Latest 21cm results from the Australian EoR team

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MWA Project Meeting 2024

Swiss Federal Institute of Technology, Lausanne

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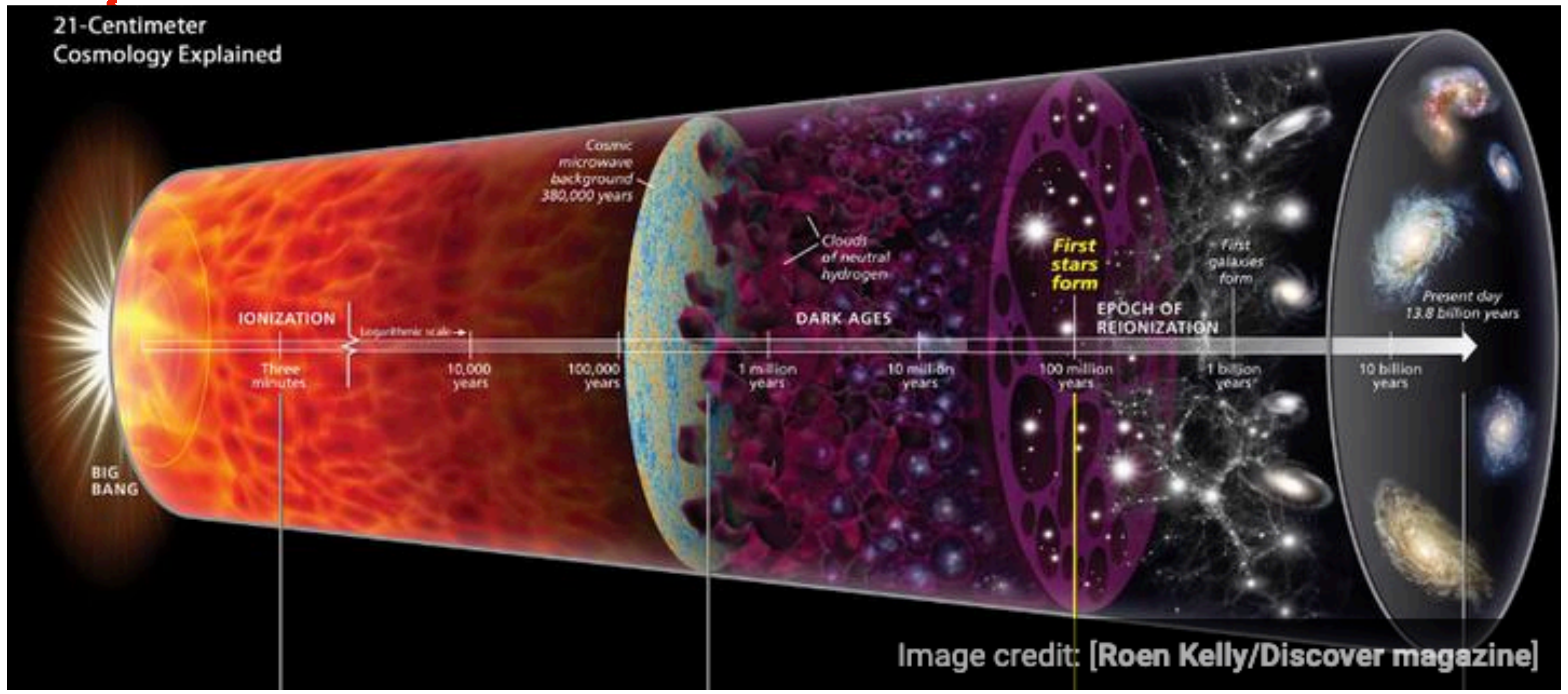
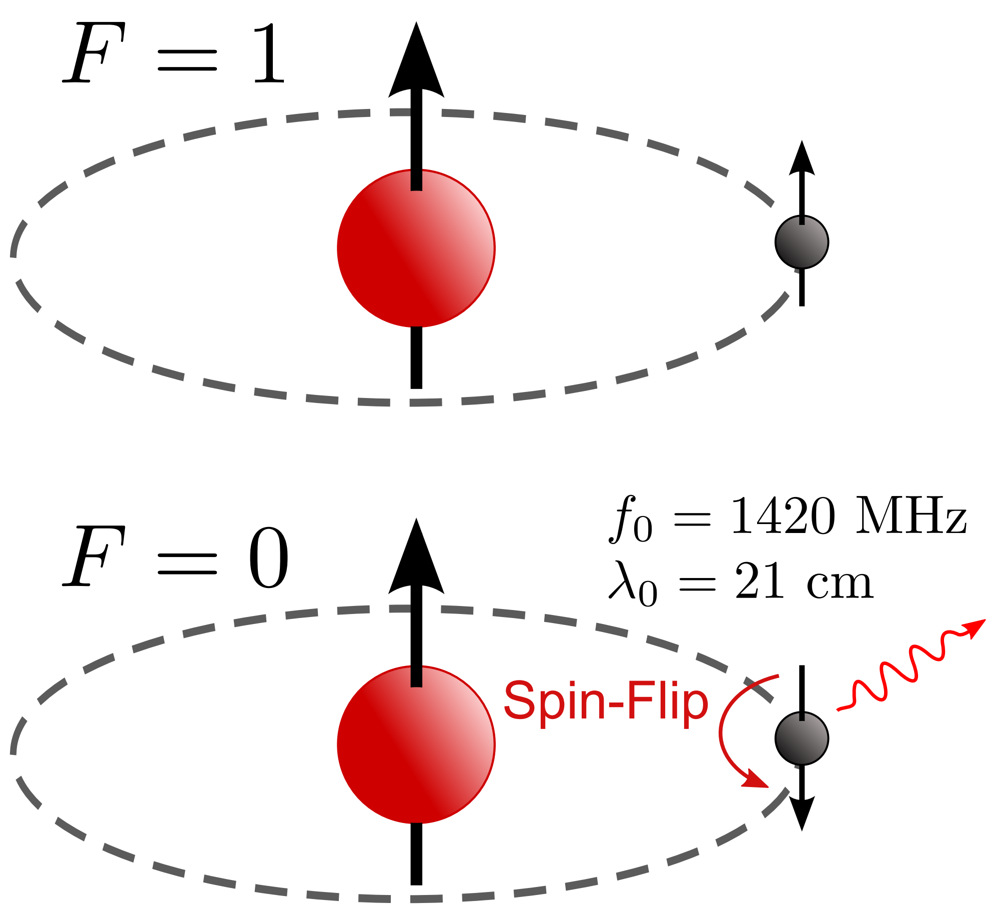
Epoch of Reionisation (EoR)



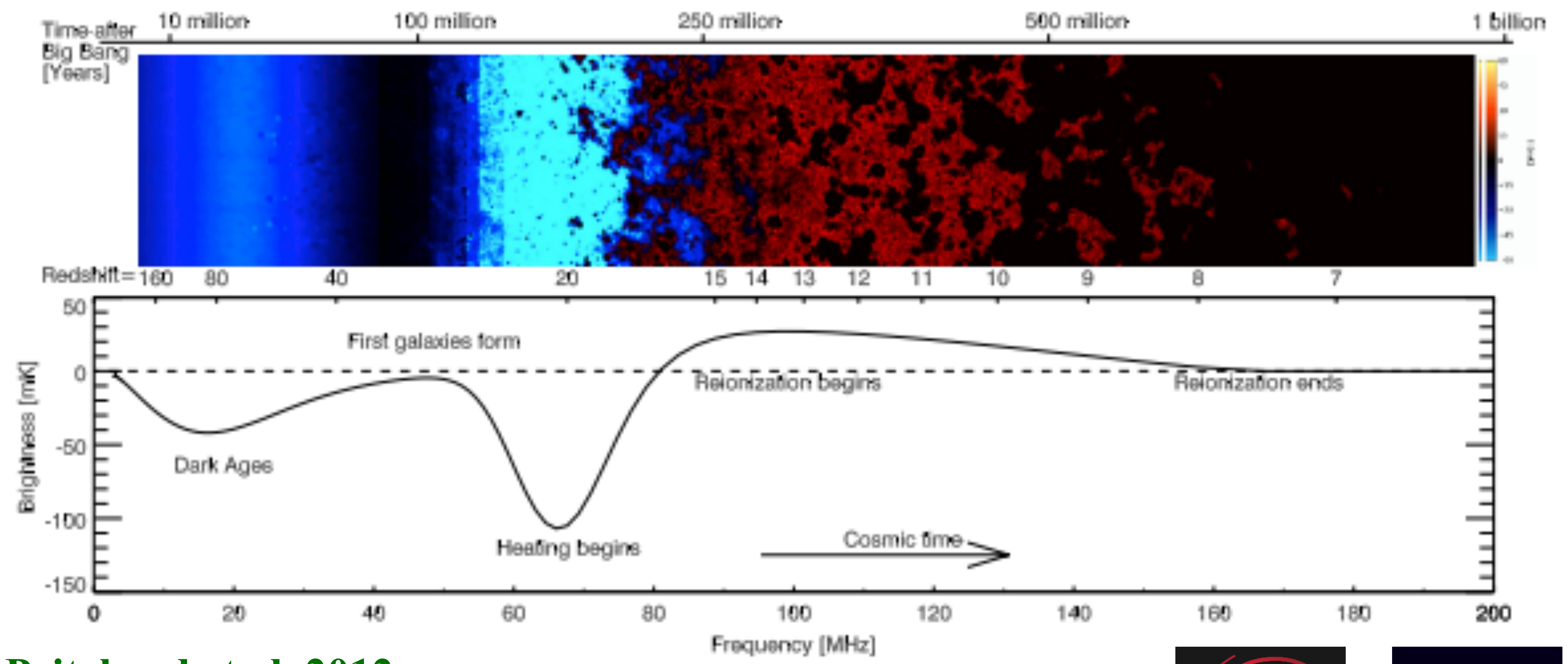
21 cm Hydrogen Line

- Hyperfine transition at restframe of 21 cm
- Measure brightness of temperature
  - physical and radiative



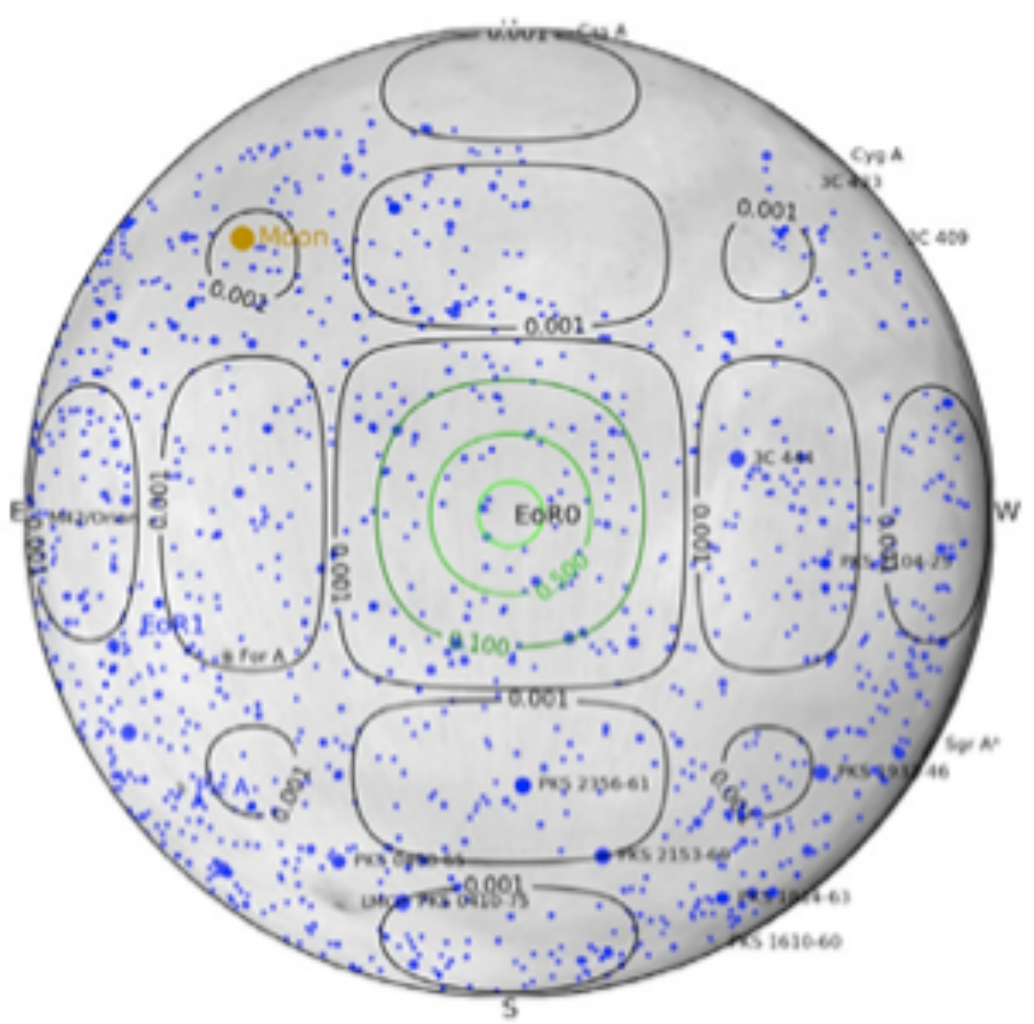
21 cm HI evolution

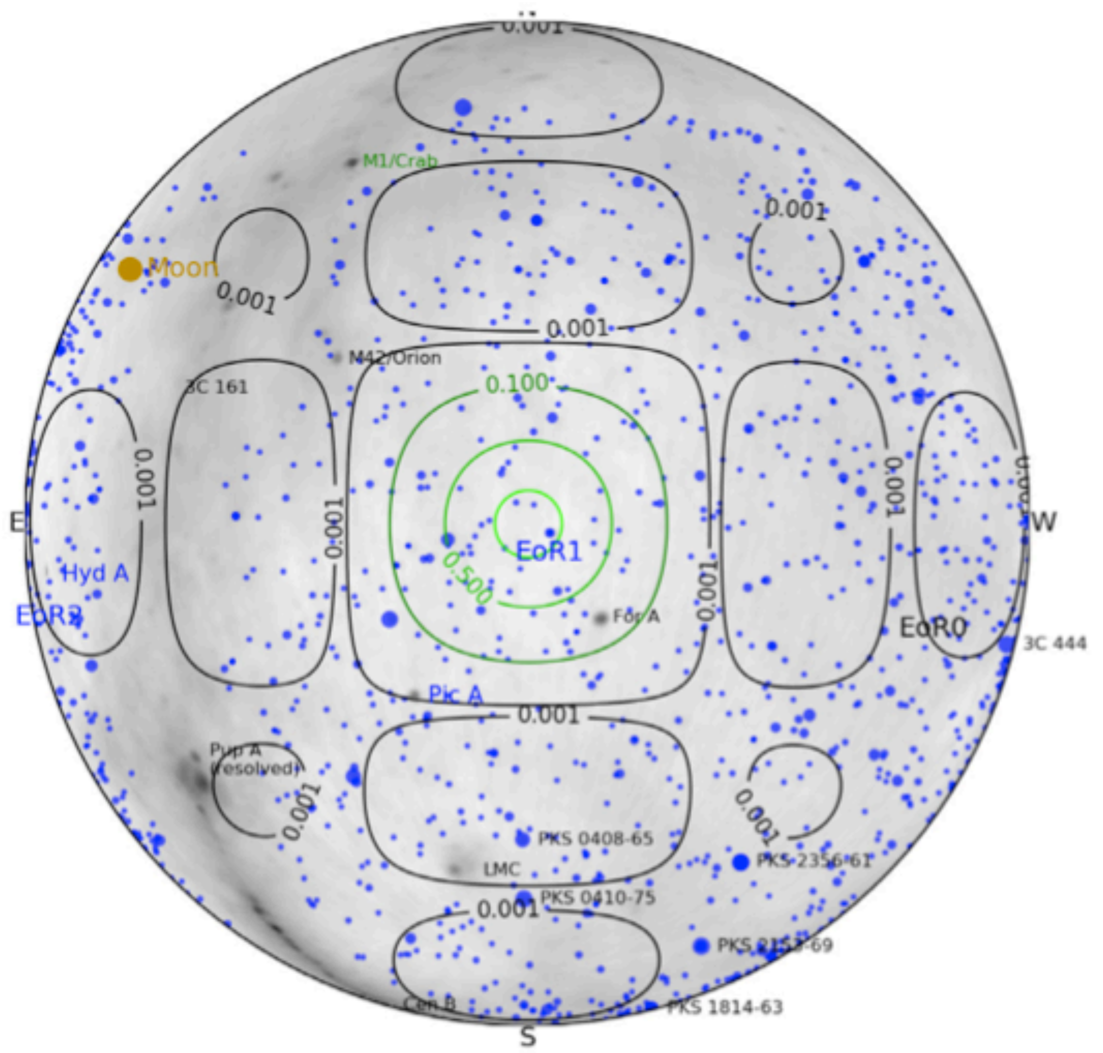
- Time evolution of fluctuations in the 21 cm brightness.
- Intensity indicates the strength of the 21 cm brightness as it evolves through two absorption phases.

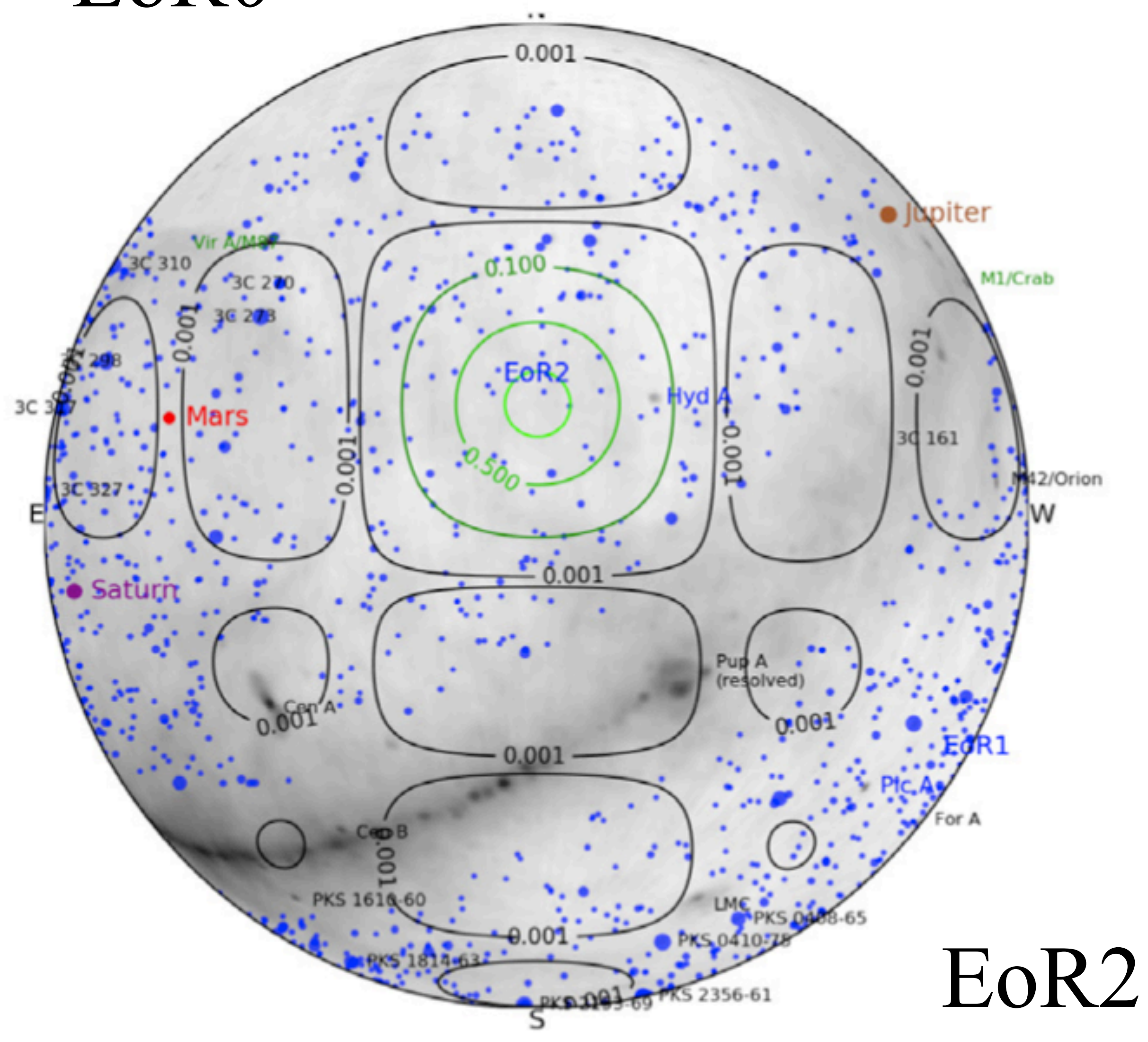


Pritchard et al. 2012

Murchison WideField Array

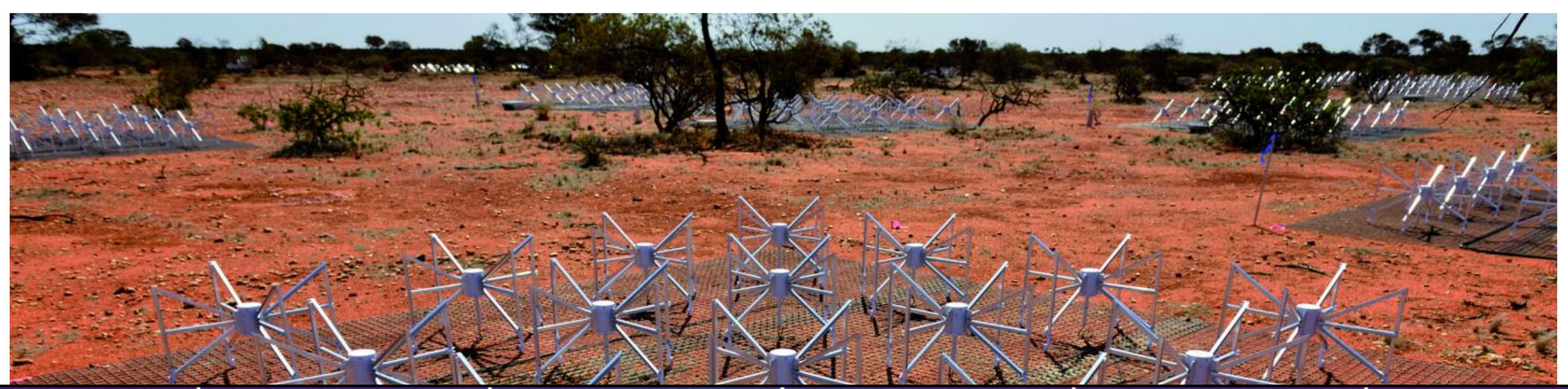


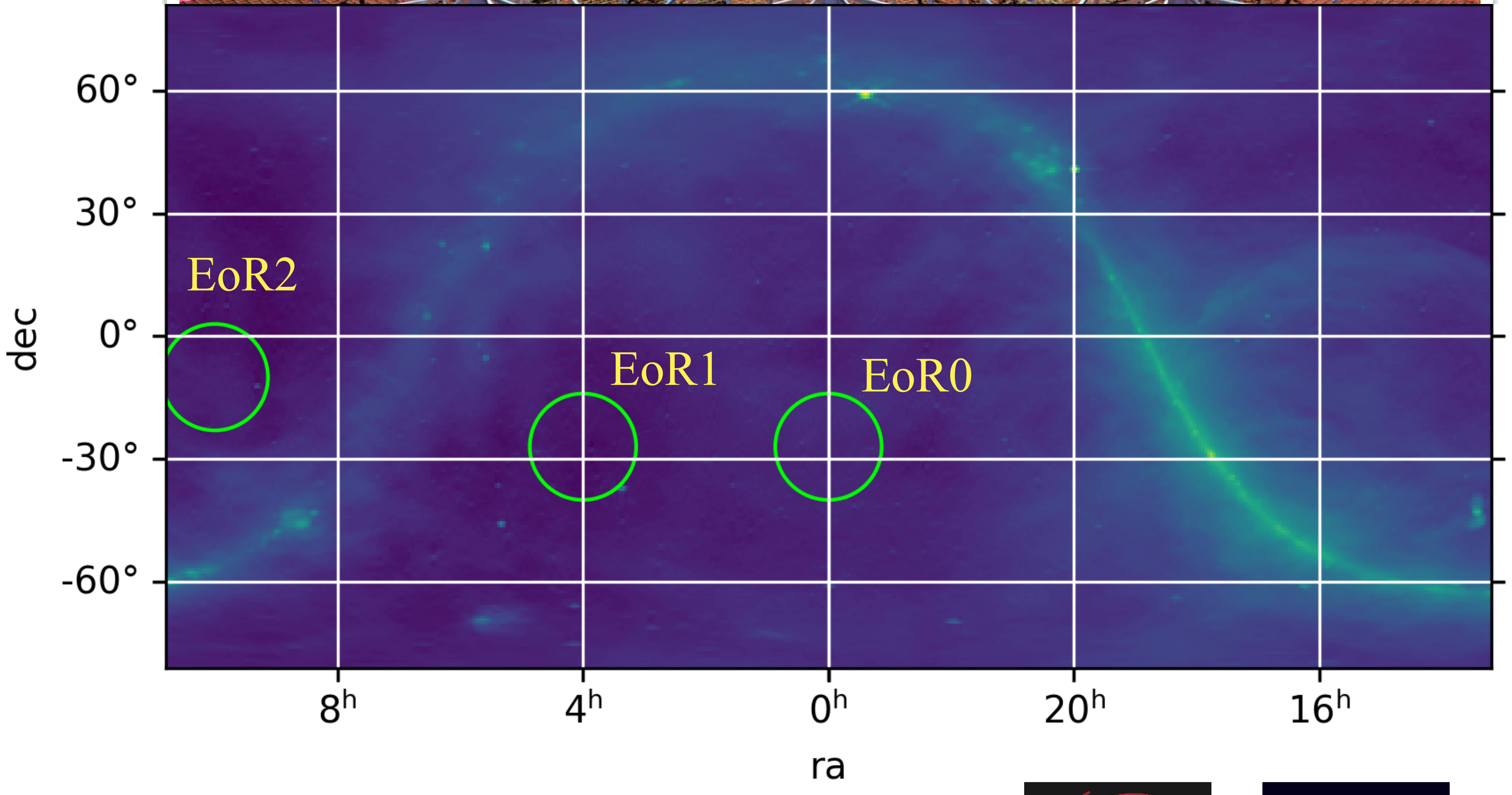




EoR Fields

- **EoR0**: Away from Galactic Centre (0h, -27 deg)
- **EoR1**: Contains Fornax A (4h, -27 deg)
- **EoR2**: Contains Hydra A (10.3h, -10 deg)





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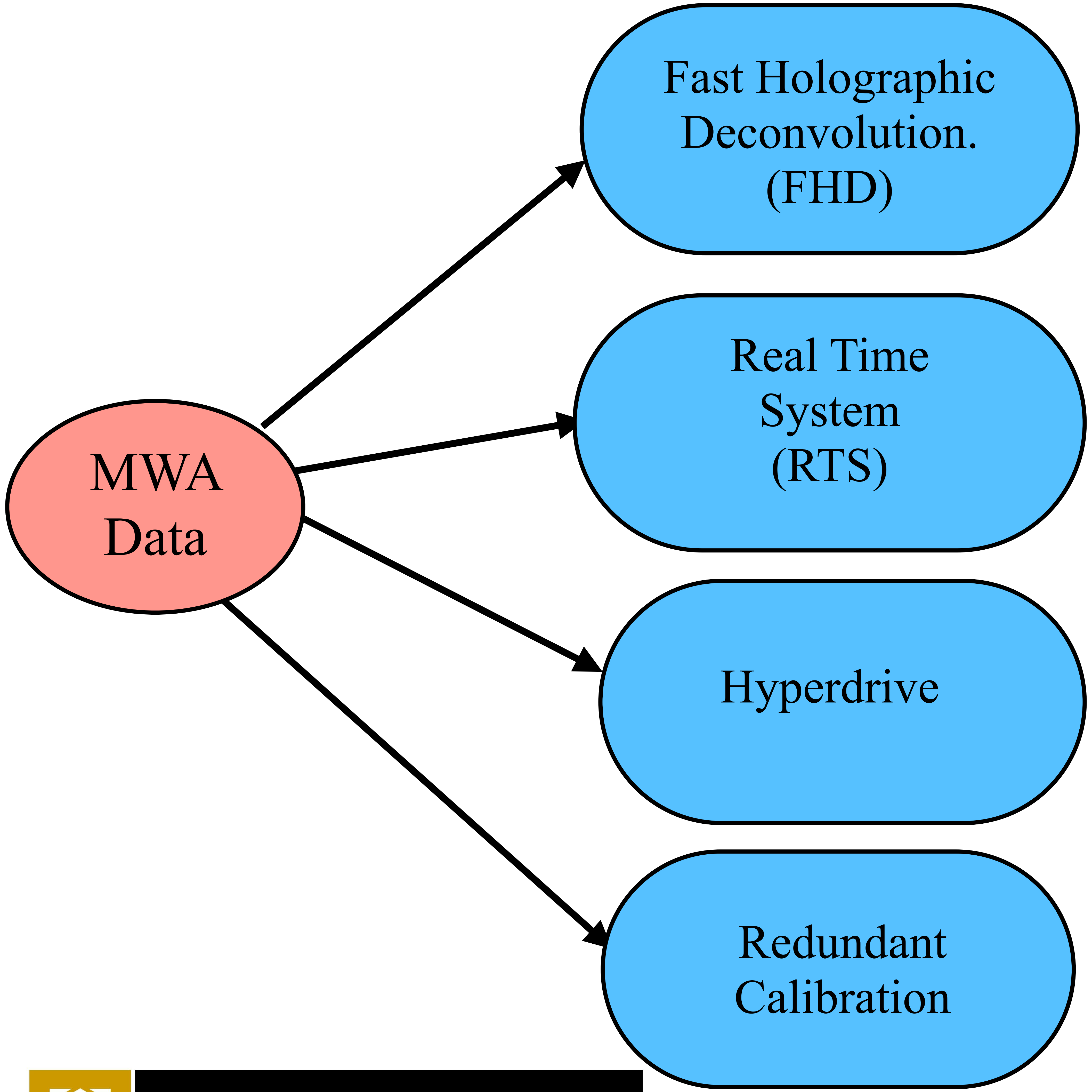
MWA EoR Pipelines across the globe

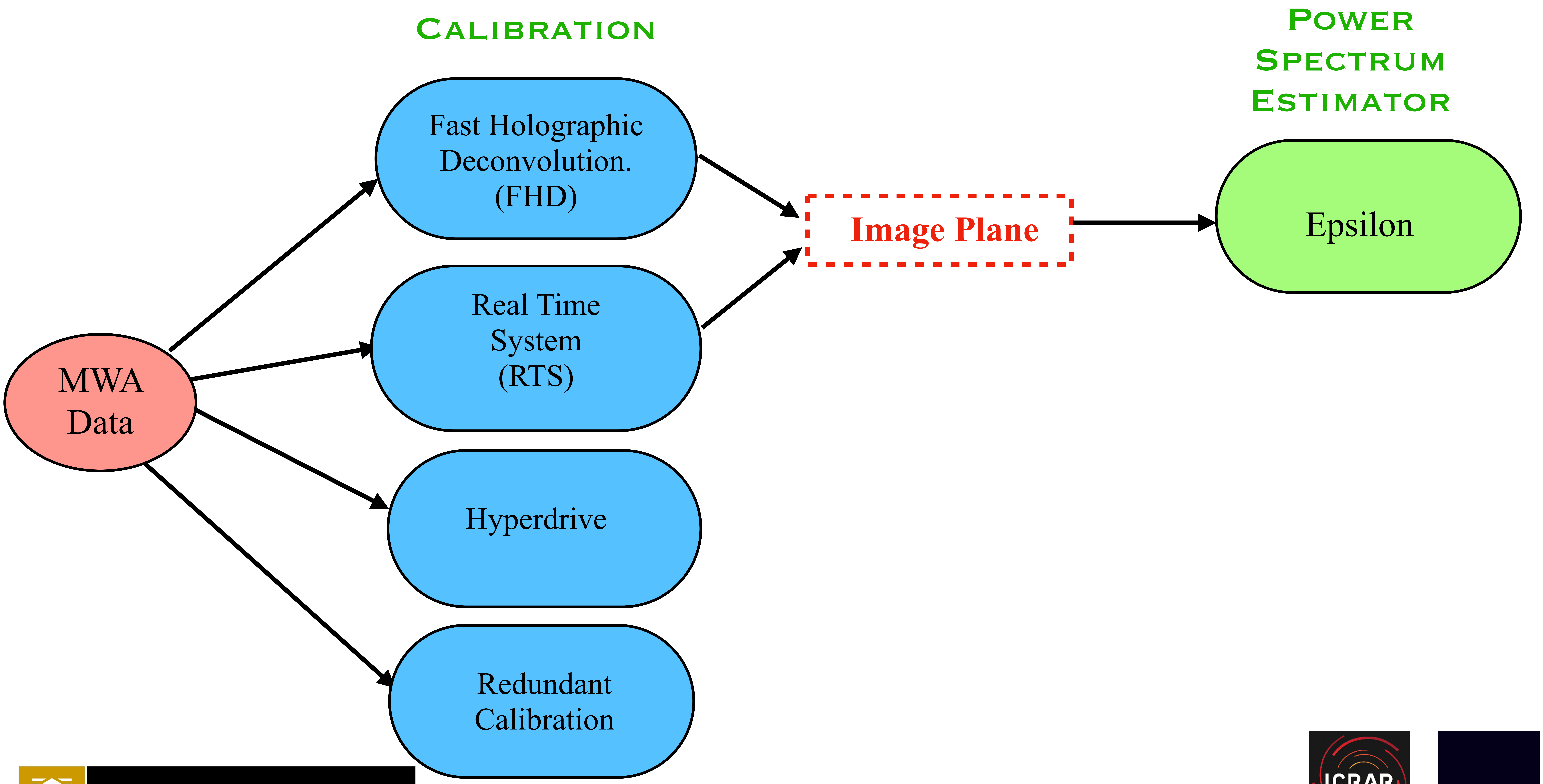
MWA
Data

MWA EoR Pipelines across the globe

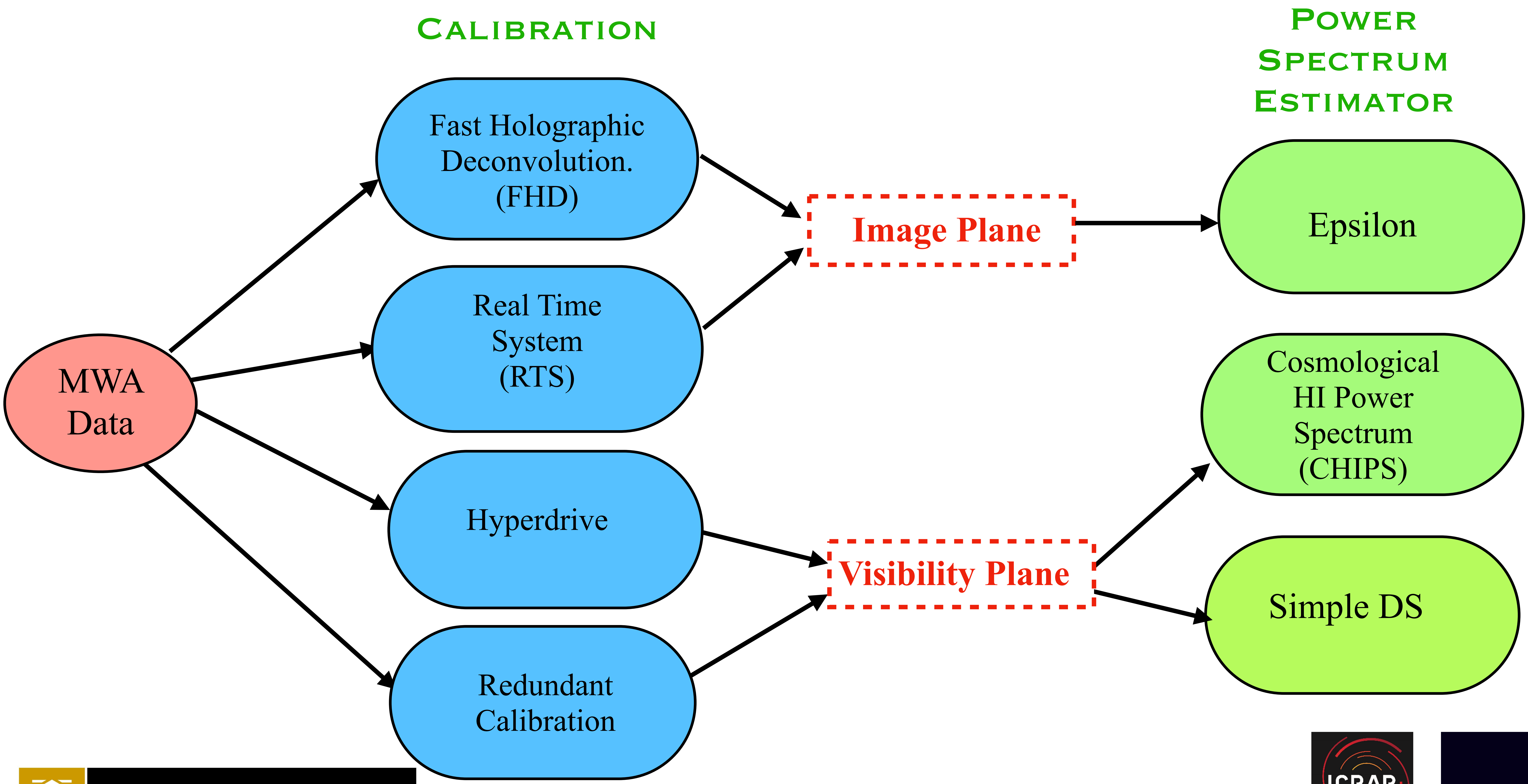
Calibration



MWA EoR Pipelines across the globe



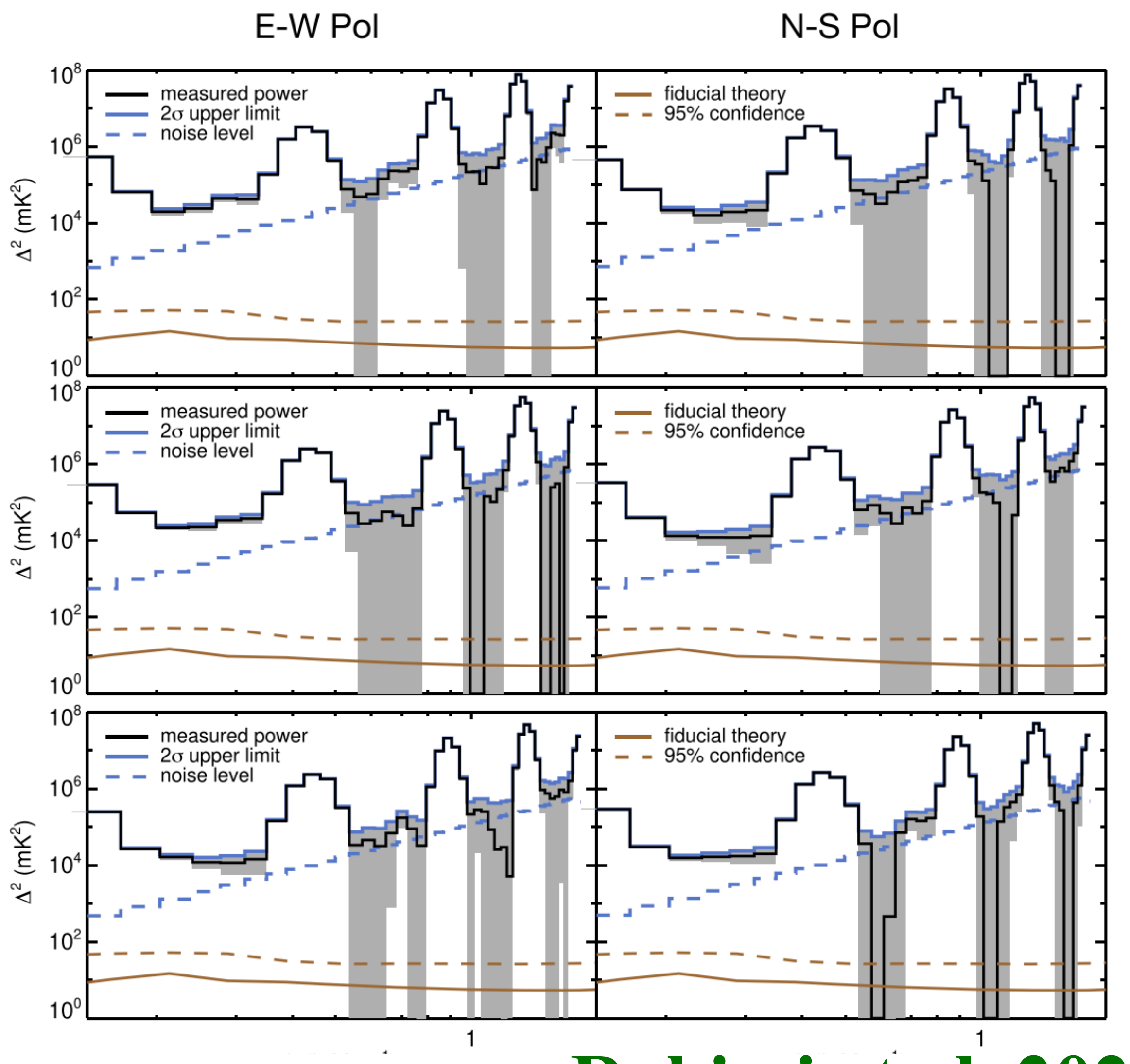
MWA EoR Pipelines across the globe



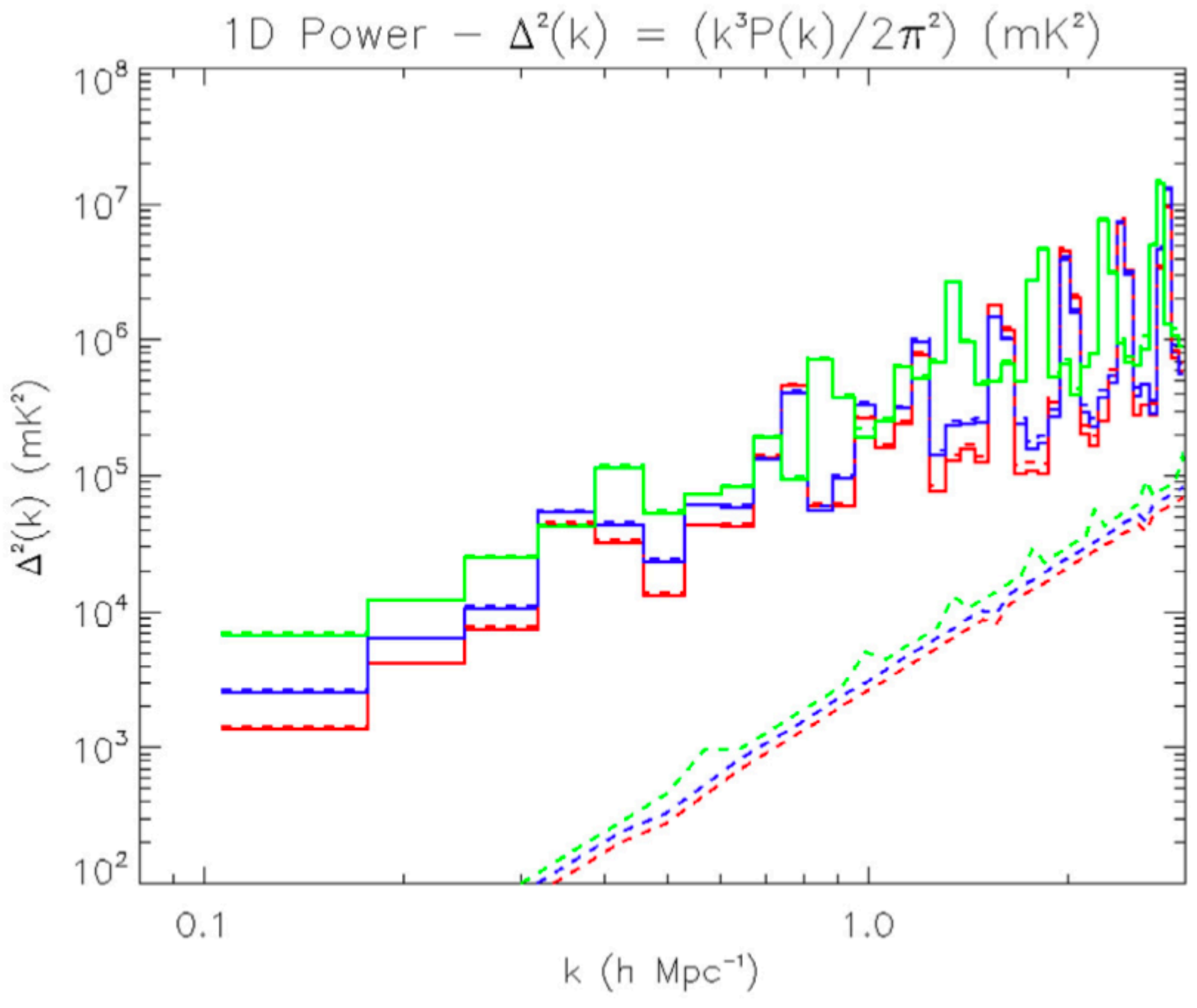
Challenges

- Calibration Errors
  - Uncertainties in model source sky e.g mis-modeling of sources, incomplete sky models.
  - Uncertainty in the beam models e.g coupling effect, instrumental leakage.
- Systematics
  - Instrumental errors at the receiver end.
  - Instrumental leakage across dipoles.
  - RFI buried under thermal noise.
  - Contribution from Galactic plane or surrounding bright sources.

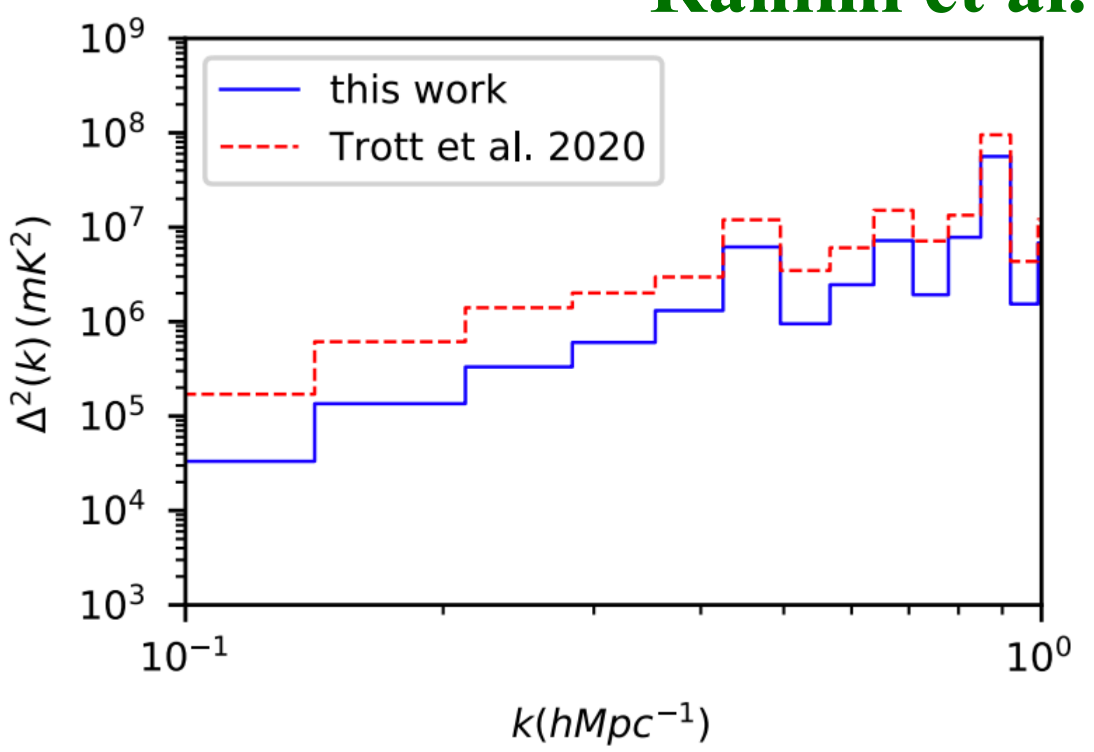
Wilensky et al. 2023

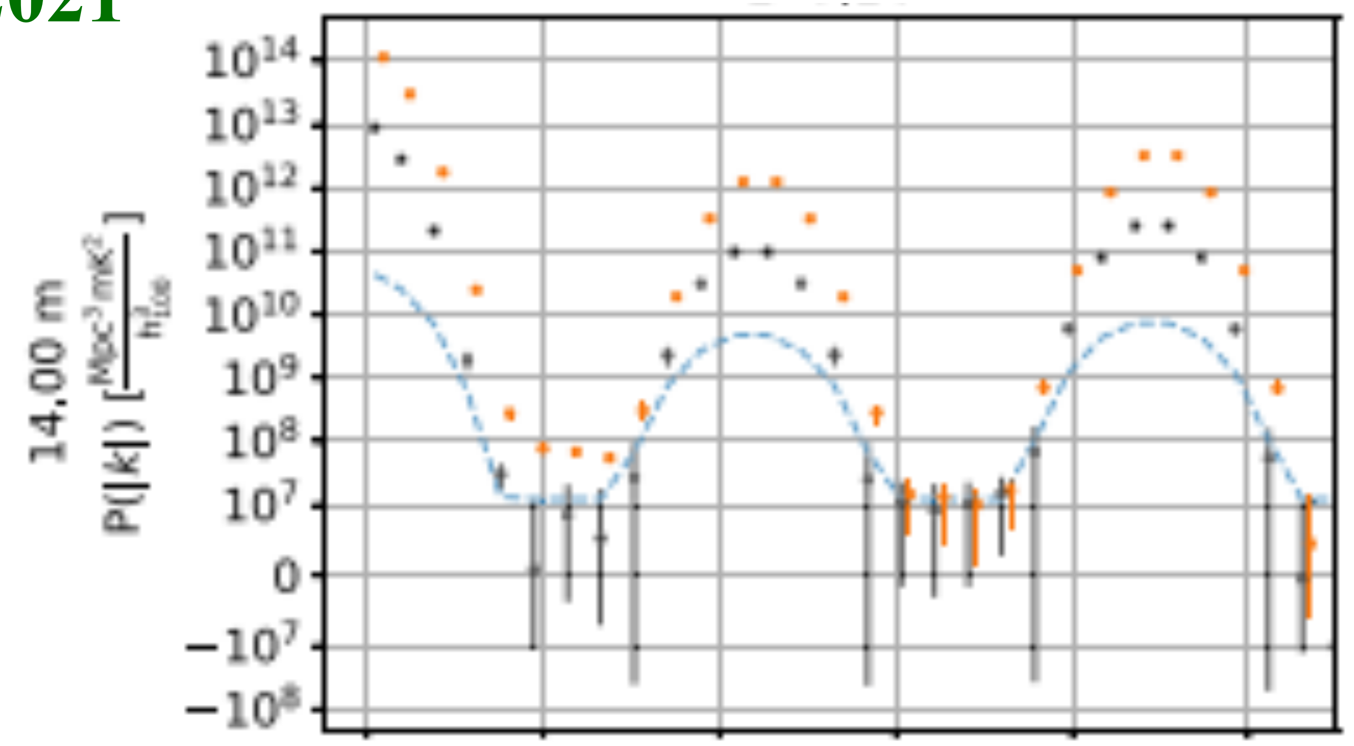


Trott et al. 2020

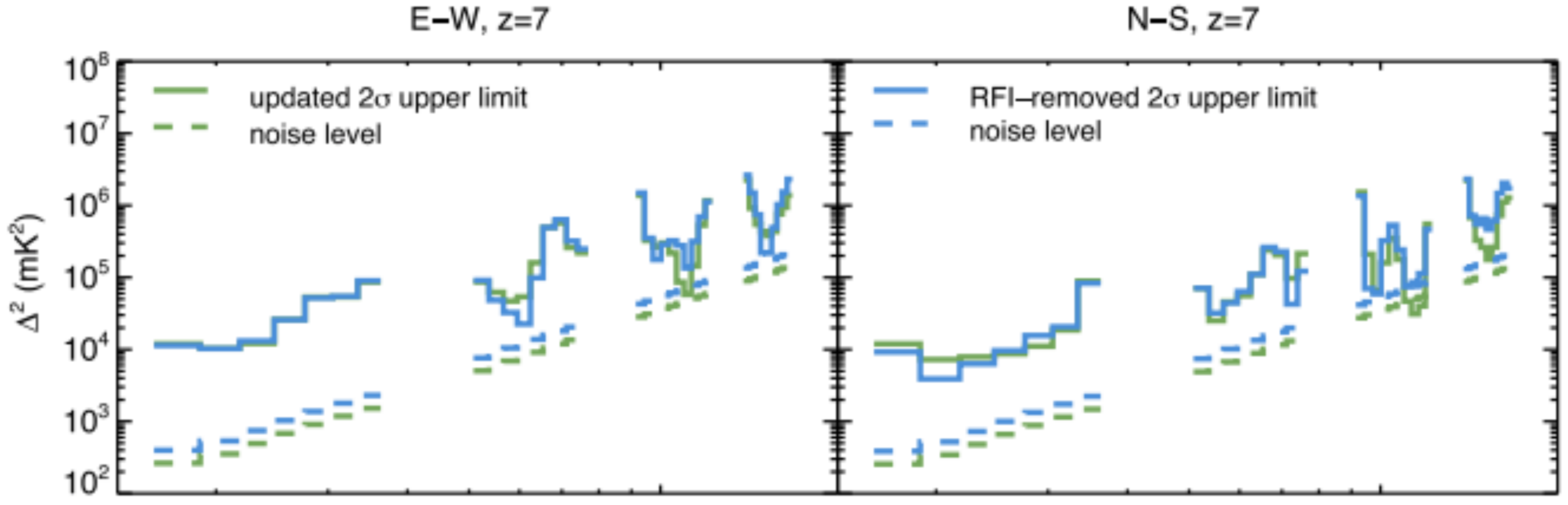


Rahimi et al. 2021





Kolopanis et al. 2023



Barry et al. 2019

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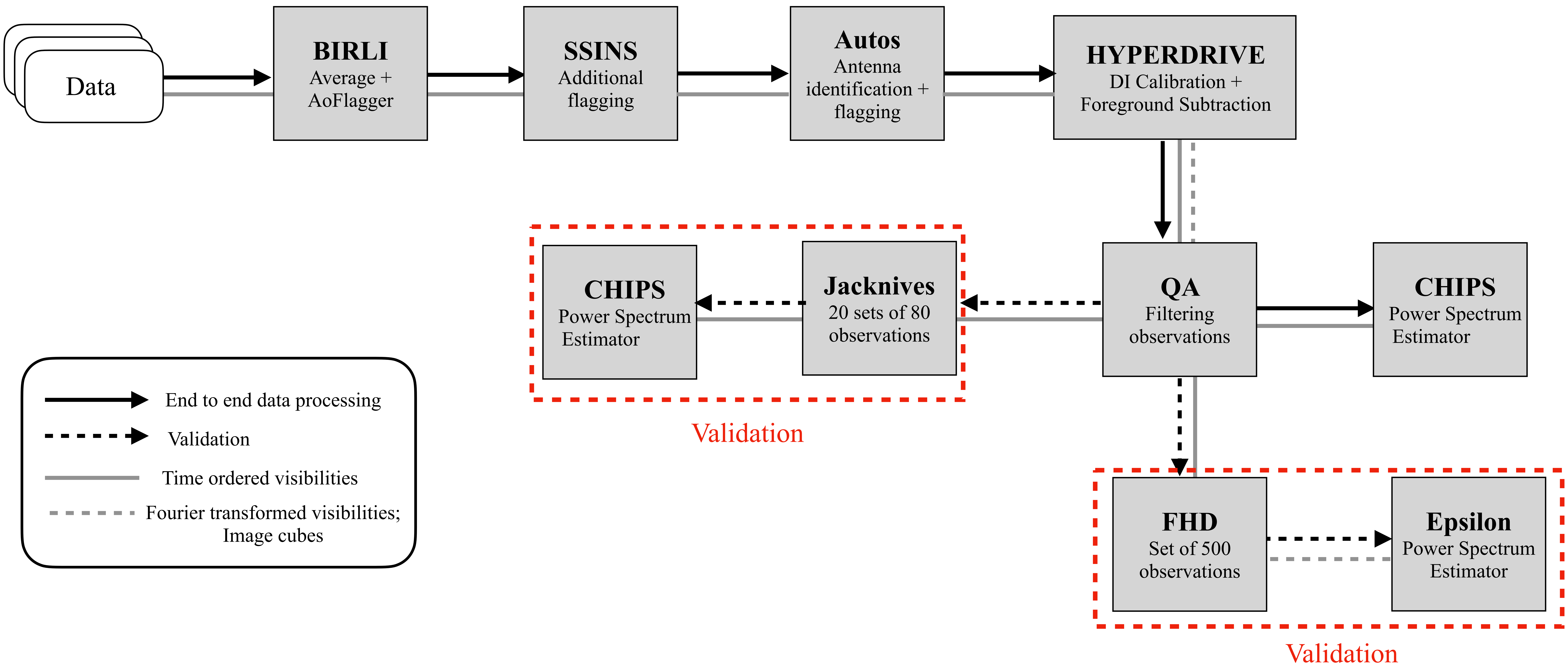
Aus EoR Pipeline



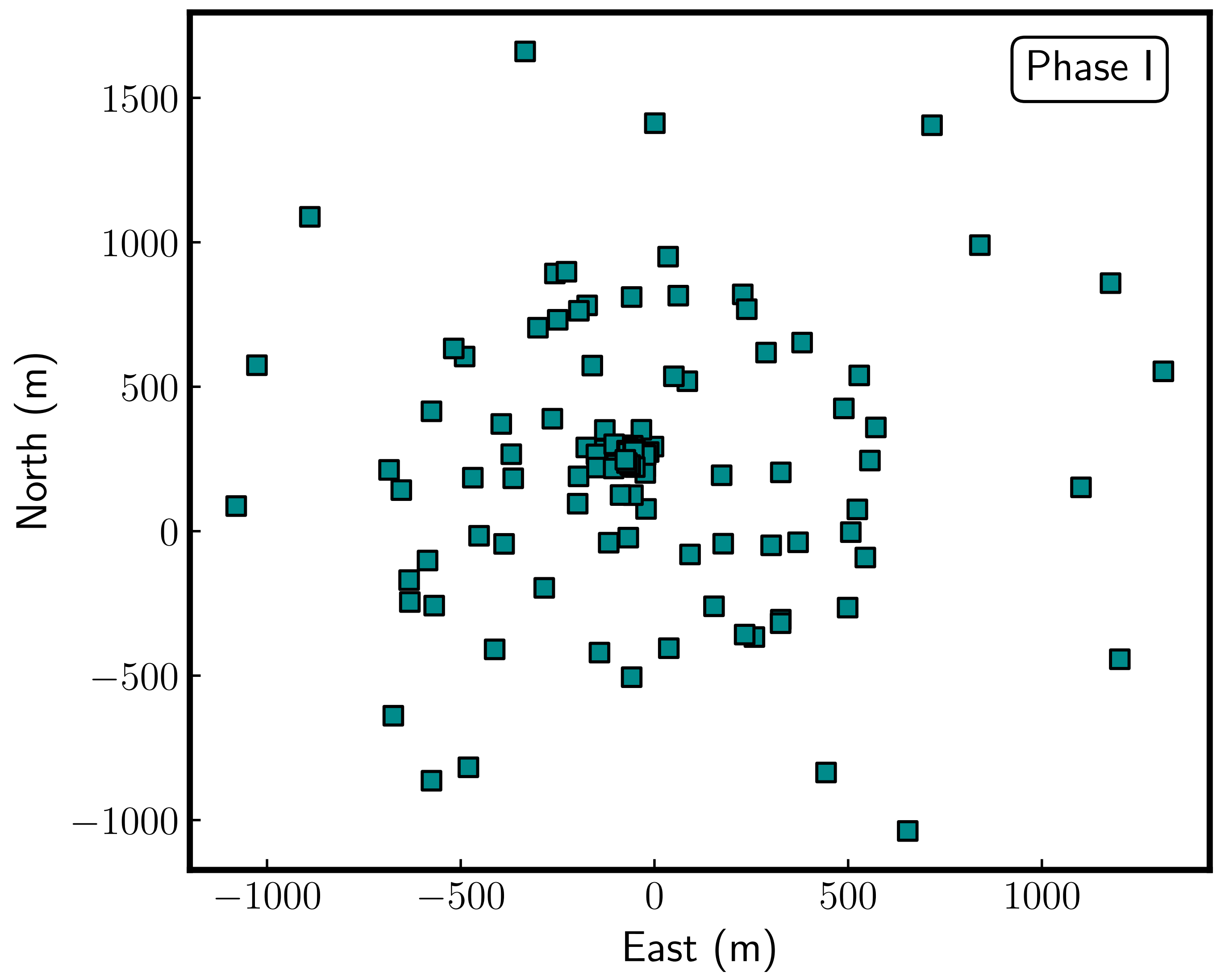
Observations

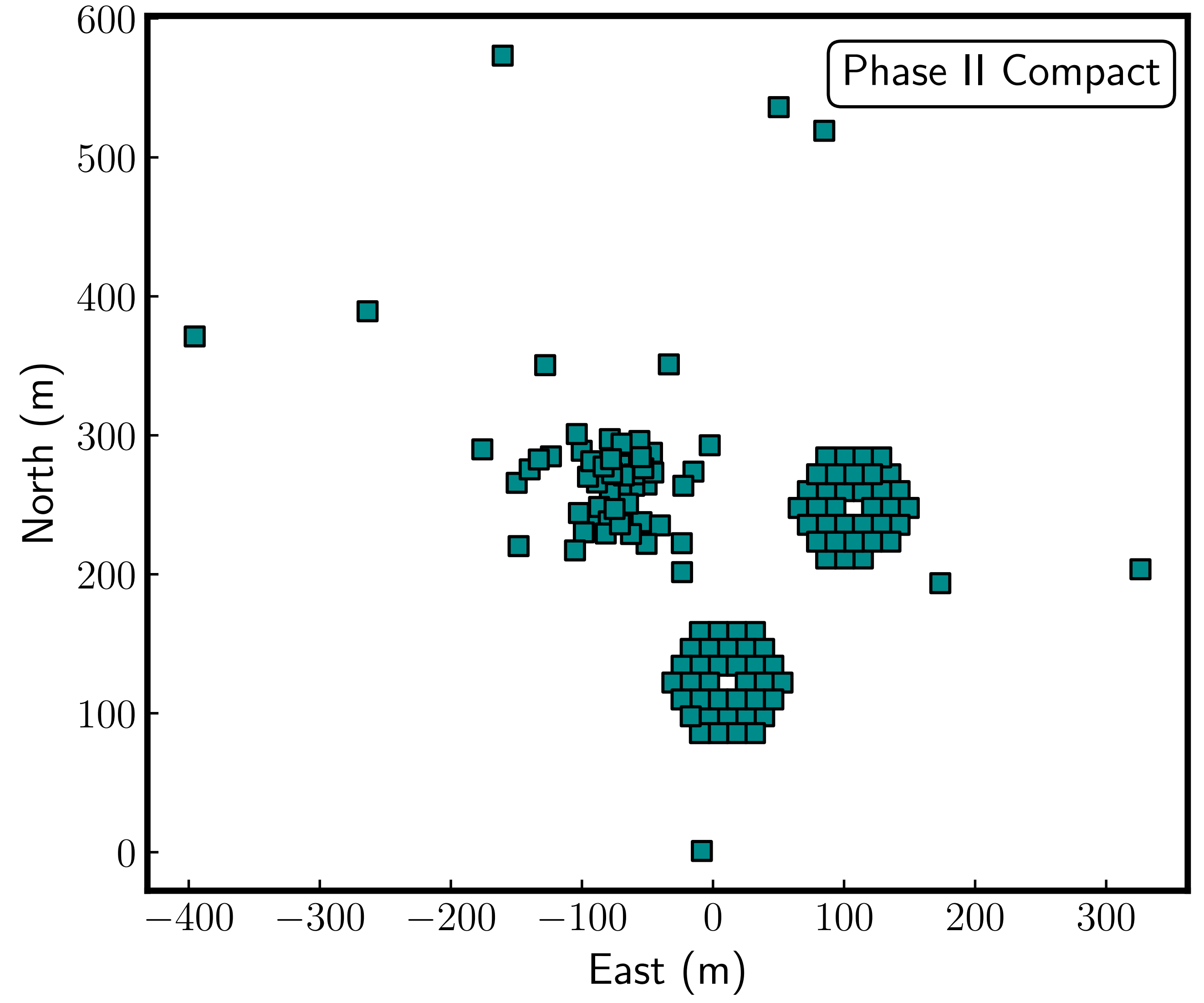
Parameter	Phase I	Phase II Compact
Maximum baseline	2864 m	749 m
Angular resolution	∼2 arcmin	∼9 arcmin
Spectral resolution	40 kHz	40 kHz
Integration time	2 s	0.5
Observing Length	112 s	112 s

- Started with 656 hours of data (19698 observations)
- High Band data (167 - 197 MHz)
- Phase I and II layout (2013-2014)
- EoR0 Field

  (RA=0 h, DEC=-27°).
- Steered at seven different pointings

East-West Pointing	Altitude (°)	Azimuth (°)
Pointing -3	69.2°	90°
Pointing -2	76.3°	90°
Pointing -1	83.2°	90°
Pointing 0	90°	0°
Pointing 1	83.2°	270°
Pointing 2	76.3°	270°
Pointing 3	69.2°	270°

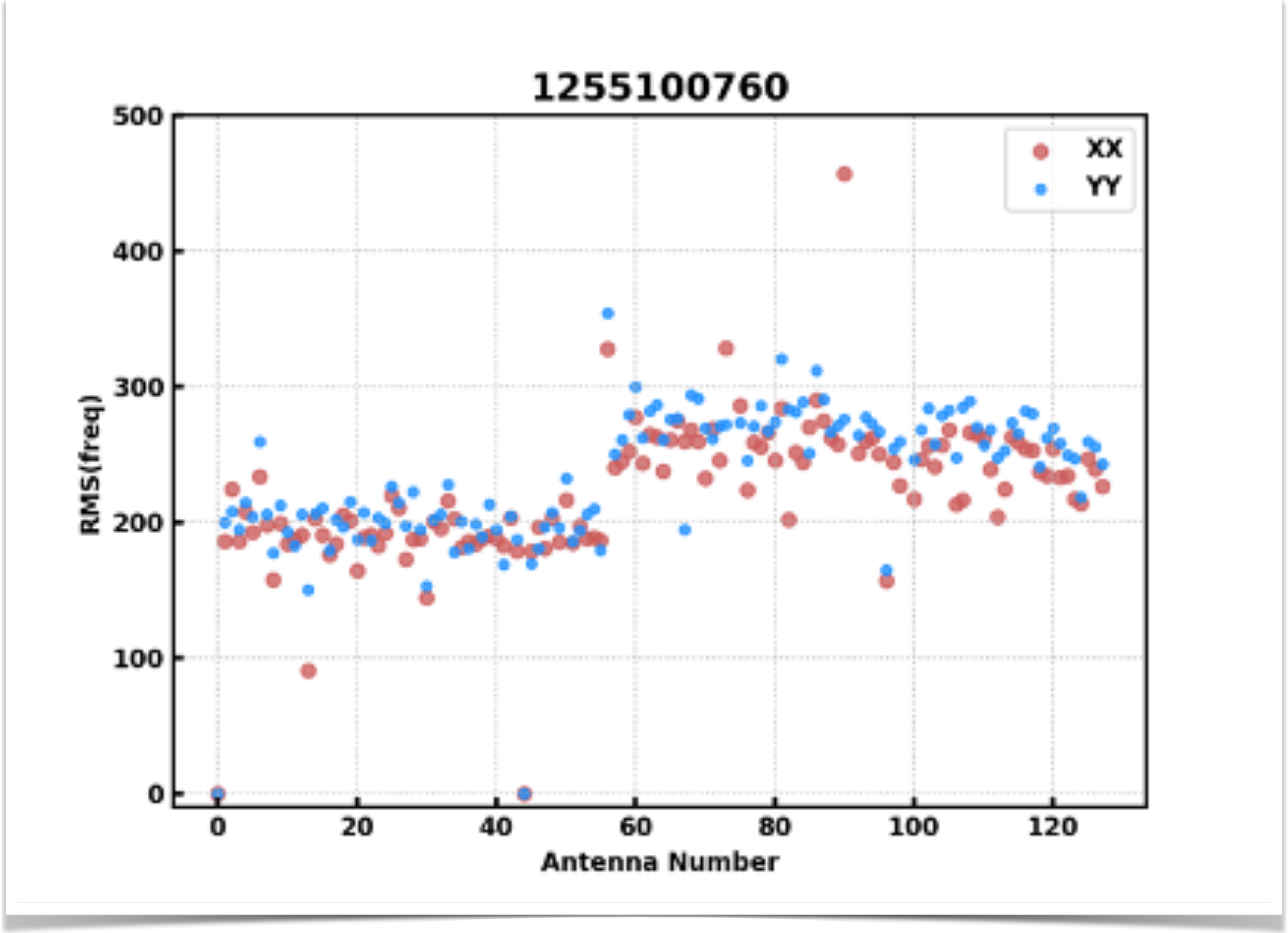




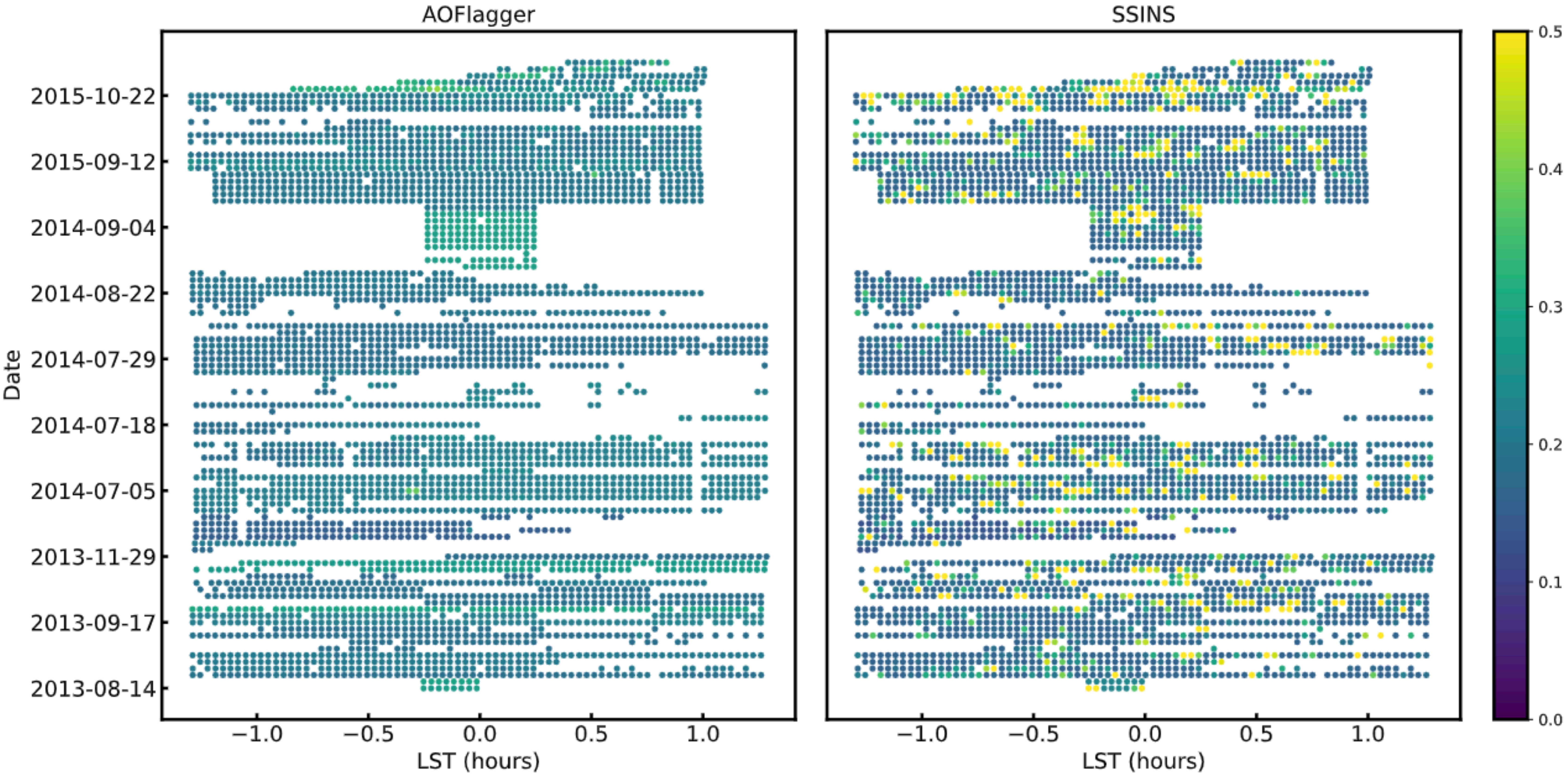
Pre-processing & Flagging

Pre-processing:

- Identify quality issues and discarded observations
- Errors in the beam former communication
- Recorded events from the Monitor & Control System
- Presence of two or more dead dipoles
- High level of ionospheric activity (RM > 5)
- Apply AoFlagger and SSINS to identify and mitigate RFI
- Average visibilities to 40 kHz across frequency and 2s across time
- Use autocorrelations to identify misbehaving antennas



Flagging Filters



- **AOF Flagging Occupancy** > 25%
- **SSINS Flagger:**
  - SSINS Streak > 30 %
  - SSINS DAB > 0 %
  - SSINS Narrowband > 60 %
  - SSINS Occupancy > 25%

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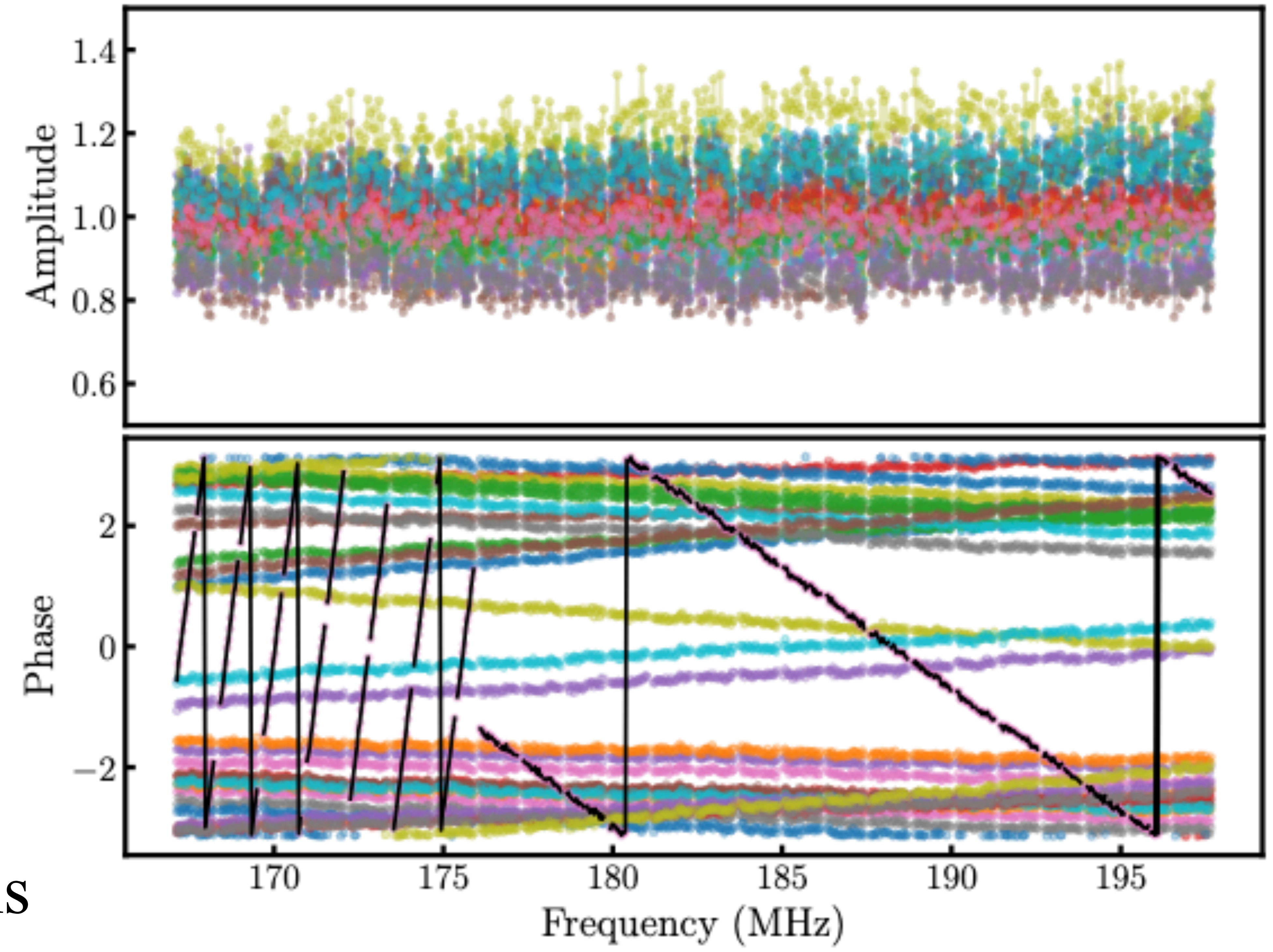
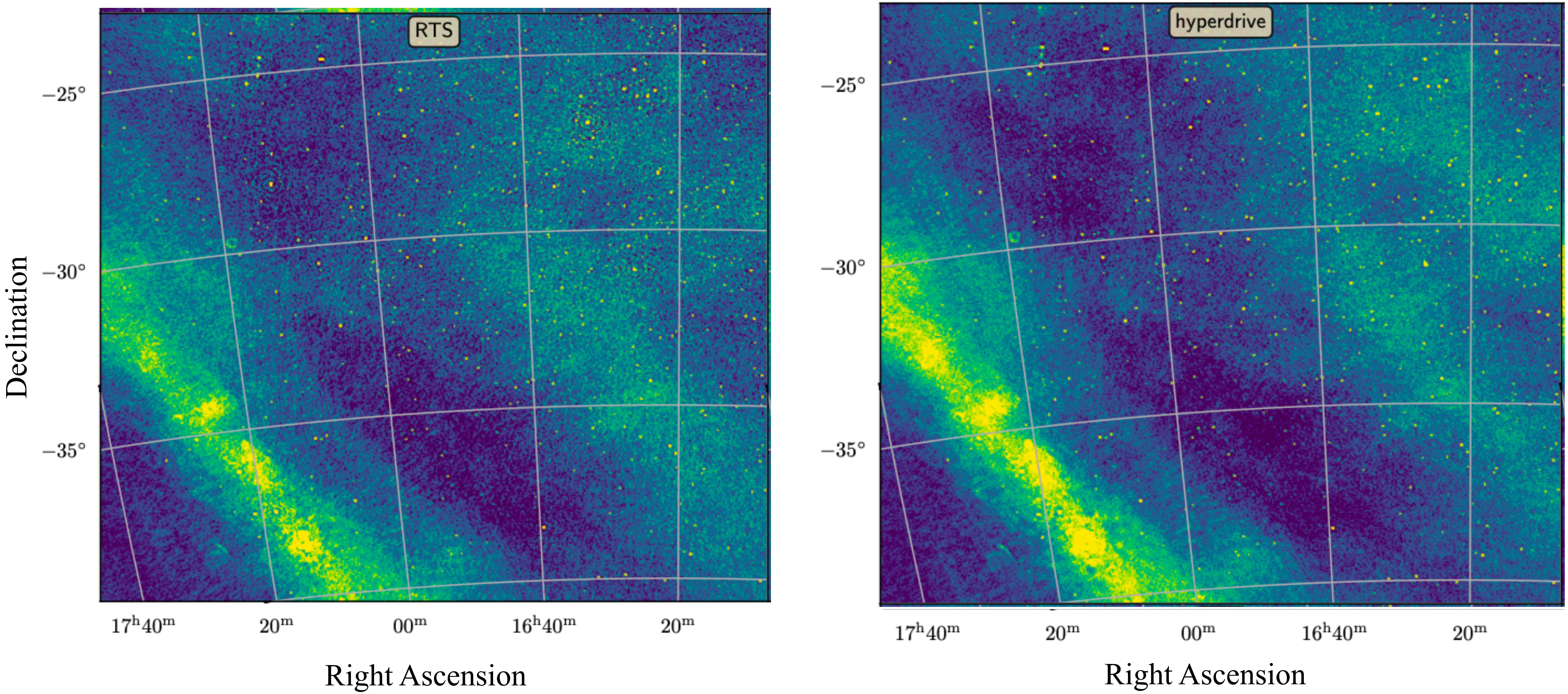
Calibration

- Use Hyperdrive calibration software (Jordan et al. in prep)
- LoBES catalogue as source model (Lynch et al.2021)
  - 3096 square degree survey on phase I and phase II extended layout
  - Targeting EoR0 field
- Full Embedded Element (FEE) (Sokolowski et al. 2019)
- Number of iterations: 300
- Number of sources: 8000
- Baseline cutoff < 30 lambda
- Use convergence value of the least square function to identify performance of calibration
- Use amplitude and phase to check quality of calibration solutions



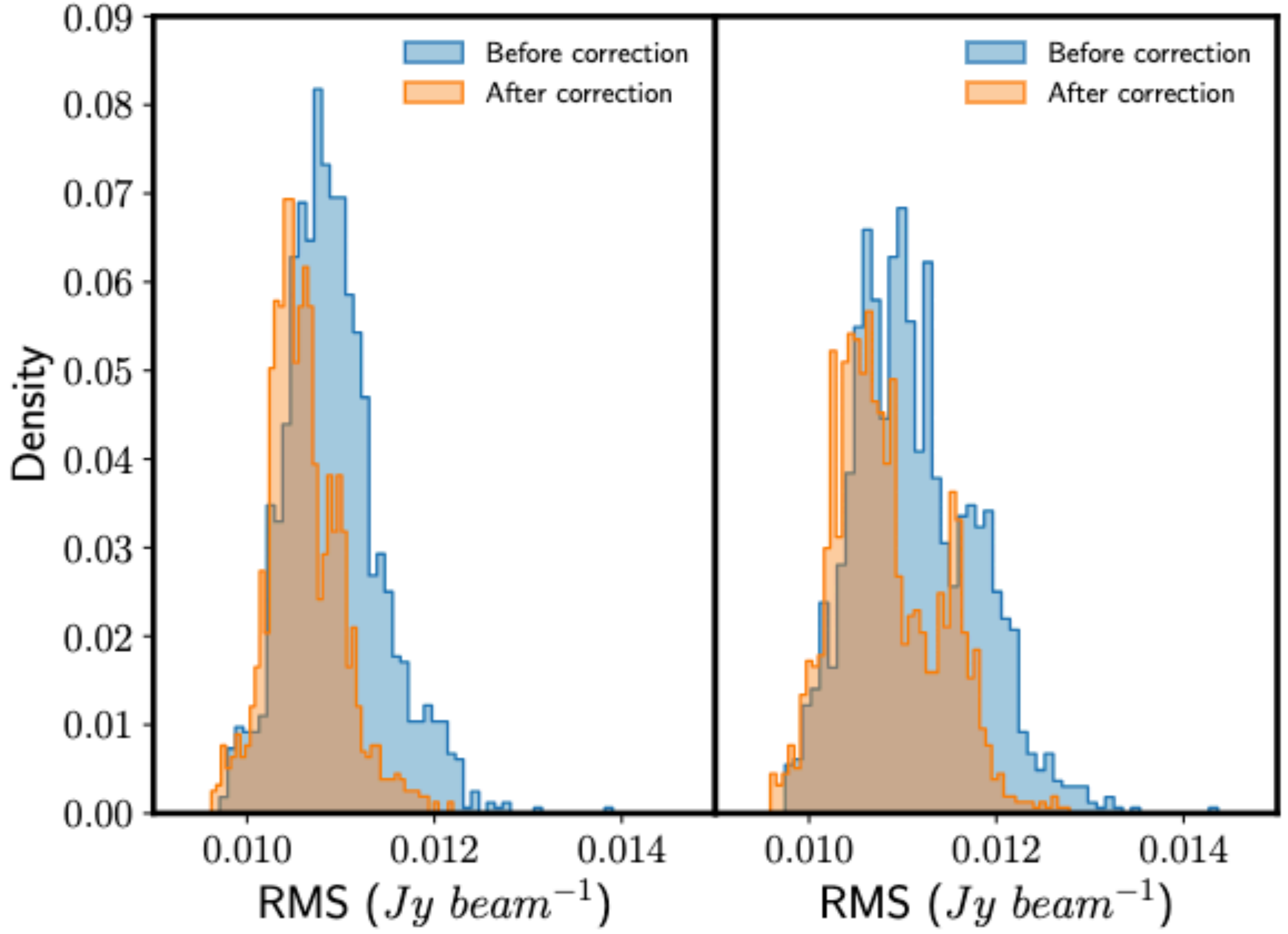
Calibration

Jordan et al. in prep

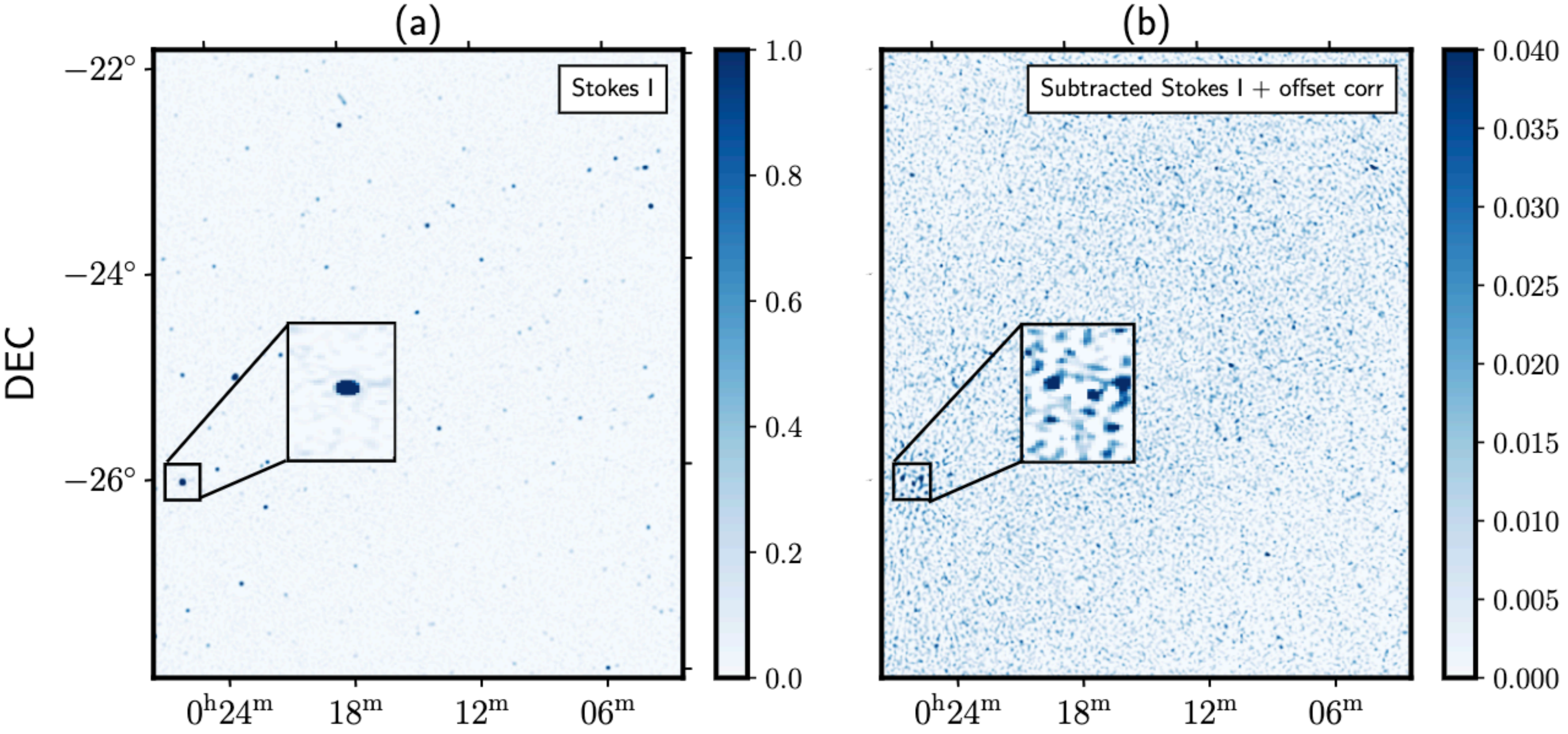


Foreground Subtraction

- Use Hyperdrive for foreground subtraction (Jordan et al. submitted)
- LoBES catalogue as source model (Lynch et al.2021)
- Full Embedded Element (FEE) (Sokolowski et al. 2019)
- Direct subtraction of 4000 brightest sources
- Correct for phase offset due to ionospheric activity of 1000 brightest sources



Foreground Subtraction



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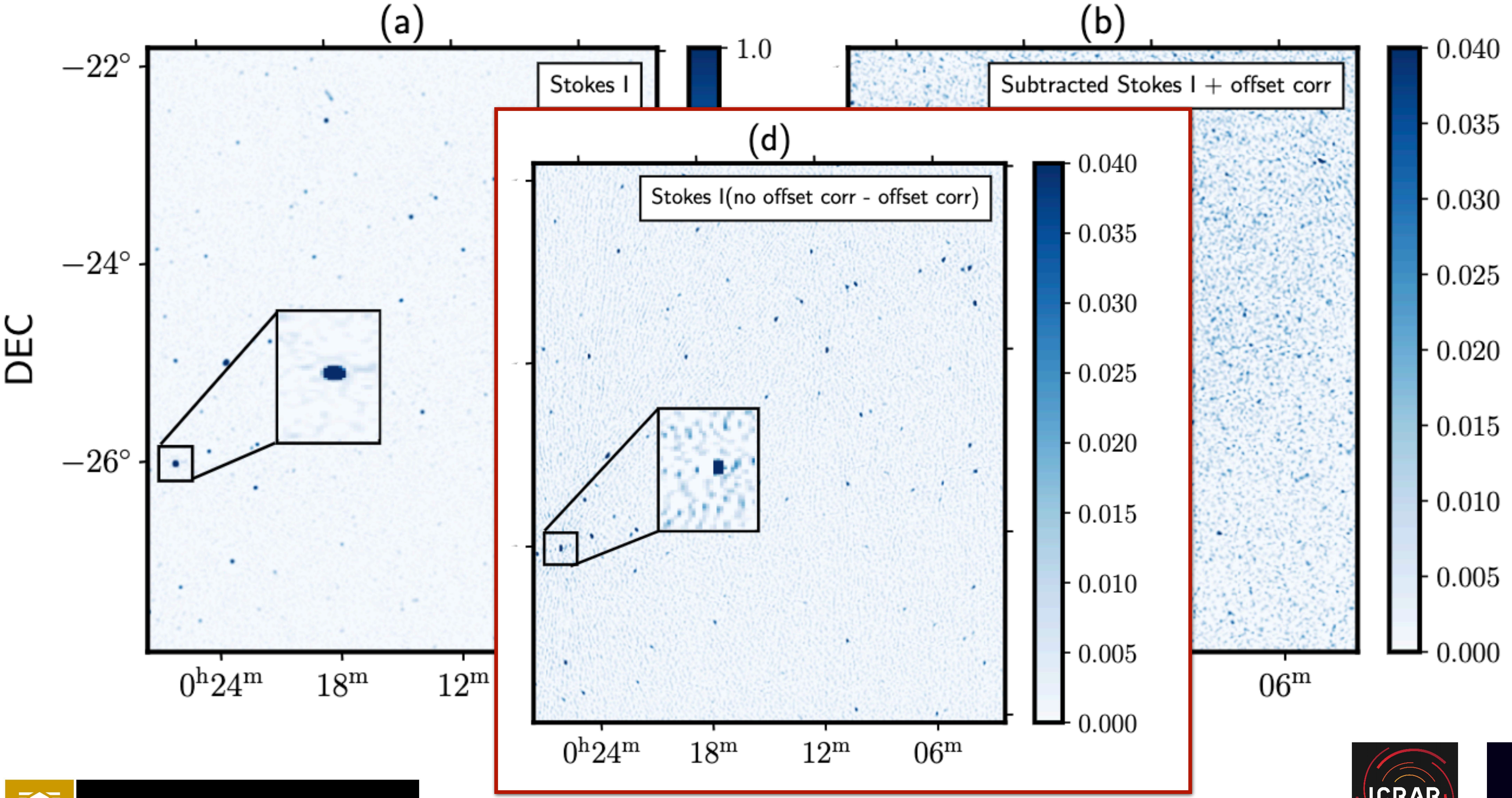
Foreground Subtraction



Quality Assessment

Window Power (unsubtracted)

Ratio window power to wedge power

Delay-transformed Metrics

Ratio window power (Sub/unsub)

Ratio Wedge power (Sub/unsub)

Quality Assessment

Delay-transformed Metrics

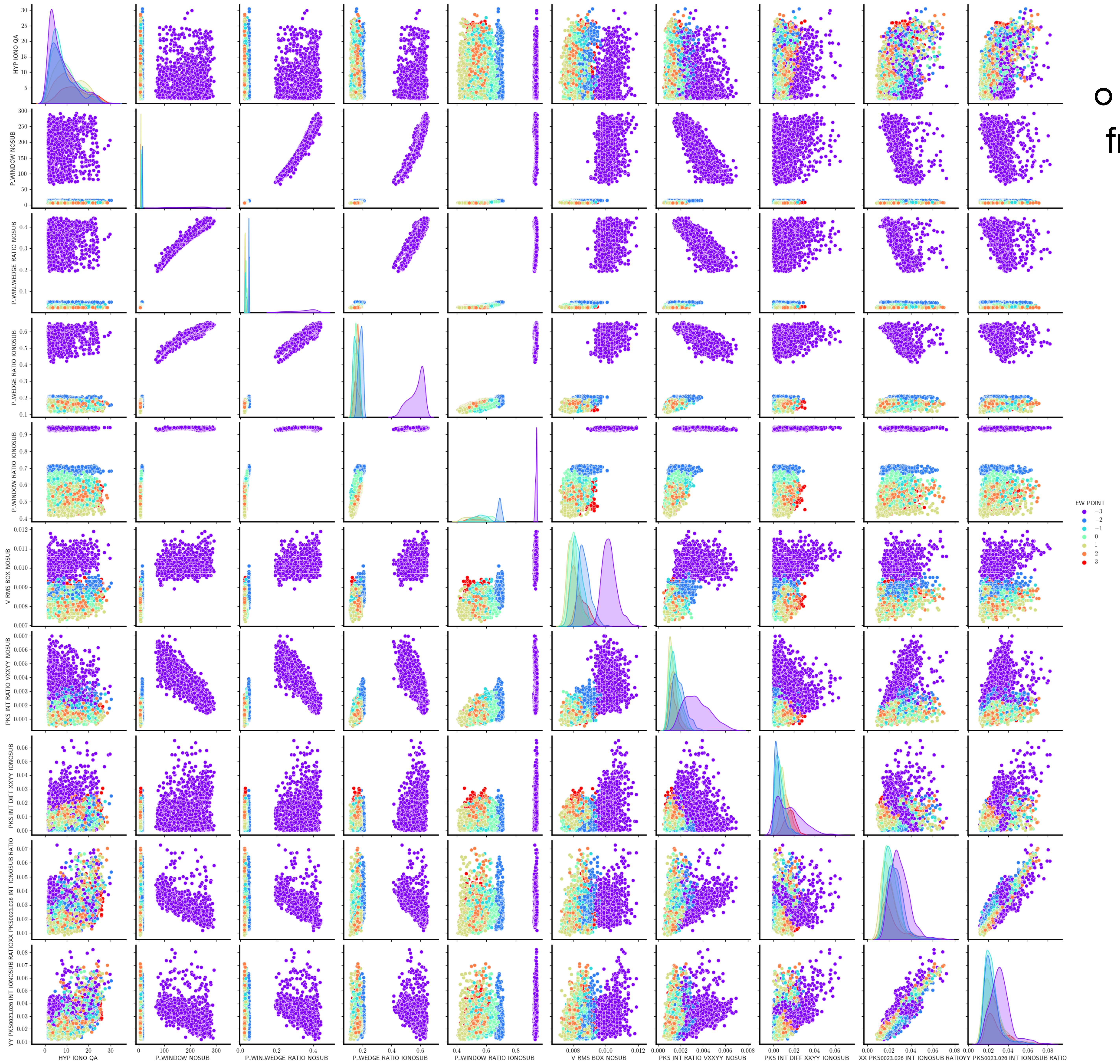
- Window Power (unsubtracted)
- Ratio window power to wedge power
- Ratio window power (Sub/unsub)
- Ratio Wedge power (Sub/unsub)

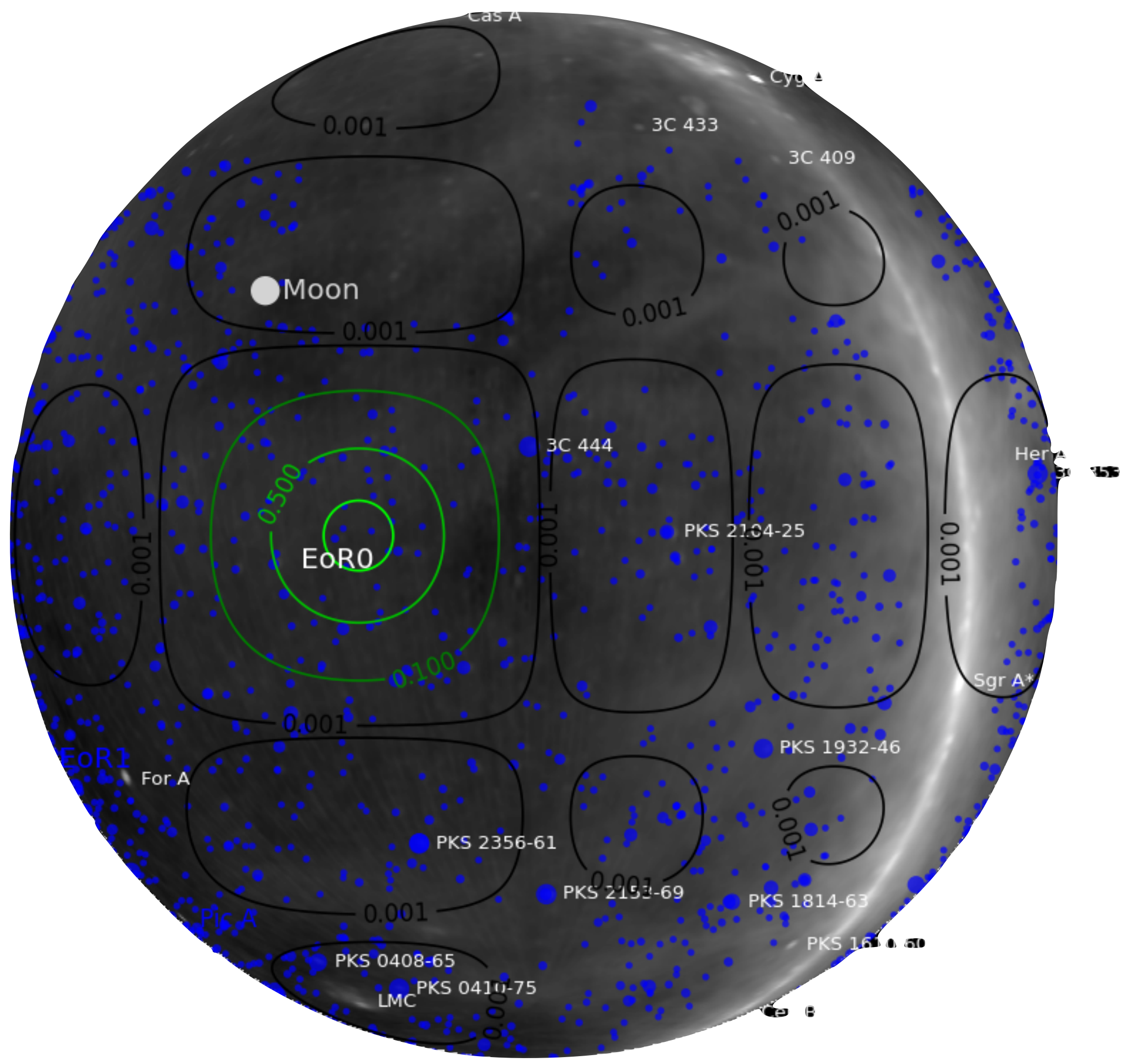
Image Statistics

- Stokes V RMS (unsubtracted)
- Ratio PKS 026-23 sub/unsub
- Ratio PKS 026-23 V / (XX+YY)
- Diff PKS 026-23 (XX,YY)

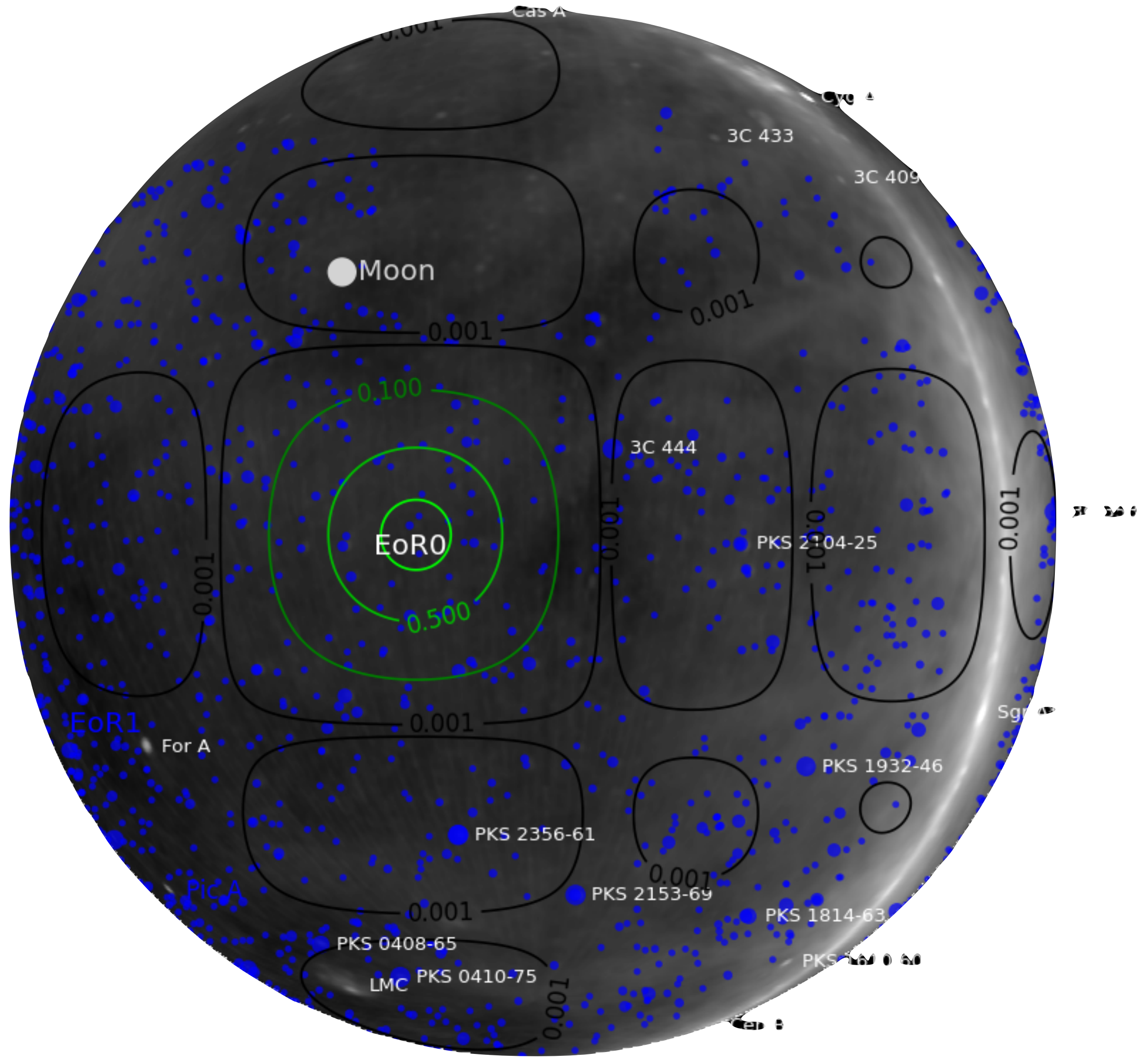
Quality Assessment

- Pointing -3 consists of dominant contribution from the Galactic plane



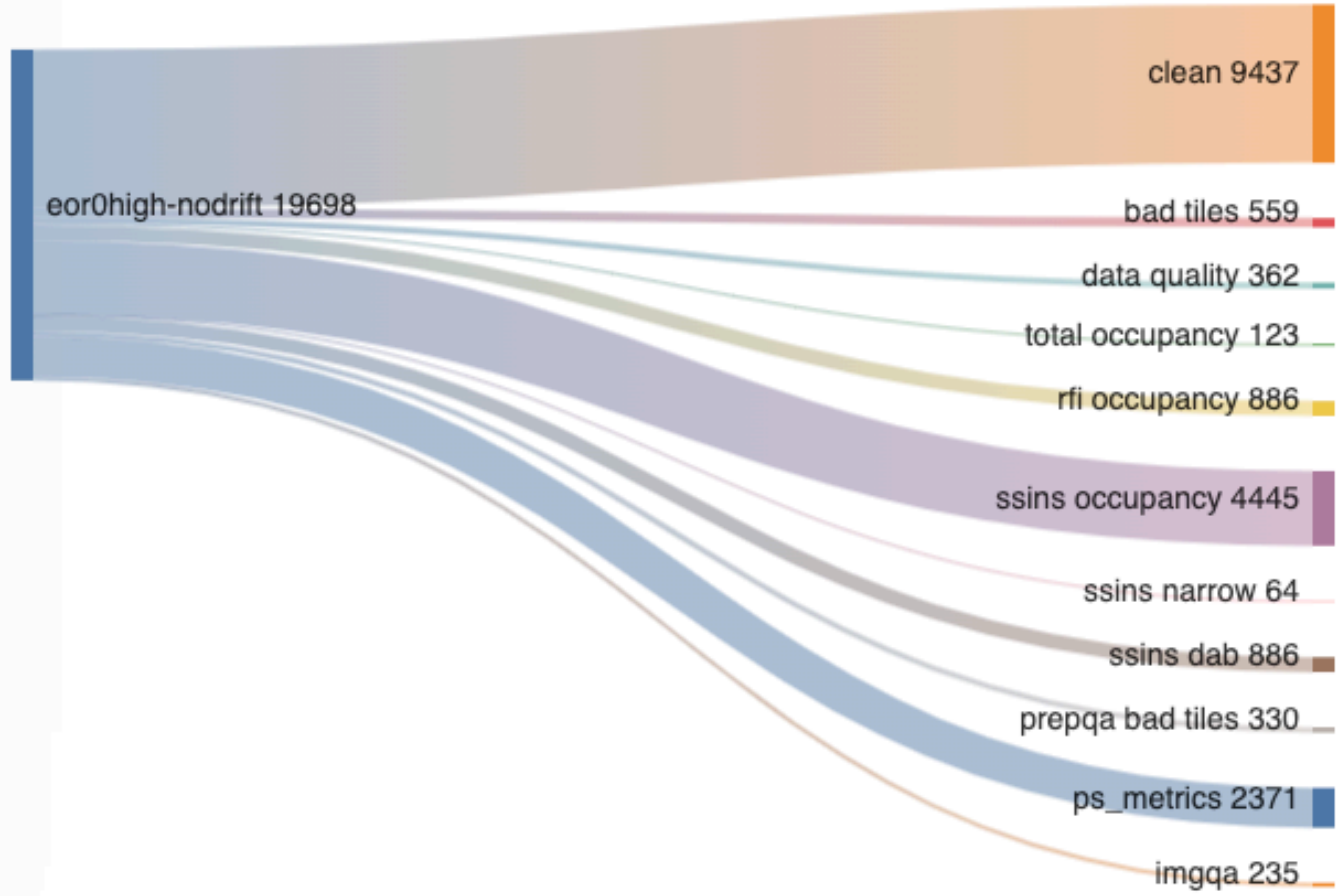


Pointing -3
$(69.2°, 90°)$



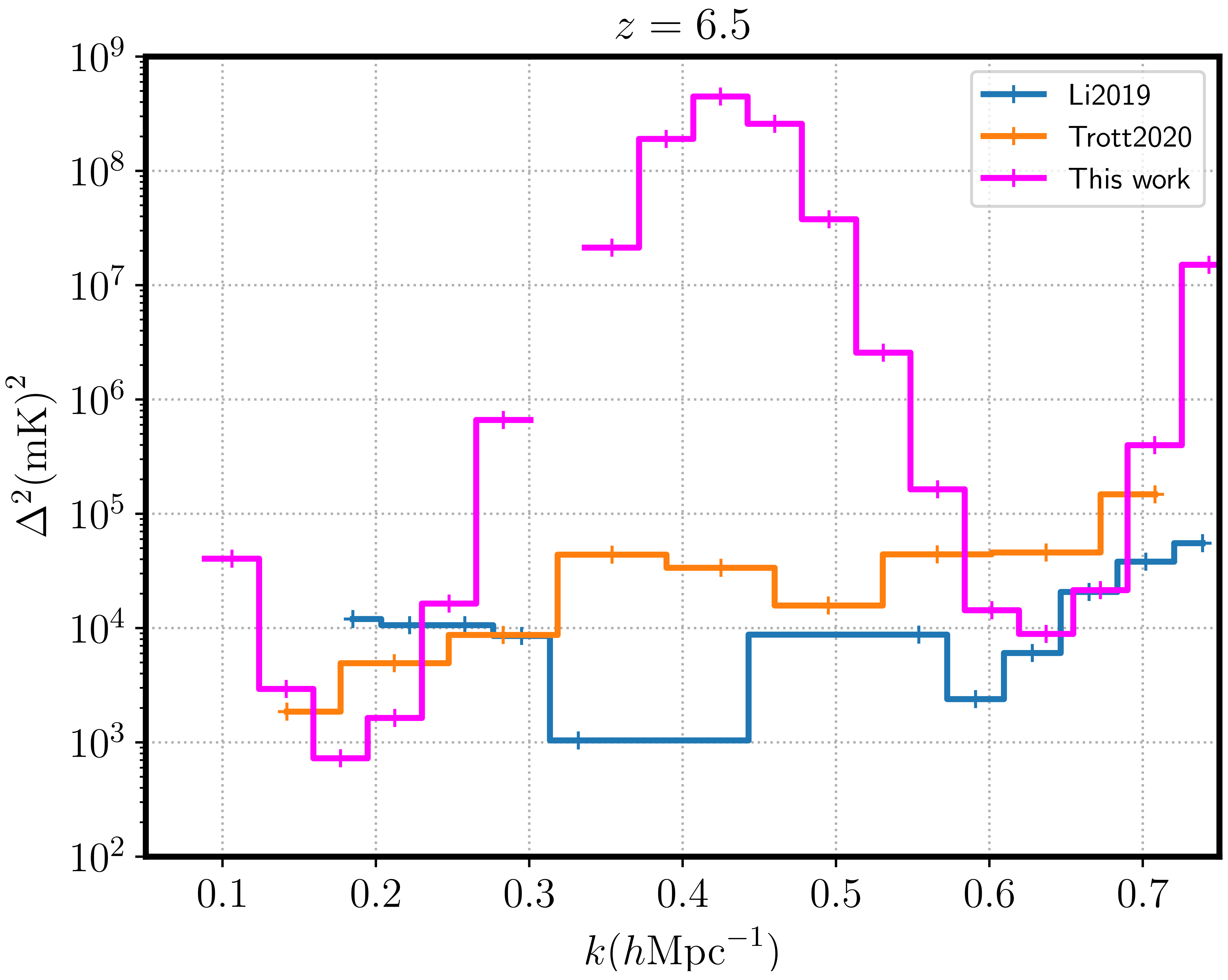
Pointing -2
$(76.3°, 90°)$

Quality Assessment

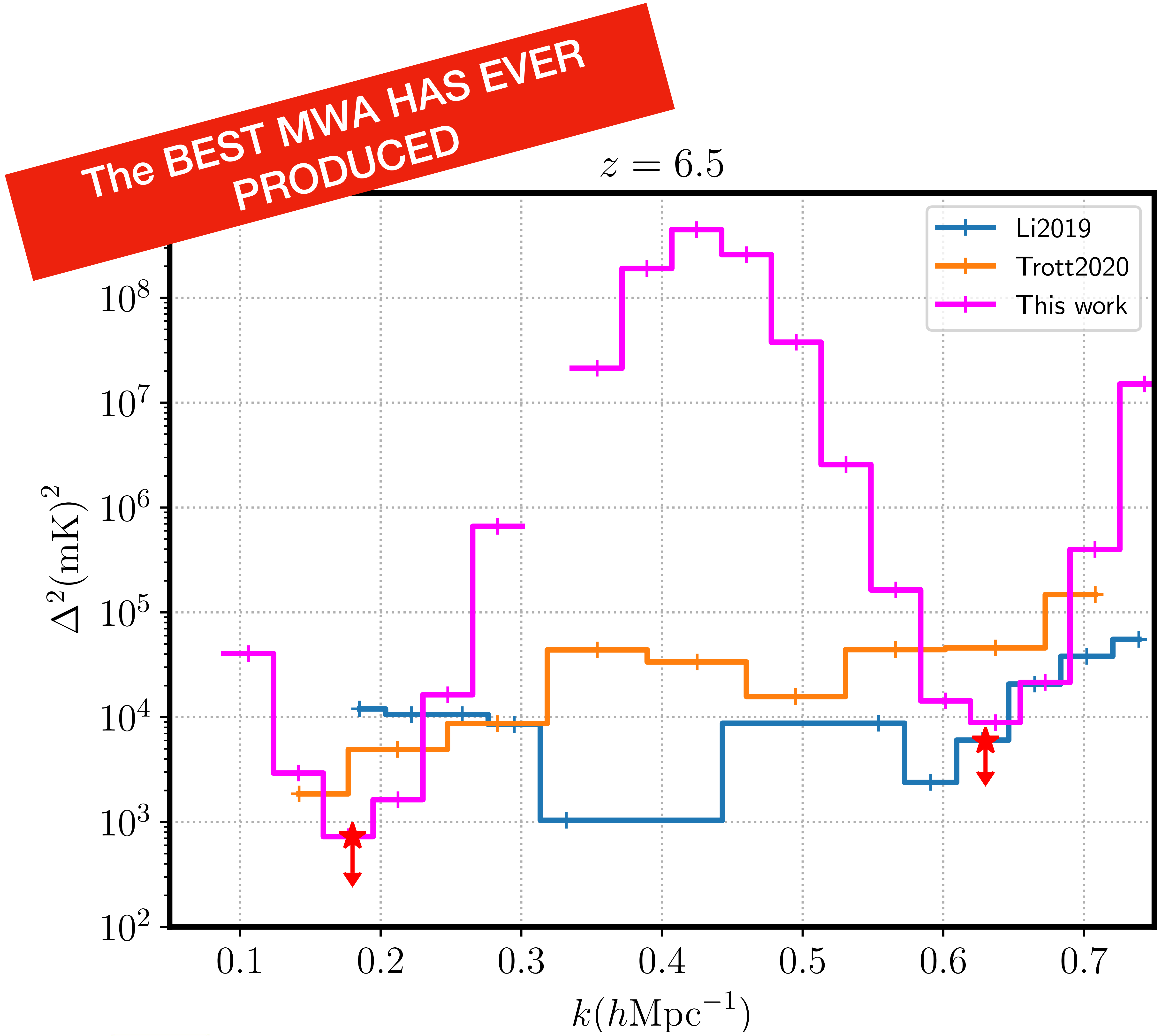


- Started with 656 hours (19698 observations)
- 52 % of data discarded

Latest 21 cm Upper Limits



Latest 21 cm Upper Limits



Z = 6.5

$$\Delta^2(k) < (27.0)^2\,\mathrm{mK}^2\ at\ k = 0.18\,h\mathrm{Mpc}^{-1}$$

$$\Delta^2(k) < (76.0)^2\,\mathrm{mK}^2\ at\ k = 0.63\,h\mathrm{Mpc}^{-1}$$

Z = 6.8

$$\Delta^2(k) < (35.9)^2\,\mathrm{mK}^2\ at\ k = 0.18\,h\mathrm{Mpc}^{-1}$$

$$\Delta^2(k) < (94.9)^2\,\mathrm{mK}^2\ at\ k = 0.63\,h\mathrm{Mpc}^{-1}$$

Z = 7

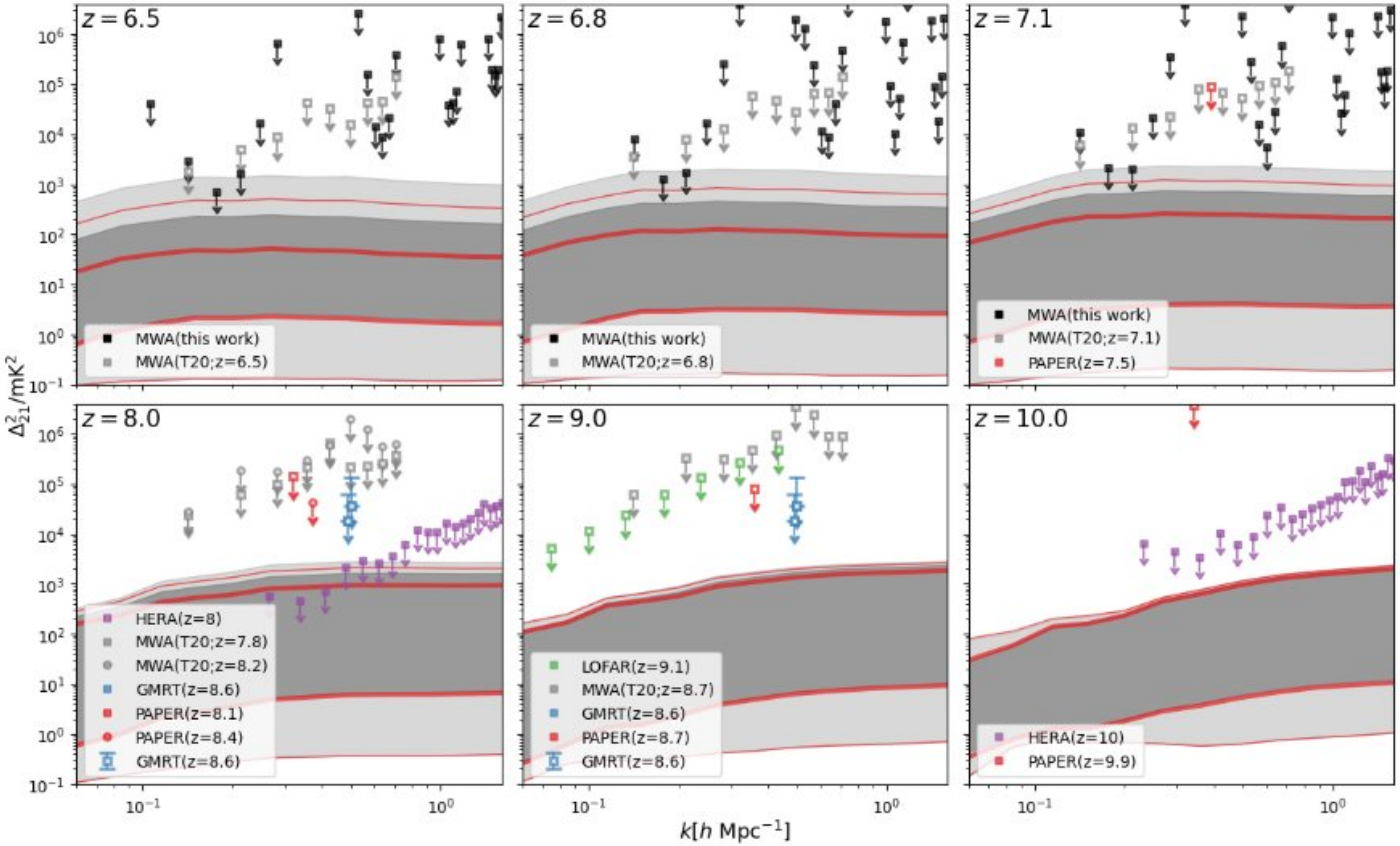
$$\Delta^2(k) < (45.3)^2\,\mathrm{mK}^2\ at\ k = 0.2\,h\mathrm{Mpc}^{-1}$$

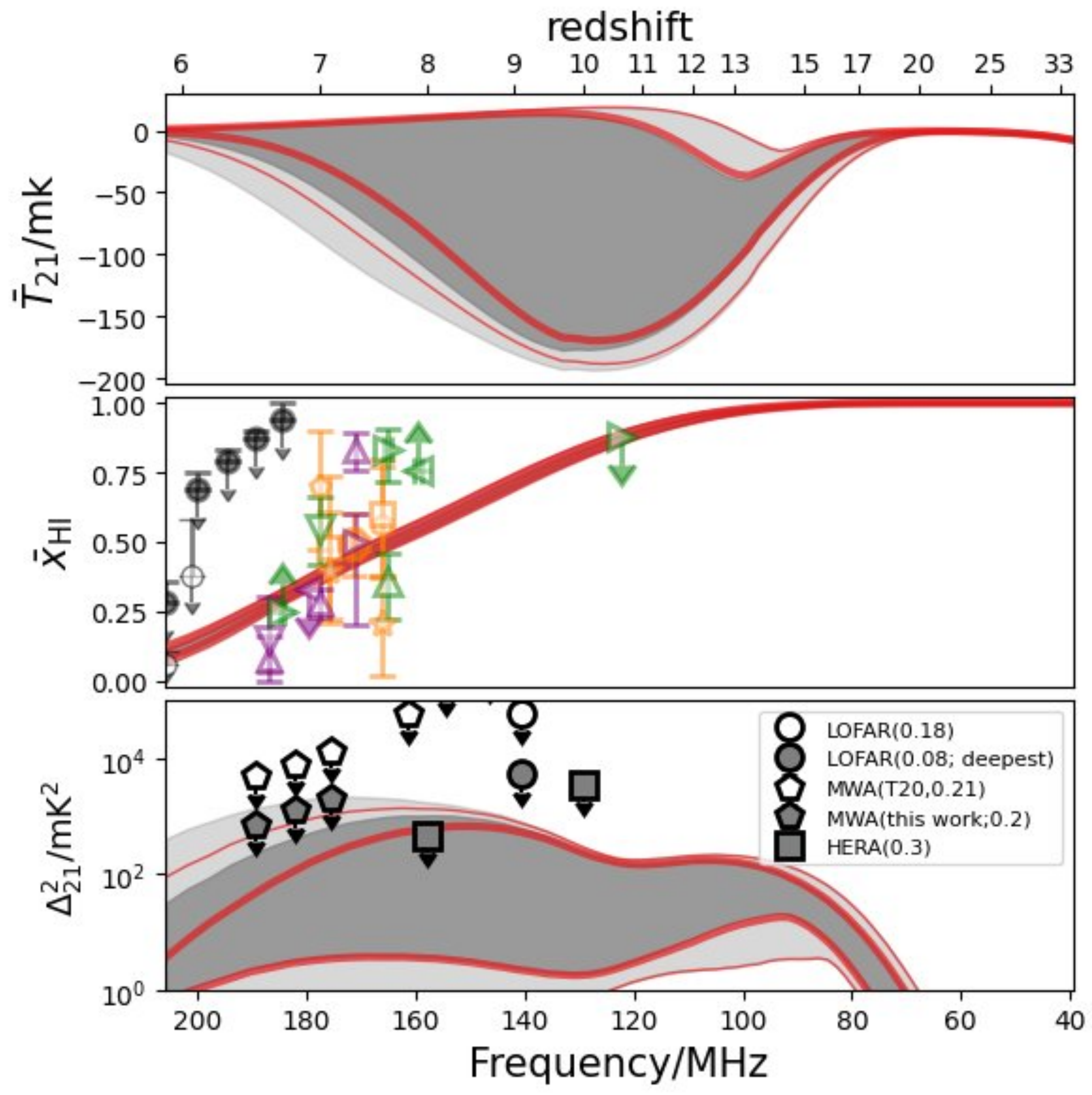
$$\Delta^2(k) < (73.6)^2\,\mathrm{mK}^2\ at\ k = 0.6\,h\mathrm{Mpc}^{-1}$$

Cosmological Inference

- Using 21cm FAST/ 21cm EMU/MultiNest

Dr. Yuxiang Qin
University of Melbourne





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Conclusion & Future Work

- Aus EoR pipeline produce upper limits an order of magnitude better than previous results

- Validation Tests
  - Jacknives Test or Bootstrapping : produced power spectra from different set of observations
  - Systematic Mitigation (Nunhokee et al. submitted)
  - Signal Loss (Line et al. submitted)
  - Validate against other pipelines (FHD)

- Van-Vleck Correction
  - Small-scale non-linear scale due to quantisation

- Using Kernel Density Function to measure spatial fluctuations in the EoR power spectrum (Trott et al. 2019)




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