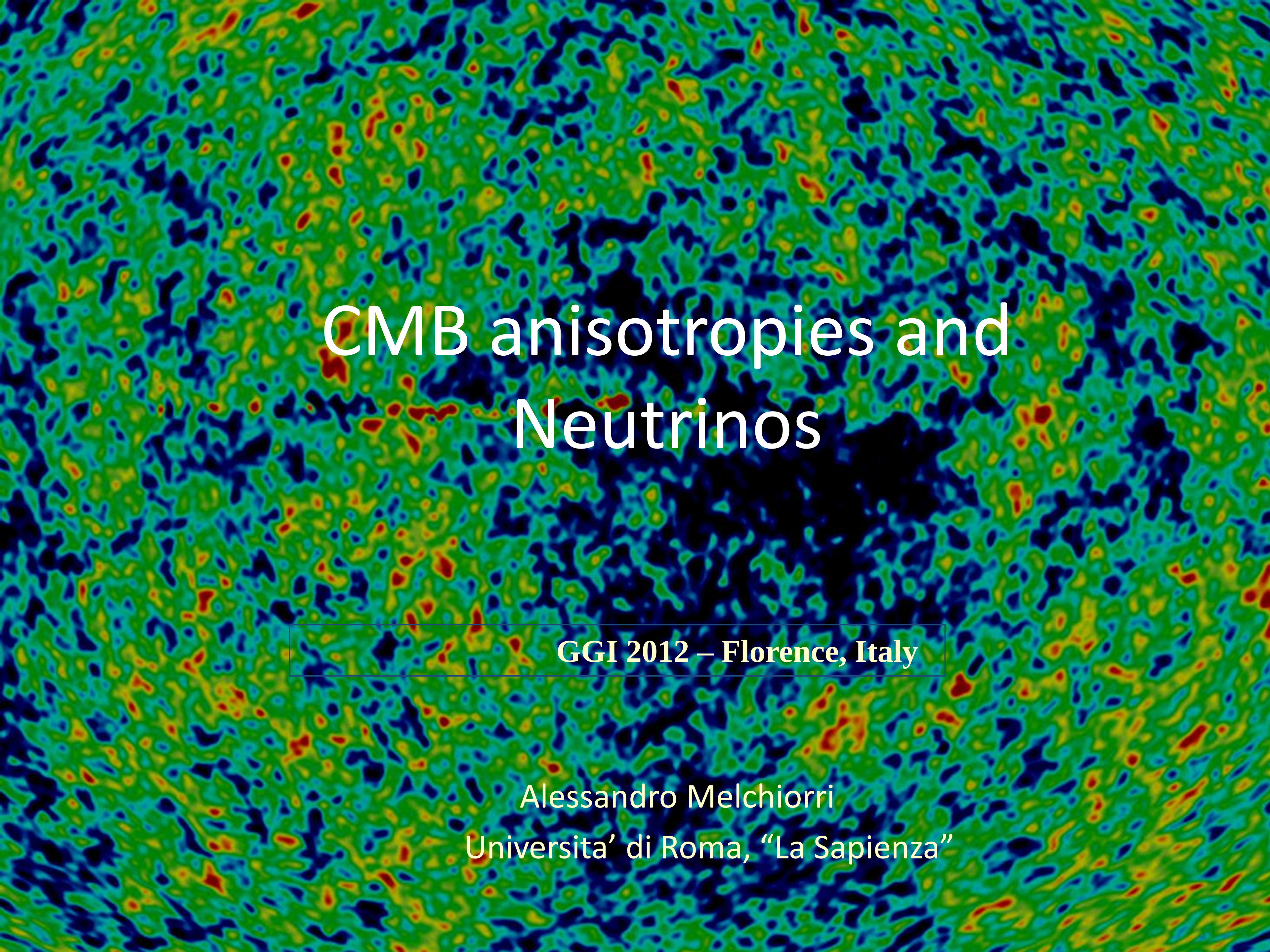


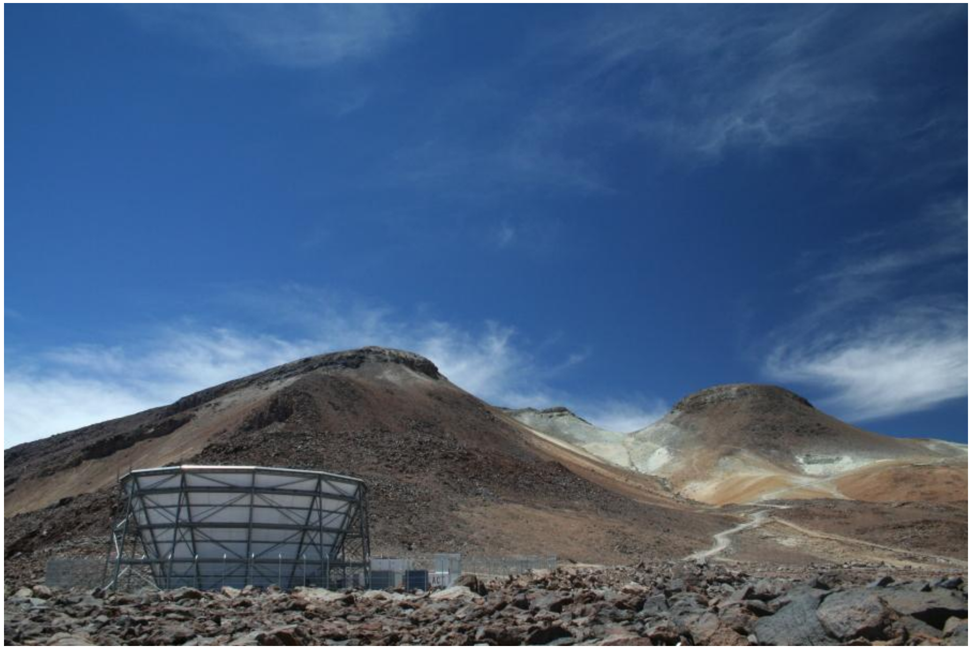
CMB anisotropies and Neutrinos

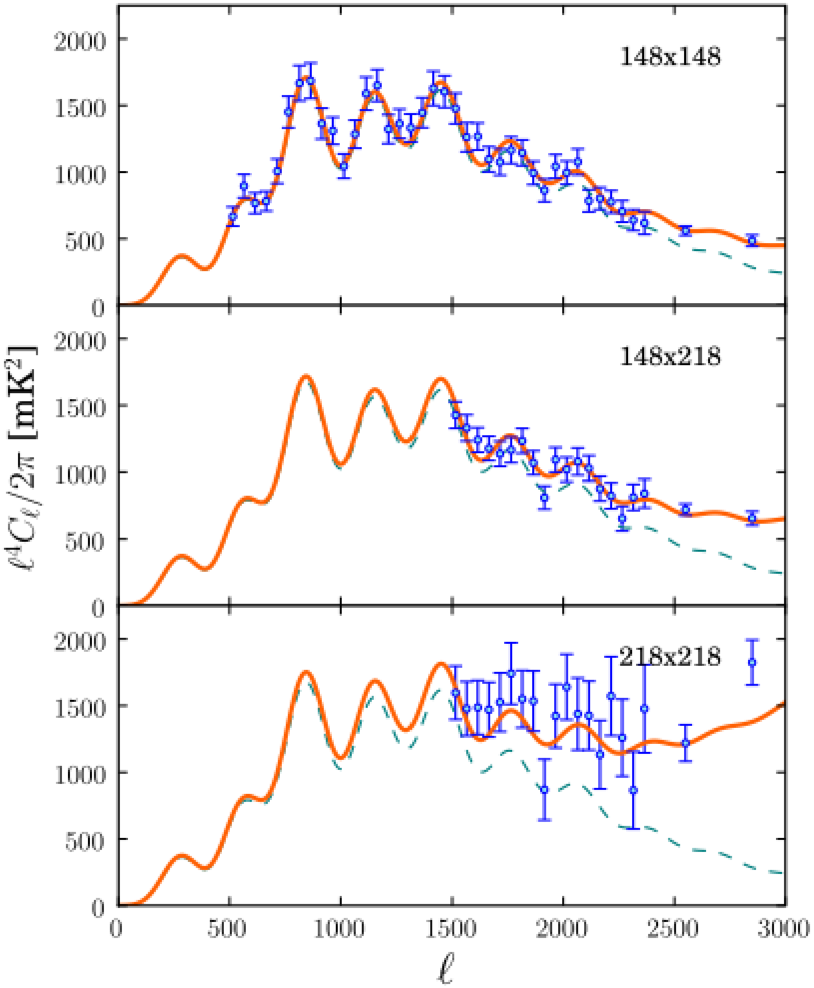
GGI 2012 – Florence, Italy

Alessandro Melchiorri
Universita' di Roma, "La Sapienza"

New ACT results

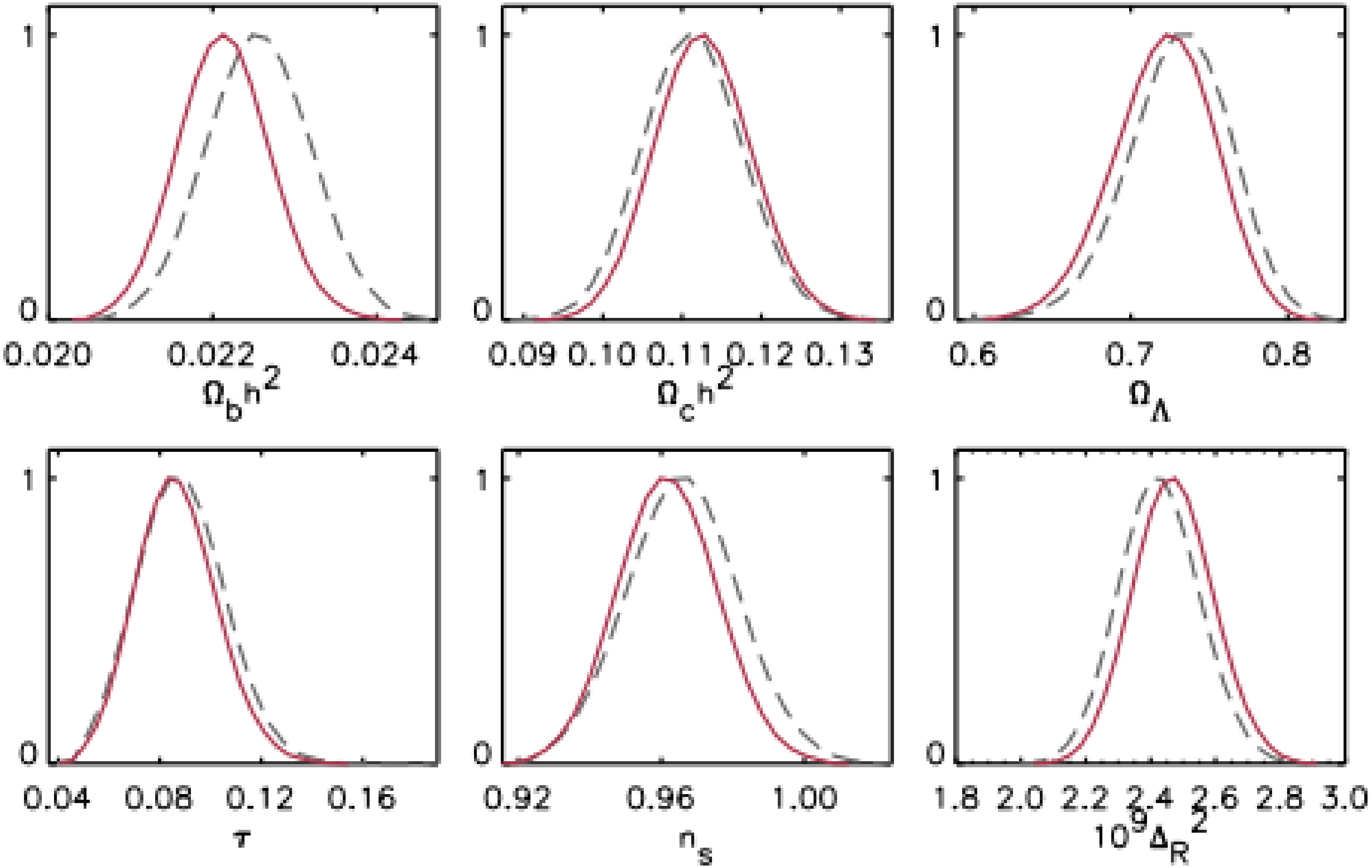
The **Atacama Cosmology Telescope** (**ACT**) is a six-meters telescope on Cerro Toco in the Atacama Desert in the north of Chile, at an altitude of 5190 metres.





S. Das et al, **Astrophys.J. 729 (2011) 62**

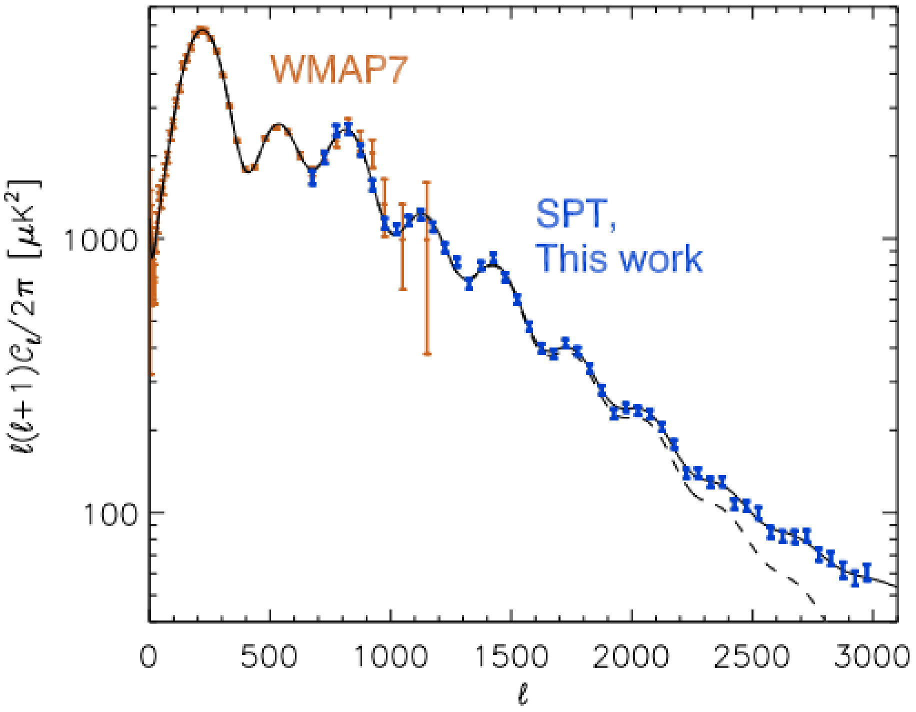
Constraints on the standard Λ-CDM parameters are not significantly improved by the new ACT data.

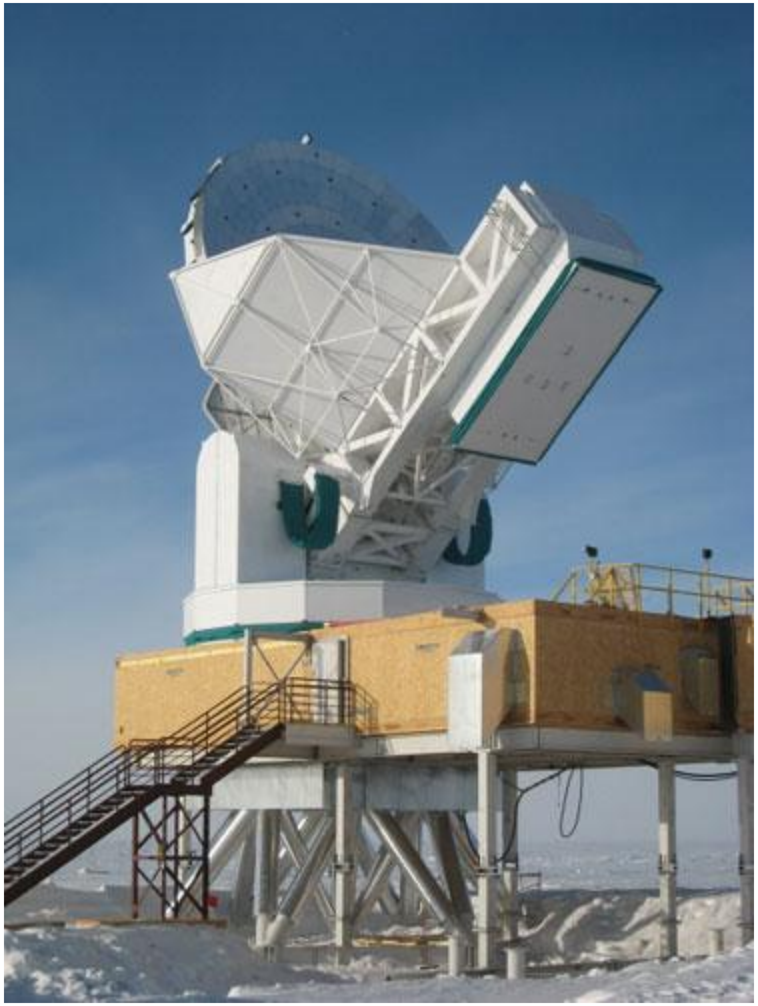


J. Dunkley et al, **Astrophys.J. 739 (2011) 52**

New SPT results

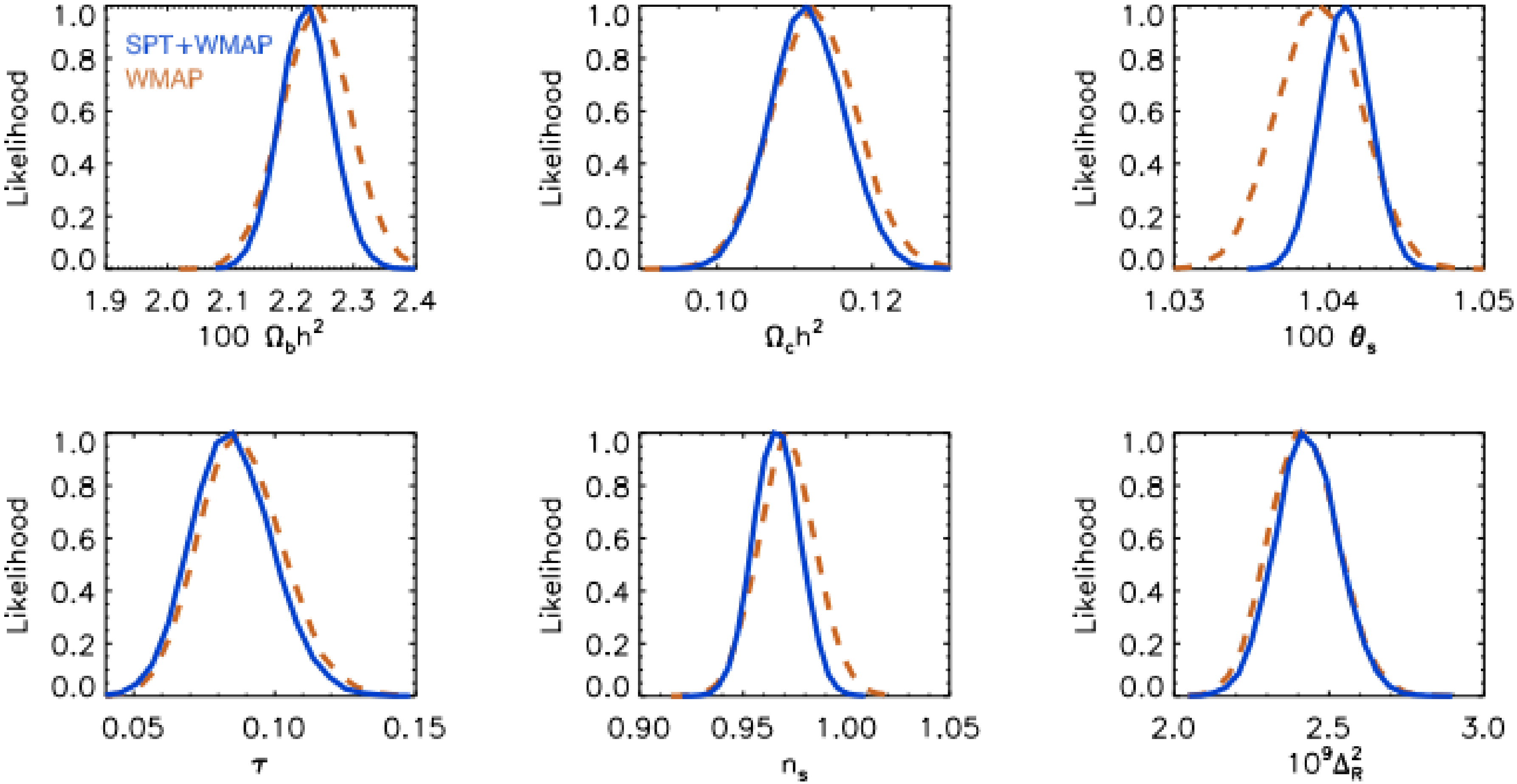
The South Pole Telescope (SPT) is a 10 meters diameter telescope located at the Amundsen-Scott South Pole Station, Antarctica.
The data consist of 790 square degrees of sky observed at 90, 150 & 220 GHz.





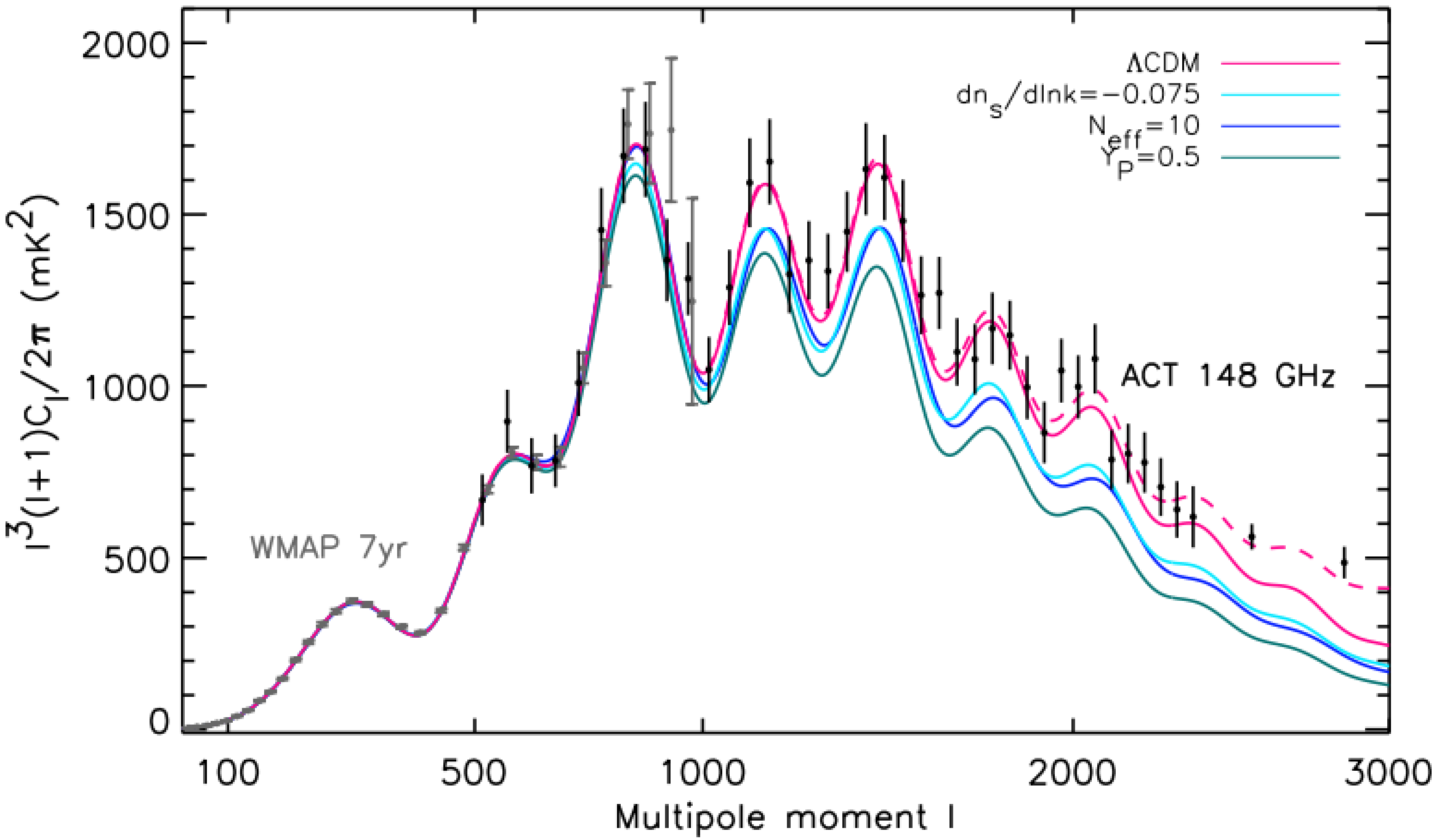
R. Keisler et al, **Astrophys.J. 743 (2011) 28**

Constraints on the standard Λ-CDM parameters are not significantly improved by the new SPT data.



R. Keisler et al, **Astrophys.J. 743 (2011) 28**

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

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

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

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

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 **parametrized** as:

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

Caveat: Neff 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 Neff > 3.046 is equivalent to the presence of a new «dark radiation» component :

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

Probing the Neutrino Number with CMB data

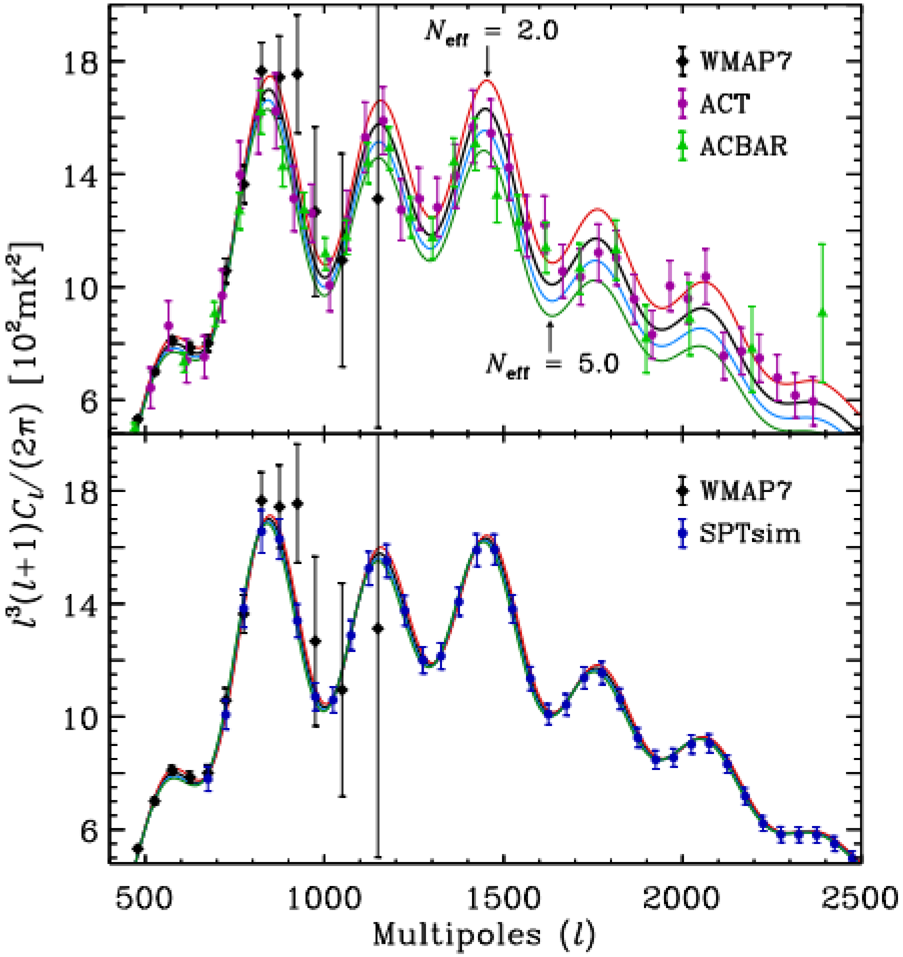
Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

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

and the damping scale at recombination:

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

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

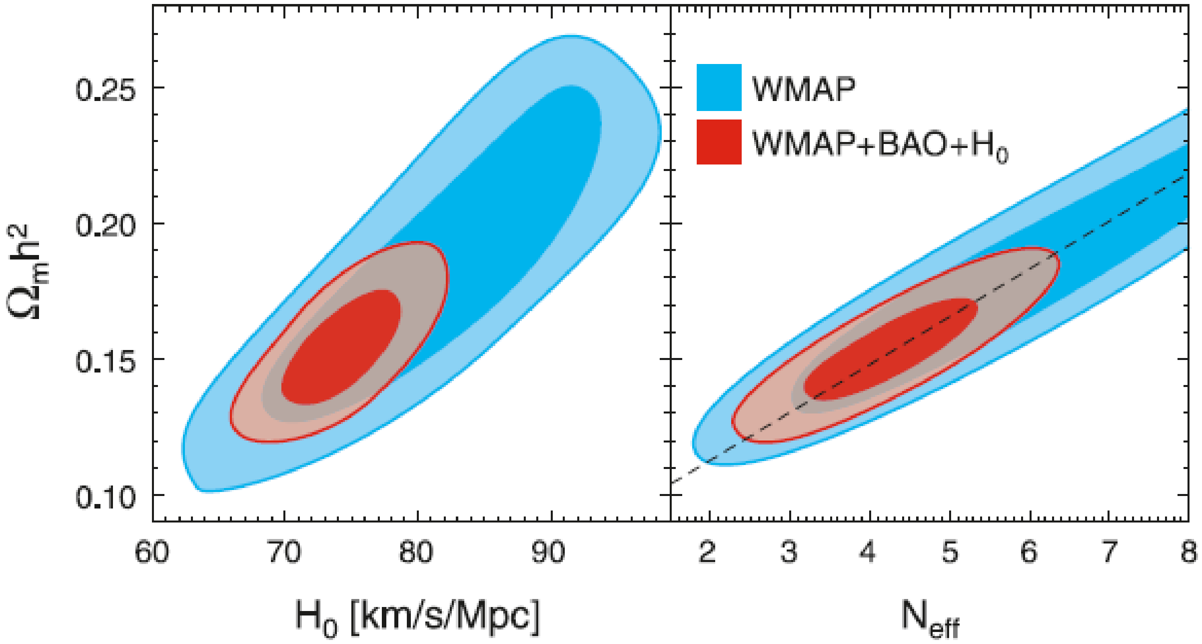


Measuring the damping scale helps in breaking the degeneracy with H0 !!

Hou et al, 2011
Bowen et al, 2002

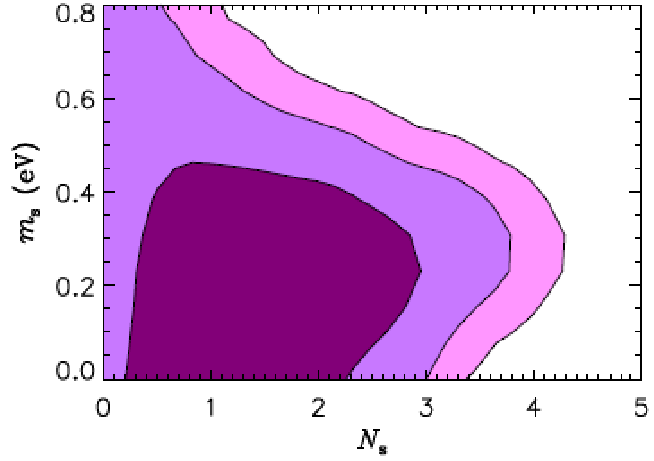
Komatsu et al, 2010, 1001.4538

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

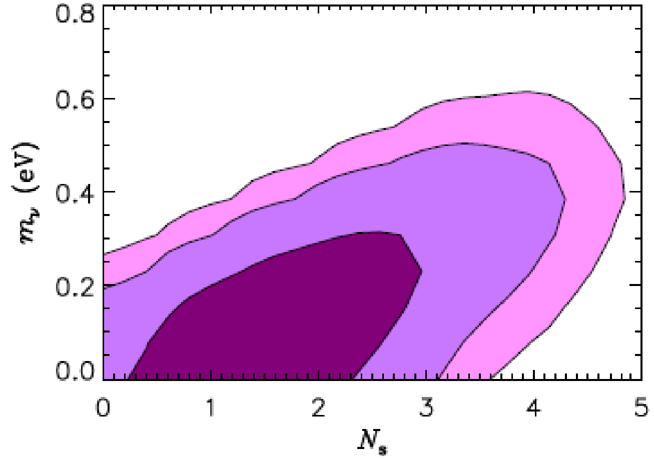


Parameter	Year	*WMAP* only	*WMAP*+BAO+SN+*HST*	*WMAP*+BAO+H_0	*WMAP*+LRG+H_0
$z_{\rm eq}$	5-year	3141^{+154}_{-157}	3240^{+99}_{-97}		
	7-year	3145^{+140}_{-139}		3209^{+85}_{-89}	3240 ± 90
$\Omega_m h^2$	5-year	$0.178^{+0.044}_{-0.041}$	0.160 ± 0.025		
	7-year	$0.184^{+0.041}_{-0.038}$		0.157 ± 0.016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

Subsequent analysis with WMAP+ACBAR+BICEP+QUAD+SDSS DR7+HST confirmed the «preference» for $N_{eff} > 3$.



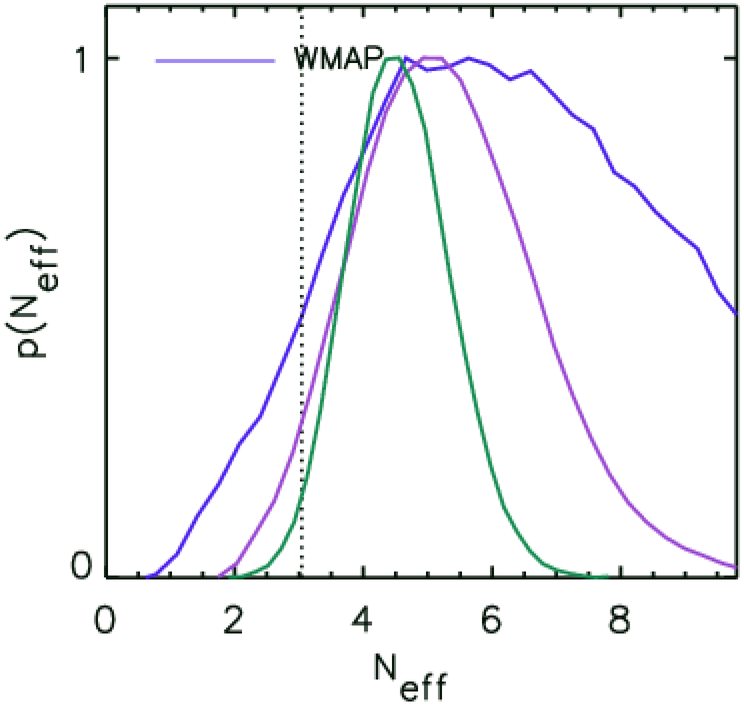
3 Active massless neutrinos+
N_s massive neutrinos

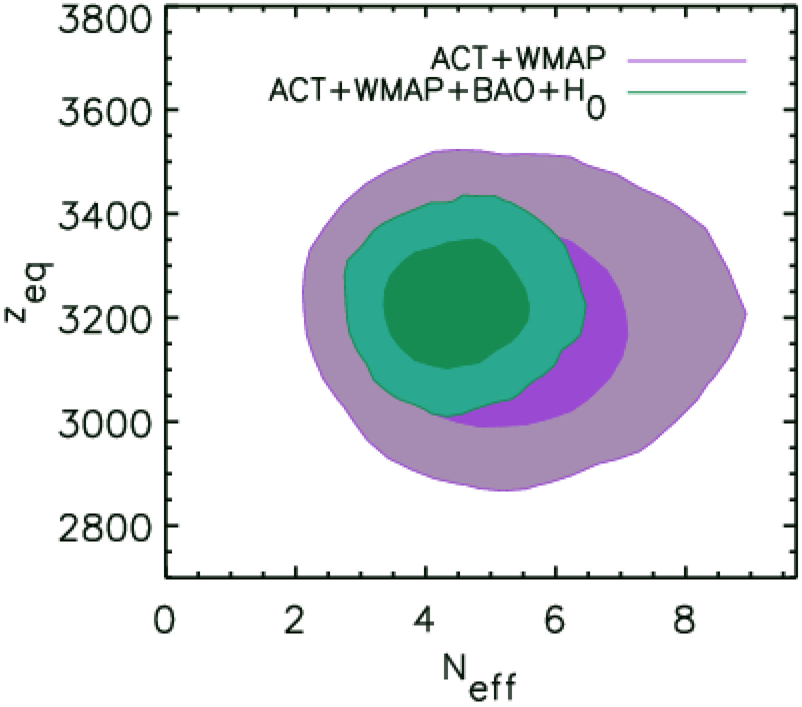


3 Active massive neutrinos +
N_s massless neutrinos

J. Hamann et al, Phys.Rev.Lett.105:181301,2010

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





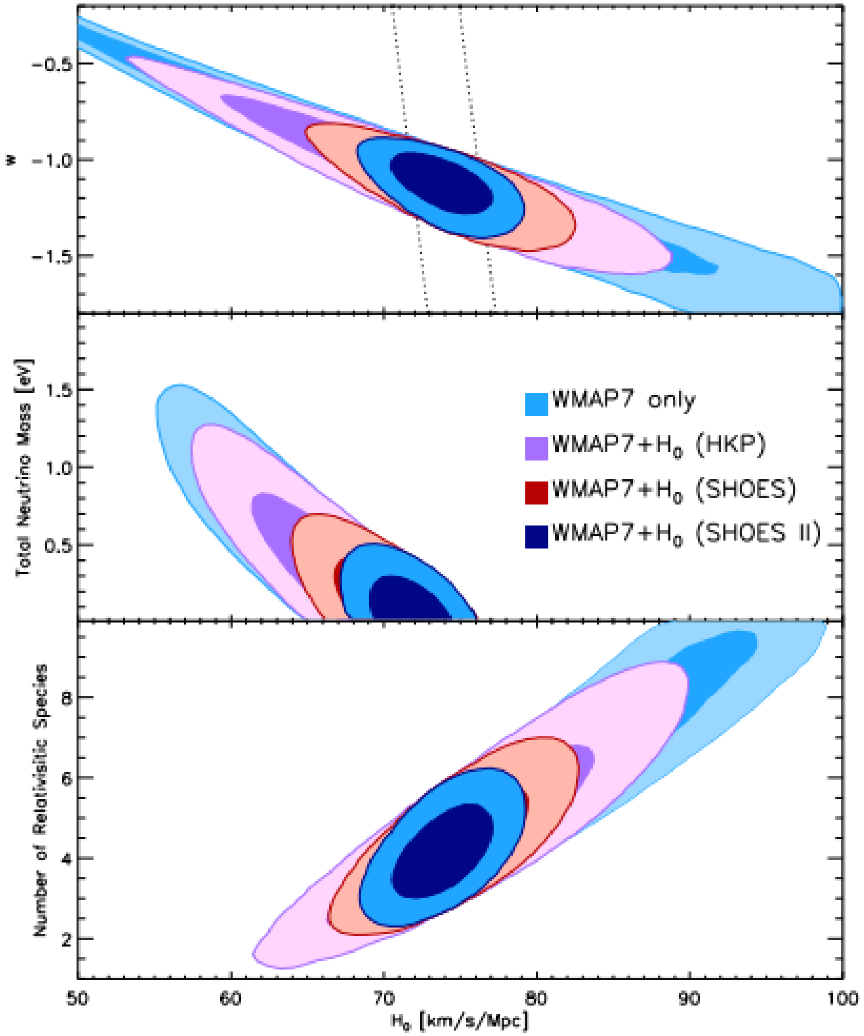
Latest results from ACT, Dunkley et al. 2010
(95 % c.l.)

$Neff = 5.3 \pm 1.3$ ACT+WMAP

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

New HST determination of H_0

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.

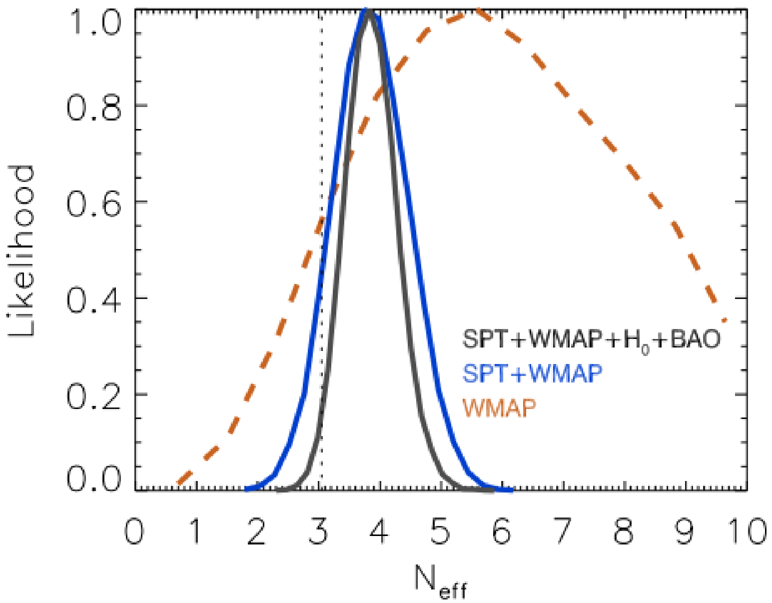


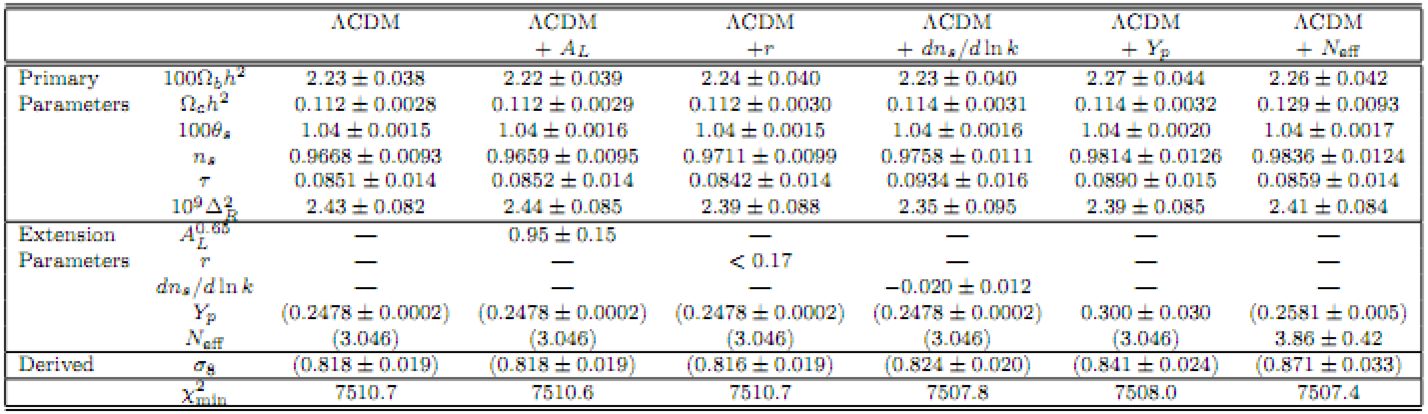
$h = 0.738 \pm 0.024$

$N_{eff} = 4.2 \pm 0.7$

Riess et al, **ApJ, 730, 119, 2011**

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

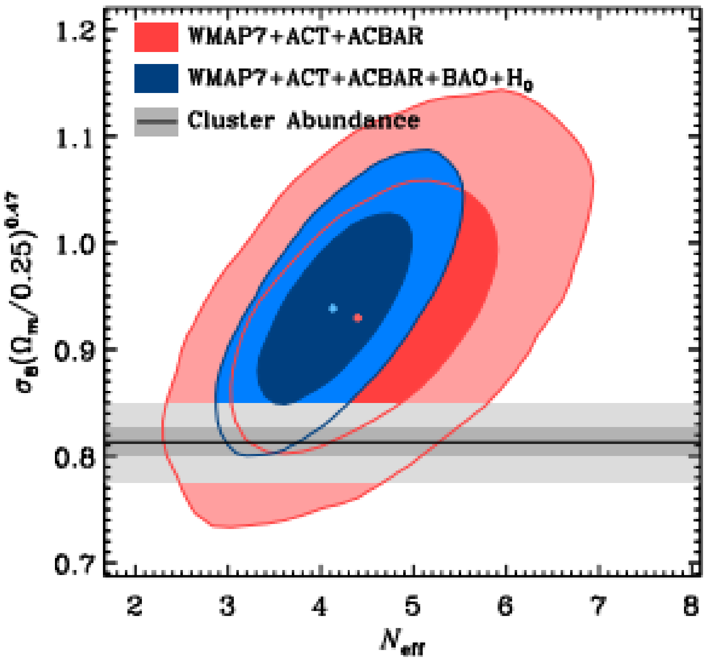


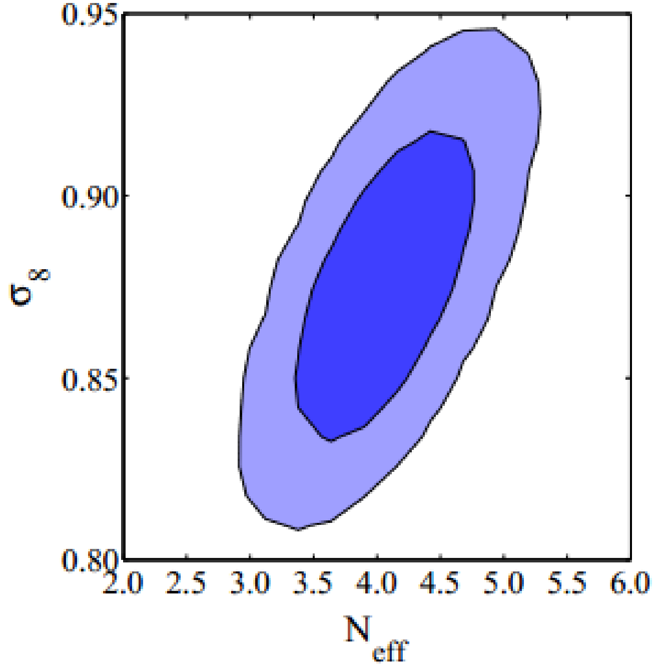


		ΛCDM	ΛCDM $+ A_L$	ΛCDM $+r$	ΛCDM $+ dn_s/d\ln k$	ΛCDM $+ Y_p$	ΛCDM $+ N_{\rm eff}$
Primary Parameters	$100\Omega_b h^2$	2.23 ± 0.038	2.22 ± 0.039	2.24 ± 0.040	2.23 ± 0.040	2.27 ± 0.044	2.26 ± 0.042
	$\Omega_c h^2$	0.112 ± 0.0028	0.112 ± 0.0029	0.112 ± 0.0030	0.114 ± 0.0031	0.114 ± 0.0032	0.129 ± 0.0093
	$100\theta_s$	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 Parameters	$A_L^{0.65}$	—	0.95 ± 0.15	—	—	—	—
	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)
	$N_{\rm eff}$	(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)
	$\chi^2_{\rm min}$	7510.7	7510.6	7510.7	7507.8	7508.0	7507.4

WMAP7+ACT+SPT+H0+BAO Analyses

Most recent analyses they all point towards Neff>3 at about 2.6-2.8 standard deviations.





$$N_{eff}^{\nu} = 4.08^{+0.71}_{-0.68}$$

At 95% c.l.

Archidiacono, Calabrese, AM, **Phys.Rev. D84 (2011) 123008**
Hou et al**, arXiv:1104.2333, (2011)**
Smith et al**, Phys.Rev. D85 (2012) 023001**
Hamann**, JCAP 1203 (2012) 021**

Probing the Neutrino Number with BBN data

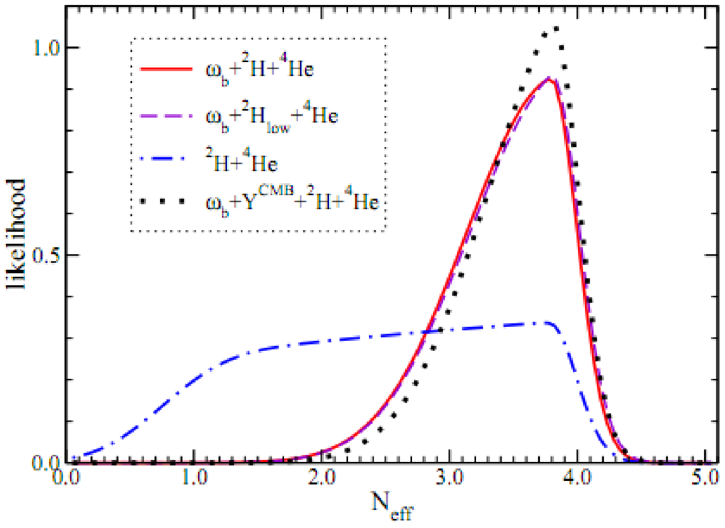
- BBN element abundances depend on nuclear interaction rates and expansion rate.

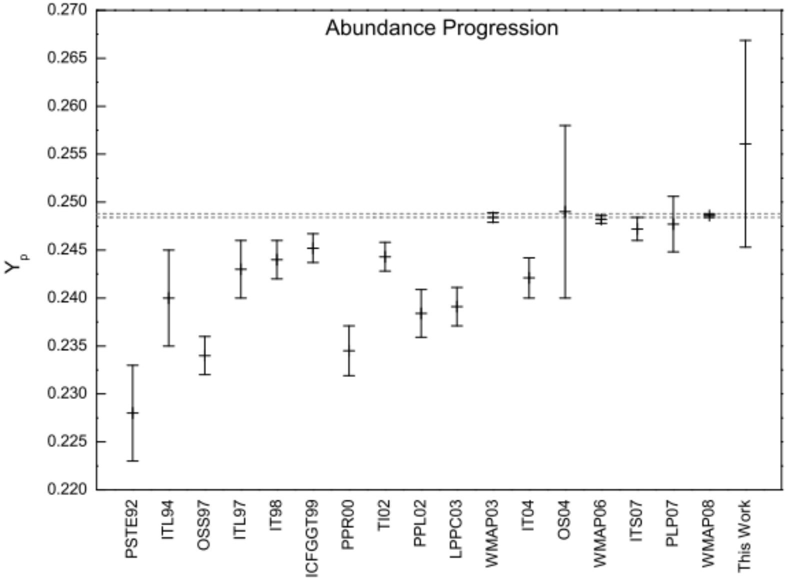
- Helium abundance Yp is the most sensitive probe for the neutrino number. Larger Helium -> Larger N_{eff}

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

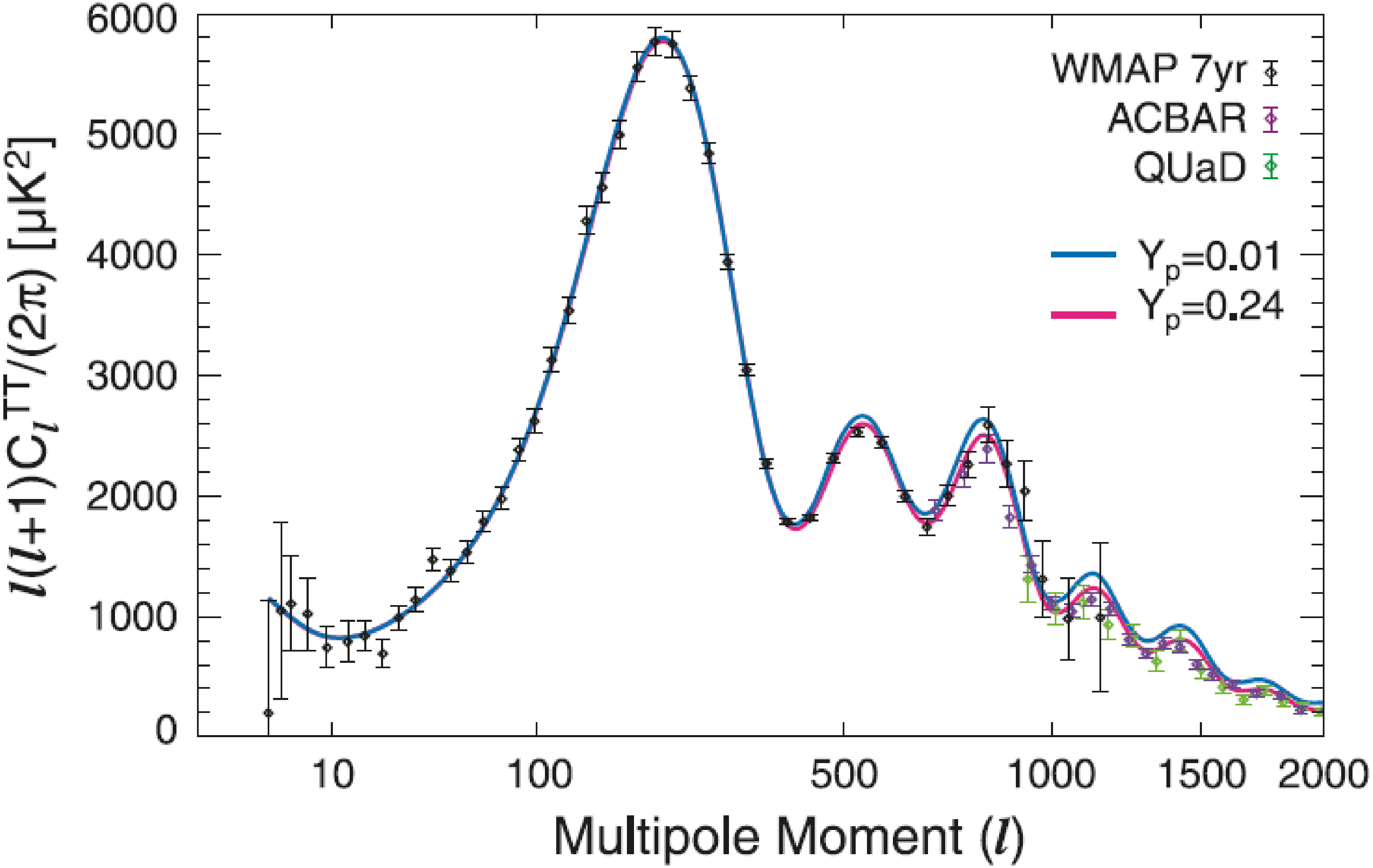
$N_{eff} < 4$ at 95 % c.l.

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





Small scale CMB also probes 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.

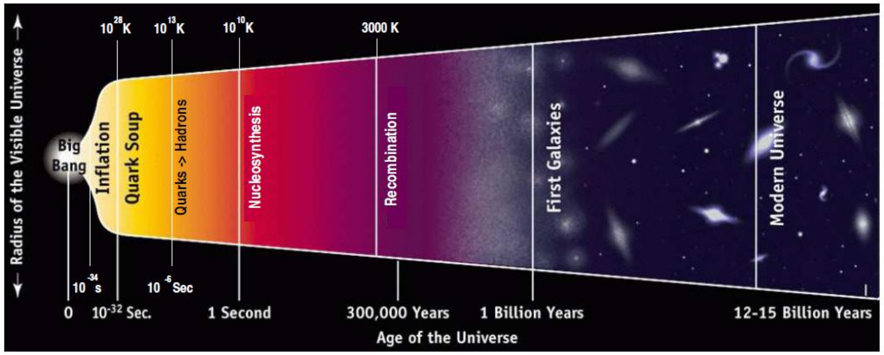
– Prior to recombination, Thomson scattering efficient and mean free path short cf. expansion time

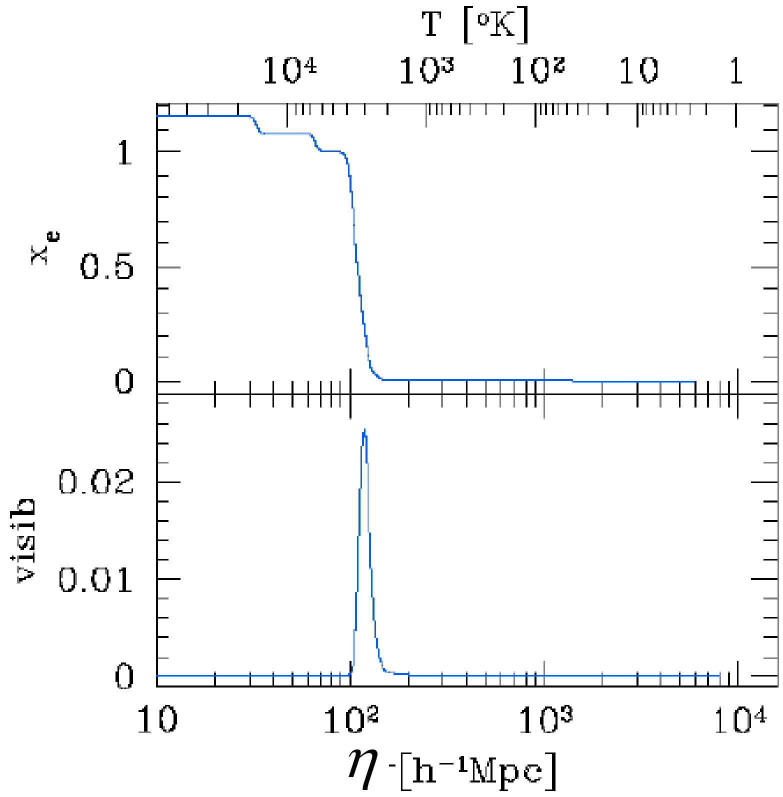
– Little chance of scattering after recombination ! photons free stream keeping imprint of conditions on last scattering surface

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

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

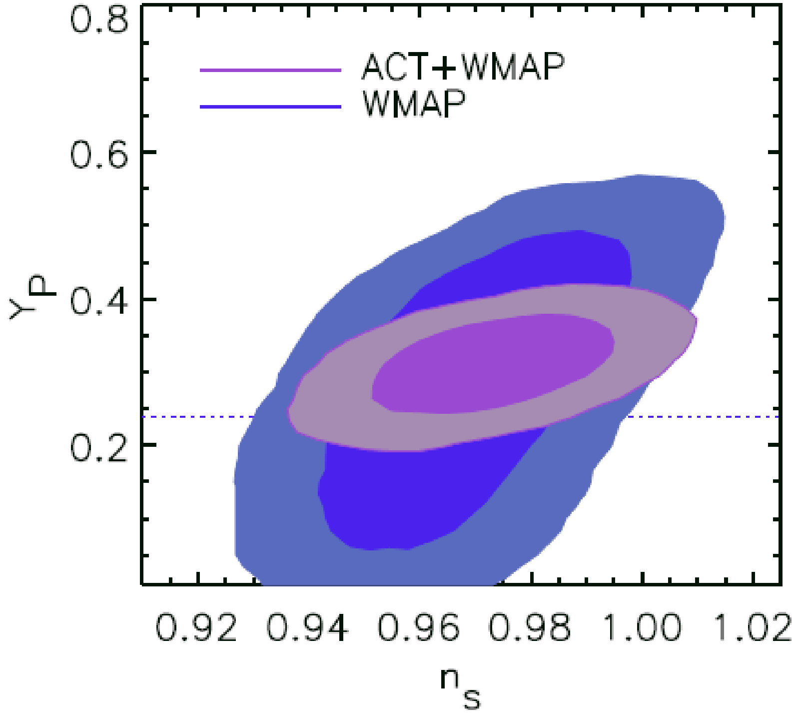
- The visibility function $-\dot{\tau}e^{-\tau}$ is the density probability of photon last scattering at time η





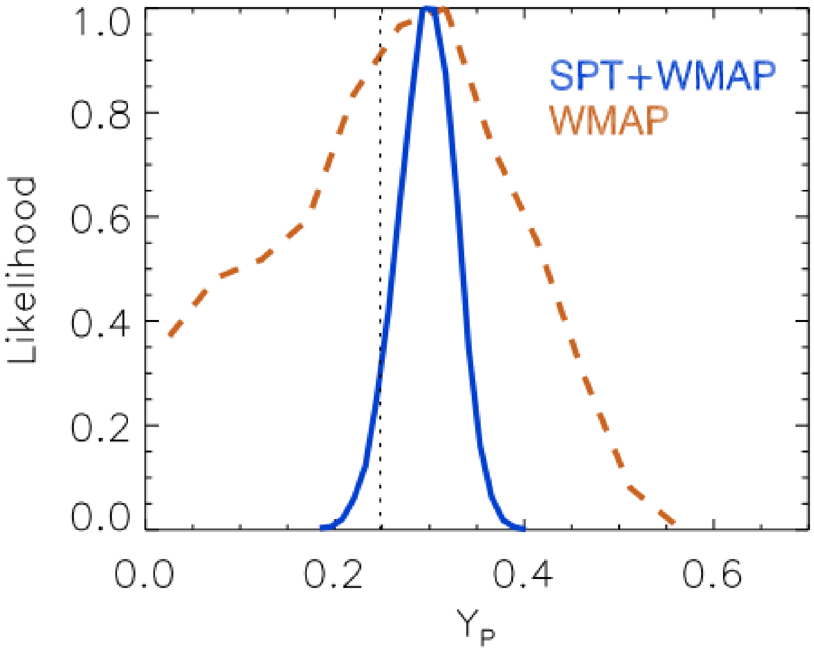
Primordial Helium: Current Status

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



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

$Y_P = 0.313 \pm 0.044$



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

$Y_P = 0.296 \pm 0.030$

Probing the Neutrino Number with CMB data (now varying Helium!!)

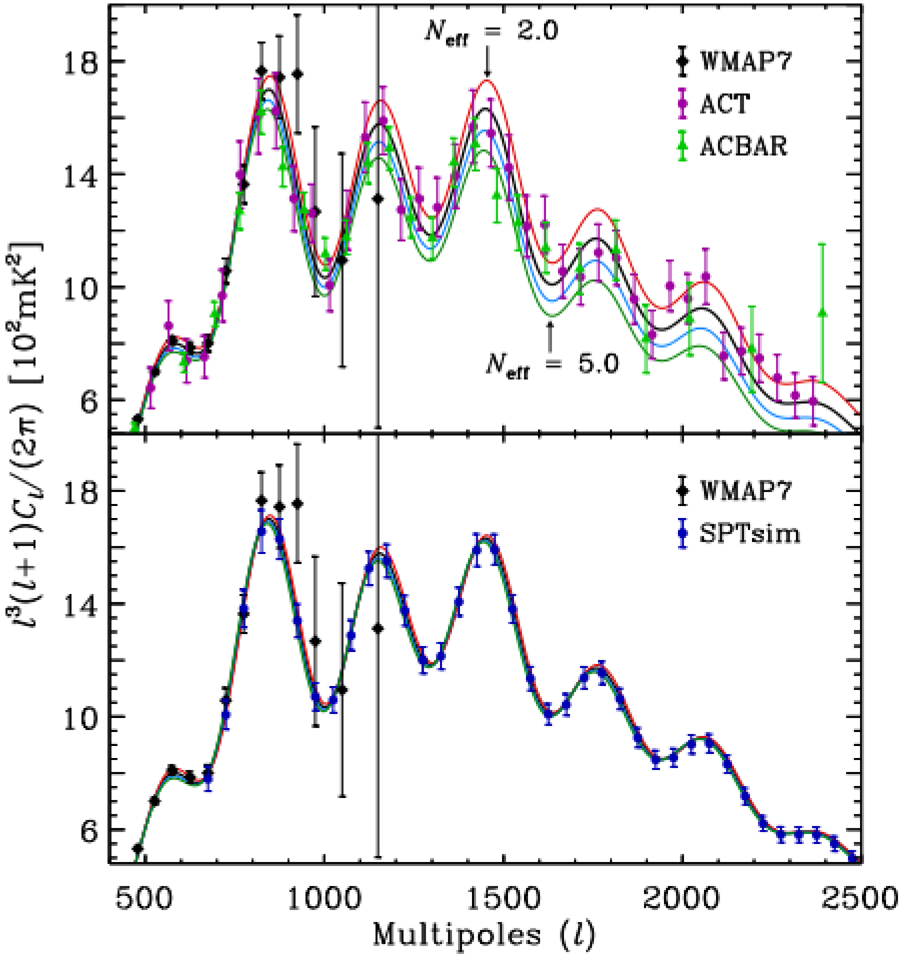
Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

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

and the damping scale at recombination:

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

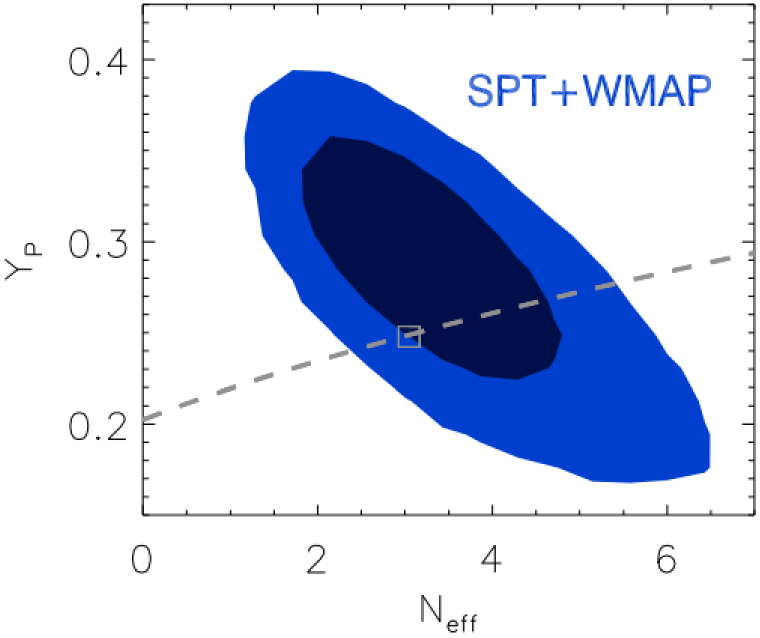
$$\theta_s = \frac{r_s}{D_A} \qquad \theta_d = \frac{r_d}{D_A}$$

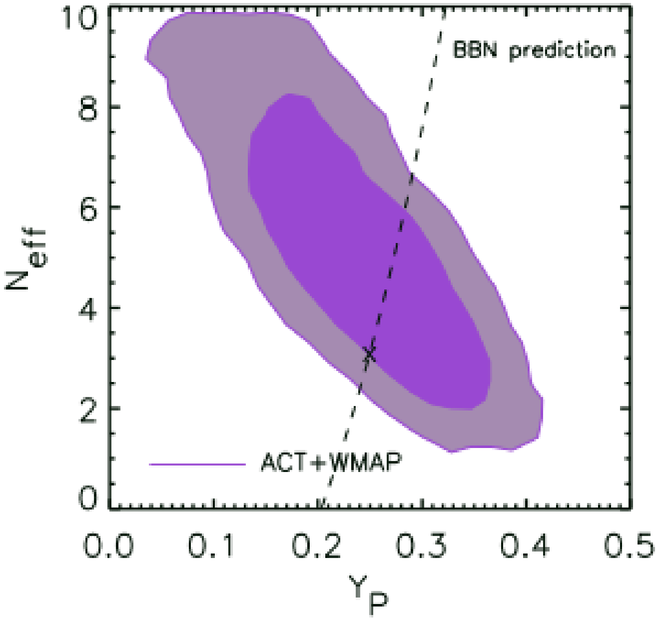


Varying Helium changes ne and can affect CMB neutrino constraints !!

Hou et al, 2011
Bowen et al, 2002

Helium-Neutrino BBN/CMB complementarity





Current bounds on Neff from CMB only data are degenerate with the Helium abundance. When consistency with BBN is assumed current evidence for dark radiation is **weaker** (but still at about two standard deviations).

Why $N_{eff}>3$ is interesting

We have 1000 ways to explain this !!!

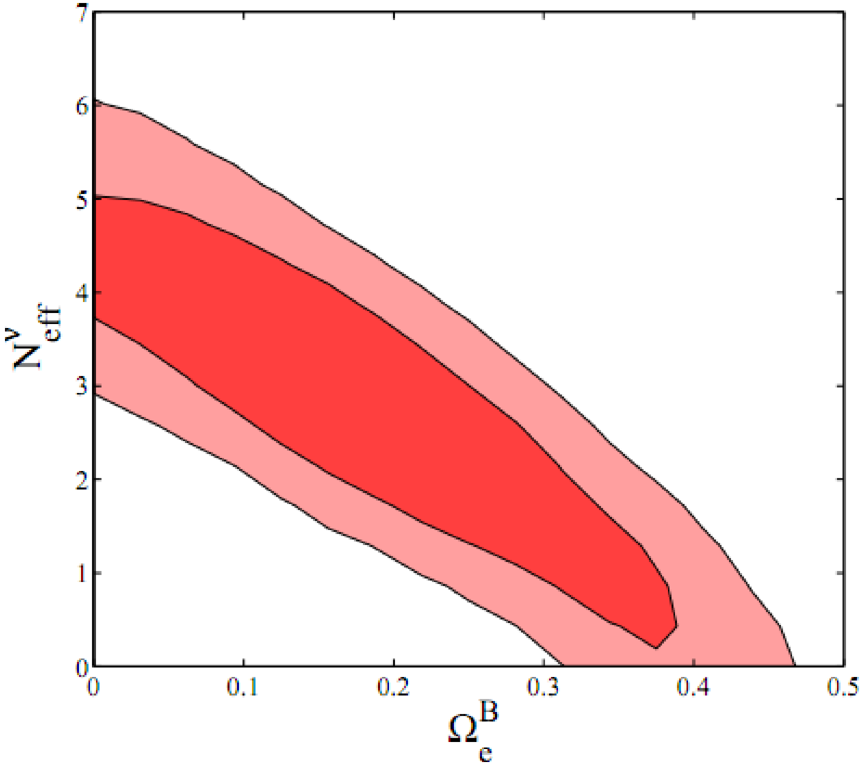
- Sterile Neutrino (hints from short base line experiments LSND, MiniBooNE).
- Non Standard Neutrino Decoupling
- Modified Gravity (Extra Dimensions)
- «Early» Dark Energy
- Gravity Waves
- Axions
- Variation of fundamental constants
- …

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 !

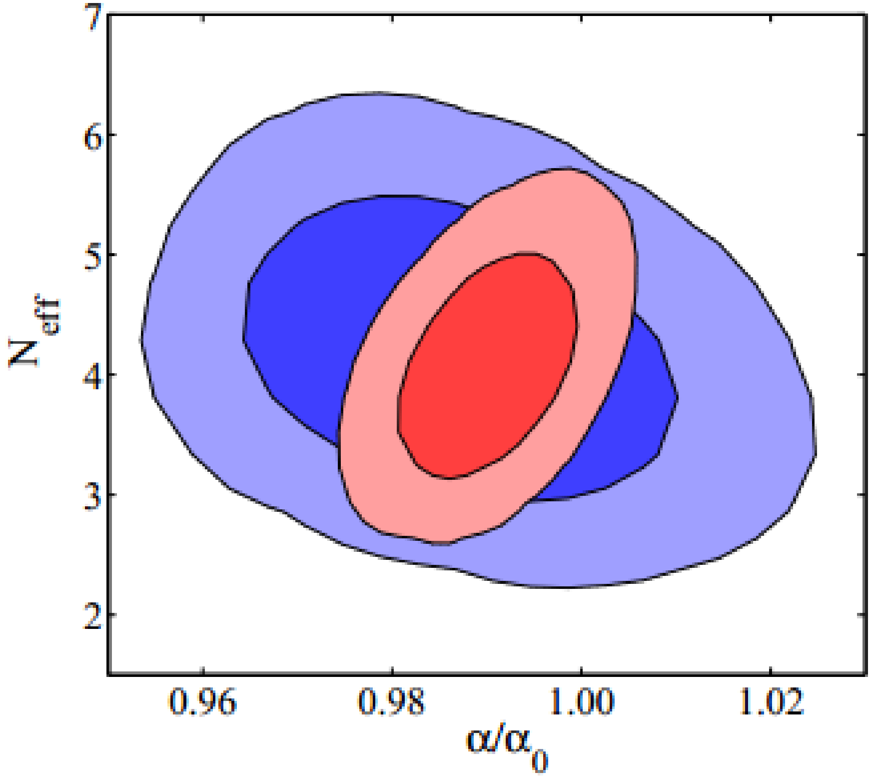
Barotropic component:

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



E. Calabrese et al, Phys.Rev.D83:123504,2011
E. Calabrese et al, Phys.Rev.D83:023011,2011

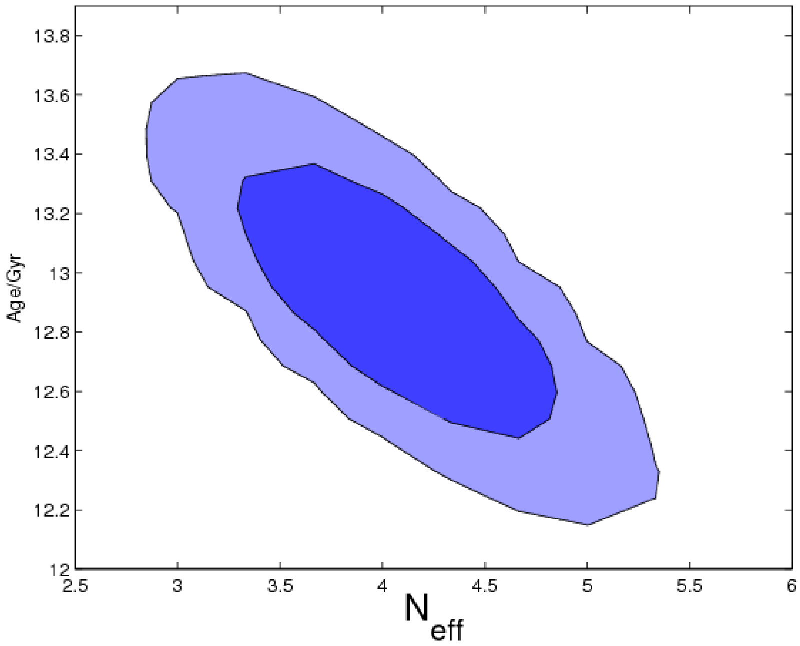
A variation in the fine structure constant at recombination ?



Red: analysis with Helium abundance fixed to Yp=0.24.
Blue: Yp is varied.

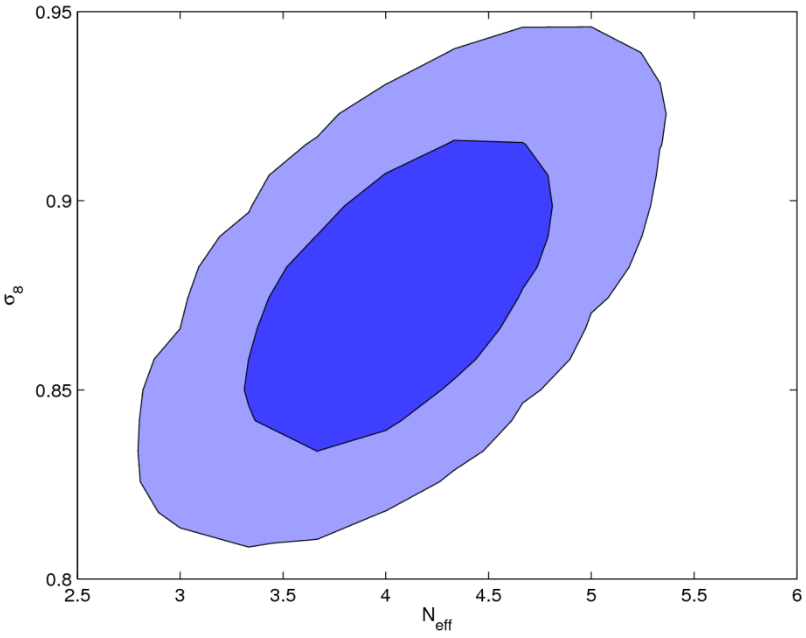
Menegoni et al, **Phys.Rev. D85 (2012) 107301**

What disfavours $N_{eff}>3$?

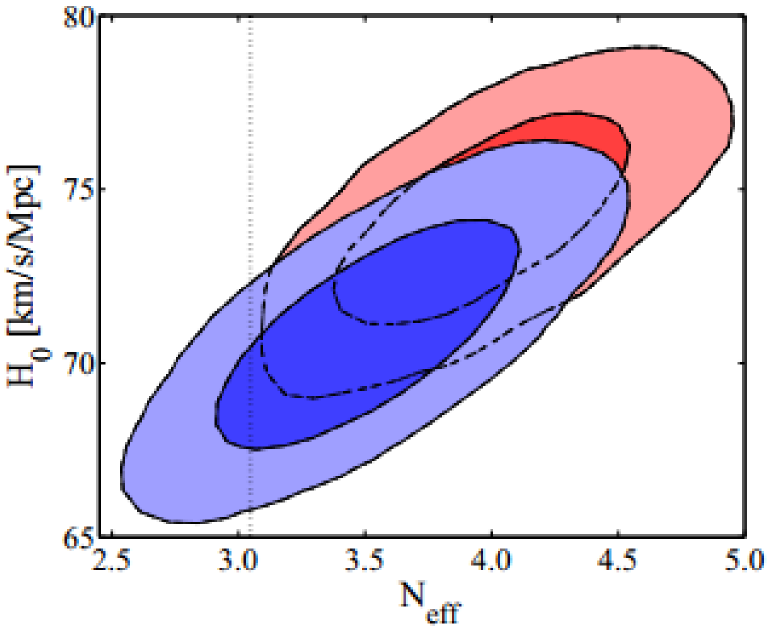


Larger values of the effective neutrino number are in better agreement with **lower** ages of the universe.
Globular clusters suggest **higher** ages.

Larger values of the effective neutrino number are in better agreement with **higher** σ_8.
Clusters abundance measurements prefer **lower** σ_8.

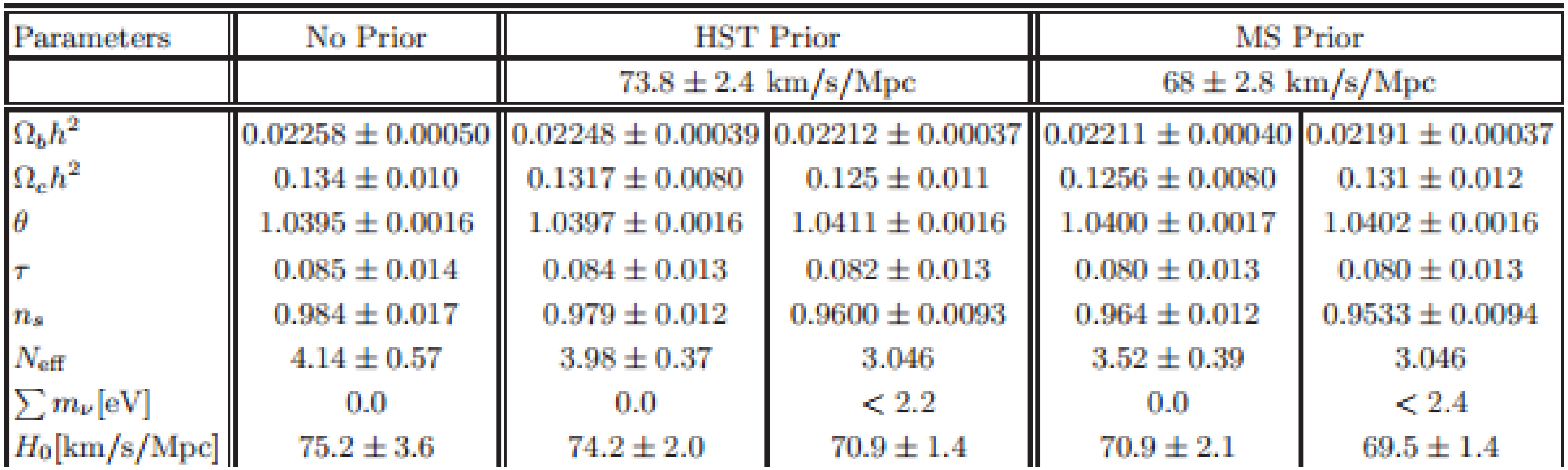


Is the HST prior driving N$_{eff}$>3 ?



The HST prior on the Hubble constant plays and important role in the current evidence for Dark Radiation.

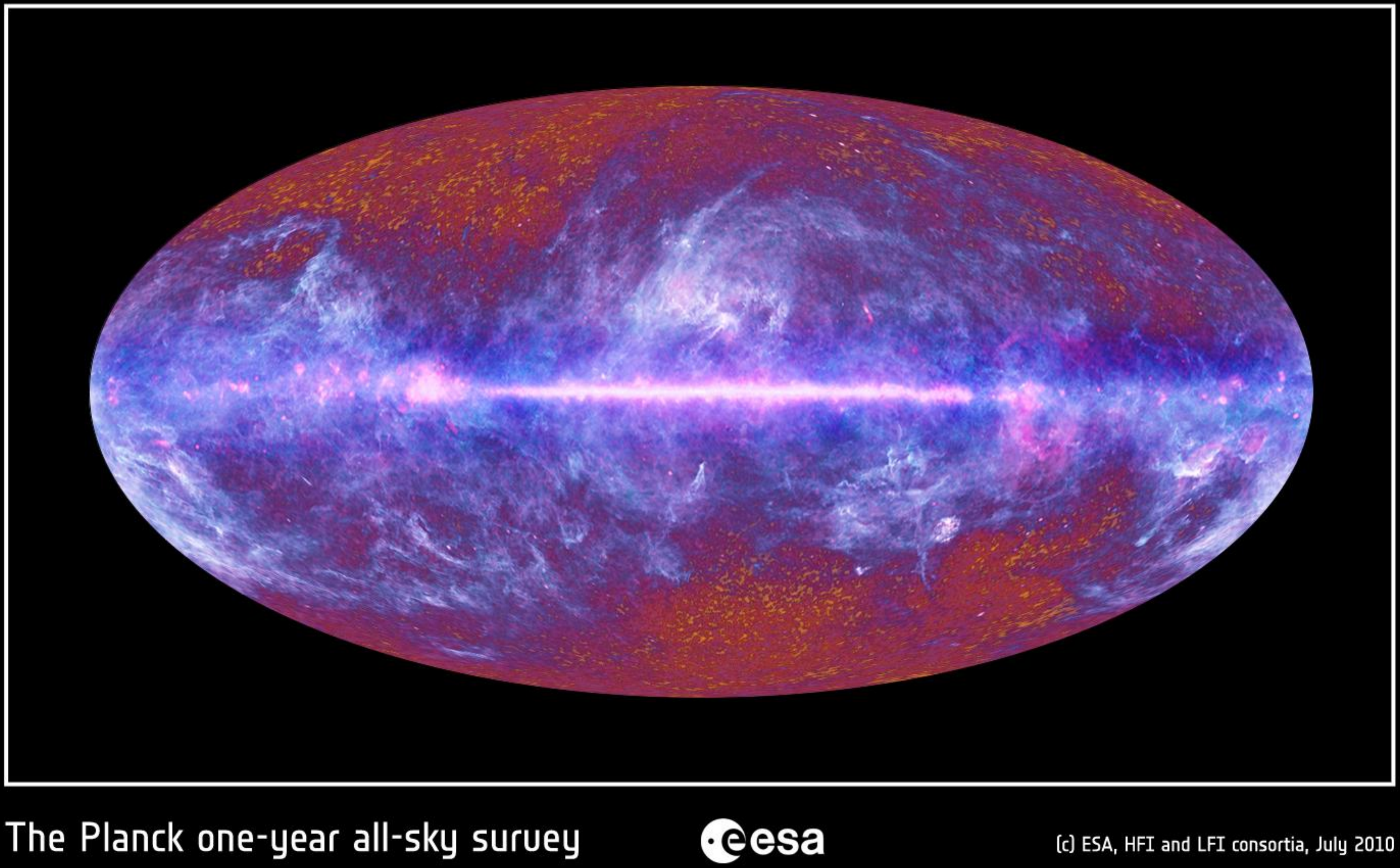
Constraints from CMB data alone on H0 are in tension with HST value when N_eff=3.046. This tension is solved when a fourth neutrino is included.
Assuming a different prior on HST, like the one coming from median statistics makes the evidence for dark energy below 2 sigma.



Parameters	No Prior	HST Prior		MS Prior	
		73.8 ± 2.4 km/s/Mpc		68 ± 2.8 km/s/Mpc	
$\Omega_b h^2$	0.02258 ± 0.00050	0.02248 ± 0.00039	0.02212 ± 0.00037	0.02211 ± 0.00040	0.02191 ± 0.00037
$\Omega_c h^2$	0.134 ± 0.010	0.1317 ± 0.0080	0.125 ± 0.011	0.1256 ± 0.0080	0.131 ± 0.012
θ	1.0395 ± 0.0016	1.0397 ± 0.0016	1.0411 ± 0.0016	1.0400 ± 0.0017	1.0402 ± 0.0016
τ	0.085 ± 0.014	0.084 ± 0.013	0.082 ± 0.013	0.080 ± 0.013	0.080 ± 0.013
n_s	0.984 ± 0.017	0.979 ± 0.012	0.9600 ± 0.0093	0.964 ± 0.012	0.9533 ± 0.0094
$N_{\rm eff}$	4.14 ± 0.57	3.98 ± 0.37	3.046	3.52 ± 0.39	3.046
$\sum m_\nu$[eV]	0.0	0.0	< 2.2	0.0	< 2.4
H_0[km/s/Mpc]	75.2 ± 3.6	74.2 ± 2.0	70.9 ± 1.4	70.9 ± 2.1	69.5 ± 1.4

Calabrese et al., 2012, **arXiv:1205.6753**

Planck
Satellite launch
14/5/2009

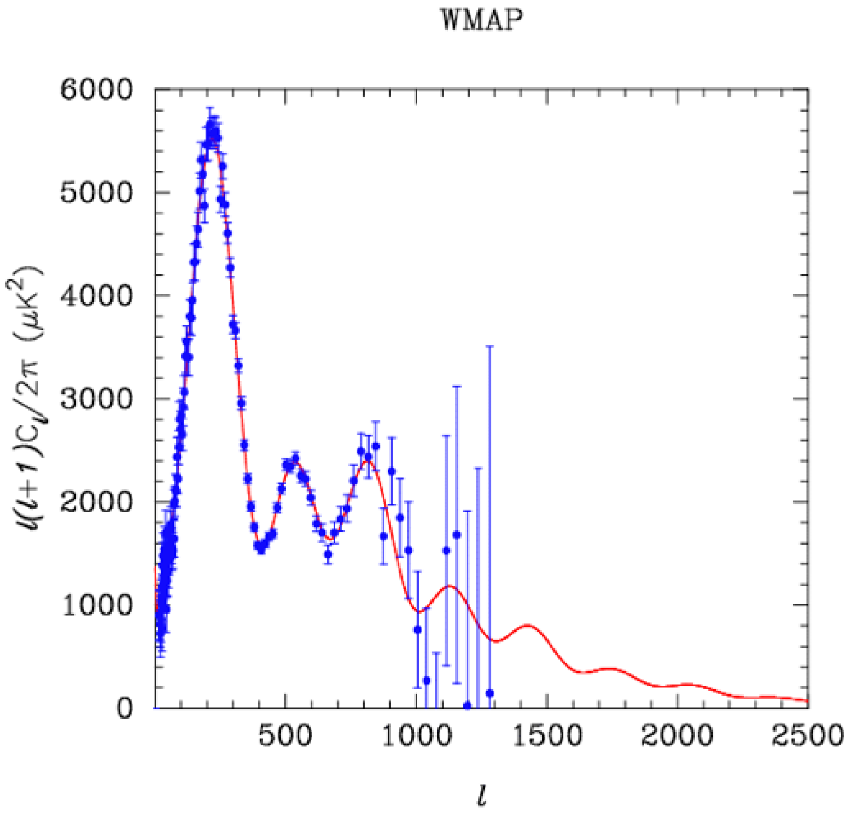


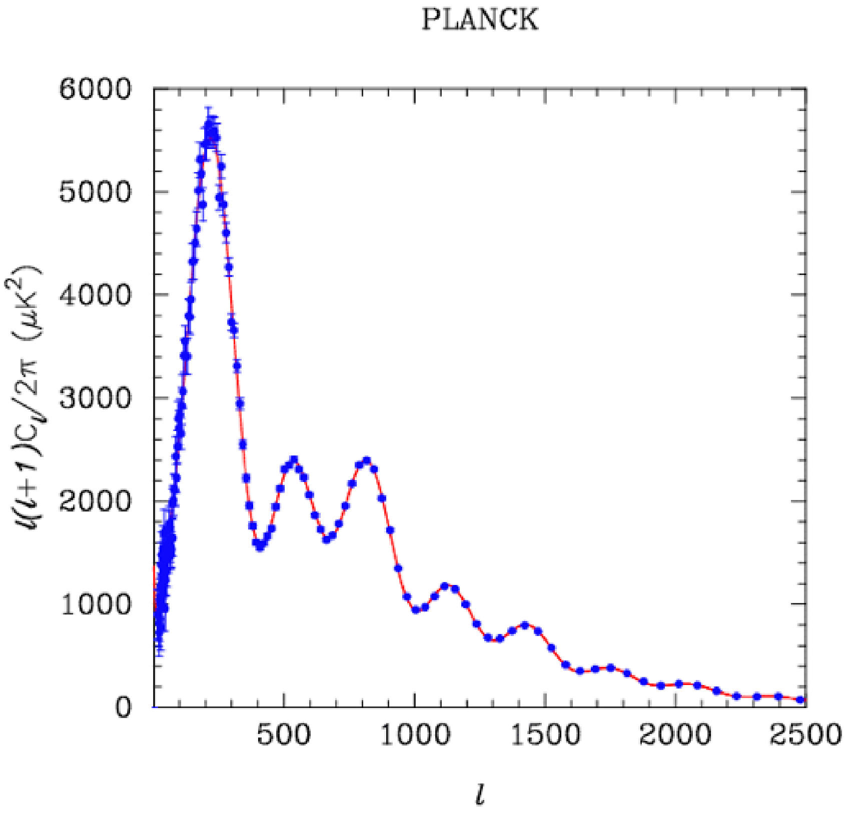
The Planck one-year all-sky survey

(c) ESA, HFI and LFI consortia, July 2010

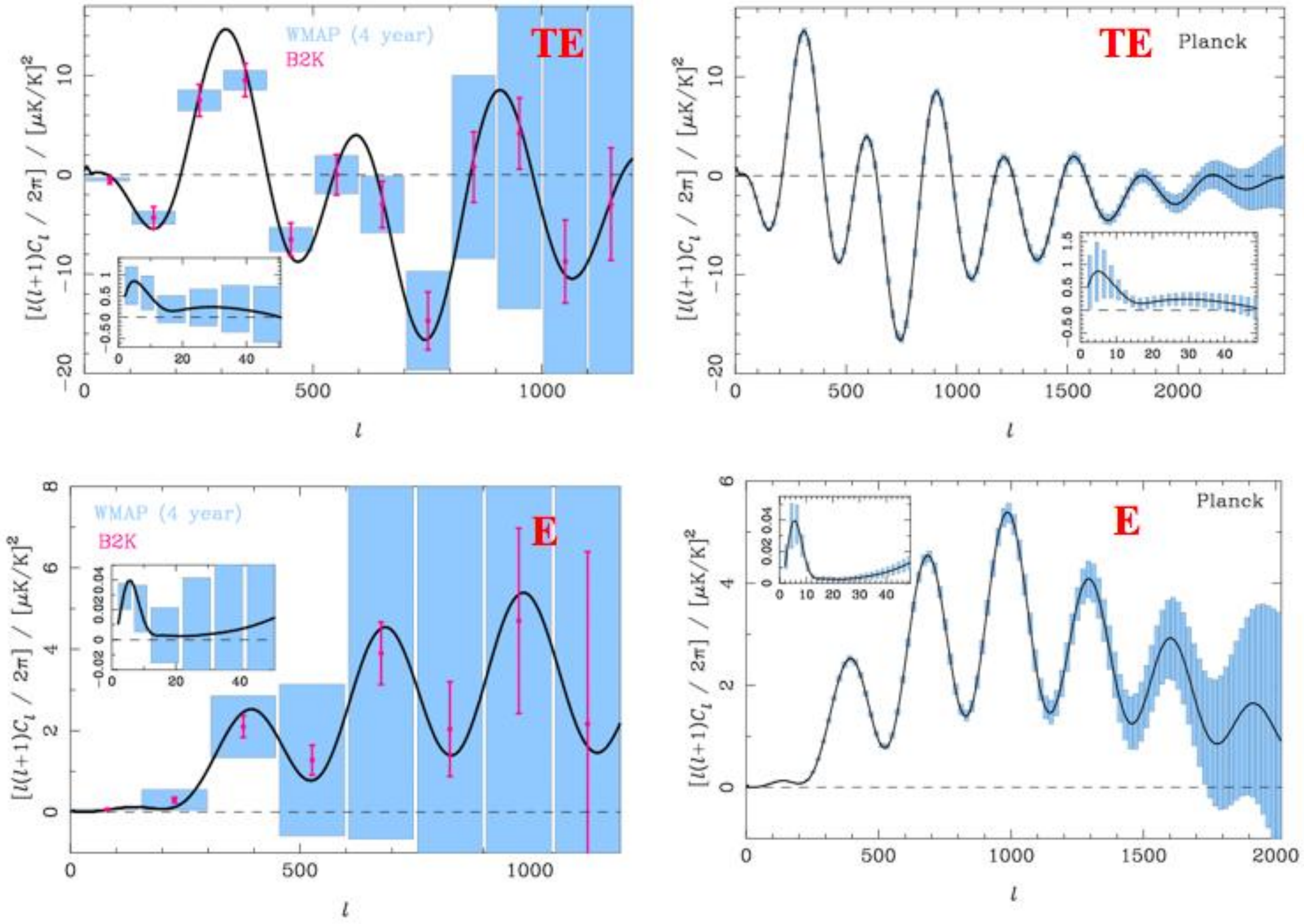
First all-sky map (after 17 years Planck proposal accepted by ESA!)

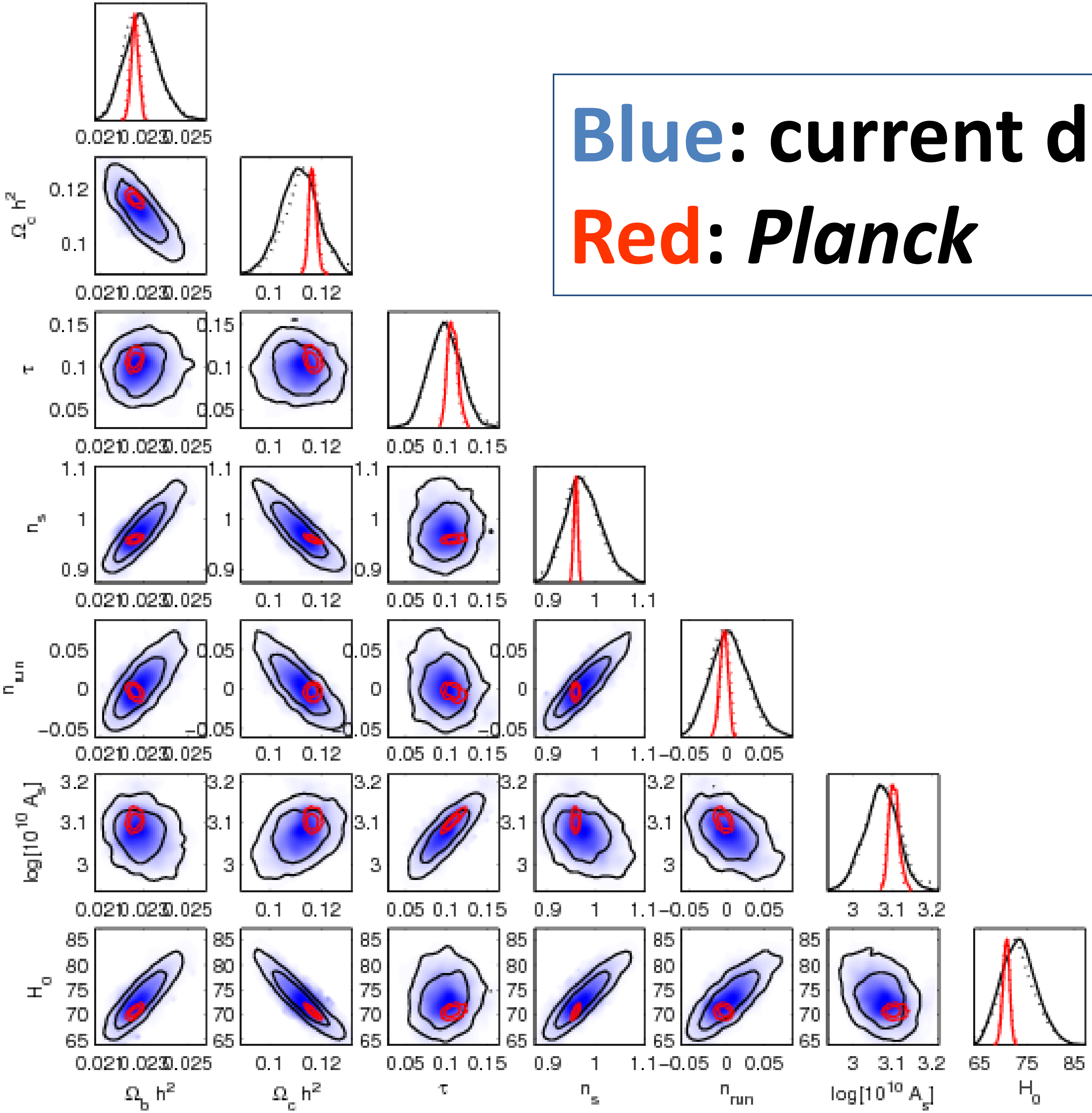
Expected improvement on TT respect to WMAP (Real data in January 2013)





Expected improvement on TE and EE respect to WMAP (real data in January 2013 o 2014)

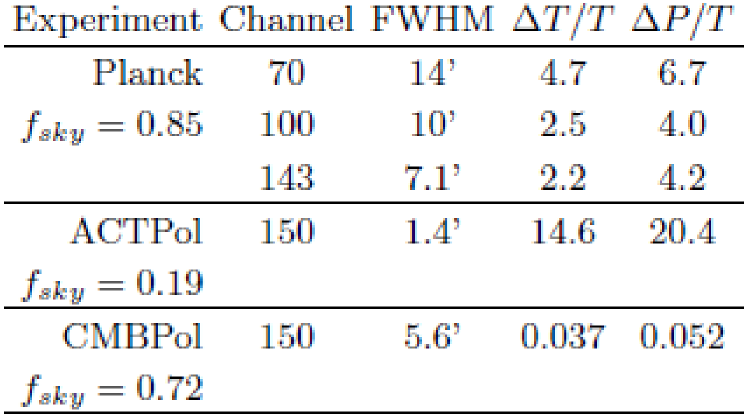




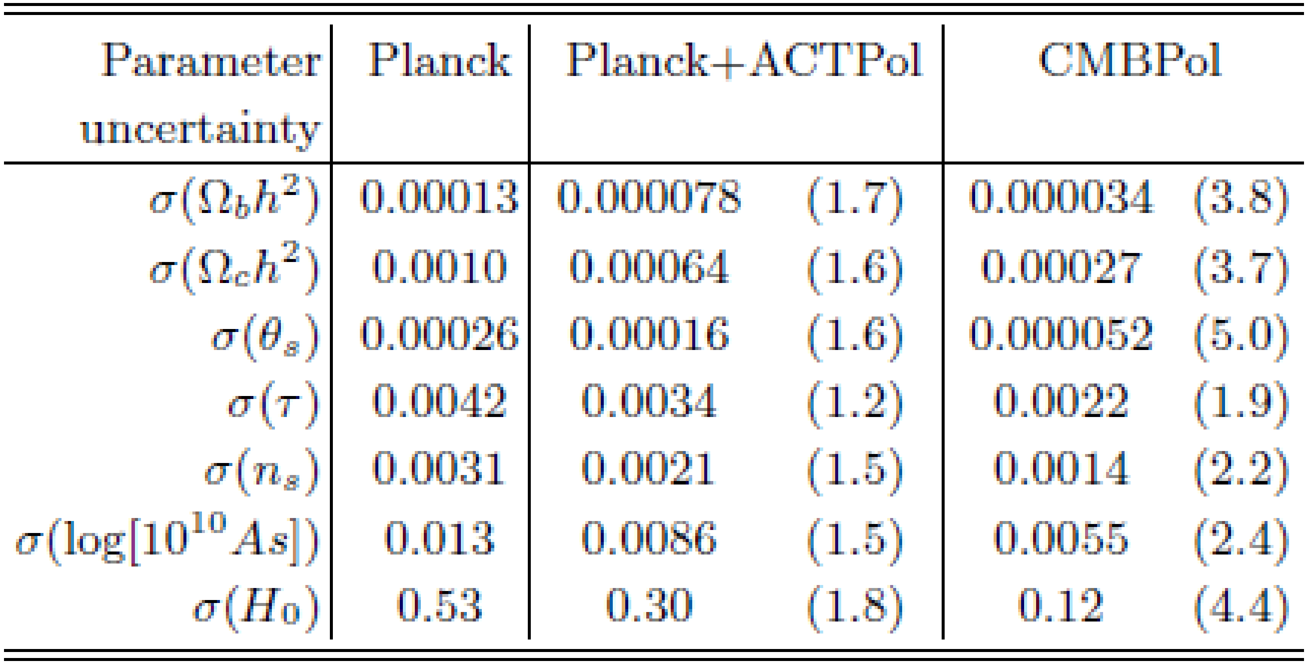
Blue: **current data**

Red: ***Planck***

Let’s consider not only Planck but also
ACTpol (From Atacama Cosmology Telescope, Ground based, results expected by 2013)
CMBpol (Next CMB satellite, 2020 ?)



Experiment	Channel	FWHM	$\Delta T/T$	$\Delta P/T$
Planck	70	14’	4.7	6.7
$f_{sky} = 0.85$	100	10’	2.5	4.0
	143	7.1’	2.2	4.2
ACTPol	150	1.4’	14.6	20.4
$f_{sky} = 0.19$				
CMBPol	150	5.6’	0.037	0.052
$f_{sky} = 0.72$				

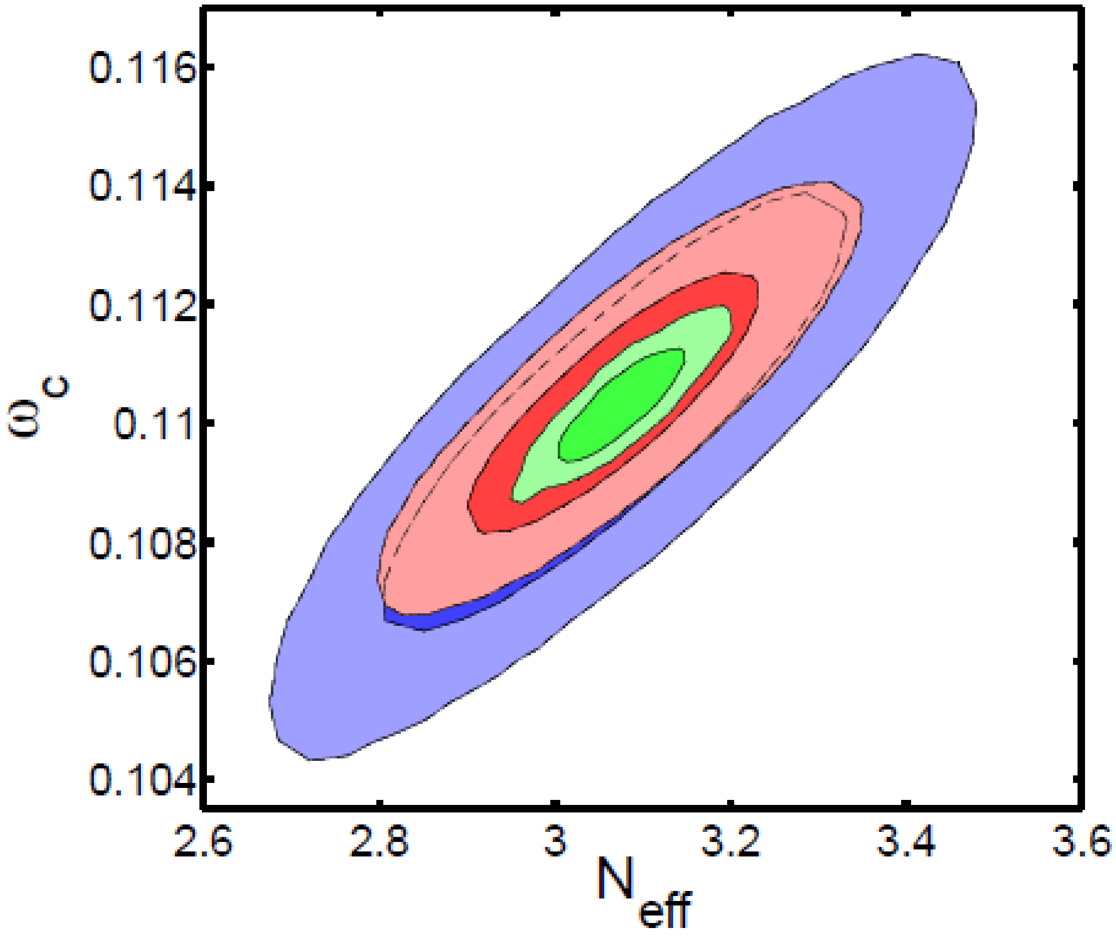


Parameter uncertainty	Planck	Planck+ACTPol		CMBPol	
$\sigma(\Omega_b h^2)$	0.00013	0.000078	(1.7)	0.000034	(3.8)
$\sigma(\Omega_c h^2)$	0.0010	0.00064	(1.6)	0.00027	(3.7)
$\sigma(\theta_s)$	0.00026	0.00016	(1.6)	0.000052	(5.0)
$\sigma(\tau)$	0.0042	0.0034	(1.2)	0.0022	(1.9)
$\sigma(n_s)$	0.0031	0.0021	(1.5)	0.0014	(2.2)
$\sigma(\log[10^{10} As])$	0.013	0.0086	(1.5)	0.0055	(2.4)
$\sigma(H_0)$	0.53	0.30	(1.8)	0.12	(4.4)

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys.Rev.D82:123504,2010

See also Shimon et al 2010.

Constraints on Neutrino Number



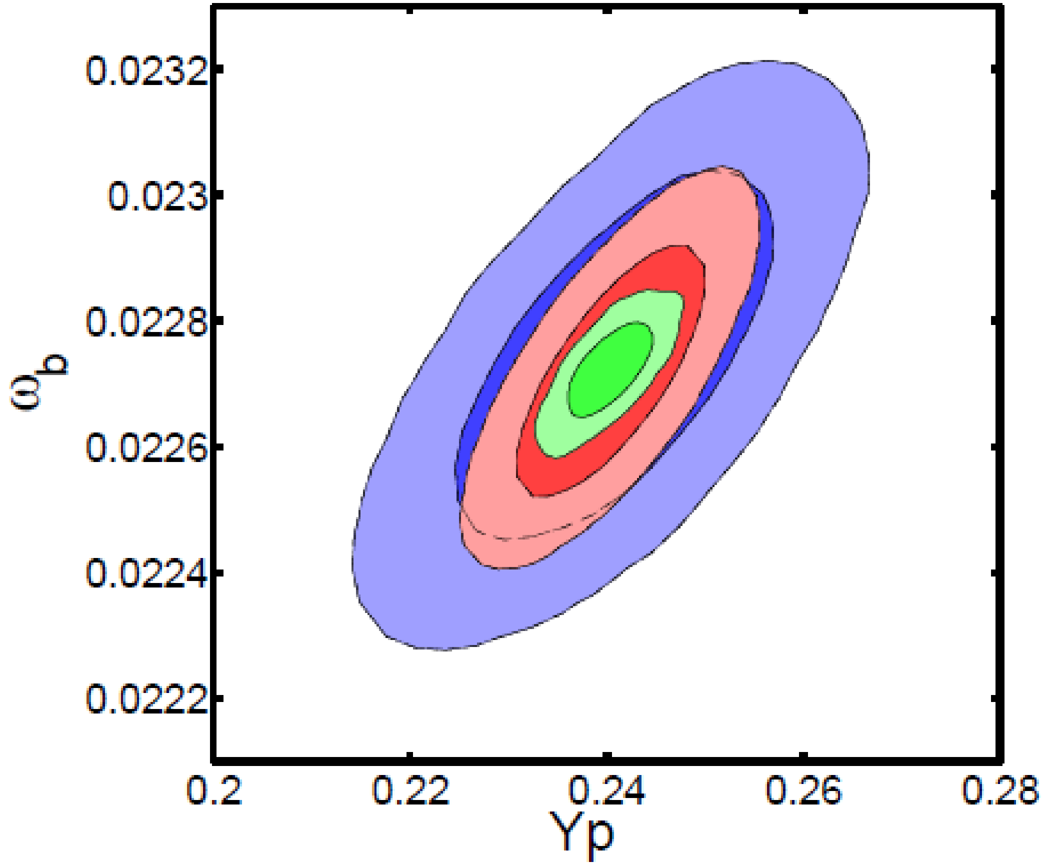
Blue: Planck $\Delta N\nu=0.18$

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

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

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys.Rev.D82:123504,2010

Constraints on Helium Abundance



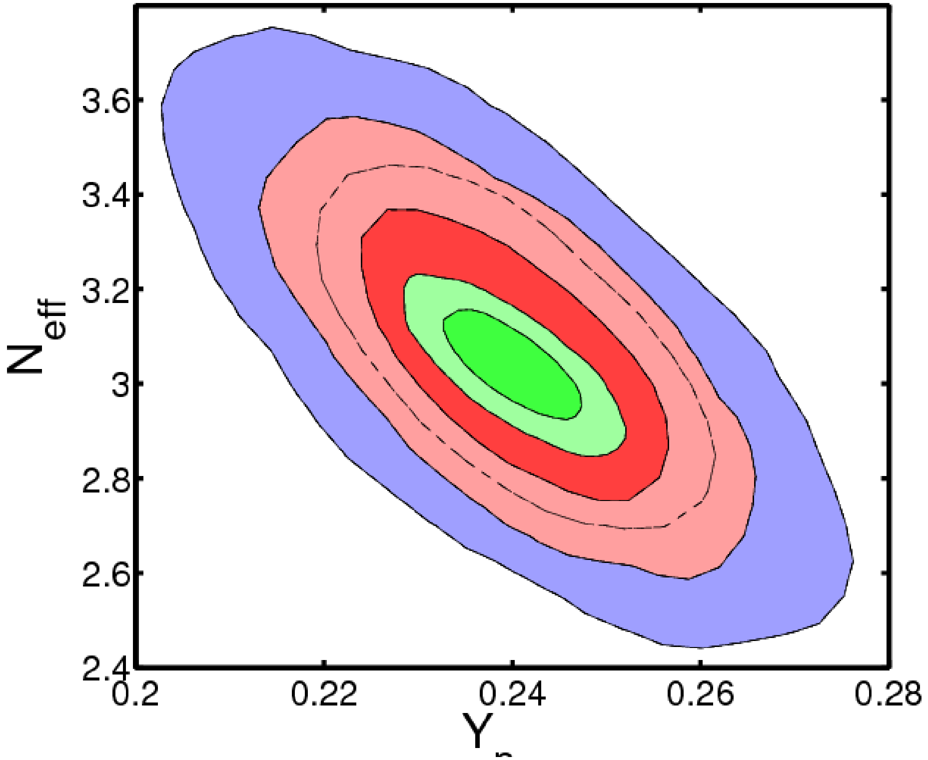
Blue: Planck $\Delta Yp=0.01$

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

Green: CMBPol $\Delta Yp=0.003$

Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys.Rev.D82:123504,2010

Constraints on Helium Abundance AND neutrino number



Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys.Rev.D82:123504,2010

CONCLUSIONS

- Recent CMB measurements fully confirm Λ-CDM.

- Hints for extra relativistic neutrino background (or something new) but HST prior is driving this result.

\- Planck experiment working as expected. Early results promising.

In early 2013 from Planck we may know:

- If the total neutrino mass is less than 0.4eV from CMB only data (assuming LCDM).
- If there is evidence for an extra background of relativistic particles in cosmological data.
- Helium abundance with 0.01 Yp accuracy.

… and much more !