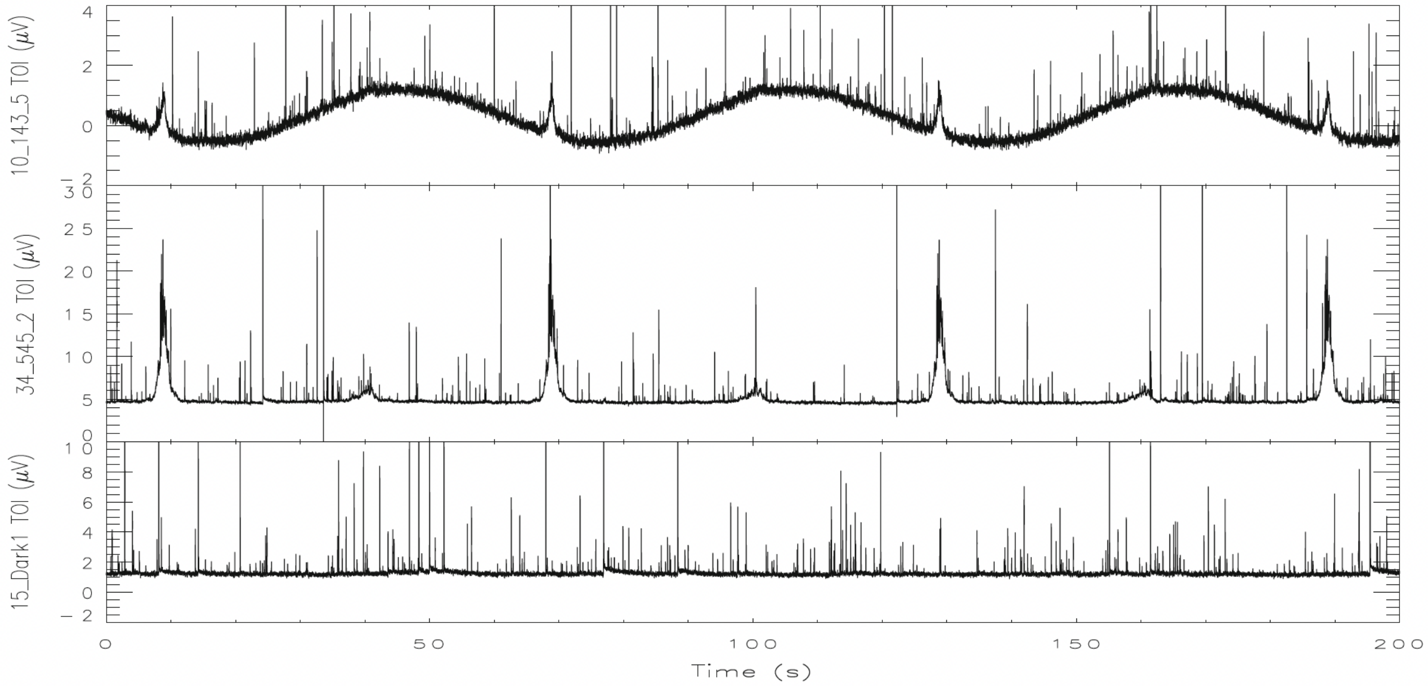
Modeling thermal contribution produced by Cosmic Rays impact on a sub-K bolometric array at L2

G. Pascual-Cisneros, S. Della Torre, A. Besnard, F. J. Casas, M. Gervasi, T. Ghigna, B. Maffei, T. Matsumura, V. Sauvage, G. Patanchon, F. Piacentini, S. Stever, G. Signorelli, A. Tartari and M. Zannoni for the LiteBIRD collaboration.

Introduction

- Cosmic Rays (CR) impact on cryogenic detectors produce transient signals (“glitches”) that will downgrade detector performance.
- In the case of Planck HFI, more than 30% of the acquired data was affected by CR events, requiring expensive post-processing efforts to mitigate their impact.
- Modelling of this systematics will allow us to test different instrumental configurations that can mitigate them.



Catalano, A., et al. "Characterization and physical explanation of energetic particles on Planck HFI instrument." *Journal of Low Temperature Physics* 176.5 (2014): 773-786.

CR simulation pipeline

CR flux
- CR flux on L2 is estimated

Deposited Energy on wafer
- CR interaction with matter is simulated

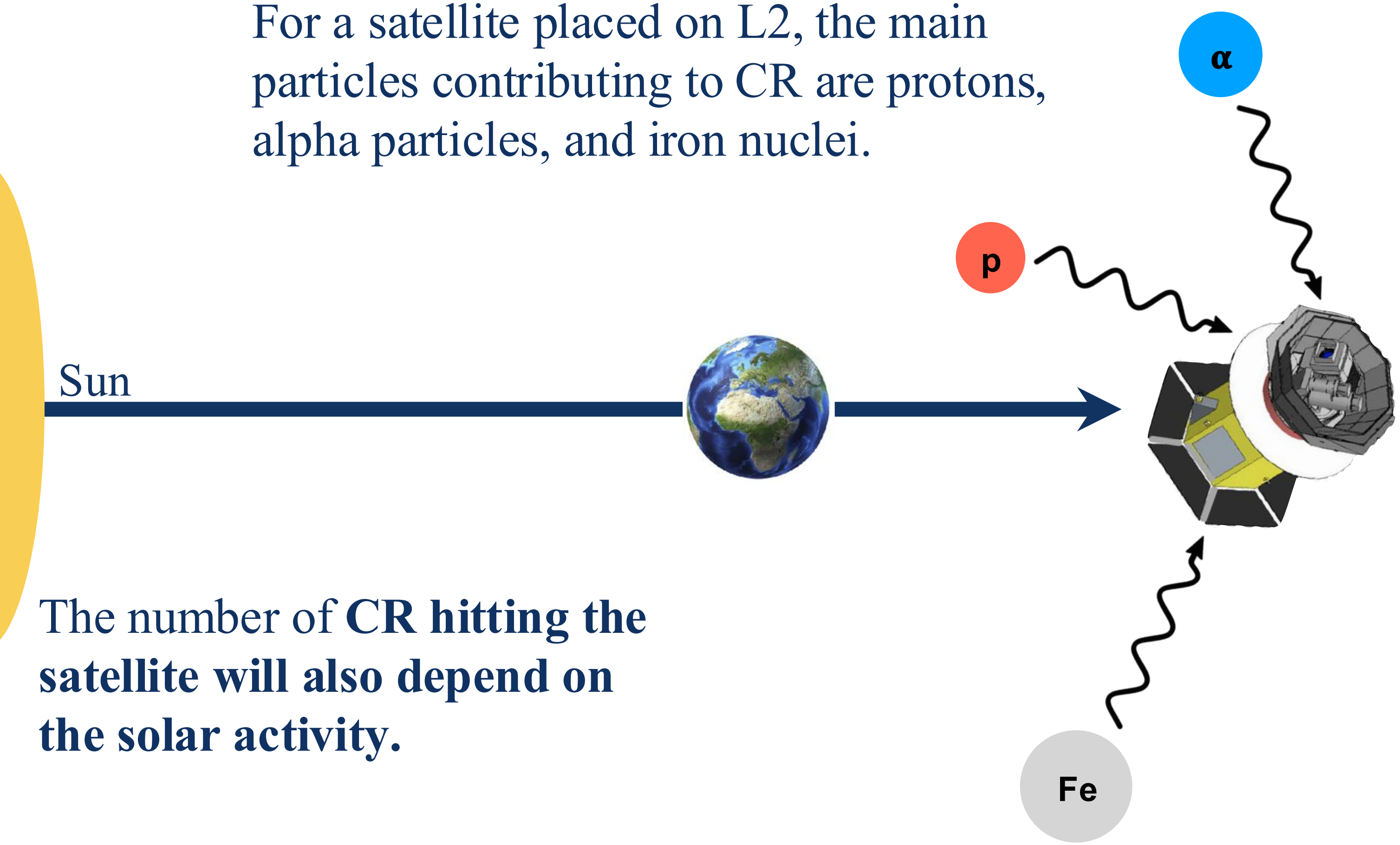
TOD generation
- Using a random poissonian generator we construct a TOD

Thermal Response
- Obtain thermal fluctuations by solving the heat equation

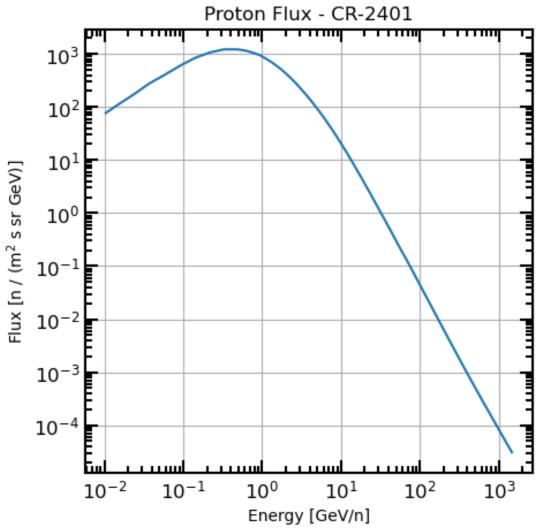
Detector Response
- Bolometer model is solved under the modeled thermal fluctuations

CR flux

For a satellite placed on L2, the main particles contributing to CR are protons, alpha particles, and iron nuclei.



The number of CR **hitting the satellite will also depend on the solar activity.**



Flux for each particle at a specific epoch can be modelled using specific software: ***HelMod*.**

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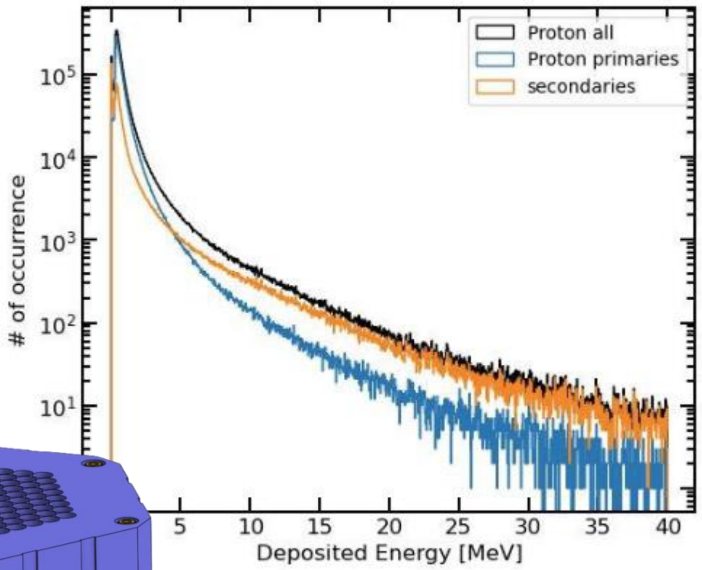
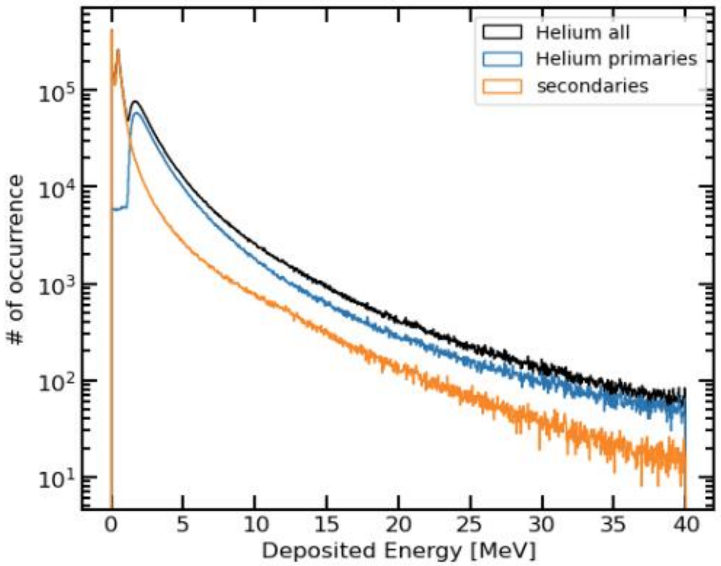
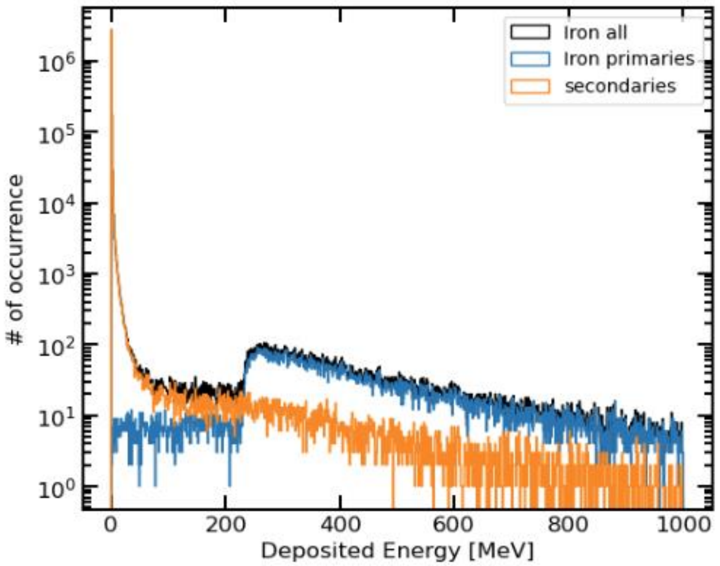
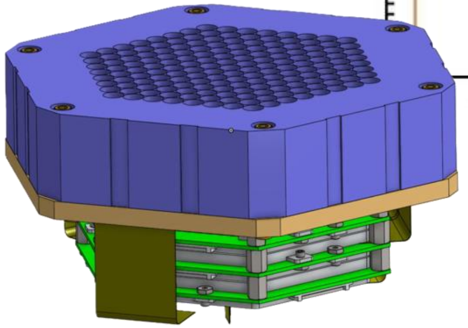
Deposited Energy

- We use the HFT full focal-plane configuration to model how particles interact with all the different components using ***GEANT4***.
- We obtain the deposited energies produced by direct hits and secondary hits on the wafer, obtaining the **distribution of energy deposited events.**









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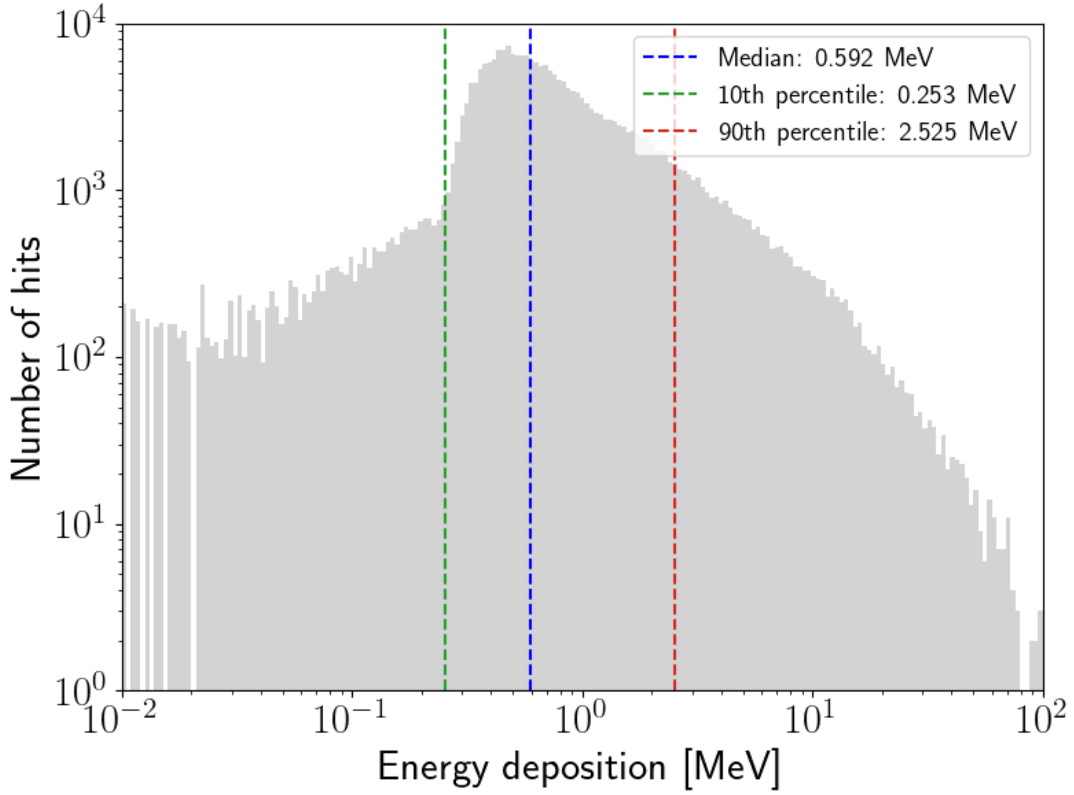

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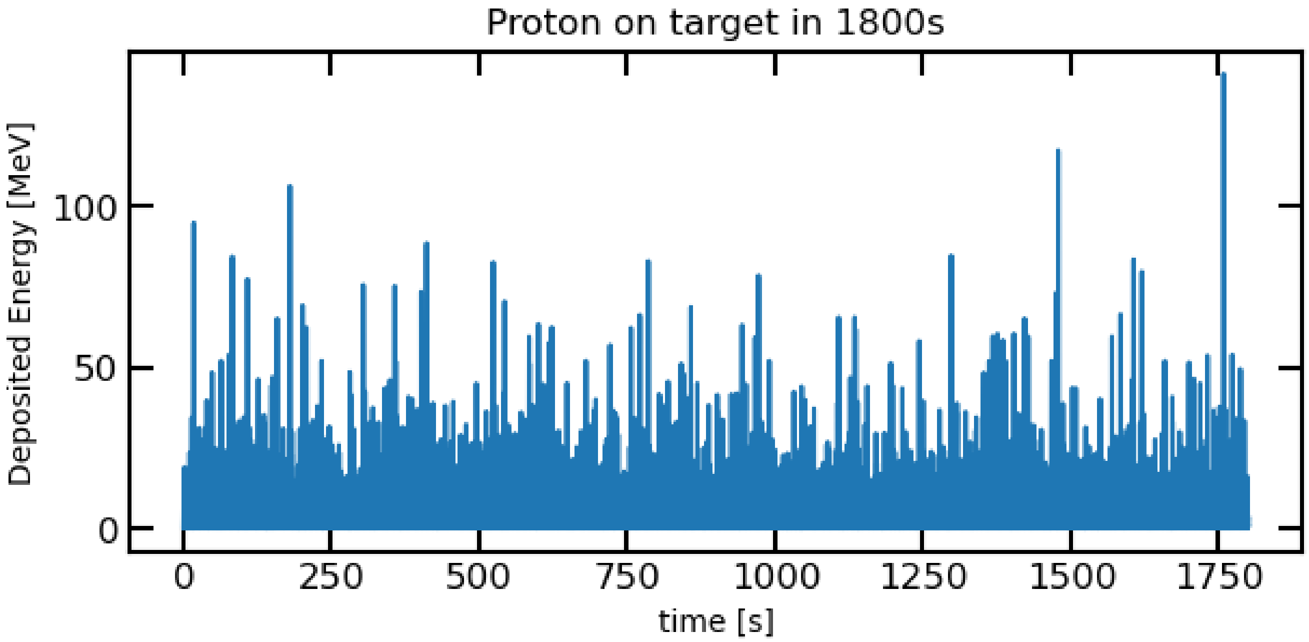
TOD

- As CR impact can be described by poissonian statistic, we can generate an energy deposition TOD using random numbers.



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Thermal Simulations

- Two different methodologies to solve the heat equation has been adopted:

1. **Comsol-based simulator** solving the detailed full focal plane design.
2. Numerical solver of the heat equation for the **“thin plate” approximation**.

- In the upcoming slides we will add some detail on the numerical solver and compare the results obtained with both methods.

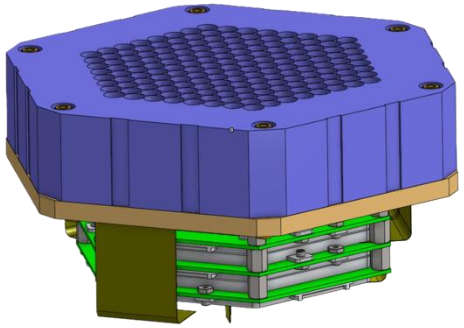
Thin Plate approximation

- This approximation is ruled by the next equations, which describe a system formed by two thermally linked thin layers, one for the detector wafer and the other for the horns array.

$$\rho_W c_W(T_W) t_W \frac{\partial T_W}{\partial t} = k_W(T_W)\nabla^2 T_W + Q_{\mathrm{CR}}(t) - \frac{T_W - T_H}{R_{\mathrm{eq}}},$$

$$\rho_H c_H(T_H) t_H \frac{\partial T_H}{\partial t} = k_H(T_H)\nabla^2 T_H + \frac{T_W - T_H}{R_{\mathrm{eq}}},$$

$$Q_{\mathrm{CR}}(t) = \frac{E_{\mathrm{dep}}}{2\tau} \exp\left(-|t - t_{\mathrm{hit}}|/\tau\right),$$



- Applying also Robin boundary condition to model the heat dissipated by the cryostat

$$k_i \frac{\partial T_i}{\partial n} = \frac{G}{A}\left(T_i - T_{\mathrm{bath}}\right),$$

Thin plate: Results

- We run the model for the next thermal parameters related to Si:

$$k_{Si} = 100 \left(\frac{T}{1\mathrm{K}}\right)^3 \left[\frac{W}{m\ K}\right];$$

$$c_\rho(T) = \frac{12\pi^2}{5}\frac{N_A k_B}{M}\left(\frac{T}{\theta_D}\right)^3 \left[\frac{J}{K\ m^3}\right],$$

$$G_{bath} = 3.3e-4\left[\frac{W}{K}\right]$$

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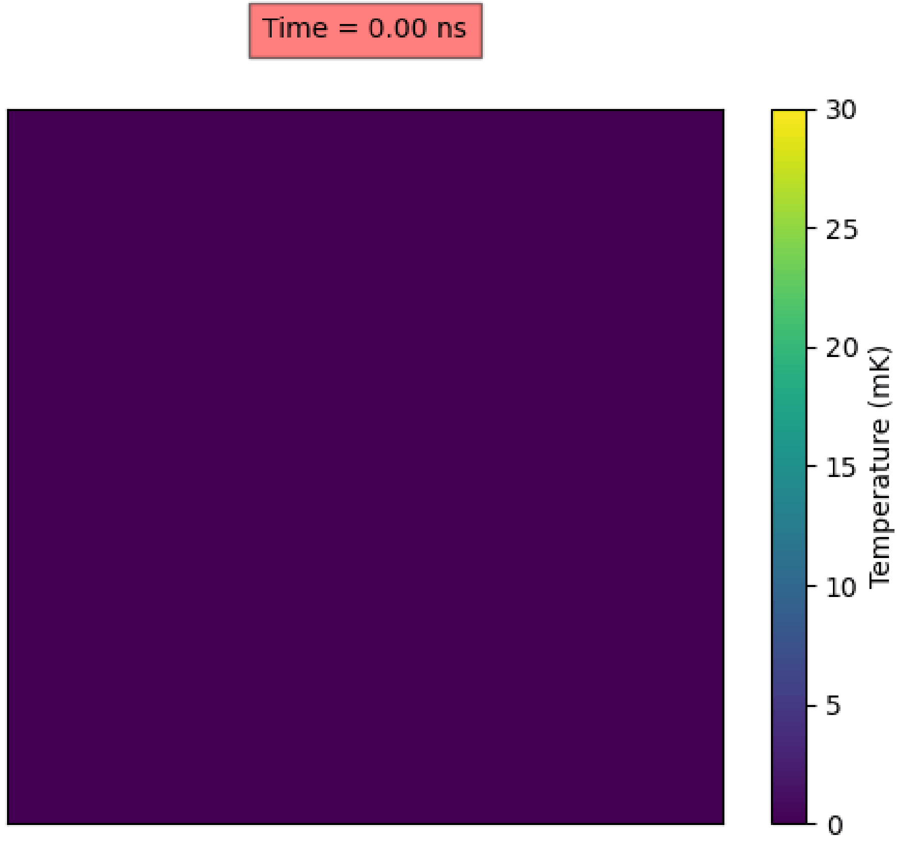
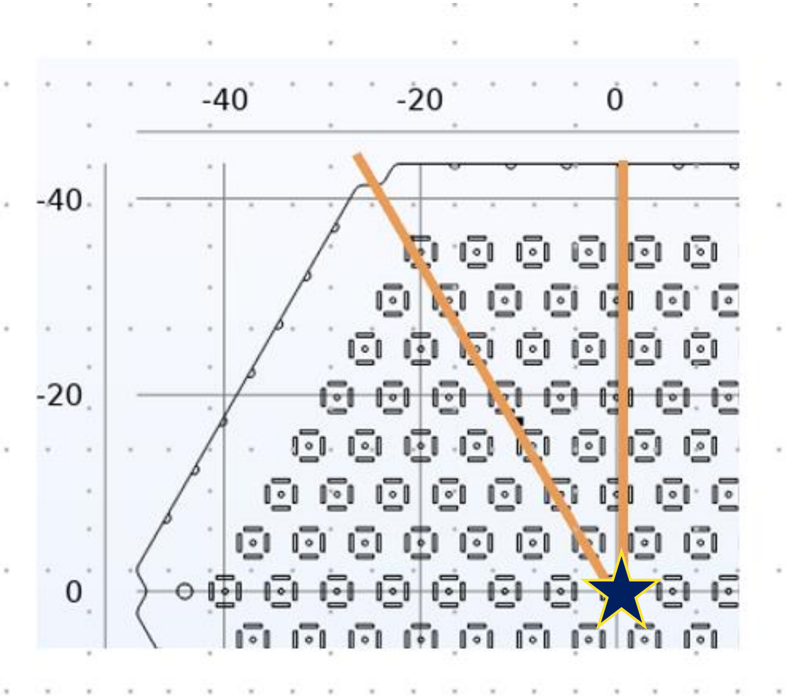


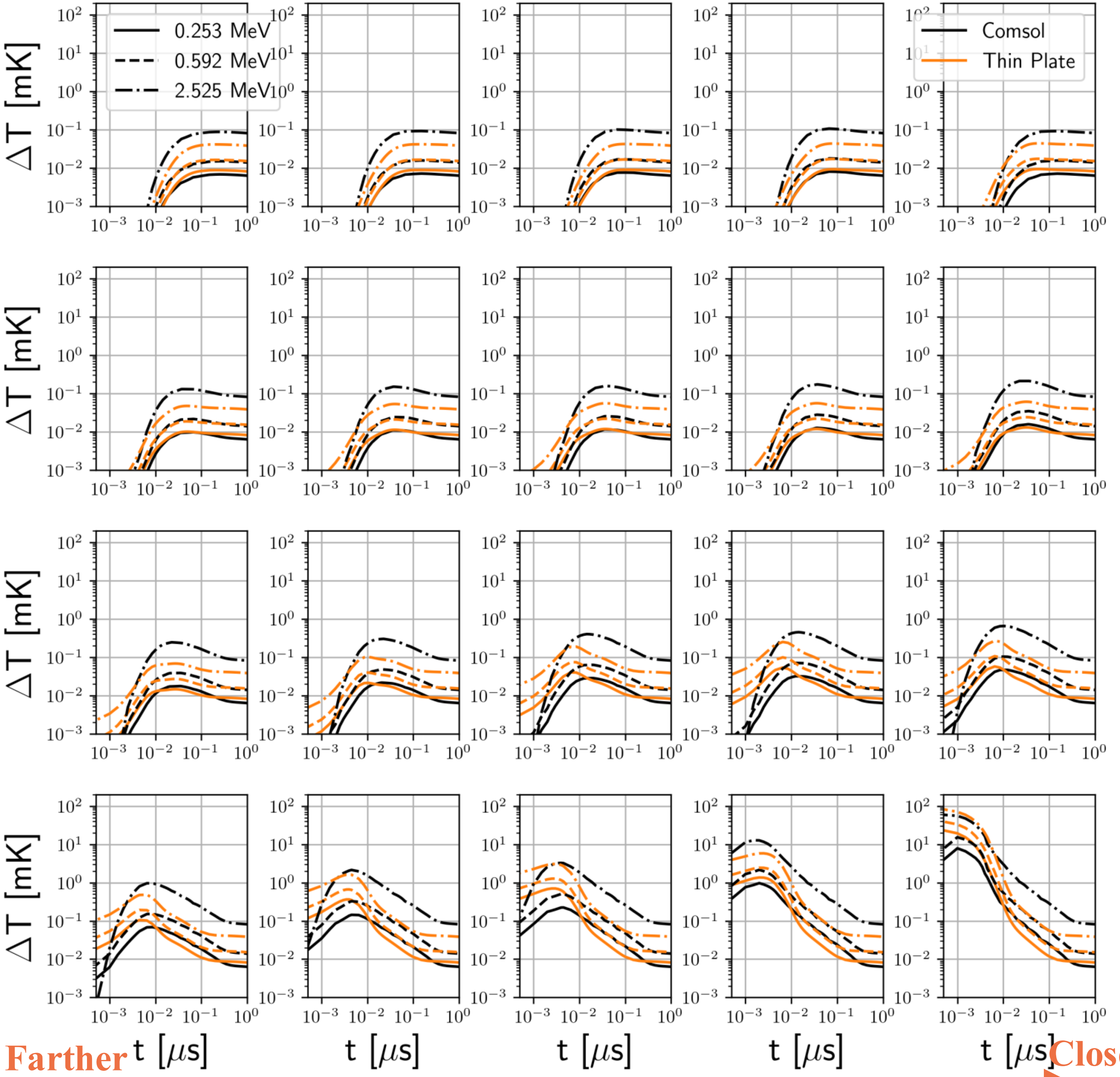
VS Comsol

- We recover the thermal fluctuations at different positions related to different detectors to compare both models.



Farther

Closer

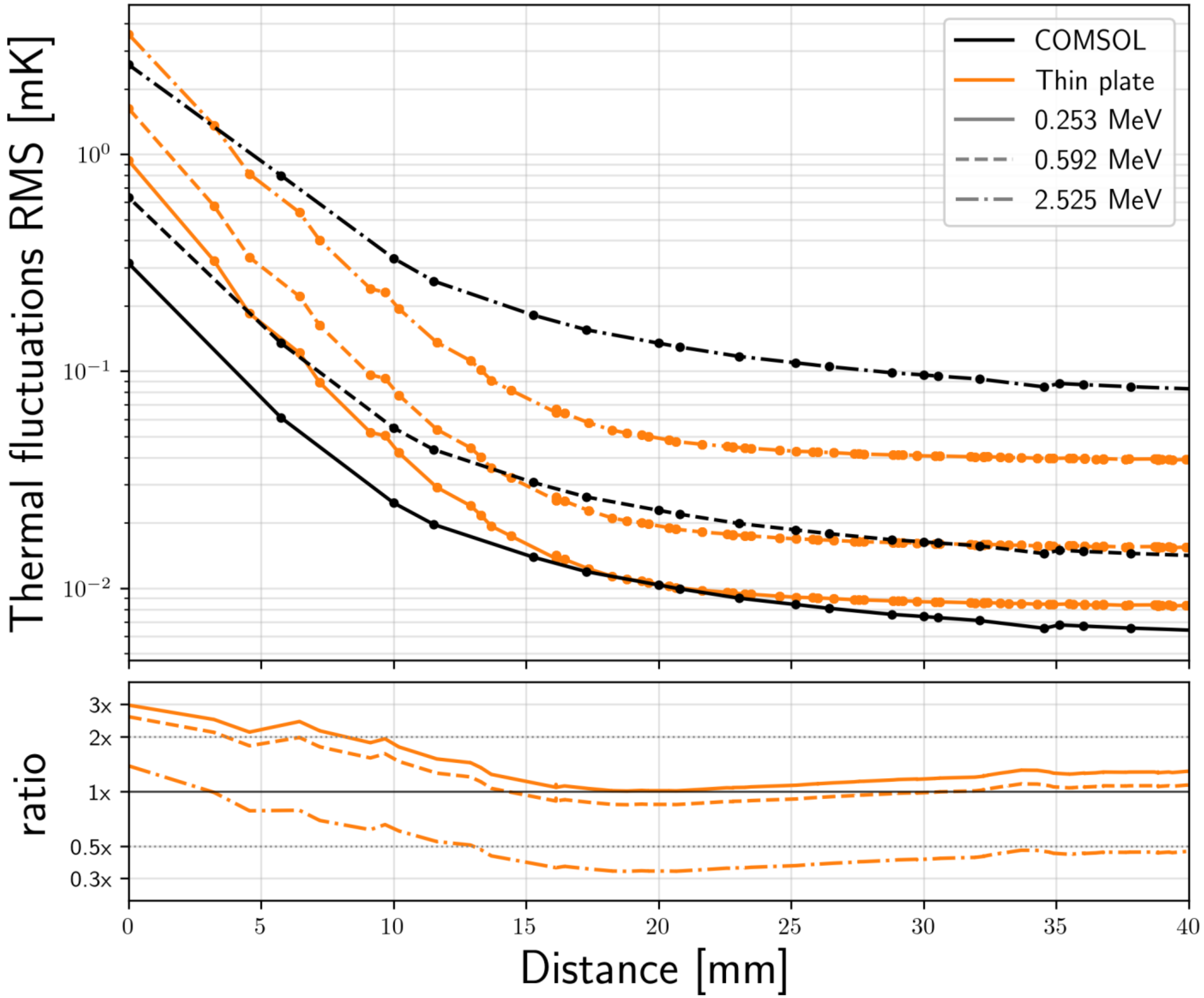


Farther

Clos

RMS values

- As detectors work as a low pass filter, a better statistic to compare both models is the RMS of the fluctuations
- We spot different energy scaling issues and inconsistencies at the smaller scales.
- Inconsistencies at smaller scales may be produced by 3D diffusion effects.
- Energy scaling issue is being studied and may be related to COMSOL accuracy.

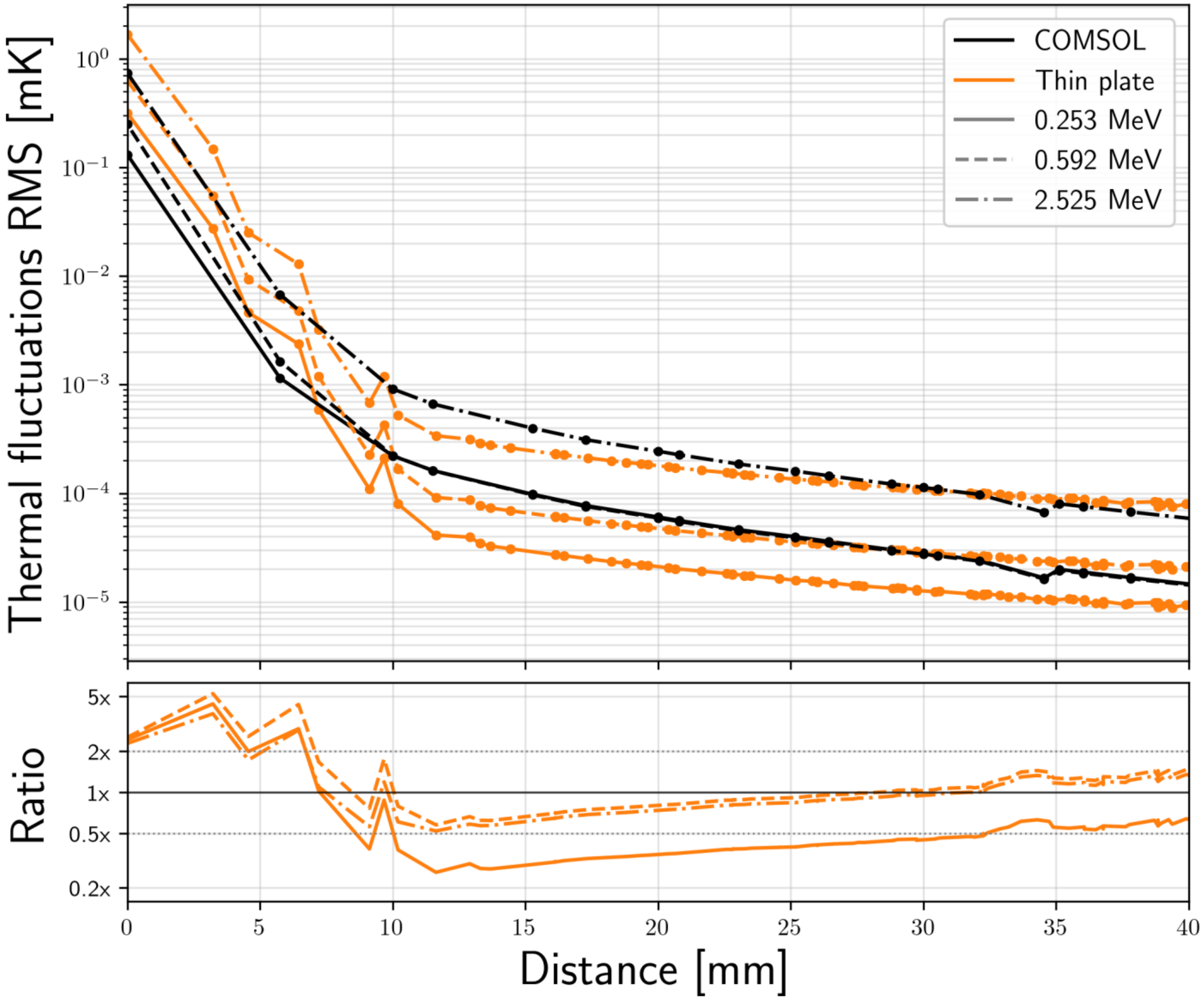


Aluminium Horns

- We made the same comparison for another case of study in which horns are made of aluminum.

$$\vec{k}(T) = (17.05, 17.05, 12.80)\frac{\mathrm{W}}{\mathrm{m\,K}}\left(\frac{T}{1\,\mathrm{K}}\right)^{0.14}$$

$$c_\rho(t) = 648 \times 10^{-6}\frac{\mathrm{J}}{\mathrm{K\,m^3}}\left(\frac{T}{1\,\mathrm{K}}\right)^{3}$$



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Detector Response

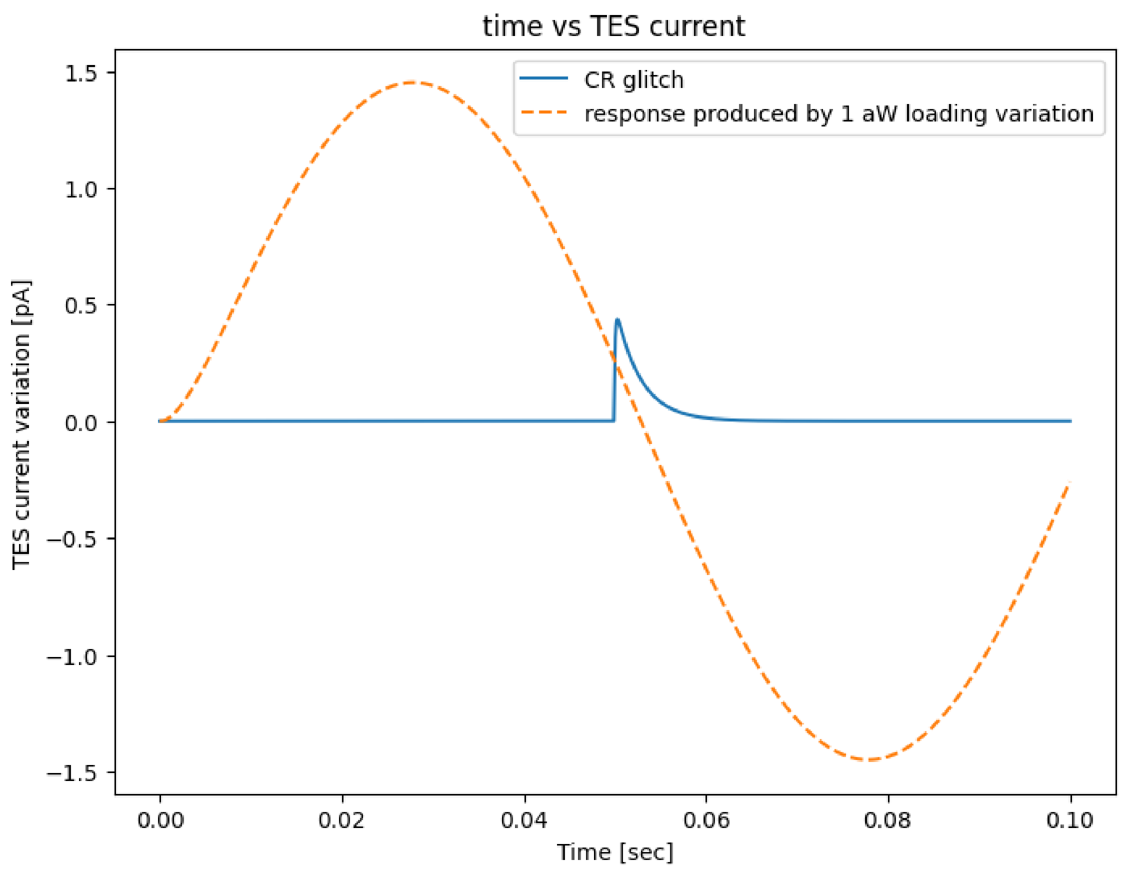
- Thermal fluctuations can be transform into detector response by solving the next expressions:

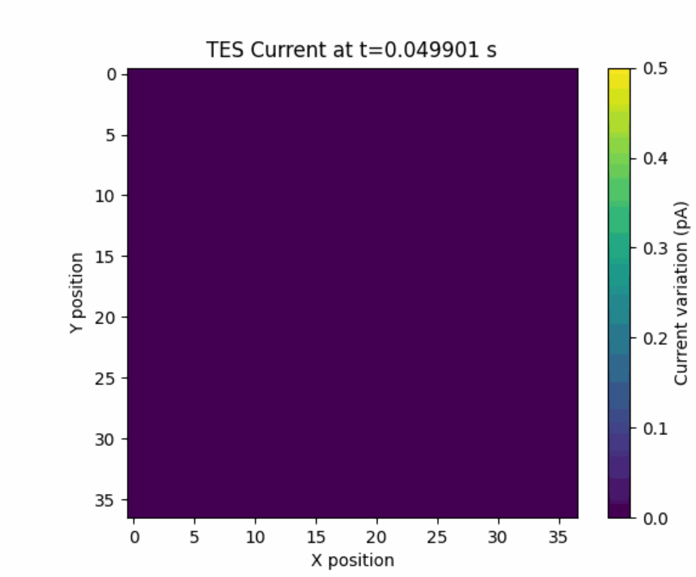
$$C\frac{dT}{dt} = I^2R(T,I) + P_{\text{opt}} - K(T^n - T_b^n),$$
$$L\frac{dI}{dt} = V_{\text{bias}} - I[R(T,I) + R_L].$$

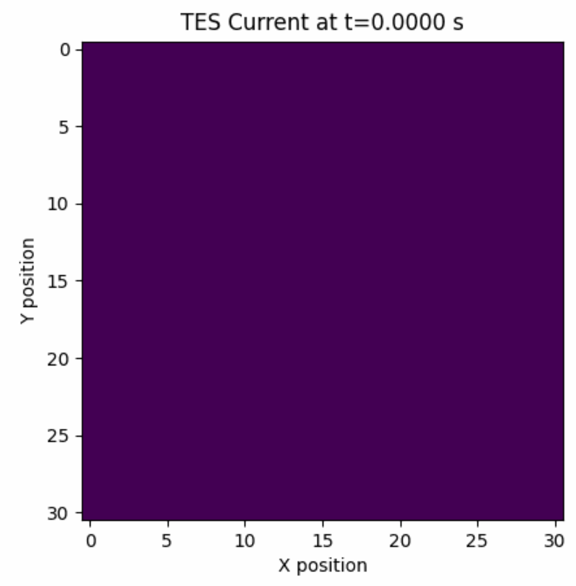
- A numerical solver of this expressions has been already implemented by Tomasso Ghigna, [github link].

Detector Response

- Adding now the thermal fluctuations as bath temperature, we can obtain TES signal







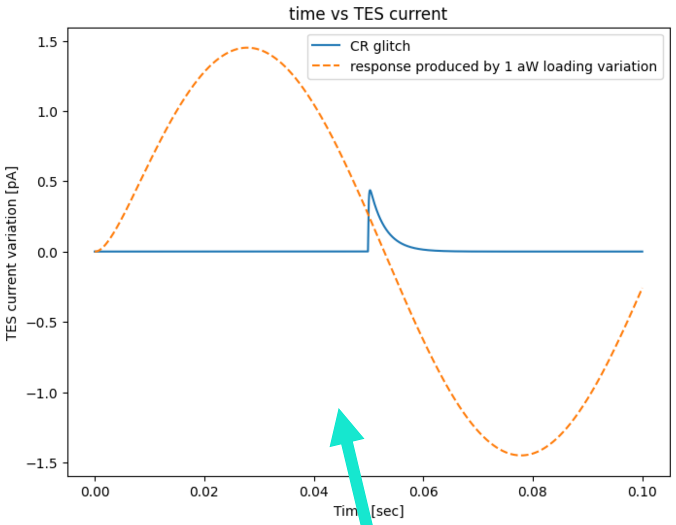
Noise level contribution

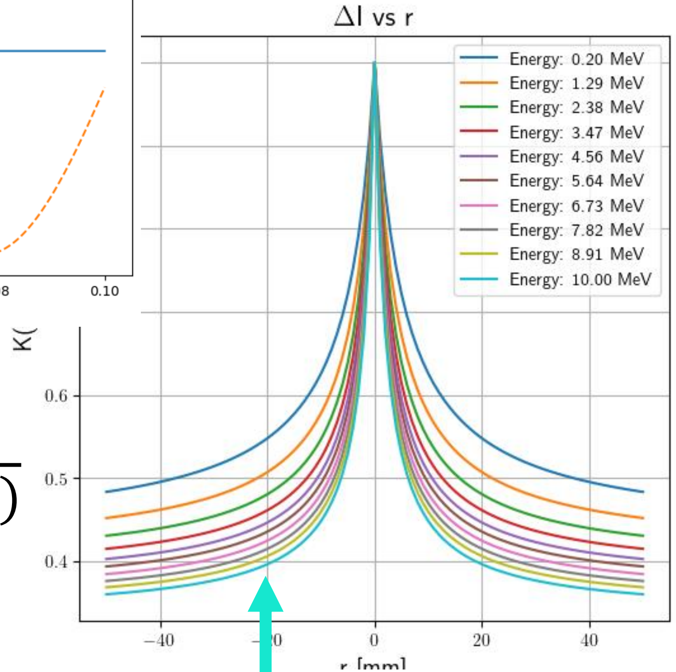
- We now proceed to derive the expected CR contribution on detector noise and its correlation.

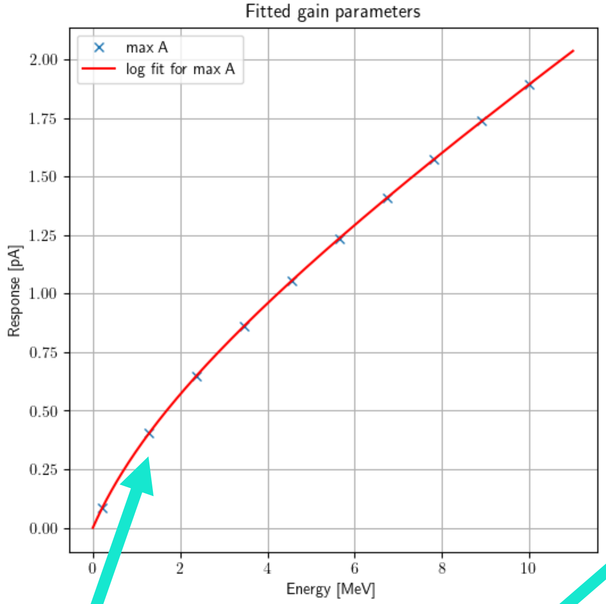
- We have analytically derived the next covariance matrix, to describe both the equivalent white noise level contribution and the correlation between pixels.

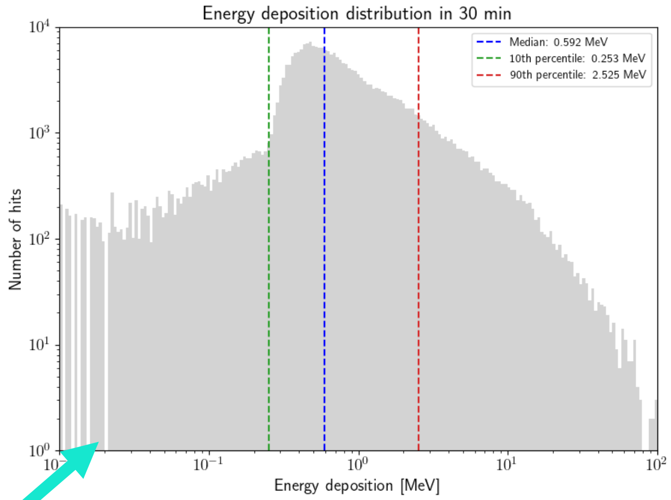
$$
\begin{aligned}
C_{ij}(qT_{\mathrm{samp}}) = \alpha_i \alpha_j \int_S K(\vec{r} - \vec{r_i}) K(\vec{r} - \vec{r_j})\, \mathrm{d}^2\vec{r} \int g(E)^2 \frac{\mathrm{d}N}{\mathrm{d}t\, \mathrm{d}S\, \mathrm{d}E}\, \mathrm{d}E \\
\times \int \langle (\Pi_{T_{\mathrm{samp}}} * s_r)(t) (\Pi_{T_{\mathrm{samp}}} * s_{r'})(t + qT_{\mathrm{samp}}) \rangle_r \, \mathrm{d}t,
\end{aligned}
$$

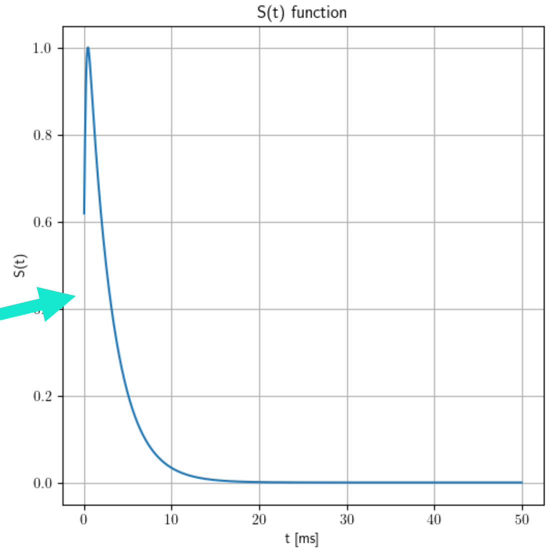
Noise level contribution: terms







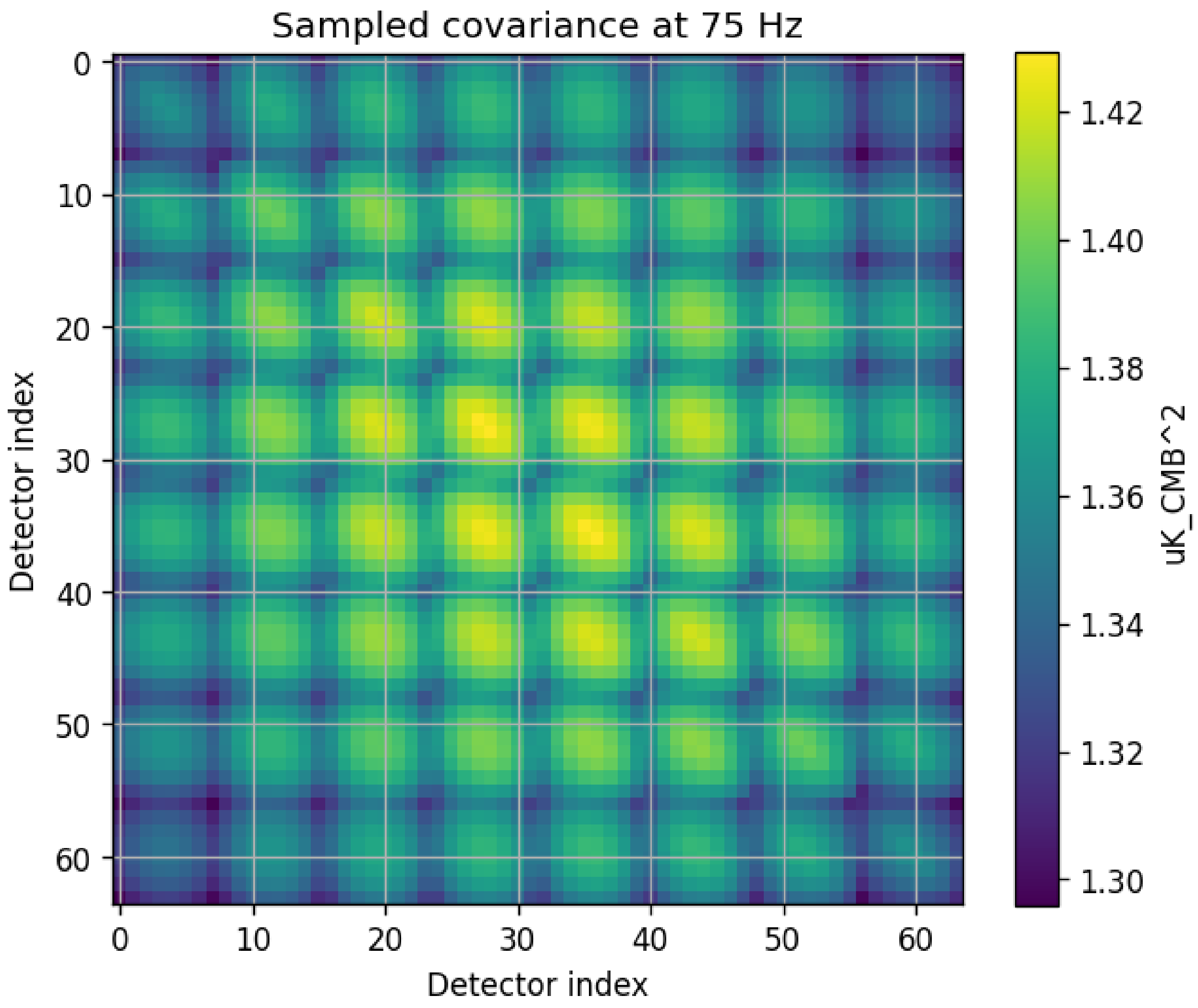




$$\Delta T_{CMB} = dI * \frac{dI/dP}{k_b \Delta\nu g(x_0)}$$

$$C_{ij}(qT_{\mathrm{samp}}) = \alpha_i\alpha_j \int_S K(\vec{r}-\vec{r_i})K(\vec{r}-\vec{r_j})\,\mathrm{d}^2\vec{r} \int g(E)^2 \frac{\mathrm{d}N}{\mathrm{d}t\,\mathrm{d}S\,\mathrm{d}E}\,\mathrm{d}E$$
$$\times \int \langle (\Pi_{T_{\mathrm{samp}}} * s_r)(t)(\Pi_{T_{\mathrm{samp}}} * s_r)(t+qT_{\mathrm{samp}})\rangle_r\,\mathrm{d}t,$$

Covariance Matrix result



For an 8x8 grid of detectors

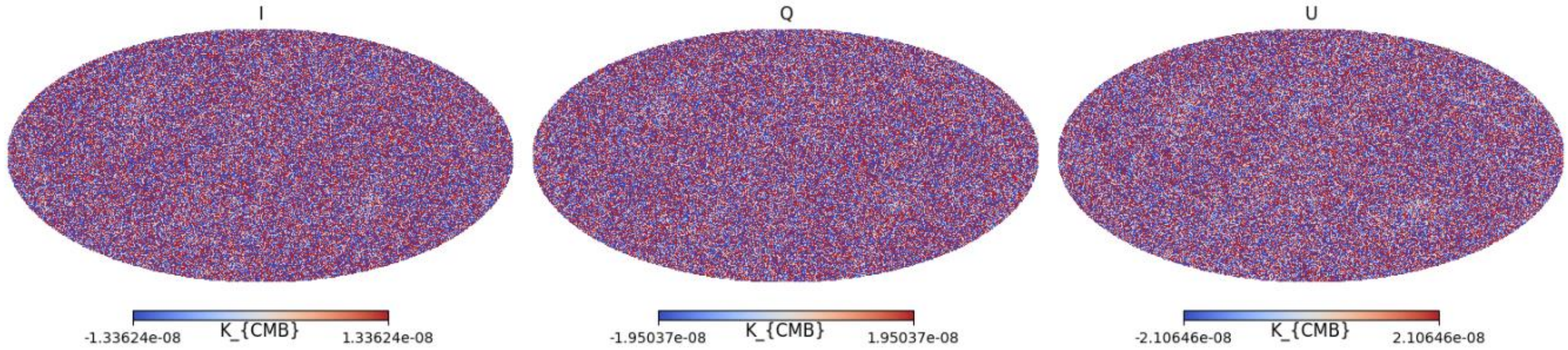
Map level projection

- Using LiteBIRD-sims toolbox, We have simulated the map level contribution of CRs after 1 year using 2 different methods:

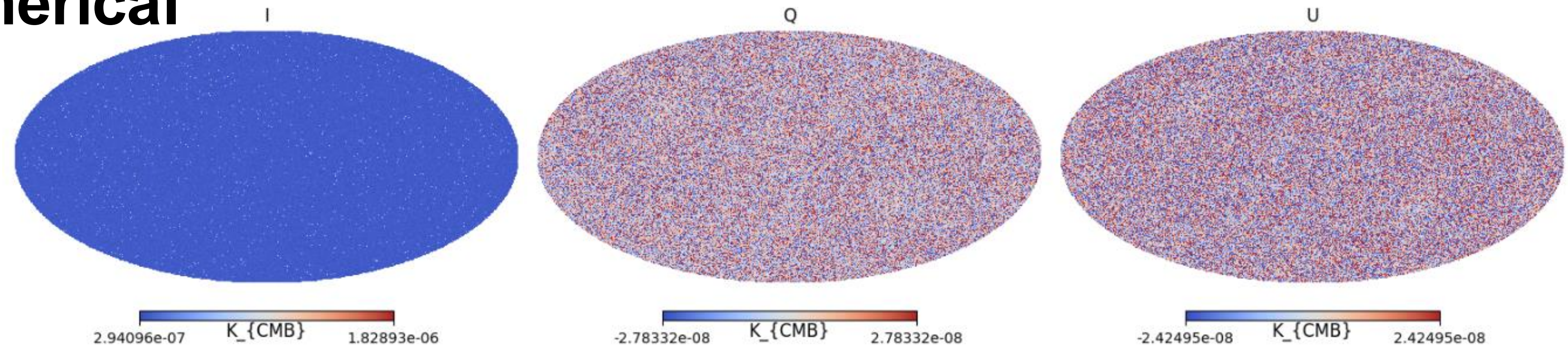
1. From the previously derived covariance matrix.
2. Creating a full simulation with random deposition events generated considering all the simulated information.

Map level projection

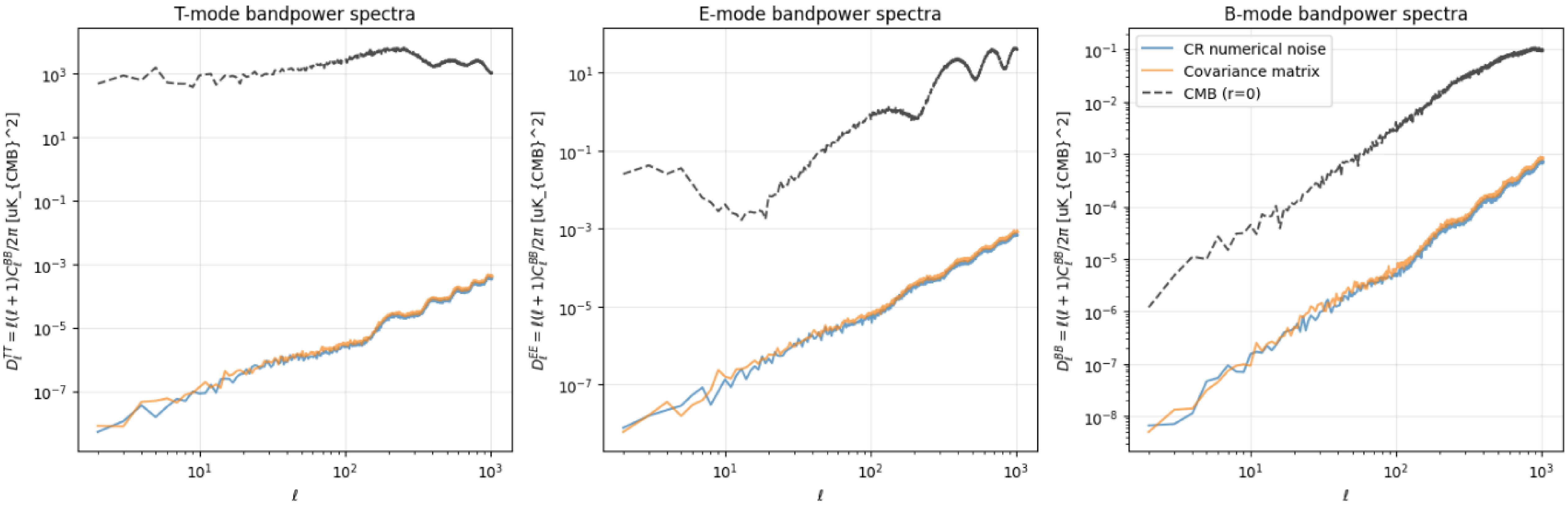
Covariance



Numerical



Power spectra



Conclusions & Future Work

- We present a full pipeline to simulate CR influence, that allow us to derive detector response and to estimate map level noise contribution
- We have derived a thermal model that reduces computation time from several hours to less than a minute while recovering similar thermal fluctuations.

- Explore thermal parameters to understand if the agreement between models can be improved.
- Study different configurations of the focal plane to reduce CR influence.
- Apply simulations to the study of possible mitigation techniques