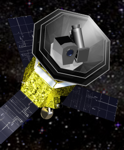

# Progress towards a tool for evaluating the effect of common-mode cosmic ray systematic effects – the LiteBIRD case

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[d]*KEK*
[e]*Saitama U.*

# The summary slide

**Why do we care?**

- Any space mission will interact with its radiative environment in some way. CMB missions are very sensitive and use bolometric detectors. This gives them vulnerability (see Planck case).

**What is the goal?**

- Estimate the contribution of cosmic rays to the overall thermal noise, as well as its attributes. Check the effect in projected sky maps.

In this talk, we present our work towards an **end-to-end simulator tool for evaluating this effect in a future CMB space mission**. This has been applied to LiteBIRD.

Because of the complex relationship between the probable radiative environment, the interplayed thermal responses of various portions of telescope FPU, response of electronics, and specifics of mapmaking, **we follow each of these processes one by one in our simulator to evaluate CR effects**.

The simulator we produce gives us a **1st order estimate of CR noise**, whilst also providing an **iterative tool for probing hardware changes and mitigation mechanisms** in hardware and software.

# Common mode noise from cosmic rays (LiteBIRD case)

**What is the source of the common-mode noise?**

→ Galactic CRs impact telescope, and showers deposit energy into detector wafer

→ Particle energy heats up the wafer and thermal excursions propagate throughout

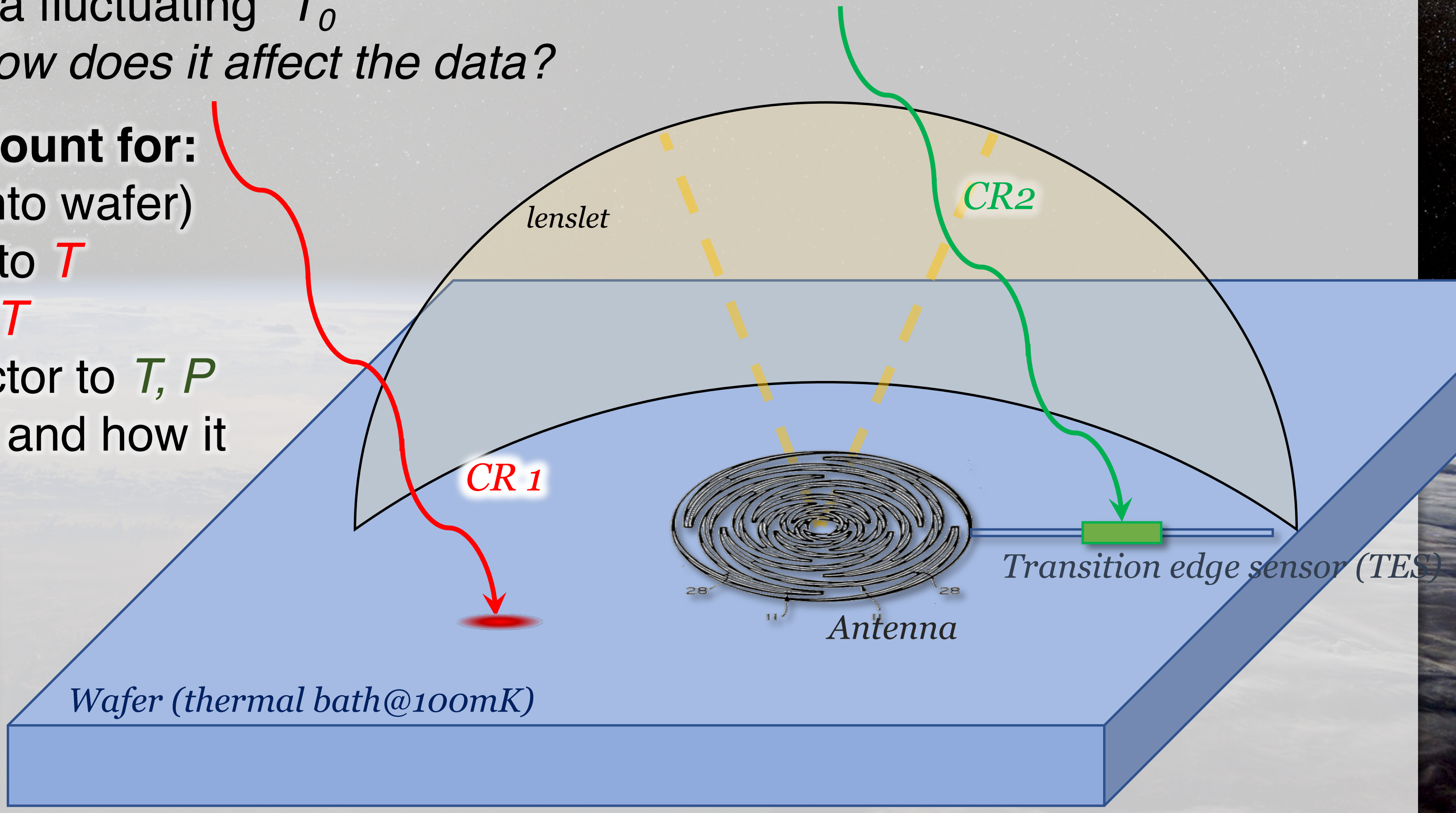
→ TES on wafer surface see this as a fluctuating "$T_0$"

→ *What is the scale of this effect? How does it affect the data?*

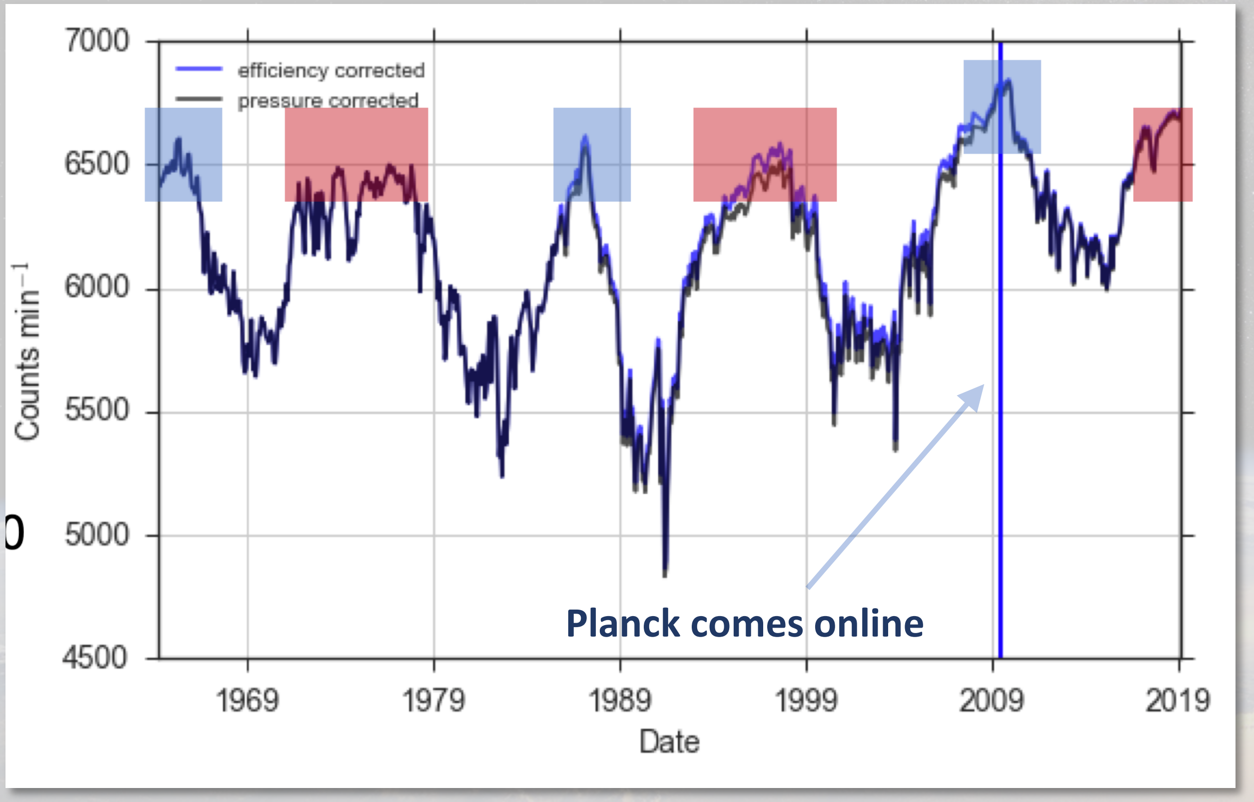
**How do we determine it? Must account for:**

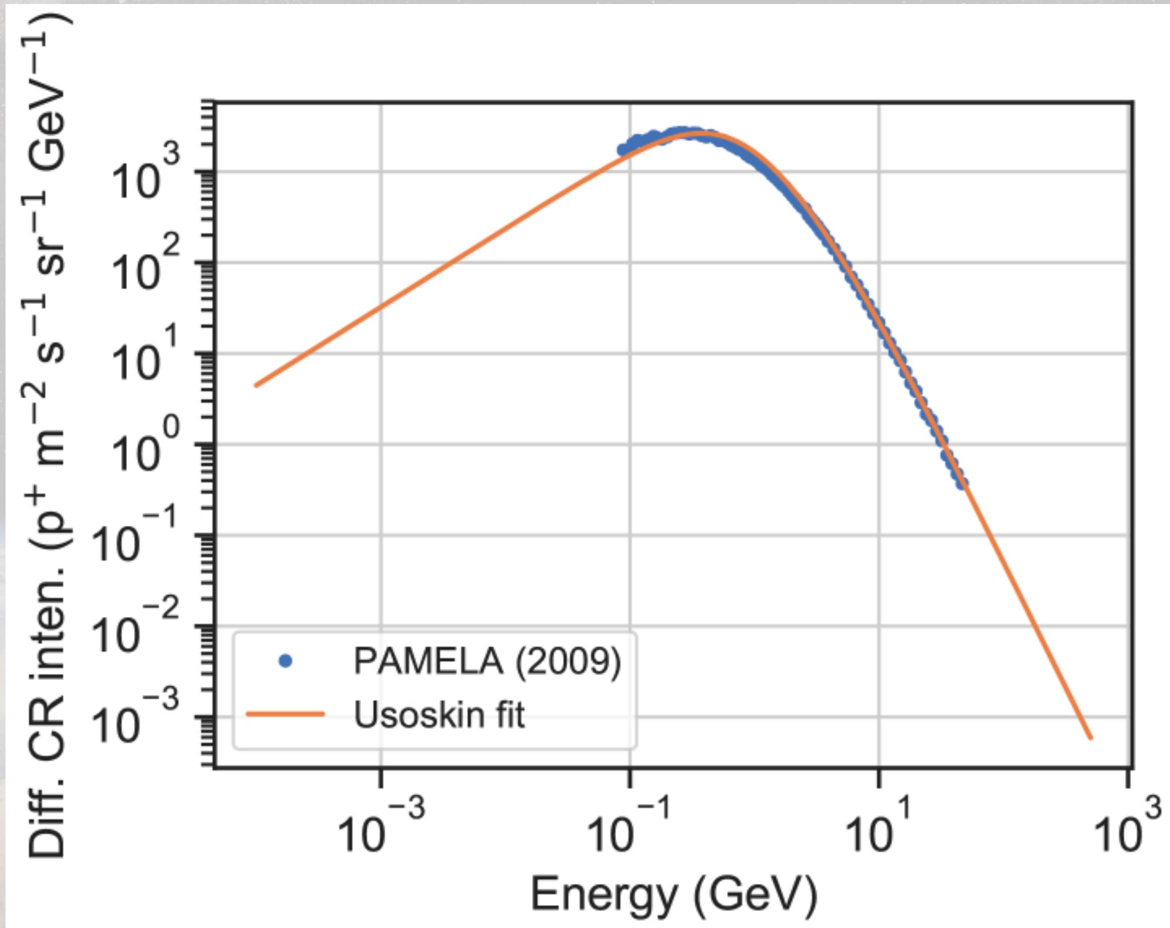
1. Radiative environment (energy into wafer)
2. Thermal response of wafer/FPU to *T*
3. Thermal response of detector to *T*
4. Electrothermal response of detector to *T, P*
5. Response of readout/decimation and how it propagates to sky data

Important note: CR susceptibility is strongly dependent on hardware configuration. So we cannot assume that the Planck case will define the next missions.



# Step 1: Radiative environment

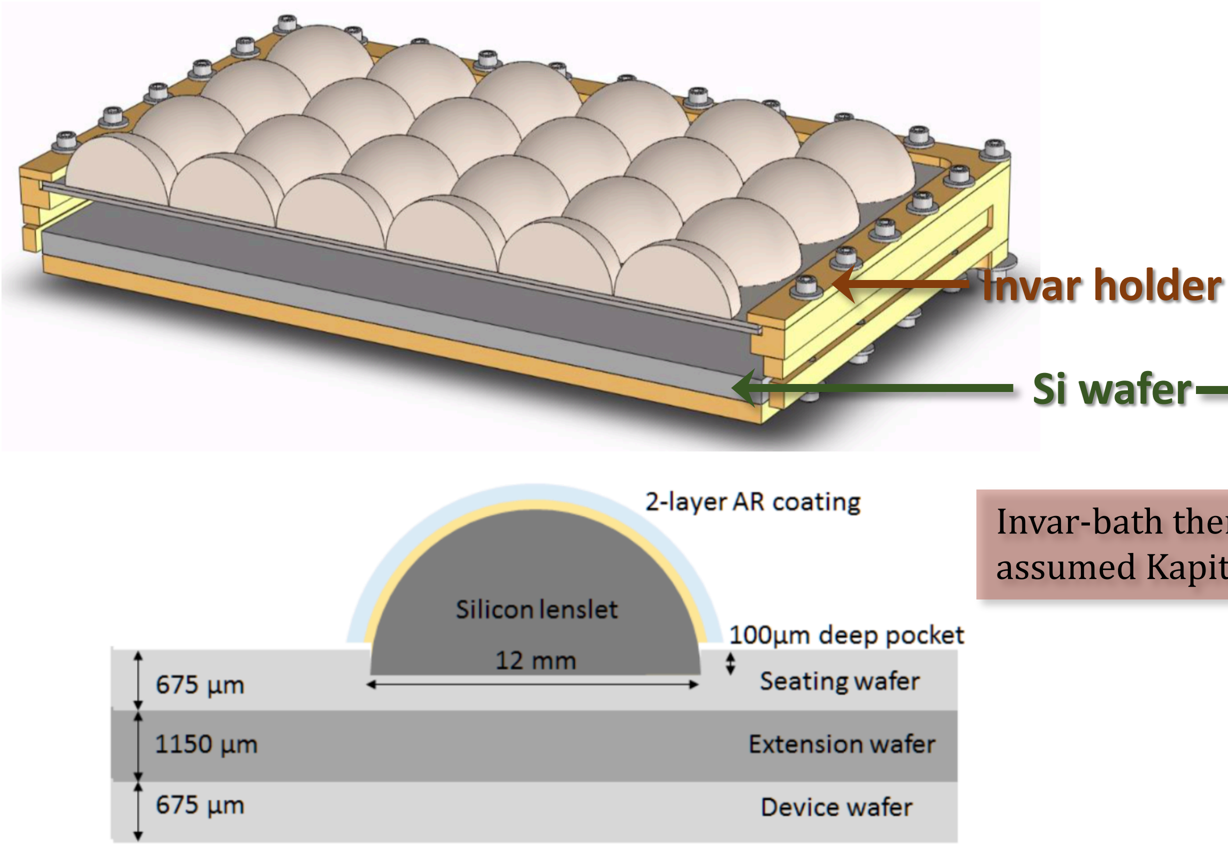


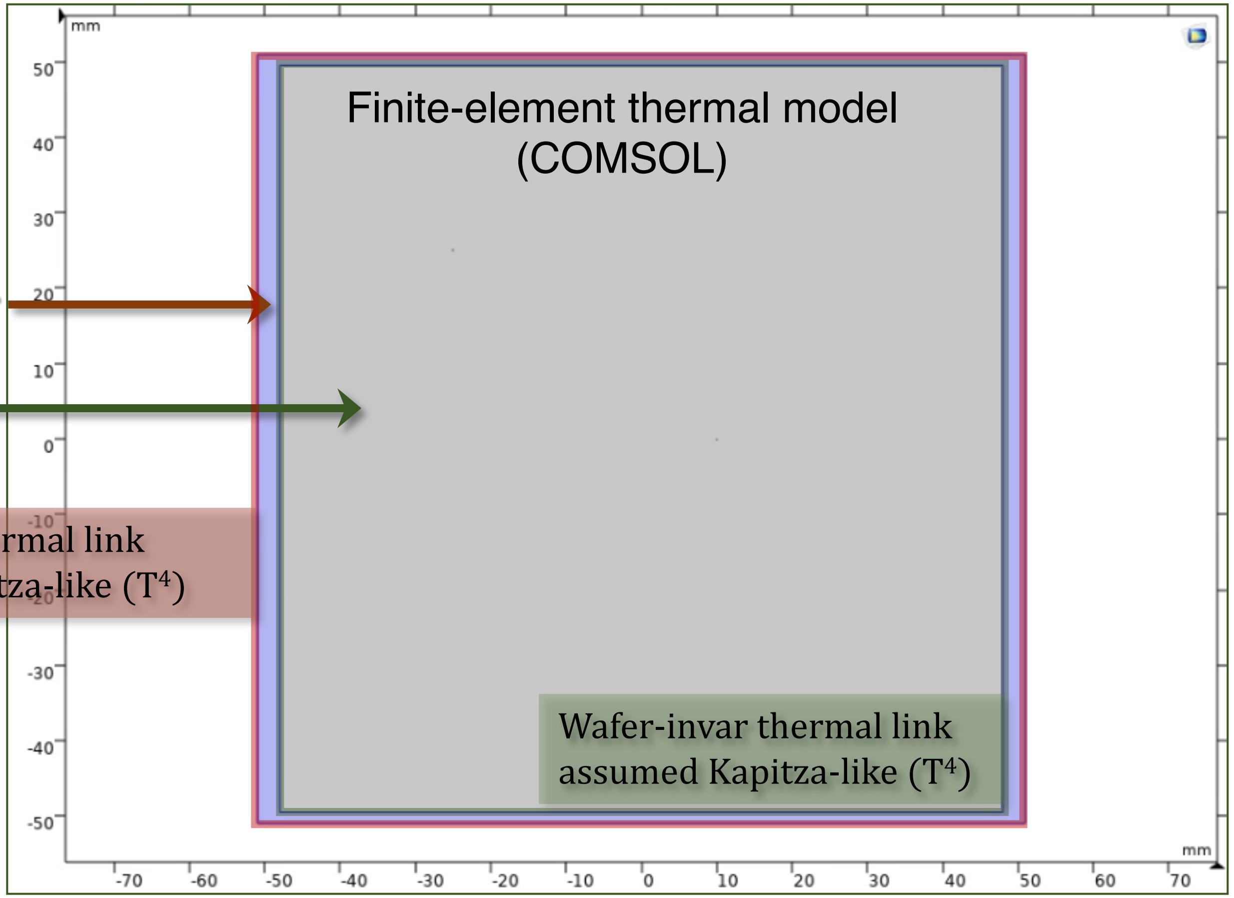

- Use PAMELA data from last solar minimum for input into end-to-end simulator.
- Use end-2009 case as worst-case scenario (Planck-era) and mid-2006 spectra as nominal case.
- We use the calculated impact rate (5 p cm$^{-1}$ s$^{-1}$) from previous work

# Step 2: Thermal Response of Wafer

Using the hardware example of LiteBIRD



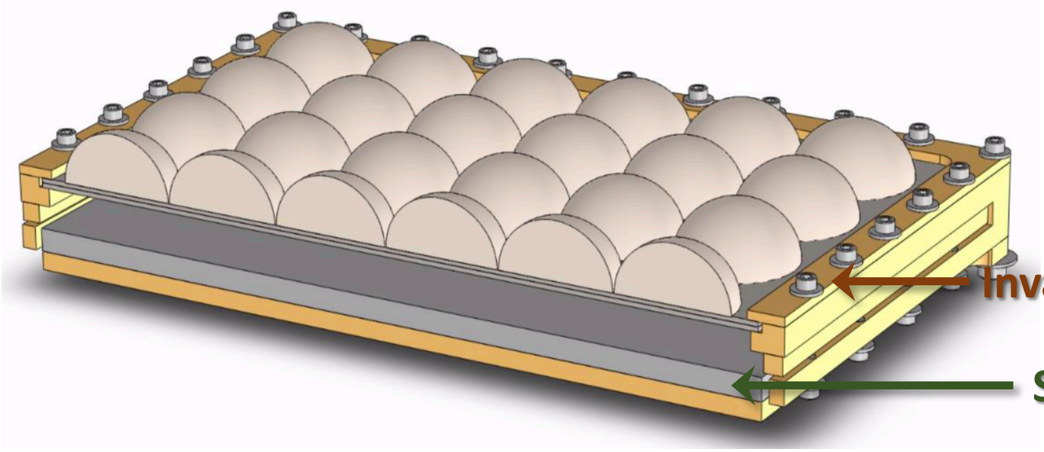

Design from LBNL (Berkeley)

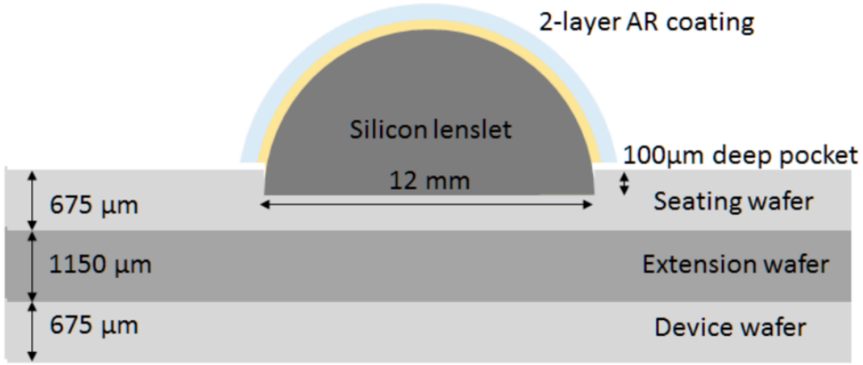


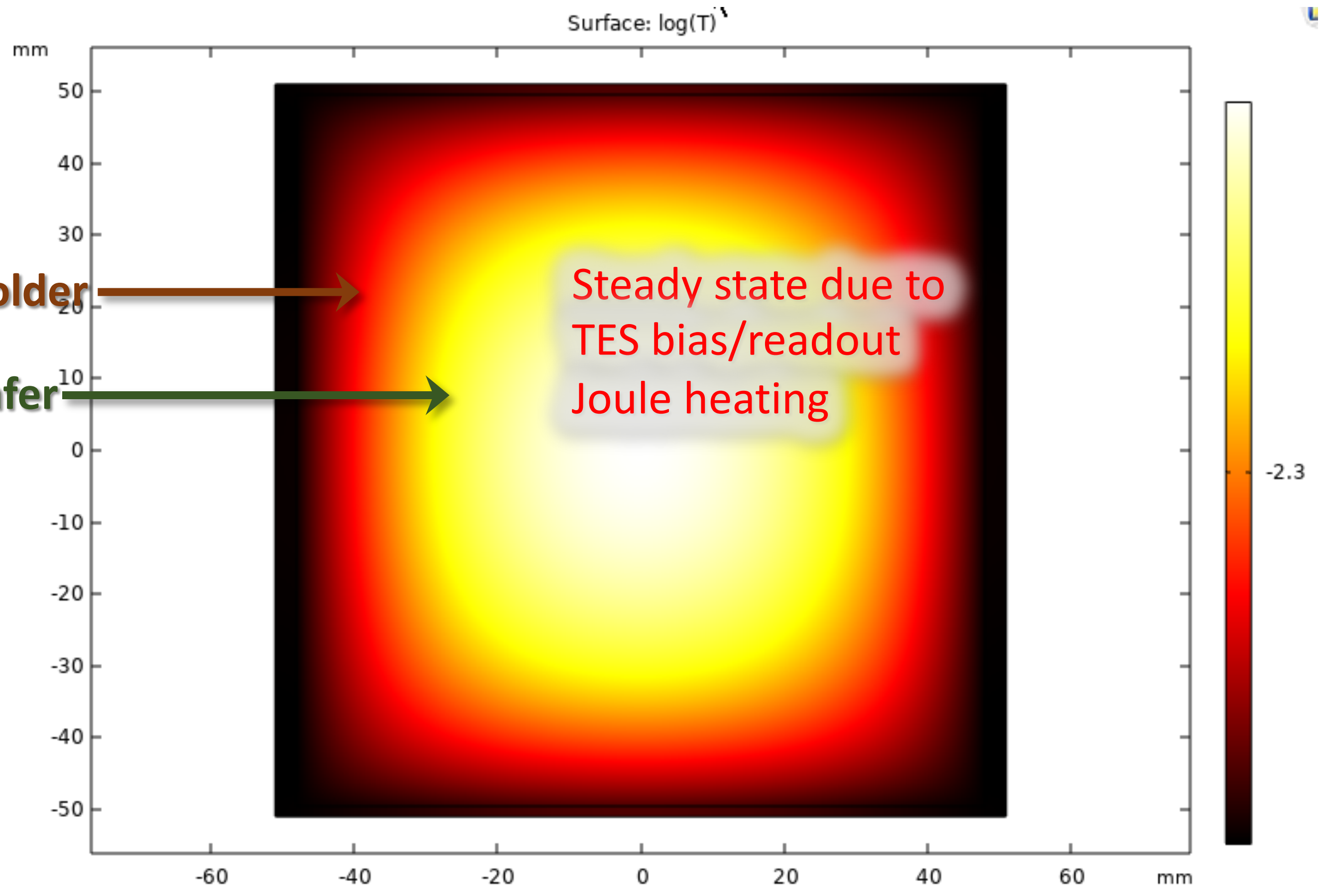

Finite-element thermal modelling (solution of diffusion equation inside a mesh)
→ Response of wafer temperature as a function of CR *E* and location

# Step 2: Thermal Response of Wafer

Using the hardware example of LiteBIRD



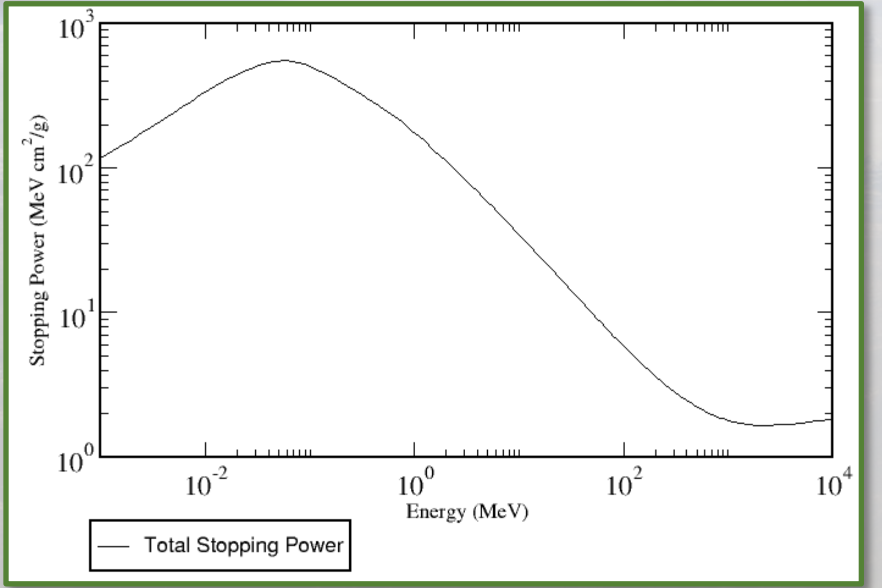



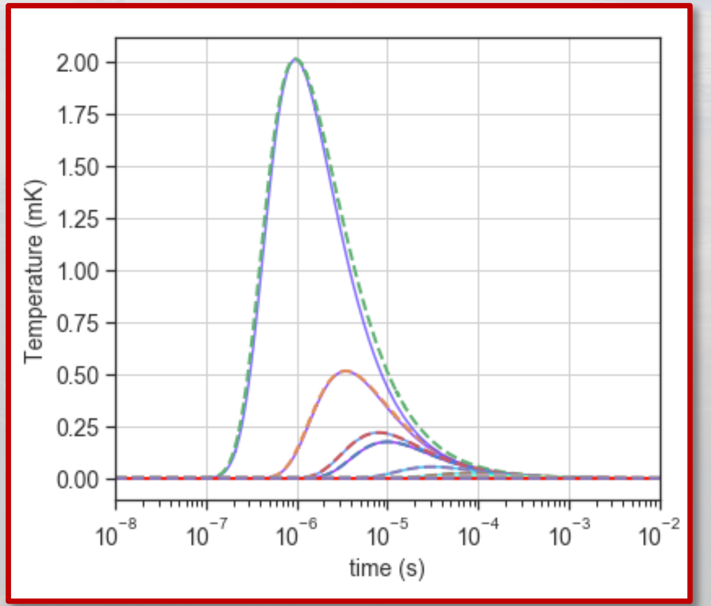

Finite-element thermal modelling (solution of diffusion equation inside a mesh)
→ Response of wafer temperature as a function of CR *E* and location

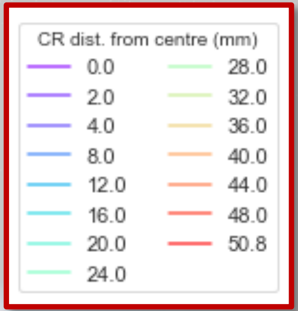
# Step 3 and 4: Generate TOD and get detector response

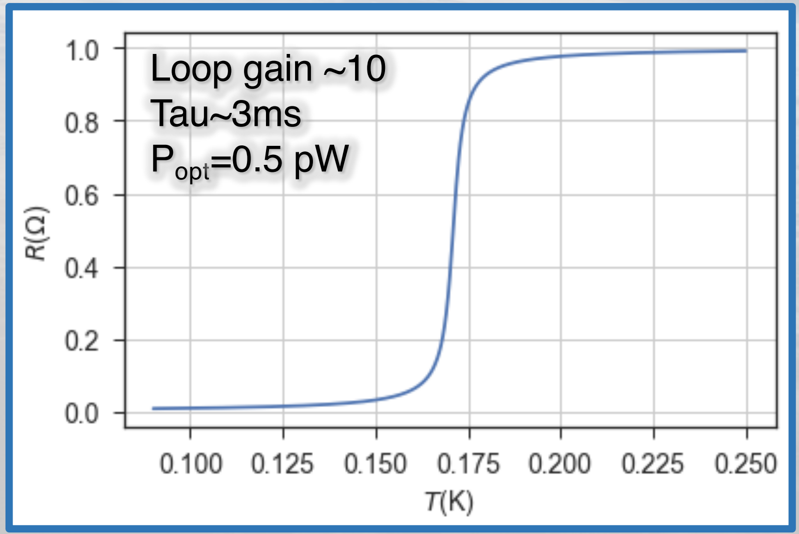
**Production of TOD (1 script to generate data products + 1 to generate events + 1 to generate TOD)**

- Assumed impact rate into wafer: 4 hits $cm^{-2}$ $s^{-1}$ x wafer surface area = **about 400 hits $s^{-1}$**
- Primary proton energy drawn from PDF of incoming energies with 50 MeV low *E* cutoff (Planck HFI)
- Random *xy* location on wafer surface, random striking angle $\theta$
- Energy into Si wafer calculated using stopping power range tables (PSTAR, NIST)
- Appropriate pulse is chosen from master pulse library array, scaled up/down in energy
- If location of CR is within area of TES, power ($E/\tau_{samp}$) $P = P_{opt} + P_{CR}$ where *E* is calculated assuming 100nm Pd absorber and 100 nm Al(Mn) thermistor (if thermistor is in impact area)
- $T_{wafer} \rightarrow I_{TES}$ (TES sim, T. Ghigna, IPMU)
- Decimated using 1st CIC comb based on LiteBIRD design → 10e3 Hz to 156 Hz

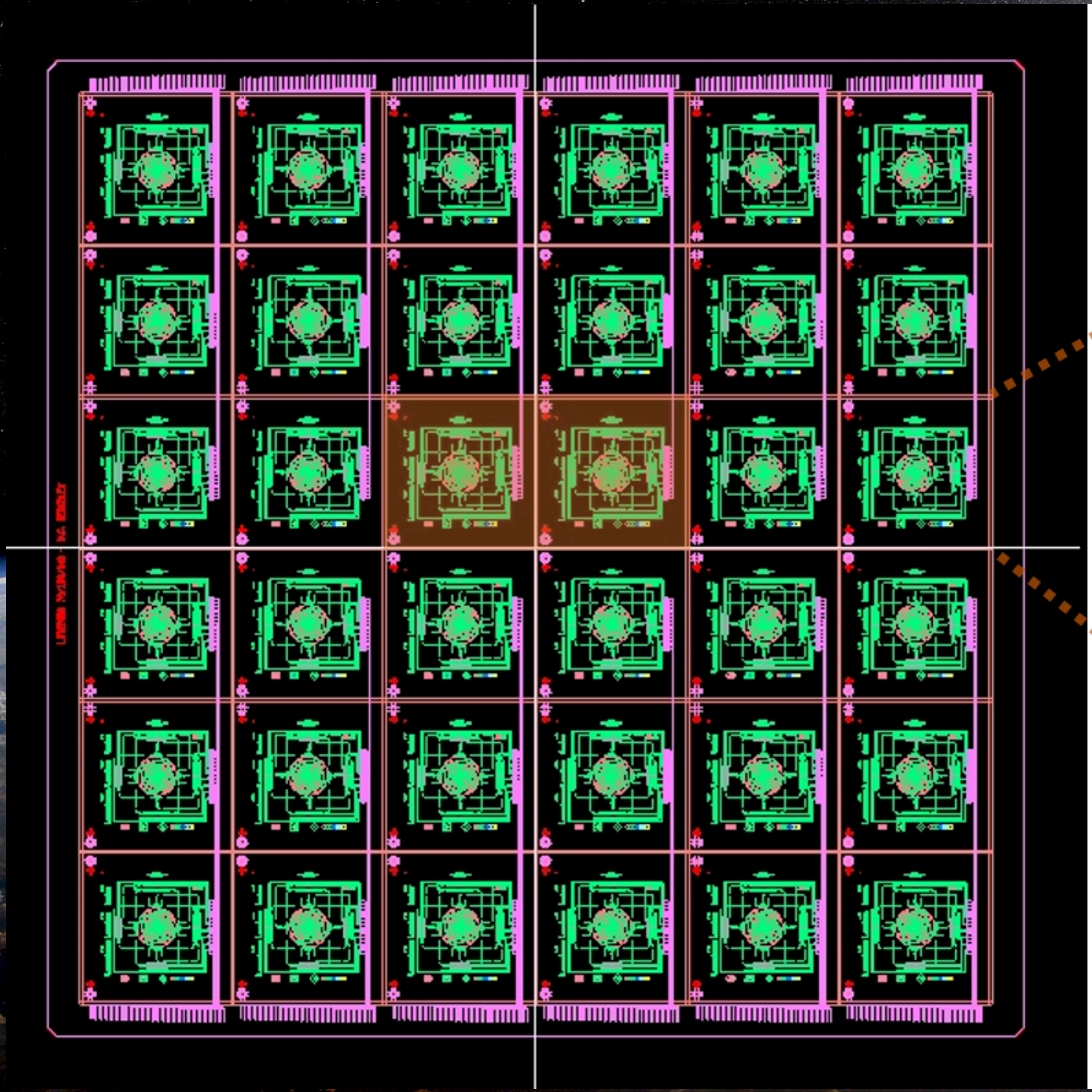


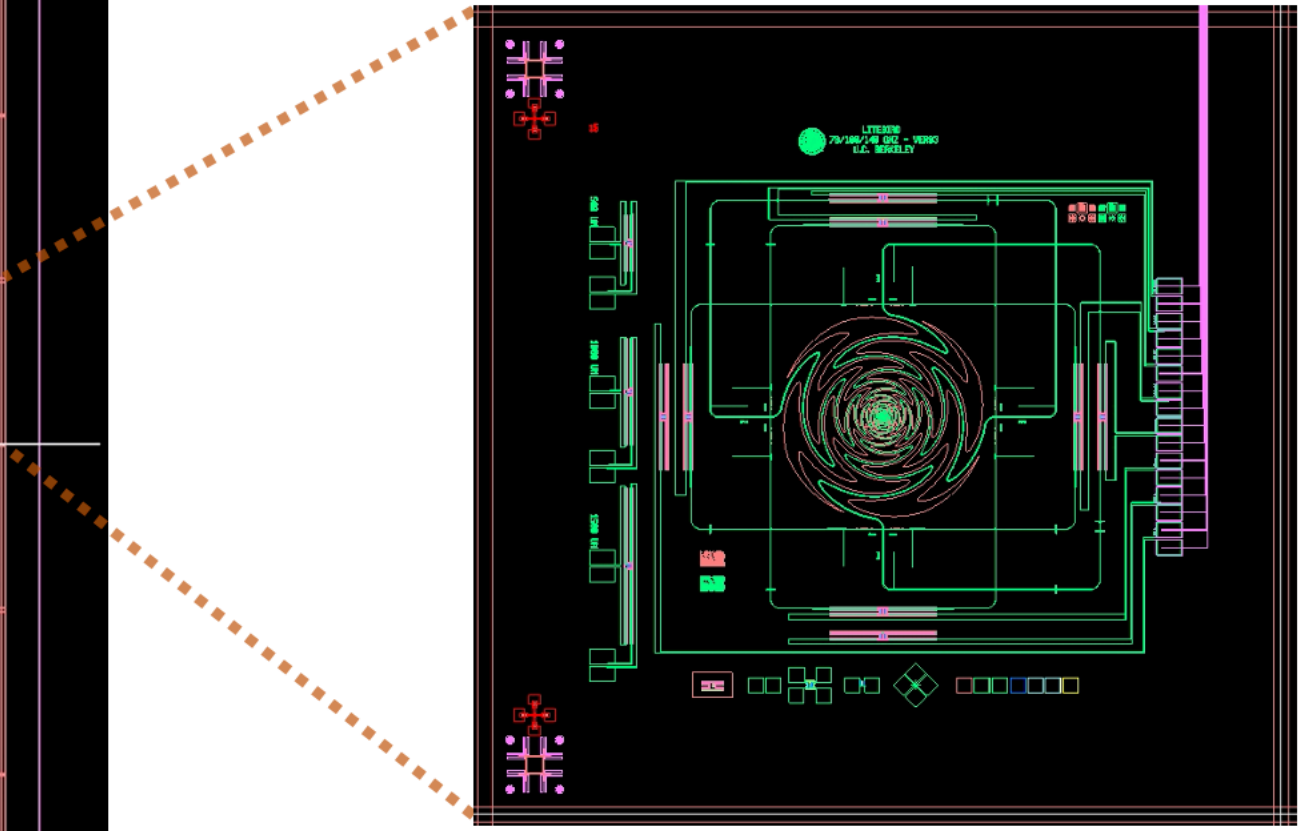



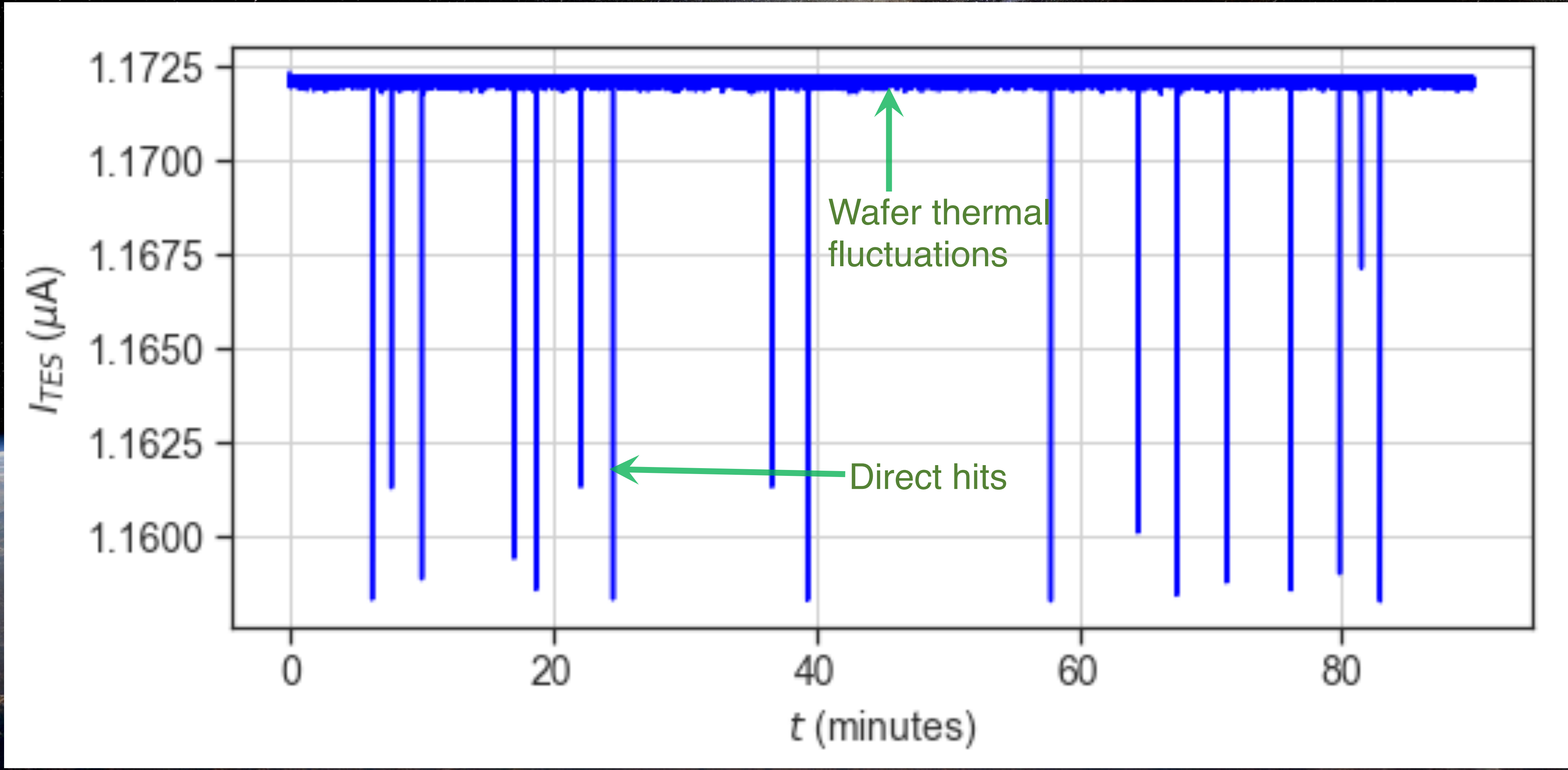
# Treatment of multiple TES



2 pixels with 16 TES

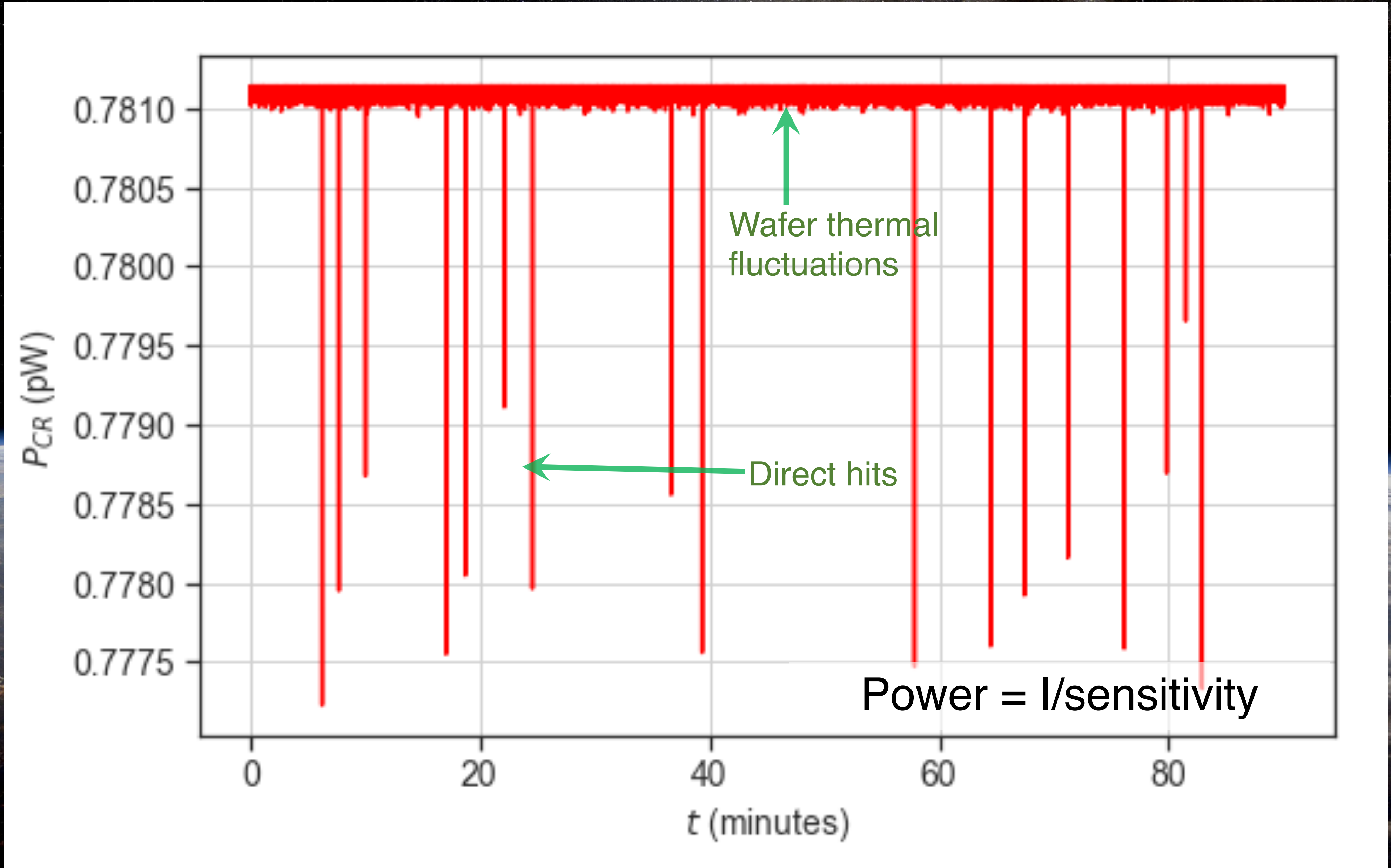


# Generated TOD

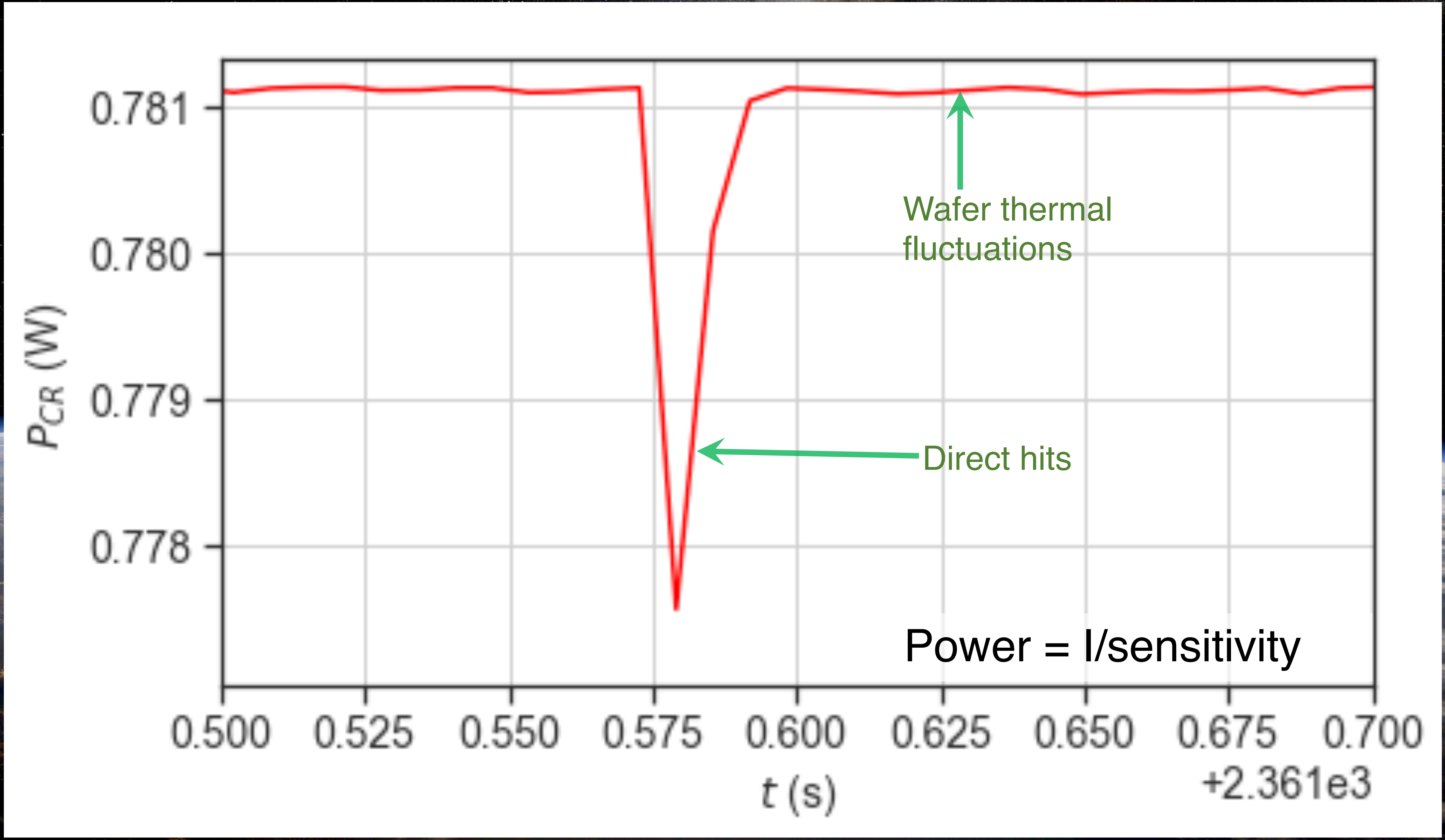



TES current

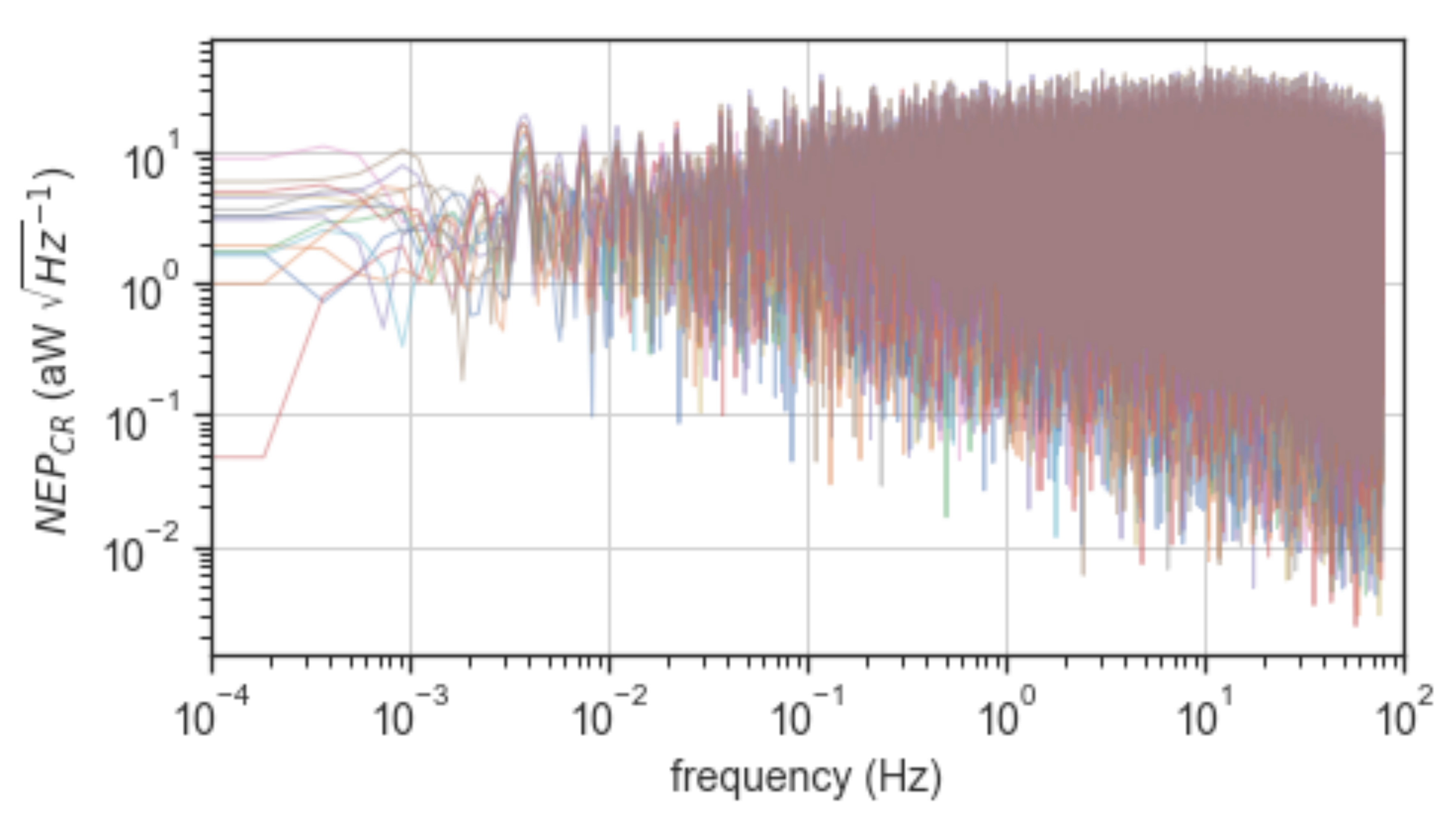
# Generated TOD



# Generated TOD



# Noise power



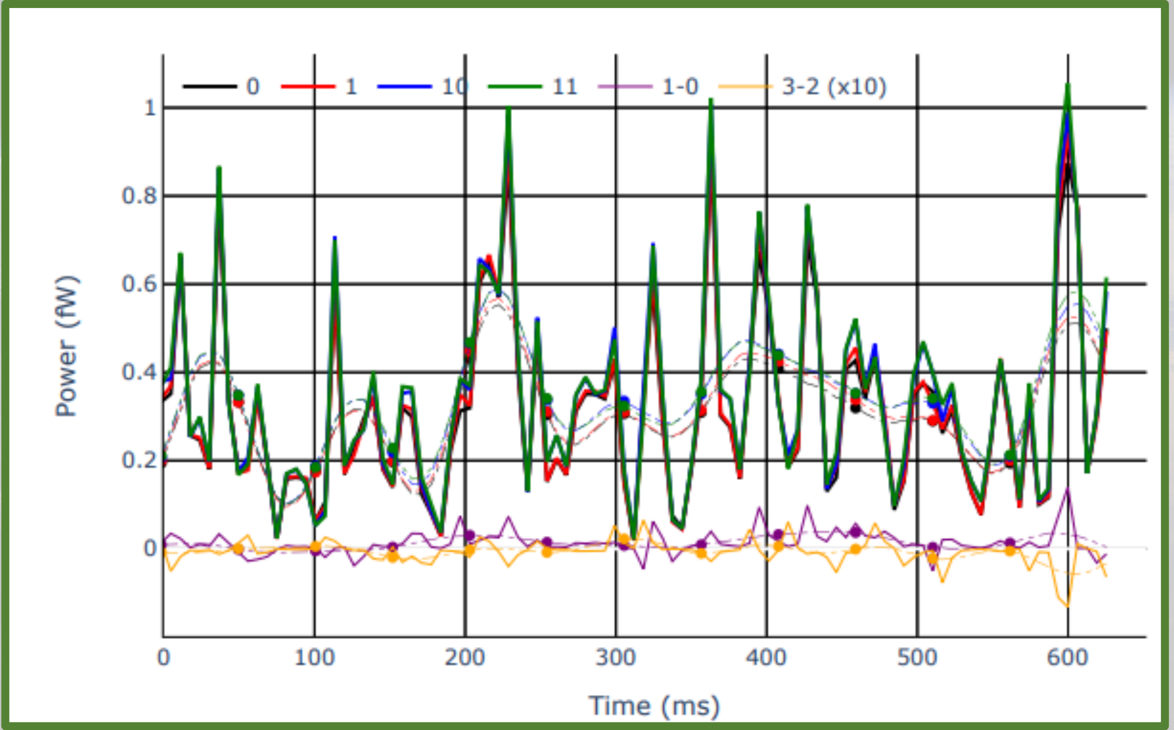

To compare with the LiteBIRD example:

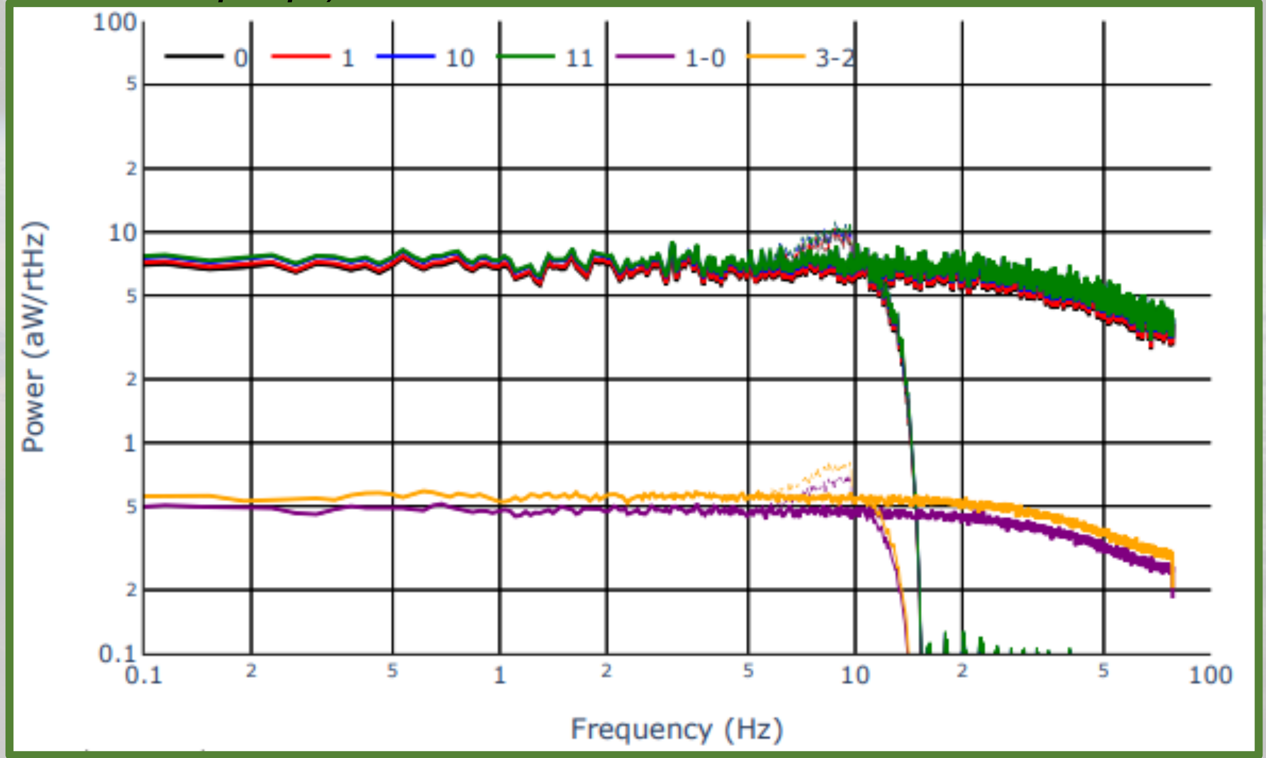
$NEP_{\mathrm{det}} \sim 10\mathrm{aW}/\sqrt{Hz}$

i.e. the simulated NEP per detector under our conditions is **comparable with the background,** but the effect on sky maps and instrument noise has a more complicated relationship.

1. Generate 90 minutes of TOD for 16 TES in 2 pixels
2. Decimate by FIR to 19 Hz
3. Split 90 minutes of TOD into chunks → 1 year of TOD for 12 TES [M. Tominaga, ISAS JAXA]
4. Mapmaking in TOAST [M. Tominaga, ISAS JAXA]
5. Conversion to CMB temperature units over all LiteBIRD frequency bands
6. Calculation of cosmic ray *dr*

*(M. Tominaga et al. 2020 in prep.)*



# From TOD to maps

1. Generate 90 minutes of TOD for 16 TES in 2 pixels
2. Decimate by FIR to 19 Hz
3. Split 90 minutes of TOD into chunks → 1 year of TOD for 12 TES [M. Tominaga, ISAS JAXA]
4. Mapmaking in TOAST [M. Tominaga, ISAS JAXA]
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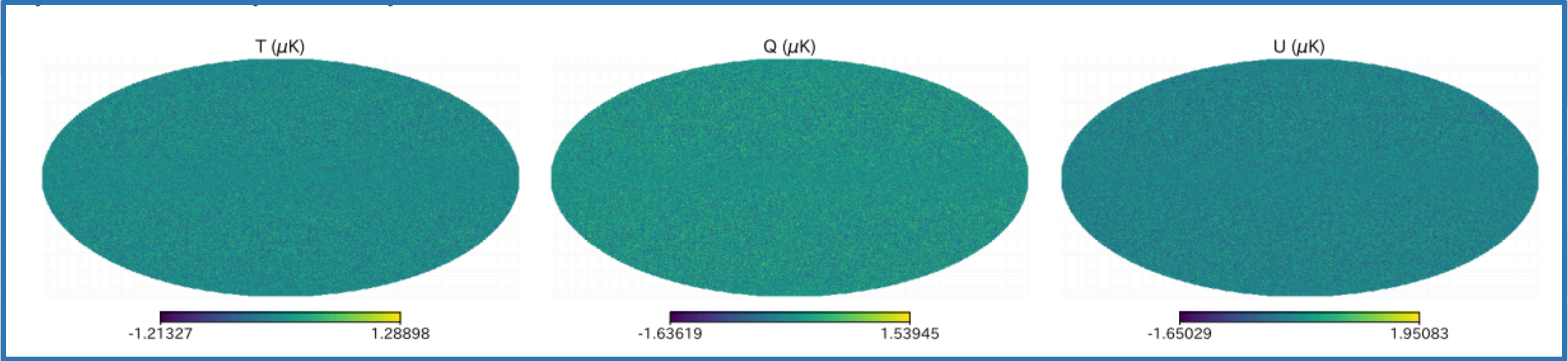
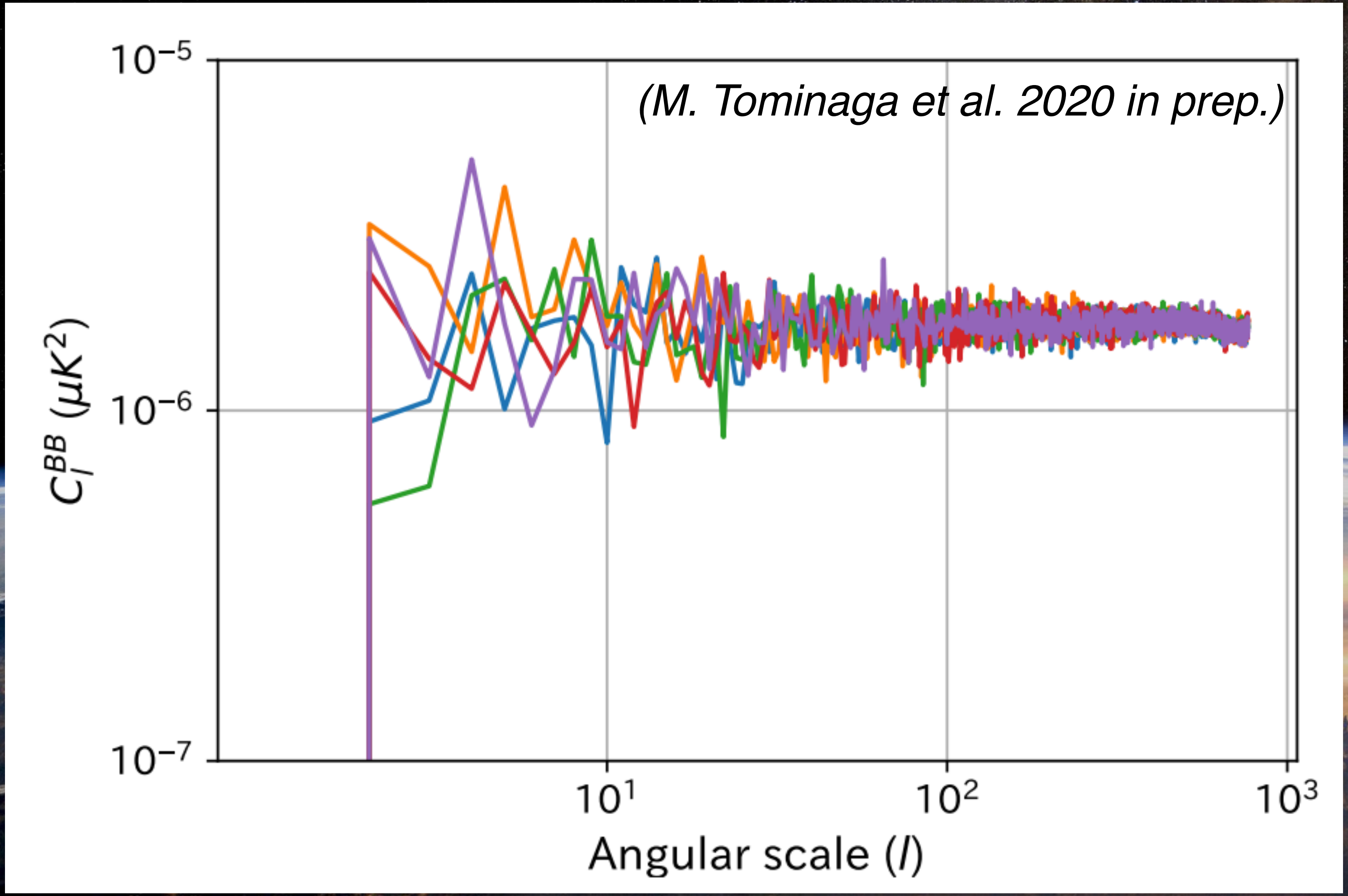
6. Calculation of cosmic ray maps and *dr*




*(M. Tominaga et al. 2020 in prep.)*

# From maps to Cl spectra




Power spectra of $C_l^{BB}$ of cosmic ray effects for 5 one-year map realisations (co-added).

The observed power spectrum is flat, and the level is consistent with estimations, assuming TOD power $\sim 1\ \mathrm{aW}/\sqrt{\mathrm{Hz}}$ for differential mode of two channels.
The CR noise is nearly Gaussian, yielding $Cl^{BB} \sim 2 \times 10^{-6}\ \mu K_{CMB}$, scaling with $N_{det}$ and $t_{Obs}$. In this case the CR effect would be at a manageable level.

Future work will ascertain the details of scalability (due to thermal gradients and strong coupling) which will likely be more complex than a simple inverse square law.

# Future work and conclusions

- **Hardware tests** are required on TES detectors and wafer response to energy deposition, direct measurement of wafer *G* etc.
- Inclusion of **mitigation mechanisms** in wafer design (simulation and test)
- Scalability studies including a larger number of detectors and the variation in thermal coupling power as a function of various detector designs.
- Sensitivity studies, including the addition of external wafer wirebonds, etc.

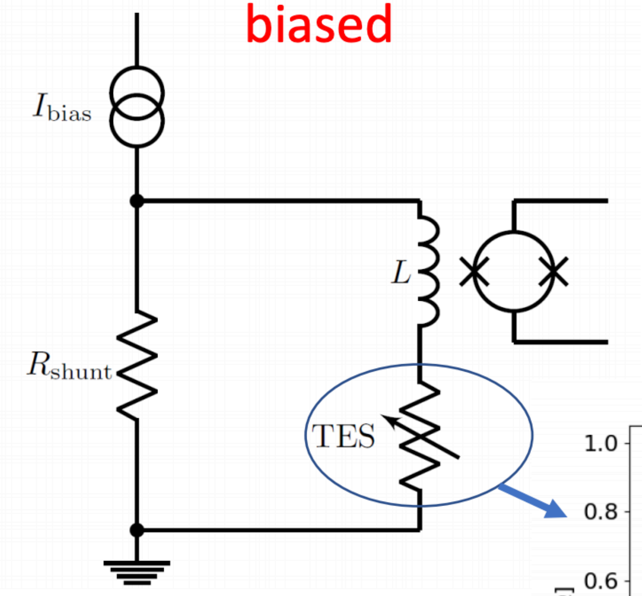
**Conclusions**

- We present progress on an **end-to-end simulator for evaluating the effect of cosmic rays** in a next-generation space-borne CMB *B*-mode mission, and a TOAST framework for projecting the simulated data into sky maps.
- This simulator represents an important tool for testing the effect of **hardware properties and changes on sky data and mission outcomes**.
- This work is a first step towards defining a realistic model for LiteBIRD and precisely defining/refining the impact of CR effects.

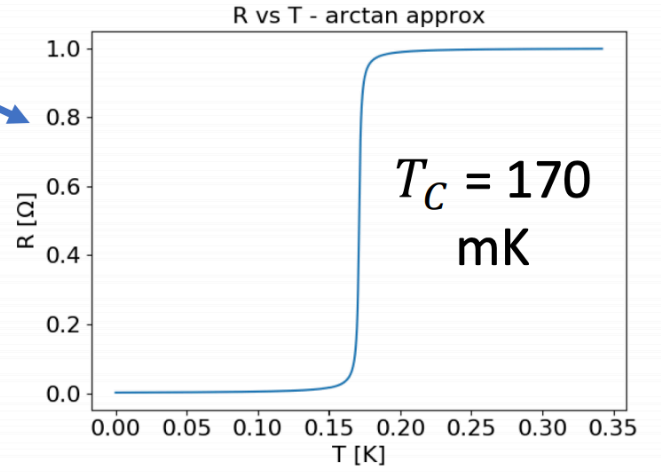
(T. Ghigna)

# TES Model (Minimal complexity)

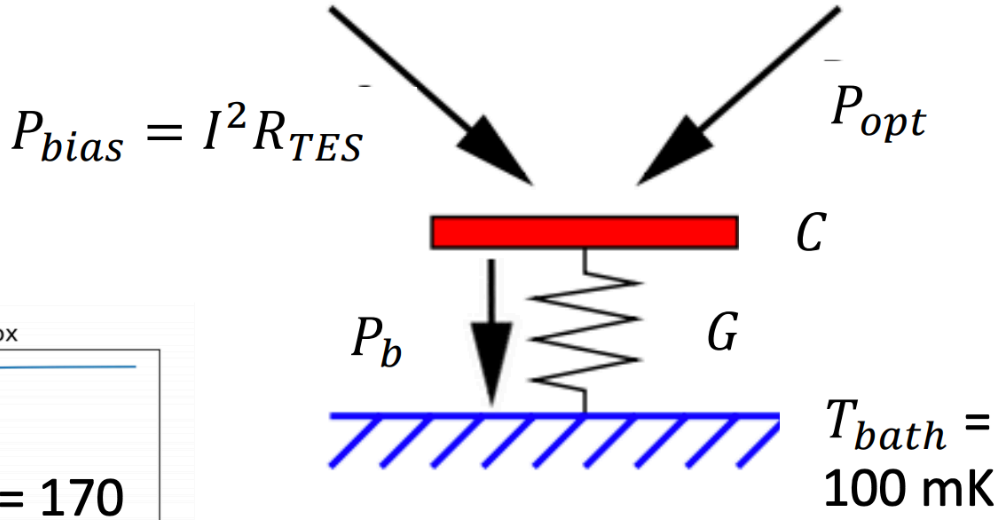
**Electrical circuit – DC biased**




$$L\frac{dI}{dt} = V - IR_{TES} - IR_{shunt}$$




**Thermal circuit**




$$C\frac{dT}{dt} = -P_b + I^2 R_{TES} + P_{opt}$$

$$P_b = \frac{G}{nT^{n-1}}(T^n - T^n_{bath})$$ with n=4

Irwin & Hilton. Transition-edge sensors, 2005: https://doi.org/10.1007/10933596_3.

T. Ghigna

# Varying Optical Power

- Saturation Power = 2.5 x Optical Power
- G gets calculated for the given expected optical power
- Adjust bias current to fix the same operation point ~0.5 Ω

| Optical Power [pW] | G [pW/K] | Bias Current [μA] |
|---|---|---|
| 0.1 | 6.6 | 14.3 |
| 0.2 | 13.2 | 20.3 |
| 0.3 | 19.8 | 24.7 |
| 0.4 | 26.49 | 28.6 |
| 0.5 | 33.11 | 32.0 |
| 0.75 | 49.66 | 39.0 |
| 1.0 | 66.22 | 45.3 |

# Further investigation and optimisation