21cm Cosmology: Reionization, Heating, and the Dark Ages

Jacqueline N. Hewitt

(with Adrian Liu)

21cm Cosmology: Reionization, Heating, and the Dark Ages

The Big Picture: First-Order Models of Global Properties

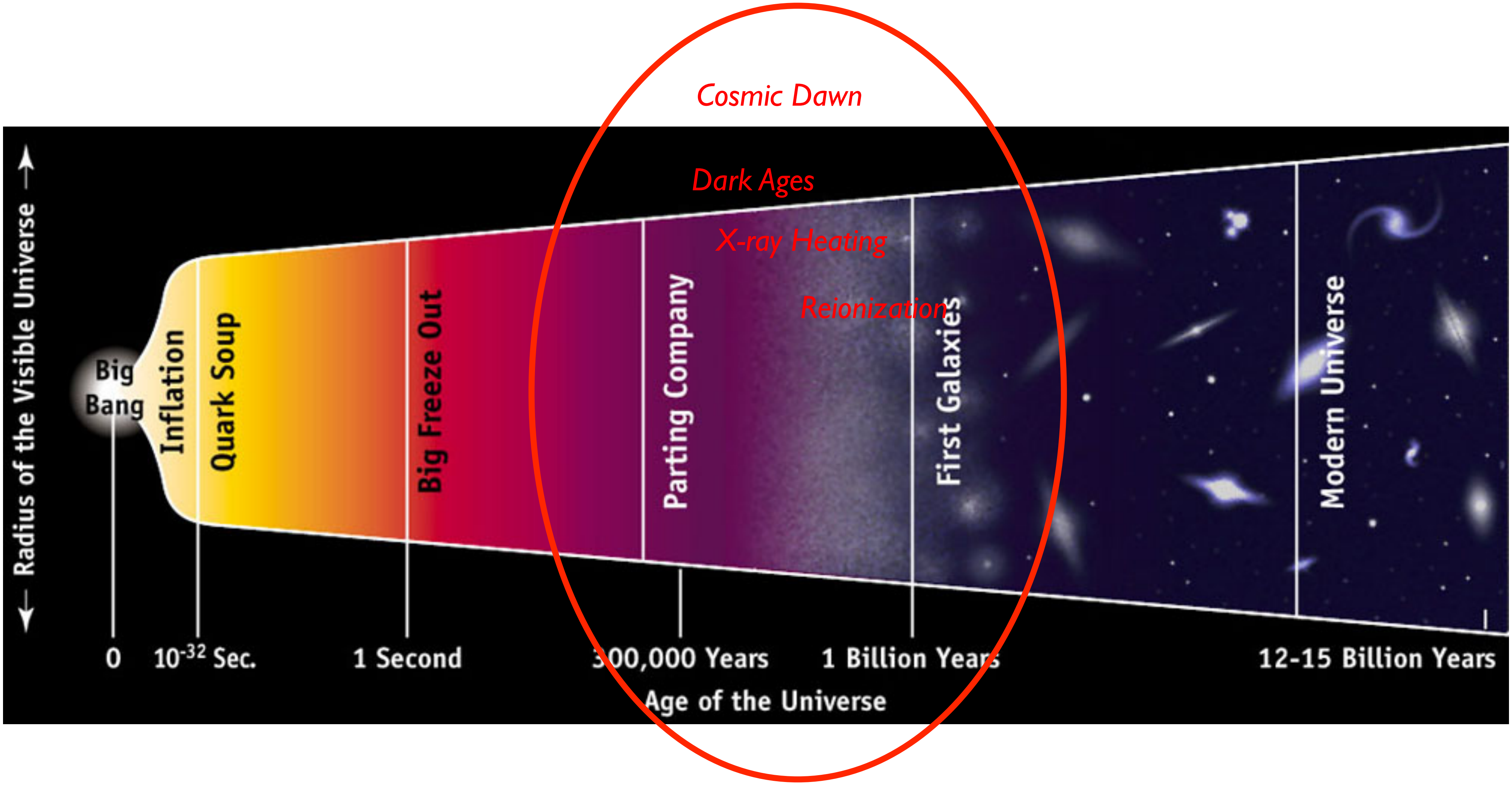
Reionization and Beyond: Second-Order Models of Fluctuations

The Ideal: Cosmology from 21cm Tomography

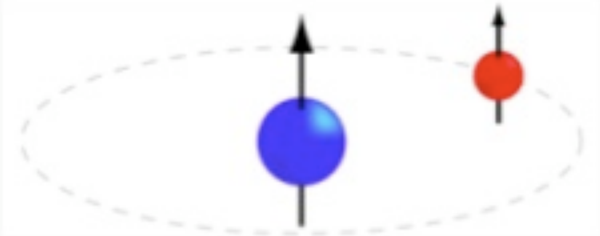
The Reality: Astrophysics, Foregrounds, RFI, and Instruments

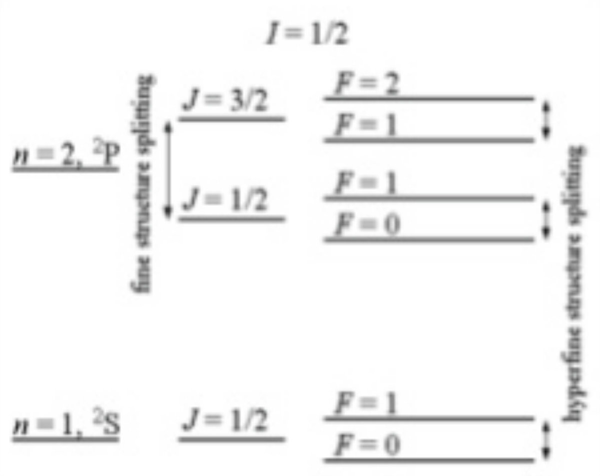
Experiments Past and Future

GOALS: Map the emergence of structure (short term) and probe cosmology and inflation (long term)



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





Source: Wikipedia

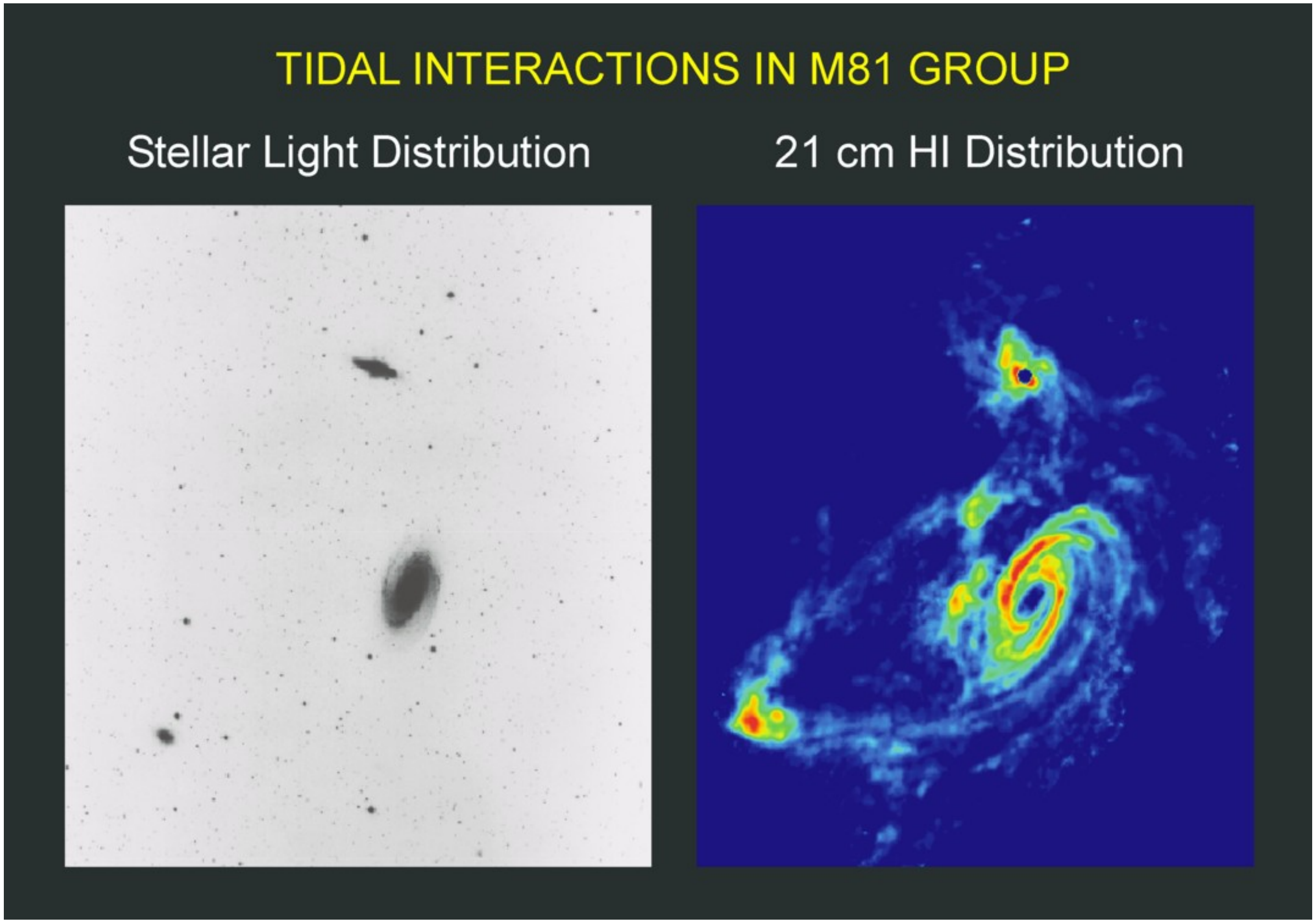
Neutral hydrogen is a tracer of structures

Hyperfine splitting in ground state causes emission and absorption of radio waves at a frequency of

1420.40575177 MHz

Redshift > 6 means observe at < 200 MHz
Low-Frequency Radio Astronomy

STRATEGY: Map hydrogen structures



TIDAL INTERACTIONS IN M81 GROUP

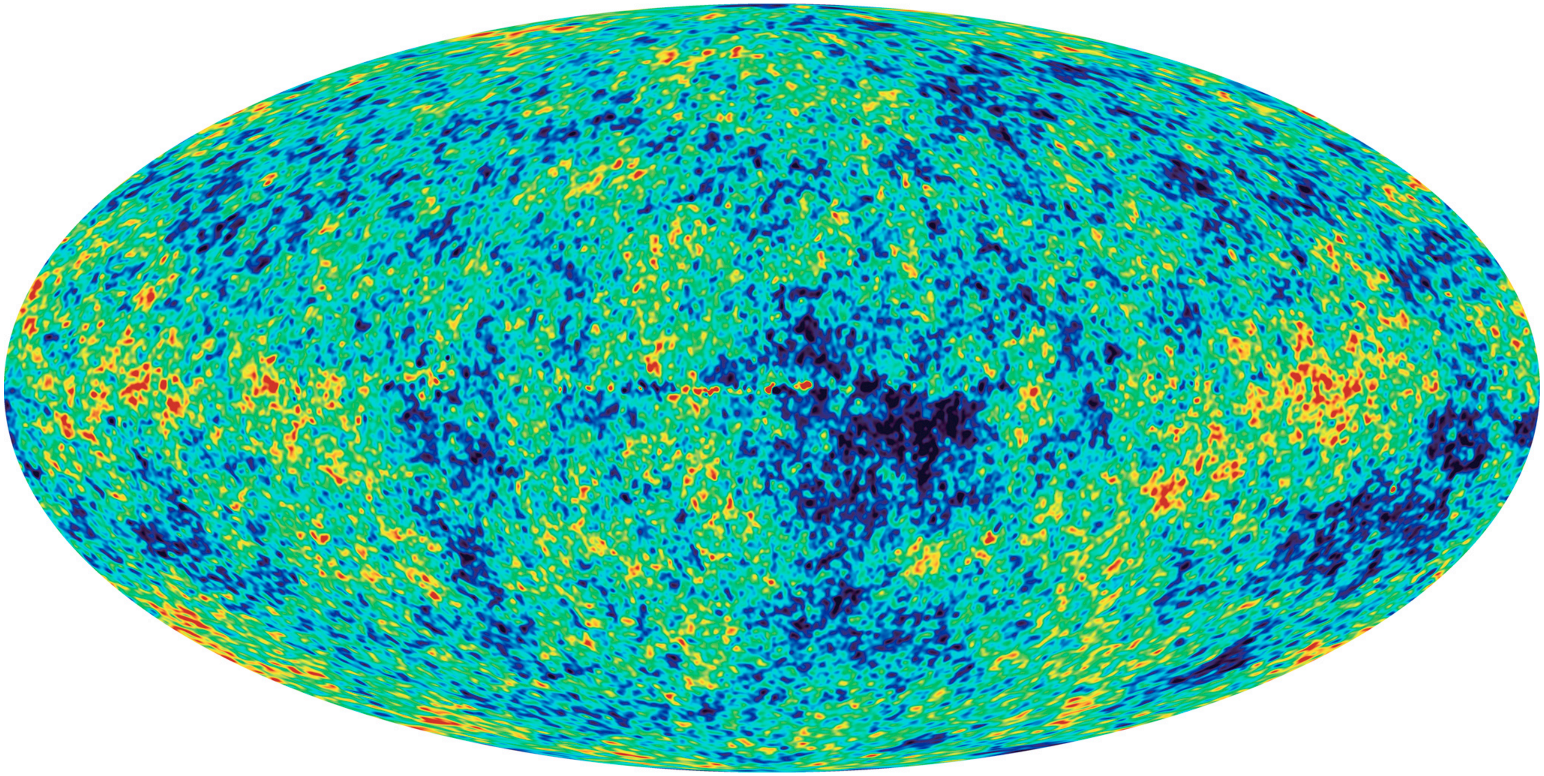
Stellar Light Distribution

21 cm HI Distribution

Example: the M81 group of galaxies

Source: National Radio Astronomy Observatory

THEORETICAL PREDICTIONS:
The cosmic microwave background gives us the initial conditions for simulations of structure formation



- Expanding Universe: everything (photons and matter) cools
- (Dark Energy)
- Big Bang nucleosynthesis: dark matter, hydrogen, (deuterium, helium, lithium)
- Gravity: collapse and form structures
- Astrophysics: gas clumps, shocks, stars form, heating, ionization (messy)

21cm line emission or absorption against the CMB

$$\delta T_B = 27 x_{HI}(1+\delta_b)\left(\frac{T_S - T_{\rm CMB}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

Predictions involve - temperature evolution

- initial power spectrum and density evolution

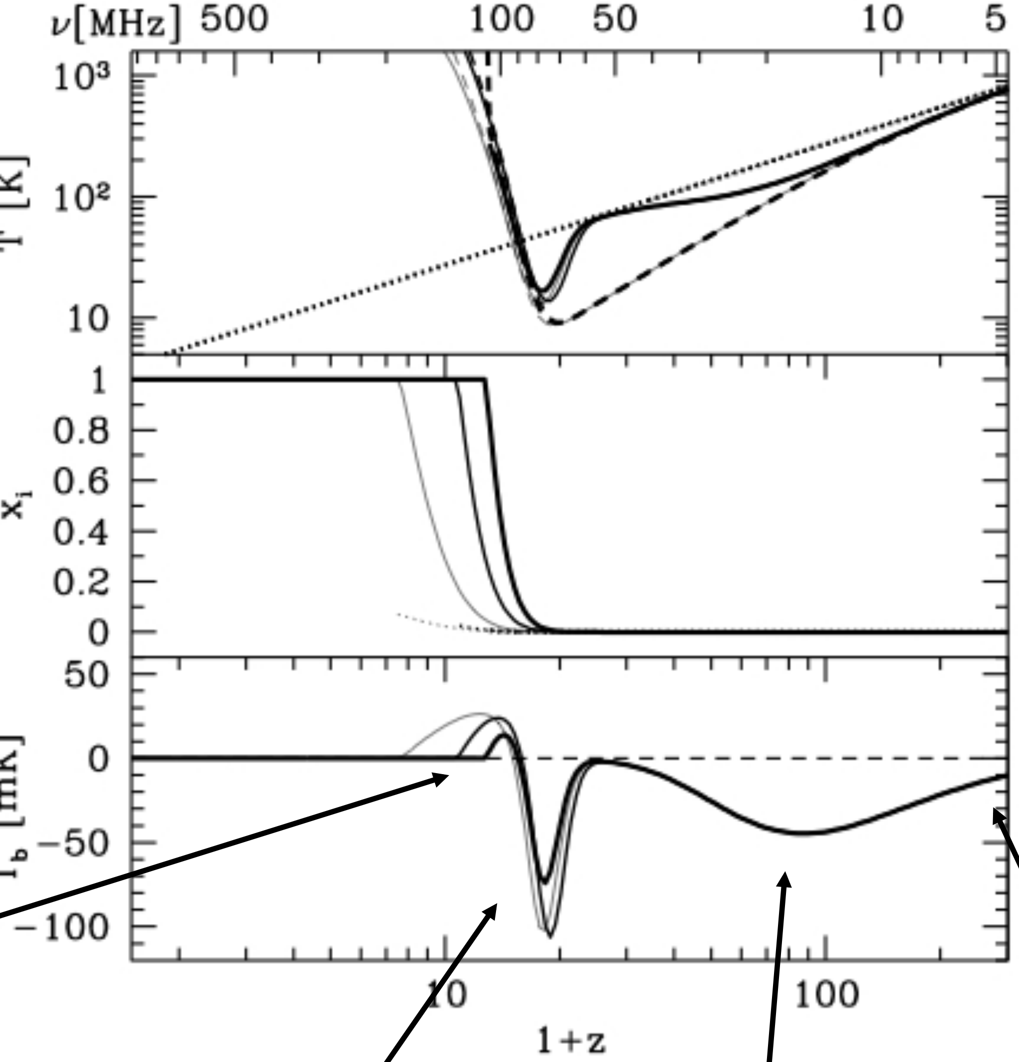
- ionization

- background cosmology

- and redshift distortions due to proper motion

FIRST ORDER: Models of Global Properties of the Universe

Pritchard & Loeb 2008



CMB temperature
Spin temperature
Gas temperature

Ionization fraction; three models consistent with WMAP

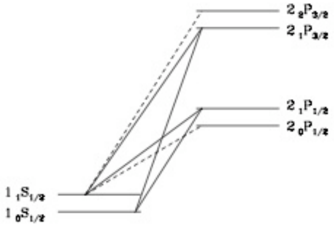
Brightness temperature in 21cm line; three models again

Ly-alpha pumping important; gas hot

Ly-alpha pumping (Wouthuysen-Field effect) important; gas cold

Gas collisions important

Thomson scattering important



GOALS: Map the emergence of structure (short term) and probe lambda-CDM cosmology model and inflation (long term)

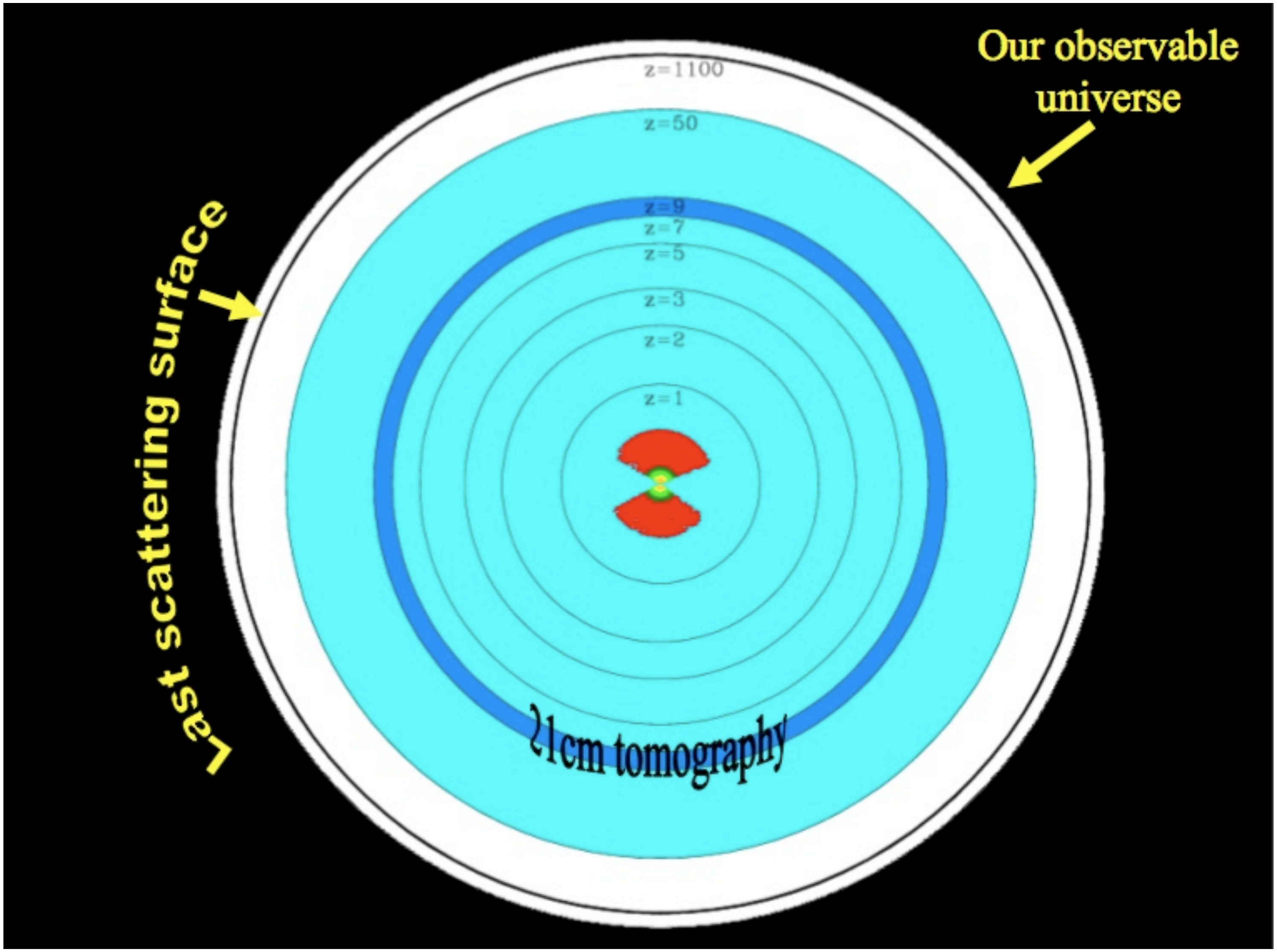
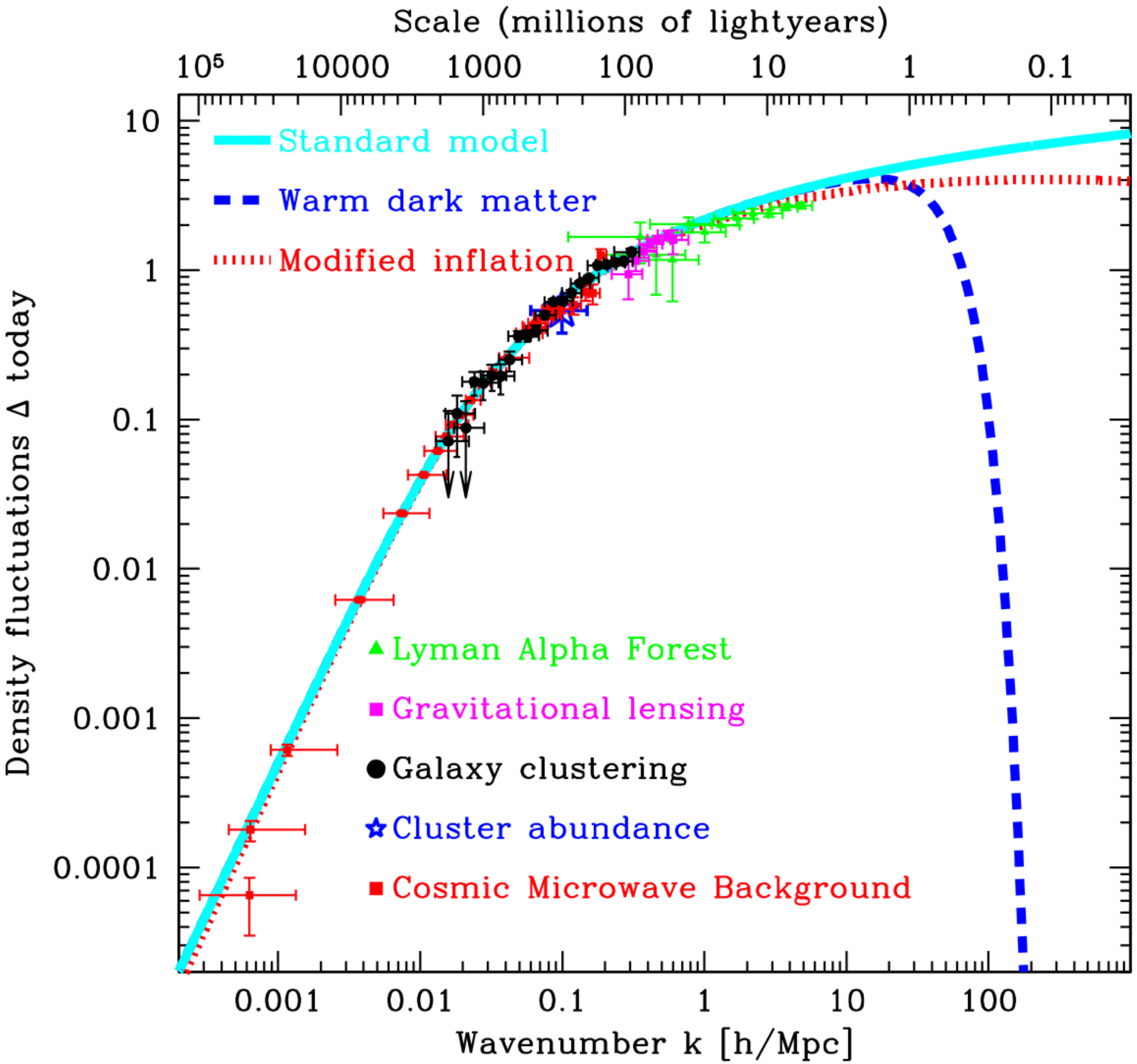


Figure courtesy of Max Tegmark



Tegmark & Zaldarriaga 2009

In principle, mapping the large volume would give us

- Tests of the standard model prediction of T(z), H(z), and linear clustering growth
- Tests of modified gravity
- Precision tests of inflation by extending power spectrum to small scales
- Neutrino mass via power spectrum
- Precision tests of inflation via small-scale non-Gaussianity
- Precision tests of non-cold DM by probing galactic scales when linear
- Heating signatures of DM annihilation
- Non-standard physics
- Primordial features in inflation or oscillations in massive fields
- Primordial non-Gaussianity f_NL ~0.03
- Measure cosmological parameters with higher precision through high SNR made possible by large number of measurable modes

Tegmark & Zaldarriaga 2009
Chen, Meerburg & Münchmeyer 2016
Munoz, Ali-Haimoud & Kamionkowski 2015

SEPARATING ASTROPHYSICS FROM COSMOLOGY

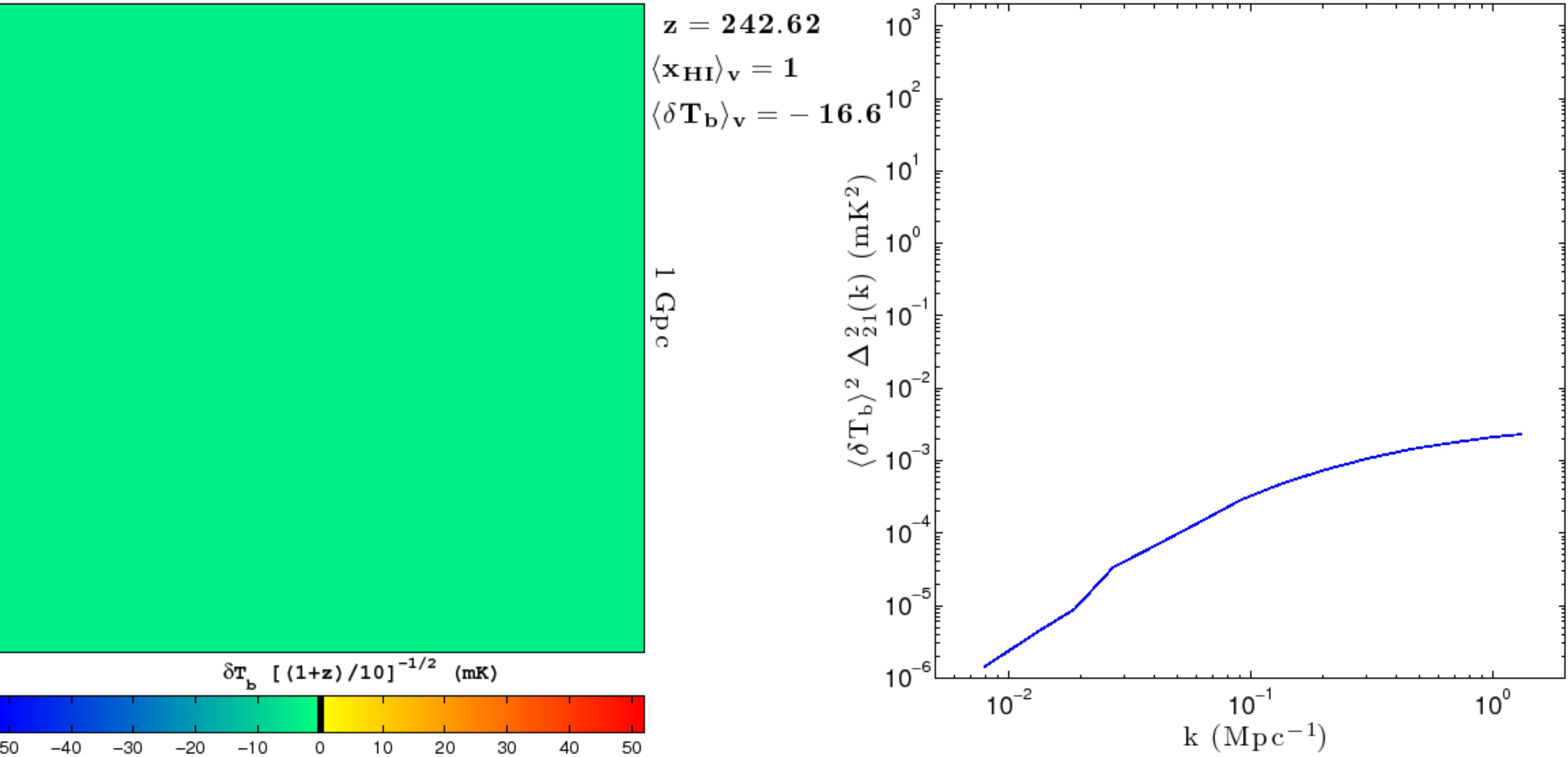
- Model the astrophysics well and marginalize over it
- Separate via redshift distortions (use cosine-line-of-sight dependence)
- Go to the highest redshifts when astrophysics is not important ($z > 25$ or 30 or so)
- BUT: foregrounds are $>10^4$ larger during EoR and scale as $T^{-2.5}$

CHALLENGING.

SECOND ORDER: Models of Fluctuations   z=243 to z=6.8
(More astrophysics)

A "slice" through space

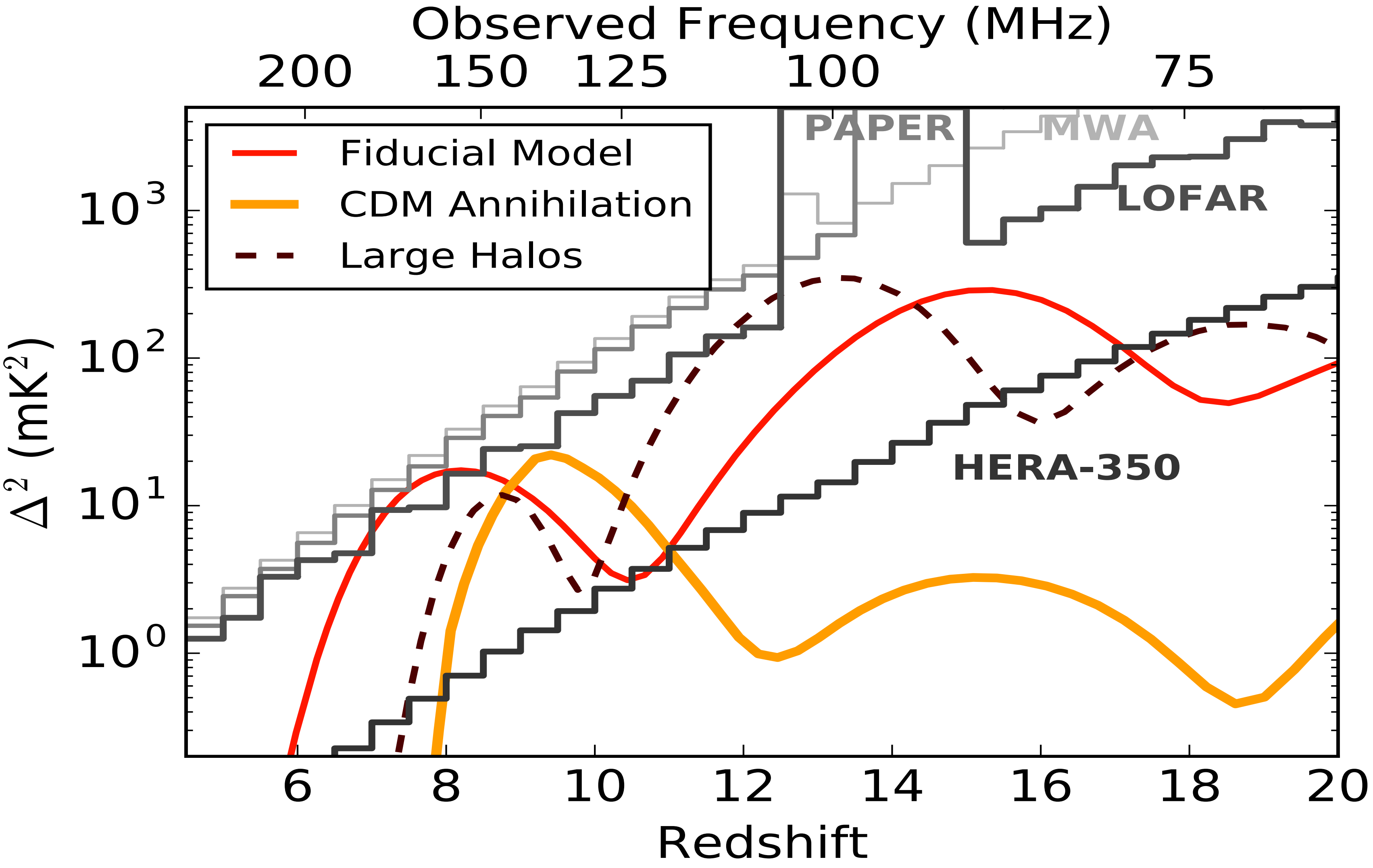
Square amplitude of 3-D Fourier transform, averaged over spheres in k-space



Relative to microwave background

Source: http://homepage.sns.it/mesinger/21cm_Movie.html

Power spectrum science z>6 :



See Mesinger, Ewall-Wice & Hewitt 2014

IMPORTANT POINTS

- There are (in most plausible models) three power spectrum peaks
- The first and second (reionization and (X-ray) heating) are roughly equally detectable in principle (just considering SNR)
- The third one is much harder to detect in principle (just considering SNR)
- The second and third ones are harder in practice because of systematics (foregrounds, RFI, calibration)
- Astrophysics *and* cosmology form these peaks – can we learn to separate them?
- Dark Ages will be really hard

Mao et al. 2008 – in-depth study of extracting fundamental cosmology during EoR (perfect calibration)

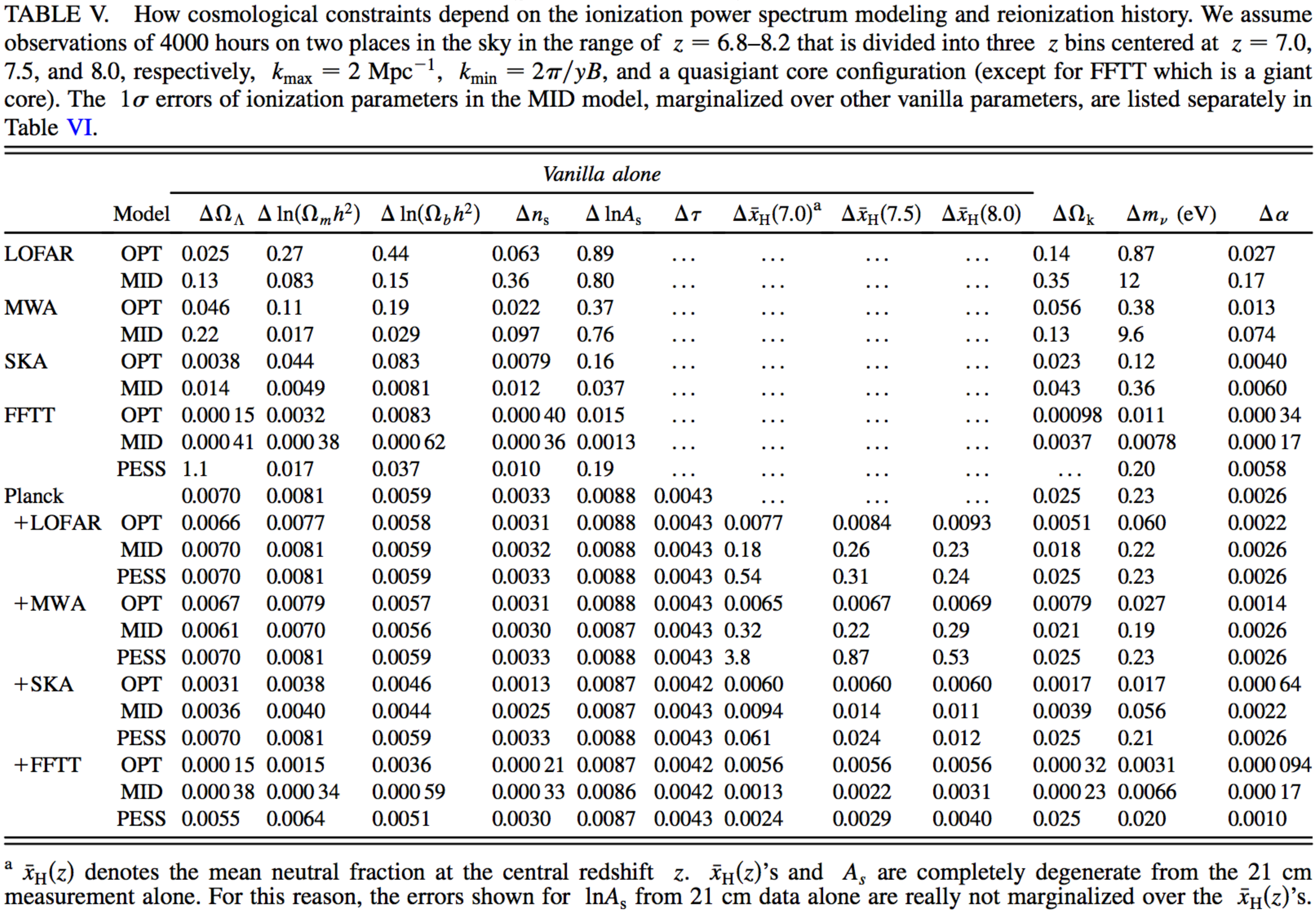


TABLE V. How cosmological constraints depend on the ionization power spectrum modeling and reionization history. We assume observations of 4000 hours on two places in the sky in the range of $z = 6.8$–8.2 that is divided into three z bins centered at $z = 7.0$, 7.5, and 8.0, respectively, $k_{\max} = 2\ \mathrm{Mpc}^{-1}$, $k_{\min} = 2\pi/yB$, and a quasigiant core configuration (except for FFTT which is a giant core). The 1σ errors of ionization parameters in the MID model, marginalized over other vanilla parameters, are listed separately in Table VI.

		Vanilla alone											
	Model	$\Delta\Omega_\Lambda$	$\Delta \ln(\Omega_m h^2)$	$\Delta \ln(\Omega_b h^2)$	Δn_s	$\Delta \ln A_s$	$\Delta\tau$	$\Delta\bar{x}_H(7.0)$[a]	$\Delta\bar{x}_H(7.5)$	$\Delta\bar{x}_H(8.0)$	$\Delta\Omega_k$	Δm_ν (eV)	$\Delta\alpha$
LOFAR	OPT	0.025	0.27	0.44	0.063	0.89	…	…	…	…	0.14	0.87	0.027
	MID	0.13	0.083	0.15	0.36	0.80	…	…	…	…	0.35	12	0.17
MWA	OPT	0.046	0.11	0.19	0.022	0.37	…	…	…	…	0.056	0.38	0.013
	MID	0.22	0.017	0.029	0.097	0.76	…	…	…	…	0.13	9.6	0.074
SKA	OPT	0.0038	0.044	0.083	0.0079	0.16	…	…	…	…	0.023	0.12	0.0040
	MID	0.014	0.0049	0.0081	0.012	0.037	…	…	…	…	0.043	0.36	0.0060
FFTT	OPT	0.000 15	0.0032	0.0083	0.000 40	0.015	…	…	…	…	0.00098	0.011	0.000 34
	MID	0.000 41	0.000 38	0.000 62	0.000 36	0.0013	…	…	…	…	0.0037	0.0078	0.000 17
	PESS	1.1	0.017	0.037	0.010	0.19	…	…	…	…	…	0.20	0.0058
Planck		0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	…	…	…	0.025	0.23	0.0026
+LOFAR	OPT	0.0066	0.0077	0.0058	0.0031	0.0088	0.0043	0.0077	0.0084	0.0093	0.0051	0.060	0.0022
	MID	0.0070	0.0081	0.0059	0.0032	0.0088	0.0043	0.18	0.26	0.23	0.018	0.22	0.0026
	PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.54	0.31	0.24	0.025	0.23	0.0026
+MWA	OPT	0.0067	0.0079	0.0057	0.0031	0.0088	0.0043	0.0065	0.0067	0.0069	0.0079	0.027	0.0014
	MID	0.0061	0.0070	0.0056	0.0030	0.0087	0.0043	0.32	0.22	0.29	0.021	0.19	0.0026
	PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	3.8	0.87	0.53	0.025	0.23	0.0026
+SKA	OPT	0.0031	0.0038	0.0046	0.0013	0.0087	0.0042	0.0060	0.0060	0.0060	0.0017	0.017	0.000 64
	MID	0.0036	0.0040	0.0044	0.0025	0.0087	0.0043	0.0094	0.014	0.011	0.0039	0.056	0.0022
	PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.061	0.024	0.012	0.025	0.21	0.0026
+FFTT	OPT	0.000 15	0.0015	0.0036	0.000 21	0.0087	0.0042	0.0056	0.0056	0.0056	0.000 32	0.0031	0.000 094
	MID	0.000 38	0.000 34	0.000 59	0.000 33	0.0086	0.0042	0.0013	0.0022	0.0031	0.000 23	0.0066	0.000 17
	PESS	0.0055	0.0064	0.0051	0.0030	0.0087	0.0043	0.0024	0.0029	0.0040	0.025	0.020	0.0010

[a] $\bar{x}_H(z)$ denotes the mean neutral fraction at the central redshift z. $\bar{x}_H(z)$'s and A_s are completely degenerate from the 21 cm measurement alone. For this reason, the errors shown for $\ln A_s$ from 21 cm data alone are really not marginalized over the $\bar{x}_H(z)$'s.

STUDY OF IDEAL SKA MEASUREMENTS
(no contribution from astrophysics; i.e., neutral fraction = 1 or astrophysics modeled perfectly)

Pritchard et al. 2014

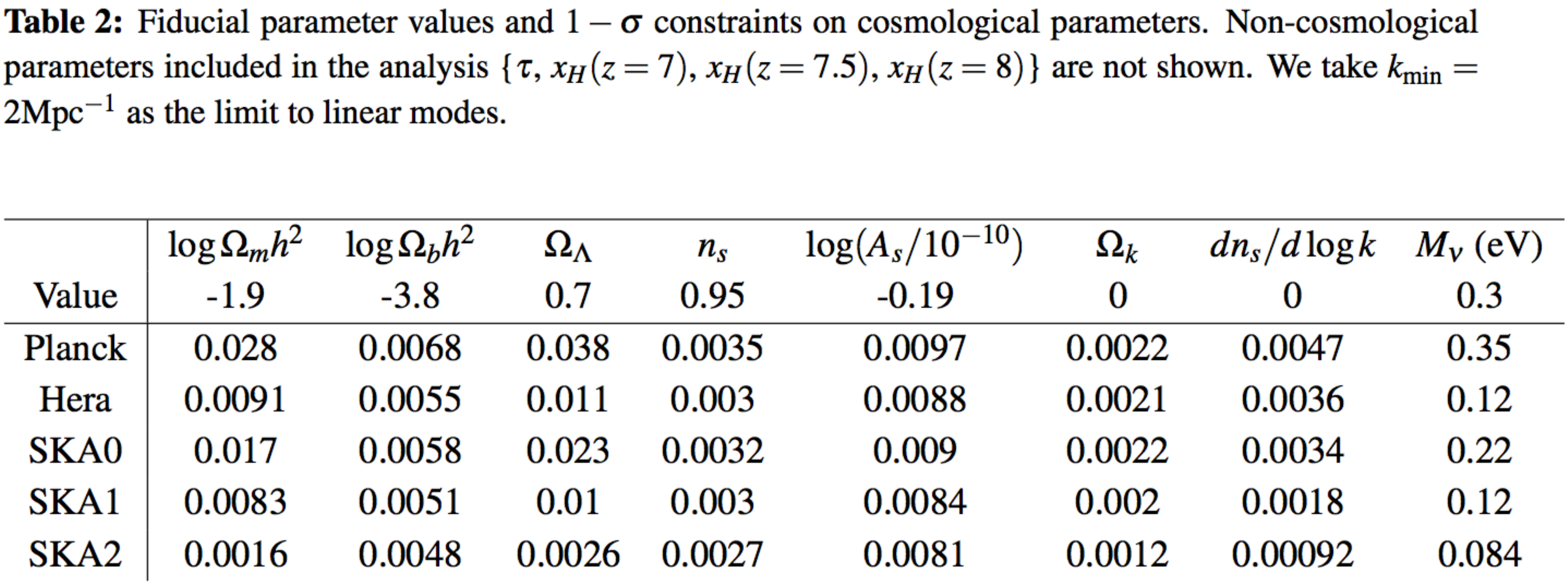


Table 2: Fiducial parameter values and $1-\sigma$ constraints on cosmological parameters. Non-cosmological parameters included in the analysis $\{\tau, x_H(z=7), x_H(z=7.5), x_H(z=8)\}$ are not shown. We take $k_{\rm min} = 2{\rm Mpc}^{-1}$ as the limit to linear modes.

	$\log\Omega_m h^2$	$\log\Omega_b h^2$	Ω_Λ	n_s	$\log(A_s/10^{-10})$	Ω_k	$dn_s/d\log k$	M_ν (eV)
Value	-1.9	-3.8	0.7	0.95	-0.19	0	0	0.3
Planck	0.028	0.0068	0.038	0.0035	0.0097	0.0022	0.0047	0.35
Hera	0.0091	0.0055	0.011	0.003	0.0088	0.0021	0.0036	0.12
SKA0	0.017	0.0058	0.023	0.0032	0.009	0.0022	0.0034	0.22
SKA1	0.0083	0.0051	0.01	0.003	0.0084	0.002	0.0018	0.12
SKA2	0.0016	0.0048	0.0026	0.0027	0.0081	0.0012	0.00092	0.084

Challenges of Low-Frequency Radio Astronomy

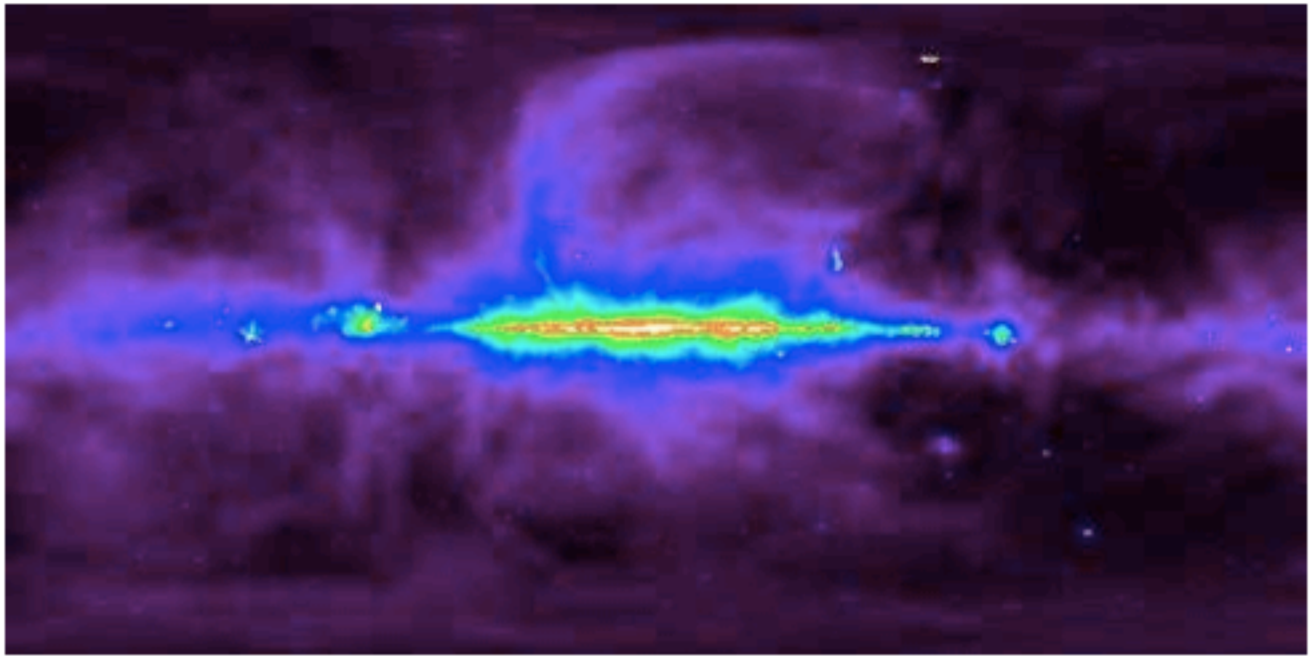
- Sky noise
- Foregrounds
- RFI
- Ionospheric fluctuations
- Calibration difficult

Require high speed computation to address – starting to be affordable only now
Instrument design must incorporate calibration requirements

The Galaxy - main source of sky noise – plus other radio galaxies

408 MHz Radio Map of the Sky – 1982

Resolution 0.85 degrees



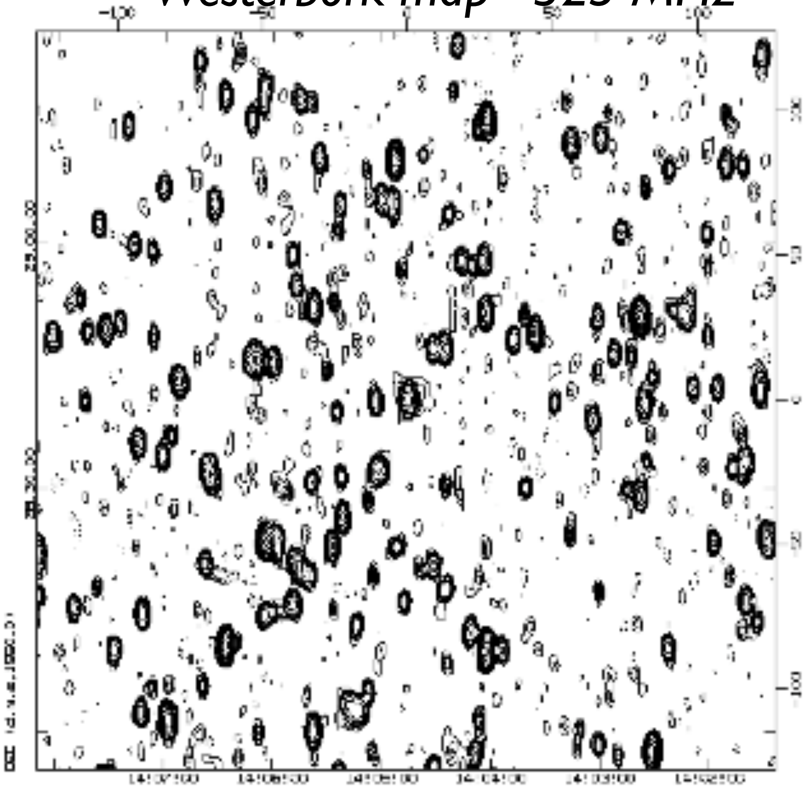
Haslam et al 1982 A&A Supp 47 1

Foregrounds

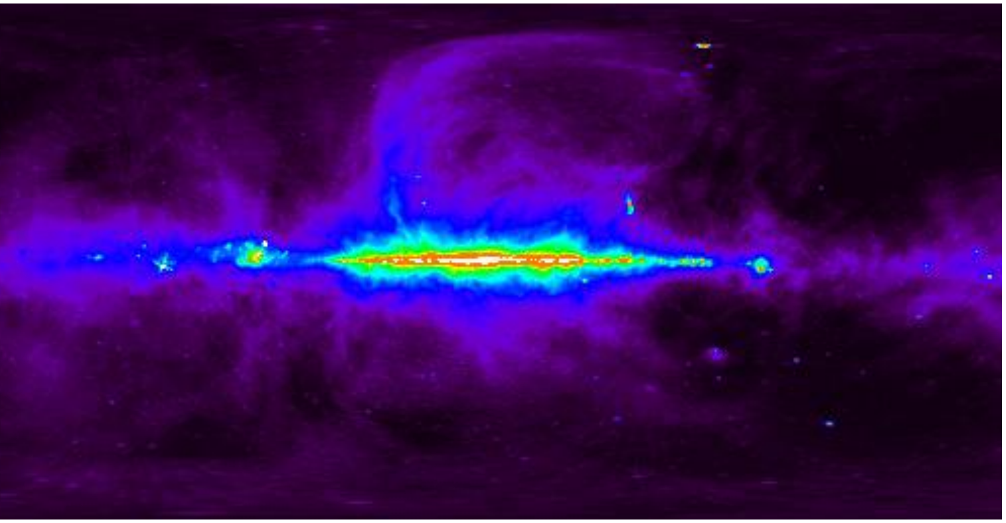
As large as 10,000 times the signal, and polarized!

- *Our Galaxy – synchrotron, free-free, spinning dust*
- *Radio sources – galaxies, AGN*
- *Diffuse cluster emission – halos and relics*
- *IGM free-free emission*
- *Radio recombination lines*

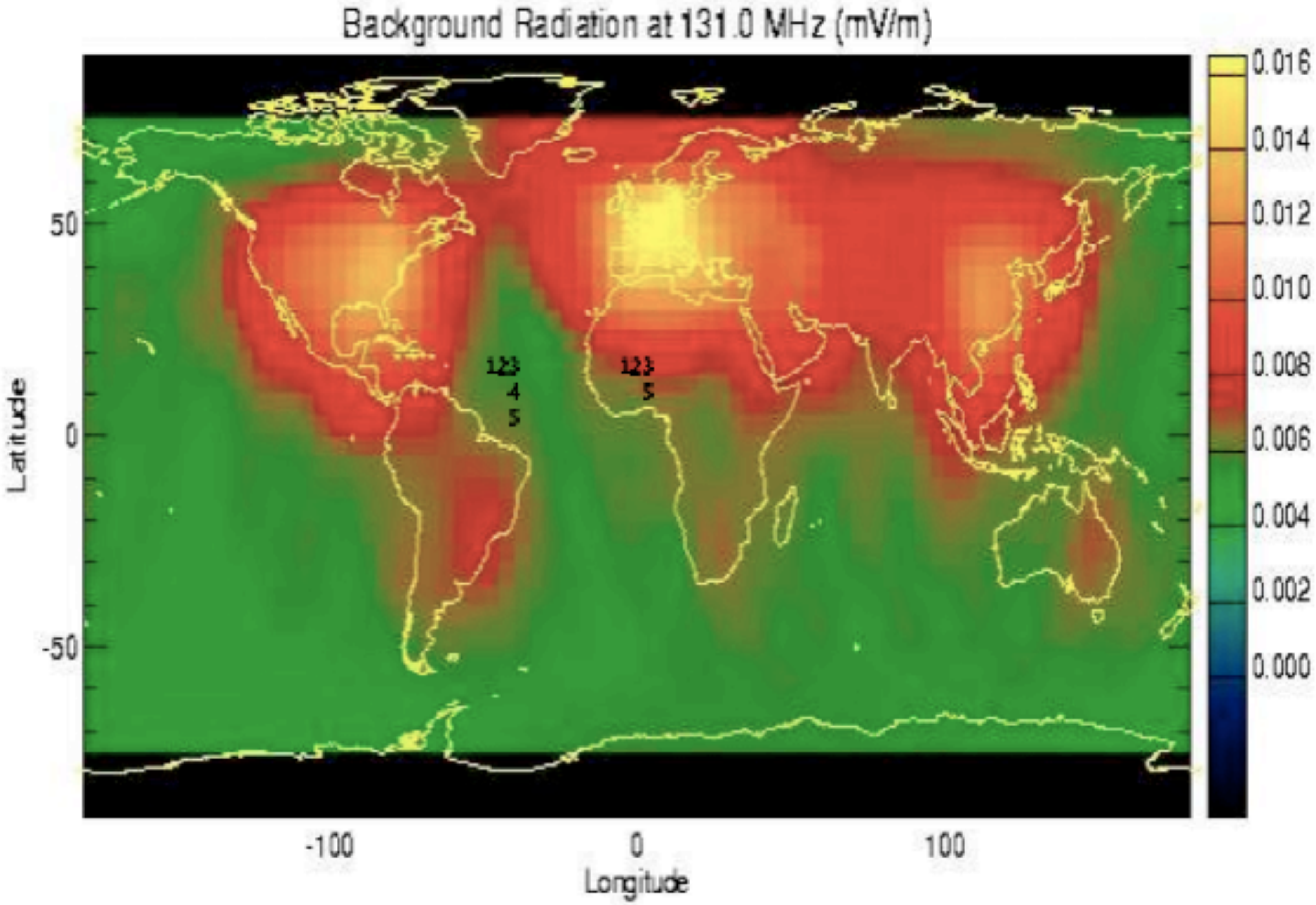
Westerbork map - 325 MHz



Haslam et al. 1982 - 408 MHz

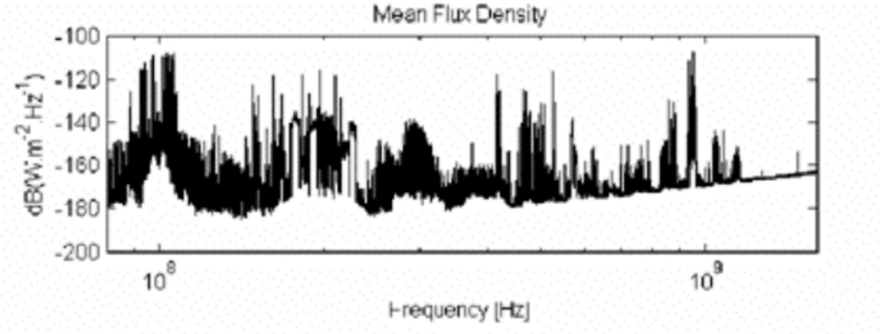


Challenge; Radio Frequency Interference

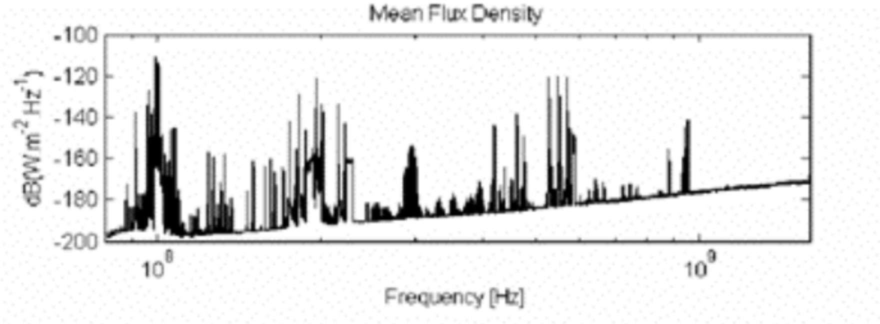


FORTES satellite

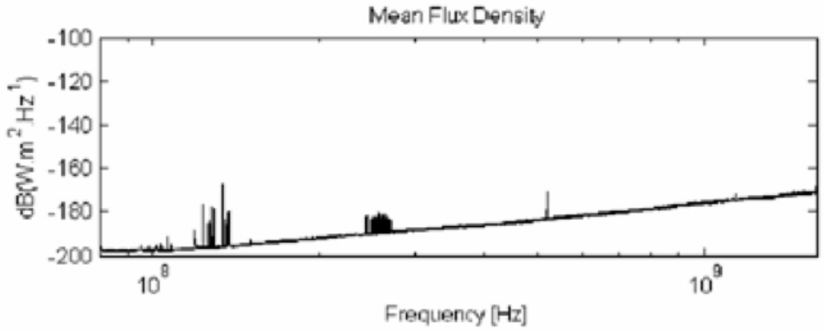
Sydney



Narrabri



Mileura



Chippendale and Beresford 2007

NOW THE REALITY: THE EXPERIMENTS

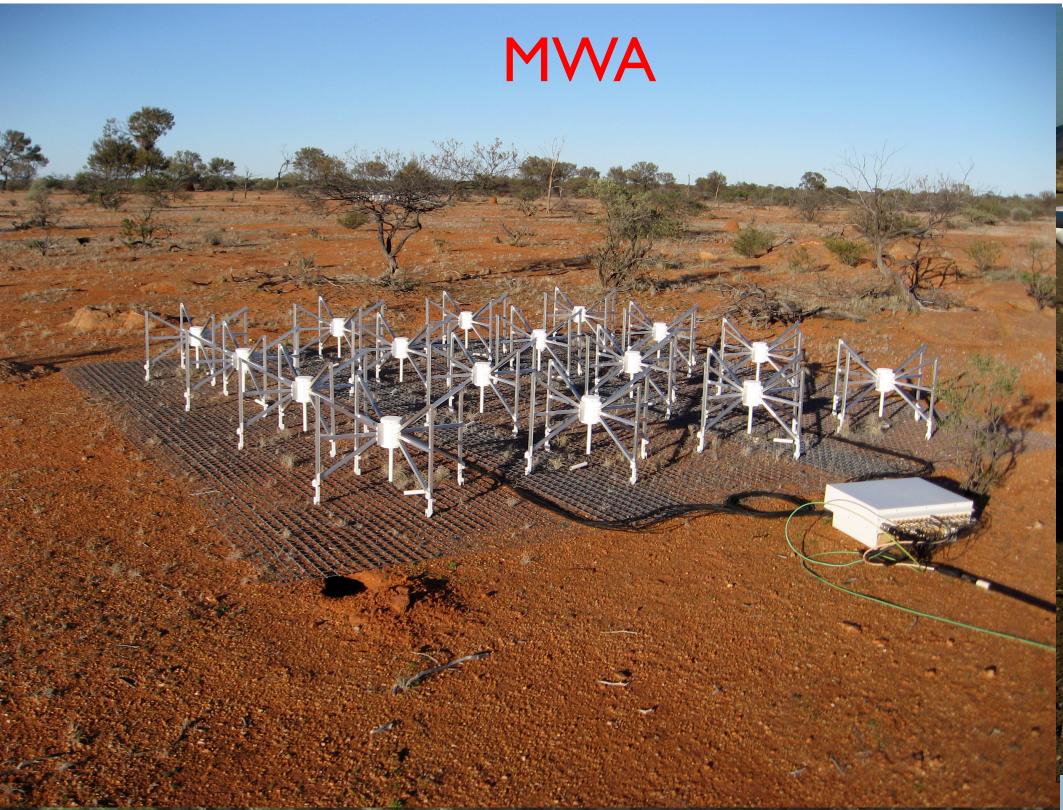
FIRST GENERATION EOR EXPERIMENTS:

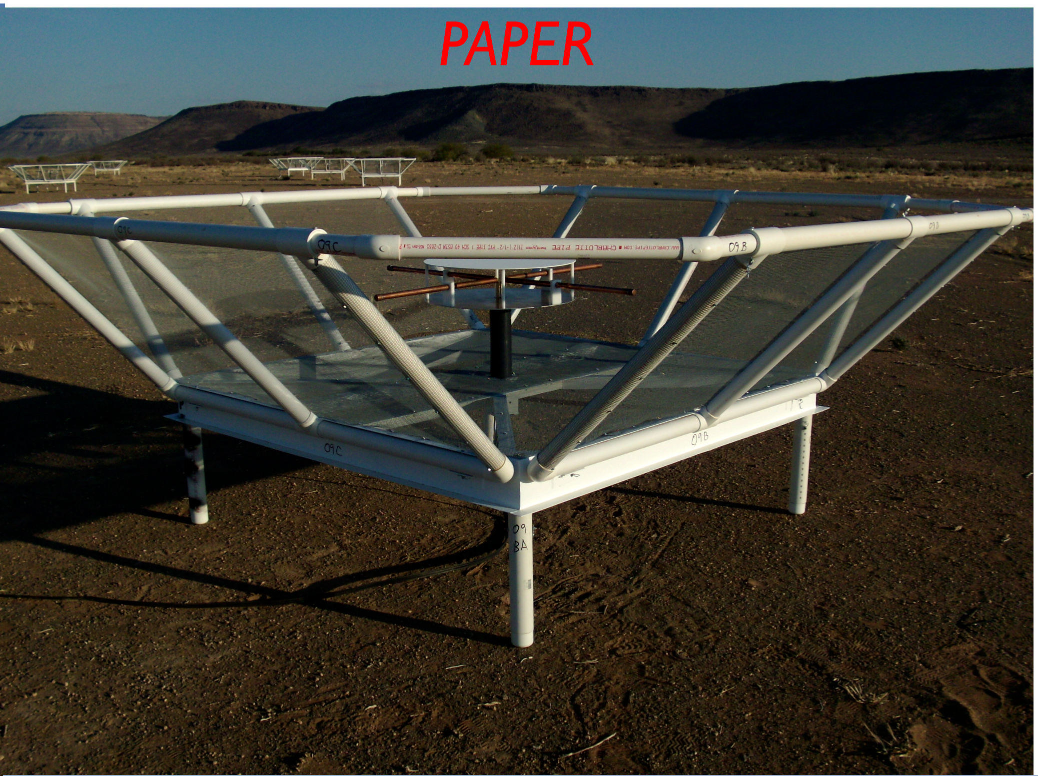
Murchison Widefield Array (MWA)

Precision Array for Probing the Epoch of Reionization (PAPER)

Low-Frequency Array (LOFAR)

MIT EoR experiment (MITEoR)

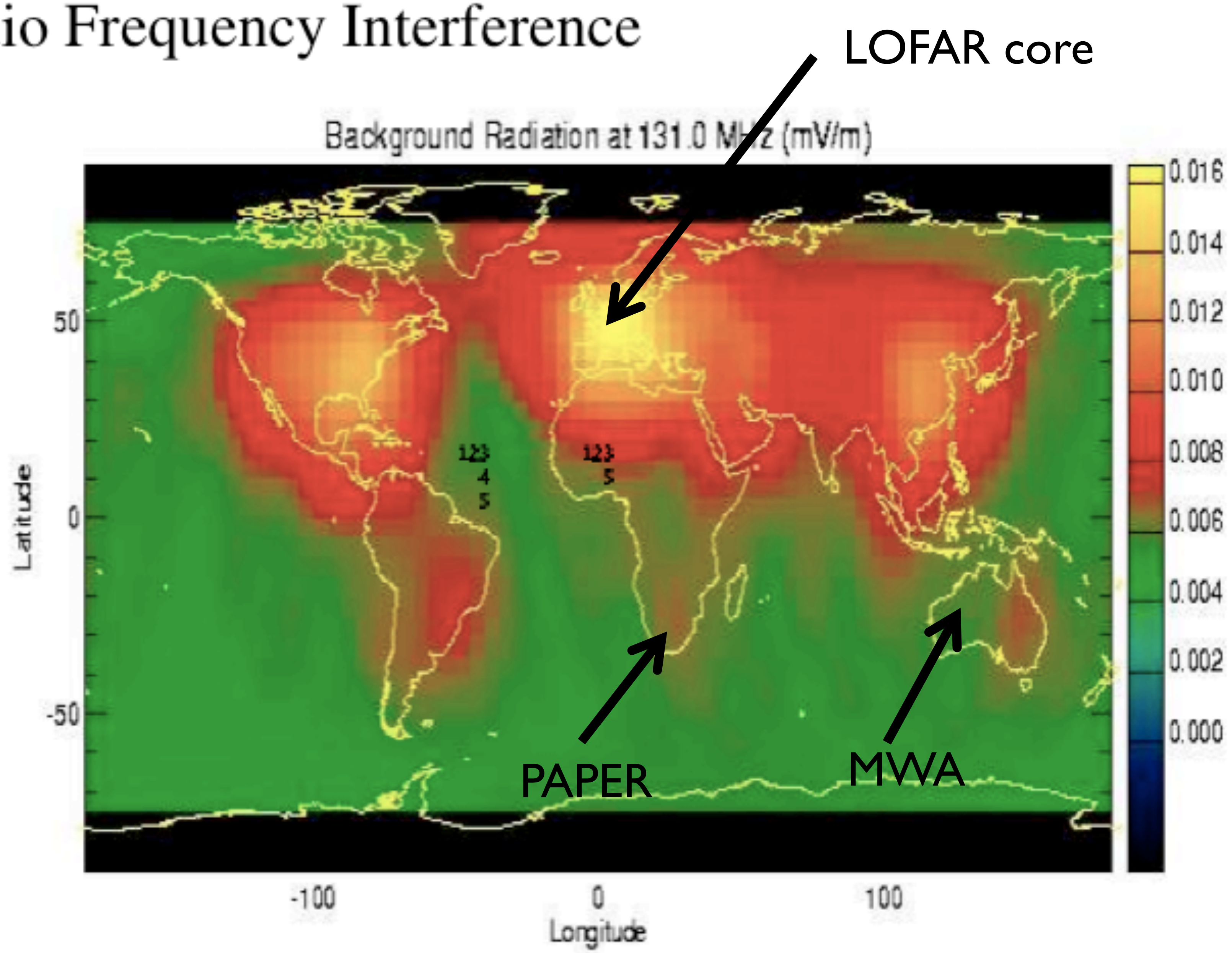

MWA


PAPER


MITEoR (Technology development)


LOFAR ("core" of low band antenna array)

Radio Frequency Interference

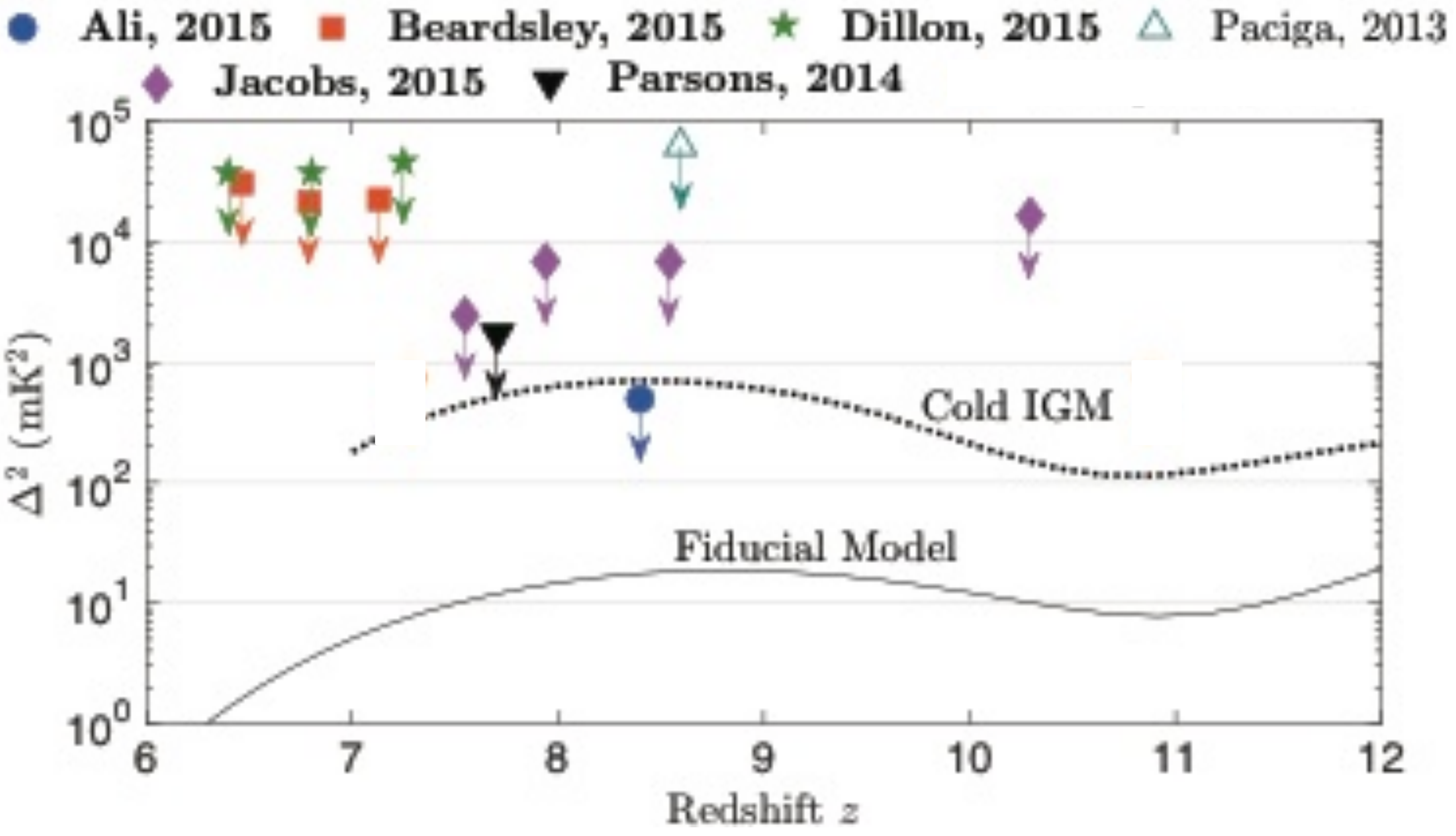


LOFAR core

PAPER

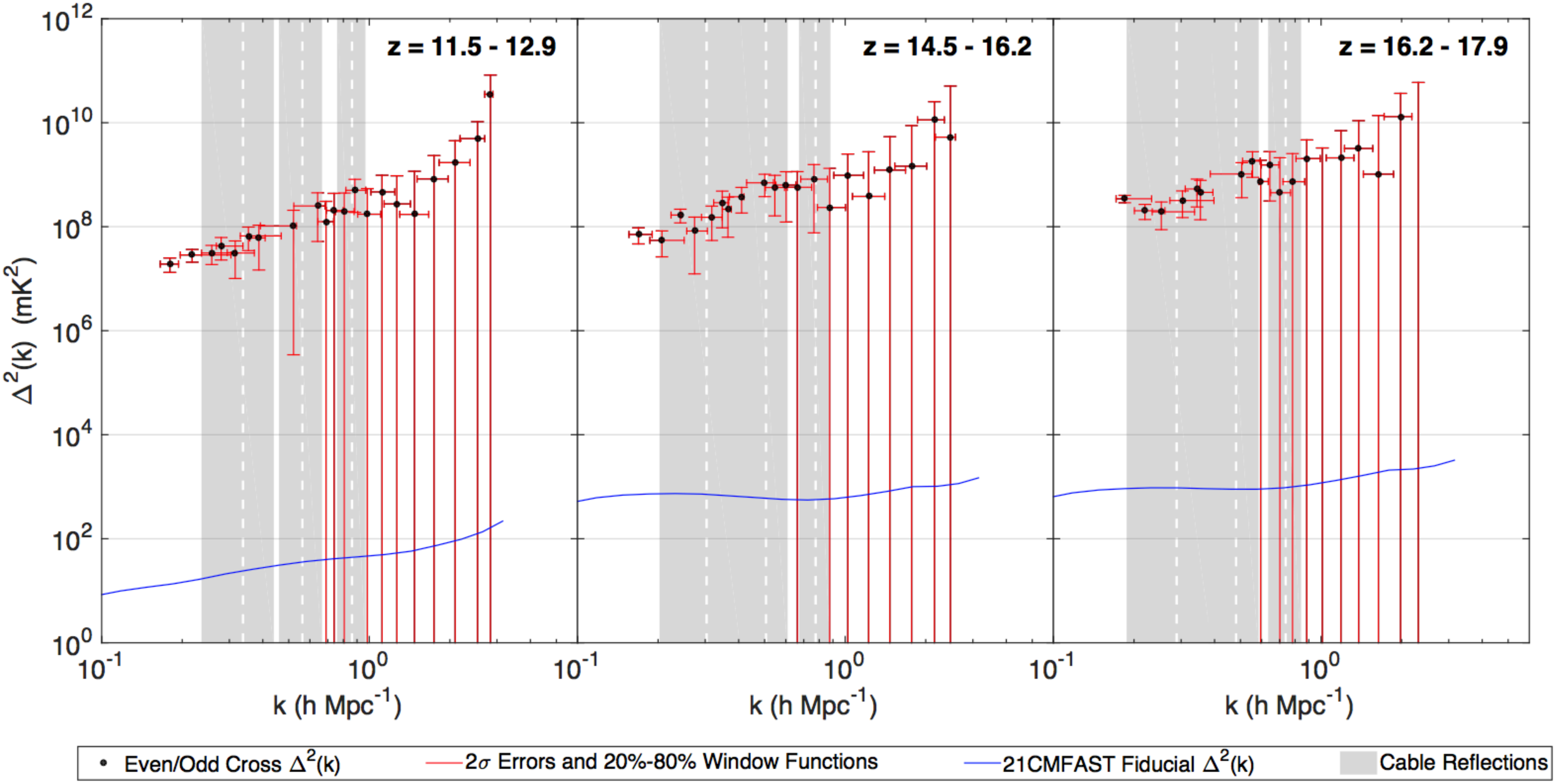
MWA

FORTES satellite


● Ali, 2015
■ Beardsley, 2015
★ Dillon, 2015
△ Paciga, 2013
◆ Jacobs, 2015
▼ Parsons, 2014
Δ^2 (mK^2)
10^5
10^4
10^3
10^2
10^1
10^0
Cold IGM
Fiducial Model
6
7
8
9
10
11
12
Redshift z

First power spectra at 12 < z < 18
Sensitivity of 10,000 mK at large k
Limited by MWA cable reflections at small k

Ewall-Wice, Dillon, Hewitt, et. al.
In press



MODELING THE ASTROPHYSICS WITH 6 PARAMETERS

Zeta = ionization efficiency (uv photons entering IGM)

R = mean free path of ionization photons

T_vir = minimum virial temperature of haloes that contribute to heating and reionization

f_x = X-ray efficiency (X-ray photons per baryon in star formation)

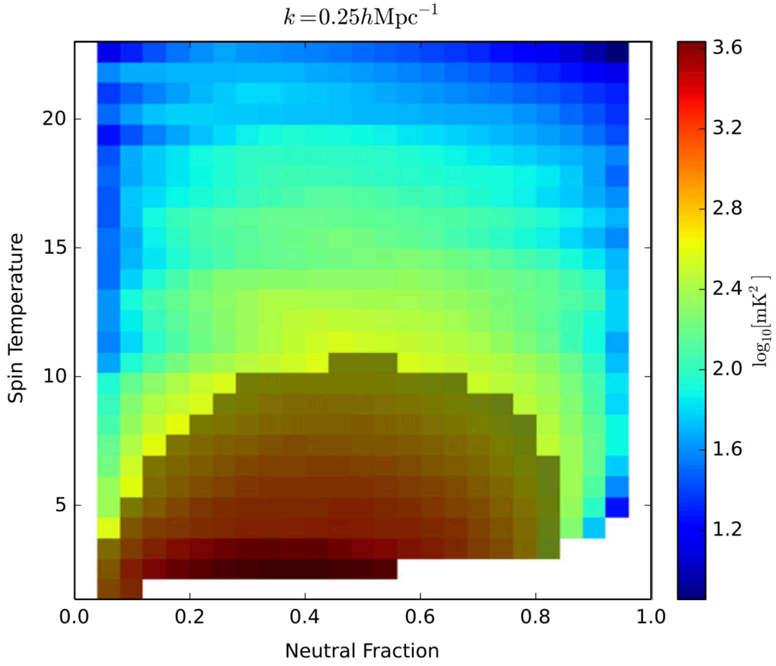
alpha_x = spectral index of X-ray spectrum (black holes vs hot ISM)

nu_min = X-ray obscuration threshold (X-ray which escape)

See Mesinger, Ferrara & Spiegel 2013; Mesinger, Ewall-Wice & Hewitt 2014;
Ewall-Wice et al. 2016

FIRST COMPARISON OF DATA TO MODELS

In regime of "cold reionization", only vary
Zeta = ionization efficiency (uv photons entering IGM)



Spin T > 10 K at z = 8.4

PAPER 21cm data and Planck constraints on neutral fraction only

See Pober et al. 2015

THE FUTURE

FUNDED SECOND GENERATION EOR/HEATING EXPERIMENTS:

Hydrogen Epoch of Reionization Array (HERA)
U.S. + Cambridge, UK ~$12M

Square Kilometer Array Phase 1 – Low (SKA0/1-Low)
International E650M Low-freq part around E200M

THIRD GENERATION EOR/HEATING/COSMOLOGY EXPERIMENT:

Full Square Kilometer Array? (SKA2) – estimates at $2B - $6B

HERA on steroids?

SKA2 with HERA-like EoR/EoX/DA core?

HERA – Hydrogen Epoch of Reionization Array

- *HERA-1 is MWA and PAPER*
  128 16-dipole tiles and 128 dipoles-with-shaped-ground-screen

- *HERA-II is now called "HERA"*
  350 14-m dishes

- *HERA-III might be part of SKA (?)*

Arizona State, Brown, Berkeley, UCLA, Cambridge, MIT, NRAO, Penn, SNS Pisa, SKA-SA, Capetown, UWash

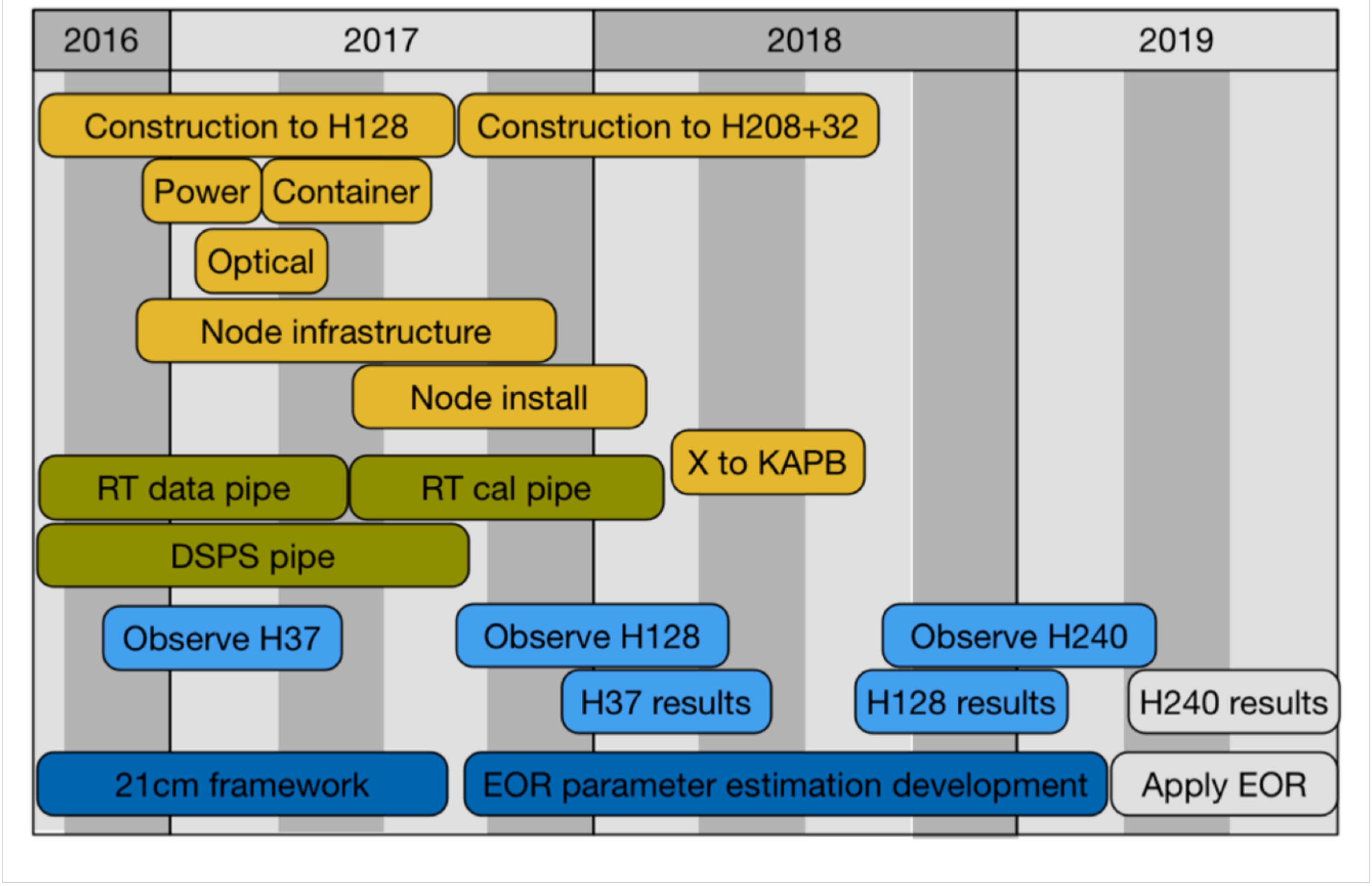
HERA-240 has been funded

Seeking additional funding for full build-out to 350 and extension to 50 MHz

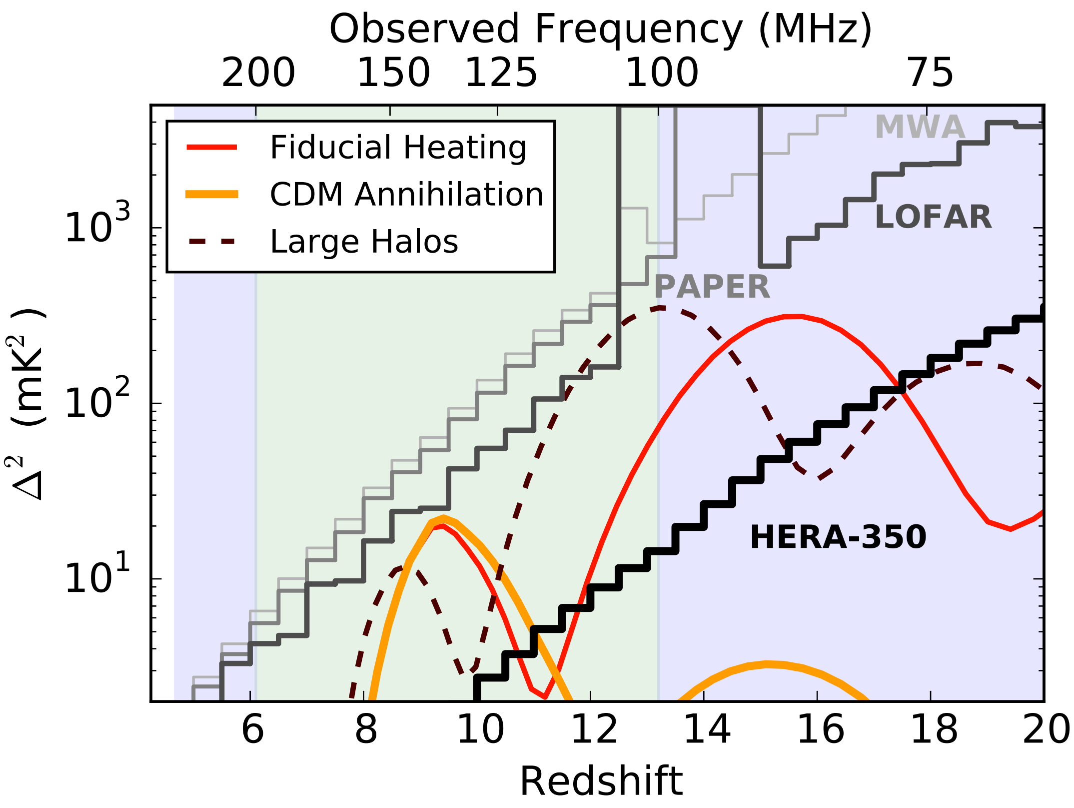
First array of 37 antennas undergoing commissioning

Fig. 1.— Rendering of the 320-element core (left) of the full HERA-350 array and picture of 19 HERA 14-m, zenith-pointing dishes (with PAPER elements in the background) currently deployed in South Africa (right).

HERA TIMELINE



HERA DESIGN CHOICES



Sensitivities assuming foreground avoidance strategy

Fixed dishes to maximize collecting area per dollar

Focal length chosen so reflections are outside EoR window

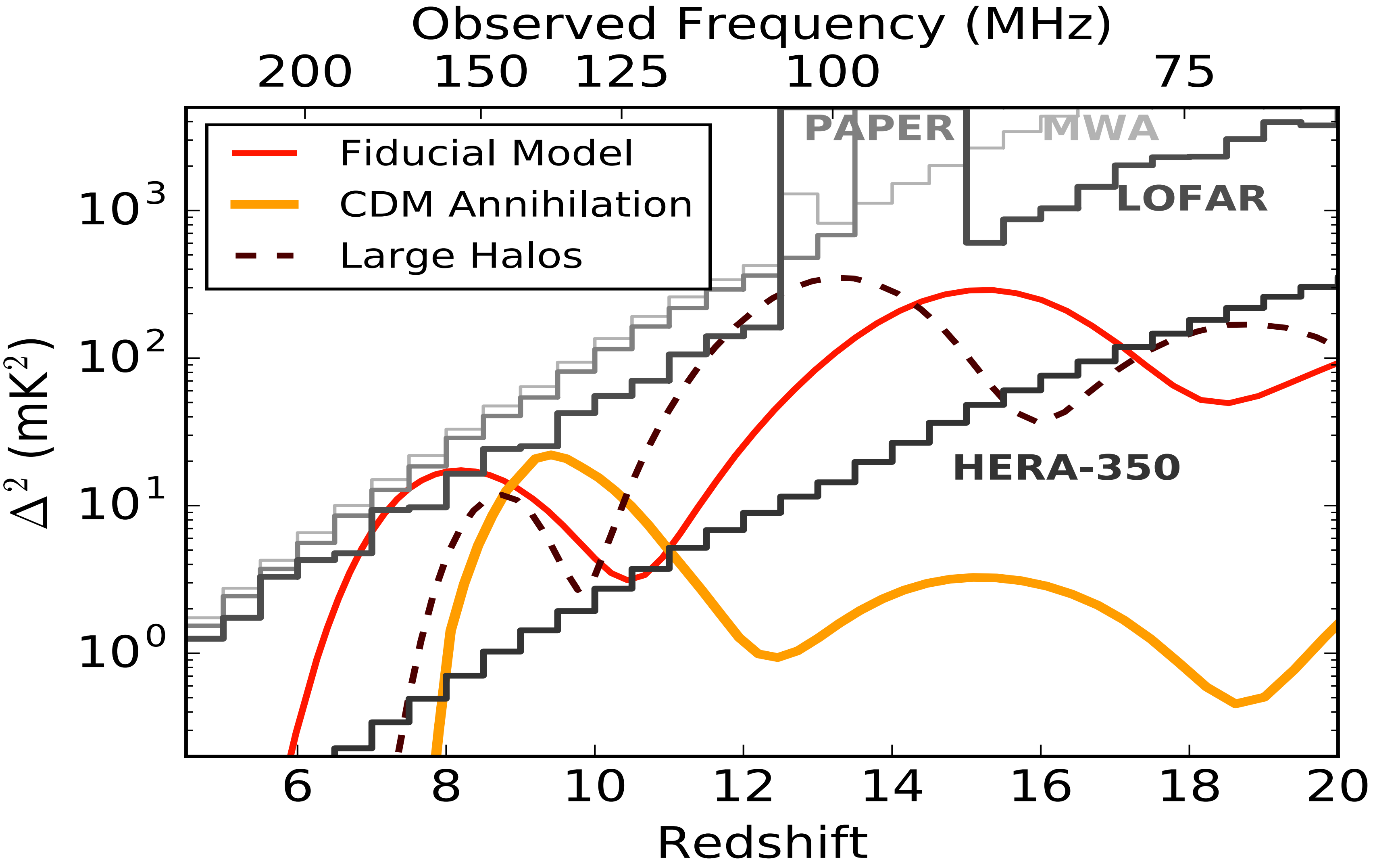
Smaller field for better calibration and to suppress foregrounds on the horizon

Redundant array for better calibration and power spectrum sensitivity

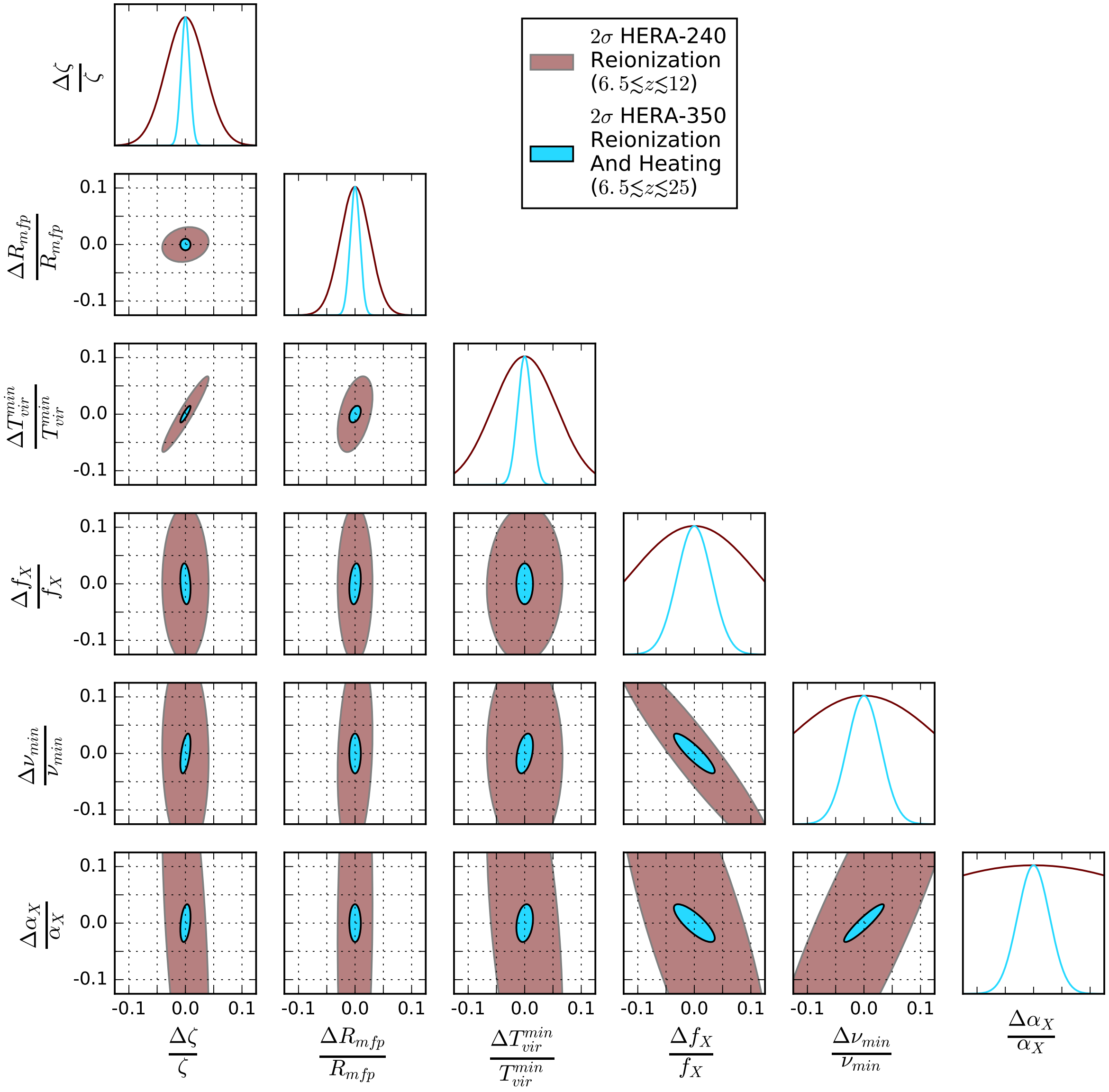
Compact array for more baselines in EoR window (foreground avoidance strategy)

Outliers and "fractured crystal" for better imaging

Power spectrum science z>6 :



See Mesinger, Ewall-Wice & Hewitt 2014



HERA capabilities:
Funded HERA-240 and pending HERA-350-lowfreq

Currently studying cosmology constraints with HERA-350-lowfreq

Calculations by A. Ewall-Wice

SQUARE KILOMETRE ARRAY

Composed of
- SKA-Mid in South Africa
- SKA-Low in Australia
- Headquarters in the UK

SKA Phase 1 –
- Finishing design
- Construction 2018 - 2020
- Target first science in 2020
- Cost-capped at 650M Euros
- Rebaseled in 2015 to meet cap
- All (almost?) subsystem PDRs done
- System PDR in November

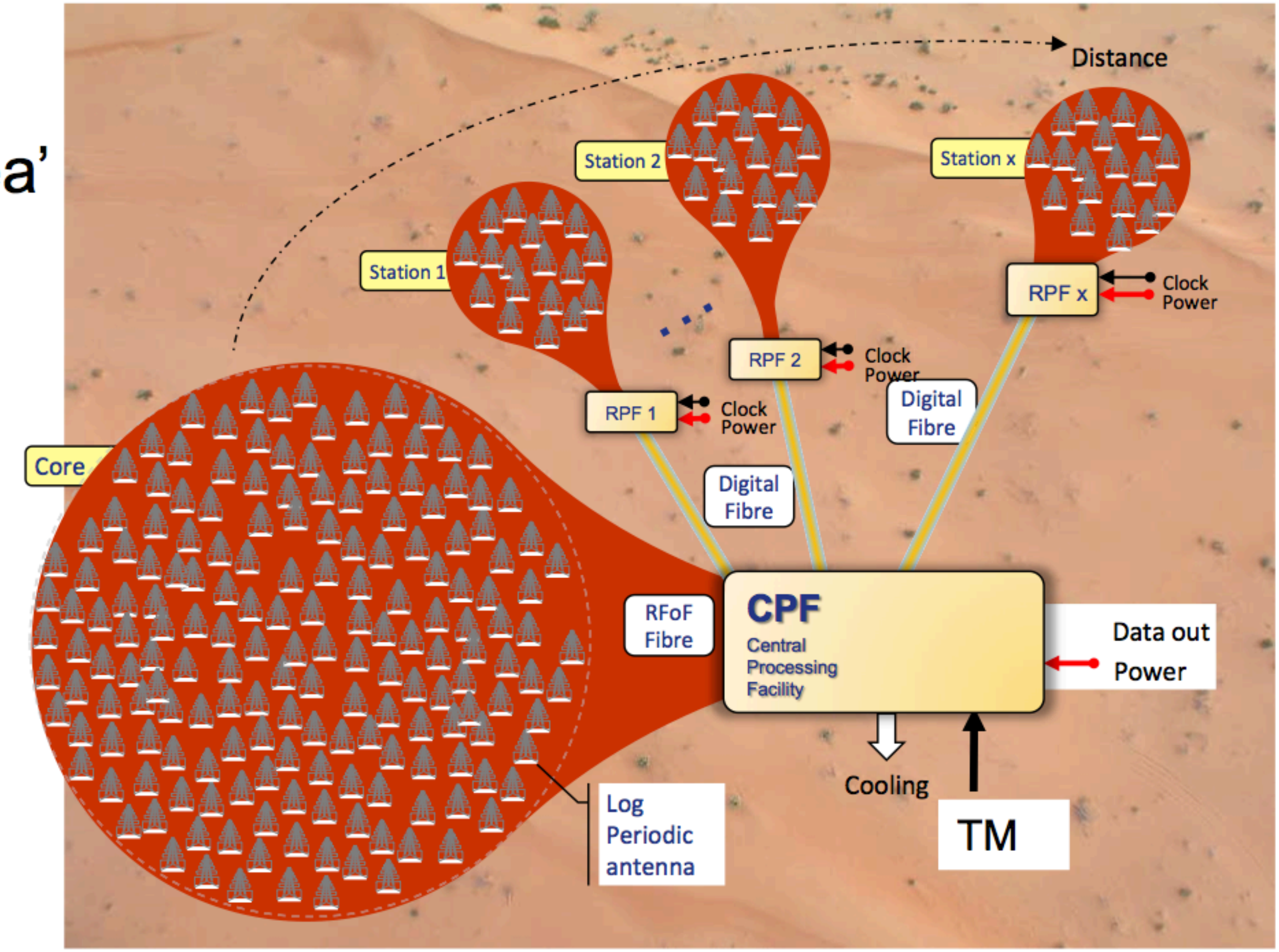
SKA Phase II –
- In the future.....

SKA-low test array

SKA1-LOW Baseline Design

Similar to LOFAR

- 262144 antennas
- 1024 stations
- 95% in 'Inner Area' of 3km
- 40km arms
- Large central processing F
- Flexible or Focused



Project rebaselining recommendations; approved by Board in 2015

SKA1-Low in Australia should be built.

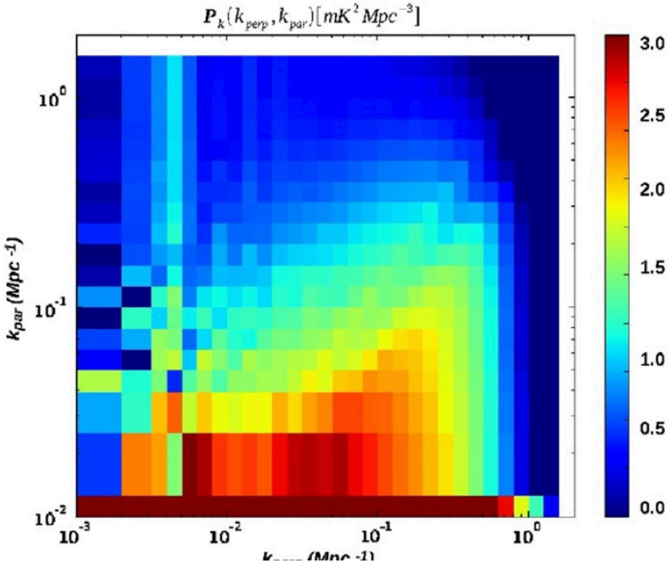
50% of the planned 262,144 low frequency dipoles should be deployed.

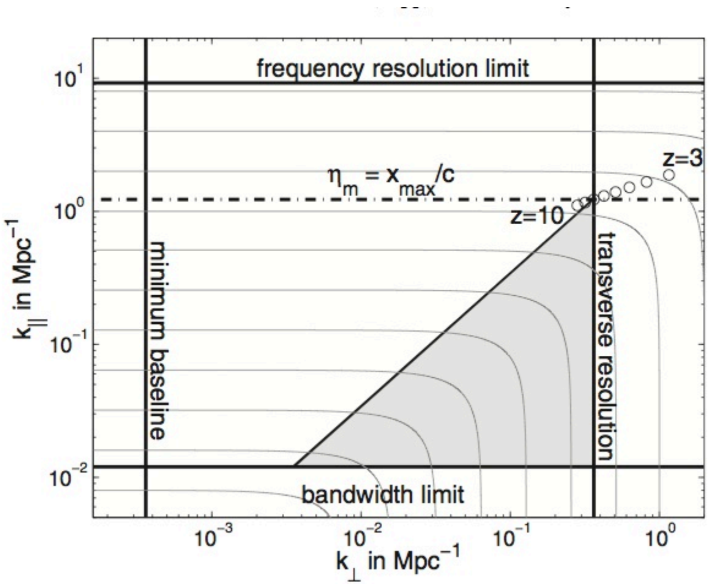
The array should cover the frequency range 50-350 MHz, as planned.

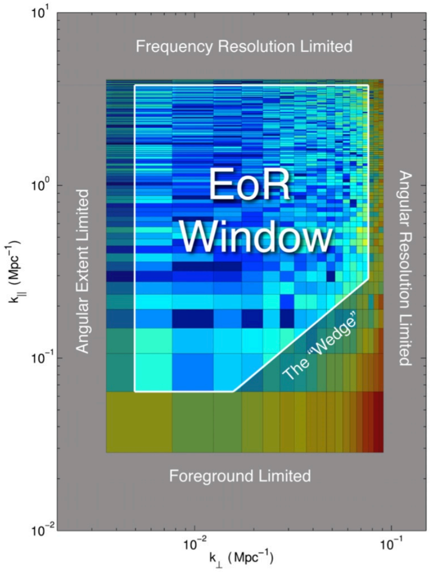
The current planned baseline lengths of ~80km should be retained.

The inclusion of a pulsar search capability for SKA1-Low (currently an Engineering Change Proposal on hold) should be actively explored.

*We can **avoid** foregrounds in Fourier space because foregrounds have "flat" spectra and the cosmological density fluctuations have rapid spectral fluctuations.*
Frequency-dependent instrumental response => "wedge"







Datta, Bowman & Carilli (2010) ApJ, 724, 526
Vendantham, Shankar & Subrahmanyan (2012) ApJ, 745, 176
Trott, Wayth & Tingay (2012) ApJ, 757, 101
Morales et al. (2012) ApJ, 752, 137
Parsons et al. (2012) ApJ, 756, 165
Dillon, Liu et al. (2014) Phys Rev D, 89, 023002

COMPARISONS OF HERA AND SKA

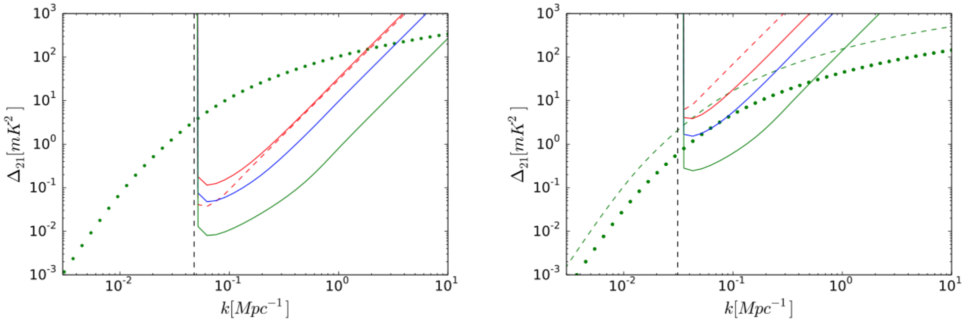


Figure 2: Sensitivity plots of HERA (red dashed curve), SKA0 (red), SKA1 (blue), and SKA2 (green). Dotted curve shows the predicted 21cm signal *from the density field alone* assuming $x_H = 1$ and $T_S \gg T_{\rm CMB}$. At $z = 20$, we also plot the case of $T_S = 20$K in the $z = 20$ panel to give a better sense of the expected 21 cm signal during absorption. Vertical black dashed line indicates the smallest wavenumber probed in the frequency direction $k = 2\pi/y$, which may limit foreground removal. *Left panel:* $z = 8$ *Right panel:* $z = 20$.

Pritchard et al. 2014

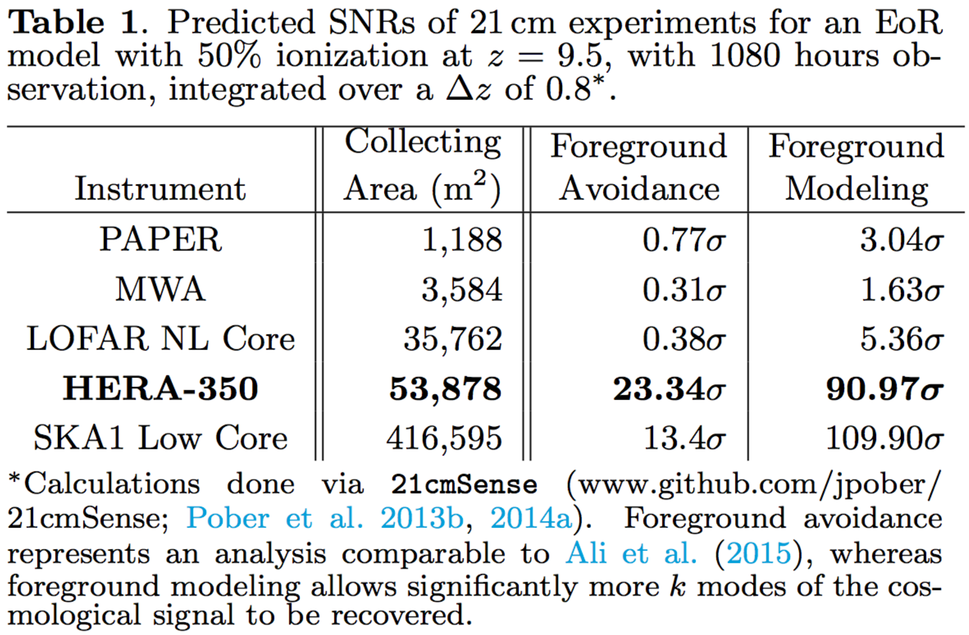


Table 1. Predicted SNRs of 21 cm experiments for an EoR model with 50% ionization at $z = 9.5$, with 1080 hours observation, integrated over a Δz of 0.8*.

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**	**23.34σ**	**90.97σ**
SKA1 Low Core	416,595	13.4σ	109.90σ

*Calculations done via `21cmSense` (www.github.com/jpober/21cmSense; Pober et al. 2013b, 2014a). Foreground avoidance represents an analysis comparable to Ali et al. (2015), whereas foreground modeling allows significantly more k modes of the cosmological signal to be recovered.

DeBoer et al. 2016