21 cm Power Spectrum Experiments

UC Irvine, Oct. 1, 2015

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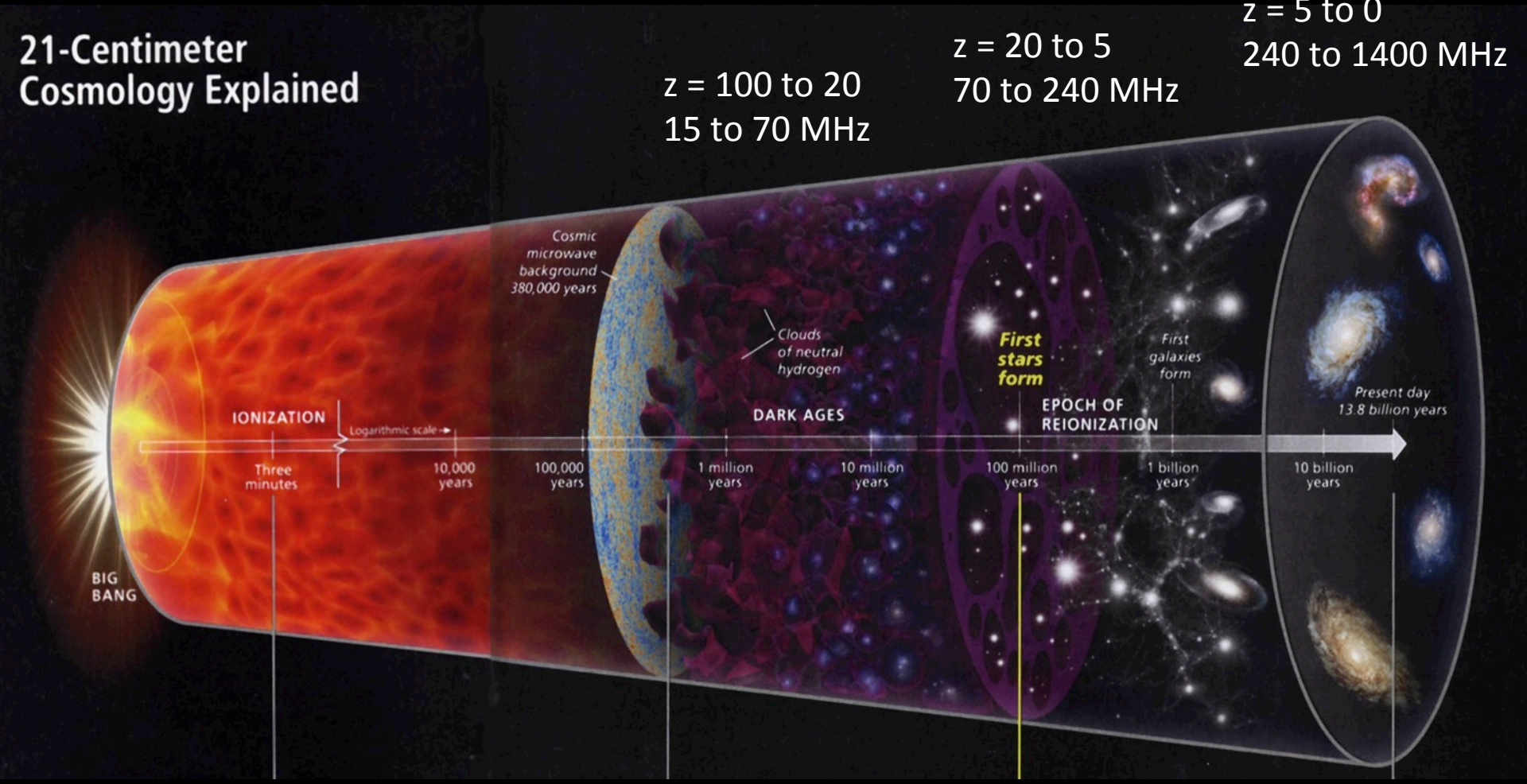
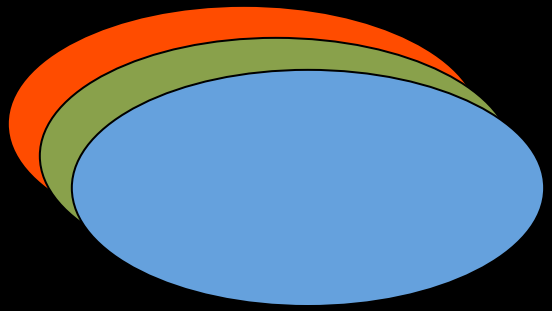

21-Centimeter Cosmology Explained
z = 100 to 20
15 to 70 MHz
z = 20 to 5
70 to 240 MHz
z = 5 to 0
240 to 1400 MHz
Cosmic microwave background 380,000 years
Clouds of neutral hydrogen
First stars form
First galaxies form
Present day 13.8 billion years
IONIZATION
Logarithmic scale
DARK AGES
EPOCH OF REIONIZATION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

Why 21cm Cosmology

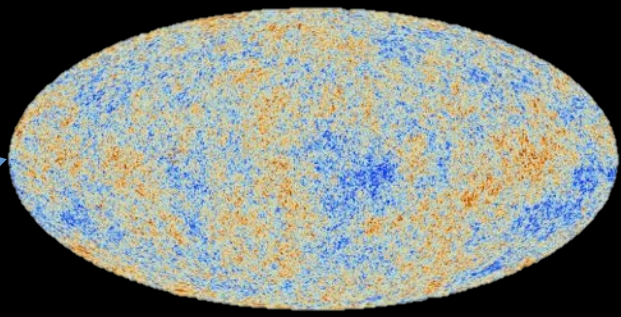
- Line Emission
  - Optically thin
  - Observable even into Dark Ages
  - Directly probes redshift evolution
- Sensitive to
  - Ly-α: Wouthuysen Field Effect
  - X-ray: Heating
  - UV: Ionization
- Integrated measure of galactic properties
  - includes low-mass tails
  - bubble size breaks some degeneracies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

The (21cm) Frequency Axis

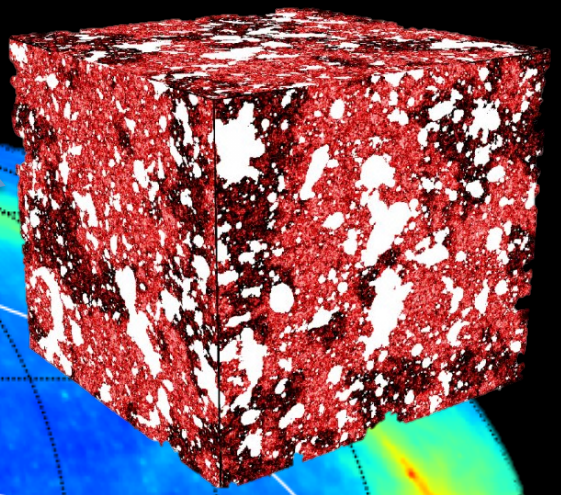


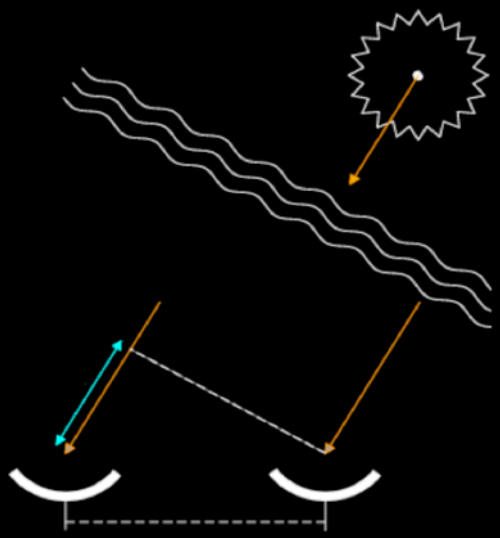
Measurements vs. frequency

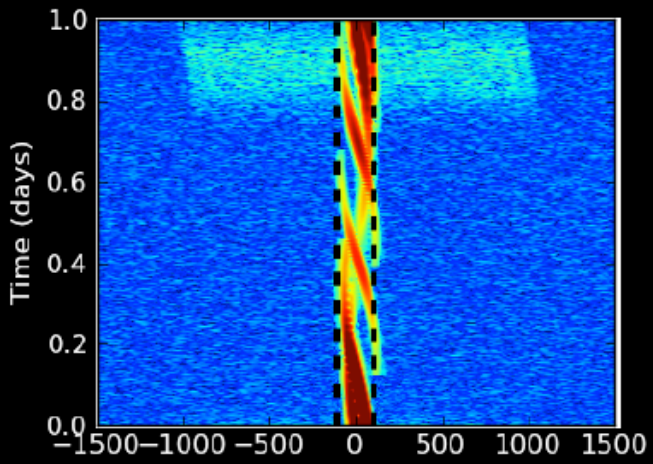
CMB

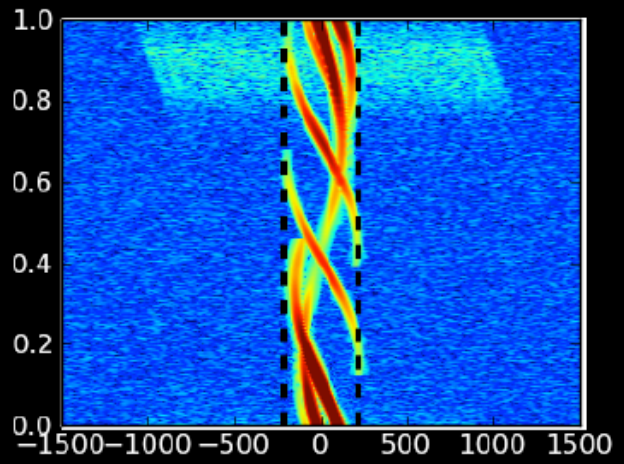


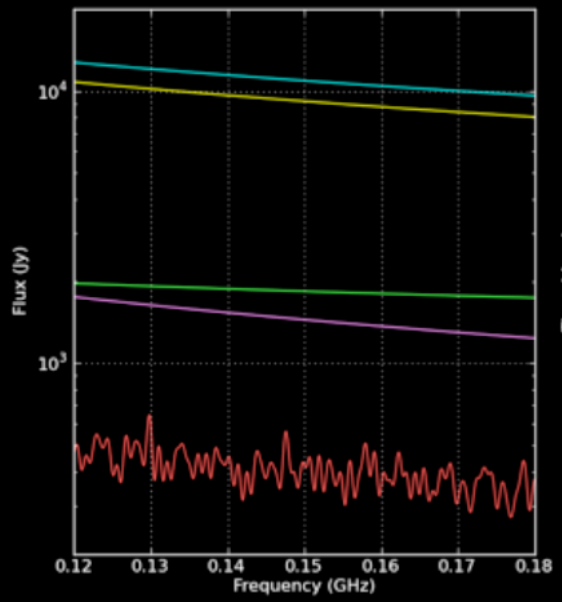
21cm

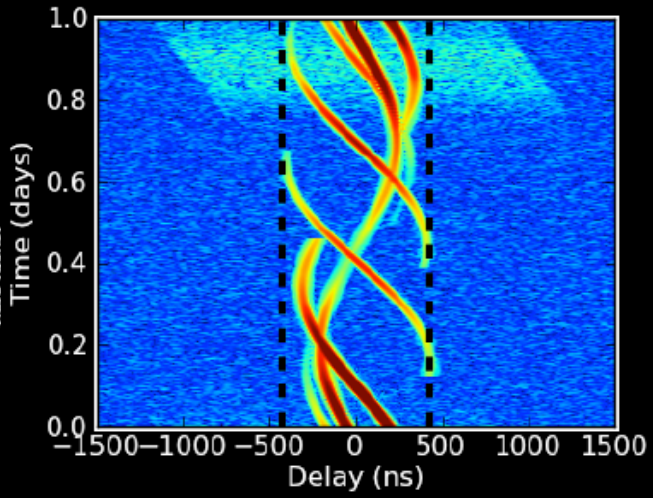


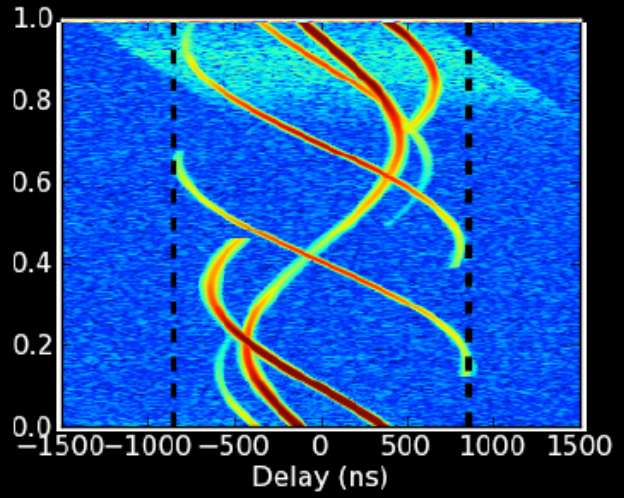




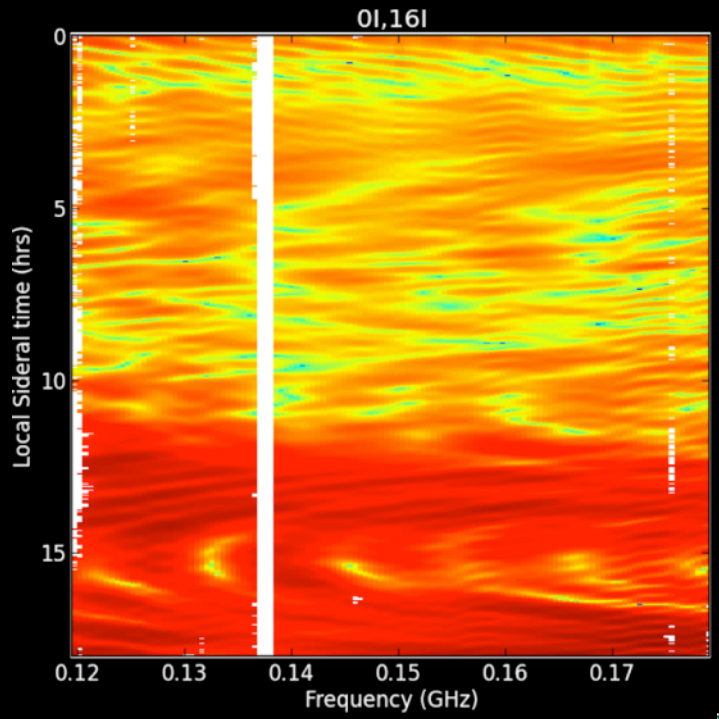


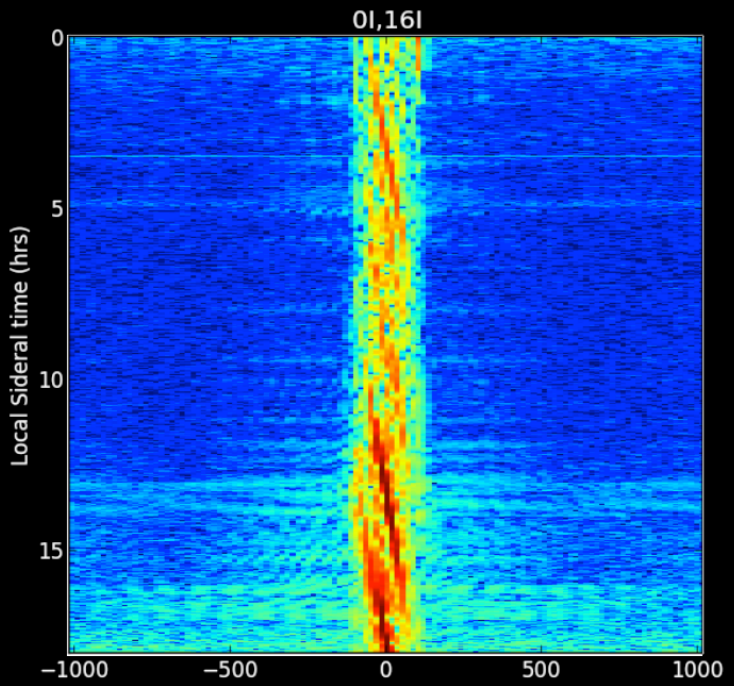


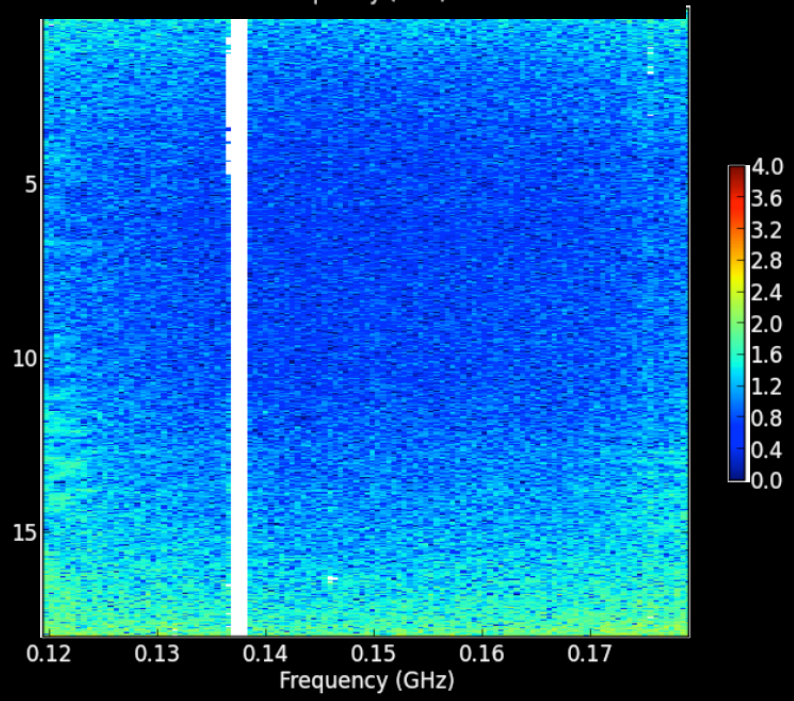


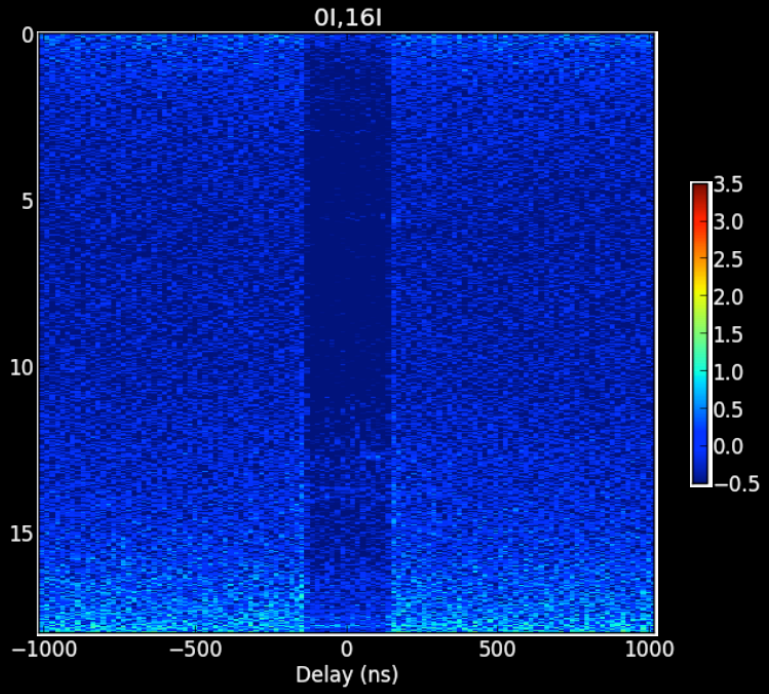


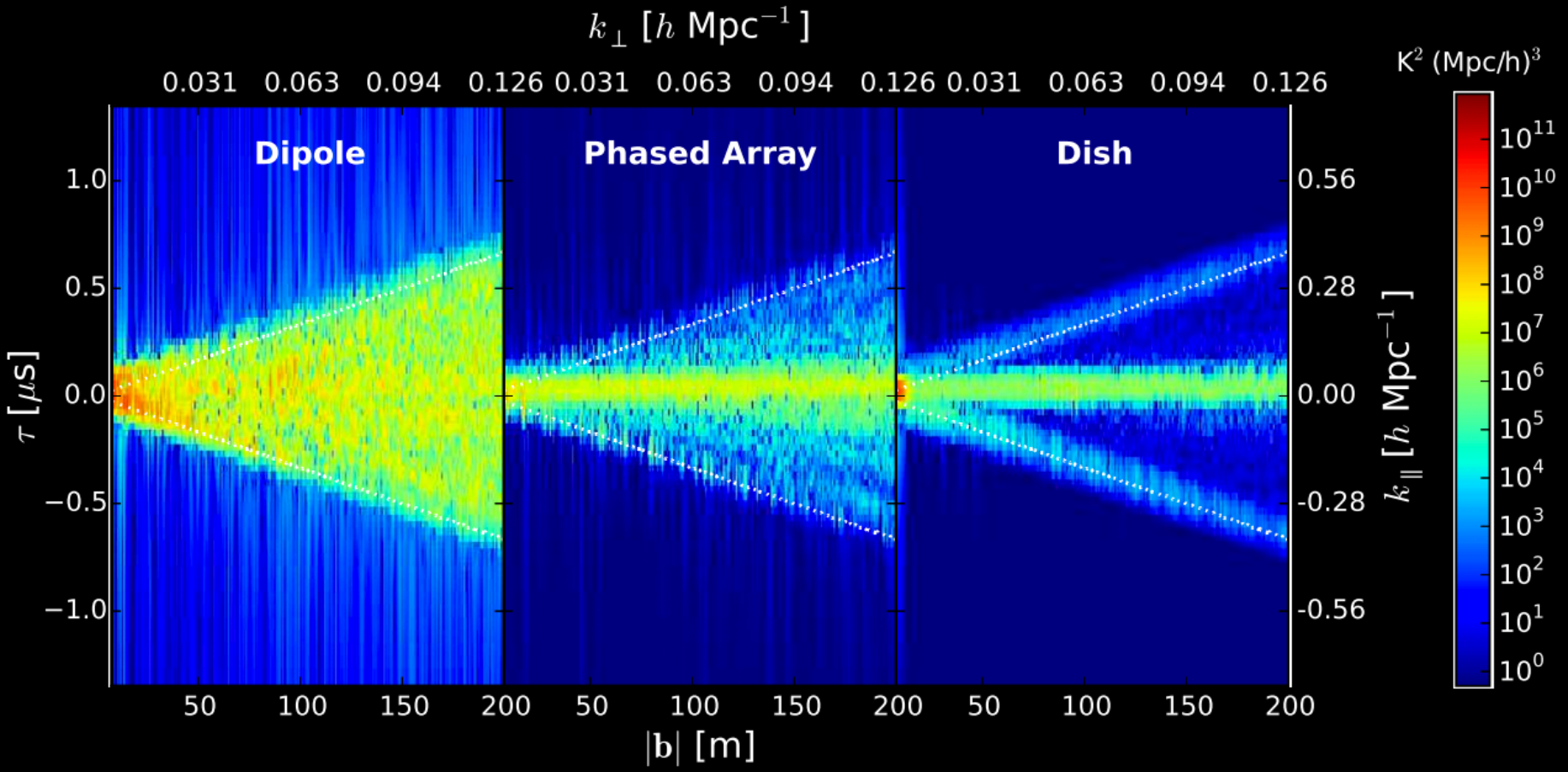
Parsons et al. (2012b) arXiv:1204.4749


0I,16I
Local Sideral time (hrs)
Frequency (GHz)
0
5
10
15
0.12
0.13
0.14
0.15
0.16
0.17

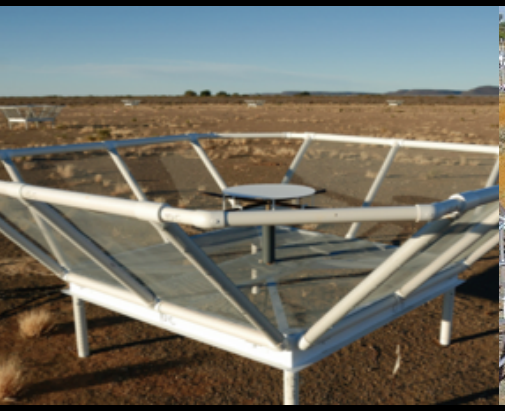
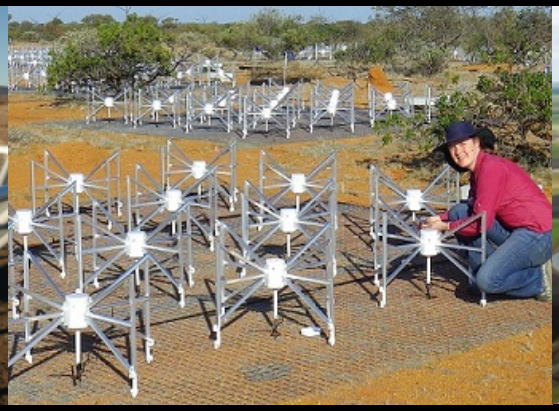

0I,16I
Local Sideral time (hrs)
0
5
10
15
−1000
−500
0
500
1000

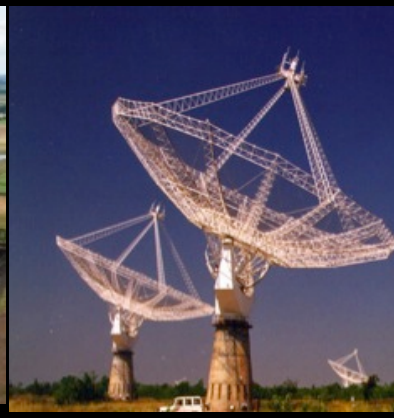

Frequency (GHz)
5
10
15
0.12
0.13
0.14
0.15
0.16
0.17
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

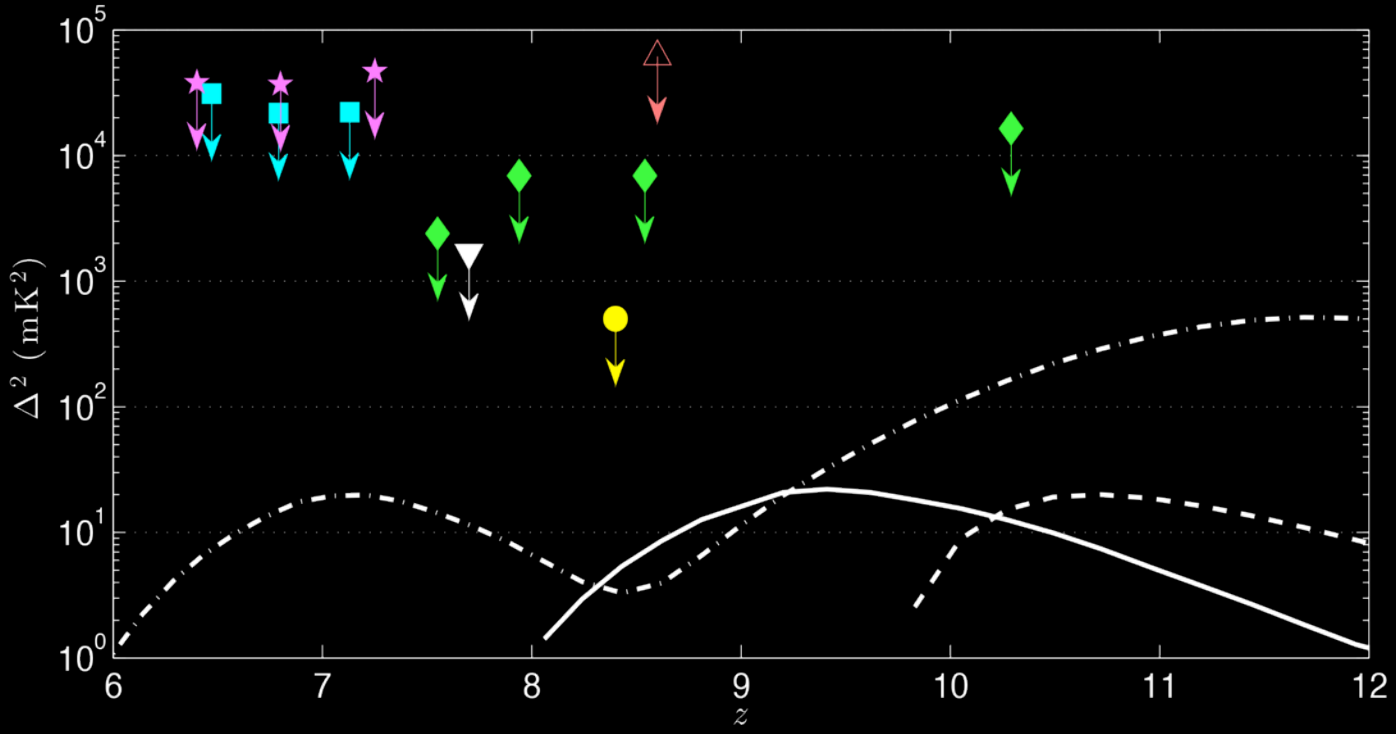

0I,16I
Delay (ns)
0
5
10
15
−1000
−500
0
500
1000
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5



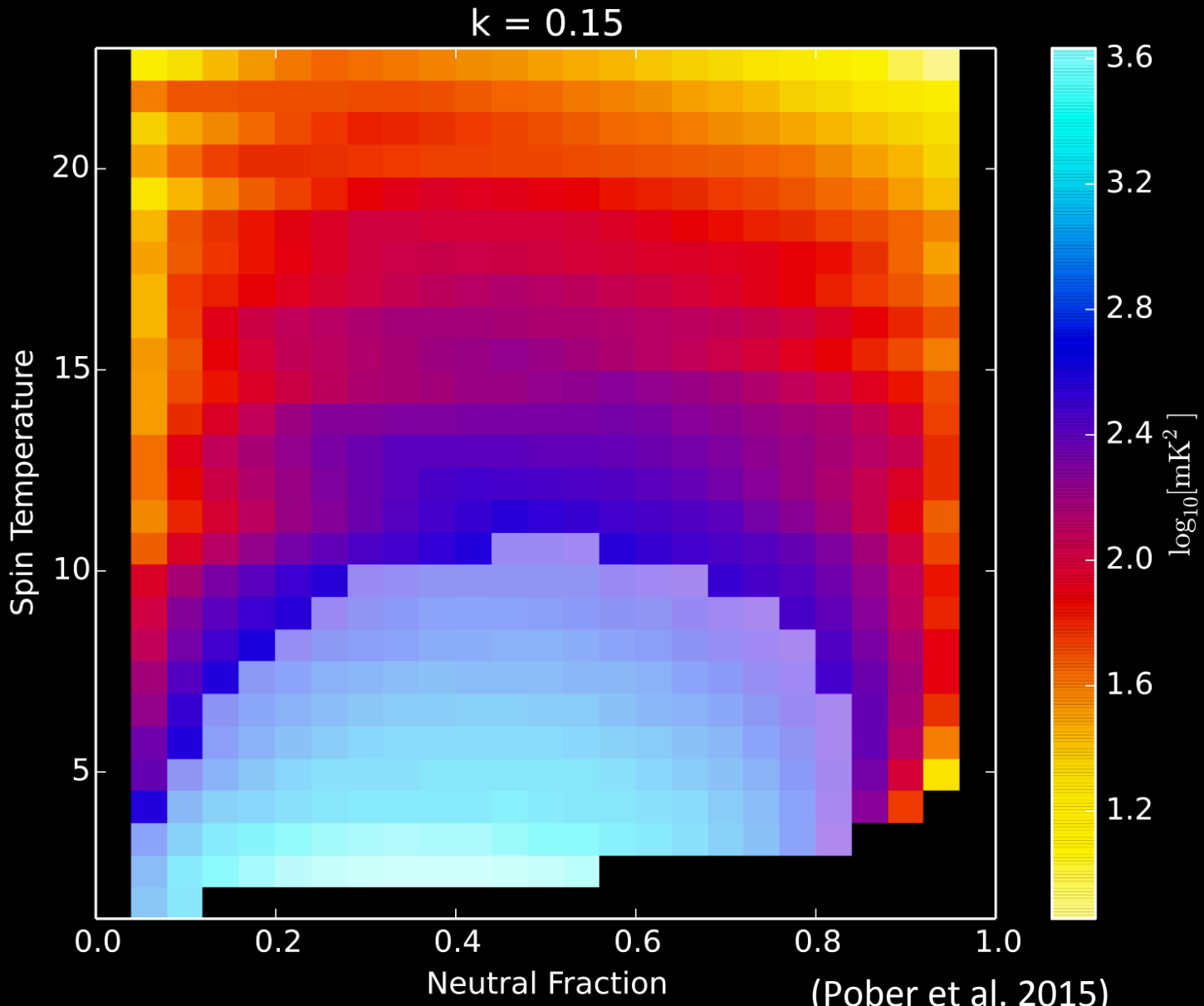
(Thyagarajan et al. 2015)




10^5
10^4
10^3
10^2
10^1
10^0
Δ^2 (mK^2)
6
7
8
9
10
11
12
z
Ali, 2015
Beardsley, 2015
Dillon, 2015
Jacobs, 2015
Parsons, 2014
Paciga, 2013
CDM Extreme
CDM Fiducial
WDM Fiducial

$$\delta T_b(\nu) \approx 9 x_{\rm HI}(1+\delta)(1+z)^{\frac{1}{2}} \left[1 - \frac{T_{\rm CMB}(z)}{T_S}\right] \left[\frac{H(z)/(1+z)}{{\rm d}v_\parallel/{\rm d}r_\parallel}\right] {\rm mK}$$



(Pober et al. 2015)

Location: S30° 34′, E21° 25′ E (South Africa)

Configuration: 331 hex-pack, 21 outriggers

- **Min baseline:** 14.6m (7.8° scale)
- **Max baseline:** 1066m (9′ beam)

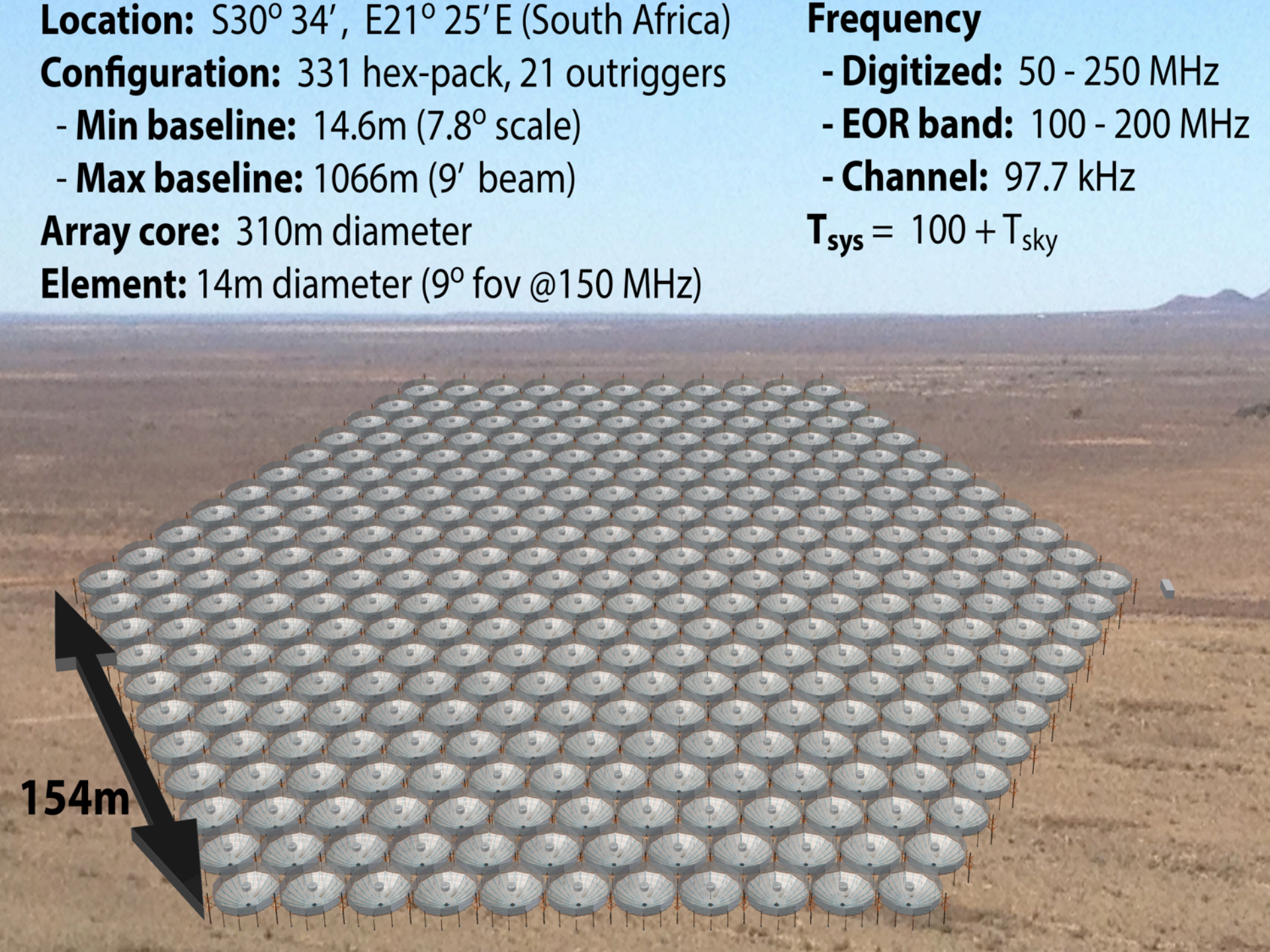
Array core: 310m diameter

Element: 14m diameter (9° fov @150 MHz)

Frequency

- **Digitized:** 50 - 250 MHz
- **EOR band:** 100 - 200 MHz
- **Channel:** 97.7 kHz

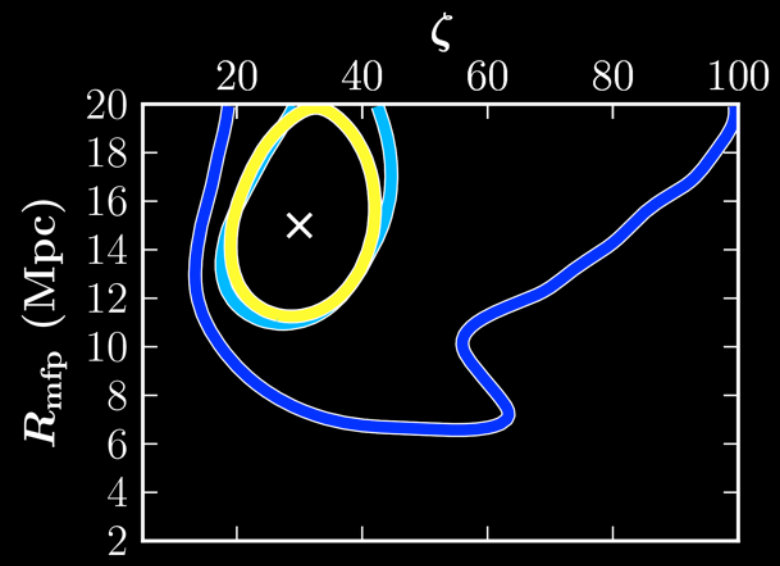
$T_{sys} = 100 + T_{sky}$



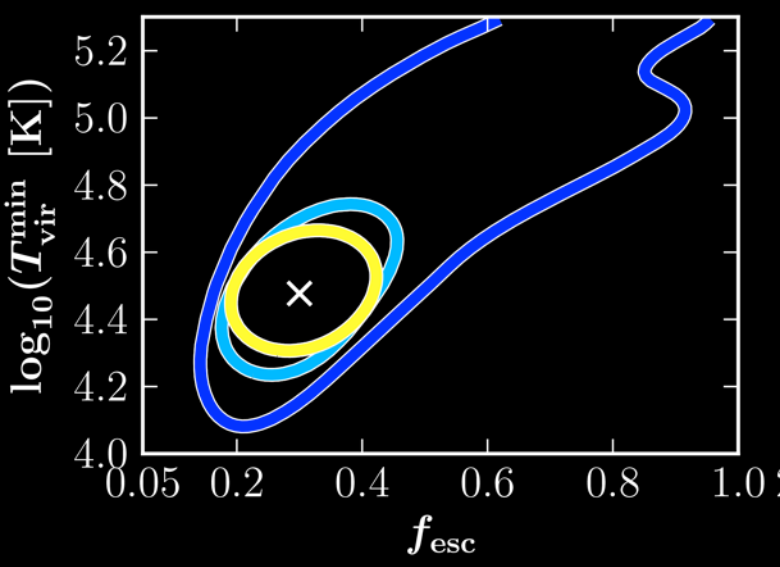
EOR Power Spectrum - Array Sensitivities*

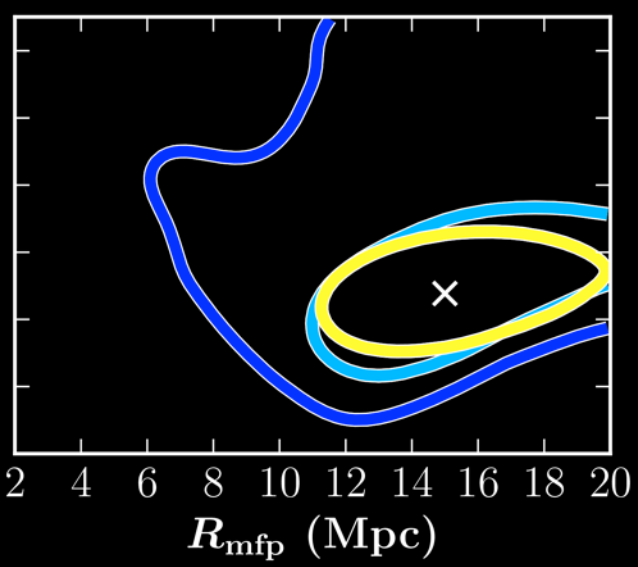
Instrument	Avoidance		Subtraction	
	Drift	Track	Drift	Track
PAPER 128	1.56	-	4.46	-
MWA 128	0.66	0.86	2.50	3.15
LOFAR (core)	0.70	1.90	7.48	12.22
HERA 37	5.67	-	15.46	-
HERA 331	38.75	-	111.69	-
MWA 256	2.40	2.81	8.28	9.64
SKA1 Low	21.23	26.92	139.07	115.13

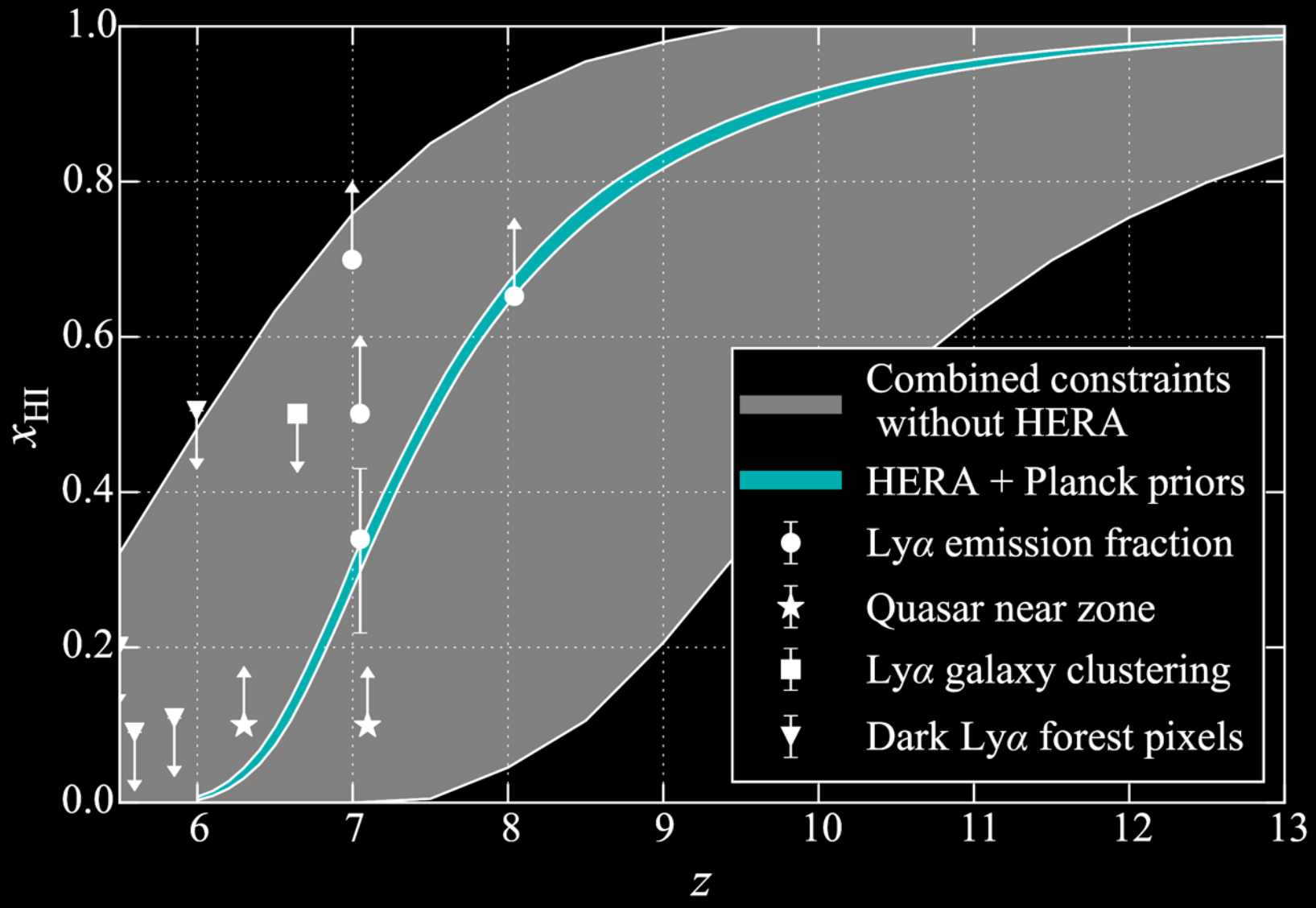
✳ **Updated 21 cm Experiment Sensitivites**, J. Pober, HERA Memo #3, Table 2 (http://reionization.org/memos)

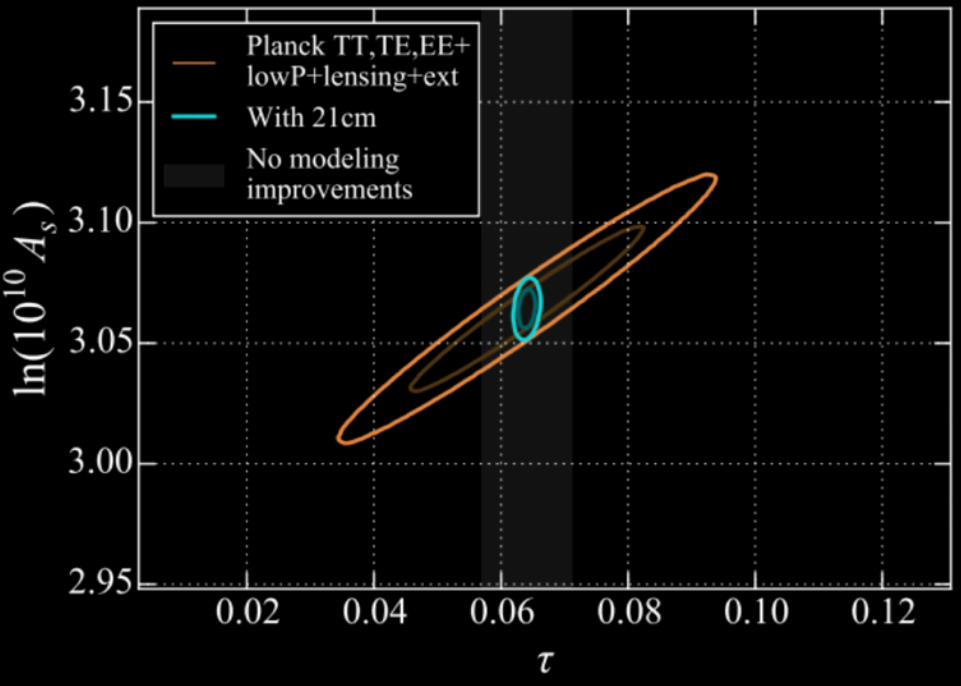


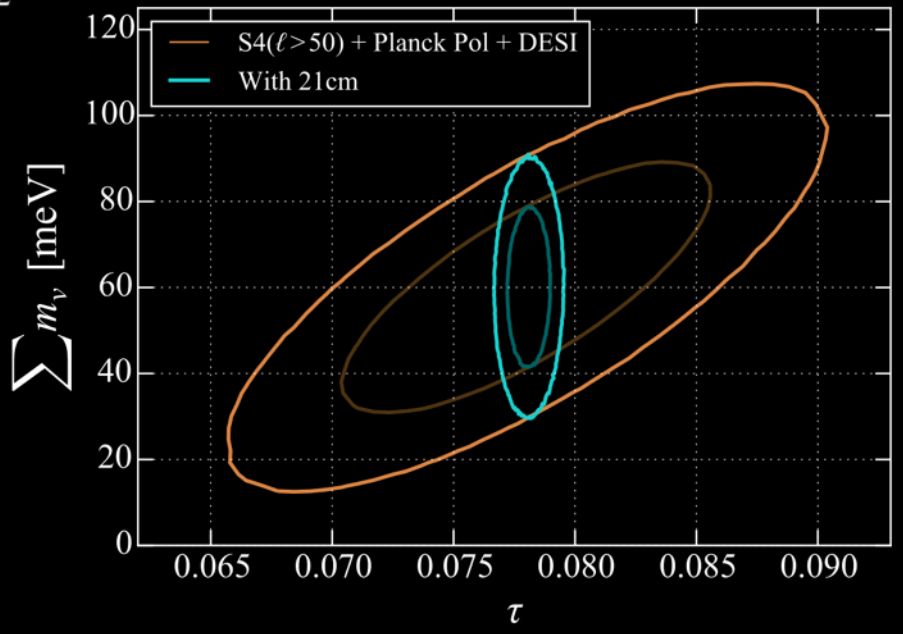
Instrument (multi-z)	Parameter (% error)		
	$\frac{\zeta}{\zeta_{\rm fid}}$	$\frac{R_{\rm mfp}}{R_{\rm fid,mfp}}$	$\frac{\log_{10}(T_{\rm vir}^{\rm min})}{\log_{10}(T_{\rm vir,fid}^{\rm min})}$
LOFAR	1.32 (40.38)	1.03 (20.06)	1.05 (5.43)
HERA	1.03 (11.81)	1.00 (11.99)	1.00 (1.95)
SKA	1.02 (6.11)	1.00 (10.04)	1.00 (0.96)

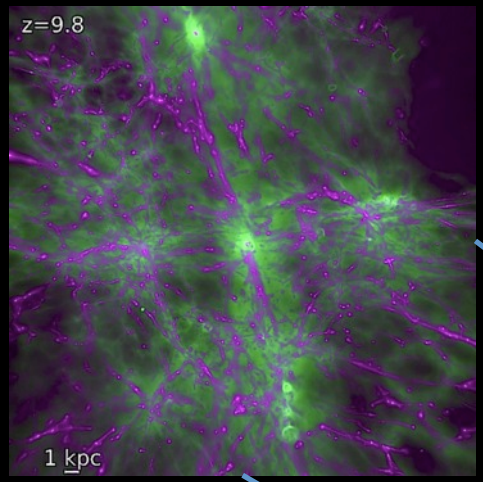


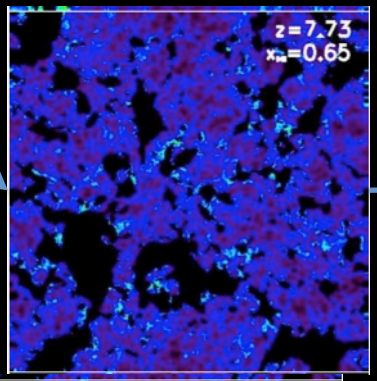


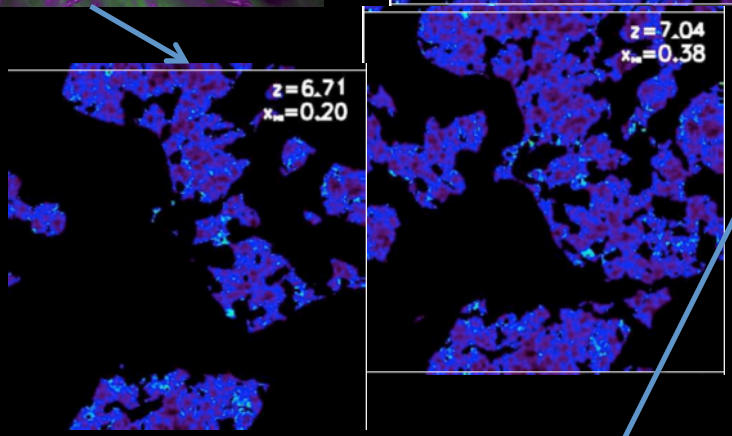

1.0
0.8
0.6
0.4
0.2
0.0
$x_{\rm HI}$
6
7
8
9
10
11
12
13
z
Combined constraints without HERA
HERA + Planck priors
Lyα emission fraction
Quasar near zone
Lyα galaxy clustering
Dark Lyα forest pixels


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

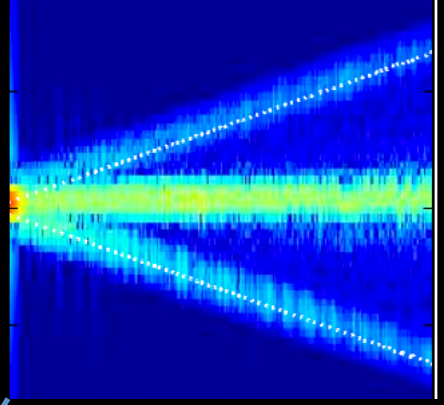

S4(ℓ>50) + Planck Pol + DESI
With 21cm
120
100
80
60
40
20
0
$\sum m_\nu$ [meV]
0.065
0.070
0.075
0.080
0.085
0.090
τ



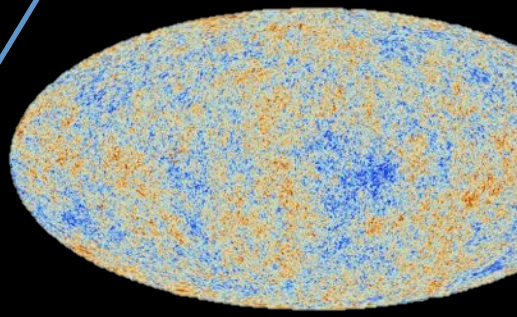




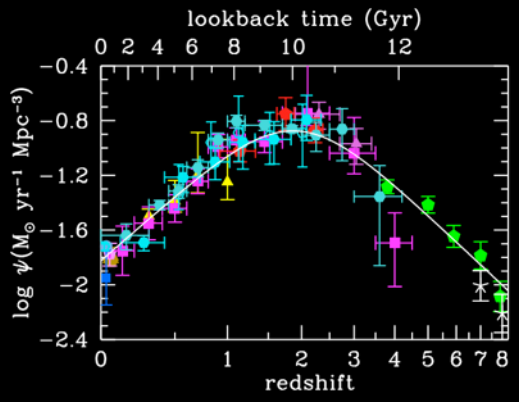
$T_{\rm vir}$ [K]
$R_{\rm mfp}$ [Mpc]
ζ

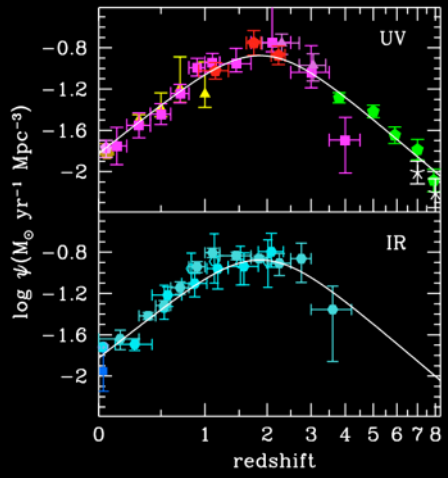


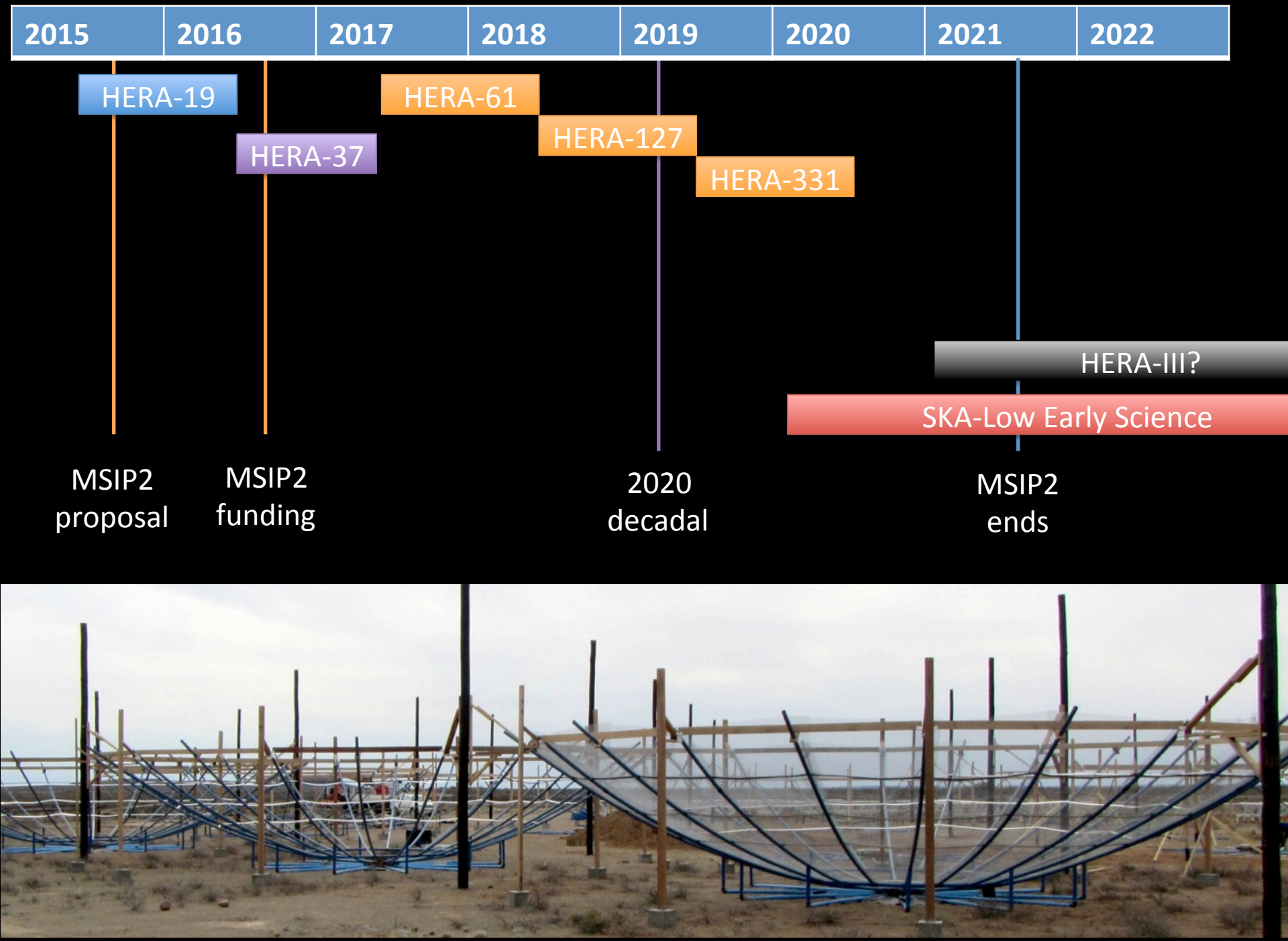
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{\rm MC}$
$\ln(10^{10} A_s)$
n_s
τ



$$\rho_{\rm SFR}(z) = a_p \frac{(1+z)^{b_p}}{1+[(1+z)/c_p]^{d_p}}$$






2015
2016
2017
2018
2019
2020
2021
2022
HERA-19
HERA-37
HERA-61
HERA-127
HERA-331
HERA-III?
SKA-Low Early Science
MSIP2 proposal
MSIP2 funding
2020 decadal
MSIP2 ends