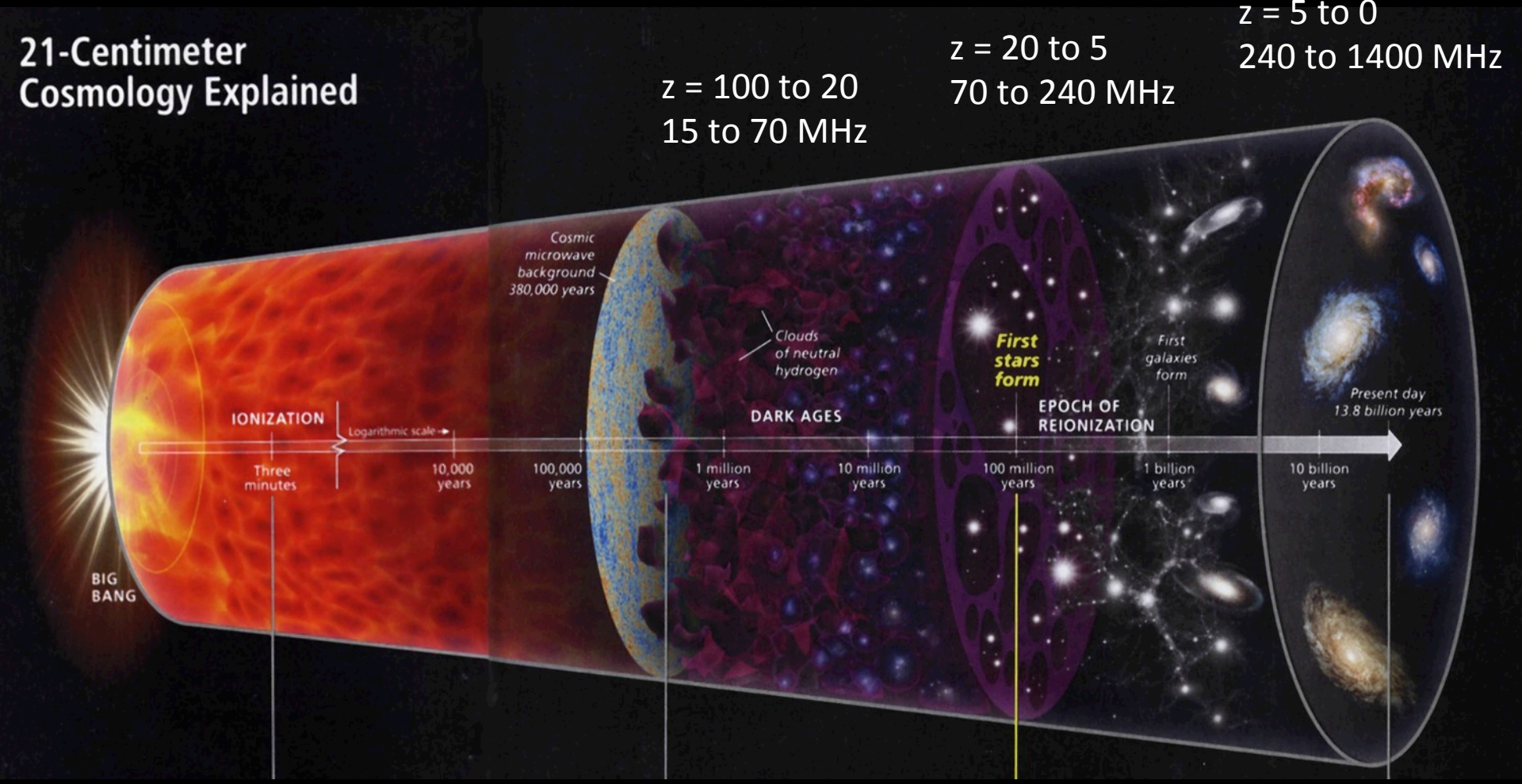
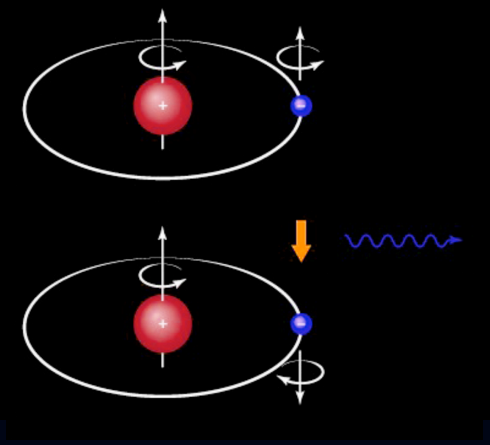
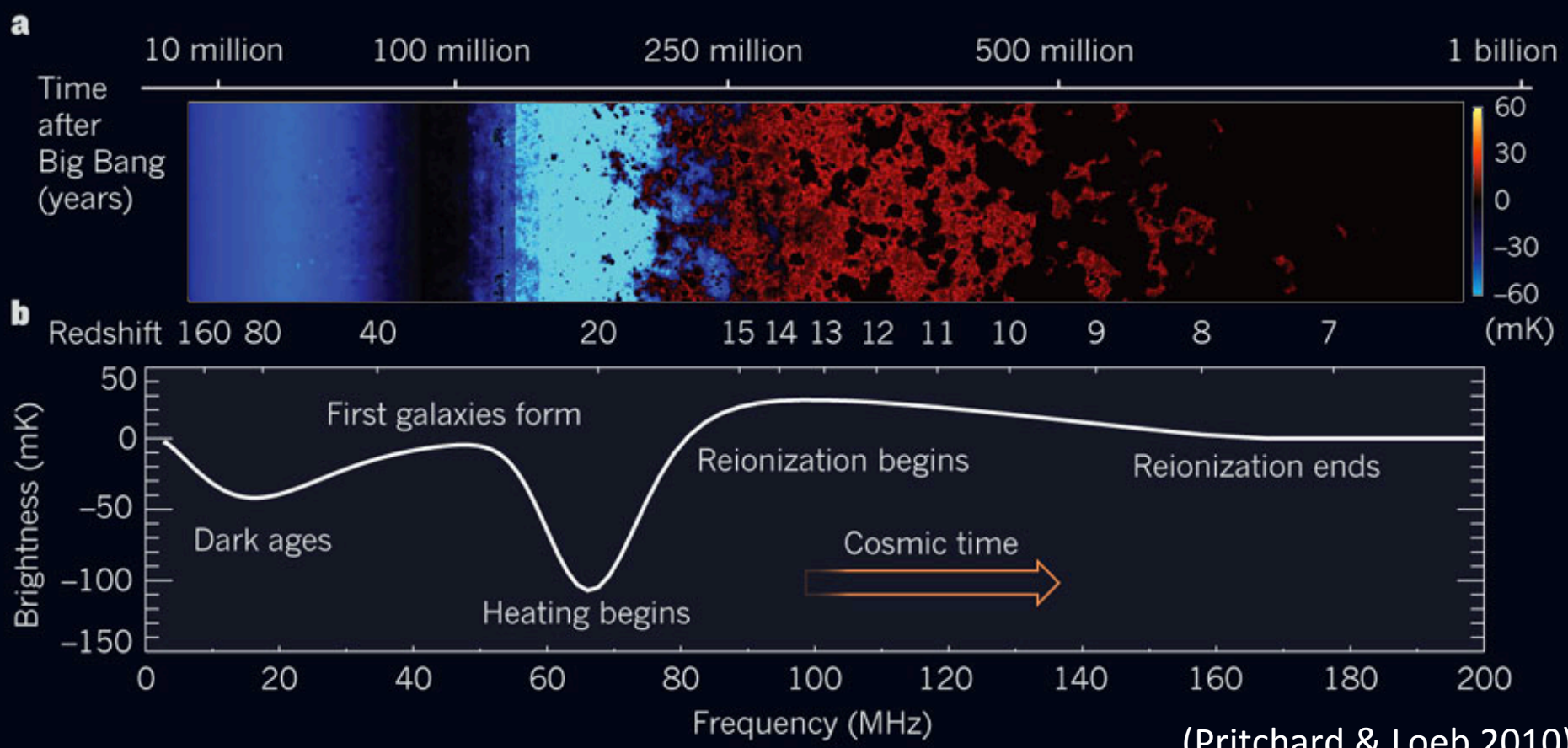
The 21cm Reionization Power Spectrum

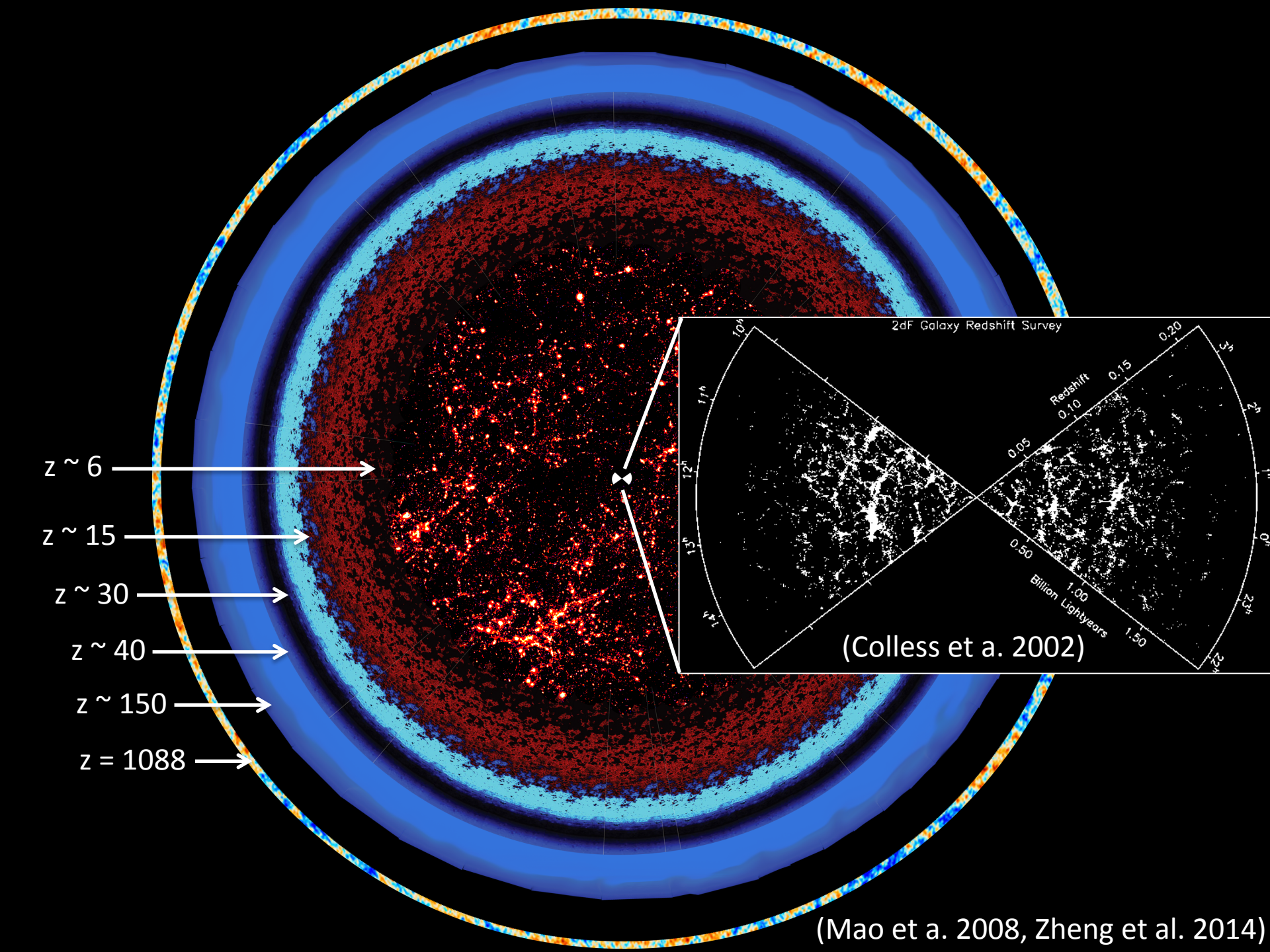
Aaron Parsons


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





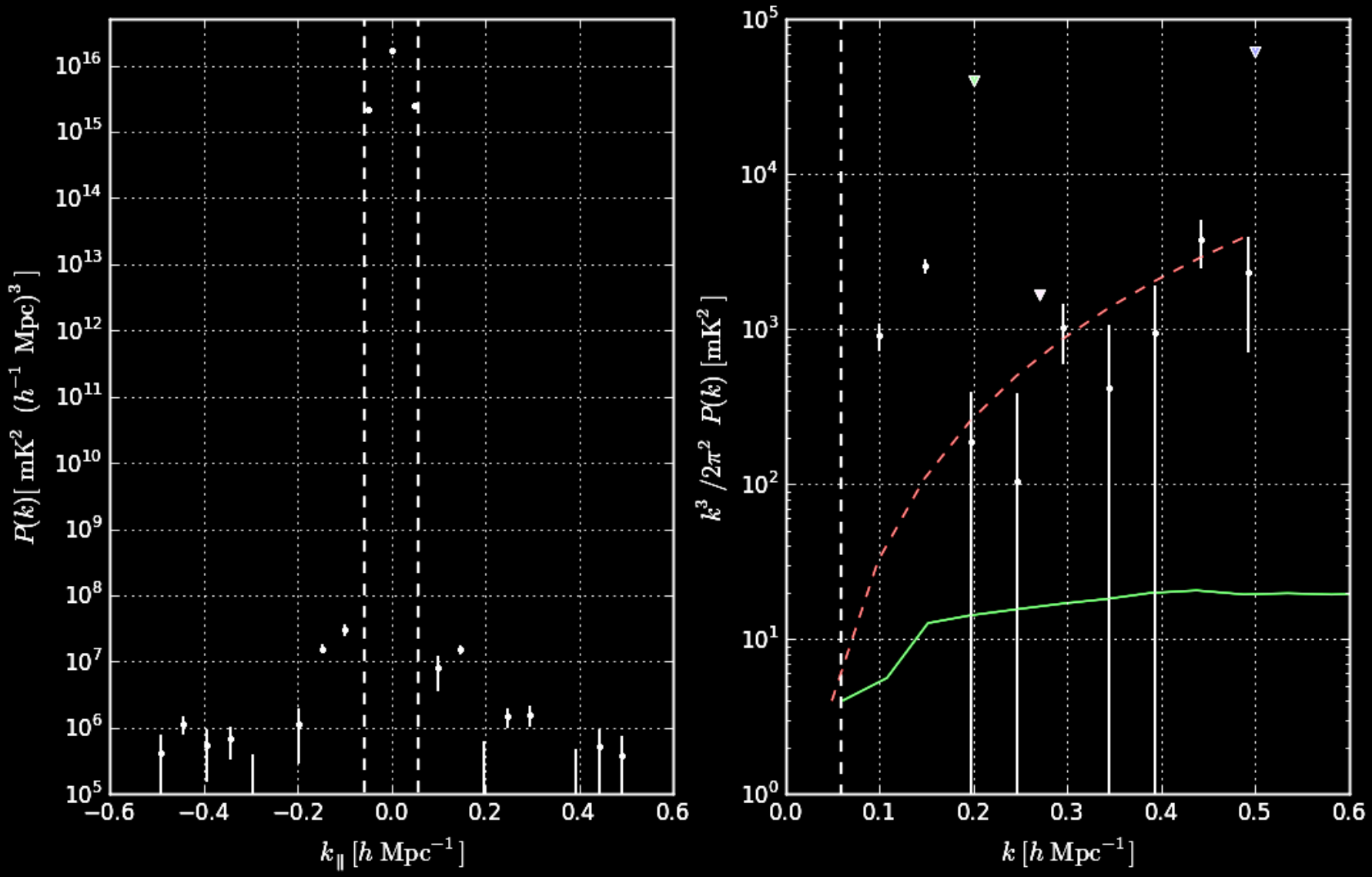
(Pritchard & Loeb 2010)


z ~ 6
z ~ 15
z ~ 30
z ~ 40
z ~ 150
z = 1088
2dF Galaxy Redshift Survey
Redshift
0.05
0.10
0.15
0.20
0.50
1.00
1.50
Billion Lightyears
(Colless et a. 2002)
(Mao et a. 2008, Zheng et al. 2014)

Why 21cm Cosmology

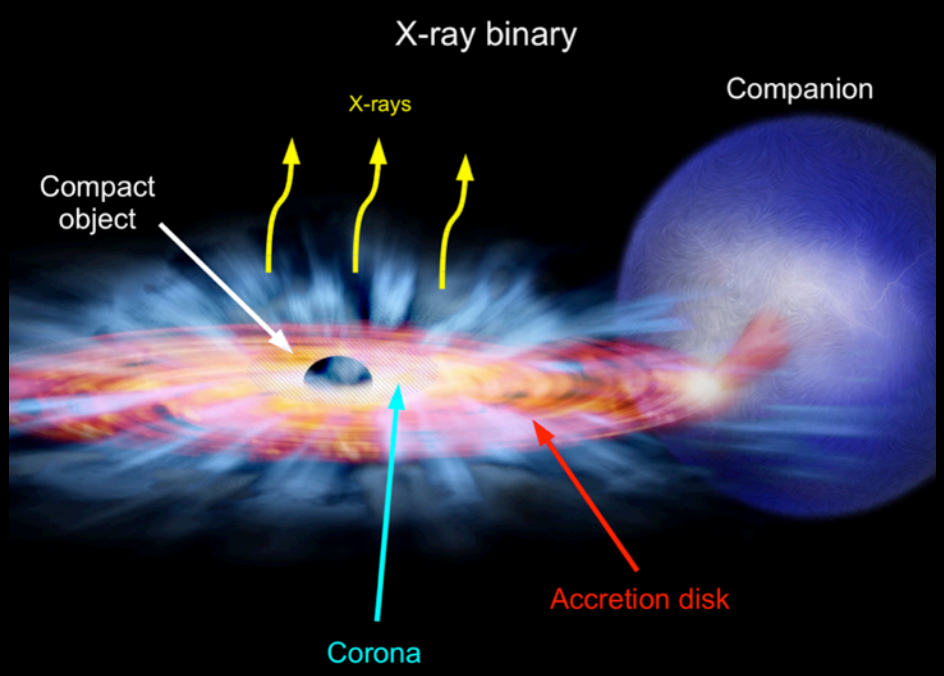
- Line Emission
  - Optically thin
  - Observable even into Dark Ages
  - Directly probes redshift evolution
- Sensitive to
  - Ly-α: Wouthuysen Field Effect
  - X-ray/DM: Heating
  - UV: Ionization
- Integrated measure of galactic properties
  - includes low-mass tails
  - bubble size breaks some degeneracies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

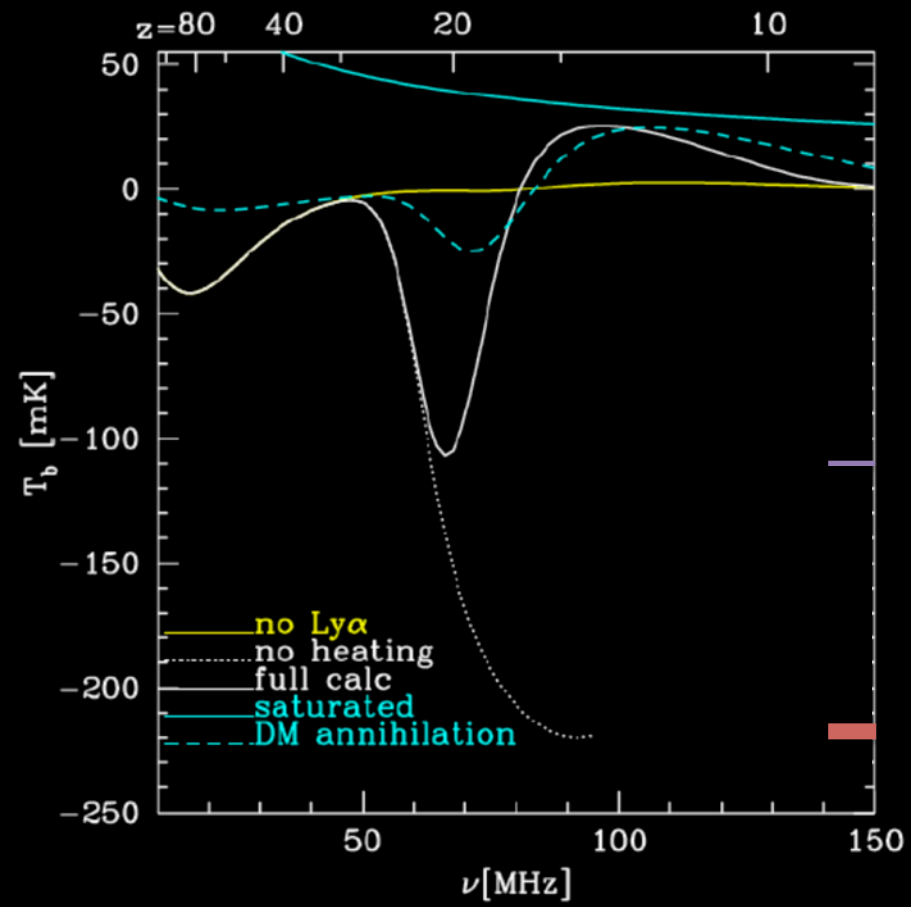
21cm Cosmology:
Global + Power Spectrum



(Ali et al. 2015)

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





Pritchard & Loeb (2012)
Mesinger et al. (2013)
Parsons et al. (2014)
Ali 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)

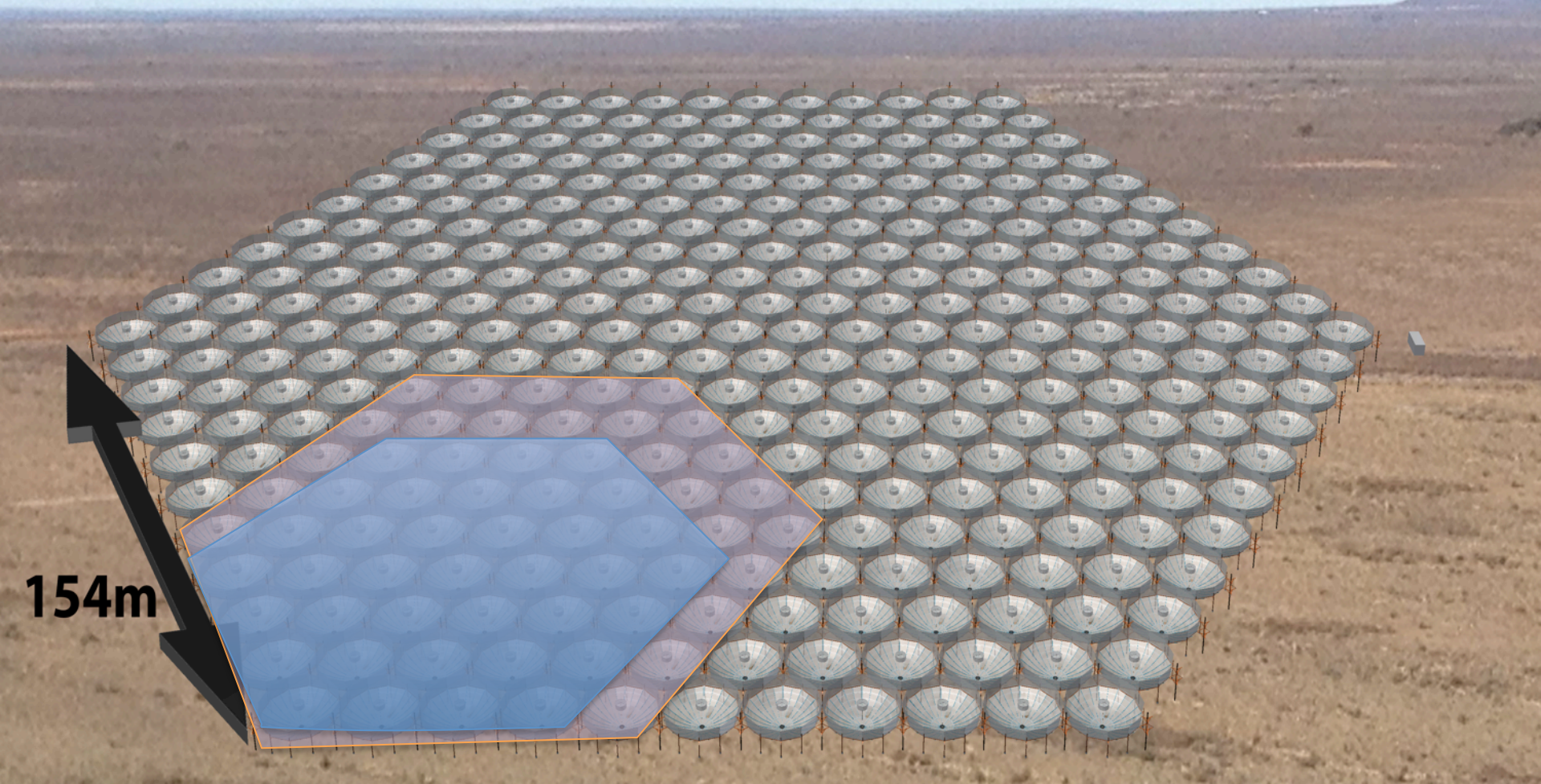
Array core: 310m diameter

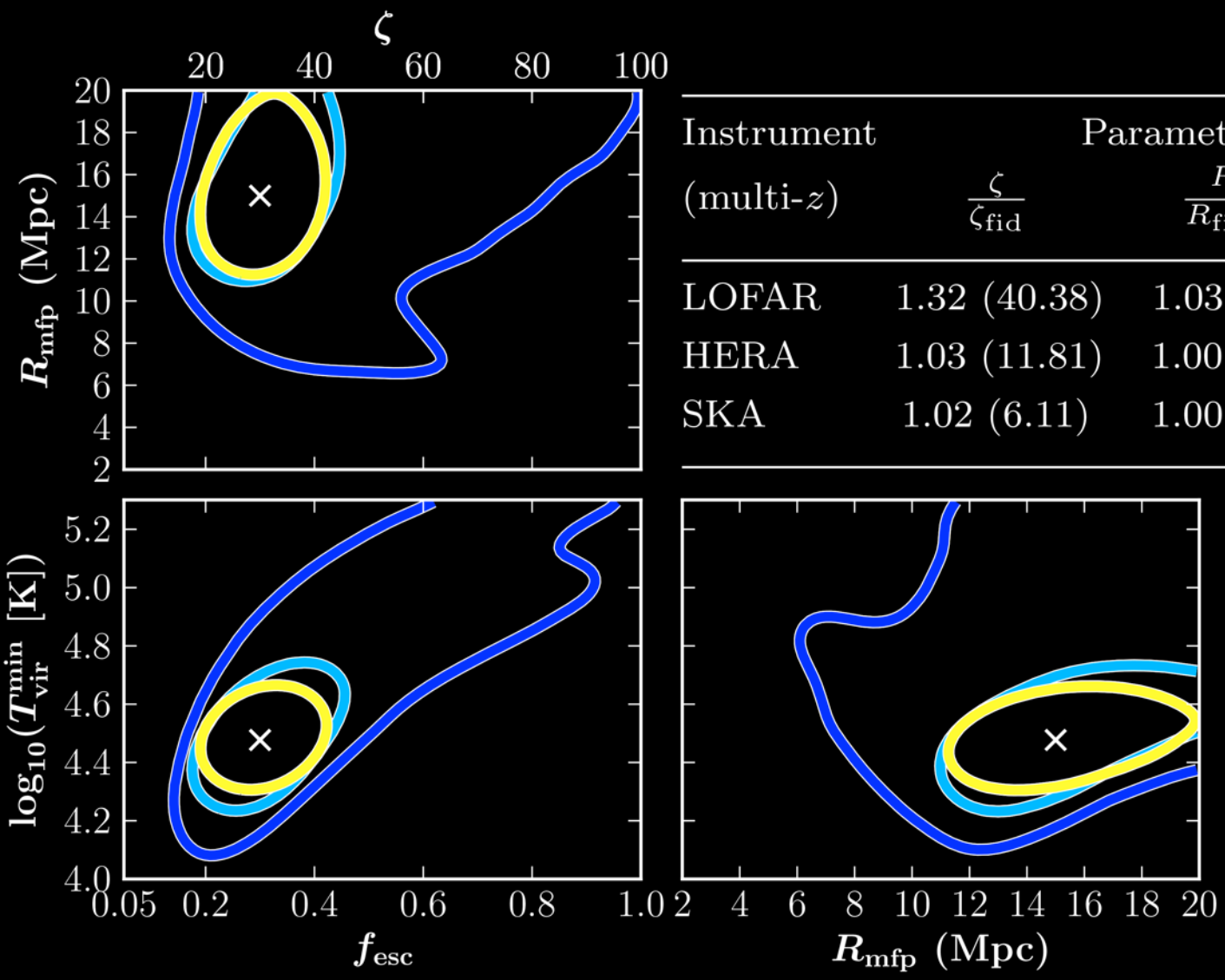
Element: 14m diameter (9° fov @150 MHz)

Frequency

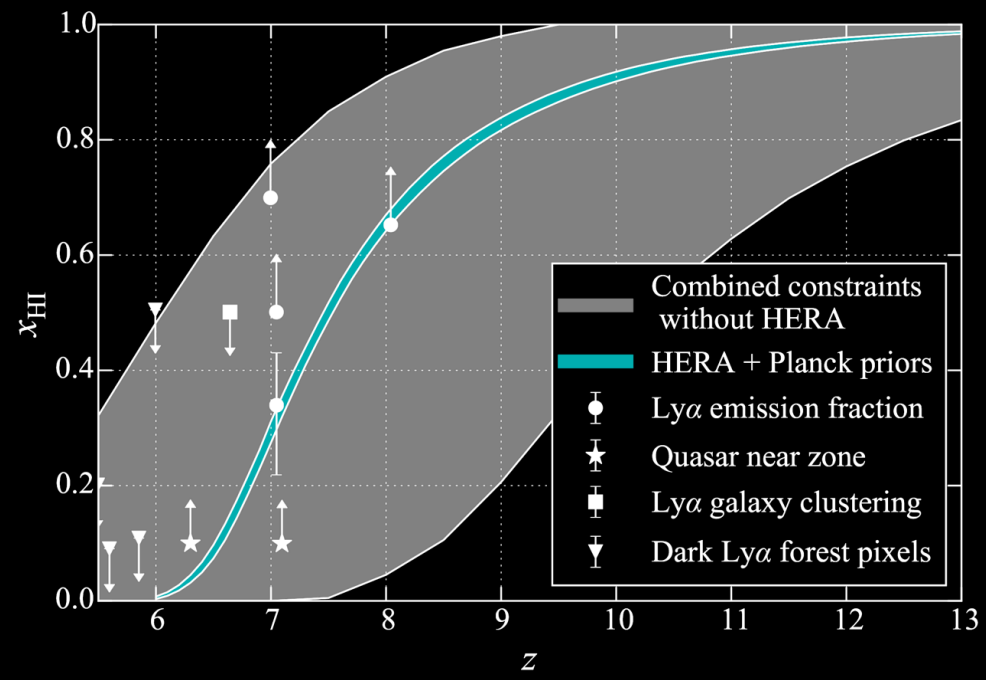
- **Digitized:** 50 - 250 MHz
- **EOR band:** 100 - 200 MHz
- **Channel:** 97.7 kHz

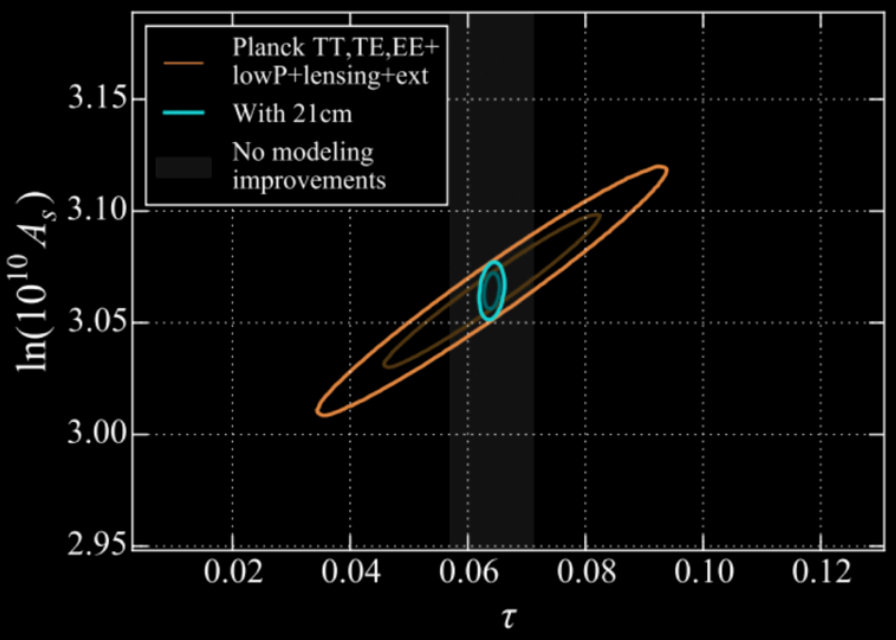
$\mathbf{T_{sys}} = 100 + T_{sky}$

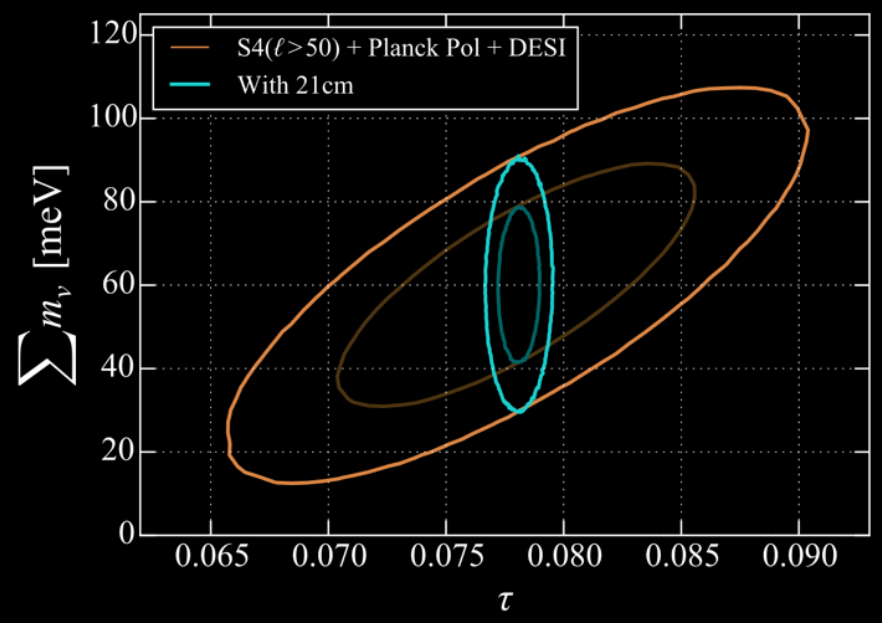


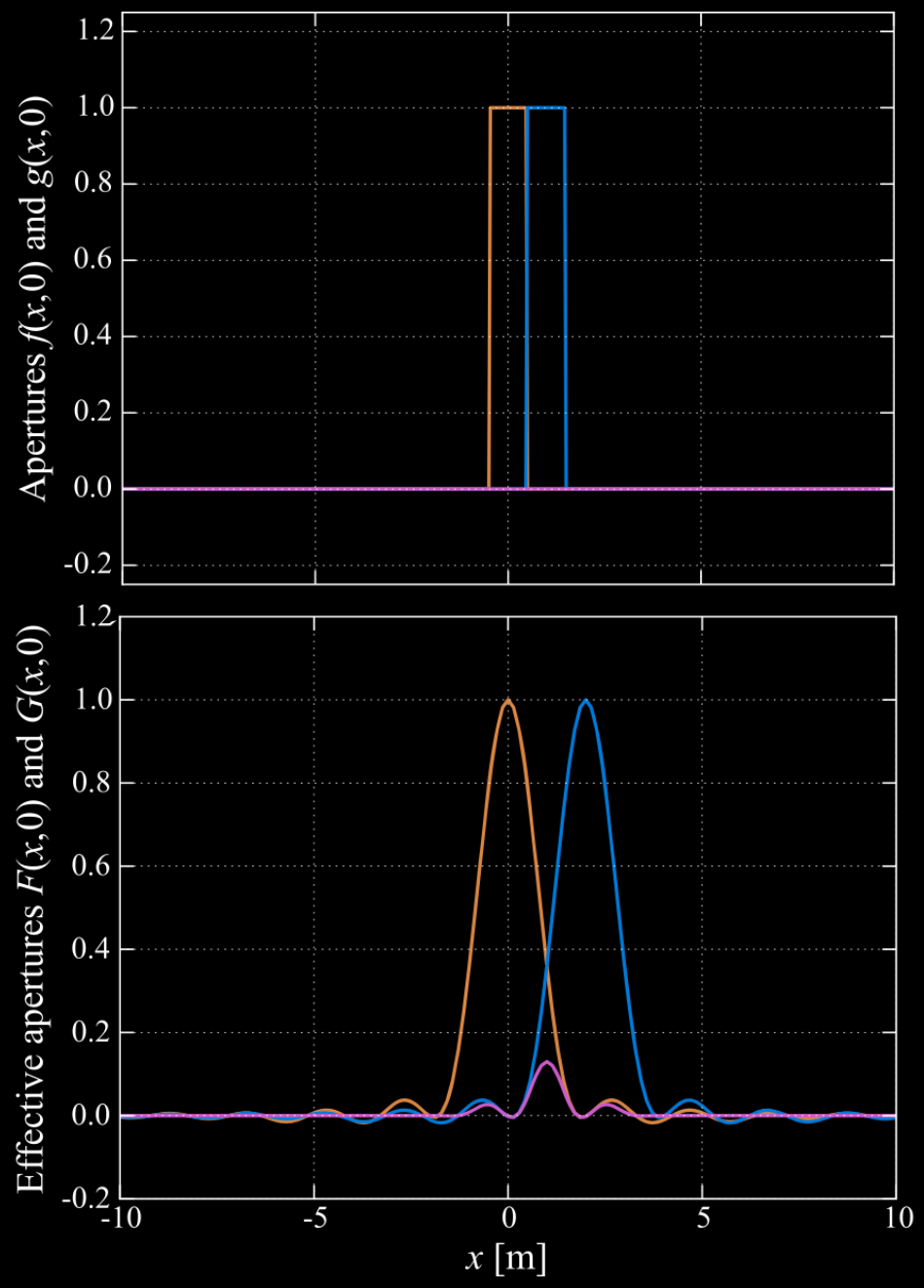


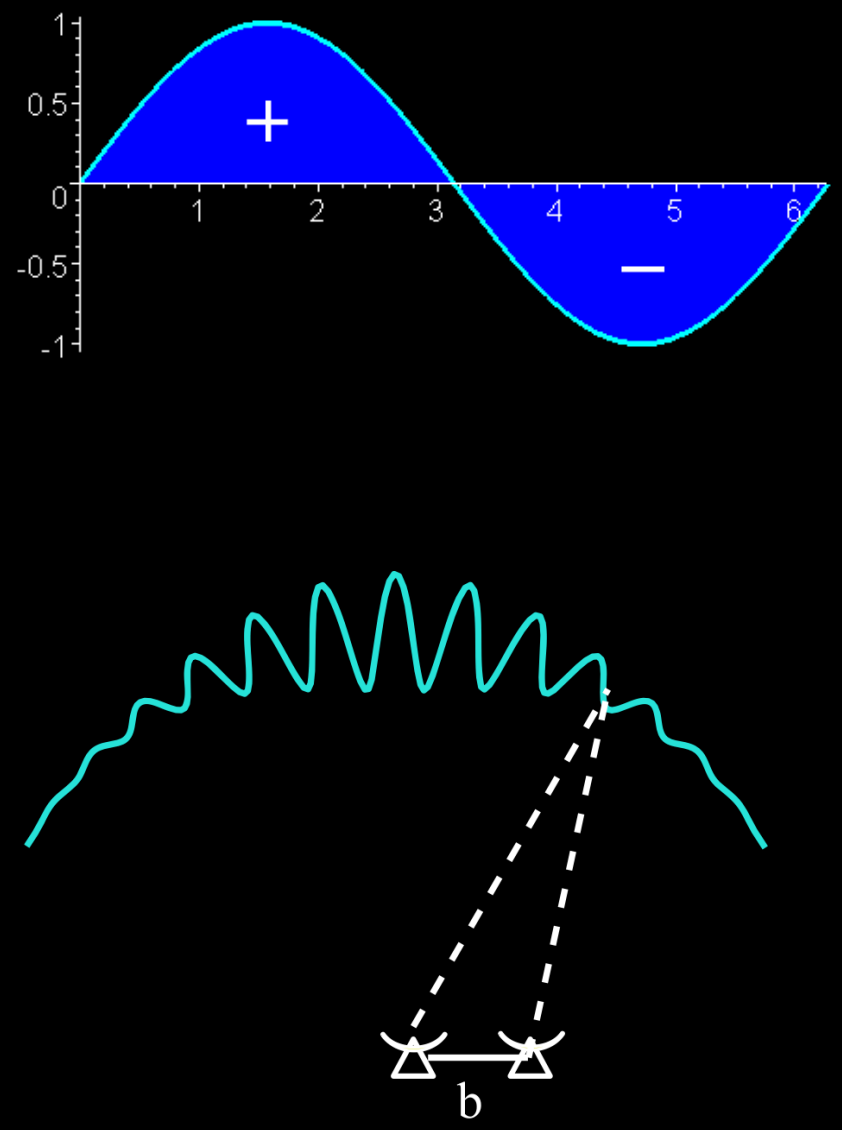
Instrument (multi-z)	Parameter (% error) $\frac{\zeta}{\zeta_{\rm fid}}$	$\frac{R_{\rm mfp}}{R_{\rm fid,mfp}}$	$\frac{\log_{10}(T_{\rm vir}^{\rm min})}{\log_{10}(T_{\rm vir,fid}^{\rm min})}$
LOFAR	1.32 (40.38)	1.03 (20.06)	1.05 (5.43)
HERA	1.03 (11.81)	1.00 (11.99)	1.00 (1.95)
SKA	1.02 (6.11)	1.00 (10.04)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


Combined constraints without HERA
HERA + Planck priors
Lyα emission fraction
Quasar near zone
Lyα galaxy clustering
Dark Lyα forest pixels
x_{HI}
z

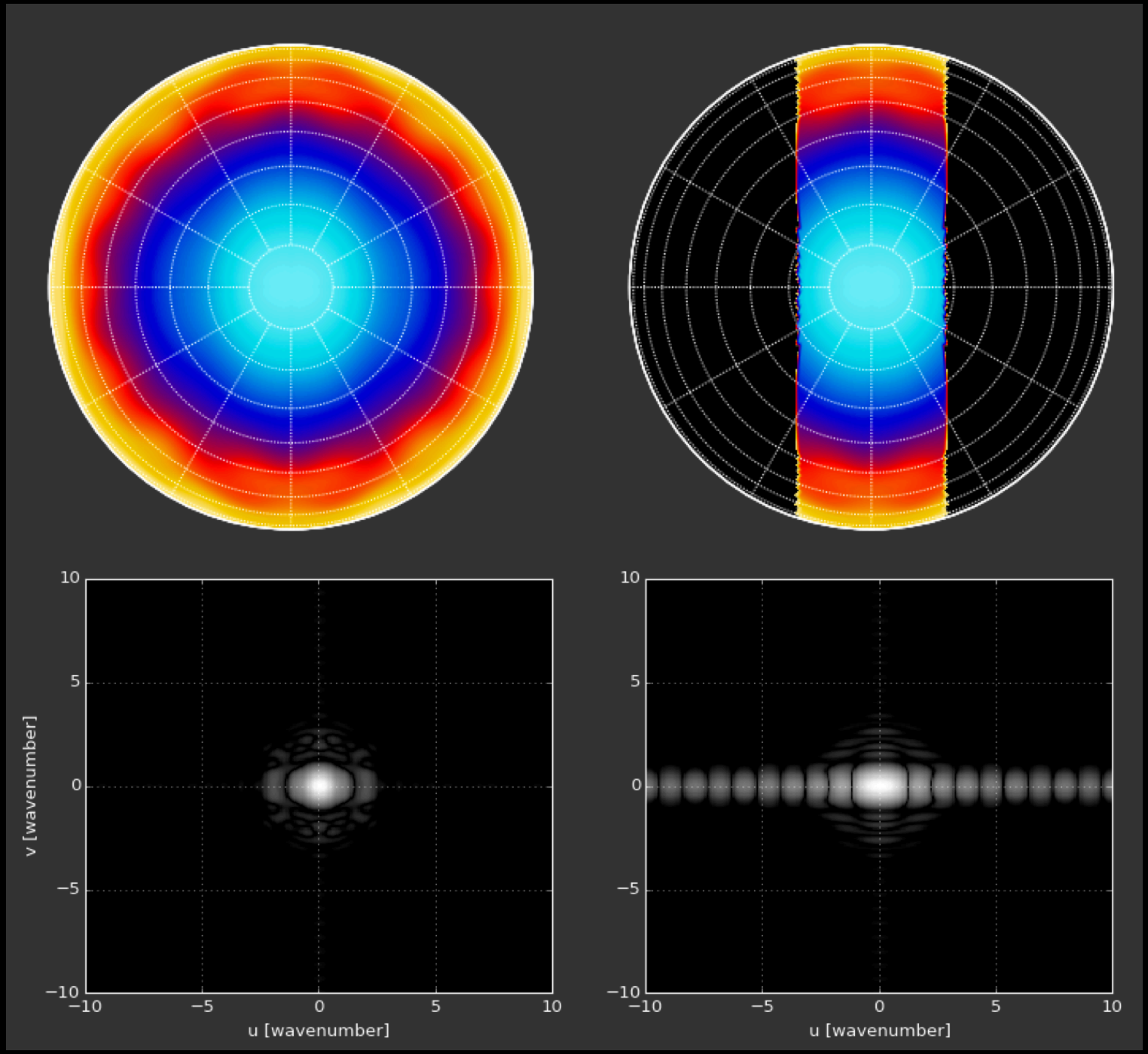

Planck TT,TE,EE+ lowP+lensing+ext
With 21cm
No modeling improvements
$\ln(10^{10} A_s)$
τ


S4(ℓ>50) + Planck Pol + DESI
With 21cm
$\sum m_\nu$ [meV]
τ

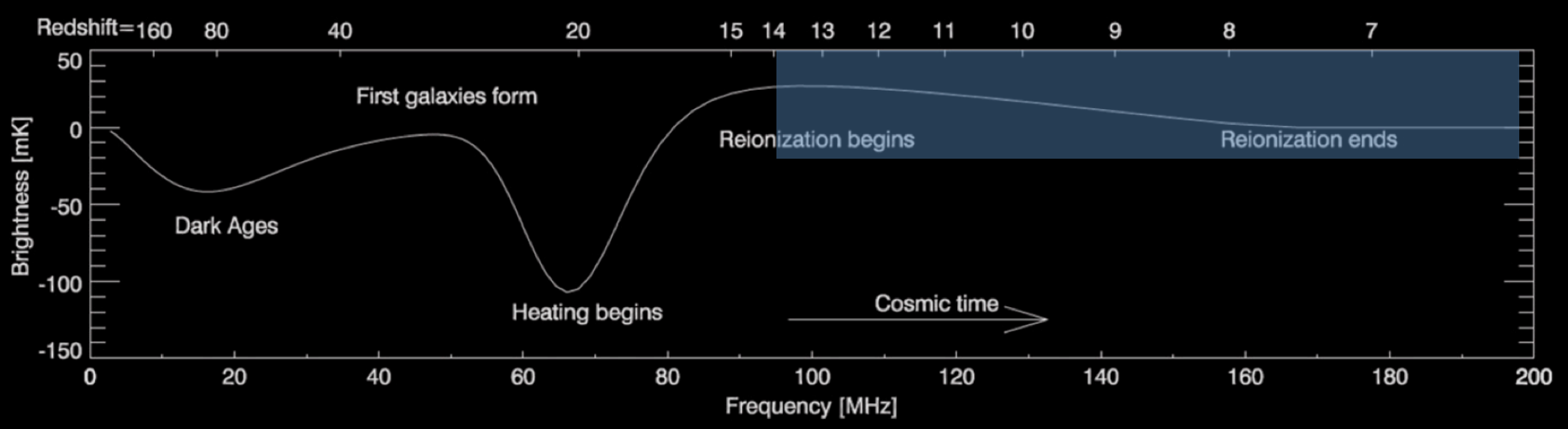




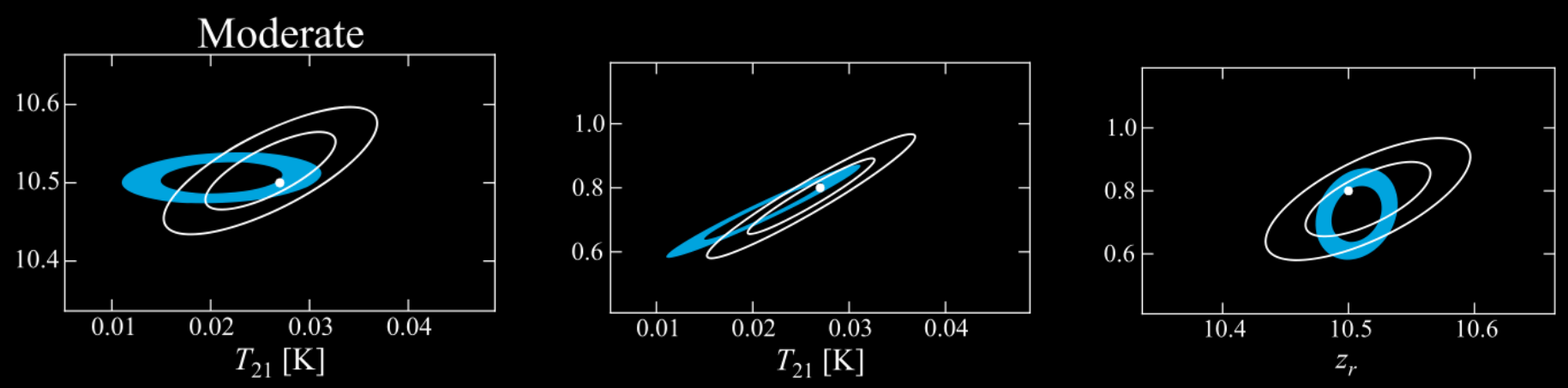
Presley, Liu, Parsons (2015)


10
5
0
−5
−10
v [wavenumber]
−10
−5
0
5
10
u [wavenumber]
10
5
0
−5
−10
−10
−5
0
5
10
u [wavenumber]

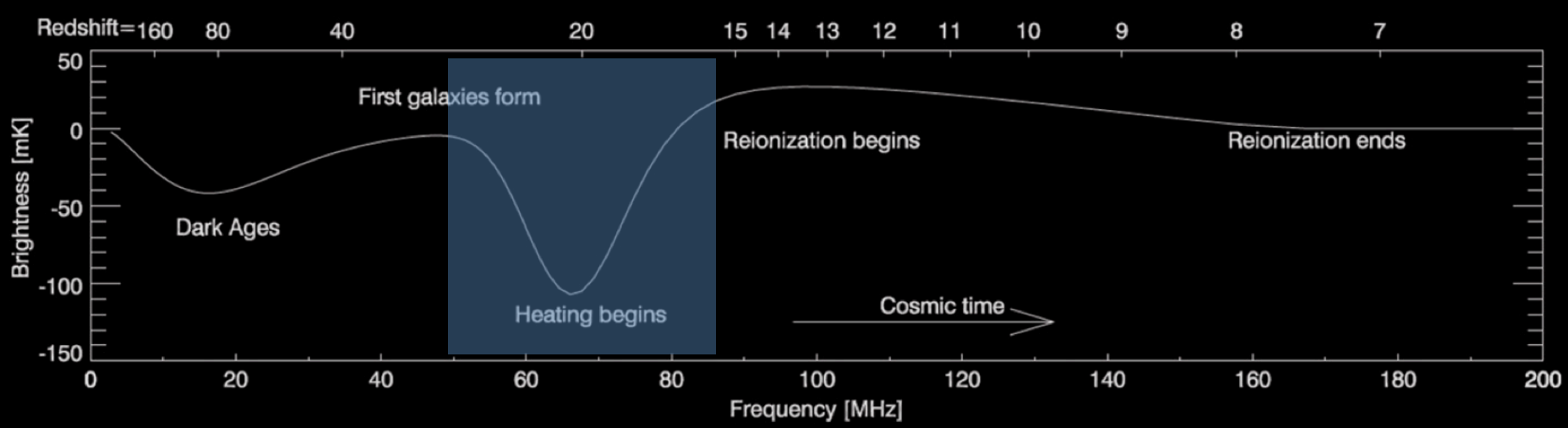
21cm Cosmology:
Global + Power Spectrum



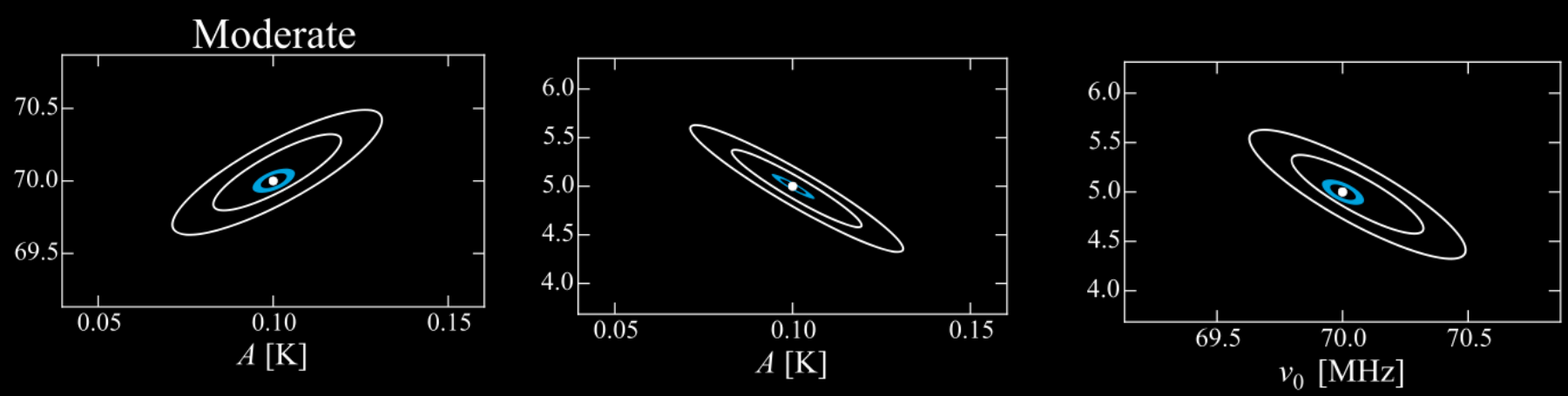
$$T_{\rm reion}(\nu) = \frac{T_{21}}{2}\sqrt{\frac{1+z}{10}}\left[1+\tanh\left(\frac{z-z_r}{\Delta z}\right)\right],$$



Presley, Liu, Parsons (2015)

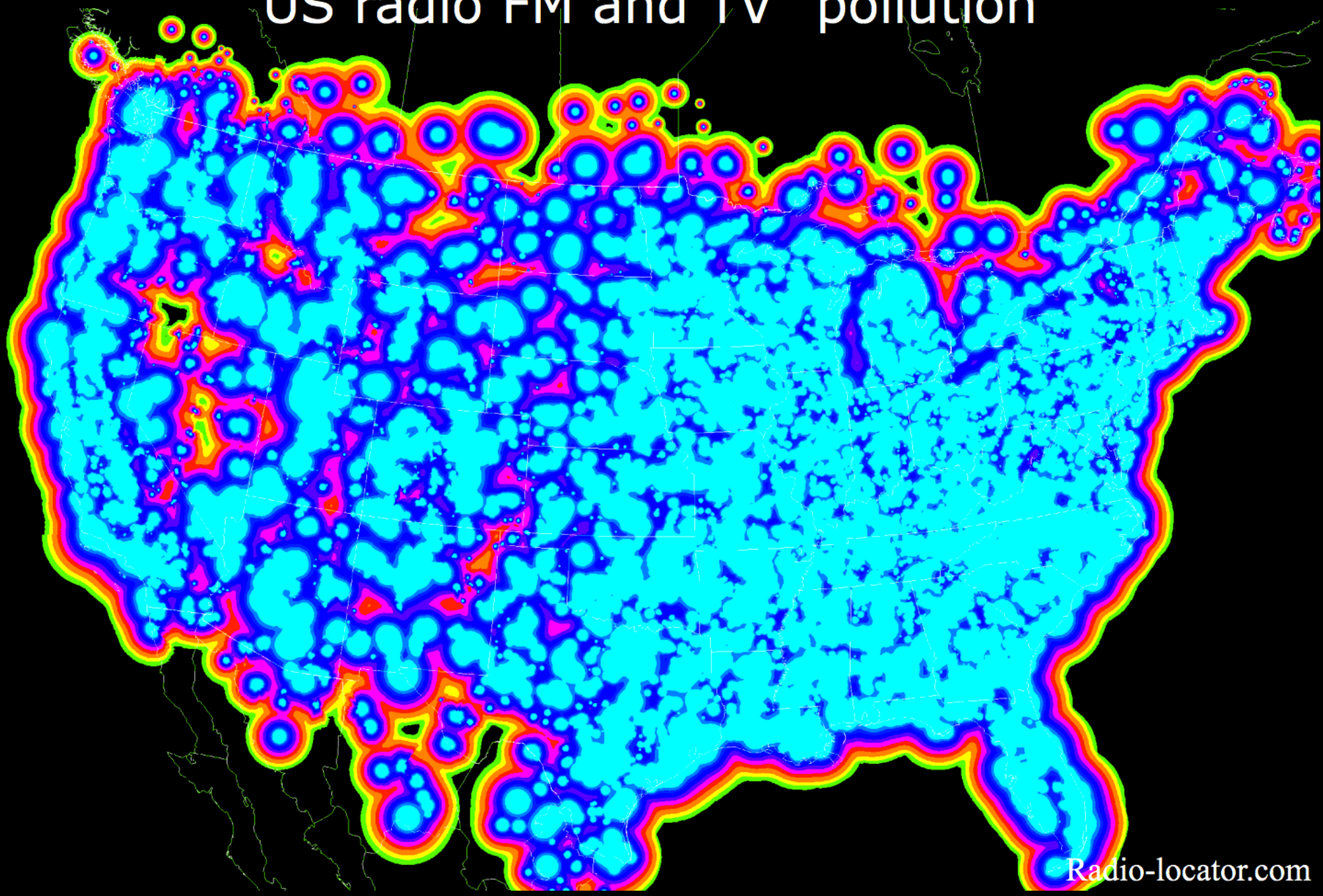


$$T_{\rm dip}(\nu) = -A \exp\left(-\frac{(\nu-\nu_0)^2}{2\sigma^2}\right),$$



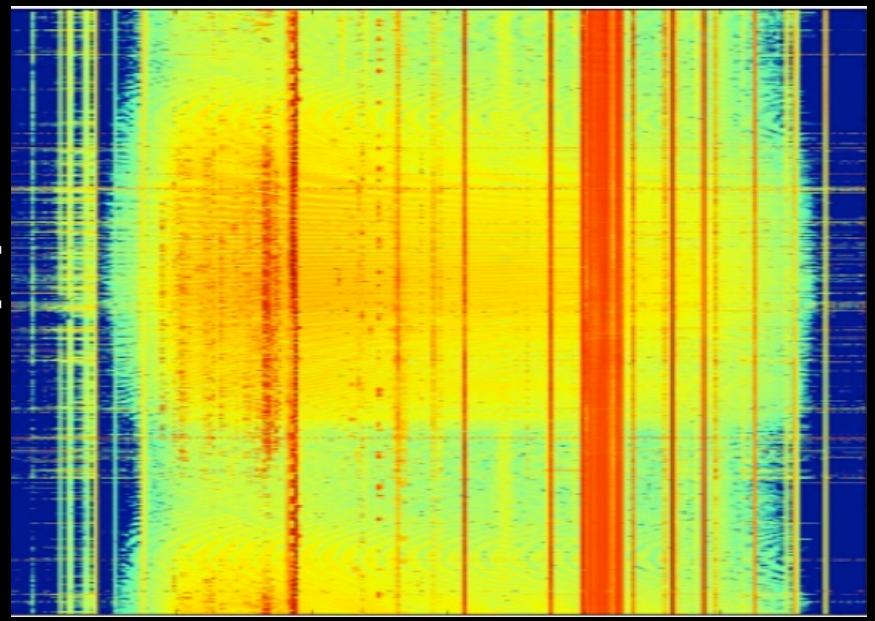
Presley, Liu, Parsons (2015)

US radio FM and TV "pollution"

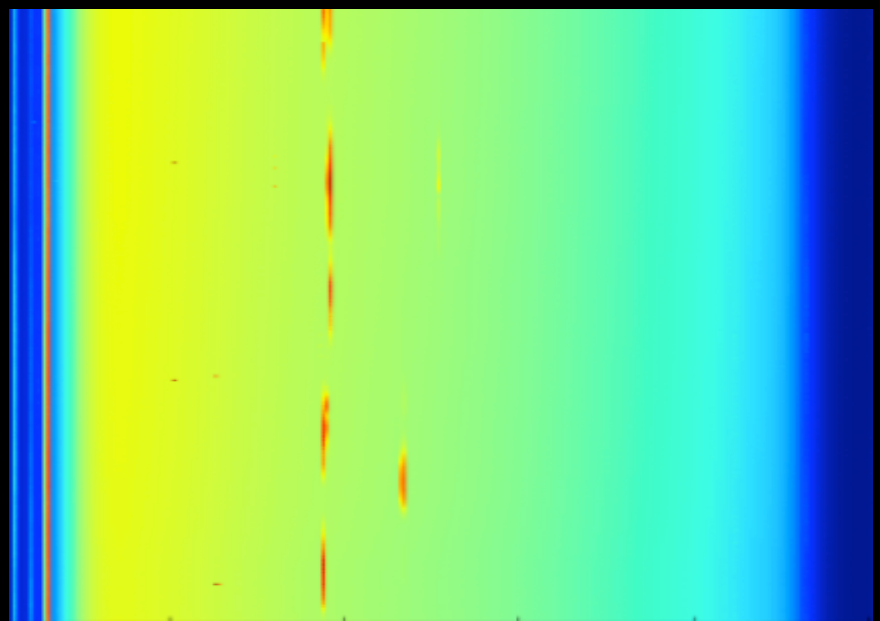


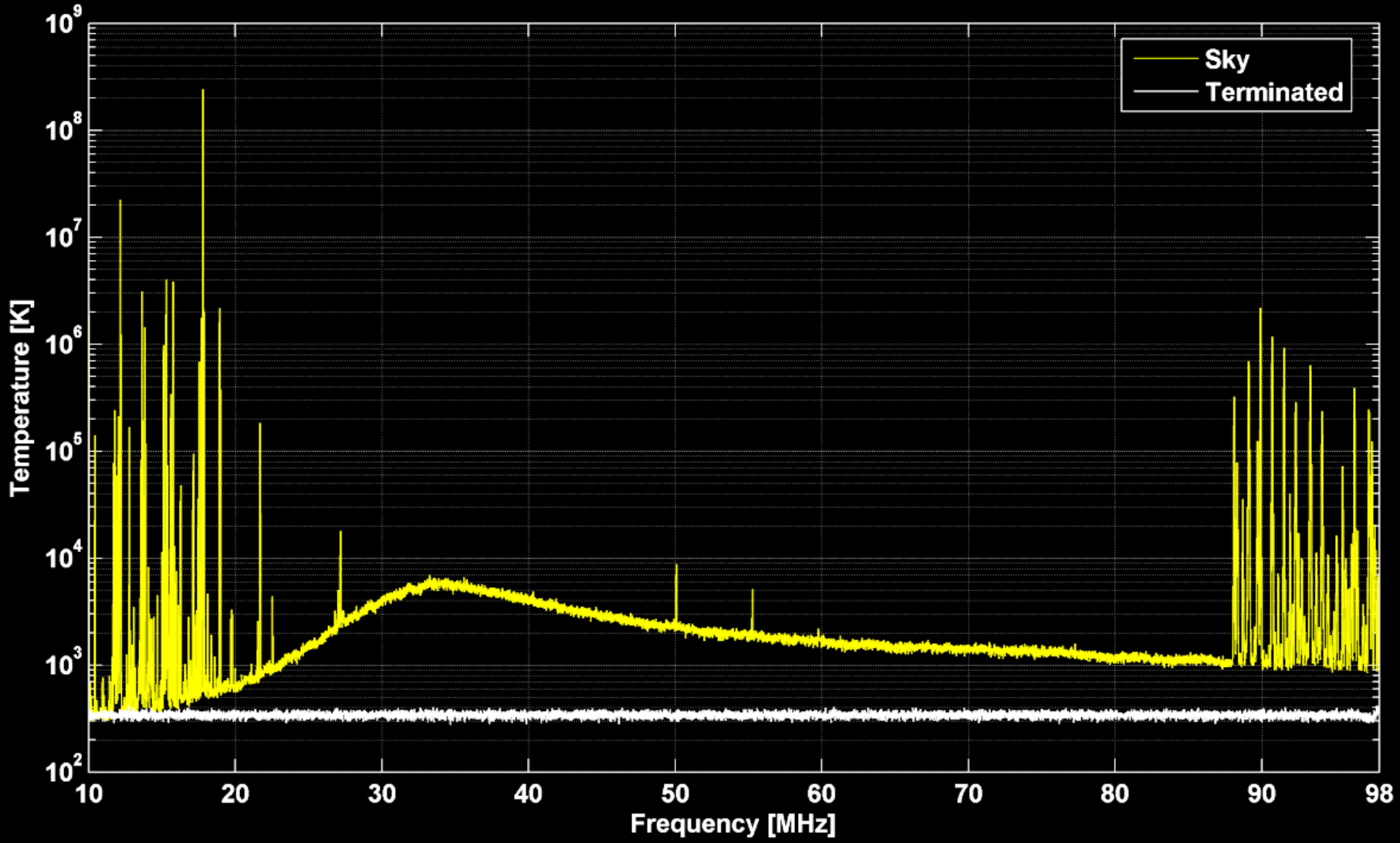
Radio-locator.com
Bowman & Rogers (2010)

PGB: PAPER Green Bank

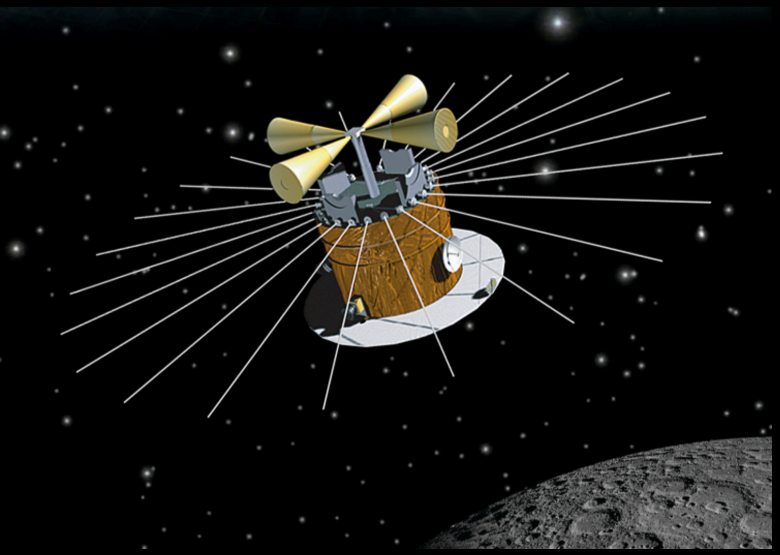


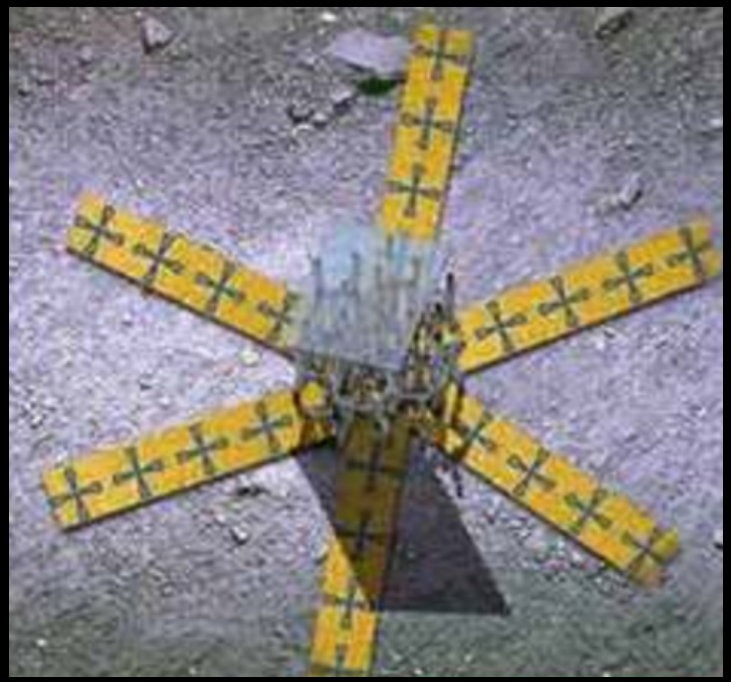
PSA: PAPER South Africa





(Ellingson et al. 2013)





- Low Lunar Orbiter
  - Moon as RFI shield
  - Moon as a Tref, mask
  - 1 to 4 elements
- Lunar Lander
  - Far side of moon (shield)
  - 10 to 20 elements
- Future
  - Dark Ages Lunar Array
  - 100s of elements
  - Dark Ages Power spectrum

- The science case
  - cosmology
  - formation of structure
  - first stars and galaxies