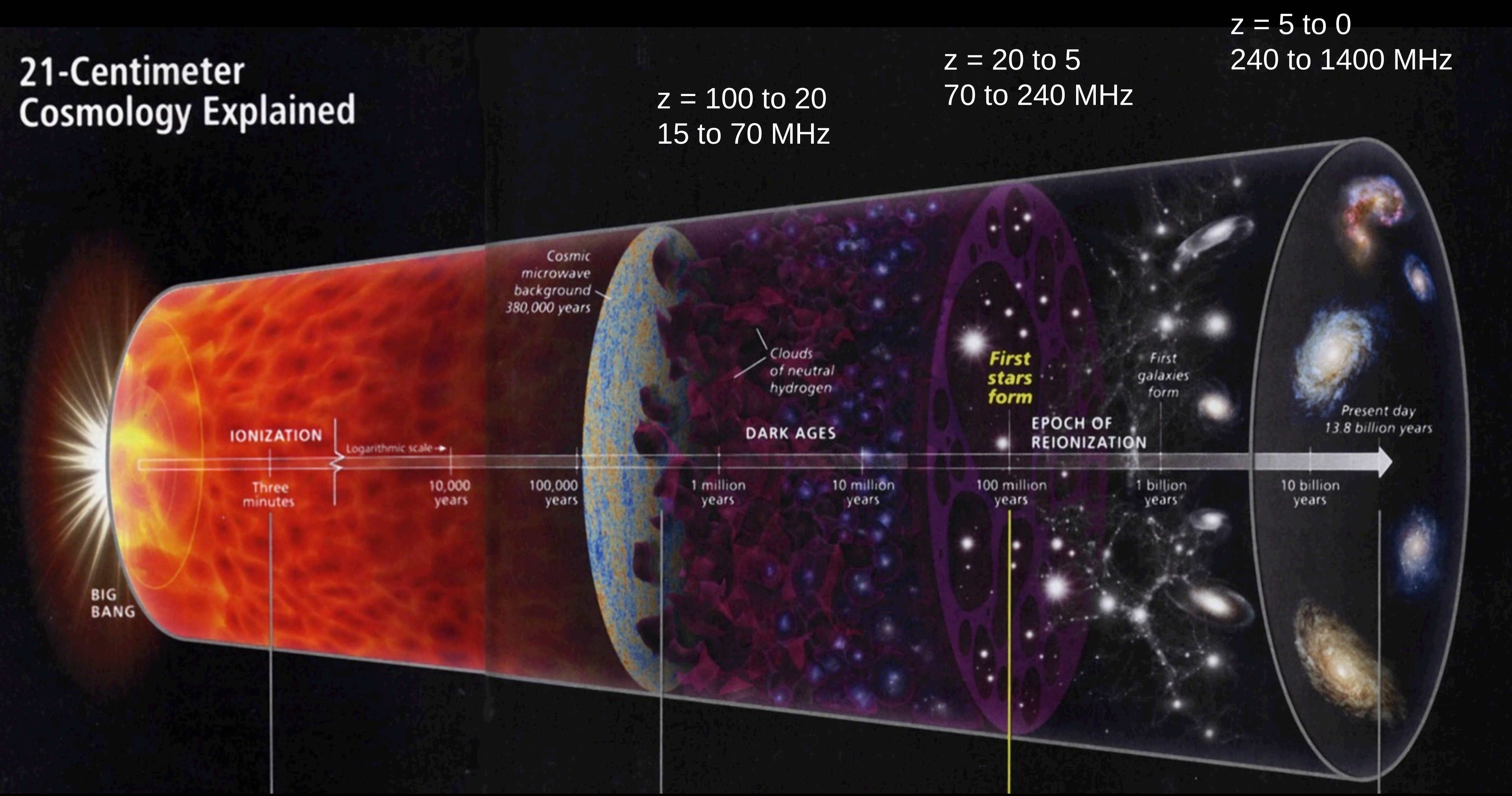
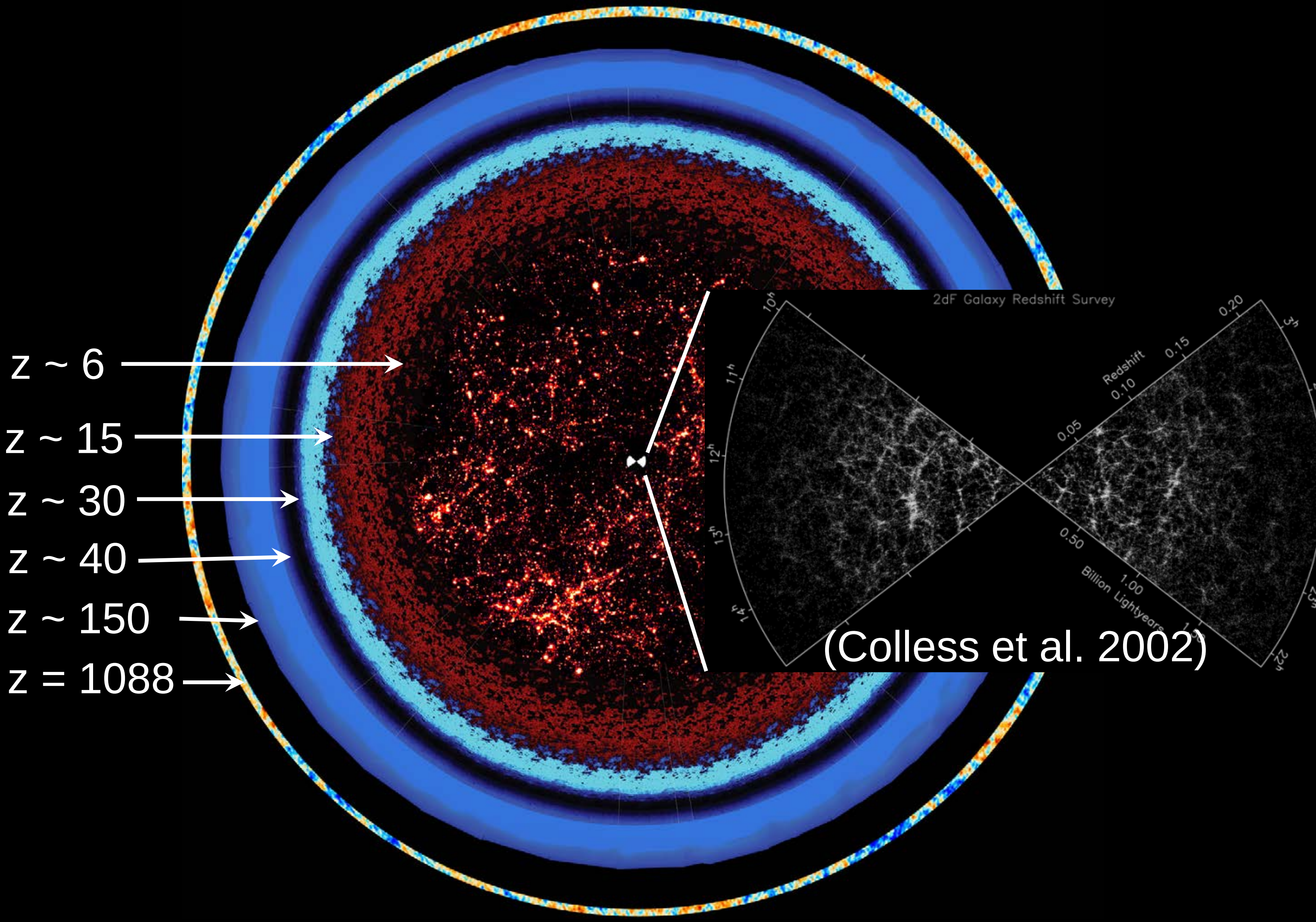
21cm Cosmology After HERA


21-Centimeter Cosmology Explained
z = 100 to 20
15 to 70 MHz
z = 20 to 5
70 to 240 MHz
z = 5 to 0
240 to 1400 MHz
Cosmic microwave background 380,000 years
Clouds of neutral hydrogen
First stars form
First galaxies form
Present day 13.8 billion years
IONIZATION
Logarithmic scale
DARK AGES
EPOCH OF REIONIZATION
Three minutes
10,000 years
100,000 years
1 million years
10 million years
100 million years
1 billion years
10 billion years
BIG BANG

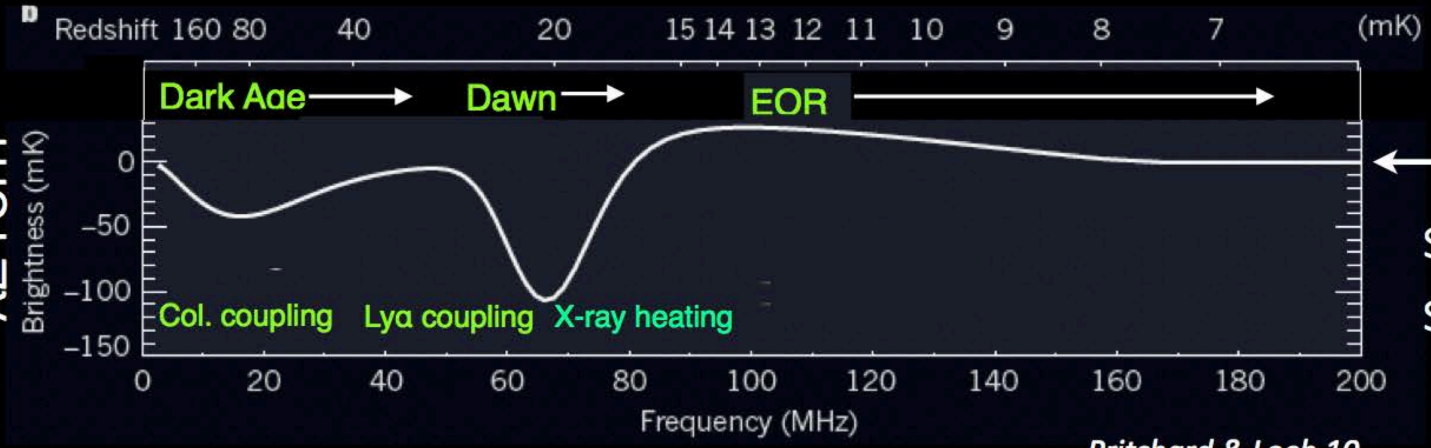


(Mao et a. 2008, Zheng et al. 2014)

Why 21cm Cosmology

- Line Emission
  - Optically thin
  - Observable even into Dark Ages
  - Directly probes redshift evolution
- Sensitive to
  - Ly-α: Wouthuysen Field Effect
  - X-ray/DM: Heating
  - UV: Ionization
- Integrated measure of galactic properties
  - includes low-mass tails
  - bubble size breaks some degeneracies
- Complementary to
  - CMB
  - optical probes of galaxies
  - other potential lines (e.g. CO, C+)
- c

Tracer



λ21cm

T_{CMB}

sky-avg'd spectrum

Pritchard & Loeb 10

- Mode
  - 0^{th} : all-sky, frequency spectrum
  - N^{th} : fluctuations, 2D / 3D power spectrum
- Challenge: calibration
  - advantage to optimized, purpose-built instruments

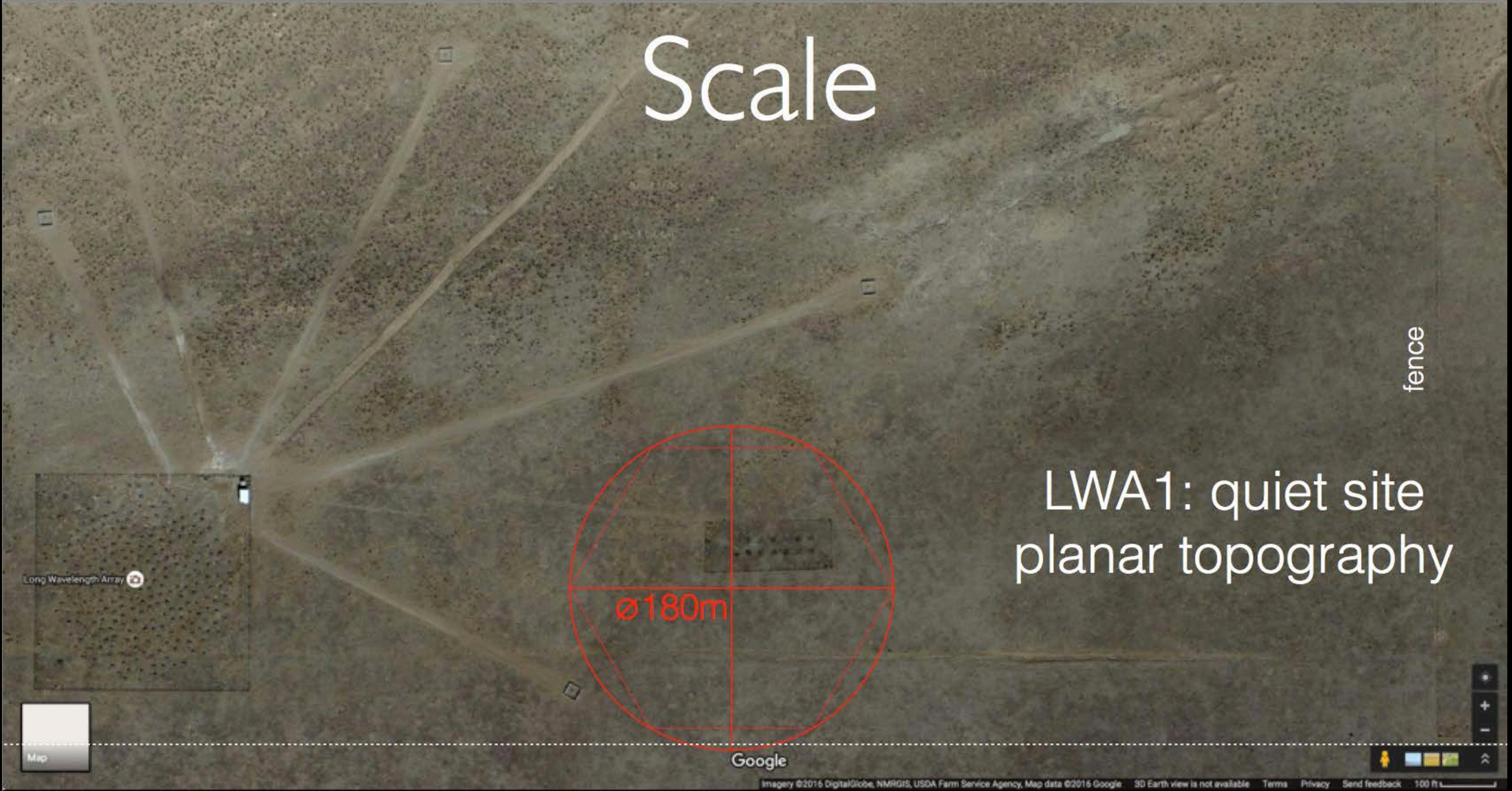

Voytek et al.
SCI-HI


EDGES
Bowman et al.


SARAS
Patra et al.


Sokolowski et al
BIGHORNS

Scale

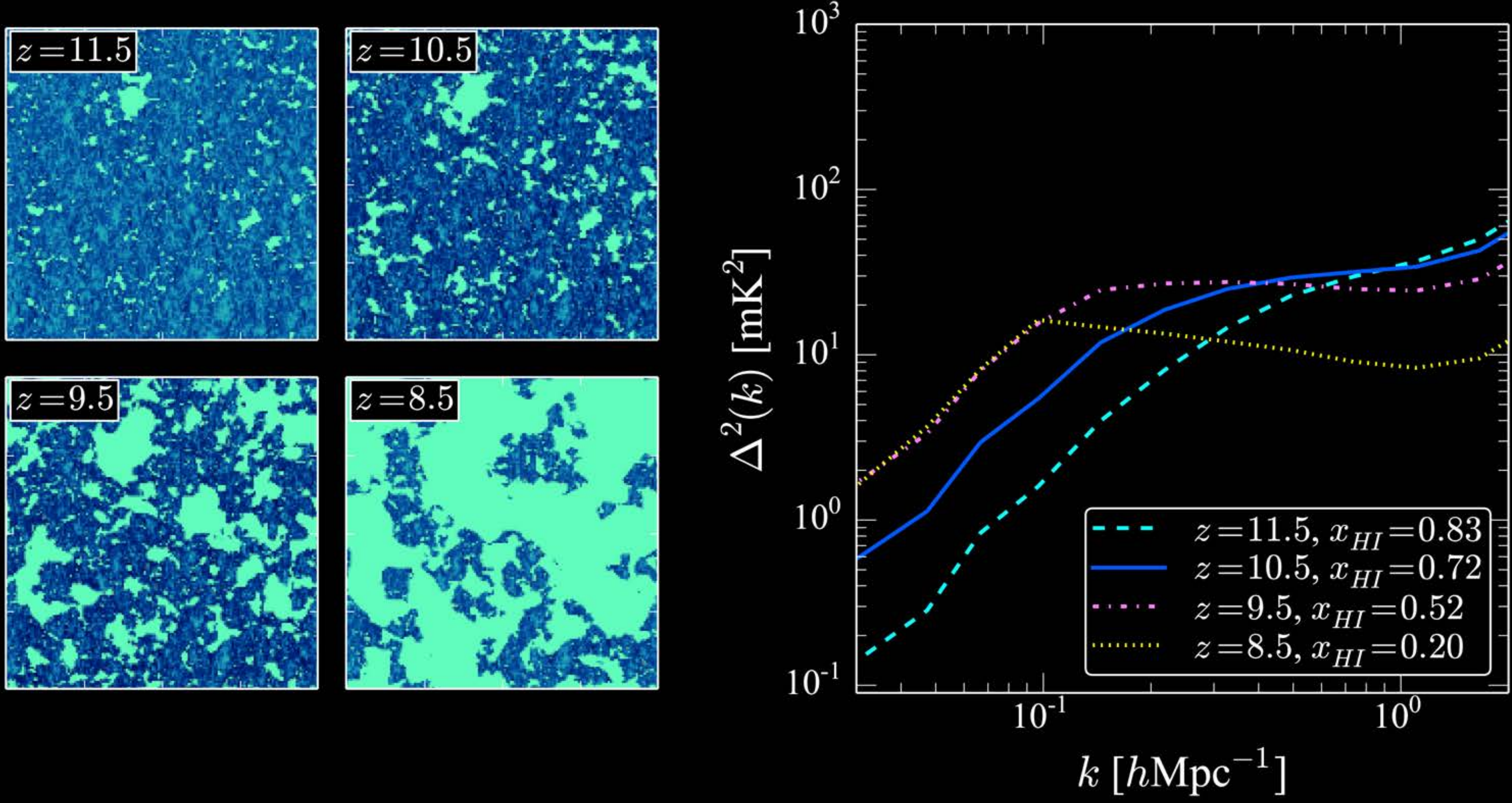


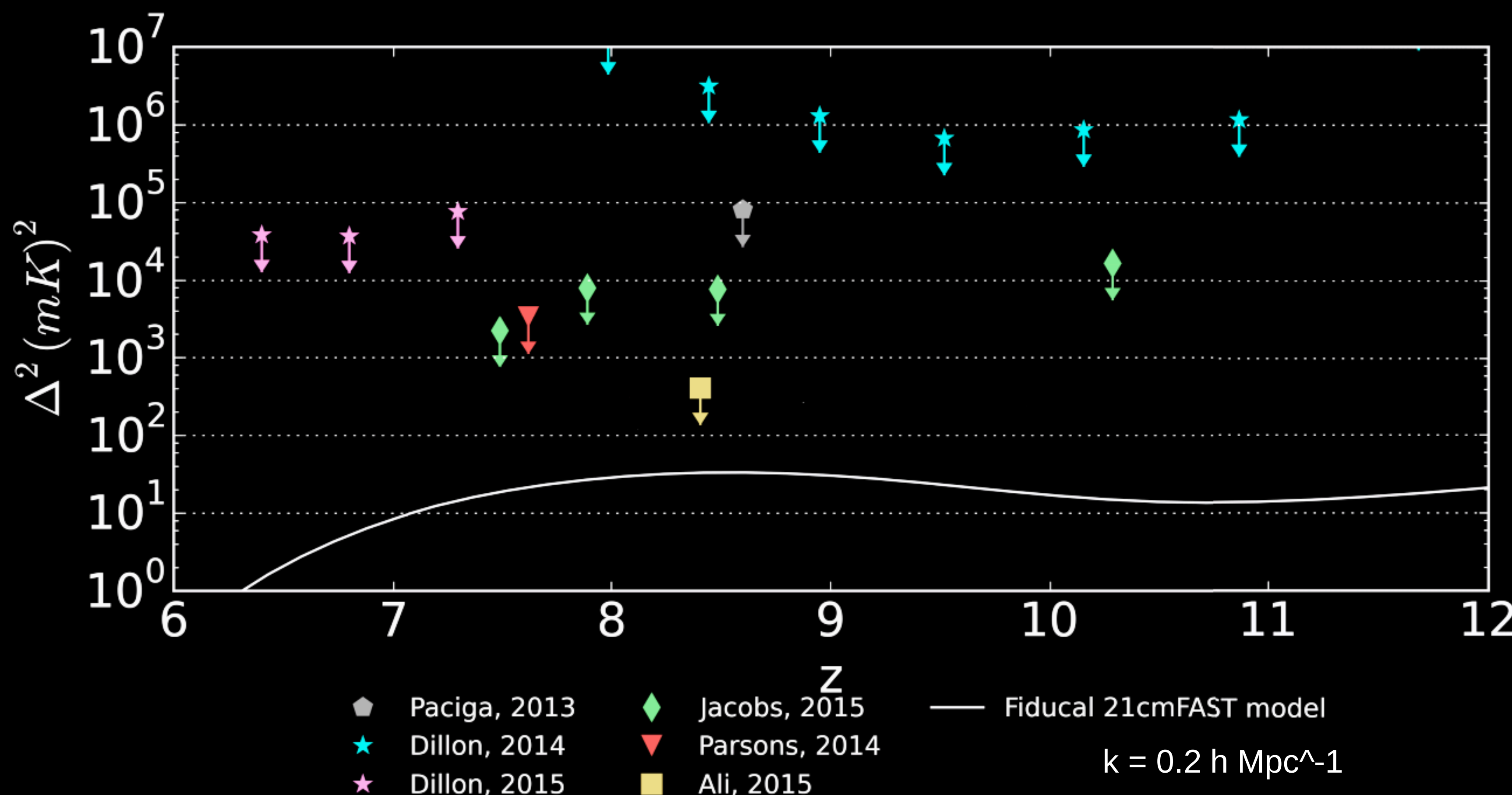
Hexagons¶ 127 ants. ⌀120m
169 ants. ⌀140m
217 ants. ⌀160m
271 ants. ⌀180m¶

external cal: 4 LWA1 bms.
plus LEDA outriggers

¶ Assumes 2λ spacing at 60 MHz (z=22.7)

The 21cm Power Spectrum





10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
$\Delta^2 (mK)^2$
6
7
8
9
10
11
12
z
Paciga, 2013
Dillon, 2014
Dillon, 2015
Jacobs, 2015
Parsons, 2014
Ali, 2015
Fiducal 21cmFAST model

k = 0.2 h Mpc^-1

HERA is moving forward!

Funded to 2019:

- Construct 240-350 HERA elements in a compact core
- Measure the 21cm power spectrum with HERA-37, HERA-127, and HERA-240
- Constrain key reionization parameters
- Official SKA precursor

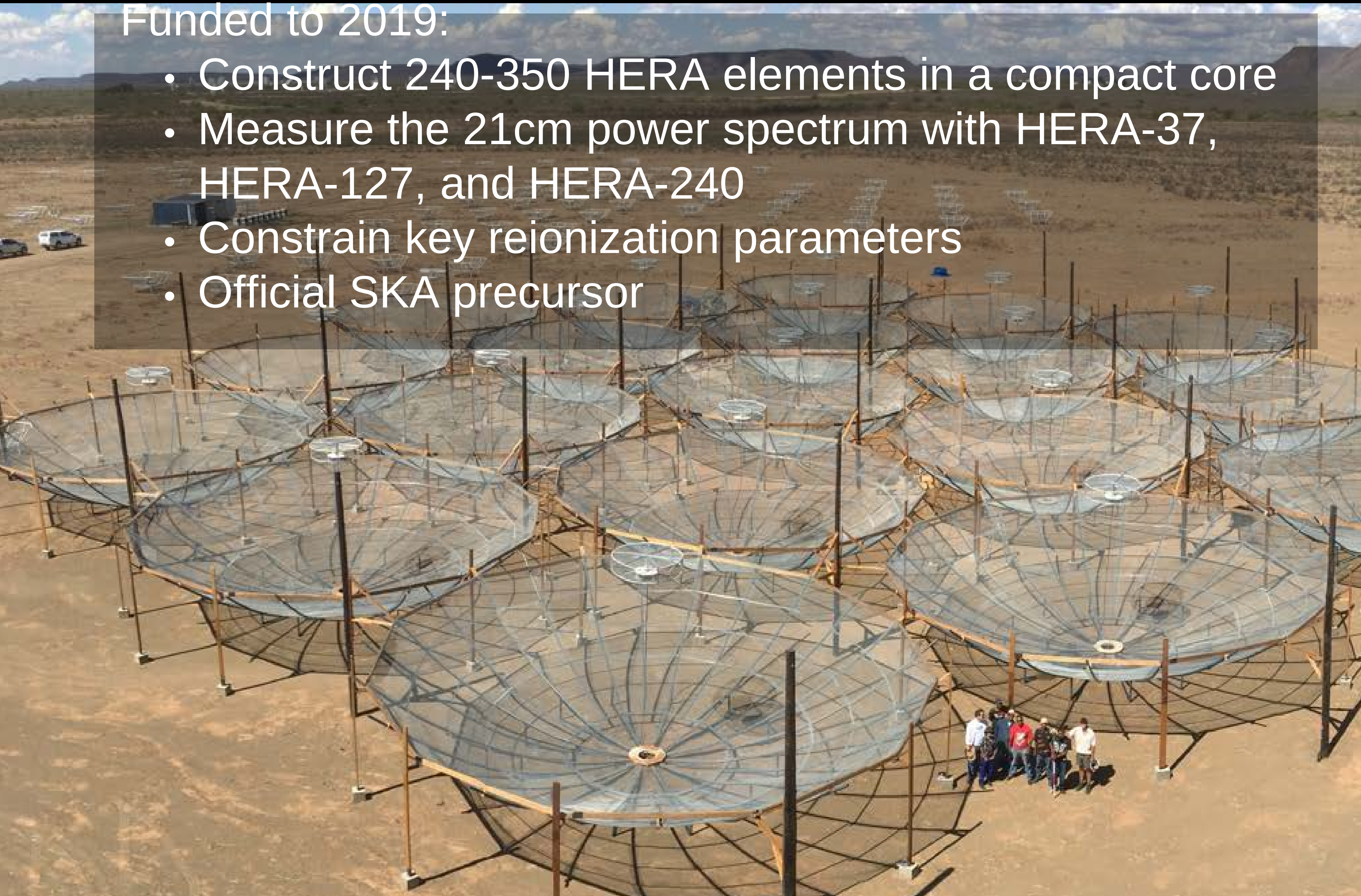
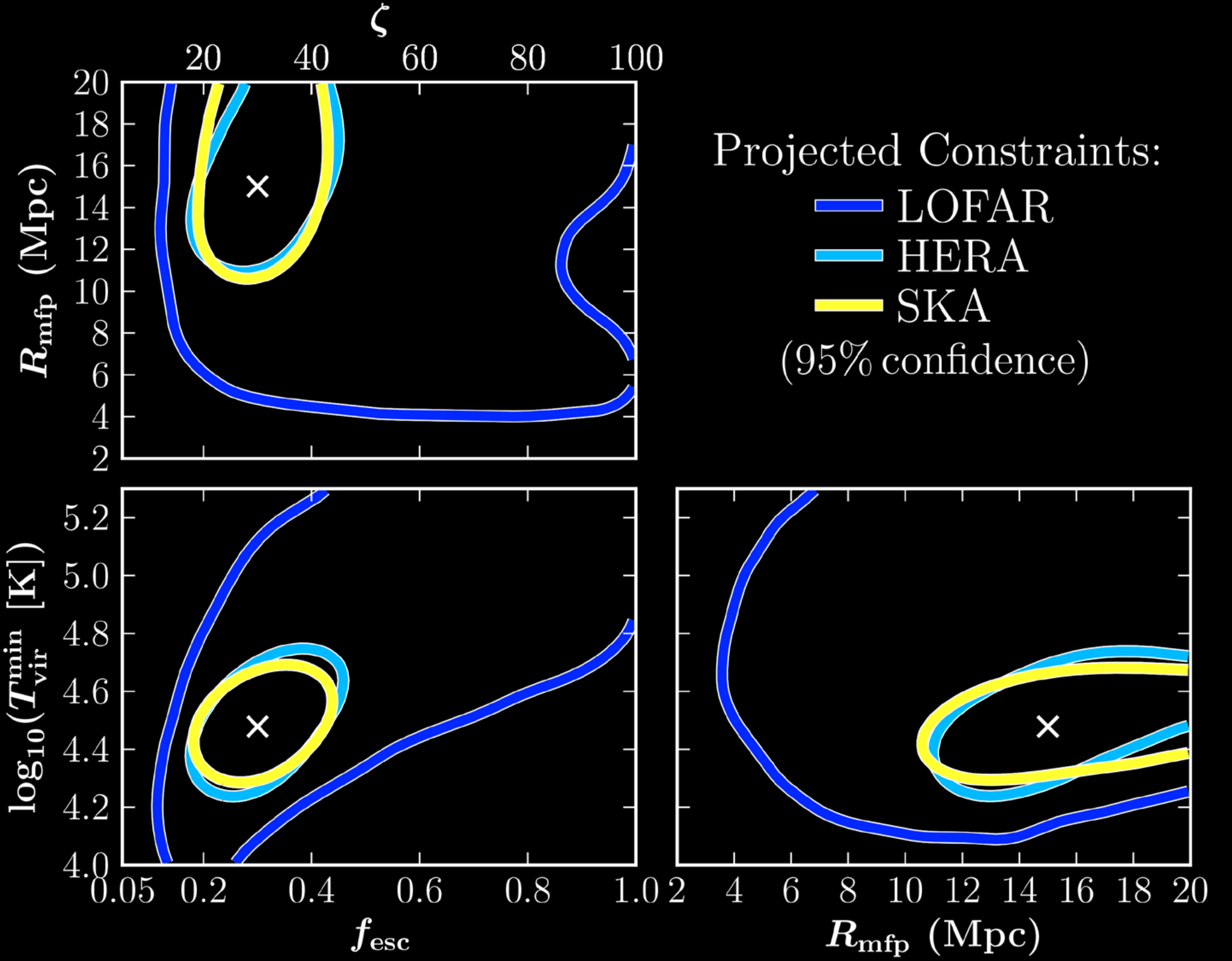


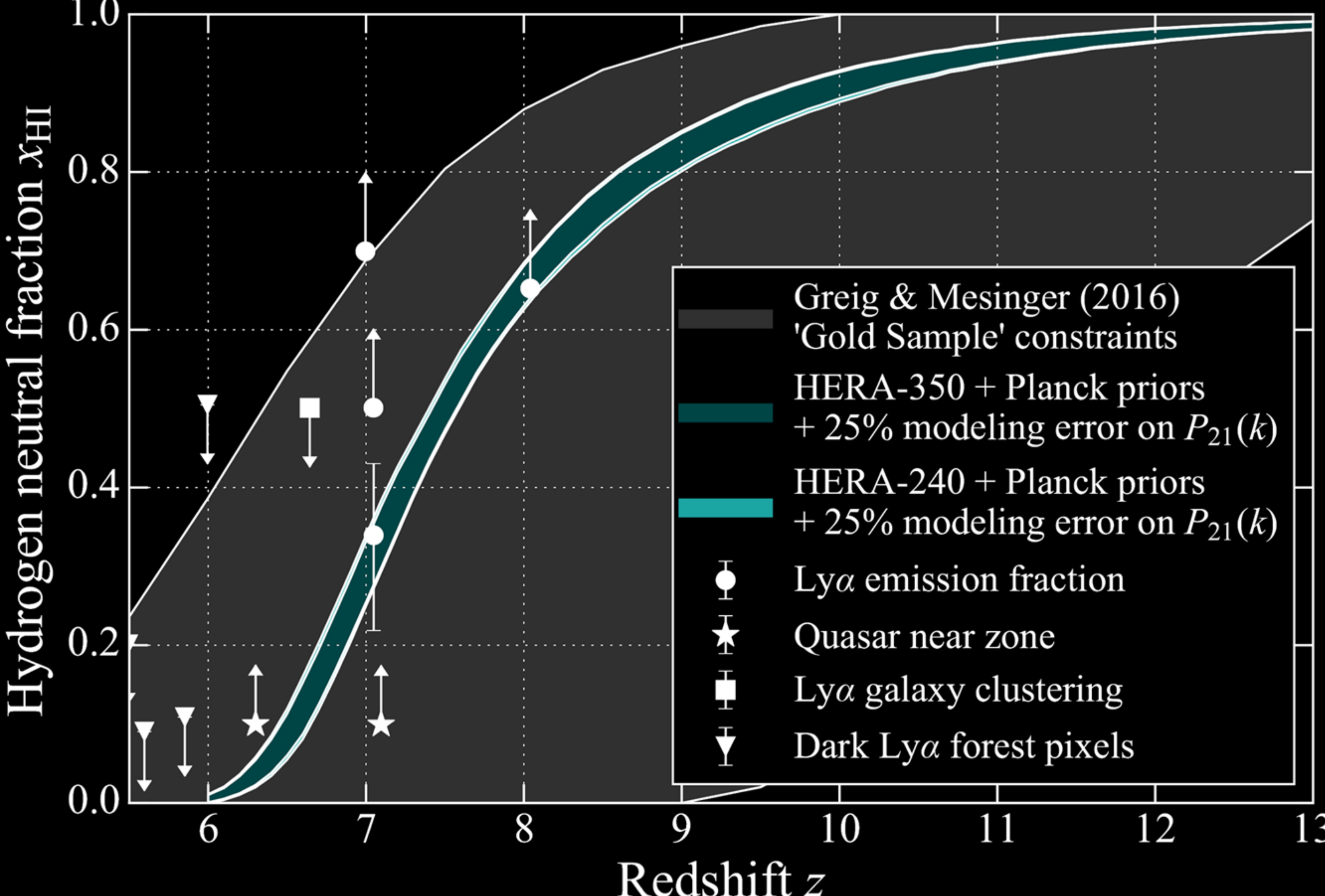
Table 1. Predicted SNRs of 21 cm experiments for an EoR model with 50% ionization at $z = 9.5$, with 1080 hours observation, integrated over a Δz of 0.8*.

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

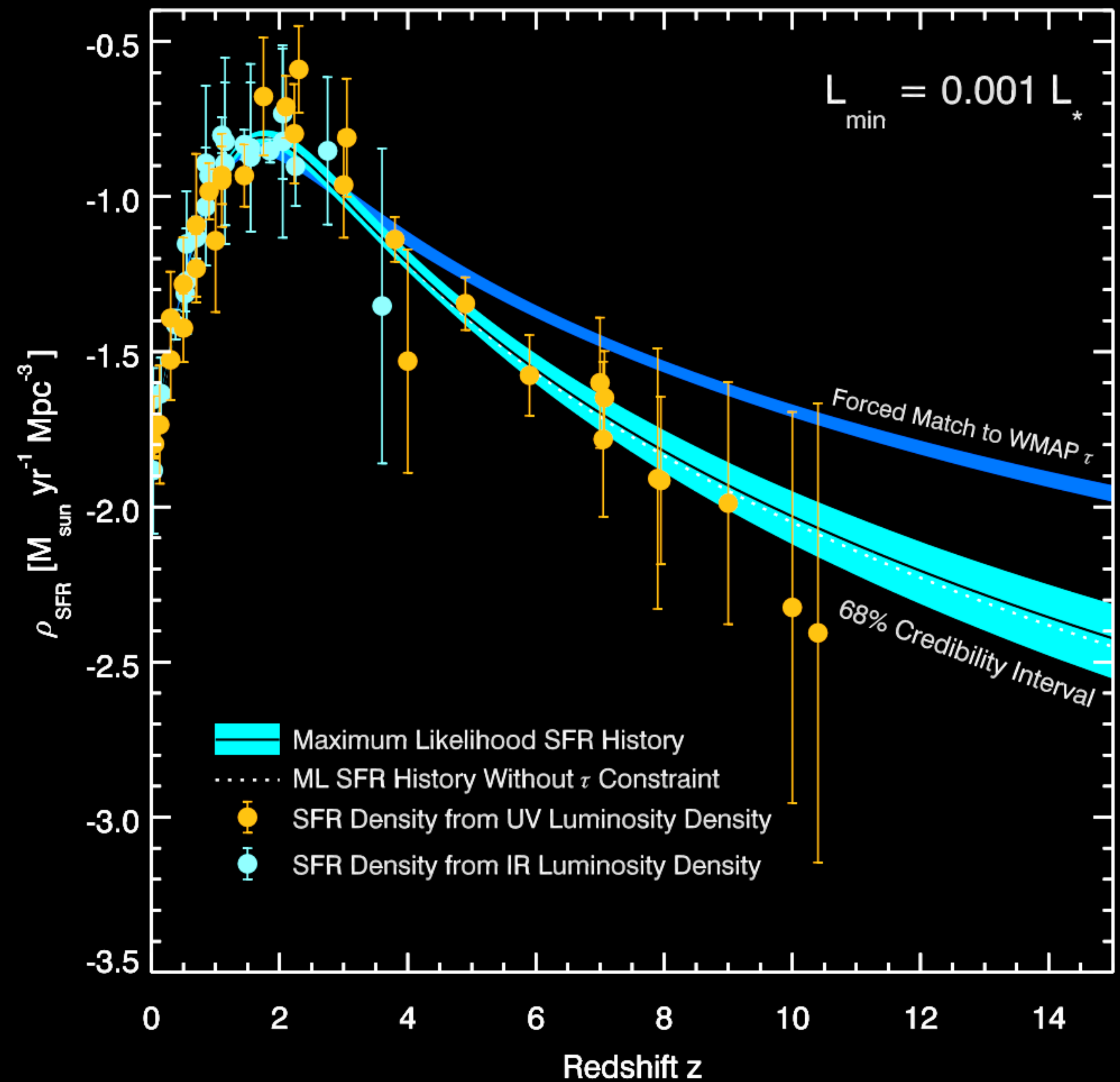
*Calculations done via **21cmSense** (www.github.com/jpober/21cmSense; Pober et al. 2013b, 2014a). Foreground avoidance represents an analysis comparable to Ali et al. (2015), whereas foreground modeling allows significantly more k modes of the cosmological signal to be recovered.



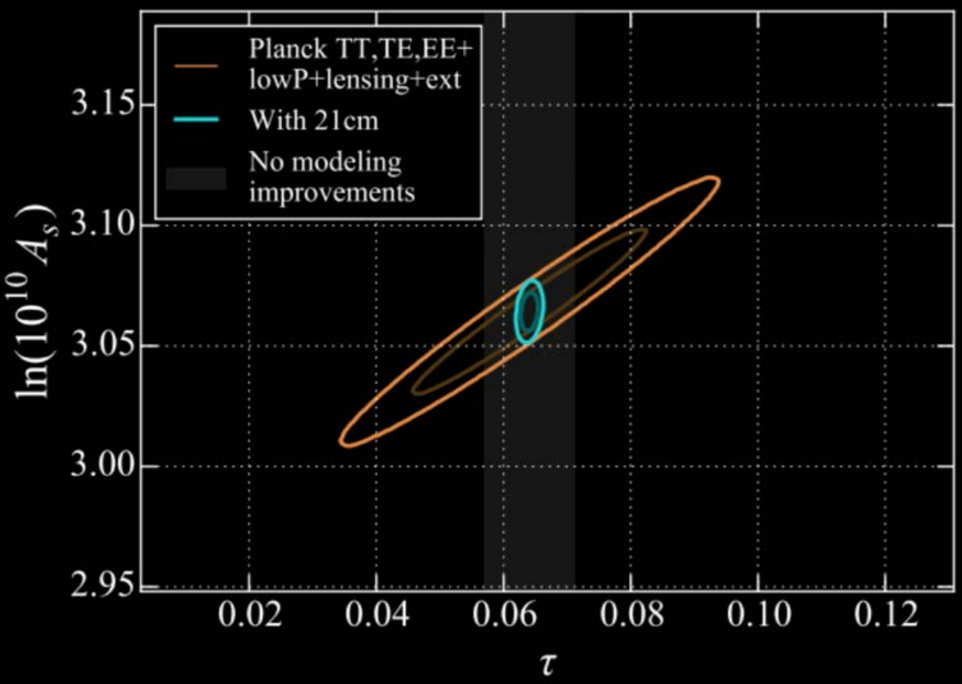
ζ
20
40
60
80
100
$R_{\rm mfp}$ (Mpc)
20
18
16
14
12
10
8
6
4
2
Projected Constraints:
LOFAR
HERA
SKA
(95% confidence)
$\log_{10}(T_{\rm vir}^{\rm min}$ [K])
5.2
5.0
4.8
4.6
4.4
4.2
4.0
0.05
0.2
0.4
0.6
0.8
1.0
$f_{\rm esc}$
2
4
6
8
10
12
14
16
18
20
$R_{\rm mfp}$ (Mpc)

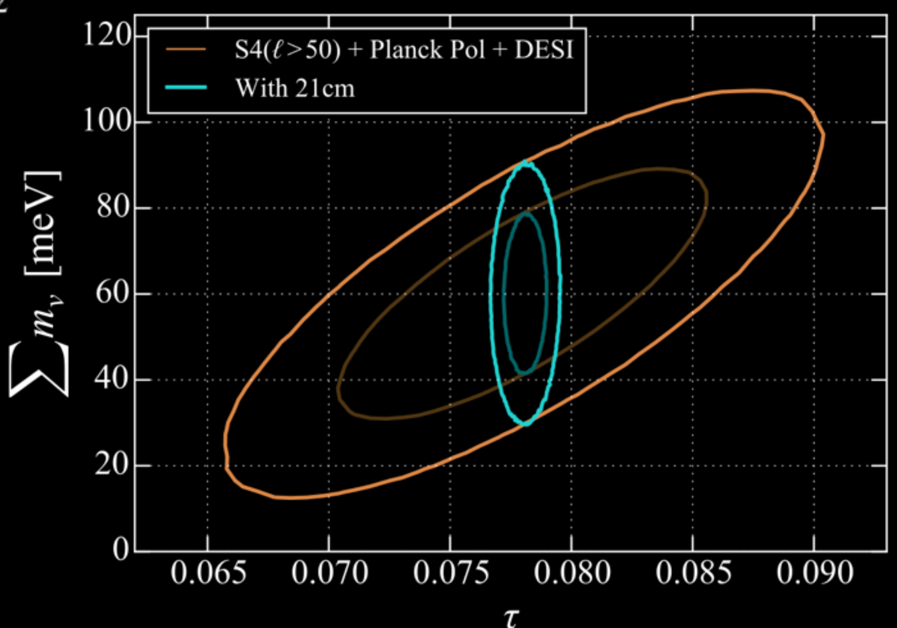


Hydrogen neutral fraction x_{HI}
Redshift z
1.0
0.8
0.6
0.4
0.2
0.0
6
7
8
9
10
11
12
13
Greig & Mesinger (2016)
'Gold Sample' constraints
HERA-350 + Planck priors
+ 25% modeling error on $P_{21}(k)$
HERA-240 + Planck priors
+ 25% modeling error on $P_{21}(k)$
Lyα emission fraction
Quasar near zone
Lyα galaxy clustering
Dark Lyα forest pixels

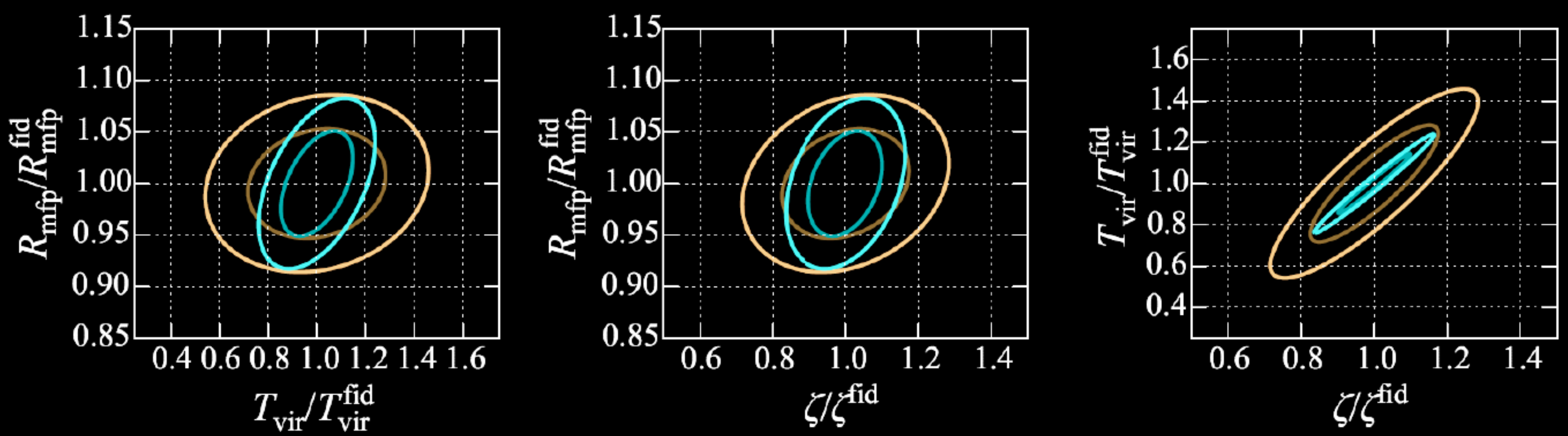


Robertson et al. 2015


Planck TT,TE,EE+
lowP+lensing+ext
With 21cm
No modeling
improvements
$\ln(10^{10}A_s)$
3.15
3.10
3.05
3.00
2.95
0.02
0.04
0.06
0.08
0.10
0.12
τ


S4($\ell > 50$) + Planck Pol + DESI
With 21cm
$\sum m_\nu$ [meV]
120
100
80
60
40
20
0
0.065
0.070
0.075
0.080
0.085
0.090
τ

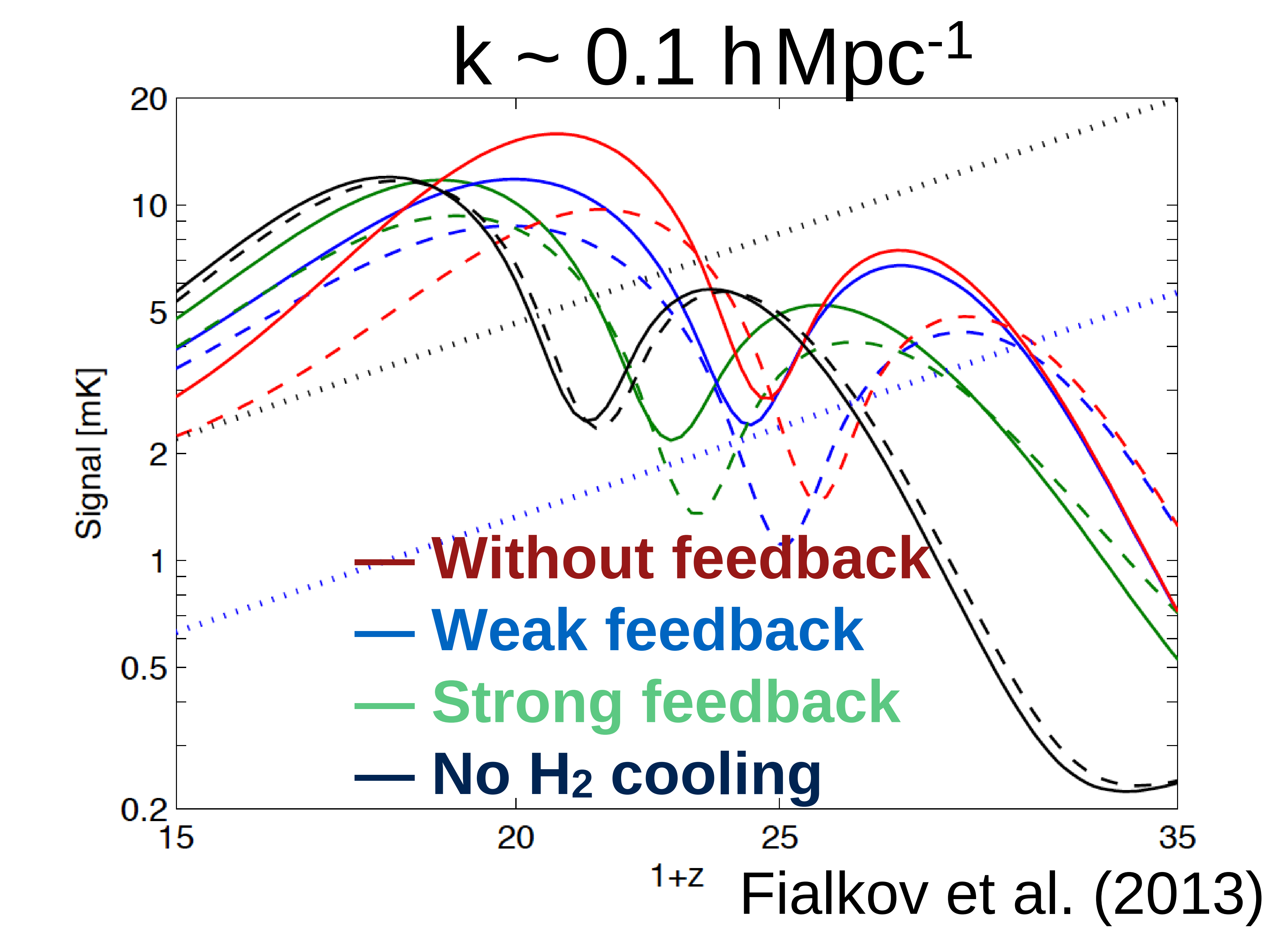
HERA will provide the first astrophysical constraints on Cosmic Dawn, and will have some sensitivity to cosmology



Cosmo params fixed

Cosmo params varied

AL & Parsons (2016)


k ~ 0.1 h Mpc^{-1}
Signal [mK]
20
10
5
2
1
0.5
0.2
15
20
25
35
1+z
Without feedback
Weak feedback
Strong feedback
No H_2 cooling
Fialkov et al. (2013)

What Next?

- Enable cross-correlation science
  - Image domain, or at least de-wedging our data
  - Matching observing parameters

- Dark Ages Science (higher z, 30-100 MHz)
  - LEDA, DARE, HERA

- 21cm Monopole
  - EDGES, LEDA, SciHi, SARAS, Hyperion, et al.

- Define Relationship to SKA-Low
  - What US funding streams are available
  - What is the supported community

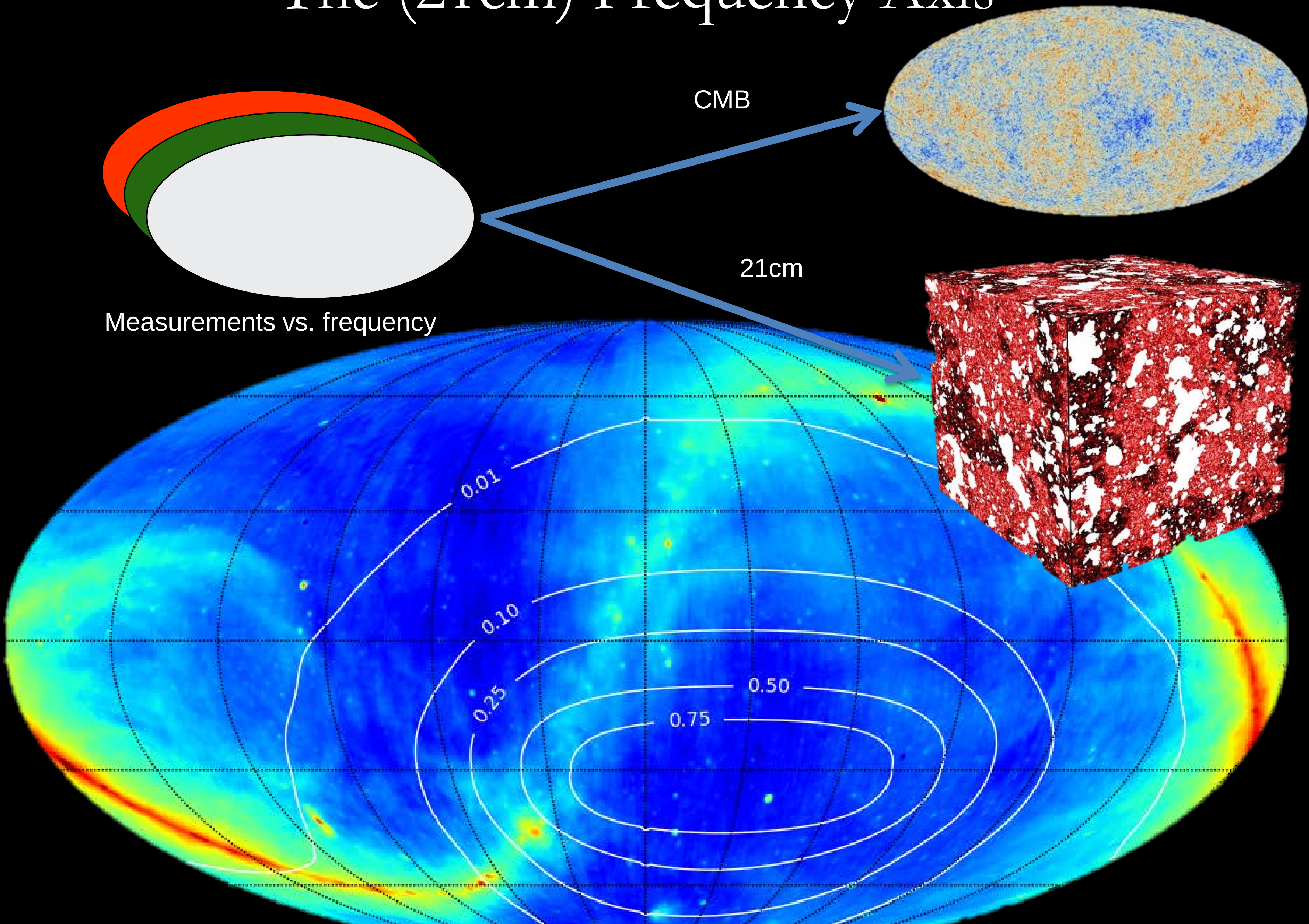
Science Goals for Next Decade

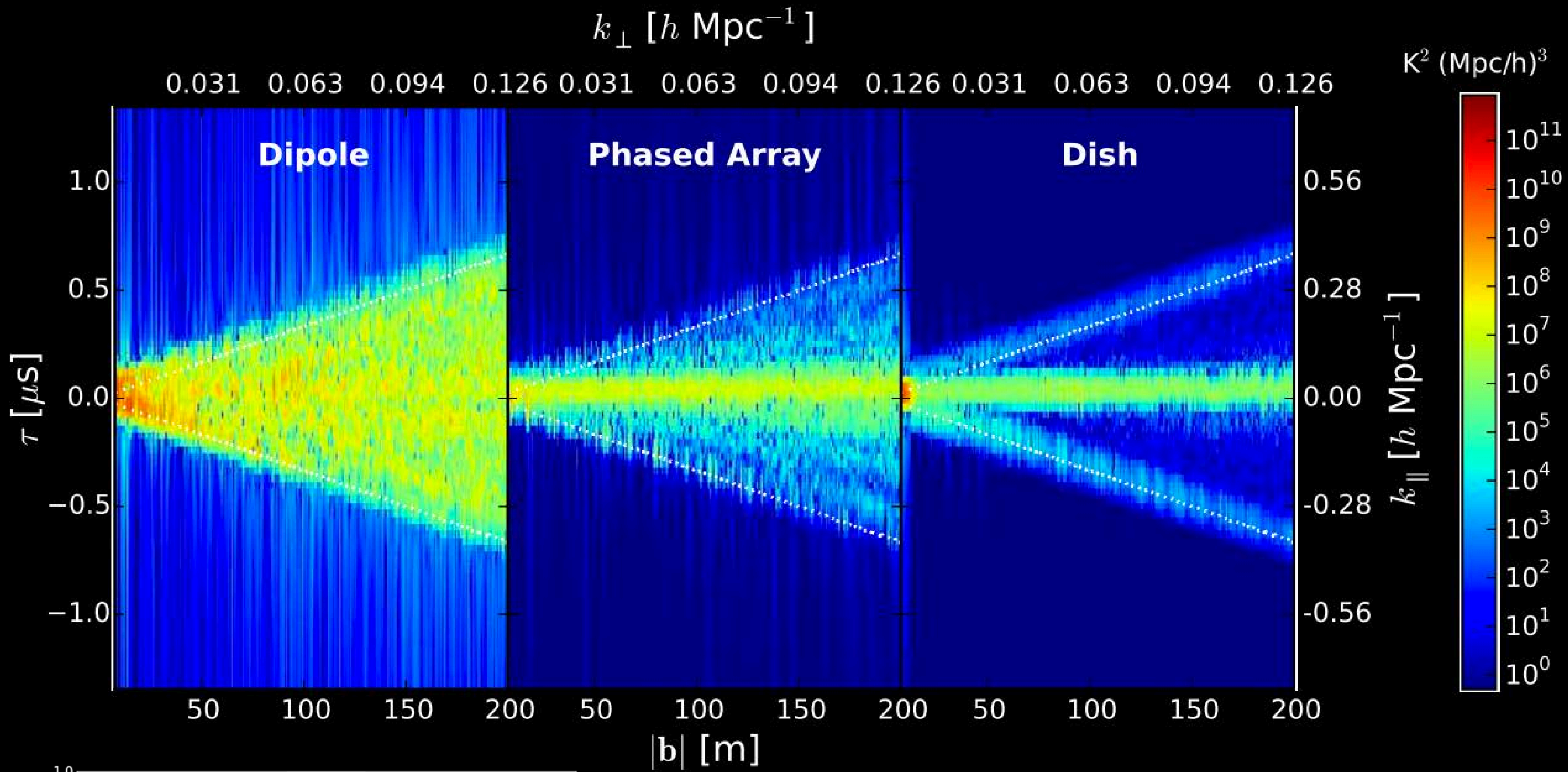
- Power Spectrum
  - Redshift ($6 < z < 30$)
  - Sensitivity
  - Size Scale
- "Imaging"
  - cross-correlations (CO, C+, EE, Ly-α, WFIRST)
- Astrophysics & Cosmology
  - feedback models
  - baryonic winds
  - WDM damping at high k
  - sum of neutrino masses
  - CMB optical depth
  - context for high-z galaxy surveys

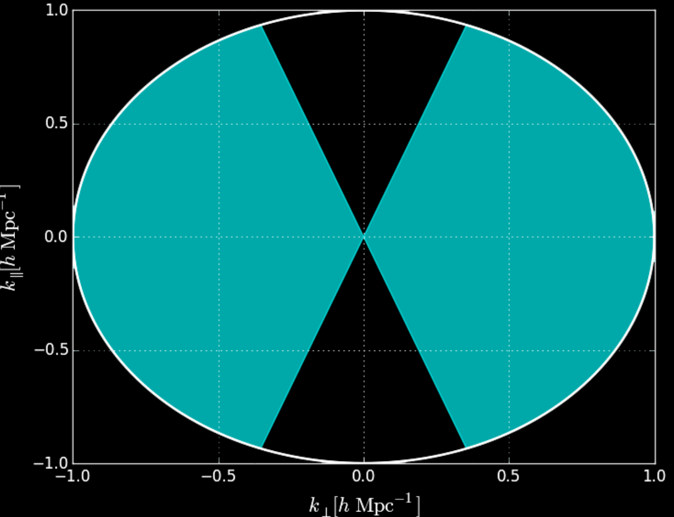
Science Take-home messages

- Rich astrophysical and cosmological information available beyond HERA by pushing redshift, sensitivity, and scale frontiers.
- 21cm surveys are much better suited for probing radial fluctuations than angular fluctuations.
- Sensitivity rather than cosmic variance will be the limiting factor; compact arrays are still advantageous.
- Astrophysics can act as an amplifier for cosmology.
- Simultaneously pushing the redshift, sensitivity, and scale frontiers is challenging, but with potentially great science rewards.

The (21cm) Frequency Axis

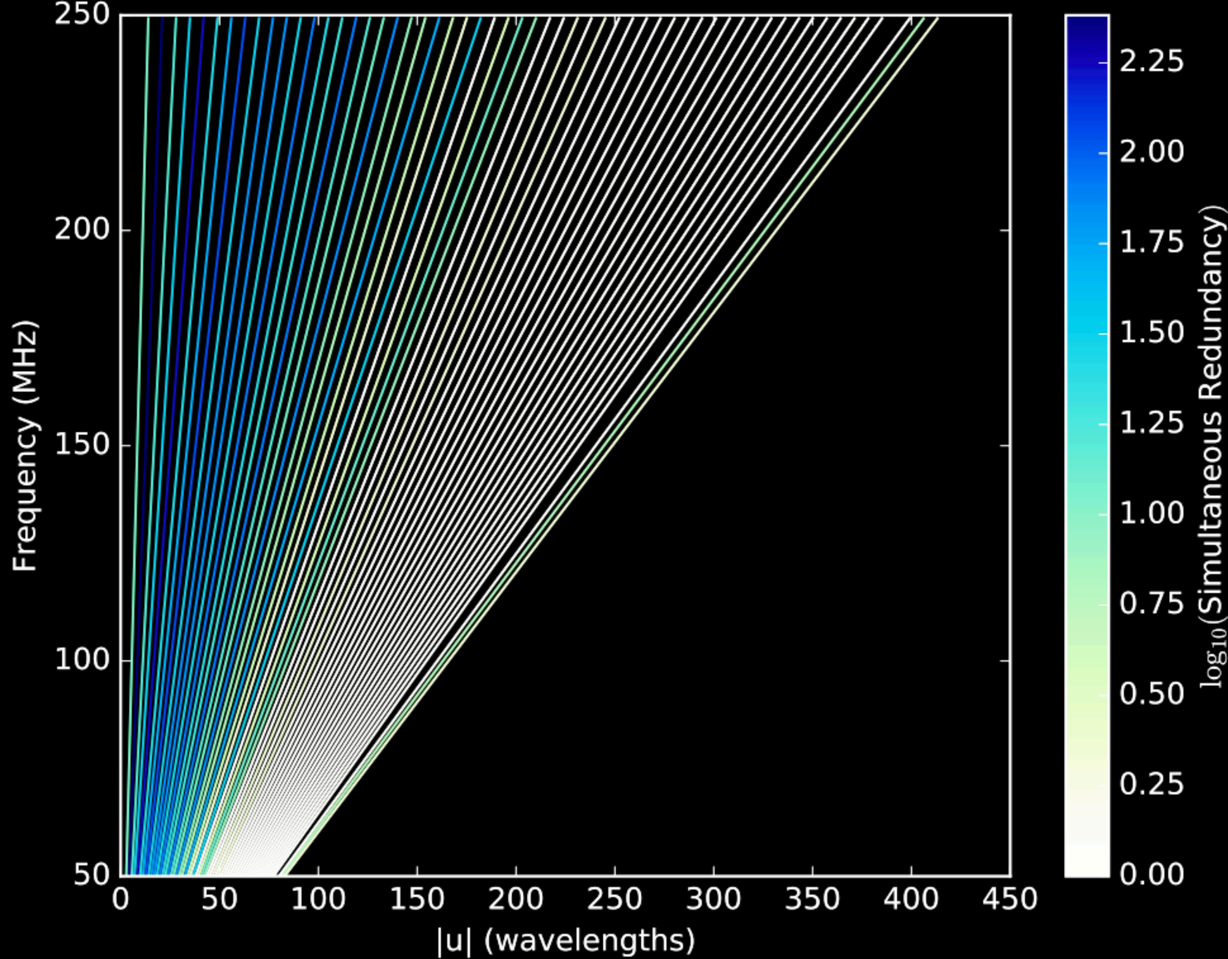


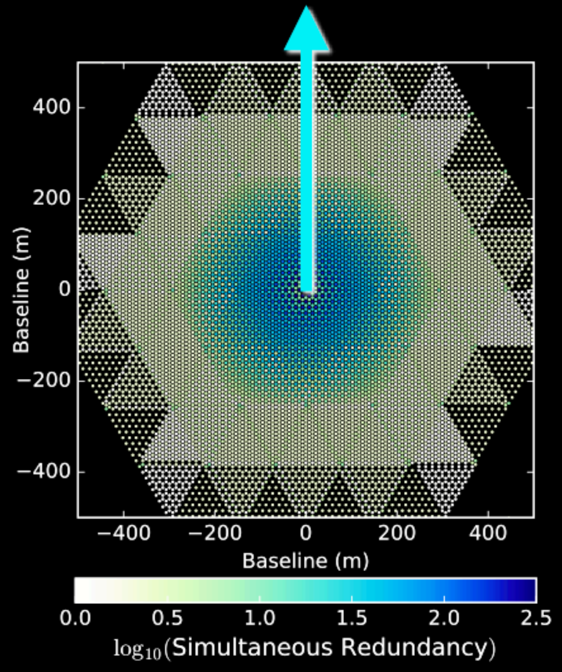




(Thyagarajan et al. 2015)

The split core also increases the frequency sampling at fixed (u,v).





Notes

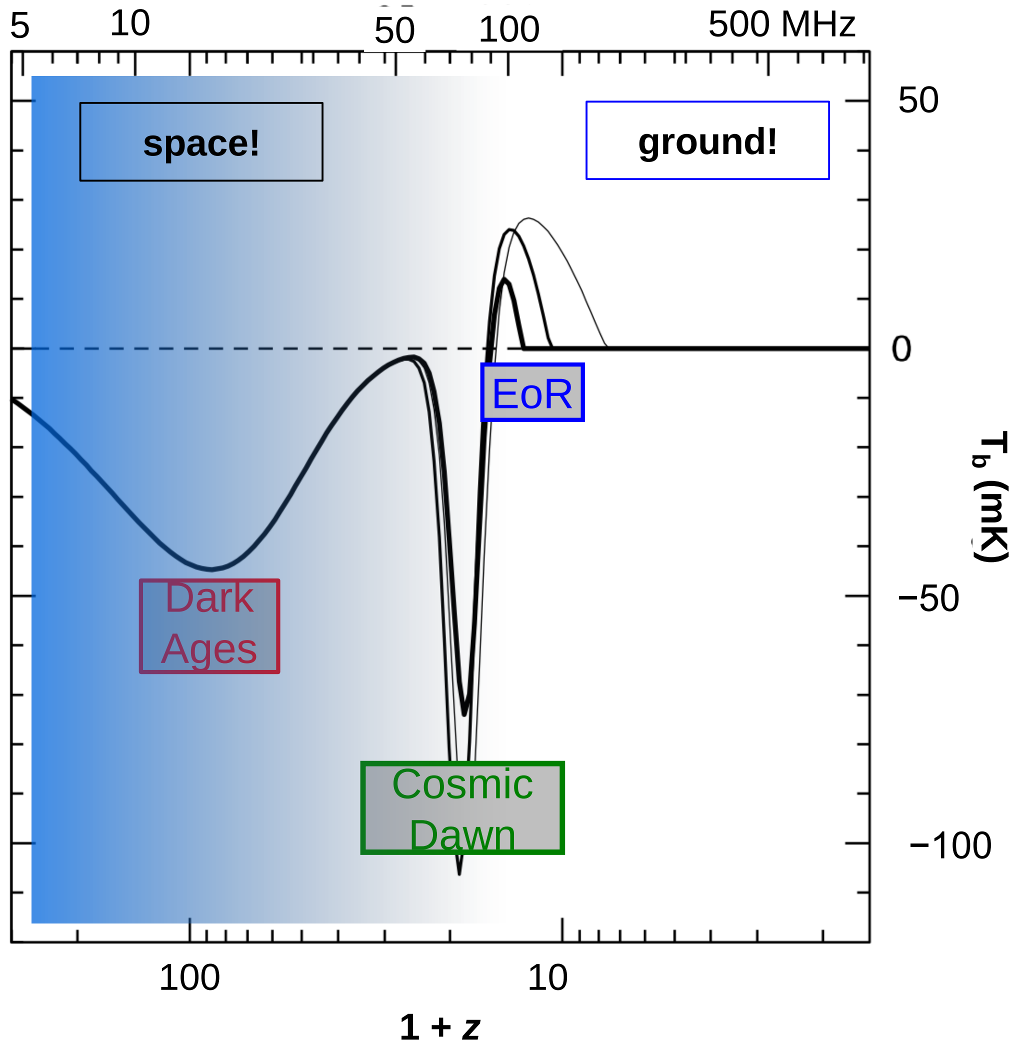
- Cosmic variance not an issue
- Angular modes are not going to be very useful
- Array redundancy is important
- Design parameters: element size, antenna sep, packing, split cores, outriggers, hierarchy
- 1e-5 calibration of bandpass and beam cal are critical issues for all experiments
- Need better sky models, characterization of low-frequency polarization

Strawman Proposal

- HERA-III (2010 whitepaper), $65M in hardware
  - 40,000 dipoles, 3.5m diameter, 0.5 km^2 collecting area
  - FFT correlation
  - $15 < z < 5$
  - designed for overlapping uv coverage vs frequency
- Dark Ages Telescope
  - $30 < z < 15$
- Monopole experiments (ground + space)
  - $100 < z < 5$

Hydrogen Signal from EoR and Before

A Role for Space?

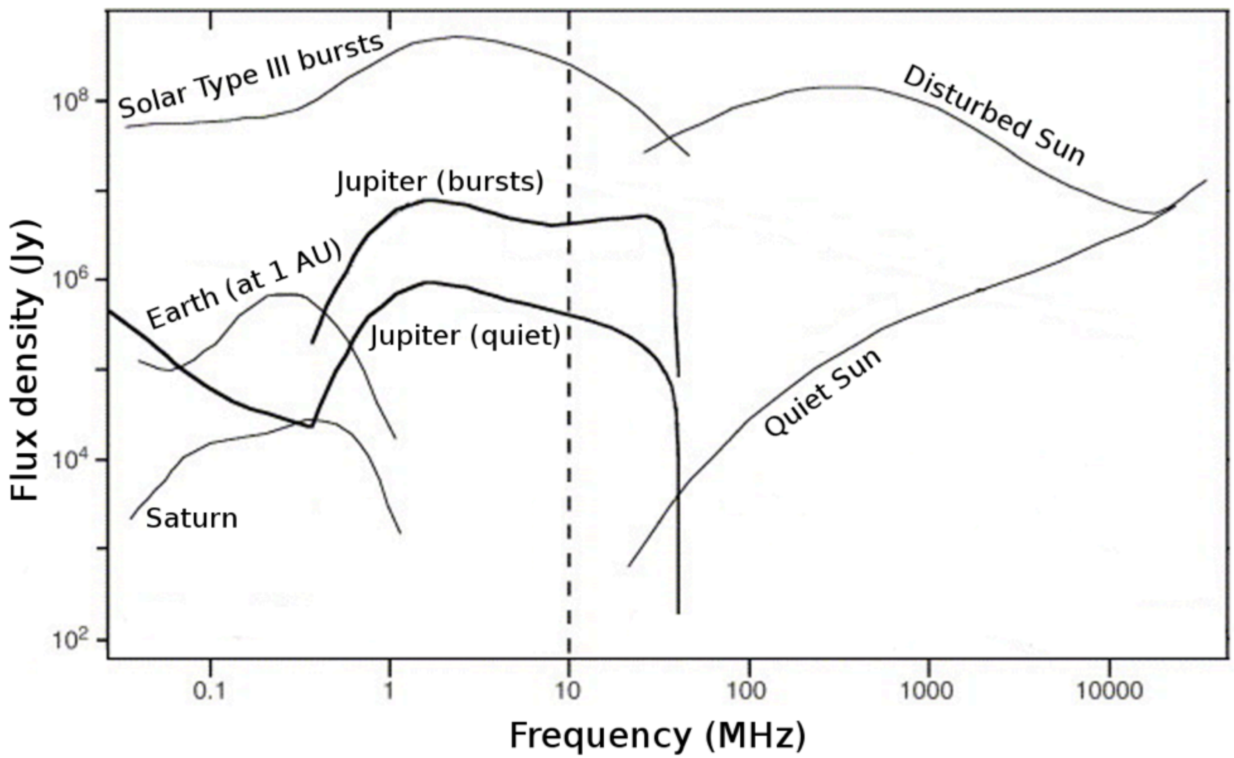


Consider atmospheric (ionospheric) opacity …

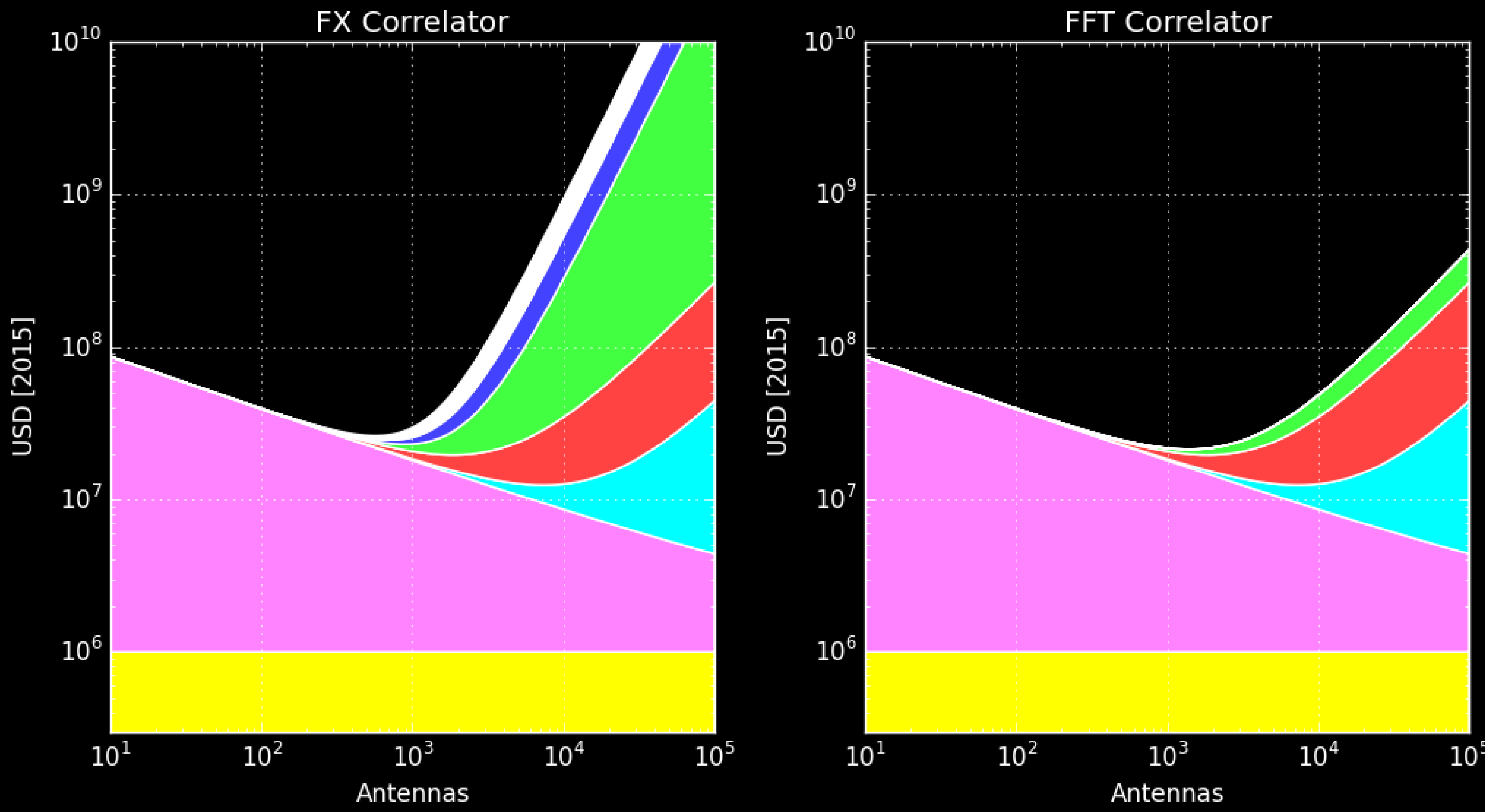
Caveat: RFI

Very long term, we must beat the ionosphere.

Unless the universe *really* surprises us, expect the most exciting planets to emit below the ionospheric cutoff.



Zarka (2007)



yellow=infrastructure, magenta=reflector, cyan=feed, red=signal chain, green=correlator, blue=data storage, white=computing.

2020 Budget (to OoM)

Assume: 40,000 elements, 3.5m diameter, 0.5 km^2 collecting area

- FFT Correlation
- Improved Signal Chain (integrated post-amp, digitizer, CAT5 out?)
- 2 Moore's Law capability doublings in ~6 years

Total cost divided by # of antennas

	Now	2022 (2 Moore's Laws)
Infrastructure	$100	$100
Reflector	$150	$150
Feed	$400	$400
Signal Chain	$1600	$500*
Correlator	$1600 ($98,000 if FX)	$400
Data	$100	$25
Computing	$100	$25
TOTAL	$4,050	$1,600

Overall: ~$64M in hardware, ~$180M total project budget

Questions

US-led “21cm+” facility vs. SKA-Low

- Experiment vs. Observatory
- 2010 Decadal’s “HERA-III” at MREFC level (~$150M)
- auxiliary science: FRB, planetary B fields, ionosphere, …?
- supported community:
-     low-frequency observing vs. SKA observing
-     high-z astro, cosmology, galaxy evolution

Split EoR/Dark Ages arrays, or can they be the same?

- do instruments benefit from being co-located? (e.g. SKA)

How to match other high-z probes

- sky coverage, angular scale, sensitivity

Funding as omnibus package, or just a scientific framework?
What is the right size?