Cosmological Constraints on Neutrino Physics

Workshop Beyond3ν, LNGS, 4^{th} May 2011

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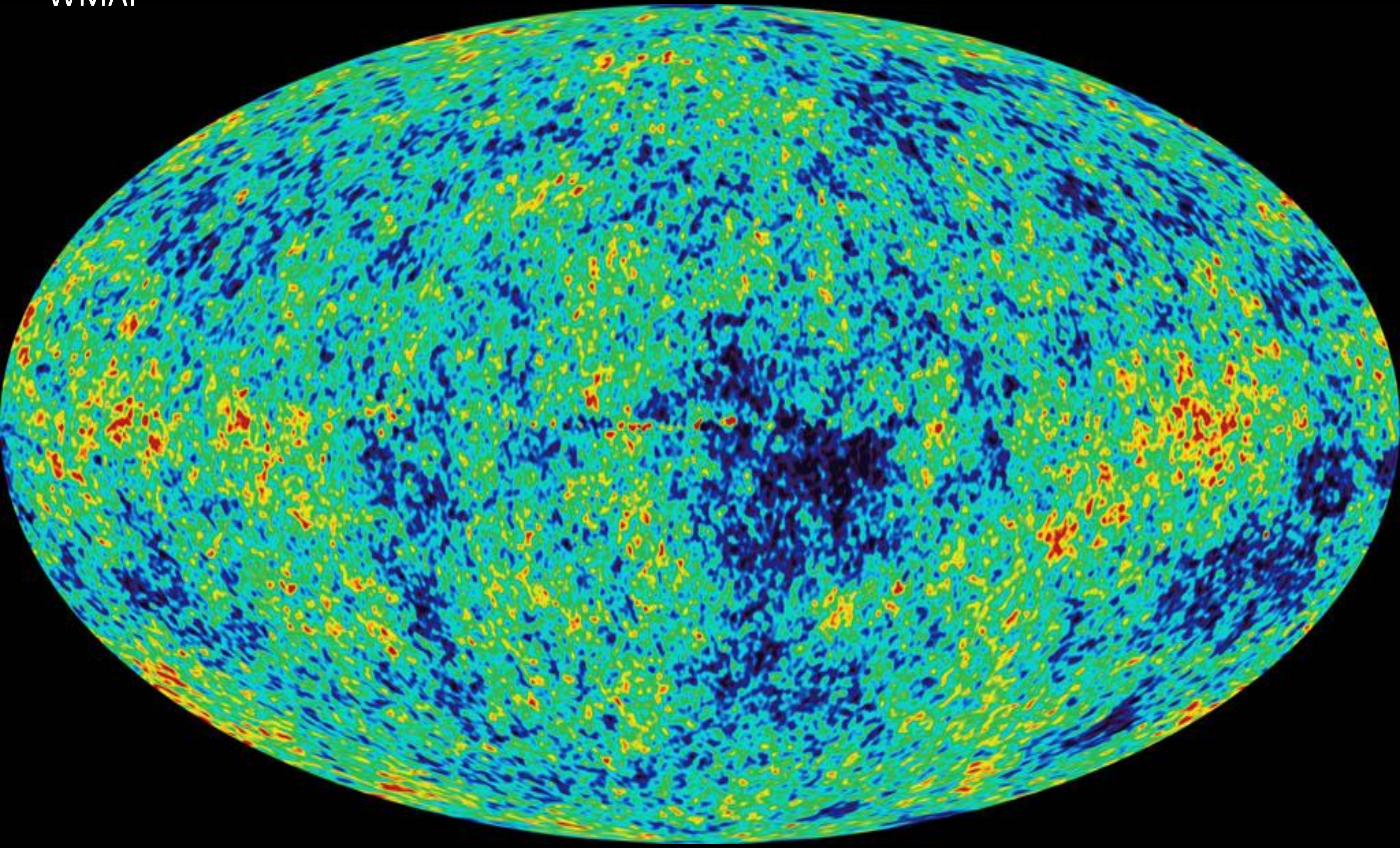
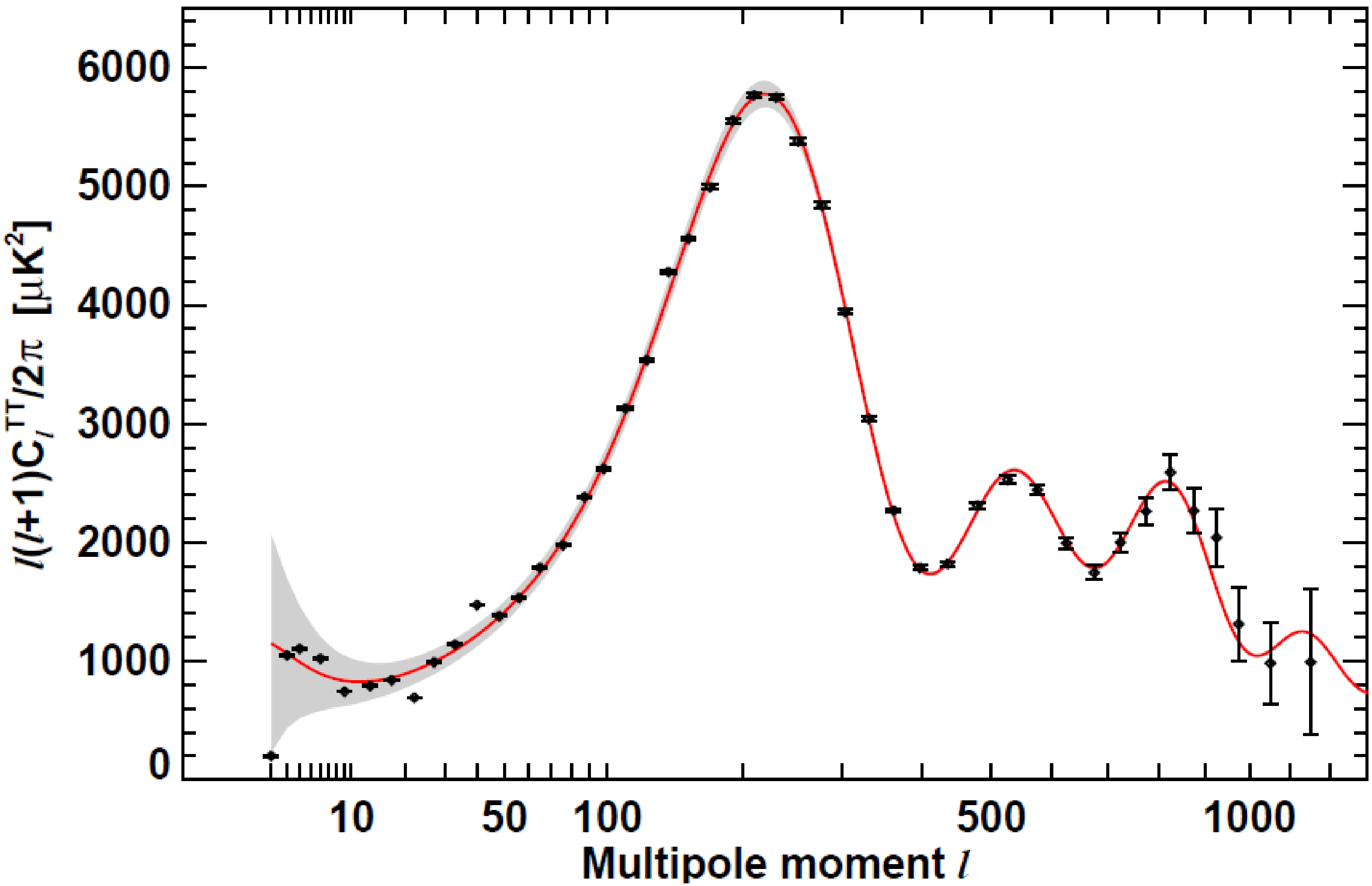
WMAP



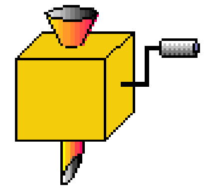
New WMAP results from 7 years of observations

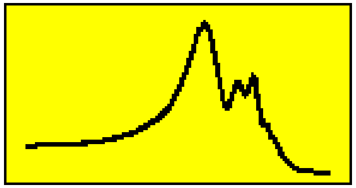


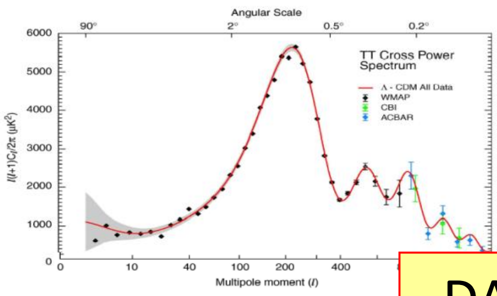
Komatsu et al, 2010, 1001.4538

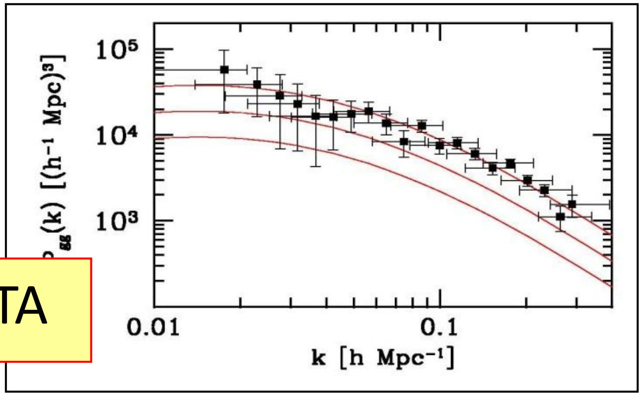
How to get a bound (measurement) of a cosmological parameter from CMB or Galaxy Survey data

Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau , \Sigma m_\nu)$

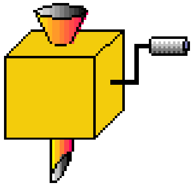








DATA



PARAMETER ESTIMATES

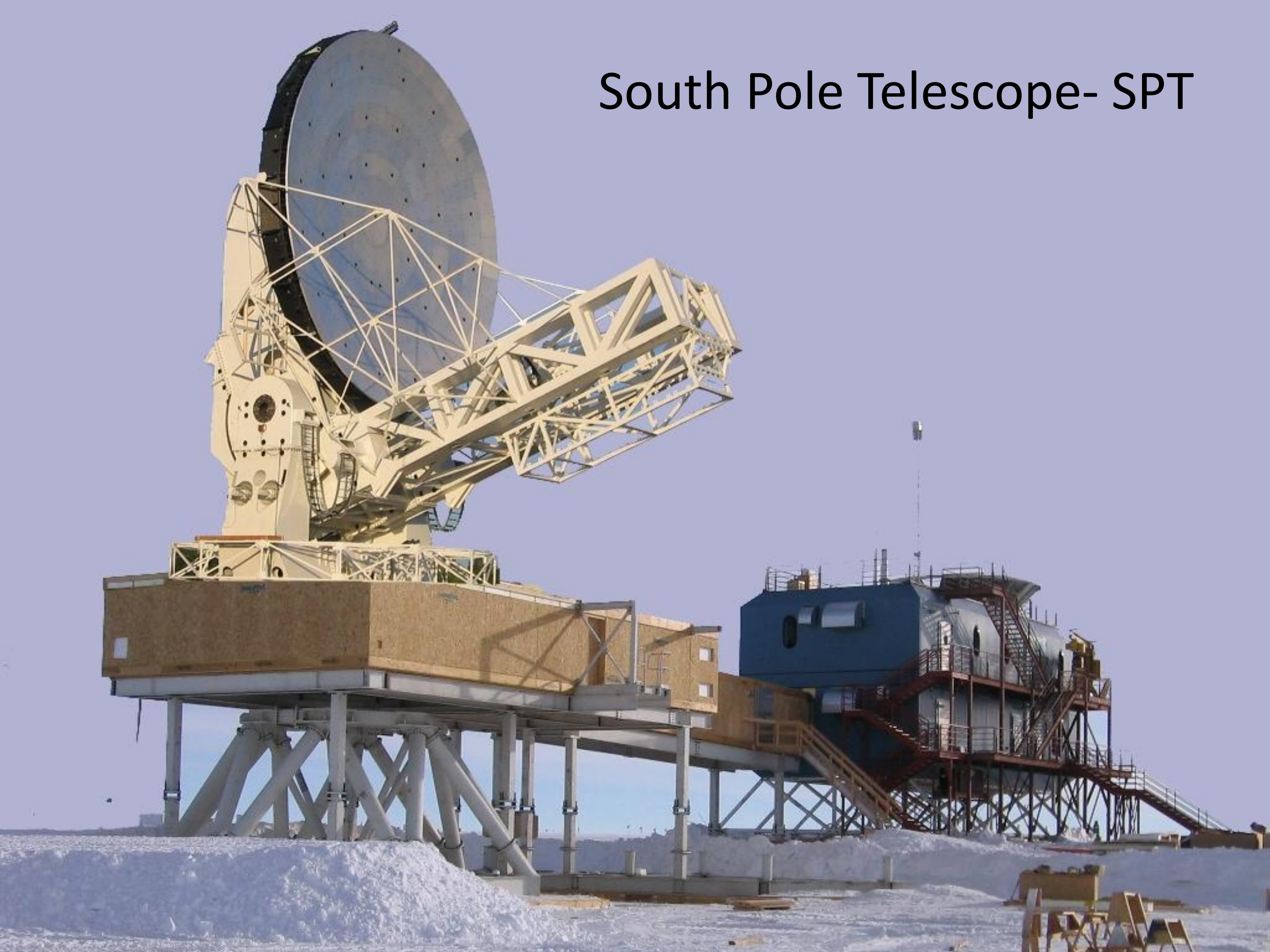
WMAP constraints didn't change much in the past 2 years

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
$z_{\rm eq}$	3196^{+134}_{-133}	3176^{+151}_{-150}
$z_{\rm reion}$	10.5 ± 1.2	11.0 ± 1.4

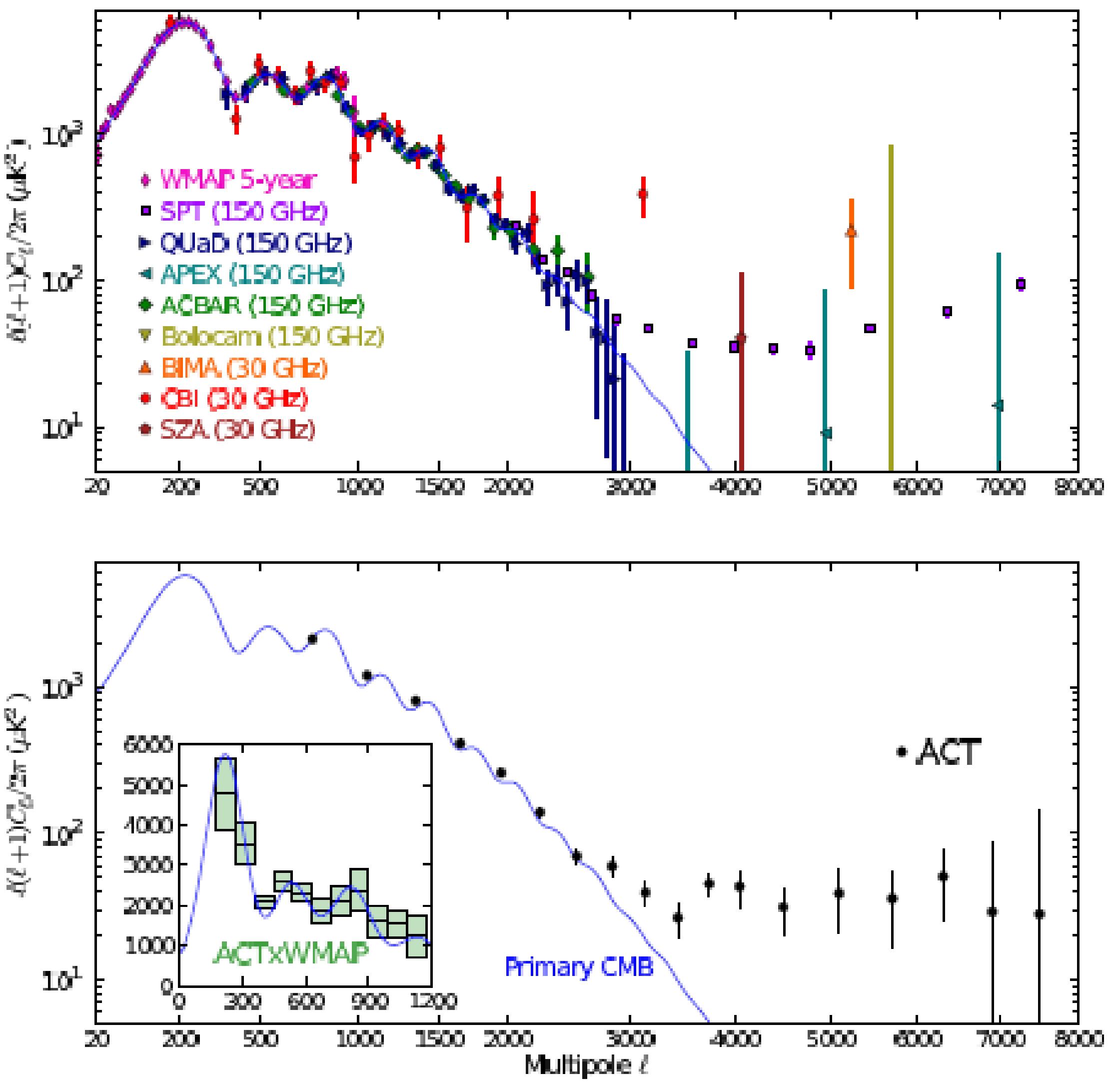
Komatsu et al, 2010, 1001.4538

South Pole Telescope- SPT



Atacama Cosmology Telescope ACT

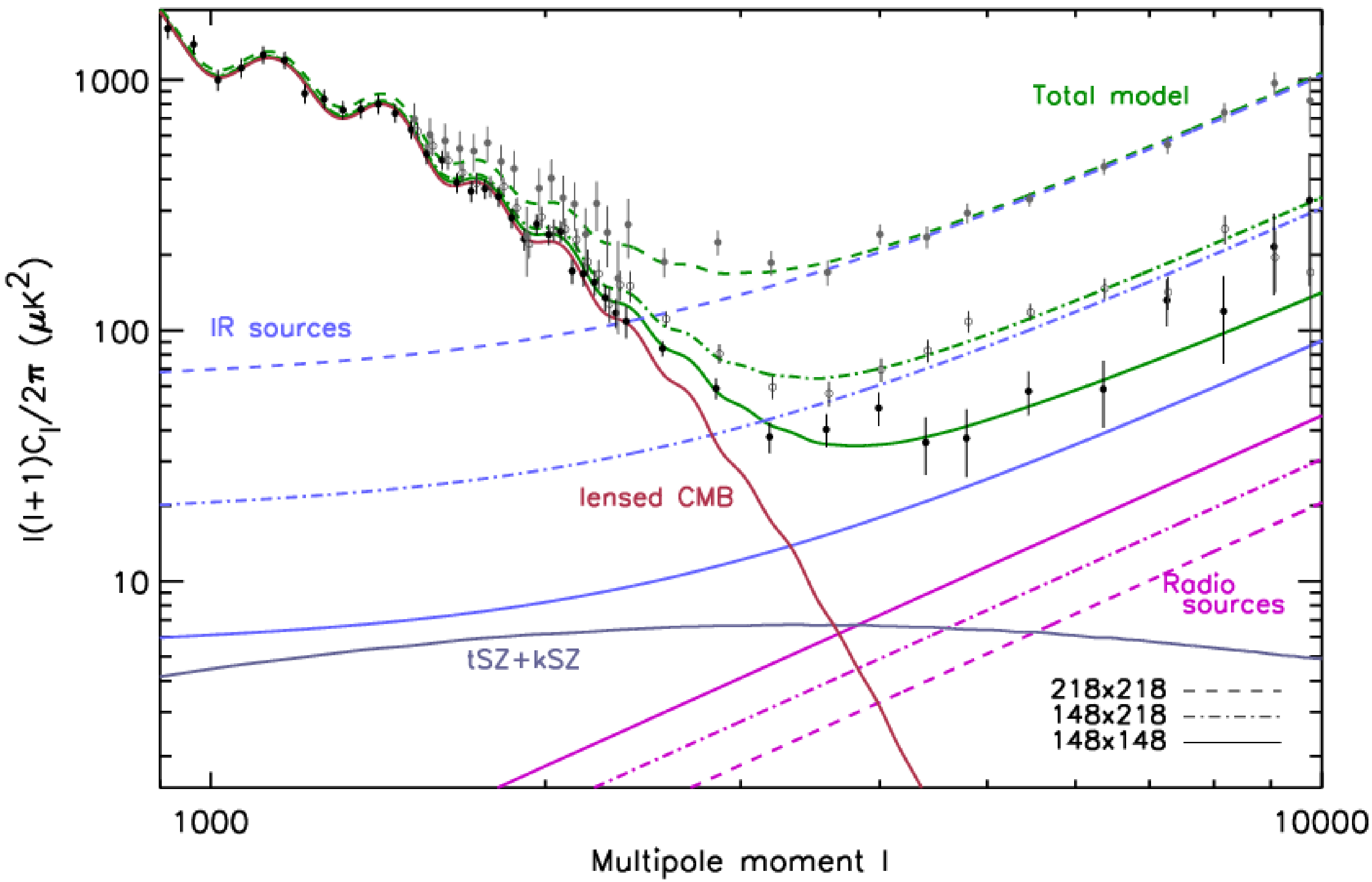
New small-scale CMB measurements by ACT and SPT



These experiments sample small scale anisotropies were th contribution from the local universe plays an important role (point sources, SZ, Lensing). Measuring the damping tail of primary CMB helps in constraining the parameters. Multifrequency is needed.

Flowler et al (ACT collaboration), 2010

New Results: ACT



S. Das et al, http://arxiv.org/abs/1009.0847

J. Dunkley et al., http://arxiv.org/abs/1009.0866

These new measurements improve the constraints also on «new» parameters:

- Neutrino masses Σm_ν
- Neutrino effective number N_ν^{eff}
- Primordial Helium Y_P

Cosmological (Active) 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:

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

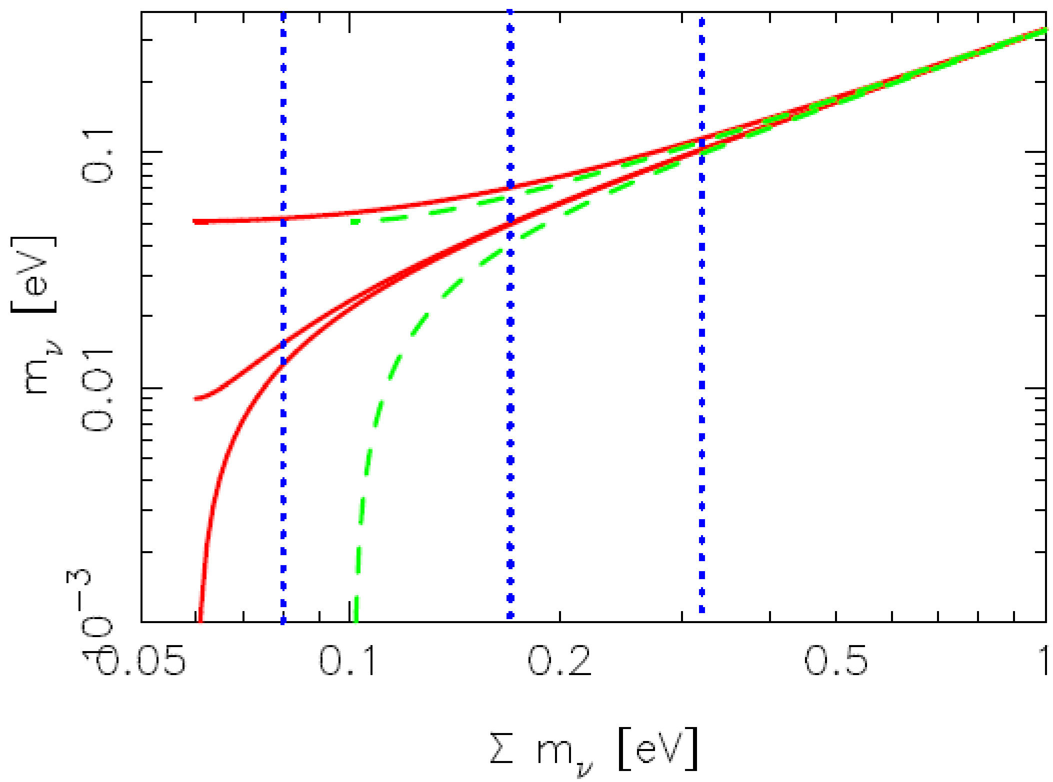
With a density of:

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

That, for a massive neutrino translates in:

$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{92.5eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_k m_k}{92.5eV}$$

Testing the neutrino hierarchy



Degenerate Hierarchy predicts:

$$\sum m_v > 0.15\ eV$$

Inverted Hierarchy predicts:

$$\sum m_v > 0.10\ eV$$

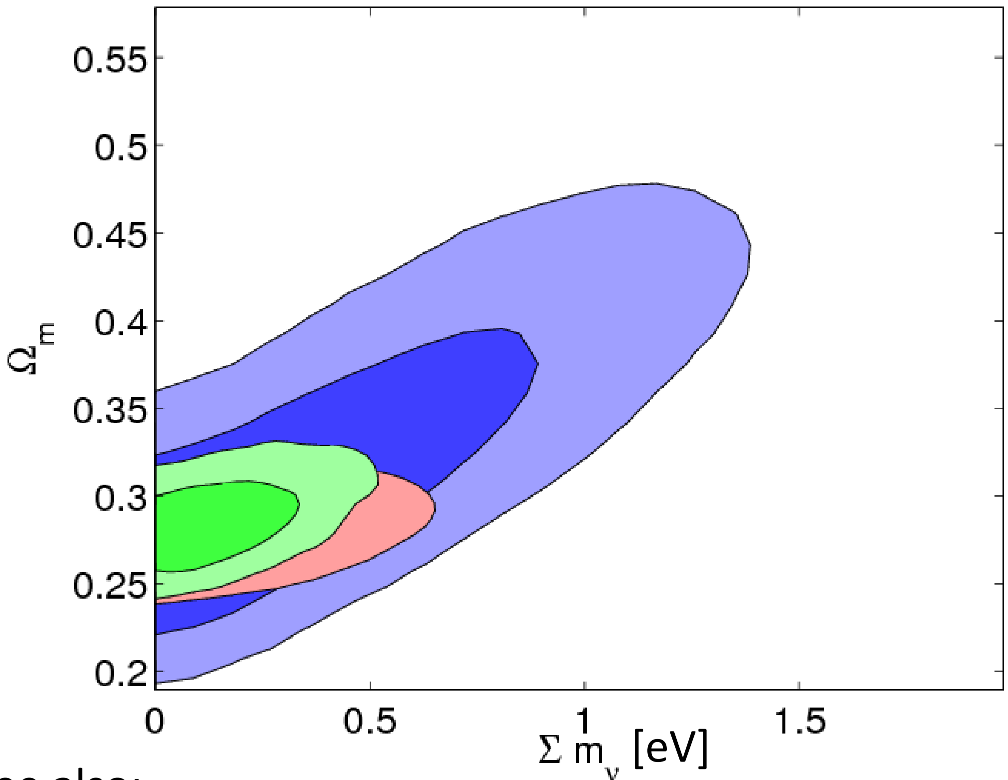
Normal Hierarchy predicts:

$$\sum m_v > 0.05\ eV$$

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

Current constraints on active neutrino mass from Cosmology

Fogli et al, 2011 in preparation



Blue: WMAP-7

Red: w7+SN+Bao+H0

Green: w7+CMBsuborb+SN+LRG+H0

Current constraints (assuming ΛCDM):

$\Sigma m_\nu < 1.3$ [eV] CMB

$\Sigma m_\nu < 0.7$-0.5 [eV] CMB+other

$\Sigma m_\nu < 0.3$ [eV] CMB+LSS (extreme)

See also:

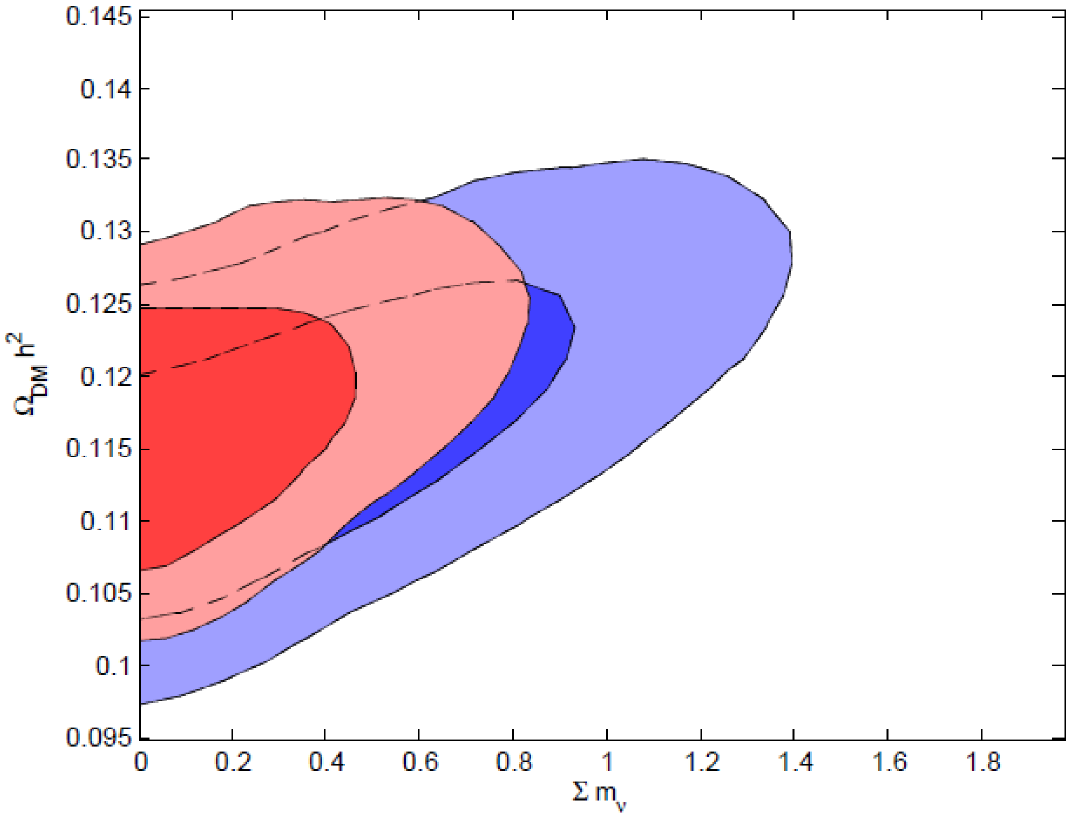
M. C. Gonzalez-Garcia, Michele Maltoni, Jordi Salvado, **arXiv:1006.3795**

Toyokazu Sekiguchi, Kazuhide Ichikawa, Tomo Takahashi, Lincoln Greenhill, **arXiv:0911.0976**

Extreme (sub 0.3 eV limits):

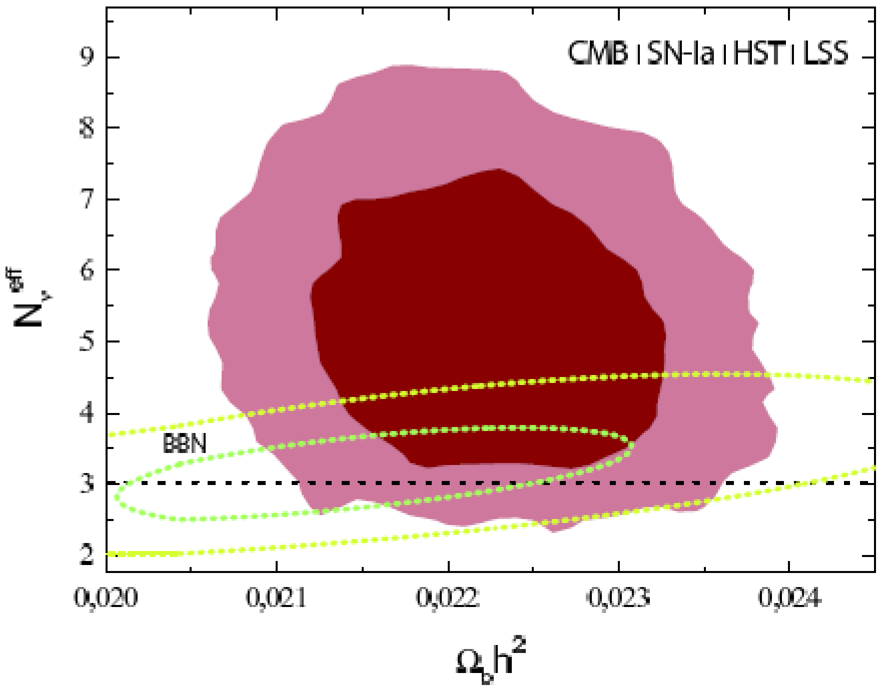
F. De Bernardis et al, Phys.Rev.D78:083535,2008, Thomas et al. Phys. Rev. Lett. 105, 031301 (2010)

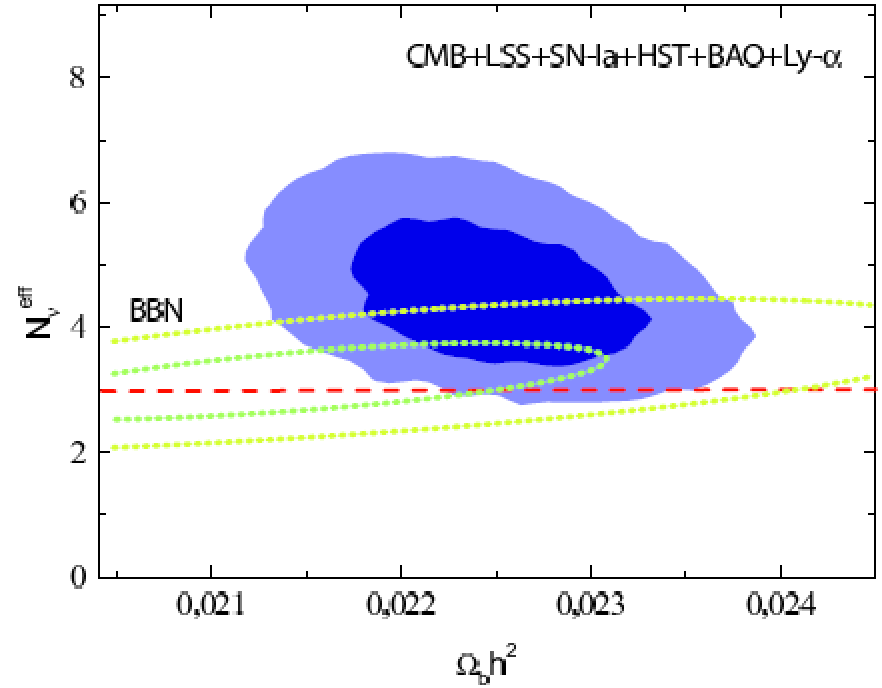
New ACT data improves CMB Bound on neutrino mass



Blue: WMAP-7
Red: w7+ACT

Hints for sterile neutrinos from cosmology ?

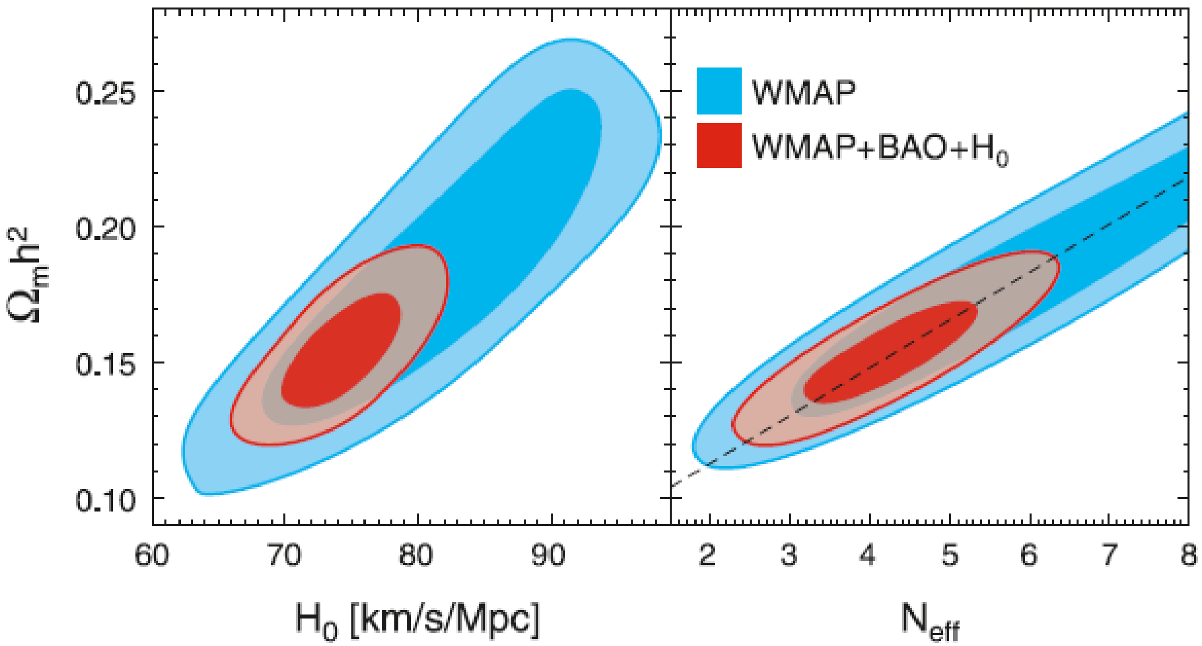




Gianpiero Mangano, Alessandro Melchiorri, Olga Mena, Gennaro Miele, Anze Slosar

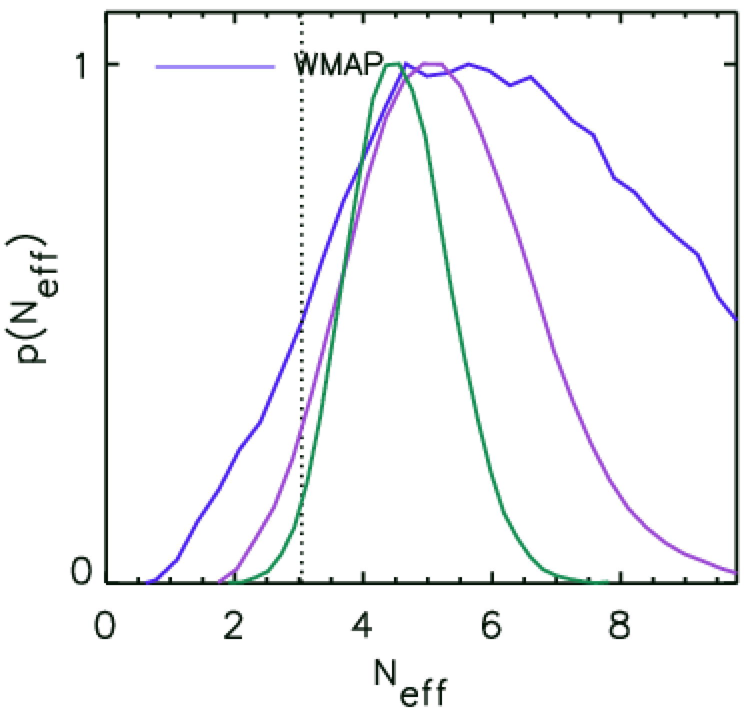
Journal-ref: JCAP0703:006,2007

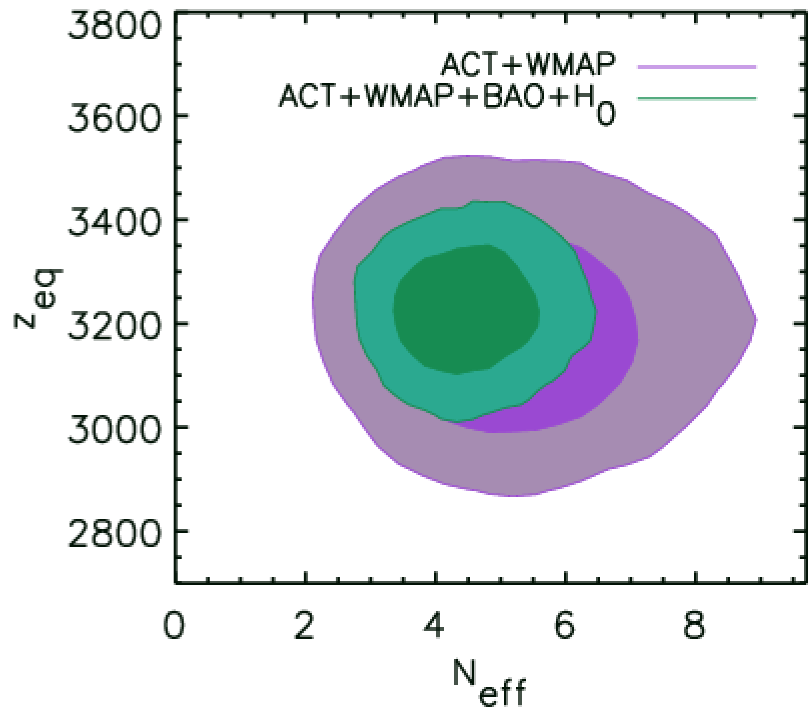
Komatsu et al, 2010, 1001.4538



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)		$4.34^{+0.86}_{-0.88}$	$4.25^{+0.76}_{-0.80}$

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





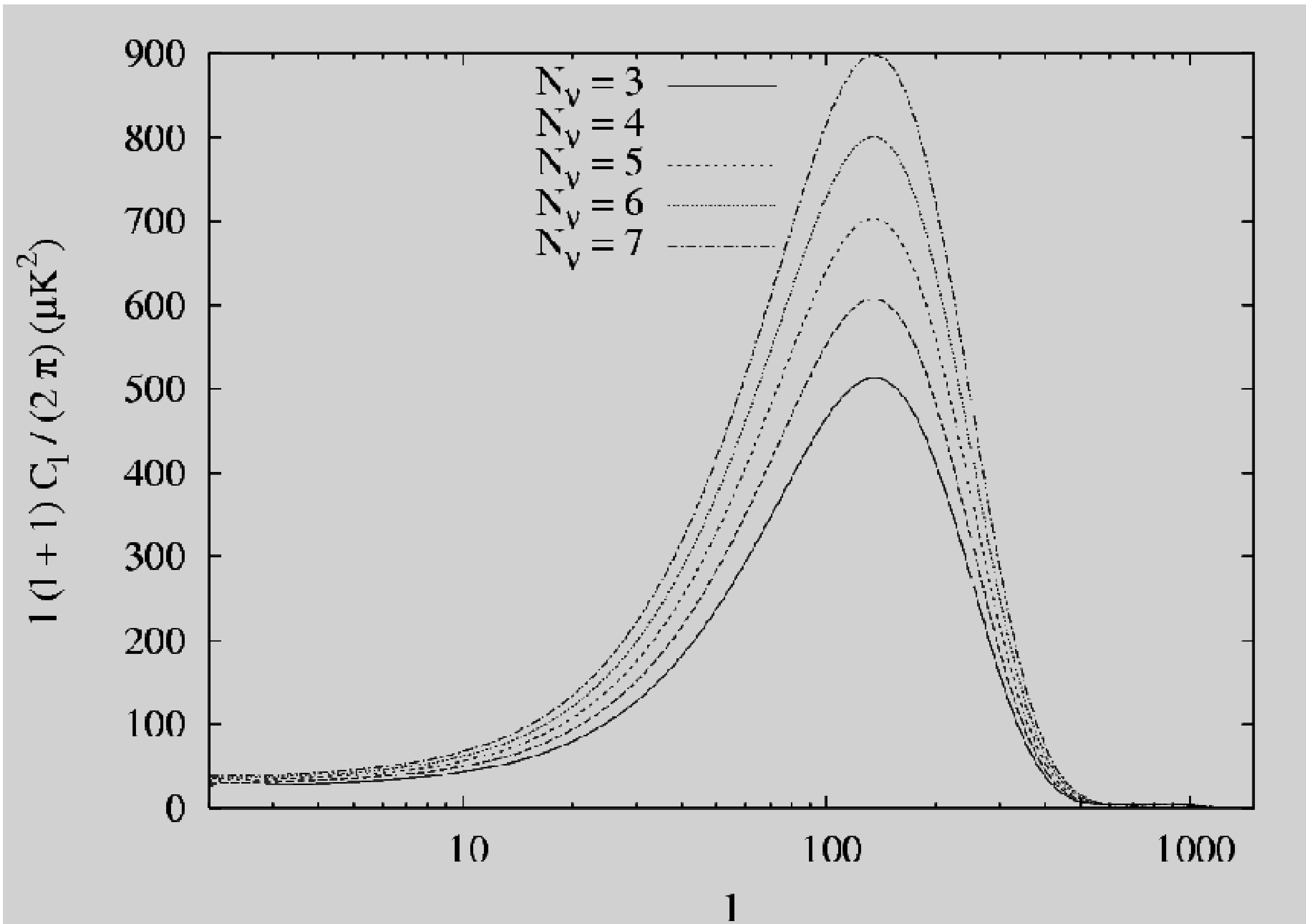
Latest results from ACT, Dunkley et al. 2010
(95 % c.l.)

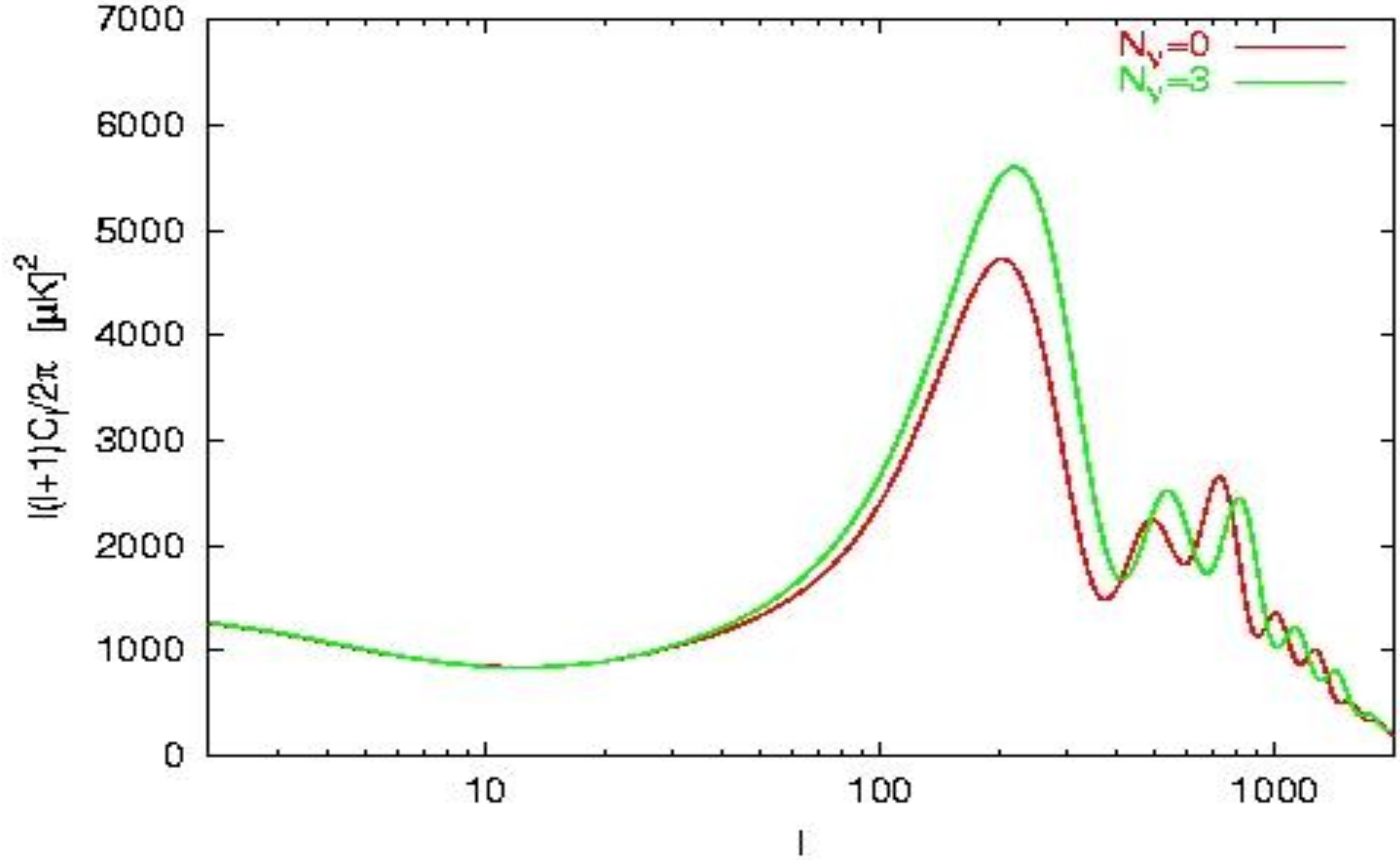
$Neff = 5.3 \pm 1.3$ ACT+WMAP

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

Effect of Extra Massless Neutrinos in the CMB: Early ISW

Changing the number of neutrinos (assuming them as massless) shifts the epoch of equivalence, increasing the Early ISW:

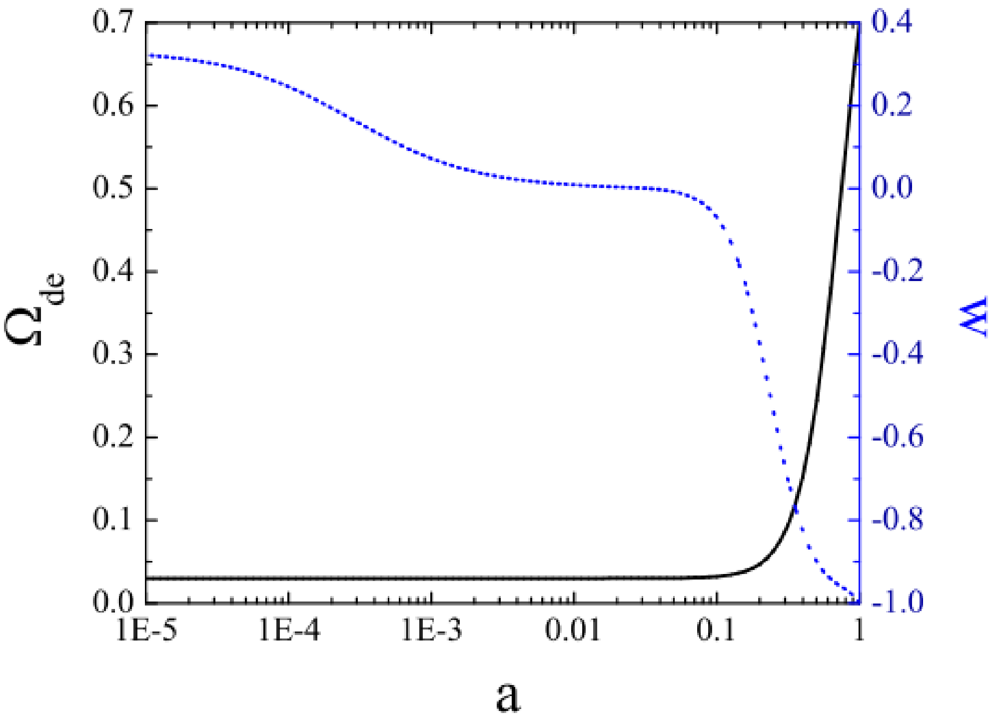


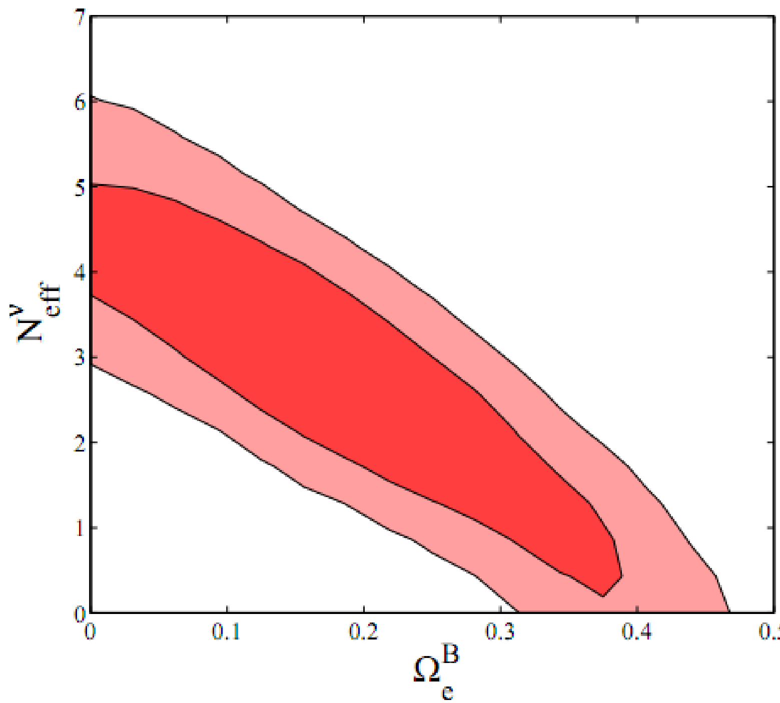


Caveat: CMB is NOT sensitive just to Neutrinos But to ANY extra relativistic contribution at recombination (extra dimensions, axions…dark energy).

Extra Neutrinos or Early Dark Energy ?

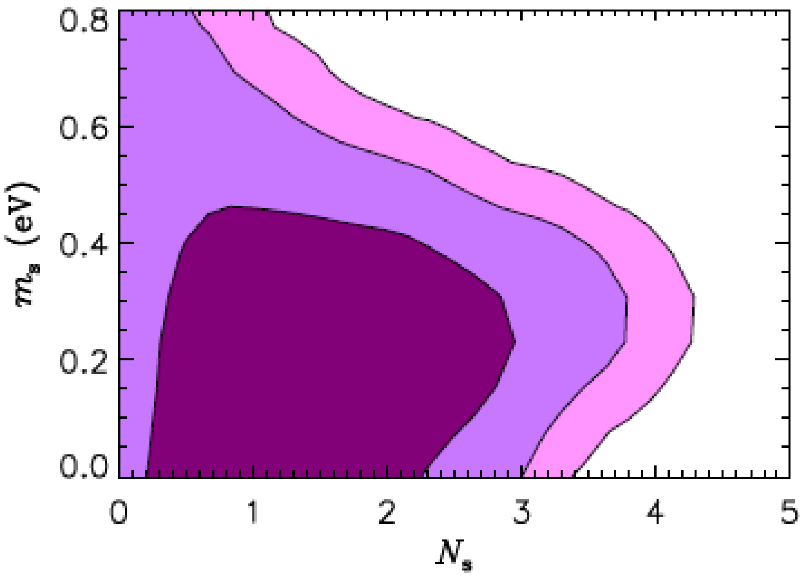
An «Early» dark energy component could be present in the early universe at recombination and nucleosynthesis. This component could behave like radiation (tracking properties) and fully mimic the presence of an extra relativistic background !



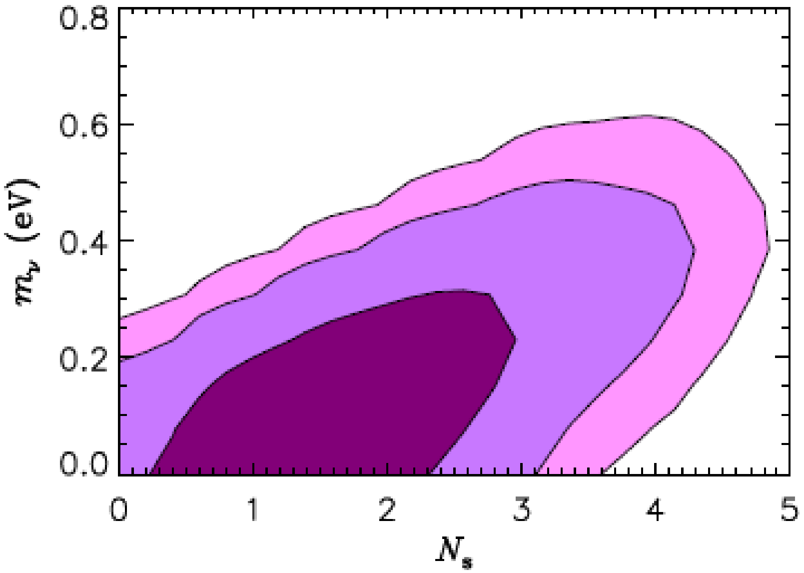


E. Calabrese et al, **arXiv:1103.4132**

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



3 Active massless neutrinos+
N_s massive neutrinos

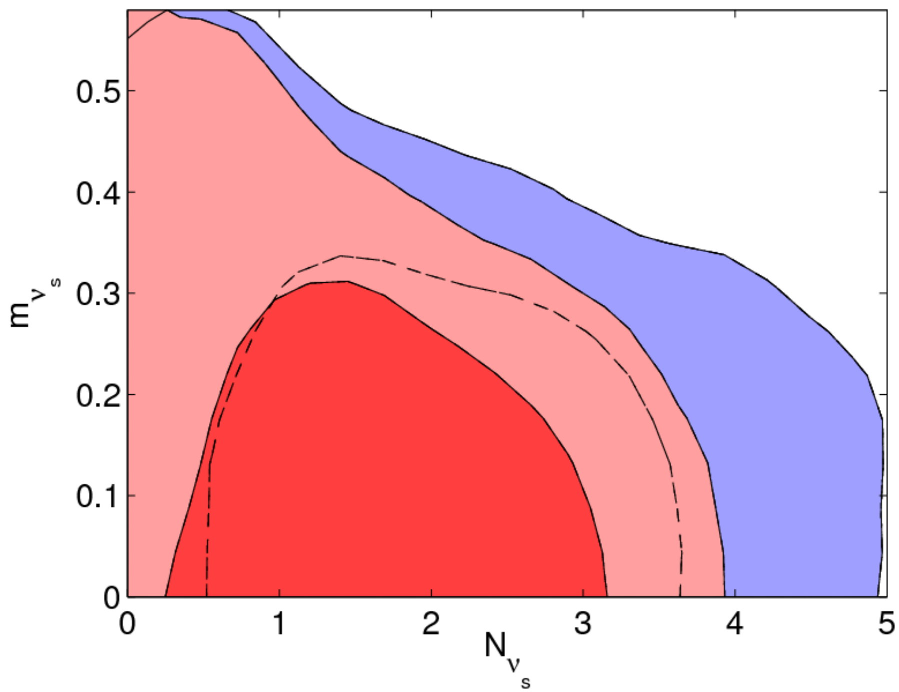


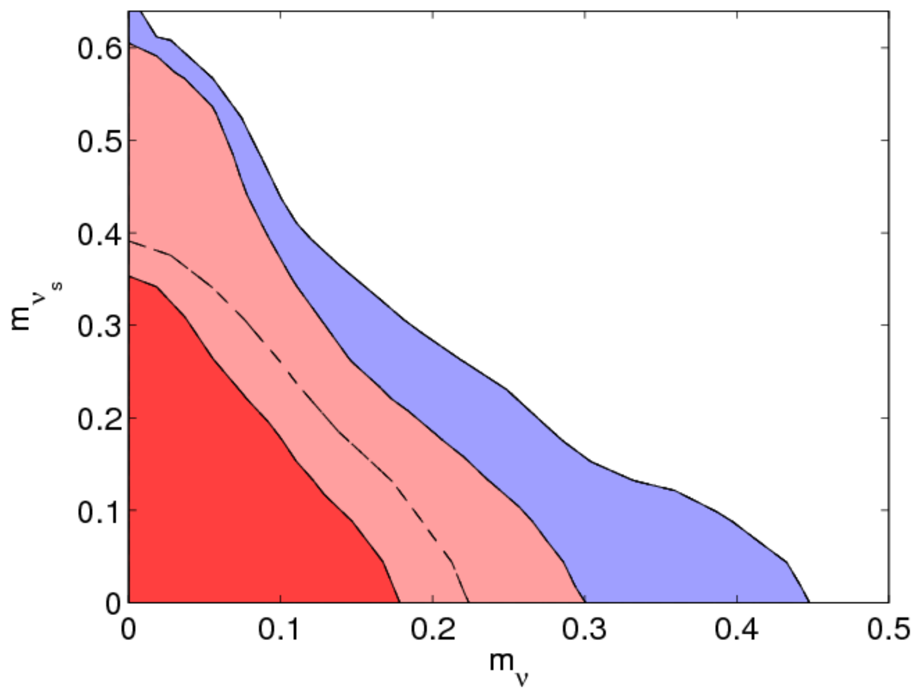
3 Active massive neutrinos +
N_s massless neutrinos

J. Hamann et al, [arXiv:1006.5276]

Latest analysis

Giusarma et al., 2011 http://arxiv.org/abs/1102.4774
includes masses both in active and sterile Neutrinos.

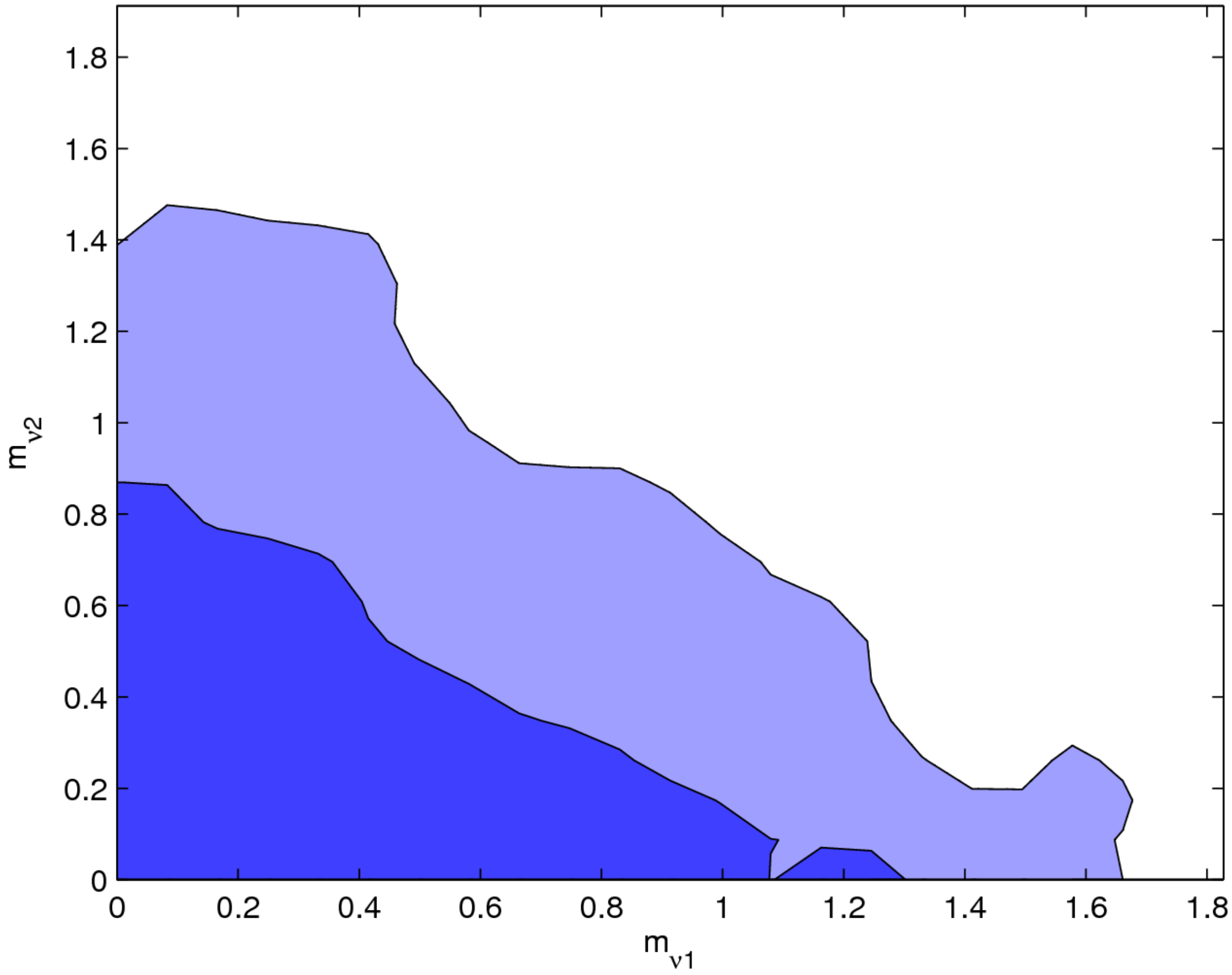




Blue: CMB+HST+SDSS
Red: CMB+HST+SDSS+SN-Ia

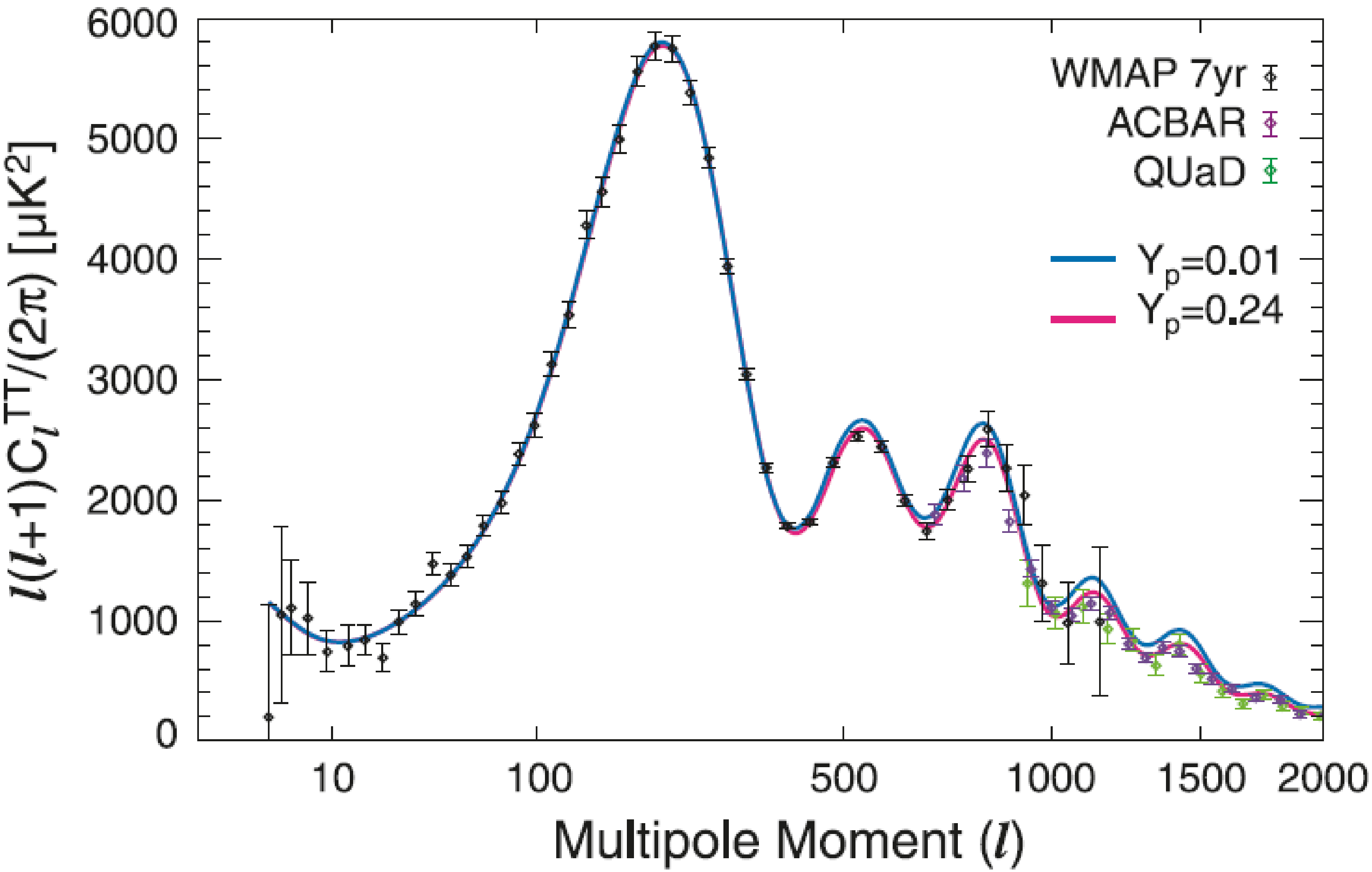
Parameter	68% CL(r1)	95% CL(r1)	68% CL (r2)	95% CL (r2)
N_{ν_s}	$0.94 - 3.16$	$0.21 - 4.63$	$0.69 - 2.53$	$0.13 - 3.56$
m_ν [eV]	$0.02 - 0.19$	< 0.36	$0.01 - 0.14$	< 0.24
m_{ν_s} [eV]	$0.04 - 0.31$	< 0.70	$0.03 - 0.30$	< 0.70

Preliminarly constraints from WMAP7 (only) for N_ν=5 case (3 active massless+2 steriles)



Archidiacono, Fornengo, Giunti, Melchiorri in preparation (2011 ?).

Small scale CMB can probe Helium abundance at recombination.

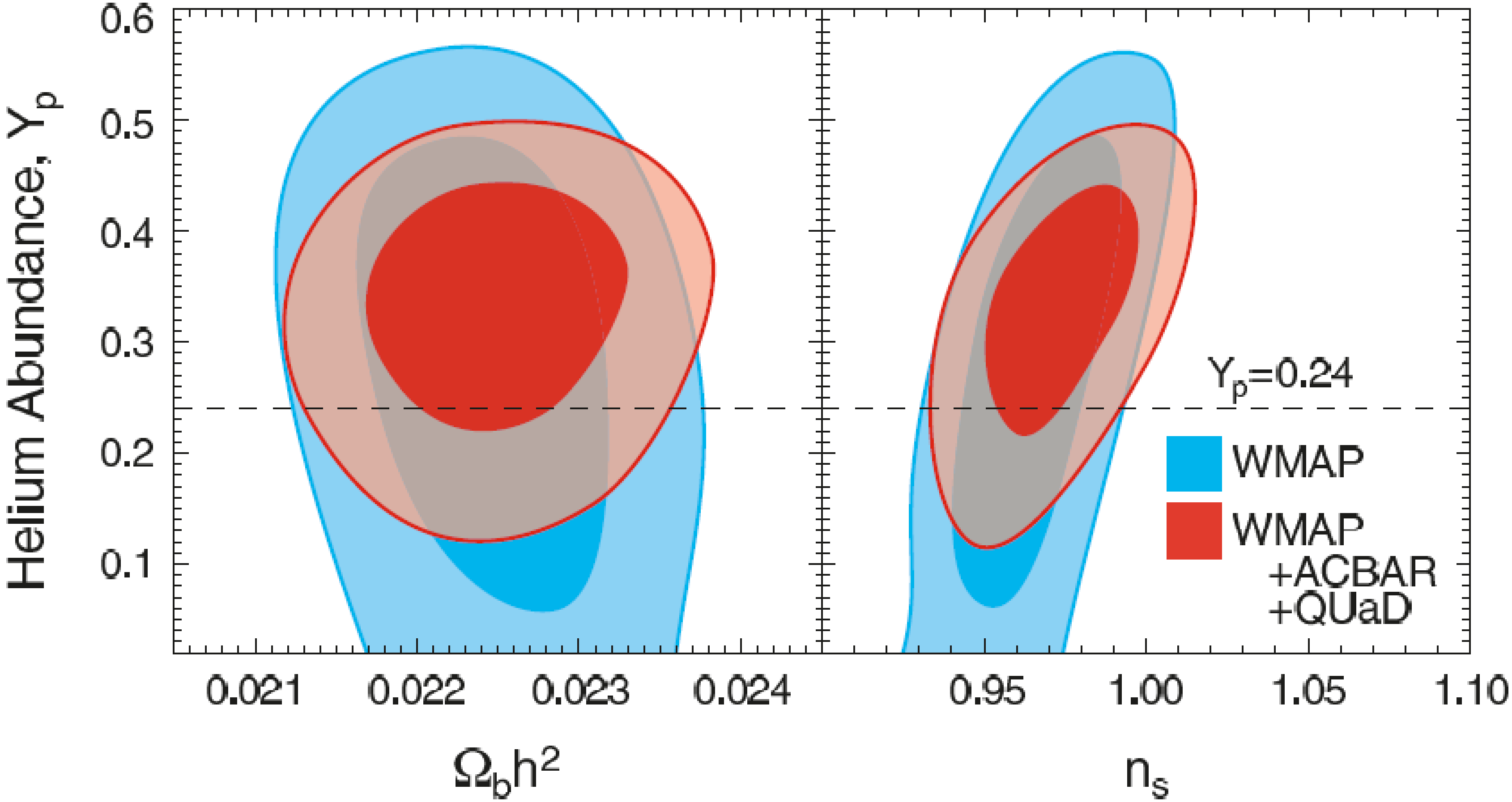


See e.g.,

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

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

WMAP7 Provides indication for primordial Helium

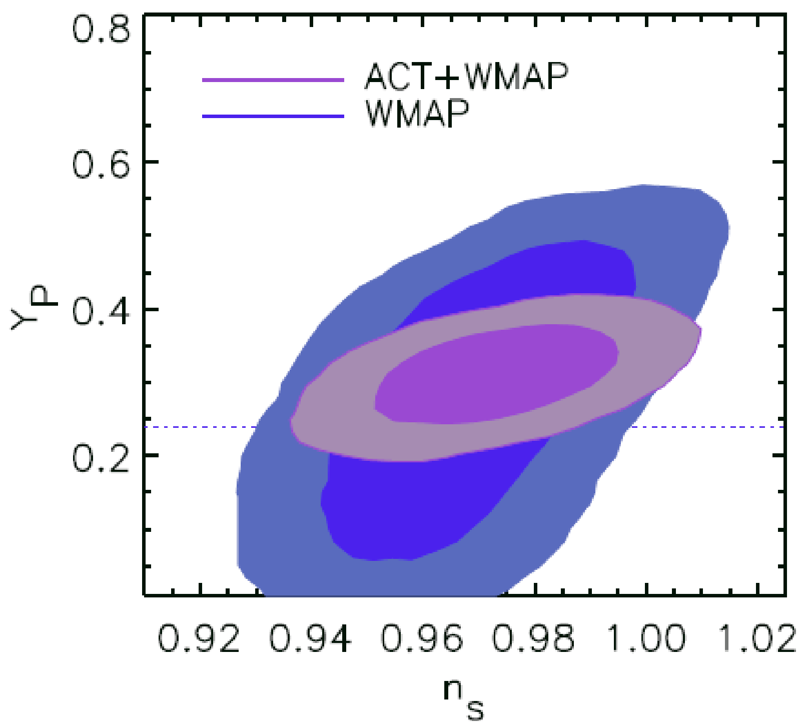


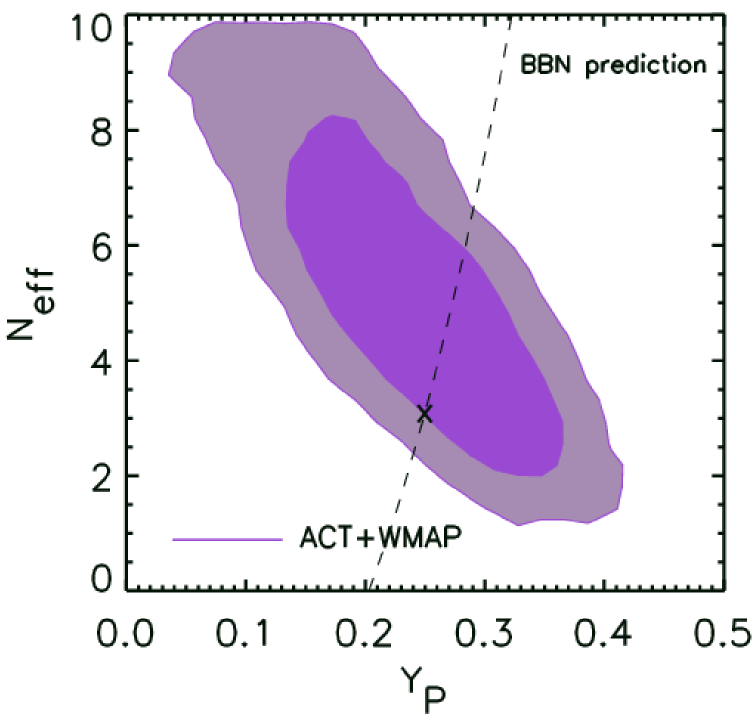
	WMAP only	*WMAP*+ACBAR+QUaD
Y_p	< 0.51 (95% CL)	$Y_p = 0.326 \pm 0.075$ (68% CL)[b]

Komatsu et al, 2010, 1001.4538

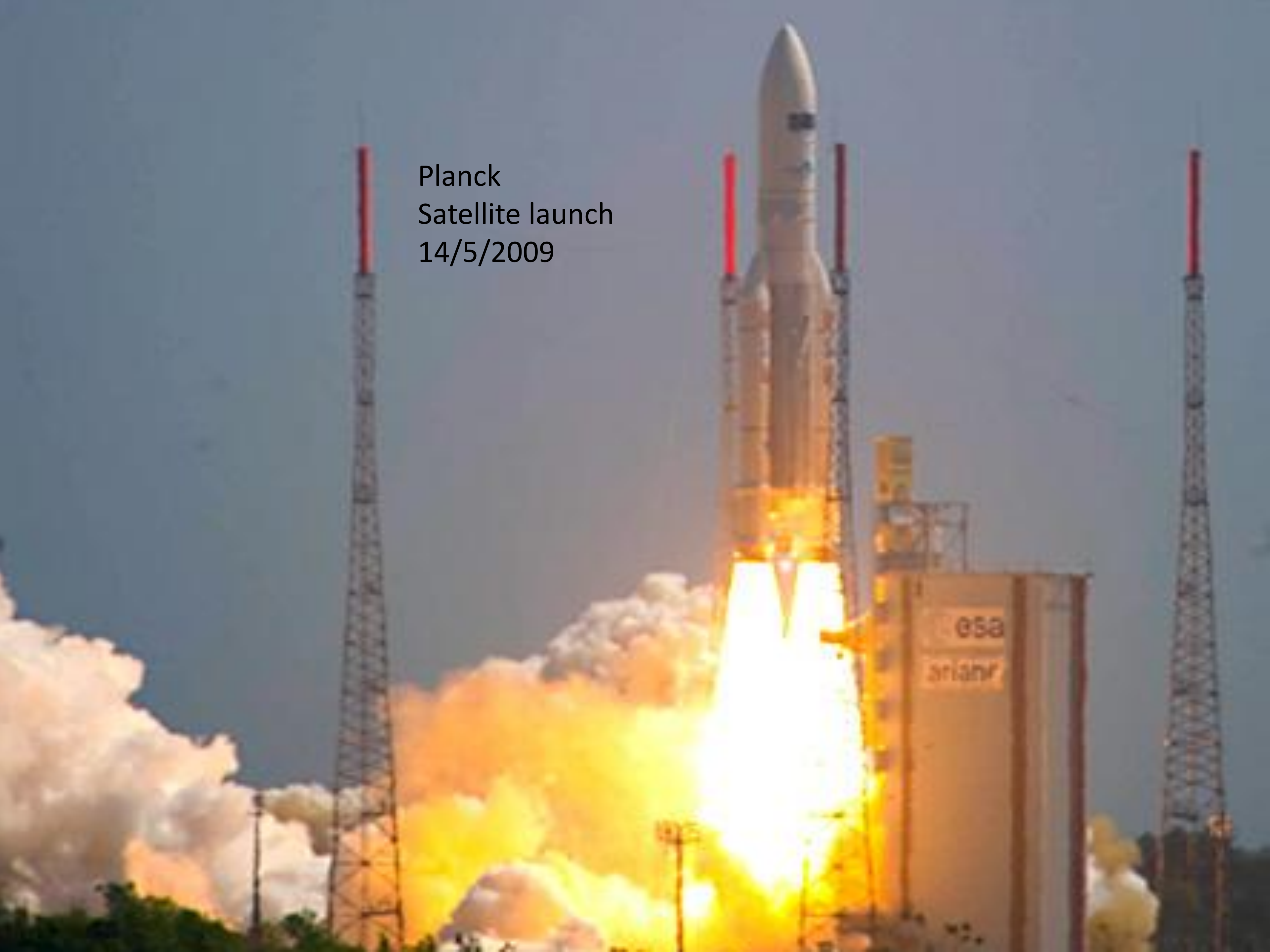
Further indication for primordial Helium from ACT

$$Y_P = 0.313 \pm 0.044 \text{ (68\% CL)}$$

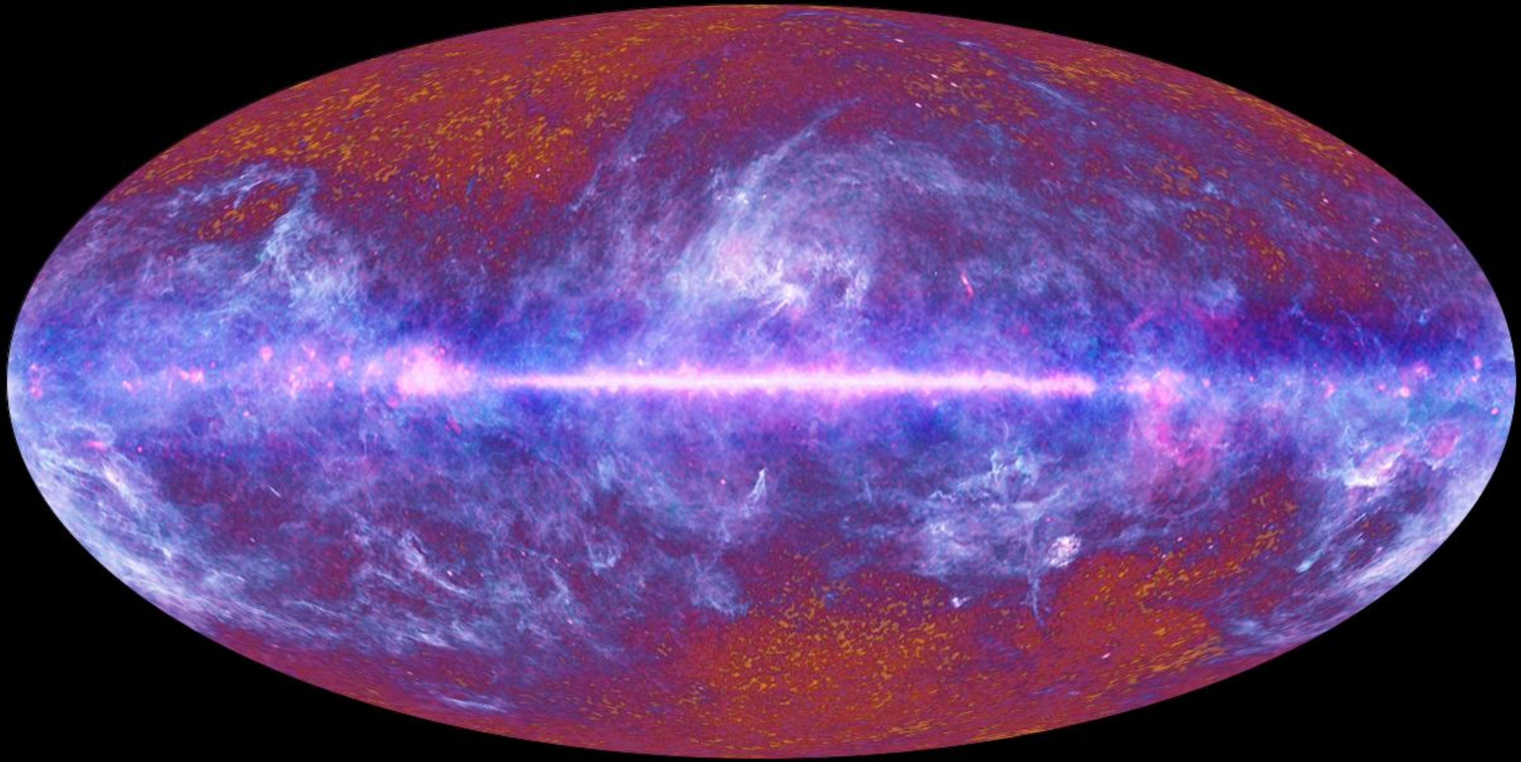




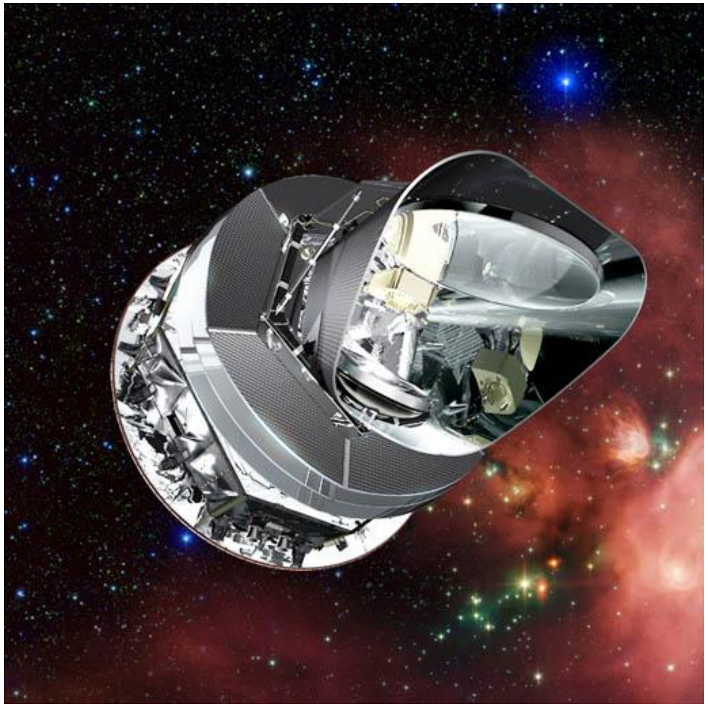
S. Das et al, http://arxiv.org/abs/1009.0847
J. Dunkley et al., http://arxiv.org/abs/1009.0866



Planck
Satellite launch
14/5/2009



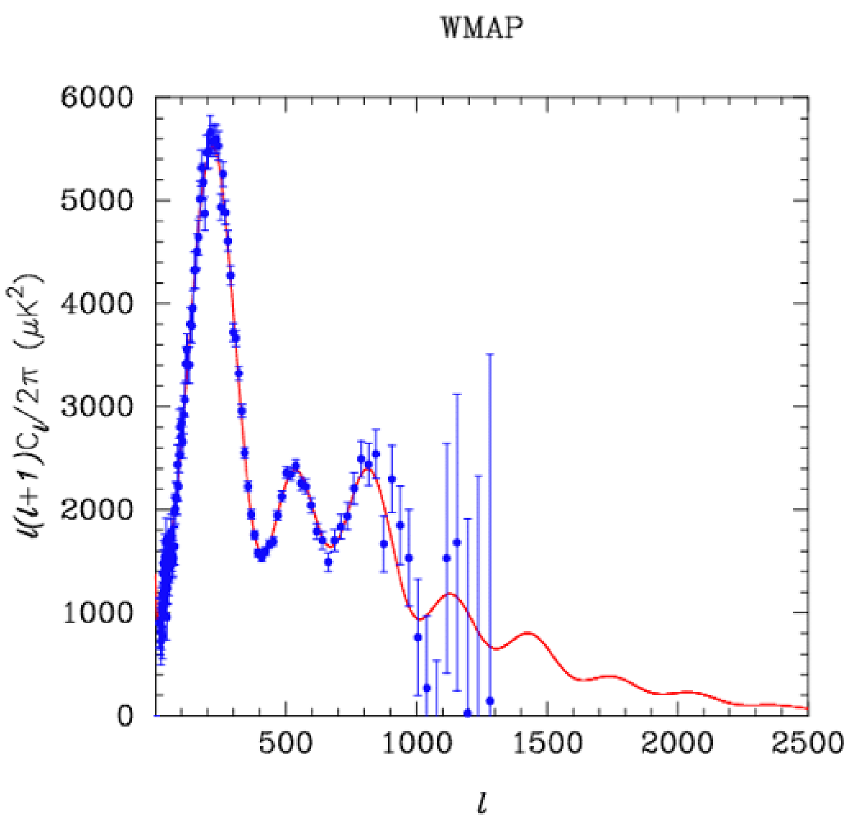
The Planck one-year all-sky survey

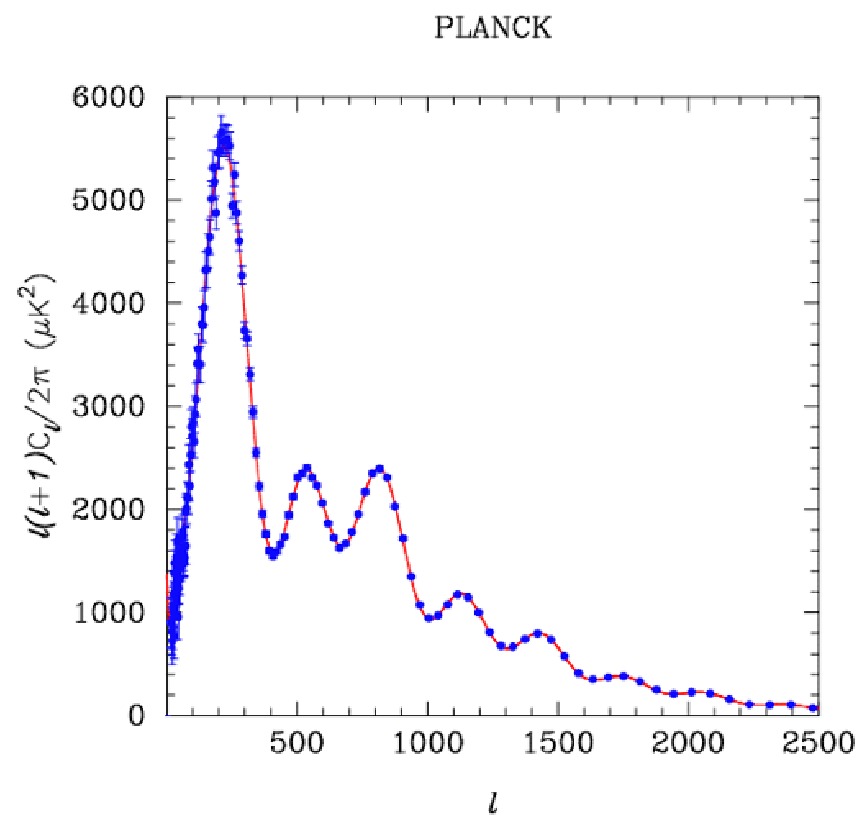


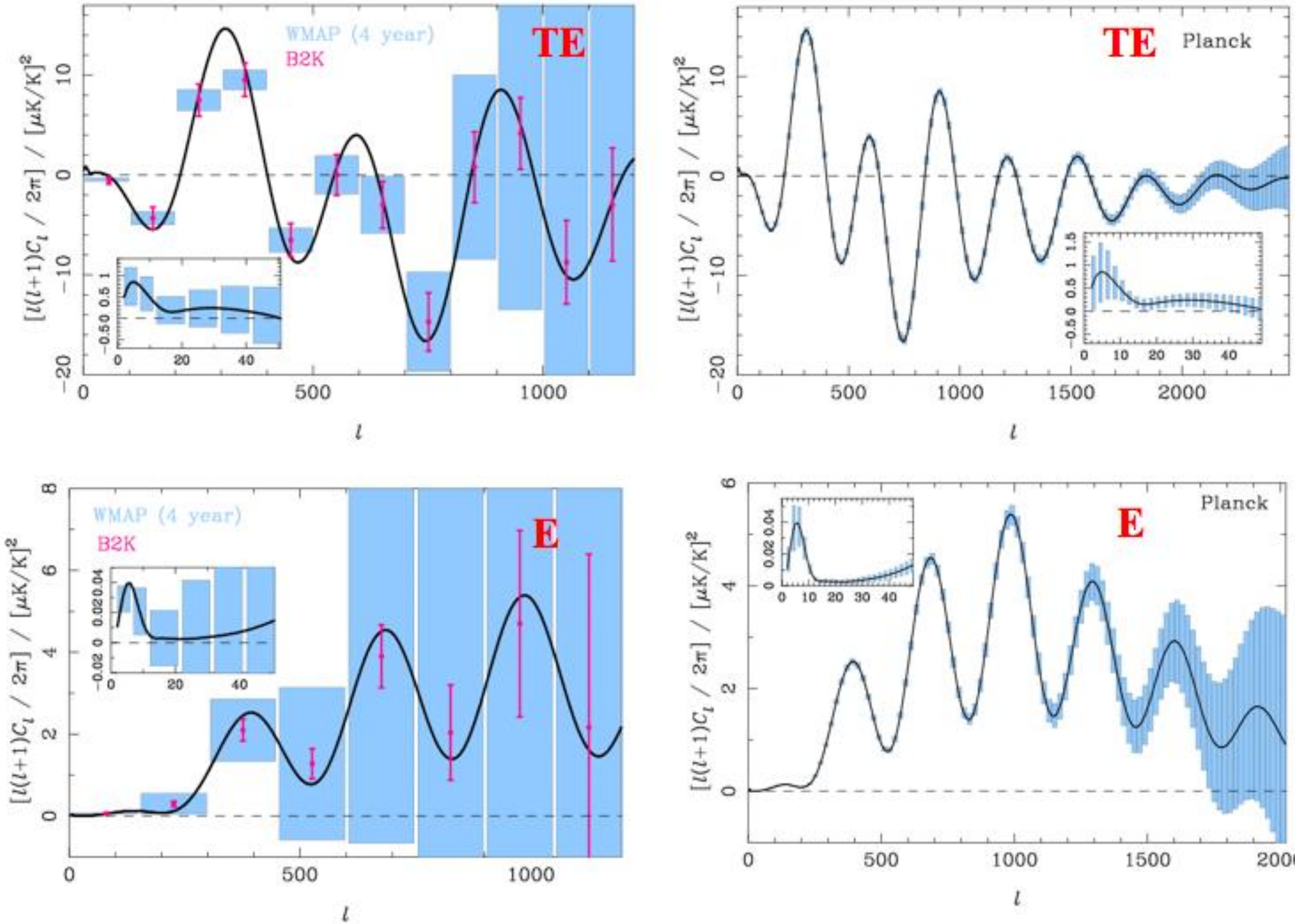
The Planck Collaboration
Released 23 Early Papers last January.
Results are mostly on astrophysical
sources (no cosmology).
Other 30 papers expected to be
Released on 2012 (but still
«just» astrophysics).
Papers on cosmology (and neutrinos)
WILL be released in January 2013.

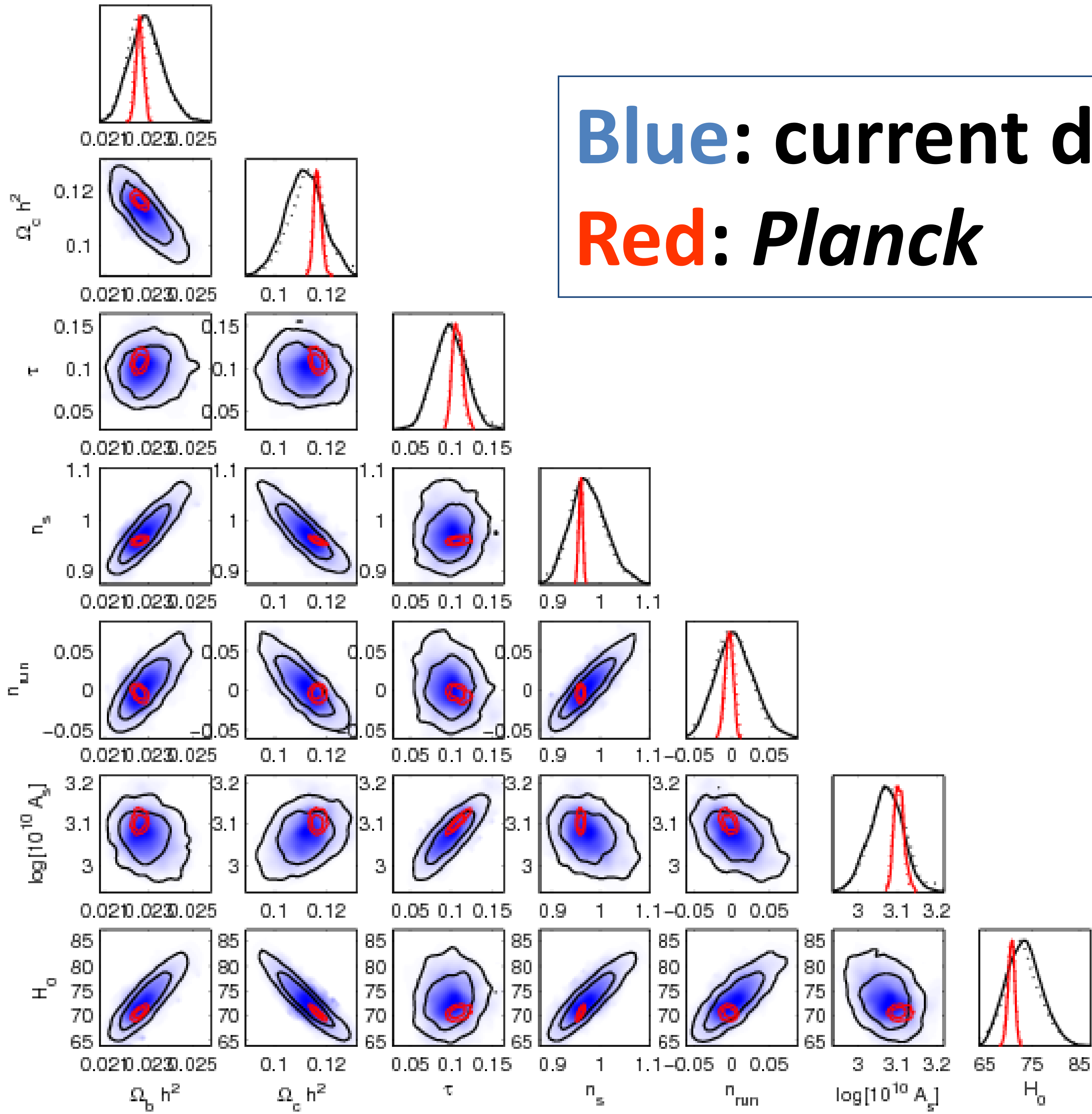
Papers submitted on Jan 11 2011

Planck identifier	Title (all titles are prefixed with "*Planck* Early Results: ")
2011a	The *Planck* mission
2011b	The thermal performance of *Planck*
2011c	First assessment of the Low Frequency Instrument in-flight performance
2011d	First assessment of the High Frequency Instrument in-flight performance
2011e	The Low Frequency Instrument data processing
2011f	The High Frequency Instrument data processing
2011g	The Early Release Compact Source Catalogue
2011h	The all-sky early Sunyaev-Zeldovich cluster sample
2011i	*XMM-Newton* follow-up for validation of *Planck* cluster candidates
2011j	Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters
2011k	Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations
2011l	Cluster Sunyaev-Zeldovich optical scaling relations
2011m	Statistical properties of extragalactic radio sources in the *Planck* Early Release Compact Source Catalogue
2011n	Early Release Compact Source Catalogue validation and extreme radio sources
2011o	Spectral energy distributions and radio continuum spectra of northern extragalactic radio sources
2011p	The *Planck* view of nearby galaxies
2011q	Origin of the submillimetre excess dust emission in the Magellanic Clouds
2011r	The power spectrum of cosmic infrared background anisotropies
2011s	All-sky temperature and dust optical depth from *Planck* and *IRAS* — constraints on the "dark gas" in our Galaxy
2011t	New light on anomalous microwave emission from spinning dust grains
2011u	Properties of the interstellar medium in the Galactic plane
2011v	The submillimetre properties of a sample of Galactic cold clumps
2011w	The Galactic cold core population revealed by the first all-sky survey
2011x	Dust in the diffuse interstellar medium and the Galactic halo
2011y	Thermal dust in nearby molecular clouds


WMAP
6000
5000
4000
3000
2000
1000
0
500
1000
1500
2000
2500
l(l+1)C_l/2π (μK^2)
l


PLANCK
6000
5000
4000
3000
2000
1000
0
500
1000
1500
2000
2500
l(l+1)C_l/2π (μK^2)
l


WMAP (4 year)
B2K
TE
[l(l+1)C_l / 2π] / [μK/K]^2
l
TE
Planck
[l(l+1)C_l / 2π] / [μK/K]^2
l
WMAP (4 year)
B2K
E
[l(l+1)C_l / 2π] / [μK/K]^2
l
Planck
E
[l(l+1)C_l / 2π] / [μK/K]^2
l



Blue: current data

Red: *Planck*

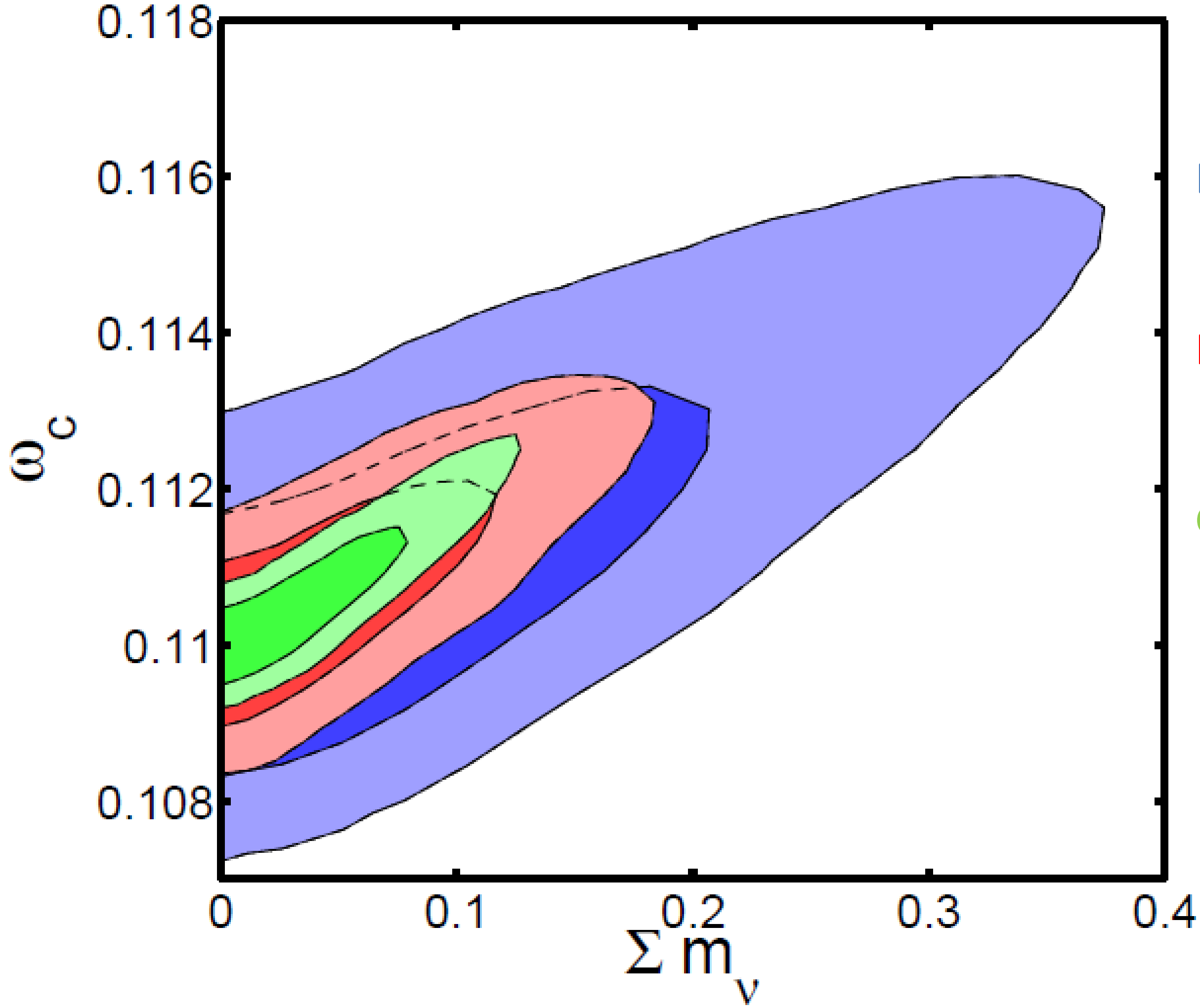
Let's consider not only Planck but also
ACTpol (From Atacama Cosmology Telescope, Ground based, results expected by 2013)
CMBpol (Next CMB satellite, 2020 ?)

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

Constraints on Neutrino Mass



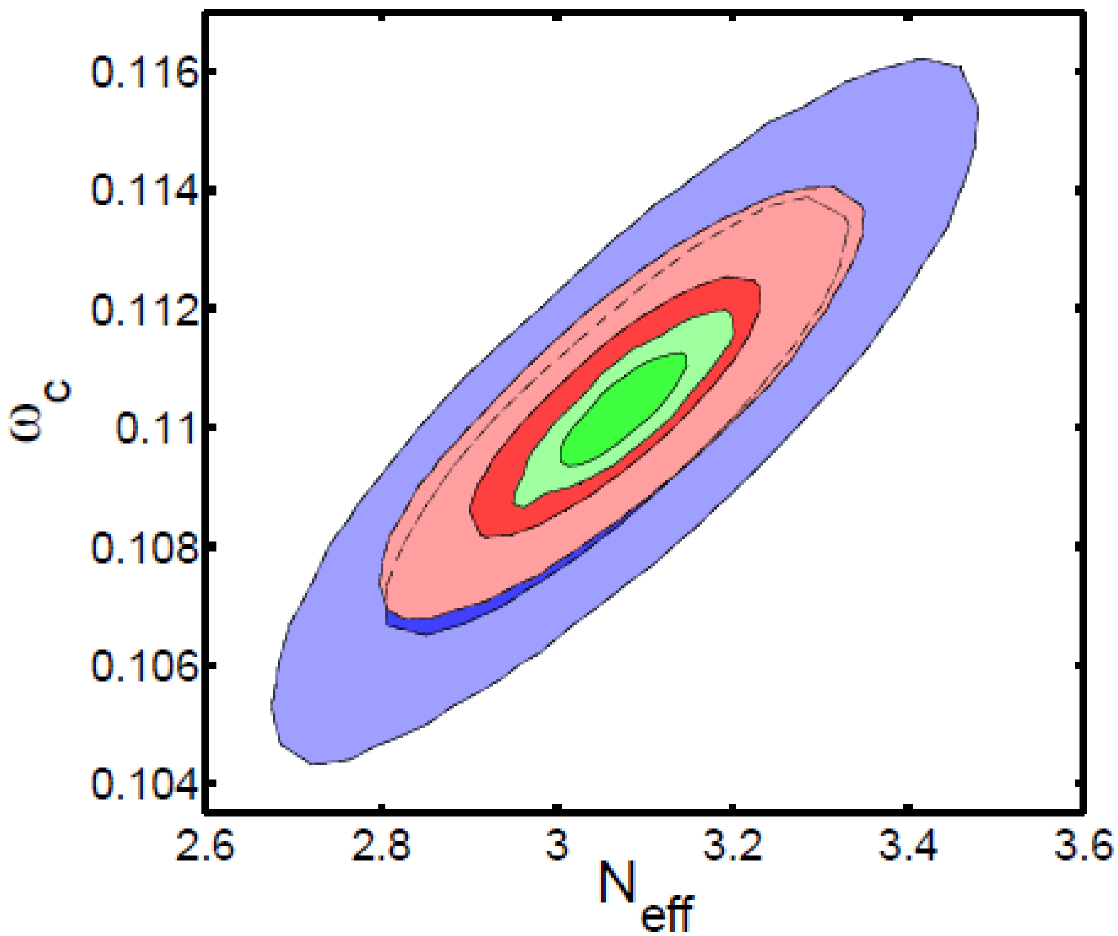
Blue: Planck $\Delta\Sigma m_\nu$=0.16

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.D82:123504,2010

Constraints on Neutrino Number



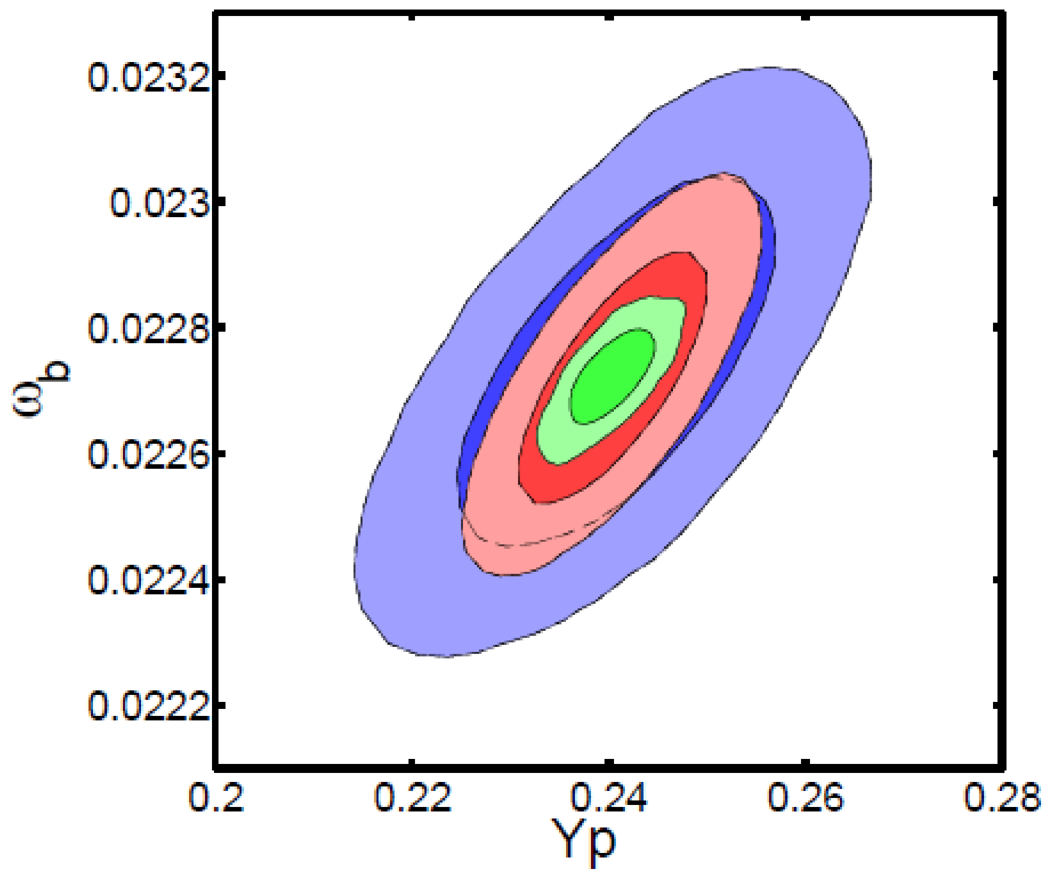
Blue: Planck $\Delta N\nu=0.18$

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

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

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

Constraints on Helium Abundance



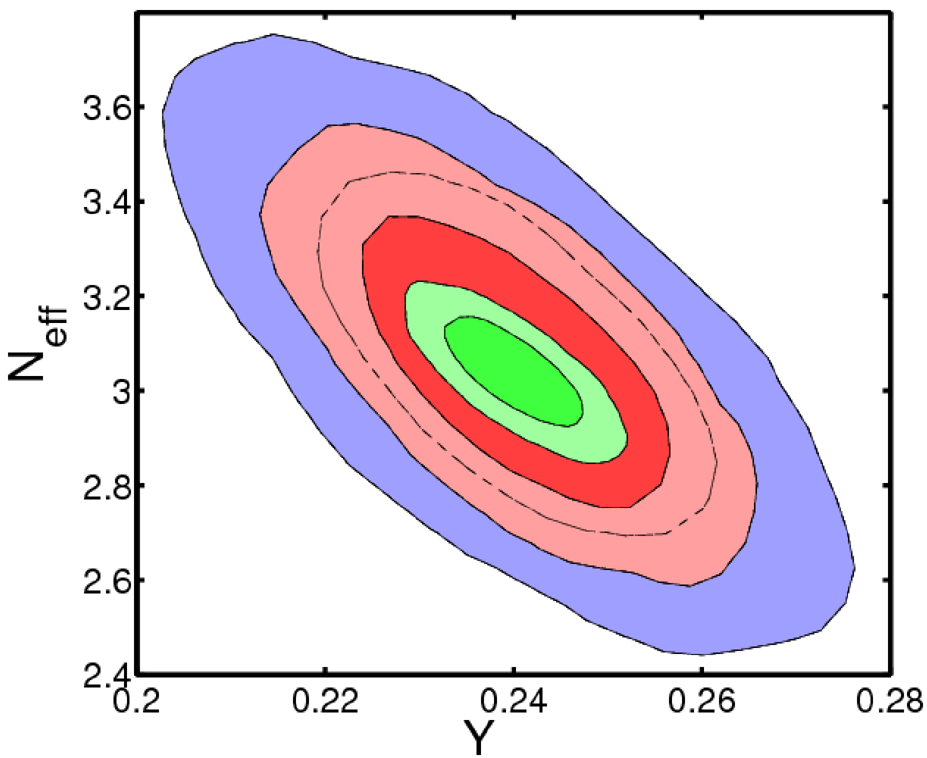
Blue: Planck $\Delta Yp=0.01$

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

Green: CMBPol $\Delta Yp=0.003$

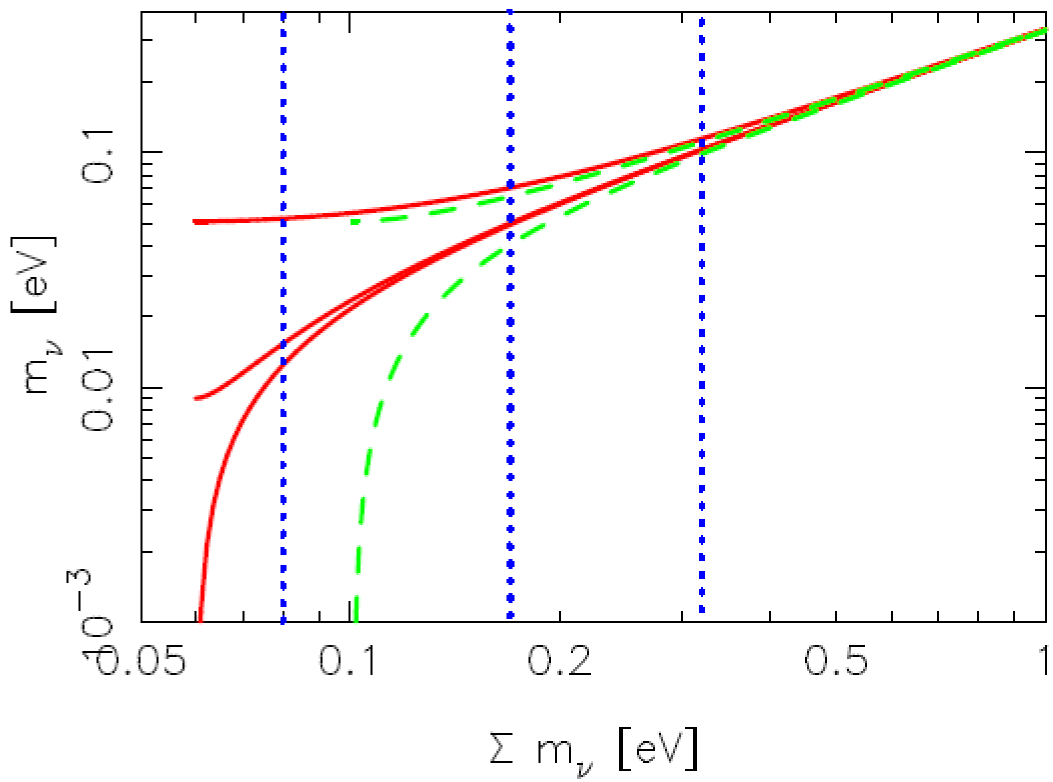
Galli, Martinelli, Melchiorri, Pagano, Sherwin, Spergel, Phys.Rev.D82:123504,2010

Constraints on Helium Abundance AND neutrino number



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

Testing the neutrino hierarchy



Degenerate Hierarchy predicts:

$$\sum m_n > 0.15\ eV$$

Inverted Hierarchy predicts:

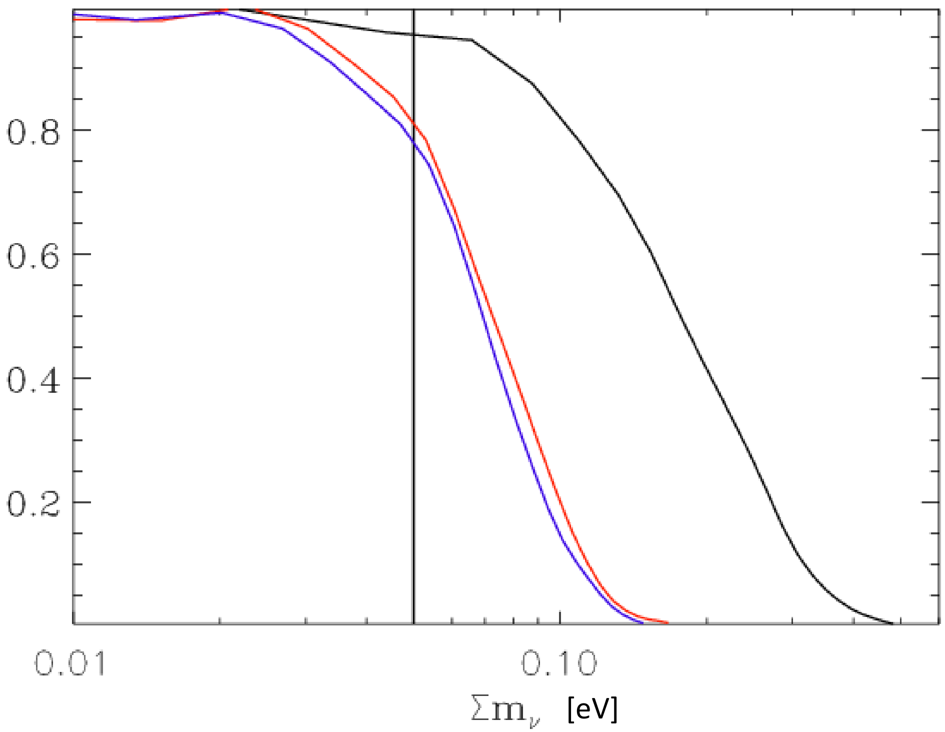
$$\sum m_n > 0.10\ eV$$

Normal Hierarchy predicts:

$$\sum m_n > 0.05\ eV$$

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

Constraints on Neutrino Masses from CMB (after Planck)



Limits at 95% c.l.:

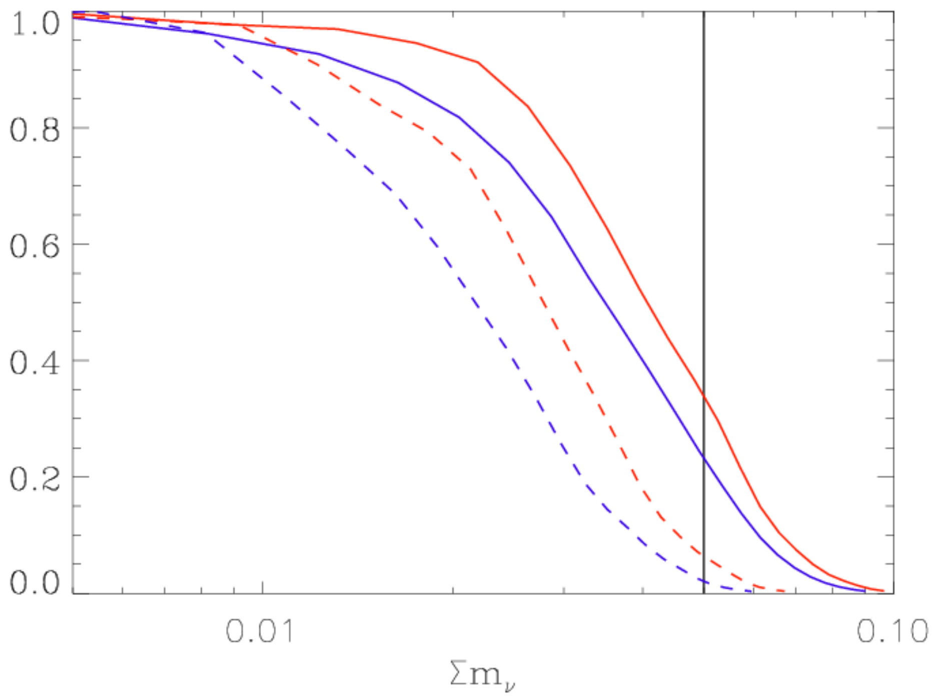
Black: Planck $\sum m_n < 0.28\ eV$

Red: Planck+
New exp. 1000 bol. $\sum m_n < 0.098\ eV$

Blue: Planck+
New exp. 5000 bol. $\sum m_n < 0.093\ eV$

Combining a new CMB experiment to Planck coud improve the bounds on the neutrino mass by a factor 3. This would:
Falsify Degenerate Hierarchy and Probe the Inverted Hierarchy

Constraints on Neutrino Masses from CMB+Priors



Limits at 95% c.l.:

Red: 1000 riv+ Prior 1% H0+ Priori 2% Ωm $\sum m_n < 0.057\ eV$

Blue: 1000 riv+ Prior 1% H0+ Priori 2% Ωm $\sum m_n < 0.054\ eV$

Red Dashed: 1000 riv+ Prior 0.5% H0+ Priori 1% Ωm $\sum m_n < 0.040\ eV$

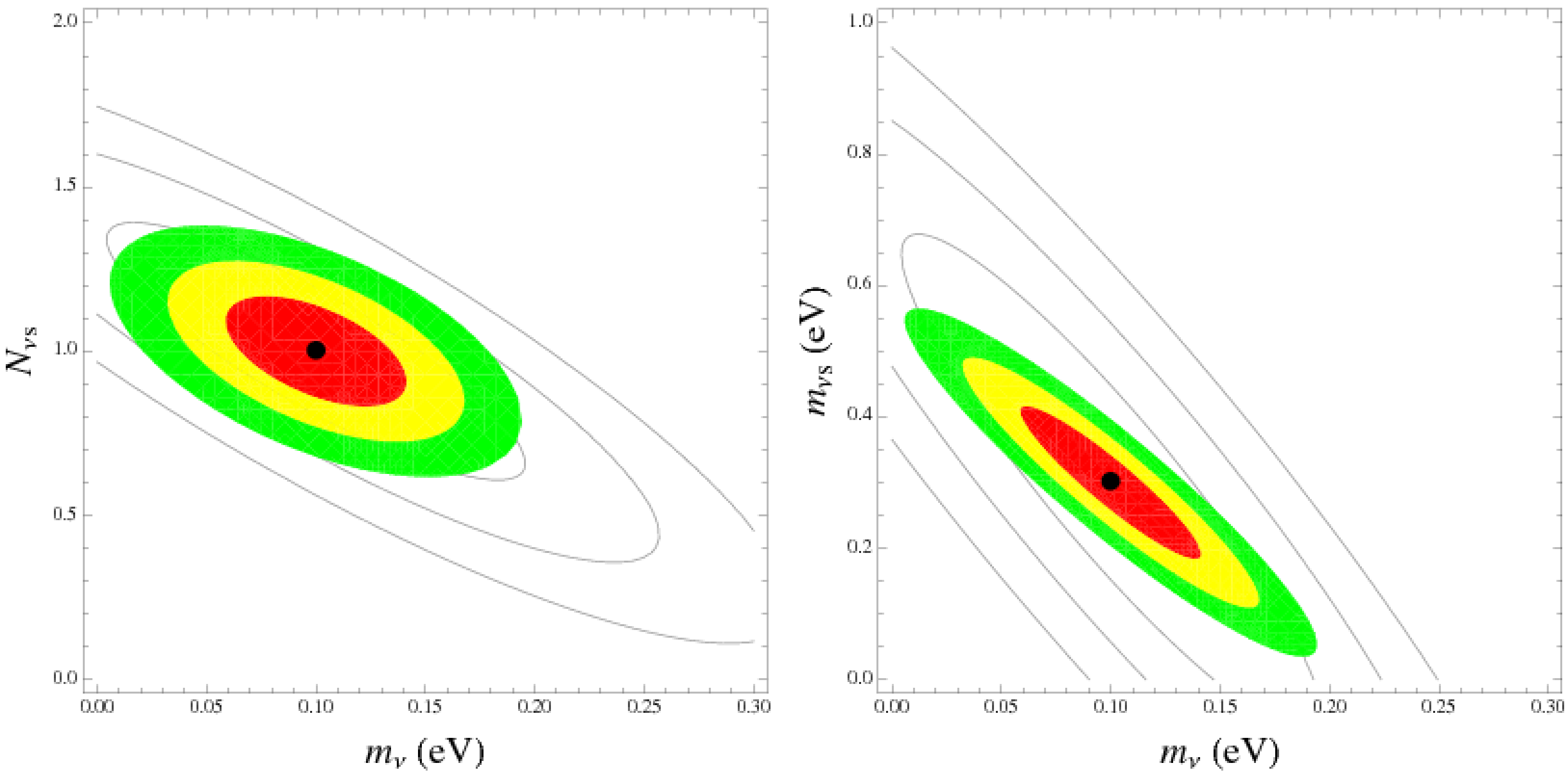
Blue Dashed: 1000 riv+ Prior 0.5% H0+ Priori 1% Ωm $\sum m_n < 0.035\ eV$

With external priors on the Hubble parameter And the matter density also the Normal Hierarchy can be probed: safe detection of a neutrino mass.

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	0.2 – 0.05	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	0.1 – 0.006	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

Abazajan et al, arXiv:1103.5083

Future constraints on steriles masses and numbers (Planck+Euclid/BOSS)



Giusarma et al., 2011 http://arxiv.org/abs/1102.4774.

CONCLUSIONS

• Recent CMB measurements fully confirm Λ-CDM. New bounds on neutrino mass.

• Hints for extra relativistic neutrino background.

• With future measurements constraints on new parameters related to laboratory Physics could be achieved.

In early 2013 from Planck we may know:

- If the total neutrino mass is less than 0.4eV.
- If there is an extra background of relativistic particles.
- Helium abundance with 0.01 accuracy.

- Combining Planck with a small scale future CMB experiment can reach 0.1 eV sensitivity.

Announcement

Scuola di Formazione INFN, «Neutrini in Cosmologia»,
Padova 16-19 May 2011
Organizers: Marco Laveder, Alessandro Melchiorri, Mauro Mezzetto.