21cm views of IGM reionization

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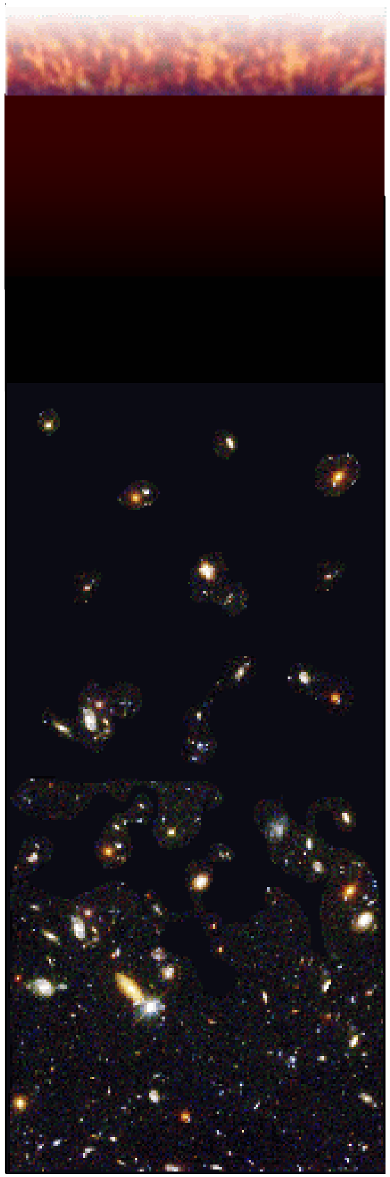
Timeline in cosmic history

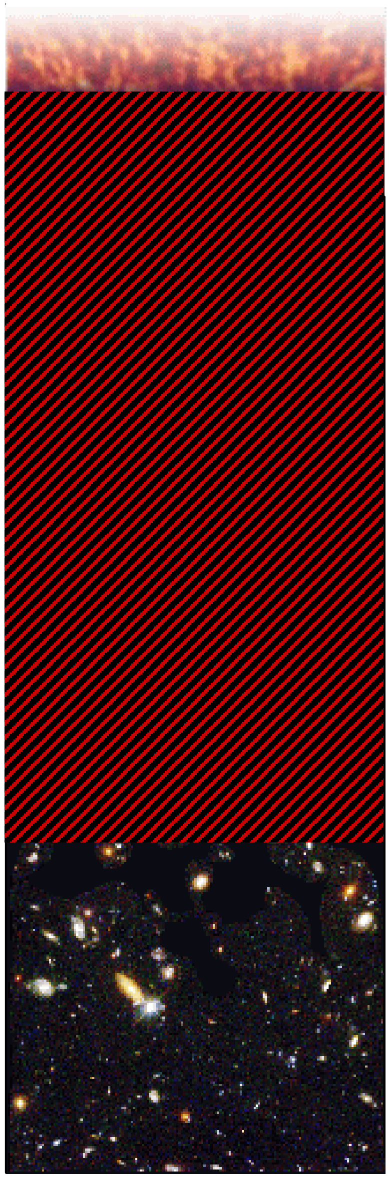
Years since the Big Bang



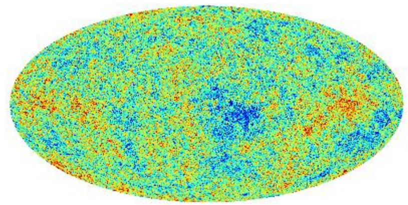
Years since the Big Bang	
	← Big Bang: the Universe is filled with hot plasma
~350000 (z~1000)	← The gas cools and becomes neutral: recombination
~100 million (z~20-40)	← The first structures begin to form: reionization starts
~1 billion (z~6)	← Reionization is complete
~13 billion (z=0)	← Today's structures

Timeline in cosmic history

Years since the Big Bang



~350000 (z~1000) ← Cosmic Microwave Background



~100 million (z~20-40)

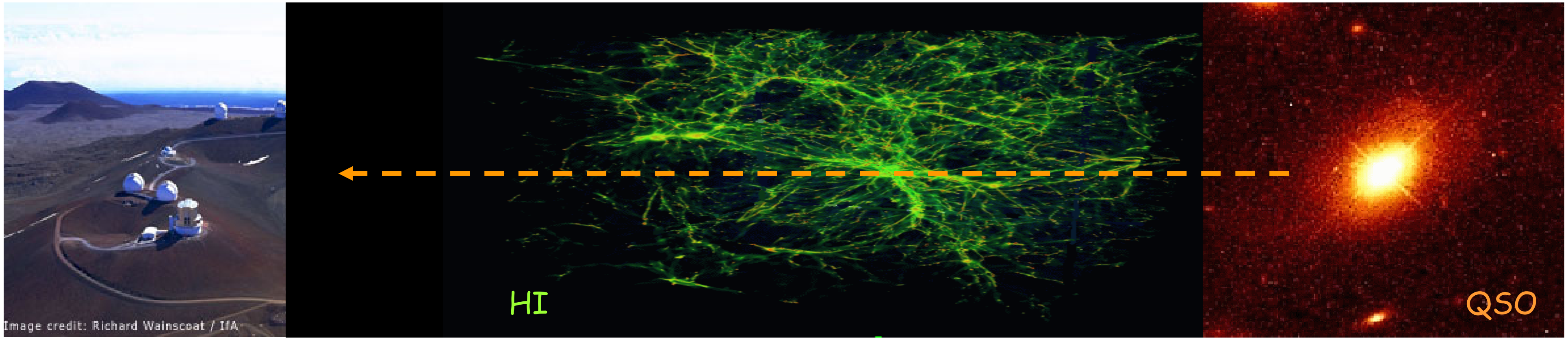
FIR/Radio?

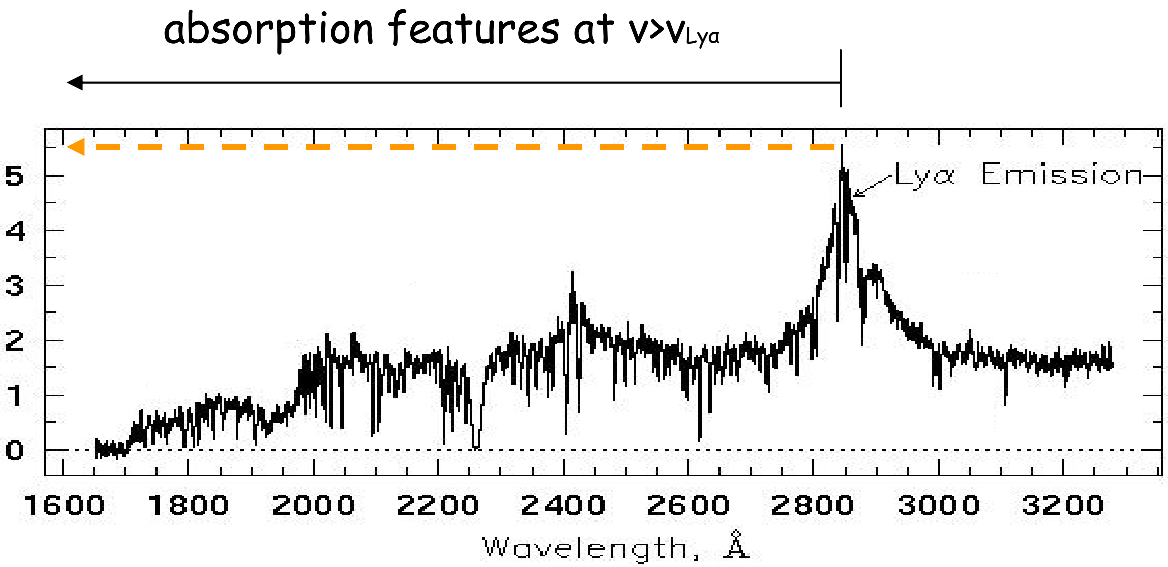
~1 billion (z~6)

UV/Optical/IR

~13 billion (z=0)

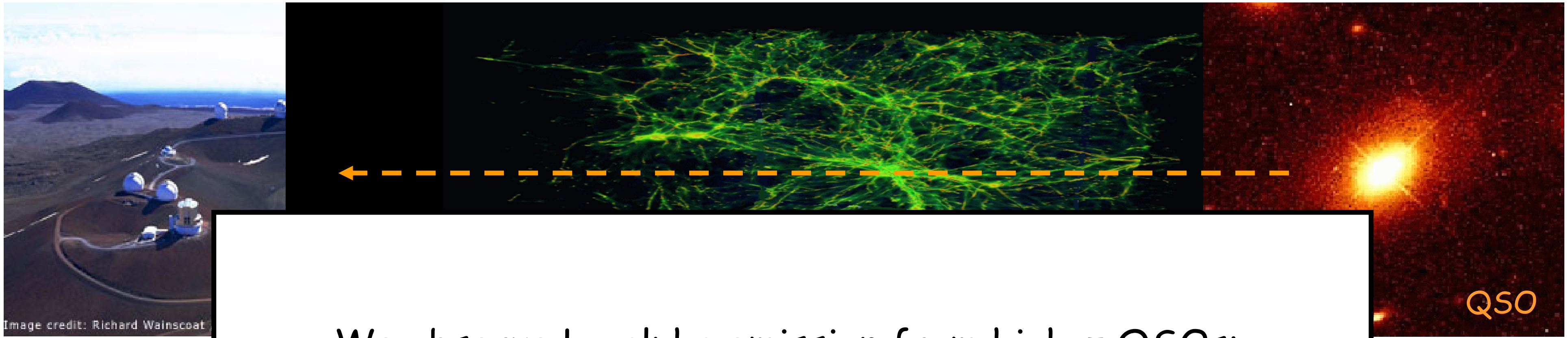
Evidence for IGM reionization





$$\tau_{HI} \approx 6.5\cdot 10^5 x_{HI}\left(\frac{1+z}{10}\right)^{3/2}$$

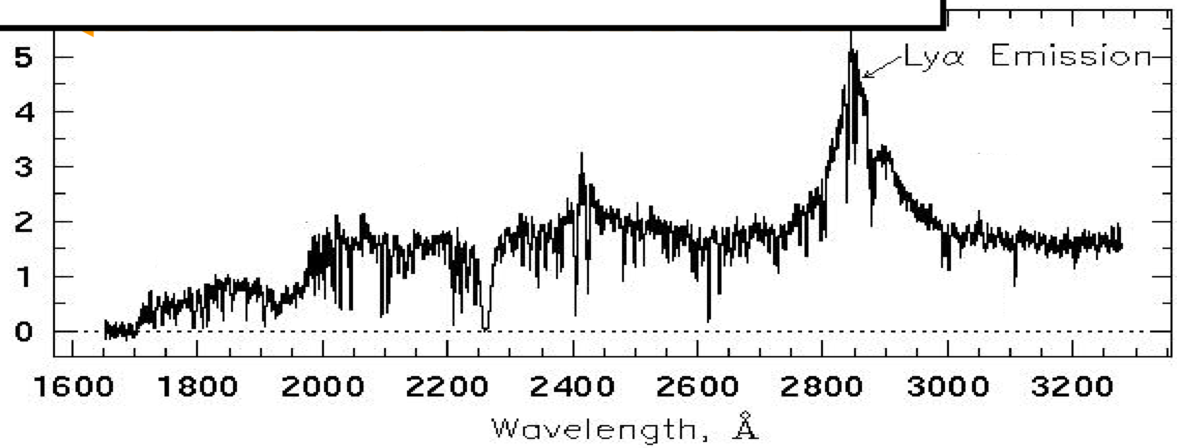
Evidence for IGM reionization



We observe Ly-alpha emission from high-z QSOs:

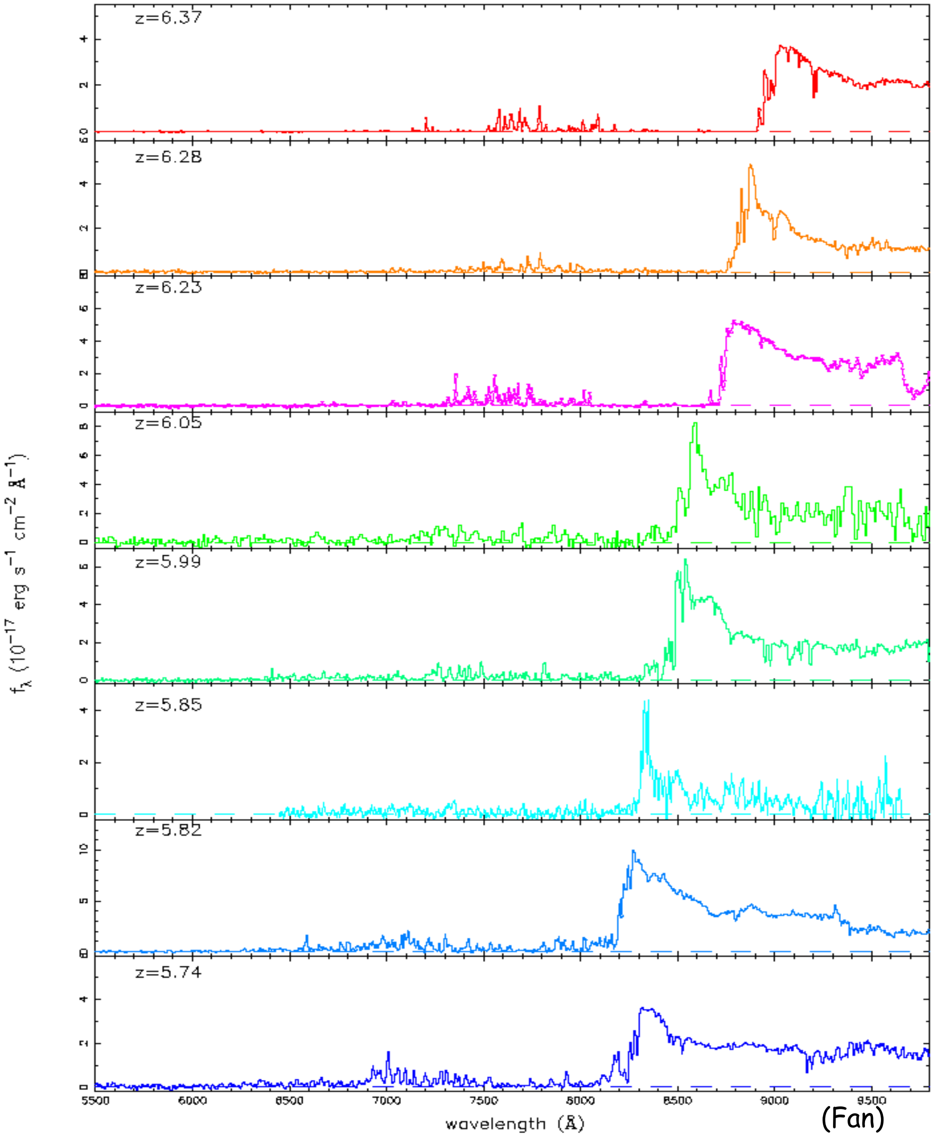
this indicates that the IGM is highly ionized

$$\tau_{HI} \approx 6.5 \cdot 10^5 x_{HI} \left(\frac{1+z}{10} \right)^{3/2}$$



Constraints on the epoch of reionization

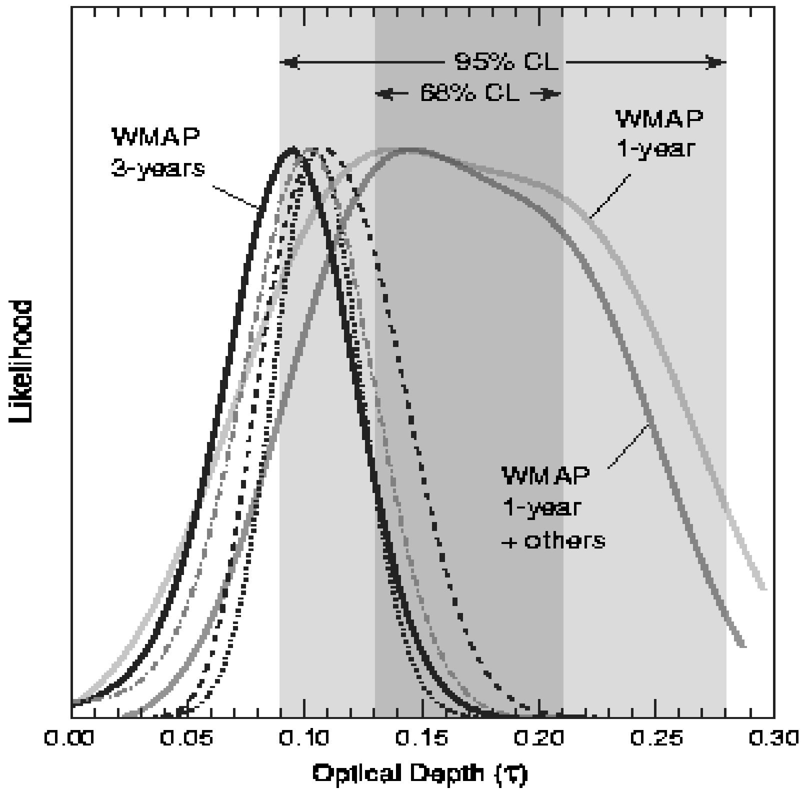
Spectra of high-z QSOs



(Fan)

Constraints on the epoch of reionization

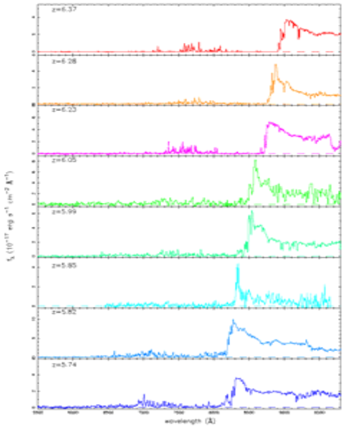
CMB anisotropies



(Page et al 2006)

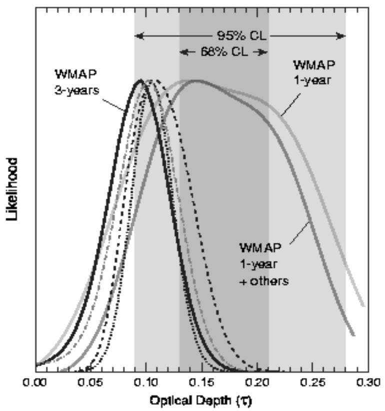
Thomson scattering optical depth: $\tau(z) = \int \ldots n_e(z')\,dz'$

Constraints on the epoch of reionization



High-z QSOs → latest stages of reionization at z~6

& galaxies



CMB anistotropies → global amount of electrons

Modelling of cosmic reionization: ingredients

✓ Model of galaxy formation (feedback effects)

Semi-analytic model

$$M\frac{dn}{dM} = \left(\frac{2}{\pi}\right)^{1/2} \frac{-d(\ln\sigma)}{d(\ln M)} \frac{\rho_0}{M} \upsilon_c e^{-\upsilon_c^2/2}$$

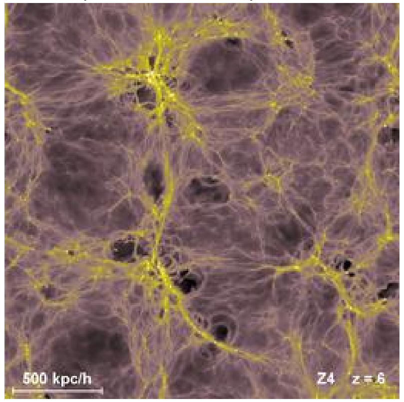
$$\dot{M}_* = \alpha \frac{dM}{dt}$$

$$t_{cool} < t_{dyn}$$

...

+

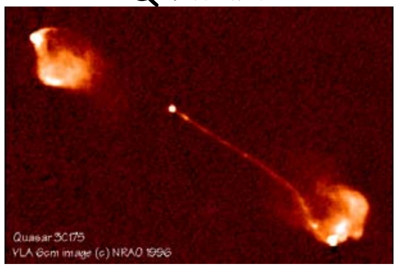
Numerical simulations



✓ Properties of the sources of ionizing radiation

Stellar type

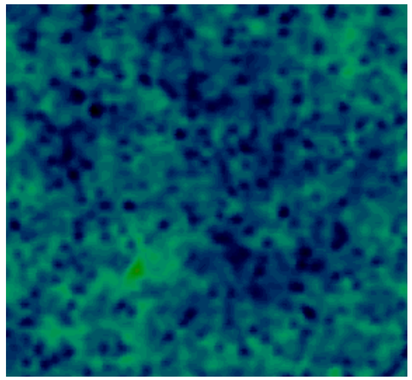
Quasars



DM annihilation/decay

- light dark matter
- neutralinos
- gravitinos
- sterile neutrinos
- ...

✓ Radiative transfer of ionizing radiation



Simulations of reionization

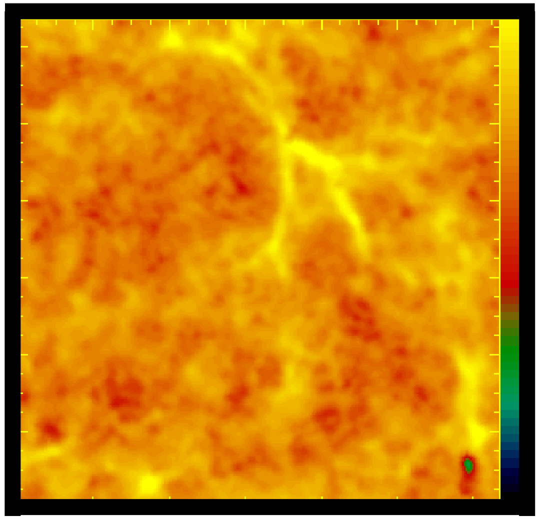
- Simulations of galaxy formation → gas & galaxy properties

  (Springel et al. 2000; Stoehr 2004)

- Stellar type sources → emission properties

- → propagation of ionizing photons

  (BC et al. 2001; Maselli, Ferrara & BC 2003)



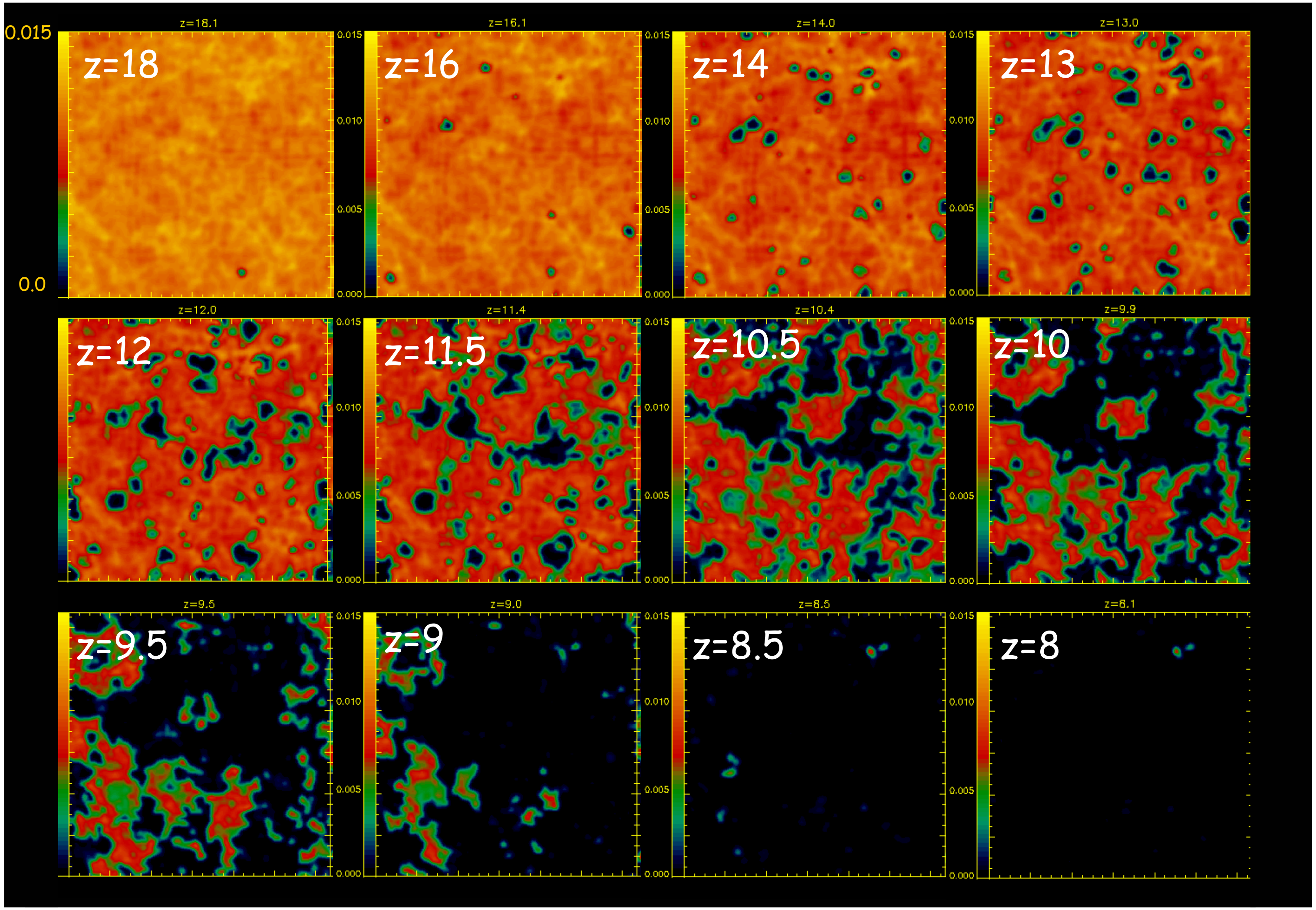
Simulation properties

- $M \sim 10^9 M_o$
- L=10-20/h Mpc com.

Source properties

- metal-free stars
- Salpeter/Larson IMF
- Fesc=5-20%

Redshift Evolution of HI density



BC, Stoehr & White 2003

Early/Late Reionization

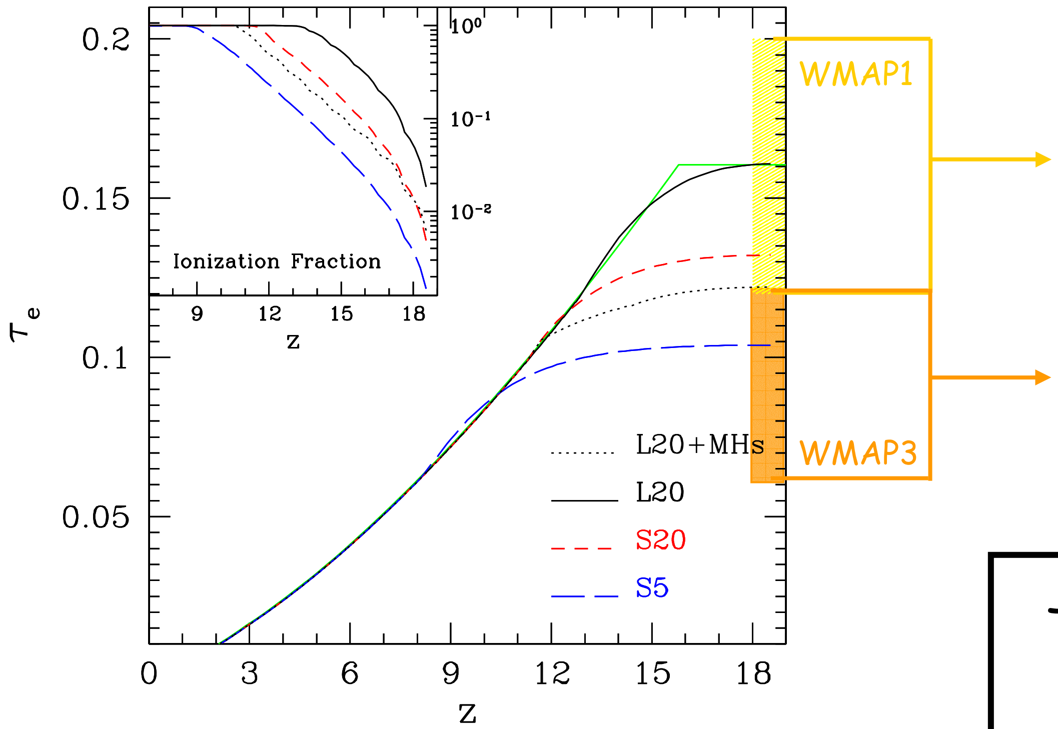
Source properties (metal-free stars):

S5: Salpeter IMF+fesc=5% (late reion. case; zion~8.5)

S20: Salpeter IMF+fesc=20%

L20: Larson IMF+fesc=20% (early reion. case; zion~13.5)

L20 + MHs: addition of sub-grid physics to include MHs absorption



$$\tau_e = 0.16 \pm 0.04$$

(Kogut et al. 2003)

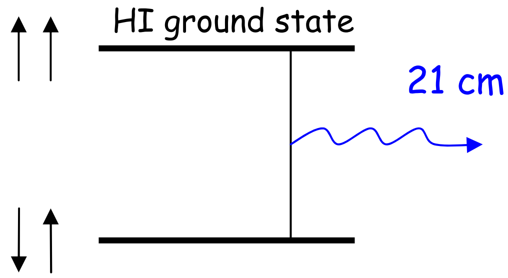
$$\tau_e = 0.09 \pm 0.03$$

(Spergel et al. 2006)

The simulations are consistent with the WMAP results

BC, Stoehr & White 2003; BC, Ferrara & White 2003; BC et al 2006

21cm line diagnostic

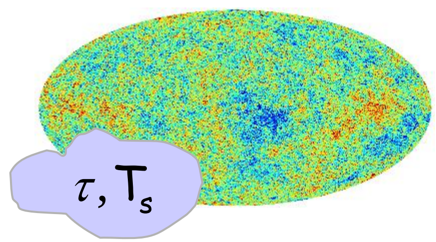


Ideal probe of neutral H at high-z
different observed frqs. → different z

Differential brightness temperature:

spin temperature

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



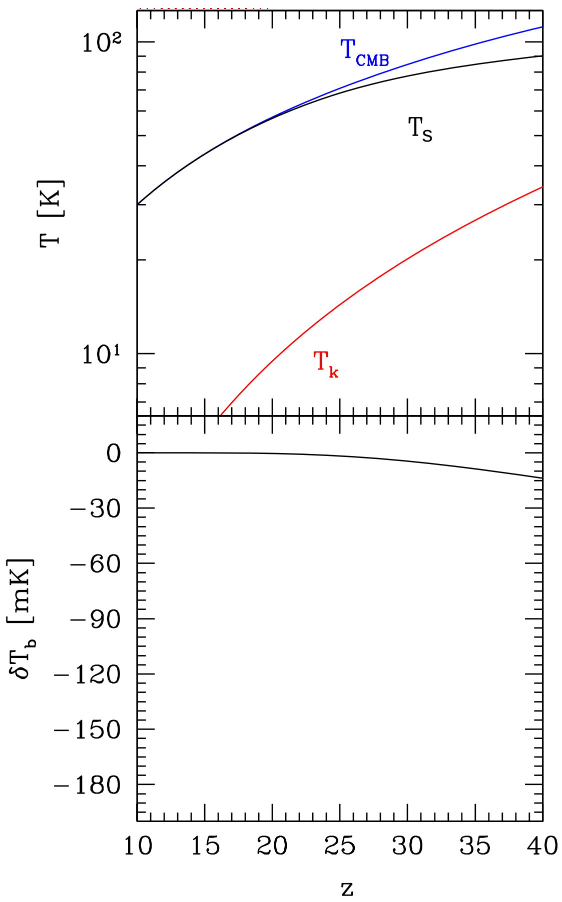
$T_{CMB} = T_s \Rightarrow$ no signal

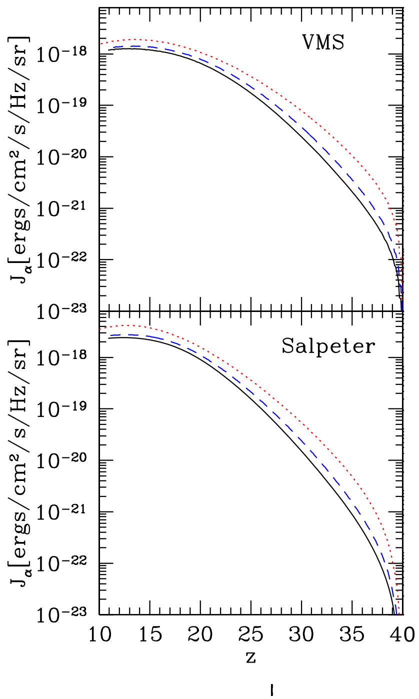
$T_{CMB} >> T_s \Rightarrow$ absorption

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

Lya scattering & heating

- In the absence of other decoupling mechanisms 21cm line will not be visible at z<20

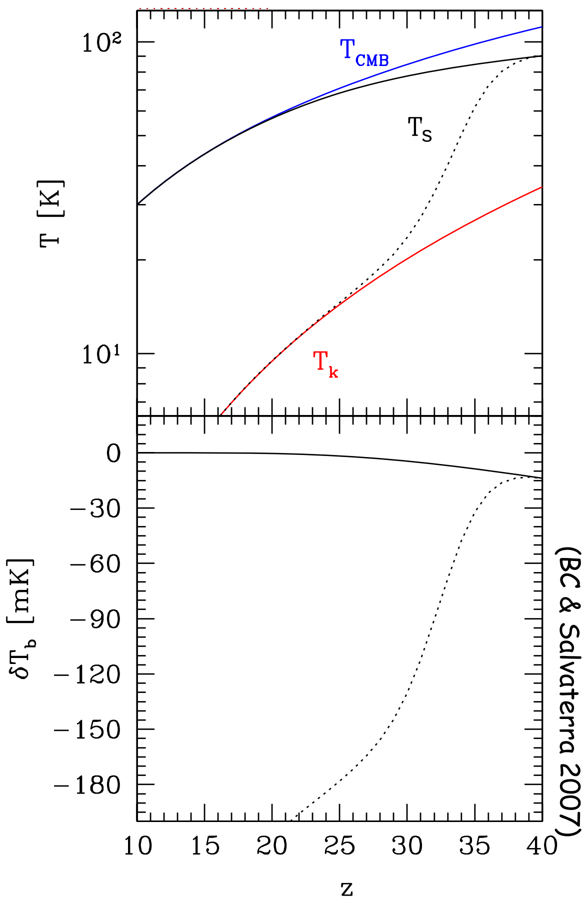




(BC & Salvaterra 2007)

Lya background from metal-free stars with Salpeter IMF or VMS with M=300Msun

Lya scattering & heating



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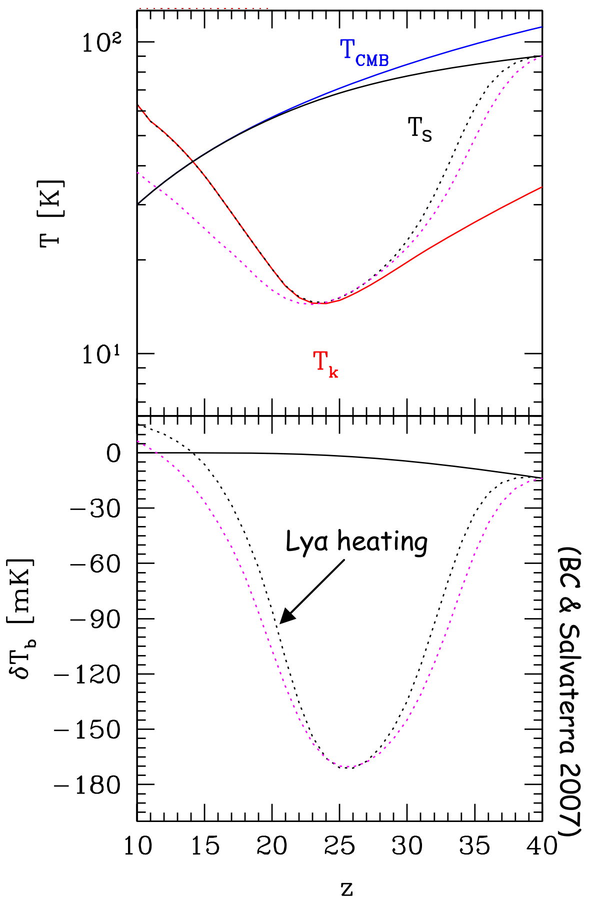
- Lya photon scattering decouples T_s from T_{CMB} → 21cm line can be observed

Lya scattering & heating



- In the absence of other decoupling mechanisms 21cm line will not be visible at z<20

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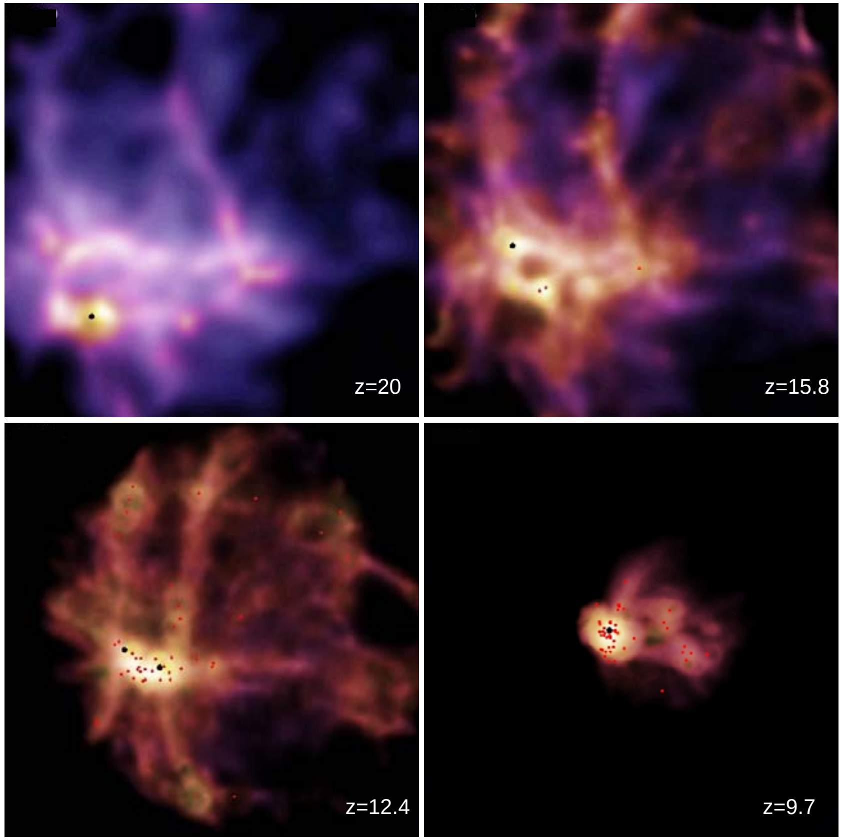
- Lya photon scattering heats the gas → 21cm line can be observed in emission

Lya heating is effective for z ≤ 15

Metal-free stars, Salpeter IMF

Very massive metal-free stars

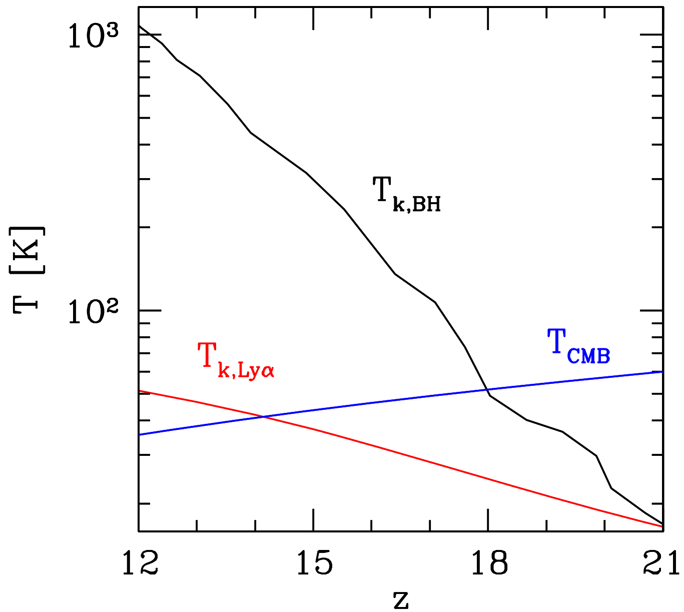
X-ray heating



200 kpc com.

(Pelupessy, Di Matteo, BC 2007)

- SPH simulations to study the formation of z~6 QSOs
- Merger of BHs hosted by parent halos and accretion onto them are followed



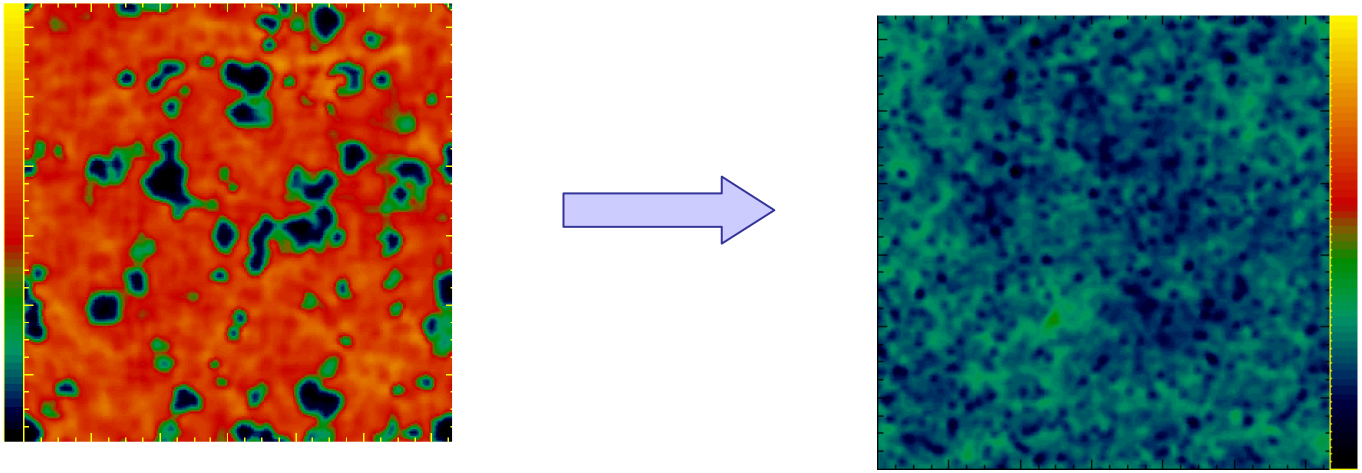
Accretion onto the BHs → X-ray emission → heating

21cm line diagnostic

The 21cm line is observed in emission if:

$$T_s >> T_{CMB} \Rightarrow \quad \delta T_b \propto n_{HI}$$

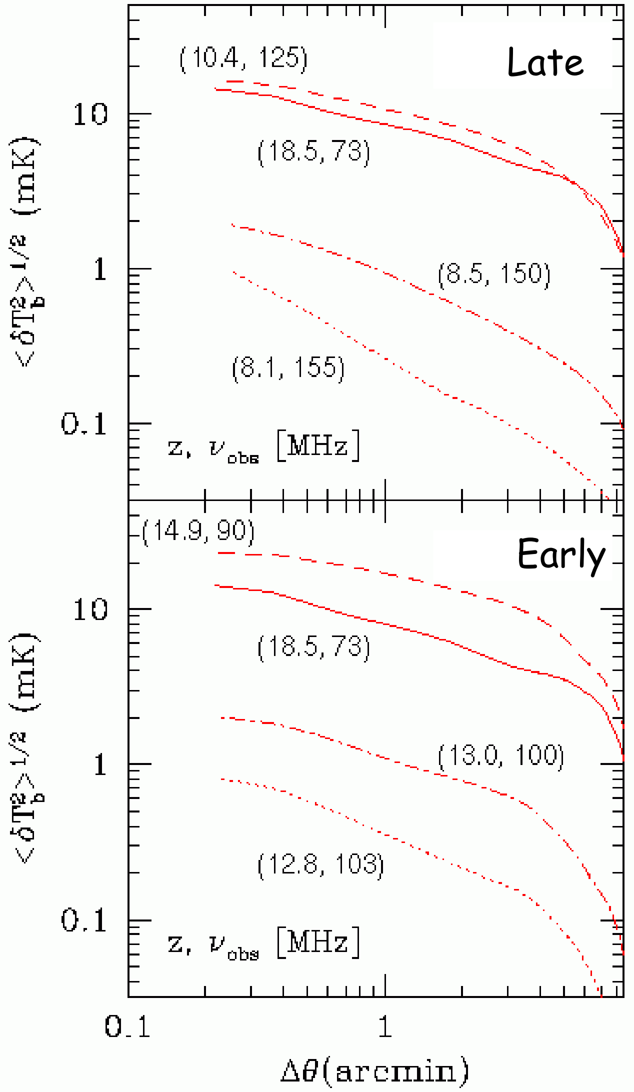
$\log(\delta T_b/k)$



(BC & Madau 2003)

Fluctuations of brightness temp.

The fluctuations are due to variations in HI distribution
(density distrib. + ionized regions)



(BC & Madau 2003)

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

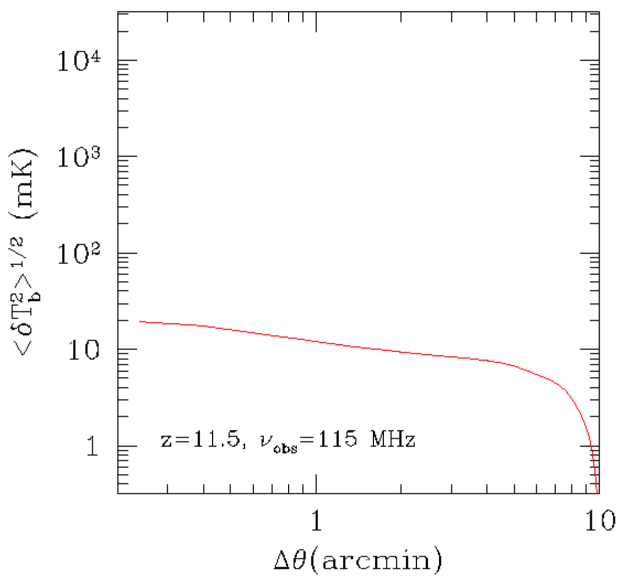
Planned radio telescopes should be able to detect such signal

Extra-galactic foreground contamination

(Di Matteo, BC & Miniati 2004)

- 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 & relics

Late reionization



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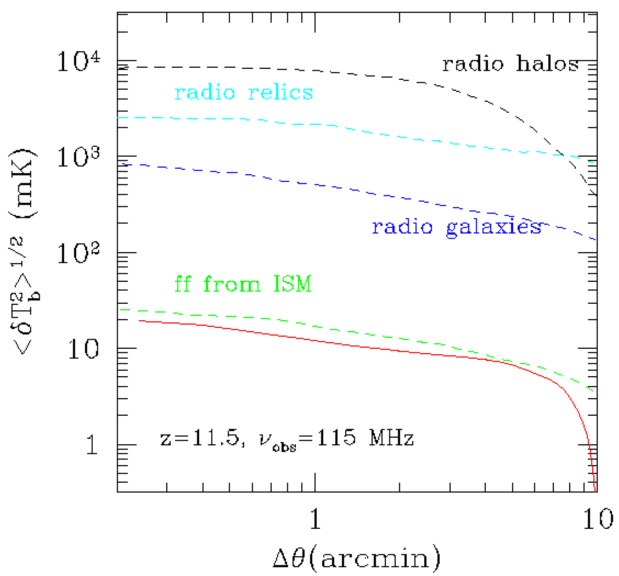

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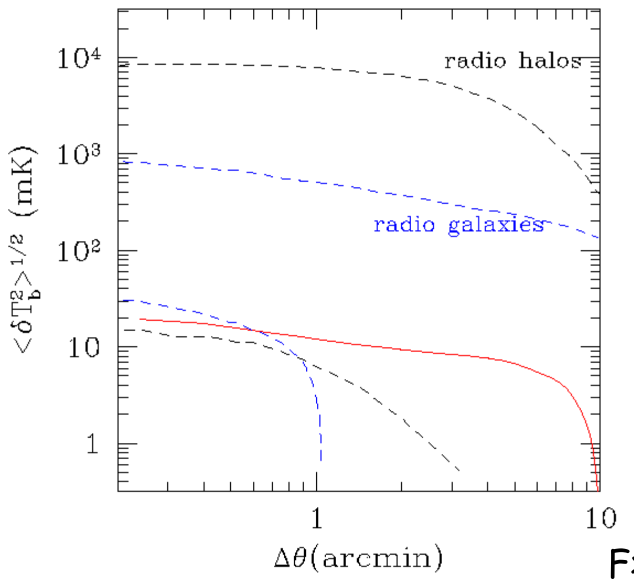


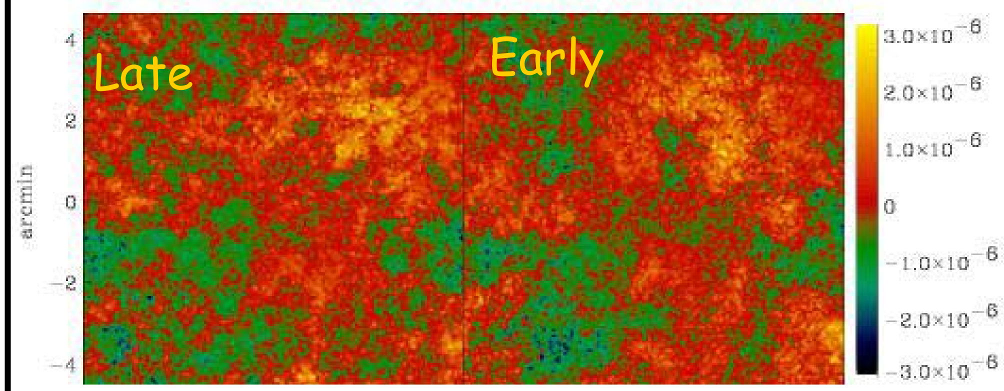
F>0.1 mJy

After removal of bright sources (F>0.1 mJy), at scales >1 arcmin 21cm emission line is free from extra-galactic foreground contamination

CMB/21cm line correlation

(Salvaterra, BC, Ferrara & Baccigalupi 2005)

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



(δT/T)

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

CMB/21cm line correlation

(Salvaterra, BC, Ferrara & Baccigalupi 2005)

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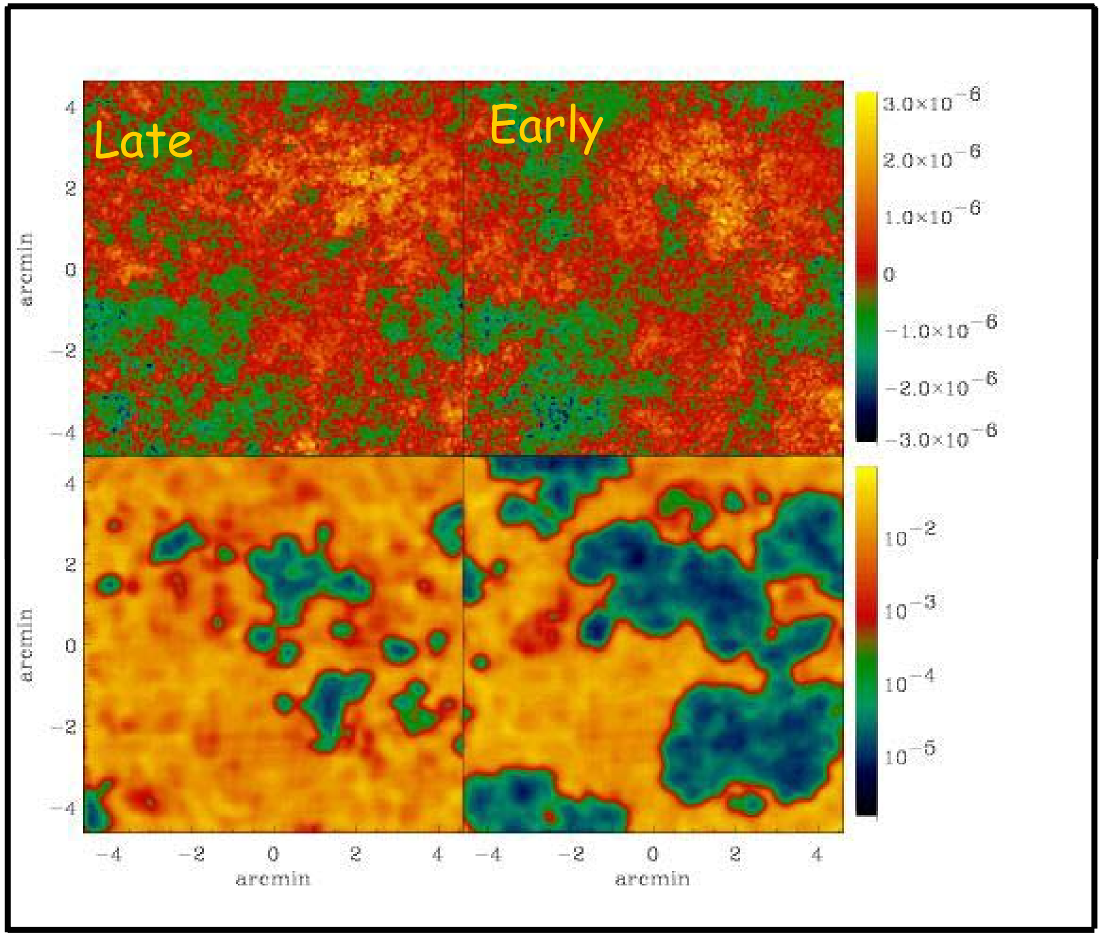
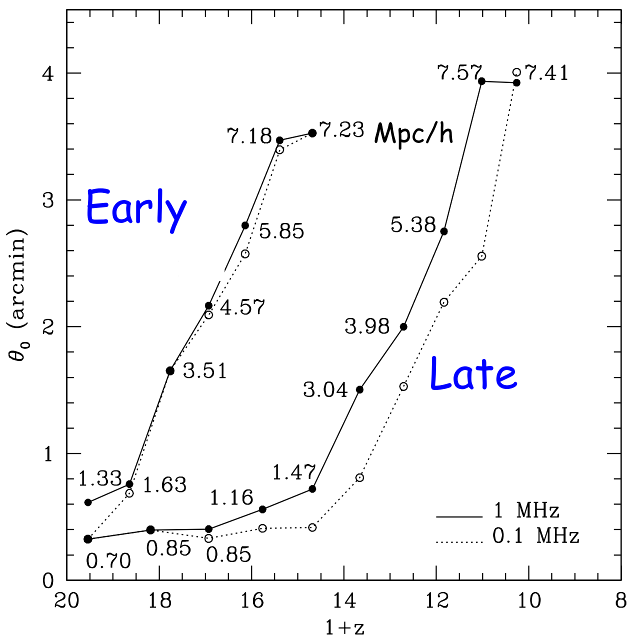


(δT/T)

CMB/21cm line correlation

We find an anti-correlation below a characteristic angular scale, θ_0, when the correlation function becomes < 0.

Characteristic angular scale of the cross-correlation function



The characteristic angular scale of the cross-correlation function gives an estimate of the typical dimension of the HII regions at redshift of the 21cm emission line.

(Salvaterra, BC, Ferrara & Baccigalupi 2005)

Planned generation of radio telescopes

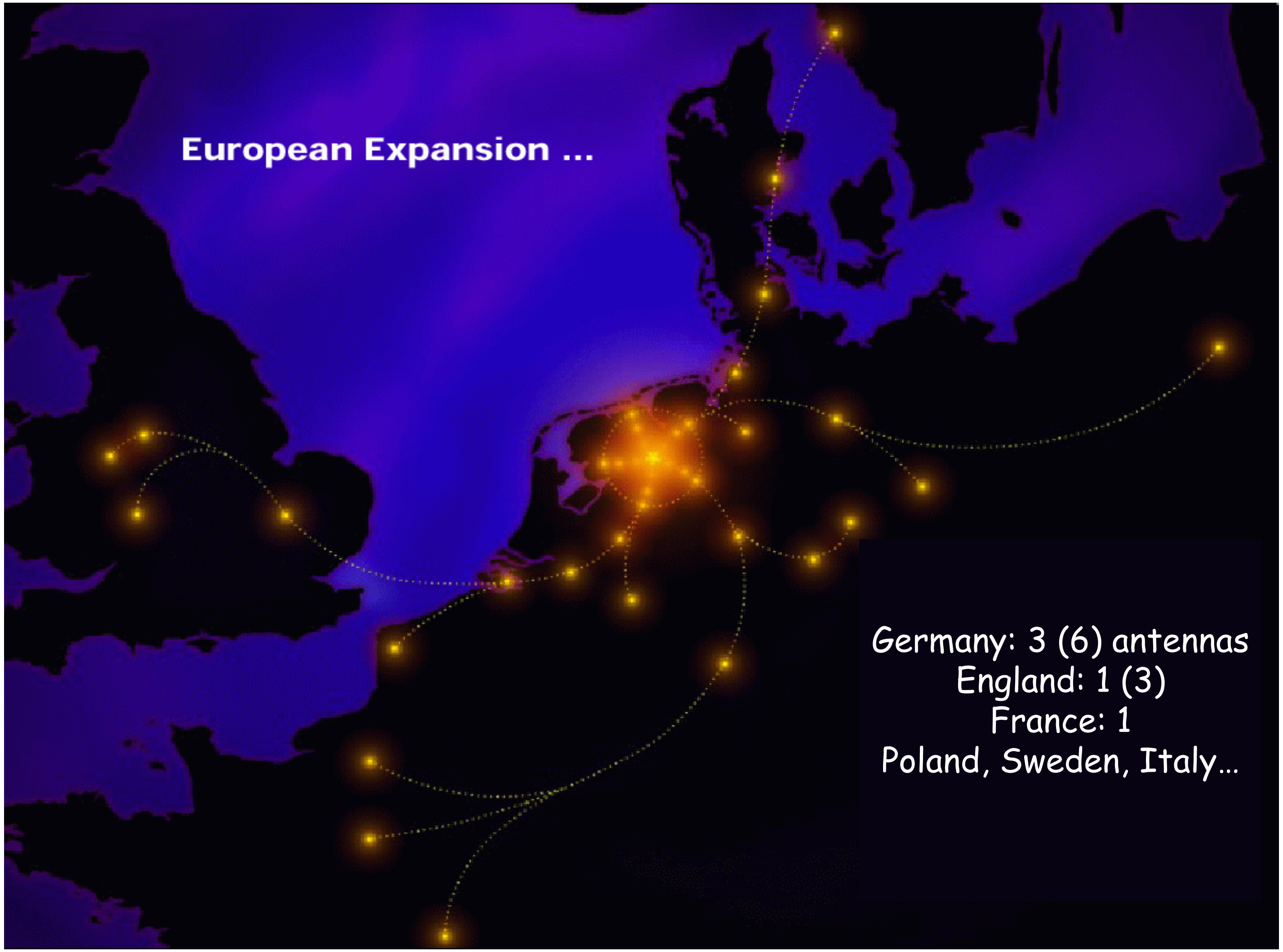
LOFAR: Low Frequency ARray; Netherlands
www.lofar.org

21cmA/PAST: Primeval Structure Telescope; China
web.phys.cmu.edu/~past

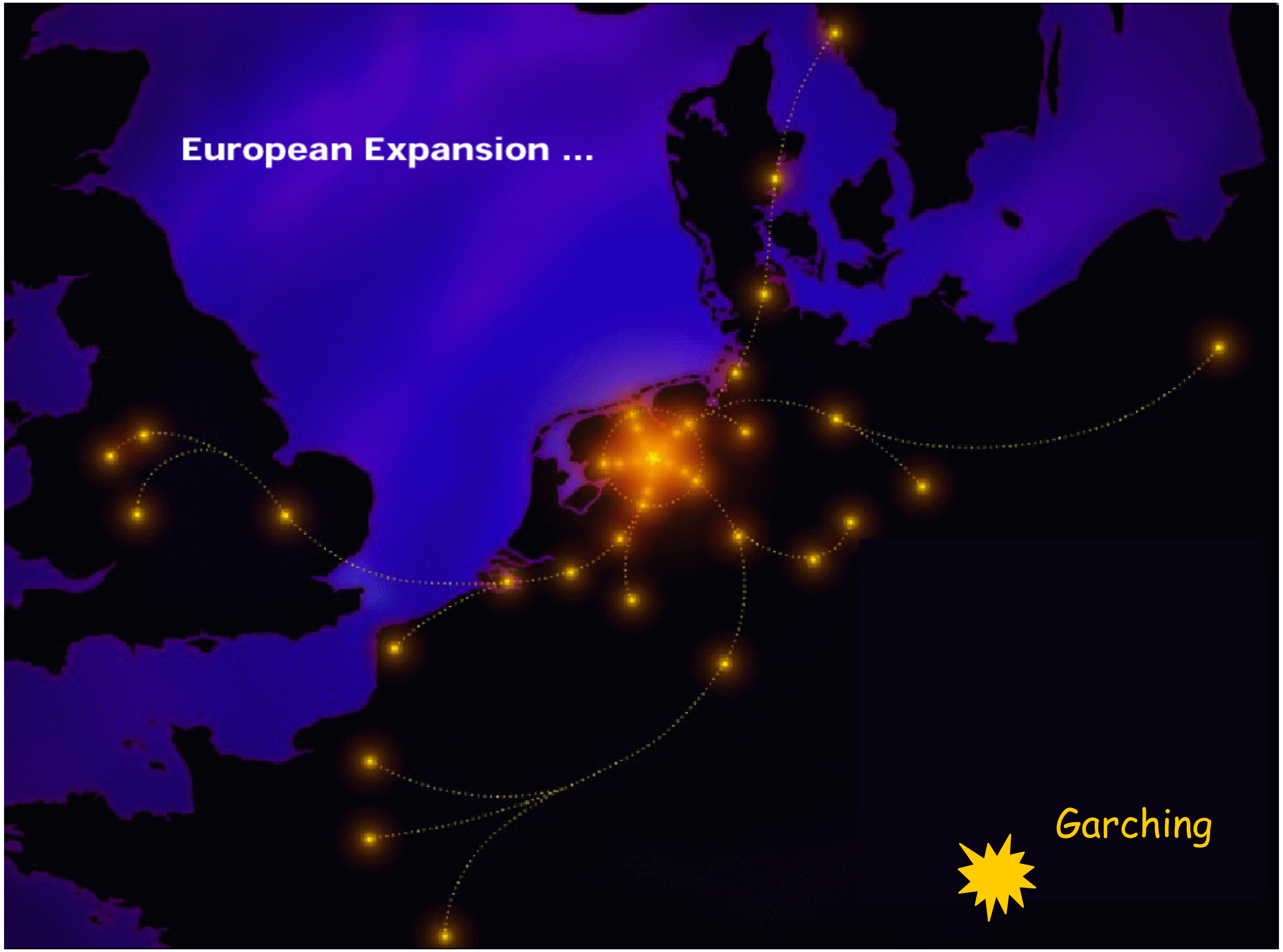
MWA: Mileura Widefield Array; Australia
space.mit.edu/RADIO/research/mwa.html

SKA: Square Kilometre Array
www.skatelescope.org

LOFAR in Europe



LOFAR in Europe



LOFAR at MPA