Cath Trott & EoR Collaboration

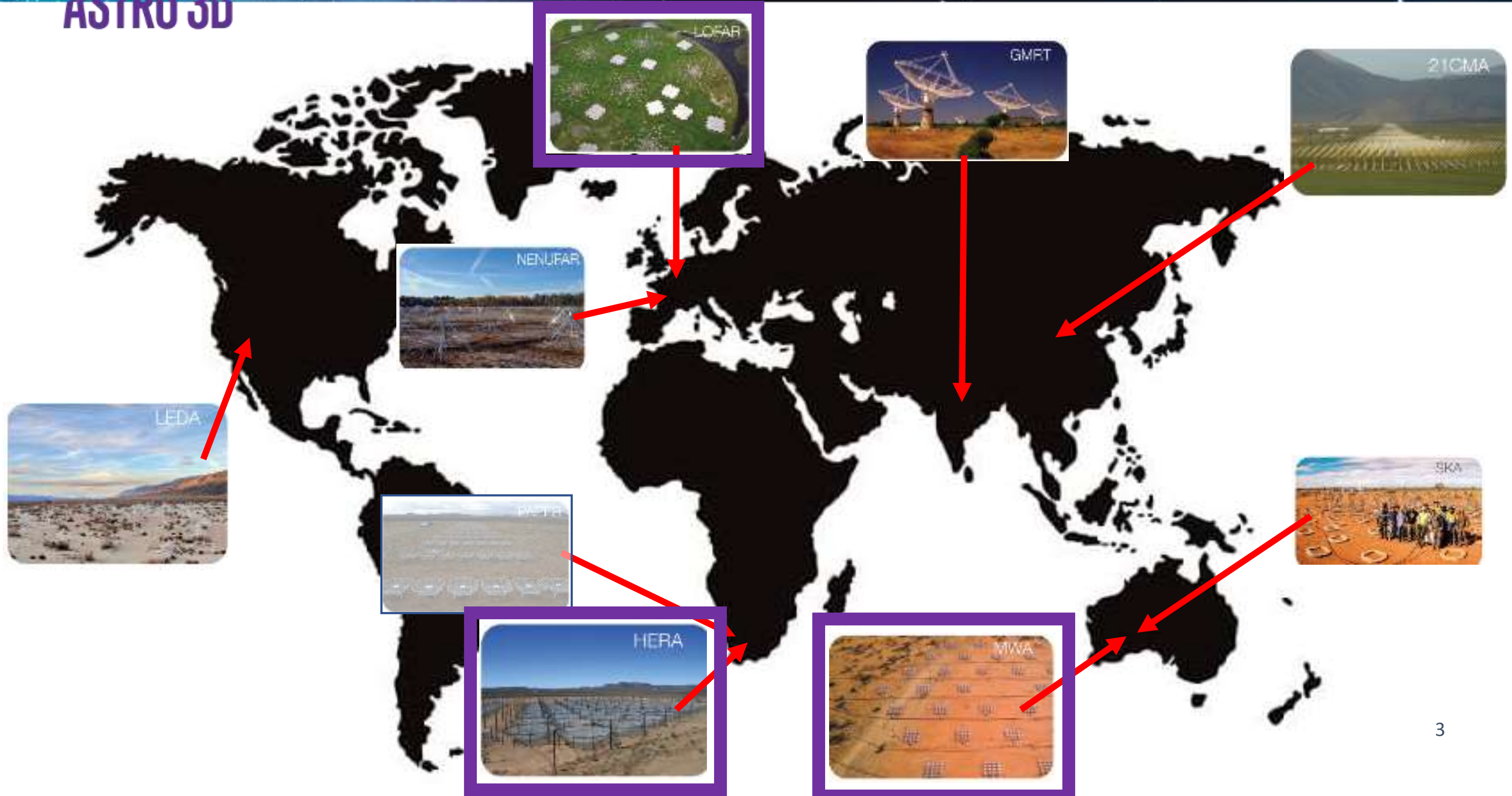
MWA EPOCH OF REIONISATION PROJECT – 2013-2023

We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site
Inyarrimanha Ilgari Bundara

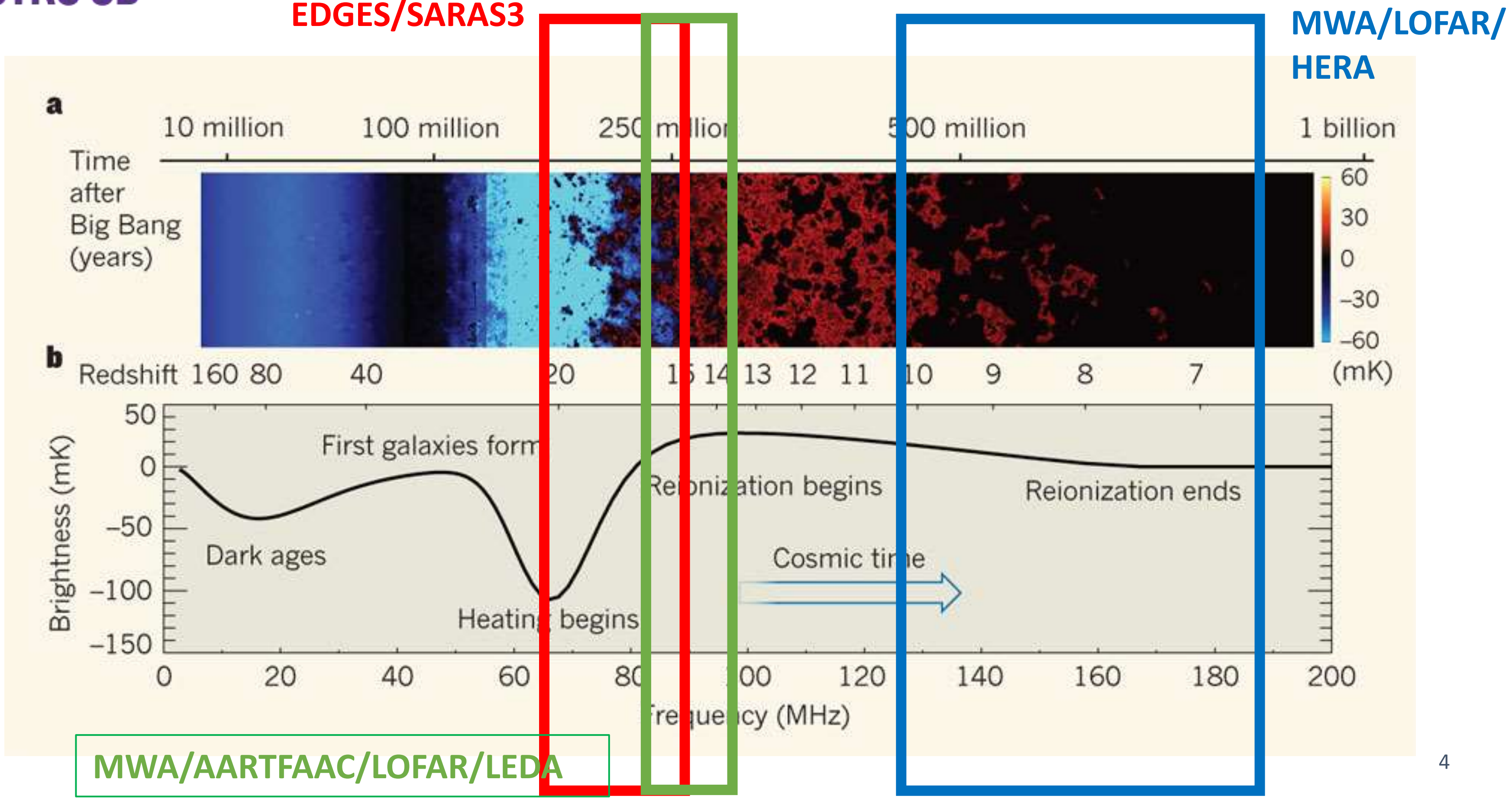
International Centre for Radio Astronomy Research

MWAEOR MEMBERS: FOUR COUNTRIES HIGHLY ACTIVE

GLOBAL LANDSCAPE



21CM OBSERVATIONS

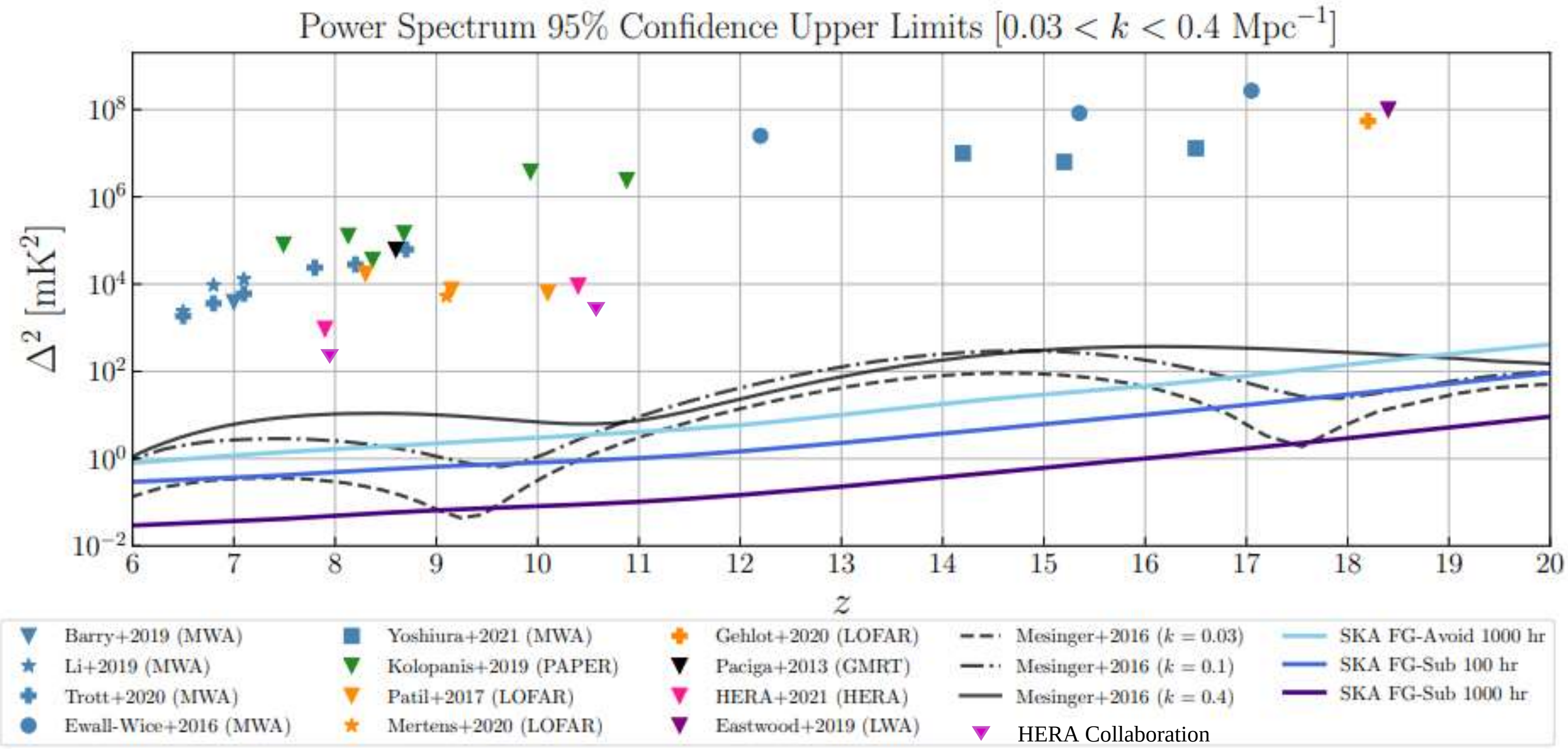


21CM RESULTS

ASTRO 3D

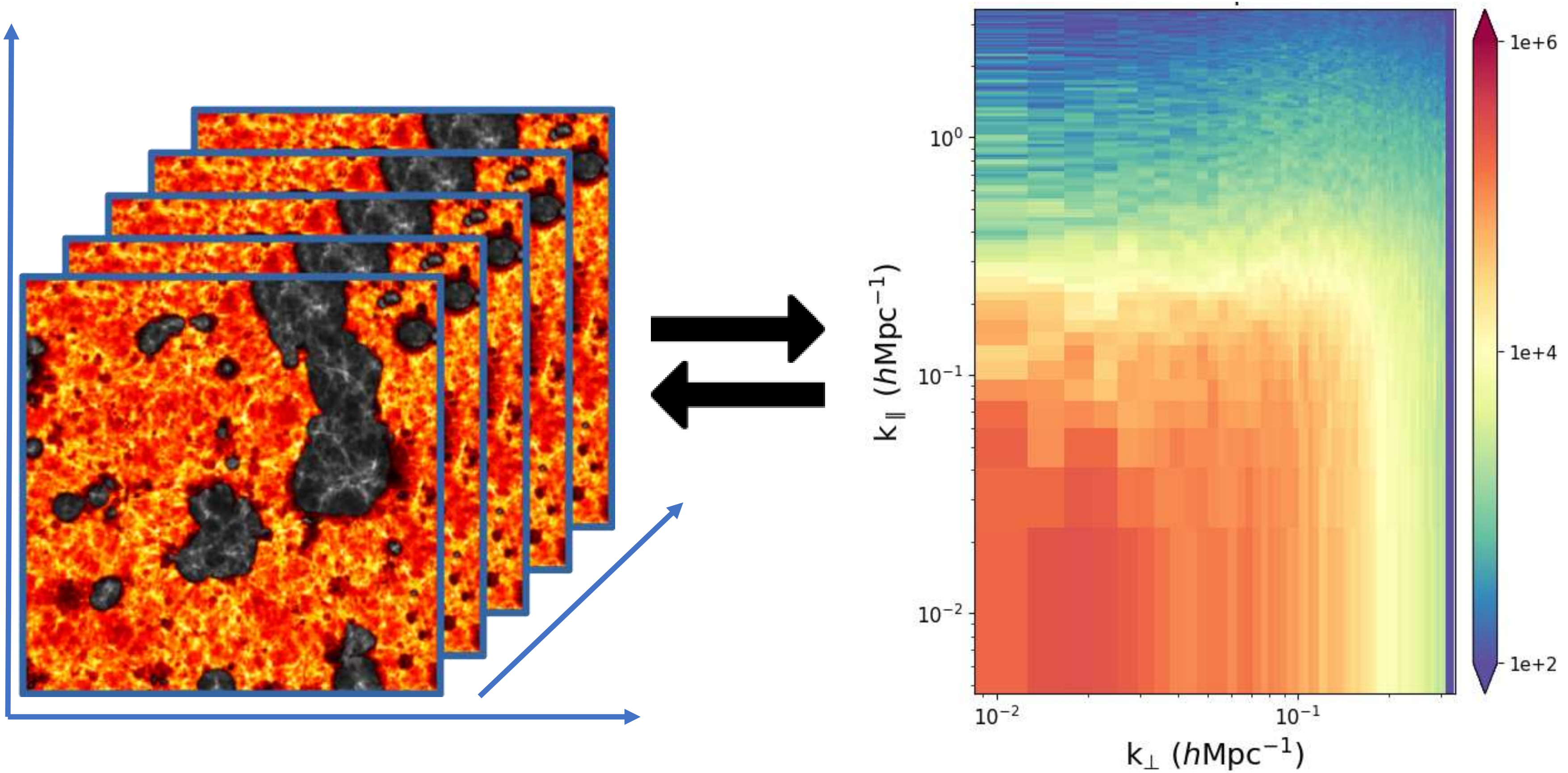
EDGES/SARAS3

MWA/LOFAR/



MWA/AARTFAAC/LOFAR/LEDA

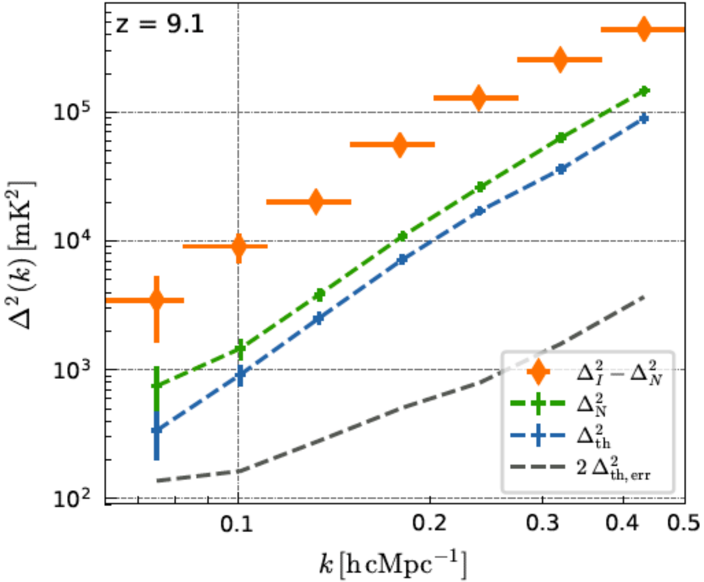
SPATIAL TEMPERATURE FLUCTUATION POWER SPECTRUM – PRIMARY OUTPUT STATISTIC



LOFAR EOR RESULTS 2020

ASTRO 3D

Low-Frequency Array (LOFAR) – Netherlands
Aperture array stations
EoR experiment made from core; long baselines used for sky model



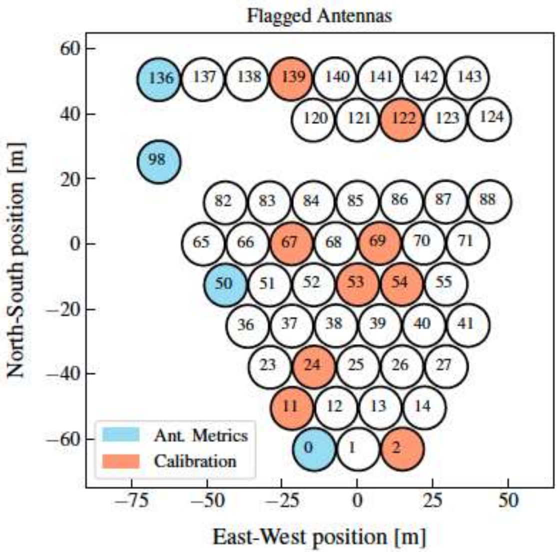
z = 9.1 (k=0.075 h $cMpc^{-1}$)
141 hours
$\Delta^2 < (72.9\ \mathrm{mK})^2$

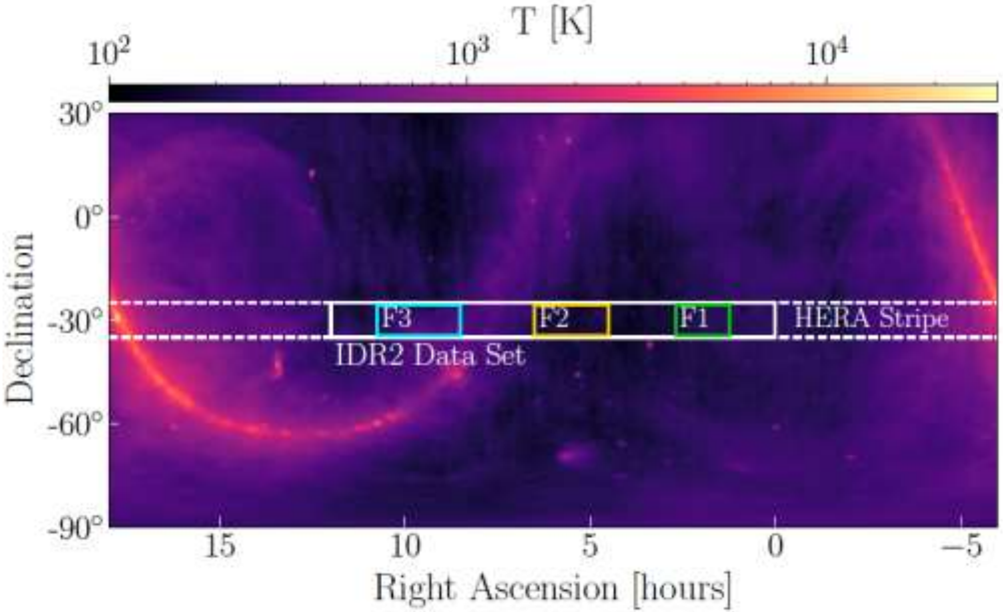
Mertens et al (2020)

HERA EOR RESULTS 2021

ASTRO 3D

Hydrogen Epoch of Reionization Array (South Africa)
Fully-redundant configuration
Designed specifically to do just this experiment





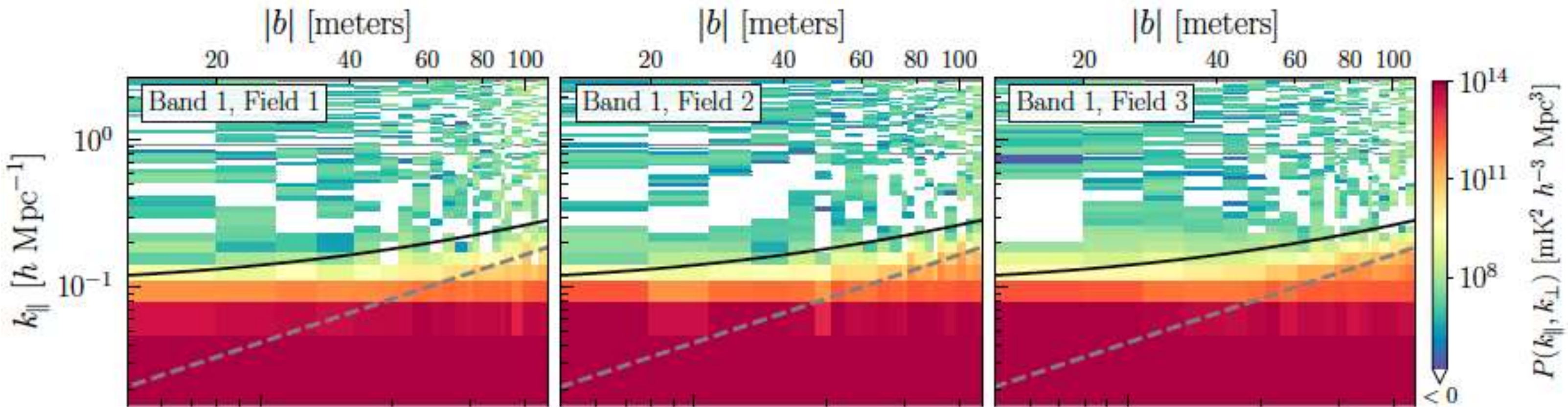
The HERA Collaboration (2021)

HERA RESULTS 2021

Hydrogen Epoch of Reionization Array (South Africa)
Fully-redundant configuration
Designed specifically to do just this experiment

36 hours integration

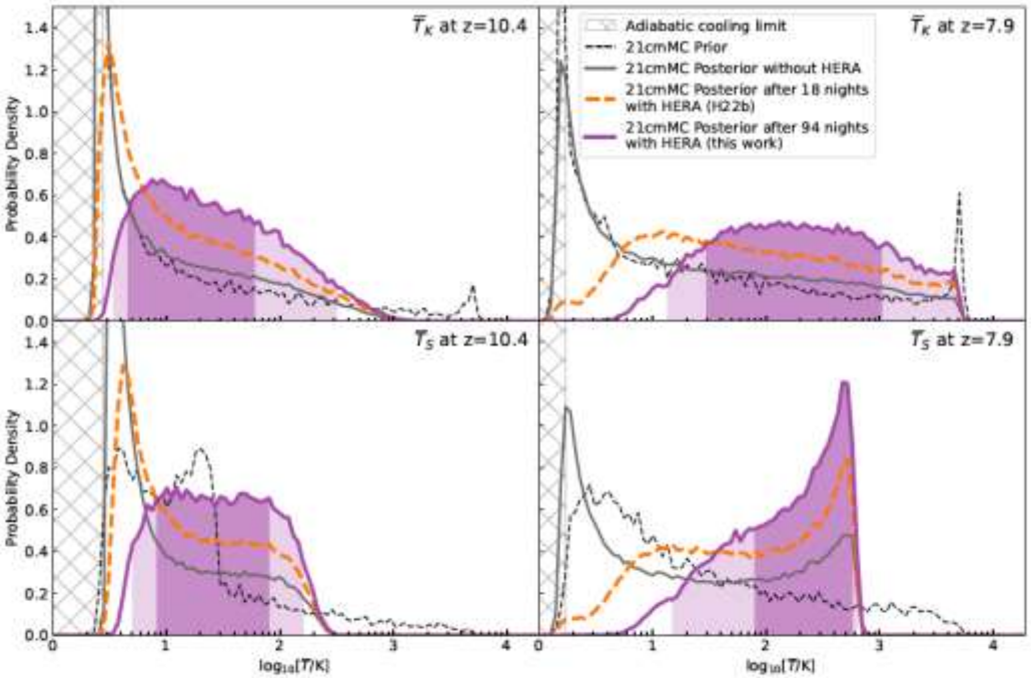
	k (h Mpc^{-1})	Δ^2 (mK^2)
z=7.9	0.192	$(30.76)^2$
z=10.4	0.256	$(95.74)^2$



The HERA Collaboration (2021)

HERA EOR RESULTS 2022

Hydrogen Epoch of Reionization Array (South Africa)
Fully-redundant configuration
Designed specifically to do just this experiment



The HERA Collaboration (2022) – arxiv.org/abs/2210.04912

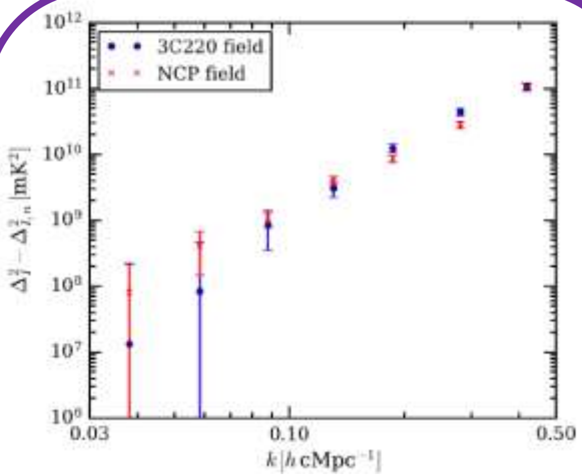
90 nights integration

	k (h Mpc^{-1})	Δ^2 (mK^2)
z=7.9	0.34	$(21.4)^2$
z=10.4	0.36	$(59.1)^2$

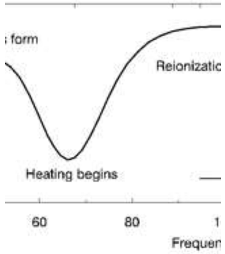
"The intergalactic medium must have been heated above the adiabatic cooling limit at least as early as z=10.4.

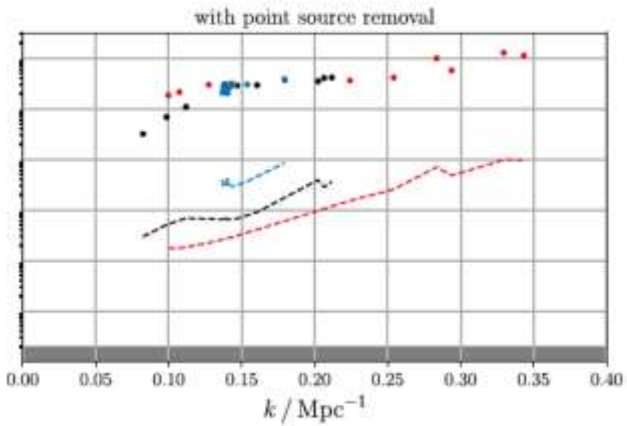
If this heating is due to high-mass x-ray binaries during the Cosmic Dawn … our result's credible interval excludes the local relationship between soft x-ray luminosity and star formation…"

EPOCH OF HEATING…. NENUFAR SOON



Gehlot+ (2019) LOFAR
z = 19.8 – 25.2 (k=0.038 h $cMpc^{-1}$)
14 hours
$\Delta^2 < (14{,}500\ mK)^2$



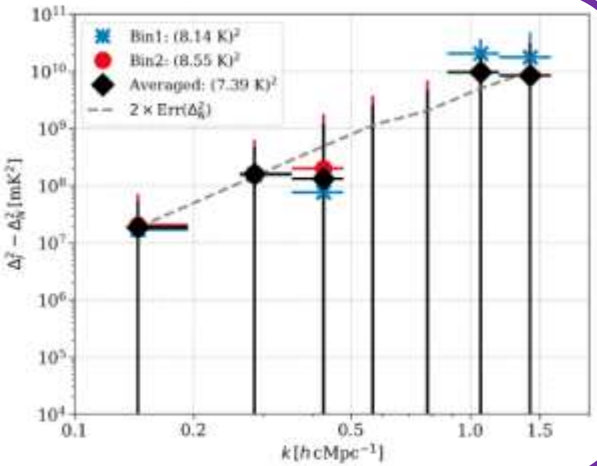


Eastwood+ (2019) OVRO-LWA
z = 18.4 (k=0.1 h $cMpc^{-1}$)
28 hours
$\Delta^2 < (10^4\ mK)^2$

m-mode imaging; spherical harmonic basis

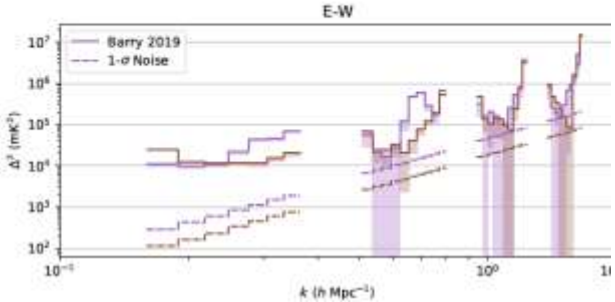
Gehlot+ (2020) AARTFAAC
z = 17.9 – 18.6 (k=0.144 h $cMpc^{-1}$)
4 hours
$\Delta^2 < (7{,}388\ mK)^2$

Gaussian Process Regression foreground removal

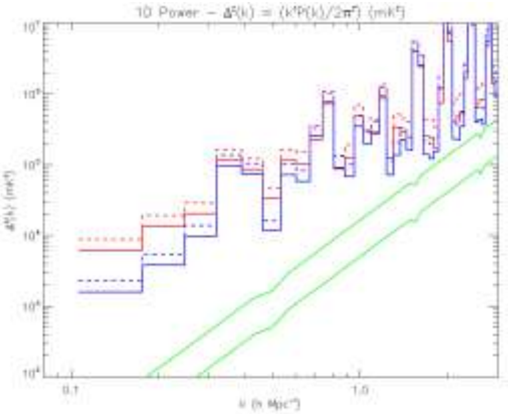


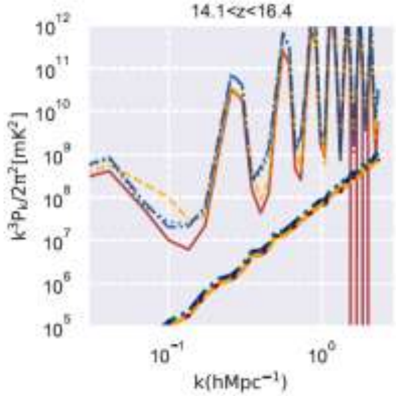
MWA RESULTS: POWER SPECTRA AND LIMITS

Barry et al (2019), Li et al (2019) – z=7.1

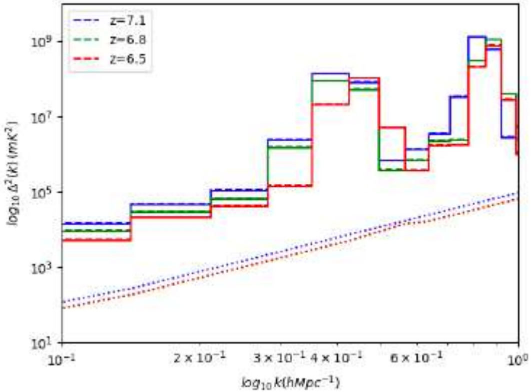


Trott et al (2020) – z=6.5-8.7



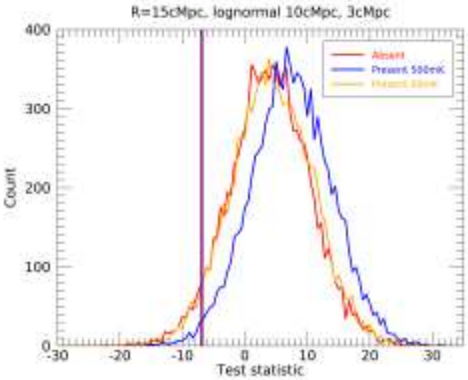


Yoshiura et al (2021) – z=15.2

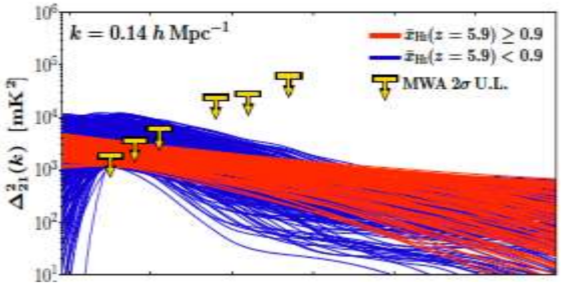


Rahimi et al (2021) – z=6.5

IGM Temperature <30mK at z=6.6
Trott et al (2021)



Astrophysical inference
Greig et al (2021)



MWA RESULTS: HOW DID WE GET HERE?

Results publications

1. 2023MNRAS.521.5120K 2023/06 cited: 2
   New EoR power spectrum limits from MWA Phase II using the delay spectrum method and novel systematic rejection
   Kolopanis, Matthew; Pober, Jonathan C.; Jacobs, Daniel C. *and 1 more*
2. 2021MNRAS.508.5954R 2021/12 cited: 18
   Epoch of reionization power spectrum limits from Murchison Widefield Array data targeted at EoR1 field
   Rahimi, M.; Pindor, B.; Line, J. L. B. *and 28 more*
3. 2021MNRAS.505.4775Y 2021/08 cited: 24
   A new MWA limit on the 21 cm power spectrum at redshifts 13-17
   Yoshiura, S.; Pindor, B.; Line, J. L. B. *and 29 more*
4. 2021MNRAS.504.2062P 2021/06 cited: 11
   Extracting the 21 cm EoR signal using MWA drift scan data
   Patwa, Akash Kumar; Sethi, Shiv; Dwarakanath, K. S.
5. 2020MNRAS.493.4711T 2020/04 cited: 125
   Deep multiredshift limits on Epoch of Reionization 21 cm power spectra from four seasons of Murchison Widefield Array observations
   Trott, Cathryn M.; Jordan, C. H.; Midgley, S. *and 33 more*
6. 2019ApJ...887..141L 2019/12 cited: 80
   First Season MWA Phase II Epoch of Reionization Power Spectrum Results at Redshift 7
   Li, W.; Pober, J. C.; Barry, N. *and 44 more*
7. 2019ApJ...884....1B 2019/10 cited: 110
   Improving the Epoch of Reionization Power Spectrum Results from Murchison Widefield Array Season 1 Observations
   Barry, N.; Wilensky, M.; Trott, C. M. *and 27 more*
8. 2016ApJ...833..102B 2016/12 cited: 172
   First Season MWA EoR Power spectrum Results at Redshift 7
   Beardsley, A. P.; Hazelton, B. J.; Sullivan, I. S. *and 63 more*
9. 2016MNRAS.460.4320E 2016/08 cited: 86
   First limits on the 21 cm power spectrum during the Epoch of X-ray heating
   Ewall-Wice, A.; Dillon, Joshua S.; Hewitt, J. N. *and 62 more*
10. 2016ApJ...818..139T 2016/02 cited: 117
    CHIPS: The Cosmological H I Power Spectrum Estimator
    Trott, C. M.; Pindor, B.; Procopio, P. *and 49 more*
11. 2014PhRvD..89b3002D 2014/01 cited: 178
    Overcoming real-world obstacles in 21 cm power spectrum estimation: A method demonstration and results from early Murchison Widefield Array data
    Dillon, Joshua S.; Liu, Adrian; Williams, Christopher L. *and 16 more*

2023

2021

2019

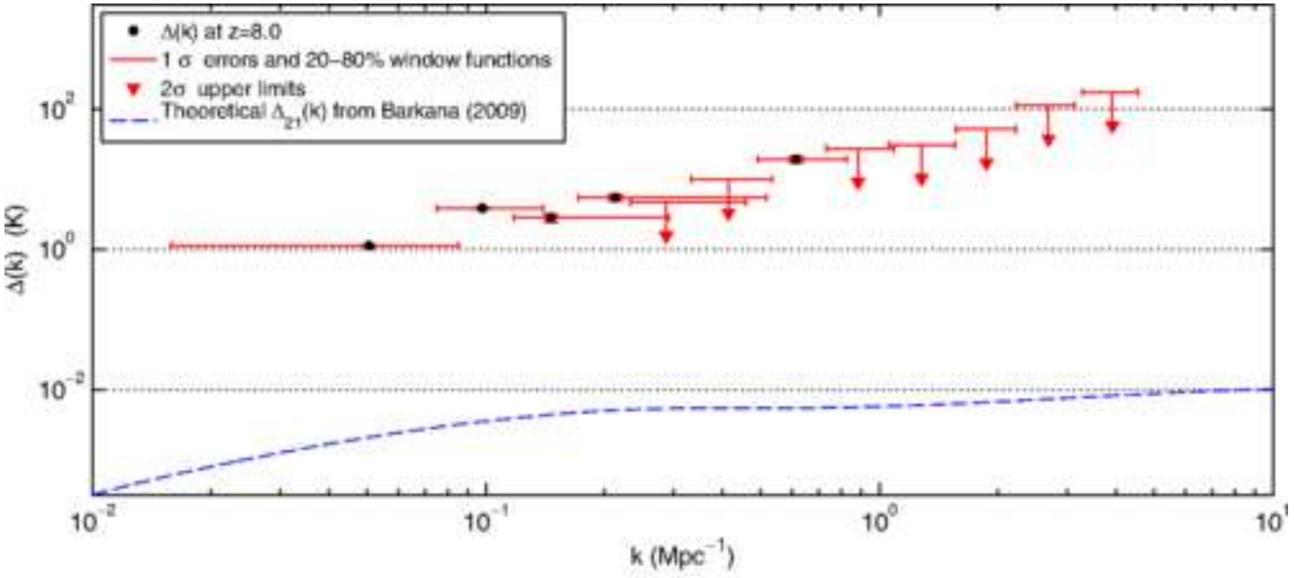
2016

2014

MWA RESULTS: HOW DID WE GET HERE? 2014 32T

ASTRO 3D

32T 2014 Dillon et al



$P < 10^6$ mK^2

$k = 0.07$ Mpc^{-1}

MWA RESULTS: HOW DID WE GET HERE? 2016 128T

ASTRO 3D

Ewall-Wice et al

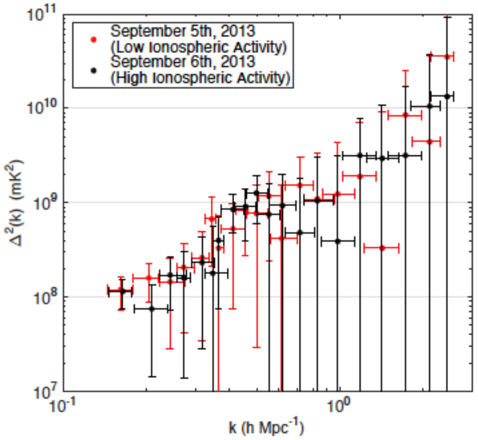
Beardsley et al

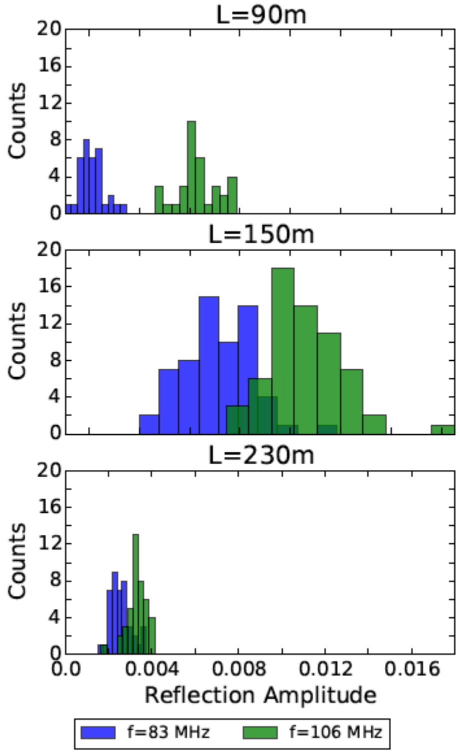
Trott et al

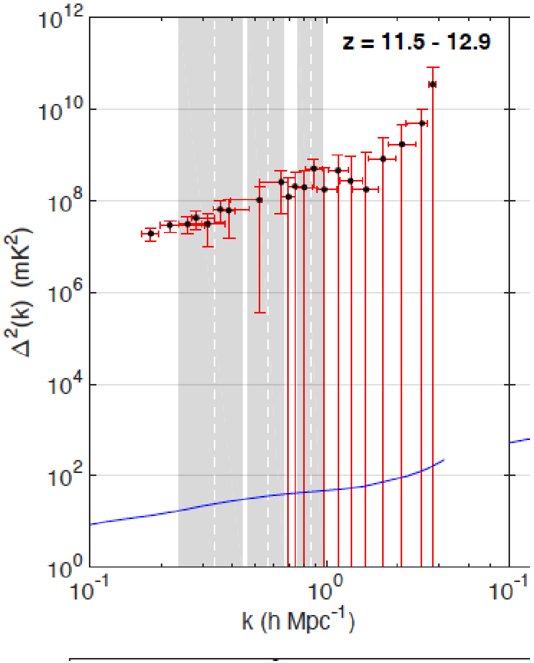
z =12.2

P < 2×10^7 mK^2

k = 0.2 Mpc^{-1}







Ionosphere

Cable reflections

MWA RESULTS: HOW DID WE GET HERE? 2016 128T

Ewall-Wice et al

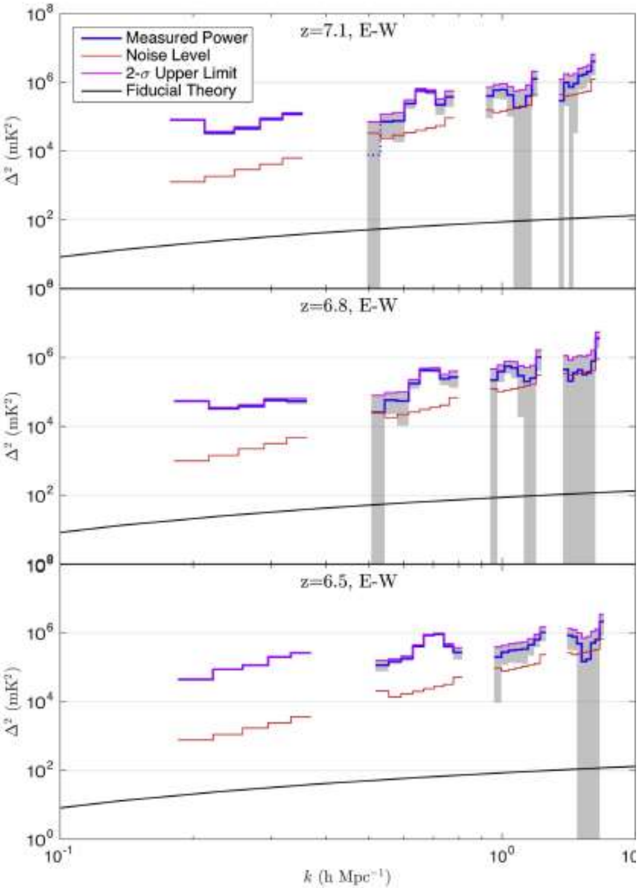
Beardsley et al

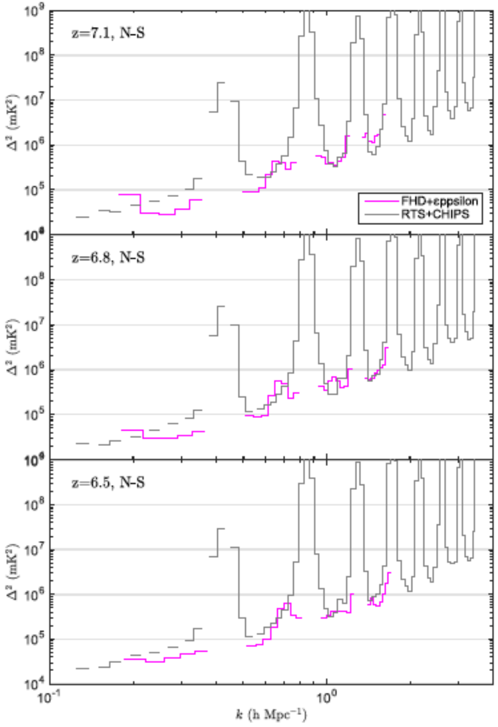
Trott et al

z = 7

P < 2.7×10^4 mK^2

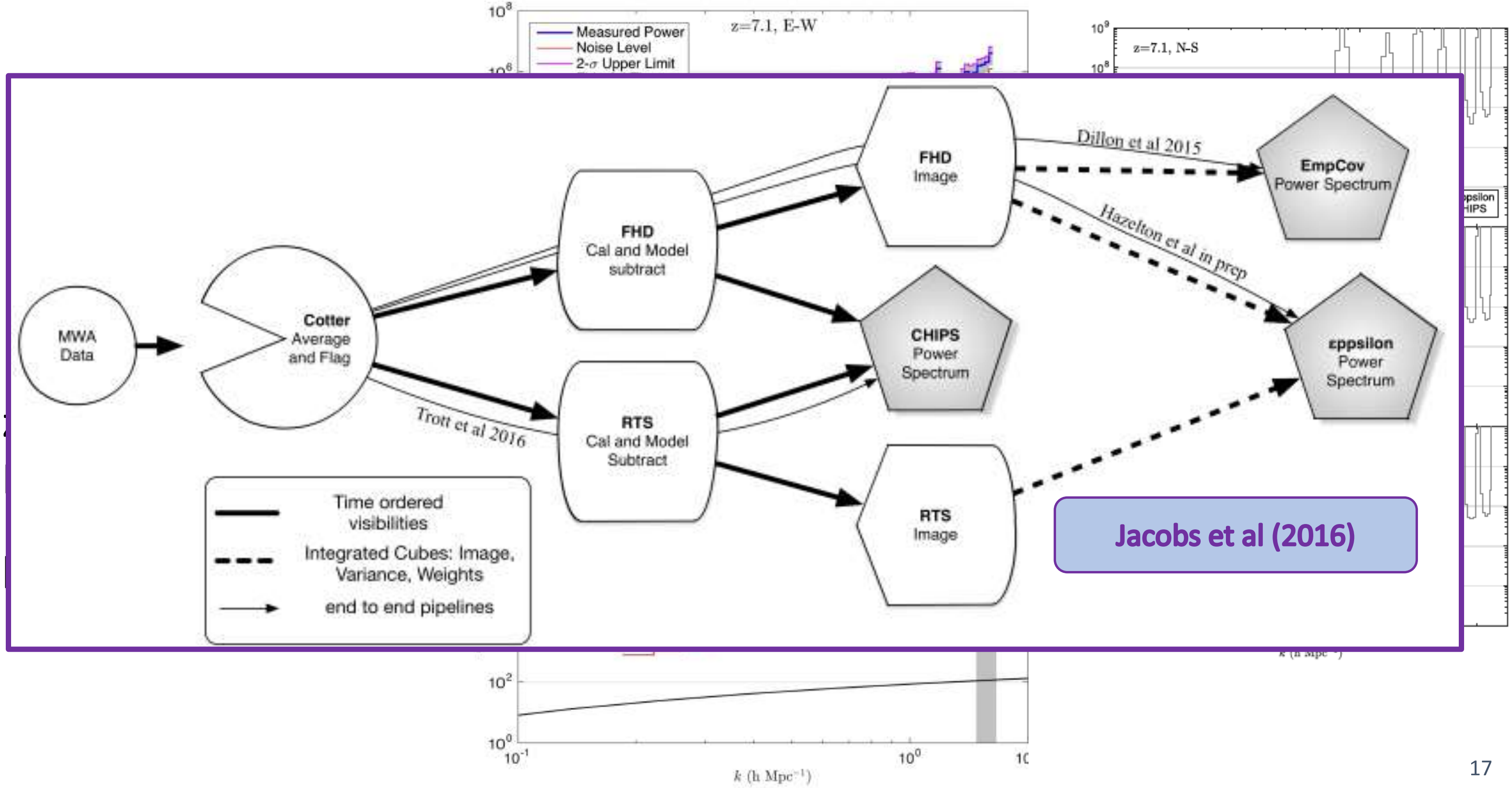
k = 0.27 Mpc^{-1}





Pipeline comparison

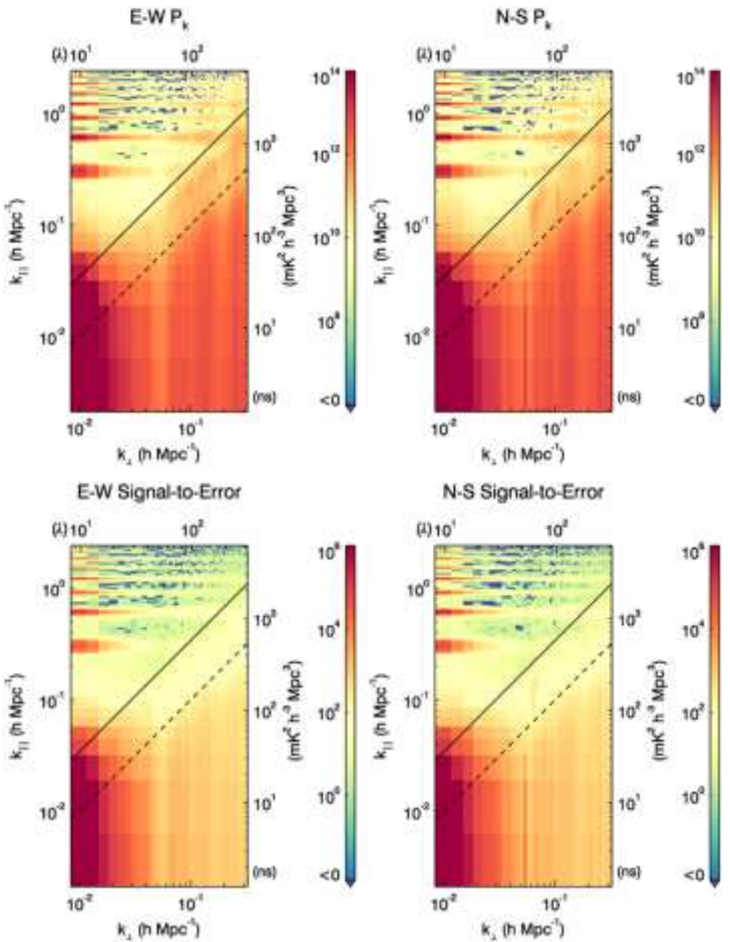
MWA RESULTS: HOW DID WE GET HERE? 2016 128T



Jacobs et al (2016)

MWA RESULTS: HOW DID WE GET HERE? 2016 128T

ASTRO 3D



Ewall-Wice et al
Beardsley et al
Trott et al

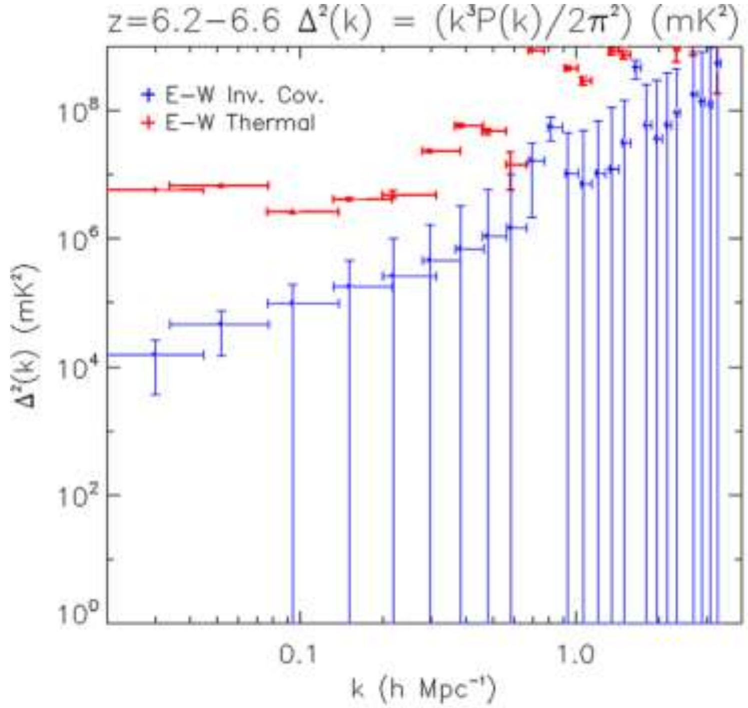
z = 6.5

P < 7×10^4 mK^2

k = 0.05 Mpc^{-1}

Thermal noise weighting

Full inverse covariance (foreground model)



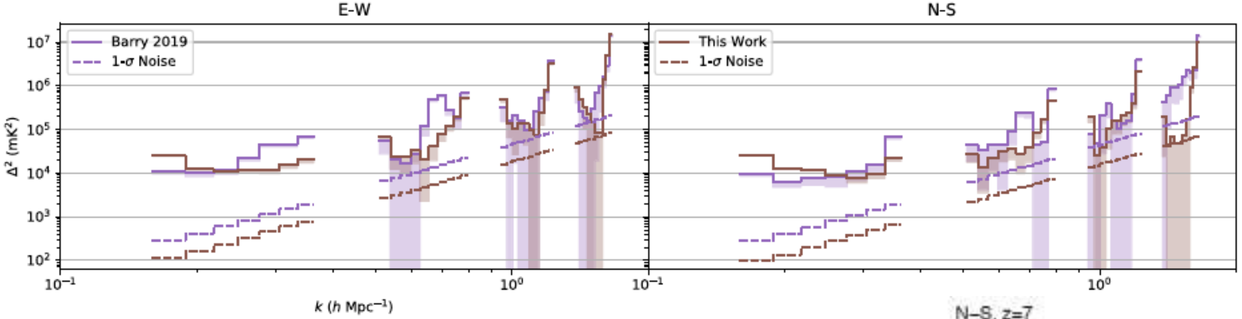
MWA RESULTS: HOW DID WE GET HERE? 2019-23 128T

ASTRO 3D

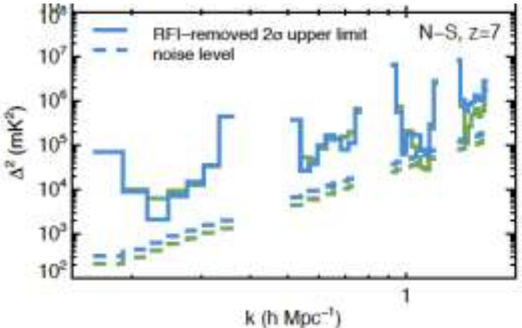
Li et al
Barry et al
Trott et al
Rahimi et al
Patwa et al
Yoshiura et al
Kolopanis et al

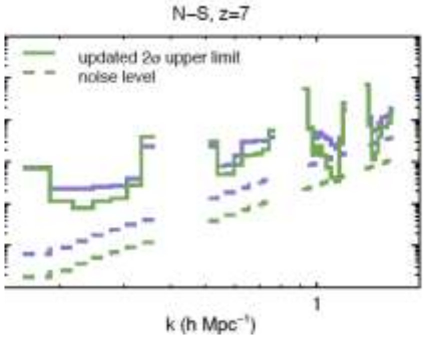
Key features:

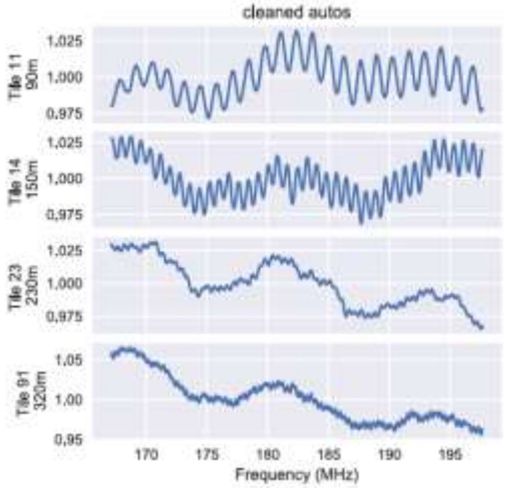
- Phase II data analysed
- Move away from inverse covariance and foreground fitting, and toward FG avoidance
- Re-analysis of data with better calibration, identification of systematics etc
- Analysis of a larger fraction of data
- More redshifts and approaches to statistical detection



Comparisons, re-analysis, RFI removal







Autos to fit bandpass

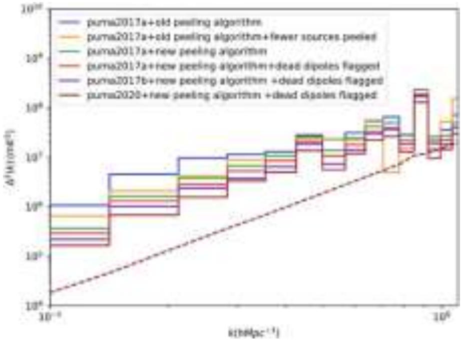
MWA RESULTS: HOW DID WE GET HERE? 2019-23 128T

ASTRO 3D

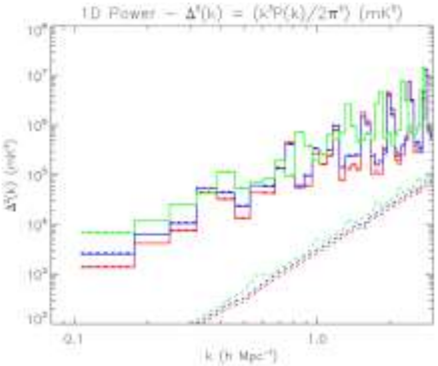
Li et al
Barry et al
Trott et al
Rahimi et al
Patwa et al
Yoshiura et al
Kolopanis et al

Key features:

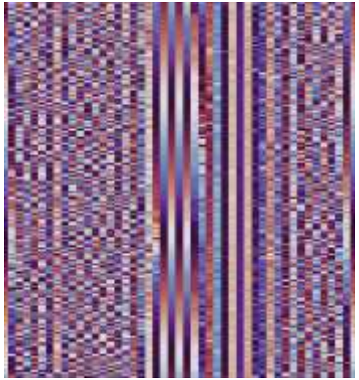
- Phase II data analysed
- Move away from inverse covariance and foreground fitting, and toward FG avoidance
- Re-analysis of data with better calibration, identification of systematics etc
- Analysis of a larger fraction of data
- More redshifts and approaches to statistical detection



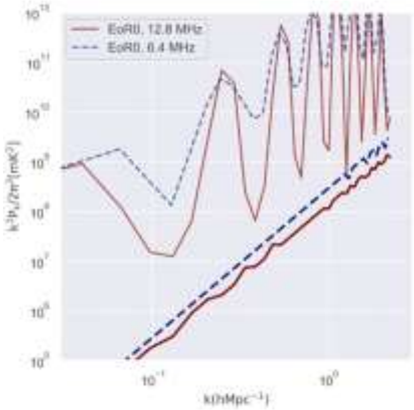
Updated for a model



Deepest integration



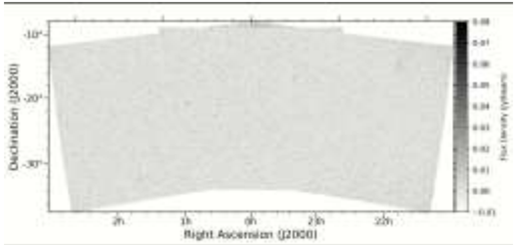
Redundant baselines and negative bias

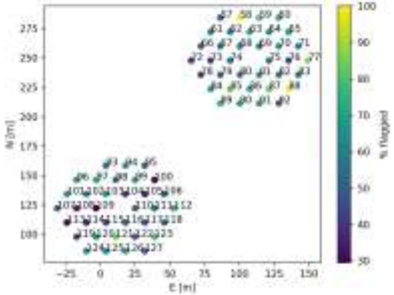


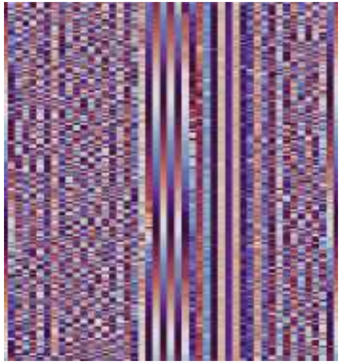
z = 16.5

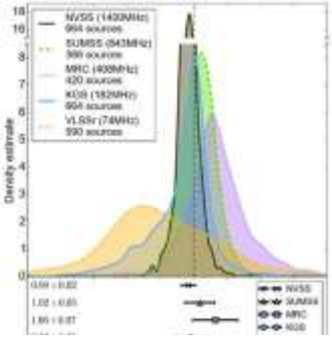
MWA RESULTS: HOW DID WE GET HERE? ENABLERS

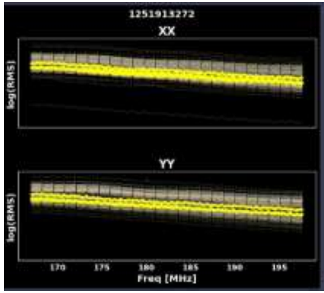
Jordan et al
Li et al
Ewall-Wice et al
Barry et al
Kolopanis et al
Lynch et al
Carroll et al
Line et al
Cook et al
Chege et al
Procopio et al
Wilensky et al
Nunhokee et al

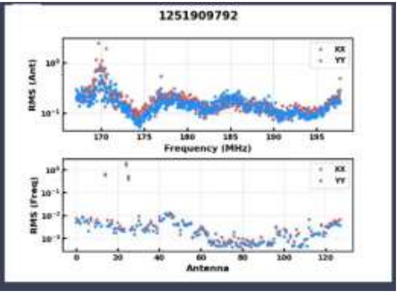


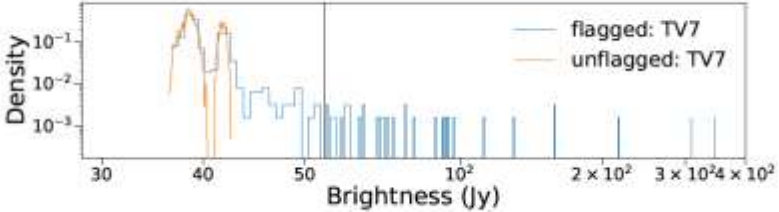


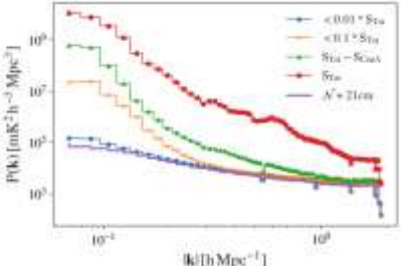


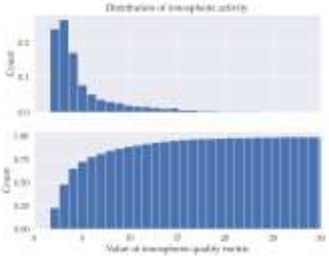




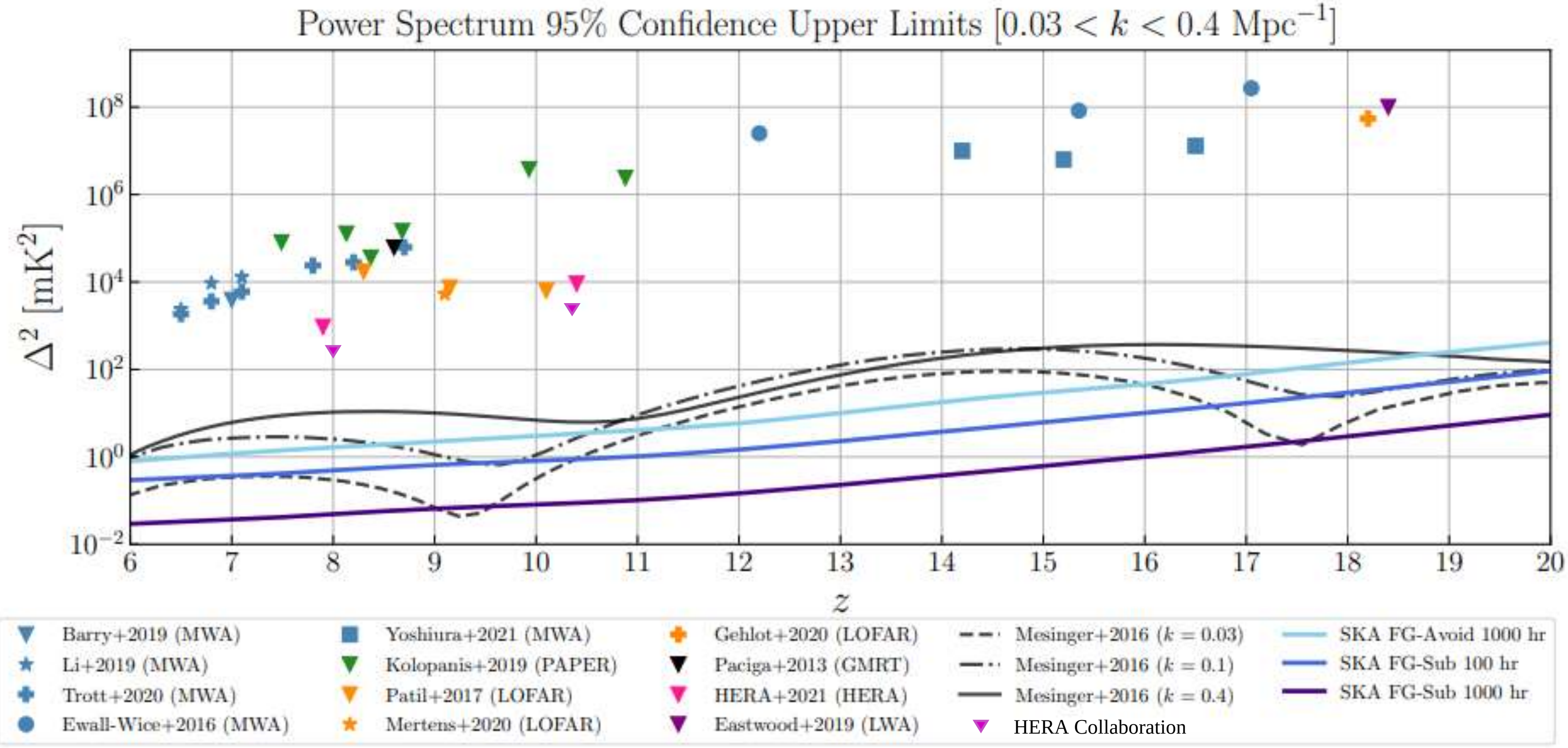






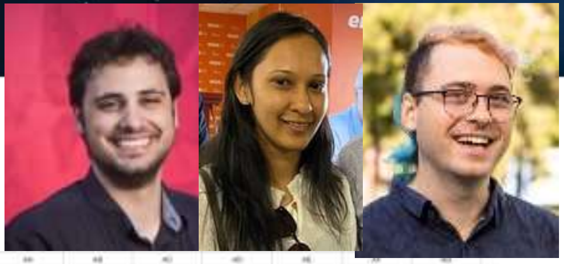


21CM RESULTS



WHERE ARE WE GOING? DATA METRICS!!

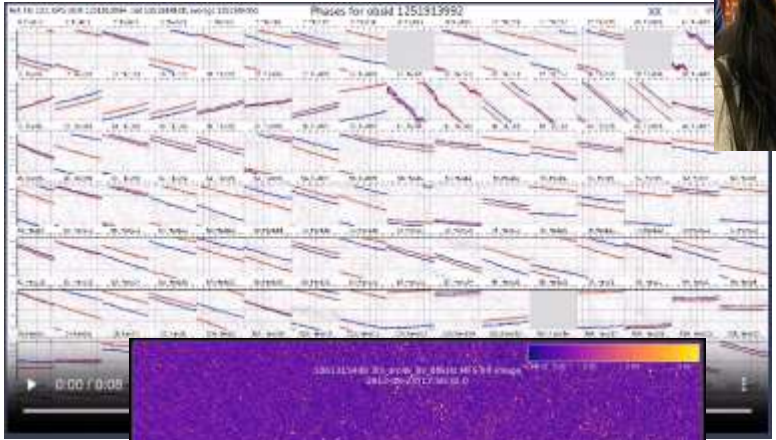
ASTRO 3D

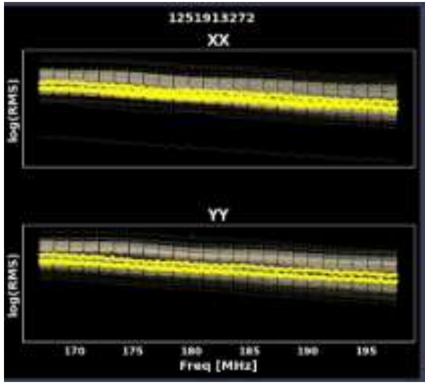


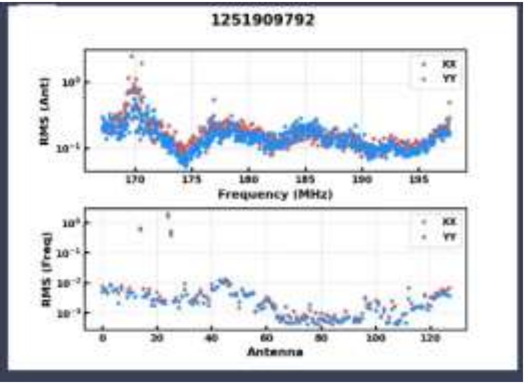
Data quality metrics directly captured via Google docs API

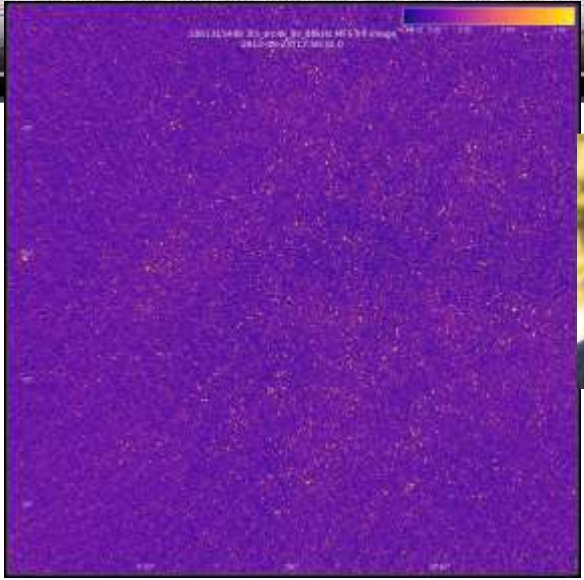
MWAEOR PROCESSING – QA METRICS

- **Huge** range of metadata and quality metrics:
  - Telescope pointing & LST
  - Telescope health
  - Calibration solutions
  - Ionospheric activity
  - Visibility amplitude/RMS/Skew
  - Window/Wedge power from 2D PS
  - XX vs Stokes V image flux for calibrators
  - Stokes V image RMS





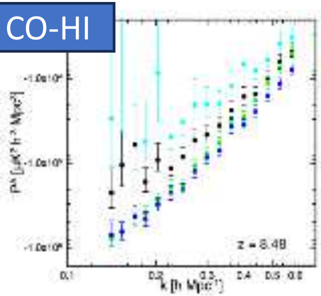




LOOKING TO THE FUTURE: 21CM CROSS-TRACER STUDIES

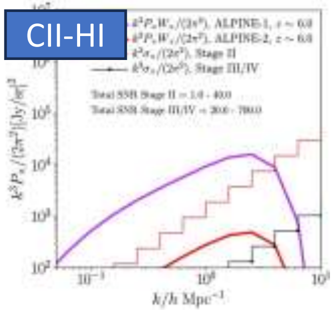
CO Cold molecular gas Galaxy tracer in the EoR Anti-correlated with 21cm	ALMA COMAP – OVRO
CII Dusty SF galaxies	ALMA FYST CONCERTO EXCLAIM
Ly-alpha Saturates easily, end of EoR, LAEs trace ionized regions	Subaru Silverrush X-Shooter VLT MUSE

CO-HI

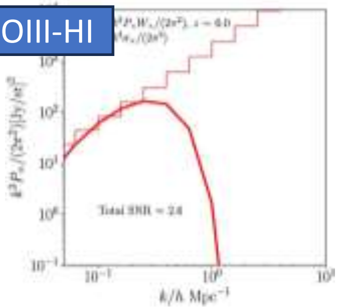


Zhou+ (2021)
Anti-symmetric cross-correlation due to different redshift evolution

CII-HI

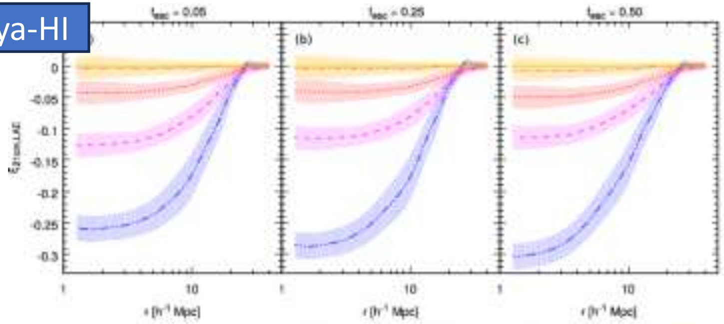


OIII-HI



Padmanabhan+ (2022, 2023)

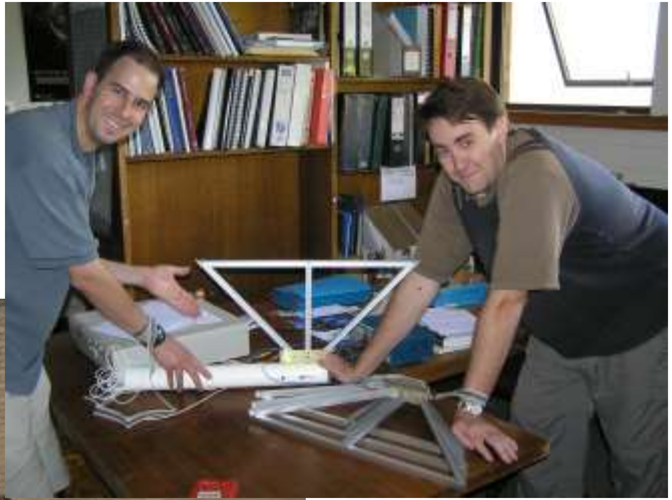
Lya-HI



Hutter+ (2017)

THE EARLY EARLY DAYS: PRE-2013

Courtesy Stu Wyithe

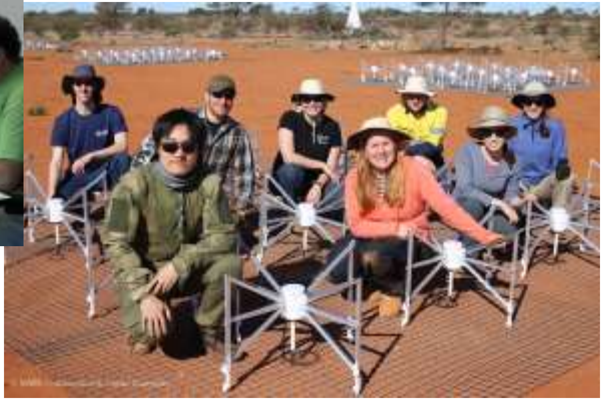


THE EARLY DAYS: PROTOTYPES, 32T AND BEYOND

Courtesy Adam Beardsley

THE PEOPLE! BUSY WEEKS AND SITE TRIPS

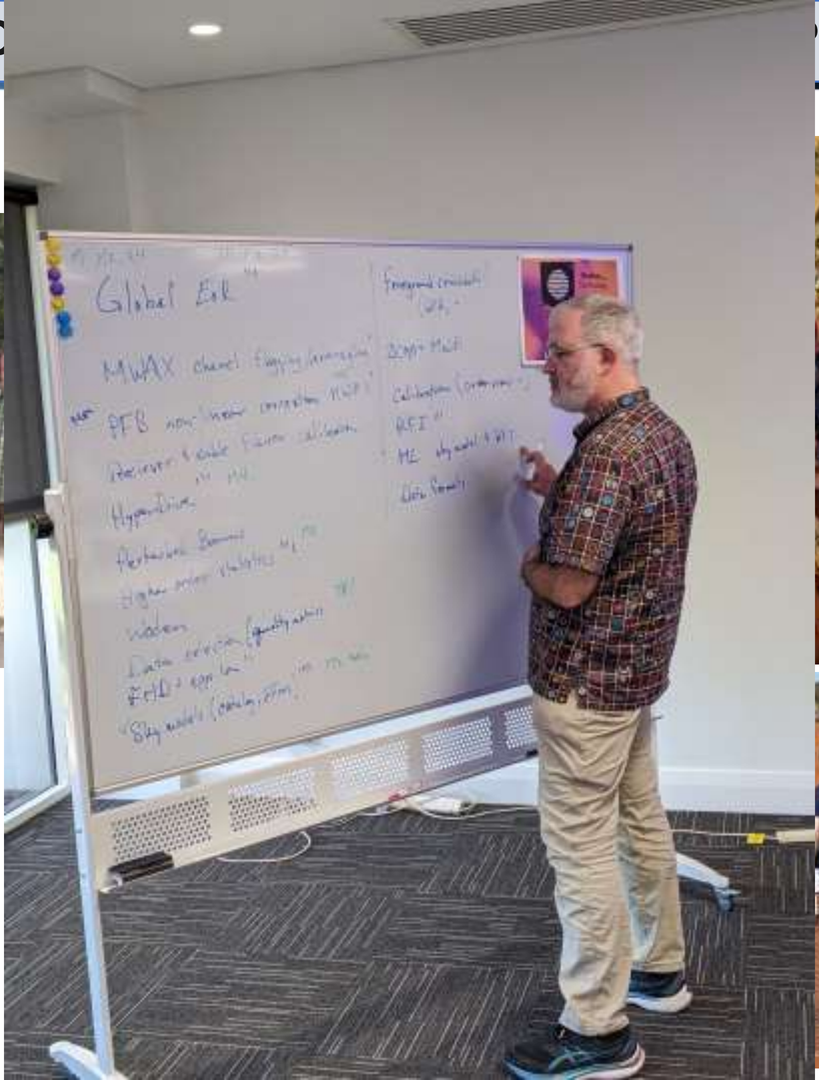
Courtesy Miguel Morales

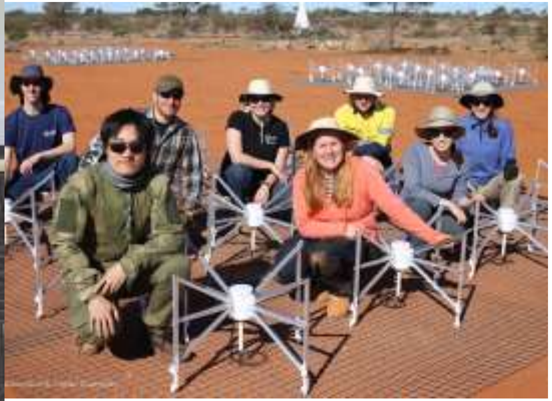


THE PEO … PS

ASTRO 3D

Courtesy Miguel Morales





HOW DO YOU DESIGN AN EOR/CD EXPERIMENT?

Wish list (my personal view, aka what I've learned)

- Station diameter 5 – 30m
- Bandpass – smooth and no holes
- Coax cables - keep them shorter than 10m
- Ability to apodize (shape) beam to reduce horizon source / far sidelobe contamination
- Stable, spatially- and spectrally-smooth (calibratable at the per-channel level) beam response
- Good polarization purity
- Excellent snapshot uv-coverage
- Baselines 15m – 50km (measurement – calibration)
- Place bright/A-team sources at phase centre
- Do not place extended sources down in the beam
- Multi-step RFI rejection (narrowband, broadband, low-level)

Foes:

- Ionosphere
- RFI (narrow, broad, faint….)
- Galaxy near the horizon

Friends:

- Smoooooooooth bandpass
- End-to-end simulations
- Efficient calibration
- Fringe-stopping correlator
- 256T for calibration+EoR goodness

ASTRO 3D

Foes:

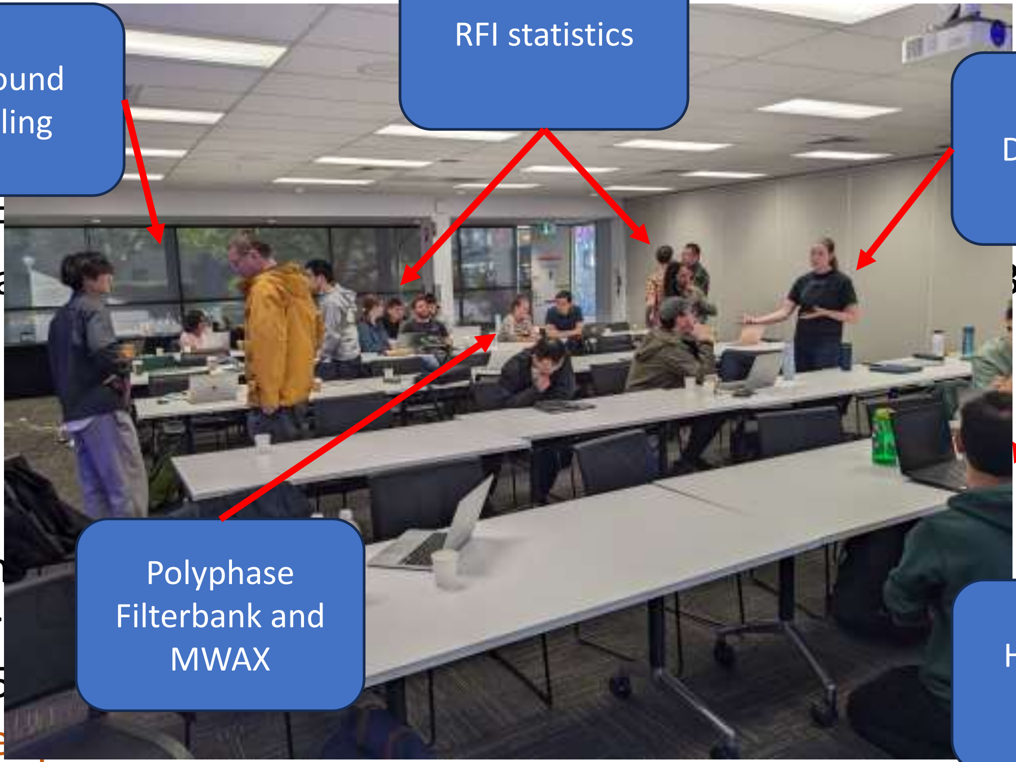
- Ionosphere Good metrics – easier with long baselines
- RFI (narrow, broad, faint….) Jonnie Pober’s group
- Galaxy near the horizon (likely to be absent from 2023B proposal)

Friends:

- Smooooooooooth bandpass – new receivers
- End-to-end simulations WODEN – Jack Line
- Efficient calibration Hyperdrive, PyFHD
- Fringe-stopping correlator MWAX
- 256T for calibration+EoR goodness Have our cake and eat it
- People!

"ONE EOR" TINGAY 2023

ASTRO 3D



- RF
- Ga … ƎB proposal)

Frien

- Sn
- Fr
- 25
- Pe