Gas in Galaxies: from Cosmic Web to Molecular Clouds

Kloster Seeon, 14-18 June 2011

Cosmic Reionization

Benedetta Ciardi

Max Planck Institute for Astrophysics

Outline

✧ Theoretical modelling of cosmic reionization

✧ 21cm line observations

Modelling of cosmic reionization: ingredients

✧ Model of galaxy formation

Semi-analytic models

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

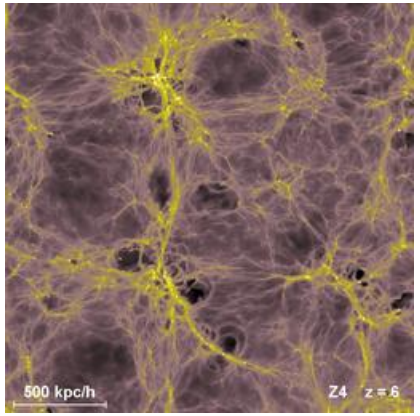
$$\dot{M}_* = \alpha \frac{dM}{dt}$$

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

...

+

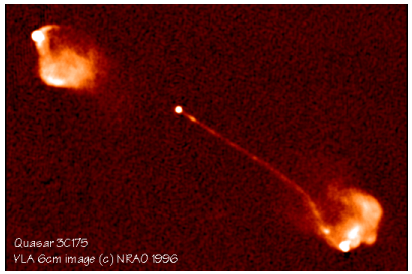
Numerical simulations



✧ Properties of the sources of ionizing radiation

Stellar type

Quasars



DM annihilation/decay

light dark matter

neutralinos

gravitinos

sterile neutrinos

...

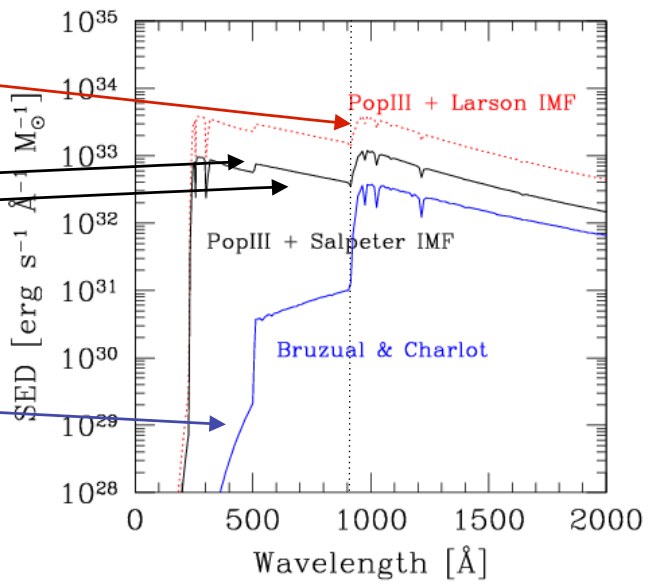
Properties of the sources of ionizing radiation

? Initial Mass Function and spectrum:

Salpeter or Larson IMF?

Zero or higher metallicity?

Spectral Energy Distribution



? Escape Fraction:

Fesc <20% but there is a big variation in the number both theoretically & observationally

Fesc > 70% for primordial, very-massive stars

Modelling of cosmic reionization: ingredients

✧ Model of galaxy formation

Semi-analytic models

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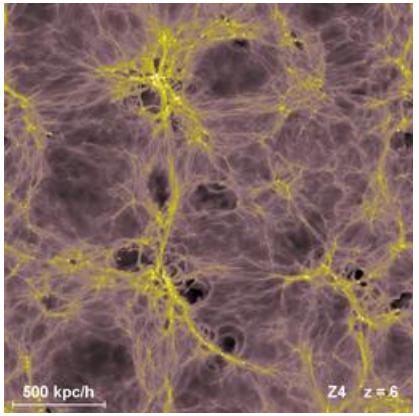

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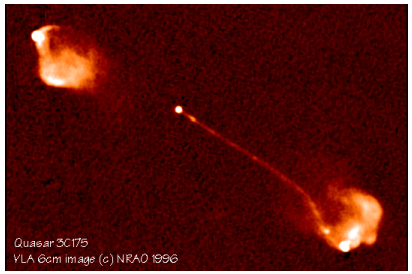

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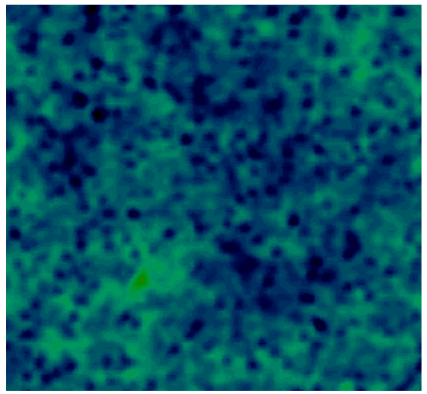
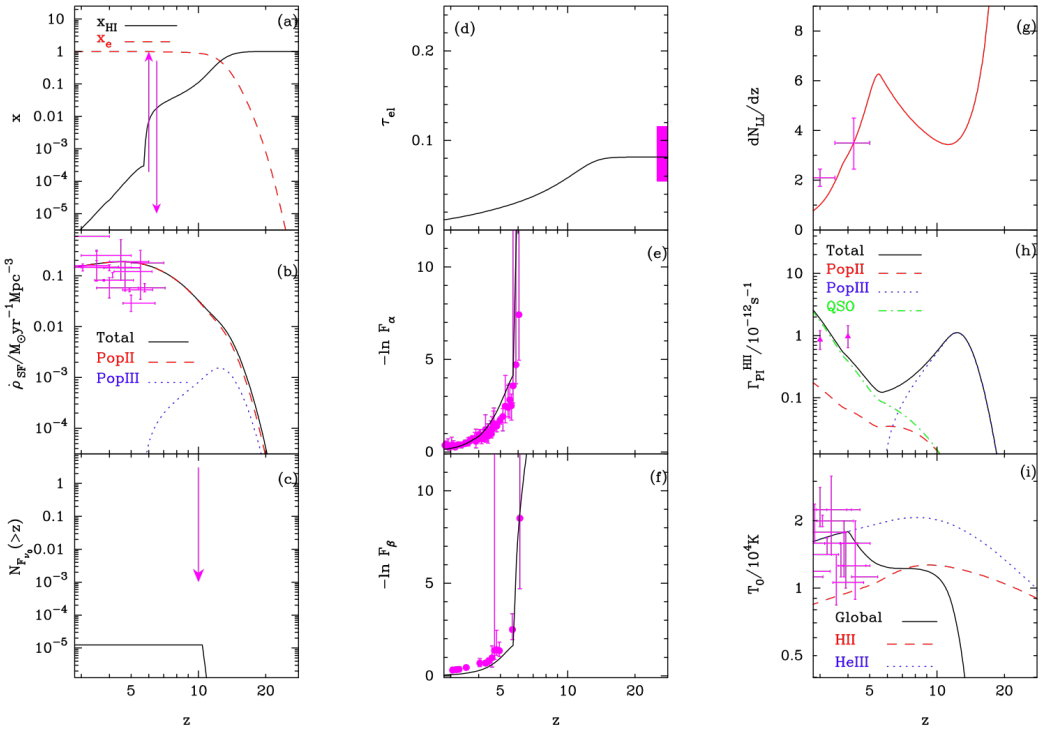


✧ Evolution of the HII regions

Modelling of cosmic reionization

✧ Fully semi-analytic approach

e.g. Shapiro & Giroux 1987; Madau, Haardt & Rees 1999; Miralda-Escude, Haehnelt & Rees 2000; Wyithe & Loeb 2003; Furlanetto, Zaldarriaga & Hernquist 2004; Choudhury & Ferrara 2006; Bolton & Haehnelt 2007



+ Fast
+ Average quantities

- No full 3D information

Choudhury & Ferrara 2006

Modelling of cosmic reionization

✧ Fully semi-analytic approach

✧ Numerical simulations

e.g. Gnedin & Ostriker 1997; Sokasian+ 2002; Ciardi+ 2003; Iliev+ 2006; Trac & Cen 2007; Baek+ 2010

+ Full 3D information
+ More accurate physics

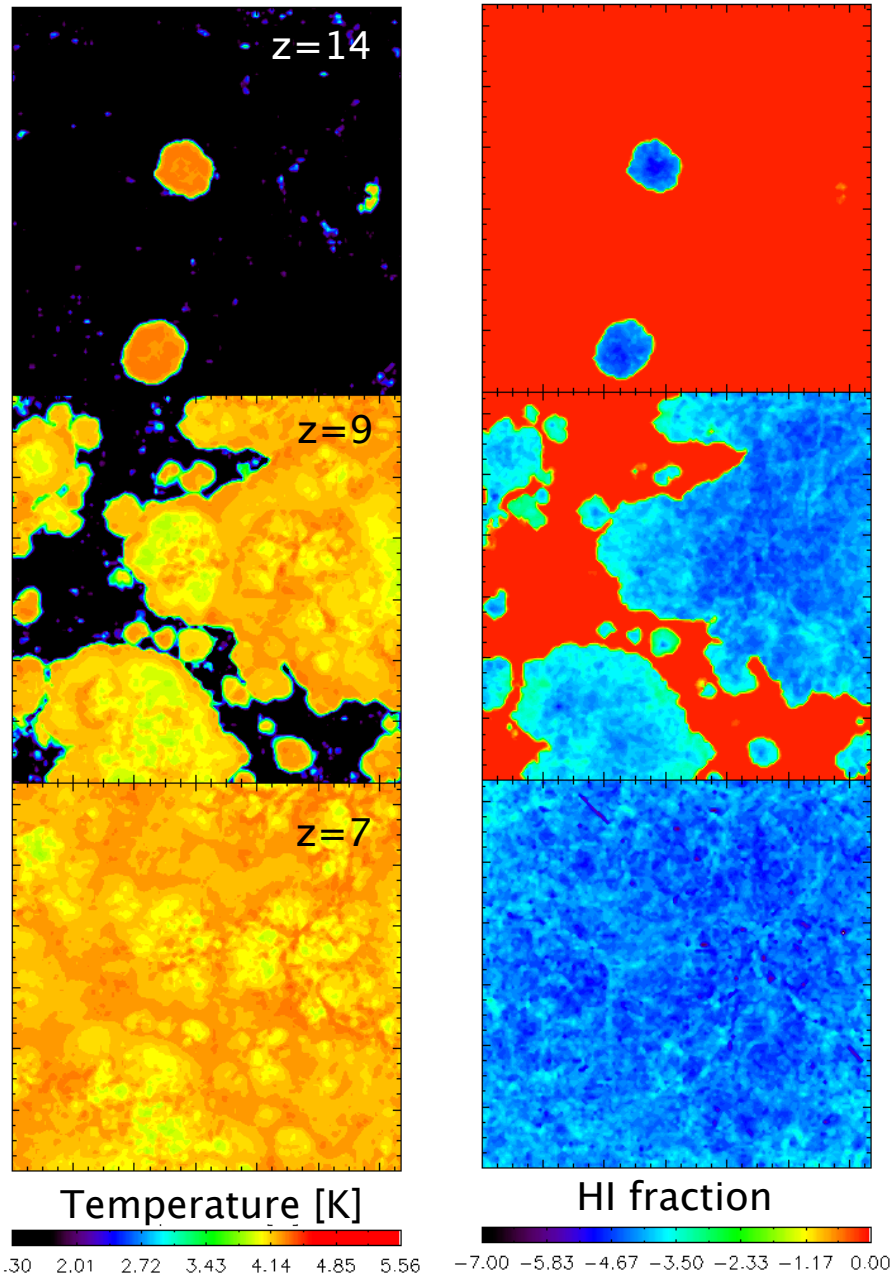
- Slow

Modelling of cosmic reionization

✧ Fully semi-

✧ Numerical

e.g. G



v+ 2006; Trac & Cen 2007; Baek+ 2010

+ Full 3D information
+ More accurate physics

- Slow

BC+

Modelling of cosmic reionization

✧ Fully semi-analytic approach

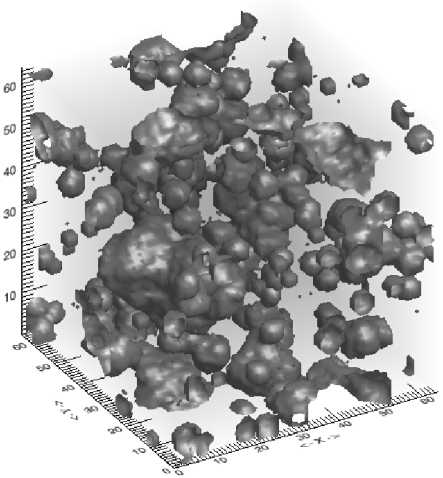
✧ Numerical simulations

✧ Semi-numeric approach

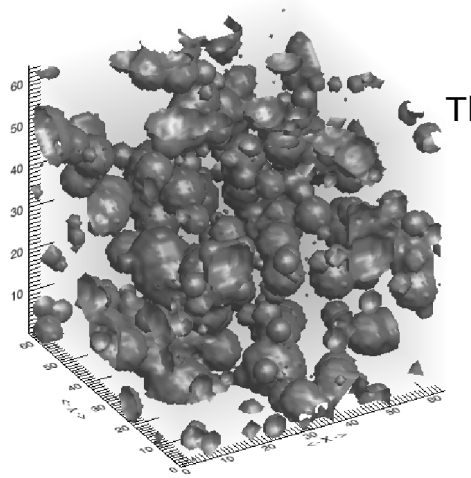
e.g. Ciardi+ 2000; Zhang, Hui & Haiman 2007; McQuinn+ 2007; Mesinger & Furlanetto 2007; Choudhury, Haehnelt & Regan 2009; Geil & Wyithe 2009; Thomas+ 2009; Santos+ 2010

CRASH

BC+ 2001;
Maselli, Ferrara & BC 2003;
Maselli, BC & Kanekar 2009;
Partl+ 2011



12.5 Mpc/h com.



12.5 Mpc/h com.

BEAR

Thomas & Zaroubi 2008

Thomas+ 2009

Modelling of cosmic reionization

✧ Fully semi-analytic approach

✧ Numerical simulations

✧ Semi-numeric approach

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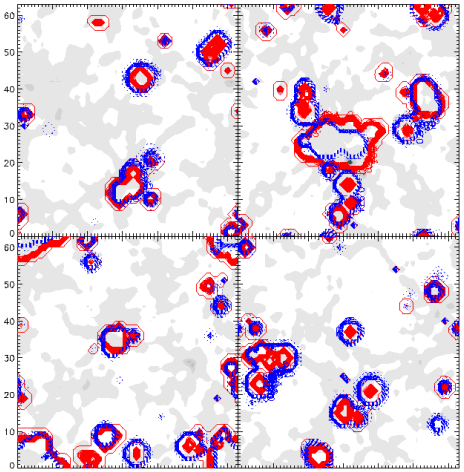
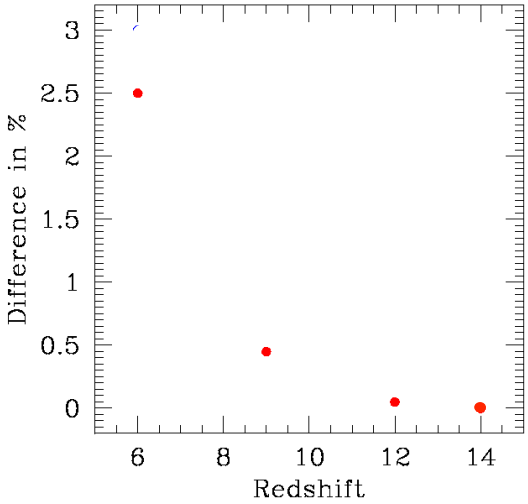
Isocontours ion fraction

CRASH

BEAR



Mean neutral fraction



Thomas+ 2009

Simulations of H & He reionization

BC, Bolton, Maselli & Graziani in prep

Model of galaxy formation

Gadget-3 simulations from J. Bolton

Properties of the sources of ionizing radiation

Emissivity(z) and distribute it among the halos with power-law spectrum

Index α	% of sources
1.8	100
3 - 1	70 - 30
3	100

Radiative transfer of ionizing photons

CRASH BC+ 2001; Maselli, Ferrara & BC 2003; Maselli, BC & Kanekar 2009; Pierleoni, Maselli & BC 2009; Partl+ 2011

Simulations of H & He reionization

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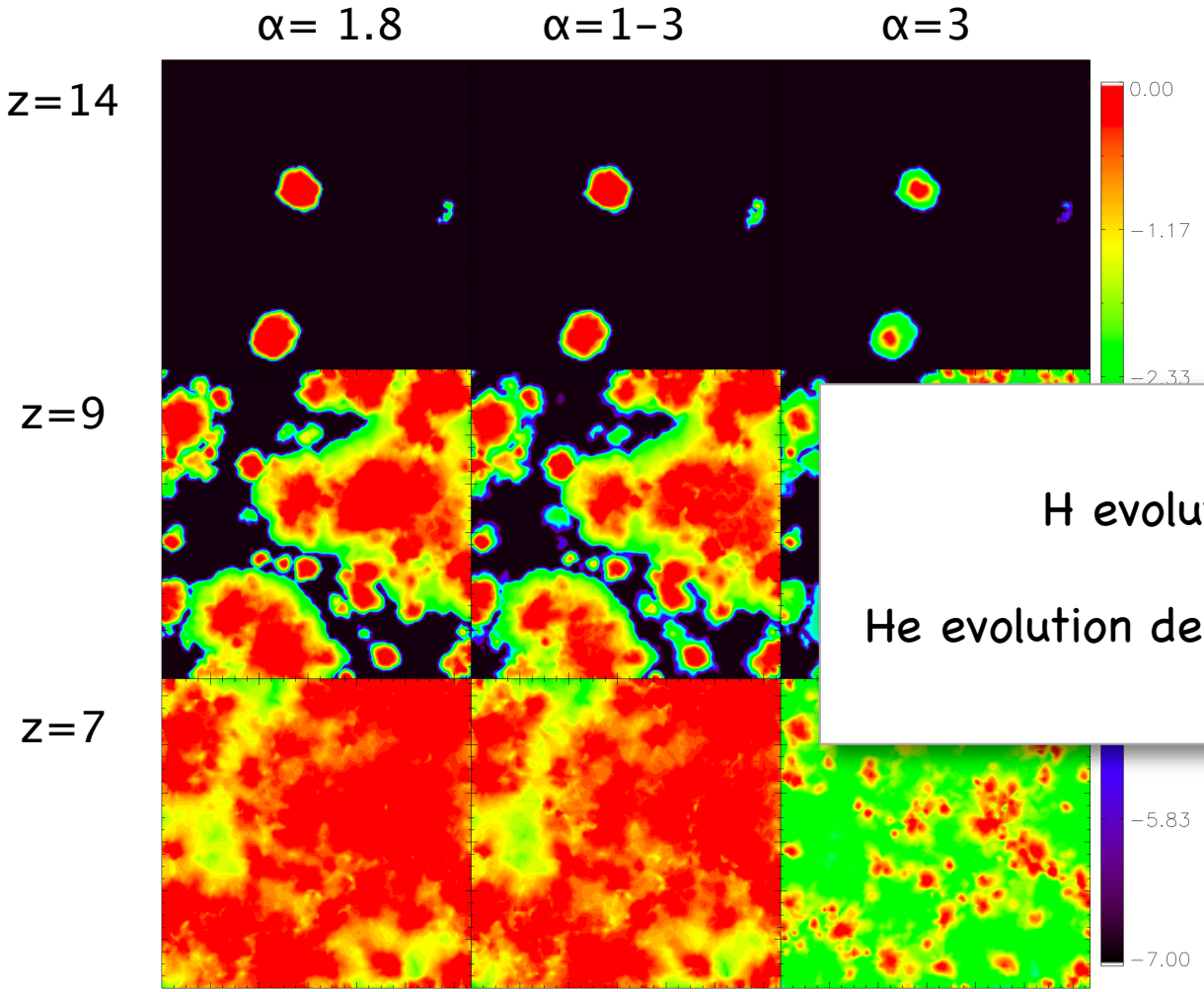
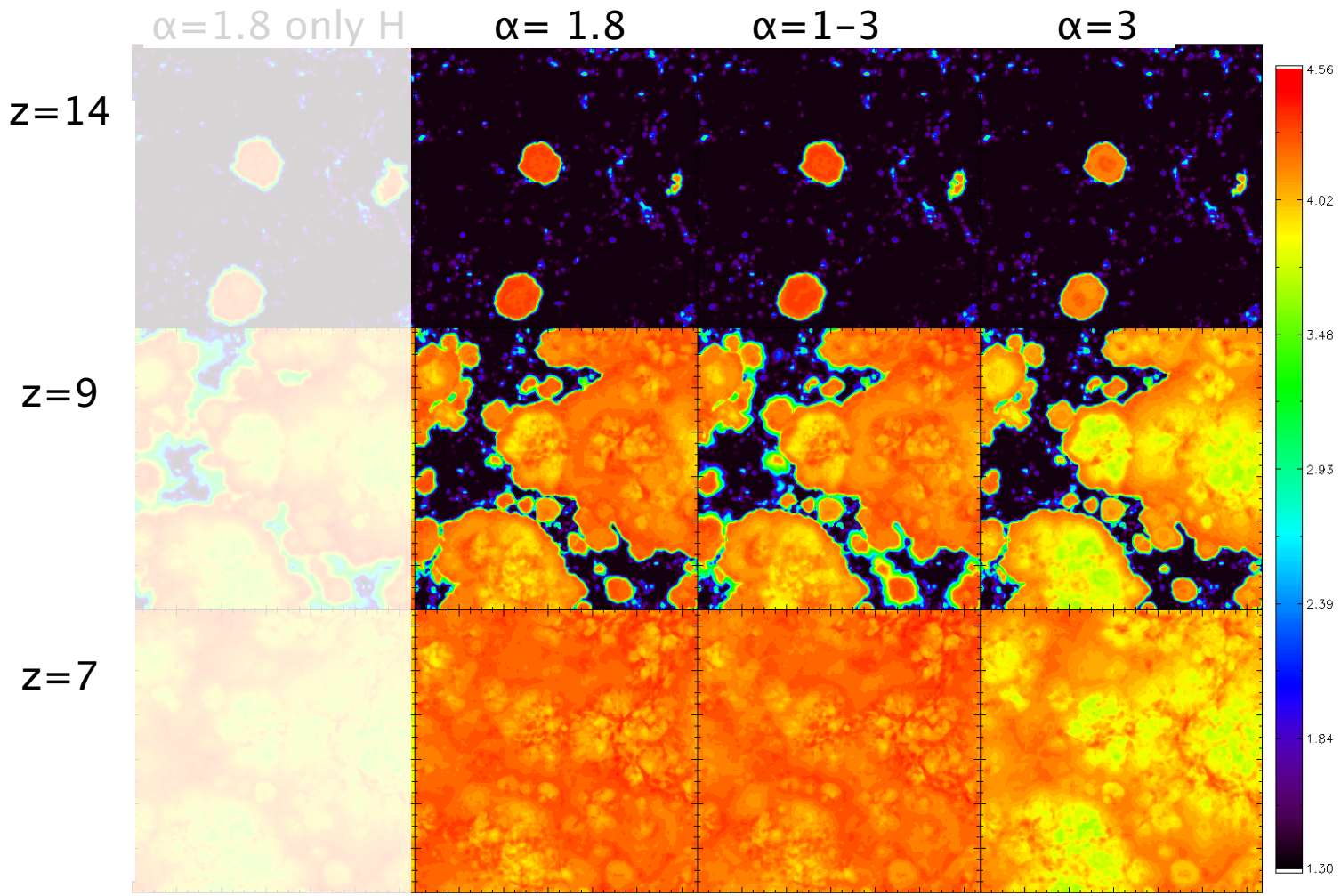


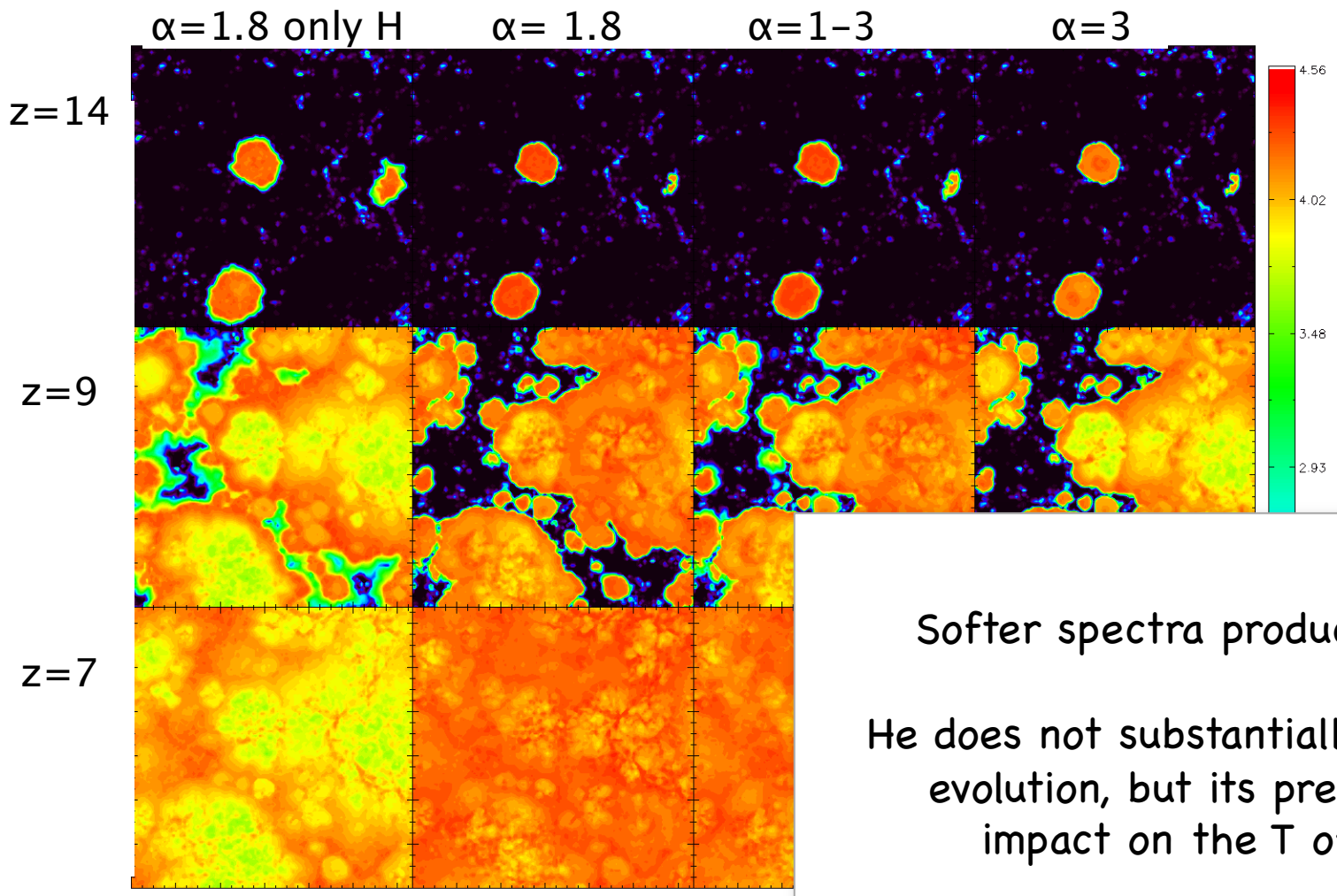
H evolution very similar

He evolution depends on spectral shape

Simulations of H & He reionization



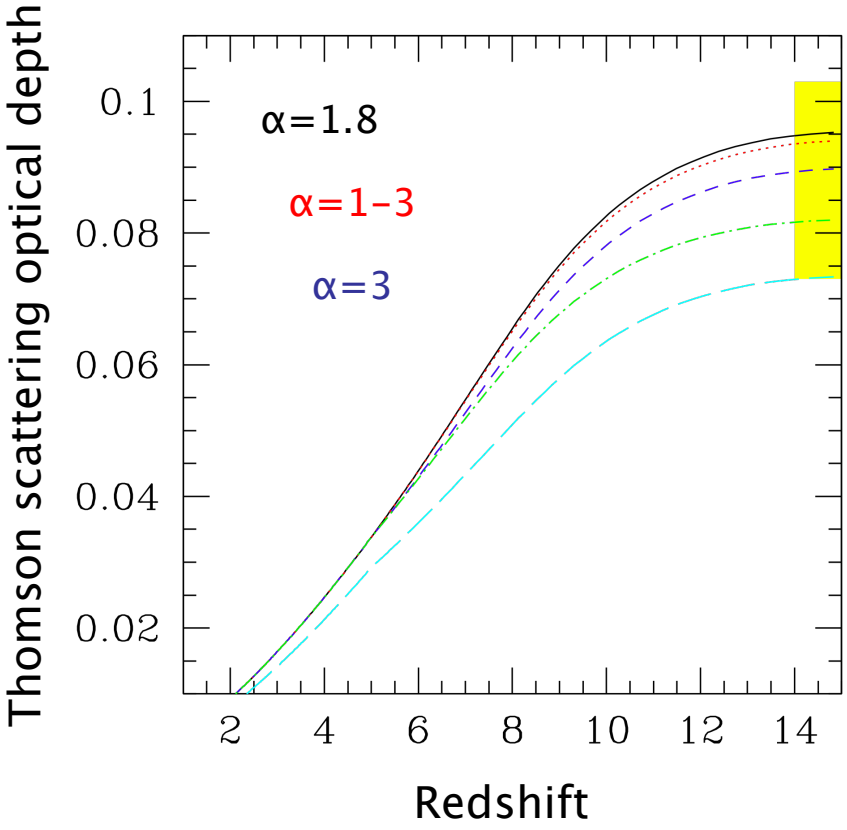
Simulations of H & He reionization



Softer spectra produce lower T

He does not substantially affect HII evolution, but its presence has an impact on the T of the IGM

Simulations of H & He reionization

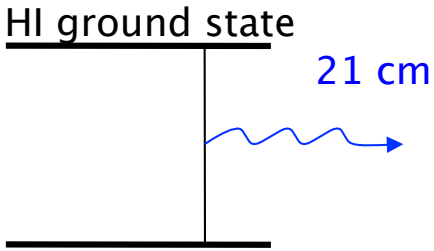


$$\tau_e = 0.088 \pm 0.015$$

(Larson et al. 2010)

Models are consistent
with WMAP measurements

21cm line observations

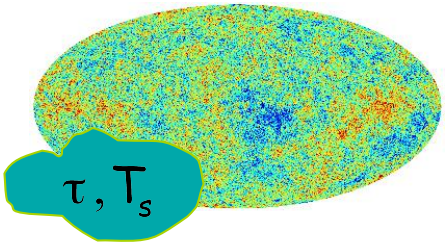


Ideal probe of neutral H at high-z
different observed frqs. → different z

Differential brightness temperature:

spin temperature

$$\delta T_b \approx \frac{T_S - T_{CMB}}{1+z}\tau \propto n_{HI}\left(1 - T_{CMB}/T_S\right)$$



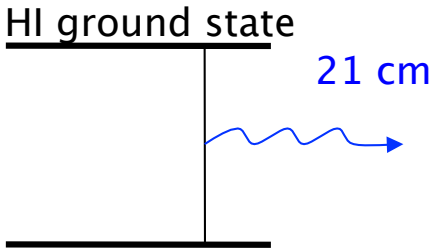
$T_S = T_{CMB} \Rightarrow$ no signal

$T_S < T_{CMB} \Rightarrow$ absorption

$T_S > T_{CMB} \Rightarrow$ emission

The value of Ts is critical

21cm line observations



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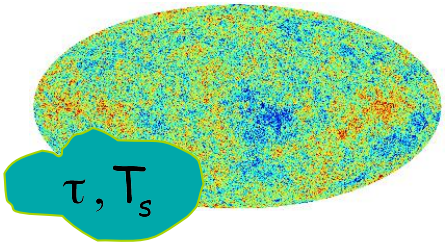

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$T_S < T_{CMB} \Rightarrow$ absorption

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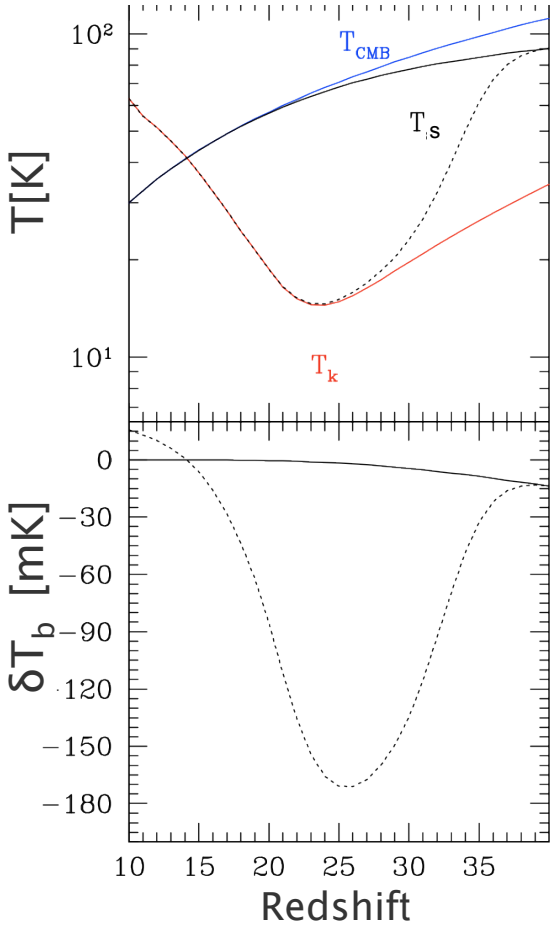
kinetic temperature of the gas

$$T_S = \frac{T_{CMB} + (y_\alpha + y_c)T_k}{1 + y_\alpha + y_c}$$

Lyalpha scattering and collisional efficiency

T_s & δT_b evolution

Madau, Meiksin & Rees 1997; Chen & Miralda-Escude' 2006; Chuzhoy & Shapiro 2006; Hirata 2006; Pritchard & Furlanetto 2006; BC & Salvaterra 2007; Santos+ 2007; Valdes+ 2007; Ripamonti, Mapelli & Zaroubi 2008



$$\delta T_b \approx n_{HI}(1-T_{CMB}/T_S)$$

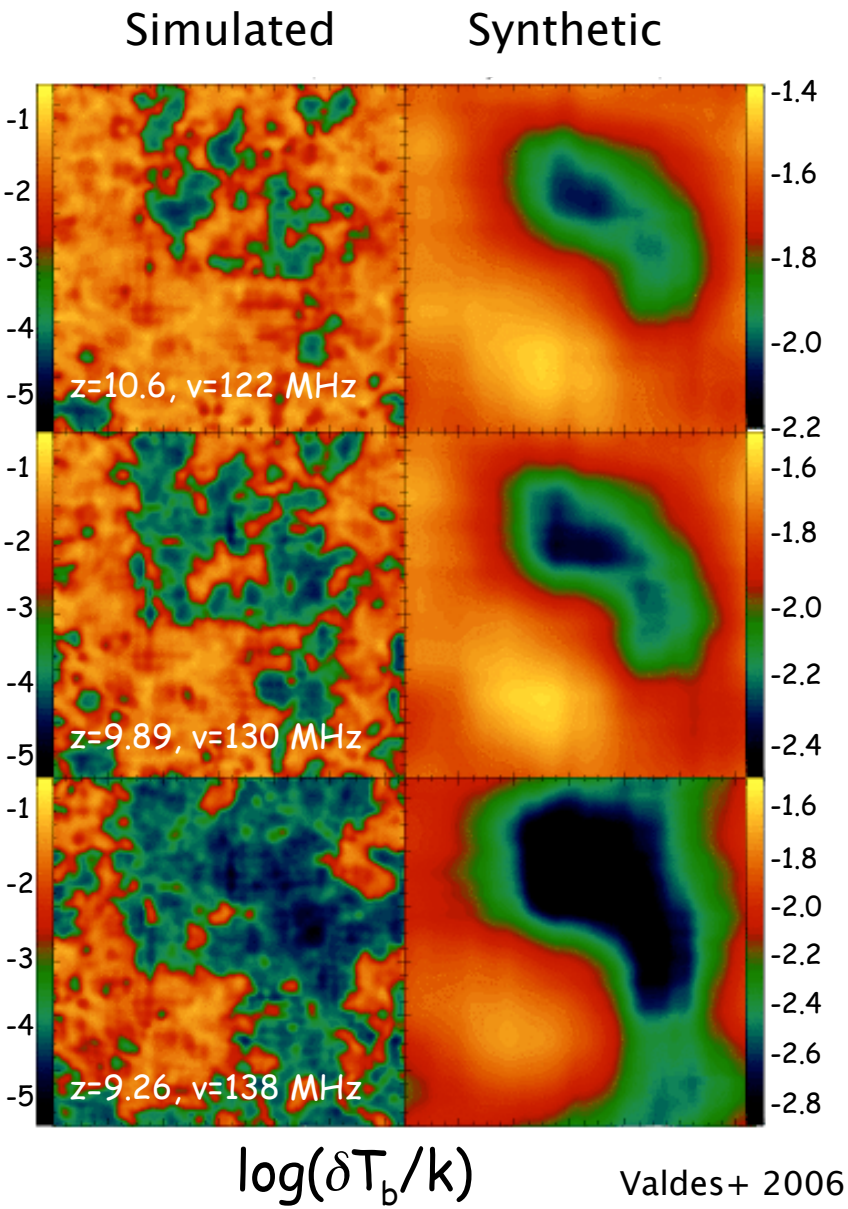
$$T_S >> T_{CMB} \rightarrow \delta T_b \approx n_{HI}$$

Pelupessy, Di Matteo, BC 2007; BC, Salvaterra 2007; BC, Salvaterra, Di Matteo 2009

21cm line observations

21cm line observations: tomography

Tozzi+ 2000; BC & Madau 2003; Furlanetto, Sokasian, Hernquist 2004;
Mellema+ 2006; Valdes+ 2006; Santos+ 2008; Baek+ 2009; Geil & Wyithe 2009



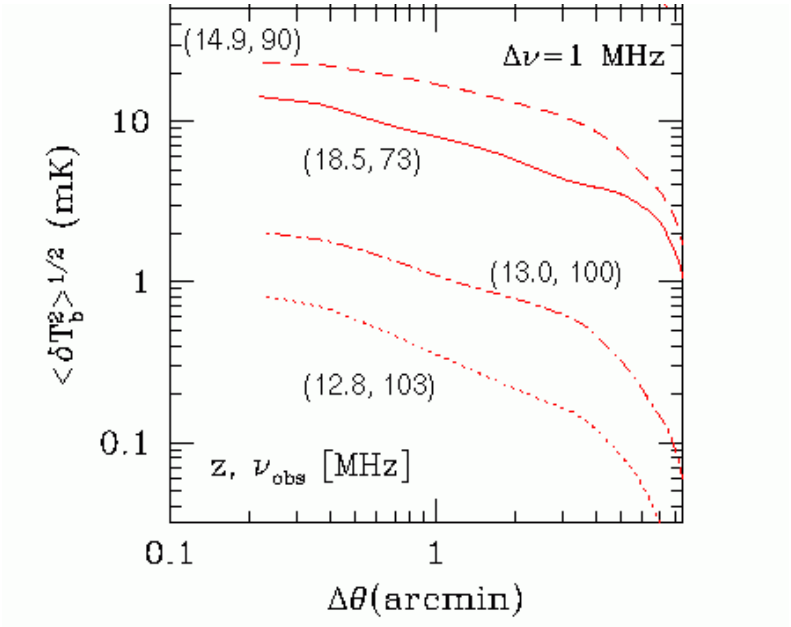
Valdes+ 2006

Topology of HII regions
Information on sources
When reionization occurred

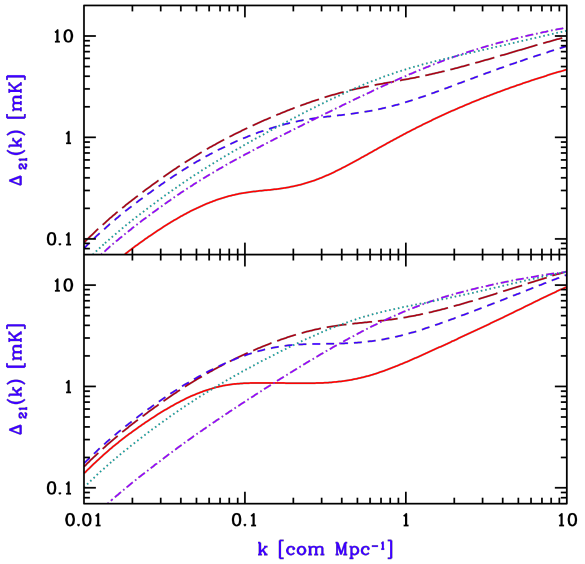
21cm line observations: δT_b fluctuations & PS

e.g. Madau, Meiksin & Rees 1997; Shaver+ 1999; Tozzi+ 2000; BC & Madau 2003; Furlanetto, Sokasian, Hernquist 2004; Mellema+ 2006; Valdes+ 2006; Datta+ 2008; Pritchard & Loeb 2008; Santos+ 2008; Baek+ 2009; Geil & Wyithe 2009

BC & Madau 2003



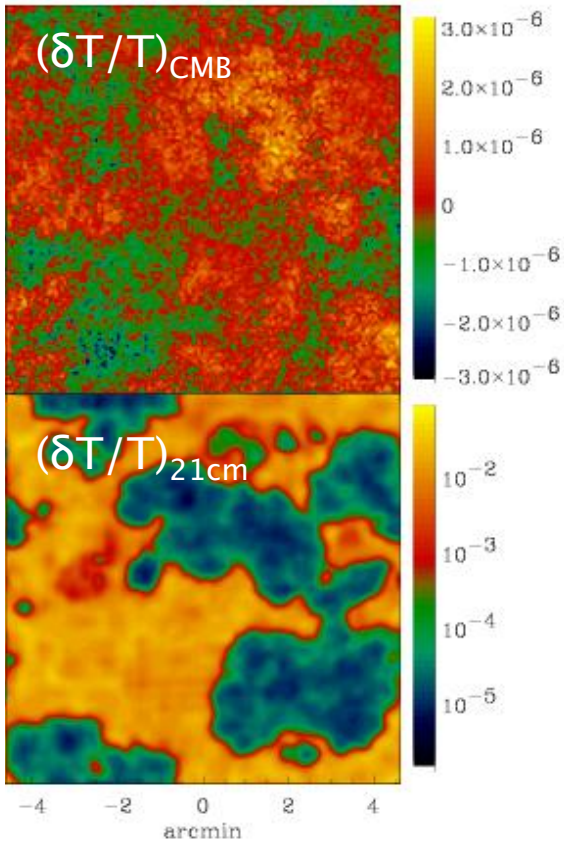
Barkana 2007



Statistical estimates

21cm line observations: cross-correlation (CMB)

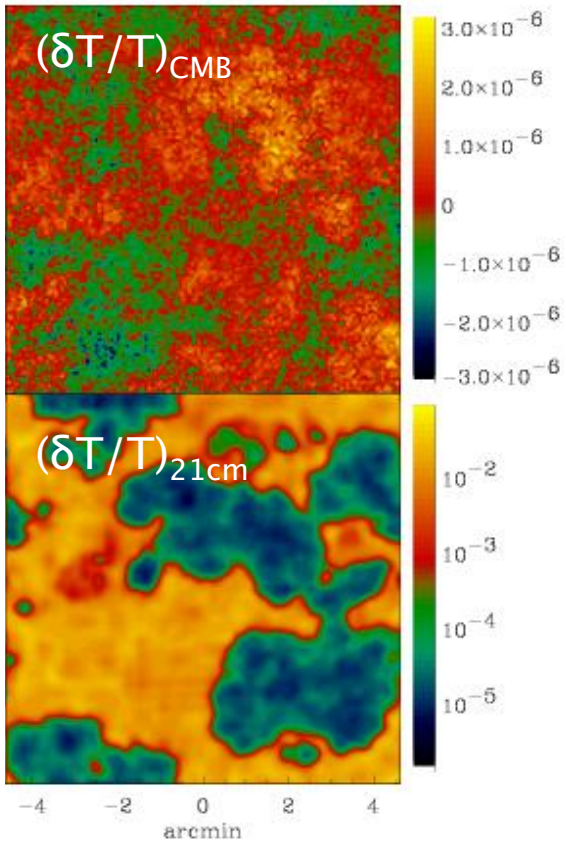
e.g. Cooray 2004; Salvaterra+ 2005; Alvarez+ 2006;
Holder, Iliev & Mellema 2007;
Adshead & Furlanetto 2007; Jelic+ 2010; Tashiro+ 2010



Salvaterra+ 2005

21cm line observations: cross-correlation (galaxies)

e.g. Lidz+ 2009; Wiersma+ in prep



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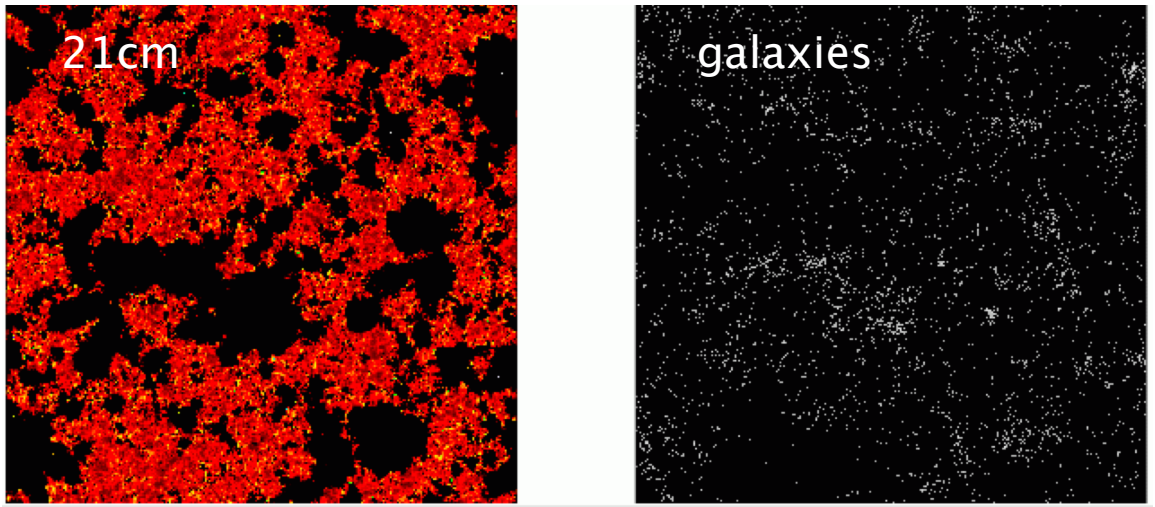
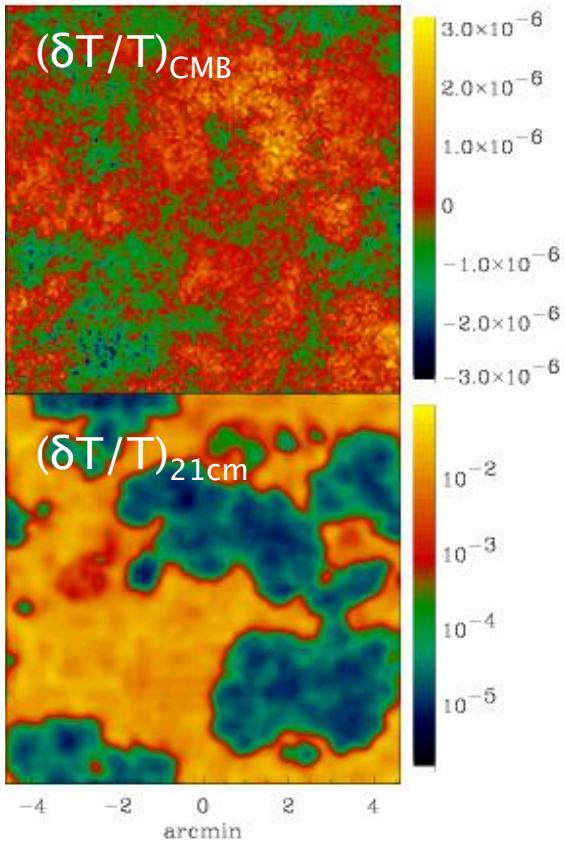
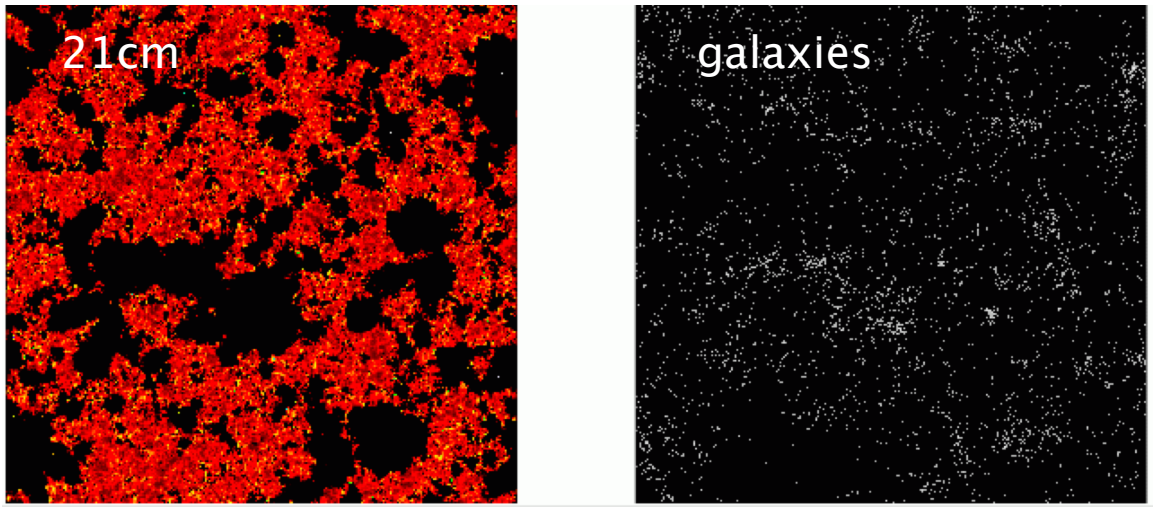


Lidz+ 2009

21cm line observations: cross-correlation



Salvaterra+ 2005



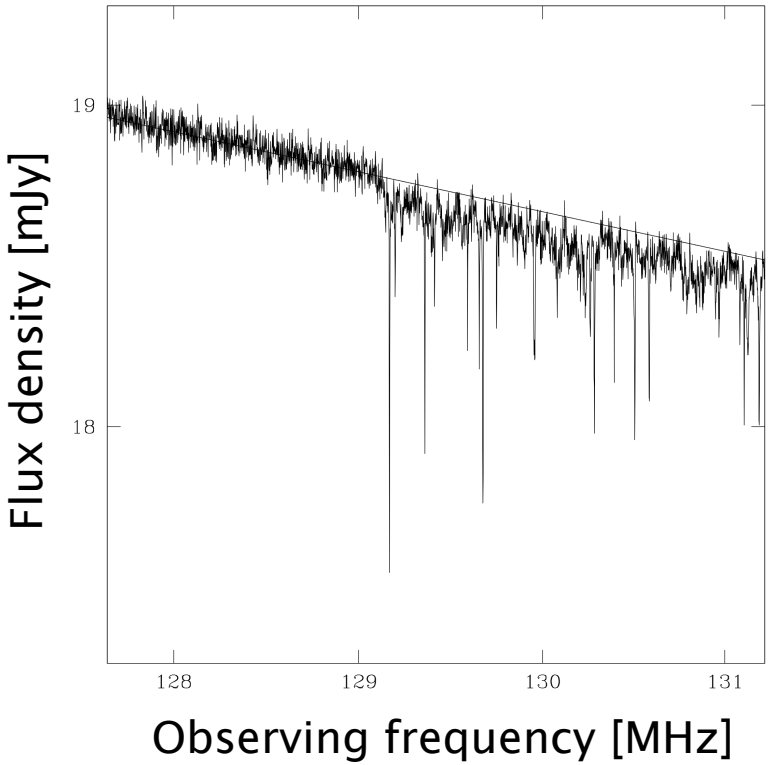
Lidz+ 2009

Information on typical dimension of HII regions

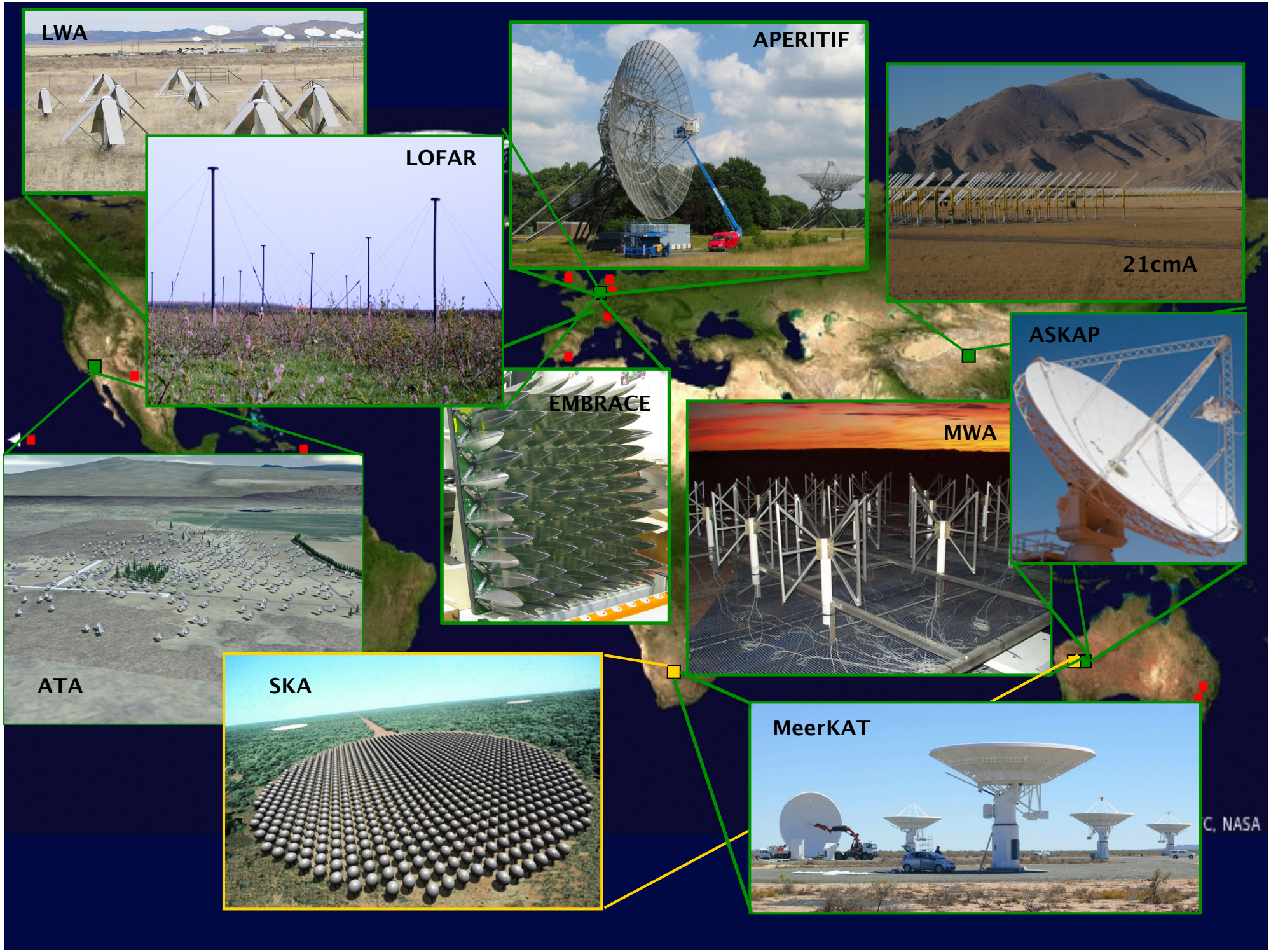
21cm line observations: 21cm forest

e.g. Carilli, Gnedin & Owen 2002; Furlanetto 2006;
Xu+ 2009; Mack & Wyithe 2011; BC+ in prep

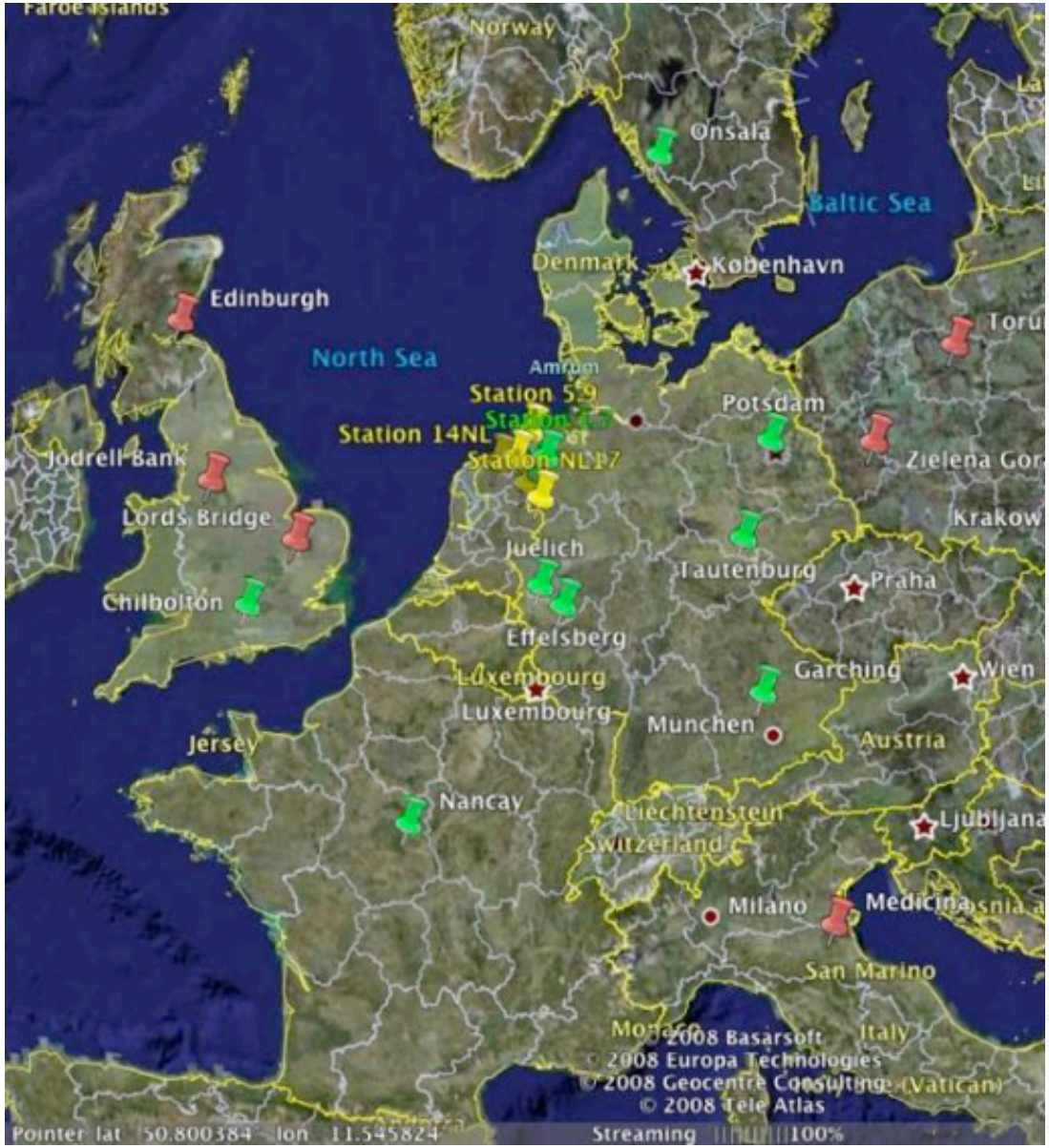
Carilli, Gnedin & Owen 2002



Information along the l.o.s.


LWA
APERITIF
LOFAR
21cmA
ASKAP
EMBRACE
MWA
ATA
SKA
MeerKAT
C, NASA

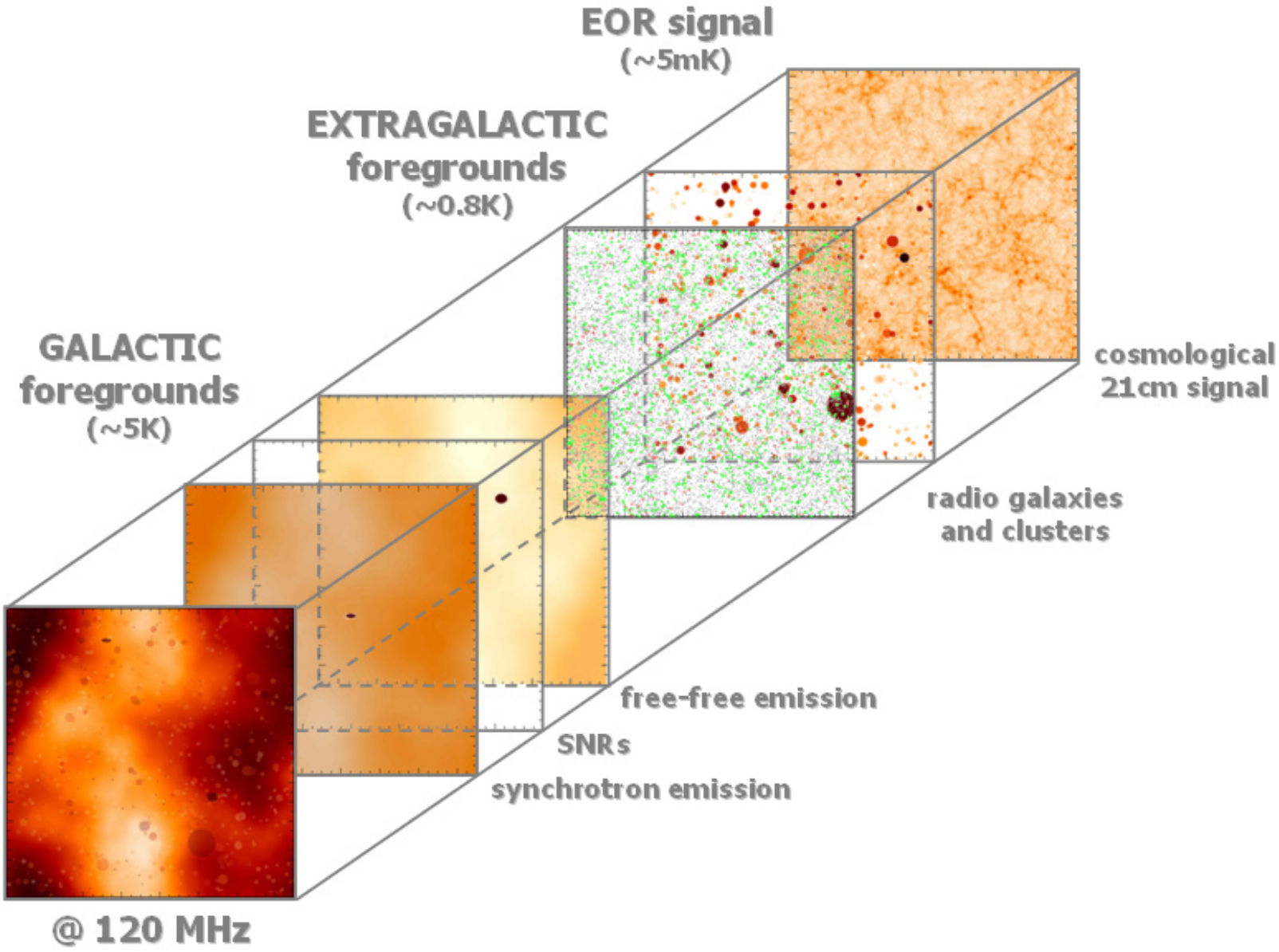
LOFAR: LOw Frequency ARray



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						
CS003						
CS004						
CS005						
CS006						
CS007						
CS024						
CS201						
CS101						
CS026						
RS205						
CS017						
CS011						
CS013						
CS028						
CS031						
RS104						
RS210						
RS310						
RS404						
RS406						
RS407						
RS409						
RS410						
RS508						
Effelsberg						
Tautenburg						
Garching						
Potsdam						
Juelich						
Nancay						
Onsala						
Chilbolton						
Totals	41	40	40	40	38	33

LOFAR EoR WG

e.g. Harker+ 2009; Jelic+ 2009; Thomas+ 2009;
Bernardi+ 2010; Harker+ 2010



Conclusions

✧ Theoretical modelling of cosmic reionization is constantly being improved

✧ More stringent observational constraints are needed

✧ 21cm line measurements could offer a wealth of information unavailable elsewhere