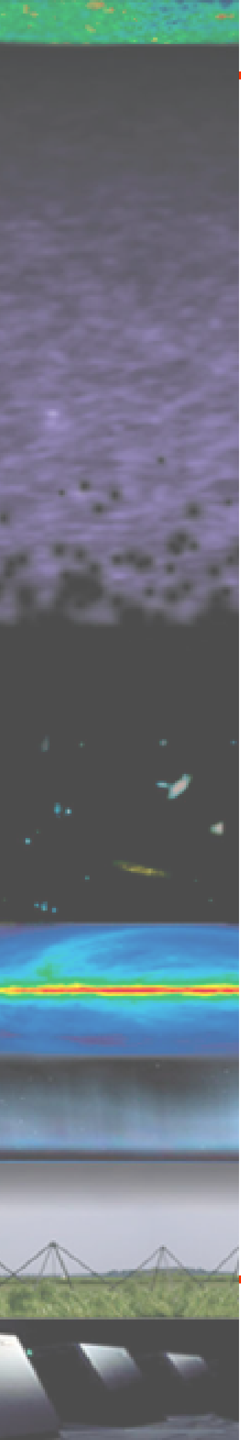

Probing the Epoch of Reionization with LOFAR

Saleem Zaroubi

Kapteyn Astronomical Institute

University of Groningen

The LOFAR-EoR Core team

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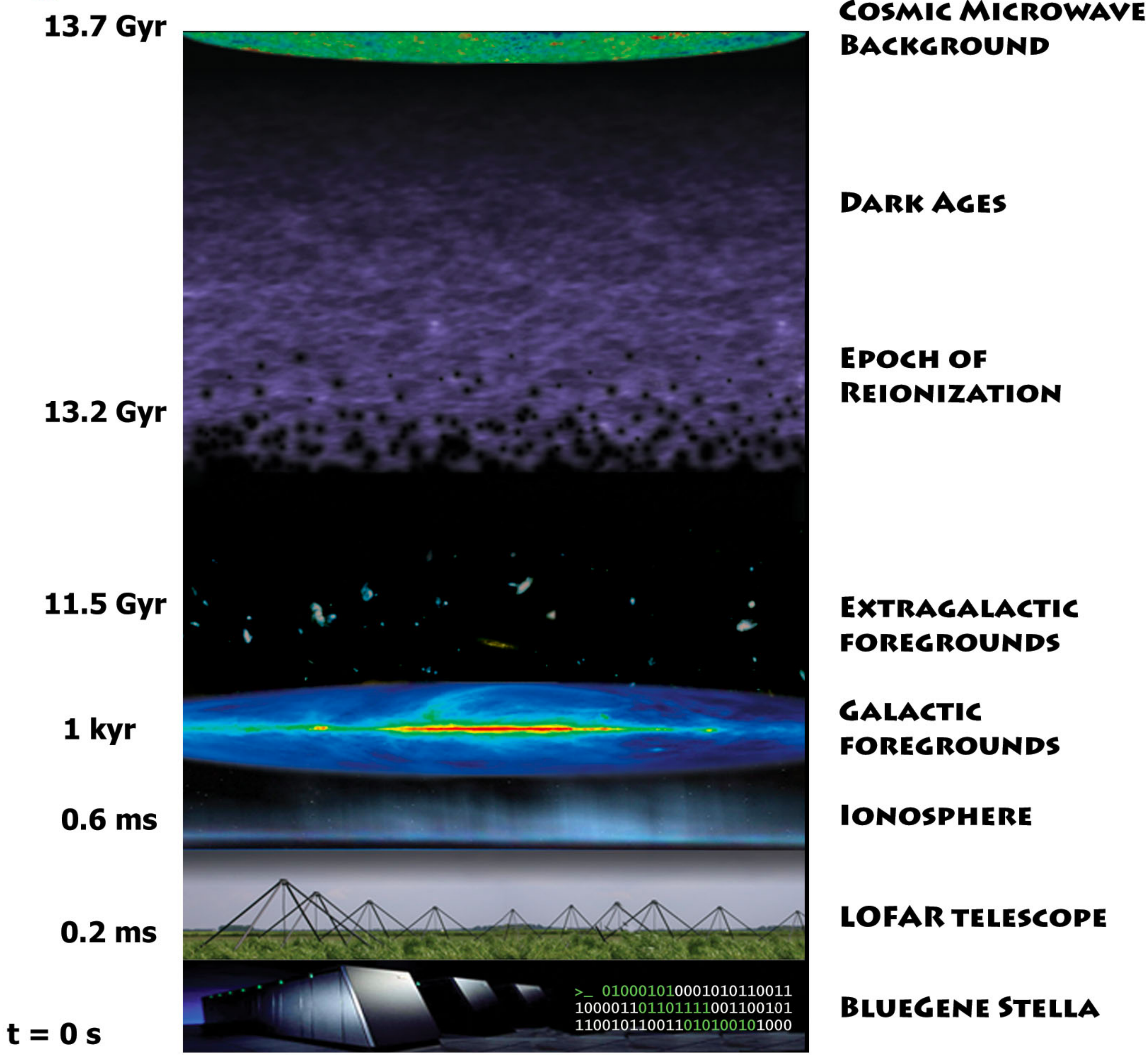
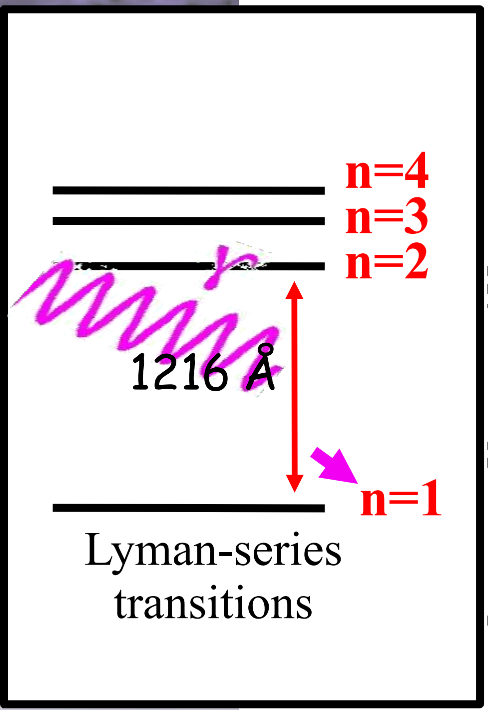
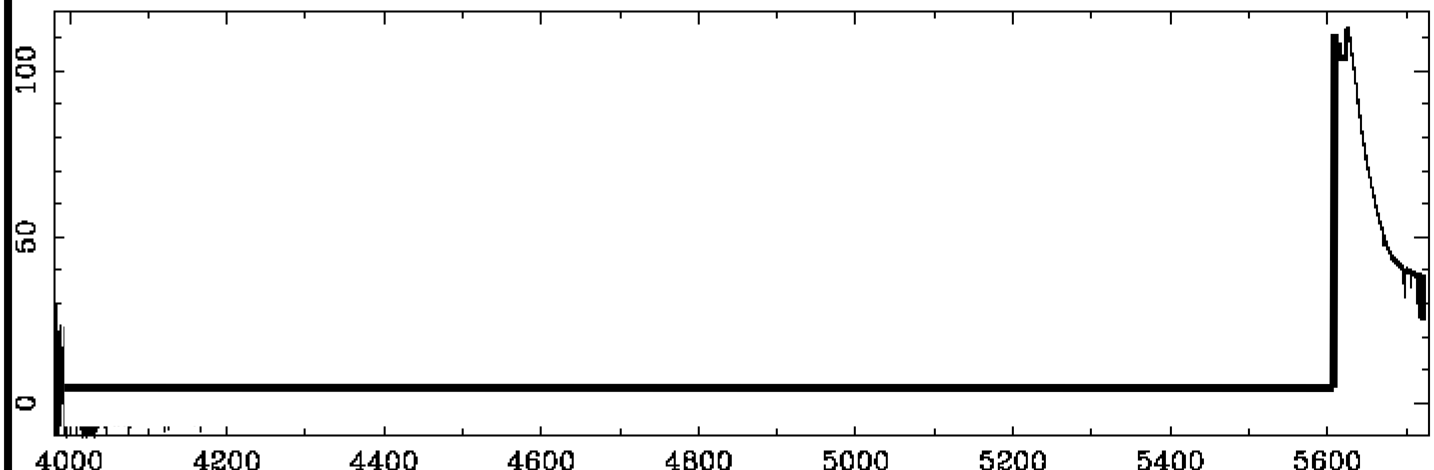
Garrelt Mellema, Stockholm University


13.7 Gyr
Cosmic Microwave Background
Dark Ages
Epoch of Reionization
13.2 Gyr
11.5 Gyr
Extragalactic foregrounds
1 kyr
Galactic foregrounds
0.6 ms
Ionosphere
0.2 ms
LOFAR telescope
t = 0 s
BlueGene Stella
>_ 01000101000101010110011
10000110110111100110010 1
11001011001101010010 1000

How do we know the Universe is ionized

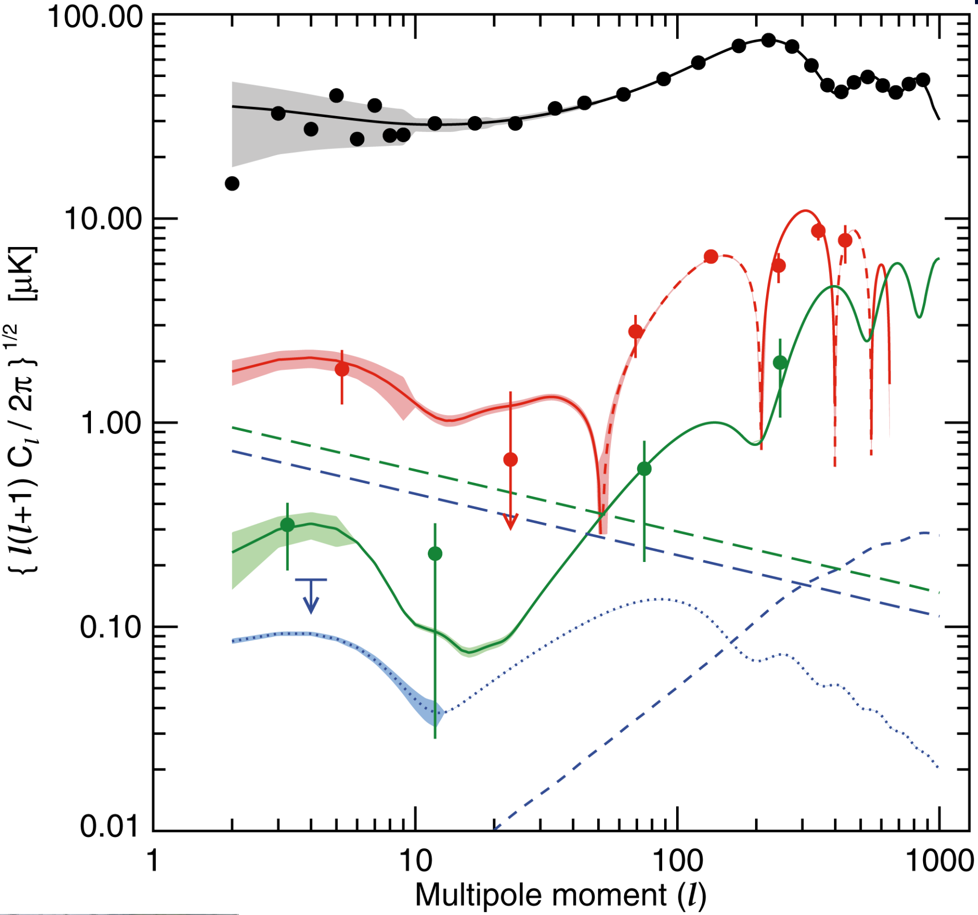


The Lyman-α Forest Along Distant Quasar Spectra ($t_{Universe}$~1 Billion yr)



At z ~ 4 the IGM is 10^{-4} neutral

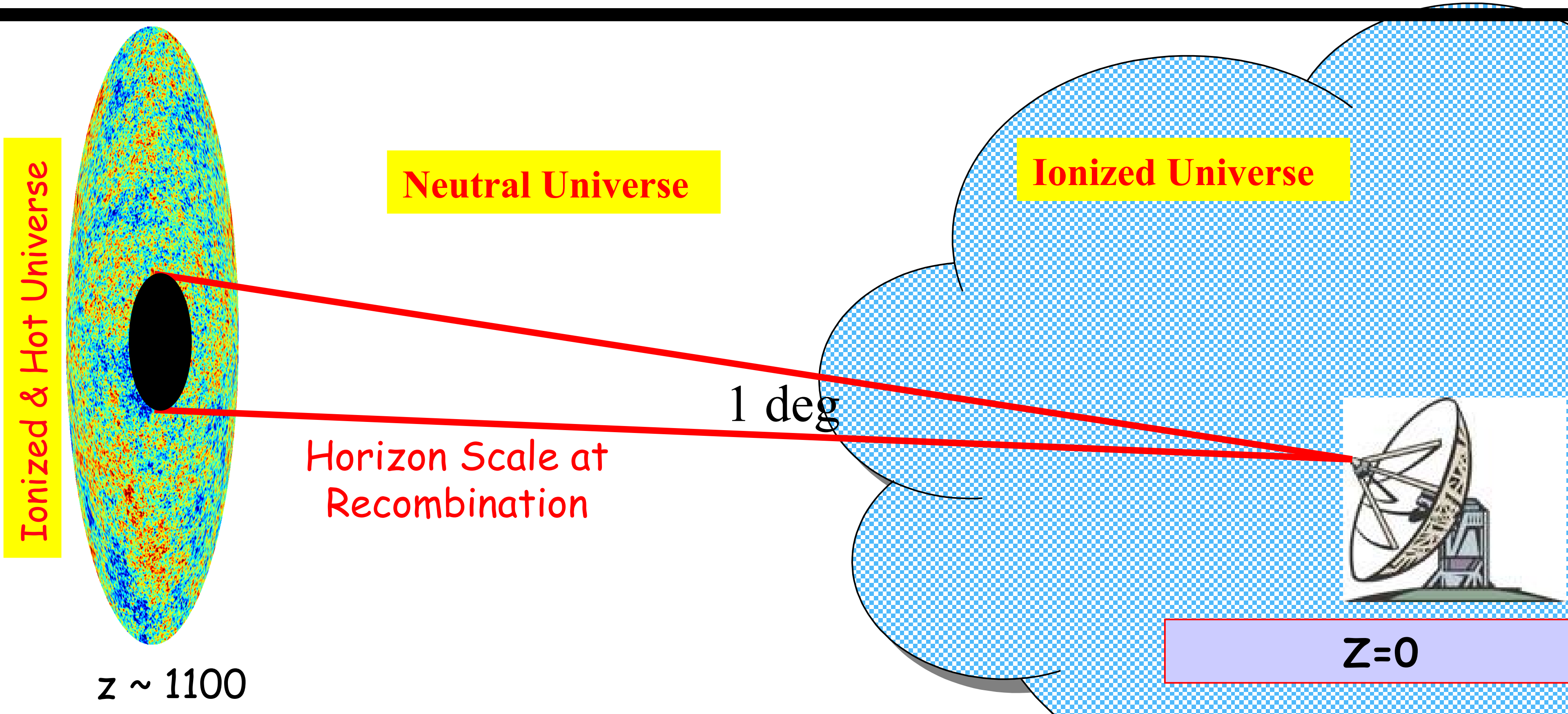
What constraints do we have on the EoR? The CMB.



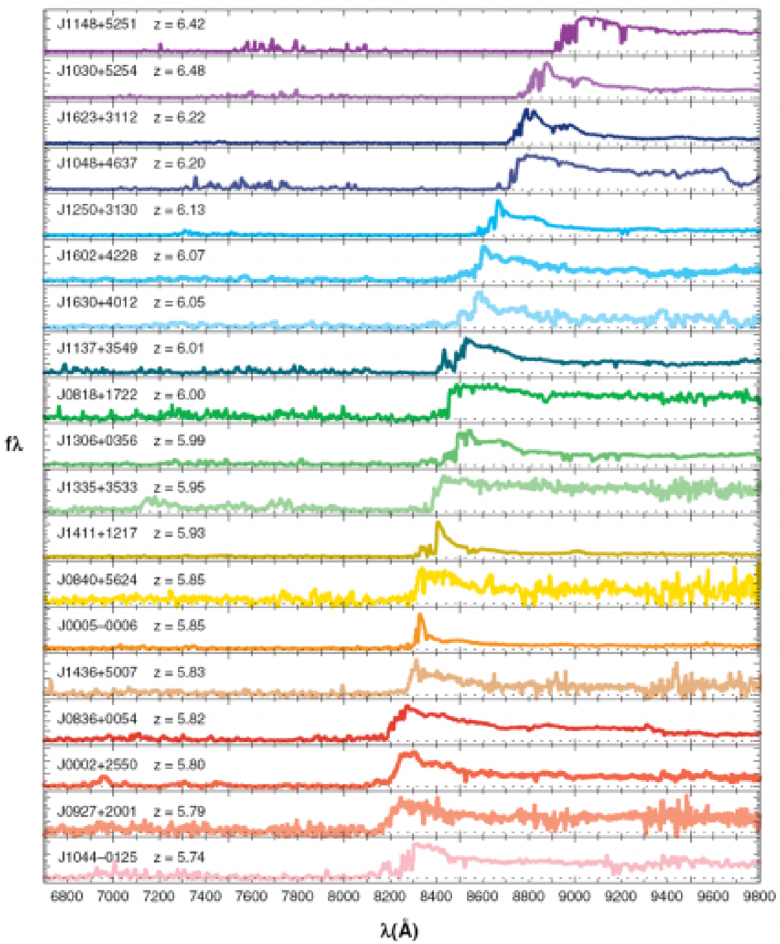
- The WMAP polarisation measurement suggest that ionization has happened at about z~10.

τ~0.09

The CMB constraint



What constraints do we have on the EoR? The Lyman-α forest

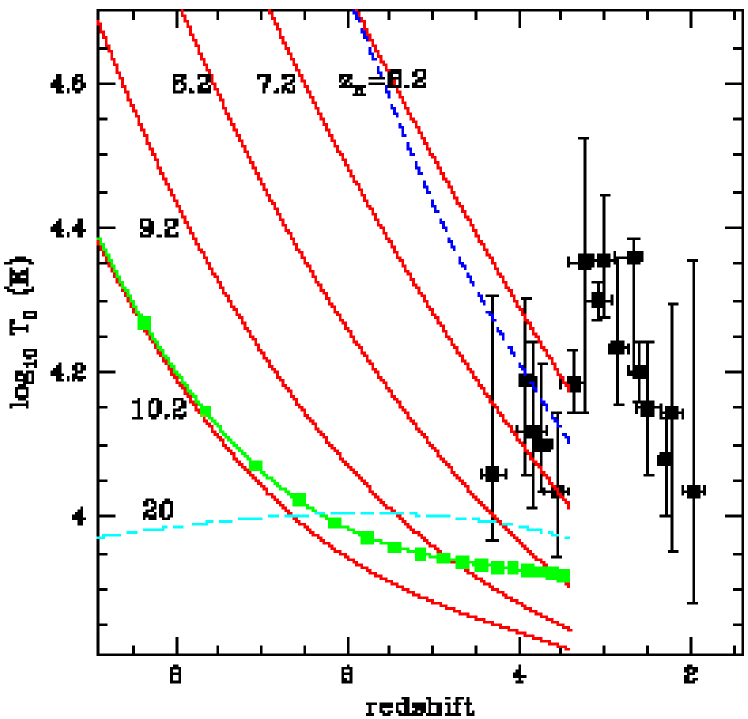


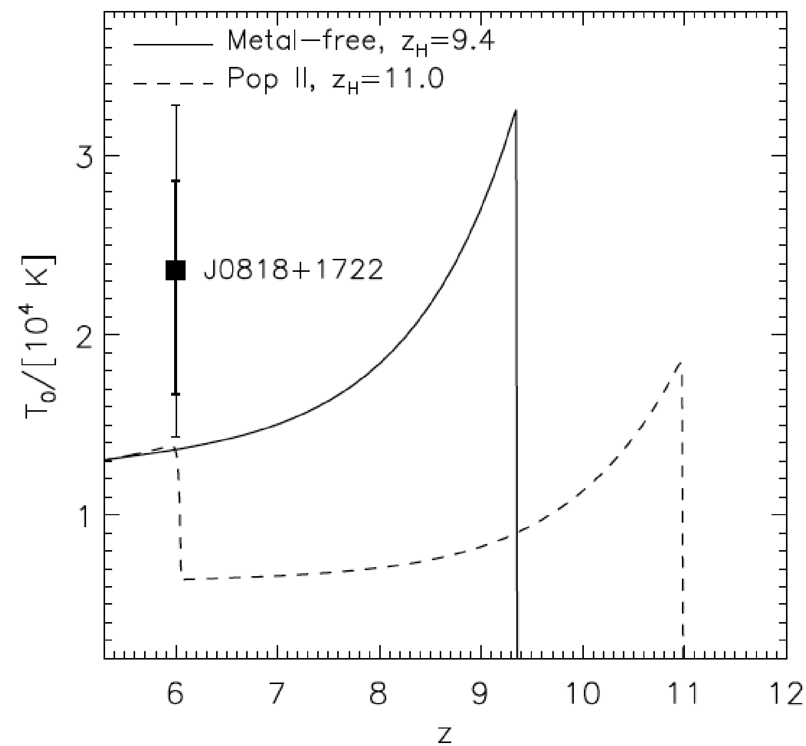
- The Lyman-alpha forest: At z<6 he Universe is completely ionized
- The Universe has completed its ionization by redshift 6: SSDS quasars (however Mesinger 2009 claims it is still about 10% neutral)

Fan et al. 2006

The IGM temperature at low z

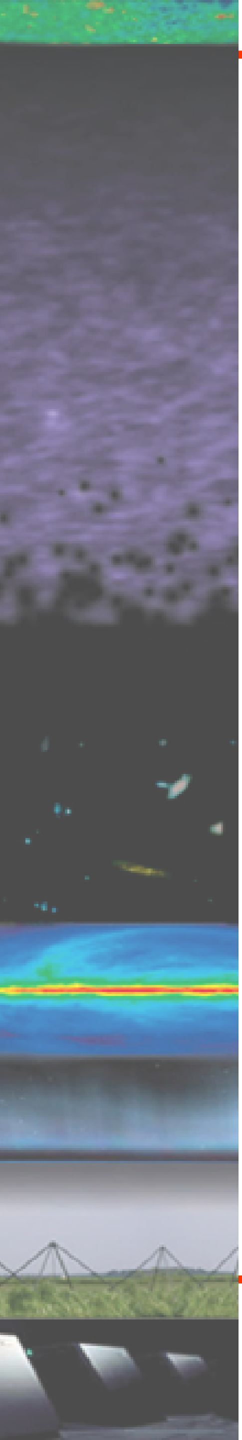
$$\frac{1}{T_0}\frac{dT_0}{dt} - \frac{1}{\mu}\frac{d\mu}{dt} = -2H_0 + \frac{\mu\Delta_\epsilon}{-\frac{3}{2}k_B T_0}$$





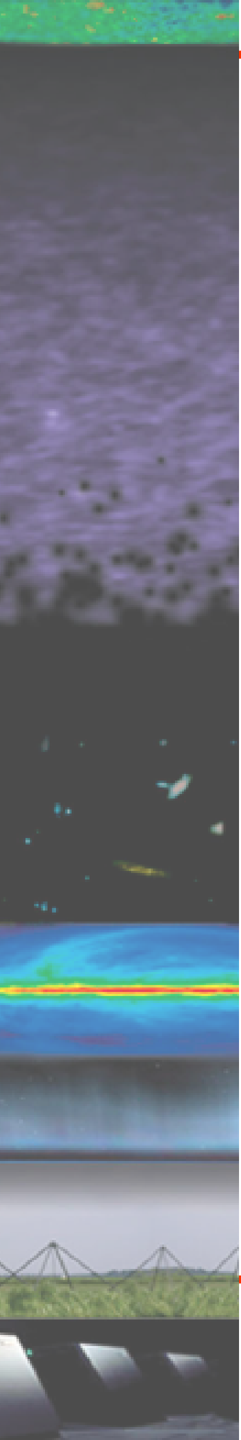
Theuns et al. 2002
Haiman & Hui 2003

Bolton et al. 2010



Key Questions in Reionization

- What are the first sources?
  - Stars: How did they form? The role of H_2 & HI cooling.
  - Pop.II vs Pop III
  - BH + mini-QSOs
  - DM decay or annihilation.
- How did reionization proceed? Topology of the IGM during the EoR.
- When reionization became complete?
- Typical size of ionized regions
- Thermal history of the IGM
- Influence of the EoR on subsequent structure and evolution
- Do we know that reionization is photon starved? Is this a strong constraint of reionization?
- What could the EoR teach us about Cosmology?

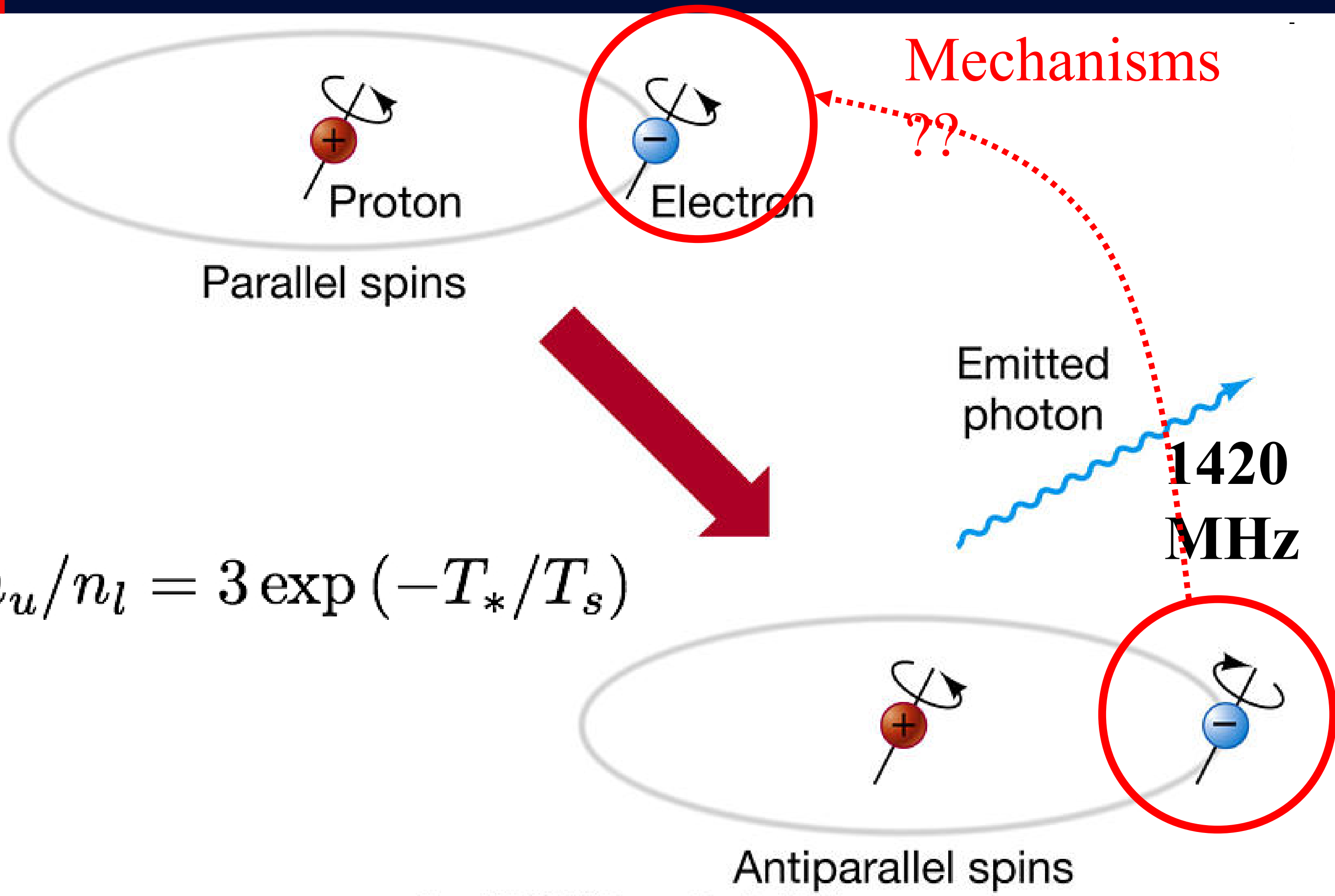


Key Probes of Reionization

- 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-alpha absorption system: ionization, metallicity, thermal history, UV fluctuations, proximity effect.
- Lyman alpha emitters
- Abundance of metals at high redshift.
- Using the local volume to study reionization.

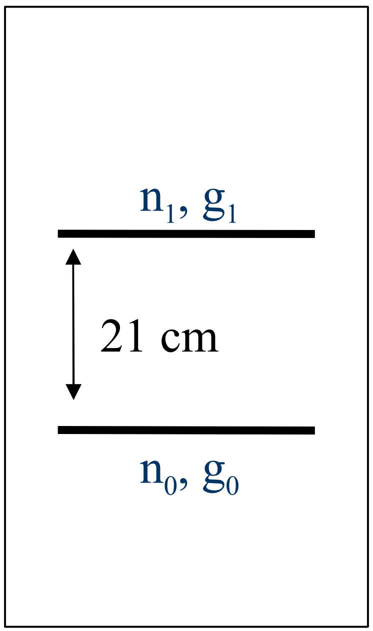
Probing the EoR with redshifted 21 cm radiation

21-cm Physics



$$n_u/n_l = 3\exp\left(-T_*/T_s\right)$$

The 21 cm transition



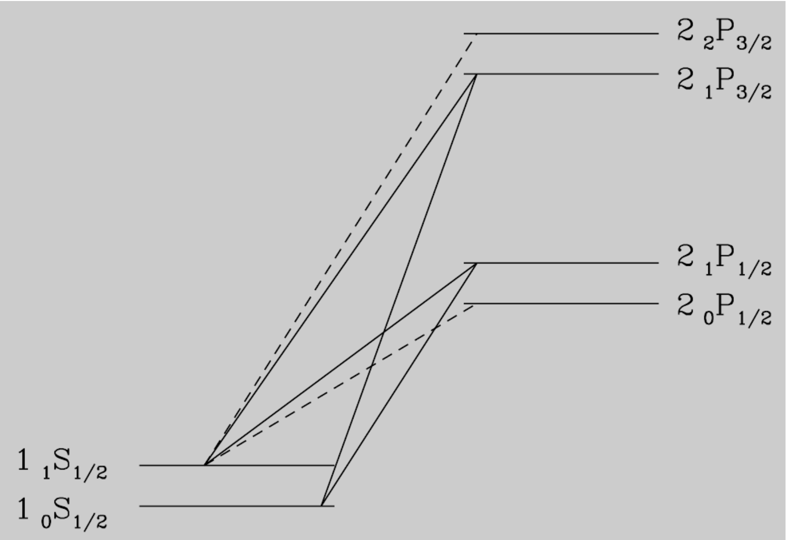
- The value of the T_s is given by:

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

Field 1958
Madau et al 98
Ciardi&Madau 2003

Lyman-alpha 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.

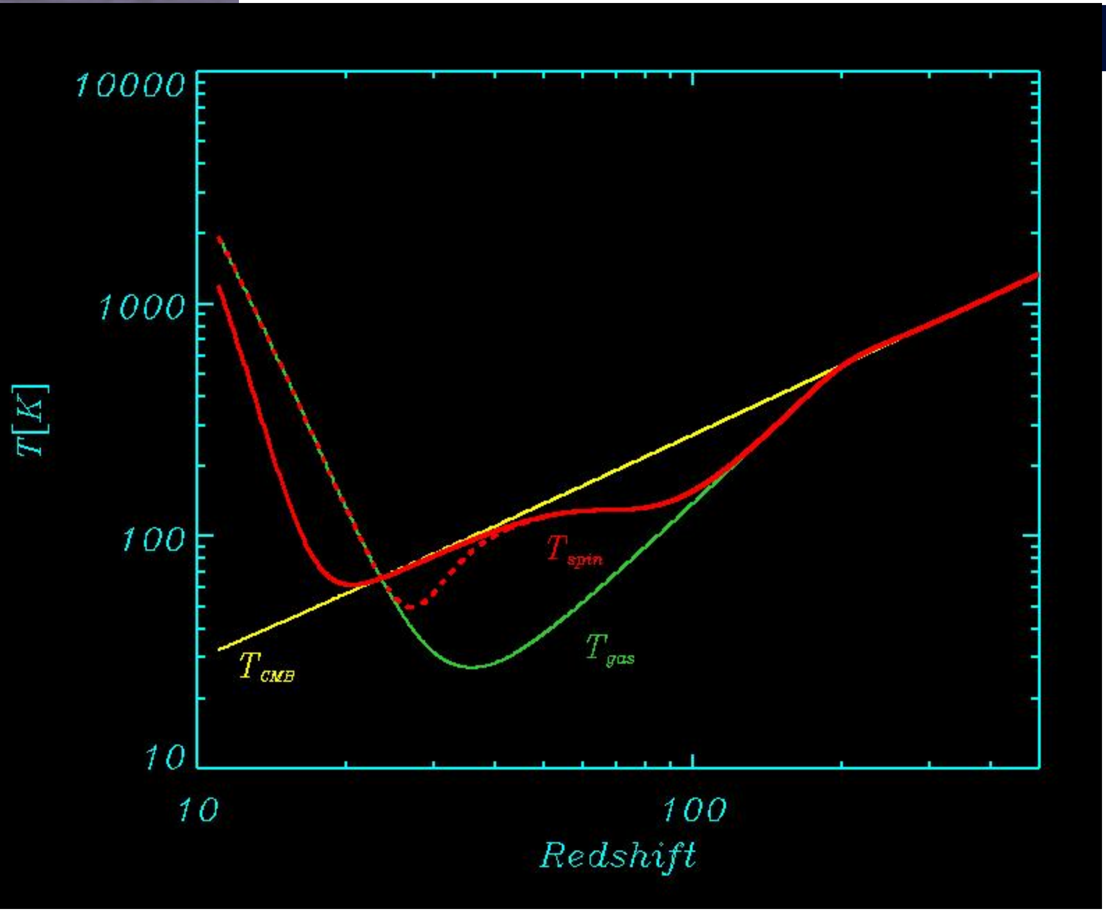
Collisional Coupling

- 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.**

Chuzhoy et al. 06

Zaroubi et al. 06

The Global evolution of the Spin Temperature



Loeb & Zaldarriaga 04, Baek et al. 08, Thomas & Zaroubi 2009

At z~10 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.

δT_b: Brightness temperature

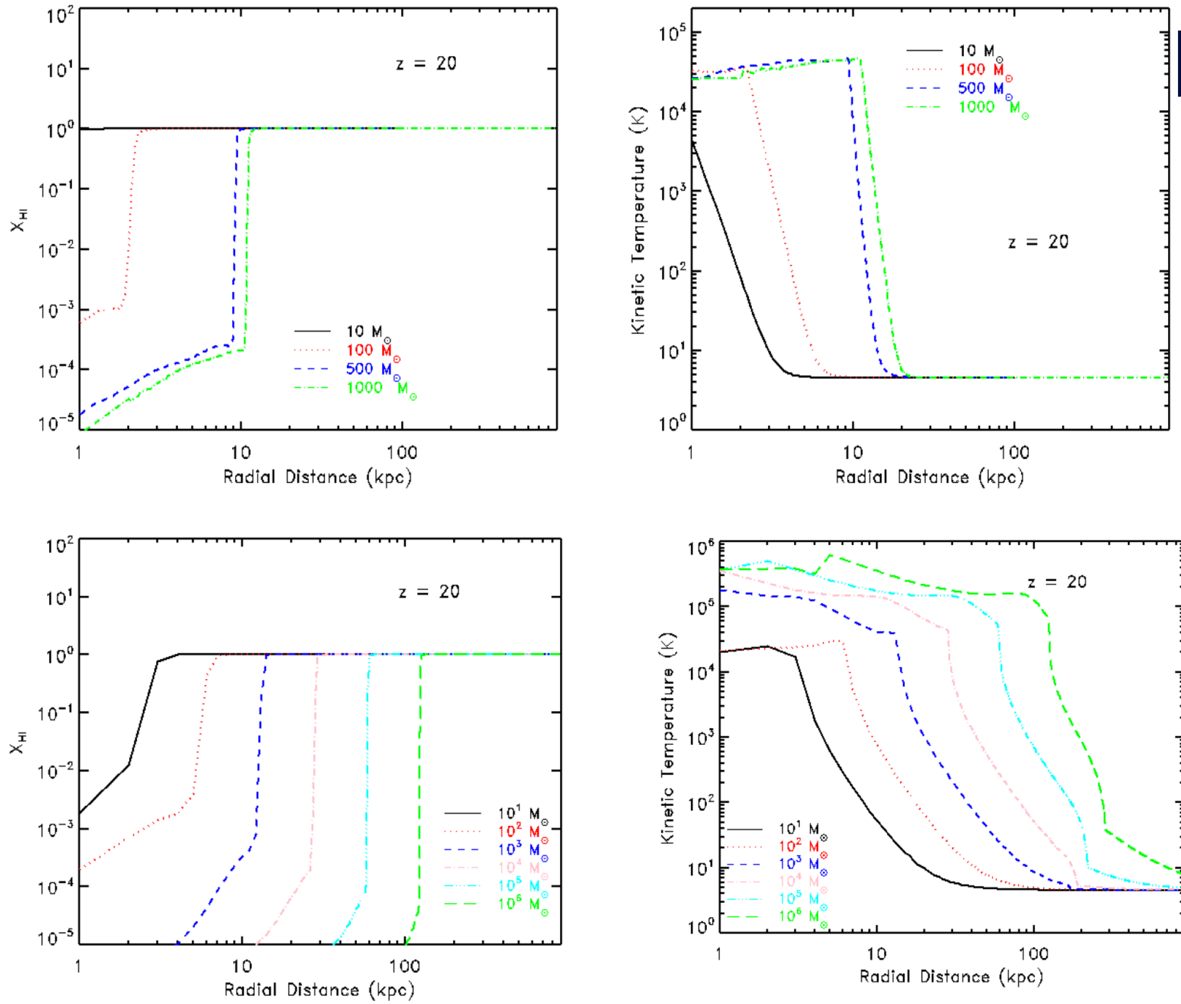
$$\delta T_b \approx 28\text{mK}\,(1+\delta)\,x_{HI}\,\frac{T_s - T_{CMB}}{T_s}\,\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Astrophysics

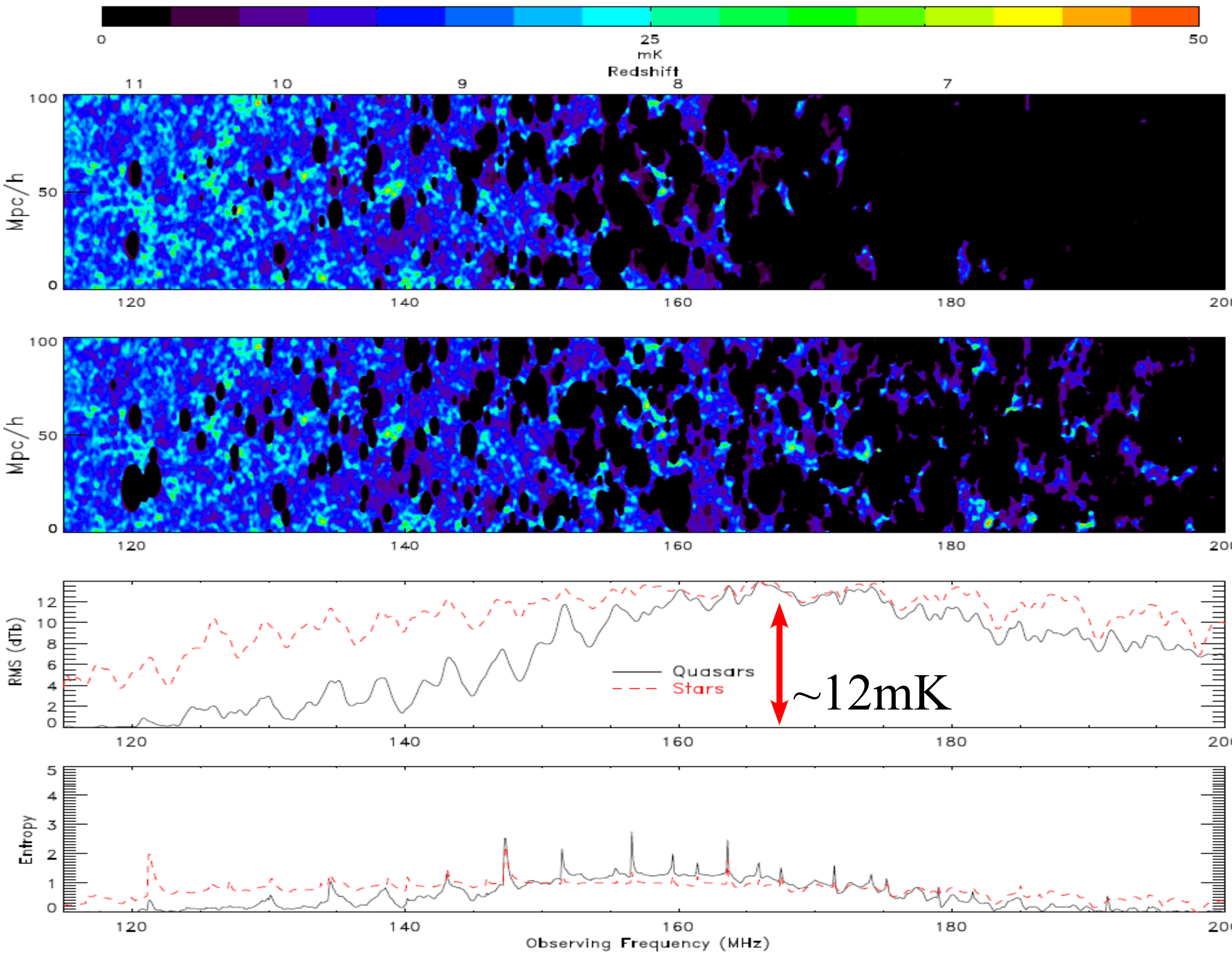
Cosmology

- The Interpretation might be very complicated

The signal: Stars vs. Miniqsos



Thomas & Zaroubi 2008



Thomas et al. 2008
Thomas & Zaroubi 2010

The Measurement

LOFAR

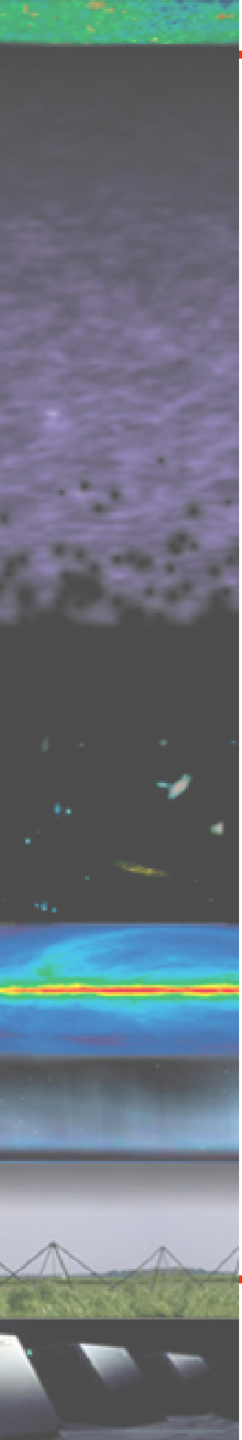
MWA

PAPER

GMRT

SKA

21CMA



The LOFAR observatory

LBA (10) 30 - 90 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)

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

A station will have 24 - 96 antennas / tiles
FOV: dipole ~100^o, tile ~20^o, station ~3^o

Principle of **Aperture Synthesis**
Array resolution: sub-arcsec to degrees

Sensitivity (after 4 h, 4 MHz, ~ 50 stations)
@ 60 MHz ~ 3 mJy
@ 150 MHz ~ 0.1 mJy

At least 8 simultaneous 6 MHz beams (or 'users') possible

LOFAR science

The specifications and capabilities of LOFAR were mainly driven by

6 Key Science Projects (KSP)

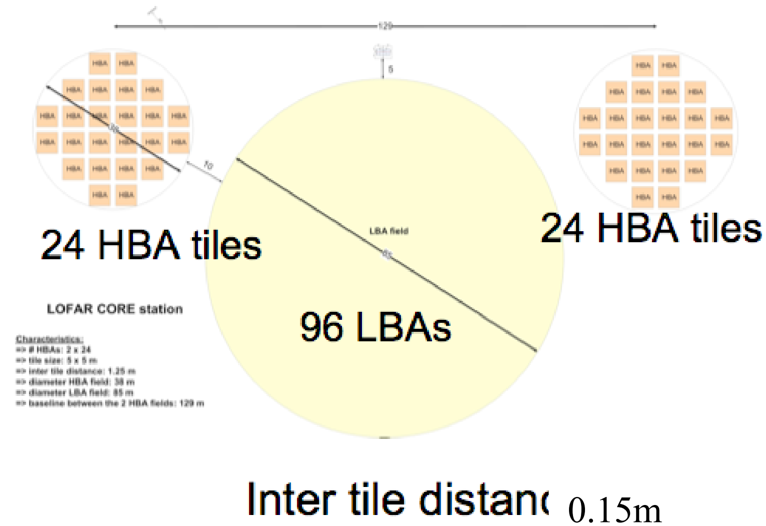
1) Surveys of the (northern) sky
2) Transients, Pulsars, (exo-)Planets
3) Epoch of Reionization
4) (UHE) Cosmic Rays + other near-field science
5) Cosmic Magnetism (polarimetry)
6) Sun and Solar system science

\+ other science applications still coming in…

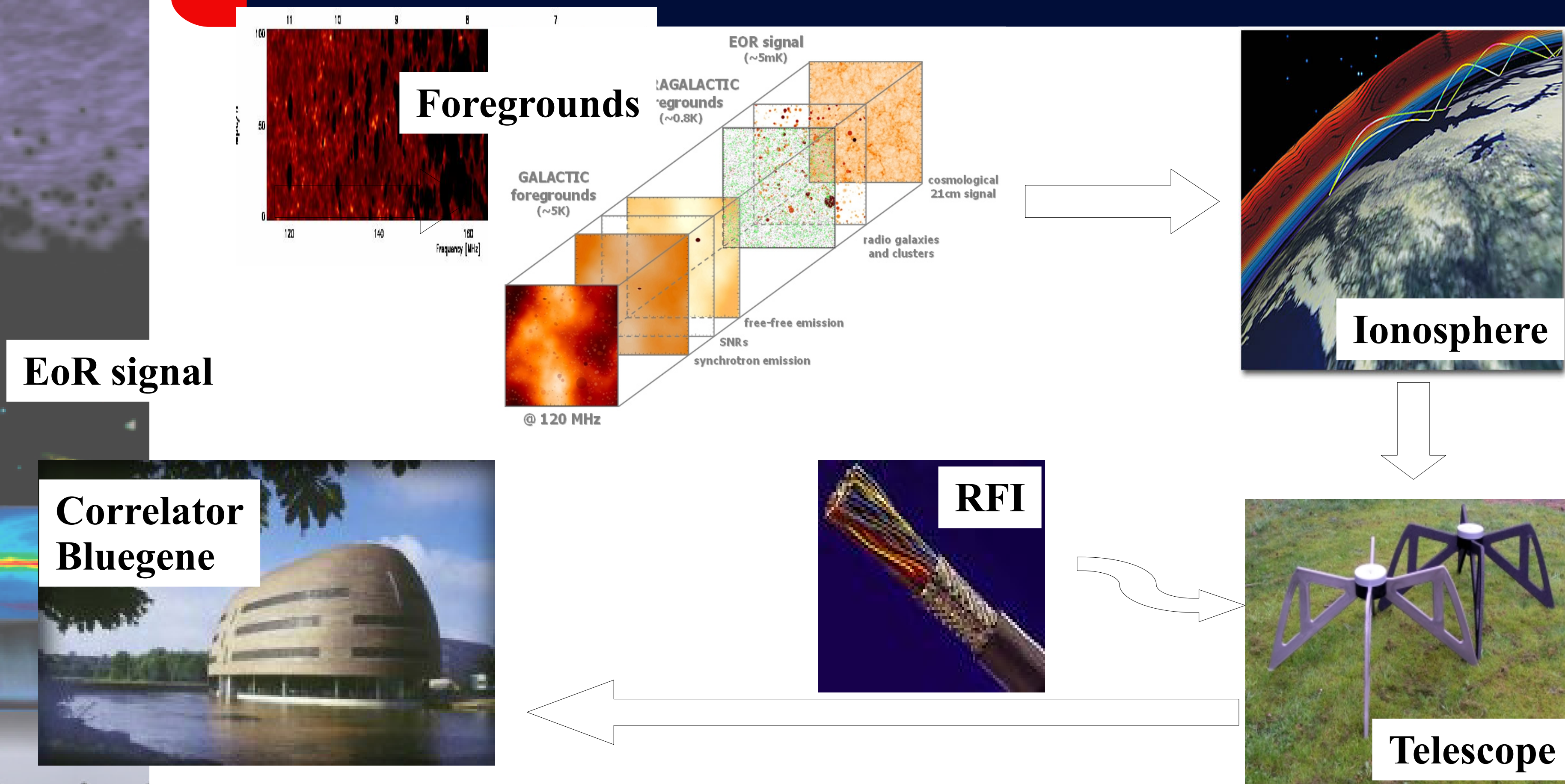
All science done under ‘umbrellas’ of International Key Science Project teams, based at Leiden, Amsterdam, Groningen, Nijmegen (all NL) Bonn, Potsdam (Germany) Total more than 100 scientists involved. For their efforts they will be rewarded with guaranteed observing time (a fraction declining over a 5 year period)

LOFAR core configuration (18, 24, 32 stations)

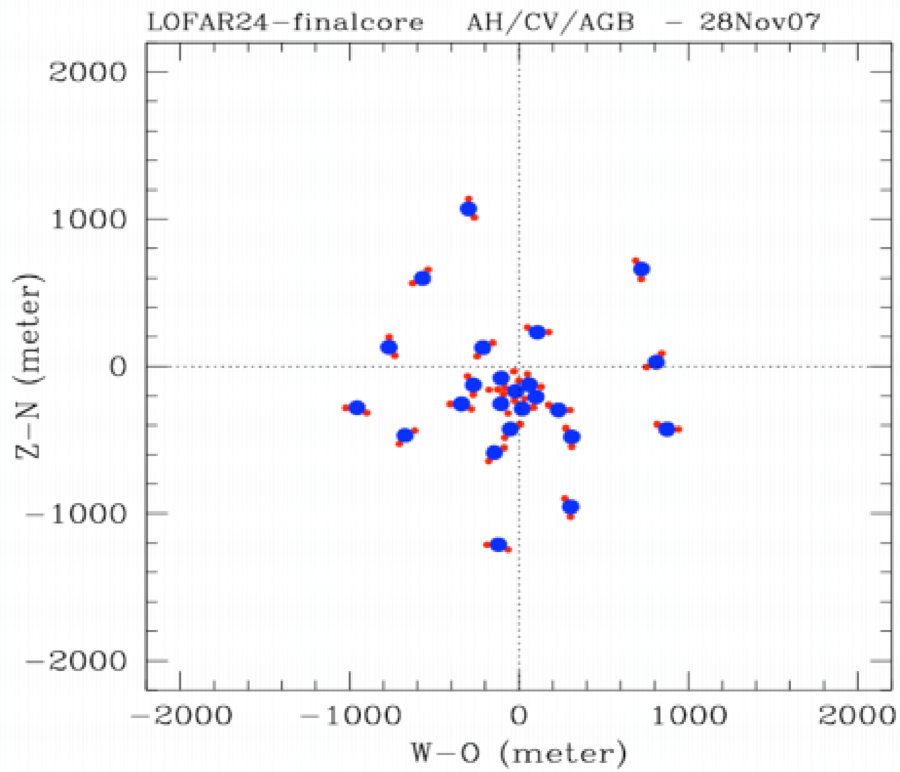
A core station



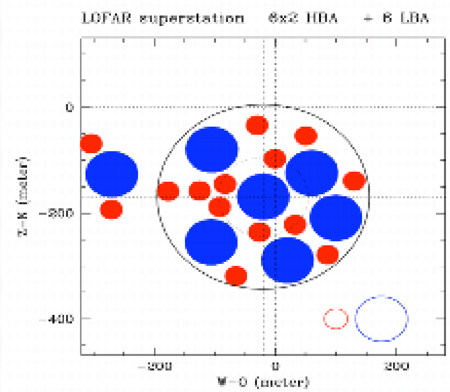
The Observation



LOFAR core 24LBA and 2x24HBA



- ~ 1300 baselines
- Large data rate
- Storage of uv data
- Recalibration
- Flexibility
- Multiple beams



Autumn weather and muddy soil cause delays….

Nov 2008

field flattening activities

‘Field flattening’ for non-astronomers

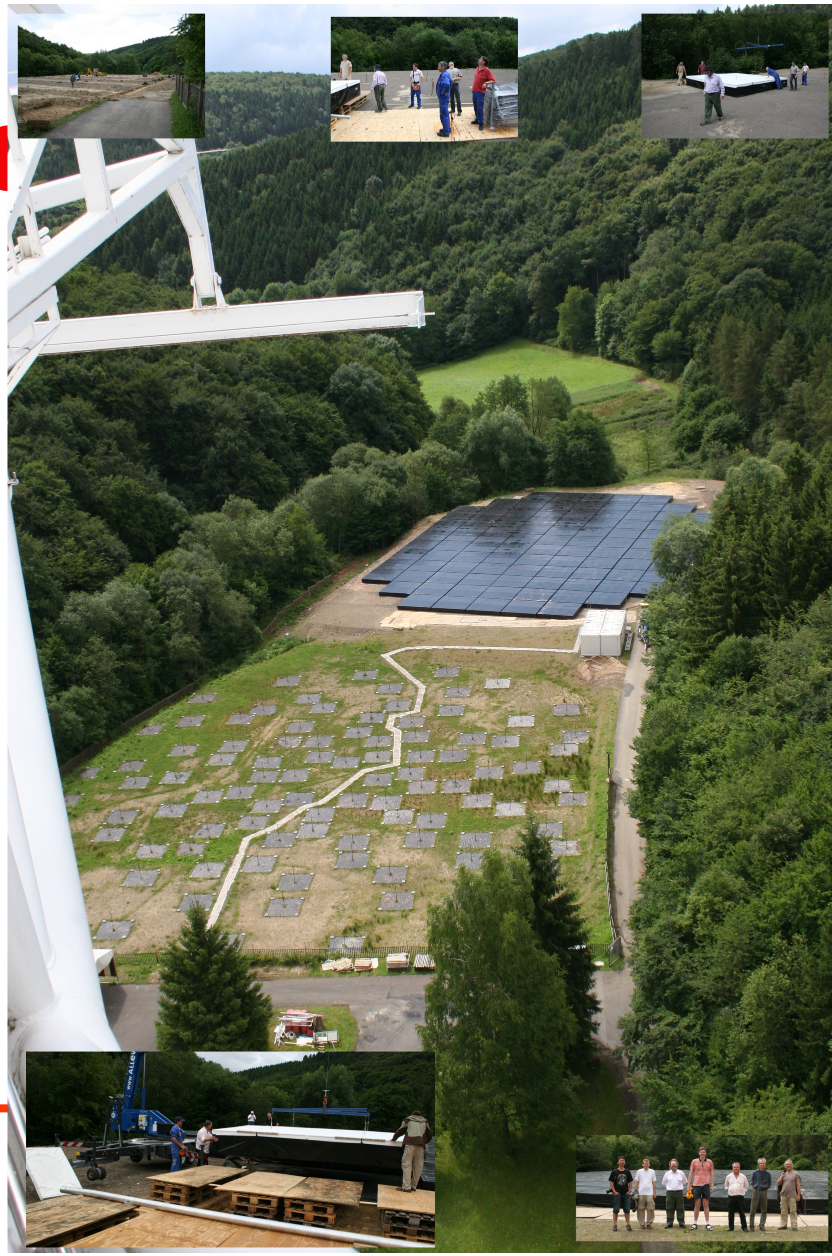
The ‘superterp’ a 350 m diameter raised ‘island’

Zeppelin-view of part of the core

The superterp, river and 'wetlands-to-be'

Finally: the 1st LOFAR station (May '09)

The first international station (Effelsberg, Germany)



96-tile station

(in 8x12 configuration,
with corners cut

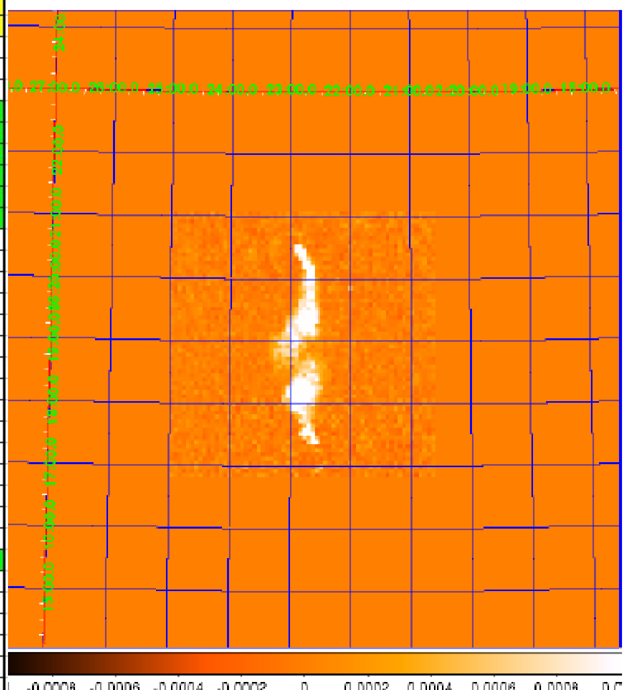
standard will be 11x11)

Anderson, AJDI July '09

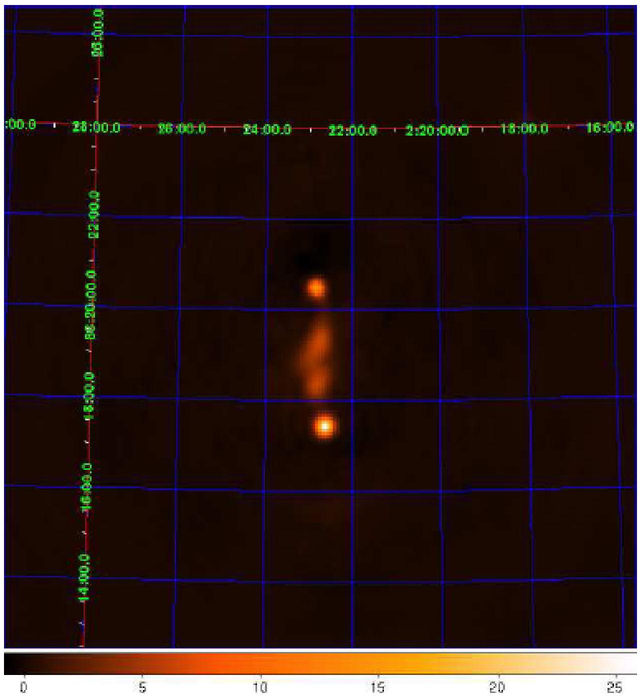
Recent results from LOFAR

Station/Item	Cabinet	LBA	HBA	Fibre	CEP connection	Validated
CS302						
RS307						
RS503						
RS106						
RS208						
CS030						
CS401						
CS021						
CS032						
RS306						
CS301						
CS501						
RS509						
CS103						
CS001						
CS002						2 L nok
CS003						2 H nok
CS004						
CS005						~8 H nok
CS006						
CS007						
CS024						
CS201						
CS101						
CS026						
RS205						
CS017						
RS104						
RS210						
RS310						
RS404						
RS406						
RS407						
RS409						
RS410						
RS508						
Effelsberg						
Tautenburg						
Garching						
Potsdam						
Juelich						
Nancay						
Onsala						
Chilbolton						
Totals	31	28	25	27	23	15

3C61.1

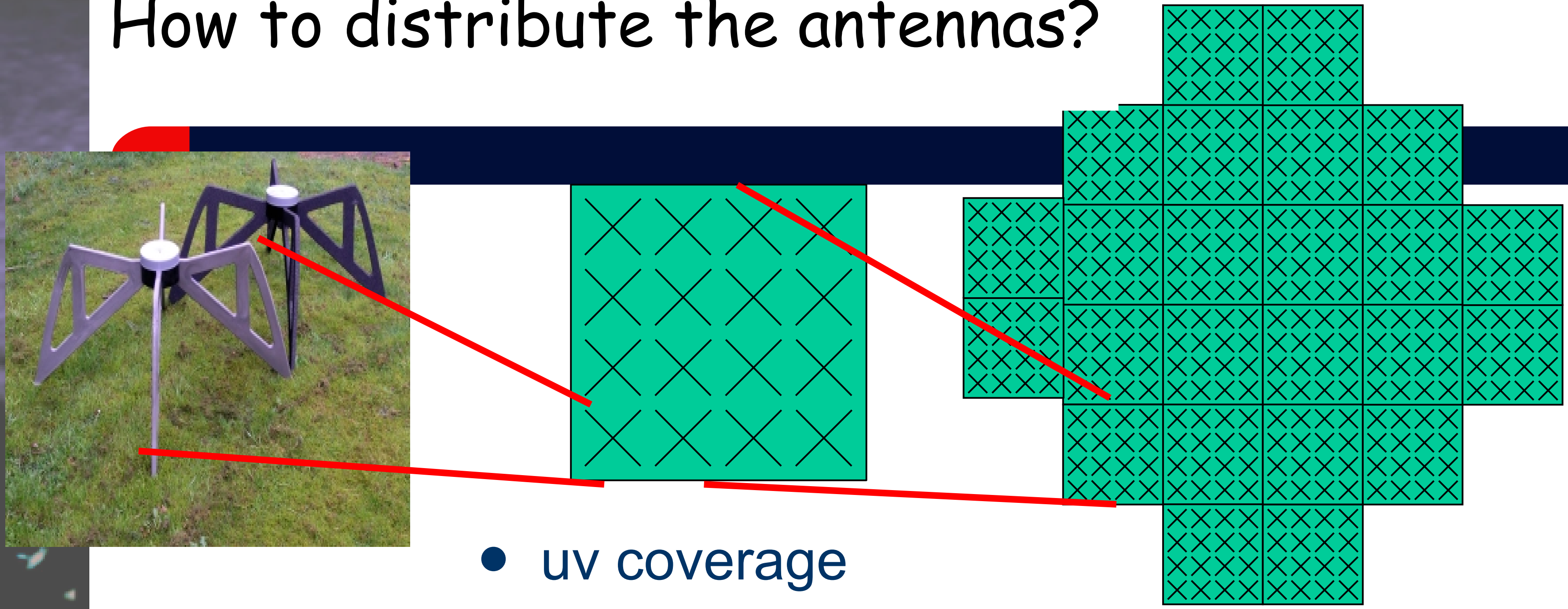


VLA, 4.8 GHz Image



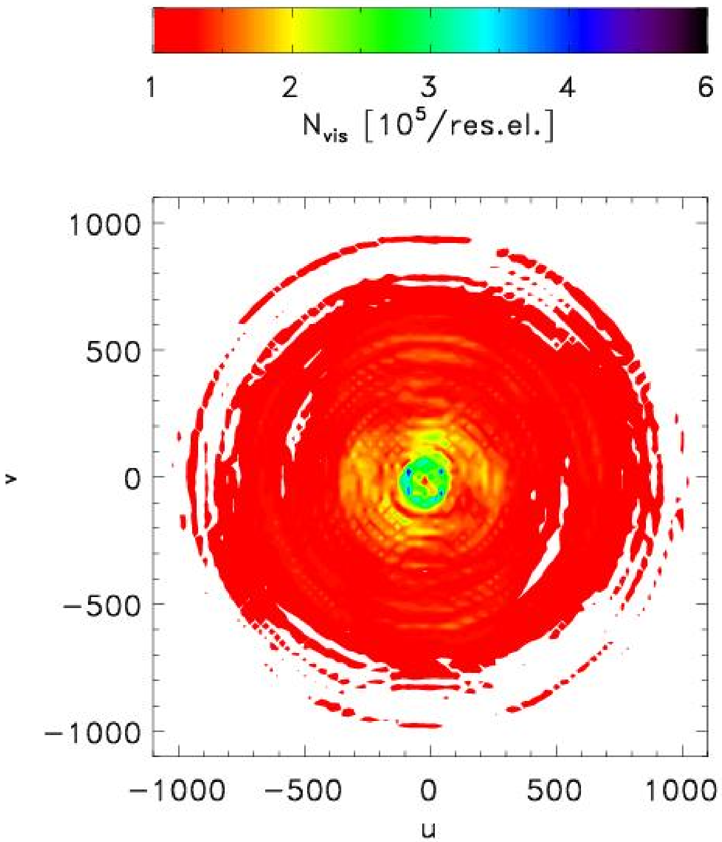
LOFAR 130 MHz Image

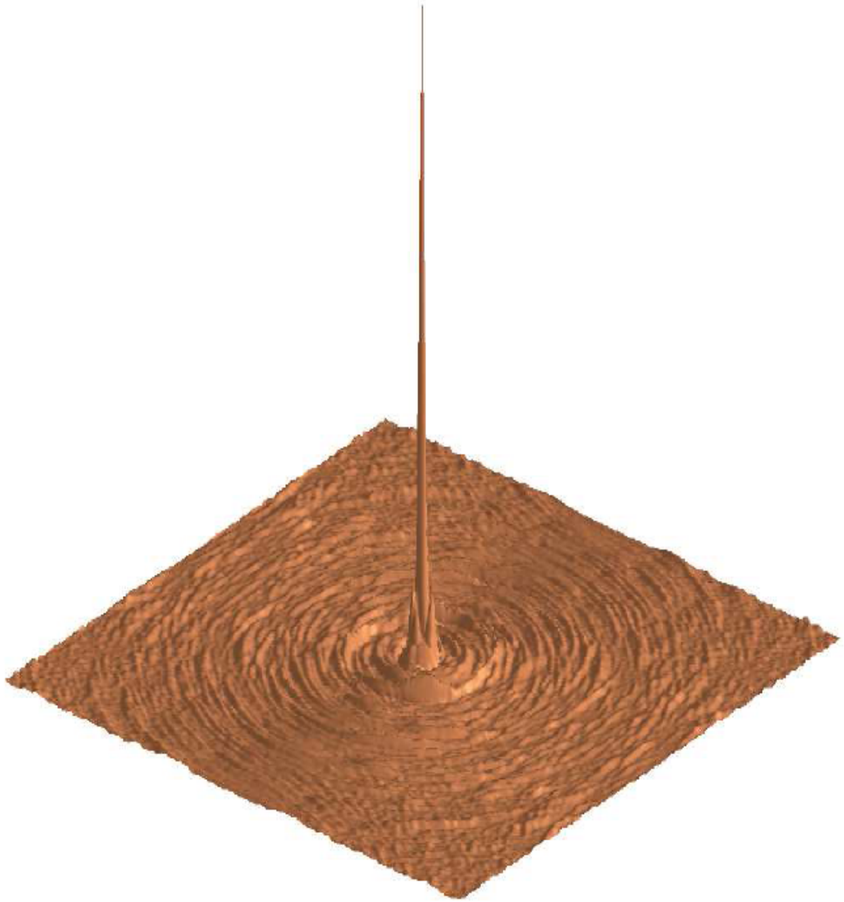
How to distribute the antennas?



- uv coverage
- Signal/Noise
- Flexibility
- Calibration
- ....

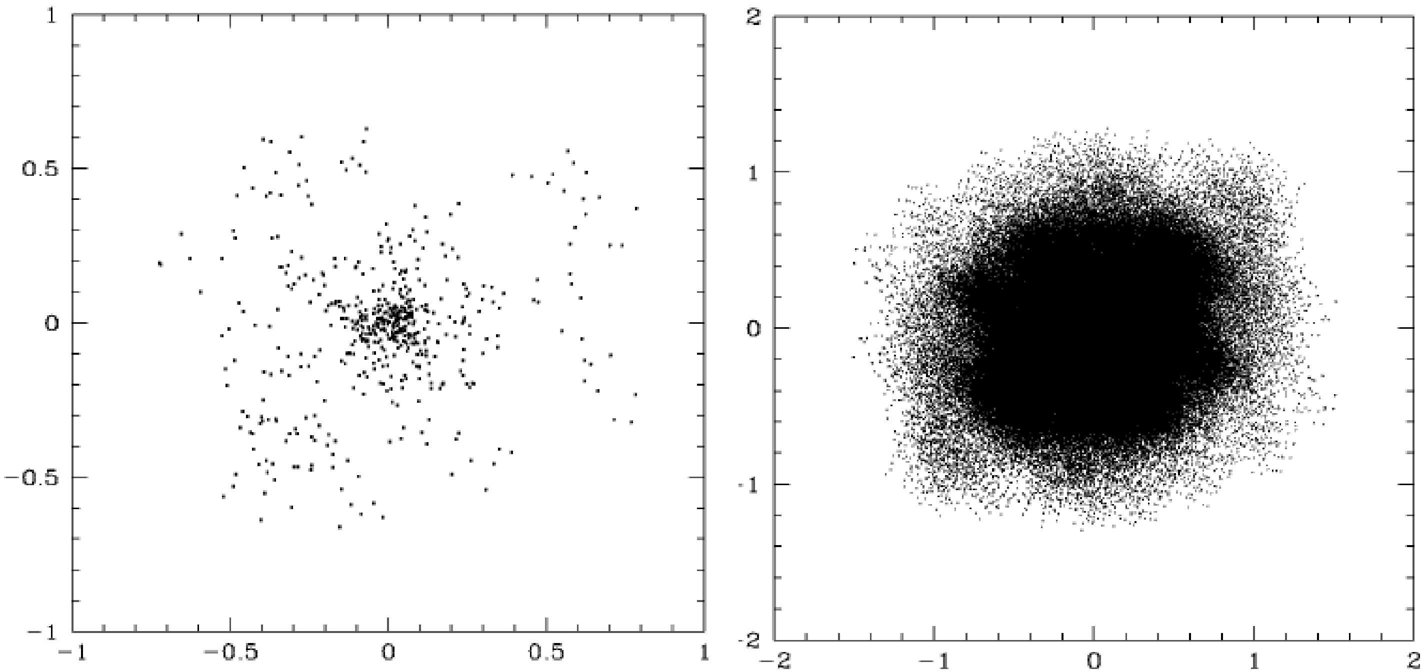
LOFAR uv coverage and beam





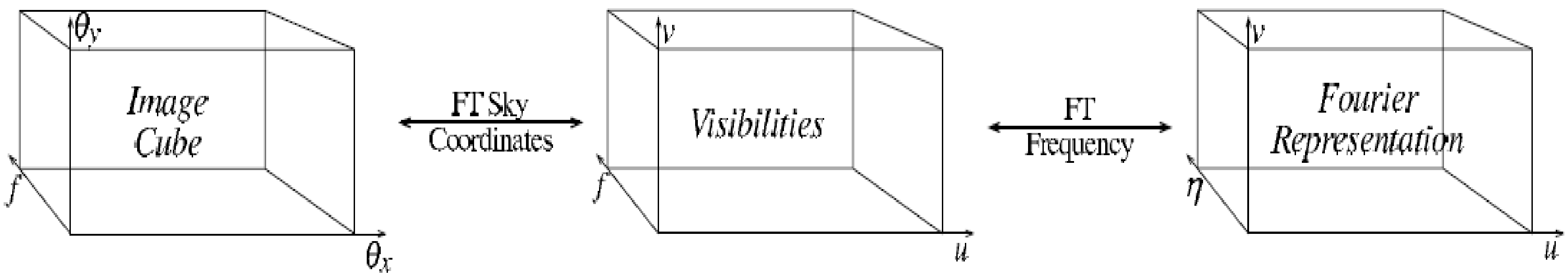
Labropulous et al, 2010

MWA layout and UV coverage



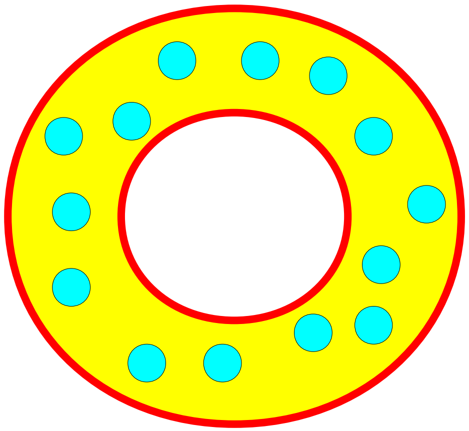
~ 125000 baselines, staggeringdata rate, image storage, real time calib.

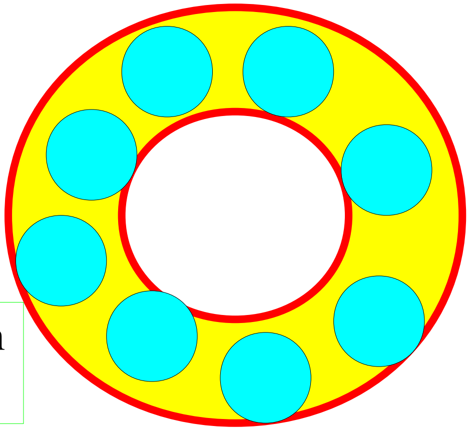
Sensitivity & S/N



Morales& Hewitt 2004

Sensitivity & Signal/Noise





# of beams

# of cells in an annulus

System Temp.

$$\left[\overline{C_{ij}^N(|\mathbf{u}|)}\right]_{rms}^{\frac{1}{2}} \approx 2N_{beam}^{-\frac{1}{2}} N_{cell}^{-\frac{1}{4}} \left(\frac{2k_B T_{sys}}{\epsilon d A d\eta}\right) \left(\frac{1}{B\bar{n}(|\mathbf{u}|)t}\right)^{\frac{1}{2}}$$

B =Bandwidth
dη=inv. Bandwidth
n= mean # of baselines

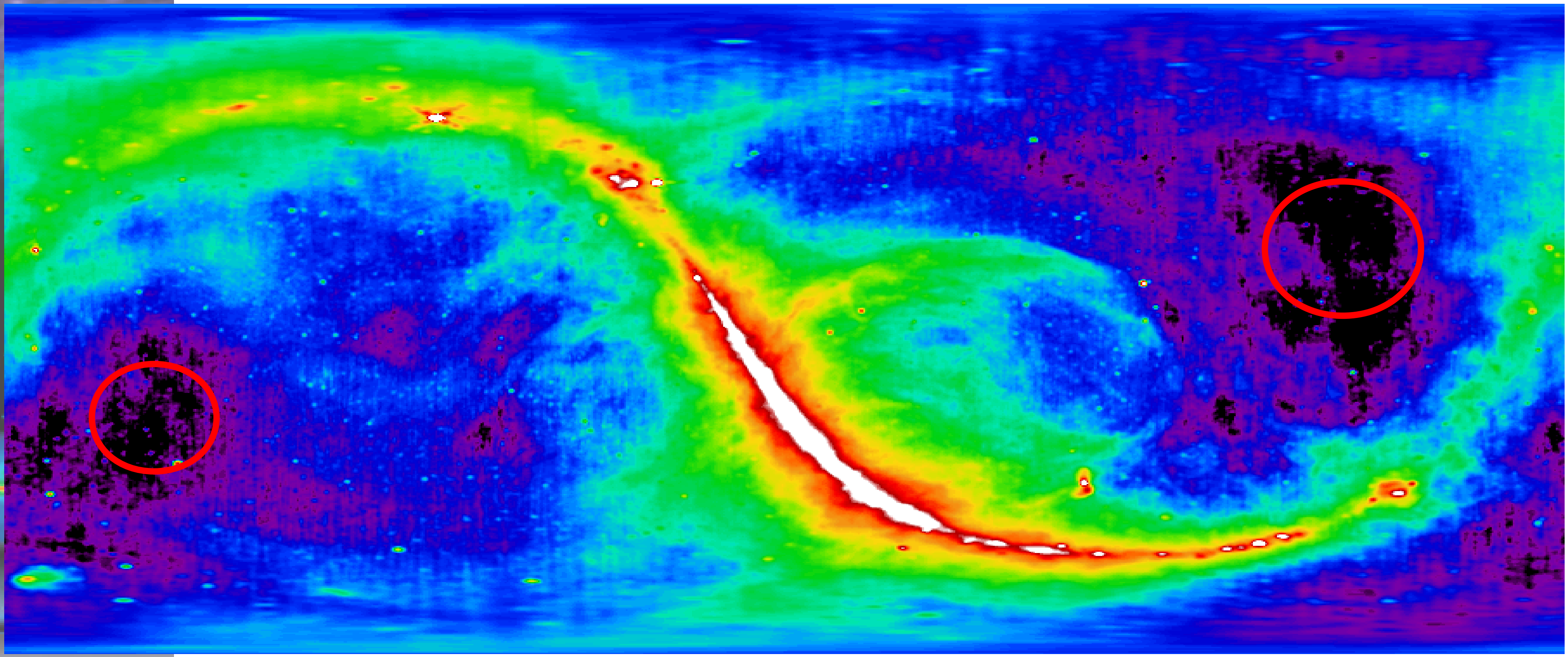
efficiency

Station area

Integration time

Foregrounds

$T_{sys} = T_{sky} + T_{Receiver}$ At 150 MHz T_{sky} ~200K



Radio sky at 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%)**

Exrtagalactic foreground

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

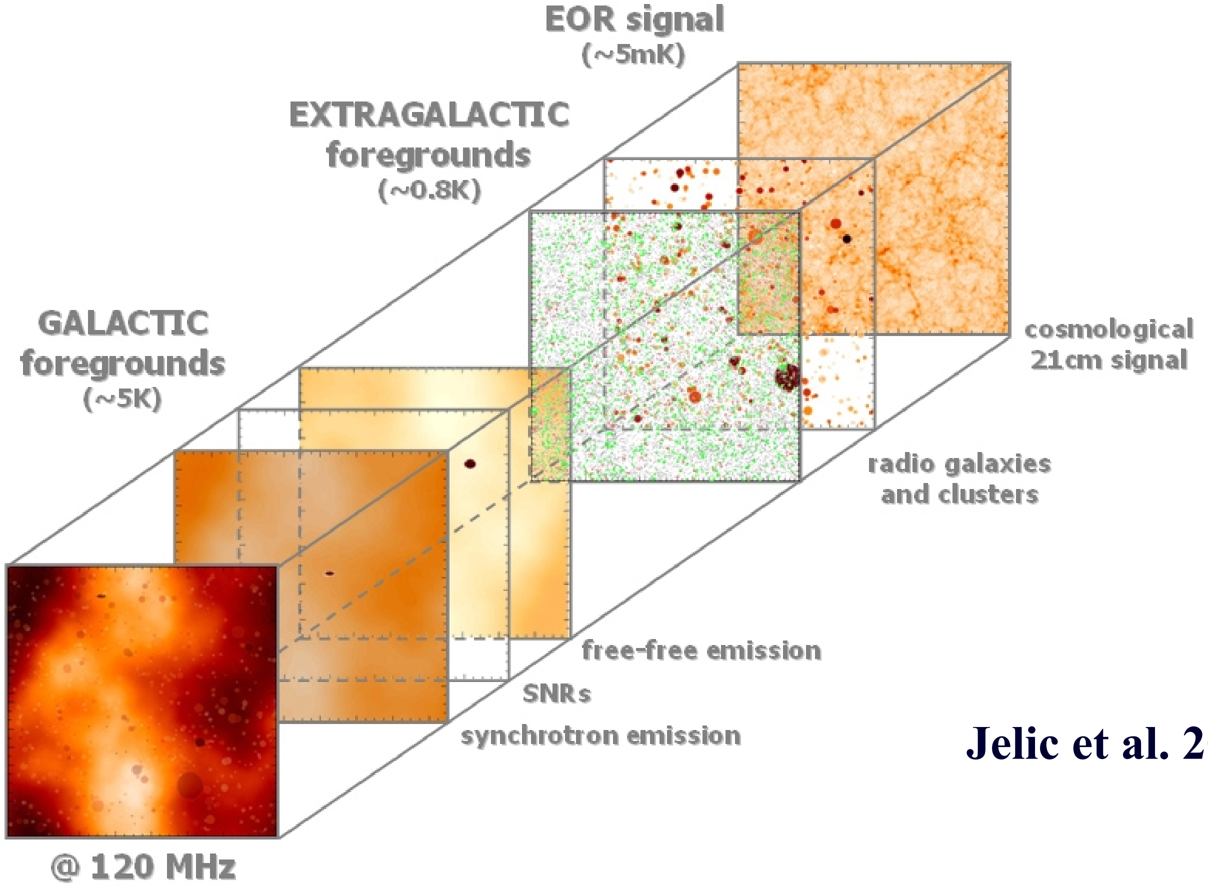
  — **based on radio sky simulations by Jackson et al. 2005**

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

- **Galaxy Clusters**

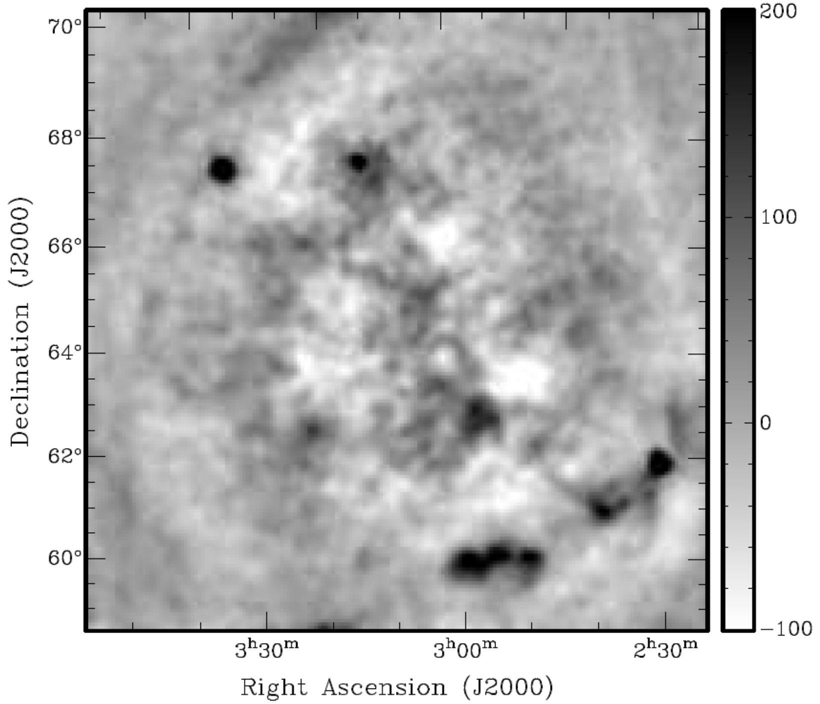
  — **The Hubble Volume Simulation Cluster Catalogue (Virgo Consortium, 2002)**
  —**DMH Mass – Xray correlation (Jenkins et al., 2001)**
  — **X ray – radio luminosity correlation (Ensslin & Röttgering, 2002). 30% with radio properties.**
  — **Redshift, virial radius ⇒ angular size**
  — **Spectral index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

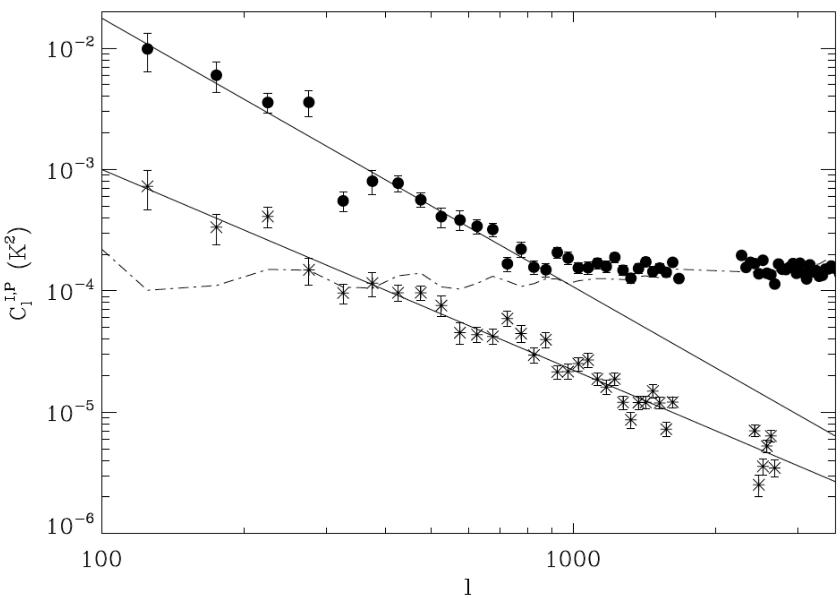
The signal + Foregrounds

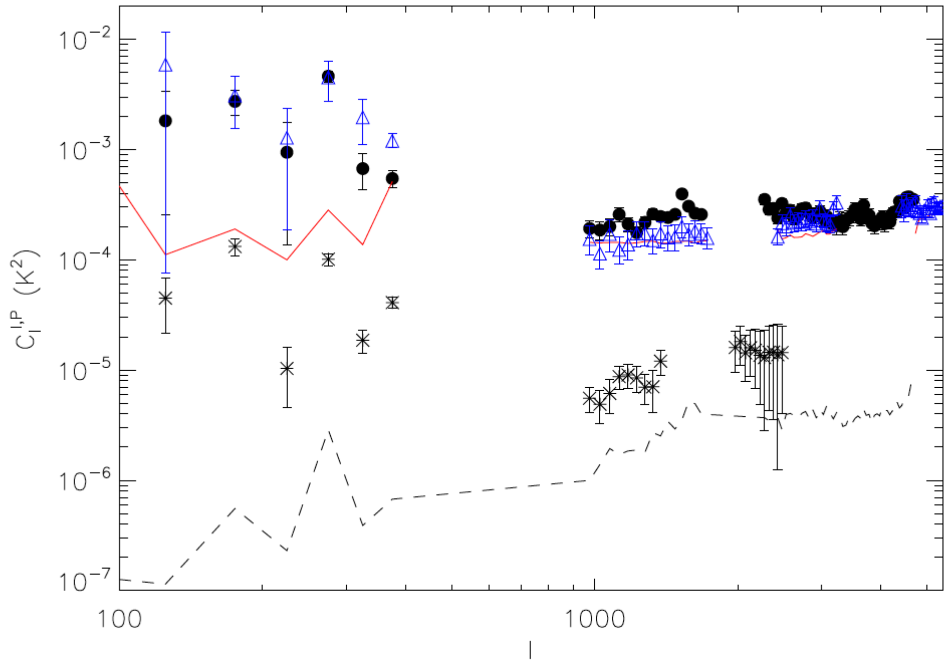


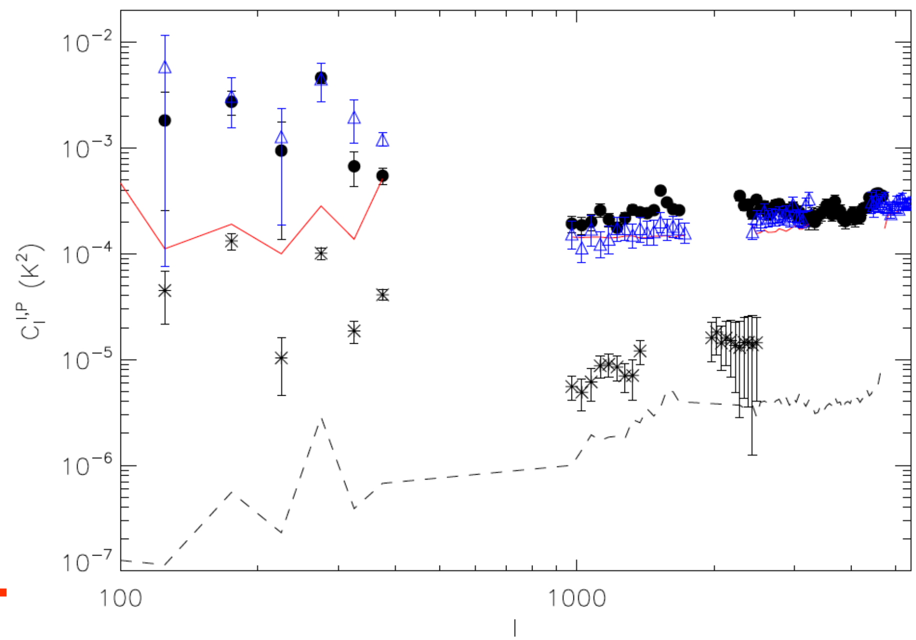
Jelic et al. 2008

For simulated FG data please contact Vibor Jelić





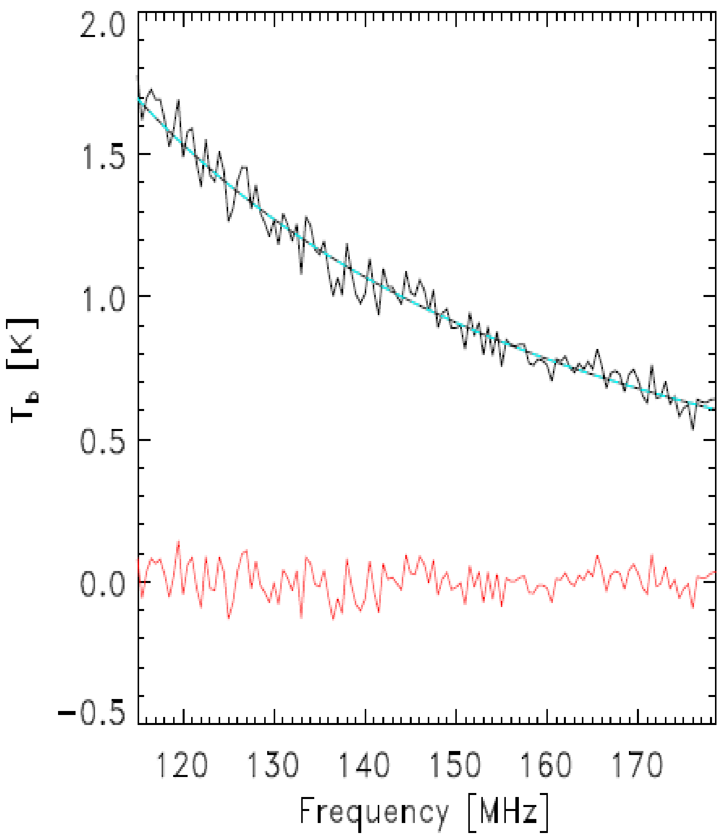


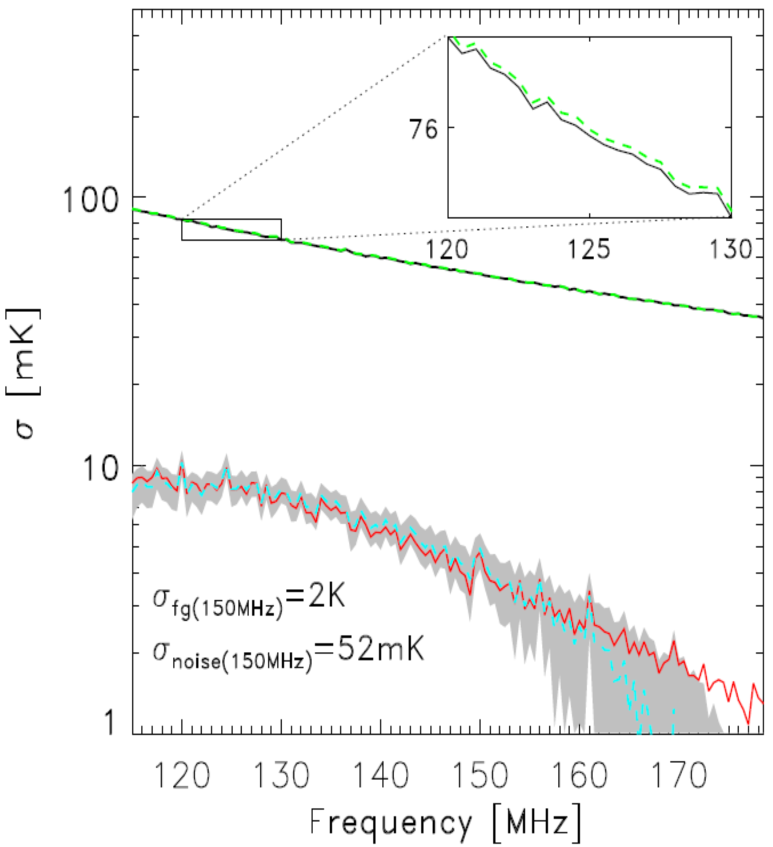


Bernardi et al. 2009, 2010

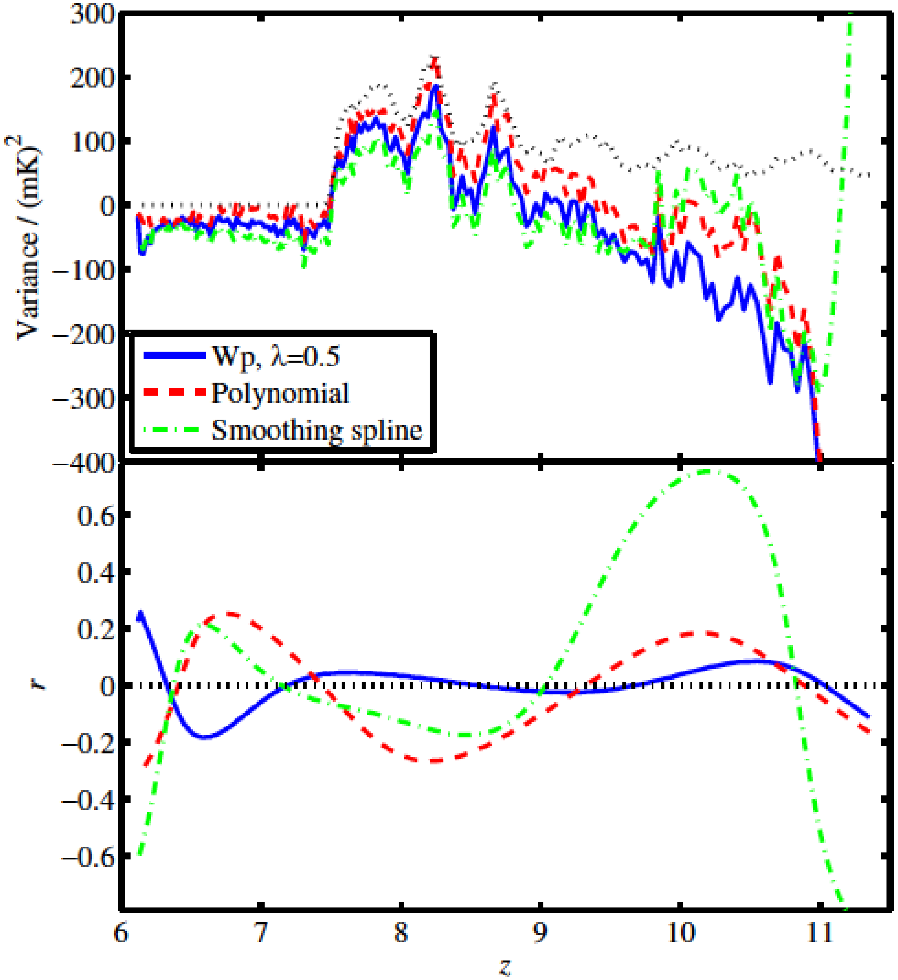
Extraction

Extraction with Polynomials





Cross-correlation of residuals with foregrounds

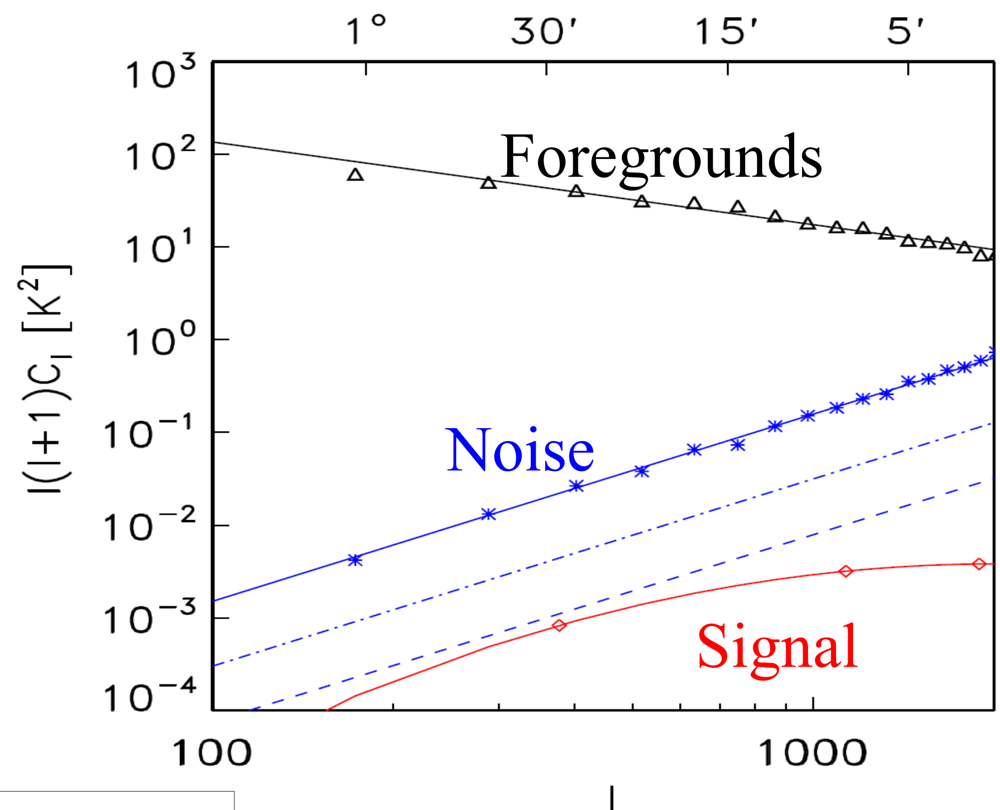


The fitting here is using a non-parametric algorithm called Wp which is well suited for this problem.

It avoids over- and under-fitting. It also minimizes the cross talk between the the fitted FG and the residuals.

Harker et al 2009

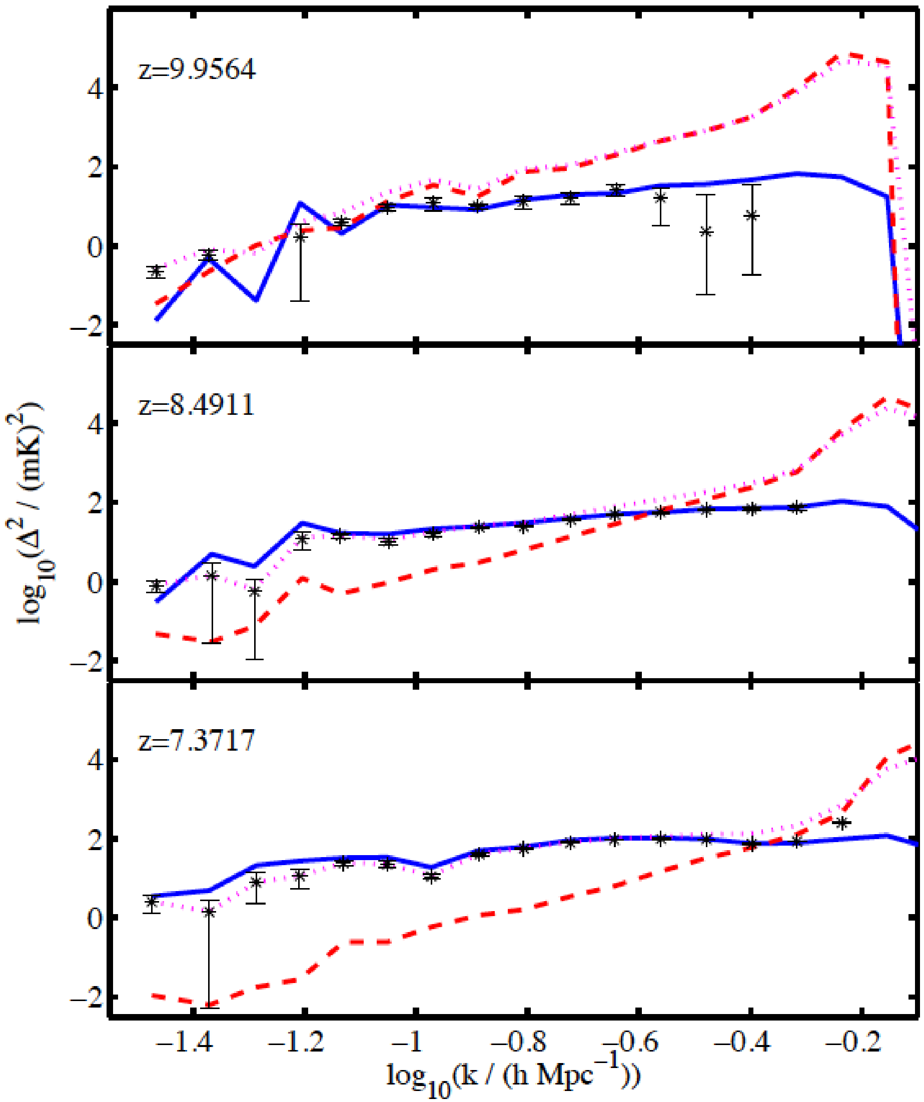
Angular power spectra of various contributions



Fitting is expected to be worse at large scales (small *l*)

Santos et al.2006
Jelic at el. 2009

Power Spectrum Measurements

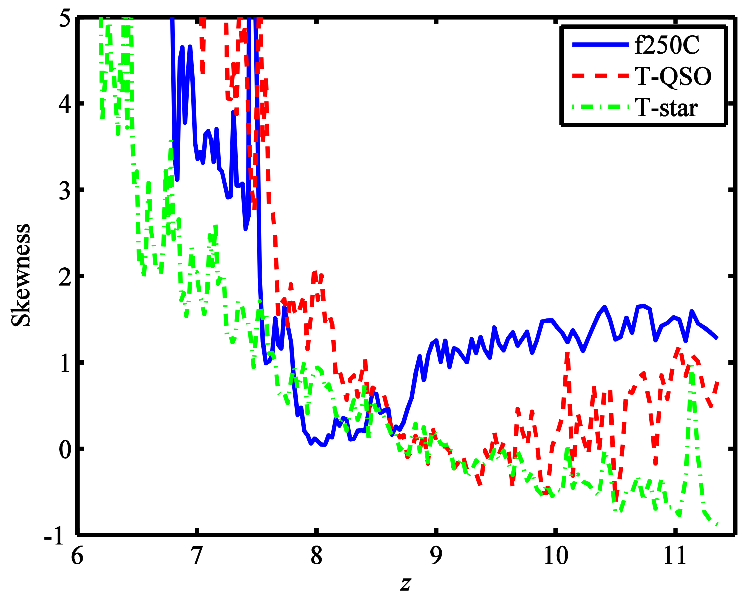


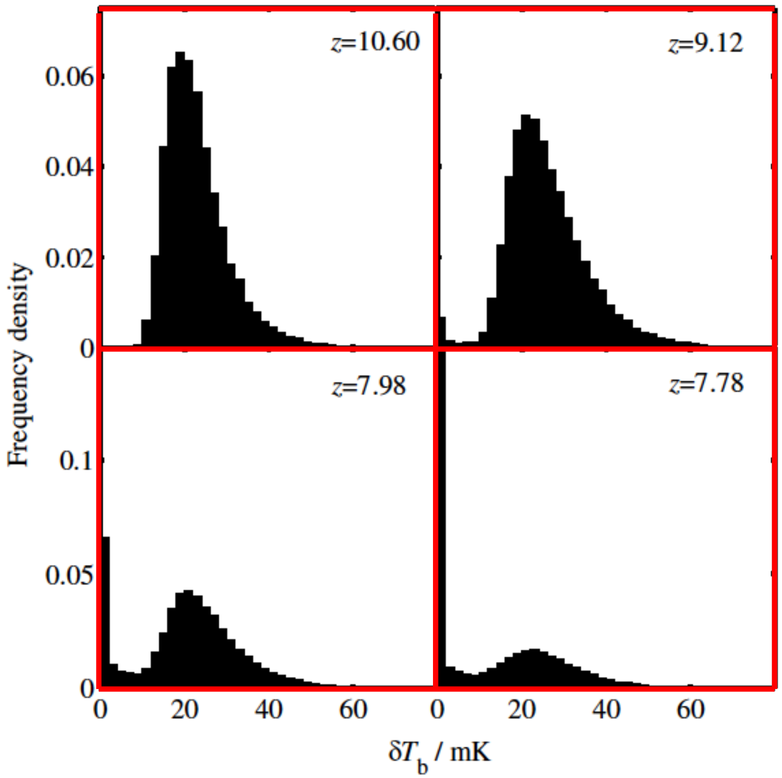
Harker et al. 2010

High Order Statistics

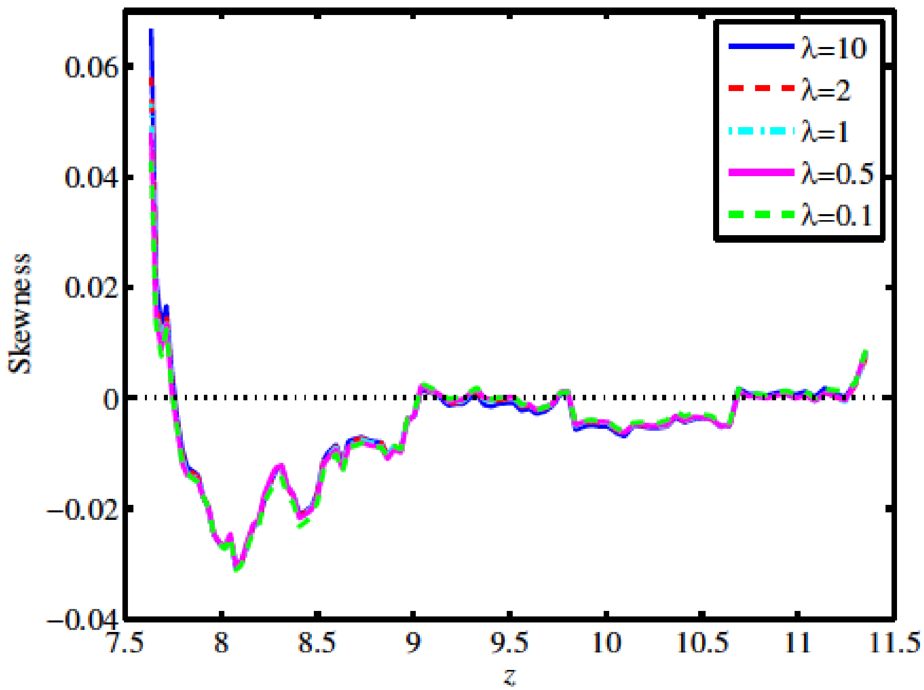
The Skewness

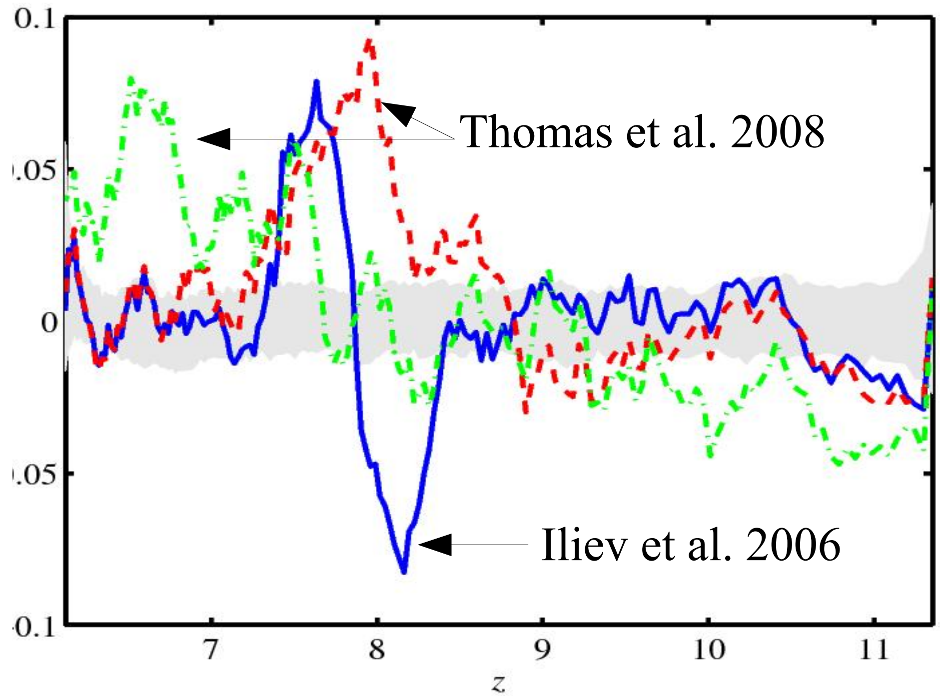
Original simulations





Extraction through the skewness



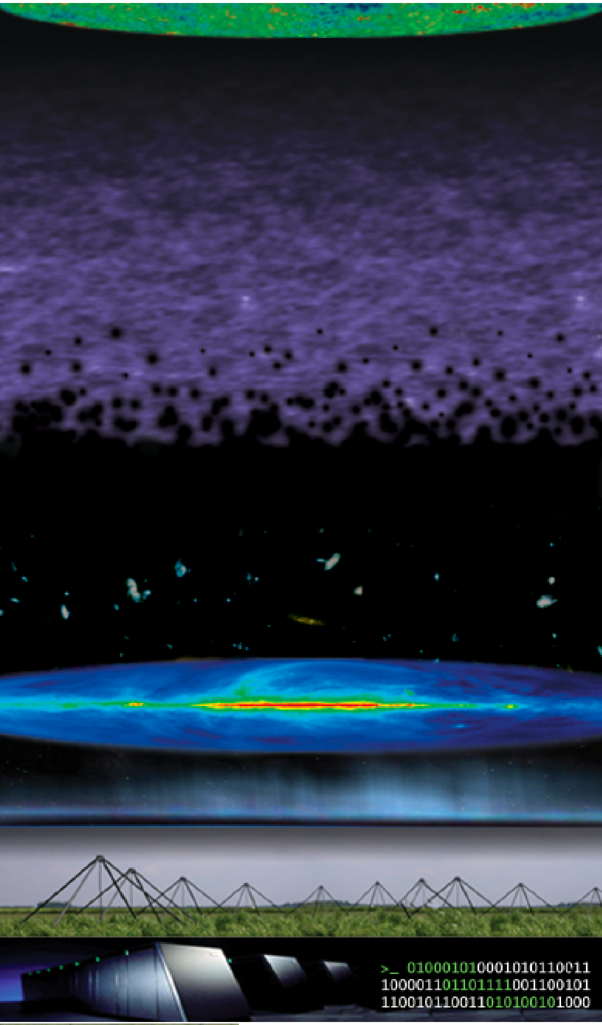


Harker et al. 2009

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
- This is all doable and will usher us into a new era in studying the Universe.

Observation Extraction Interpretation



End of talk

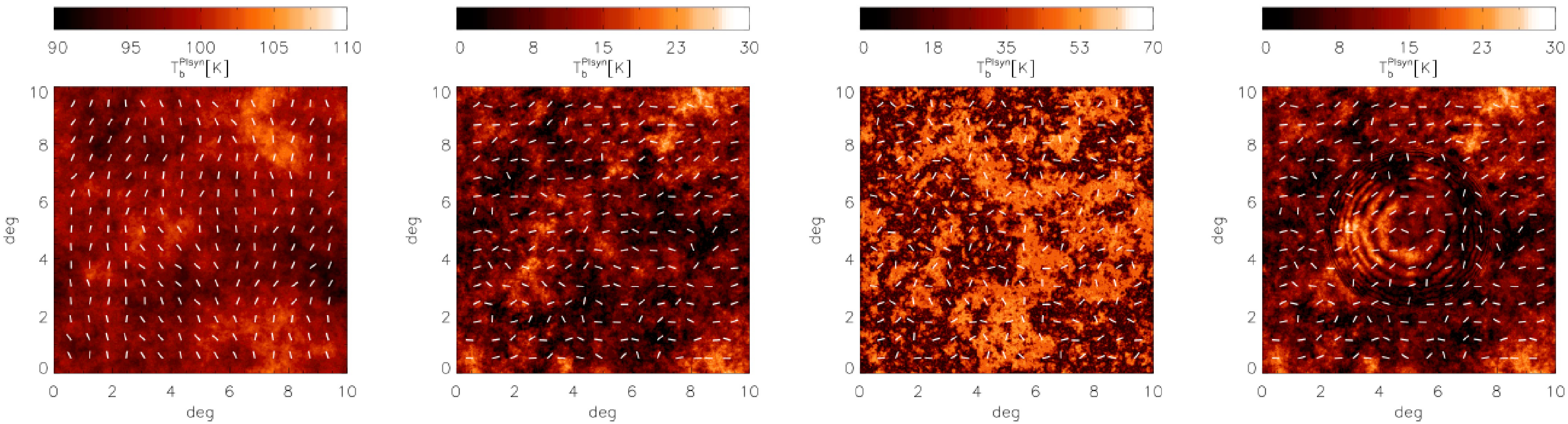
The Ionosphere and the calibration problem

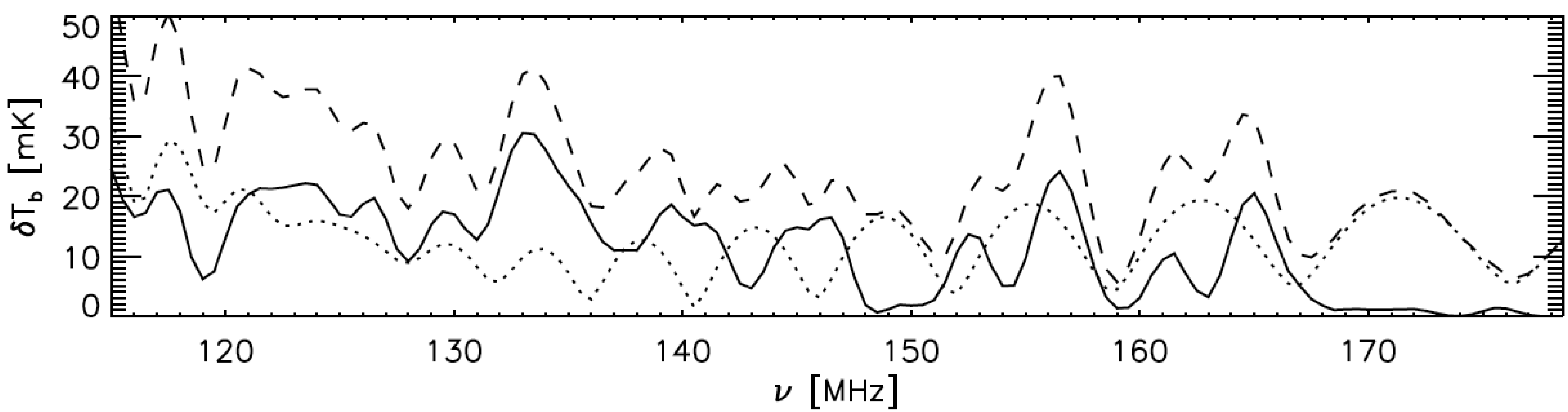
- The measurement equation
- Global and local sky models
- Calibrate out the:
  - ionospheric distortion
  - variation of gain (e.g., cows shewing your cables)
  - antenna polarized response.
  - ...
-

The Calibration Problem

Polarized Foregrounds

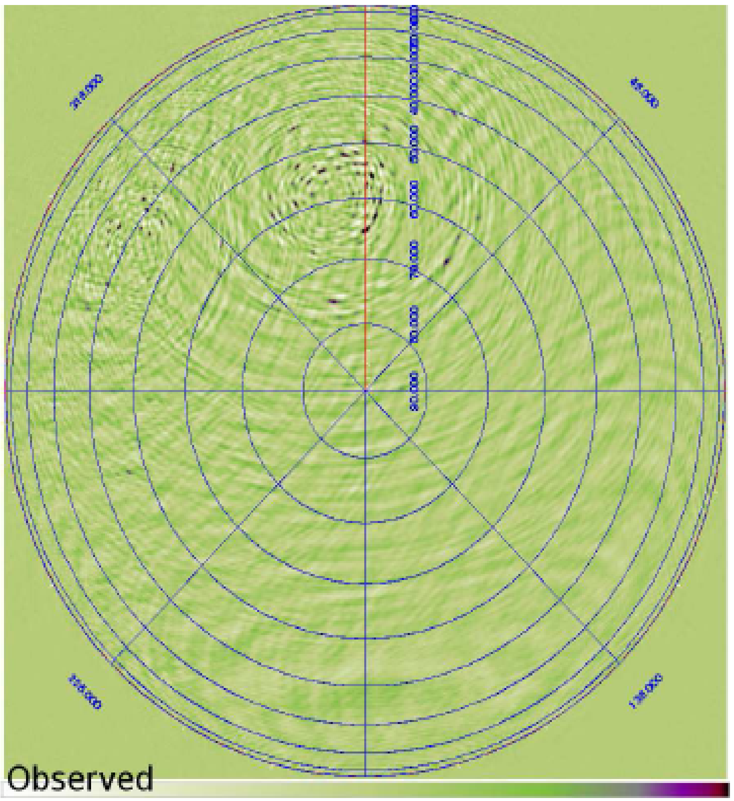
Jelic et al. 20 in prep



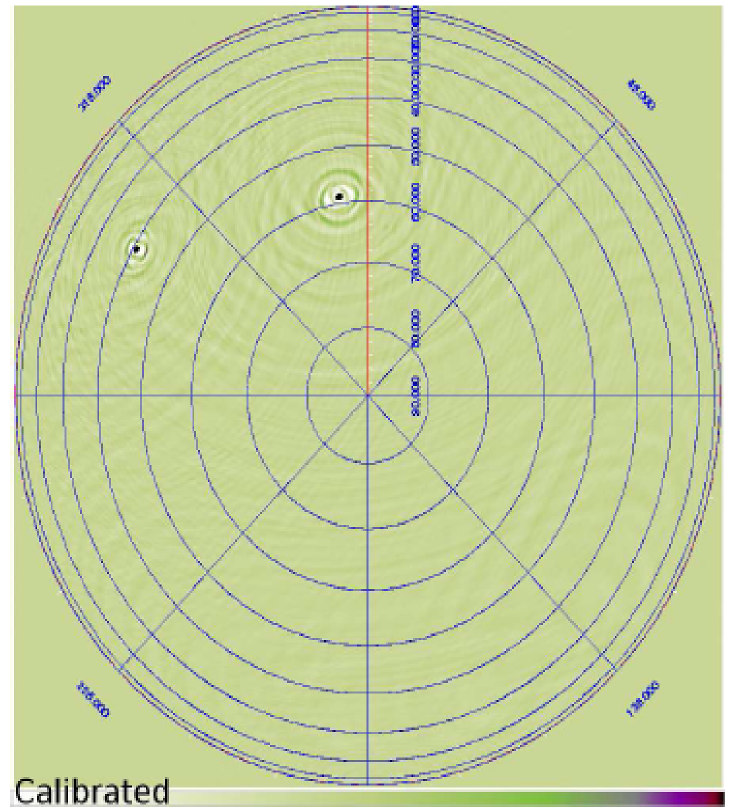


The LOFAR calibration an example

Yatawatta et al, 2009



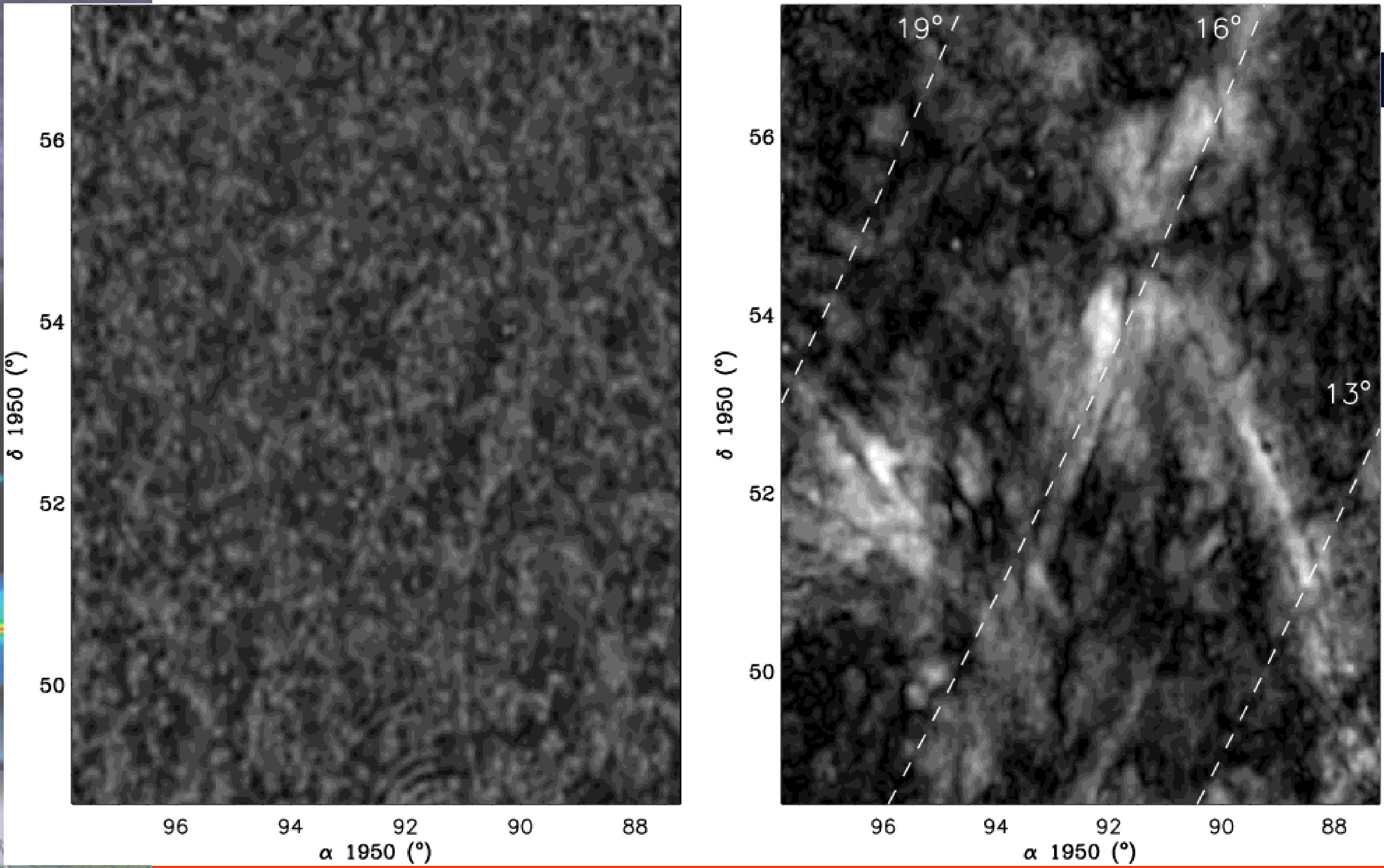
North Celestial Pole (NCP), LBA



North Celestial Pole (NCP), LBA, Cas A, Cyg A

The 'DOGLEG area' in Auriga WSRT ~ 350 MHz

Total intensity ← same intensity scale → Polarised intensity



Haverkorn et al, 2003