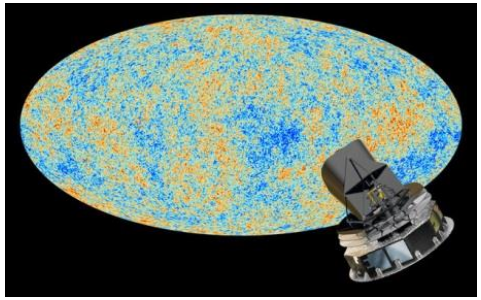
Cosmic Dawn and Reionization with the SKA

Garrelt Mellema
Department of Astronomy
Stockholm University

Contents

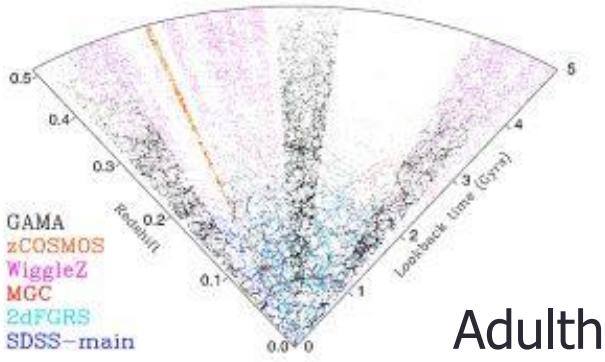
- What is the Cosmic Dawn & Reionization?
- What is the radio signal from this period?
- What is the relation between studies with LOFAR and the SKA?



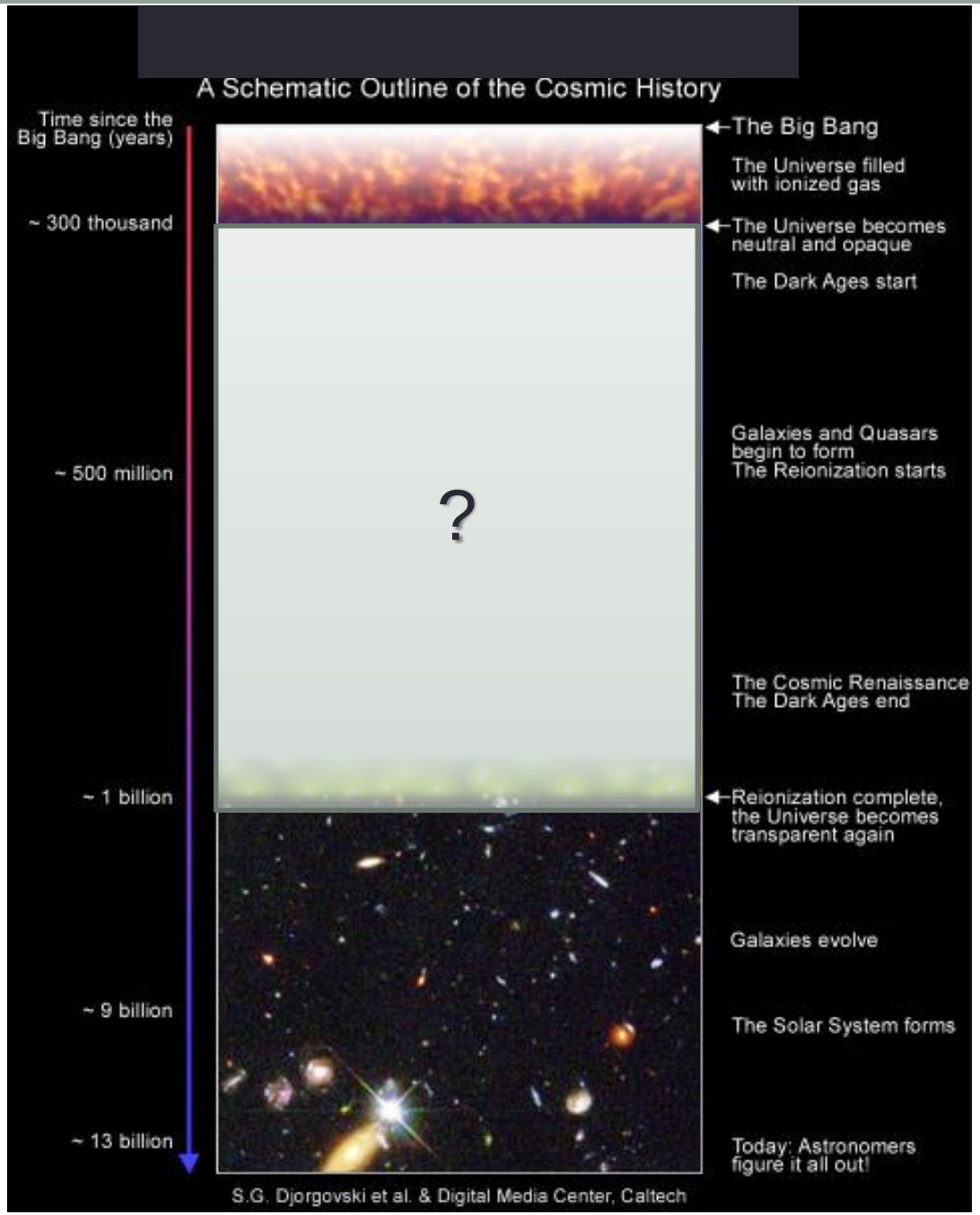
Infancy

Time line

Tell me about your childhood...



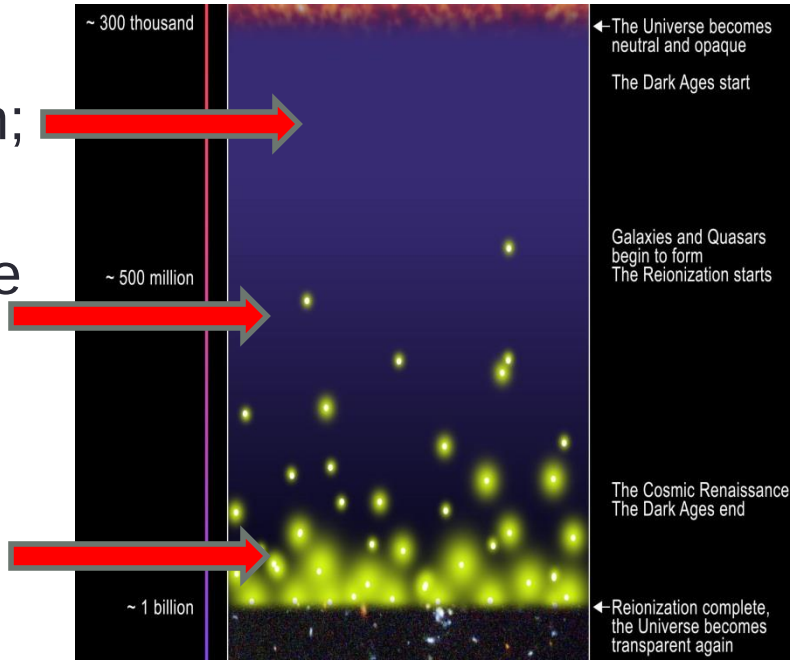
Adulthood



The Universe's childhood

- `Childhood´ phases:

1. **Dark ages**: no sources of radiation; Universe neutral.
2. **Cosmic Dawn**: first stars; Universe mostly neutral.
3. **Reionization**: earliest galaxies; neutral hydrogen starts to disappear.



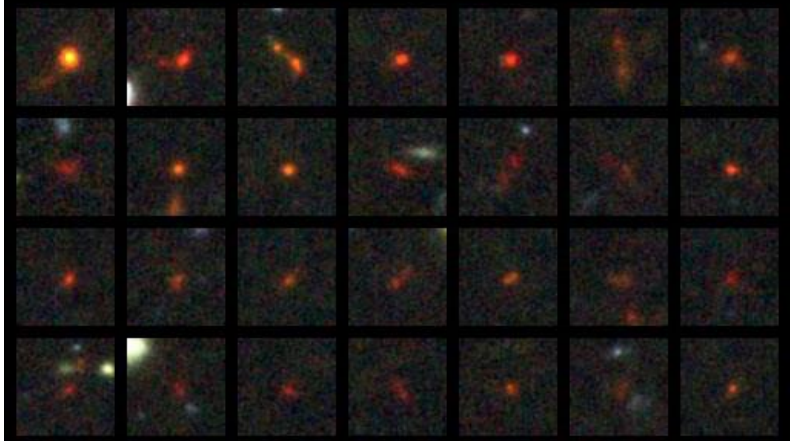
- `Adolencence/adult´ phase:

4. **Post-reionization**: galaxies grow, clusters of galaxies form, Universe filled with ionized hydrogen.

Studying the CD/EoR

- Two complementary approaches:

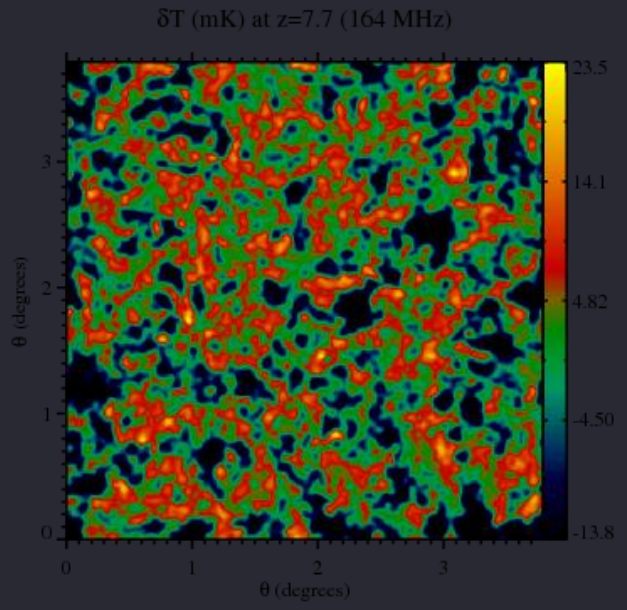
Find the galaxies



Credit: R. Bouwens

HST, Subaru, JWST, E-ELT, etc.

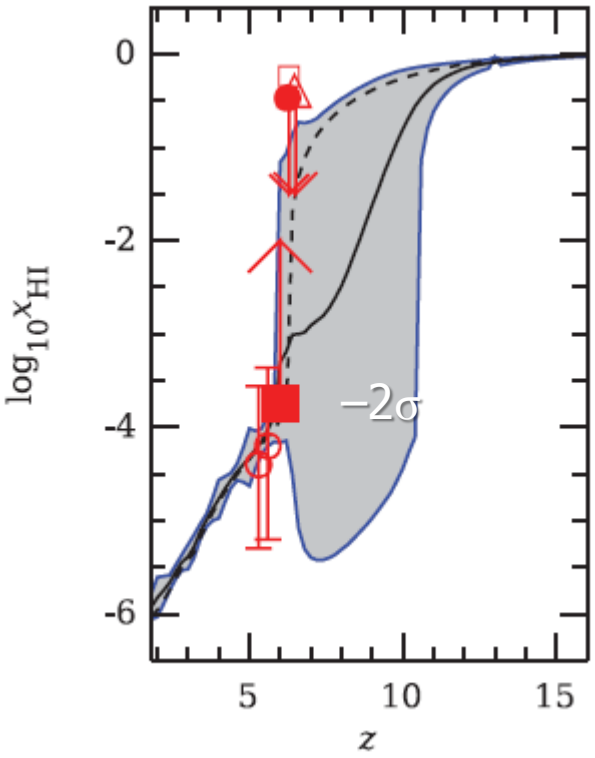
Find the Intergalactic Medium



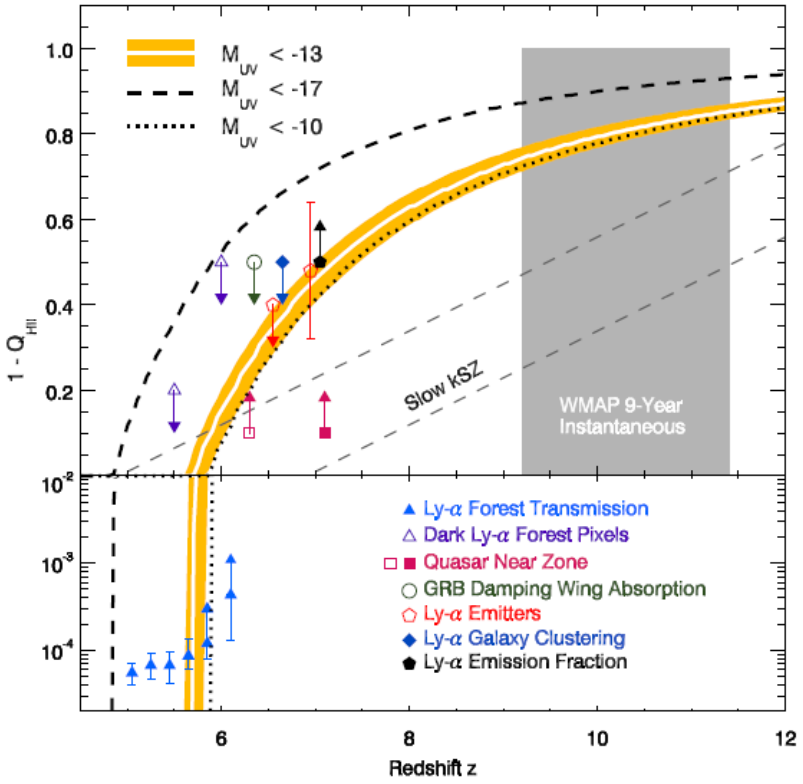
LOFAR, MWA, PAPER, GMRT, **SKA**

Combining Existing Constraints

- Current data: WMAP, SPT, QSO, LAEs/LBGs, ...

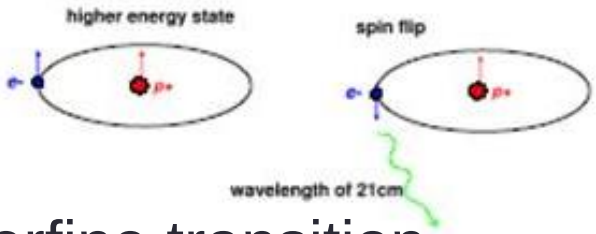


Mitra et al. (2012)



Robertson et al. (2013)

The Perfect Tool



- Neutral hydrogen has a forbidden, hyperfine transition between the two $1^2s_{1/2}$ ground level states: **21cm.**

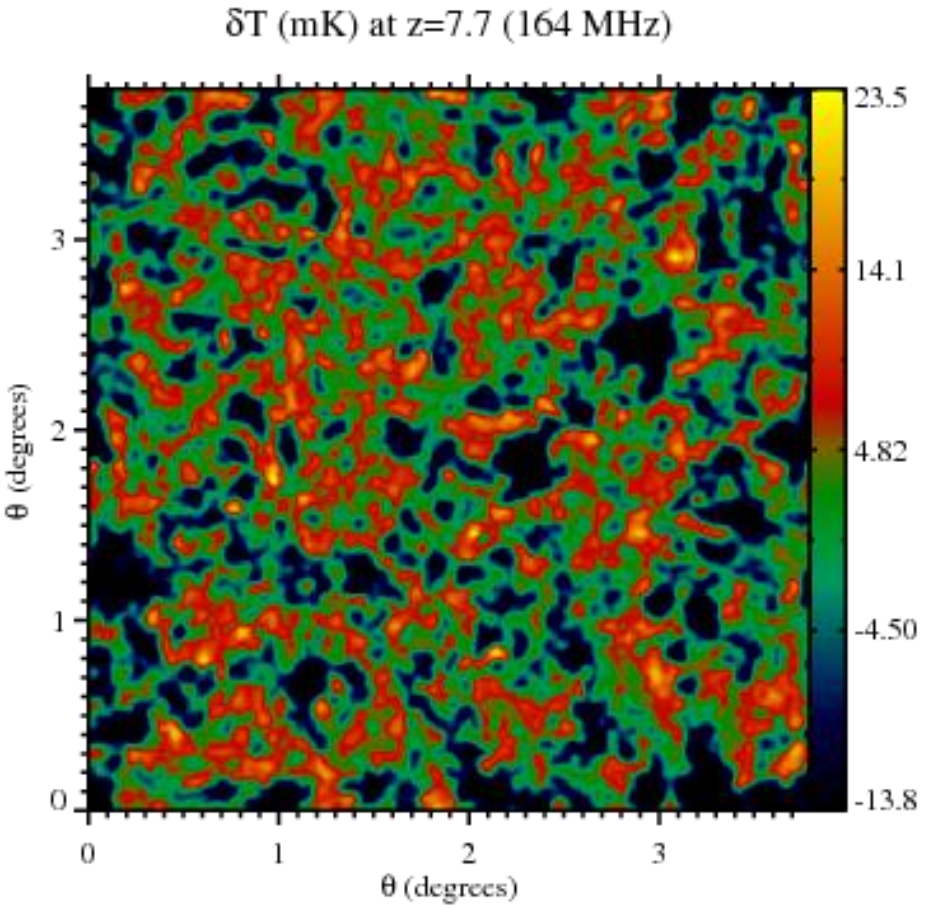
- The measurable signal, differential brightness temperature δT_b

$$\approx 28 x_{\rm HI}(1+\delta)\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\left(1-\frac{T_{\rm CMB}(z)}{T_s}\right)\left(\frac{\Omega_{\rm b}}{0.042}\frac{h}{0.73}\right)\left(\frac{\Omega_{\rm m}}{0.24}\right)^{\frac{1}{2}}$$
$$\left(\frac{1-Y_{\rm p}}{1-0.248}\right)\left(1+\frac{1}{H(z)}\frac{{\rm d}v_\parallel}{{\rm d}r_\parallel}\right)^{-1} \quad {\rm mK} \qquad (2)$$

  - It is found at radio frequencies below 200 MHz.

The 21cm map

- The signal fills the sky.
- It has *intrinsic* fluctuations due to
  - Gas density (δ)
  - Ionized regions (x_{HI})
  - Excitation variations (T_s)
- It has *additional observed* fluctuations due to
  - LOS velocity gradient.

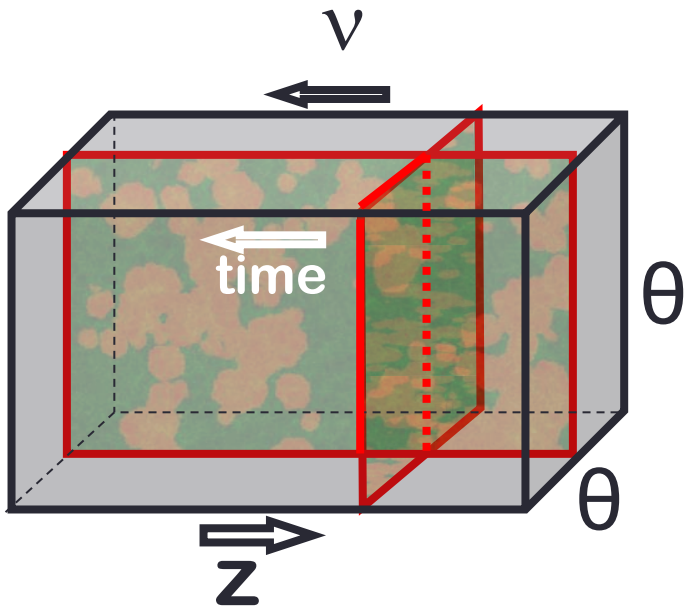


Mellema et al. (2012)

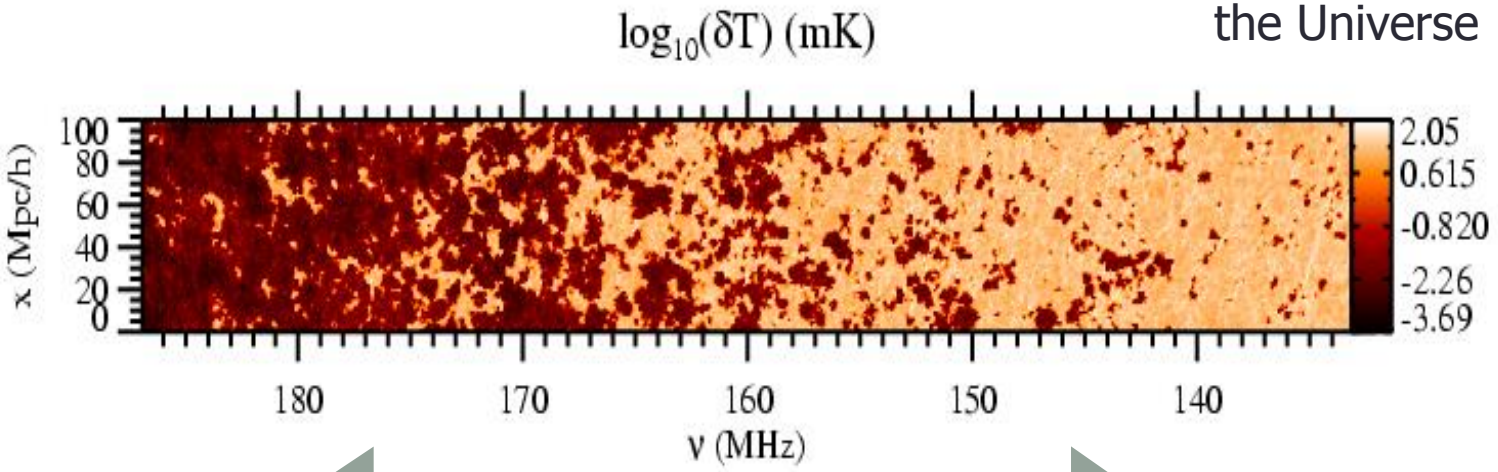
δT_b
3′ beam

The 21cm image cube

- The signal is *line* emission: due to Doppler shifting it carries spatial, temporal and velocity information.



The image cube: tomography of the Universe



Frequency / Time

Redshift

Mellema et al. (2006)

Spin Temperature

Populations of the triplet and singlet states of HI follow Boltzmann distribution, with excitation temperature, a.k.a. the spin temperature.

$$n_1/n_0 = 3 \exp(0.068\ \mathrm{K} / T_s).$$

Processes affecting spin temperature:

- Collisions ($T_s \rightarrow T_k$), z > 30
- Radiative
  - CMB photons ($T_s \rightarrow T_{CMB}$)
  - Ly-α photons ($T_s \rightarrow T_{Ly\text{-}\alpha} \approx T_k$) (”Wouthuysen-Field effect”)

$$T_s = \frac{T_{CMB} + y_\alpha T_k + y_c T_k}{1 + y_\alpha + y_c}$$

IGM @ EoR: competition between CMB and Ly-α photons.

Spin Temperature Regions

$$\frac{T_s - T_{CMB}}{T_s}$$

- Depending on T_k and local Ly-α flux: different regions of 21cm signals in IGM (for z<30).

	Heated IGM	Unheated IGM
Ly-α present	$\delta T_b > 0$	$\delta T_b < 0$
No Ly-α present	$\delta T_b = 0$	$\delta T_b = 0$

Late EoR: $T_{IGM} \gg T_{CMB}$, and Ly-α present: $\delta T_b > 0$

In this case: **δT_b independent of T_s.**

Cosmic Dawn: $T_{IGM} < T_{CMB}$, and Ly-α present: $\delta T_b < 0$

Fluctuations due to T_s variations.

History of Temperatures

- $T_{CMB} \propto (1+z)^{-1}$
- $T_{kin,IGM} \propto (1+z)^{-2}$

Dark Ages

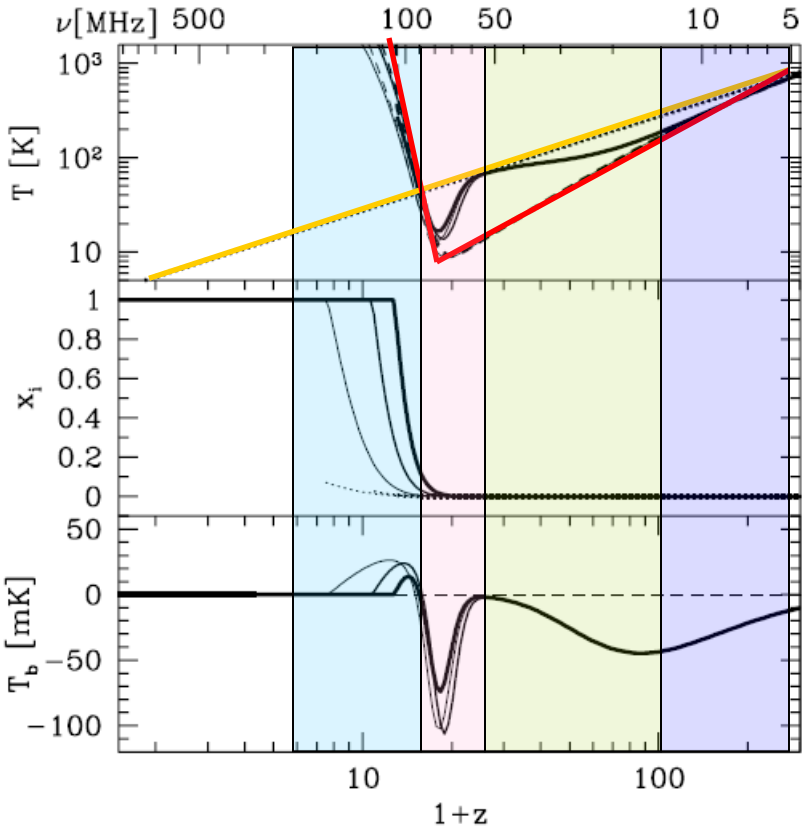
- **z >90: collisions couple T_s to T_{IGM} (< T_{CMB} for z<160).**
- **z ~ 30-50: collisional coupling weakens, and T_s tends to T_{CMB} (z ~ 30-50).**

Cosmic Dawn

- **z<25 (?): Coupling to Ly-α drives T_s back to low T_{IGM}** (Wouthuysen-Field effect).

EoR

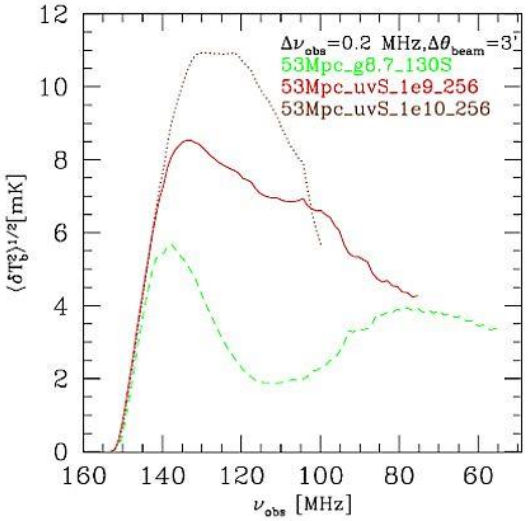
- **z<15 (?): IGM heated (X-rays, shocks) + substantial ionization.**



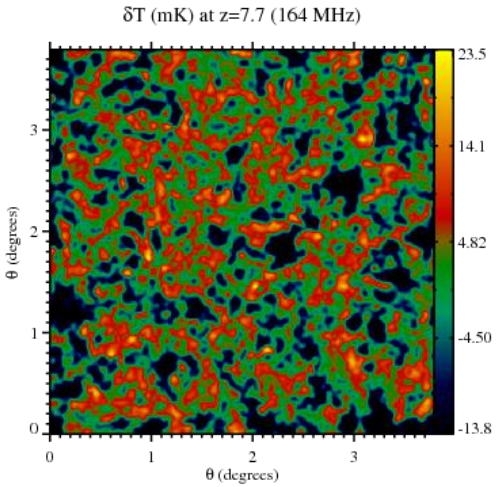
Pritchard & Loeb (2008)

Analysis 21cm Signal

- Statistical:
  - Variance measurements (as function of frequency)
  - Power spectra
  - Redshift space distortions
  - Higher order statistics



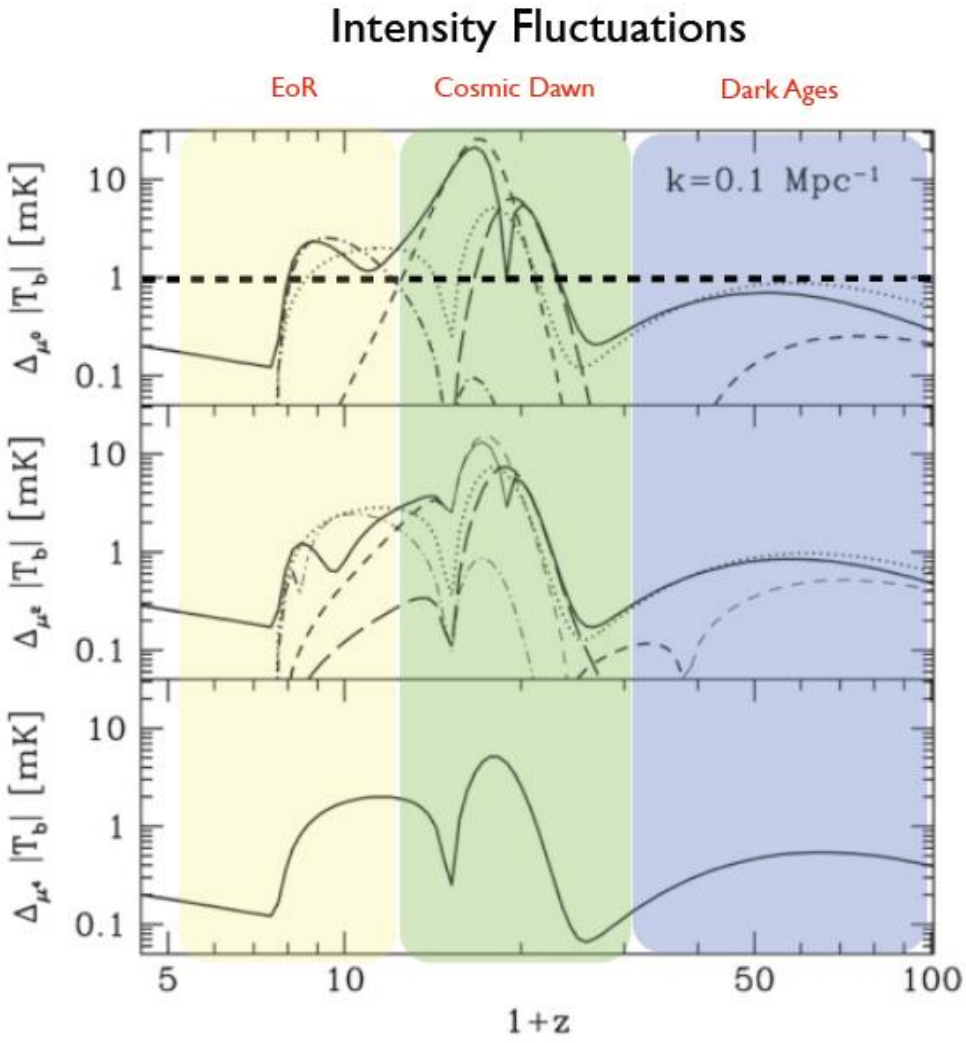
- Tomography:
  - Morphologies of HII regions
  - Special objects (QSOs)
  - Special regions (Galaxy surveys)
  - Density fluctuations



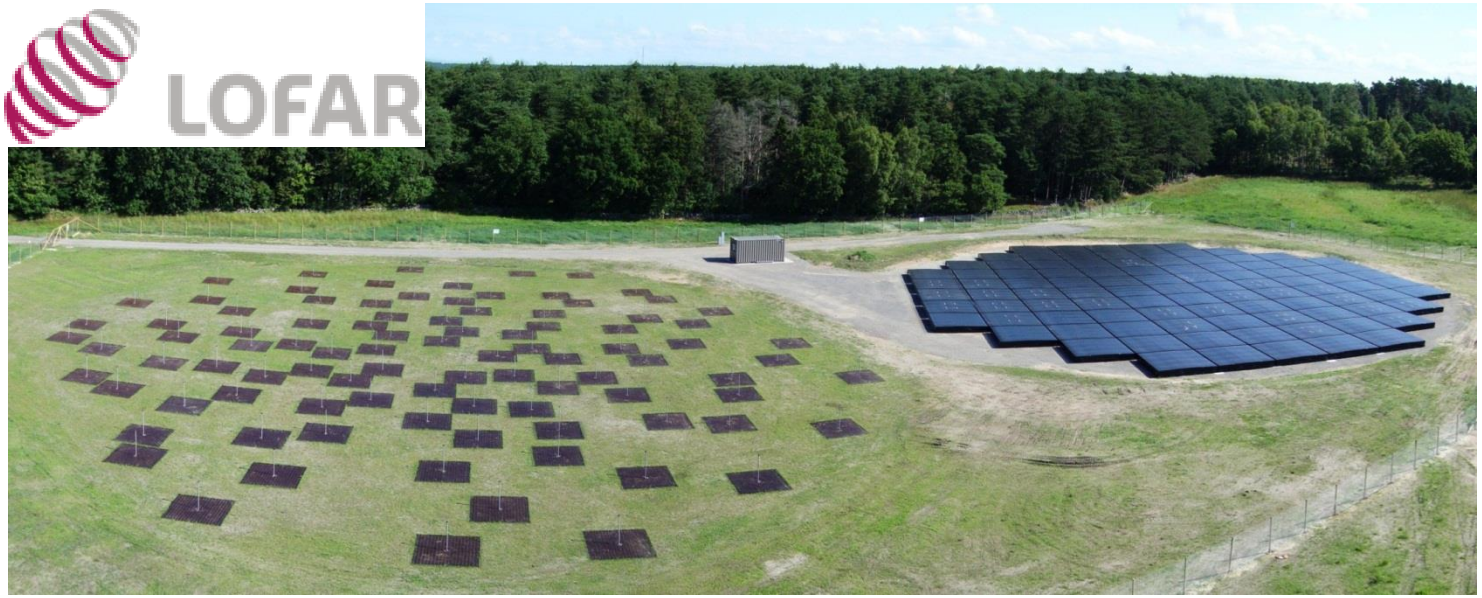
- SKA WP CD/EoR: Mellema et al. (2013)

Evolution of Power Spectrum

- Different models (Pritchard & Loeb 2009): many uncertainties.
- Three phases:
  - Ly-a coupling (CD)
  - X-ray heating (CD/EoR)
  - Photo-ionization (EoR)



LOFAR

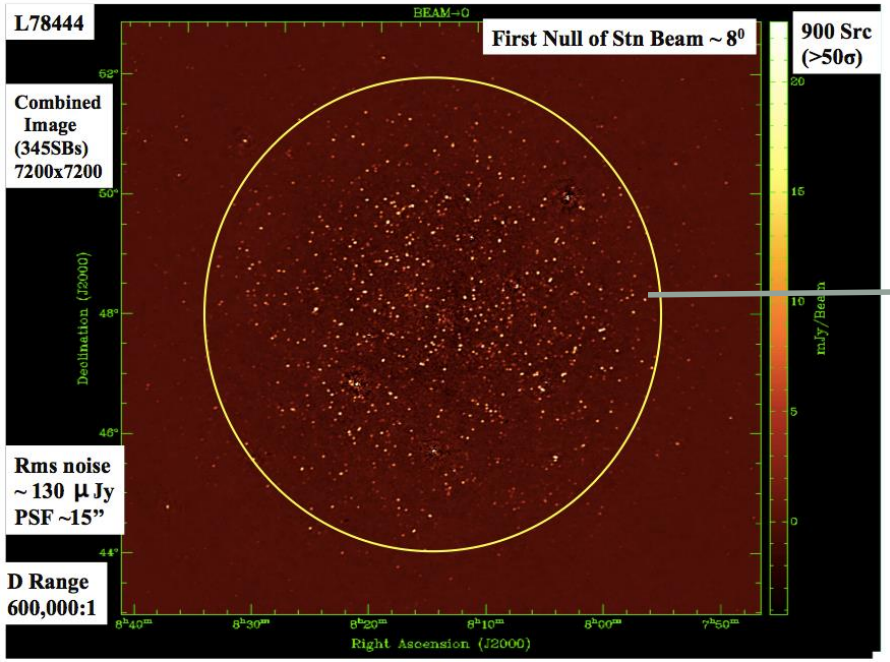


SKA
SQUARE KILOMETRE ARRAY
www.skatelescope.org

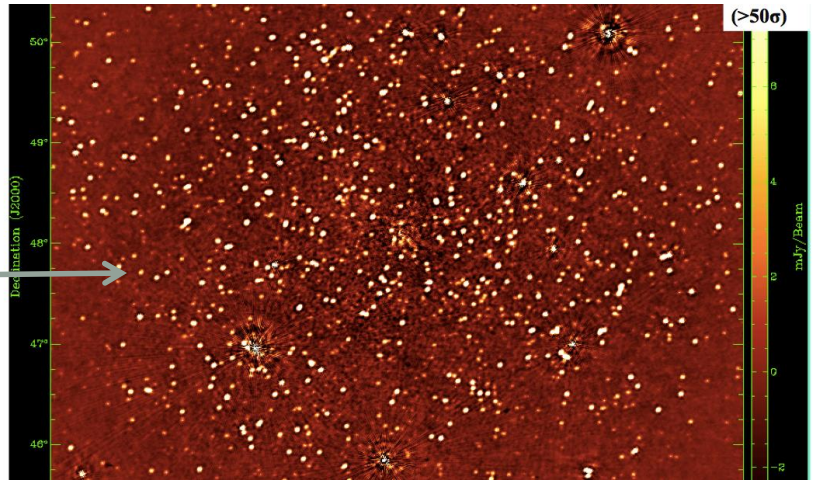
LOFAR EoR Project

- Observing since December 2012.
- Can deliver for z < 11:
  - Variance measurements
  - Power spectra
  - Skewness & kurtosis
  - Redshift space distortions (Jensen et al. 2013).
- A statistical HI detection experiment.
  - Smallest scales: ~4’
  - Largest scales: ~5°

LOFAR Precursor EoR studies



North Celestial Pole



Images with 10^6:1 dynamic range.

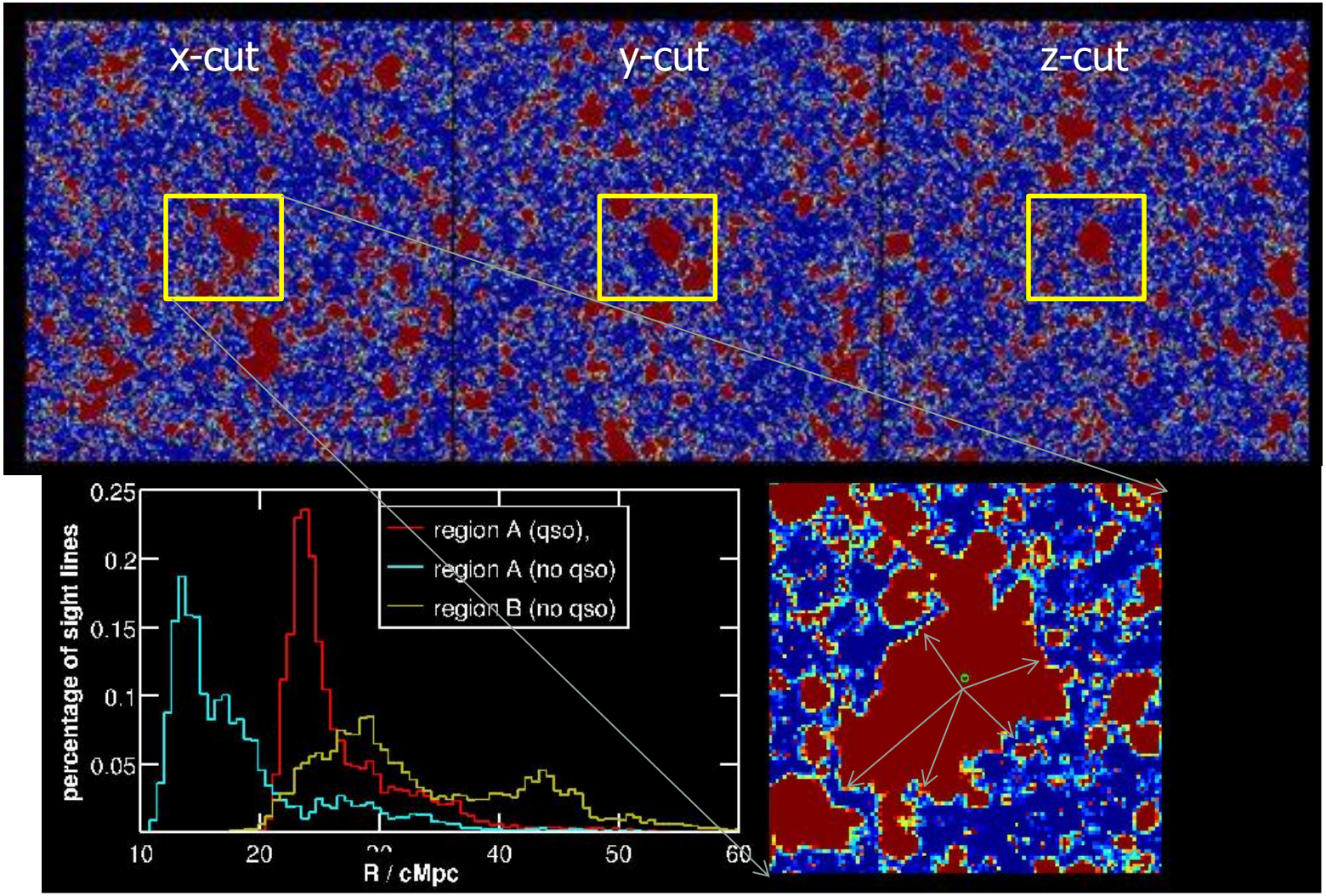
Frequency range 115 – 200 MHz

First statistical detection of EoR HI signal (for z<11) by end of 2014?

SKA Transformational

- The SKA, even in Phase I, can deliver
  - Power spectra for the entire Cosmic Dawn/EoR period ($6 < z < 25$).
  - Tomography at several arcmin scales for the entire EoR ($6 < z < 15$).
  - Range of scales: ~5’ to ~5° (frequency dependent).
- Will provide the first ever measurements of
  - The heating of the Universe before redshift 10.
  - The earliest star formation in the Universe.

Tomography Example: QSO HII Region



Datta et al. 2012

CD/EoR Science

- Astrophysics:
  - Obtaining a census of earliest star formation and galaxies.
  - Mapping the early development of the cosmic web.
  - Analysing the growth of Black Holes.
  - Establishing the effect of radiative feedback on galaxy growth/formation
- Cosmology:
  - Testing the ΛCDM model of the Universe in new regimes.
  - Measuring the statistics of the Universe's matter distribution.
  - Imposing constraints on the nature of dark matter.

Summary

- The SKA will allow the first observations of
  - The Cosmic Dawn ($15 < z < 25$)
  - Tomography of the Epoch of Reionization ($z < 15$) at arcmin scales.
- The redshifted 21cm data is essential for constraining the reionization process.
- Beyond z=10, the 21cm signal is currently the only observable for our Universe!
- It's going to be exciting!