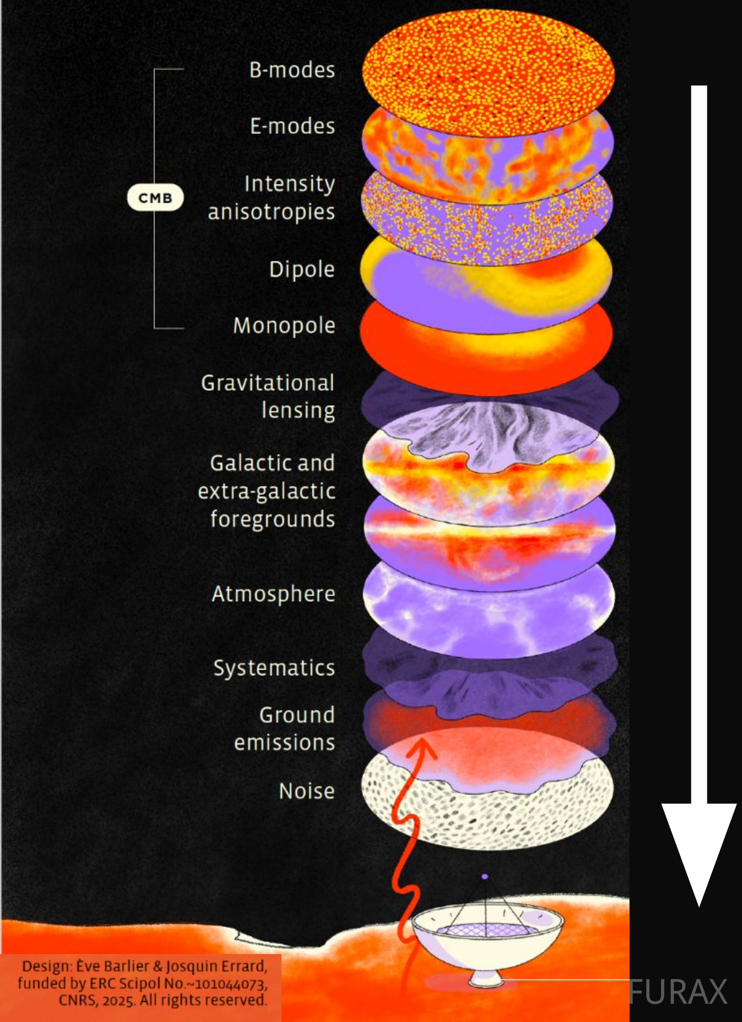
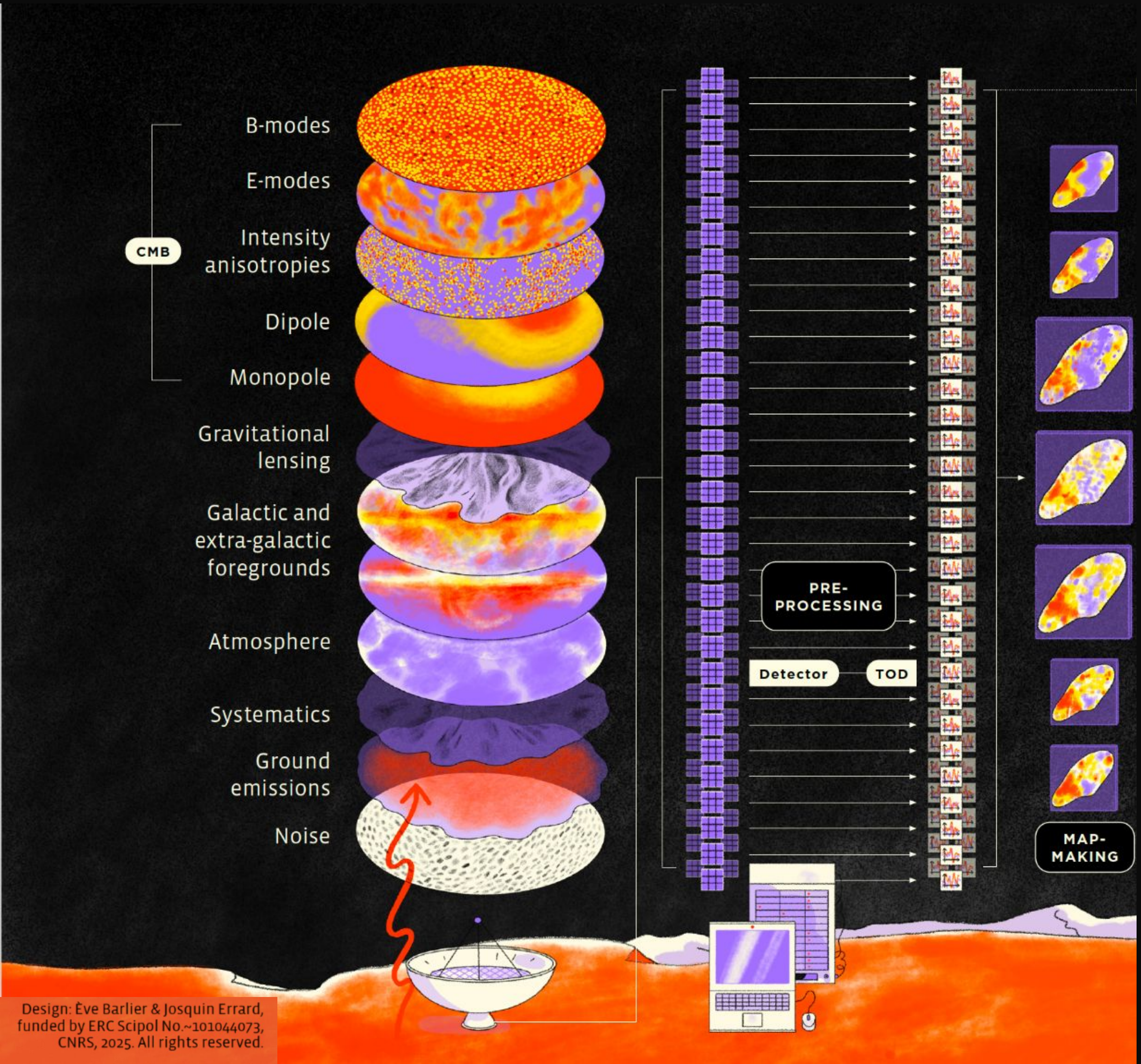
CMB Applications of FURAX

Wuhyun Sohn (APC / CNRS)
on behalf of the FURAX team



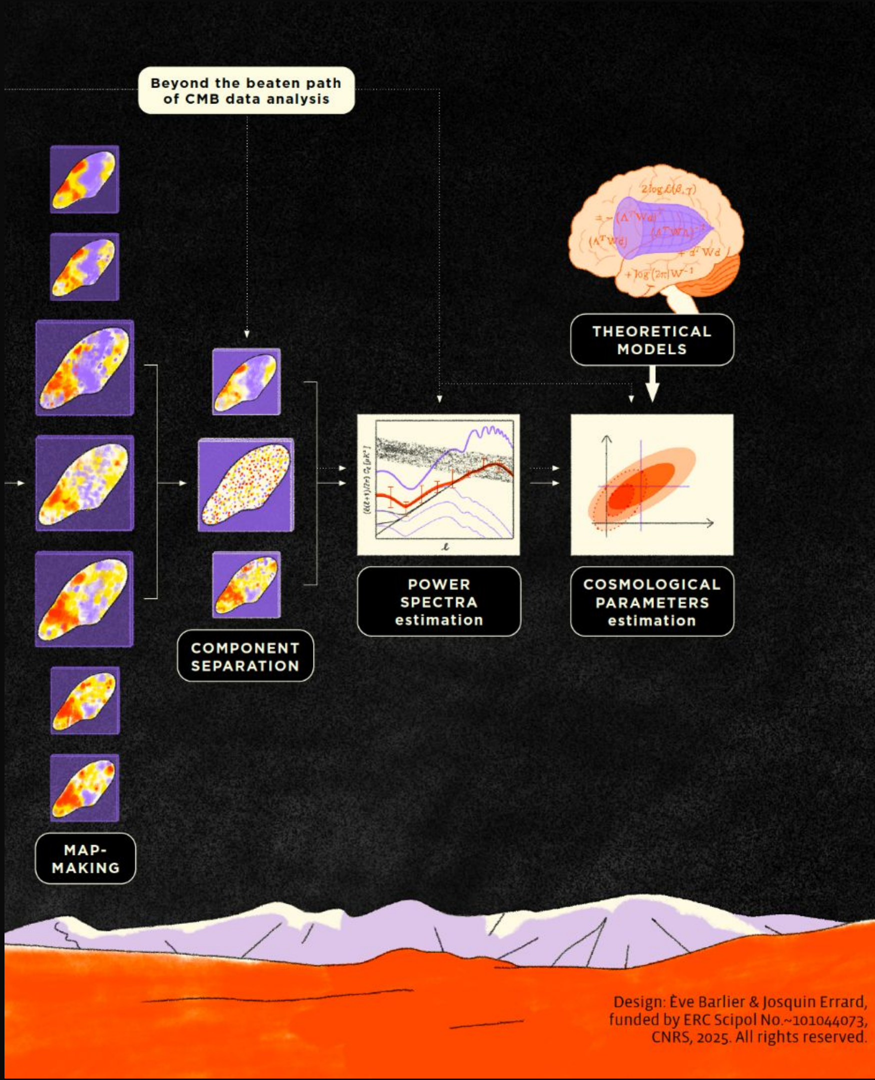
The telescopes measure the CMB and everything else on the way to them

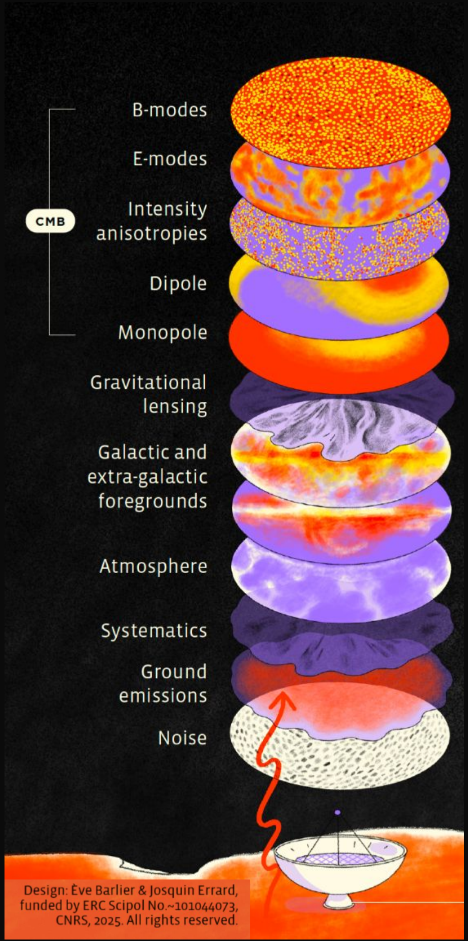
FURAX



We convert the time-ordered data (TOD) to sky maps through
1 - Mapmaking

The CMB is separated from
2 - astrophysical foregrounds
and **3 - the atmosphere.**
We analyse the results to draw
physical insights for our universe.





Complex Systematics

↓

Modularity

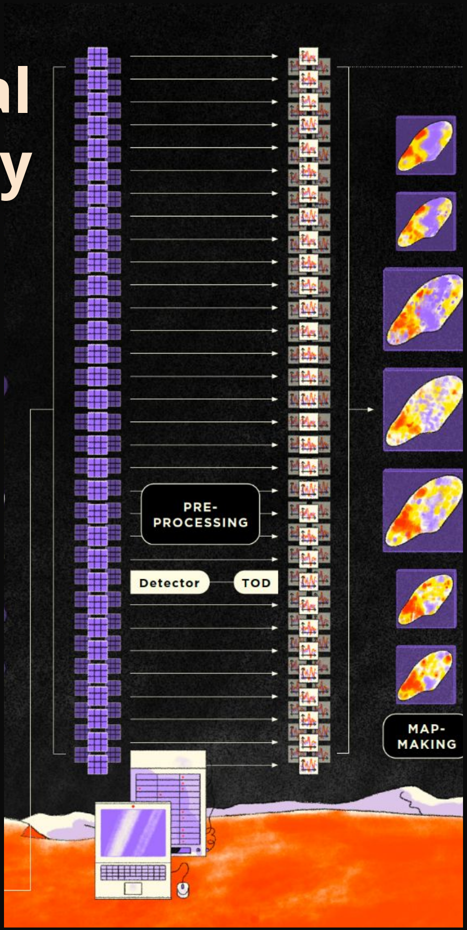
Computational Complexity

↓

Efficiency

FURAX

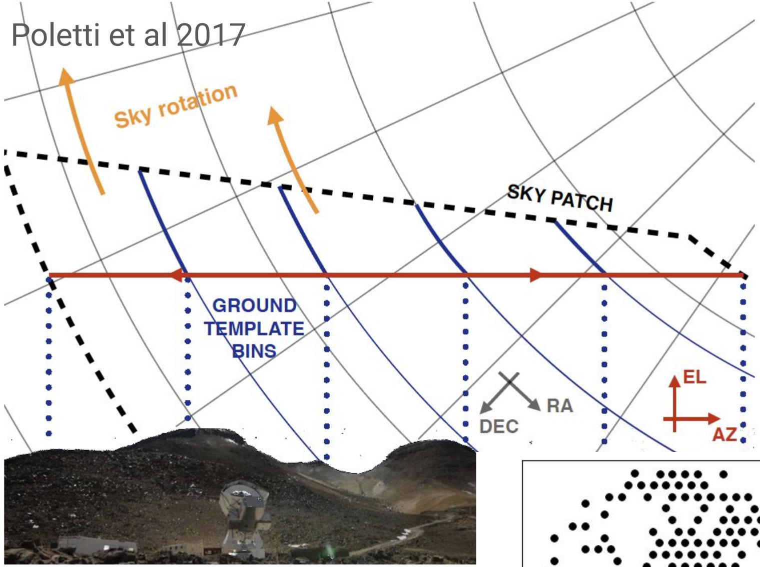
See Pierre's Talk

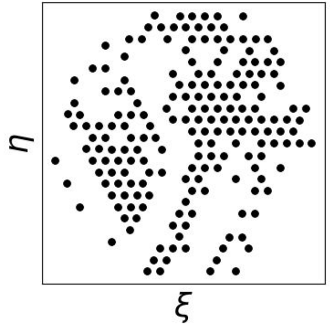


1. Mapmaking & FURAX

WS, Simon Biquard, Pierre Chanial, and the FURAX team *(in prep.)*

Pointing



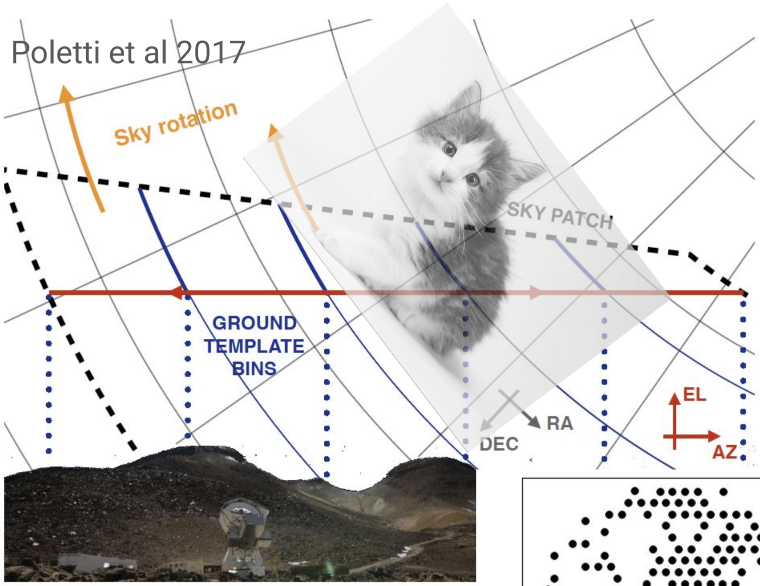


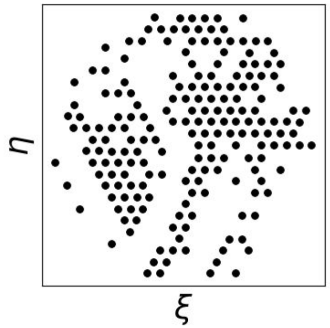
- Telescopes scan the sky back and forth in azimuth at constant elevation (CES)
- Determined by the boresight pointing info (azimuth, elevation, …), focal plane info (xi, eta, …), and site info (time, location)
- The **pointing** operator:

Sky Pixel → **Sample**

i_{pix} → (i_{det}, t)

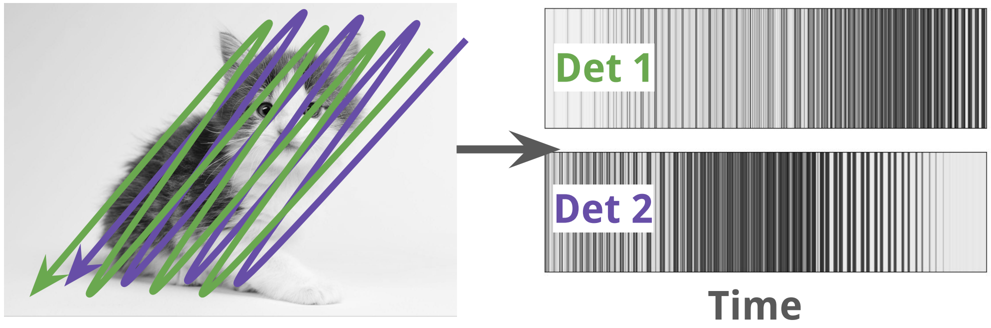
Pointing





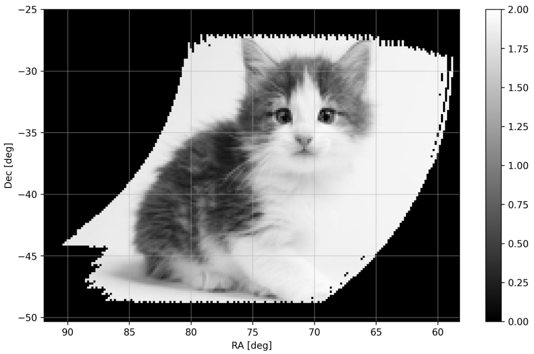
- The **pointing** operator:

$$\mathbf{d} = P\mathbf{s}$$



- The simplest **mapmaking**:

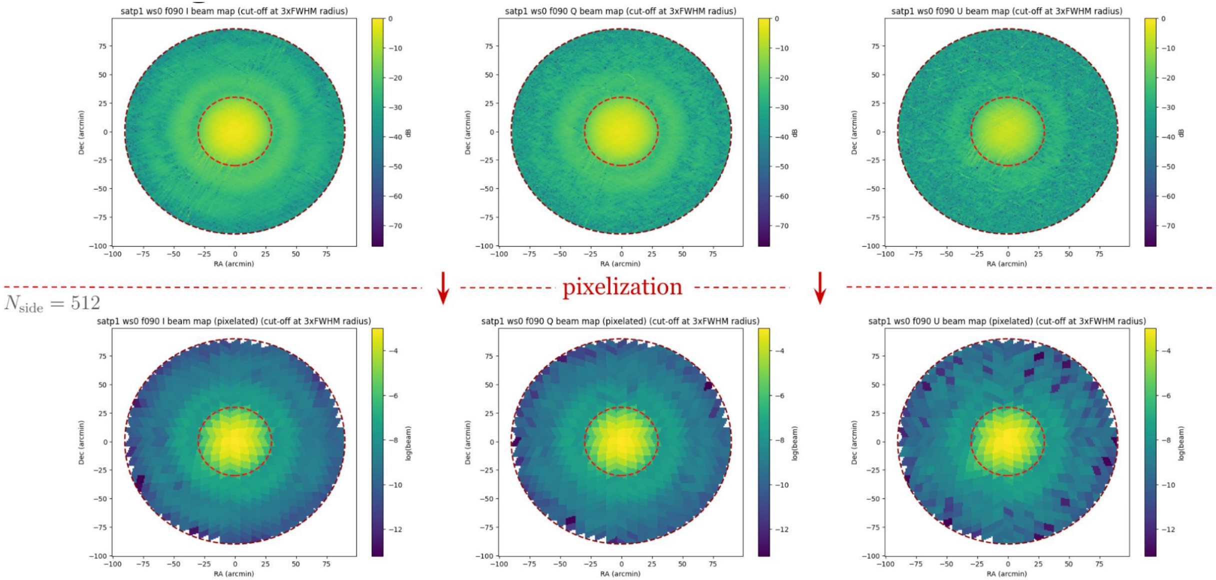
$$\hat{\mathbf{s}} = (P^\top P)^{-1} P^\top \mathbf{d}$$



Pointing - Challenges

- **Complex beams** and **pointing errors** can induce inaccurate mapping between the sky pixels and the data samples
- See Artem's talk:

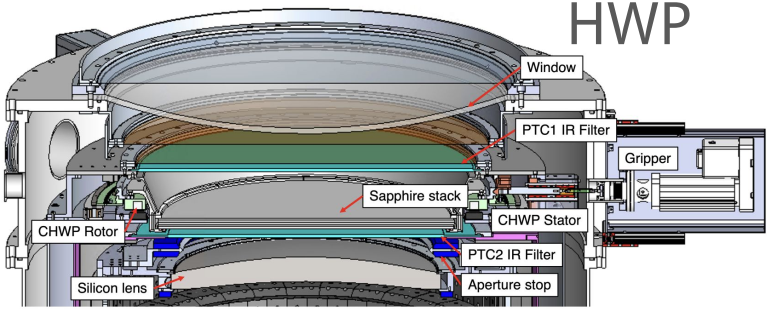
Artem BASYROV



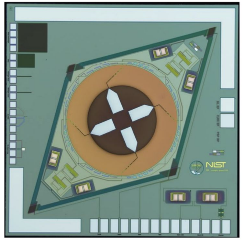
Half Wave Plate

Simons Observatory SAT

HWP



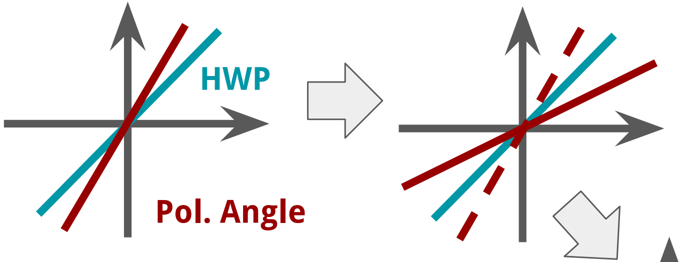
Yamada *et al.* 2023



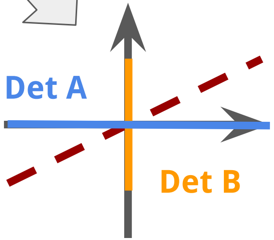
Detectors

Duff *et al.* 2024

- Rotating Half Wave Plate (HWP) modulates the polarised signal to 4x the frequency



- Detector pairs measure the linear polarisation

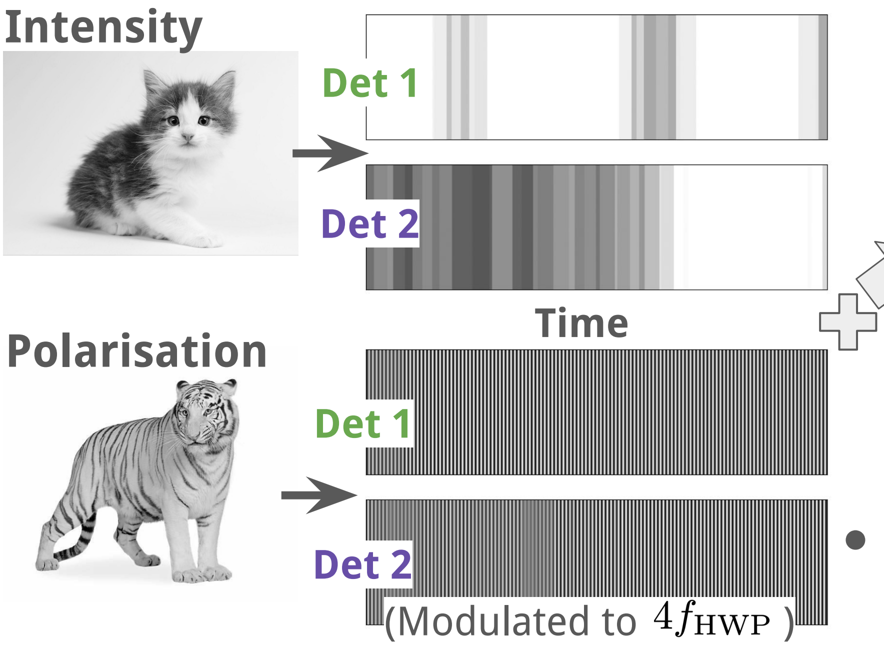


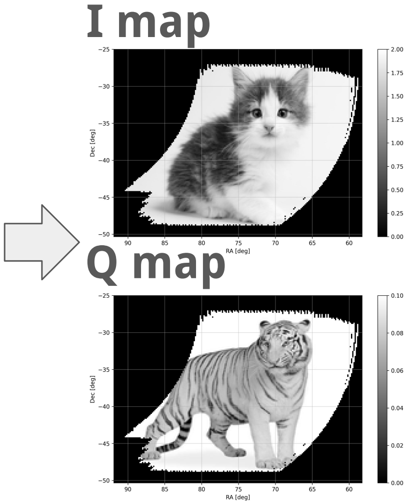
- The (de-)**polarizer** operator:

Stokes I/Q/U → **Data Signal**

Half Wave Plate

- Ideal HWP: $\mathbf{d}(t) = T \cdot I(t) + \epsilon \mathrm{Re}[(Q(t) + iU(t))]e^{-4i\phi_{\mathrm{HWP}}(t))}$





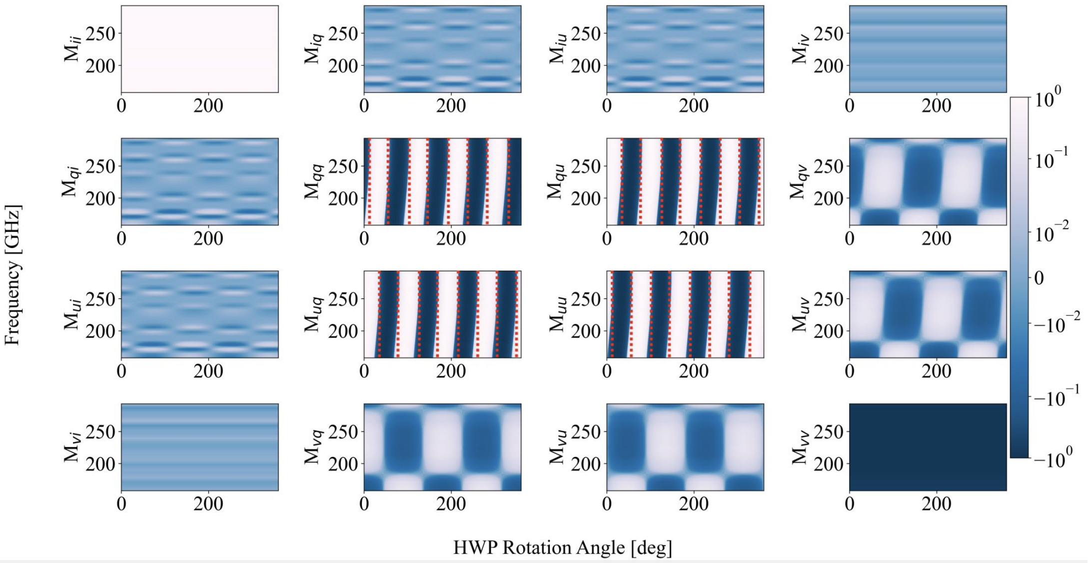
$$\hat{\mathbf{s}} = (P^\top P)^{-1} P^\top \mathbf{d}$$

- Demodulated **during** mapmaking; I/Q/U components at each pixel fitted simultaneously

Half Wave Plate - Challenges

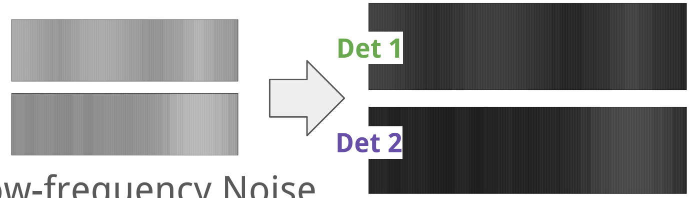
- **Non-ideal HWP** can induce frequency-dependent response on the light rays and other systematic effects
- See Ema's talk:

Ema TSANG KING SANG

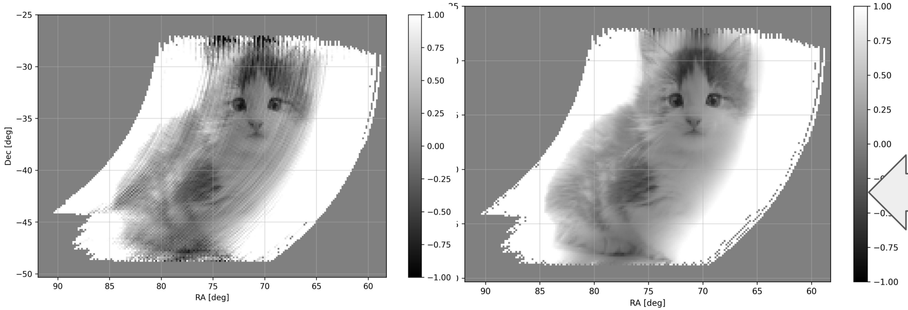


Noise & Atmosphere

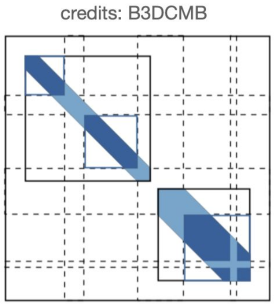
- Instrumental and atmospheric noise contaminate our measurements
- Noise introduces time- and detector- correlations in the samples



+ Low-frequency Noise



- The **noise covariance** operator N:



$$\mathbf{n} \sim \mathcal{N}(\mathbf{0},\ N)$$

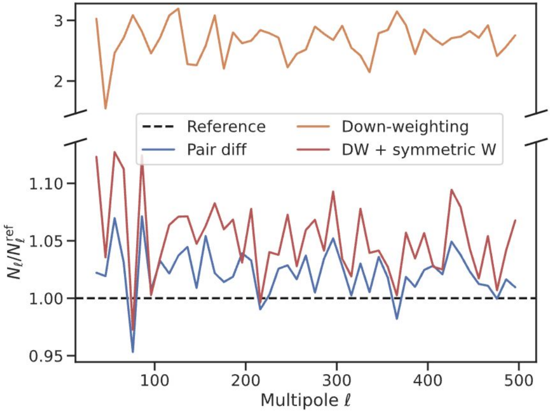
- Maximum Likelihood (ML) mapmaking:

$$\hat{\mathbf{s}} = (P^\top N^{-1} P)^{-1} P^\top N^{-1} \mathbf{d}$$

Noise & Atmosphere - Challenges

- Accounting for correlations between detectors
- Accurate treatment of gaps in the data (glitch masks, turnarounds, …)
- Computational complexity of applying Toeplitz matrices
- Utilising the (lack of) correlations between **detector pairs** to our advantage
- See Simon’s talk:

Simon BIQUARD

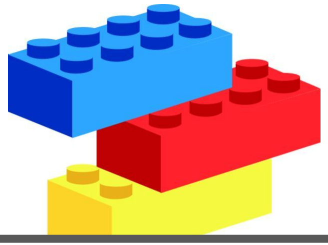


Mapmaking and FURAX

- **FURAX** provides **modular building blocks** for mapmaking

$$\mathbf{d} = P\mathbf{s} + \mathbf{n}$$

$$\hat{\mathbf{s}} = (P^\top N^{-1} P)^{-1} P^\top N^{-1} \mathbf{d}$$



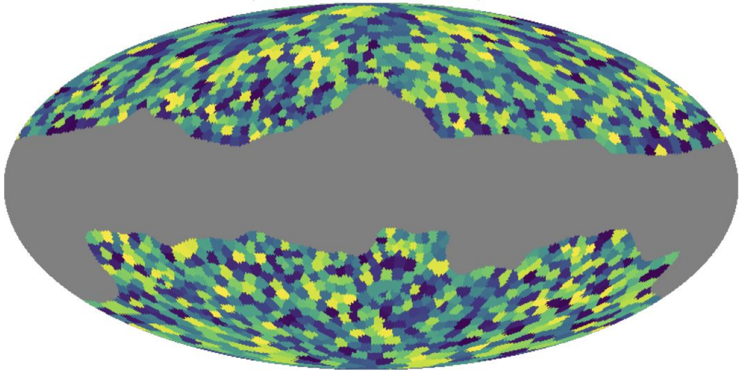
- Using **FURAX**,

```
s = jax.jit((P.T @ inv_N @ P).I @ P.T @ inv_N)(d)
```

See FURAX git repo (CMBSciPol/furax) and an example notebook

Next steps

- The FURAX mapmaking package is evolving rapidly
- We are currently working on:
  - Full support for various **templates** during the mapmaking for mitigating systematics
  - Full **GPU parallelisation** support
  - Code optimisation and documentation
  - Applications to Simons Observatory SAT data!
- Collaborations/contributions always welcome!



Wassim KABALAN

2. Astrophysical Component Separation & FURAX

Wassim Kabalan, Arianna Rizzieri, WS, Benjamin Beringue, Artem Basyrov, Pierre Chanial, Alexandre Boucaud, Josquin Errard. 2510.xxxxx

Component Separation

- CMB observations are contaminated by significant **astrophysical foregrounds**
- Multi-frequency sky maps can be modeled as a superposition of components, each with distinct spectral behaviors:

$$\mathbf{d} = \mathbf{A}(\boldsymbol{\beta})\mathbf{s} + \mathbf{n}$$

- **Galactic synchrotron** and **thermal dust emission** dominate the polarised foregrounds, both exhibiting **spatially varying spectral properties**

  [*Planck Collaboration* 2020; *Meisner & Finkbeiner* 2015]

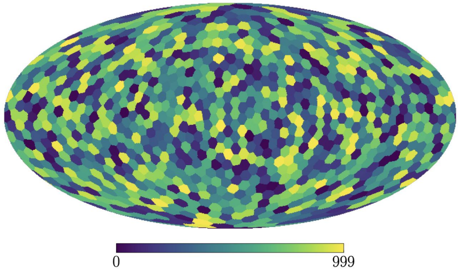
Spectral Likelihood

- The best-fit spectral parameters are found at the map domain by maximising the **spectral likelihood** [*Stompor et. al.* 2009], which also enable new approaches such as the cluster optimization

$$\ln \mathcal{L}_{\mathrm{spec}}(\boldsymbol{\beta}) = \mathrm{const} + \frac{1}{2}\left(\mathbf{A}^\top \mathbf{N}^{-1}\mathbf{d}\right)^\top \left(\mathbf{A}^\top \mathbf{N}^{-1}\mathbf{A}\right)^{-1}\left(\mathbf{A}^\top \mathbf{N}^{-1}\mathbf{d}\right)$$

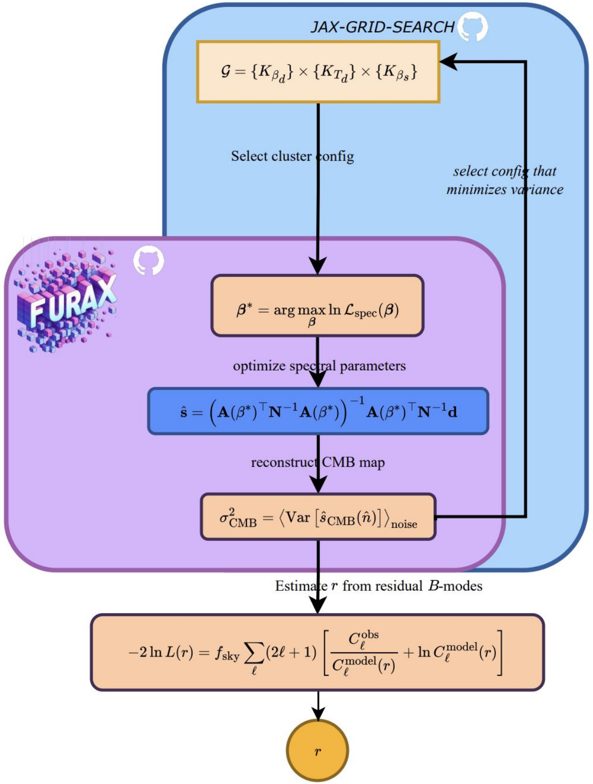
- We incorporate the spatial variability of β via spherical k-means algorithm, where the sky is partitioned into disjoint regions with

$$\boldsymbol{\beta}(\hat{n}) = \boldsymbol{\beta}_k \quad \text{for all} \quad C_k$$

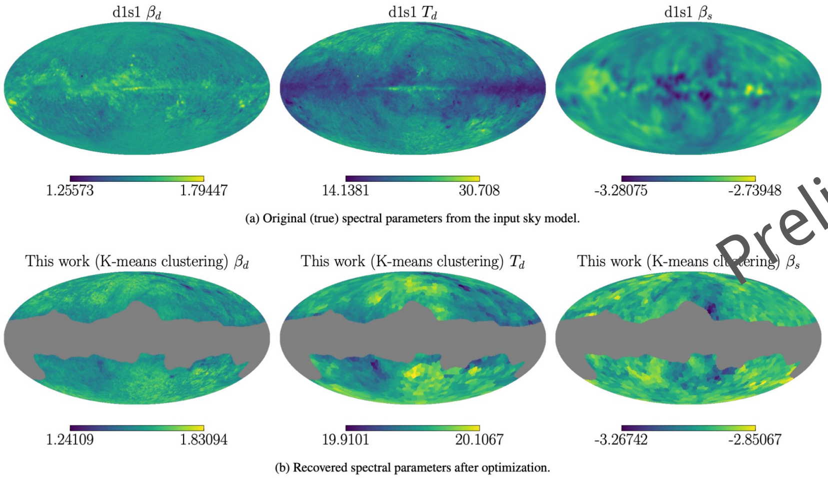


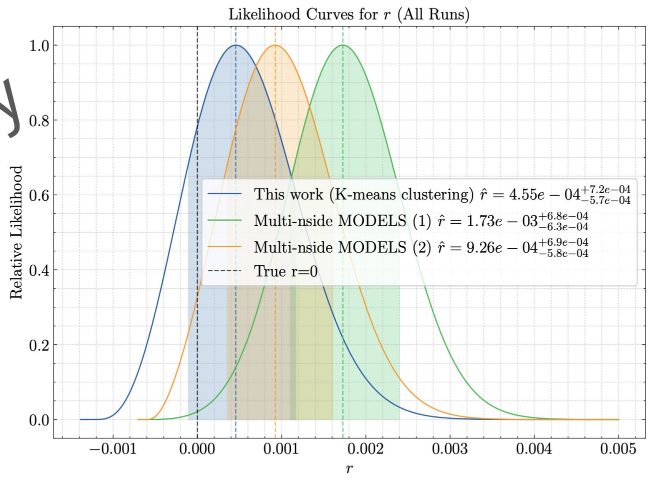
JAX Implementation

- The cluster configuration is optimised together with the spectral parameters, powered by **FURAX** and the jax-grid-search package
- This JAX-based implementation is >**O(10) times faster** than the previous implementation (fgbuster [*Poletti & Errard* 2023 + Rizzieri et al. 2025])
- The formalism can also incorporate beam response as well as the observation matrix within MEGATOP – see Amalia & Pierre's talk



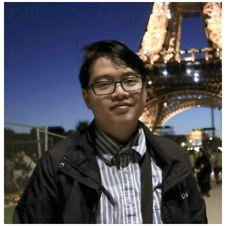
Results



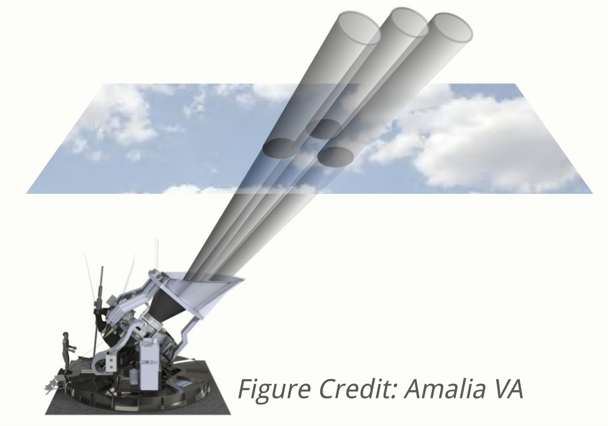


- The adaptive k-means method **effectively capture the spatial variations in β** and gives unbiased estimates of ***r***
- Paper to come out soon… stay tuned!

+ Also see Viet's talk




Amalia Villarrubia Aguilar




Benjamin Beringue

3. Atmosphere & FURAX

Amalia Villarrubia Aguilar, Benjamin Beringue, Élise Goutaudier

and the FURAX team

Reconstructing atmospheric emission

- Driven by water vapour fluctuations, **atmospheric emission introduces correlated noise** and dominates the raw signal from CMB observations
- The atmospheric signal can be modelled using the **precipitable water vapor** (**PWV**) level and **wind speed** (w):

$$\mathbf{d}_{\rm atm} = \mathbf{A}(\mathrm{PWV})\,\mathbf{P}(\mathbf{w})\,\mathbf{s}_{\rm atm} + \mathbf{n}$$

- The best-fit PWV and wind speed can be found by maximising the likelihood in **time domain**:

$$-2\ln\mathcal{L} = \text{const.} + (\mathbf{d}_{\rm atm} - \mathbf{AP}\hat{\mathbf{s}}_{\rm atm})^\top N^{-1}(\mathbf{d}_{\rm atm} - \mathbf{AP}\hat{\mathbf{s}}_{\rm atm})$$

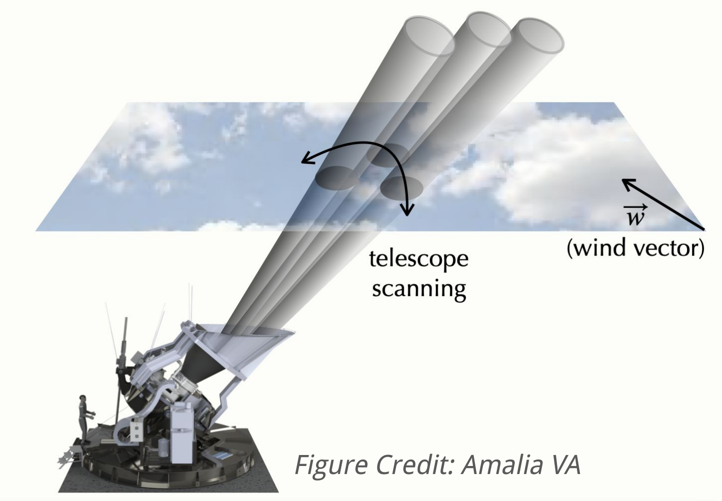
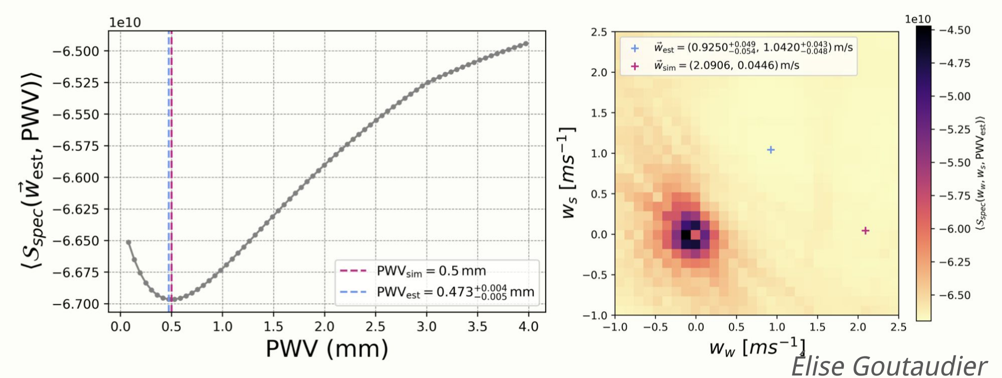


Figure Credit: Amalia VA

Modelling atmospheric emission

- Testing on 3D atmospheric simulations, the PWV level and wind direction are recovered!



Élise Goutaudier

- Active work in progress!
  - Studying potential degeneracies with other sky components & refining simulations

- With this framework, we could study the benefit of having external information with data from e.g. a Lidar *[CosmoLidar]*


Amalia VA


Benjamin Beringue

Conclusion

- Modern CMB surveys are complex and require **modular** & **efficient** pipelines
- **The** [FURAX framework] is ideal for such task:
  - For **CMB mapmaking**, we developed tools to accurately account for **systematic effects** and **accelerate** the process using GPUs
  - For **component separation**, we used it to power general pixel-based methods via effective optimisers, accounting for spatial variability
- The **code base is public** and evolving fast; collaborations are always welcome!

Wuhyun Sohn (sohn@apc.in2p3.fr)