The Hydrogen Epoch of Reionization Array (HERA):

A next generation experiment for reionization studies

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for the HERA Collaboration

Outline

- The Epoch of Reionization and the Dark Ages with the 21 cm line
- Designing a telescope exclusively for 21 cm studies
- The path from PAPER (and MWA) to HERA
- Science with HERA

HERA Science Goals

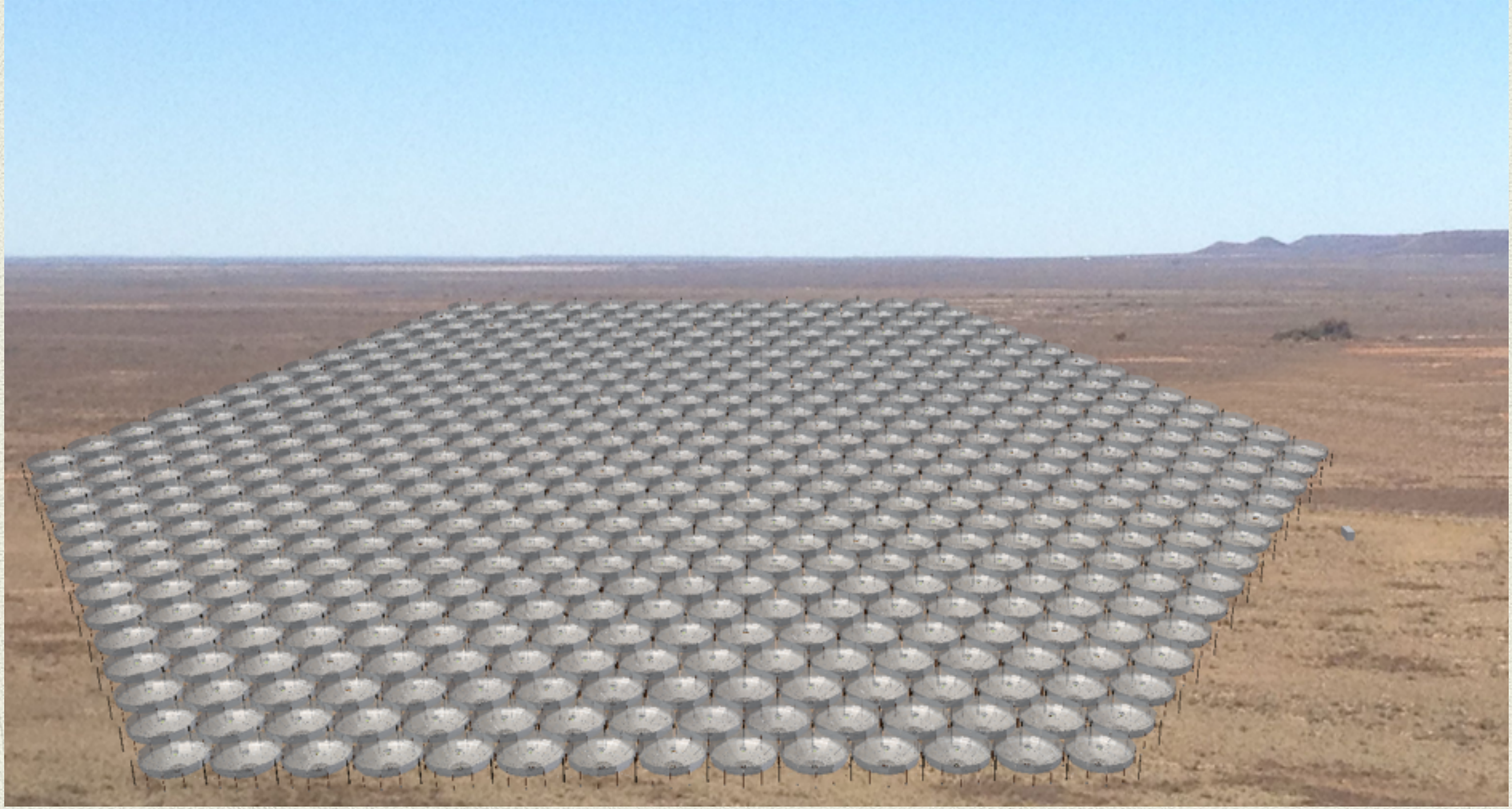
- Probing the history of the Universe via the 21cm emission from HI
- Focus primarily on the Epoch of Reionization (EoR), with capacity for probing earlier times
- Key Questions:
  - What objects first lit up the Universe and reionized the neutral IGM?
  - Over what redshift range did this occur?
  - How did the process proceed (wrt heating, feedback, scale-dependence)?
  - How did this lead to the large scale galaxy structure seen today?

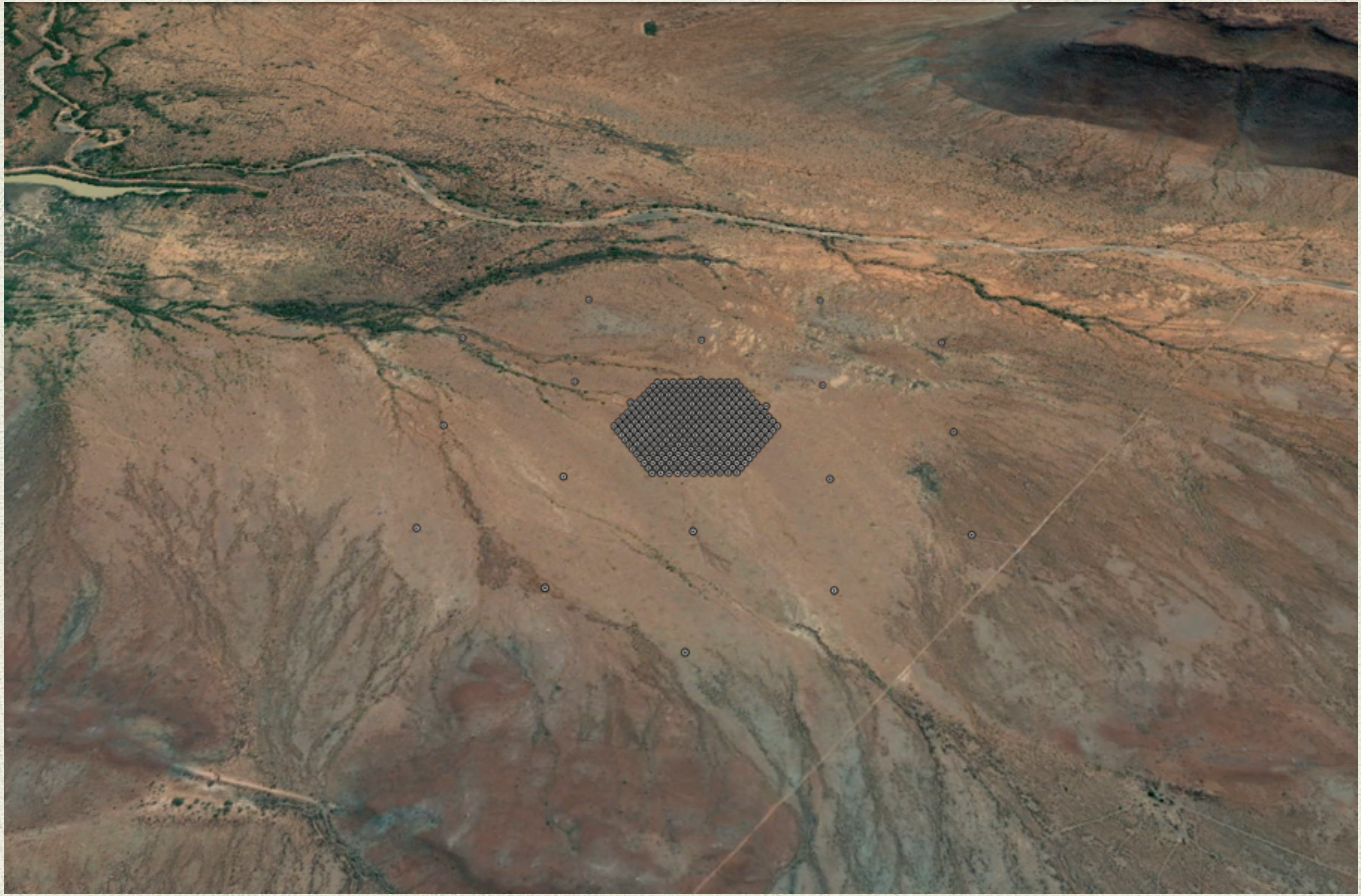
The HERA Approach

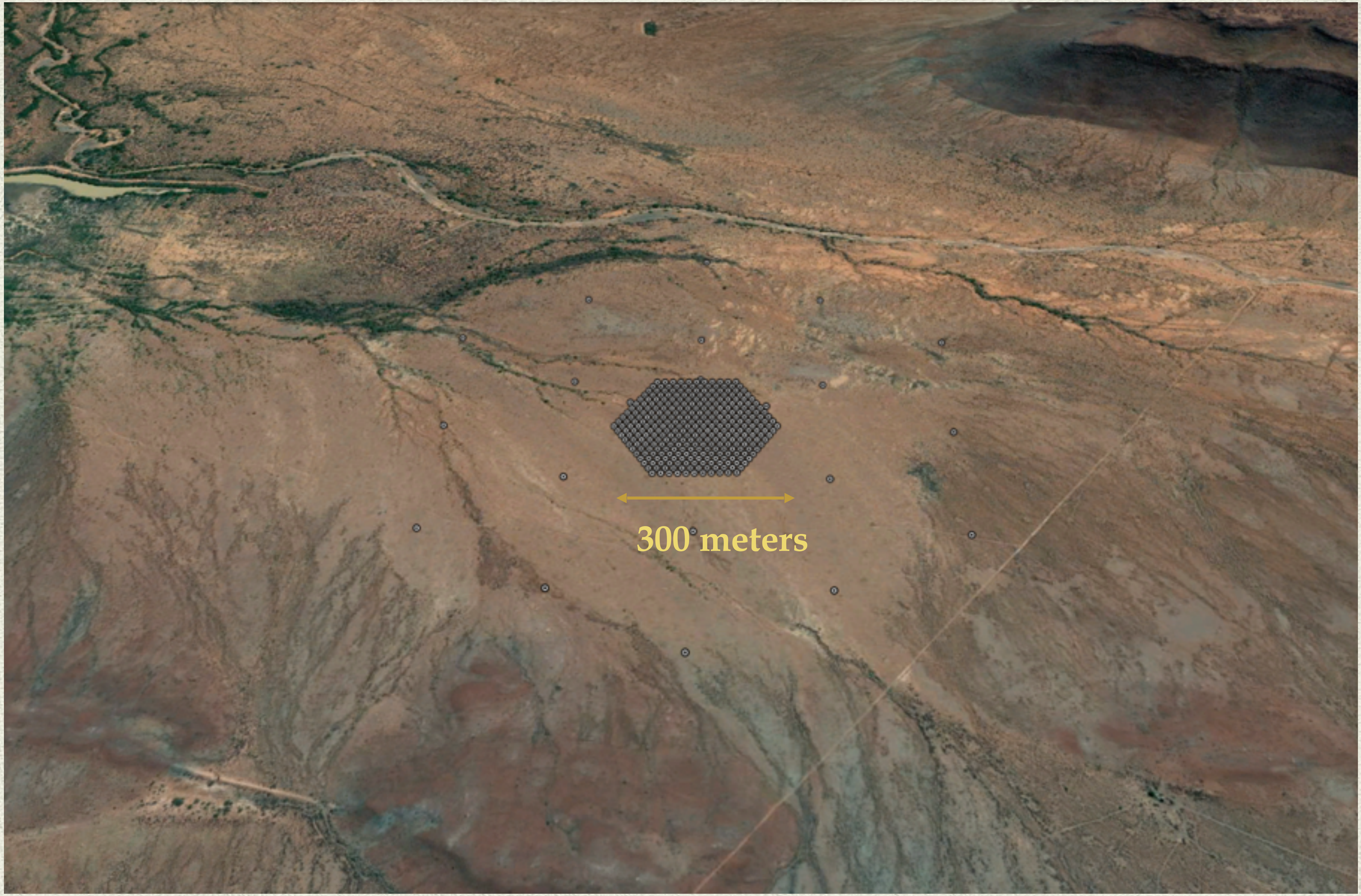
- HERA is a focussed experiment, not a facility
- Designed to increase sensitivity greatly in the near future
- Obtain a robust detection and characterization of EOR
- Continue development of multiple techniques (including the delay spectrum (talk by Liu) and imaging)

What will HERA be?

- Collecting area of order Arecibo (40,000 m^2)
- Bandwidth: 50 – 250 MHz digitized, ~100 MHz correlated
- Located in the Karoo Desert of South Africa near the future SKA-mid and current MeerKAT arrays
- 331 hexagonally close packed 14-meter parabolic dishes with dipole feeds (full Stokes) with 21 outriggers; 352 total antennae. This will be done in two stages, with 127 elements using existing PAPER elements, and 351 with an upgrade to the signal chain with digitization close to the antenna
- A HUGE leap forward in sensitivity, redshift coverage and imaging over PAPER, with proven technology and a staged instrument and analysis build-out






300 meters

What is HERA *right now*?

- FUNDED! by US NSF Mid-Scale Instrumentation Program for a pilot instrument. One of 6 selected from field of 38 from across astronomy.
- International collaboration (US, SA, UK, and others)
- We are targeting a 19 element array by September 2015, and 37 elements by September 2016, which will have > 5 times more sensitivity than PAPER

Berkeley
PI: Aaron Parsons
David DeBoer
Adrian Liu (BCCP, now Hubble, Fellow)
Dan Werthimer
Zaki Ali
Carina Cheng

Arizona State University
Judd Bowman
Danny Jacobs (NSF AAPF Fellow)
Adam Beardsley

Cambridge / NRAO
Chris Carilli
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Nima Razavi-Ghods

University of Kwa-Zulu Natal
Cynthia Chiang
Jon Sievers

UCLA
Steve Furlanetto

MIT
Jackie Hewitt
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Josh Dillon
Aaron Ewell-Wice
Abraham Neben
Jeff Zheng

Stellenbosch University
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University of Washington
Miguel Morales
Bryna Hazelton
Patricia Carroll
Nichole Barry

University of the Western Cape
Mario Santos

Scuola Normale Superiore SNS, Pisa
Andrei Mesinger

Brown University
Jonnie Pober

Recall the challenges

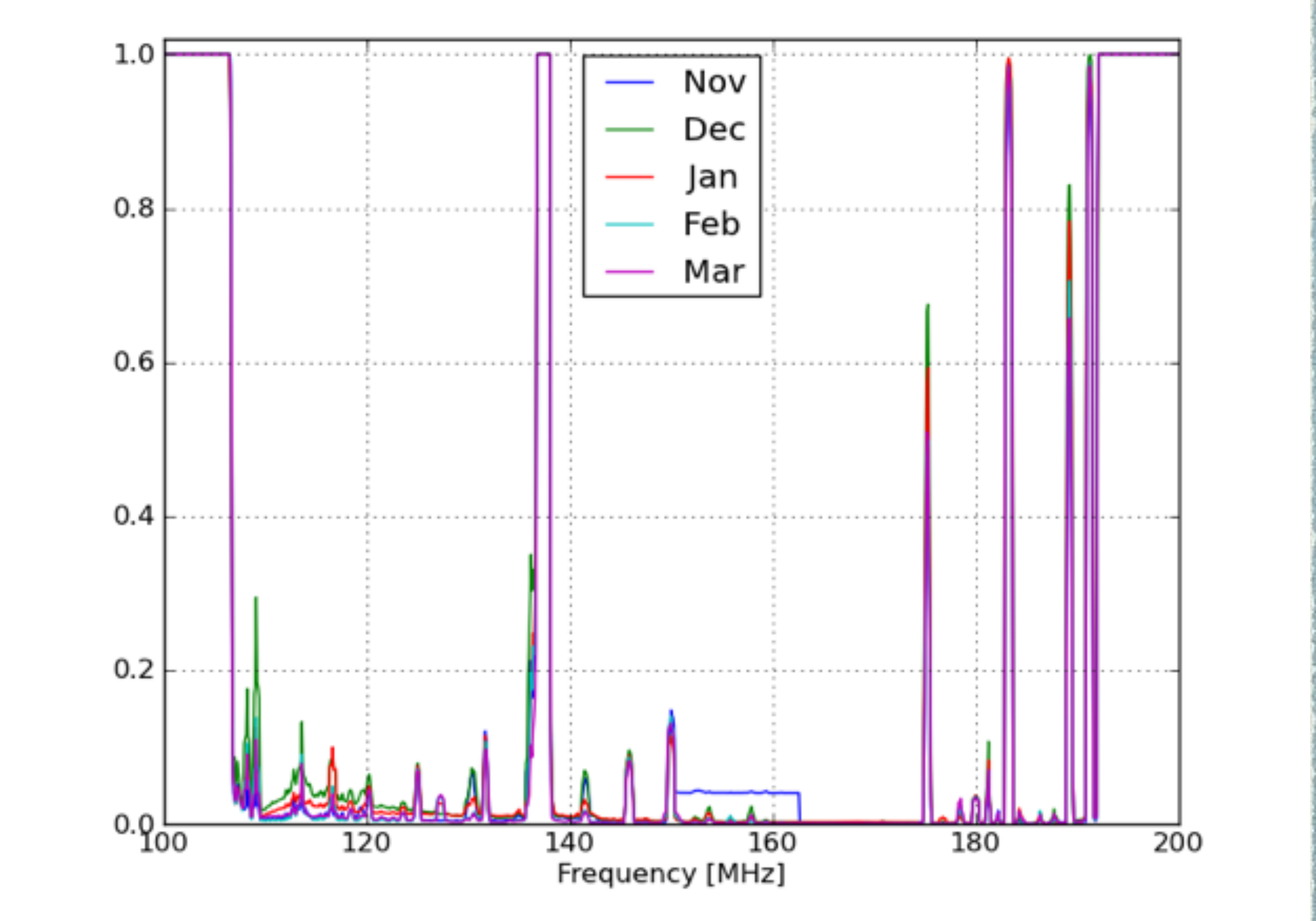
- Thermal noise (sensitivity)
- Strong foregrounds, including polarized foregrounds
- Radio frequency interference
- Instrument calibration and stability
- Data analysis of large, complex data set: we reduce 200 TB to ~100 numbers plus error bars

Design choices: frequency coverage

- The sampled range is necessarily larger than the useful range, but we expect to be able to use 70 MHz (z=19.3) to 220 MHz (z=5.5).
- This allows us to probe to when (H) reionization is expected to be fully over (giving a null result), and also to probe *before* reionization
- Importantly, the full frequency coverage is sampled simultaneously (no sub-bands, no mixing): full frequency coverage is available for foreground analysis, and for scientific analysis

A little reality: RFI is not zero

- We will lose some frequency coverage to satellites, especially 137 MHz (z=9.4)
- The contamination of the FM radio band is being explored



Design choices: number of antennas and collecting area

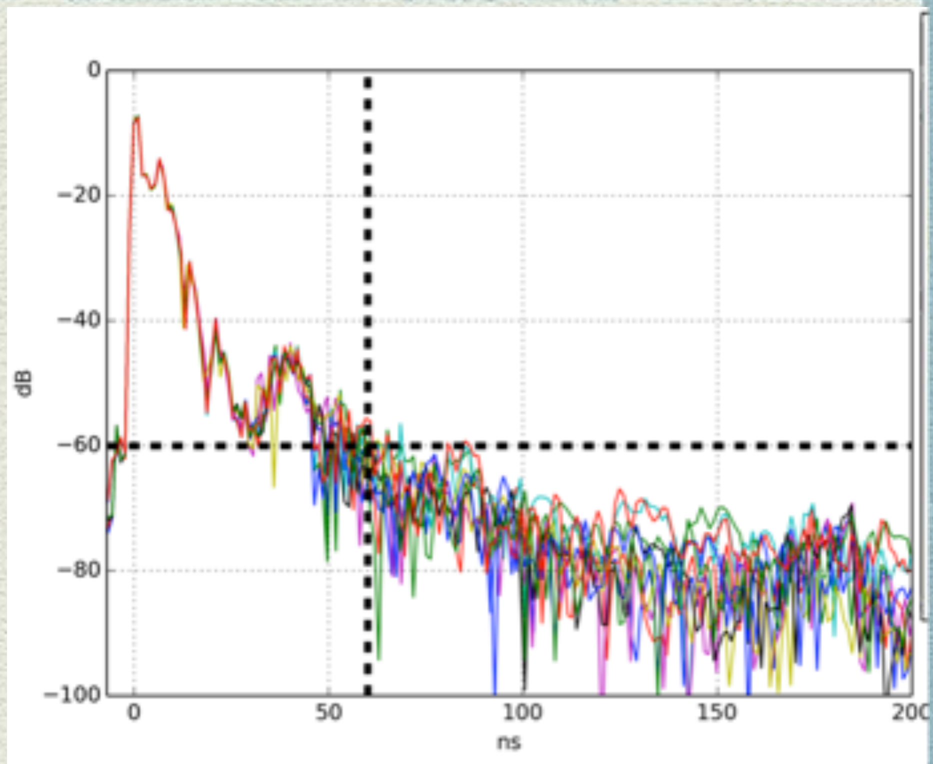
- Minimizing number of antennas keeps correlator cost down (N^2 scaling)
- Collecting area designed to give sufficient sensitivity to detect most models of reionization in a season of observing

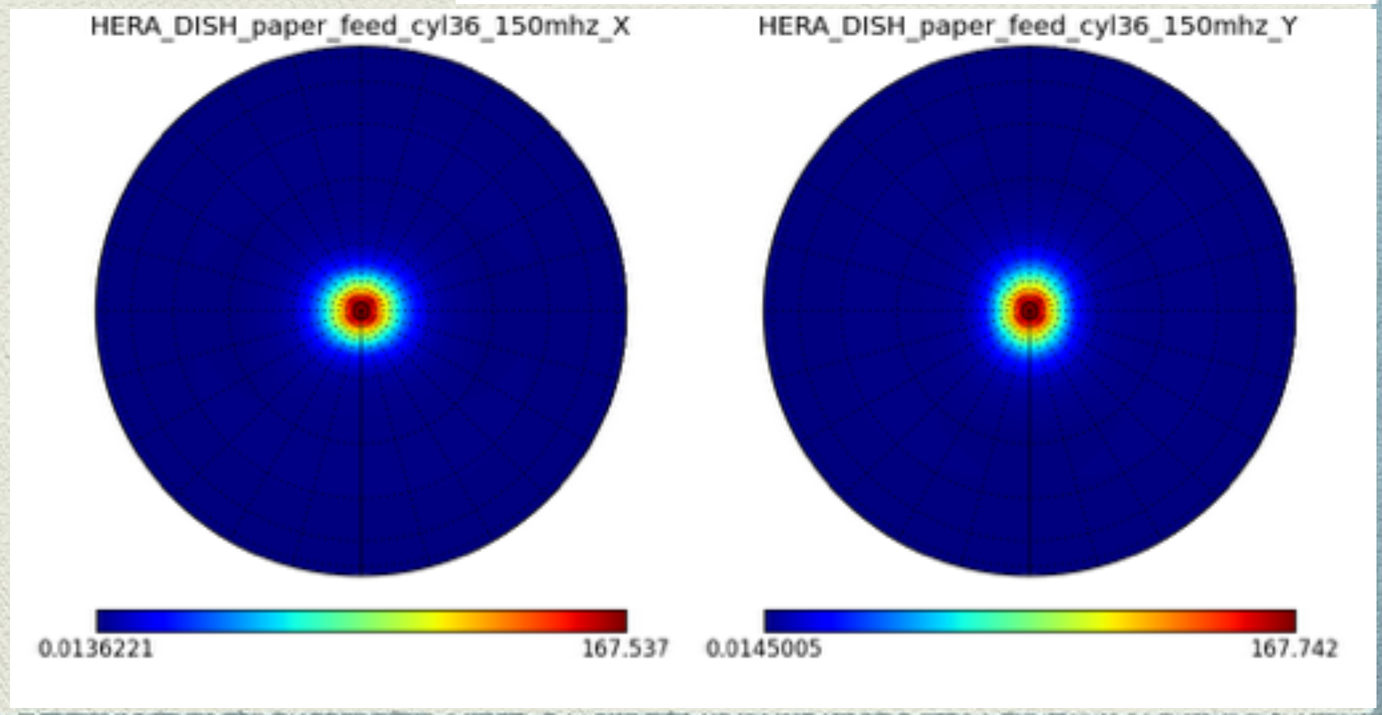
Design choices: hexagonal close-packing

- Array configuration is highly redundant: of 54,615 baselines, only 630 are unique
- Redundancy allows coherent averaging of redundant baselines
- Calibration using redundancy minimizes the need for a sky model and is fast and linearizable
- *uv*-plane is densely sampled

Design choices: antenna element

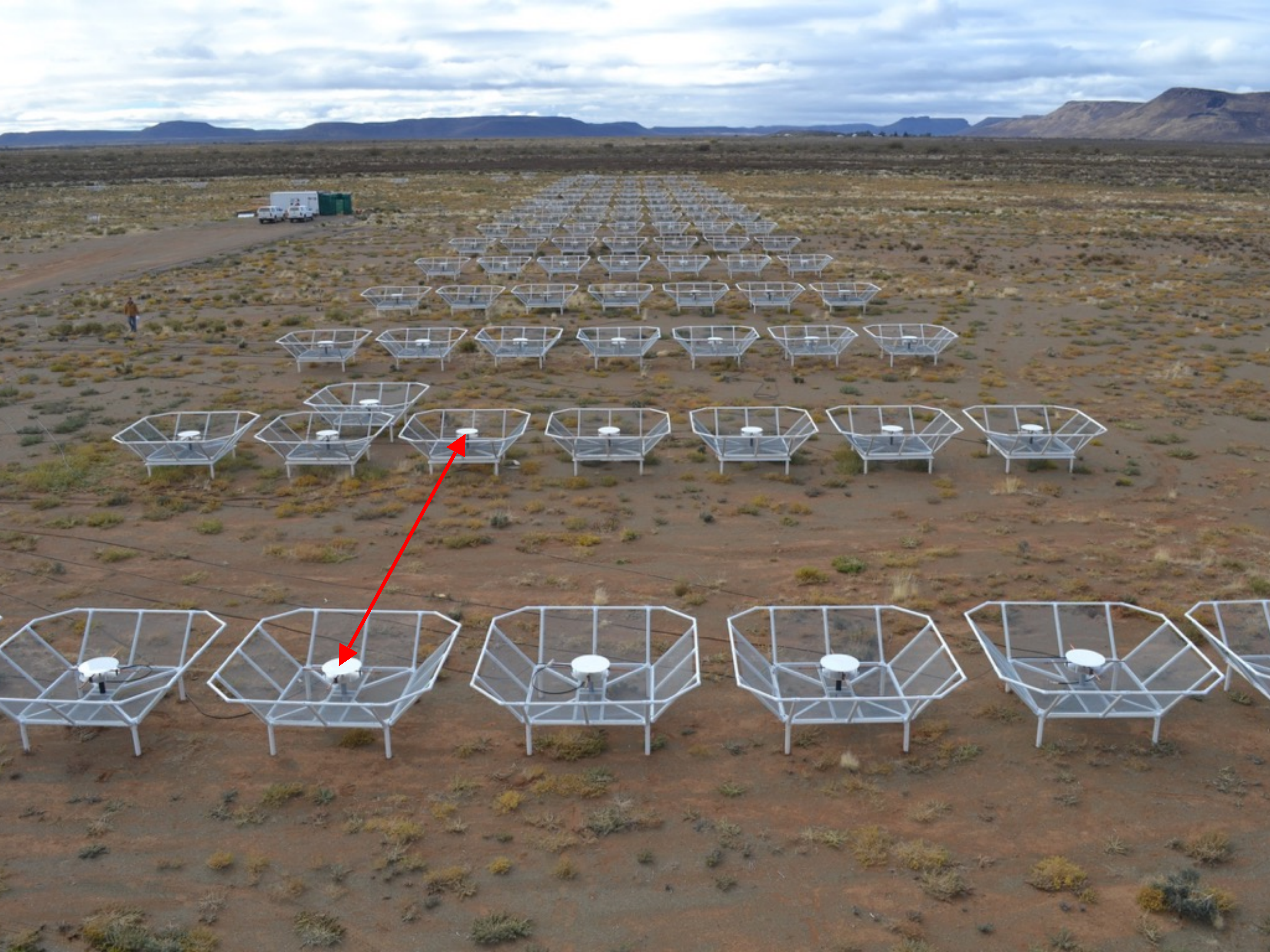
- Minimize systematic effects due to frequency non-smoothness (limit delay of internal reflections)
- Minimize systematic effects due to polarization
- Optimize over full frequency range
- Maximize area per element while retaining
  - manufacturability
  - sufficient field of view

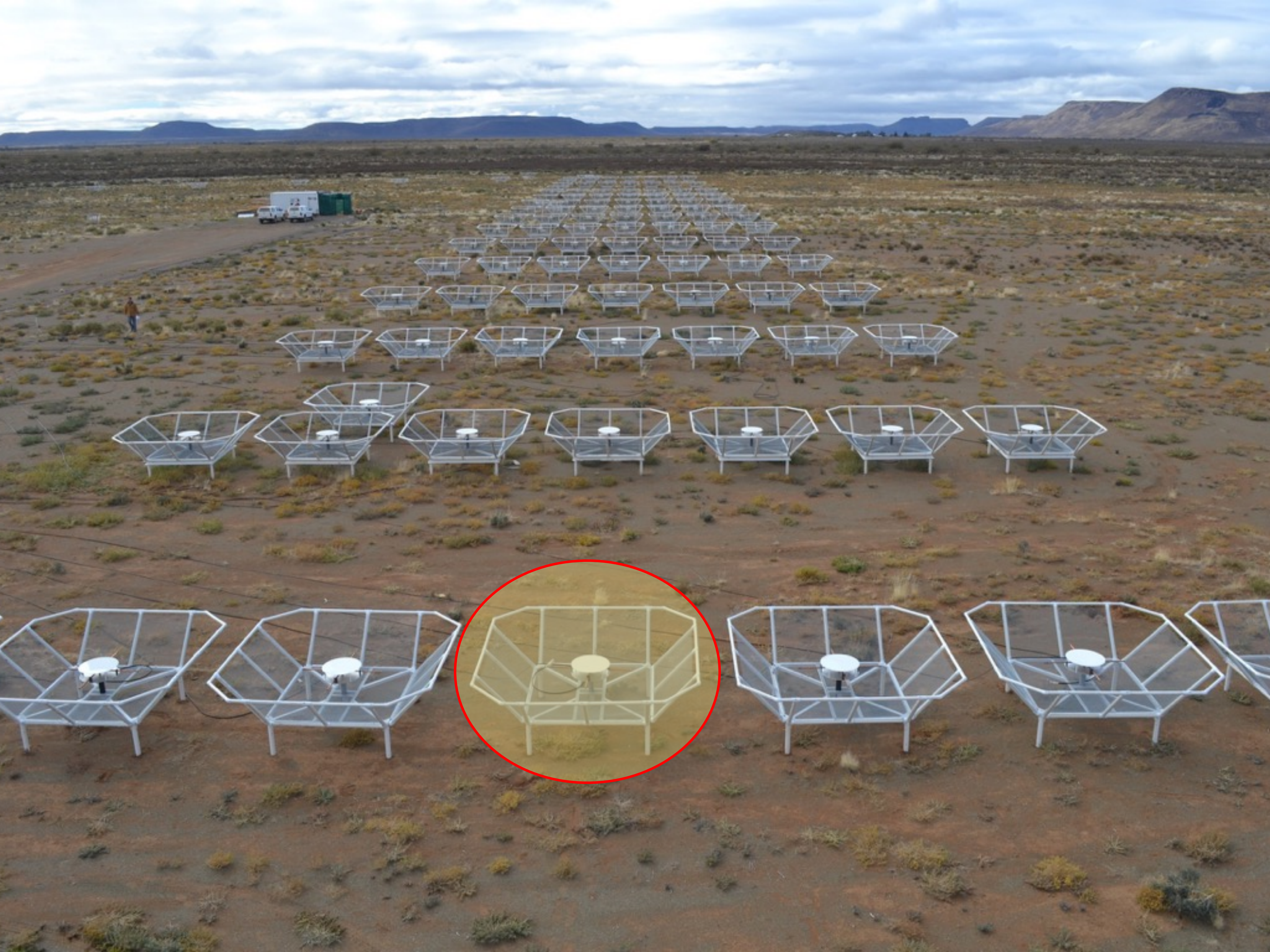


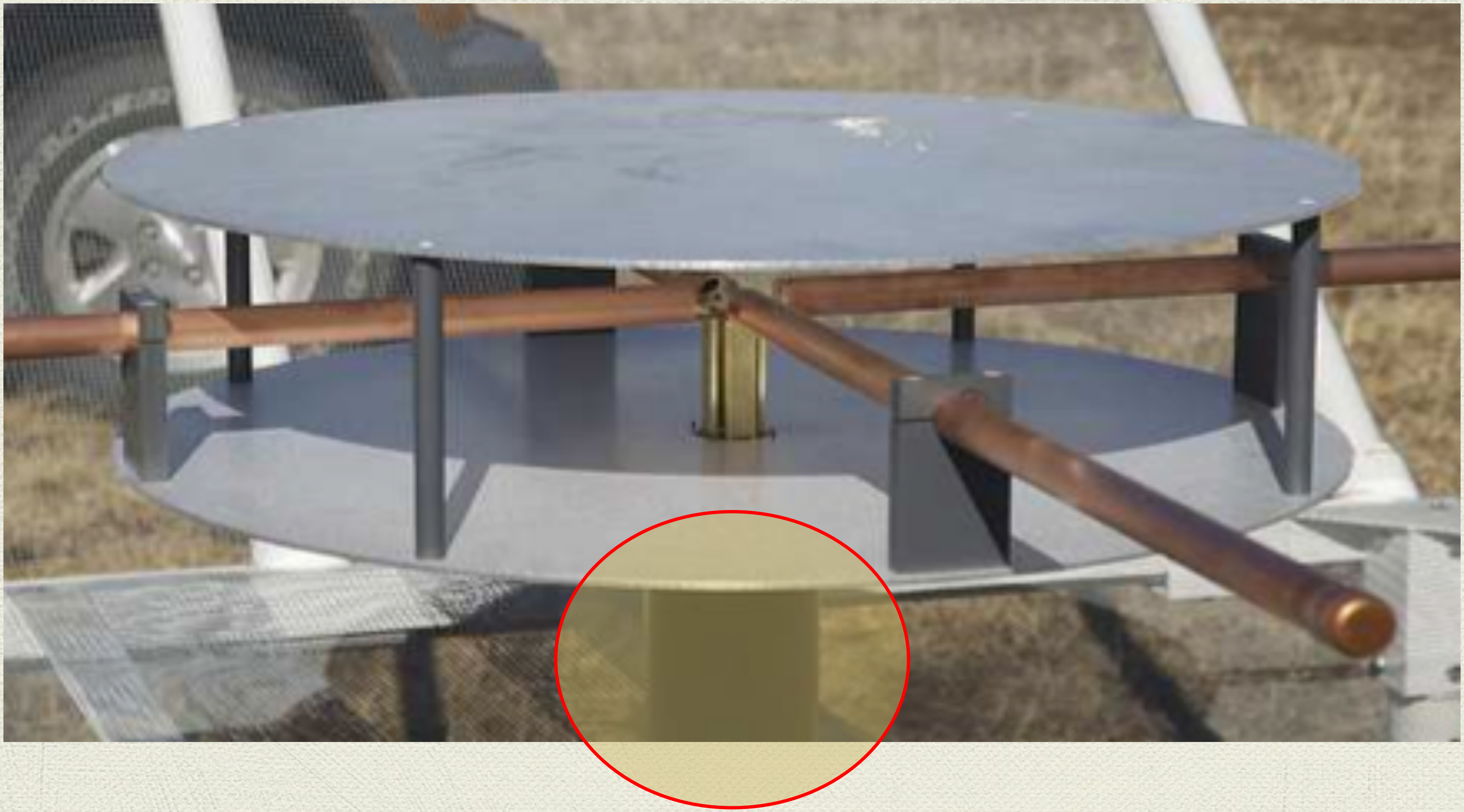


HERA Specifications

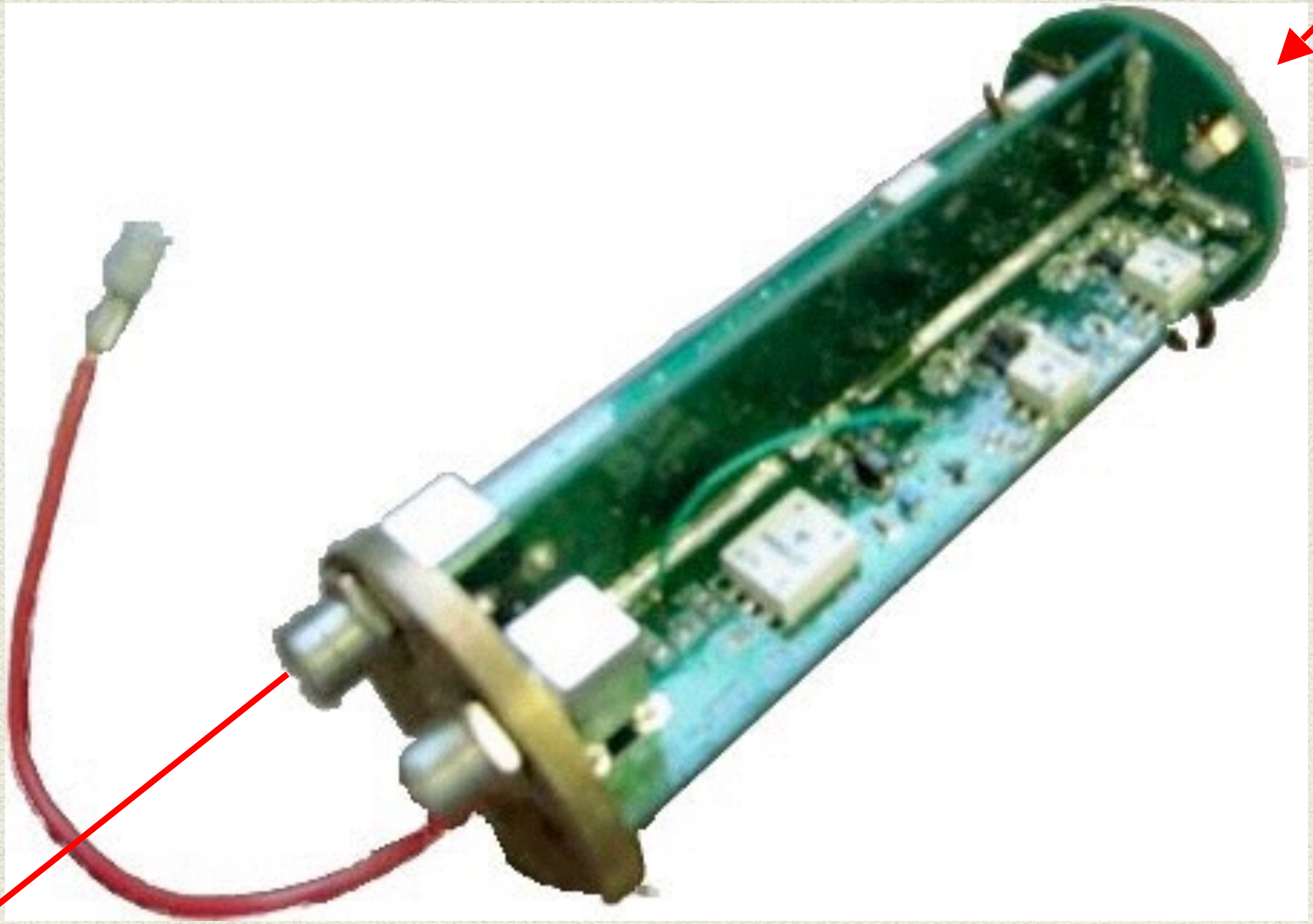
Parameter	Design	Performance
Element diameter / FoV	14 m	$9°$
Min baseline length / largest scale	14.6 m	$7.8°$
Max core baseline length / synthesized beam	306.6 m	$24'$
Max outrigger baseline length	1066.5 m	$9'$
Frequency / redshift range	50 - 250 MHz digitized	
	70 - 230 MHz useable	19.2 - 5.2
	100 MHz correlated	
Spectral channel width	97.7 kHz	
System temperature / sensitivity	$100 + 120(\nu/150\ \mathrm{MHz})^{-2.55}$ K	$50\ \mu\mathrm{Jy\ beam}^{-1}\ \sqrt{\mathrm{hour}}$



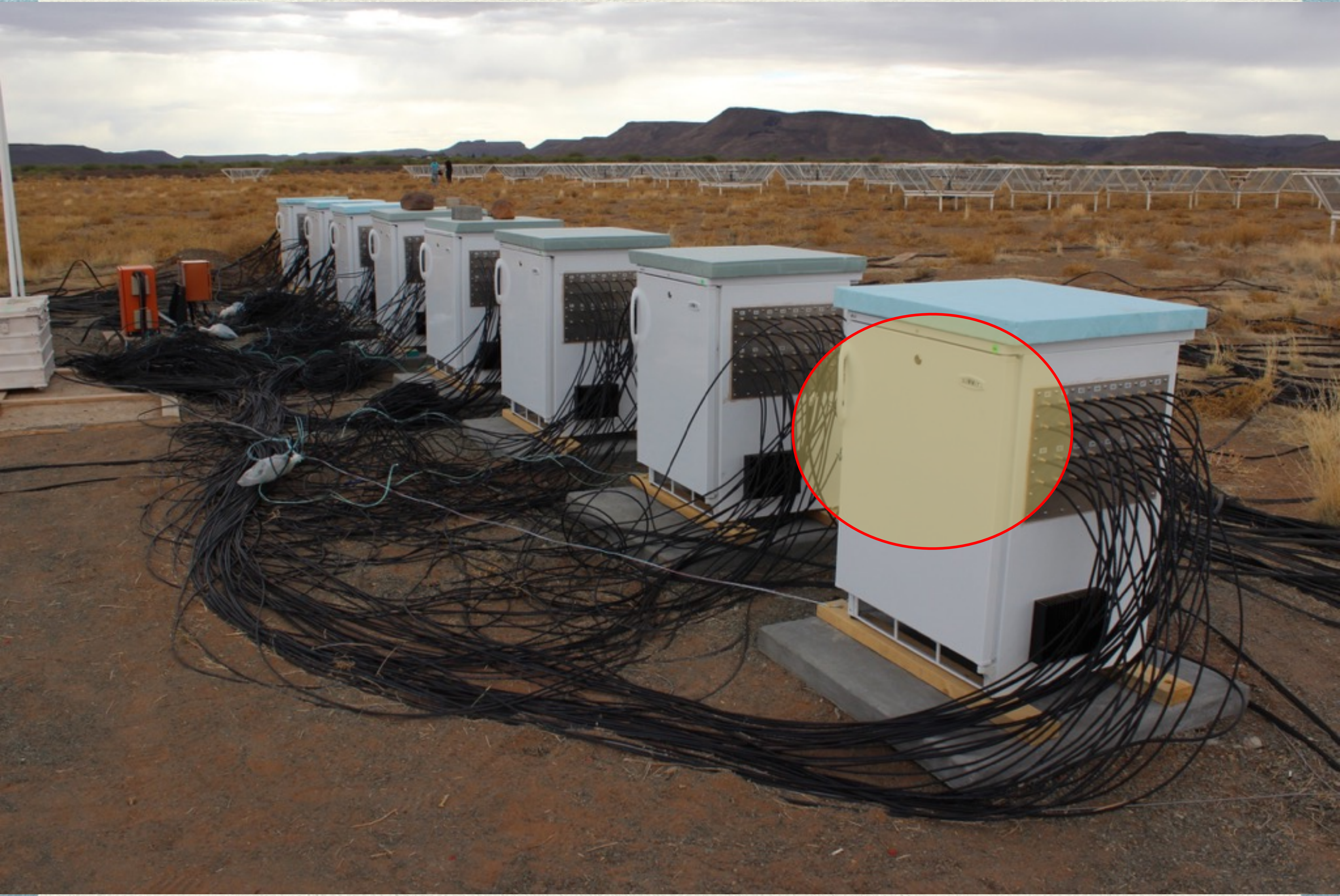


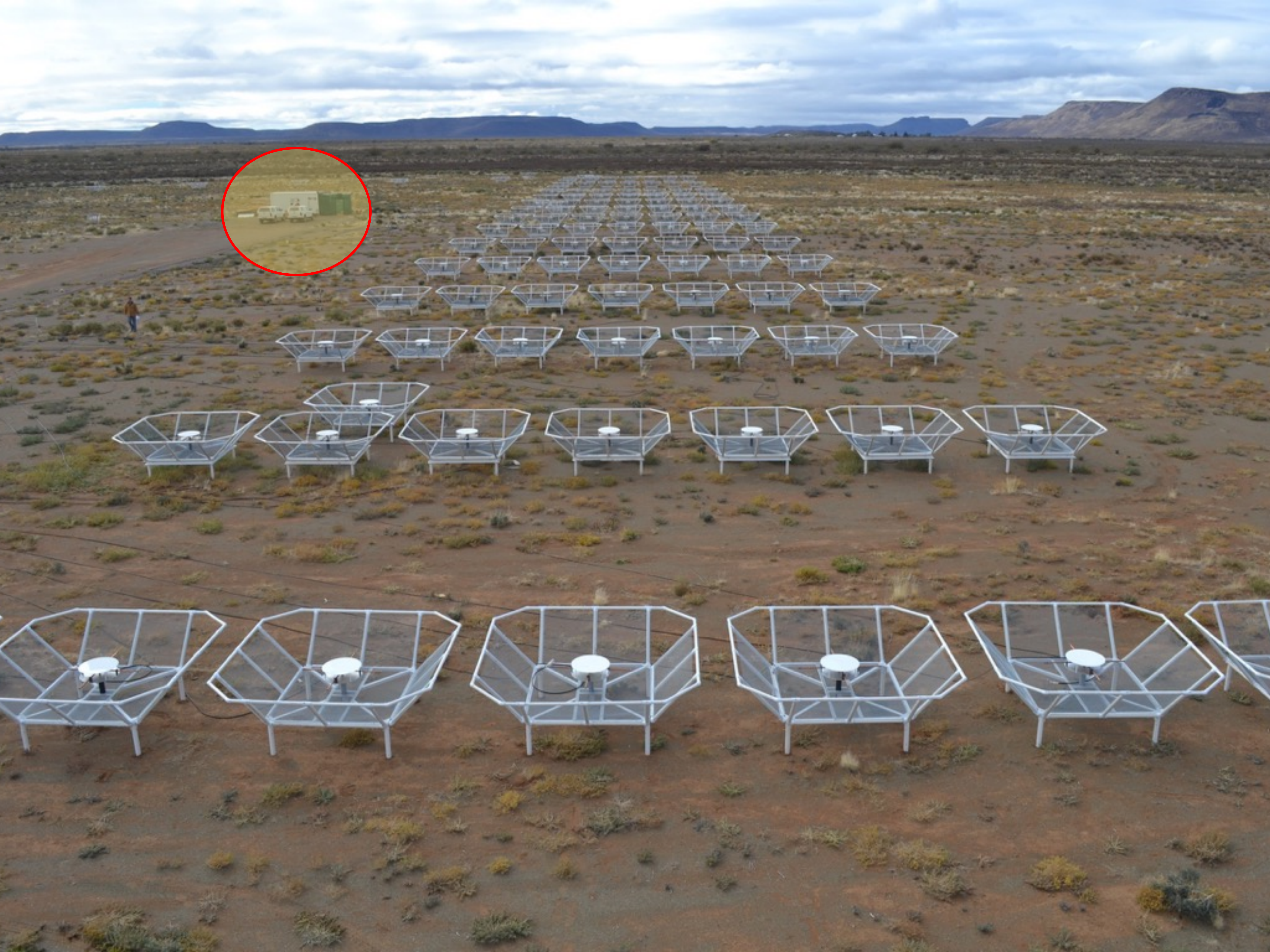


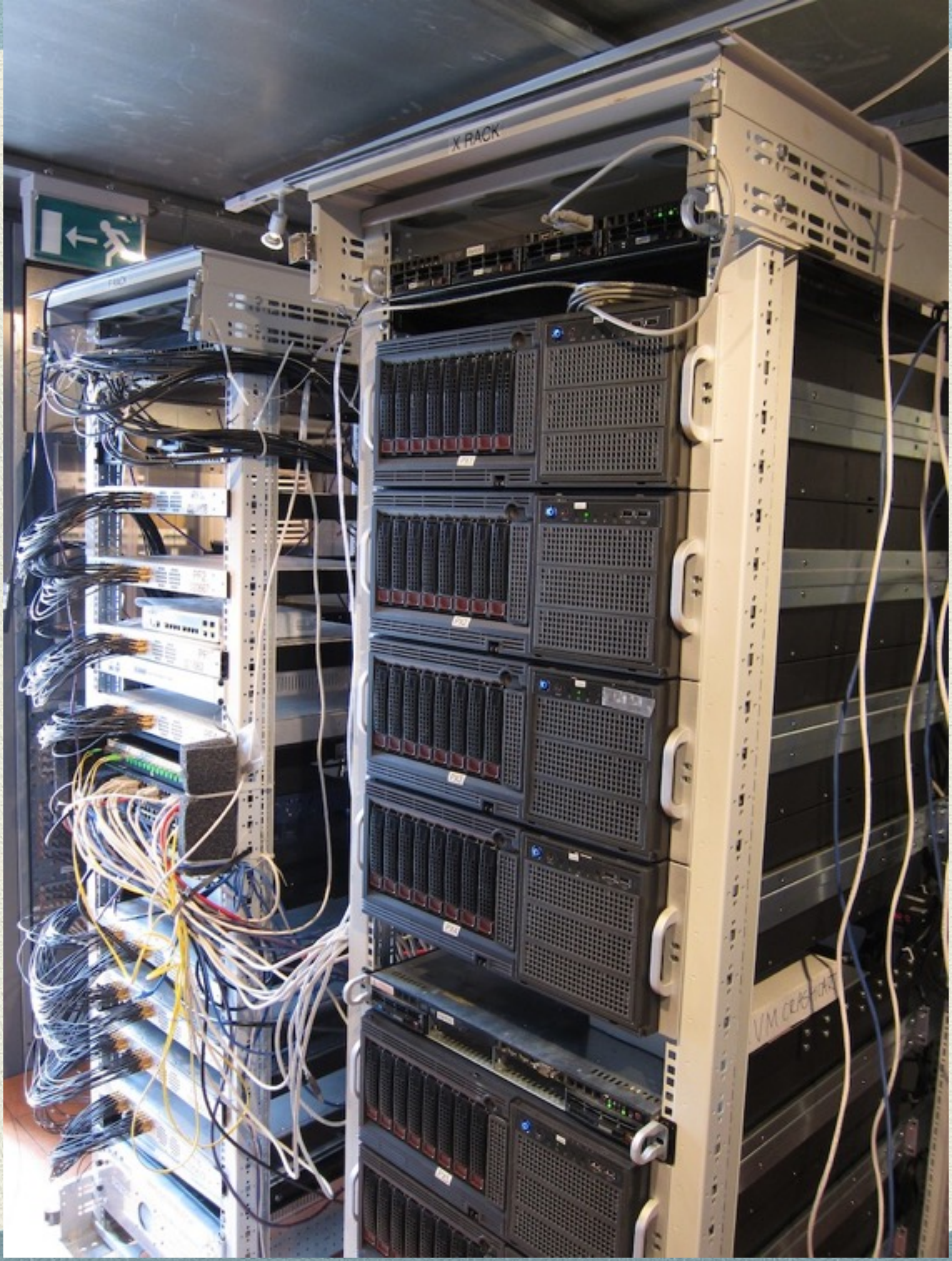
From antenna

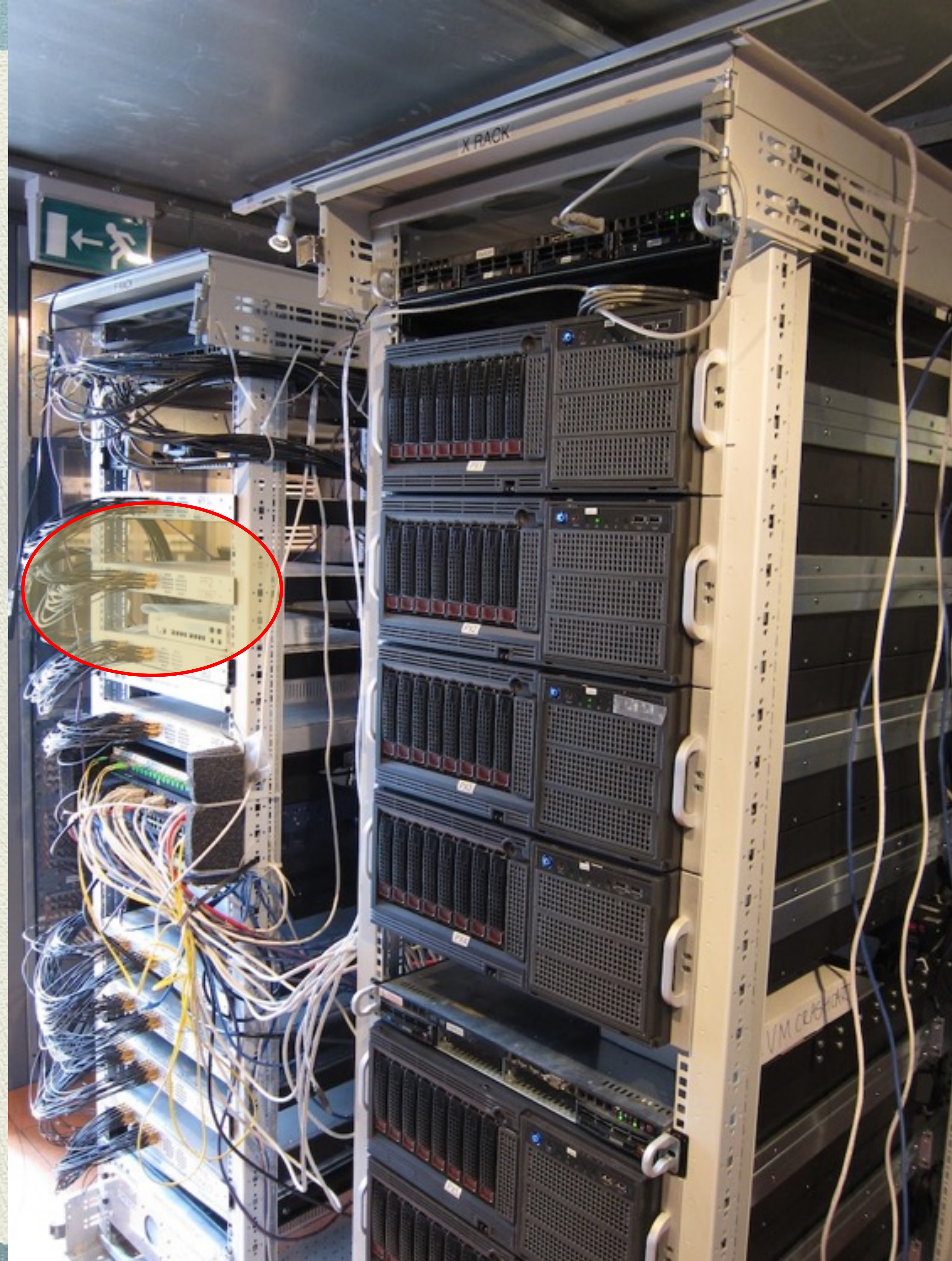


To coax cable

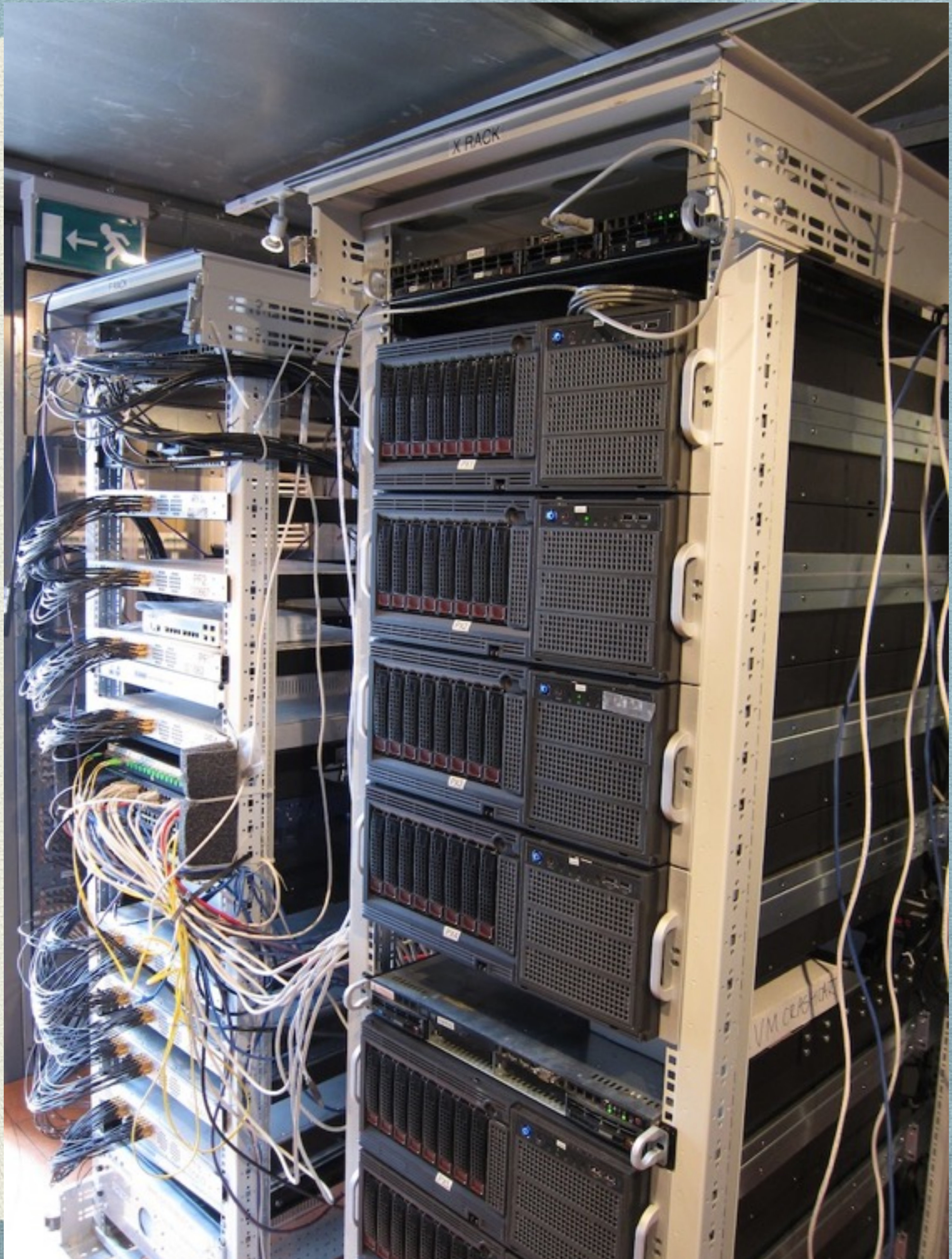





X RACK


X RACK

For PAPER-128, the data rate is
215 Mb/s
1.1 TB in 12 hours (one night)
This will increase by more than an order of magnitude for HERA-351

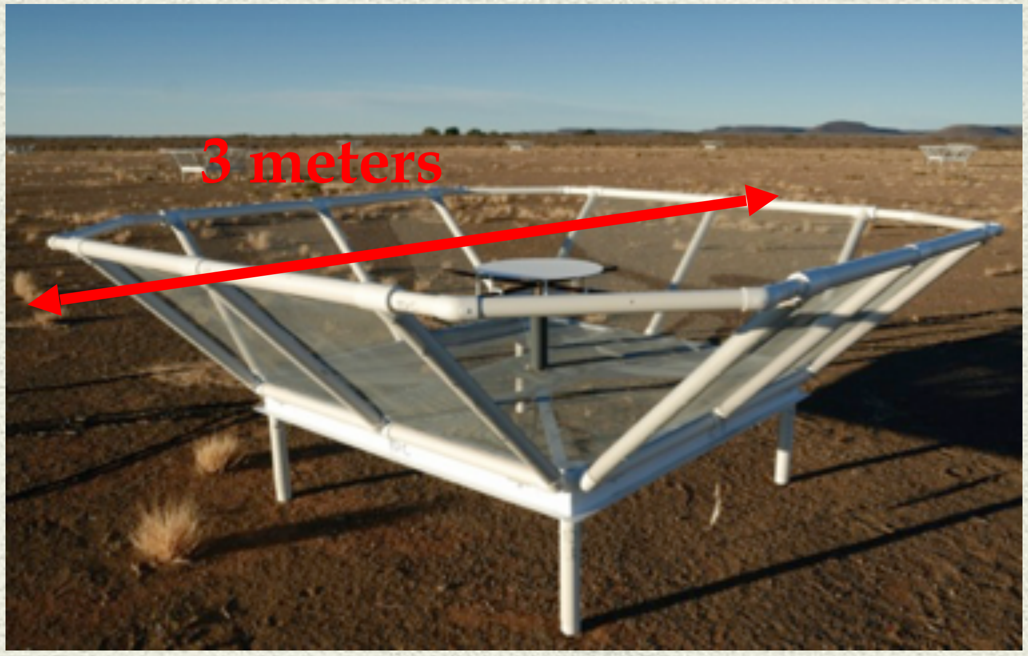


Computing and Storage

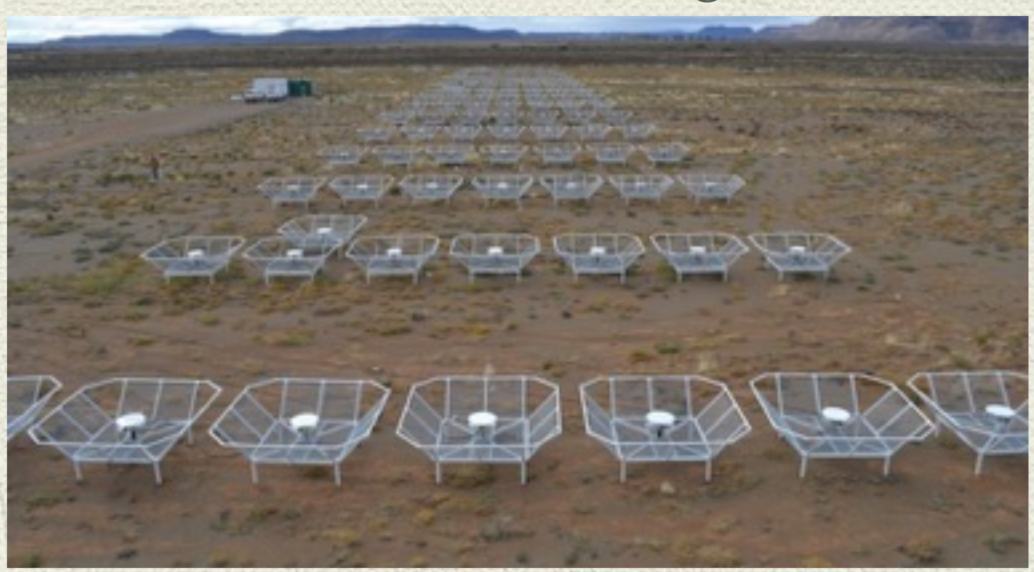
- Penn leads the computing for PAPER
- Computing cluster at Penn: 22 nodes, 200 cores
- Data compression in South African done with small 4-node cluster, plus 110 TB RAID storage

140 TB of storage space using Dell HPC NFS Storage Solution (NSS), with 10 Gbe connection to compute nodes and parallel access, with full RAID backup

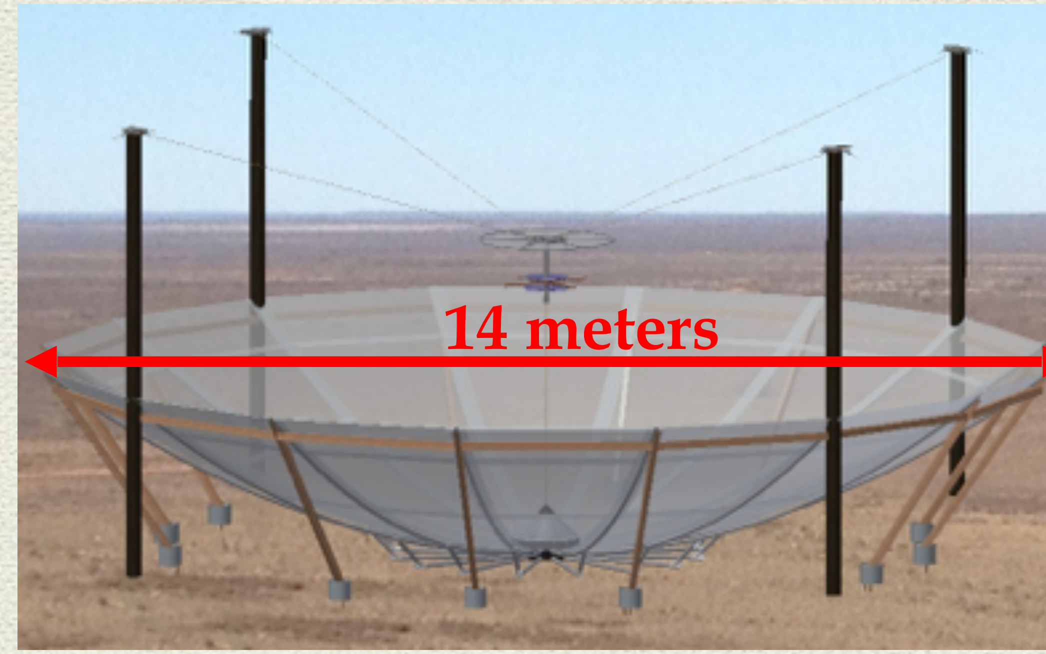
~5 m^2 collecting area per element



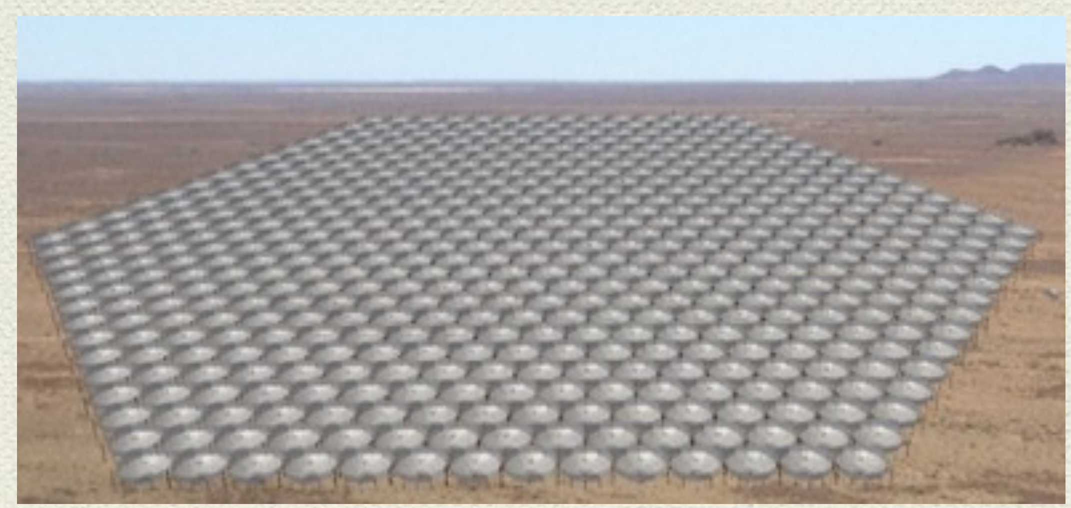
128 antennas
540 m^2 total collecting area



108 m^2 collecting area per element

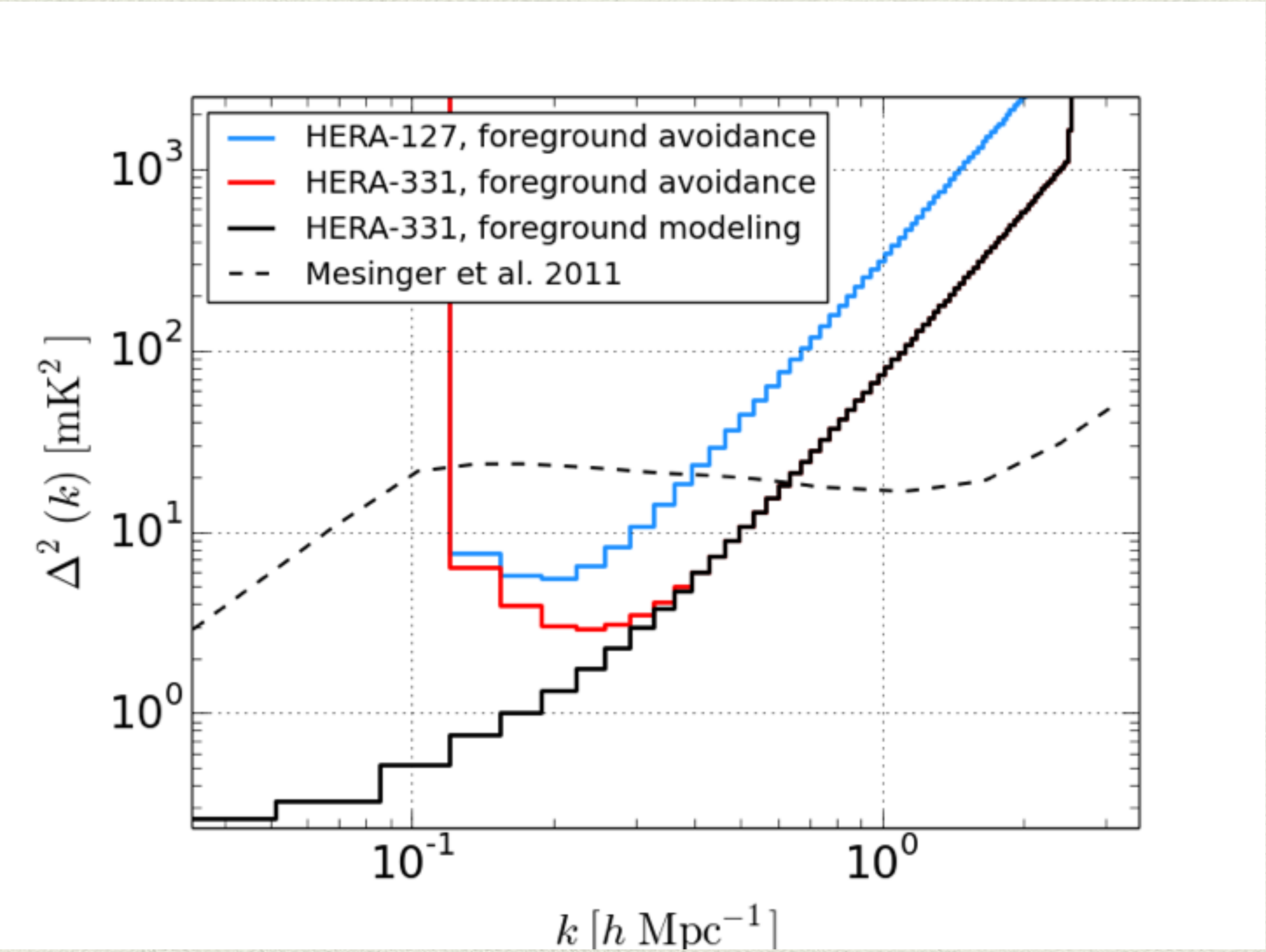


352 antennas
38,000 m^2 total collecting area



Useful frequency range increased down to 70 MHz (z ~ 20)

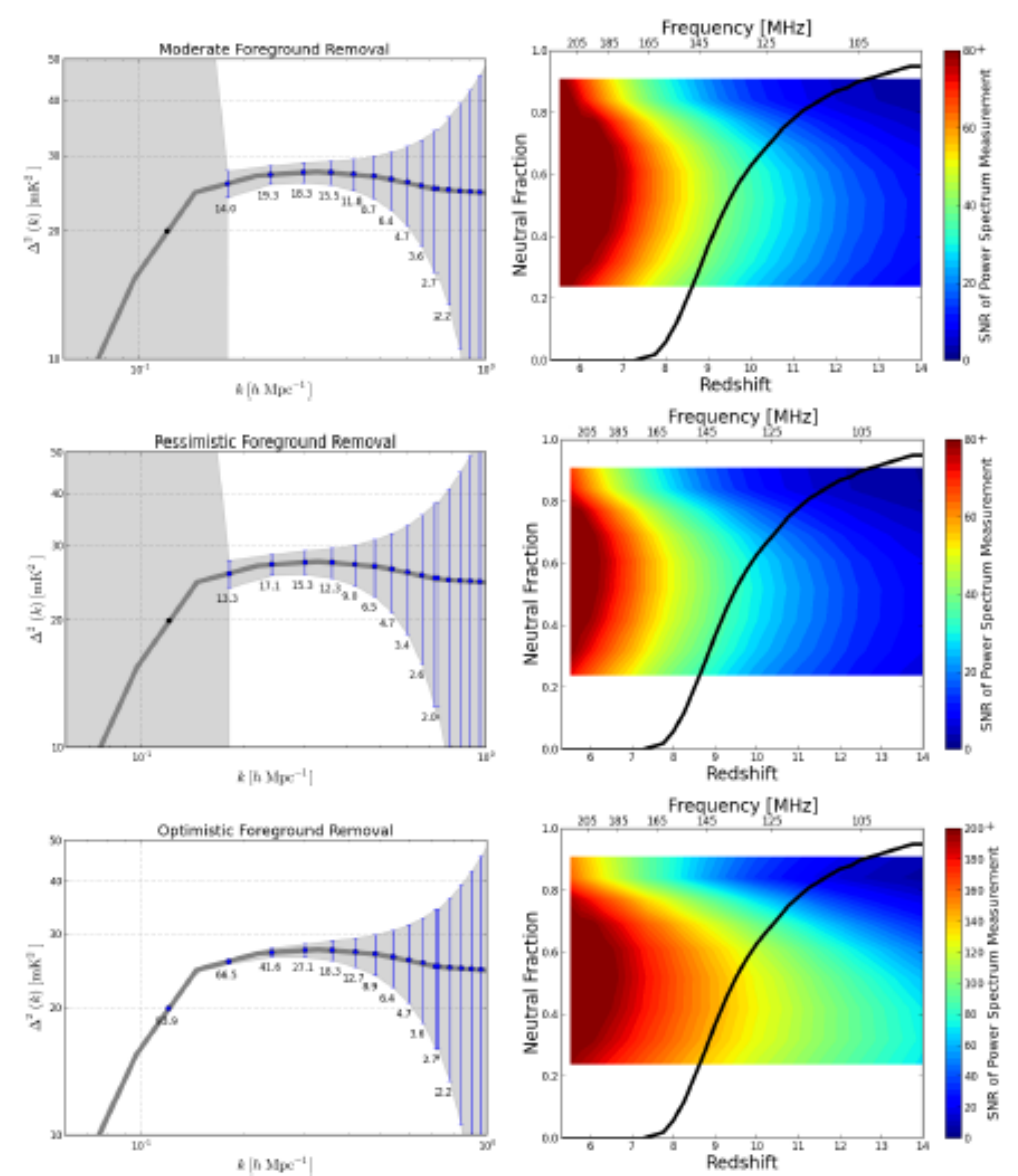
HERA Sensitivity



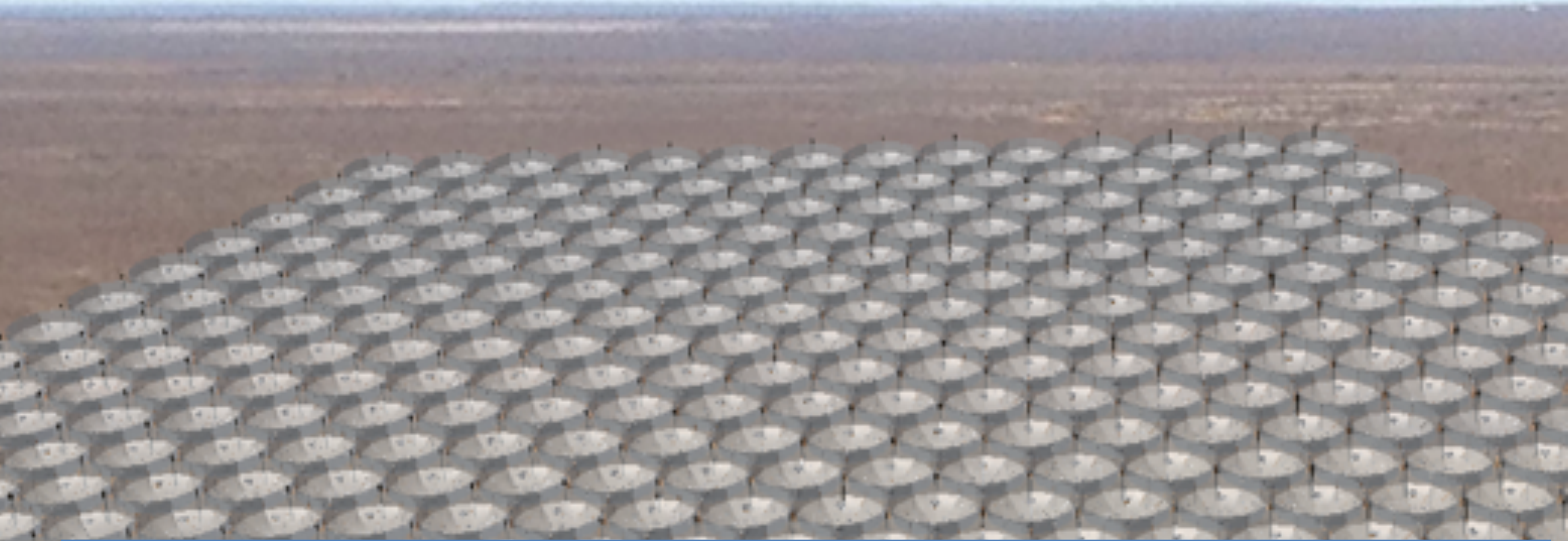
Science with HERA:

Power Spectrum Constraints

Pober, Liu, Dillon et al 2014
ApJ 782 66



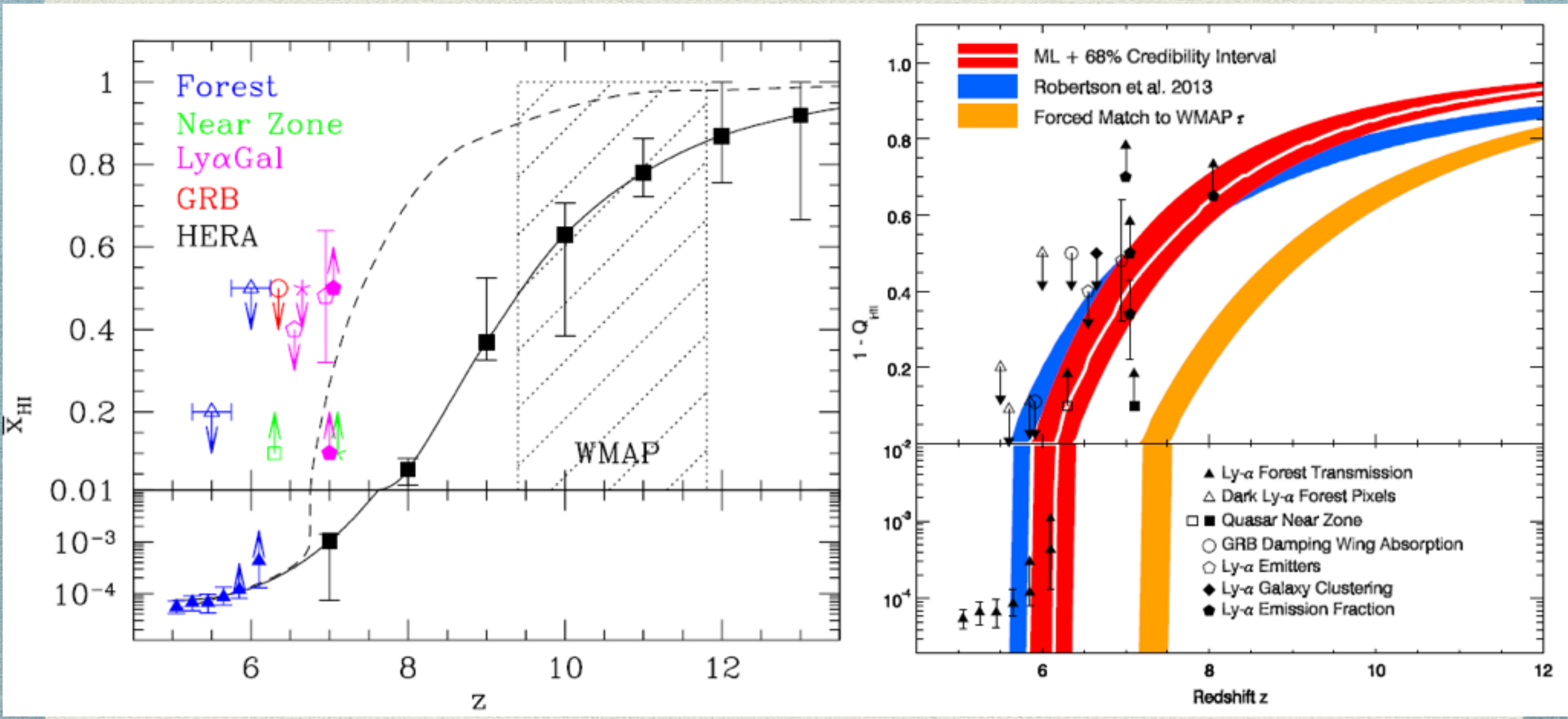
HERA-331



	Area (m^2)	SNR Pessimistic	SNR Moderate	SNR Optimistic
SKA-low	***8e5***	***14***	***98***	***280***
HERA	***5e4***	***19***	***23***	***80***
LOFAR-core	***3e4***	***1.4***	***2.8***	***17***
MWA-128	***900***	***0.6***	***2.5***	***6.4***
PAPER-128	***530***	***1.7***	***1.9***	***8.9***

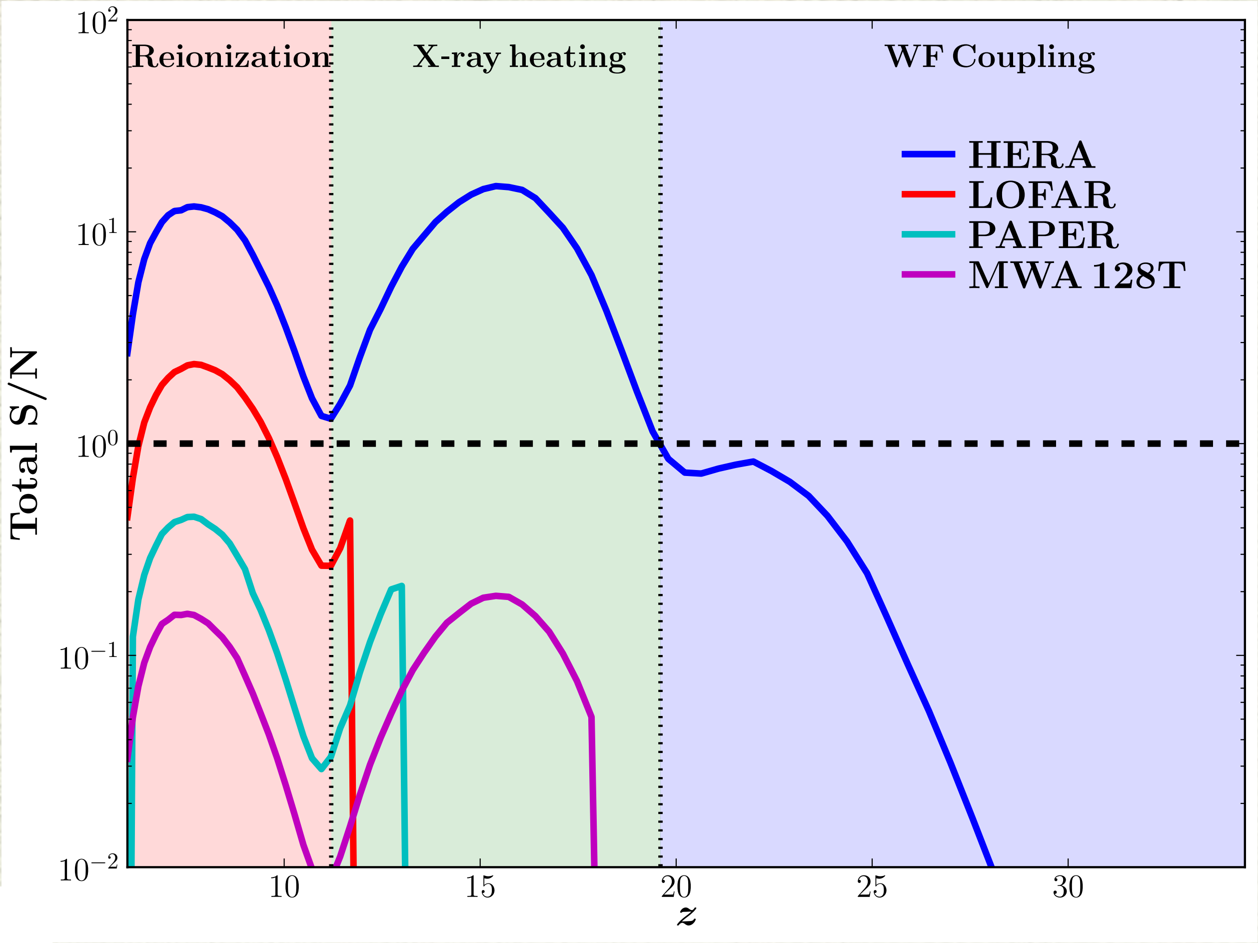
Science with HERA:

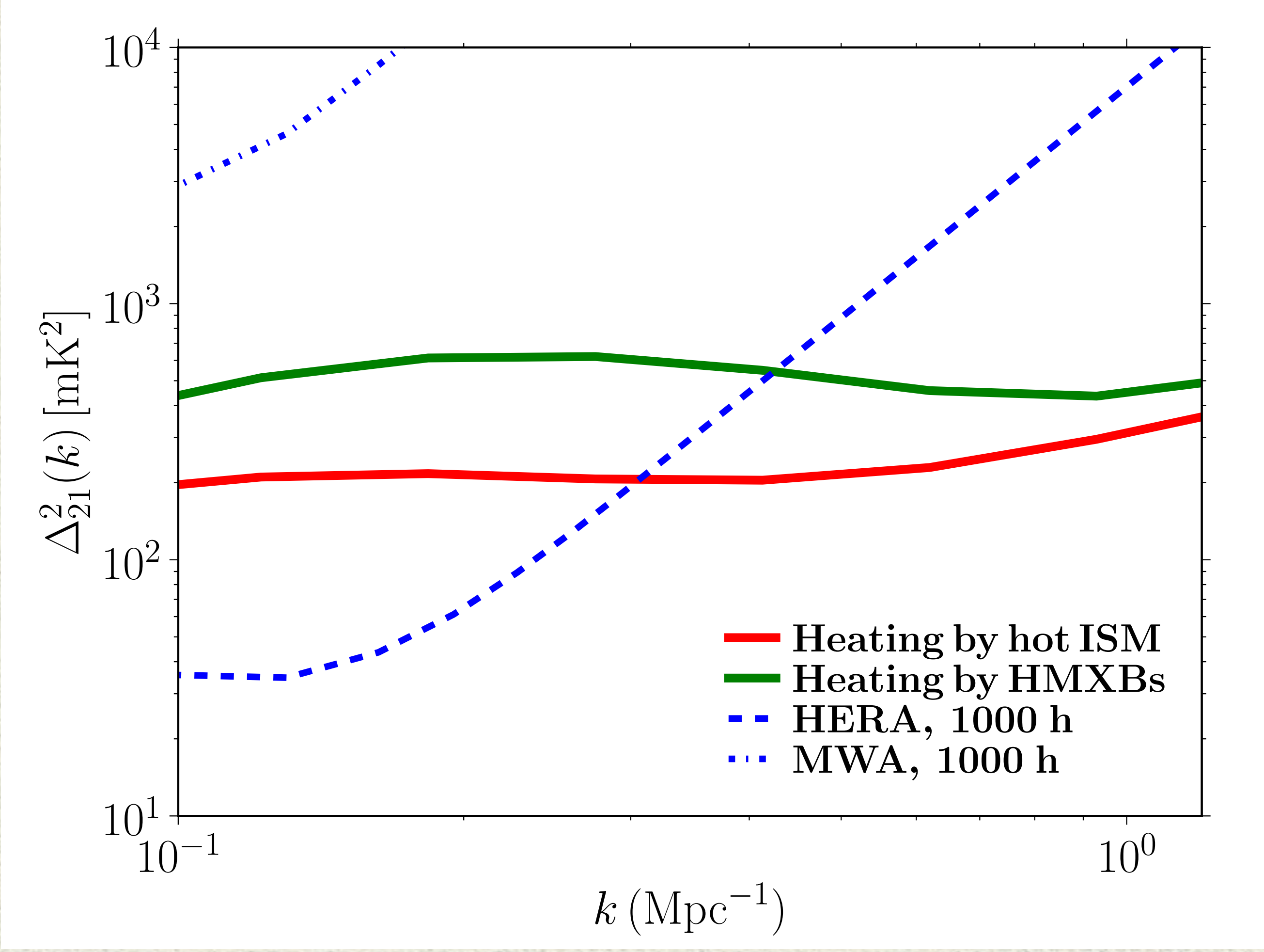
The ability to constrain the evolution of the neutral fraction unambiguously



Error simulations from Judd Bowman

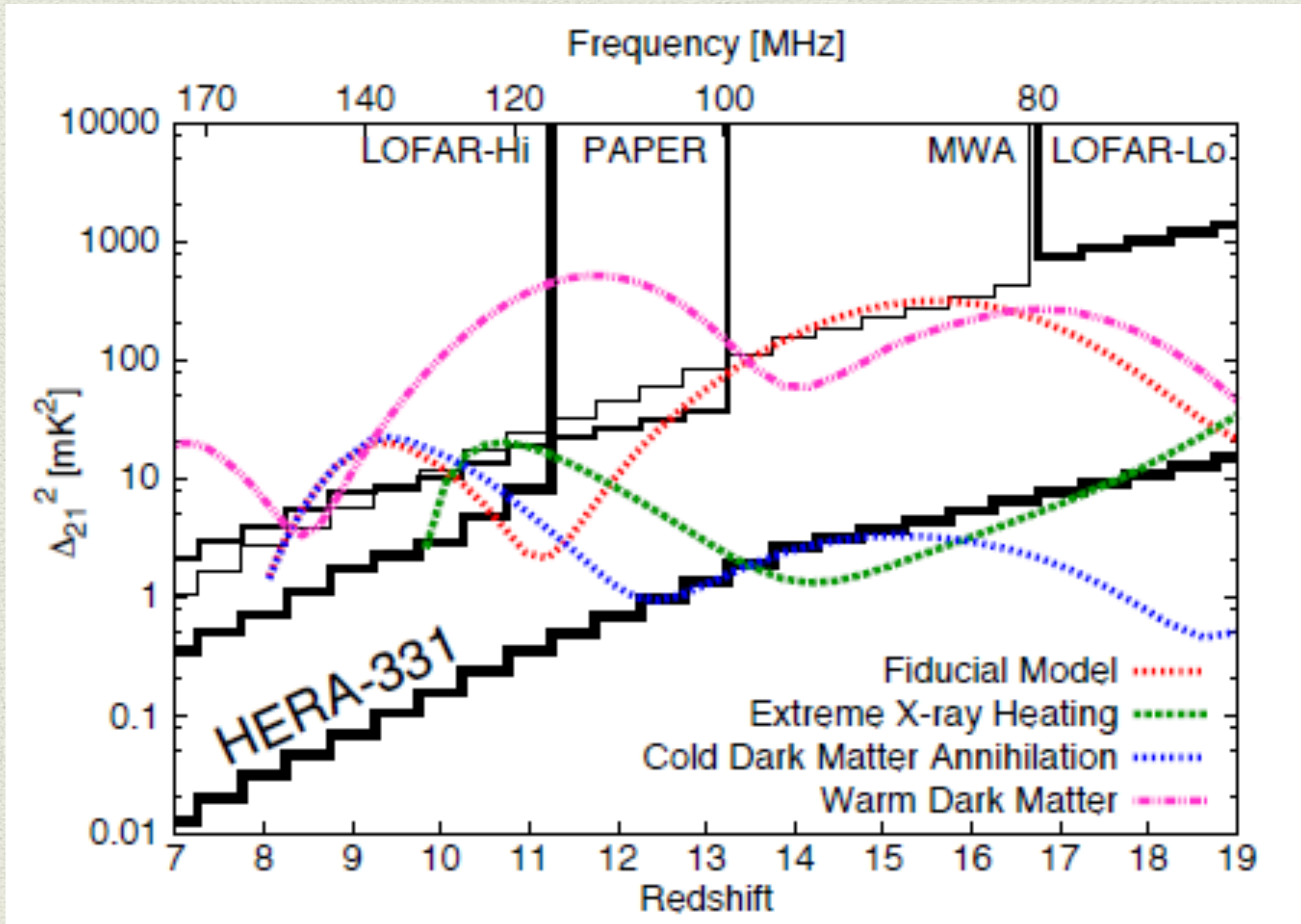
HERA should be one of the first experiments to reach beyond reionization to the era of X-ray heating





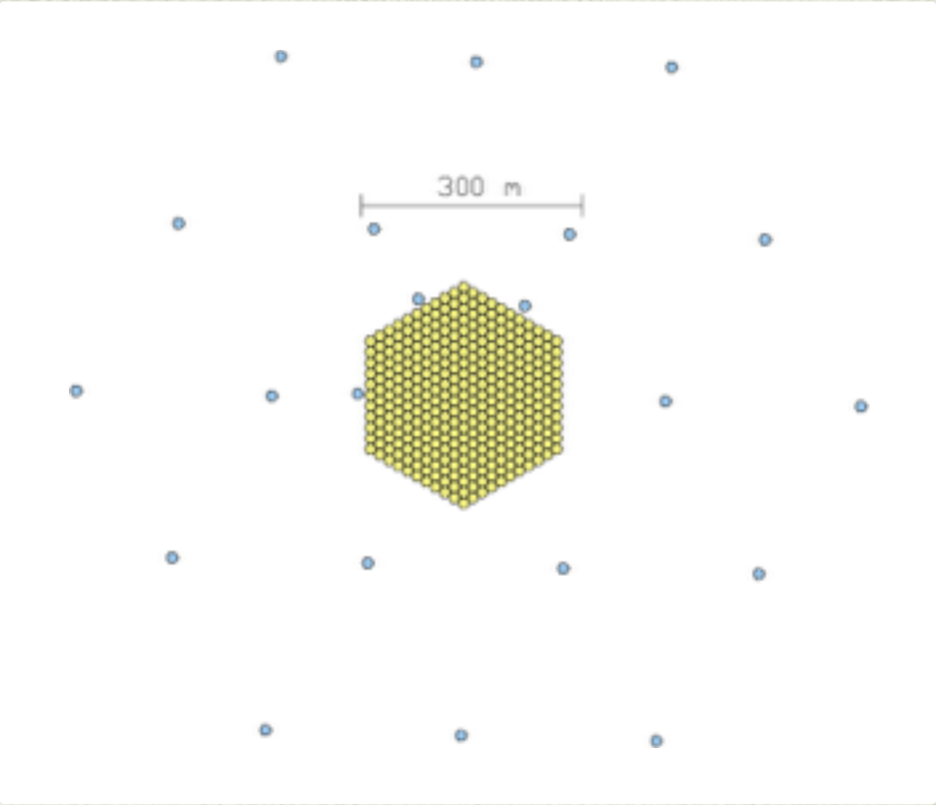
The Early Universe with HERA

based on calculations in Mesinger, Ewall-Wice, & Hewitt 2014
MNRAS 439 3262

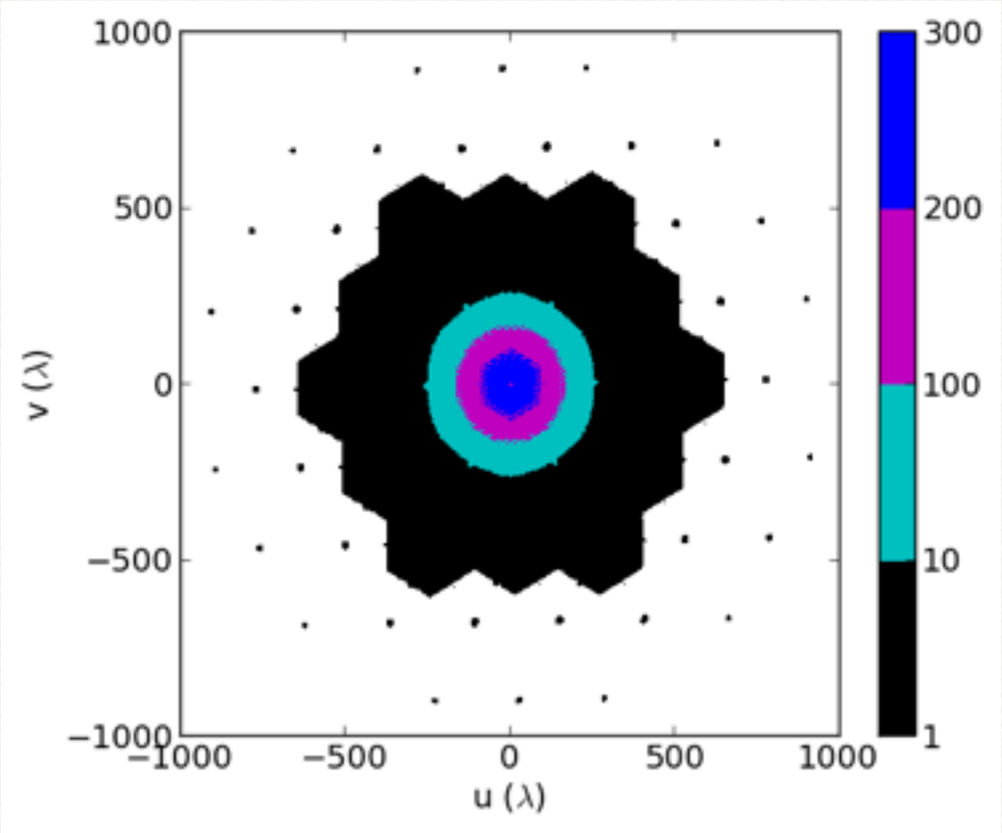


HERA will be a powerful imaging instrument

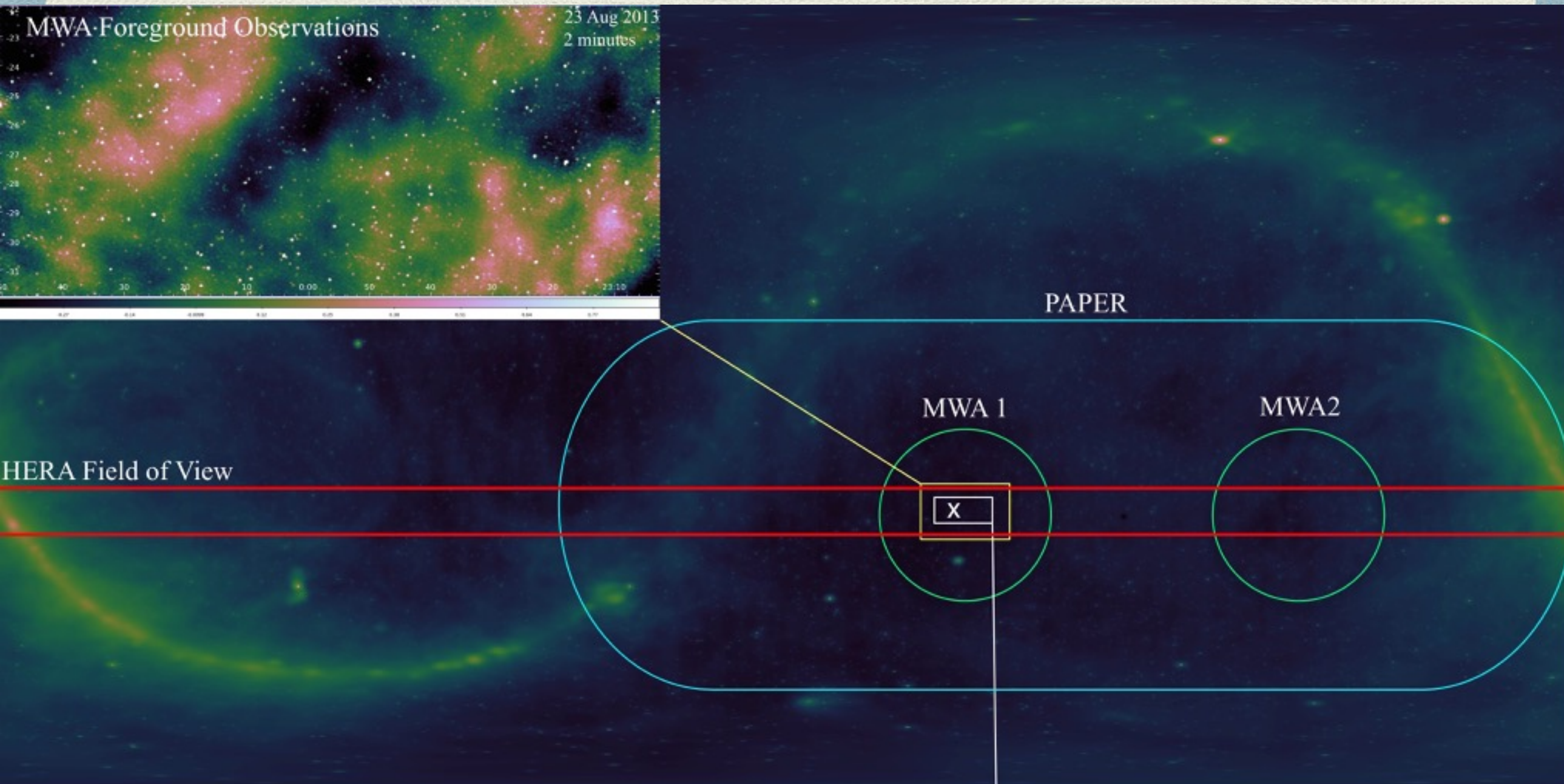
Physical configuration

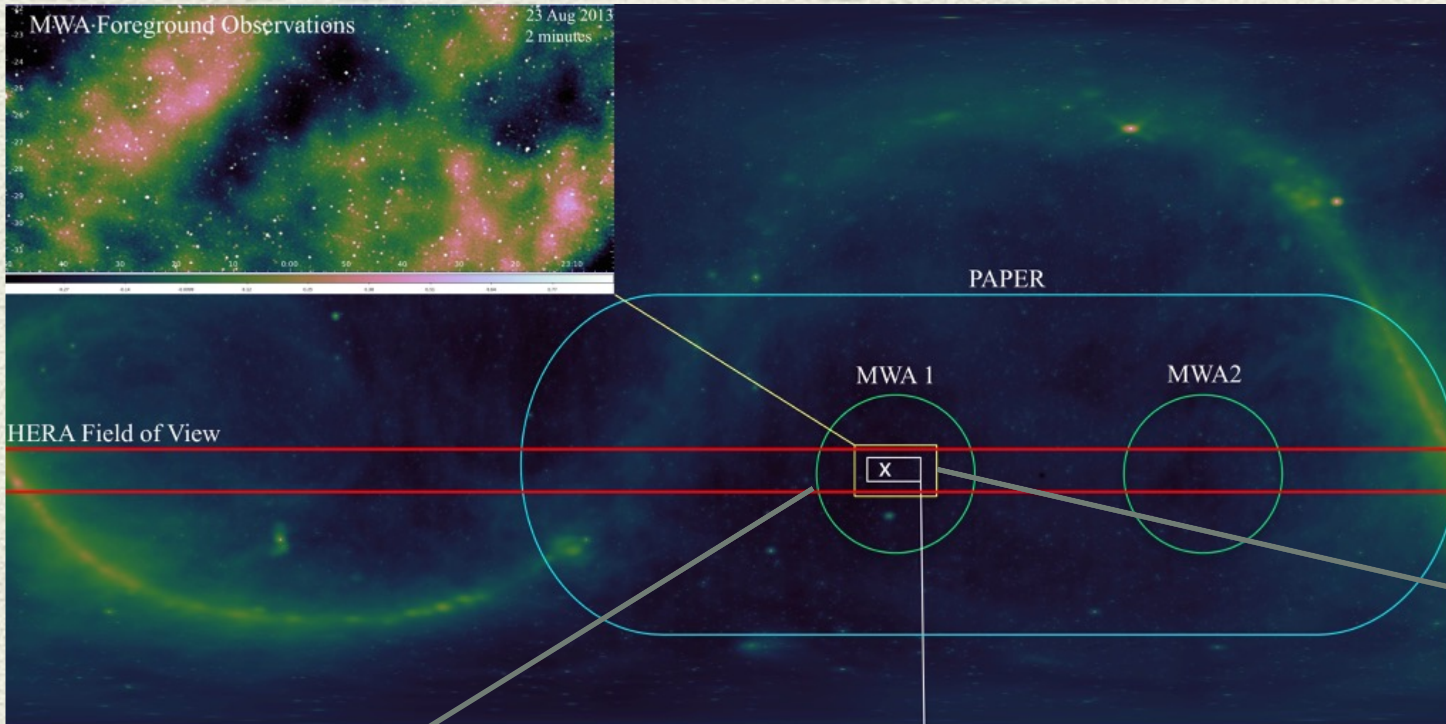


Fourier plane coverage

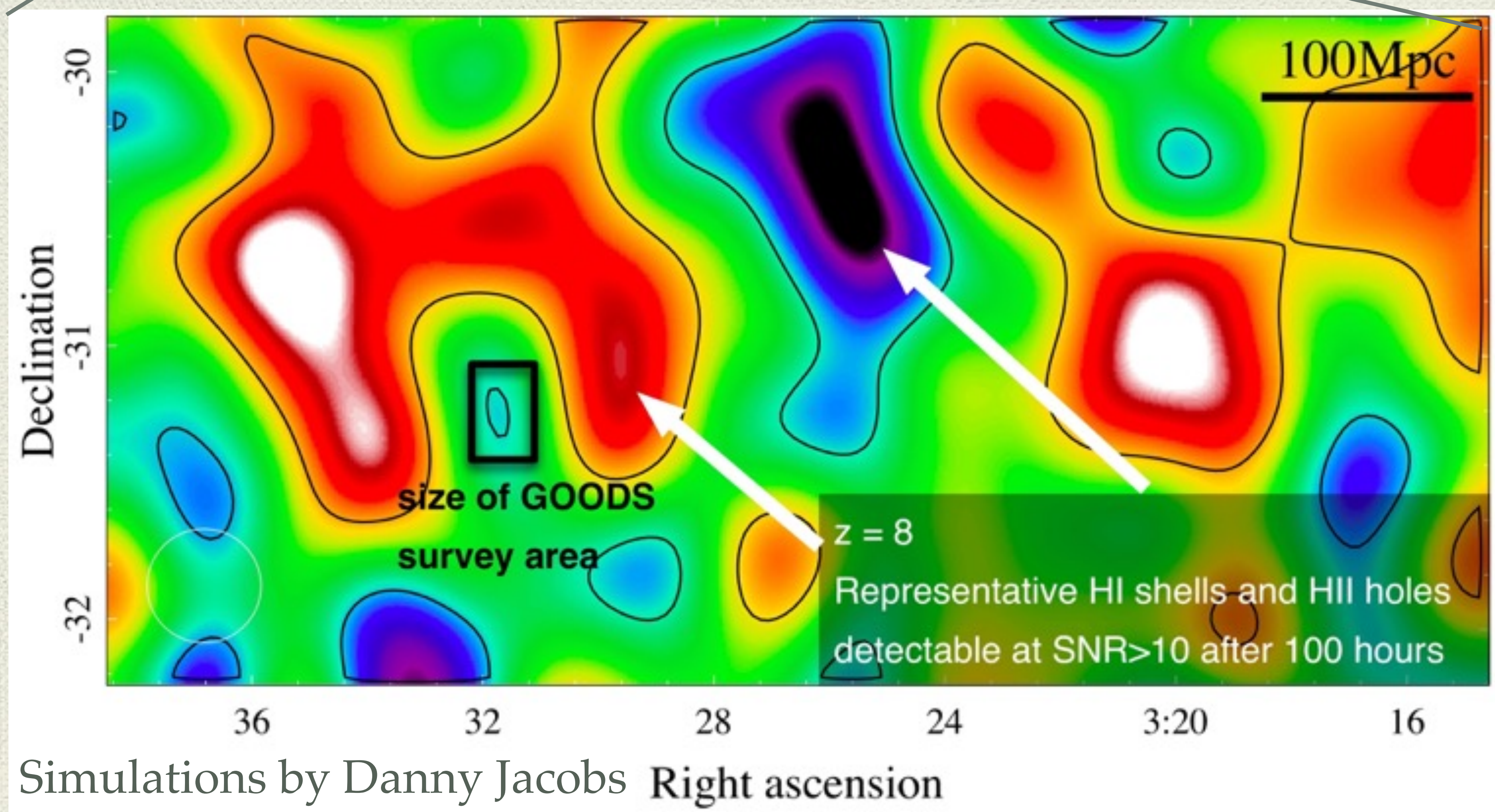


The final configuration of 331 antennas in dense core, with 21 outriggers, gives excellent uv coverage and a well-behaved synthesized beam


MWA Foreground Observations
23 Aug 2013
2 minutes
PAPER
MWA 1
MWA2
HERA Field of View
X



See Beardsley et al 2015 ApJ 800 128 for identifying bubbles for JWST and other follow-up



Conclusions

- HERA will be a highly sensitive imaging and power spectrum instrument for 21 cm studies on the timescale of the next 5 years
- It will be able to determine the reionization history with high significance, and have sensitivity to probe beyond the epoch of reionization
- HERA builds on existing techniques and instruments, and allows for incorporation of new ideas
- Construction is underway!!!