Contribution to LiteBIRD mission design (et al.)

D. Molinari

In collaboration with A. Gruppuso, M. Lattanzi, L. Pagano, P. Natoli

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Brief overview

A brief summary of the status of my main research projects:

- Contribution to **LiteBIRD** mission design phase A1
  - Scanning strategy optimization
  - Auto and cross-correlated detector noise and impacts to the goals of the mission (*LiteBIRD internal note 022*, *LiteBIRD internal note in prep.*)

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  - Validation of the Likelihood in temperature (*Planck 2016 results V in prep.*)
  - Validation of the component separated products (*Planck 2016 results IV accepted by JCAP*)
  - Testing the Gaussianity of the CMB and checking for the presence of anomalies (*Planck 2016 results VII, submitted to JCAP*)

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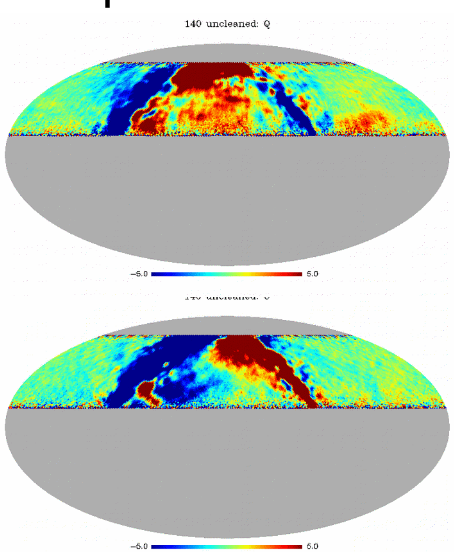
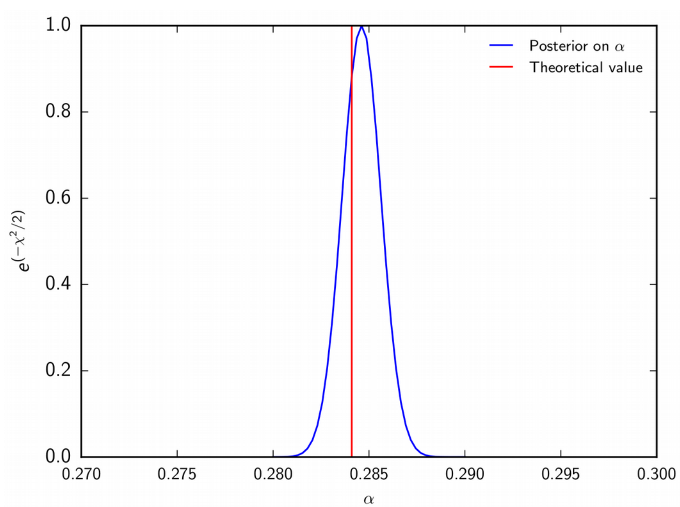
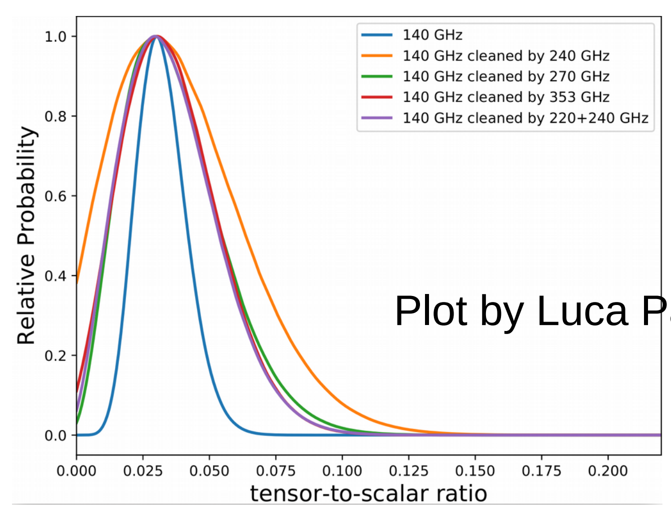
- Participation to the preparation of the **LSPE mission**
  - Optimization of the component separation pipeline via template fitting technique







Plot by Luca Pagano

Close connection with F. Piacentini and D. Poletti and SISSA

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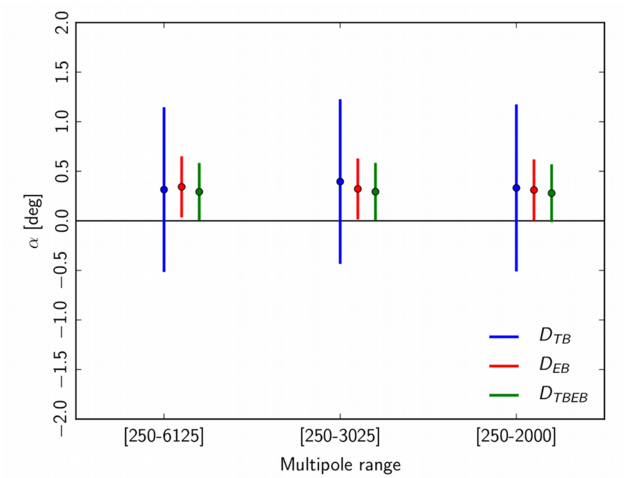
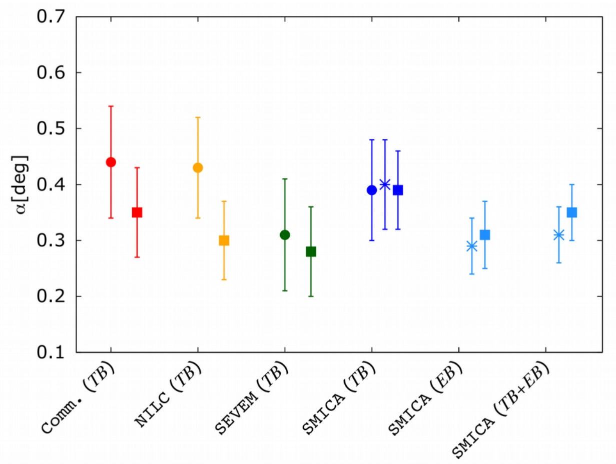
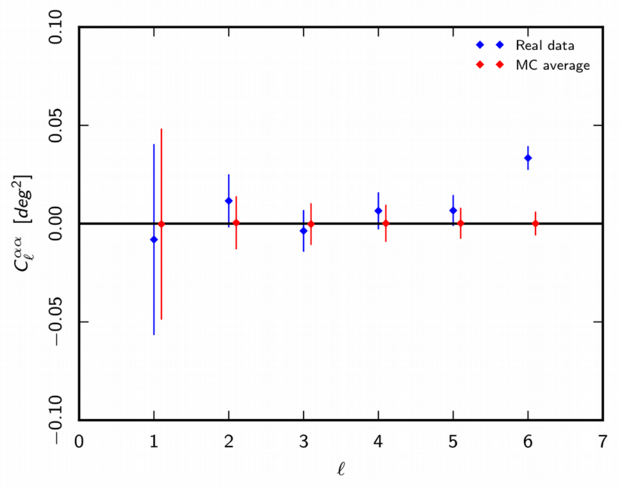
  - Analysis of fundamental physics through the search of birefringence signals both isotropic and anisotropic in the sky







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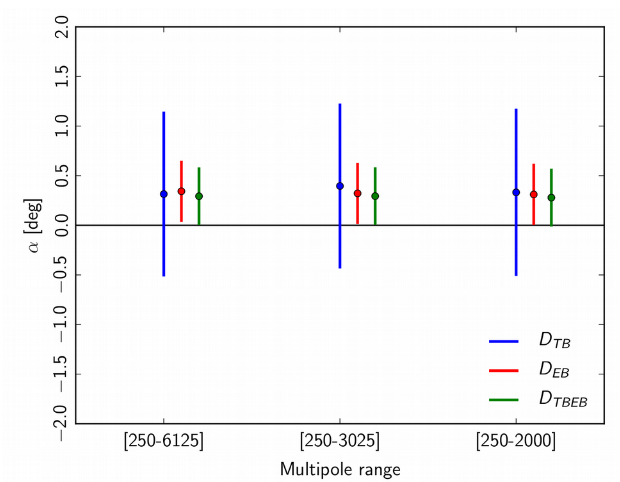
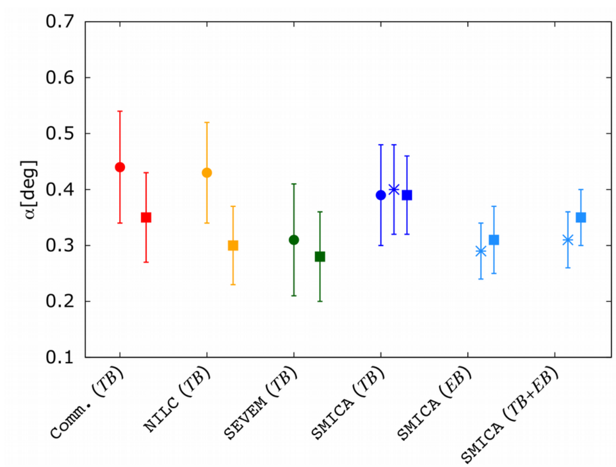
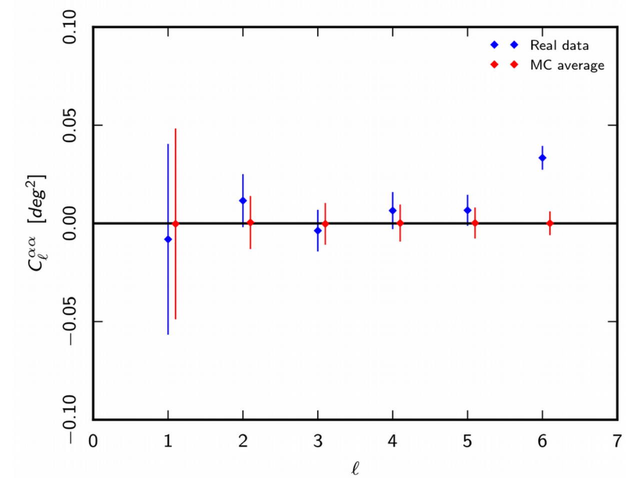
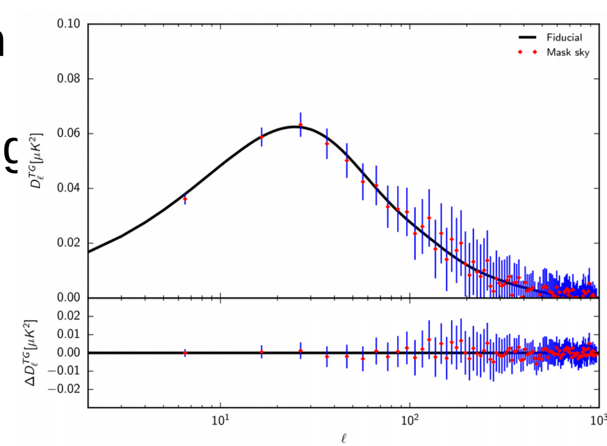
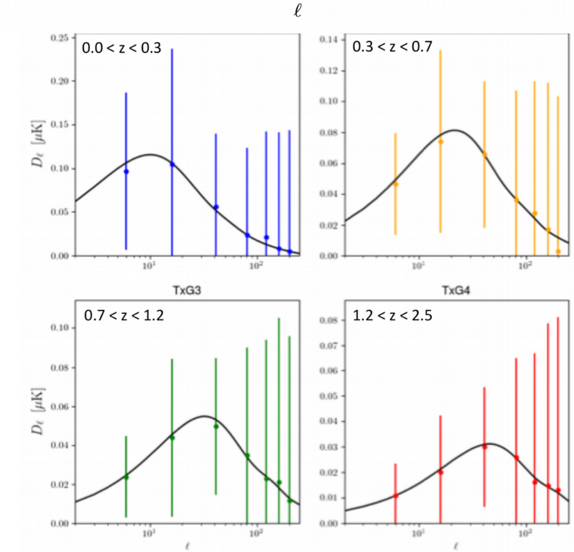






- Member of the **Euclid consortium**
  - Combining Planck legacy data with LSS Euclid survey analysing the ISW signal for the Dark Energy characterization

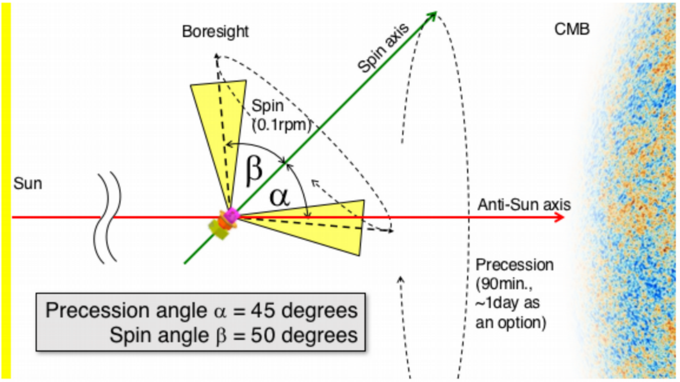




LiteBIRD scanning strategy optimization

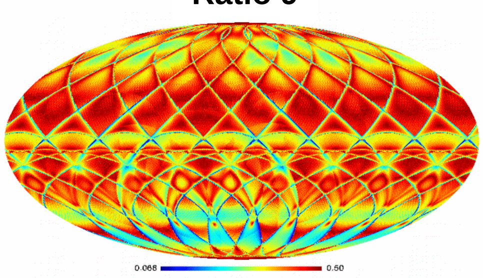
Initially the scanning strategy parameters were

Alpha [deg.]	Beta [deg.]	Precession rate [hour]	Spin rate [rpm]
45	50	1.5	0.1



The choice of an integer ratio is such that after one precession period the satellite turns back to the same position!
This creates a non uniform pattern in inverse condition numbers which we would like to avoid.

Ratio 9



Mean 0.378

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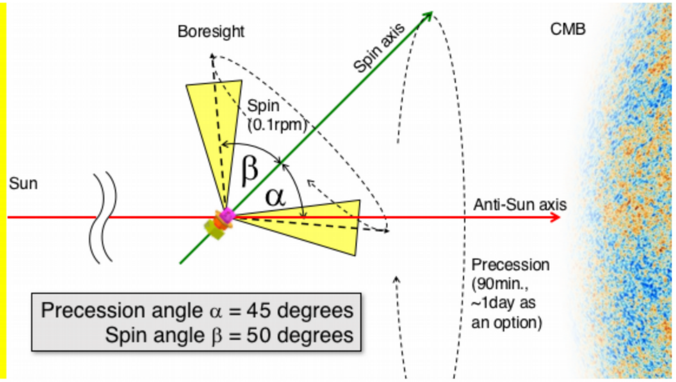
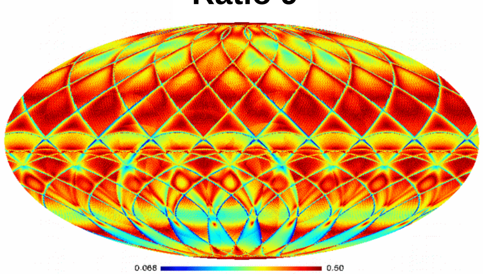
45	50	1.5	0.1



The choice of an integer ratio is such that after one precession period the satellite turns back to the same position!
This creates a non uniform pattern in inverse condition numbers which we would like to avoid.
We therefore explored other options:

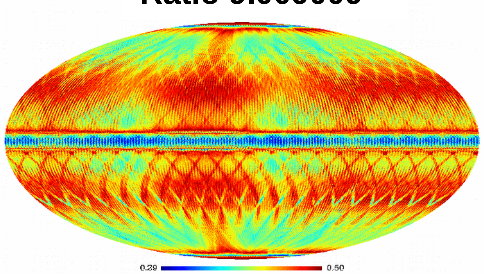
spin rate	rpm	0.1	0.3
prec rate	rpm	0.0111111111	0.033333333
spin period	min	10	3.33
prec period	hours	1.5	0.5
prec period	min	90	30
ratio		9	9.009009009

Ratio 9



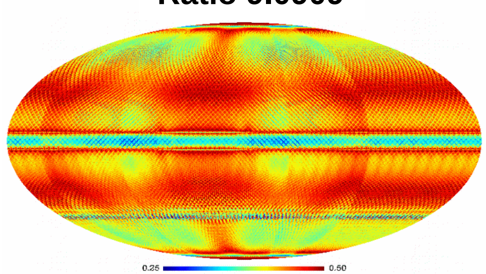
Mean 0.378

Ratio 9.009009



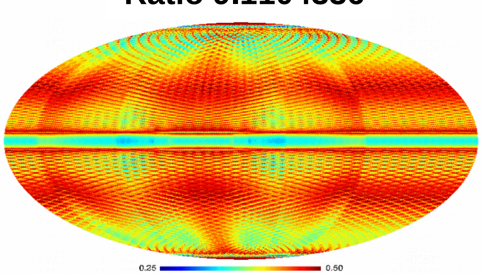
Mean 0.431

Ratio 9.0909



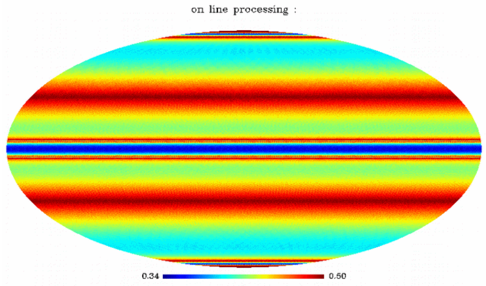
Mean 0.431

Ratio 9.1104336



Mean 0.430

Ratio 9.61803



Mean 0.4381

We verified that using an irrational number from Hoang et al 2017 the cyclic patterns almost disappear and we maximize the average of the inverse condition numbers map

Auto-correlated noise

We evaluated the impact of detector auto-correlated (1/f) noise down to the sensitivity on the tensor to scalar ratio for LiteBIRD in the absence of a half-wave plate modulator.

Using the TOAST packages we simulated the LiteBIRD scanning strategy generating noise timelines with power spectral density (PSD) like:

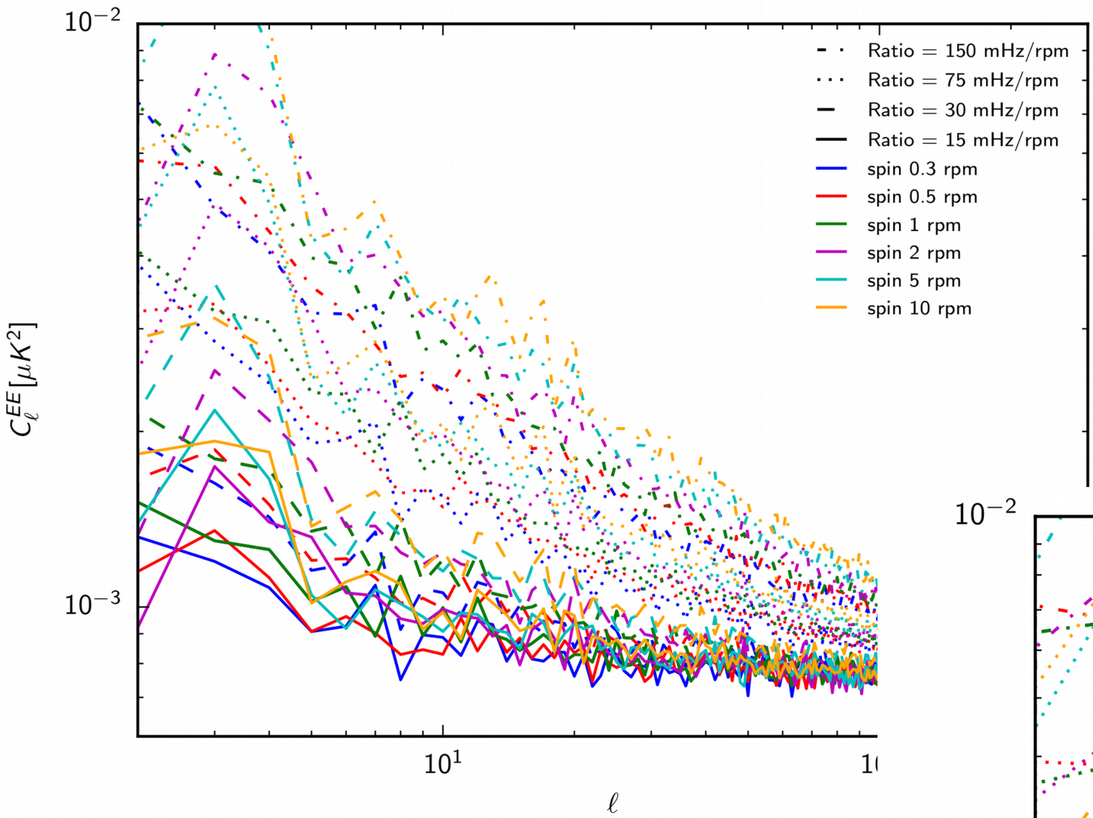
$$P(f) = A\left[\left(\frac{f_k}{f}\right)^{\alpha} + 1\right]$$

with A=NET^2 and alpha=1.0
We considered several combinations of spin rates and f_k frequencies.

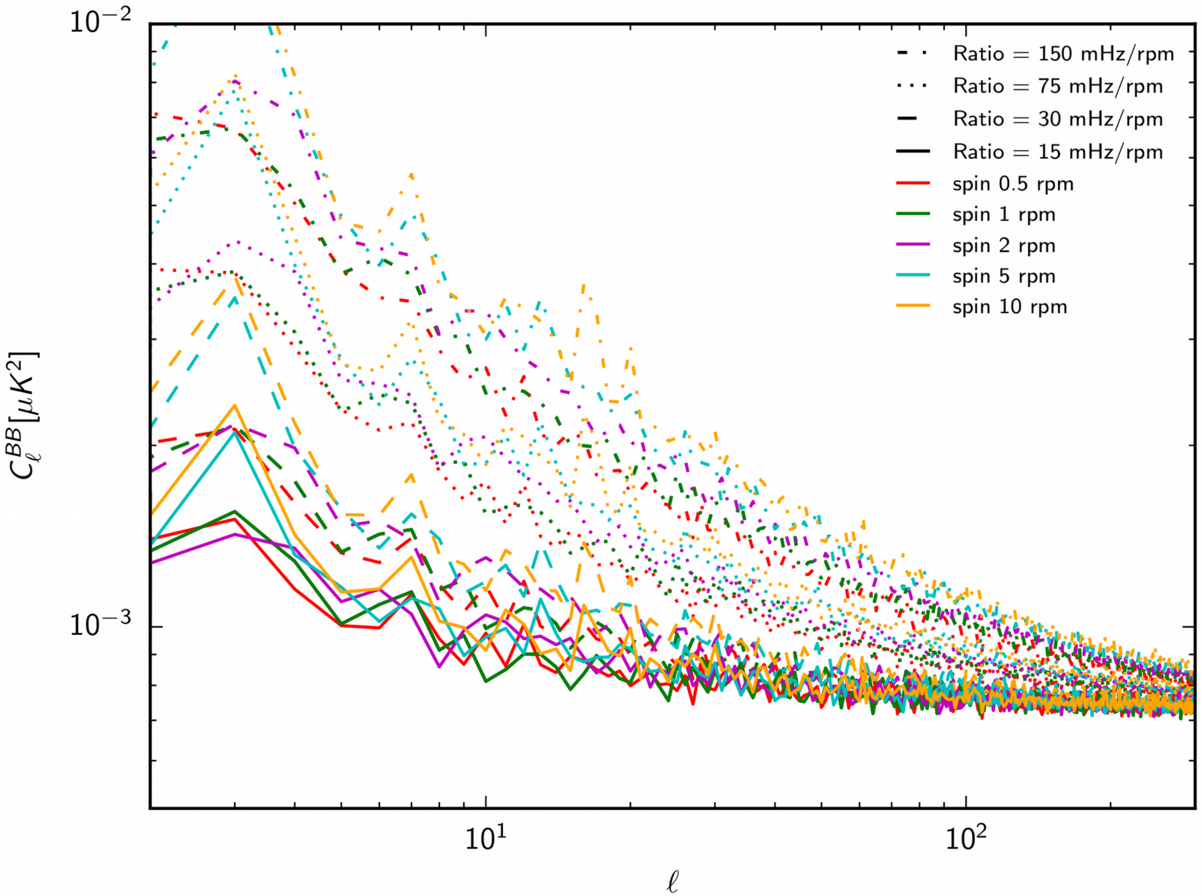
		$f_{\rm spin}$ [rpm]					
		0.3	**0.5**	**1.0**	**2.0**	**5.0**	**10.0**
$f_k/f_{\rm spin}$ [mHz/rpm]	**15**	4.5	7.5	15	30	75	150
	30	9	15	30	60	150	300
	75	22.5	37.5	75	150	375	750
	150	45	75	150	300	750	1500
	333.33	100	166.67	333.33	666.67	1666.67	3333.33

We also used our optimized scanning strategy parameter and set the sampling rate accordingly.
We considered a couple of detectors at the boresight with orthogonal polarization sensitivity.
We simulated 1 year of observation and averaged the results over 20 MC realizations.

Auto-correlated noise: E and B APS



Full sky angular power spectra of the noise maps

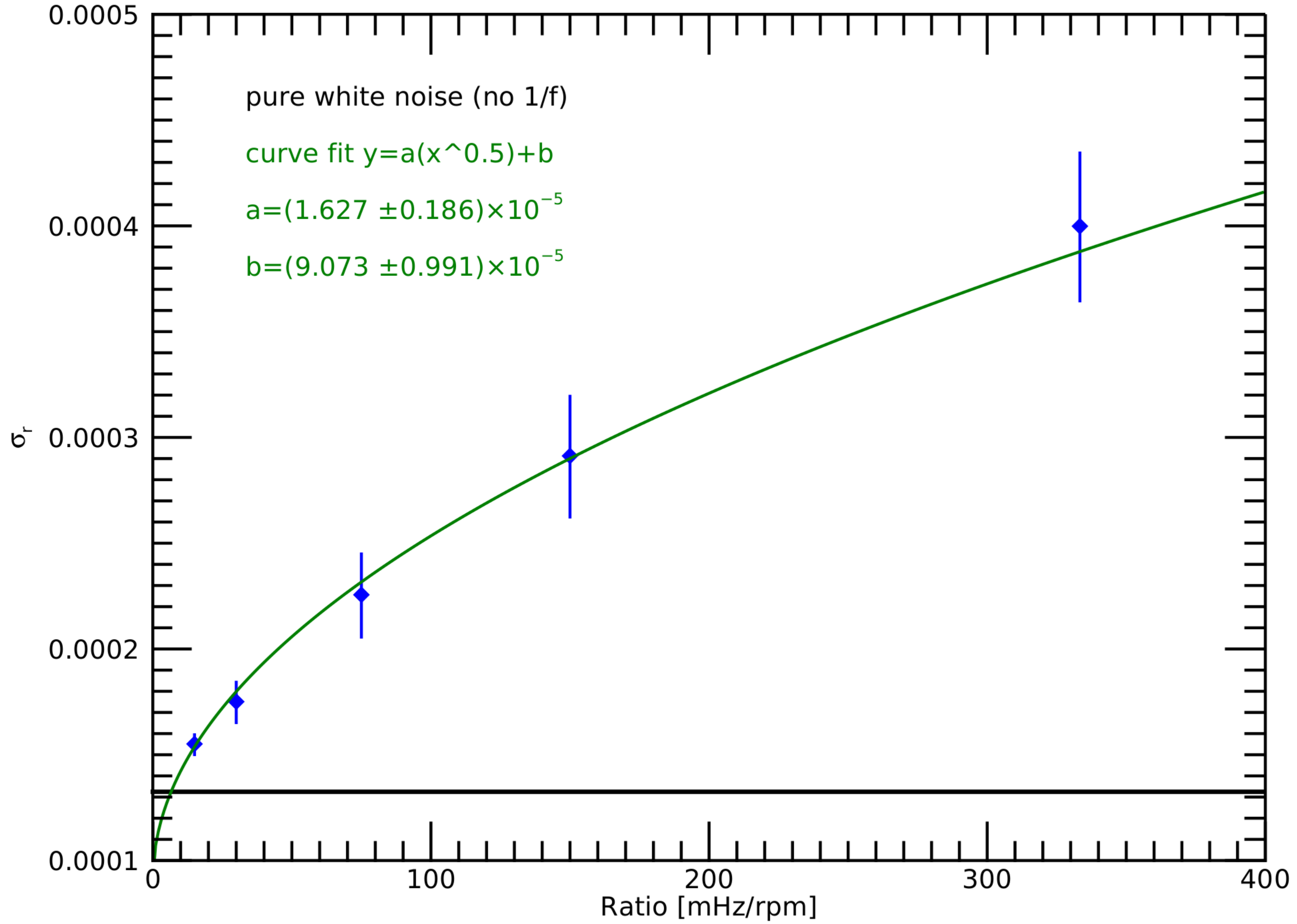


A similar 1/f residual contamination at large scales is observed for different knee frequencies and spin rates when they have the same ratio

Ratio [mHz/rpm] = knee freq / spin rate

Impact on r

Implementing a simple likelihood formula we propagated these realistic noise simulations to the sensitivity on tensor-to-scalar ratio.



We found that a function of the form of y=a*sqrt(x)+b is a better fit of the results with respect to a simple linear fit.

Cross-Correlated noise

To further improve the reality of our noise simulations we started to implement a correlated noise between two superimposed orthogonal detectors. In a first very simple attempt

$$N_1 = \tilde{N}_1 + B_0 N_c$$

$$N_2 = \tilde{N}_2 + B_1 N_c$$

$$< \tilde{N}_1 \tilde{N}_2 >= 0$$

Where inside TOAST they are defined as:

$$P_i(f) =< \tilde{N}_i \tilde{N}_i >= A\left[\frac{(f_k)^\alpha + (f)^\alpha}{(f)^\alpha + (f_{min})^\alpha}\right] \approx A\left[\left(\frac{f_k}{f}\right)^\alpha + 1\right]$$

$$P_c(f) =< N_c N_c >= \tilde{A}\left[\frac{(f_{k,c})^\beta + C(f)^\beta}{(f)^\beta + (f_{min})^\beta}\right] \approx \tilde{A}\left[\left(\frac{f_{k,c}}{f}\right)^\beta + C\right]$$

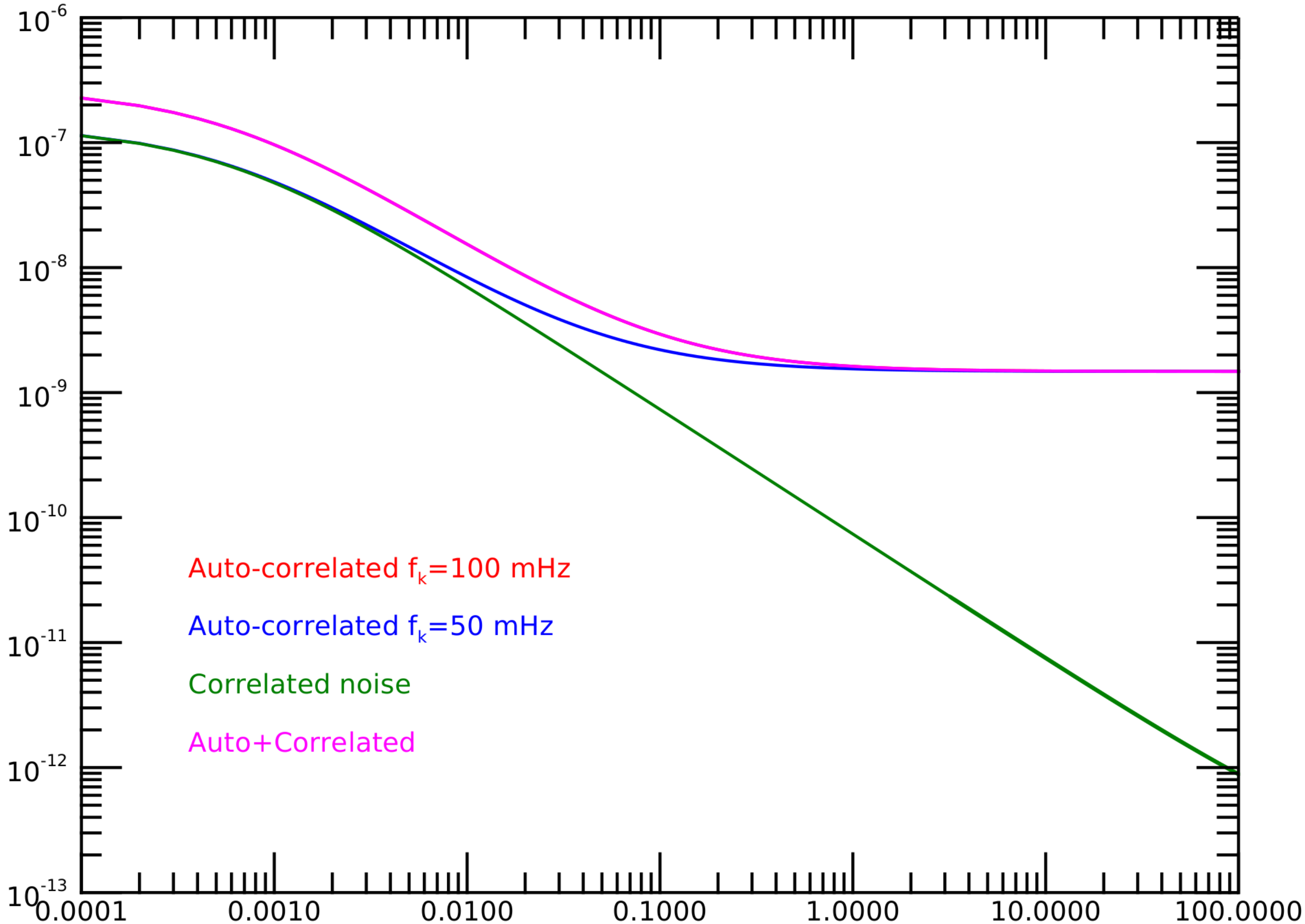
$$f_{min} \ll f$$

At the moment we set C as negligible to not affect the white noise limit.

We implemented a simple code that generates the correlated noise that is then summed to the detector autocorrelated noise and finally is feed to Madam to produce noise maps.

Cross-Correlated noise

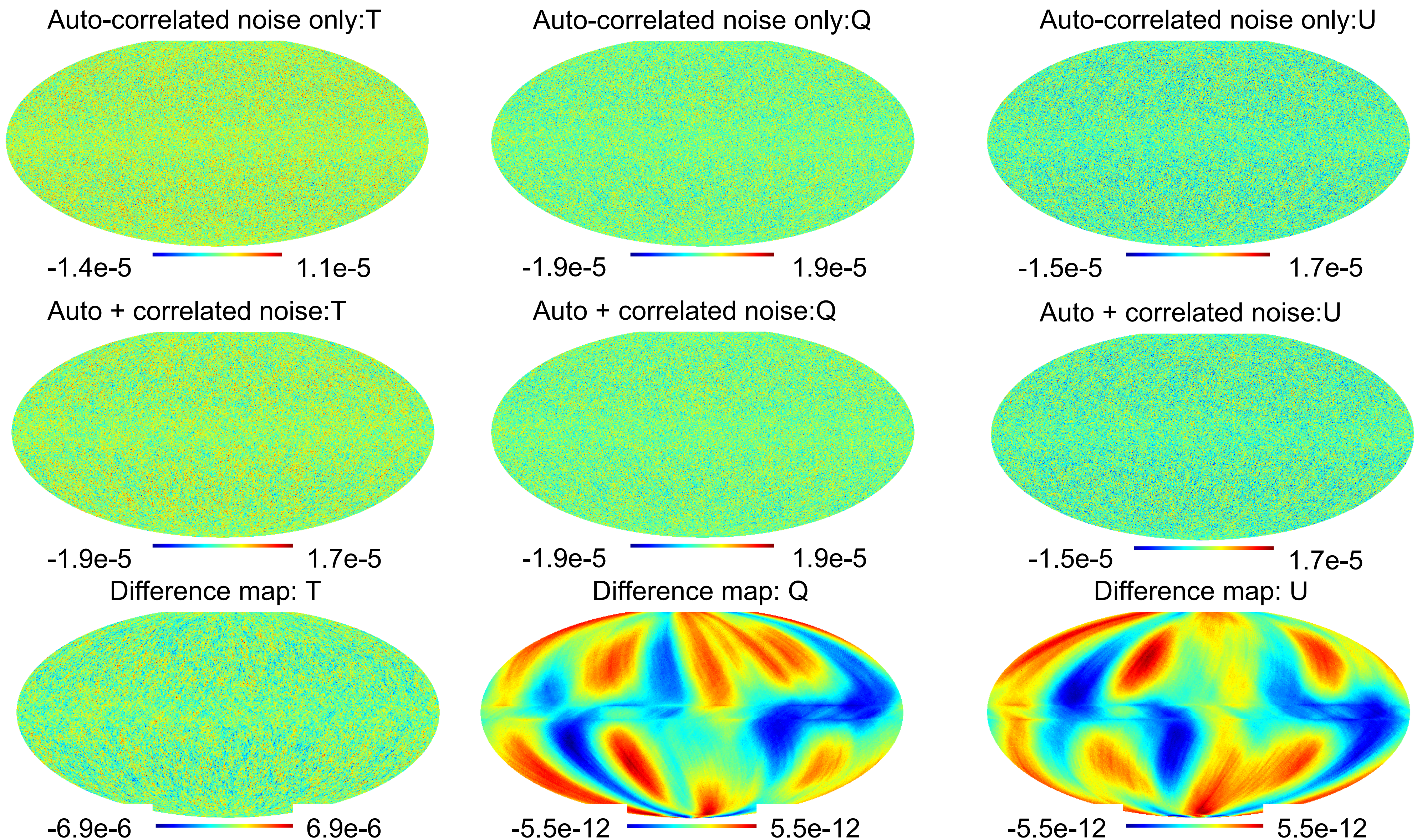
Which values for the correlated noise?
We started with simple cases to validate and debug the code we developed.



We set $\beta = 1.0$ and $\tilde{A} f_{k,c}$ such that at low frequency the amplitude is similar to the auto-correlated noise.
For all the other parameters we selected the case with spin rate 0.3 rpm

Cross-Correlated noise

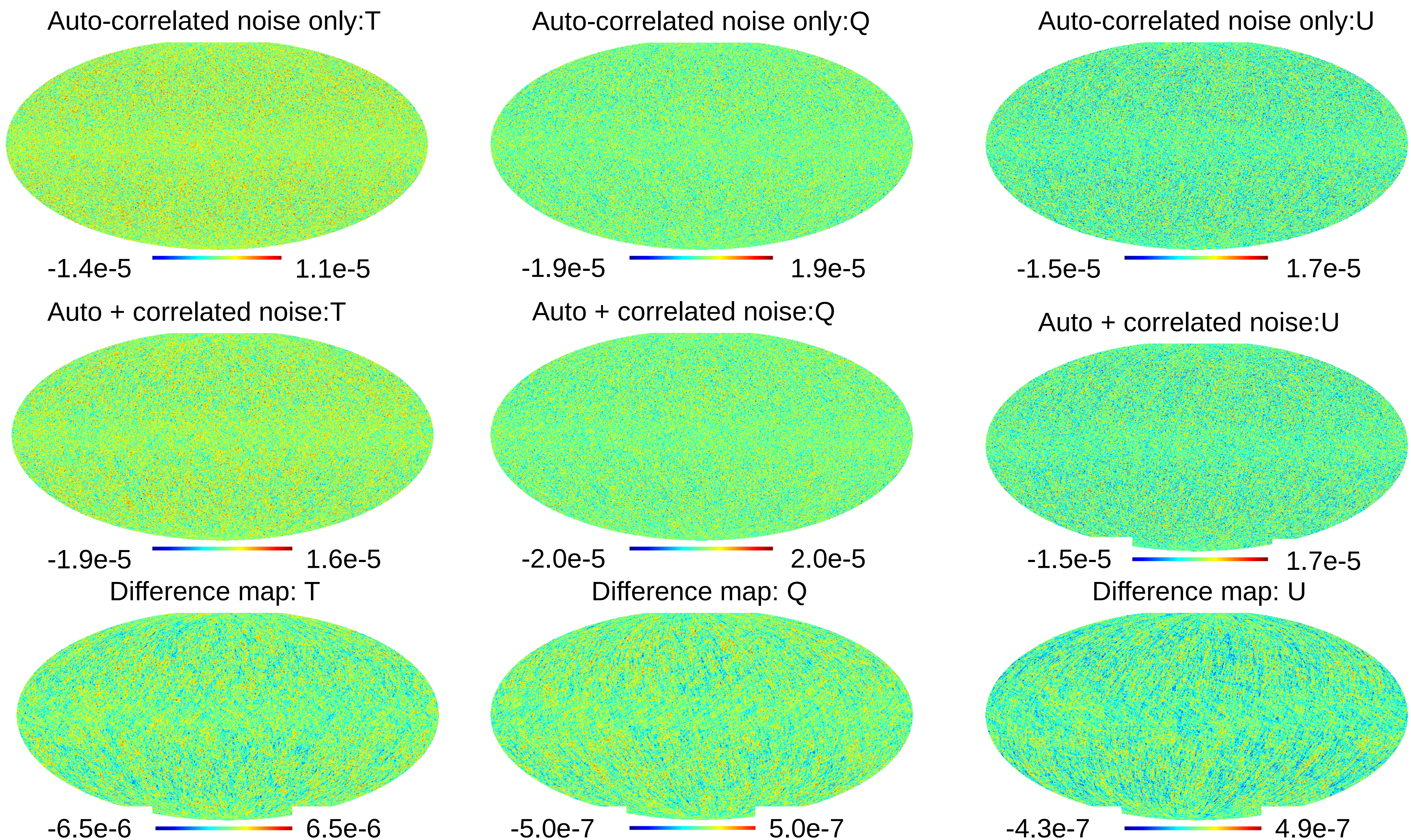
In the simplest case we set $B = [B_0, B_1] = [1.0, 1.0]$



Apparently, Madam subtracts the timelines of the two detectors to reconstruct polarization.
As a consequence a perfectly correlated component is wiped out in the map-making process.

Cross-Correlated noise

In the case of not perfectly correlated component $B = [B_0, B_1] = [1.0, 0.9]$

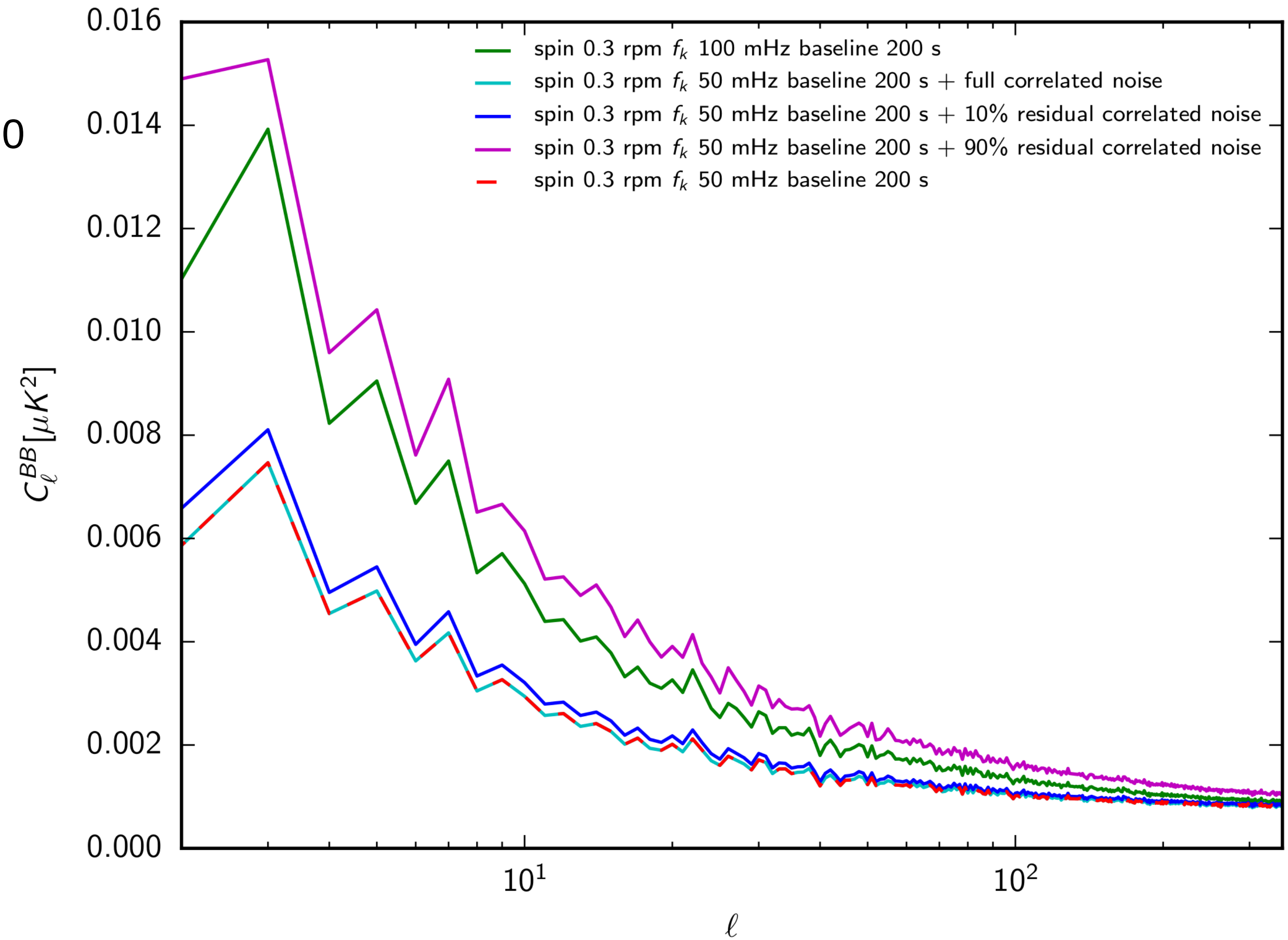


When the correlated noise is not perfectly correlated (simulated by considering different weights) there is a residual correlated noise in the destriped maps.

Cross-Correlated noise

Impact at the level of the angular power spectrum.

alpha=1.0

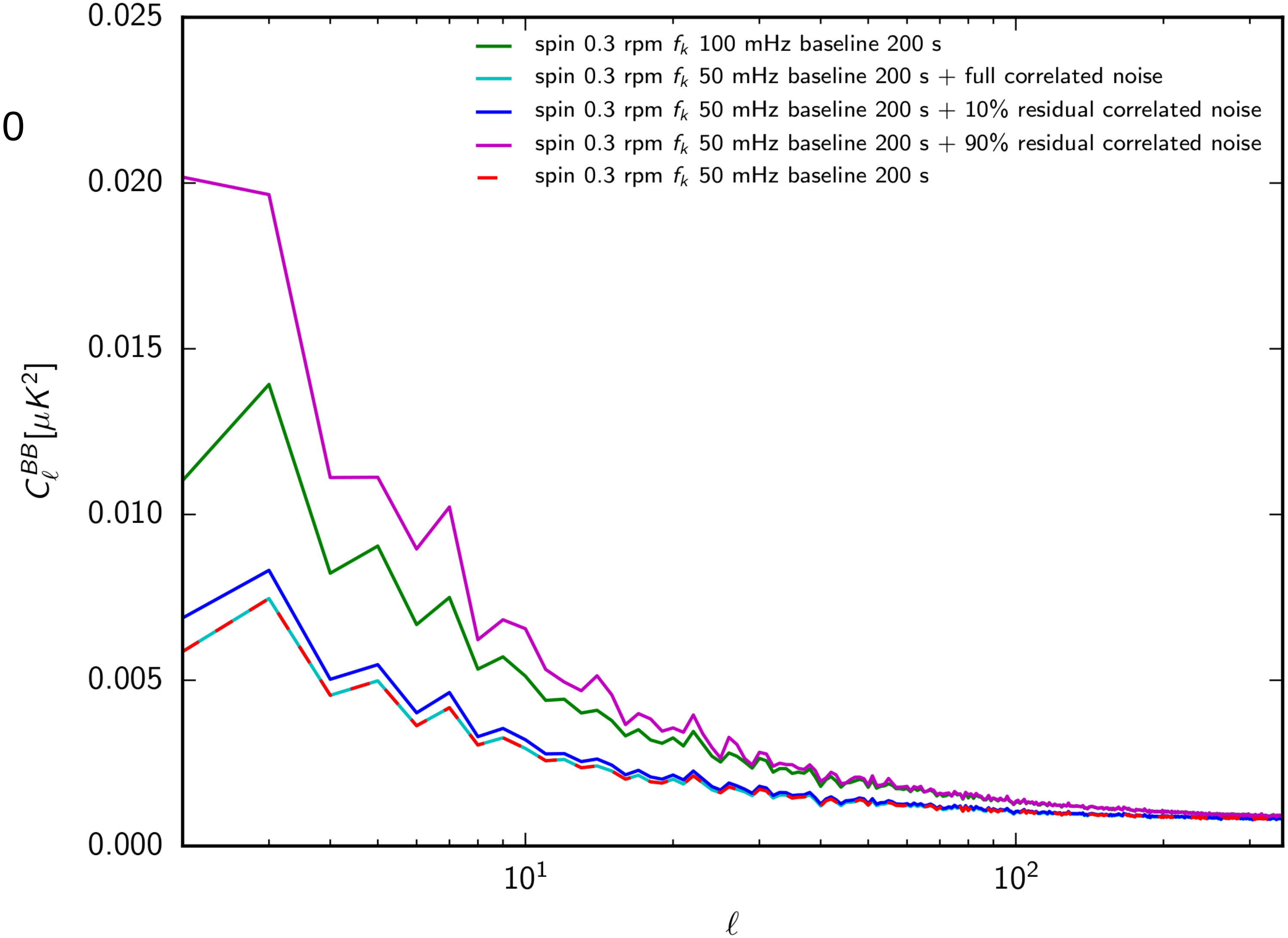


The residual correlated noise increases the amplitude of the noise at large scale depending on the percentage of the residual.

Cross-Correlated noise

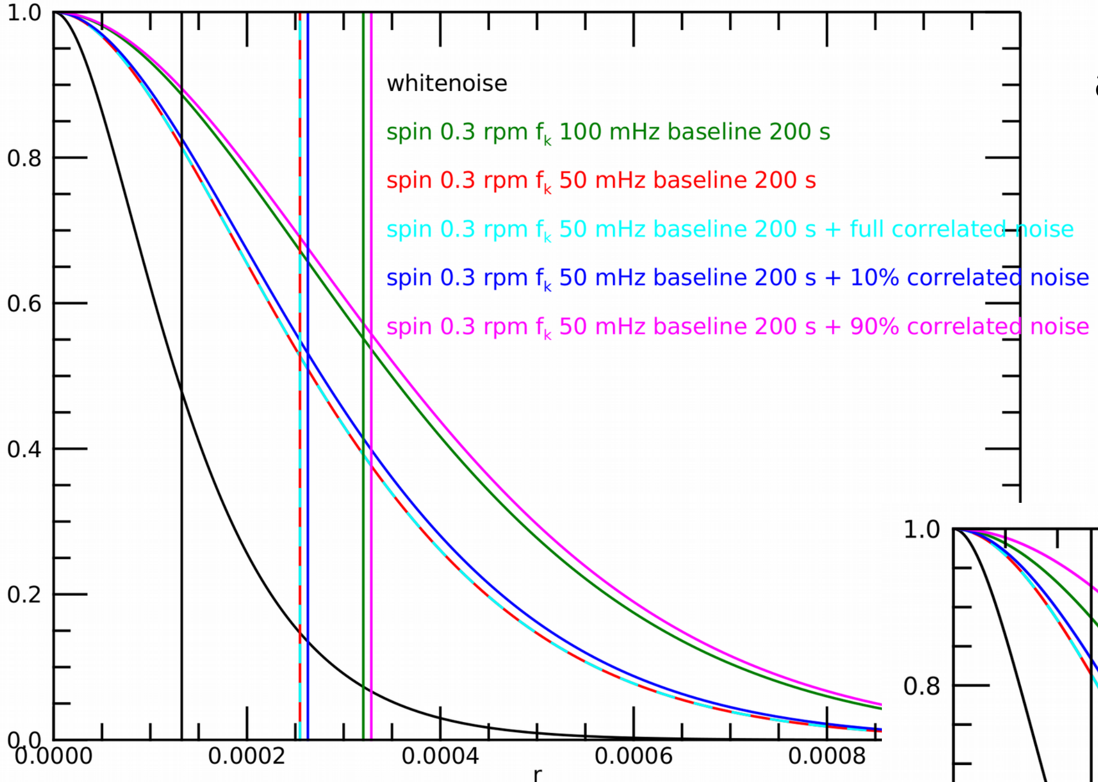
Impact at the level of the angular power spectrum.

alpha=2.0

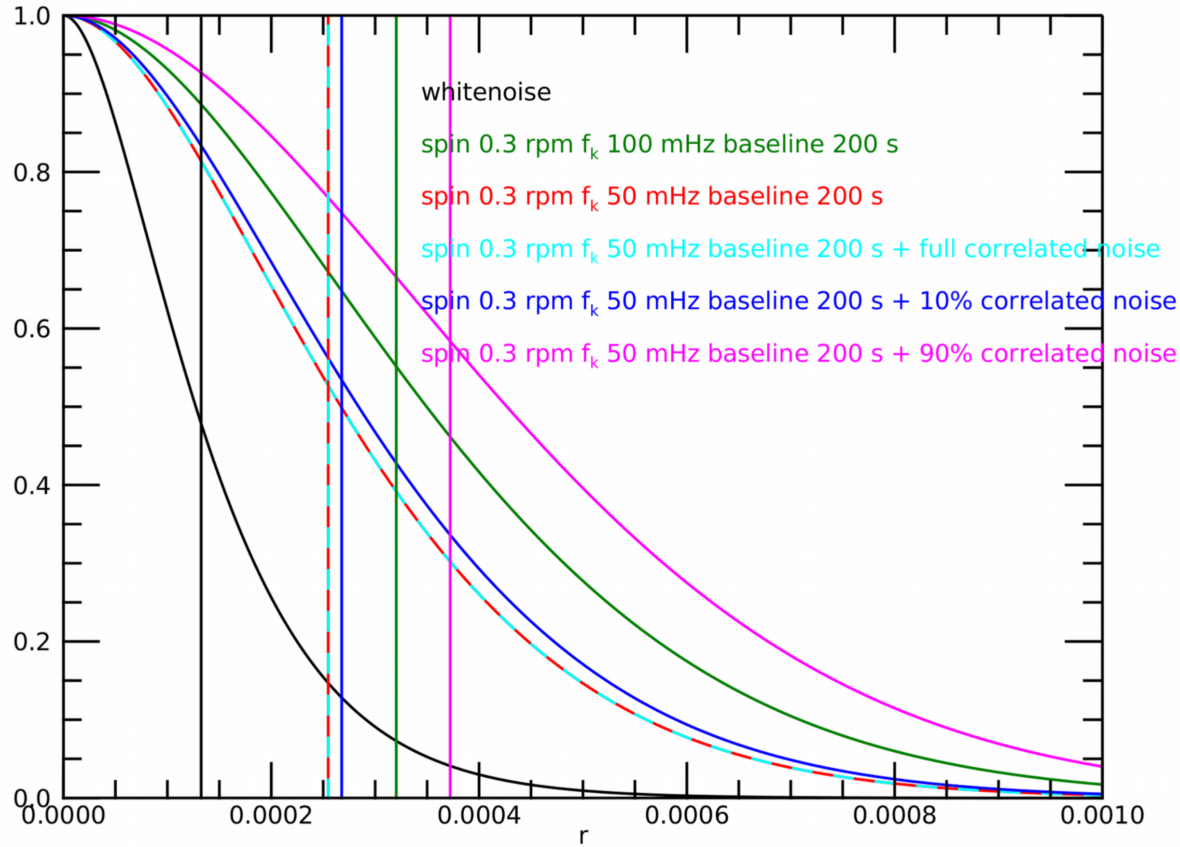


We observe a larger impact at lower multipoles as expected

Impact on tensor-to-scalar ratio



alpha=1.0



alpha=2.0

It is important to define which are the relevant values for LiteBIRD

Moving further

We are now moving towards a more refined description starting from the PSD descriptions.
We start from a noise covariance of the form:

$$C = \begin{pmatrix} \sigma_{11}^2 & \sigma_{12}^2 \\ \sigma_{21}^2 & \sigma_{22}^2 \end{pmatrix}$$

$$\sigma_{11}^2 = \sigma_{22}^2 = \tilde{A}\left[\left(\frac{f_k}{f}\right)^{\alpha} + 1\right] + A\left[\left(\frac{f_{k,c}}{f}\right)^{\beta} + B\right]$$

$$\sigma_{12}^2 = \sigma_{21}^2 = A\left[\left(\frac{f_{k,c}}{f}\right)^{\beta} + B\right]$$

We may make the covariance diagonal

$$E_1 = \sigma_{11}^2 - \sigma_{12}^2 = \tilde{A}\left[\left(\frac{f_k}{f}\right)^{\alpha} + 1\right]$$

$$E_2 = \sigma_{11}^2 + \sigma_{12}^2 = \tilde{A}\left[\left(\frac{f_k}{f}\right)^{\alpha} + 1\right] + 2A\left[\left(\frac{f_{k,c}}{f}\right)^{\beta} + B\right]$$

$$v_1 = \left(\frac{-1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)$$

$$v_2 = \left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)$$

We use the diagonal covariance to generate noise timelines and then rotate them

$$n_1 = \frac{-1}{\sqrt{2}} n_A + \frac{1}{\sqrt{2}} n_B'$$

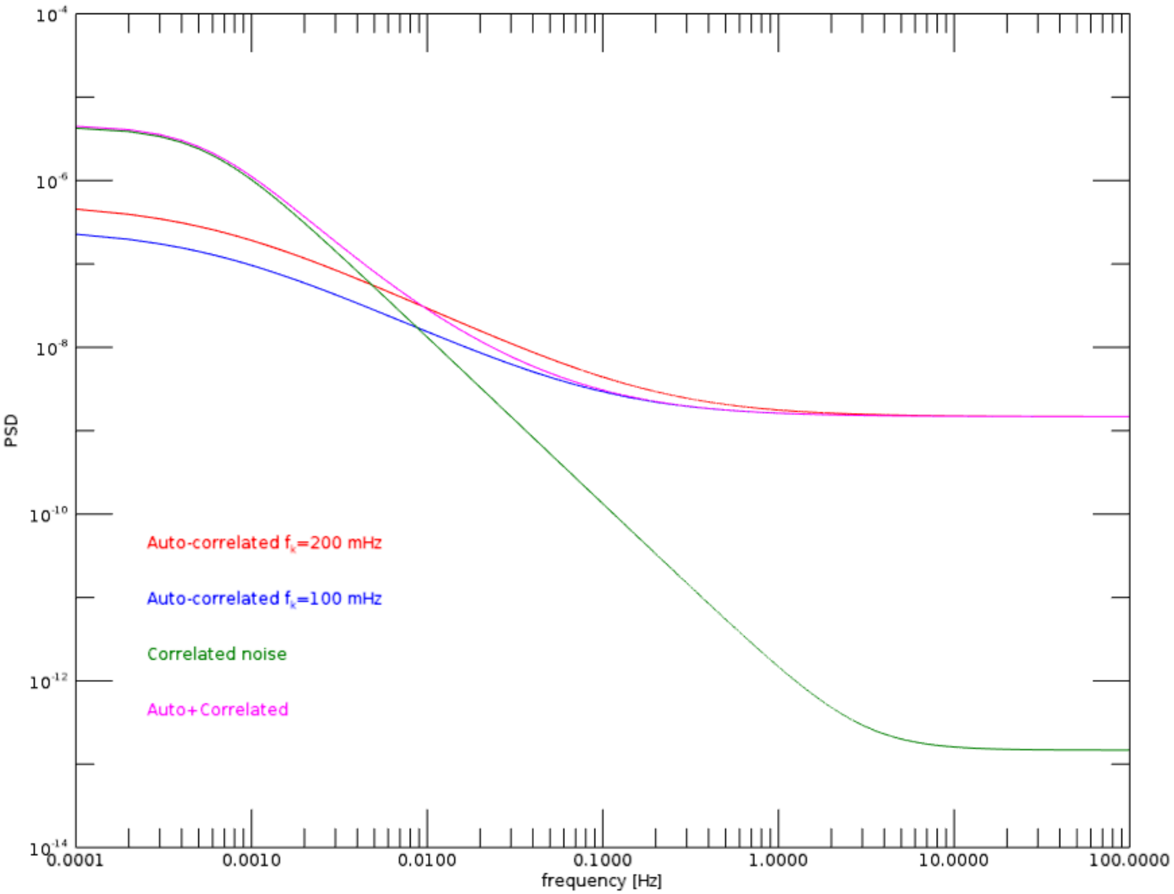
$$n_2 = \frac{1}{\sqrt{2}} n_A + \frac{1}{\sqrt{2}} n_B'$$

to obtain cross correlated noise timelines. We checked that we recover the original covariance C

Moving further

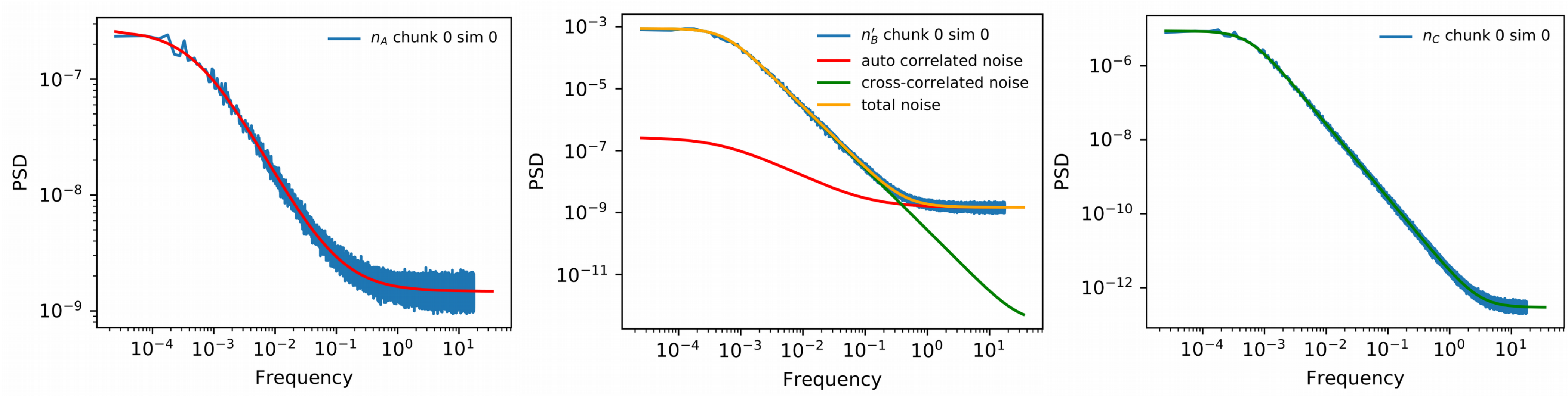
We started with a simple toy model

	$< n_A n_A >$	$< n_c n_c >$ case 1
NET	$3.84 * 10.0^{-5}\,\mu K\sqrt{s}$	$5.43058 * 10.0^{-7}\,\mu K\sqrt{s}$
f_k	0.100 Hz	3.0 Hz
f_{min}	0.00055	0.00055
α	1.0	2.0



Moving further

And checked that our implementation works as expected.



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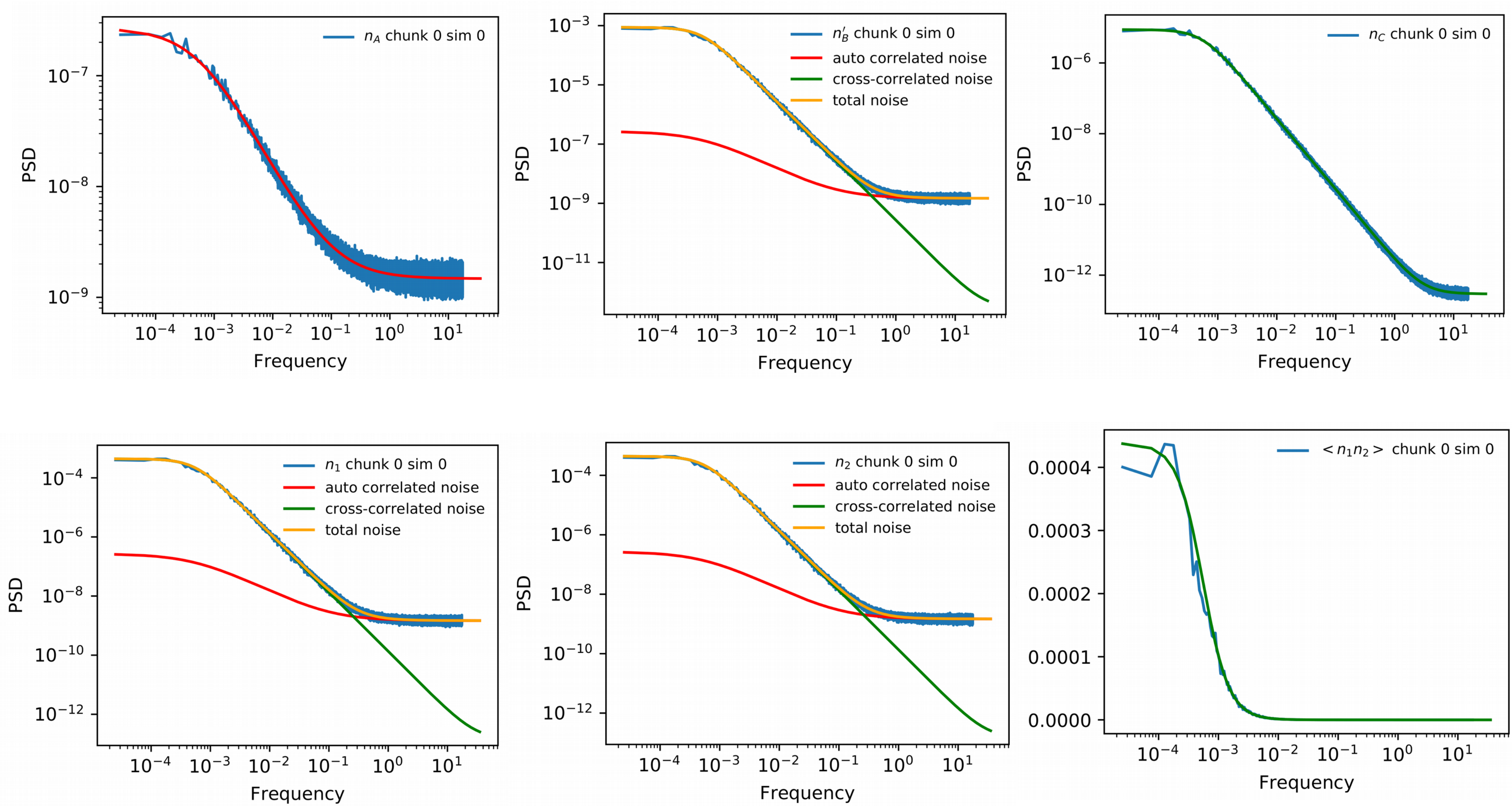

The noise timelines show the expected behaviour after rotation.
We are now propagating these timelines to noise maps to study the impact on r measurement.

Summary and conclusions

- We are contributing in the definition of the LiteBIRD design mission with contribution to the optimization of the scanning strategy and to the simulation of the impact of detector auto-correlated noise.to tensor-to-scalar ration measurement.

- We are moving forward to include also the effect of cross-correlated noise among detectors and evaluate its impact on tensor-to-scalar ratio measurement.

- I am also working on other research activities that are included in different COSMOS Working Packages.
    - template fitting optimization in LSPE mission design
    - exploitation of Planck legacy data
        - Cosmic birefringence search
        - Anomalies
    - combination of CMB data (not only Planck) with Euclid survey in the CMBXC Euclid Science Working Group