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Velocity Acoustic Oscillations Signature on the 21 cm Signal of Cosmic Dawn

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The history of the Universe:

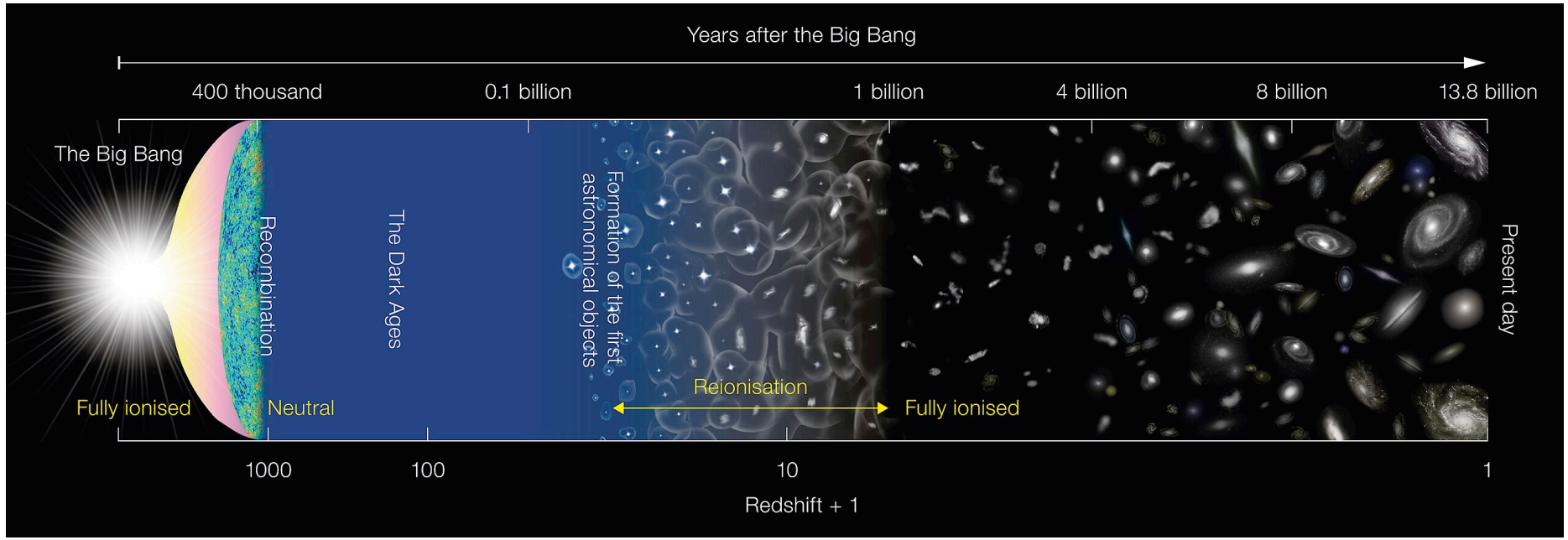
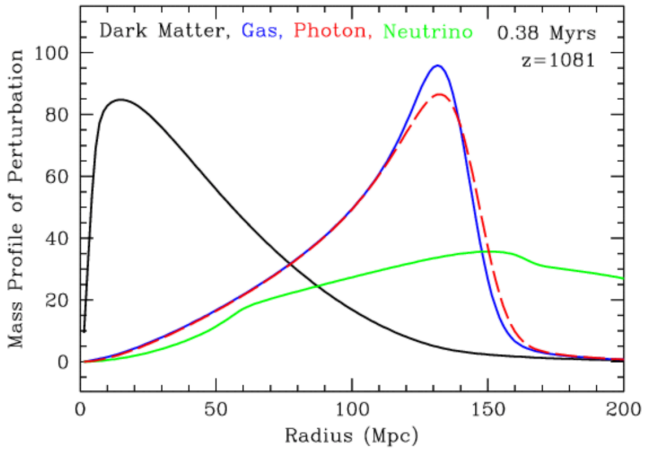


image credit: NAOJ

pre-recombination



after recombination

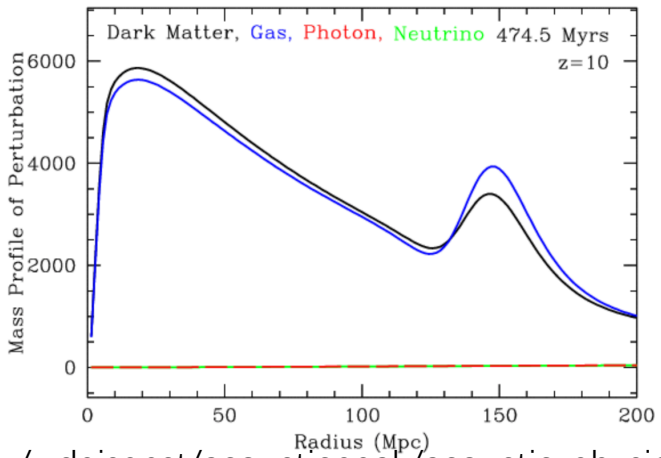
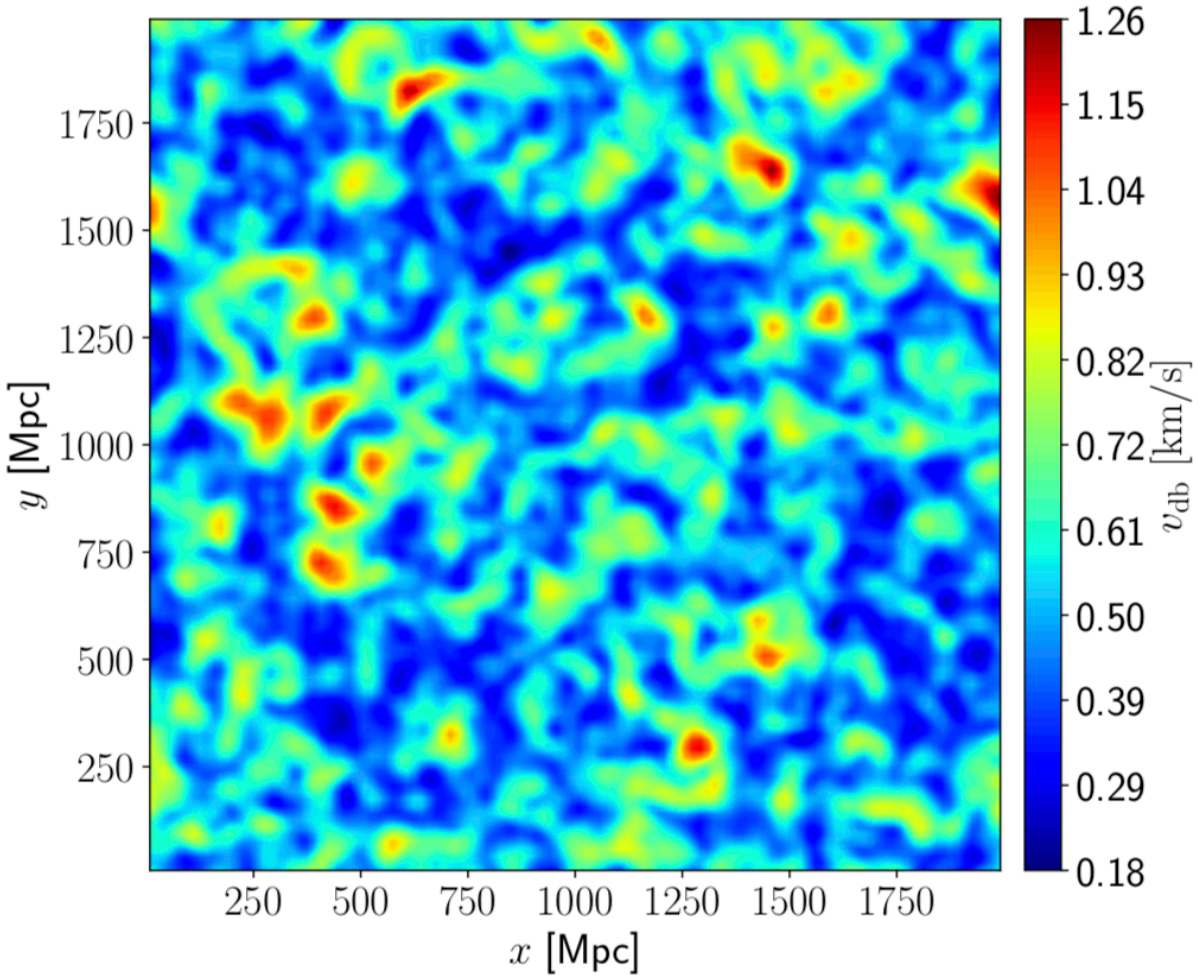


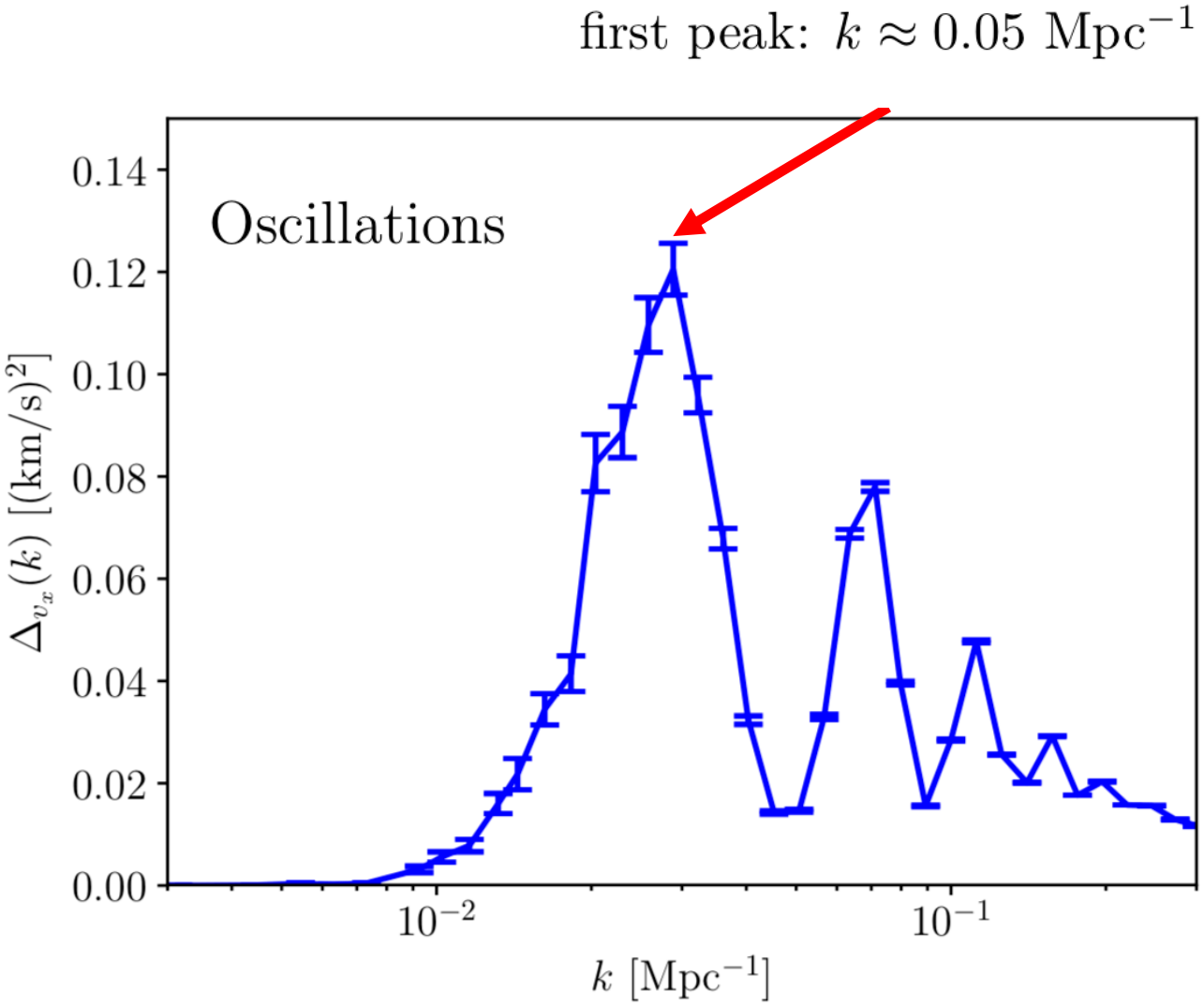
image credit: https://lweb.cfa.harvard.edu/~deisenst/acousticpeak/acoustic_physics.html

- Before recombination: baryon couples with photons while DM not, their **density** and **velocity** are all different;
- After recombination, DM density profile approaching to baryon via gravity, **relative velocity** decaying.

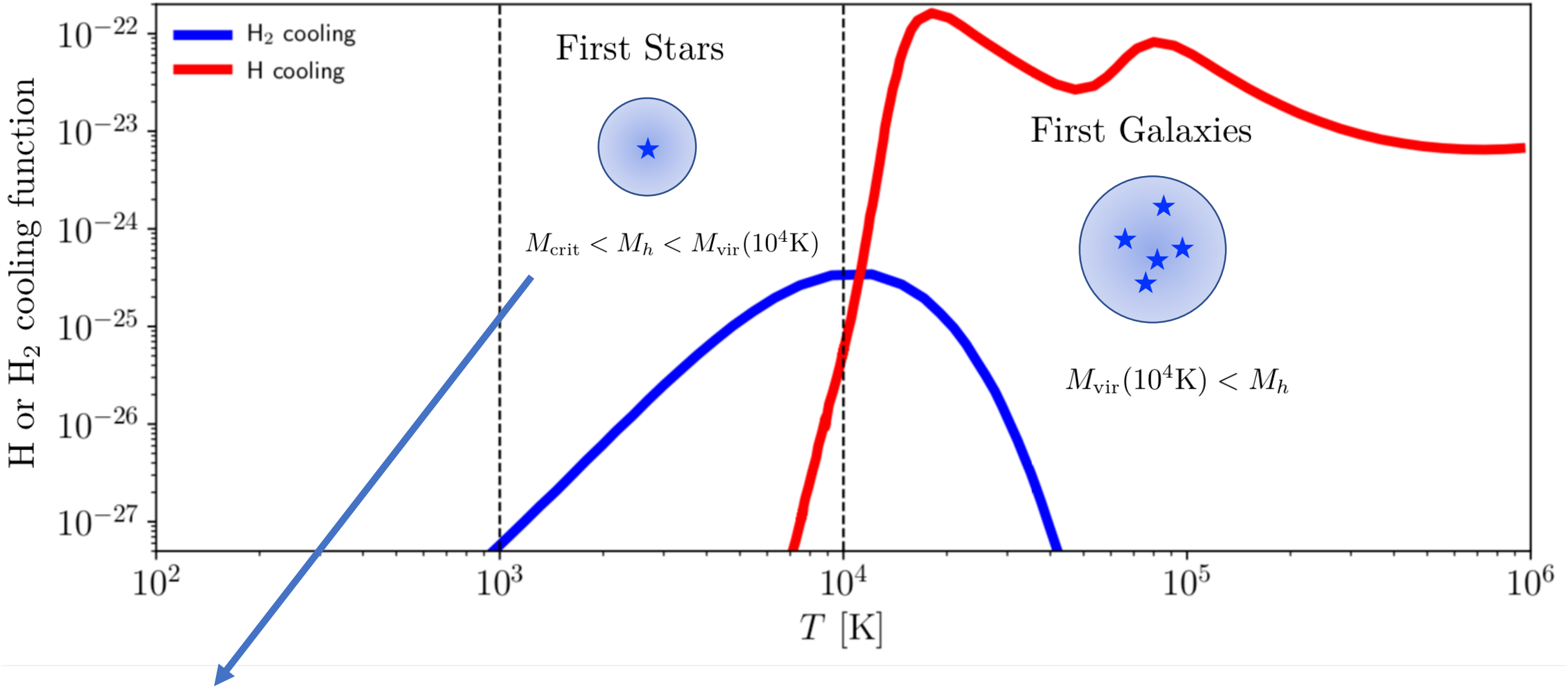
Velocity Acoustic Oscillations (VAO)：



DM-baryon relative velocity field



relative velocity power spectrum

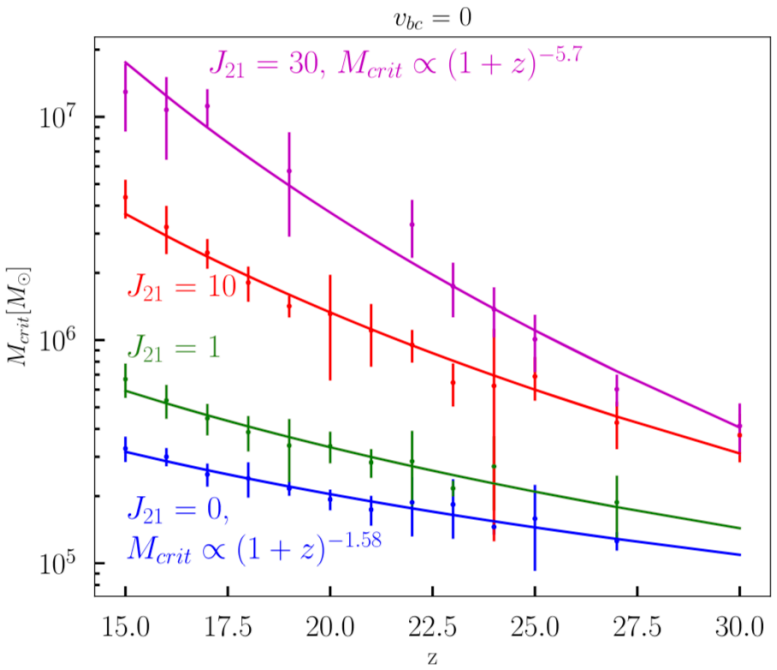


$M_{\rm crit}$: the minimum halo mass for Pop III formation; depends on cooling mechanism, LW, X-ray, and $v_{\rm db}$...

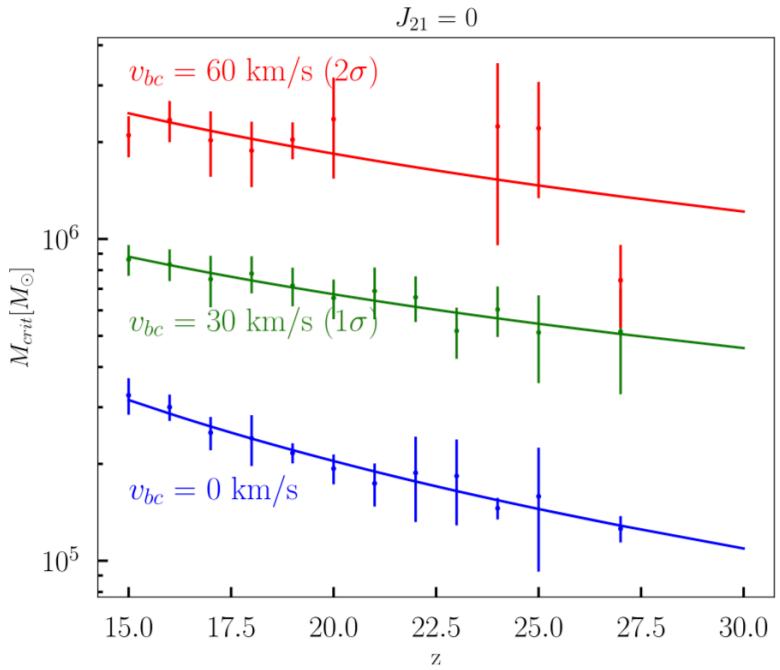
The velocities of relative streaming motion: $\left\langle v_{\rm db}^2 \right\rangle^{1/2} \approx 30 \left(\frac{1+z}{1081} \right)$ [km/s]

At Cosmic Dawn, it is not negligible compared with the circular velocity of a minihalo with $T_{\rm vir} \sim 10^3$ K, so it may reduce the gas content and star formation rate in that halo.

Dependence on LW:



Dependence on relative velocity:



Kulkarni et al. 2021

$$f_{\rm coll}(z|\delta_{\rm cell}, M_{\rm cell}, v_{\rm cell}^{\rm db}) = \int_{M_{\rm crit}(z, J_{\rm cell}^{\rm LW}, v_{\rm cell}^{\rm db})}^{M_{\rm max}} M \frac{dn}{dM}(z|\delta_{\rm cell}, M_{\rm cell}) dM$$

BAO

VAO

$$\rho_{\rm cell}^{\rm SFR} = f_* \frac{\Omega_b}{\Omega_m} \rho_m \frac{df_{\rm coll}}{dt}$$

21cmFAST

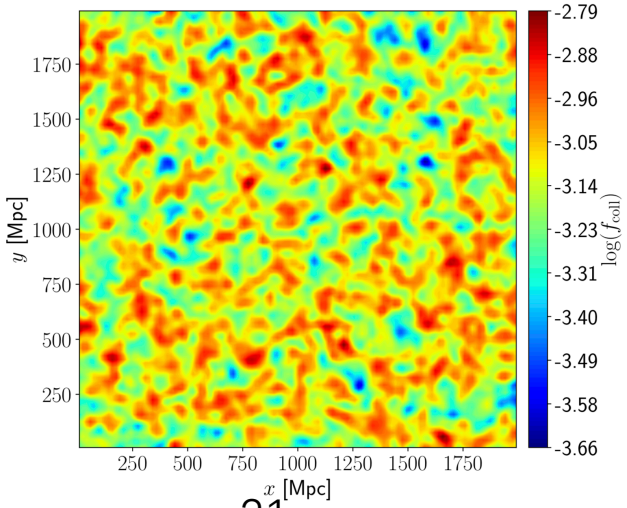
$$\epsilon_{\rm cell}^{\alpha} \propto \rho_{\rm cell}^{\rm SFR}, \epsilon_{\rm cell}^{X} \propto \rho_{\rm cell}^{\rm SFR}$$

Lyα

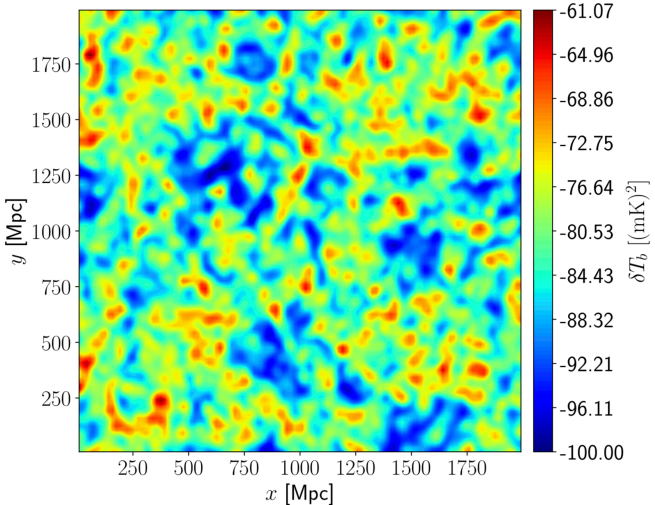
$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_k^{-1}}{1 + x_\alpha + x_c}$$ ← X-ray

$$\delta T_b = 27 x_{\rm HI}(1+\delta_b) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} \left(1 - \frac{T_\gamma}{T_s}\right) \left[\frac{\partial v/\partial r}{(1+z)H(z)}\right] \ {\rm mK}$$

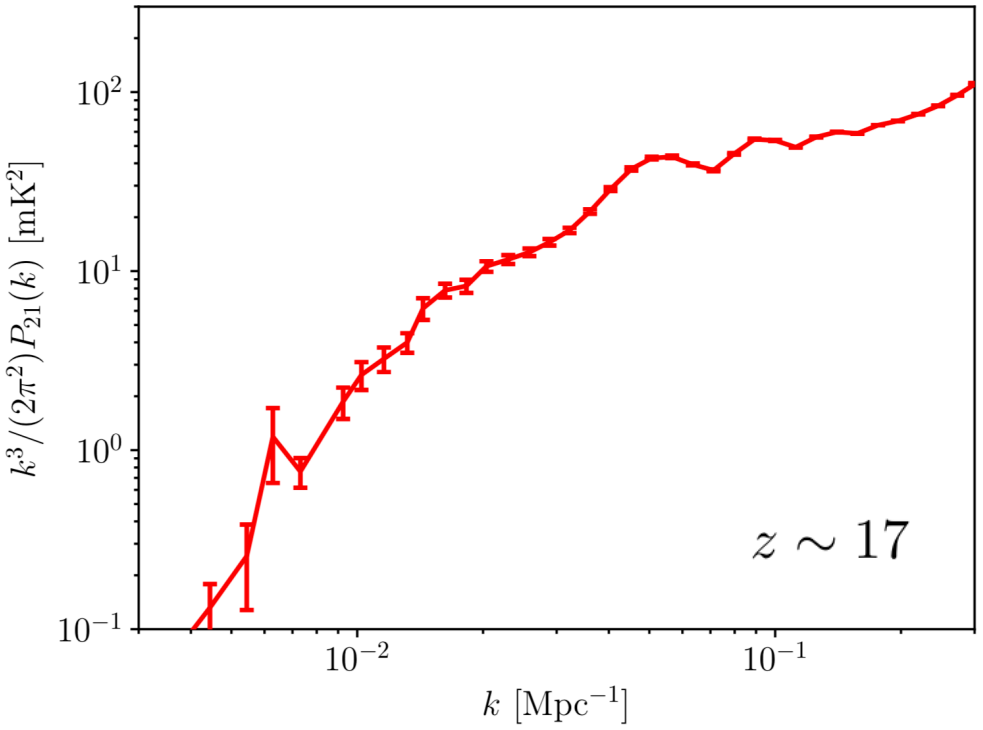
collapse fraction



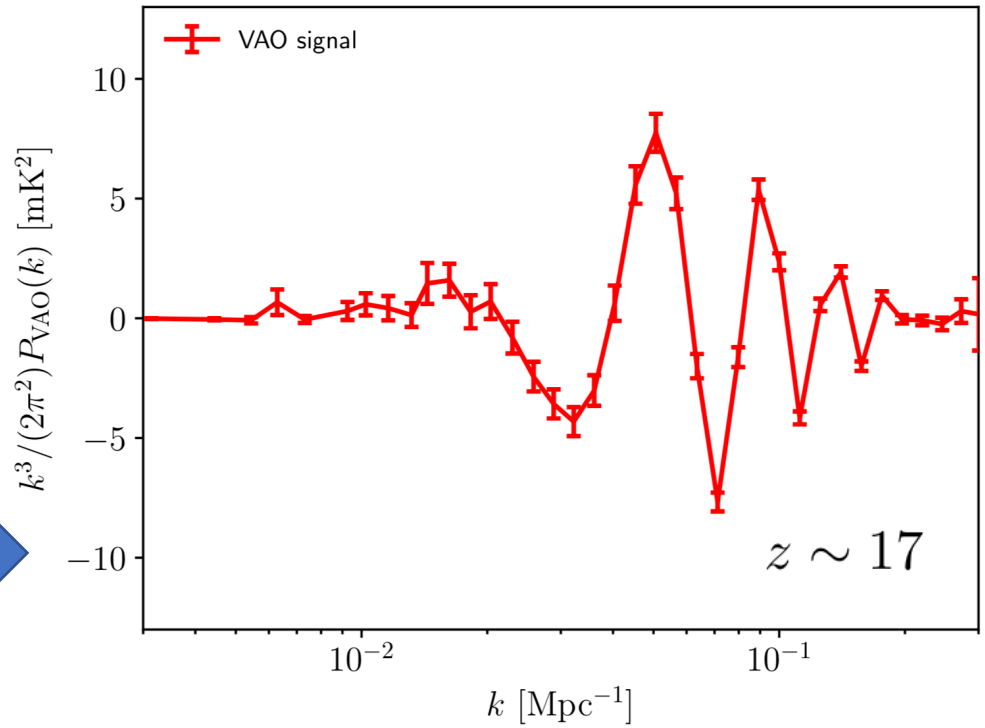
21 cm



21 cm power spectrum:



net oscillations signature:



$$P_{\rm VAO}(k) = P_{21}(k) - P_{21}^{\rm smooth}(k).$$

polynomial

Relic DM-baryon relative velocity generates oscillations signature on the 21 cm spatial structures.

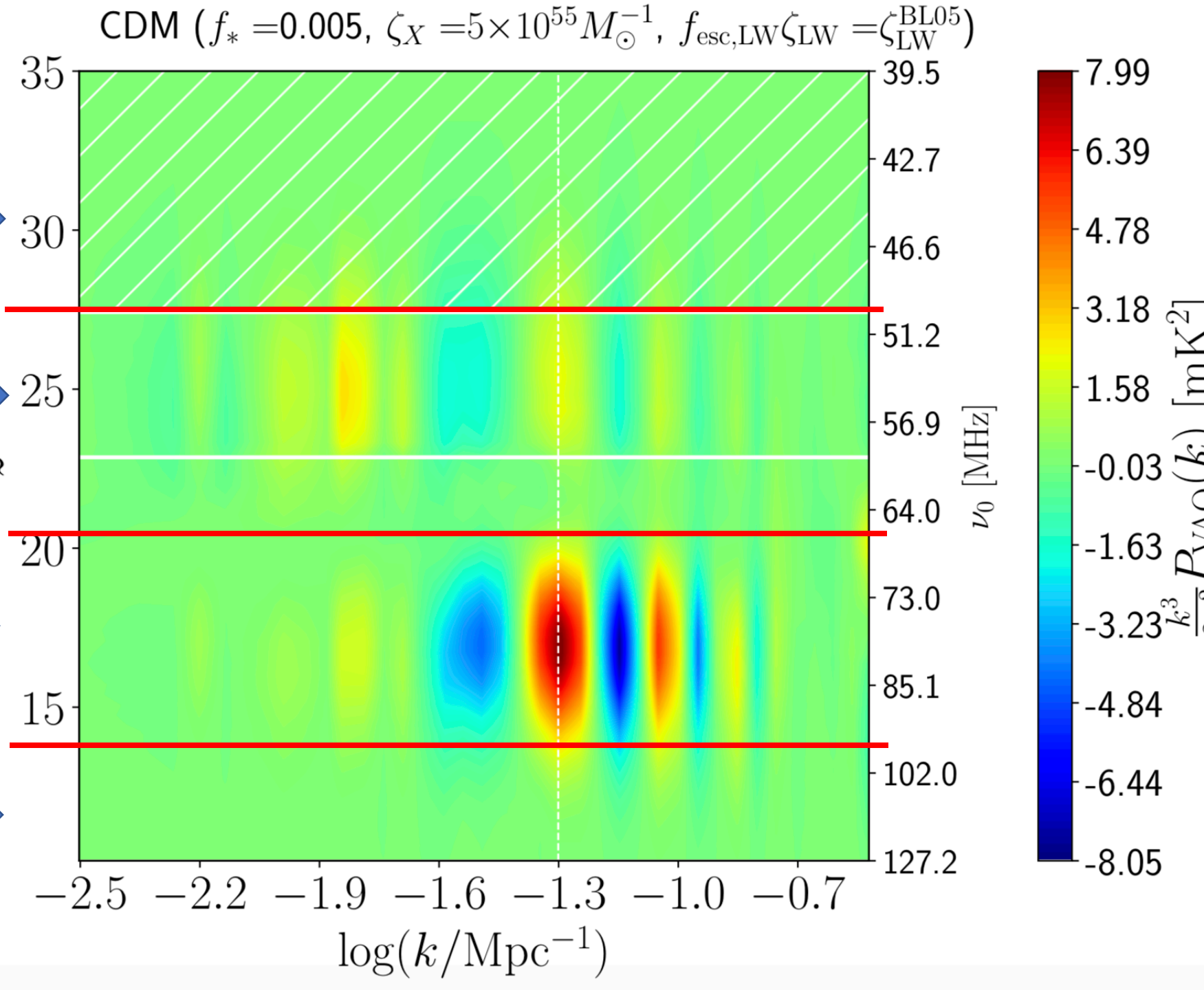
VAO signal evolves with redshift:

below SKA-low band limit

Pop III not abundant enough, weak signal, dominated by Lyα fluctuations

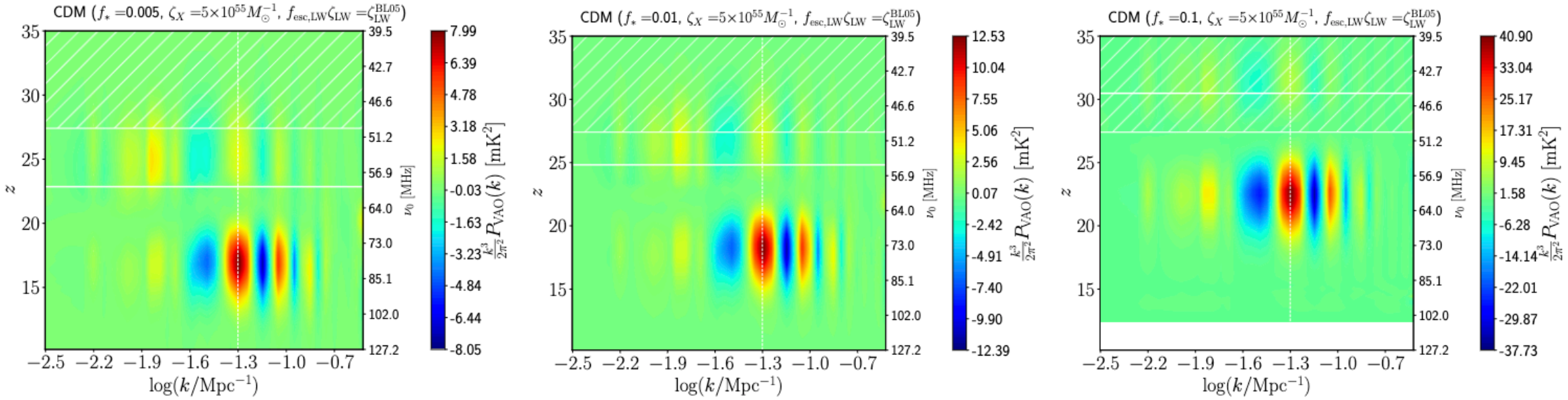
Strong signal, dominated by X-ray fluctuations, golden stage for detecting VAO signal

Lyα saturated and IGM largely heated， 21 cm is almost independent of T_s, VAO signal disappear



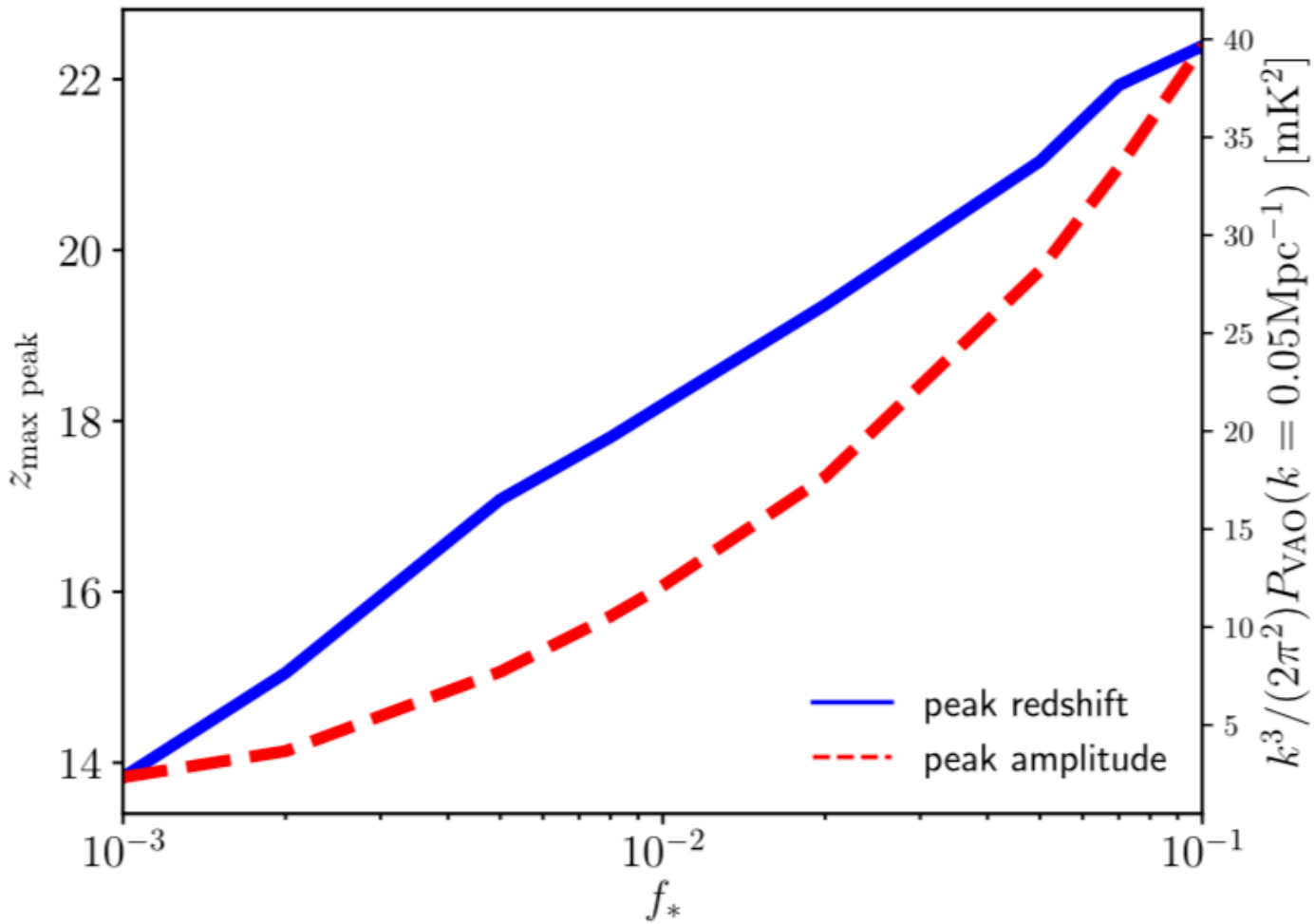
Dependence on Pop III properties: the star formation efficiency

$f_* = 0.005$ $f_* = 0.01$ $f_* = 0.1$



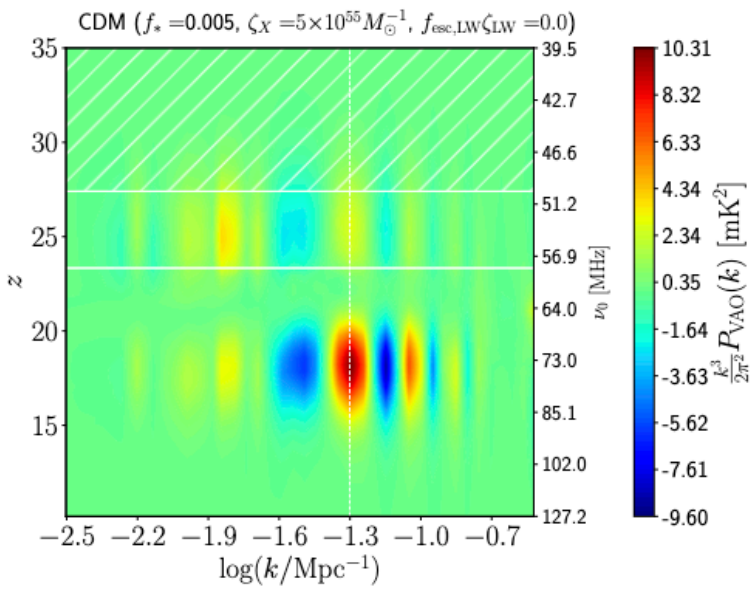
The larger the f_*, the stronger & earlier the VAO signal

The VAO peak amplitude & redshift as a function of f_*

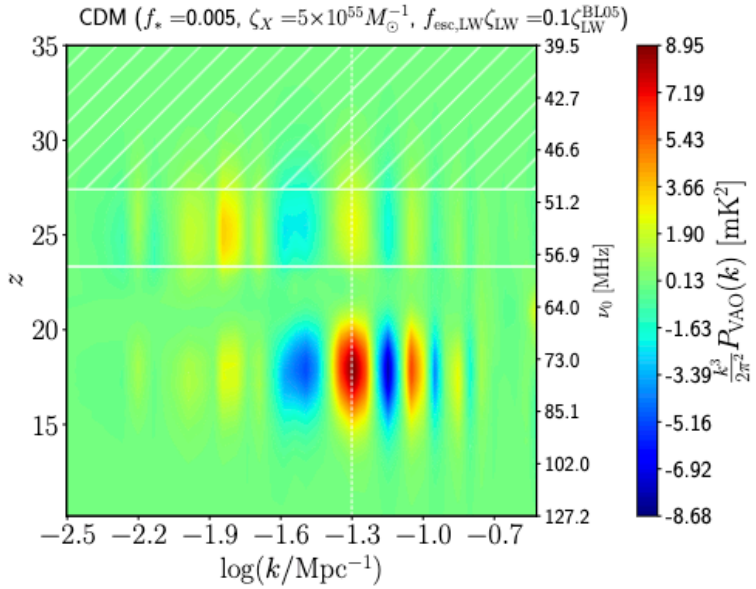


Dependence on Pop III properties: LW feedback

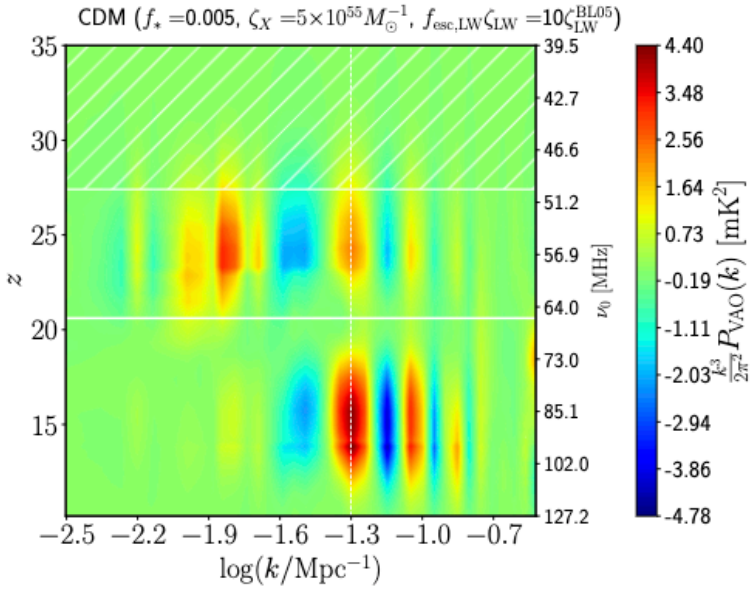
no LW feedback



weaker LW



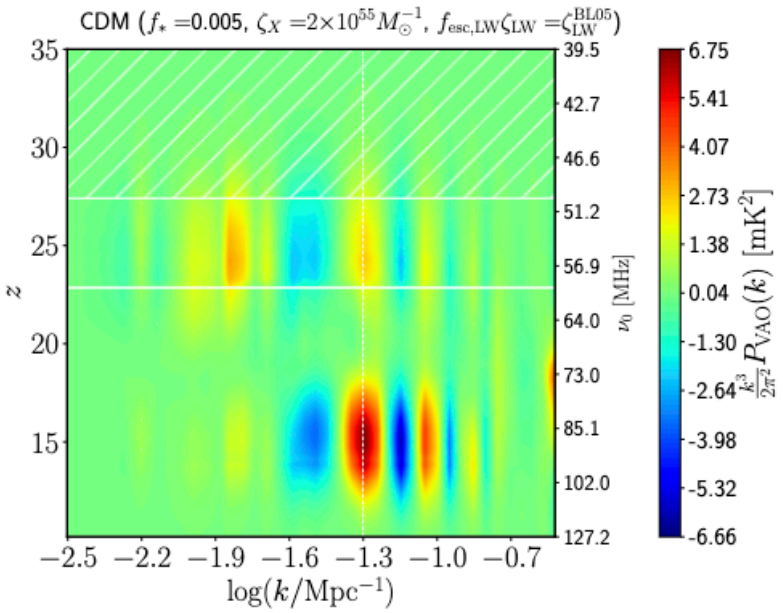
stronger LW



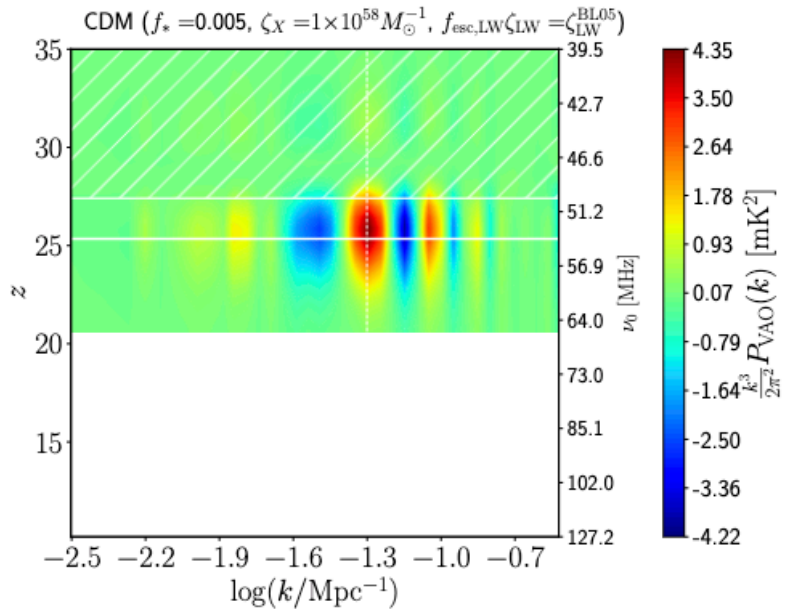
- Pop III stars in smaller minihalos source the VAO signal, they are more sensitive to LW feedback;
- LW feedback may reduce the VAO signal, but unlikely fully suppress it:
  1. LW feedback is self-limited,
  2. part of Lyα and X-ray is actually from Pop III stars already formed previously when LW is still weak.

Dependence on Pop III properties: X-ray

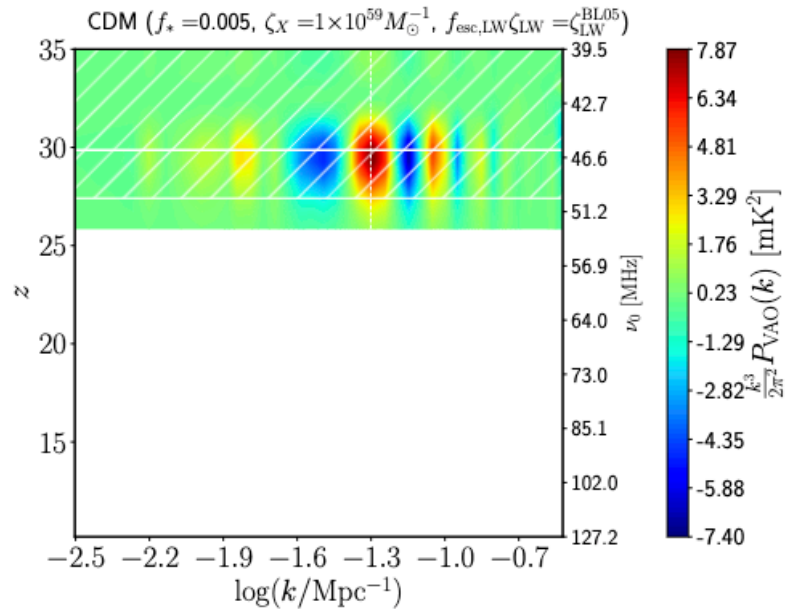
weaker X-ray



stronger X-ray



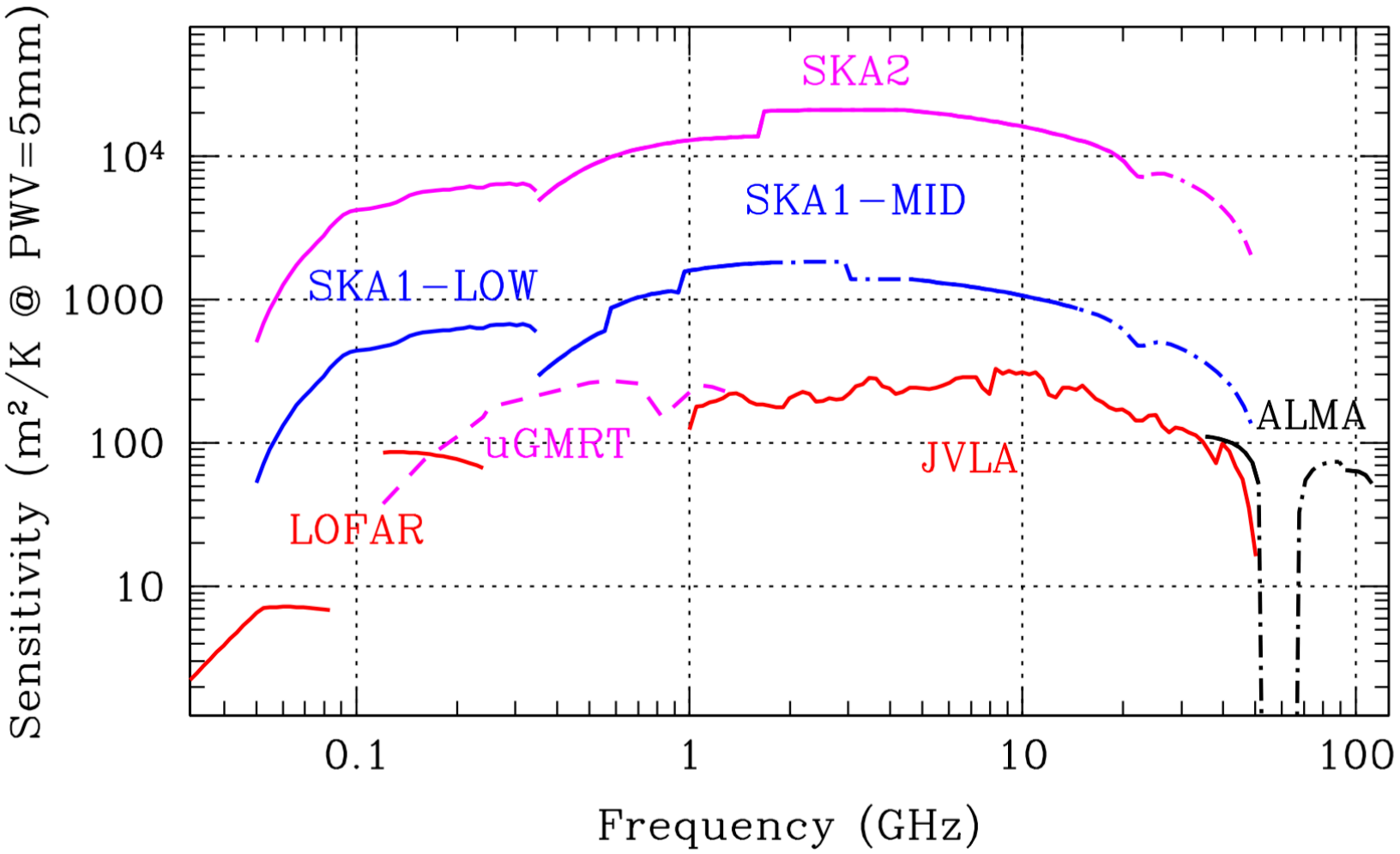
extremely strong X-ray



X-ray

- heat T_k >> T_{CMB}, erase VAO signal
- inhomogeneous heating, promote VAO signal
- source Lyα, promote VAO signal

Detectability for SKA-low：

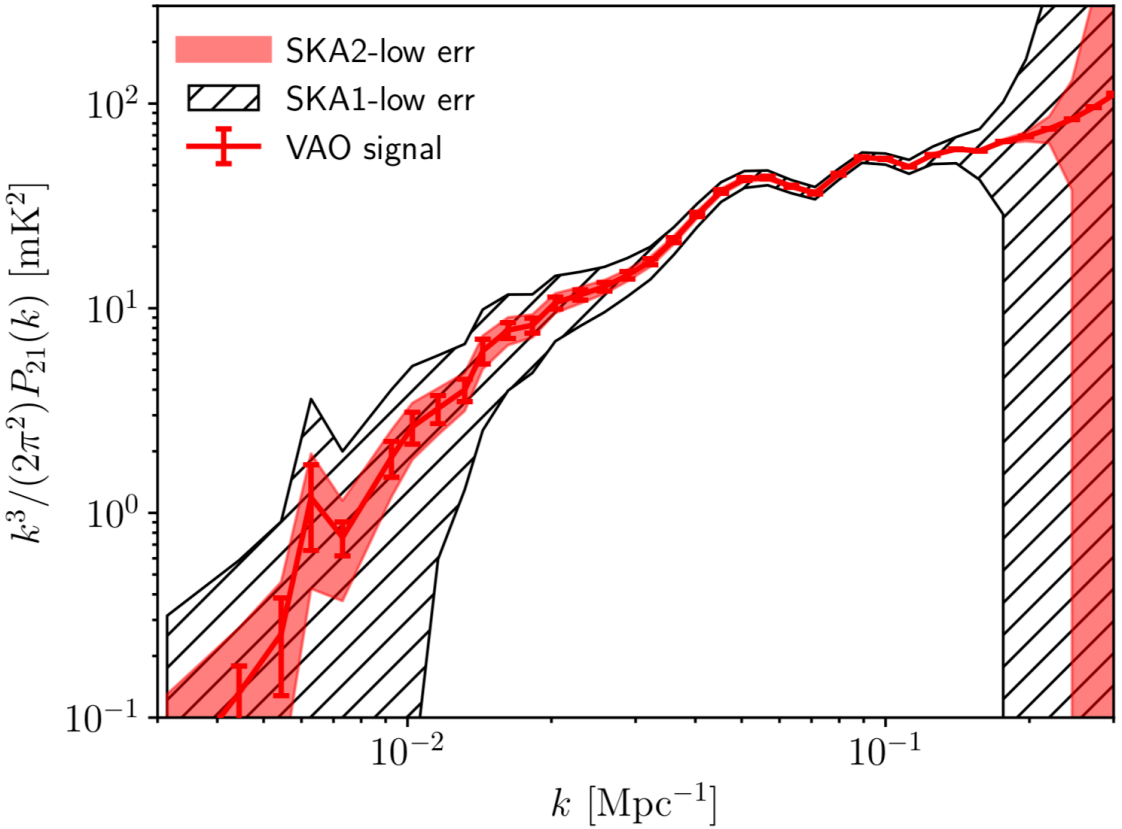


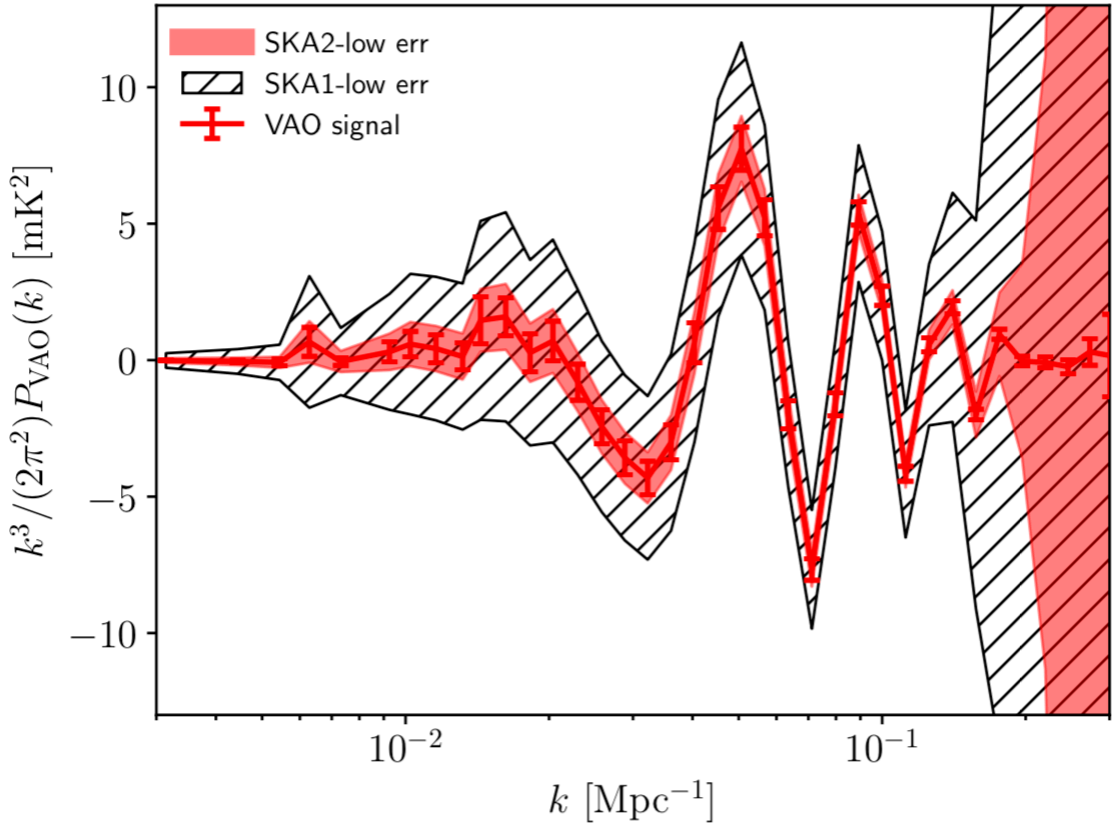
SKA1 & SKA2 sensitivity, Braun et al. (2019)

Forecast on SKA1-low & SKA2-low errors:

Assume:
integration time: 2000 hr
survey area: SKA1-low 20 deg^2; SKA2-low 200 deg^2

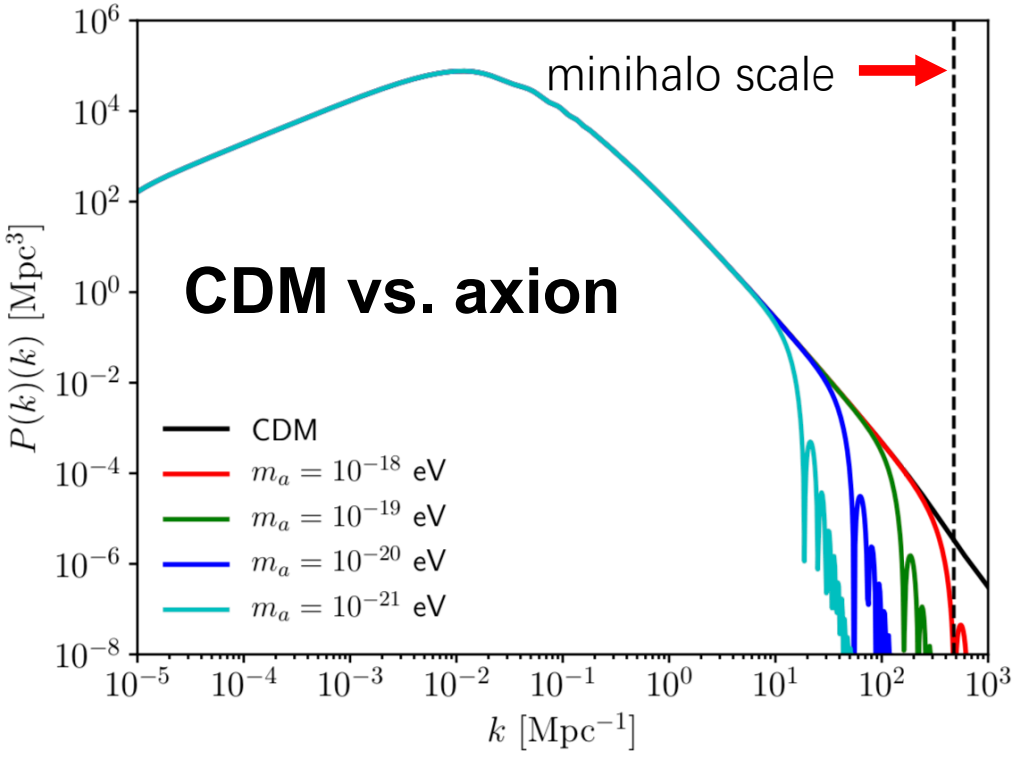
Total S/N :
SKA1-low, ~6
SKA2-low, ~22

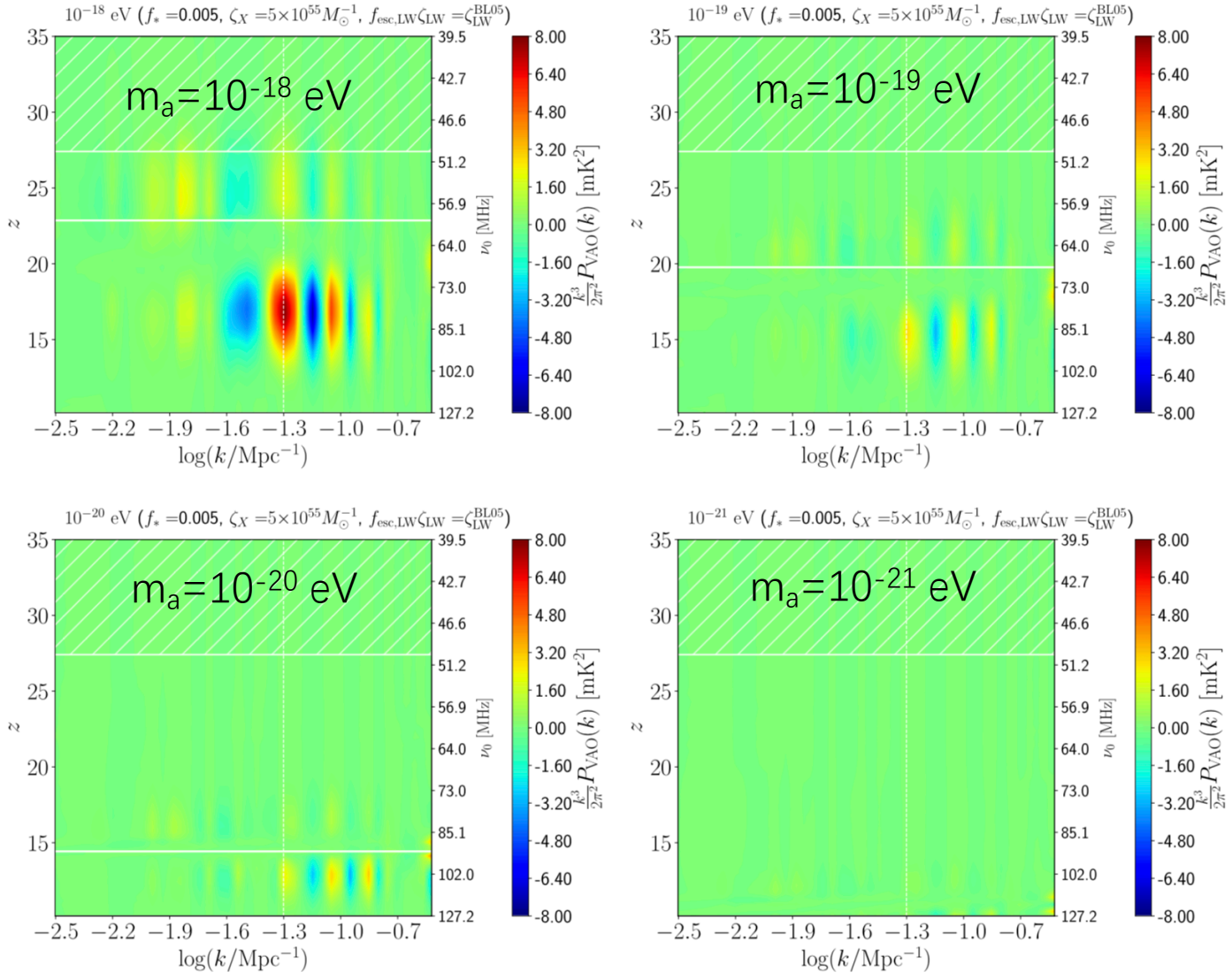




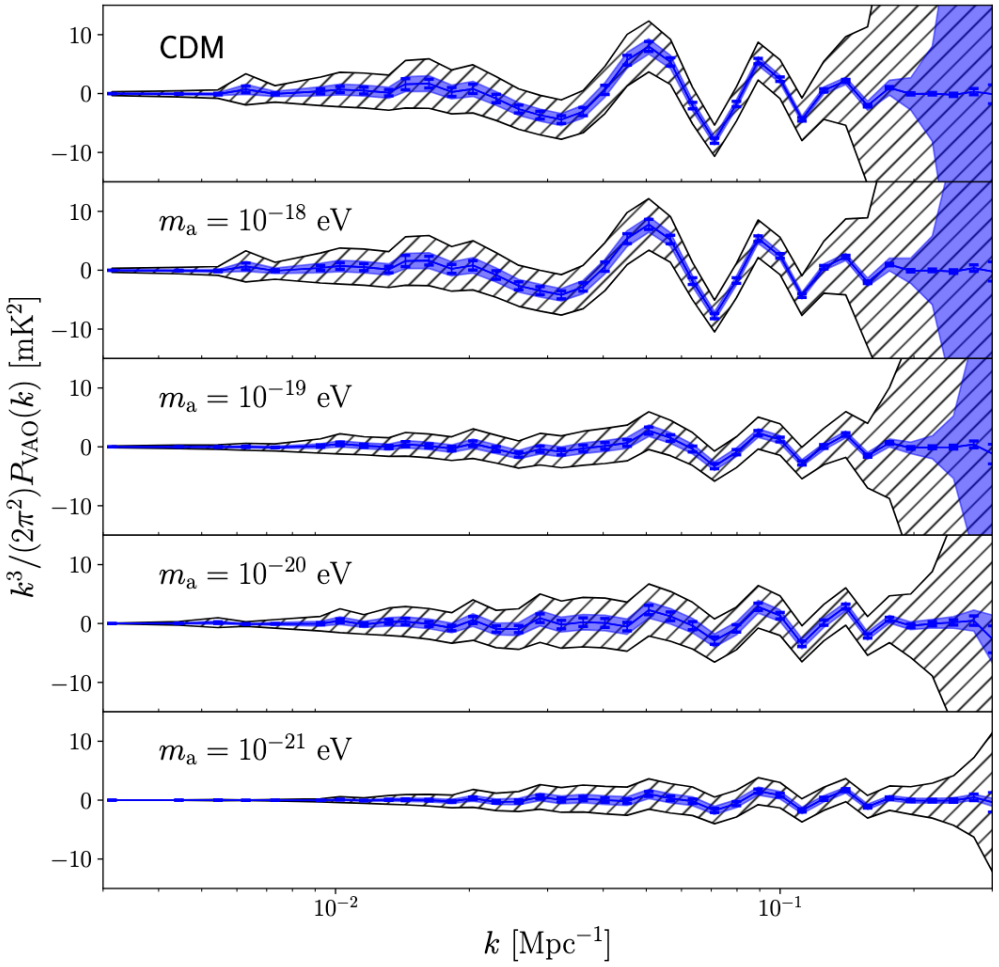
VAO signal is a probe of dark matter model

- In axion model, the lack of small-scale structures（minihalos）leads to the lack of Pop III & VAO signal
- VAO makes it possible to study small-scale density field via large-scale 21 cm signal

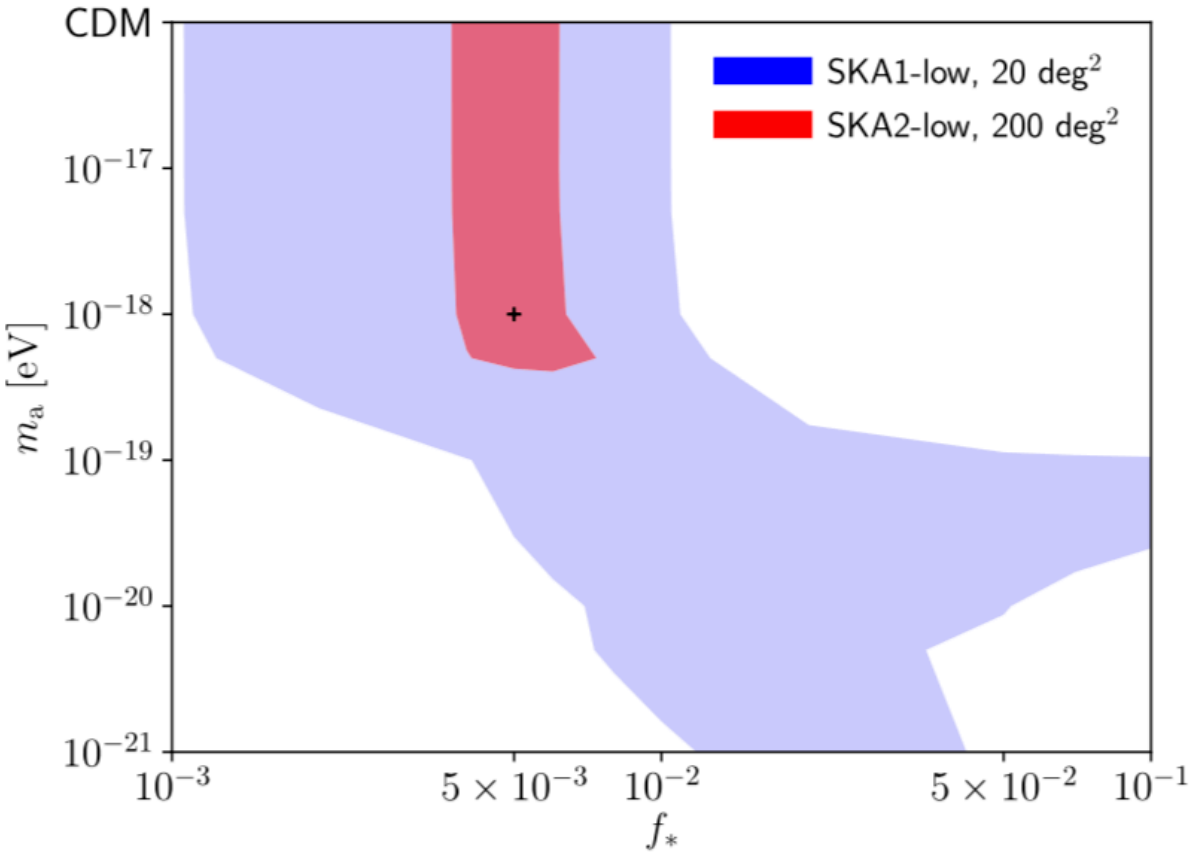




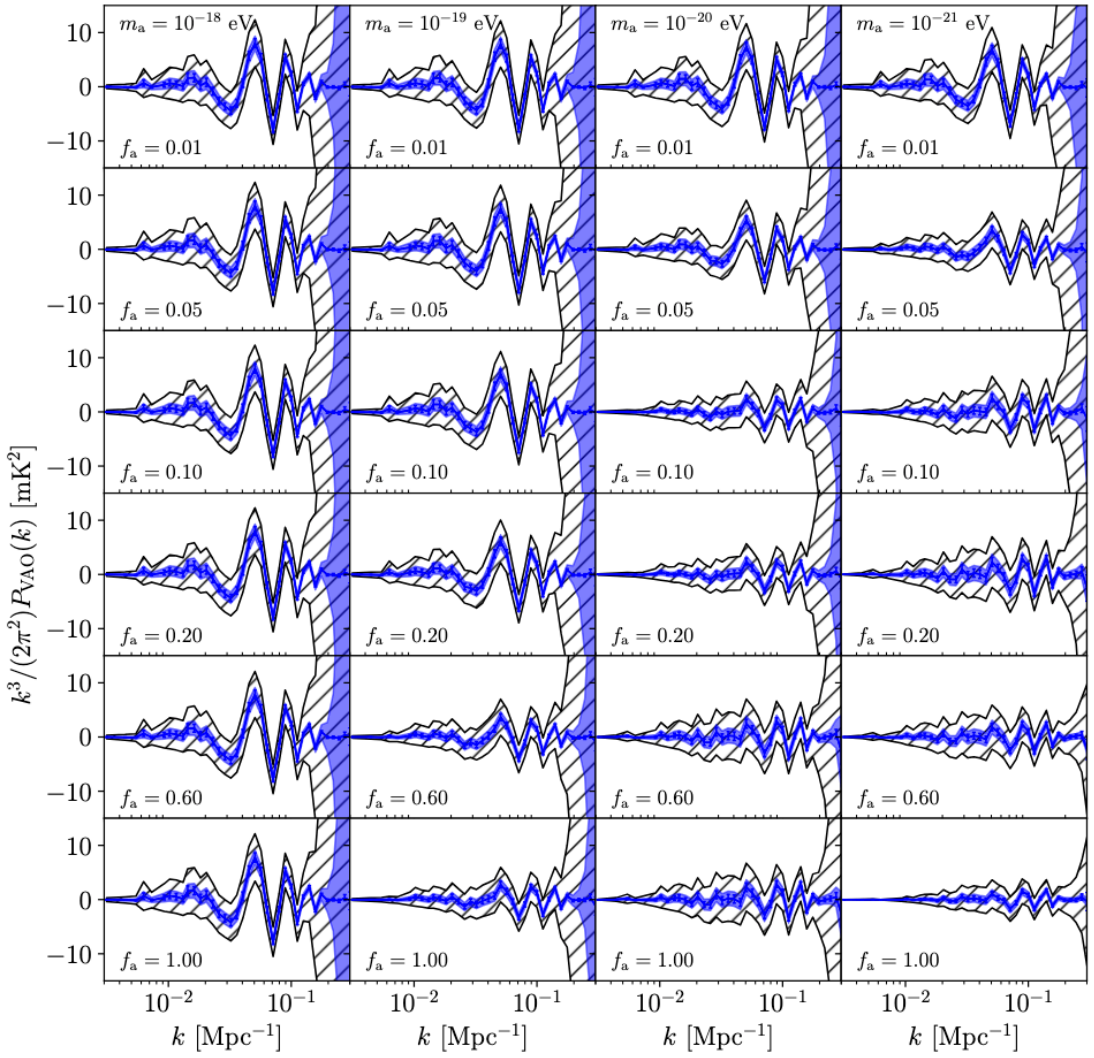
VAO signal in CDM or axion models:



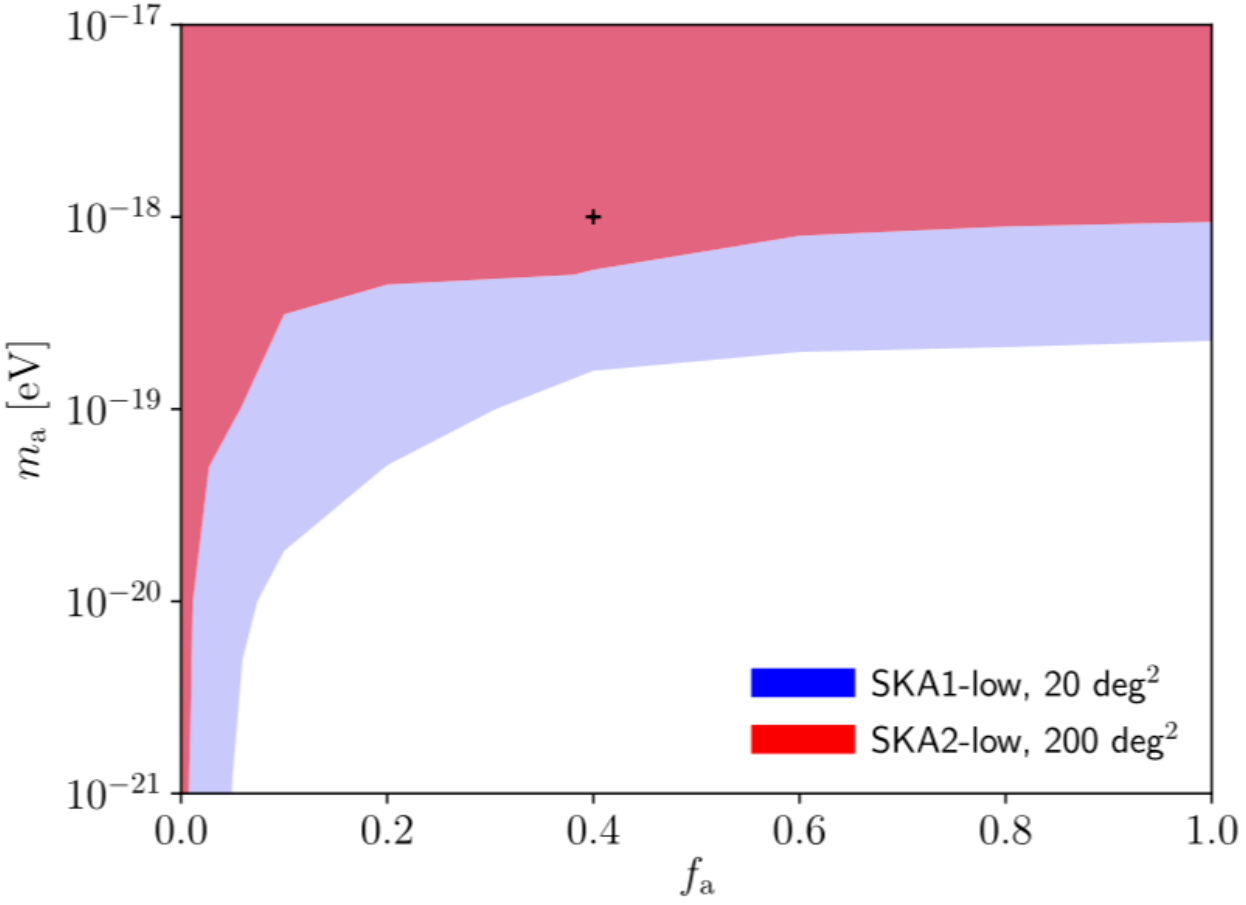
SKA constraint forecast:



VAO signal in CDM-axion mixed models:



SKA constraint forecast:



foreground wedge:

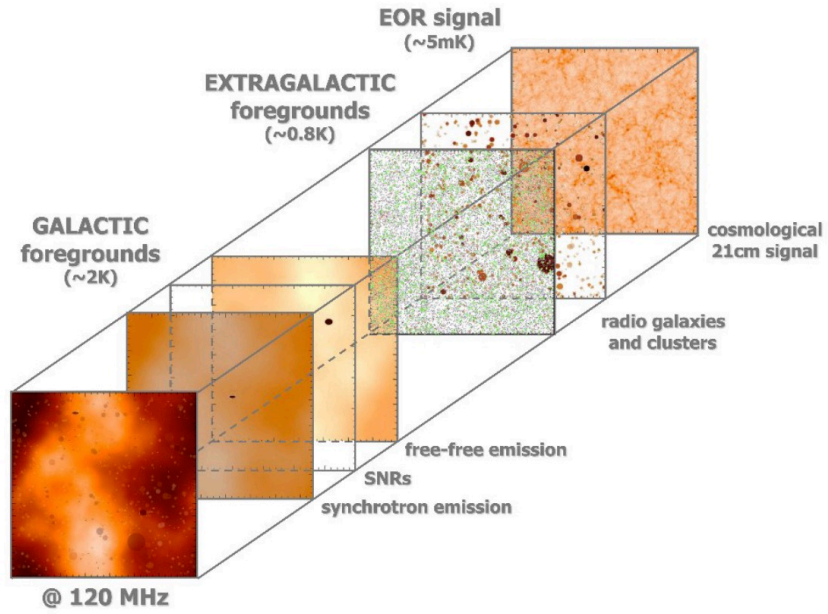
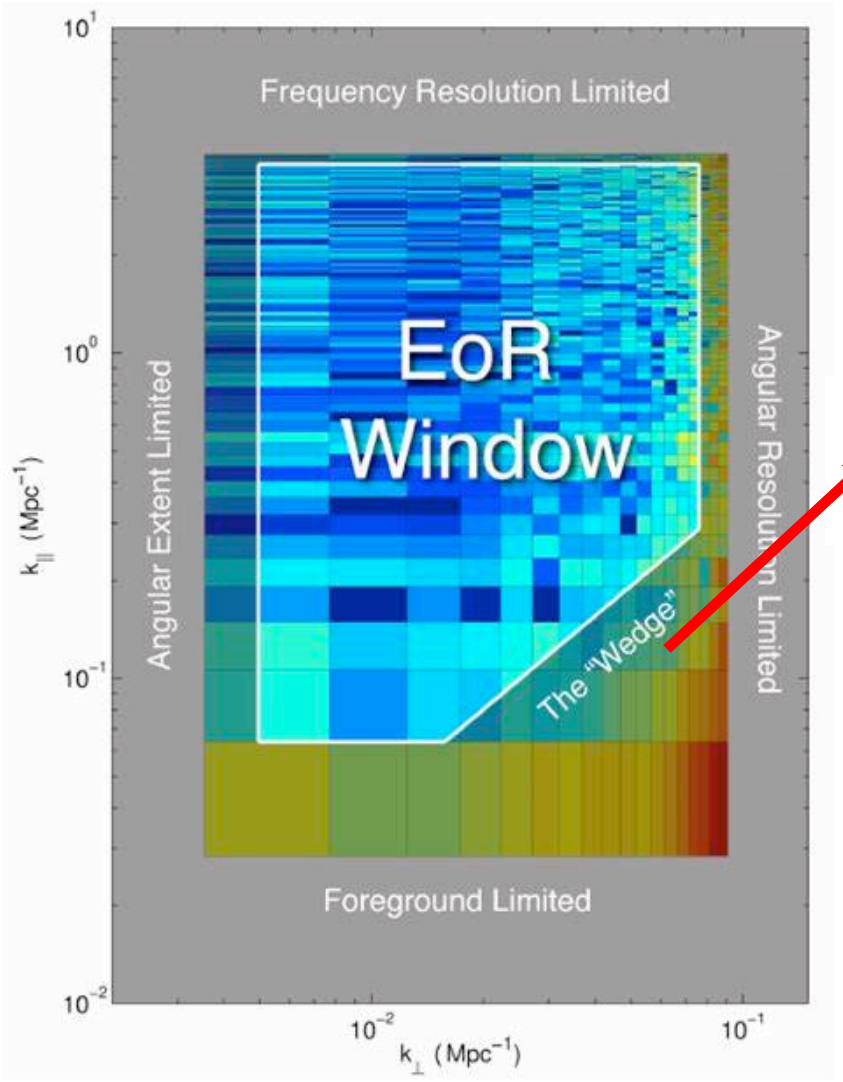


Image credit: Jelic

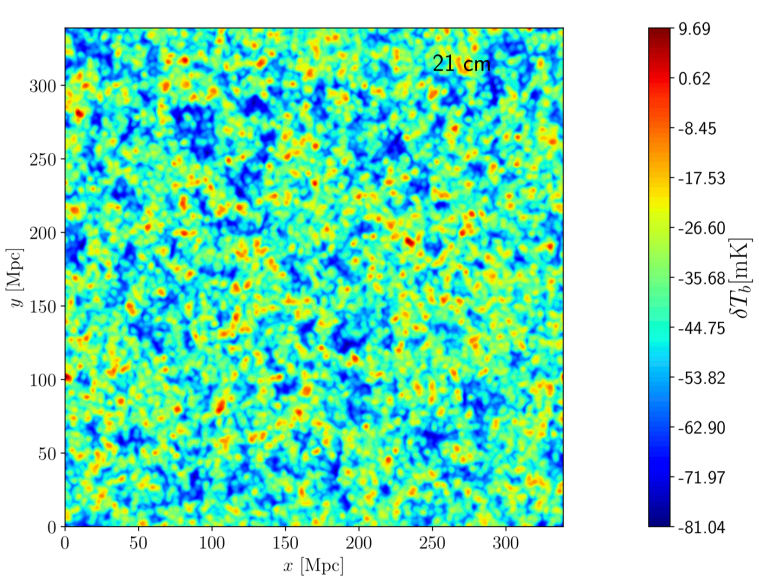


$$k_{\parallel} \lesssim \sin(\theta_{\mathrm{FoV}}) k_{\perp} \left(\frac{D_M(z) E(z)}{D_H (1+z)} \right),$$

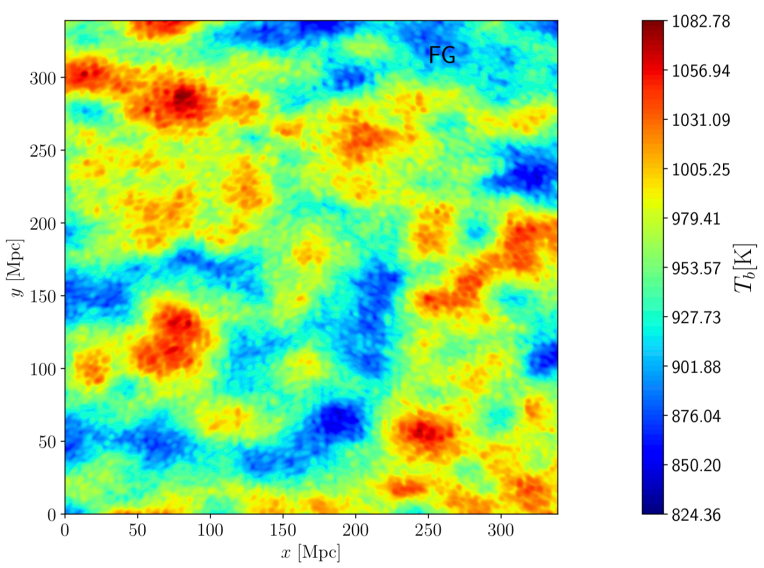
Modes in this wedge is easily contaminated by foreground

VAO is large-scale signal, while foreground removal generally leads to power loss at large-scale, so it may bias the VAO signal estimate.

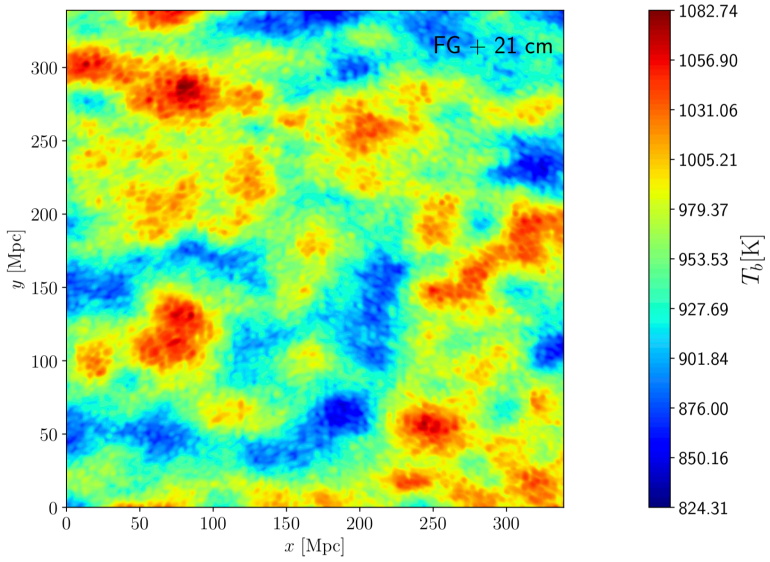
21 cm signal



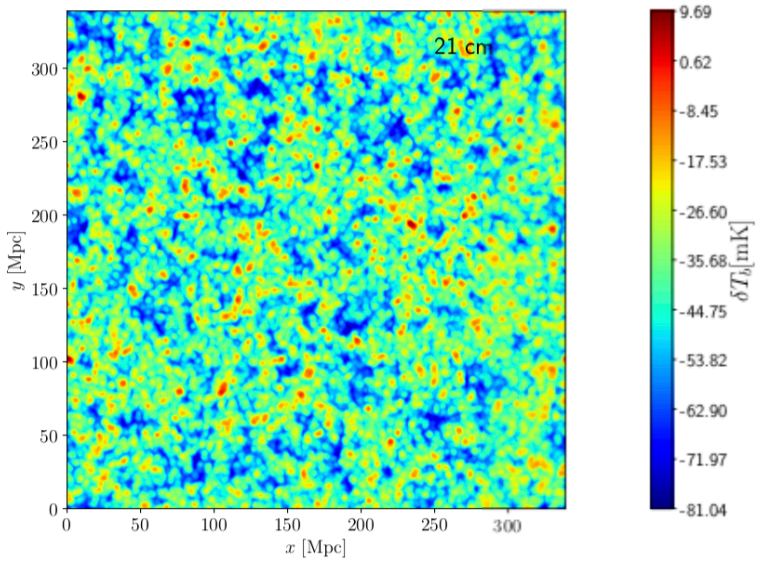
foreground （from GSM）

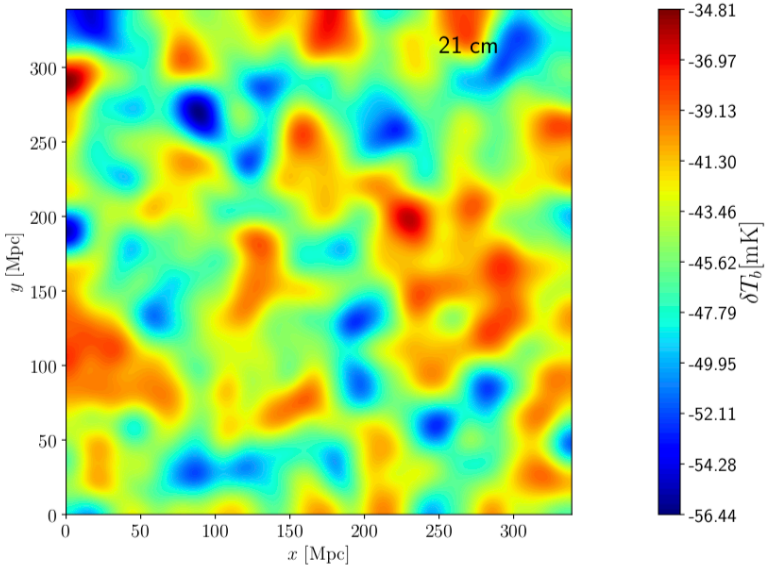


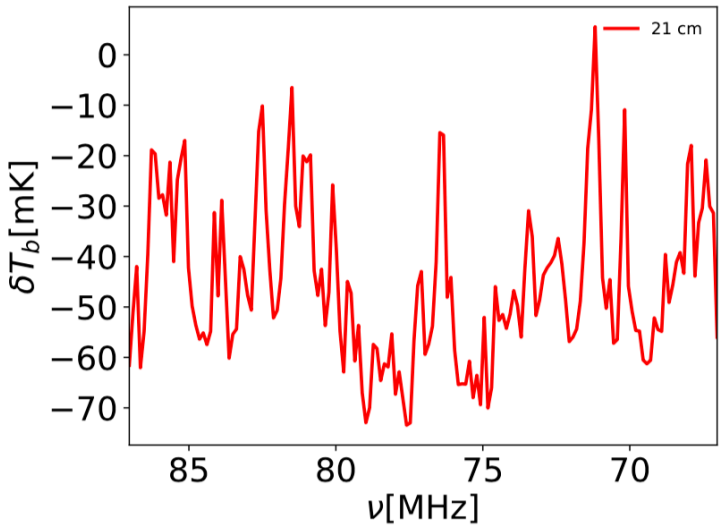
Signal + foreground

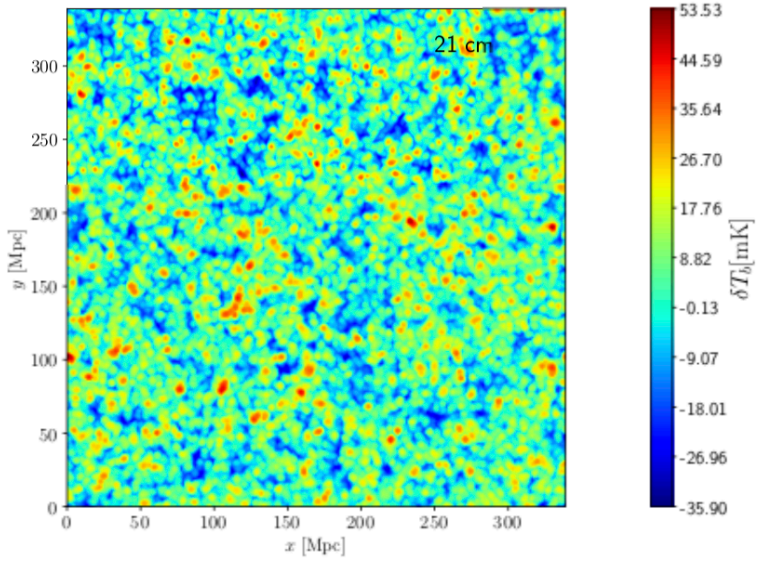


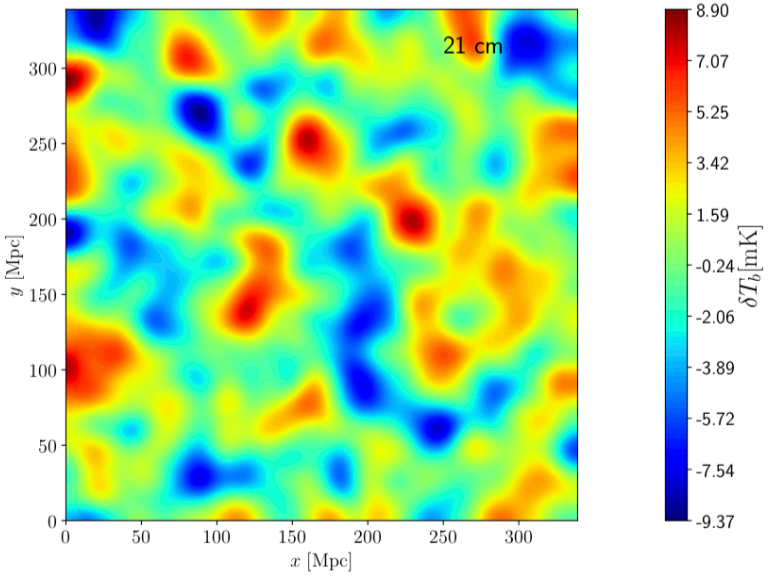
top row： original 21 cm signal；
bottom row： the 21 cm signal after removing the foreground via SVD

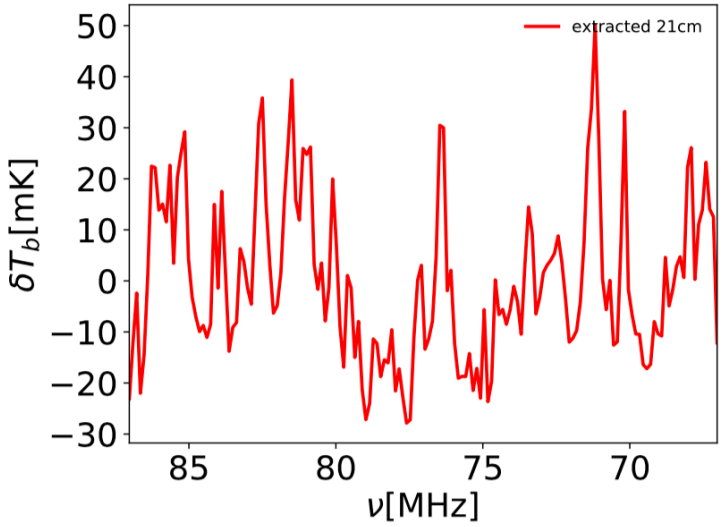








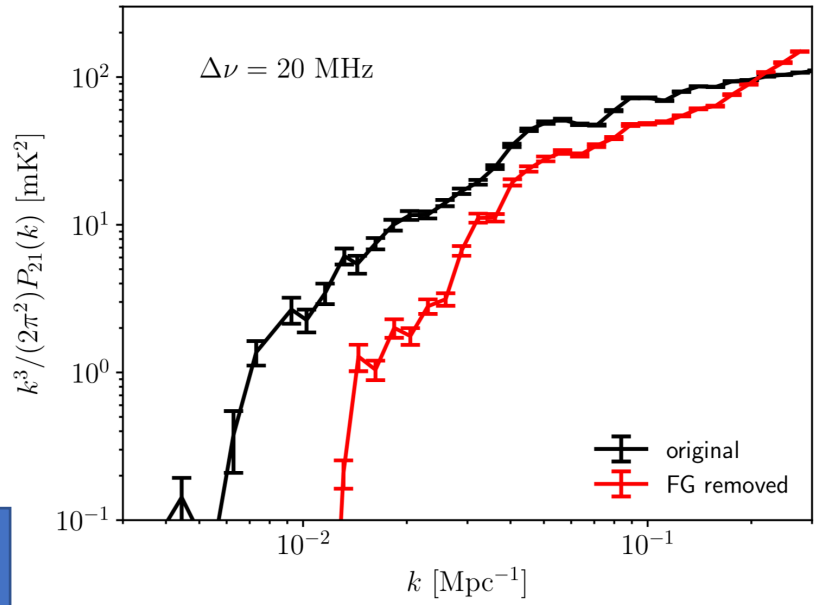


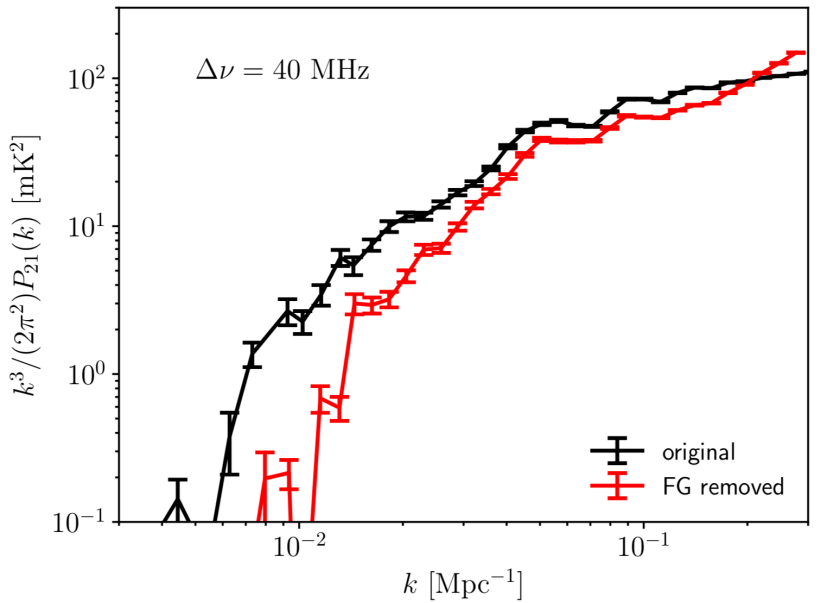


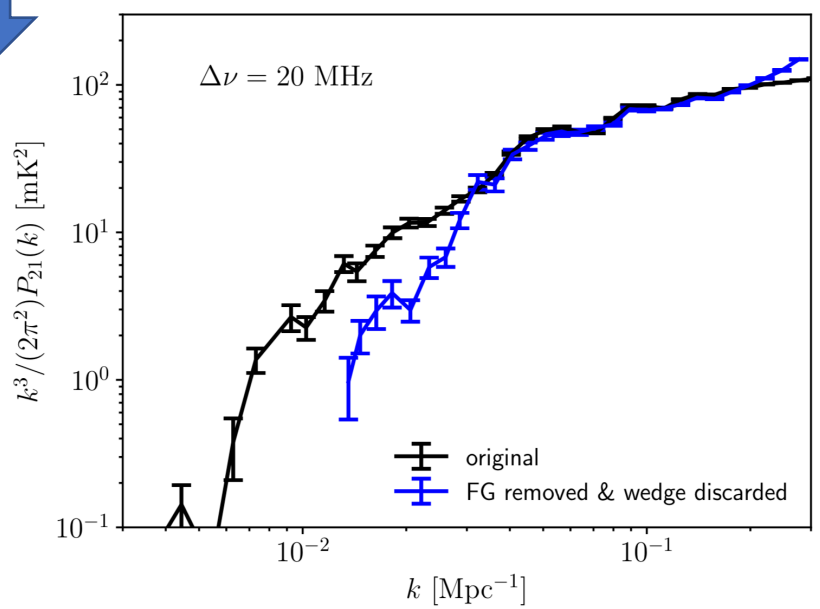
foreground

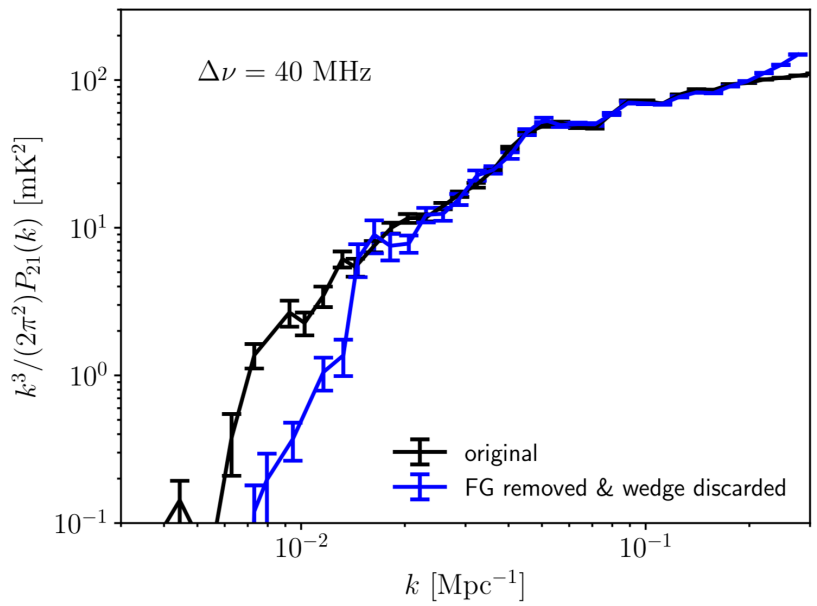
discard modes in foreground wedge

increase bandwidth









foreground

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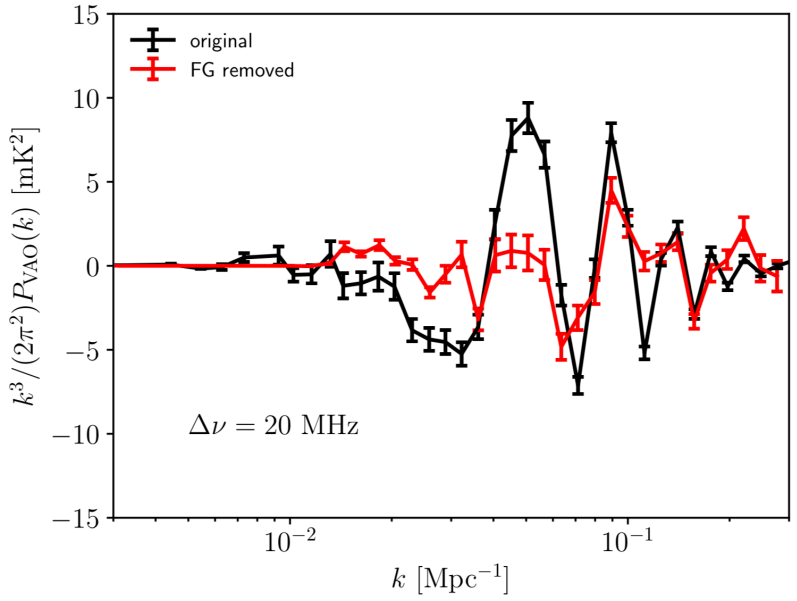
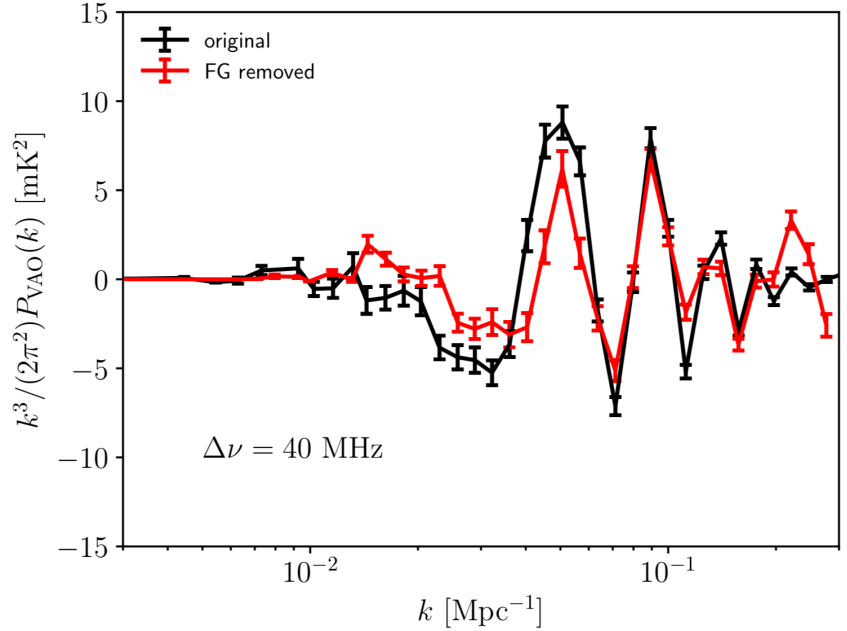
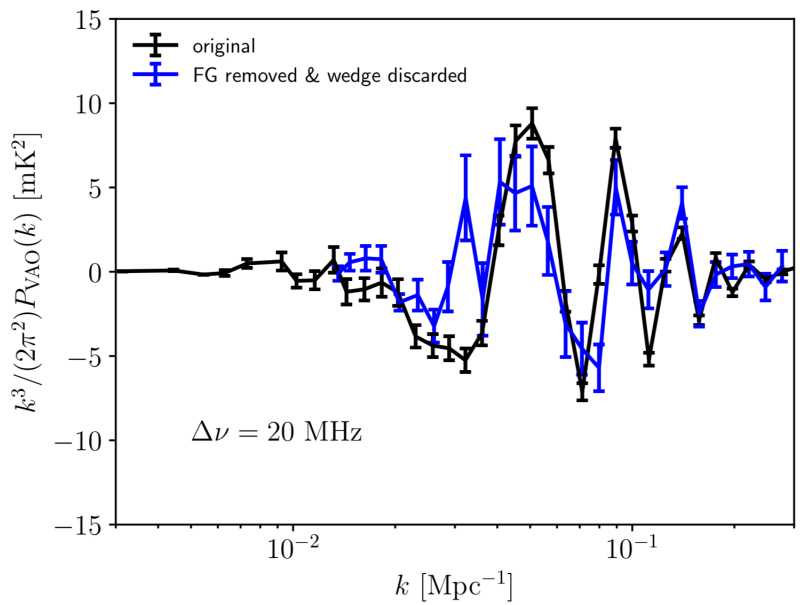
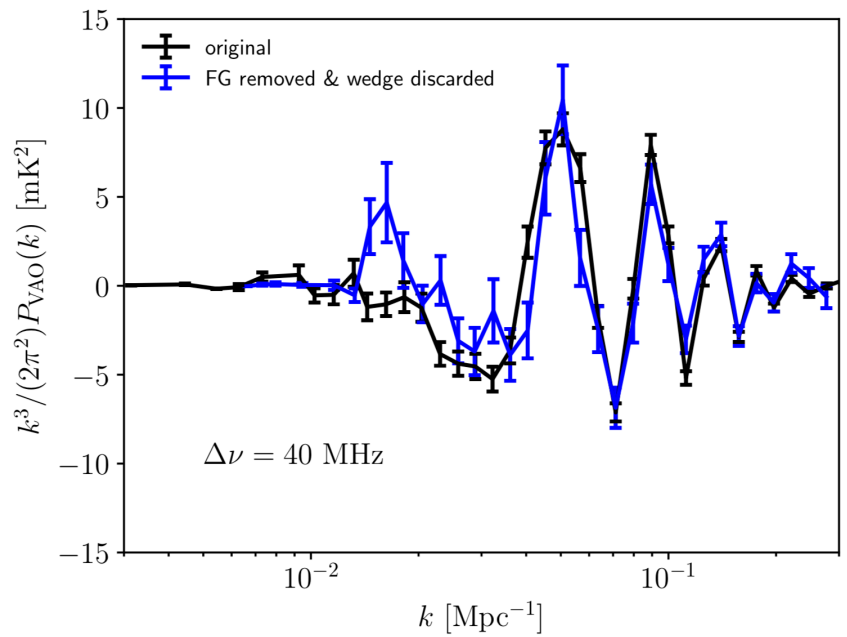
increase bandwidth









Summary：

① 21 cm VAO features *appear* when first stars start to form rapidly in the Universe; *disappear* when IGM is sufficiently heated;

② translate the small-scale structure information into large-scale signal, a probe of both first stars and DM (e.g. CDM vs. fuzzy dark matter);

③ SKA1-low & SKA2-low have the ability to detect VAO features;

④ helpful for verifying the 21 cm signal sources (only Cosmic Dawn signal has VAO features)。

Thanks谢谢！

Our paper： Zhang et al. 2024ApJ...964...62Z