# Detectability of 21cm-signal during the Epoch of Reionization with 21cm-LAE cross-correlation

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and others

based on
KH et al., 2016, arXiv: 1603.01961
Kubota, KH, et al., 2018, arXiv: 1708.06291
Yoshiura, KH, et al., 2018 arXiv: 1709.04168
Inoue, KH et al. 2018, arXiv: 1801.00067

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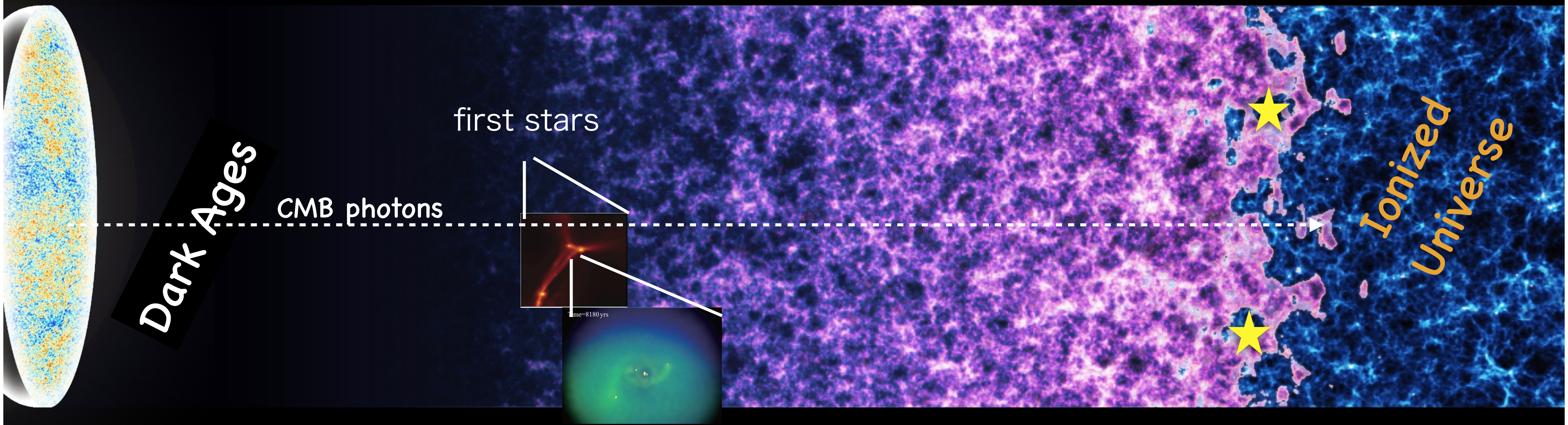
Recombination
z~1100

First Star
Formation
z~10-30

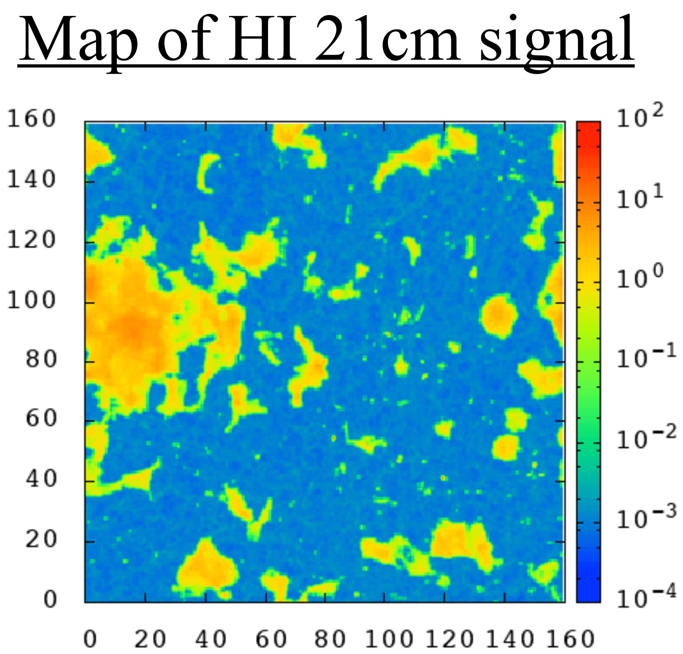
(First) galaxies
& AGN
formation?
z<10

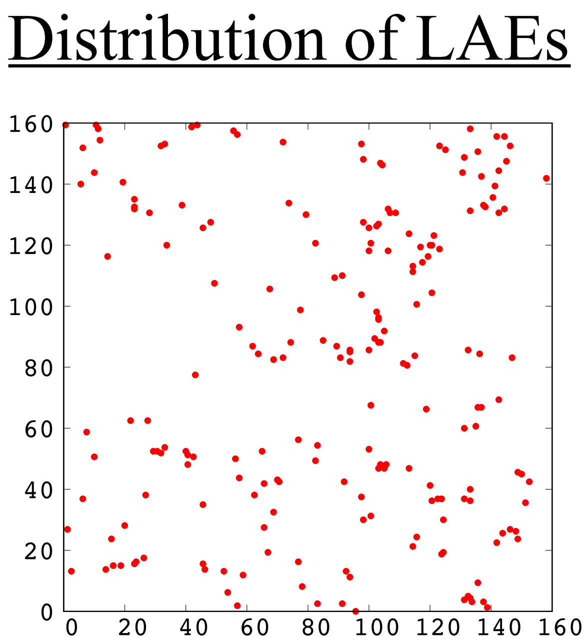
IGM is
almost ionized.
z~f6




- HI 21cm line : tracer of neutral hydrogen during the Epoch of Reionization (EoR)
  => Provides us with fruitful information on the reionization process
- Difficulty: Intense foreground emission ~K >> EoR signal ~mK

# 21cm-LAE cross correlation




## ◎Why cross correlation?

21cm observation $\cdots\ \delta_{21} = \delta_{21\text{sig}} + \delta_{21\text{noise}} + \delta_{21\text{FG}}$

galaxy survey $\cdots\ \delta_{\text{gal}} = \delta_{\text{gal sig}} + \delta_{\text{gal noise}}$

$$\langle \delta_{21}\delta_{\text{gal}} \rangle = \langle \delta_{21\text{sig}}\delta_{\text{gal sig}} \rangle + \cdots + \underbrace{\langle \delta_{21\text{FG}}\delta_{\text{gal sig}} \rangle}_{\sim 0} + \underbrace{\langle \delta_{21\text{FG}}\delta_{\text{gal noise}} \rangle}_{\sim 0}$$

- Estimate the detectability of 21cm - LAE cross power spectrum(CPS).
- Modeling reionization process and LAEs.

# Reionization Simulation

Two-Step Approach:

1) High resolution cosmological Radiation Hydrodynamics (RHD) simulation (radiative transfer is consistently coupled with hydrodynamics) in a $(20\mathrm{Mpc})^3$ box. (e.g., KH & Semelin, 2013, KH et al. 2016)

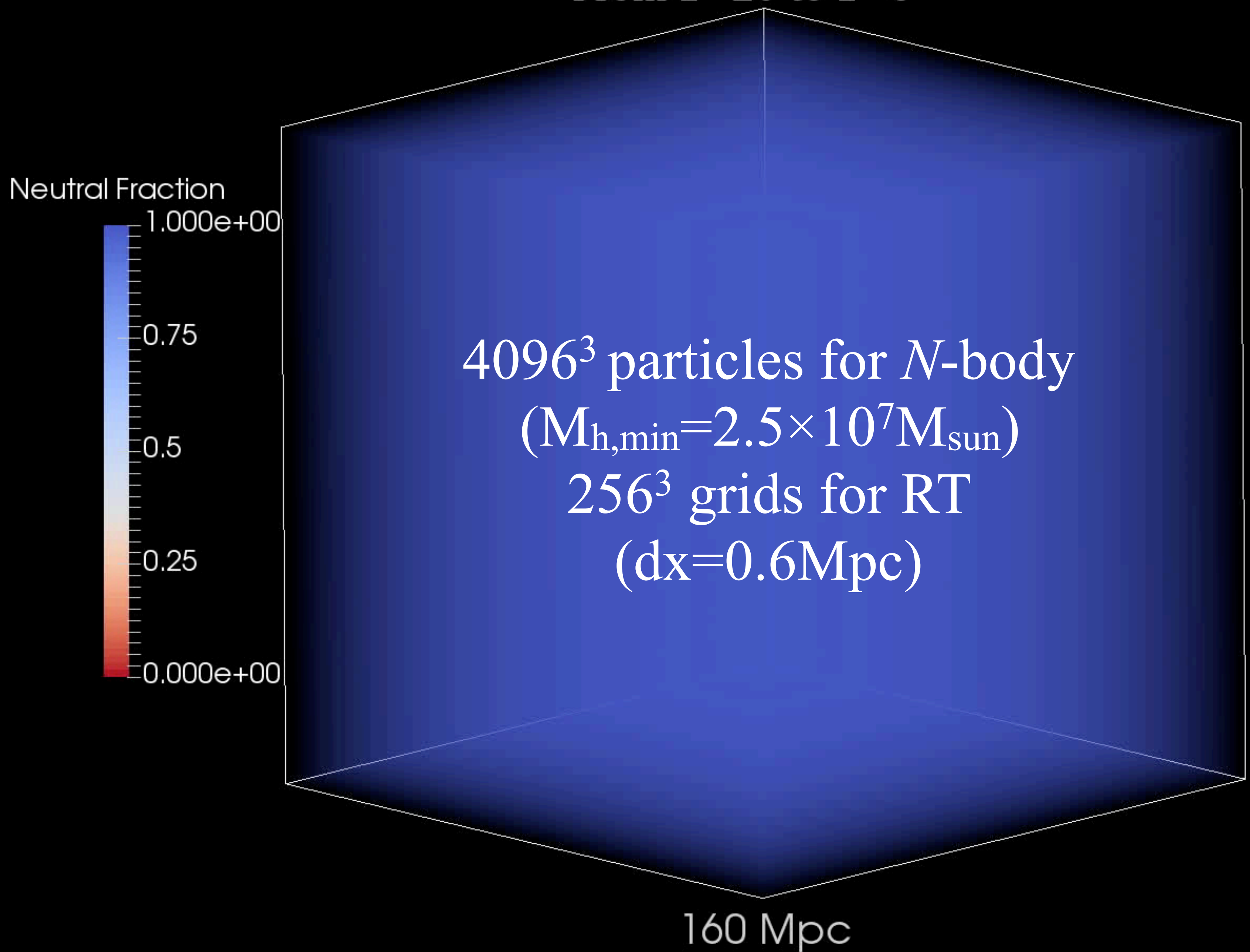
- Properties of galaxies (e.g., intrinsic ionizing photon emissivity, Lyα Luminosity, escape fraction of ionizing photons as a function of halo mass).
- Small-scale clumping factor in the IGM

2) Large-scale Radiative Transfer simulation (160Mpc) with the models of galaxies and clumping factor. (e.g., Kubota et al. 2018, Yoshimura et al. 2018)

- Representative reionization history
- Spatial Distributions of HI.

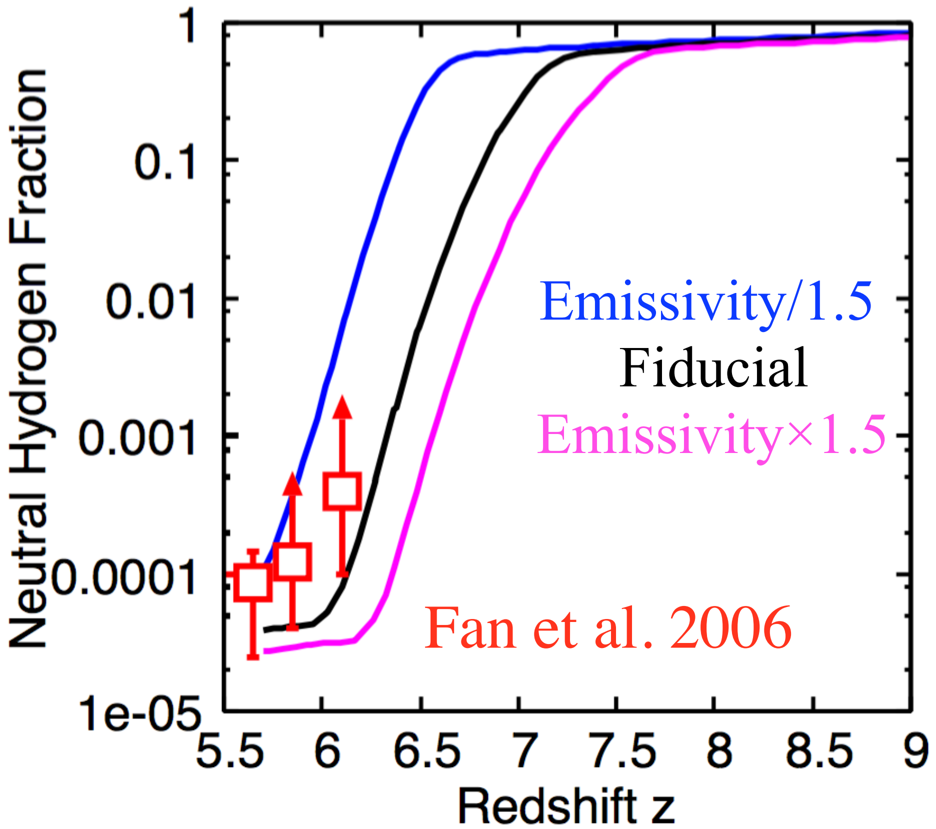
# Cosmic Reionization

From z=20 to z=6

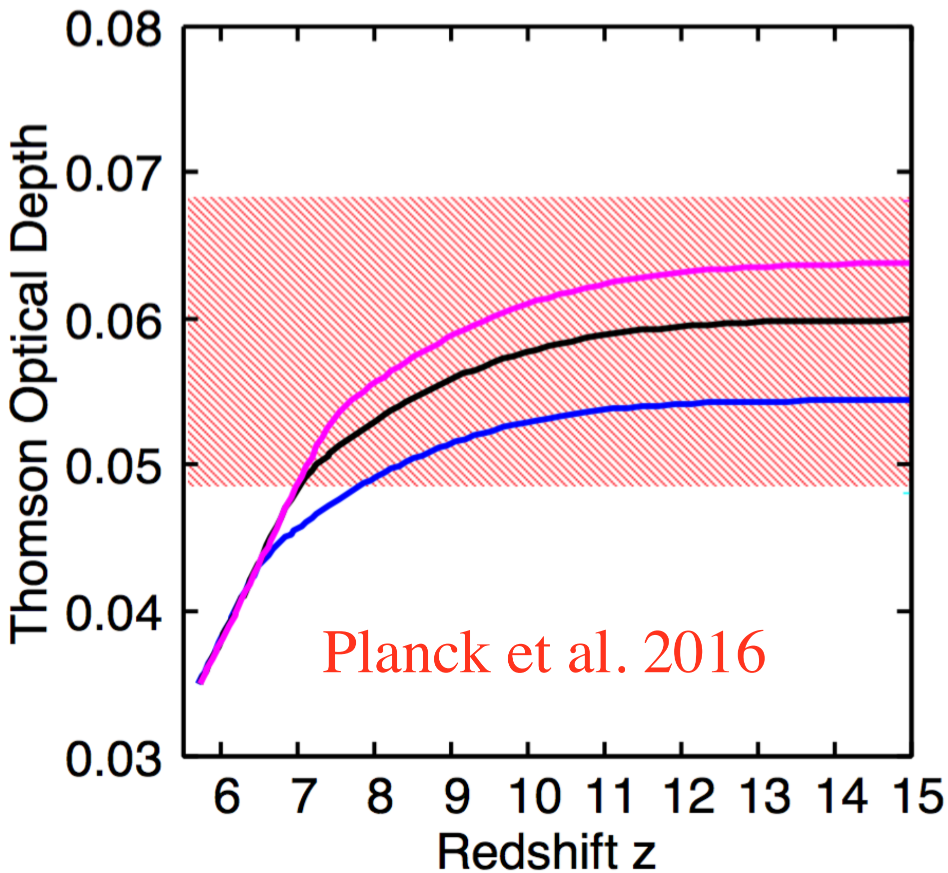


# Comparison : Simulations vs Observations

Constraint by QSO spectra



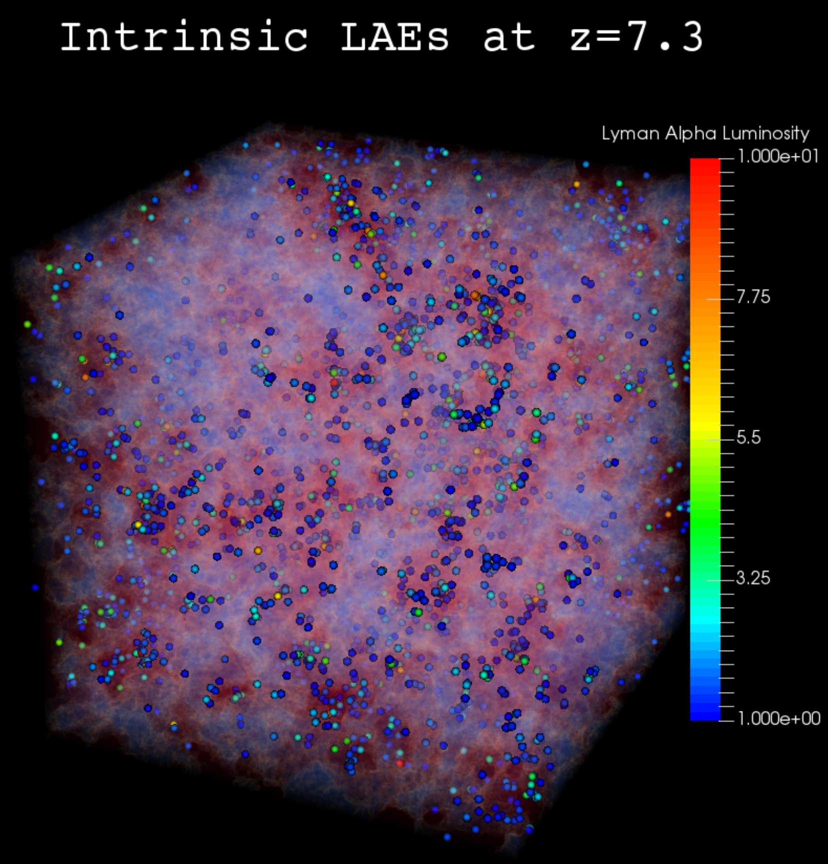

Thomson Opt. Depth




- Our simulation well reproduces the observations.
- ~factor 2 uncertainty in the ionizing photon emissivity is allowed to reproduce the observations.

What about LAEs?

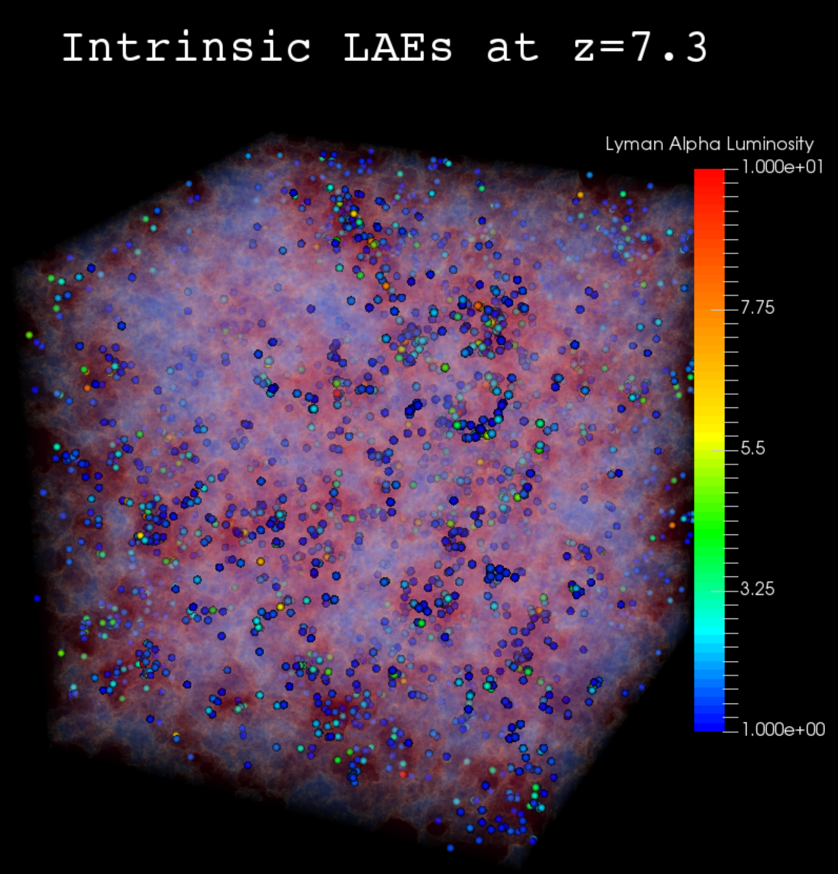
# Distribution of Observable Lyα Emitting Galaxies

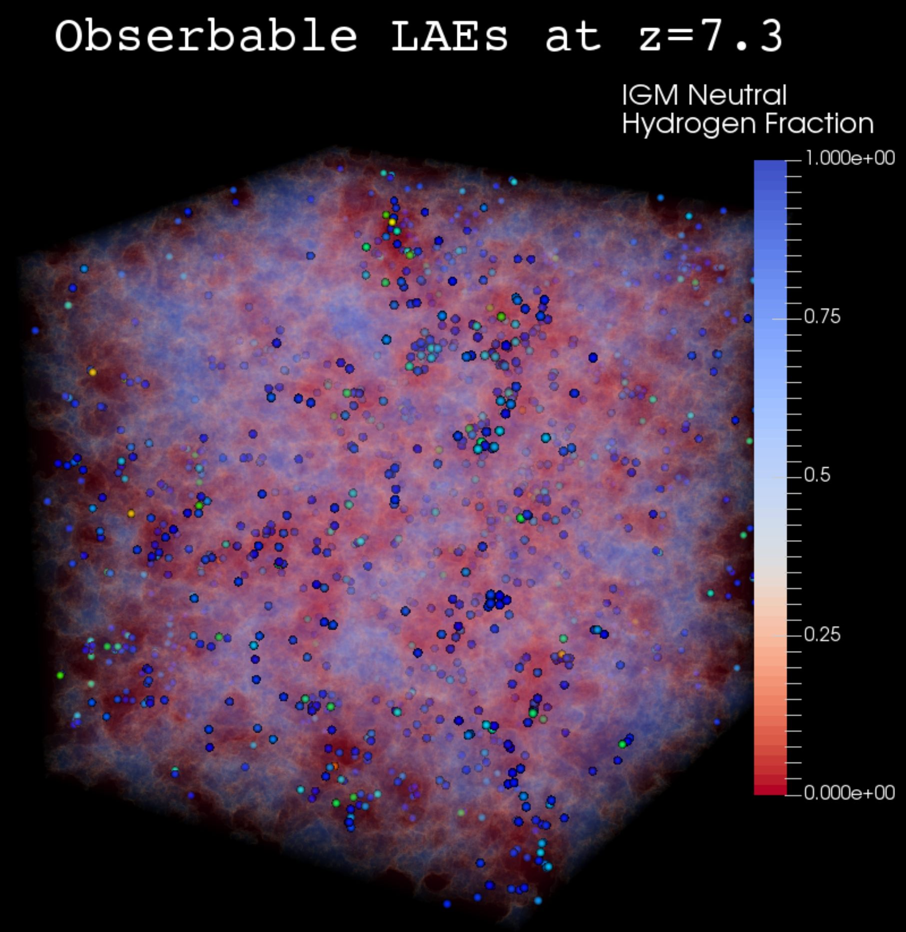



From RHD simulation

$$L_{\alpha,\mathrm{int}} \approx 10^{42}\left(\frac{M_\mathrm{h}}{10^{10}\mathrm{M}_\odot}\right)^{1.1}[\mathrm{erg/s}],$$

# Distribution of Observable Lyα Emitting Galaxies




From RHD simulation

$$L_{\alpha,\mathrm{int}} \approx 10^{42}\left(\frac{M_{\mathrm{h}}}{10^{10}\mathrm{M}_{\odot}}\right)^{1.1}[\mathrm{erg/s}],$$

Lyα escape fraction : Parameter

$$L_{\alpha,\mathrm{obs}} = f_{\mathrm{esc},\alpha} T_{\alpha,\mathrm{IGM}} L_{\alpha,\mathrm{int}}.$$

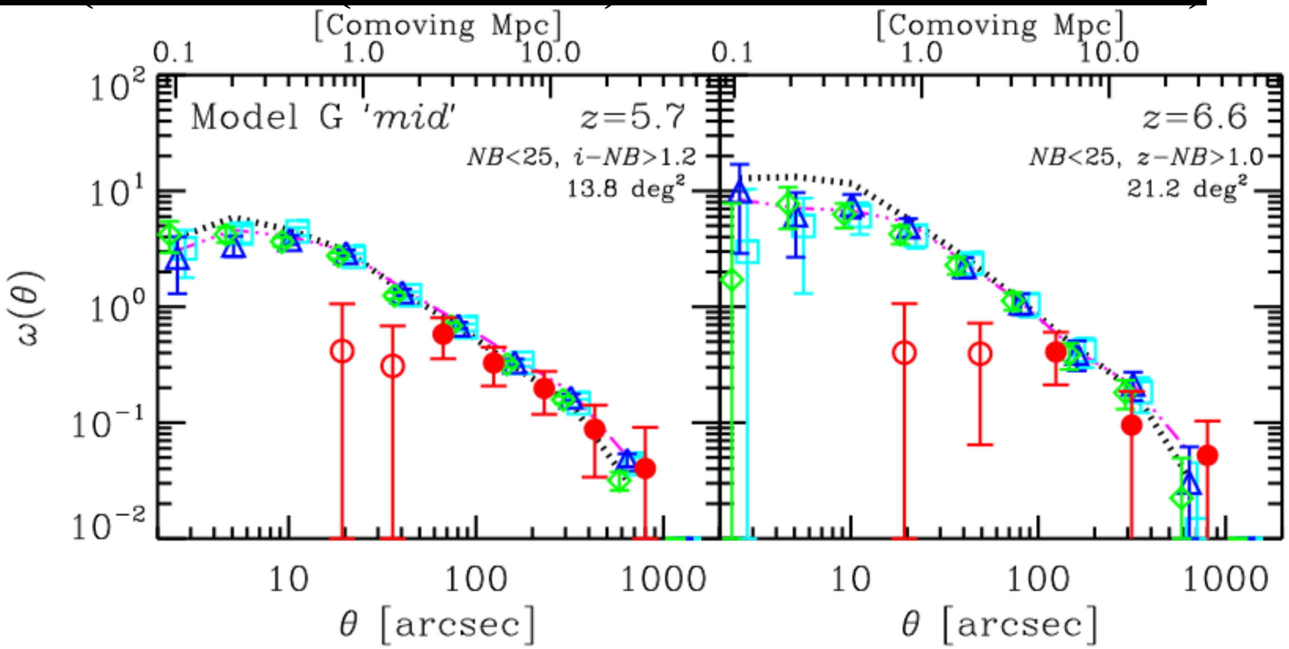
Ray-tracing through the IGM
(Yajima, Sugimura, KH+, 2018)

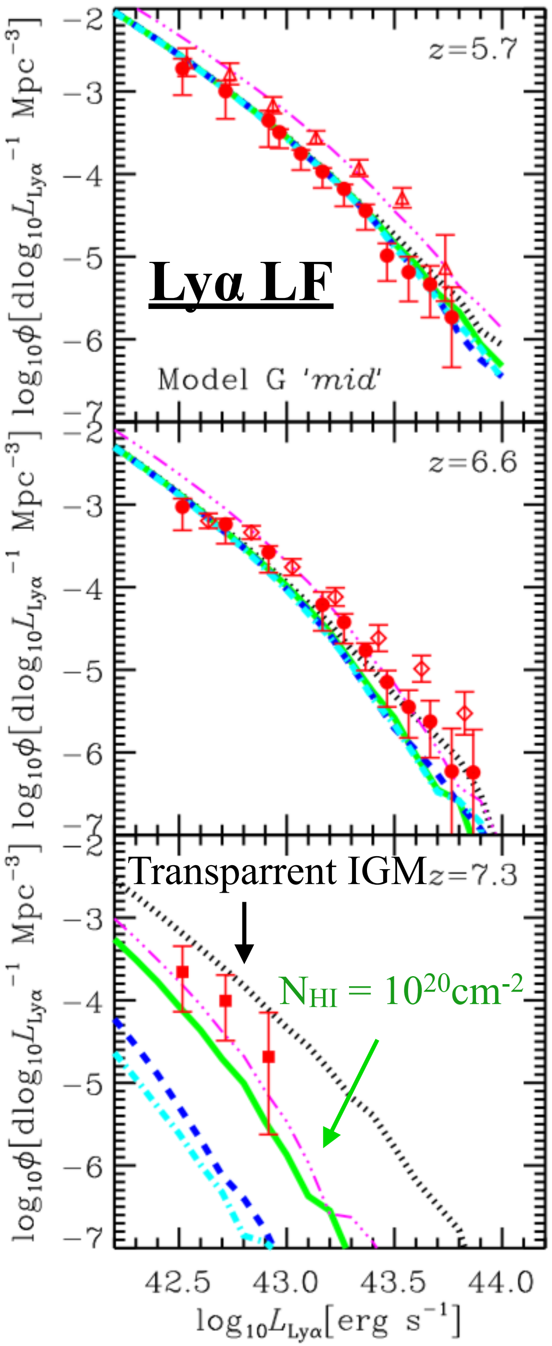
# Modelling Lyα Emitting Galaxies

Collaboration with a Subaru HSC project (SILVERRUSH)
Inoue, KH, et al. 2018

- To reproduce observed Angular Correlation Function and Luminosity function, $M_{\rm halo}$-dependent escape fraction ( $\langle\tau\rangle \propto M_{\rm halo}^{1/3}$) with a large scatter is favored.
- Lyα RT simulations (e.g., Yajima et al. 2014) show the similar trend.

**ACF (Obs data (red circles) from Ouchi et al. 2018)**

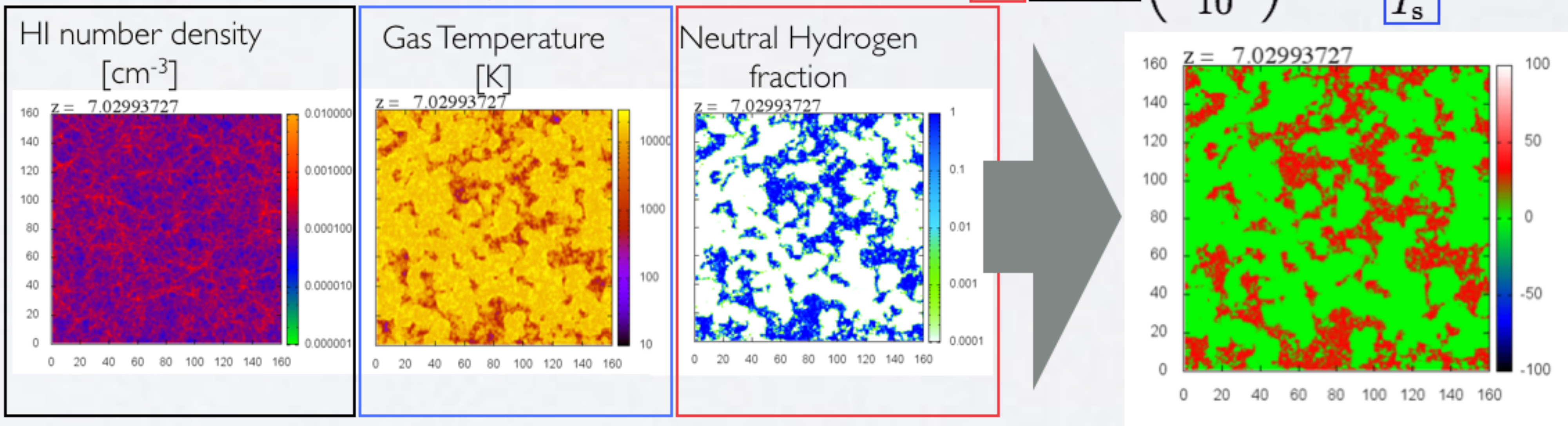


# Preparation for estimating the detectability of the CPS

## HI 21cm signal estimated from our simulation

HI 21cm brightness temperature module $\delta T_b \approx 28 \boxed{x_{HI}} \boxed{(1+\delta)} \left(\frac{1+z}{10}\right)^{\frac{1}{2}} \frac{\boxed{T_s} - T_{CMB}}{\boxed{T_s}}$ [mK]




**HSC**

Deep:

Total survey Area : 27 [deg$^2$] ~ 0.5 $h^{-3}$Gpc$^3$, Limiting Luminosity : $4.1 \times 10^{42}$ erg/s @z=6.6,

redshift error =0.0007 w/ PFS
=0.1 w/o PFS

**SKA**

FoV: ~25 [deg$^2$]

670 antennae within 1000m

1000hrs observing time

# Errors on the cross-power spectrum

based on Furlanetto&Lidz(2007)

## Error on 21cm observation

$\mu$=cos$\theta$: angle between LOS and k

$$\delta P_{21}(k,\mu) = P_{21}(k,\mu) + \boxed{\frac{T_{\rm sys}^2}{Bt_{\rm int}}\frac{D^2\Delta D}{n(k_\perp)}\left(\frac{\lambda^2}{A_e}\right)^2},$$

sample variance + $\boxed{\text{thermal noise}}$

$\sigma_{\rm N}$

## Error on LAE survey

$$\delta P_{\rm gal}(k,\mu) = P_{\rm gal}(k,\mu) + \boxed{n_{\rm gal}^{-1}\exp(k_\parallel^2\sigma_r^2)},$$

sample variance + $\boxed{\text{shot noise*z error}}$

$\sigma_{\rm g}$

## Error on the spherically averaged cross-power spectrum

$$2[\delta P_{21,\rm gal}^2(k,\mu)] = P_{21,\rm gal}^2(k,\mu) + \delta P_{21}(k,\mu)\delta P_{\rm gal}(k,\mu).$$

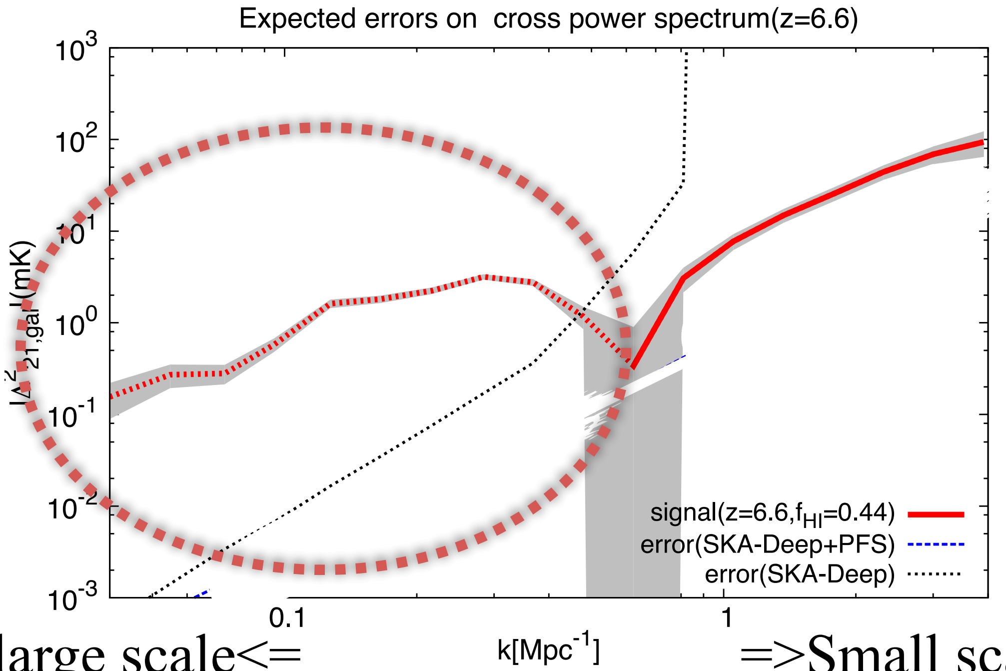
$$\frac{1}{\delta P_{21,\rm gal}^2(k)} = \sum_\mu \Delta\mu\frac{\epsilon k^3 V_{\rm sur}}{4\pi^2}\frac{1}{\delta P_{21,\rm gal}^2(k,\mu)},$$

$$\delta P_{21,\rm gal}(k) = \sigma_{\rm A}(k) \propto \sqrt{\underbrace{P_{21,\rm gal}^2 + P_{21}P_{\rm gal} + P_{21}\sigma_{\rm g} + \sigma_{\rm N}P_{\rm gal}}_{\text{sample variance}} + \underbrace{\sigma_{\rm N}\sigma_{\rm g}}_{\text{detection limit}}}.$$

# Detectability of 21cm-LAE CPS w/o FG

$$\sigma_A(k) \propto \sqrt{\boxed{P_{21,\mathrm{gal}}^2 + P_{21}P_{\mathrm{gal}} + P_{21}\sigma_g + \sigma_N P_{\mathrm{gal}}} + \boxed{\sigma_N \sigma_g}}$$

variance = shaded    detection limit = curve




large scale<=    =>Small scale

**SKA1** (1000h) **×HSC**

z=6.6

red: simulated cross-power spectrum
black: sensitivity

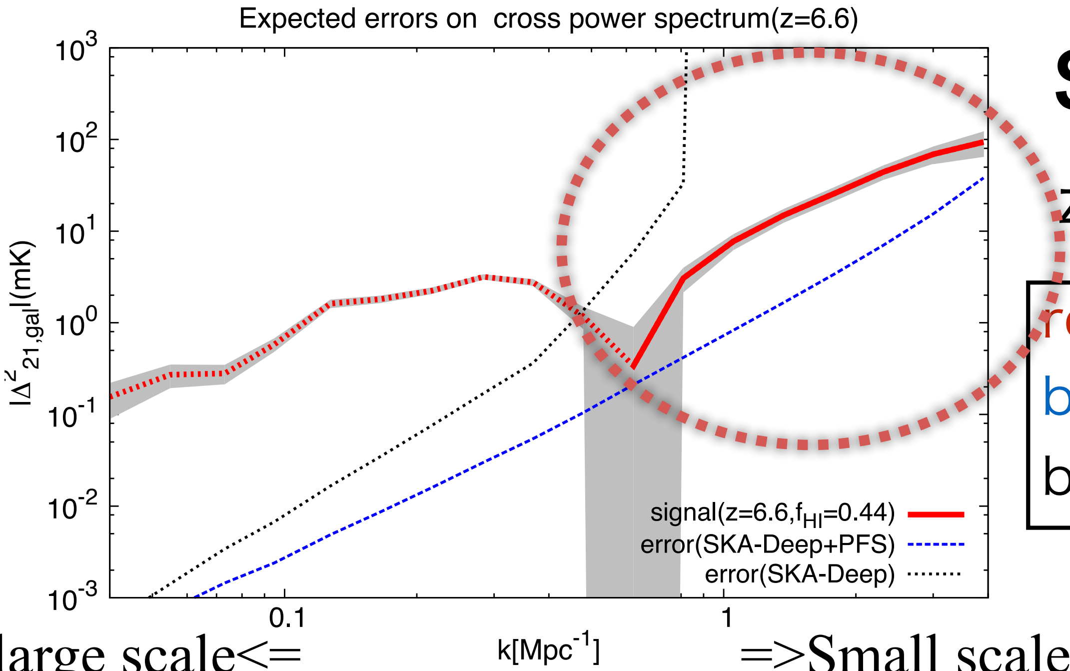
- SKA×HSC Deep is expected to detect the signal at large scales

(k<0.5 $\mathrm{Mpc}^{-1}$)

# Detectability of 21cm-LAE CPS w/o FG

$$\sigma_{\rm A}(k) \propto \sqrt{\boxed{P^2_{21,{\rm gal}} + P_{21}P_{\rm gal} + P_{21}\sigma_{\rm g} + \sigma_{\rm N}P_{\rm gal}} + \boxed{\sigma_{\rm N}\sigma_{\rm g}}}$$

variance = shaded        detection limit = curve

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**SKA1(1000h)×HSC**

z=6.6

red: simulated cross-power spectrum
blue: sensitivity w/ PFS
black: sensitivity w/o PFS

- SKA×HSC Deep is expected to detect the signal at large scales (k<0.5 Mpc$^{-1}$)
- Spectroscopy by PFS enhances the detectability at small scales.

# Detectability of 21cm-LAE CPS w/o FG

$$\sigma_A(k) \propto \sqrt{\boxed{P^2_{21,\mathrm{gal}} + P_{21}P_{\mathrm{gal}} + P_{21}\sigma_g + \sigma_N P_{\mathrm{gal}}} + \boxed{\sigma_N \sigma_g}}$$

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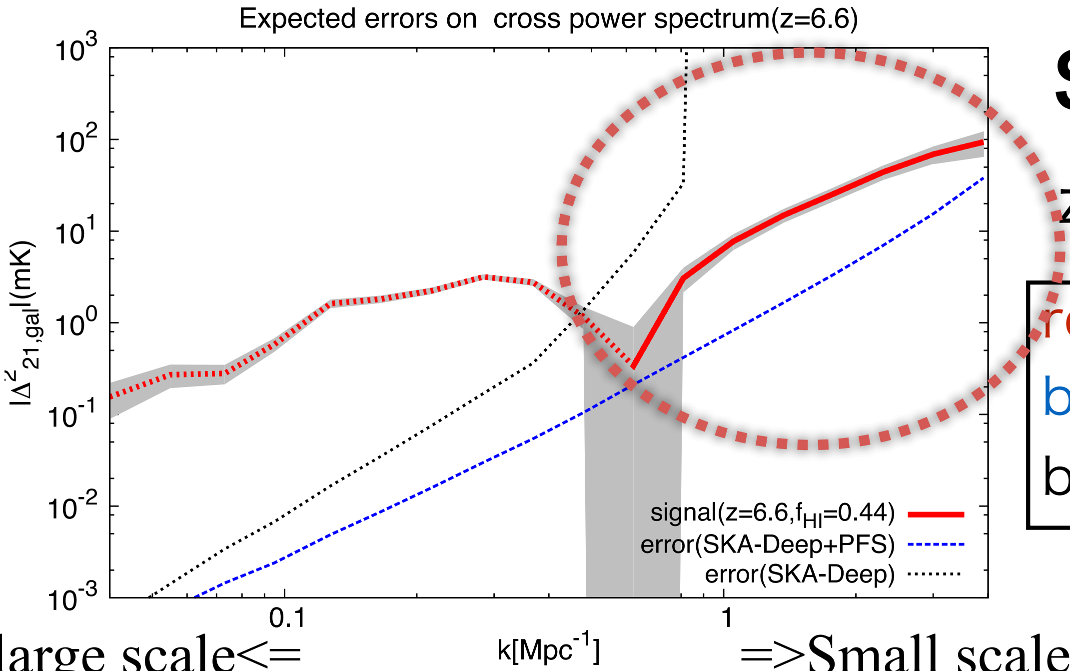


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- SKA×HSC Deep is expected to detect the signal at large scales (k<0.5 Mpc$^{-1}$)
- Spectroscopy by PFS enhances the detectability at small scales
- Behavior of the CPS at small scales is sensitive to the ionizing photon emissivities of LAEs (Kaneuji, KH; preliminary)

# Impact of Foreground Emission

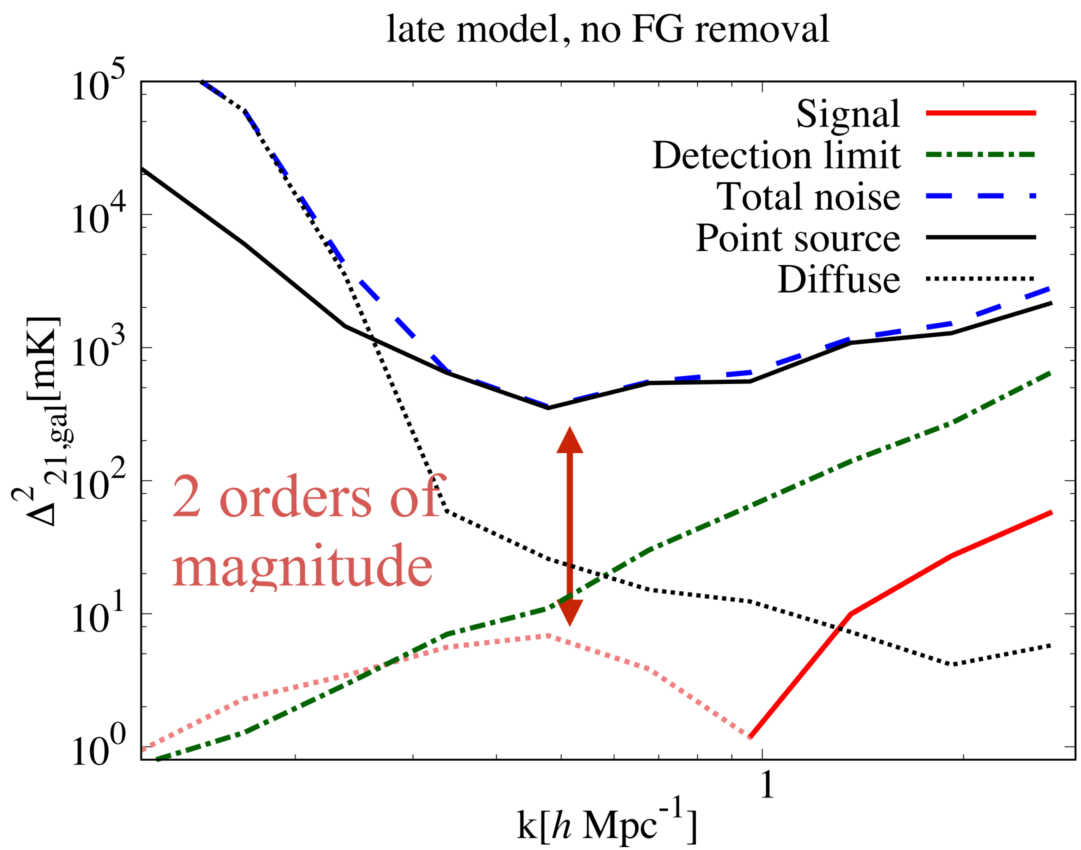
**Point sources**

MWA GLEAM catalogue (Hurley-Walker+2017)

Modeled by J. Line

**Diffuse emission**

A parametric model of diffuse emission from our Galaxy (Jelic et al 2008, Trott et al 2016)




- The contribution from foreground does not vanish.
- Foreground removal is still required for detecting the EoR 21cm signal, even in the case of CC analysis.

# Summary

- A two-step approach (RHD + large-scale post-processing radiative transfer) to simulate the large-scale cosmic reionization process
- Modelling LAEs (Inoue, KH et al. 2018)
  $M_{\mathrm{h}}$-dependent Lya escape fraction is favored
- PFS enhances the detectability of the 21cm-LAE CPS at low scales. (Kubota, KH et al. 2018)
- Many efforts for foreground removal is required even in the case of the CPS measurement. (Yoshiura, KH et al. 2018)