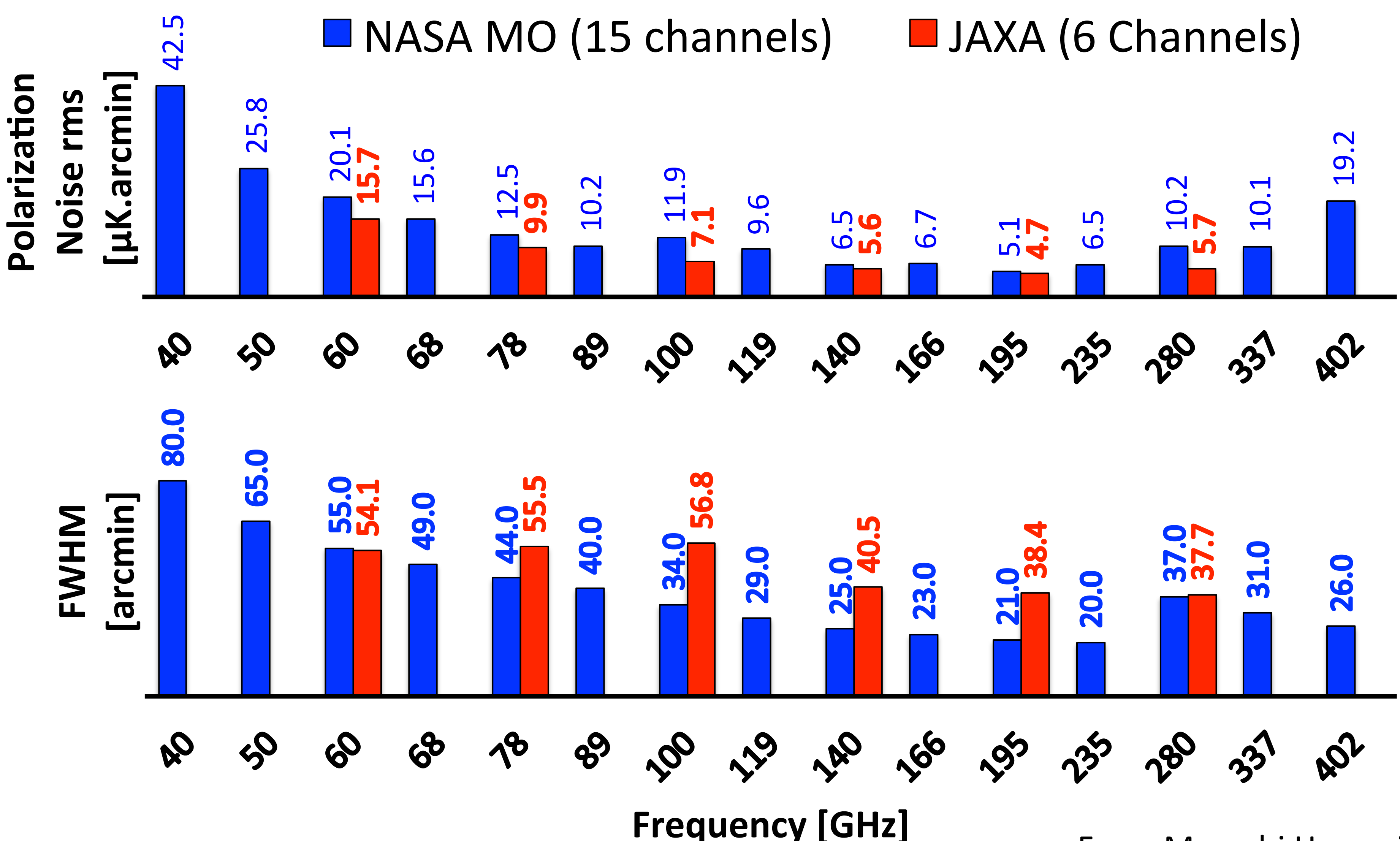
Foreground cleaning for LiteBIRD using NILC

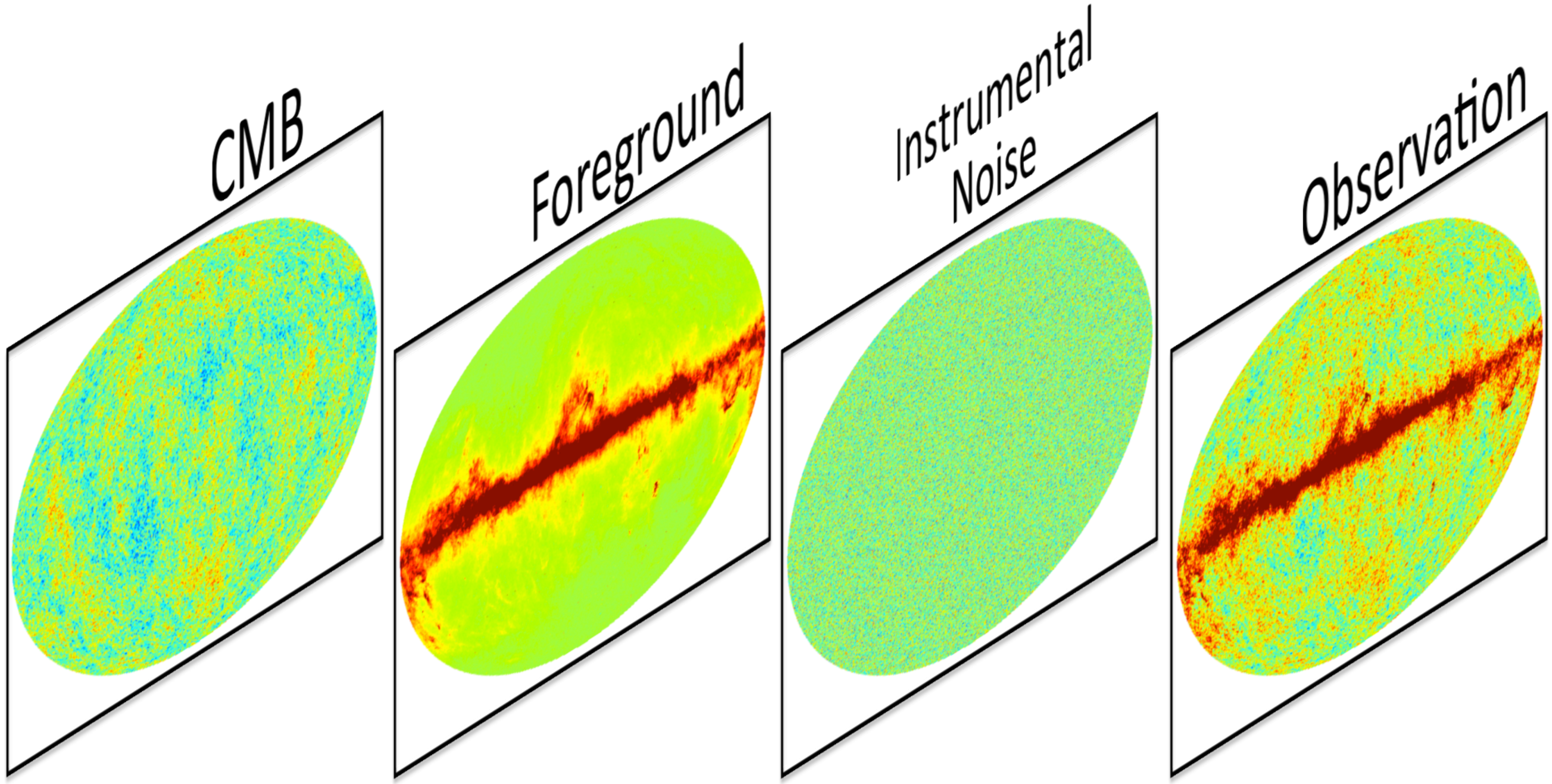
Soumen Basak
SISSA, Trieste, Italy

LiteBIRD configurations



From Masashi Hazumi

Model of the sky



Sky maps contain foreground signals and instrumental noise superimposed on the true CMB.

Internal Linear Combination (ILC)

Assumptions

- **CMB is frequency independent while contaminants are not.**
- **CMB is uncorrelated to contaminants (foregrounds and noise)**

Model

$$\mathrm{X_c = a_c\, S + \left(F + N\right)_c \quad c = 1, 2, \ldots, n_c} \quad \ni a_c = 1 \ \forall \ c$$

Estimate

$$\mathrm{\widehat{S} = \sum_{c=1}^{n_c} W_c X_c \qquad \sum_{c=1}^{n_c} W_c a_c = 1}$$

$$\mathrm{Var\left[\widehat{S}\right] = \sum_{c=1}^{n_c} \sum_{c'=1}^{n_c} W_c R_{cc'} W_{c'} \qquad R_{cc'} = Cov[X_c X_{c'}]}$$

Weight

$$\mathrm{\min_{w.r.t\ \ W_c} \left\{ Var\left[\widehat{S}\right] \right\} \xrightarrow{\sum_{c=1}^{n_c} W_c a_c = 1} \widehat{W}_c = \frac{\sum_{c'=1}^{n_c} \widehat{R}^{-1}_{cc'} a_{c'}}{\sum_{c=1}^{n_c} \sum_{c'=1}^{n_c} a_c \widehat{R}^{-1}_{cc'} a_{c'}}}$$

Solution

$$\mathrm{\widehat{S} = S + \sum_{c=1}^{n_c} \widehat{W}_c F_c + \sum_{c=1}^{n_c} \widehat{W}_c N_c}$$

Needlets

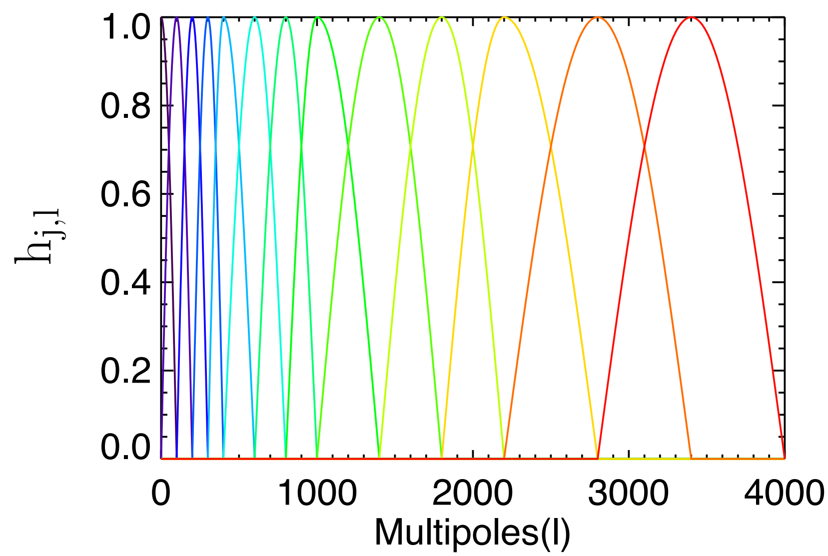
$$\Psi_{j,k}(\widehat{n}) = \sqrt{\lambda_{jk}} \sum_{l=l_{min}}^{l=l_{max}} h_{j,l} \sum_{m=-l}^{l} Y^*_{lm}(\widehat{n}) Y_{lm}(\widehat{\xi}_{jk})$$

$$j = 1, 2, \ldots, n_j \quad k = 0, 1, \ldots, n^j_{pix} - 1$$

$$\widehat{n} \equiv (\theta, \phi) \quad \theta \in [0, \pi] \quad \phi \in [0, 2\pi)$$

$$\lambda_{jk} = \frac{4\pi}{n^j_{pix}} \quad \xi_{jk} \equiv \text{HEALPix Grid Points}$$

$$h_{j,l} > 0 \quad \forall\, l \in \left[l^j_{min}, l^j_{max}\right] \quad \sum_j h^2_{j,l} = 1$$



$$h_{j,l} = \begin{cases} \cos\left[\left(\frac{l^j_{peak}-l}{l^j_{peak}-l^j_{min}}\right)\frac{\pi}{2}\right] & \textbf{for } l^j_{min} \leqslant l < l^j_{peak}, \\ 1 & \textbf{for } l = l_{peak}, \\ \cos\left[\left(\frac{l-l^j_{peak}}{l^j_{max}-l^j_{peak}}\right)\frac{\pi}{2}\right] & \textbf{for } l^j_{peak} < l \leqslant l^j_{max} \end{cases}$$

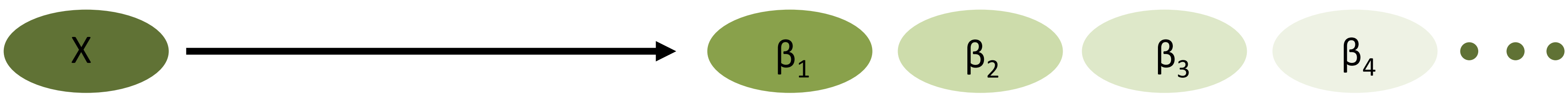
The use of spherical needlets makes possible localized filtering both in pixel space and harmonic space, so that the ILC weights are adjusted as a function of location on the sky and of angular scale.

Needlet transforms on sphere

Needlet analysis:

– Gives the needlet coefficients from spin-zero square-integrable function on sphere

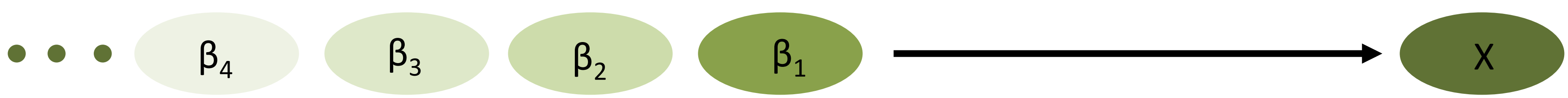
$$\beta_{j,k} = \int_{S^2} X(\hat{n})\, \Psi_{j,k} d\Omega_{\hat{n}} = \sum_{l} h_{j,l} \sum_{m=-l}^{l} X_{lm} Y_{lm}(\hat{\xi}_{jk})$$



Needlet synthesis:

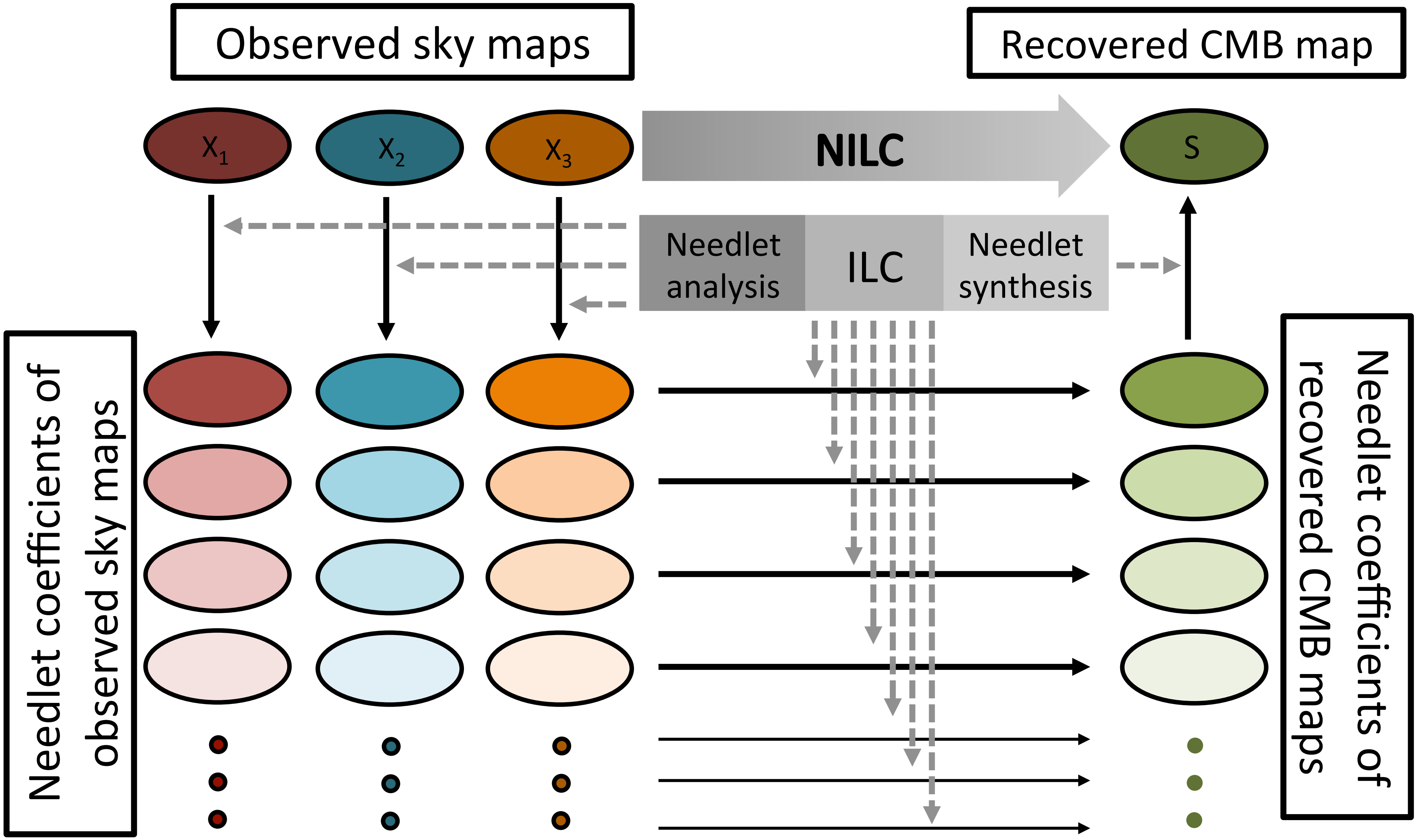
– Gives back original spin-zero square-integrable function from needlet coefficients

$$X(\hat{n}) = \sum_{j,k} \beta_{j,k}\, \Psi_{j,k}(\hat{n}) = \sum_{l} \left(\sum_{j} h_{j,l}^2 \right) \sum_{m=-l}^{l} X_{lm} Y_{lm}(\hat{n})$$



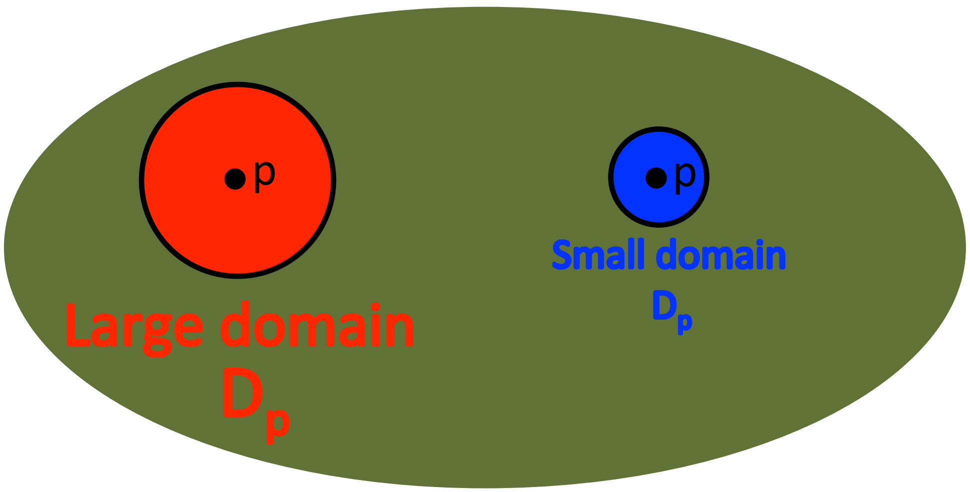
– Condition for perfect reconstruction: $\sum_{j} h_{j,l}^2 = 1$

Needlet ILC



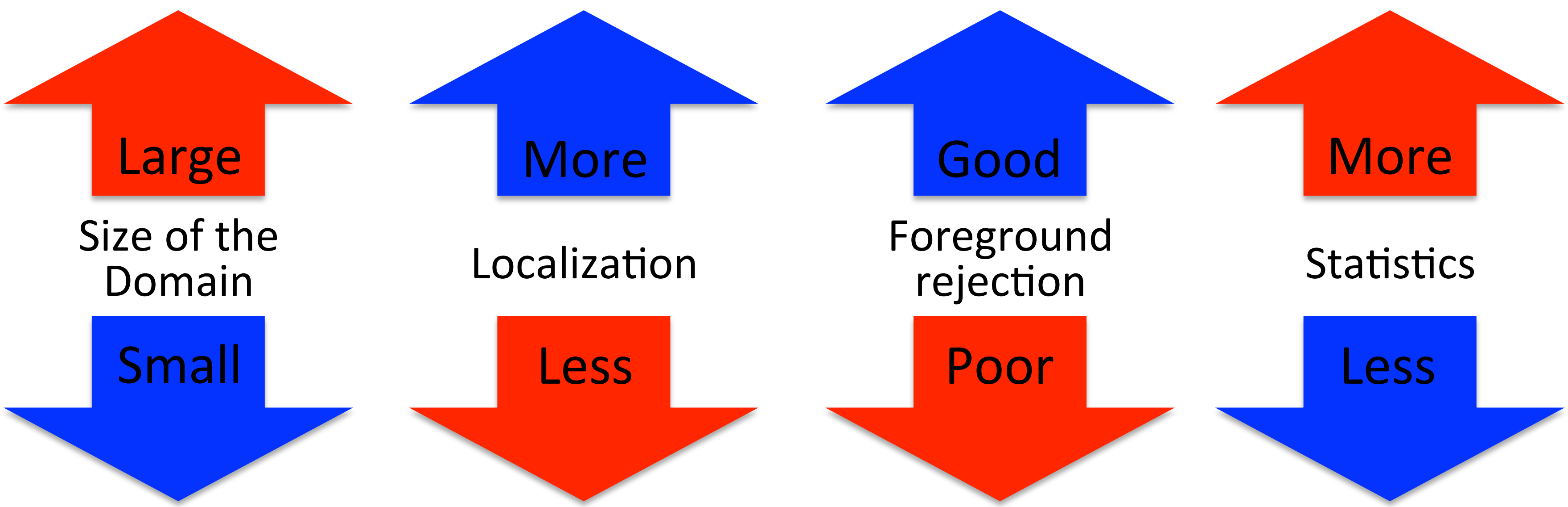
Basak & Delabrouille 2102, 2013

Estimation of Covariance Matrix



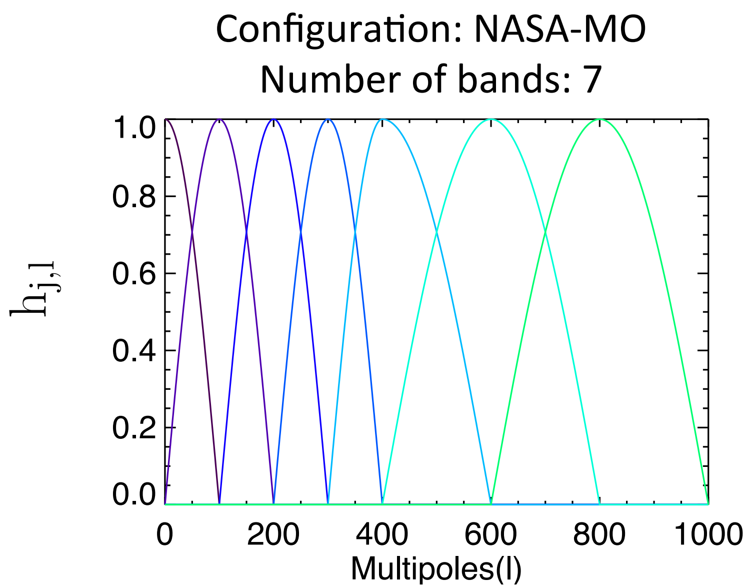
Covariance matrix has been estimated over patches, instead over full sky

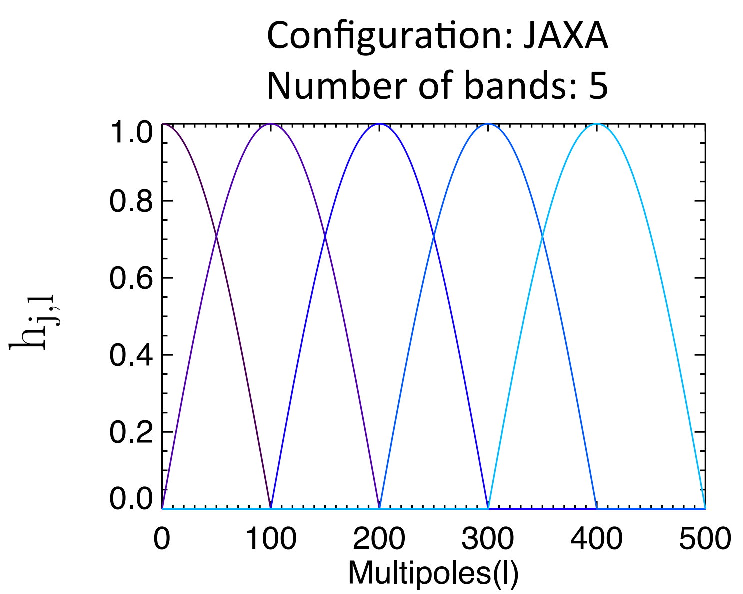
$$\widehat{R}_{cc'}(p) = \frac{1}{n_p} \sum_{k \in D_p} X_c(k) X_{c'}(k)$$



Basak & Delabrouille 2102, 2013

Needlet bands for LiteBIRD



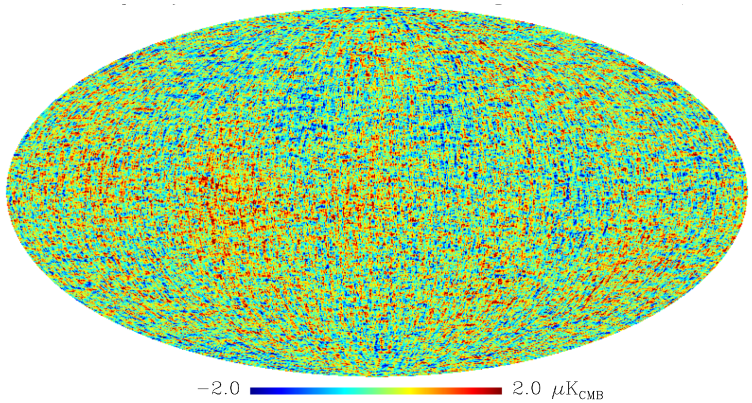


$$
\mathrm{h}_{\mathrm{j,l}} = \begin{cases} \cos\left[\left(\frac{l^j_{peak}-l}{l^j_{peak}-l^j_{min}}\right)\frac{\pi}{2}\right] & \textbf{for } l^j_{min} \leqslant l < l^j_{peak}, \\ 1 & \textbf{for } l = l_{peak}, \\ \cos\left[\left(\frac{l-l^j_{peak}}{l^j_{max}-l^j_{peak}}\right)\frac{\pi}{2}\right] & \textbf{for } l^j_{peak} < l \leqslant l^j_{max} \end{cases}
$$

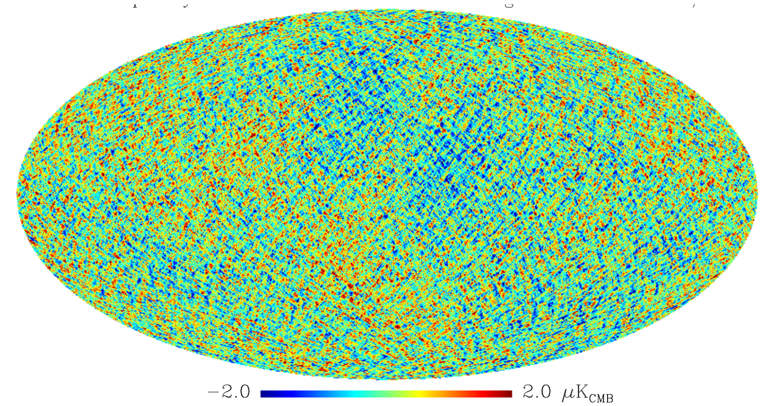
Band	l_{min}		l_{peak}		l_{max}		nside	
	NASA MO	JAXA	NASA MO	JAXA	NASA MO	JAXA	NASA MO	JAXA
1	0	0	0	0	100	100	64	64
2	0	0	100	100	200	200	128	128
3	100	100	200	200	300	300	256	256
4	200	200	300	300	400	400	256	256
5	300	300	400	400	600	500	512	256
6	400		600		800		512	
7	600		800		1000		512	

LiteBIRD Simulation: Gaussian CMB maps
(publicly available version of PSM, Delabrouille et al. 2013)

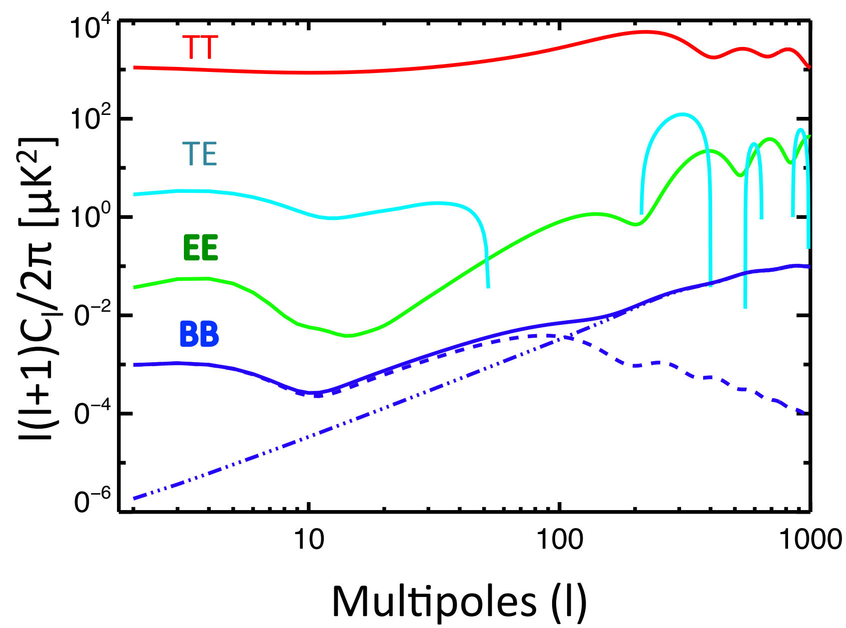
Field: Q Frequency: 140 GHz FWHM: 40.5 arcmin
Configuration: JAXA T/S: 0.05



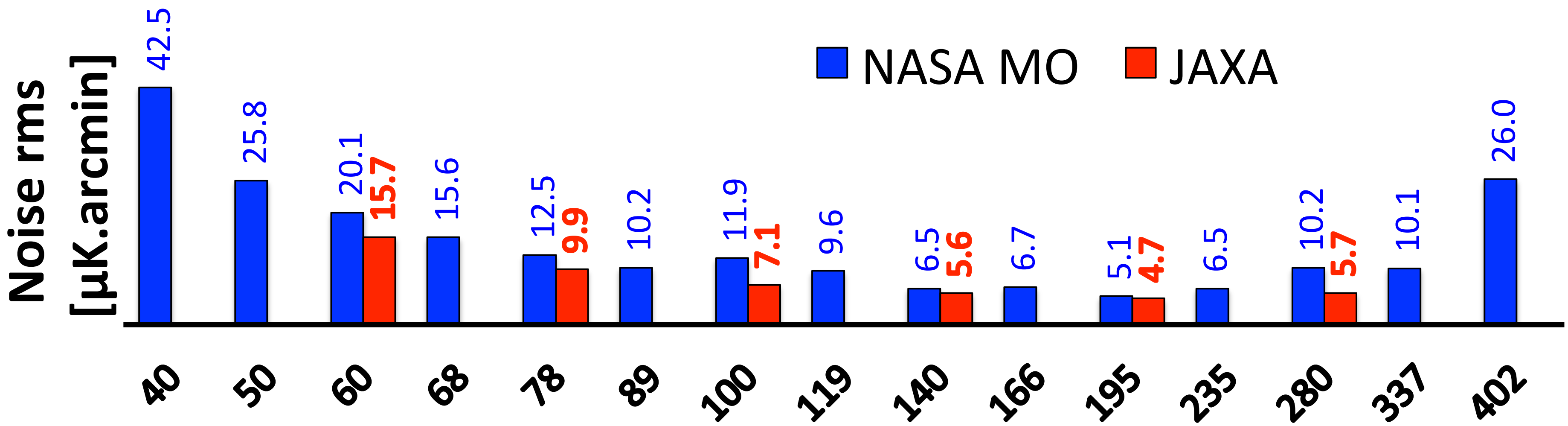
Field: U Frequency: 140 GHz FWHM: 40.5 arcmin
Configuration: JAXA T/S: 0.05



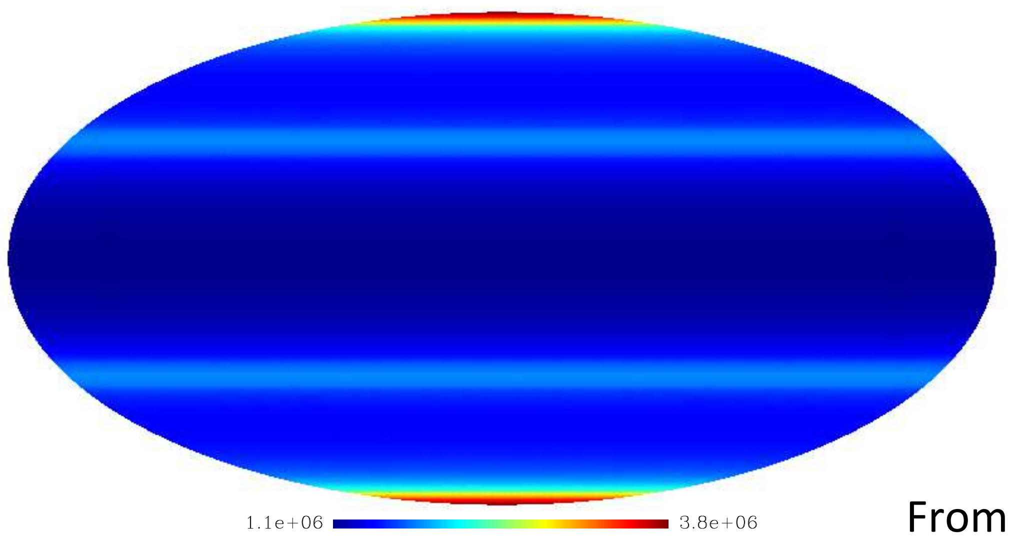
Cosmological parameters	
$\Omega_b h^2$	**0.02230**
$\Omega_c h^2$	**0.1188**
θ_{MC}	**1.04093**
τ	**0.066**
$\ln(10^{10} A_s)$	**3.064**
n_s	**0.9667**
r	**0.05**



LiteBIRD Simulation: Inhomogeneous Gaussian noise maps (publicly available version of PSM, Delabrouille et al. 2013)

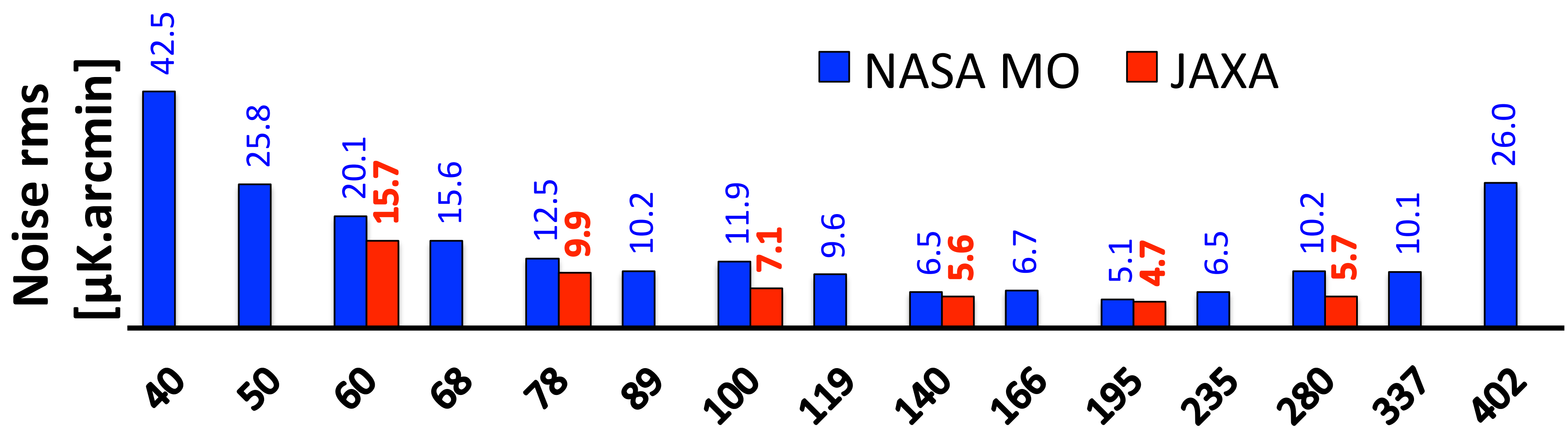


N_{OBS} map

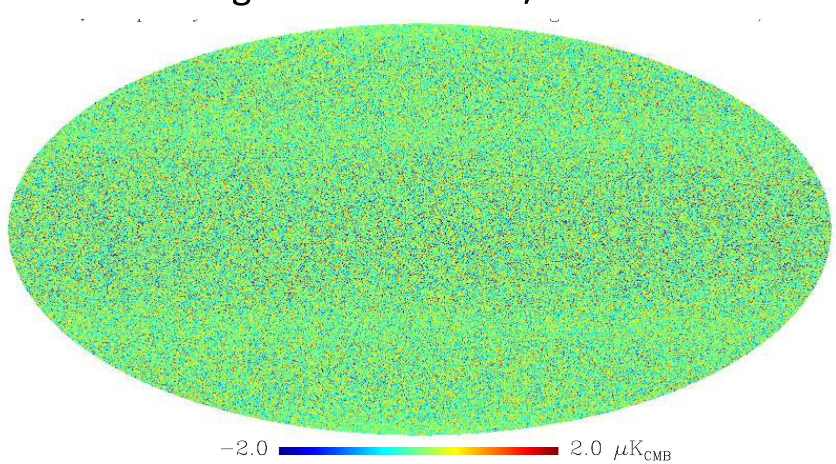


From Tomotake Matsumura

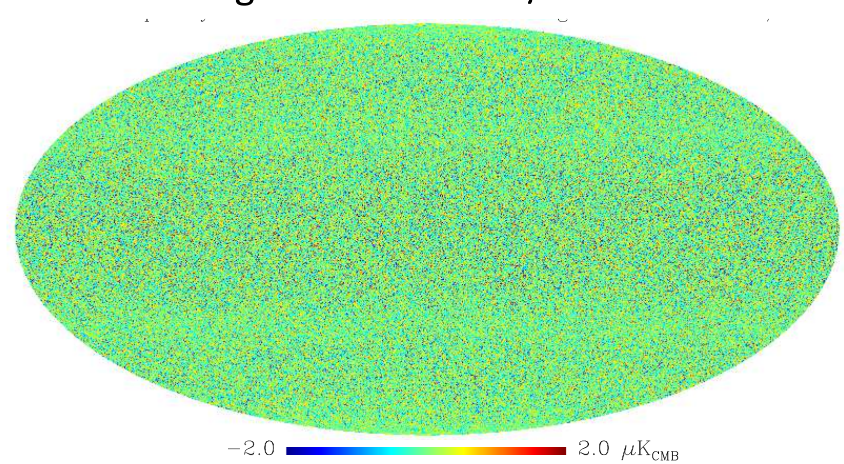
LiteBIRD Simulation: Inhomogeneous Gaussian noise maps (publicly available version of PSM, Delabrouille et al. 2013)



Field: Q Frequency: 140 GHz FWHM: 40.5 arcmin
Configuration: JAXA T/S: 0.05



Field: U Frequency: 140 GHz FWHM: 40.5 arcmin
Configuration: JAXA T/S: 0.05

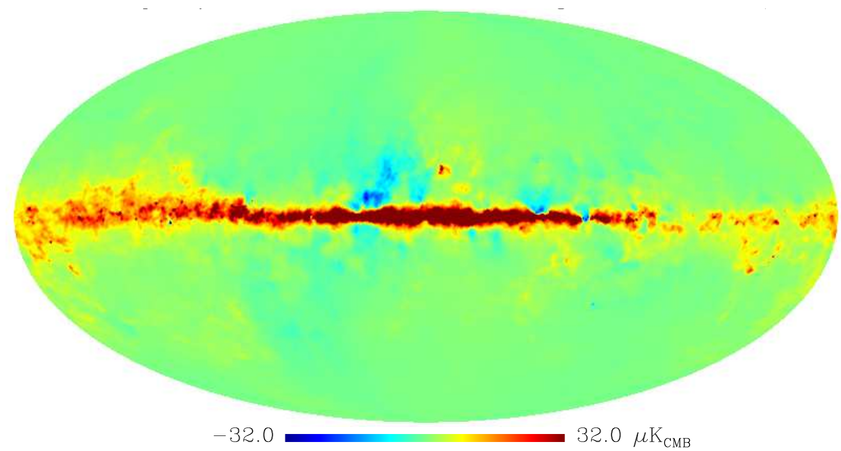


LiteBIRD Simulation: Foreground maps (publicly available version PSM)

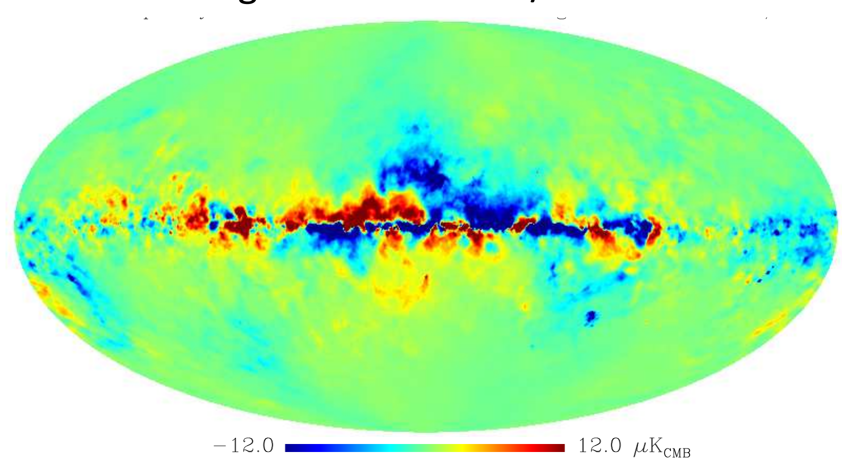
Polarized foreground components:

- Synchrotron
- Thermal dust
- Point sources

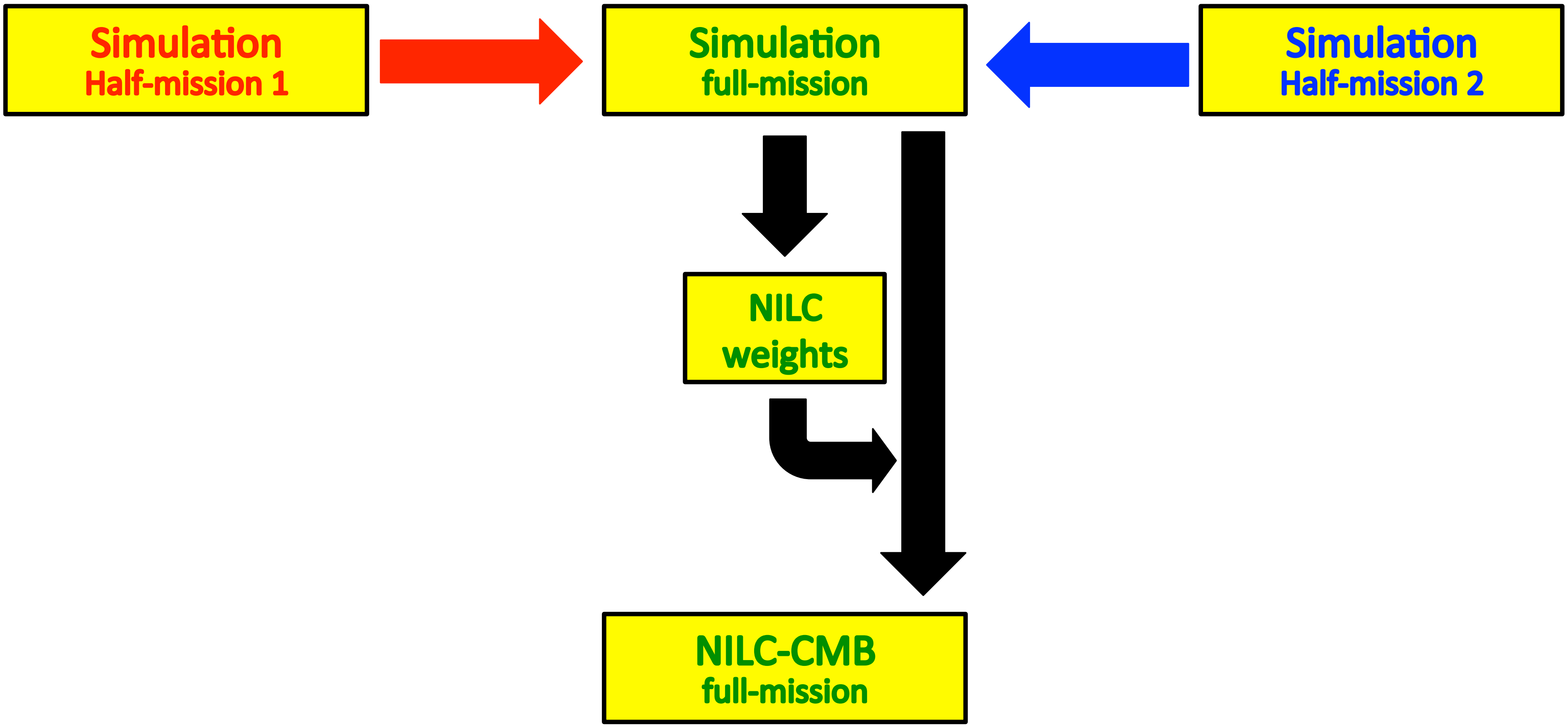
Field: Q Frequency: 140 GHz FWHM: 40.5 arcmin
Configuration: JAXA T/S: 0.05



Field: U Frequency: 140 GHz FWHM: 40.5 arcmin
Configuration: JAXA T/S: 0.05

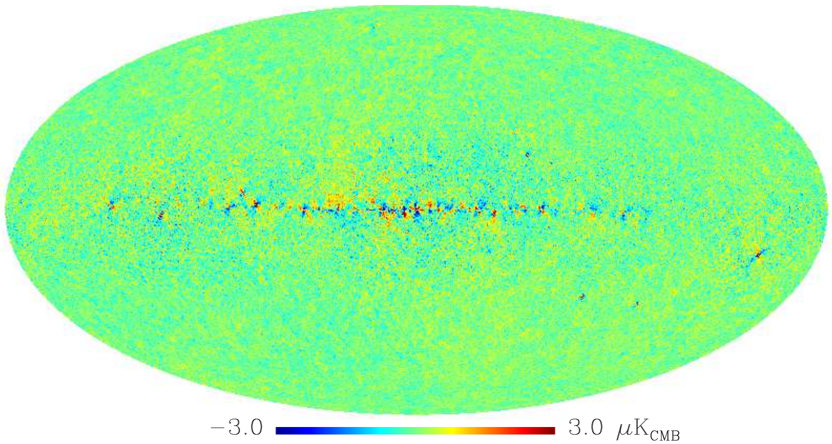


Estimation of CMB map

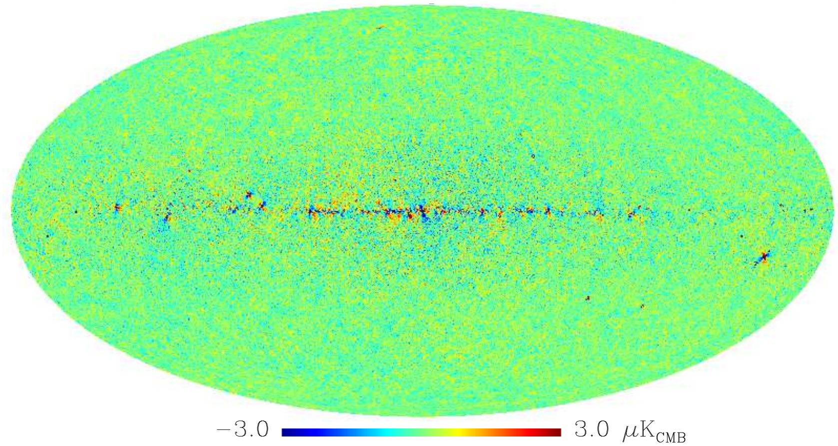


LiteBIRD CMB maps

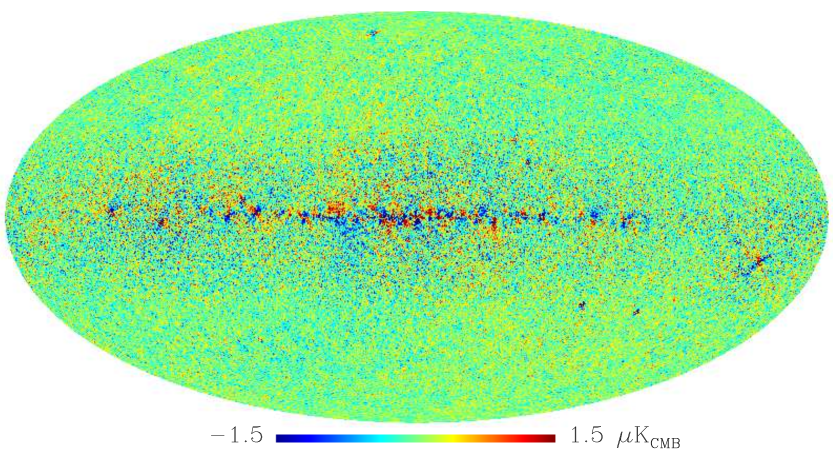
NILCCMB
Field: B FWHM: 37.7 arcmin
Configuration: JAXA T/S: 0.05



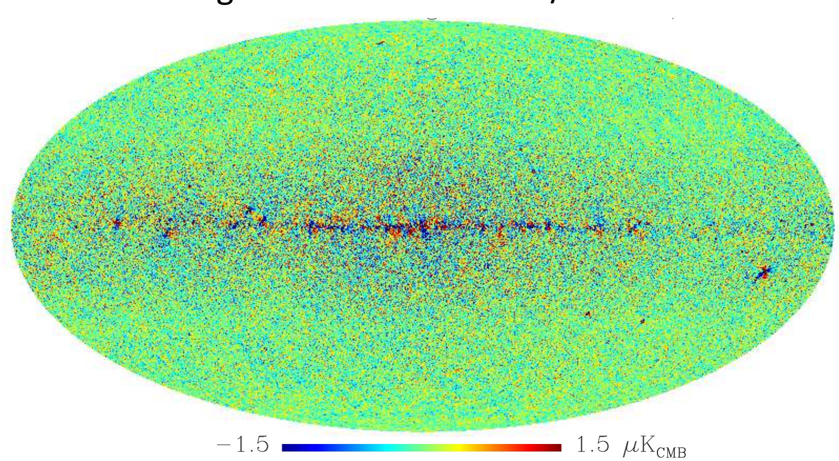
NILC CMB
Field: B FWHM: 26 arcmin
Configuration: NASA-MO T/S: 0.05



(NILC-INPUT) CMB
Field: B FWHM: 37.7 arcmin
Configuration: JAXA T/S: 0.05

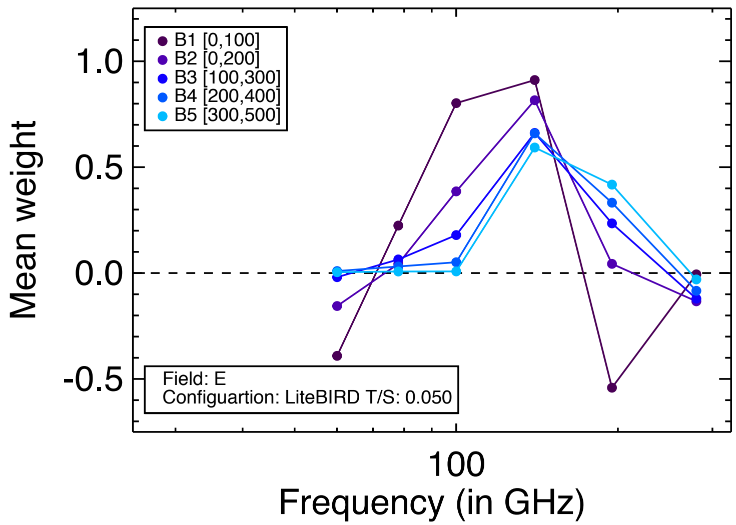


(NILC-INPUT) CMB
Field: B FWHM: 26 arcmin
Configuration: NASA-MO T/S: 0.05

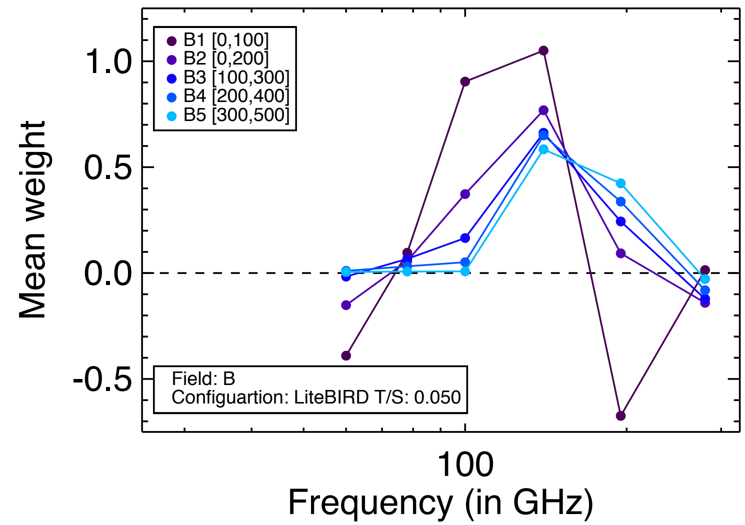


Needlet ILC weights

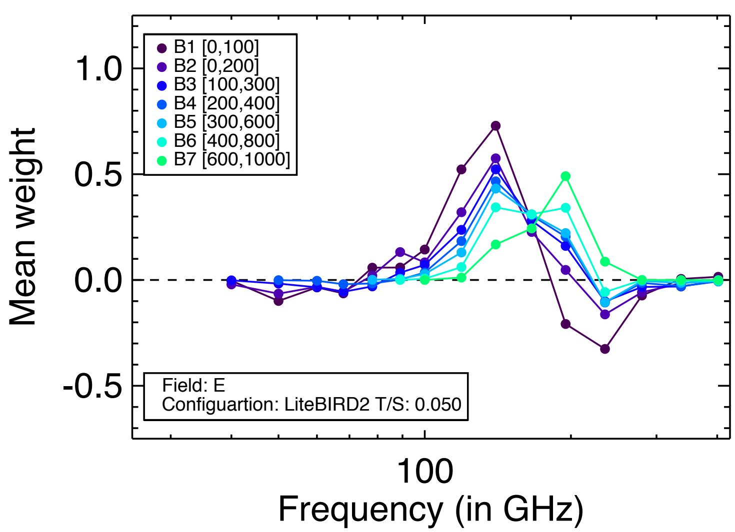
Field: E Configuration: JAXA T/S: 0.05



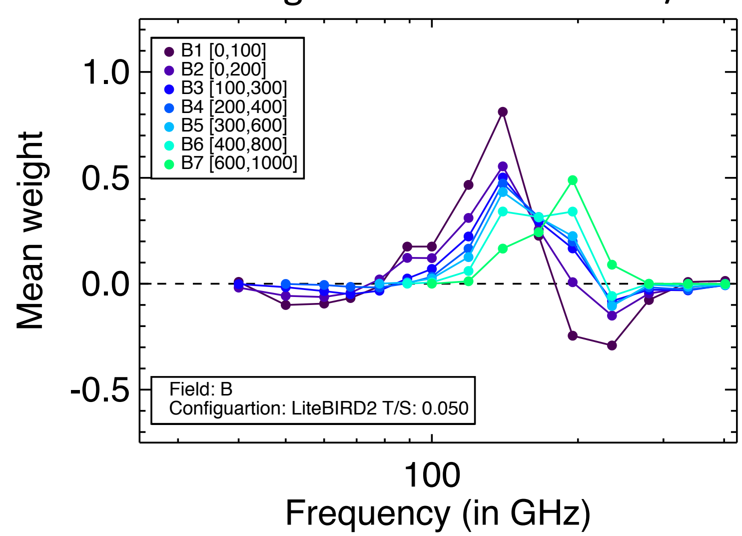
Field: B Configuration: JAXA T/S: 0.05



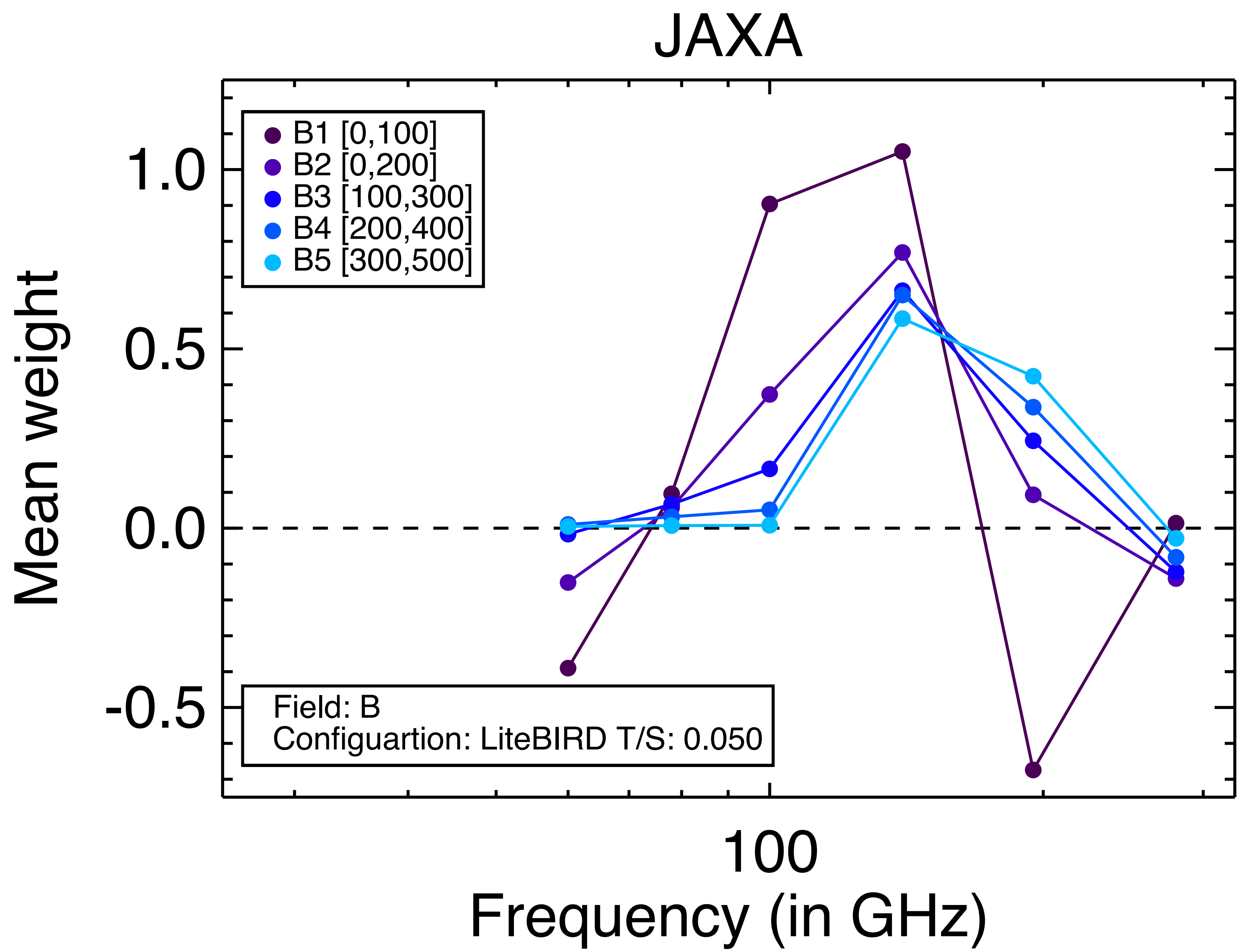
Field: E Configuration: NASA-MO T/S: 0.05



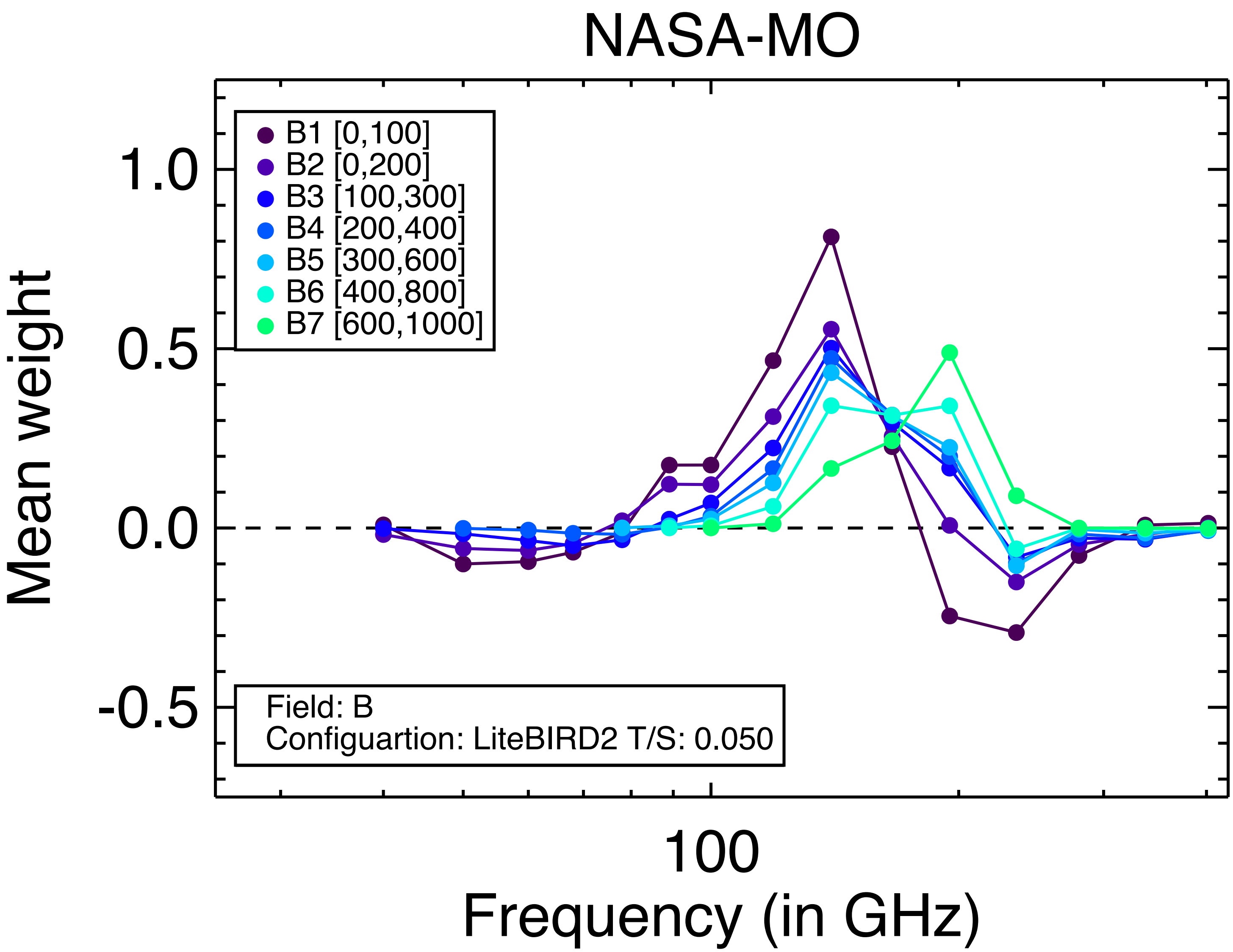
Field: B Configuration: NASA-MO T/S: 0.05



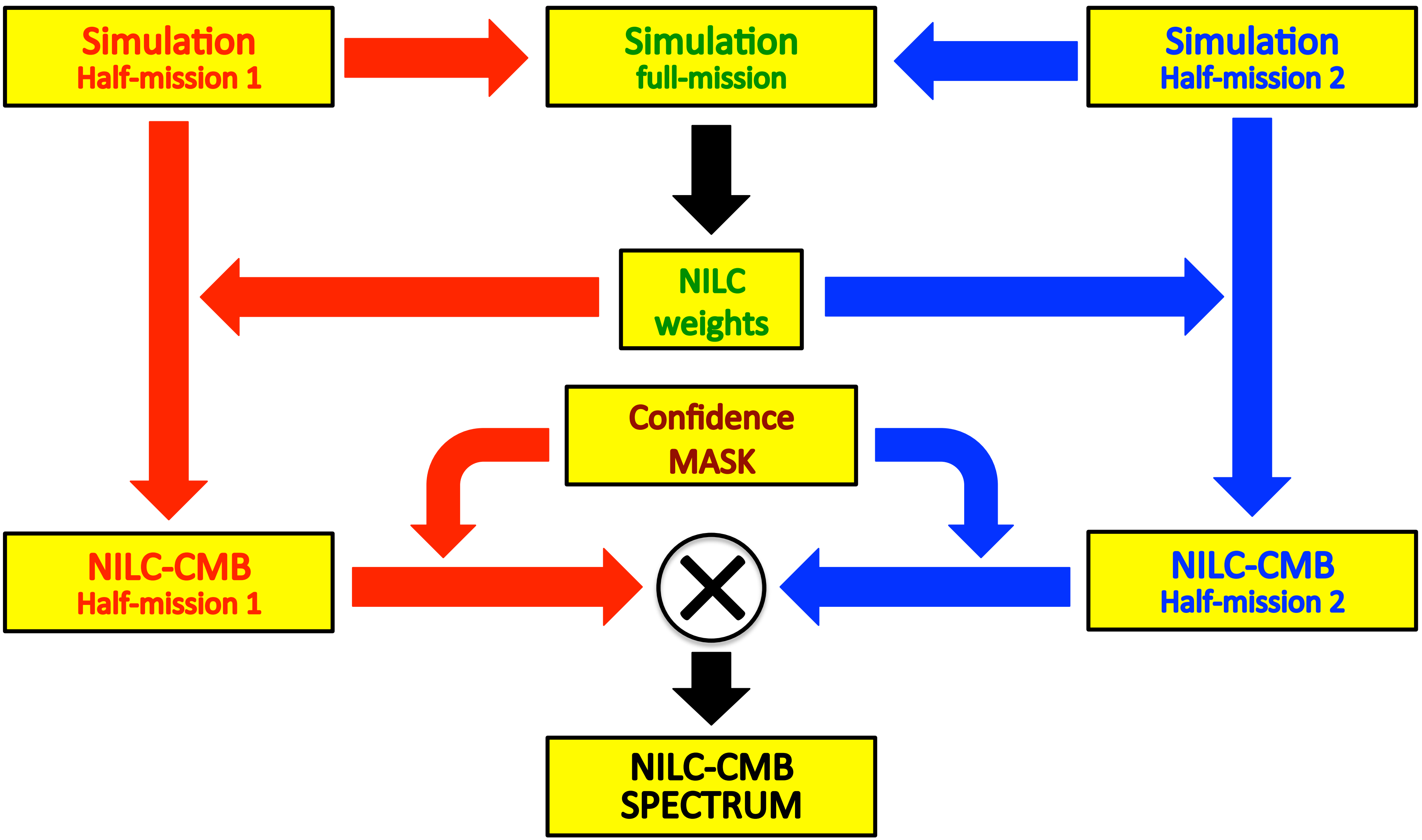
Needlet ILC weights



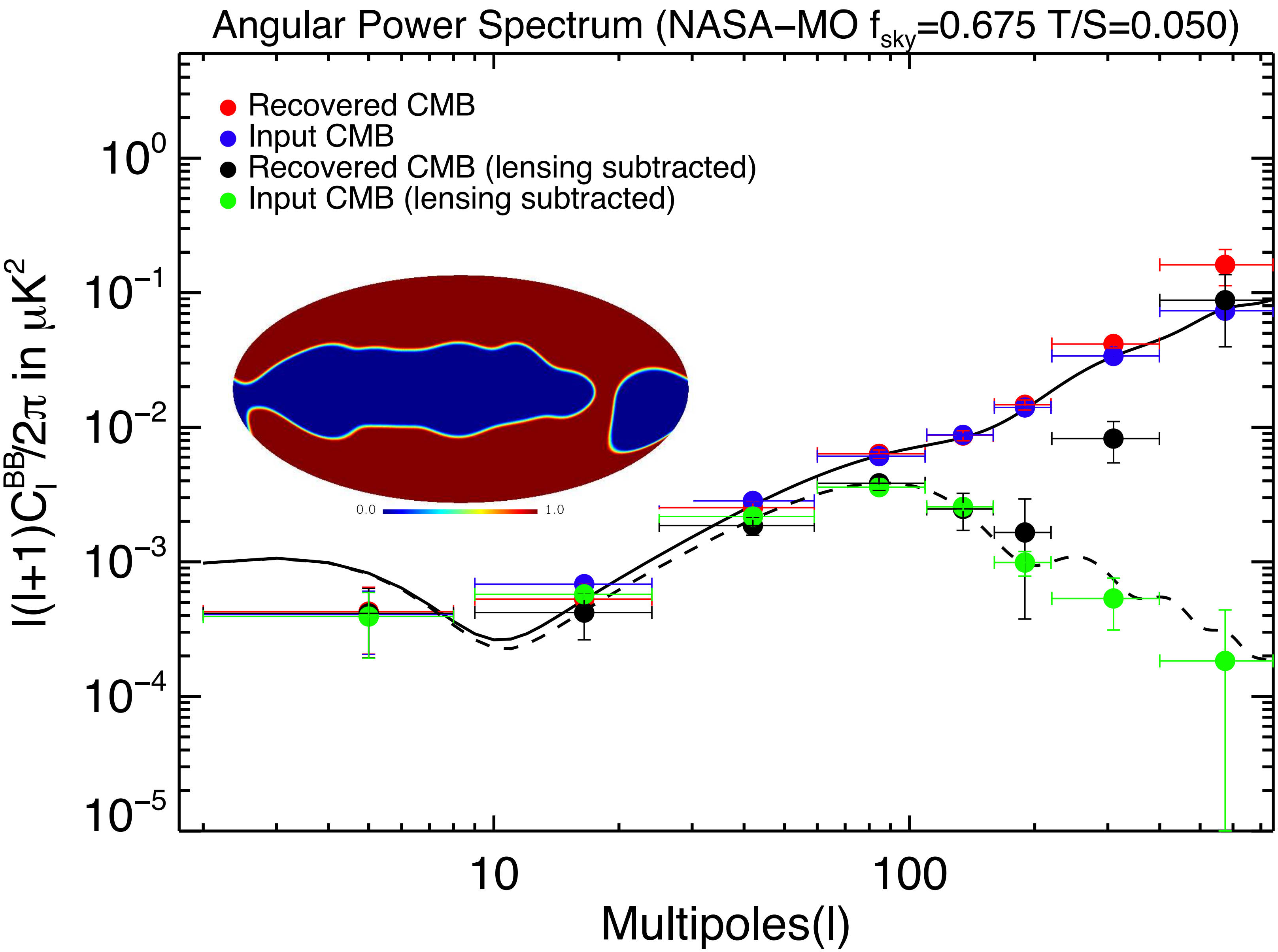
Needlet ILC weights



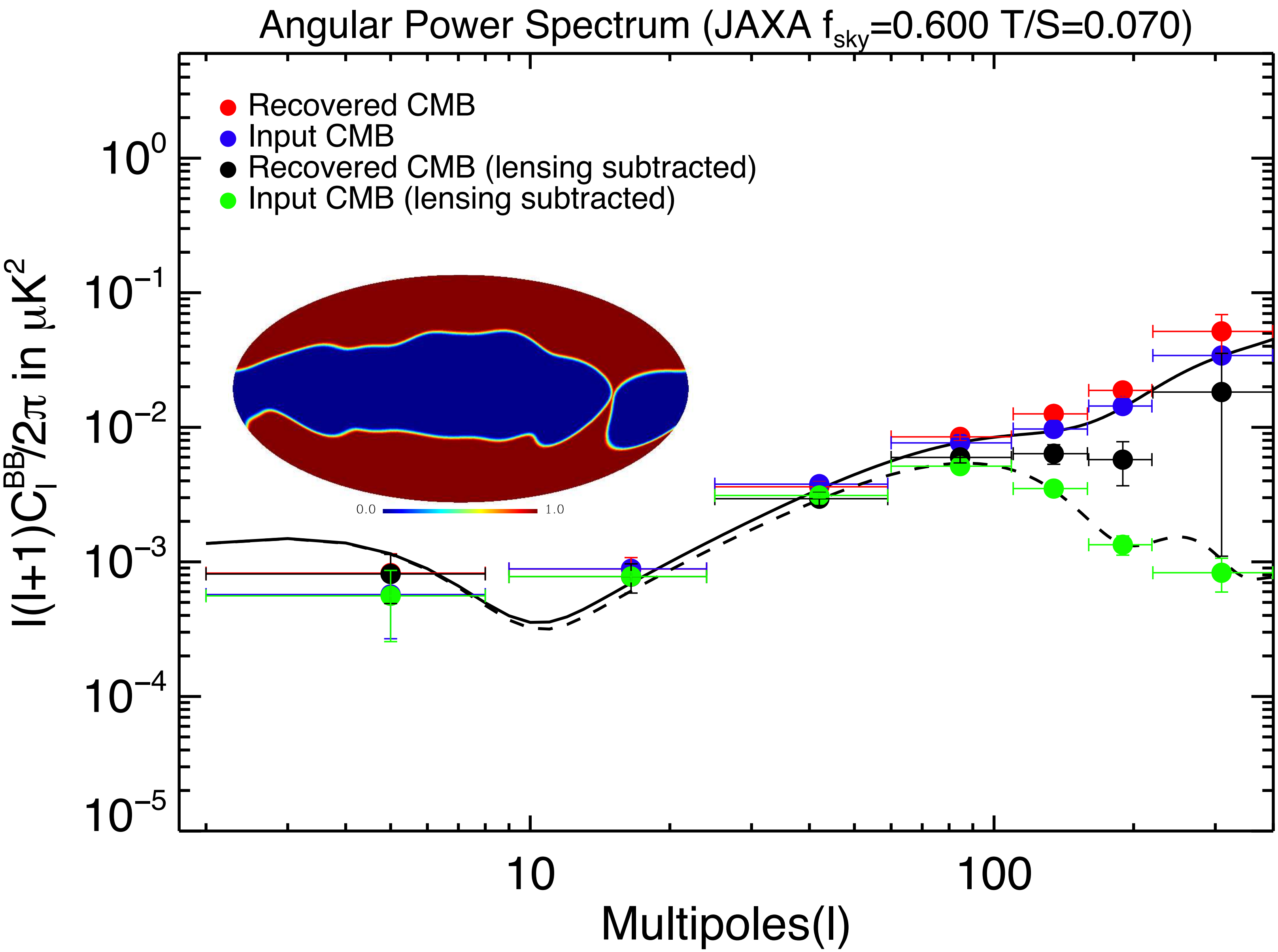
Estimation of CMB spectrum



LiteBIRD CMB spectra



LiteBIRD CMB spectra



Summary

- We have analyzed simulated sky maps for two LiteBIRD configurations (JAXA and NASA-MO), with the main scientific objective of measuring of B-mode of CMB by removing the foreground signals and instrumental noise superimposed on them.
- The method used is an implementation of a constrained linear combination of the channels with minimum error variance on a frame of spherical wavelets called needlets, allowing localized filtering in both pixel space and harmonic space.
- We have obtained a full sky, low foreground, low noise CMB map, which can be used to study the scientific potential of the mission.
- The 60, 100, 140 and 195 GHz channels contributes the most to the final CMB polarization maps for JAXA configuration. However, in case of NASA-MO configuration, the most of the comes from 140, 195 and 235 GHz frequency channels only.
- We have found that the level of the residuals of contaminants is higher in case of JAXA configuration compared to that in case NASA-MO configuration. In case of NASA-MO configuration, our measurement of CMB angular spectra clearly show detection of B-mode with tensor scalar ratio equal to 0.05 on 67.5% of the sky.
- We would like to redo our analysis on more complex simulation with non-Gaussian CMB and error on calibration coefficients.

Thank you