
Detection of
the Cosmic Dawn and Epoch of Reionization

FACTS

1. Hydrogen: 75% of baryonic matter
2. Neutral hydrogen: 21cm line
3. Cosmic signal: 1-10 mK
4. Foregrounds: 1000K
5. VHF techniques: mature (60 yrs!)

Measurements of the EOR

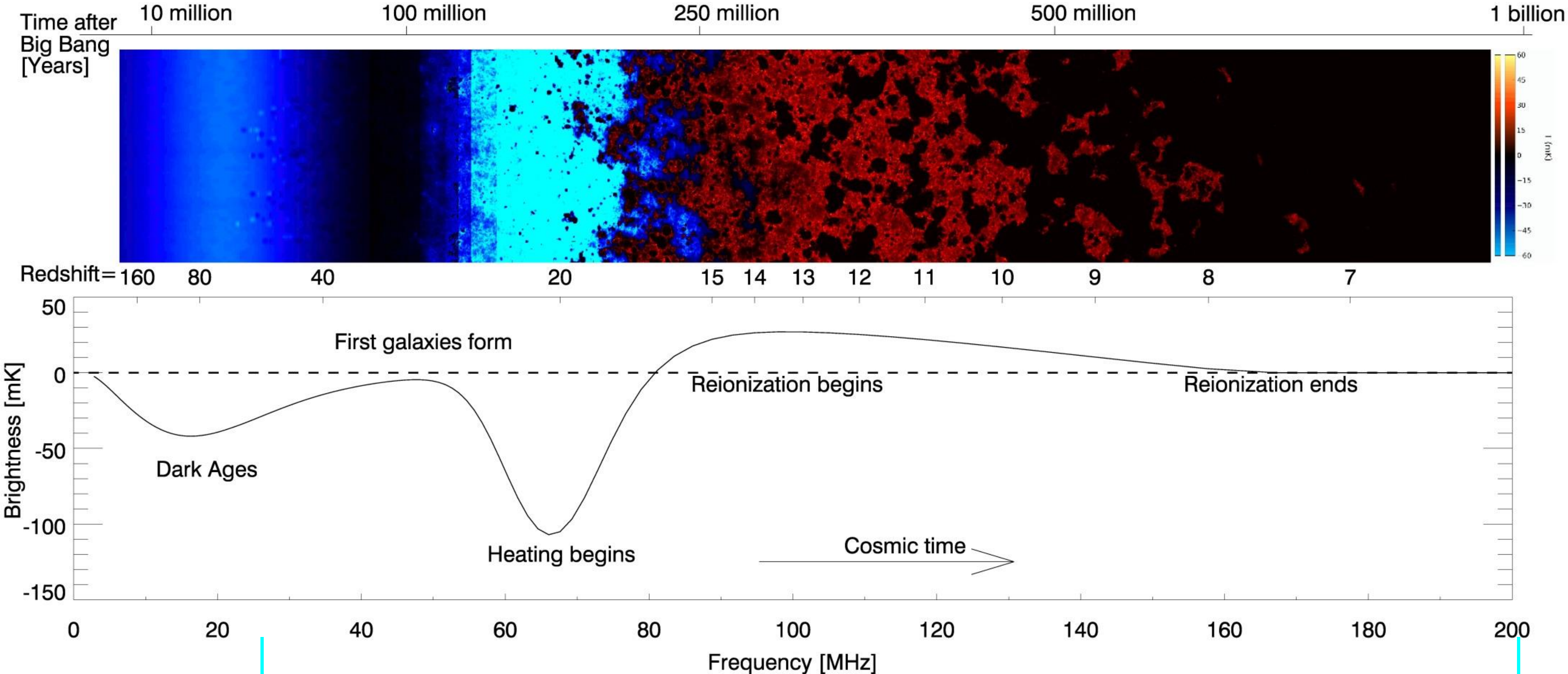
1. Global Signatures (total power)

2. Imaging (structures)

3. Fluctuations (power spectrum)

$$\nu = 1420 \text{ MHz } / (1+z)$$

$$\lambda = 21\,(1+z) \text{ cm}$$



The best window

Pritchard & Loeb (2011)

Measurements of the EOR

1. Global Signatures (total power)

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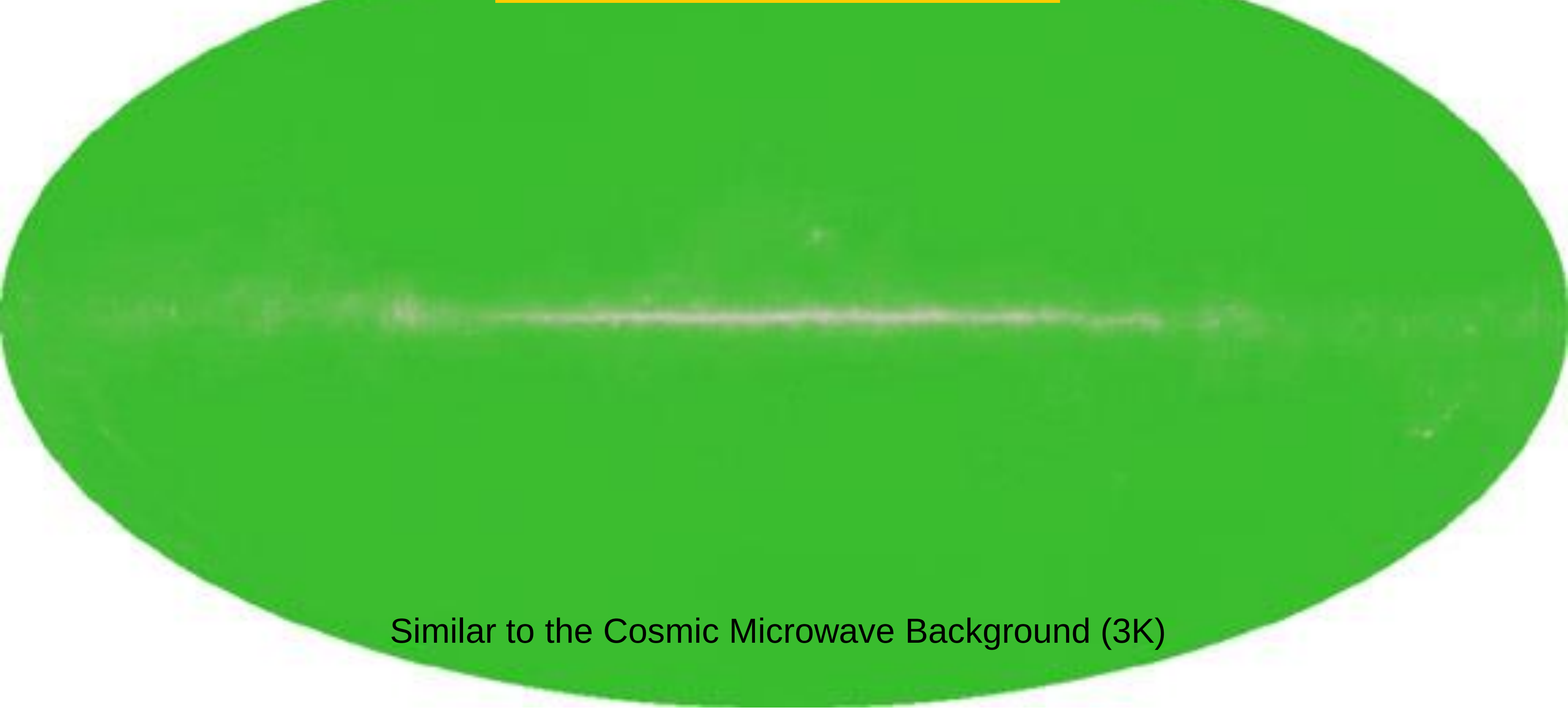
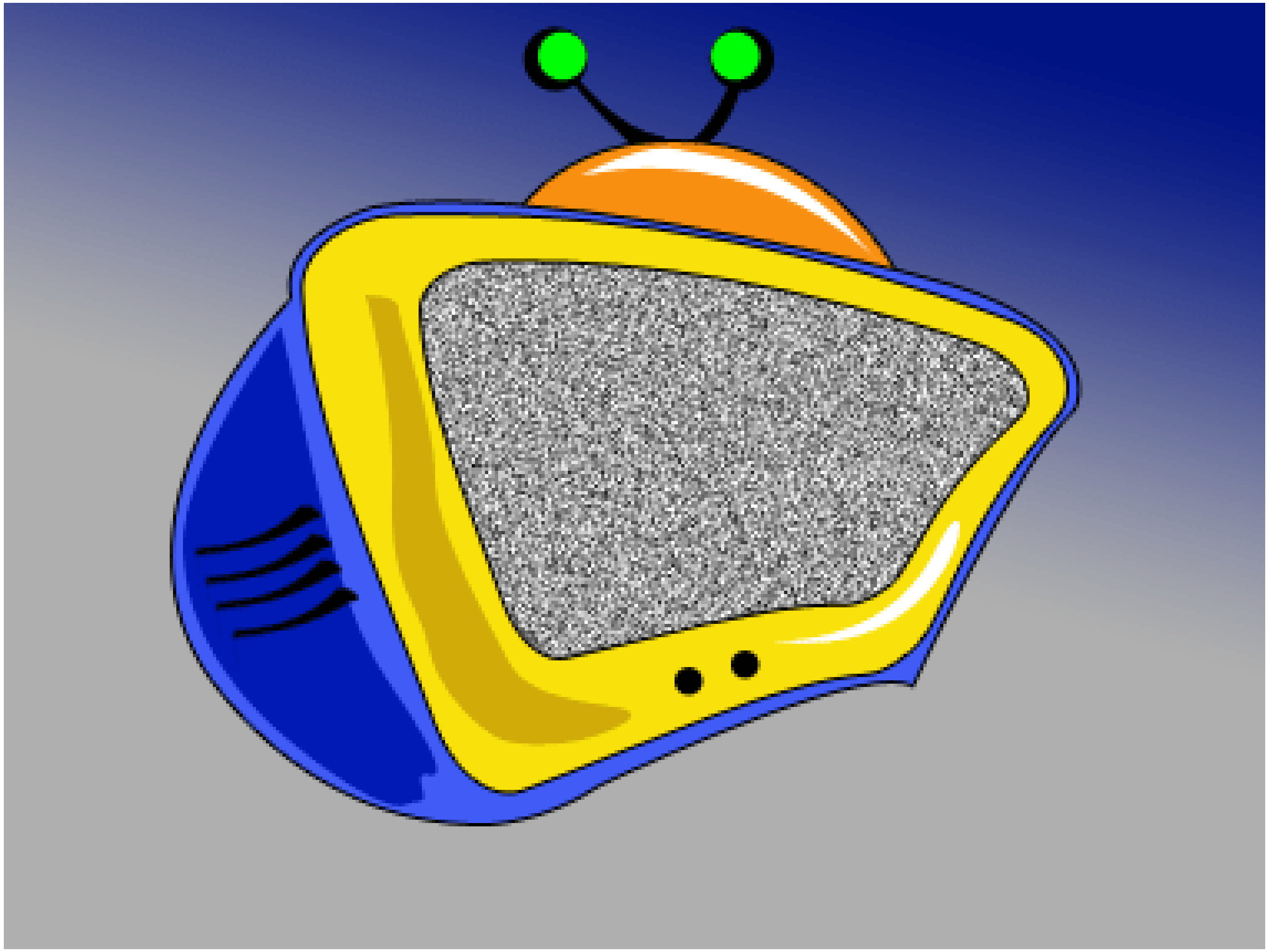
The Global Signal from EoR

$$\delta T \approx 23.5\, x_H \left(\frac{1+z}{10}\right)^{1/2} \text{mK}$$



Similar to the Cosmic Microwave Background (3K)

1/100 of the noise comes from CMB



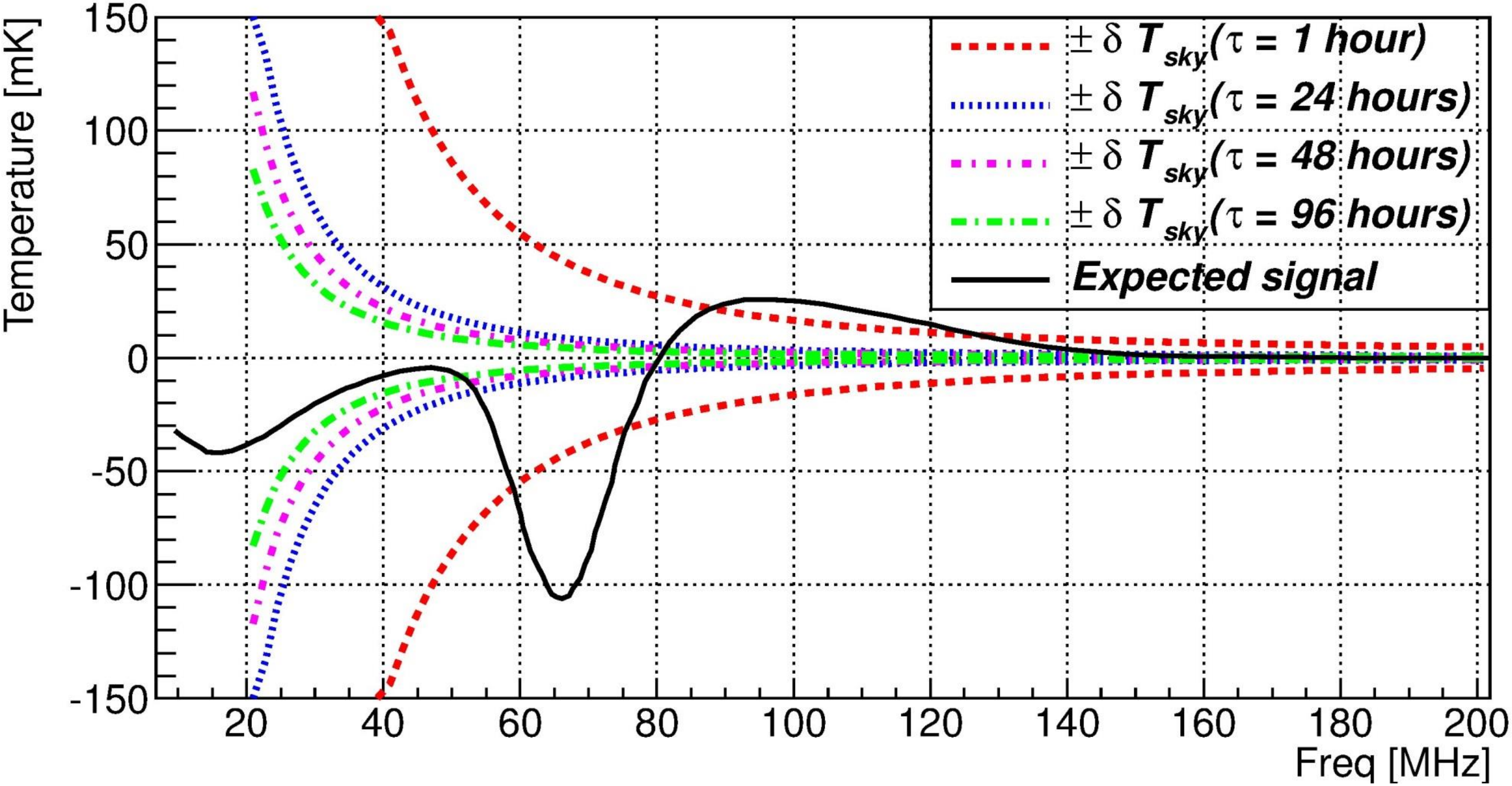
$$\frac{3K}{300K} \sim \frac{1}{100}$$

1/10,000 of the signal arises from Cosmic EoR background

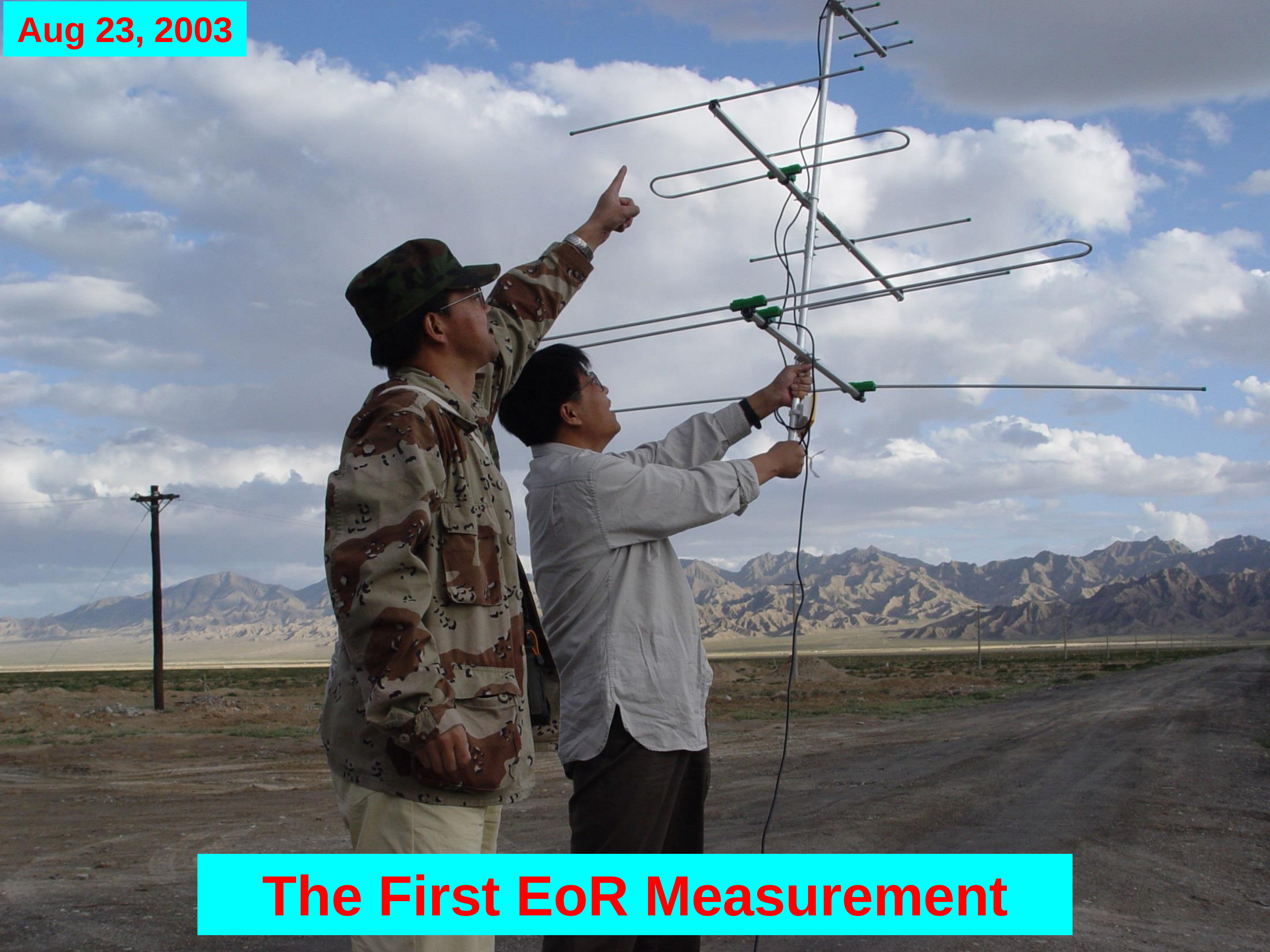
$$\frac{0.03\mathrm{K}}{300\mathrm{K}} \sim \frac{1}{10,000}$$

Instrument of EoR Detection

Turn on !



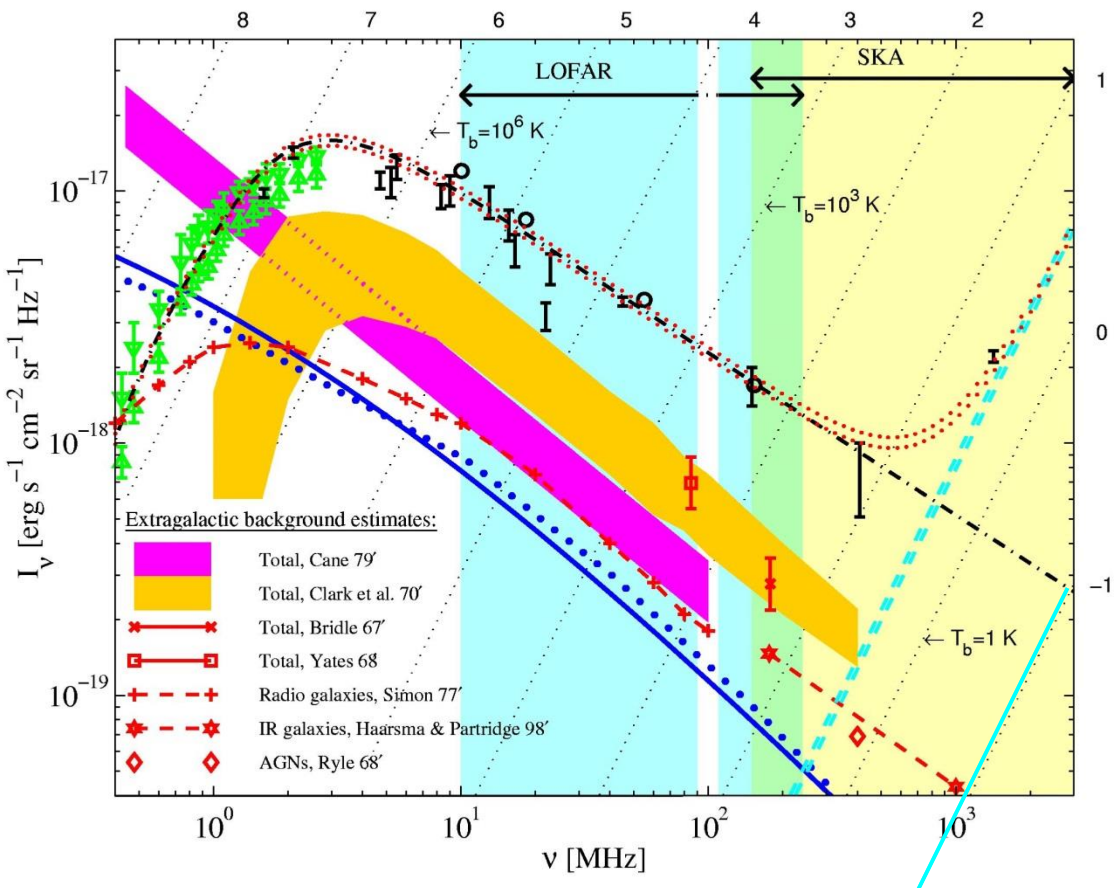
(arXiv.1501.02991)


Aug 23, 2003
The First EoR Measurement

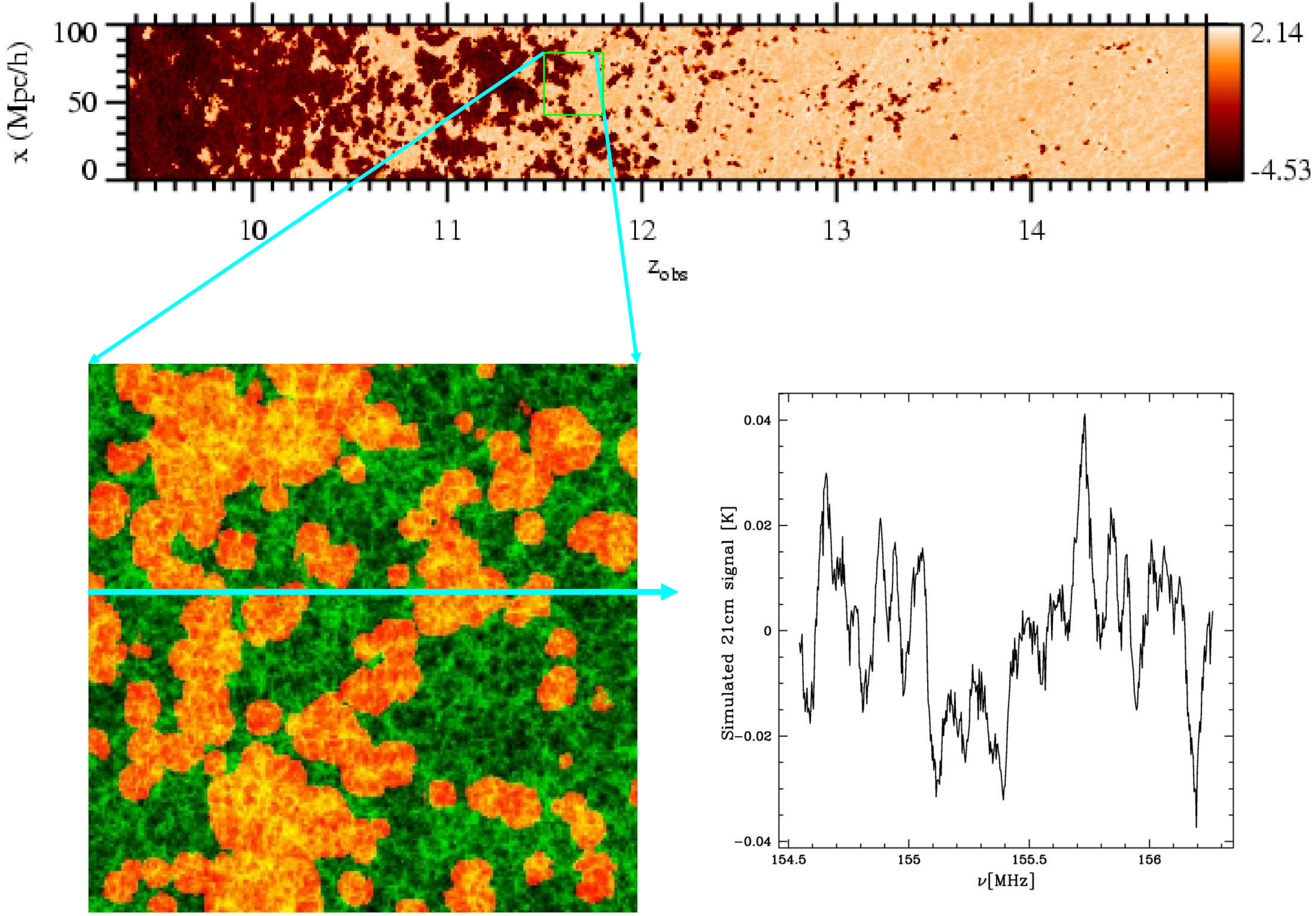
1. **Stability over 24h**
2. **Calibration at mK**
3. **FG removals to mK**

The Low Frequency Radio Sky

Keshet, Waxman & Loeb (astro-ph/0402320)



T=100mK



Iliev et al. (2005)

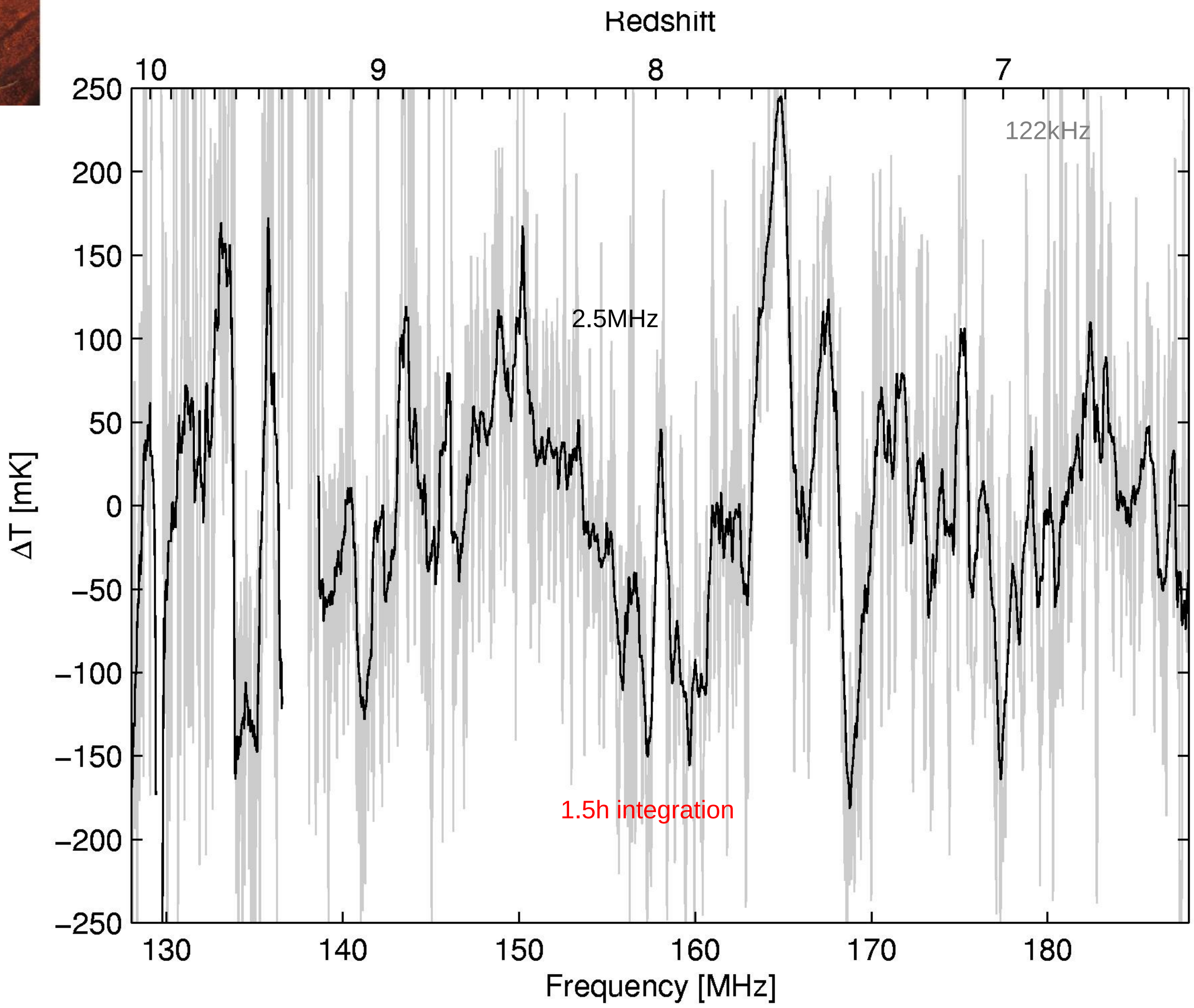
Wang, Tegmark, Santos & Knox (2006)

Detect the Global EOR Signature (EDGES)

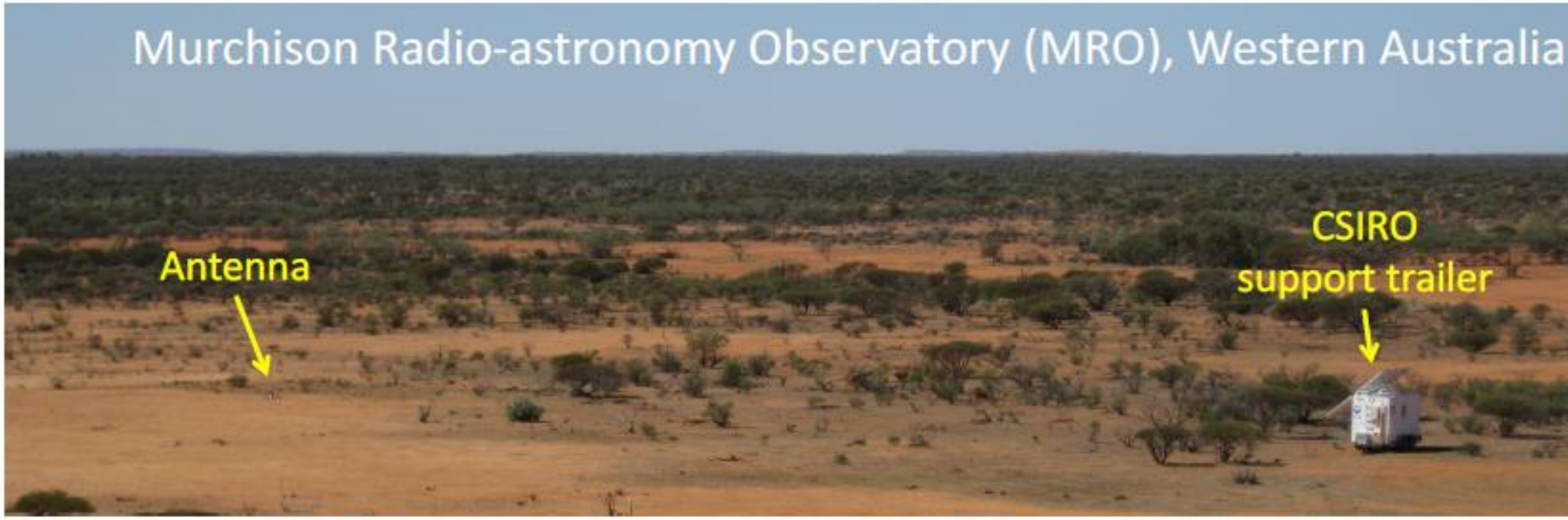
Credit: Judd Bowman (Arizona State University)

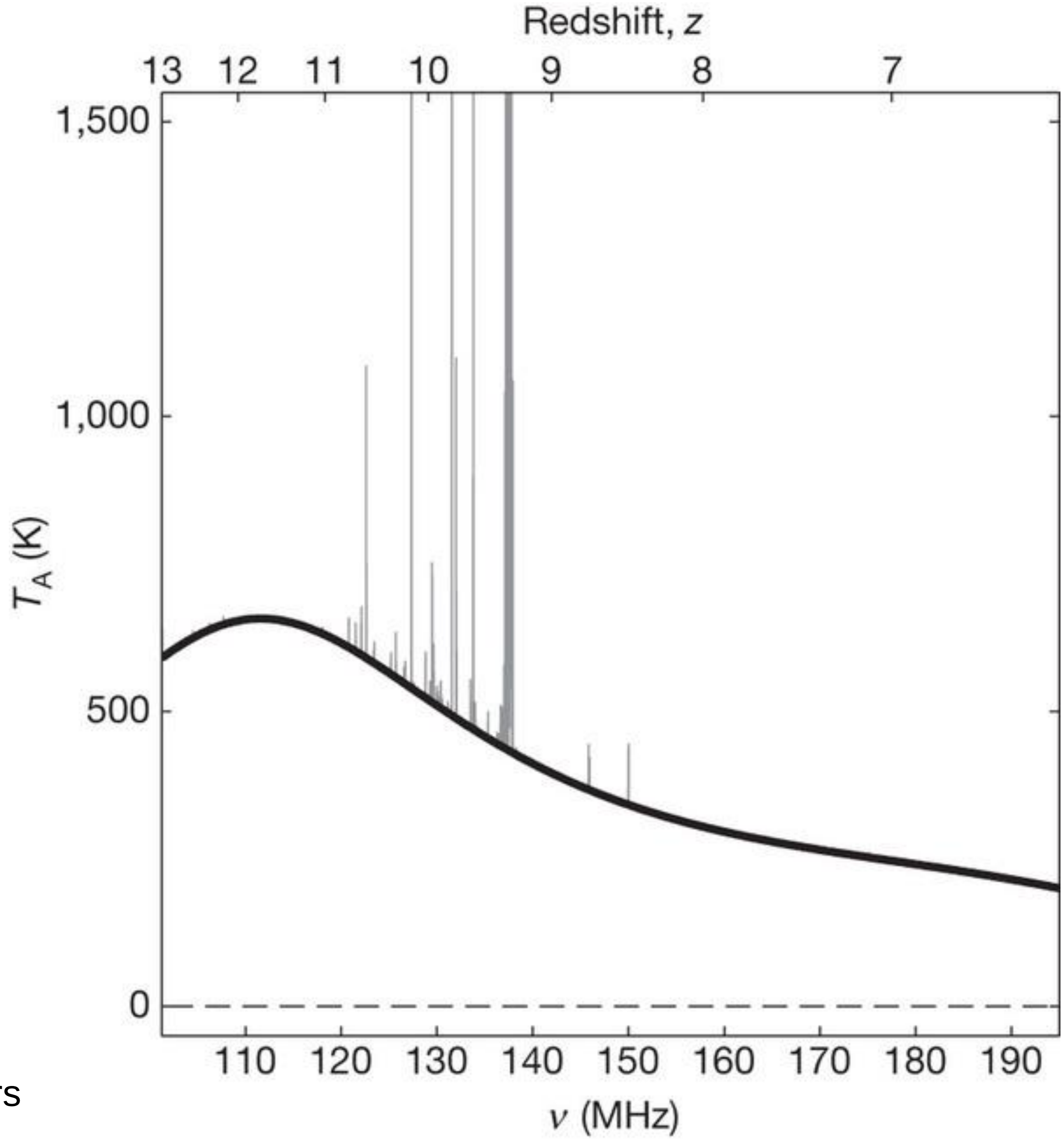
Bowman, Rogers & Hewitt (2008, ApJ, 676,1)

Tb<450 mK at 100-200 MHz



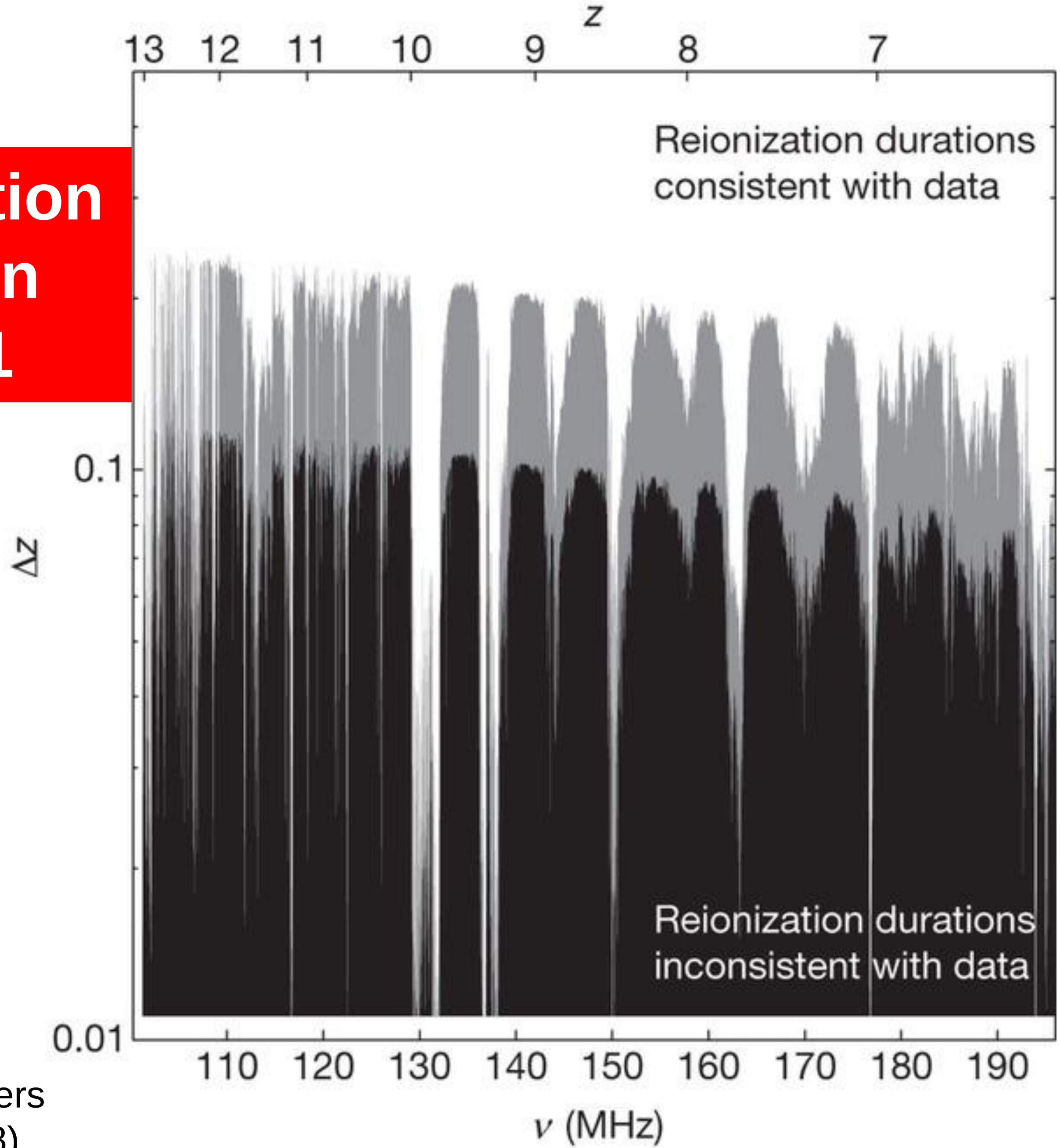
EDGES – Experiment to Detect the Global EoR Signature





Bowman & Rogers
(2010, Nat 468)

Reionization duration Δz>0.1



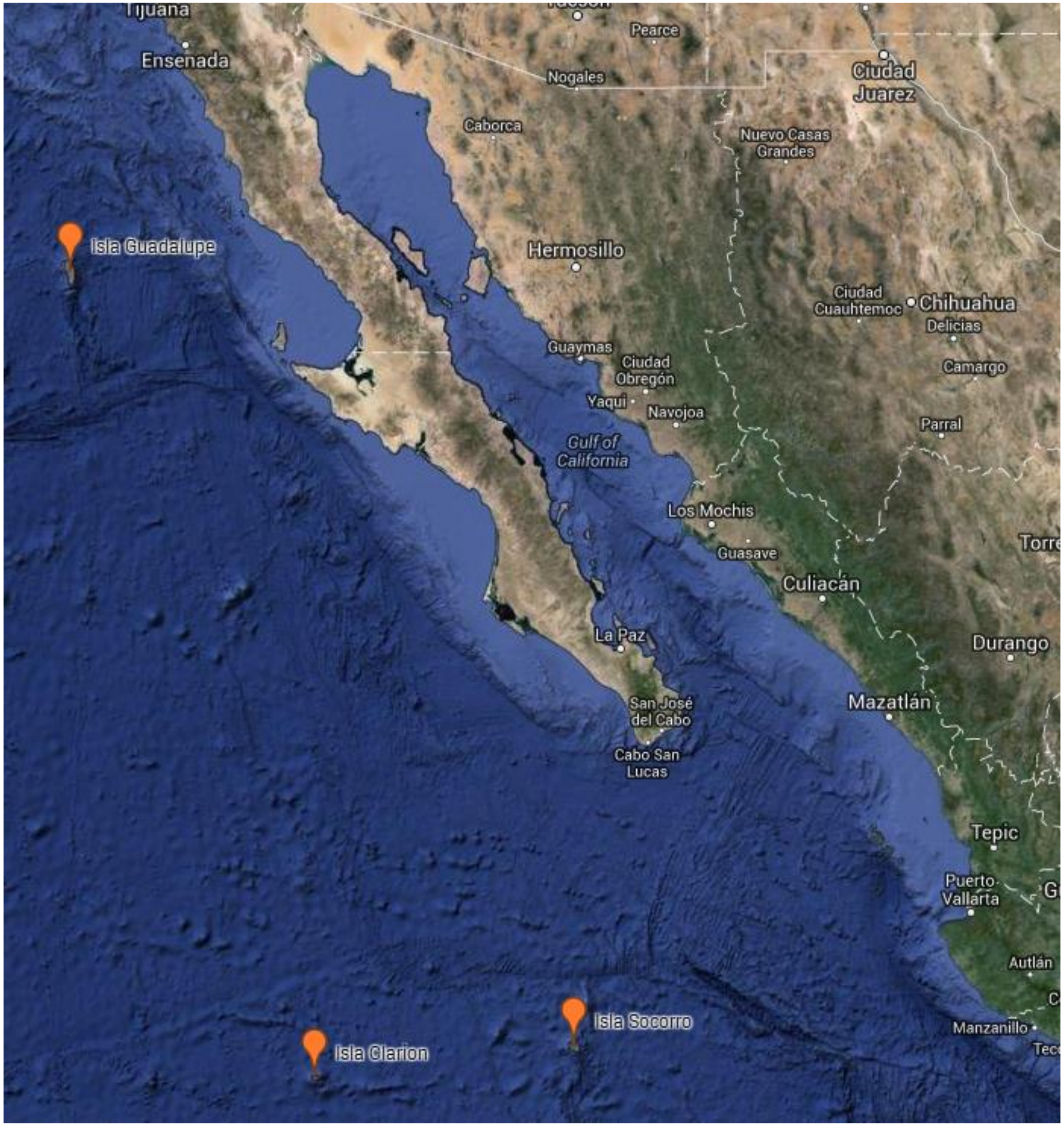
Bowman & Rogers (2010, Nat 468)

SCI-HI

(Sonda Cosmologica de las Islas para la Deteccion de Hidrogeno Neutro)

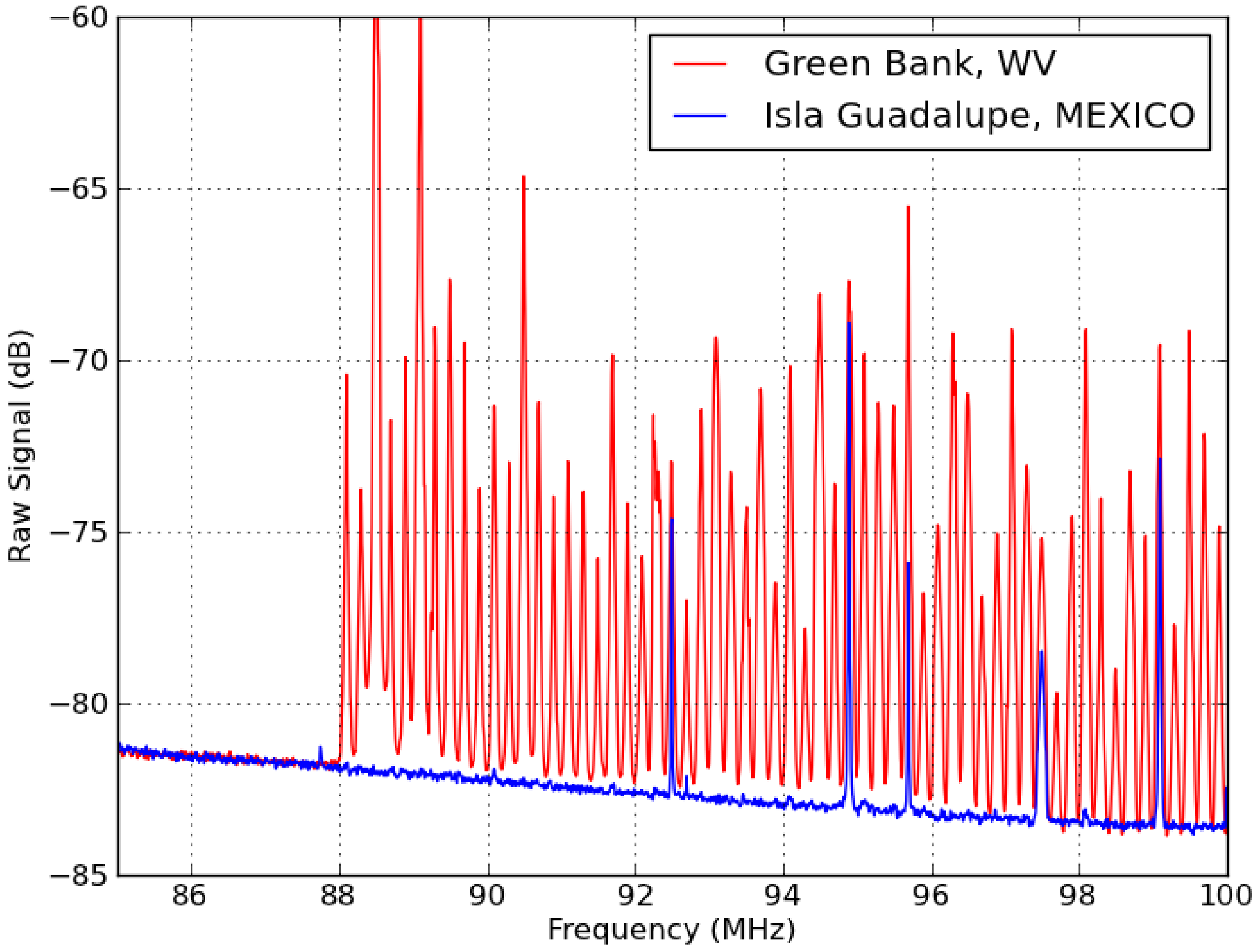
The HIbiscus antenna (40-130MHz)

(Carnegie Mellon University, arXiv.1311.0014)



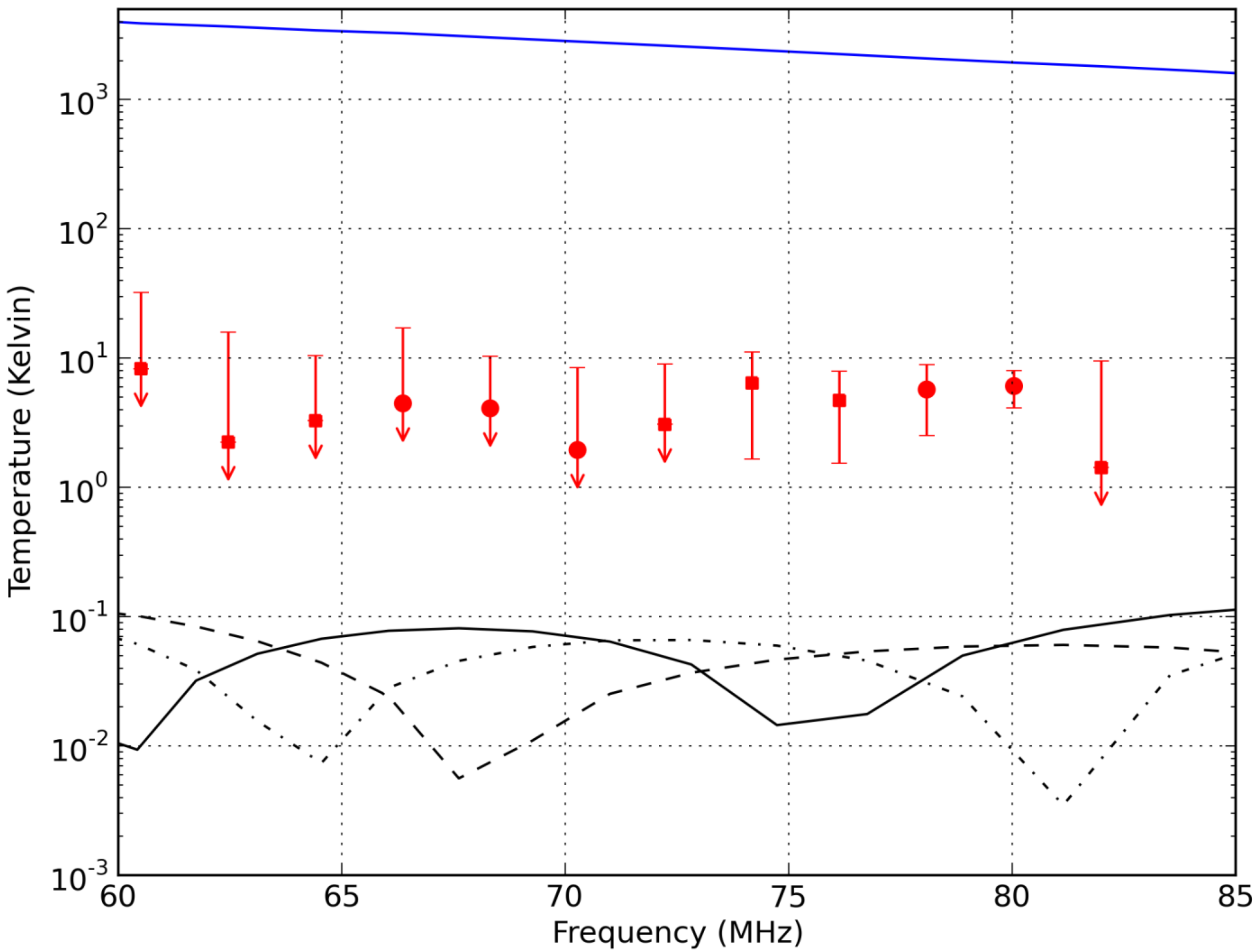
Isla Guadalupe, Eastern Pacific Ocean
(arXiv.1311.0014)

SCI-HI



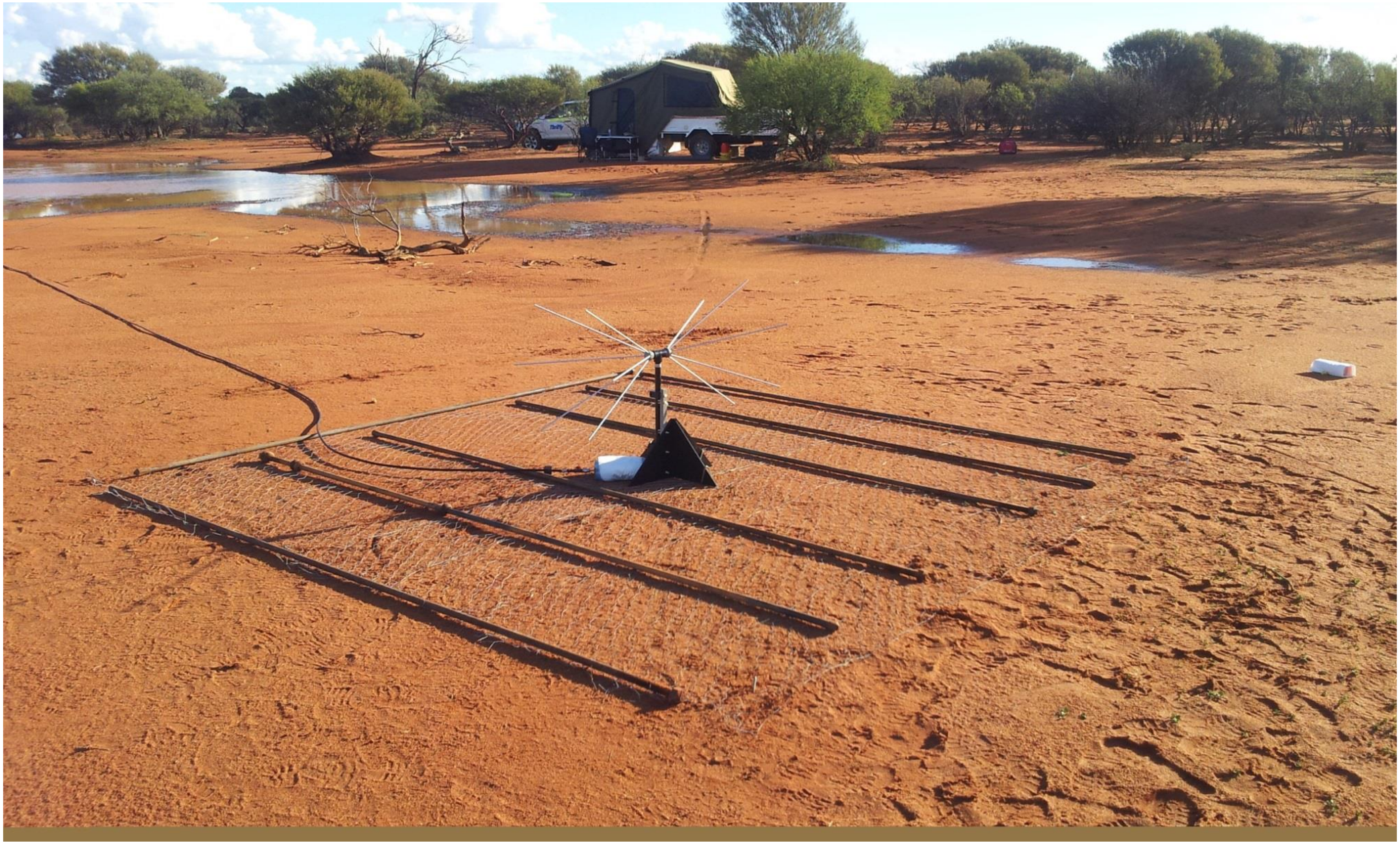
Comparison of RFI in the FM band between Green Bank and Isla Guadalupe

SCI-HI



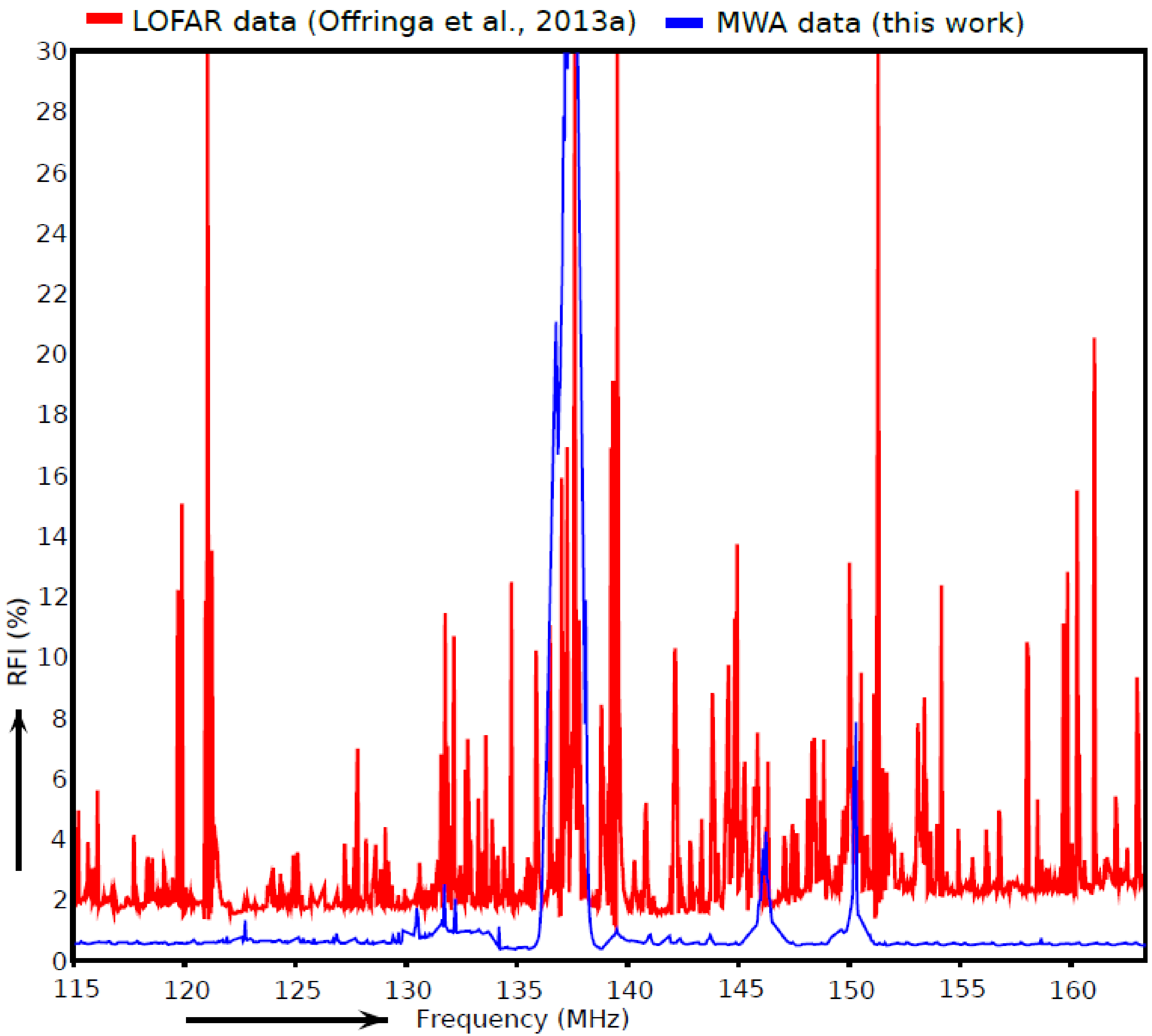
Magnitude comparison of foregrounds (blue), residuals from 4.4h of integration(red) and predictions (black)

BIGHORNS
(Broadband Instrument for Global Hydrogen Reionisation Signal)



The broadband off-the-shell biconical antenna
(Curtin University, arXiv.1501.02991)

(arXiv.1501.02991)



The broadband conical log spiral antenna
(arXiv.1501.02991)

Many More Experiments……

Subrahmanian, Ekers &
Chippendale: CORE at ATNF, Australia)

SARAS (2013)

Gauribidanur Observatory, India

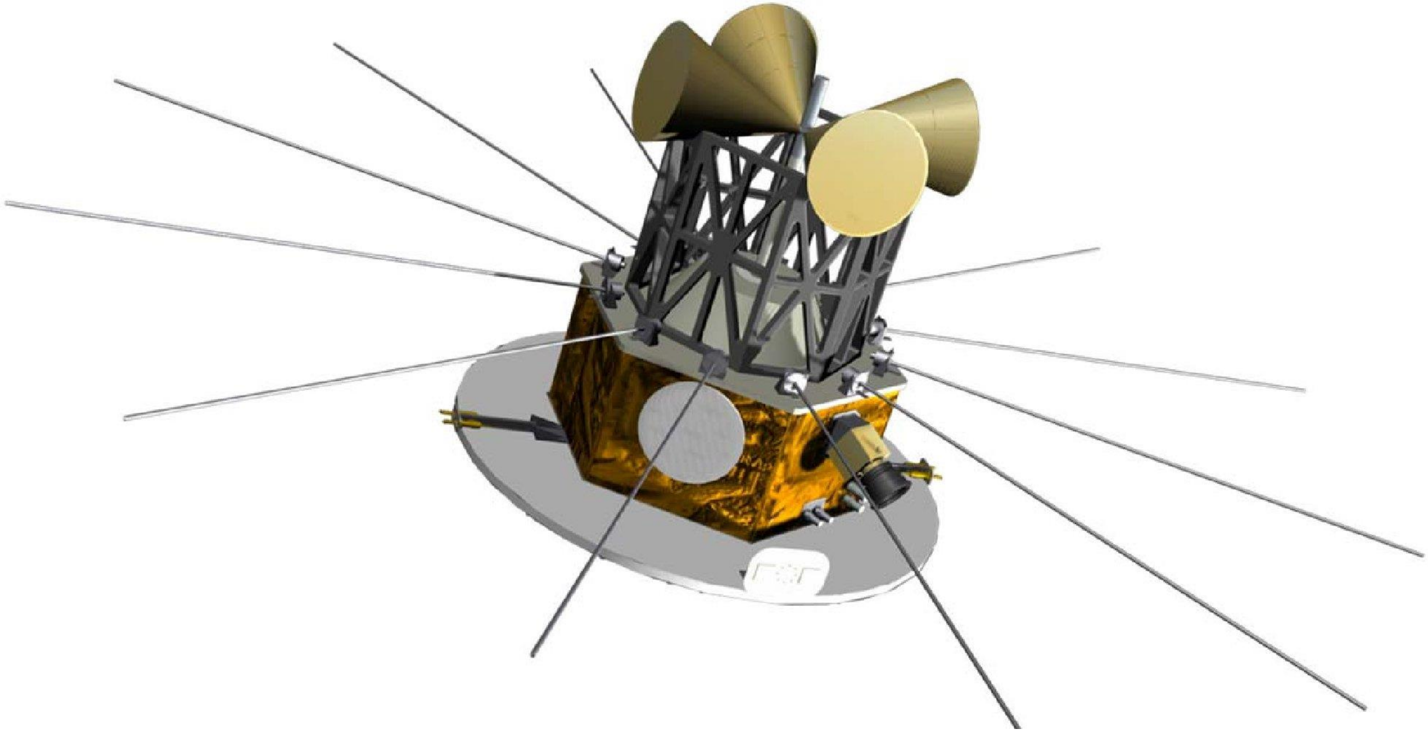
(Shaped Antenna measurement of the background Radio Spectrum)

87.5-175 MHz

The Large Aperture Experiment to Detect the Dark Ages (LEDA)

z=15-30

http://www.cfa.harvard.edu/LEDA



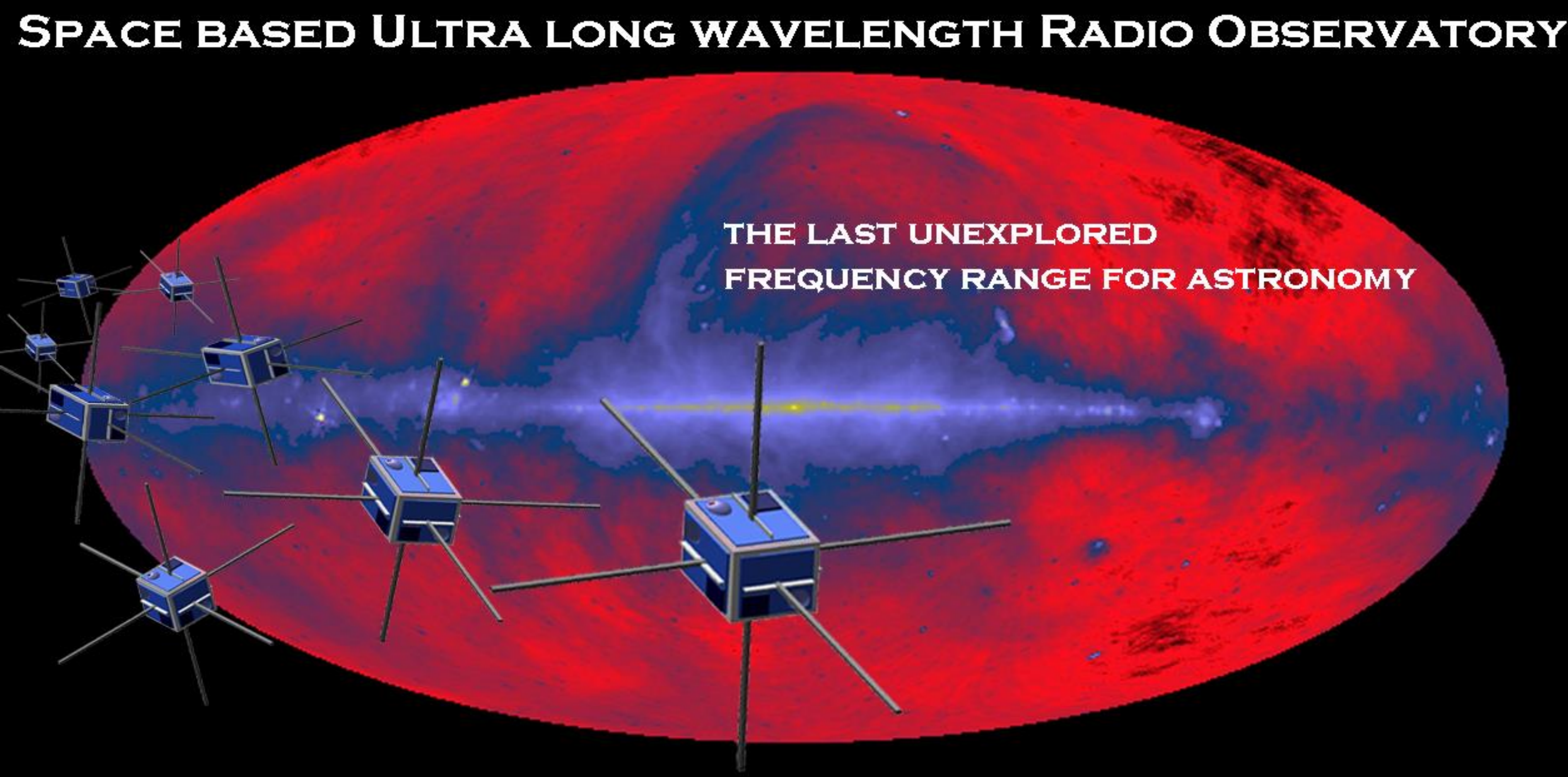
Dark Ages Radio Explores (DARE)

(f=40-120MHz   z=11-35)

Burns et al (2011)

SURO-LC

(DSL)



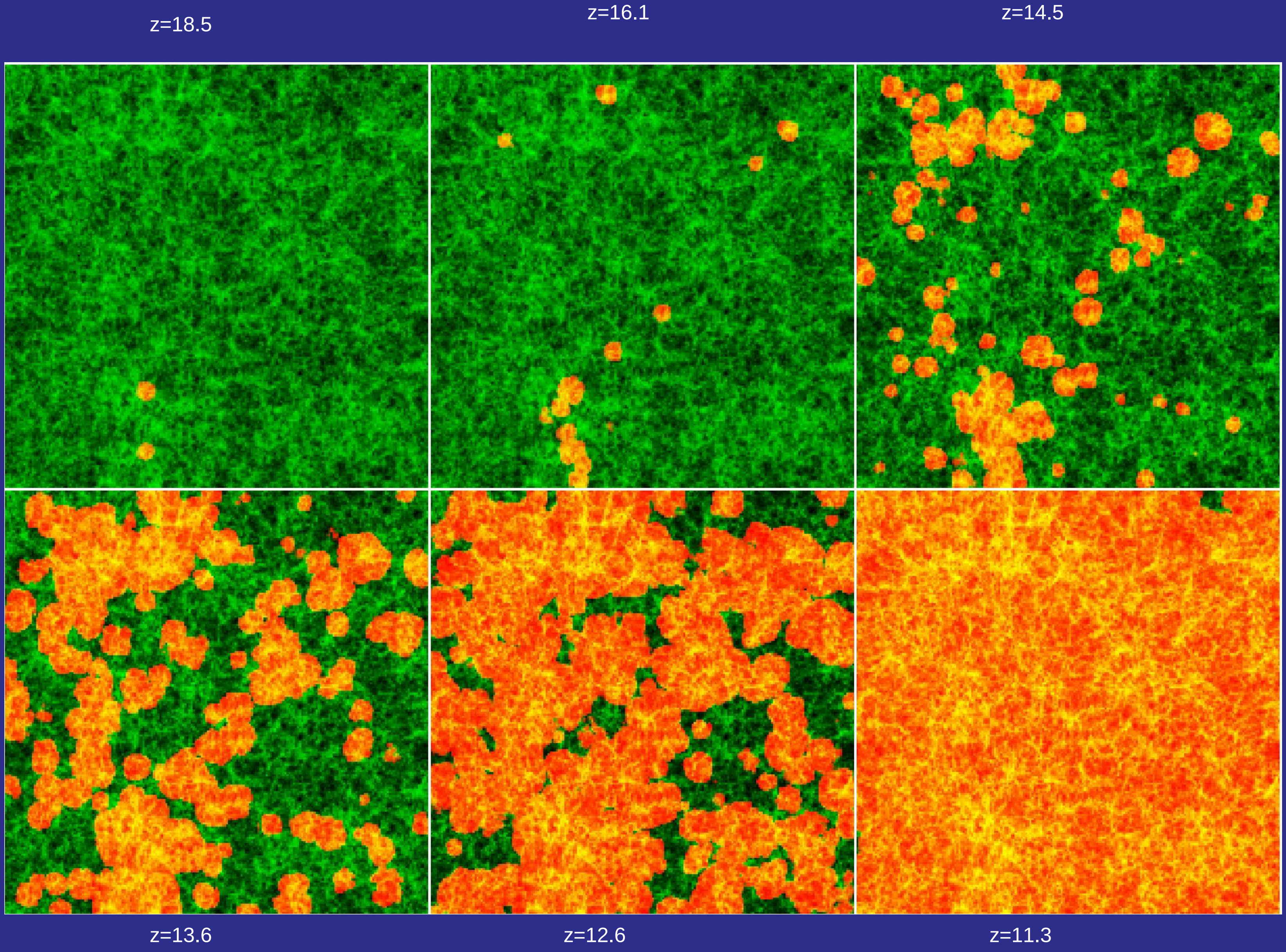
0.1 – 70 MHz

Measurements of the EOR

1. Global Signatures (total power)

2. Imaging (structures)

3. Fluctuations (power spectrum)



Reionization History

Iliev et al. (2005)

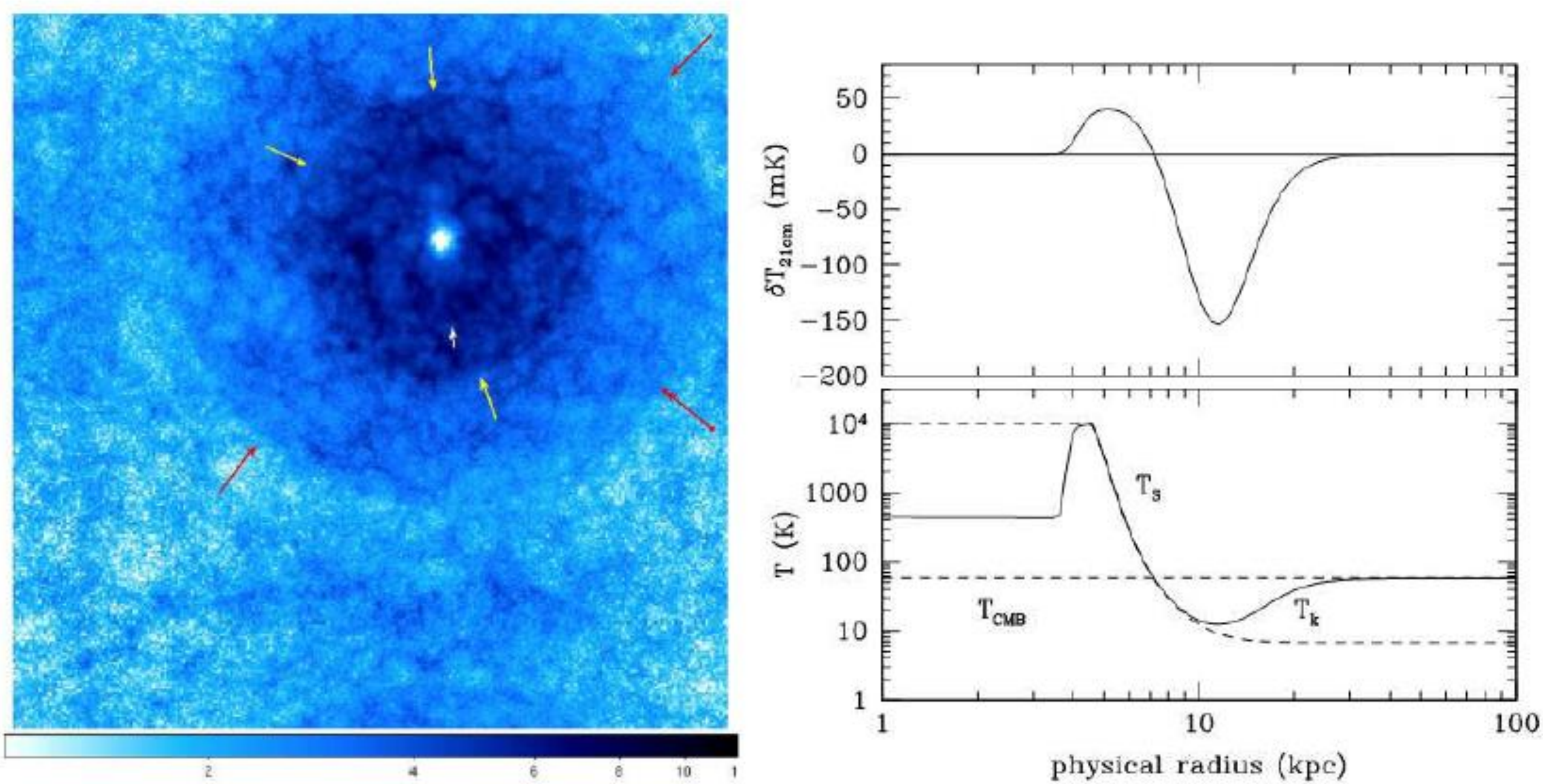


Figure 3: (a:left) Distinct ring structure due to the step-wise Lyα pumping around a point source. $-\delta T_b \times r^2$ at $z = 13.42$ is plotted with an arbitrary unit, to show these distinct rings (pointed by arrows) as boundaries of sudden change in color: each annulus bound by adjacent rings, where Lyα flux decreases as $1/r^2$, shows about the same color. The box size is 137 Mpc coming and the angular size is $51'$ (Vonlanthen et al. 2011). (b:right) Radial profile of an isolated radiation source of the UV and the X-ray. From inside out, $\delta T_b = 0$ (H II region), $\delta T_b > 0$ (X-ray heated region), $\delta T_b < 0$ (Lyα-pumped region).

Imaging of EoR

Sensitivity & Resoluton

$$\frac{\lambda^2 T_{sys}}{A_e \Omega_b \sqrt{\Delta \nu \tau}}$$

$$1.22\lambda/D$$

1 mK

1′-10′

Square Kilometre Array (SKA)

Imaging of EoR

Sensitivity & Resoluton

$$\frac{\lambda^2 T_{sys}}{A_e \Omega_b \sqrt{\Delta \nu \tau}}$$

$$1.22\lambda/D$$

1000 hr for SKA1

$6''(\lambda/3\mathrm{m})(\mathrm{L}/100\mathrm{km})^{-1}$

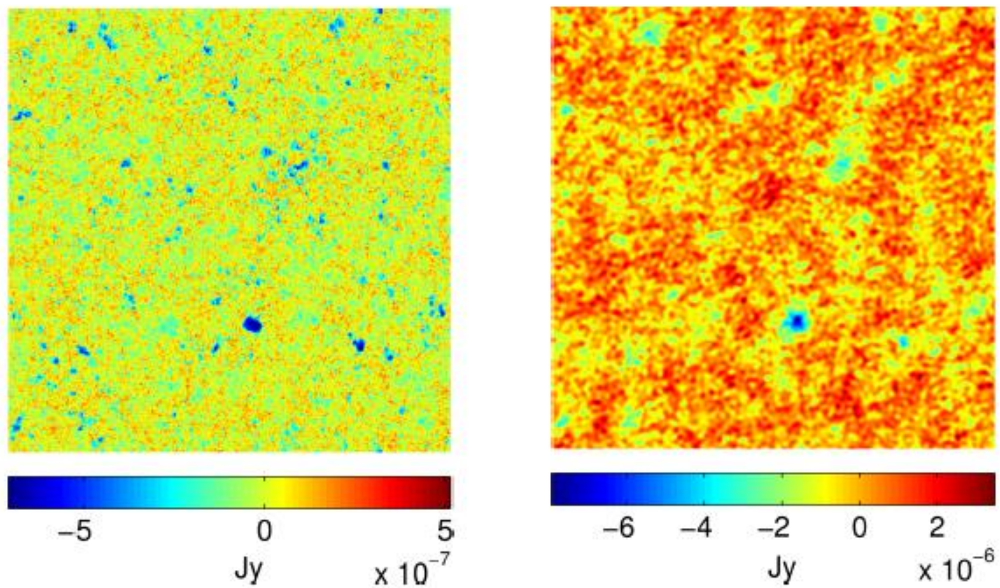
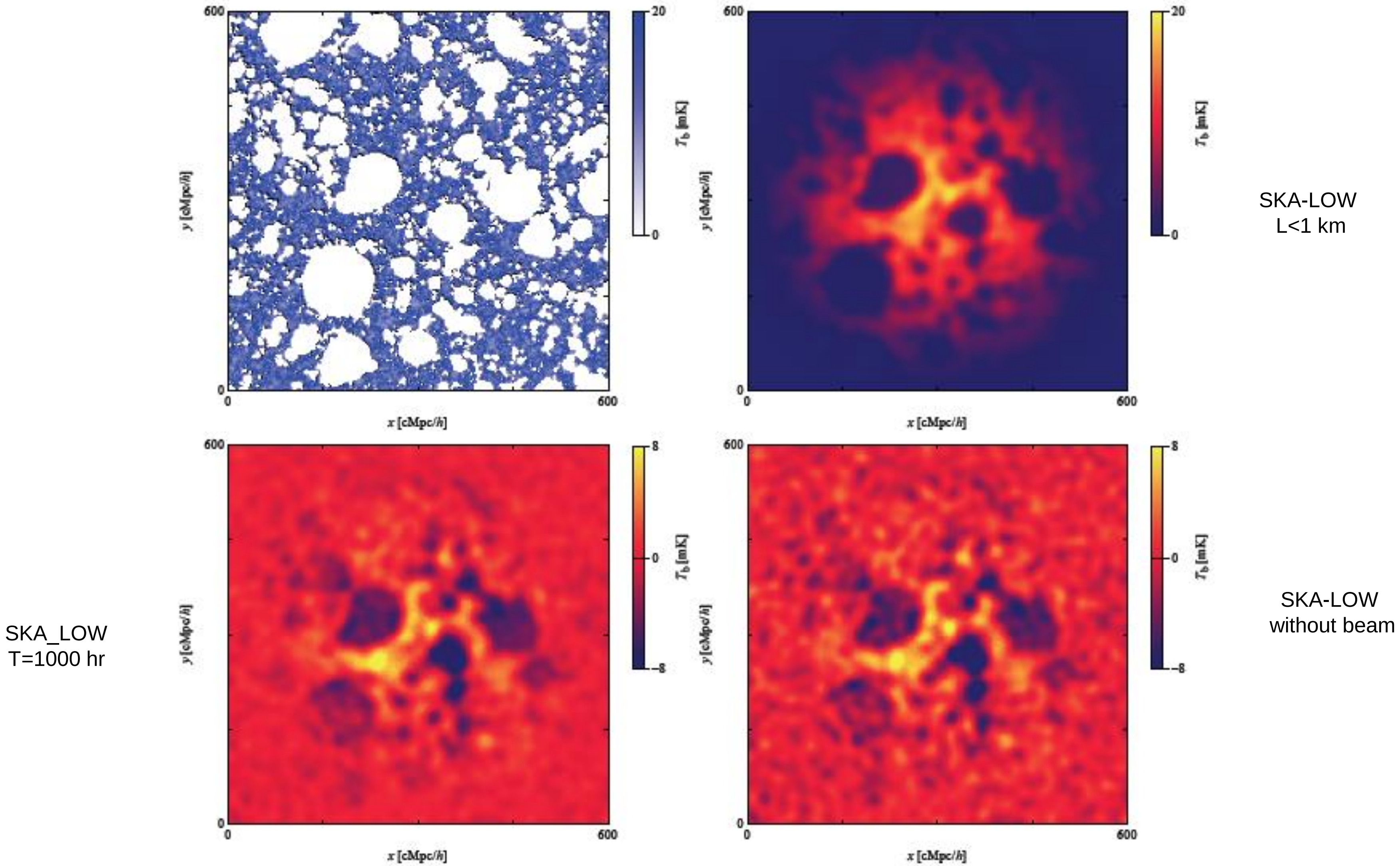


Figure 3: Left panel: The 21cm signal from a simulation of reionization in a 425 h^{-1} Mpc volume (Iliev et al. 2014). The redshift is $z = 8.515$ and it is assumed that $T_s \gg T_{CMB}$. The field is 3.64×3.64 degrees on the sky. Right panel: the 21cm signal plus thermal noise when observed with SKA1-Low for 1000 hours.[2] The frequency is 150 Mhz, bandwidth 1 MHz and only baselines less than 2 km are used. This gives a synthesized beam of $3.7' \times 3.2'$. The large HII region in the lower half of the image is 18.55 h^{-1} Mpc or $9.5'$ in size and is clearly recovered in the observed image.



(Wyithe et al   ArXiv:1501.04246)

Simulations of the SKA1-LOW response to the ionisation structure in the Gigglez 1 Gpc=h simulation in which galaxy formation is assumed to include an efficient SNe feedback, and reionisation has progressed to a neutral fraction of 0.45. The upper-left panel shows the model slice of depth 2 Mpc=h (corresponding to 171 kHz at z = 7:27). The upper-right panel shows an image of this slice assuming an estimate of the primary beam gain, accounting only for the power on scales that can be observed by baselines shorter than 1000 m (corresponding to the diameter of the core). The lower-left and lower-right panels show simulations of observed maps (without a primary beam correction) assuming the base-line SKA1-LOW with1000 hr integration and an early deployment where the collecting area is decreased by a factor of 2. The model observations have a depth of 1.2 MHz, which corresponds to 14 Mpc=h along the line-of-sight, at a central frequency of 173 MHz for HI at z = 7:27, and is equivalent to the FWHP of the synthesised beam.

SKA Key Science
(Christopher Carilli, 2014)

Killer Applications

- Pulsars: double precision gravity and gravitational waves
- HI 21cm cosmology: Imaging reionization and first light

Foundational applications of radio astronomy

- Cosmic magnetism
- Milky way and nearby galaxies: eg. star formation, cool gas and baryon cycle
- Galaxy formation (e.g. star formation through deep fields, HI mass function)
- AGN, XRBs, and other high energy phenomena
- Time domain and synoptic phenomena

Possible game changers (high risk/high return)

- FRBs: as profound impact as pulsars ?
- BAO intensity mapping and other cosmology apps: beat the Boss ?
- Dark ages and linear HI 21cm cosmology
- Exoplanets/biology: band 5+
- SETI

SKA1-LOW

(50-200MHz, 250,000 antennas, 2018-2023)

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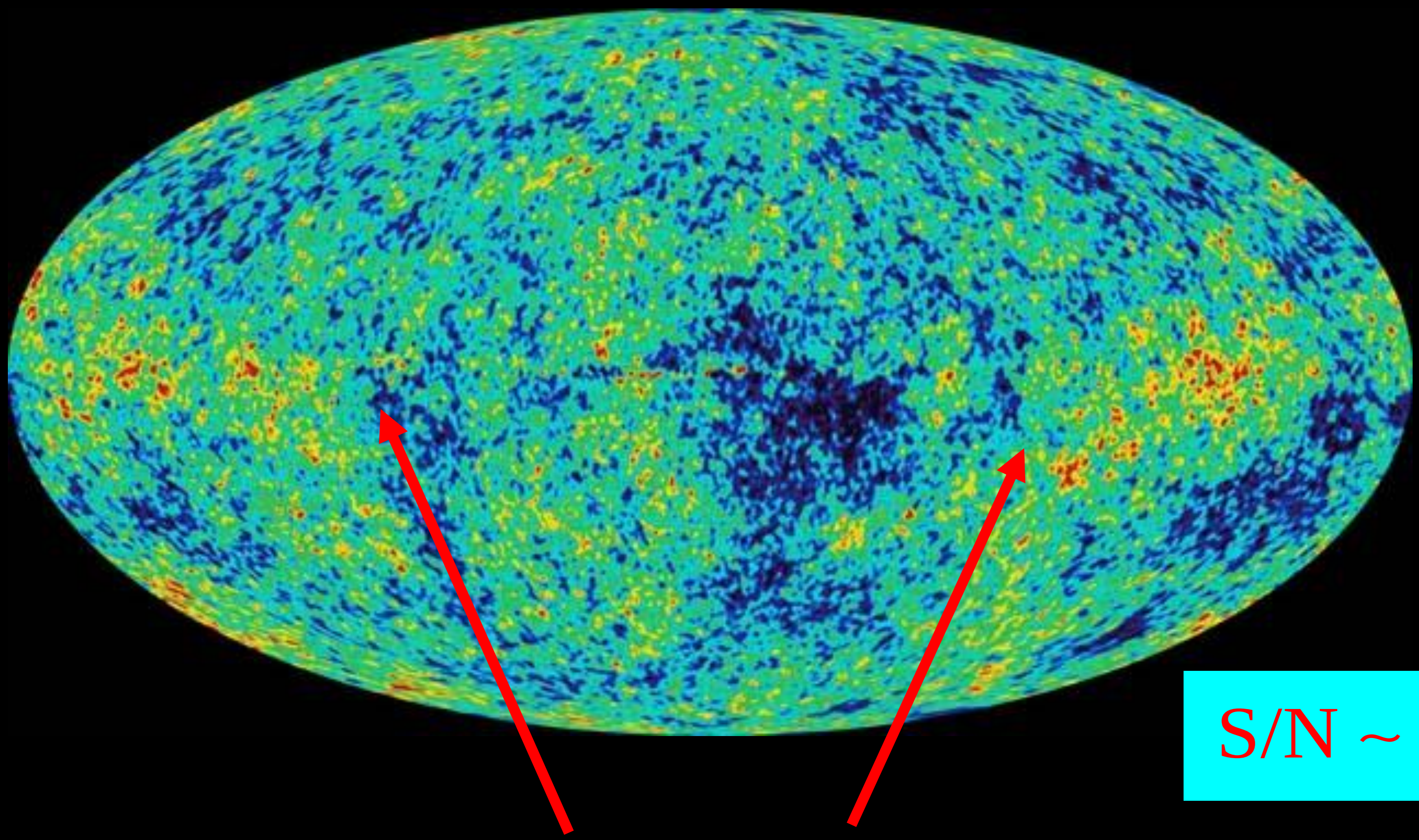


$$\mathrm{S/N} \sim 1/\sqrt{N_\ell}$$

$$C(\theta) = \left\langle \frac{\Delta T(\vec{n})}{\bar{T}} \frac{\Delta T(\vec{n}+\vec{\theta})}{\bar{T}} \right\rangle$$

$$= \frac{1}{4\pi} \sum_\ell (2\ell+1) C_\ell P_\ell(\cos\theta)$$



interferometers

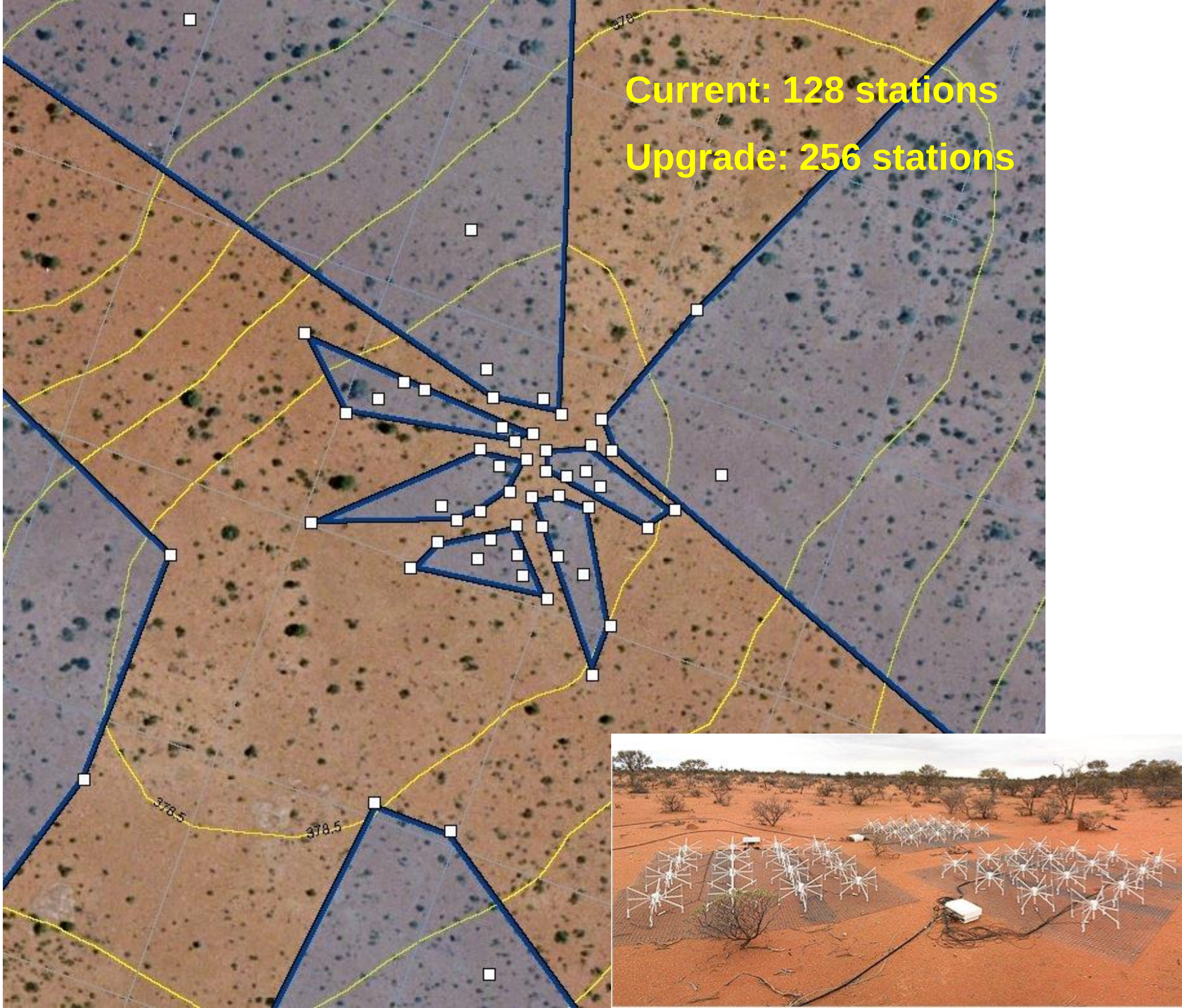




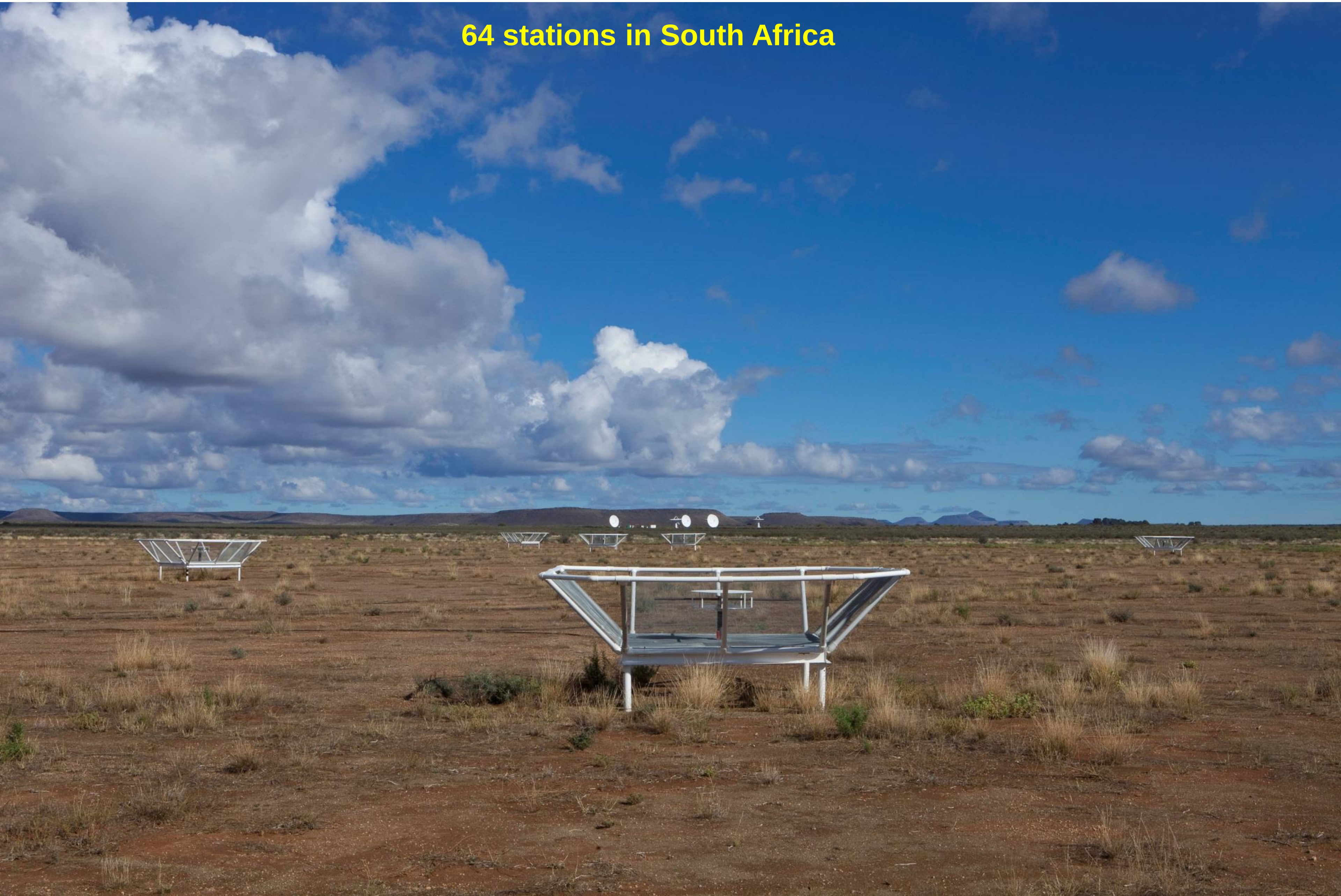

LOFAR
(Low Frequency Array)
30-80   120-240 MHz
45 + 32 stations

Superterp core stations

Murchison Wide-field Array (MWA)


Current: 128 stations
Upgrade: 256 stations
378.5
378.5

Precision Array to Probe Epoch of Reionization (PAPER)



Precision Array to Probe Epoch of Reionization (PAPER)

Giant Metrewave Radio Telescope (GMRT)

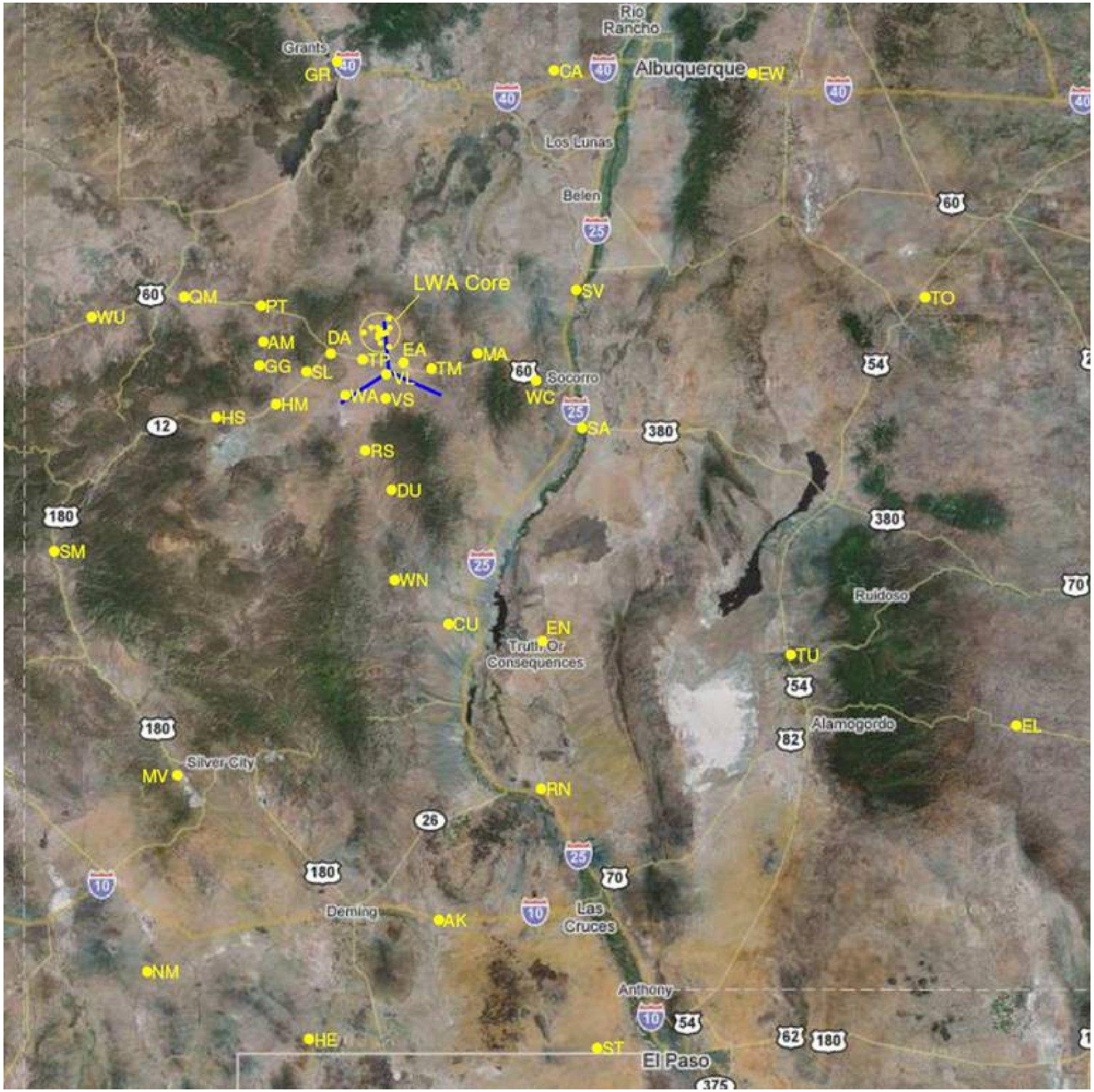
150MHz

21 CentiMeter Array (21CMA)

50-200 MHz

The Long Wave Array (LWA)

Planned LWA Stations across the state of New Mexico



53 stations

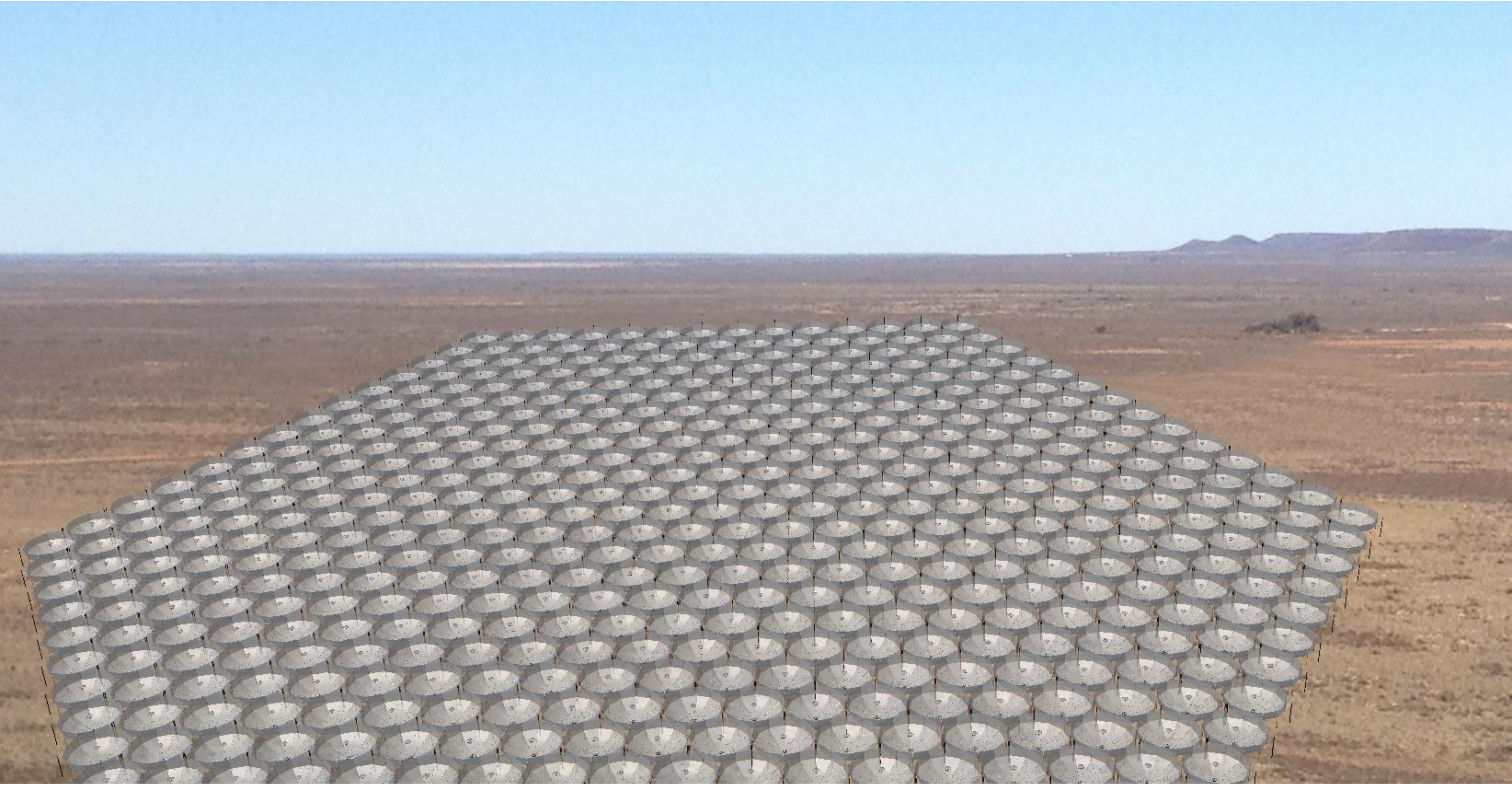
Henning et al. (arXiv:1009.0666)

MITEoR: A Scalable Interferometer for Precision 21cm Cosmology

May 2015

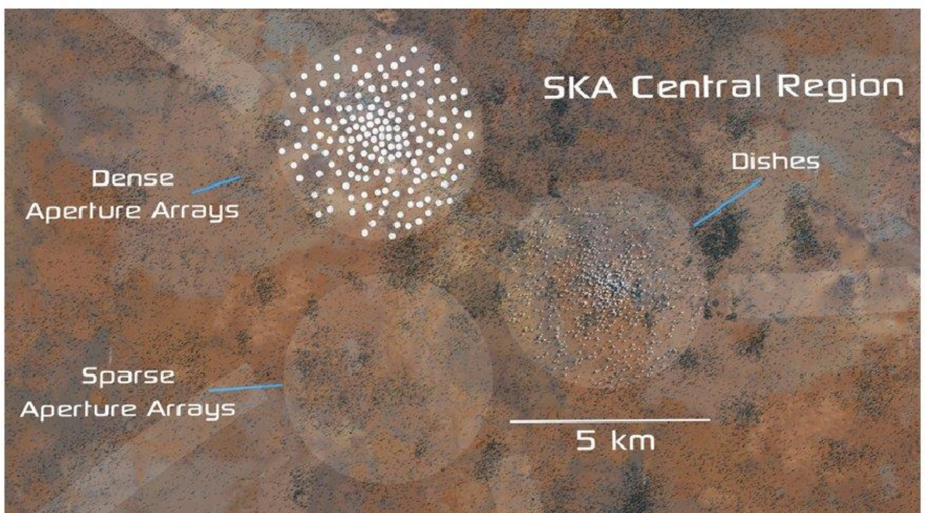
(arXiv：1405.5527)

The Hydrogen Epoch of Reionization Array (HERA)

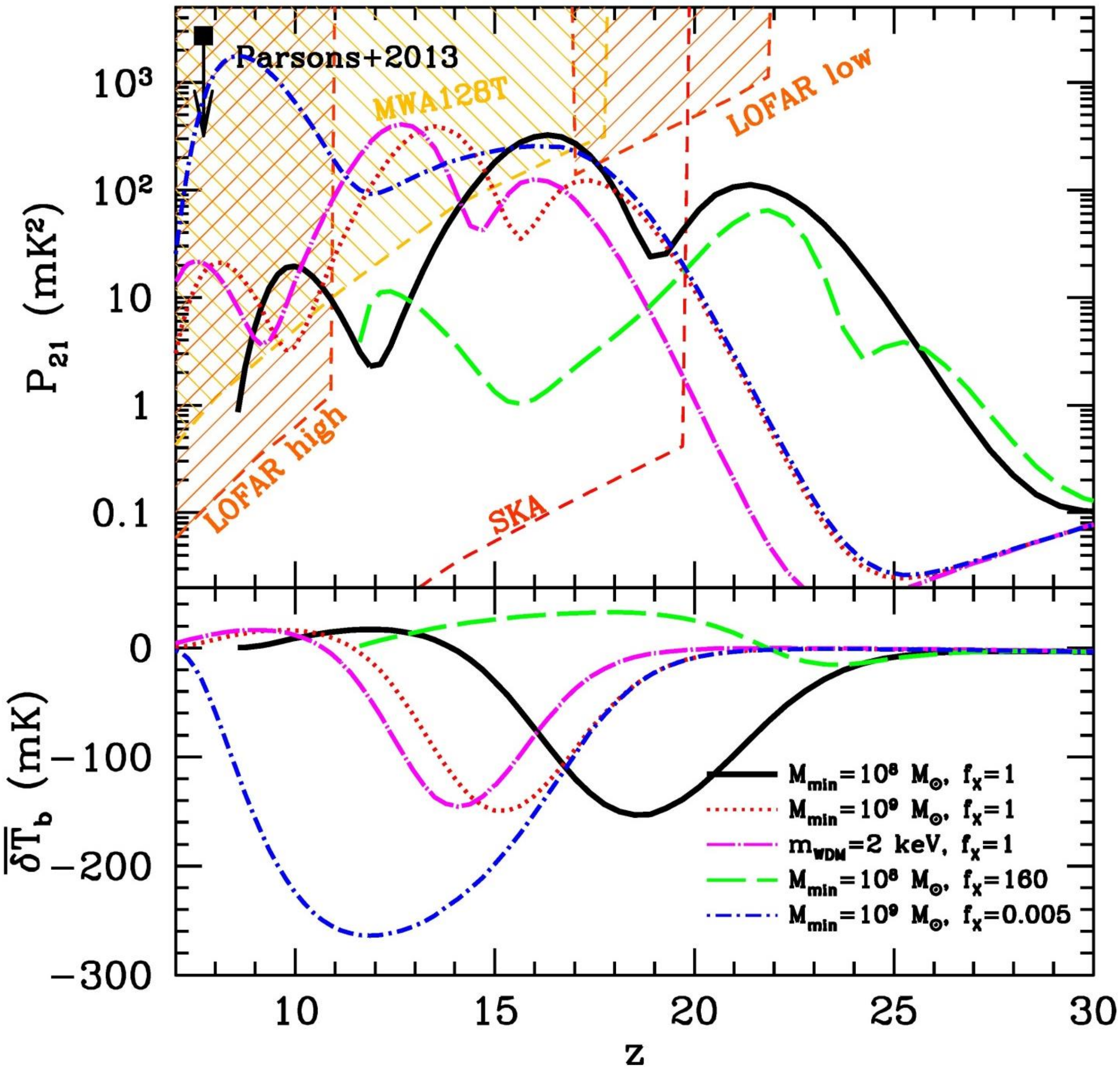


A hexagonal packing of 547 elements (14m) provides enough sensitivity to measure HI emission at 12>z>6 while avoiding foregrounds.

SKA
SQUARE KILOMETRE ARRAY

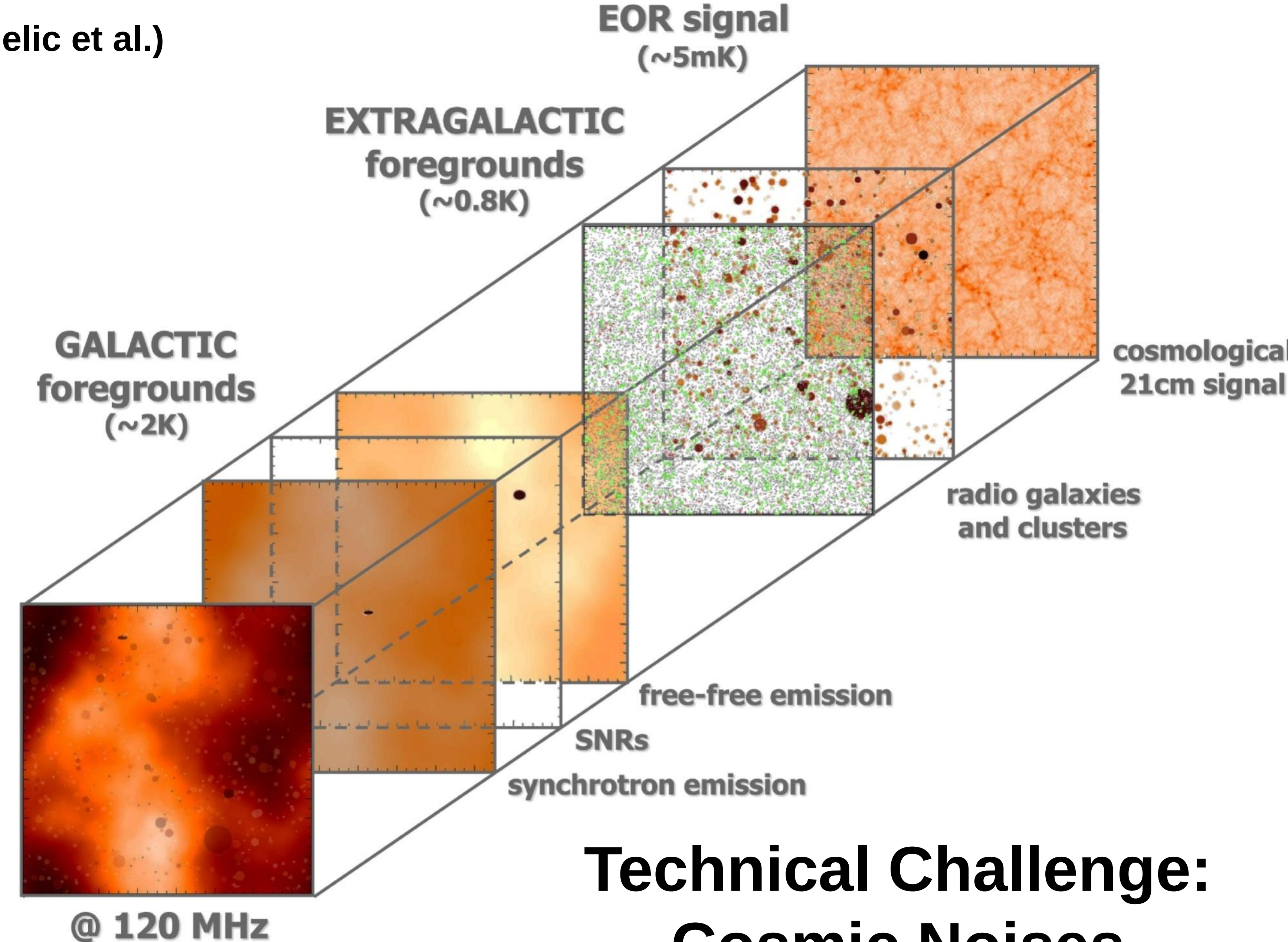


Sensitivity of Various Planned Observations

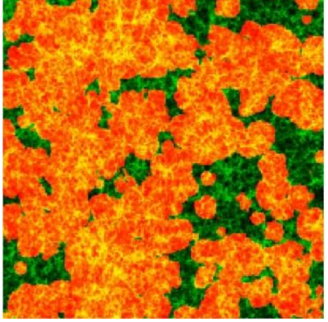


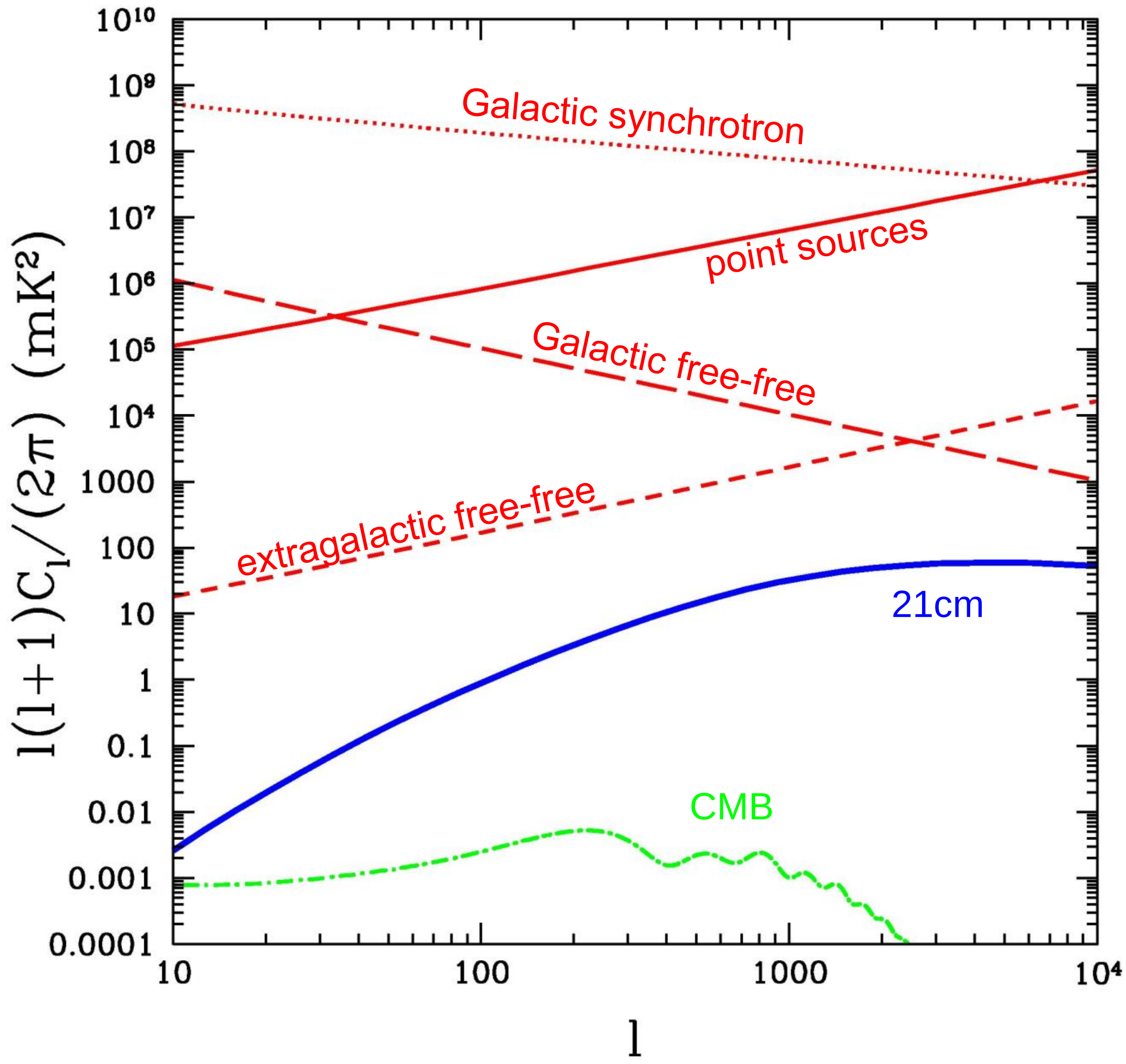
ArXiv:1501.04141

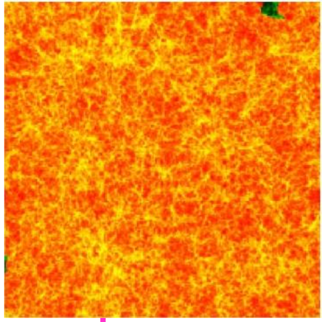
(Jelic et al.)



Technical Challenge: Cosmic Noises



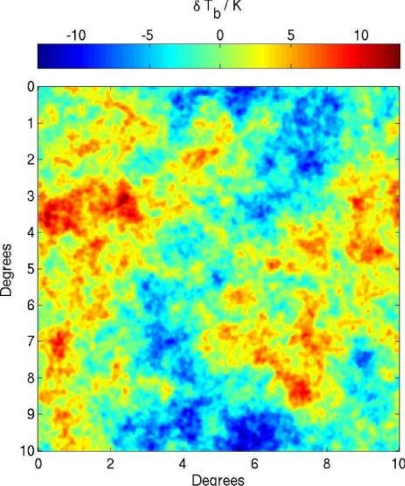




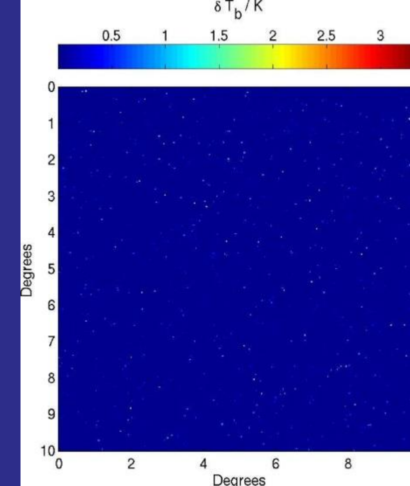
10^6

$$\left\langle \Delta T^2 \right\rangle = 10^6$$

The 21cm power spectrum at z=9.2 (freq=140MHz) (Santos, Cooray & Knox 2005)



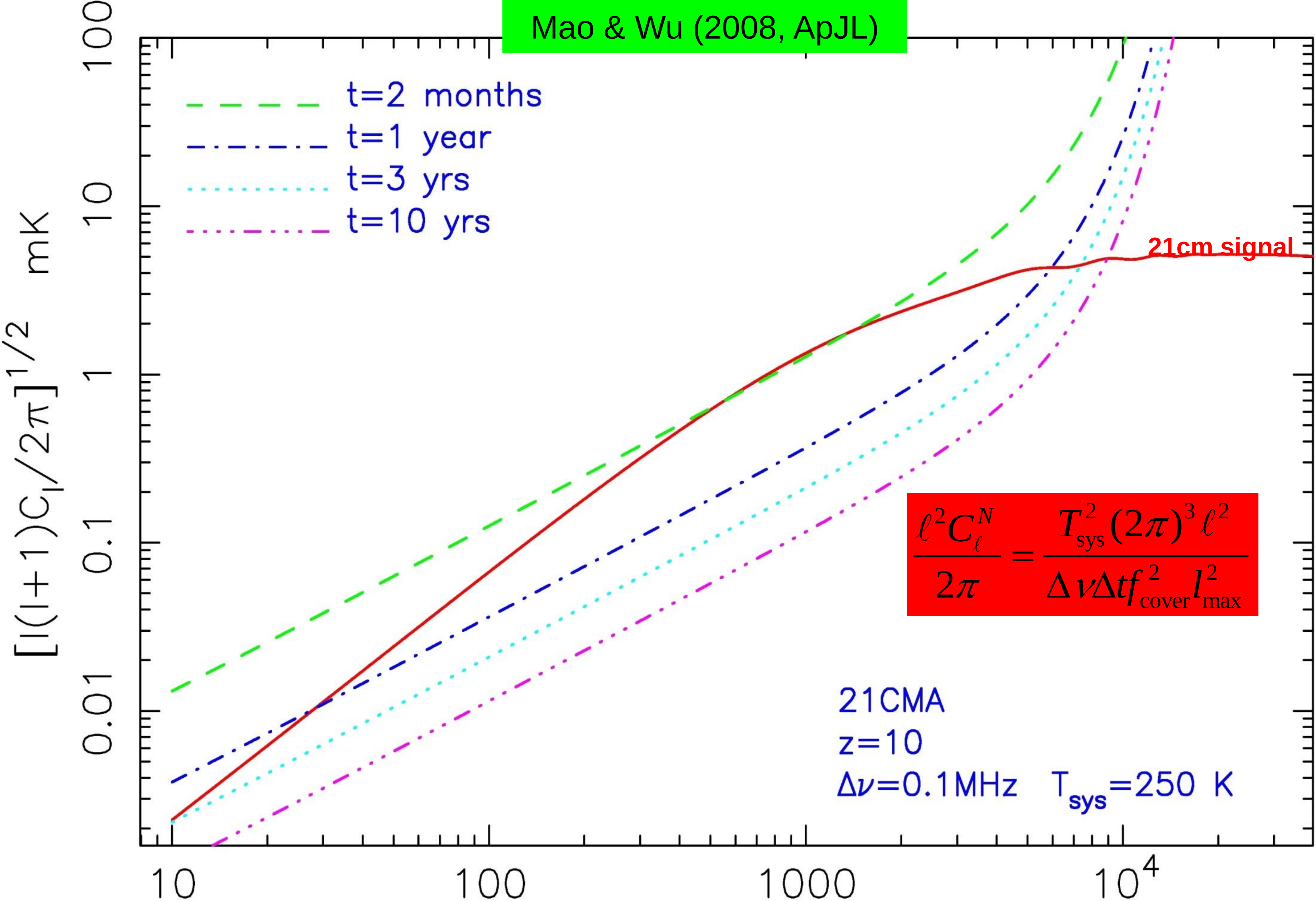
Noise Power Spectra



$$\frac{\ell^2 C_\ell^{\mathrm{thermal}}}{2\pi} = (10\mathrm{mk})^2 \left(\frac{\ell}{1000}\right)^2 \left(\frac{T_{\mathrm{sys}}}{300\mathrm{K}}\right)^2 \left(\frac{\nu}{150\mathrm{MHz}}\right)^2 \left(\frac{\Delta\nu}{1\mathrm{MHz}}\right)^{-1} \left(\frac{\Delta t}{\mathrm{yr}}\right)^{-1}$$

$$\frac{\ell^2 C_\ell^{\mathrm{shot}}}{2\pi} = (33\mathrm{mk})^2 \left(\frac{\ell}{1000}\right)^2 \left(\frac{\nu}{150\mathrm{MHz}}\right)^{-4} \left(\frac{S_{\mathrm{cut}}}{1\mathrm{mJy}}\right)^2$$

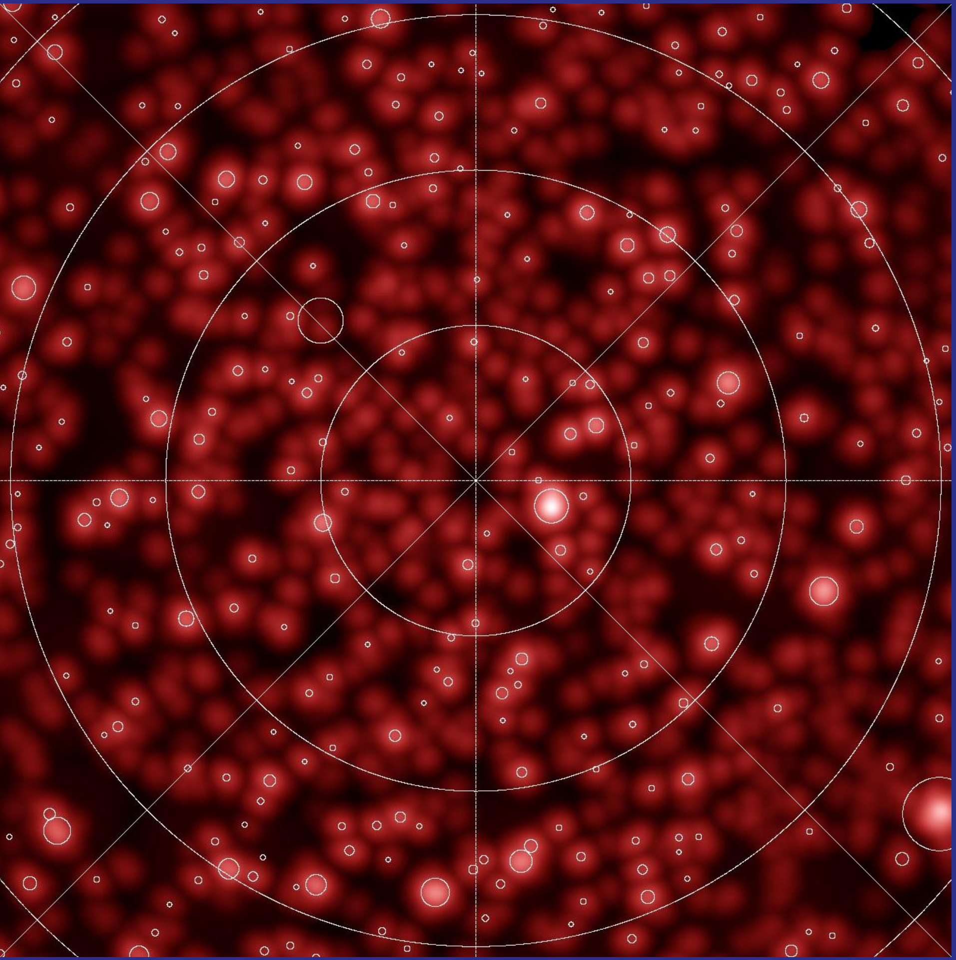
Mao & Wu (2008, ApJL)



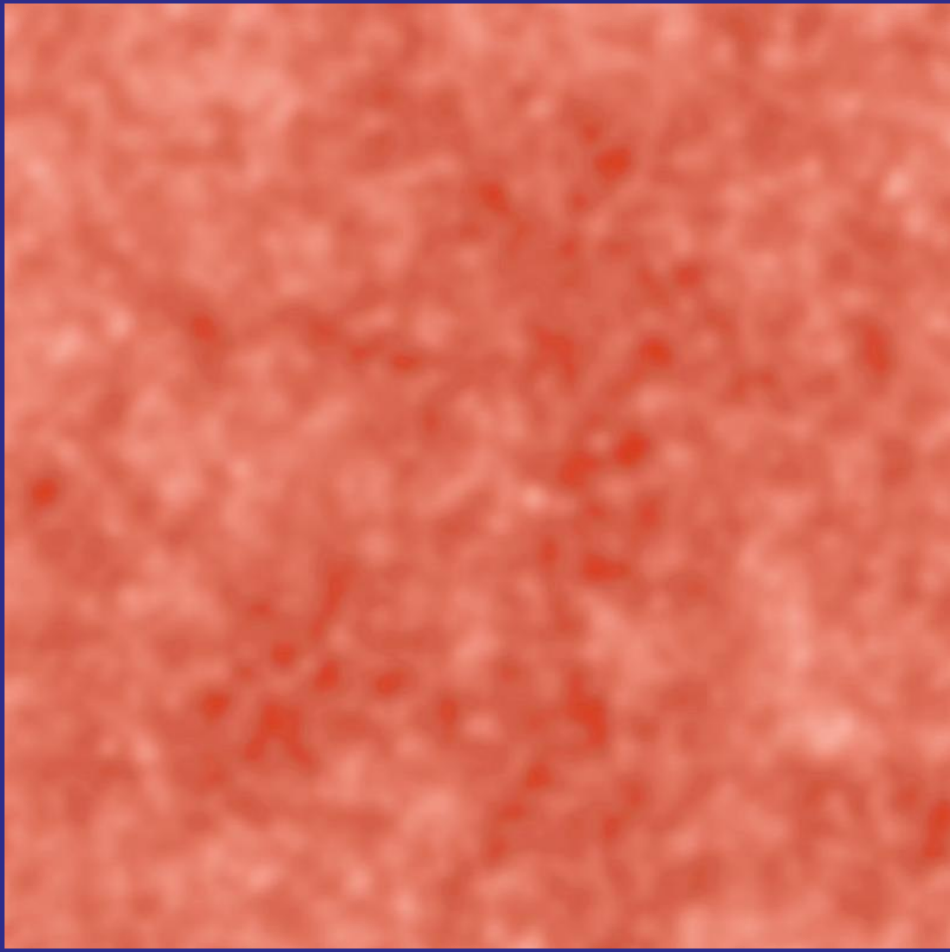
$$\frac{\ell^2 C_\ell^N}{2\pi} = \frac{T_{\rm sys}^2 (2\pi)^3 \ell^2}{\Delta\nu \Delta t f_{\rm cover}^2 l_{\max}^2}$$

Noise power spectra at z=10(freq=130MHz) with freq width 0.1MHz

Point source removals

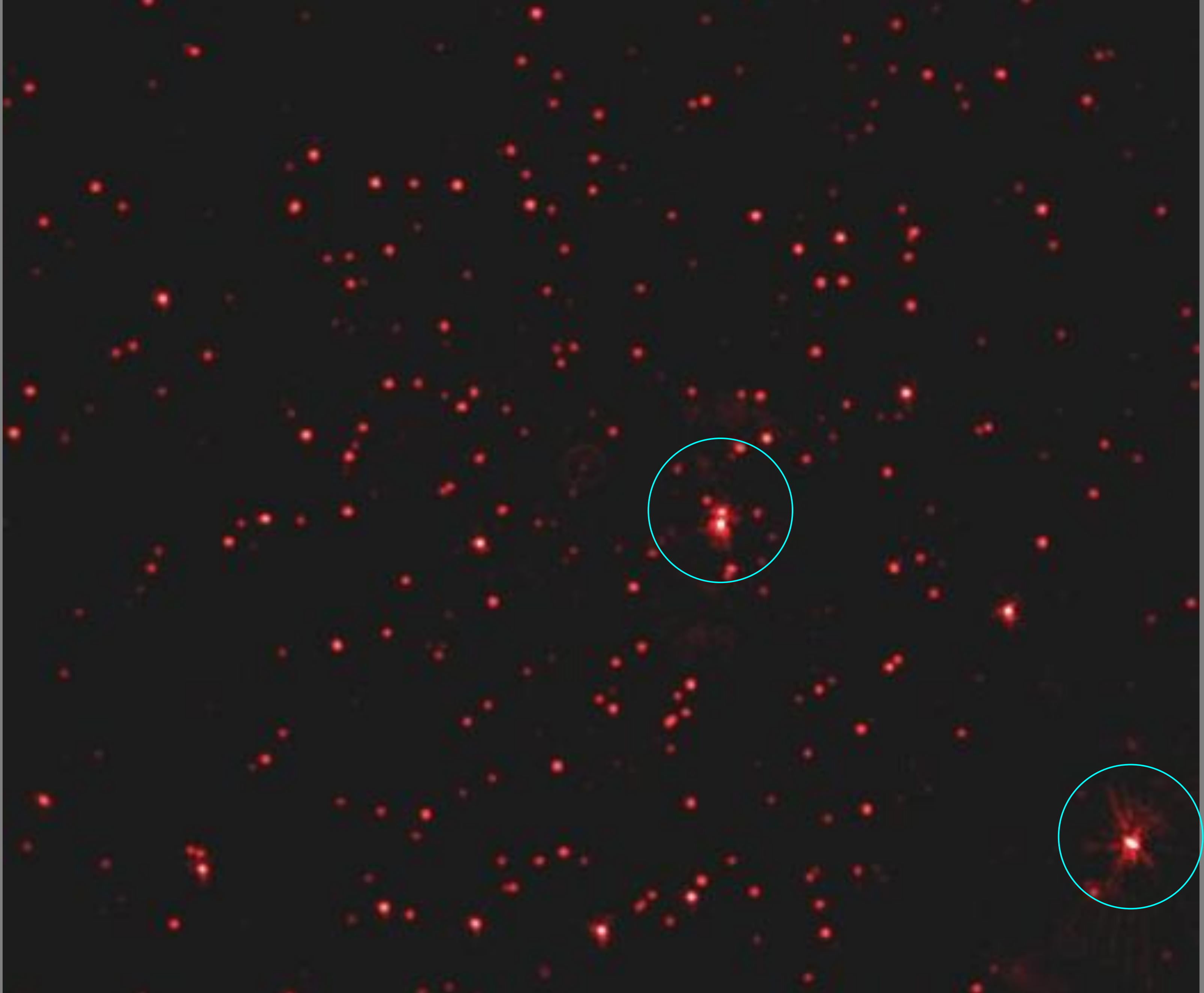


VHF sky @ 21CMA

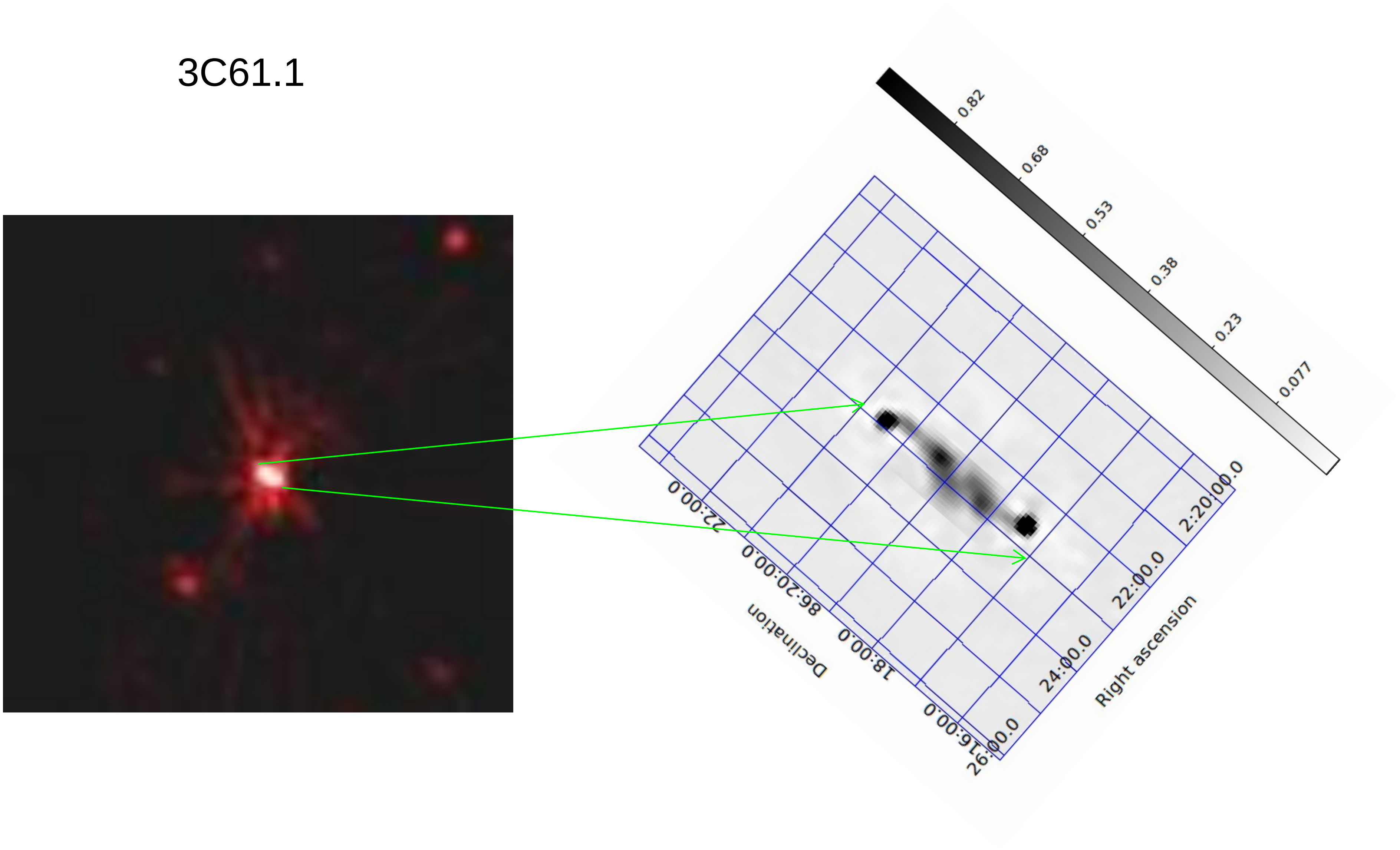


Residuals

Brightest Sources @ 21CMA Field

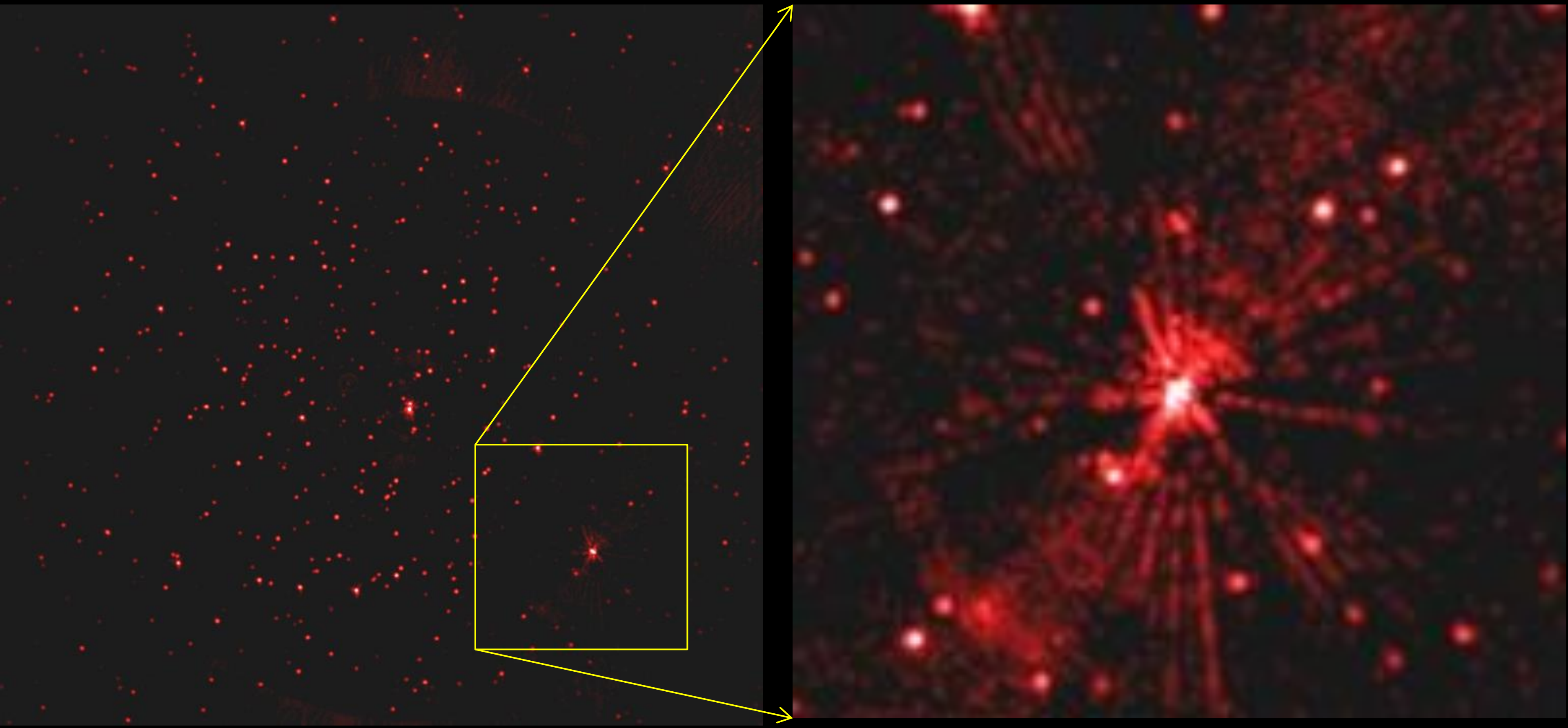


3C61.1


0.82
0.68
0.53
0.38
0.23
0.077
22:00.0
86:20:00.0
18:00.0
16:00.0
Declination
2:20:00.0
22:00.0
24:00.0
26:00.0
Right ascension

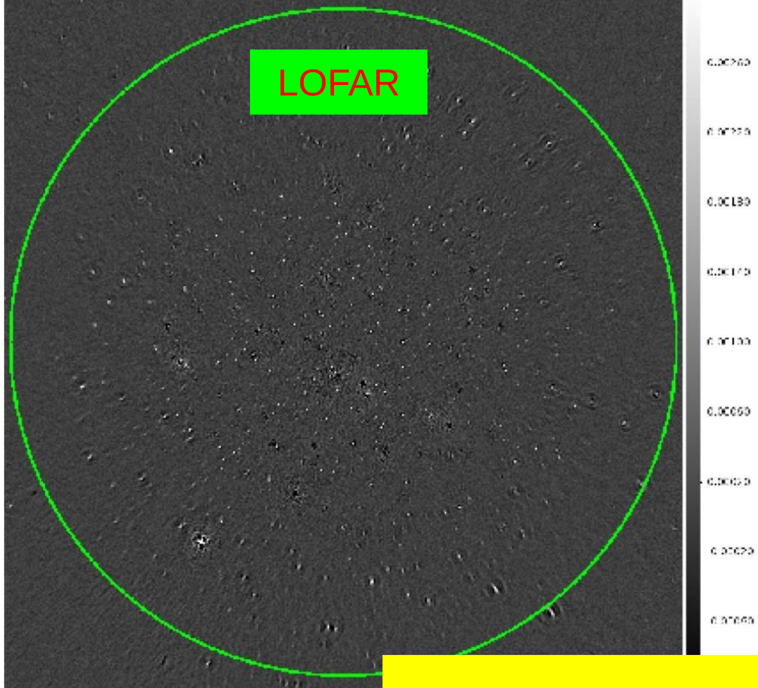
NCP field observed with 21CMA

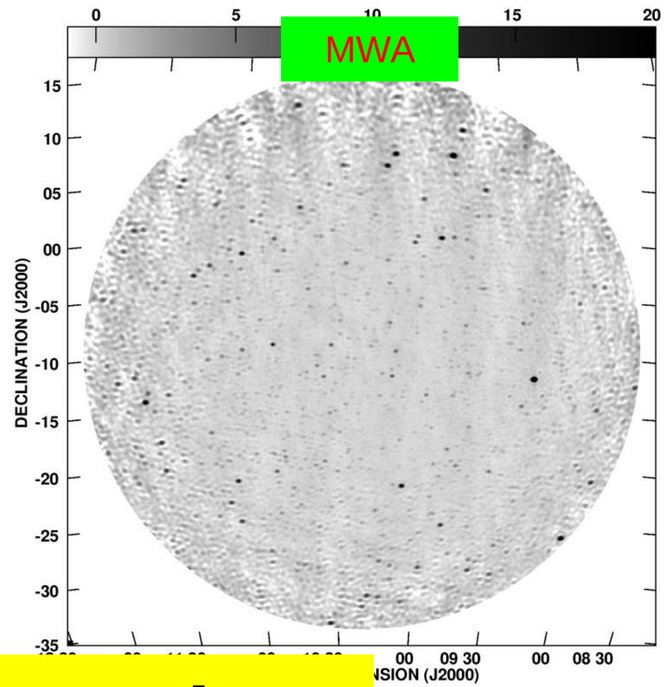
image | **residual**



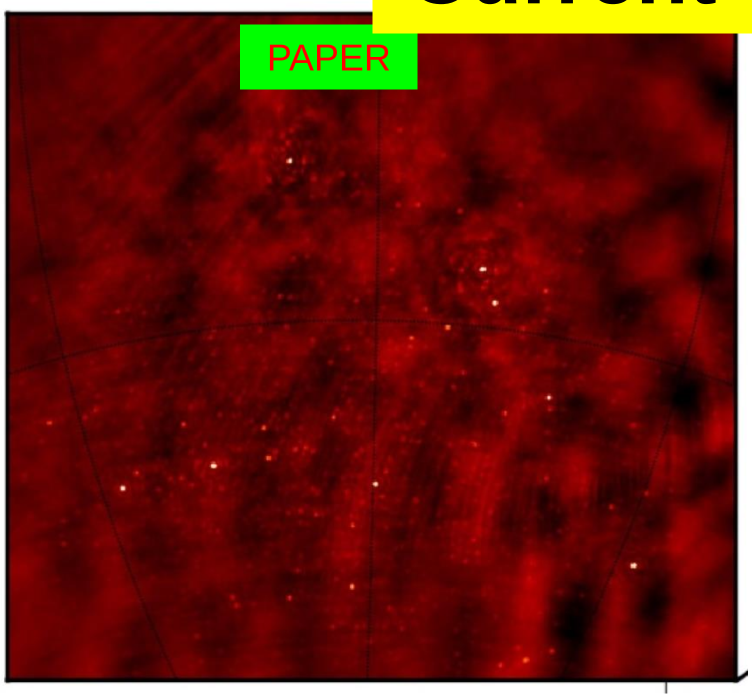
3C61.1

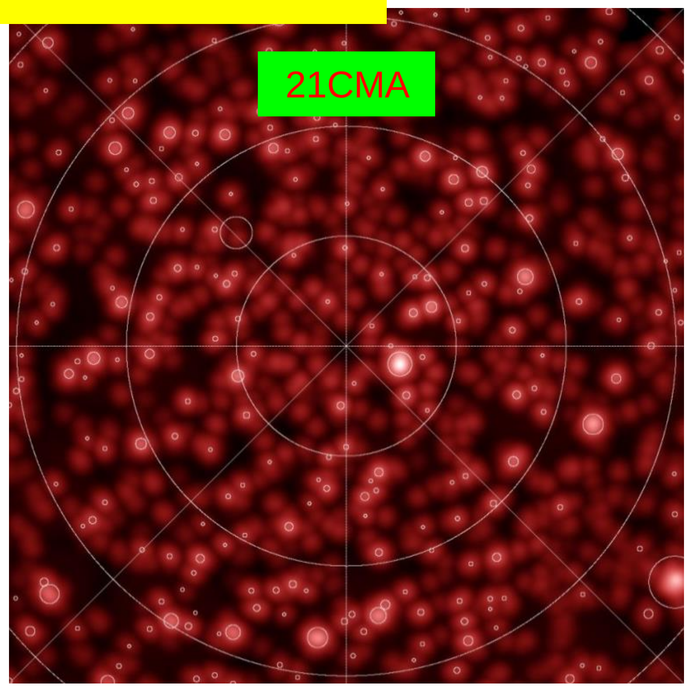
residual = image / 10^5

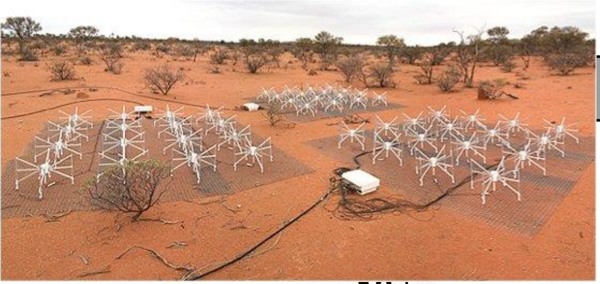


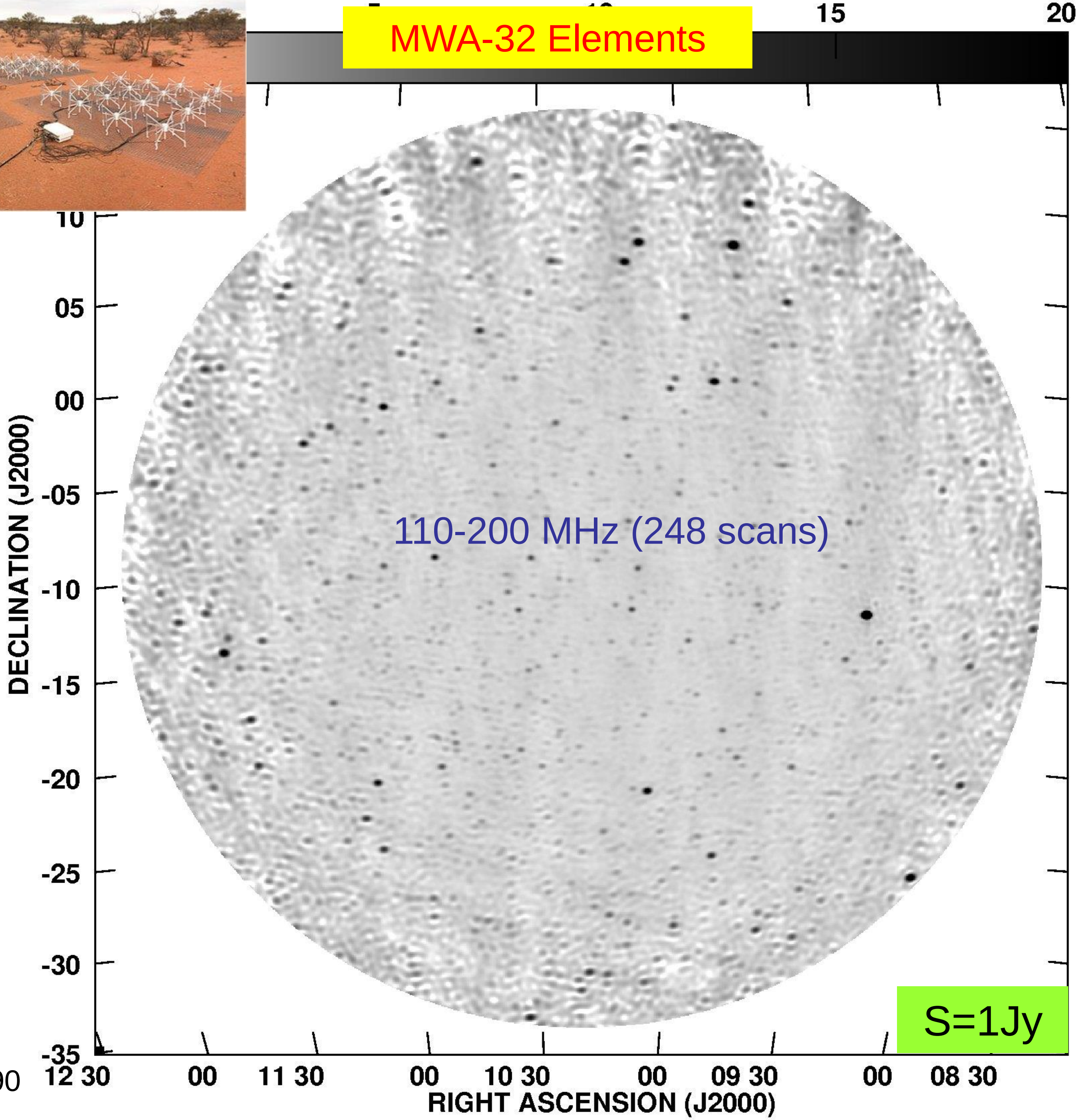


Current Constraints



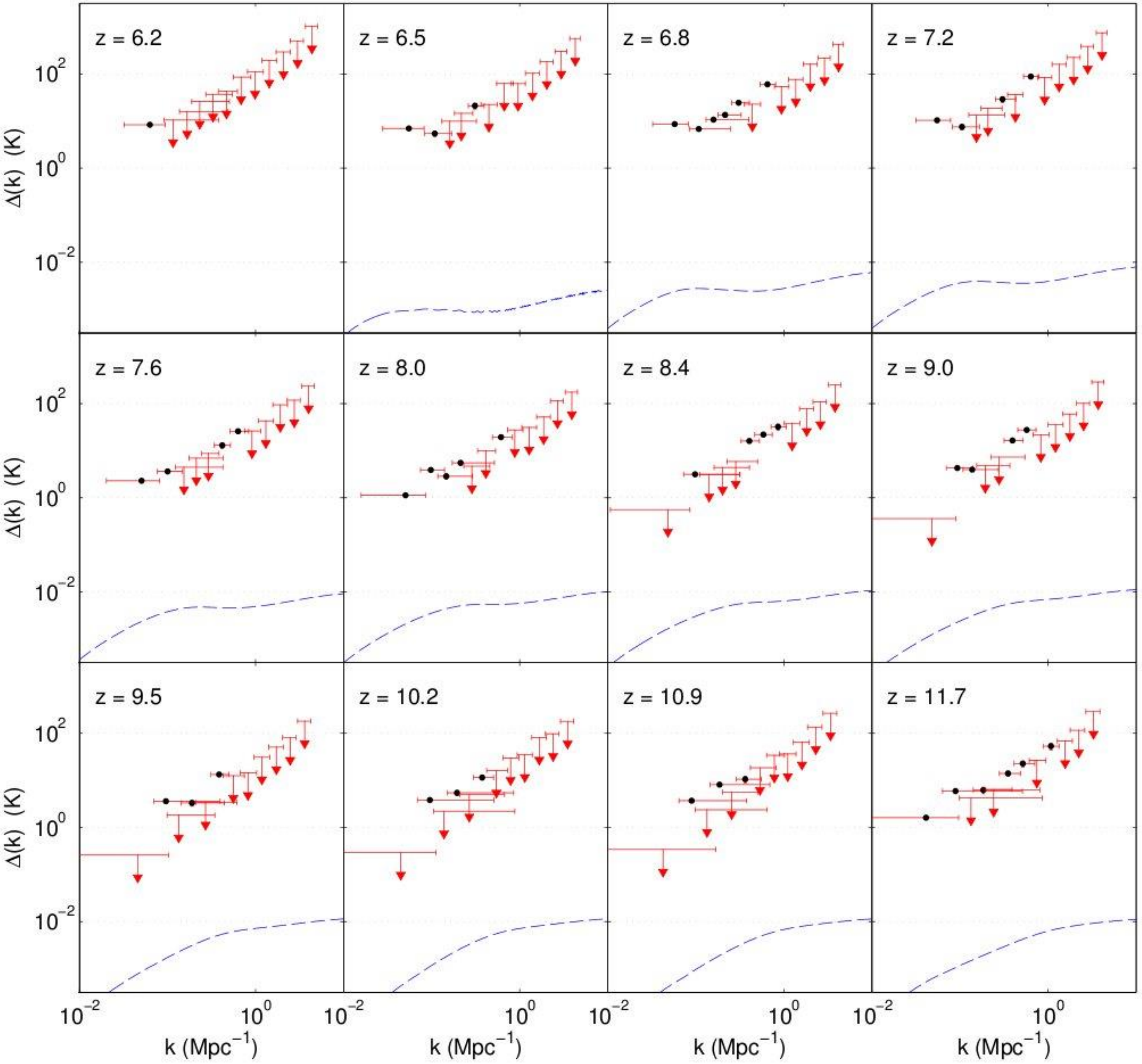




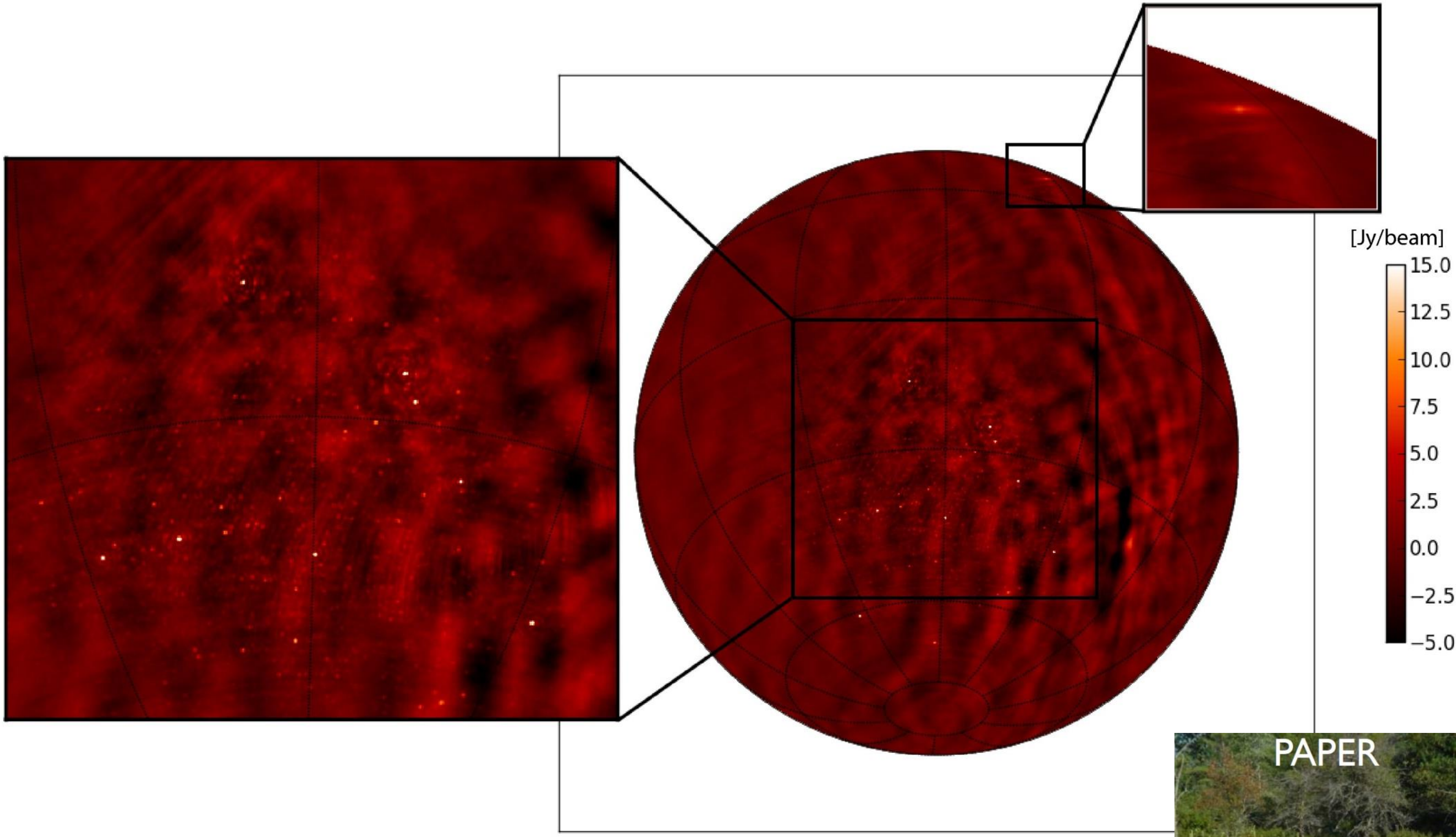


arXiv:1203.5790

Power Spectrum (MWA: March 2010)
ArXiv:1304.4229



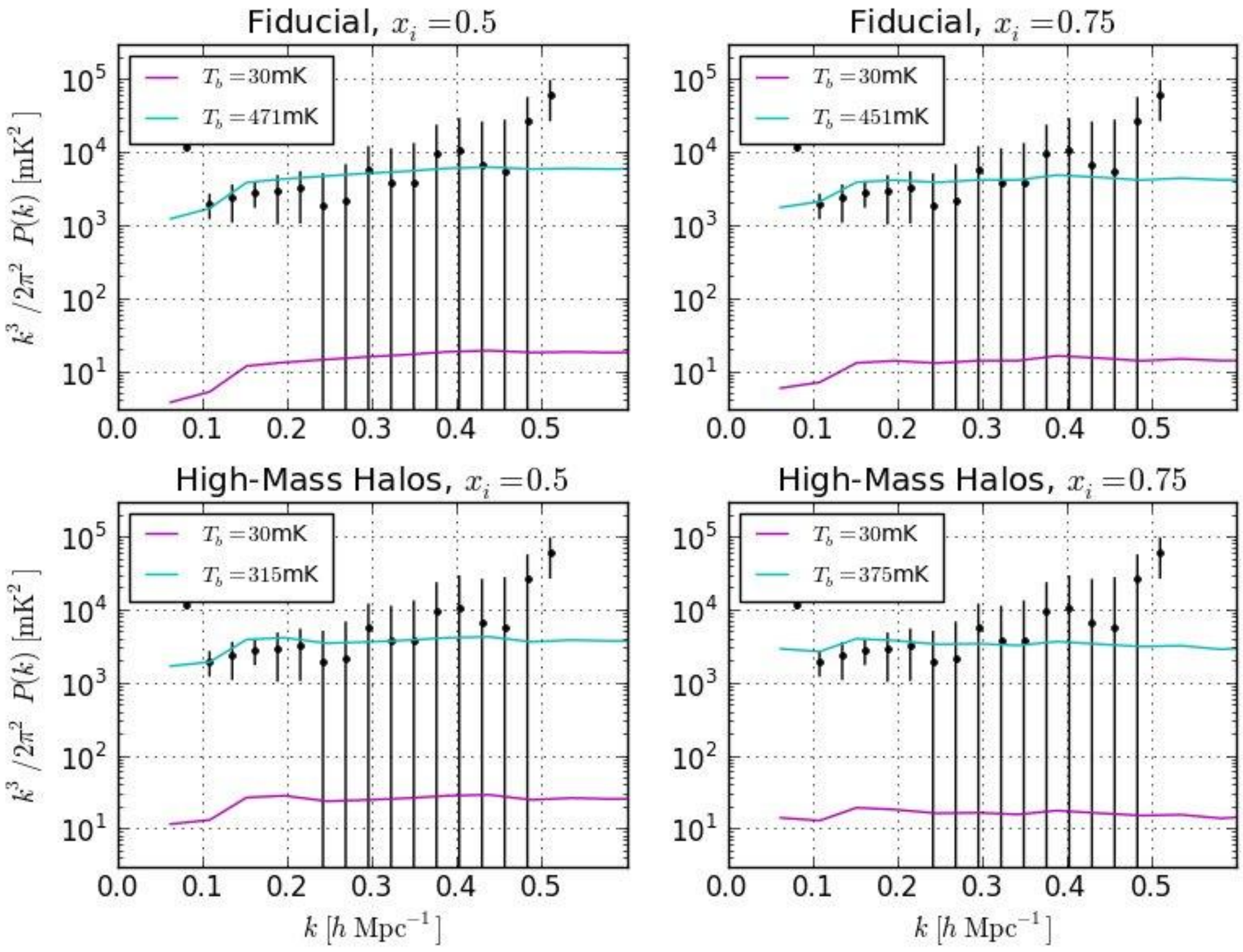
PAPER-64 Elements

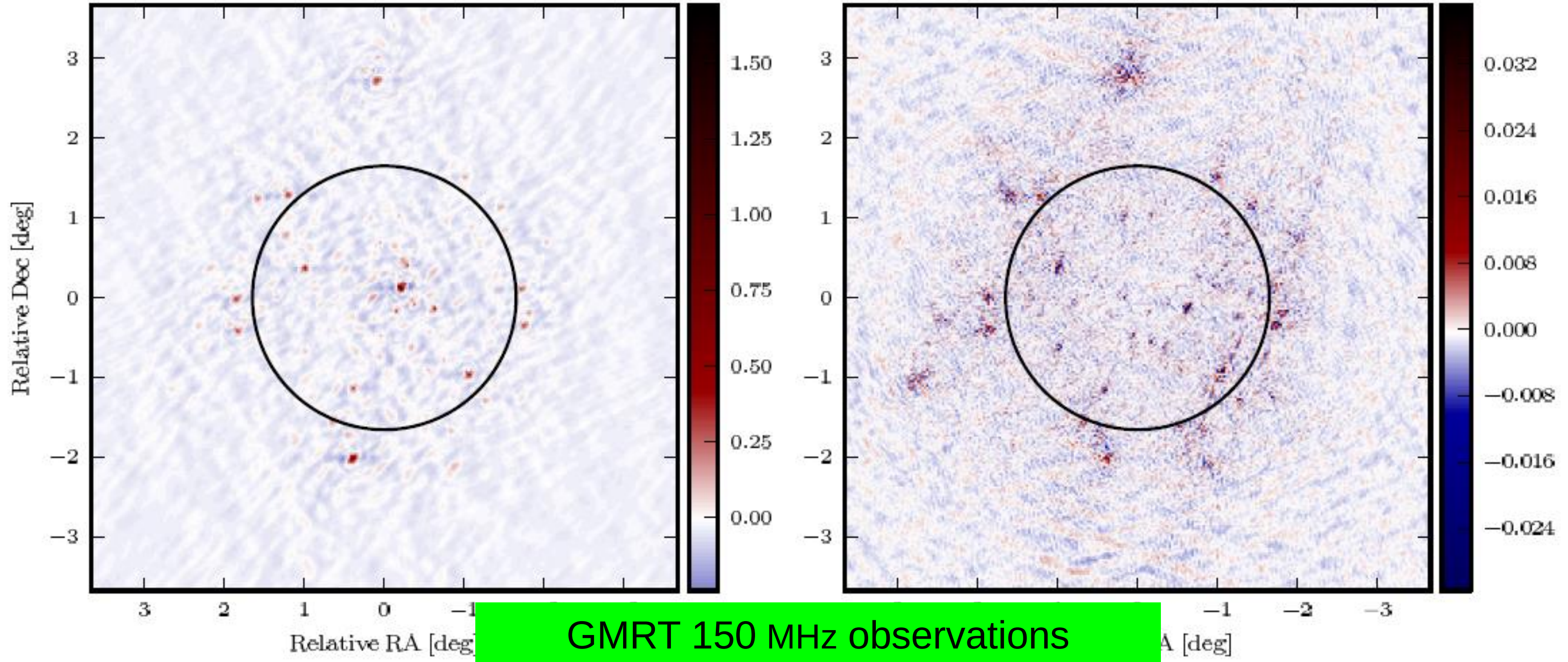


S=1Jy

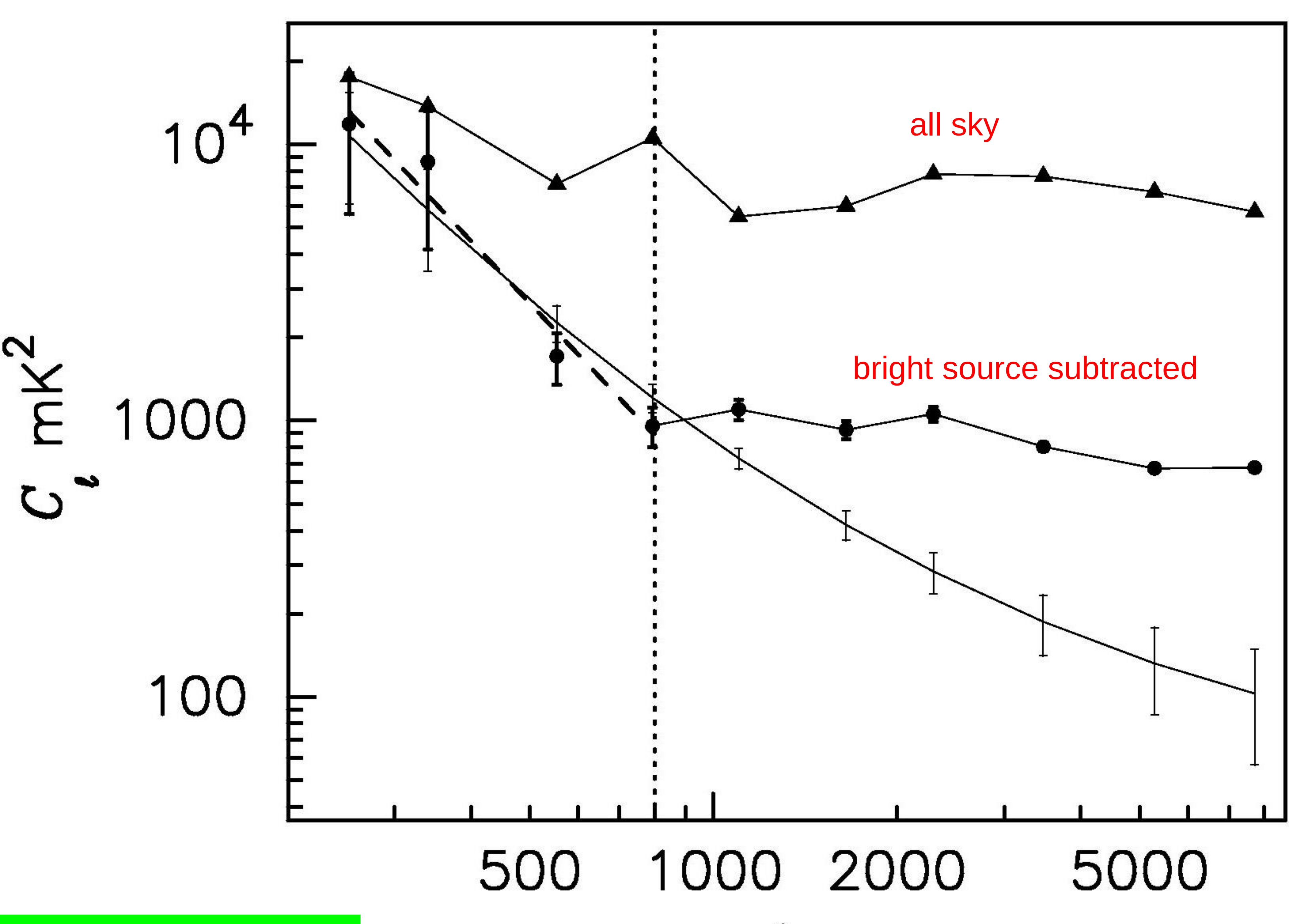
arXiv:1301.7099

90 days of observations with PAPER-32





GMRT 150 MHz observations
Ghosh et al. (2012)



Ghosh et al. (2012)

Measurements of the EOR

1. Global Signatures (total power)

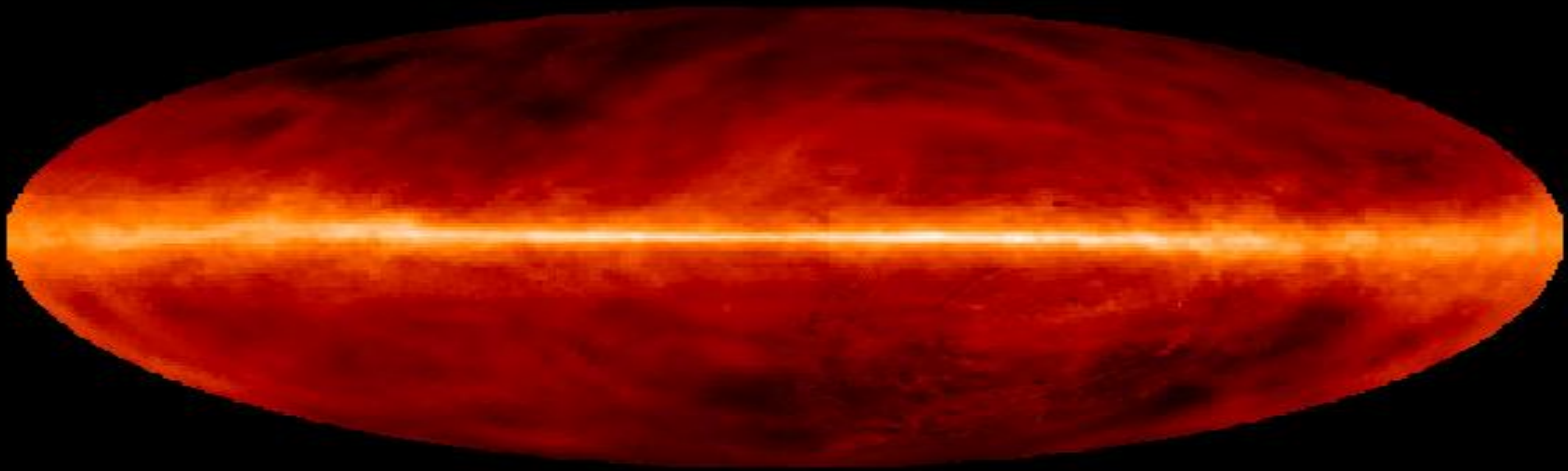
2. Imaging (structures)

3. Fluctuations (power spectrum)

The First Detection ?

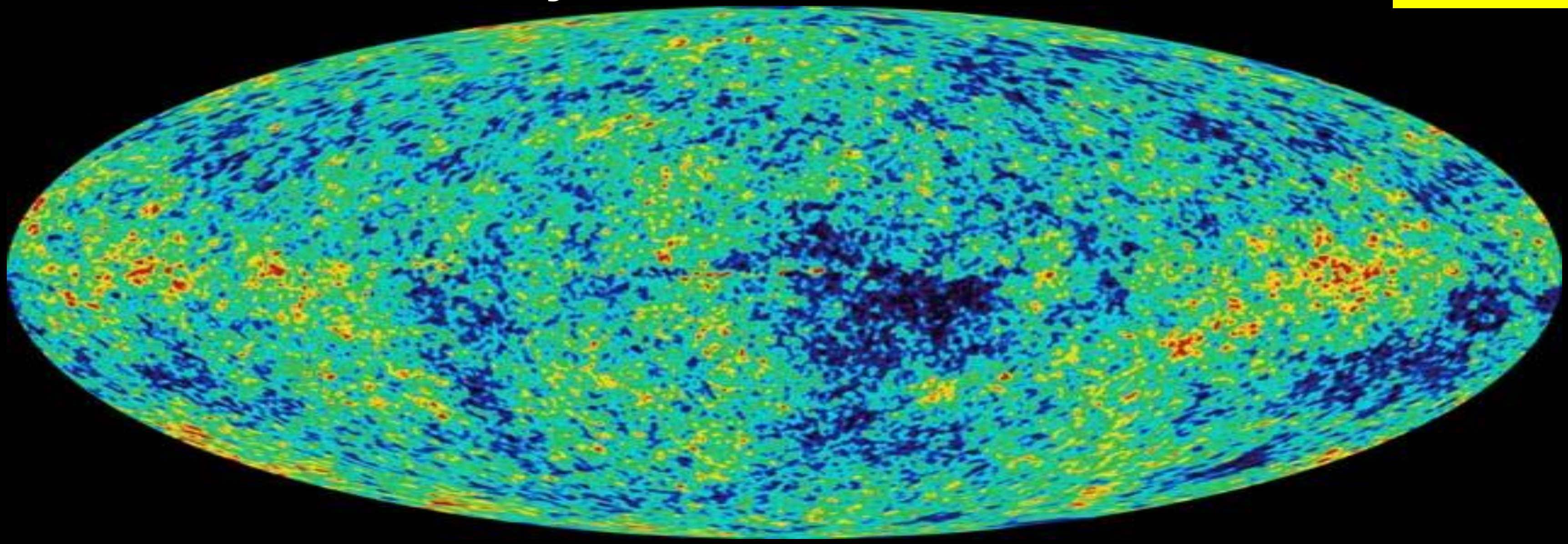
A Sky Map of Hydrogen

Credit: J. Dickey (UMn), F. Lockman (NRAO)



A Sky of EoR Fluctuatons ?

$\left\langle \Delta T \right\rangle = 10^5$




21CMA Site
Thanks