Detectability of 21cm-signal during the Epoch of Reionization with 21cm-LAE cross-correlation. Ⅰ. & Ⅱ.

arXiv:1708.06291 & 1709.04168

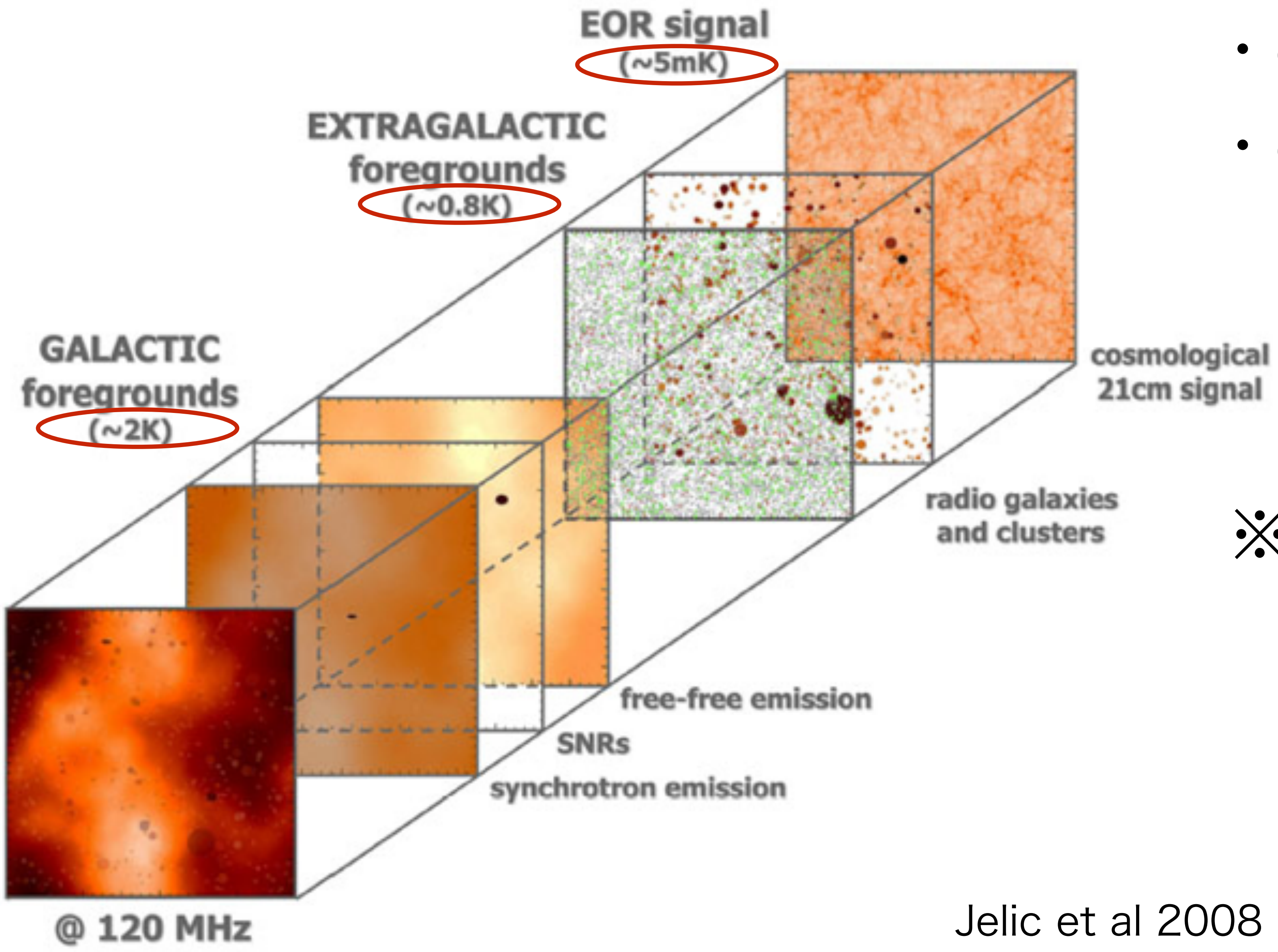
Kenji Kubota(Kumamoto University)
Shintaro Yoshiura(Kumamoto University)
Keitaro Takahashi(Kumamoto University)
Kenji Hasegawa(Nagoya University)
Hidenobu Yajima(Tohoku University)
Masami Ouchi(University of Tokyo)
Bart Pindor(University of Melbourne)
Rachel L. Webster(University of Melbourne)

熊本大学
Kumamoto University

MWA
MURCHISON
WIDEFIELD
ARRAY

SKA-JP
Square Kilometre Array
Japanese Consortium

Problem of 21cm observation



Jelic et al 2008

Foreground

- galactic synchrotron
- extragalactic radio

etc…

※21cm signal : ~mK

foreground : ~K

foreground >> 21cm

The detection of 21cm-signal is very challenging!

21cm-signal from the EoR has not been detected.

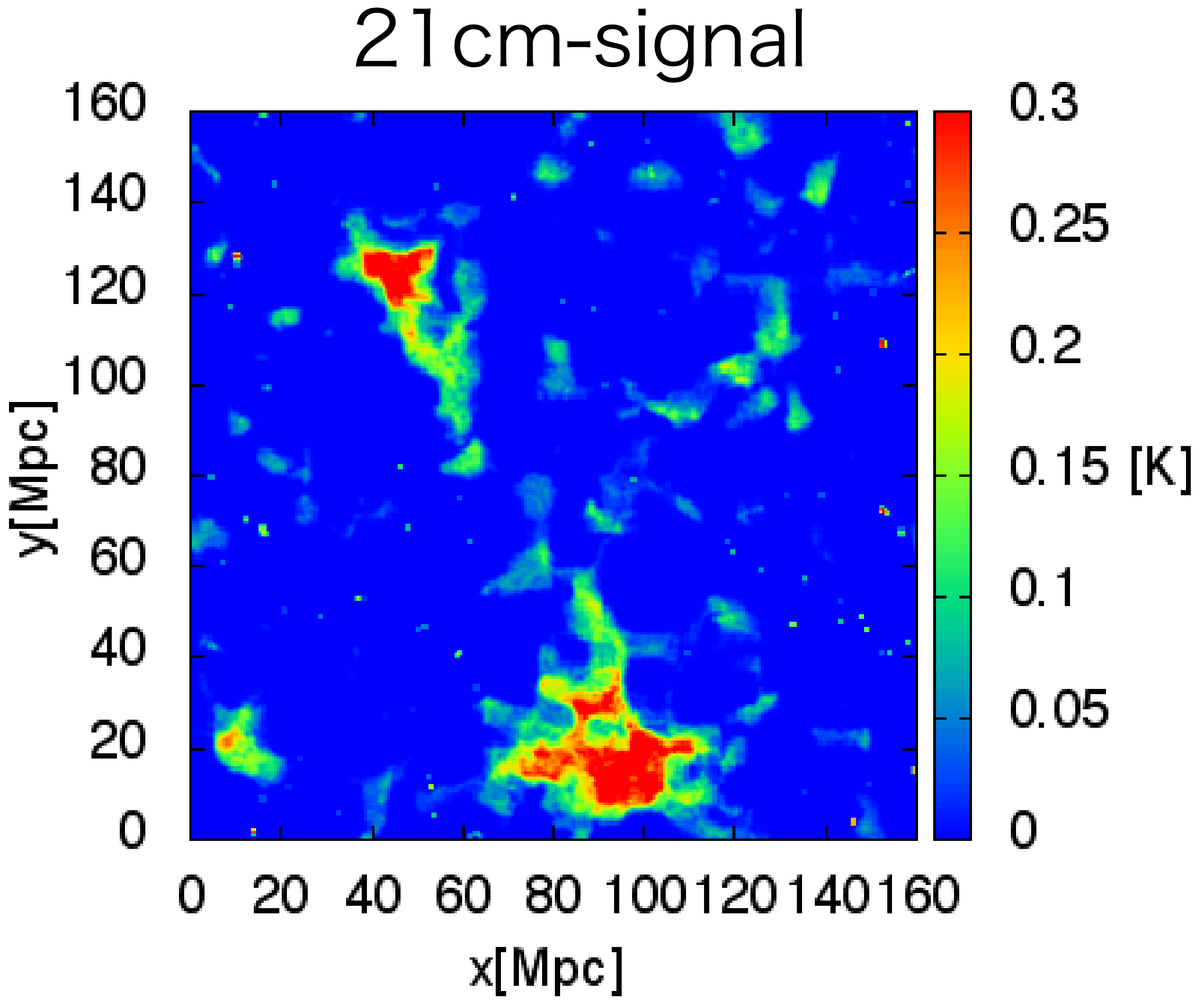
Strategy for detection

① foreground removal
② foreground avoidance
③ 21cm-LAE cross-correlation … this work

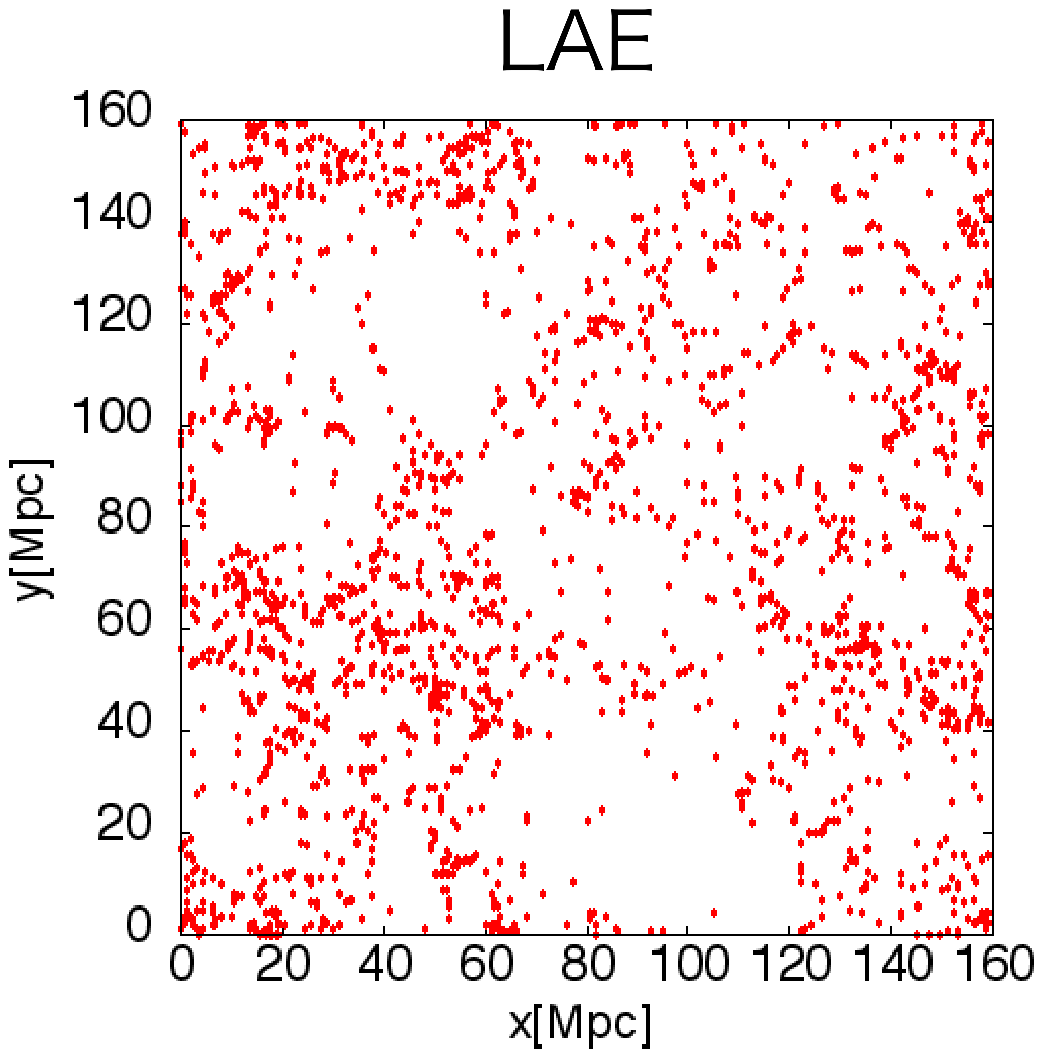
In the case of auto-correlation,
even if foregrounds are removed, it is not easy to say
if the residual is actually the 21cm-signal.

◎ Cross-correlation is effective to identify the signal.

21cm-LAE cross-correlation


21cm-signal

×


LAE

・The region around LAEs is dark in 21cm.

・The region far from LAEs is bright in 21cm.

→ **Negative correlation**

21cm-LAE cross-correlation

$$\langle \tilde{\delta}_{21}(\mathbf{k_1})\tilde{\delta}_{\mathrm{gal}}(\mathbf{k_2})\rangle \equiv (2\pi)^3\delta_D(\mathbf{k_1}+\mathbf{k_2})\boxed{P_{21,\mathrm{gal}}}(\mathbf{k_1}),$$

Cross-power spectrum

◎How to reduce foregrounds?

21cm observation ··· $\delta_{21} = \delta_{21\mathrm{sig}} + \delta_{21\mathrm{noise}} + \delta_{21\mathrm{FG}}$

galaxy survey ··· $\delta_{\mathrm{gal}} = \delta_{\mathrm{gal\ sig}} + \delta_{\mathrm{gal\ noise}}$

$$\langle \delta_{21}\delta_{\mathrm{gal}}\rangle = \langle \delta_{21\mathrm{sig}}\delta_{\mathrm{gal\ sig}}\rangle + \cdots + \underset{\sim 0}{\underline{\langle \delta_{21\mathrm{FG}}\delta_{\mathrm{gal\ sig}}\rangle}} + \underset{\sim 0}{\underline{\langle \delta_{21\mathrm{FG}}\delta_{\mathrm{gal\ noise}}\rangle}}$$

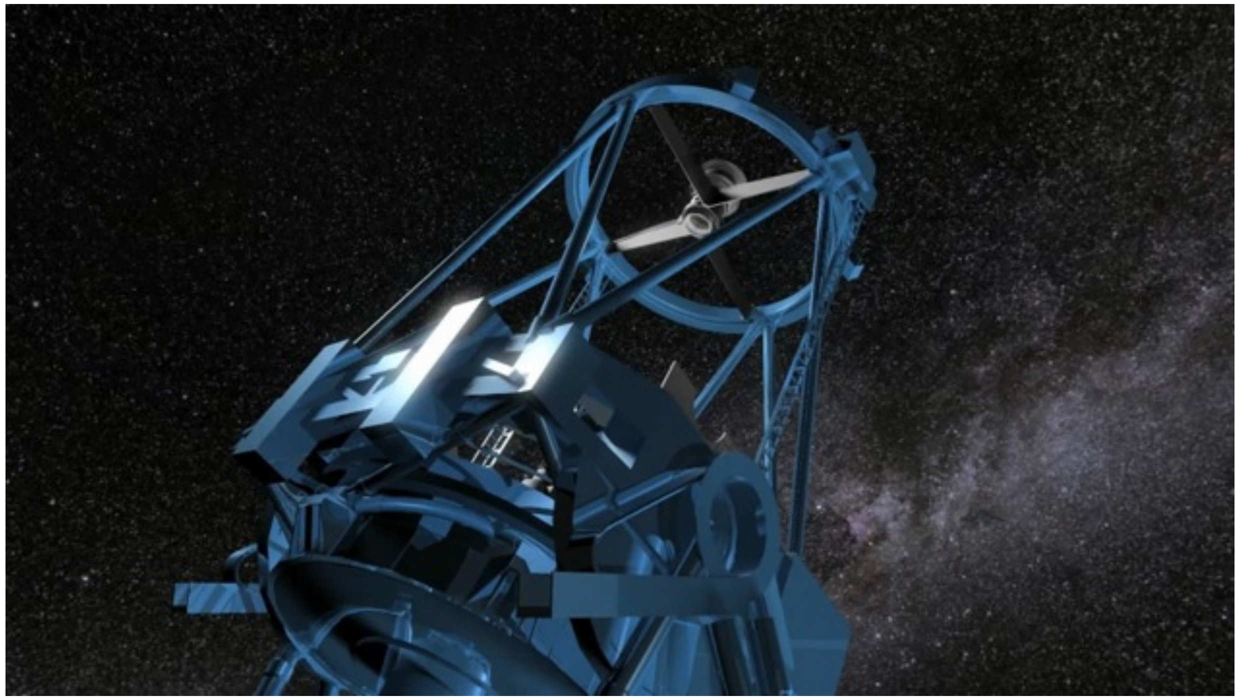
21cm-signal is correlated with LAE distribution.
FG in 21cm is not correlated with LAE.

→ Foregrounds don not contribute to the average of the cross-power.
(But they contribute to the variance.)

Lyman-α emitter(LAE)

- High-z galaxy with a strong emission line @λ=1216Å
- **SILVERRUSH** project reported the initial results by Hyper Suprime-Cam(HSC) on Subaru telescope.

Subaru HSC



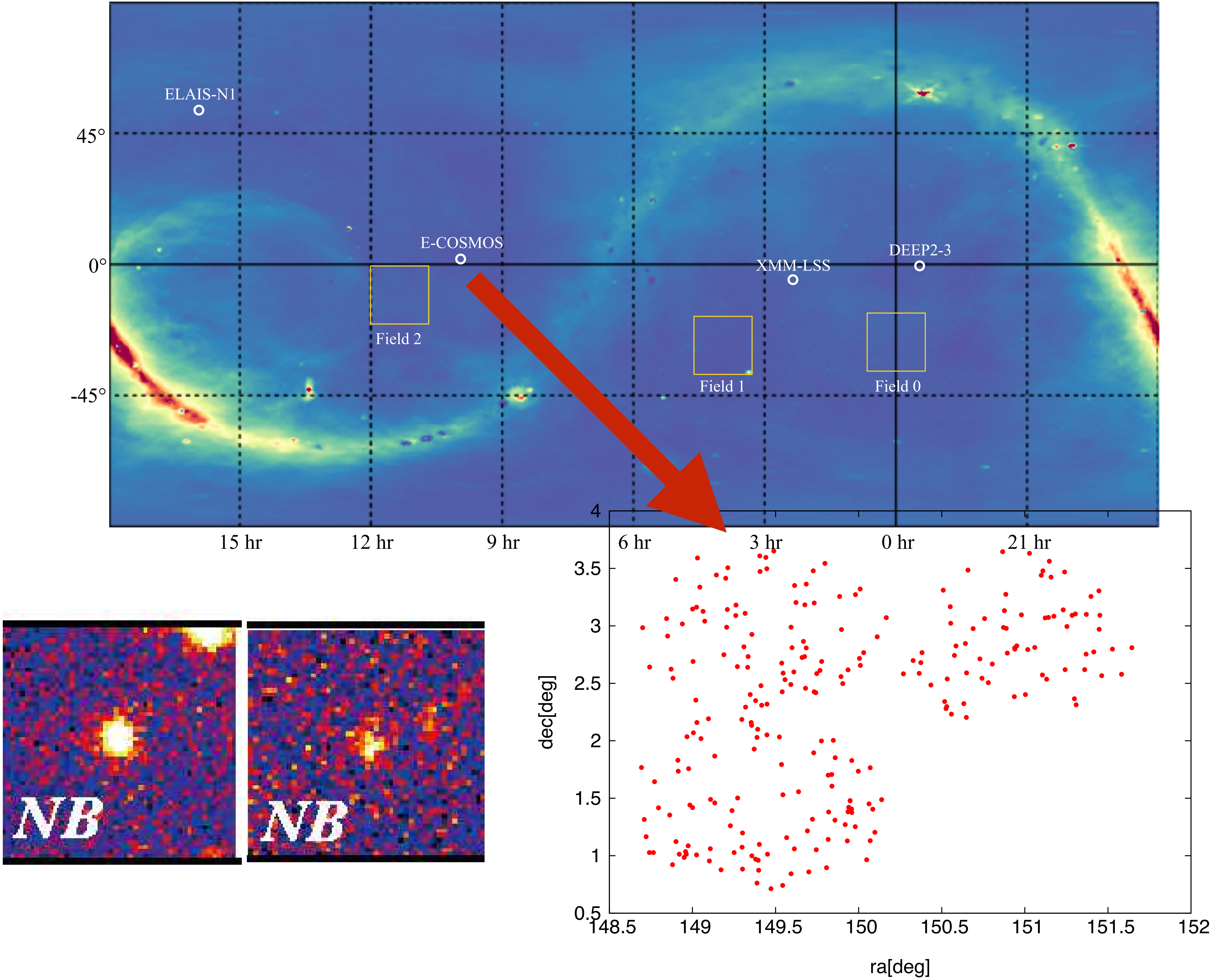
- Wide FoV ~ $1.8\mathrm{deg}^2$
- Deep field @z=6.6
  $27\ \mathrm{deg}^2$, $L_\alpha > 4.1\times10^{42}$ erg/s
- redshift uncertainty Δz=0.1

Prime Focus Spectrograph(PFS) Δz=0.0007

- spectrograph system on HSC
- determine the precise redshift of LAEs discovered by HSC.

→ We can take the cross-correlation in 3D space.

MWA EoR fields & HSC Deep fields

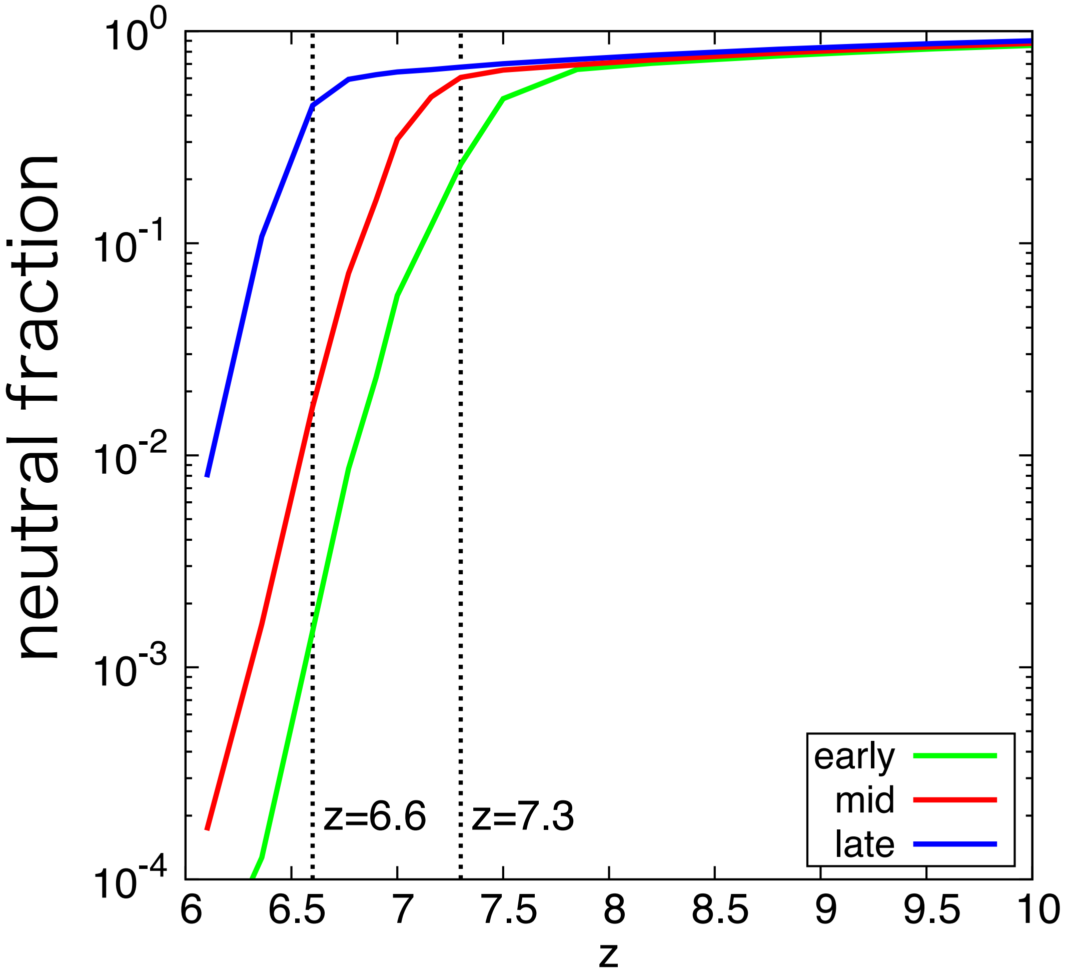


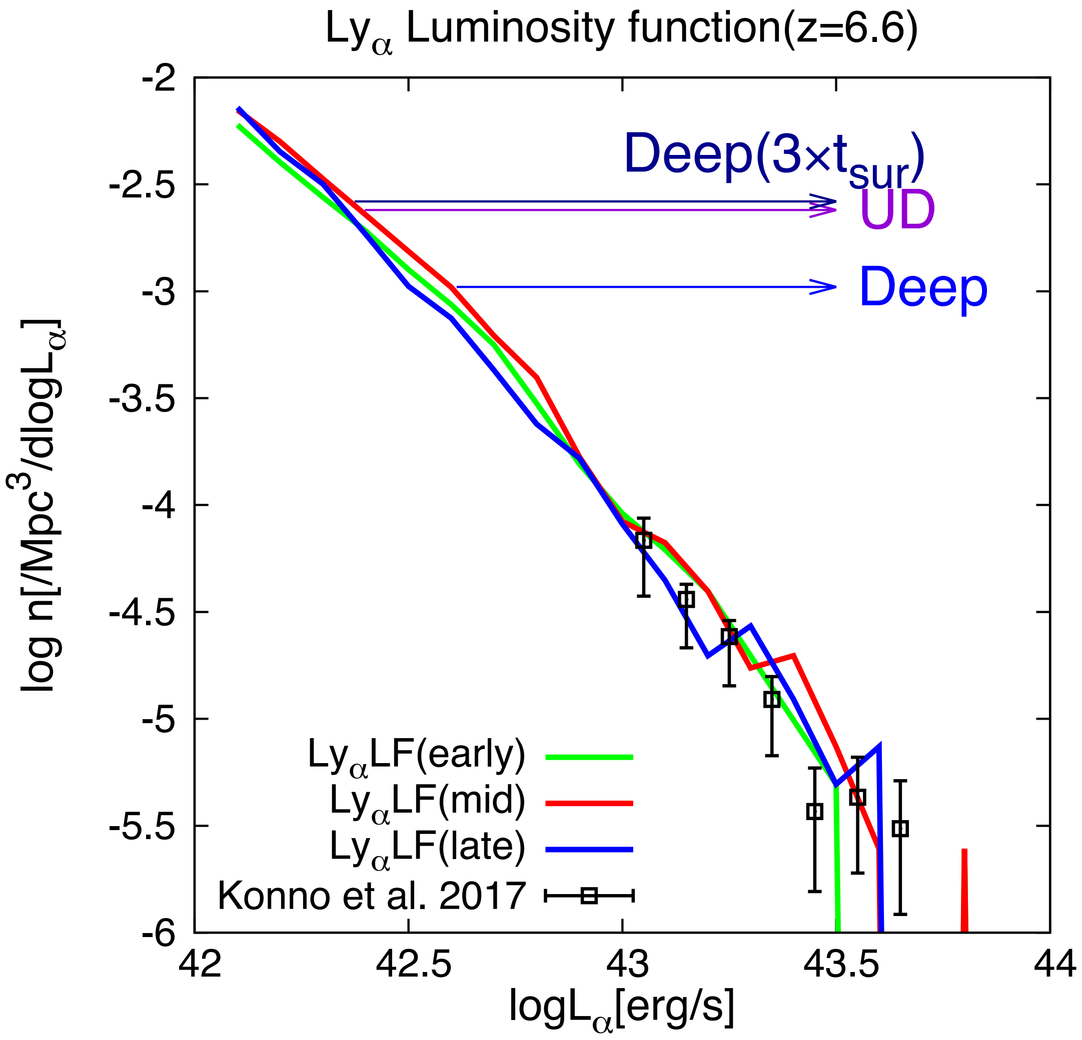
Reionization & LAE model

N-body+radiative transfer simulation considered UV feedback

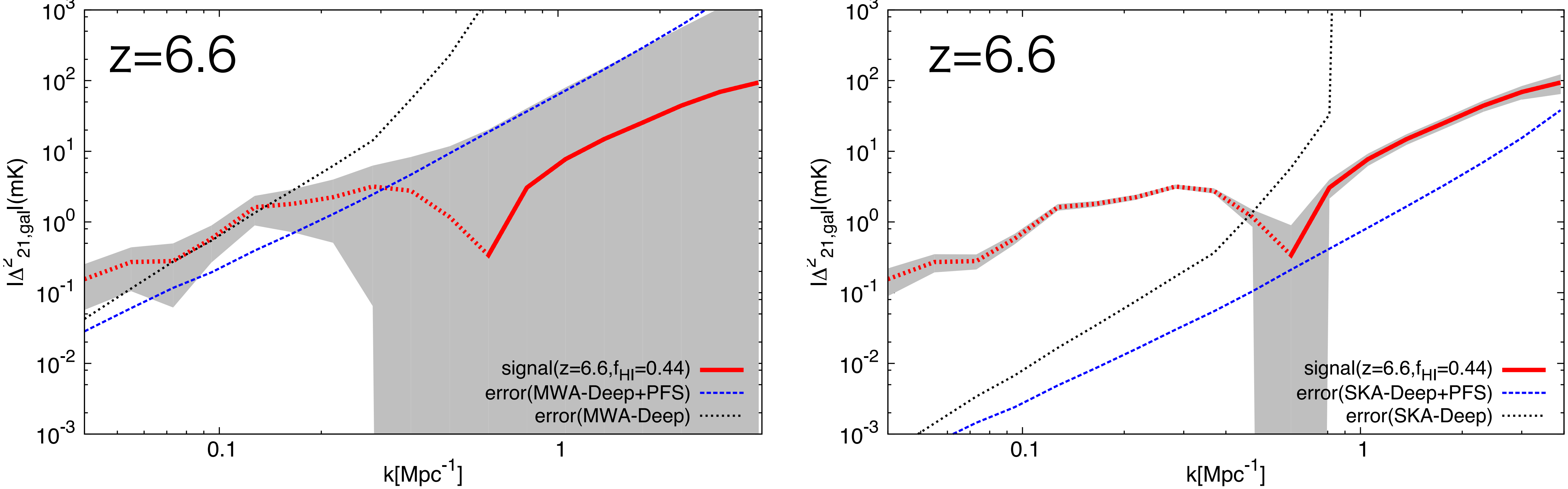
(K-computer@RIKEN AICS, XC30 @NAOJ CfCA
K.Hasegawa et al. in prep)

- Reionization models well reproduce neutral fraction at z~6 indicated by QSO spectra and the CMB optical depth.
- The simulated Lα luminosity functions match the observed Lα LF.





Detectability



MWA(1000h,256T)×**Deep** **SKA1**(1000h)×**Deep**

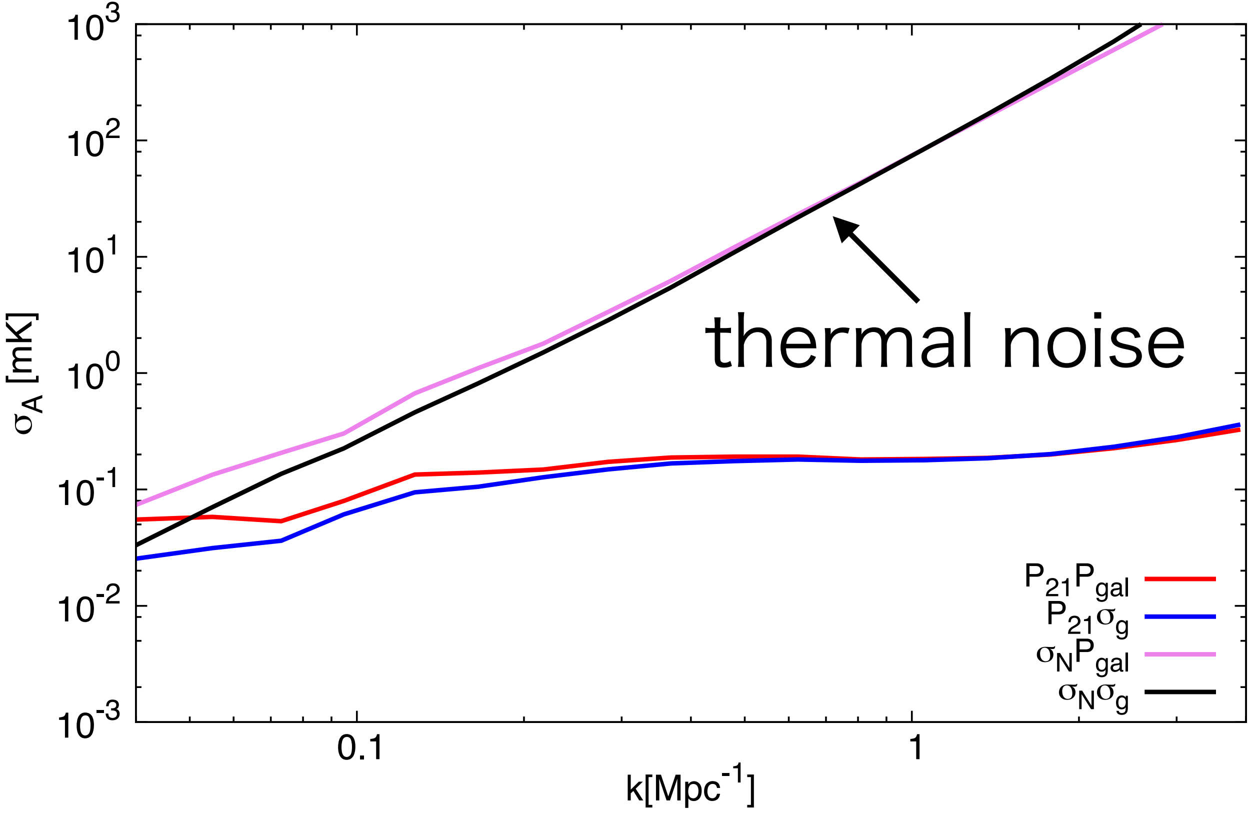
red: cross-power spectrum
blue: sensitivity w/ PFS
black: sensitivity w/o PFS

- MWA×Deep could be able to detect the signal at large scales.
- PFS enhances the detectability at small scale.
- SKA is able to detect the signal even at small scales with PFS.

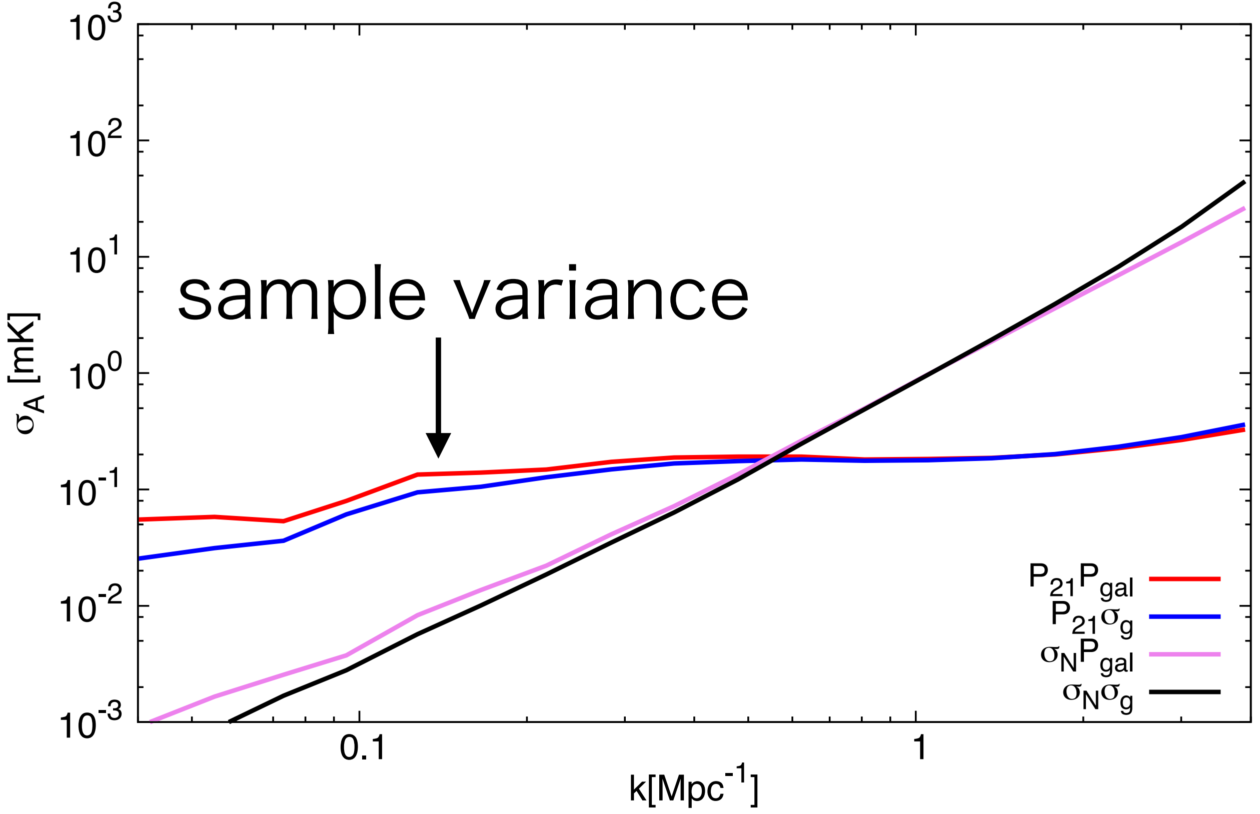
Strategy to enhance detectability

$$\sigma_{\rm A}(k) \propto \sqrt{\underbrace{P^2_{21,{\rm gal}} + P_{21}P_{\rm gal} + P_{21}\sigma_{\rm g} + \sigma_{\rm N}P_{\rm gal}}_{\text{sample variance}} + \underbrace{\sigma_{\rm N}\sigma_{\rm g}}_{\text{observational error}}}.$$

MWA(1000hrs, 256tiles)



SKA1(1000hrs)

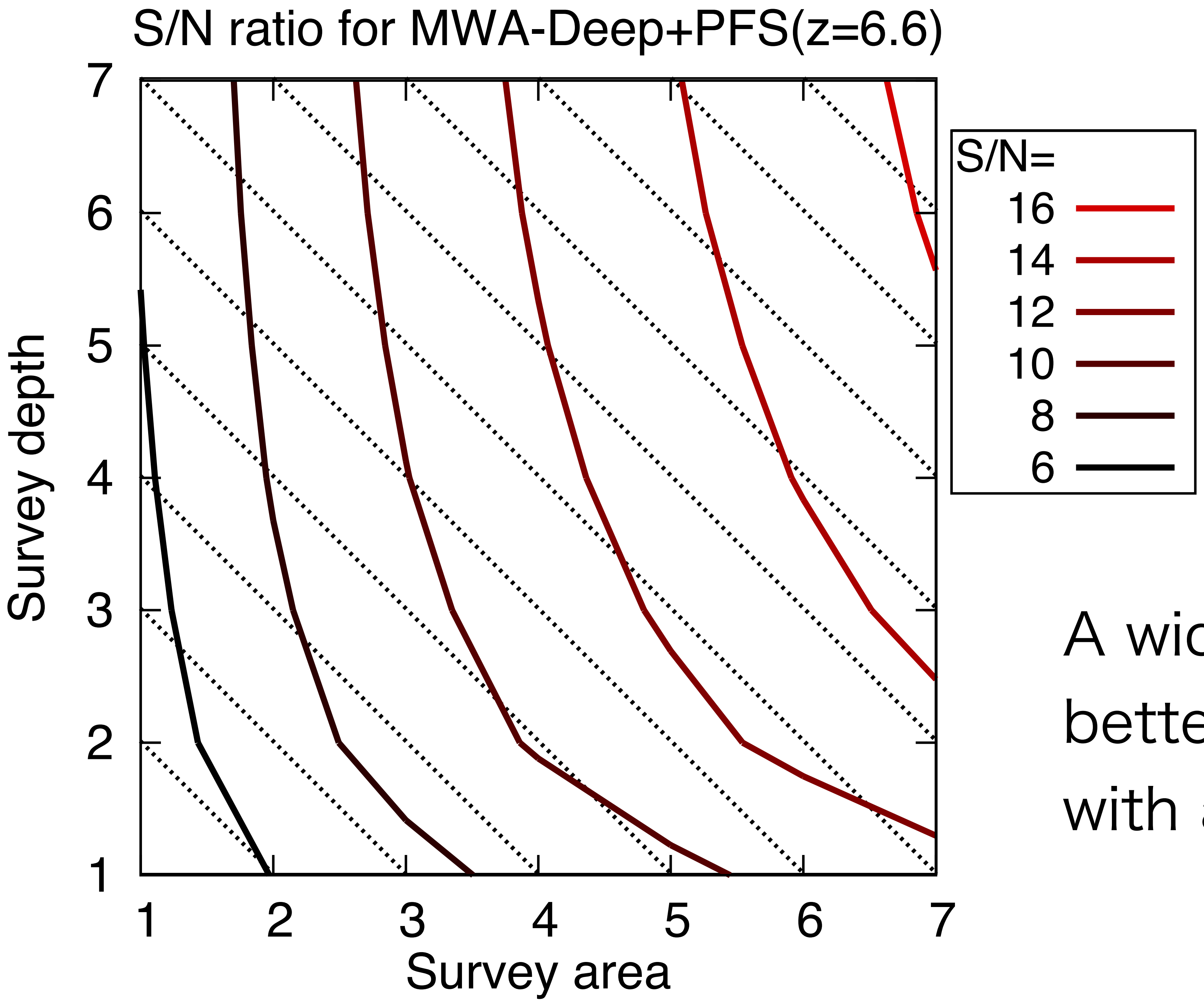


- The thermal noise is dominant at all scales in MWA case.
- In SKA1, the sample variance terms of 21cm-line are dominant at large scale and the thermal noise is dominant at small scale.

Extensions of Subaru HSC Deep

(1) a larger survey area

(2) a longer observation time per pointing



solid line: the S/N contour

dot line: equal survey-time

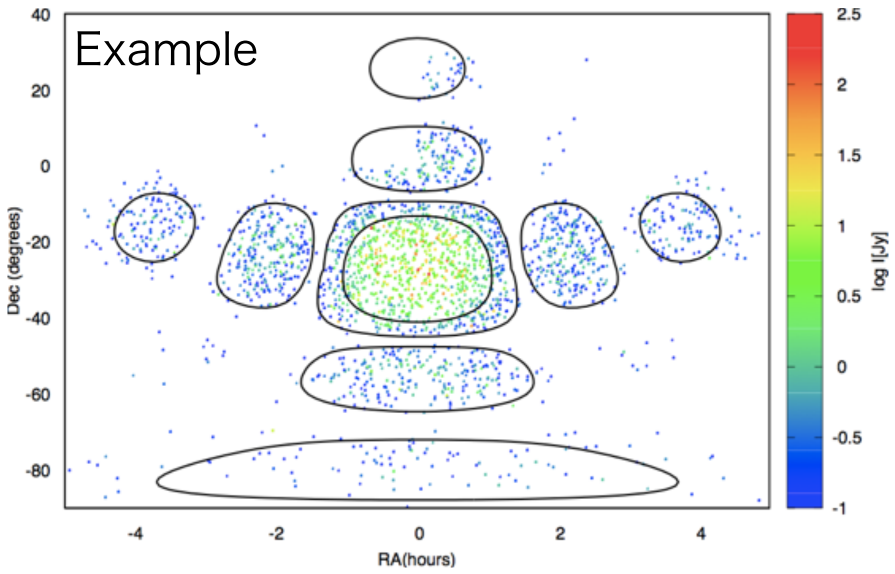
A wider LAE survey is better than deeper survey with a fixed observation time.

Impact of Foreground (Yoshiura, K.K+ 2017)

FGs contribute to the statistical variance.

We take into account contributions from

- extra galactic point sources
- galactic synchrotron emission



◎Point sources

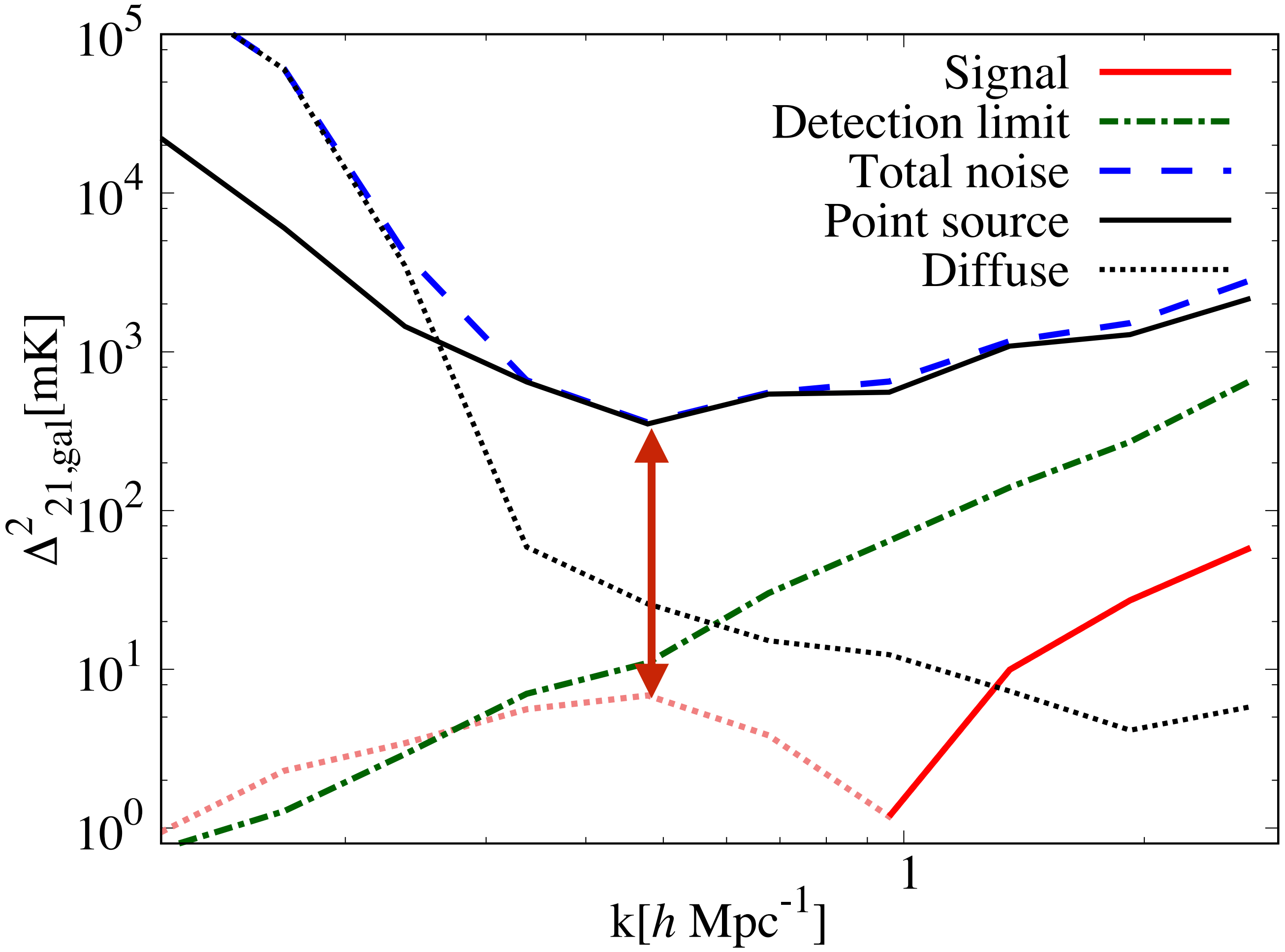
- Based on GLEAM survey catalogue
- Modeled by Jack Line(U. Melbourne)

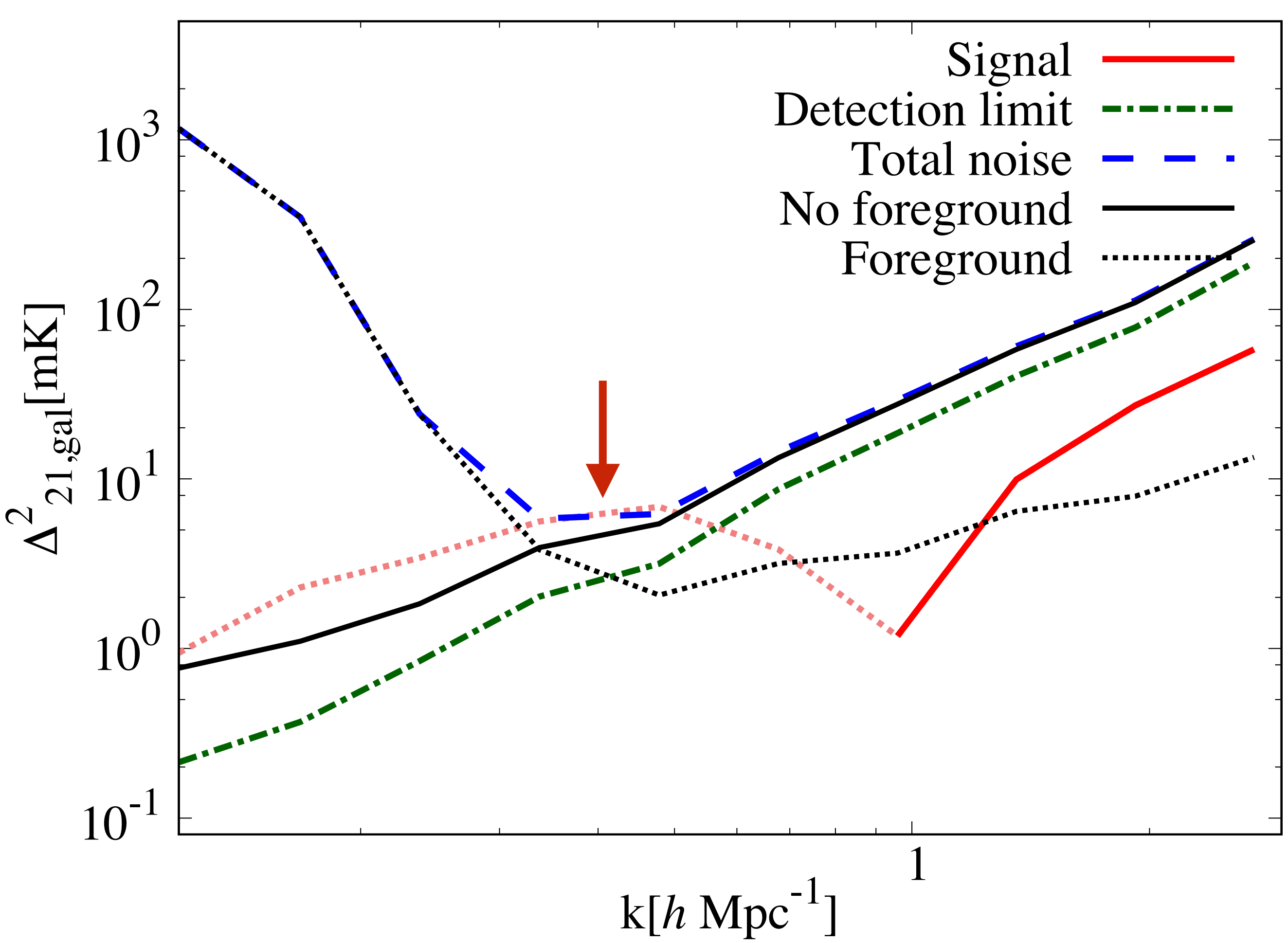
◎Diffuse foreground

- parametric foreground model(Jelic et al. 2008)
- intrinsic temperature power spectrum:

$$P_{\rm FG,D} = (\eta T_{\rm FG,D})^2 \left(\frac{u}{u_0}\right)^{-2.7} \left(\frac{\nu}{\nu_0}\right)^{-2.55}$$

Requirement for detection


late model, no FG removal


late model, 99% FG removal, MWA256tiles, 3V$_{sur}$

- Total noise is larger than the signal by two orders at least.
- The signal is barely comparable to total noise if 99% FG removal, and the extended HSC survey area by 3 factors.

Summary

We investigated the detectability with 21cm-LAE cross-correlation and proposed strategies to enhance the S/N.

The cross-correlation allows us to identify the 21cm-signal.

- MWA×Deep could be able to detect the signal at large scales.

- PFS is very effective to enhance the detectability at small scales and SKA×Deep is able to detect the signal at even small scale with PFS.

- MWA can improve the S/N by increasing observation time and the number of antennae.

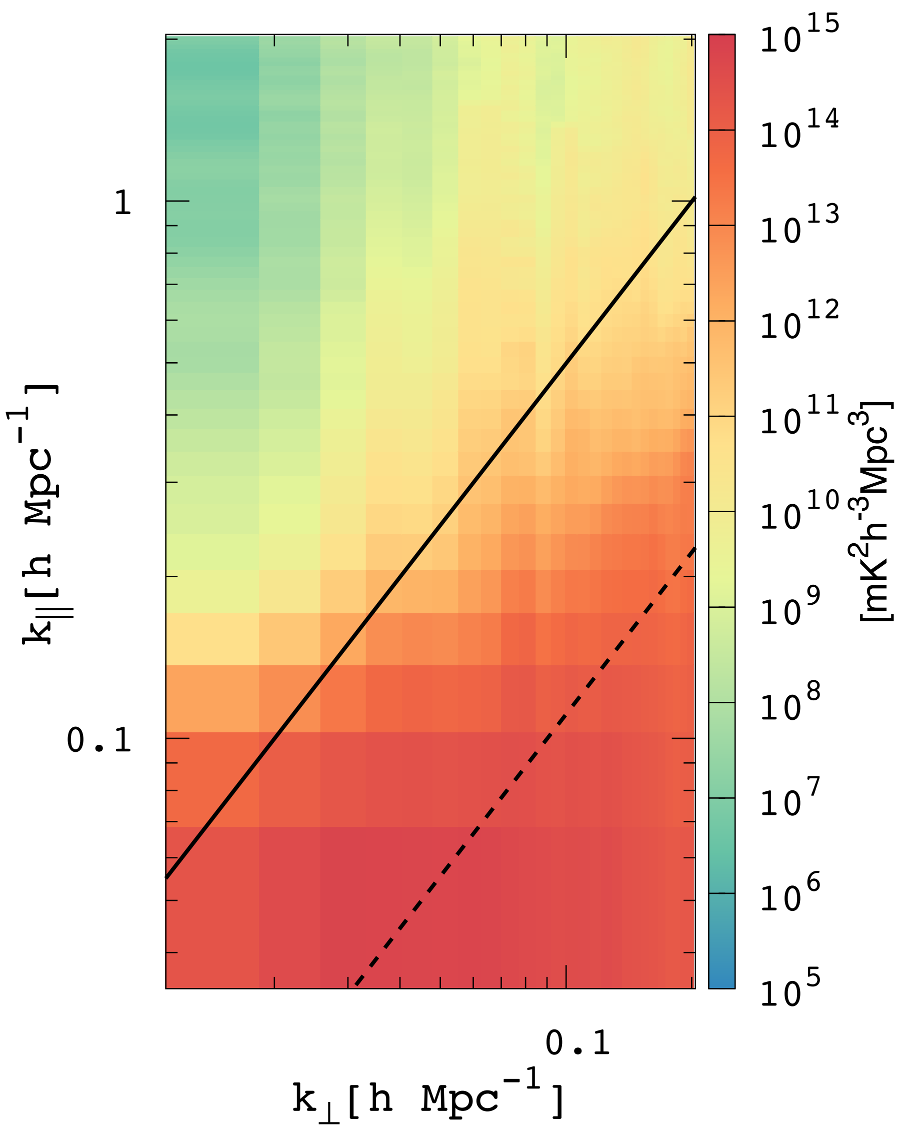
- Another way to increase the S/N is to expand the survey area rather than to perform deeper observation.

- Foregrounds contribute to the variance and 99% FG removal is required to reduce the statistical errors.

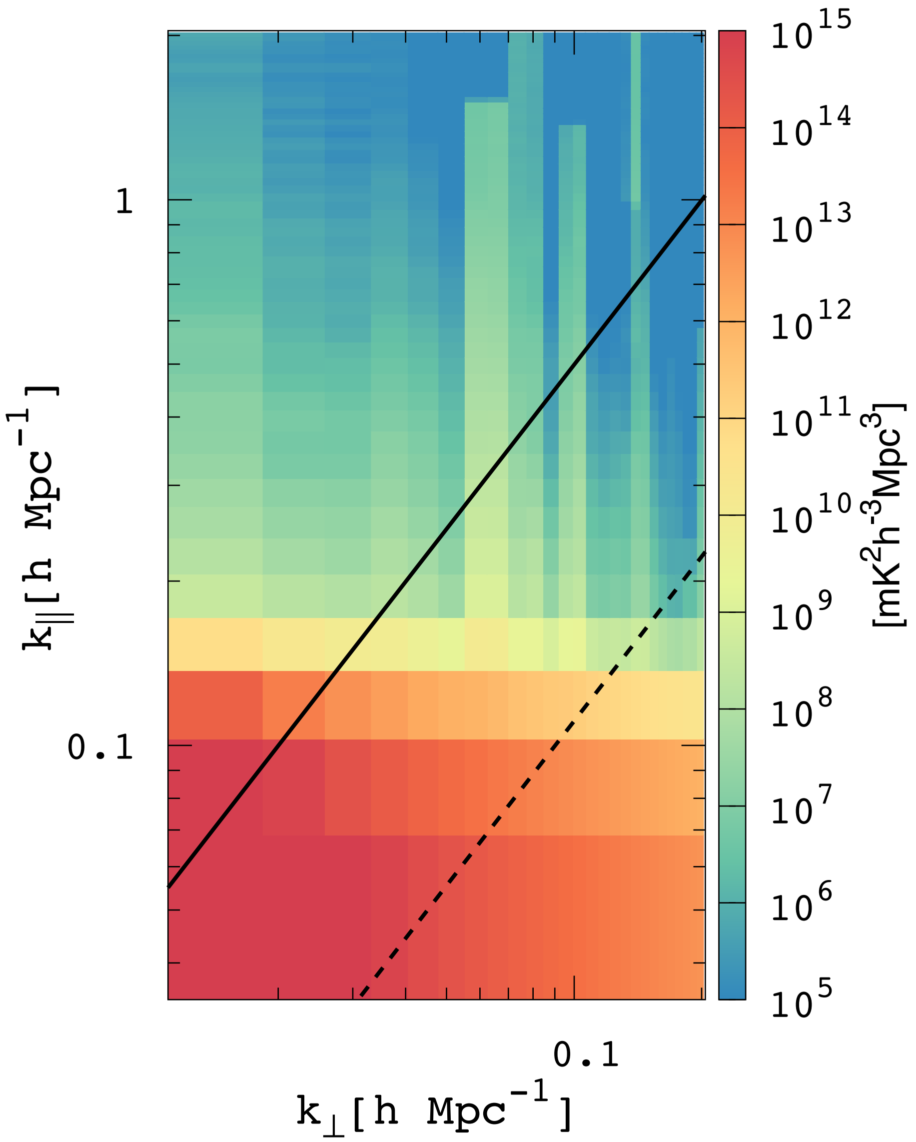
Back up

2D power spectrum

Point sources



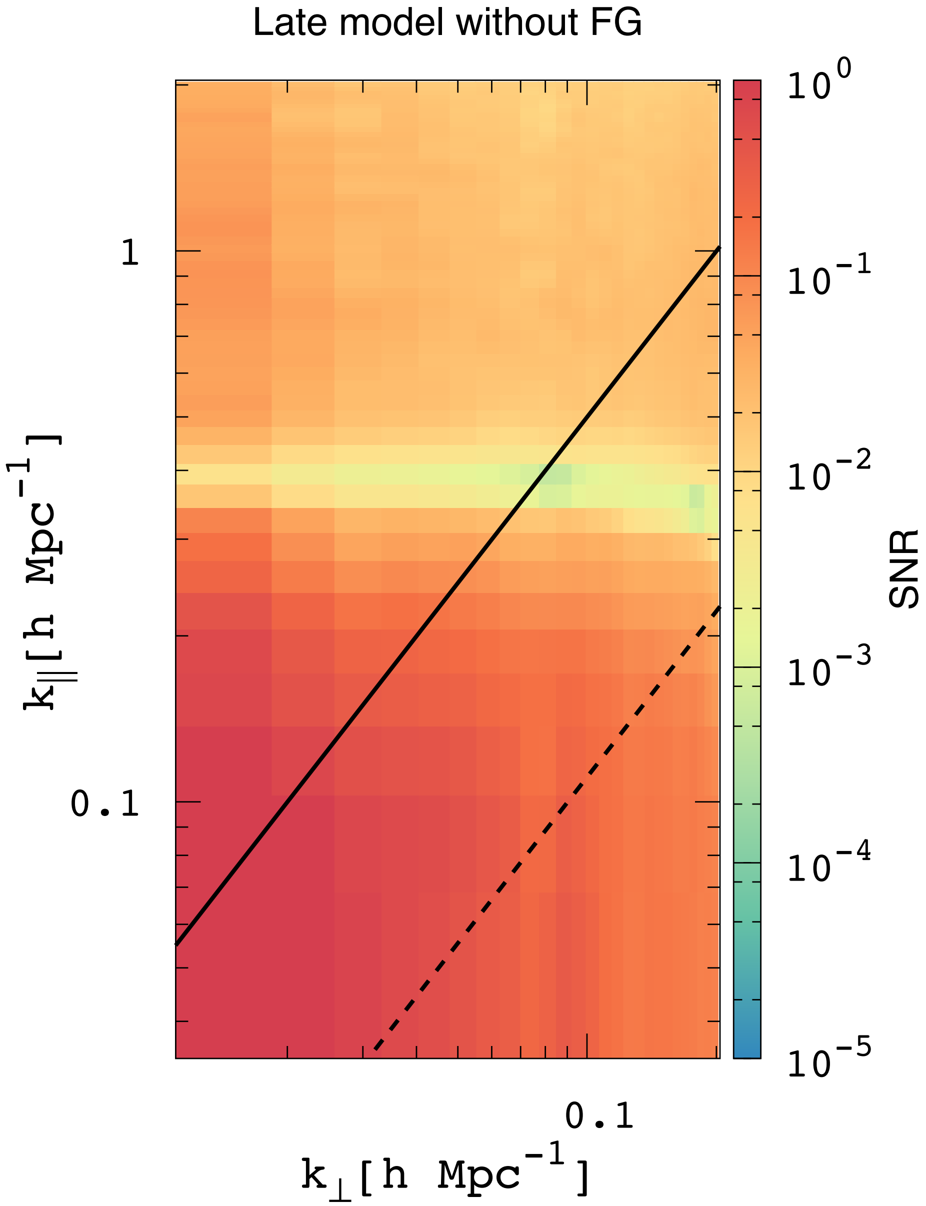
Diffuse foreground



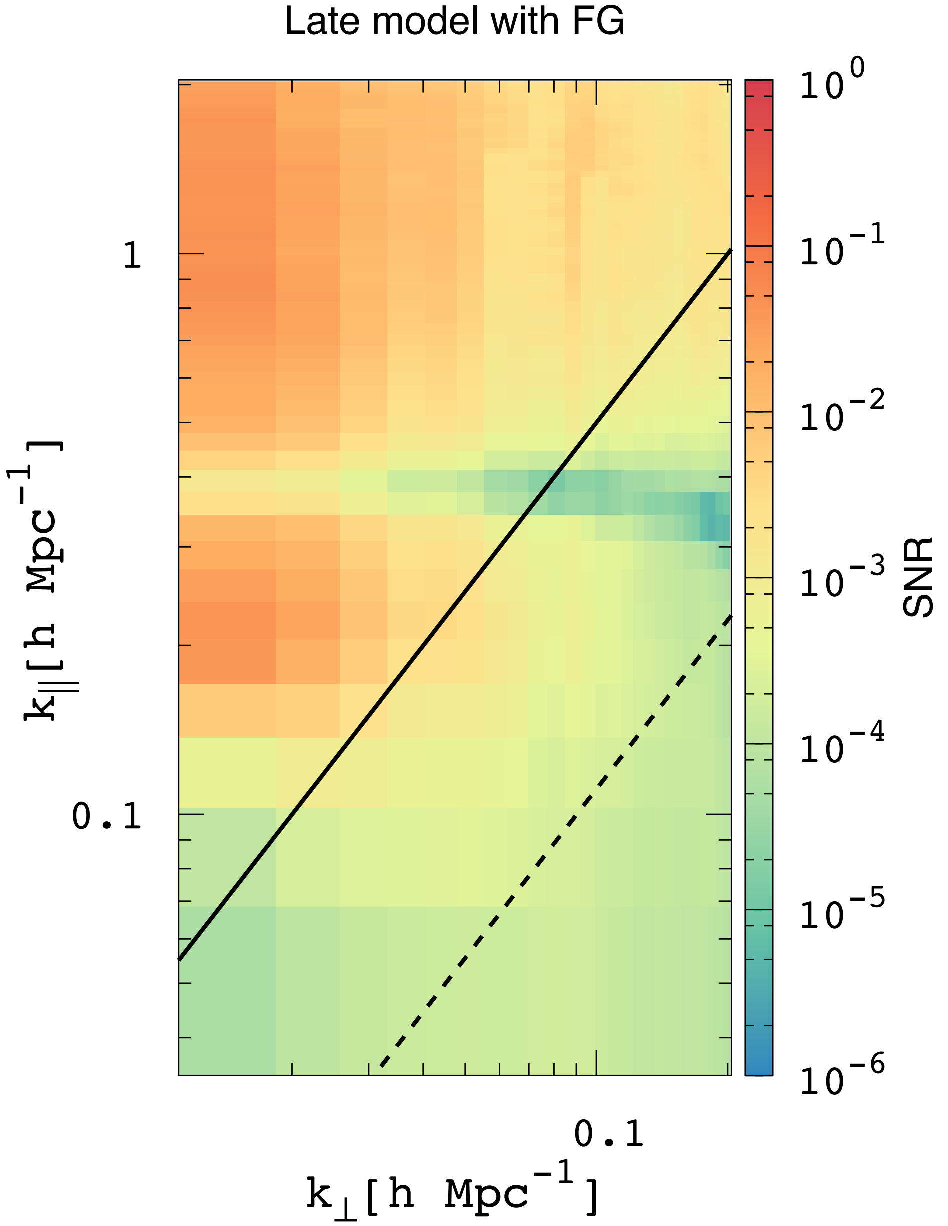
- Foreground wedge and EoR window structure are shown.
- The leakage of foreground power into EoR window
- Diffuse FG is strong at large scales.

S/N ratios in 2D plane

without FG



with FG



S/N is drastically reduced in the wedge by the FG.

S/N is relatively high in the EoR window(S/N~0.1).

We need to subtract FGs in order to detect the signal.

Lyα transmission rate

$$T_{\alpha,\mathrm{IGM}} = \frac{\int \phi_\alpha(\nu_0)\ e^{-\tau_{\nu_0,\mathrm{IGM}}} d\nu_0}{\int \phi_\alpha(\nu_0) d\nu_0}\ ,$$

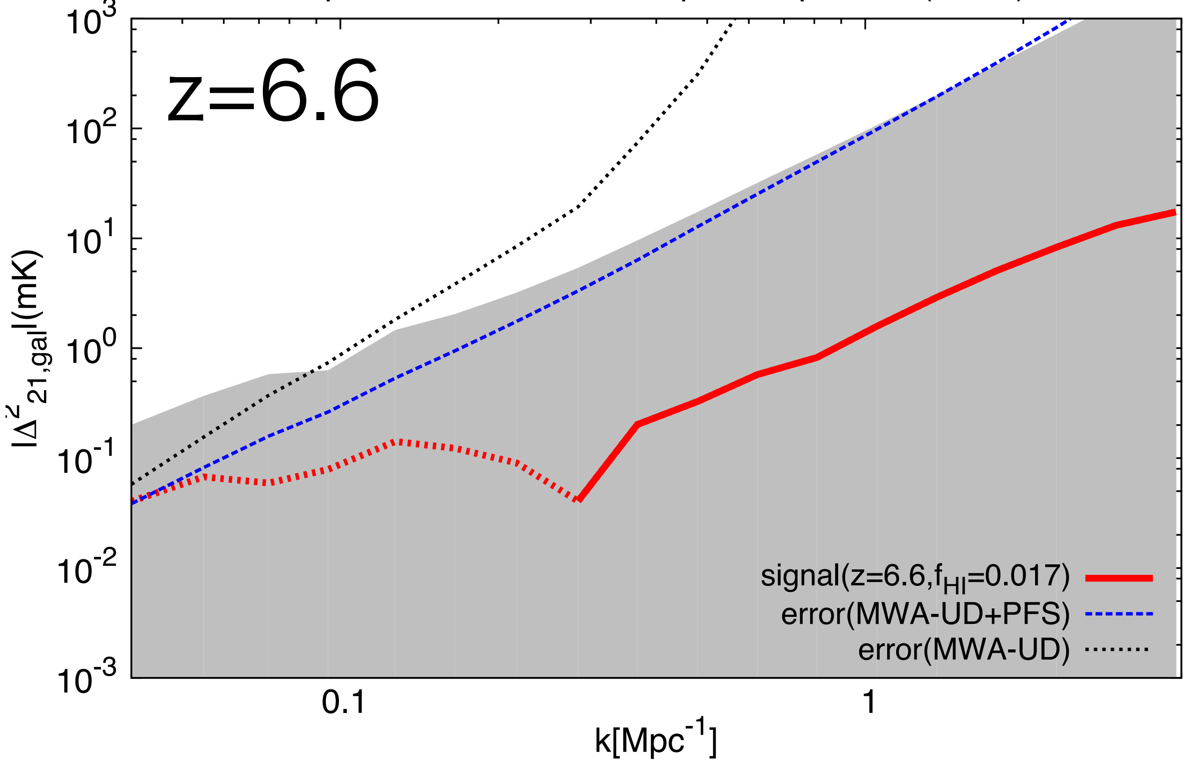
Optical depth thorough the IGM

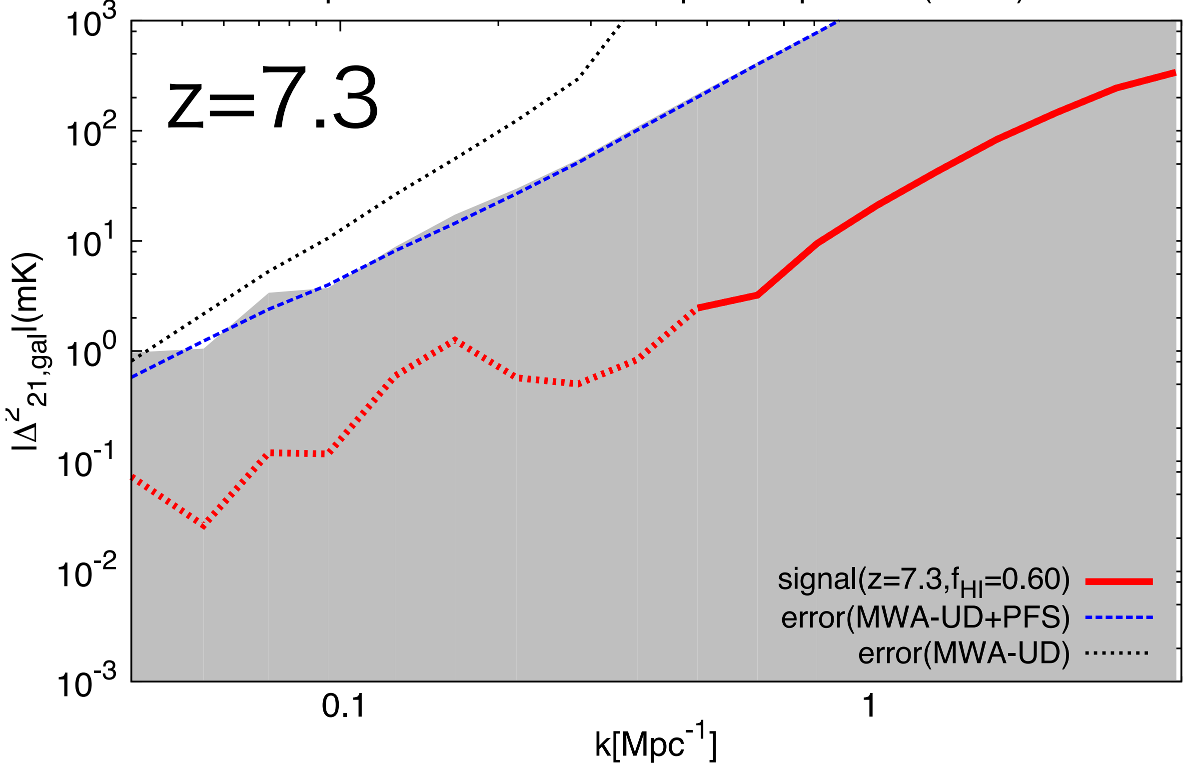
$$\tau_{\nu_0,\mathrm{IGM}} = \int_{r_{\mathrm{vir}}}^{l_{\mathrm{p,max}}} s_\alpha(\nu, T_{\mathrm{g}}) n_{\mathrm{H\,I}} dl_{\mathrm{p}},$$

S_α is the Lymanα cross section of neutral hydrogen.

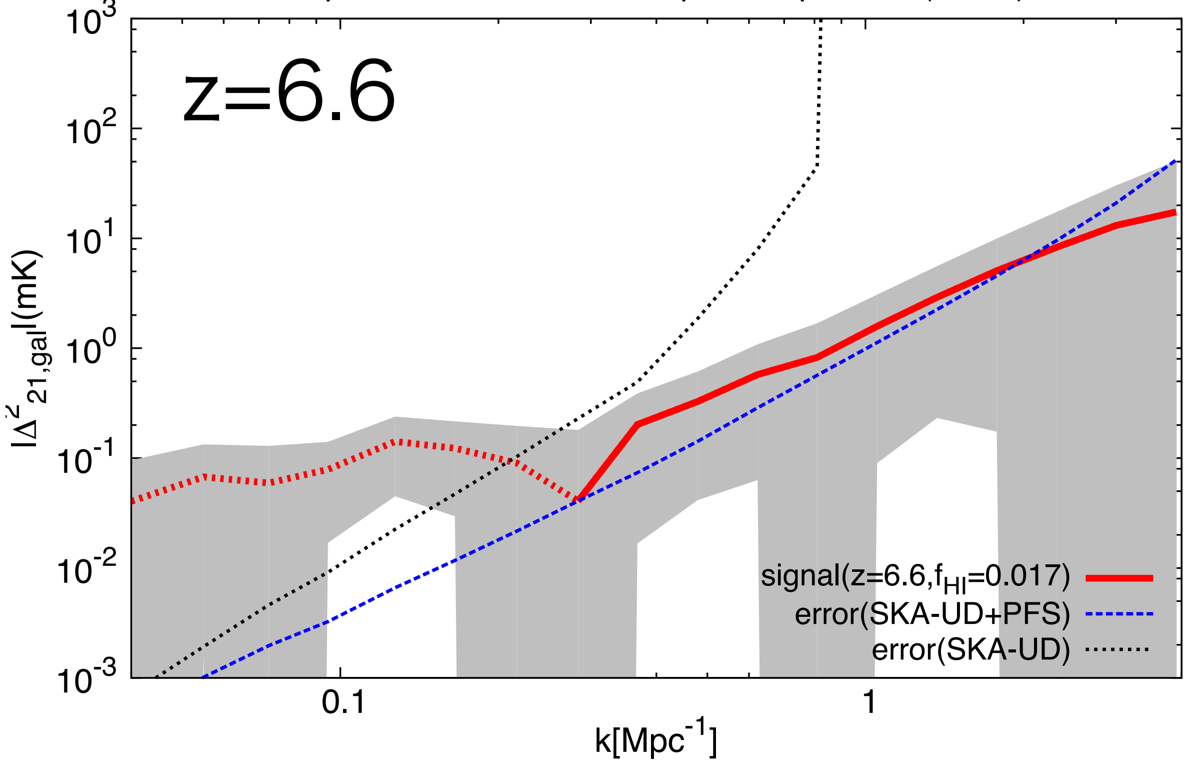
- The line profile is obtained by solving Lyα transfer with an expanding spherical cloud model(Yajima et al 2017).
- The line profile is controlled by the galactic window velocity and HI column density in a galaxy.

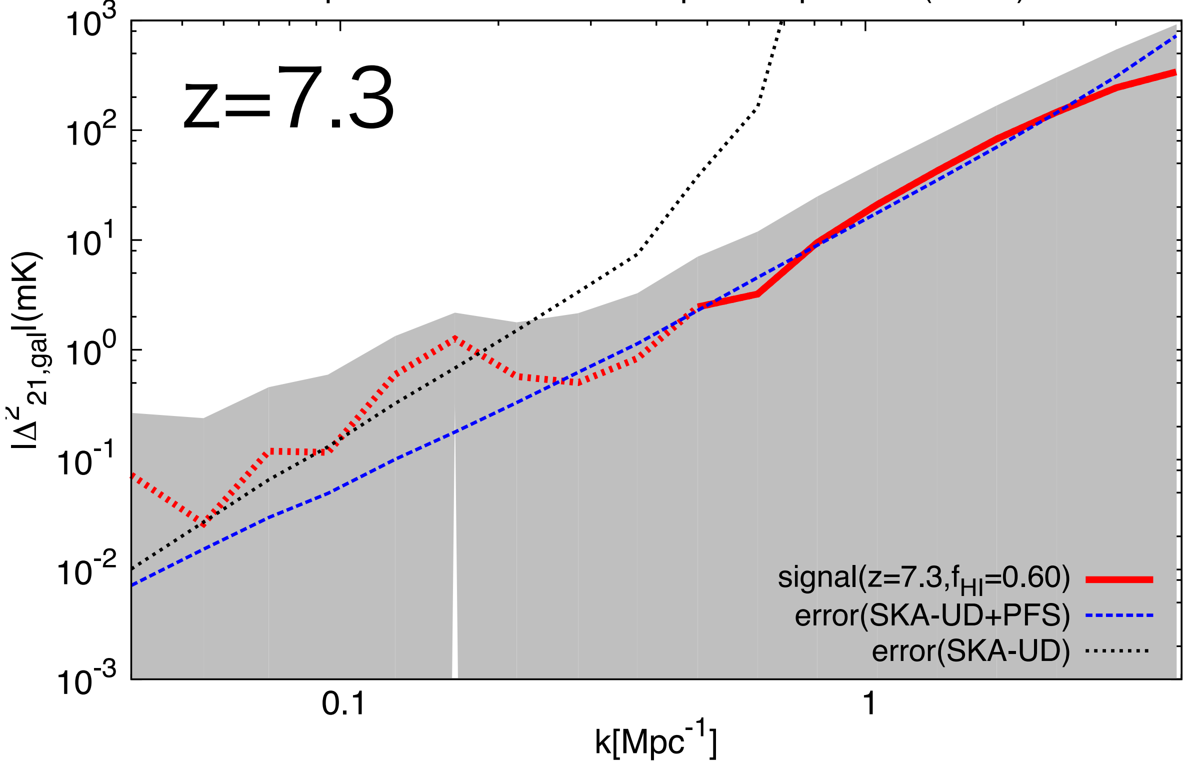
MWA×UD


Expected errors on cross power spectrum(z=6.6)

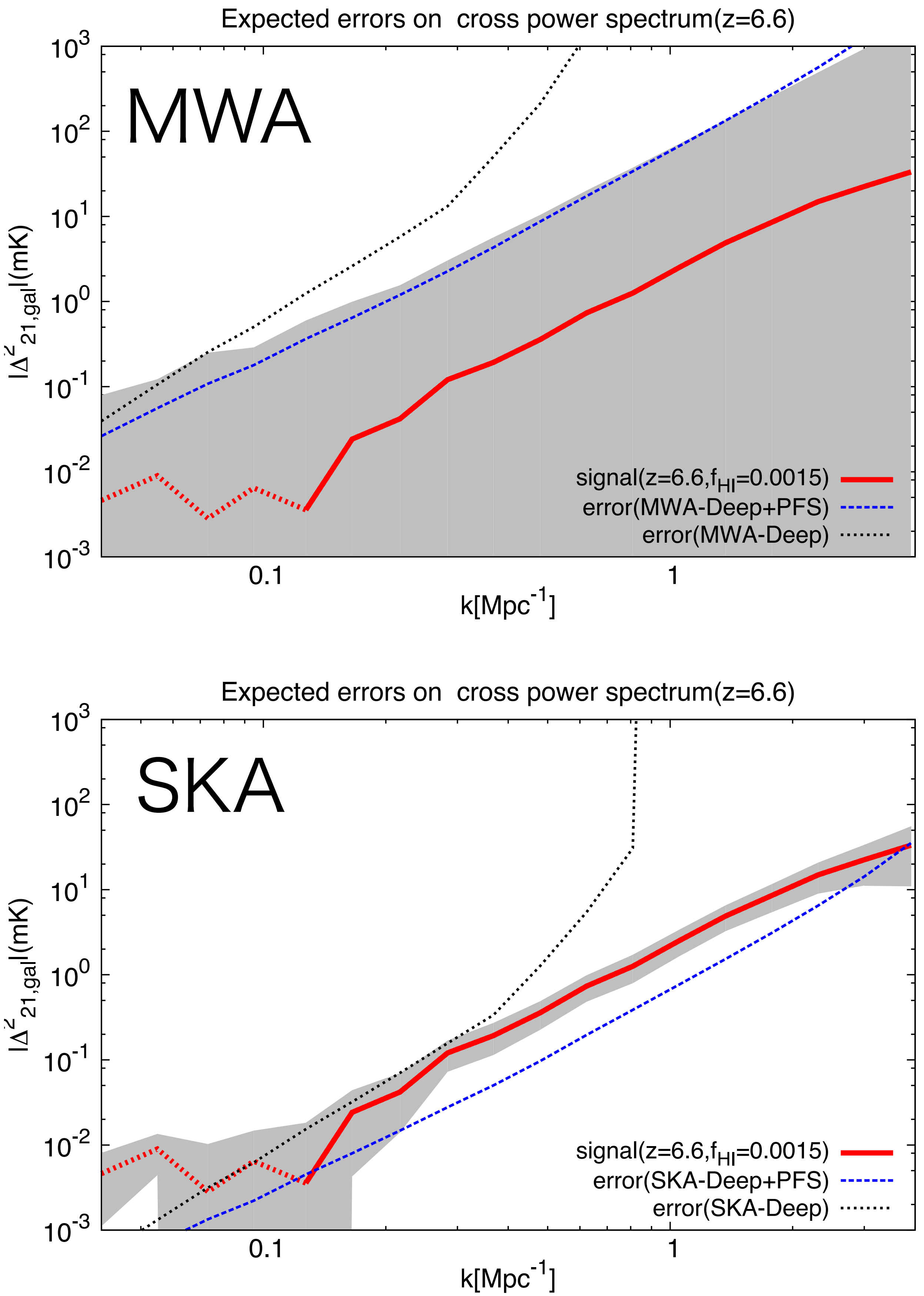

Expected errors on cross power spectrum(z=7.3)

SKA×UD

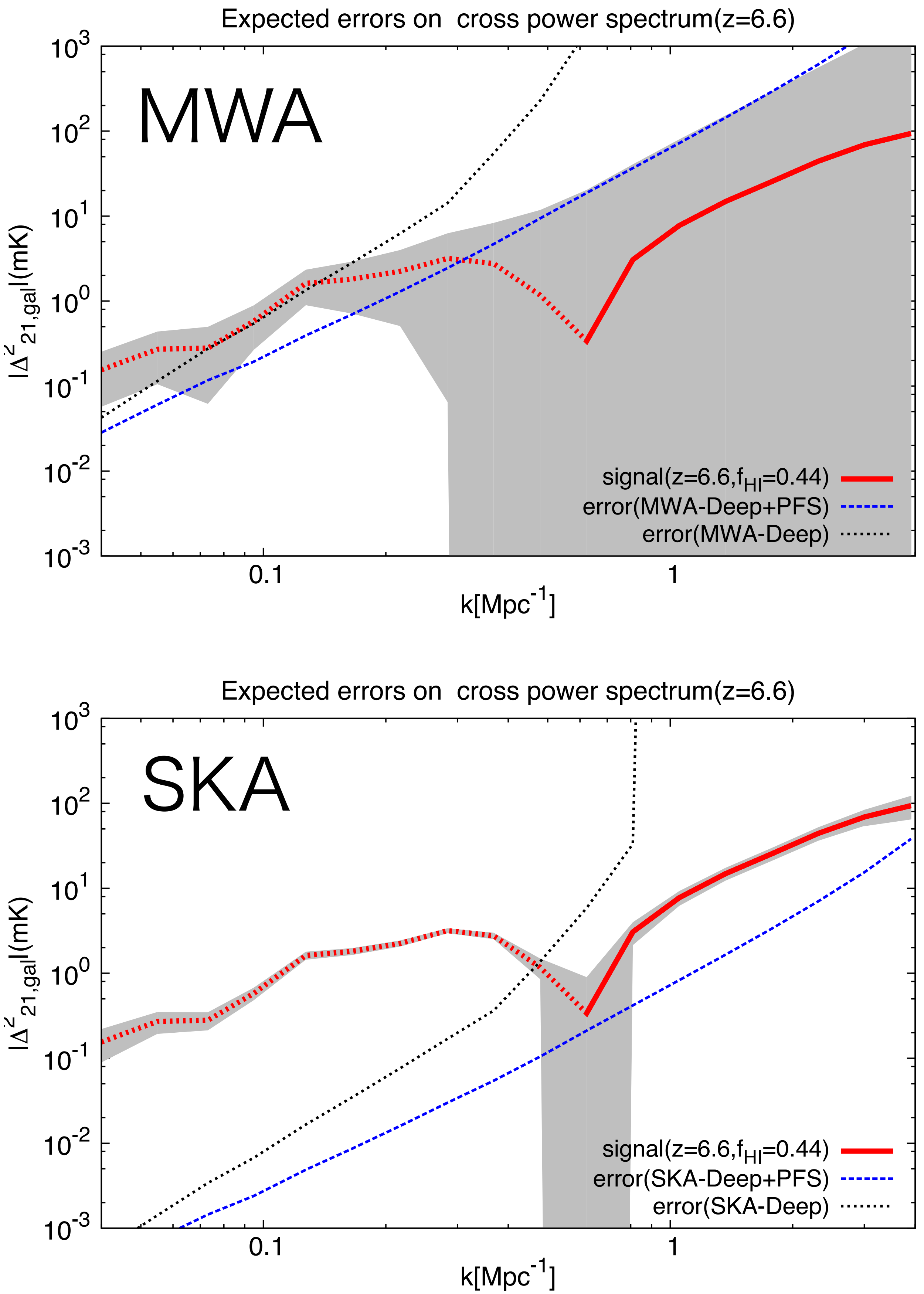

Expected errors on cross power spectrum(z=6.6)


Expected errors on cross power spectrum(z=7.3)

early model(f_HI=0.0015)



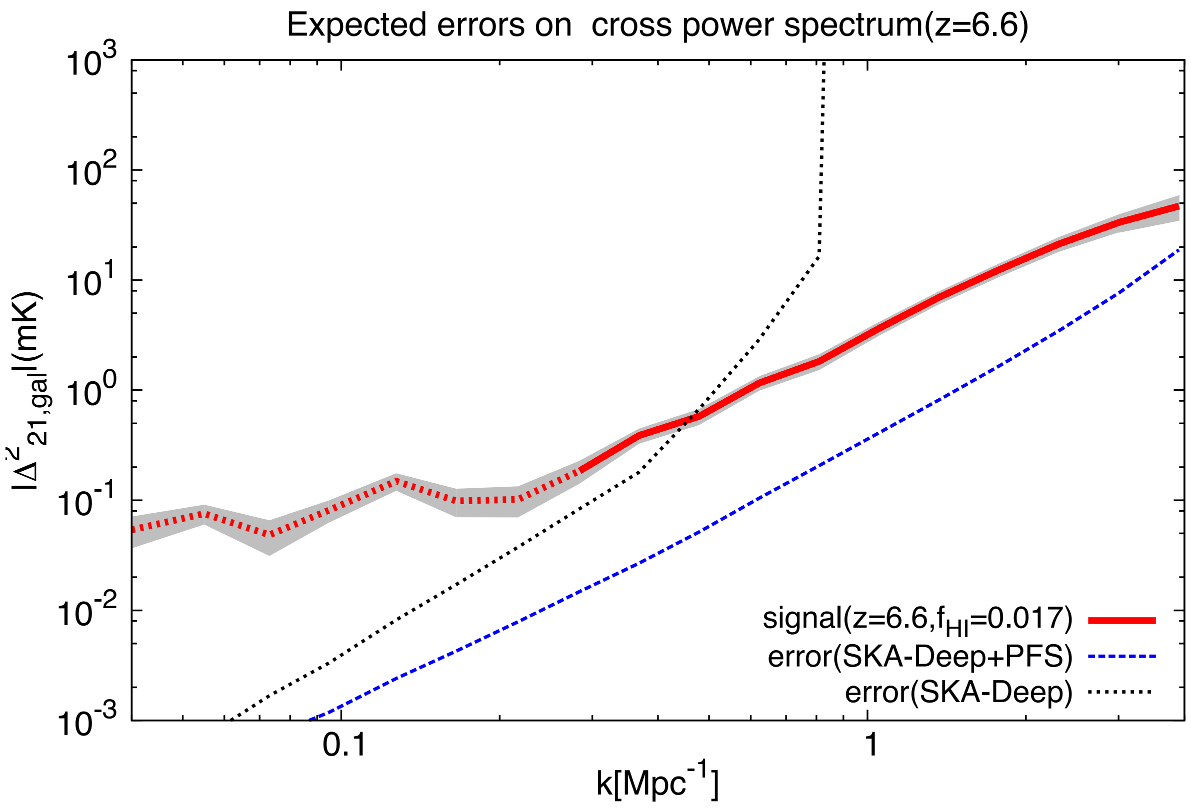
late model(f_HI=0.44)



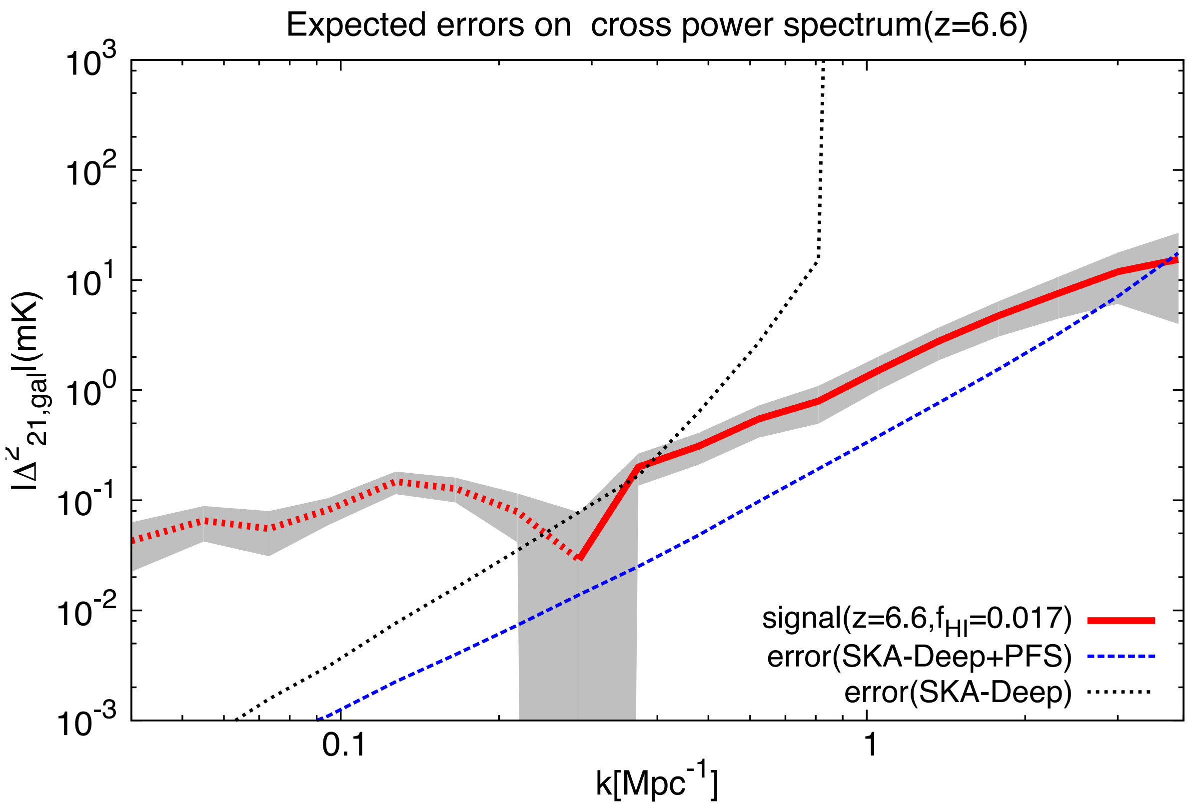
Extensions of HSC Deep(SKA)

(1) a larger survey area

(2) a longer observation time per pointing

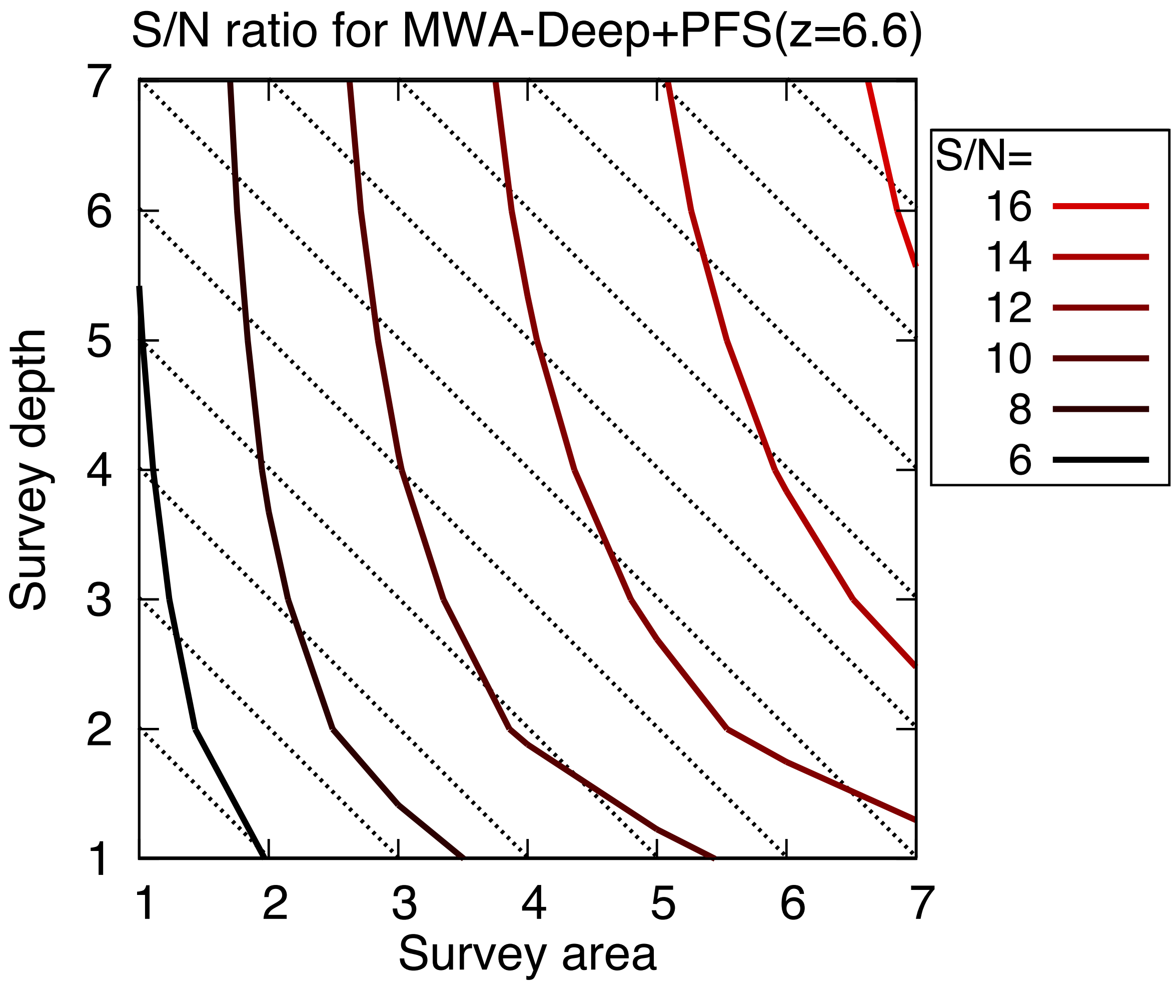


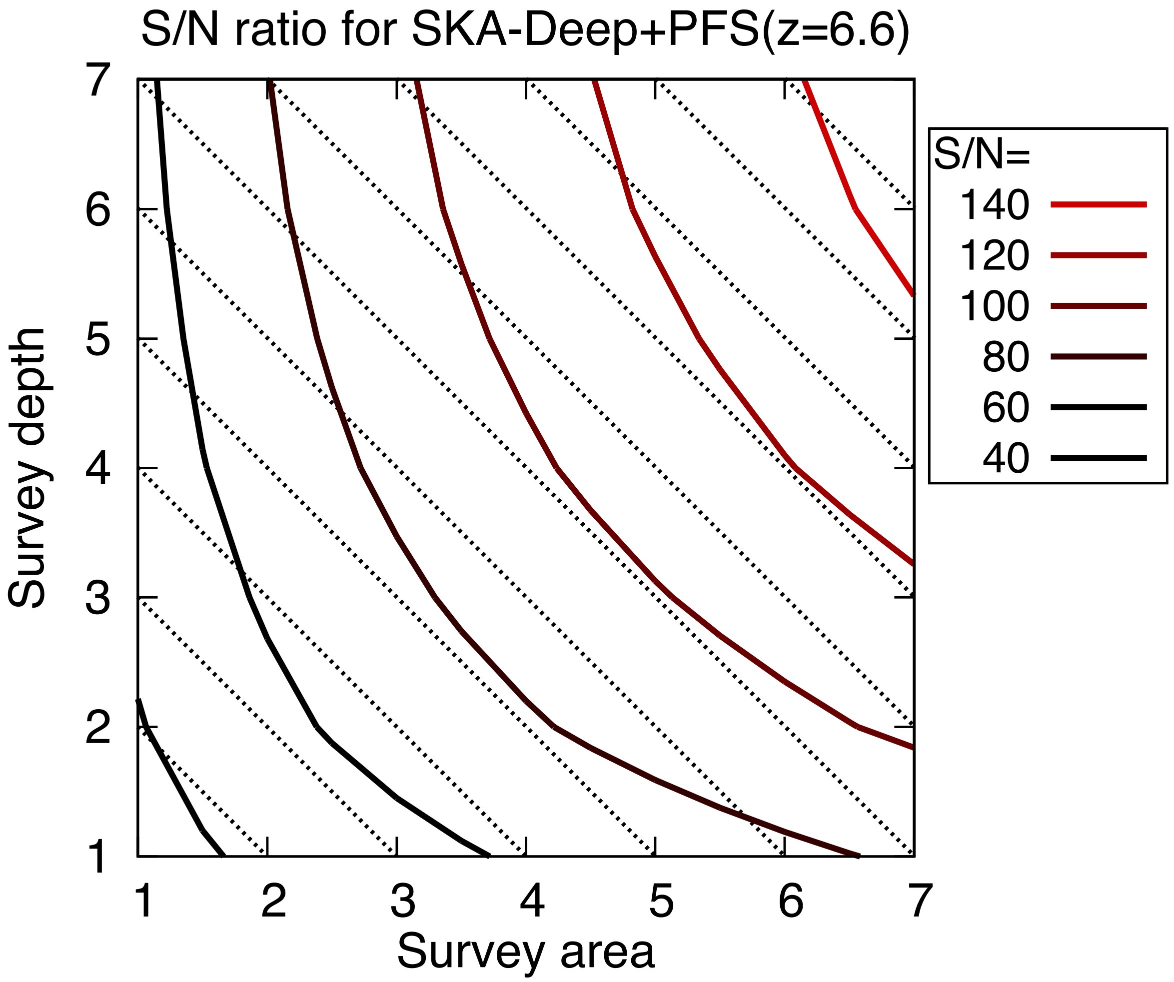
(1) S/N=20



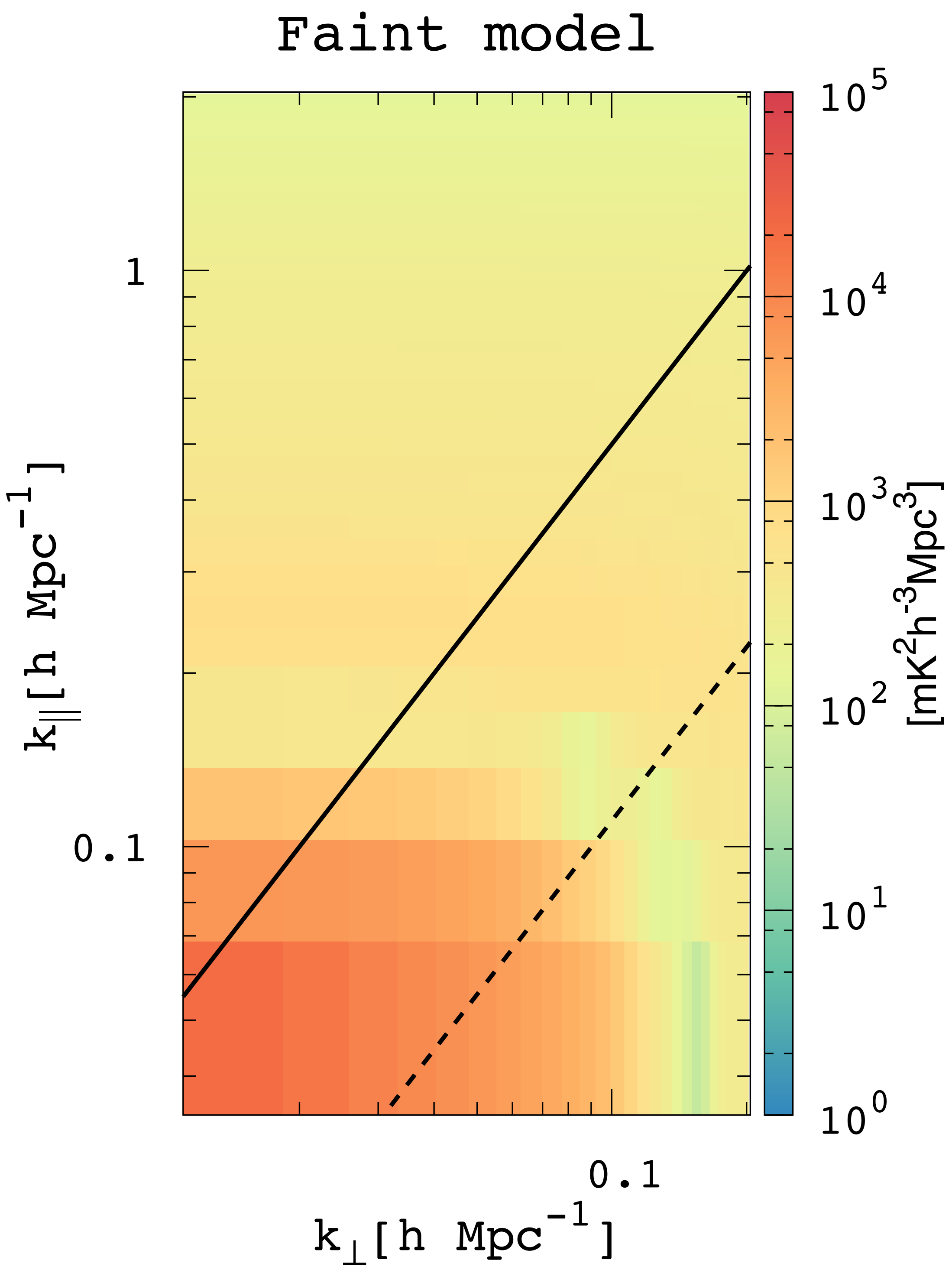
(2) S/N=11

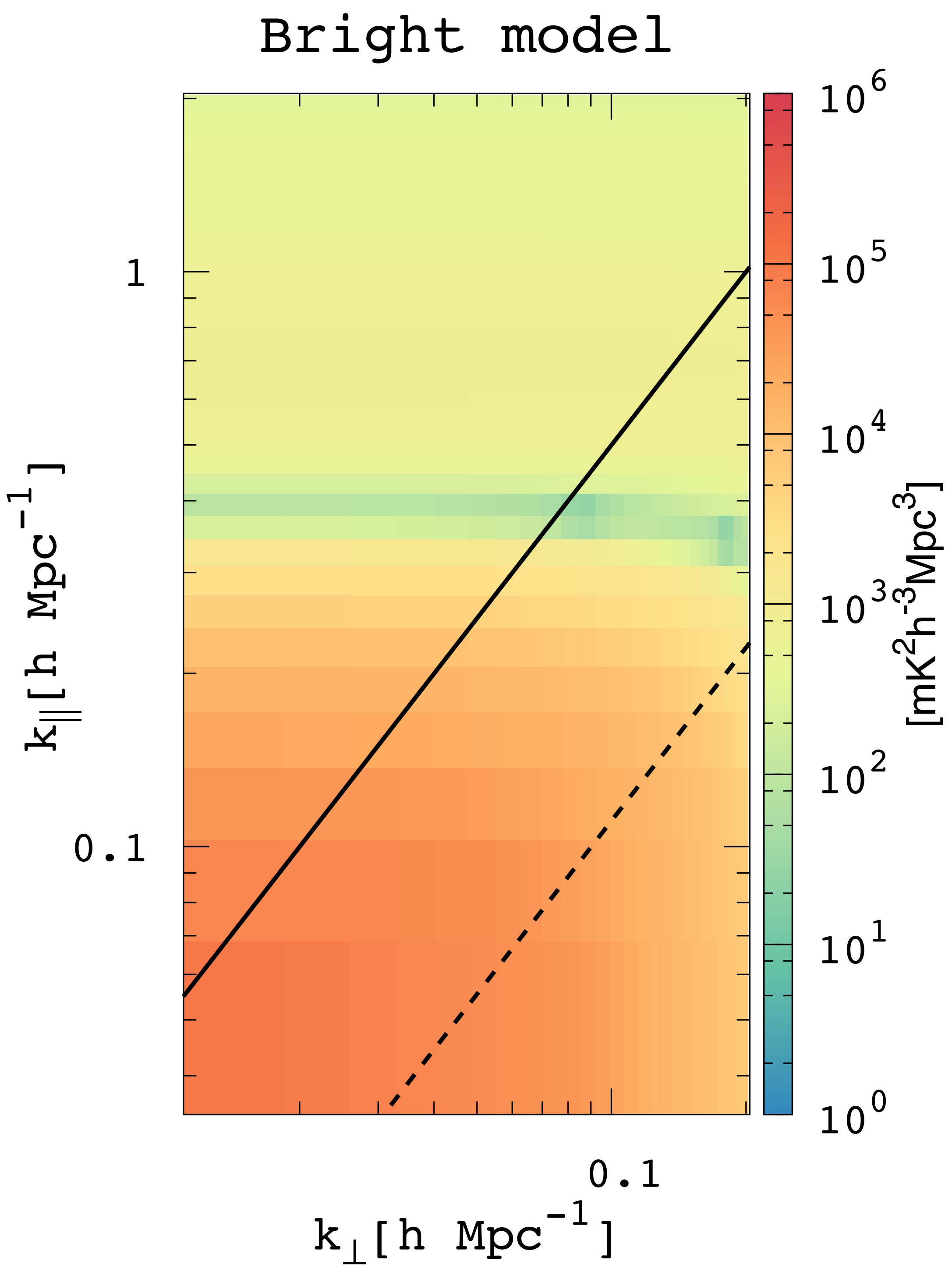
Extensions of HSC Deep(late)





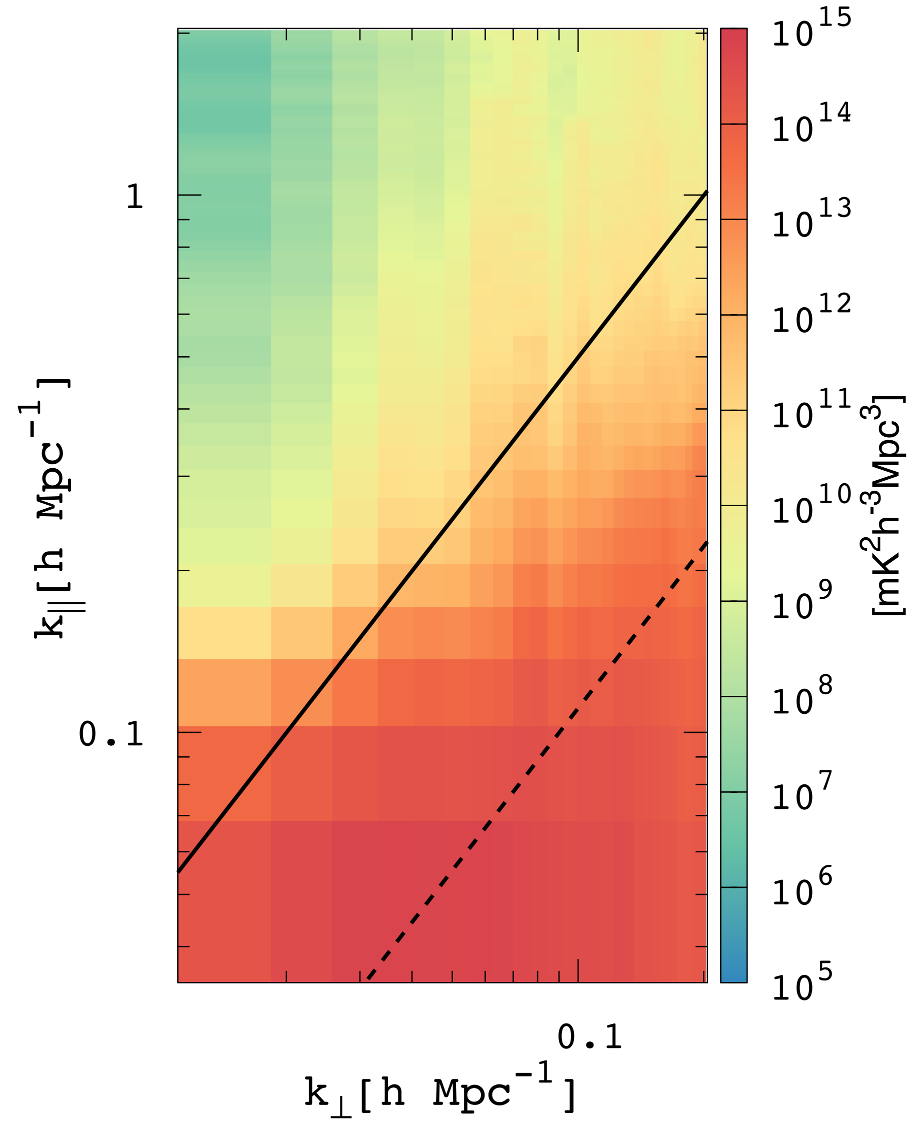
2D power spectrum



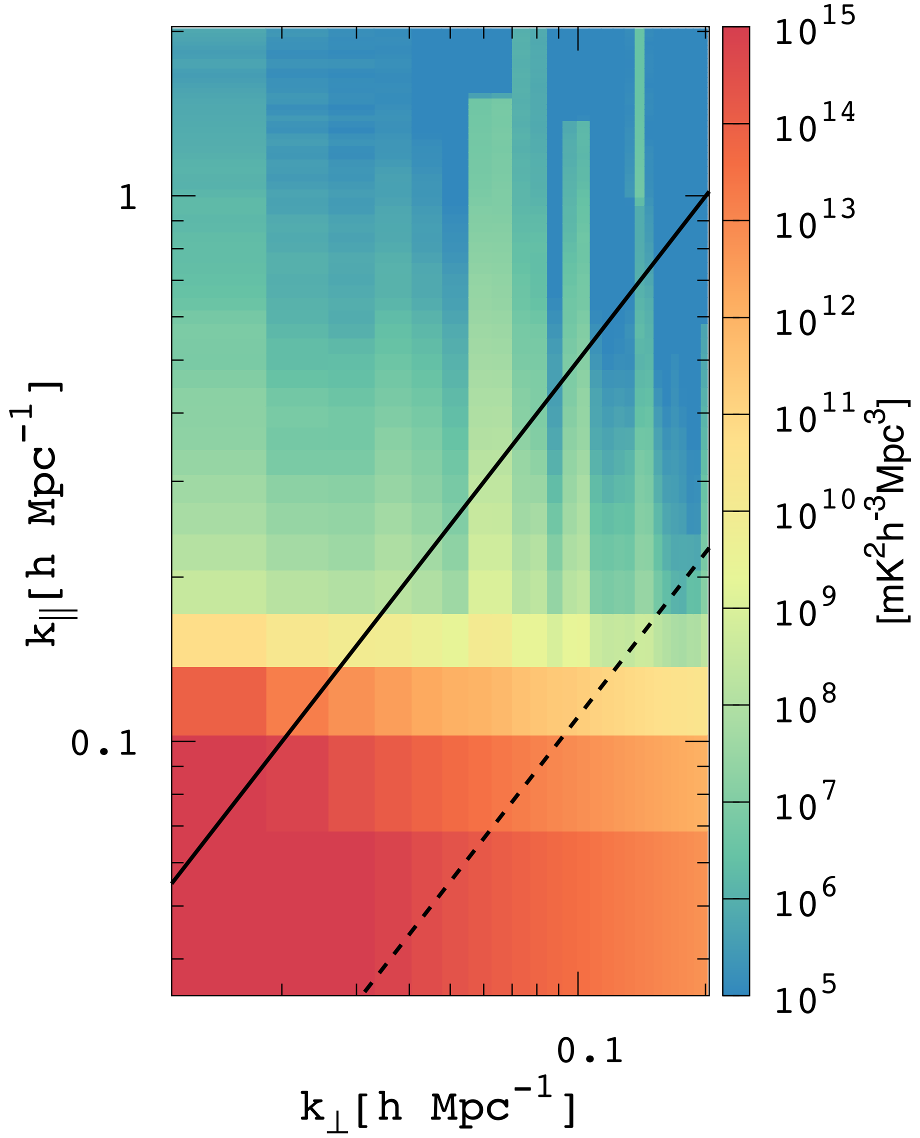


2D power spectrum

Point sources



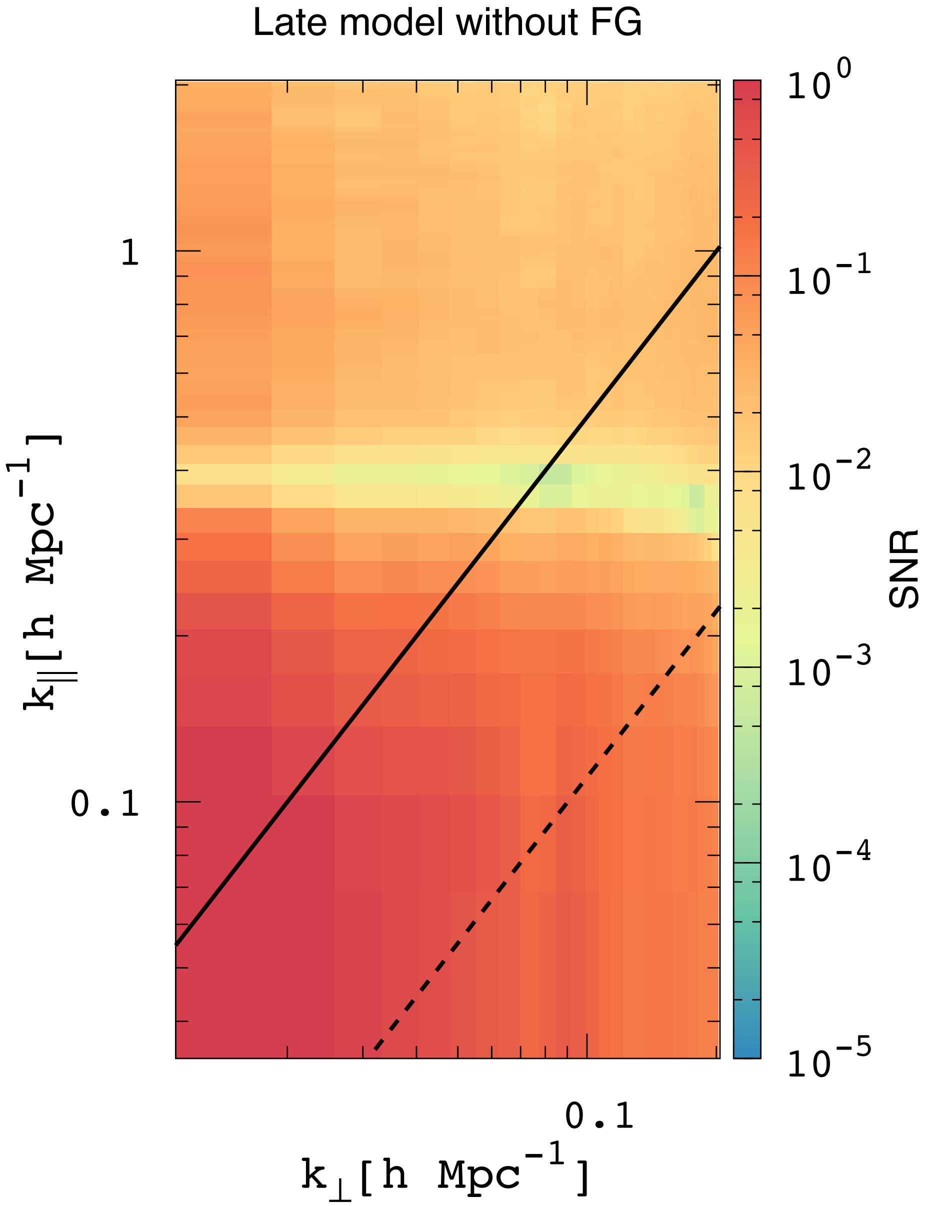
Diffuse foreground



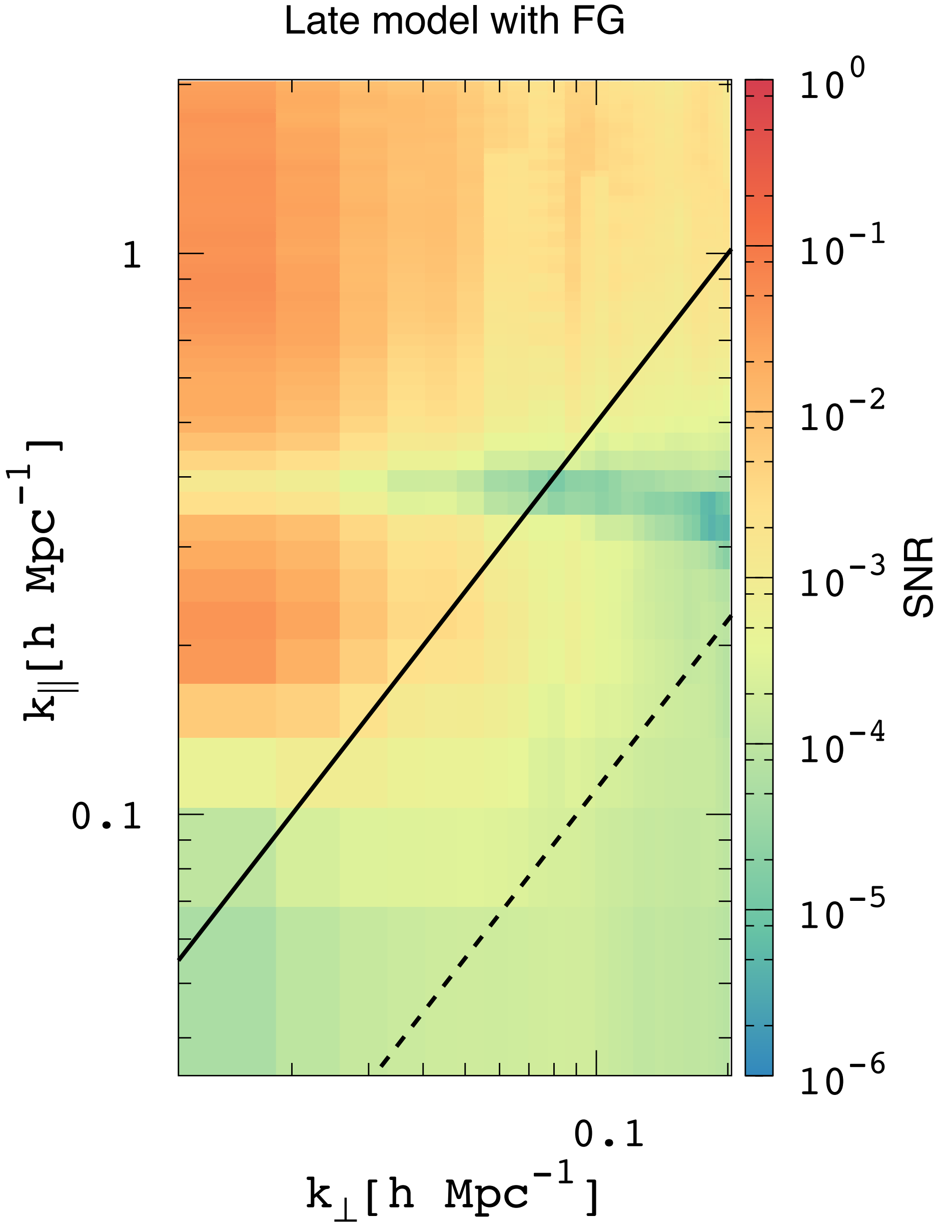
- Foreground wedge and EoR window structure are shown.
- The leakage of foreground power into EoR window
- Diffuse FG is strong at large scales.

S/N ratios in 2D plane

without FG



with FG



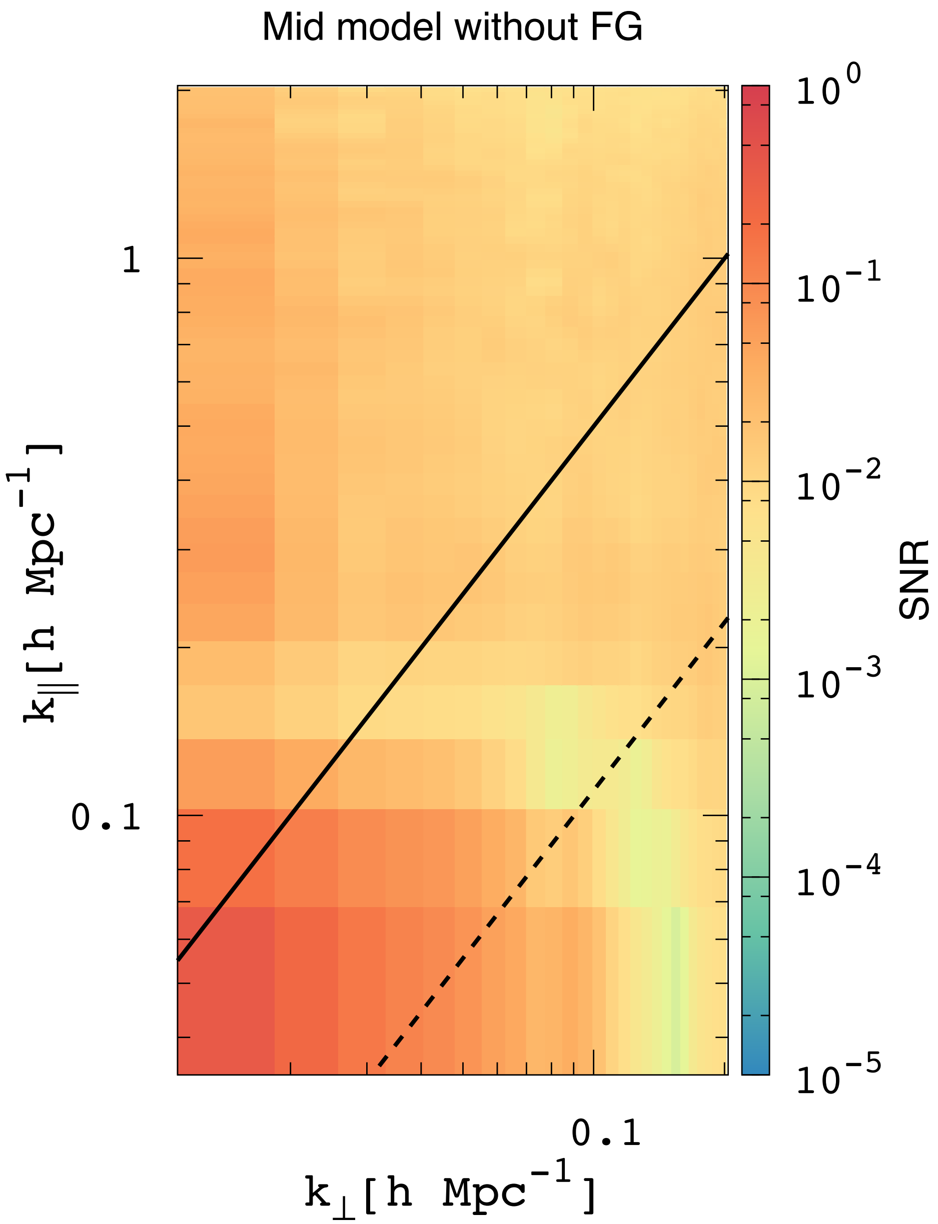
S/N is drastically reduced in the wedge by the FG.

S/N is relatively high in the EoR window(S/N~0.1).

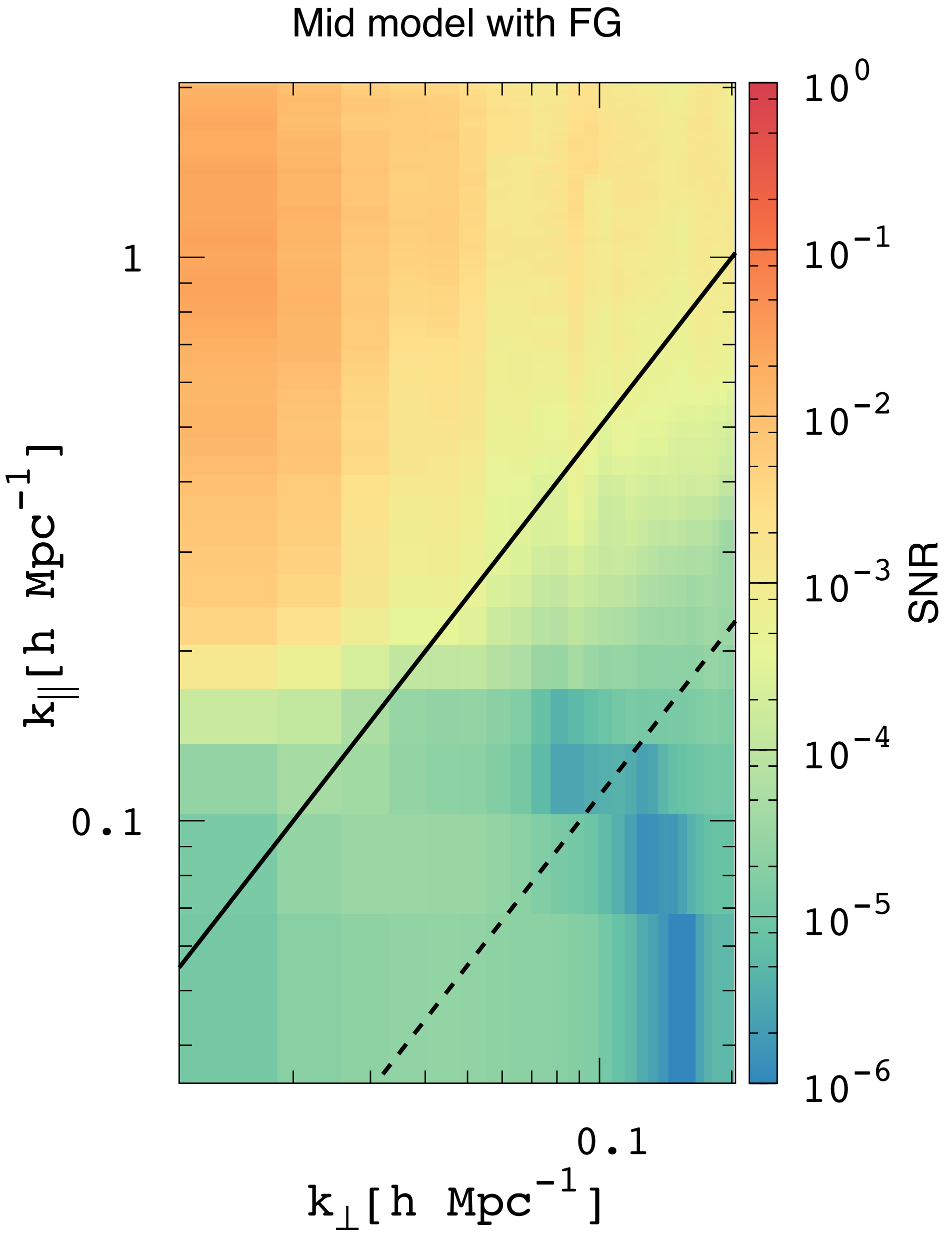
We need to subtract FGs in order to detect the signal.

S/N ratios in 2D plane(mid model)

without FG



with FG



S/N is high at large scales without FG.

S/N is drastically reduced in the wedge by the FG.

1D power spectrum(21cm auto)