Progress in 21cm Hydrogen Line Measurements of the Epoch of Reionization and the Cosmic Dawn

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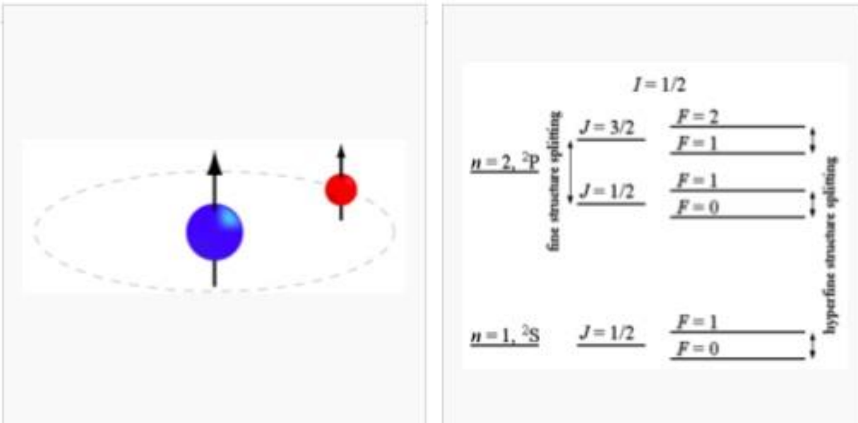
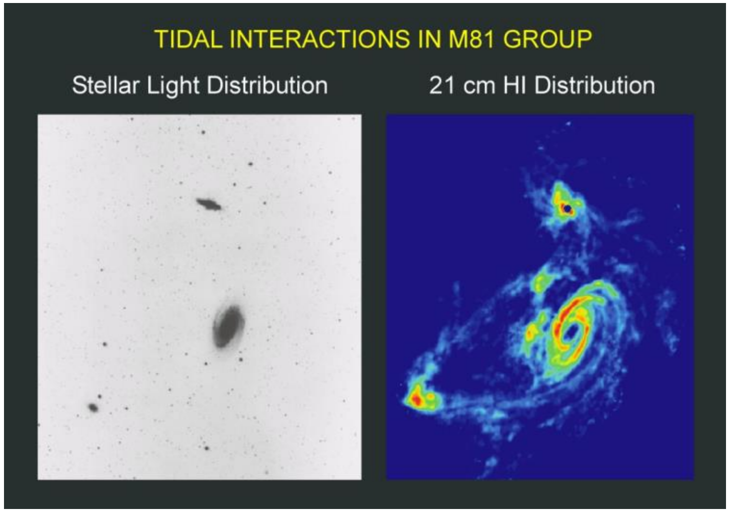
STRATEGY: Map hydrogen structures during and even before the Epoch of Reionization



Source: Wikipedia

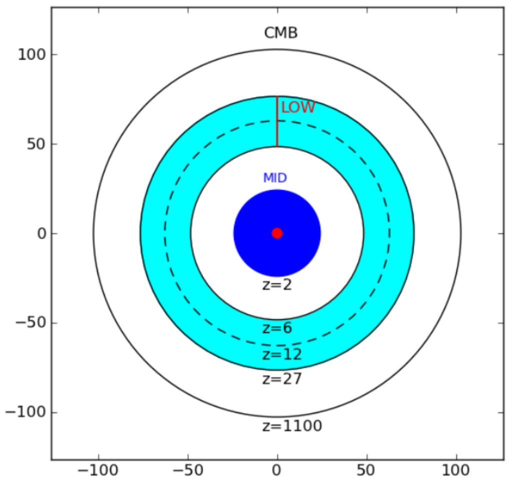


Source: National Radio Astronomy Observatory

1420.40575177 MHz

Optically thin - enables 3-dimensional mapping

$$\delta T_b \approx 27 x_{\mathrm{HI}} (1+\delta) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{(1+z)}{10}\right)^{1/2} \left(\frac{T_s - T_{bg}}{T_s}\right) \ \mathrm{mK}$$

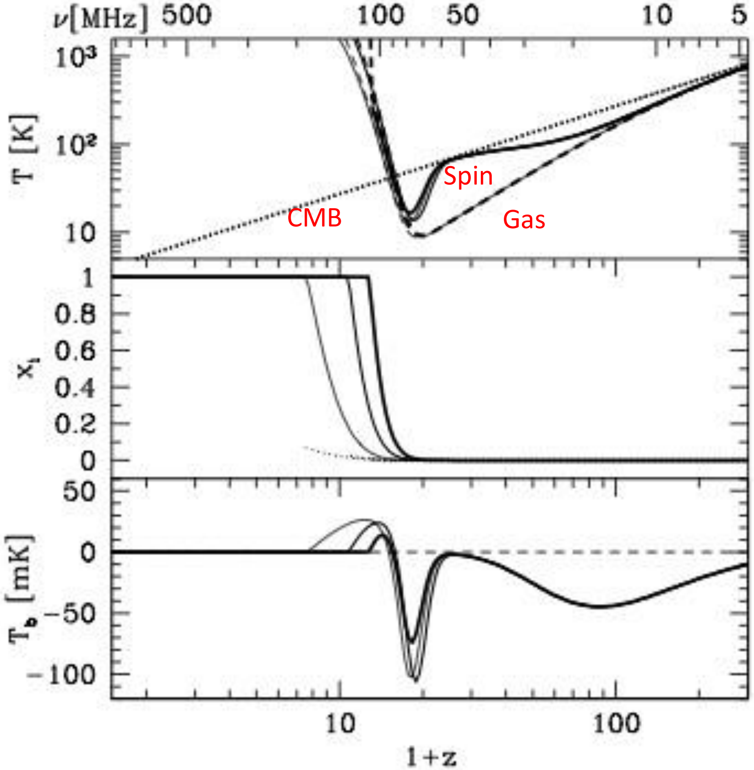


Intensity mapping

Has been detected at z ~1 through cross-corr with optical

Sky-Averaged Brightness Temperature = “Global Signal”

Volume-averaged quantities, or observed and averaged over the entire sky - for three different plausible models



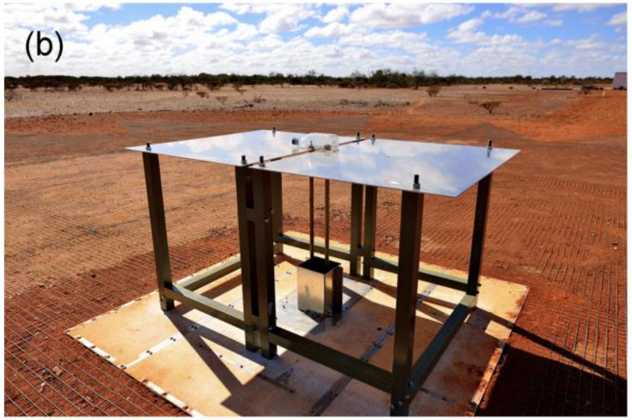
CMB, gas, and hydrogen spin temperatures

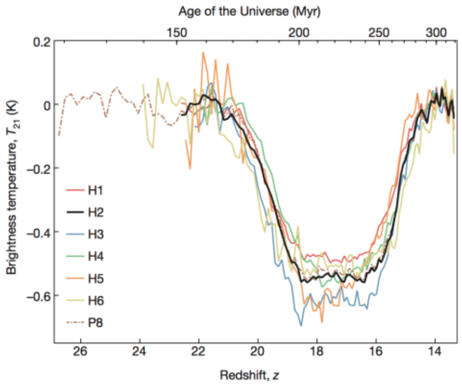
Ionized fraction for hydrogen gas

Brightness temperature of observed hydrogen 21cm spectral line

Pritchard & Loeb (2012), “21cm Cowmology in the 21st Century”

EDGES Experiment





Bowman, Rogers, Monsalve, et al. (2018), “An Absorption Profile Centred at 78 MHz in the Sky-Averaged Spectrum”

--- See A. Fialkov talk for further discussion ---

Brightness Temperature Fluctuations: The Power Spectrum and Beyond

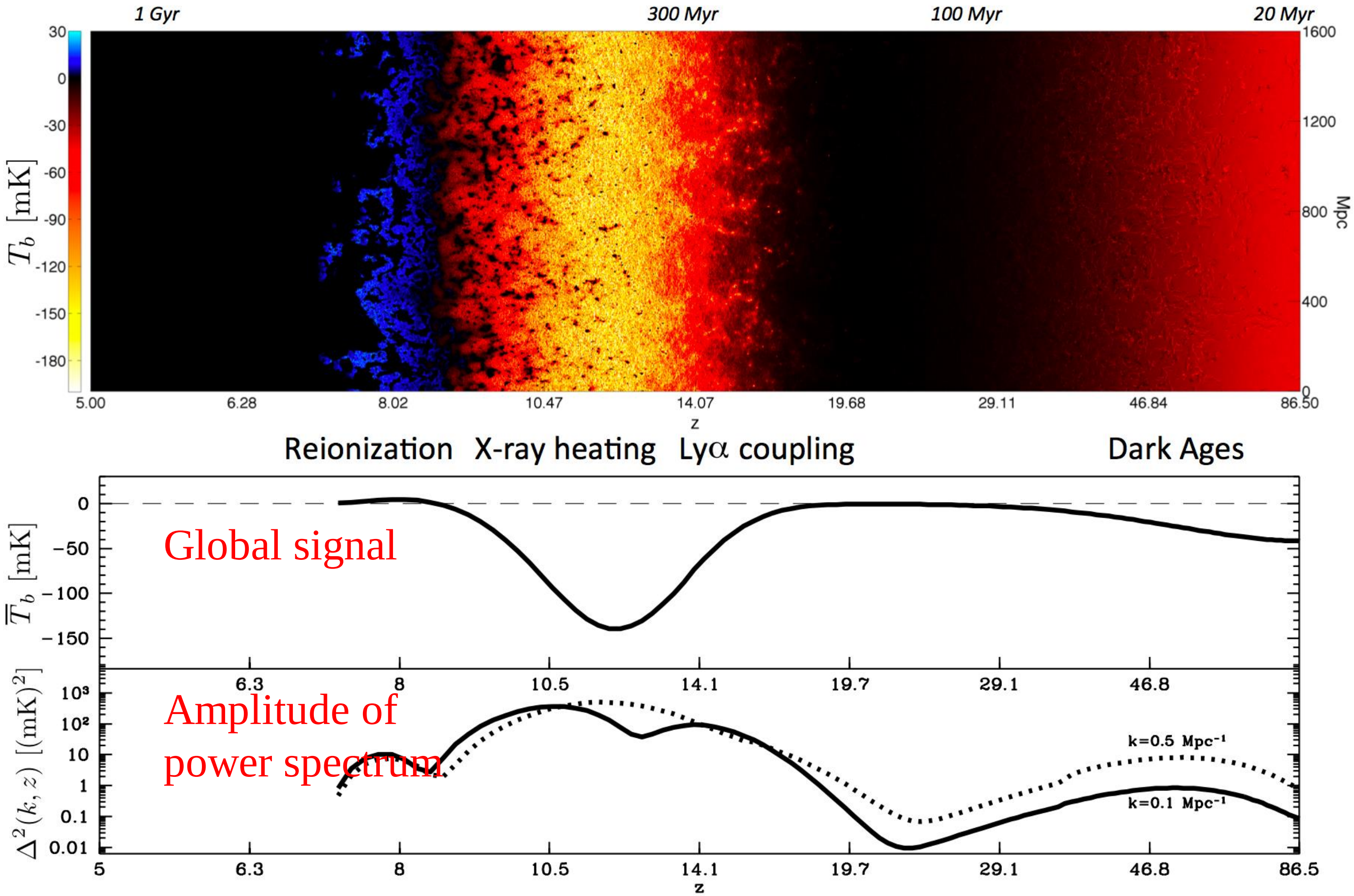


Figure from Liu & Shaw (2019), "Data Analysis for Precision 21cm Cosmology"

Potential Observables

Global Signal

Temperature history of IGM

Power spectrum of fluctuations and its evolution

When and how quickly reionization occurred (versus z)

Nature of ionizing sources (versus spatial scale)

Constraints on cosmologies (more complicated/difficult)

Higher order statistics of fluctuations (expect strong non-gaussianity)

Cross-correlation with other tracers (esp. Infrared redshifted Ly-alpha)

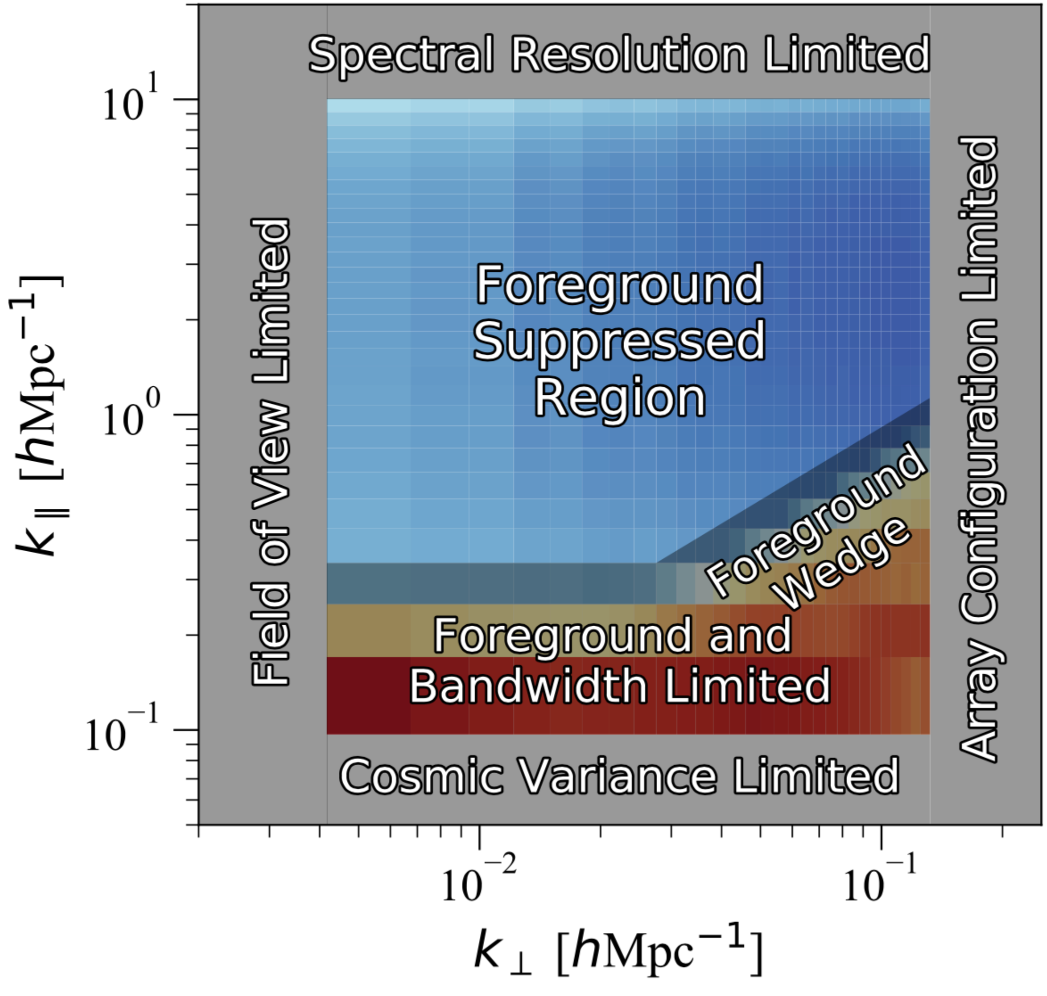
Integrated density-weighted ionization fraction (reionization optical depth)

Ionized regions around known quasars (neutral fraction, escape fraction)

Cosmic string wake structures

Fuzzy dark matter structures

Greatest Challenge: Foregrounds
10^4 - 10^5 as strong as signal (like CMB polarization maps)



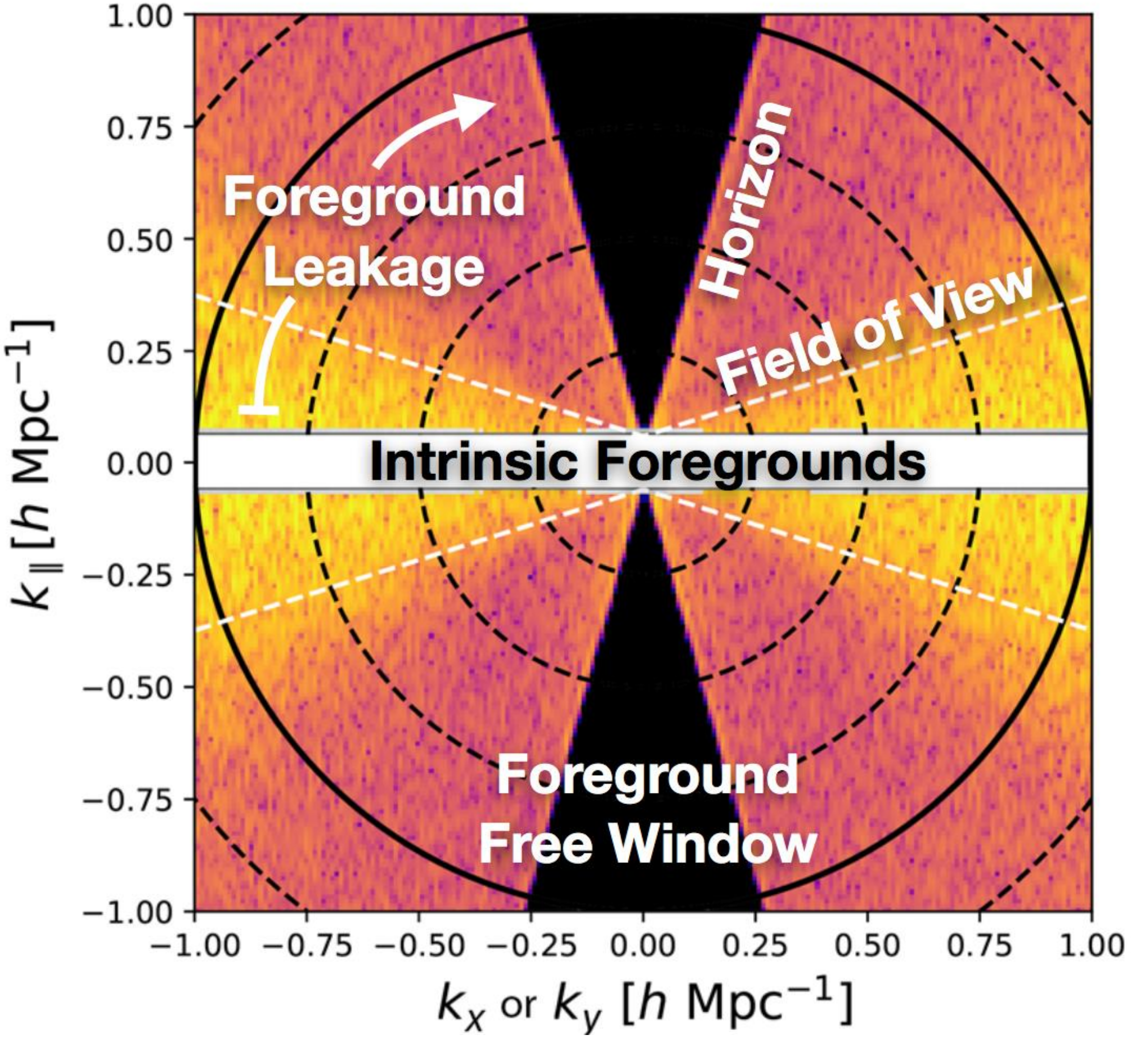
Avoid

Subtract

Simultaneously fit*

**Peter Sims talk later*

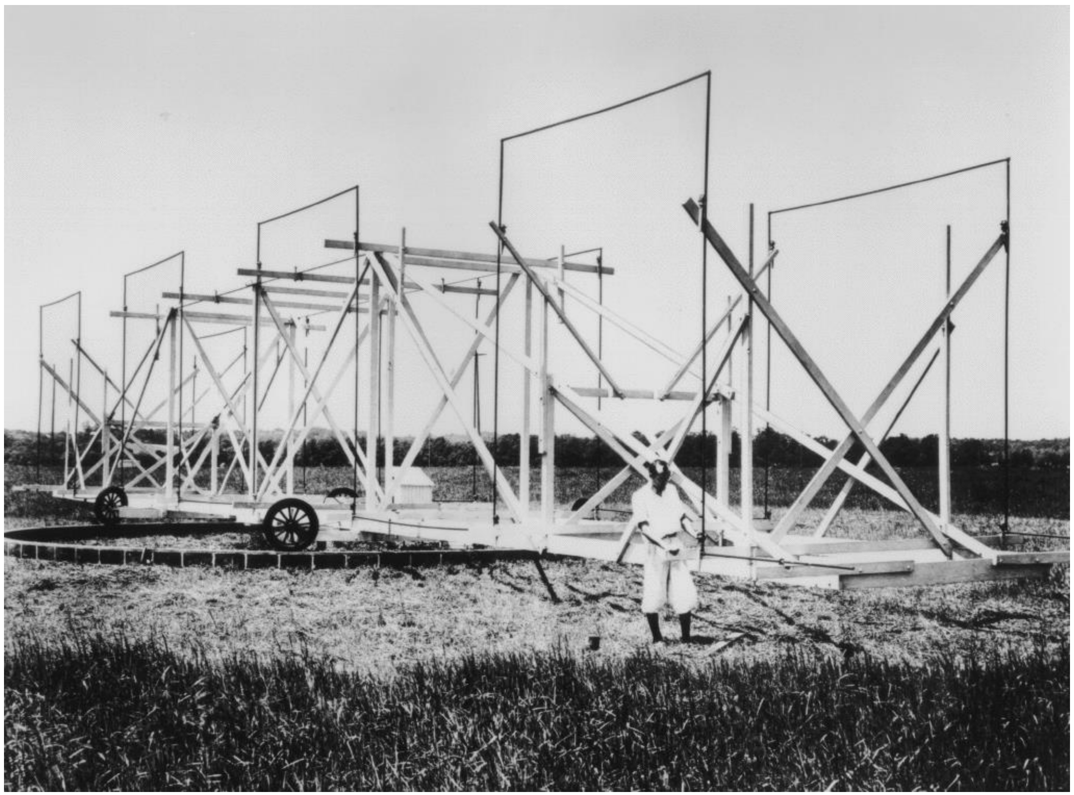
EoR window drawn to scale
Frequency axis important for signal (unlike CMB)



Source: HERA Collaboration

Low frequencies…retro

Radio Astronomy ca. 1930



Hogan & Rees 1979

21cm emission or absorption might be visible with present techniques out to 1+z ~ 10 (150 MHz)…These observations would be a valuable probe of cosmic structure at early times.

Design Choices: Performance and Cost

Single antenna or interferometer?

Size, number of elements?

Configuration: redundant (calibration, coherent power spectra) or not (imaging)

Which baseline lengths to target?

Size of field of view?

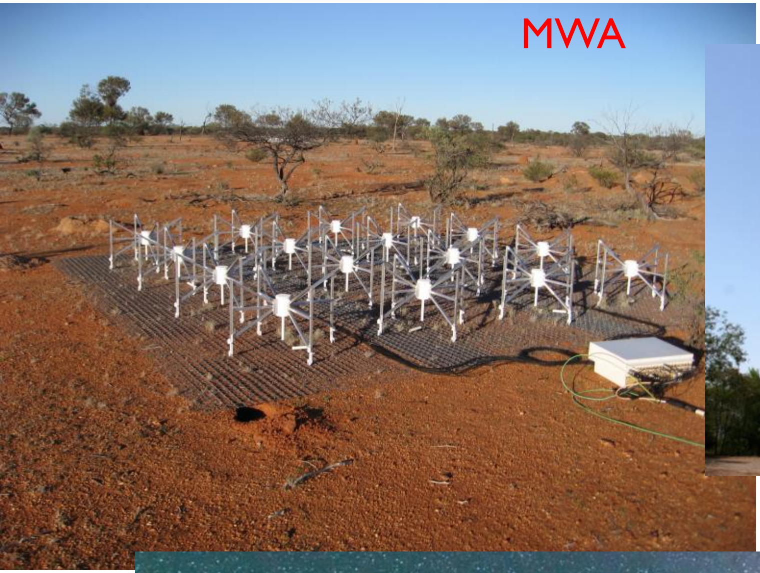
Drift scan or track?

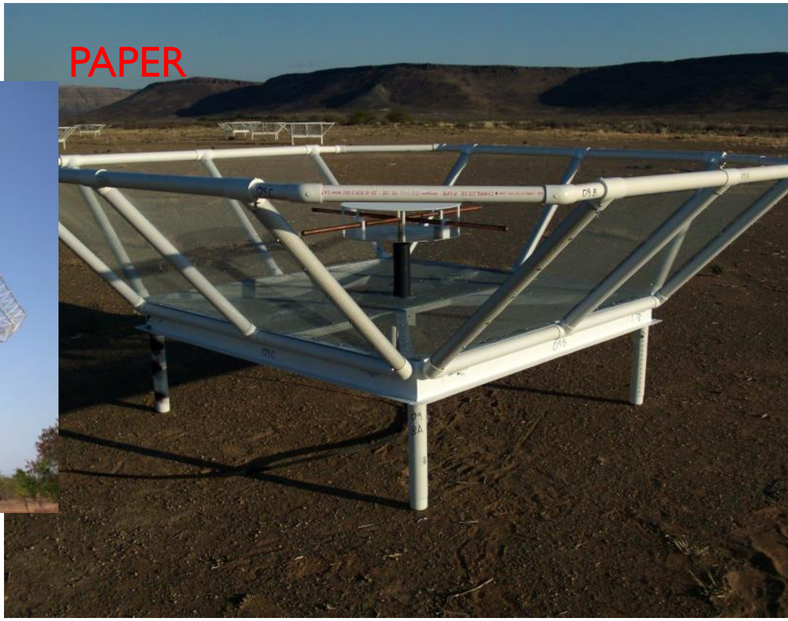
Analyze visibilities or produce images?

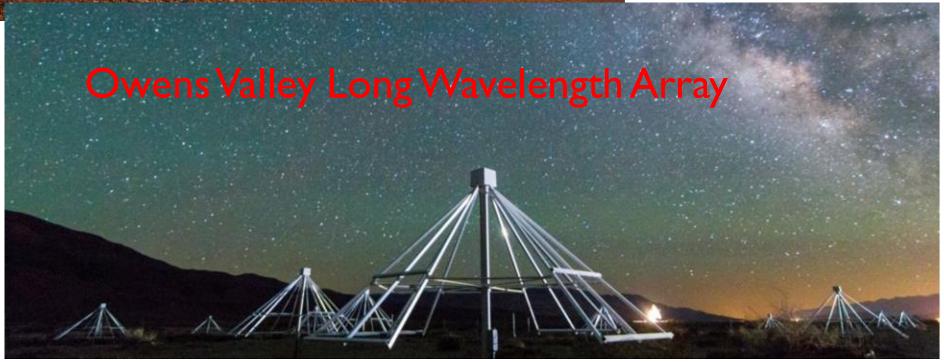
Assume foreground avoidance, subtraction, or simultaneous fitting?

Calibration strategy – redundant or sky-based?

First Generation Interferometers for 21cm Cosmology







Many different approaches used by the different experiments:

Sky calibration, redundant calibration, direction-dependent sky calibration

Direct delay spectrum analysis of visibilities
Gridded Fourier inversion to make image – then Fourier analysis
Gridded Fourier inversion to make image – then optimal quadratic estimator
Optimal quadratic estimator of visibilities
Optimal mapping
New: Bayesian cosmology+foregrounds parameter estimation*

Foreground avoidance
Foreground model subtraction
Down-weighting power spectrum modes according to foreground strength

*Peter Sims talk

See *Liu & Shaw (2019), "Data Analysis for Precision 21cm Cosmology"*

Current Limits on the 21cm Power Spectrum

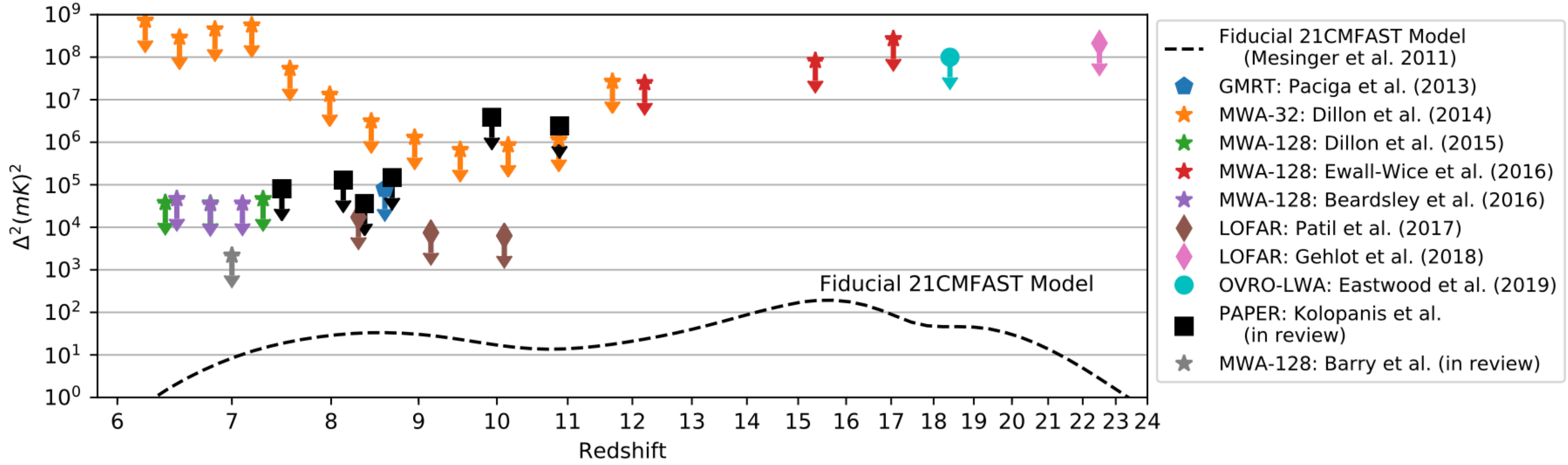


Figure 7. A summary of current upper limits on EoR power spectrum measurements. The limits are expressed as $\Delta^2(k) \equiv k^3P(k)/2\pi^2$ values evaluated at the k bin that gives the most competitive (i.e., lowest) upper limit for each experiment. Thus, different points on the plot come from different k values. A direct comparison between them is thus unfair in principle, and in practice is somewhat reasonable only because the theoretical predictions for $\Delta^2(k)$ are often fairly flat in the range $0.1\,h\mathrm{Mpc}^{-1} < k < 1\,h\mathrm{Mpc}^{-1}$ (see Figure 4). (Only the LOFAR points fall outside this range). Also shown is a fiducial theoretical model from the **21cmFAST** semi-analytic code (Mesinger et al. 2011)

Figure from Liu & Shaw (2019), "Data Analysis for Precision 21cm Cosmology"

Most recent limit achieved via:

MWA Phase I 2013 data

Instrument-based and RFI editing; raw data averaging

Imaging (FHD): calibrate, uv grid, accumulate in images, back to uv

Power spectrum: Lamb-Scargle periodogram over f to get (u,v,eta), error propagation,

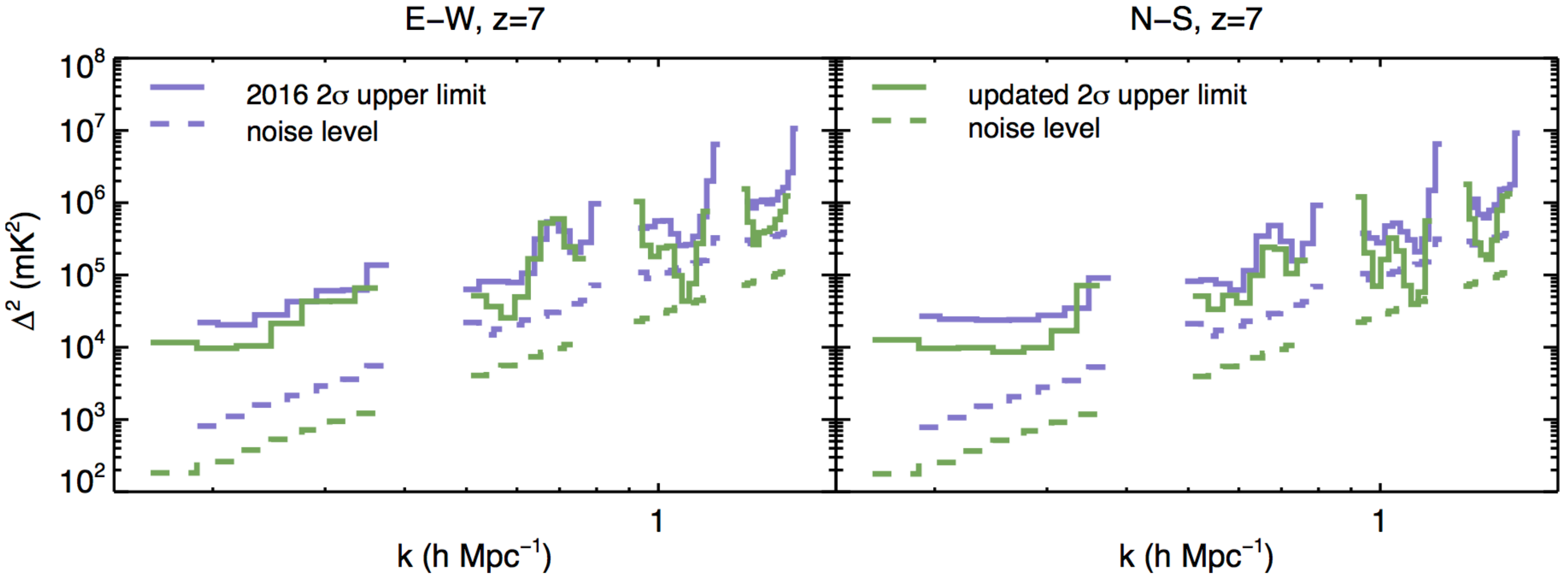
3D Fourier transform => 2D, 1D spectra

Improved since 2016 analysis:

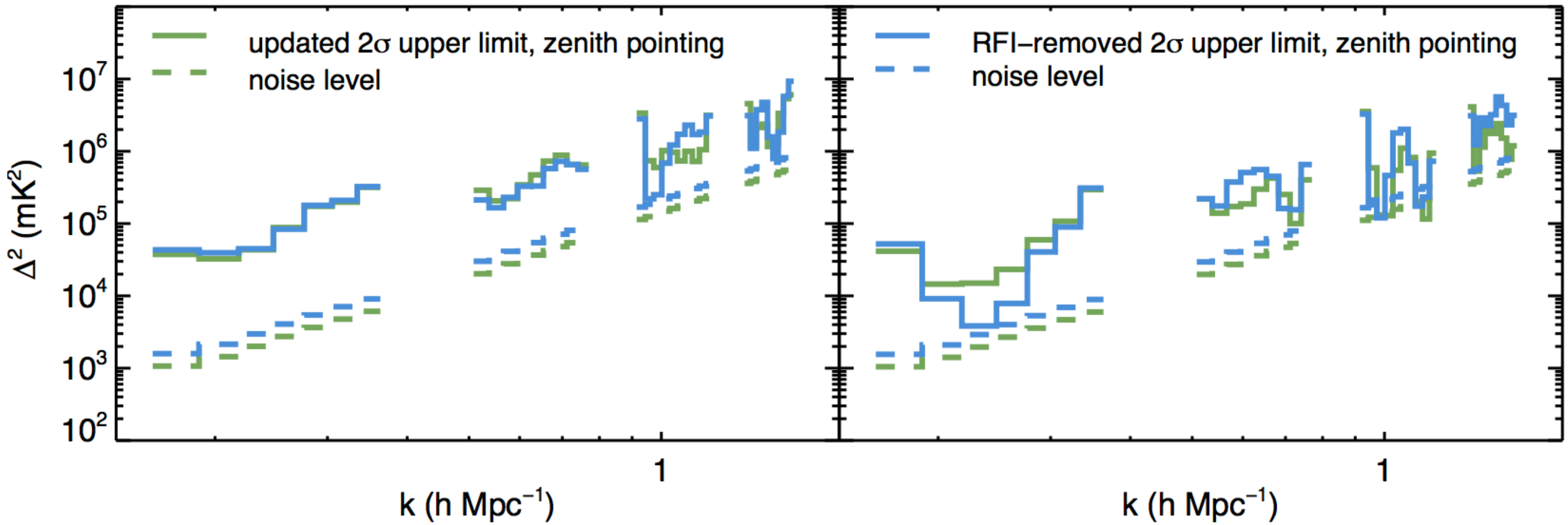
- Flux calibration (GLEAM survey) and bandpass calibration
- More aggressive instrument-based editing
- Reduction of aliasing effects in image accumulation
- Better RFI detection

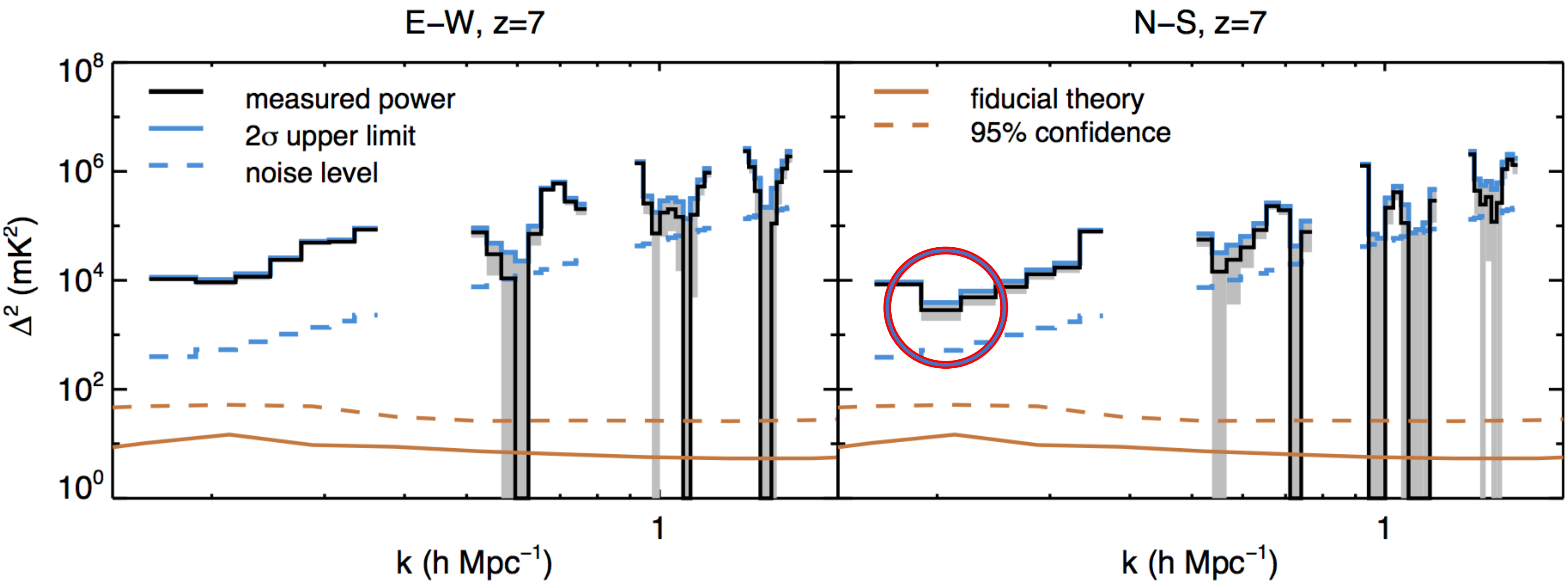
Barry, Wilensky, Trotter et al. (2019), "Improving the EoR Power Spectrum Results from MWA Season 1 Observations

Comparing same data – analysis improvements



Additional RFI editing for zenith pointing



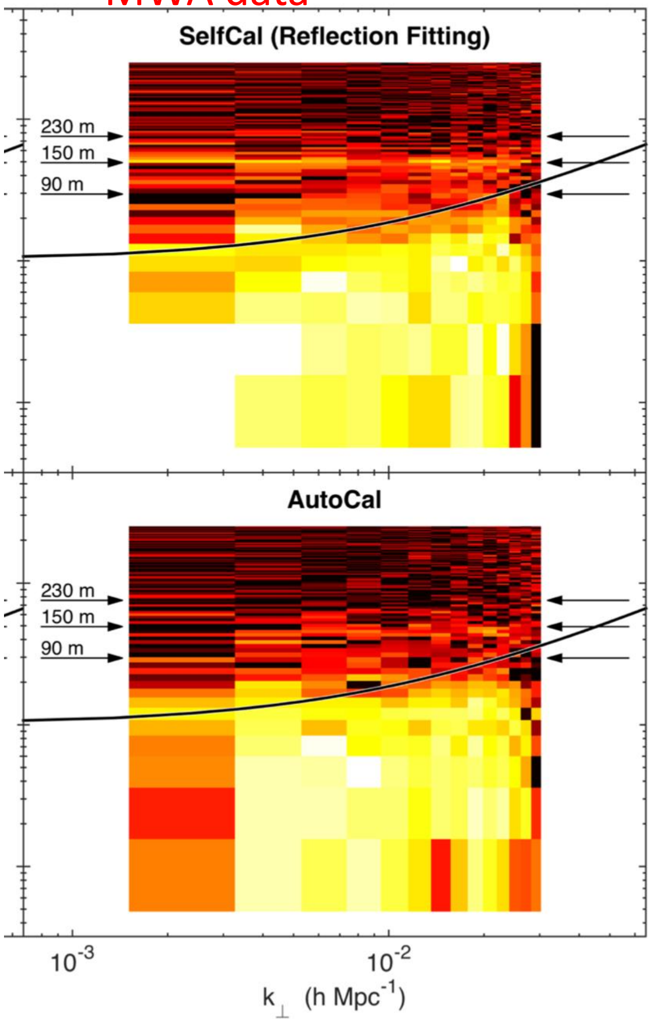


Upper limit is 3900 mK^2

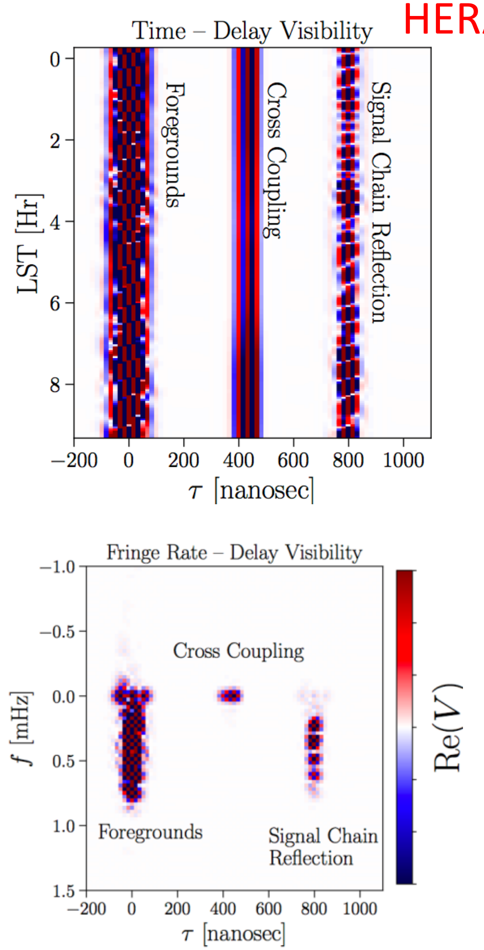
Barry, Wilensky, Trotter et al. (2019), "Improving the EoR Power Spectrum Results from MWA Season 1 Observations

Steady Progression of Identification of Systematic Errors and Their Removal

MWA data



HERA simulations



Cable Reflections
Ewall-Wice, Dillon, Hewitt et al. (2016)

Reflections and cross-coupling
Kern, Parsons, Dillon, & Lanman (2019)

Second generation experiment are under construction:

Hydrogen Epoch of Reionization Array (HERA)

MWA Phase II

SKA1- Low

Funded by the United States National Science Foundation (A. Parsons, PI)
and the Gordon and Betty Moore Foundation (J. Hewitt, PI)

DeBoer, Parsons, Aguirre, et al. (2017), "Hydrogen Epoch of Reionization Array"

Motivations for HERA:

- Detect and study evolution of EoR power spectrum
- Include Epoch of X-ray heating, before reionization
- Do other studies of EoR (cross-correlation, search for bubbles, etc.)
- Implement design changes - lessons learned from first generation experiments
- Technology/technique development for further expansion of arrays in the future

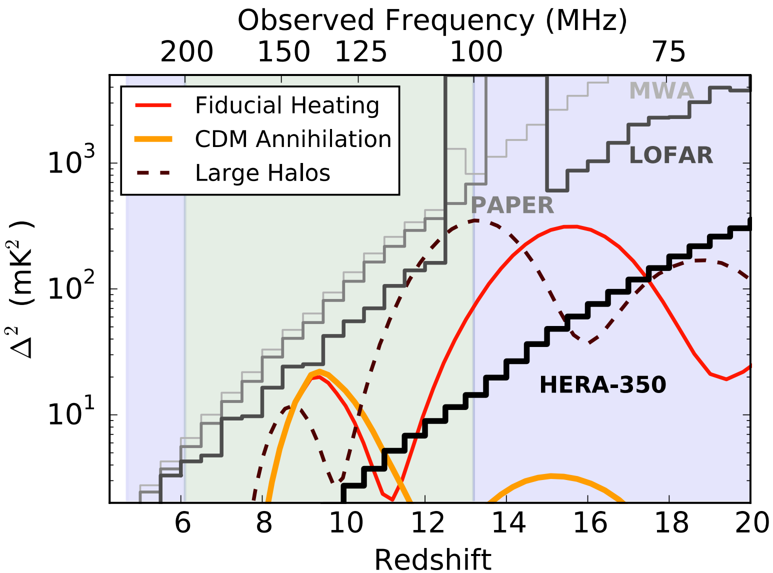
HERA is optimized for power spectrum studies
and foreground *avoidance* (does not assume foreground *subtraction*)

Table 1
Predicted S/N of 21 cm Experiments for an EoR Model with 50% Ionization at $z = 9.5$, with 1080 hr Observation, Integrated over a Δz of 0.8

Instrument	Collecting Area (m^2)	Foreground Avoidance	Foreground Modeling
PAPER	1,188	0.77σ	3.04σ
MWA	3,584	0.31σ	1.63σ
LOFAR NL Core	35,762	0.38σ	5.36σ
HERA-350	**53,878**	**23.34**σ	**90.97**$\boldsymbol{\sigma}$
SKA1 Low Core	416,595	13.4σ	109.90σ

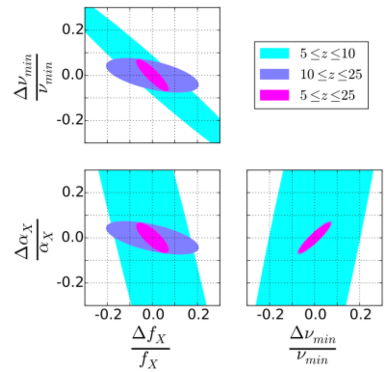
DeBoer, Parsons, Aguirre, et al. (2017), "Hydrogen Epoch of Reionization Array"

Theoretical Power Spectrum Sensitivity of HERA

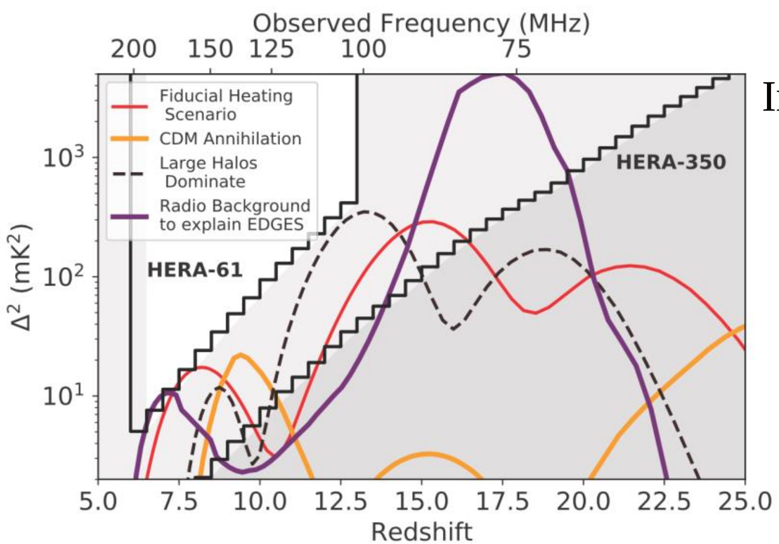


"Normal" models

Extension to low frequencies under way



Ewall-Wice, Hewitt, Mesinger et al. (2016)



Including an EDGES-consistent model

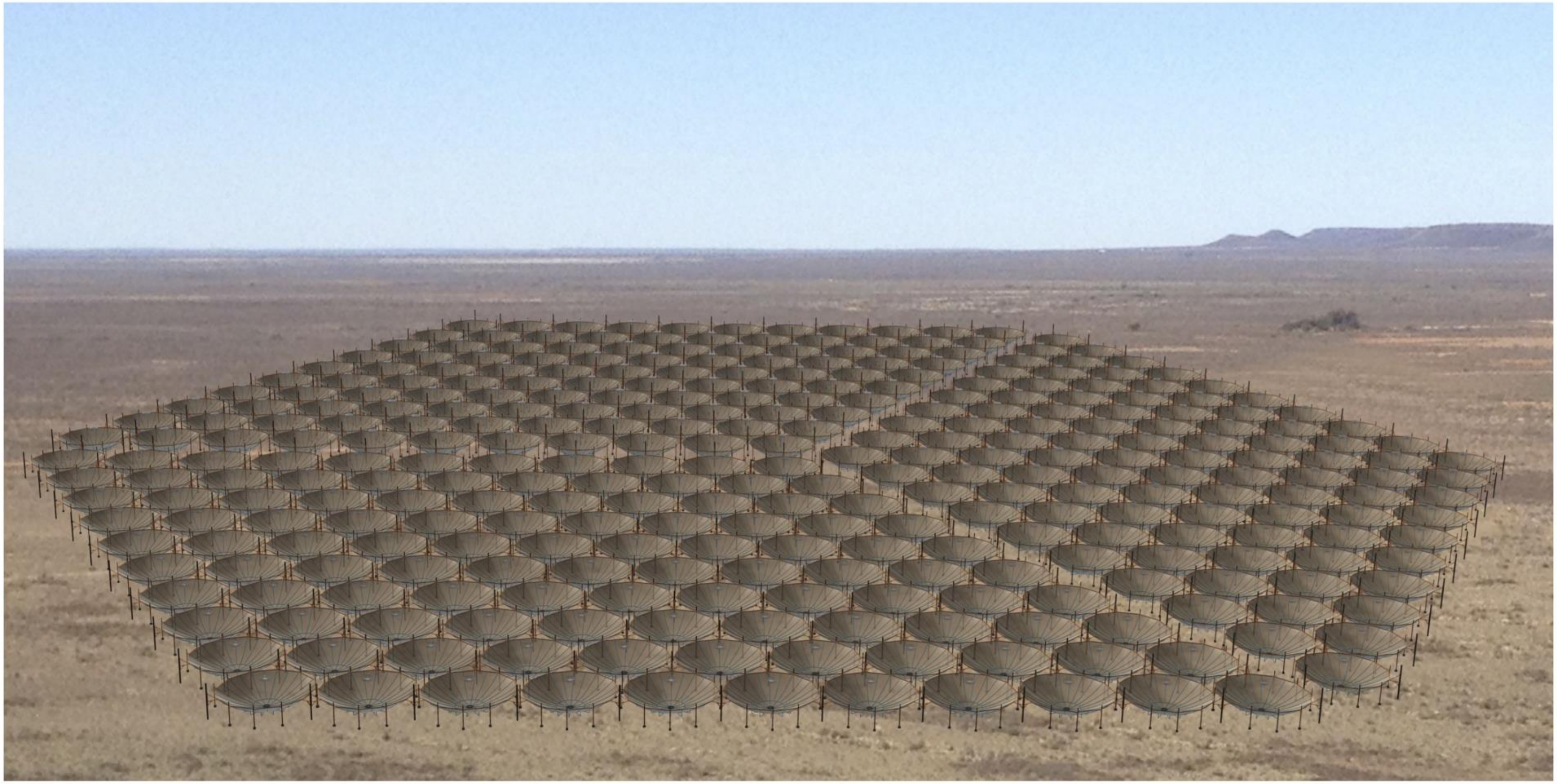
Figures by A. Ewall-Wice

HERA Design Choices

- Fixed dishes to maximize collecting area per dollar
- Focal length and cable lengths chosen so reflections are outside EoR window
- Smaller field for better calibration and to suppress foregrounds on the horizon
- Redundant array for better calibration and power spectrum sensitivity
- Compact array for more baselines in the EoR window (foreground avoidance strategy)
- Outliers and “fractured crystal” for better imaging

For a full discussion see *DeBoer, Parsons, Aguirre, et al. (2017), “Hydrogen Epoch of Reionization Array”*

Artist’s rendering of 320-element HERA core



There are also 30 “outliers”
For the analysis leading to this design choice see *Dillon & Parsons (2016), “Redundant Array Configurations for 21cm Cosmology”*

SEASON 1 OBSERVATIONS DONE

50-Element High-Band (100-200 MHz) System

Redshifts 6.1 - 14

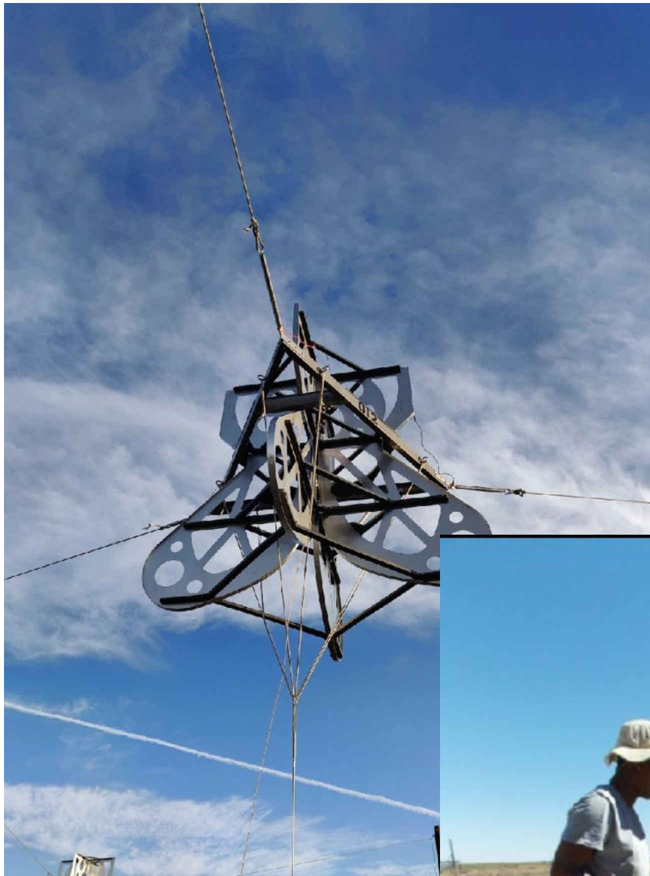
Data taken during Sep 2017-May 2018 season

Analysis in Progress; Power Spectrum limits forthcoming

Photo credit: J. Dillon

Photo credit: J. Dillon

Six prototype broadband feeds were installed and operated in South Africa; accepted after Critical Design Review in April



Extra cable to delay reflections outside the EoR window

48 broadband feeds and electronics are currently installed; production and installation continue

Correlator expansion complete

Plan to begin N=96 science observations in late October

Critical path set by availability of eyebolts in South Africa

How I spent (part of) my sabbatical – installing eyebolts

Status of 21cm Cosmology Experiments

EDGES global signal result
- Extremely important if cosmology interpretation of absorption line is correct
- Further EDGES measurements and other global signal experiments under way

First generation power spectrum experiments essentially complete
- Series of limits placed over a broad range of redshifts
- Important lessons have been learned and limits are improving

Second generation experiments – construction/data-taking/analysis under way
- Results…soon…