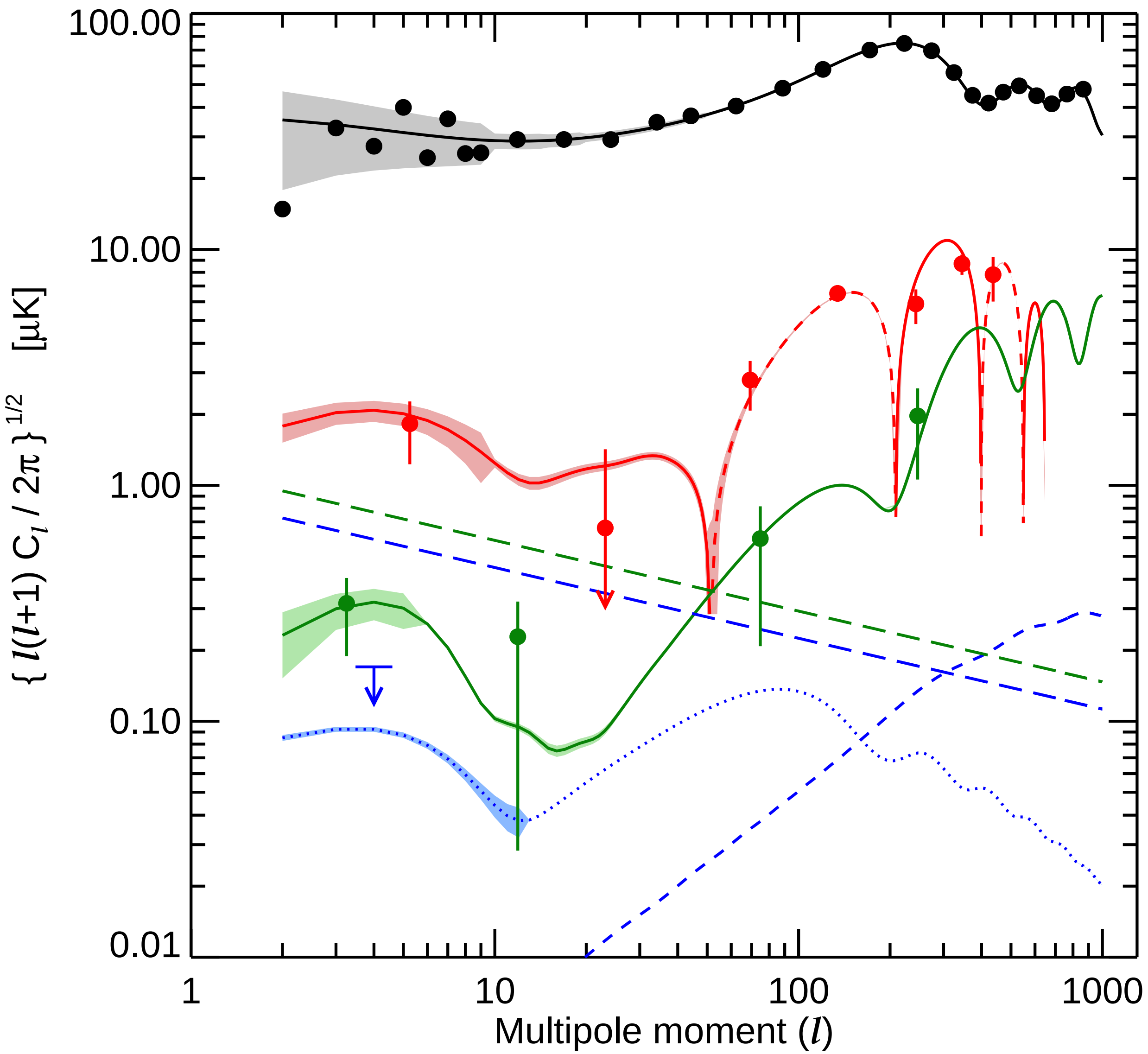
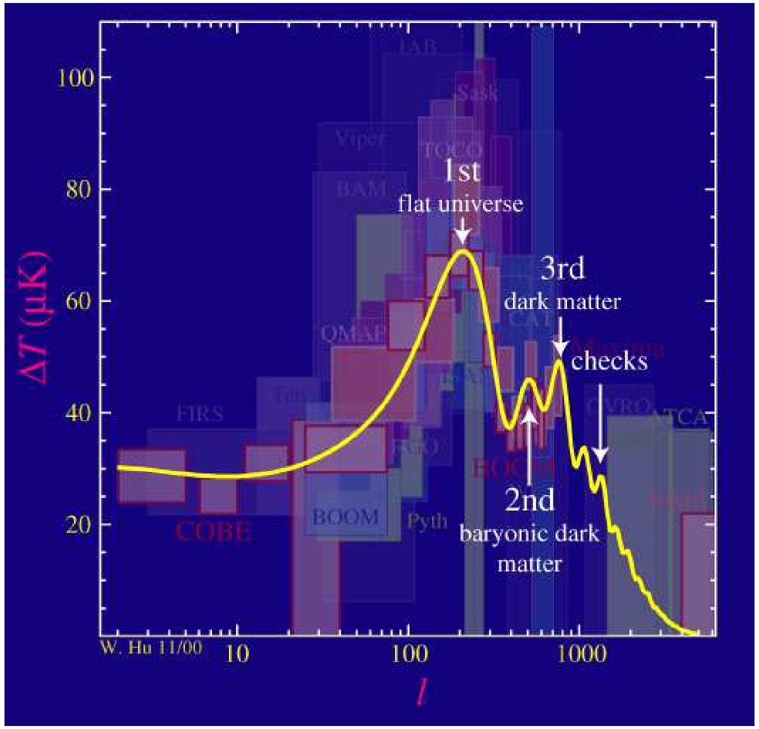
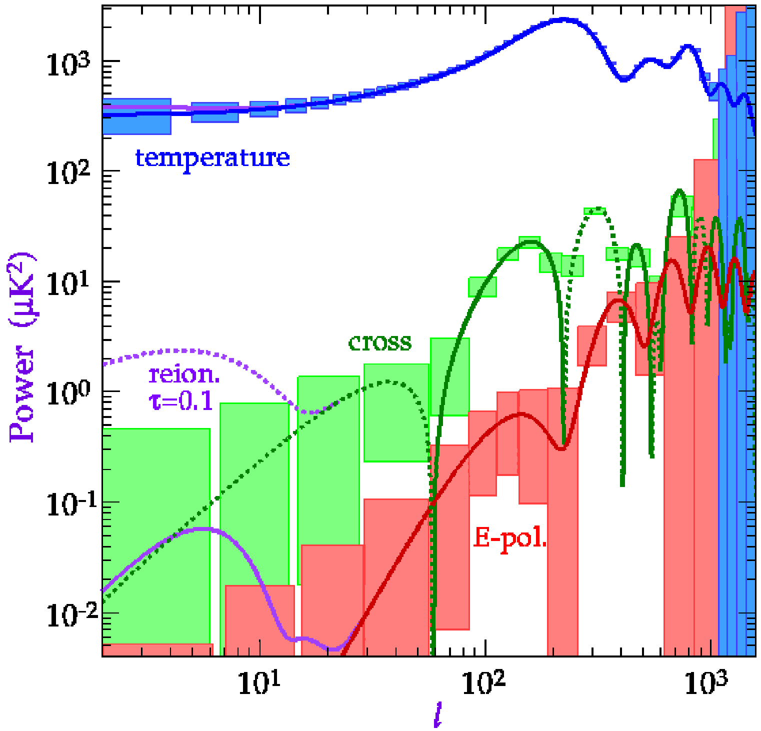
New Results from WMAP



Spergel et al., astro-ph/0603449

CMB Primer





IMPORTANCE OF POLARIZATION: **There is a strong degeneracy between the optical depth for reionization τ and the tensor-to-scalar ratio r, which can only be broken by polarization measurements.**

$E \gg B$ Scalar modes dominate

$E \ll B$ Vector modes dominate

$E \sim B$ Tensor modes dominate

Three-Year Data Release: What's new?

- **Improved models for instrument gain & beam response**
- **Noise variance a factor three lower**
- **Improved foreground model and subtraction**
- **Measurements of EE and BB polarization**

IMPLICATIONS

- **ΛCDM models with power-law power-spectrum fit all data.**
- **No evidence for non-Gaussianity; weak indication for axis-of-evil**
- **Problems at low l have largely dissapeared**
- **High reionization redshifts ruled out: reduction in τ, Ω_m, σ_8 and n_s!**

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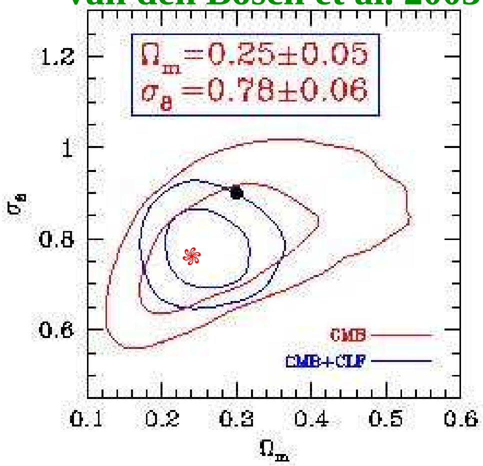
I was right!

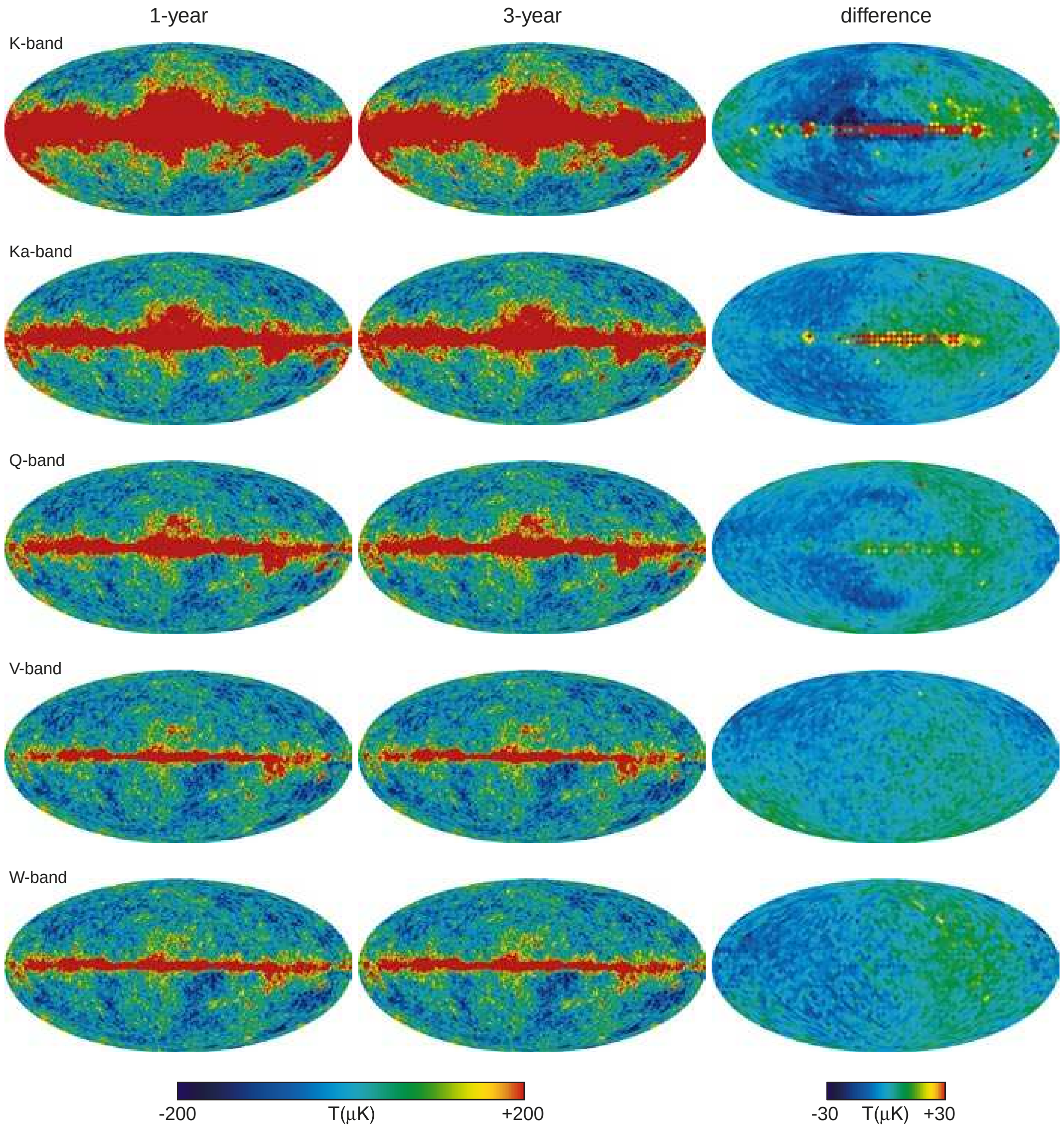
$$\Omega_m = 0.23 \pm 0.04$$

$$\sigma_8 = 0.76 \pm 0.05$$

van den Bosch et al. 2003

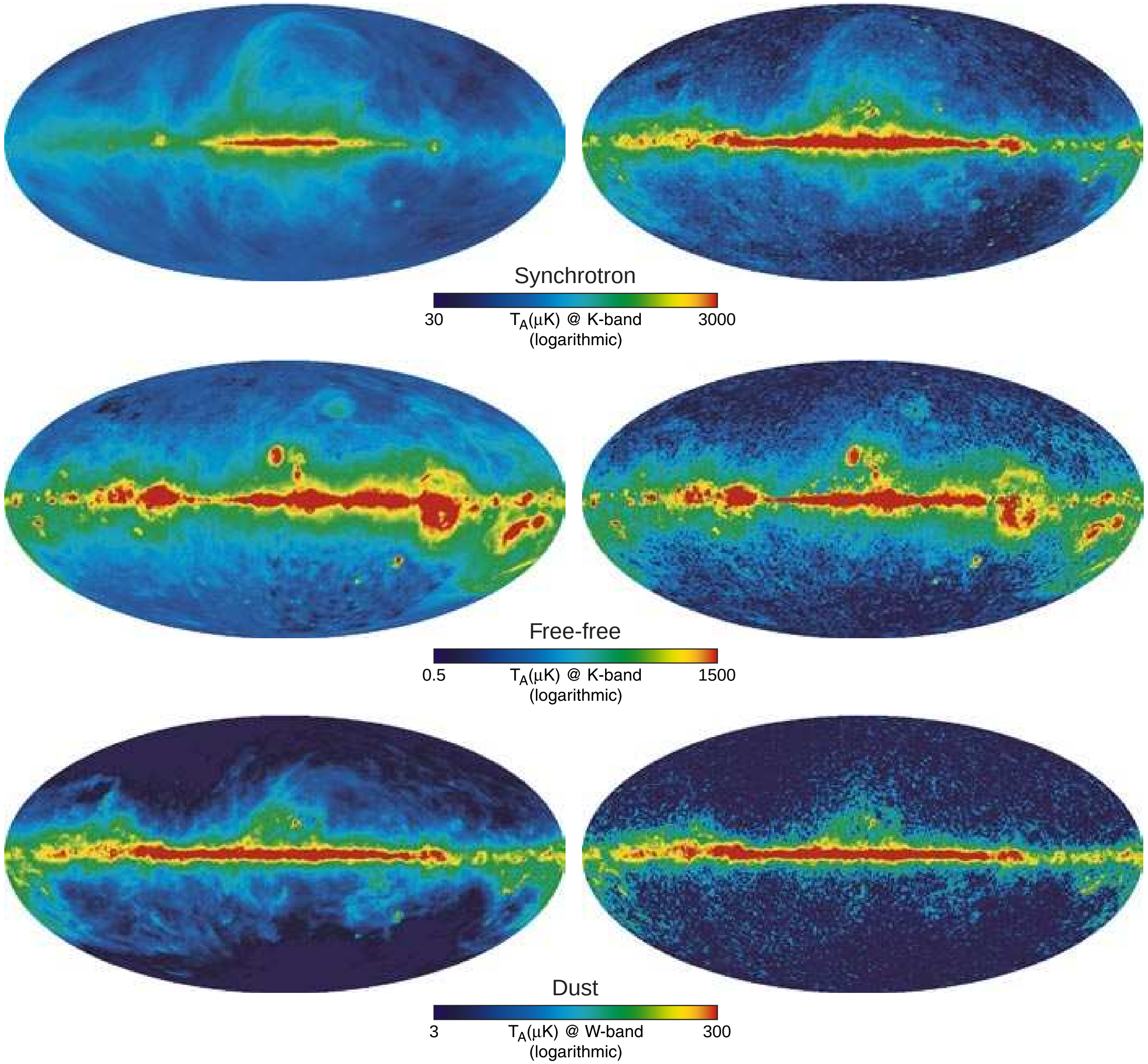


The TT Maps



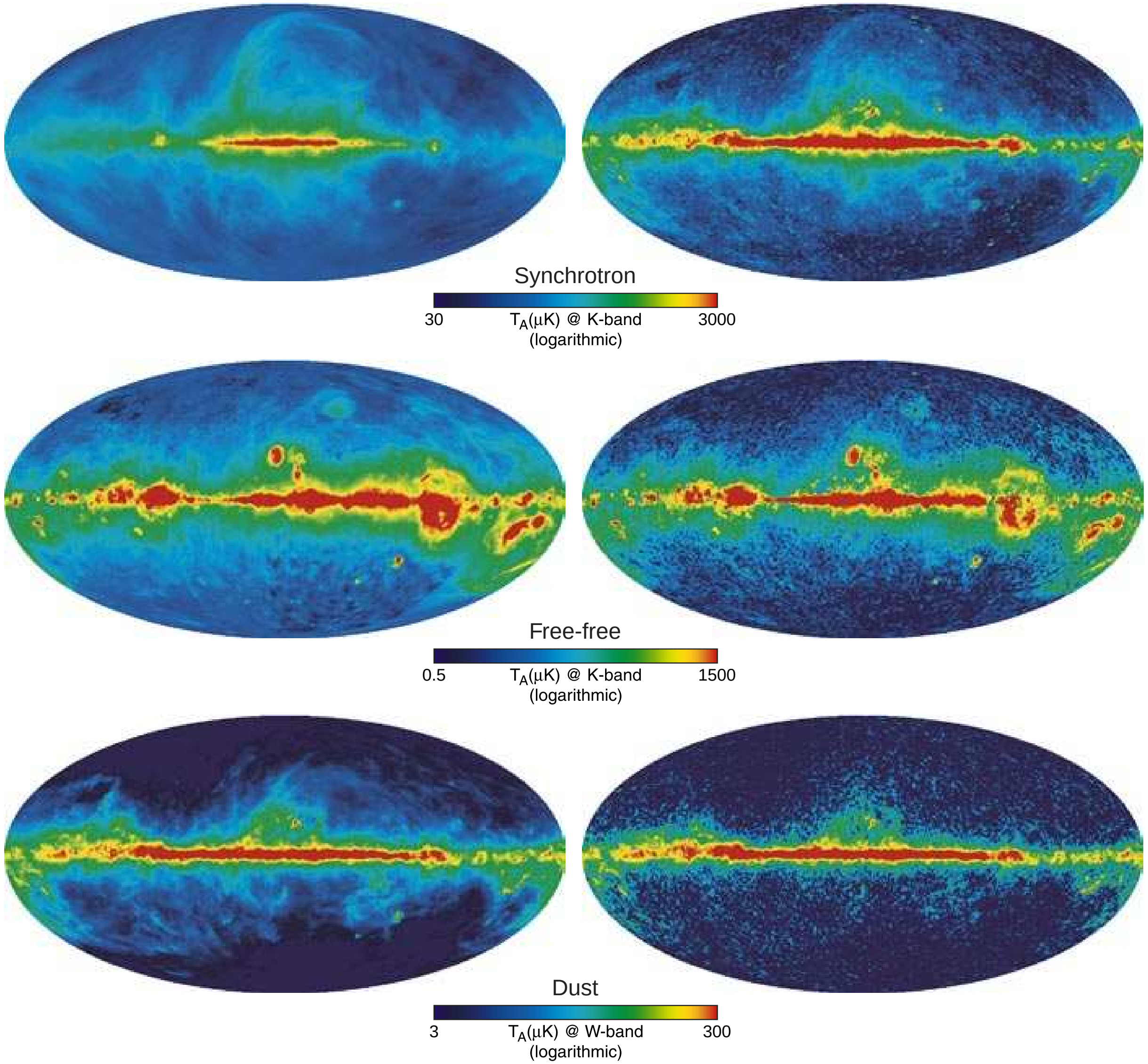
Difference at low l mainly due to improved gain model of instrument

Foregrounds



Left: **input prior maps.** **Right:** **Output WMAP maps**

Foregrounds



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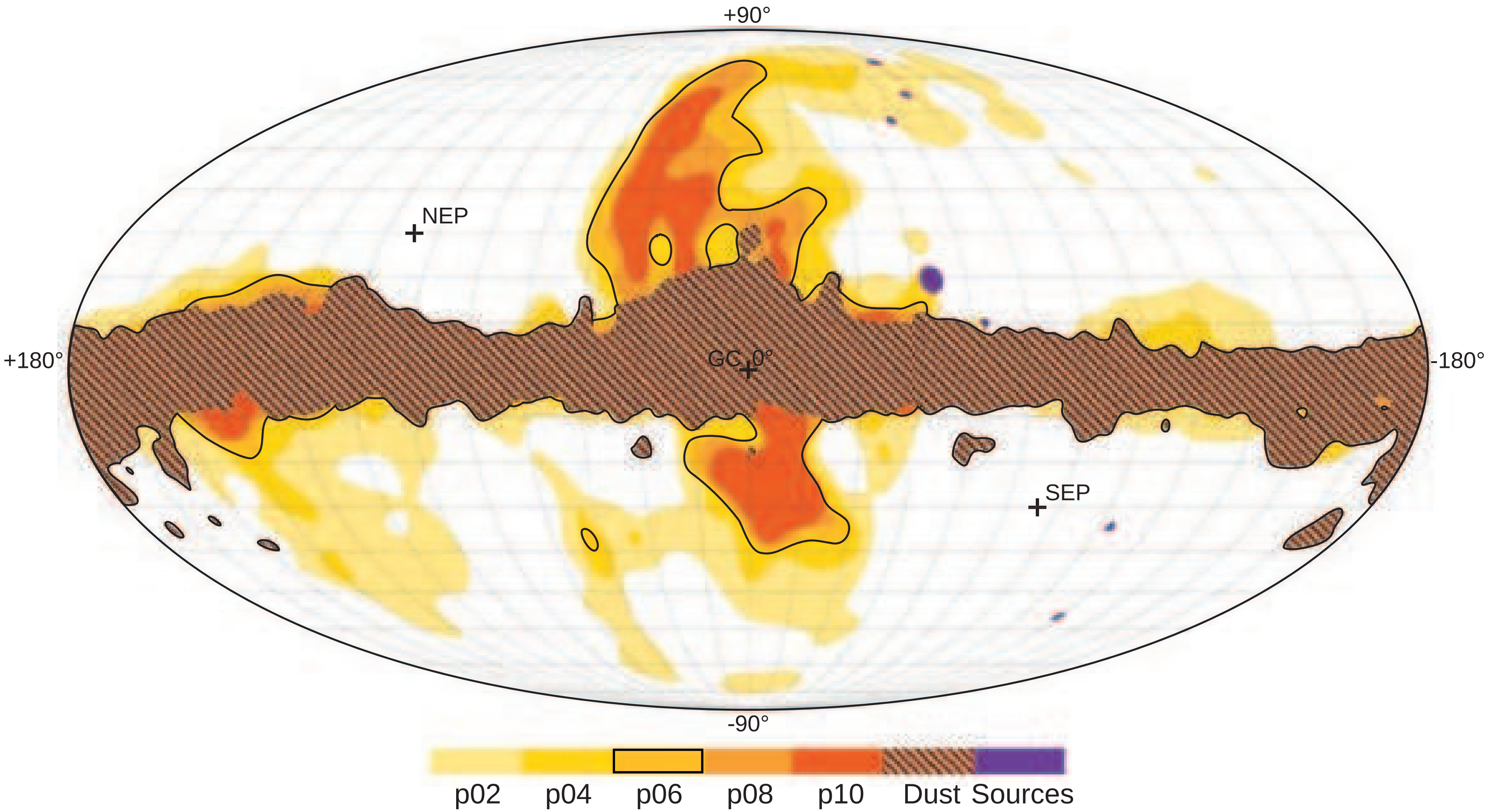
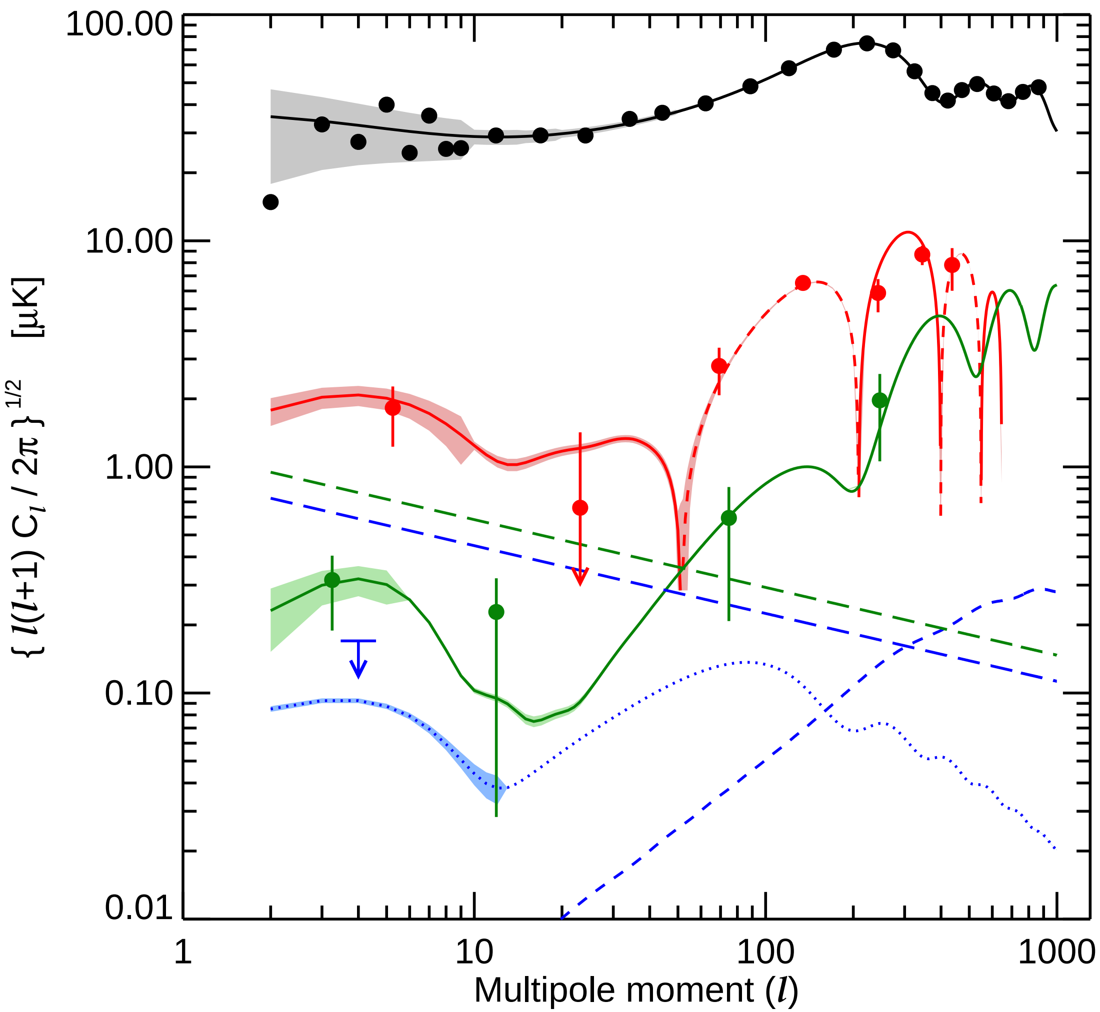
Polarization Masks

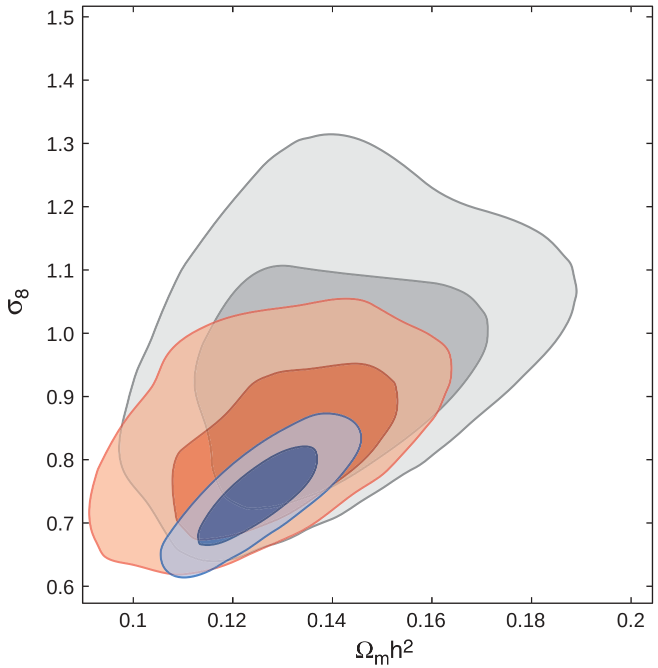


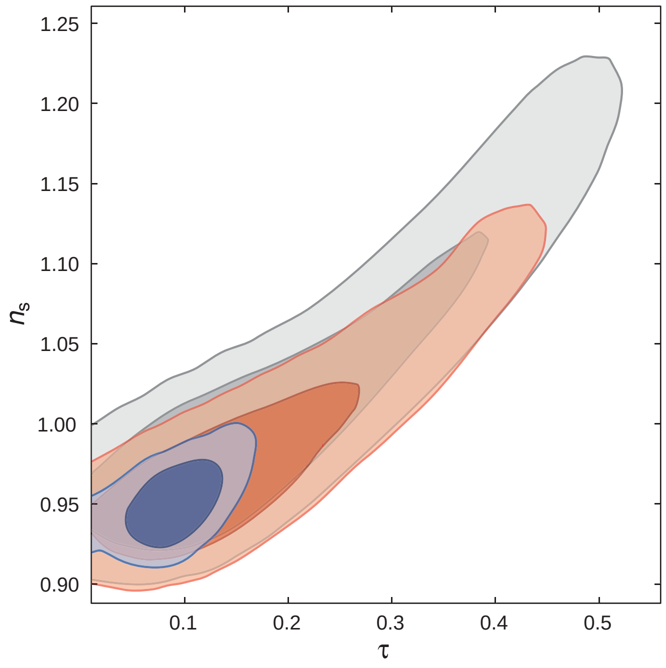
The TT, TE, EE, and BB Power Spectra



Only upper limit for BB mode

Improved Constraints



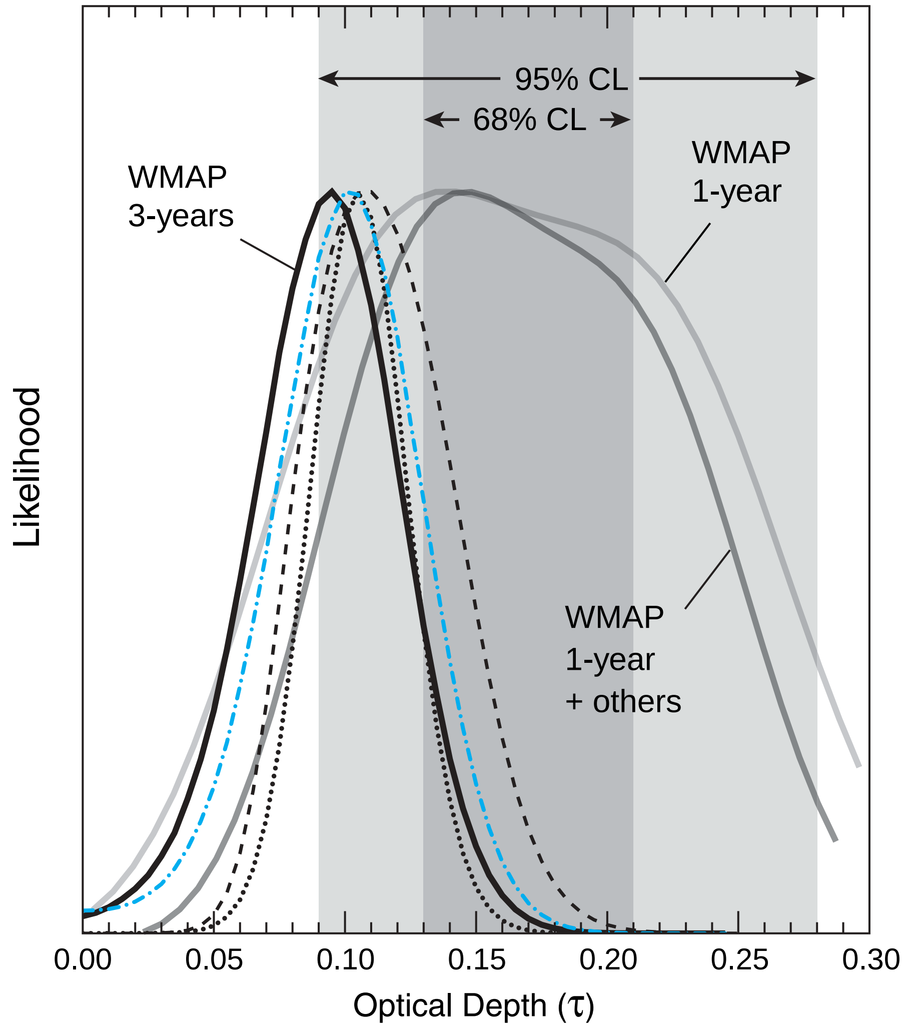


The mean Ω_m, σ_8, n_s and τ have all become smaller:

$$\Omega_m \quad 0.29 \longrightarrow 0.23$$
$$\sigma_8 \quad 0.92 \longrightarrow 0.76$$
$$n_s \quad 0.99 \longrightarrow 0.96$$
$$\tau \quad 0.17 \longrightarrow 0.09$$

NOTE: these values correspond to 6-parameter power-law ΛCDM models

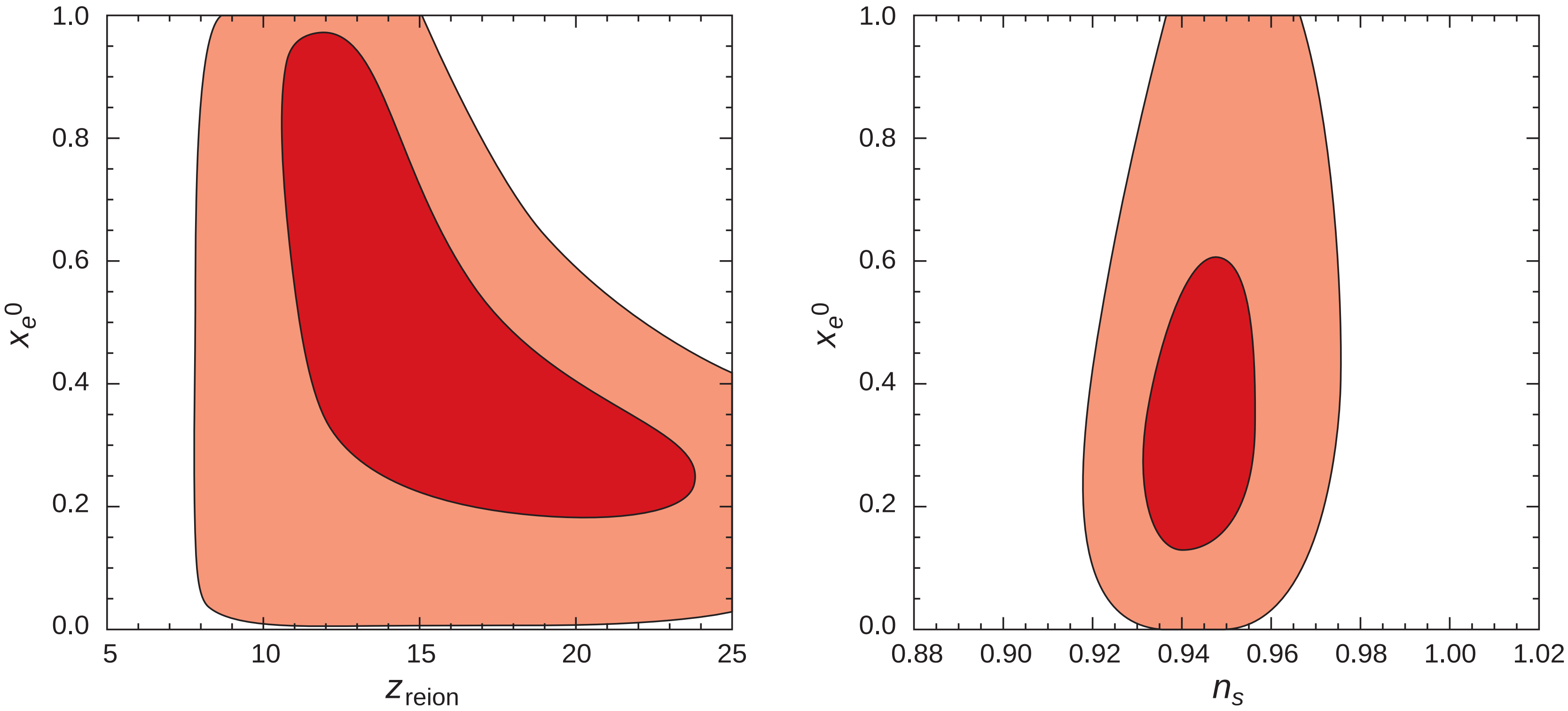
Reionization



Due to polarization measurements τ much better constrained

Without polarization measurements strong degeneracy between τ and n_s, impacting also on Ω_m and σ_8

Reionization



No meaningful constraints on detailed reionization history

Maximum Likelihood peak: $z_{\rm reion} = 10.9^{+2.7}_{-2.3}$

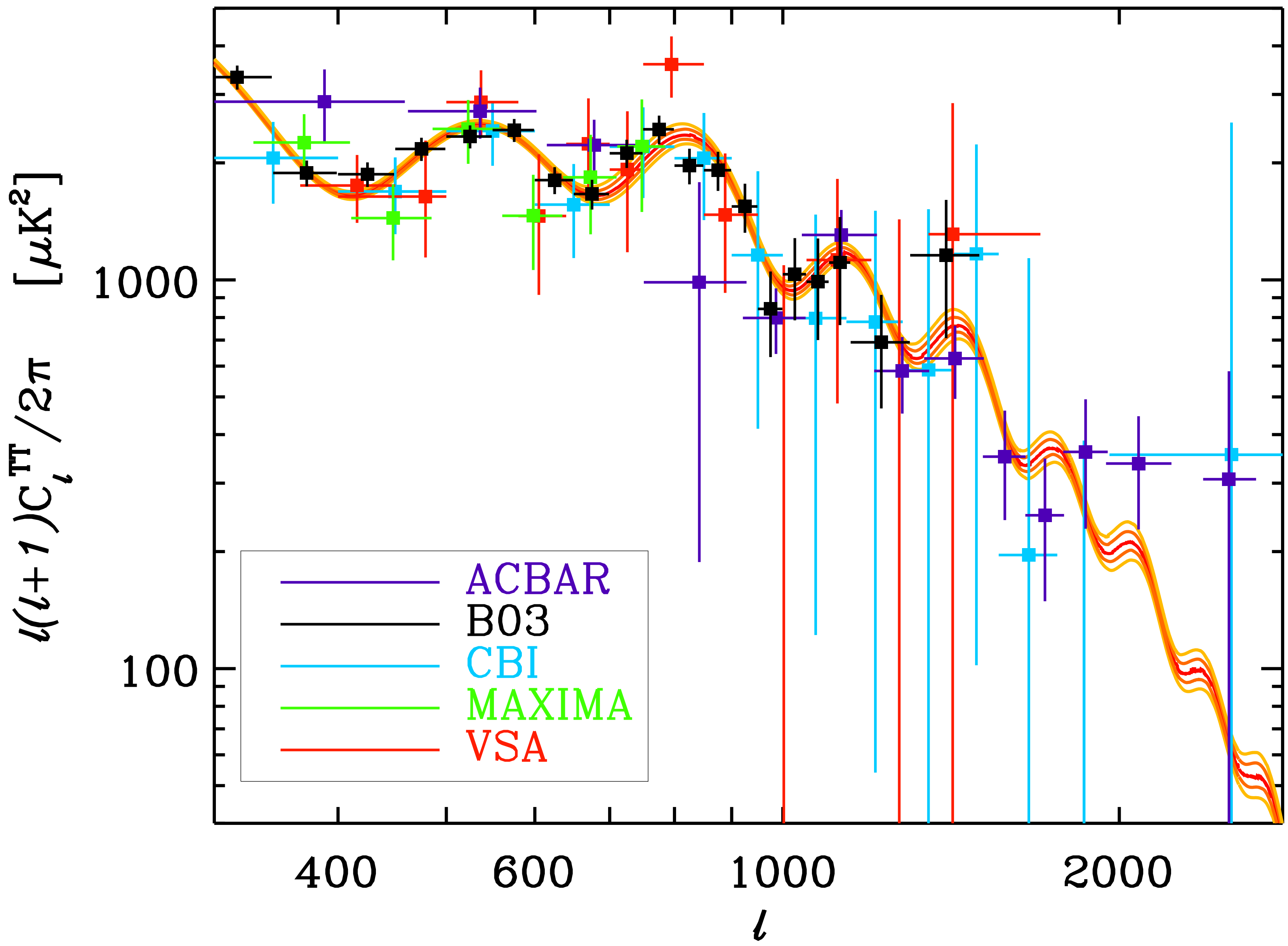
Different Models

Table 3: Goodness of Fit, $\Delta\chi^2_{eff} \equiv -2\ln\mathcal{L}$, for WMAP data only relative to a Power-Law ΛCDM model. $\Delta\chi^2_{eff} > 0$ is a worse fit to the data.

	Model	$-\Delta(2\ln\mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	Power Law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d\ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	-22	20

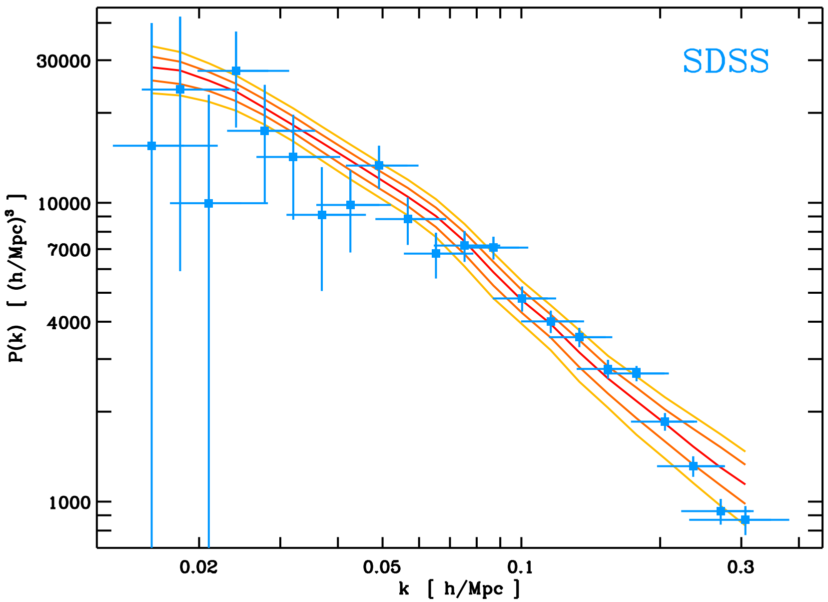
- **Harrison-Zeldovich spectrum $n_s = 1$ does not fit data well**
- **Strong evidence for CDM = strong evidence against MOND**
- **$\Omega_\Lambda = 0$ is consistent with the data, but it implies that $H_0 = 30\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_m = 1.3$**
- **No need for quintessene, RSI, massive neutrinos tensor modes, sharp cut-off: significant constraints on inflationary models**

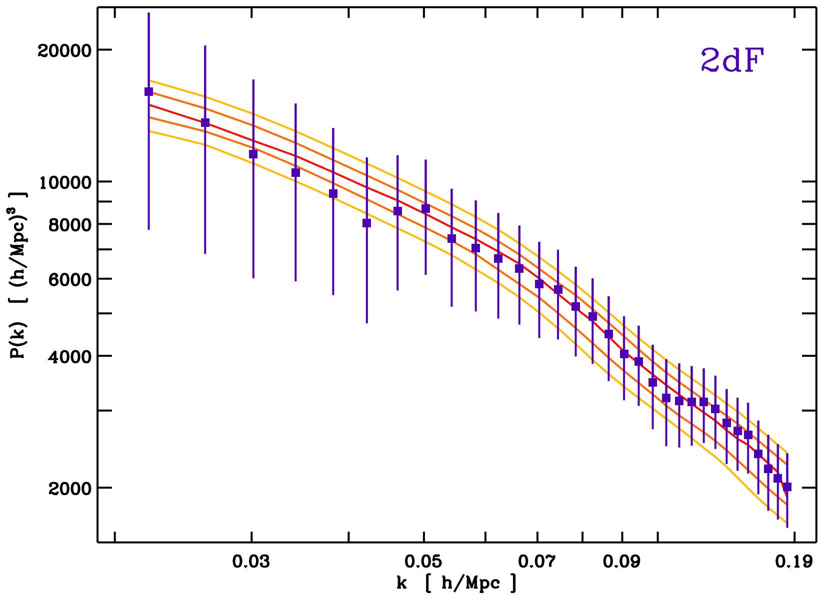
Comparison with other CMB experiments



Best fit ΛCDM model accurately fits all other CMB data

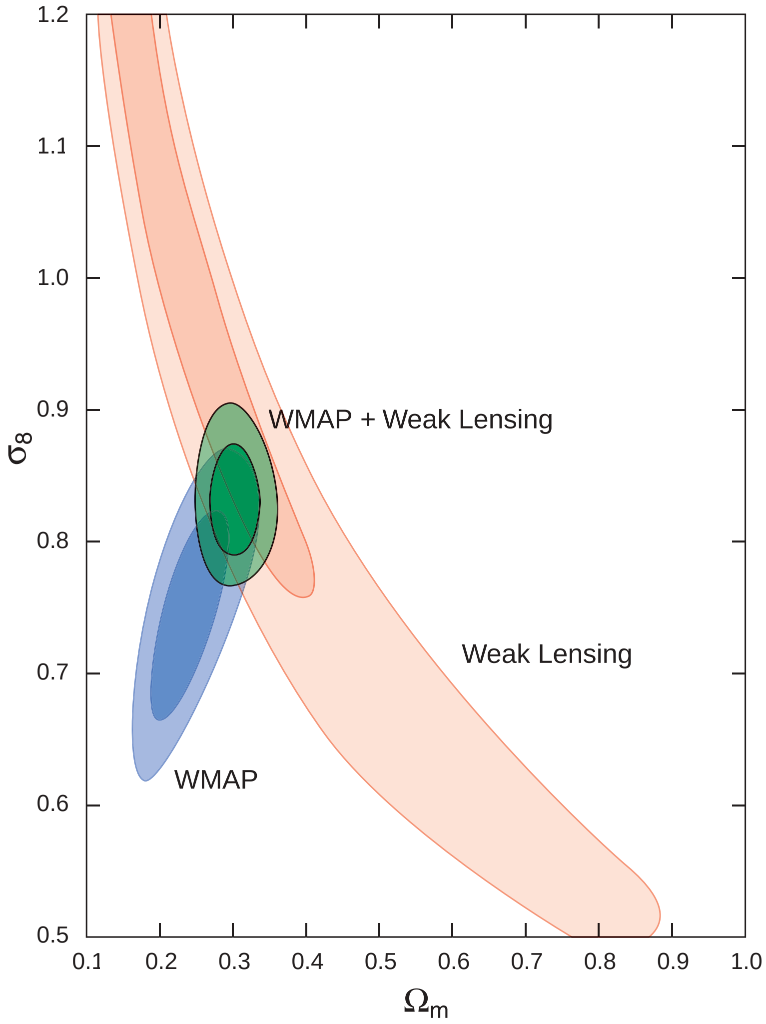
Comparison with Large Scale Structure





Powerspectrum of best-fit ΛCDM model accurately fits galaxy power spectra of 2dFGRS and SDSS

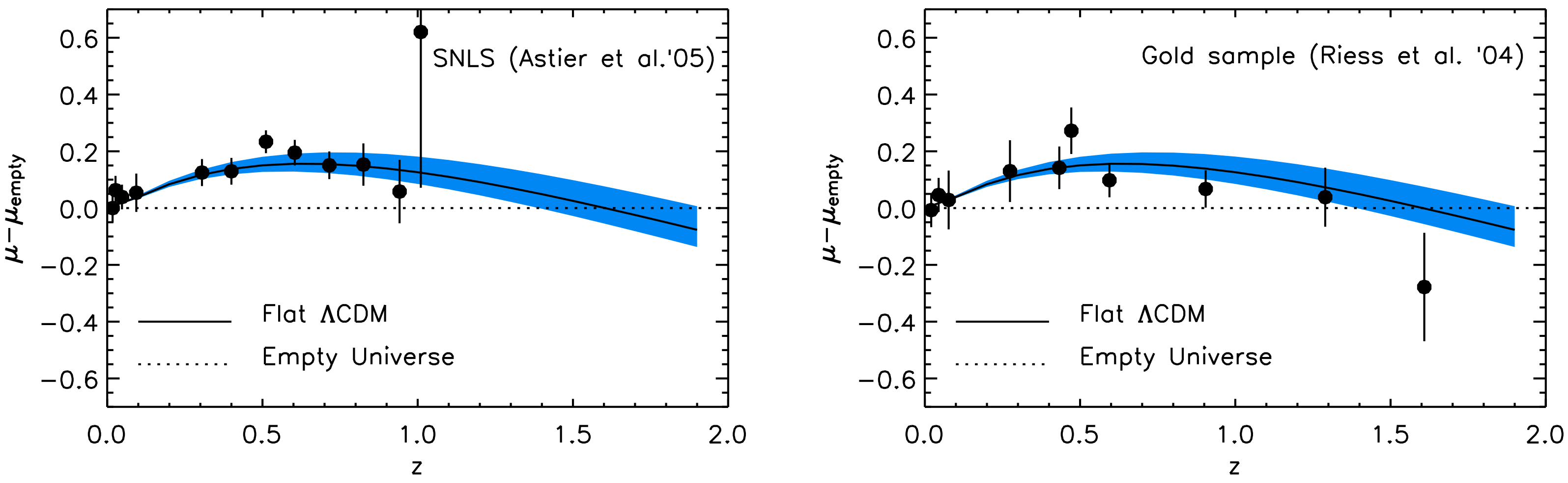
Comparison with Weak Lensing



Poor agreement with CFTHLS weak lensing survey. Similar results from RCS and VIRMOS-DESCART surveys

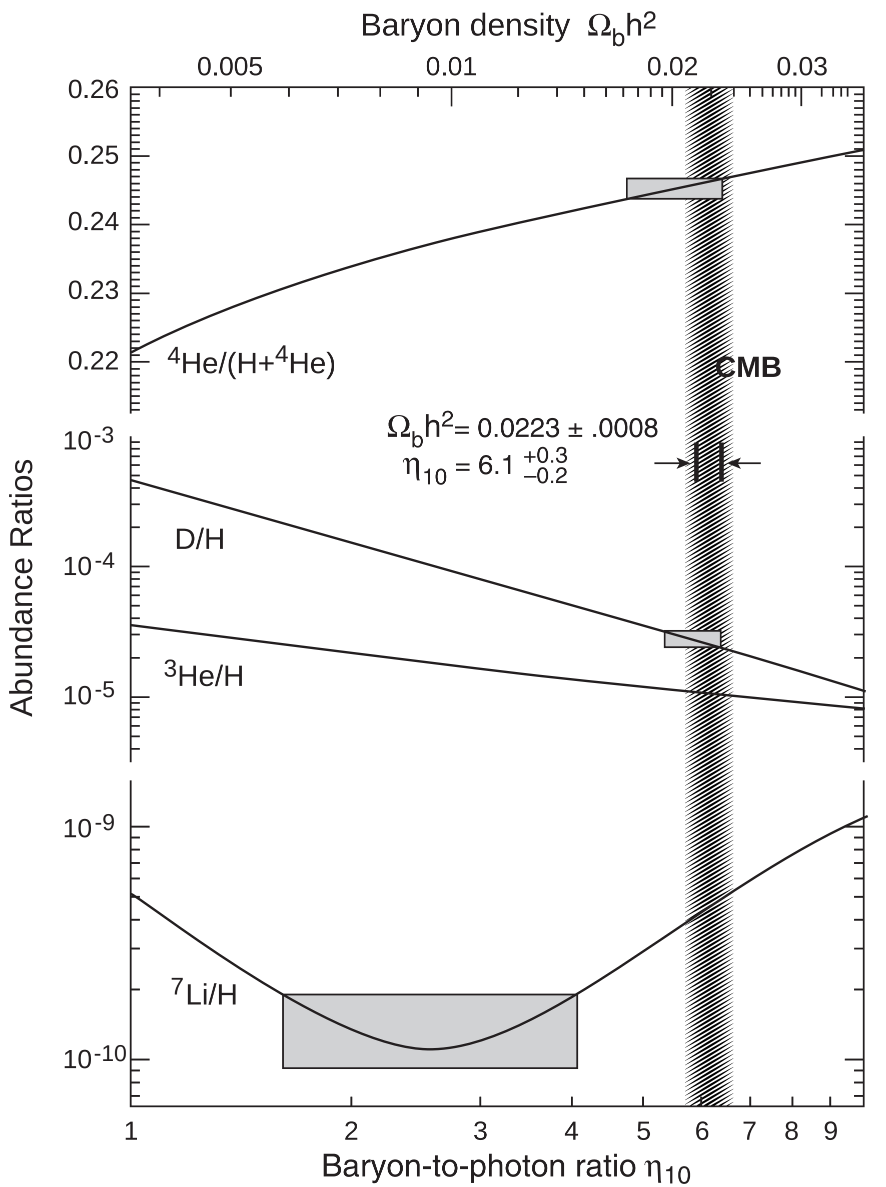
However, 75° CTIO survey finds lower σ_8, in better agreement with WMAP.

Comparison with Supernovae



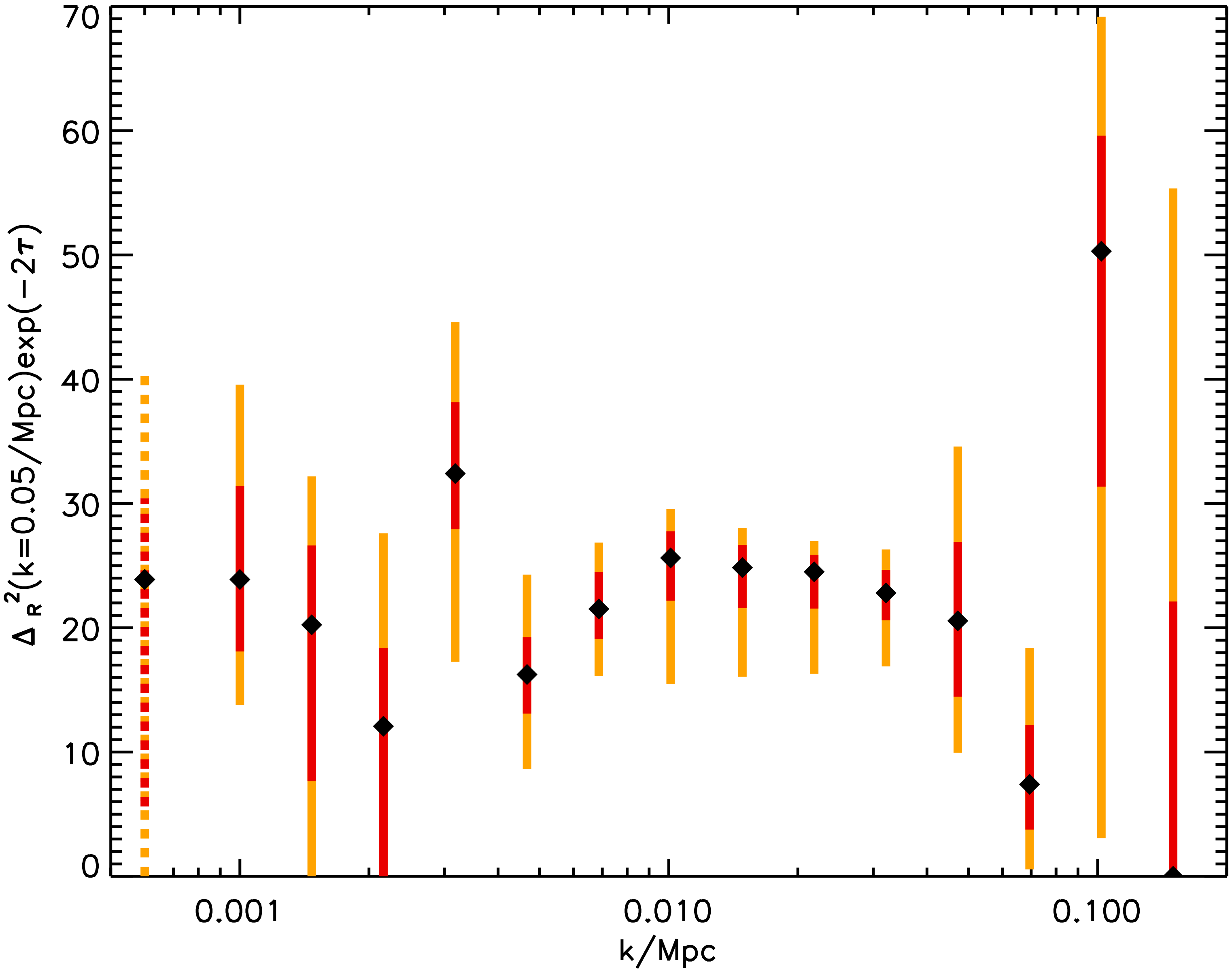
luminosity distance-redshift relation measured from SN Ia in perfect agreement with best-fit ΛCDM WMAP model.

Big Bang Nucleosynthesis



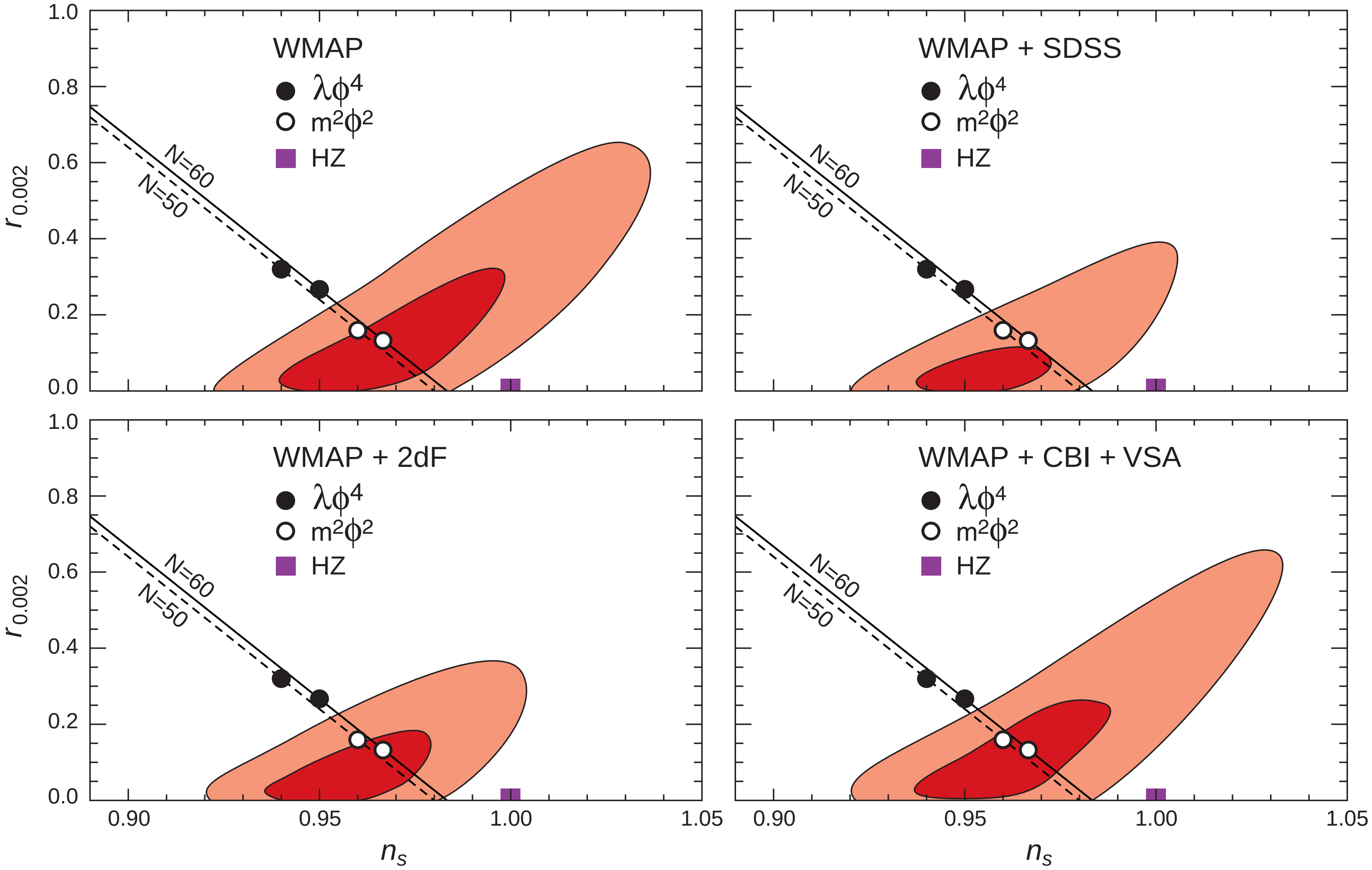
Observed Lithium abundances inconsistent with WMAP, Helium and Deuterium.

Power-Spectrum Shape



No need for running spectral index.

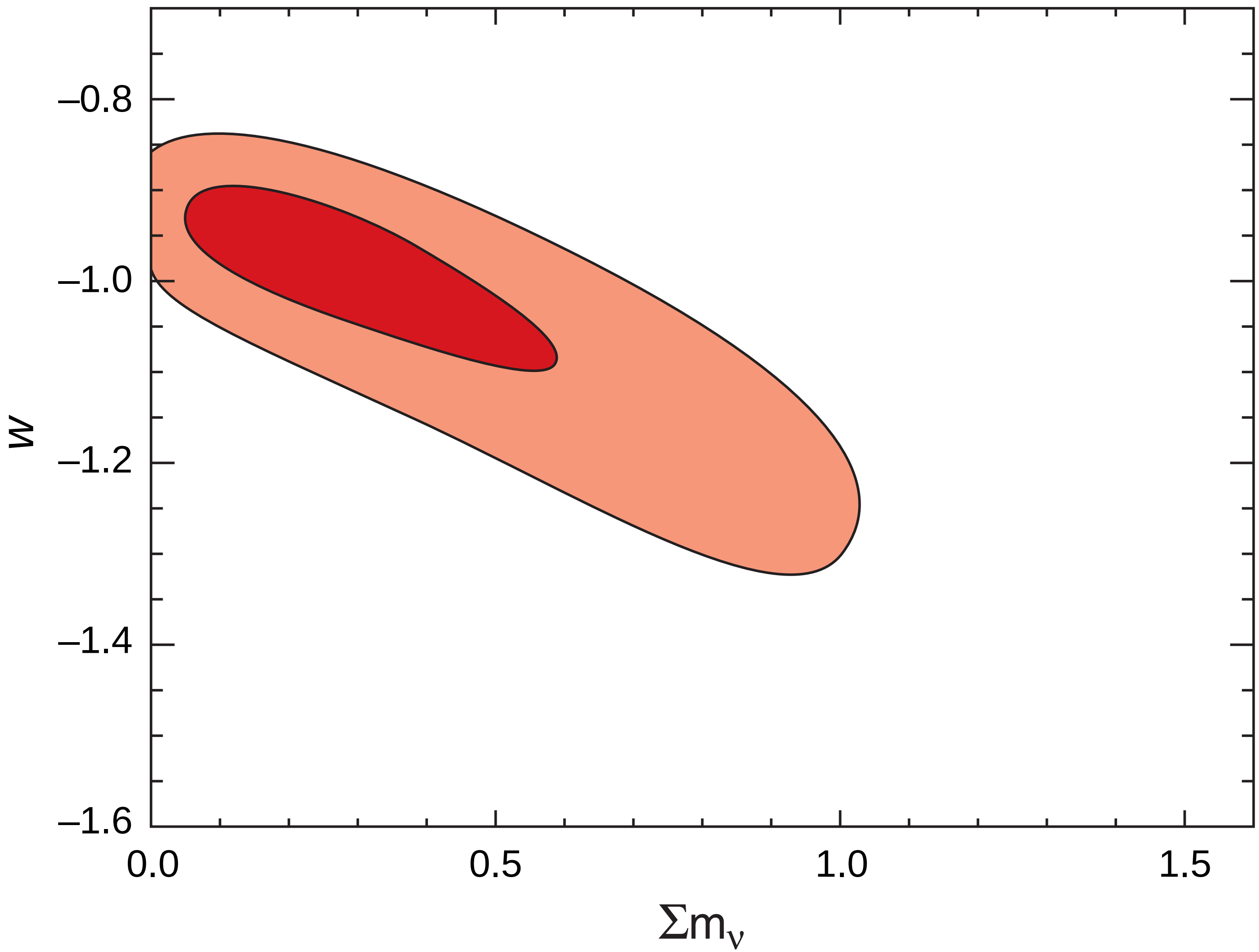
Constraints on Inflation



Constraints on Power-Spectrum shape and tensor-to-scalar ratio yield significant constraints on Inflation models.

We are starting to taste a hint of non-Vanilla

Dark Energy & Neutrino Masses



Constraints based on WMAP+2dFGRS+SDSS+SN.

$\sum m_\nu < 1.0\text{eV}$ **(95% CL) and** $w = -1.06^{+0.13}_{-0.10}$ **(68% CL)**

Summary

Power-Law ΛCDM cosmologies with Gaussian, adiabatic primordial fluctuations fit a large amount of data.

Mean Likelihoods, Power-Law ΛCDM, WMAP only

$$\Omega_m = 0.238 \quad h = 0.734 \quad \sigma_8 = 0.744$$
$$\Omega_b = 0.042 \quad \tau = 0.088 \quad n_s = 0.951$$

- **WMAP + other CMB experiments**
- **Large Scale Structure from 2dFGRS and SDSS**
- **Big Bang Nucleosynthesis (except Lithium)**
- **Galaxy Motions & PVDs**
- **Cluster Abundances**
- **Supernovae Ia**

The following two data sets are marginally inconsistent with the above mentioned ΛCDM concordance cosmology:

- **Weak Lensing: $\sigma_8 \sim 0.9$???**
- **Lyα forest: $\sigma_8 \sim 0.9$???**