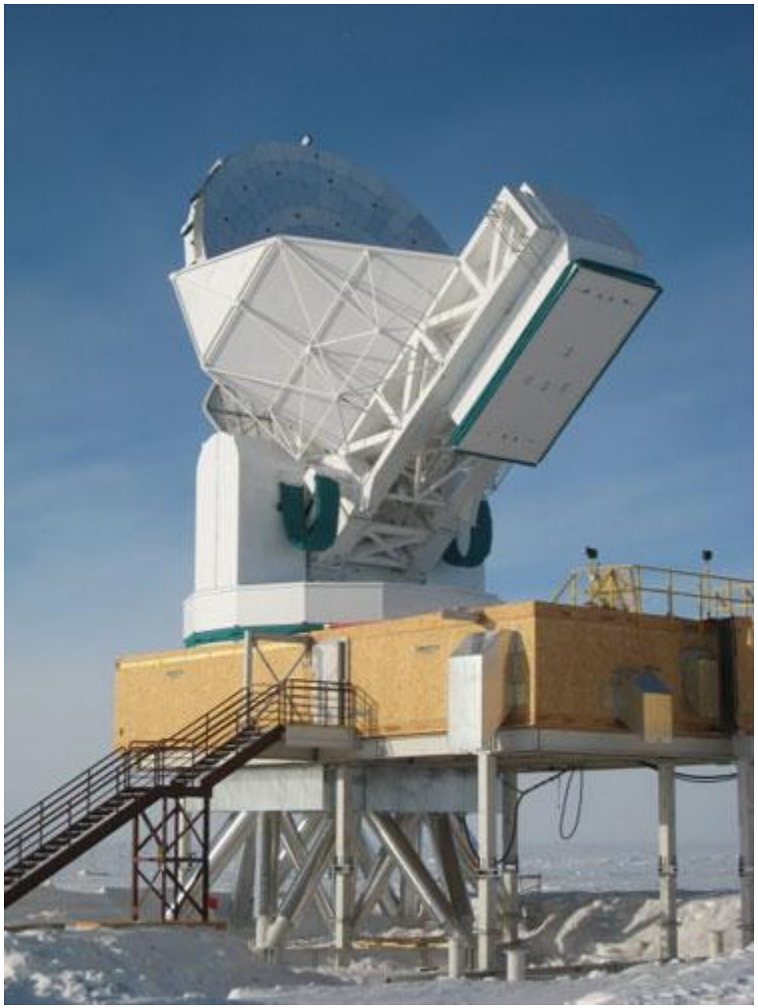
S. Das et al, 2011, [arXiv:1009.0847v1]

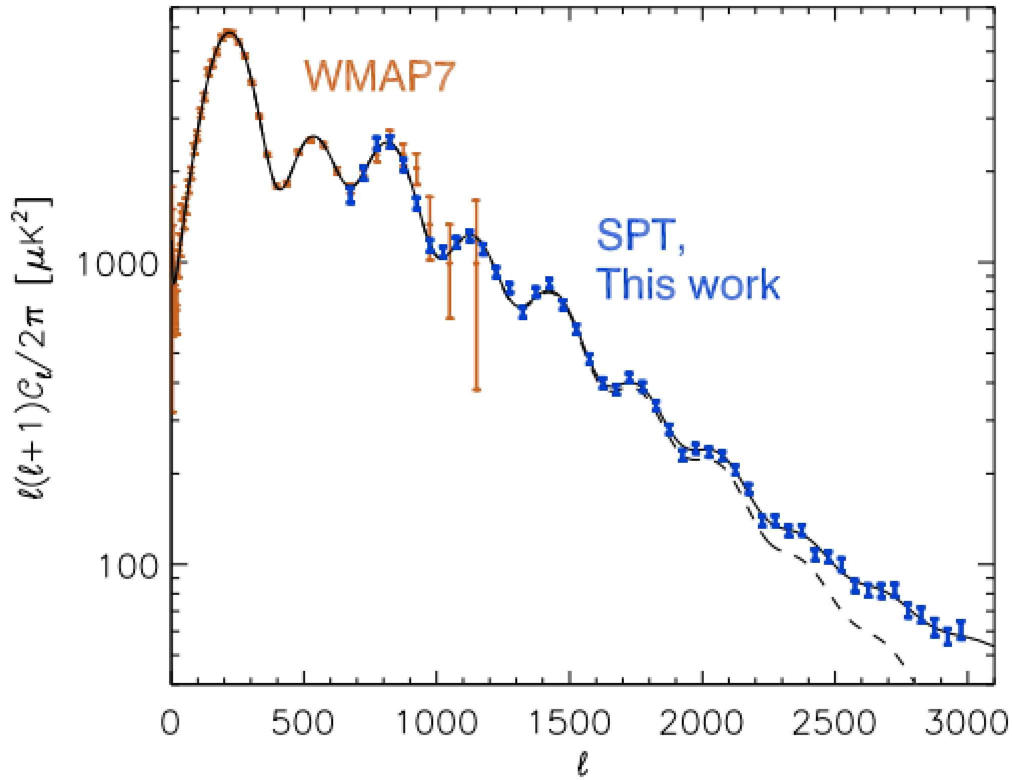


Constraints on the standard Λ-CDM parameters are not significantly improved By the new ACT data.

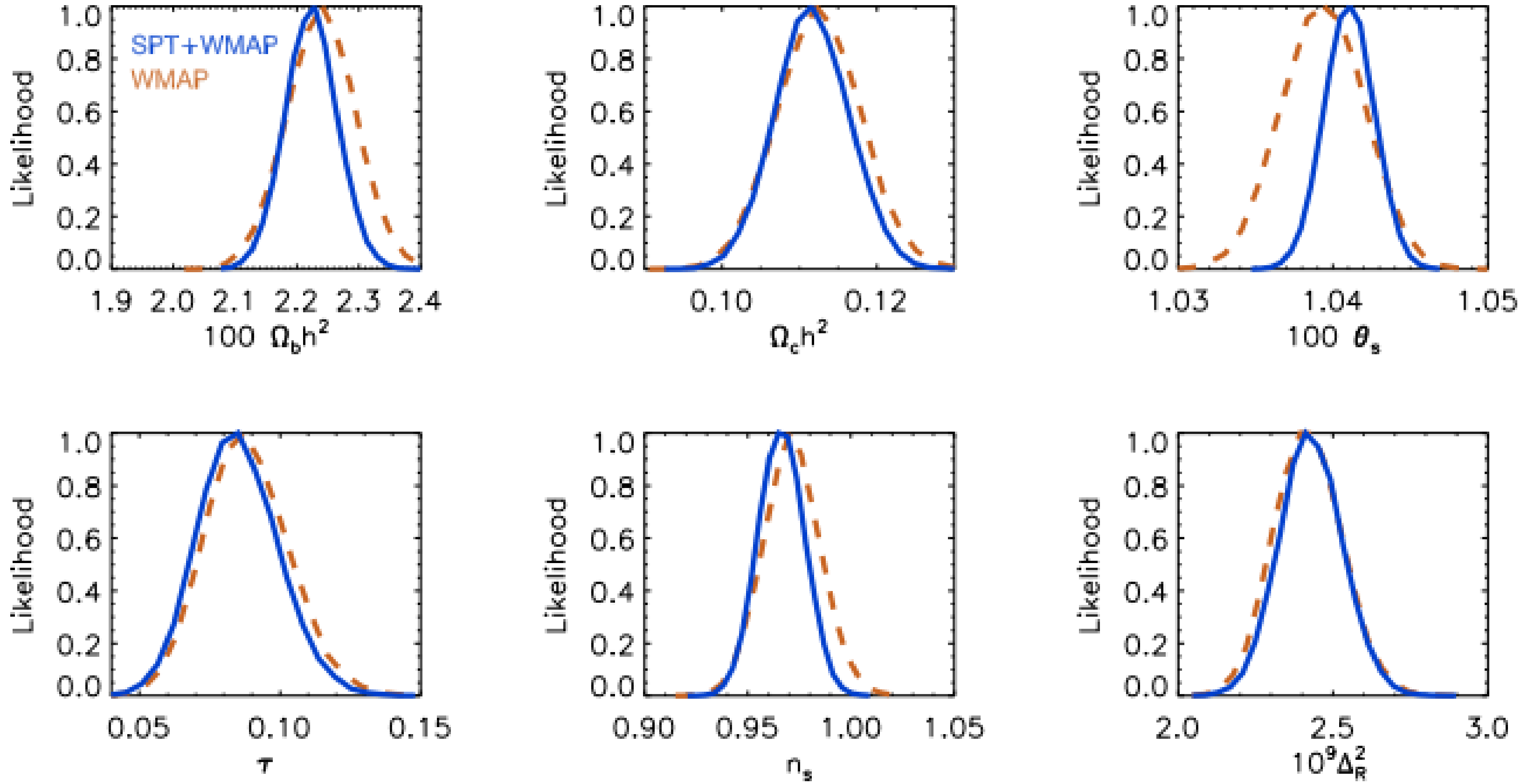
J. Dunkley et al, 2011

New SPT results



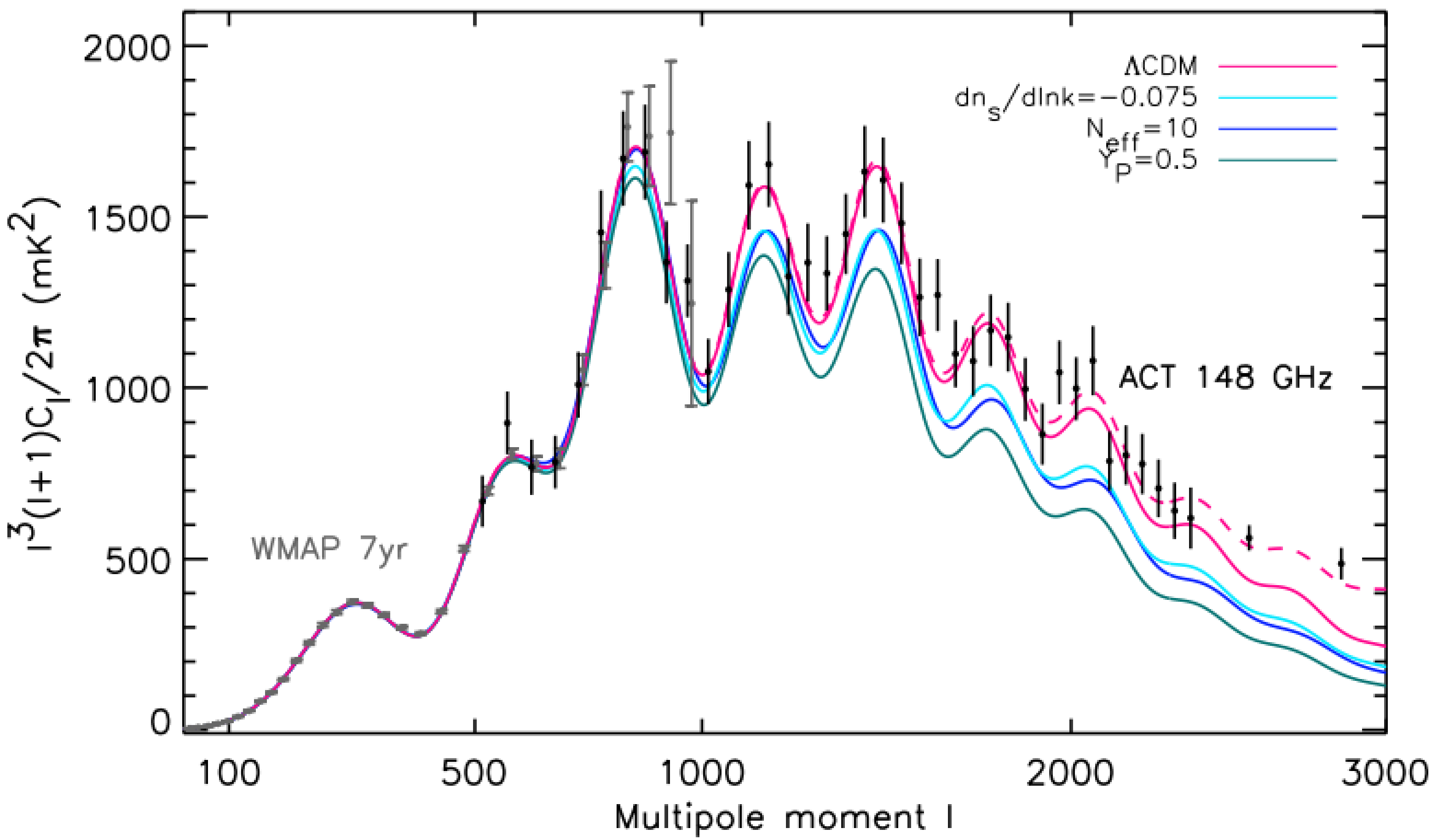


R. Keisler et al, 2011, **arXiv:1105.3182**



R. Keisler et al, 2011

Small Scale CMB measurements test new parameters



Cosmological Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma} \approx 1.945K \rightarrow kT_{\nu} \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_{\nu}^3 \approx 112 cm^{-3}$$

That, for a relativistic neutrinos translate in a extra radiation component of:

$$\Omega_{\nu} h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^{\nu} \Omega_{\gamma} h^2$$

Standard Model predicts:

$$N_{eff}^{\nu} = 3.046$$

Dark Radiation

The total amount of relativistic particles in the Universe is therefore parametrized
In the following way:

$$\Omega_R h^2 = \left[1 + \frac{7}{4} \left(\frac{4}{11} \right)^{4/3} N_{eff}^{\nu} \right] \Omega_\gamma h^2$$

Caveat: N_{eff} can be a function of time (i.e. massive neutrinos).
For most of the cases we consider here is assumed to be a constant.
A value of $N_{eff} > 3.046$ is equivalent to the presence of a new «dark radiation» component :

$$\left(\frac{H}{H_0} \right)^2 = \frac{\Omega_M}{a^3} + \frac{\Omega_\gamma}{a^4} + \frac{\Omega_\nu}{a^4} + \Omega_\Lambda + \frac{\Omega_{DR}}{a^4}$$

Probing the Neutrino Number with CMB data

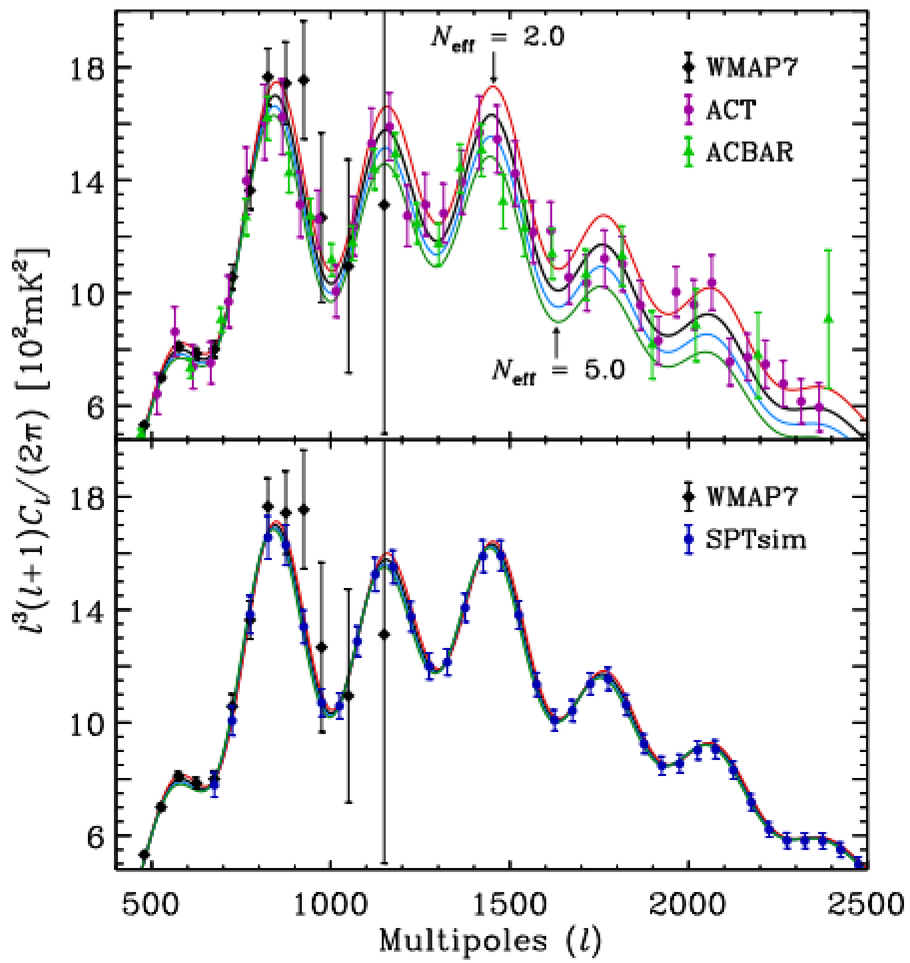
Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}.$$

and the damping scale at recombination:

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

$$\theta_s = \frac{r_s}{D_A} \qquad \theta_d = \frac{r_d}{D_A}$$

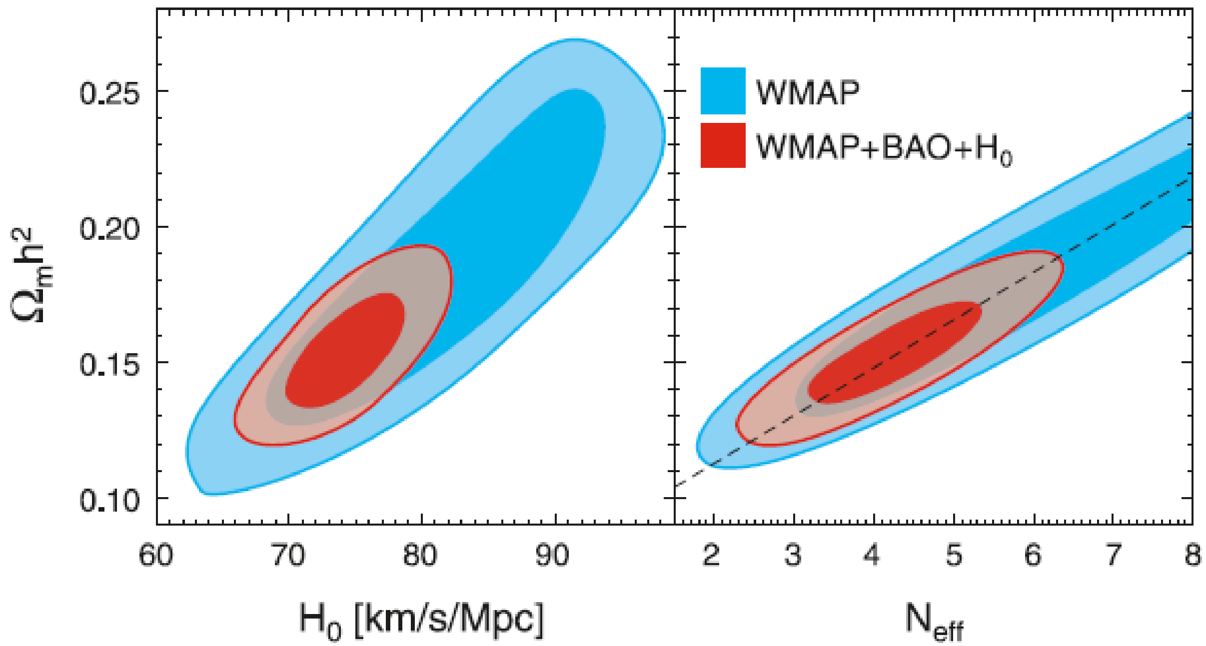


Moreover increases early ISW at Recombination (phase shift)

Hou et al, 2011

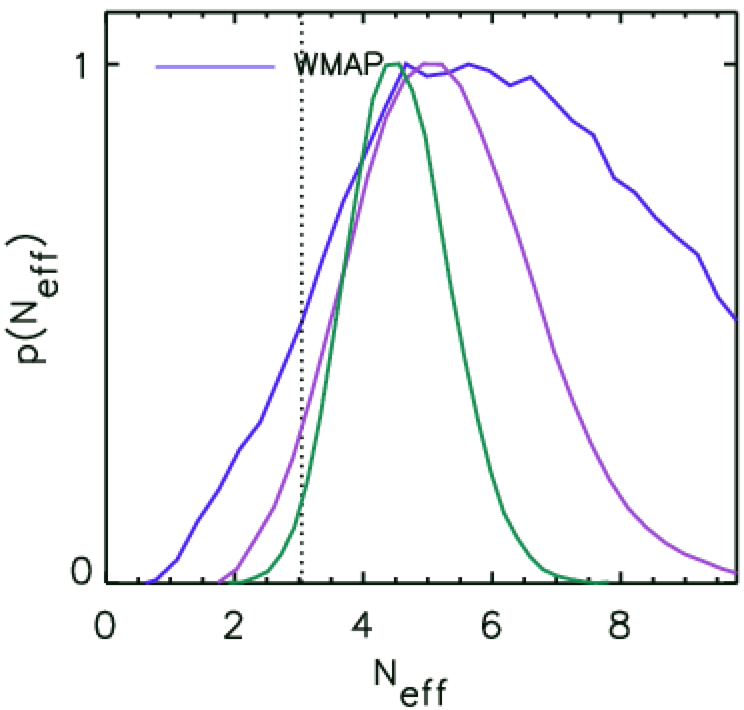
Komatsu et al, 2010, 1001.4538

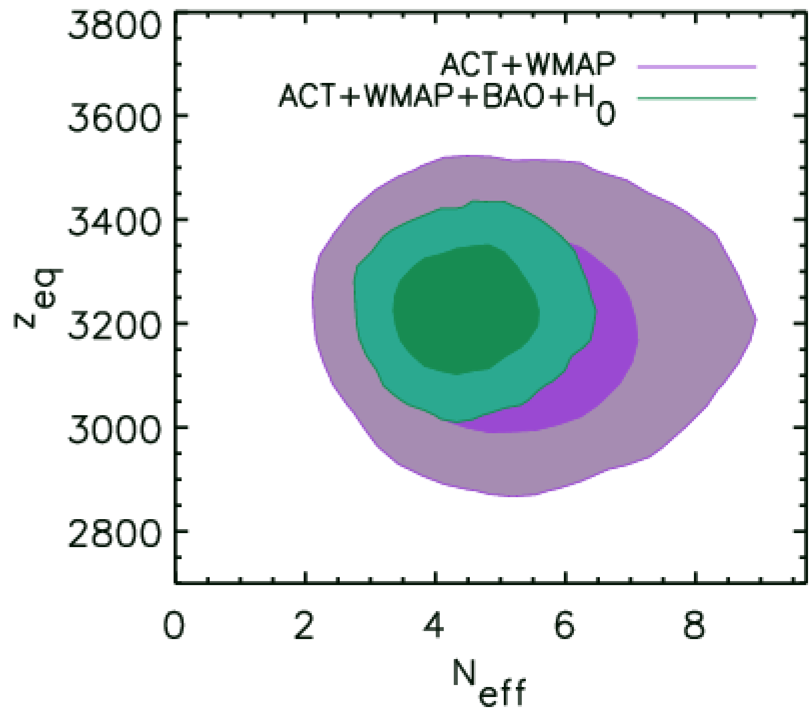
WMAP provides first indication for the existance of the neutrino background from CMB data only.



Parameter	Year	*WMAP* only	*WMAP*+BAO+SN+*HST*	*WMAP*+BAO+H_0	*WMAP*+LRG+H_0
z_{eq}	5-year	3141^{+154}_{-157}	3240^{+99}_{-97}		
	7-year	3145^{+140}_{-139}		3209^{+85}_{-89}	3240 ± 90
$\Omega_m h^2$	5-year	$0.178^{+0.044}_{-0.041}$	0.160 ± 0.025		
	7-year	$0.184^{+0.041}_{-0.038}$		0.157 ± 0.016	$0.157^{+0.013}_{-0.014}$
N_{eff}	5-year	> 2.3 (95% CL)	4.4 ± 1.5		
	7-year	> 2.7 (95% CL)		$4.34^{+0.86}_{-0.88}$	$4.25^{+0.76}_{-0.80}$

ACT confirms indication for extra neutrinos but now at about two standard deviations





Latest results from ACT, Dunkley et al. 2010
(95 % c.l.)

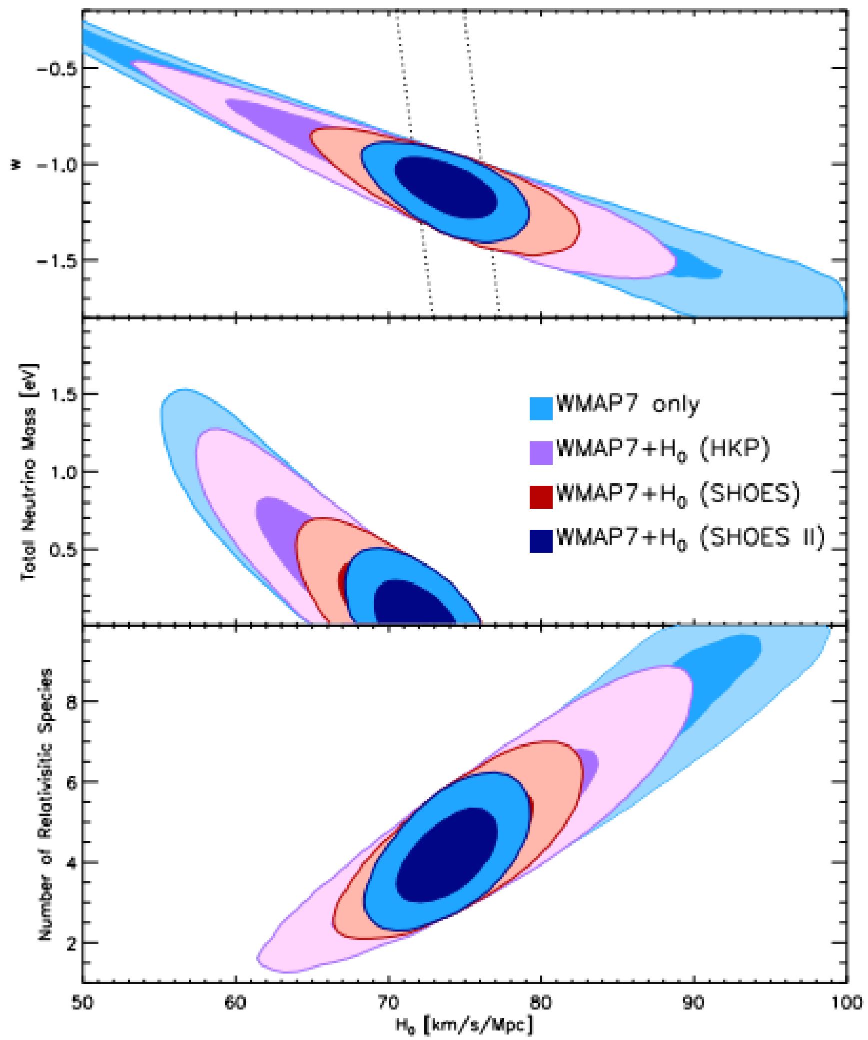
$Neff = 5.3 \pm 1.3$ ACT+WMAP

$Neff = 4.8 \pm 0.8$ ACT+WMAP+BAO+H0

The new 3% determination of the Hubble Constant with the Hubble Space Telescope and Wide Field Camera 3 points towards $N_{eff} > 3$ when combined with WMAP-only data.

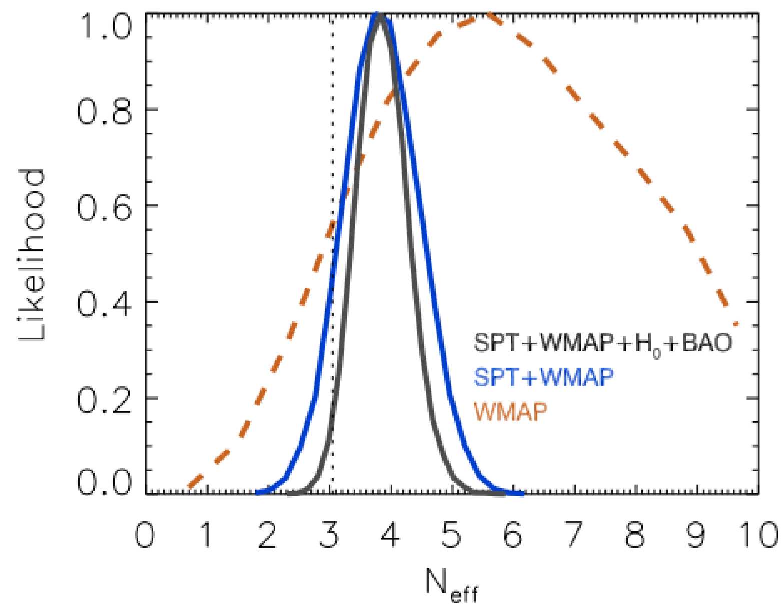
$h = 0.738 \pm 0.024$

$N_{eff} = 4.2 \pm 0.7$



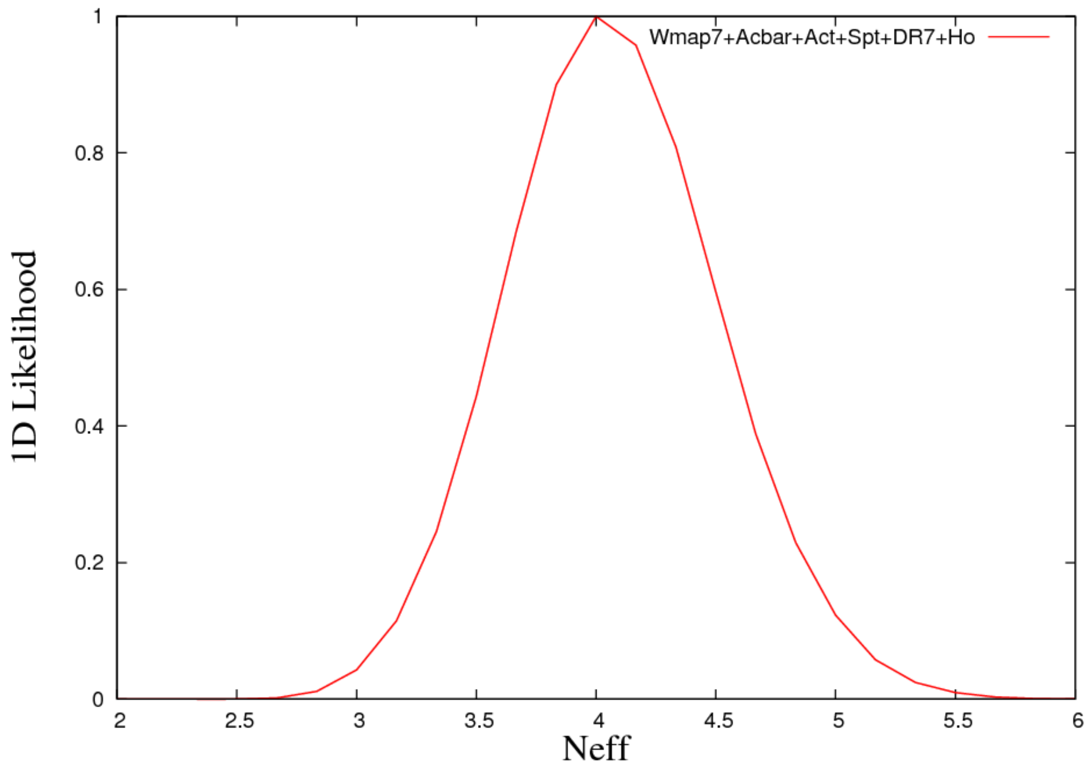
Riess et al, ApJ, 730, 119, 2011

SPT confirms indication for extra neutrinos but at less than two standard deviations (and closer to 3)



		ΛCDM	ΛCDM $+ A_L$	ΛCDM $+r$	ΛCDM $+ dn_s/d\ln k$	ΛCDM $+ Y_p$	ΛCDM $+ N_{eff}$
Primary	$100\Omega_b h^2$	2.23 ± 0.038	2.22 ± 0.039	2.24 ± 0.040	2.23 ± 0.040	2.27 ± 0.044	2.26 ± 0.042
Parameters	$\Omega_c h^2$	0.112 ± 0.0028	0.112 ± 0.0029	0.112 ± 0.0030	0.114 ± 0.0031	0.114 ± 0.0032	0.129 ± 0.0093
	$100\theta_s$	1.04 ± 0.0015	1.04 ± 0.0016	1.04 ± 0.0015	1.04 ± 0.0016	1.04 ± 0.0020	1.04 ± 0.0017
	n_s	0.9668 ± 0.0093	0.9659 ± 0.0095	0.9711 ± 0.0099	0.9758 ± 0.0111	0.9814 ± 0.0126	0.9836 ± 0.0124
	τ	0.0851 ± 0.014	0.0852 ± 0.014	0.0842 ± 0.014	0.0934 ± 0.016	0.0890 ± 0.015	0.0859 ± 0.014
	$10^9 \Delta_R^2$	2.43 ± 0.082	2.44 ± 0.085	2.39 ± 0.088	2.35 ± 0.095	2.39 ± 0.085	2.41 ± 0.084
Extension	$A_L^{0.65}$	—	0.95 ± 0.15	—	—	—	—
Parameters	r	—	—	< 0.17	—	—	—
	$dn_s/d\ln k$	—	—	—	-0.020 ± 0.012	—	—
	Y_p	(0.2478 ± 0.0002)	(0.2478 ± 0.0002)	(0.2478 ± 0.0002)	(0.2478 ± 0.0002)	0.300 ± 0.030	(0.2581 ± 0.005)
	N_{eff}	(3.046)	(3.046)	(3.046)	(3.046)	(3.046)	3.86 ± 0.42
Derived	σ_8	(0.818 ± 0.019)	(0.818 ± 0.019)	(0.816 ± 0.019)	(0.824 ± 0.020)	(0.841 ± 0.024)	(0.871 ± 0.033)
	χ^2_{min}	7510.7	7510.6	7510.7	7507.8	7508.0	7507.4

Last Analysis



$$N_{eff}^{\nu} = 4.08^{+0.71}_{-0.68}$$ At 95% c.l.

Archidiacono, Calabrese, AM, in prep. 2011

Further test: Neutrino Perturbations

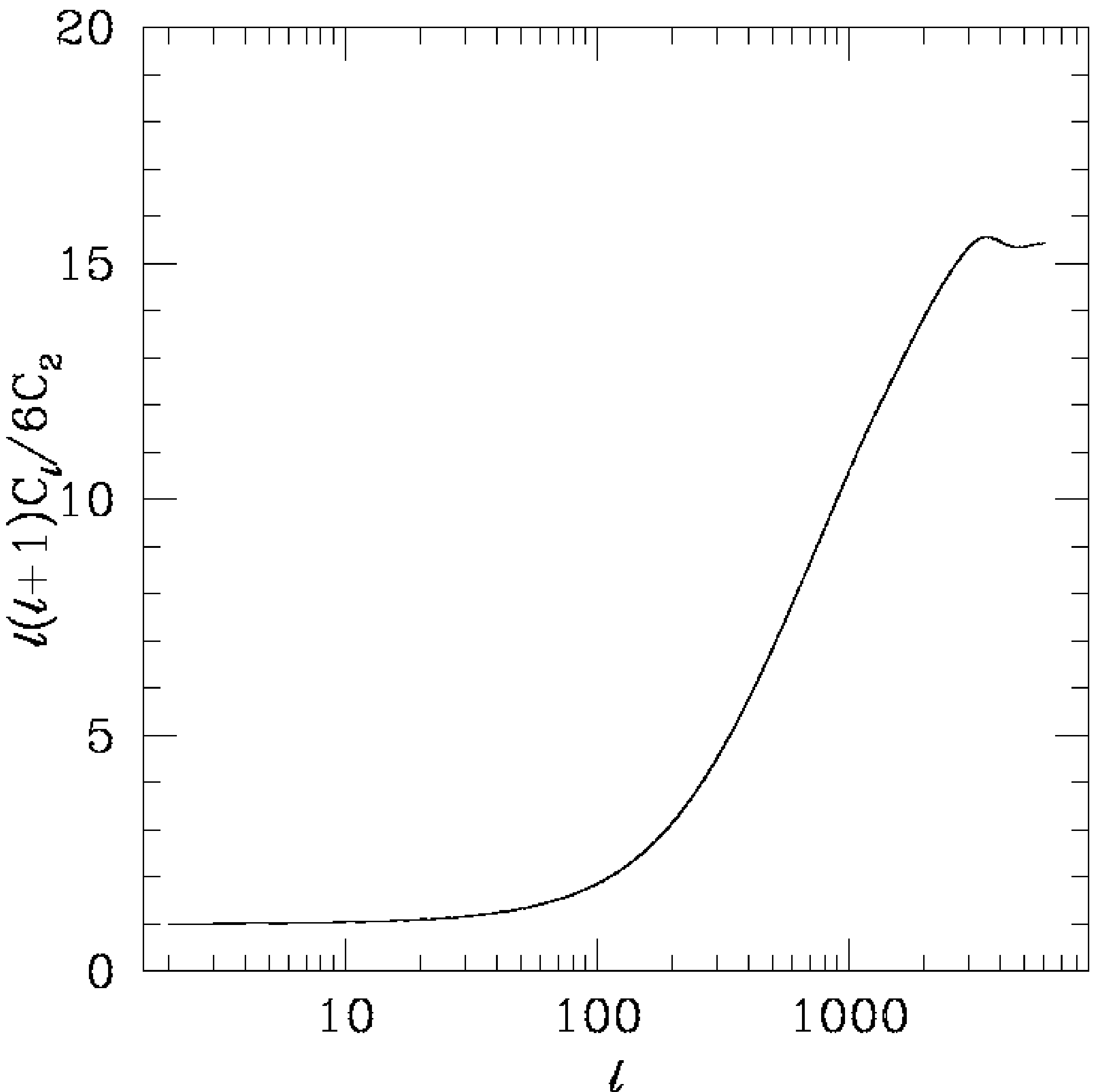
Massless neutrinos, like photons, have perturbations and anisotropies which follow a set of differential equations:

$$
\begin{aligned}
\dot{\delta}_\nu + k\left(q_\nu + \frac{2}{3k}\dot{h}\right) &= \frac{\dot{a}}{a}(1-3c_{\rm eff}^2)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) \\
\dot{q}_\nu + \frac{\dot{a}}{a}q_\nu + \frac{2}{3}k\pi_\nu &= c_{\rm eff}^2\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right), \\
\dot{\pi}_\nu + \frac{3}{5}kF_{\nu,3} &= 3c_{\rm vis}^2\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right), \\
\frac{2l+1}{k}\dot{F}_{\nu,l} - lF_{\nu,l-1} &= -(l+1)F_{\nu,l+1},\ l \geq 3,
\end{aligned}
$$

For the standard massless neutrino case:

$$c_{eff}^2 = c_{vis}^2 = \frac{1}{3}$$

Can we see them ?



Hu et al., astro-ph/9505043

CMB Anisotropy: BASICS

Their evolution is governed by a nasty set of coupled partial differential equations:

CDM:

$$\dot{\delta}_c = -\theta_c + 3\dot{\phi}\,, \quad \dot{\theta}_c = -\frac{\dot{a}}{a}\,\theta_c + k^2\psi$$

Baryons:

$$\begin{aligned}\dot{\delta}_b &= -\theta_b + 3\dot{\phi}\,,\\ \dot{\theta}_b &= -\frac{\dot{a}}{a}\theta_b + c_s^2 k^2 \delta_b + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b} a n_e \sigma_T (\theta_\gamma - \theta_b) + k^2\psi\,.\end{aligned}$$

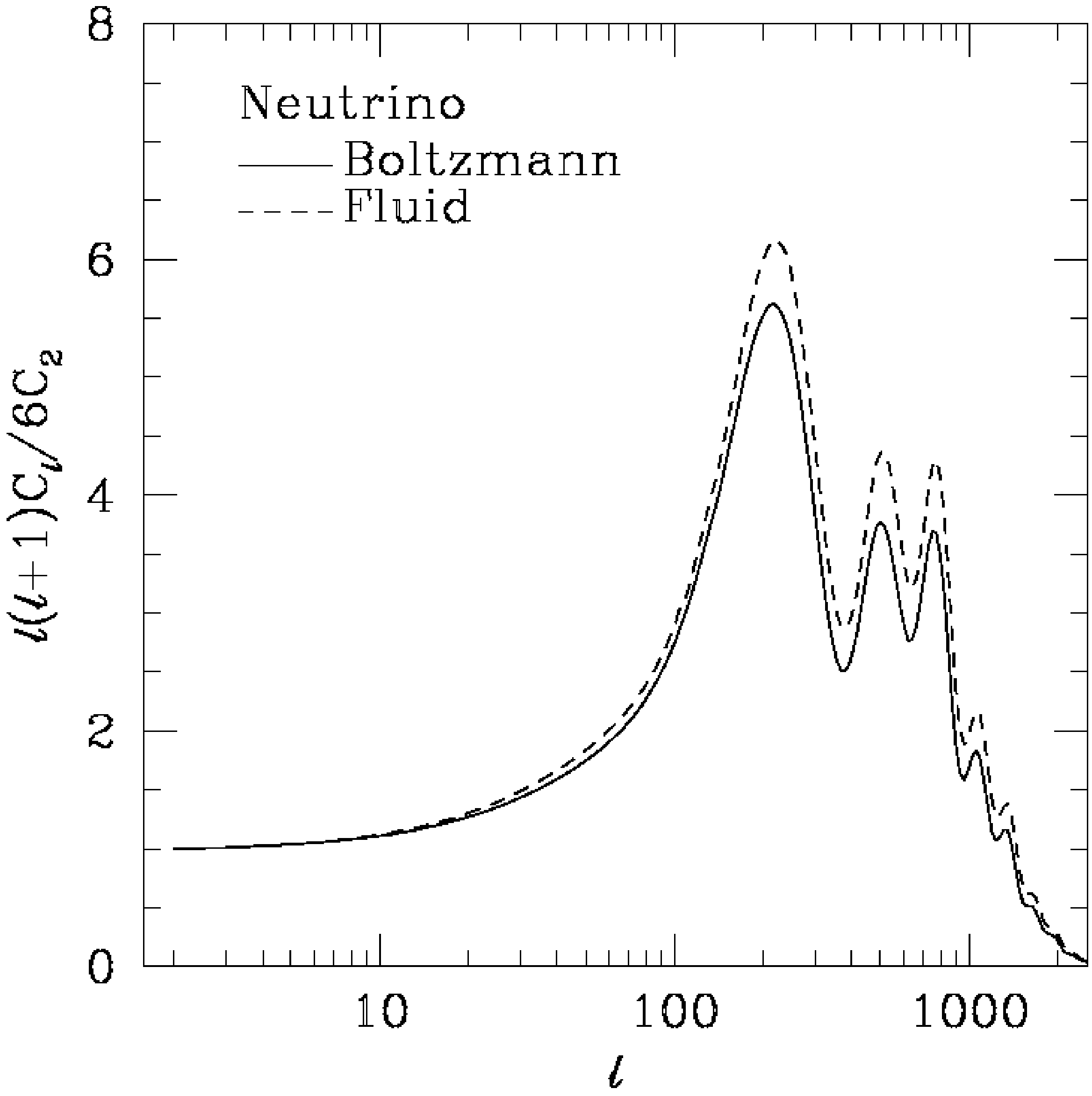
Photons:

$$\begin{aligned}\dot{\delta}_\gamma &= -\frac{4}{3}\theta_\gamma + 4\dot{\phi}\,,\\ \dot{\theta}_\gamma &= k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + k^2\psi + a n_e \sigma_T (\theta_b - \theta_\gamma)\,,\\ \dot{F}_{\gamma\,2} &= 2\dot{\sigma}_\gamma = \frac{8}{15}\theta_\gamma - \frac{3}{5}kF_{\gamma\,3} - \frac{9}{5}a n_e \sigma_T \sigma_\gamma + \frac{1}{10} a n_e \sigma_T \left(G_{\gamma\,0} + G_{\gamma\,2}\right)\,,\\ \dot{F}_{\gamma\,l} &= \frac{k}{2l+1}\left[lF_{\gamma\,(l-1)} - (l+1)F_{\gamma\,(l+1)}\right] - a n_e \sigma_T F_{\gamma\,l}\,, \quad l \geq 3\\ \dot{G}_{\gamma\,l} &= \frac{k}{2l+1}\left[lG_{\gamma\,(l-1)} - (l+1)G_{\gamma\,(l+1)}\right] + a n_e \sigma_T \left[-G_{\gamma\,l} + \frac{1}{2}\left(F_{\gamma\,2} + G_{\gamma\,0} + G_{\gamma\,2}\right)\left(\delta_{l0} + \frac{\delta_{l2}}{5}\right)\right]\end{aligned}$$

Neutrinos:

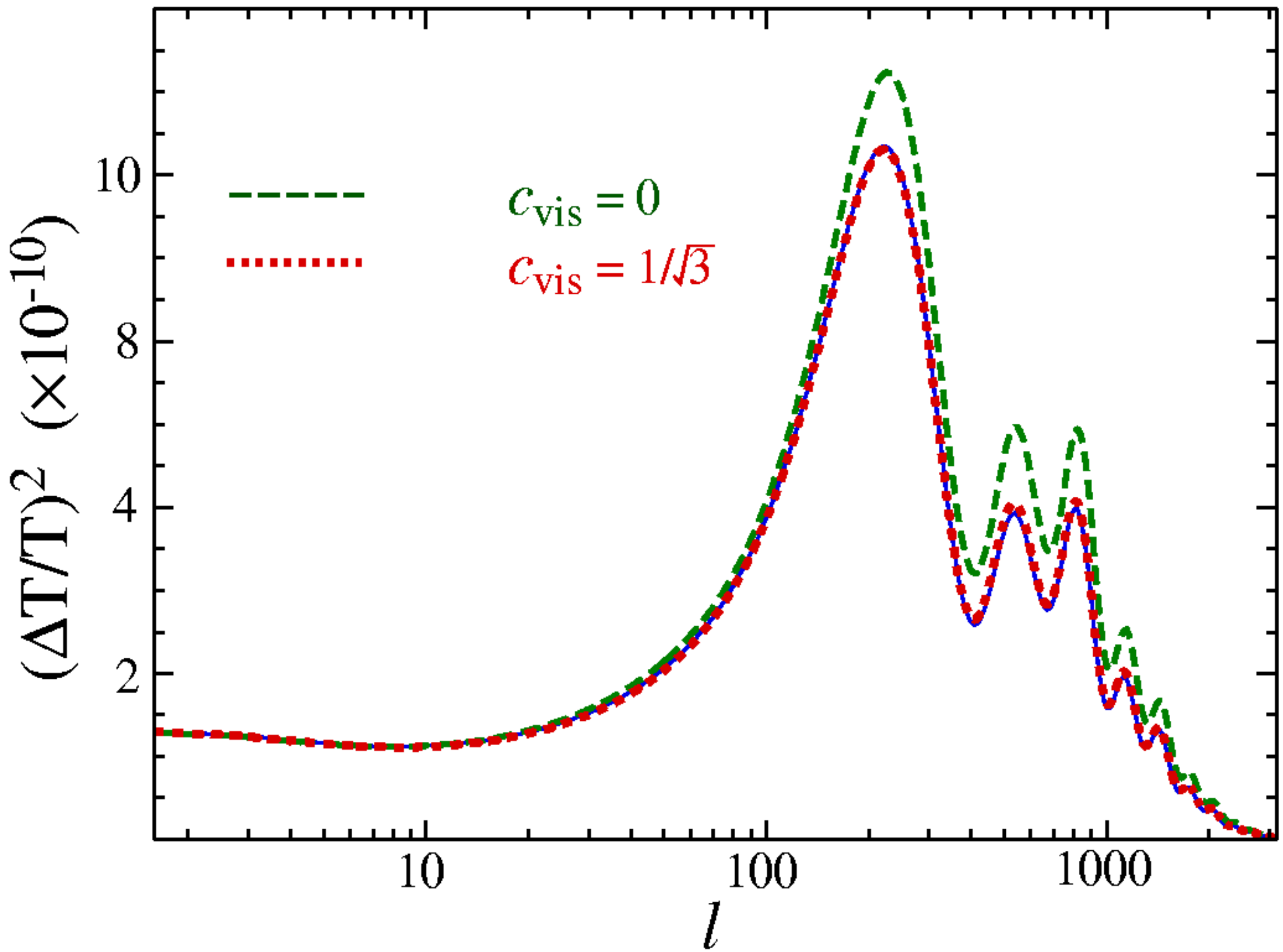
$$\begin{aligned}\dot{\delta}_\nu &= -\frac{4}{3}\theta_\nu + 4\dot{\phi}\,,\\ \dot{\theta}_\nu &= k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi\,,\\ \dot{F}_{\nu\,l} &= \frac{k}{2l+1}\left[lF_{\nu\,(l-1)} - (l+1)F_{\nu\,(l+1)}\right]\,, \quad l \geq 2\end{aligned}$$

Not directly!
But we can see the effects on the CMB angular spectrum !
CMB photons see the NB anisotropies through gravity.



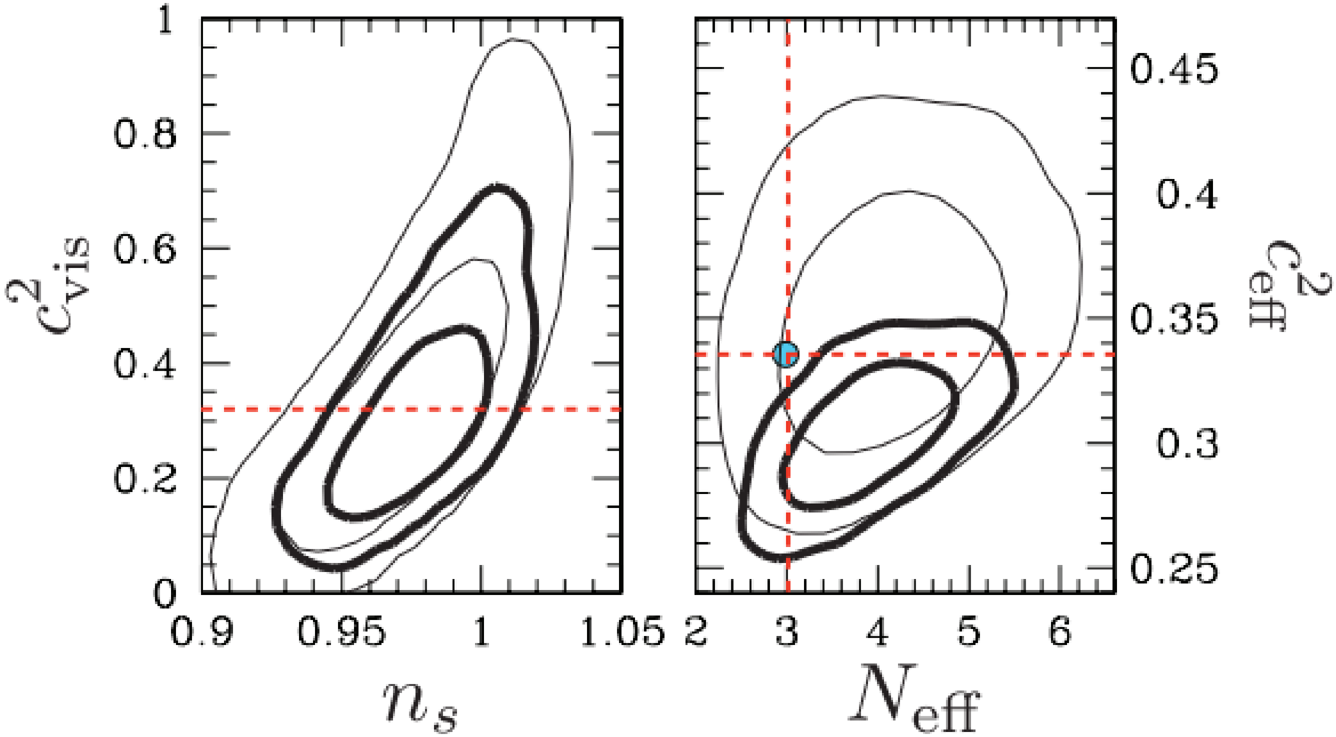
Hu et al., astro-ph/9505043

The Neutrino anisotropies can be parameterized through the "speed viscosity" c_{vis}. which controls the relationship between velocity/metric shear and anisotropic stress in the NB.



Hu, Eisenstein, Tegmark and White, 1999

Recent analysis suggests smaller effective sound speed when SDSS Ly-α data are included

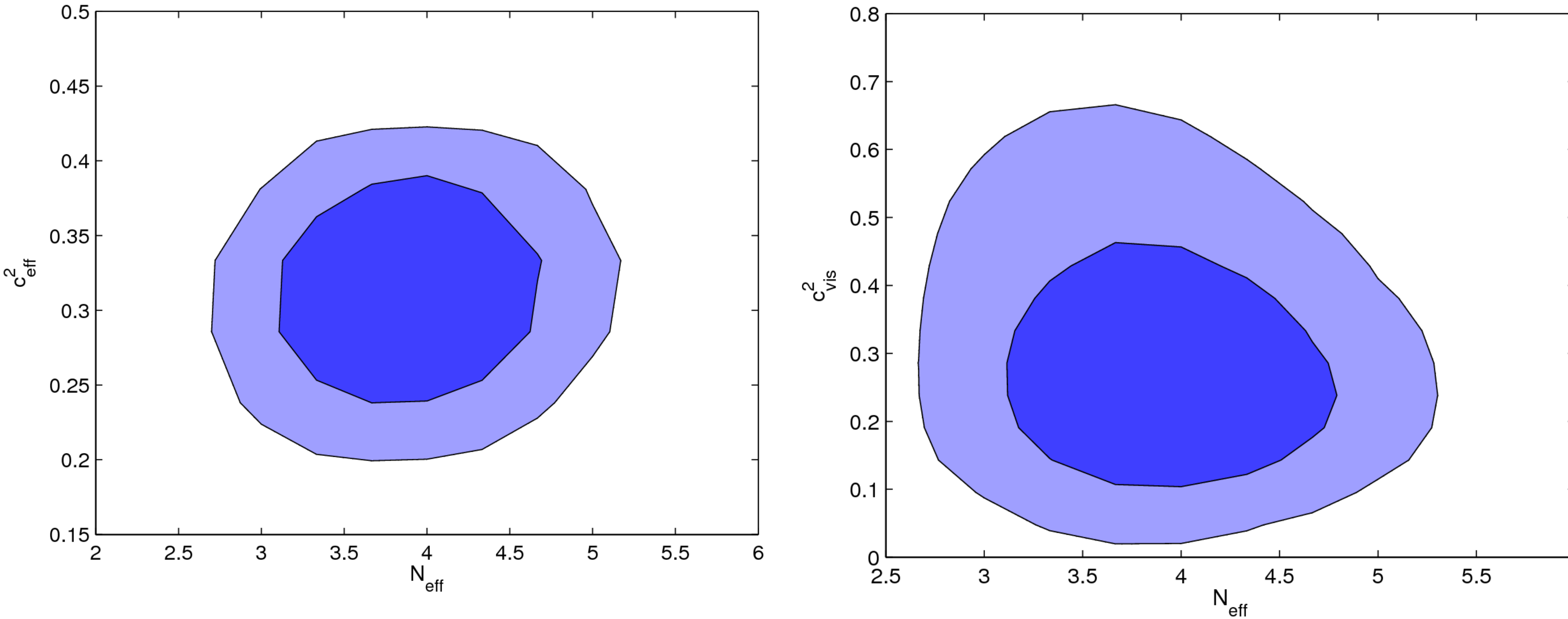


Thin line: CMB only.
Solid line has Ly-a included

T. Smith et al, **arXiv:1105.3246,** 2011

Our Analysis (with no Ly-α)

WMAP+ACBAR+ACT+SPT+SDSS DR7+HST



Why $N_{eff}>3$ is interesting

We have 1000 ways to explain this !!!

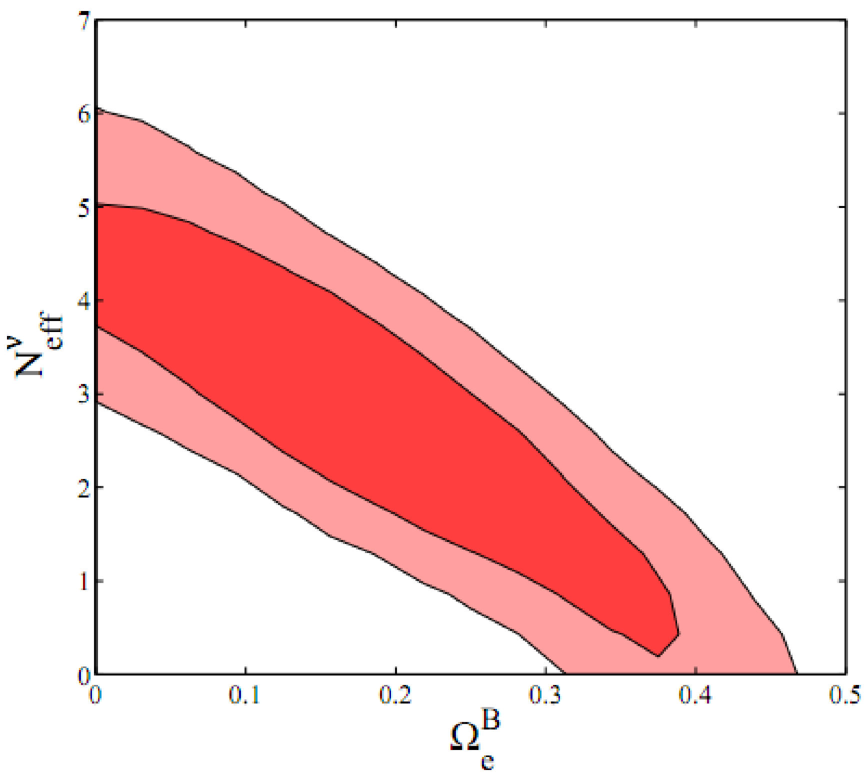
- Sterile Neutrino (hints from short base line experiments LSND, MiniBooNE).
- Non Standard Neutrino Decoupling
- Modified Gravity (Extra Dimensions)
- «Early» Dark Energy
- Gravity Waves
- Axions
- Variation of fundamental constants
- …

Extra Neutrinos or Early Dark Energy ?

An «Early» dark energy component could be present in the early universe at recombination and nucleosynthesis. This component could behave like radiation (tracking properties) and fully mimic the presence of an extra relativistic background !

Barotropic component:

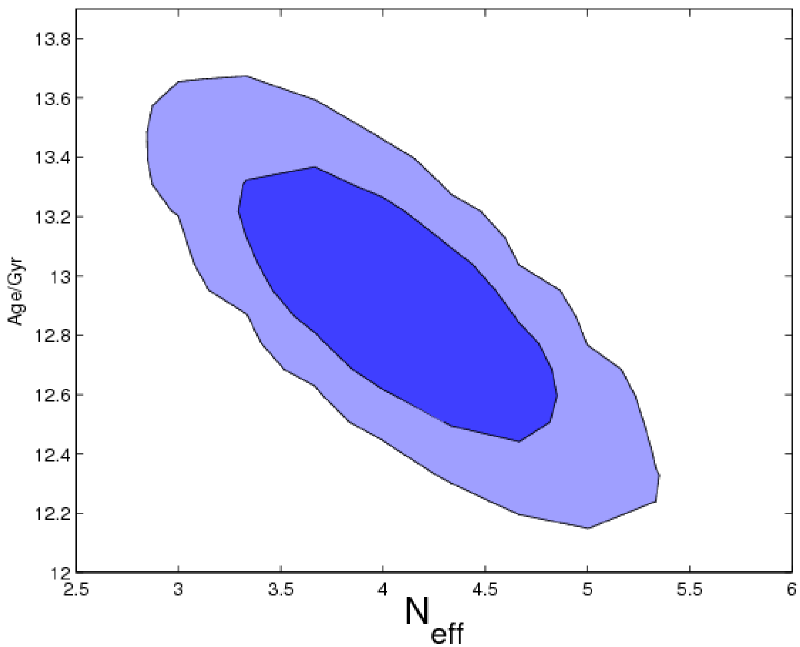
$$\rho_{\rm baro}(a) = \rho_\infty + C\rho_{r,0}a^{-4}$$



E. Calabrese et al, Phys.Rev.D83:123504,2011

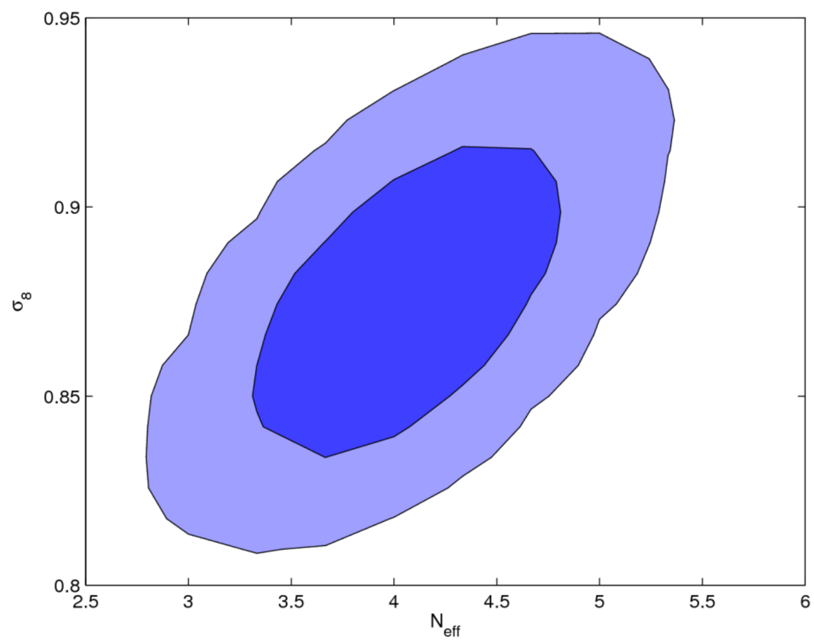
E. Calabrese et al, Phys.Rev.D83:023011,2011

What disfavours $N_{eff}>3$?



Larger values of the effective neutrino number are in better agreement with lower ages of the universe.

Larger values of the effective neutrino number are in better agreement with lower σ_8. Clusters move to N_{eff}=3.

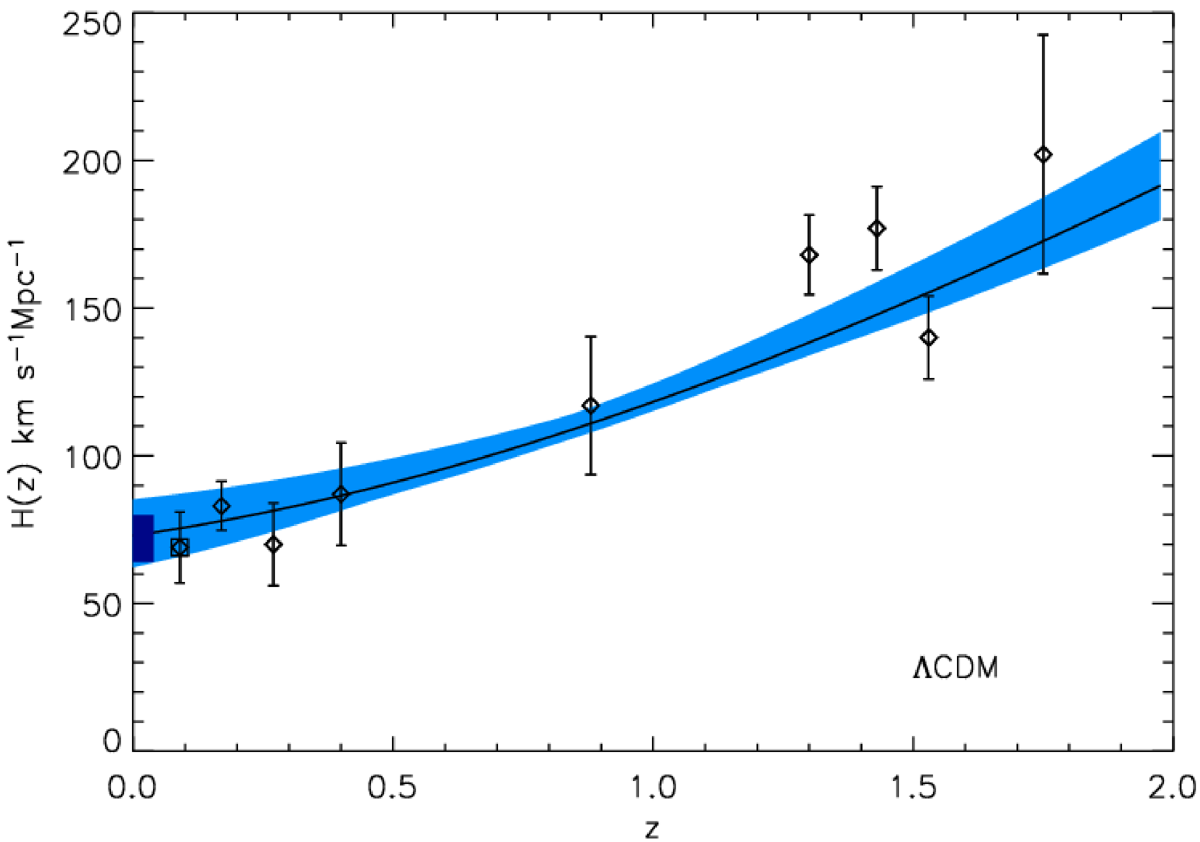


Age of the Universe

CMB data are able to tightly constrain the age of the Universe (see e.g. Ferreras, AM, Silk, 2002). For WMAP+all and LCDM:

$$t_0 = 9.8 H_0^{-1} \int_0^1 \frac{a\,da}{\sqrt{\Omega_m a + \Omega_\Lambda a^4 + \Omega_r}} = 13.84 \pm 0.23 \text{ Gyrs} \longrightarrow 13.83 \pm 0.3 \text{ Gyrs}$$

(if w is included)



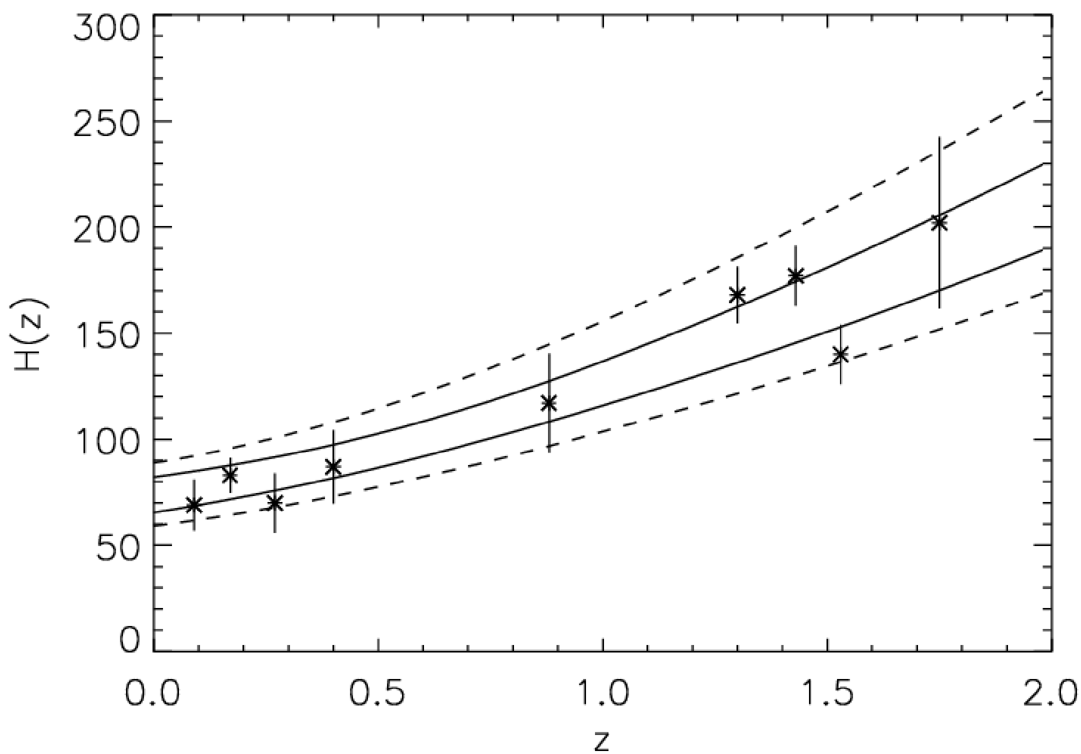
Direct and "model independent" age aestimates have much larger error bars ! Not so good for constraining DE

Spergel et al., 2007

Age of the Universe

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

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

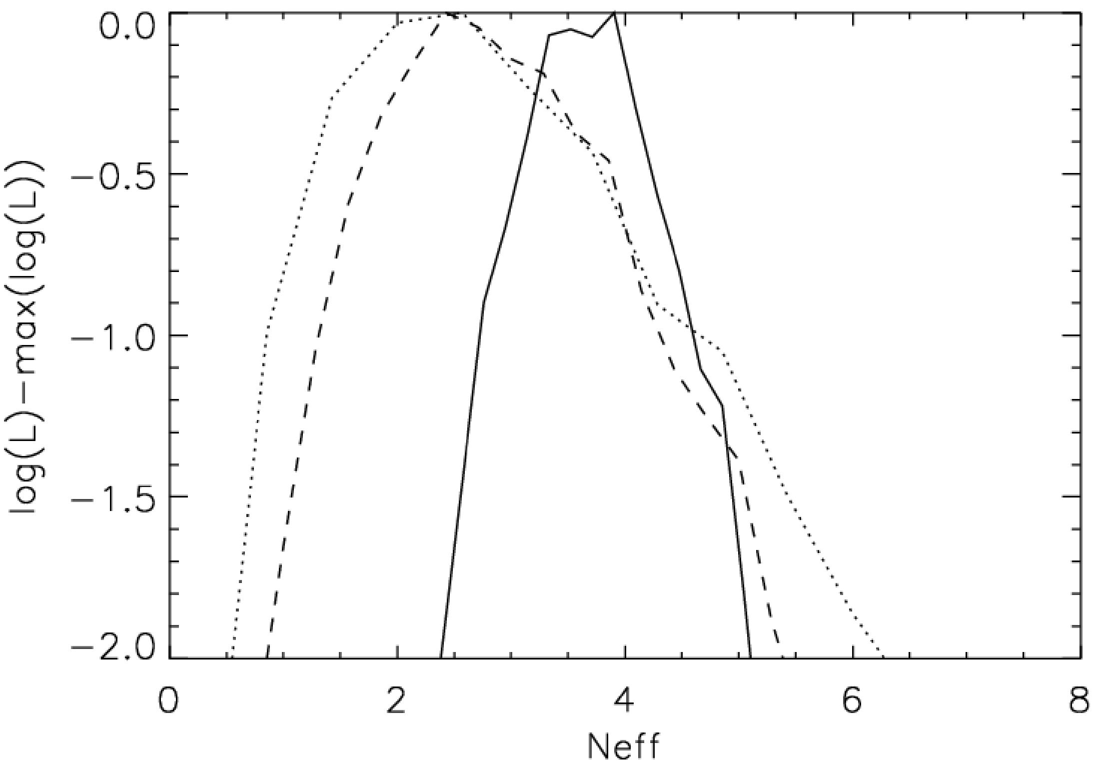


Error bars on age a factor 10 larger when Extra Relativistic particles are Included.

F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, JCAP 03(2008)020

Independent age aestimates are important.
Using Simon, Verde, Jimenez aestimates plus WMAP we get:

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



F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, JCAP 03(2008)020

Probing the Neutrino Number with BBN data

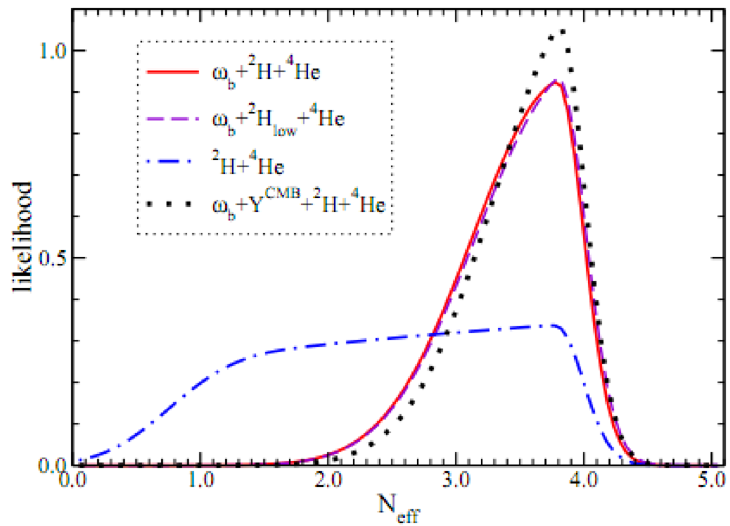
- BBN element abundances depend on nuclear interaction rates and expansion rate.

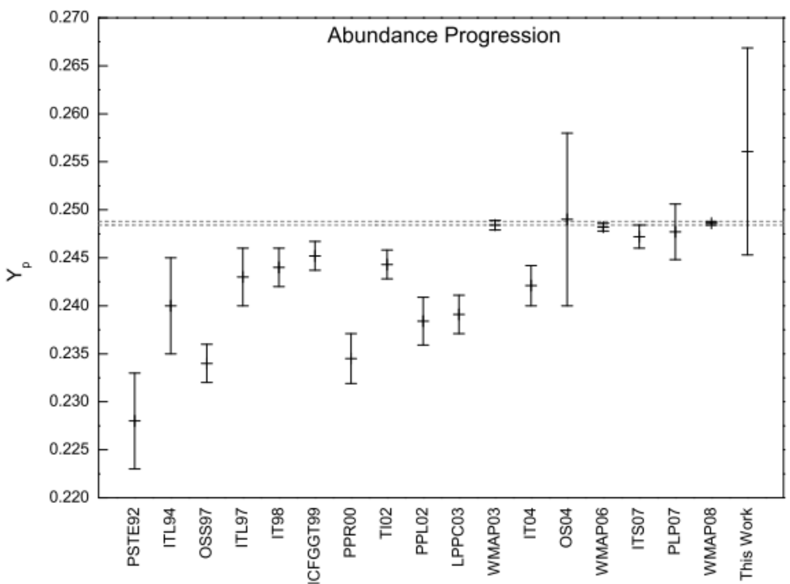
- Helium abundance Yp is the most sensitive probe for the neutrino number. Larger Helium -> Larger N_{eff}

Recently Mangano and Serpico (Mangano, Serpico, PLB 2011) obtained the upper limit:

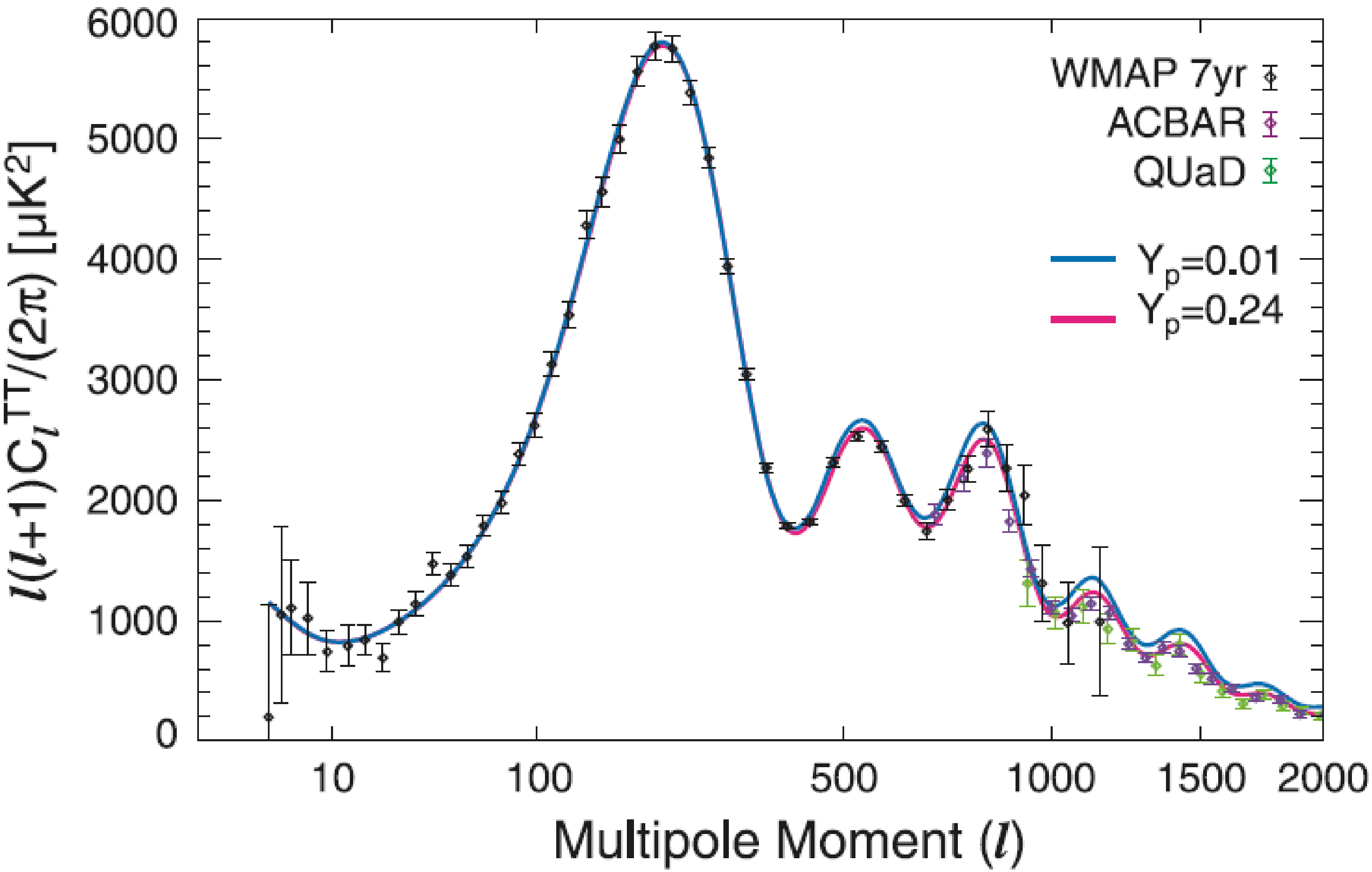
$$N_{eff} < 4 \text{ at } 95\ \%\ \text{c.l.}$$

However Yp is measured in metal-poor H-II regions subject to systematics (see Aver, Olive and Skillman, 2010)





Small scale CMB can probe Helium abundance at recombination.



See e.g.,

K. Ichikawa et al., Phys.Rev.D78:043509,2008

R. Trotta, S. H. Hansen, Phys.Rev. D69 (2004) 023509

Thermal History and Recombination

- Dominant element hydrogen recombines rapidly around z 1000.

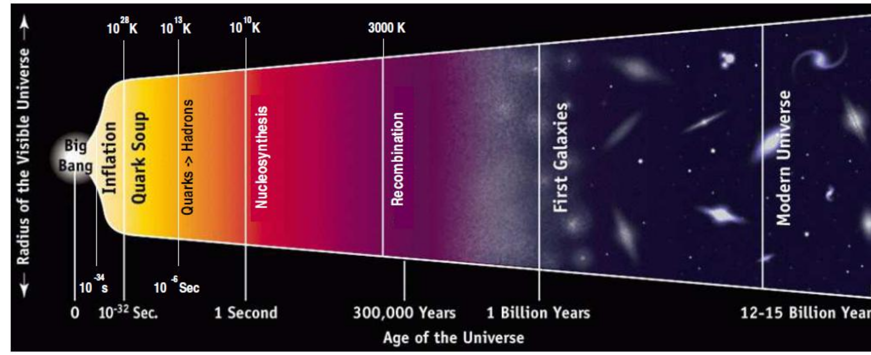
– Prior to recombination, Thomson scattering efficient and mean free path short cf. expansion time

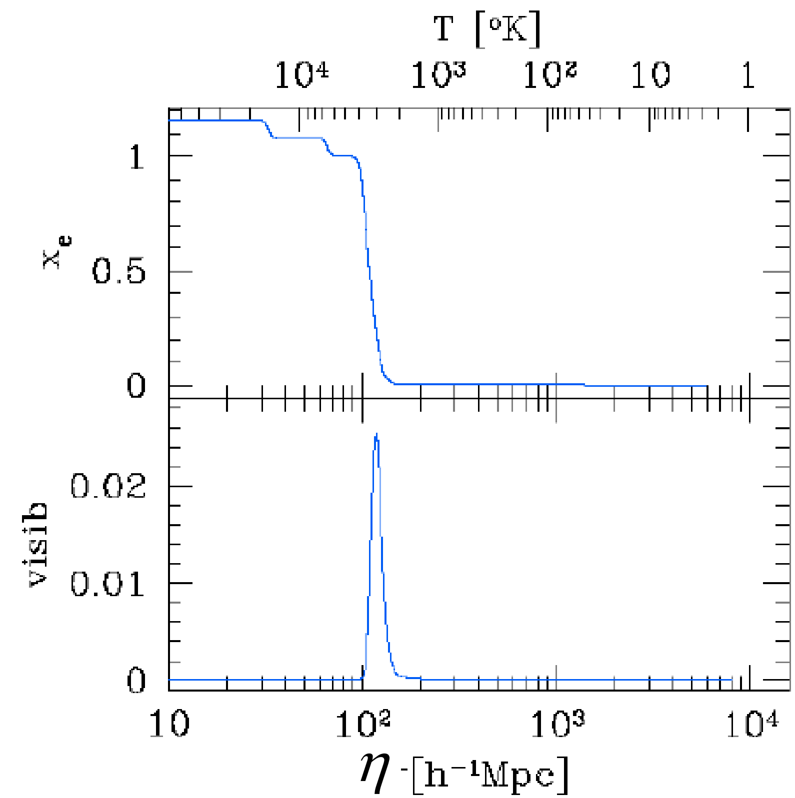
– Little chance of scattering after recombination ! photons free stream keeping imprint of conditions on last scattering surface

• Optical depth back to (conformal) time η_0 for Thomson scattering:

$$\tau(\eta) = \int_{\eta}^{\eta_0} a n_e \sigma_T \, d\eta'$$

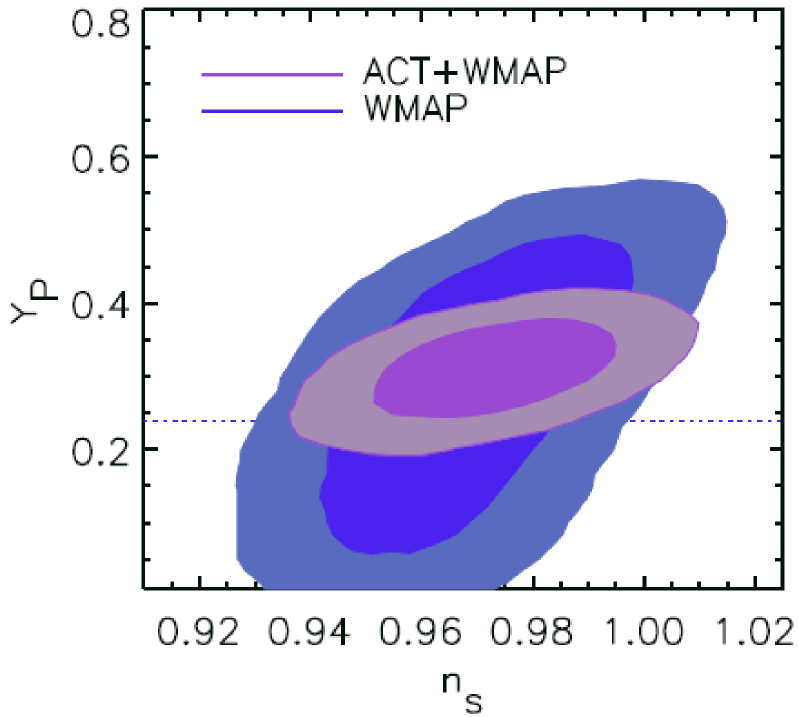
• The visibility function $-\dot{\tau}e^{-\tau}$ is the density probability of photon last scattering at time η

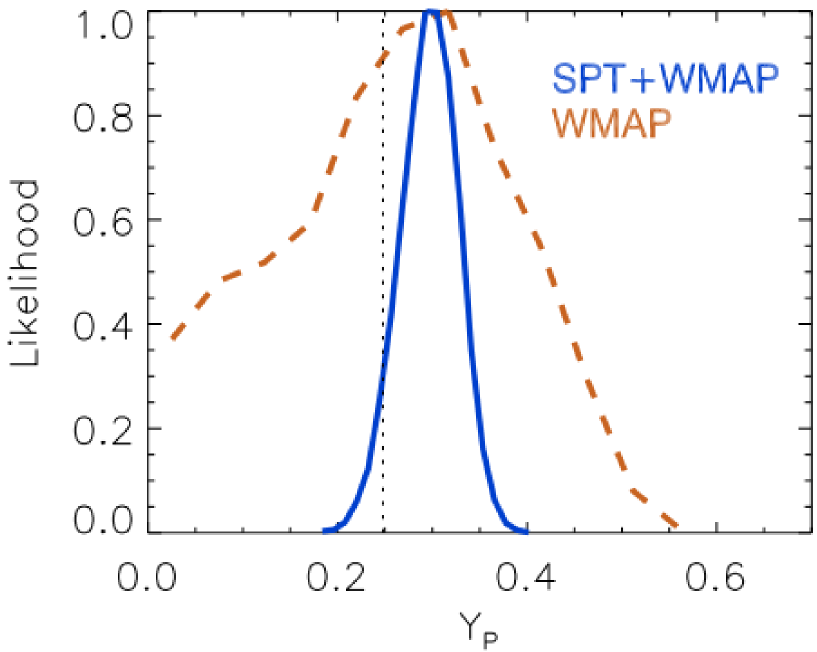




Primordial Helium: Current Status

Current CMB data seems to prefer a slightly higher value than expected from standard BBN.





WMAP+ACT analysis gives
(Dunkley et al., 2010):

$Y_P = 0.313$+-0.044

WMAP+SPT analysis gives
(Keisler et al, 2011):

$Y_P = 0.296$+-0.030

Probing the Neutrino Number with CMB data

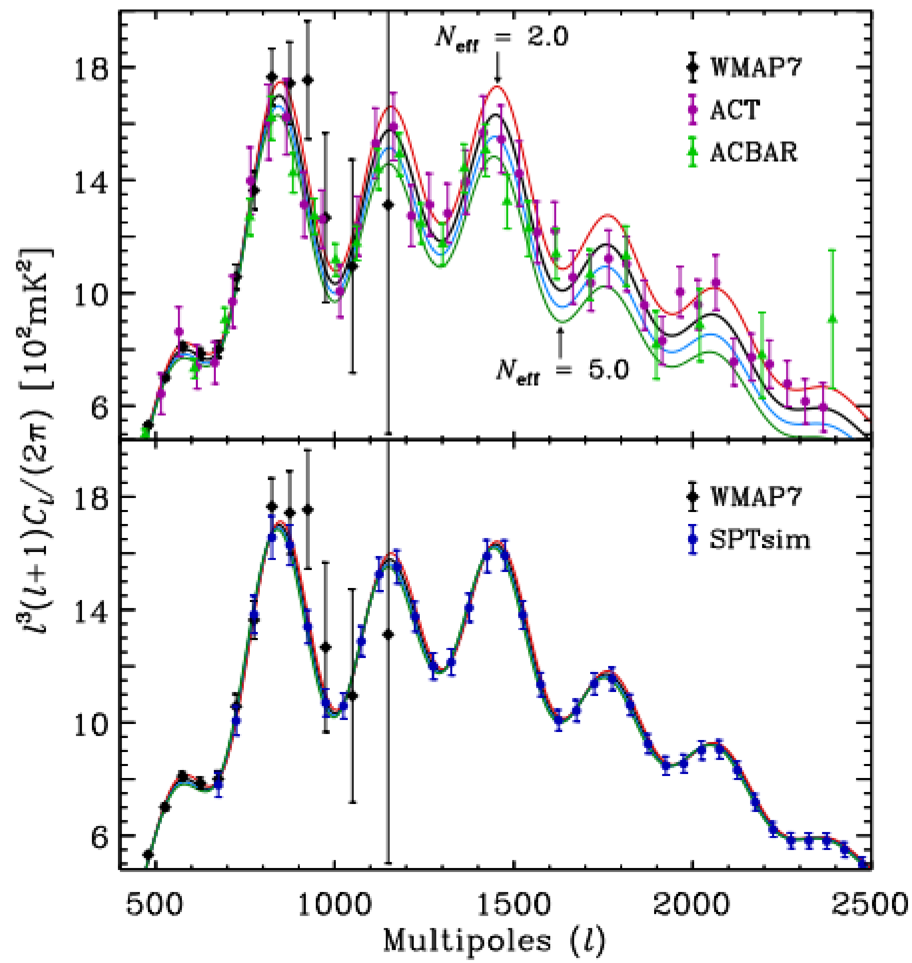
Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s \, dt/a = \int_0^{a_*} \frac{c_s \, da}{a^2 H}.$$

and the damping scale at recombination:

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

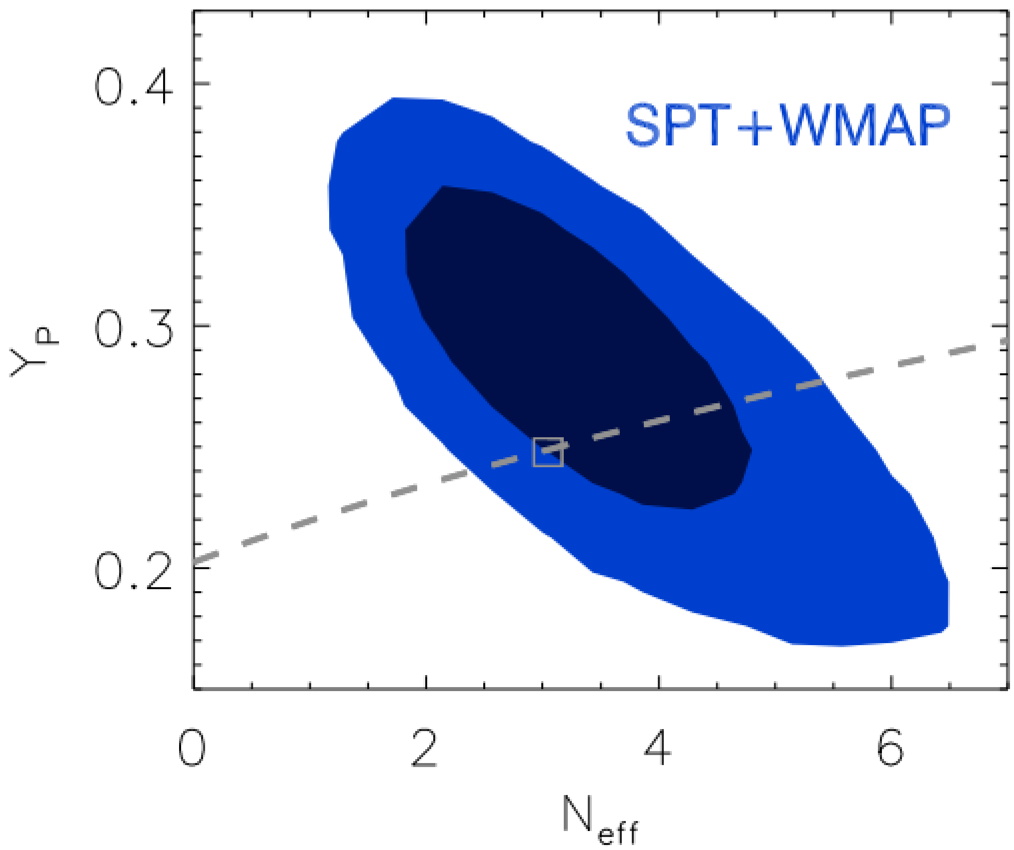
$$\theta_s = \frac{r_s}{D_A} \qquad \theta_d = \frac{r_d}{D_A}$$



Moreover increases early ISW at Recombination (phase shift)

Hou et al, 2011

Helium-Neutrinos BBN/CMB complementarity



Neutrino Mass

Laboratory bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale:

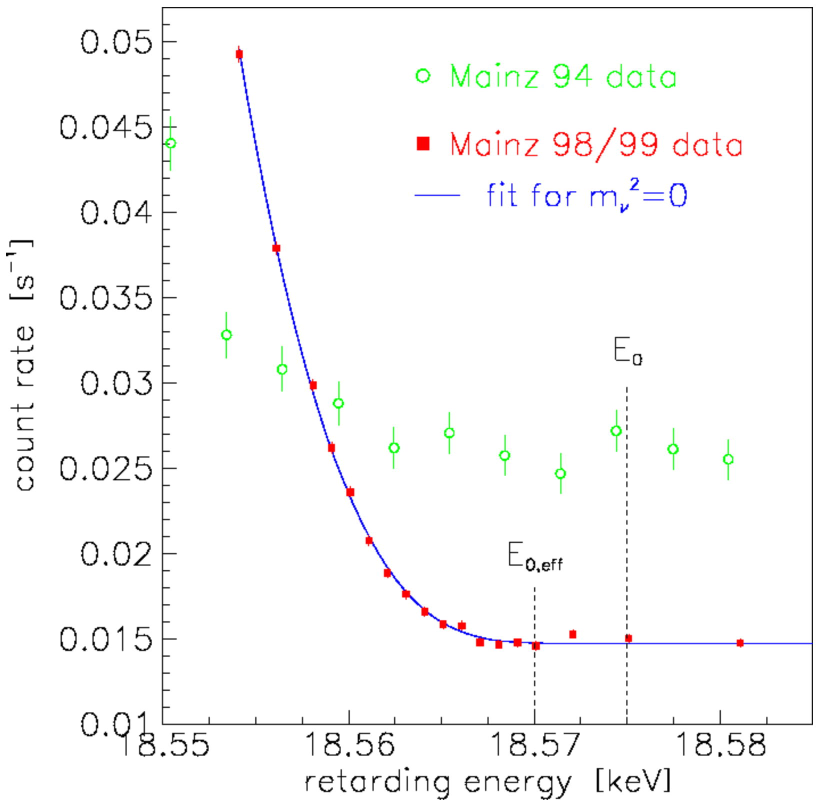
Tritium beta decay:

$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2}$$

Best fit gives a negative mass !!!

$$m_\beta^2 = -1.2 \pm 3.0 \quad eV^2 \text{ (Mainz)}$$

$$m_\beta^2 = -2.3 \pm 3.2 \quad eV^2 \text{ (Troitsk)}$$



$$\boxed{m_\beta < 1.8 \quad eV \qquad (2\sigma)}$$

Bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale :

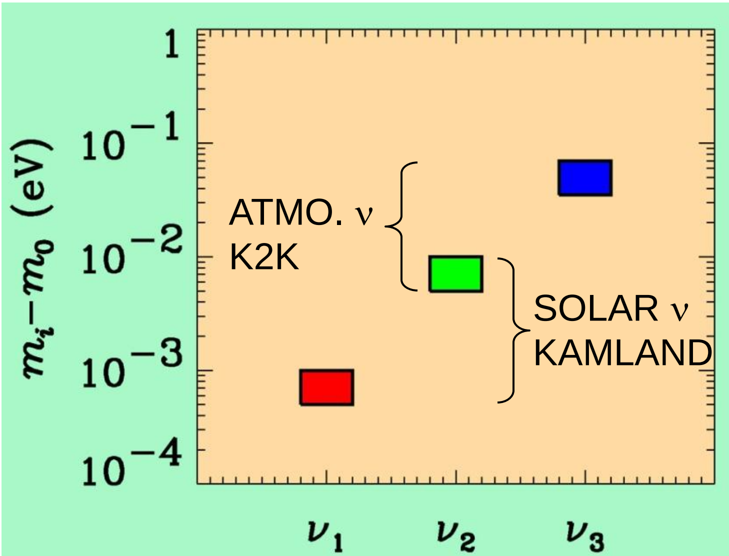
Neutrinoless double beta decay (only if neutrino are majorana particles!):

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

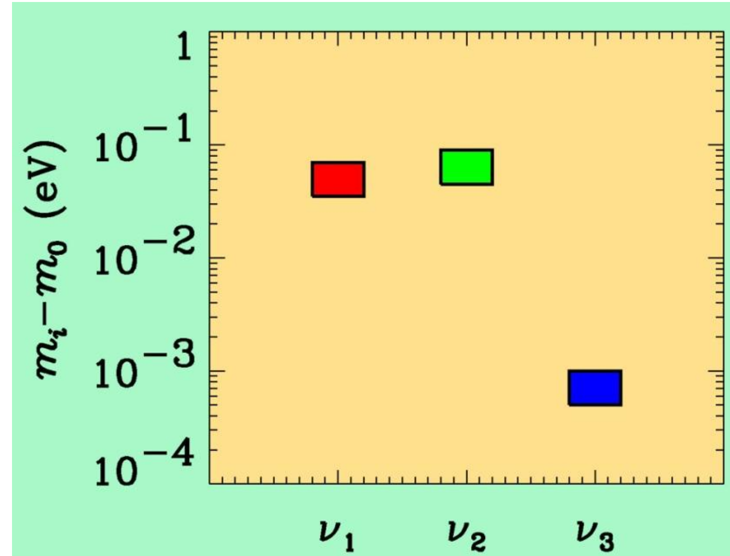
Neutrinoless double beta decay processes have been searched in many experiments with different isotopes, yielding negative results. Recently, members of the Heidelberg-Moscow experiment have claimed the detection of a $0\nu2\beta$ signal from the ^{76}Ge isotope. If the claimed signal is entirely due to a light Majorana neutrino masses then we have the constraint:

$$0.16 \;\; eV < m_{\beta\beta} < 0.52 \;\; eV \;\; (2\sigma)$$

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy



Inverted hierarchy

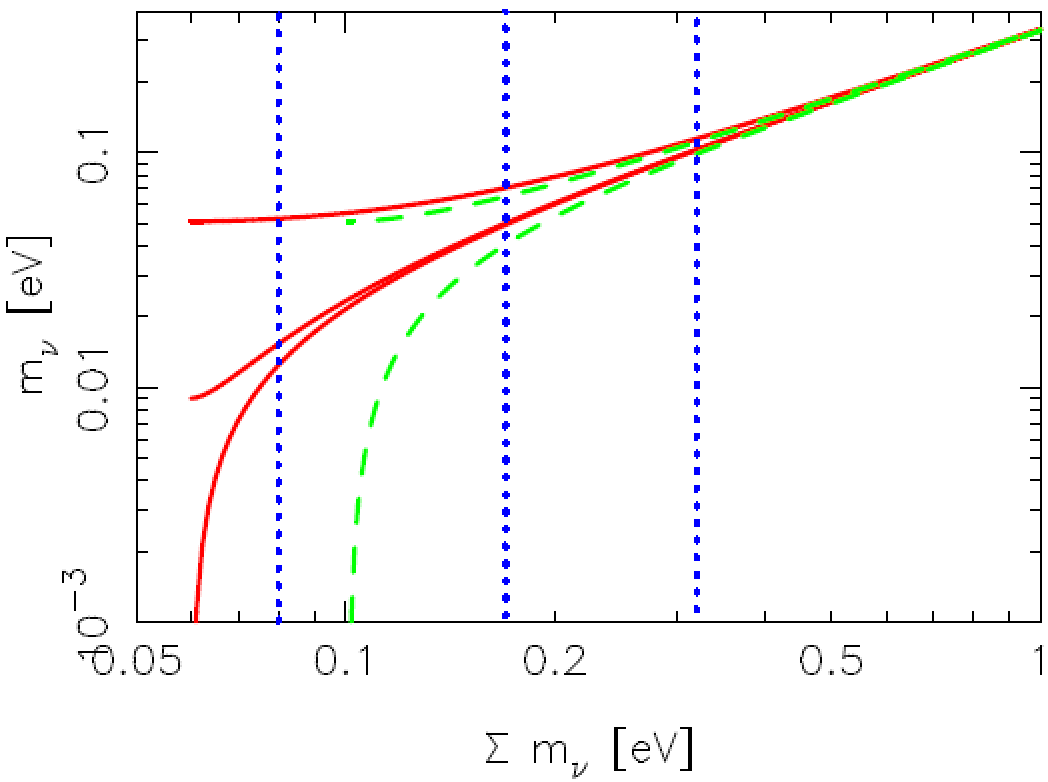
$$m_3 > m_2 > m_1$$

$$m_2 > m_1 > m_3$$

Moreover neutrino masses can also be degenerate

$$\boxed{m_1, m_2, m_3 >> \delta m_{\text{atmospheric}}}$$

Testing the neutrino hierarchy



Degenerate Hierarchy predicts:

$$\sum m_v > 0.15\ eV$$

Inverted Hierarchy predicts:

$$\sum m_v > 0.10\ eV$$

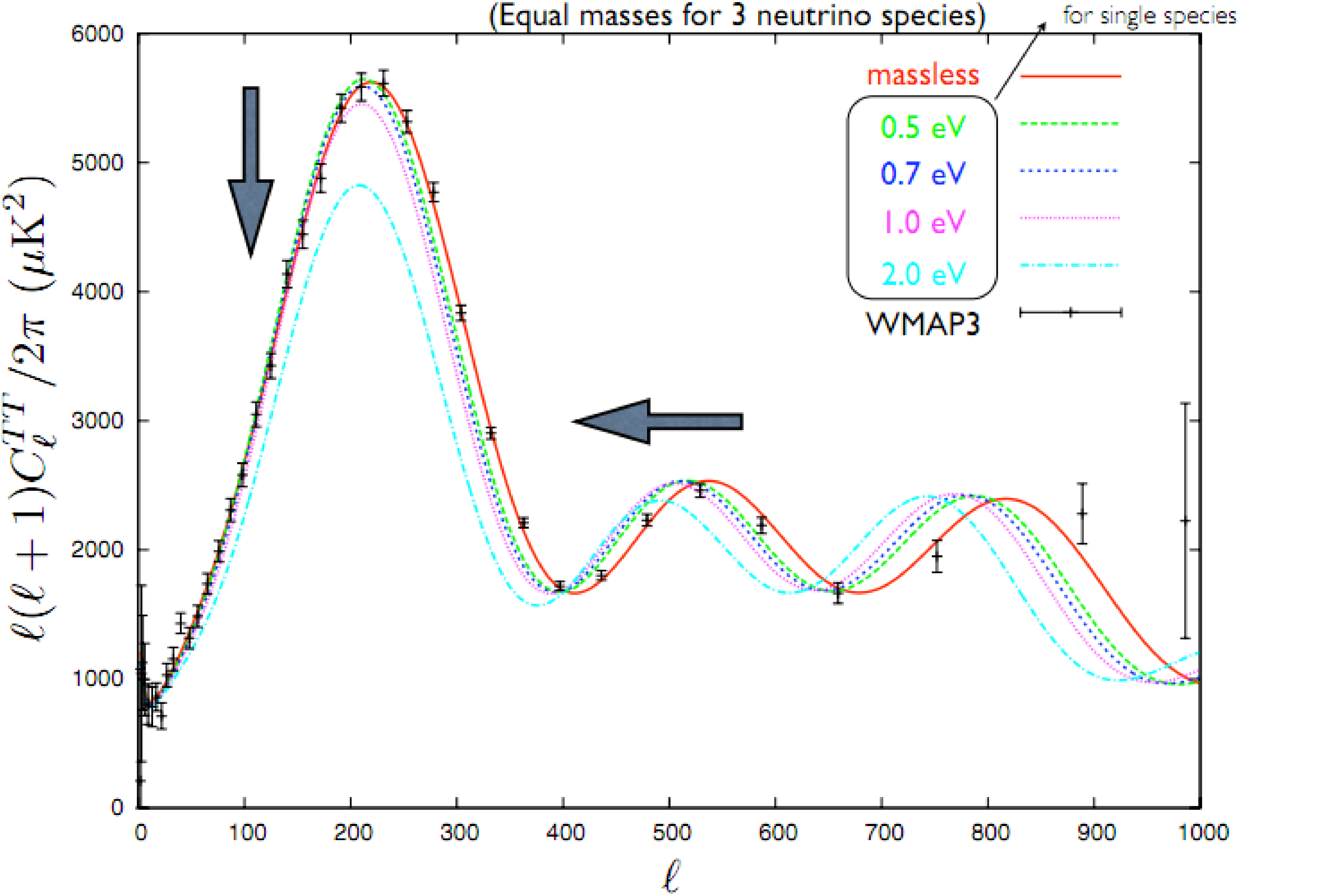
Normal Hierarchy predicts:

$$\sum m_v > 0.05\ eV$$

we assume $\Delta m^2 = 0.0025 eV^2$

Effect of neutrino masses on CMB power spectrum

(Equal masses for 3 neutrino species)



1. Horizontal shift (to smaller multipoles)

$m_\nu \uparrow$ implies smaller Ω_Λ (flatness assumed)

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94.1 \text{ eV}} \longrightarrow$$

1eV corresponds to $\Omega_\nu h^2 \sim 0.03$

But this effect is absorbed by decreasing the Hubble constant.

[Only for $m_\nu \gtrsim 0.6 \text{ eV}$]

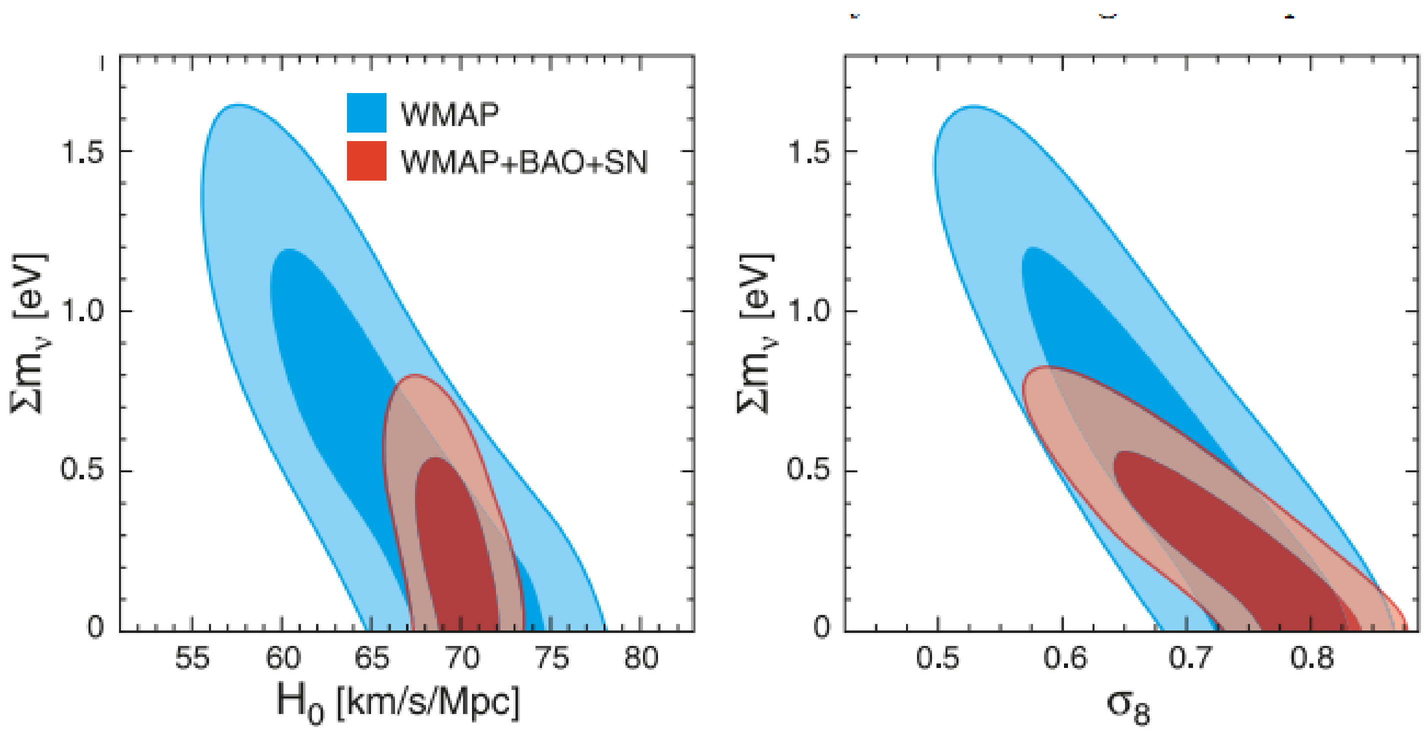
2. Relative enhancement of 2nd or higher peaks w.r.t 1st peak

The epoch of recombination z_{rec} ~ 1088 ~ 0.3 eV

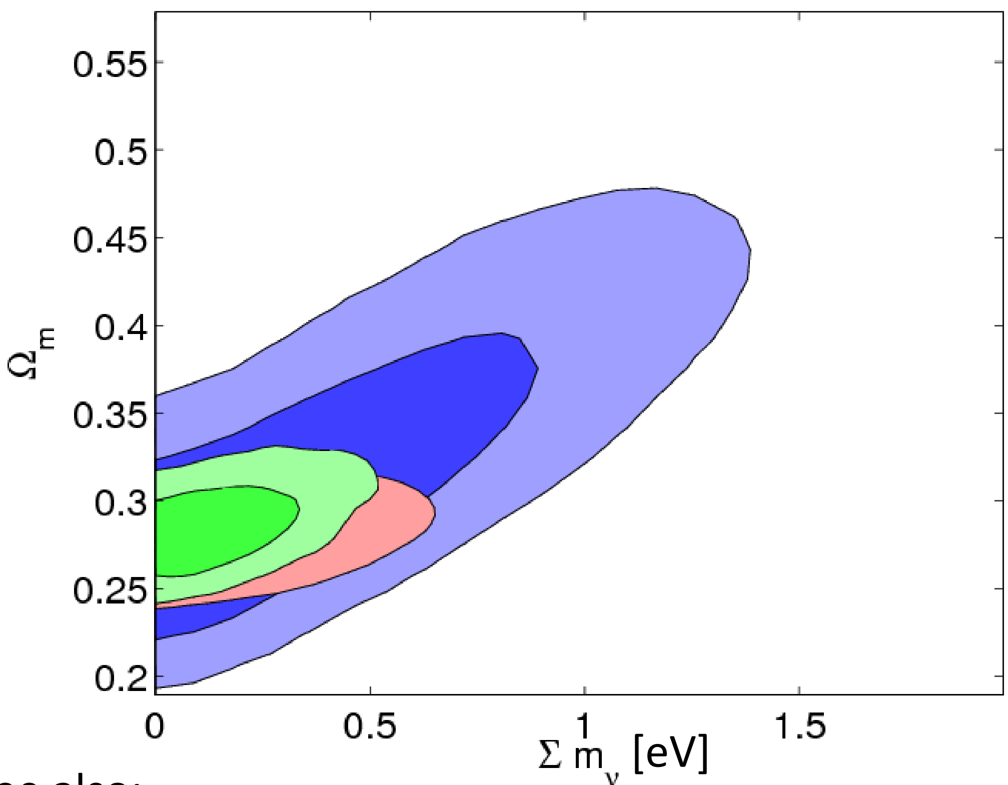
$\longrightarrow$ Massive neutrinos become nonrelativistic before the epoch of recombination if $m_\nu \gtrsim 0.6 \text{ eV}$

Characteristic signals imprinted in acoustic peaks.

WMAP7 Constraints



Current constraints on neutrino mass from Cosmology



Blue: WMAP-7
Red: w7+SN+Bao+H0
Green: w7+CMBsuborb+SN+LRG+H0

Current constraints (assuming ΛCDM):

Σm_ν<1.3 [eV] CMB (but see Maria's talk)

Σm_ν<0.7-0.5 [eV] CMB+other

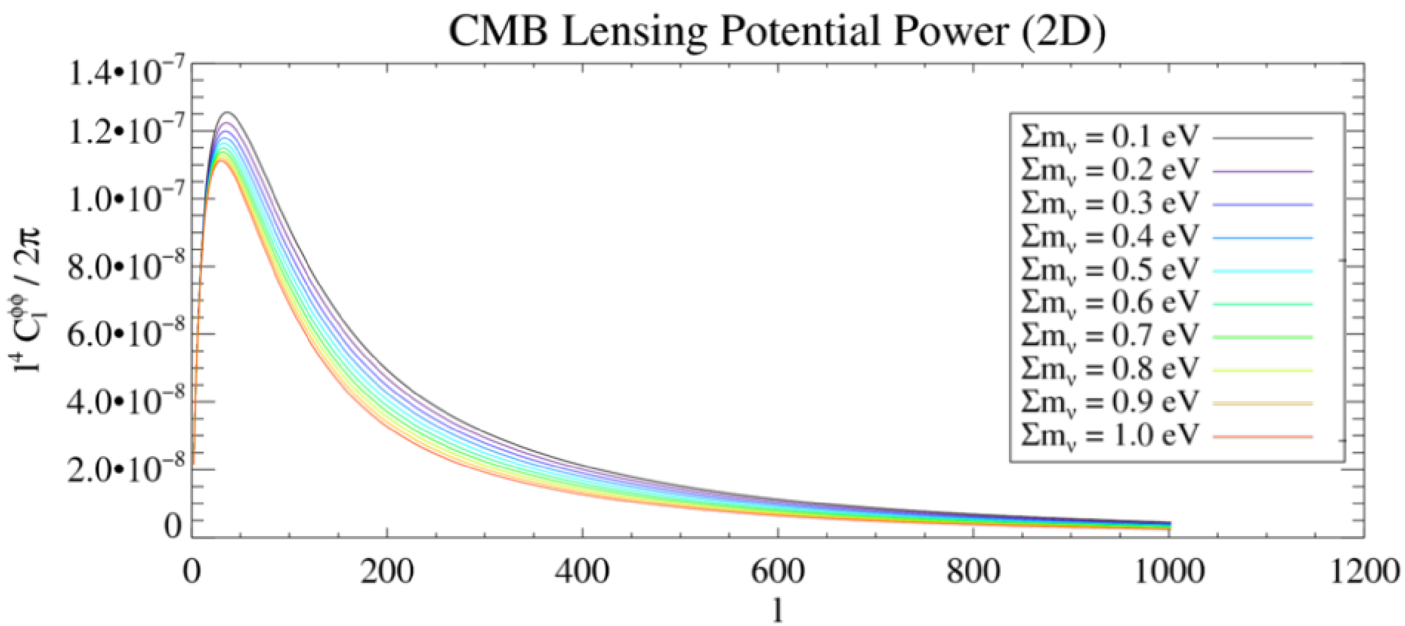
Σm_ν<0.3 [eV] CMB+LSS (extreme)

See also:
M. C. Gonzalez-Garcia, Michele Maltoni, Jordi Salvado, **arXiv:1006.3795**
Toyokazu Sekiguchi, Kazuhide Ichikawa, Tomo Takahashi, Lincoln Greenhill, **arXiv:0911.0976**
Extreme (sub 0.3 eV limits):
F. De Bernardis et al, Phys.Rev.D78:083535,2008, Thomas et al. Phys. Rev. Lett. 105, 031301 (2010)

Katrin experiment will have similar sensitivity than current cosmological bounds

Neutrinos and CMB Lensing

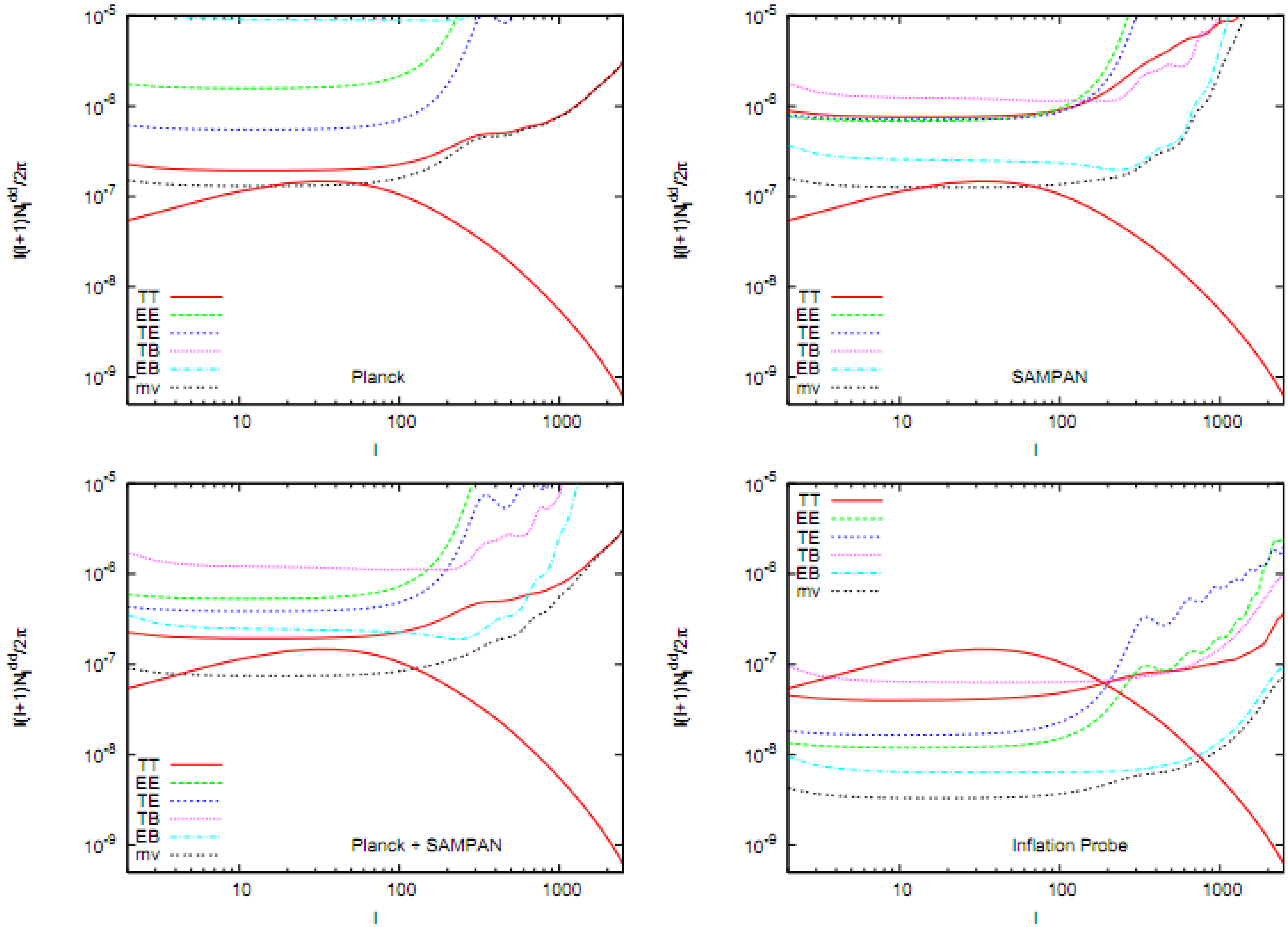
CMB lensing is sensitive to variations in the neutrino mass.
Higher neutrino masses -> less clustering -> less lensing



Lensing:

- Smoothing of high l CMB anysotropies (both Temperature and Polarization)
- Non Gaussianities (detectable in Trispectrum)
- B Modes Polarization.

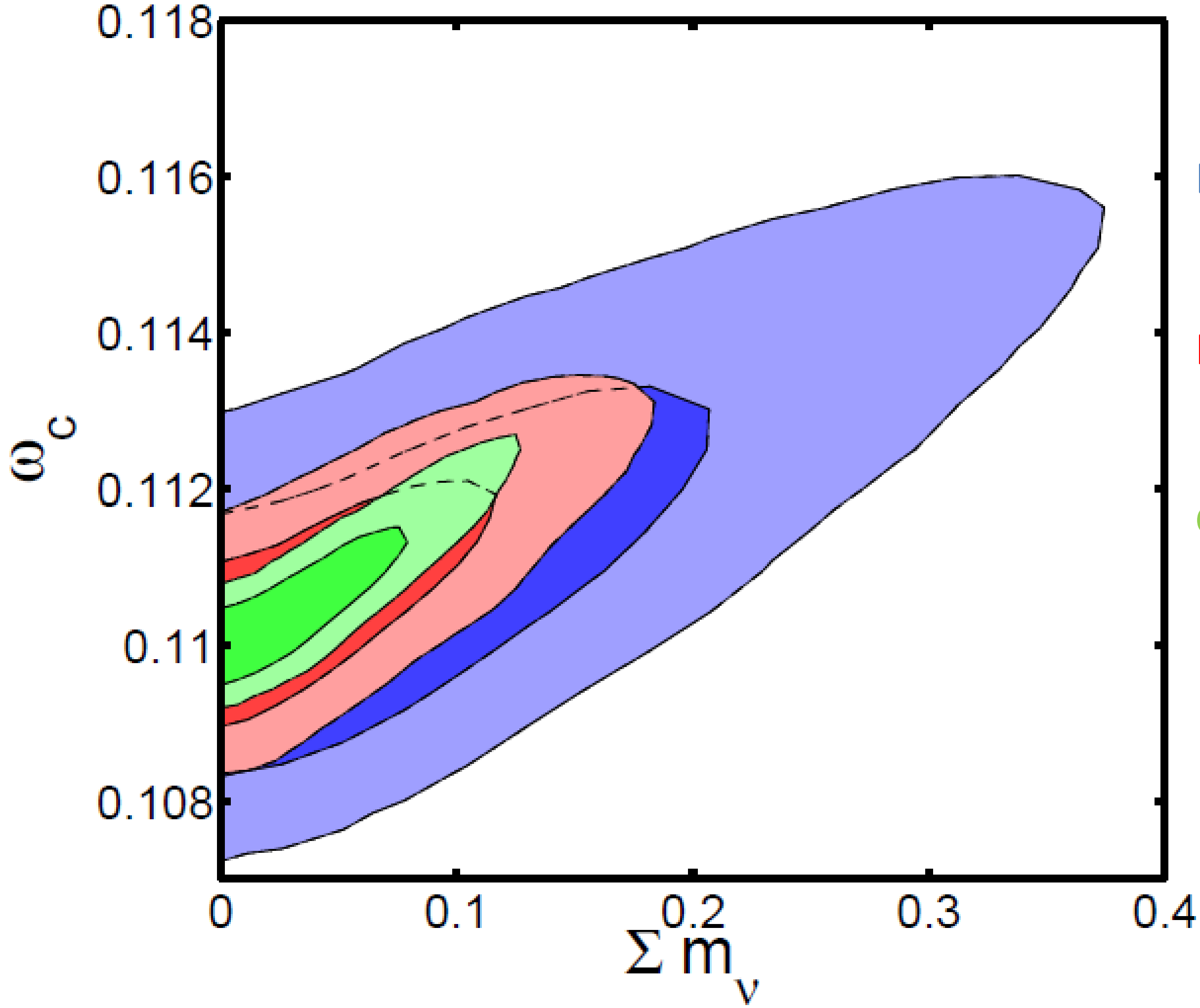
Neutrinos and CMB Lensing



Lesgourgues et al, Phys.Rev.D73:045021,2006

Planck
Satellite launch
14/5/2009

Constraints on Neutrino Mass



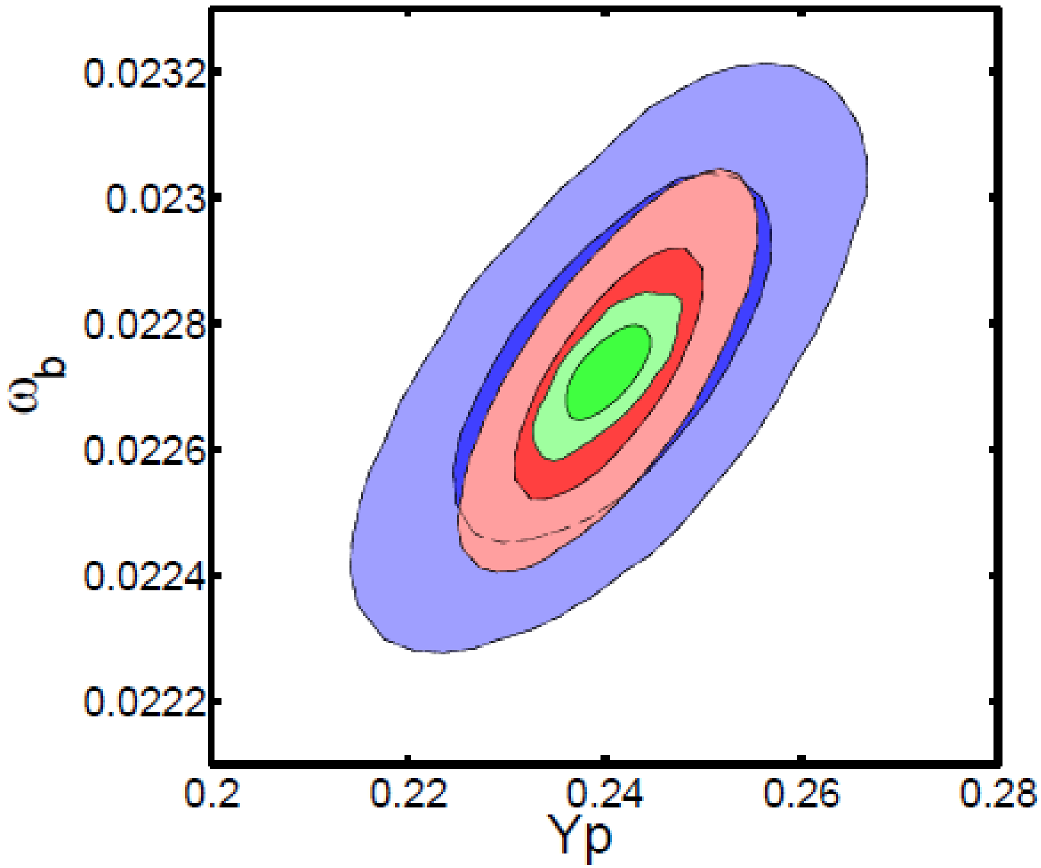
Blue: Planck $\Delta\Sigma m_\nu = 0.16$

Red: Planck+ACTpol $\Delta\Sigma m_\nu = 0.08$

Green: CMBPol $\Delta\Sigma m_\nu = 0.05$

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys. Rev. D **82**, 123504 (2010)

Constraints on Helium Abundance



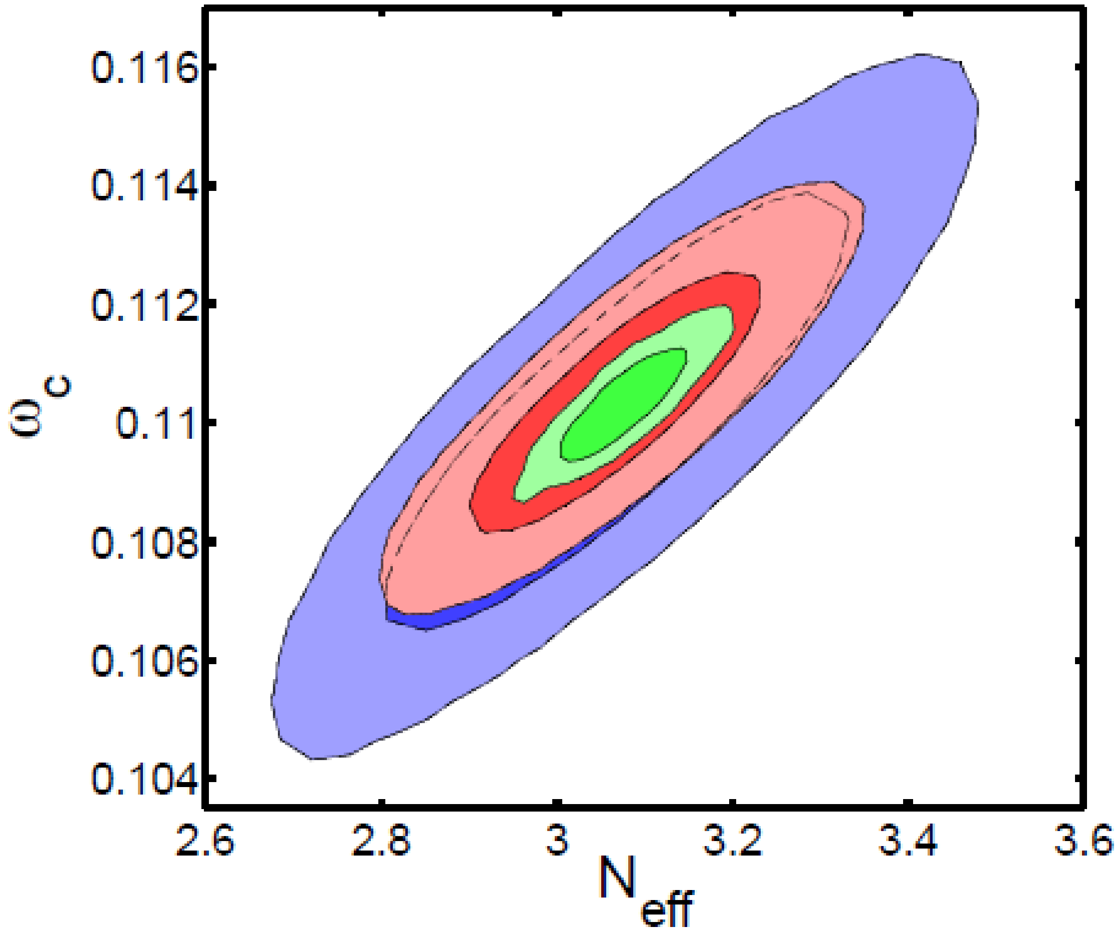
Blue: Planck $\Delta Yp=0.01$

Red: Planck+ACTpol $\Delta Yp=0.006$

Green: CMBPol $\Delta Yp=0.003$

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys. Rev. D **82**, 123504 (2010)

Constraints on Neutrino Number



Blue: Planck $\Delta N\nu=0.18$

Red: Planck+ACTpol $\Delta N\nu=0.11$

Green: CMBPol $\Delta N\nu=0.044$

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys. Rev. D **82**, 123504 (2010)

THANK YOU