The Reionization History of the Universe
Bielefeld 08.-09.03.2018

Cosmic Reionization: Theoretical Modeling and Challenging Observations

Benedetta Ciardi

Max Planck Institute for Astrophysics

Thanks to the LOFAR Epoch of Reionization Key Science Project

Modelling of cosmic reionization

✧ Model of structure formation
(gas distribution & source type and location)

Semi-analytic

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

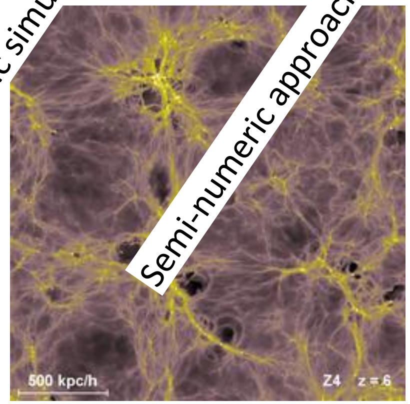
$$\frac{M}{dt}$$

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

...

N-body/Hydrodynamic simulations

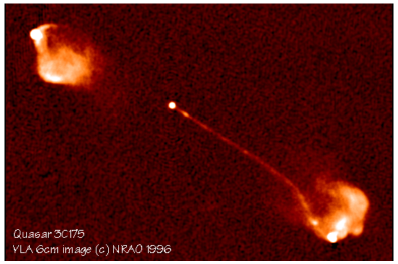
Semi-numeric approach



✧ Properties of the sources of ionizing radiation

Stellar type

Black holes; X-ray binaries



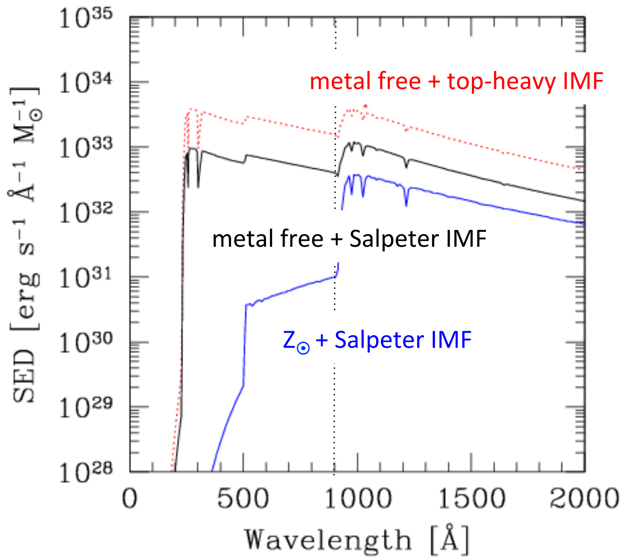
DM annihilation/decay

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

Stellar type sources

- ✧ Initial Mass Function and spectrum
- ✧ Primordial (PopIII) → standard (PopII/I) star formation
- ✧ Escape fraction

Spectral Energy Distribution



Large uncertainties associated to high-z stellar type sources

MODELLING OF COSMIC REIONIZATION

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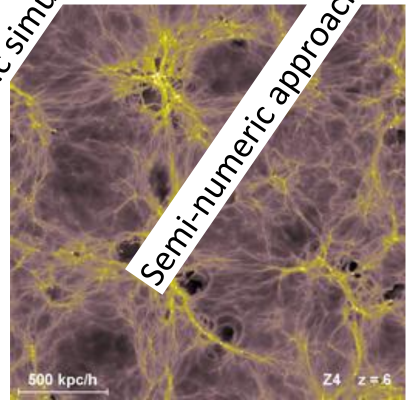

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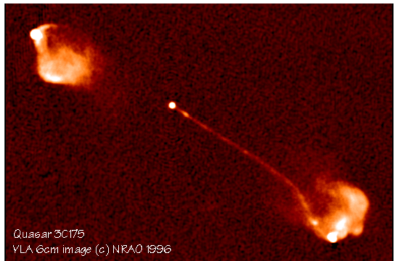

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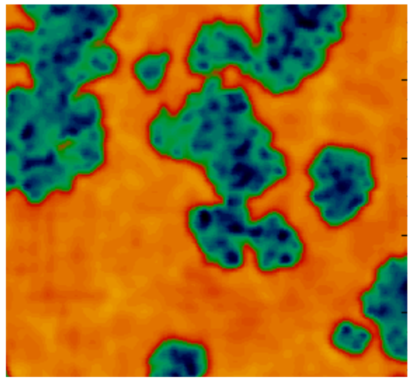
✧ Evolution of ionized regions



Evolution of ionized regions

Cosmological radiative transfer codes comparison I

Code (Authors)	Grid	Gasdyn.	He	Rec. rad.
CRASH (Maselli, Ferrara, BC)	Fixed	No	Yes	Yes
C2-Ray (Mellema et al)	Fixed/AMR	Yes	No	No
OTVET (Gnedin, Abel)	Fixed	No	Yes	Yes
ART (Nakamoto et al)	Fixed	No	No	Yes
RSPH (Susa, Umemura)	Particle-based	Yes	No	No
FLASH-HC (Rijkhorst et al)	Fixed/AMR	Yes	No	No
SimpleX (Ritzerveld, Icke, Rijkhorst)	Unstructured	No	No	Yes
Zeus-MP (Whalen, Norman)	Fixed	Yes	No	No
IFT (Alvarez, Shapiro)	Fixed/AMR	No	No	No
Coral (Iliev et al)	AMR	Yes	Yes	No
FTTE (Razoumov)	Fixed/AMR	Yes	Yes	yes

Iliev+ (2006)

Evolution of ionized regions

Cosmological radiative tra

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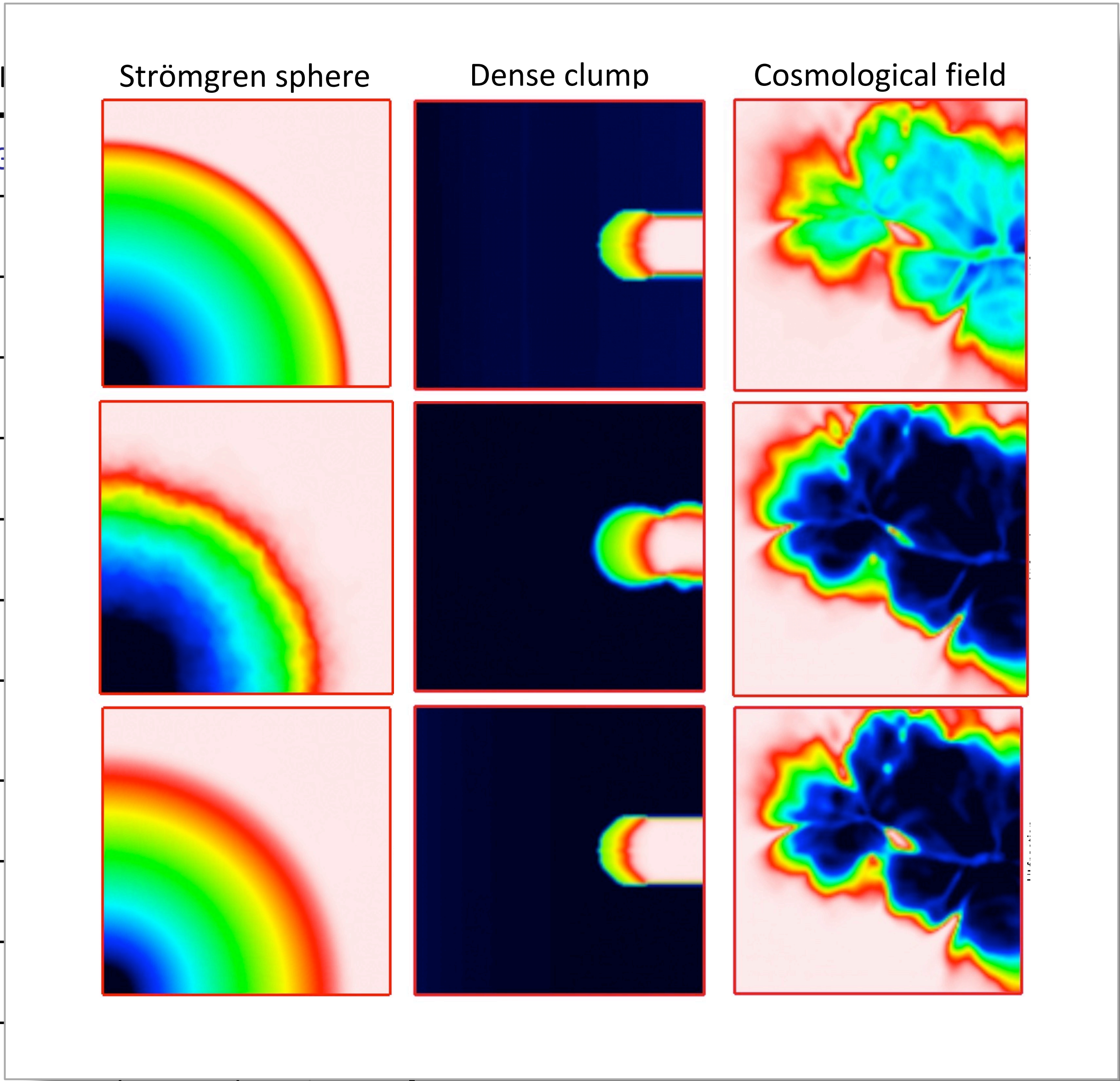

Iliev+ (2006)

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Iliev+ (2006)

1. Post-processing: He, high-energy photons
2. Coupled: properties of galaxies

STAY TUNED!

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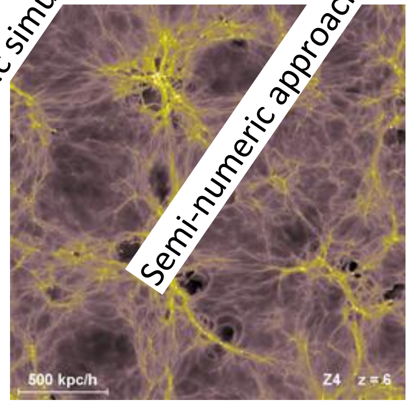

Semi-numeric approach

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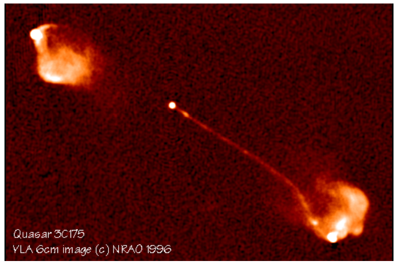

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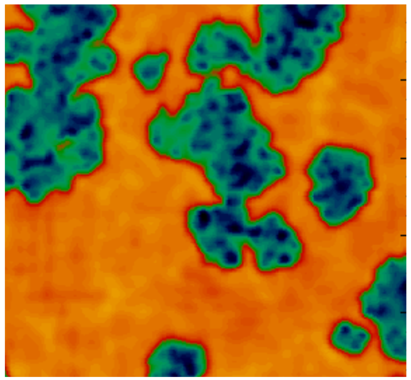

Modelling of cosmic reionization

Eide+ 2018; Eide+ in prep

Model of structure formation

MassiveBlack II (Khandai+ 2015)

Hydrodynamic simulations

	L [Mpc/h com.]	Particles	Mgas [Msun/h]
	533	2 x 3200^3	5.7 x 10^7
MBII	100	2 x 1792^3	2 x 10^6
	35.12	2 x 512^3	4.15 x 10^6
	8.78	2 x 256^3	6.48 x 10^4
	4.39	2 x 256^3	8.11 x 10^3
	2.20	2 x 256^3	1.01 x 10^3

Modelling of cosmic reionization

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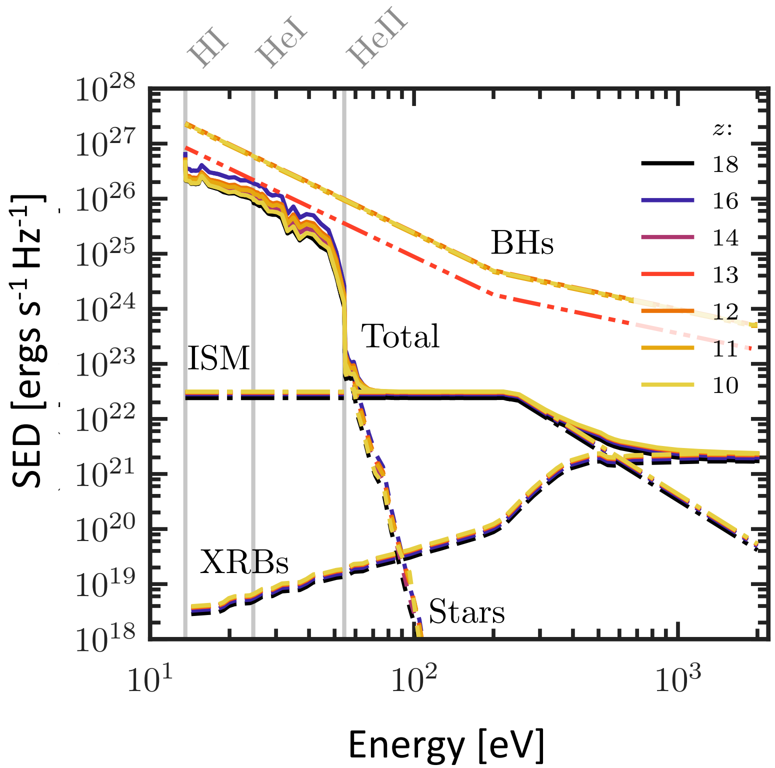
Properties of the sources of ionizing radiation

Stars, BHs, XRBs, ISM



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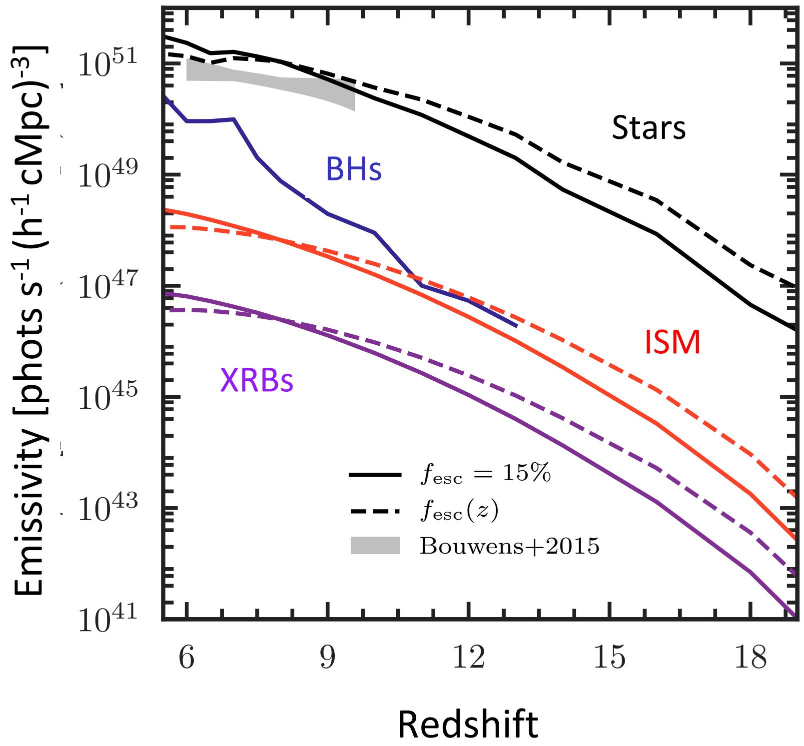

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Evolution of ionized regions (3D radiative transfer approach)

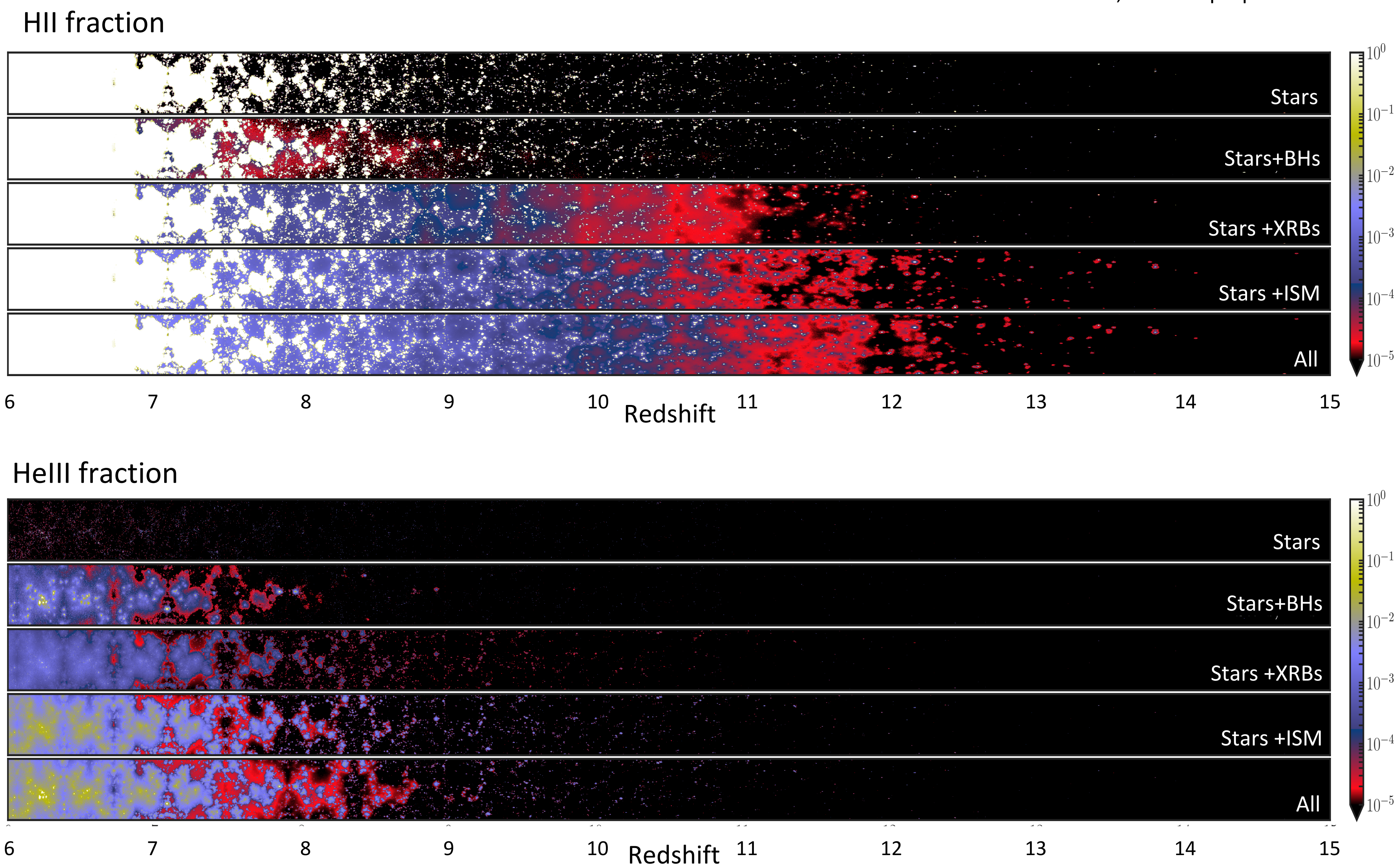
CRASH

BC+ 2001; Maselli, Ferrara, BC 2003; Maselli, BC, Kanekar 2009; Pierleoni, Maselli, BC 2009; Partl+ 2011; Graziani, Maselli, BC 2013; Hariharan+ 2017; Graziani, BC, Glatzle 2018; Glatzle, BC, Graziani 2018

UV, x-rays, Lyα photons in H, He, metals, dust
radiation from recombination, background

Modelling of cosmic reionization

Eide+ 2018; Eide+ in prep



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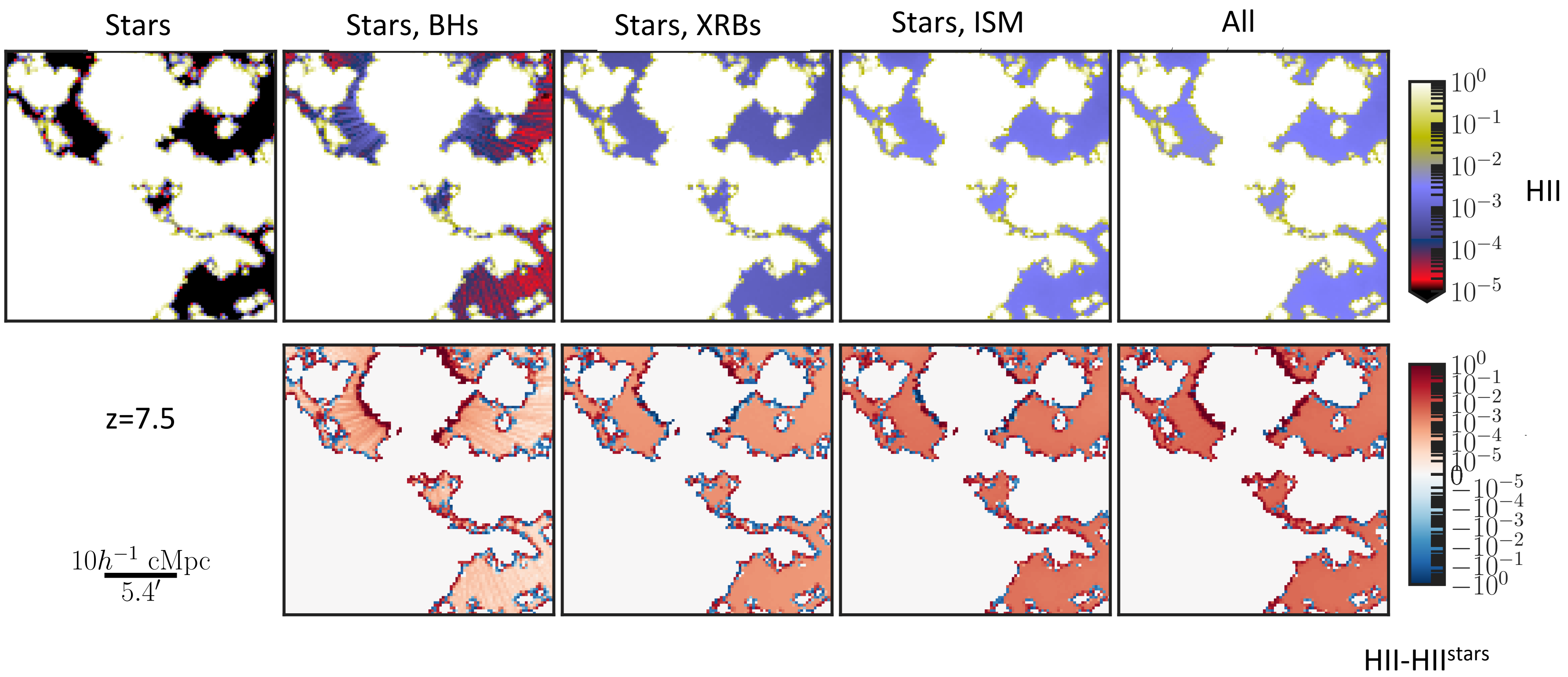

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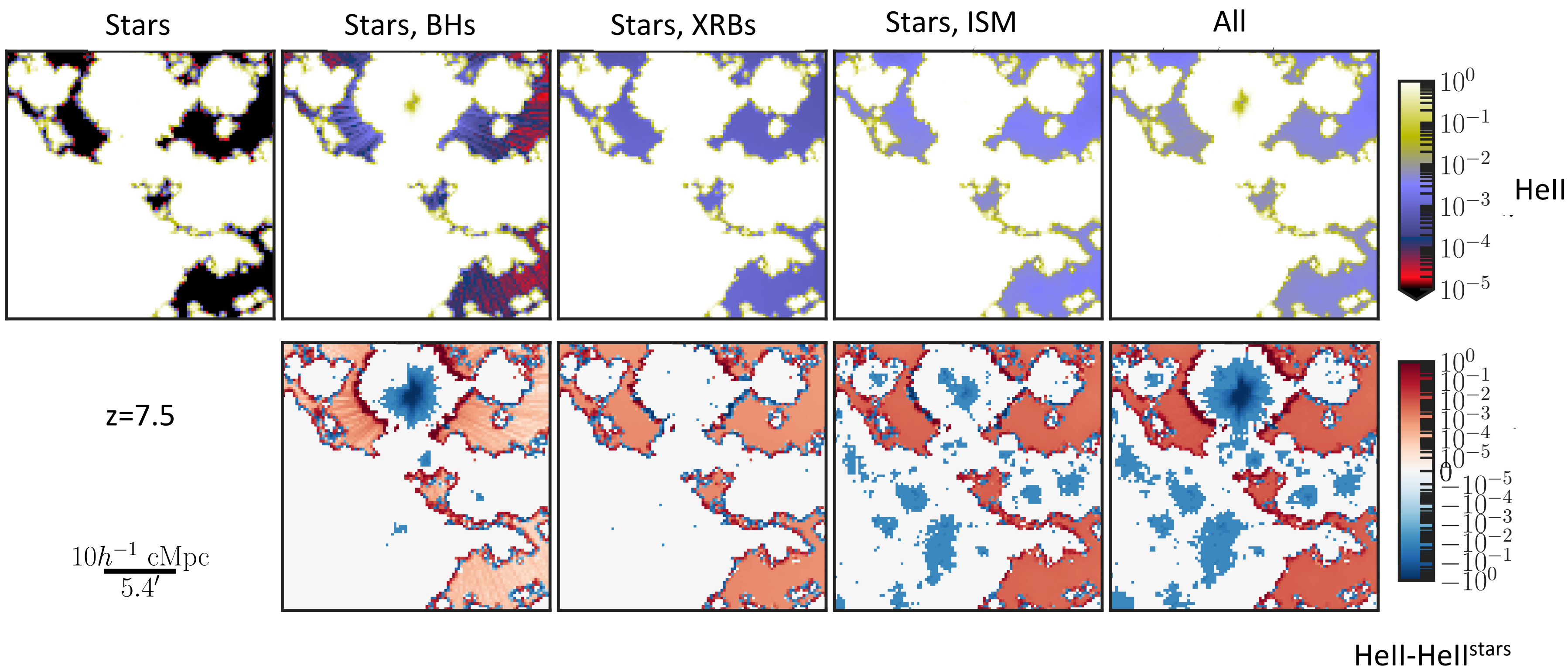

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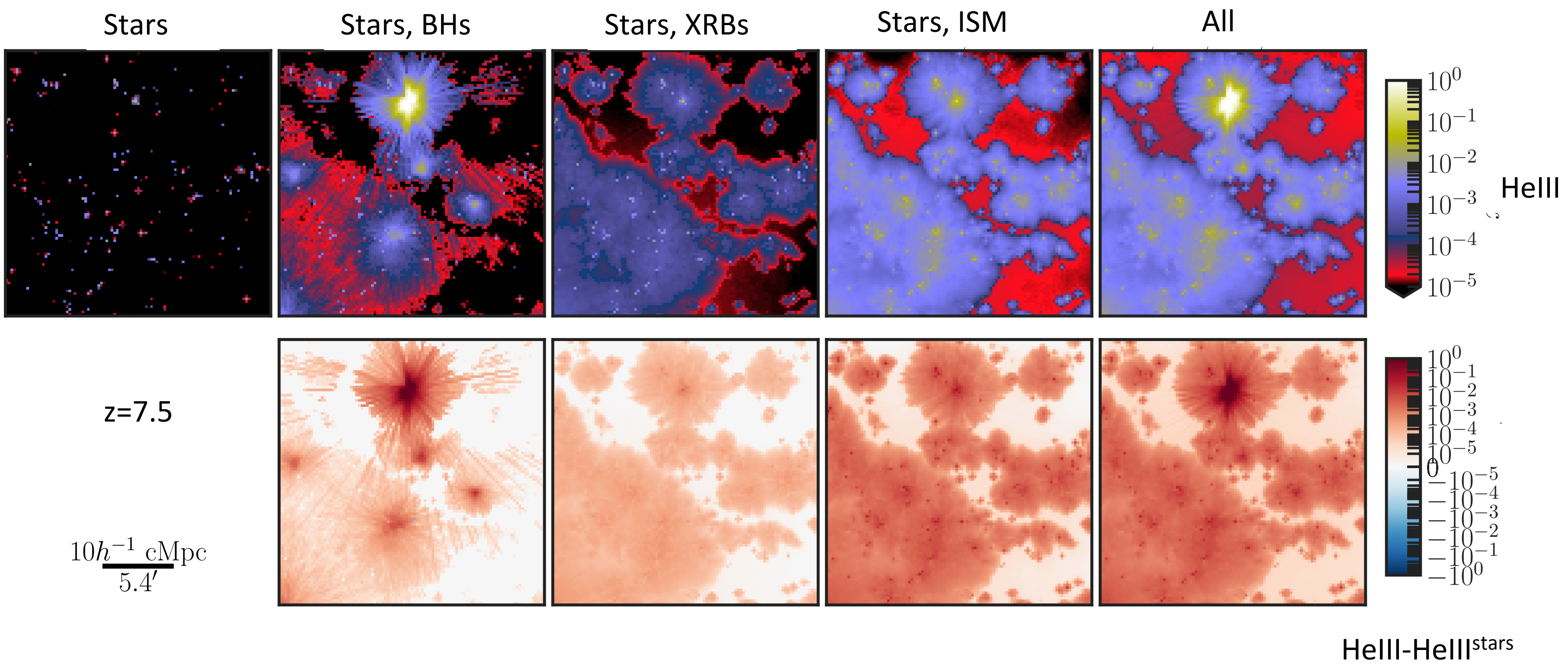

MODELLING OF COSMIC REIONIZATION

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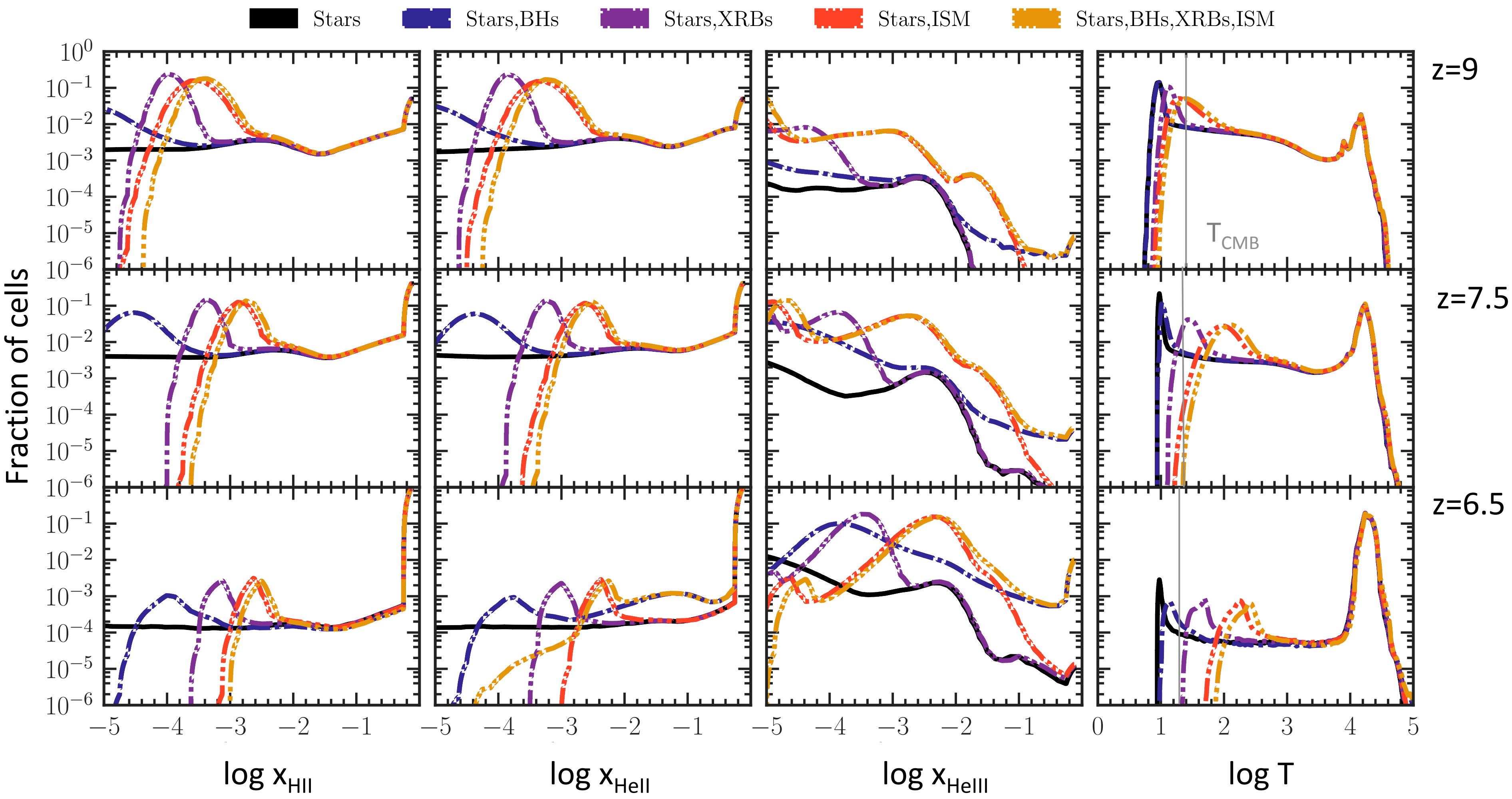
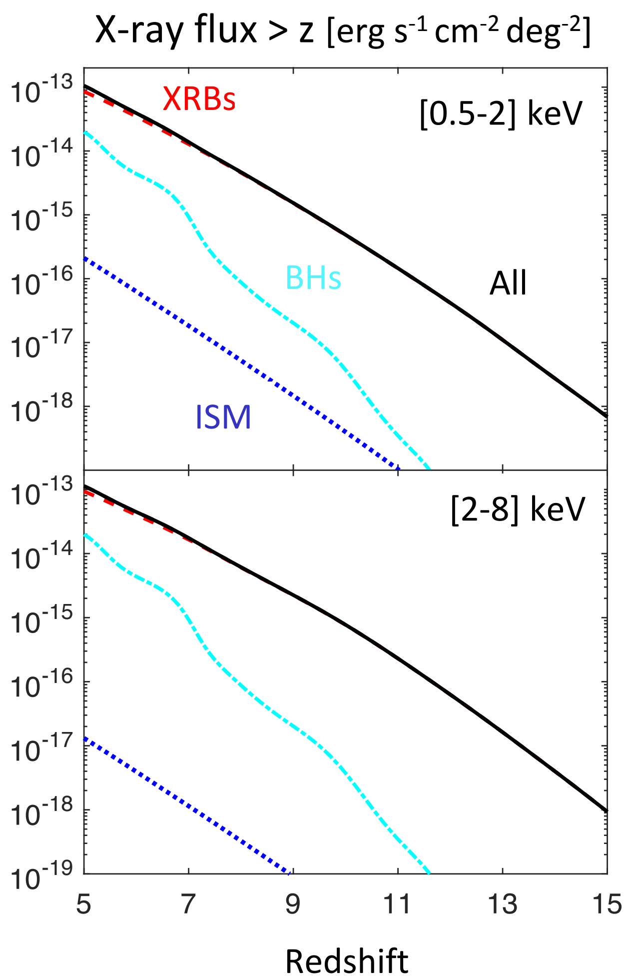


X-RAY BACKGROUND

Ma+ in prep



$F(z>5)=1.02 \times 10^{-13}$ erg s^{-1} cm^{-2} deg^{-2}

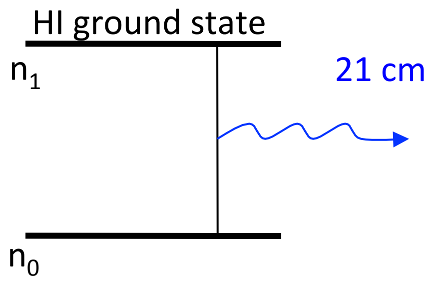
$F_{chandra}(z>5)=(1.98\pm0.35) \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2}

$F(z>5)=1.09 \times 10^{-13}$ erg s^{-1} cm^{-2} deg^{-2}

$F_{chandra}(z>5)=(3.05\pm2.25) \times 10^{-12}$ erg s^{-1} cm^{-2} deg^{-2}

High energy sources contribution could be higher

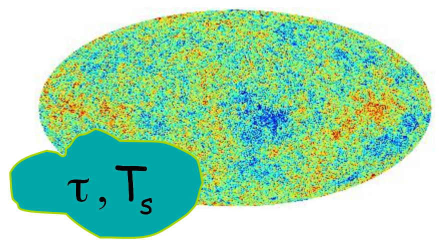
21cm line observations: basics



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

Differential brightness temperature:

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



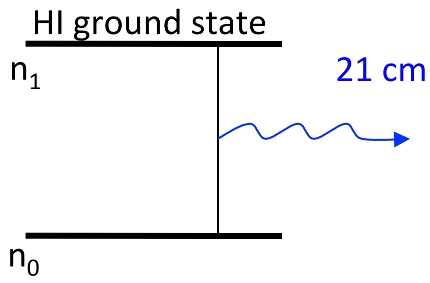
$T_S = T_{CMB} \Rightarrow$ no signal

$T_S < T_{CMB} \Rightarrow$ absorption

$T_S > T_{CMB} \Rightarrow$ emission

The value of T_s is critical

21cm line observations: basics



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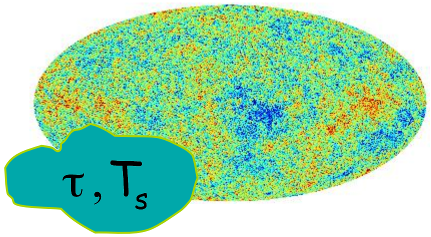


$$T_S = T_{CMB} \Rightarrow \text{no signal}$$

$$T_S < T_{CMB} \Rightarrow \text{absorption}$$

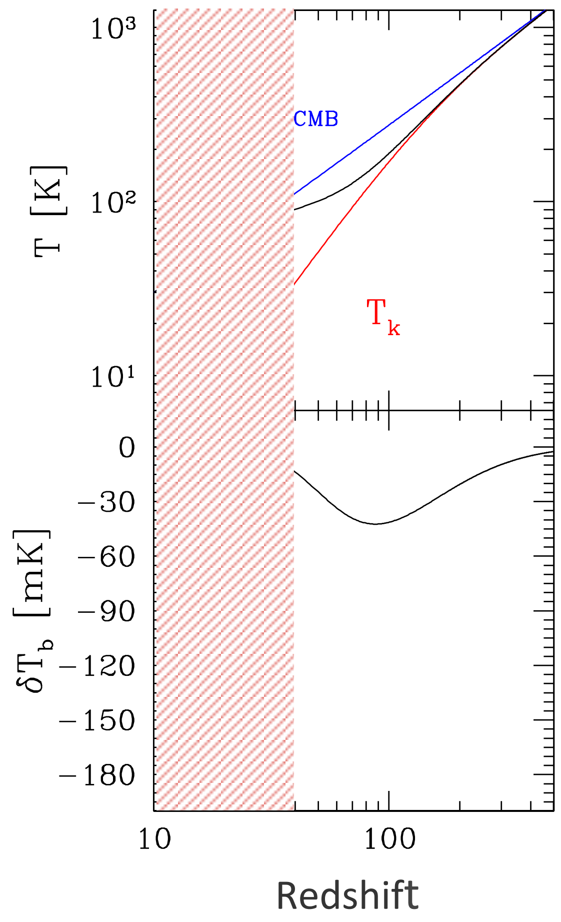
$$T_S > T_{CMB} \Rightarrow \text{emission}$$

kinetic temperature of the gas

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

Lyalpha scattering and heating

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

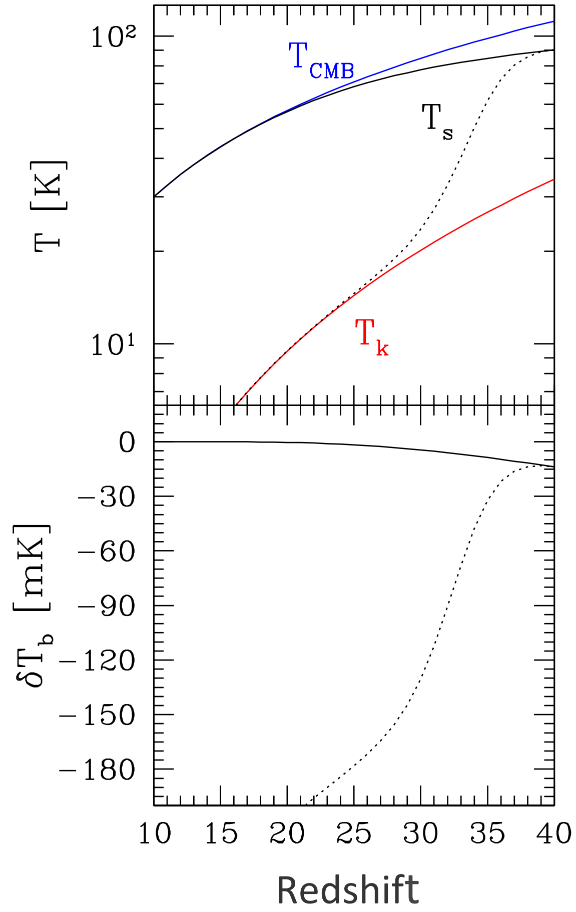


✧ In the absence of decoupling mechanisms, other than collisions, 21cm line will not be visible at z<20

See also e.g. Madau+; Chen & Miralda-Escude ‘; Pritchard & Loeb; Chuzoy & Shapiro; Furlanetto+; Mesinger+; Warszawski+

LYALPHA SCATTERING AND HEATING

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



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

Lyalpha scattering and heating

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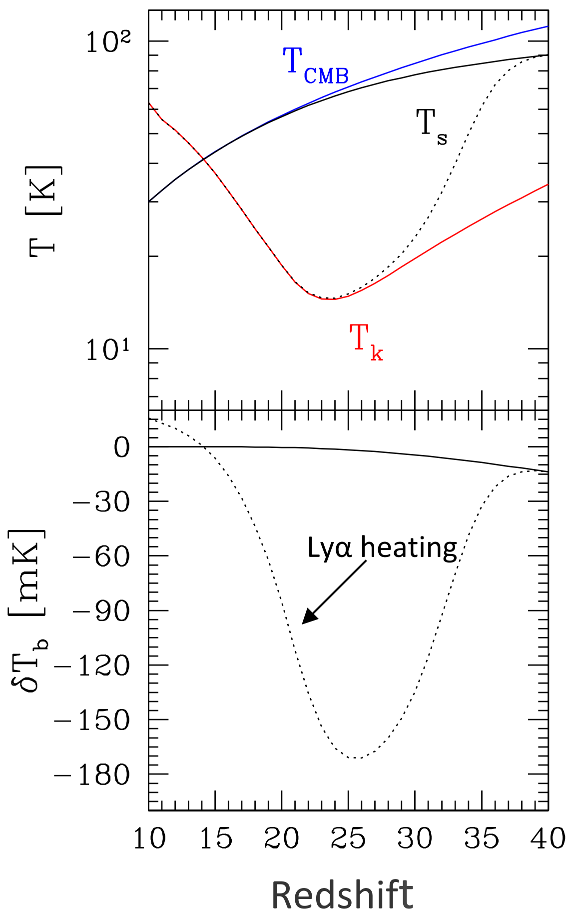


- ✧ In the absence of decoupling mechanisms, other than collisions, 21cm line will not be visible at z<20
- ✧ Lyα photon scattering decouples T_S from T_{CMB} → 21cm line can be observed
- ✧ Lyα photon scattering heats the gas → 21cm line can be observed in emission

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

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

21cm line observations: what?

✧ *Imaging:* 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

✧ *Cross-correlation:* confirm origin of signal; reduce systematic effects

e.g. Salvaterra+ 2005; Lidz+ 2009; Jelic+ 2010; Wierma+ 2013
Fernandez+2013; Vrbanec+ 2016; Hutter+ 2016; Sobacchi+ 2016; Ma+ 2017

✧ *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

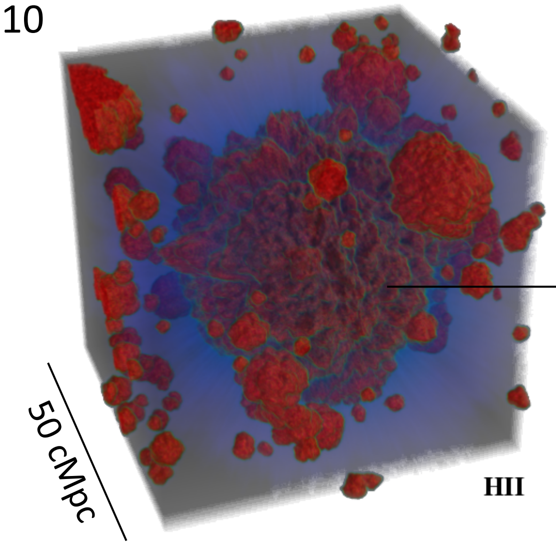
LOFAR/SKA's potential

- ✧ Simulations
- ✧ Add foregrounds, instrumental response, noise → mock data
- ✧ Extract signal from mock data
- ✧ Compare to input from simulations

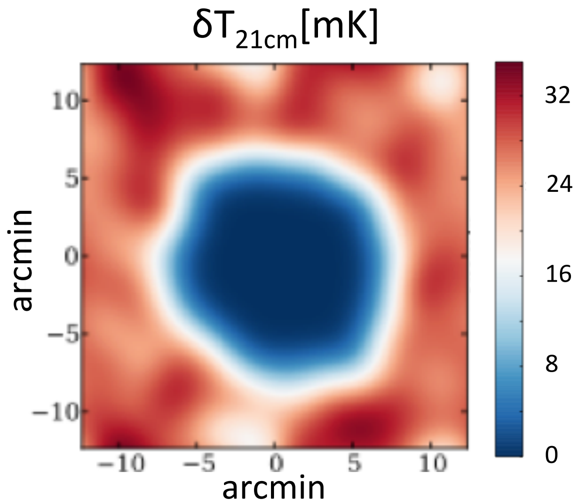
Imaging with LOFAR: QSOs' ionized regions

Zaroubi+ 2012; Kakiichi+ 2016; Kakiichi+ in prep

z=10



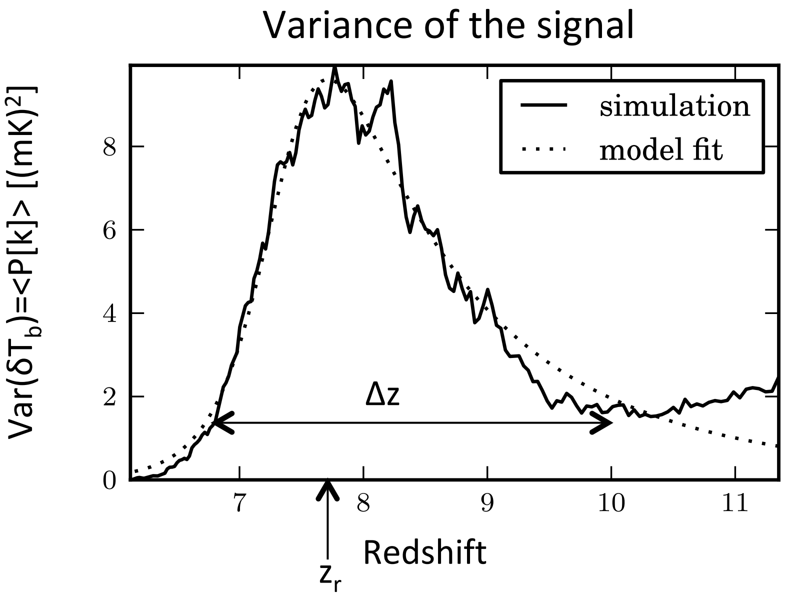
2000h



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

Statistical measures with LOFAR

Patil+ 2014



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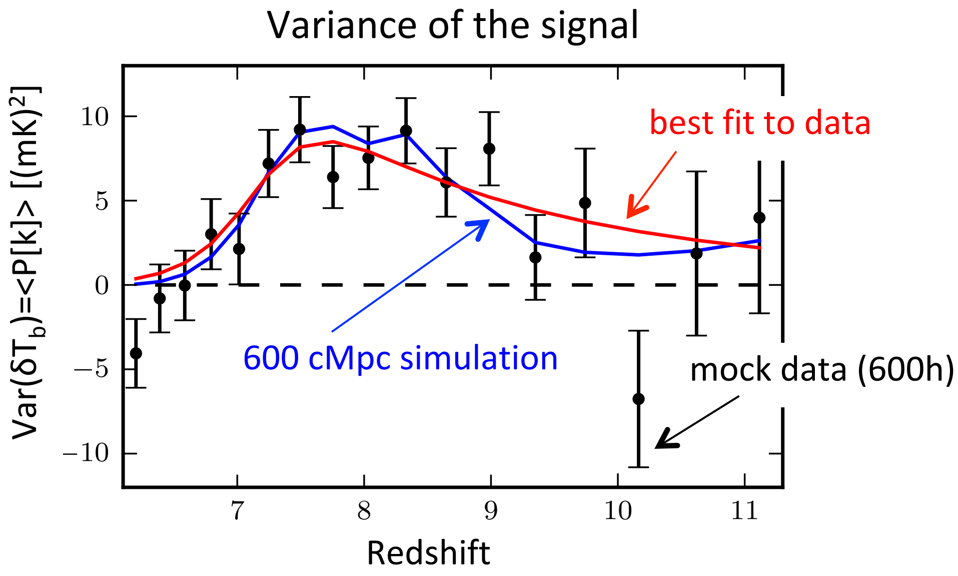
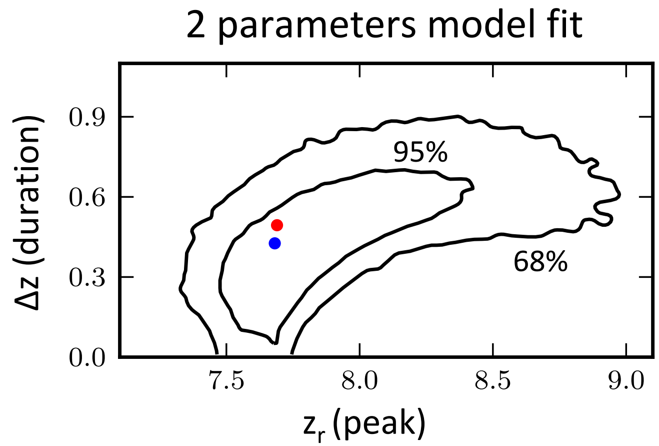




z_r=7.68, Δz=0.43

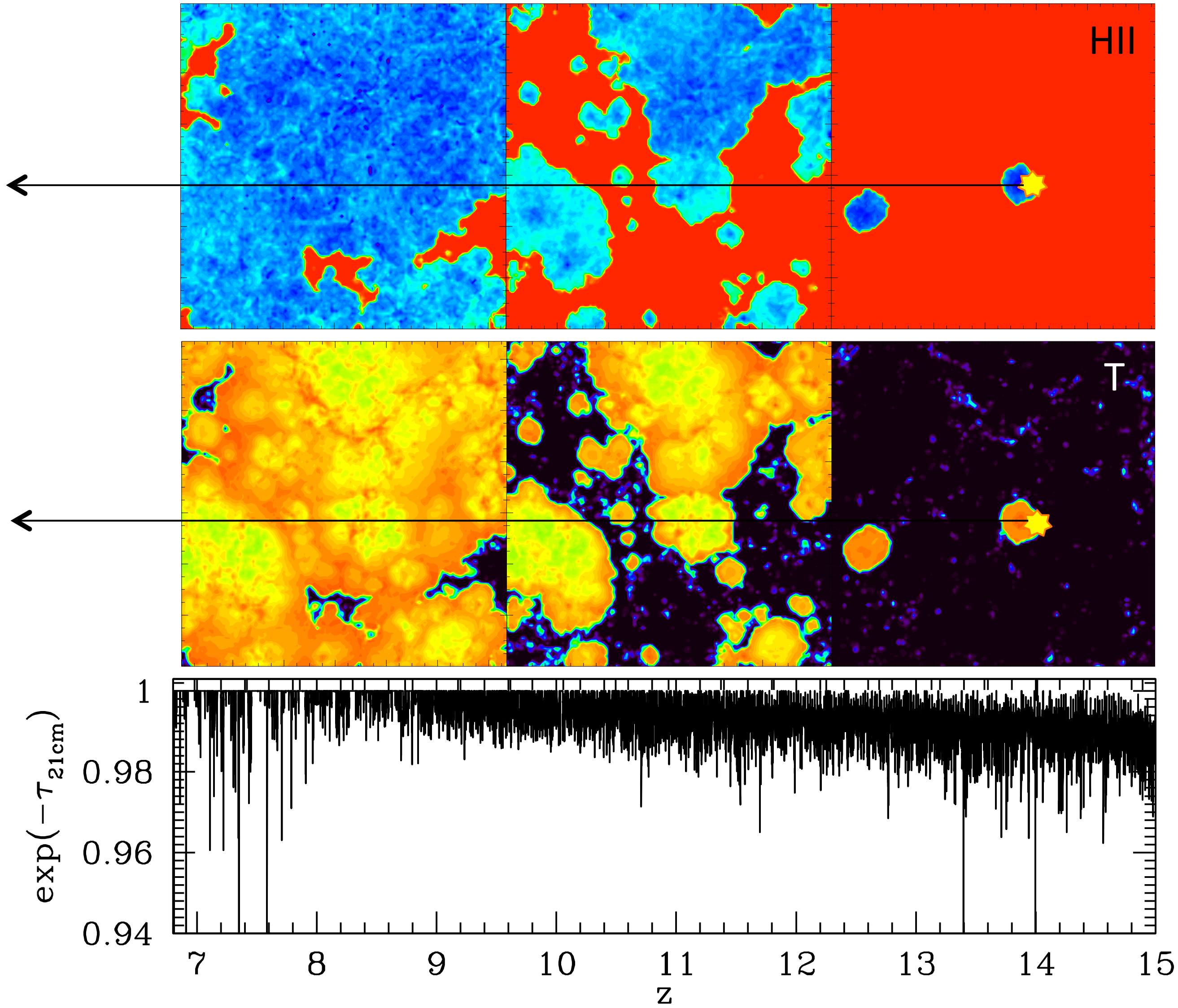
$z_r=7.72^{+0.37}_{-0.18}$, $\Delta z=0.53^{+0.12}_{-0.23}$

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

THE 21CM FOREST

BC+ 2013, 2015

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

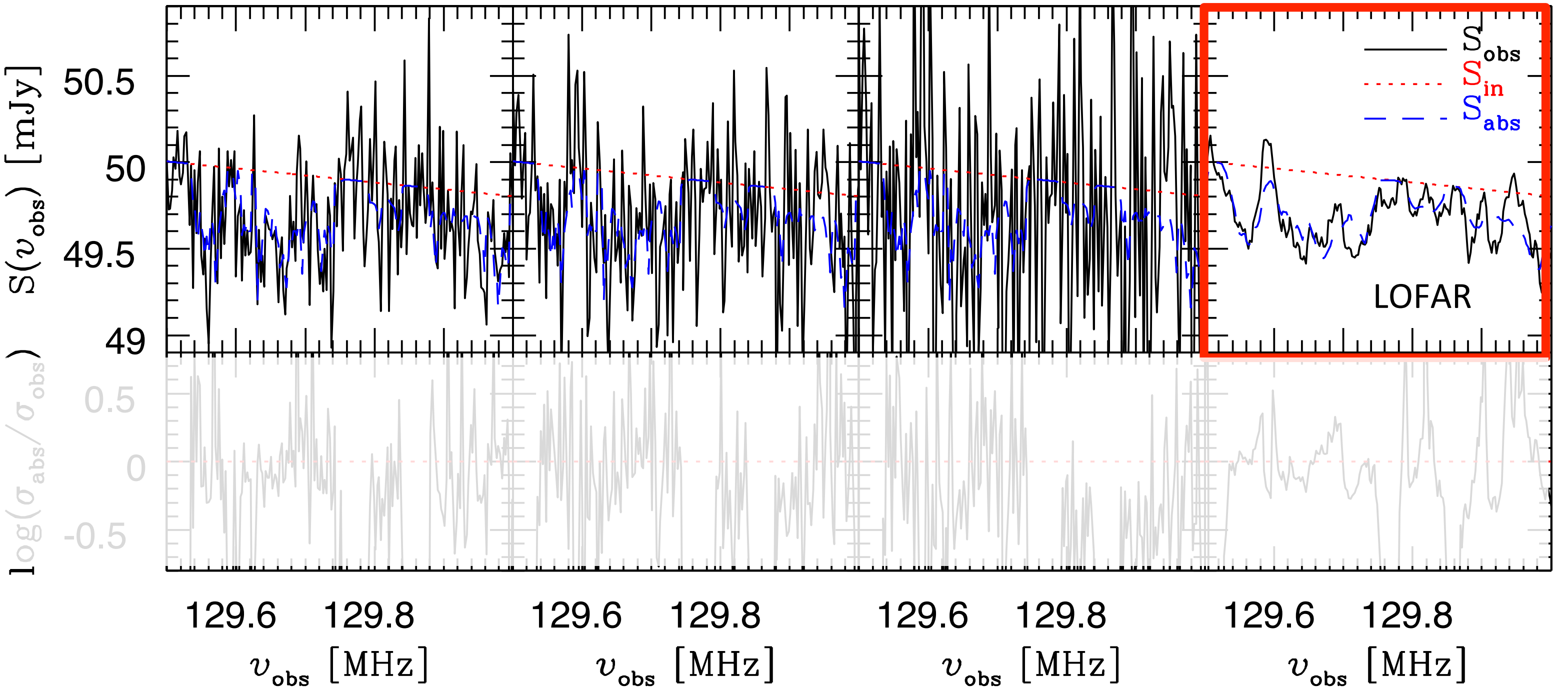


THE 21CM FOREST WITH QSOs

BC+ 2013, 2015

z=10, S=50 mJy, α=1.05

BW=10 kHz, t=1000 h



QSO spectrum

QSO spectrum
+
IGM absorption

Observed
spectrum

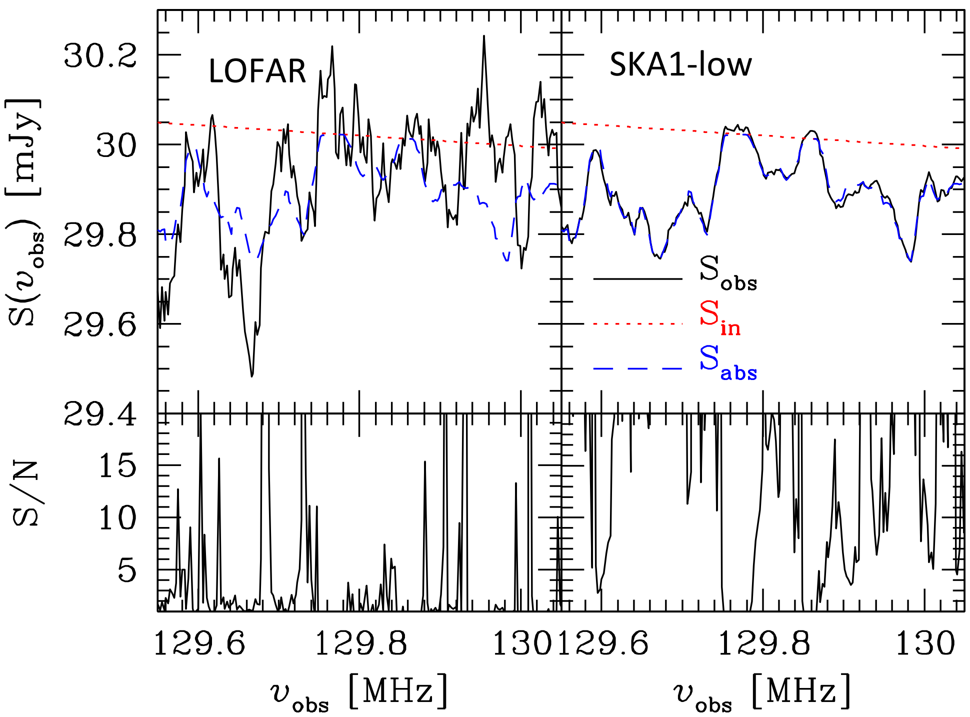
The 21cm forest with GRBs

BC+ 2013, 2015

z=10, S=30 mJy, α=0.6

BW=10 kHz, t=1000 h

GRBIII



GRB spectrum

GRB spectrum + IGM absorption

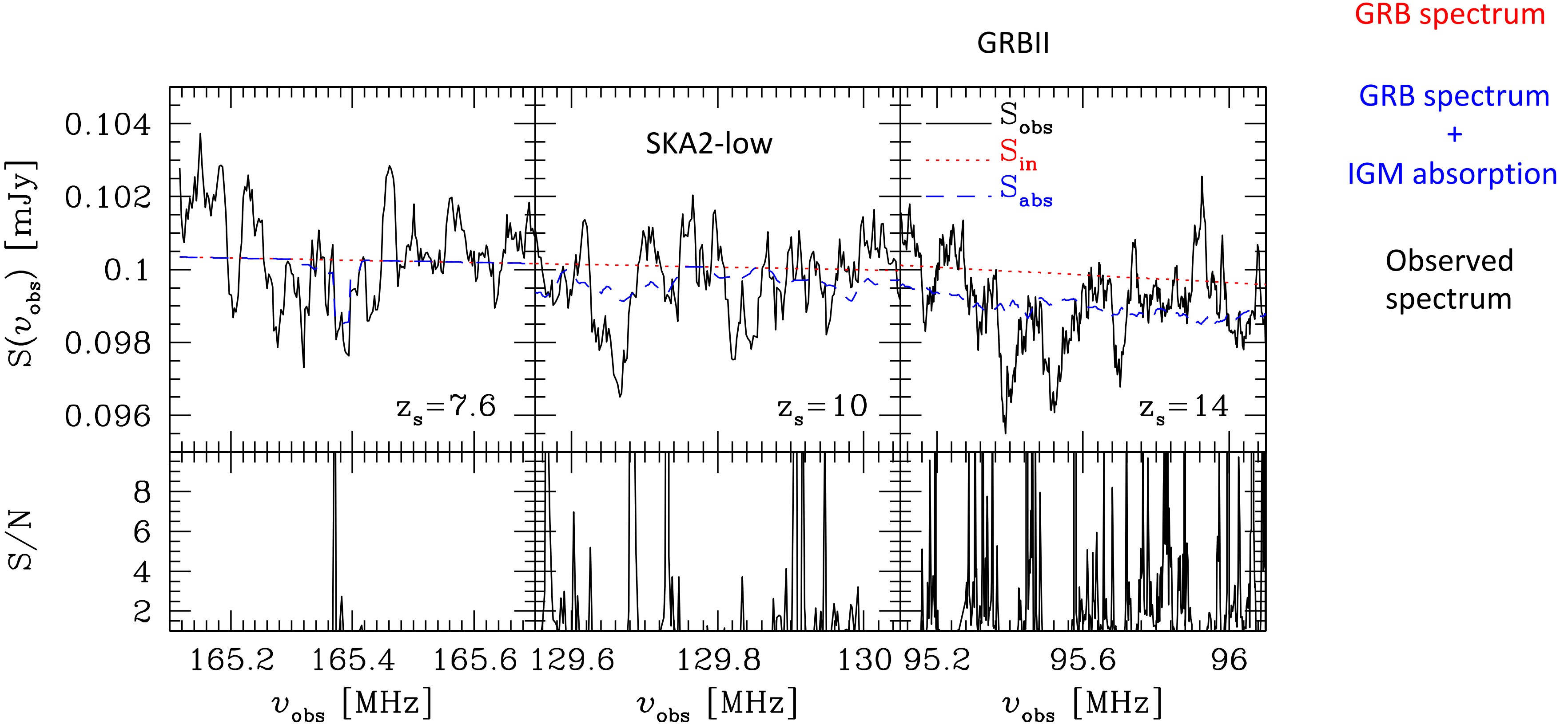
Observed spectrum

THE 21CM FOREST WITH GRBs

BC+ 2013, 2015

S=0.1 mJy, α=0.6

n=0.01, t=1000 h



THE 21CM FOREST WITH GRBS

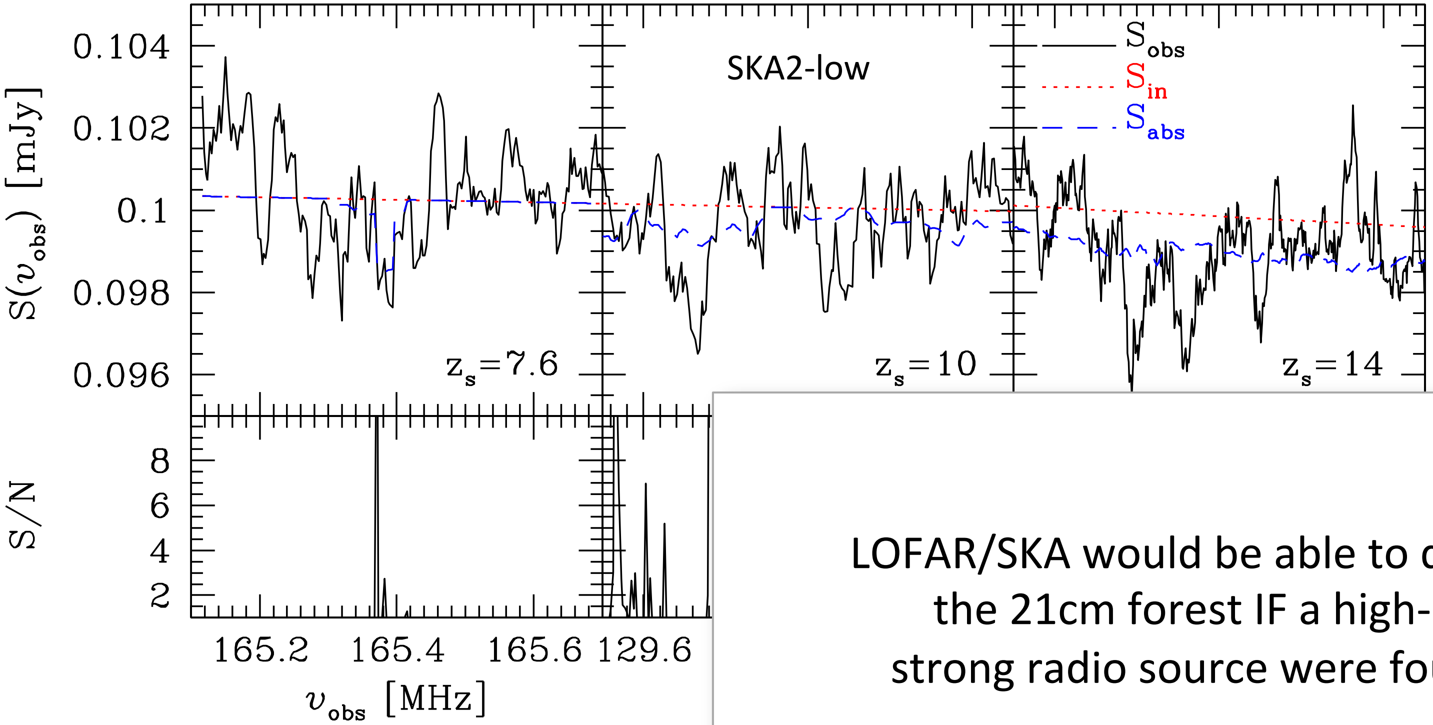
BC+ 2013, 2015

S=0.1 mJy, α=0.6

n=0.01, t=1000 h

GRB spectrum

GRBII



GRB spectrum
+
IGM absorption

Observed spectrum

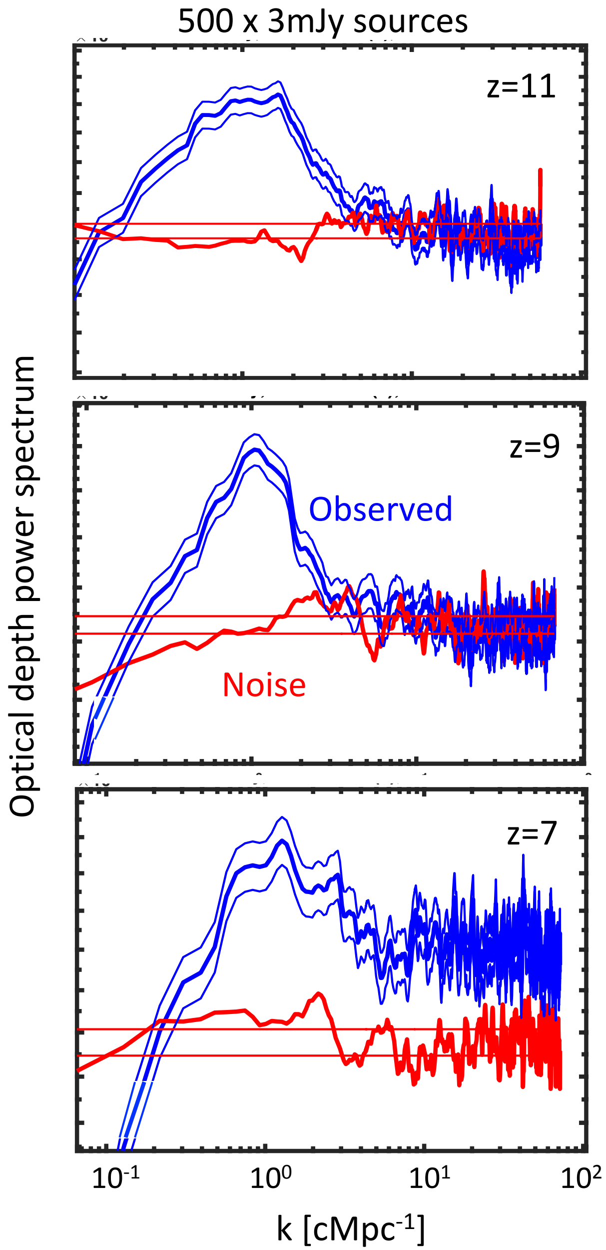
LOFAR/SKA would be able to detect the 21cm forest IF a high-z, strong radio source were found

THE 21CM FOREST: STACKING

Koopmans+ in prep.

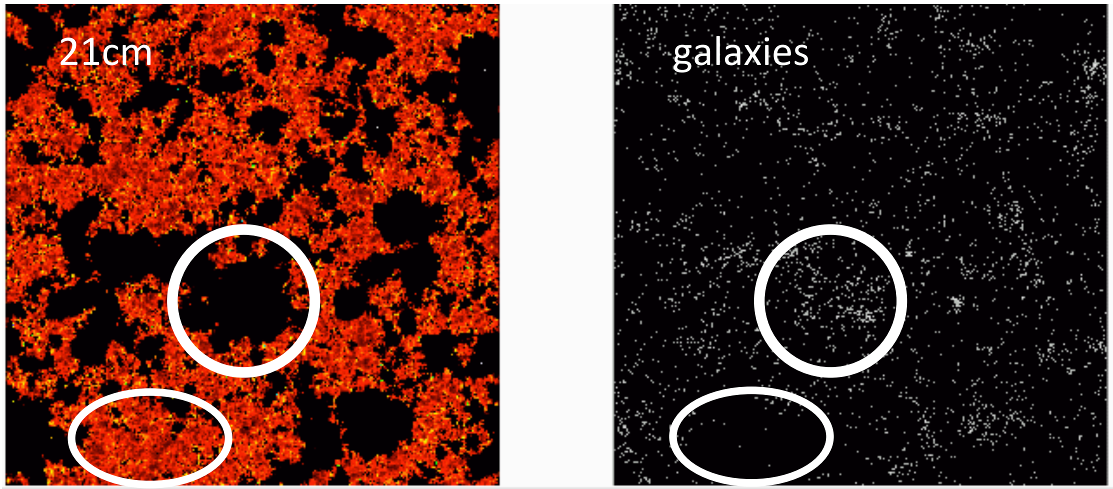
t=1000 h

SKA-1 could probe in absorption scales ~ kHz



Cross-correlation 21cm–LAE surveys

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

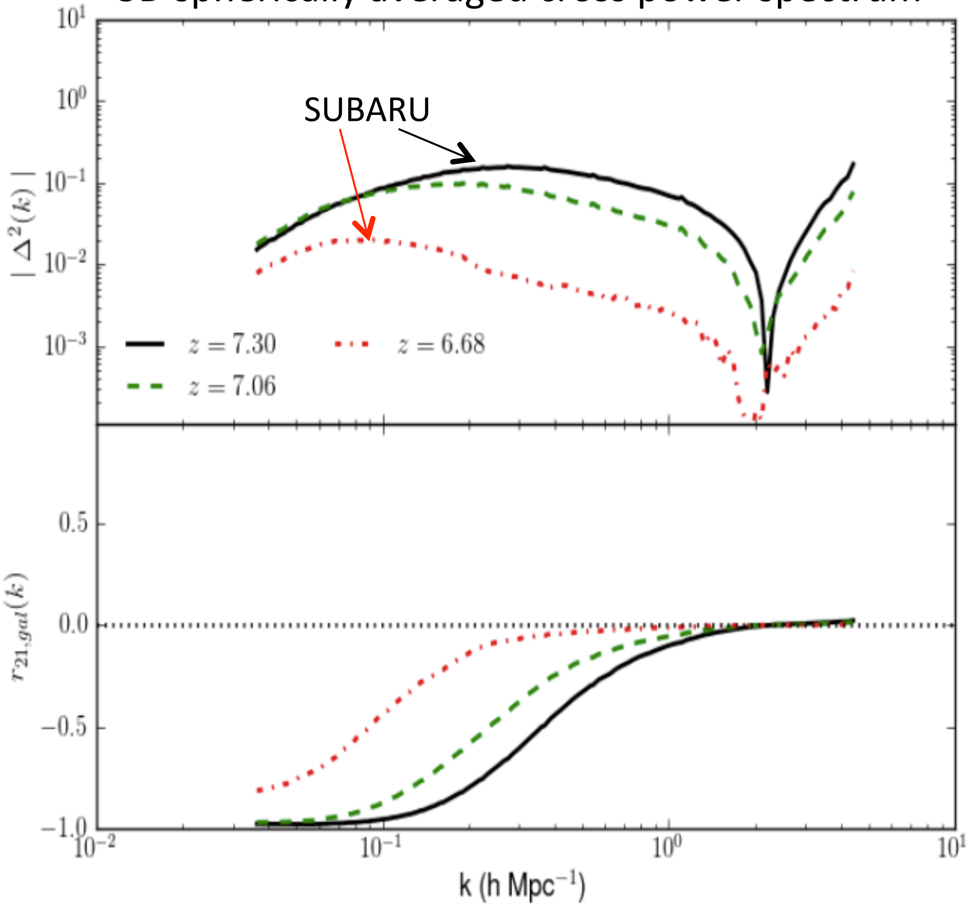


Lidz+ 2009

Cross-correlation 21cm–LAE surveys

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

3D spherically averaged cross power spectrum



600^3 $cMpc^3$ simulations

Iliev+ 2012; Jensen+ 2013

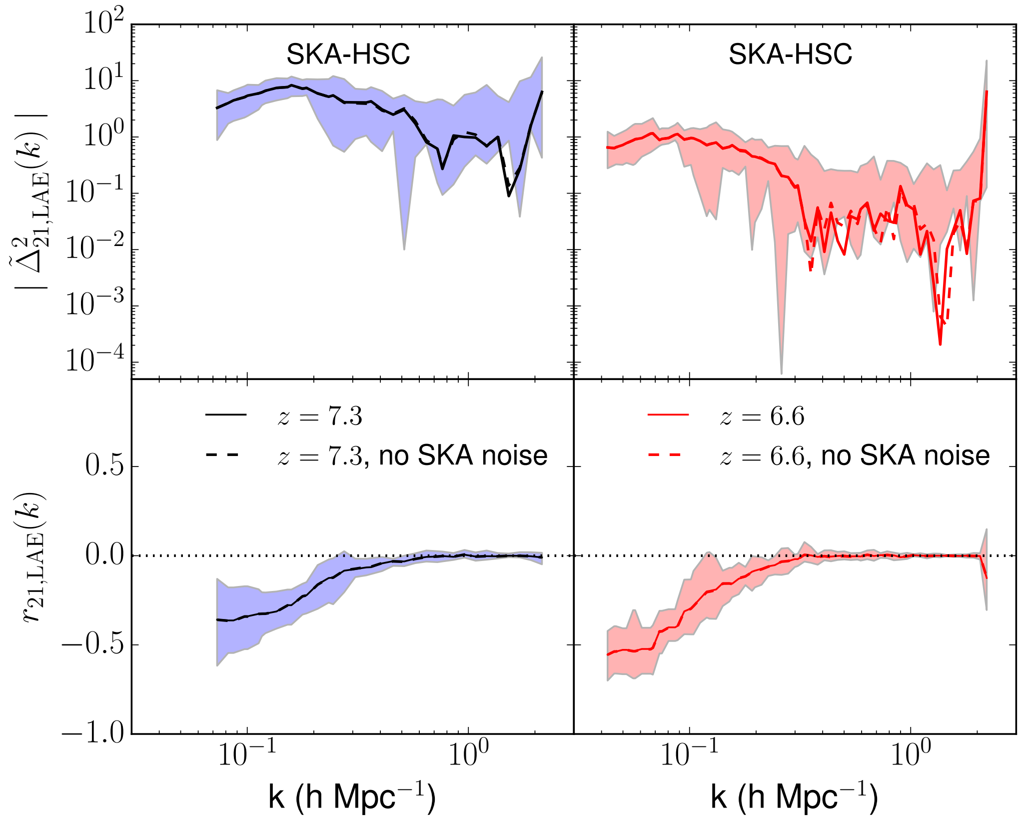
$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

- ✧ 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

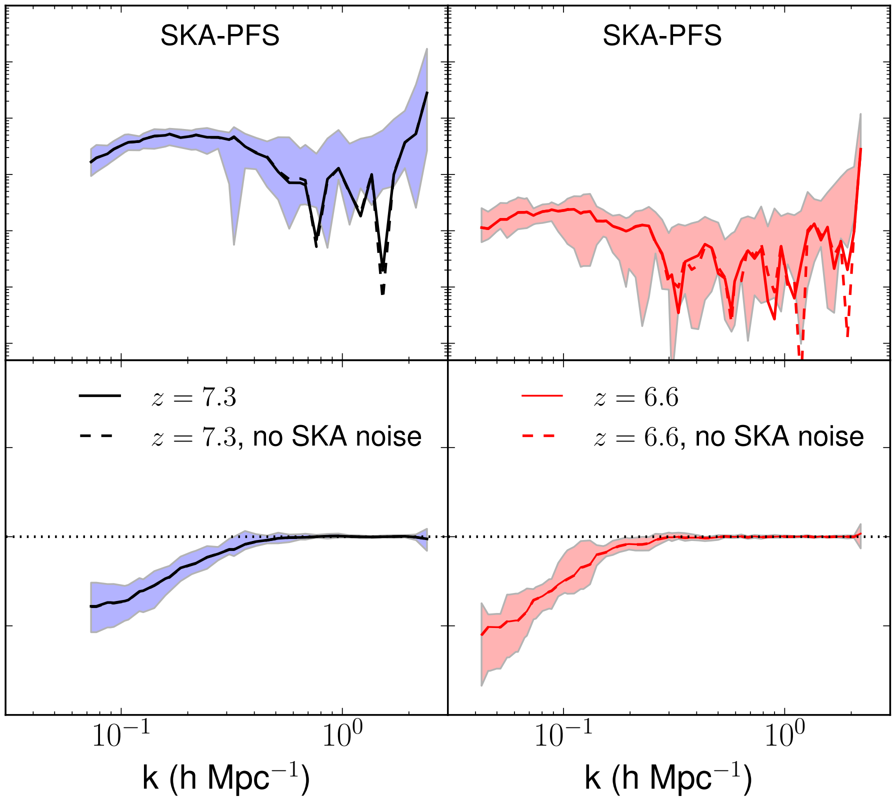
$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

- ✧ 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

3D spherically 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

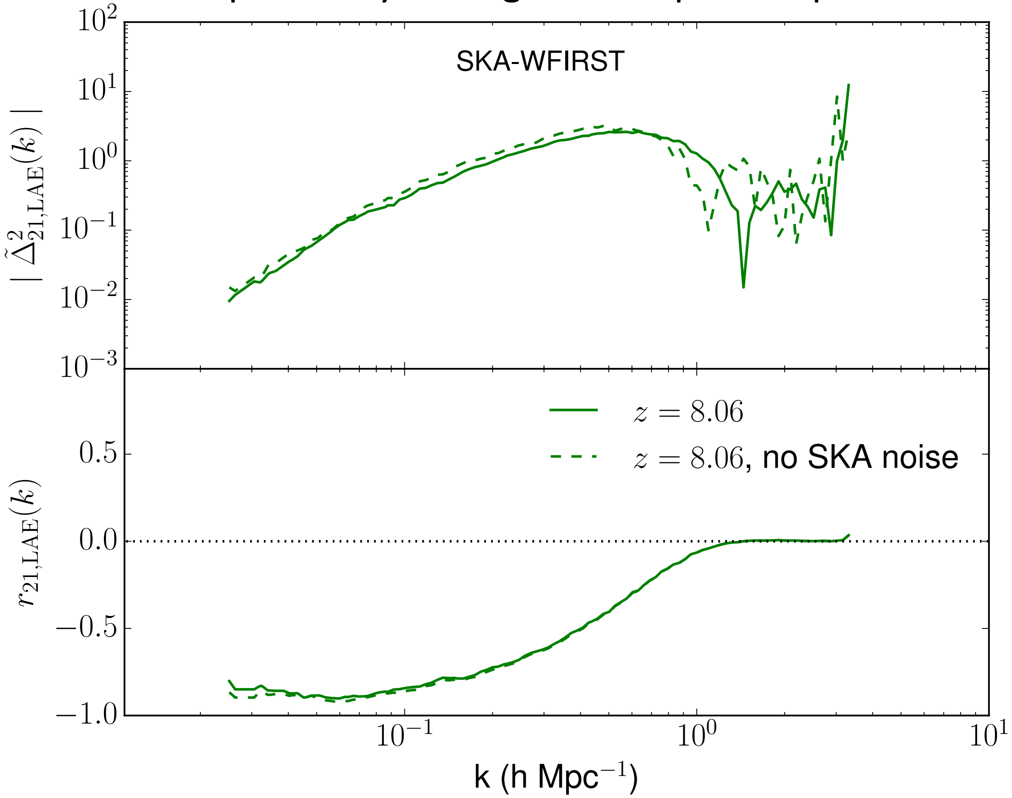
$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

- ✧ 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

3D spherically averaged cross power spectrum



$\Delta z=1$

N(7.5<z<8.5)=900 deg^{-2}

FoV~16 deg^2

t_{obs}=600h

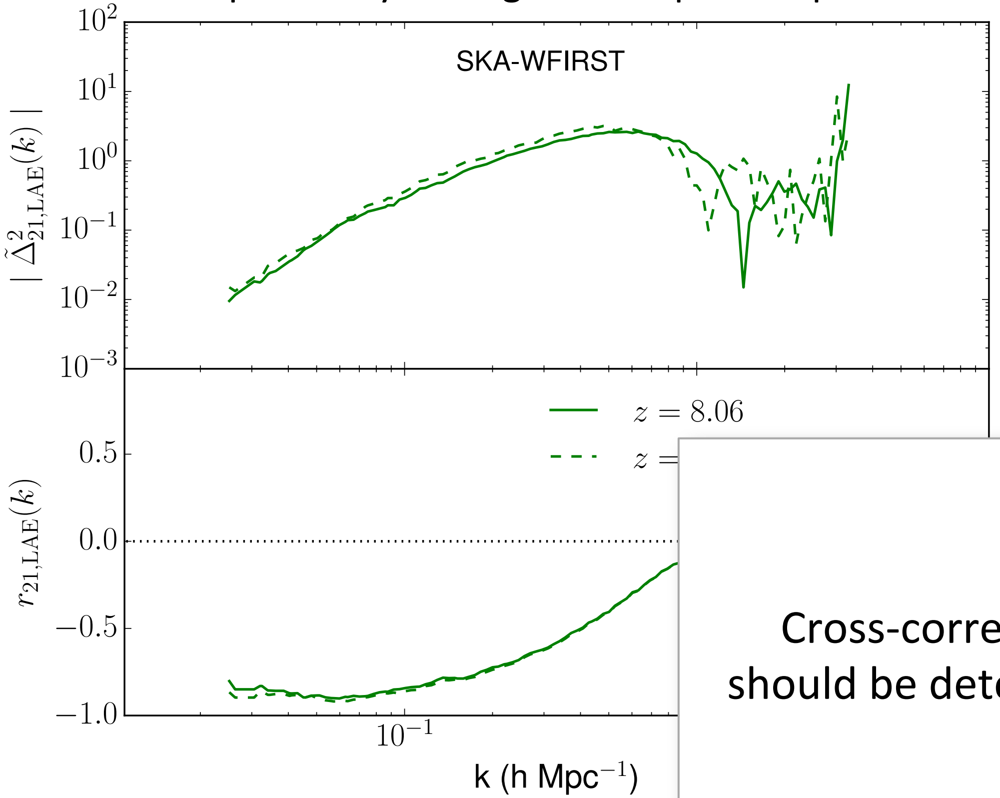
$$r_{21cm,gal}(k) = \frac{P_{21cm,gal}(k)}{\left[P_{21cm}(k)P_{gal}(k)\right]^{1/2}}$$

- ✧ 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

3D spherically averaged cross power spectrum



$\Delta z=1$

$N(7.5<z<8.5)=900\ \mathrm{deg}^{-2}$

FoV~16 deg^2

t_{obs}=600h

Cross-correlation SKA-SUBARU/WFIRST should be detectable on scales > 30 h^{-1} cMpc

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

Conclusions

- ✧ Exciting times for reionization studies!