Panorama of the Evolving Cosmos
Hiroshima 28.11.-02.12.2016

Cosmic Reionization: Theoretical Modeling and Challenging Observations

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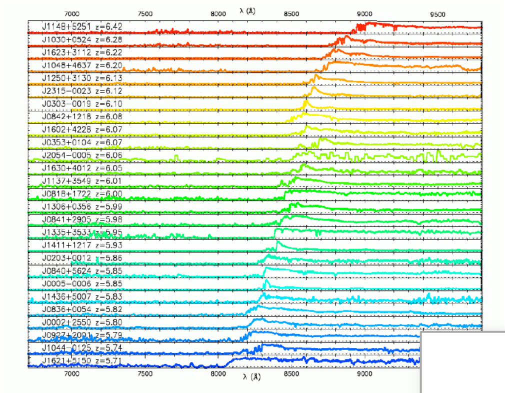
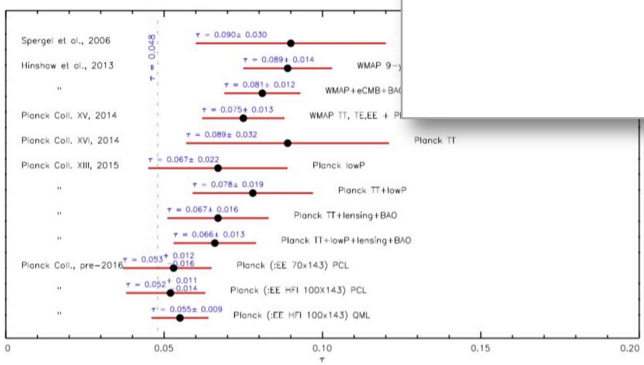
Thanks to the LOFAR Epoch of Reionization Key Science Project

CONSTRAINTS ON THE EPOCH OF REIONIZATION



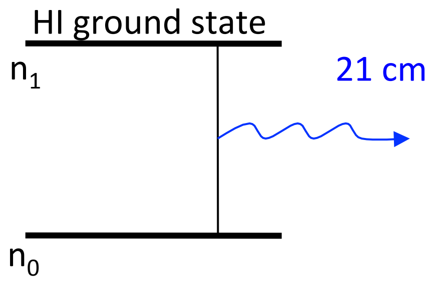
High-z QSOs,
galaxies, GRBS → latest stages of reionization at z~6-8

How did the reionization process evolve?



CMB anisotropies → global amount of electrons

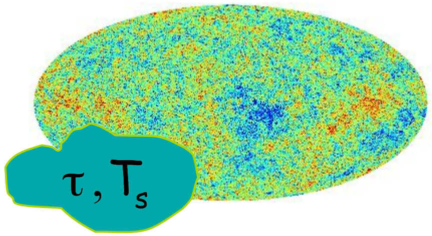
21cm line observations: basics



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

Differential brightness temperature:

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



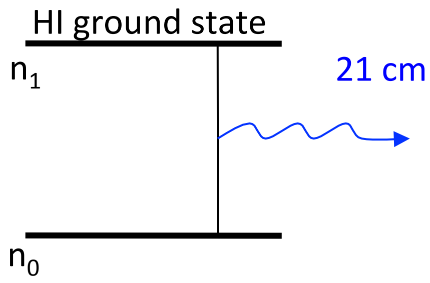
$T_S = T_{CMB} \Rightarrow$ no signal

$T_S < T_{CMB} \Rightarrow$ absorption

$T_S > T_{CMB} \Rightarrow$ emission

The value of T_s is critical

21cm line observations: basics



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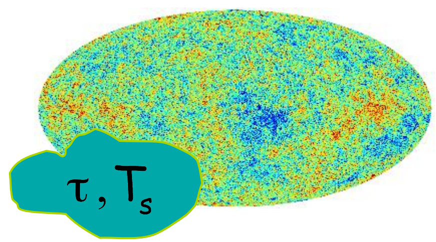

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kinetic temperature of the gas

$$T_S = \frac{T_{CMB} + AT_k}{1+A}$$

21cm line observations: what?

✧ *Tomography:* topology of HII regions; information on sources; when reionization occurred

e.g. Tozzi+ 2000; BC & Madau 2003; Furlanetto, Sokasian, Hernquist 2004;
Mellema+ 2006; Valdes+ 2006; Santos+ 2008; Baek+ 2009;
Geil & Wyithe 2009; Zaroubi+ 2012; Malloy & Lidz 2013

✧ *δT_b fluctuations and Power Spectrum:* statistical estimates

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; Patil+ 2014

✧ *21cm forest:* information on HI along the l.o.s.

e.g. Carilli, Gnedin & Owen 2002; Furlanetto 2006;
Xu+ 2009; Mack & Wyithe 2011; Meiksin 2011;
Xu, Ferrara & Chen 2011; BC+ 2013; Vasiliev & Shchekinov 2012;
Ewall-Wice at al. 2014; BC+ 2015; Semelin 2015

✧ *Cross-correlation:* information on typical dimension of HII regions

e.g. Salvaterra+ 2005; Lidz+ 2009; Jelic+ 2010; Wierma+ 2013
Fernandez+2013; Vrbanec+ 2016; Hutter+ 2016; Sobacchi+ 2016

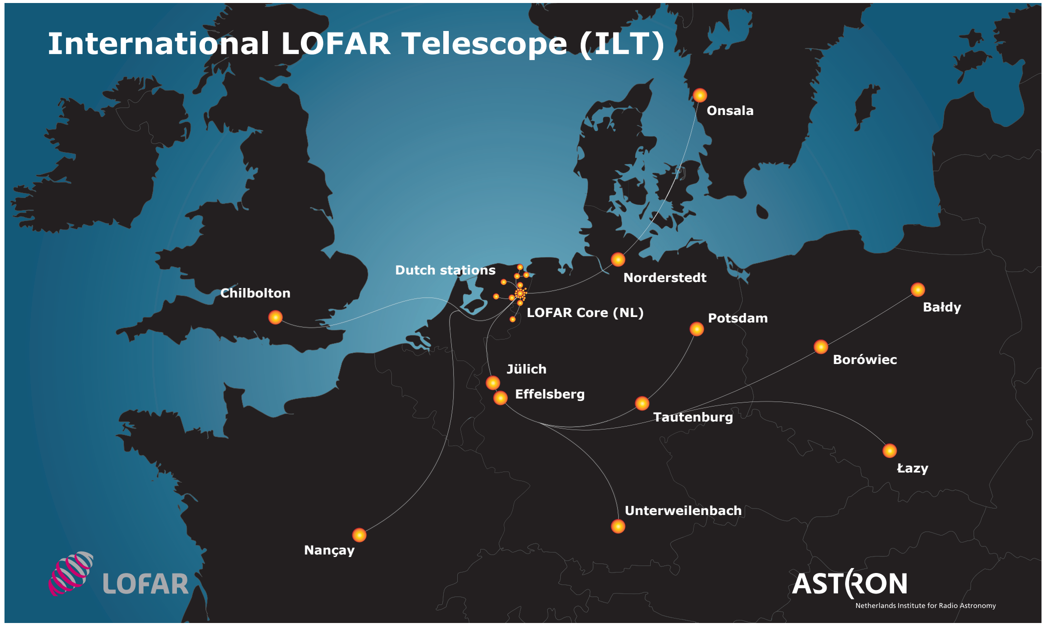
LOFAR: LOw Frequency ARray

LBA (10) 20 - 80 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)

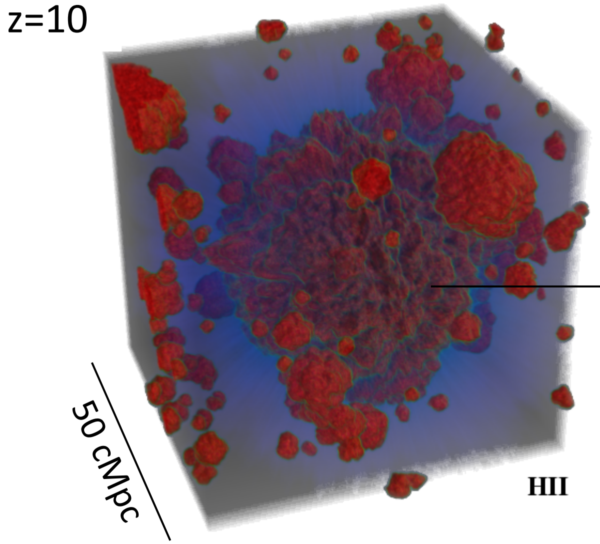
A station has 24/48/96 dipoles/tiles

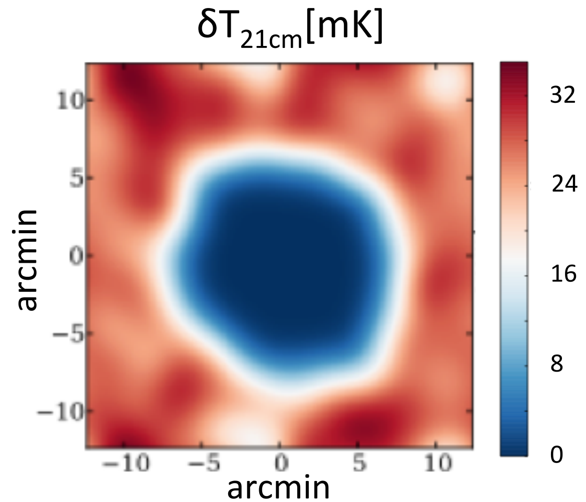
Core:	2 km	18+ stations
Netherlands:	80 km	18+ stations
Europe:	>1000 km	9+ stations



Imaging with LOFAR: QSOs' ionized regions

Kakiichi+ 2016; Kakiichi+ in prep





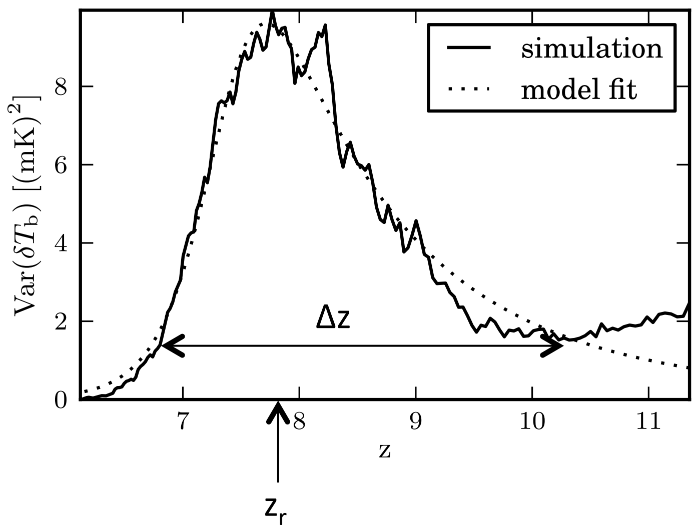
Gadget-3 hydrodynamic simulations + CRASH 3D radiative tranfer

LOFAR could be able to detect large high-z HII regions

Statistical measures with LOFAR

Patil+ 2014

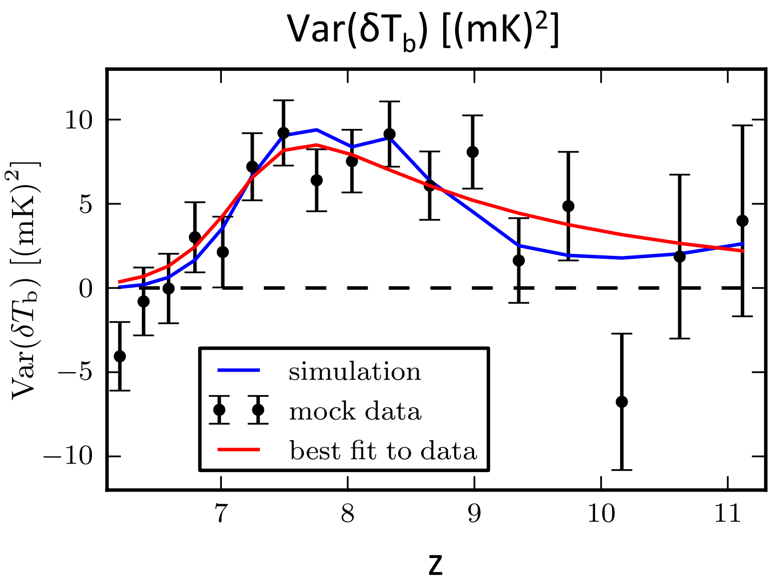
Variance of the signal



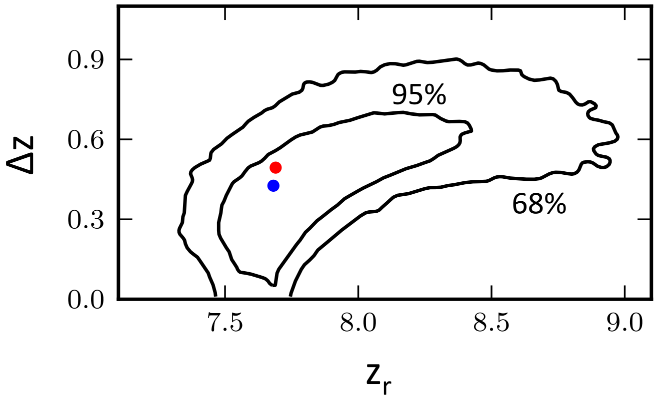
- ✧ Simulation in 600 cMpc with 21cmFast
- ✧ $\mathrm{Var}(\delta T_b)$=<P[k]> fitted with 2 parameters model: z_r and Δz
- ✧ Foregrounds, instrumental response, noise (600h) → simulated data
- ✧ Signal variance is extracted from simulated data
- ✧ Estimate best fitting parameters

Statistical measures with LOFAR

Patil+ 2014



LOFAR should be able to provide information on duration and peak of the reionization signal in less than 1000h



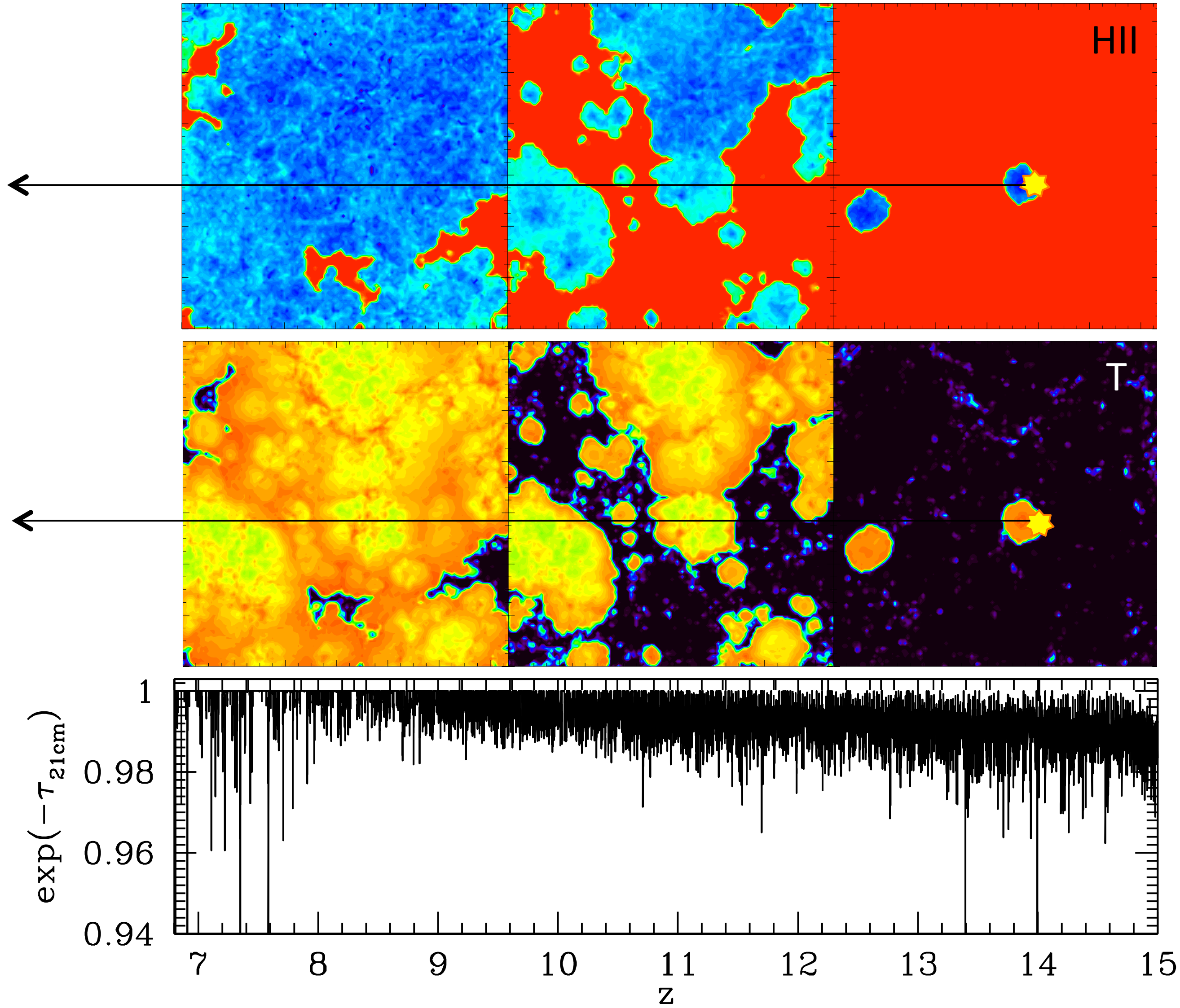
z_r=7.68, Δz=0.43

z_r=7.72$^{+0.37}_{-0.18}$, Δz=0.53$^{+0.12}_{-0.23}$

The 21cm forest

BC+ 2013, 2015

Hydrodynamic simulations + CRASH 3D radiative tranfer



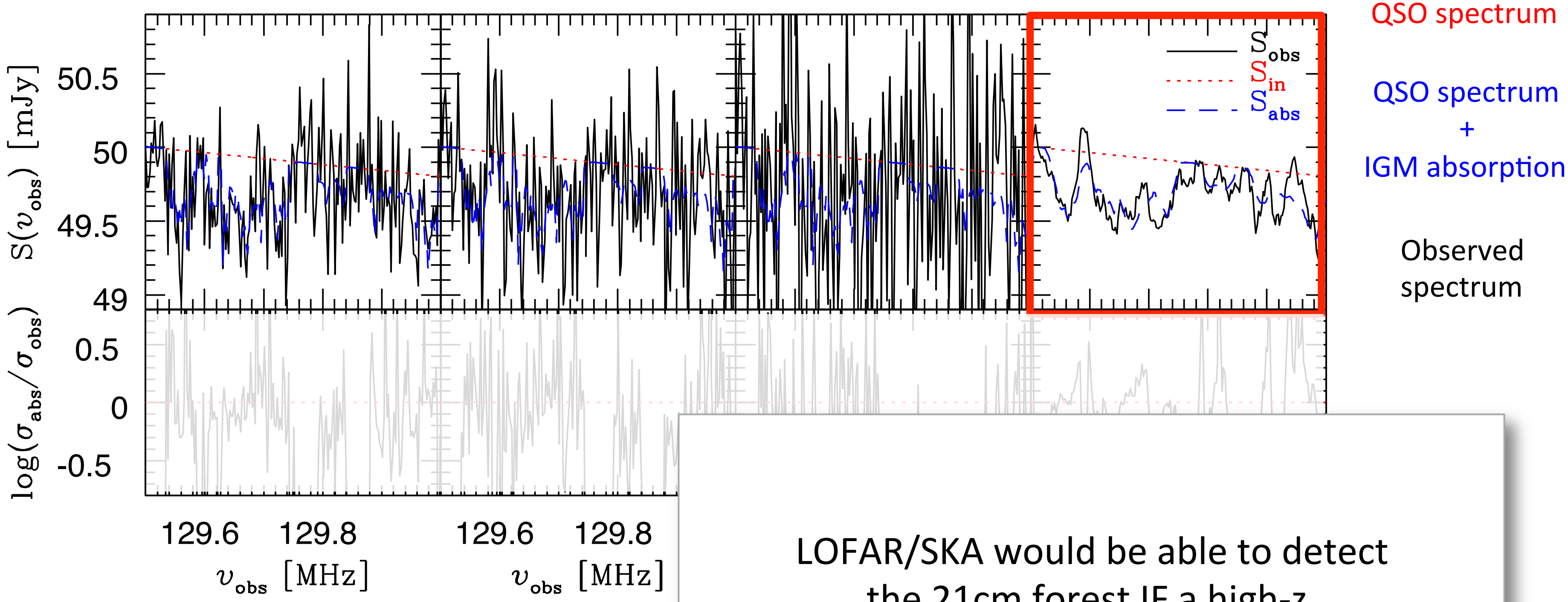
$$\tau_{21cm} \propto x_{HI}(1+\delta)\frac{1}{T_s}$$

THE 21CM FOREST

BC+ 2013, 2015

z=10, S=50 mJy, α=1.05

BW=10 kHz, t=1000 h



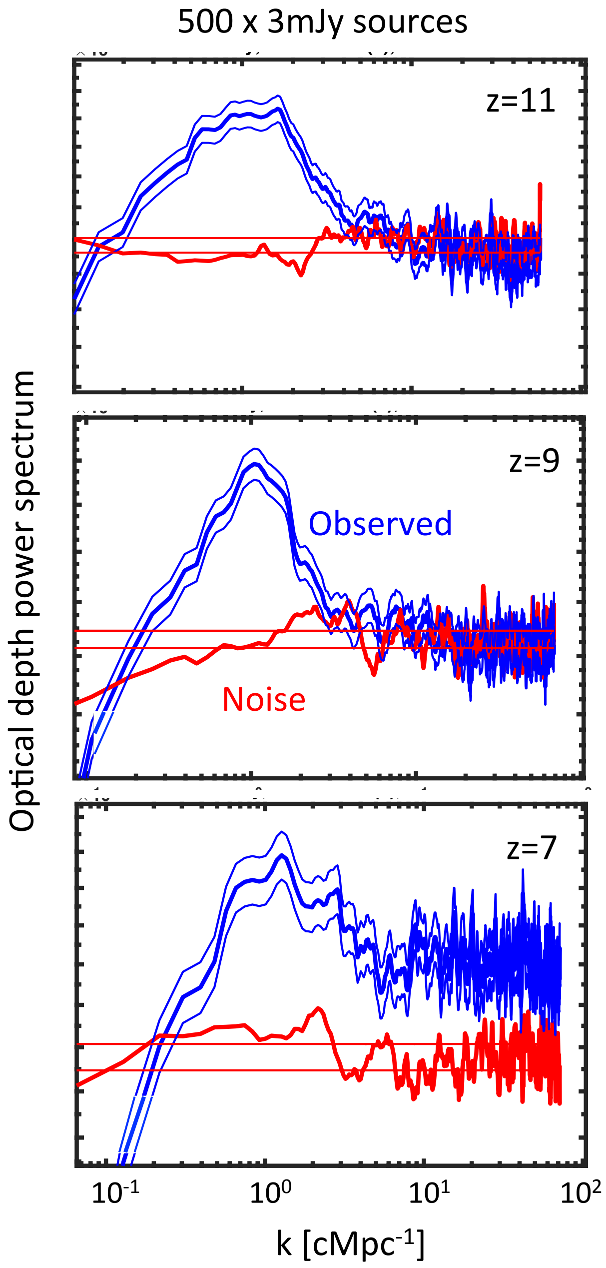
LOFAR/SKA would be able to detect the 21cm forest IF a high-z, strong radio source were found (GRBs?)

THE 21CM FOREST: STACKING

Koopmans+ in prep.

t=1000 h

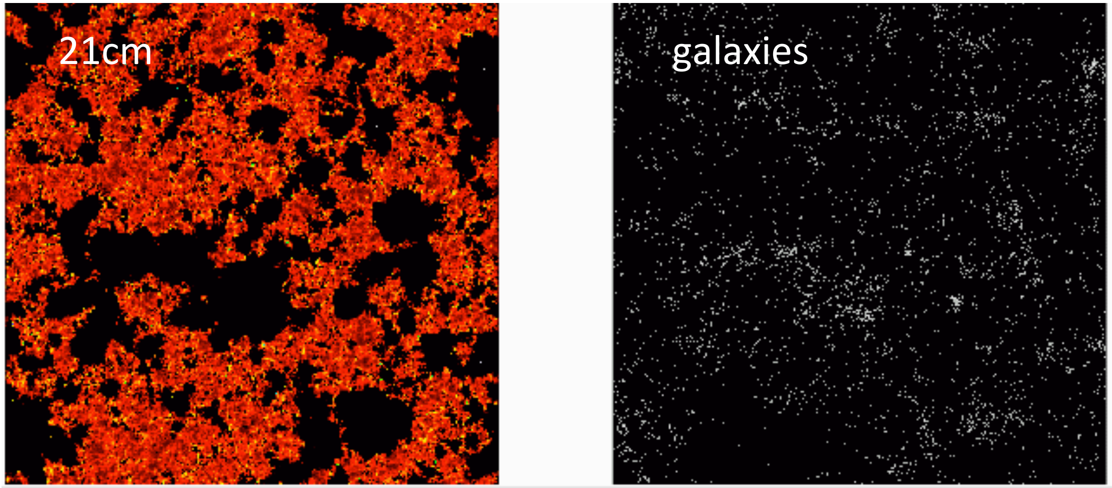
SKA-1 could probe in absorption scales ~ kHz



Cross-correlation 21cm–LAE surveys

Wiersma+ 2013; Vrbanec+ 2016; Vrbanec+ in prep

LOFAR - SUBARU



Lidz+ 2009

✧ ~600^3 $cMpc^3$ Nbody+RT simulations (LOFAR FoV~5x5 deg^2)

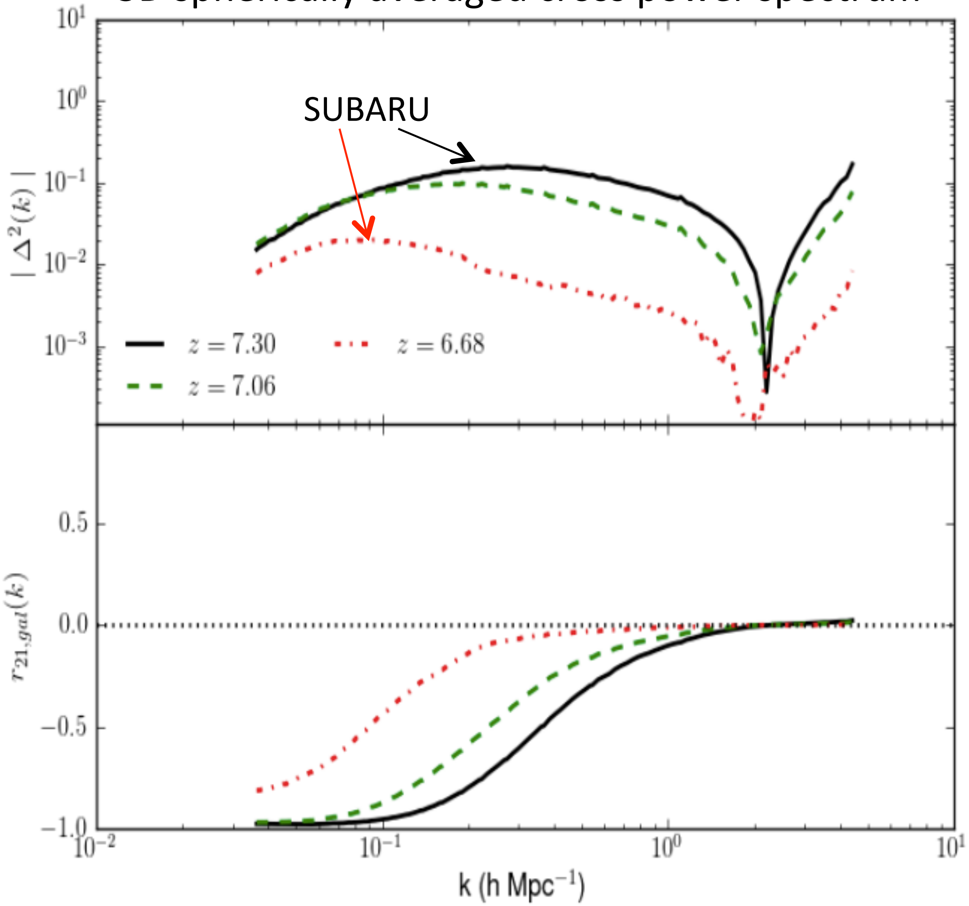
✧ LAEs model

Iliev+ 2012; Jensen+ 2013

Cross-correlation 21cm–LAE surveys

Wiersma+ 2013; Vrbanec+ 2016; Vrbanec+ in prep

3D spherically averaged cross power spectrum



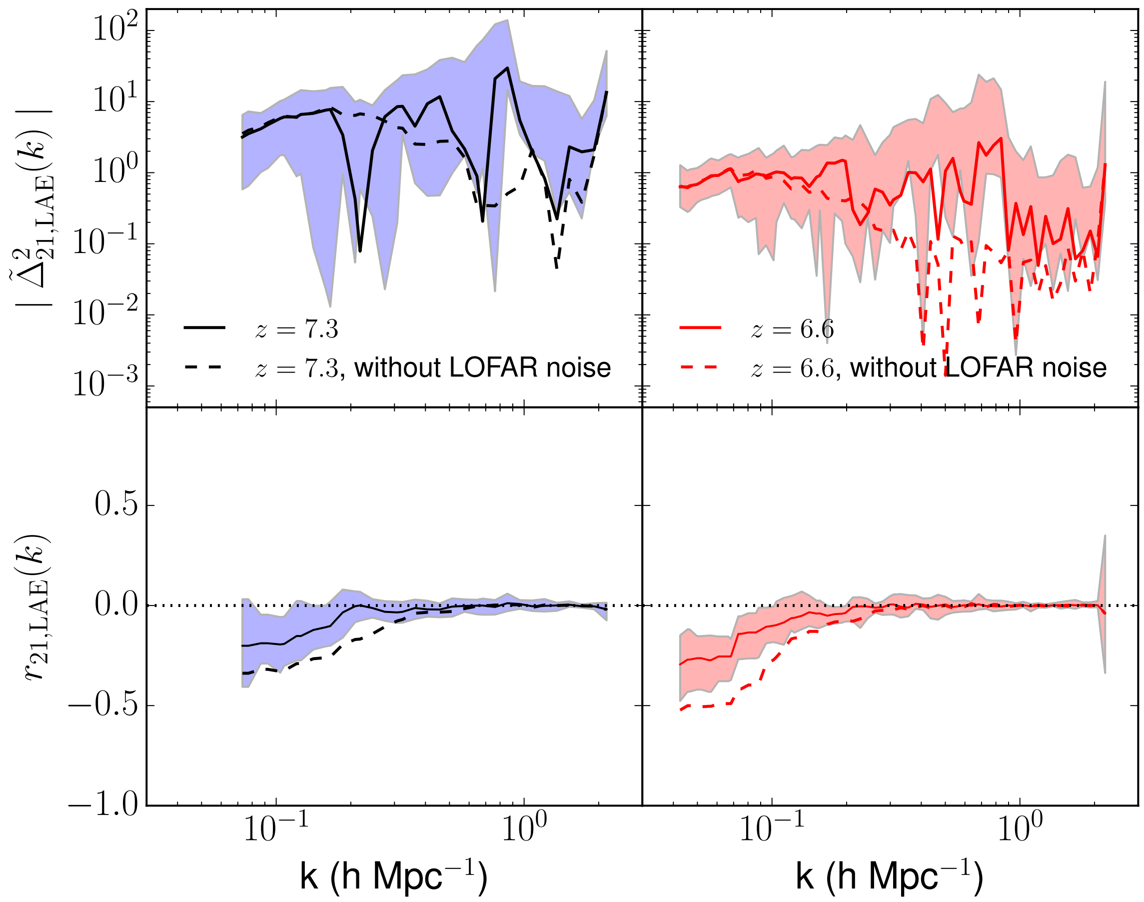
$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

- ✧ Intensity of the power spectrum → volume average HI
- ✧ Correlation coefficient → typical dimension of the HII regions

Cross-correlation 21cm–LAE surveys

Wiersma+ 2013; Vrbanec+ 2016; Vrbanec+ in prep

2D circularly averaged cross power spectrum



Δz=0.1

N(z=7.3)=20, FoV~1.7 deg^2

N(z=6.6)=1375, FoV~7 deg^2

t_{obs}=600h

$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

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CROSS-CORRELATION 21CM–LAE SURVEYS

Wiersma+ 2013; Vrbanec+ 2016; Vrbanec+ in prep

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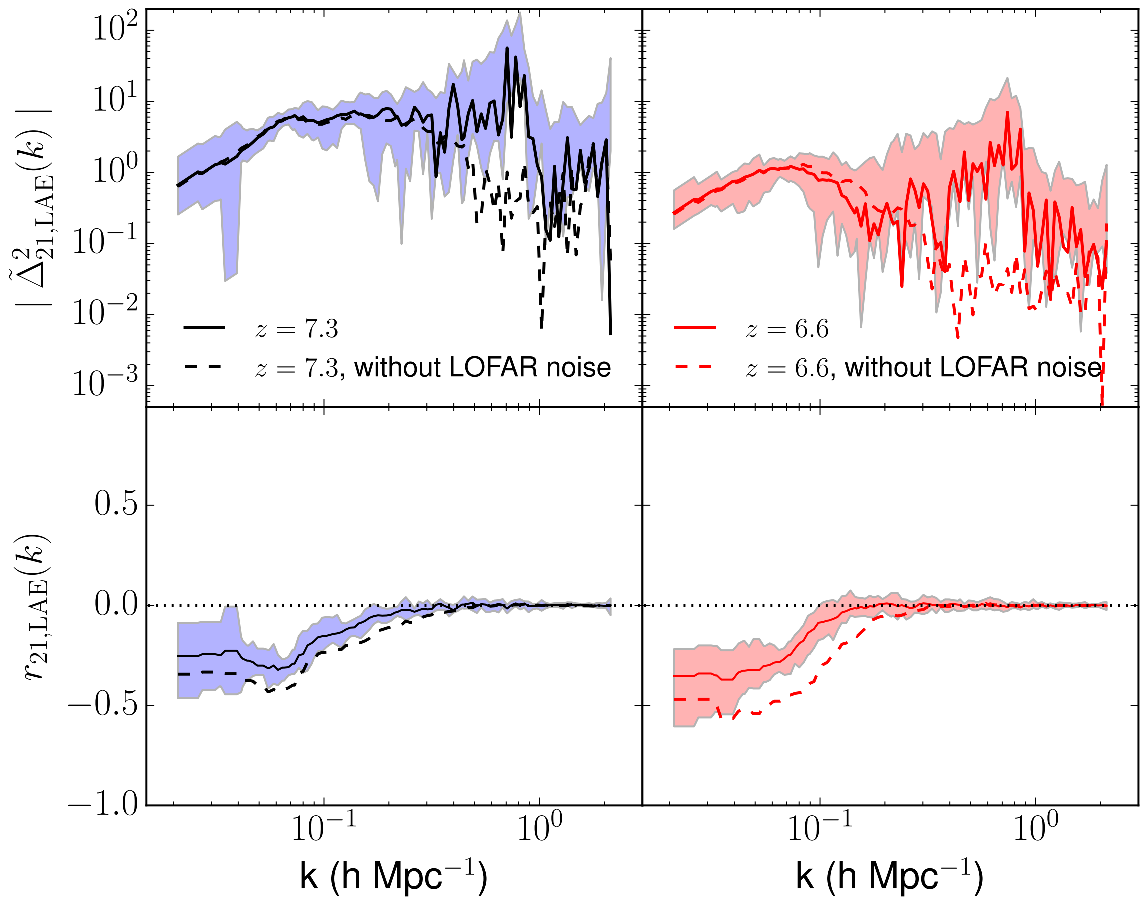

Δz=0.1
N(z=7.3)=90, FoV~25 deg^2
N(z=6.6)=3140, FoV~25 deg^2

t_{obs}=600h

$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

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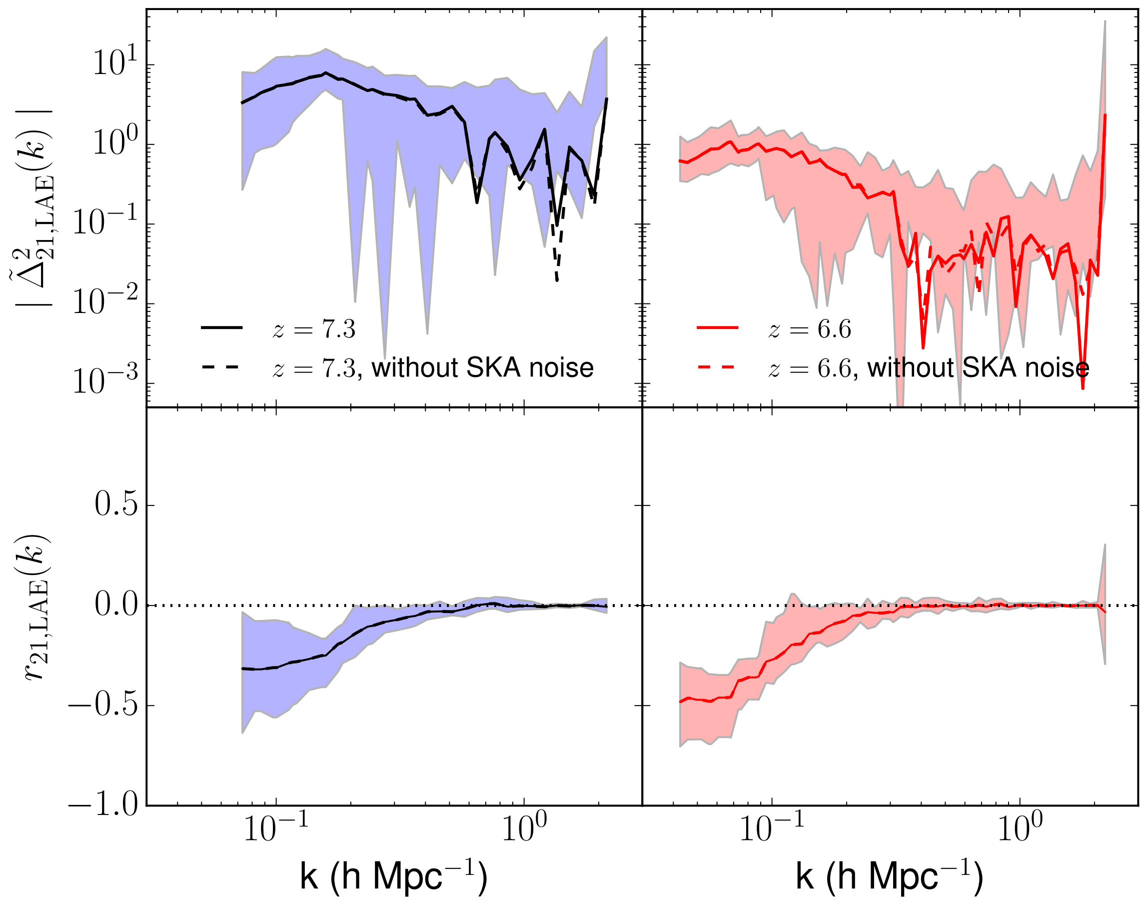

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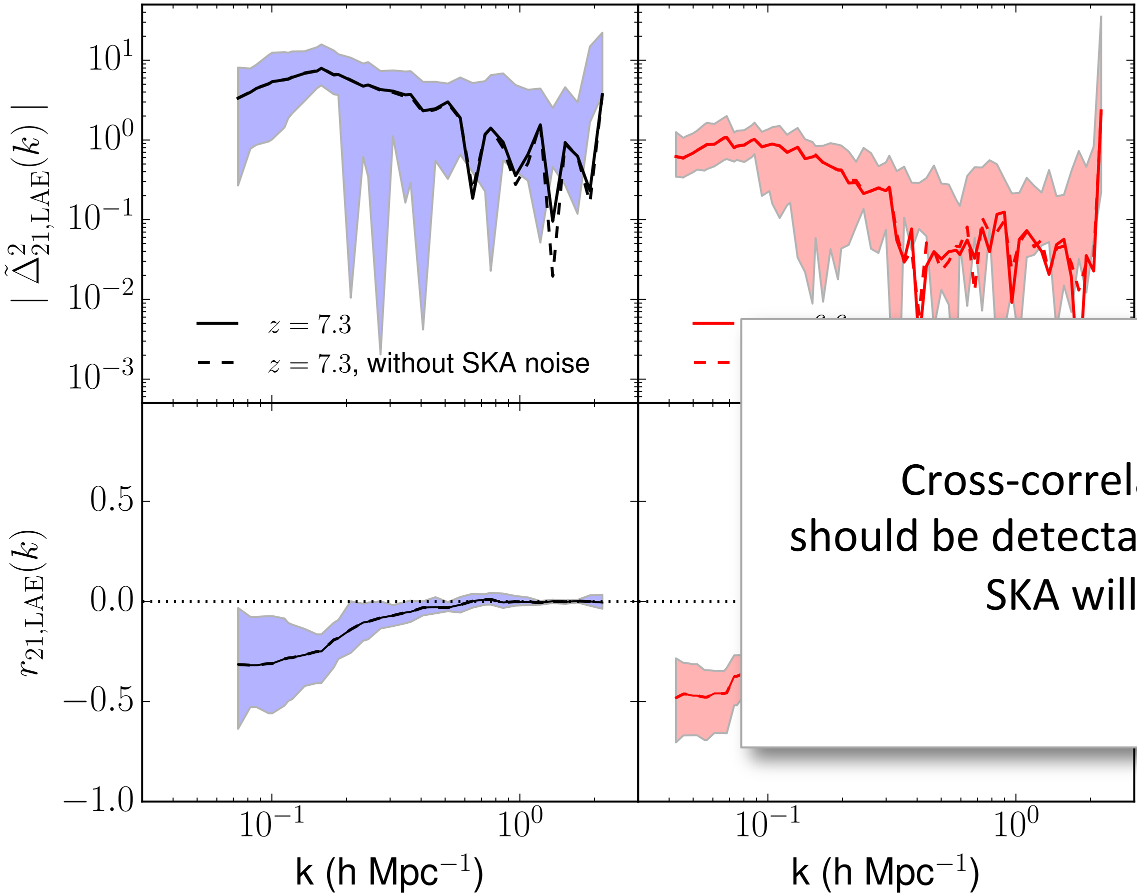

Δz=0.1
N(z=7.3)=20, FoV~1.7 deg^2
N(z=6.6)=1375, FoV~7 deg^2

Cross-correlation LOFAR-SUBARU
should be detectable on scales >60 h^{-1} cMpc.
SKA will do much better!

- ✧ Intensity of the power spectrum → volume average HI
- ✧ Correlation coefficient → typical dimension of the HII regions

Conclusions

- ✧ Imaging of high-z QSOs' HII regions should be possible with a S/N~few
- ✧ LOFAR should reveal statistical information on duration and peak of the EoR
- ✧ 21cm forest is feasible IF a high-z radio-loud source is found or by stacking
- ✧ Cross-correlation with high-z LAEs should reveal anti-correlation on large scales