21cm forest probes on axion dark matter

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Based on Shimabukuro, Ichiki and Kadota [PRD 102,023522 (2020)]

Axion particles

- **Axion as a candidate of dark matter particle**

In QCD theory, it is known that there exists the term that **violates CP symmetry** in Lagrangian.

$$L = L_0 + \frac{\theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

However, experiments show that the Lagrangian **conservers CP symmetry**.

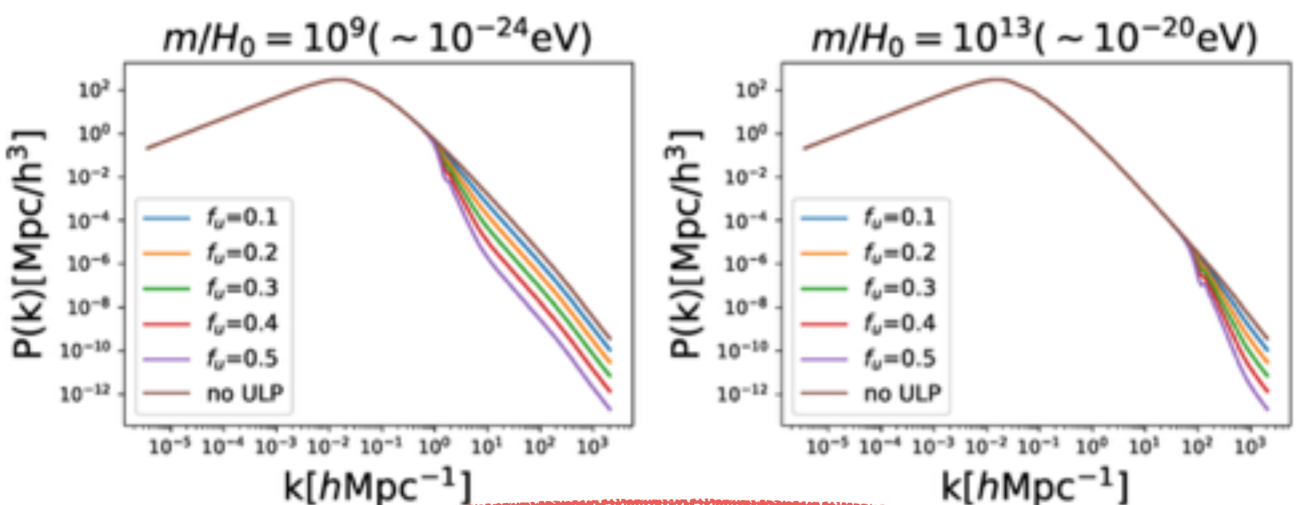
In order to conserve CP symmetry, Peccei-Quinn(PQ) symmetry was introduced (Peccei &Quinn, 1977).

As the result of breaking PQ symmetry, axion particles are generated. **Axions is one of the candidates of dark matter.**

When did PQ symmetry break?

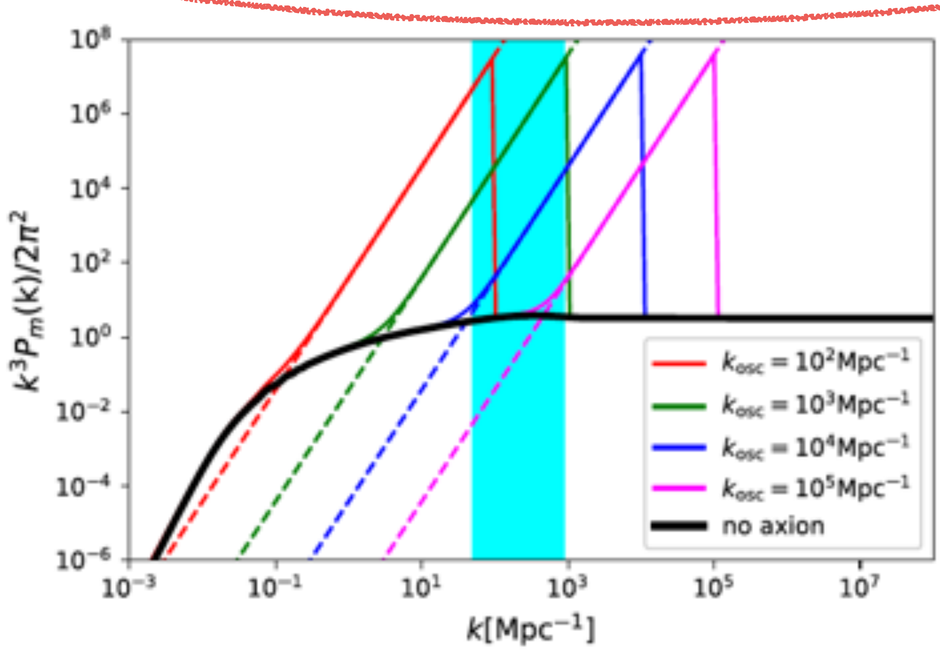
If PQ symmetry breaks **before** inflation

Shimabukuro et al (2020a)



P(k) is **suppressed** inside Jeans scale because the pressure of axion prevents matter fluctuations from growing.

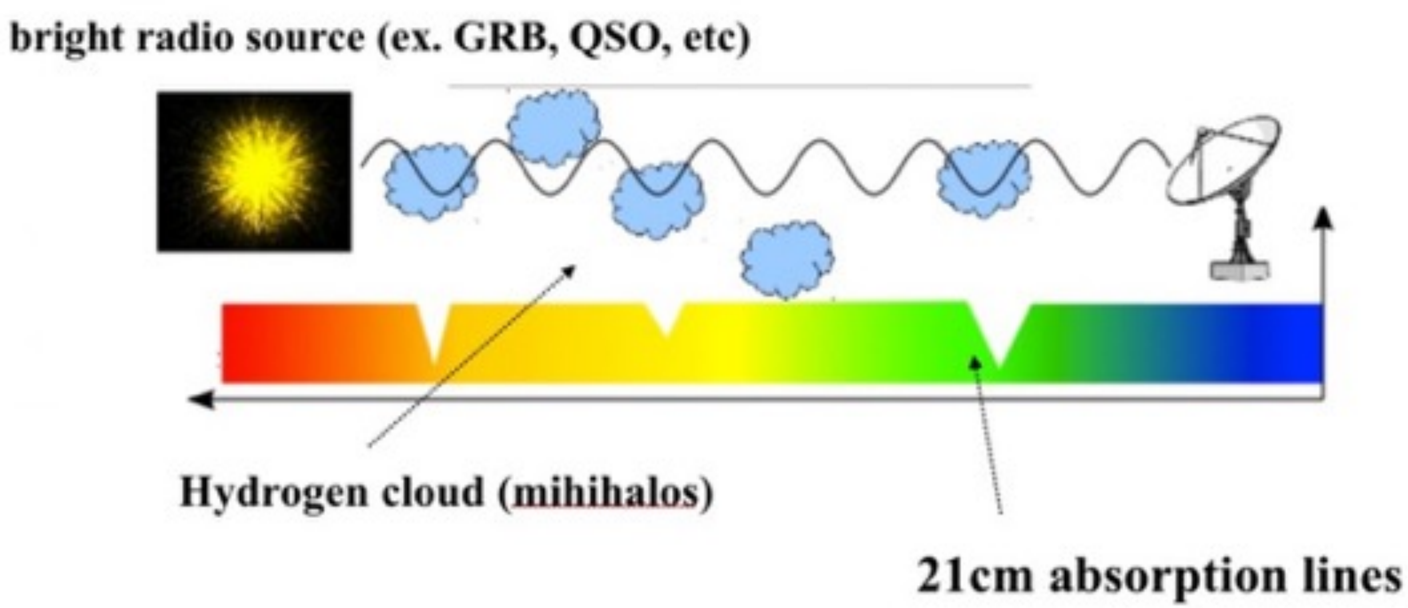
If PQ symmetry breaks **after** inflation



P(k) is **enhanced** because isocurvature fluctuations are generated as the result of acquiring axion mass.

Formation of small scale structures (**minihalo**) are also enhanced.

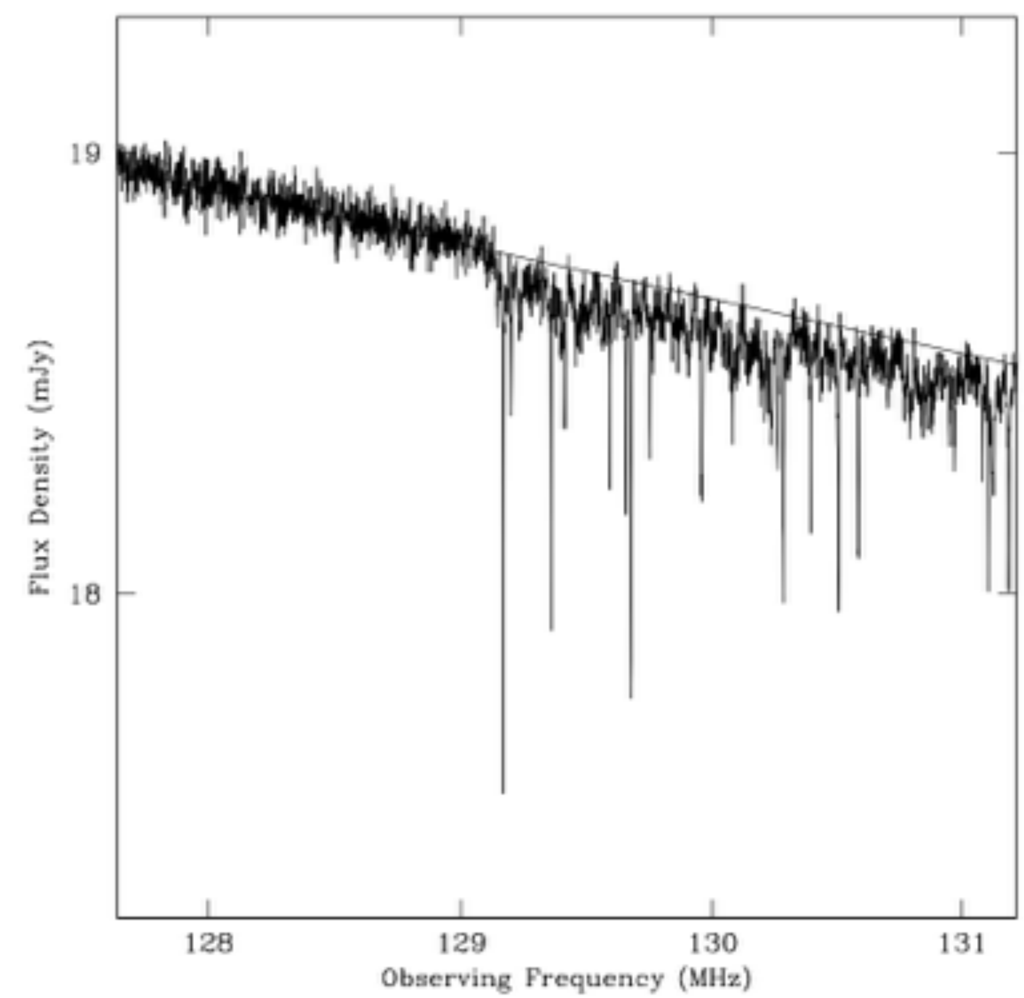
21cm forest



21cm forest can explore small scales.

21cm forest is 21cm absorption lines appeared in continuum spectrum due to intervened HI gas (e.g. IGM, minihalo). (Furlanetto & Loeb 2002)

Carilli et al 2002



The depth of 21cm absorption lines is characterised by optical depth τ

We consider the 21cm forest at **z=10**

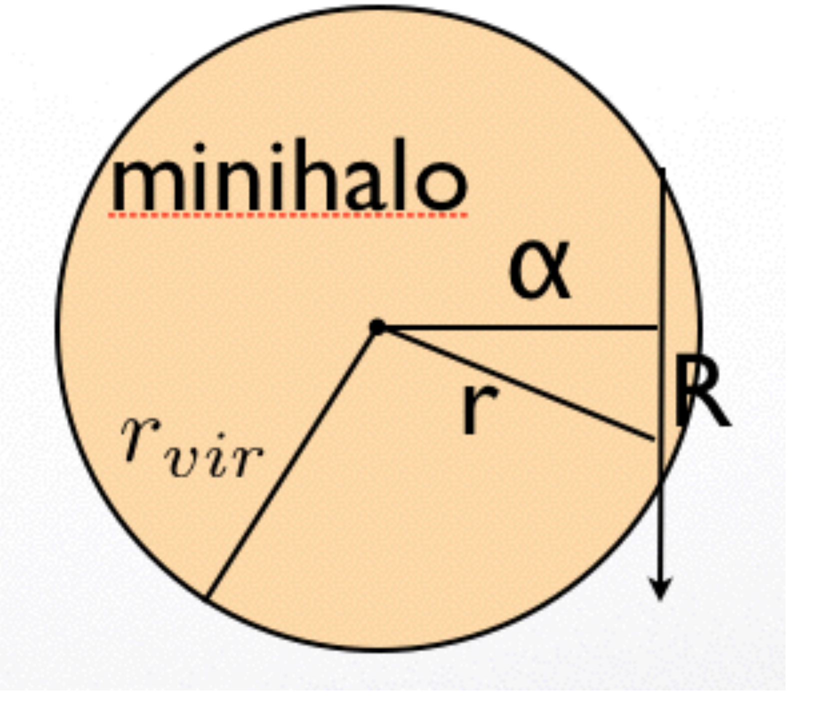
Minihalo properties

•Optical depth

Number density

$$\tau_\nu = \frac{3h_{\rm p}c^3A_{10}}{32\pi k_{\rm B}\nu_{21}^2}\int_{-R_{\rm max}}^{R_{\rm max}} dR\frac{\boxed{n_{\rm HI}(r)}}{\underline{T_{\rm S}(r)}\sqrt{\pi}b(r)}\exp\left(-\frac{v^2(\nu)}{b^2}\right)$$

Spin temperature



•The number of 21cm absorption lines

$$\frac{dN(>\tau)}{dz} = \frac{dr}{dz}\int_{M_{\rm min}}^{M_{\rm max}} dM\boxed{\frac{dN}{dM}}\pi r_\tau^2(M,\tau),$$

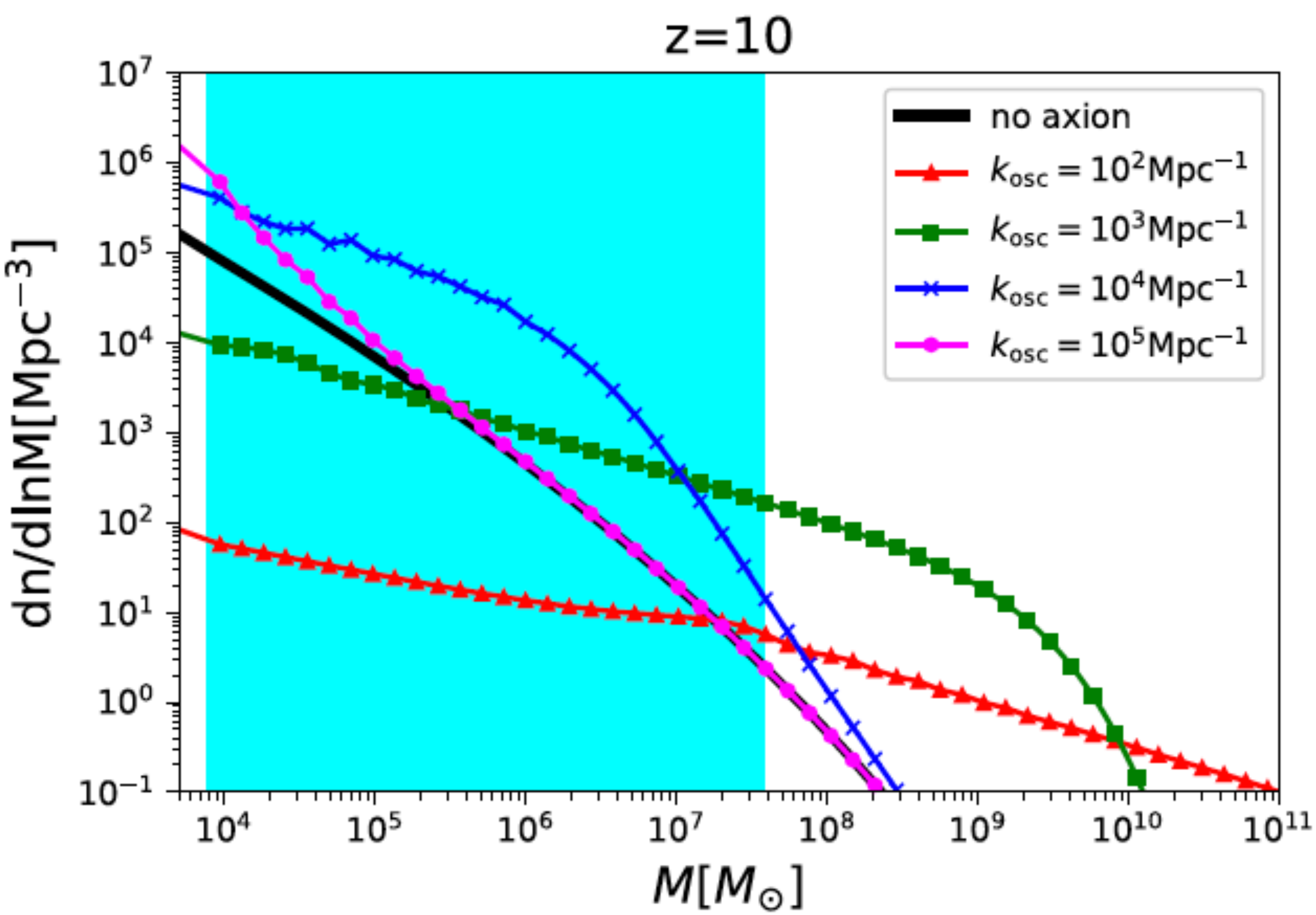
The effect of axion

Maximum mass > **Virial mass** at T=10^4K

Minimum mass > **Jeans mass** at IGM temperature

The effect of axion on MF

k_{osc} is the scale that axion oscillates , which is related to axion mass.



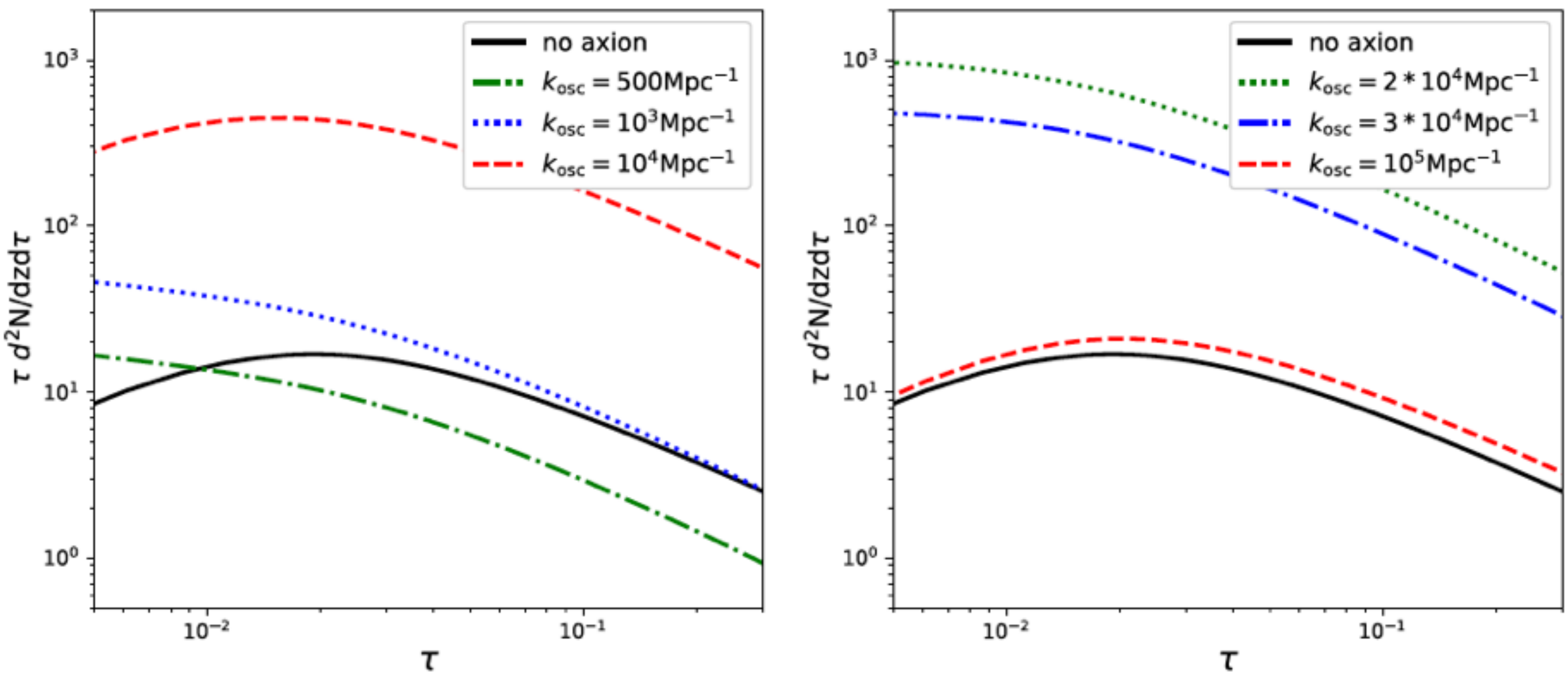
$$k_{\rm osc} \sim 10^4 {\rm Mpc}^{-1}$$

most enhanced scale at our investing scales

21cm absorption lines

The number of 21cm absorption lines as function of optical depth.

$k_{\rm osc} = 500 - 10^5 {\rm Mpc}^{-1}$



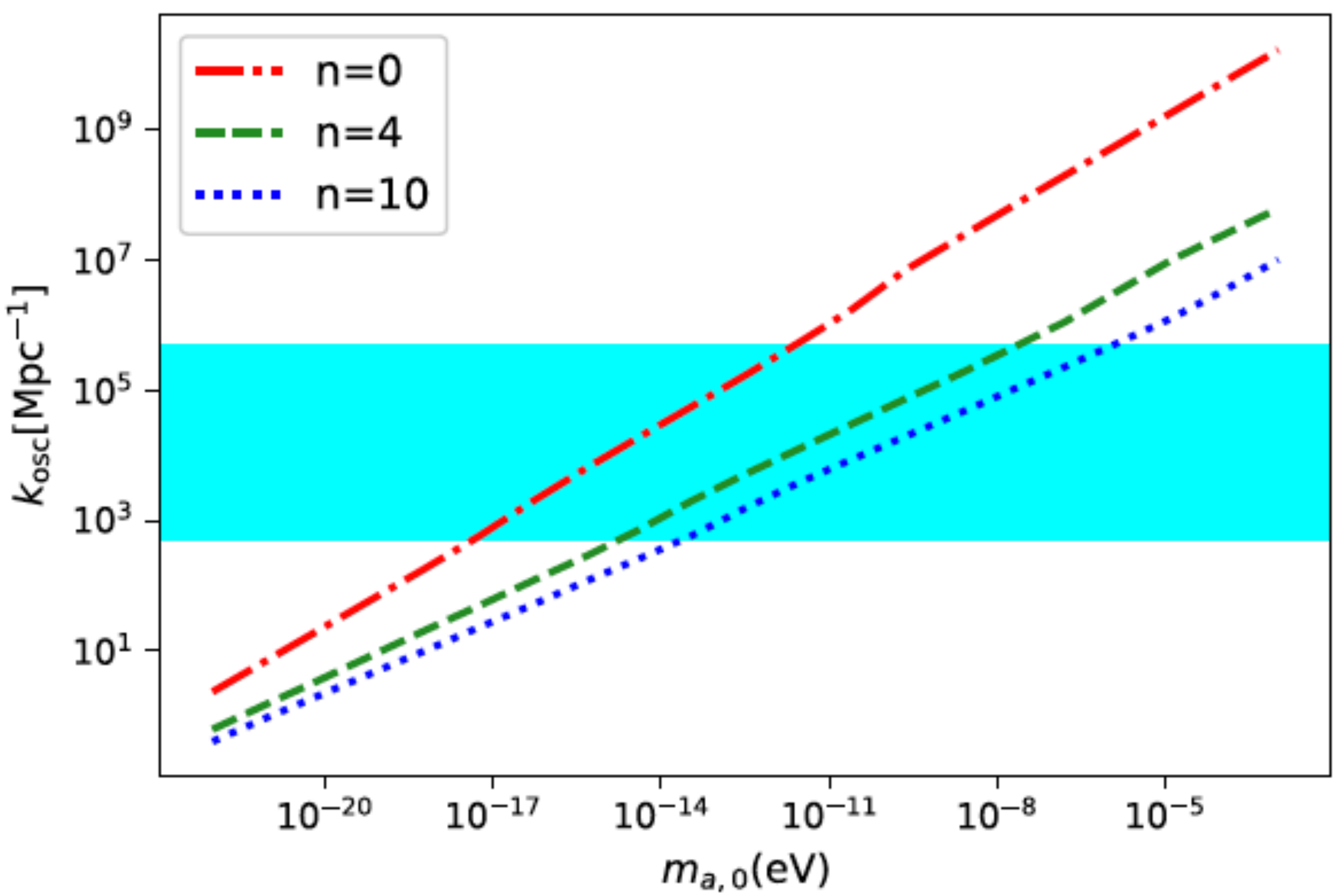
At $k_{\rm osc} \sim 2 \times 10^4 {\rm Mpc}^{-1}$ the number of 21cm absorption lines are most enhanced.

$k_{\rm osc} < 500{\rm Mpc}^{-1},\ k_{\rm osc} > 10^5{\rm Mpc}^{-1}$ the number of 21cm absorption lines is less than no axion case or equal to no axion case.

Covert to axion mass

The axion oscillation scales where 21cm forest can explore

$k_{\rm osc} \sim 530 - 5 \times 10^5 {\rm Mpc}^{-1}$ $\longrightarrow$ $10^{-18} \lesssim m_a \lesssim 10^{-12}$ eV



for n=0 model (axion mass in independent on temperature)

Lyman-alpha forest observations exclude

$$m_a \lesssim 2 \times 10^{-17} {\rm eV}$$

for n=0 case

Irisic et al (2020)

complementary to other probes!

Discussion(1) -background source-

•Required minimum brightness of background

$$S_{\rm min} = 10.4 \text{ mJy} \left(\frac{0.01}{\tau}\right) \left(\frac{S/N}{5}\right) \left(\frac{1 \text{ kHz}}{\Delta\nu}\right)^{1/2} \times \left(\frac{5000 \text{ [m}^2\text{/K]}}{A_{\rm eff}/T_{\rm sys}}\right) \left(\frac{100 \text{ hr}}{t_{\rm int}}\right)^{1/2},$$

Assuming **SKA** specification

•Do bright radio background sources exist at high redshift?

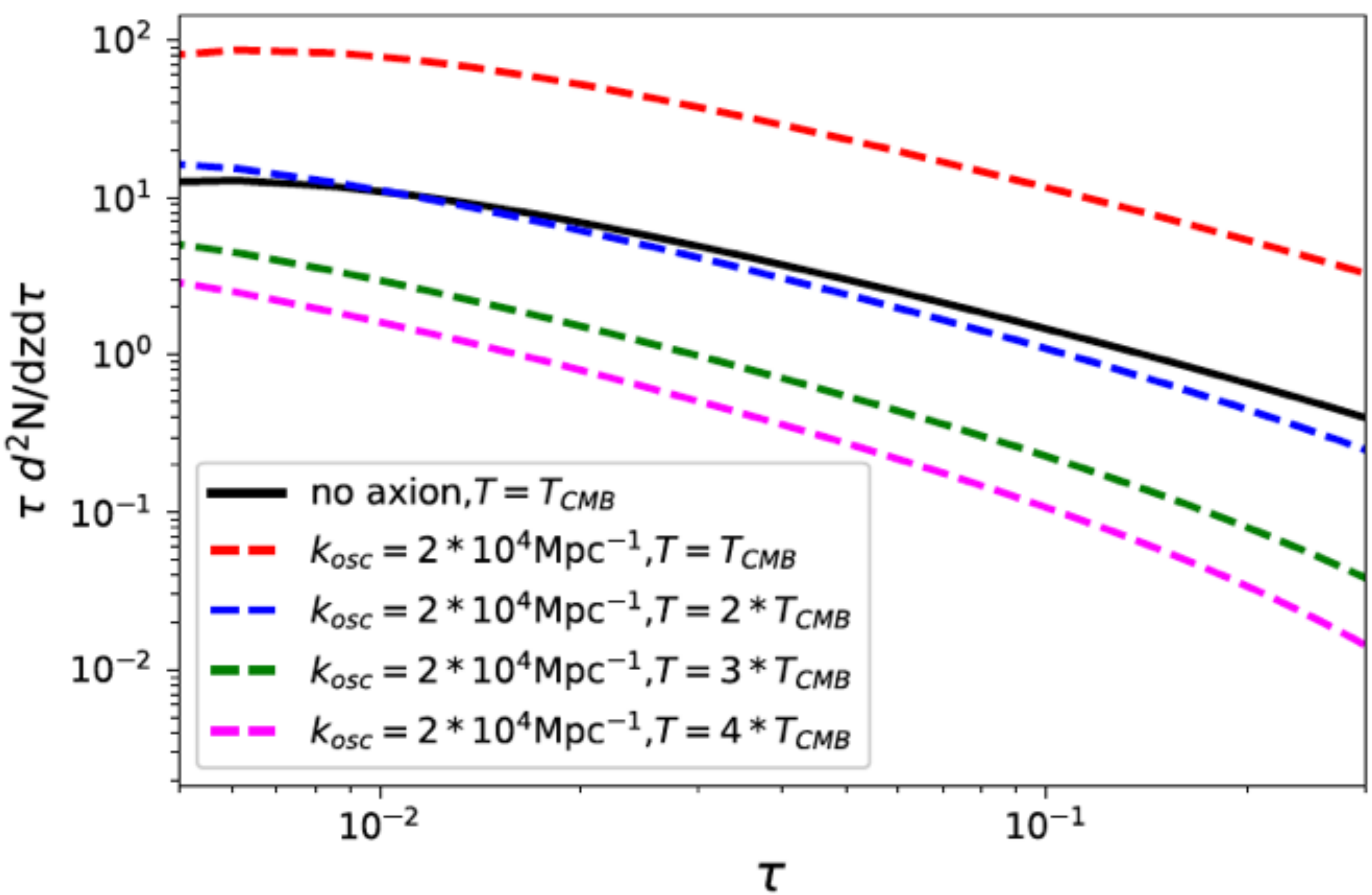
Recently, radio loud quasar @ z~6 has been reported (Banados et al 2018).

However, there still remains uncertainty on radio background sources at high redshift.

Discussion(2) IGM temperature

Enhanced structure formation causes more X-ray sources and heats IGM

→ We test 21cm forest by varying IGM temperature



Below 4*T_CMB, the number of 21cm absorption lines is still O(1) at small optical depth

Summary

- Axion is generated as the result of PQ symmetry breaking.
- If PQ symmetry breaks after inflation, isocurvature perturbation enhances matter fluctuations.
- We see the effect of this enhancement via 21cm forest.
- We explore the axion mass scale by 21cm forest.
- The existence of radio-back ground source is very crucial for 21cm forest study.