21 cm Emission Line from the Epoch of Reionization

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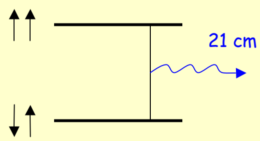
Outline

- Introduction on the physics of the 21cm line
- Brief overview of 21cm line literature
- IGM reionization and 21cm emission line diagnostic
- Information from the 21cm/CMB cross-correlation
- Extra-galactic foreground contamination

21cm line



Probe of neutral H at high-z

$$T_S \not\leftrightarrow T_{CMB}$$

1. Spin-exchange collisions between H atoms:
   - IGM at z>30
   - structure formation
2. Scattering by Lyalpha photons:
   - radiation from first sources

$$P_\alpha = 4\pi J_\alpha \sigma_\alpha / h\nu_\alpha$$

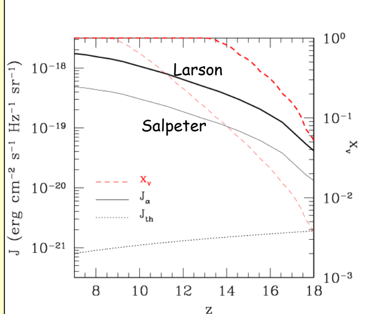
$$P_{th} \Rightarrow J_{th} = 10^{-22}(1+z) \;\; \mathrm{erg\ cm^{-2} s^{-1} Hz^{-1} sr^{-1}}$$

Lyalpha background

Scattering Rate:

$$P_\alpha = 4\pi J_\alpha \sigma_\alpha / h\nu_\alpha$$

$$P_{th} \Rightarrow J_{th} = 10^{-22}(1+z) \;\; \mathrm{erg\ cm^{-2} s^{-1} Hz^{-1} sr^{-1}}$$



(BC & Madau 2003)

$$J_\alpha > J_{th} \Rightarrow T_s \not\leftrightarrow T_{CMB}$$

➨ The Lyalpha background is strong enough to decouple the temps.

Absorption or emission?

Differential brightness temperature:

$$\delta T_b \approx \frac{T_s - T_{CMB}}{1+z}\tau \propto (1 - T_{CMB}/T_s)$$

$T_{CMB} >> T_s \Rightarrow$ absorption

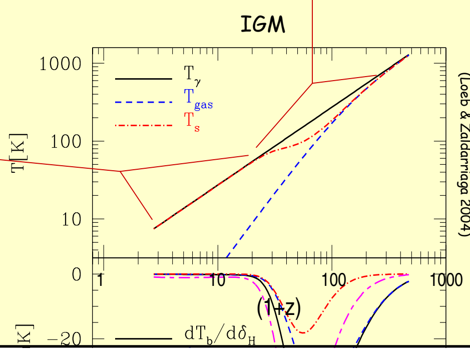
$T_s >> T_{CMB} \Rightarrow$ emission

30<z<200 → absorption

z_ion<z<30 → emission

Heating by Lyalpha or X-ray photons, shock heating

(Madau, Meiksin & Rees 1997; Giroux & Shull 2001; Glover & Brand 2002; Chen & Miralda-Escude' 2003; Gnedin & Shaver 2004)



Absorption

- Absorption of CMB flux prior to structure formation (Loeb & Zaldarriaga 2004)
- IGM absorption toward high-z radio sources (Carilli, Gnedin & Owen 2002)
- Absorption by minihalos and protogalactic disks (Furlanetto & Loeb 2002)

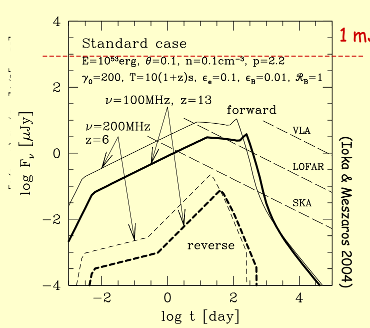
Pb. Observations at frequencies <50MHz are extremely challenging

Pb. Are there bright enough sources of radio radiation at high-z?

Sources of radio radiation with

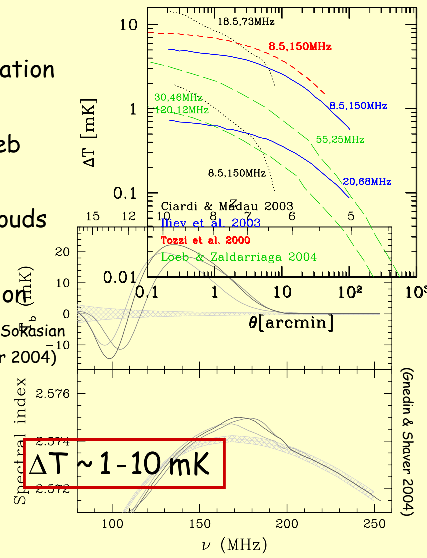
$$S_{min} \approx 1\,\text{mJy}\,(0.002/\tau) \qquad \tau \propto 1/T_s$$

- Radio source at z~10 could have S~10 mJy (Carilli, Gnedin & Owen 2002)
- Radio afterglow of GRBs (Ioka & Meszaros 2004)



Emission

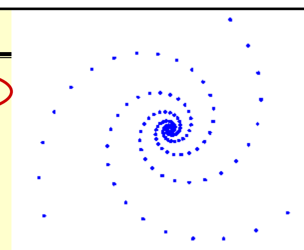
- Global signature associated with reionization
  (Shaver et al. 1999; Gnedin & Shaver 2004)
- Signal and fluctuations due to cosmic web
  (Tozzi et al. 2000)
- Emission from minihalos or hydrogen clouds
  (Iliev et al. 2002, 2003; He et al. 2004)
- Signal and fluctuations due to reionization
  (Ciardi & Madau 2003; Gnedin & Shaver 2004; Furlanetto, Sokasian & Hernquist 2004; Ricotti, Ostriker & Gnedin 2004; Nusser 2004)

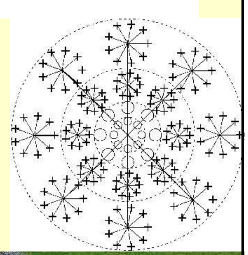


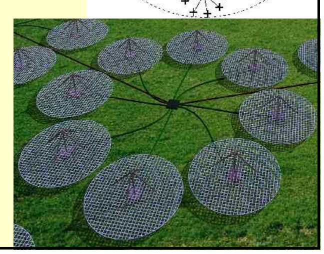
LOFAR Design Goals

Frequency range	Low	10-90 MHz#
	High	110-220 MHz
Effective Collecting Area (A_e)	Low	$10^{6.1}(\nu/15\,\mathrm{MHz})^{-2}\,\mathrm{m}^2$
	High	$10^{5.6}(\nu/110\,\mathrm{MHz})^{-2}\,\mathrm{m}^2$
Point Source Sensitivity (Surface Brightness Sensitivity)	75 MHz:	
	Full array	1.0 mJy in 1 hour (7.2×10^4 K)
	Virtual core	4.0 mJy in 1 hour (7.3 K)
	200 MHz:	
	Full array	0.03 mJy in 1 hour (2.5×10^3 K)
	Virtual core	0.14 mJy in 1 hour (0.25 K)
Redshift coverage (HI)		$z > 5.5$
Instantaneous sky coverage		1 sterad at 20 MHz
Angular resolution		1.3 arcsec at 120 MHz
Number of receptors	Low	13,365 dipoles
	High	213,840 dipoles
Number of clusters		1485
Number of stations		~ 100
Configuration	Core array	$\lesssim$2 km
	Extended array	~400 km
Baselines		0.1 – 400 km
Multibeam capability (within FOV)		Full mapping
Number of independent FOV		2 to 8
Instantaneous bandwidth		322 MHz (digitized) 2-4 MHz (transported)
Number of spectral channels		4 k
Image dynamic range		$\gtrsim 10^5$
Time resolution		1 ms
Polarization		Full Stokes

LOFAR may include the 90 to 110 MHz band.





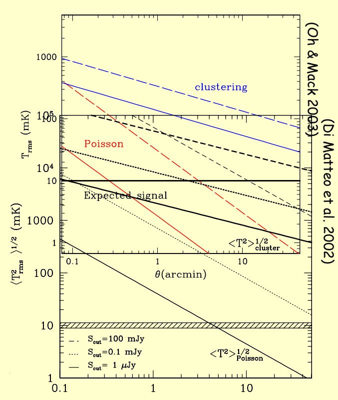


Specifications of PAST @ 150 MHz

Total antennae:	10,000
Effective Elements:	20
Effective Area:	70,000 sq m
Sky brightness temperature:	90 K
Instantaneous imaging field of view:	2 sq deg
Angular resolution:	3 arcmin
Instantaneous frequency coverage:	50-200 MHz
21cm redshift range:	>6
Frequency resolution:	4 kHz
Comoving radial spatial resolution:	0.6 Mpc
Brightness temperature sensitivity:	20 mK/day^1/2

Foreground contamination

- Galactic foreground
  (e.g. Shaver et al. 1999)
- Free-free emission from ionizing sources
  (Oh & Mack 2003; Cooray & Furlanetto 2004)
- Radio galaxies
  (Di Matteo et al. 2002)
- Point sources and extended sources
  (Di Matteo, Ciardi & Miniati 2004)



Comparing maps closely spaced in frequency is the most efficient mechanism to remove foreground contamination, BUT it relies on the spectral index distribution of the sources.

(Zaldarriaga, Furlanetto & Hernquist 2004; Santos, Cooray & Knox 2004; Gnedin & Shaver 2004)

Simulations of reionization

- ΛCDM N-body simulation → DM+gas distribution (Yoshida, Sheth & Diaferio 2001; Stoehr 2003)
- Semi-analytical model for galaxy formation → galaxy SFR... (Kauffmann et al. 1999; Springel et al. 2000)

$M \sim 10^9 M_o$

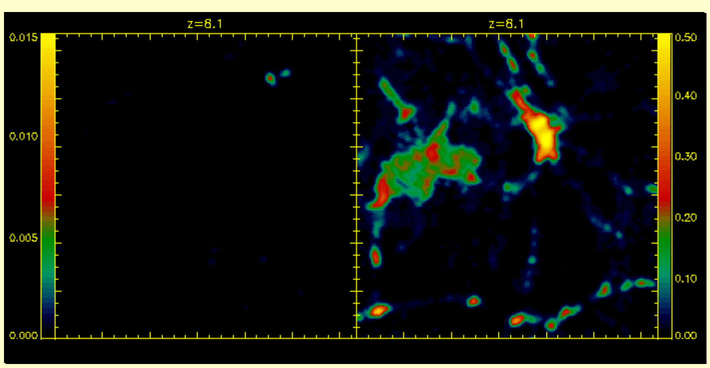
L~30 Mpc comov.

Salpeter/Larson IMF
PopIII stars
Fesc=5-20%

CRASH Cosmological RAdiative transfer Scheme for Hydrodynamic
(BC, Ferrara, Marri & Raimondo 2001; Maselli, Ferrara & BC 2003)

- o Different environments
- o Different stellar emission properties

H0 number density



(BC, Stoehr & White 2003; BC, Ferrara & White)

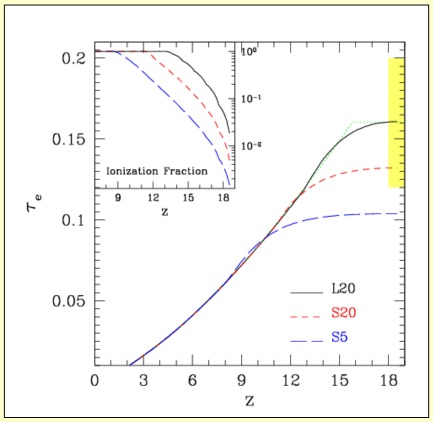
'Field': 30 Mpc

'Proto-Cluster': 15 Mpc (Springel et al. 2000)

L20: early reionization z~13.5
S5 : late reionization z~8

Early/late reionization

S5: Salpeter IMF+fesc=5%
S20: Salpeter IMF+fesc=20%
L20: Larson IMF+fesc=20%



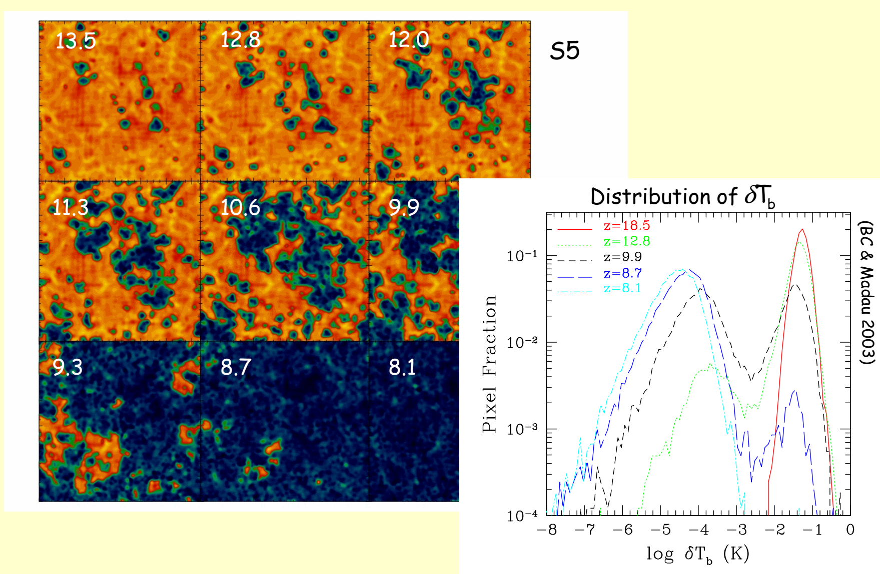
(BC, Ferrara & White 2003)

$$\tau_e = 0.16 \pm 0.04$$

68% CL
(Kogut et al. 2003)

We don't need exotic assumptions!!!

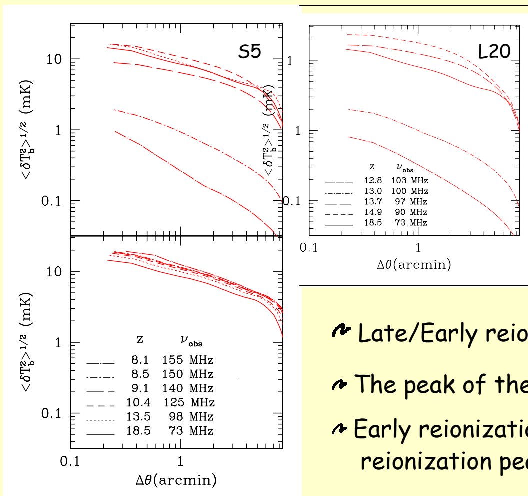
Maps of brightness temperature



(BC & Madau 2003)

Fluctuations of brightness temp.

The fluctuations are due to variations in HI distribution
(cosmic web + ionized regions)

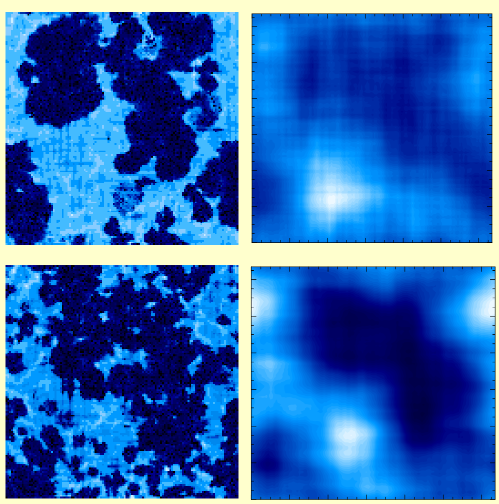


- Late/Early reionization show similar behaviour
- The peak of the emission is ~10 mK
- Early reionization peaks @ 90MHz, late reionization peaks @ 115MHz

LOFAR expected response

(Valdes et al. , in prep)

L20 @ z~14.5 (~90 MHz)



S5 @ z~10 (~130 MHz)

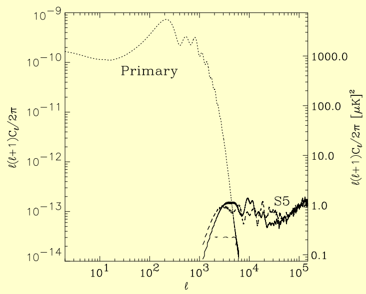
- Instrument sampling
- Gaussian noise
- Convolution with a Gaussian beam (σ=3 arcmin)

- It will be possible to map the reionization history
- The latest stages of reion. will be easier to probe

CMB/21cm line correlation

(Salvaterra, BC, Ferrara & Baccigalupi 2004)

$$\left(\frac{\delta T}{T}\right)_{CMB}(\hat{\gamma}) = \tau_0 \int_0^1 \frac{d\eta}{\eta^4} \chi_{HII}(\vec{x},\eta)\hat{\gamma}\cdot\vec{v}(\vec{x},\eta)$$



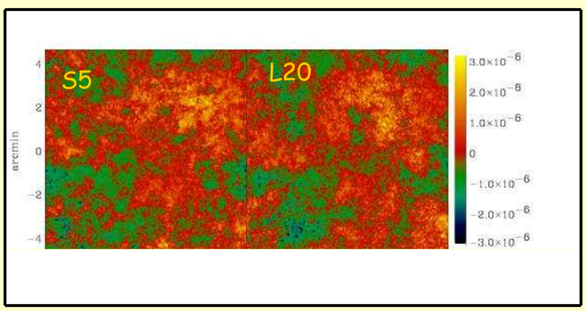
ALMA, ACT

- CMB anisotropies are produced by free electrons
- 21cm line is emitted by neutral hydrogen

We expect anti-correlation between CMB anisotropy maps & 21cm emission line maps on scales of the order of the angle subtended by typical HII regions at the z of the 21cm line emission.

CMB/21cm correlation

(Salvaterra, BC, Ferrara & Baccigalupi 2004)

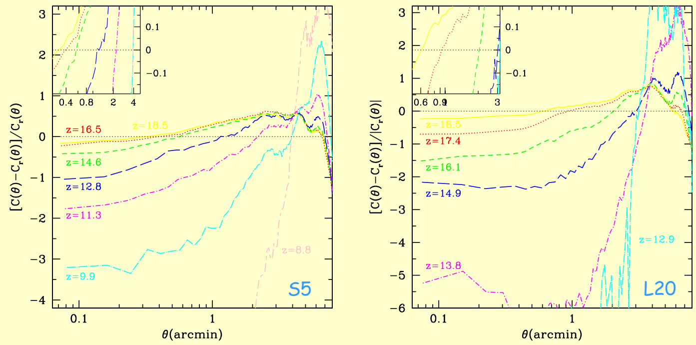


(δT/T)

$l(l+1)C_l/2\pi \sim 10^{-13}$ @ l>4000 →

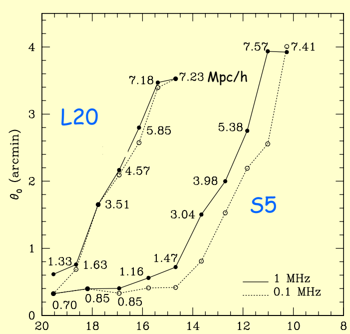
It should be observed by ALMA or ATC (foregrounds contamination!)

Cross-correlation between CMB and 21cm maps



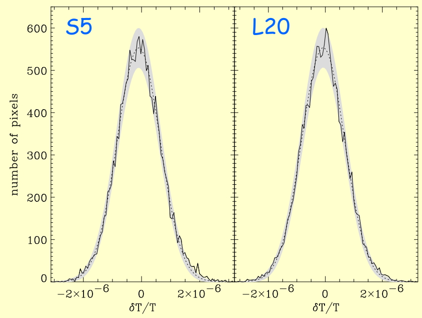
- The CMB anisotropies & the 21cm emission line are anti-correlated on scales smaller than the zero-point of the cross-correlation function

Zero-point of the cross-correlation function

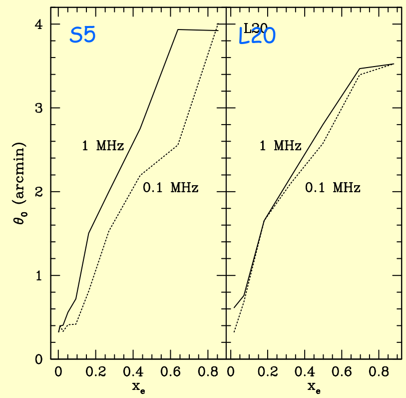


- The zero-point of the cross-correlation function gives an estimate of the typical dimension of the HII regions

Pixels distribution



Zero-point/mean ion. frac. relation



Extra-galactic foreground contamination

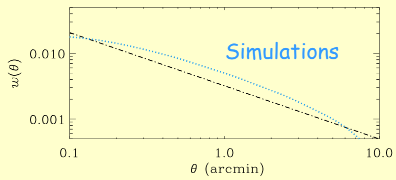
(Di Matteo, BC & Miniati 2004, in print)

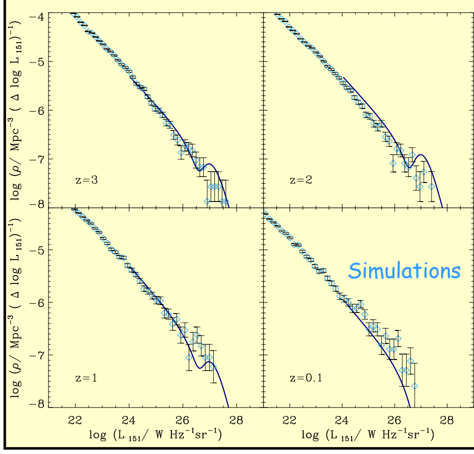
- Point Sources:
  - Free-free emission from IS HII regions
  - Low-z radio galaxies
- Extended Sources:
  - Free-free emission from IG HII regions
  - Syncrotron emission from cluster radio halos (regular morphology) & relics (irregular)

Radio Galaxy Modeling

Angular correlation function

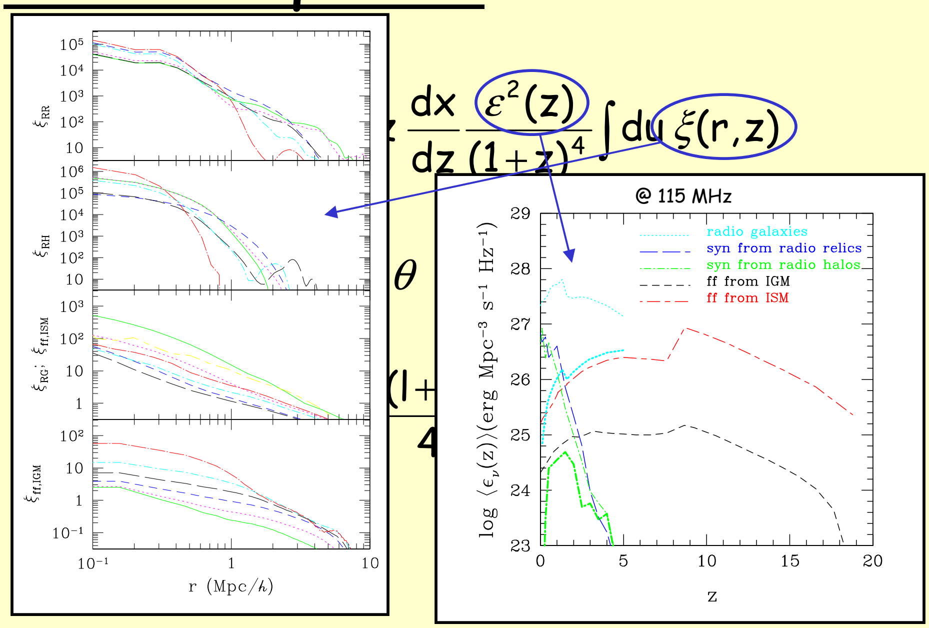
$$w(\theta) = A\theta^{1-\gamma}$$



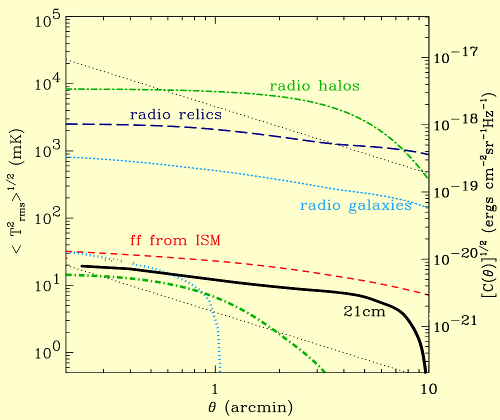


Luminosity functions @150 MHz

Relevant Equations

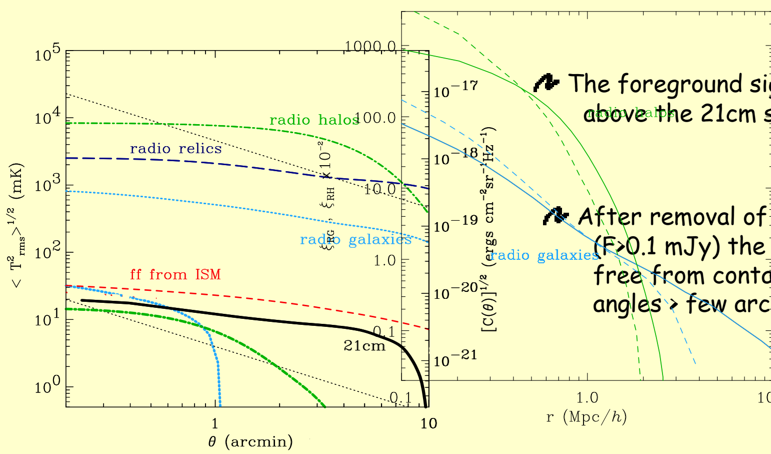


Foreground Contamination



- The foreground signals are above the 21cm signal
- After removal of bright sources (F>0.1 mJy) the 21cm signal is free from contamination at angles > few arcmin

Foreground Contamination



- The foreground signals are above the 21cm signal
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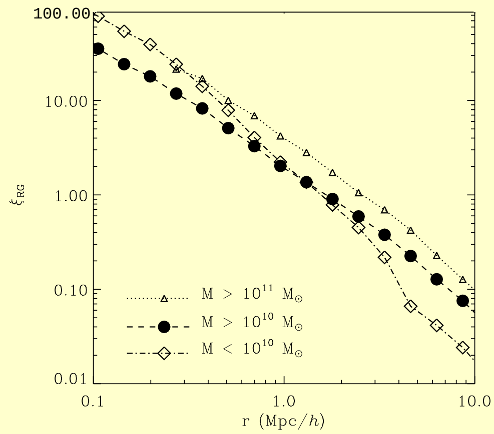
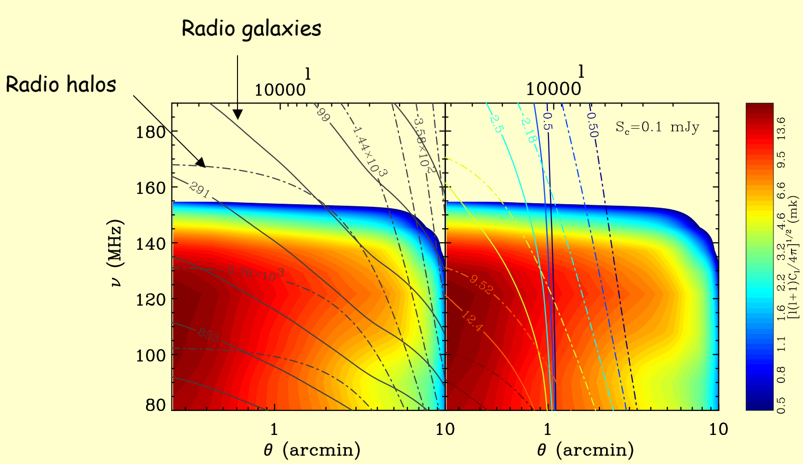
Spatial correlation function of galaxies



Foreground Contamination



At scales >1 arcmin 21cm emission line is free from extra-galactic foreground contamination, but cleaning is still needed (multi-frequency maps).

Conclusions

- 21cm line emission from neutral IGM (from reionization simulations)
- CMB/21cm line cross-correlation
- Extra-galactic foreground contamination calculated self-consistently with emission signal

- LOFAR and SKA should be able to map the reionization process, at least its latest stages
- More detailed information will be acquired implementing the above observations with CMB anisotropies measurements (discriminate different reionization histories and sources of ionization)
- Observations of 21cm line at angles > 1 arcmin could be free from extra-galactic foreground contamination
- Find a discussion on these subjects in Ciardi & Ferrara 2004