ASTRODD

O MWA Collaboration & Currin University

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

ASTRU JU

EDGES/SARAS3





LOFAR EOR RESULTS 2020

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 Δ² < (72.9 mK)²

Mertens et al (2020)

HOIKU JU



HERA EOR RESULTS 2021

HOLKO OD

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



The HERA Collaboration (2021)



8



HERA RESULTS 2021

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

		k (h Mpc⁻¹)	Δ ² (mK ²)				
36 hours integration	z=7.9	0.192	(30.76) ²				
	z=10.4	0.256	(95.74) ²				



The HERA Collaboration (2021)

ASTRU JU

HERA EOR RESULTS 2022

HOIKU JU



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

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

90 nights integration

	k (h Mpc⁻¹)	Δ² (mK²)
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

AOIKU JU







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

m-mode imaging; spherical harmonic basis

Gehlot+ (2020) AARTFAAC z = 17.9 – 18.6 (k=0.144 h cMpc⁻¹) 4 hours Δ² < (7,388 mK)²

Gaussian Process Regression foreground removal



MWA RESULTS: POWER SPECTRA AND LIMITS

HOLKO OD

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



Trott et al (2020) – z=6.5-8.7







Rahimi et al (2021) – z=6.5

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



10

10

MWA RESULTS: HOW DID WE GET HERE?

Results publications

ASTRU JU

10	2023MNRA5.521.5120K New EoR power spectra and novel systematic re	2023/06 um limits fro	otted: 2 m MWA Phase II u	ing the delay spectrum method	2023
	Kolopanis, Matthew; Pobe	r, Jonathan C.	; Jacobs, Daniel C.	and 1 more	↑
2 🗆	2021MNRAS.508.5954R Epoch of reionization p- targeted at EoR1 field Rahimi, M.; Pindor, B.; Lin	2021/12 ower spectru	cited: 16 im limits from Mun d 28 more	🗟 📰 🛢 chison Widefield Array data	
20	2021MNRAS.505.4775Y A new MWA limit on the Yoshiura, S.; Pindor, B.; L	2021/08 e 21 cm pow ine, J. L. B. a	cited; 24 er spectrum at red nd 29 more	III III ■ Ishifts 13-17	2021
40	2021MNRAS.504.2082P Extracting the 21 cm Ec Patwa, Akash Kumar, Set	2021/06 DR signal usi hi, Shiv; Dwan	cited: 11 ng MWA drift scan skanath, K. S.	data 🗎 🗎	
5 🖸	2020MNRAS,493.4711T Deep multiredshift limit seasons of Murchison V	2020/04 s on Epoch o Nidefield Arr	cited: 125 of Reionization 21 of ay observations	I III III	
	Trott, Cathryn M.; Jordan,	C, H.; Midgle	y, S. and 33 more		
6 🖂	2019ApJ887141L First Season MWA Phas	2019/12 se II Epoch o	cited: 80 If Reionization Pov	er Spectrum Results at Redshift 7	
	Li, W.; Pober, J. C.; Barry,	N. and 44 m	CU7101		2019
70	2019ApJ88418 Improving the Epoch of Array Season 1 Observa Barry, N.; Wilensky, M.; Tr	2011/10 Reionization ations ott, C. M. and	cited: 110 Power Spectrum 127 more	Results from Murchison Widefield	1
6	2018ApJ.,.833102B First Season MWA EoR Beardsley, A. P.; Hazelton,	2016/12 Power spec B. J.; Sullivar	cited: 172 trum Results at Re 1, I.S. and 63 mom	dshift 7	
90	2016MNPA5.460.4320E First limits on the 21 on Ewall-Wice, A.; Dillon, Jos	2016/08 n power spec hua S.; Hewit	cited: 86 strum during the E t, J. N. and 62 more	D I≣ T poch of X-ray heating	2016
00	2016ApJ.,.818.,139T CHIPS: The Cosmologic Trott, C. M.: Pindor, B.: Pr	2016/02 al H I Power	cited: 117 Spectrum Estimat	lin I≡ ■	Ī
10	2014PhRvD_89b3002D	2014/01	cited: 178		
	Overcoming real-world demonstration and result Dillog, Joshua S.; Liu, Arte	obstacles in Its from earl	21 cm power spec y Murchison Widef	trum estimation: A method ield Array data	2014

32T 2014 Dillon et al

AOTKU JD



 $P < 10^{6} \, mK^{2}$

k = 0.07 Mpc⁻¹

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

AOIKU JU

Ewall-Wice et al Beardsley et al Trott et al







 $\Delta^2(k)$ (mK²)

z =12.2

HOIKU OD

Ewall-Wice et al Beardsley et al Trott et al

z = 7 P < 2.7x10⁴ mK²

k = 0.27 Mpc⁻¹





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

ASTRU JU



 $k (h Mpc^{-1})$

17

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

AOTKU JU



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



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





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

Key features:

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- Re-analysis of data with better calibration, identification of systematics etc
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- More redshifts and approaches to statistical detection



Updated for a model



Deepest integration



and negative bias



MWA RESULTS: HOW DID WE GET HERE? ENABLERS

ASTKU JU

Li et al

Barry et al

Lynch et al

Carroll et al Line et al

Cook et al

Chege et al

Density 10-1 10-2

10-3

30

Brightness (Jy)



1072

1

1.00

184 111128 2 35

Volution of transmitteness (and ity rescale).

108

Ikith Mec-11

21CM RESULTS

HOLKO OD



WHERE ARE WE GOING? DATA METRICS!!

AOTKU JU



Data quality metrics directly captured via Google docs API

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126	109293608	O Press i		0	-25.58	0.00	0 -27	00.	114	13.15	8.12	0.88 2.9	8 178	14	15	8.21	0.78		6 5.00	0.0000002080	1. 1.190	706.3	368040.0	296.6	10.7	507	N 8.4	4 58.78	6.43	0.0000	1,5585	0.009	11
1000	108293820	0 Prass i		0 1	S - 16 54	0.00	0 -27	90	100	4.02	1.12	0.28 .2.8	118	14	11	2.21	0.18		0 100	1 0000002073	0.140	801.8	365476.2	199.7	40.0	6 20	40 8.0	44.00	0.04	0.0000	1,2009	4.007	-
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1401	100293609	6 Press i		0		0.00	0	400	2.17	2.56	8.10	060 37	811 . 1		-	0.01	4.18		6 10	0.0000000184		882.1	303145.0	317.8	8.0		41	T 45.04		0.0078	2.1134	0.007	10
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1965	104/101010	D Press I		0. 14		0.00	0. 42	00	1.1	-	1.00		1 120		25	8.21	10.10		2.00	d (management)	a.arr		Distant, T	292.2		1	10 .4.5	44.00	6.00	0.0070	2 2467	-2.008	1
tave	100053708	C Press 1		0. 11		0.00	0	00	- 12	4.07	2.08	0.13 8.4	D. 128	- AL	-	0.21	4.18		6 5.00	0.000000000	0.104	812.2	second 3	214	6 84		4 43	44.04	6.38	0.0075	2 5482	3.007	10
1965	100235718	6 Press i		0. 1/	-28.55	0.00	0 .27	90	2	-5.54	8.08	0.75, 19.0	125	4	35	8.21	-0.18		100	3.0000001686	0.085	858.7	354578.0	313.5	1. 65	45.5	41	2 41.05	422	1.0078	2.4209	2.004	iii
1970	109293736	A Prass I		0 11		0.00	022	40	2115	-5.04	1.00	0.77 15.5	4 10	1.	20	1.21	0.18	1.0	6 1.0	0.0000001580	0(12)	808.3	3625221	205.0		45.5	41	T. 43.20	+.07	0.0078	2,4004	3,009	
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100	100255718	2 Phase 1		0 - 20	0.11	0.00	0 -27	001		1.00	8.00	0.75 8.3	0 127	14	24	\$ 20	0.18		1.0	d obtoor ma	1 Aver	10.7	TRANSIT OF	- 227.4	14.5	45.0	10 10.0	0.4	60.00	1.007	TRIDE	4.004	80
1280	108255791	2 Phase I		02 40	-	0.00	0 27	100		4.00	1.00	0.77. 18.8	12	1	11	1.00	0.18		11 11	0.0000001775	EXCHEN	100.0	ITETRO.	317.1	11.7		15 77	T 15.40	1.11	0.0077	1 8124	4.005	50
101	109295803	2 Prase 1		0 2	a	0.00	0 -00	40	12	200	1.10	0.76 18.3	127	- A	25	4.30	0.18		12 60	0.000000-0070	1.8.81	601.2	NACES OF A	218.0	1 11.2	54.1		1 . La m	1.20	0.0077	1.7785	4.002	M
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1210.	108283828	0 Phase I		0 11	1.01.75	0.00	0	ani i	- 12	4.00	8.10	0.17. 18.4	1. 127	1	22	8.30			1 3.50	1.0000001040	1.040	705.3	TTUNNA.	219.4	10.0	1. 101.0	45 4.5	81.42	6.53	6.0077	1 5000	3.008	80
1278	100293840	0 Prass 1		0.44	-26.75	0.00	0 -27	100	10.0	448	1.14	0.85 4.5	9, 927	14	25	8.20	4.18		4 8.96	100000-000	5.677	872.5	INCOME AND INCOME.	101.0	90.1	1 50.0	4 13	0 19.03	4.11	0.0078	2 2040	1.007	76
1210.	1093822008	0 Phase I		0	-35.55	0.00	0	-00	214	11.17	8.94	0.88 7.1	2 127	14	25	8.20	0.16	1.000	1.00	a debracatory	1.942	816.2	Minines.c	100.0	11.4	54.9	10 2.1	1 24.11	7.51	1.0000	1,3965	0.004	1
1280	104102204	R Phase I		0 21	te da la	0.00	0 .07	100	21-1	12.14	8.74	0.88 7.7	8 127		25	1.20	0.18	18	6 8.00	a cederation in the	0.130	738.8	proven to	204.9	1 10.00	1		a 171.40		0.0080	1.8087	0.007	14
1271	100301238	5 Phase I		0 23		0.00	0	80	-8	444	8.15	1168 4.5	4 127	19	25	4.20	10.10		1 2.00	a canadata	0.111	728.8	BOTHET D	347.0	70.4			1 84.92	4.21	0.0000	1.8016	-8.004	
1110	100332248	5 Phase I		0	-21.00	0.00	0 -22	90	10	415	8.14	0.00 8.1	4 177		11	1.20	0.18		6 10	-	0.130		308540.7	312.4	10.1			0 48.81	5.00	0.000	1,0107	0.004	
1110	104302269	0 Prase i		0 .11		0.00	0 27	190		4.00	3.94	0.82 4.5	4 127	1	24	1.00	0.18		6 1.00	0.0000002180	12.134	754.8	368781.0	316.0	4 0.T	1 401	H 33	48.00	5.01	0.0000	1,0000	4,065	
1480	1093022773	i Phase I		0 44		0.00	0 -40	00	-2-	4.10	8.94	0.83 4.8	0 120	1	11	1.00	0.18		6 6.00	a oppropriate/o	0.000	712.8	307060.0		4.5	4		47.04	5.55	11.0000	1.8077	4.007	12
1091	1203012008	i mate i		0 41		0.00	0. 07	100	12	1.	2.58	1101 1.0	E 127	1	28	1.01			1 1.00	IL COLOROD VIEW		-	BITAL	238.4		1 213	12 8.0	47.22	4.04	1.0000	2 0497	8.000	11
1000	108382292	5 Phase I		03 83	II - 28.46	0.00	027	00	- 223	100	1.12	0.62 47	8. 177	1	-	0.20	0.18		1.00		1.000	111.0	100003.2	104.0				T 48.43	4,87	1.0000	2.1784	2.008	1
1285	1003302310	6 Phase I		0 11		0.00	0 -27	190	100	4.56	2.65	0.65 1.1	127	1	25	6.30	-0.18		6 1.00	1.0000000085	A.190	-	365257.0	008.0	7. 0.7	-	41 4.1	45.50	4.01	0.0078	2,3634	2.004	87
1284	109302329	4 Phase I		0 11		0.00	0. 42	100	211	4.06	8.12	0.64. 11	1 127	14	28	8.30	.0.18		6 1.90	0.000000-084	4.131	104.2	THE PARTY OF	230.4		1 453	15 4.4	45.04		0.0079	2 3 344	0.000	10
1 and 1	108302214	e Phase I		0. 14		0.00	0 -02	00	2	4.54	8.52	0.58 2.9	8 127	1	23	\$ 20	10.78	1.8	1 2.00	1 000000 mm	6.135	817.2	-	122.0	r	1 843	it 43	44.00	4.01	0.0078	2,6360	-0.006	1
1280	10830348	E Prese I		0 23	11.08.00	0.00	0 . 27	100	2	4.08	8.12	0.88 2.9	8 127	1	25	8,20	a 18	18	1 1.00	4.0000001785	0.074	800.8	364129.7	75418	84	e	12 42	44.78	4.21	0.0015	2.4714	4.007	12
100	100502356	2 Prese i		0 21	-28.91	0.00	0 -27	90	110	4.52	8.52	0.85 3.1	4 127	- a 1	35	8.20	. 0.18		6 8.00	0.0000001485	0.000	218.3	360480.0	030.5	6.0	1 44.2	4.5	6 44.78	4.13	0.0019	2.5752	0.007	21
1988	100302271	2 Phase I		0 10	6 -15 5	0.00	0 -27	190	2.5	4.00	2.14	0.72 81	ti 127	+	41	1.20	12.18	1.1	6 100	3.0000001080	1.111	718.2	360001.6	212.0	8.4	40.3	9 43	43.74	4000	0.0078	2,8145	0.000	44
1.080	109302200	2 Phase I		0200	11 26.16	0.00	0 - 22	60		0.02	2.16	0.73 8.6	127	1	35	1.00	0.19		1/1 4.00	110000001787	10,004	BOLD	1100017	215.0	11.0	1 864	N 33		1.04	0.0079	1,4740	-0.006	
1899	1093021408	O'Phaia I		1 24		t1.00	0	100	. 6 3	2.18	1.18	11.78 18.7	1 127	14	28	4.21	Contract of the local division of the local		(1)	A CONSIGNATION	LUIST	806.2	TT2KOLE		E	E 803	18 24	1 66.00	- fait	1.0078	1.8480	0.007	11
1291	108362426	i man i		0 21	2 28 78	0.00	027	(a)	_15	4.99	8.07	0.29 1.7	9 127	11	15	\$.20			1 1.00	1.0000001724	111000	718.0	I STRAIGHT	817,0	E 11.1	E 162	M 17.1	04.22	7.14	0.0019	1,7140	4,004	0
1860	109422829	6 Prese I		0	1.05.00	0.00	0 -27	90)	200	10.14	8.07	0.55 1.5	0. 127		12	1.00	4.0	1.1.1	1.00	0.0000000445	0.015	858.5	392145.5	352.0	9.2	1 12.0	8 73	0 52.00	100	0.0000	C 9,3679	4.004	0
1448	109422843	e Prase i		0	45.00	0.00	022	.00	201	12.04	8.07	0.00 17	2 127		23	\$.30	0.18	2 4	6 6.00	0.0000000485	4 0.000	801.5	301050.1	200.7	10.0	7: III.	8 68	10.00	6.01	0.0078	13000	1.004	
1214	109422858	A Phase I		0 4)		0.00	0 42	400	-214	12.14	8.07	0.81, 2.2	12 127	1.	25	0.00		1	1 L M	A CONSTRUCTION	6. 6.68	671.1	and the second	388.11	10.0	1 . MA	LT 4L1	1. 48.77	6.71	1.0001	TAUMA	-2.00	1 C
tint	109422906	C Phase 1		0 .23	28.40	0.00	0	00	1	0.04	8.07	0.88 1.8	8 177	-9F	22	8.20	4.18	1	0 0.00	0.0000002317	0.824	ST1.8	318101.0	288.0	70.1	1. 49.0	0 83	6 48.49	0.00	0.0080	1,7138	3.000	
1,796	109422878	E Phase i		013	28.55	0.00	0 .22	.90	2	4.94	1.05	0.62 23	0 127	1	35	8.20	.0.18		0 10	0.000002184	126.0	807.8	308299.0	300.0	9.71	472	5 55	8 47.71	5.58	8.0078	1,7912	4.007	15
1487	109423891	2 Phase I		0 -1.	8 -35.55	0.00	0 .27	190	1	-8.60	1.00	0.57 1.5	8 10	1	11	8.20	0.18	1	0 1.00	0.0000002327	3 4.777	878.4	307967.4	306.7	9.3		60 5.1	0 46.01	5.30	0.0079	1.8002	3.007	15
1740	109422903	2 Prase 1		0 44	a 46.56	0.00	0 -27	taq:	2	4.10	\$.00	0.08 . 3.5	E. 127	13	25	2.20	10.10	1	6 8 DE	3 3000007911	0.003	101.1	2003055	211.1	0.2	46.7	12 1.1	E 46.74	8.24	p.0078	2.0127	4.005	41
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MWAEOR PROCESSING – QA METRICS

HOLKO OD

•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





ASTRU JU



THE EARLY EARLY DAYS: PRE-2013

ASTRU JU

Courtesy Stu Wyithe



THE EARLY DAYS: PROTOTYPES, 32T AND BEYOND

AOTKU JU

Courtesy Adam Beardsley



THE PEOPLE! BUSY WEEKS AND SITE TRIPS

ew.

AOTKU JU

Courtesy Miguel Morales



THE PEC

AOTKU JU

Courtesy Miguel Morales





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

• Station diameter 5 – 30m

HOLKO OD

- 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)

"ONE EOR" TINGAY 2023

Foes:

AOIKU JD

- 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

Foes:

HOLKO OD

- 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:

- Smooooooooth 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



