Probing Reionization with the Redshifted 21 cm line

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Overview

i. Introduction.

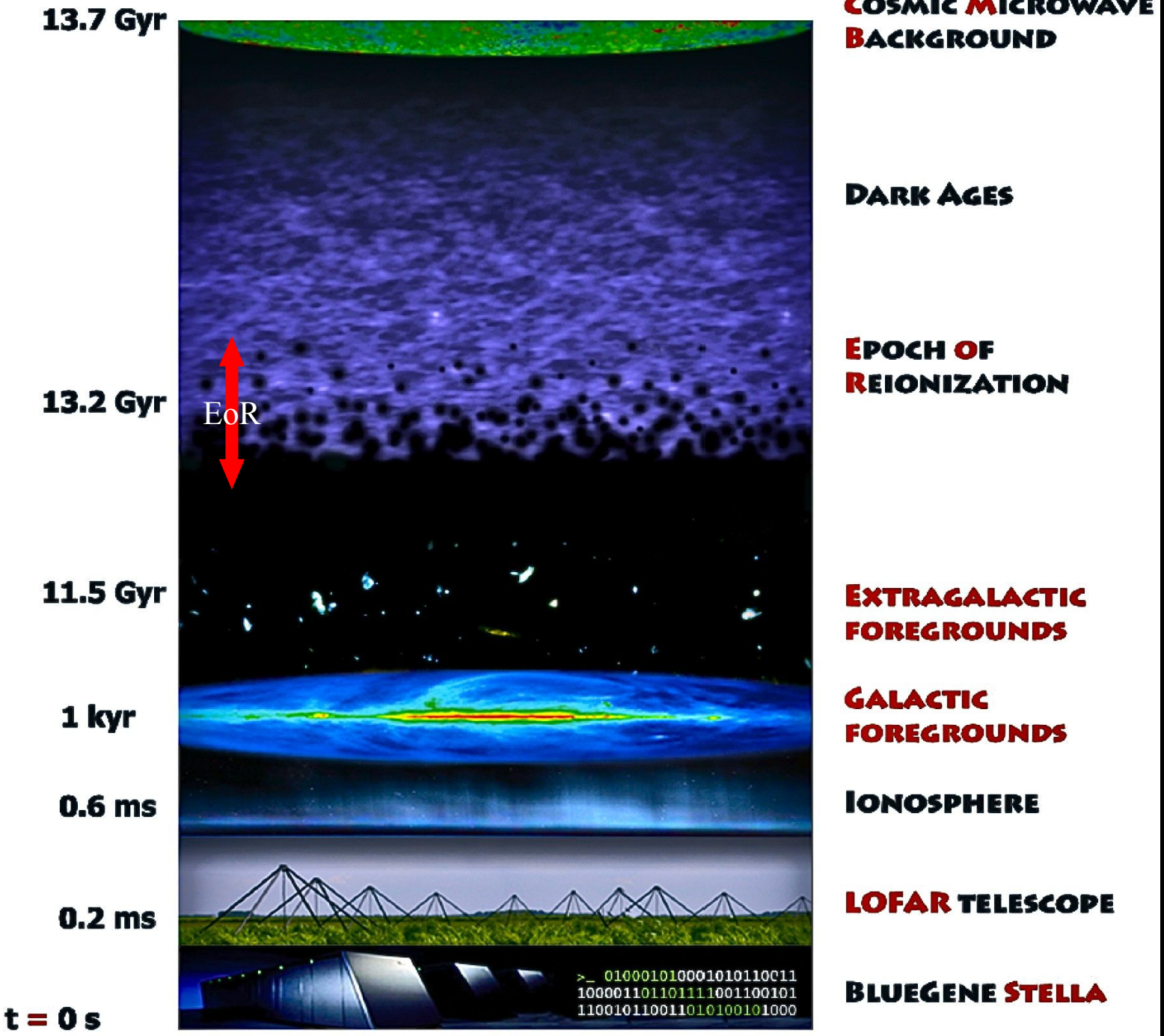
ii. Current observational constraints.

iii. Physical sources of cosmic reionization.

iv. The 21 cm probe and its physics.

v. The experiment and its challenges

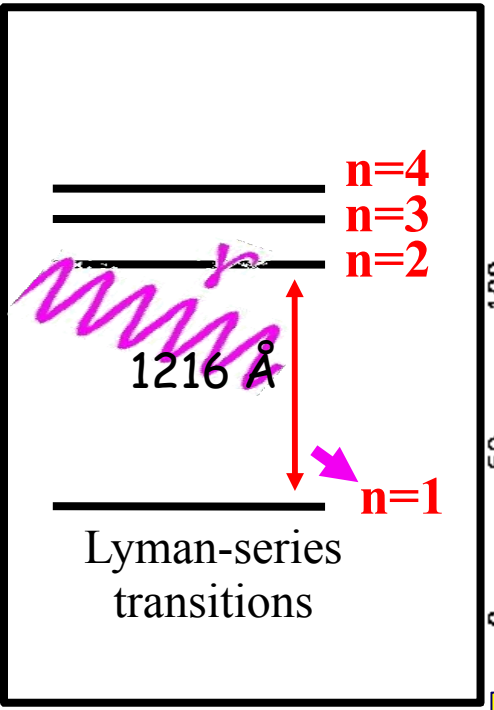
vi. Summary


13.7 Gyr
13.2 Gyr
11.5 Gyr
1 kyr
0.6 ms
0.2 ms
t = 0 s
EoR
Cosmic Microwave Background
Dark Ages
Epoch of Reionization
Extragalactic foregrounds
Galactic foregrounds
Ionosphere
LOFAR telescope
BlueGene Stella

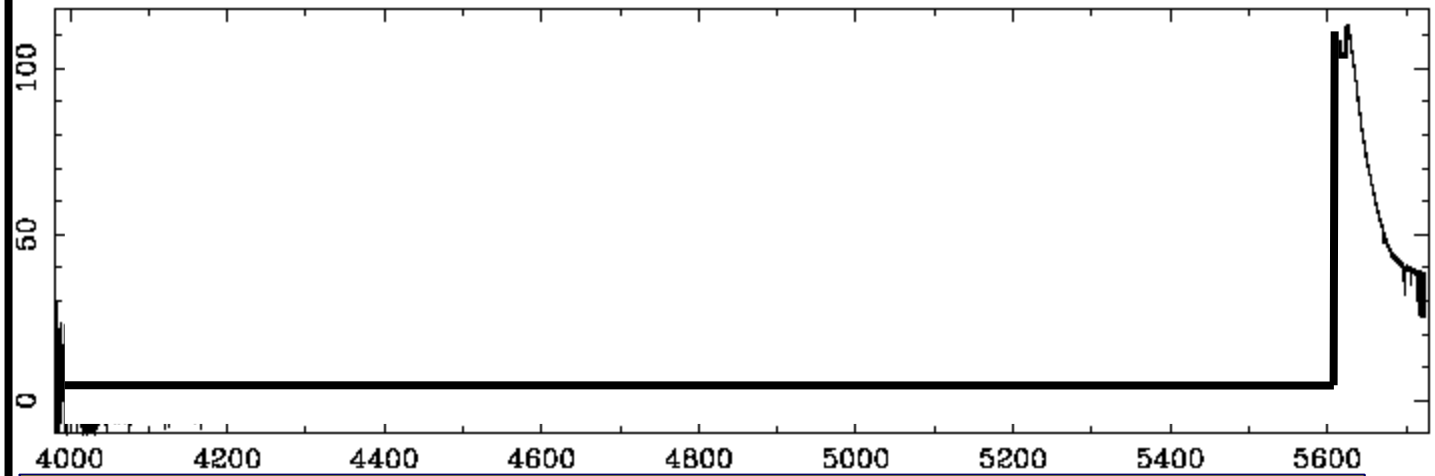
What do we know?

The Lyman-alpha forest

The Lyman-α optical depth from Quasar spectra

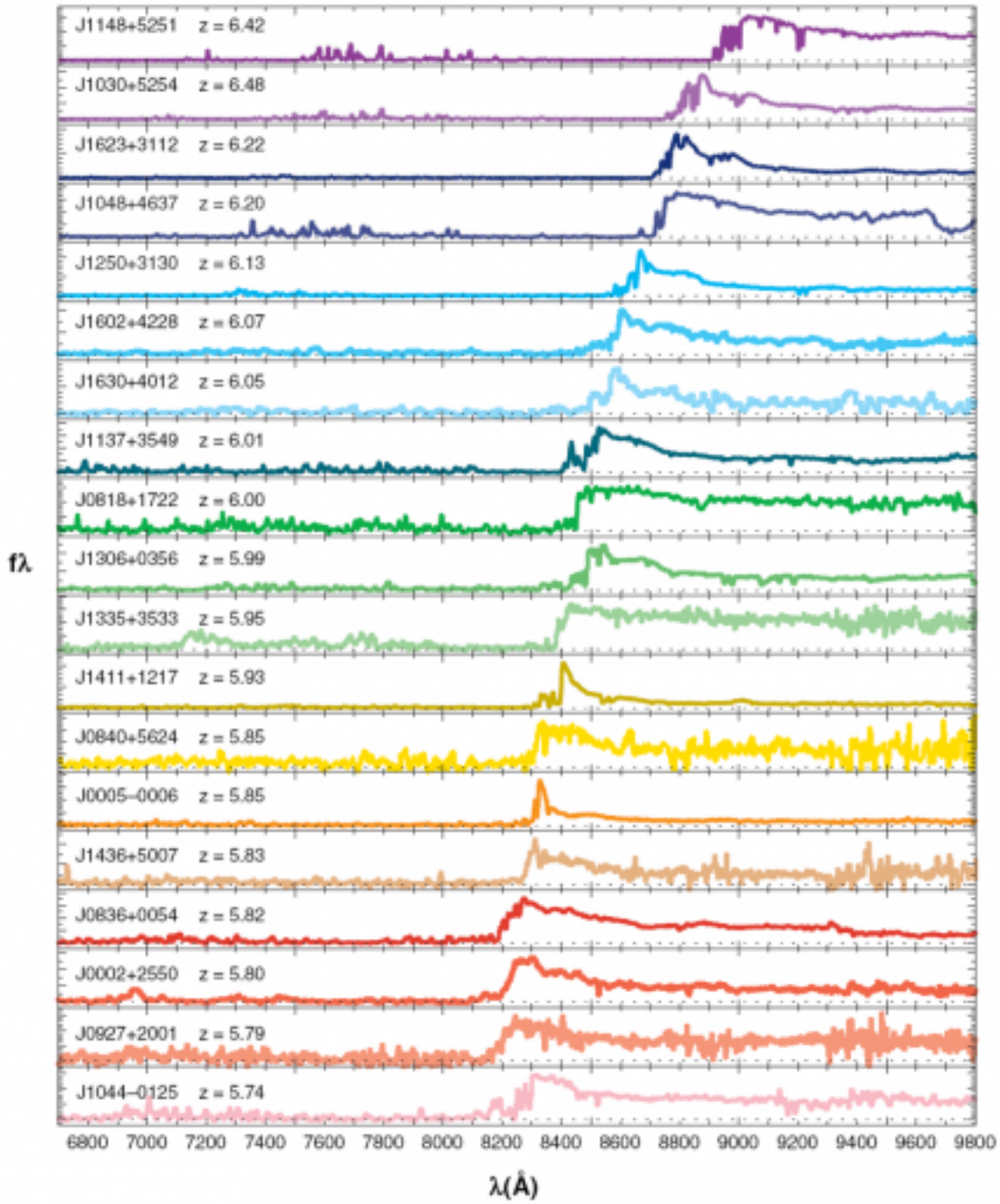


The Lyman-α Forest Along Distant Quasar Spectra ($t_{Universe}$~1 Billion yr)



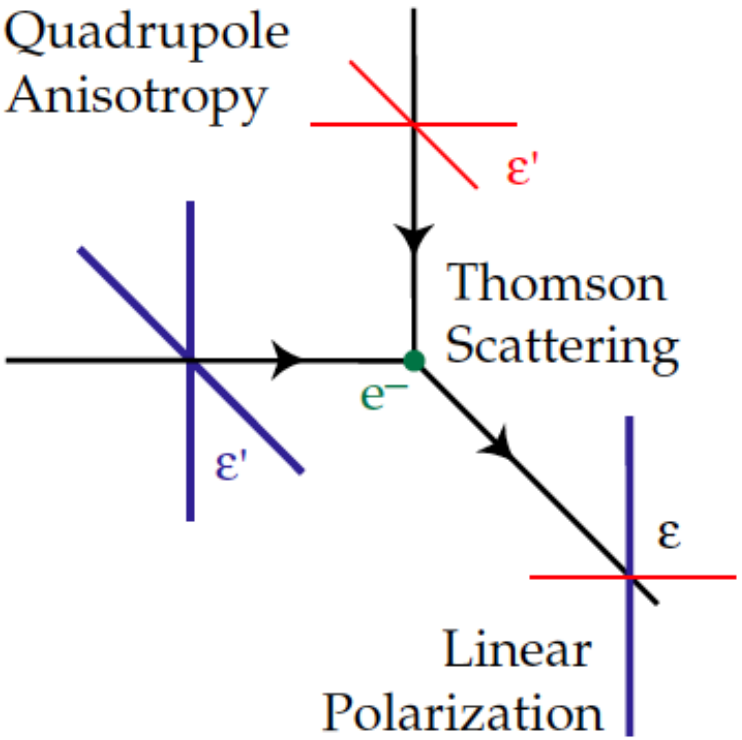
At z < 6 the highly ionized (10^{-4} neutral)

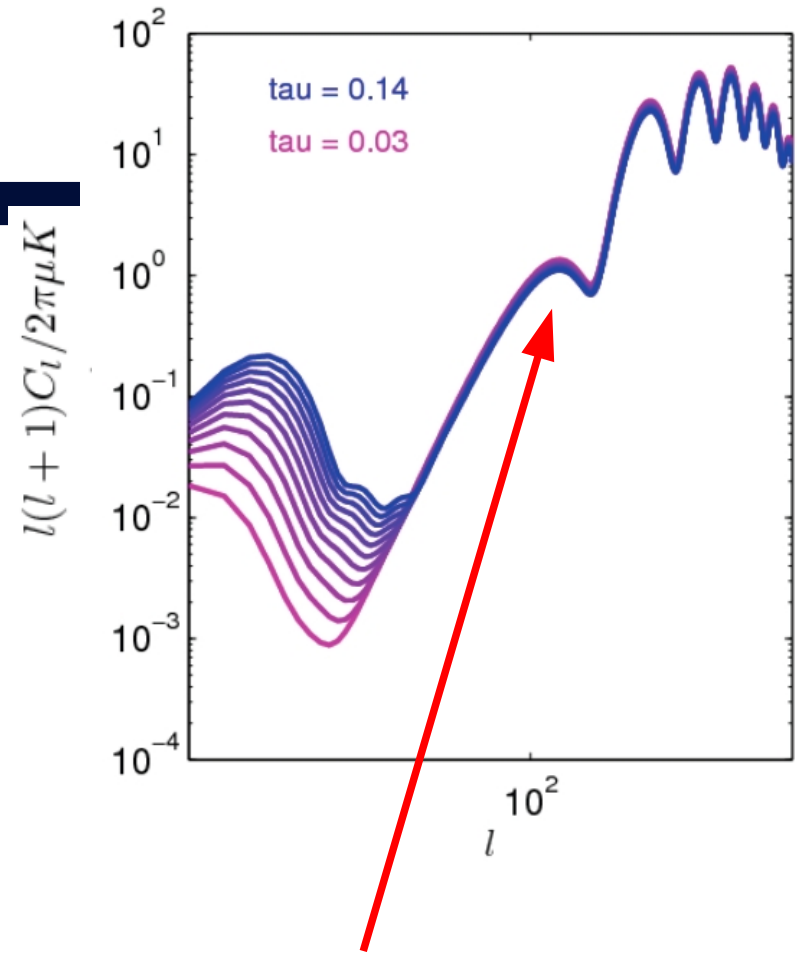
High redshift Sloan Digital Sky Survey quasars. The Lyman-α forest at z~6.



Fan et al. 2003, 2006

CMB polarization

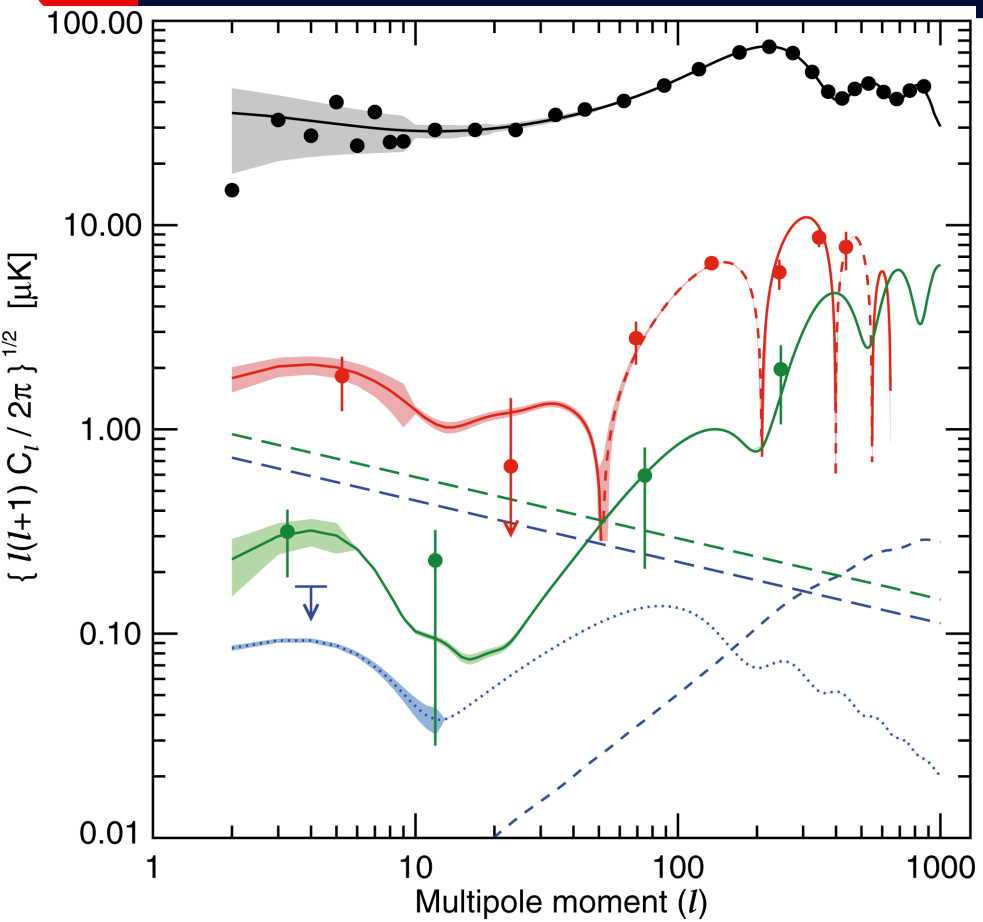




The Horizon Scale at recombination (z=1100)

From A. Lewis

The WMAP constraint

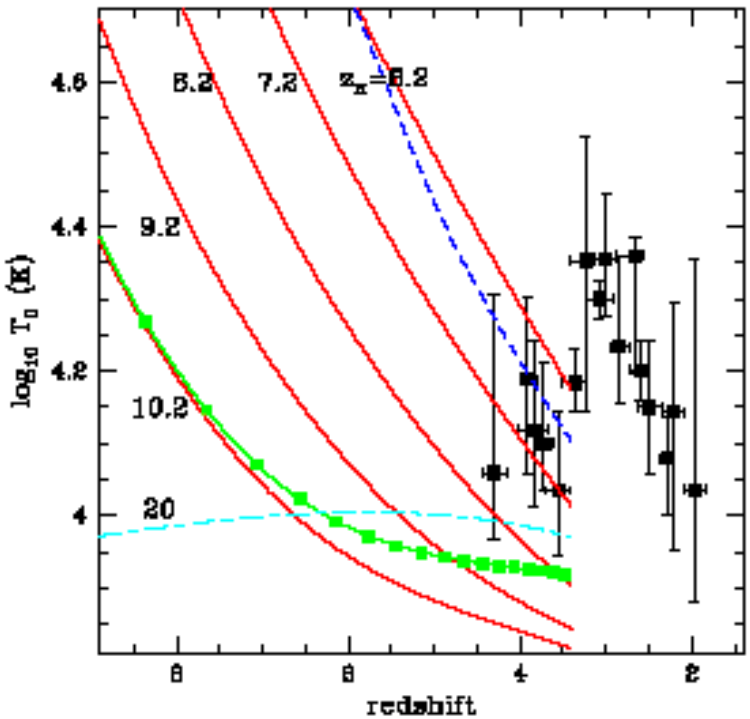


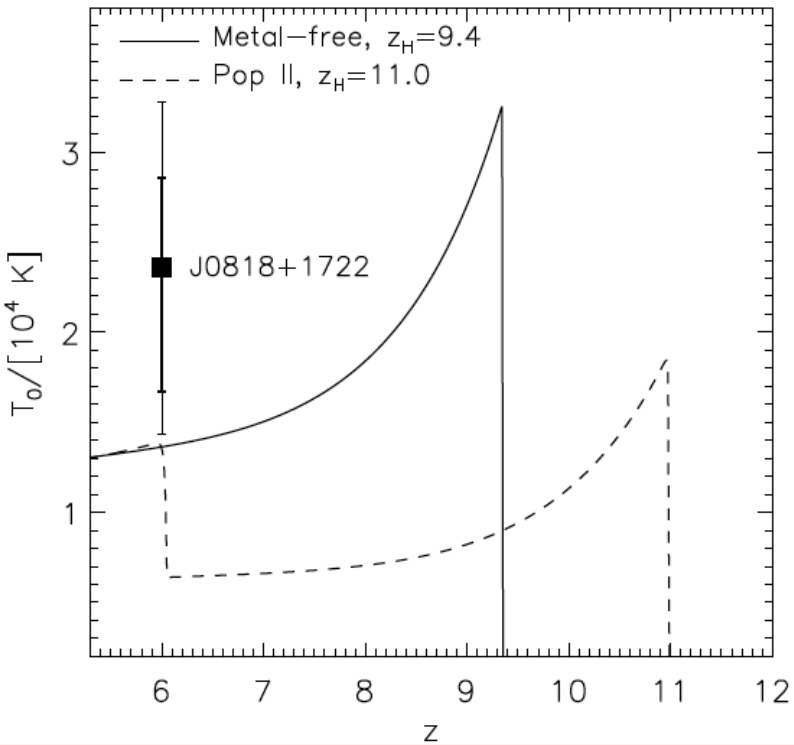
$\tau \sim 0.088$

The WMAP polarization measurement tells us only about the optical depth not about exact ionization redshift. For that one needs a reionization history model. However, reasonable reionization models suggest that ionization has happened at about z~10.

The IGM temperature at low z

$$\frac{1}{T_0}\frac{dT_0}{dt} - \frac{1}{\mu}\frac{d\mu}{dt} = -2H_0 + \frac{\mu\Delta_\epsilon}{-\frac{3}{2}k_B T_0}$$





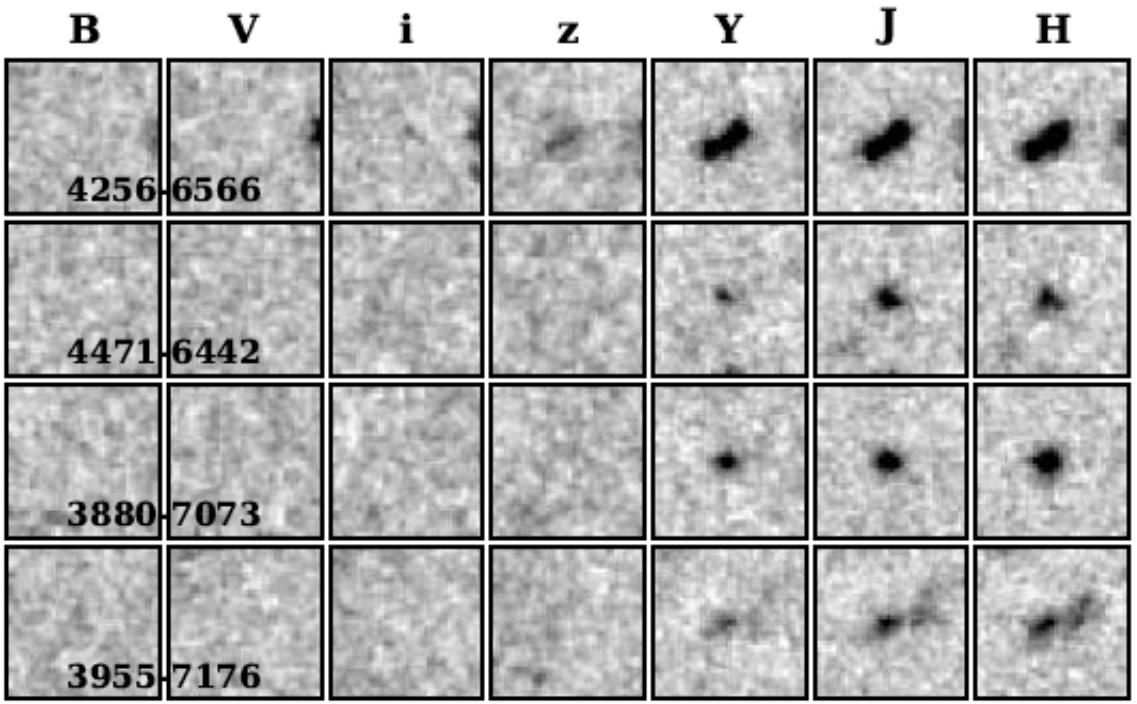
Theuns et al. 2002
Haiman & Hui 2003

Bolton et al. 2010

Galaxies at z~7-9
HST WPC3 data

WFC3/IR: 850 - 1170nm
2.1 × 2.3 arcmin field of view
0.13 arcsec pixel^{-1}
10 times survey power of NIC3

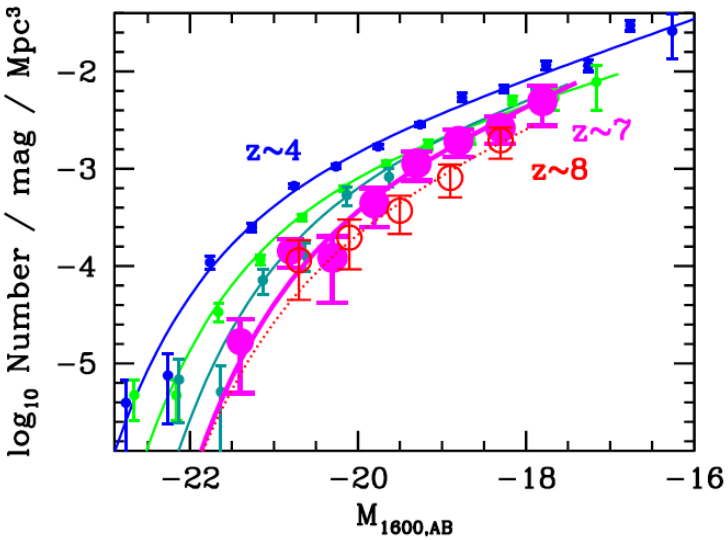
UDF 4.7 arcmin^2
60 orbits in YJH
Reaches m_{AB}~29 (5σ)

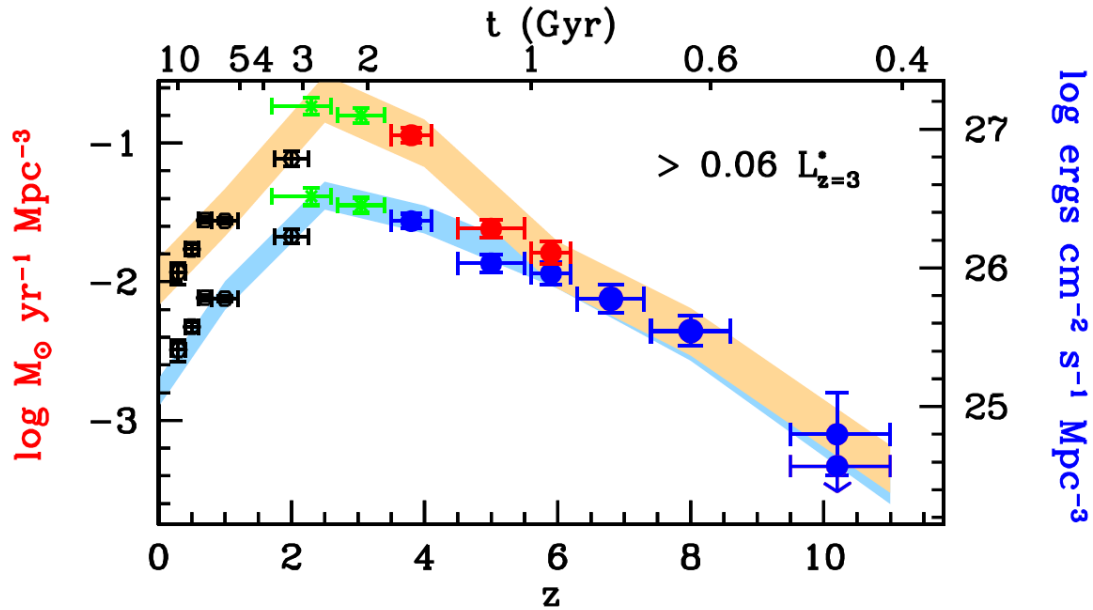


Oesch et al 2010
Bouwens et a. 2010

Galaxies

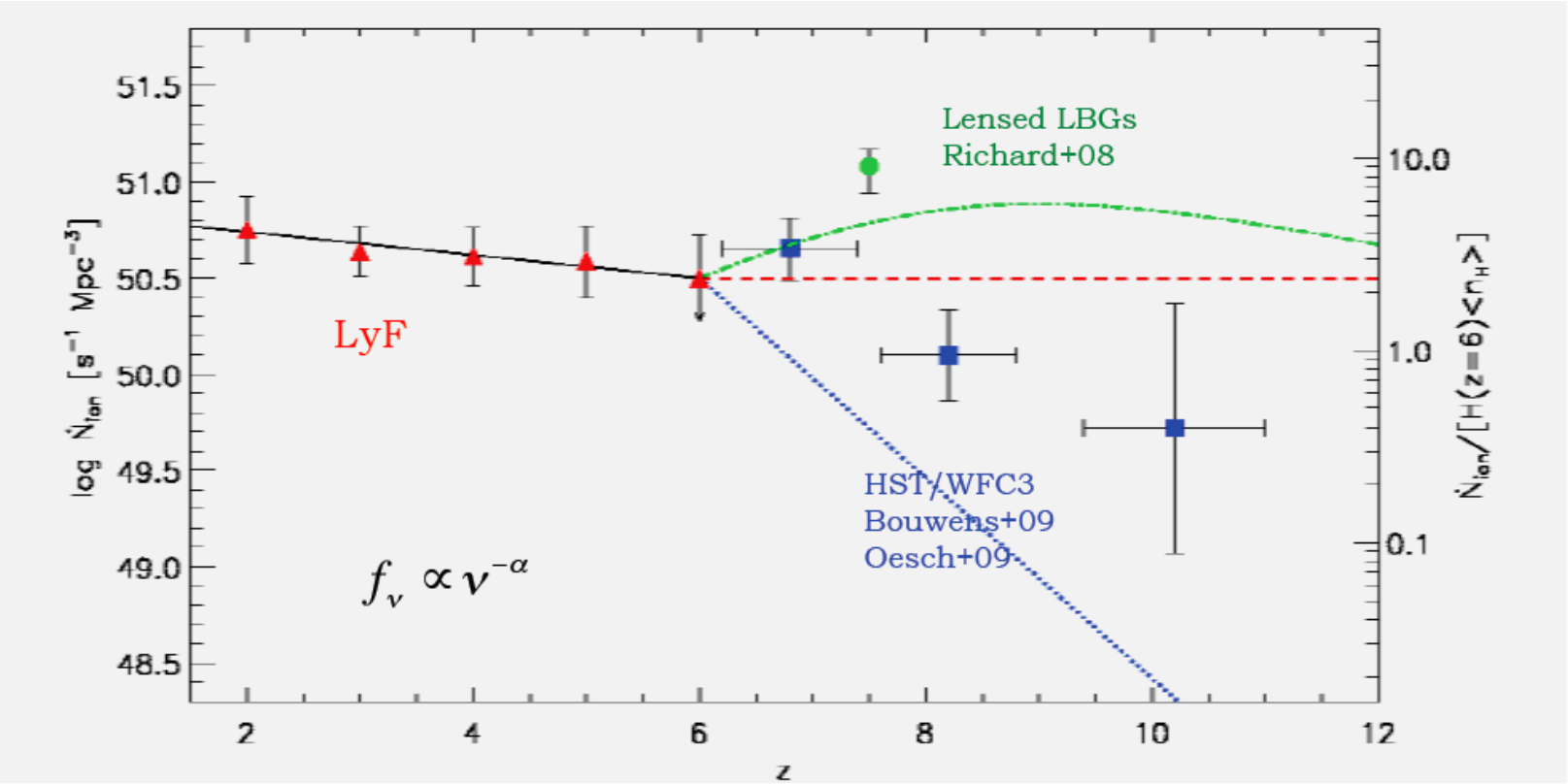
Galaxies appear to become bluer and show more Lyα with decreasing luminosity and increasing redshift.





Bouwens et al. 2010

Are we missing photons?



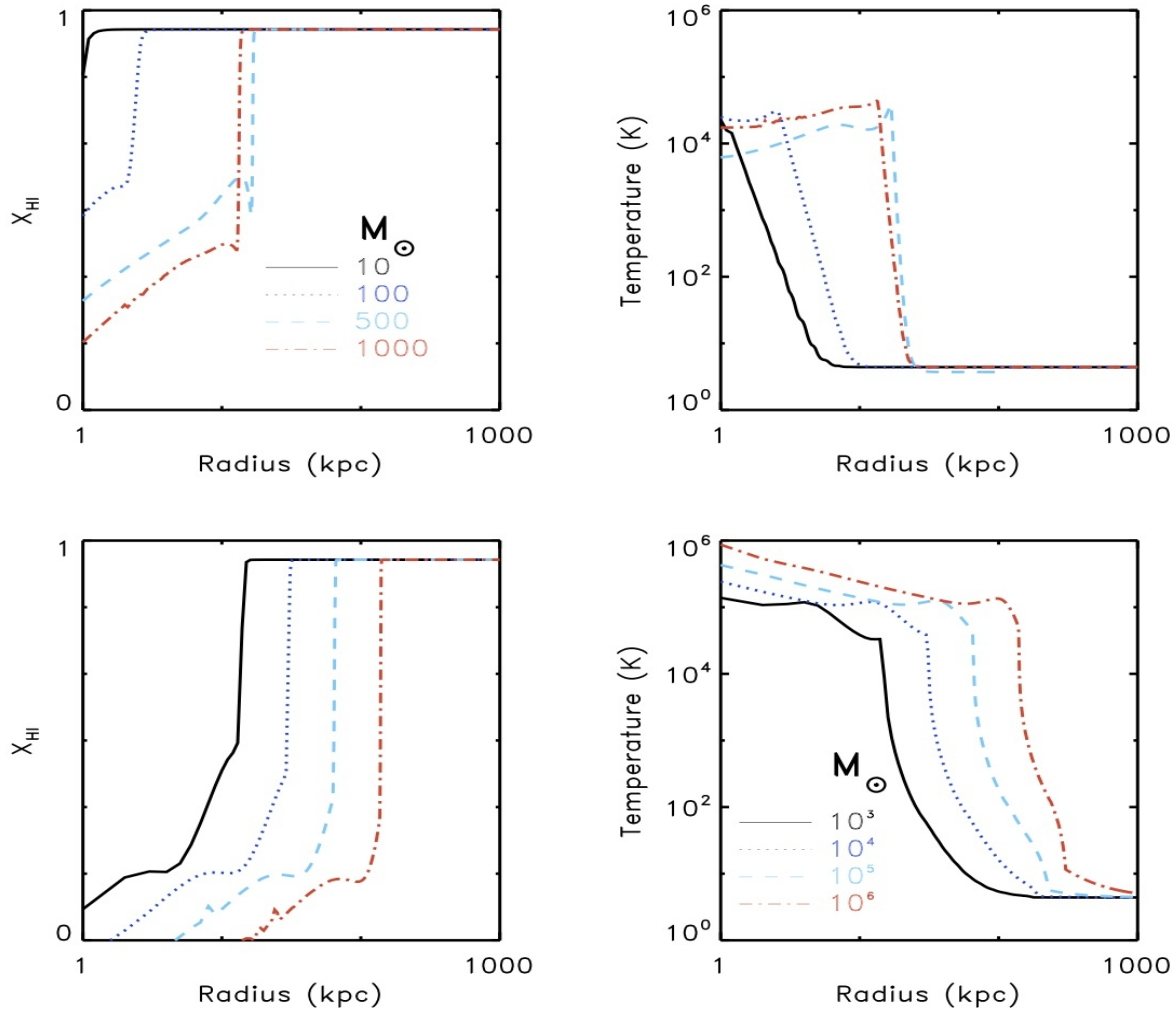
Courtesy of M. Haehnelt

What don't we know?

- When did the reionization happen?
- What are the sources of ionizing radiation? Stars, miniqsos, decaying DM, exotic physics,...
- How fast did it spread and in what fashion?
- How did the reionization influence the subsequent galaxy and structure formation in the Universe?
- .....

Key Probes of Reionization

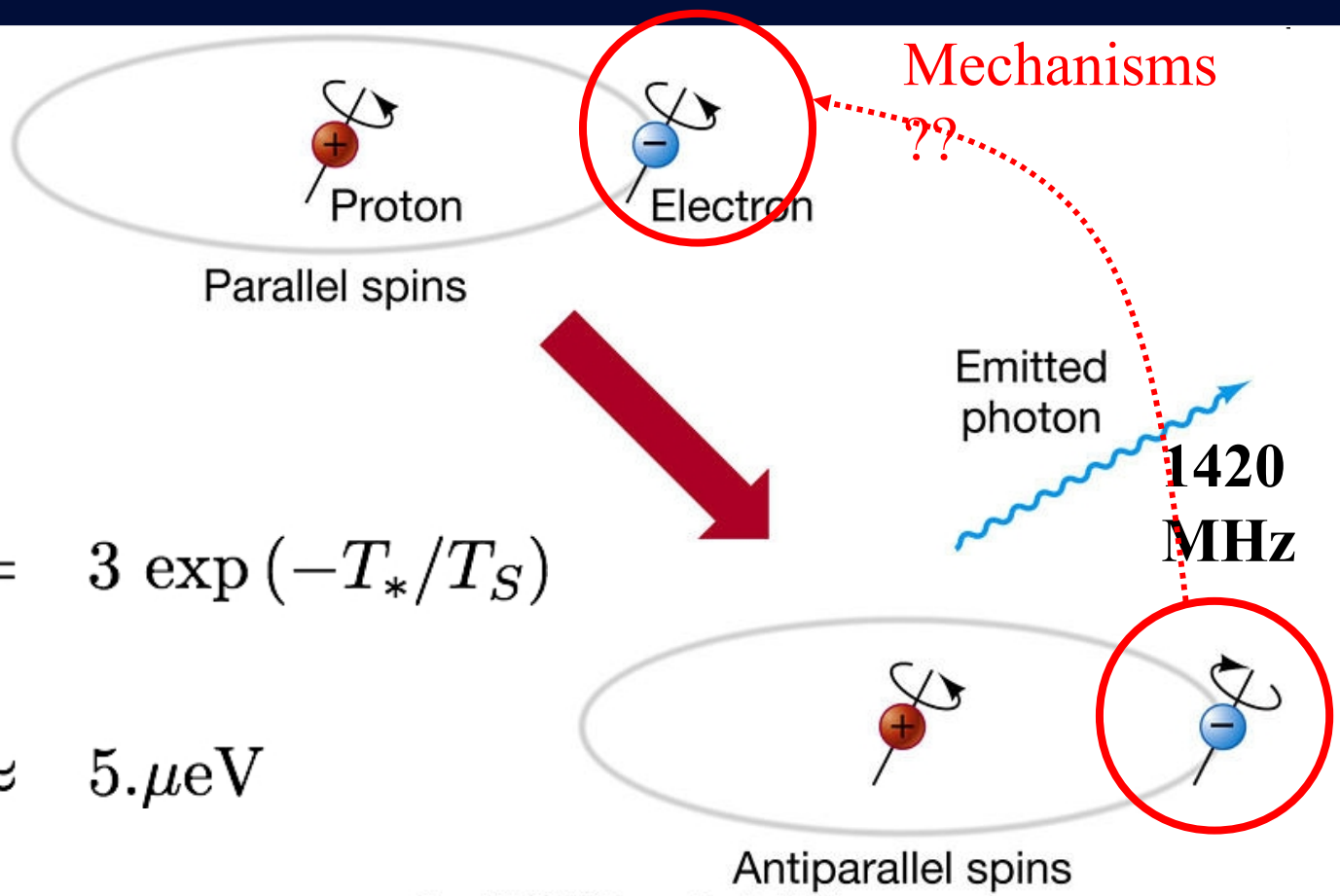
- CMB (integral constraint)
- Redshifted 21 cm emission (absorption)
- 21 cm forest at high z
- Gamma ray bursts: How many we should have to constrain reionization?
- Luminosity function of first objects, e.g., Galaxies: Recent results from the new WFC3 aboard HST.
- Background detections: IR, soft x-ray.
- Lyman-α absorption system: ionization, metallicity, thermal history, UV background, proximity effect.
- Lyman alpha emitters
- Metals at high redshift.
- Using the local volume to study reionization.


1
0
X_{HI}
1
1000
Radius (kpc)
$M_\odot$
10
100
500
1000
10^6
10^4
10^2
10^0
Temperature (K)
1
1000
Radius (kpc)
1
0
X_{HI}
1
1000
Radius (kpc)
10^6
10^4
10^2
10^0
Temperature (K)
$M_\odot$
10^3
10^4
10^5
10^6
1
1000
Radius (kpc)

Possible Sources of Reionization

- Population III stars (Hydrogen & Helium)
  - Very massive, short lived, low abundance, intense UV radiation. Never observed but must have existed!
- Population II stars
  - Normal masses, long lived, abundant, moderate UV radiation. These are the old stars observed all around us.
- Mini-quasars (Black hole mass 100-million M_{sun})
  - Black hole driven, very intense, very energetic photons.
- Decaying/annihilating Dark matter particles
- More esoteric physics, e.g., Decaying cosmic strings

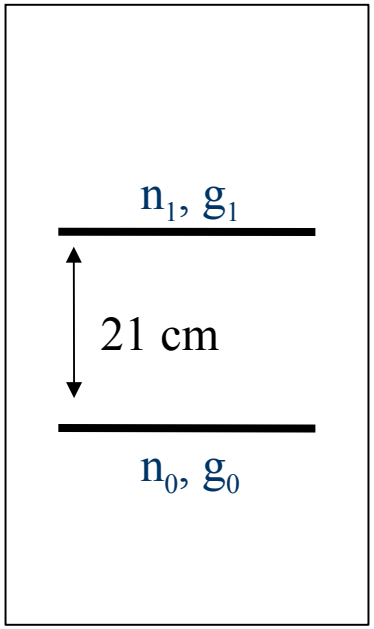
21-cm Physics



$$\frac{n_1}{n_0} = 3\,\exp\left(-T_*/T_S\right)$$

$$T_* \approx 5.\mu\mathrm{eV}$$

The 21 cm transition



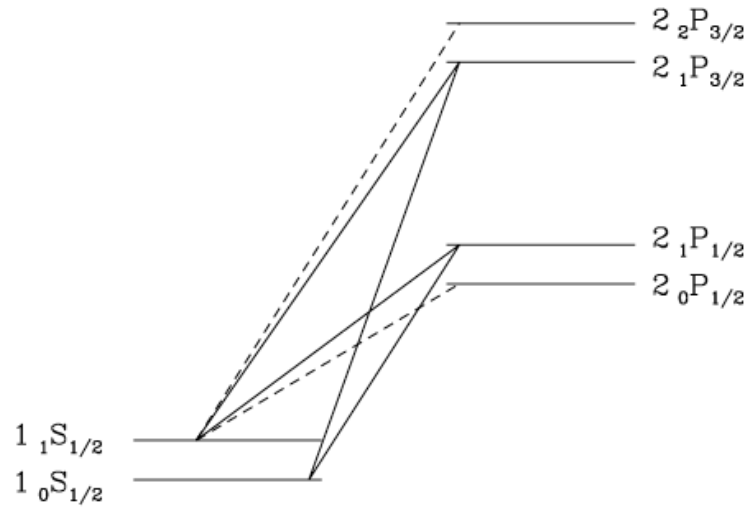
- The value of the T_s is given by:

$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_k^{-1} + x_c T_k^{-1}}{1 + x_\alpha + x_c}$$

Field 1958
Madau et al 98
Ciardi & Madau 2003

Lyman-α Coupling

- The Wouthuysen-Field effect, also known as Lyman-alpha pumping.



Dominant in both in the case of stars and Black-holes, due to photo and collisional excitations, respectively.

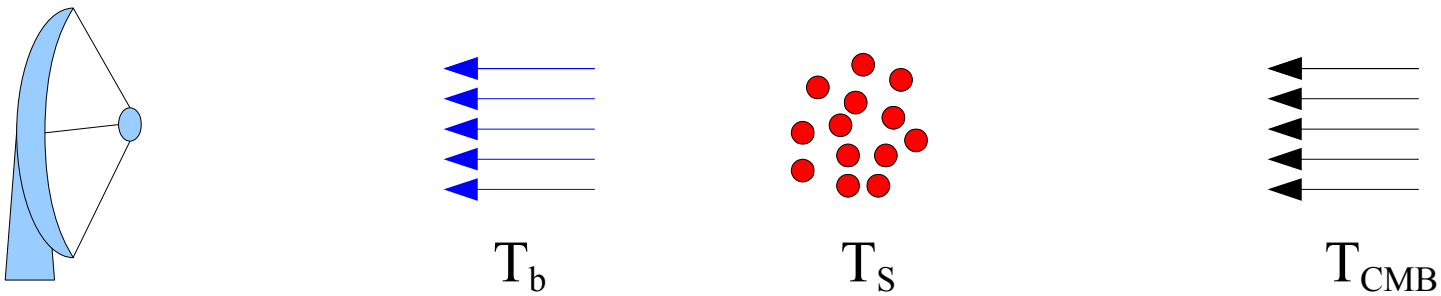
Wouthuysen 1952
Field 1958

Collisional Coupling

- H-H collisions that excite the 21 cm transition. This interaction proceeds through electron exchange.
- H-e collisions. Especially important around primordial X-ray sources (mini-quasars).
  - This effect might also excite Lyman-alpha transition which adds to the T_s- T_{CMB} decoupling efficiency.

Furlanetto & Furlanetto 2007

δT_b, The Brightness Temperature

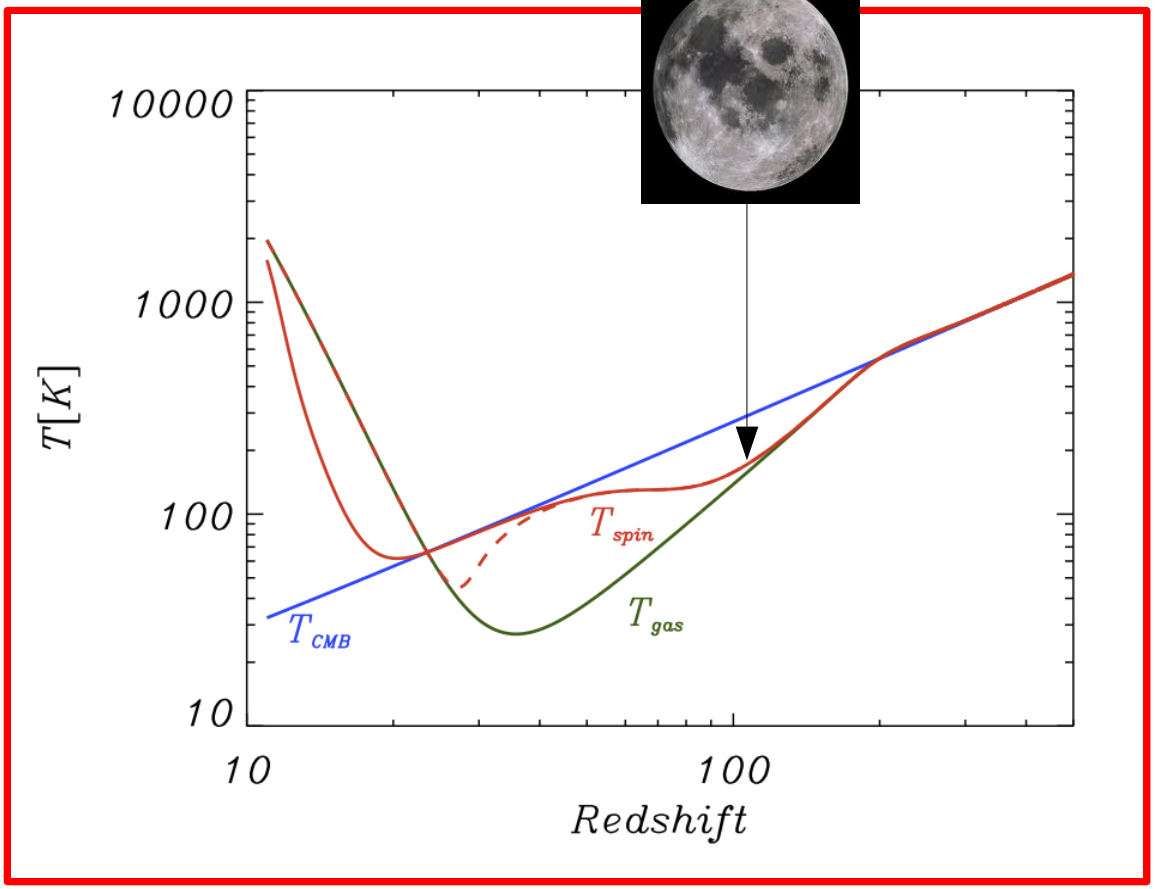


$$\delta T_b \approx 28\text{mK}\,(1+\delta)\,x_{HI}\,\frac{T_s - T_{CMB}}{T_s}\,\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Astrophysics

Cosmology

The Global evolution of the Spin Temperature



At z~20 T_s is tightly coupled to T_{CMB}. In order to observe the 21 cm radiation decoupling must occur.

Heating much above the CMB temp. and decoupling do not necessarily occur together.

Loeb & Zaldarriaga 2004,Pritchard & Loeb 2008, Baek et al. 2010, Thomas & Zaroubi 2010

Simulations of the EoR

- Cosmological Hydro simulations:

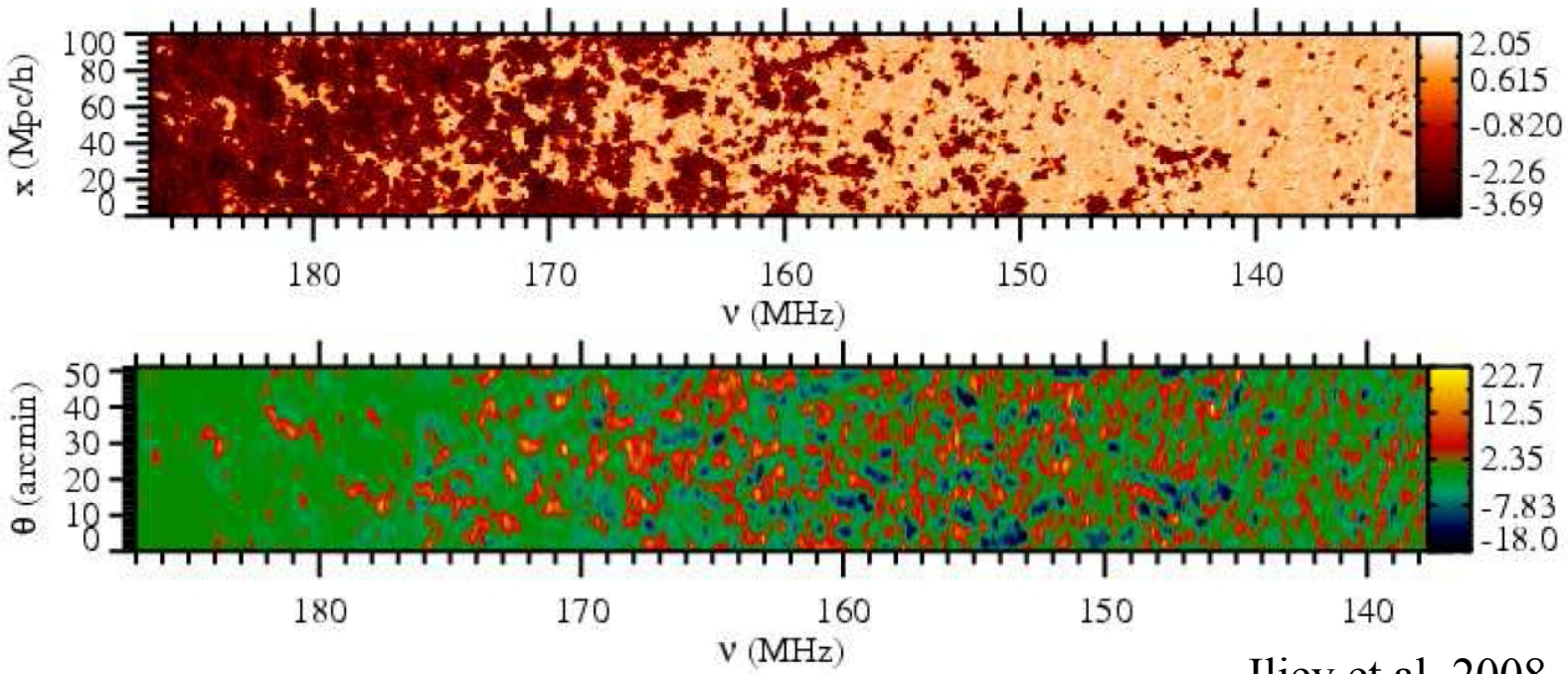
  1- High enough resolution to resolve halos in which ionization sources form. 2- Span Large Scales as well as small scales, especially since designed arrays have small 1' res. 3- In certain cases DM only simulations are sufficient.

- Out of equilibrium Radiative Transfer:

  1- Sources and their SED. 2- Ionization of H and He (not always done). 3- Heating due to the radiative processes. 4- Spin temp decoupling (Lyα & x-ray RT).

- It is very difficult to account for all the physical aspects of the problem and approximations are normally made.

Results from 3D RT

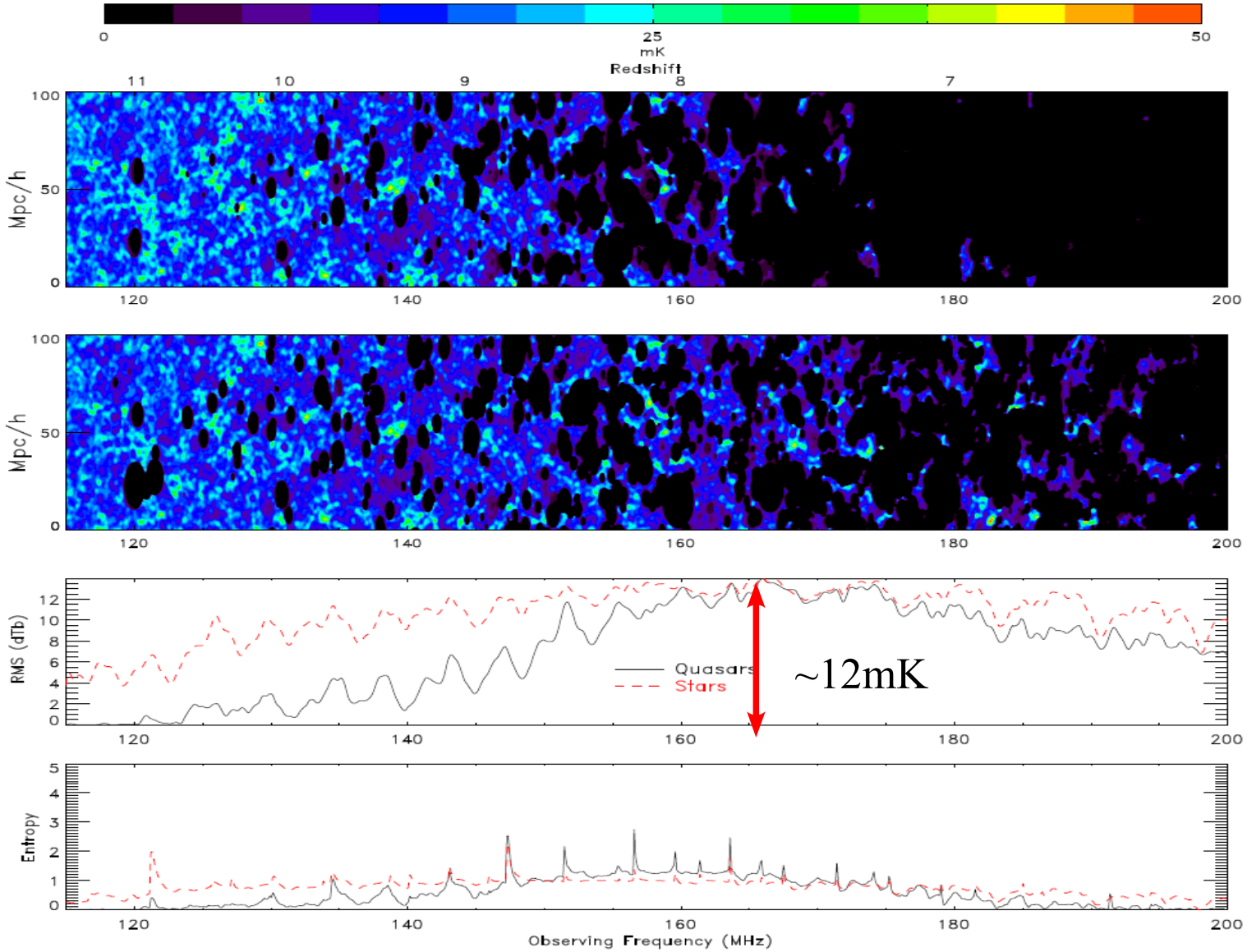


Iliev et al. 2008

At half ionization the signal rms is about 8mK

$$\delta T_b \approx 28\text{mK}\,(1+\delta)x_{HI}\cancel{\frac{T_s - T_{CMB}}{T_s}}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

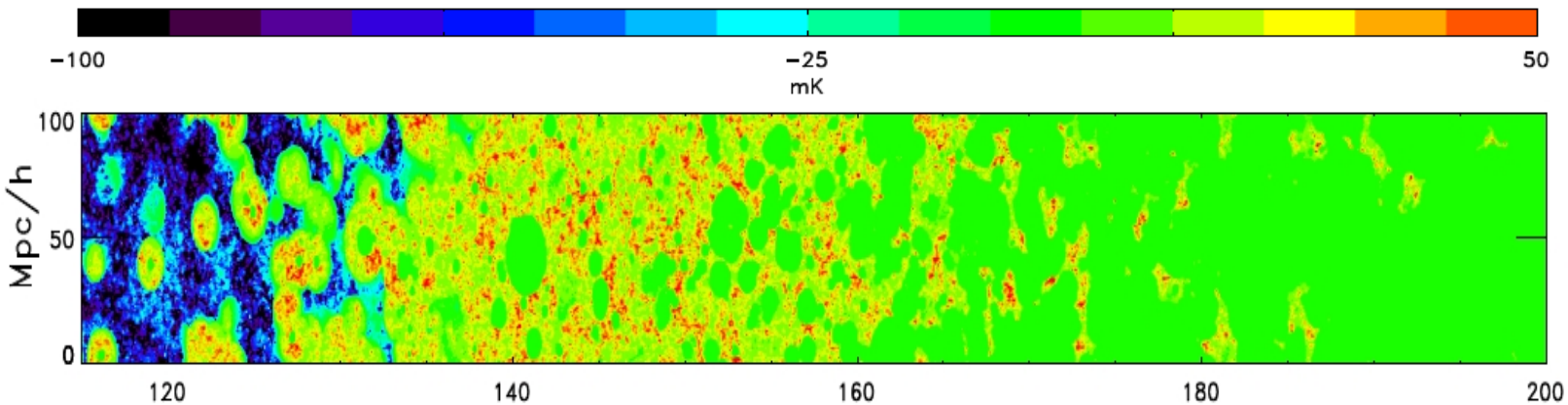
Results from approximate methods



Thomas & Zaroubi 2008, Thomas et al 2009

Spin Temperature issues

In case the spin temp. is of the order the CMB temp. or smaller an absorption signature is expected at high redshifts.



$$\delta T_b \approx 28\text{mK}\,(1+\delta)x_{HI}\frac{T_s - T_{CMB}}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Thomas & Zaroubi 2010
See also Baek et al. 2010

LOFAR

MWA

PAPER

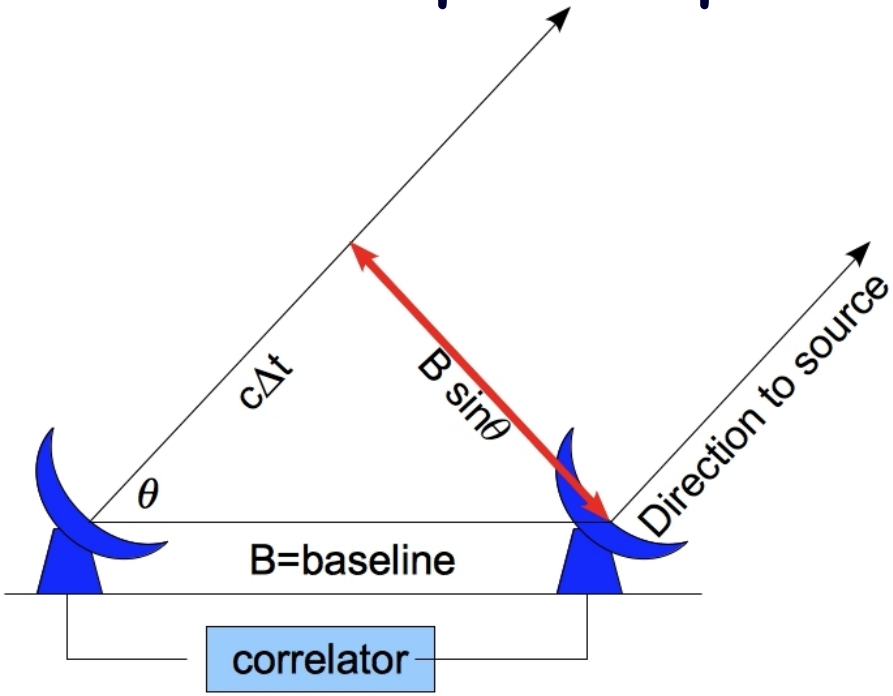
GMRT

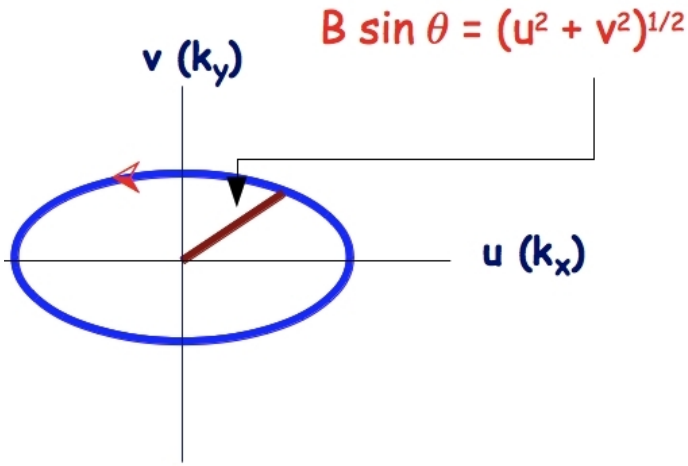
SKA

21CMA

Radio interferometry (Fourier space measurement)

An interferometer measures coherence in the electric field between pairs of points (baselines).



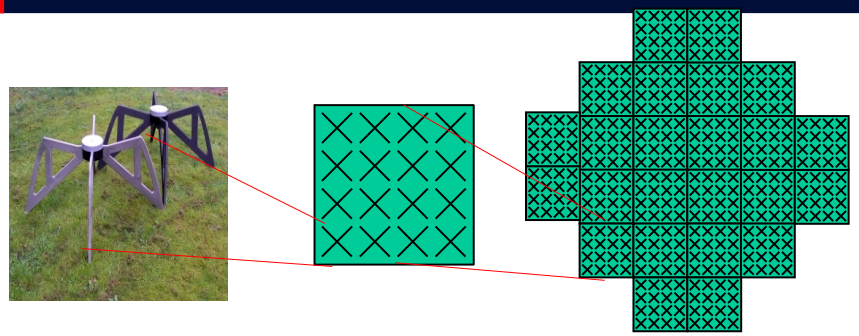


Time delay is essential to measure the same phase of the wavefront

The LOFAR observatory

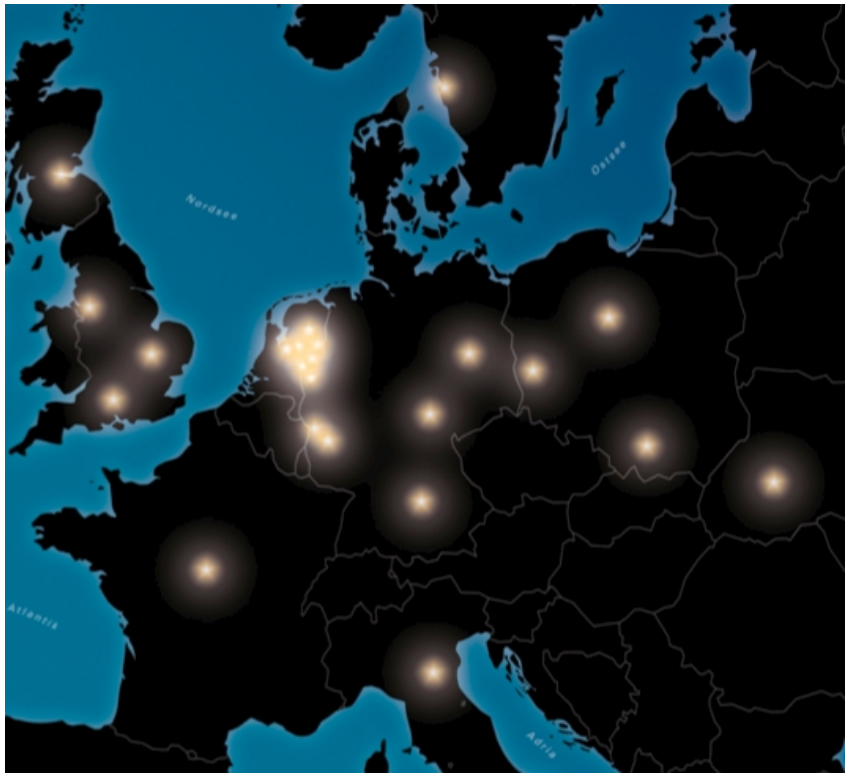
LBA (10) 30 - 90 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)



Core	2 km	23+ stations
NL	80 km	18+ stations
Europe	>1000 km	8+ stations

Total # of HBA dipoles: ~ 50000.

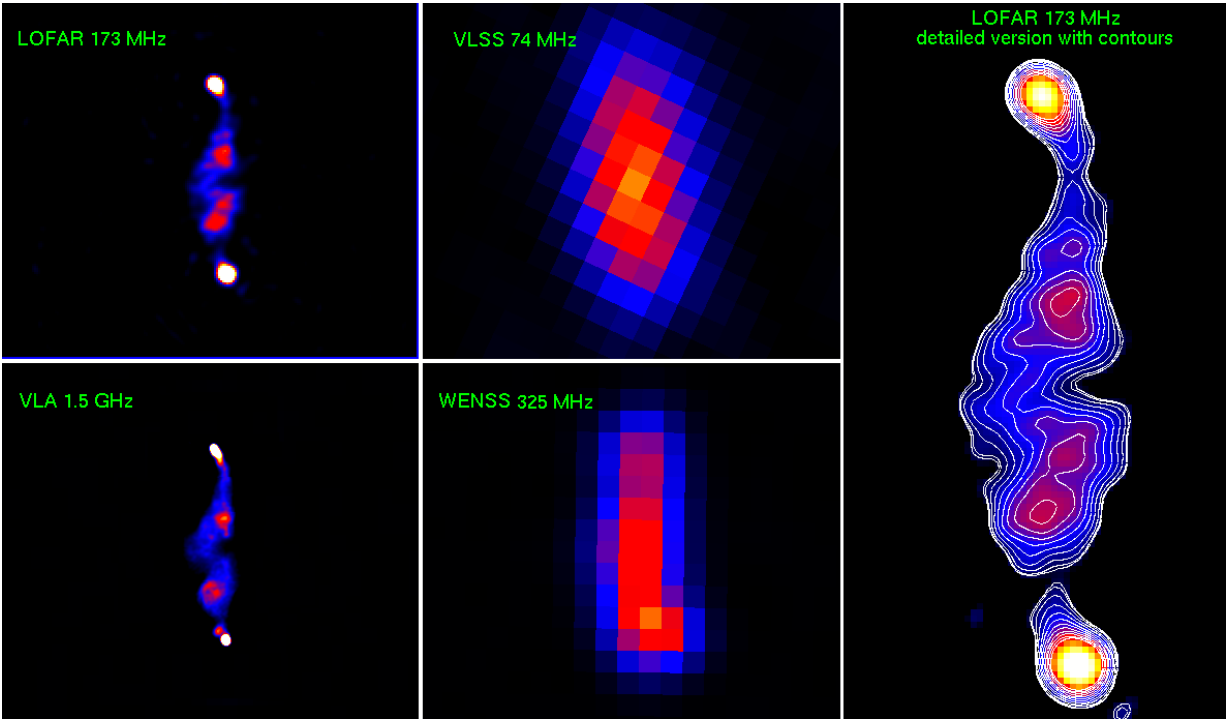


Timeline:
1. Official opening: June 2010
2. Data for our project starts: Jan. 2011
3. First results (hopefully) mid 2012

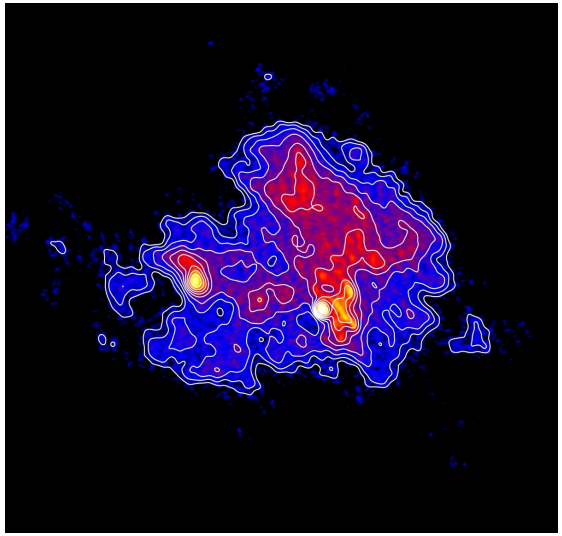
June 2010:
Queen Beatrix opens LOFAR

LOFAR images

3C61.1

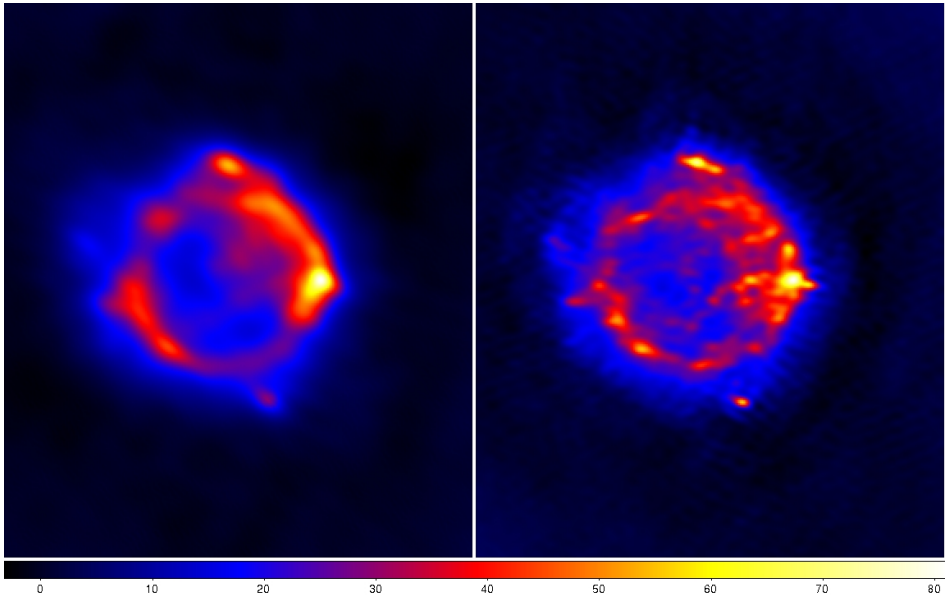


Abel 2256

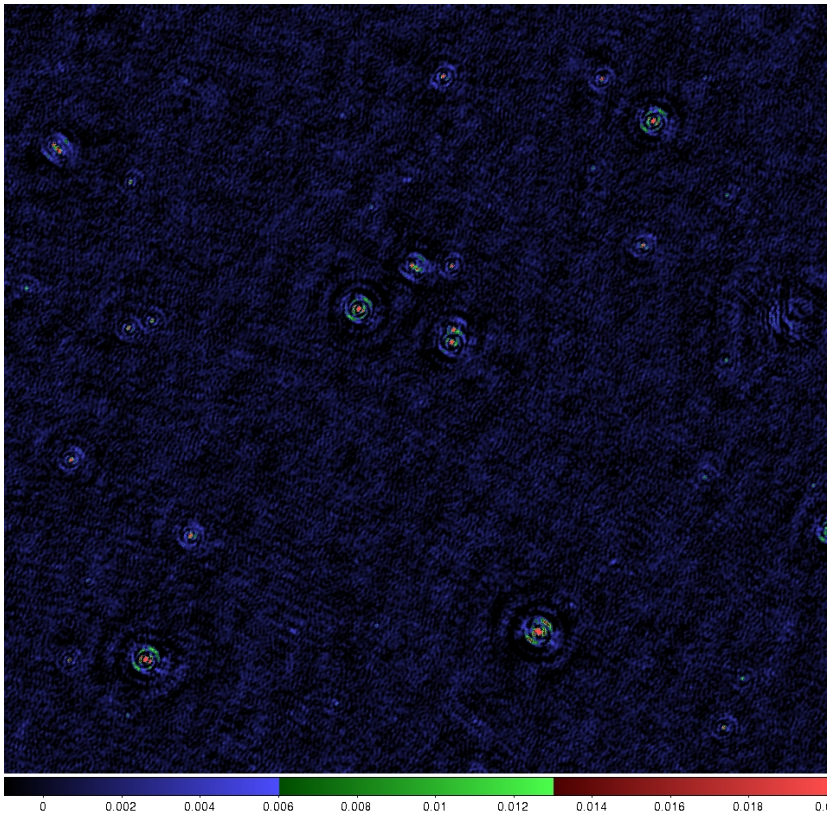


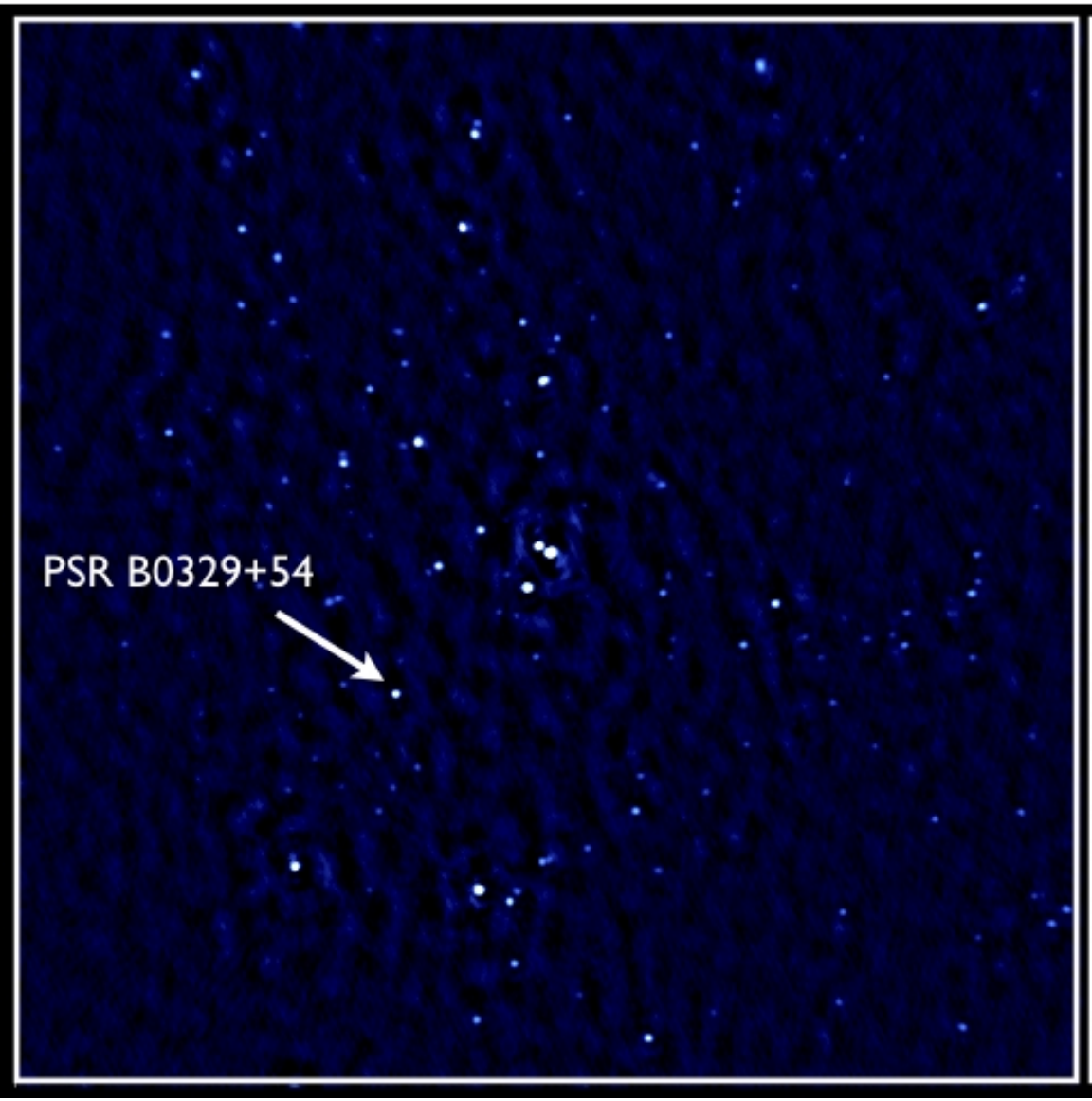
LOFAR images

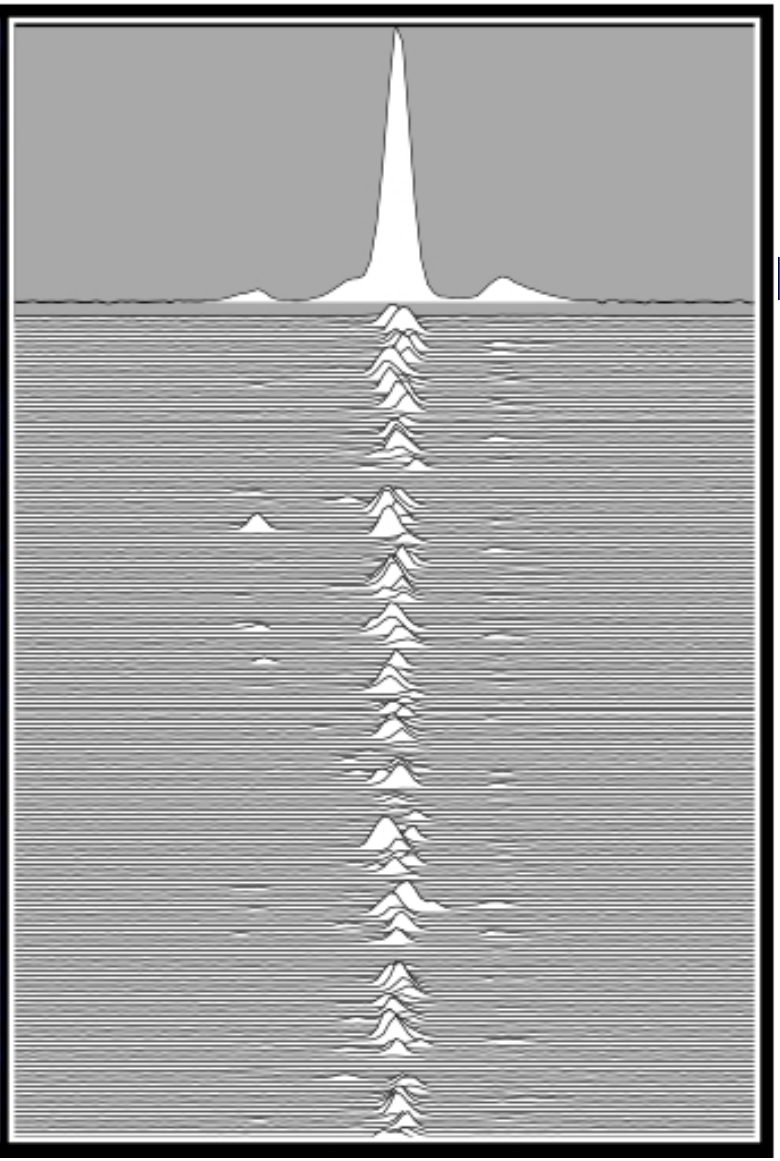
Cas. A



Deep Image sub mJy noise

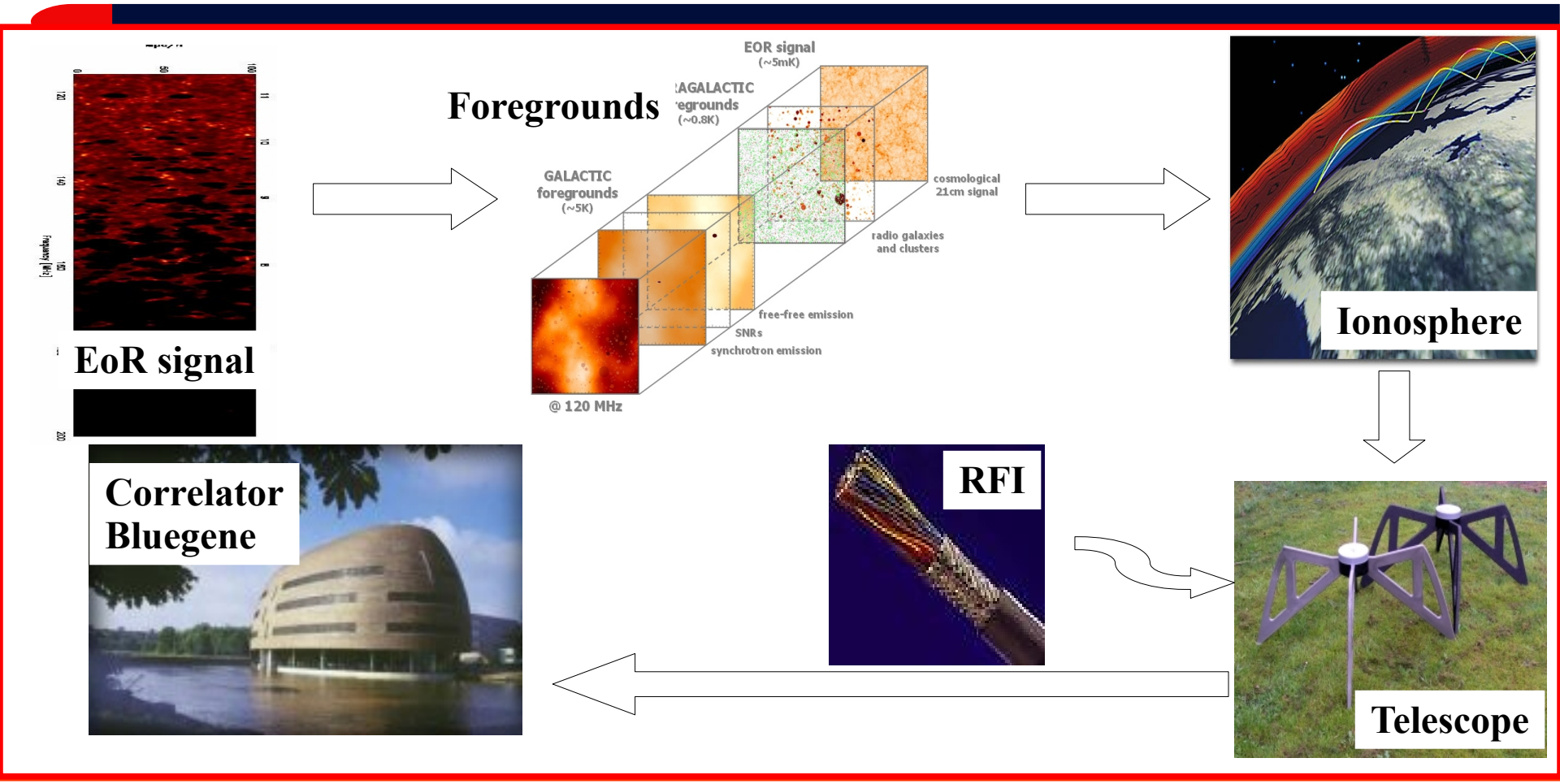






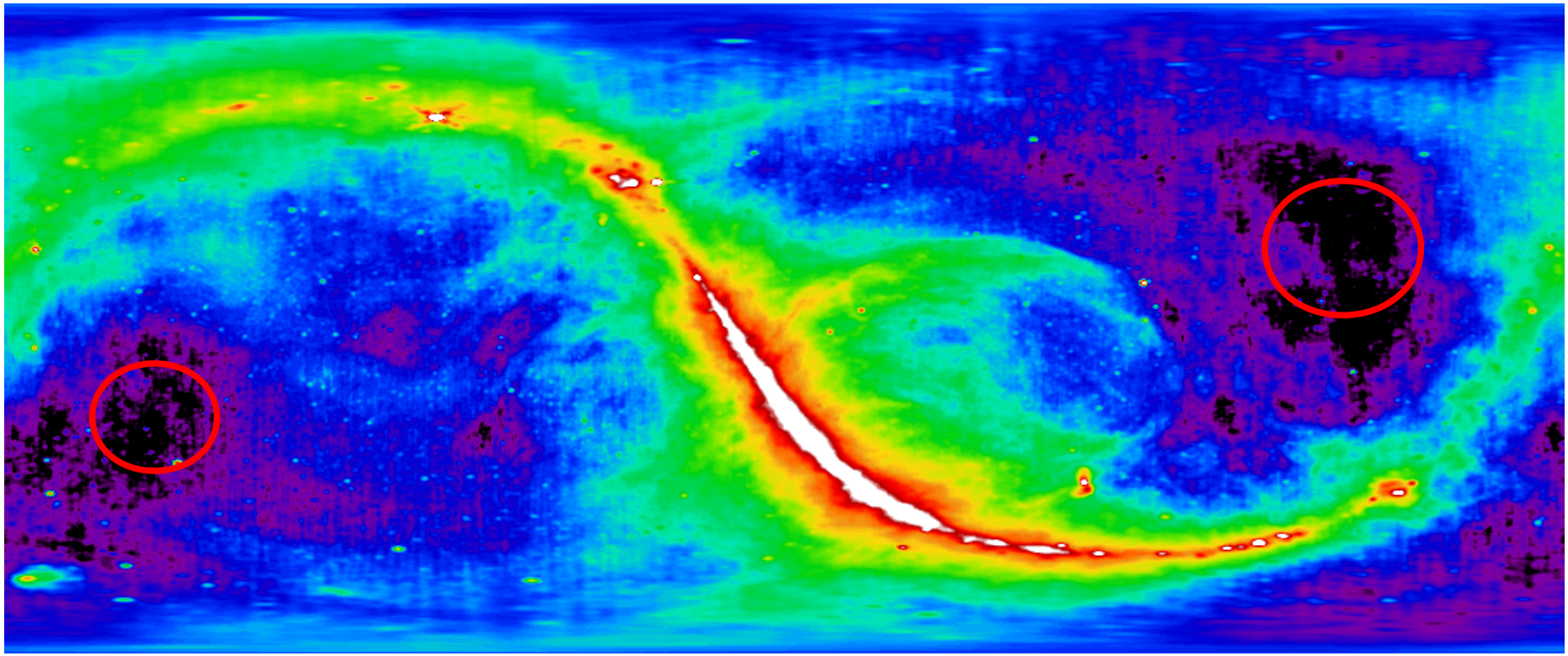
LOFAR 12-hr Simultaneous Imaging and Timing Observation of a Pulsar

The Observation



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

At 150 MHz T_{sky}~200K



Radio sky in 408 MHz continuum

Haslam et al, 1982

Galactic foreground

- **SYNCHROTRON EMISSION (~70%)**
  - **SOURCES:** electrons trapped in the magnetic fields of discrete galactic supernovae remnants and diffuse emission from interaction of cosmic-ray electrons with galactic magnetic field
  - **DIFFUSE SYNCHROTRON EMISSION**

    ⇨ **Spectrum is close to a featureless power law with a smooth variation in spectral index.**

    ⇨ **average spectral index (100 MHz) b=-2.55, with position dispersion s(b)~0.1 (Shaver et al. 1999)**
  - **SUPERNOVAE REMENANTS**
- **Free-Free emission (1%)**

Extragalactic foreground

- **Radio galaxies (AGNs, starburst etc.)**

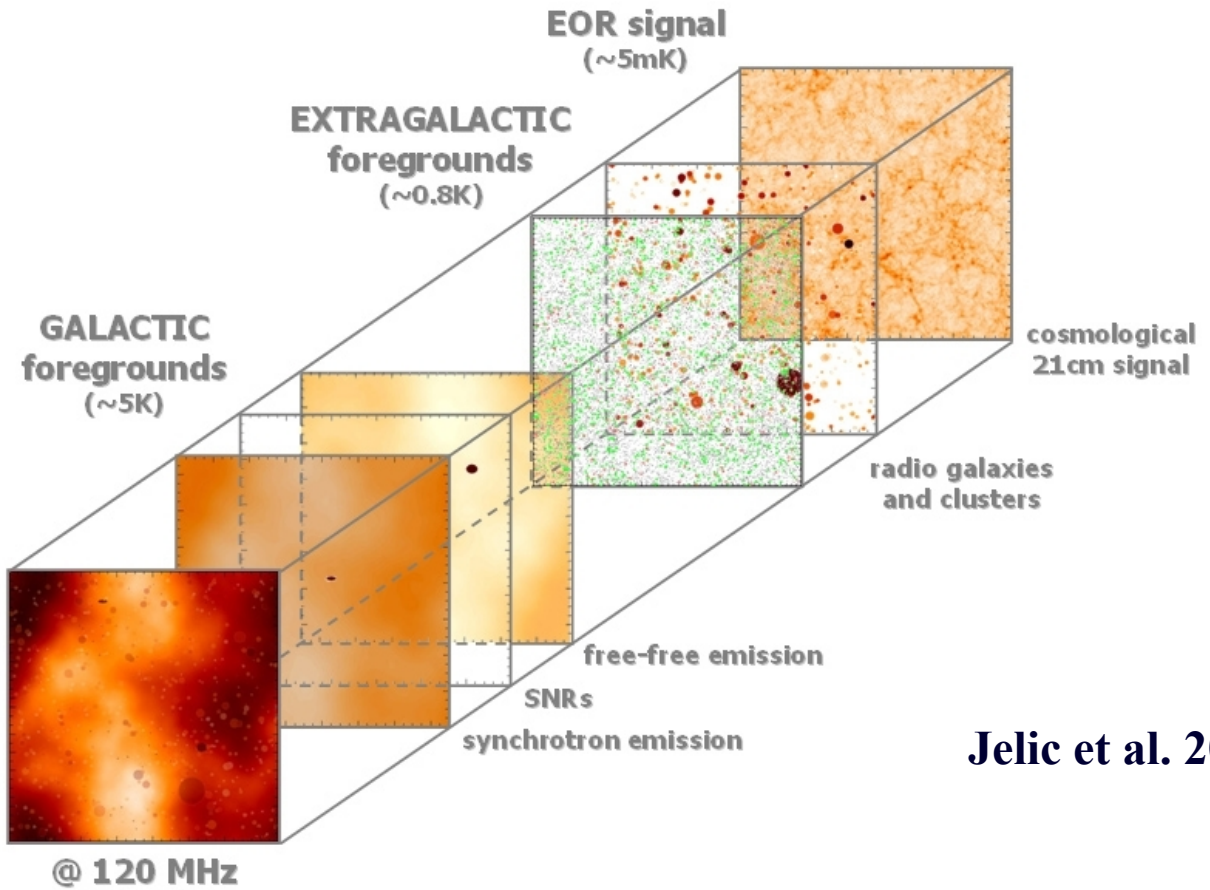
  — based on radio sky simulations by Jackson et al. 2005

  — 3 TYPES OF SOURCES: FRI, FRII (Fanaroff & Riley 1972) & star forming (SF) galaxies

- **Galaxy Clusters**

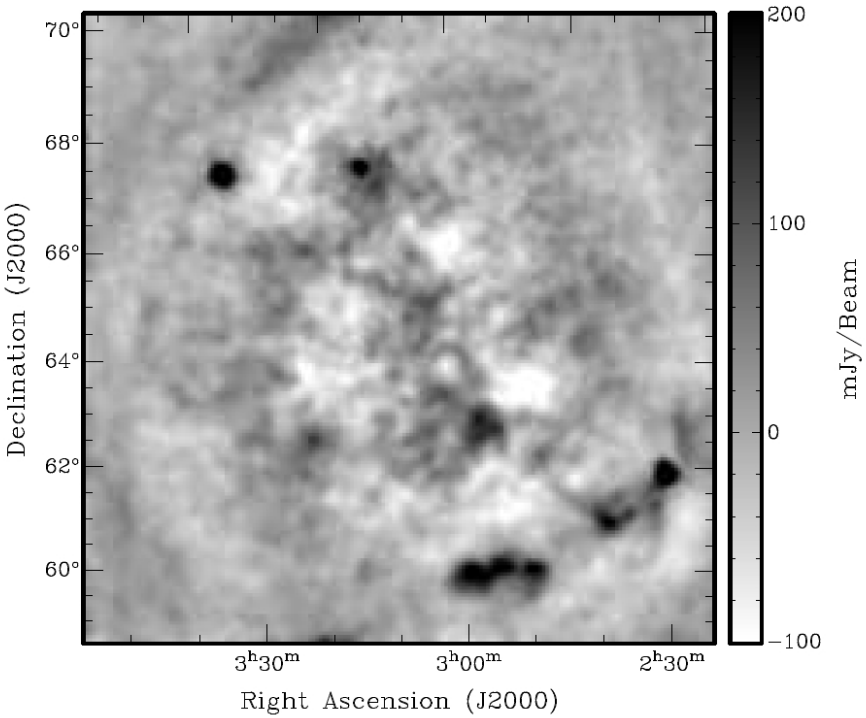
  — The Hubble Volume Simulation Cluster Catalogue (Virgo Consortium, 2002)
  —DMH Mass – Xray correlation (Jenkins et al., 2001)
  — X ray – radio luminosity correlation (Enβlin & Röttgering, 2002).
  30% with radio properties.
  — Redshift, virial radius ⇒ angular size
  — Spectral index distribution from Cohen et al. 2004

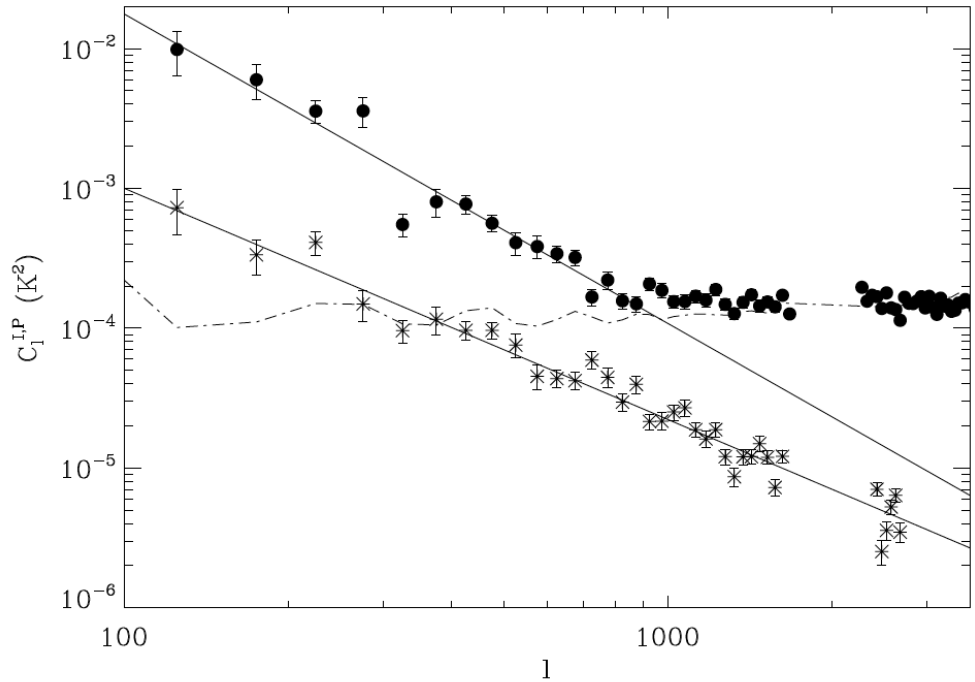
The signal + Foregrounds



Jelic et al. 2008

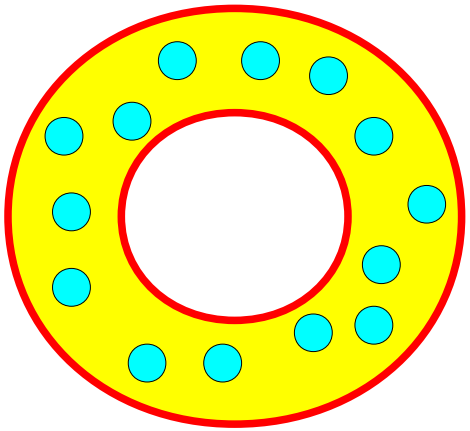
Measurement of Diffuse Foregrounds



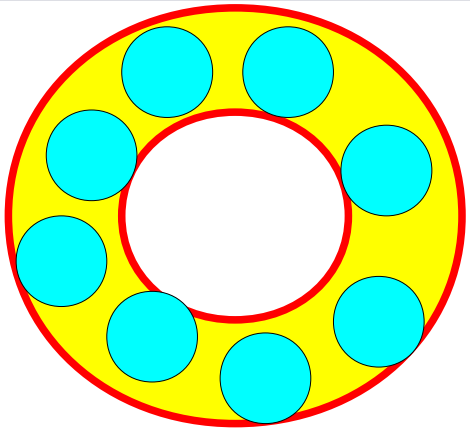


Bernardi et al. 2009, 2010

Sensitivity & Signal/Noise



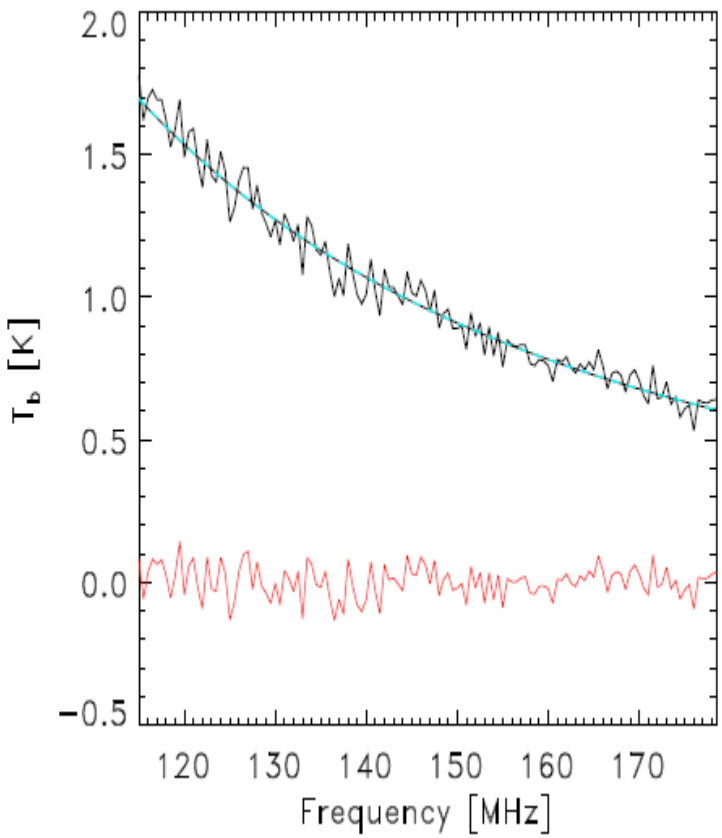
MWA

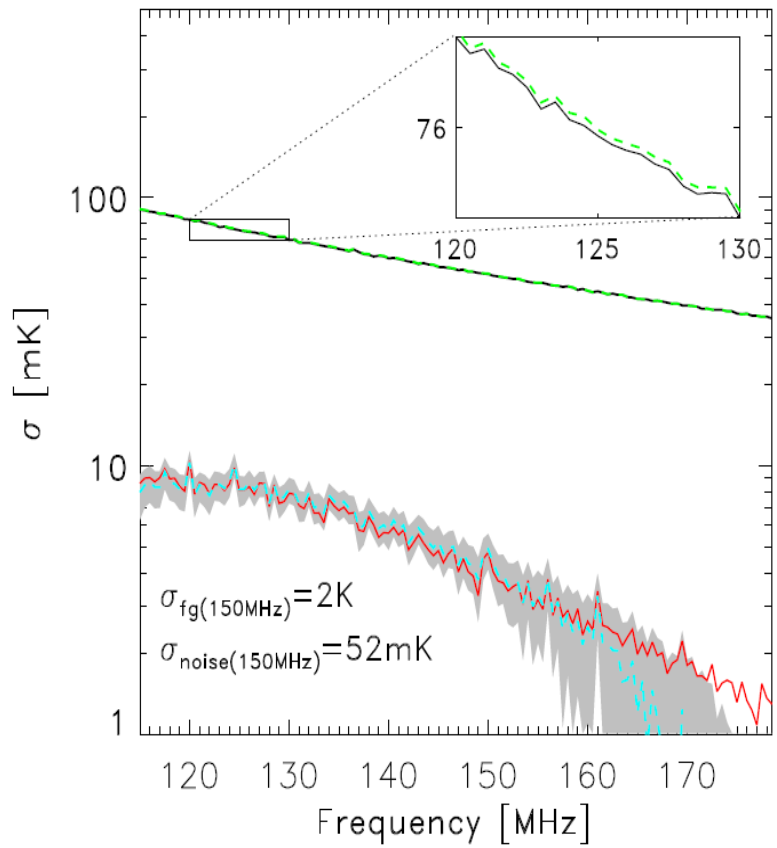


LOFAR

$$\sigma^2_{Noise} \propto \frac{k_B T_{sys}}{N_{cell}^{\frac{1}{2}} \times N_{beam} \times A^2_{total} \times time \times \Delta\nu}$$

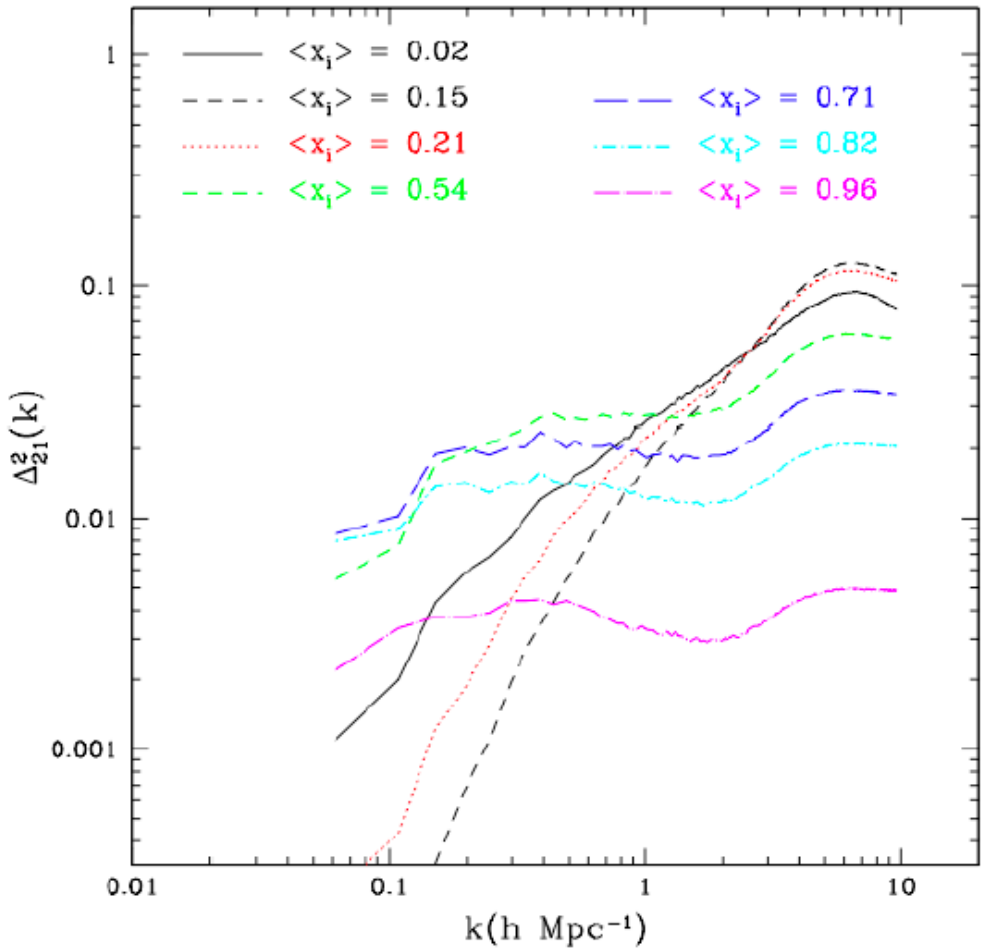
Extraction of the Signal





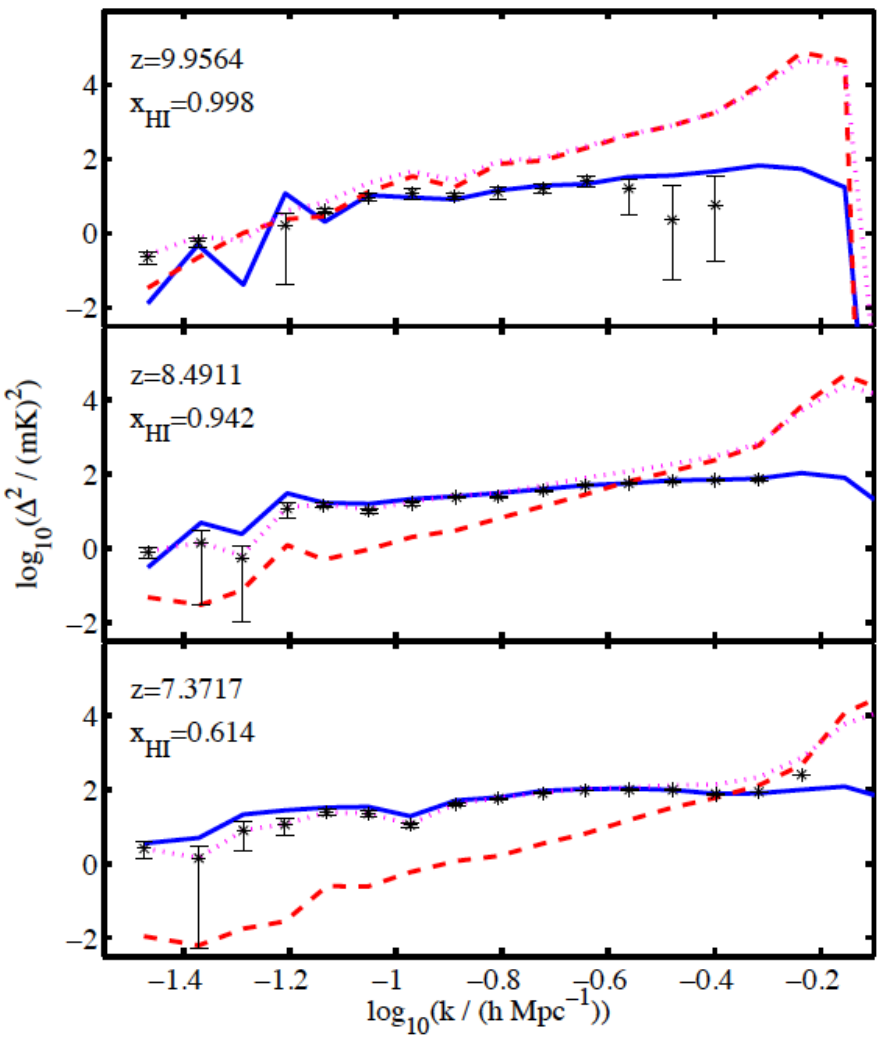
Jelic et al. 2009

δT_b Power spectrum



Lidz et al. (2007)

Power Spectrum Measurements



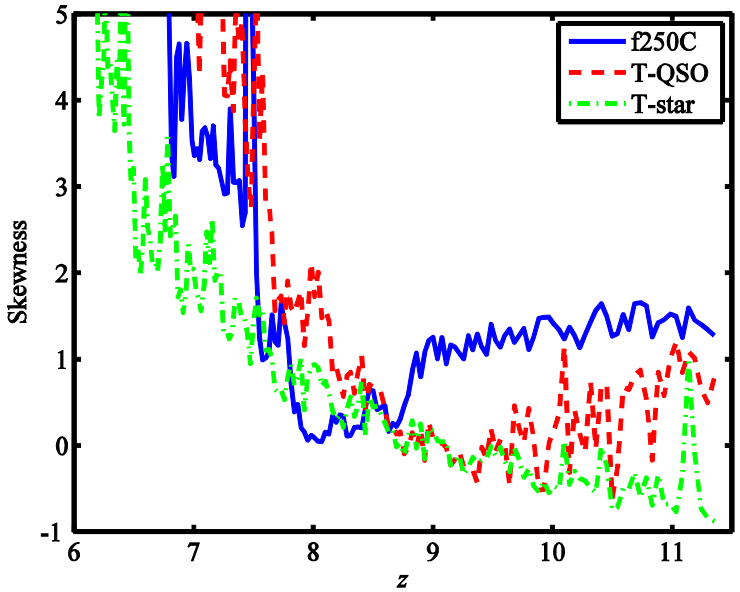
Harker et al. 2010

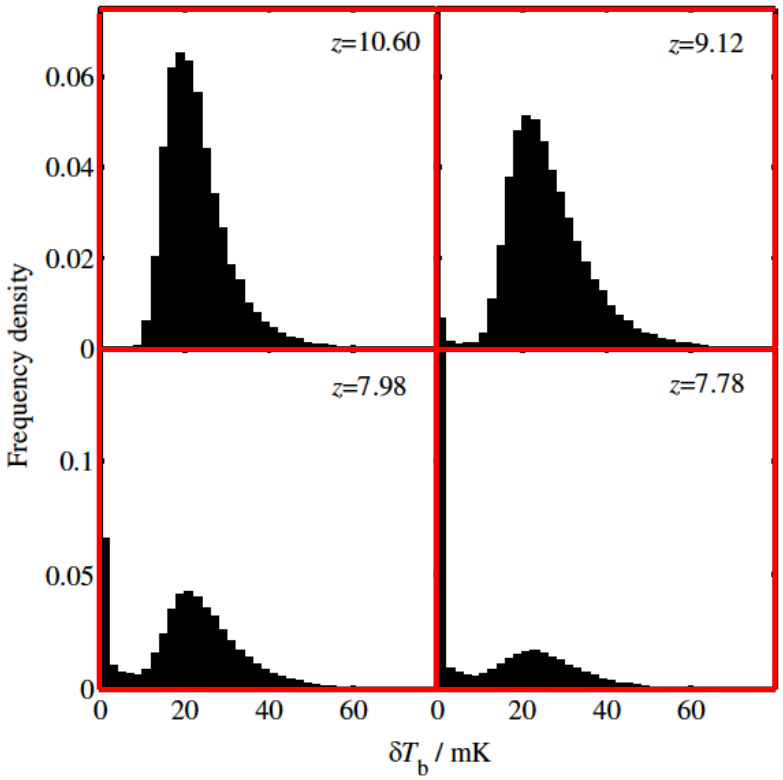
Power spectra of the Cosmic Signal, the noise, the residuals and the extracted signal. We have assumed 300 hours of observation per frequency channel with a single station beam (600 hours of total observations).

and the foreground fitting is done using Wp smoothing in Fourier space.

PDF and Skewness

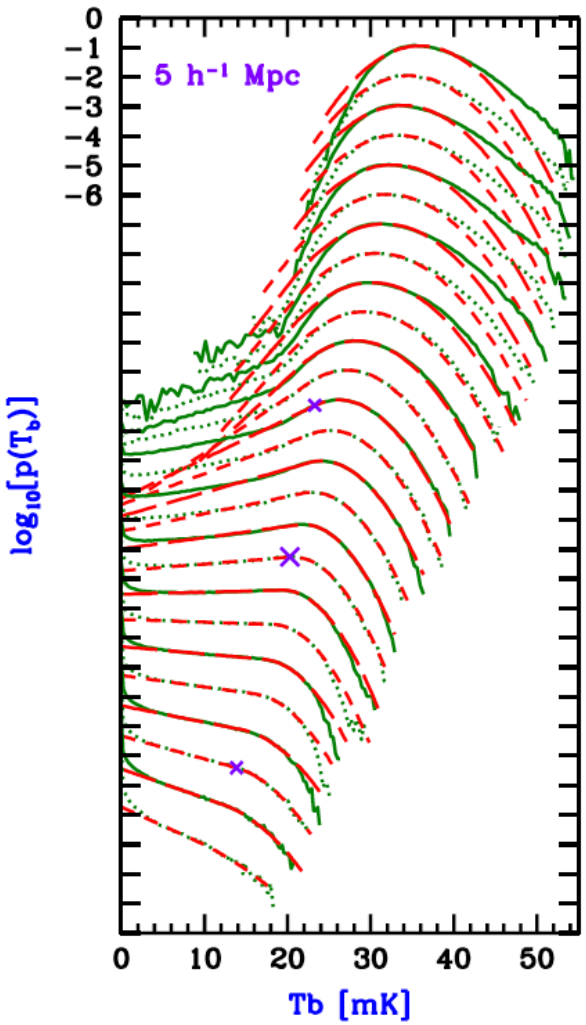
Original simulations





Harker et al 2009

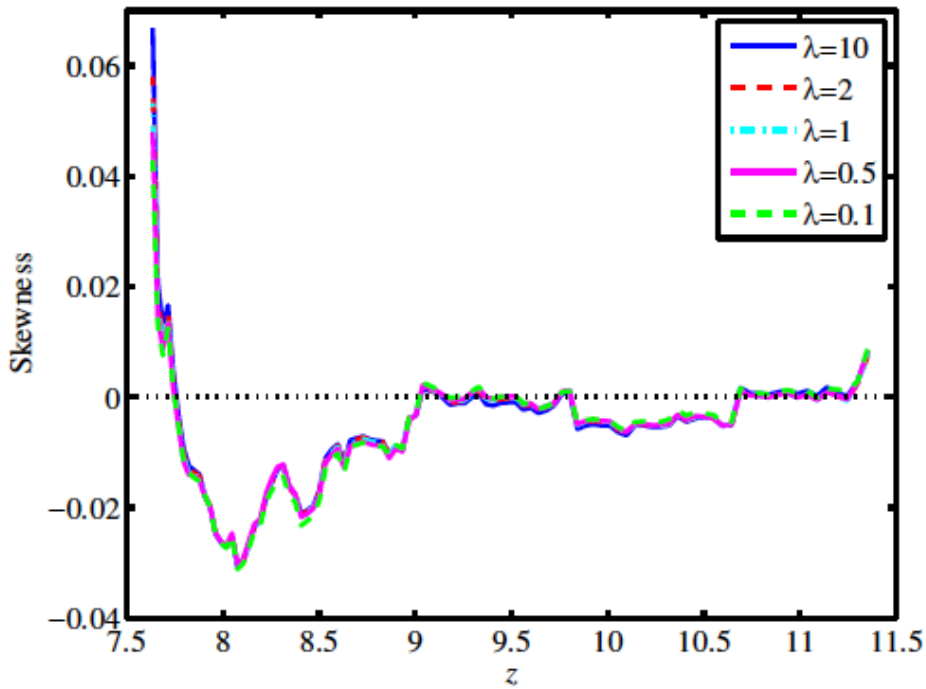
PDF of the brightness temp.

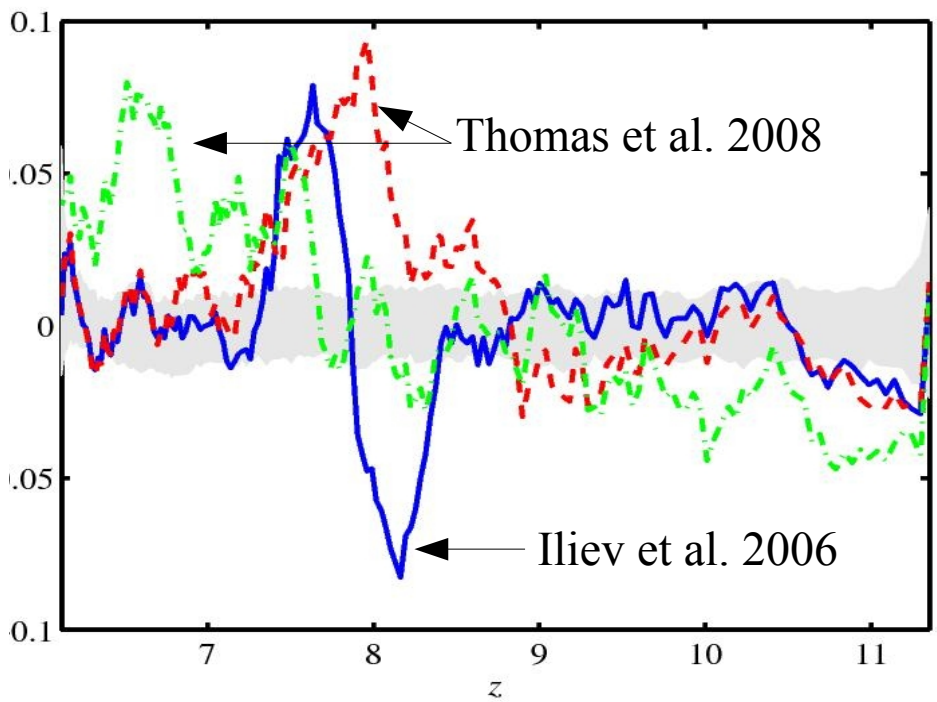


The evolution of the PDF of the brightness temp. as a function of redshift could be used to set constraint on reionization.

Ichikawa et al. 2010

Extraction through skewness

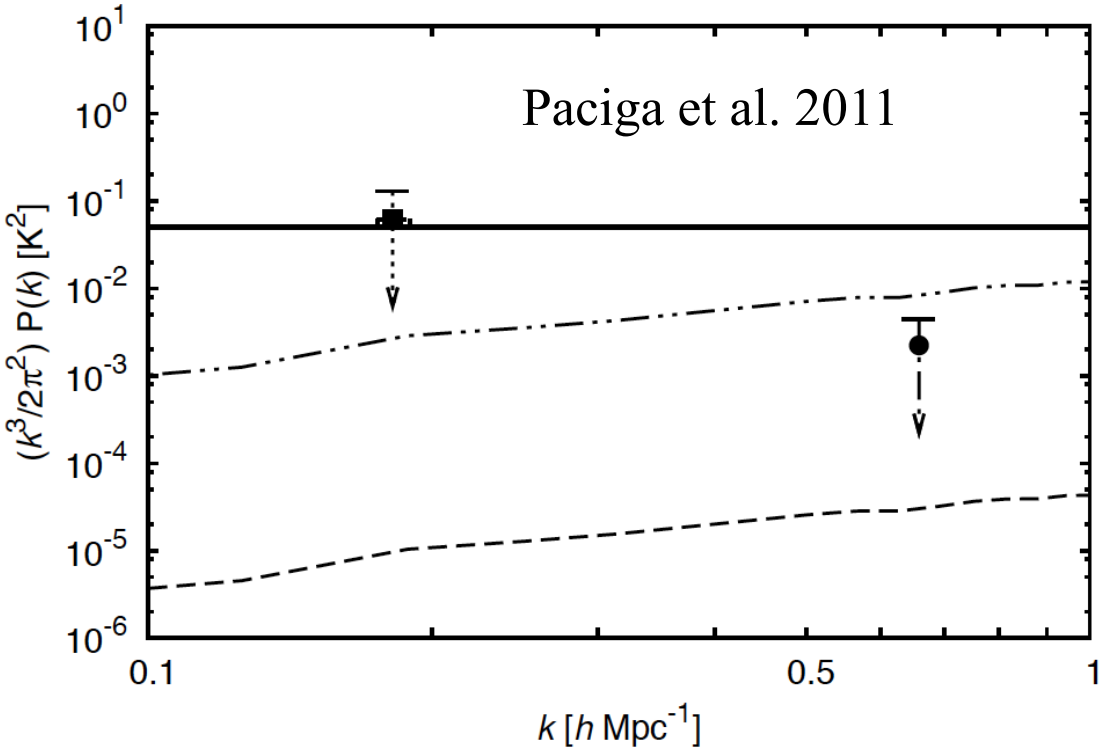




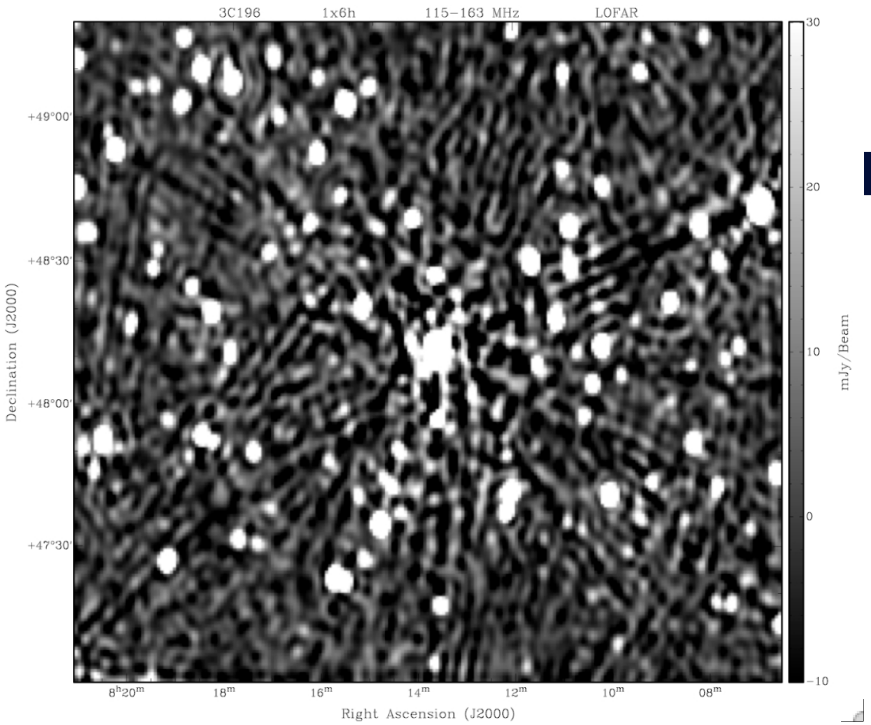
Harker et al. 2009

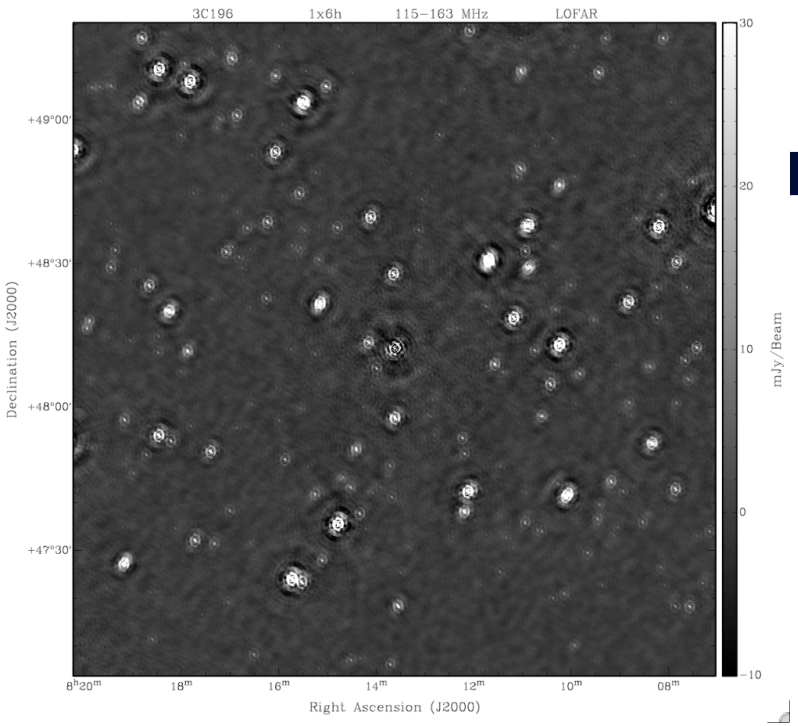
Results

The GMRT-EoR Experiment: HI Power Spectrum



3C196: WSRT versus LOFAR 115-163 MHz





WSRT 72h thermal noise 0.6 mJy
confusion noise 3 mJy

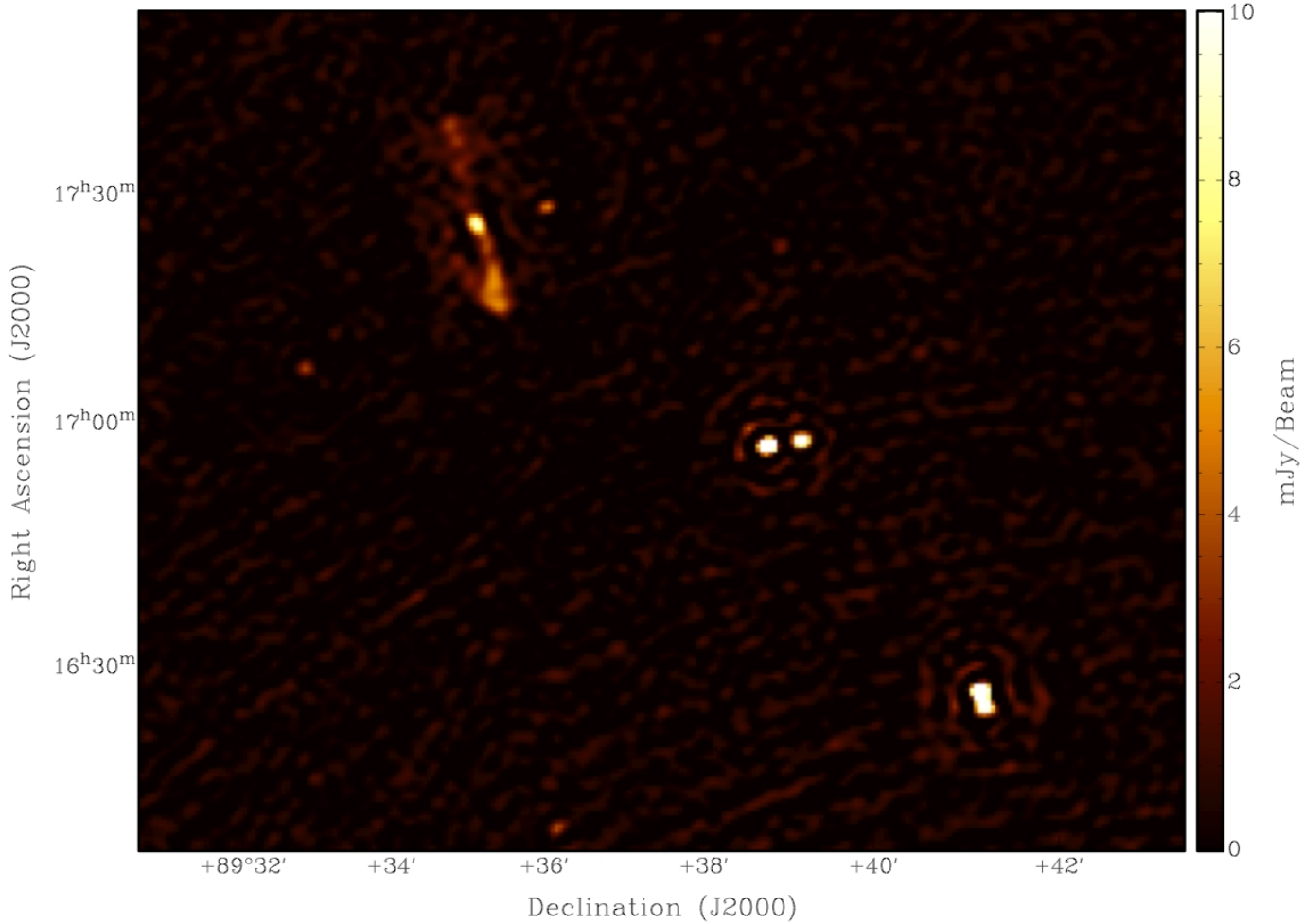
Bernardi et al (2010)

LOFAR 6h thermal noise ~ 0.15 mJy
image noise ~ 0.3-0.7 mJy
CS +RS, ~ 30 km, 200+ subbands

DR ~ 83 Jy/0.5 mJy ~ 200,000:1 !!

Labropoulos et al (in prep)

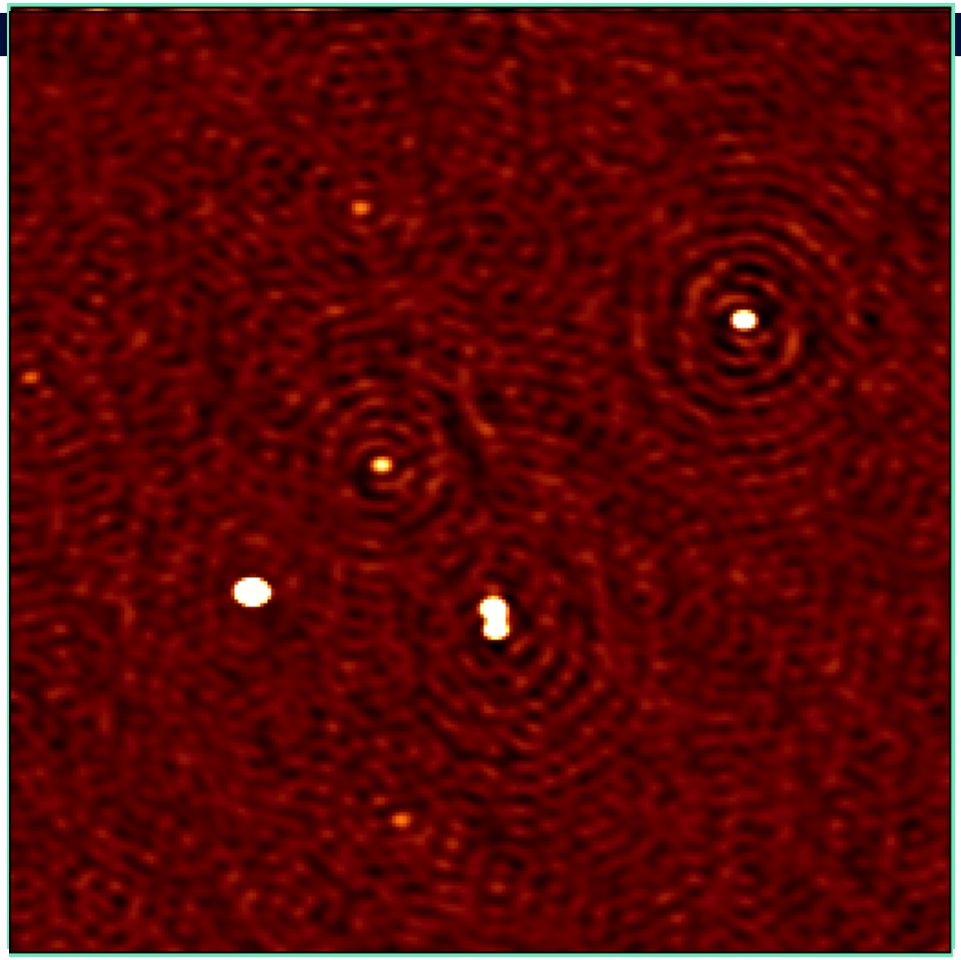
LOFAR: 3C196



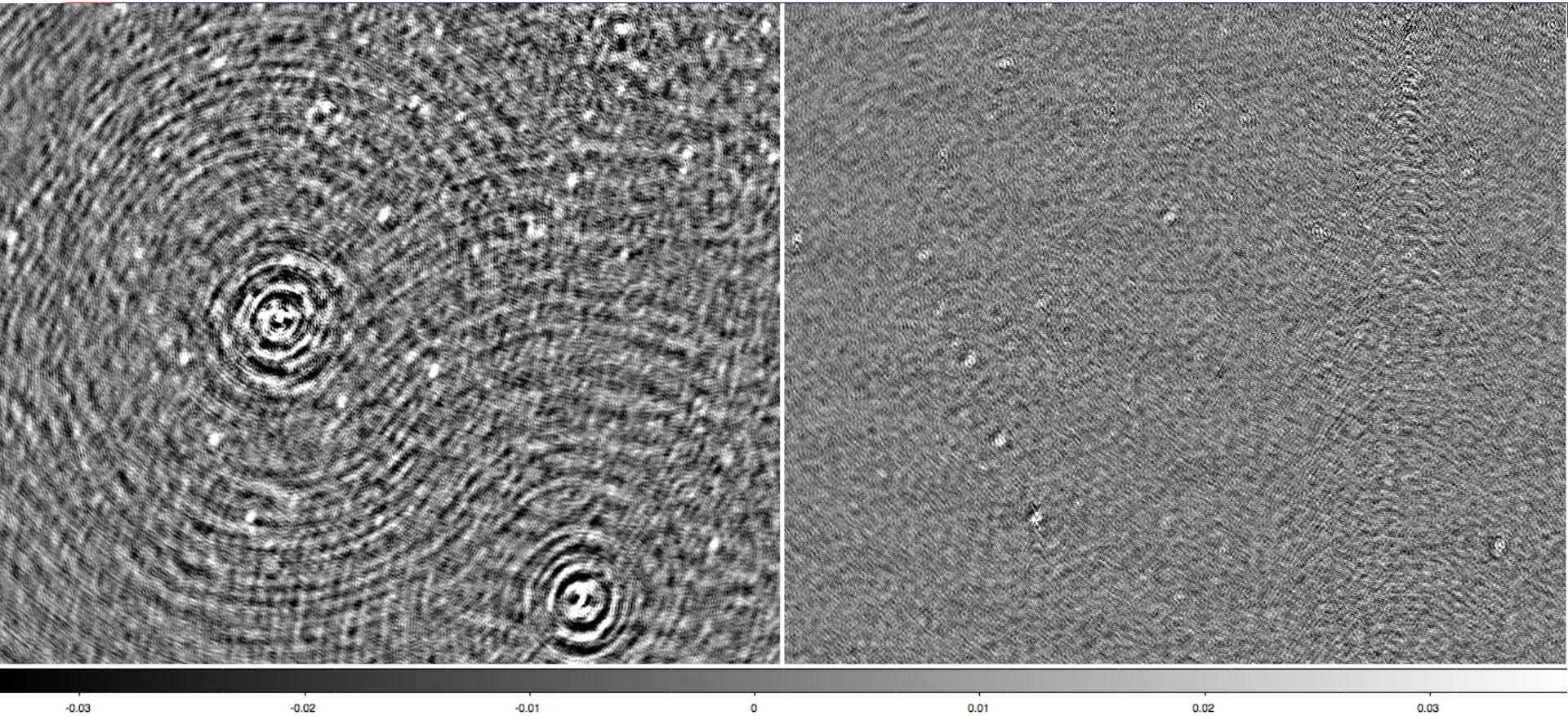
6 hours of observation, 200000:1 dynamic range, 0.3 mJy sensitivity

CALSAGE Calibration

Yatawatta et al. 2009
Kazemi et al. 2011



CalSAGE algorithm: 49 sources simultaneously used. The algorithm takes 24 hours in this case



Courtesy of Labropolous

Summary

- High sensitivity data in the frequency range 115-190MHz will be available in the coming few years.
- Extracting the EoR signal involves many challenging step:
  - Very accurate Calibration
  - Very accurate modeling of noise
  - "Fitting" very prominent foregrounds
- We are on the verge of exploring the Universe in a completely new window