Spectral Datacube Cleaning for CCAT Deep Spectroscopic Survey

SFB 1601

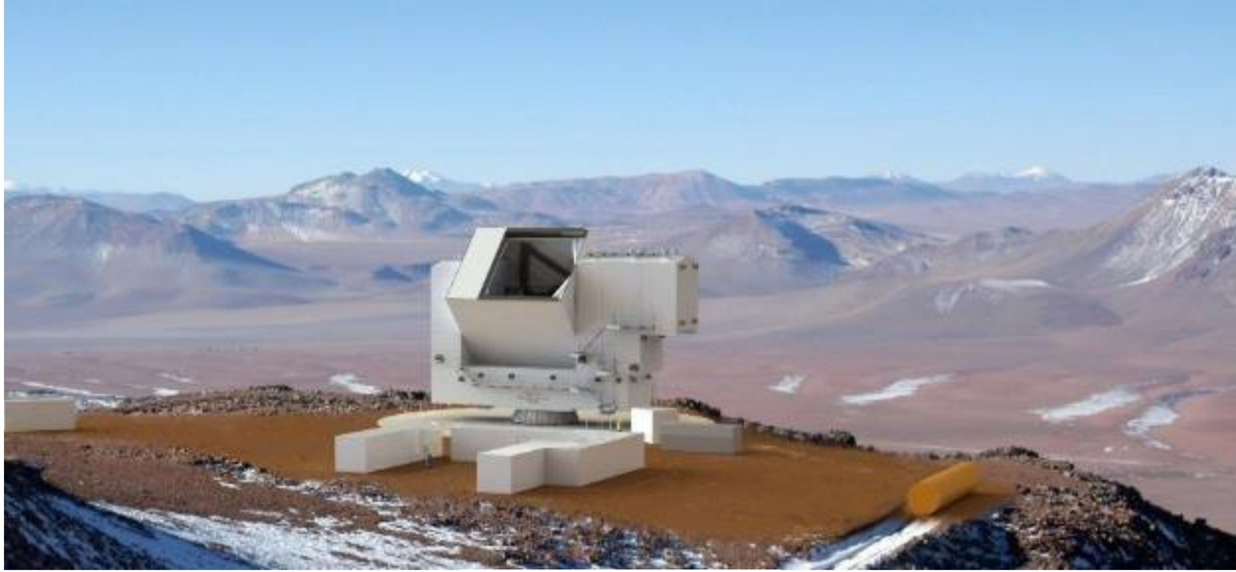
IMPRS astronomy & astrophysics Bonn and Cologne

UNIVERSITÄT BONN

Argelander-Institut für Astronomie

Ankur Dev
Doctoral Student

In collaboration with:



Christos Karoumpis[1] ; Dongwoo Chung [3] ; Frank Bertoldi [1] ; Gordon Stacey [3] ; Jonathan Clarke [2] ; Kaustuv Basu [1] ; Rodrigo Freundt [3] ; Tejas Oak [1] ; Thomas Nikola [3] ; Yoko Okada [2]
+ CCAT Collaboration

[1] University of Bonn,
[2] University of Cologne,
[3] Cornell University

Canadian Consortium

EoR-Spec Detector Arrays

Each FPI setting allows simultaneous spectral and spatial multiplexing

- 2 frequency bands, 210-315 GHz (two LF arrays) and 315-420 GHz (one HF array)

- FPI 2nd and 3rd order resonance modes observed simultaneously by low and high freq arrays respectively

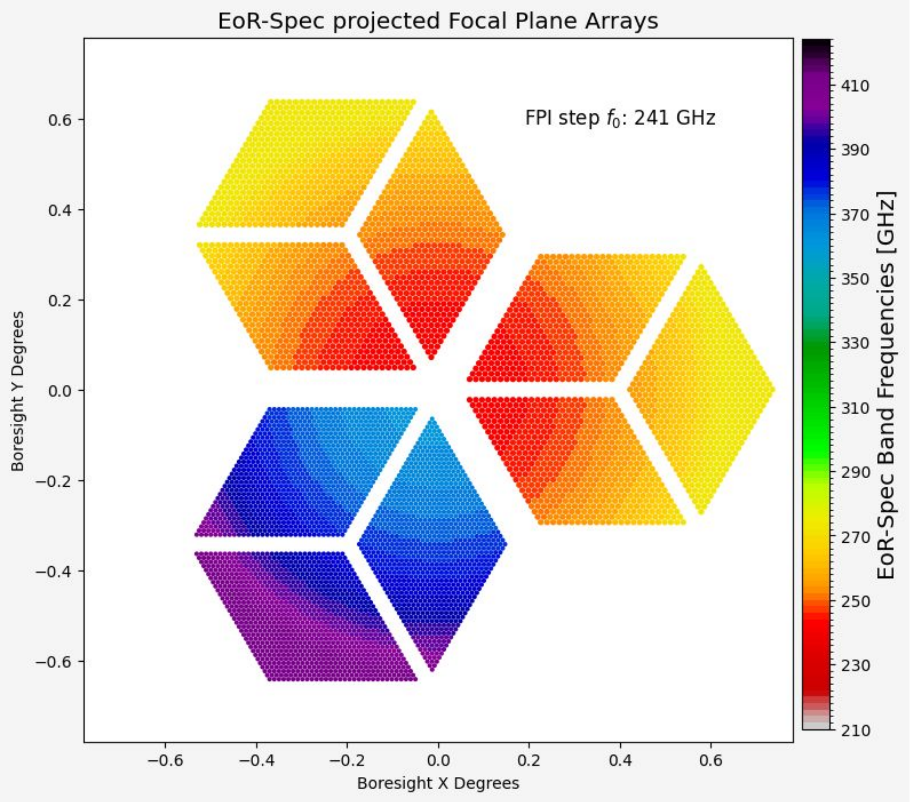


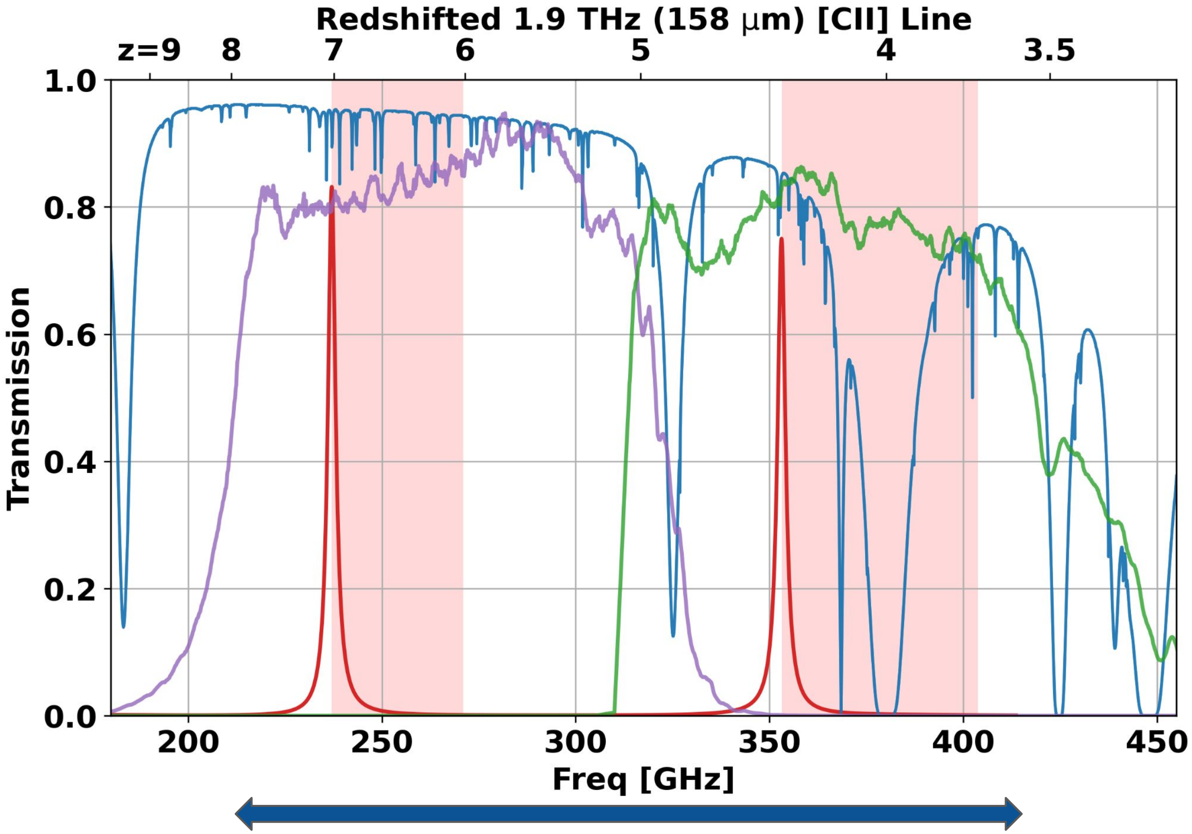
Fig: Mock EoR-Spec simulation for an FPI step, built on TOAST framework

EoR-Spec Spectral Coverage

Lab testing of the instrument passbands is currently underway at Cornell University

Preliminary Lab Results

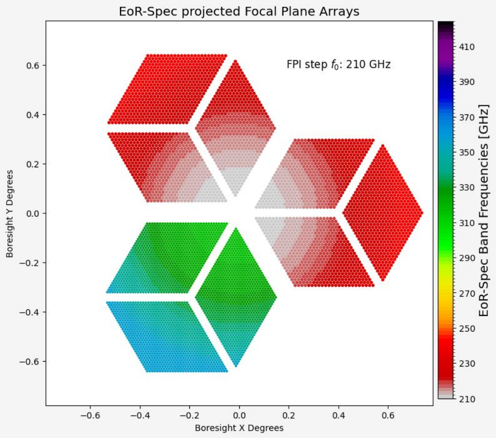
Fig: EoR-Spec Passband (feedhorn simulations and filter measurements) overlaid with atmospheric transmission for 2nd quartile weather is shown.



Credits: Thomas Nikola, Rodrigo Freundt, Yoko Okada, Gordon Stacey, EoR-Spec instrument team

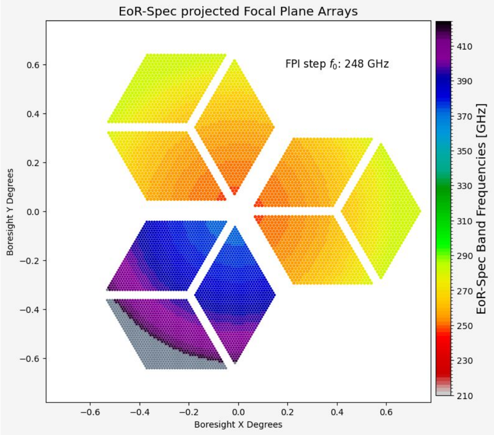
EoR-Spec Spatial and Spectral scanning

Continuous and Uniform spectral coverage achieved in 15 FPI steps



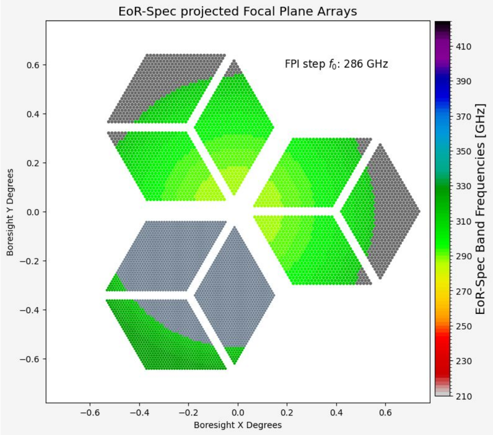
Step 1

....



Step 7

....



Step 12

15 FPI Steps

15 steps: shifting the FPI resonant frequencies (f_0)

More info on: Yoko Okada’s talk on Friday !

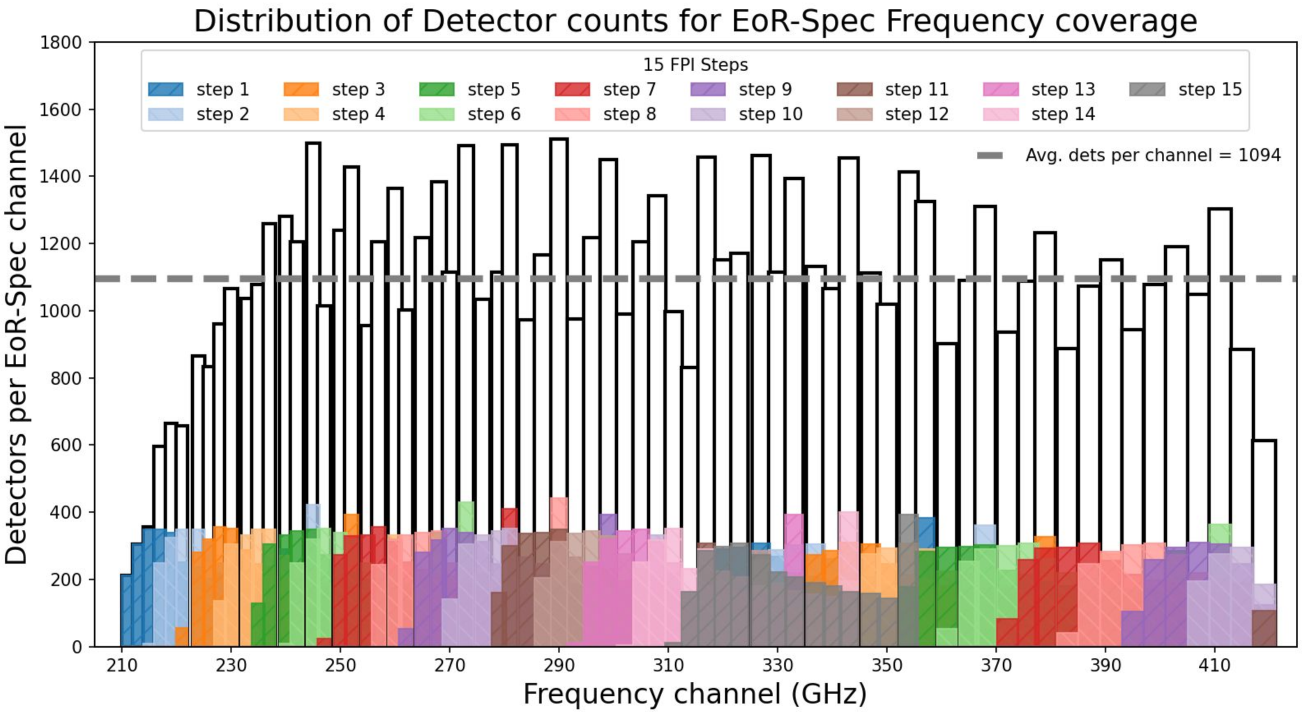
Detector distribution across Frequency bins

Spectral binning to equalize detector coverage per channel

- Each frequency bin integrates signal contributions from multiple FPI steps

- Each FPI step has a Lorentzian spectral profile with

$$\mathrm{FWHM} = \Delta\nu = \frac{\nu}{R}$$



Impact of systematics: Atmospheric Noise

Atmosphere introduces a low frequency noise (1/f) component

- Atmospheric turbulence: source of brightness temperature variations, with spectral and temporal correlations
- Water vapour emission : inhomogeneously distributed
- Significant contribution at sub-mm frequencies
- Harder to recover large scale power: **Quantify signal loss**

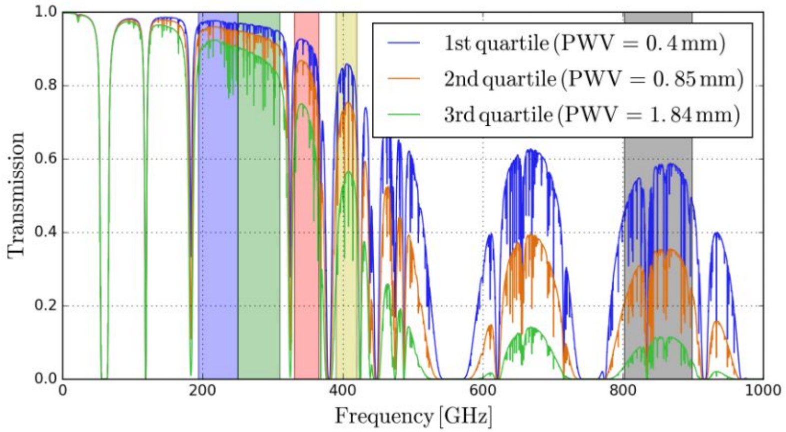


Fig: Atmospheric transmission at Cerro-Chajnantor (Choi+2020)

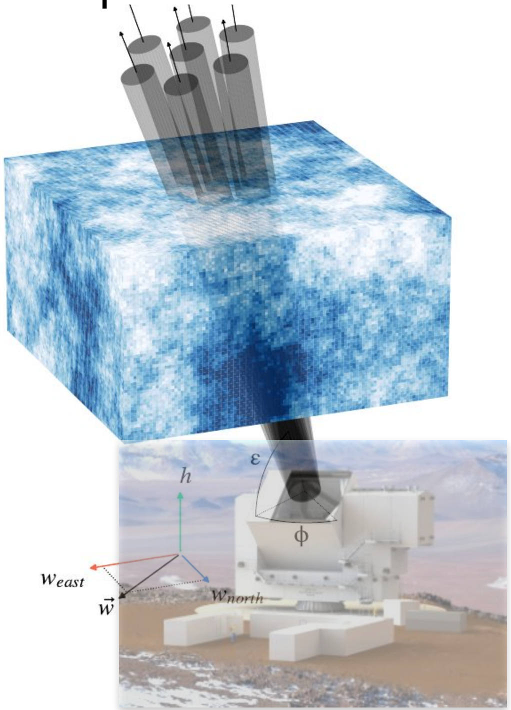
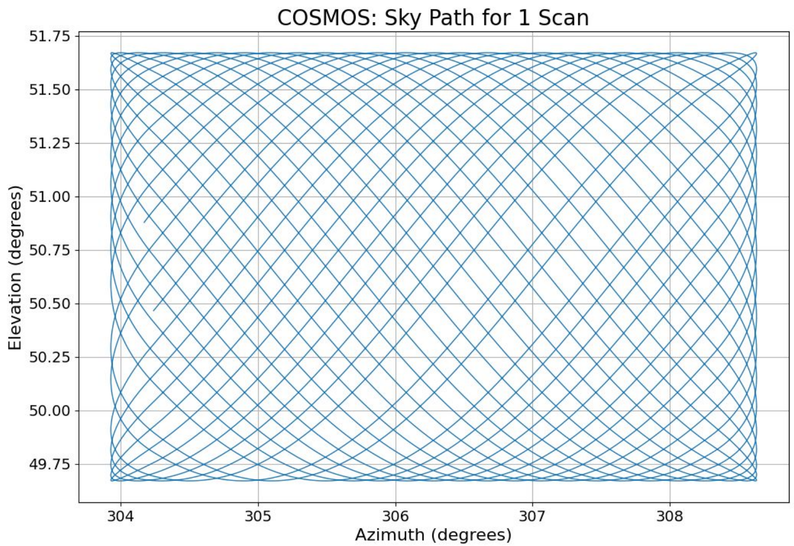
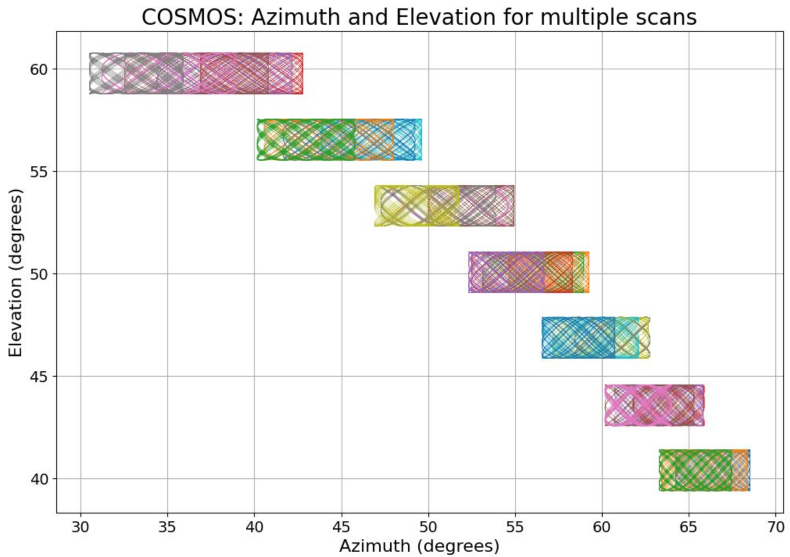


Fig: Array of detectors observing through inhomogeneous atmosphere (Morris+2022) ;
Adapted with FYST model at Cerro Chajnantor (www.ccatobservatory.org)

Scanning E-COSMOS with Lissajous pattern

We simulate E-COSMOS field scans with 135 hours of integration per FPI step





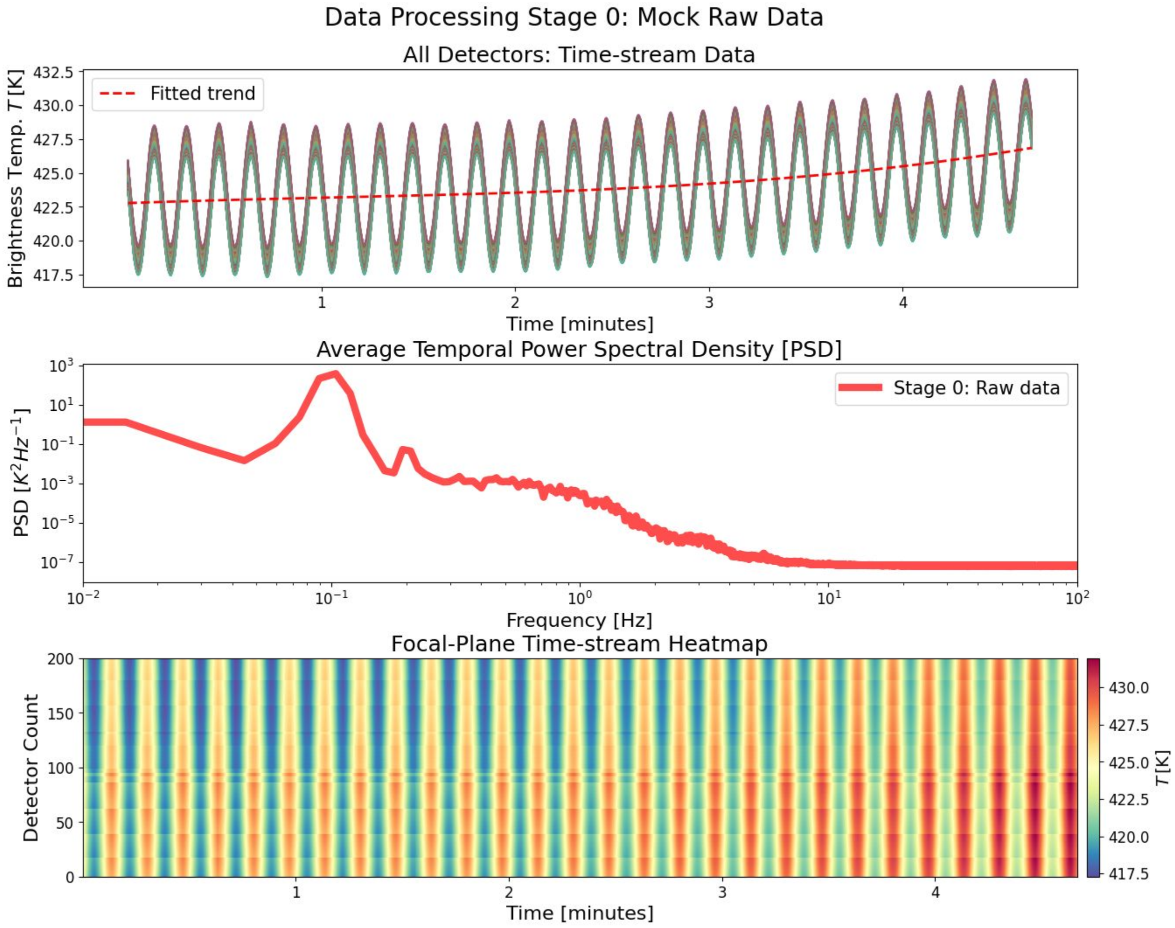
- Simulating 333 - 368 GHz spectral range, observing [CII] signal map including instrument and atmospheric 1/f noise
- Mock observation with 500 detectors per spectral bin (50% of total detectors to be deployed)

Fig: Scanning E-COSMOS field with Lissajous scans at different elevations

Data Processing Pipeline:

Raw time-stream data includes low-frequency drifts and motion-induced variations

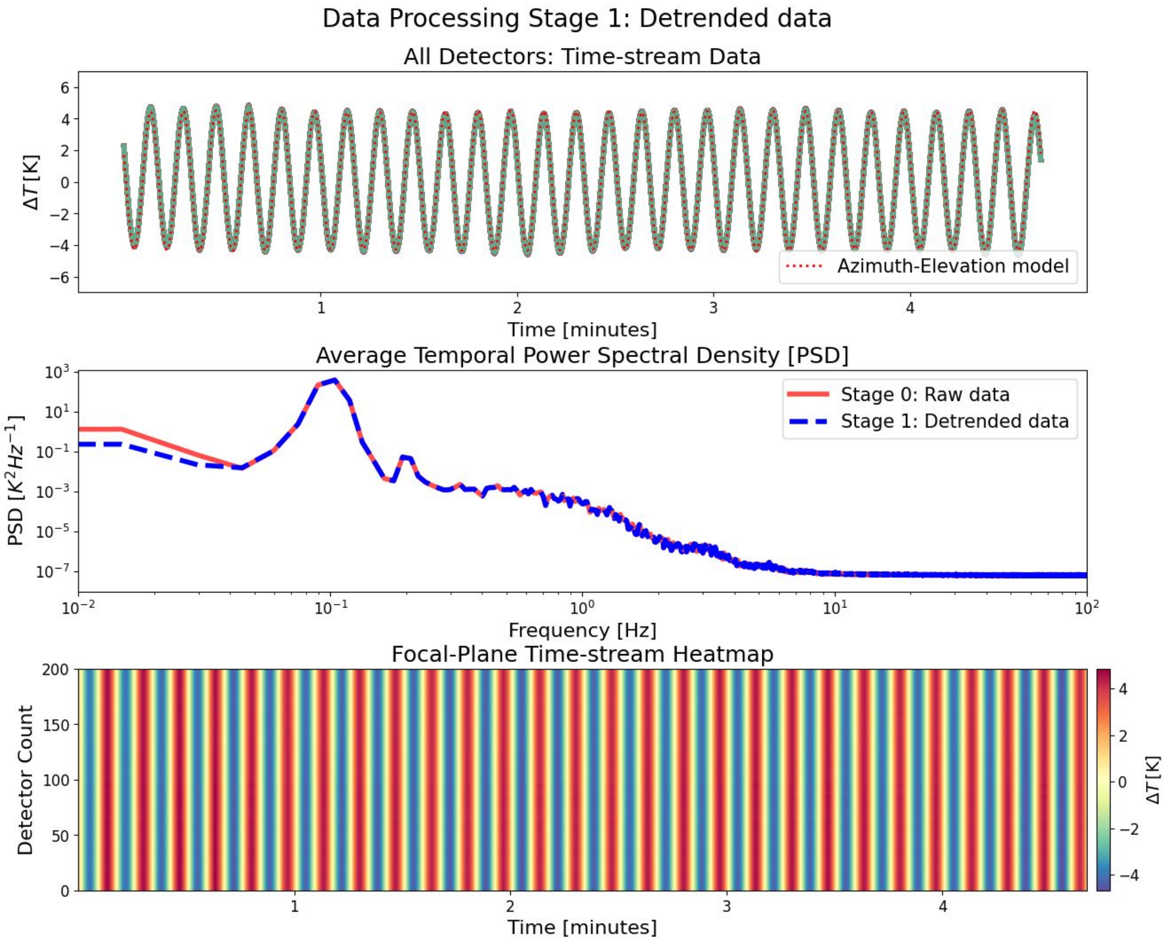
- **Data Stage 0 : Mock Raw Data**
- **Data Stage 1 : Detrended Data**
- **Data Stage 2 : Az-El model corrected data**
- **Data Stage 3 : Common Mode Removal**
- **Data Stage 4 : Leading components removal with PCA**



Data Processing Pipeline:

Low-order polynomial filtering removes slow drift trends from time-stream data

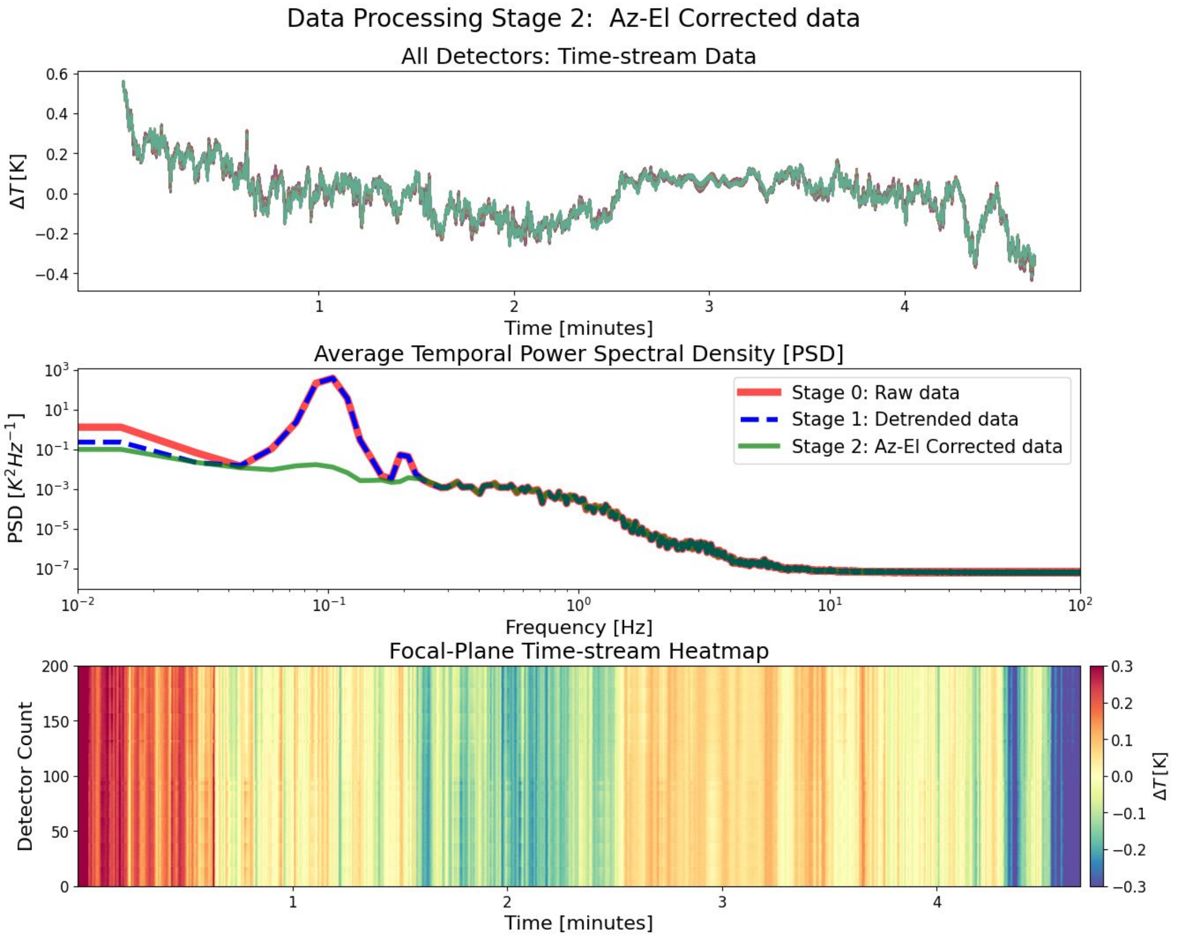
- **Data Stage 0 : Mock Raw Data**
- **Data Stage 1 : Detrended Data**
- **Data Stage 2 : Az-El model corrected data**
- **Data Stage 3 : Common Mode Removal**
- **Data Stage 4 : Leading components removal with PCA**



Data Processing Pipeline:

Az-El pointing template removes systematics from telescope motion and turnarounds

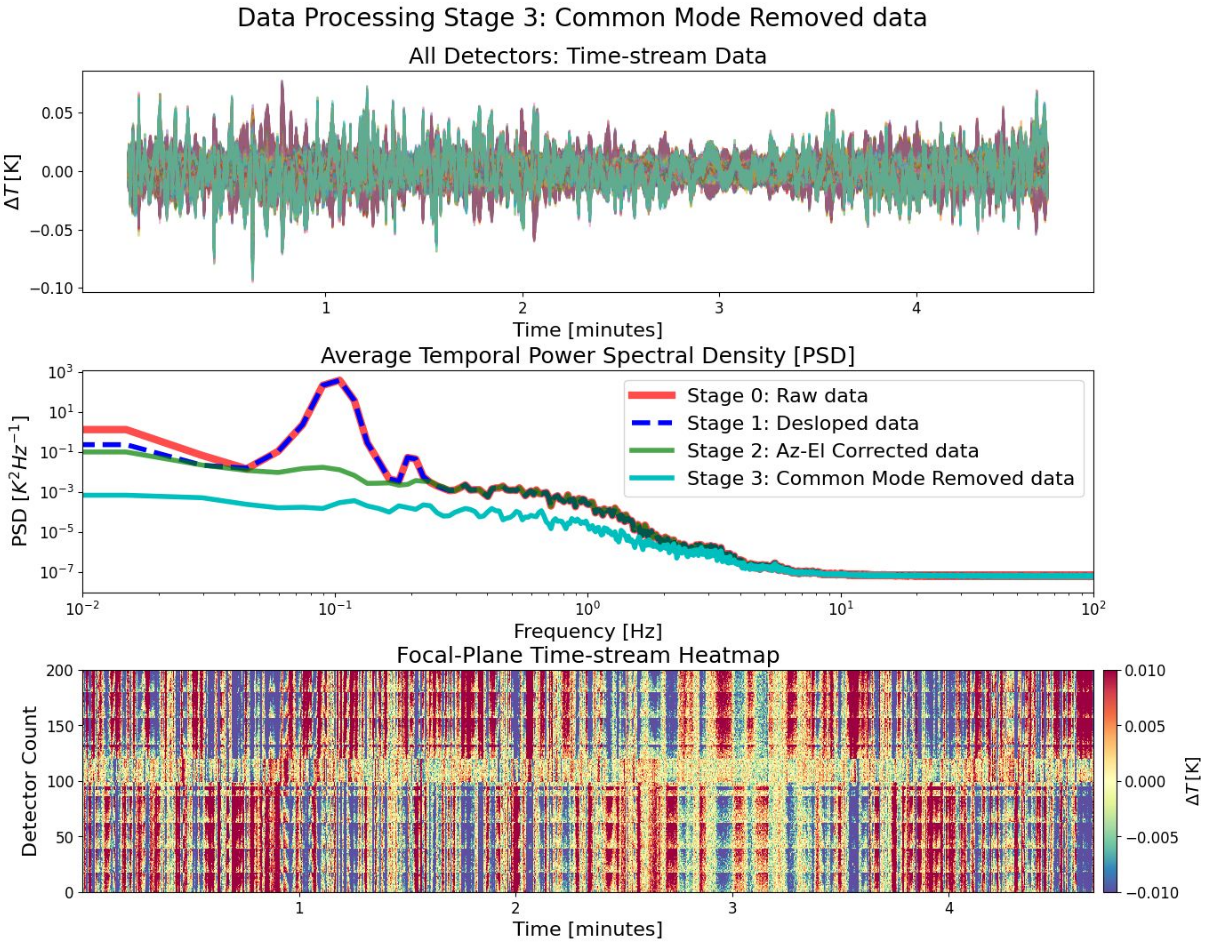
- **Data Stage 0 :**
  Mock Raw Data
- **Data Stage 1 :**
  Detrended Data
- **Data Stage 2 :**
  Az-El model corrected data
- **Data Stage 3 :**
  Common Mode Removal
- **Data Stage 4 :**
  Leading components removal with PCA



Data Processing Pipeline:

Common Mode removes time-correlated systematics shared across the entire array

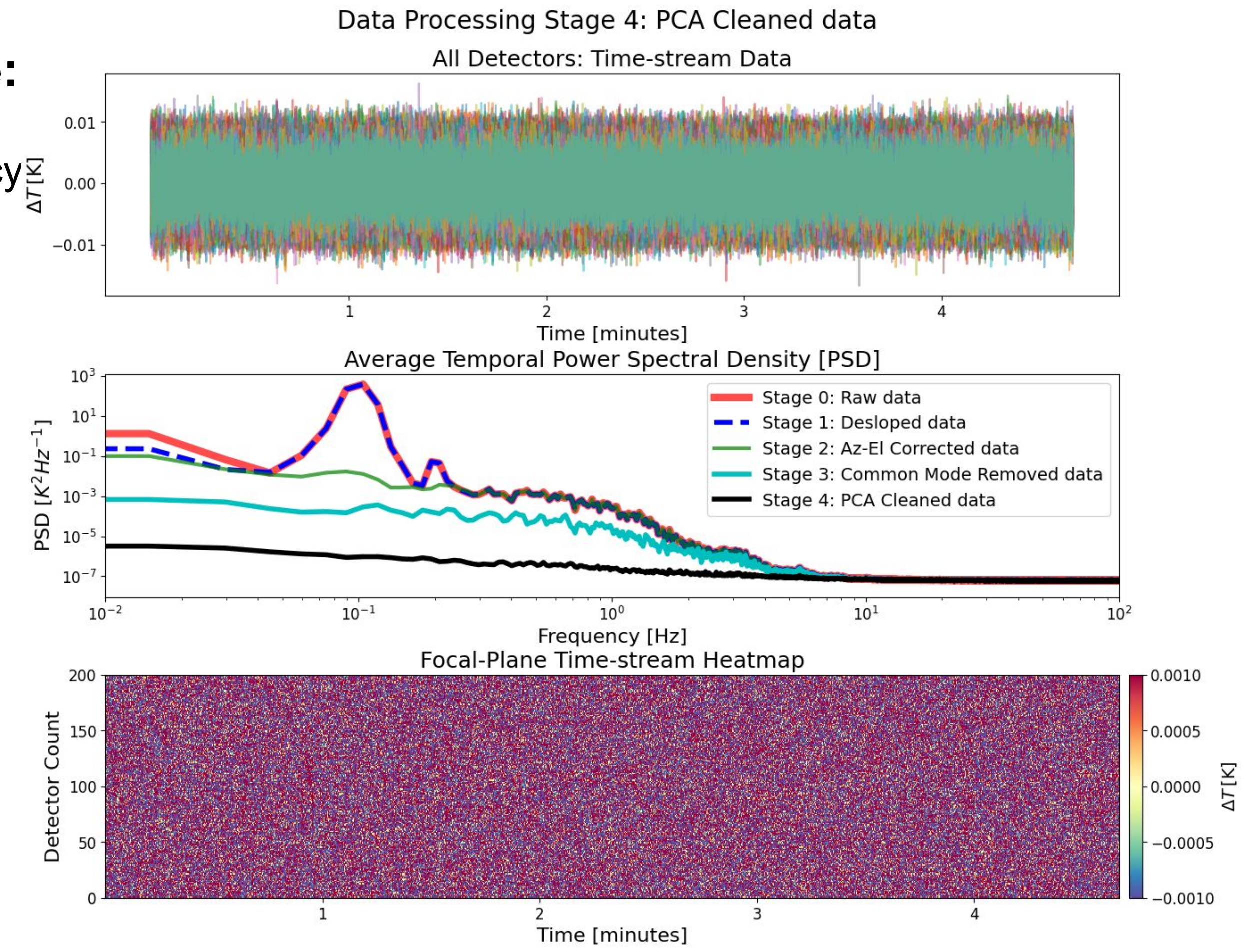
- **Data Stage 0 : Mock Raw Data**
- **Data Stage 1 : Detrended Data**
- **Data Stage 2 : Az-El model corrected data**
- **Data Stage 3 : Common Mode Removal**
- **Data Stage 4 : Leading components removal with PCA**



Data Processing Pipeline:

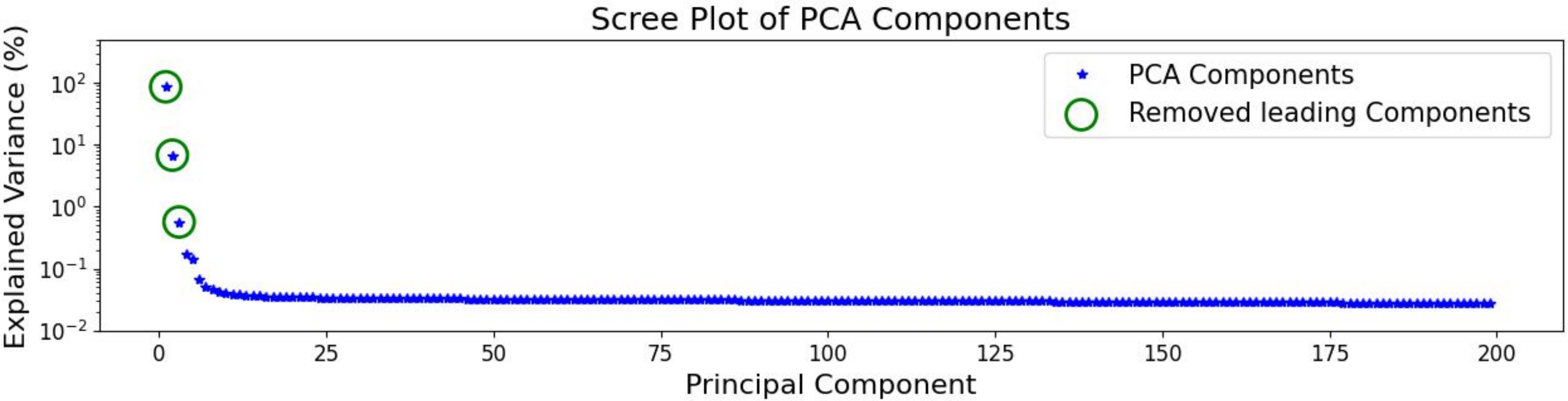
PCA removes temporally and spatially correlated low-frequency modes

- **Data Stage 0 : Mock Raw Data**
- **Data Stage 1 : Detrended Data**
- **Data Stage 2 : Az-El model corrected data**
- **Data Stage 3 : Common Mode Removal**
- **Data Stage 4 : Leading components removal with PCA**



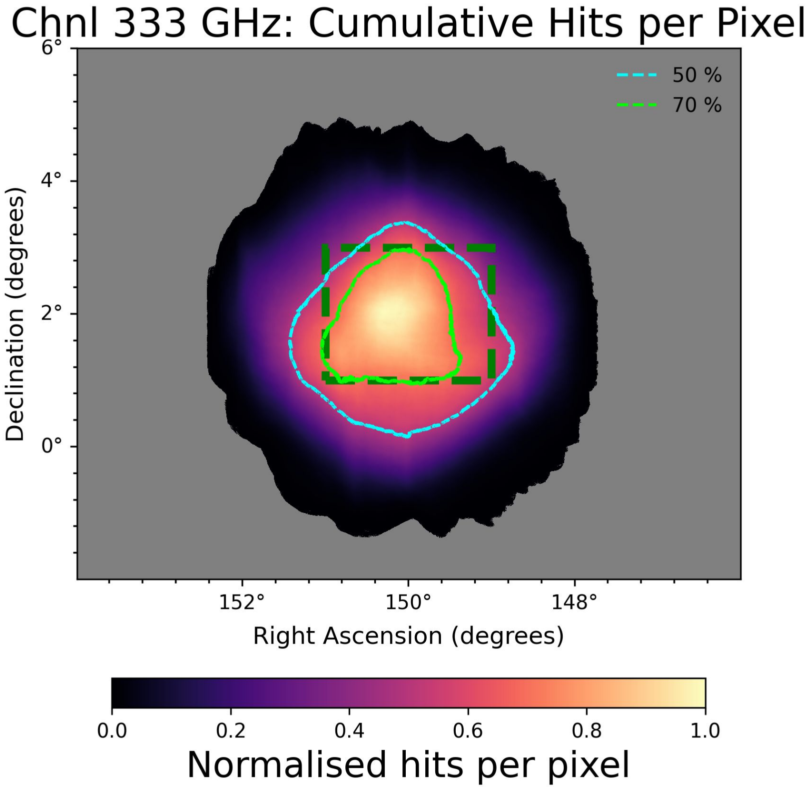
PCA on Time-stream data: Explained Variance

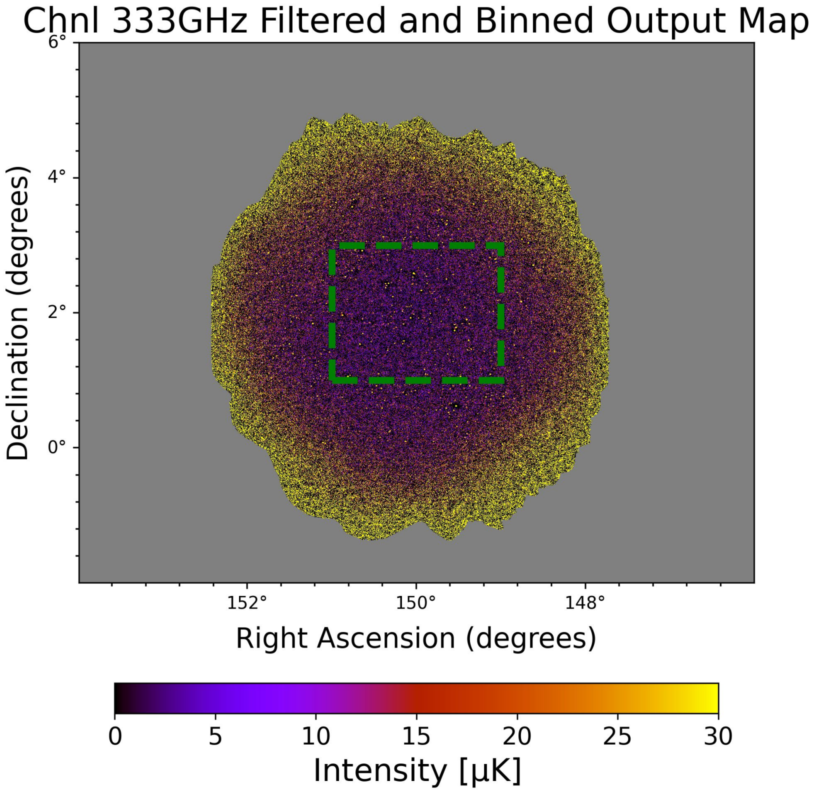
Only the most dominant components are removed to preserve astrophysical signal



Binned Maps for E-COSMOS

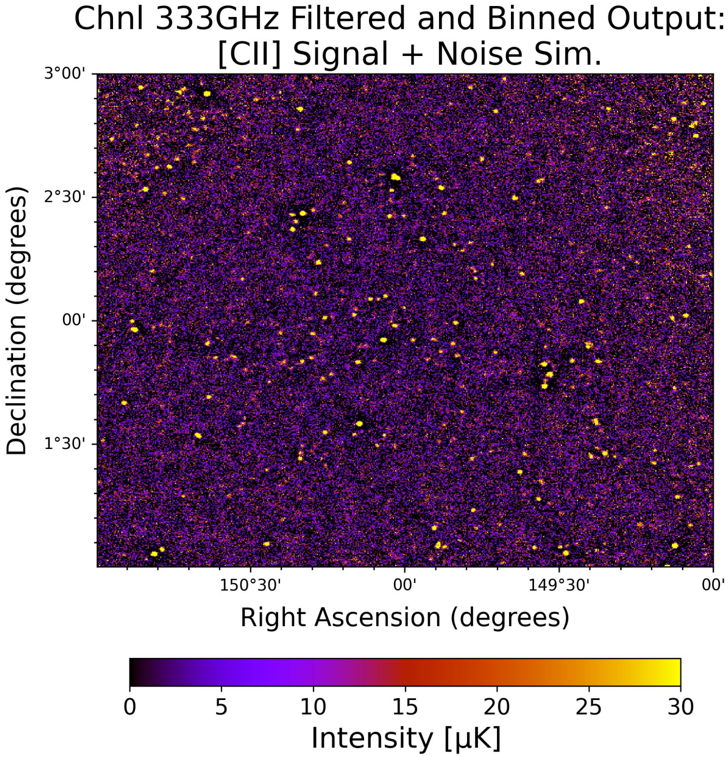
Using a 4 deg² cutout from the deepest region in the field, excluding map edges

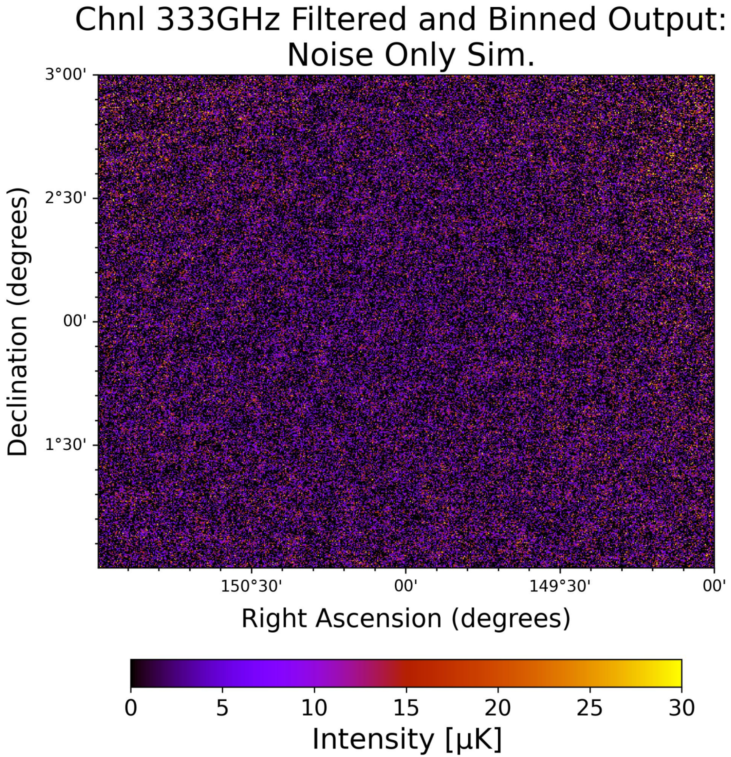




Comparison of Simulations: Signal+Noise vs. Noise-Only (No Signal)

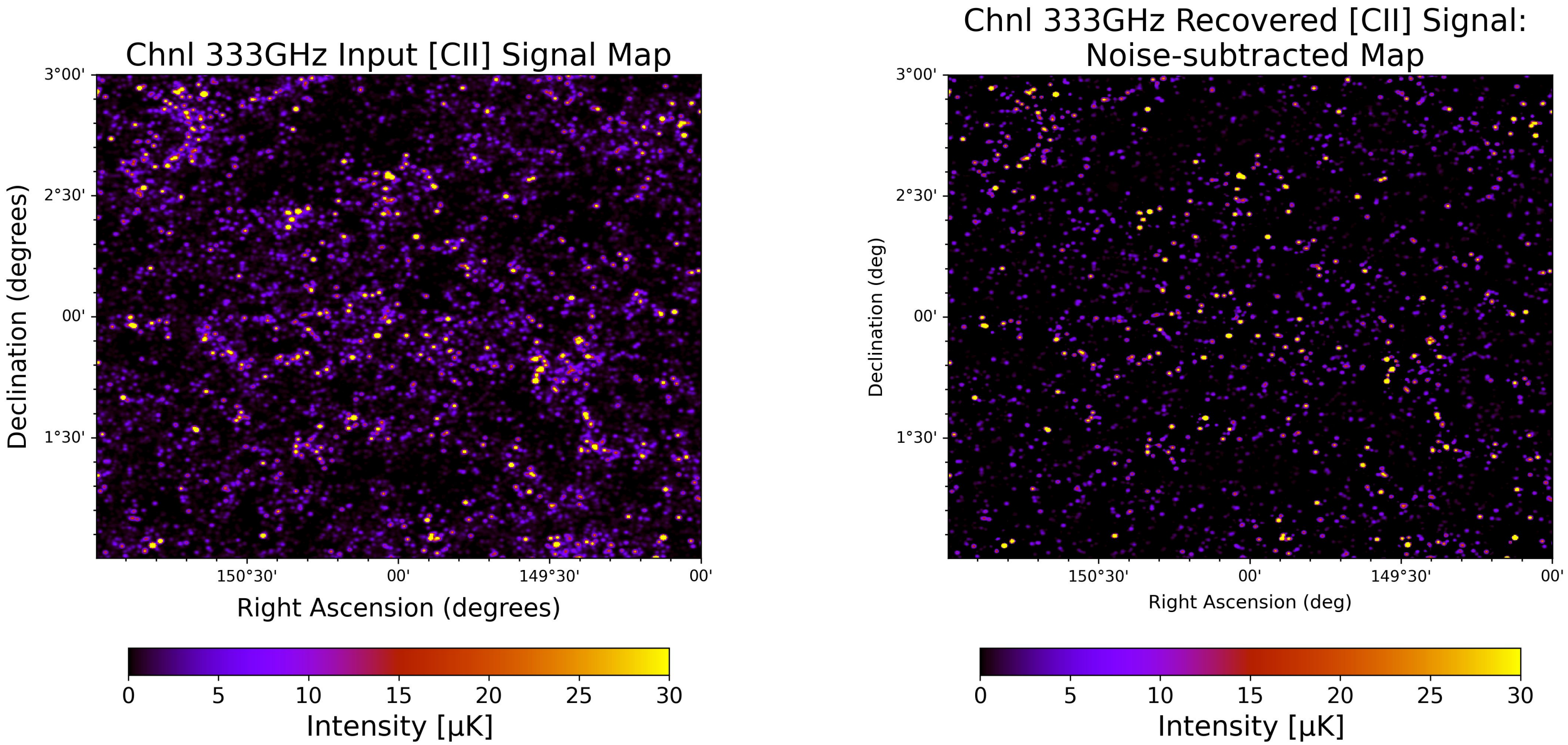
We process Signal+Noise and Noise-only simulations through the same pipeline to quantify signal attenuation



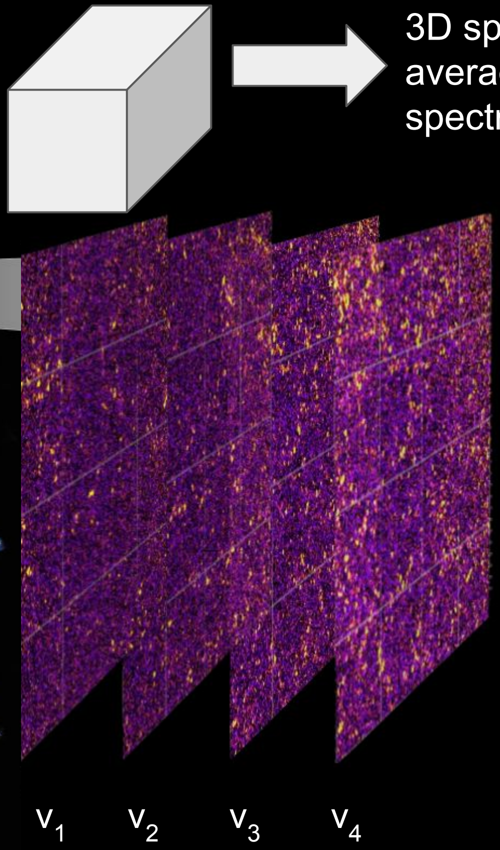


Comparison of Signal Maps: Input Intrinsic [C II] vs Recovered

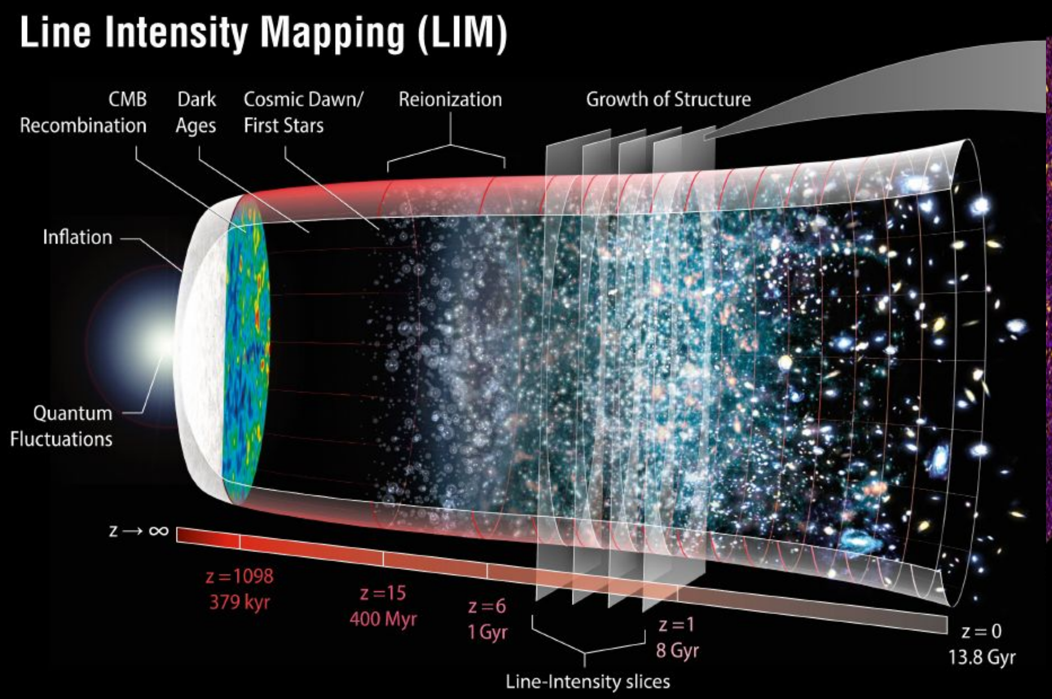
With just 50% of planned observations, bright [C II] sources are recovered (shot-noise regime), and faint clustered structures begin to emerge



Building Spectral Datacube



3D spherically-averaged power spectrum



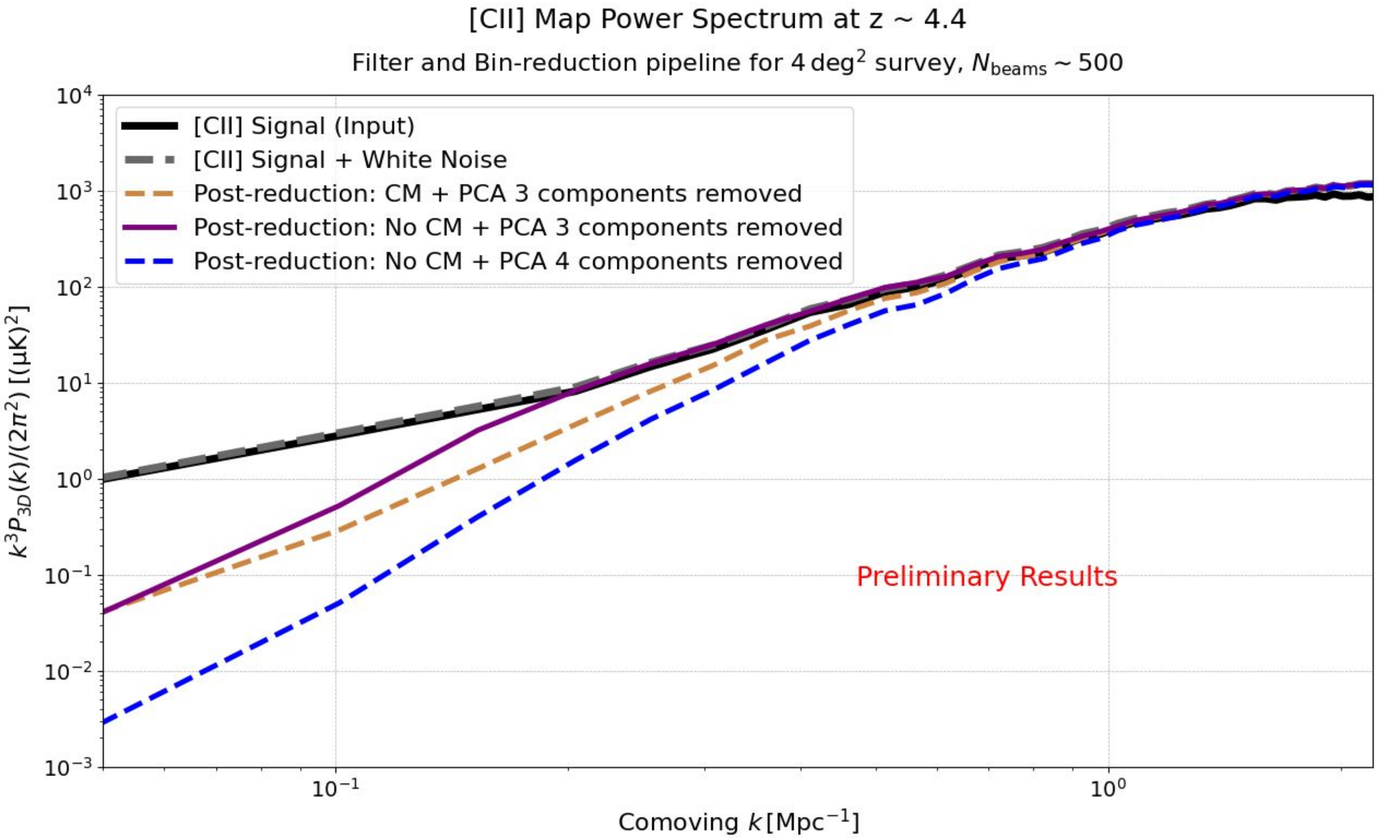
NASA LAMBDA archive

TNG based [CII] intensity simulations at z~4 (Karoumpis+2021, Dev+in_prep)

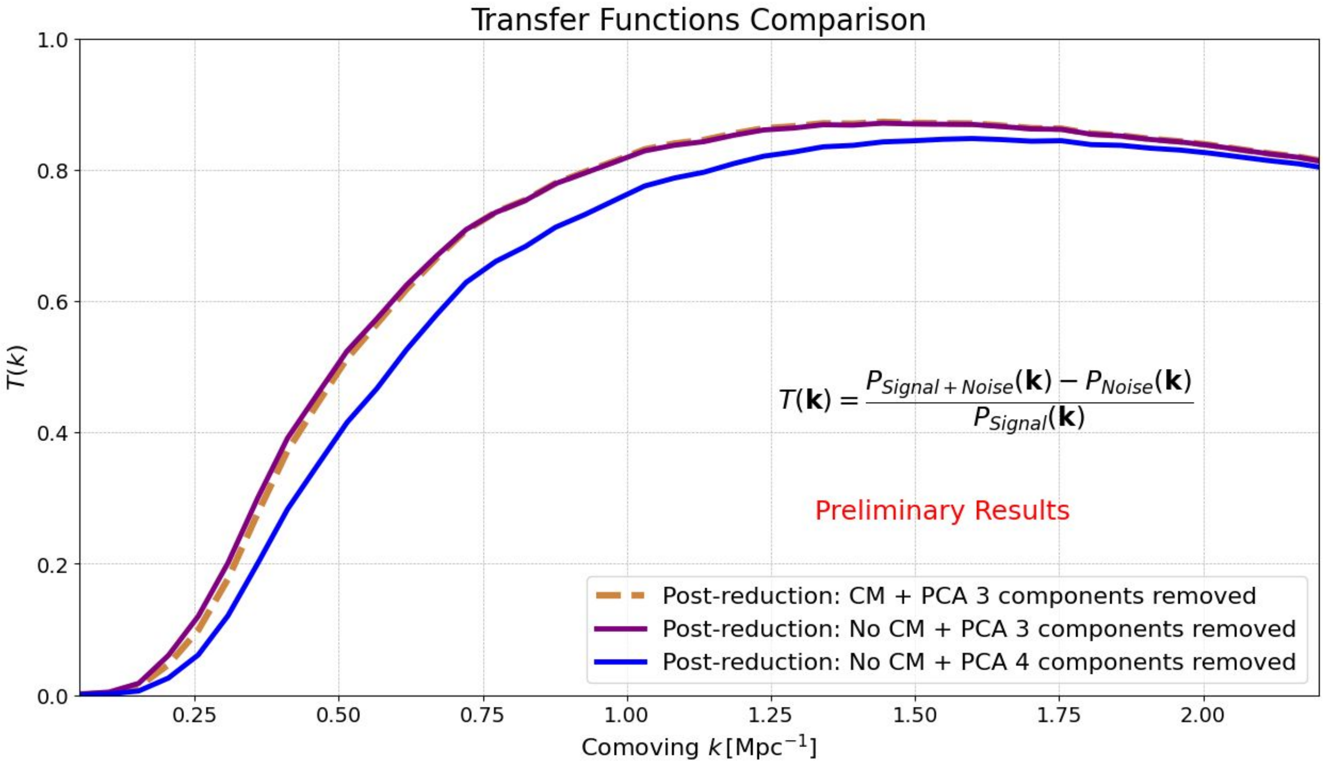
Investigating effect of filtering on [CII] Power Spectrum

- **Shot noise regime** at z ~ 4.4 can be detected and constrained even with 50% of planned observations

- **Low-k modes** shows power loss:
  Filtering affects the large scales; need alternative mitigation techniques

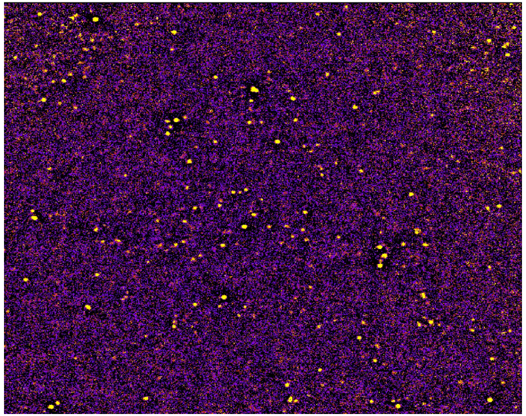


Quantifying Signal loss from mock Pipeline with Transfer Function

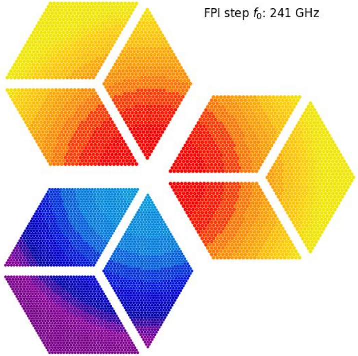


Require future work to recover large scales:

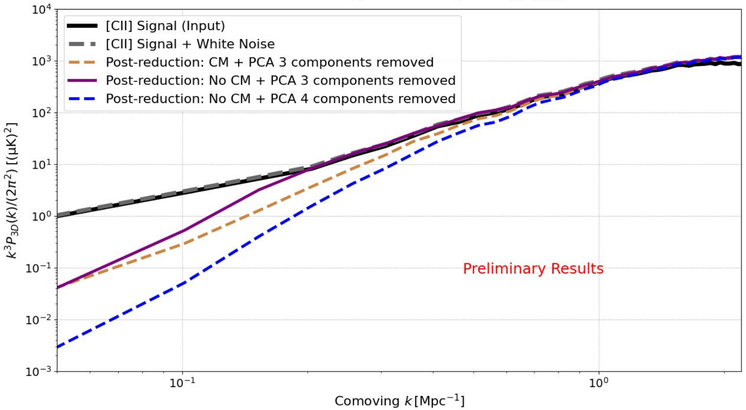
- Fourier Template fitting
- Destriping / Maximum-Likelihood
- Bayesian methods for incorporating noise priors
- Investigate higher scan speeds mitigating 1/f noise contamination

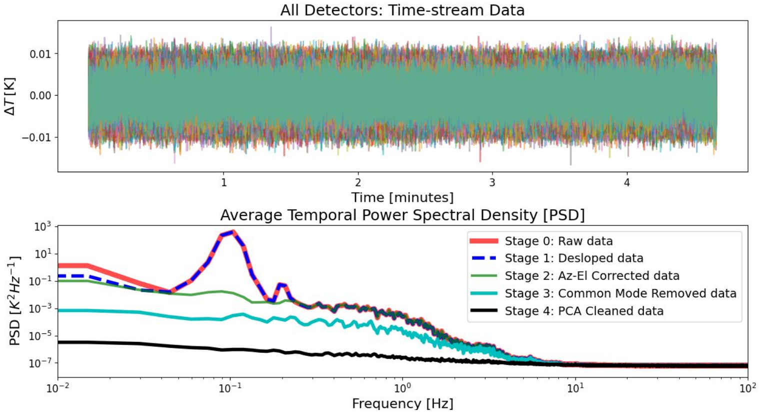


Take Away Summary



We are building LIM data reduction pipelines, investigating systematics and exploring map-making methods.





Back-up Slides follow…

TOAST framework and Atmospheric Model

- **Time Ordered Astrophysics Scalable Tools (TOAST)** software framework (https://github.com/hpc4cmb/toast)
- Built on the **Errard+2015 3D-model** of the atmosphere total intensity emission in the mm and sub-mm wavelengths.

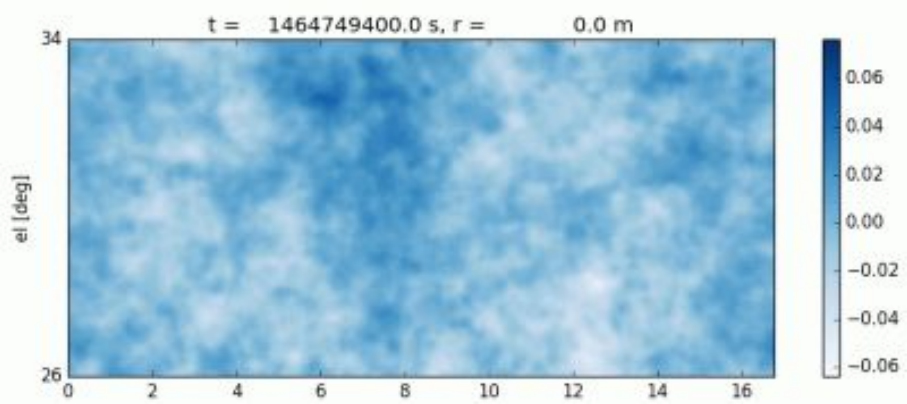


Fig left: Example of TOAST Simulated turbulent atmosphere (Image Credit: Julian Borrill, https://crd.lbl.gov/assets/Uploads/_resampled/ResizedImage400179-atm-10-30-10v1.gif)

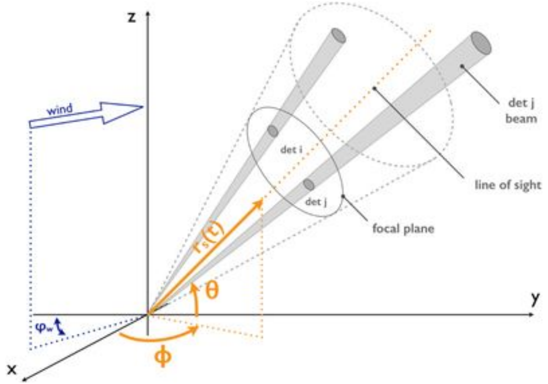
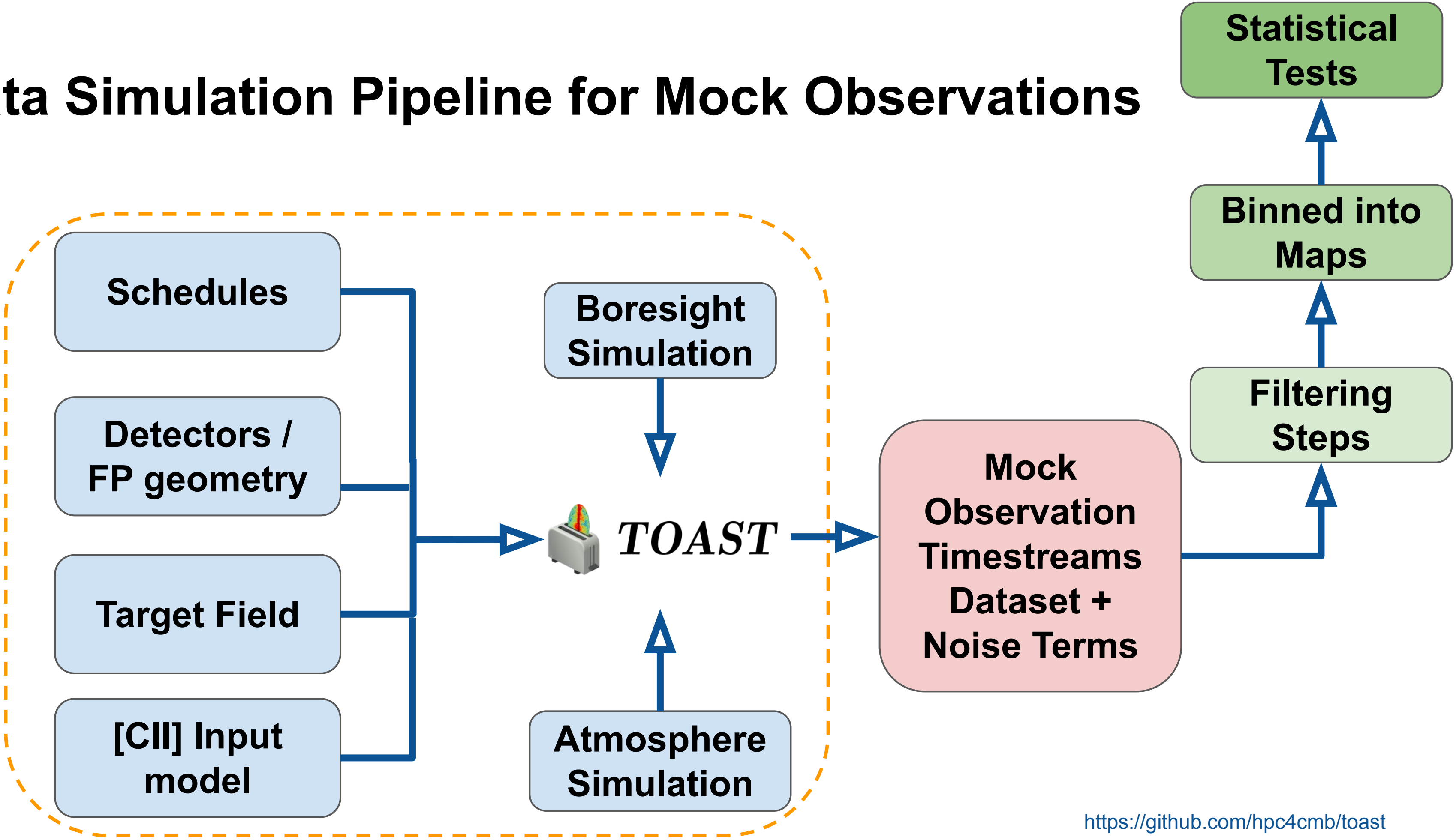


Fig right: Pair of detectors observes along a line of sight. (from Errard+2015)

Data Simulation Pipeline for Mock Observations



https://github.com/hpc4cmb/toast

PCA on Time-stream data: Removed Components