Velocity Acoustic Oscillations on Cosmic Dawn 21cm power spectrum as a probe of Axion Dark Matter

Xin Zhang, National Astronomical Observatories, Chinese Academy of Sciences, zhangxin@nao.cas.cn

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In collaboration with Hengjie Lin, Meng Zhang, Bin Yue, Yan Gong, Yidong Xu, and Xuelei Chen

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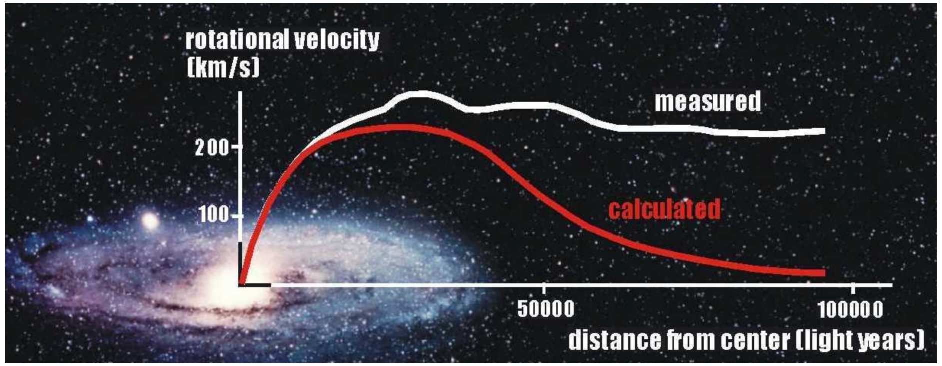
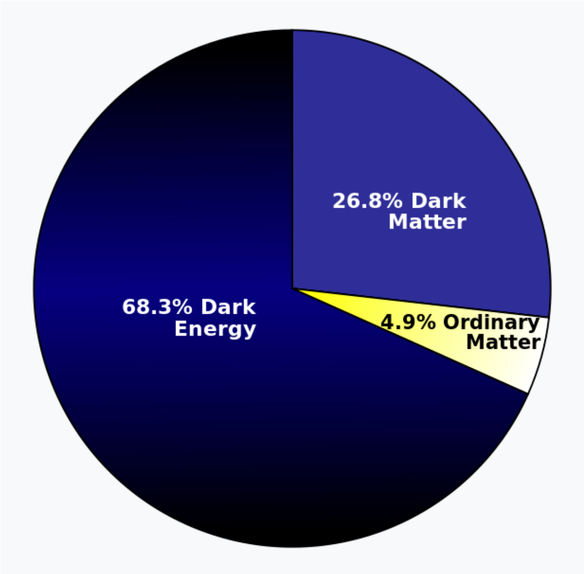
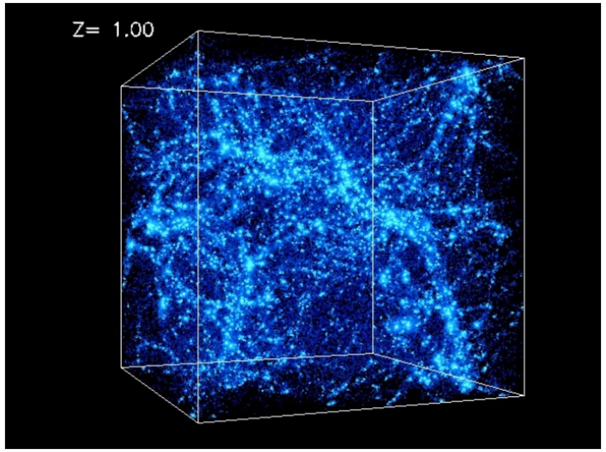
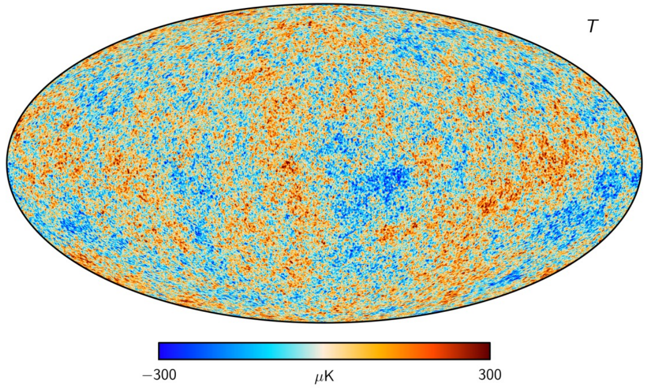
We have plenty of indirect evidences for Dark Matter









All the indirect evidences of dark matter are from gravitational effects of astronomical observation

We also have plenty of Dark Matter candidate

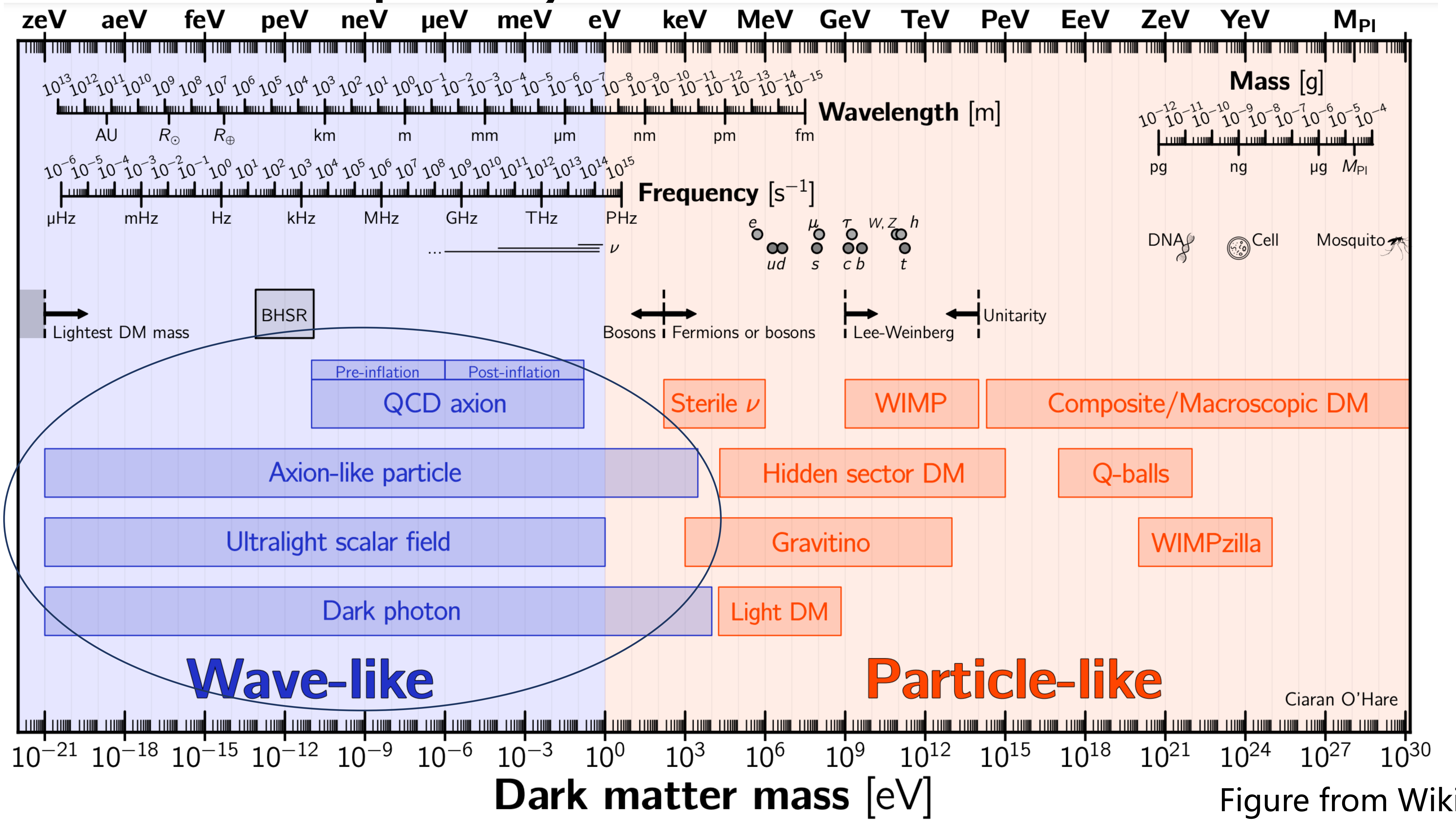


Figure from Wiki

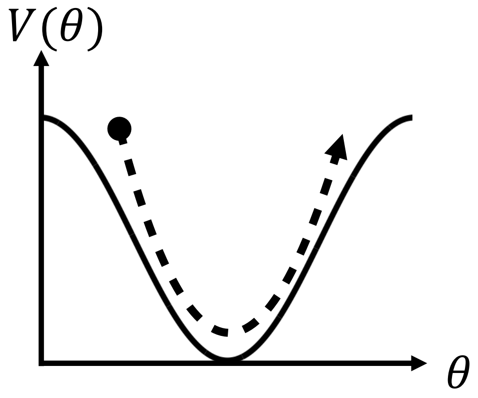
Motivation of Axion

New physics beyond the standard model (SM) in particle physics:

1.Strong CP problem $|\theta| \lesssim 10^{-10}$

Peccei-Quinn mechanism

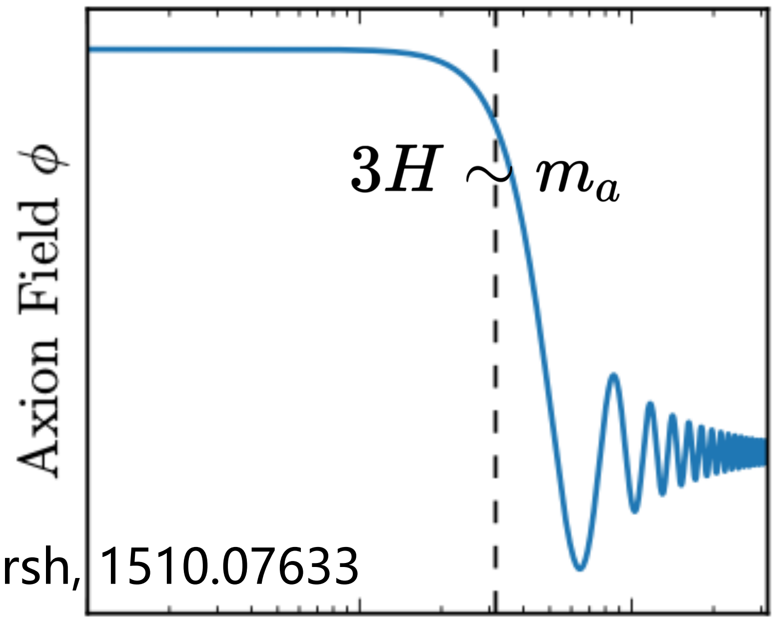
$$\mathcal{L}_\theta = \theta \frac{\mathcal{A}\alpha}{8\pi} G^{\mu\nu,i} \tilde{G}^i_{\mu\nu} \longrightarrow \theta \equiv \frac{a}{f_a} \longrightarrow$$



Misalignment mechanism(Axion DM non-thermal production)

$$\ddot{a} + 3H\dot{a} + \frac{dV_{\text{eff}}(a)}{da} = 0$$

$$V_{\text{eff}}(a) = \frac{1}{2} m_a^2 a^2 + \ldots \quad H \equiv \frac{\dot{R}}{R} = \text{Hubble rate}$$



D. J. E. Marsh, 1510.07633

2.Generic prediction of the new physics of string and M-theory compactifications

Small scale structure anomaly in cosmology

1.cusp-core problem

CDM predicts that the center of dwarf galaxies are cusp-like, observation shows they are core-like

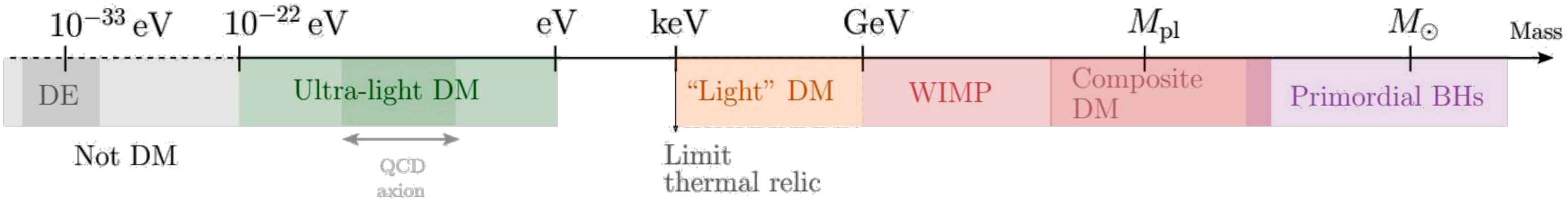
2.missing satellite problem

CDM predicts more satellite galaxies than we observed.

3. too-big-to-fail problem

Many of the satellites are so big that there must be enough stars in it so that we can see them.

Axion as Dark Matter: Fuzzy Dark Matter(FDM)



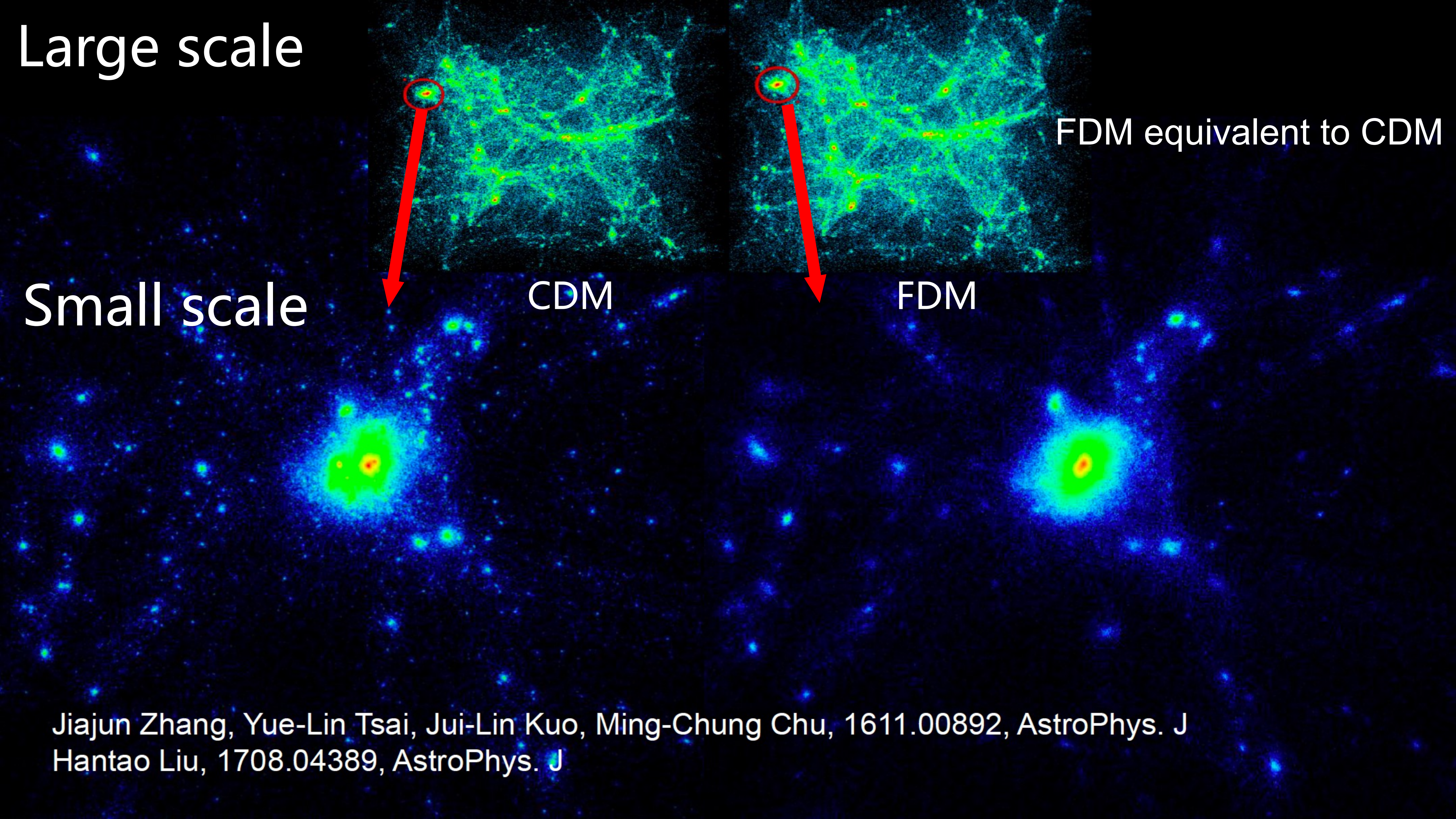
Many name in references: FCDM, BECDM, ULDM, ψDM, quantum-wave DM, (ultra-light) axion(-like) DM (ULA, UALP)…

Fuzzy Dark Matter: DM as an extremely light(pseudo) scalar particle.

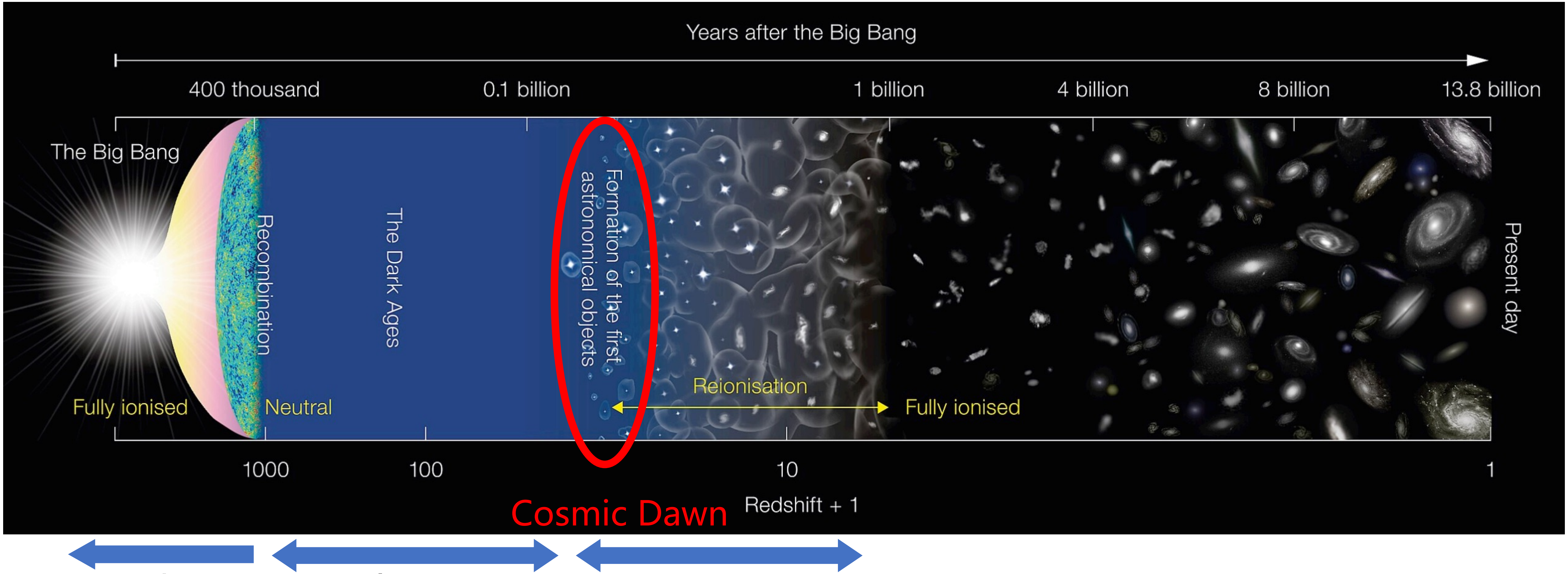
Very tiny mass ⇒ large de Broglie wavelength ($\lambda \sim 1/m$)

Macroscopic quantum (wave) effects on kpc scales(Galaxy scale):
Structures resist collapse below quantum wavelength

Lam Hui et.al Phys. Rev. D 95, 043541 (2017)


Large scale
FDM equivalent to CDM
Small scale
CDM
FDM
Jiajun Zhang, Yue-Lin Tsai, Jui-Lin Kuo, Ming-Chung Chu, 1611.00892, AstroPhys. J
Hantao Liu, 1708.04389, AstroPhys. J

Evolution history of the universe:



Pre-recombination
Photon-baryon
coupling

nonlinear structure
formation

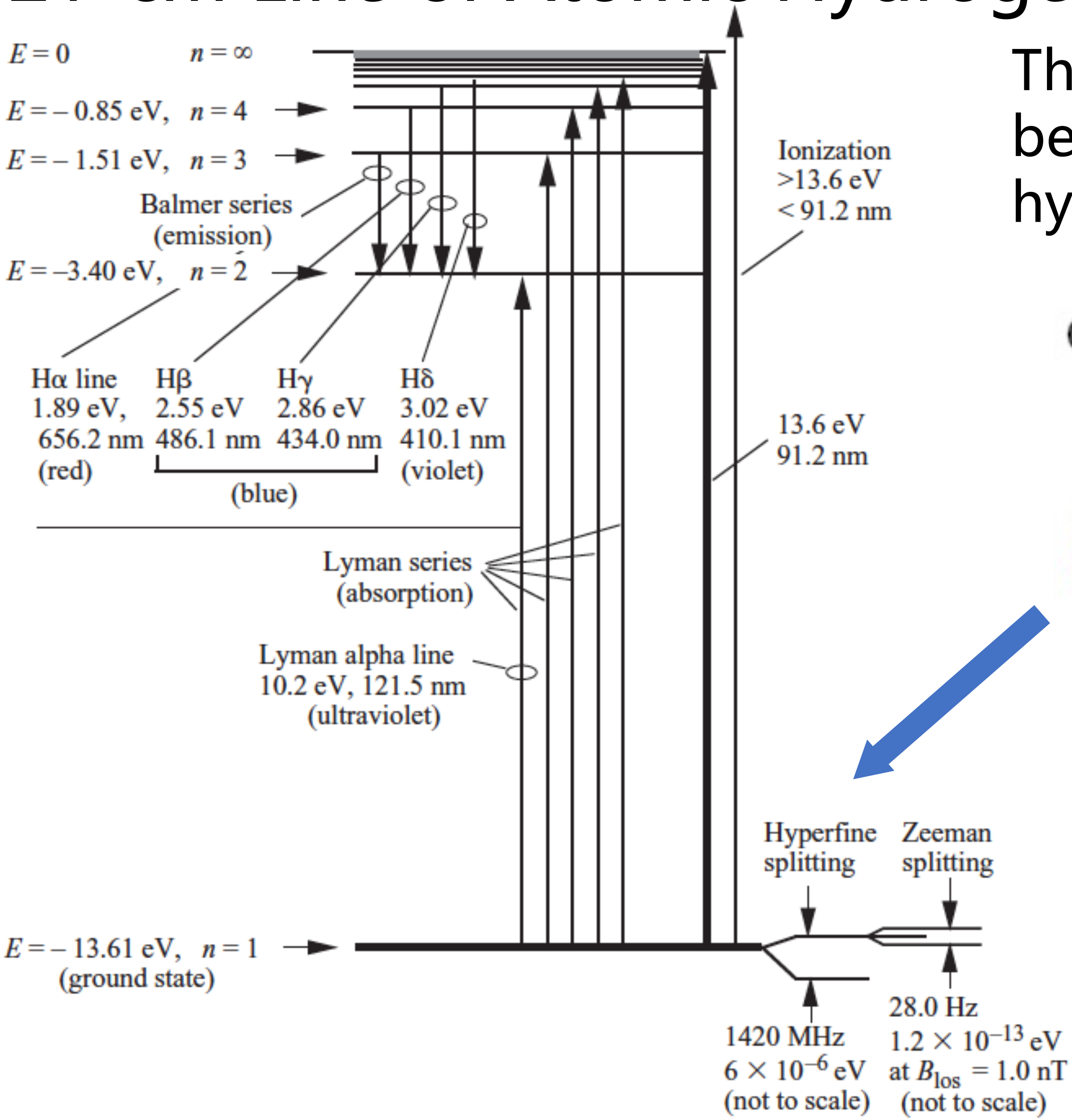
only cosmological
signals(21cm)

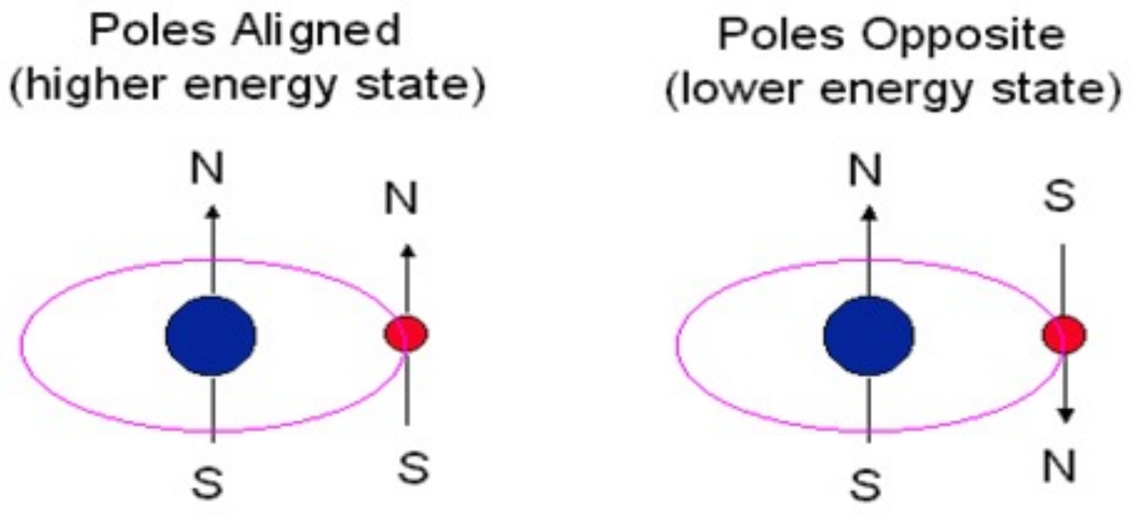
First generation stars and first
generation galaxy formation

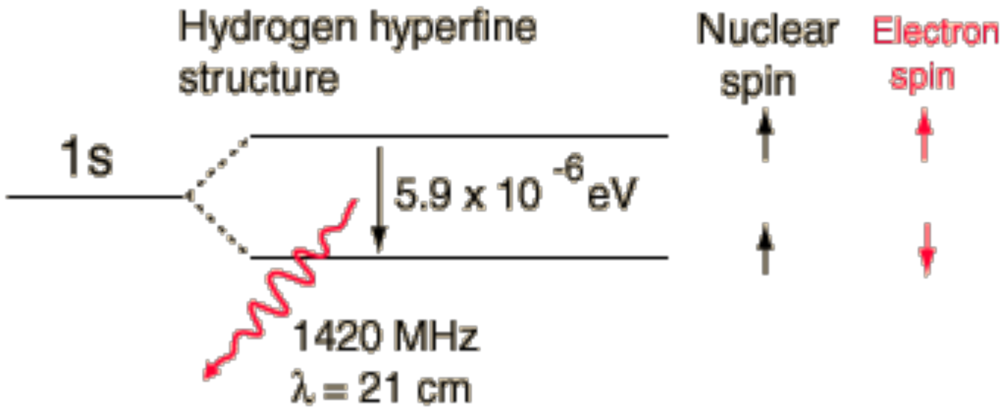
Astrophysical and cosmological
signals(21cm)

21-cm Line of Atomic Hydrogen

The 21cm line comes from the transition between two hyperfine states of the hydrogen atom 1s state.







21cm spin temperature and brightness temperature

Radiative transfer equation: $\frac{dI_\nu}{d\xi} = -\kappa_\nu I_\nu + j_\nu$

Rayleigh-Jeans limit: $I_\nu \equiv \frac{2k_B\nu^2}{c^2} T_b(\nu)$

The formal solution of radiative transfer equation:

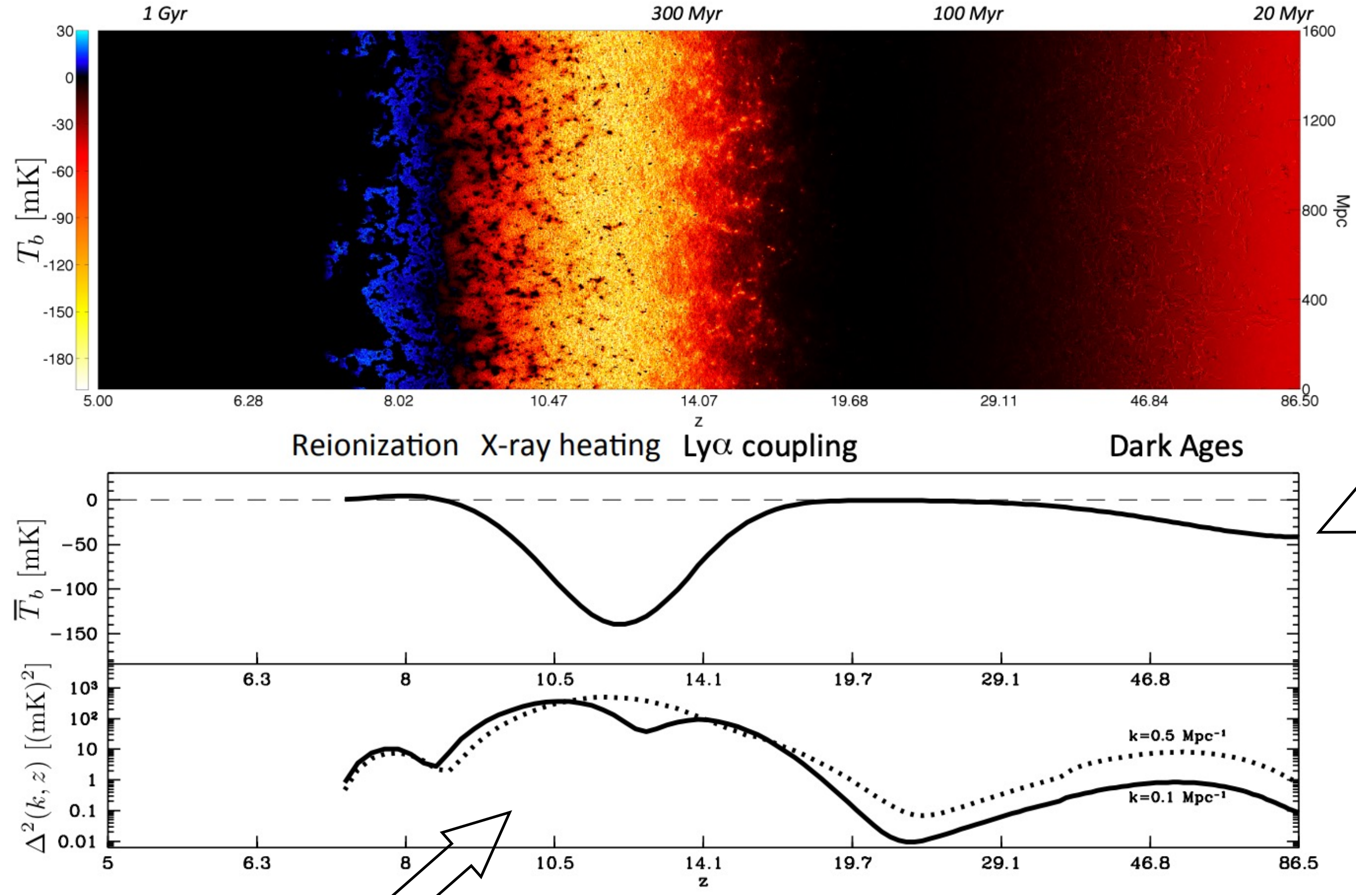
$$\delta T_b(\nu_{\rm obs}) \equiv T_b(\nu_{\rm obs}) - T_{\rm CMB,0} = a[T_s(\mathbf{x}, z) - T_{\rm CMB}(a)]\left(1 - e^{-\tau_{\nu_{\rm obs}}}\right)$$

Spin temperature: $\frac{n_1}{n_0} \equiv \frac{g_1}{g_0} e^{-\Delta E_{10}/k_B T_s} = 3e^{-T_\star/T_s}$ $\quad T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_k^{-1}}{1 + x_\alpha + x_c}$

$$\widehat{\delta T}_b(z) = 23.88 \left(\frac{\Omega_{\rm b} h^2}{0.02}\right) \sqrt{\frac{0.15}{\Omega_{\rm M} h^2} \frac{1+z}{10}}\, \bar{x}_{\rm HI,m}(z)\, {\rm mK}$$

$$\delta T_b(\nu_{\rm obs}) = \widehat{\delta T}_b(z)\, [1 + \delta_{\rho_{\rm HI}}] \left[1 - \frac{T_{\rm CMB}(a)}{T_s}\right],$$

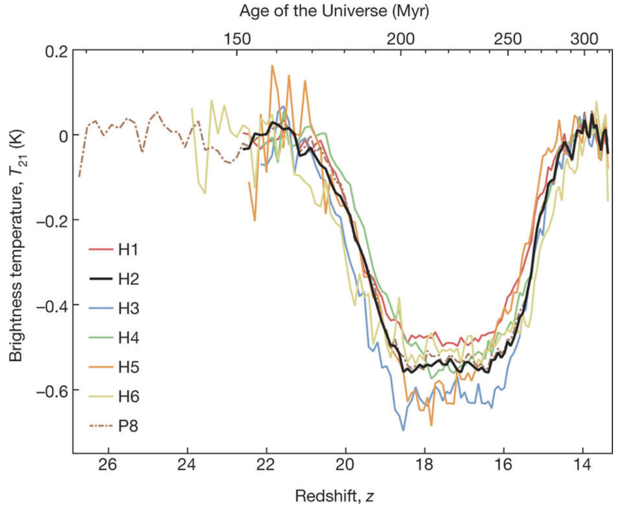
Measure the 21cm brightness temperature



Global spectrum:

$$\bar{T}_b(\nu) = \int d\Omega \delta T_b(\hat{\mathbf{r}}, \nu)$$

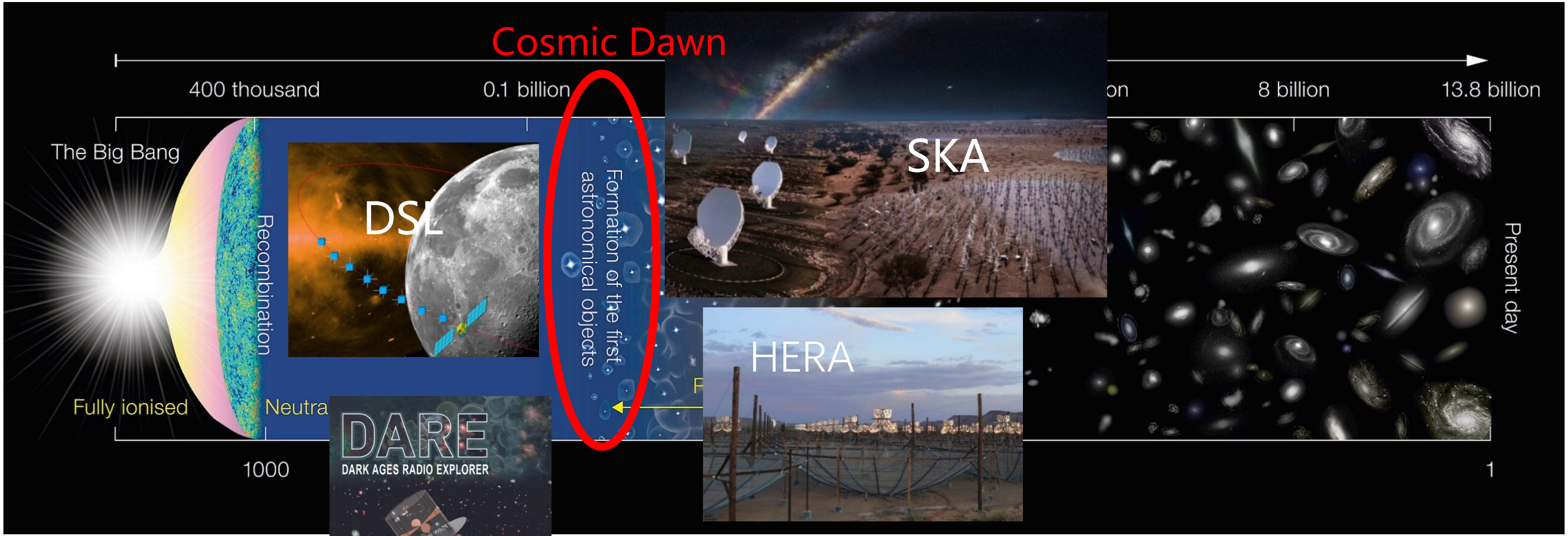
Measurement of the averaged T field over all angles on the sky



Power spectrum: $\delta T_b^2(\mathbf{r}) = \int_{-\infty}^{\infty} \frac{d^3k}{(2\pi)^3} P(k) = \int_0^{\infty} d\ln k \Delta^2(k)$

Bowman et al.(2018)

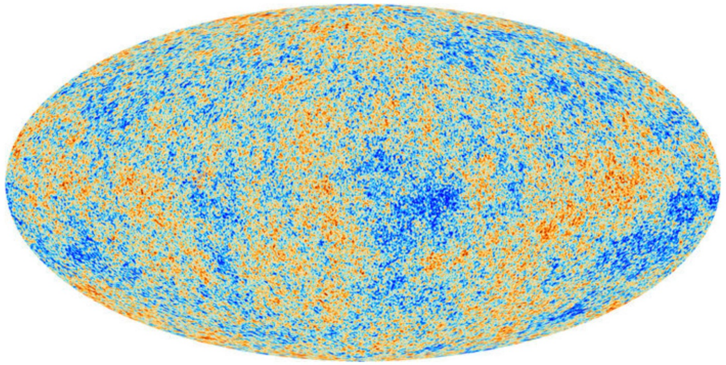
Measurement of the variance of fluctuations in a T field as a function of k

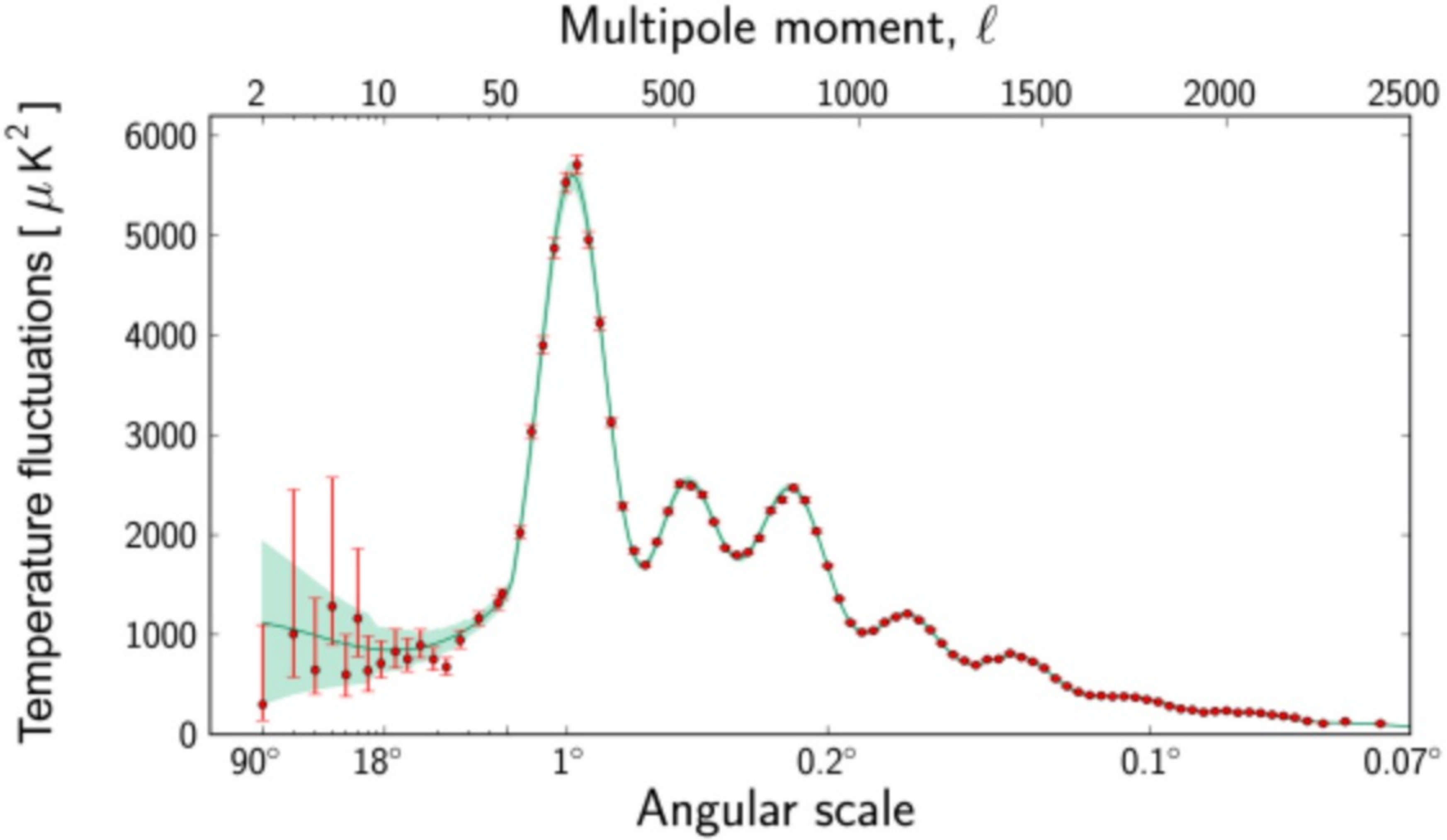


The cosmological signals in the dark age are more difficult to measure, which may require the next generation instruments:

The astrophysical and cosmological signals can be measured by current and near future instruments.

Baryon Acoustic Oscillations(BAO)





Planck 2018
ESA and the Planck Collaboration

Velocity Acoustic Oscillations(VAO)

Under the interaction of photon pressure and gravity, both the baryon density (BAO) and velocity (VAO) different from dark matter.

$$v_{\rm db} \sim 30\left(\frac{1+z}{1081}\right)[\mathrm{km/s}]$$

e.g. $z_{\rm rec} = 1020$ $\mathcal{M} \equiv v_{\rm db}/c_{\rm s} \sim 5$  $k_{\rm vdb} \equiv \left.\frac{aH}{\langle v_{\rm db}^2 \rangle^{1/2}}\right|_{\rm dec} = \frac{k_{\rm J}}{\mathcal{M}} \sim 40\mathrm{Mpc}^{-1}$

$z_{\text{cosmic dawn}} = 20$ $v_{\rm db} \sim 1[\mathrm{km/s}]$

Comparable with the circular velocities of dark matter halo has:

$$\sigma_{\rm rms} \approx 0.6\ \mathrm{km\ s}^{-1}$$

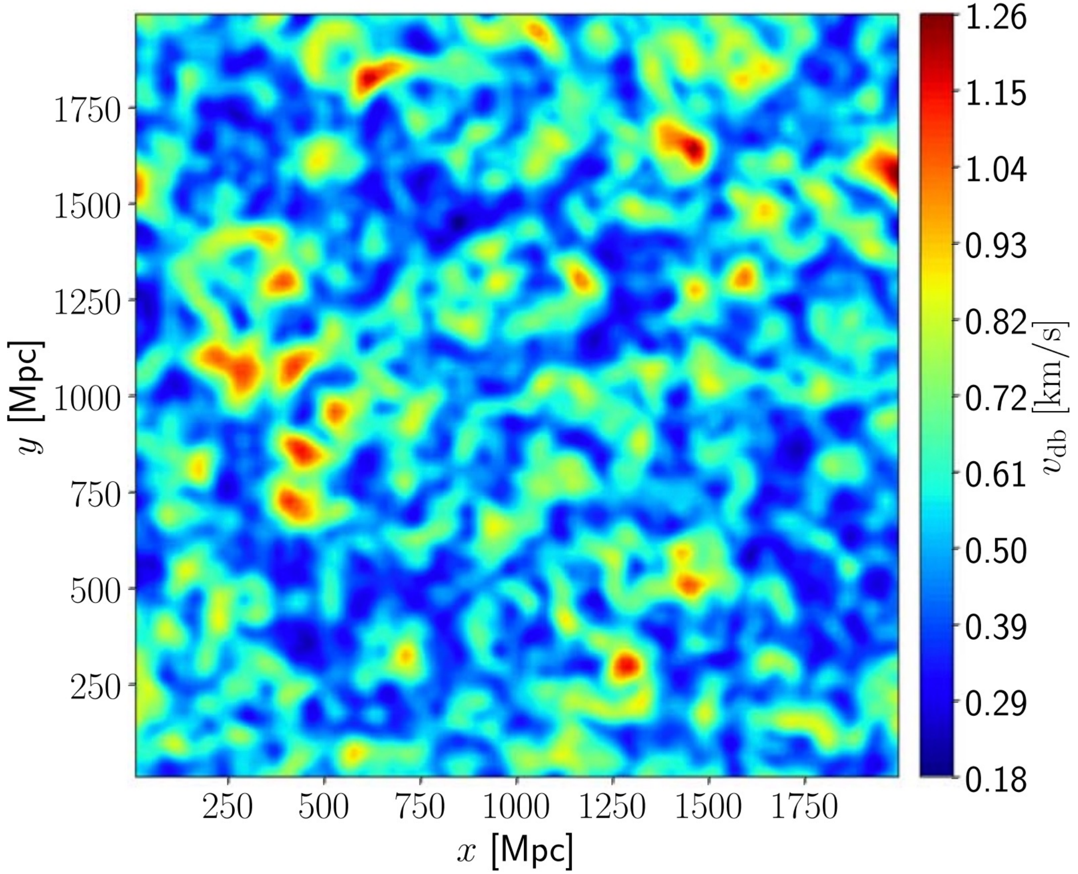
⇩

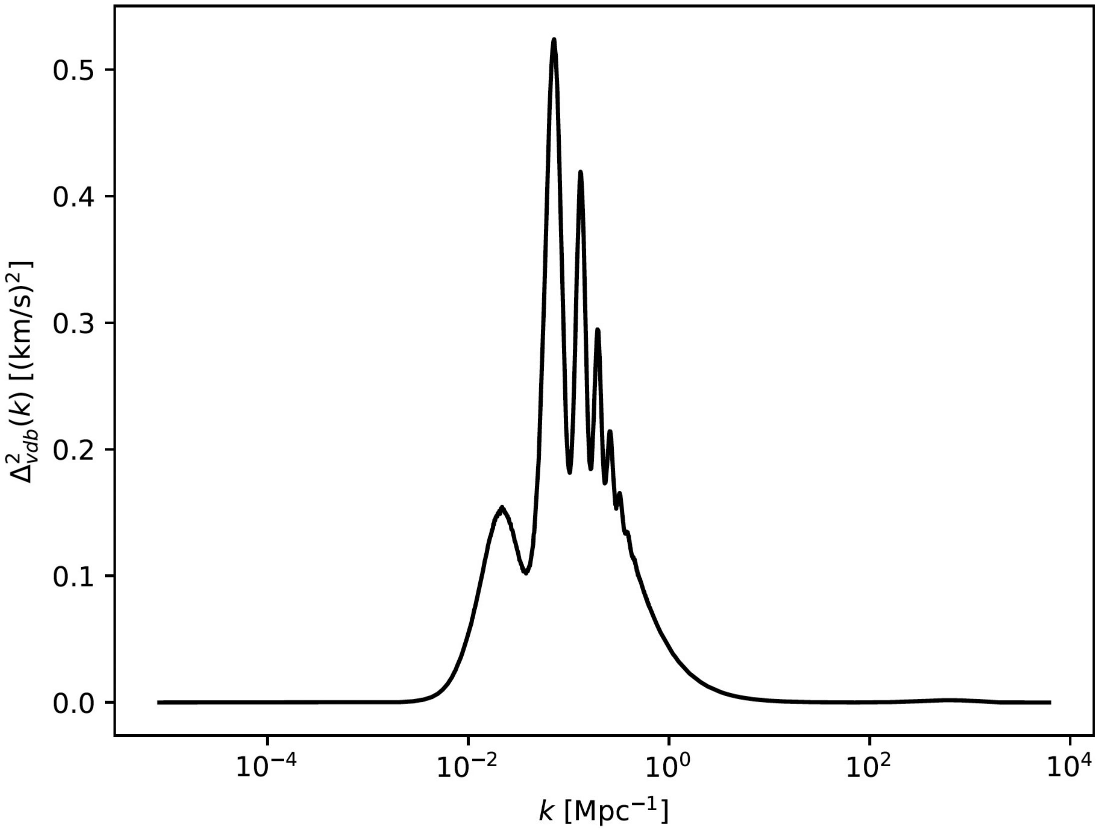
The relative velocity $\gtrsim 1\sigma_{\rm rm}$ would be significantly suppressed the formation of the first generation stars, in turn impacts the 21 cm signal

Velocity Acoustic Oscillations(VAO)

Relative velocity field of baryon and dark matter:

$$\boldsymbol{v}_{\mathrm{d/b}}(\boldsymbol{k},a) = -i\frac{a\boldsymbol{k}}{k^2}\dot{\delta}_{\mathrm{d/b}}(\boldsymbol{k},a) = -i\frac{a\boldsymbol{k}}{k^2}\dot{T}_{\mathrm{d/b}}(\boldsymbol{k},a)\delta_{\mathrm{pri}}(\boldsymbol{k})$$





Relative velocity field of baryon and dark matter

$$v^2_{\mathrm{db}}(\boldsymbol{x}) = \int \frac{\mathrm{d}k}{k}\Delta^2_{\mathrm{vdb}}(k)$$

power spectrum

The Big Picture

DM-Baryon relative velocity
(the large-scale coherently oscillating structures)

$$f_{\rm coll}\,(z \mid \delta_{\rm cell}\,, M_{\rm cell}\,, v_{\rm db}) = \frac{1}{\bar{\rho}_{\rm m}} \int_{M_{\rm crit}}^{\infty} dM M \frac{dn}{dM}(M, z \mid \delta_{\rm cell}\,, M_{\rm cell}\,)$$

Minihalo distribution (critical mass) allowing the formation of first-generation stars

$$\rho^*_{\rm cell} \sim f_* \frac{\Omega_b}{\Omega_m} \rho_m f_{\rm coll}$$

Radiation field produced by first-generation star formation

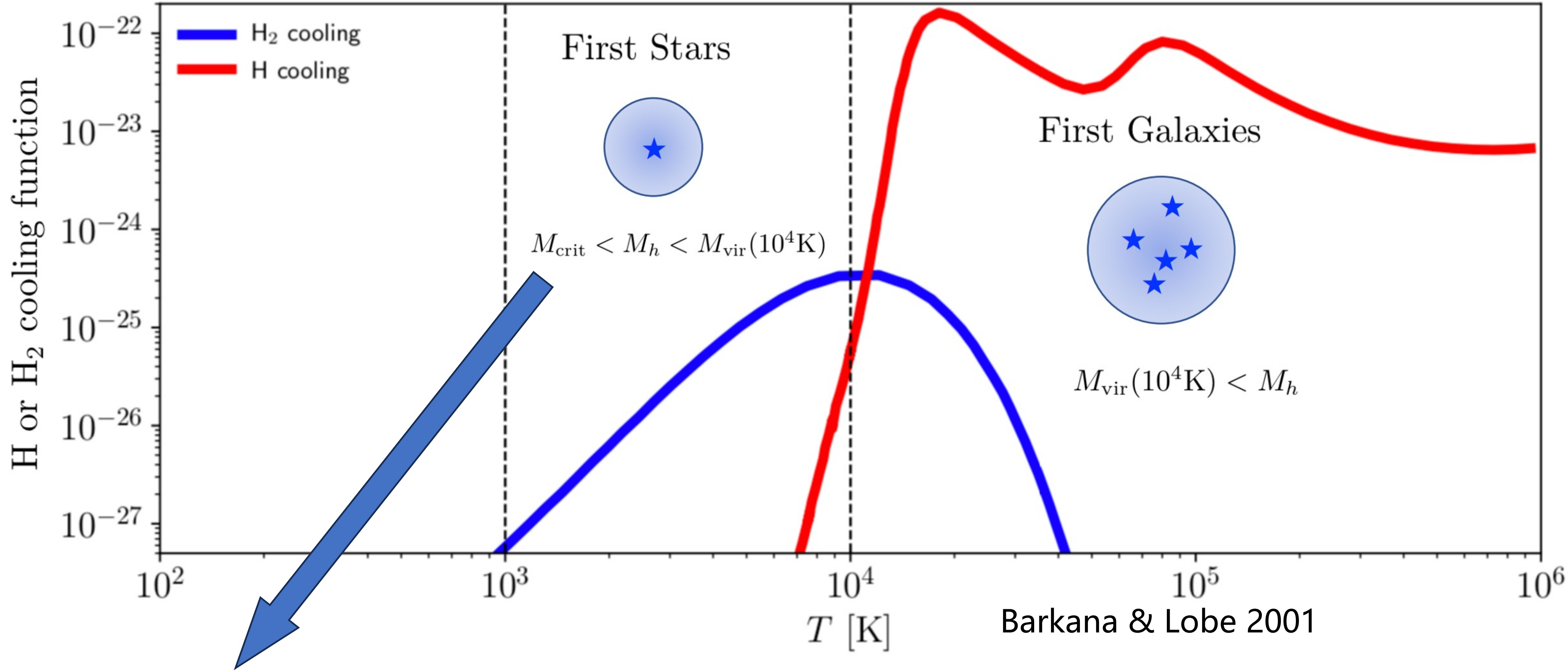
$$\epsilon^{\alpha}_{\rm cell} \propto \rho^*_{\rm cell} \qquad \epsilon^{X}_{\rm cell} \propto \rho^*_{\rm cell}$$

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

VAO feature on the 21 cm power spectrum

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

Critical Mass

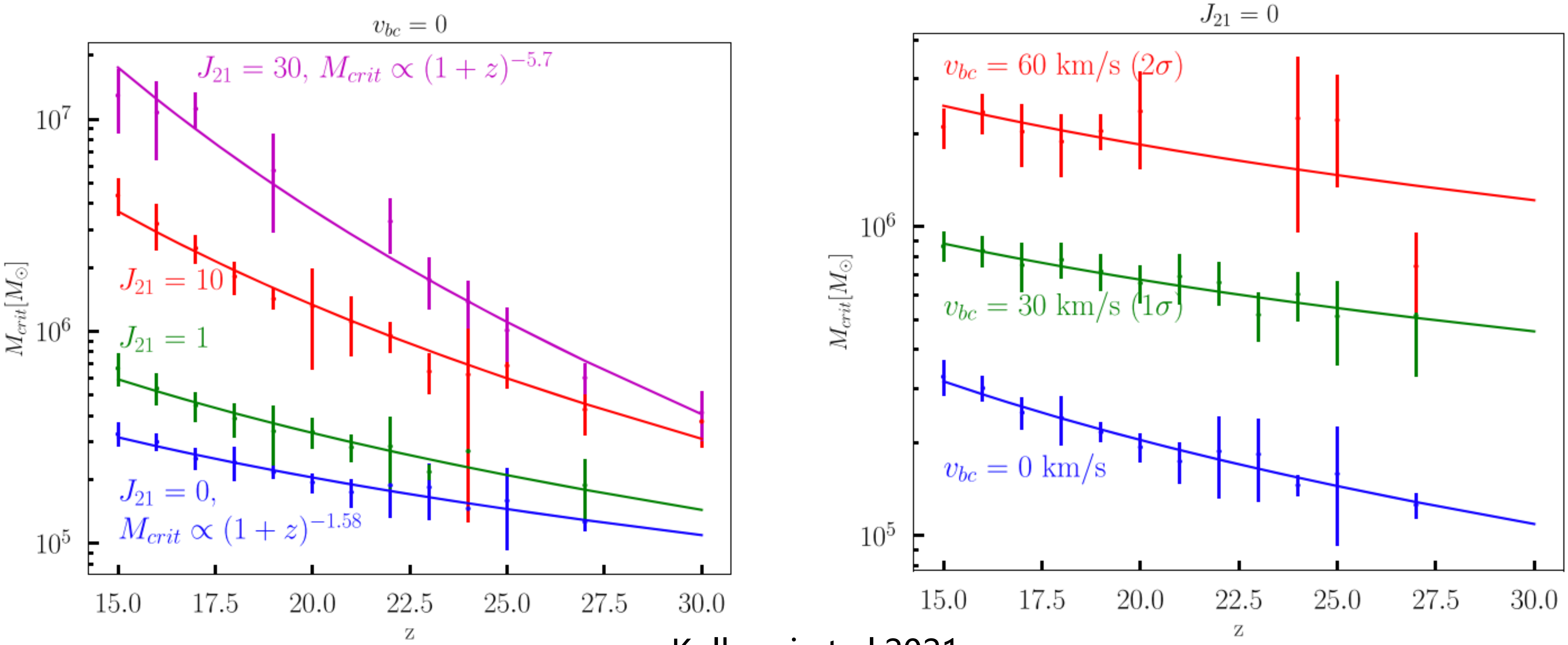


Barkana & Lobe 2001

The minimum mass of a dark matter halo allowing the formation of first-generation stars $M_{\rm crit}(J_{\rm LW,21}, v_{\rm db}^{\rm rec}, z)$

Critical Mass

The critical mass depends on the relative velocity of baryons and dark matter, the cooling mechanism of gas, LW radiation, X-rays



Kulkarni et al.2021

$$M_{\text{crit}}\left(J_{\text{LW},21}, v_{\text{db}}^{\text{rec}}, z\right) = M_{z=20}\left(J_{\text{LW},21}, v_{\text{db}}^{\text{rec}}\right) \times \left(\frac{1+z}{21}\right)^{-\alpha\left(J_{\text{LW},21}, v_{\text{bc}}^{\text{rec}}\right)}$$

VAO signal

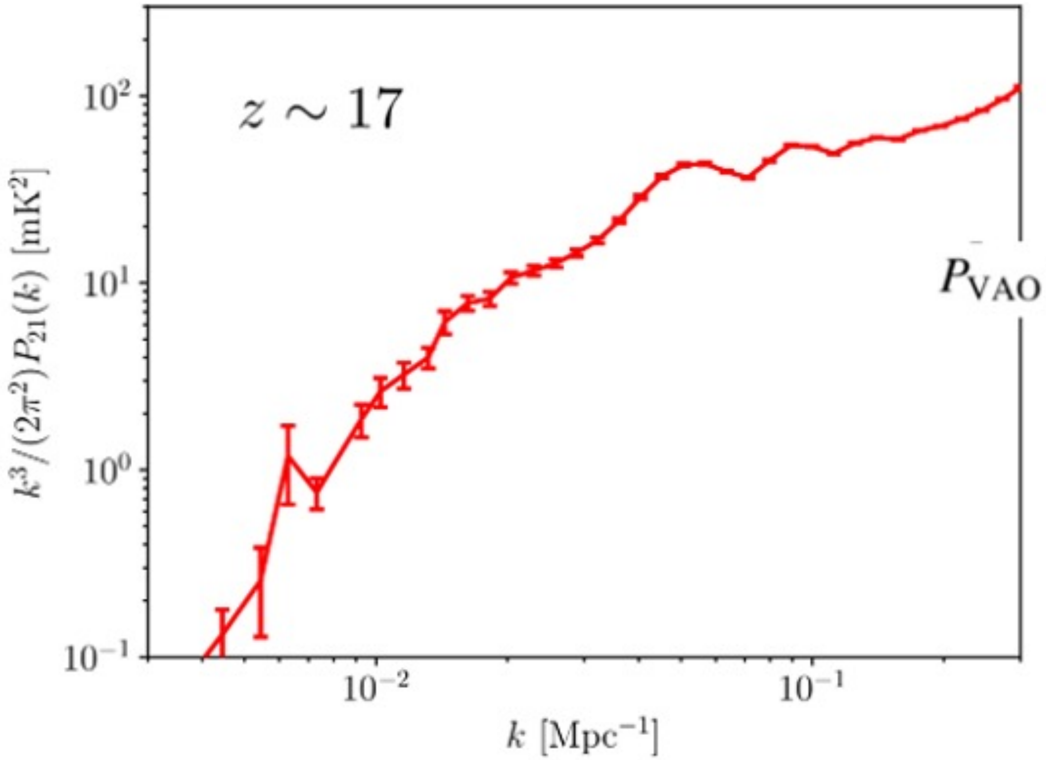
The VAOs statistically independent from density fluctuations sourced by over densities so they can be linearly added to the usual (no-vdb) 21-cm power spectrum to obtain the total signal.

Muñoz, J. B. 2019a, PhRvD, 100, 063538
Muñoz, J. B. 2019b, PhRvL, 123, 131301

$$\Delta^2_{21}(k,z) = \Delta^2_{21,\mathrm{vel}}(k,z) + \mathcal{P}_n(k,z)$$

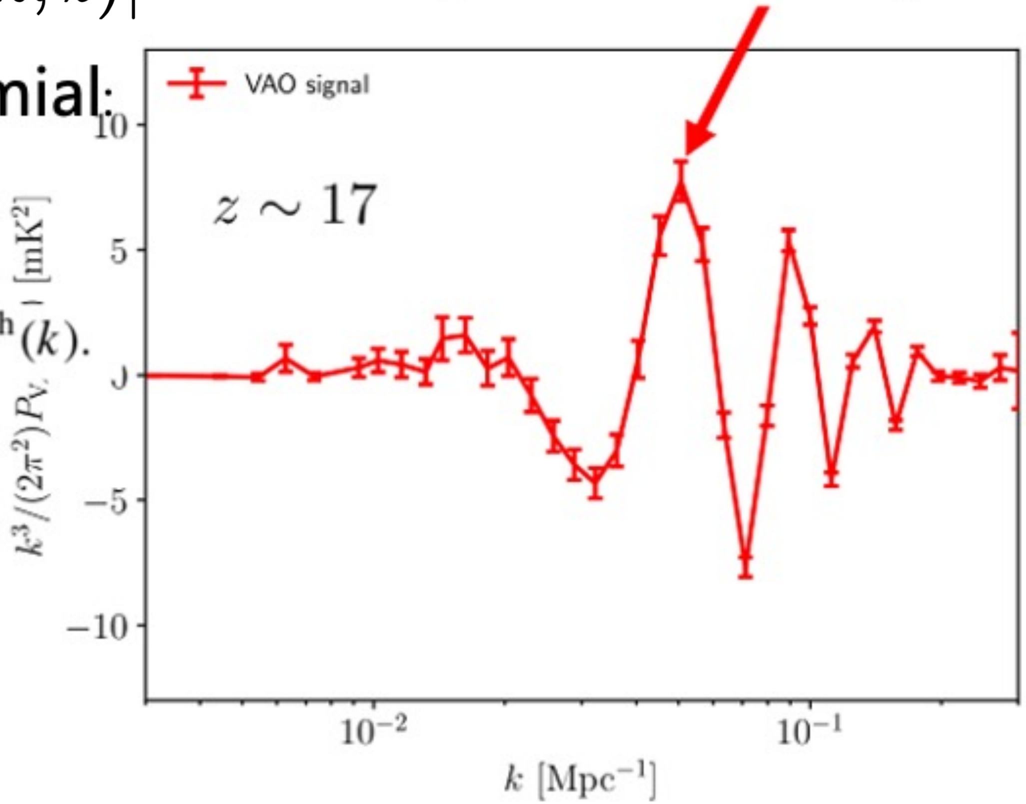
$$\Delta^2_{21,\mathrm{vel}}(k,z) = A_{\mathrm{vel}}(z)\Delta^2_{v^2}(k)|W_i(k,z)|^2$$

first peak: $k \approx 0.05\ \mathrm{Mpc}^{-1}$



polynomial:

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



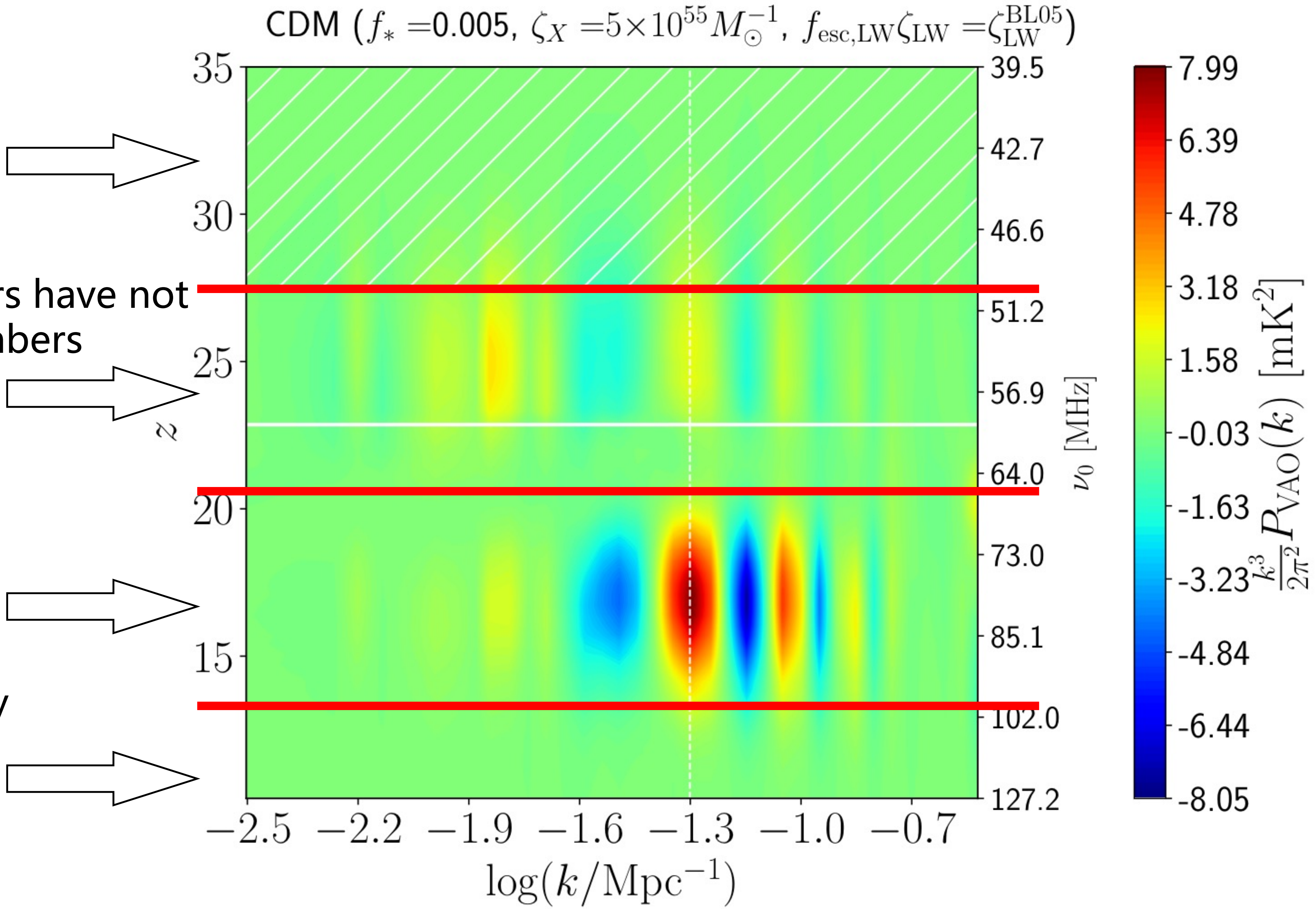
The evolution of VAO signal

beyond the frequency range of the SKA-low band.

The first-generation stars have not yet formed in large numbers
No signal

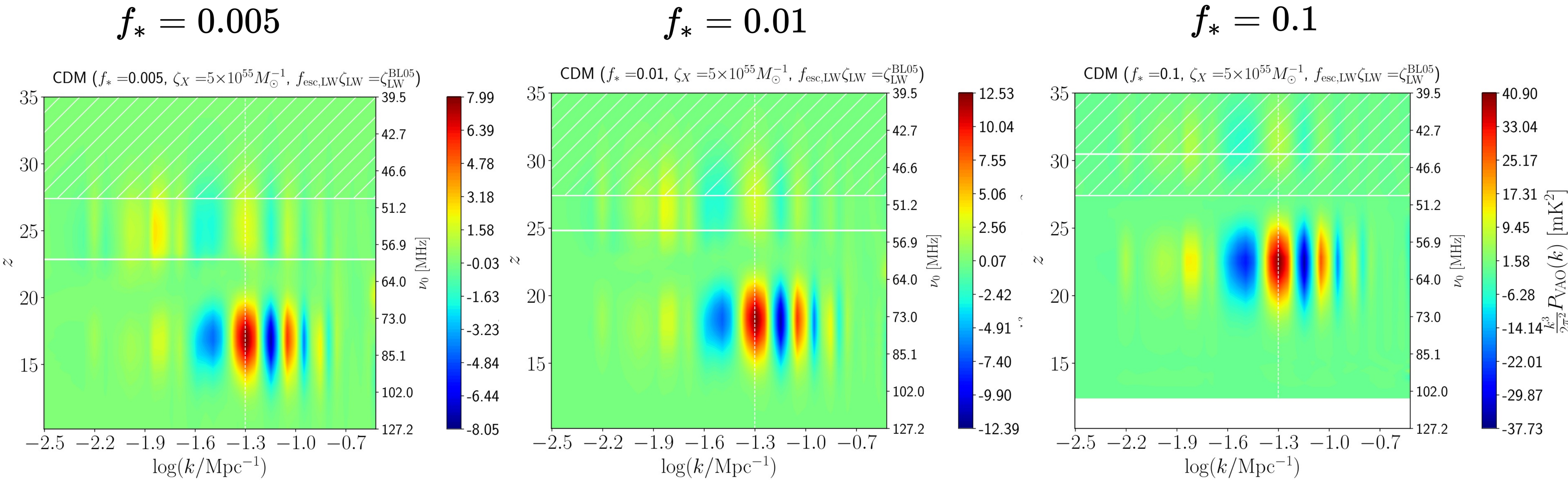
The best redshift for detecting VAO signal

Ly-α saturated, IGM fully heated, 21 cm signal independent of spin temperature
No signal



The evolution of VAO signal

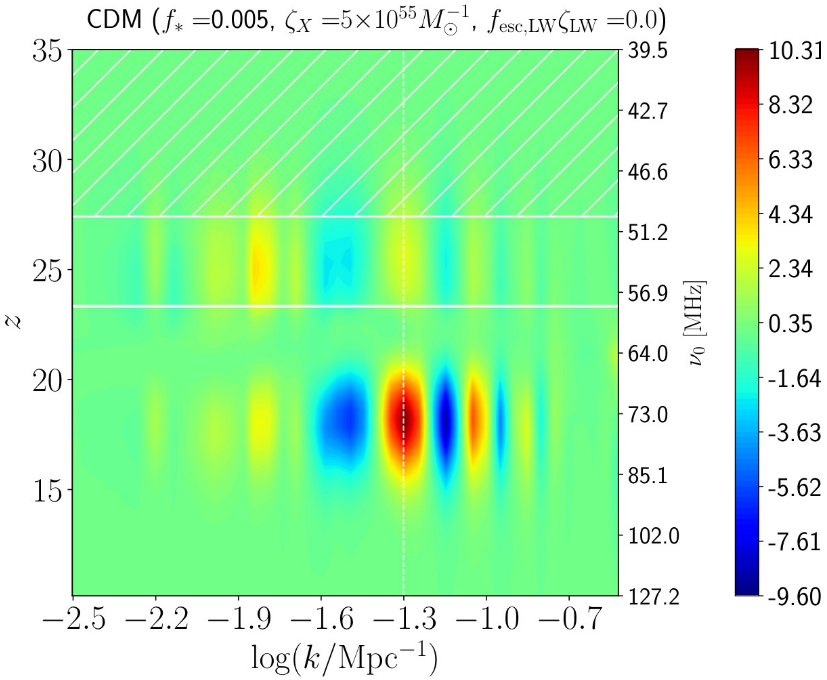
Dependence on the efficiency of first-generation star formation：



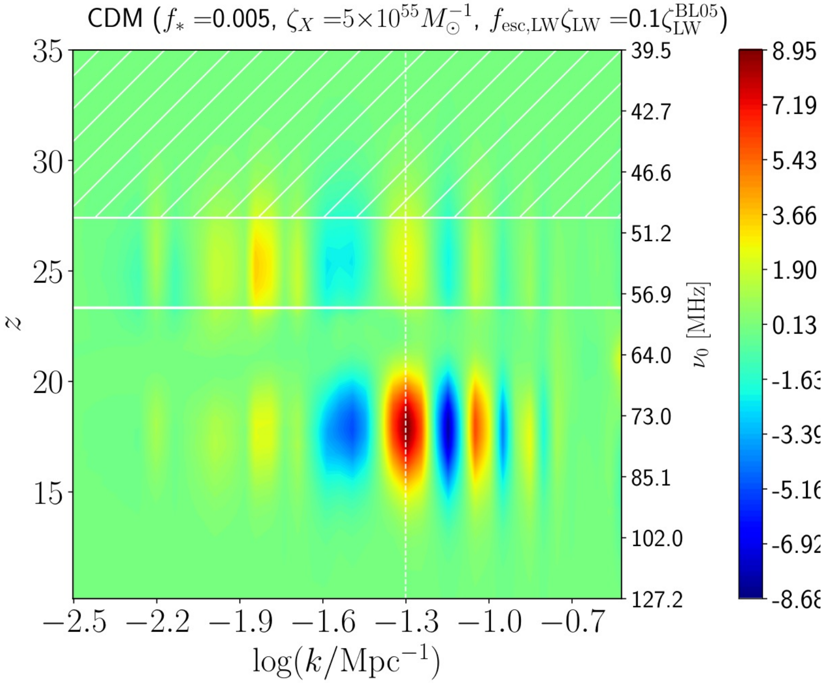
The higher the star formation efficiency, the stronger the signal, and the earlier the signal appears

Dependence on the LW feedback:

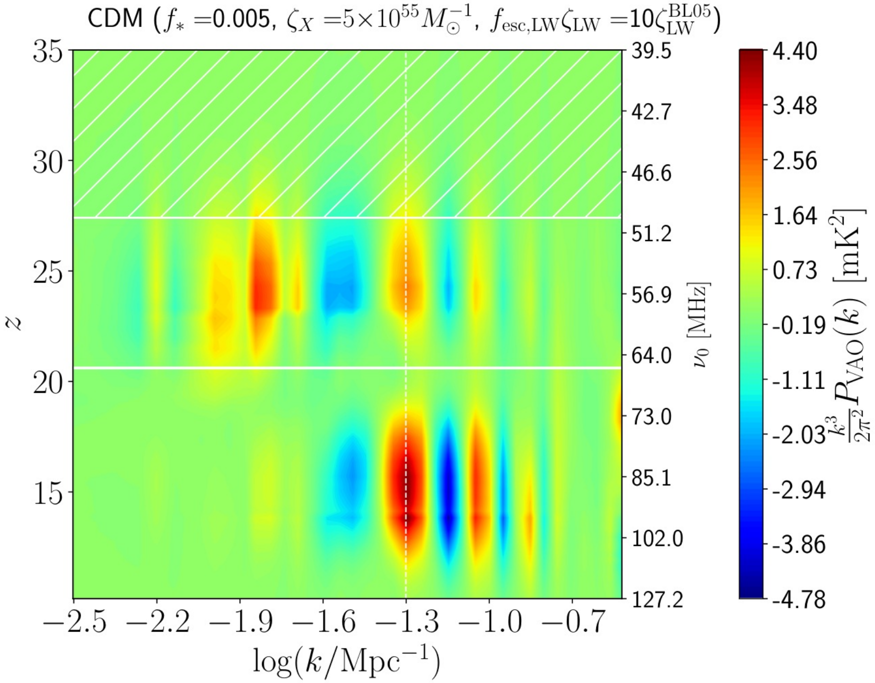
no LW feedback



weak LW feedback



Strong LW feedback

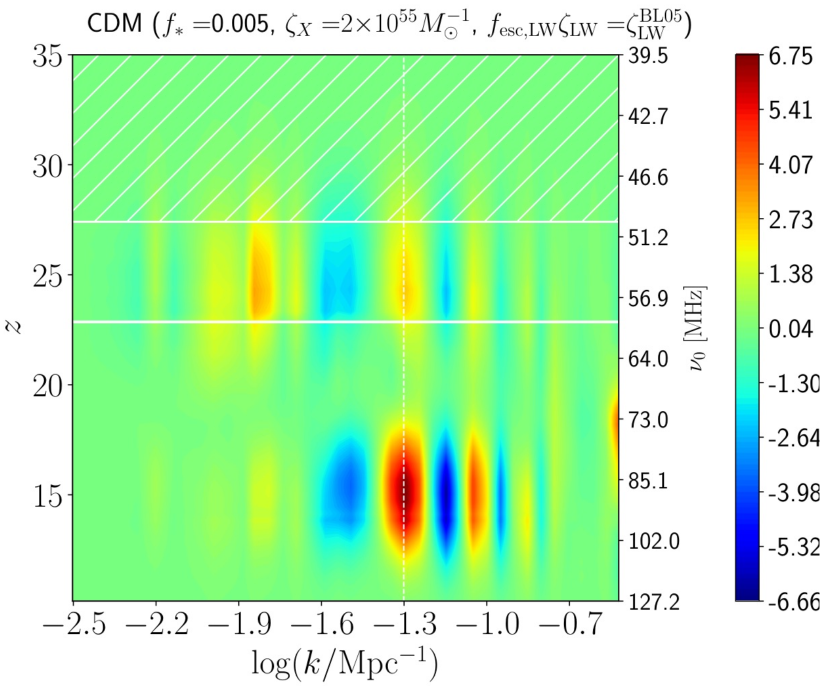


LW feedback effect will weaken VAO signal

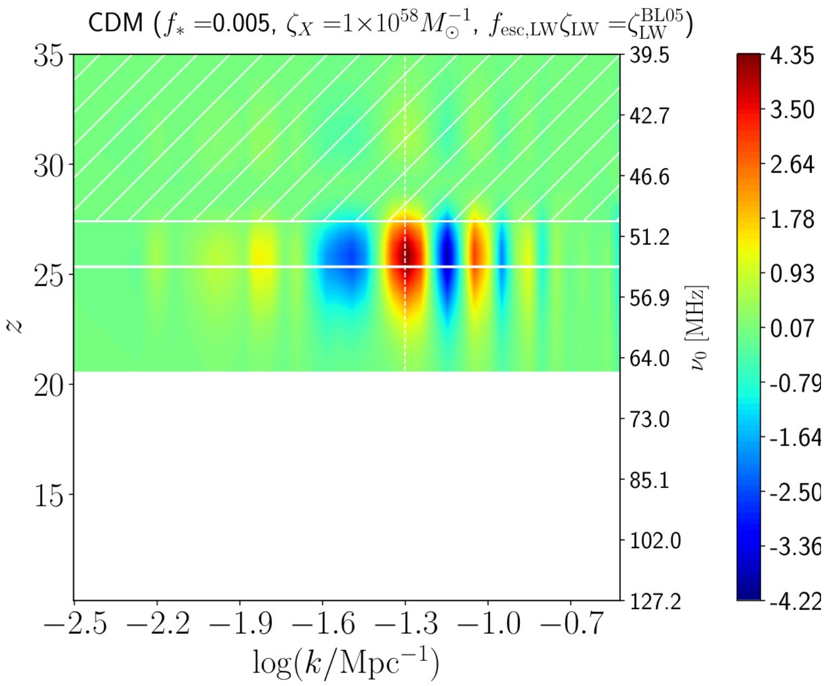
But it is not enough to make it disappear completely

Dependence on the X-rays：

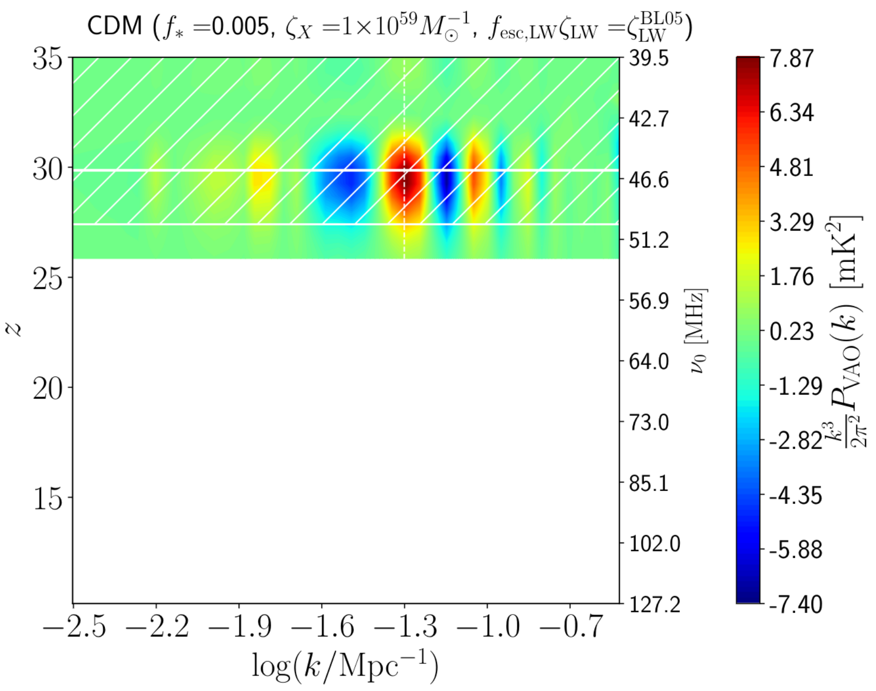
weak X-rays



strong X-rays



very strong X-rays



X-ray will weaken the VAO signal, but not monotonically decrease

X-ray is also the main ly-α source, which can make the VAO signal appear in advance and enhance its amplitude

CDM vs FDM(Axion)

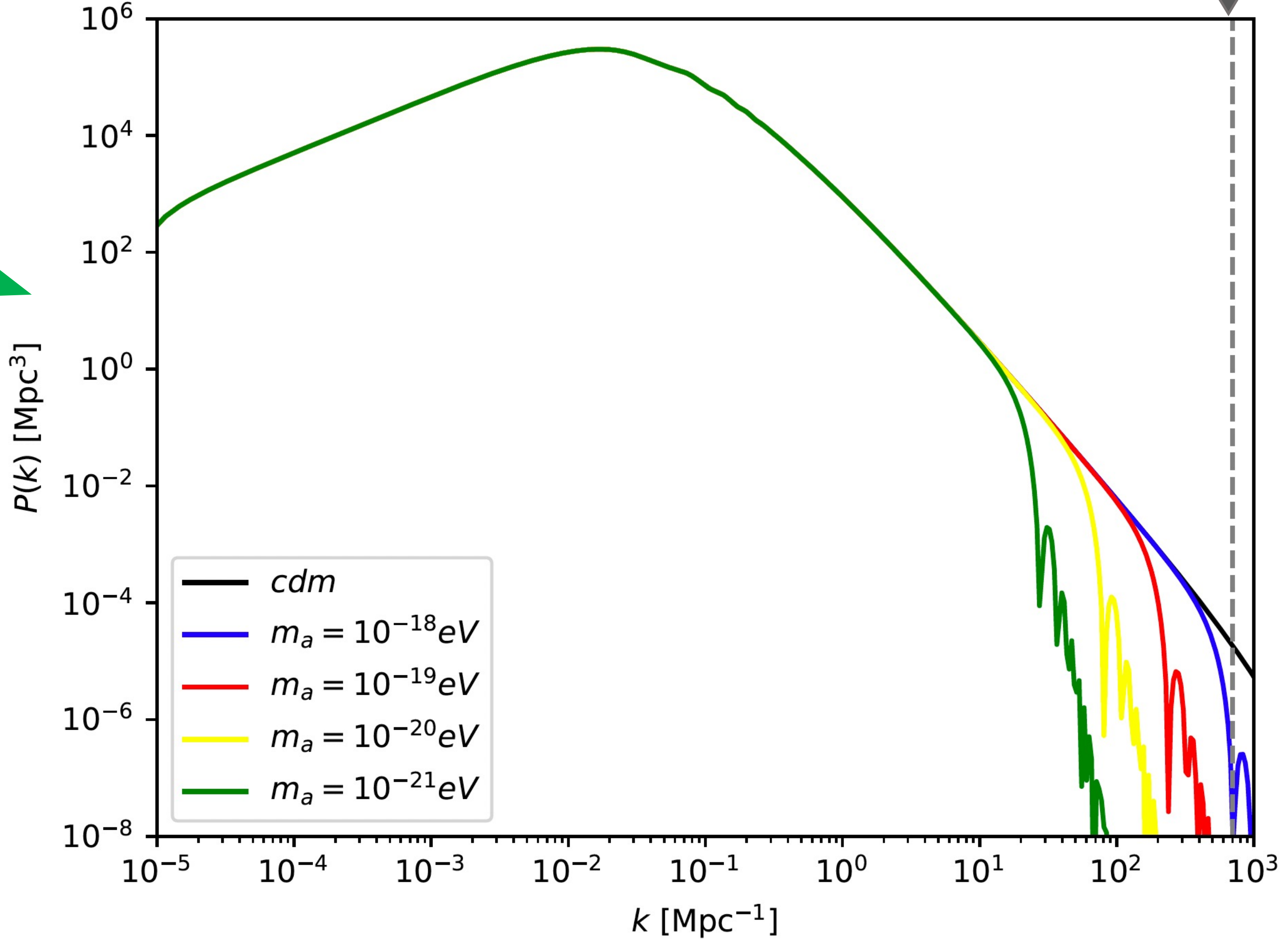
DM-Baryon relative velocity
(the large-scale coherently oscillating structures)

Minihalo distribution (critical mass) allowing the formation of first-generation stars

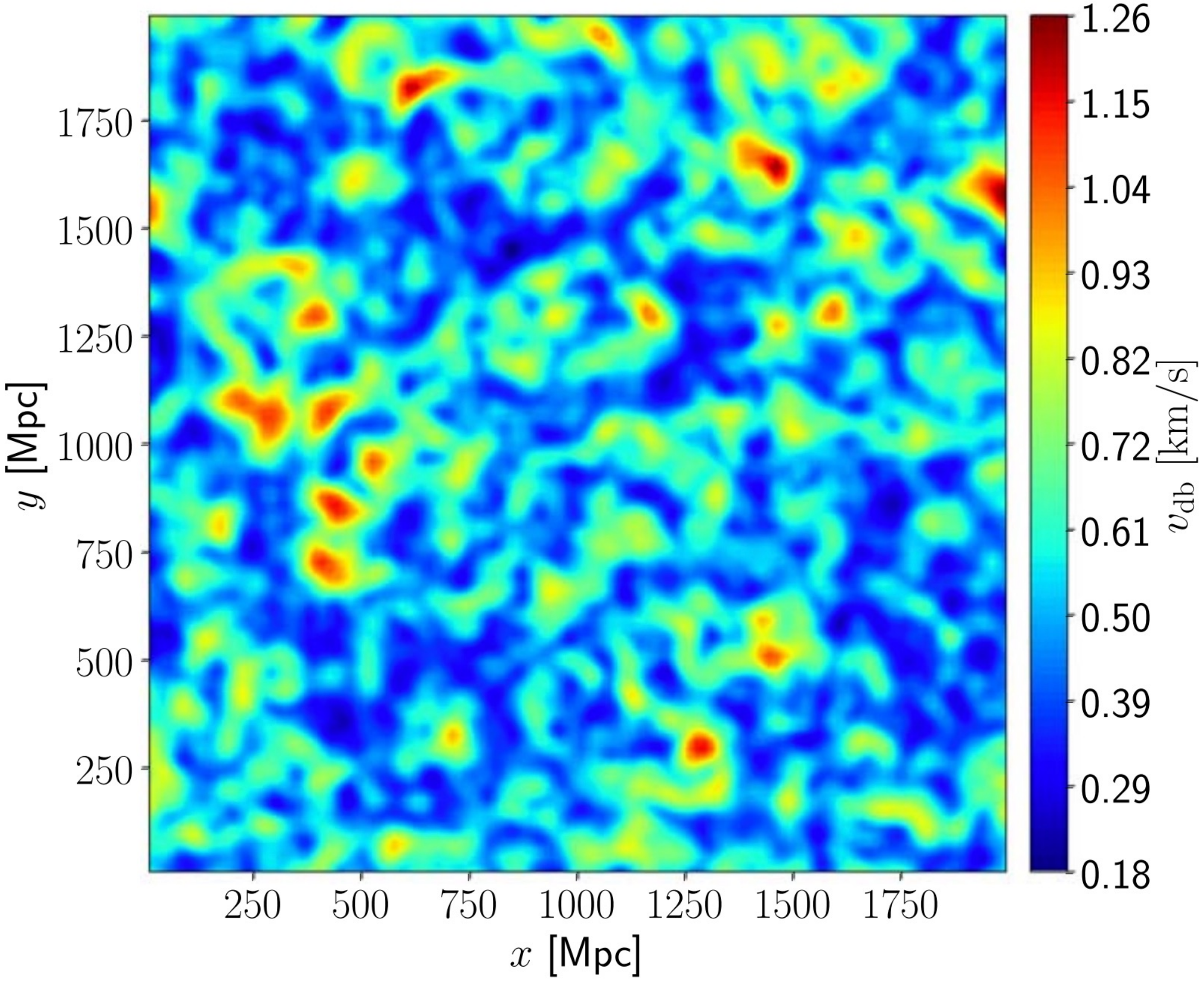
Radiation field produced by first-generation star formation

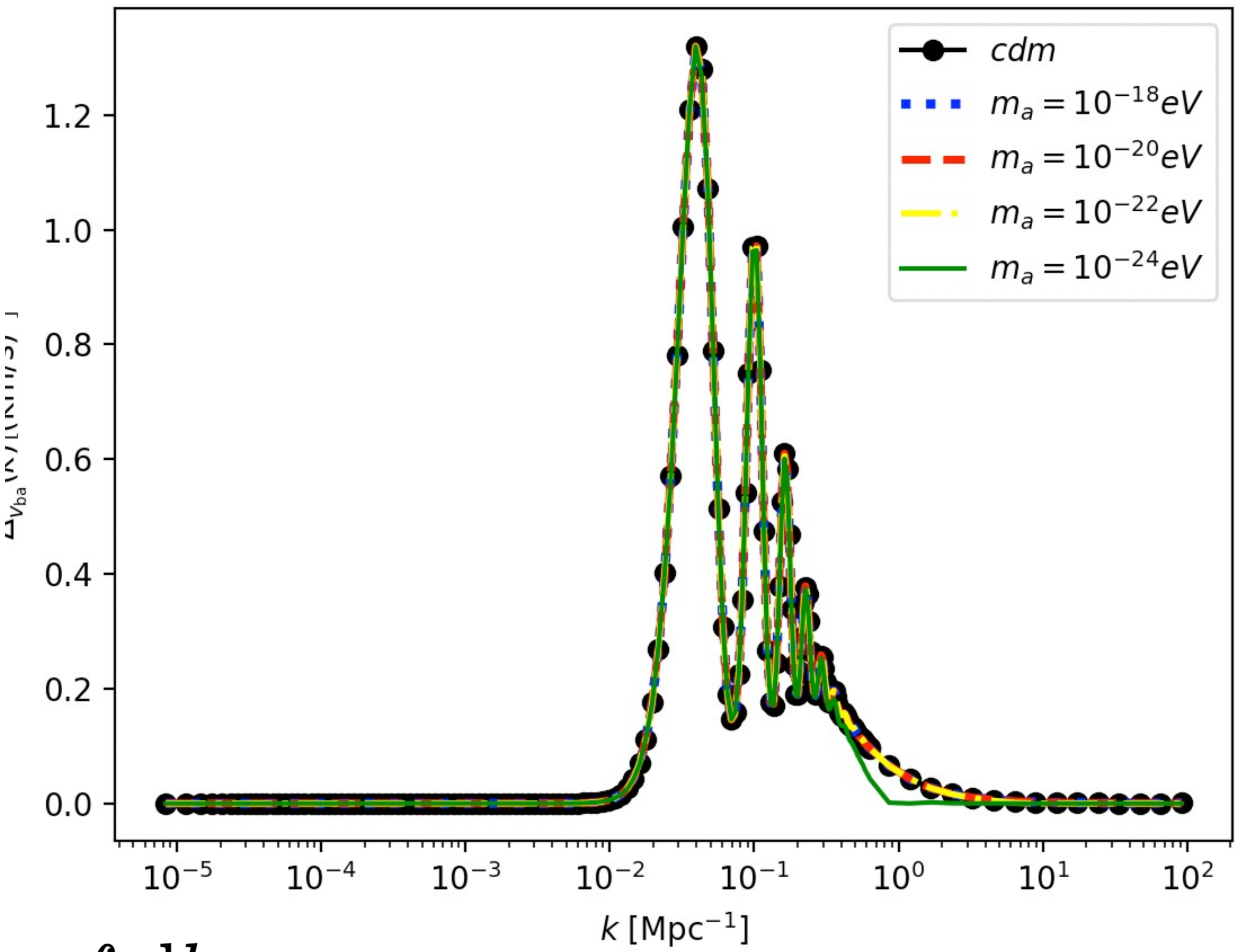
VAO feature on the 21 cm power spectrum

minihalo scale



Velocity Acoustic Oscillations(VAO)



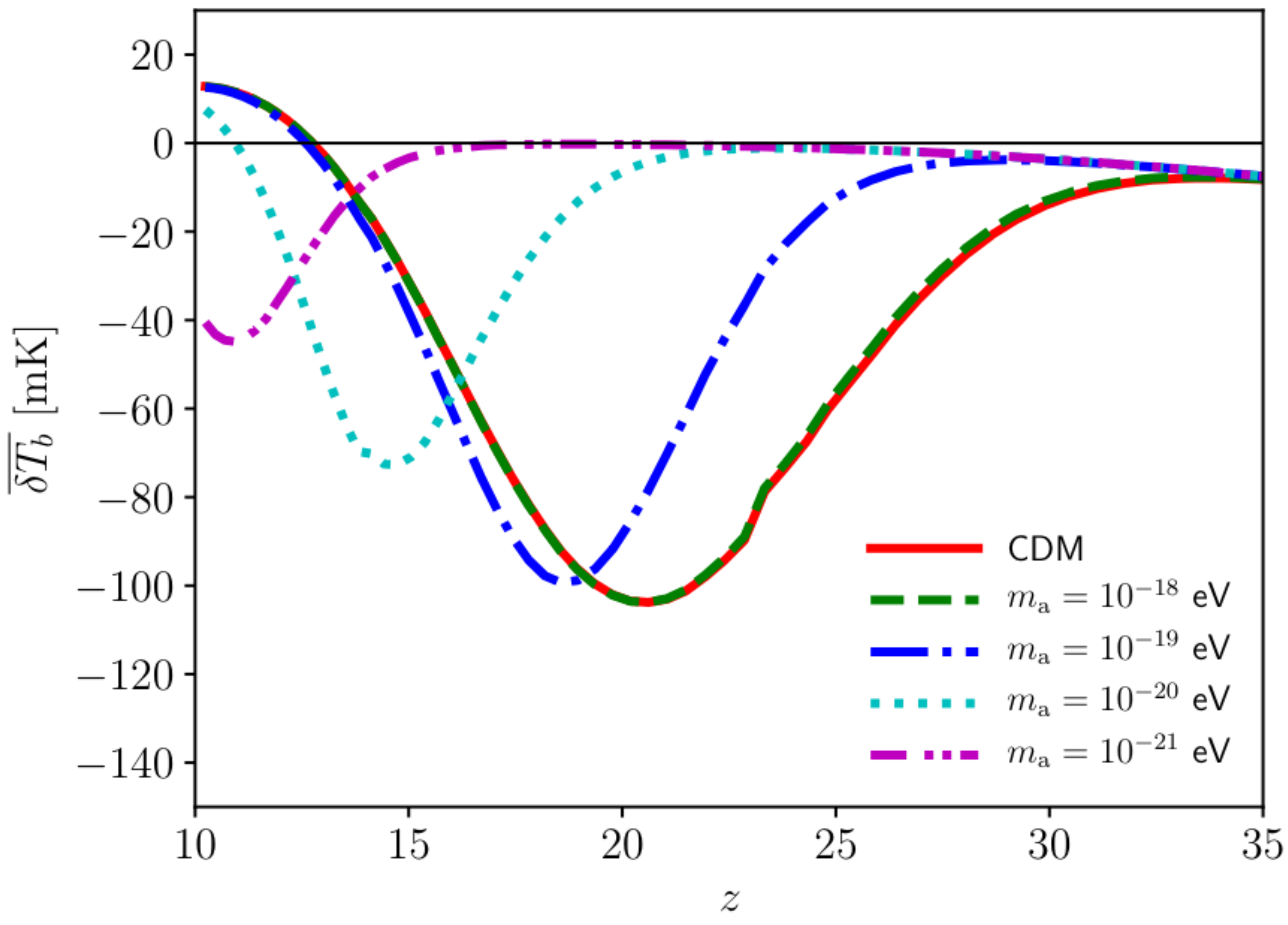


Relative velocity field of baryon and dark matter

$$v_{\rm db}^2(\boldsymbol{x}) = \int \frac{{\rm d}k}{k} \Delta_{\rm vdb}^2(k)$$

power spectrum

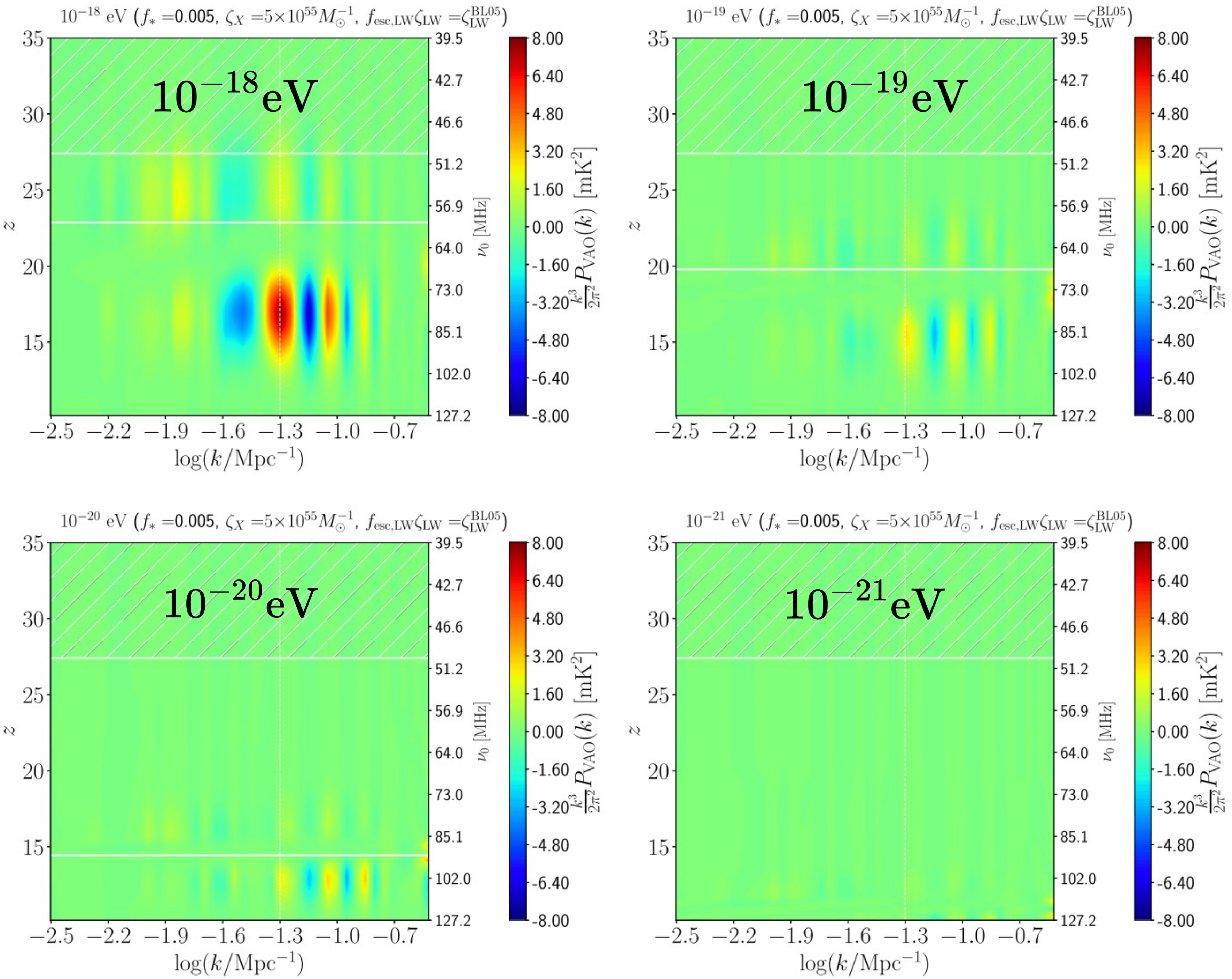
21cm Global spectrum in different dark matter model



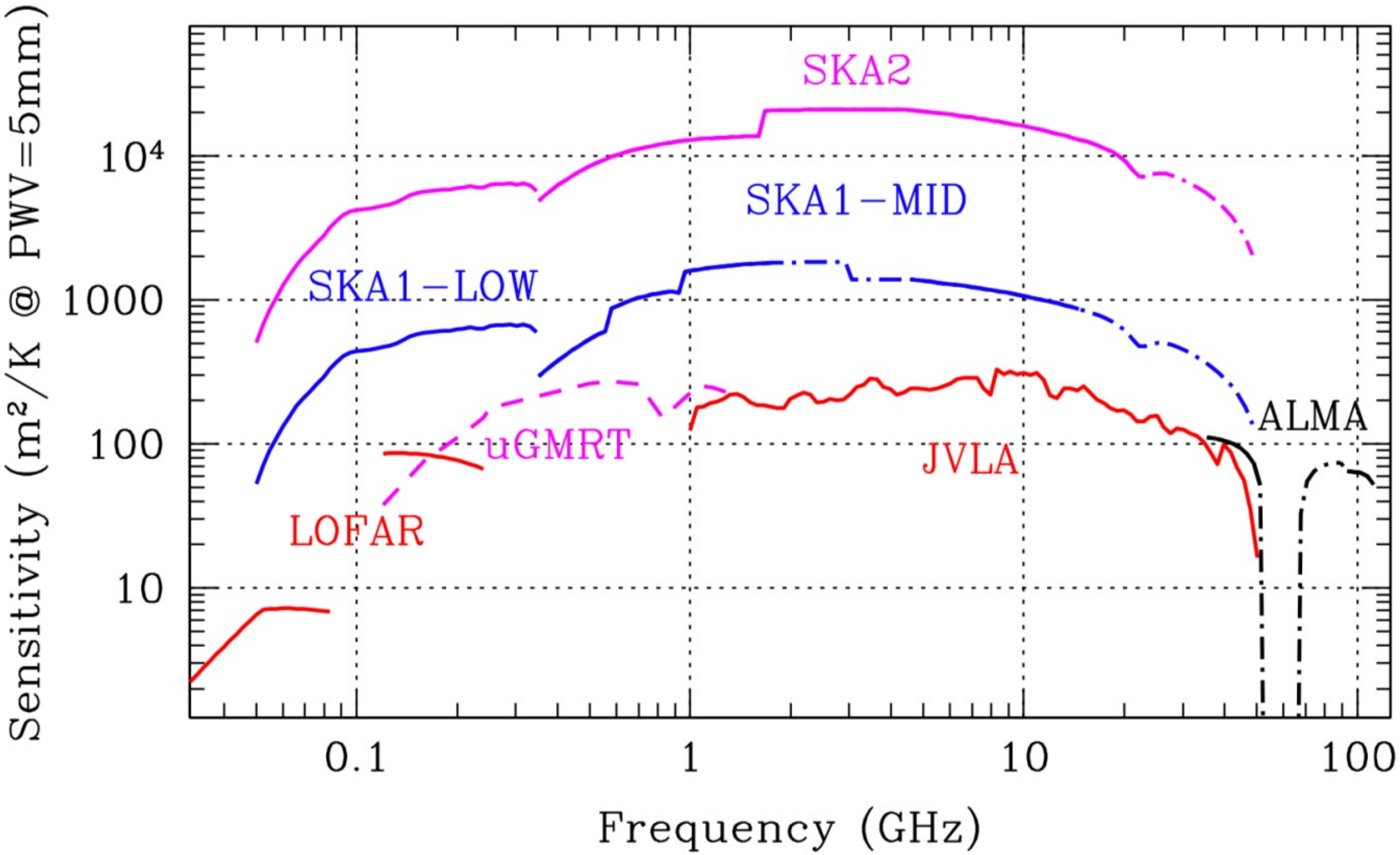
$$\delta T_b = 27 x_{HI}(1+\delta)\left(\frac{T_s - T_{CMB}}{T_s}\right) \times \left(\frac{1+z}{10}\right)^{1/2}\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_k^{-1} + x_c T_k^{-1}}{1 + x_\alpha + x_c}$$

The evolution of VAO signal (For the Axion dark matter model)

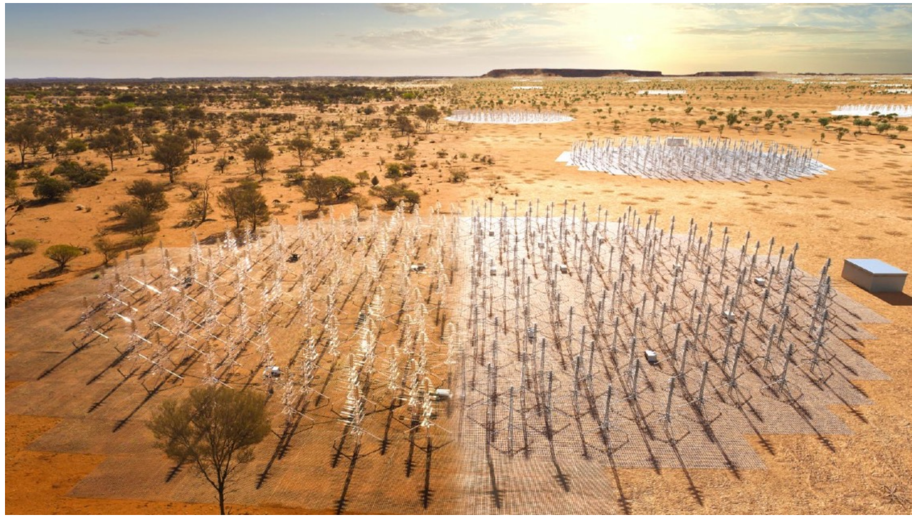


SKA-low: The detectability of VAO signal



Sensitivity parameters of SKA1 and SKA2

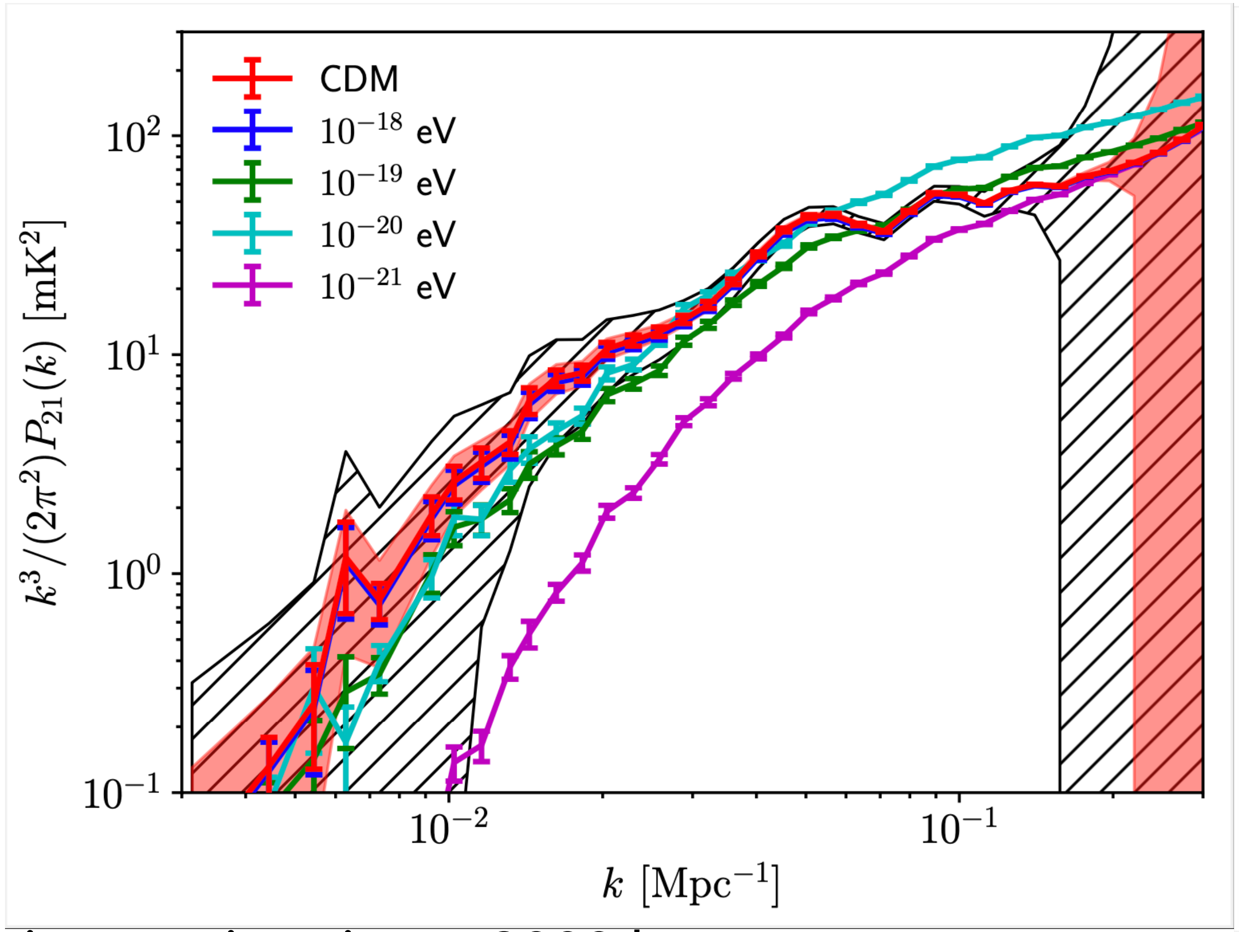
Braun et al. (2019)

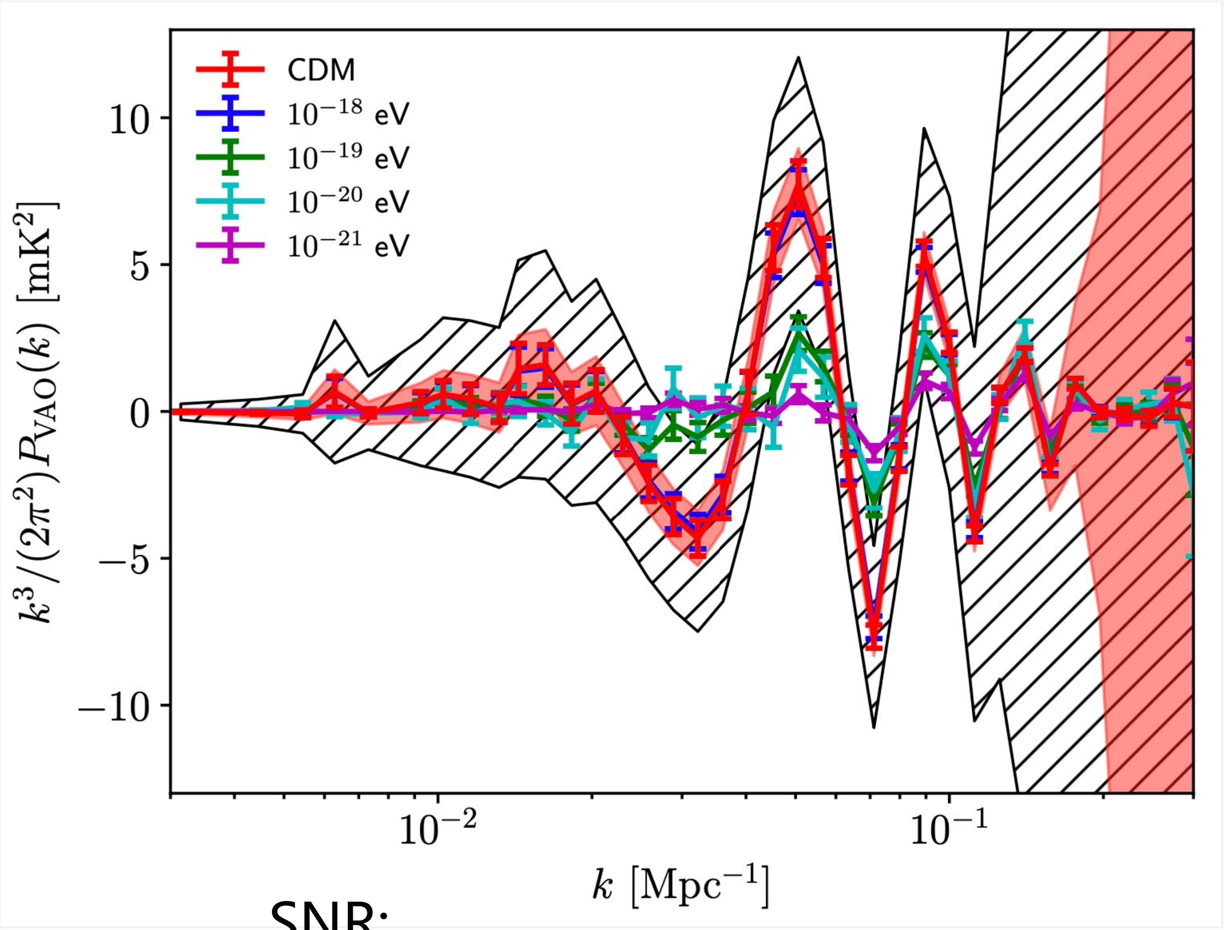


VAO signal and the expected measurement error of SKA

Fit the smooth component of the 21 cm power spectrum by a polynomial:

$$\ln\left(\frac{k^3}{2\pi^2}P_{21}^{\rm smooth}(k)\right)=\sum_{i=0}^{4}c_i(z)(\ln k)^i$$



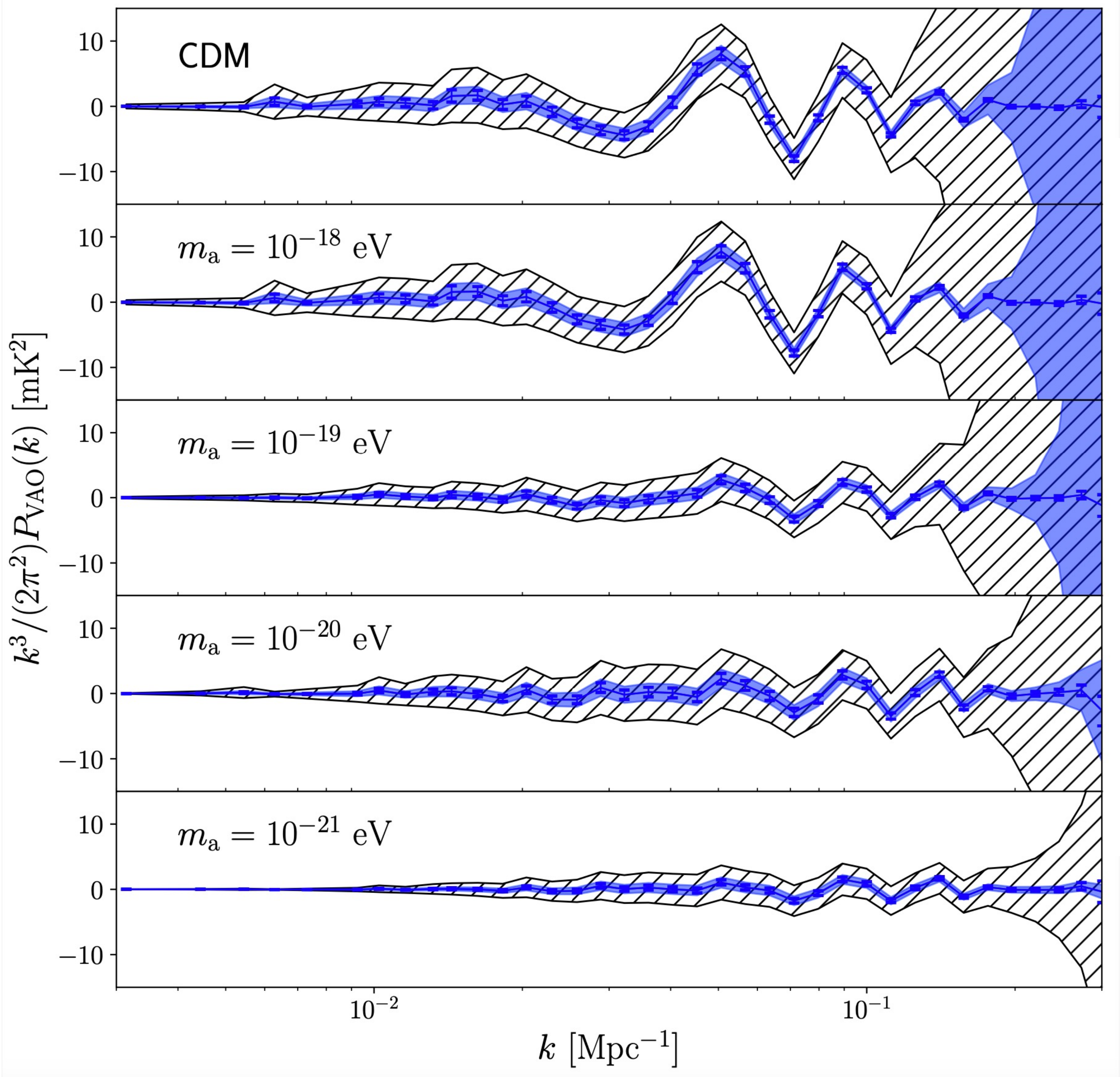


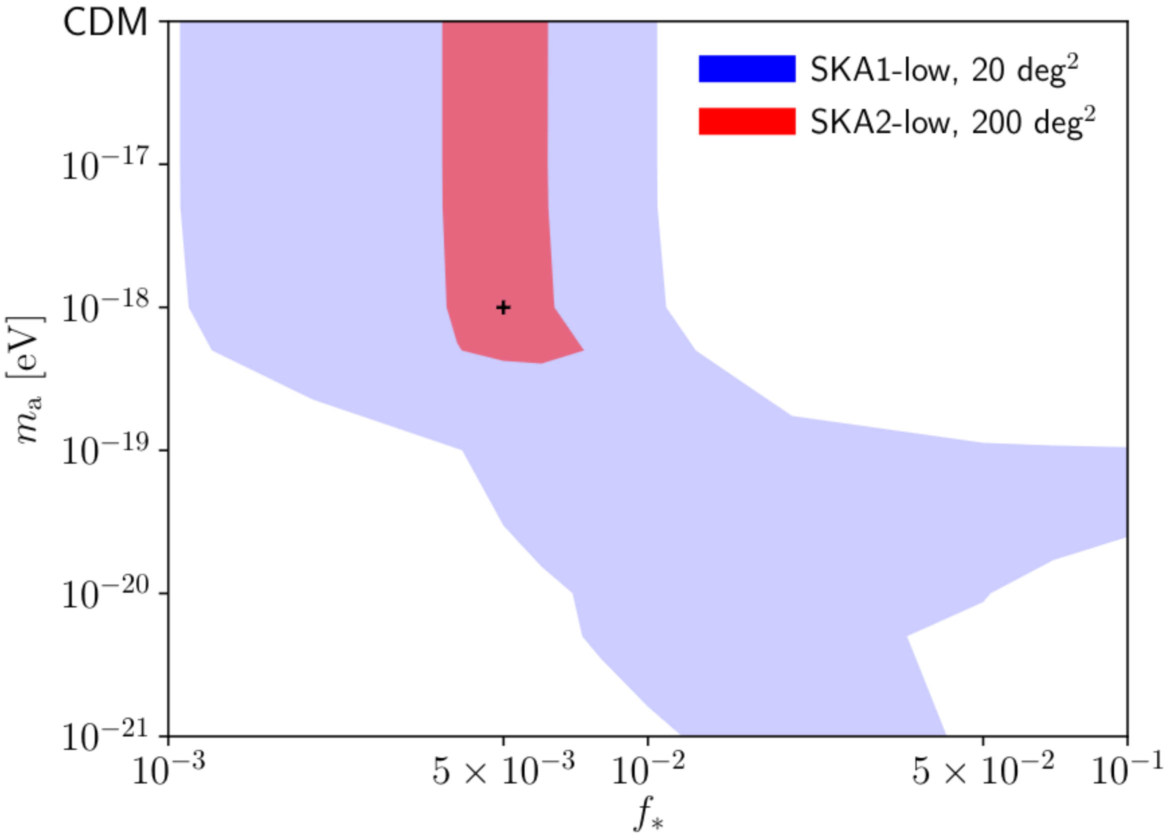
integration time: 2000 hour

survey area: SKA1-low $20\mathrm{deg}^2$ SKA2-low $200\mathrm{deg}^2$

SNR:
SKA1-low: ~6
SKA2-low: ~22

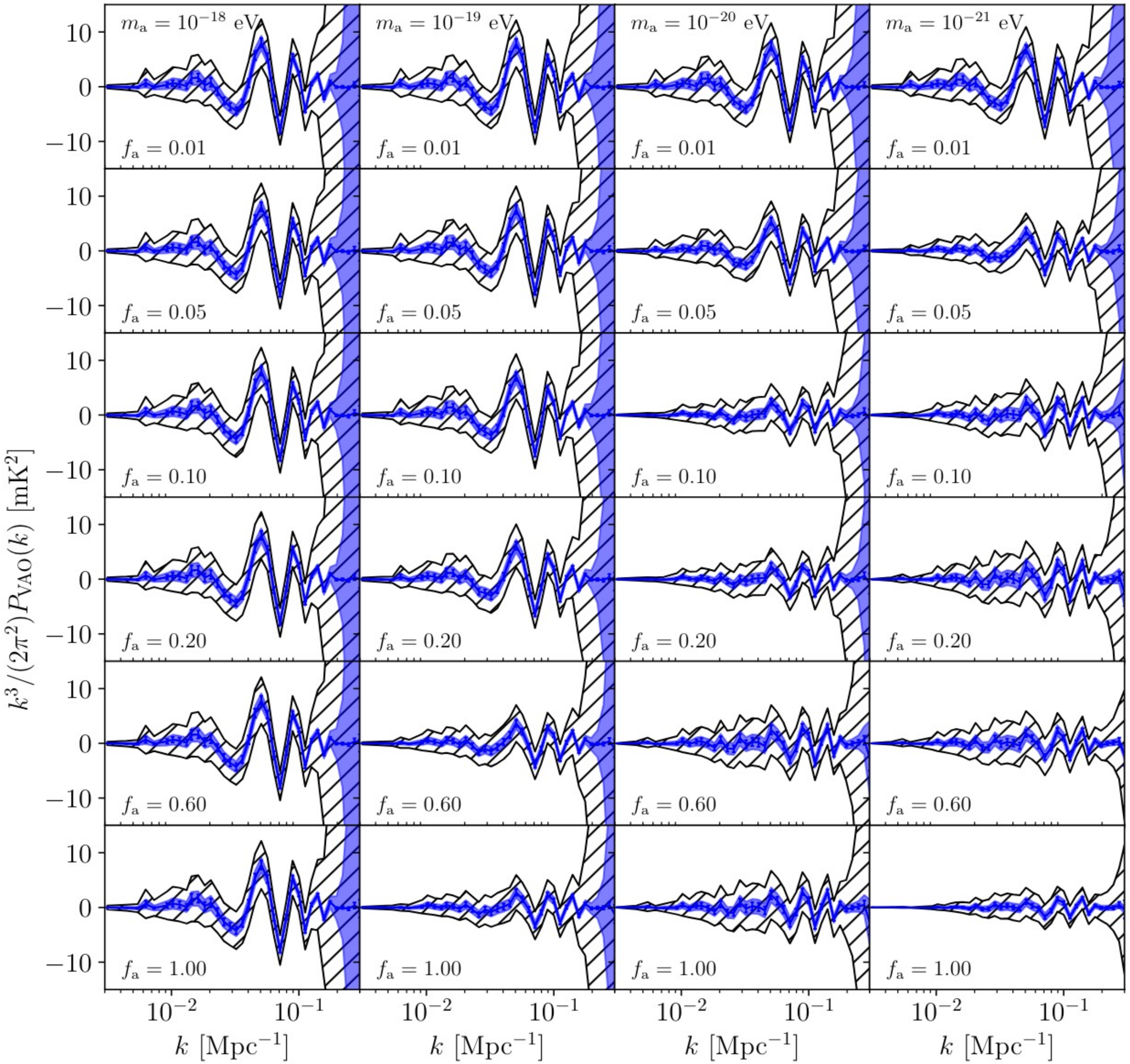
The VAO signal in various dark matter models

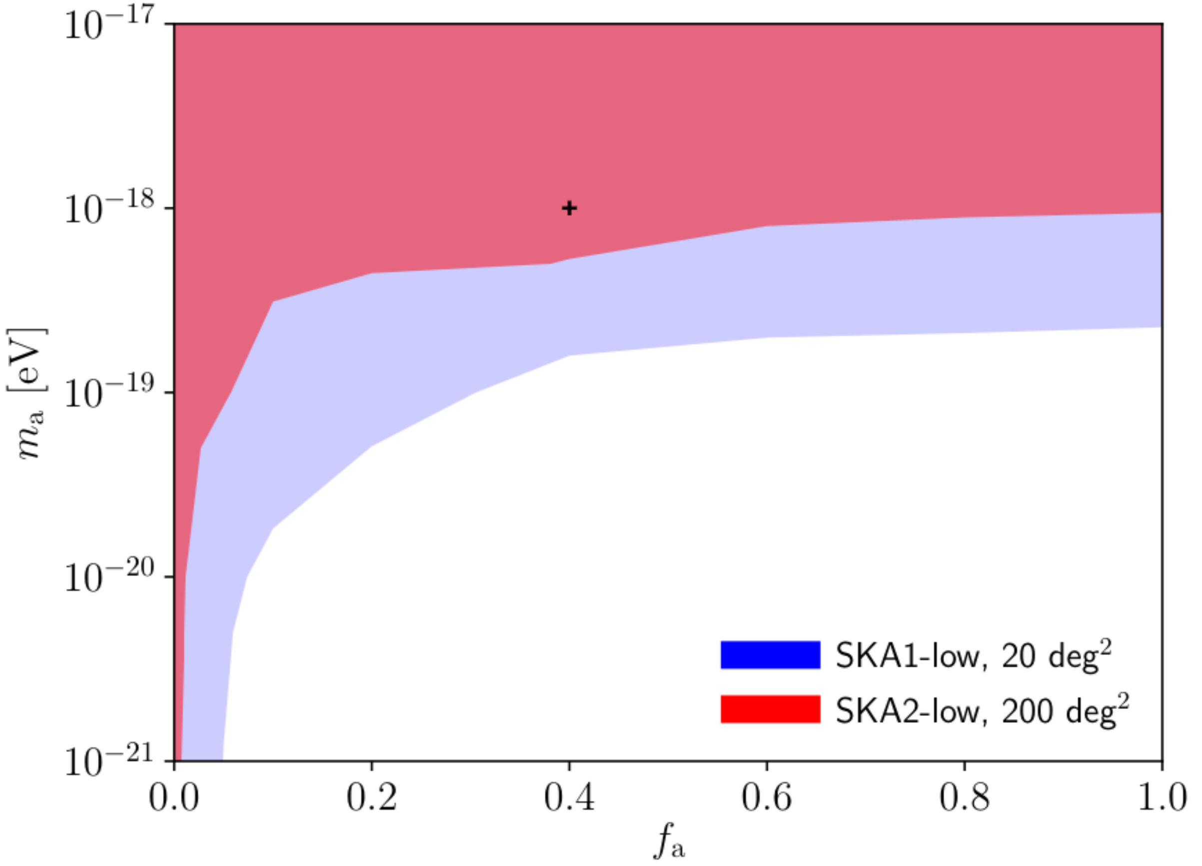




forecast the parameter constraints

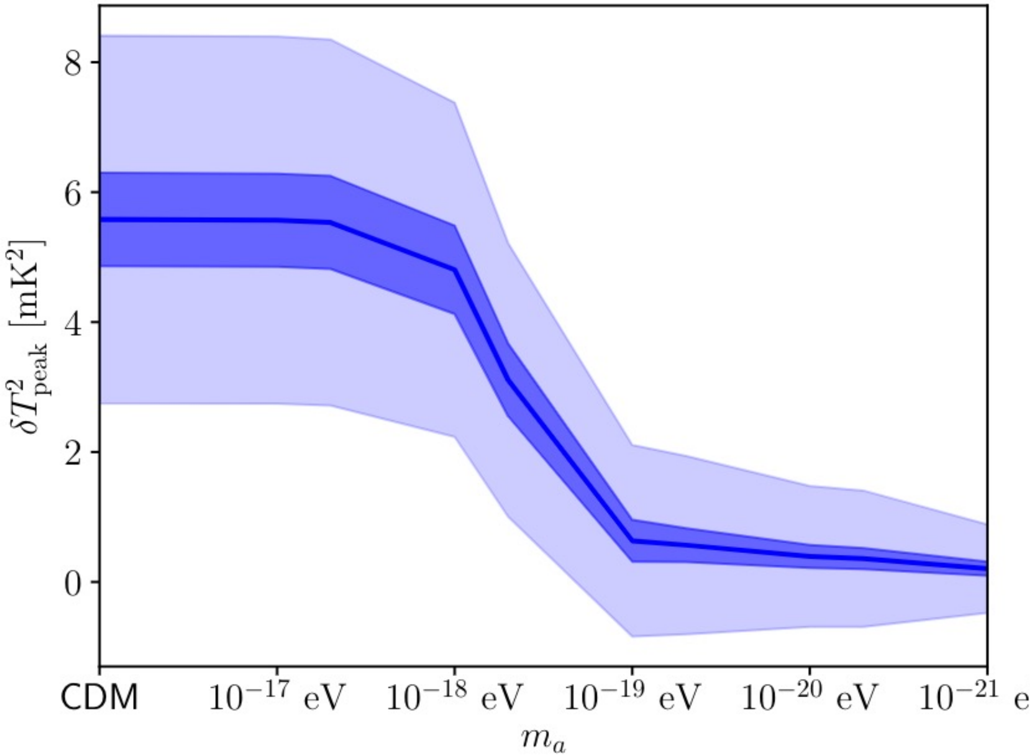
The VAO signal in mixed dark matter model

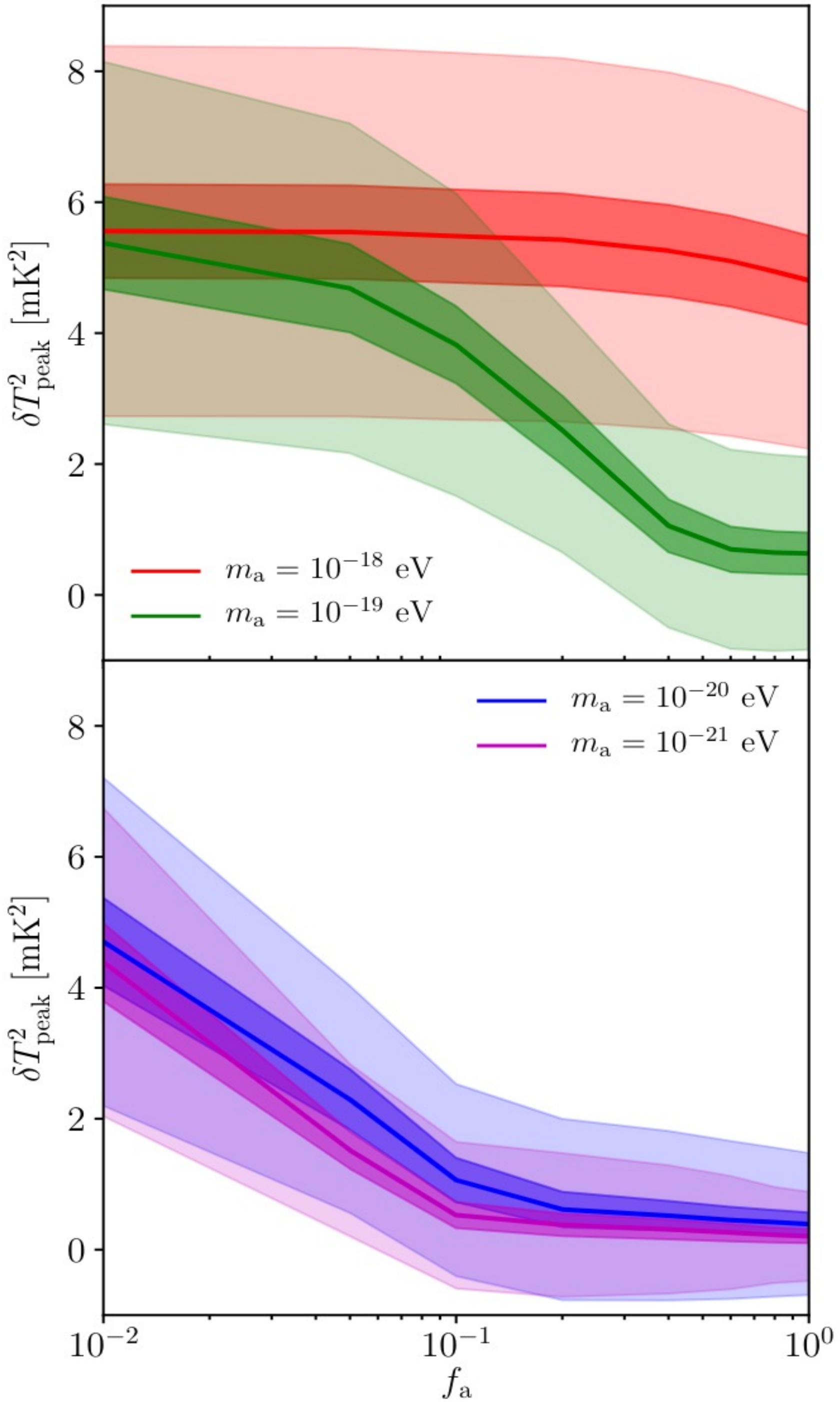




forecast the parameter constraints

The amplitude of the strongest peak vs f_{a}, for different axion masses





We find this formula can be used to quickly estimate the VAO signal:

$$\frac{\delta T^2_{\mathrm{peak}}}{(\mathrm{mK})^2} \approx [5.6 - f(m_{\mathrm{a}})g(f_*)]\tilde{f}_{\mathrm{voigt}}(f_{\mathrm{a}}, \sigma_{\mathrm{a}}, \gamma_{\mathrm{a}}) + f(m_{\mathrm{a}})g(f_*),$$

$$f(m_{\mathrm{a}}) = 2.8\{1 + \mathrm{erf}[1.35(\log m_{\mathrm{a}} + 18.5)]\},$$

$$g(f_*) = 7.34 + 4.12 \log f_* + 0.59(\log f_*)^2,$$

$$\sigma_{\mathrm{a}} = \left[10^{(-18.3 - \log m_{\mathrm{a}})}\right]^{0.2} \exp\left[-10^{(-18.3 - \log m_{\mathrm{a}})}\right],$$

$$\gamma_{\mathrm{a}} = 0.1 \exp\left[-2(-19.0 - \log m_{\mathrm{a}})^2\right] + 0.03.$$

Summary:

1. The 21cm signal at the cosmic dawn contains important information of cosmology and astrophysics.

2. With the formation of the first-generation stars at the cosmic dawn and the radiation field is build up, the VAO characteristics appear on the 21cm power spectrum in a specific window period.

3. VAO signals can be used as good tools to distinguish whether the dark matter has small scale structure(different dark matter model)

4. SKA1-low and SKA2-low may measure such special 21cm signal characteristic.

Thank You!

The CMB, cosmic gas temperature, and 21 cm spin temperature in the dark ages, cosmic dawn and the epoch of reionization

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