International Centre for Radio Astronomy Research

Progress towards the EoR with the Murchison Widefield Array

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CAASTRO ALL-SKY ASTROPHYSICS
Curtin University
The Government of Western Australia
The University of Western Australia

The Murchison Widefield Array (MWA)

SKA-Low precursor instrument

Phase I (2013-2015)

- 80 - 300 MHz (z = 4 - 16)
- 128 tiles (each 16 dipoles combined electronically)
- Resolution: 2 arcmin (1/10 Moon diameter)
- Array diameter ~3km.

Primary science goal: **statistical** detection of the signal from the EoR, and estimation of basic parameters

The Murchison Widefield Array (MWA)

SKA-Low precursor instrument

Credit: Kimberly Steele, 2016

Phase II (2016-2017)

- 80 - 300 MHz
- **200** tiles (each 16 dipoles combined electronically)
- Resolution: 2 arcmin (1/10 Moon diameter)
- Array diameter ~3km
- Two 36-tile hexagons for EoR sensitivity and calibration

The Murchison Widefield Array (MWA)

SKA-Low precursor instrument

Credit: Kimberly Steele, 2016

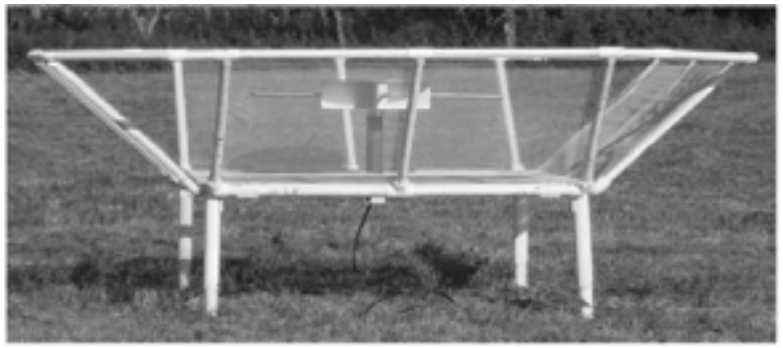
Phase III (2017-2018)

- 70 - 300 MHz
- **256** tiles (each 16 dipoles combined electronically)
- Resolution: 1 arcmin (1/10 Moon diameter)
- Array diameter ~5km
- Two 36-tile hexagons for EoR sensitivity and calibration

Suite of current 21cm experiments

- Murchison Widefield Array (MWA)
- z = 6-10
- Resolution: 2 arcmin
- Array diameter ~3km
- Effective collecting area: 3,500 m^2

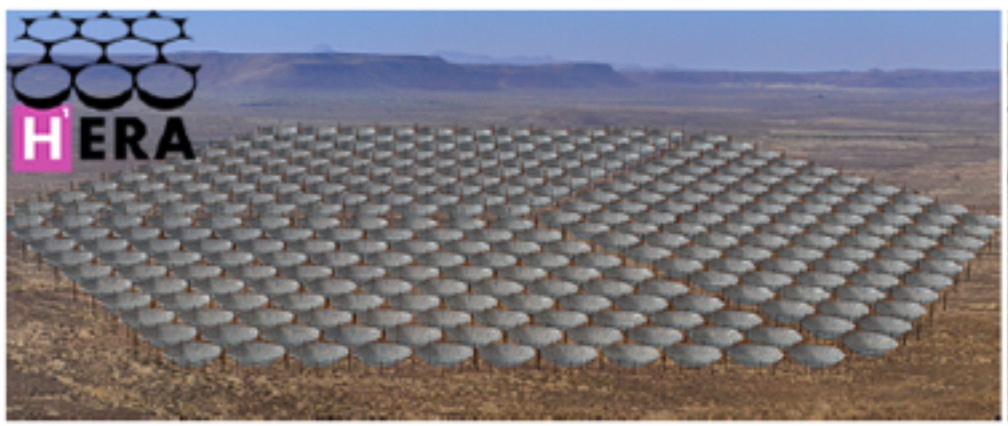
- Low-Frequency Array (LOFAR)
- z = 8-10.6
- Resolution: 4 arcsec
- Array diameter ~70km
- Effective collecting area: >18,000 m^2 (EoR experiment)



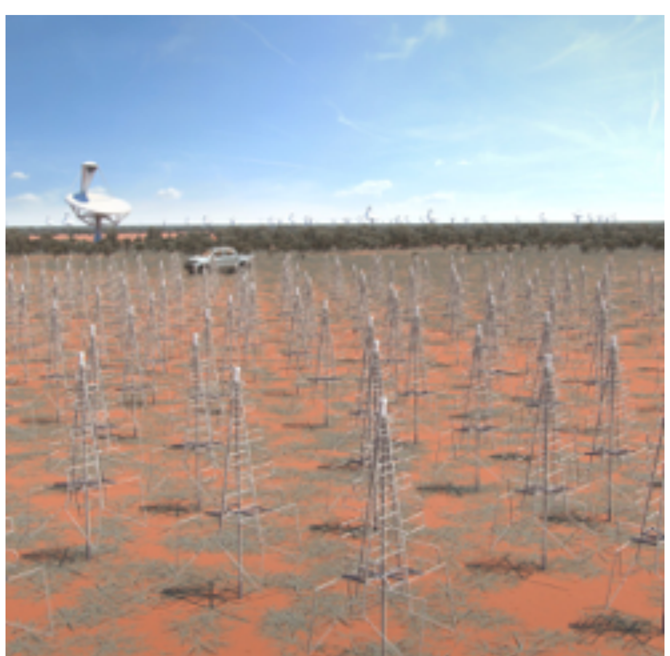
- Precision Array for Probing the Epoch of Reionization (PAPER)
- z = 8-10.6
- Resolution: 30 arcmin
- Array diameter 200m
- Effective collecting area: 1,100 m^2

Suite of future 21cm experiments

- Murchison Widefield Array Phase 2->3 (MWA; Australia)
- z = 6-11
- Resolution: 1 arcmin
- Array diameter ~5km
- Effective collecting area: 7,000 m^2

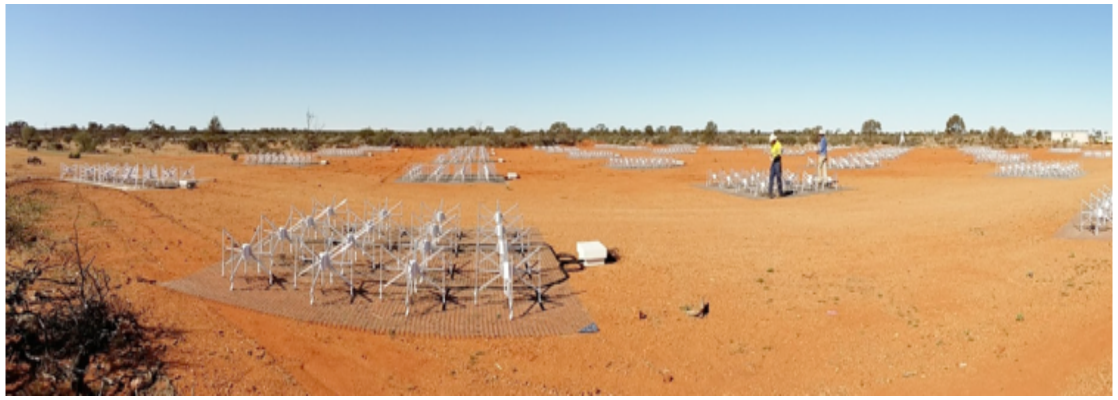


- Hydrogen Epoch of Reionisation Array (HERA; USA/South Africa)
- z = 6-13
- Resolution: 15 arcmin
- Array diameter 400m
- Effective collecting area: 53,000 m^2



- Square Kilometre Array (SKA-Low; Australia, international)
- z = 4-27
- Resolution: 3 arcsec
- Array diameter 50km
- Effective collecting area: 400,000 m^2

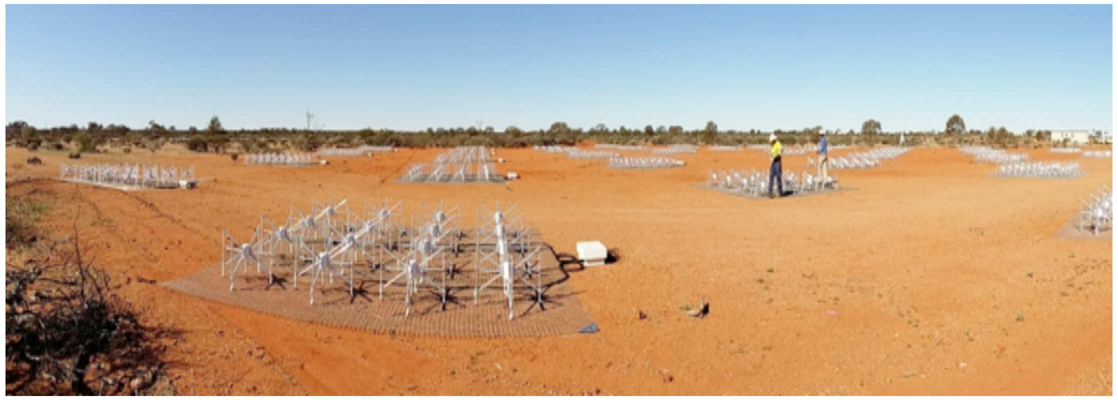
Different approaches



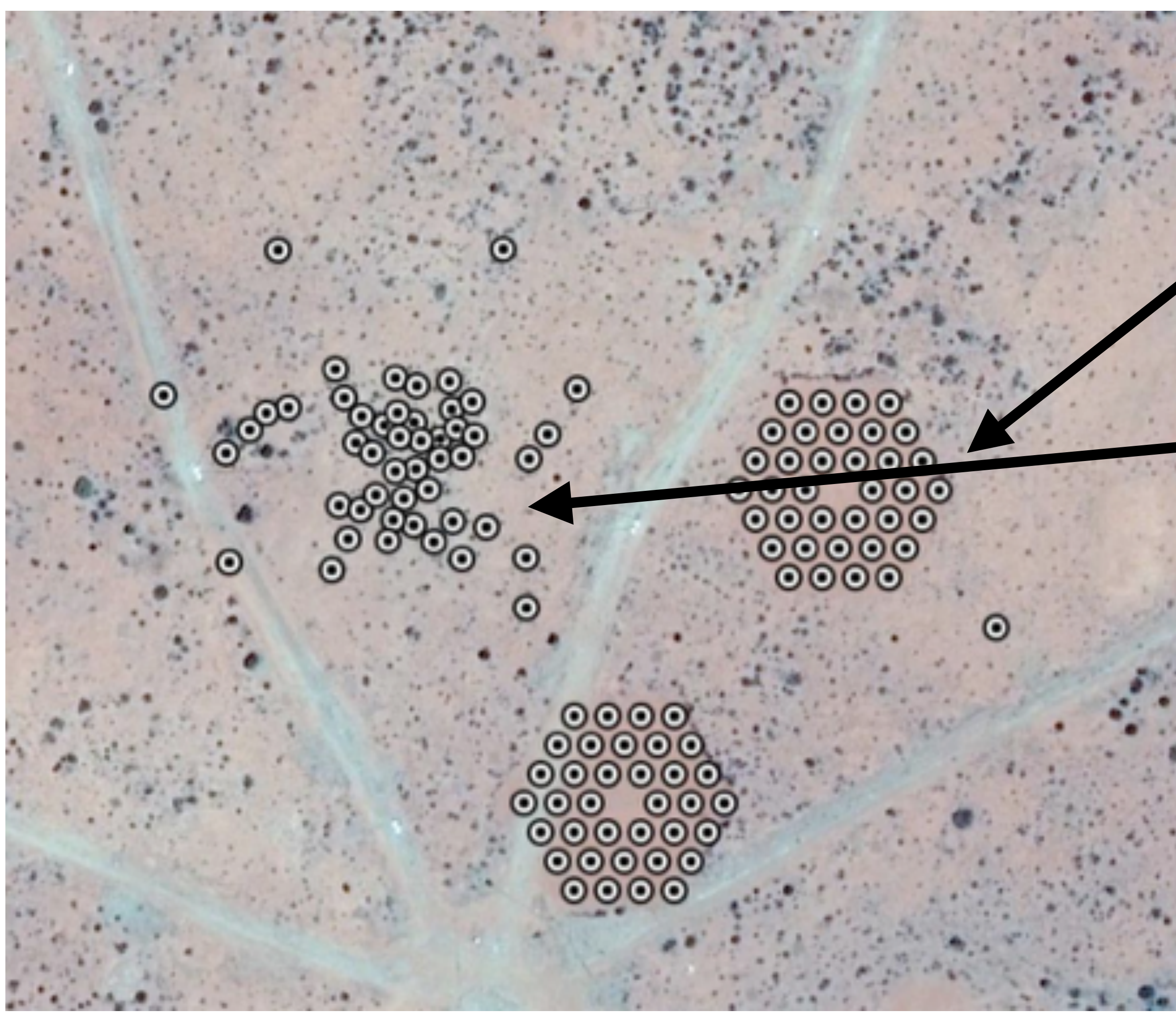
How does one design a 21cm EoR experiment?

Steps	Mode	Resolution	Array size
Instrument calibration	Redundant baselines	10s arcmin —> degrees	100s metres (EoR scales)
Instrument calibration	Fit for sky model	arcseconds	1000s metres (or longer)
Sky model subtraction	Internal instrument model	arcseconds	1000s metres (or longer)
Sky model subtraction	External instrument model	arcseconds	1000s metres (or longer)
Power spectrum		10s arcmin —> degrees	100s metres (EoR scales)

Hybrid approach - MWA Phase II



How does one design a 21cm EoR experiment?



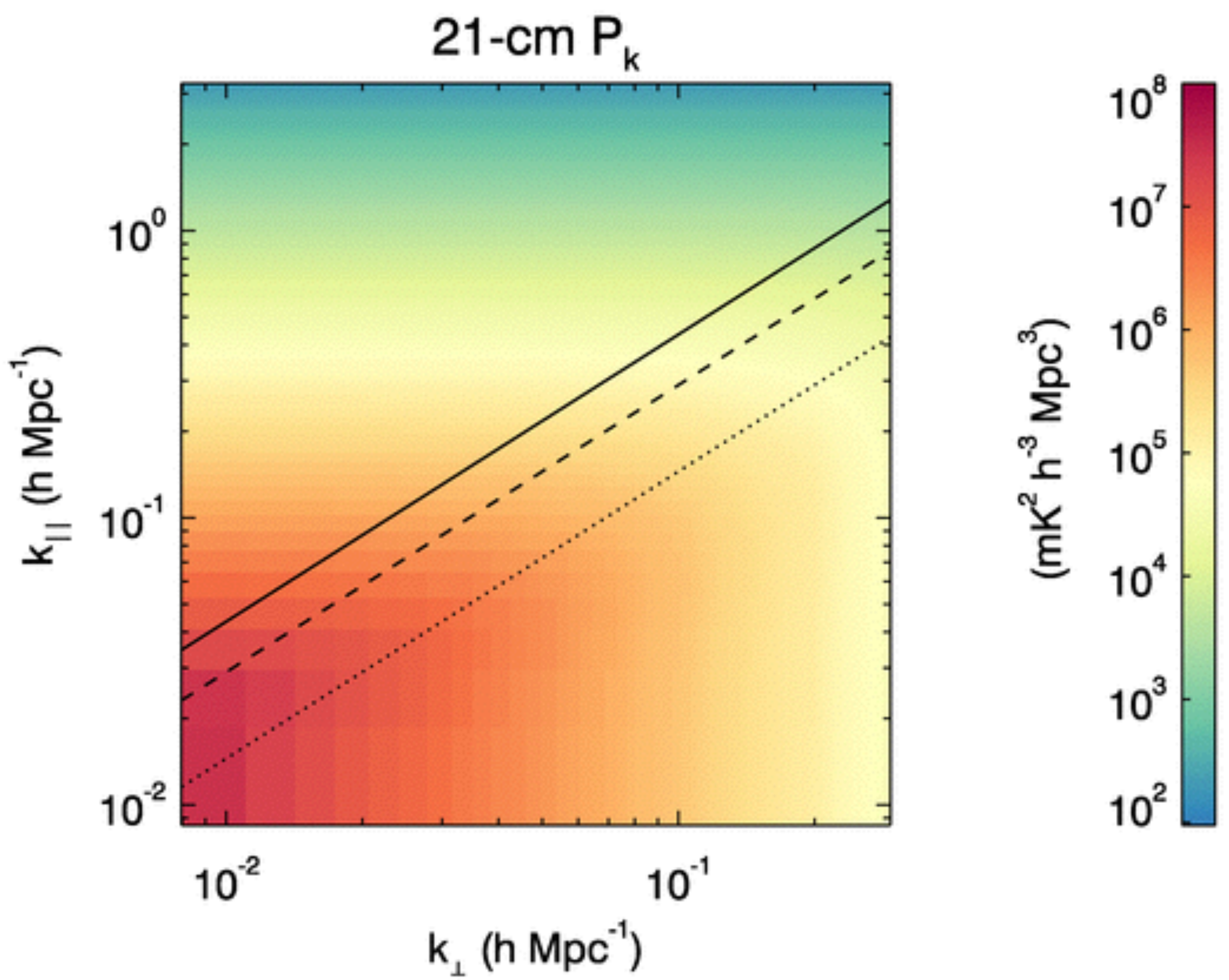
Redundant modes for calibration and measuring same EoR angular scales

Imaging-array for good uv-coverage, sky model, other science

Different systematics for different approaches: hybrid potentially best intermediate solution

The second moment: 2D power spectral density

Line-of-sight wavenumber: spatial power



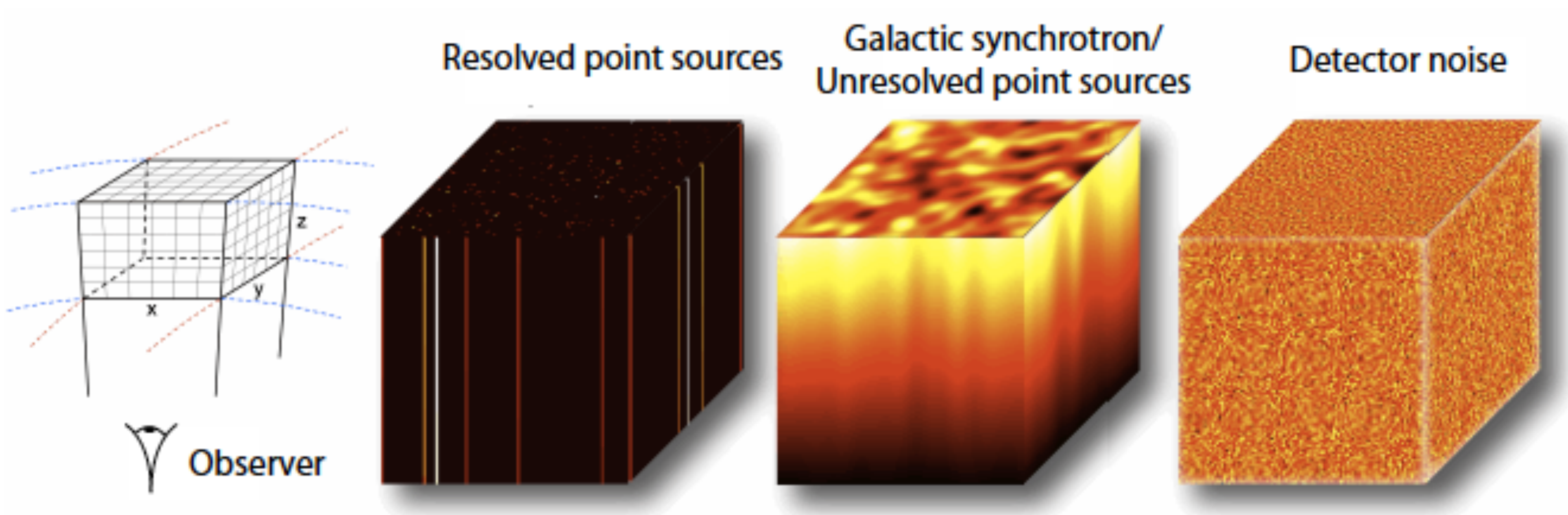
Angular wavenumber: spatial power →

$$\langle \widehat{T}_b(\mathbf{k})^* \widehat{T}_b(\mathbf{k}')\rangle = (2\pi)^3 \delta(\mathbf{k}-\mathbf{k}') P_T(k_\perp, k_\parallel),$$

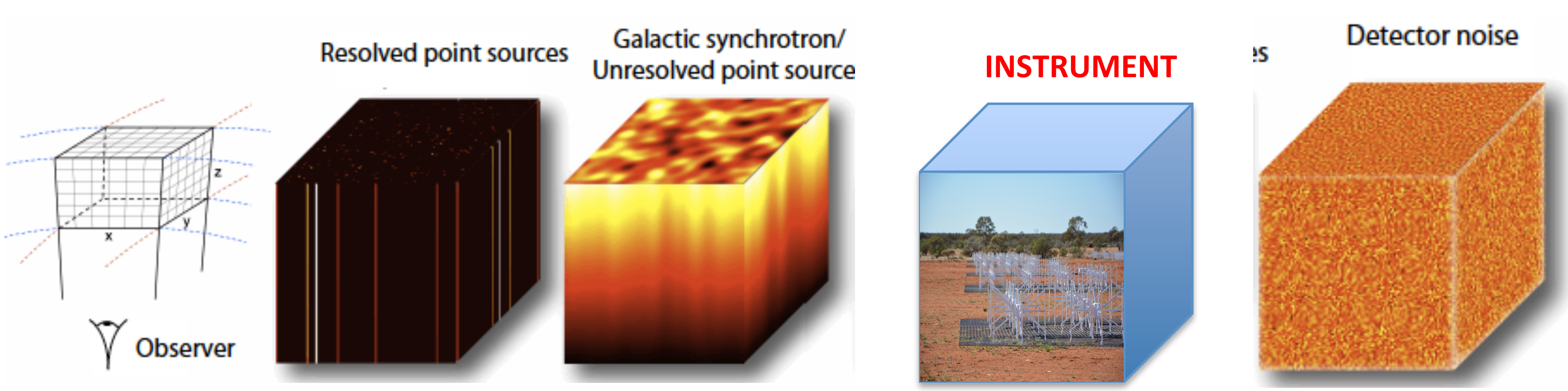
[K^2] [m^{-3}] [$m^3.K^2$]

Contaminants

Radio sources —> continuum synchrotron emission
AGN (z=0-3), SF galaxies (z<0.5)



Liu & Tegmark (2011)

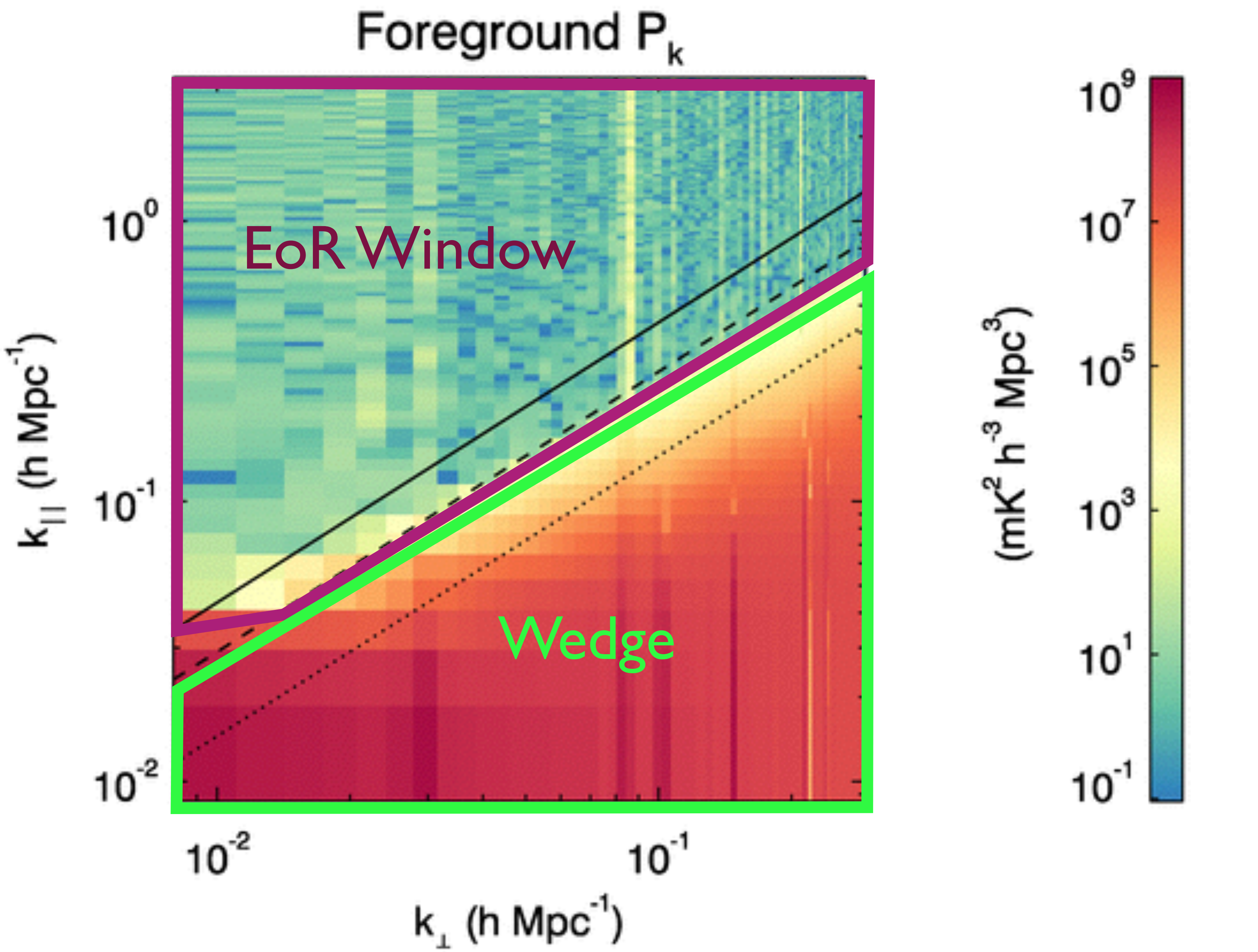


Foreground contamination

Why we separate angular and LOS modes

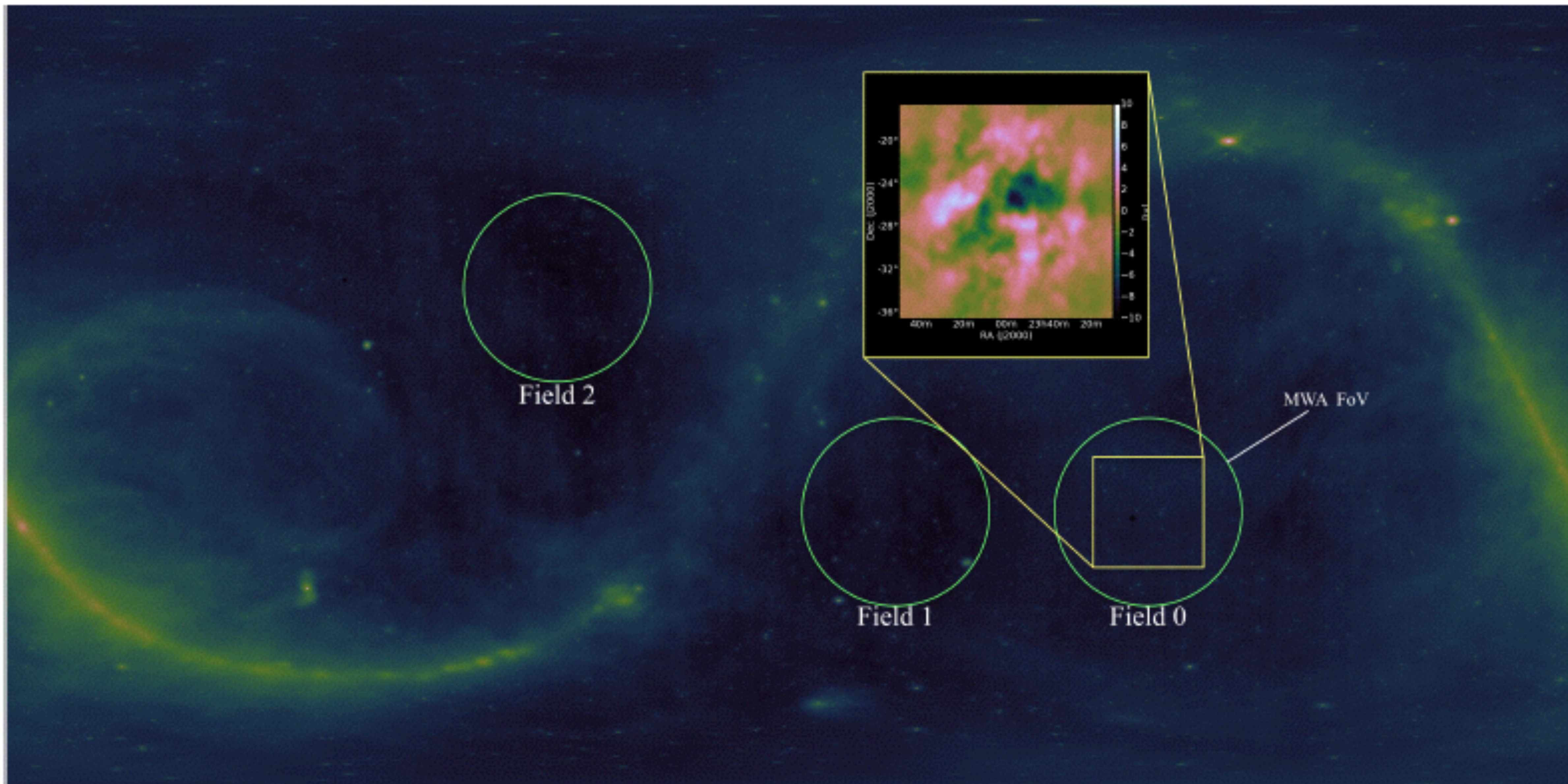
Model for confused point sources

$$P(k) = P_{21}$$



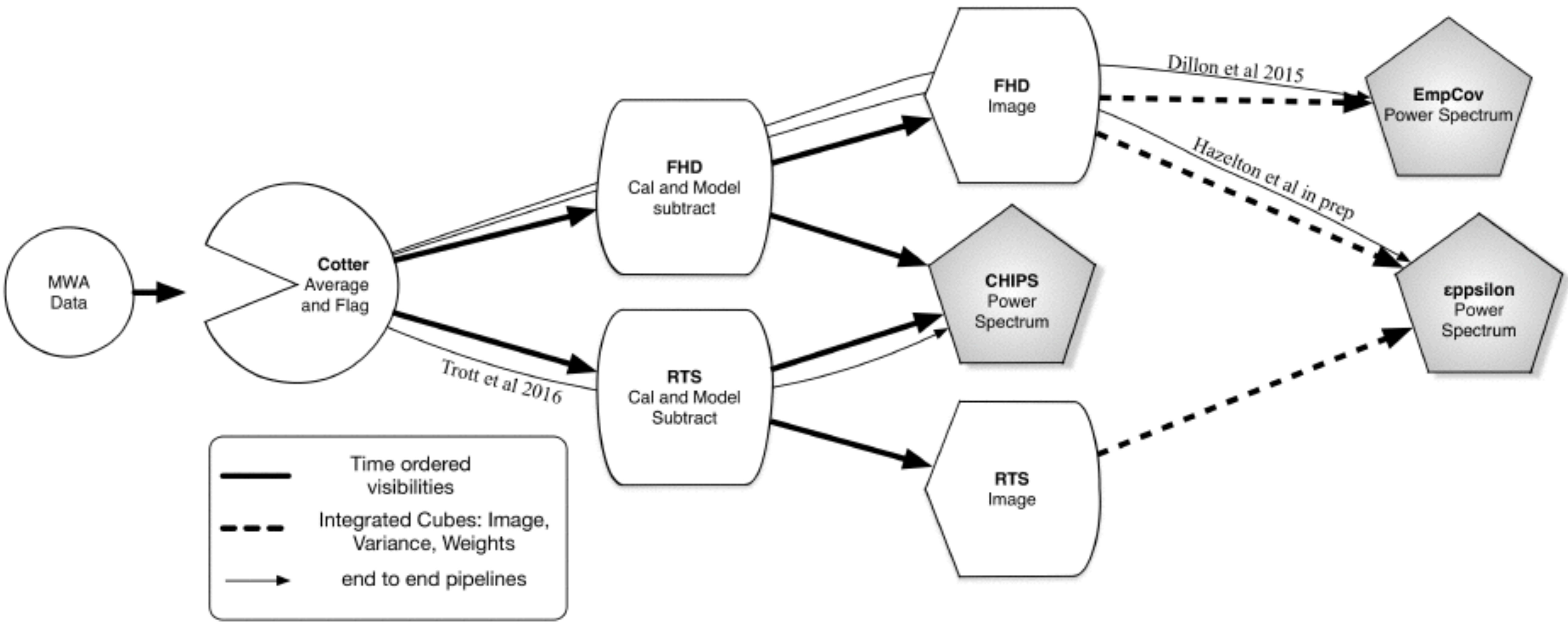
The MWA Experiment

- >2000 hours of data on 3 fields (reduce measurement noise, and sample variance)
- Frequency range: 130 - 195 MHz (z=10 - 6)
- Two calibration pipelines, two power spectrum pipelines

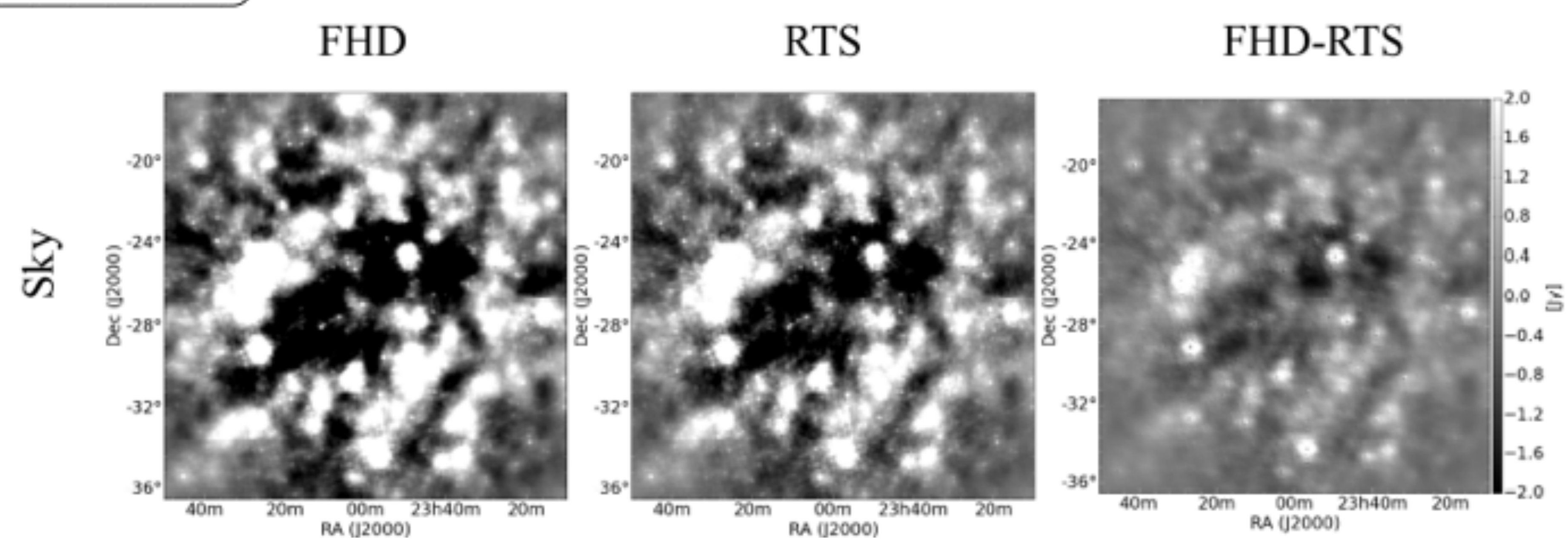


Jacobs+ (2016)

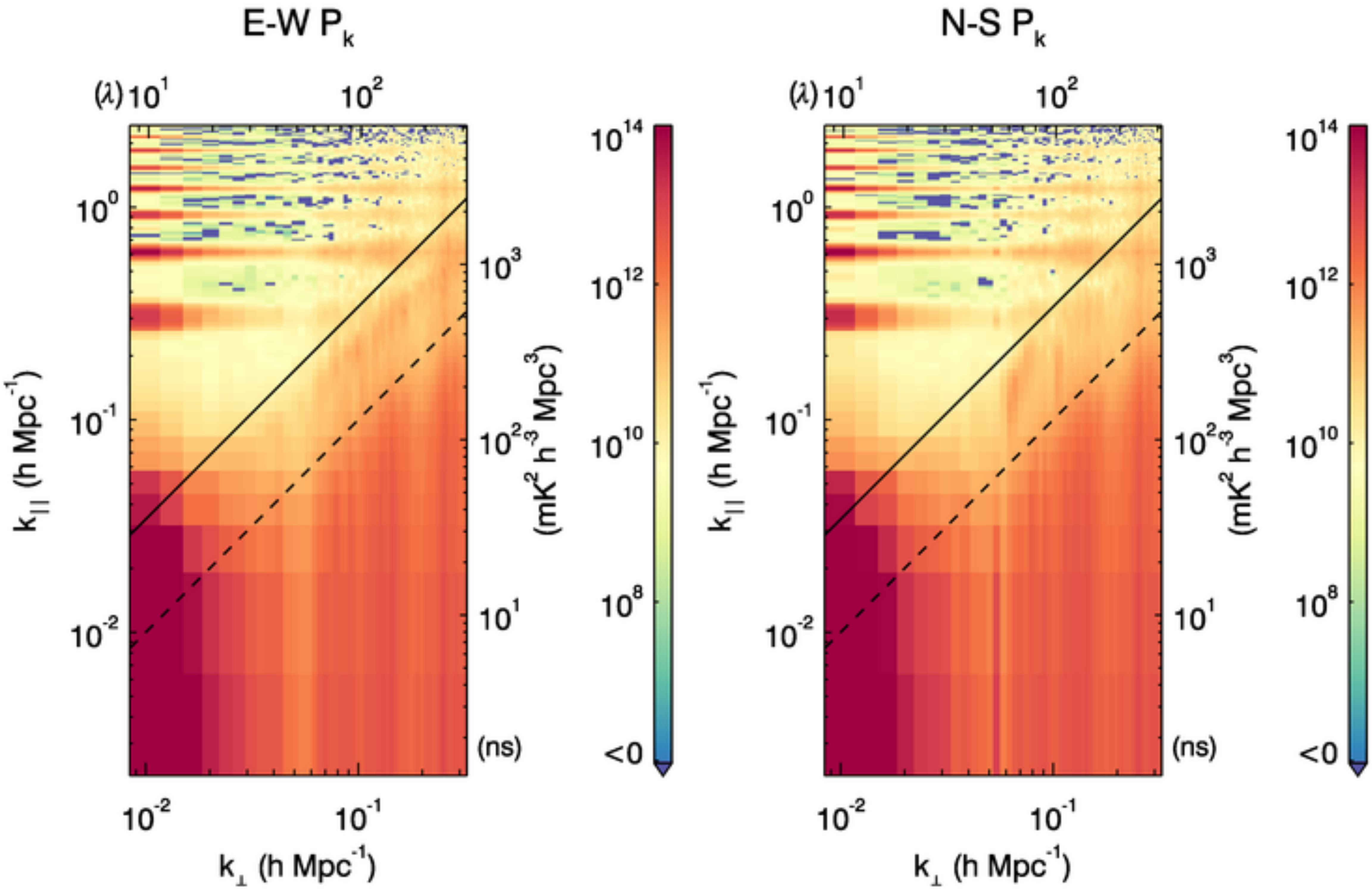
Data processing pipelines: redundant, collaborative, independent



Jacobs+ (2016)

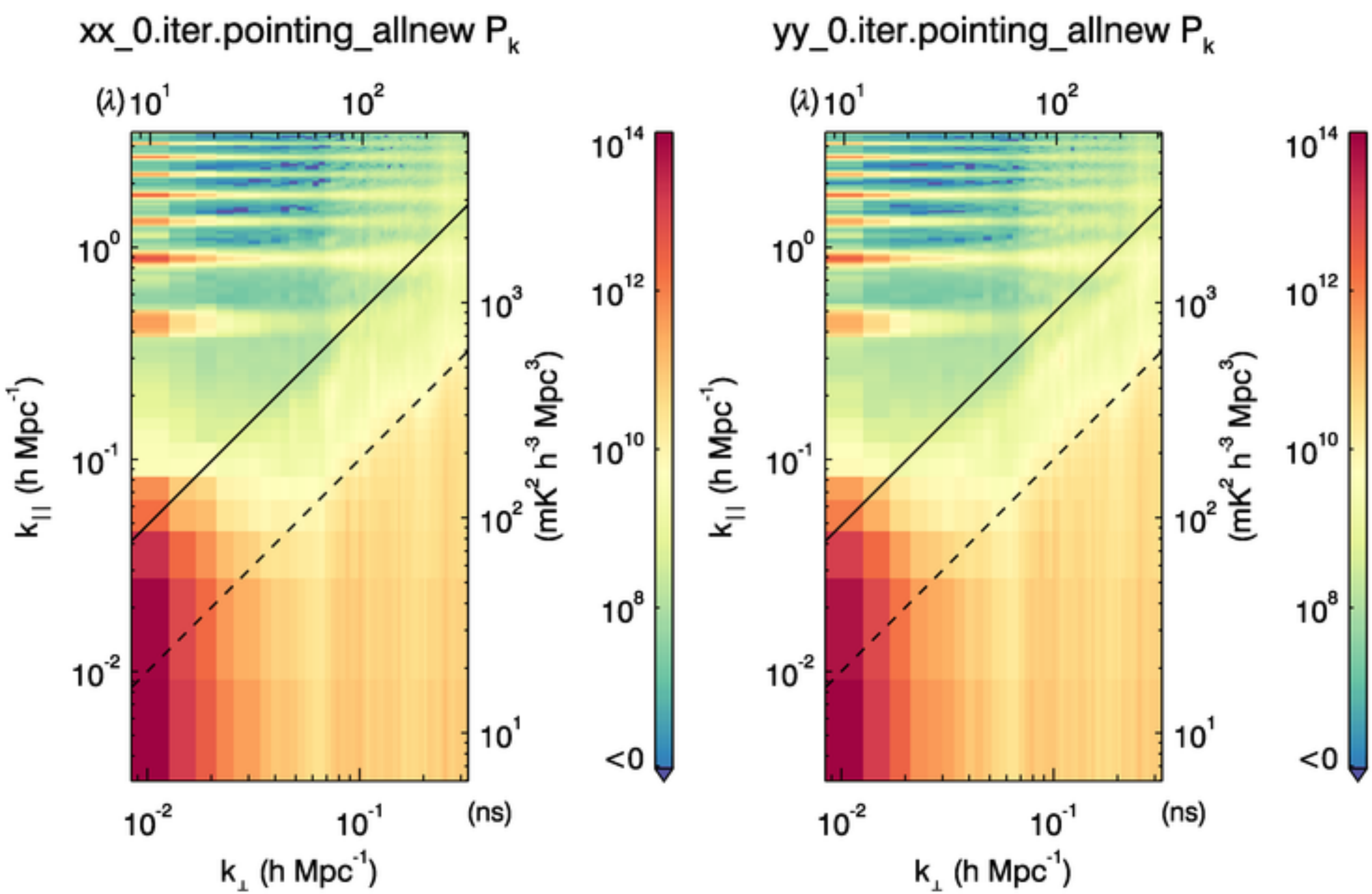


The MWA Experiment - test 3-hr data (2013B)



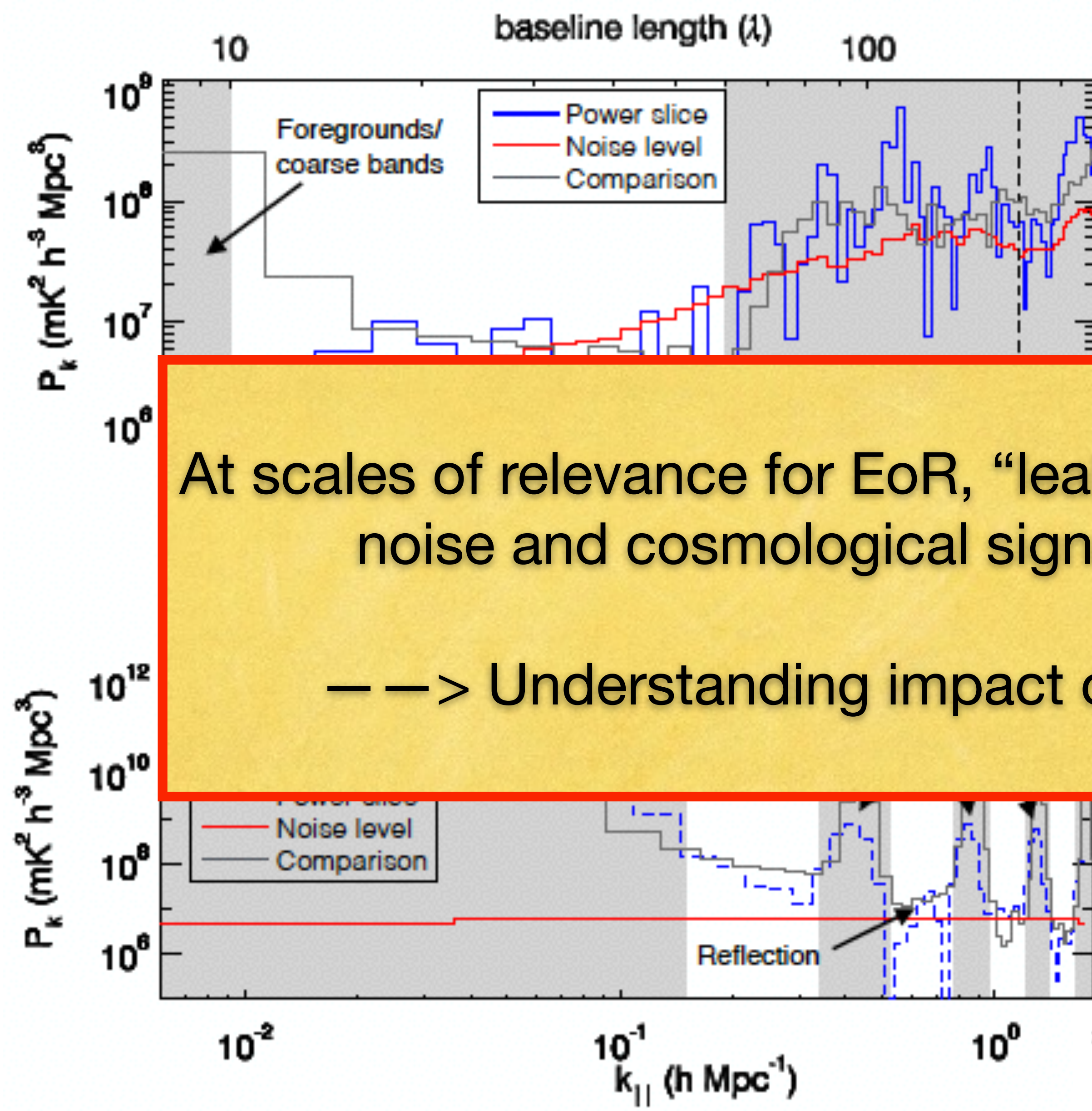
Trott+ (2016)

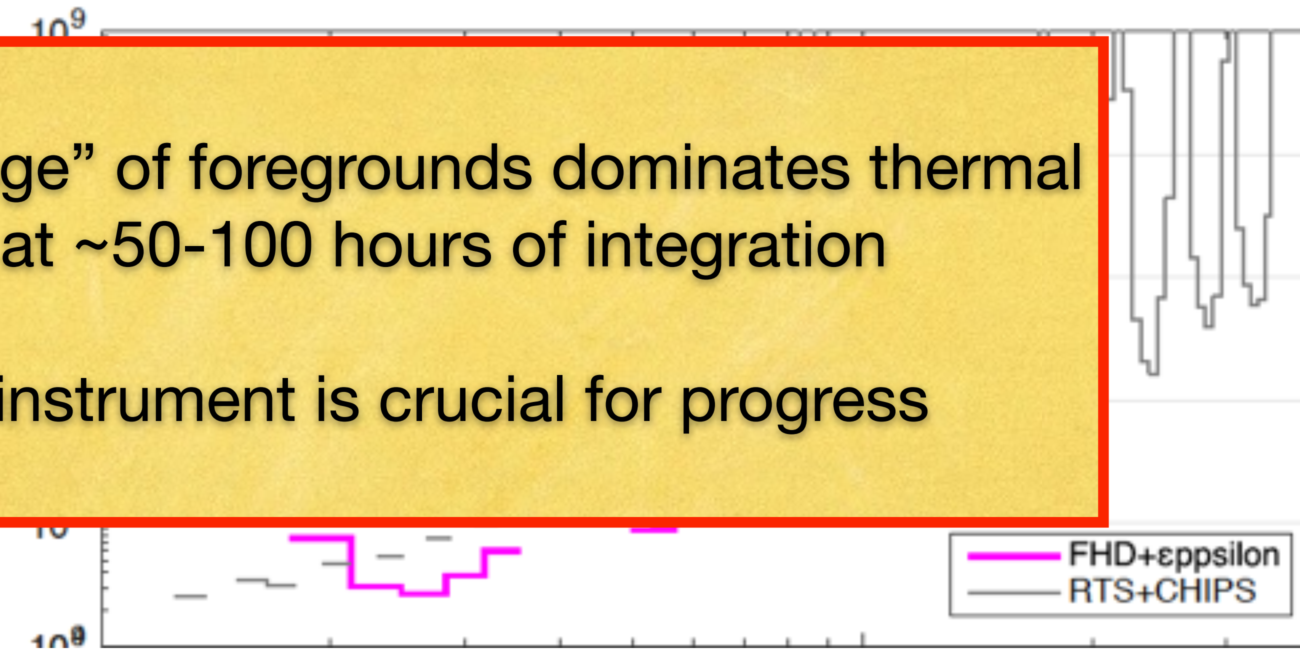
The MWA Experiment - 32-hr data (2013B)



The MWA Experiment - (86) 32-hr data

- 86h (raw) —> 32h (quality cuts)
- Best limits at z=6.5-7.2
- Foreground-limited at large scales





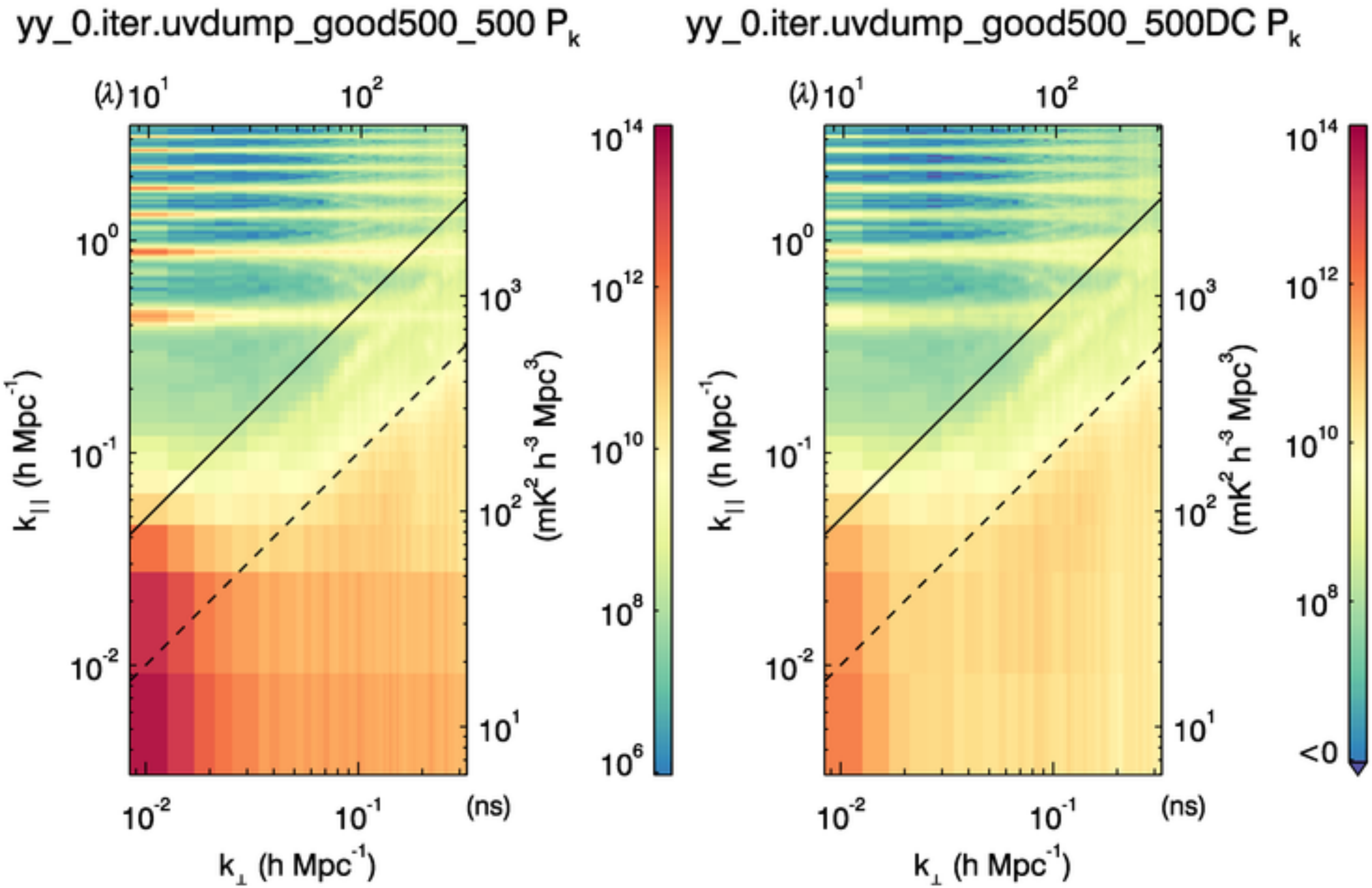
At scales of relevance for EoR, “leakage” of foregrounds dominates thermal noise and cosmological signal at ~50-100 hours of integration

— —> Understanding impact of instrument is crucial for progress

Beardsley+ (2016)

Sub-band	z_0	Pol	FHD+εppsilon k	FHD+εppsilon Δ^2_{UL}	RTS+CHIPS k	RTS+CHIPS Δ^2_{UL}
Low	7.1	E-W	0.231	3.67×10^4		
Low	7.1	N-S	0.27	2.70×10^4	0.16	3.2×10^4
Mid	6.8	E-W	0.24	3.56×10^4		
Mid	6.8	N-S	0.24	3.02×10^4	0.14	2.6×10^4
High	6.5	E-W	0.20	4.70×10^4		
High	6.5	N-S	0.24	3.22×10^4	0.14	2.5×10^4

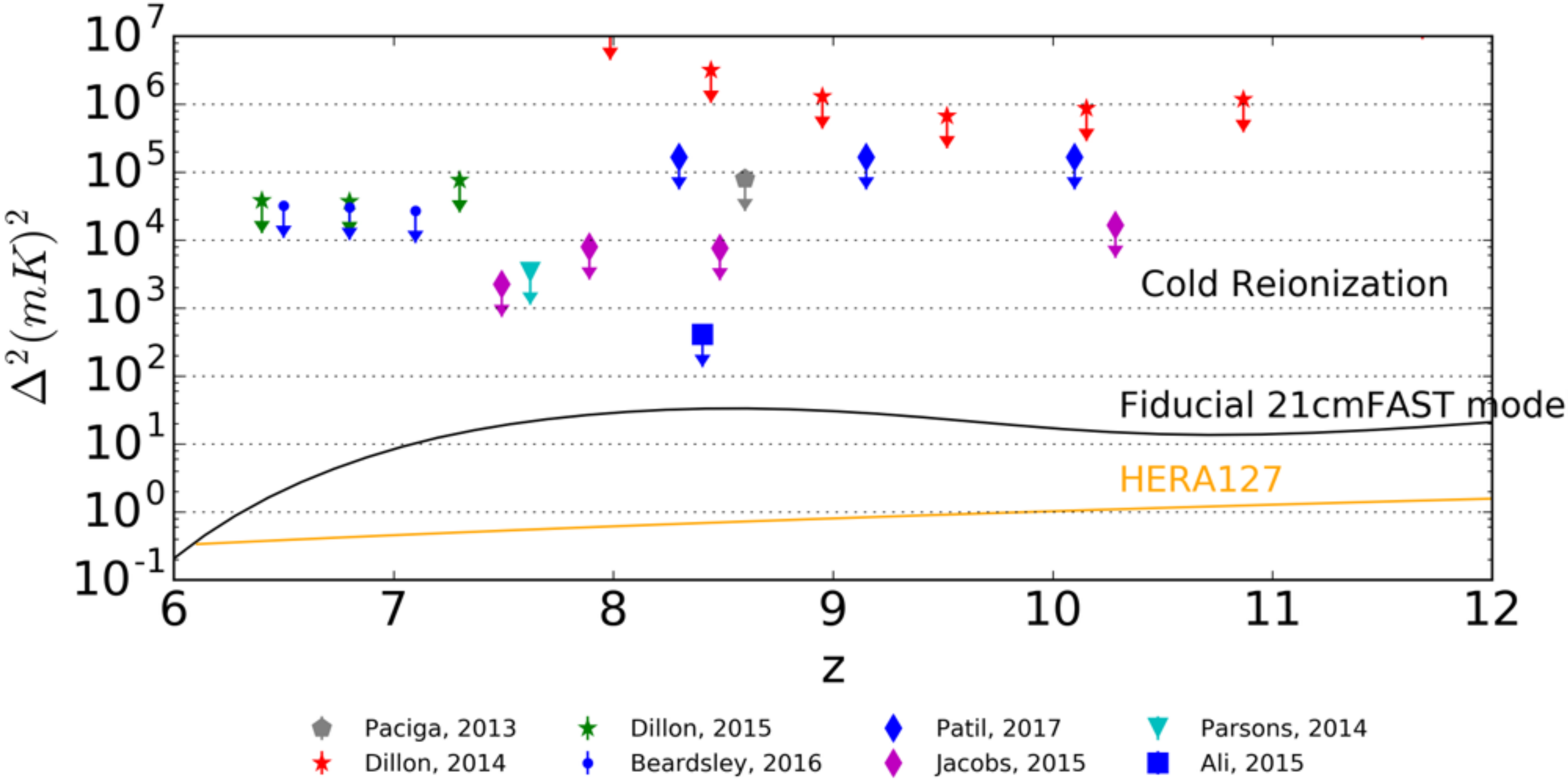
The MWA Experiment - test 17-hr data (2015B)



(115 mK)^2 at k=0.13 Mpc^{-1}

Lowest MWA EoR limit to date

Current state of the field - 2σ upper limits at $k=0.1\ h^{-1}$ Mpc

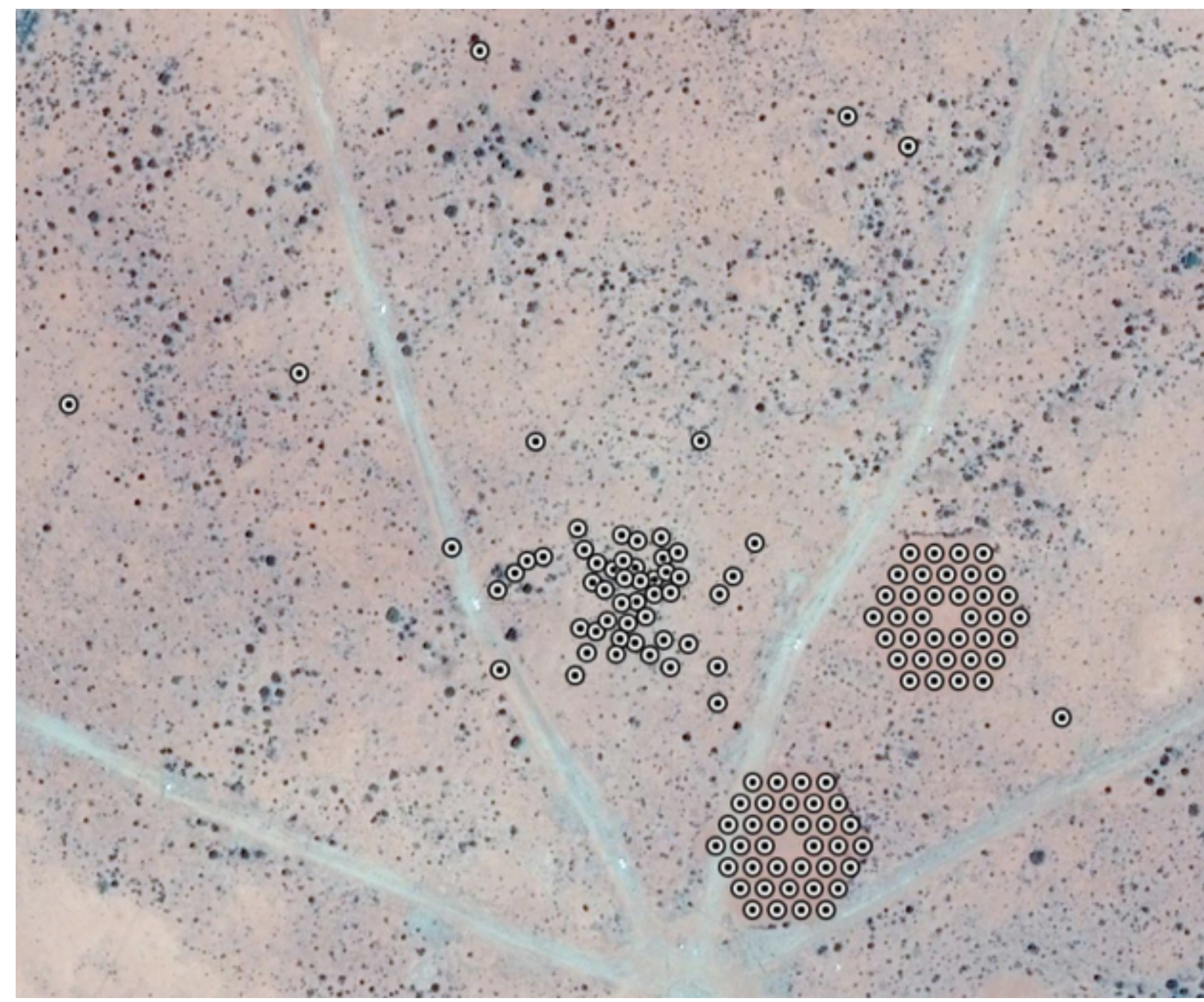


Courtesy Danny Jacobs

The MWA Experiment - 2016-17 focus

Pause data processing to improve sky and instrument model and introduce better data quality database

- Phase II Array (2016+): redundant/non-redundant calibration; high surface brightness
- Data cleanliness and curation: polarisation, ionosphere, signal processing (filterbanks), near-zenith pointings, diffuse sky model
- Data processing: restarting large-scale data processing

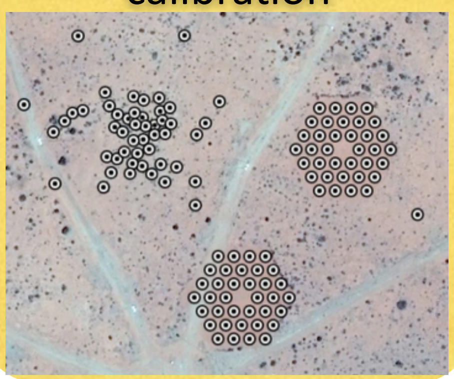


Phase II Array: currently operating

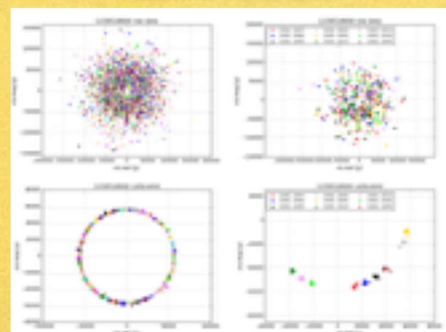
The MWA Experiment - 2016-17 focus

Instrumentation and data processing methods

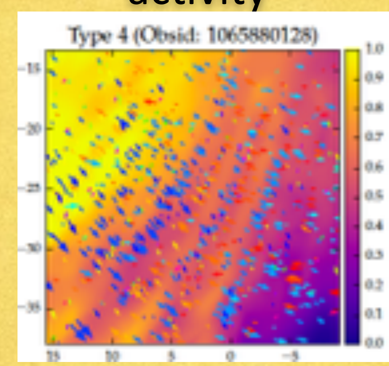
Hybrid calibration



Redundant calibration

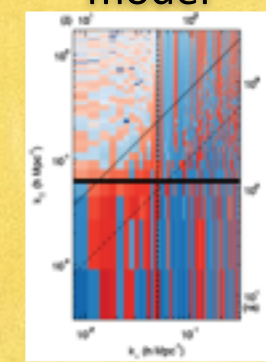


Ionospheric activity



Chris Jordan - Thurs PM

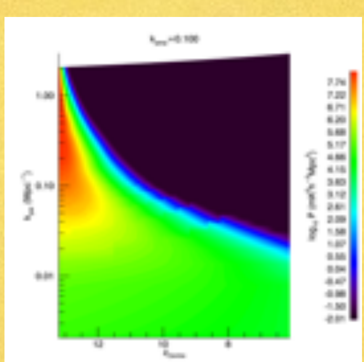
Calibration model



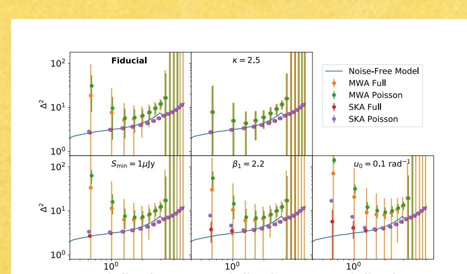
Nichole Barry - Mon AM

Foreground models and statistical signal processing

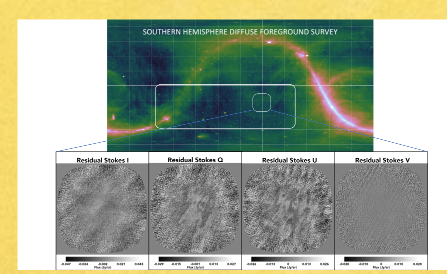
Wavelets



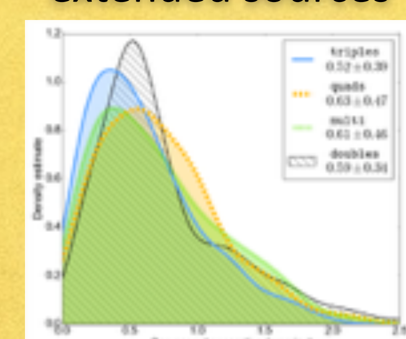
Clustered foregrounds



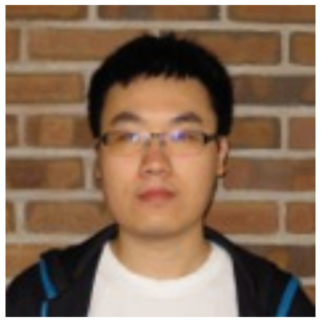
Diffuse polarised sky model



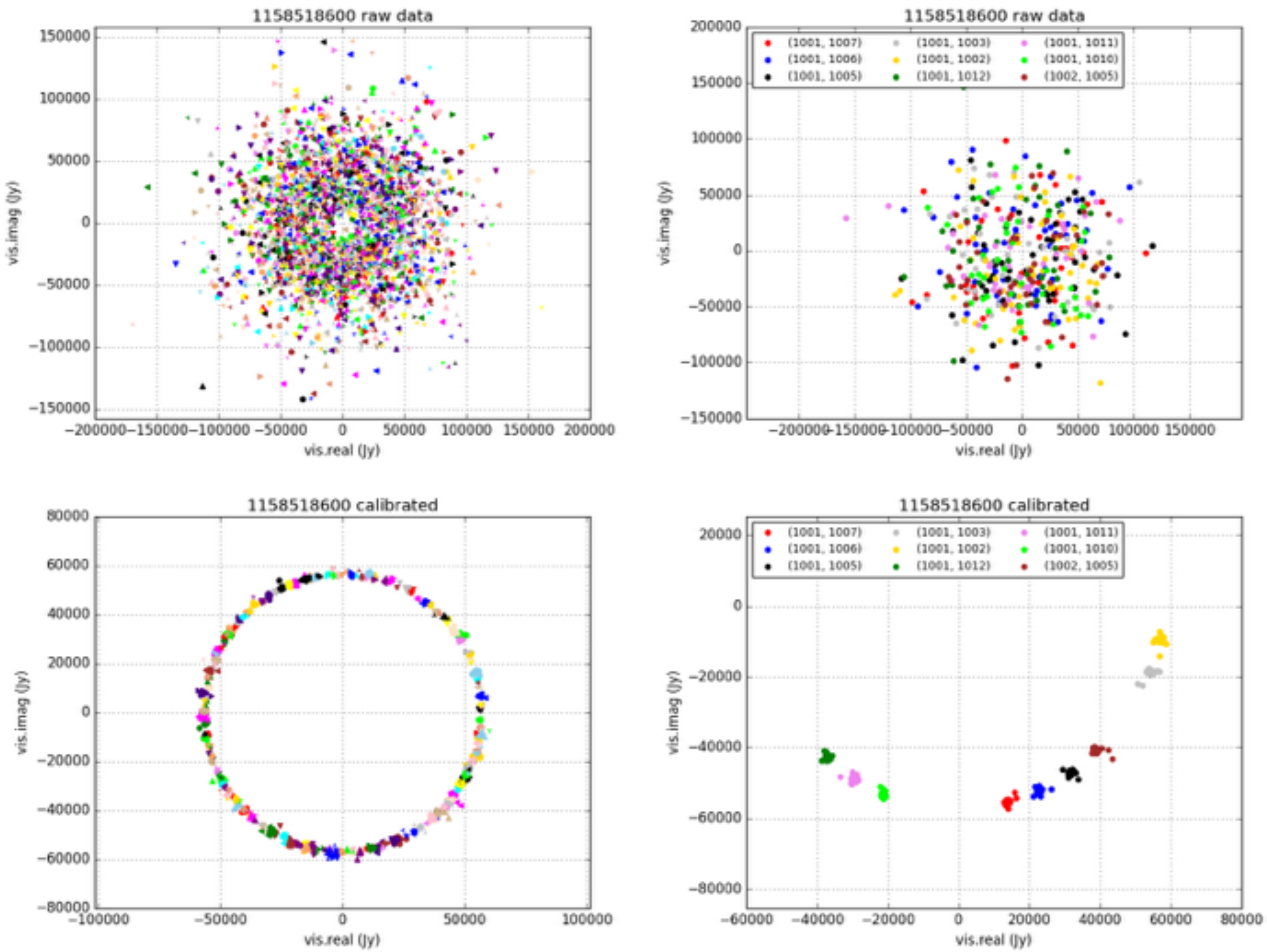
Double and extended sources



MWA EoR group: redundant calibration with Omnical

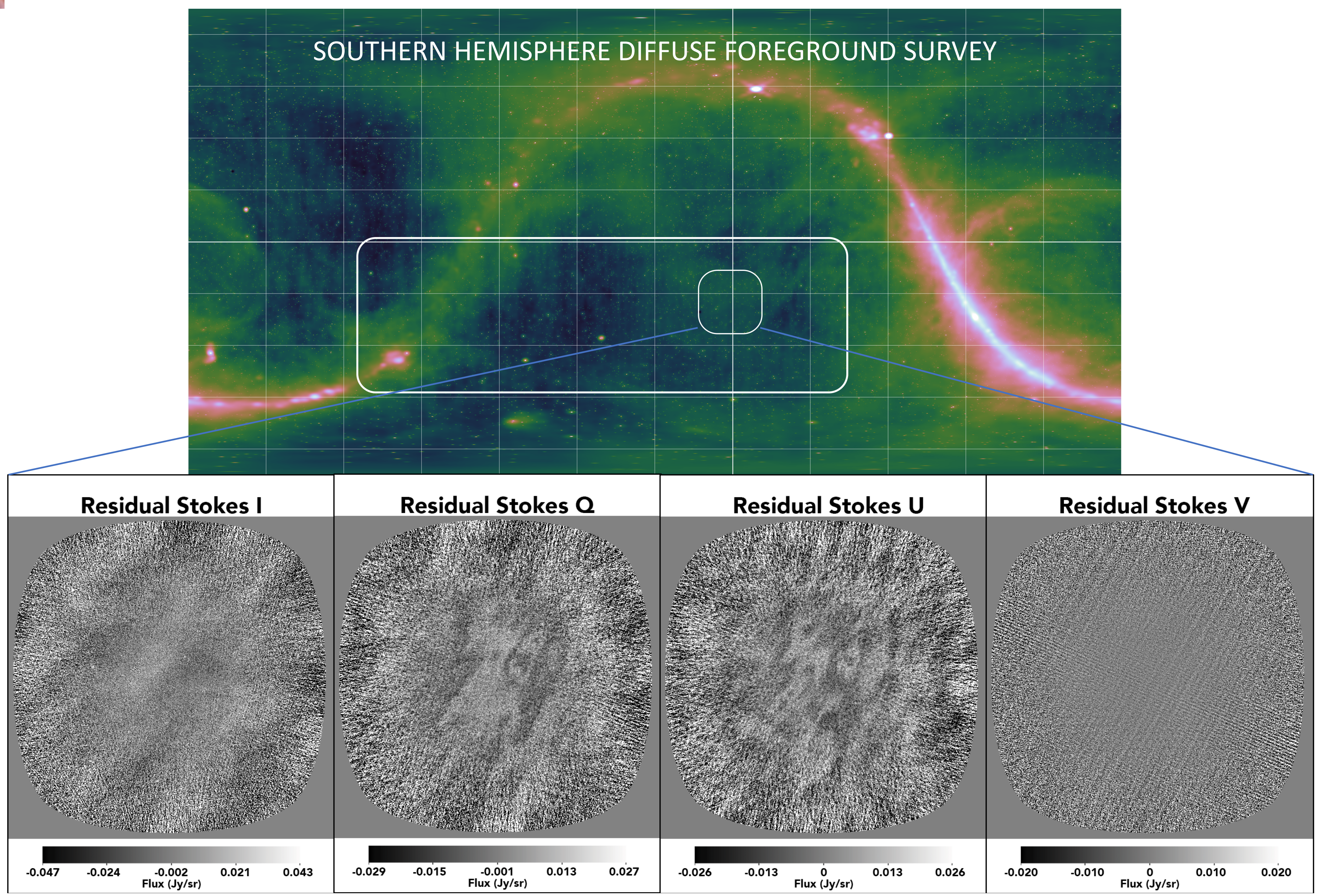


Wenyang Li (Brown) — applying Omnical redundant calibration algorithm to MWA hex calibration



MWA EoR group: diffuse sky model

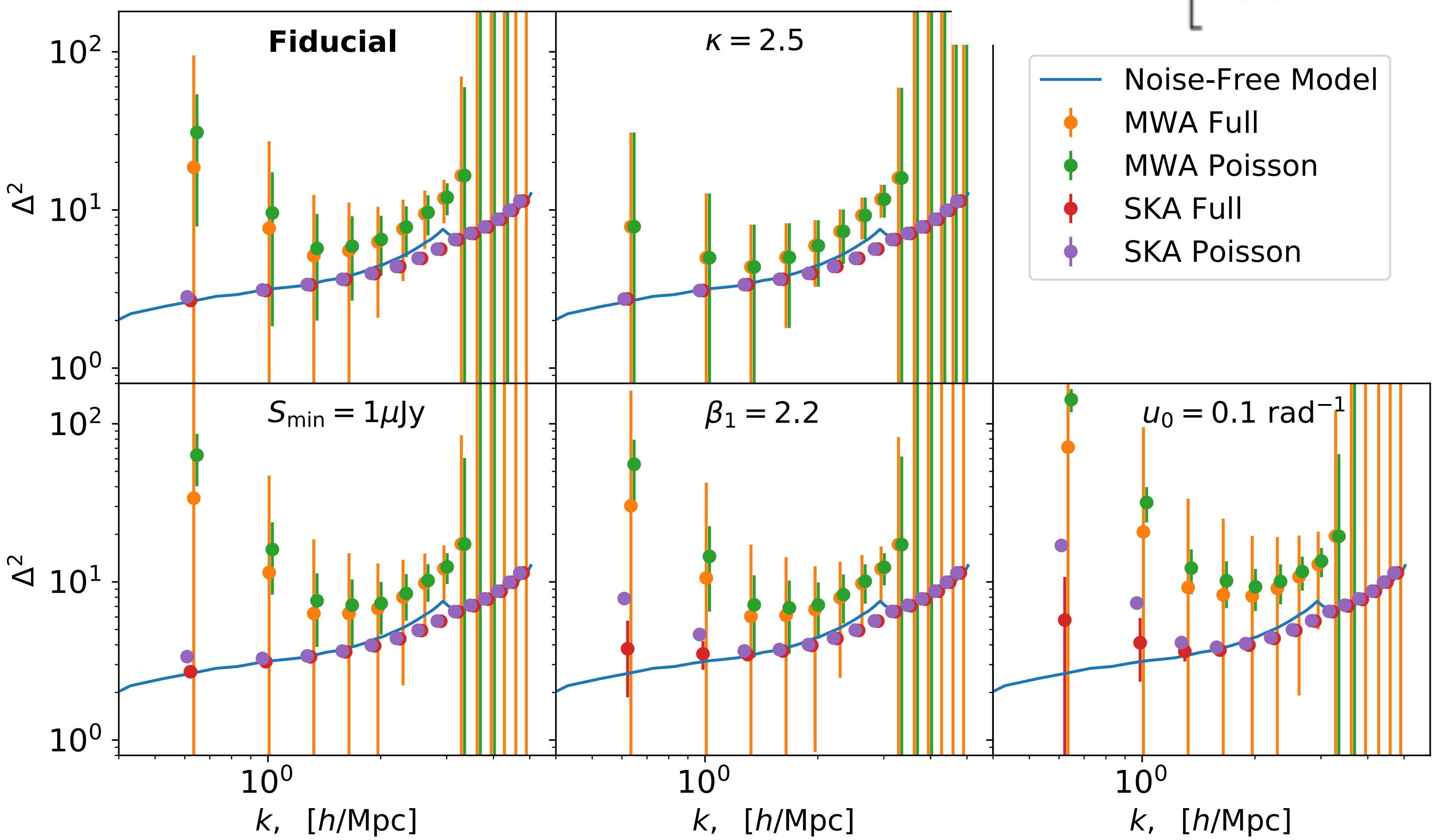
Ruby Byrne (U. Washington) — measuring polarised and unpolarised diffuse emission in EoR fields



MWA EoR group: foreground clustering

Steven Murray (ICRAR-Curtin) — improving foreground covariance model — fully-statistical extragalactic point source model, including source clustering and realistic number counts

$$\mathbf{C}_{\rm Clust} = (\pi y)^{\kappa/2} y \mu_1^2 u_0^\kappa \frac{(1+p^2)^{-a}}{f'^{\kappa+\gamma}_0 f''^{2+\gamma}_0} \times \left[\Gamma(a) e^{-2\pi y u^2} {}_1F_1\left(a; 1; \pi y \frac{(1+p)^2}{1+p^2} u^2\right)\right], \quad (46)$$



Murray, Trott & Jordan (2017, submitted)

Summary and outlook

- The MWA EoR project has collected 4.5 years of data on three fields
- Focus of 2016-2017 has been data quality, instrument models and sky models
- Embarking on processing of clean data from full 2013-2017 datasets

- International experiments increasing collaboration, sharing knowledge and techniques
- Different approaches to instrument calibration and experiment design help inform and progress the field.