

# **COrE+ component separation exercise: Correlated Component Analysis (CCA)**

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Towards a next space probe for CMB observations  
and cosmic origins exploration  
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# Overview of our method

- To estimate the foreground components spectral parameters, we use **Correlated Component Analysis (CCA)**.
- To separate components, we use a linear mixture solution, particularly a **Generalized Least Squares (GLS)** solution.
- To estimate the power spectra, we mask and use a hybrid approach: for high multipoles, a **pseudo-Cl deconvolution**; for low multipoles, a **Quadratic Maximum Likelihood (QML)**.
- To calculate the  $r$  likelihood, we use a standard  $\chi^2$  approach, plus foregrounds nuisance parameters.

# Correlated Component Analysis

- It works on harmonic domain, by exploiting the second order statistics in the covariance matrices of the signal and noise (Bonaldi+ 2006, Ricciardi +2010).
- It is applied on several sky patches, and the output is the most likely spectral parameters of the components considered.
- We consider thermal dust (sp. index and temperature) and synchrotron (only sp. index). We could also process AME emission.

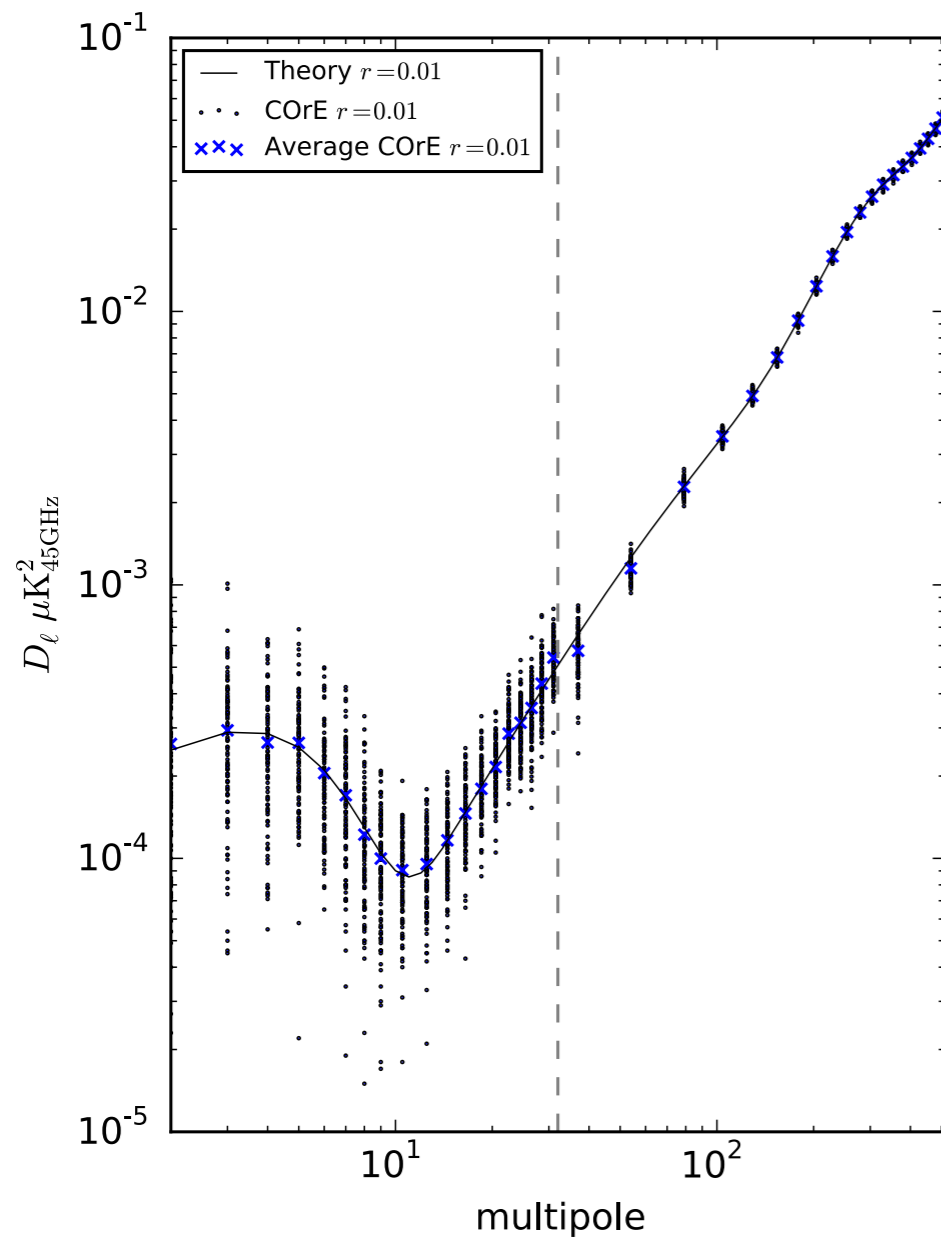
# Reconstruction of CMB map

- We use a linear combination, where we calculate the mixing matrix  $\mathbf{A}$  from the estimated parameters by CCA. They can be either constant or pixel-by-pixel maps.
- We use a Generalized Least Square solution.

$$\mathbf{W} = \left[ \mathbf{A}^\dagger \mathbf{C}_{\text{noise}}^{-1} \mathbf{A} \right]^{-1} \mathbf{A}^\dagger \mathbf{C}_{\text{noise}}^{-1}$$

- The reconstructed CMB map is masked and then we estimate the power spectra.

# Power spectra estimation



We use a **hybrid approach**.

Up to multipole 32, we use a Quadratic Maximum Likelihood code (Tegmark+ 2001) on Nside=16 maps.

For high multipoles, we use an apodized mask and a pseudo-Cl deconvolution (Brown+ 2005) on the full resolution maps (Nside=2048).

These example results are from simulations for my Phd thesis.

**COrE simulation,  $r=0.01$ , with dust and synchrotron, constant  $\beta_{\text{dust}}$  and  $\beta_{\text{syn}}$ .**

In these, we assume perfect knowledge of foregrounds. The average spectrum of 100 realizations is unbiased.

# Likelihood

We minimize

$$\chi^2(r) = \sum_{b,b'} (P_b^{\text{BB}} - C_b^{\text{theory, BB}}(r)) \mathbf{C}_{bb'}^{-1} (P_{b'}^{\text{BB}} - C_{b'}^{\text{theory, BB}}(r))$$

where  $b, b'$  loop through the multipole bins.  $P$  is the measured power spectra and  $C$  is the theory power spectra, whose amplitude depends on  $r$ .  $\mathbf{C}$  is the covariance matrix.

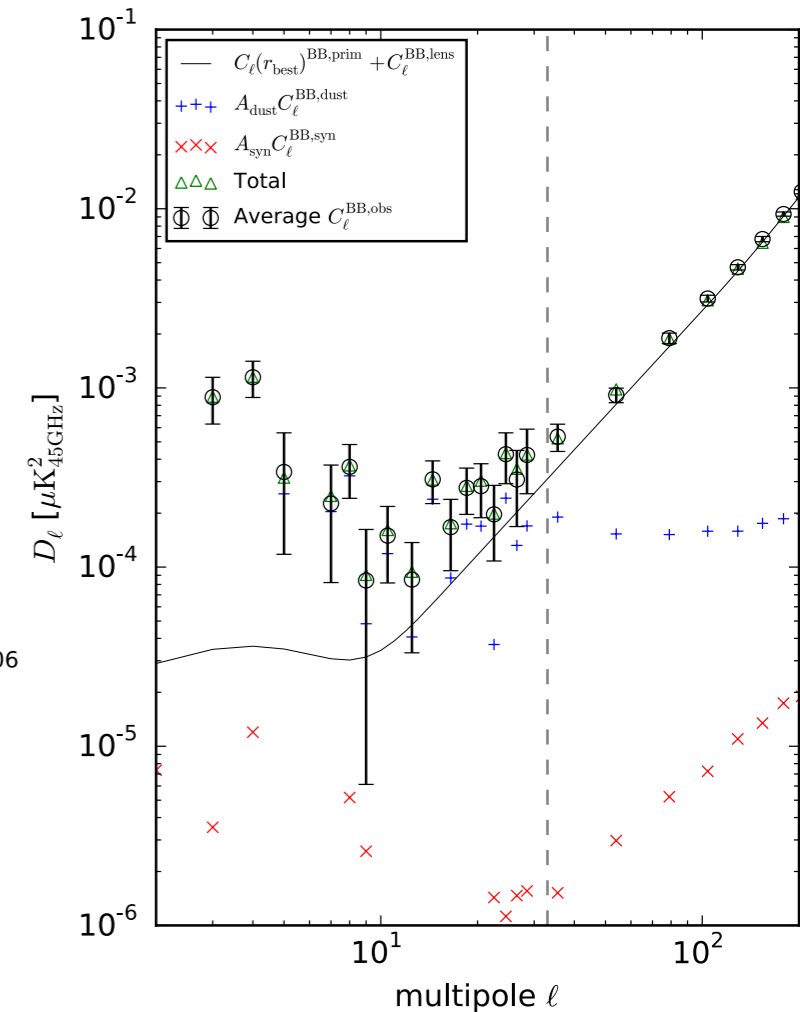
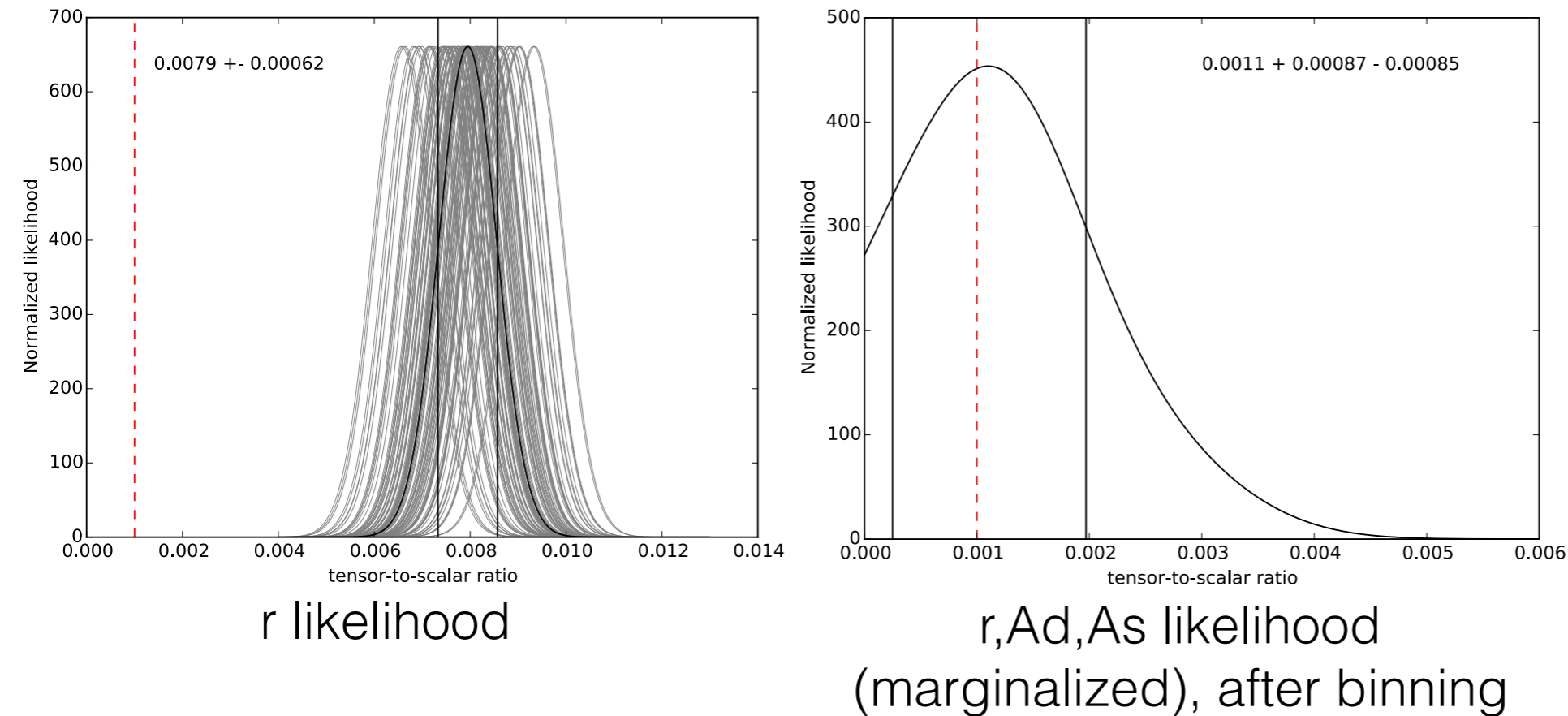
We also include an extra step to correct for the bias in  $r$ . We add the power spectra of the reconstructed dust and synchrotron foregrounds, scaled by a constant, to the theory spectrum.

$$C_\ell^{BB}(r) = \frac{r}{r_\star} C_\ell^{BB, \text{prim}}(r_\star) + C_\ell^{BB, \text{lens}} + A_d C_\ell^{BB, \text{dust}} + A_s C_\ell^{BB, \text{syn}}$$

We do a 3 parameter likelihood, for  $r$ ,  $A_d$  and  $A_s$ . You can add the foregrounds power spectra either before or after binning.

# Likelihood de-bias

These results are from the simulations made for my Phd thesis



**CorE simulation,  $r=0.001$ , constant  $\beta_{\text{dust}}$  and  $\beta_{\text{syn}}$ .**

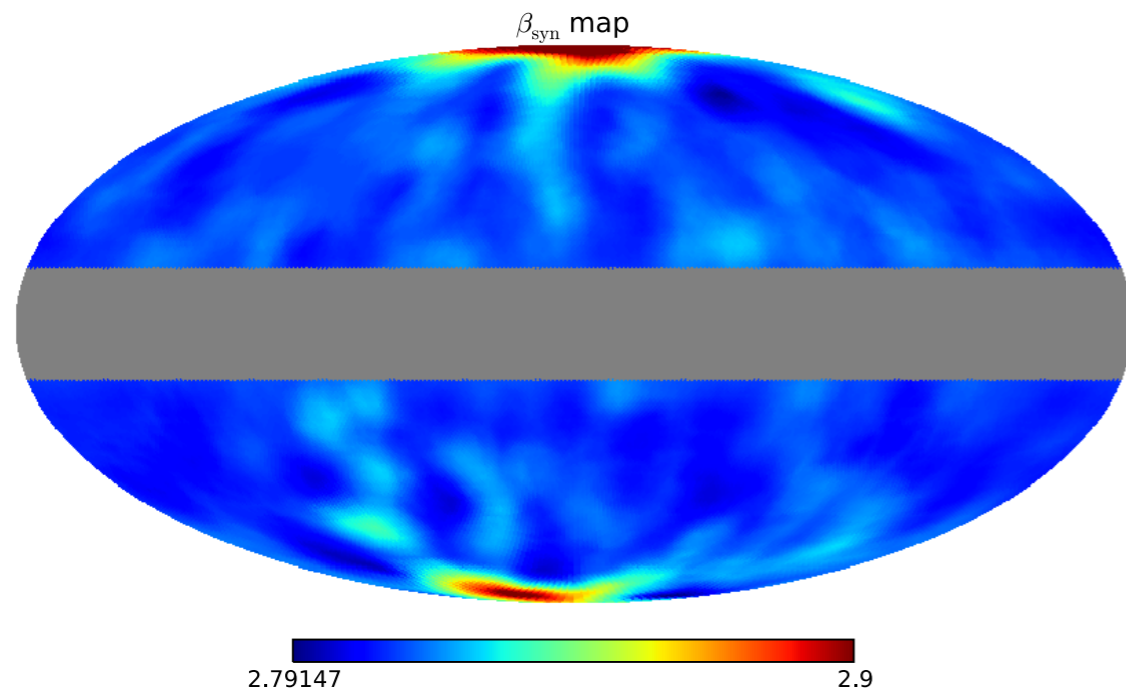
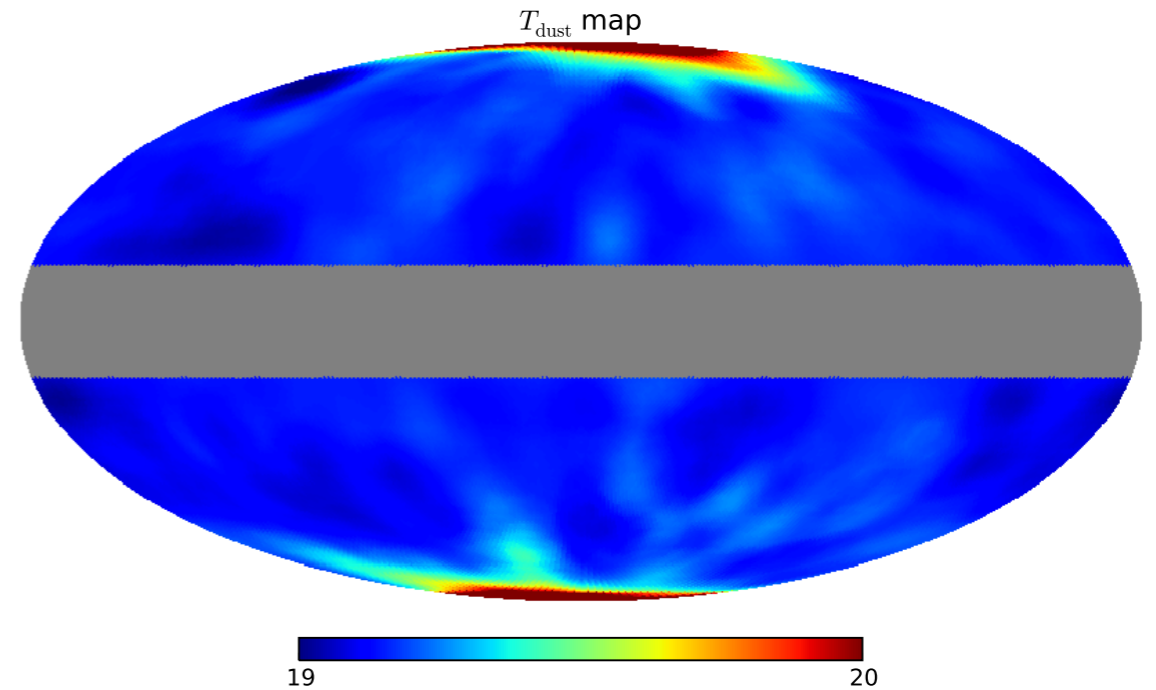
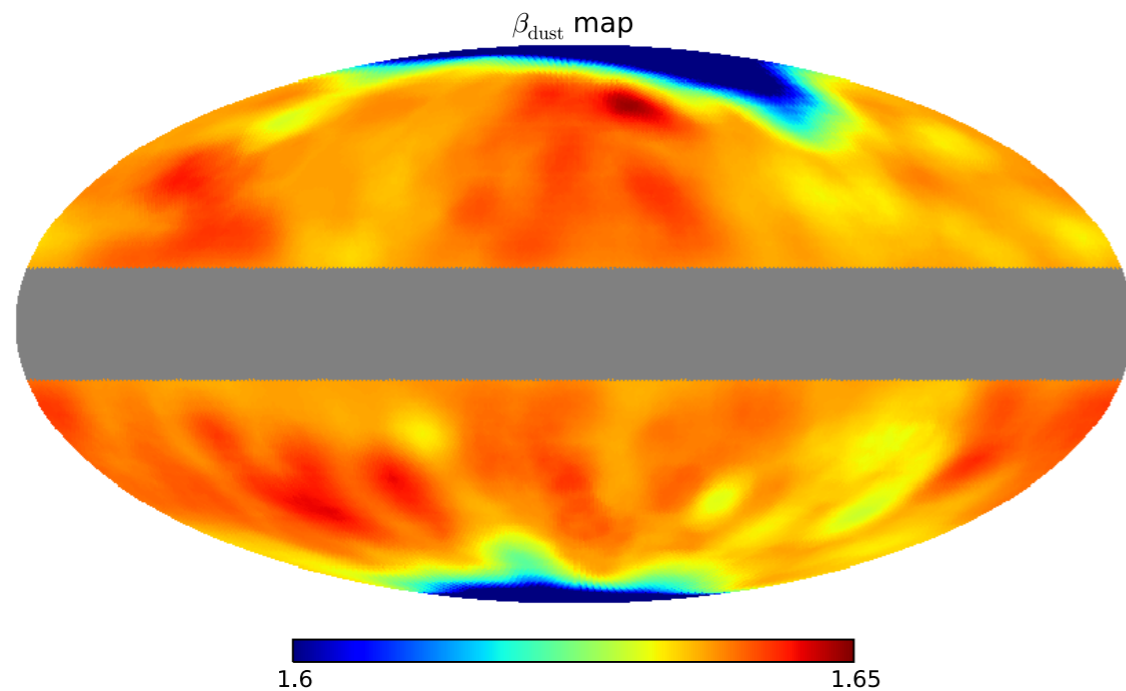
We use a **mixing matrix with 1% error** on the spectral indices.

The power spectrum estimate is hybrid, up to  $\ell=141$ .

The black solid lines are the average power spectra of 100 realizations.

The power spectrum is matched by a combination of theory (primordial + lensed) and foregrounds.

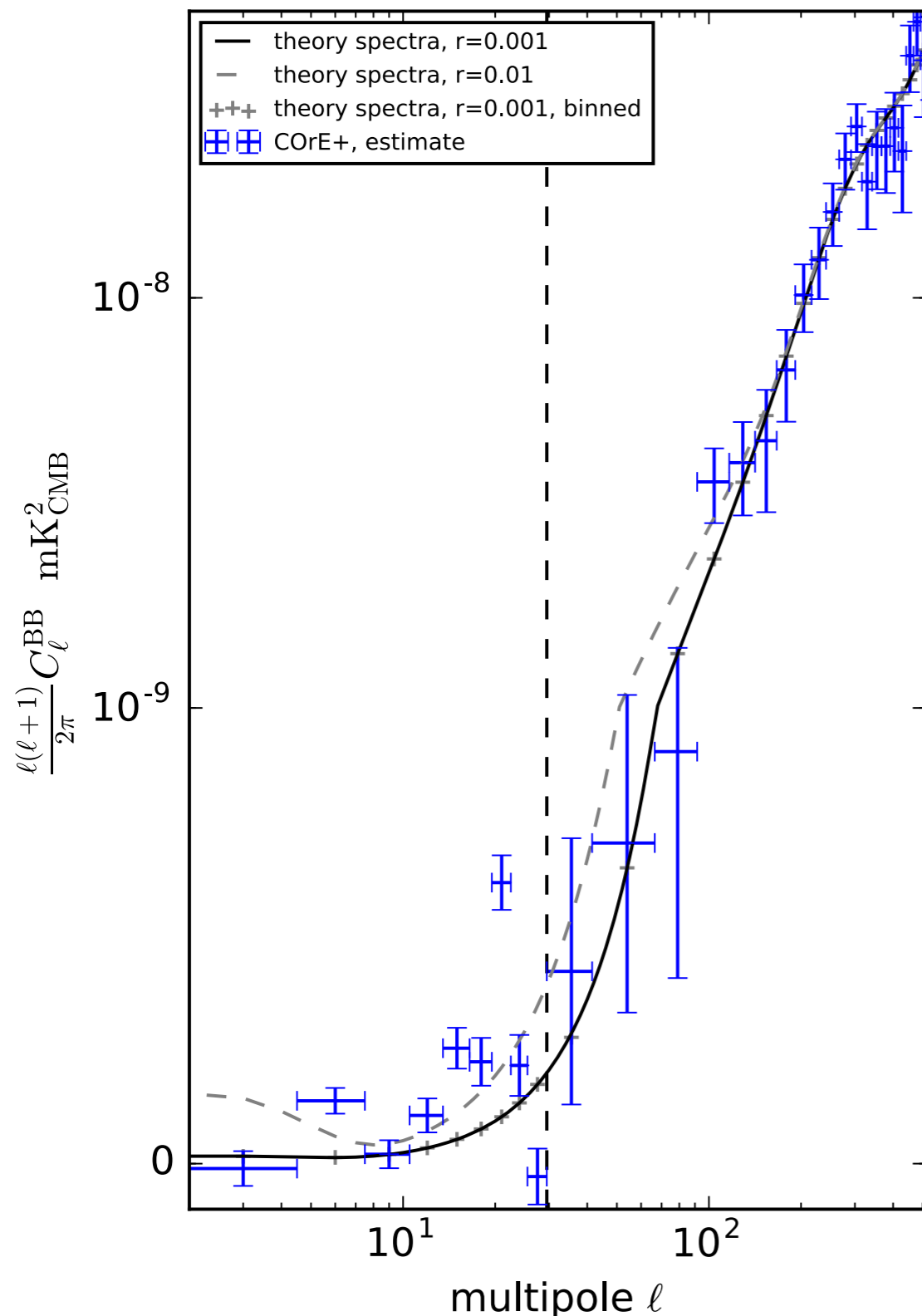
# Latest COrE+ Results: CCA



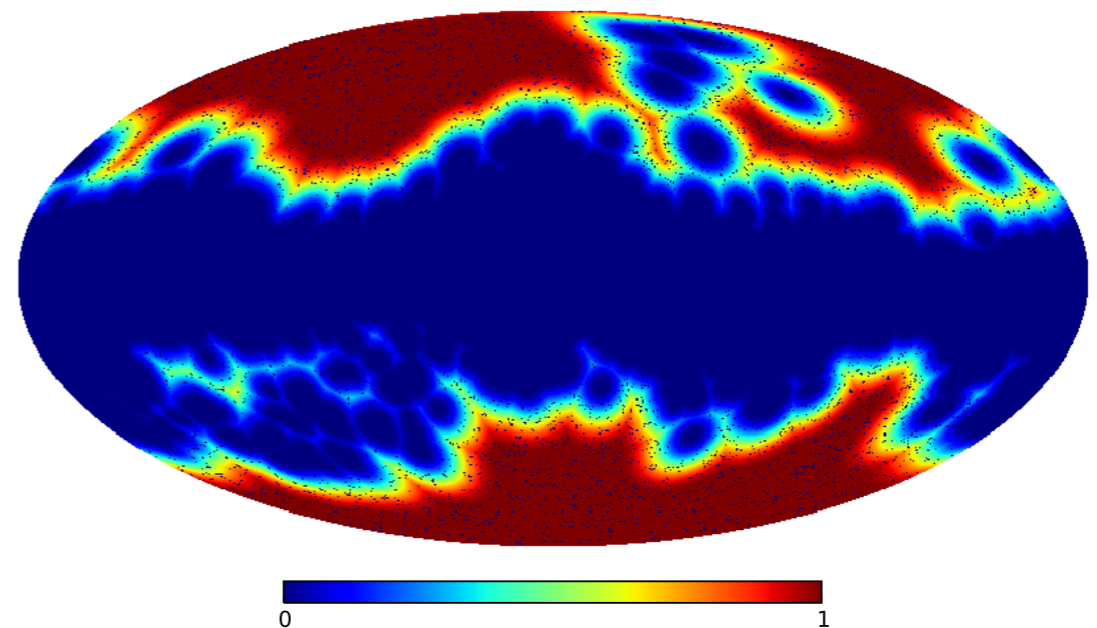
**Latest complex model**, COrE+  
 $r=0.001$ , with several components:  
dust, synchrotron, AME and point  
sources, with varying sp. indices.

- We ignore AME. We mask PSs. Sky patch size of 15 by 15°, and a spacing of 3°.

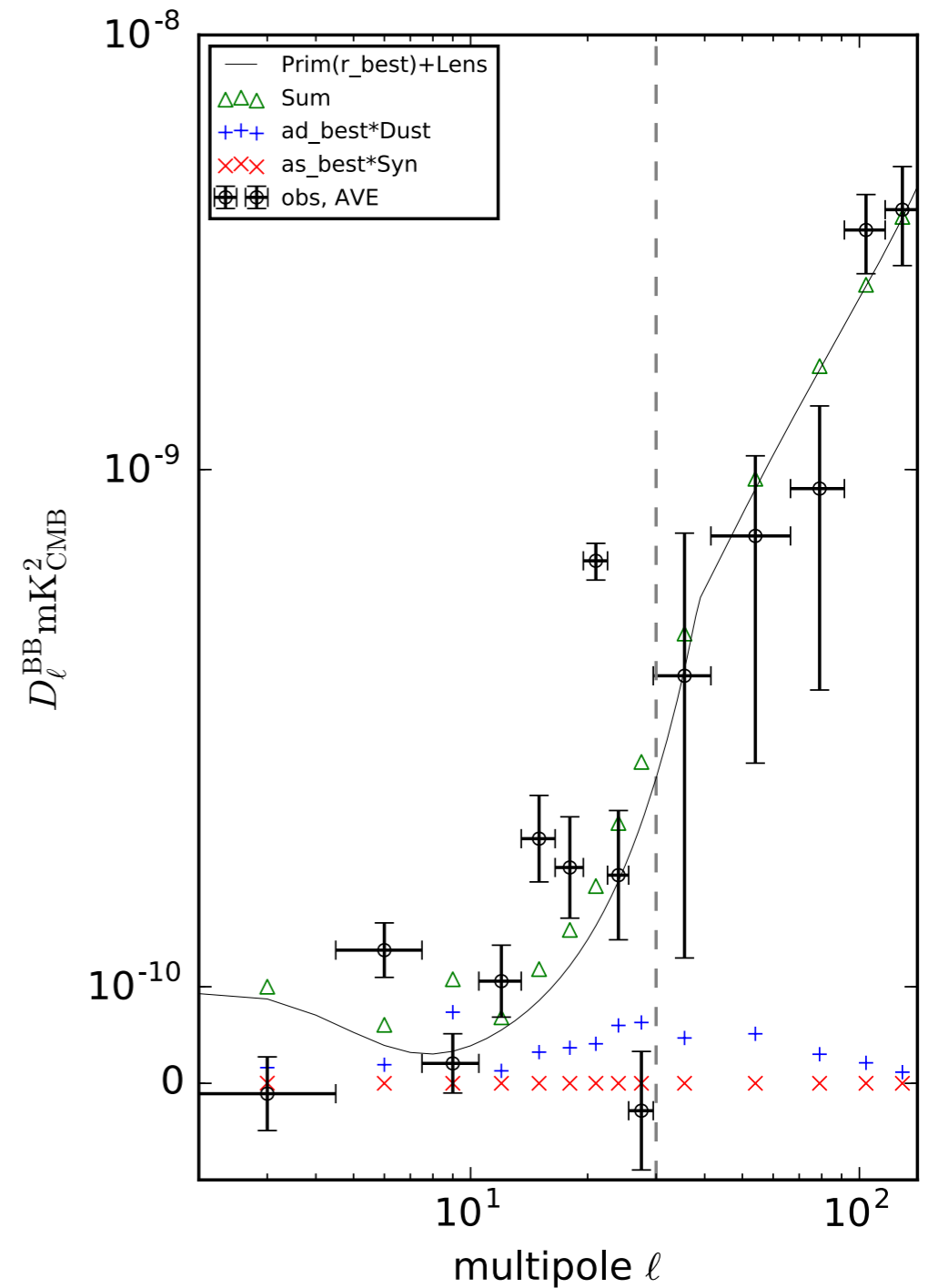
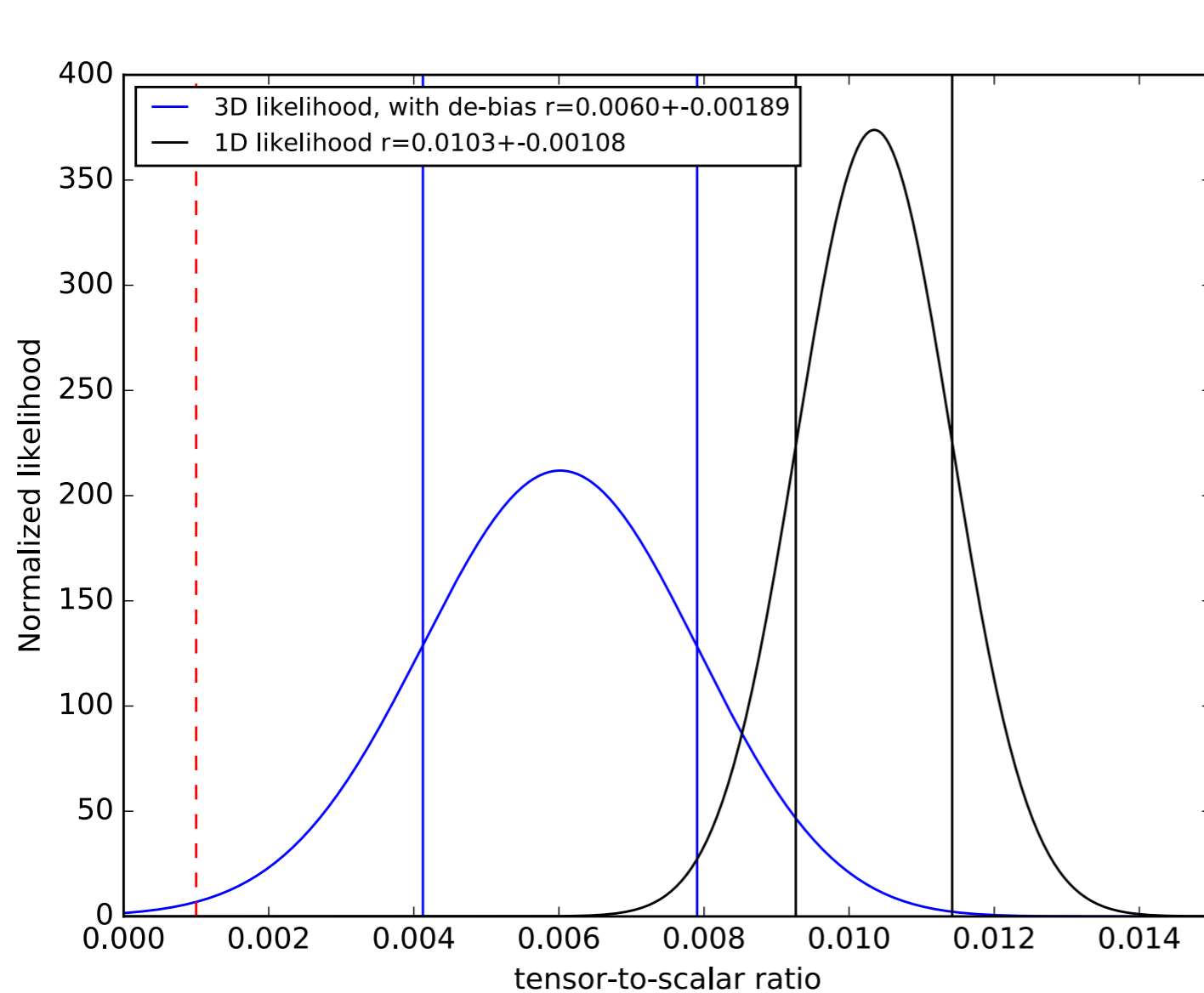
# Latest COrE+ Results: Cl estimate



- **Two thermal dust components:** For the CMB reconstruction. The second with  $(\beta_{\text{dust}}+1)$  instead of  $\beta_{\text{dust}}$ . This is a “Taylor series” to encapsulate the spatial variability (Stolyarov et al. 2005).
- **Limit the range of frequency bands** (60-340 GHz), to reduce the thermal dust residuals.
- **A posteriori masking:** Tailor the mask to the observations (threshold a foregrounds error map). We apodized and aim to mask  $\sim 60\%$  of the sky.



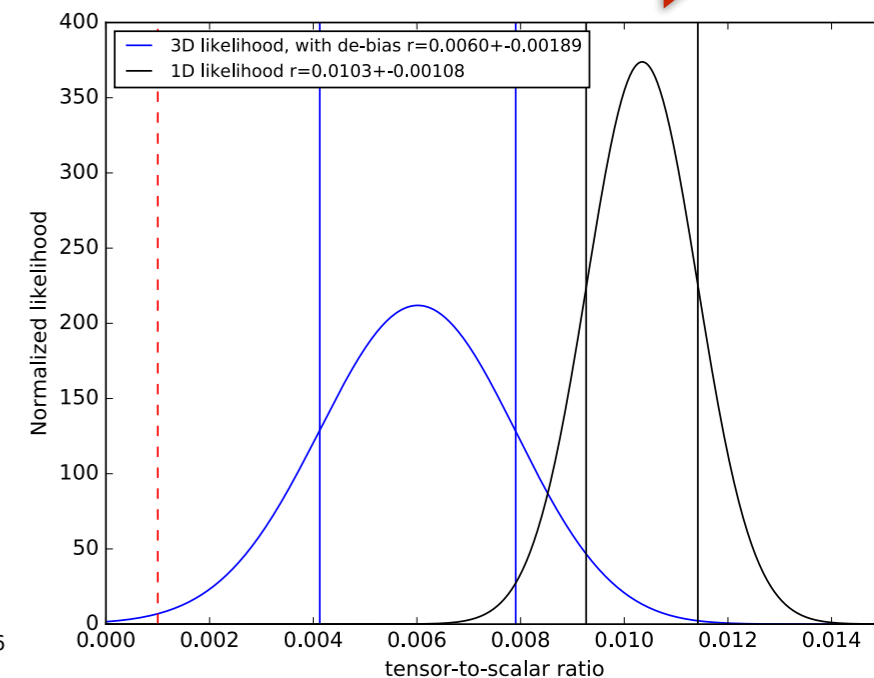
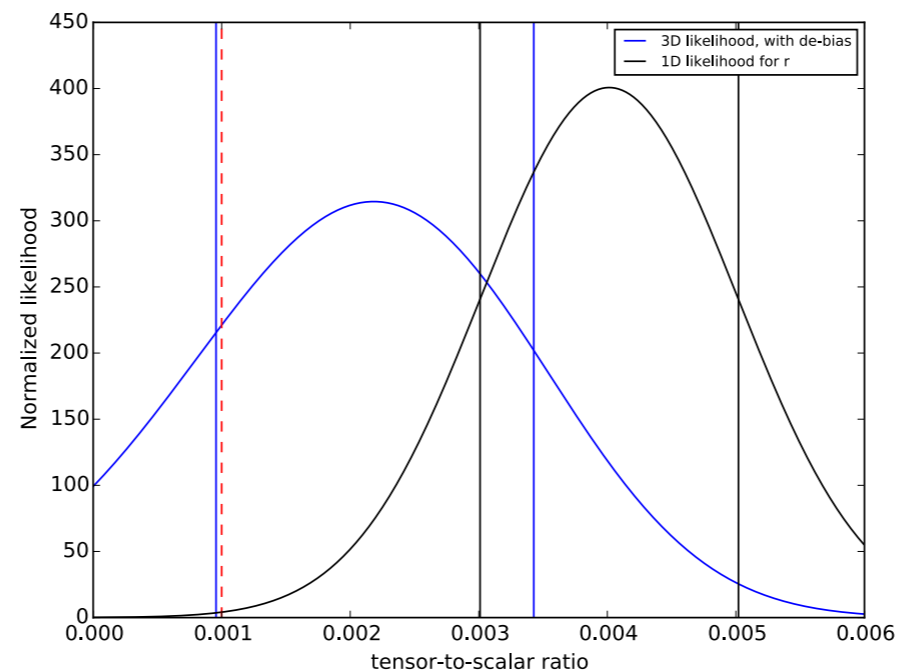
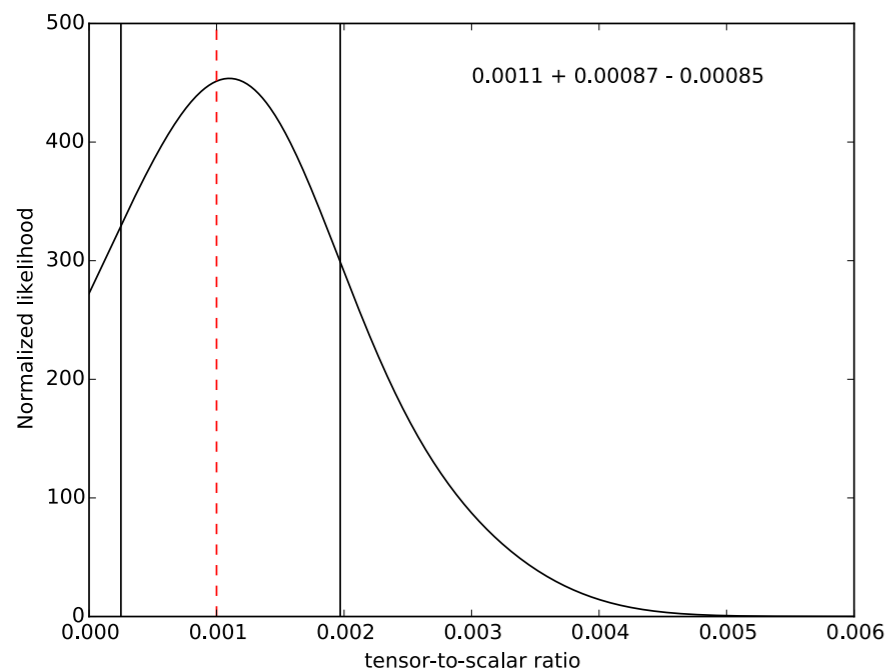
# Latest COrE+ Results: Likelihoods



- Likelihood using first 14 bins ( $\ell_{\text{max}}=141$ ).
- 1D likelihood (just fitting for  $r$ ) gives  $r \sim 0.01$ . Fitting for 2 extra nuisance foregrounds parameters de-bias to  $r \sim 0.006$ , but increases  $\sigma_r$  value.

# Overview of results: Complexity

Increasing complexity of foregrounds



COrE,  $r=0.001$ , 100  
realizations, only  
synchrotron and dust,  
**constant  $\beta_{\text{dust}}$  and  $\beta_{\text{syn}}$ .**

COrE,  $r=0.001$ , 100  
realizations, only  
synchrotron and dust,  
**variable  $\beta_{\text{dust}}$  and  $\beta_{\text{syn}}$ .**

COrE+,  $r=0.001$ ,  
synchrotron, dust, **AME**  
**and PSs. variable  $\beta_{\text{dust}}$**   
**and  $\beta_{\text{syn}}$ .**

Internal simulations for my Phd thesis

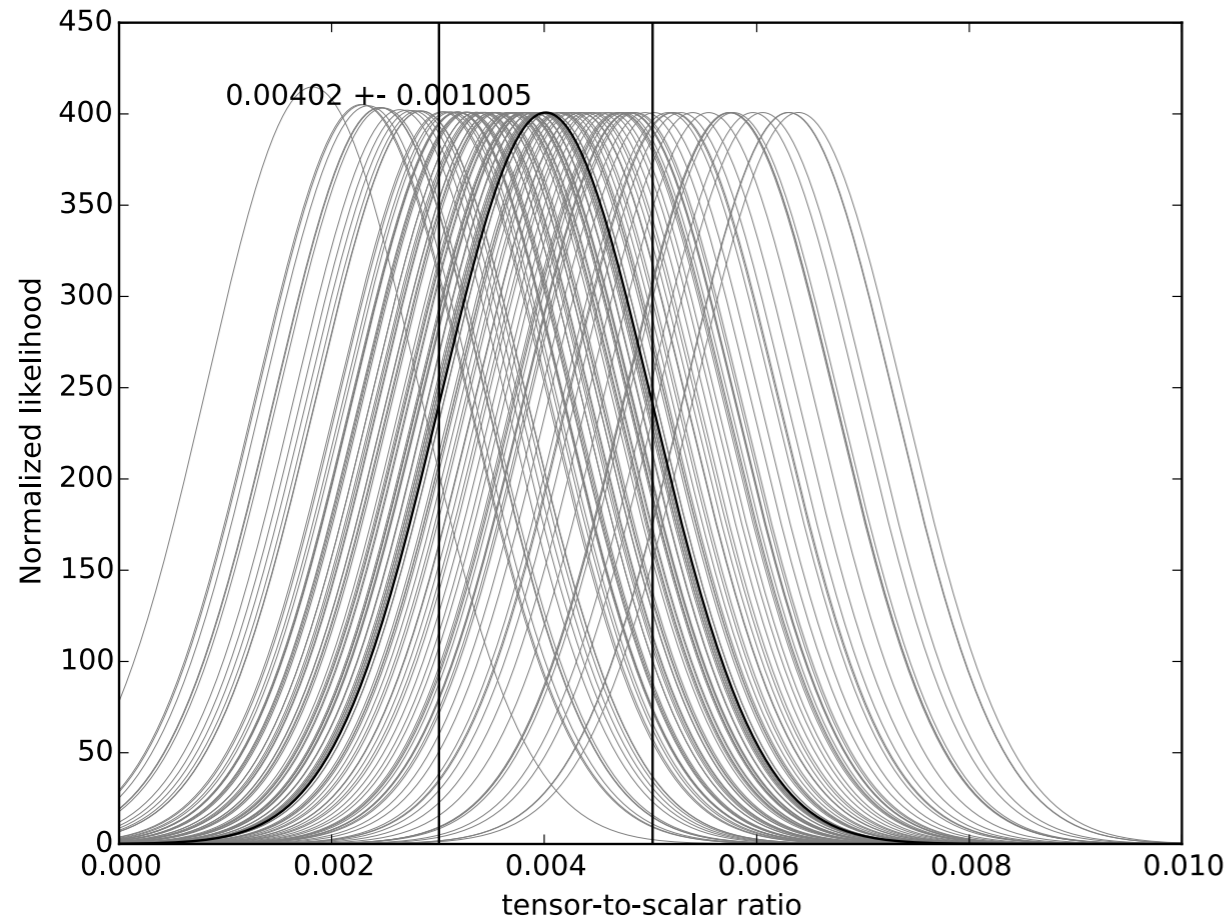
COrE+ simulation

# Summary

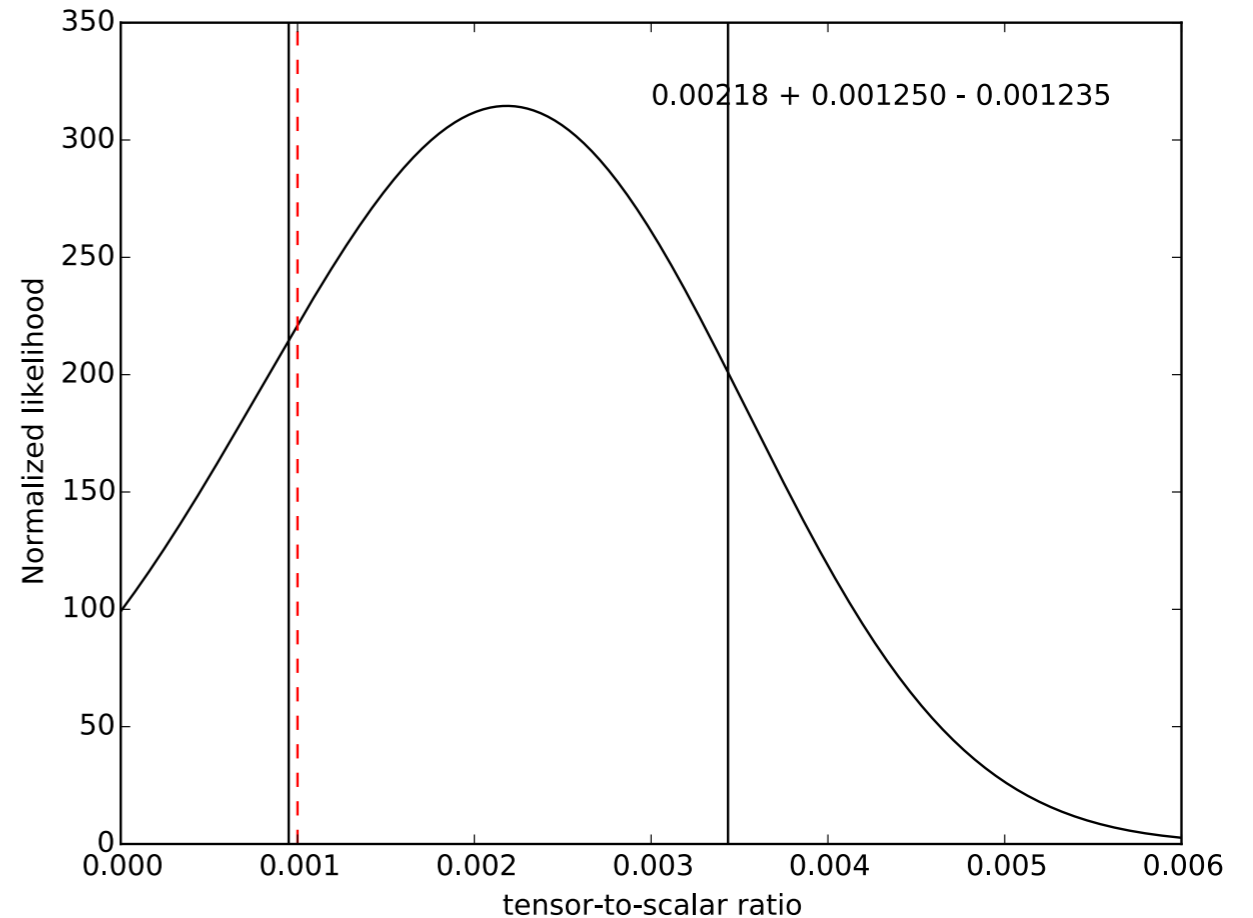
- We have a fully working pipeline, that can take several frequency maps of sky observations and measure a tensor-to-scalar ratio likelihood.
- We have validated our method with our internal simulations.
- We can measure an un-bias  $r$  on simple simulations (i.e. constant spectral indices). For example, de-bias  $r=0.001$  assuming 1% error on  $\beta$ 's.
- The COrE+ complex simulations are challenging. We can improve the spectral params. estimation and QML estimation of the power spectra.
- The complexity of foregrounds affect how much bias ends up in  $r$  likelihood. The modeling of foregrounds residuals in the CMB reconstruction and into the  $r$  likelihood will be necessary.

Thank you !

# COrE Results: our simulations



1D likelihood

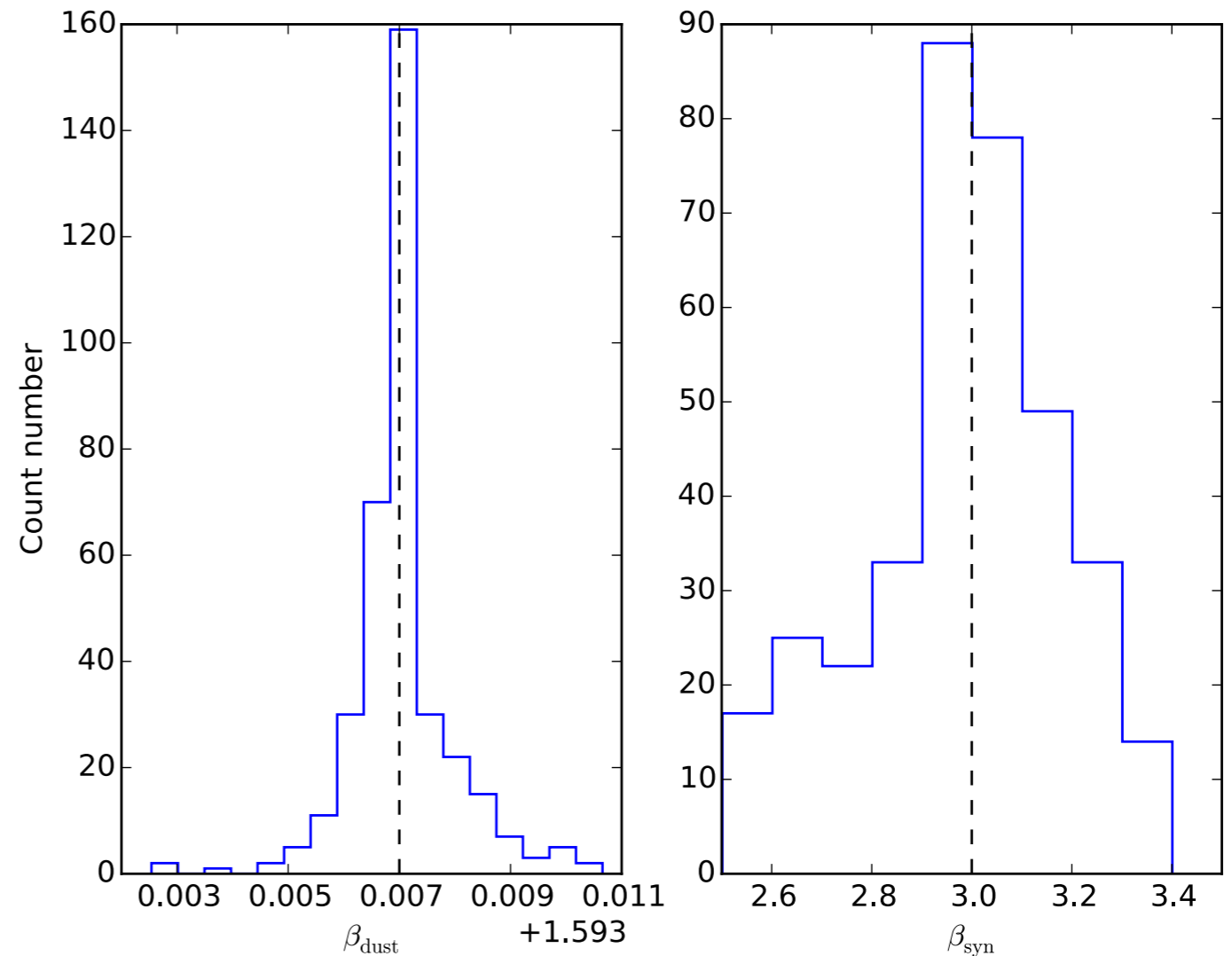


3D likelihood de-biased

$r=0.001$  COrE simulations, with dust and synchrotron, variable sp. indices. 100 realizations. Component sep. assuming constant spectral indices across the sky.

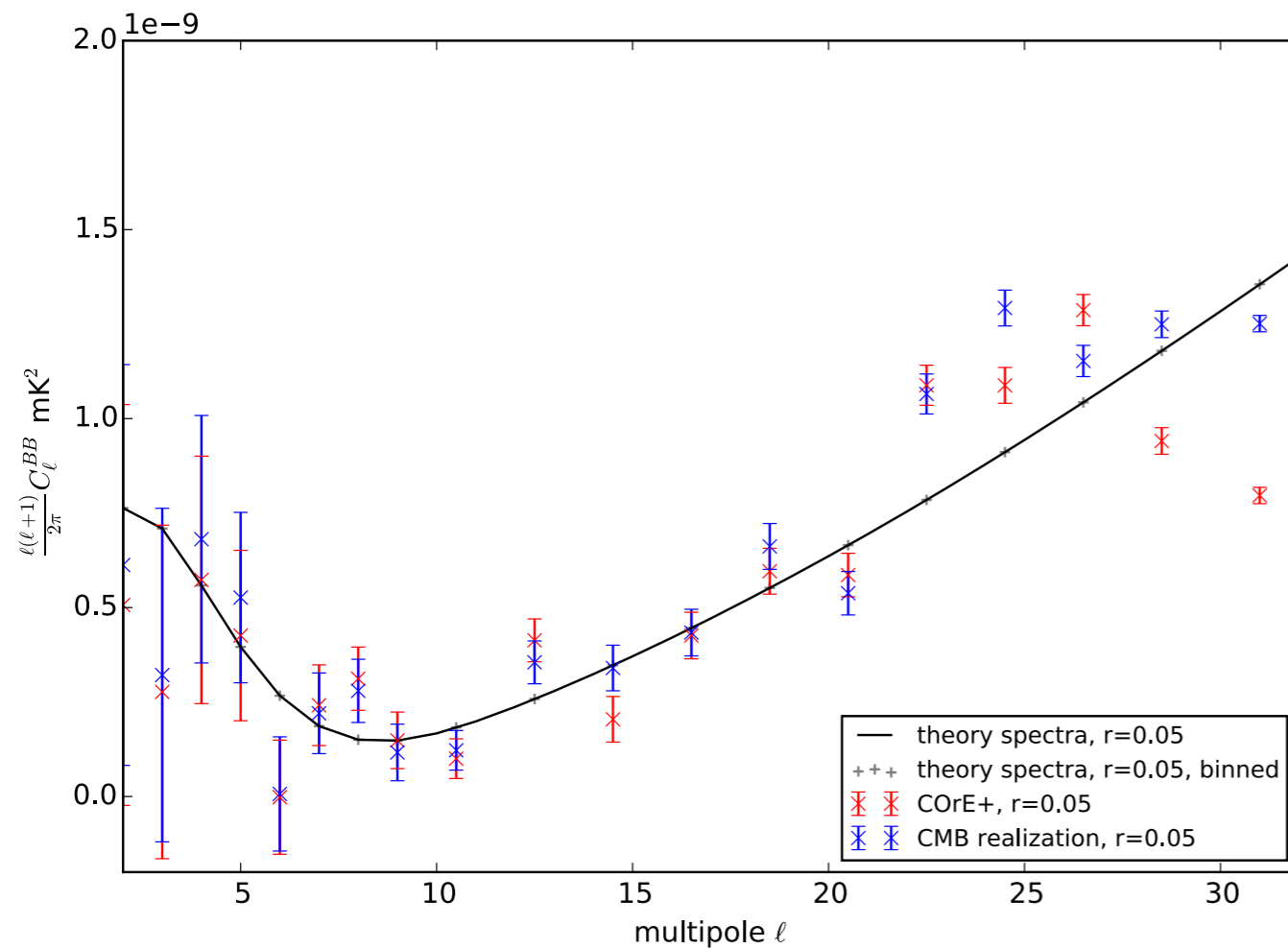
# COrE+ Results: CCA

COrE+ simulation:  
 $r=0.05$ , only dust  
and synchrotron,  
with constant sp.  
indices.



We ran CCA on sky several patches (30 by 30°). Our estimates are unbiased.

# COrE+ Results: likelihoods



**COrE+ simulation with  $r=0.05$ .** We couldn't estimate the high multipole power spectrum because of noise artifacts in the maps. These likelihood are  $\ell_{\text{max}}=30$ .

