

# Upper limits on the 21-cm signal from Cosmic Dawn with NenuFAR

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institute

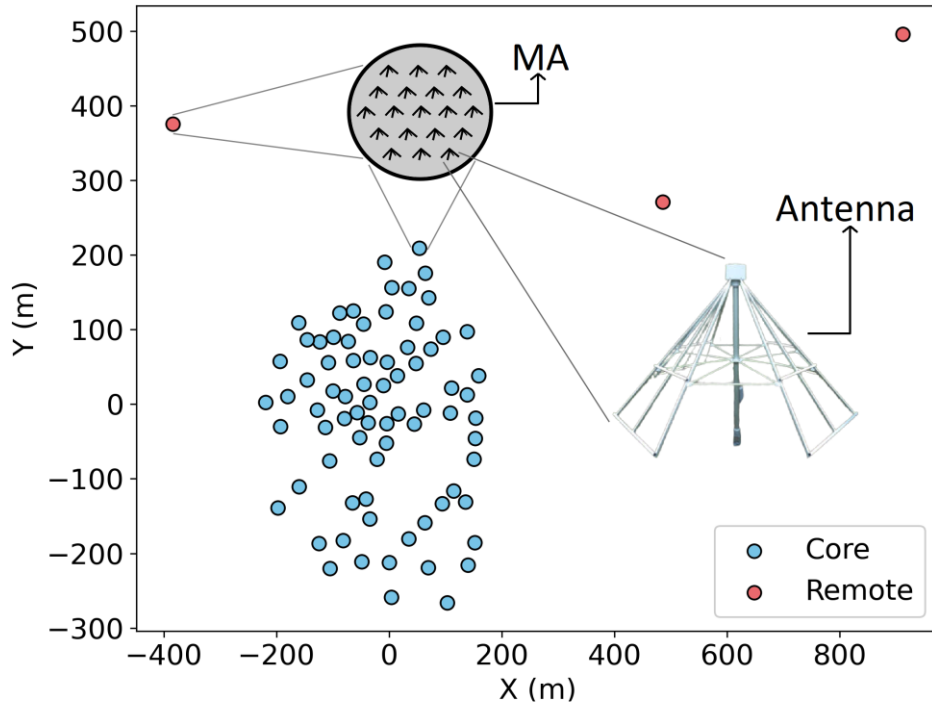
A horizontal timeline of the universe's expansion from the Big Bang to the present. The top axis shows time in billions of years after the Big Bang: 13.8 billion, 8 billion, 4 billion, 1 billion, 0.1 billion, and 400 thousands. The bottom axis shows the corresponding redshift values: 1, 10, 100, and 1000. The timeline is divided into several key epochs: **The Dark age** (from 13.8 billion years ago to the formation of the first stars), **EoR** (Epoch of Reionization, from the formation of the first stars to the formation of the first galaxies), and **CD** (Cosmic Dawn, from the formation of the first galaxies to the formation of the first stars and objects). The timeline also marks the **Reionization** period, which is the transition from a **Fully ionized** state to a **Neutralized** state. The **Recombination** event is shown as a transition from a **Fully ionized** state to a **Neutralized** state. The timeline ends with **The Big Bang** at 0.1 billion years ago. Various astronomical observatories are shown along the timeline: **VLT**, **E-ELT**, **ALMA**, **HUBBLE**, **Spitzer**, and **WEBB** (James Webb Space Telescope). The timeline is credited to **NAOJ**.

- 
- Frequency [MHz]
- $L$  [Mpc]
- Global 21-cm signal experiments:  
EDGES, SARAS 2, LEDA...
- Interferometric 21-cm experiments: LOFAR, NenuFAR, MWA, HERA, SKA...
- Redshift,  $z$
- $k = 0.1 \text{ Mpc}^{-1}$
- Credit: Mesinger & Greig



***Needs “exotic”  
model to be  
explained***

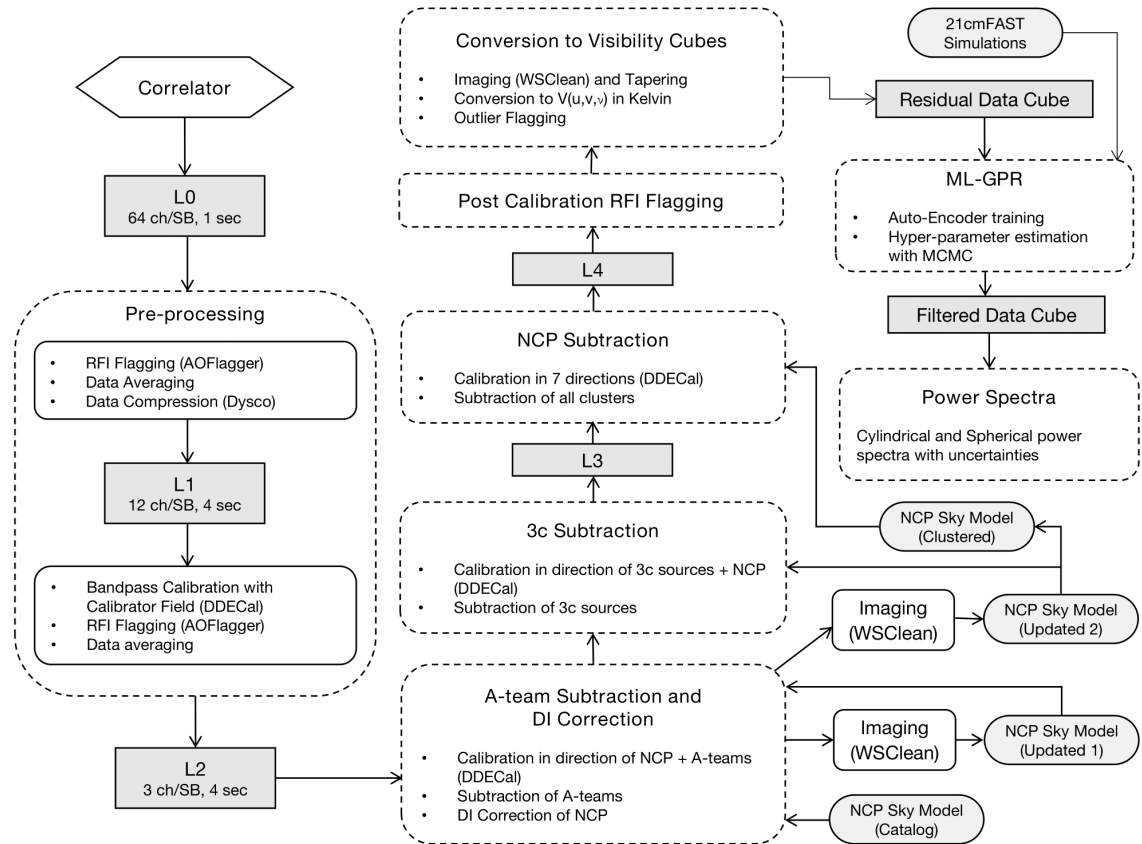
# The Instrument



- NenuFAR - Low frequency radio interferometer (37 - 85 MHz)
- At completion: 96 core and 8 remote Mini Arrays
- Very dense core - High sensitivity to large scales
- Reach levels of EDGES inspired exotic models in 100 hours of observation

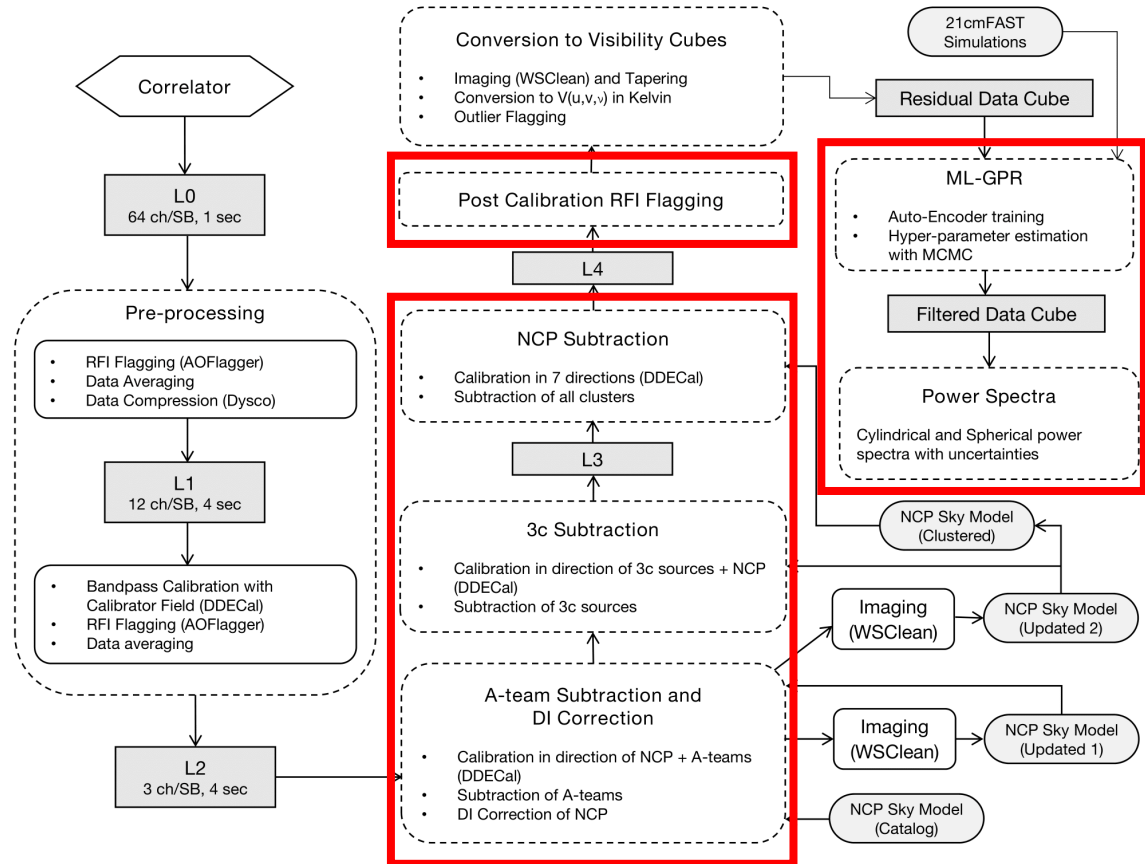
# Introduction

- Single night (11.4 h) observation of the North Celestial Pole
- 76 core MA and 3 remote MA
- 61-72 MHz ( $z=20.3$ )
- **Aim: Pilot Project to optimize the analysis pipeline**



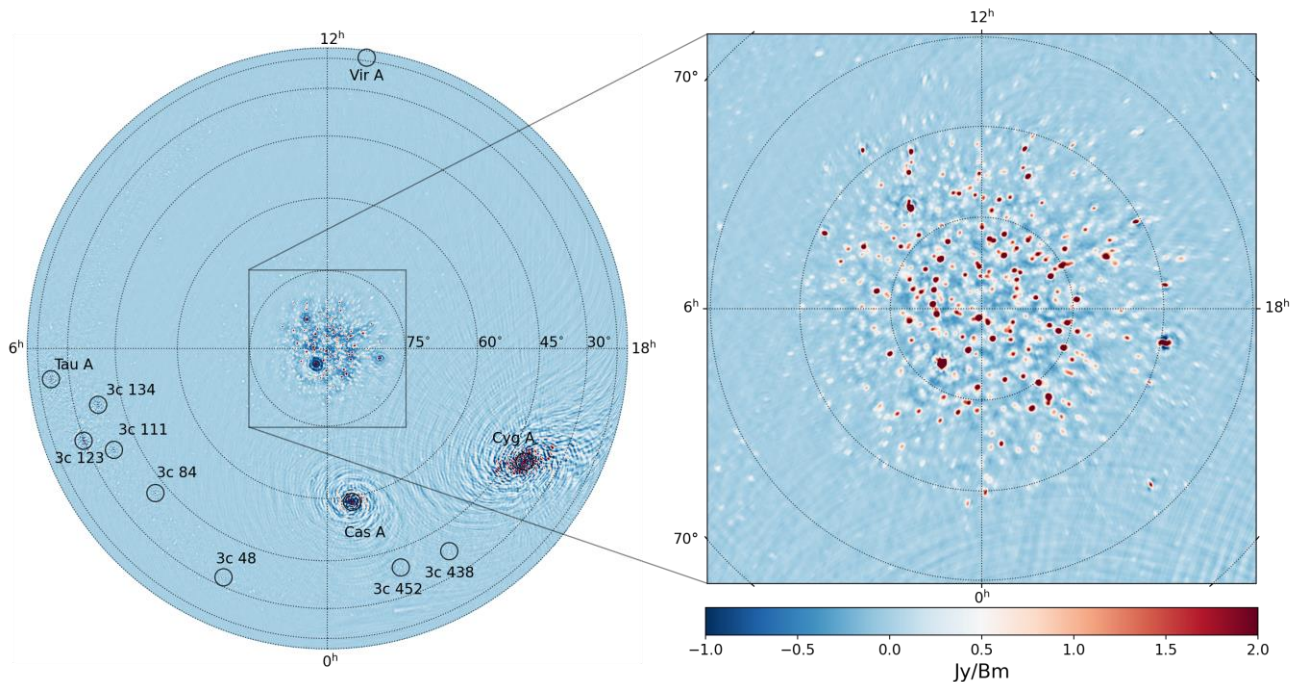
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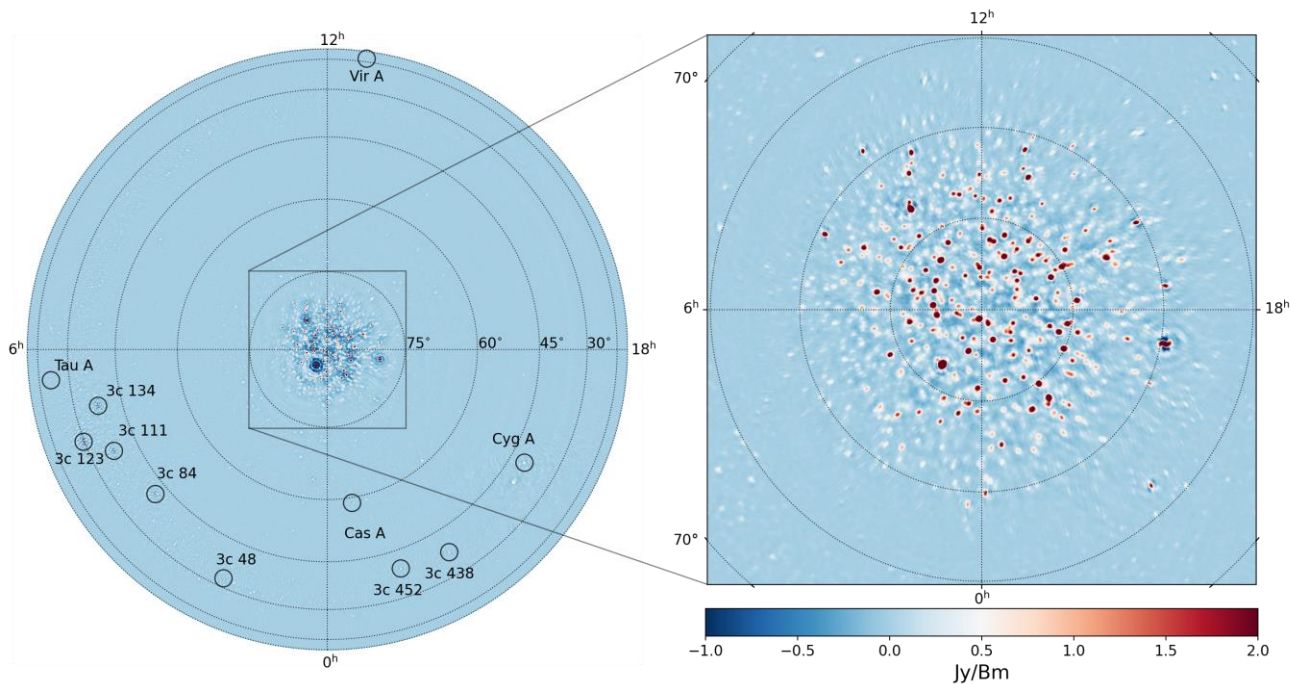


# Calibration and Sky Model Subtraction



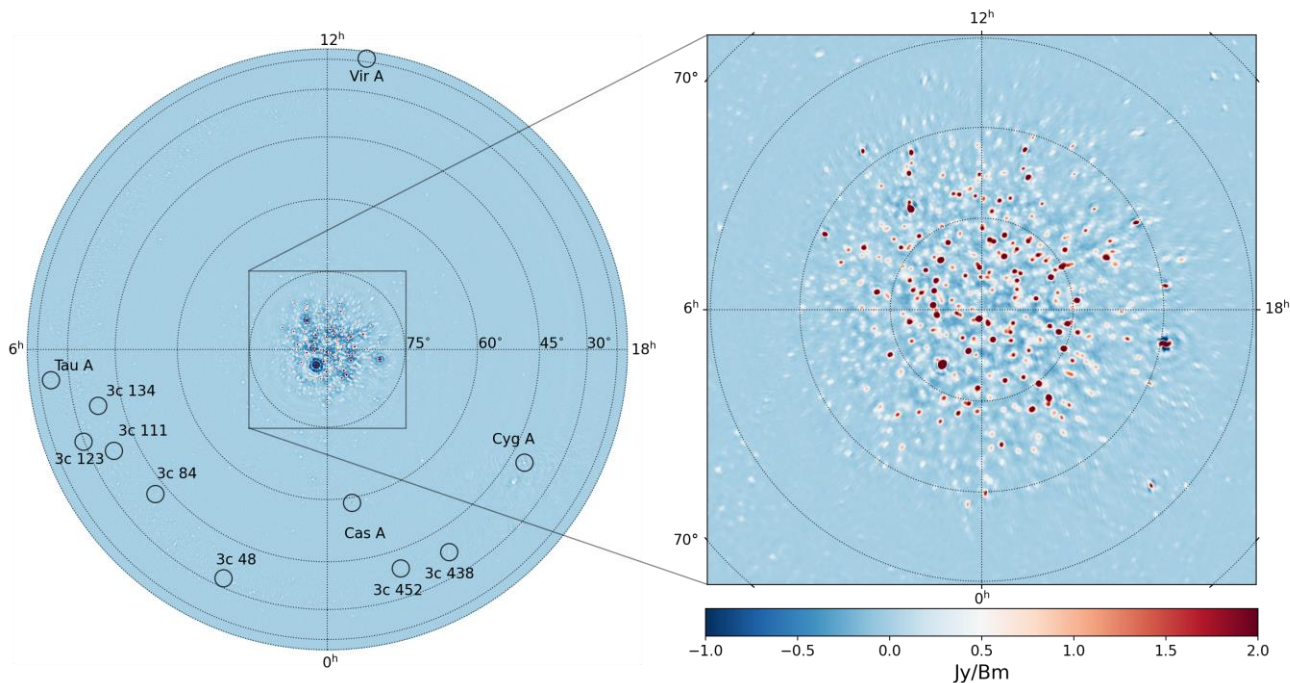
- A-teams Subtraction  
(Direction Dependent)
  - Direction Independent Correction
- 
- 3c Subtraction  
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  - NCP Subtraction  
(Direction Dependent)

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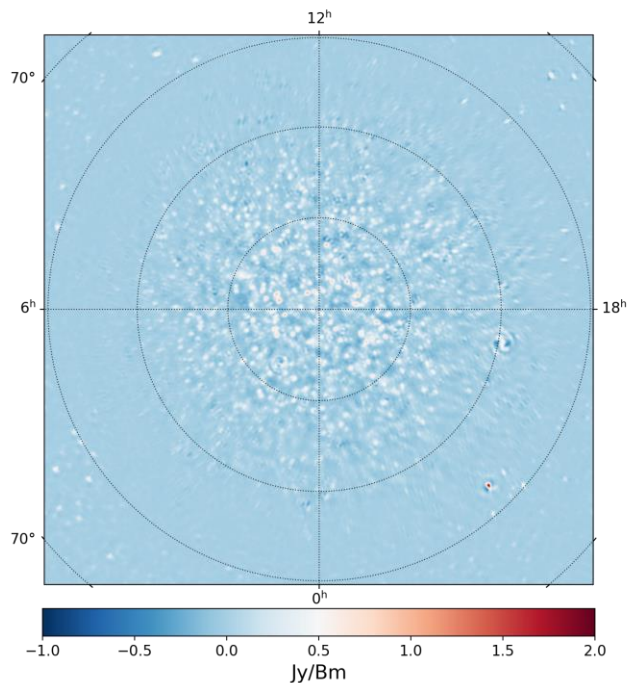
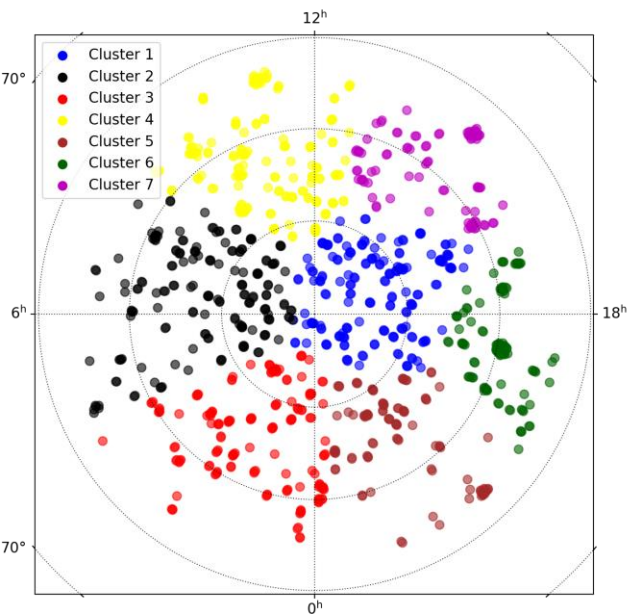
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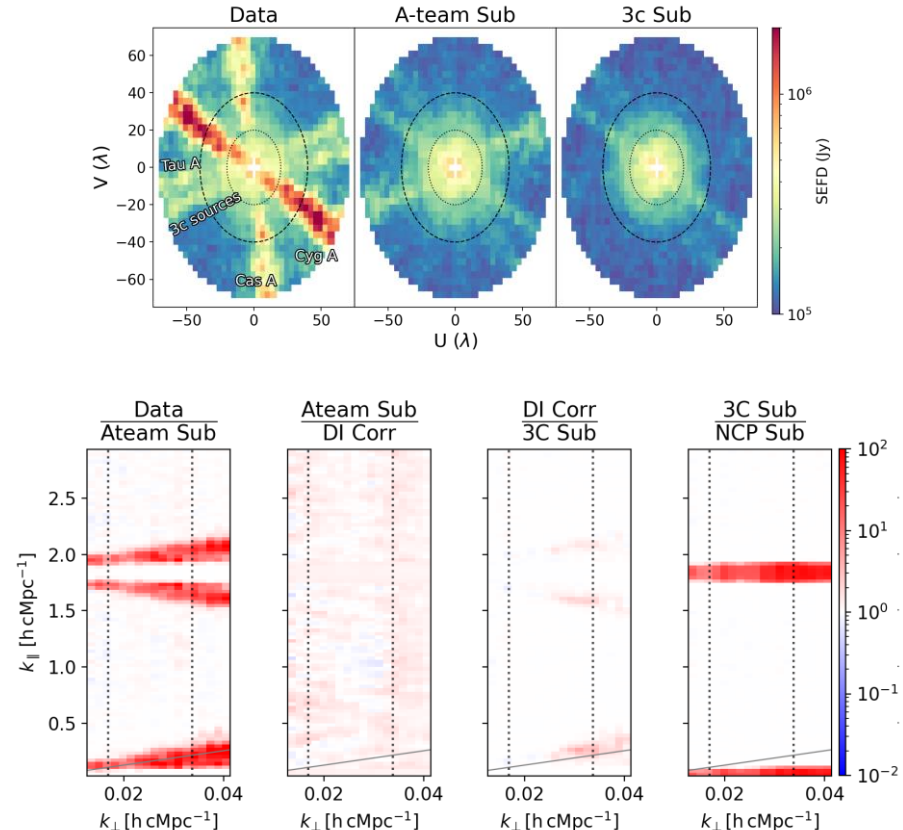
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# Cylindrical Power Spectra

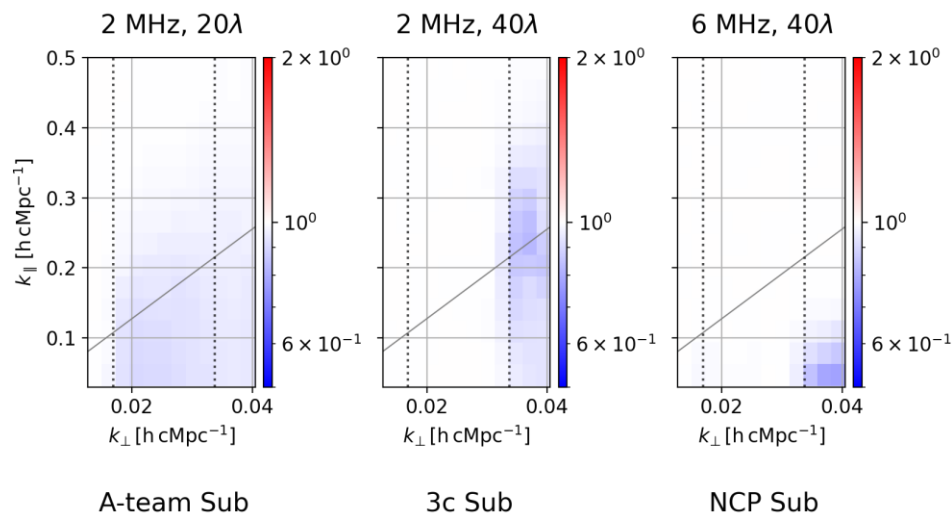
- Image the central region, apply spatial taper, FT to gridded uv plane
- Strong features in UV plane due to sidelobes of sources away from phase center
- Power Spectra computed at each stage of sky model subtraction



# Signal Injection Test

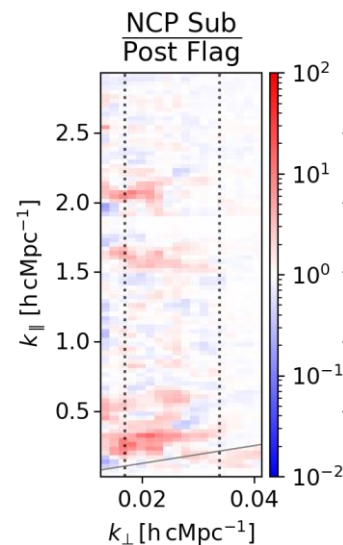
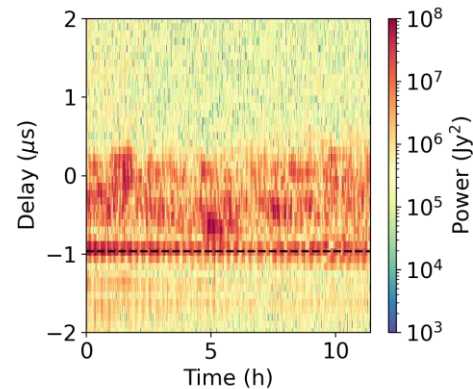
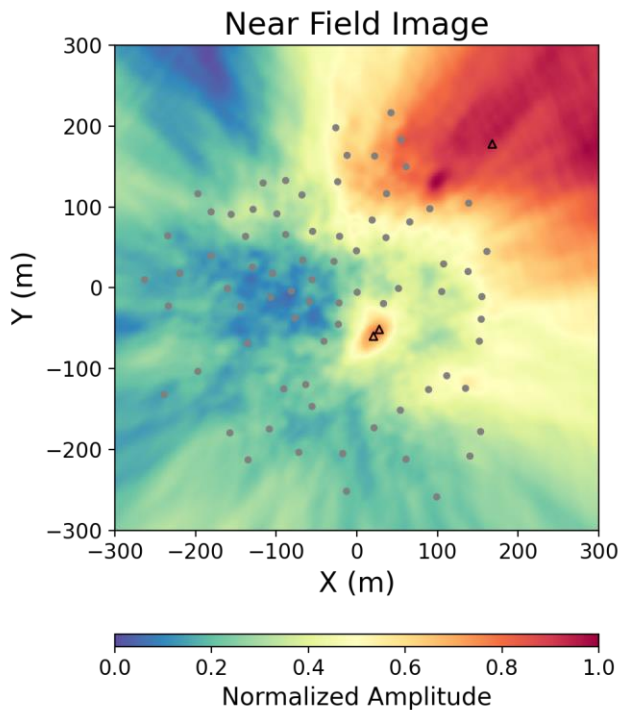
- Inject a mock 21-cm signal to the visibilities
- Compare the recovered signal with input
- Repeat for different gain frequency smoothing scales and baseline cuts

Cylindrical PS  
(Recovered / Input)



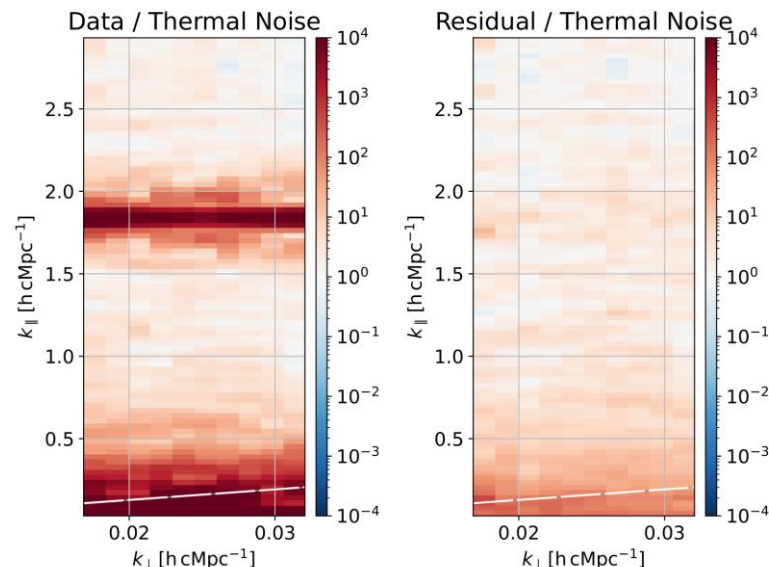
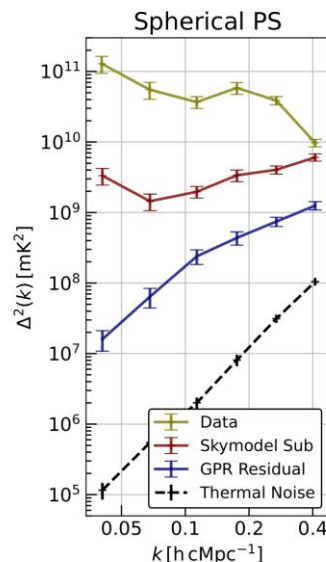
# Post Calibration RFI Flagging

- We find lot of power at high delay
- Near Field Imaging reveals source at building
- Flag baselines with strong feature in Delay power Spectra



# Residual Foreground Removal

- Subtract Residual Foregrounds with ML-GPR
- Signal injection tests: Inject 100 different signals and ensure signal is not absorbed
- Excess upto 2 orders of magnitude beyond thermal noise





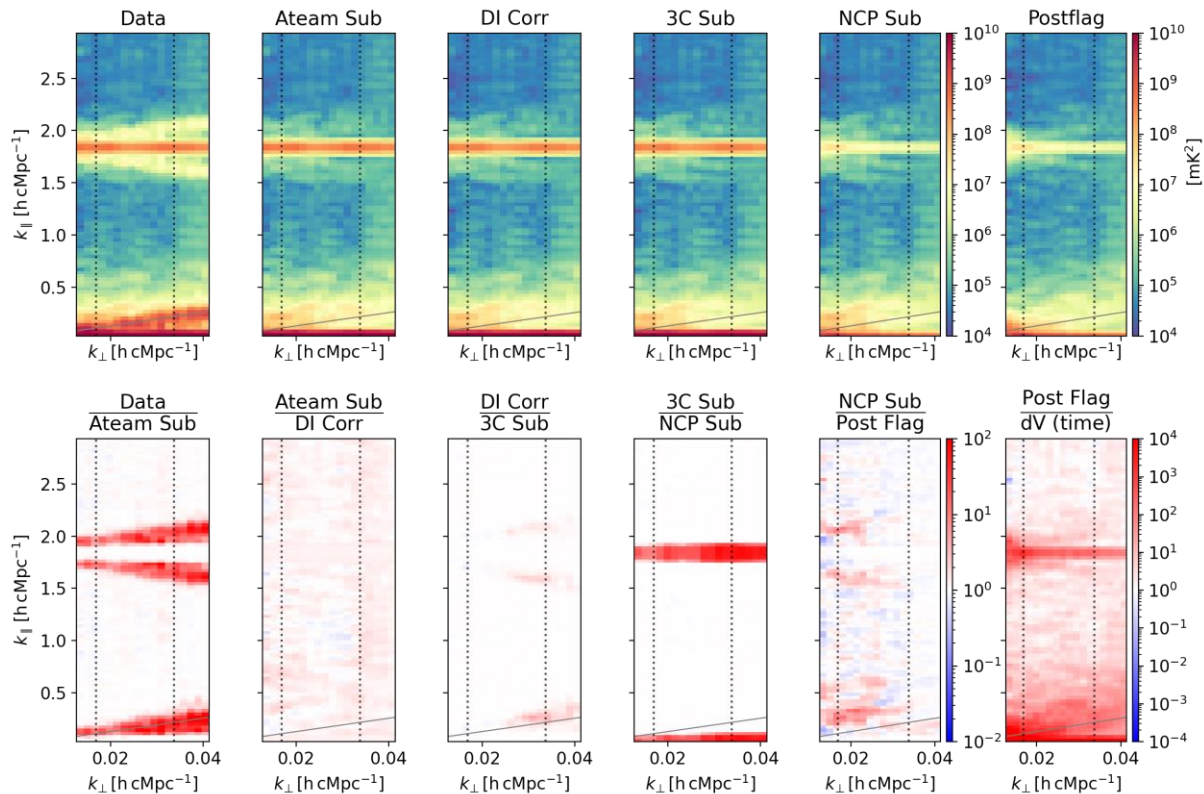
# Summary

- Many strong sources far away from phase centre - Subtracted
- NCP Subtraction confusion limited
- Near Field RFI Sources impact the power spectrum
- Excess power
  - Up to 2 orders of magnitude beyond the thermal noise
  - Causes: Near field RFI sources, wide field sources?
- Future Work
  - Model and filter RFI sources
  - Longer integrations

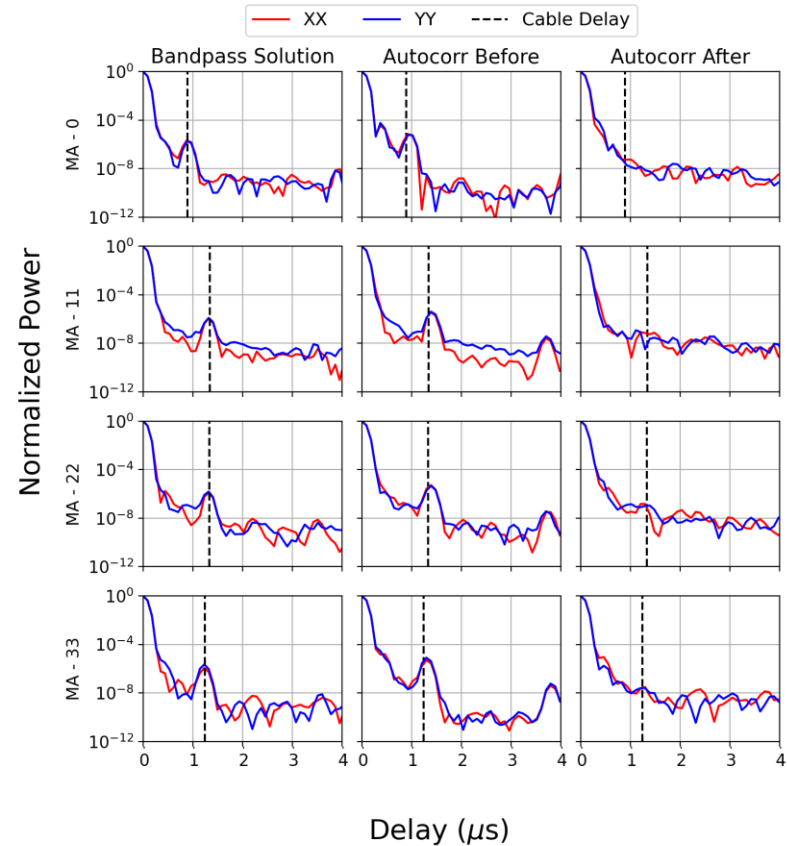
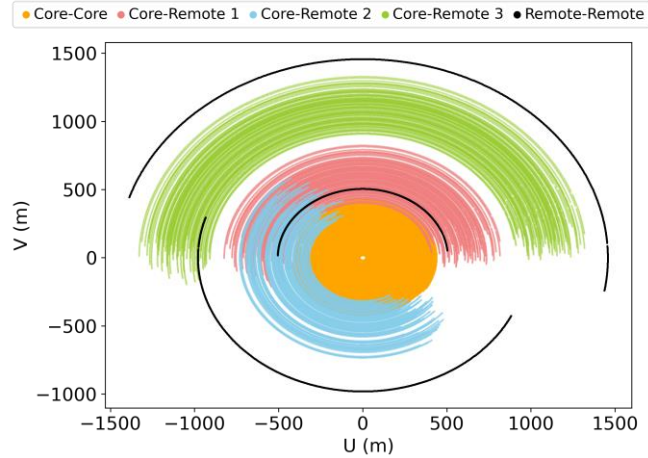


# Cylindrical PS

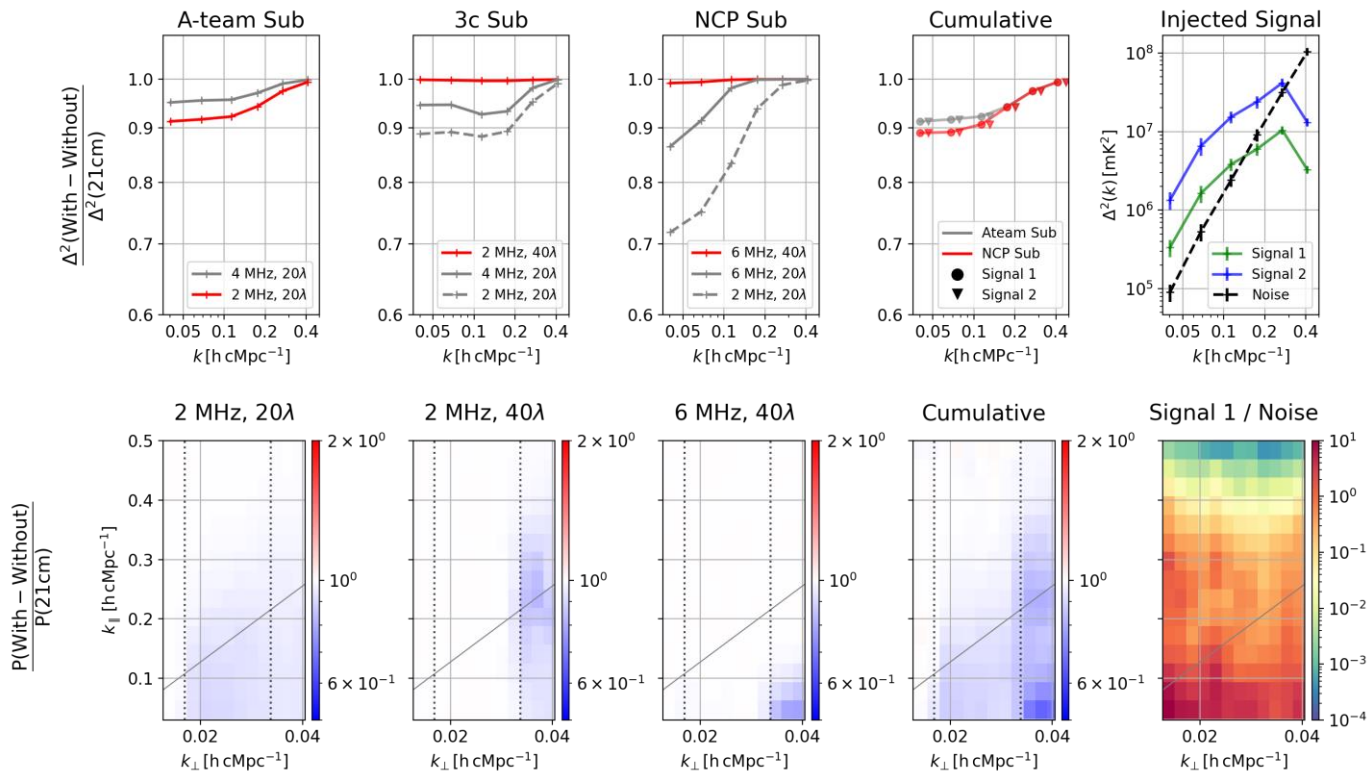
- Power Spectra computed at each stage of sky model subtraction



# UV Coverage and Bandpass

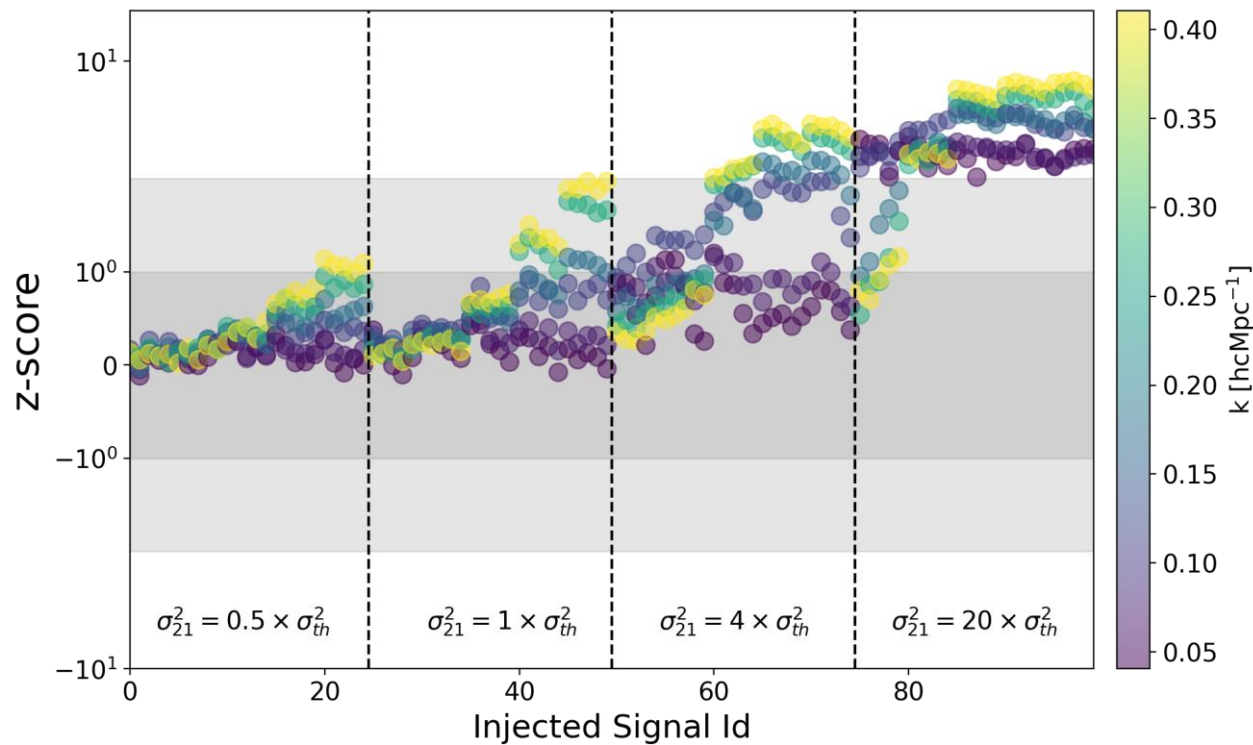


# Signal Injection (Calibration)

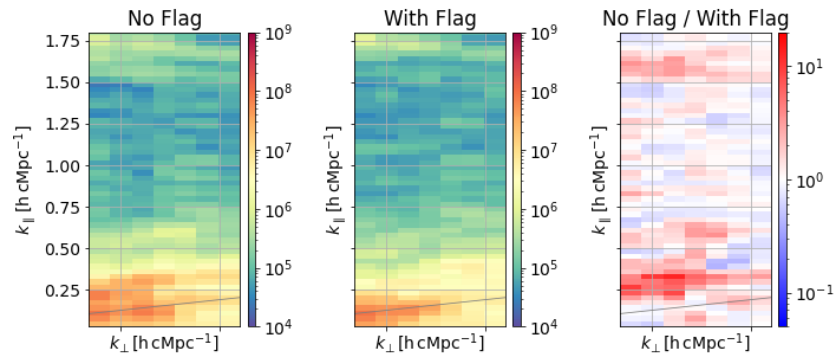
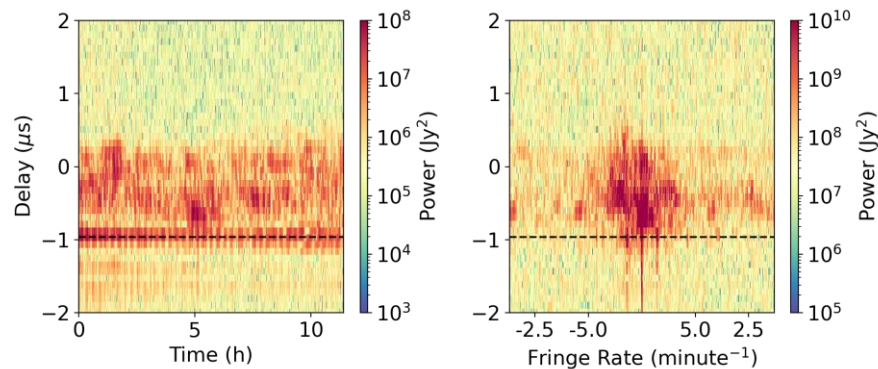
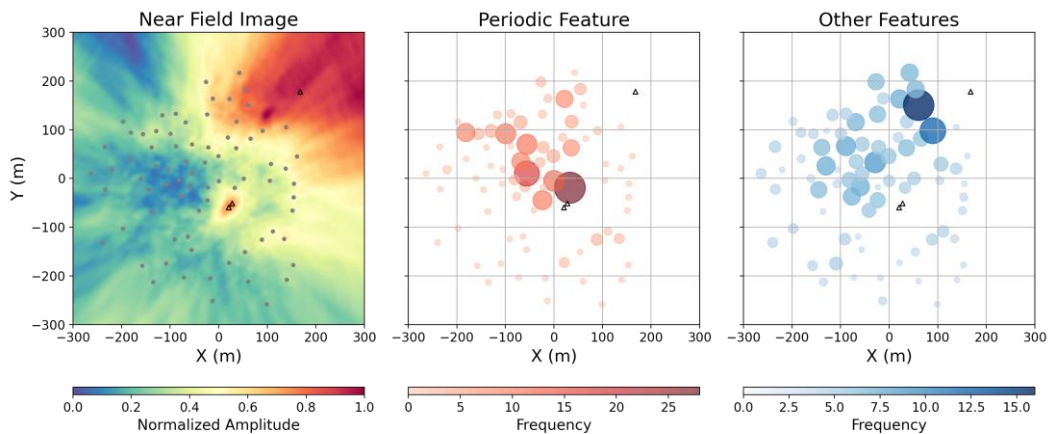




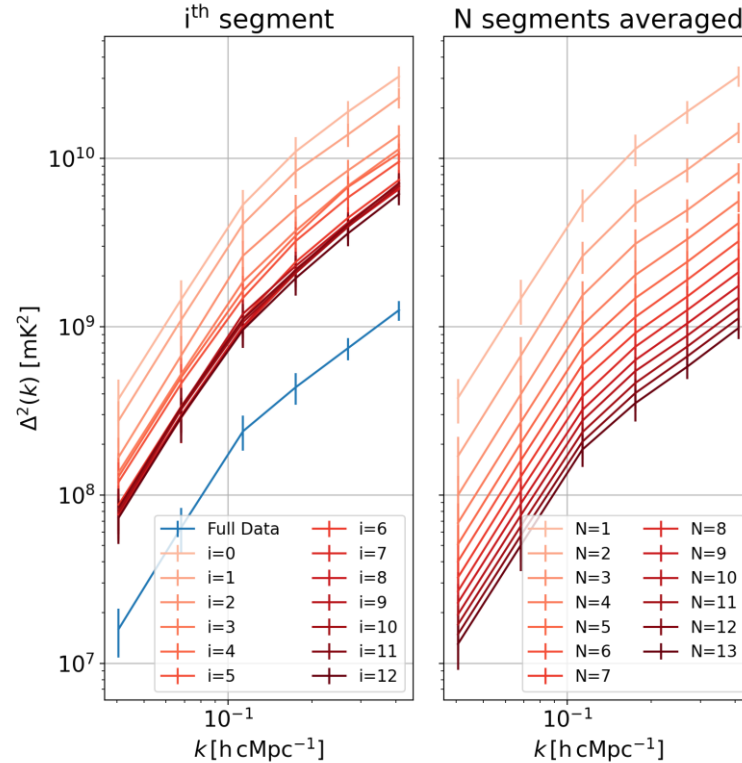
# Signal Injection (ML-GPR)



# Post Calibration RFI Flagging



# Individual segments



# Upper limits

