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The Dark Ages, Cosmic Dawn, and Epoch of Reionization

Towards the Square Kilometre Array

Léon V.E. Koopmans
(Kapteyn Astronomical Institute)

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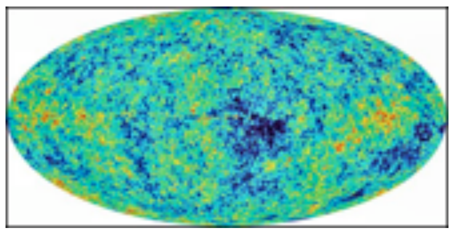
Outline

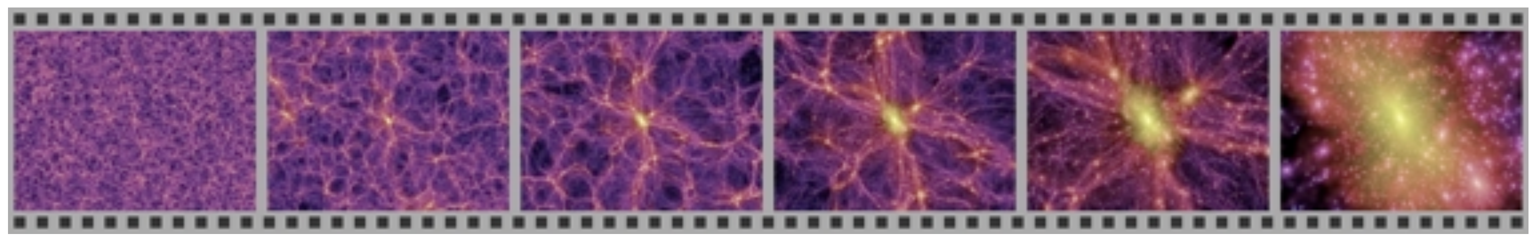
- Why study the first 10^9 years of the Universe?
- Current (non-HI) constraints on the Epoch of Reionization
- HI emission through Cosmic Time
- Current interferometric HI-detection experiments
- Beyond current pathfinders: SKA-low

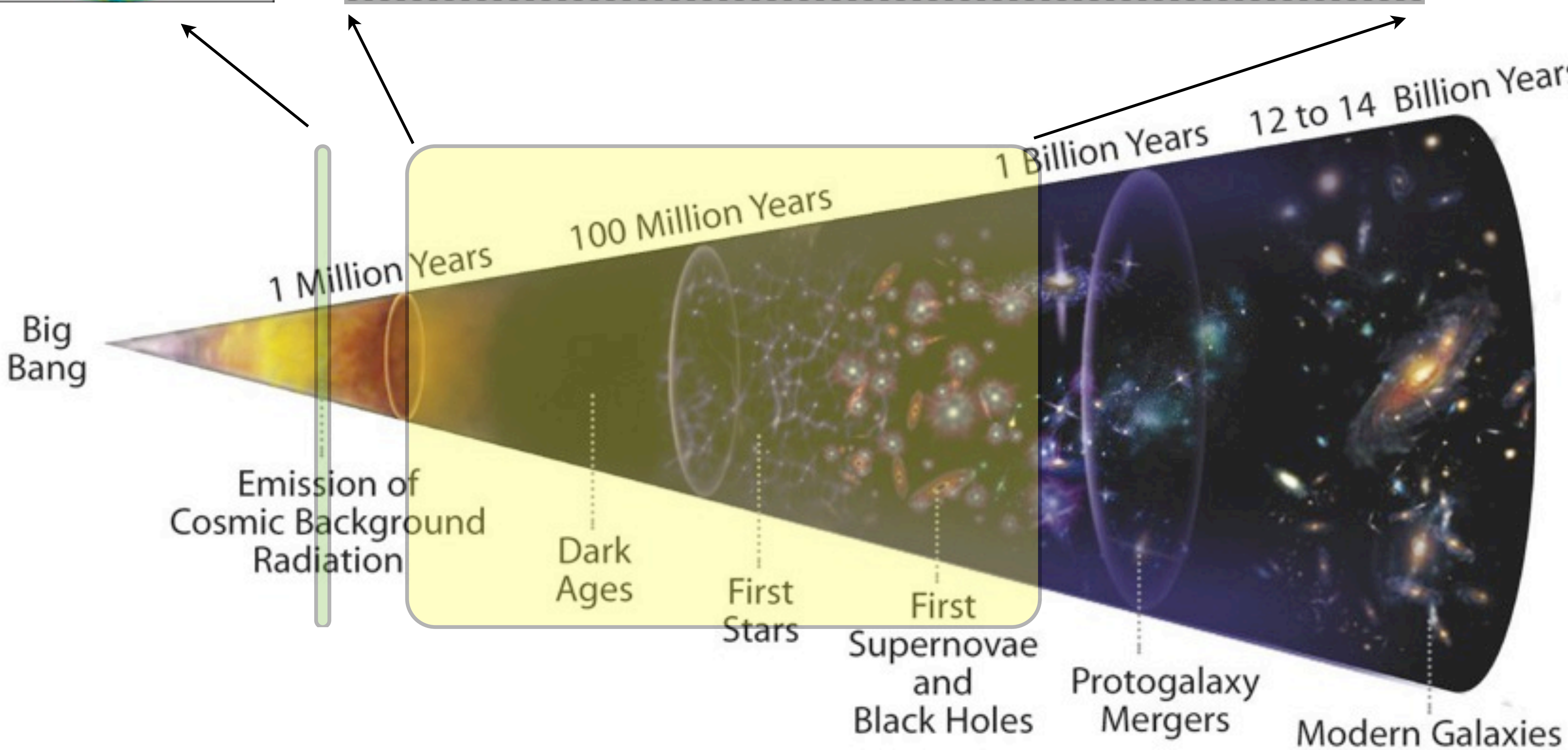
Dark Ages, Cosmic Dawn & EoR

CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving "movie" of baryonic (and DM!) structure formation at $t_{univ}<10^9$ years.



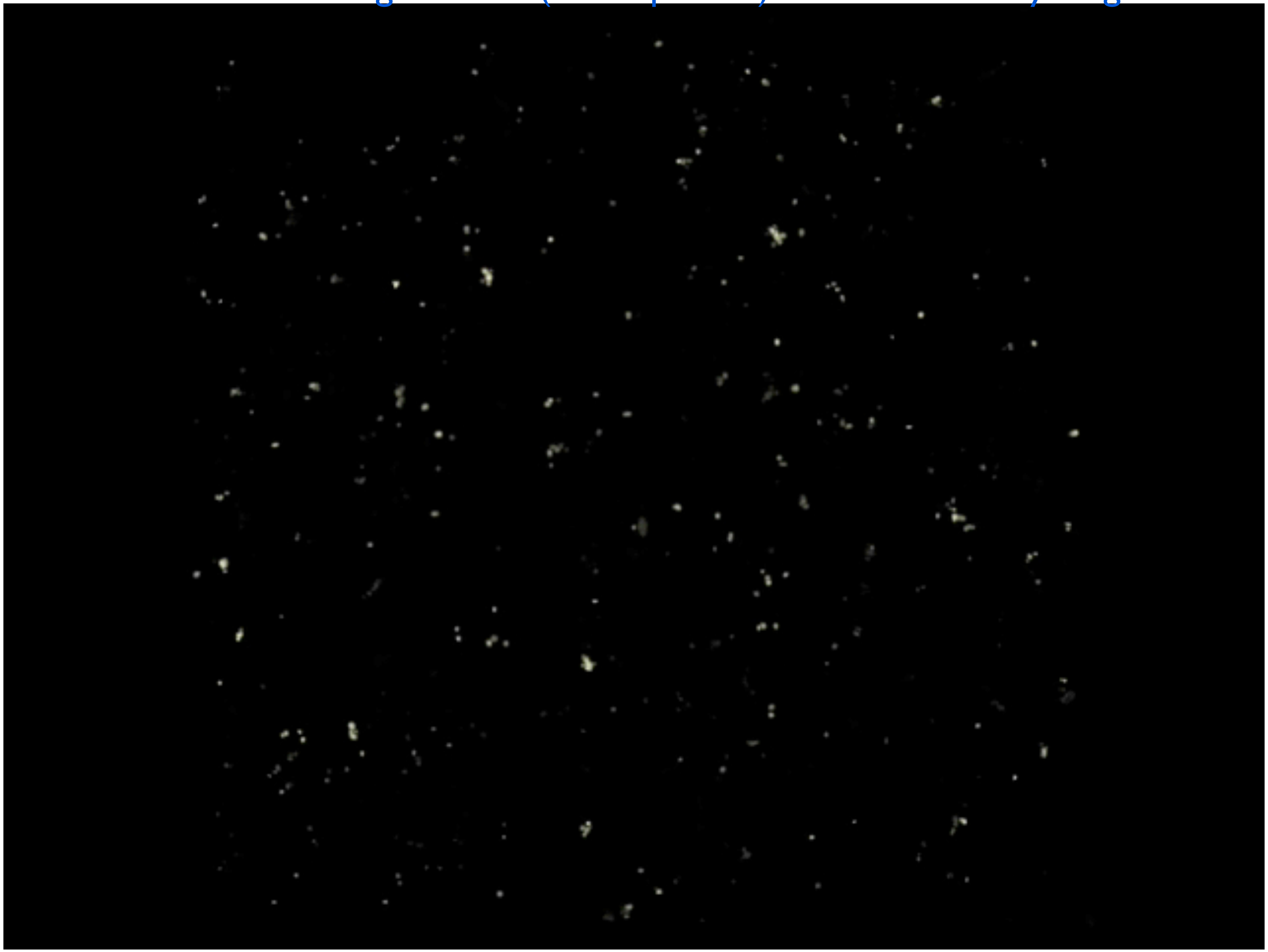




Dark Ages, Cosmic Dawn & EoR

The first radiating sources (stars/quasars) ionize neutral hydrogen

Alvarez et al. 2009



Visualization of the progress of reionization in a 1 Gpc/h volume. Ionized regions are blue and translucent, ionization fronts are red and white, and neutral regions are dark and opaque. A random sampling of 5 per cent (about 40,000) of all the halos at z = 0 are shown in yellow. Reionization is still quite inhomogeneous on these large scales, with large regions ionizing long before others.

Why and How Study the Universe's First Gyr?

Space/Moon based Interferometers

~2030

Dark Ages

DM power-spectrum evolution
DM annihilation physics
Baryonic Bulk Flows
Physics of Gravity/GR

SKA/ELT/ JWST

~2020

Cosmic Dawn

Appearance of first stars (PopIII?)
Ly-α radiation field
Impact of Baryonic Bulk Flows
First X-ray heating sources

Present day Telescopes

2013

Reionization

Reionization by stars & mini-quasars
IGM feedback (e.g. metals)
PopIII - PopII transition
Emergence of the visible universe

Short Summary of Current Constraints on the Epoch of Reionization

- Scattering optical depths from CMB observations

  Ionized medium causes CMB polarization: $z_{eor} \sim 10$

- High-z galaxies

  IR drop-outs give SFR/LF to z~10: SFR rises fast below z~10 but there are not enough UV photons to re-ionize the Universe >>> Puzzle!

- High-z QSOs

  Gunn-Peterson troughs suggest ~10% neutral HI at z~7, i.e. the end of reionization occurs close to the highest z QSO/galaxies that we observe

- High-z GRBs

  GRBs traces massive star formation. Currently rare events, but z~8.2 GRB has been seen and could be a direct tracer of the SFR.

- Temperature of the IGM

  Extrapolation of the high-z IGM temperature suggest late reionization

Most evidence points at substantial reionization (still) occurring at z<10, but its source(s) are unknown: complementary tracers are needed (i.e. HI)

What can we expect from HI brightness temperature observations?

HI emission through Cosmic Time

Hydrogen Brightness Temperature

The quantity that is measured with radio telescopes along a given line of sight and is given by:

$$
\begin{aligned}
\boxed{\delta T_b} &= \frac{T_S - T_R}{1+z}\left(1 - \mathrm{e}^{-\tau_\nu}\right) \\
&\approx \frac{T_S - T_R}{1+z}\tau \\
&\approx 27 x_{\rm HI}\,(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\,\frac{1+z}{10}\right)^{1/2} \\
&\quad \times \left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]\,\mathrm{mK},
\end{aligned}
$$

Cosmology

Ionization

(G)astrophysics

Peculiar velocities/Bulk-flows

The HI 21-cm intensity is set by a complex interplay between cosmology and (g)astrophysics.

Main Phases of HI

- "Dark Ages"

  z = 30 - 200: Most likely only accessible from space/moon and/or via total power measurements using single receivers.

- "Cosmic Dawn"

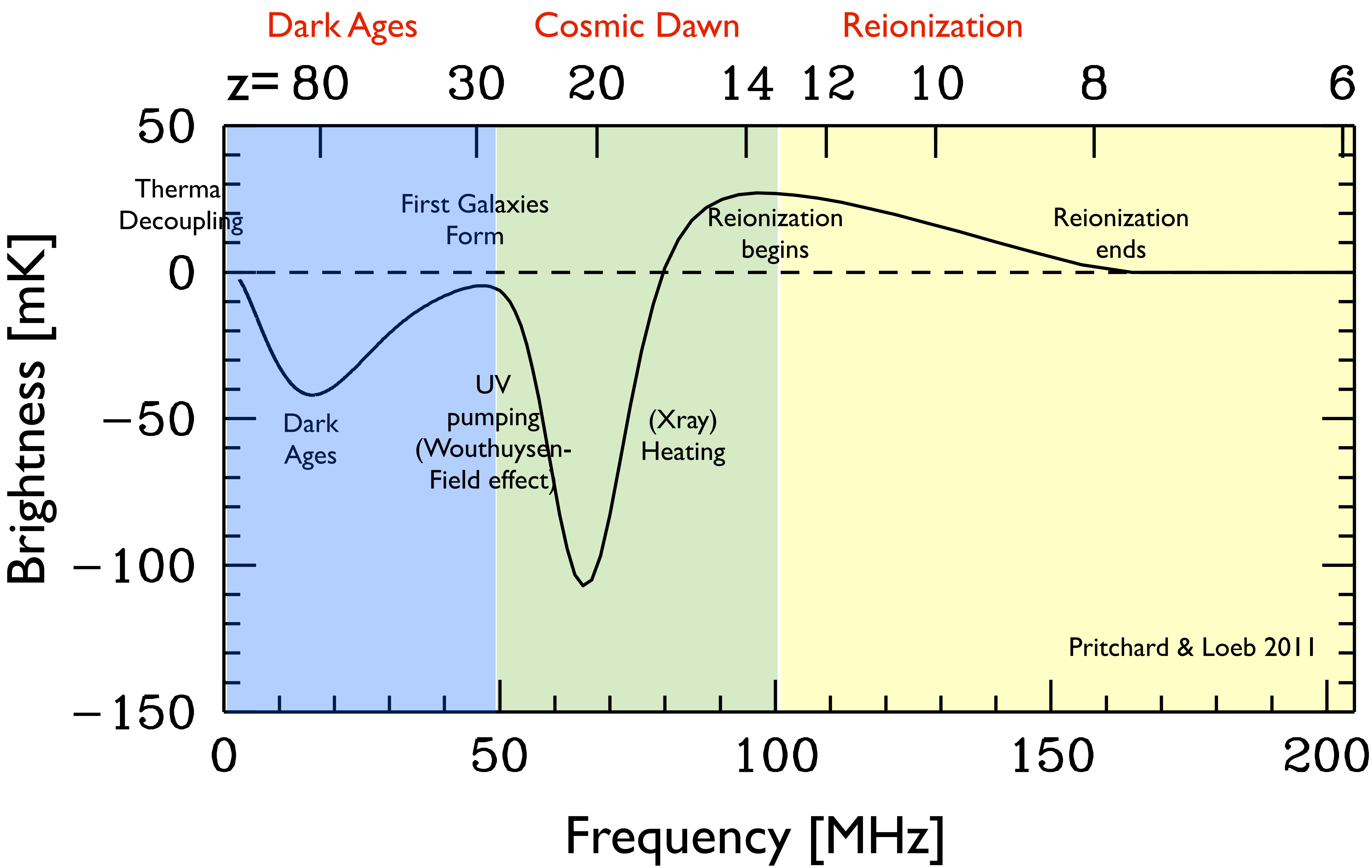
  z ~ 30 - 15: Formation of the first stars/galaxies that heat/couple the IGM mostly; impact on gas/spin-temp. T_b fluctuations will be a mixture of density and spin-T fluctuations. Maybe there is impact by bulk-flows from recombination in this redshift range.

- "Reionization"

  z ~15 - 6: Ionizing bubbles grow around first stars/galaxies and percolate. T_b is set by density fluctuations and ionized bubbles mostly.

Hydrogen Brightness Temperature

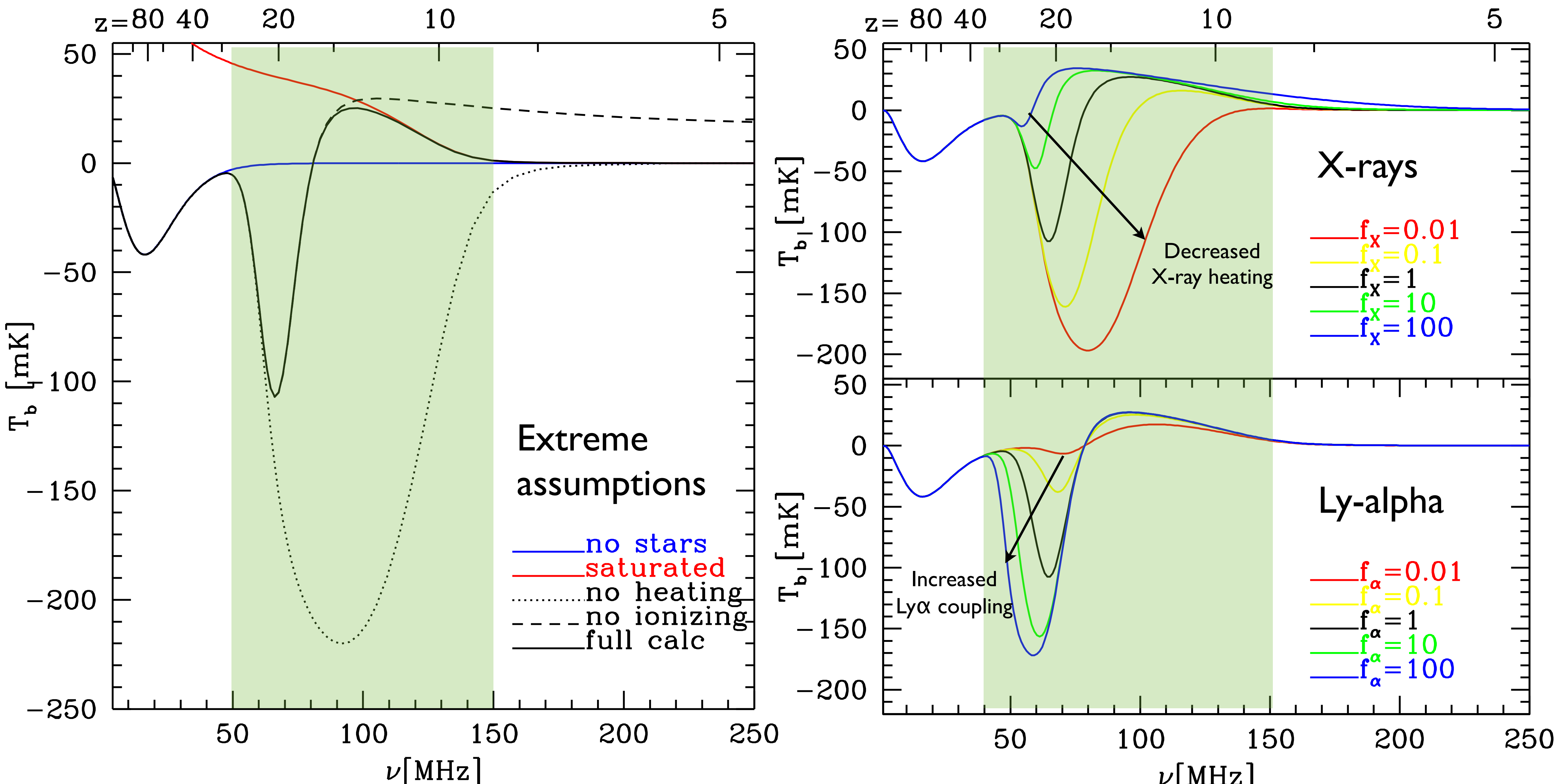
Global Signal



Hydrogen Brightness Temperature

Global Signal

The history of T_b can vary; hence measuring T_b as function of redshift/time, provides a handle on SF, Ly-α coupling (WF), (X-ray) heating, etc.



Pritchard & Loeb 2011

Hydrogen Brightness Temperature

Power-Spectrum

The HI brightness temperature shows fluctuations on a range of different scales, sourced by cosmology, spin-temperature, ionization & velocities

$$\delta_{T_b} = \beta_b \delta_b + \beta_x \delta_x + \beta_\alpha \delta_\alpha + \beta_T \delta_T - \delta_{\partial v}$$

Cosmology | Reionization | Lyα Sources | X-ray heating | Peculiar Velocities

HI-density-Fluctuations | Spin-temperate-Fluctuations | Doppler-Fluctuations

Power-spectrum

$$P_{T_b}(k,\mu) = P_{\mu^0}(k) + \mu^2 P_{\mu^2}(k) + \mu^4 P_{\mu^4}(k) + P_{f(k,\mu)}(k,\mu)$$

Isotropic Term | Terms due to peculiar velocities | Quartic Terms

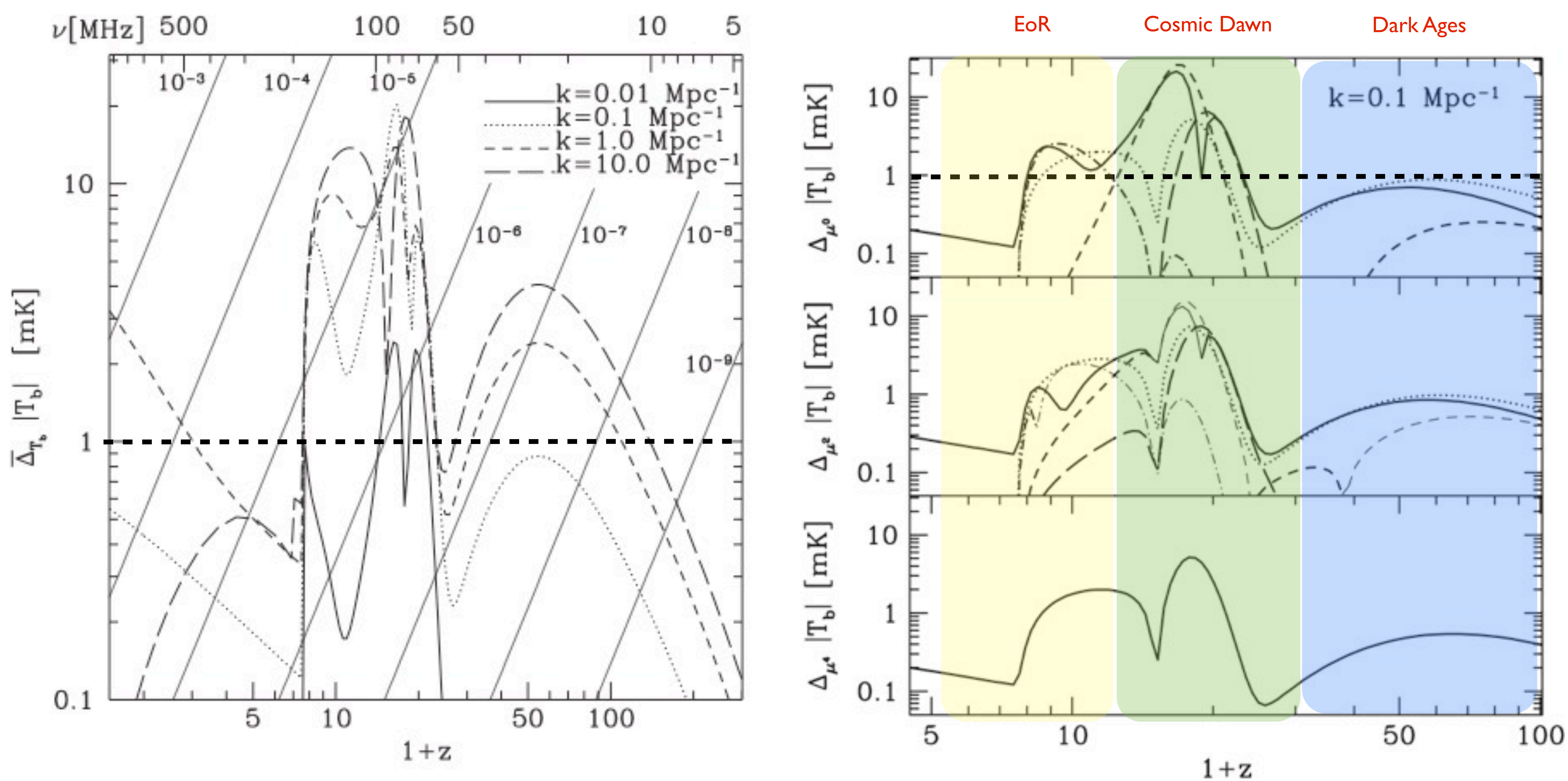
Auto- and cross-terms between b, x, α and T | ∂v∂v and cross-terms between b, x, α and T and ∂v

Hydrogen Brightness Temperature

Power-Spectrum

Intensity Fluctuations

Intensity Fluctuations

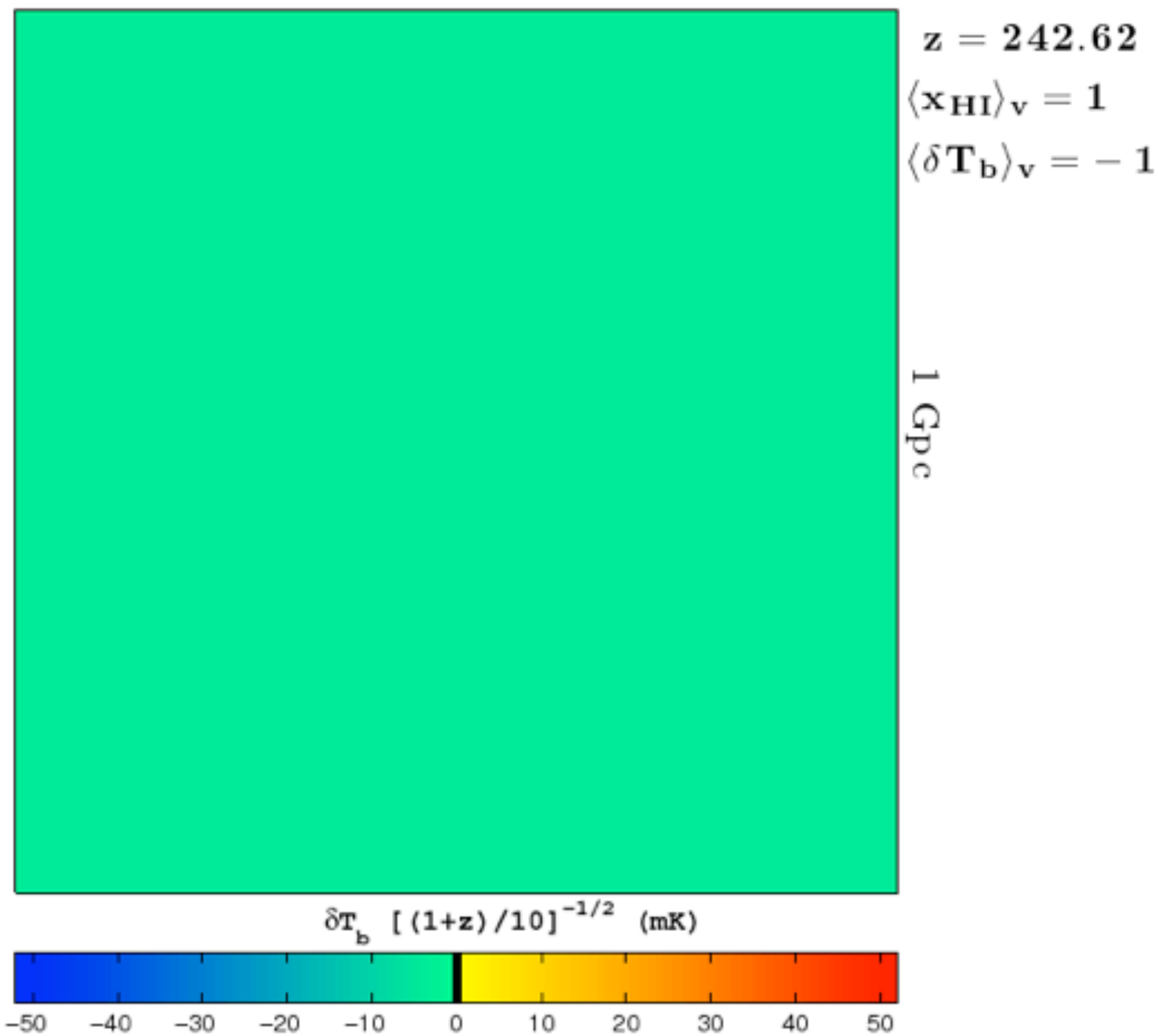


Pritchard & Loeb 2009; see also Santos et al. 2008, 2010, 2011

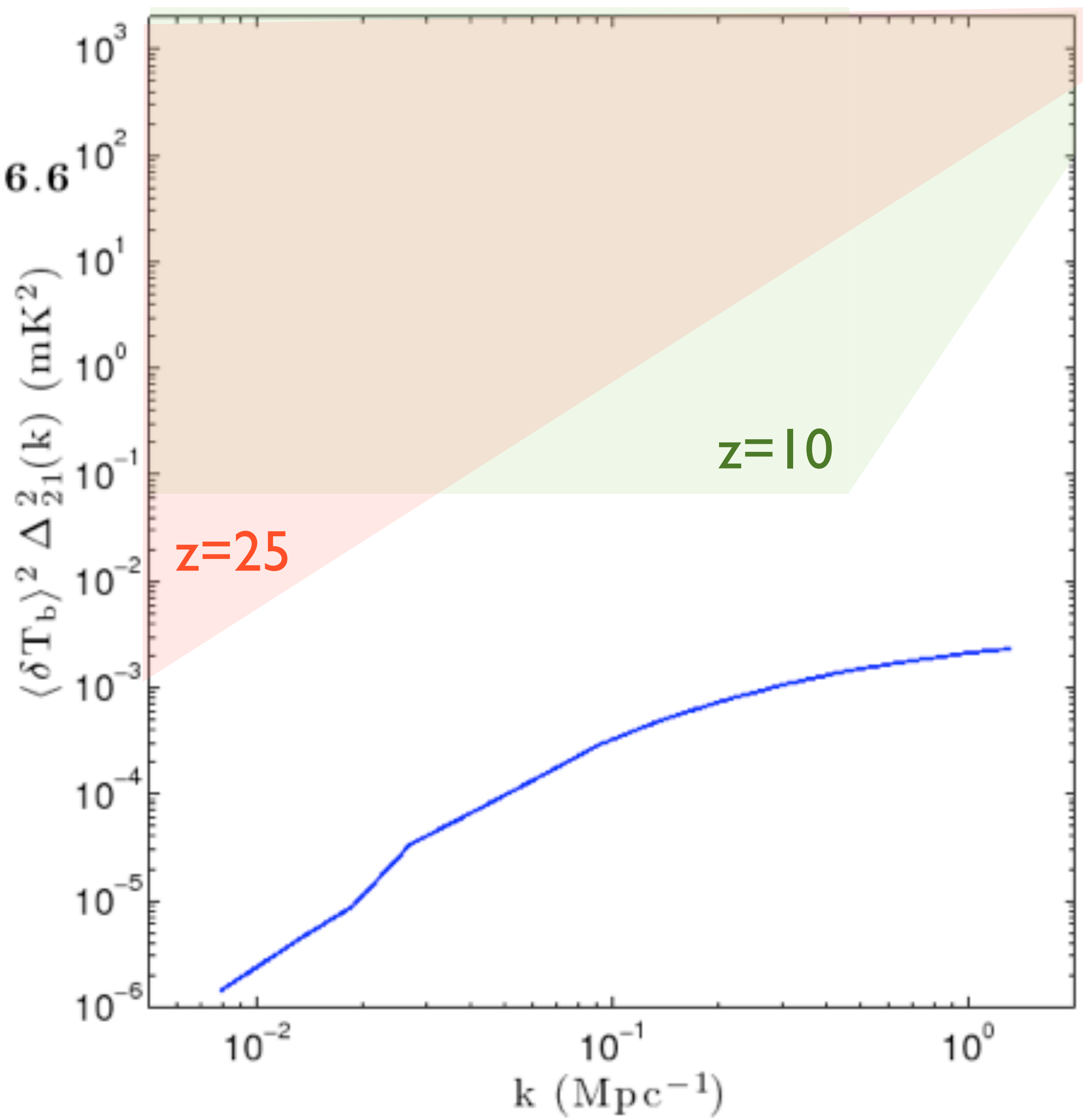
Hydrogen Brightness Temperature

Power-spectrum

Credit: Mesinger



Rough detection box for SKA

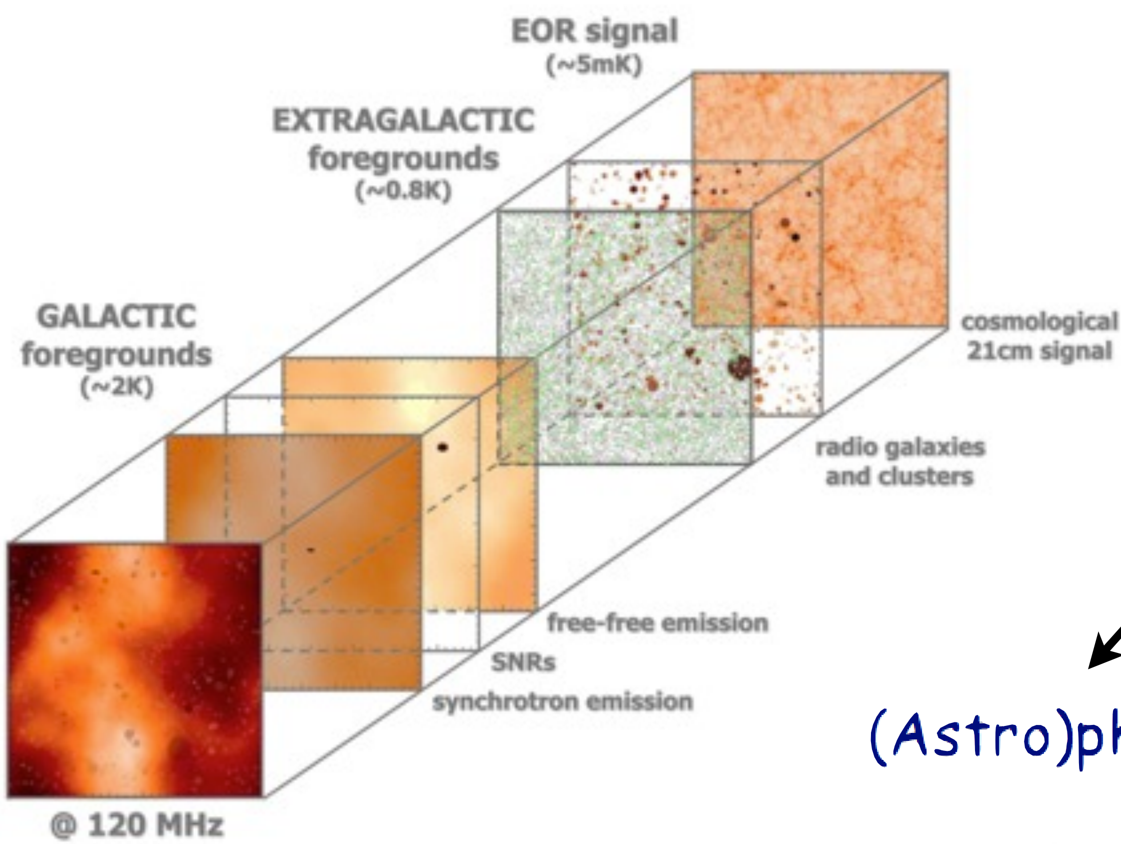


Sensitivity limits are scale dependent but Δ^2_{noise}~few mK^2 is where current instruments aim for in ~1000 hrs. SKA can go to Δ^2_{noise}~0.1 mK^2

Current HI-signal Fluctuation Detection Experiments

- Giant Meter-wave Radio Telescope [GMRT] [India]
- Murchison Widefield Array [MWA] [Australia]
- Precision Array for Probing the Epoch of Reionization (PAPER) [SA]
- Low Frequency Array [LOFAR] [NL/Europe]

Measuring the brightness temperature fluctuations of HI



Many Challenges

(Astro)physical

Extragalactic foregrounds
Galactic foregrounds
Ionosphere
Interference
Polarized emission
Variability

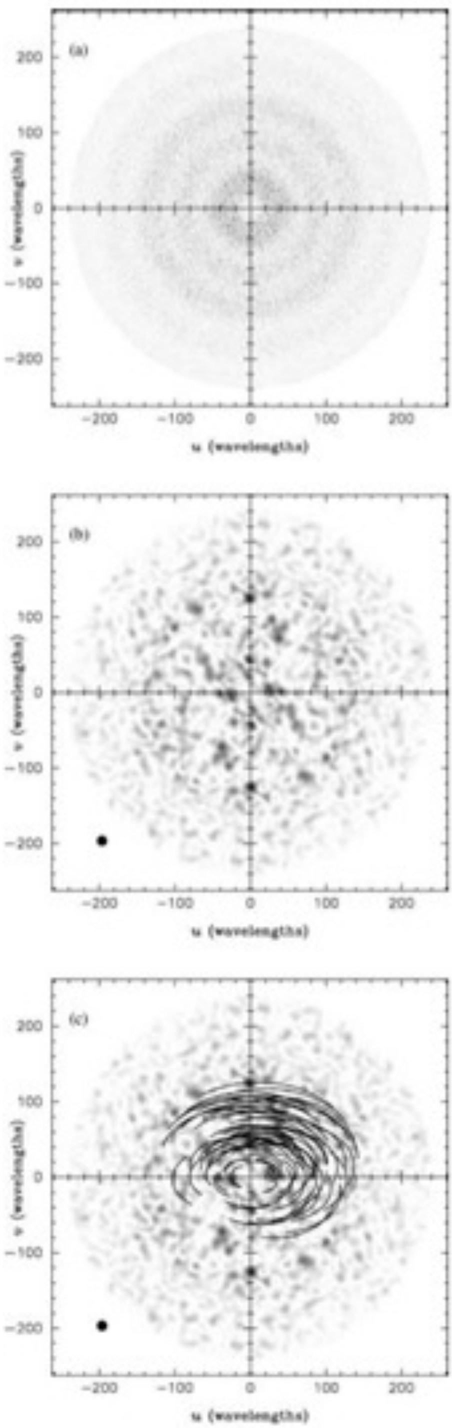
Instrumental

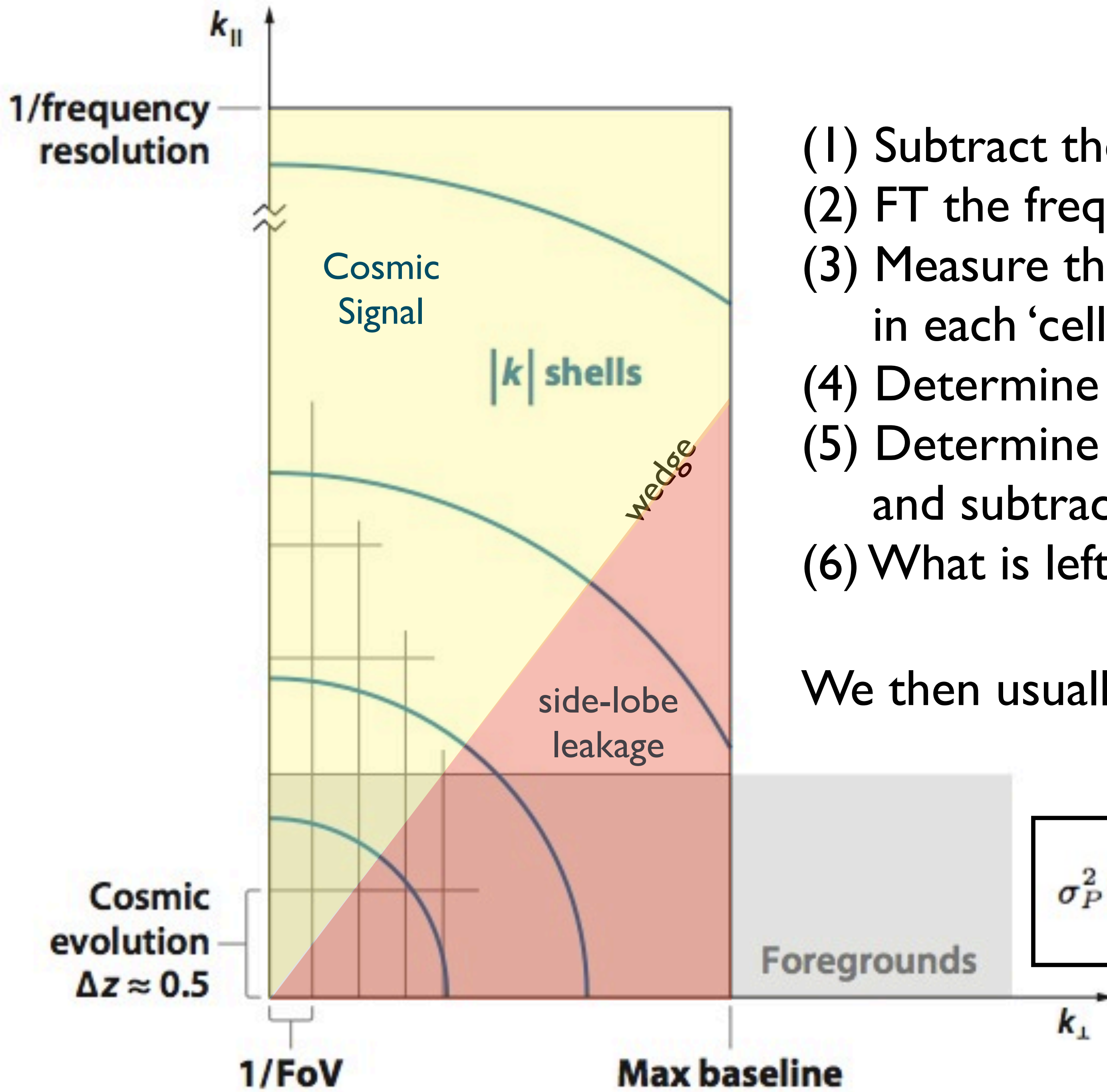
Beam stability
Sensitivity
Dynamic Range
UV Coverage
Calibratability
...

Computational

Large data rate
~1 Pb raw data
(Non)-linear optim. of coupled equations
10s Tflop*year
...

Measuring the brightness temperature fluctuations of HI





(1) Subtract the FGs [MW+extra-Gal.]
(2) FT the freq. axis of the data-cube
(3) Measure the visibility amplitudes A in each 'cell' as function of k.
(4) Determine average of A^2 => P(k)
(5) Determine the noise power-sp. $P_n(k)$ and subtract.
(6) What is left is $P_{21}(k)$ + error (below)

We then usually display $\Delta^2(k)=(k^3/2\pi^2)P(k)$

$$\sigma_P^2(\mathbf{k}) = \left(P_{21}(\mathbf{k}) + \frac{T_{\rm sys}^2 D^2 \Delta D \lambda^2}{B\tau A_e}\right)^2$$

Sample Variance per cell + Noise Variance per cell

Current EoR HI Experiments

There are currently four competing EoR arrays
that aim to detect HI T_b fluctuations at z>6.

One can follow different strategies to beat the noise power-spectrum

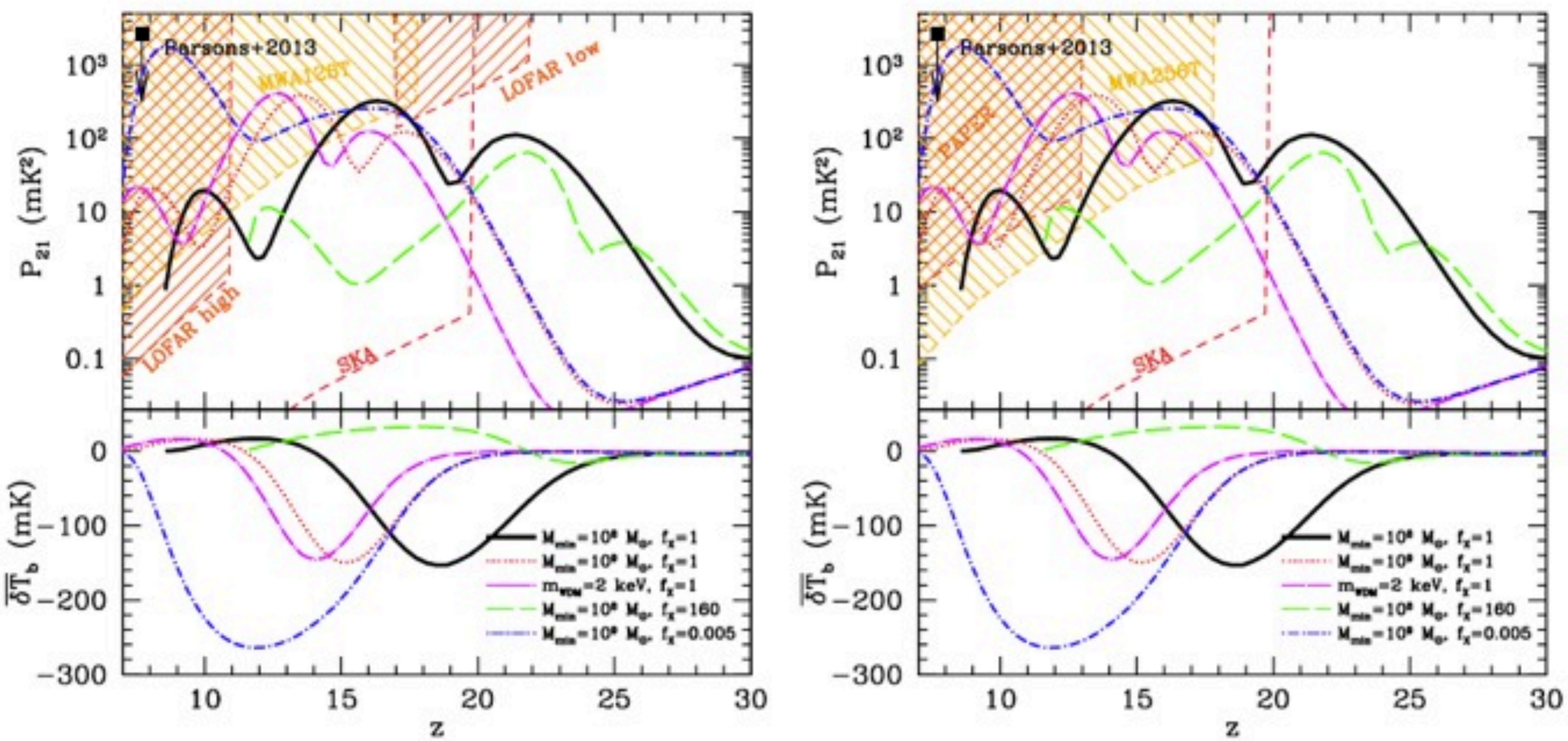
$$\Delta^2_{\rm Noise} \propto \left(\frac{A_{\rm core}\sqrt{A_{\rm eff}}}{A^2_{\rm coll}}\right) \propto \left(\frac{A_{\rm core}}{N^2_{\rm stat}A^{3/2}_{\rm eff}}\right) \propto \boxed{\left(\frac{A_{\rm core}}{\sqrt{N_{\rm stat}}A^{3/2}_{\rm coll}}\right)}.$$

Table 1. High Redshift λ21 cm Experiments

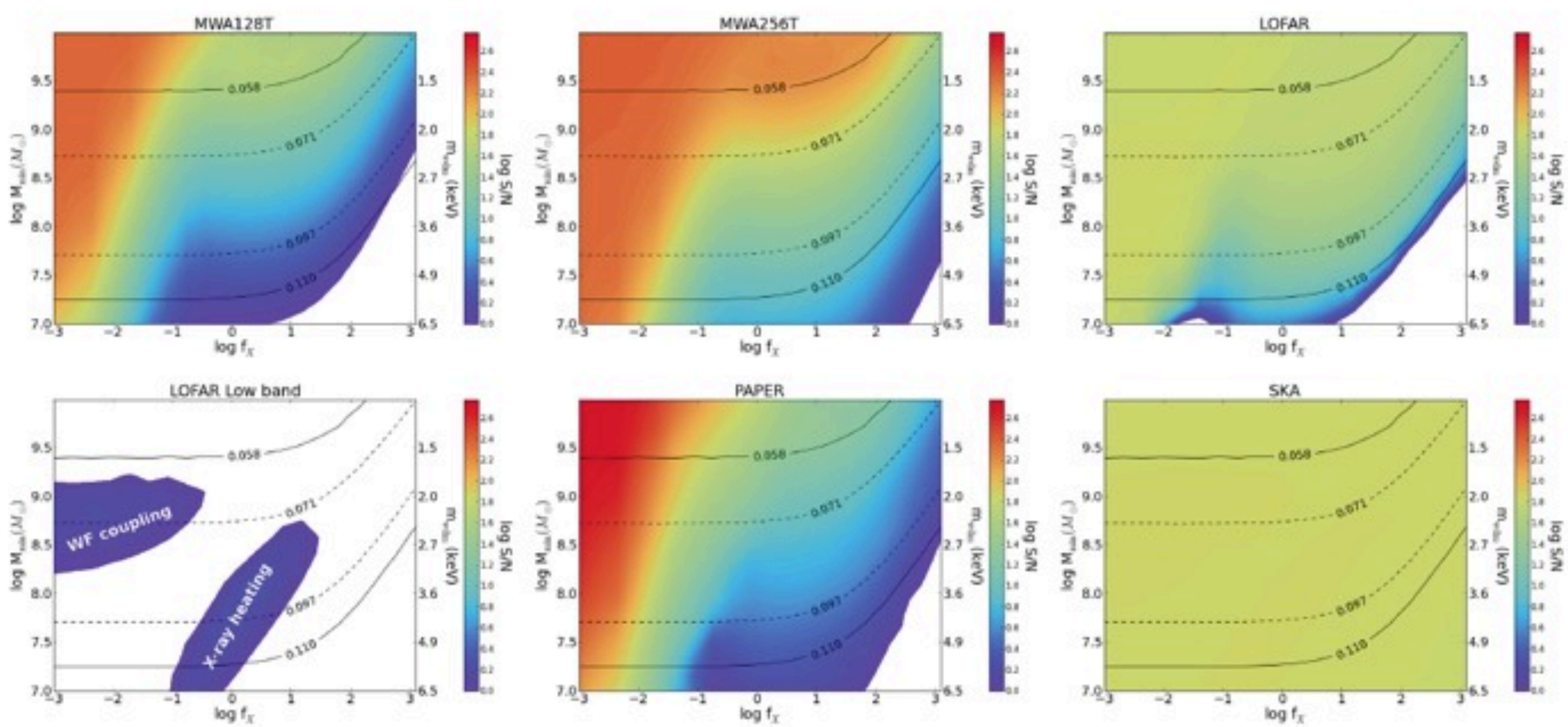
Expt.$^{(1)}$	Loc.$^{(2)}$	Elements Array	Elements Lone	Area$^{(3)}$ (m^2)	Bsln$^{(4)}$ (km)	Band$^{(5)}$ (MHz)	z
PAPER	ZA	128	–	1000	0.2	110-180	6-12
MWA	AU	128×16	–	3000	1	80-200	6-15
LEDA	US	256	4	3000/30	0.3	30-88	17-42
DAWN	US	256	–	3000	0.1	30-88	17-42
GMRT	IN	14	–	8000	1	139-156	8-9
LOFAR	NL	24×768	–	18000	3	120-200	6-10

stations/visibilities — Collecting area — Compactness

Probing parameter space



Current pathfinders can only do statistical detection and probe limited part of model space.



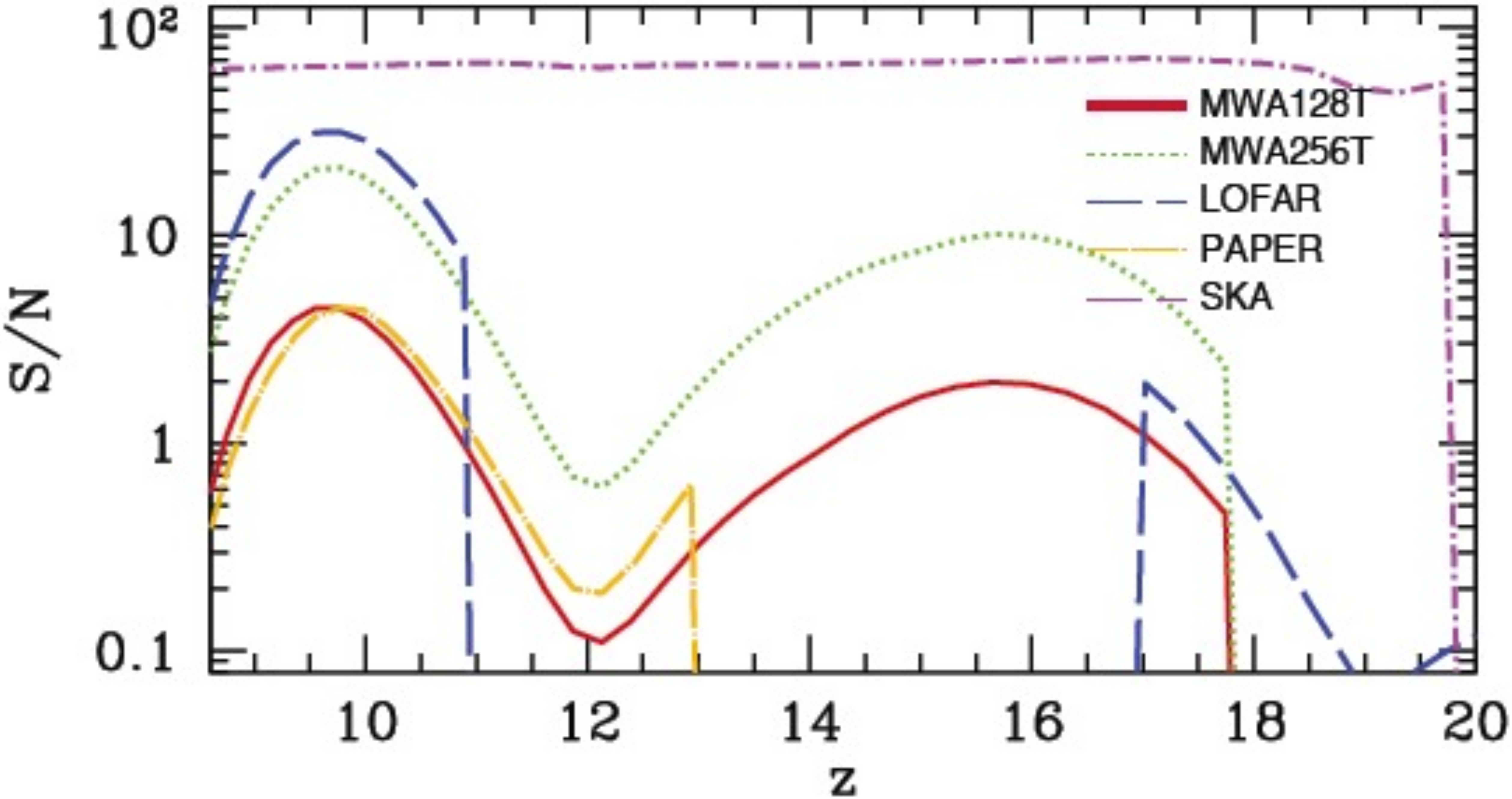
Min. halo mass

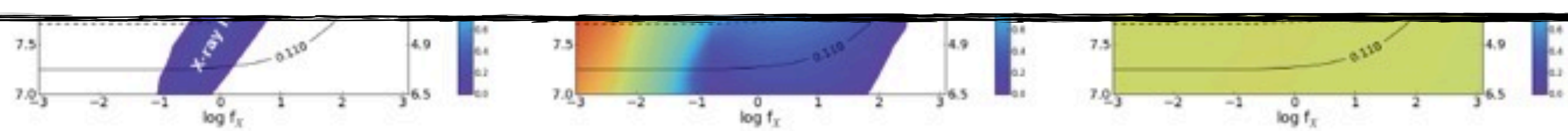
X-ray heating

SKA can probe all reasonable parameter space with high (~100) S/N.

Mesinger et al. 2013

Probing

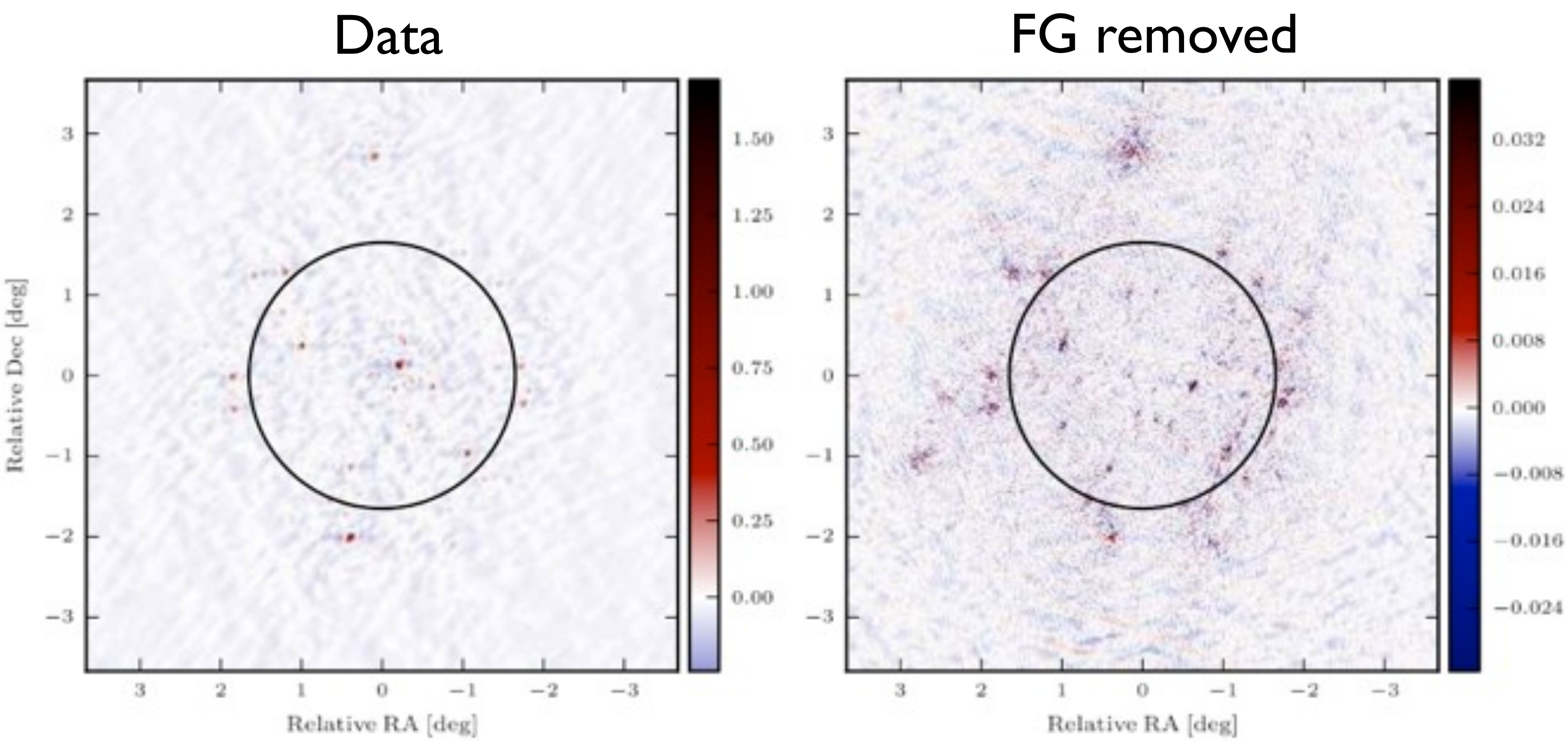




Mesinger et al. 2013

X-ray heating

GRMT Current Results

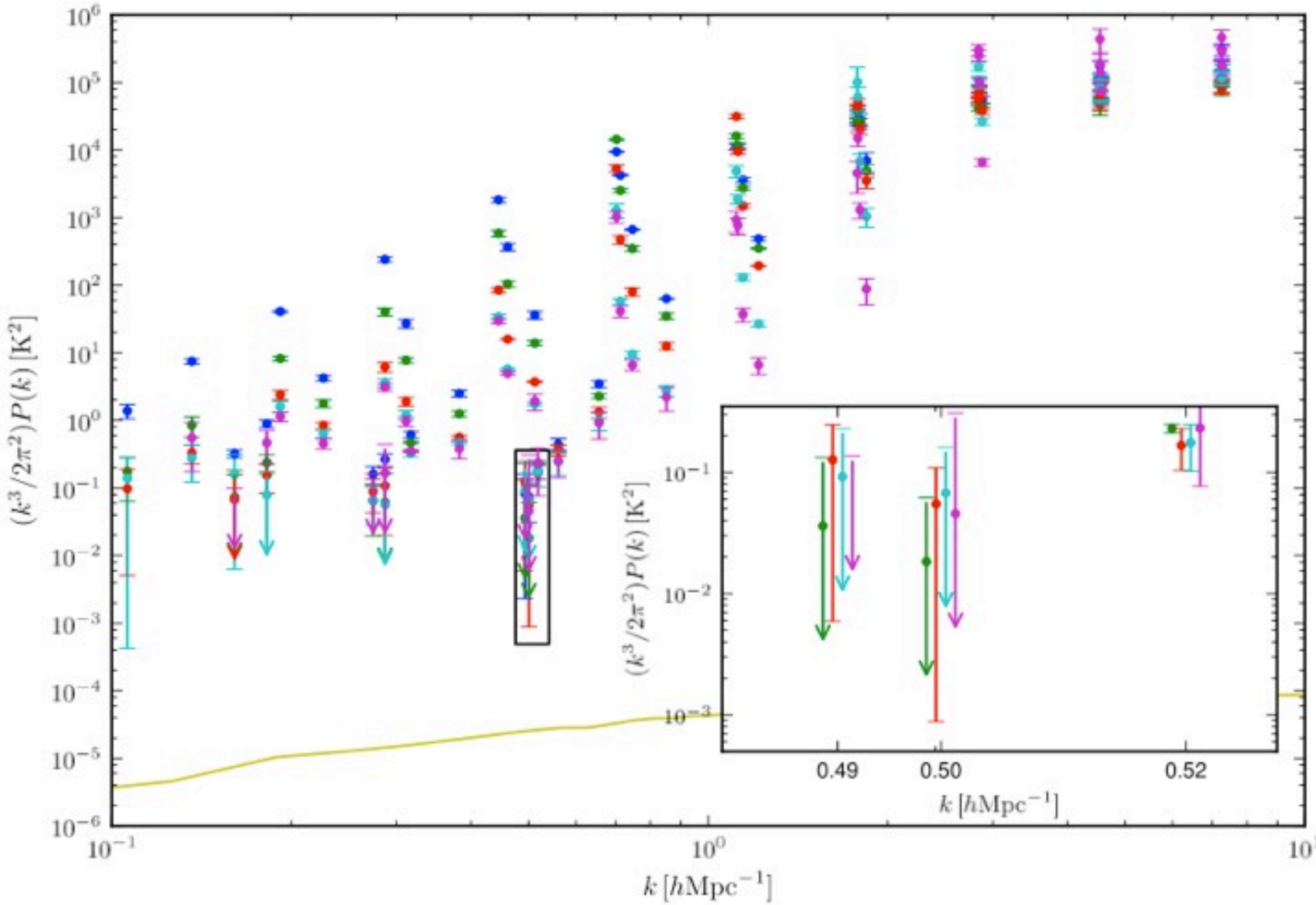


Specs

- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- z = 8.1-9.2

GRMT Current Results

GMRT: Measurement of a 2σ upper limit at $(248\ \mathrm{mK})^2$ for $k = 0.50\ h\ \mathrm{Mpc}^{-1}$.



Paciga et al. 2013

MWA Current Results

see also talk Tingay

Table 1: System parameters for MWA

Parameter	Symbol	150 MHz	200 MHz
Number of tiles	N	128	128
Area of one tile at zenith (m^2)	A_{eff}	21.5	19.8
Total collecting area (m^2)		2752	2534
Receiver temperature (K)	T_{rcv}	50	25
[a]Typical sky temperature (K)	T_{sky}	350	170
[b]Field of view (deg^2)	Ω_P	610	375
Instantaneous bandwidth (MHz)	B	30.72	30.72
Spectral resolution (MHz)		0.04	0.04
Temporal Resolution		0.5 s uncalibrated 8 s calibrated	0.5 s uncalibrated 8 s calibrated
Polarization		Full Stokes	Full Stokes
Minimum baseline (m)		7.7	7.7
Maximum baseline (m)		2864	2864
Angular resolution (1.5 km array)		~3'	~2'
Angular resolution (3 km array)		~2'	~1'

[a]Nijboer, Pandey-Pommier & de Bruyn (2009).
[b] Based on FWHM of primary beam. Imageable area is significantly larger.

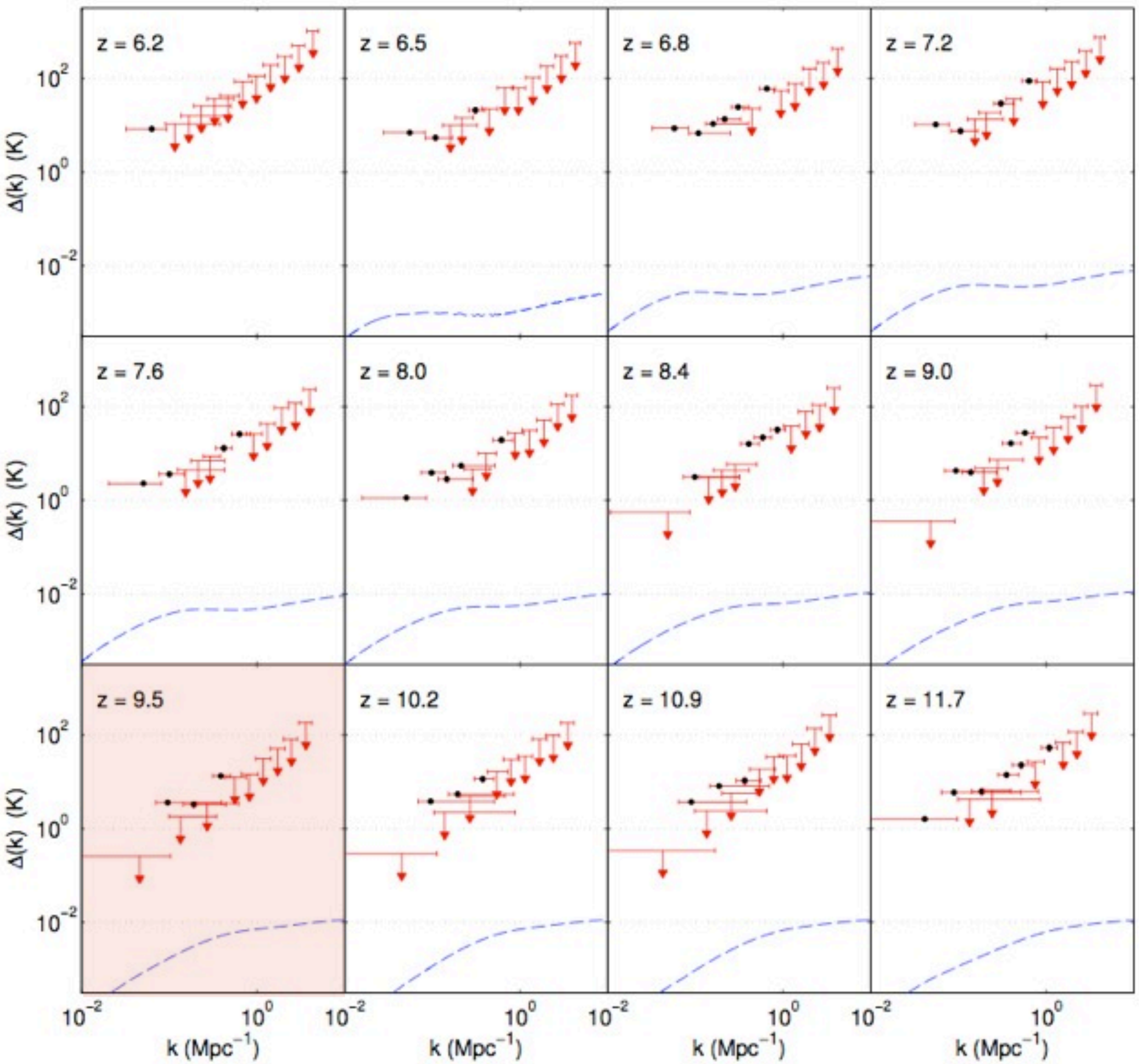
Results from Proto-type:

Dillon et al. 2013

Table 1
MWA-32 Instrument Parameters

Field of View (Primary Beam Width)	$\sim 25°$ at 150 MHz
Angular Resolution	$\sim 20'$ at 150 MHz
Collecting Area	~ 690 m^2 towards zenith at 150 MHz
Polarization	Linear X-Y
Frequency Range	80 MHz to 300 MHz
Instantaneous Bandwidth	30.72 MHz
Spectral Resolution	40 kHz

MWA Current Results



MWA-32T [proto-type]:

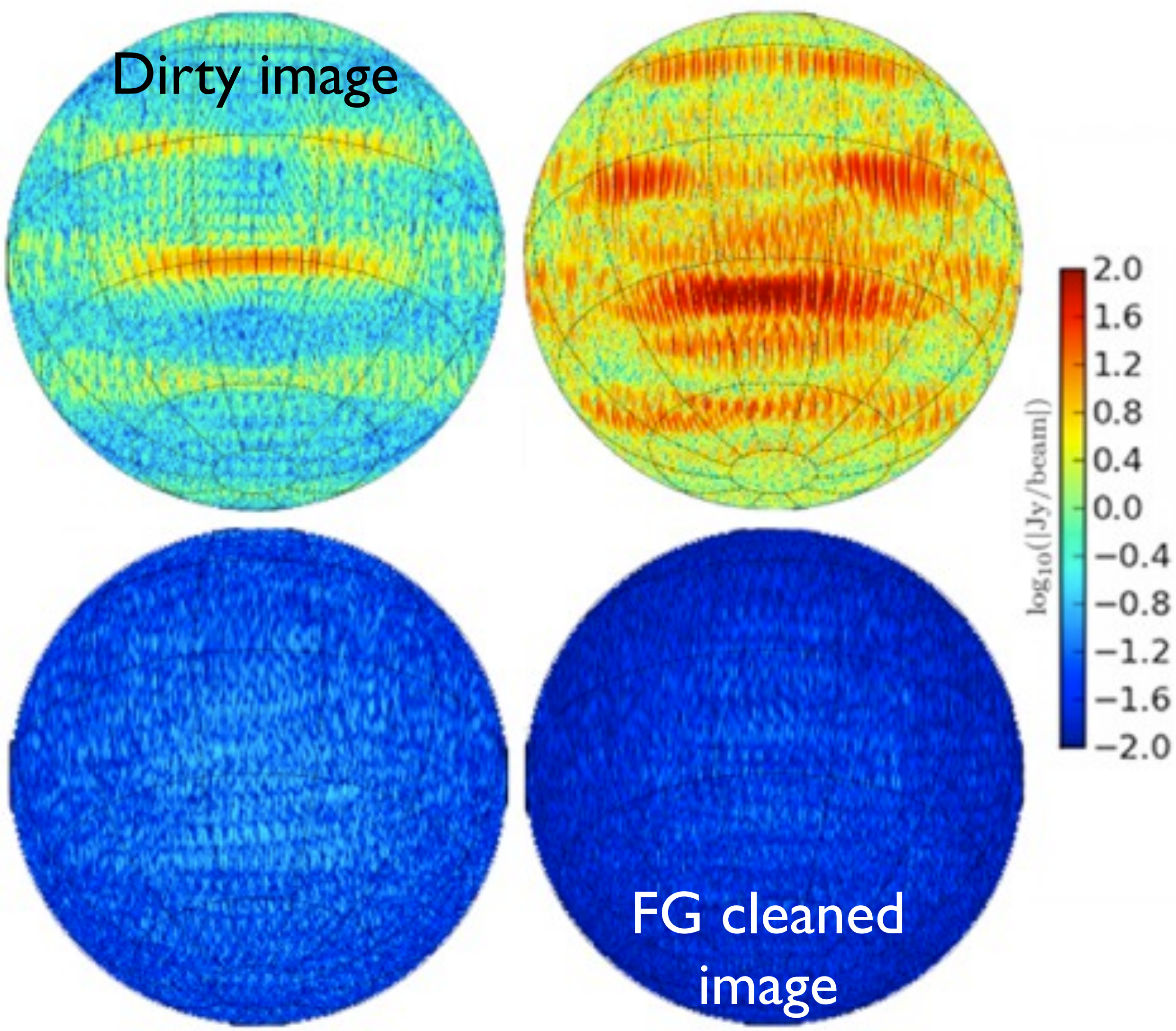
- 22 hrs of data
- March 2010
- R.A.(J2000) = 10h 20m 0s, Decl.(J2000) = $-10^\circ\ 0'\ 0''$
- 3 x 30.72 MHz bands, centered at 123.52 MHz, 154.24 MHz and 184.96 MHz, i.e. $6.1 < z < 12.1$
- 5hrs and 123.52 MHz and 154.24 MHz and 12hrs at 184.96 MHz

Upper limits on the power spectrum from z = 6.2 to z = 11.7. The lowest limit is $\Delta(k) <$ 0.3 Kelvin at 95% confidence at a comoving scale k = 0.046 Mpc $^{-1}$ at z = 9.5.

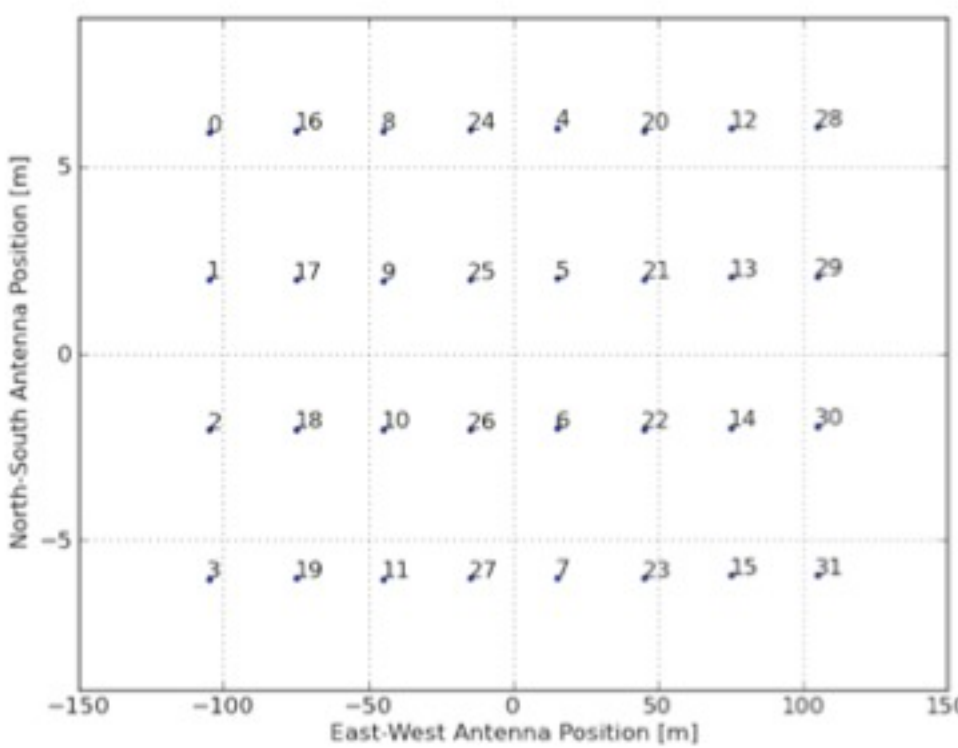
Dillon et al. 2013

PAPER Current Results

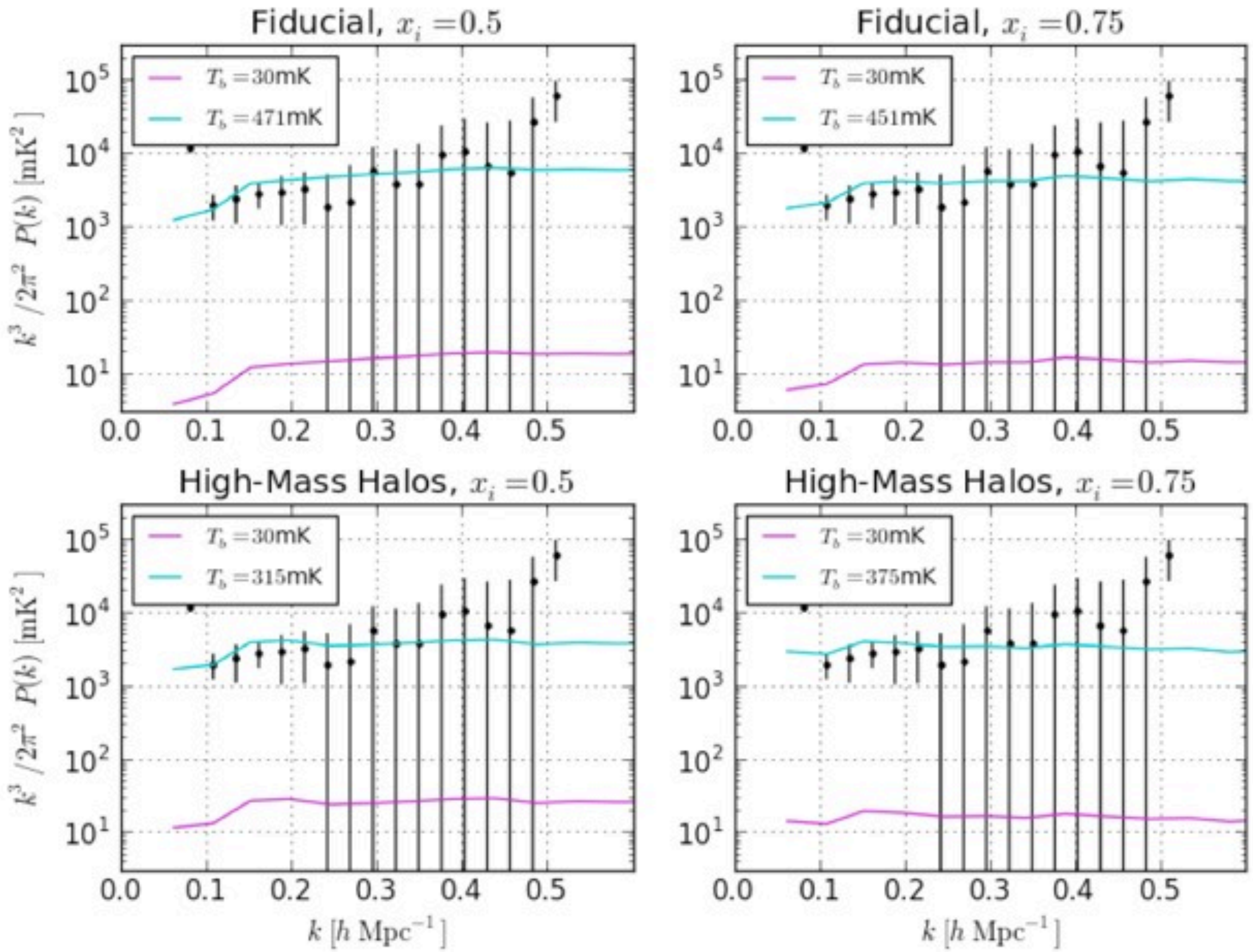
64-antenna deployment in the Square Kilometre Array South Africa (SKA-SA) reserve in the Karoo desert near Carnarvon



Current EoR results with:
32-antenna deployment at the NRAO site near Green Bank, WV



PAPER Current Results



Parsons et al. 2013

PAPER 32-antenna:

- 275 hrs of data
  (Dec. 7, 2011 to Feb. 4, 2012)
- 100 to 200 MHz, 2048 channels,
- visibility integr.: 10.7 seconds

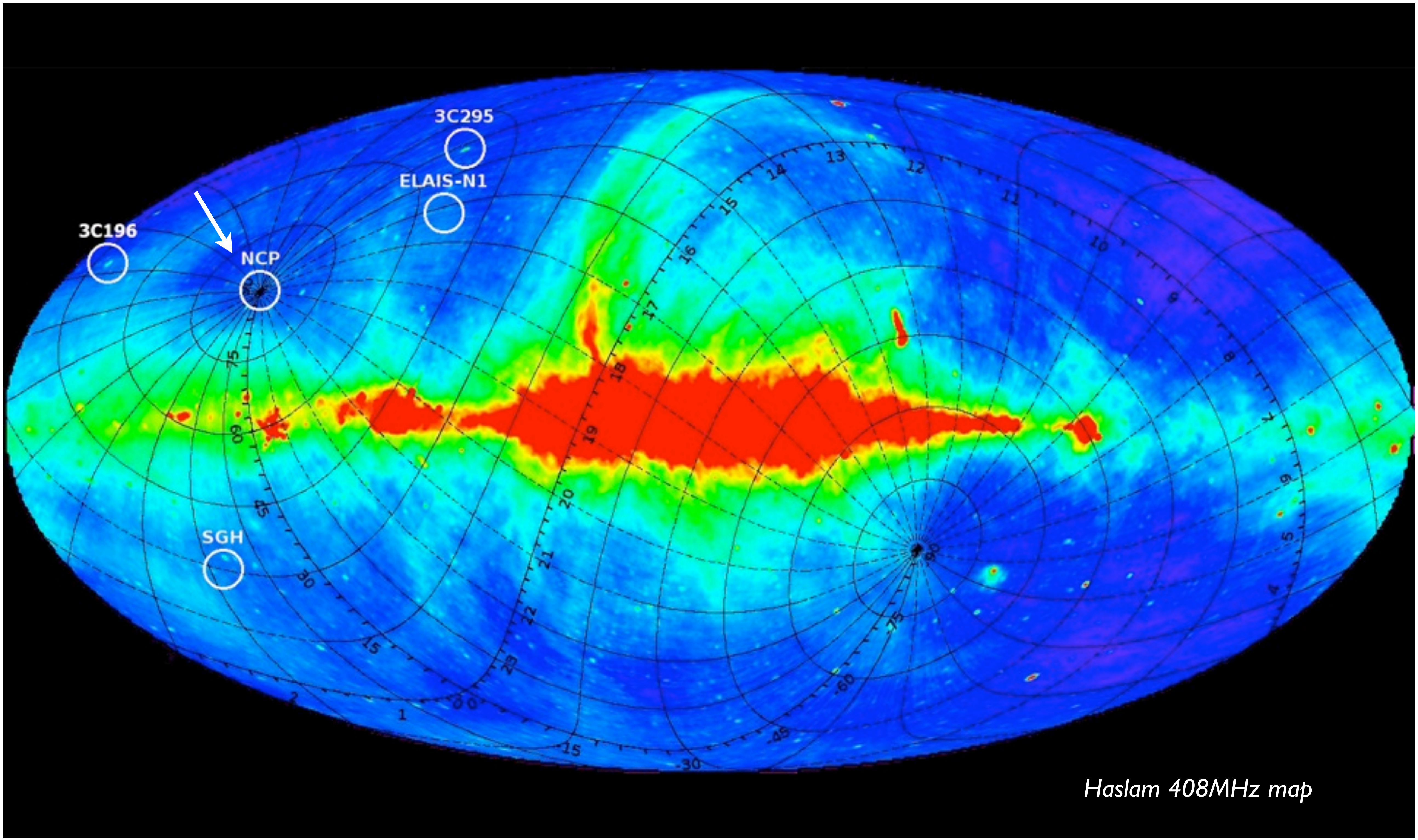
A best 2σ upper limit of 2704 mK^2 for k = 0.11 h Mpc^{-1} at z = 7.7

Heating of the neutral intergalactic medium (IGM) is necessary to remain consistent with the constraints. By z = 7.7 the HI has been warmed from its cold primordial state.

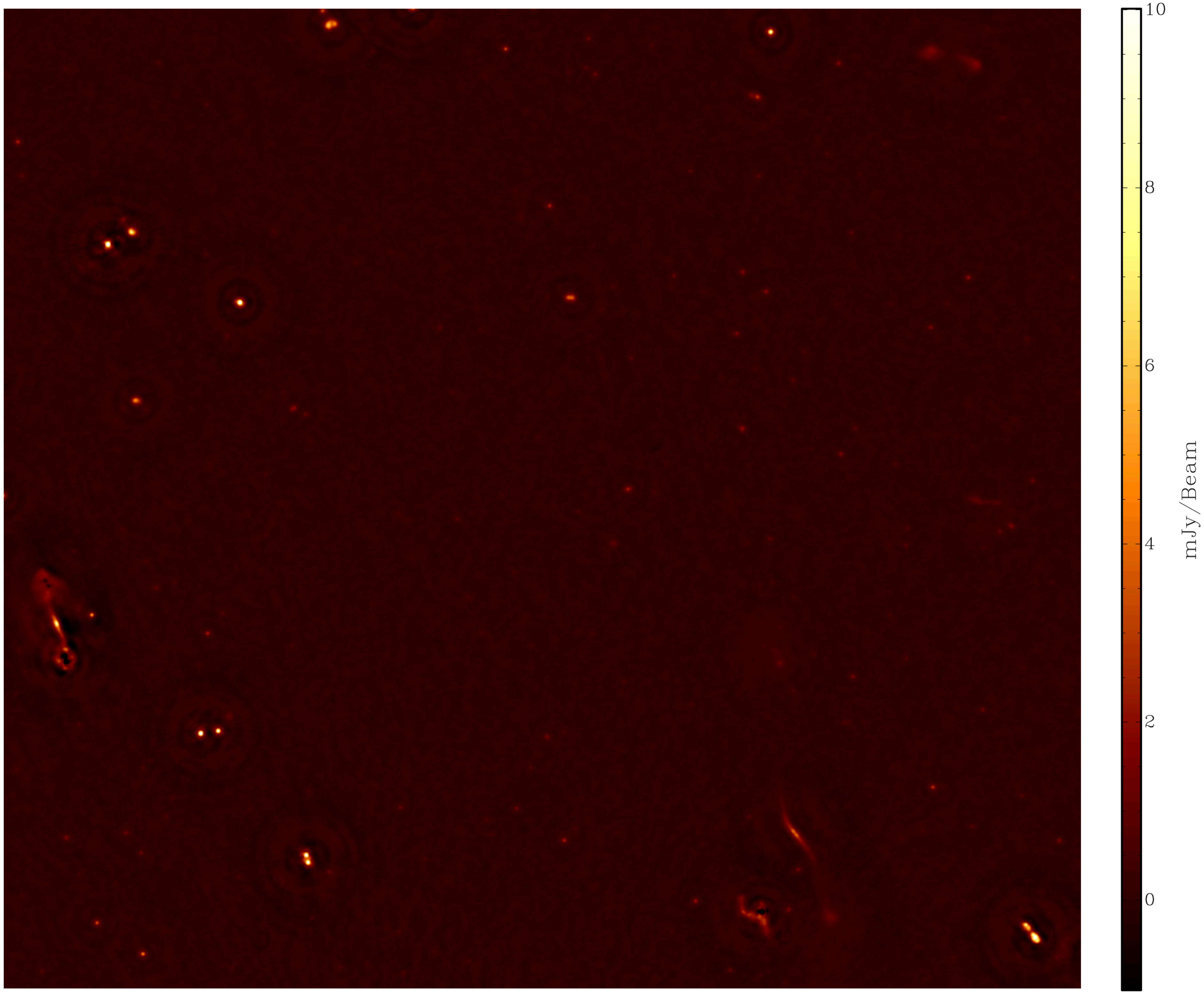
LOFAR Current Results

see also talks: Heald, Hessels, Brentjens

LOFAR Current Results

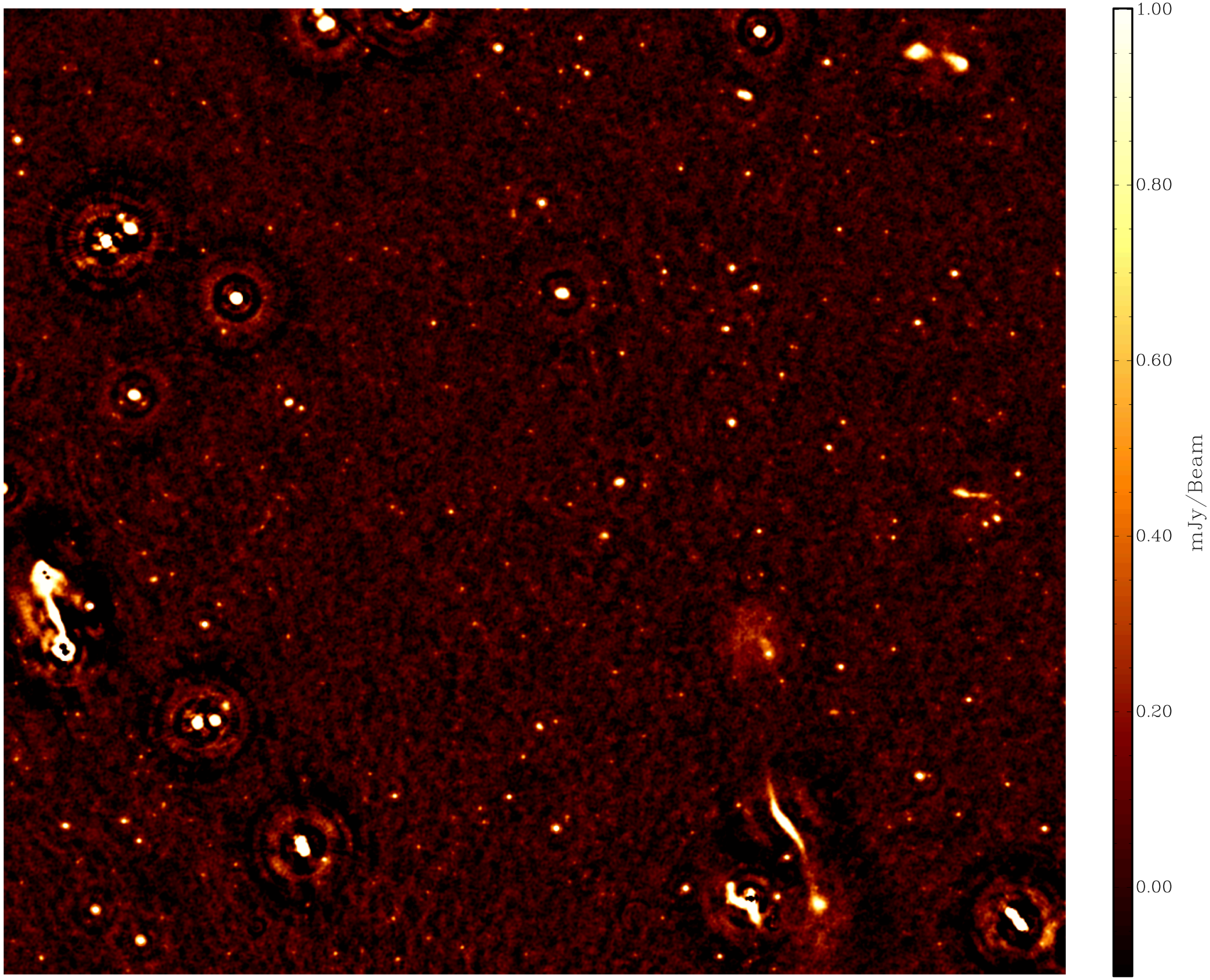


LOFAR Current Results: NCP



NCP: 114 hrs, ~30 muJy, FoV=30'x30', FWHM=6''

LOFAR Current Results: NCP



NCP: 114 hrs, ~30 muJy, FoV=30'x30', FWHM=6"

LOFAR Current Results: NCP

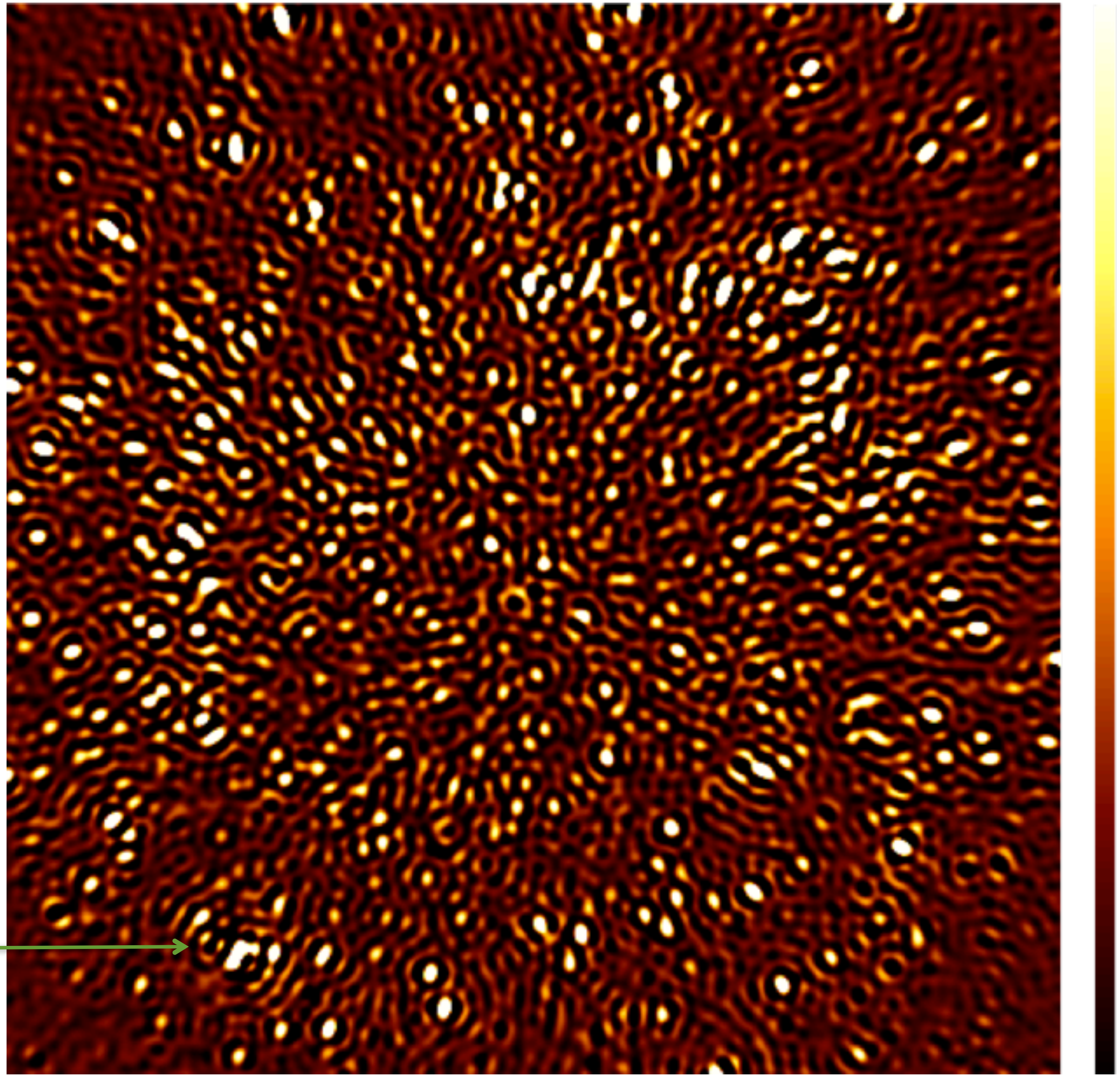
NCP core baselines:

2300 sources (>10 mJy) subtracted using *SageCal.* [currently 11000 at few mJy; not shown]

Concentration on the uv-range that is filled for the full z=7-11.4 range:

- uv-range: 70-800 λ
- resolution: 5' PSF

3C61.1
Dec + 86°



Current Analysis Approach

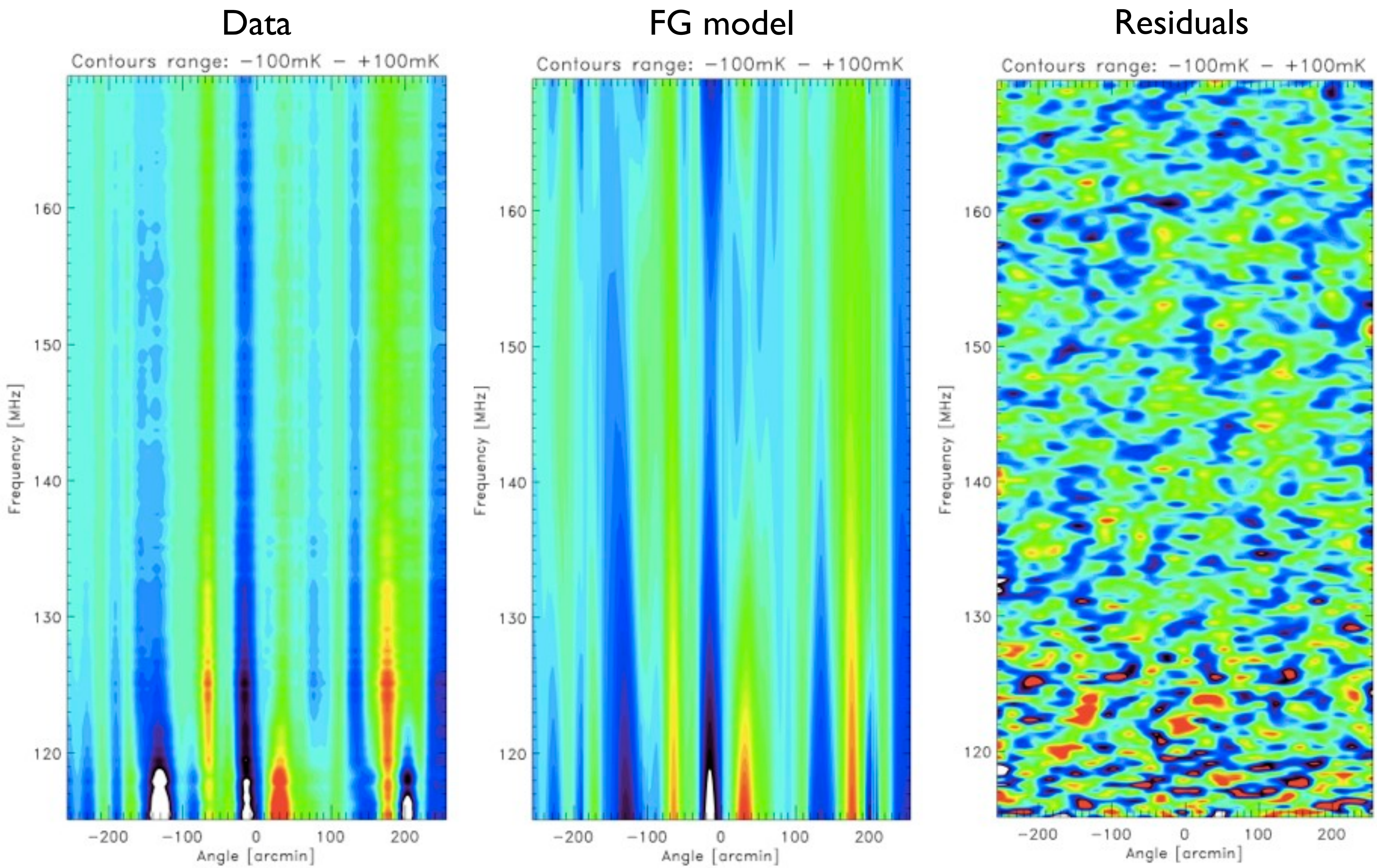
Data processing

- Calibrate (11000 src sky model/DDEs)
- Subtract sky model (*SageCal*)
- Make the uv coverage uniform
- Filter on 5’ (σ) scale (11.8’ FWHM)
- Apply a FG extraction method (preferably non parametric *GMCA*).

Signal extraction

- Analyze the residual map
- Variance as a function of frequency.
- Cross-variance as a function of frequency
- Noise, systematics

Excess Variance Analysis



FWHM = 12' scale; t_{int}=114hrs LOFAR; HBA 115-170 MHz (1MHz res.)

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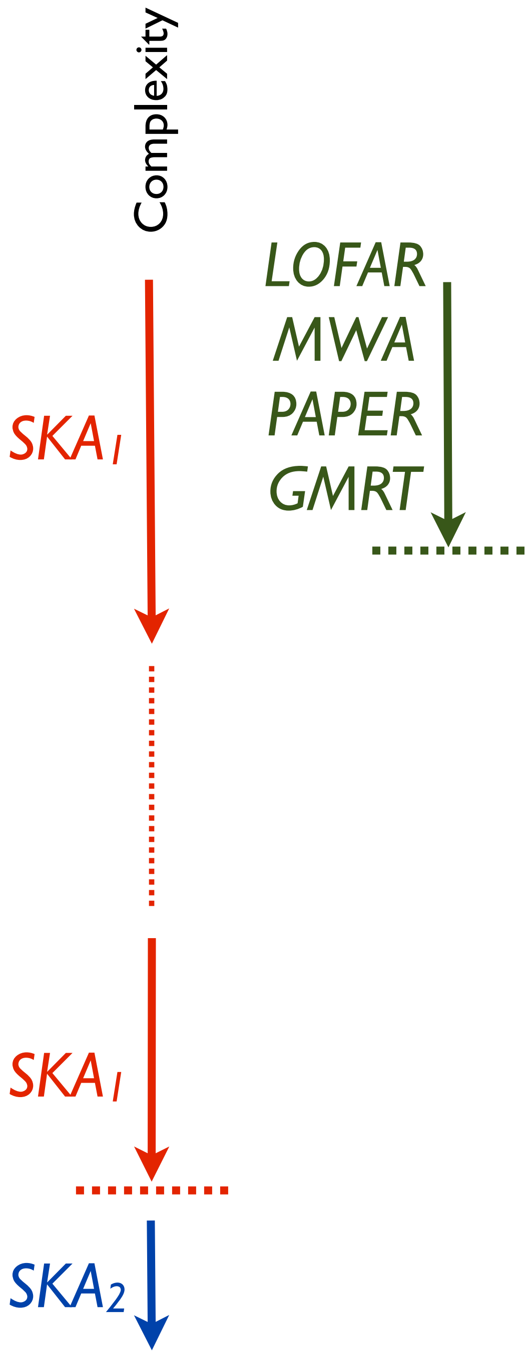
What’s coming in the next decade?

See also talk by Robert Braun

Beyond Current Pathfinders: SKA-low

General Observational Objectives



Epoch of Reionization [~ 100 to ~200 MHz]

- Absorption again high-z radio source (small scale power)
- Global signal (total power) of HI (absorption/emission)
- RMS fluctuations of HI emission with redshift
- Spatial power-spectra (1,2,3D) and higher-order statistics with redshift
- <u>HI Image data-cubes (spatial-frequency) for reionization topology</u>

Cosmic Dawn [~50 to ~100MHz]

- Absorption again high-z radio source (small scale power)
- Global signal (total power) of HI (absorption/emission)
- RMS fluctuations of HI emission with redshift
- Spatial power-spectra (1,2,3D) and higher-order statistics with redshift

- <u>HI Image data-cubes (spatial-frequency) for cosmology</u>

Science Goals beyond current pathfinders

Transition from **statistical** (*LOFAR, MWA, PAPER, GMRT*) to **tomography** (*SKA 1&2*) capabilities.

Tomography >100MHz

(1) The capability of SKA_1 to image ~3.0 mk fluctuations of neutral hydrogen at 3-sigma level in t_{int}=1000 hrs at 150 MHz with BW=1 MHz, covering z~6-15.

(2) Capability of SKA_1 to cover all EoR & Dark Ages (z=6-30) features currently expected in the HI power-spectrum and total intensity both in emission and absorption.

(3) Allow HI absorption at sub-KHz level against high-z radio sources.

Tomography 50-100MHz

(4) The capability of SKA_2 to image ~0.3 mk fluctuations of neutral hydrogen at 3-sigma level in t_{int}=1000 hrs at 150 MHz with BW=1 MHz, covering z~6-30. But imaging is feasible to z=30 after filtering (in principle).

Square Kilometre Array: SKA1-Low

Table 2 SKA1-low – Log-Periodic Dipoles

Aperture Array		
Lower Frequency	50 MHz	Dual polarization (2 orthogonal)
Upper Frequency	300 MHz	Single element covering full range
Number of antennas per station	289	Log-Periodic-Dipole antennas
Total physical aperture	$8.0 \times 10^5\ m^2$	
Area per antenna	$2.25\ m^2$	
Element filling factor in station	0.7	Areal filling factor
Dense/Sparse Transition	111 MHz	A_e per element is equal to packing density
Array Configuration		
Station Diameter	35 m	
Number of stations	911 stations	866 in core; 45 in spiral arms
Core (radius <600 m)	~50% (~433 st'ns)	Fractional total number of core stations
Core (radius <1000 m)	~75% (650 st'ns)	"
Spiral Arms	~4% (45 stations)	15 stations per spiral arm
Av'g St'n filling factor (radius <220 m)	0.91	Stations must be close-packed or overlapped to radius of 650 m.
Station Beam Forming		
Number of beams	1	"Average" number of beams per pol'n required to 300 MHz
Instantaneous bandwidth per beam	250 MHz	Assumes full bandwidth is available (50-300 MHz)
Digital Outputs		
Sample streams	2	Max - sub-bands
bits per sample	8	Sent from Beamformers
Signal Transport System		
Data rate per station	10 Gb/s *	Optical fibre to signal processor
Radius < 3000 m	8.7 Tb/s	866 stations
3 km < Radius < 50 km	450 Gb/s	45 stations
Signal Processing System		
Fine Frequency channels**	2.5×10^5	Channel Bandwidth = 1 kHz
Complex Correlations	4.1×10^{11}	$911^2/2$)baselines x (1) bms x 4 pol'n prod's x 2.5×10^5 chans
Complex Correlations: Spiral Arms	0.4×10^{11}	(911^2-866^2) / 2 baselines
Core (radius<3 km) Dump Time	~10.6 s	Station diameter = 34 m; max baseline = 6 km
Minimum Dump Time	~0.6 s	Station diameter = 34 m; max baseline = 100 km
Science Computing System		
Input data rate (1 kHz channels)	842×10^9	Byte s^{-1} av'ge from correlator (4-Byte x 2 for complex) (3.8 corr's/10.6 s + 0.3 corr's/0.6 s) x 10^{11} x 8 (8-Byte complex)
Input data rate (100 kHz channels)	8.4×10^9	Assumes some preprocessing at 1 kHz, then averaging

A=0.8 km^2; 50% in a 600m core
75% in a 1000m core
4% outer 15 stat
to 45 km radius

Station-size = 35m diameter

Freq: 50-350+MHz

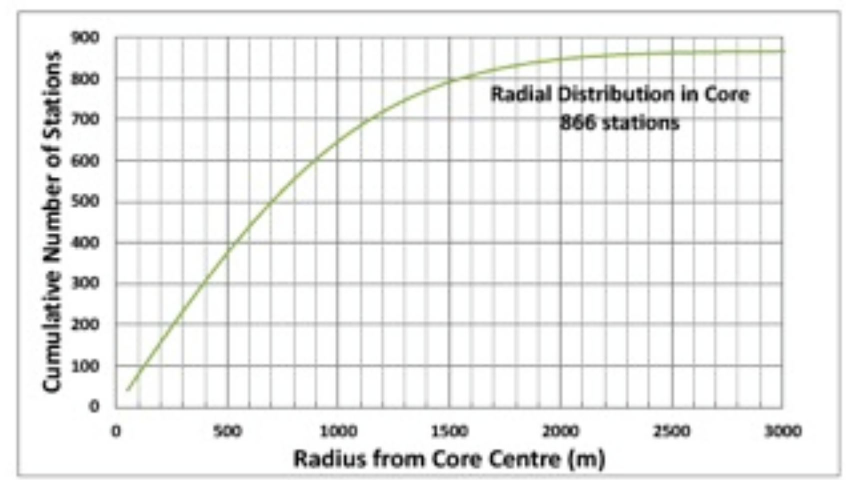
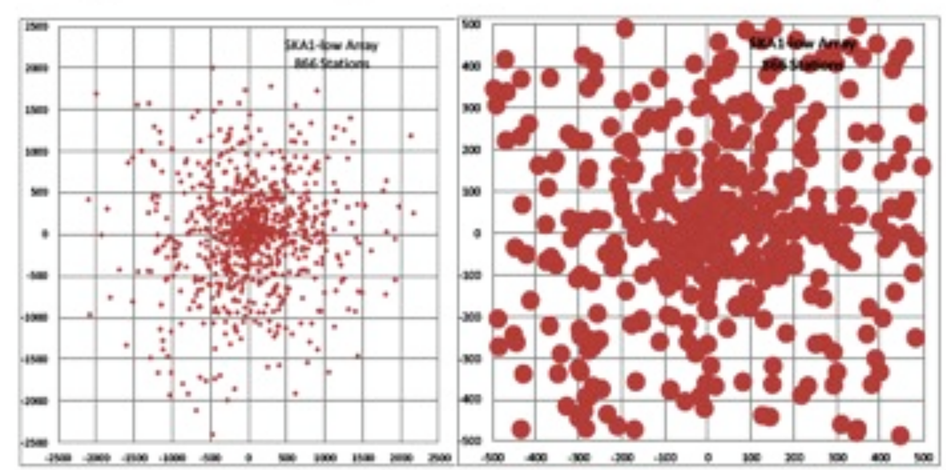


Figure 3 Cumulative collecting area as a function of core radius in the SKA1-low array.

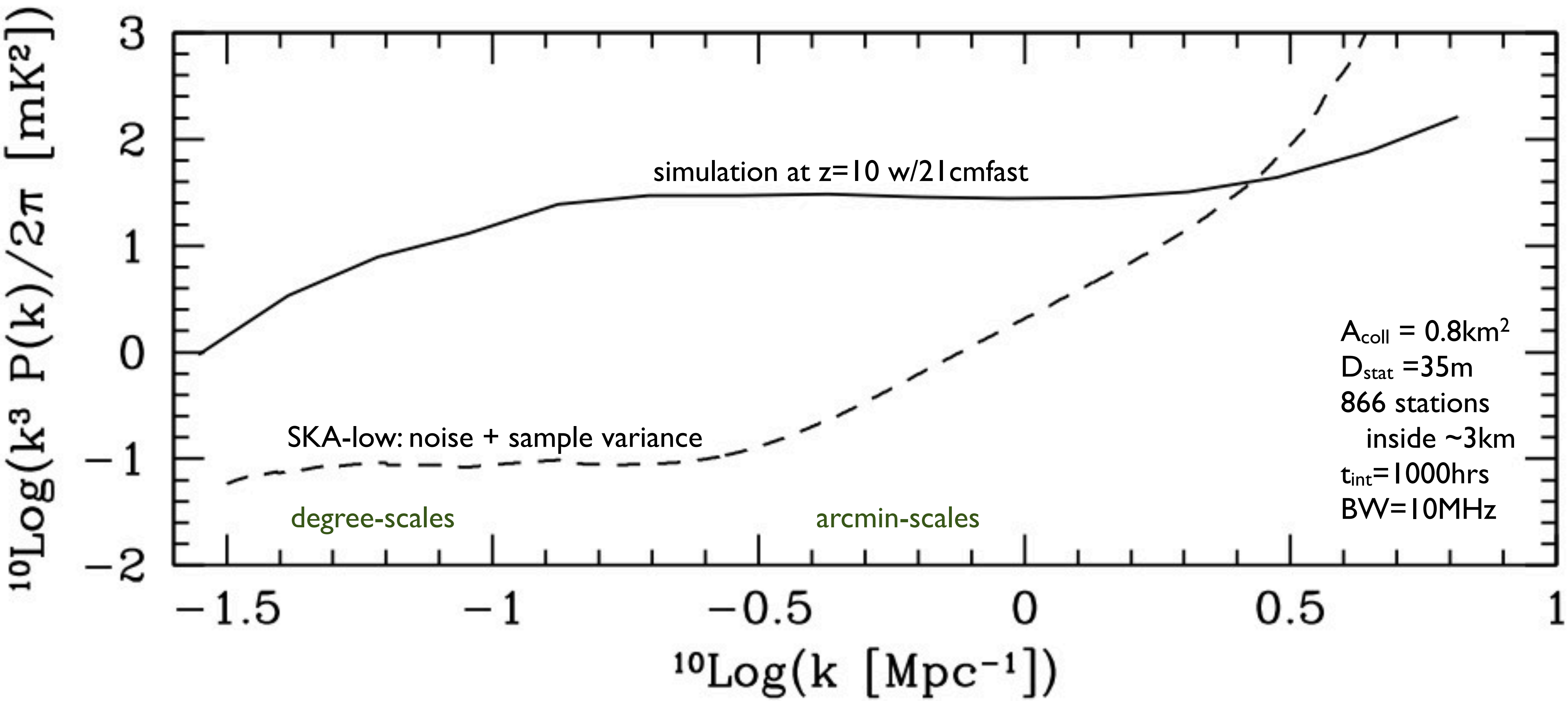


Measuring the EoR HI-T_b Power-Spectrum at z=10

Assuming the current SKA baselines design

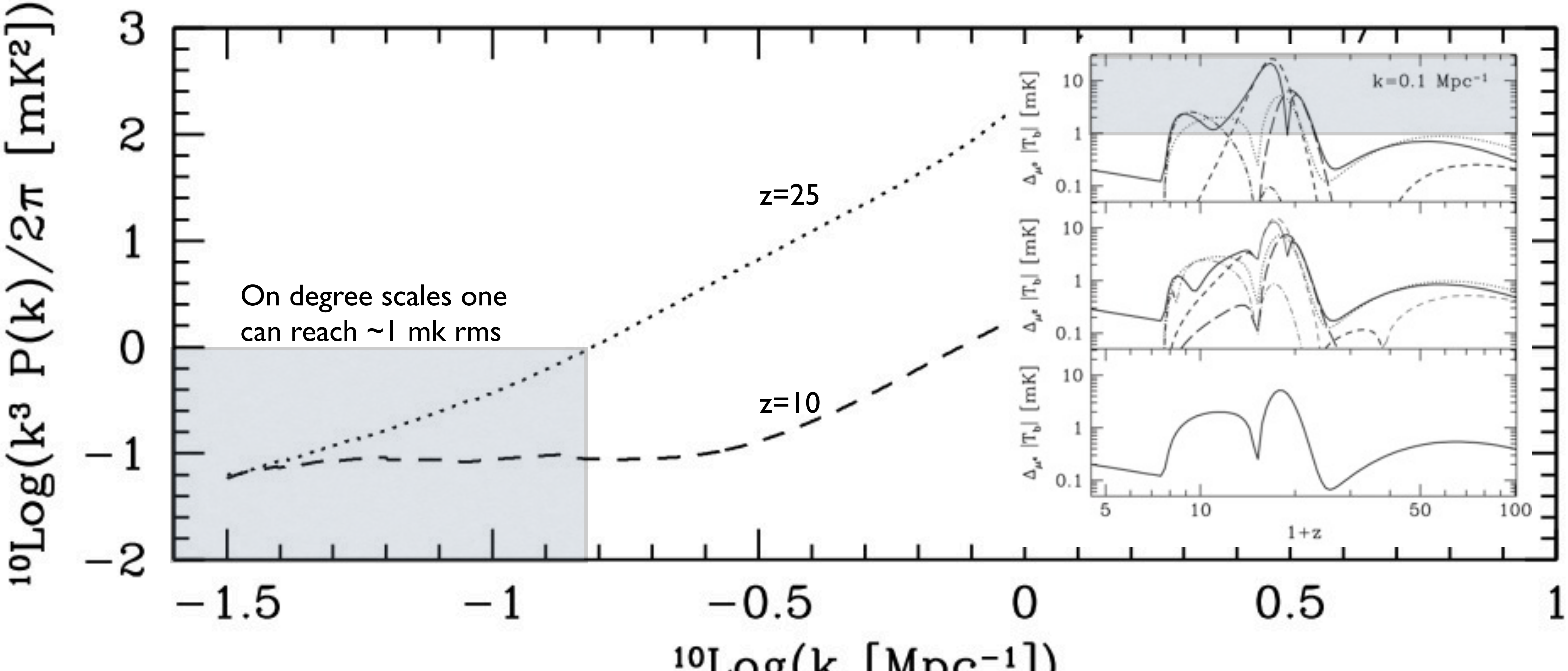
SKA1 SYSTEM BASELINE DESIGN

Document number SKA-TEL-SKO-DD-001

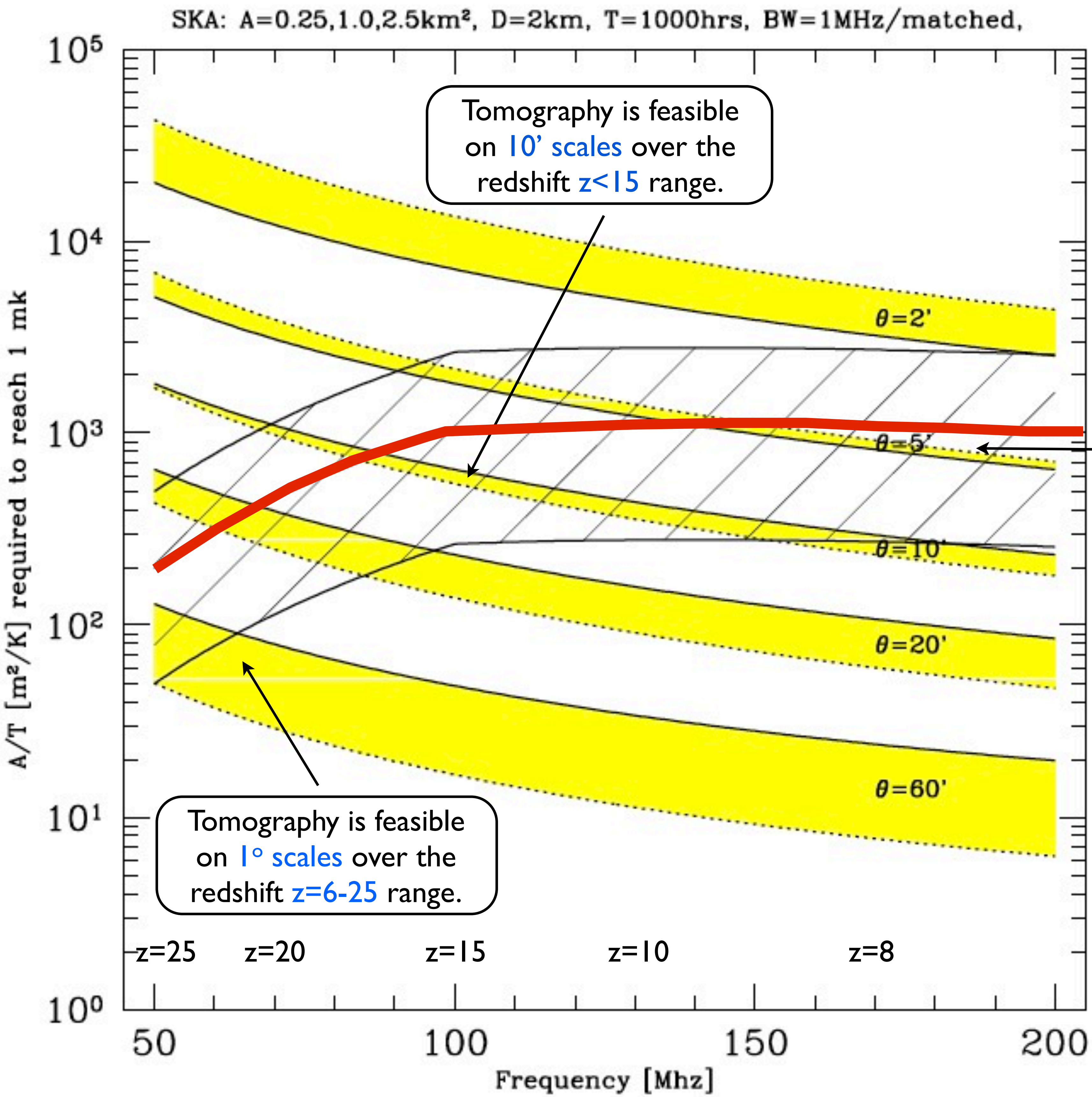


HI detection at z=25 with SKA-low

At z=25, one can reach an errors << 1mK on scales of ~1 degree within 1000hrs and BW=10MHz, using the current (March 2013) baseline design.



SKA Tomography



Tomography is feasible on 5' scales over the redshift z<8 range.

EoR: z<15

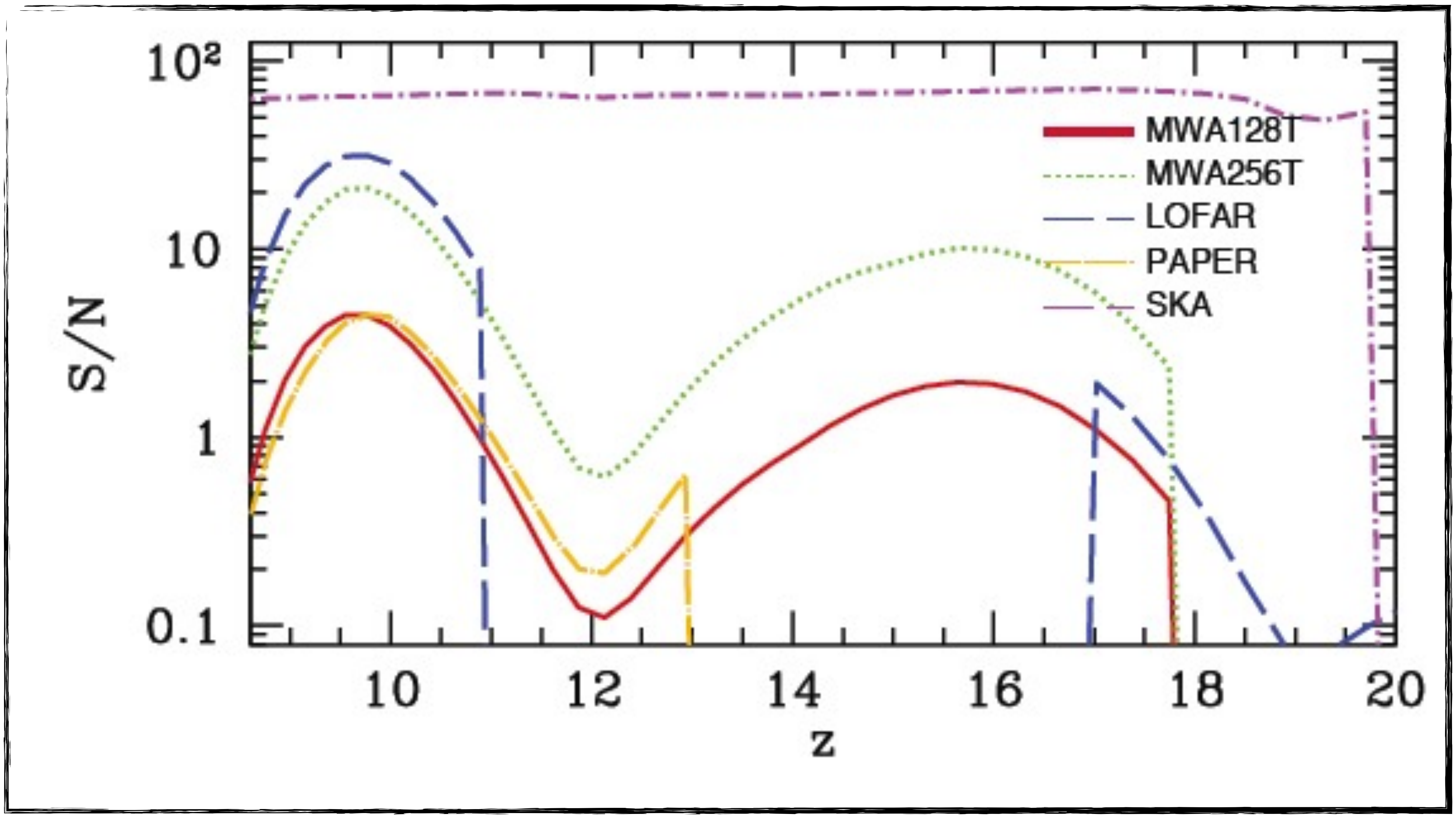
In 1000hr with a BW=1MHz or matched to angular scales, one can do tomography to the required level of ~1mK on scale >~10'

Cosmic Dawn: 15<z<25

Idem, on scales >~1°.

SKA can probe physics of the EoR and CD with high S/N

S/N of peak of power spectrum



Mesinger et al. 2013

SKA CD/EoR Science Team

SKA CD/EoR Science Team

Goal: Provide advise and input to the science director and SKA office on matters pertaining to the science goals of SKA. This is done in part in the SKA SWG of which all ST (co)Chairs are members.

Note: The study neutral hydrogen at high redshifts is one of the two science drivers of SKA phase I (see talk Braun/SKA Memo 125).

Current science-team members (open for more active members):

Fillipe Abdalla (UK), James Aguirre (US), K. Ahn (Jp), Gianni Bernardi (SA), Ilse van Bemmel (NL), Frank Briggs (AU), Robert Braun (UK), Ger de Bruyn (NL), T-C Chang (TW), Benedetta Ciardi (Ger), Andrea Ferrara (It), Muynh Minh (AU), Lincoln Greenhill (US), Mike Jones (UK), Leon Koopmans (NL, Chair) Joseph Lazio (US), Garrelt Mellema (Swe), Miguel Morales (US), Aaron Parsons (US), Ue-Li Pen (Ca), Jonathan Pritchard (UK, co-Chair), Mario Santos (PT/SA), Benoit Semelin (Fr), Akeuchi Tsutomu (Jp), Rachel Webster (AU)

First Major Activity: Science Assessment Workshop, SKA, Jodrell Bank, March 2013

3-day discussion on SKA Baseline Design

Outcome: 2-page document (available on SKA website) providing concise advise or actions to the SKA Office and ST on the impact of the BLD on the Cosmic Dawn/EoR Science case

Second Major Activity: Science & Engineering Meeting, Manchester, UK Oct. 2013

Goal: Provide input on the BLD and discuss potential requests for change.

These were presented during the meeting based on several memo's written by the ST during the summer of 2013 and discussed via telecons.

General Activities

General activities:

- Regular telecons
- Science Assessment workshop (done),
- Science and Engineering Meeting (done),
- Comment on user cases (ongoing),
- Science Chapters (ongoing) - Telecon planned
- Overall feedback on BLD (Requests for Change)
- General f2f meetings with SWG and other ST chairs
- Input on level 0 & 1 documents regarding science and instrument specifications (ongoing).
- General presence at science meetings to promote SKA!

Please get involved if you feel you have something to contribute!

Summary & Conclusions

- Observations of Ly-α emitters, dropouts, QSOs, GRBs are starting to probe the first stars/galaxies to z~10, during the EoR.

- HI is the only tracer that allows us to study many processes during the Dark Ages, Cosmic Dawn & EoR over wide range of angular scales.

- Currently four HI/EoR detection experiments are ongoing: GMRT, MWA, PAPER and LOFAR. No detection yet, but increasingly stronger upper limits. All experiments are statistical in nature [e.g. power-spectra/excess variance]

- Near Future: New or extensions of current arrays to probe Cosmic Dawn: AARTFAAC/LSS/LWA/HERA

- SKA will allow tomography (imaging!) to z=25 [Cosmic Dawn]

- To detect the Dark Ages we need to go in to space or to the moon.