CMB Constraints on Fundamental Physics

Cosmology on the Beach, January 2011

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Lecture III

CMB & MORE PARAMETERS

Things we learned from lecture 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/good 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.

- A major assumption is the cosmological constant. Moving to a model with a constant equation of state strongly affects current CMB bounds on the Hubble parameter and the matter density.

- CMB does'nt measure w and is practically insensitive to DE perturbations. However if you move to more realistic 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).

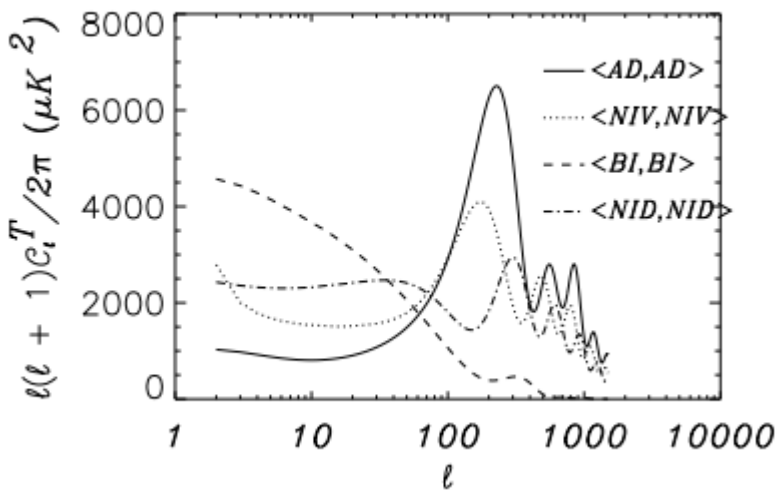
Extensions to the standard model

- 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). See lecures by Andrew Liddle at Cosmology on the Beach 2010
- 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.

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):

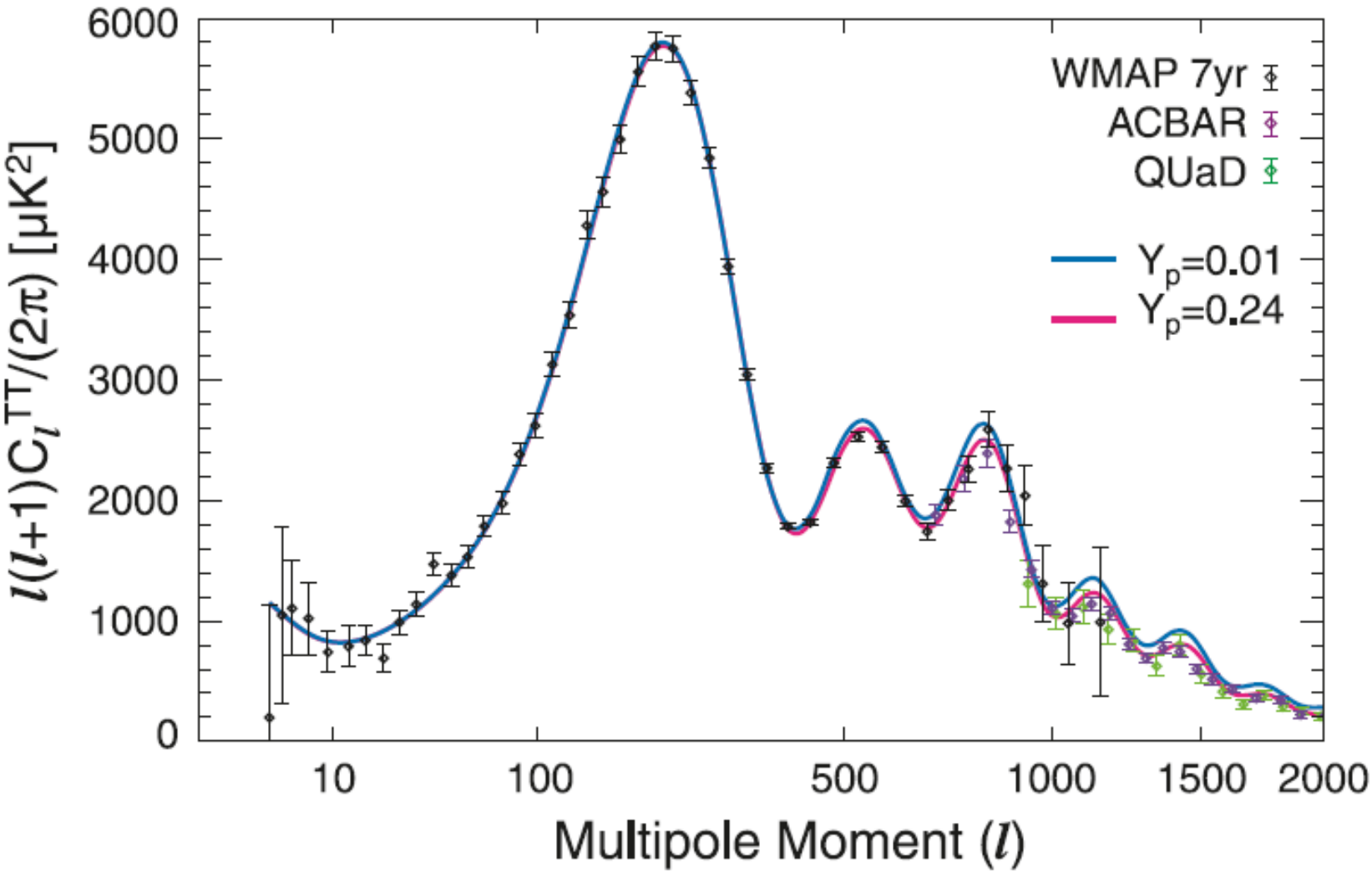
$$\alpha_{-1} < 0.011 \ (95\% \text{ CL})$$
$$\alpha_0 < 0.13 \ (95\% \text{ CL})$$

«Laboratory» Parameters

Some of the extra cosmological parameters can be measured in a independent way directly.
These are probably the most interesting parameters in the near future since they establish a clear connection between cosmology and fundamental physics.

- Neutrino masses Σm_ν
- Neutrino effective number N_ν^{eff}
- Primordial Helium Y_P
- Fundamental Constants α, G

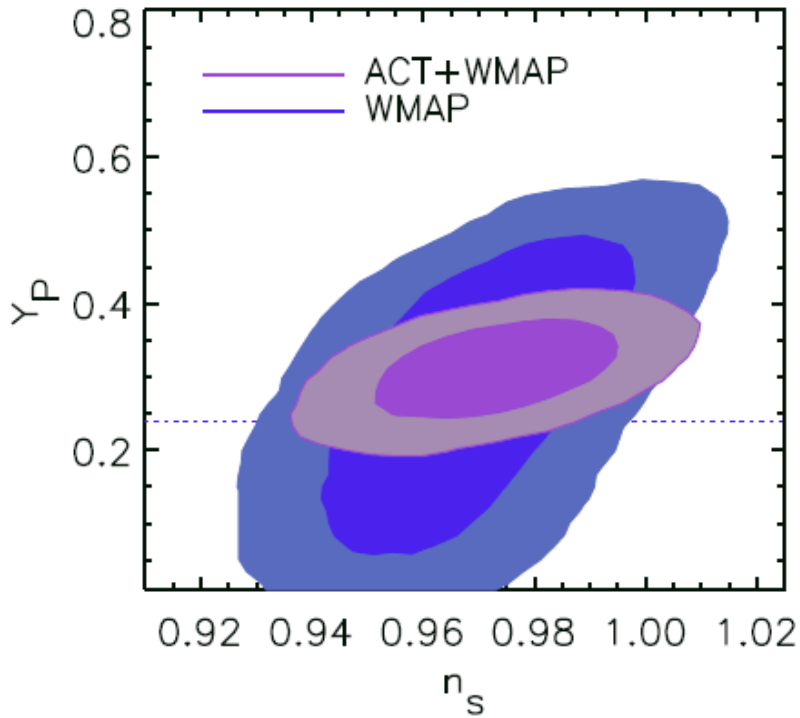
Small scale CMB can probe Helium abundance at recombination.



See e.g.,
K. Ichikawa et al., Phys.Rev.D78:043509,2008
R. Trotta, S. H. Hansen, Phys.Rev. D69 (2004) 023509

Primordial Helium: Current Status

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



WMAP+ACT analysis provides (Dunkley, 2010):

Y_P = 0.313+-0.044

Direct measurements (Izotov, Thuan 2010, Aver 2010):

Yp = 0.2565 ± 0.001 (stat) ± 0.005 (syst)
Yp = 0.2561±0.011

Assuming standard BBN and taking the baryon density from WMAP:

Yp = 0.2485 ± 0.0005

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:

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

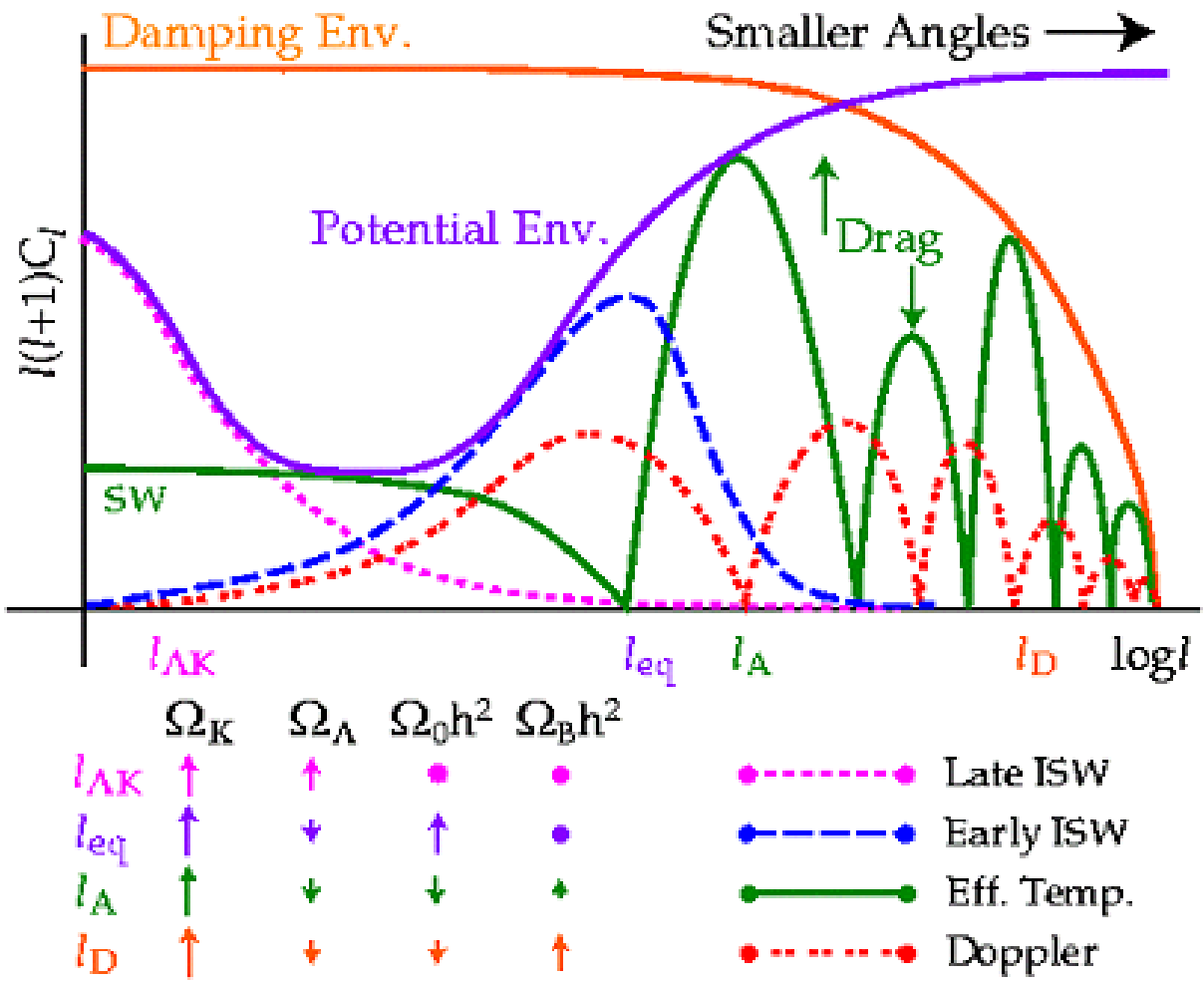
With a density of:

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

That, for a massive neutrino translates in:

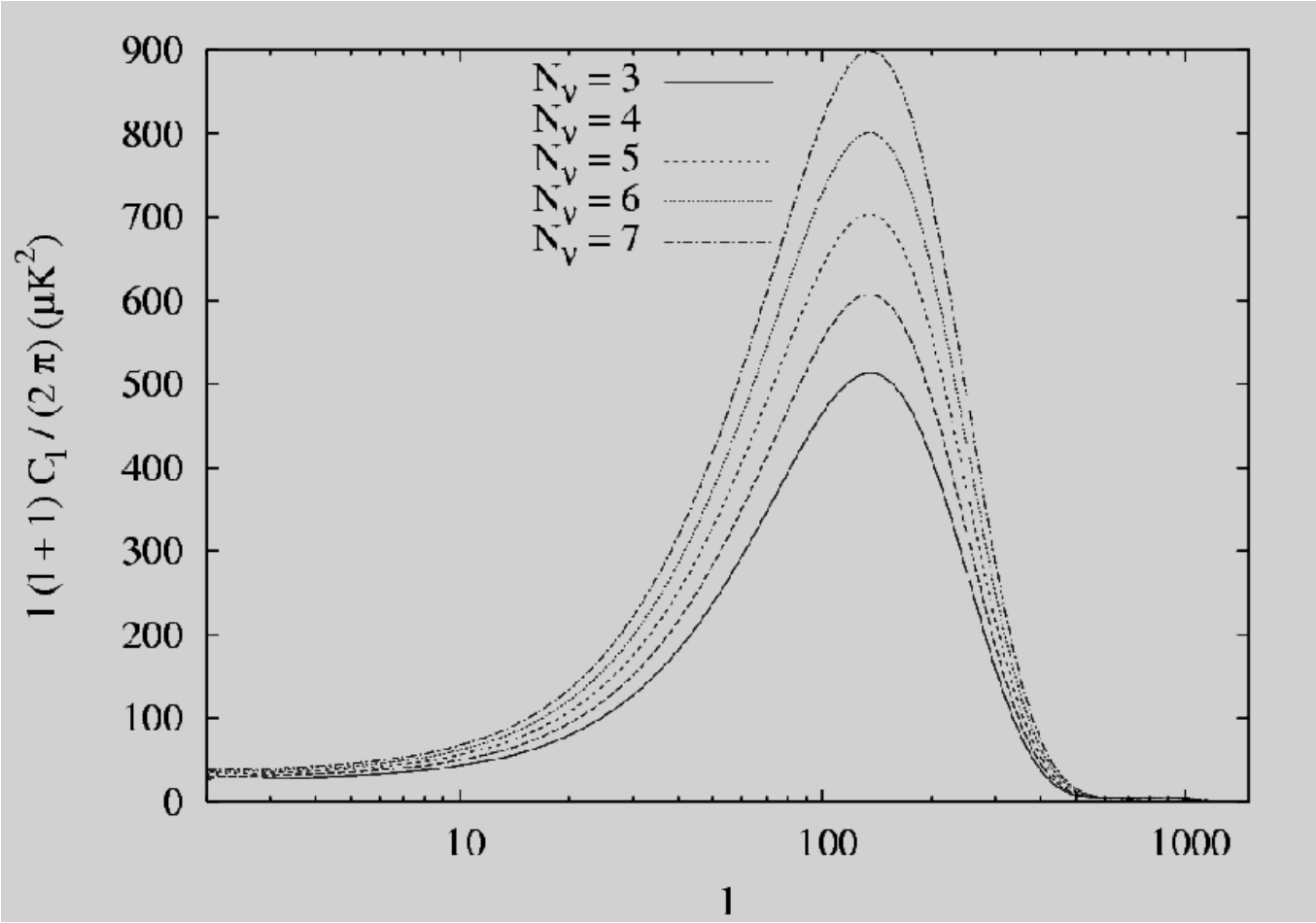
$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{92.5eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_k m_k}{92.5eV}$$

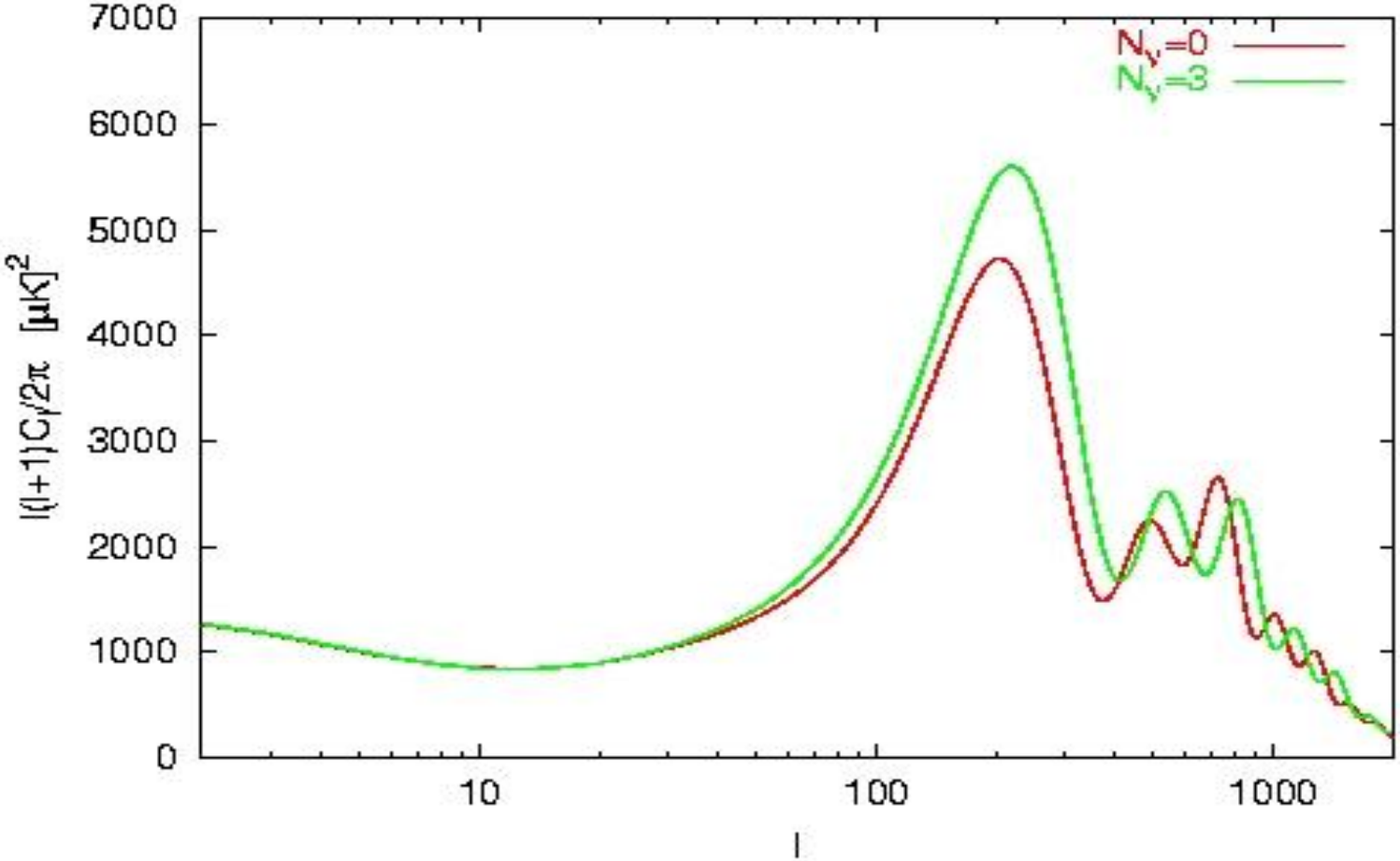
Hu, Sugiyama, Silk, Nature 1997, astro-ph/9604166

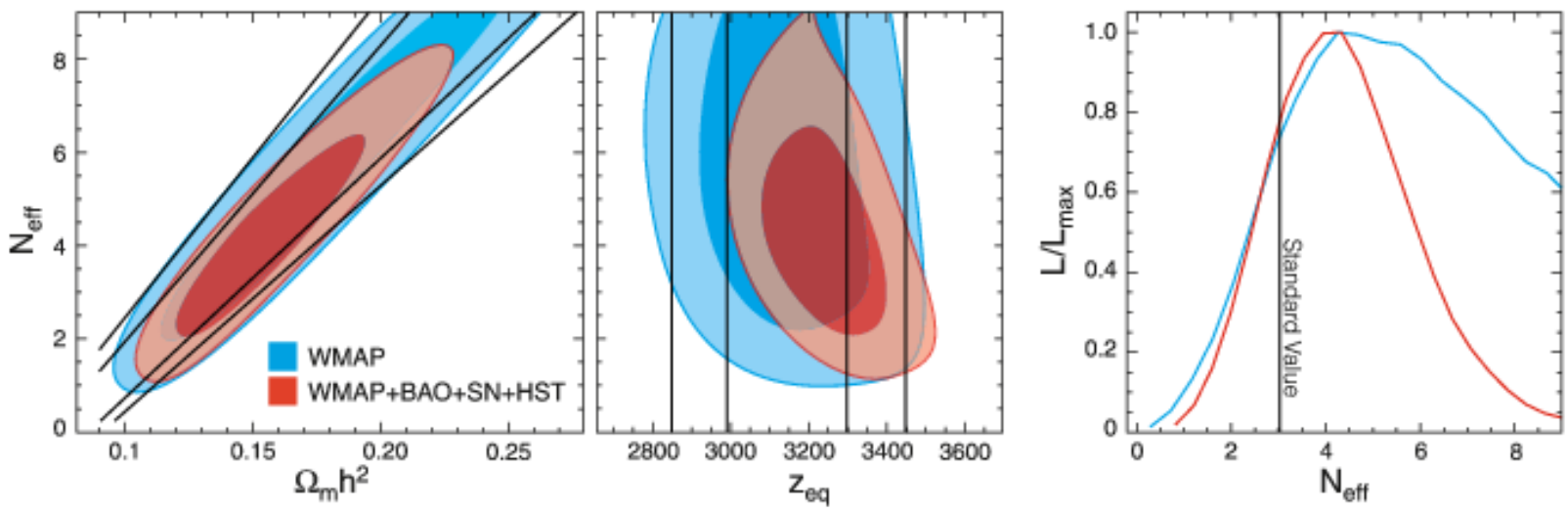


Effect of Neutrinos in the CMB: Early ISW

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




7000
6000
5000
4000
3000
2000
1000
0
10
100
1000
l
l(l+1)C_l/2π [μK]^2
N_ν=0
N_ν=3



Results from WMAP5 $N_{eff}>0$ at 95 % c.l. from CMB DATA alone (Komatsu et al., 2008).

First evidence for a neutrino background from CMB data

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:

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

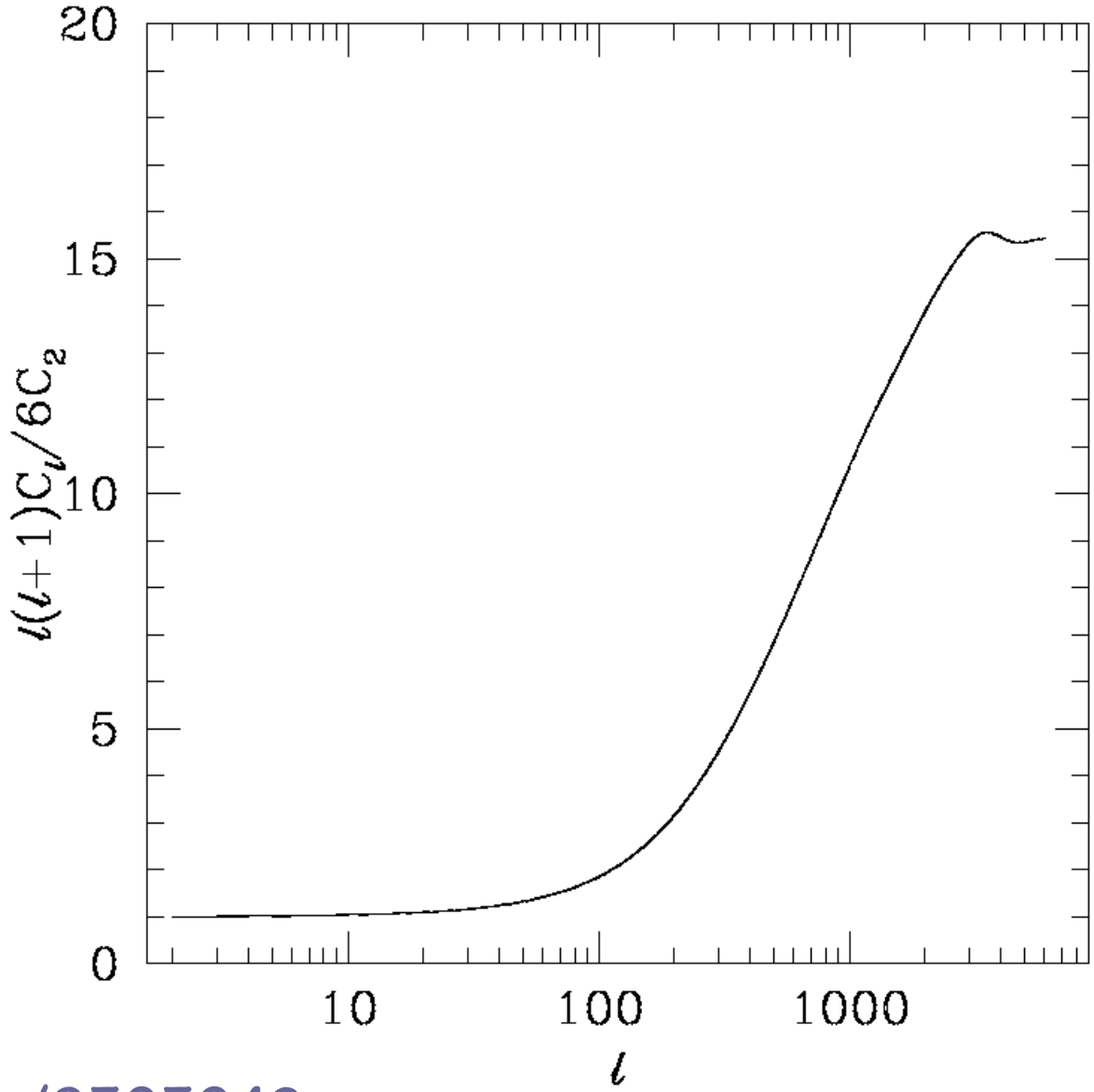
Photons:

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

Neutrinos:

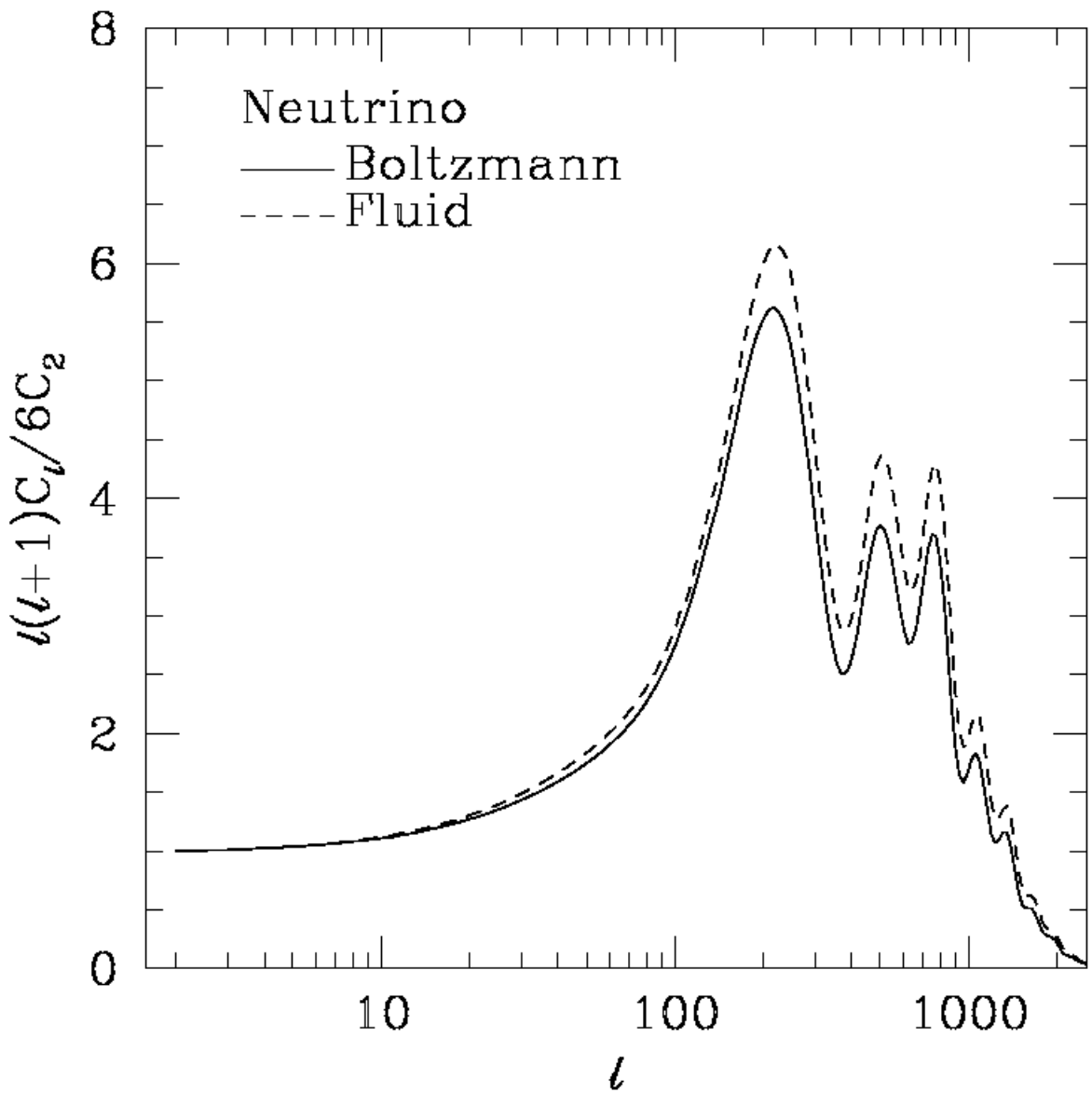
$$\begin{aligned}
\dot{\delta}_\nu &= -\frac{4}{3}\theta_\nu + 4\dot{\phi}\,, \\
\dot{\theta}_\nu &= k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi\,, \\
\dot{F}_{\nu\,l} &= \frac{k}{2l+1}\left[lF_{\nu\,(l-1)} - (l+1)F_{\nu\,(l+1)}\right]\,, \quad l \geq 2
\end{aligned}$$

Can we see them ?



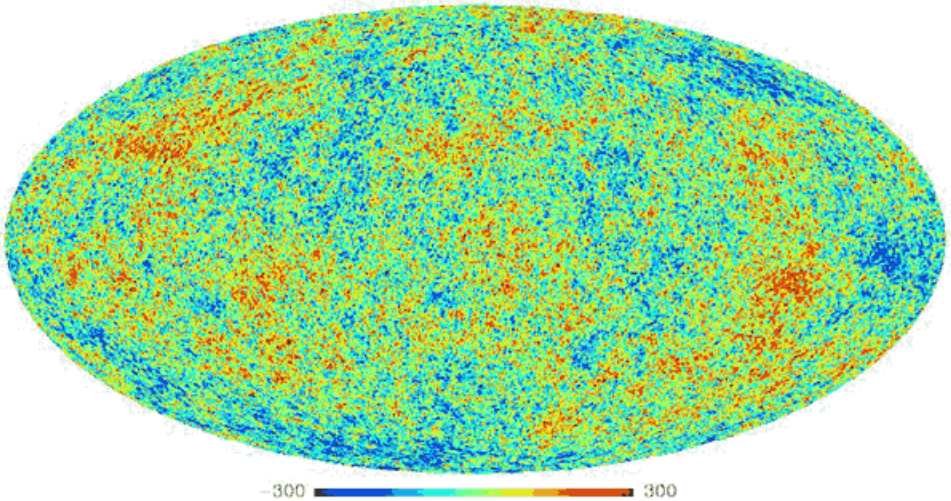
Hu et al., astro-ph/9505043

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



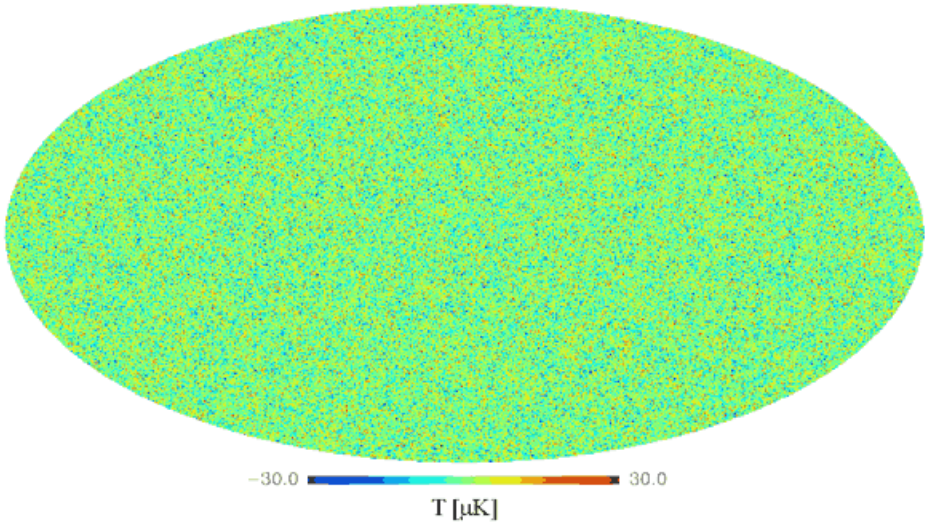
Hu et al., astro-ph/9505043

Standard Model



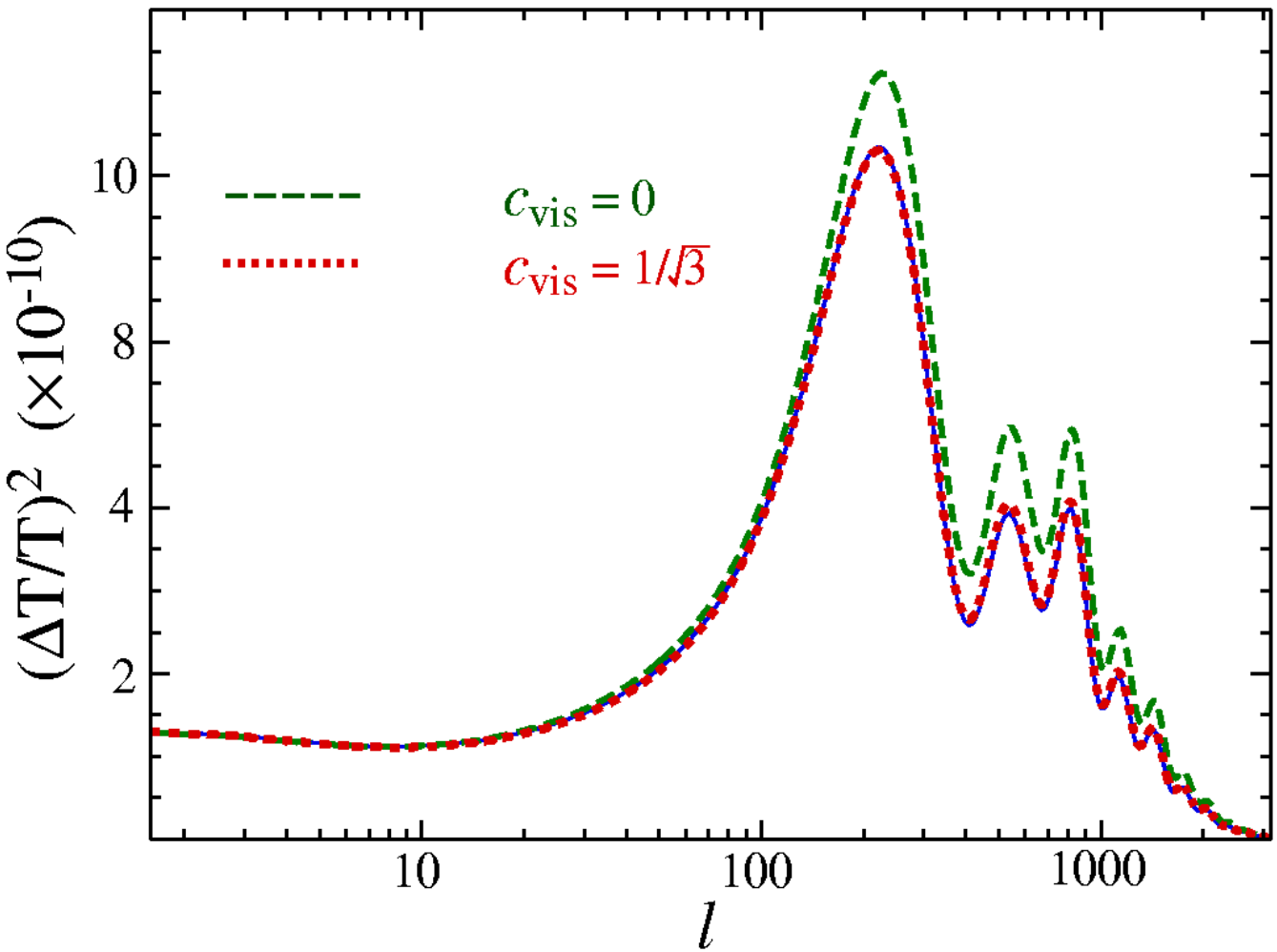
Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

Contribution from neutrino ripples



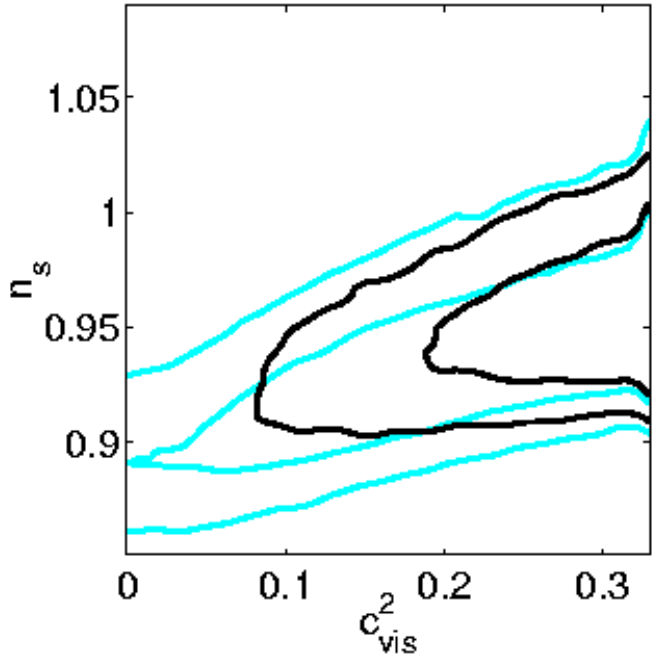
The net effect on the Microwave Background of the presence of neutrino ripples, interpreted as the signature of the existence of neutrino fluctuations as predicted in the Standard Model.

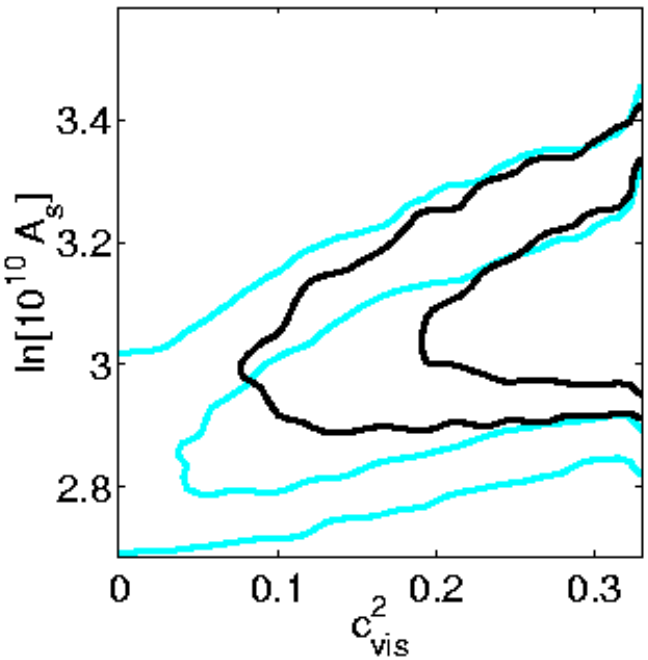
The Neutrino anisotropies can be parameterized through the "speed viscosity" c_{vis}. which controls the relationship between velocity/metric shear and anisotropic stress in the NB.



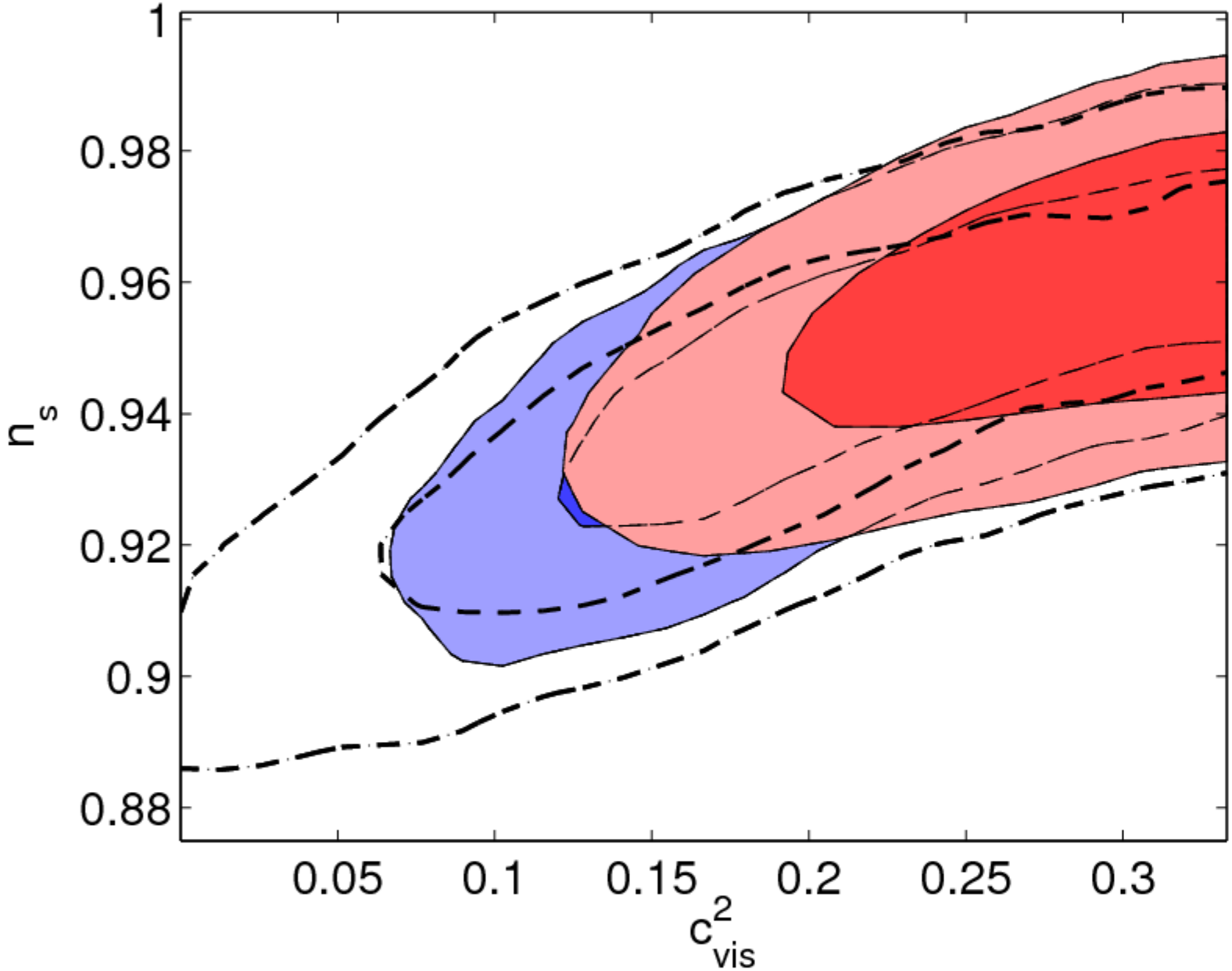
Hu, Eisenstein, Tegmark and White, 1999

WMAP1+SLOAN
data provided evidence
at 2.4 σ for anisotropies
in the Neutrino
Background.
Standard Model o.k.
R. Trotta, AM
Phys Rev Lett.
95 011305 (2005)
AM, P Serra (2007)

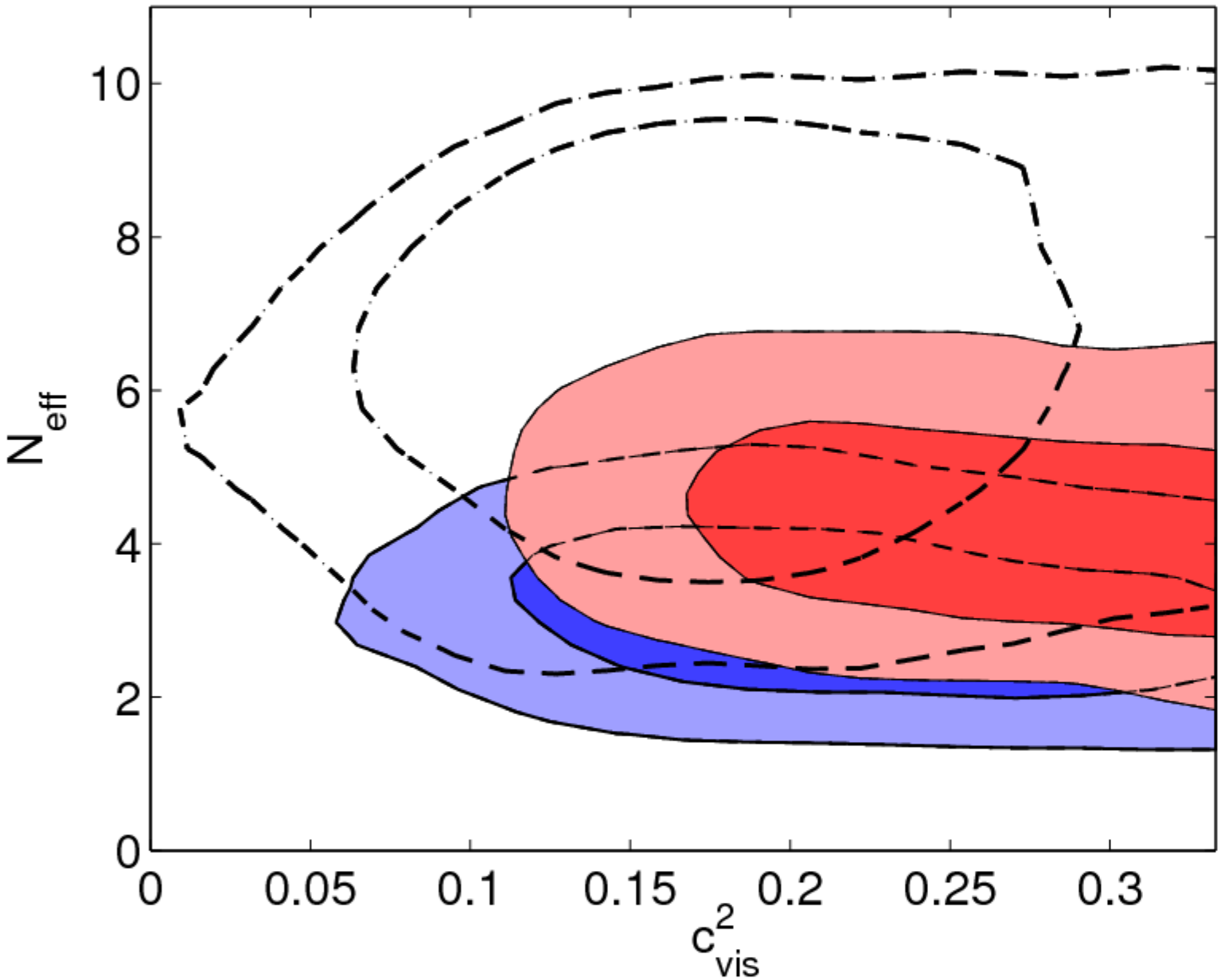




Latest analysis including WMAP5 year…more or less the same r

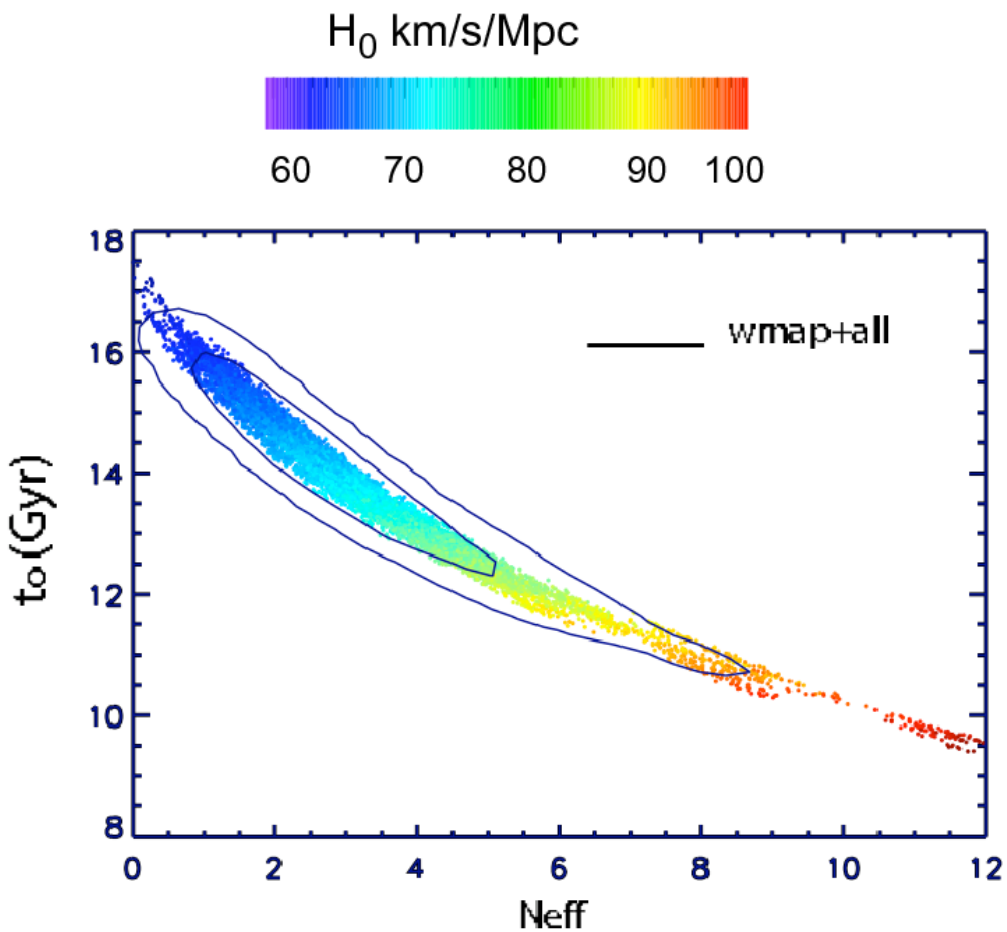


F. De Bernardis et al, JCAP06(2008)013



F. De Bernardis et al, JCAP06(2008)013

Neutrino Number is Degenerate with Several Parameters. Especially with the age Of the Universe t_0



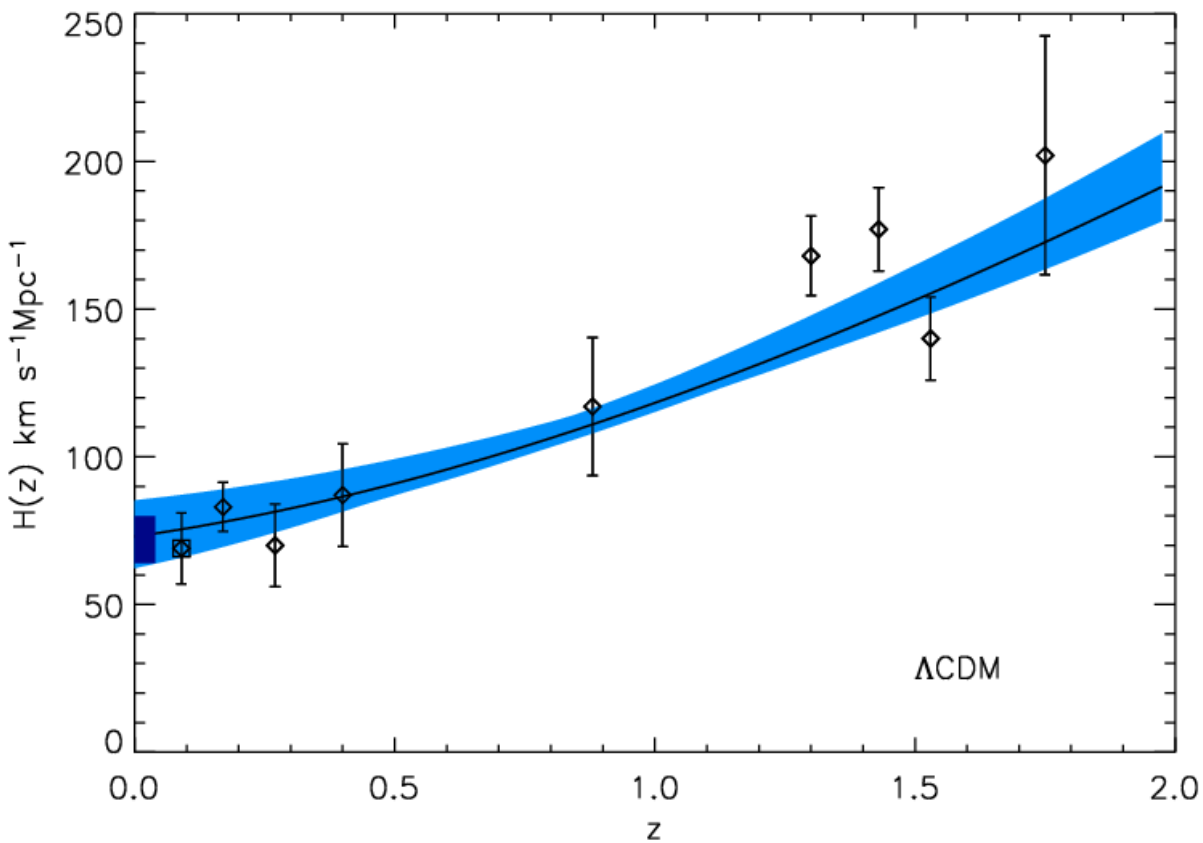
F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, JCAP 03(2008)020

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)



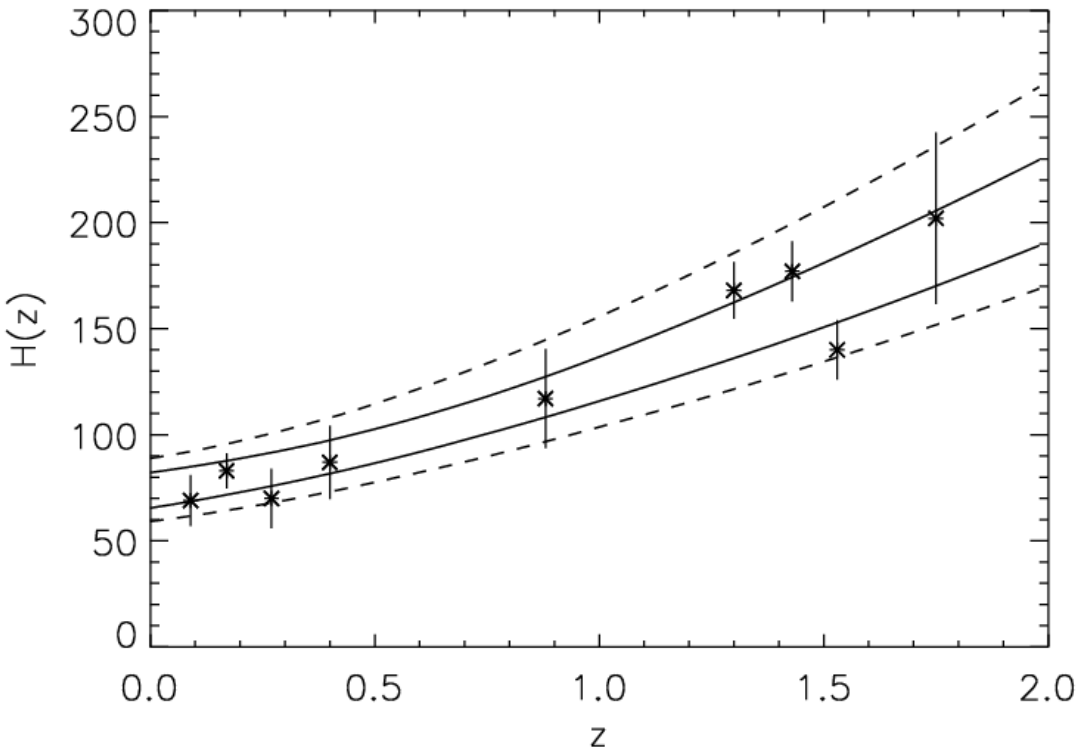
Direct and "model independent" age aestimates have much larger error bars ! Not so good for constraining DE

Spergel et al., 2007

Age of the Universe

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

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

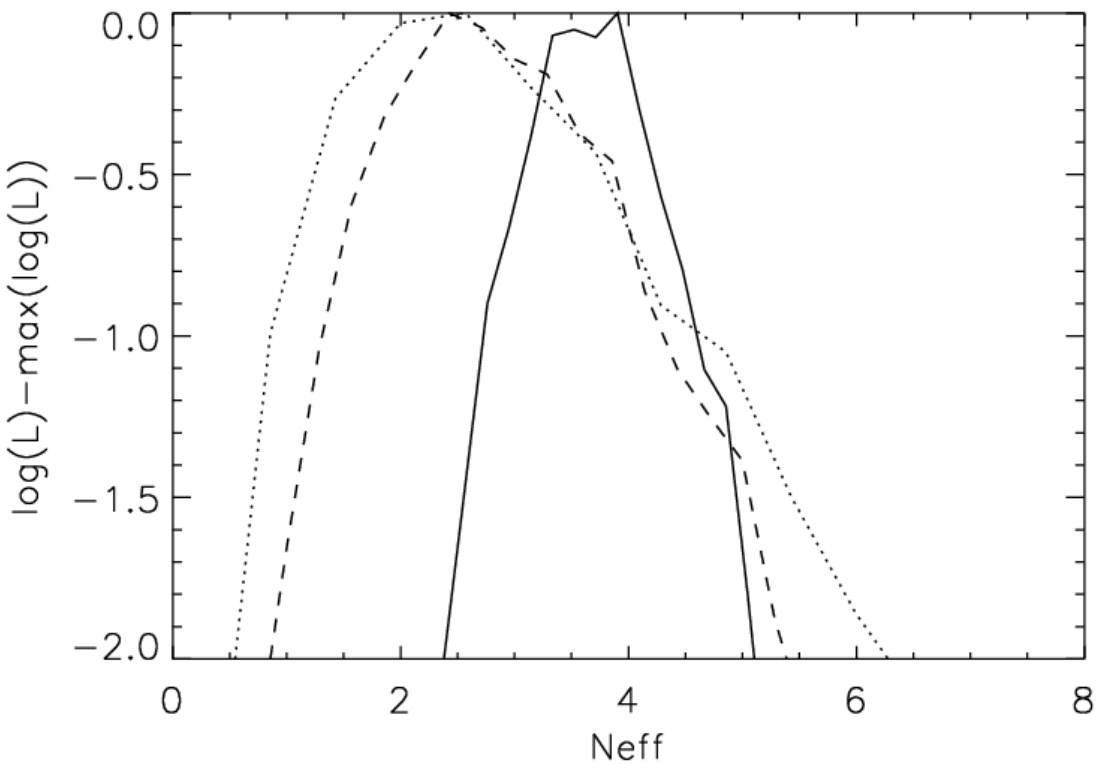


Error bars on age a factor 10 larger when Extra Relativistic particles are Included.

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:

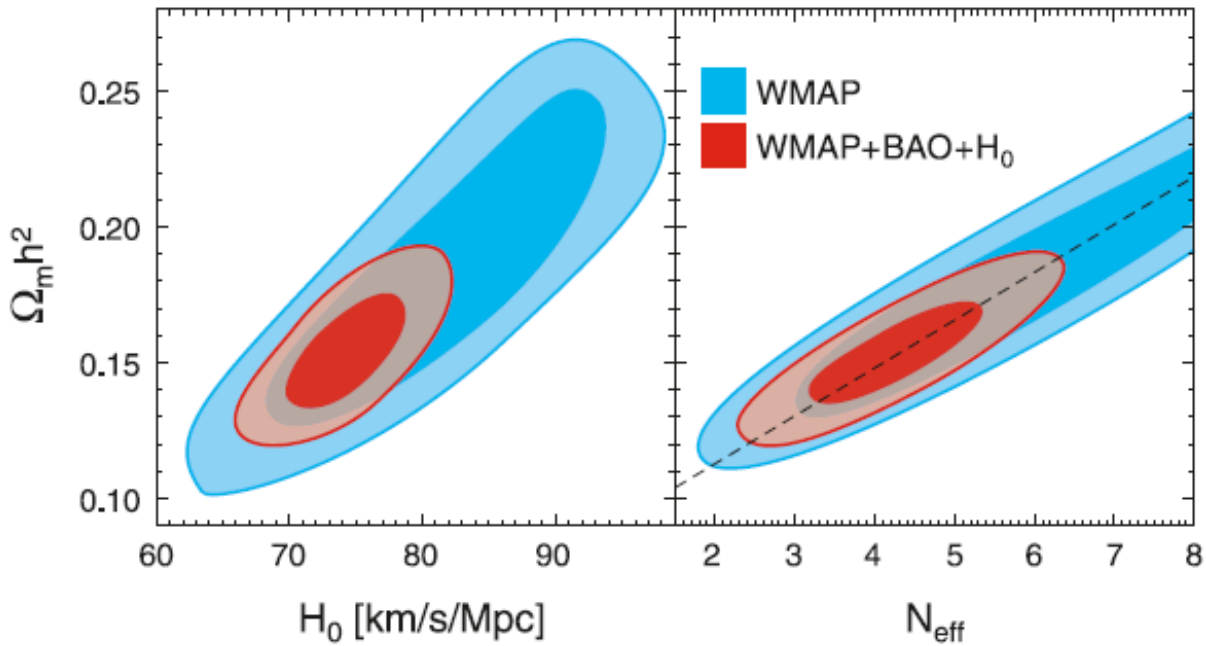
$$N_\nu^{eff} = 3.7 \pm 1.1$$



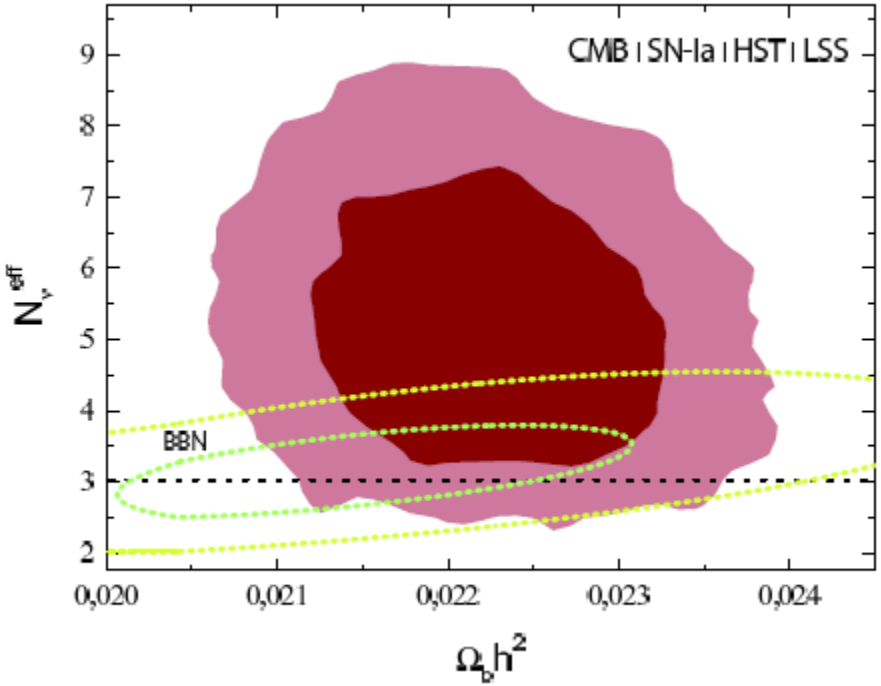
F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, JCAP 03(2008)020

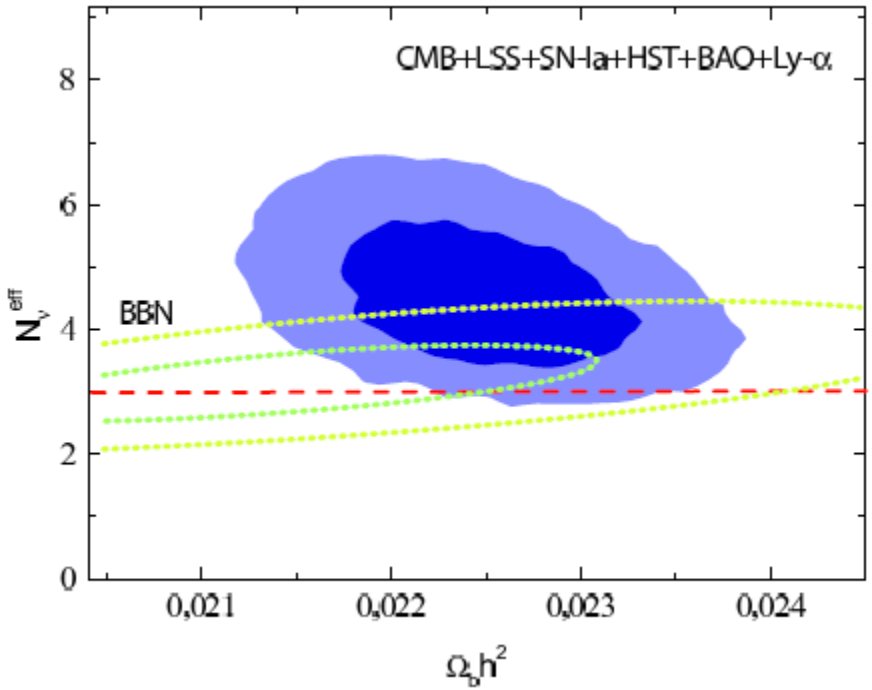
Komatsu et al, 2010, 1001.4538

Neutrino background.
Changes early ISW.
Hint for N>3 ?

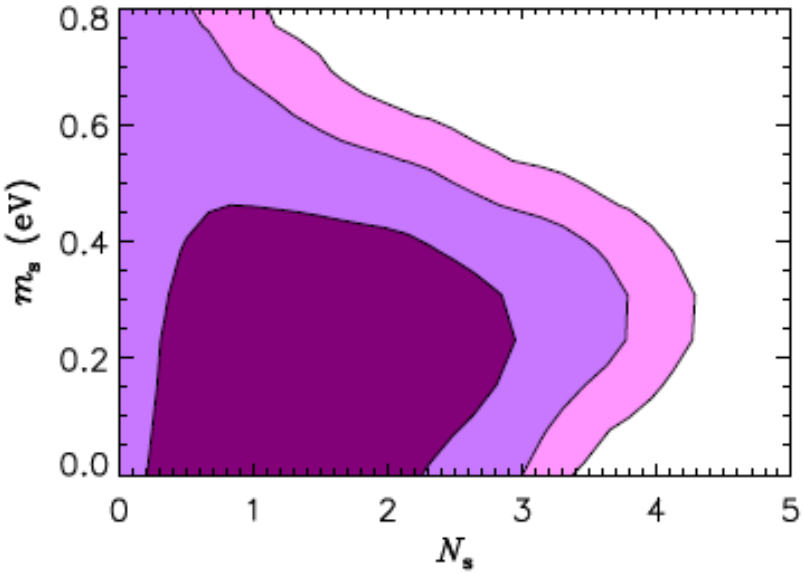


Parameter	Year	*WMAP* only	*WMAP*+BAO+SN+*HST*	*WMAP*+BAO+H_0	*WMAP*+LRG+H_0
$z_{\rm eq}$	5-year	3141^{+154}_{-157}	3240^{+99}_{-97}		
	7-year	3145^{+140}_{-139}		3209^{+85}_{-89}	3240 ± 90
$\Omega_m h^2$	5-year	$0.178^{+0.044}_{-0.041}$	0.160 ± 0.025		
	7-year	$0.184^{+0.041}_{-0.038}$		0.157 ± 0.016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

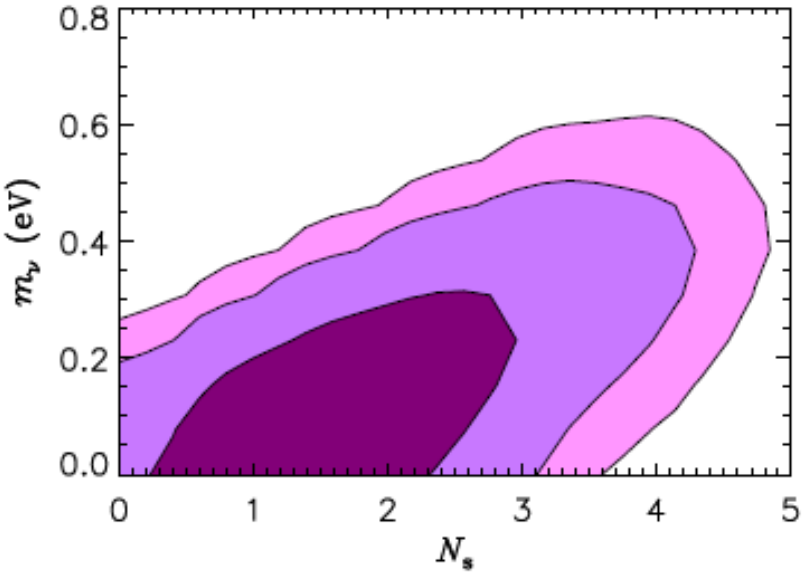




Gianpiero Mangano, Alessandro Melchiorri, Olga Mena, Gennaro Miele, Anze Slosar
Journal-ref: JCAP0703:006,2007

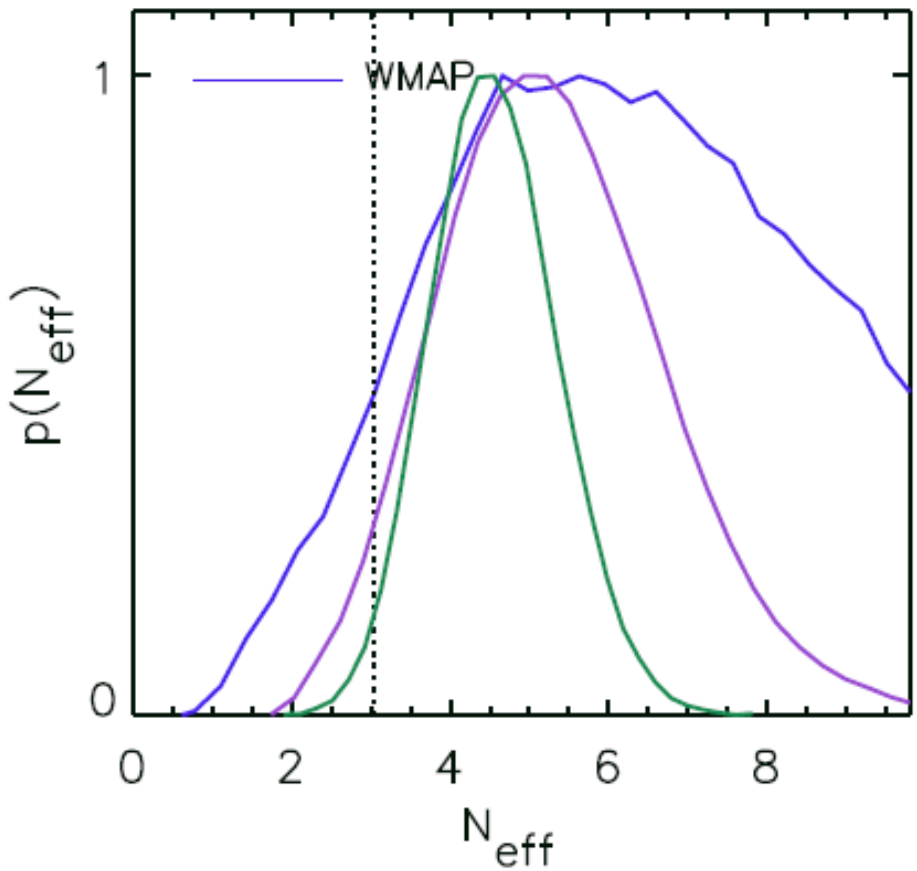


3 Active massless neutrinos+
Ns massive neutrinos



3 Active massive neutrinos +
Ns massless neutrinos

J. Hamann et al, **arXiv:1006.5276**



Latest results from ACT, Dunkley et al. 2010 $Neff = 5.3 \pm 1.3$

Neutrino Mass

Laboratory bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale :

Tritium beta decay:

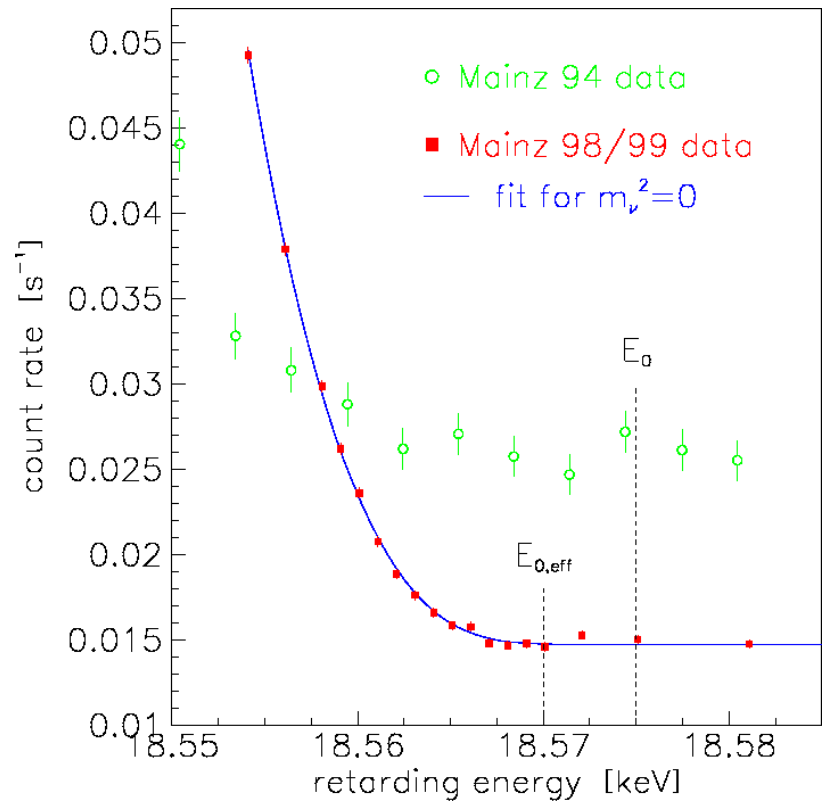
$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2}$$

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

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

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

Best fit gives a negative mass !!!



Bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale :

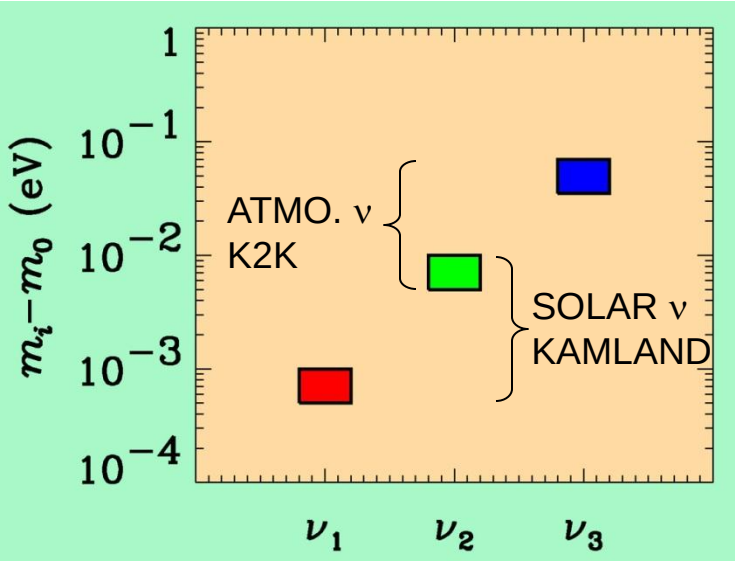
Neutrinoless double beta decay (only if neutrino are majorana particles!):

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

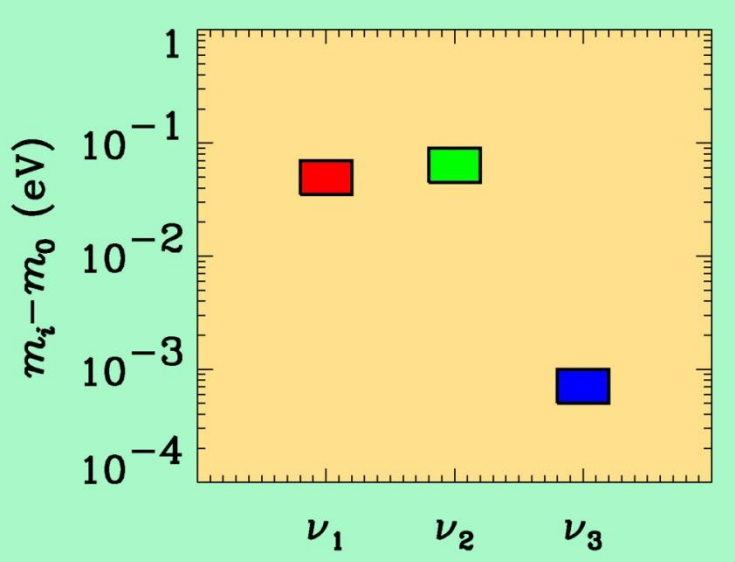
Neutrinoless double beta decay processes have been searched in many experiments with different isotopes, yielding negative results. Recently, members of the Heidelberg-Moscow experiment have claimed the detection of a $0\nu2\beta$ signal from the ^{76}Ge isotope. If the claimed signal is entirely due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

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

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



Normal hierarchy



Inverted hierarchy

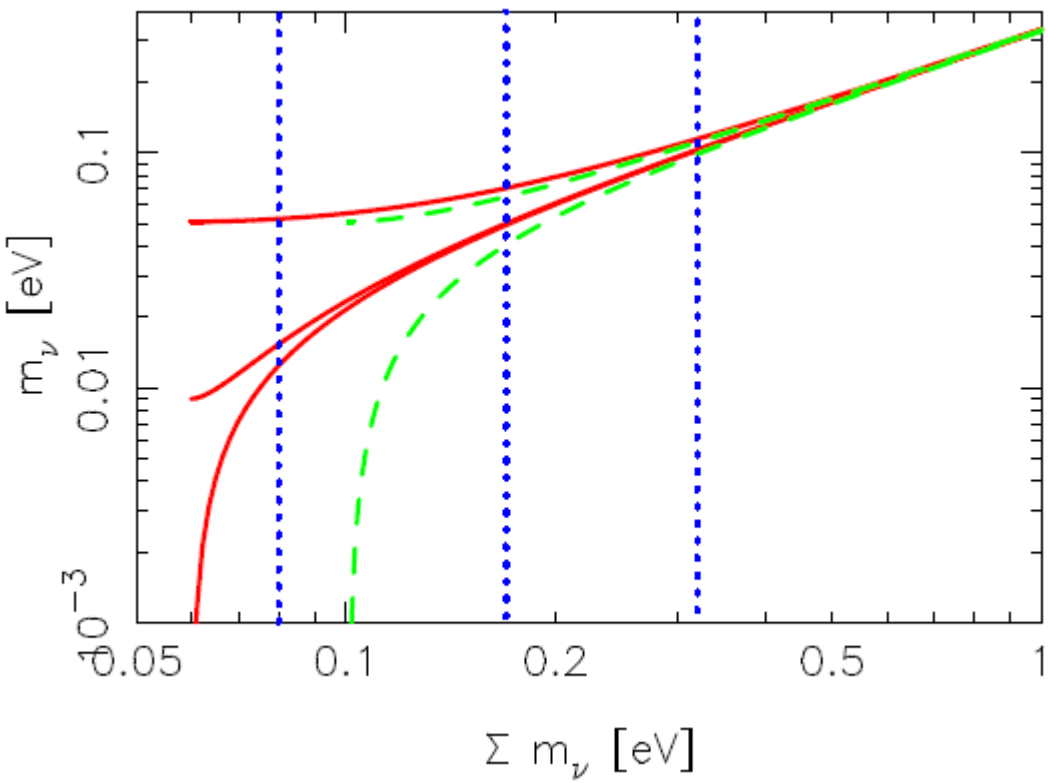
$$m_3 > m_2 > m_1$$

$$m_2 > m_1 > m_3$$

Moreover neutrino masses can also be degenerate

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

Testing the neutrino hierarchy



Degenerate Hierarchy predicts:

$$\sum m_v > 0.15\ eV$$

Inverted Hierarchy predicts:

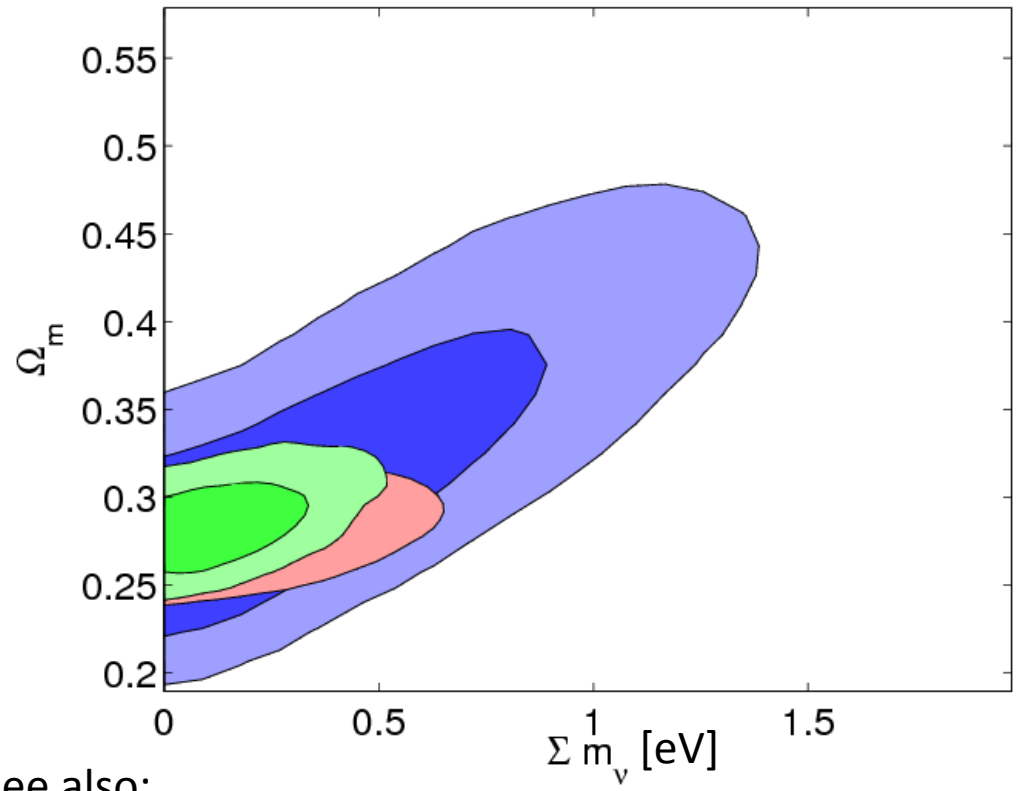
$$\sum m_v > 0.10\ eV$$

Normal Hierarchy predicts:

$$\sum m_v > 0.05\ eV$$

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

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**

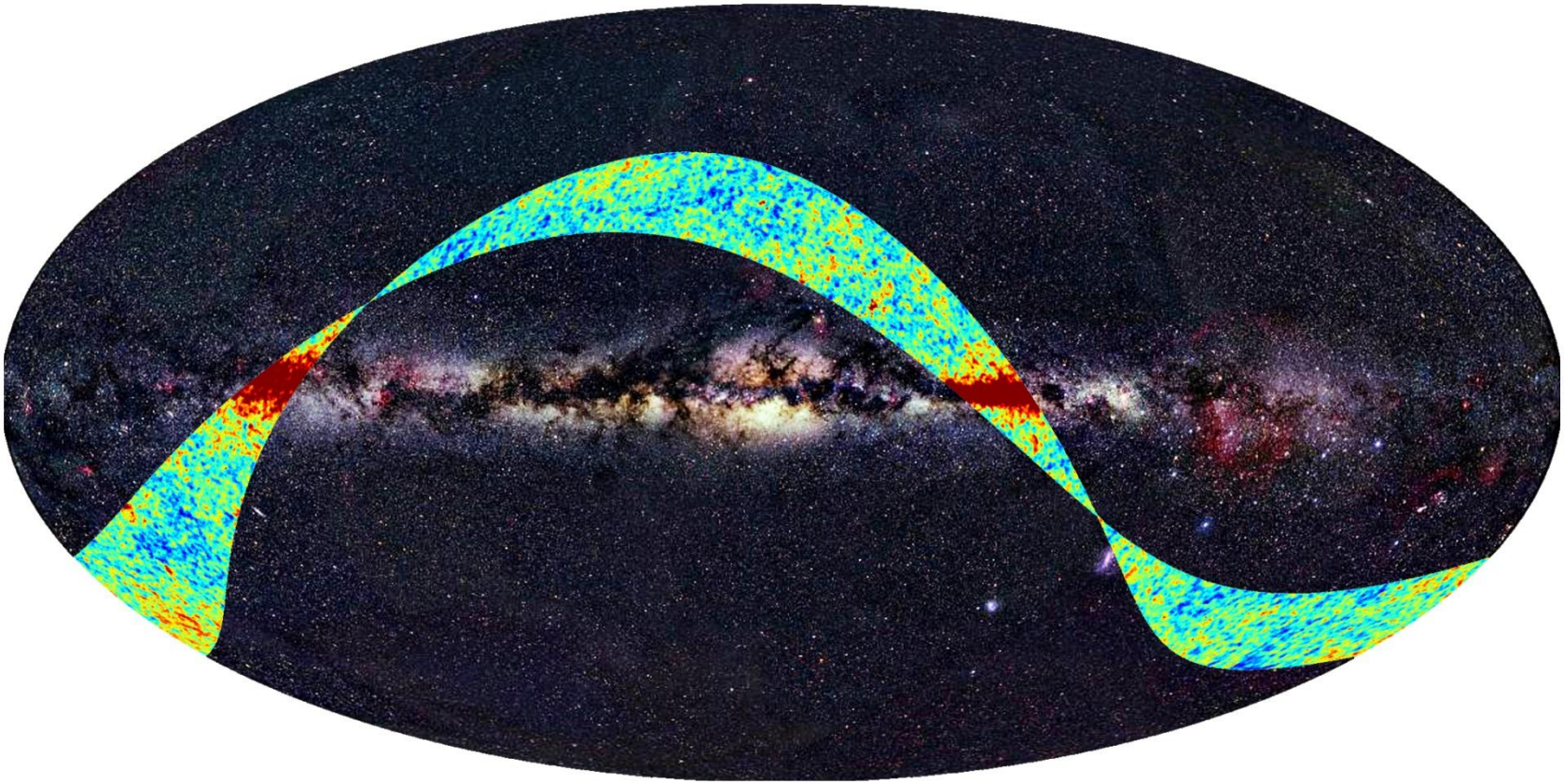
Toyokazu Sekiguchi, Kazuhide Ichikawa, Tomo Takahashi, Lincoln Greenhill, **arXiv:0911.0976**

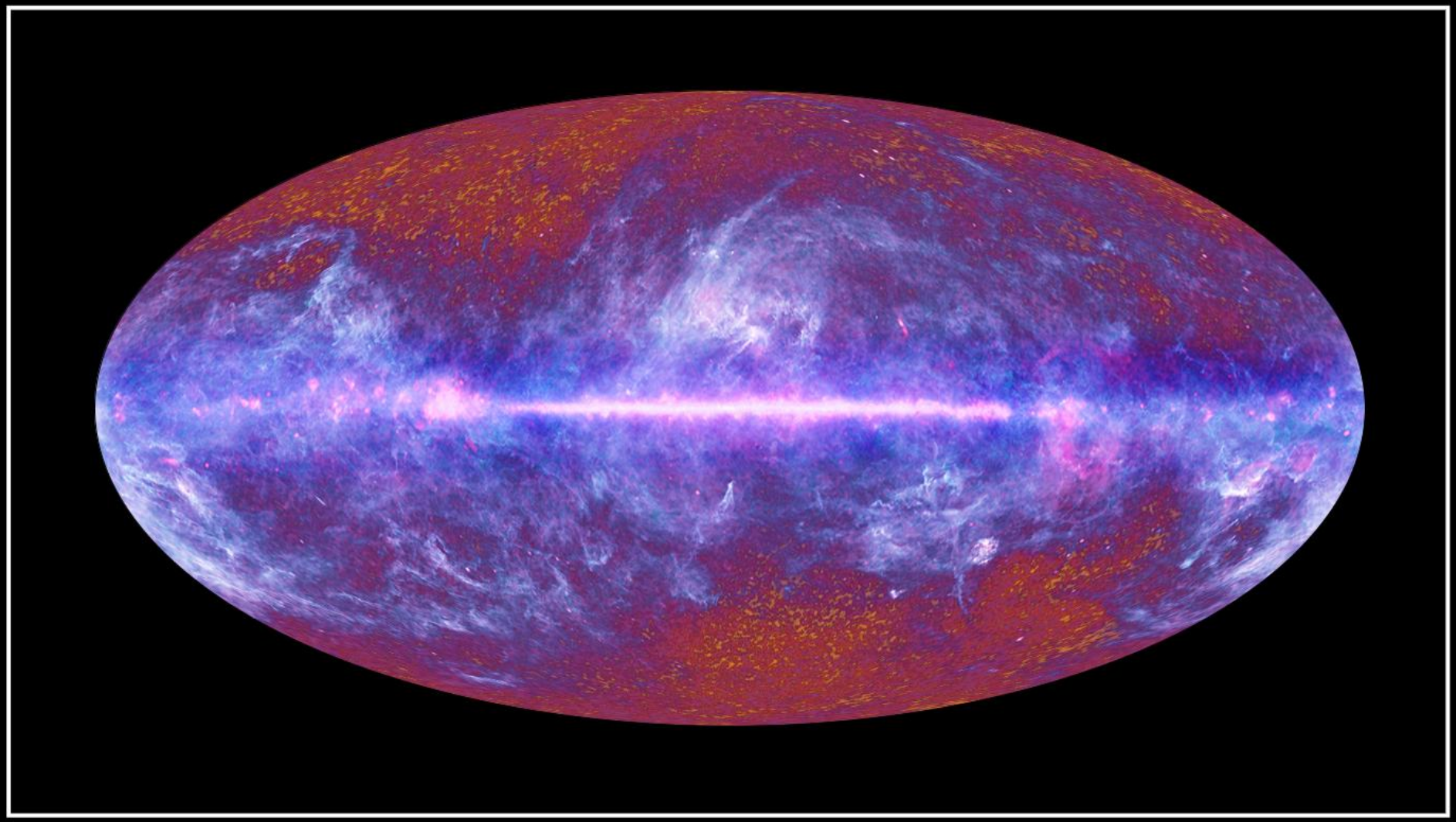
Extreme (sub 0.3 eV limits):

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

Planck
Satellite launch
14/5/2009

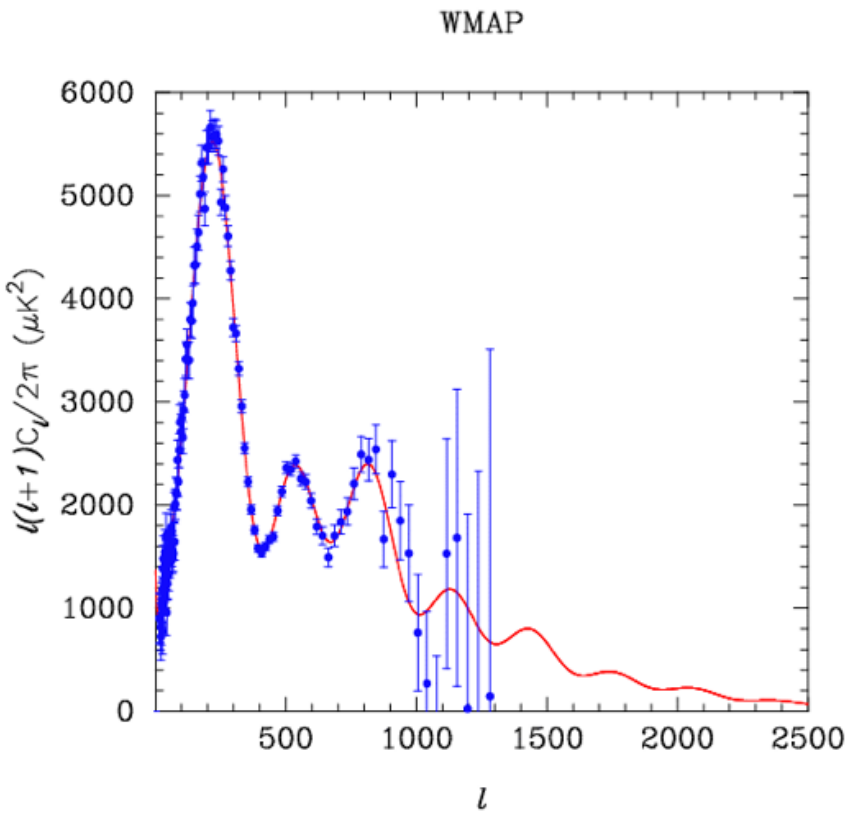
Planck First Light Survey (September 2009). Experiment is working as expected





The Planck one-year all-sky survey

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


WMAP
6000
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2000
1000
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500
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1500
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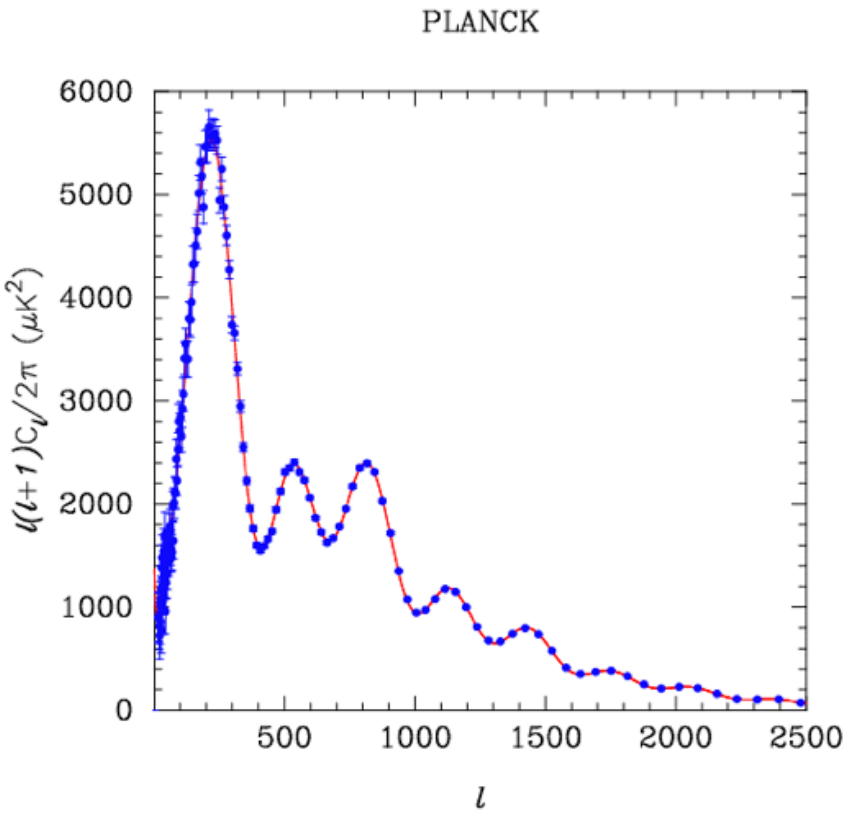
2500
l
$l(l+1)C_l/2\pi$ (μK^2)


PLANCK
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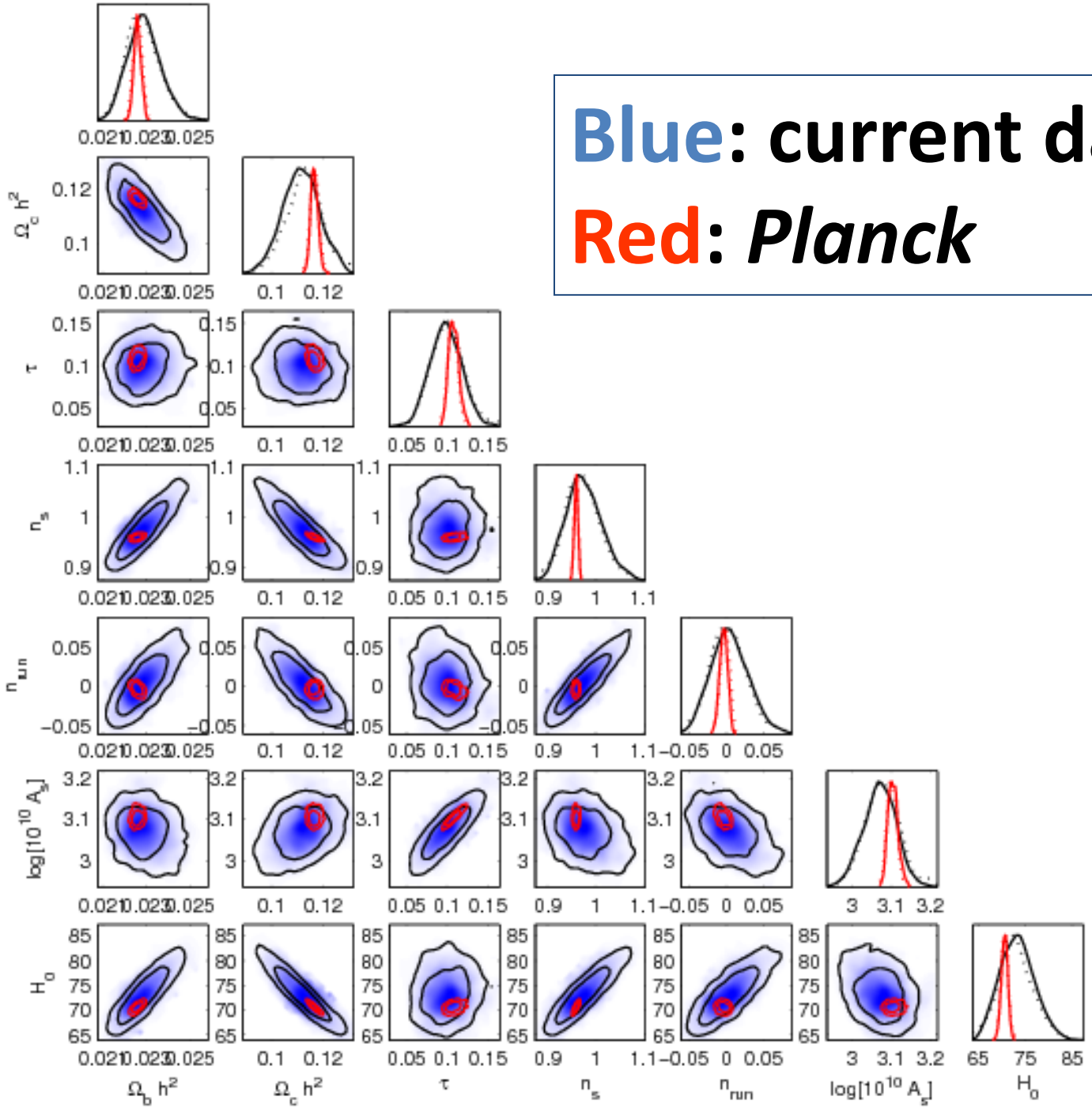
l
$l(l+1)C_l/2\pi$ (μK^2)



Blue: current data

Red: *Planck*

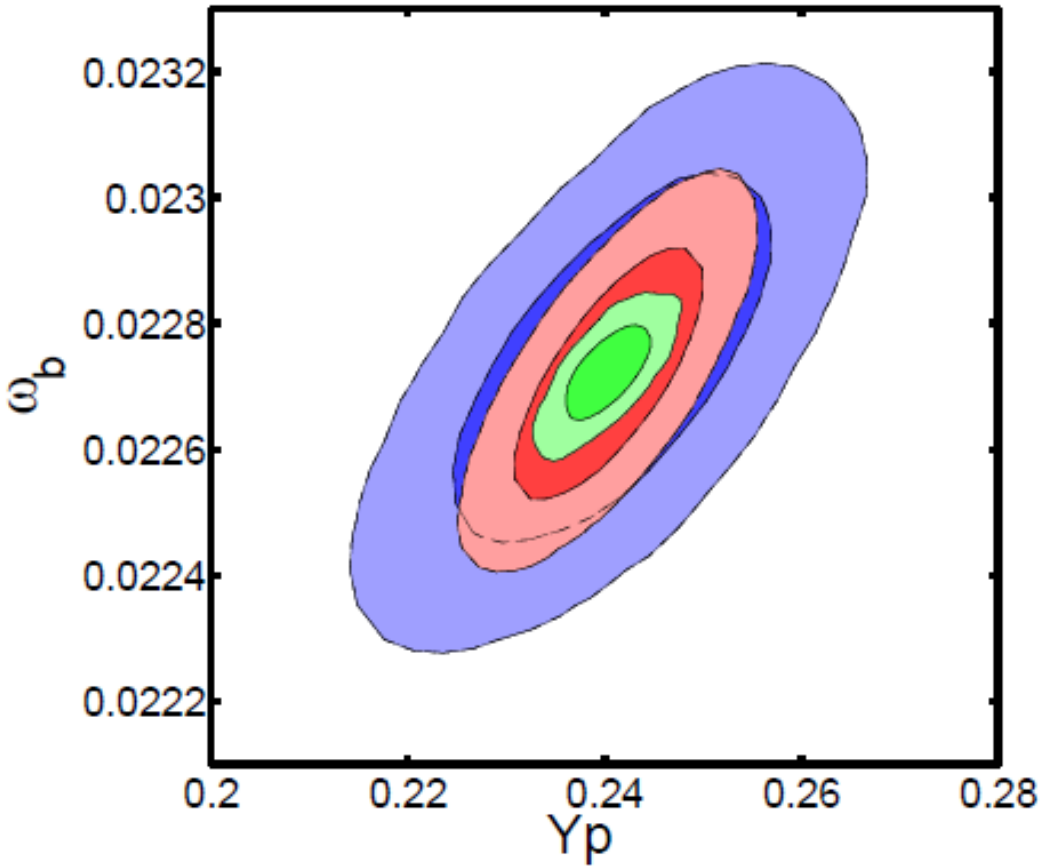
Let's consider not only Planck but also
ACTpol (From Atacama Cosmology Telescope, Ground based, results expected by 2013)
CMBpol (Next CMB satellite, 2020 ?)

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. D **82**, 123504 (2010)

Constraints on Helium Abundance



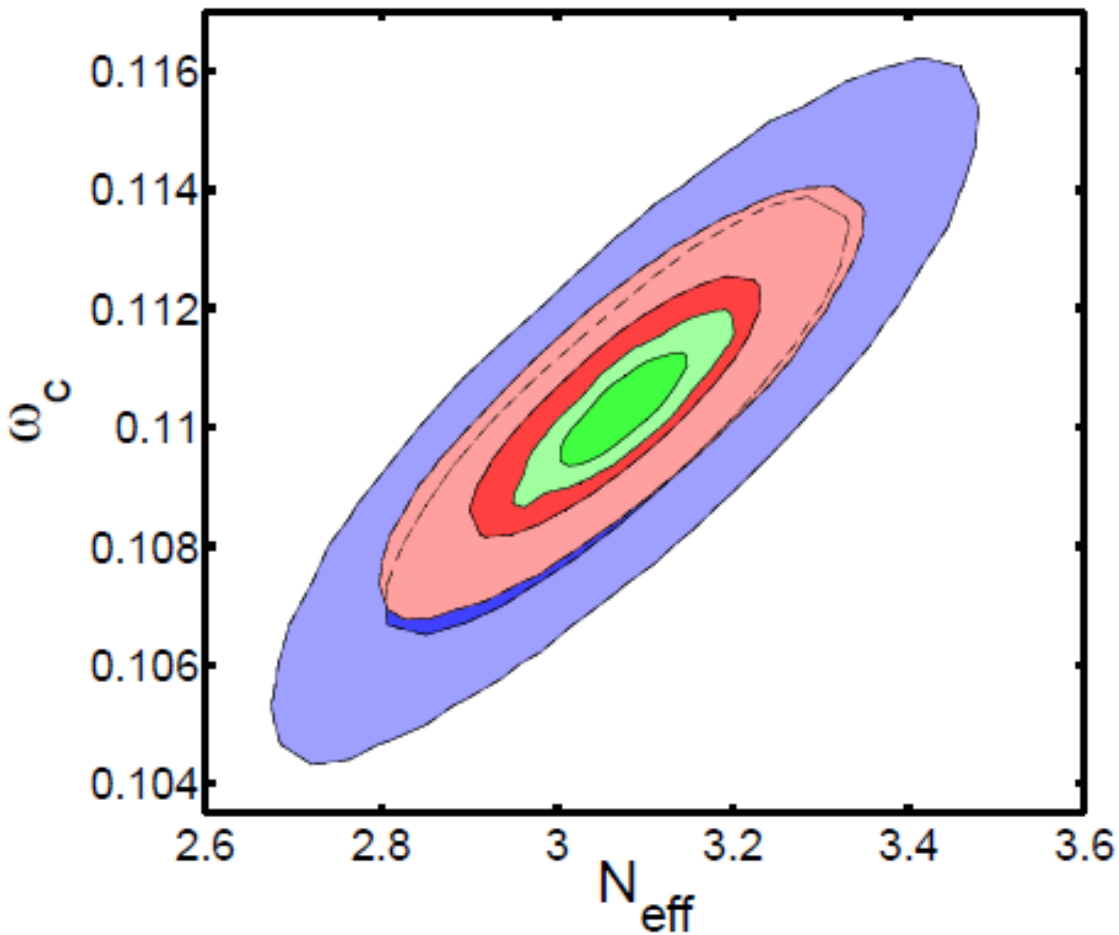
Blue: Planck $\Delta Yp=0.01$

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



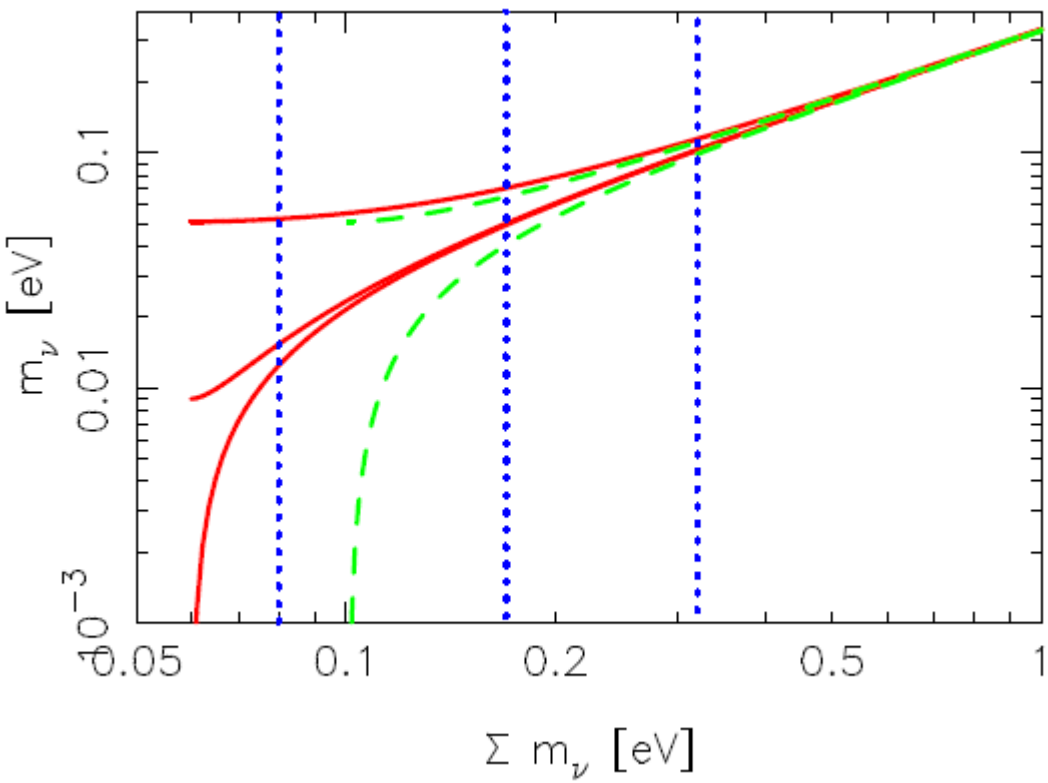
Blue: Planck ΔN_ν=0.18

Red: Planck+ACTpol ΔN_ν=0.11

Green: CMBPol ΔN_ν=0.044

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

Testing the neutrino hierarchy



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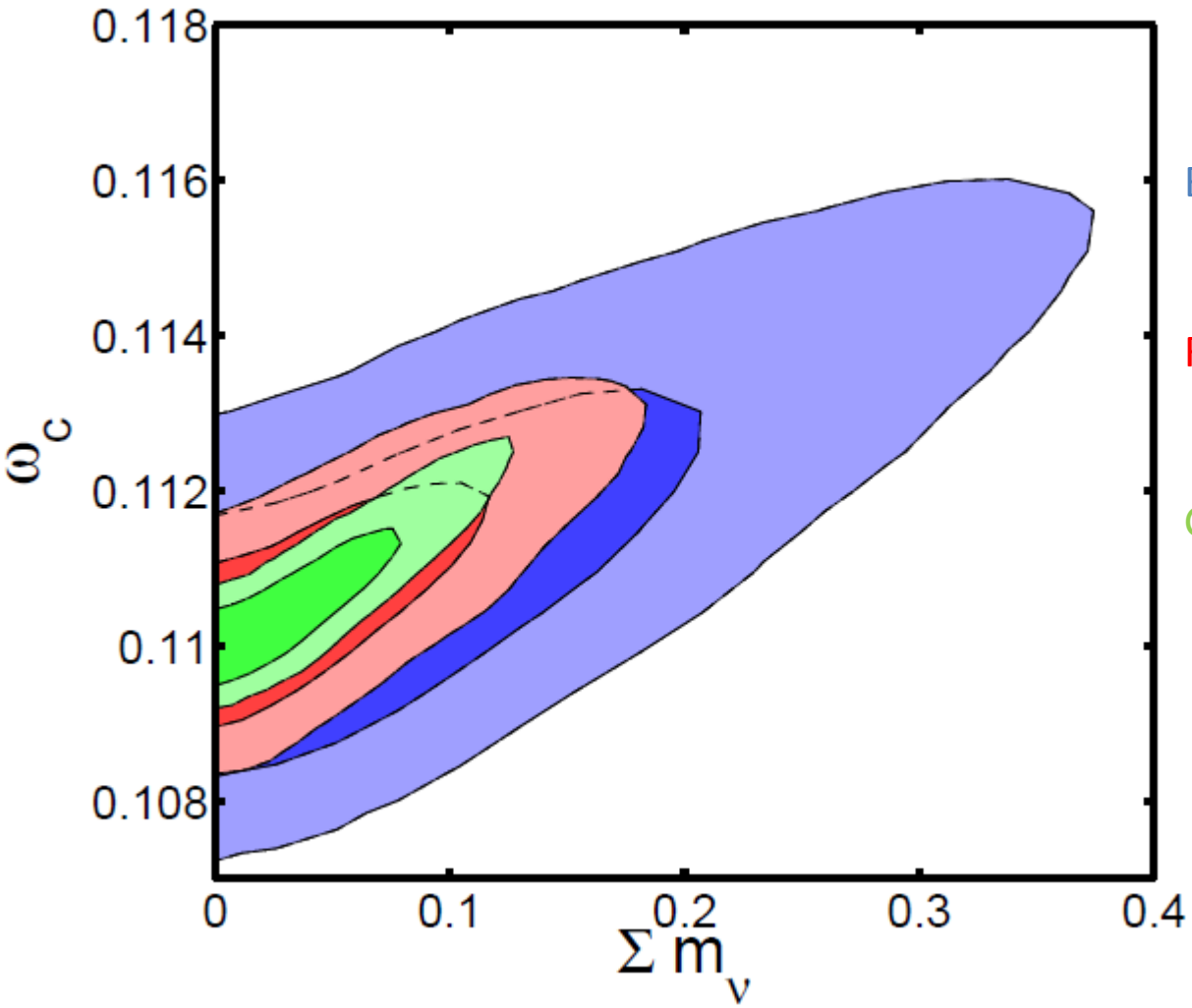
Constraints on Neutrino Mass



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)

THANK YOU