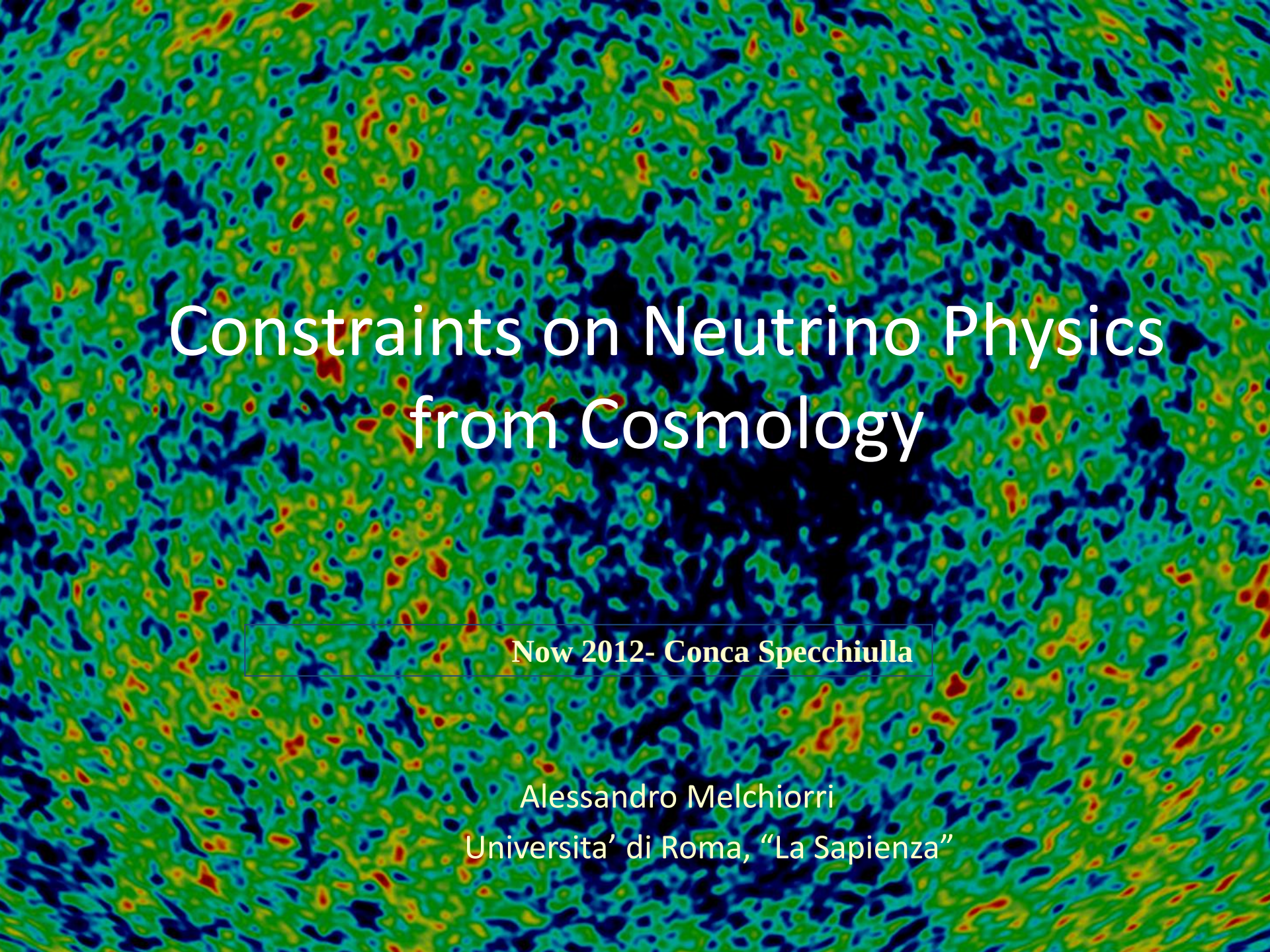


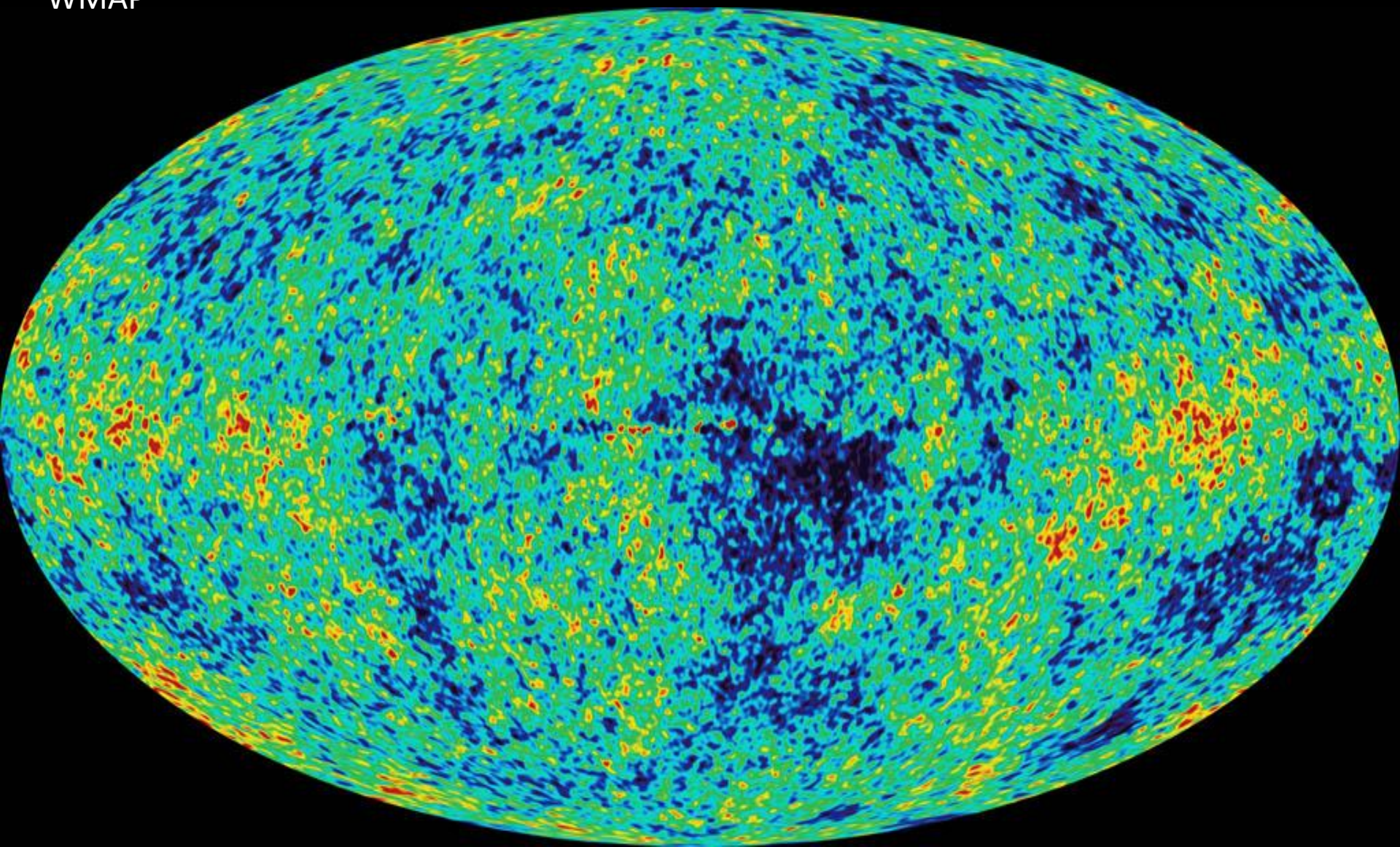
The background of the slide is a Cosmic Microwave Background (CMB) fluctuation map, showing a complex pattern of red, yellow, and blue spots against a dark background, representing temperature variations in the early universe.

Constraints on Neutrino Physics from Cosmology

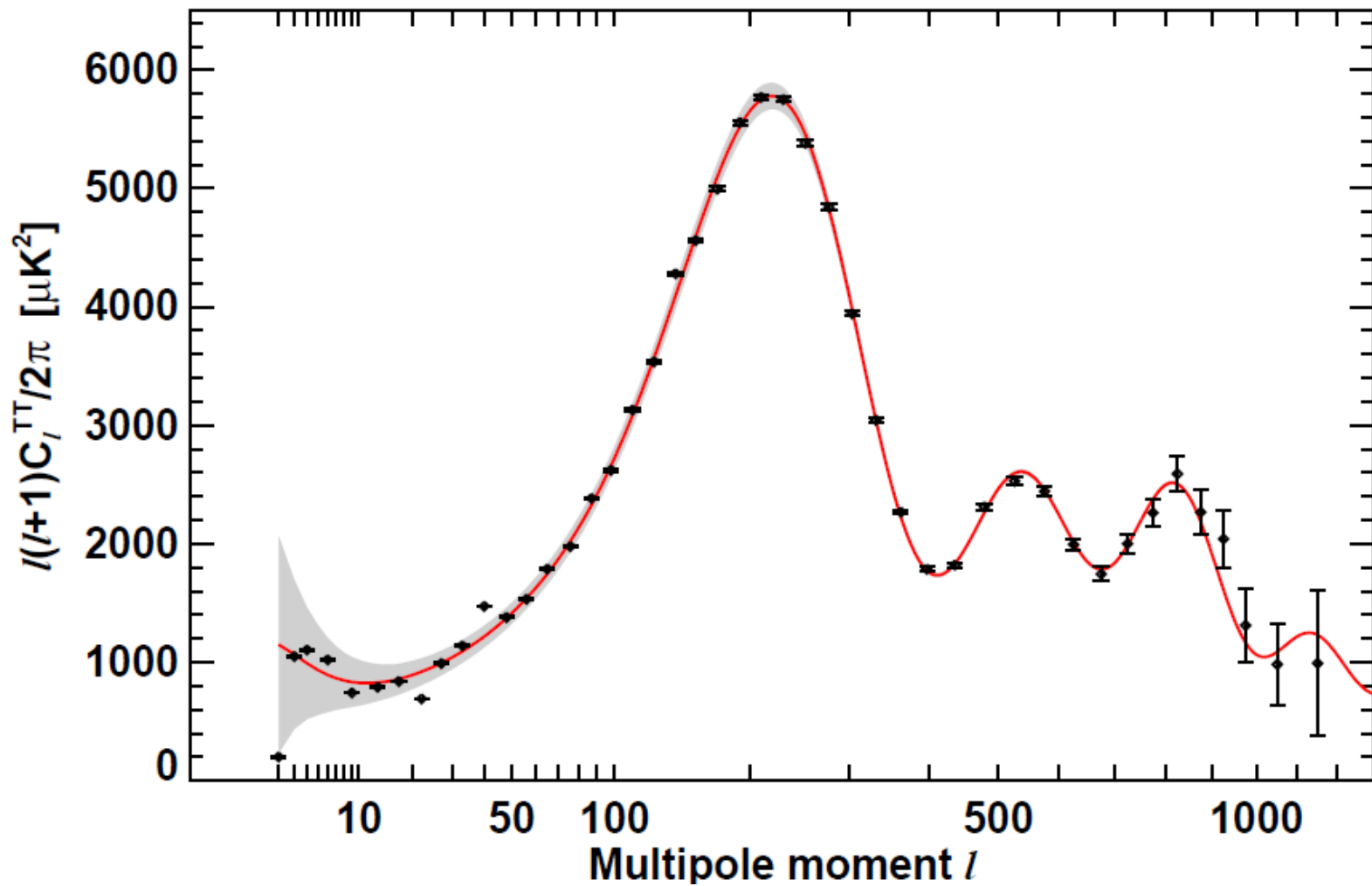
Now 2012- Conca Specchiulla

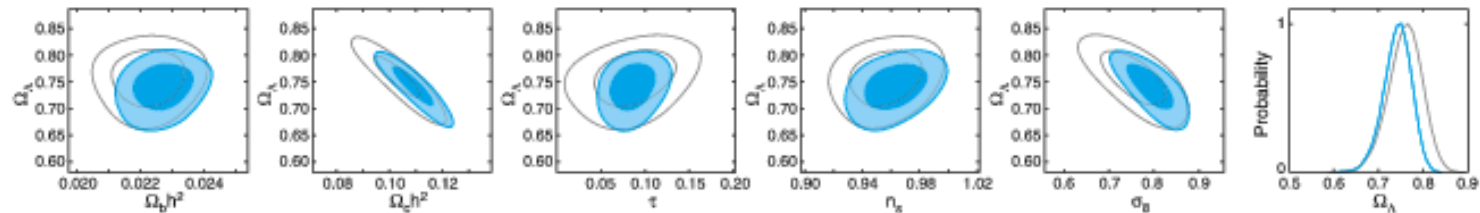
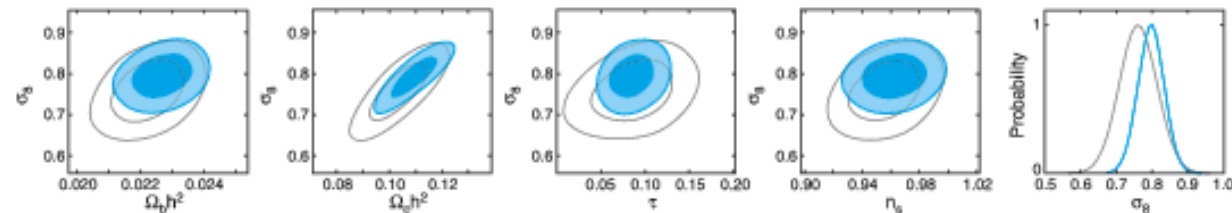
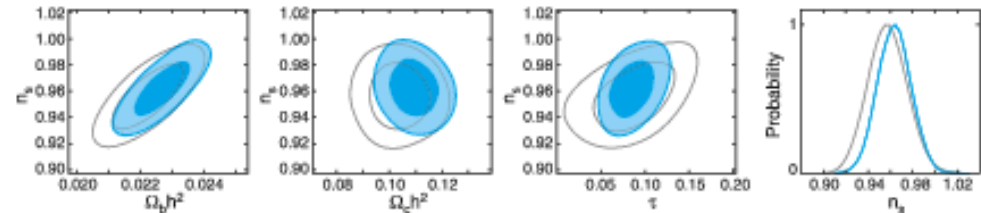
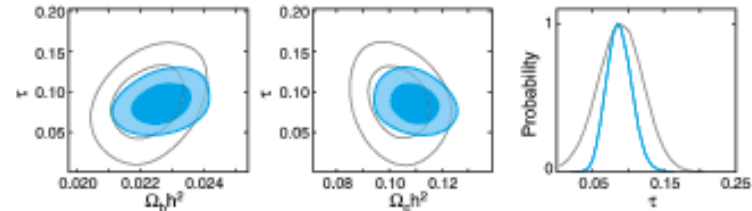
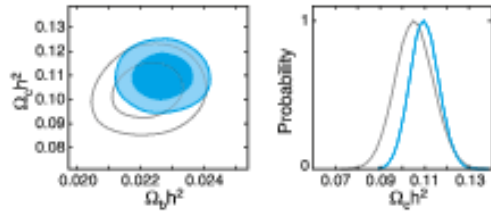
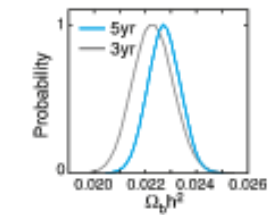
Alessandro Melchiorri
Universita' di Roma, "La Sapienza"

WMAP



New WMAP results from 7 years of observations





Parameter	3 Year Mean	5 Year Mean	5 Year Max Like
$100\Omega_b h^2$	2.229 ± 0.073	2.273 ± 0.062	2.27
$\Omega_c h^2$	0.1054 ± 0.0078	0.1099 ± 0.0062	0.108
Ω_Λ	0.759 ± 0.034	0.742 ± 0.030	0.751
n_s	0.958 ± 0.016	$0.963^{+0.014}_{-0.015}$	0.961
τ	0.089 ± 0.030	0.087 ± 0.017	0.089
$\Delta^2_{\mathcal{R}}$	$(2.35 \pm 0.13) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$	2.41×10^{-9}
σ_8	0.761 ± 0.049	0.796 ± 0.036	0.787
Ω_m	0.241 ± 0.034	0.258 ± 0.030	0.249
$\Omega_m h^2$	0.128 ± 0.008	0.1326 ± 0.0063	0.131
H_0	$73.2^{+3.1}_{-3.2}$	$71.9^{+2.6}_{-2.7}$	72.4
z_{reion}	11.0 ± 2.6	11.0 ± 1.4	11.2
t_0	13.73 ± 0.16	13.69 ± 0.13	13.7

Dunkley et al., 2008

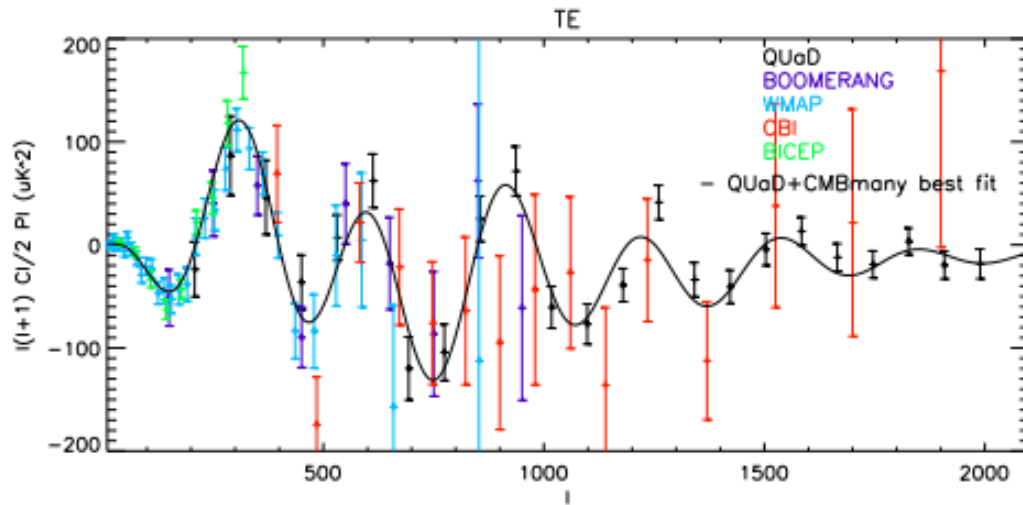
Cosmological Parameters
are fully consistent with
 Λ -CDM

From WMAP 5 to WMAP7 not much improvement...

Table 3
Six-Parameter Λ CDM 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
$\Delta_{\mathcal{R}}^2$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
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

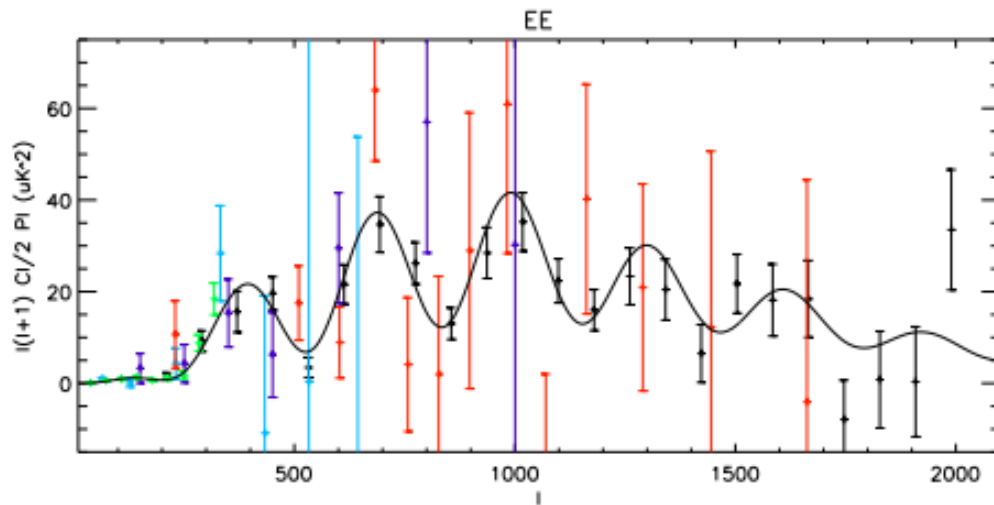
New polarization data from QUAD and BICEP experiments



QUAD, 1000 square degrees maps, observed at 43 & 95GHz.

Gupta et al,

Astrophysical Journal 716 (2010) 1 040-1046



BICEP, 2000 square degrees map, observed at 100 & 150GHz

Chiang et al,

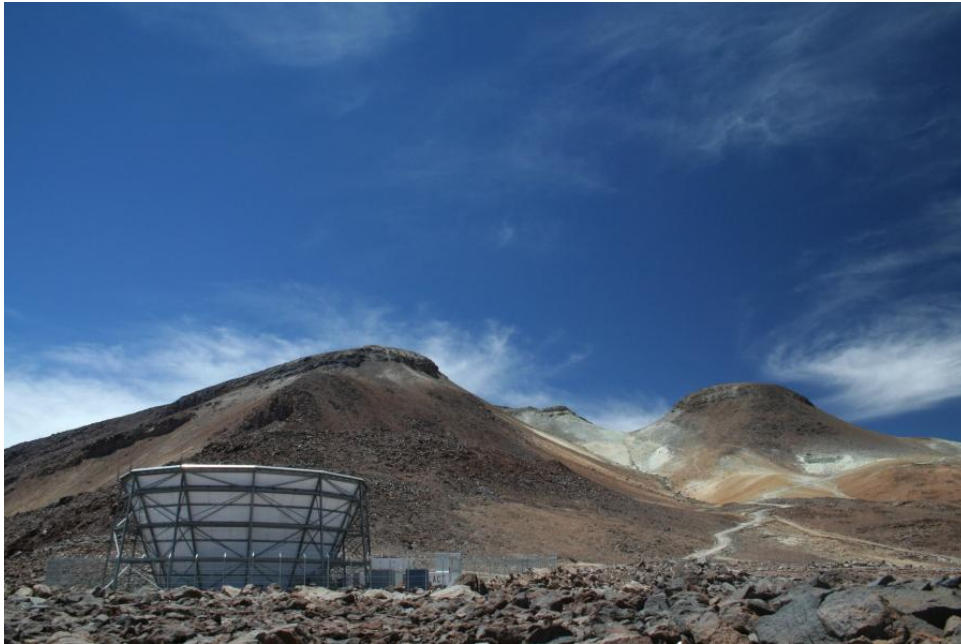
Astrophys.J.711:1123-1140,2010

Good agreement with the expectations of standard LCDM scenario.

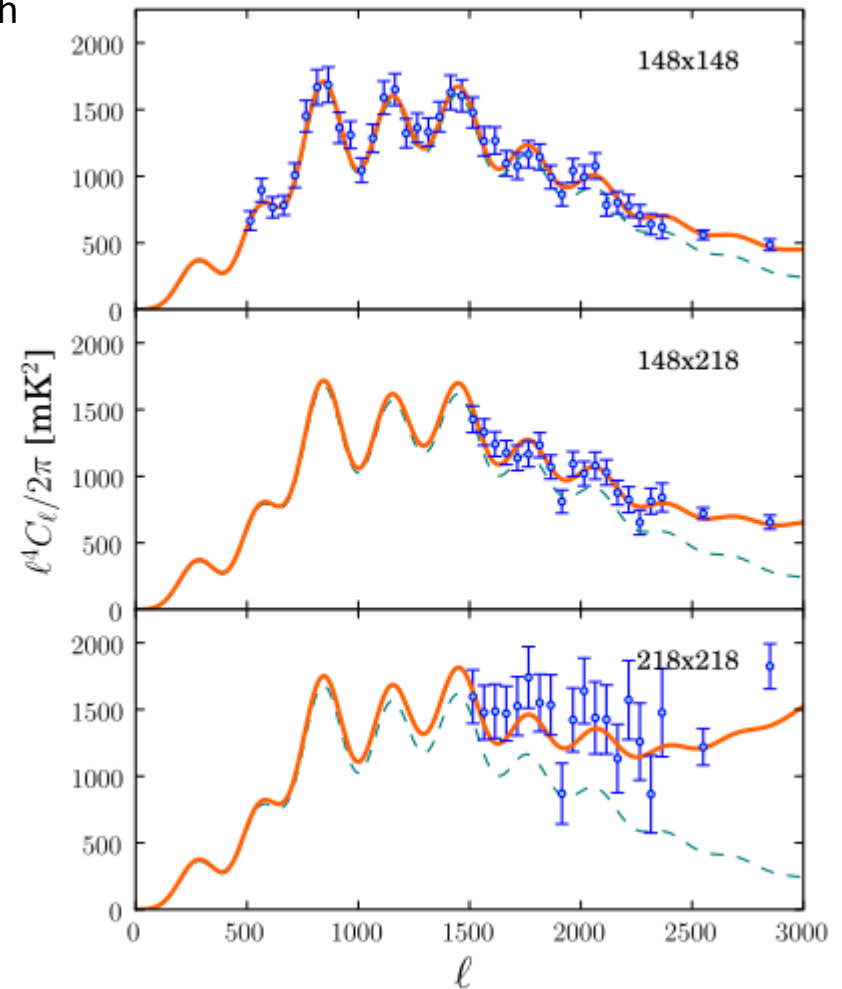
No significant improvement on parameter estimation.

New ACT results

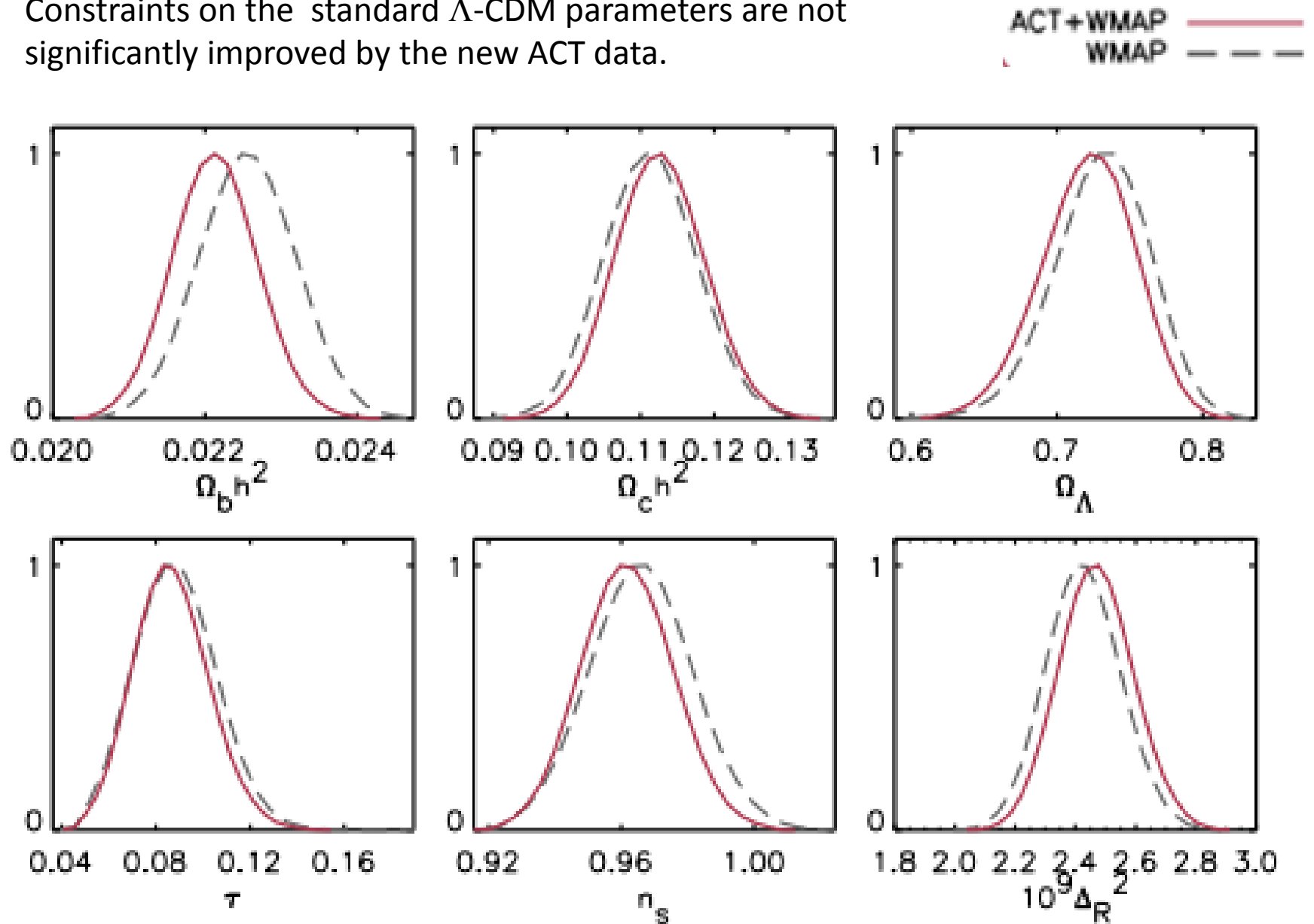
The **Atacama Cosmology Telescope (ACT)** is a six-meters telescope on Cerro Toco in the Atacama Desert in the north of Chile, at an altitude of 5190 metres.



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

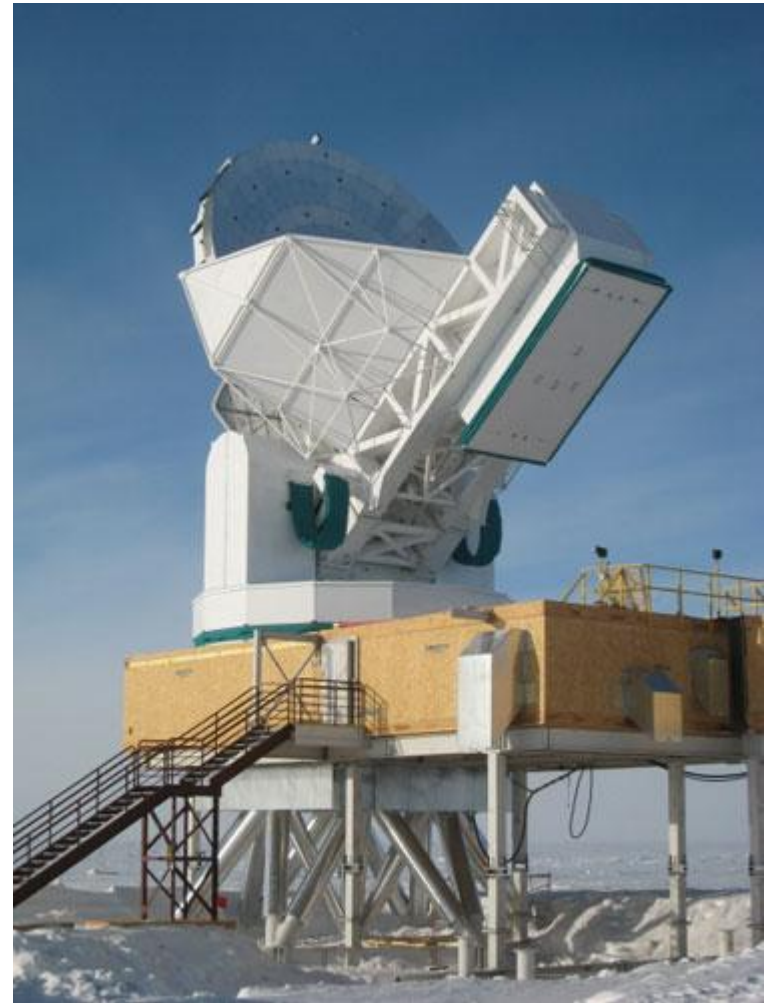
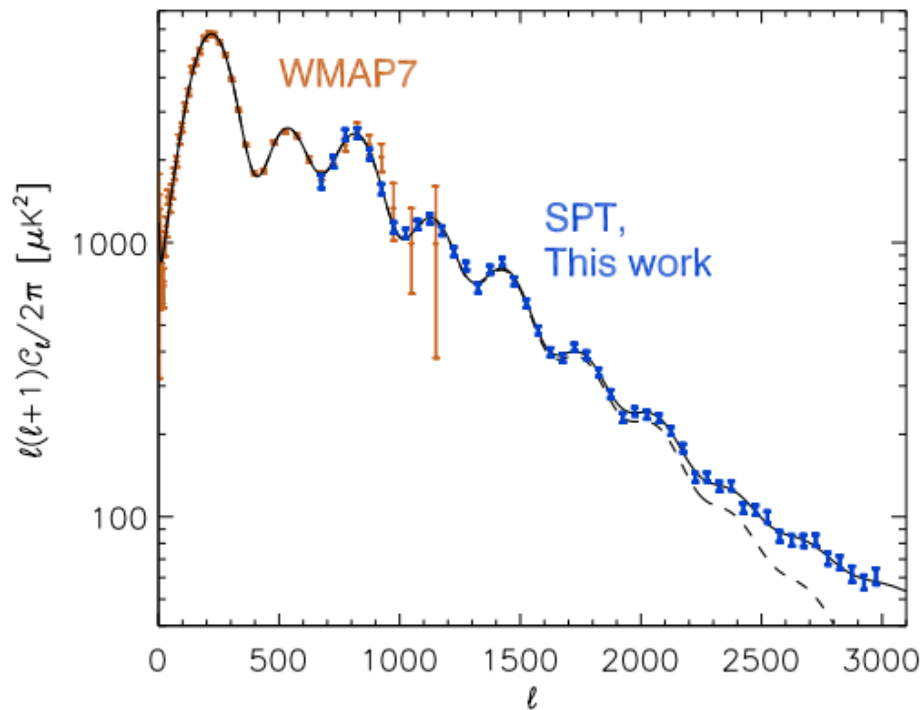


Constraints on the standard Λ -CDM parameters are not significantly improved by the new ACT data.

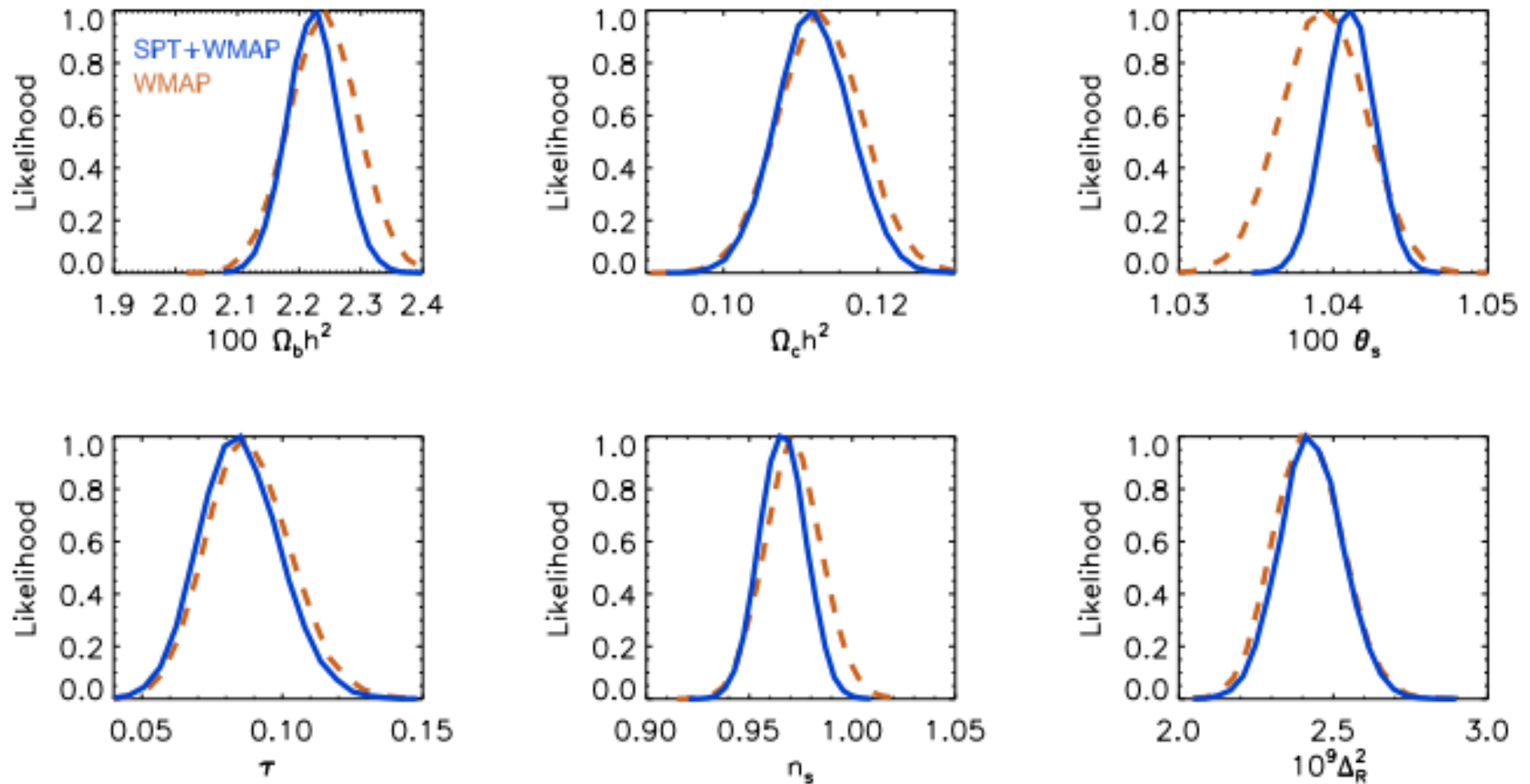


New SPT results

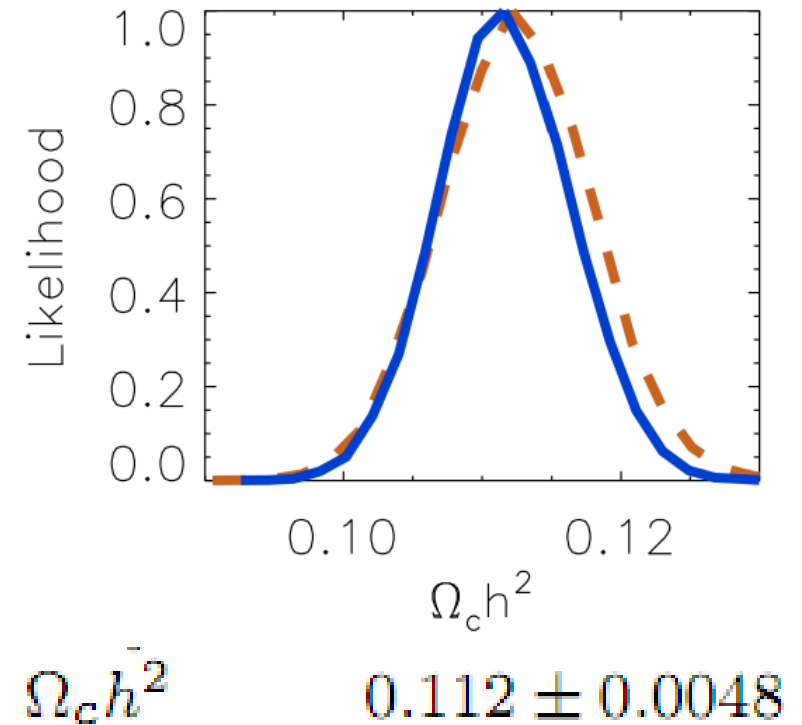
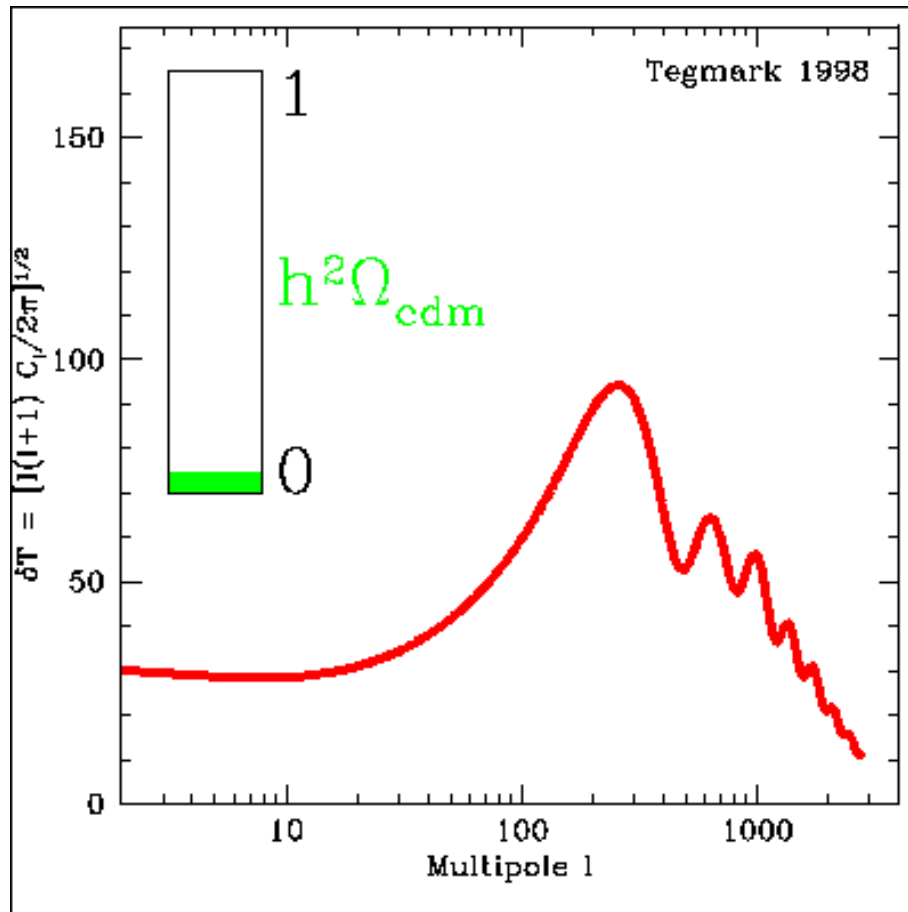
The South Pole Telescope (SPT) is a 10 meters diameter telescope located at the Amundsen-Scott South Pole Station, Antarctica. The data consist of 790 square degrees of sky observed at 90, 150 & 220 GHz.



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



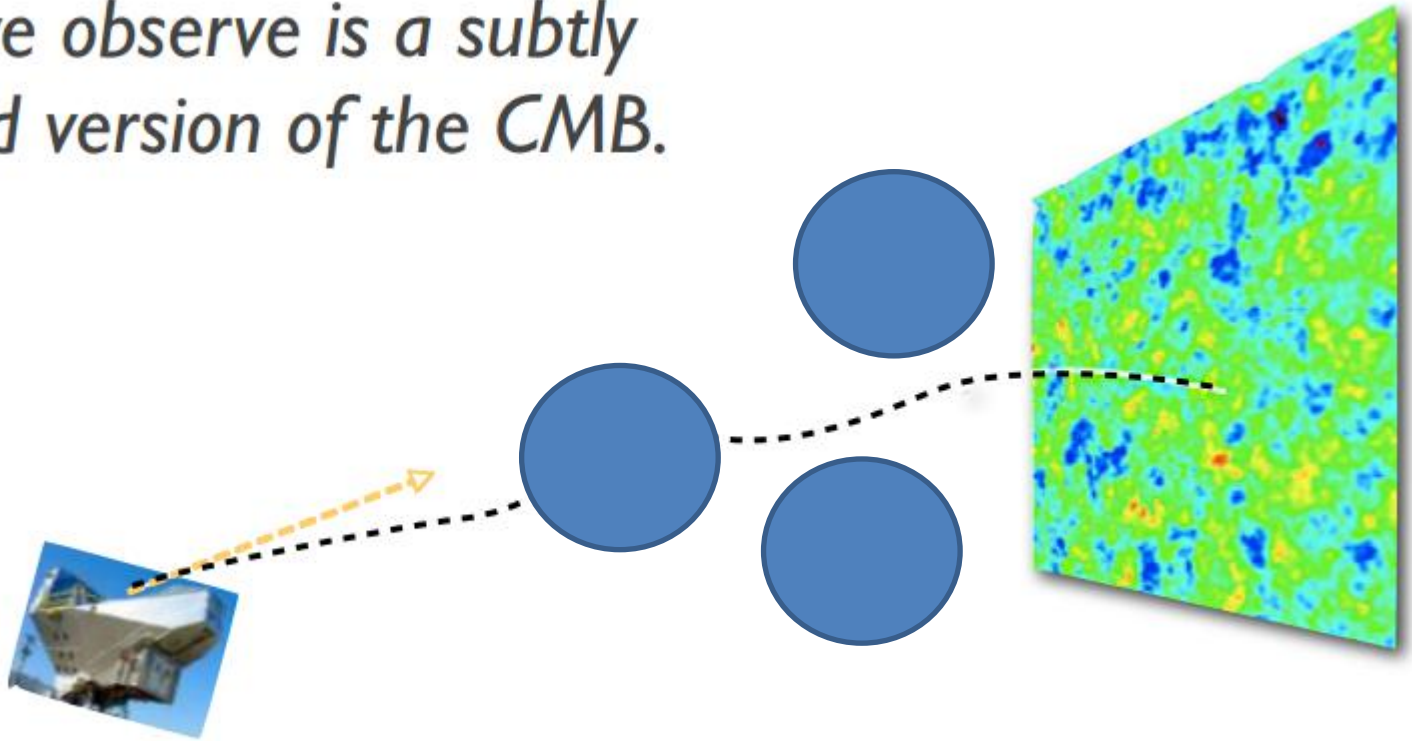
Constraints on the CDM Abundance from Current CMB data



23 sigmas
Evidence for
CDM !!

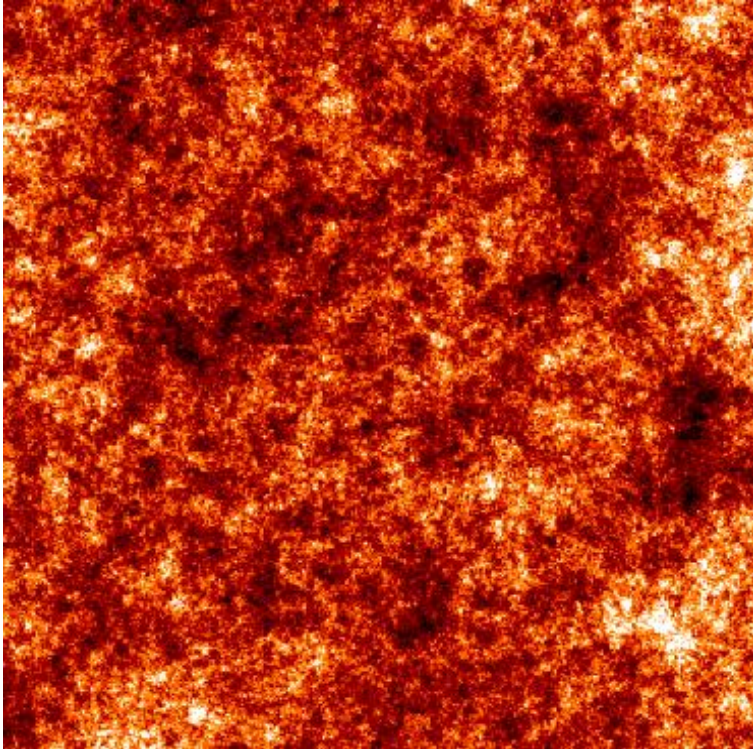
CMB Temperature Lensing

What we observe is a subtly distorted version of the CMB.

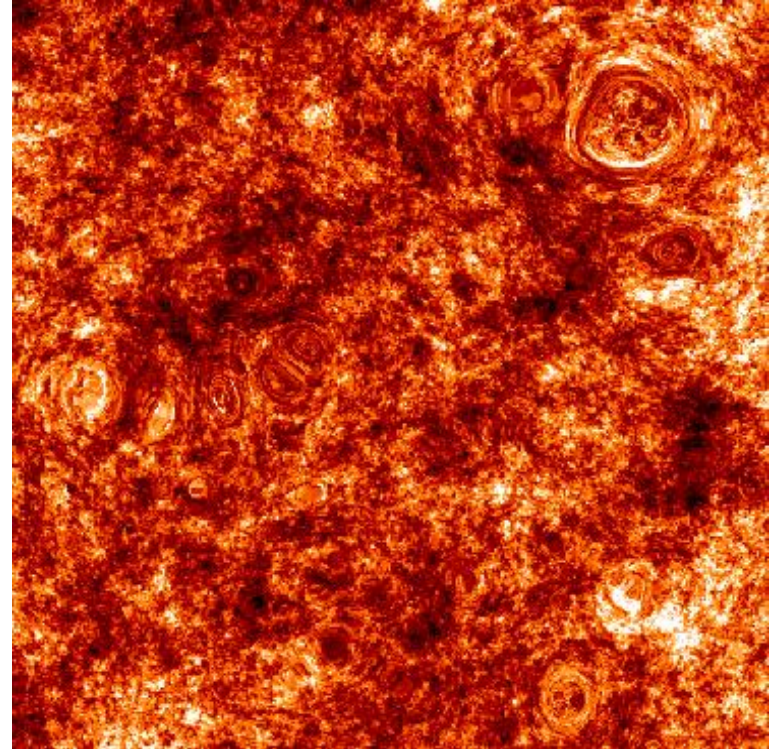


CMB Temperature Lensing

unlensed



lensed



When the luminous source is the CMB, the lensing effect essentially re-maps the temperature field according to :

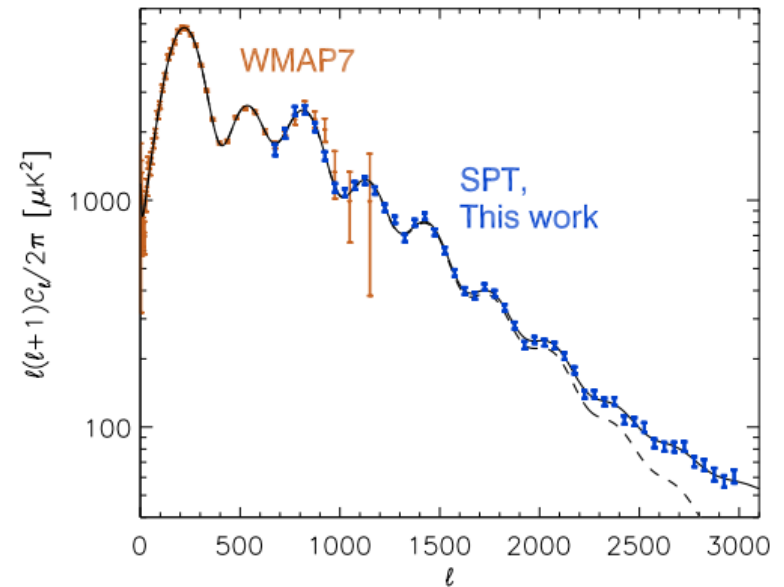
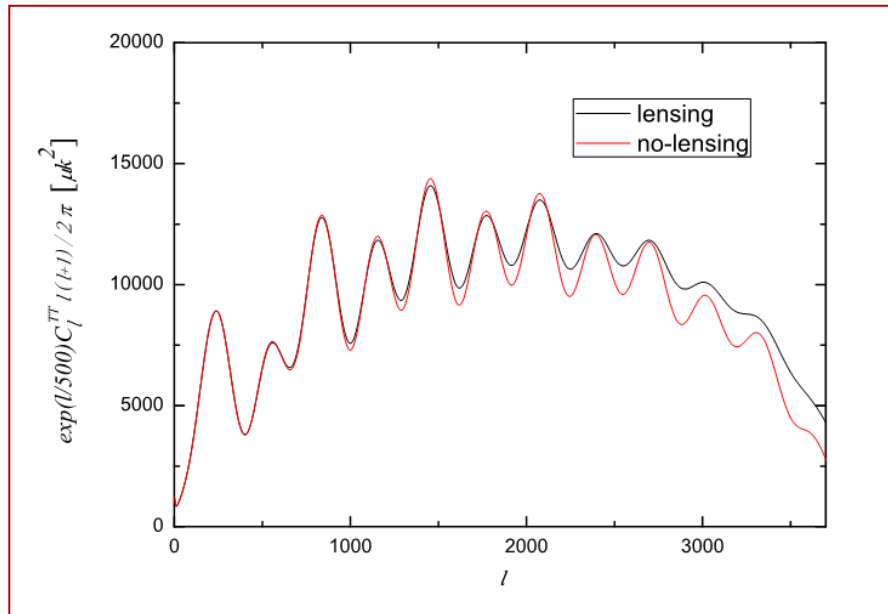
$$\begin{aligned}\tilde{\Theta}(\boldsymbol{x}) &= \Theta(\boldsymbol{x}') = \Theta(\boldsymbol{x} + \boldsymbol{\alpha}) = \Theta(\boldsymbol{x} + \nabla\psi) \\ &\approx \Theta(\boldsymbol{x}) + \nabla^a\psi(\boldsymbol{x})\nabla_a\Theta(\boldsymbol{x}) + \\ &\quad + \frac{1}{2}\nabla^a\psi(\boldsymbol{x})\nabla^b\psi(\boldsymbol{x})\nabla_a\nabla_b\Theta(\boldsymbol{x}) + \dots\end{aligned}$$

Lensing Effect on Temperature Power Spectrum

The effect is a convolution between the lensing potential power spectrum and the unlensed anisotropies power spectrum:

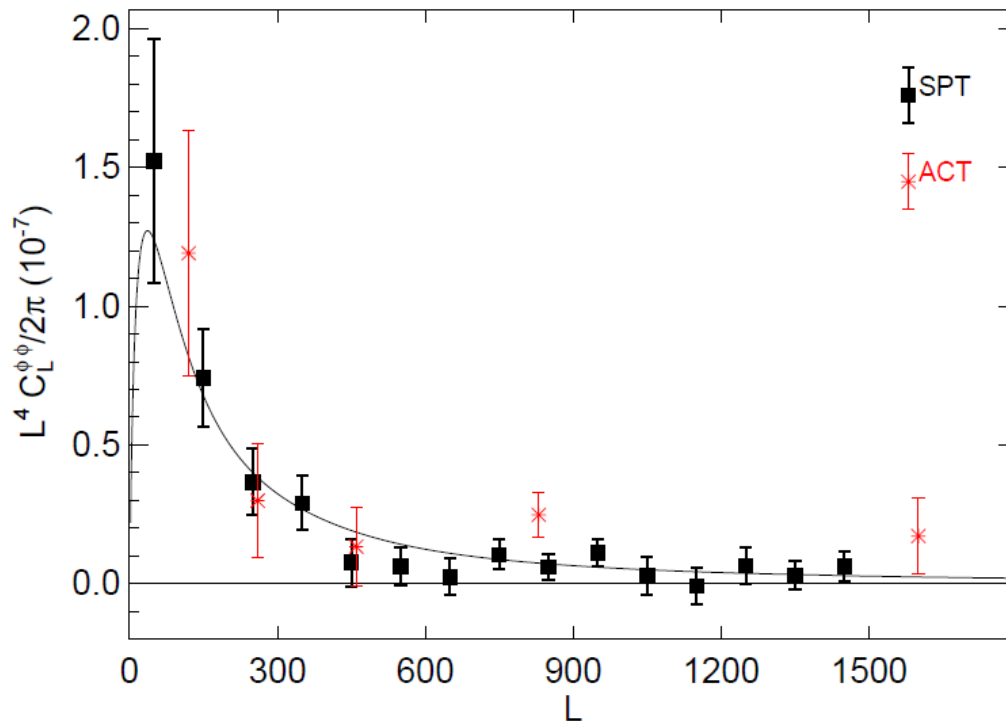
$$\tilde{C}_l^\Theta \approx C_l^\Theta + \int \frac{d^2 l'}{(2\pi)^2} [l' \cdot (l - l')]^2 C_{|l-l'|}^\psi C_{l'}^\Theta - C_l^\Theta \int \frac{d^2 l'}{(2\pi)^2} (l \cdot l')^2 C_{l'}^\psi$$

The net result is a 3% broadening of the CMB angular power spectrum acoustic peaks



Lensing Effect on Temperature Trispectrum

Another effect from lensing is the creation of non-gaussianities in CMB maps. This will produce a non-zero signal in the four-point CMB correlation function (the so-called trispectrum).



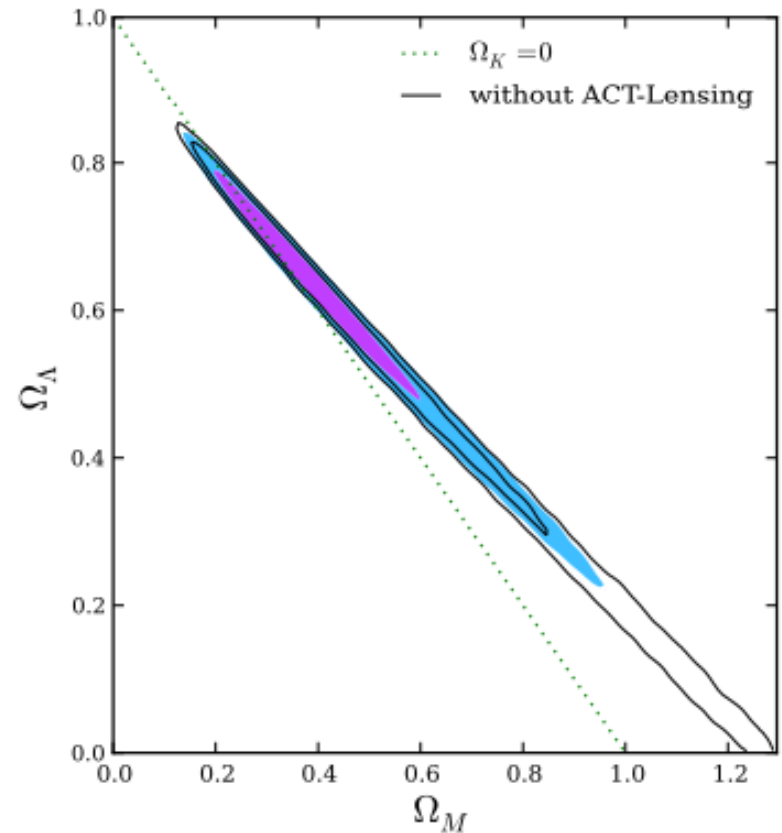
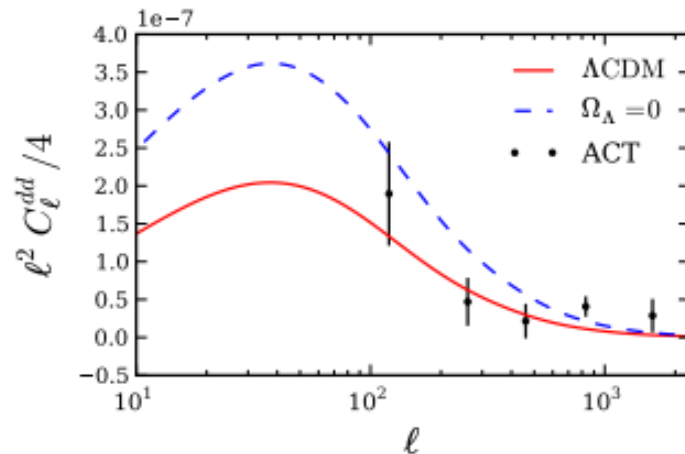
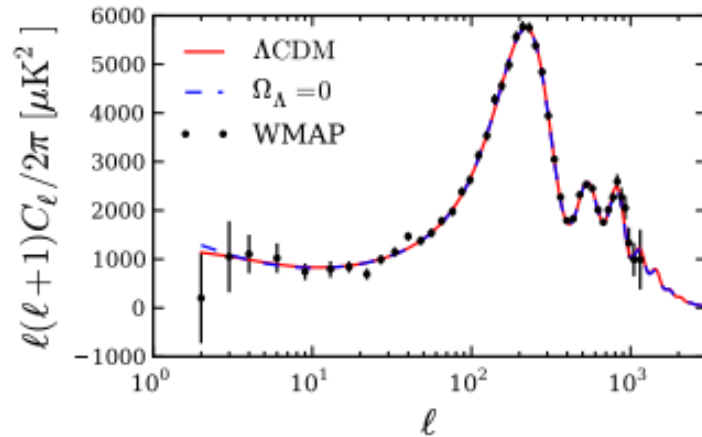
ACT: Das et al,
Phys.Rev.Lett. 107 (2011) 021301

SPT: van Engelen et al,
arXiv:1202.0546 (2012)

This non-gaussian signal has been measured by both ACT and SPT experiments, letting a reconstruction of the lensing potential.

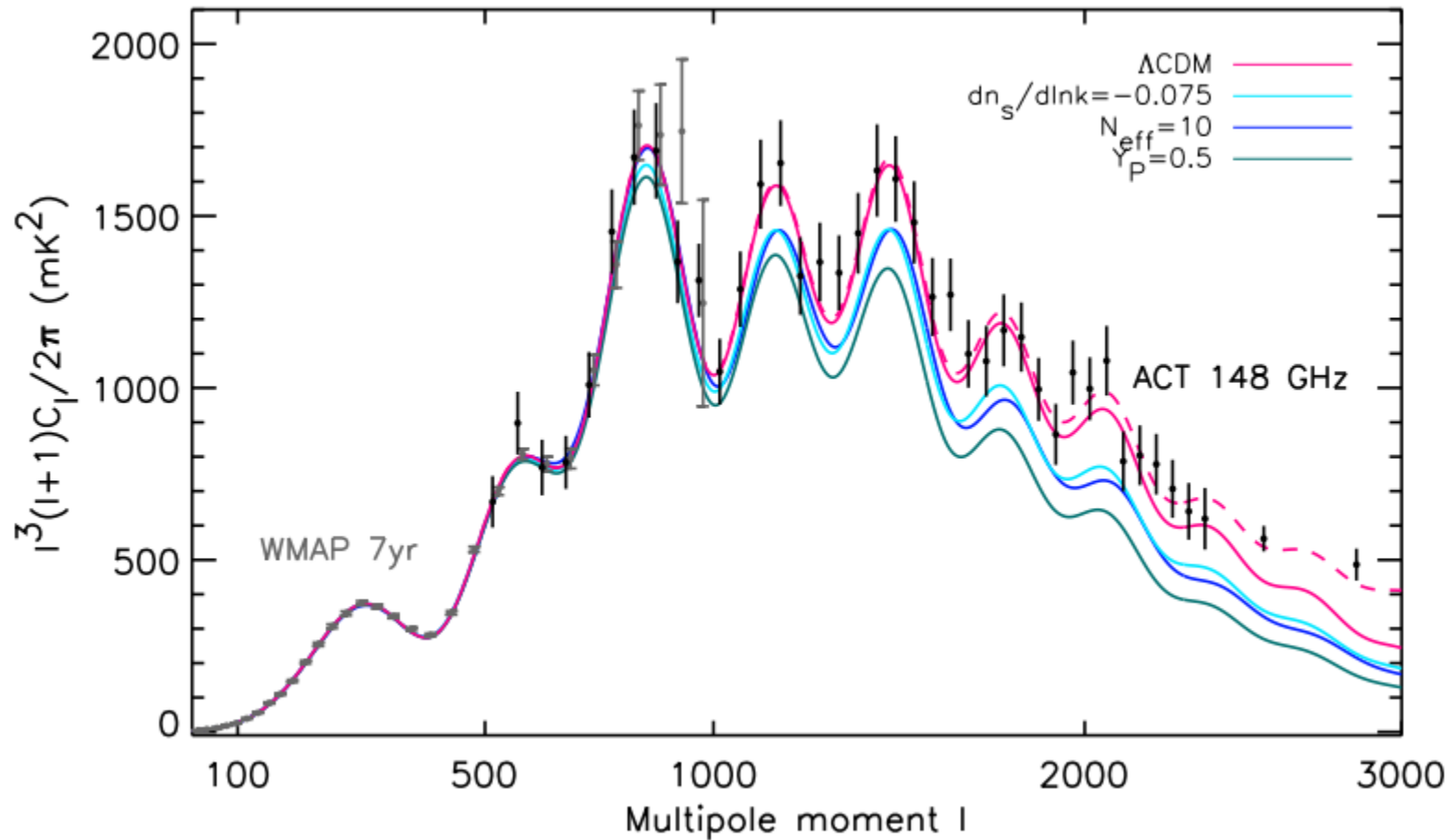
CMB Lensing and Cosmological Constant

Current CMB lensing detection breaks the geometrical degeneracy and let CMB data alone to reveal a cosmological constant. CMB lensing probes the low Redshift clustering !!



Sherwin et al.,
Phys.Rev.Lett.107:021302,2011

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

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

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

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

With a density of:

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

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).

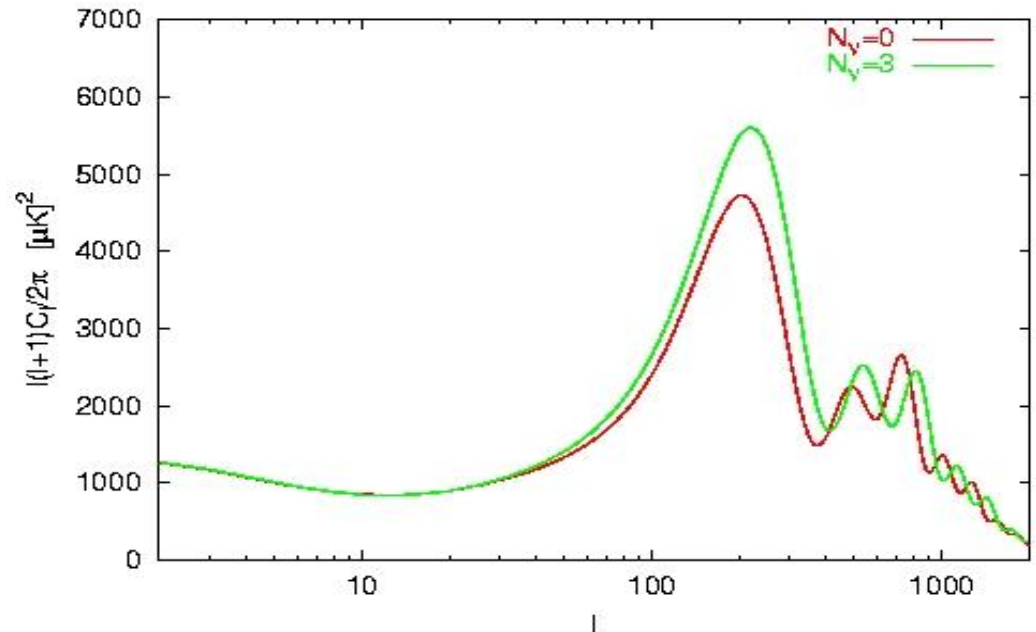
For most of the cases we consider here is assumed to be a constant.

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

Increasing the neutrino number **increases** the first peak amplitude of the CMB because of the so-called Integrated Sachs Wolfe effect.
If there is radiation the gravitational potential varies with time.
This leaves an imprint on the CMB around the first peak.
This effect is degenerate with a change in the Hubble constant.



Probing the Neutrino Number with CMB data

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.

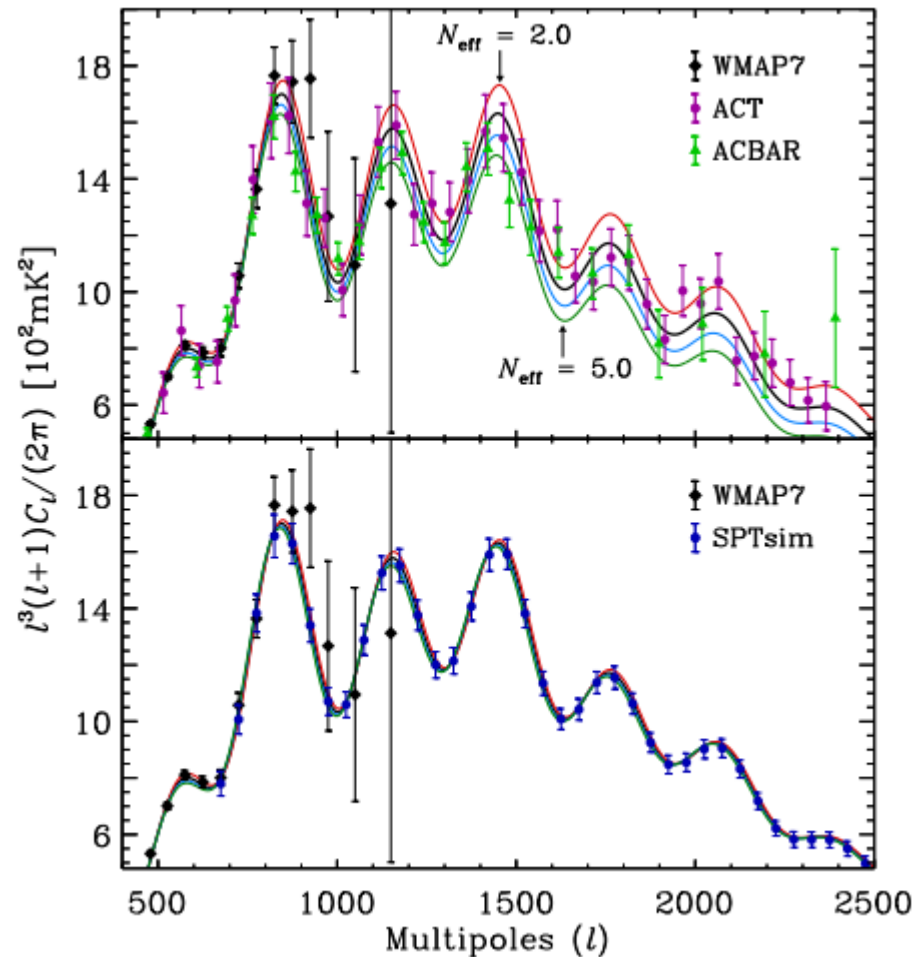
So it changes the sound horizon at recombination:

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

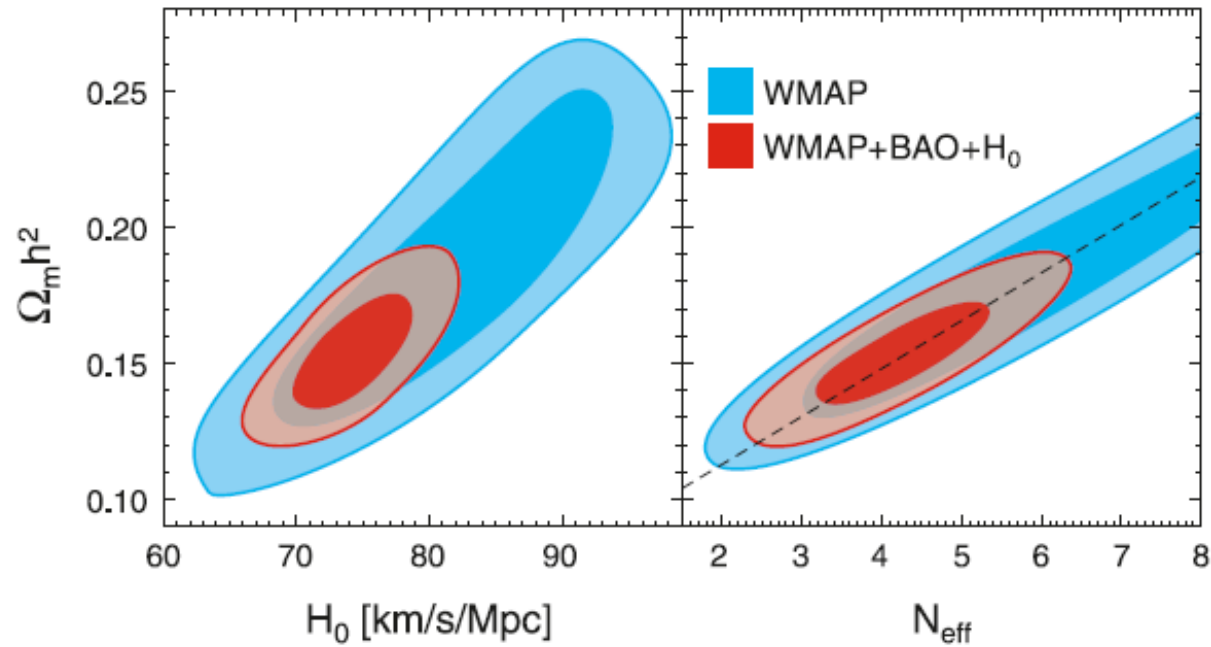
and the damping scale at recombination:

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

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

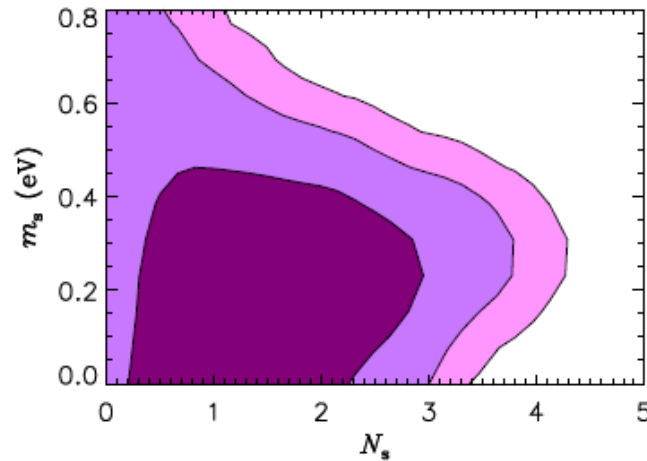


WMAP provides first indication for the existence of the neutrino background from CMB data only.

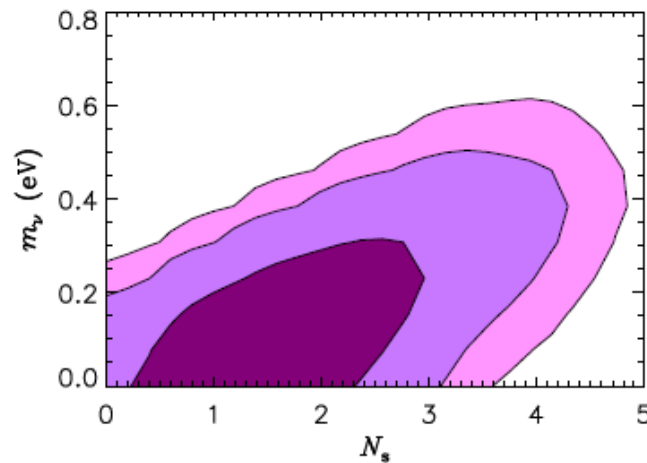


Parameter	Year	WMAP only	WMAP+BAO+SN+ <i>HST</i>	WMAP+BAO+ H_0	WMAP+LRG+ H_0
z_{eq}	5-year	3141^{+154}_{-157}	3240^{+99}_{-97}	3209^{+85}_{-89}	3240 ± 90
	7-year	3145^{+140}_{-139}			
$\Omega_m h^2$	5-year	$0.178^{+0.044}_{-0.041}$	0.160 ± 0.025	0.157 ± 0.016	$0.157^{+0.013}_{-0.014}$
	7-year	$0.184^{+0.041}_{-0.038}$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

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

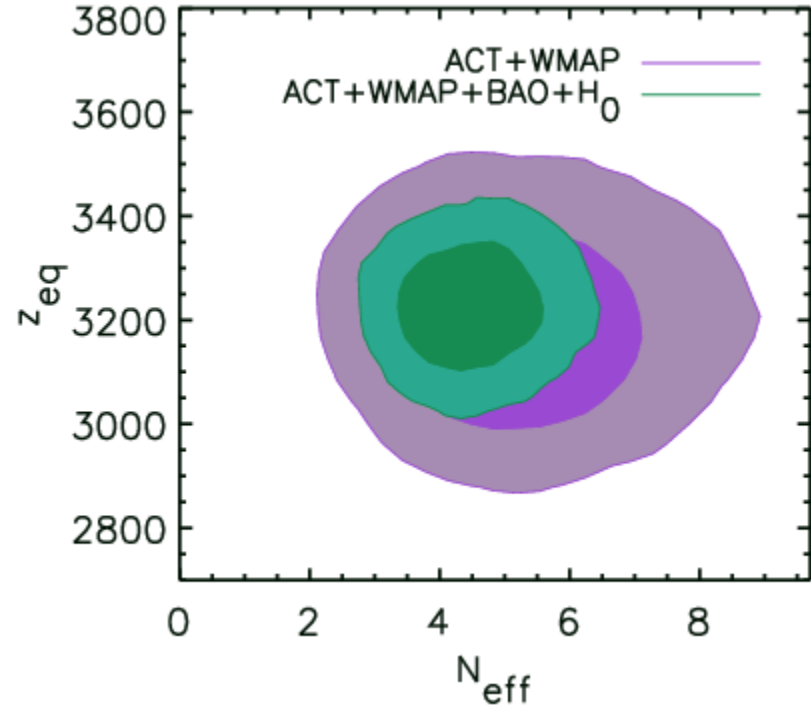
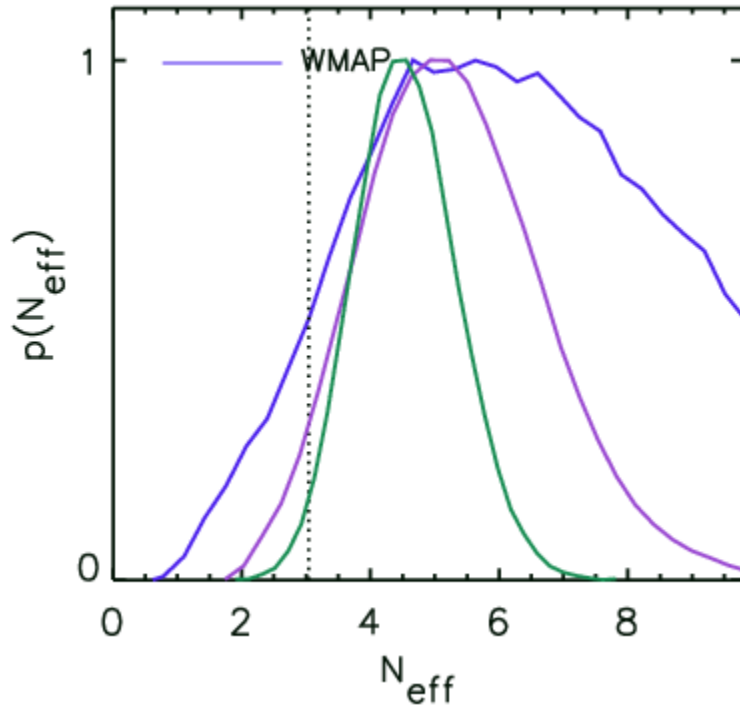


3 Active massless neutrinos+
 N_s massive neutrinos



3 Active massive neutrinos +
 N_s massless neutrinos

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

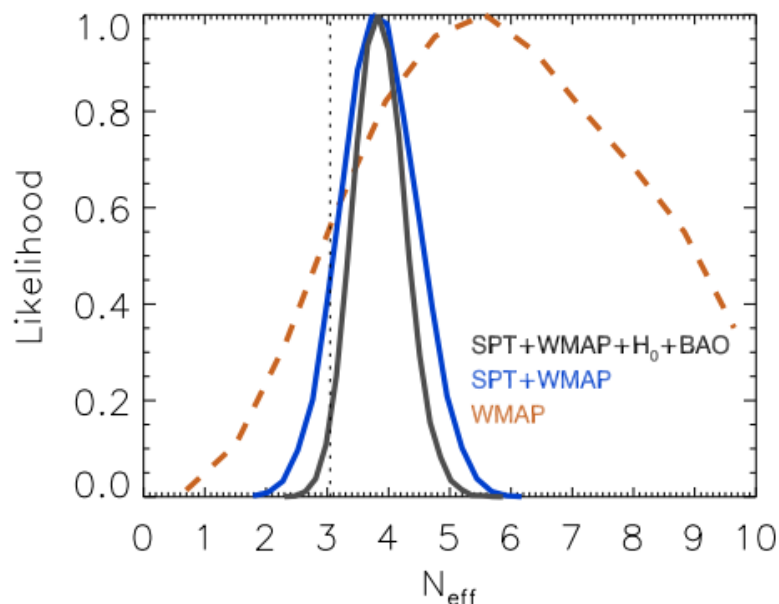


Latest results from ACT, Dunkley et al. 2010
(95 % c.l.)

$$N_{\text{eff}} = 5.3 \pm 1.3 \text{ ACT+WMAP}$$

$$N_{\text{eff}} = 4.8 \pm 0.8 \text{ ACT+WMAP+BAO+H}_0$$

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



		Λ CDM	Λ CDM + A_L	Λ CDM + r	Λ CDM + $dn_s/d \ln k$	Λ CDM + Y_p	Λ CDM + N_{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
	$10^9 \Delta_P^2$	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	$A_L^{0.68}$	—	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_{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

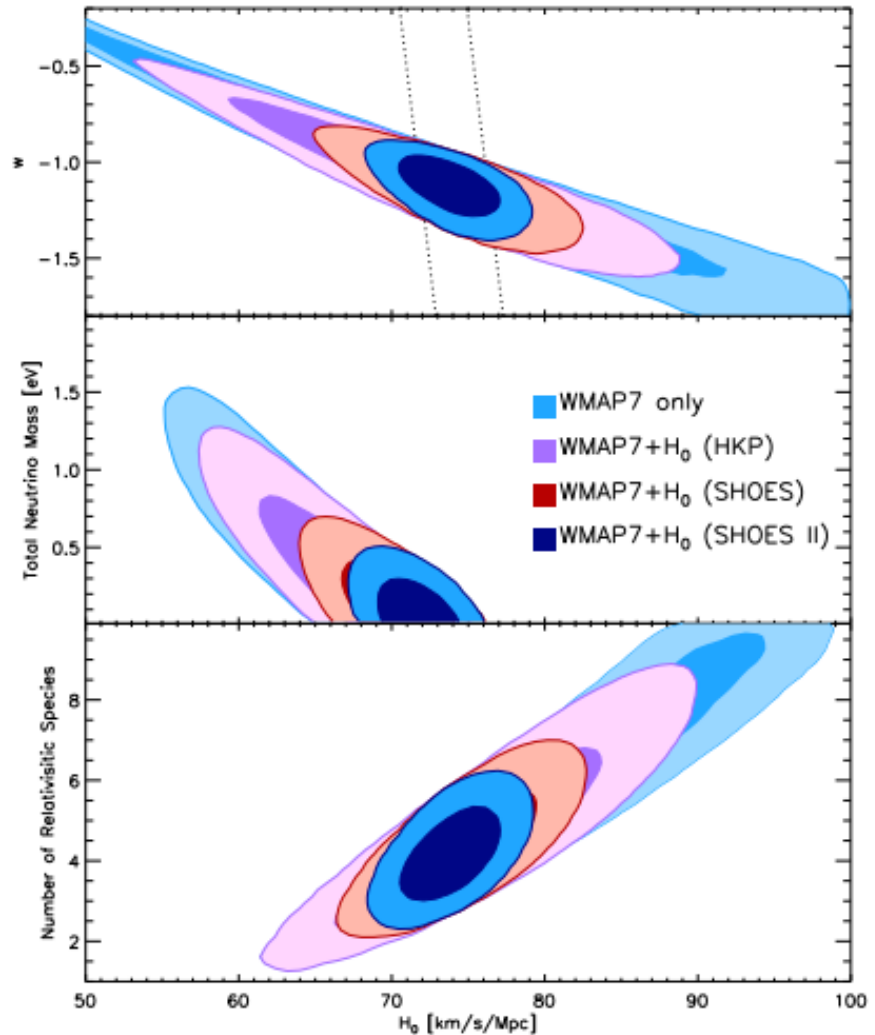
New HST determination of H_0

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

$$h = 0.738 \pm 0.024$$

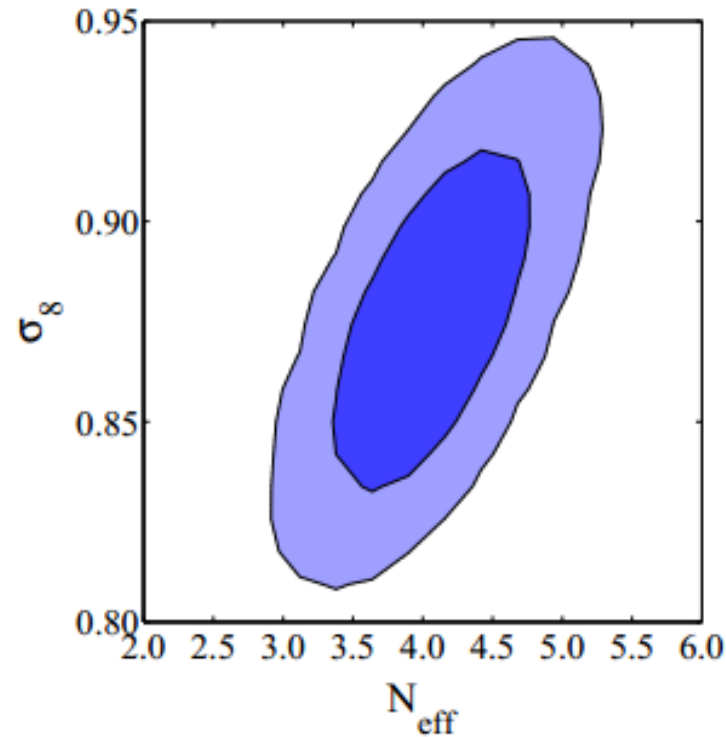
$$N_{\text{eff}} = 4.2 \pm 0.7$$

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



WMAP7+ACT+SPT+H0+BAO Analyses

Most recent analyses they all point towards $N_{\text{eff}} > 3$ at about 2.6-2.8 standard deviations.



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

Archidiacono, Calabrese, AM, **Phys.Rev. D84 (2011) 123008**

Smith et al, **Phys.Rev. D85 (2012) 023001**

Hamann, **JCAP 1203 (2012) 021**

Probing the Neutrino Number with BBN data

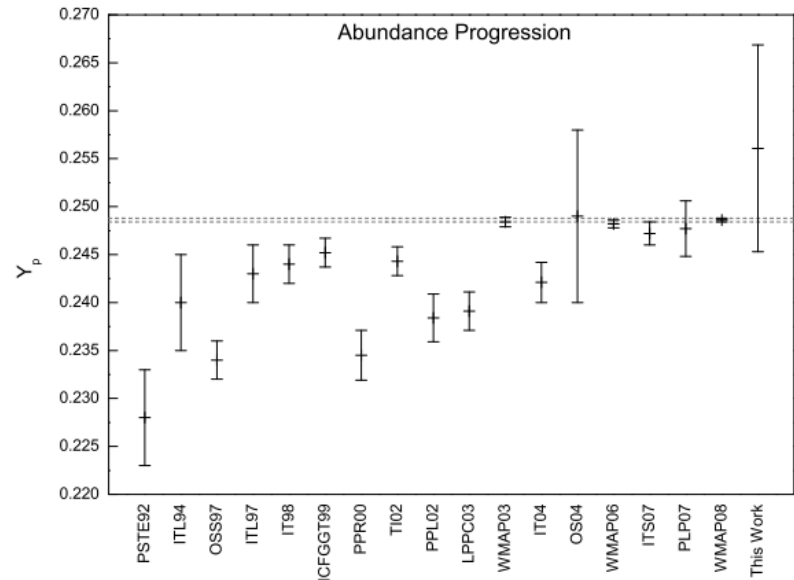
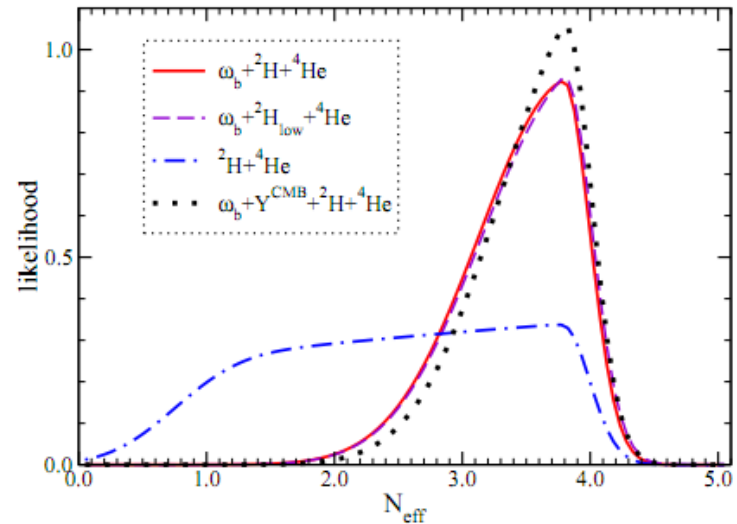
- BBN element abundances depend on nuclear interaction rates and expansion rate.

- Helium abundance Y_p is the most sensitive probe for the neutrino number. Larger Helium $\rightarrow$ Larger N_{eff}

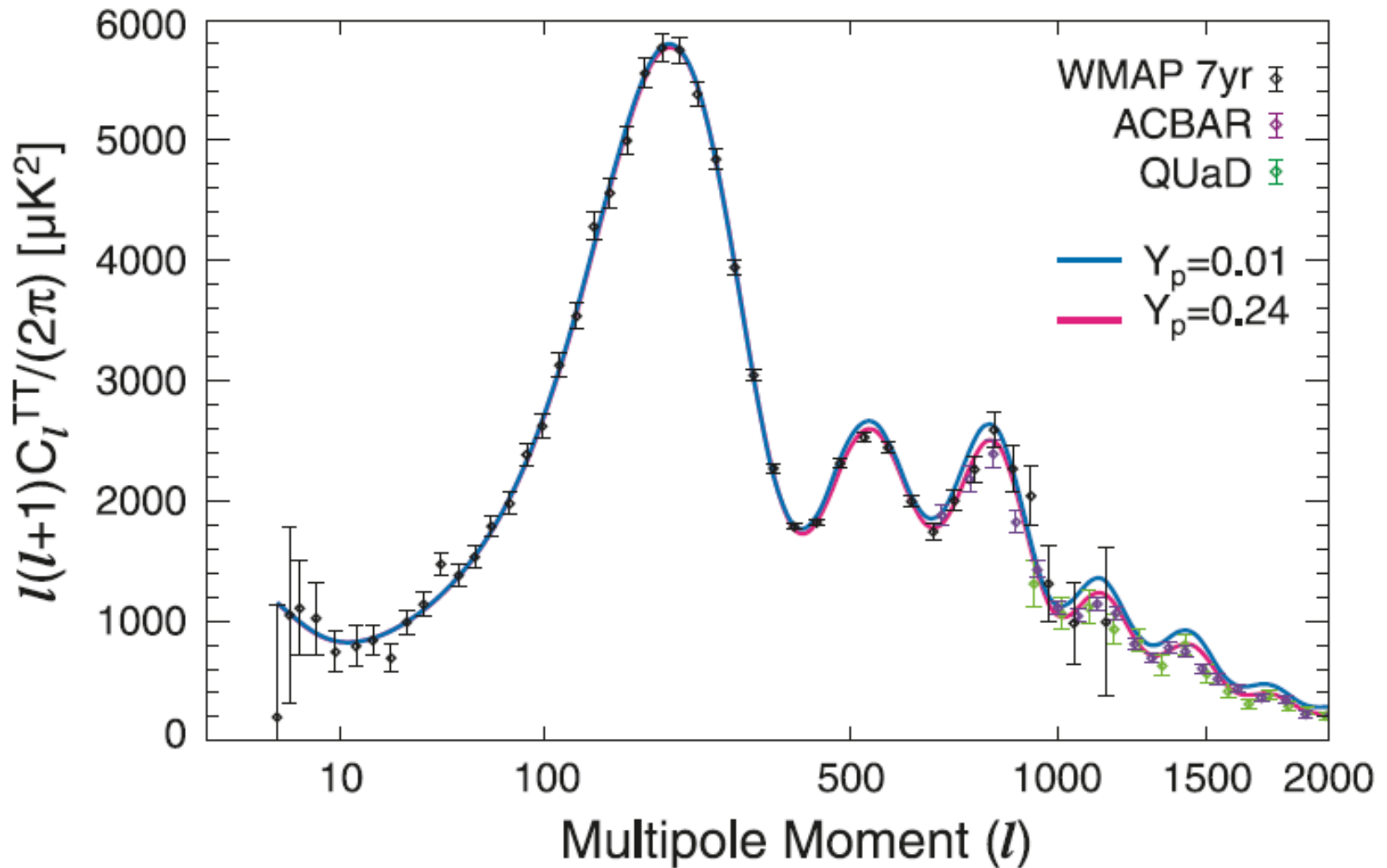
Recently Mangano and Serpico (Mangano, Serpico, PLB 2011) obtained the upper limit:

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

However Y_p 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.,

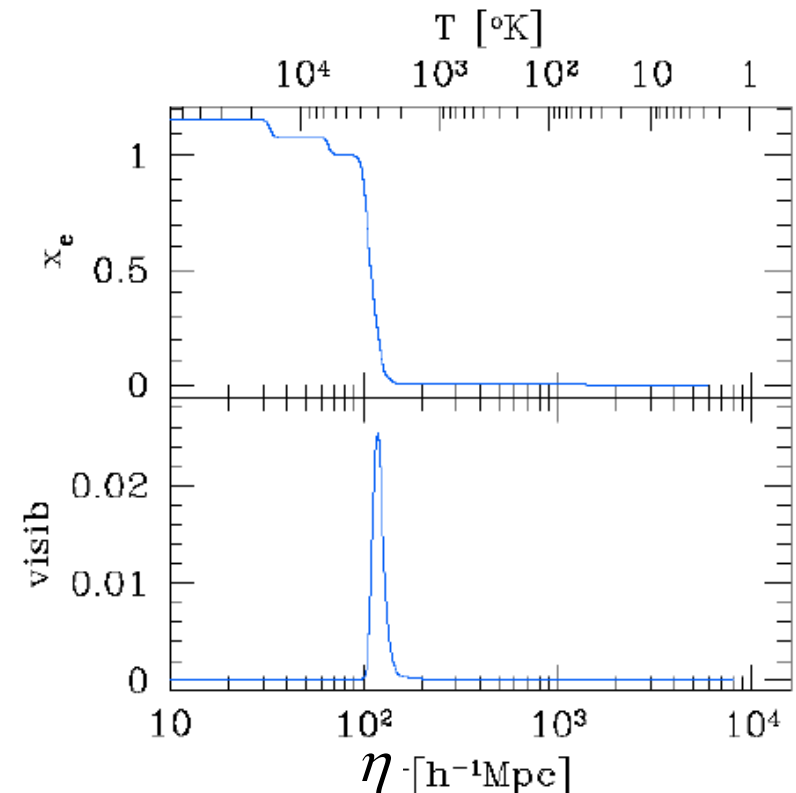
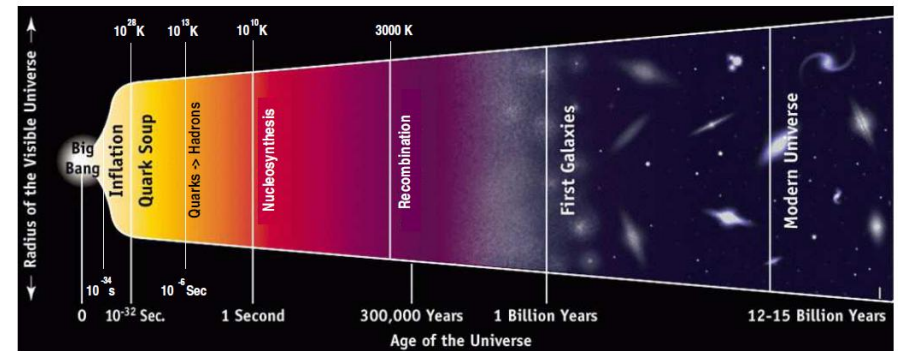
K. Ichikawa et al., Phys.Rev.D78:043509,2008

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

Thermal History and Recombination

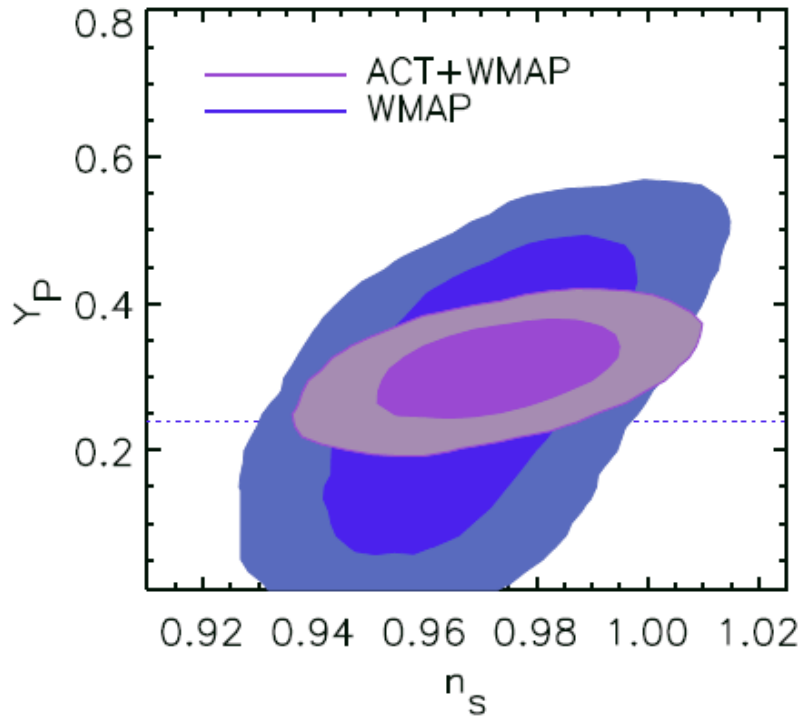
- Dominant element hydrogen recombines rapidly around $z \sim 1000$.
- Prior to recombination, Thomson scattering efficient and mean free path short cf. expansion time
- Little chance of scattering after recombination ! photons free stream keeping imprint of conditions on last scattering surface
- Changing the free electron fraction changes the damping scale and affects the CMB:

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



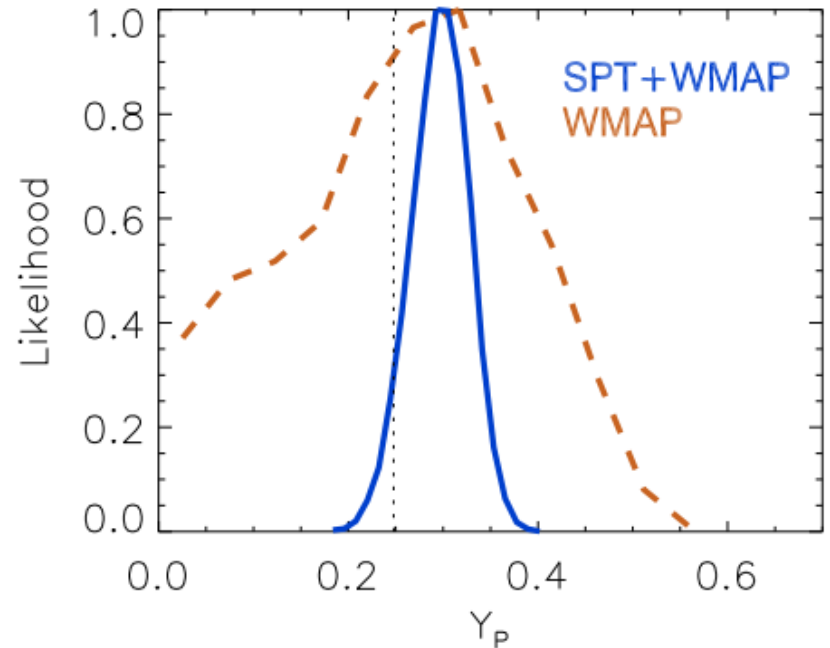
Primordial Helium: Current Status

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.

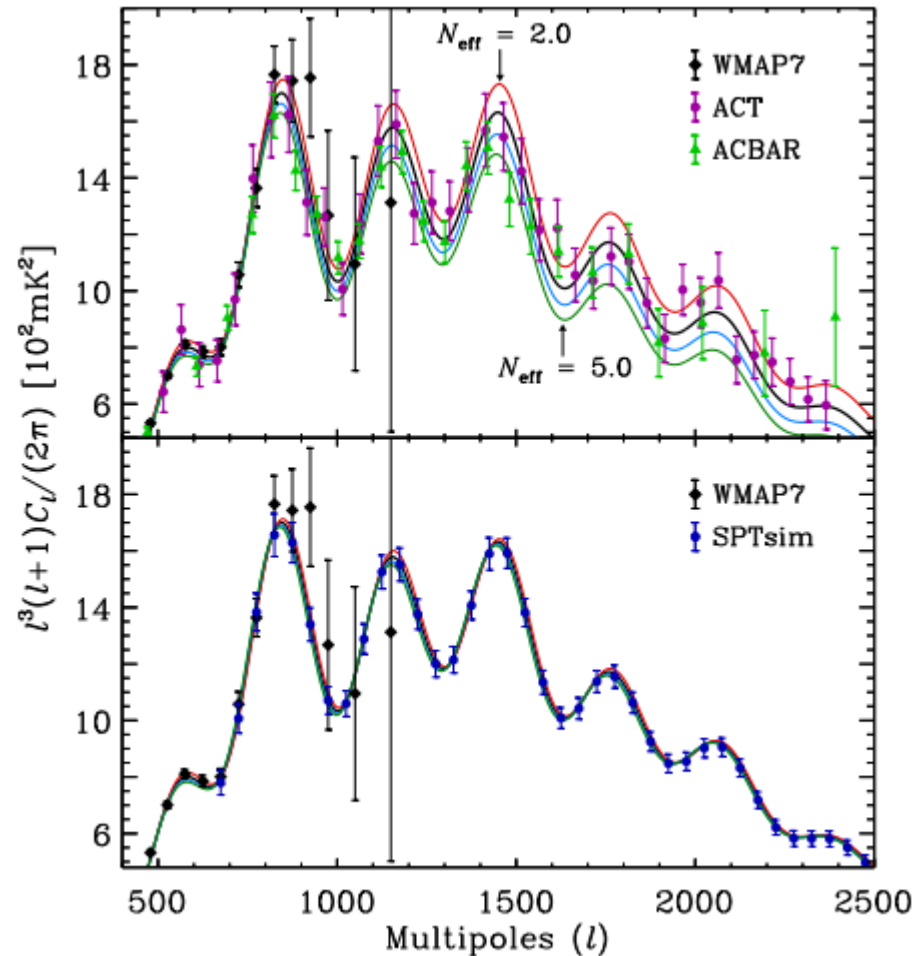
So it changes the sound horizon at recombination:

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

and the damping scale at recombination:

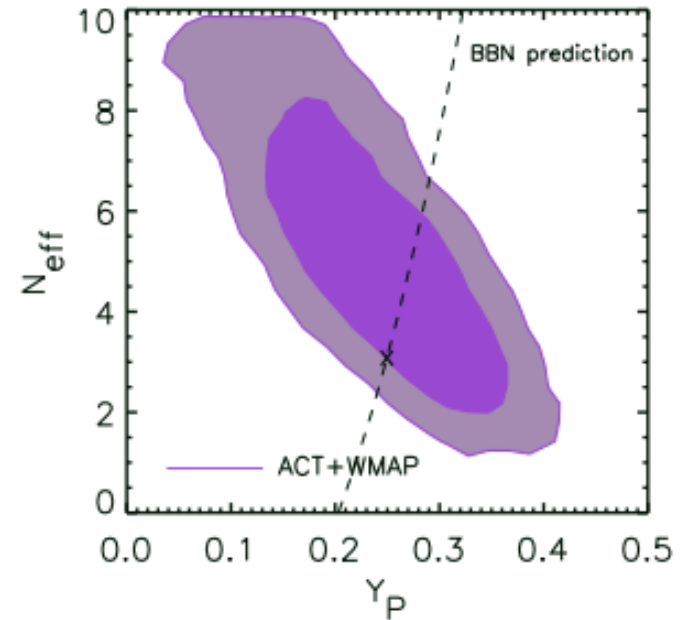
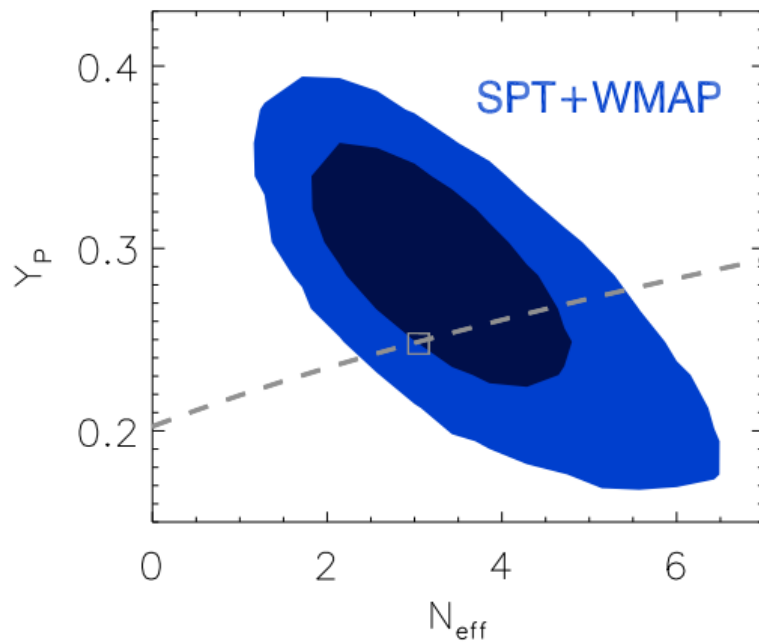
$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15} (1+R)}{6(1+R^2)} \right]$$

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



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

Helium-Neutrino BBN/CMB complementarity



Current bounds on N_{eff} 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 $N_{\text{eff}} > 3$ is interesting

We have 1000 ways to explain this !!!

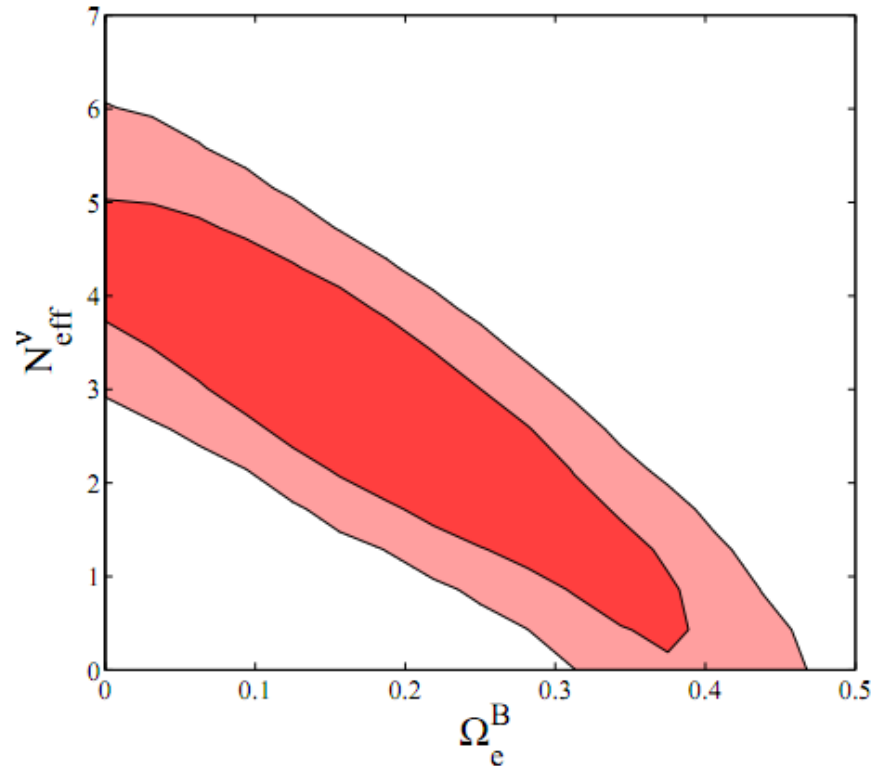
- Sterile Neutrino (see talk by Carlo Giunti).
- Non Standard Neutrino Decoupling (See talk by Gianpiero Mangano)
- Modified Gravity (Extra Dimensions)
- «Early» Dark Energy
- Gravity Waves
- Axions
- Variation of fundamental constants
- ...

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:

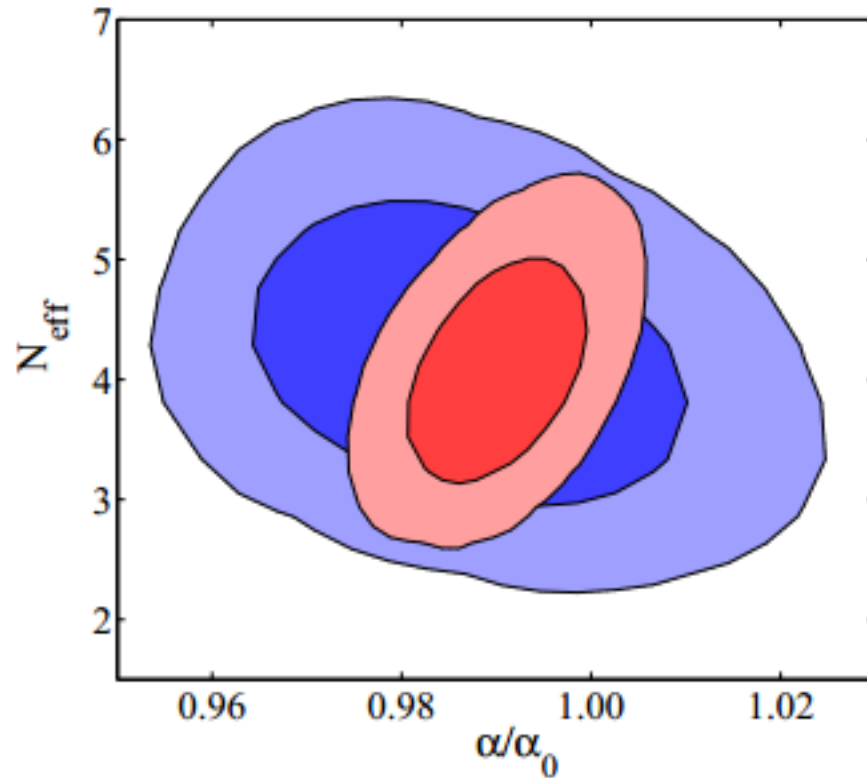
$$\rho_{\text{baro}}(a) = \rho_{\infty} + C\rho_{r,0}a^{-4}$$



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

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

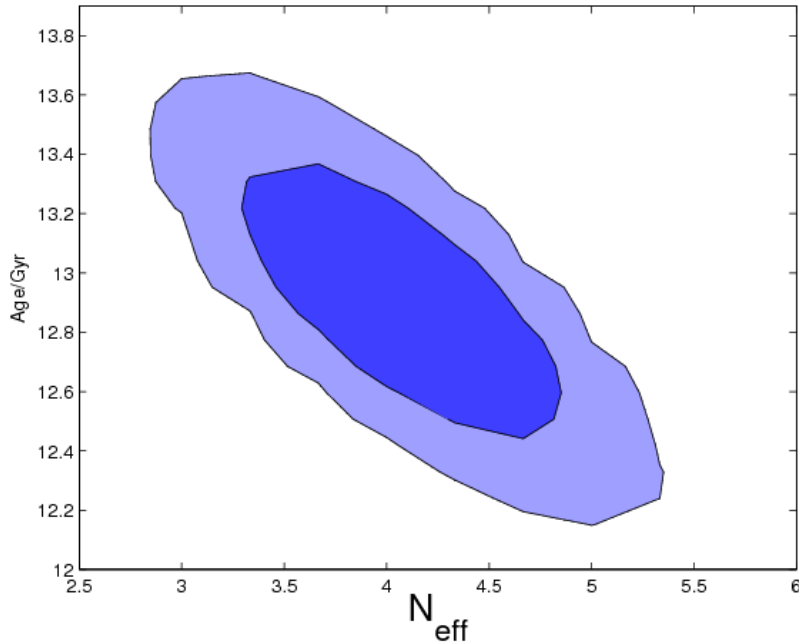
A variation in the fine structure constant at recombination ?



Red: analysis with Helium abundance fixed to $Y_p=0.24$.

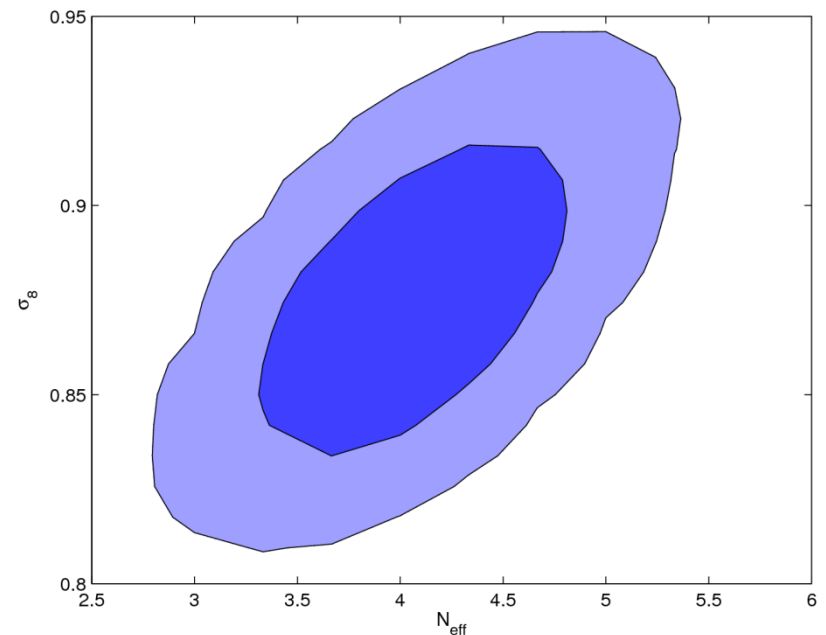
Blue: Y_p is varied.

What disfavors $N_{\text{eff}} > 3$?



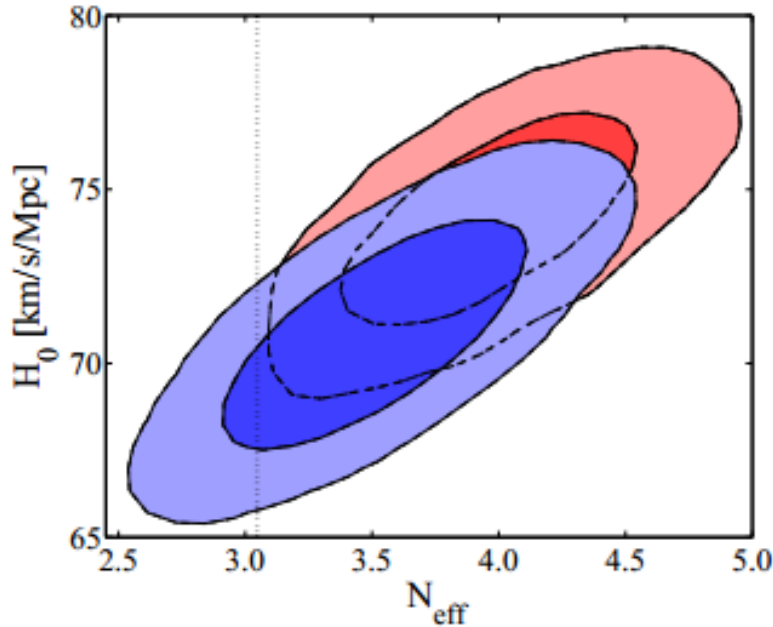
Larger values of the effective neutrino number are in better agreement with **lower** ages of the universe.

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 $N_{\text{eff}} > 3$?



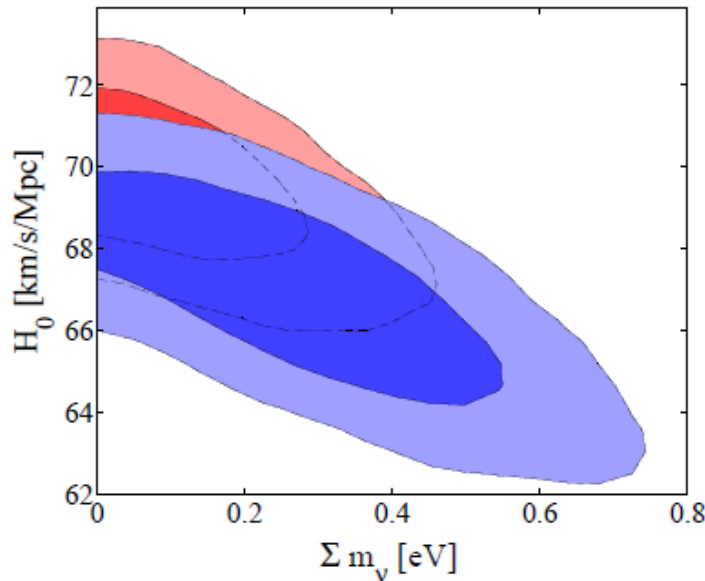
The HST prior on the Hubble constant plays an important role in the current evidence for Dark Radiation.

Constraints from CMB data alone on H_0 are in tension with HST value when $N_{\text{eff}} = 3.046$. 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	
		$73.8 \pm 2.4 \text{ km/s/Mpc}$		$68 \pm 2.8 \text{ km/s/Mpc}$	
$\Omega_b h^2$	0.02258 ± 0.00050	0.02248 ± 0.00039	0.02210 ± 0.00037	0.02211 ± 0.00040	0.02188 ± 0.00036
$\Omega_c h^2$	0.134 ± 0.010	0.1317 ± 0.0080	0.1142 ± 0.0029	0.1256 ± 0.0080	0.1181 ± 0.0032
θ	1.0395 ± 0.0016	1.0397 ± 0.0016	1.0415 ± 0.0014	1.0400 ± 0.0017	1.0409 ± 0.0014
τ	0.085 ± 0.014	0.084 ± 0.013	0.083 ± 0.013	0.080 ± 0.013	0.081 ± 0.014
n_s	0.984 ± 0.017	0.979 ± 0.012	0.9659 ± 0.0091	0.964 ± 0.012	0.9536 ± 0.0090
N_{eff}	4.14 ± 0.57	3.98 ± 0.37	3.046	3.52 ± 0.39	3.046
$\sum m_\nu [\text{eV}]$	0.0	0.0	< 0.36	0.0	< 0.60
$H_0 [\text{km/s/Mpc}]$	75.2 ± 3.6	74.2 ± 2.0	69.3 ± 1.4	70.9 ± 2.1	66.8 ± 1.8

Neutrino masses and the HST prior

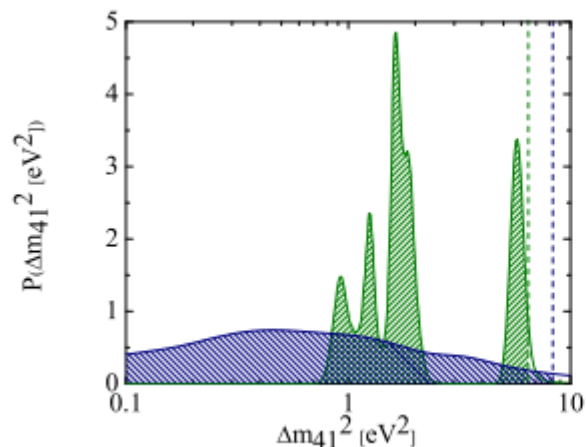


The HST prior plays also an important role in constraining neutrino masses. Higher values of H_0 are in better agreement with lower values of neutrino mass. See Carmelita Carbone's talk for more about constraints on neutrino masses from Galaxy clustering.

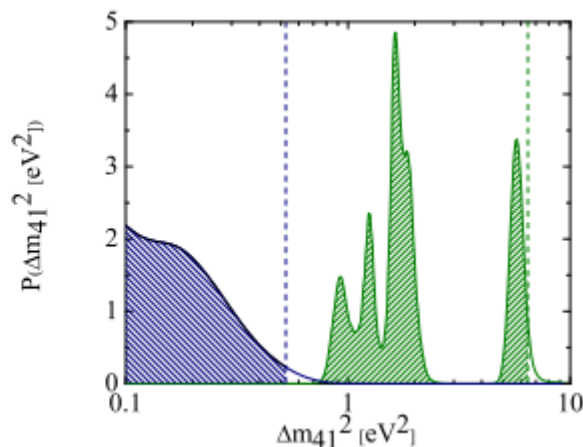
Parameters	No Prior	HST Prior		MS Prior	
		$73.8 \pm 2.4 \text{ km/s/Mpc}$		$68 \pm 2.8 \text{ km/s/Mpc}$	
$\Omega_b h^2$	0.02258 ± 0.00050	0.02248 ± 0.00039	0.02210 ± 0.00037	0.02211 ± 0.00040	0.02188 ± 0.00036
$\Omega_c h^2$	0.134 ± 0.010	0.1317 ± 0.0080	0.1142 ± 0.0029	0.1256 ± 0.0080	0.1181 ± 0.0032
θ	1.0395 ± 0.0016	1.0397 ± 0.0016	1.0415 ± 0.0014	1.0400 ± 0.0017	1.0409 ± 0.0014
τ	0.085 ± 0.014	0.084 ± 0.013	0.083 ± 0.013	0.080 ± 0.013	0.081 ± 0.014
n_s	0.984 ± 0.017	0.979 ± 0.012	0.9659 ± 0.0091	0.964 ± 0.012	0.9536 ± 0.0090
N_{eff}	4.14 ± 0.57	3.98 ± 0.37	3.046	3.52 ± 0.39	3.046
$\sum m_\nu [\text{eV}]$	0.0	0.0	< 0.36	0.0	< 0.60
$H_0 [\text{km/s/Mpc}]$	75.2 ± 3.6	74.2 ± 2.0	69.3 ± 1.4	70.9 ± 2.1	66.8 ± 1.8

Compatibility with sterile neutrinos from SBL experiments

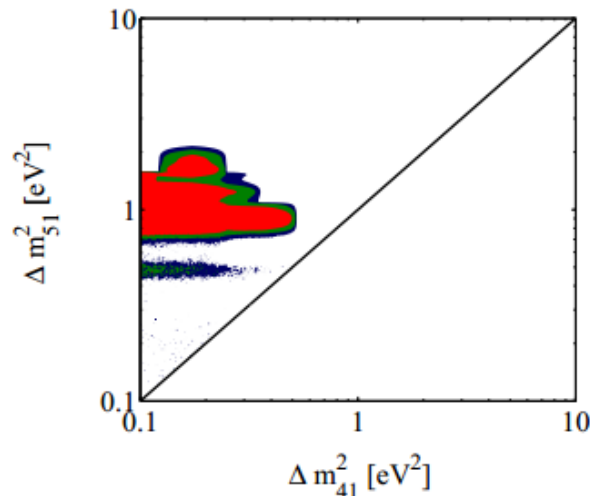
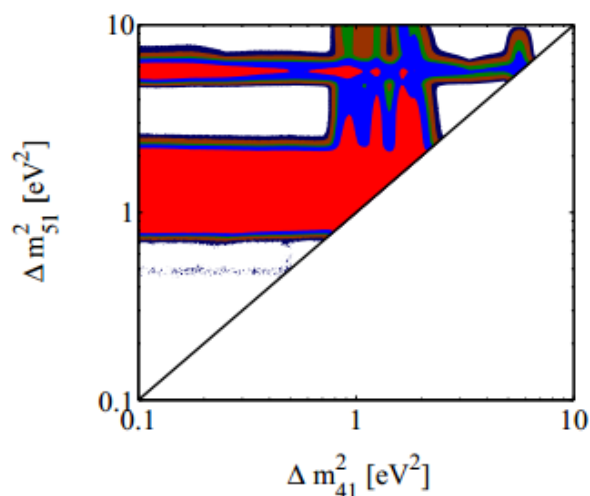
CMB only



CMB+galaxy clustering



3+1 case

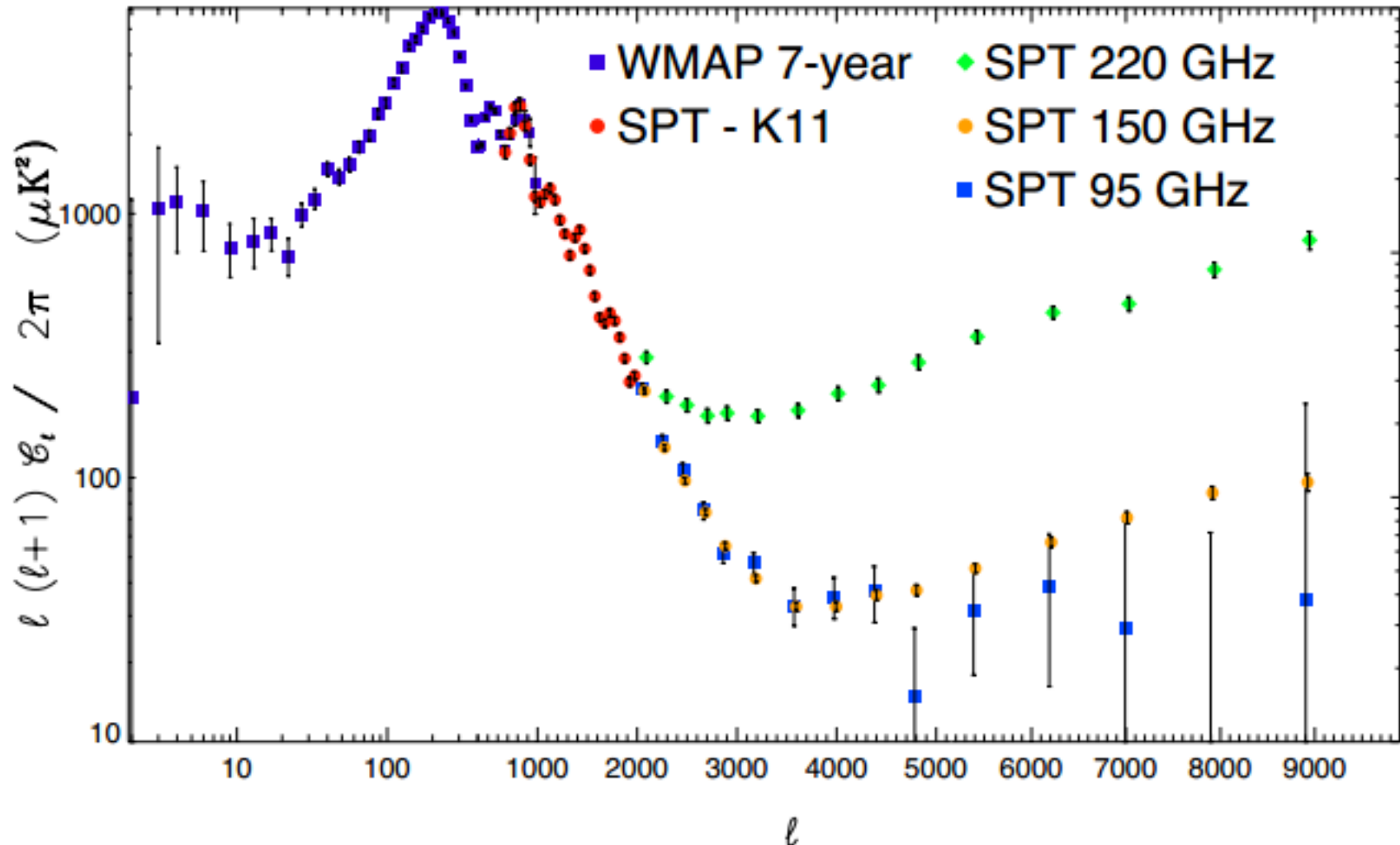


3+2 case

See Carlo Giunti's talk.

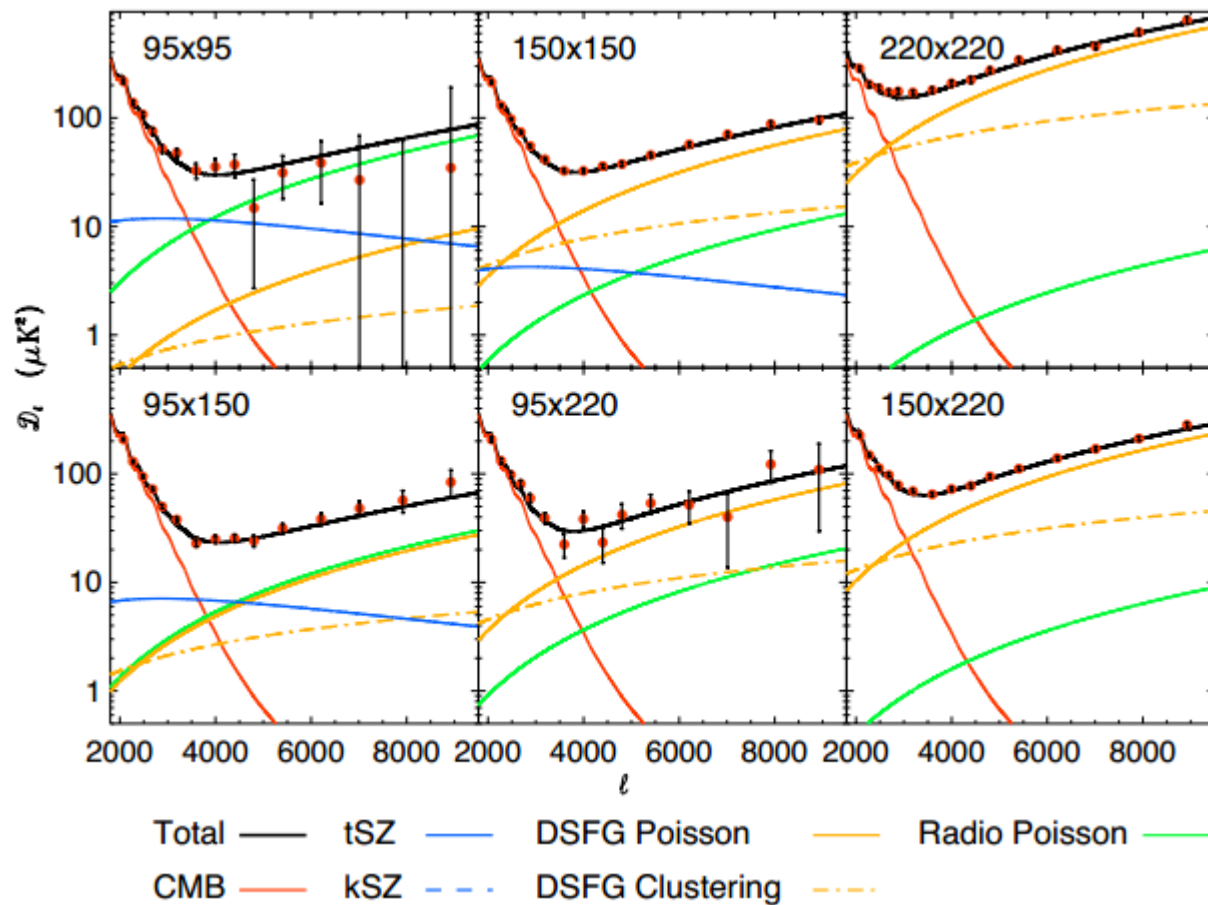
Archidiacono, Fornengo, Giunti, Melchiorri, PRD in press, [arXiv:1207.6515](https://arxiv.org/abs/1207.6515), 2012

Small Scale Foregrounds



Going at even smaller angular scales the contribution from the local universe (galaxies, SZ from clusters, etc) become dominant

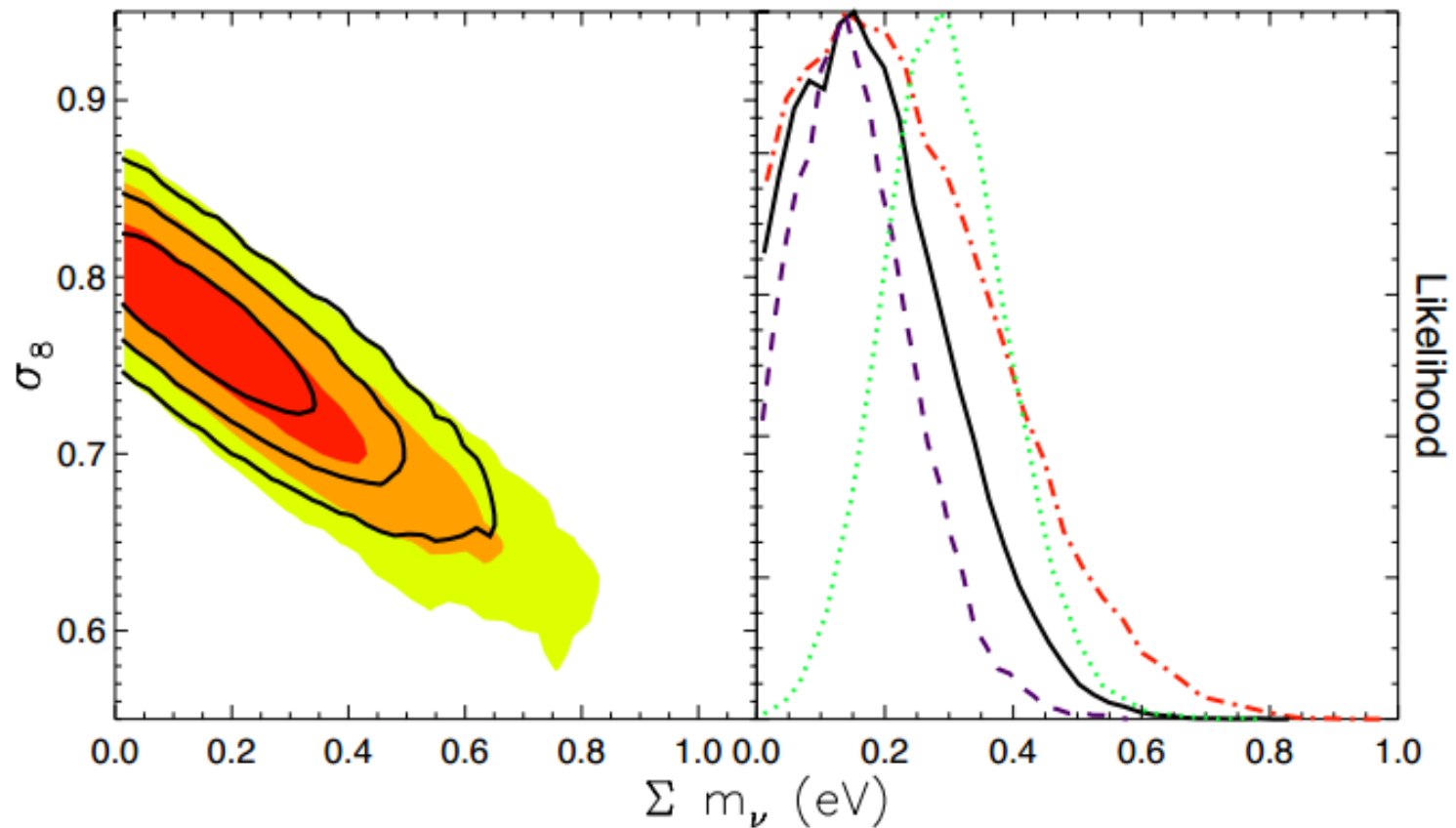
Small Scale Foregrounds



Reichardt et al, [arXiv:1111.0932](#)

Archidiacono et al, *Phys. Rev. D* **85**, 043015 (2012)

These foregrounds contributions can be parametrized and subtracted thanks to multifrequency measurements.



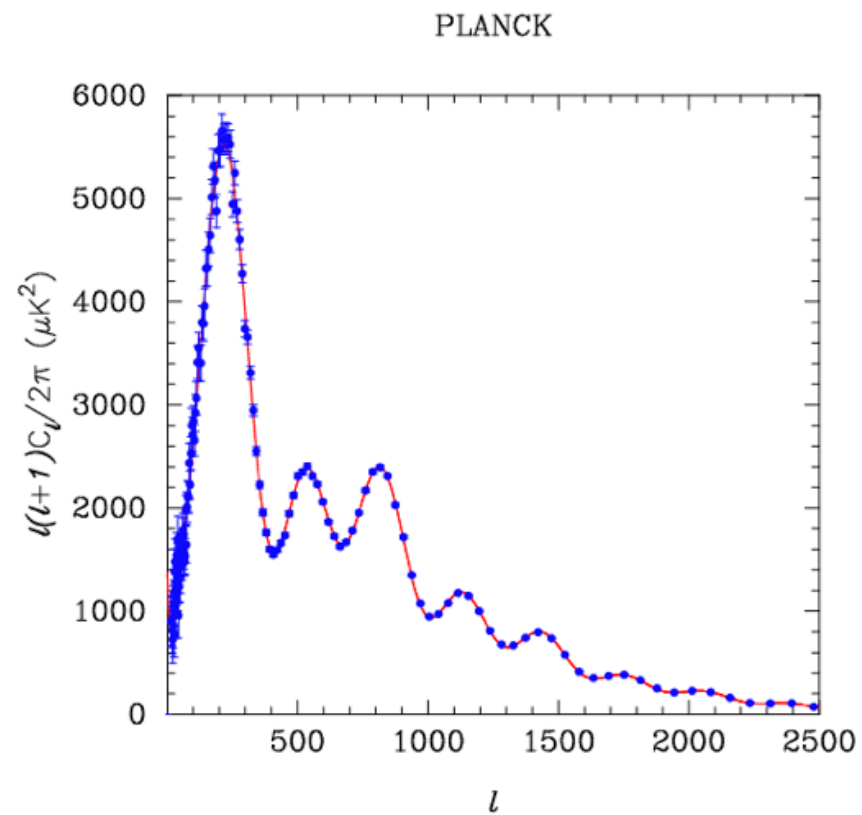
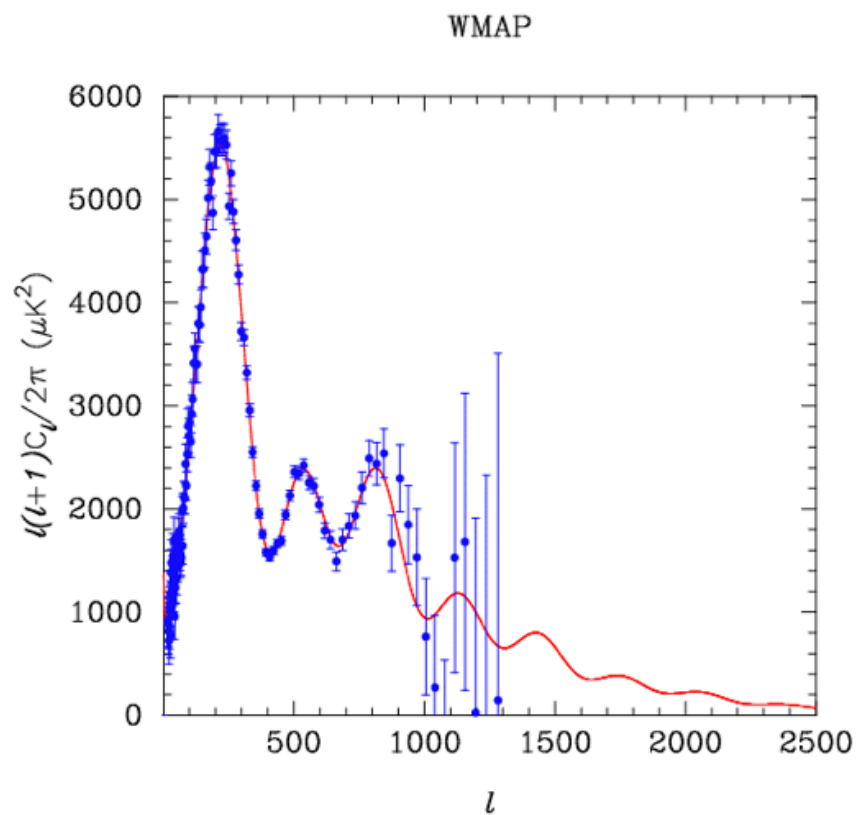
Reichardt et al, [arXiv:1111.0932](#)

Foregrounds measurements can be useful also for cosmology !
Measuring the Thermal SZ component constrains the amplitude of matter fluctuations
and improves current constraints on neutrino masses.

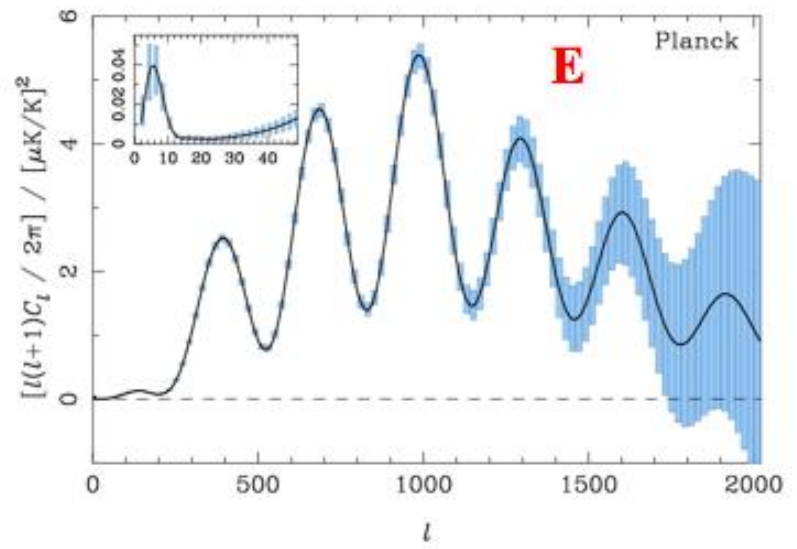
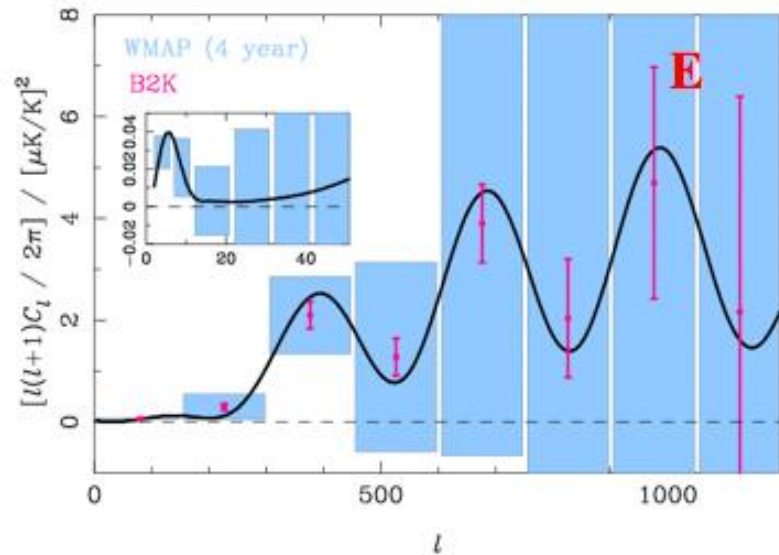
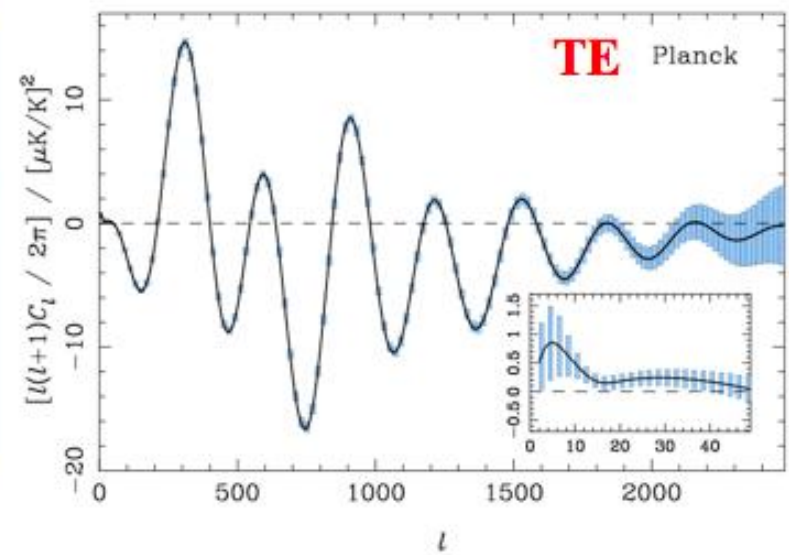
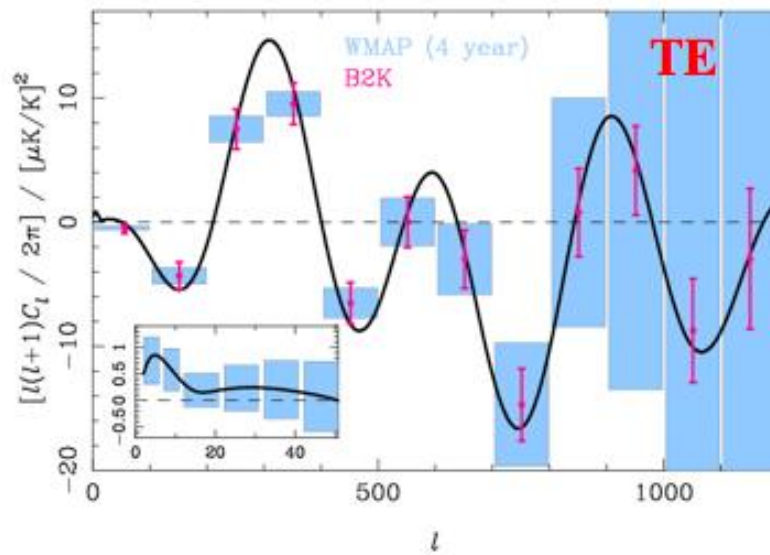
Planck
Satellite launch
14/5/2009



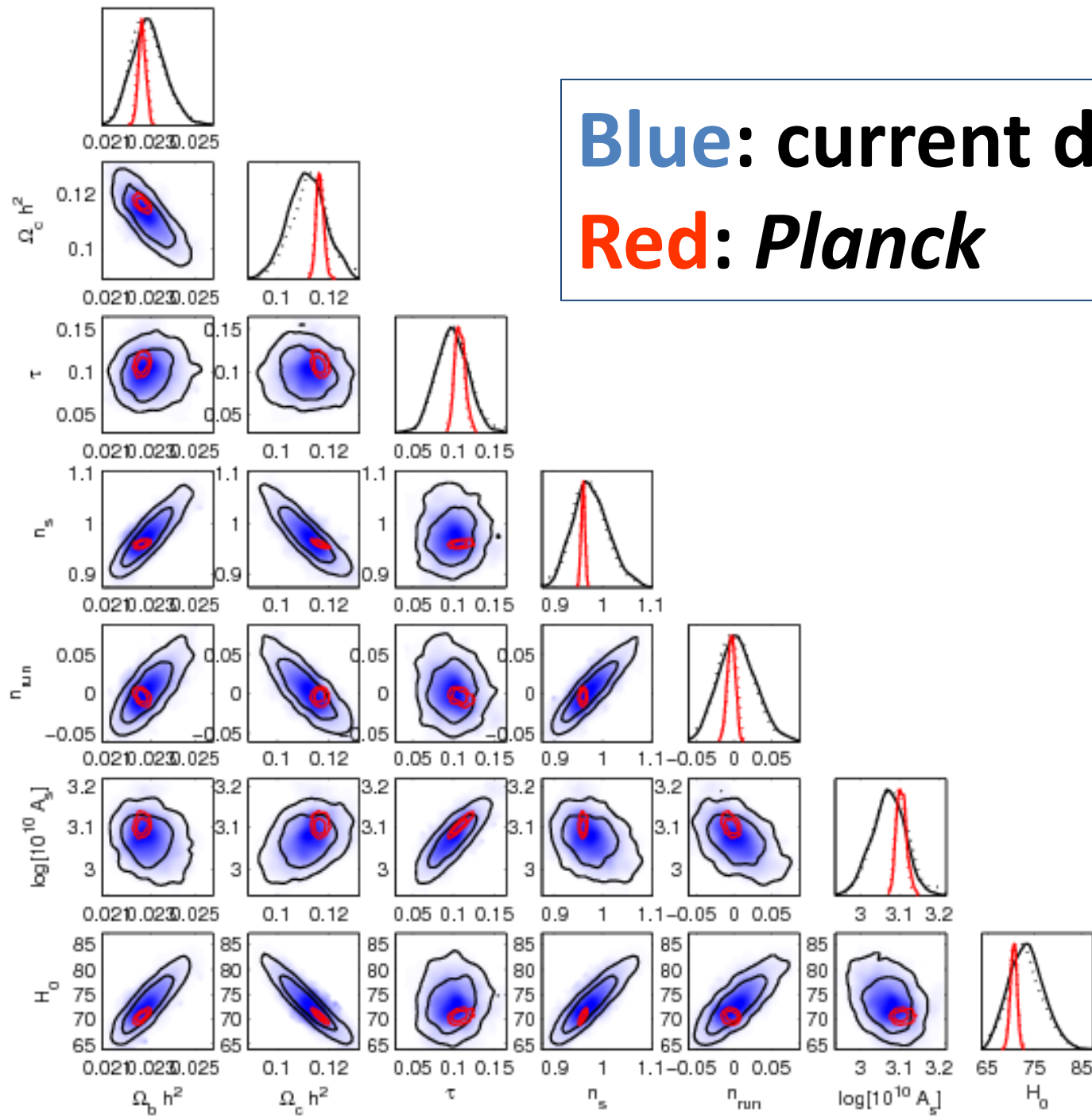
Expected improvement on TT respect to WMAP (Real data in January 2013)



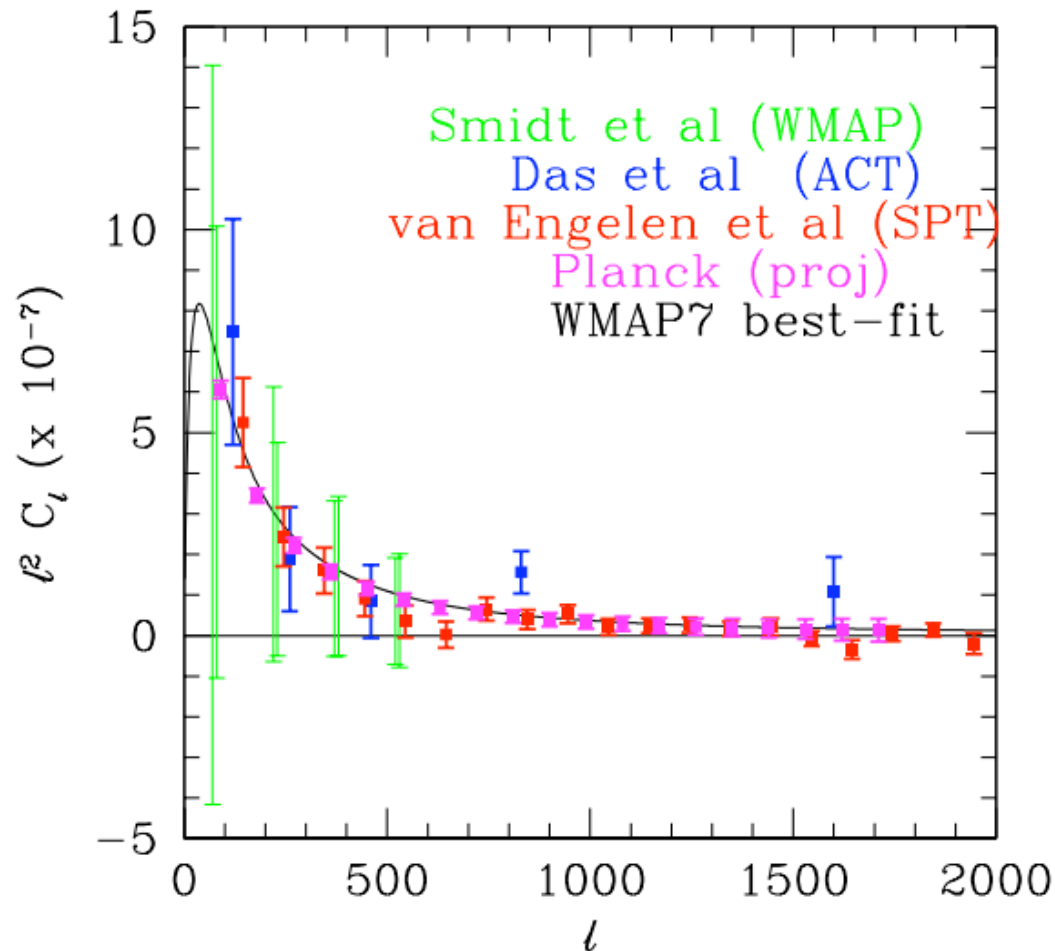
Expected improvement on TE and EE respect to WMAP (real data in January 2013 o 2014) .



Blue: current data
Red: *Planck*



PLANCK and CMB Lensing



Detection at about 20 sigmas is expected from Planck TT data in January 2013.
Greatly helpful in constraining parameters.

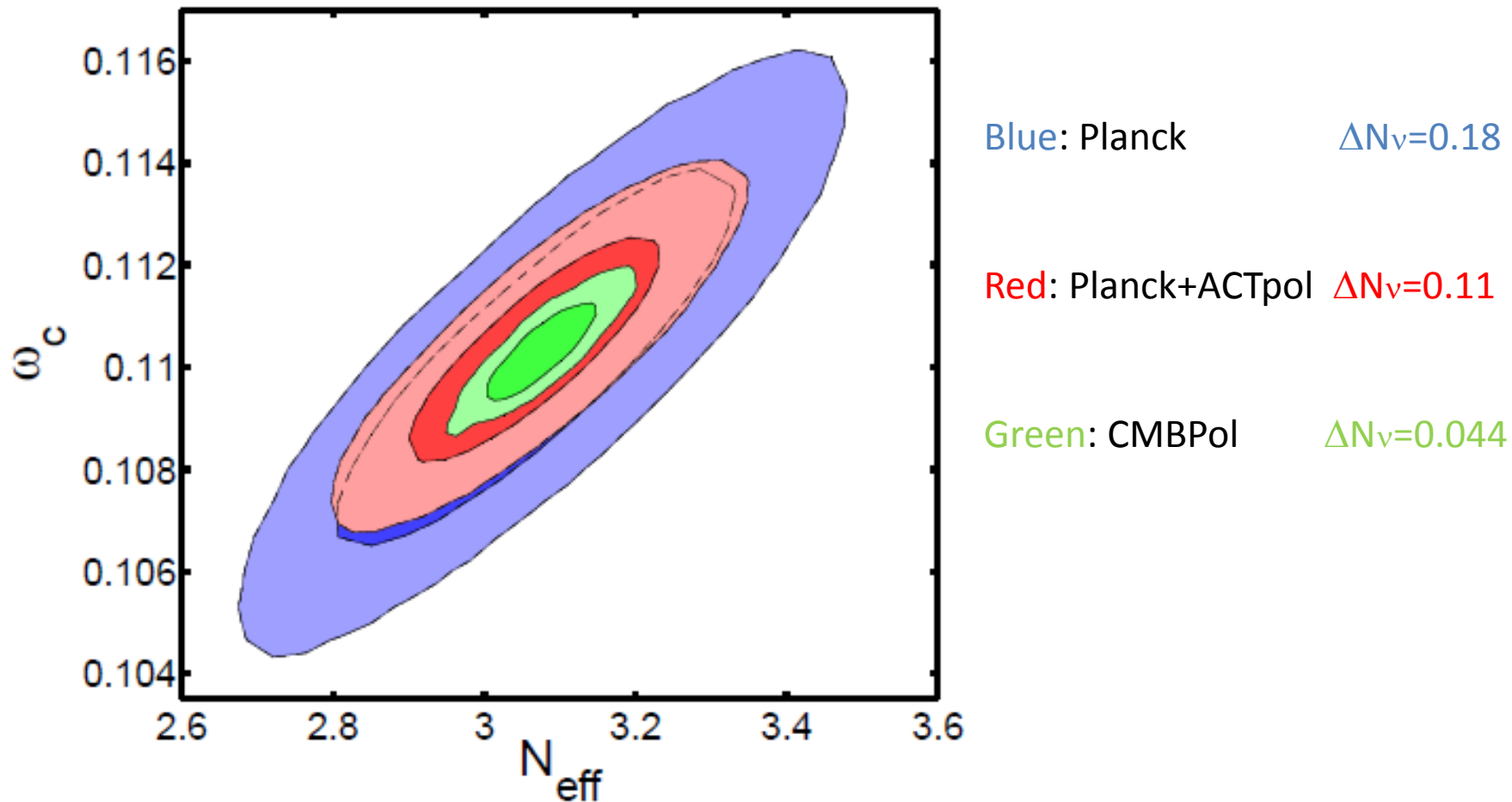
Let's consider not only Planck but also
 ACTpol (From Atacama Cosmology Telescope,
 Ground based, results expected by 2013)
 CMBpol (Next CMB satellite, 2020 ?)

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
$f_{sky} = 0.72$				

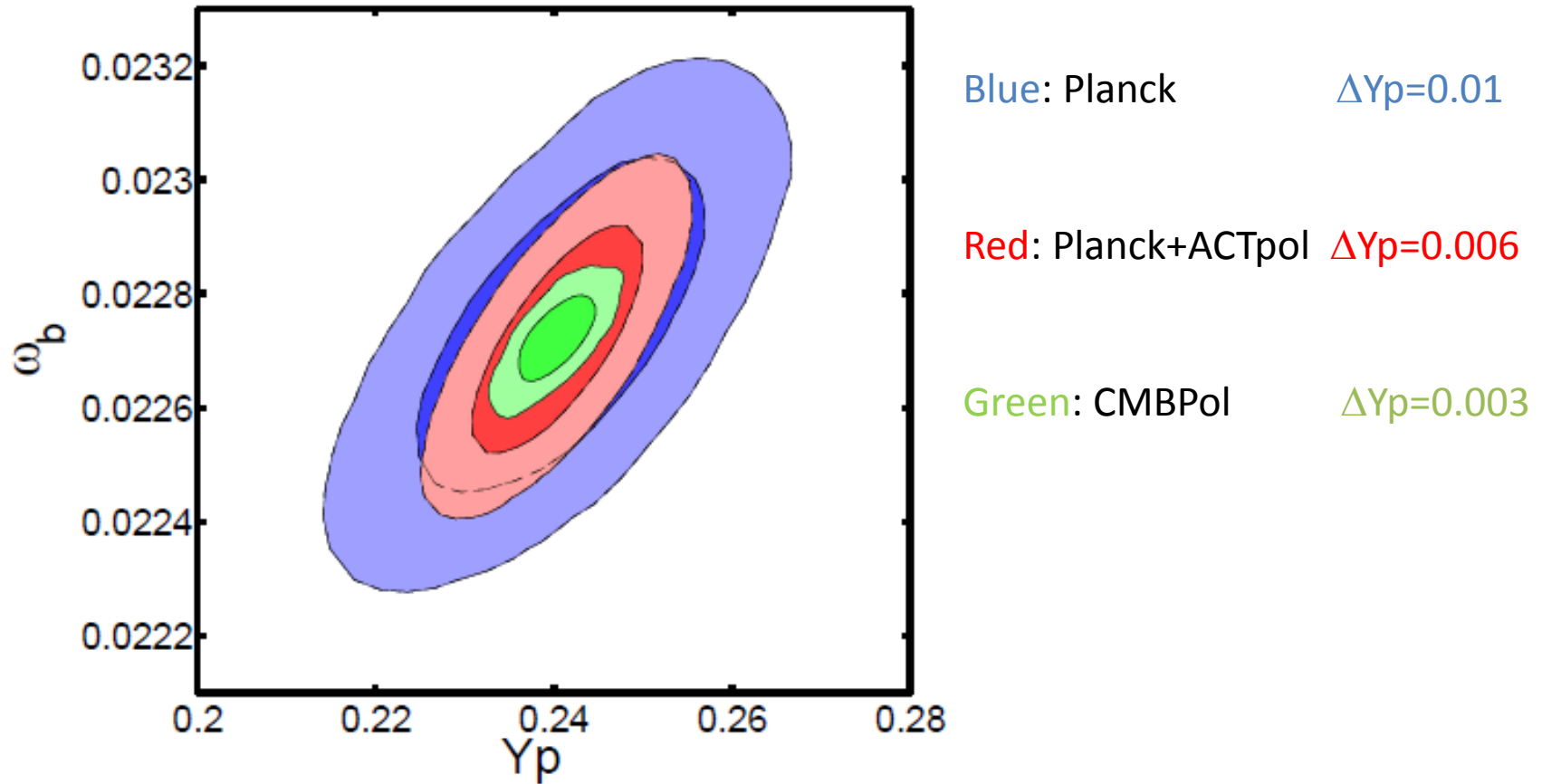
Parameter uncertainty	Planck	Planck+ACTPol		CMBPol	
$\sigma(\Omega_b h^2)$	0.00013	0.000078	(1.7)	0.000034	(3.8)
$\sigma(\Omega_c h^2)$	0.0010	0.00064	(1.6)	0.00027	(3.7)
$\sigma(\theta_s)$	0.00026	0.00016	(1.6)	0.000052	(5.0)
$\sigma(\tau)$	0.0042	0.0034	(1.2)	0.0022	(1.9)
$\sigma(n_s)$	0.0031	0.0021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

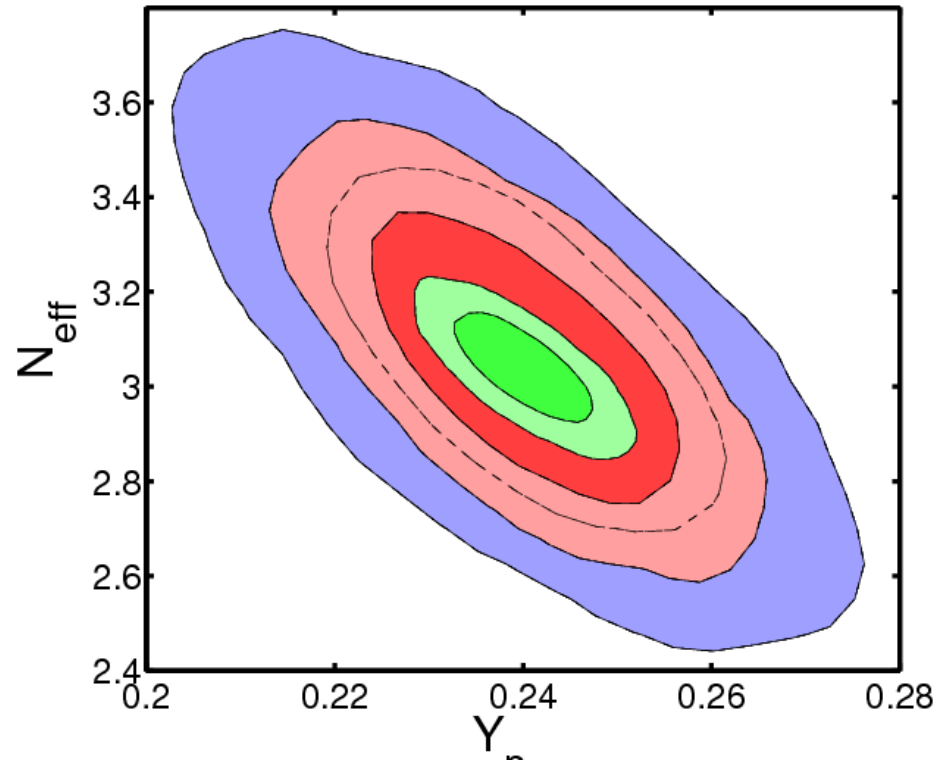
Constraints on Neutrino Number



Constraints on Helium Abundance



Constraints on Helium Abundance AND neutrino number



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

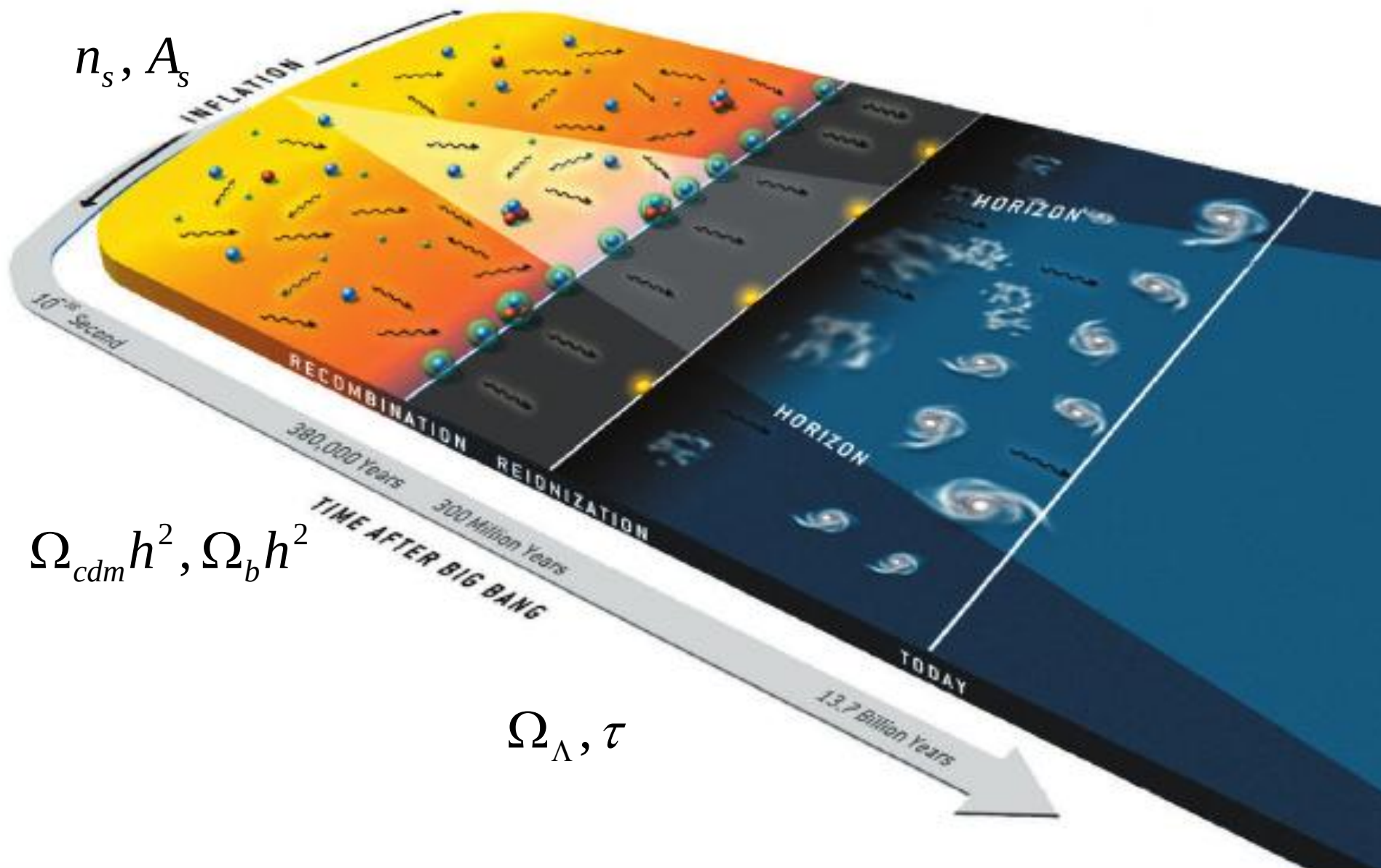
CONCLUSIONS

- 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 will know:

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

... and much more !



$$n_s, A_s$$

$$\Omega_{cdm} h^2, \Omega_b h^2$$

$$\Omega_\Lambda, \tau$$