What can the CMB still tell us?

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USC Trojan Family Magazine

Helen of Troy:

Helen was the daughter of Leda and Zeus, sister of Clytemnestra, Castor and Pollux (the Dioscuri), and wife of Menelaus. Helen's beauty was so overwhelming that Theseus and Paris abducted her and the Trojan War was fought to bring her back home.

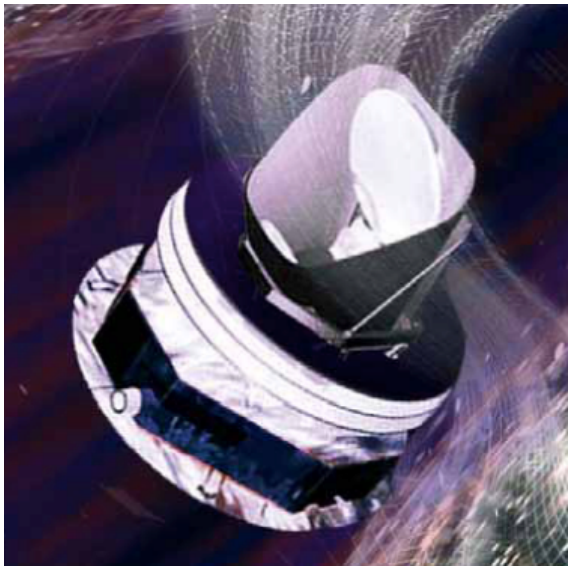
Summary

- A broad look at Planck parameter estimation
- Reionization
- Diffuse Foregrounds characterization
- Tensor-to-scalar (i.e. r estimation) for Planck and future experiments

From : Colombo & Pierpaoli (arXiv:0804.0278)
Colombo, Pierpaoli Pritchard (arXiv:0811.2622)
Betoule et al (arXiv:0901.1056)
Macellari et al (to be submitted)
+ White Papers for CMBPol

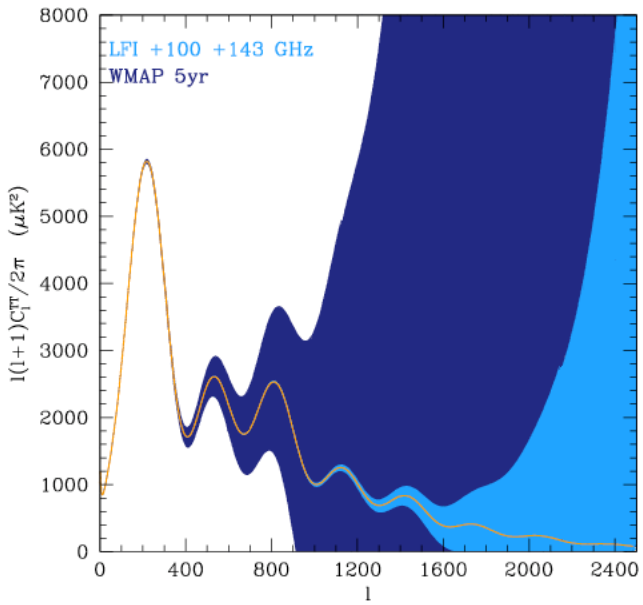
I: Near Perspectives: the Planck satellite

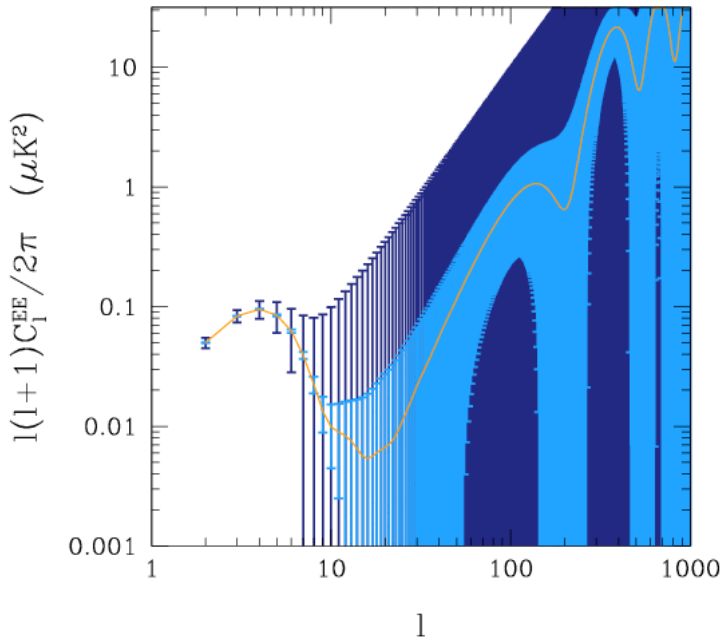
- Smaller beam
- Lower noise
- Polarization
- Better frequency coverage



	COBE	WMAP	Planck
Year data received	1992	2003	2009
Spatial resolution (deg)	7	0.23	0.08
Frequencies (GHz)	30-90	22-94	30–857
Polarization	no	yes	yes
Sensitivity (muK/30' pix)		10.5 (8yrs)	1.4

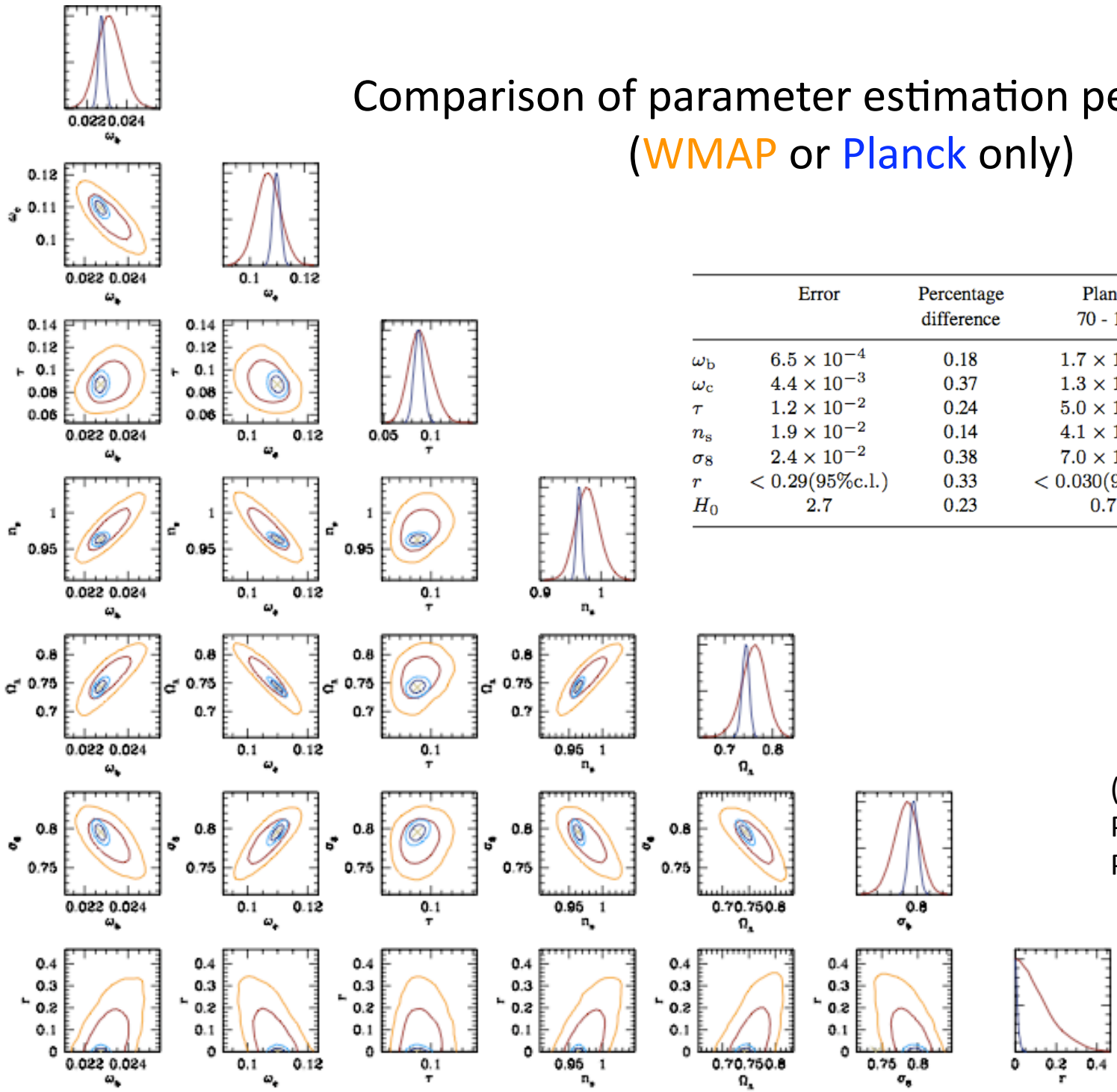
Where Planck will do better





- New information coming from:
  - second and third peak in TT spectrum
  - greater l range
  - reionization “bump” in EE and second peak

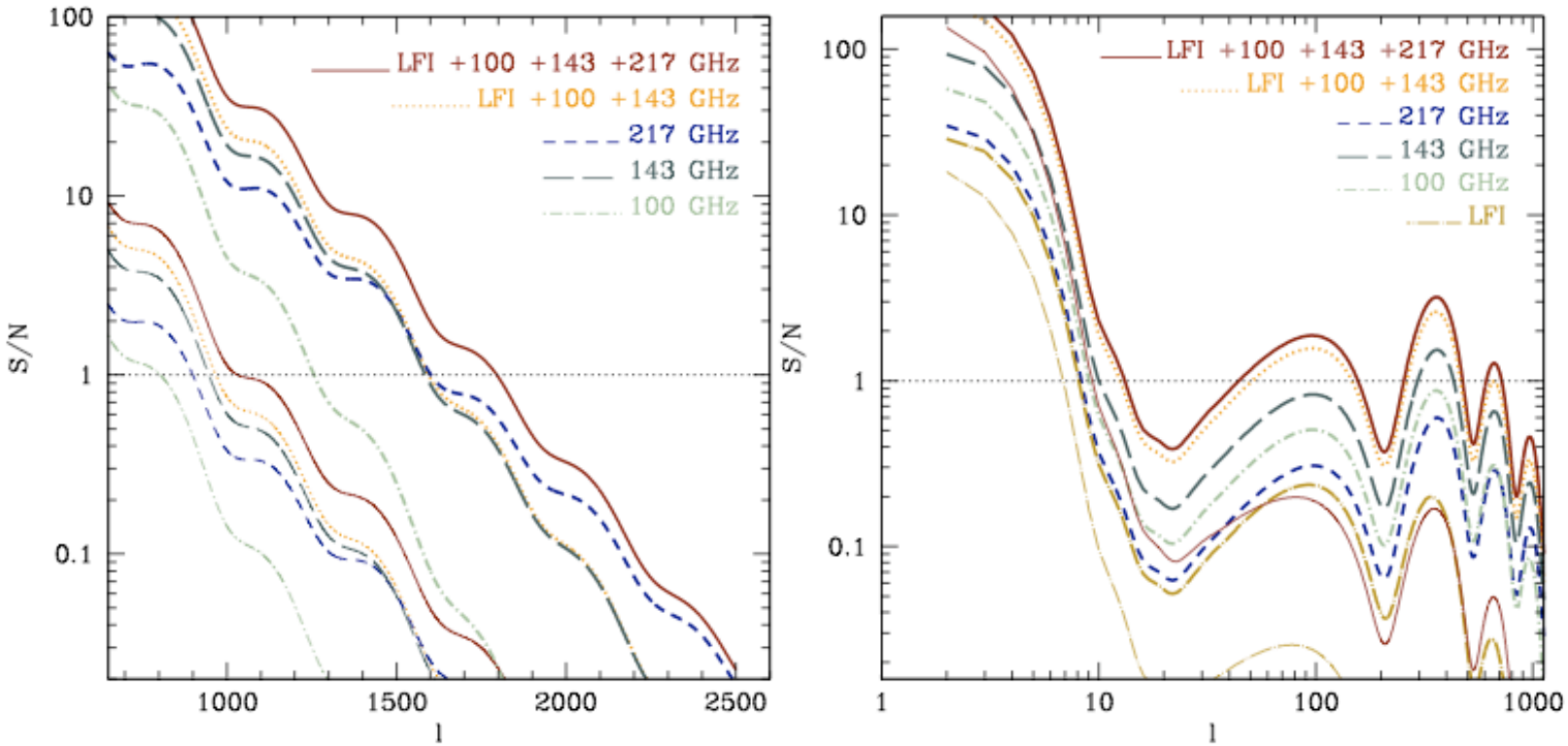
Comparison of parameter estimation performances (WMAP or Planck only)



	Error	Percentage difference	Planck 70 - 143	WMAP/Planck ratio
ω_b	6.5×10^{-4}	0.18	1.7×10^{-4}	3.9
ω_c	4.4×10^{-3}	0.37	1.3×10^{-3}	3.3
τ	1.2×10^{-2}	0.24	5.0×10^{-3}	2.5
n_s	1.9×10^{-2}	0.14	4.1×10^{-3}	4.6
σ_8	2.4×10^{-2}	0.38	7.0×10^{-3}	3.4
r	< 0.29(95%c.l.)	0.33	< 0.030(95%c.l.)	9.7
H_0	2.7	0.23	0.71	3.8

(Colombo
Pierpaoli
Pritchard 08)

Where does the information comes from?



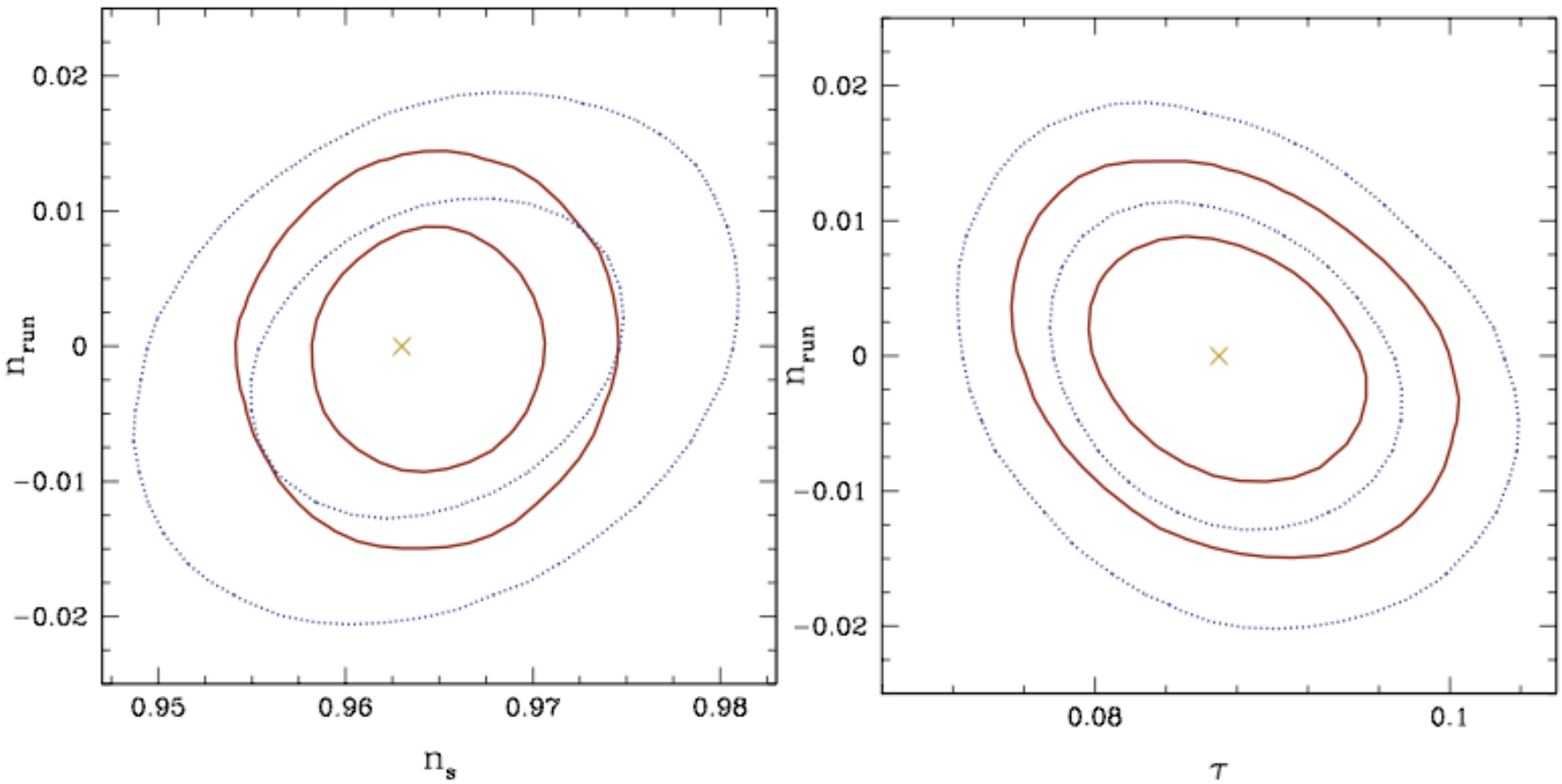
- Temperature: 217 GHz and 143GHz playing similar roles at high resolution
- Polarization: CV limited to l= 8-12, possibly sensitive to 3rd peak

Impact on parameters

	70 - 143	30 - 143	70 - 100	30 - 100	70 - 143T	30 - 143T	70 - 217	30 - 217
ω_b	1.6×10^{-4}	1.00	1.50	1.48	1.20	1.18	0.87	0.86
ω_c	1.4×10^{-3}	0.99	1.37	1.33	1.23	1.19	0.90	0.90
θ	3.1×10^{-4}	1.00	1.67	1.64	1.24	1.23	0.86	0.86
τ	4.8×10^{-3}	0.97	1.25	1.17	1.23	1.15	0.95	0.92
n_s	4.0×10^{-3}	0.99	1.51	1.47	1.18	1.14	0.87	0.87
$\mathcal{A}_s$	9.5×10^{-3}	0.99	1.24	1.16	1.23	1.15	0.95	0.92
r	< 0.03	0.90	2.19	1.75	2.15	1.73	0.84	0.76
σ_8	6.7×10^{-3}	0.99	1.31	1.25	1.23	1.17	0.92	0.91
H_0	6.9×10^{-1}	0.99	1.43	1.39	1.23	1.19	0.88	0.88

- Major information coming from 70-143 GHz. Adding 217GHz iproves parameter determination by ~10%.
- Giving up 143Ghz,pol results in a 73% (or factor 2) degradation for r estimate.
- LFI useful for improving r estimates.

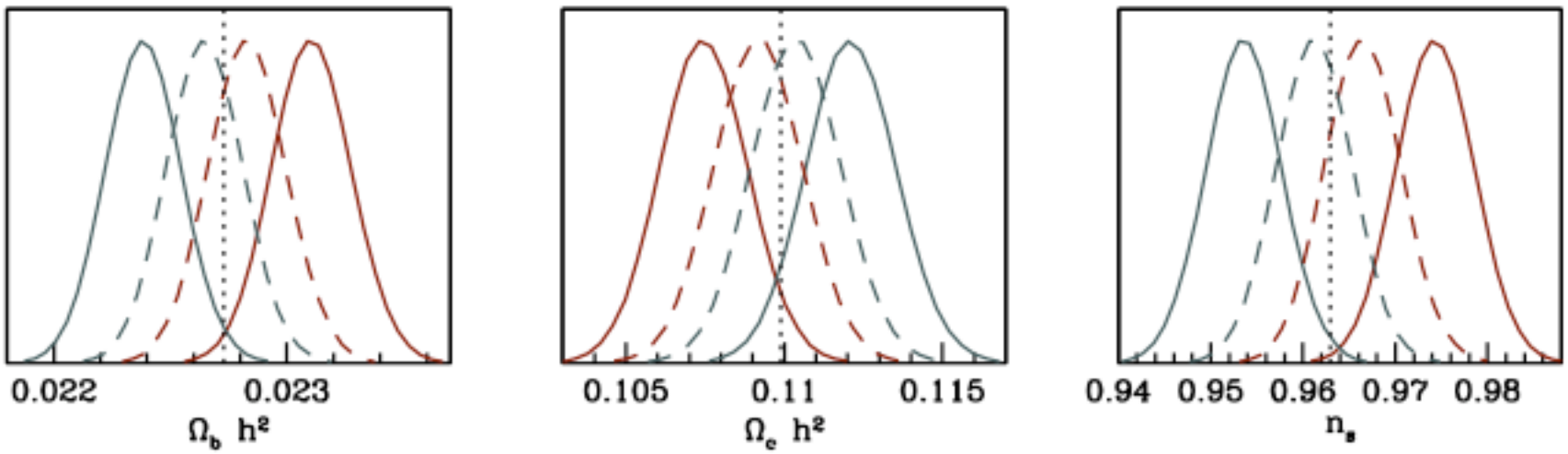
Frequency coverage and degeneracies



- Frequency coverage helps some degeneracies, not all….

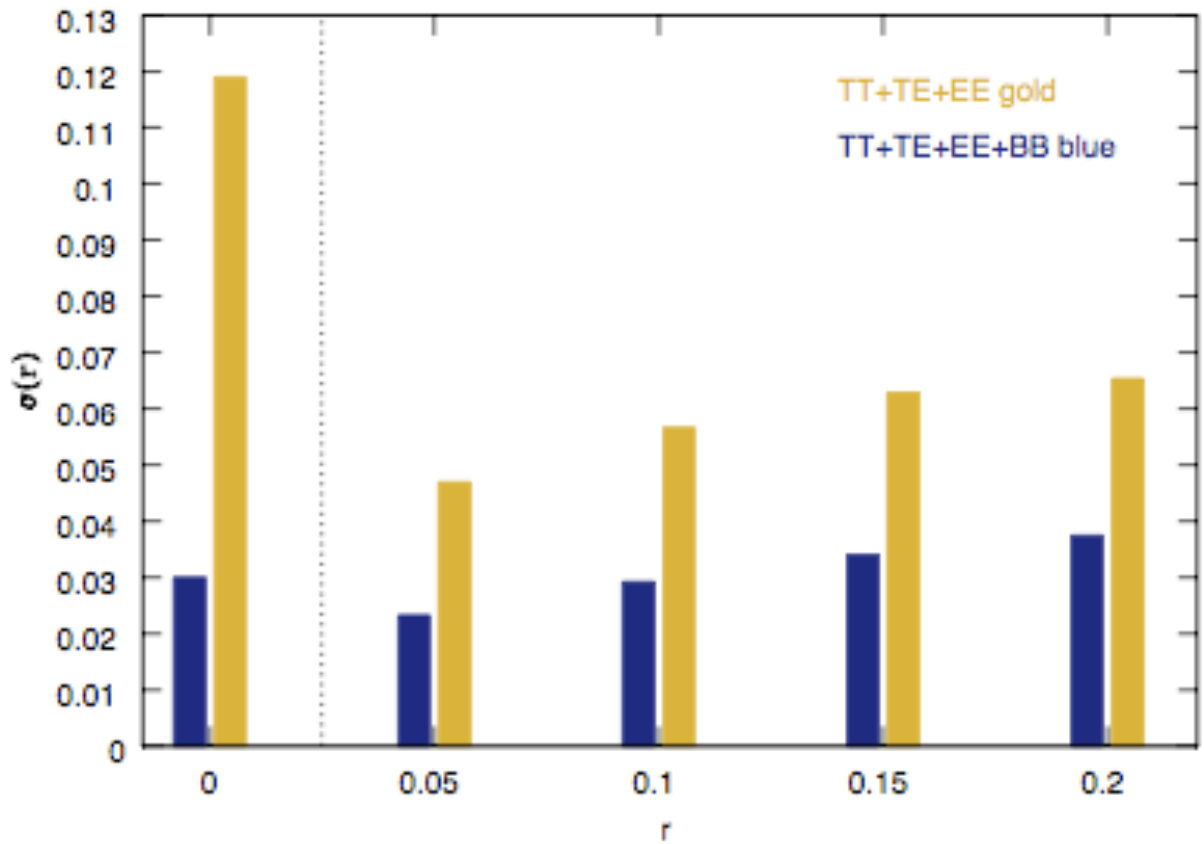
Impact of beam modeling

Under-estimating or over-estimating the beam by 0.05% (– – –) or 0.2% (——)



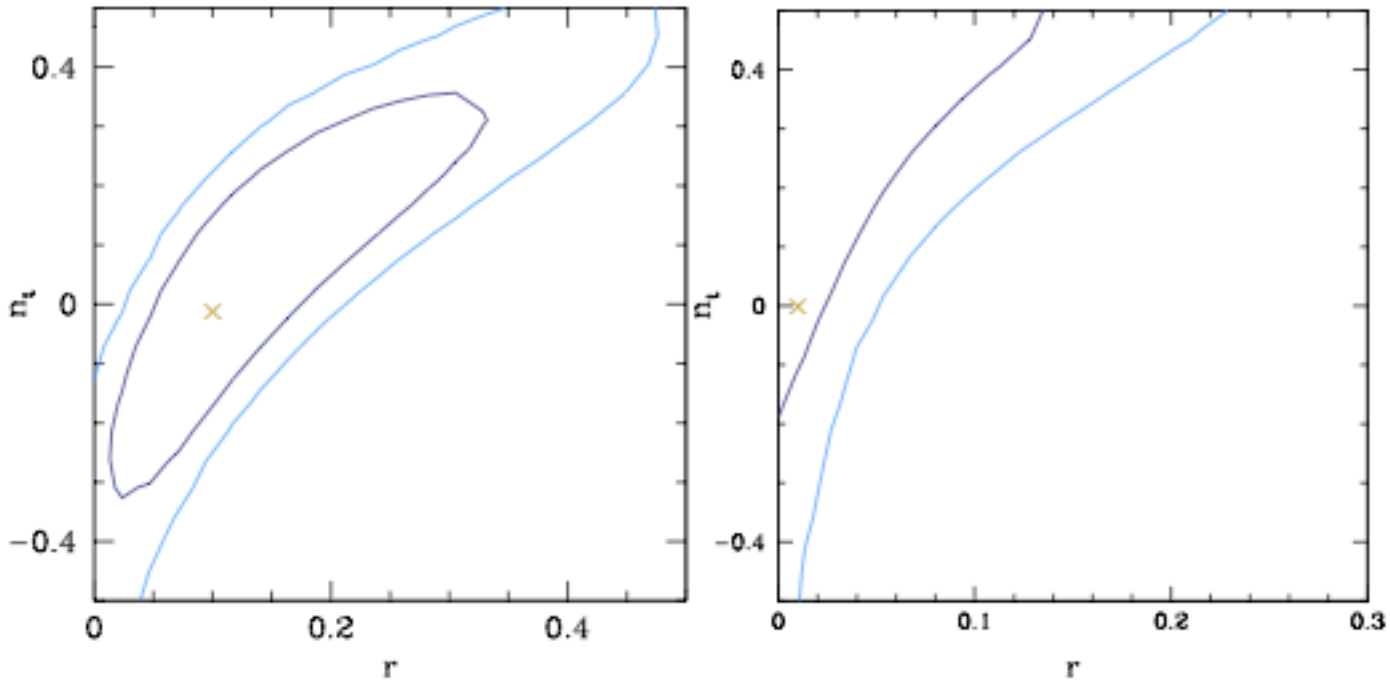
- Assuming a wrong beam by the amount consistent with current uncertainties may bias important parameters by ~sigma

Tensor to scalar ratio r from Planck



For r>0.05, half of the information comes from the BB spectrum

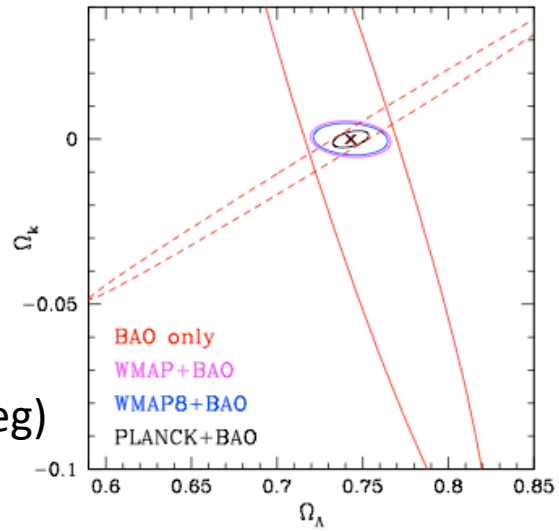
Issues with the tensor spectral index

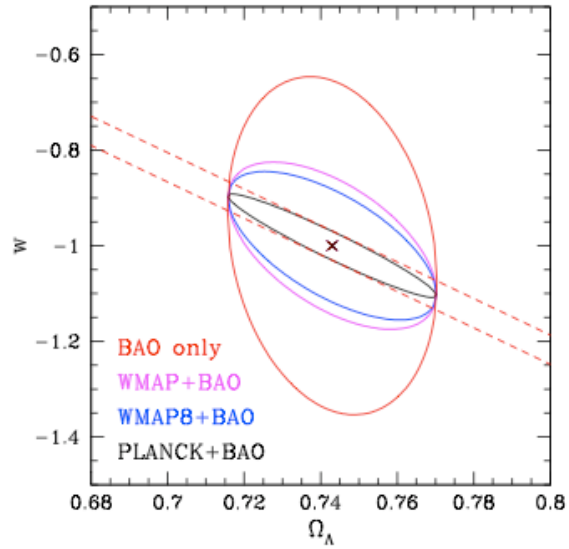


- For r~0.1, Planck will not be able to constrain r and n_t simultaneosly
- Even for an EPIC type of experiment, marginalizing on n_t increases the errors on r by a factor 3.

Synergies with other surveys

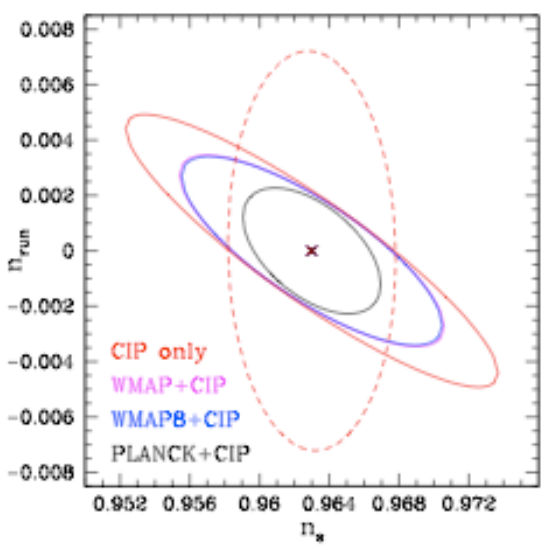
BAO ~ JDEM
(z=0.5-2,
10000 sq deg)

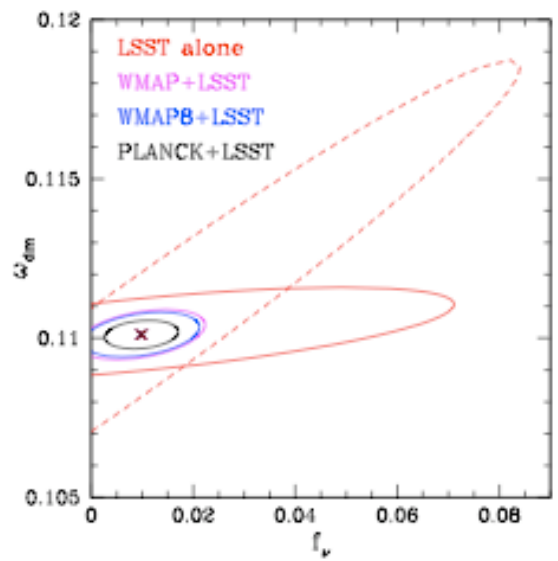




Planck only

(CIP:
z=2 – 6.5,
1000 sq deg,
2M gal)





II. REIONIZATION

The low-l parameters:
The tensor-to-scalar ratio r and reionization τ

- Reionization impacts the CMB tempertature and polarization spectra.
- The Optical depth is the only parameter currently constrained and it is determined by EE spectra.

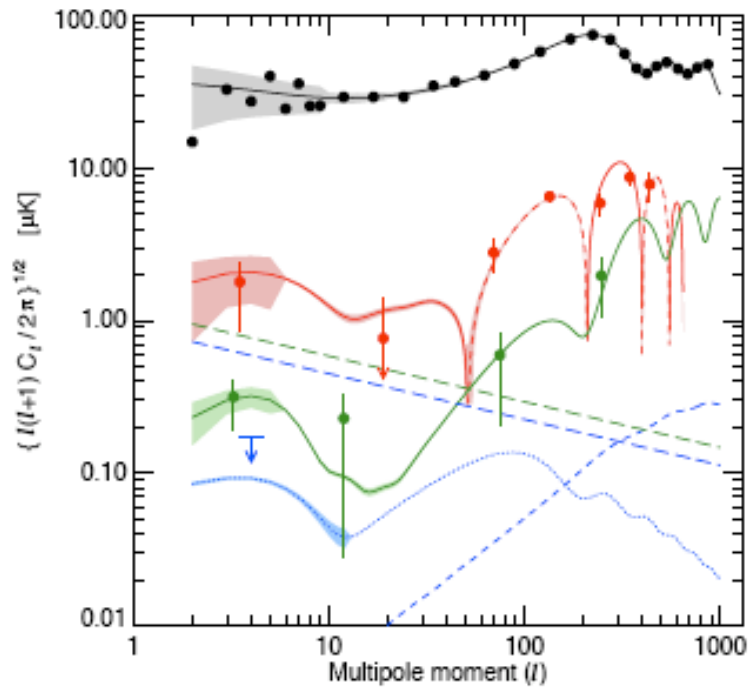
Constraints (WMAP3):

All data: $\tau = 0.09$ +/- 0.03

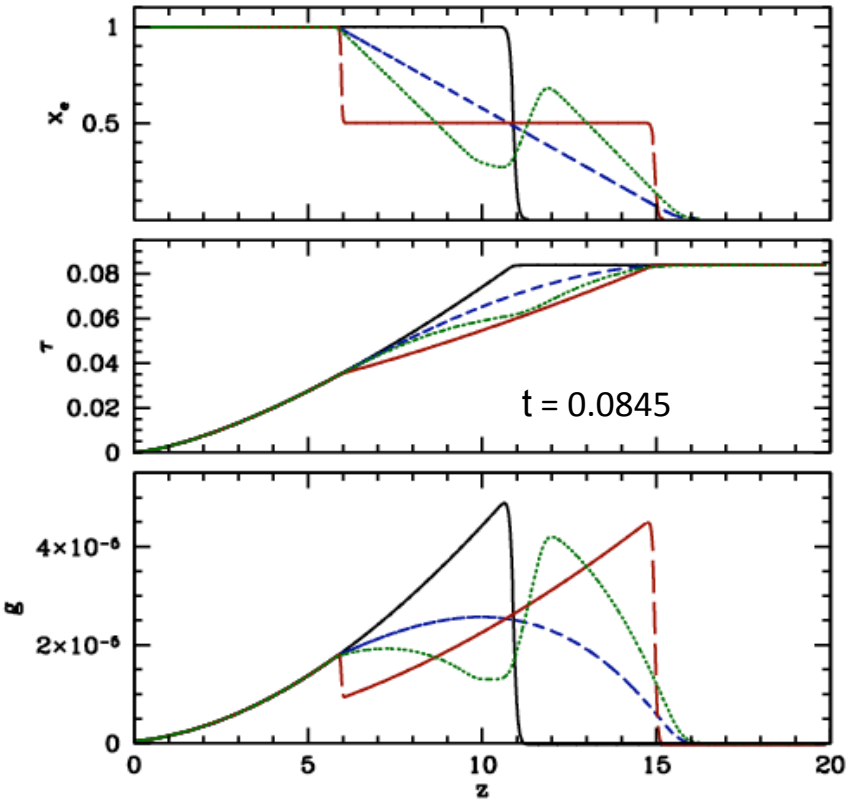
EE only: $\tau = 0.1$ +/- 0.03

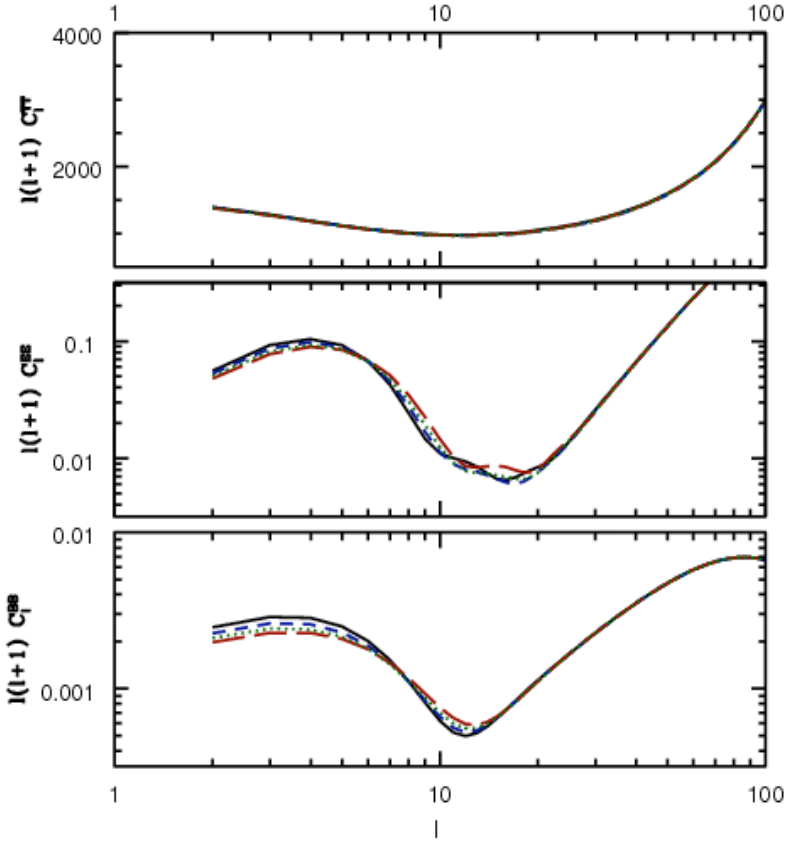
(Page et al 2006)

(WMAP5: 0.087+/- 0.017)



Looking more carefully….





- Differences at *l< 30* on EE and BB spectra are ~ 10%-20%

(see e.g. Holder Haiman, Kaplinghat, Knox 03,Hu & Holder 03 Colombo et al 05)

Colombo & Pierpaoli 08

Questions

- Current analysis models assume “sharp” reionization (possibly incorrect). How much this assumption affects Planck parameter estimation?
- Can you avoid making this assumption? At which cost? Are other parameters affected by the choice?
- Can we constrain something more than just τ?
- If you do give up that assumption, which is the best strategy to incorporate a more general reionization history?

How big is the problem?

- Get C_l's for models with different $x_e(z)$ but same t and other cosmological parameters
- Build simple Planck simulated data for 143 GHz with f_{sky} = 80% sky coverage
- MCMC analysis of simulated data assuming a sharp reionization

t= .0845

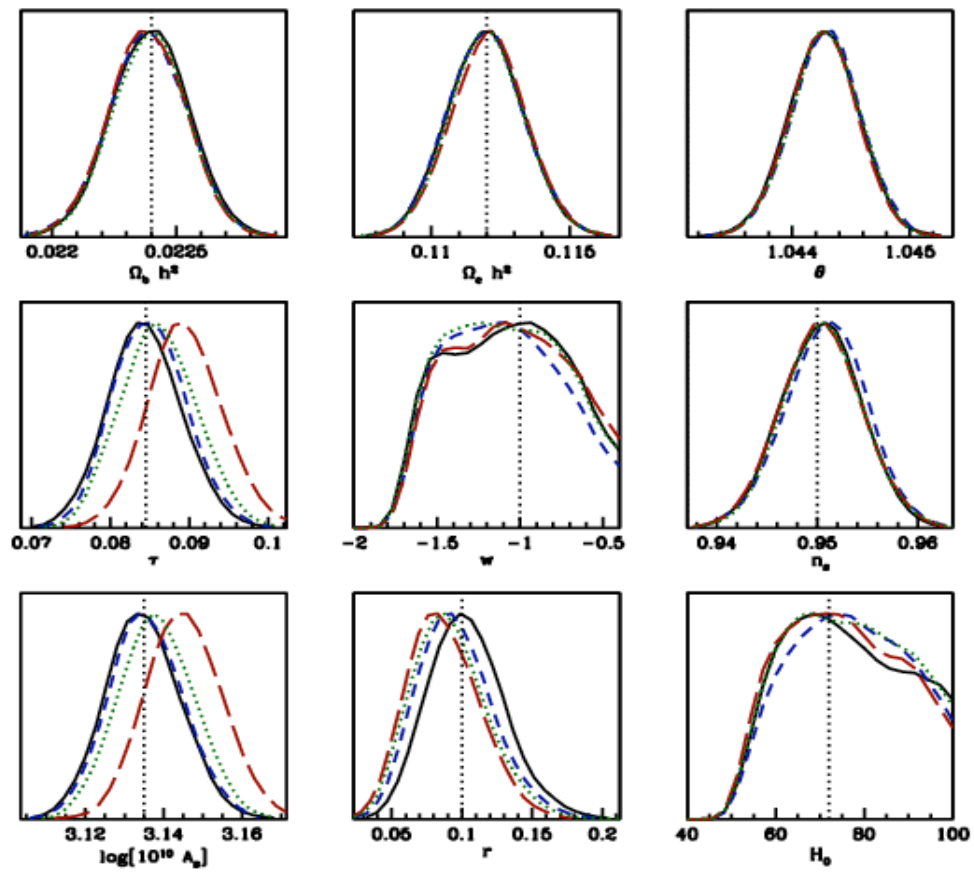
model	mean	s	bias
SR	**.0844**	**.0045**	**-.02**
ER	**.0850**	**.0044**	**.11**
2R	**.0895**	**.0046**	**1.09**
DR	**.0861**	**.0046**	**.35**

$\log[10^{10} A_s] = 3.135$

model	mean	s	bias
SR	**3.1349**	**.0092**	**-.01**
ER	**3.1356**	**.0092**	**.07**
2R	**3.1452**	**.0094**	**1.09**
DR	**3.1382**	**.0093**	**.34**

r = 0.1

model	mean	s	bias
SR	**.104**	**.029**	**.14**
LR	**.096**	**.029**	**-.14**
2R	**.088**	**.028**	**-.43**
DR	**.092**	**.030**	**-.26**



fiducial models: **sharp**, **extended**, **two-step**, **double** with t = .0845

"Agnostic" approaches to reionization

- Binned reionization (Lewis, Weller, Battye 06)
- Principal Component of reionization history (Mortonson & Hu 07)
  - Assume a fiducial binned reionization history

    $x_e^{fid}(z_i)$, $i = 1,2,\ldots, N_z$ $z_{min} \le z_i \le z_{max}$

    $X_e^{fid} = 1, \quad z<6$

    $\quad\quad\quad 0.15, \quad 6<z<30$
  - Evaluate the Fisher Matrix for the EE modes

$$F_{ij} = \sum_{l=2}^{l_{max}} \left(l+\frac{1}{2}\right) \frac{\partial \ln C_l^{EE}}{\partial x_e(z_i)} \frac{\partial \ln C_l^{EE}}{\partial x_e(z_j)}$$

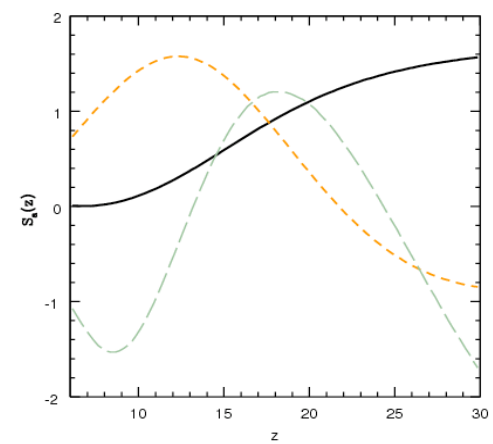
  - The principal components $S_n(z_i)$ are the eigenvectors of the Fisher matrix

$$F_{ij} = \sum_{n=1}^{N_z} S_n(z_i) \lambda_n^{-2} S_n(z_j)$$

  - A generic reionization historiy can be specified on this b

$$x_e(z) = x_{fid} + \sum \mu_n S_n(z)$$

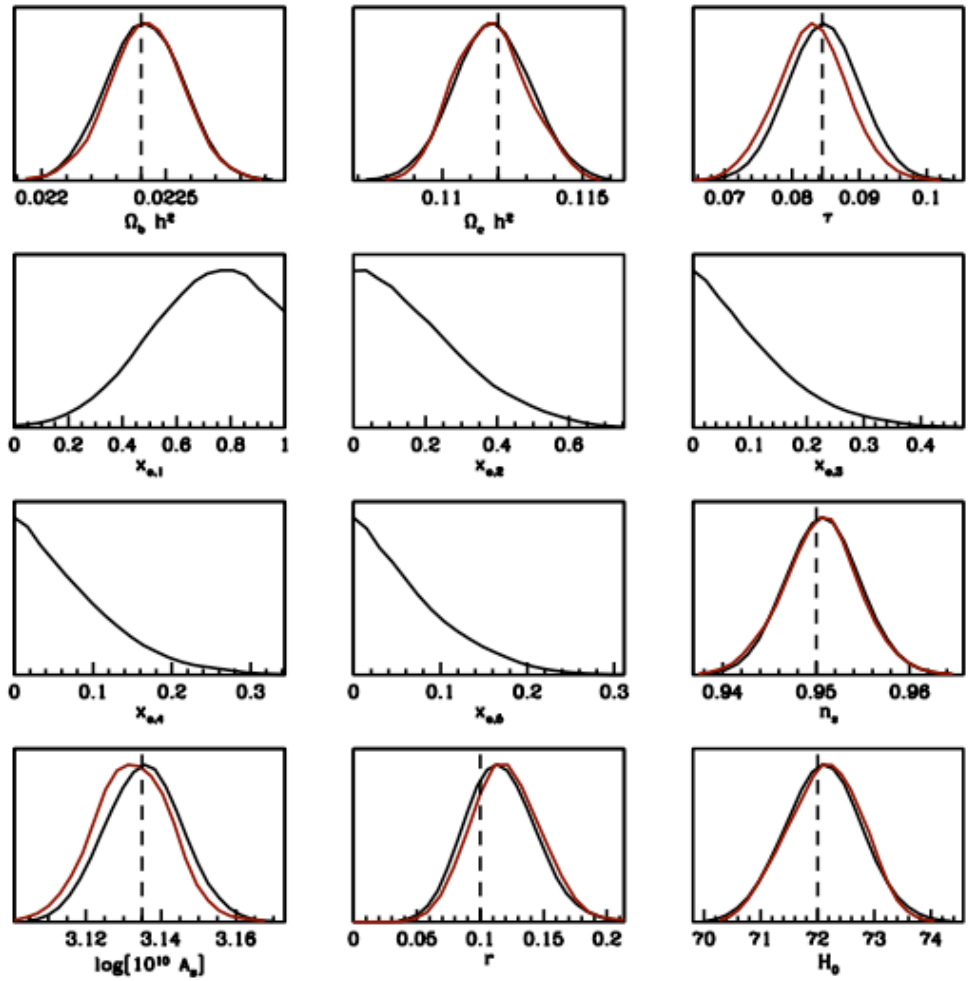
  - Evaluate a subset of these from the data



Reconstructing reionization

- Underlying model: sharp reionization (i.e.: we want to be nasty)
- Analyzed with 6 bins between z=6 and z=30 ($\Delta z=4$)

- Same bias in r observed in the two methods (other parameters are recovered equally well)
- Binned spectra less well reconstructed (a lot of correlation between bins)
- Computationally: 4 times more expensive
- Binned modeling may be better suited to introduce external constraints on reionization

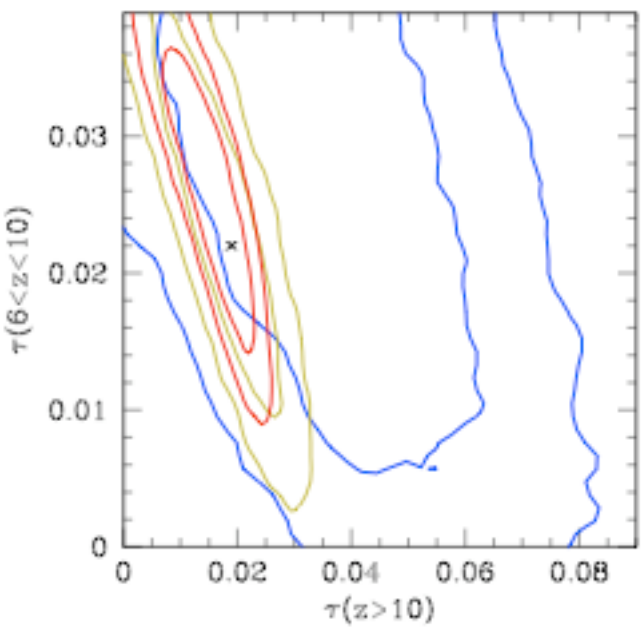


Colombo & Pierpaoli 08

Black: binned reionization

Red: 5 Eigenmodes

EPIC,Planck and WMAP reionization



WMAP5
Planck
EPIC

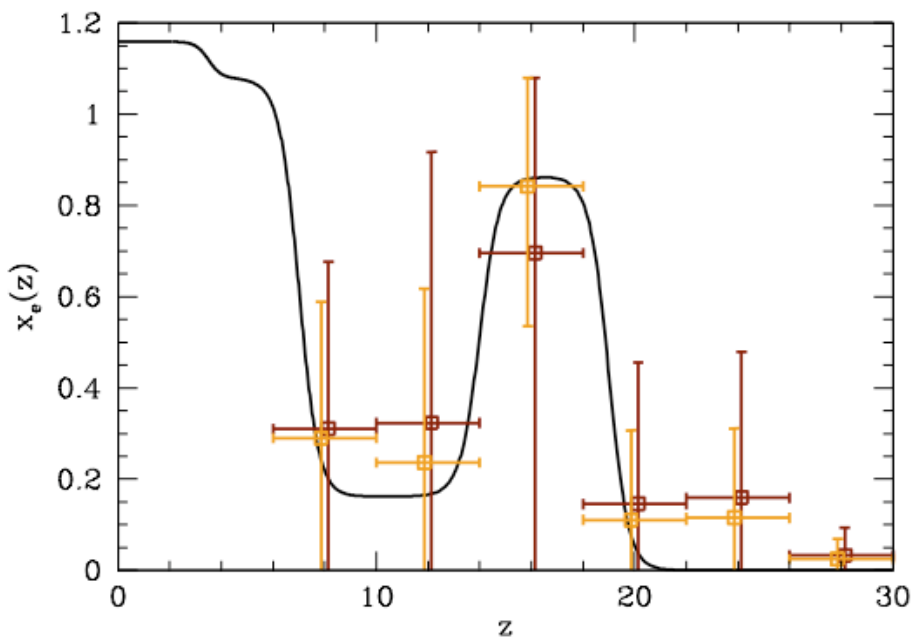
Zaldarriaga et al 2008

Planck will greatly improve on WMAP on high redshift reionization.

“Experimental” Helium contribution to the measurement of reionization history

Planck 70−143 GHz
$x_e(z)$ binned in 6 intervals of $\Delta z = 4$
Error bars show 2σ intervals

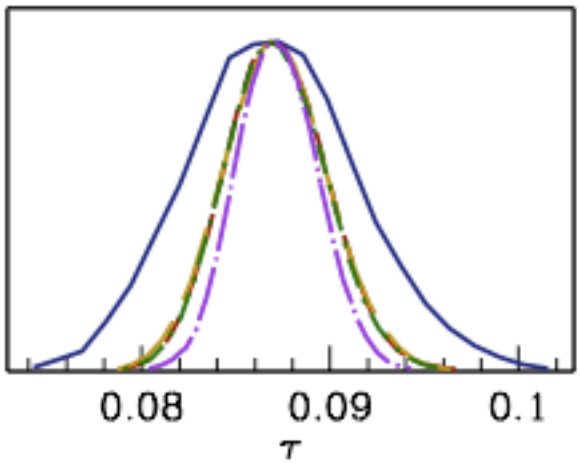
2 surveys
4 surveys

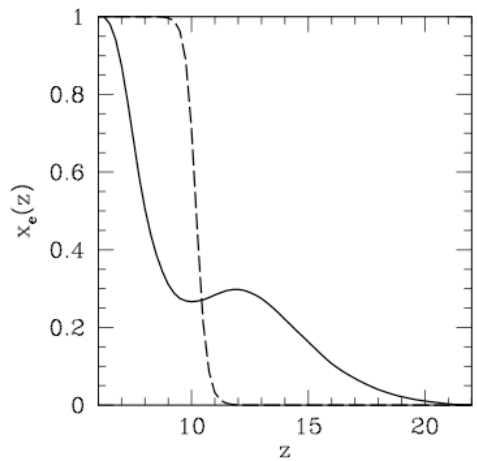


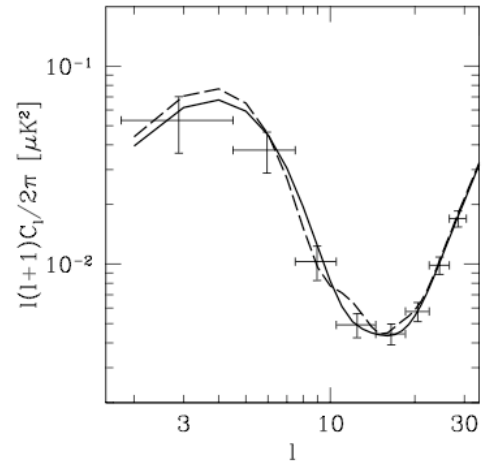
Being able to use more cooling helium would result in better constraints on the reionization history at high redshifts.

How well will a future experiment perform?

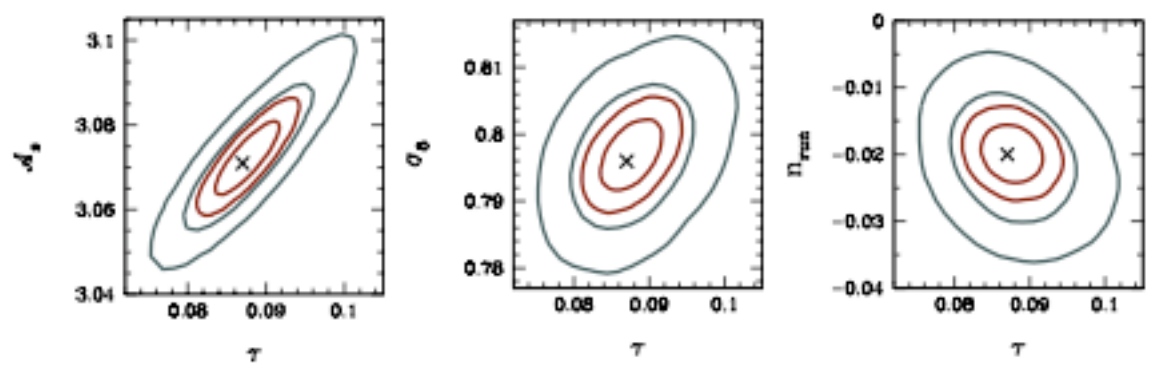
Zaldarriaga et al 08







Planck 70–217 GHz
EPIC LC
EPIC CS
EPIC 2m
CV



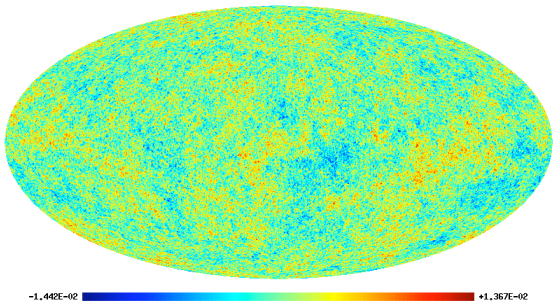
- Practically CV limited for determining the integrated reionization signal
- Not very good in determining the extent of reionization
- Will help in relieving some mild degeneracies Planck may have.

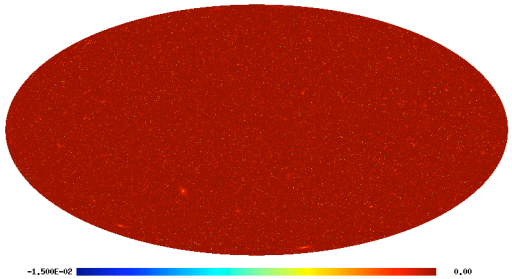
III: What we want and what we get: foregrounds issues

Observations
(real WMAP maps!)

Foregrounds

CMB





Galaxy clusters

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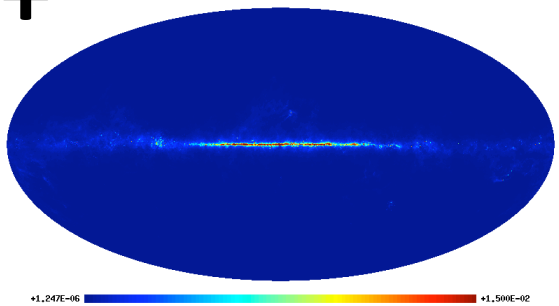

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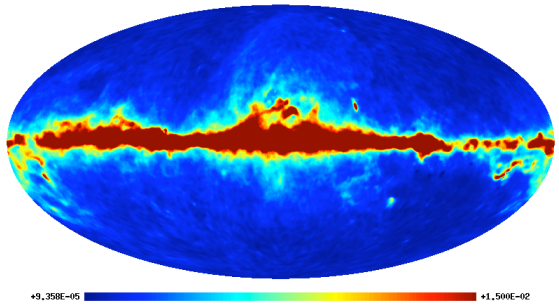
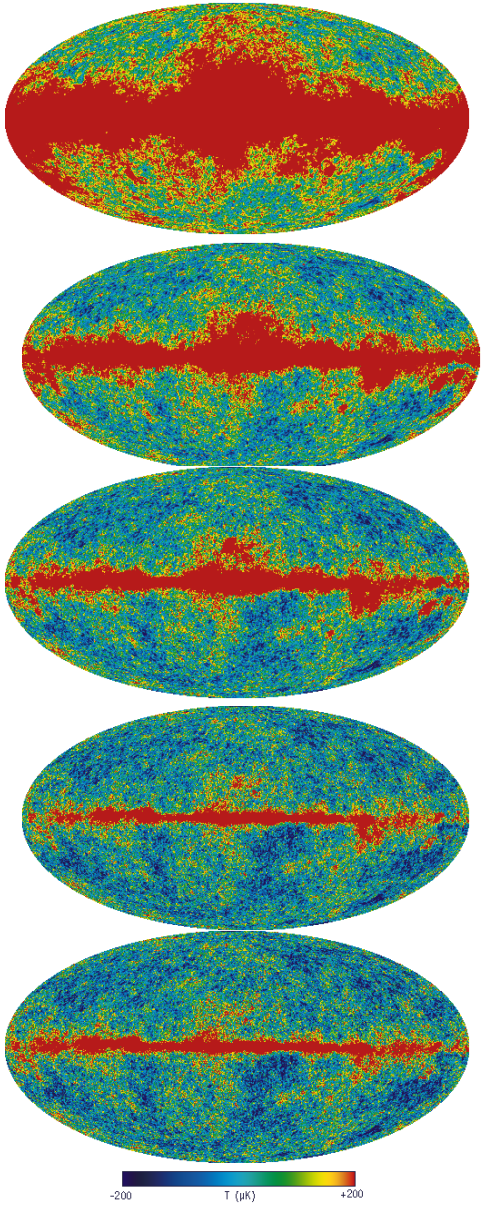
Galactic dust



Synchrotron emission

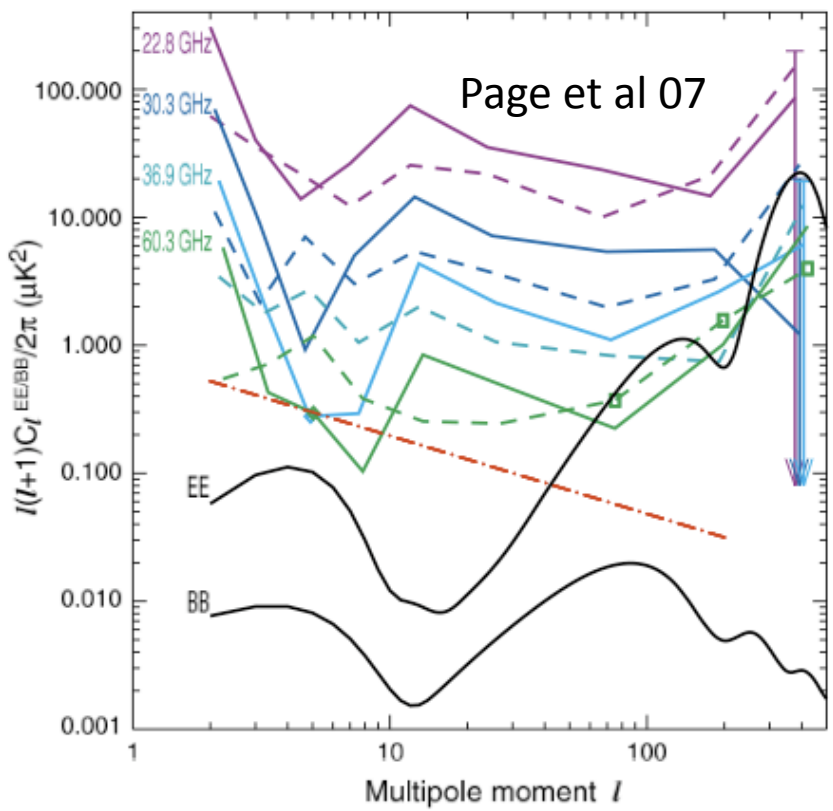


Figures credit: Loris Colombo

The search for r

- B-mode polarization would be a smoking gun for inflation but polarized foregrounds may be a limiting factor.

- How much do we know about polarized foregrounds
- How well can we handle them
- Ultimately, how low of an r can we measure, given our current knowledge of foregrounds



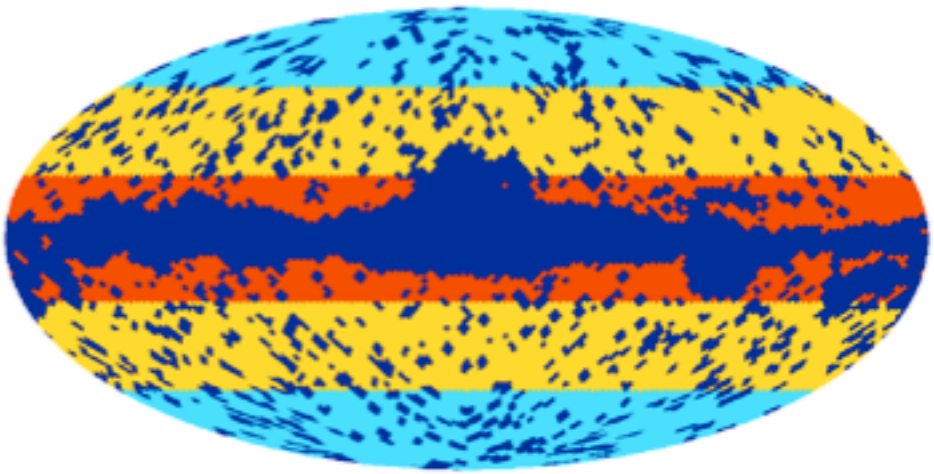
Characterizing diffuse foregrounds: Cross-correlation method

Macellari et al, in prep.

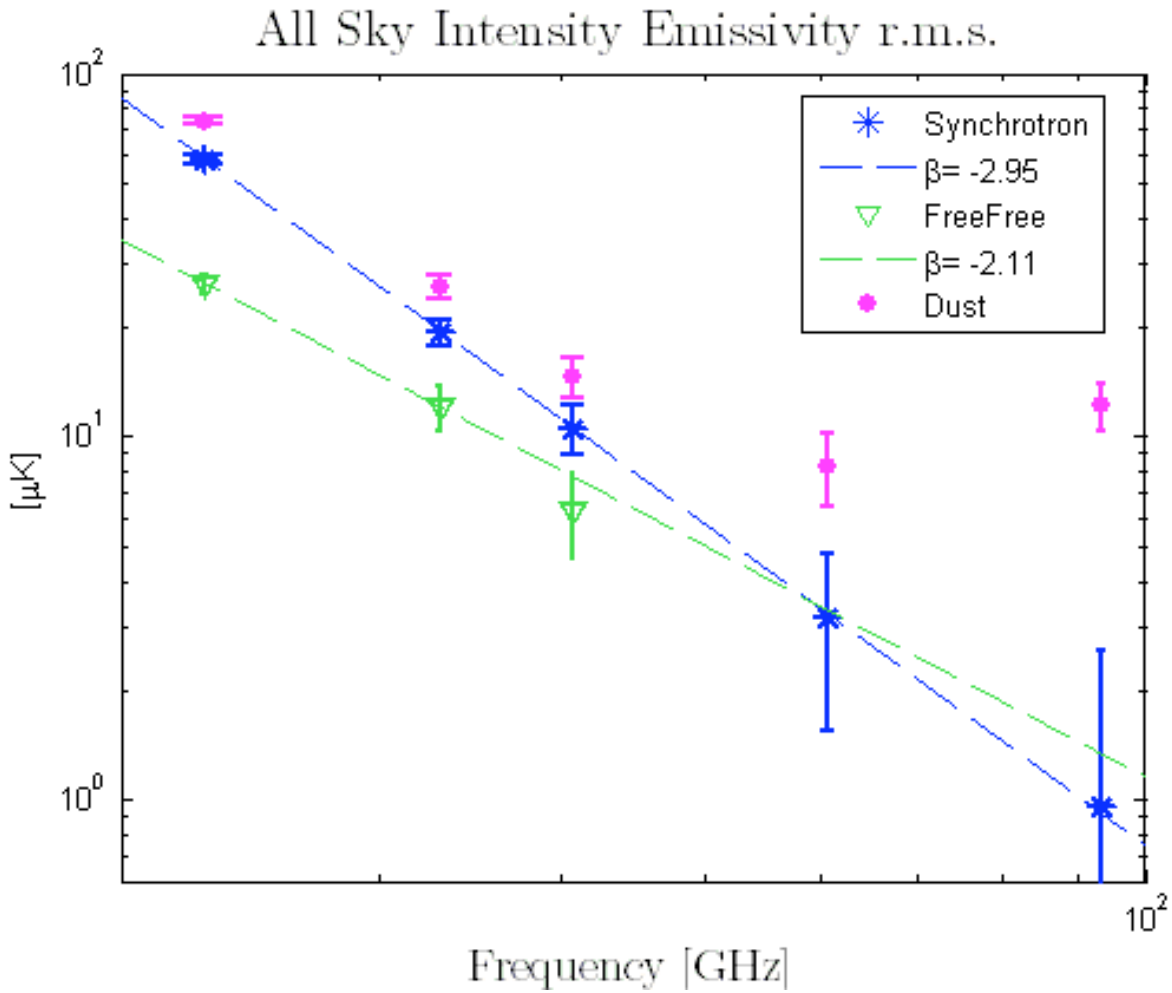
- Idea: assess foreground contribution to WMAP5 map and their properties via cross-correlations with different templates (see Davies et al 06)
- Objectives: perform an analysis at different latitudes, also including polarization
- Advantages: non-parametric
- Disadvantages: not localized, dependent on the representation of the foreground by the template.

Templates:

Syhchrotron: Haslam
Dust:FDS8
Free-free: Hα (Dickinson et al 03)



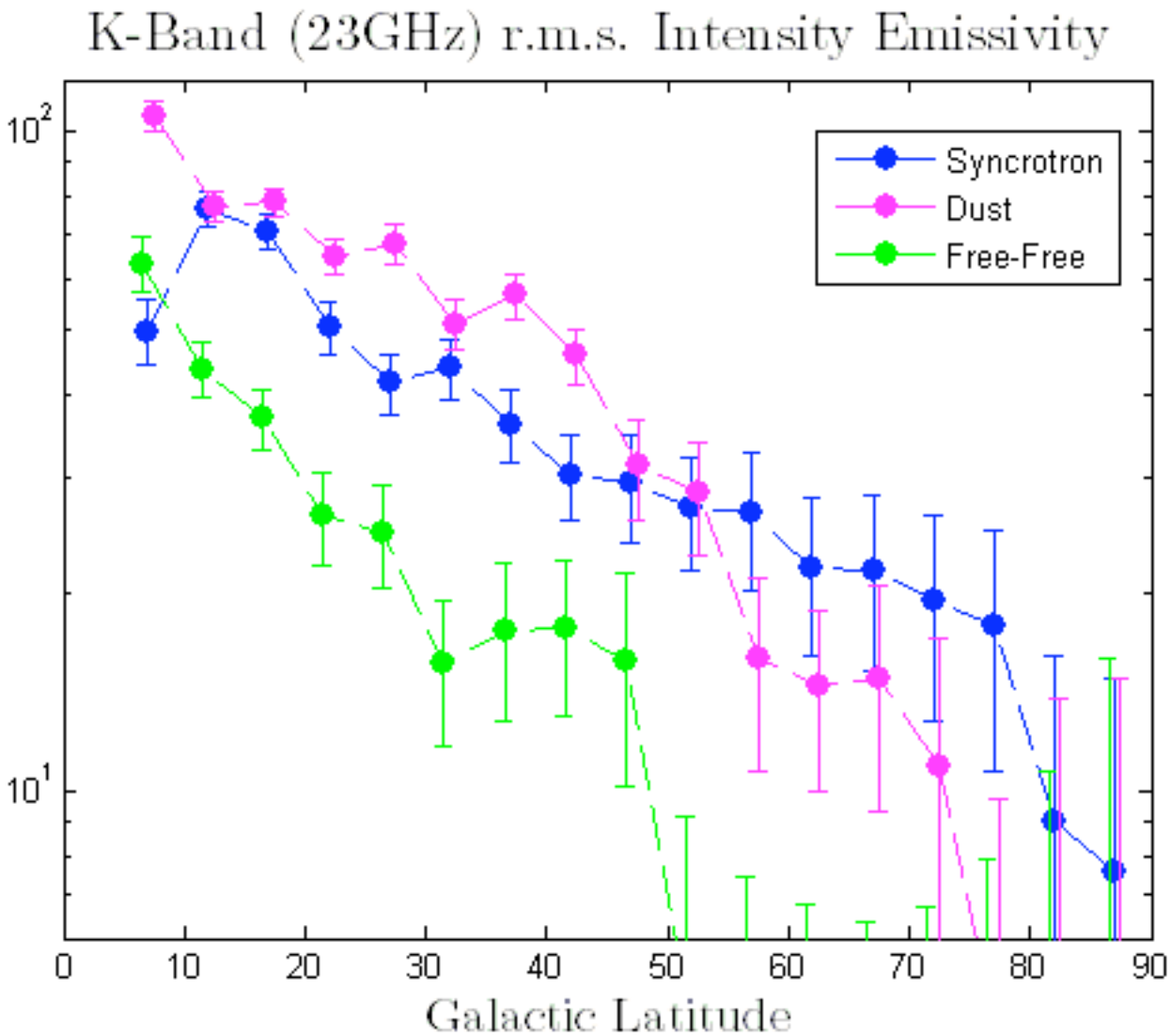
Intensity results



Cfr Davies et al 06

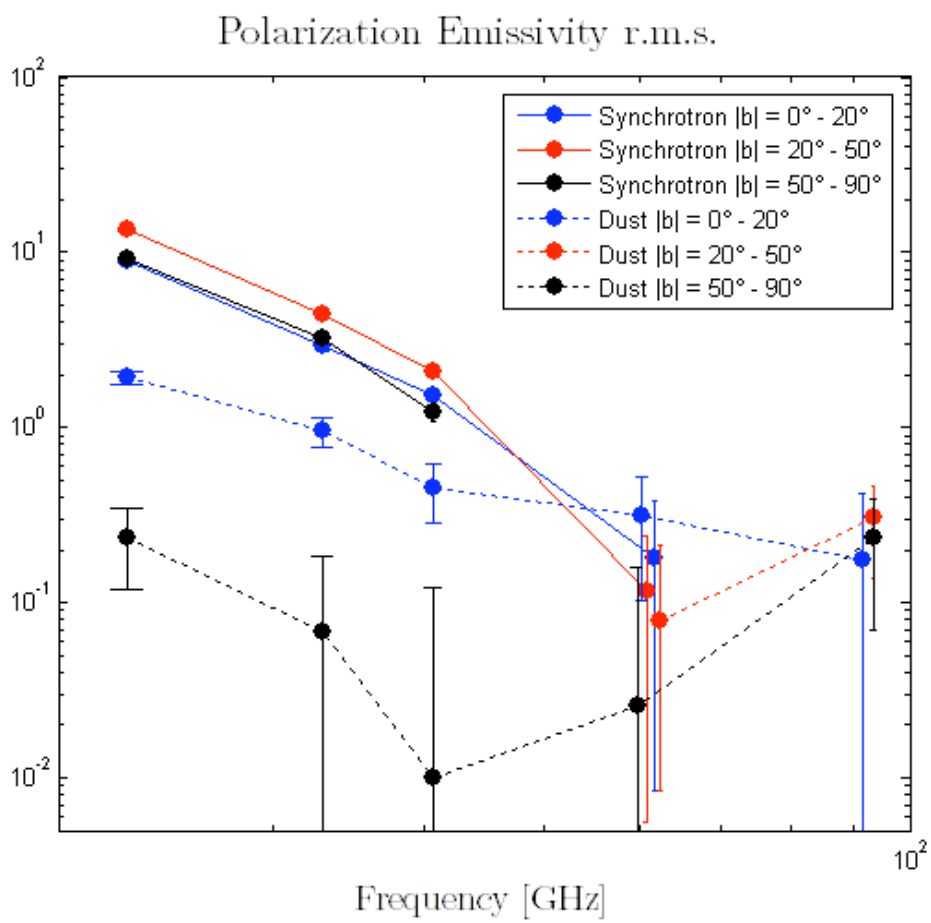
- Evidence for anomalous dust emission plus thermal dust, Free-free and synchrotron spectral index with no surprises.

Intensity results by latitude

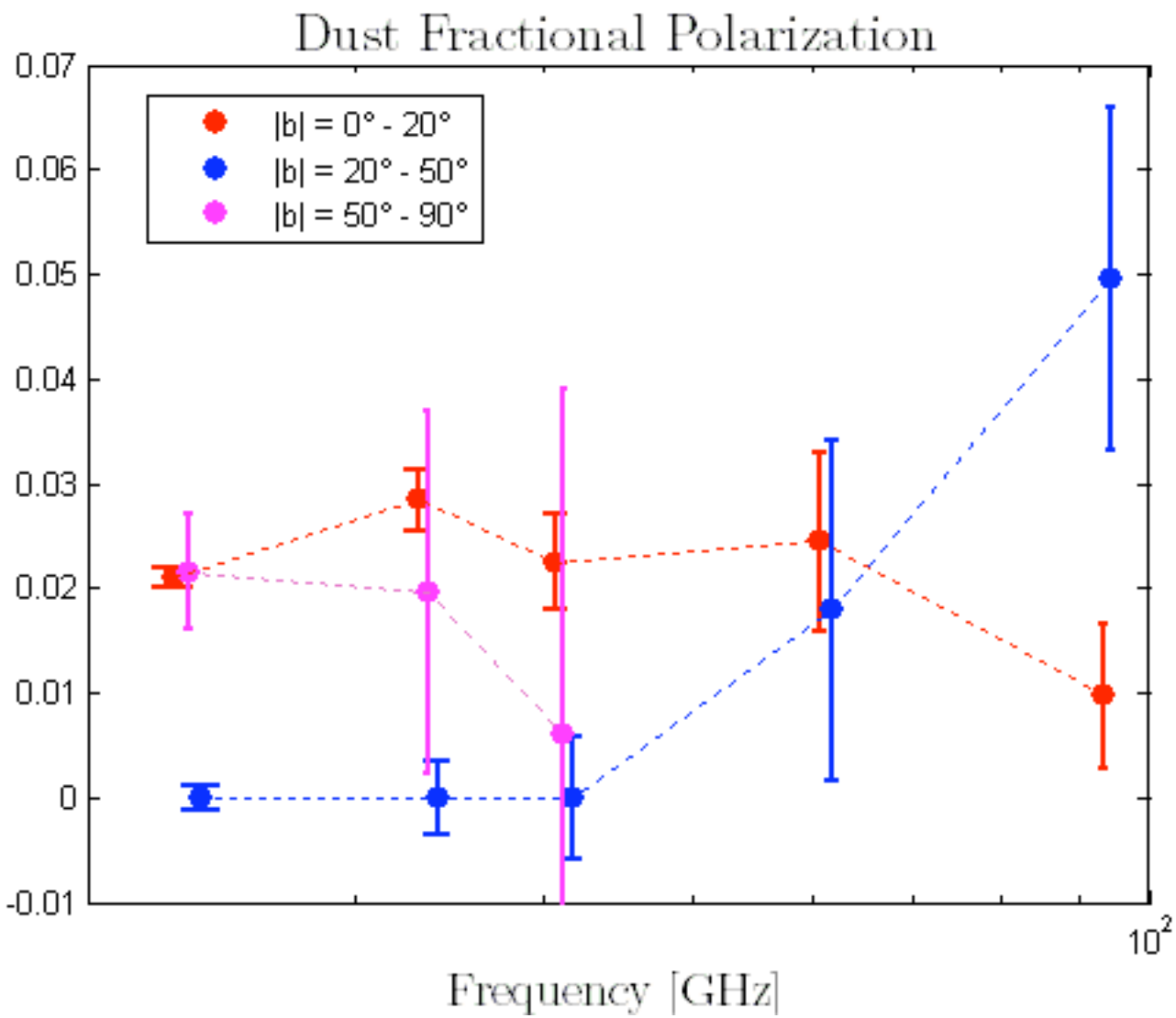


- Dust correlated component dominant on synchrotron at low and intermediate latitudes

Polarization emissivity

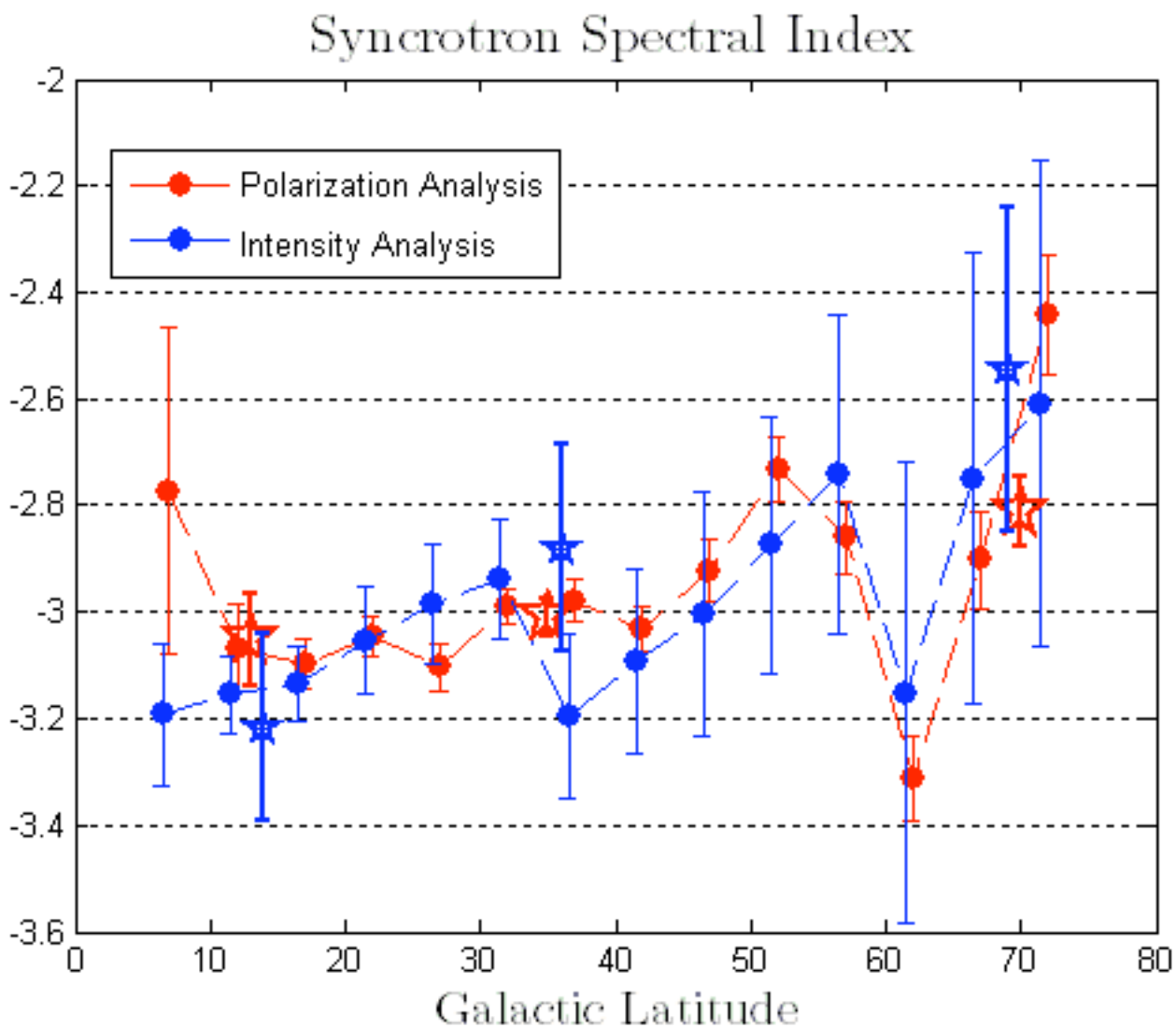


- Synchrotron dominant at low frequencies, dust at 94 GHz.

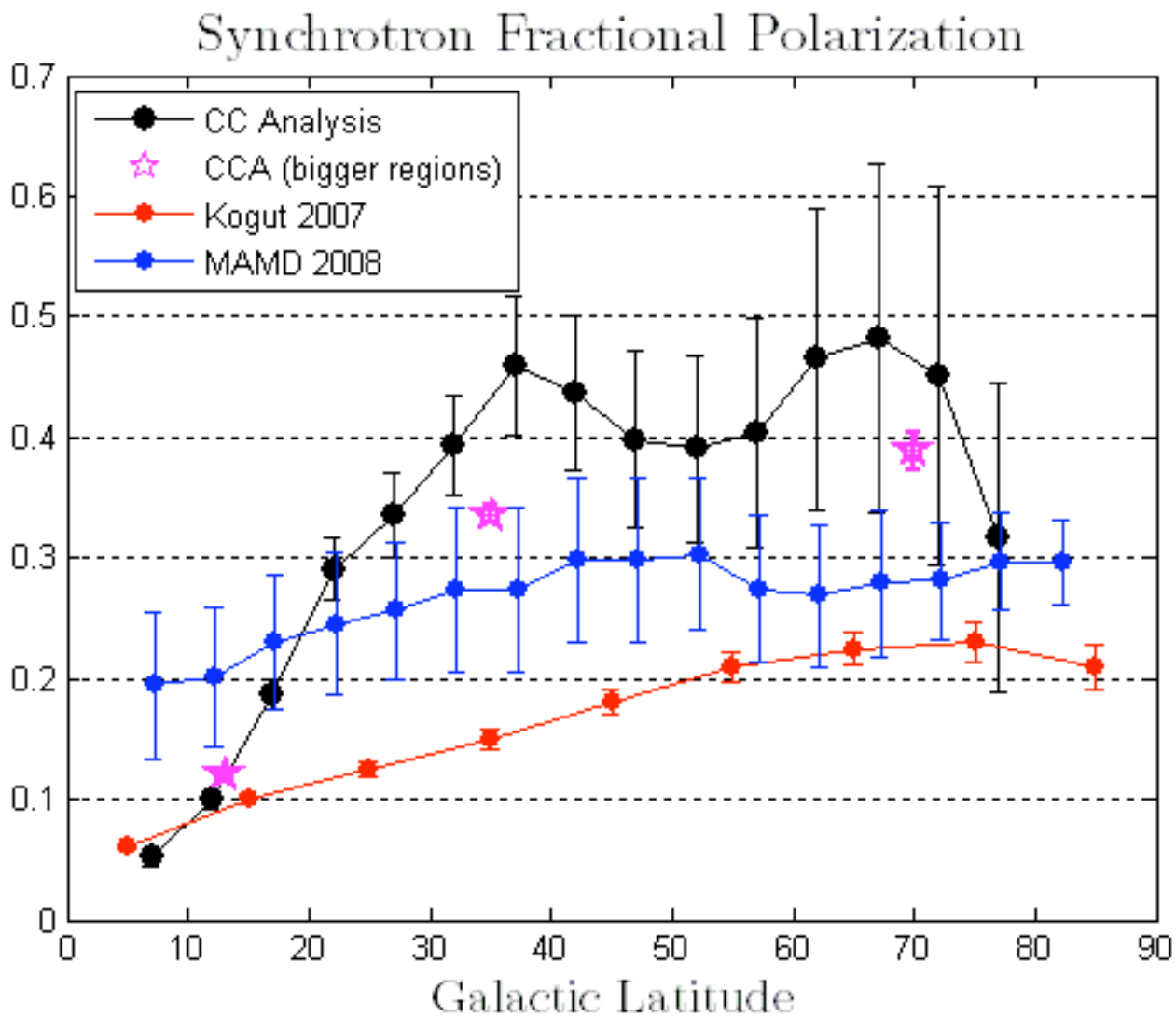


- Total dust fractional polarization below 5%.
- Trend in latitude and frequency.

Synchrotron spectral index



- Consistent results in temperature and polarization, flattening at higher latitudes



- Synchrotron fractional polarization small on the galactic plane, reaching 40-50% at intermediate/high galactic latitudes

IV: Impact of foregrounds on r determination

- Method for component separation: SMICA (Cardoso et al 2008)
- Maps: implementing B for the the Planck Sky Model
- Advantages: “best power spectrum reconstruction”
- Disadvantages: no foreground reconstruction.
- Foreground considered:
  - Synchrotron (with running)
  - Thermal dust (different amplitedes/power spectra)
  - (extra-galactic sources)
  - (Lensing)

SMICA

•The observations are modeled as an additive mixture of C components:

X = vector in frequency of observations: $$X = \sum_{c=1}^{C} X^c$$

•Assuming mutual decorrelation between the components the covariance matrices follows (see later for foregrounds correlation):

$$\boldsymbol{R} = \sum_{c=1}^{C} \boldsymbol{R}^c$$

•Building a set of localized second-order statistics on Q domains Dq

$$\hat{\boldsymbol{R}}_q = \frac{1}{p_q} \sum_{j \in D_q} X(j) X(j)^T \qquad \boldsymbol{R}_q = \boldsymbol{E}\left(\hat{\boldsymbol{R}}_q\right)$$

In our case domains are subsets of the alm space.
We are computing binned cross power spectra

$$\hat{\boldsymbol{R}}_q = \sum_{l \in D_q} \frac{1}{2l+1} \sum_m a_{lm} a_{lm}^T \qquad D_q = \left\{ l_q^{min} \leqslant l < l_q^{max} \right\}$$

The model

Usually we consider: $$\boldsymbol{R}_q(\theta) = \boldsymbol{R}_q^{CMB}(\theta^{CMB}) + \boldsymbol{R}_q^{FG}(\theta^{FG}) + \boldsymbol{R}_q^{noise}(\theta^{noise})$$

a being the emission law of the CMB:

$$\boldsymbol{R}_q^{CMB}(\theta^{CMB}) = \sigma_q^2 a a^T \qquad \theta^{CMB} = \{\sigma_1^{CMB}, \cdots, \sigma_Q^{CMB}\}$$

The noise is modeled as uncorrelated gaussian noise:

$$\boldsymbol{R}_q^{noise}(\theta^{noise}) = \begin{pmatrix} \sigma_{q,1}^2 & 0 & \cdots \\ 0 & \ddots & \vdots \\ \vdots & \cdots & \sigma_{q,m}^2 \end{pmatrix} \qquad \theta^{noise} = \{\sigma_{1,1} \cdots \sigma_{1,m}, \cdots, \sigma_{Q,1} \cdots \sigma_{Q,}$$

The foregrounds can be modeled as a single 'catch-all' component, assuming that d correlated templates compose the foregrounds:

$$\boldsymbol{R}_q^{FG}(\theta^{FG}) = \boldsymbol{A}\,\boldsymbol{\Sigma}_q\,\boldsymbol{A}^t \qquad \theta^{FG} = \{\boldsymbol{A}, \boldsymbol{\Sigma}_1 \cdots \boldsymbol{\Sigma}_Q\}$$

Mixing matrice
Frequencies
behavior

covariance matrice
spectral behavior

$$\theta = \{\sigma_q^{CMB}, \cdots, \sigma_{q,m}, \cdots, \boldsymbol{A}, \boldsymbol{\Sigma}_q \cdots\}$$

The likelihood

- Instead of the usual: $$-2\ln\mathcal{L} = \sum_\ell (2\ell+1) f_{\rm sky}\left[\ln\left(\frac{C_\ell}{\hat{C}_\ell}\right) + \frac{\hat{C}_\ell}{C_\ell}\right] + \text{const.}$$

The likelihood is given by:

$$-2\ln\mathcal{L} = \sum_\ell (2\ell+1) f_{\rm sky} K\left(\widehat{\mathsf{R}}_\ell, \mathsf{R}_\ell\right) + \text{cst}$$

$$\widehat{\mathsf{R}}_\ell = \frac{1}{2\ell+1}\frac{1}{f_{\rm sky}}\sum_{m=-\ell}^{\ell} \boldsymbol{a}_{l,m}\boldsymbol{a}^\dagger_{l,m}$$

Where K is the sprectral mismatch between the matrices:

$$K\left(\widehat{\mathsf{R}}, \mathsf{R}\right) = \frac{1}{2}\left[\text{trace}(\mathsf{R}^{-1}\widehat{\mathsf{R}}) - \log\det(\mathsf{R}^{-1}\widehat{\mathsf{R}}) - F\right]$$

We maximize the likelihood with respect to r, A and Σ_ℓ

We assume that the cosmological parameters are known from other way but r, so we fix the shape of the CMB:

$$\boldsymbol{R}_q^{CMB}(\theta^{CMB}) = \sigma_q^2 aa^T \qquad \Longrightarrow \qquad \boldsymbol{R}_q^{CMB}(\theta^{CMB}) = r\,\sigma_q^2 aa^T$$

$$\theta^{CMB} = \{\sigma_1^{CMB}, \cdots, \sigma_Q^{CMB}\} \qquad\qquad \theta^{CMB} = \{r\}$$

The framework

•Great flexibility in the model

- Various level of blindness, we can fix or leave as a free parameter:
  - the emission law of the CMB
  - the intensity of the noise, or its shape
  - ...
- The Dimension of the galactic component can be tuned to match the complexity of foregrounds, but **no other assumptions are made on the physic of foregrounds**.

•An approximation of the Fisher information matrix is available in the framework, which makes easy the computation of approximate error bars.

$$\mathsf{I}_{i,j}(\boldsymbol{\theta}) = \frac{1}{2}\sum_q w_q \,\mathrm{trace}\left(\frac{\partial \mathsf{R}_q(\boldsymbol{\theta})}{\partial \theta_i}\mathsf{R}_q^{-1}\frac{\partial \mathsf{R}_q(\boldsymbol{\theta})}{\partial \theta_j}\mathsf{R}_q^{-1}\right)$$

$$\sigma_r^2 = \mathsf{I}_{r,r}^{-1}$$

Previous attempts:

- Verde et al 06: Fisher matrix approach with instrumental noise and ~10% foreground residuals
- Amblard et al 07: Wiener filtered maps and estimate of errors including foreground residuals (need to know covariances of your foregrounds!)

$$\boldsymbol{a}_{\ell m} = \boldsymbol{A}_{\rm cmb} a^{\rm cmb}_{\ell m} + \boldsymbol{a}^{\rm cont}_{\ell m}$$

$$\mathsf{N}_\ell = \mathsf{R}^{\rm noise}_\ell + \mathsf{R}^{\rm fg}_\ell$$

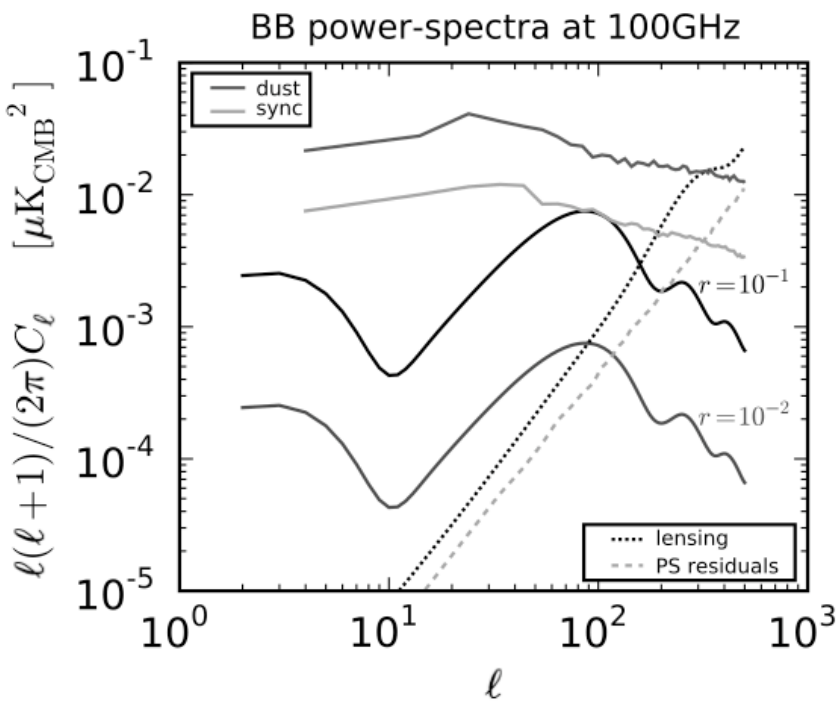
$$\boldsymbol{W}_\ell = \frac{\boldsymbol{A}^\dagger_{\rm cmb} \mathsf{N}_\ell^{-1}}{\boldsymbol{A}^\dagger_{\rm cmb} \mathsf{N}_\ell^{-1} \boldsymbol{A}_{\rm cmb}}$$

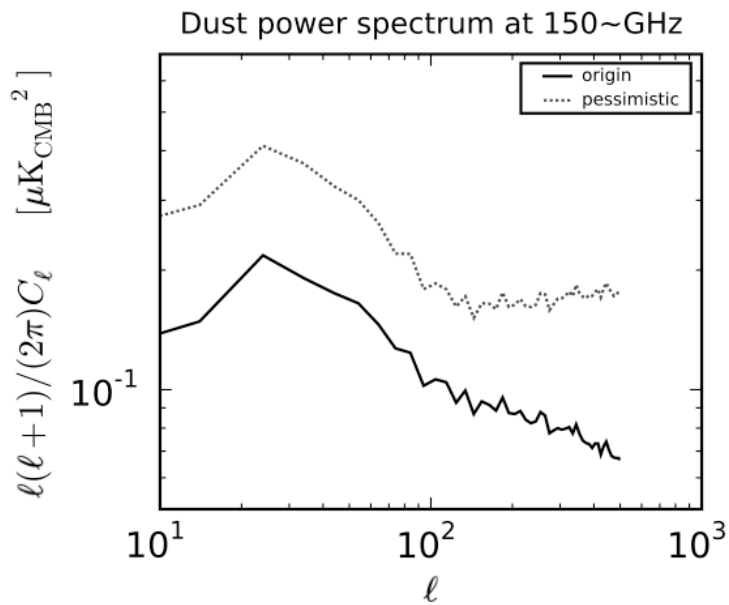
$$\mathcal{N}_\ell = E|\boldsymbol{W}_\ell \boldsymbol{a}^{\rm cont}_{\ell m}|^2 = \left(\boldsymbol{A}^\dagger_{\rm cmb} \mathsf{N}_\ell^{-1} \boldsymbol{A}_{\rm cmb}\right)^{-1}$$

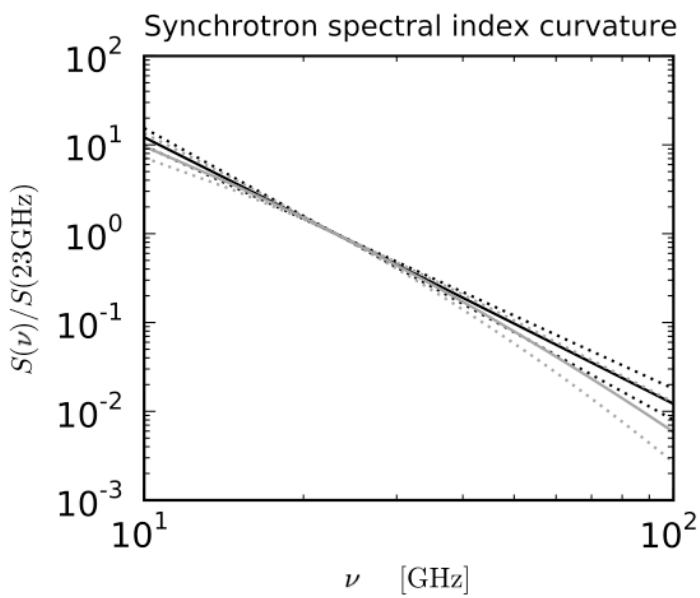
$$\sigma_r^{-2} = \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{2\ell+1}{2} f_{\rm sky} \left(\frac{\mathcal{S}_\ell}{r\mathcal{S}_\ell + \mathcal{N}_\ell}\right)^2$$

Foreground levels and modeling

Foreground modeled out of the PSM

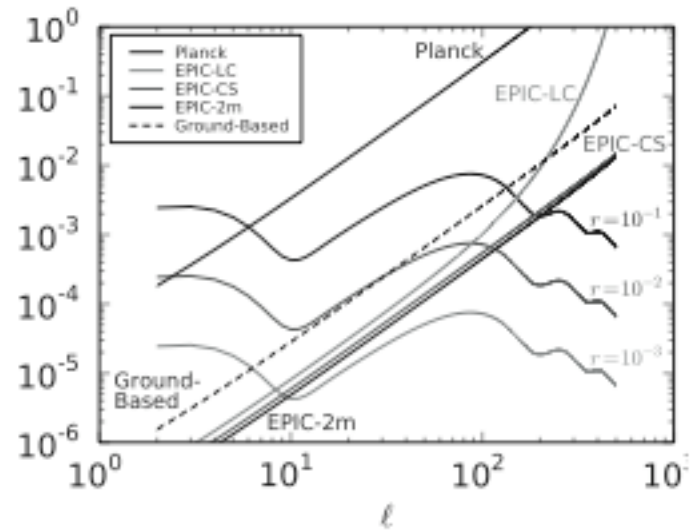






Forecasts for future experiments

Experiment	frequency (GHz)	beam FWHM (')	NET ($\mu K\sqrt{s}$)	T_{obs} (yr)	sky coverage (f_{sky})
PLANCK	30, 44, 70 100, 143, 217, 353	33, 24, 14 10, 7.1, 5, 5	96, 97, 97 41, 31, 51, 154	1.2	1
EPIC-LC	30, 40, 60 90, 135, 200, 300	155, 116, 77 52, 34, 23, 16	28, 9.6, 5.3 2.3, 2.2, 2.3, 3.8	2	1
EPIC-CS	30, 45, 70, 100 150, 220, 340, 500	15.5, 10.3, 6.6, 4.6 3.1, 2.1, 1.4, 0.9	19, 8, 4.2, 3.2 3.1, 5.2, 25, 210	4	1
EPIC-2m	30, 45, 70, 100 150, 220, 340, 500(,800)	26, 17, 11, 8 5, 3.5, 2.3, 1.5(, 0.9)	18, 7.6, 3.9, 3.0 2.8, 4.4, 20, 180(, 28k)	4	1
Ground-Based	97, 150, 225	7.5, 5.5, 5.5	12, 18, 48	0.8	0.01
Deep field	30, 45, 70, 100 150, 220, 340, 500	15.5, 10.3, 6.6, 4.6 3.1, 2.1, 1.4, 0.9	19, 8, 4.2, 3.2 3.1, 5.2, 25, 210	4	0.01



case	r	noise-only σ_r/r	noise-only $\sigma_r^{\ell\le20}/r$	noise-only $\sigma_r^{\ell>20}/r$	known foregrounds σ_r/r	known foregrounds $\sigma_r^{\ell\le20}/r$	known foregrounds $\sigma_r^{\ell>20}/r$	SMICA σ_r/r	SMICA $\sigma_r^{\ell\le20}/r$	SMICA $\sigma_r^{\ell>20}/r$	r^{est}	$l_{min}-l_{max}$	f_{sky}	D^3
PLANCK	0.3	0.075	0.17	0.084	0.1	0.2	0.12	0.15	0.22	0.2	**0.26**	2 - 130	0.95	3
	0.1	0.17	0.25	0.22	0.23	0.34	0.32	0.29	0.34	0.55	0.086			
EPIC-LC	0.01	0.019	0.084	0.019	0.05	0.18	0.053	0.079	0.18	0.1	**0.0098**	2 - 130	0.86	4
	0.001	0.059	0.15	0.064	0.27	0.4	0.38	0.37	0.43	0.82	0.00088			
EPIC-2m	0.01	0.016	0.083	0.016	0.027	0.12	0.027	0.032	0.11	0.036	**0.0096**	2 - 300	0.87	4
	0.001	0.051	0.14	0.055	0.14	0.25	0.16	0.16	0.24	0.24	**0.001**			
EPIC-CS	0.01	0.017	0.084	0.017	0.029	0.12	0.03	0.036	0.11	0.041	**0.0096**	2 - 300	0.87	4
	0.001	0.058	0.15	0.063	0.15	0.27	0.19	0.18	0.26	0.29	**0.00098**			
Ground-based	0.1	0.083	–	–	0.15	–	–	0.24	–	–	**0.11**	50 - 300	0.01	2
	0.01	0.18	–	–	0.8	–	–	1.6	–	–	0.018			
Grnd-based+Planck	0.01	0.18	–	–	0.51	–	–	0.69	–	–	0.0065	50 - 300	0.01	2
Deep field mission	0.001	0.082	–	–	0.1	–	–	0.13	–	–	**0.00092**	50 - 300	0.01	4

Variants to the main model

r	$r^{\text{no-ps}}$	r^{ideal}	$r^{\text{no-model}}$	$\sigma_r^{\text{no-ps}}$	σ_r^{ideal}	$\sigma_r^{\text{no-model}}$
0.001	$1.07 \cdot 10^{-3}$	$1.04 \cdot 10^{-3}$	$2.00 \cdot 10^{-3}$	$1.84 \cdot 10^{-4}$	$1.91 \cdot 10^{-4}$	$2.49 \cdot 10^{-4}$

Point sources (EPIC-CS)

	no lensing			lensing		
Experiment	σ_r/r	$\sigma_r^{\ell\leq 20}/r$	$\sigma_r^{\ell>20}/r$	σ_r/r	$\sigma_r^{\ell\leq 20}/r$	$\sigma_r^{\ell>20}/r$
EPIC-CS	0.17	0.25	0.28	0.2	0.24	0.36
Deep field	0.13	–	–	1.1	–	–

Lensing (r=0.001)

r	σ_r	α	r	$-\ln\mathcal{L}$
0.001	$1.8 \cdot 10^{-4}$	0	$9.78 \cdot 10^{-4}$	11.6
		1	$9.62 \cdot 10^{-4}$	11.5
		3	$1.06 \cdot 10^{-3}$	11.7

Variations in the synchrotron spectral index

$$S_\nu^X(\xi) = S_{\nu_0}^X(\xi)\left(\frac{\nu}{\nu_0}\right)^{\beta_s(\xi)+\alpha C(\xi)\log(\nu/\nu_1)}$$

Experiments	r	r^{origin}	r^{pessim}	σ_r^{origin}	σ_r^{pessim}
Ground-based	0.01	$1.84 \cdot 10^{-2}$	$1.69 \cdot 10^{-2}$	$1.62 \cdot 10^{-2}$	$1.62 \cdot 10^{-2}$
EPIC-2m	0.001	$8.77 \cdot 10^{-4}$	$8.77 \cdot 10^{-4}$	$3.68 \cdot 10^{-4}$	$3.61 \cdot 10^{-4}$

Variations in the dust

Conclusions

- WMAP naïve parameter estimates about 30% lower than real ones. Planck may improve by several factors, especially on r (with 1/2 of the information coming from the BB power spectrum). Estimates considering foreground suggest that at r~0.1 foregrounds should not degrade the significance of the detection. Planck will complement future surveys in…….
- Allowing for a general reionization model within Planck parameter estimation is necessary not to bias r and power spectrum amplitude. The implementation is practically doable. Both principal component or redshift bins may be used. Future CMB polarization missions all perform well No good reconstruction of reionization history is to be expected, apart from discriminating broadly between early and late contribution to the optical depth.
- WMAP5 Cross-correlation analysis: dust polarization below 6%, dependent on frequency and latitude. Synchrotron polarization increasing with latitude up to 40-50%. Synchrotron spectral index consistent in temperature and polarization, flattening at higher latitudes.
- As for future CMB polarization missions, foreground should not limit detection if r~0.001, with actual performances depending on configuration. Variations in the diffuse components is irrelevant for the results. Point sources, if neglected, bias the results.