State of the art

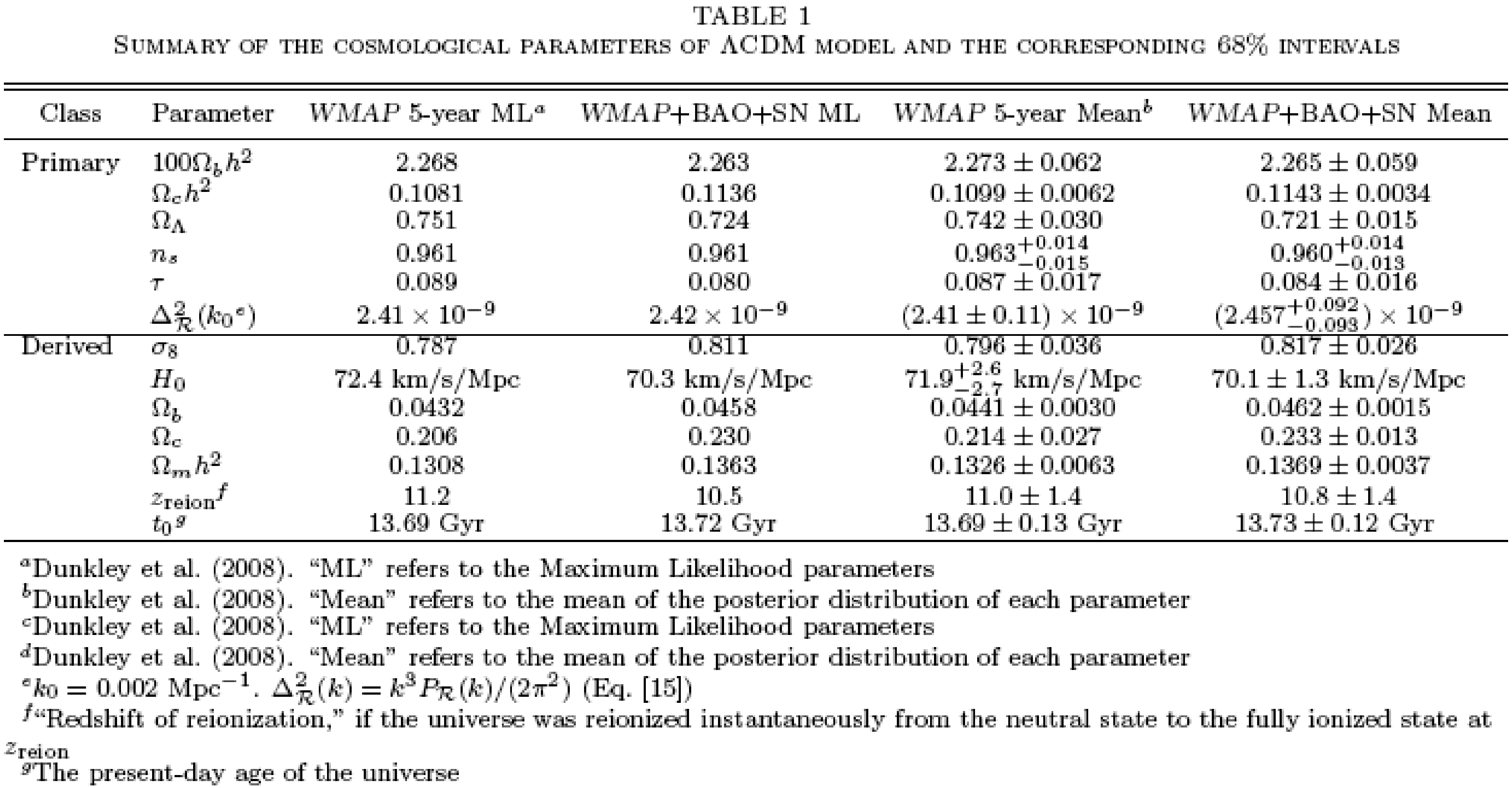


TABLE 1

SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL AND THE CORRESPONDING 68% INTERVALS

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1081	0.1136	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.751	0.724	0.742 ± 0.030	0.721 ± 0.015
	n_s	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.089	0.080	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.42×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.787	0.811	0.796 ± 0.036	0.817 ± 0.026
	H_0	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0458	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.206	0.230	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1308	0.1363	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.2	10.5	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

[a] Dunkley et al. (2008). "ML" refers to the Maximum Likelihood parameters

[b] Dunkley et al. (2008). "Mean" refers to the mean of the posterior distribution of each parameter

[c] Dunkley et al. (2008). "ML" refers to the Maximum Likelihood parameters

[d] Dunkley et al. (2008). "Mean" refers to the mean of the posterior distribution of each parameter

[e] $k_0 = 0.002$ Mpc^{-1}. $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ (Eq. [15])

[f] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$

[g] The present-day age of the universe

(Komatsu et al. 2008)

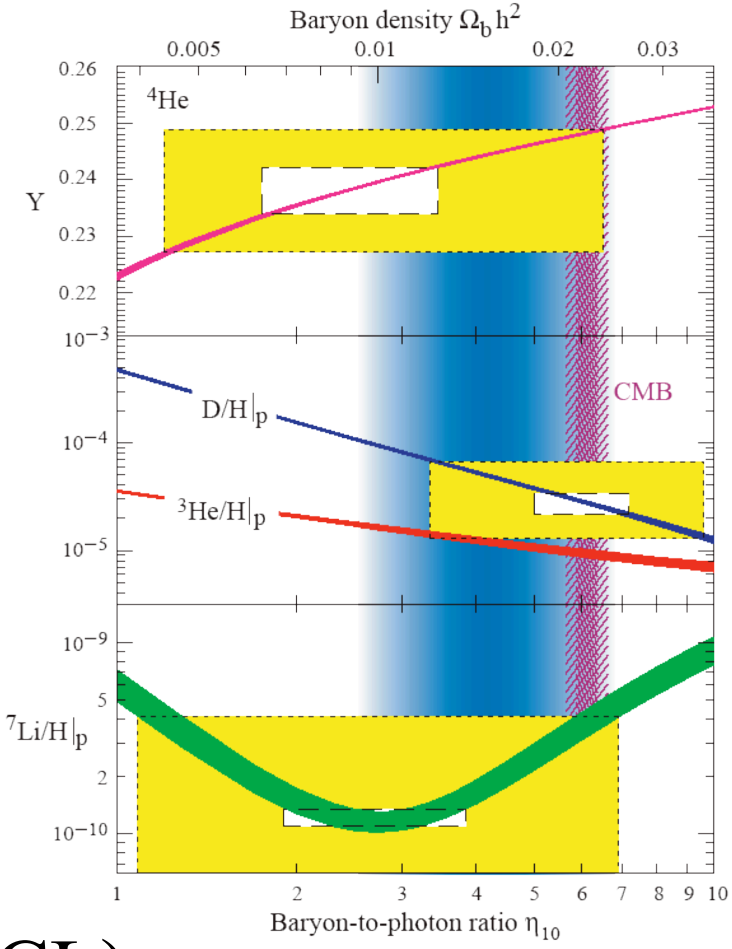
Baryon abundance

CMB, ratio of acoustic peaks amplitude (Komatsu et al. 2008):

$$\Omega_B h^2 = 0.02273 \pm 0.00062$$

Primordial abundance of deuterium + BBN (e.g. Fields & Sarkar, 2004):

$$0.012 \leq \Omega_B h^2 \leq 0.025 \quad (95\% \text{ CL})$$



Deceleration parameter

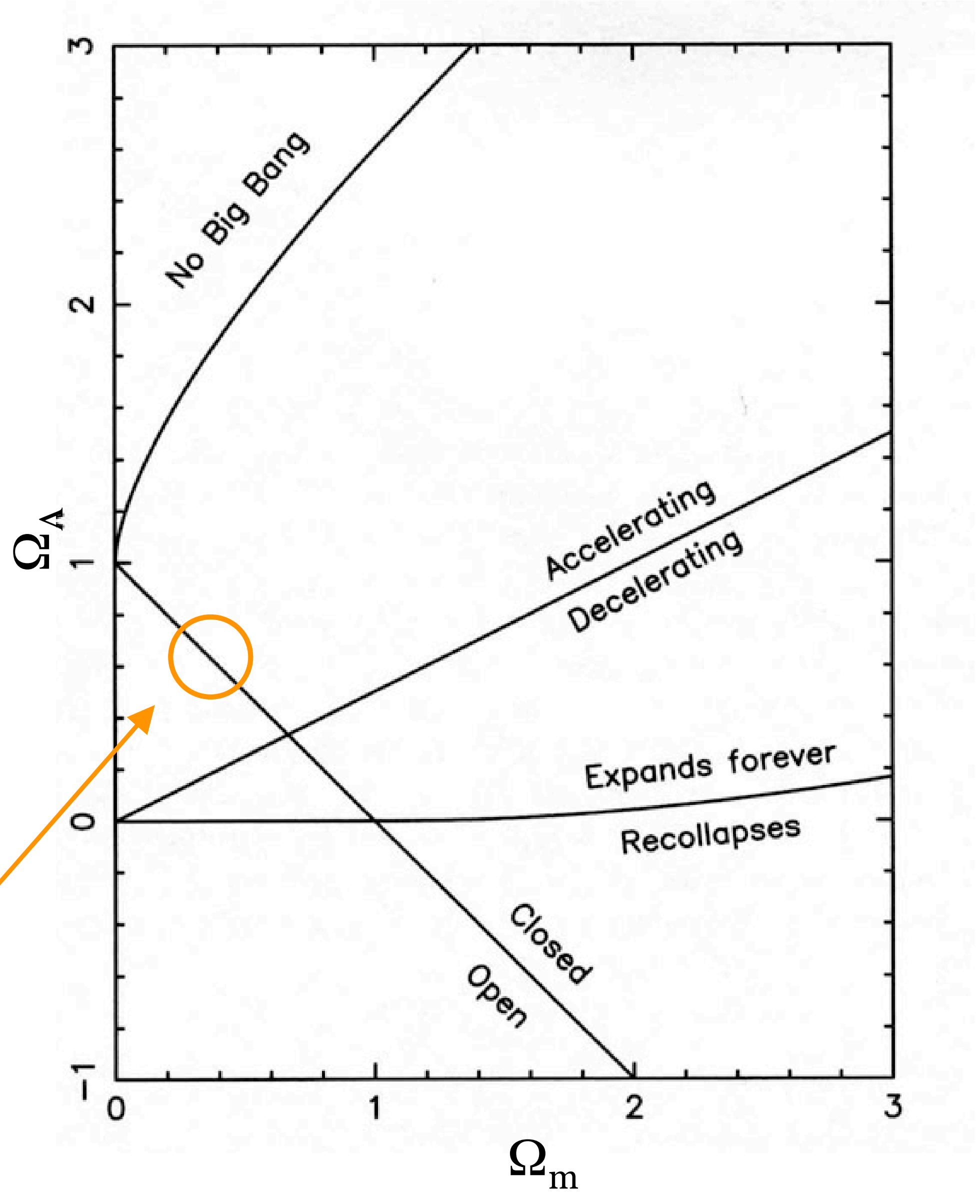
$$q_0 = \Omega_m / 2 - \Omega_\Lambda$$

Nearly flat models from the CMB:

$$\Omega = \Omega_m + \Omega_\Lambda = 1$$

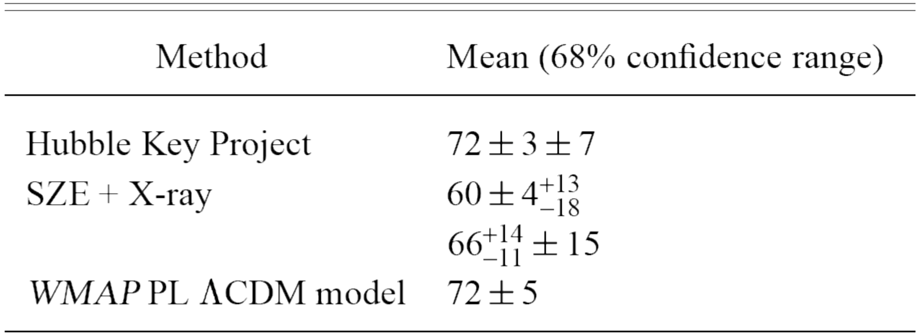
We have a concordance model

$$\Omega_m \approx 0.3, \;\; \Omega_\Lambda \approx 0.7$$

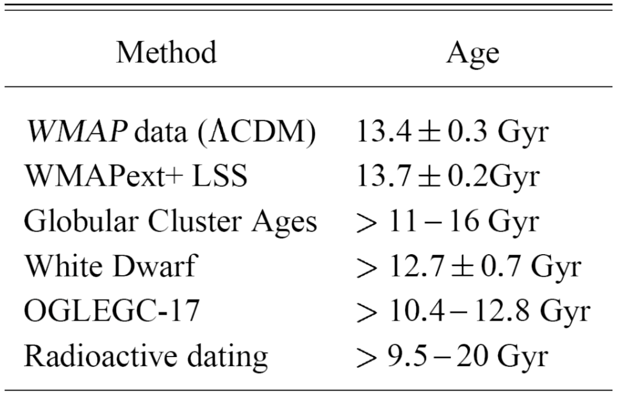


Hubble parameter + Age

- HST Key Project: use Cepheids to calibrate distance indicators (z~0)
- Combining X-ray flux and SZ effect in clusters of galaxies (z~0.5)
- CMB: conformal distance to the decoupling surface (z~1000)



Method	Mean (68% confidence range)
Hubble Key Project	$72 \pm 3 \pm 7$
SZE + X-ray	$60 \pm 4^{+13}_{-18}$
	$66^{+14}_{-11} \pm 15$
WMAP PL ΛCDM model	72 ± 5



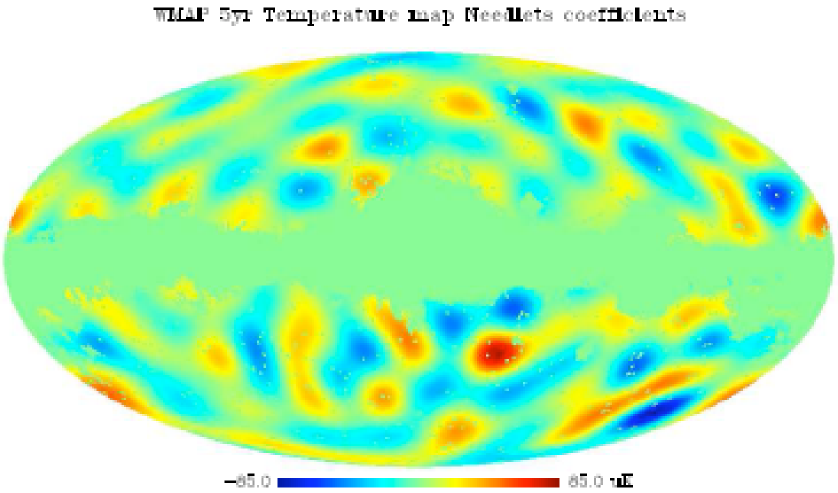
Method	Age
WMAP data (ΛCDM)	13.4 ± 0.3 Gyr
WMAPext+ LSS	13.7 ± 0.2Gyr
Globular Cluster Ages	$> 11-16$ Gyr
White Dwarf	$> 12.7 \pm 0.7$ Gyr
OGLEGC-17	$> 10.4-12.8$ Gyr
Radioactive dating	$> 9.5-20$ Gyr

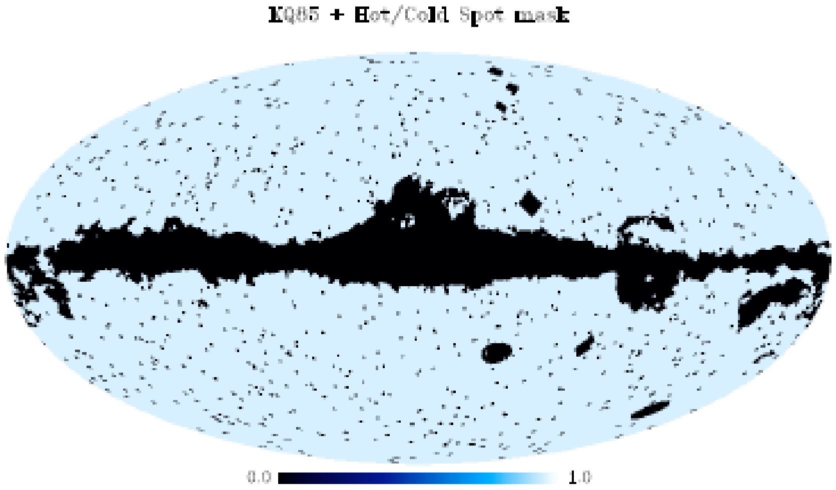
Spergel et al. 2003

What after WMAP?

- Improved tests of inflation (deviation from scale invariance, running spectral index)
- Accurate measurements of cosmological parameters (e.g. baryons and dark matter from high-l peaks, dark energy equation of state)
- E-mode polarization, to constrain detailed reionization history, and isocurvature mode contribution
- B-mode polarization? (Tensor modes)
- Tests of non gaussianity (from high S/N maps)
- Secondary anisotropy (SZ, lensing)
- Large-scale anomalies?

Hot/cold spots in the WMAP data



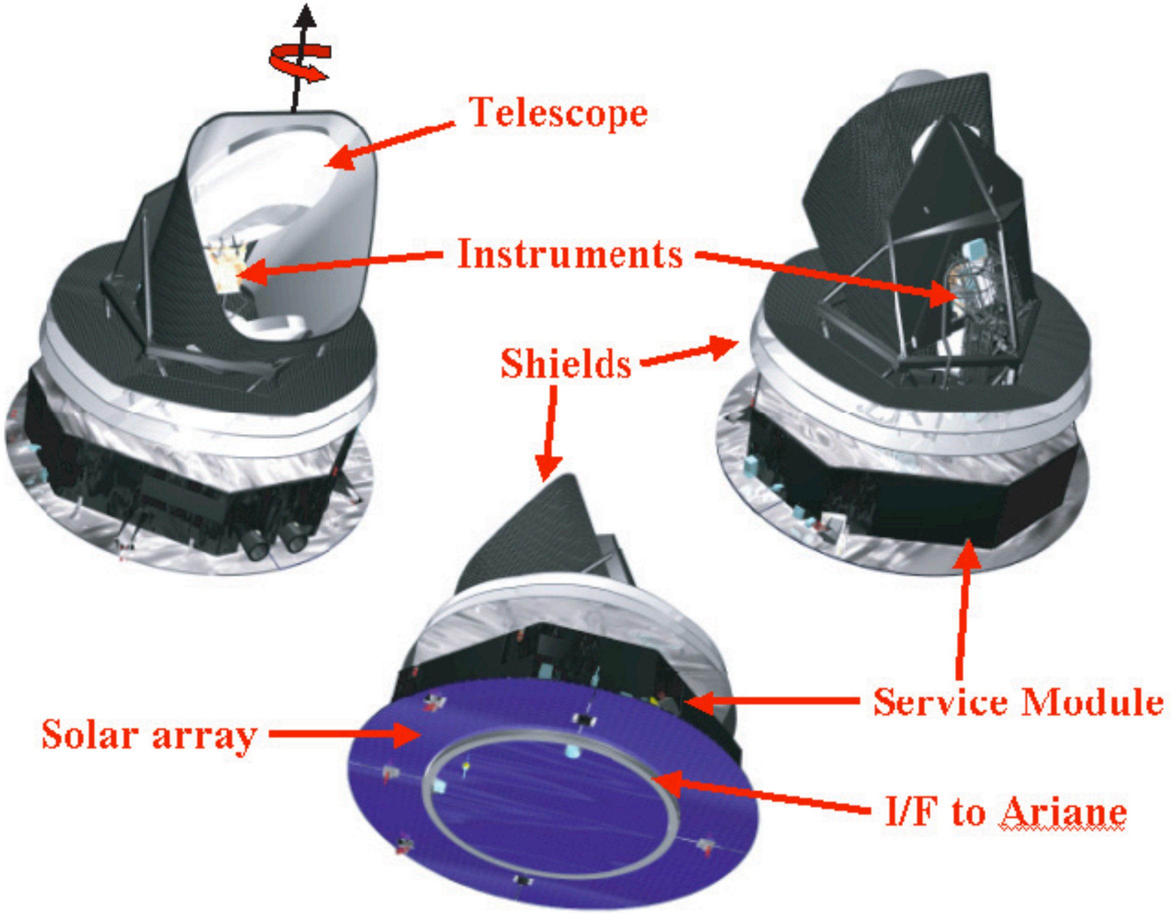


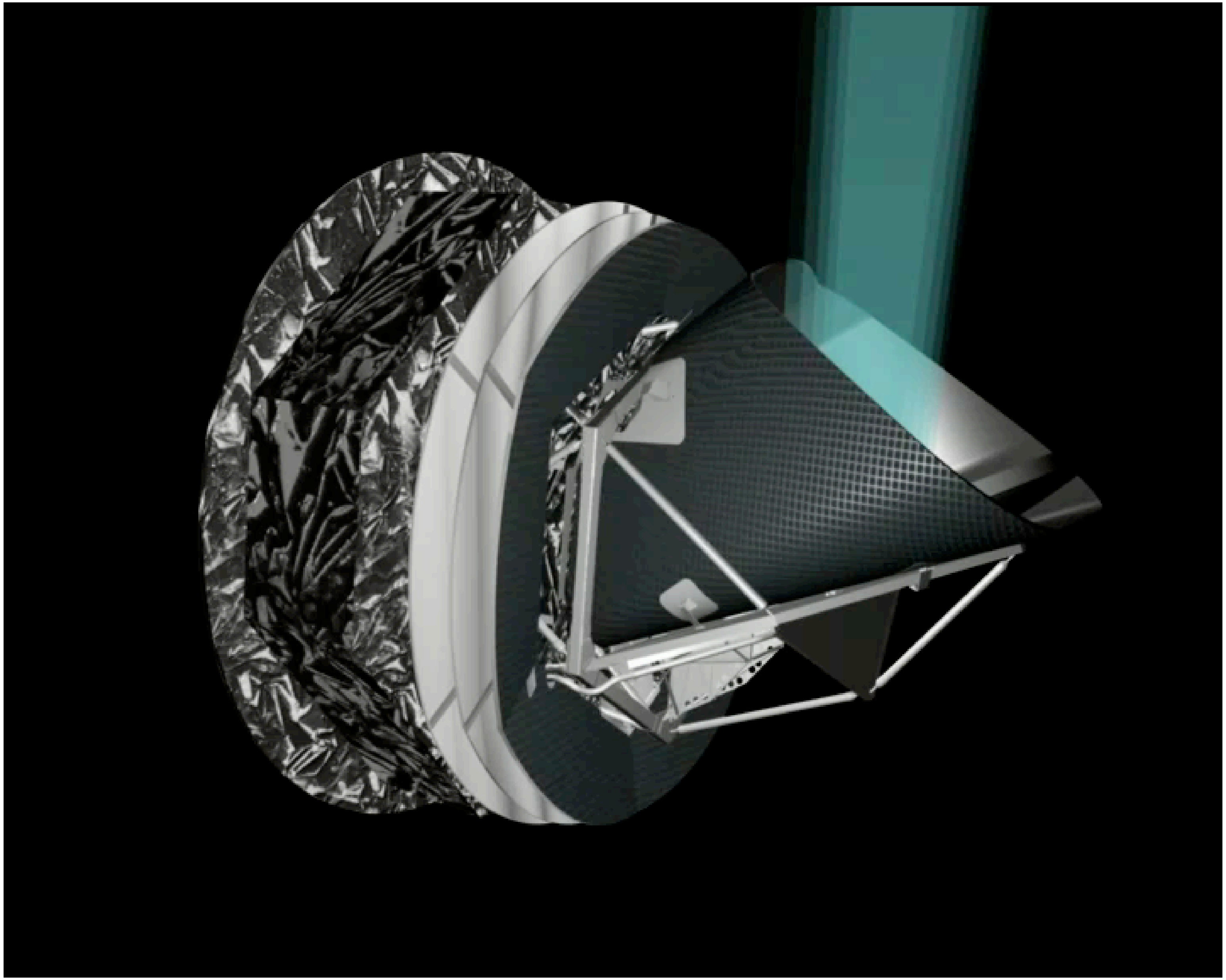
Pietrobon, Amblard, Balbi, Cabella, Cooray, Marinucci, 2008

parameter	WMAP5	Hot/Cold spot masked (*j*4)	*j*3-*j*4 mask
$\Omega_b h^2$	0.0227 ± 0.0006	0.0228 ± 0.0006	0.0228 ± 0.0006
$\Omega_c h^2$	0.110 ± 0.006	0.109 ± 0.006	0.109 ± 0.006
θ_A	1.040 ± 0.003	1.040 ± 0.003	1.040 ± 0.003
τ	0.089 ± 0.018	0.091 ± 0.017	0.089 ± 0.017
n_s	0.965 ± 0.014	0.966 ± 0.014	0.966 ± 0.014
$\ln(10^{10}A_s)$	3.18 ± 0.05	3.17 ± 0.05	3.17 ± 0.05

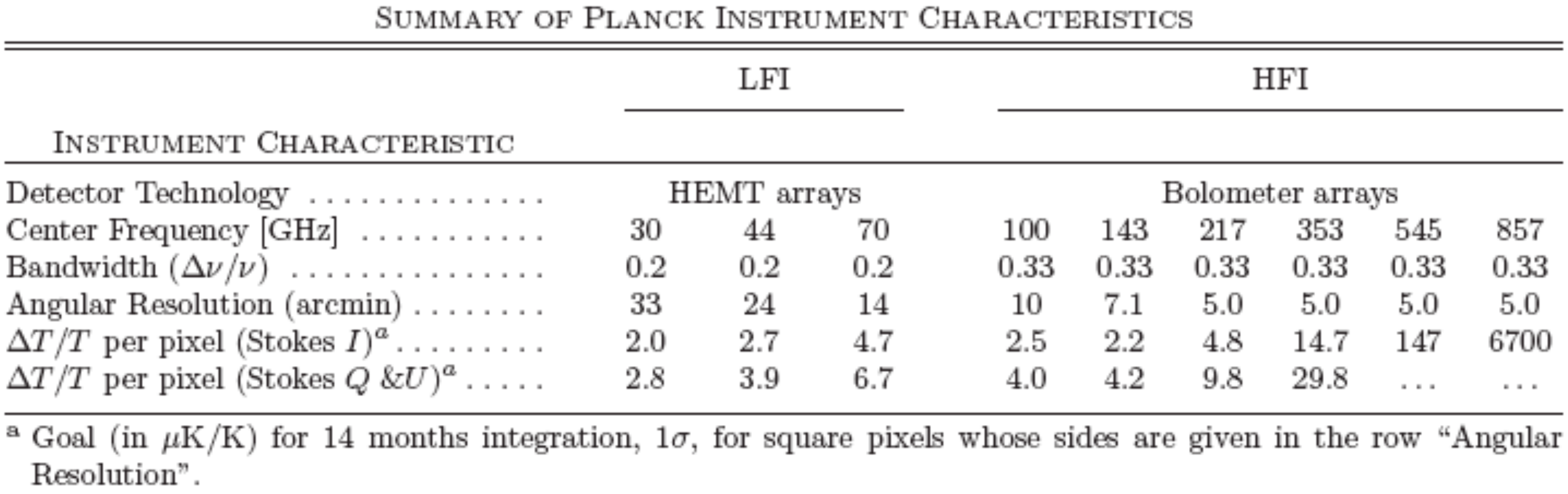
Planck has just been launched

For details: Planck Blue Book [ESA-SCI(2005)1] [astro-ph/0604069]





Expected performance



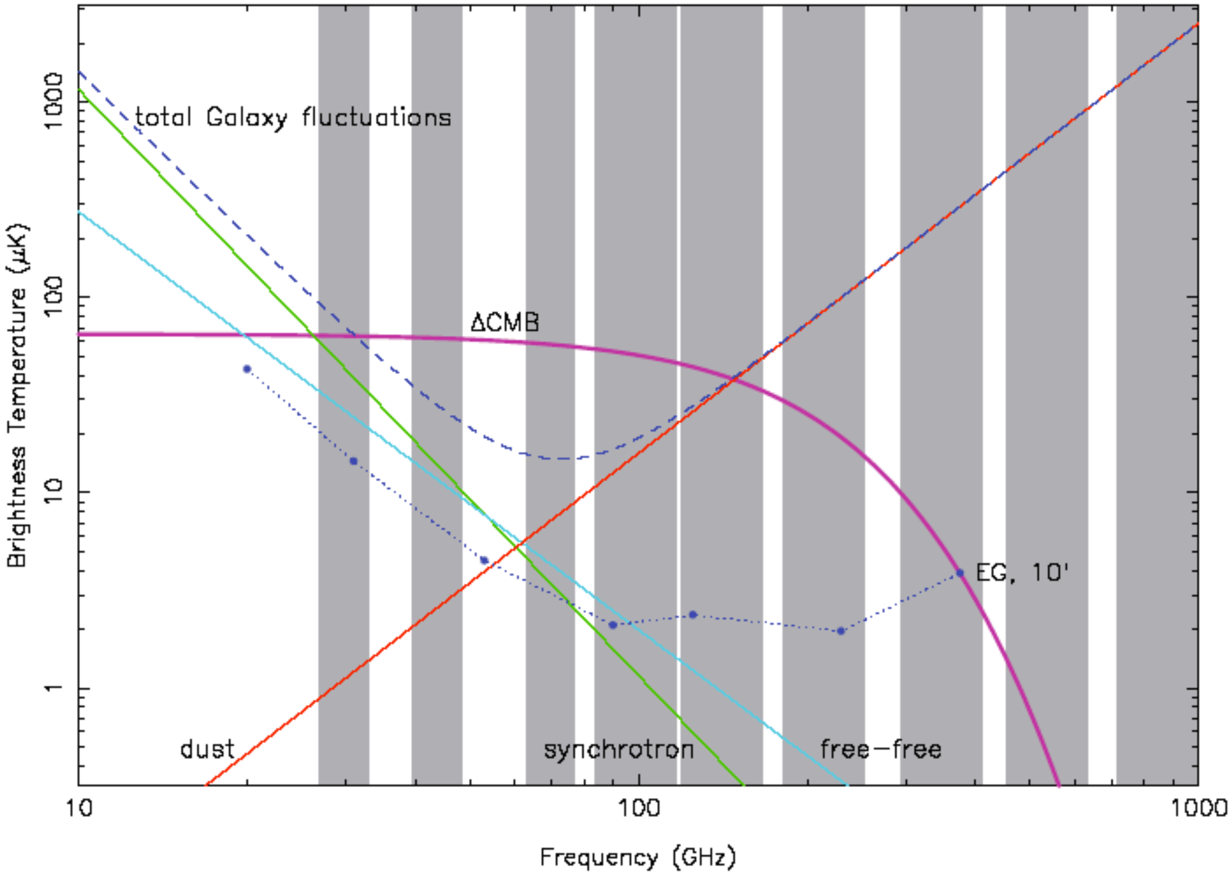
SUMMARY OF PLANCK INSTRUMENT CHARACTERISTICS

	LFI			HFI					
INSTRUMENT CHARACTERISTIC									
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q & U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row "Angular Resolution".

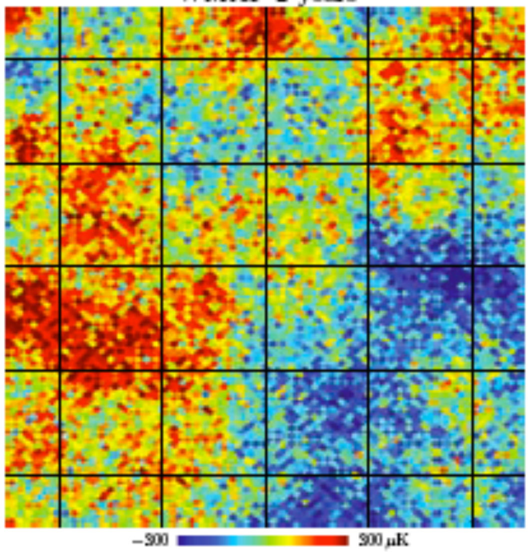
Three times better resolution than WMAP, an order of magnitude lower noise at 100 GHz. Great frequency coverage for optimal foreground subtraction.

Frequency coverage vs foregrounds

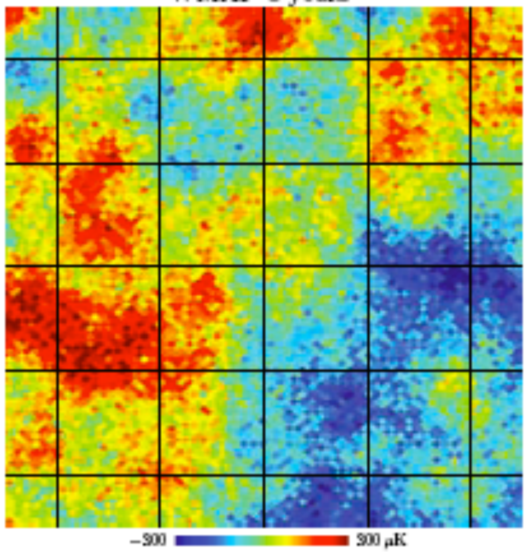


Planck vs WMAP T maps

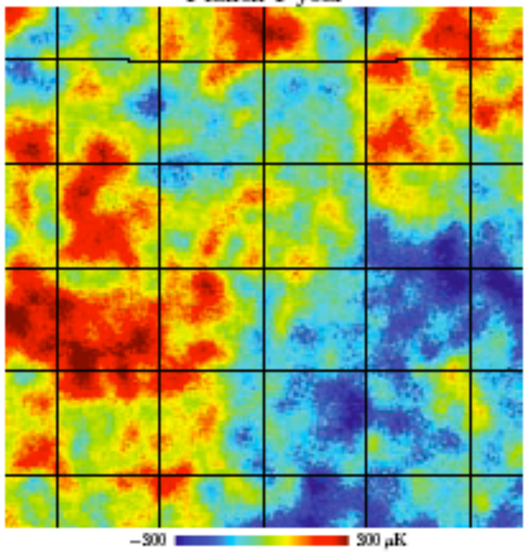
WMAP 2 years



WMAP 8 years



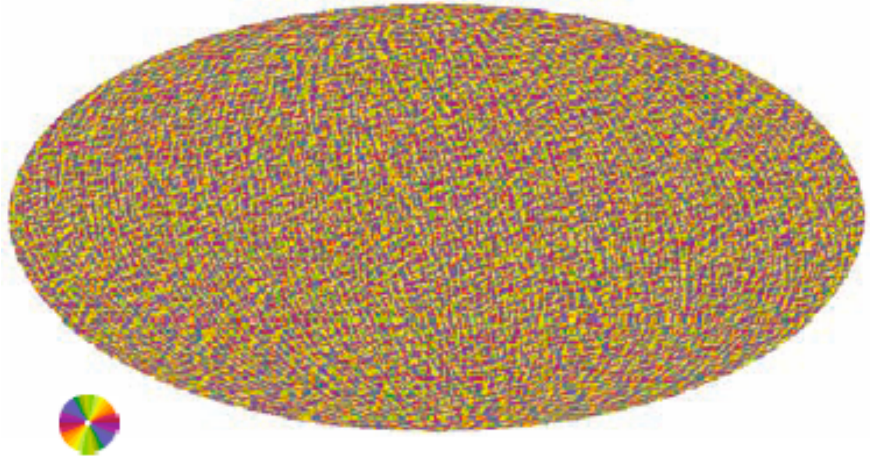
Planck 1 year

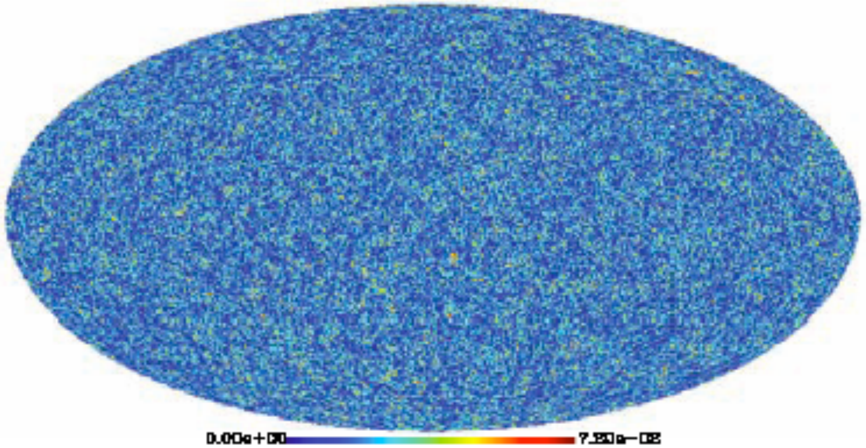


94 GHz, 15’

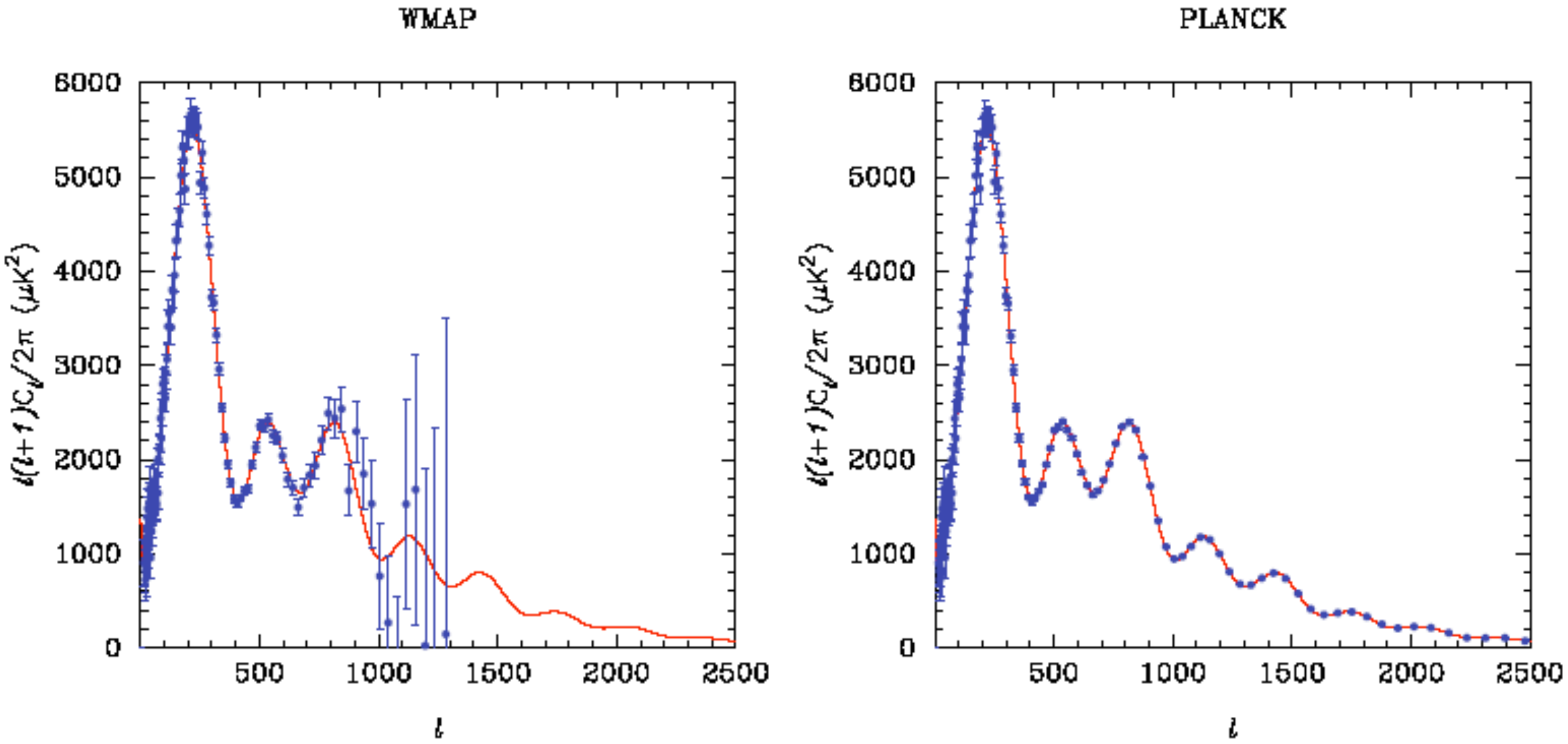
217 GHz, 5’

Planck polarization maps


Direction


Amplitude / $(\Delta T/T)_{rms}$

TT power spectrum

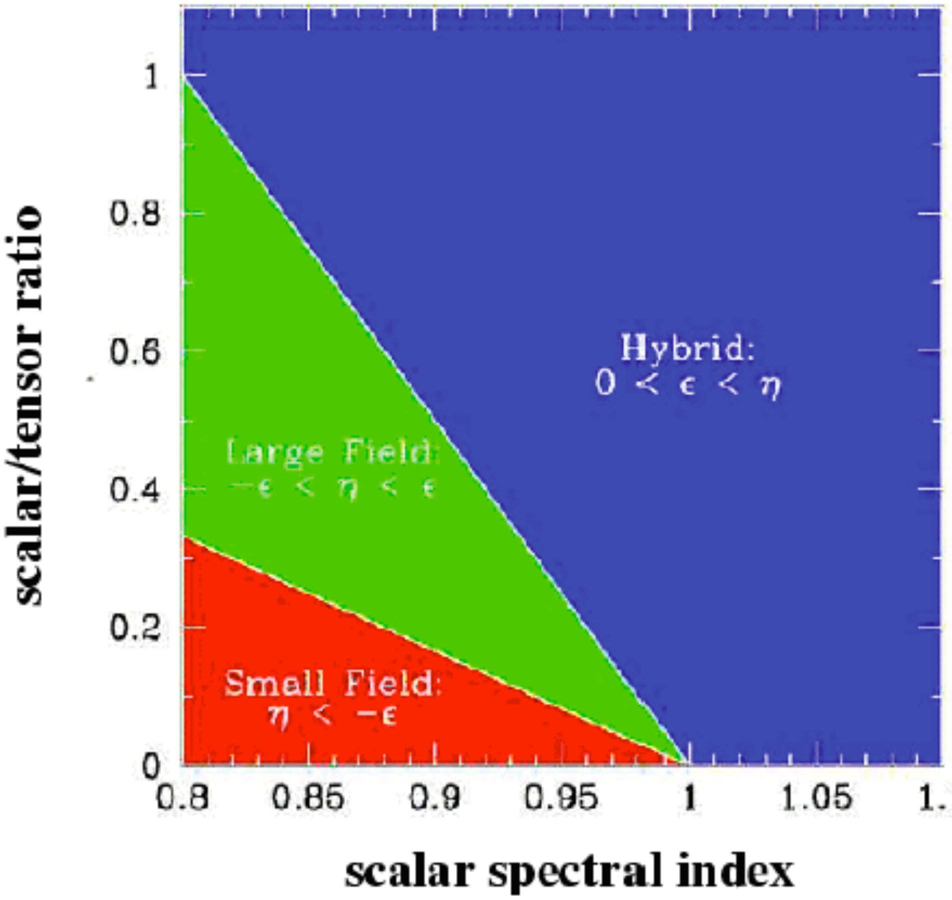


Simulation: WMAP 4 years vs Planck

Dynamics of inflation

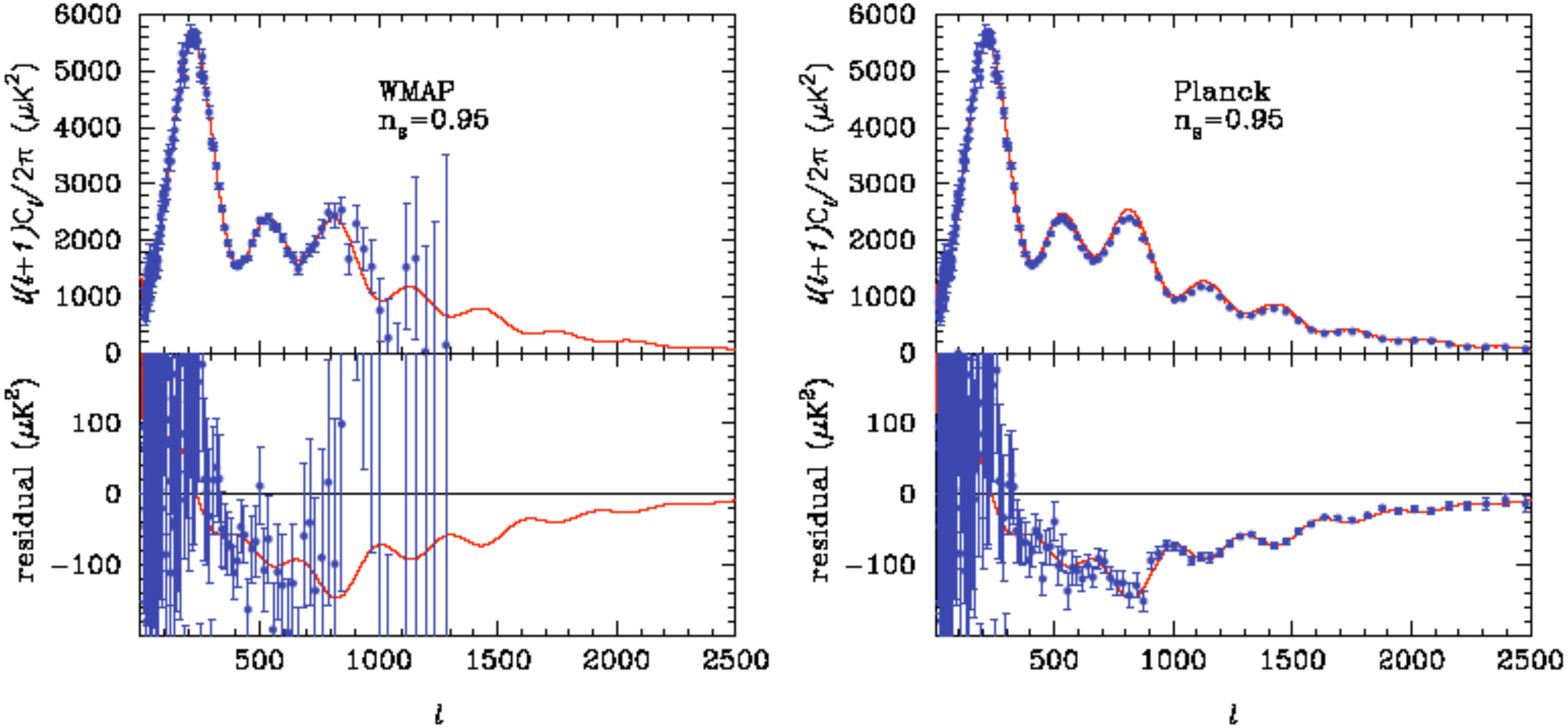
$$\epsilon = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2$$

$$\eta = \frac{m_{\rm Pl}^2}{8\pi}\left(\frac{V''}{V}\right)$$

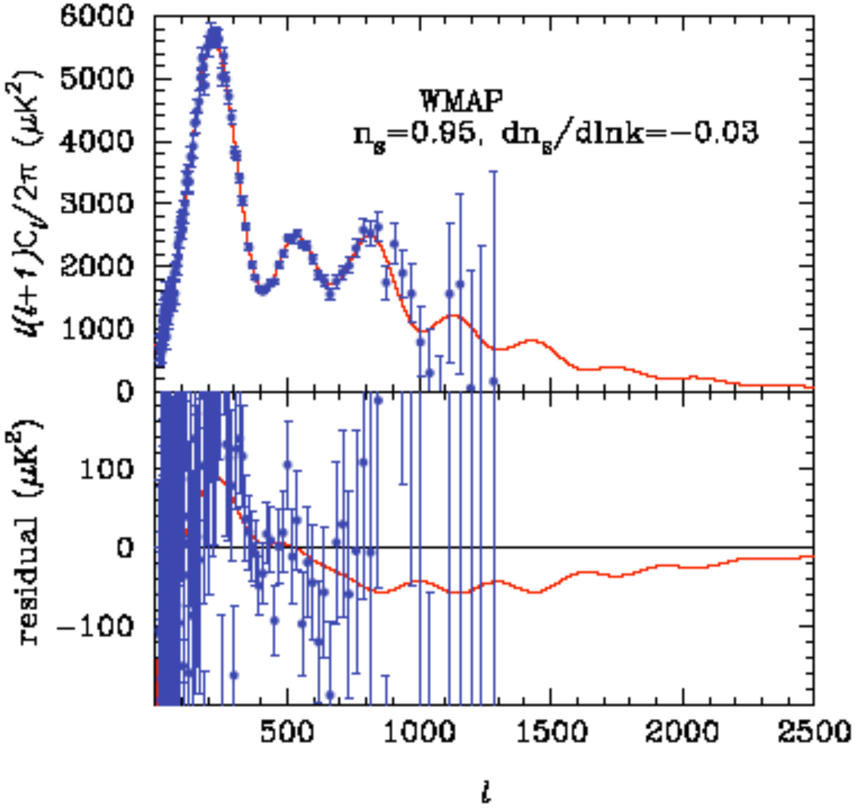


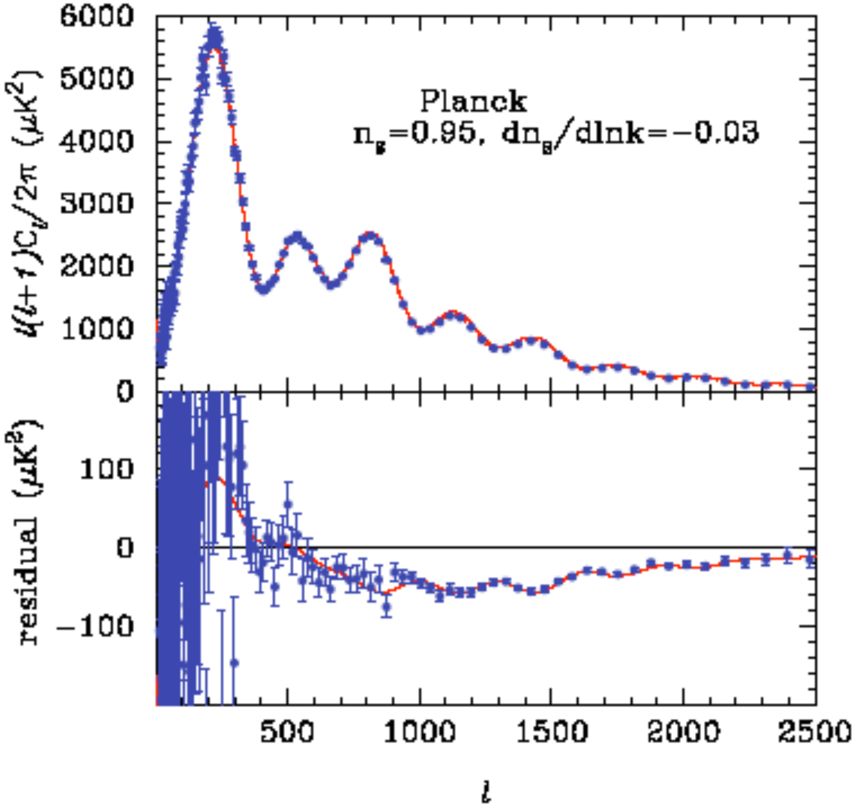
Kinney, Melchiorri & Riotto 2001

Scalar spectral index reconstruction

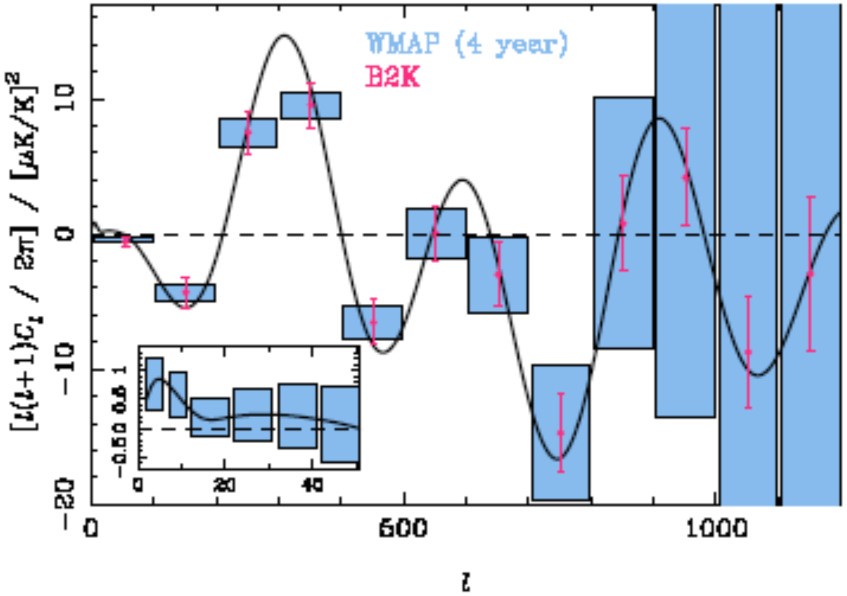


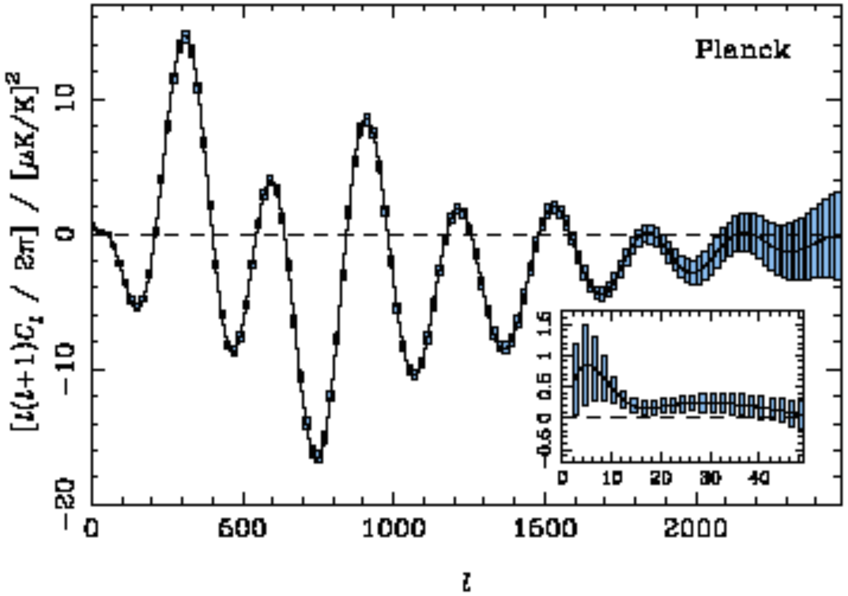
Running spectral index



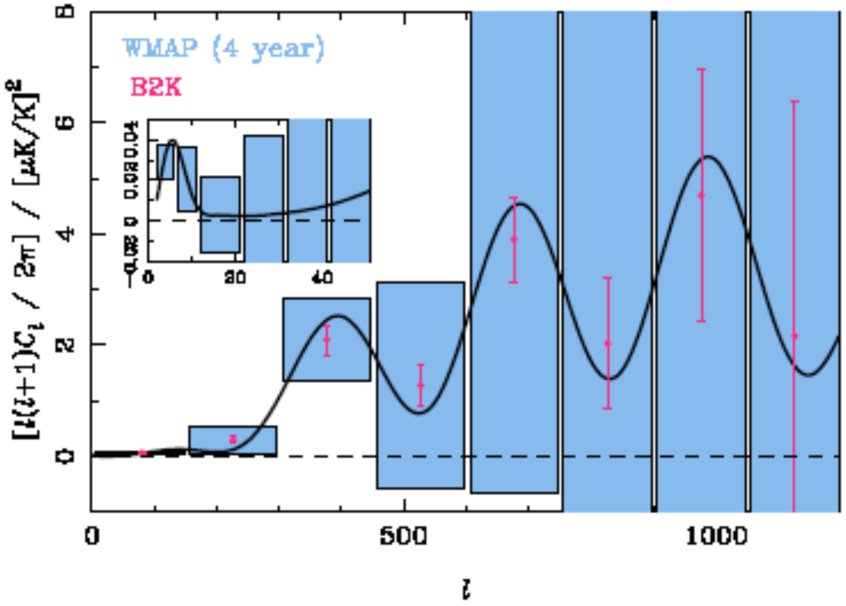


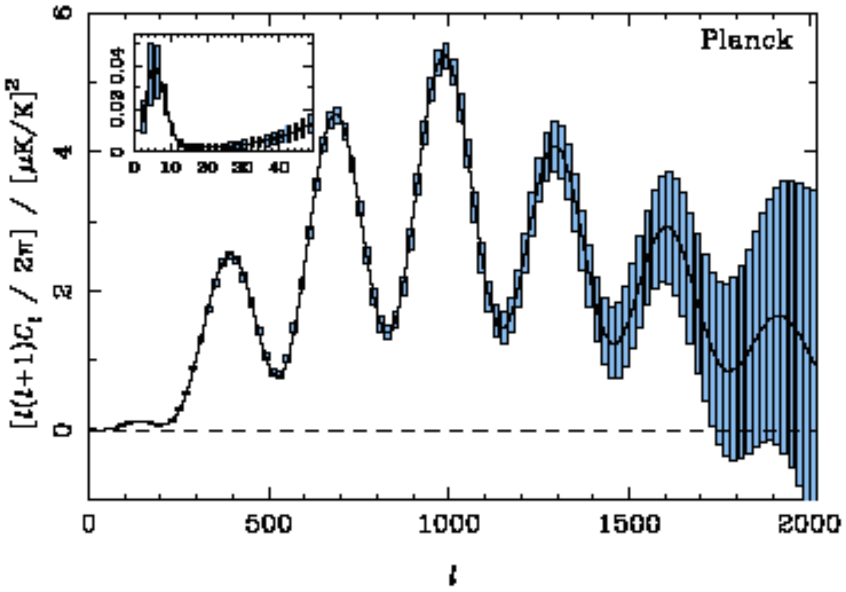
TE power spectrum





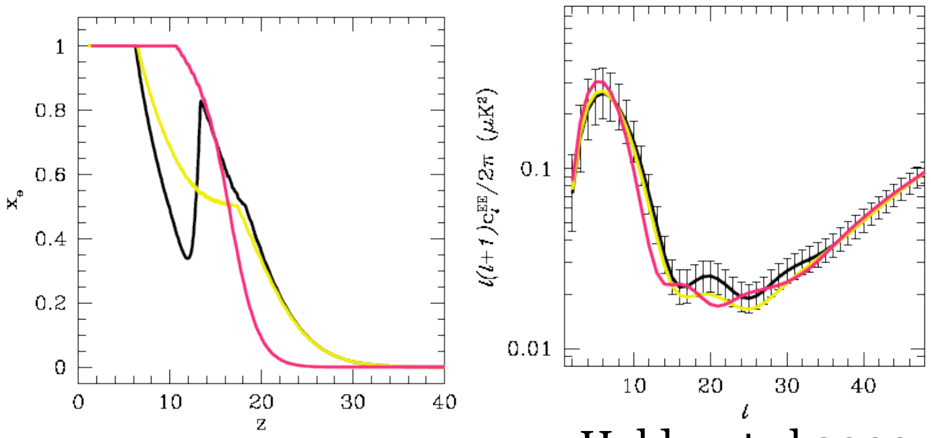
EE power spectrum





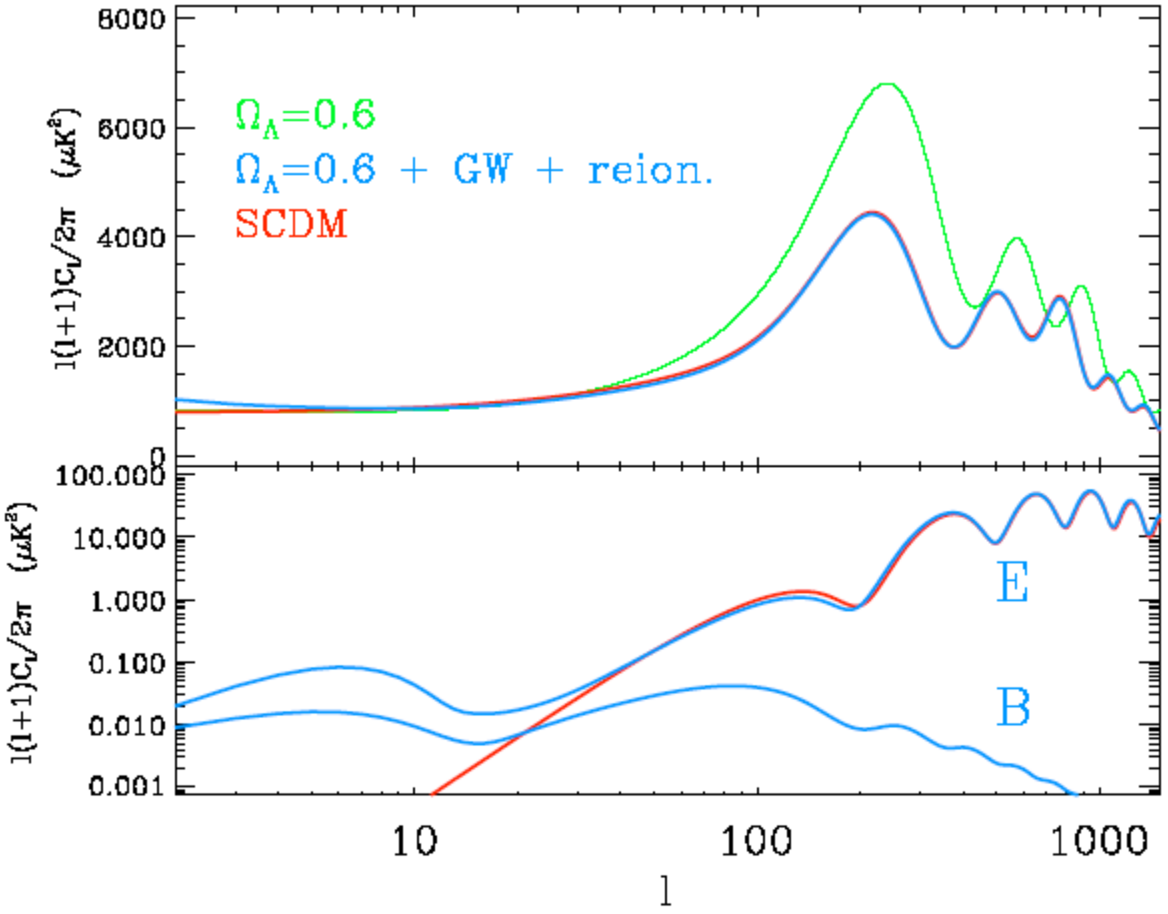
Ionization history

- Still large uncertainties: WMAP 5-year data favor optical depth ~0.08 or complete ionization at z~10 in better agreement with LCDM simulations.
- Uncertainties on the optical depth affect accuracy on the estimate of other parameters (e.g. amplitude of fluctuations, spectral index)
- Inclusion of polarization information (EE and TE) is crucial. Better data needed.
- We do not know much about detailed behaviour of ionization fraction vs redshift.

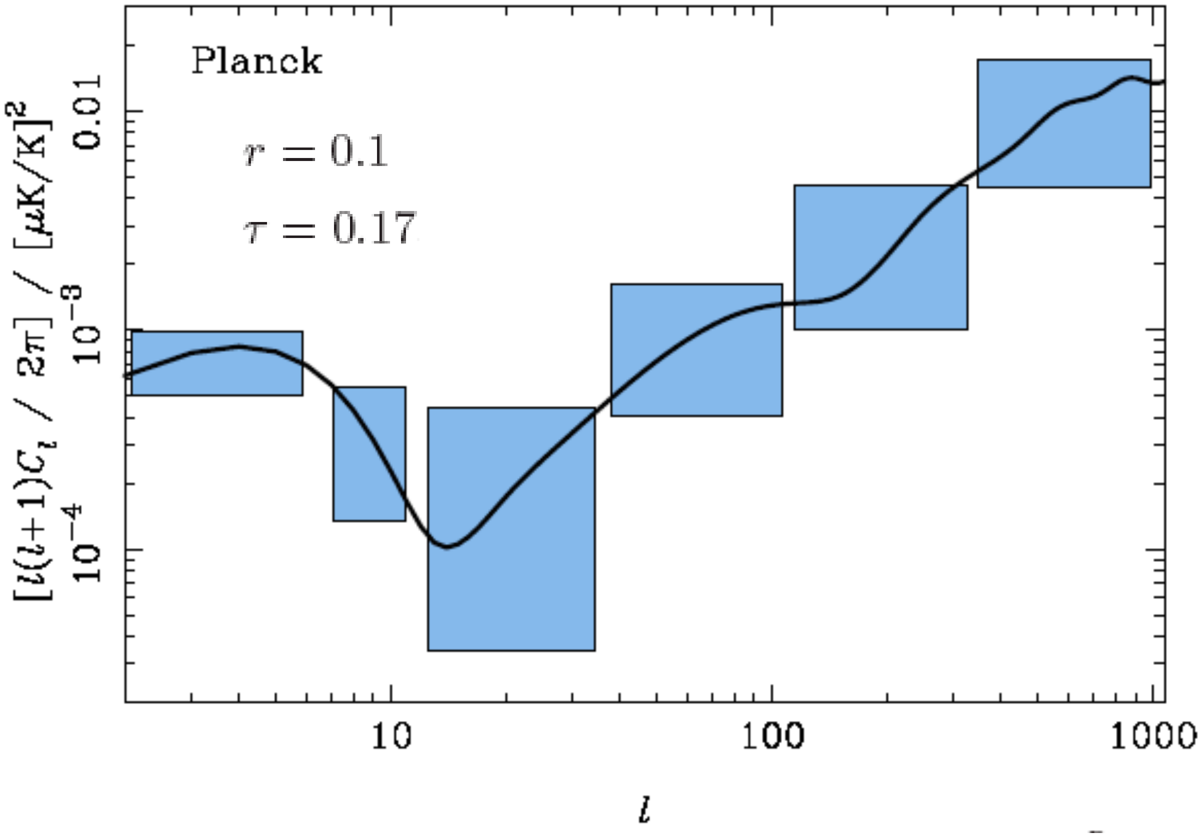


Holder et al 2003

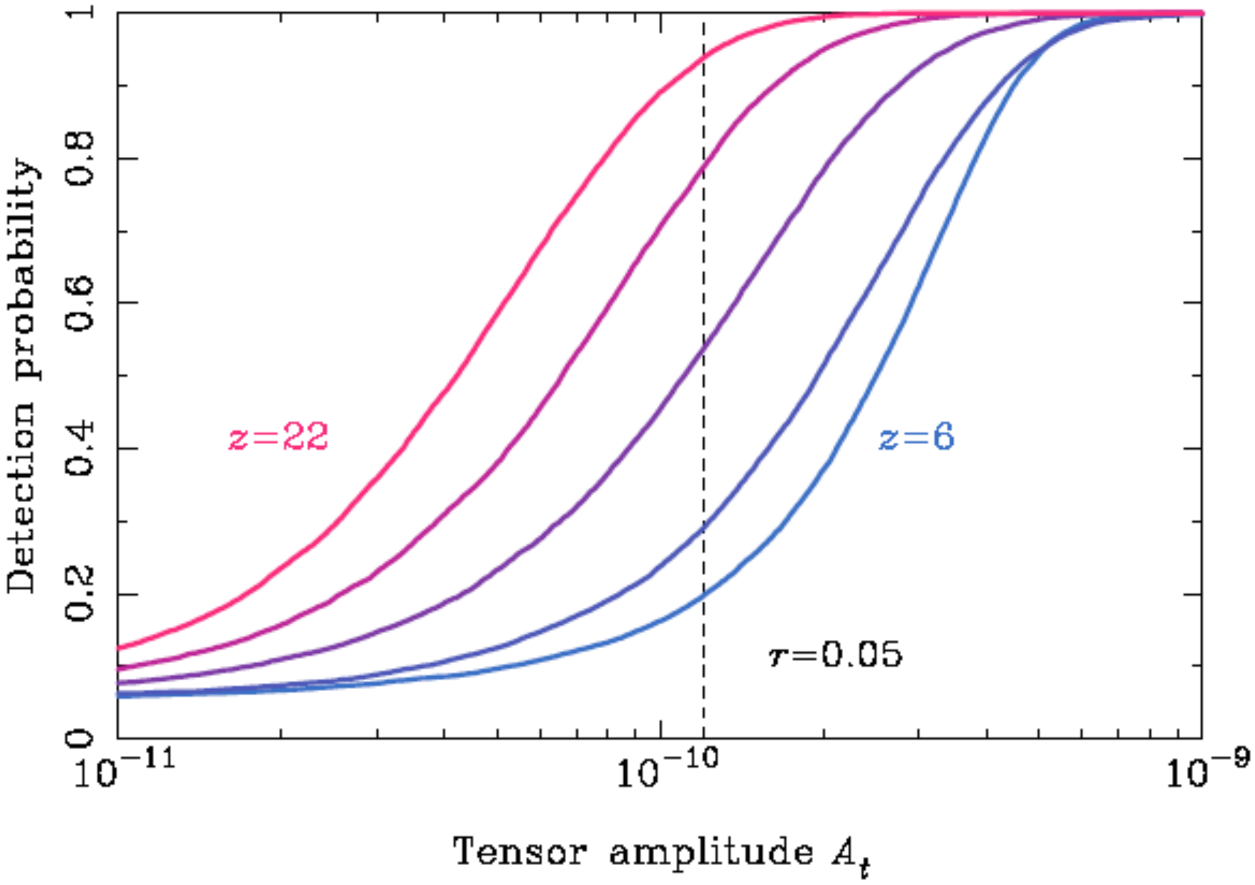
Breaking degeneracies



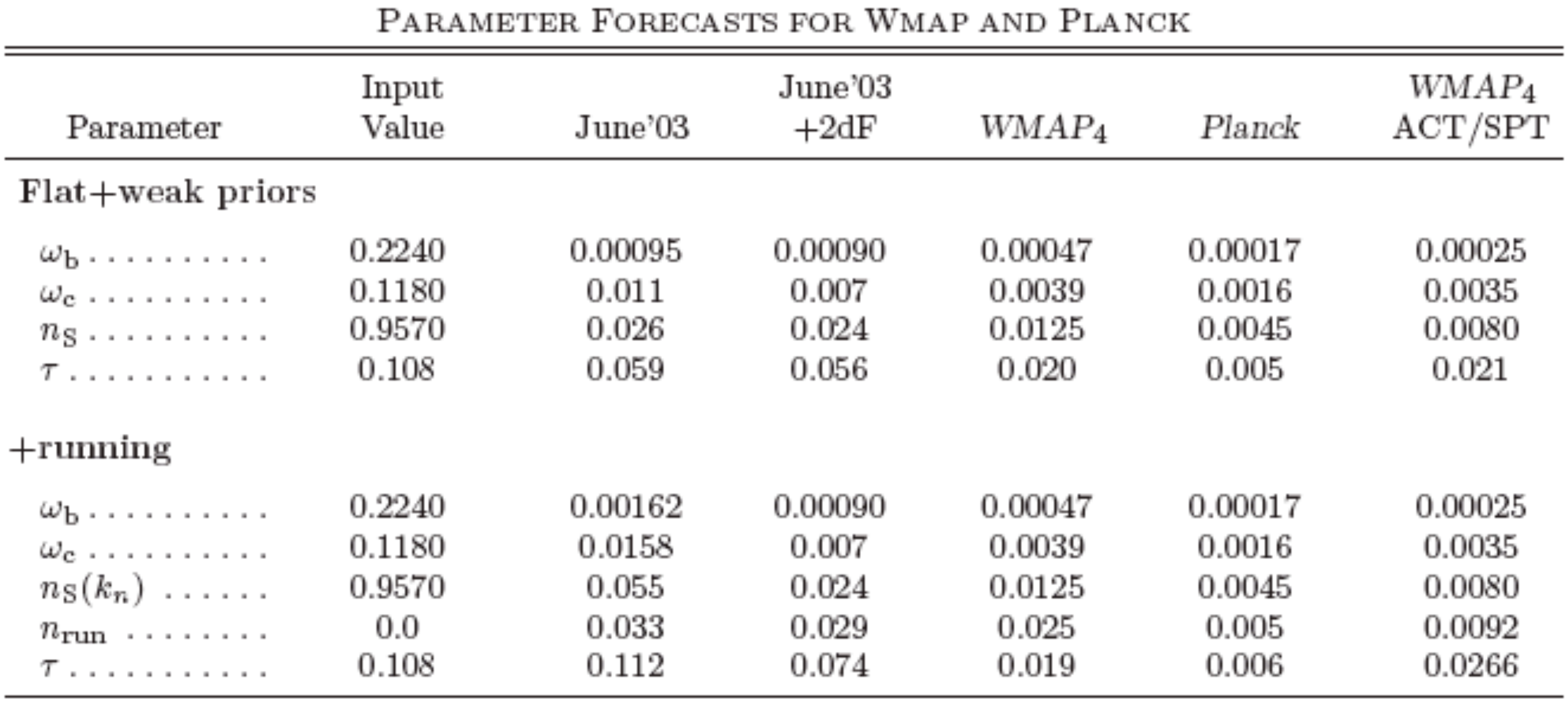
BB power spectrum



BB detection probability

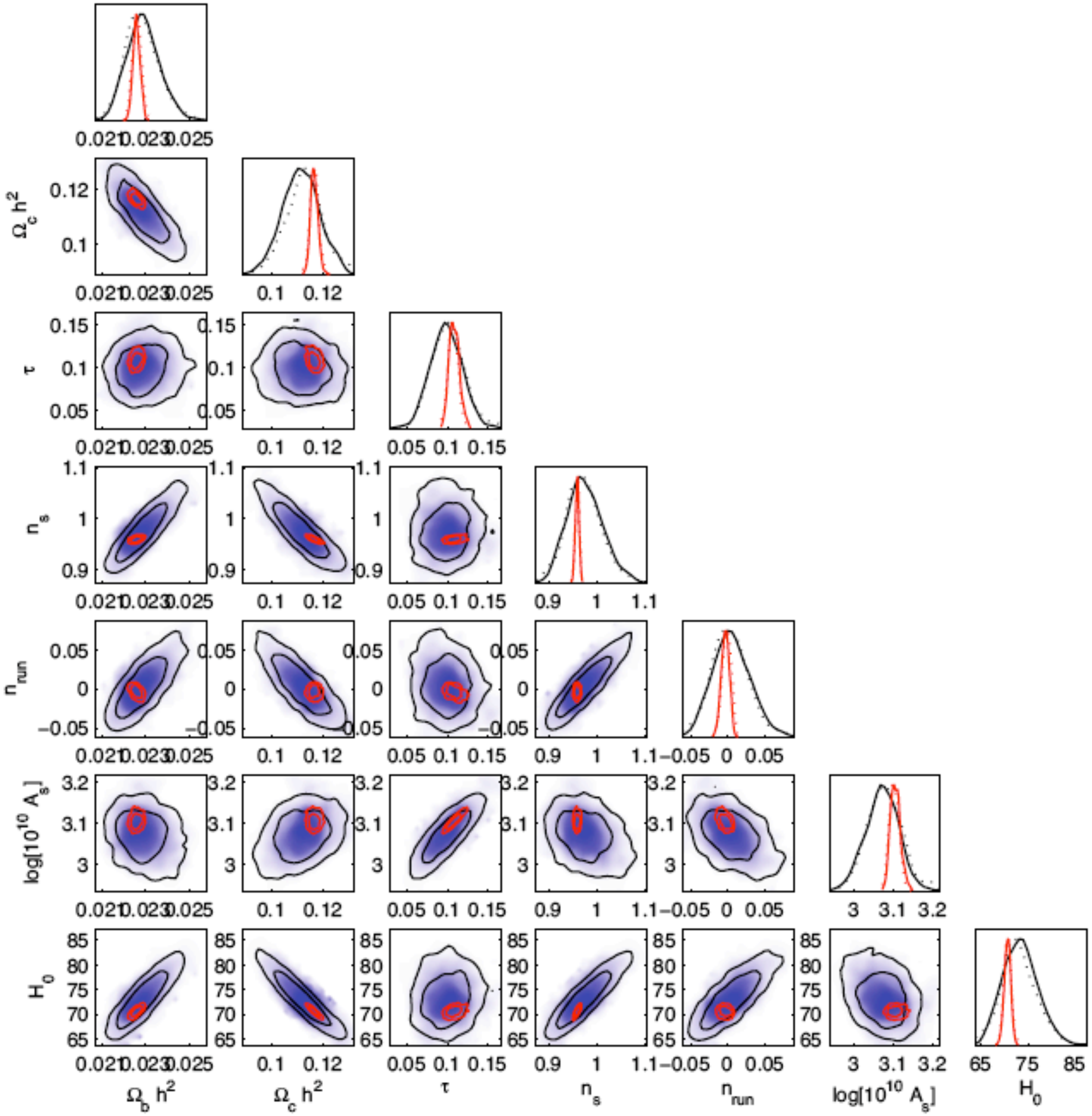


Cosmological parameters forecast

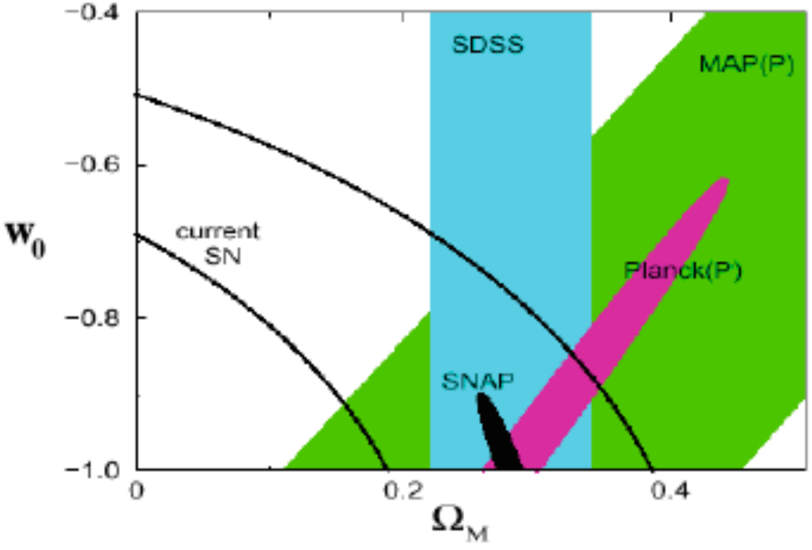


Parameter Forecasts for Wmap and Planck

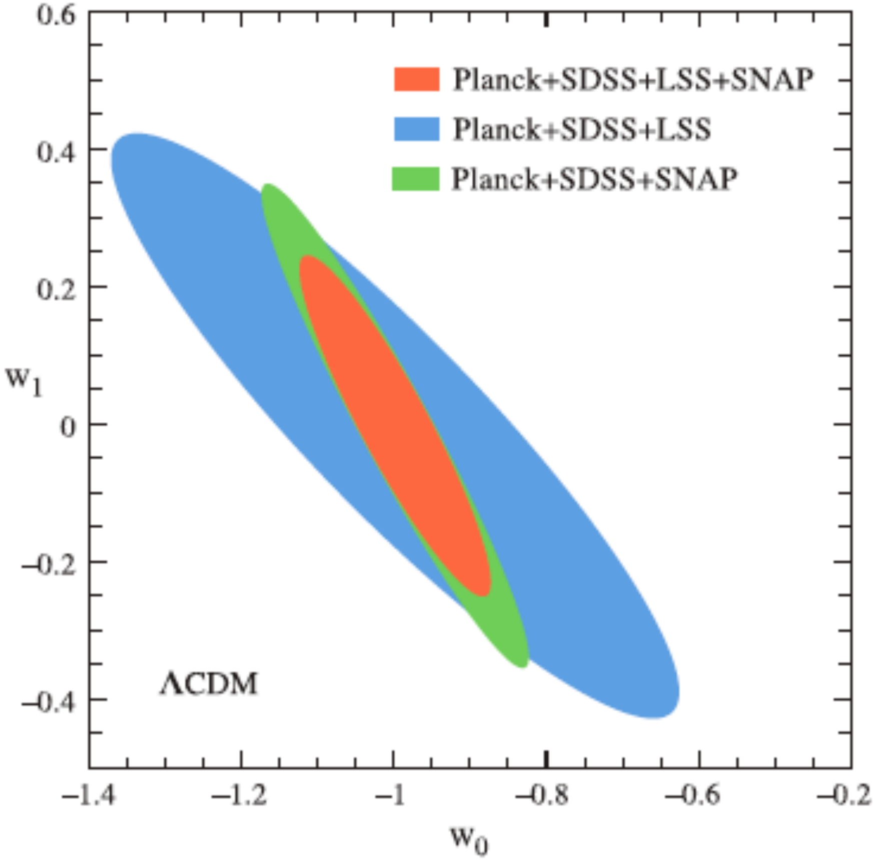
Parameter	Input Value	June'03	June'03 +2dF	*WMAP*$_4$	*Planck*	*WMAP*$_4$ ACT/SPT
Flat+weak priors						
$\omega_{\rm b}$	0.2240	0.00095	0.00090	0.00047	0.00017	0.00025
$\omega_{\rm c}$	0.1180	0.011	0.007	0.0039	0.0016	0.0035
$n_{\rm S}$	0.9570	0.026	0.024	0.0125	0.0045	0.0080
τ	0.108	0.059	0.056	0.020	0.005	0.021
+running						
$\omega_{\rm b}$	0.2240	0.00162	0.00090	0.00047	0.00017	0.00025
$\omega_{\rm c}$	0.1180	0.0158	0.007	0.0039	0.0016	0.0035
$n_{\rm S}(k_n)$	0.9570	0.055	0.024	0.0125	0.0045	0.0080
$n_{\rm run}$	0.0	0.033	0.029	0.025	0.005	0.0092
τ	0.108	0.112	0.074	0.019	0.006	0.0266


0.021
0.023
0.025
0.1
0.12
0.05
0.1
0.15
0.9
1
1.1
−0.05
0
0.05
3
3.1
3.2
65
70
75
80
85
$\Omega_c h^2$
τ
n_s
n_{run}
$\log[10^{10} A_s]$
H_0
$\Omega_b h^2$
$\Omega_c h^2$
τ
n_s
n_{run}
$\log[10^{10} A_s]$
H_0

Dark energy



Huterer et al. 20



Conclusions

- Planck will give definitive measurement of CMB T anisotropy (WMAP ~10% of the total information)
- Good (but not optimal) polarization capabilities: TE, EE, perhaps BB
- Optimal foreground separation
- Accurate imaging will allow real space tests (good for non Gaussianity)