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# The 21-cm forest as a simultaneous probe of dark matter and cosmic heating history

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The absorption features in spectra of high-redshift background radio sources, caused by hyperfine structure lines of hydrogen atoms in the intervening structures, are known collectively as the 21-cm forest. They provide a unique probe of small-scale structures during the epoch of

Hayato Shimabukuro

## Behind the paper

In 2002, it was proposed that the 21-cm forest could be used to probe for minihalos in the early Universe[2]. It was later recognized that it could also serve as a sensitive probe for the IGM temperature[3] and potentially for DM properties[4] during cosmic dawn. However, detection has never been attempted observationally owing to the extremely weak signal and difficulty identifying high-redshift radio-bright sources. Over the past three years, the discovery of high-redshift radio-loud quasars and the development of power spectrum analysis techniques sparked the idea to use the 21-cm forest to study WDM. We soon realized that the distinct features of the scale dependence between the signal and noise could be used to statistically extract the weak signal, making the 21-cm forest a viable and effective means to simultaneously measure DM properties and the thermal history of the Universe. **Y.X. & X.Z.**

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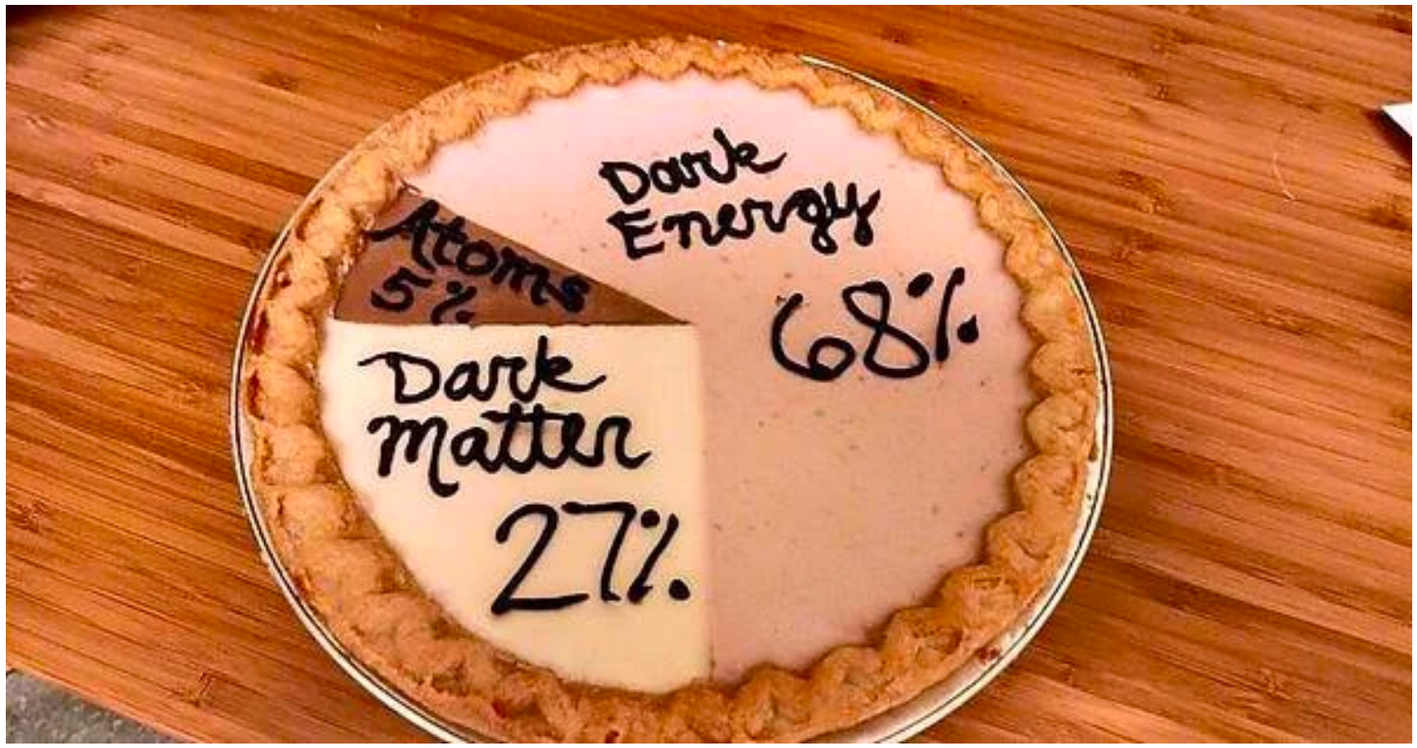
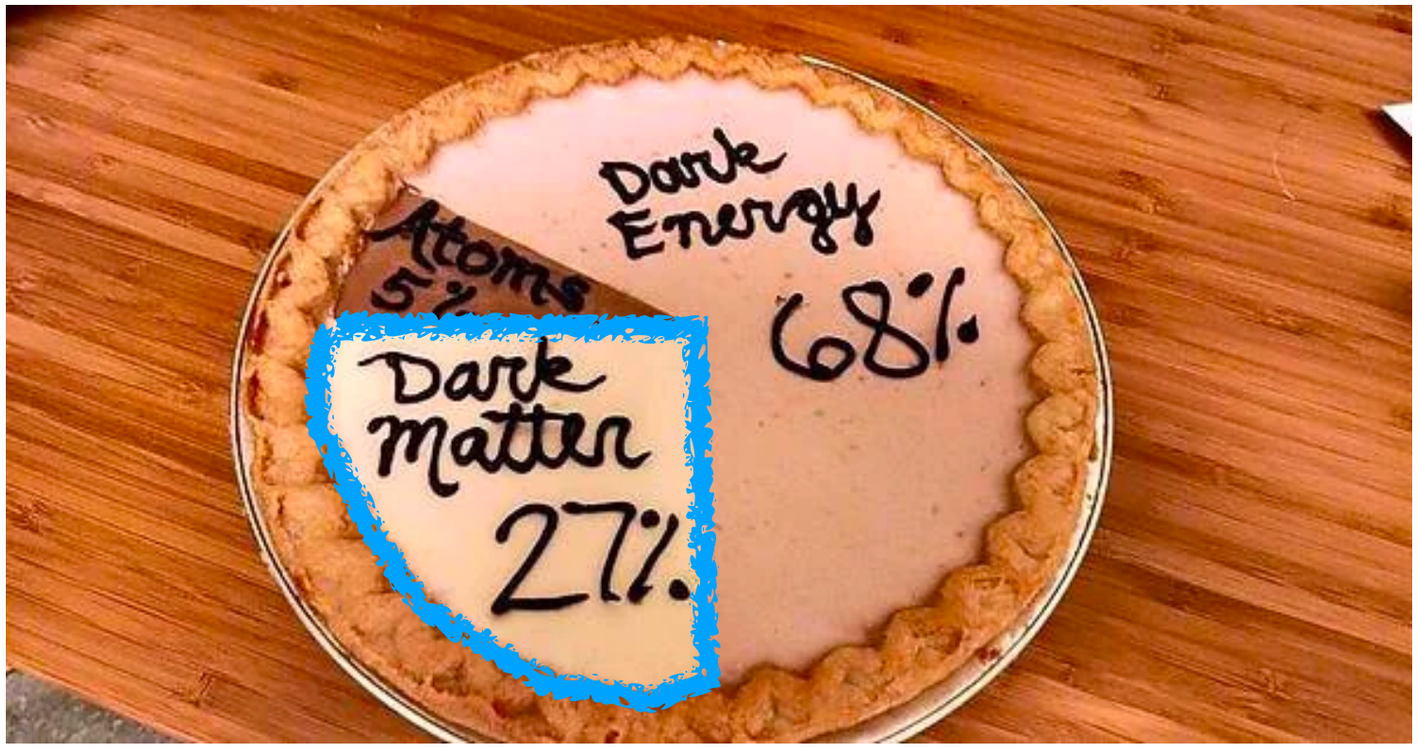
## Our paper!


4. Shimabukuro, H., Ichiki, K., Inoue, S. & Yokoyama, S. Probing small-scale cosmological fluctuations with the 21 cm forest: effects of neutrino mass, running spectral index, and warm dark matter. *Phys. Rev. D.* **90**, 083003 (2014). **This paper shows that the 21-cm forest can be used to constrain the particle mass of WDM and also identifies the degeneracy of the WDM model with the effects of IGM heating.**




•Our universe is composed of baryon(~ 5%), dark matter(~27%), and dark energy(~68%).

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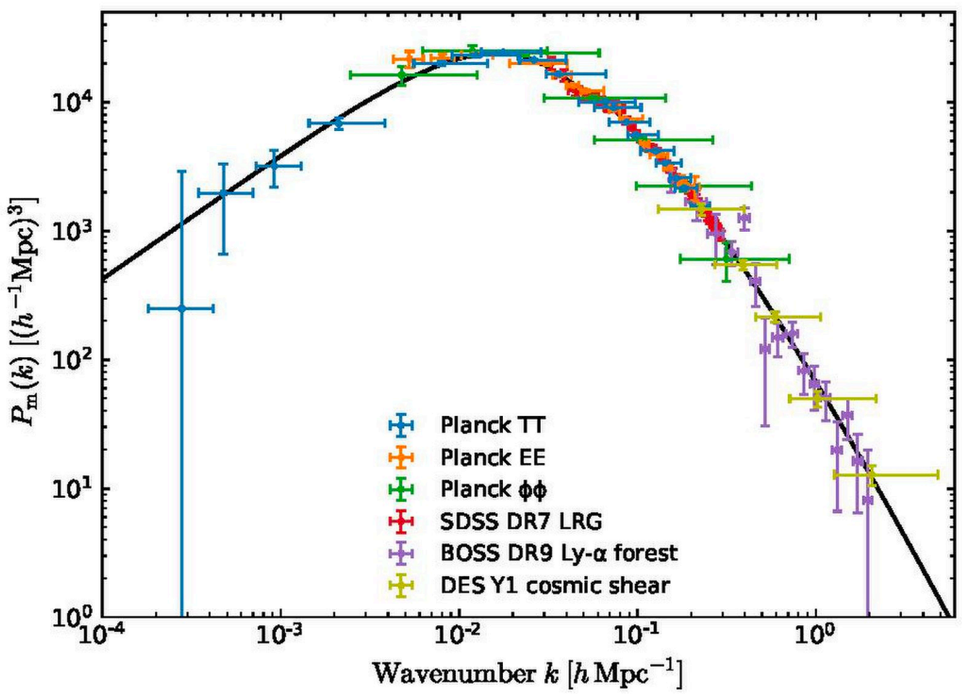
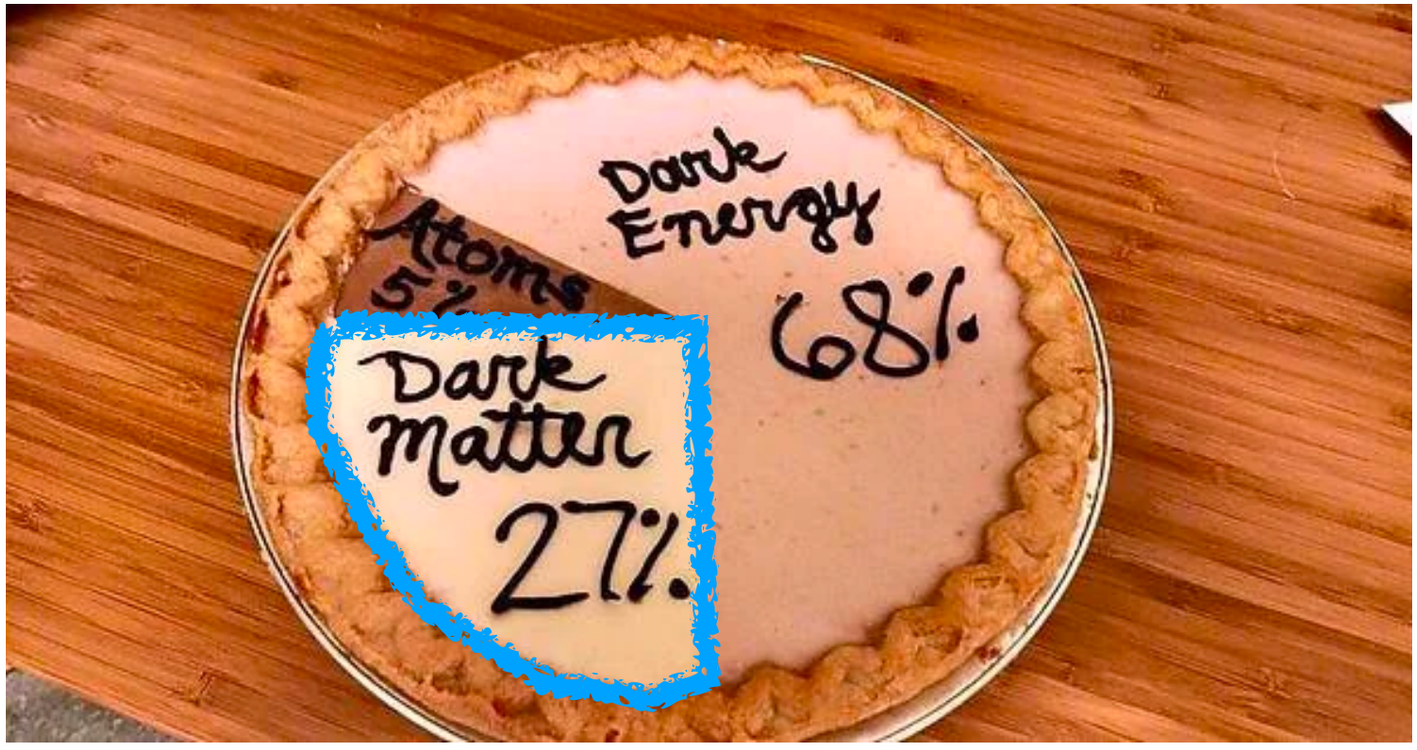



•Recent cosmological observations support “Cold Dark Matter (CDM)” scenario.

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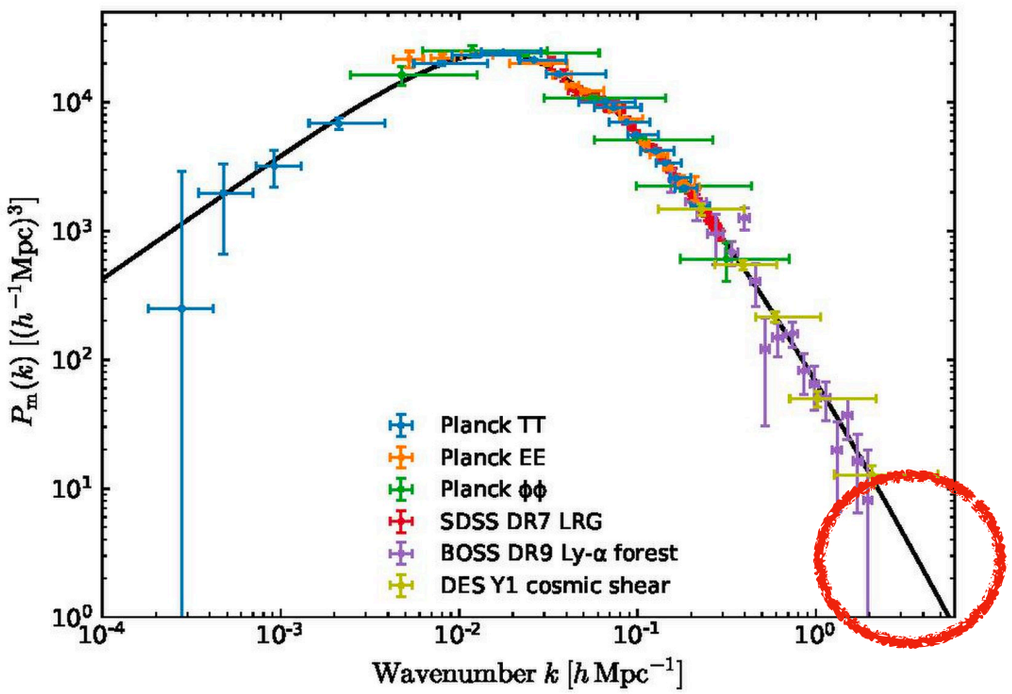
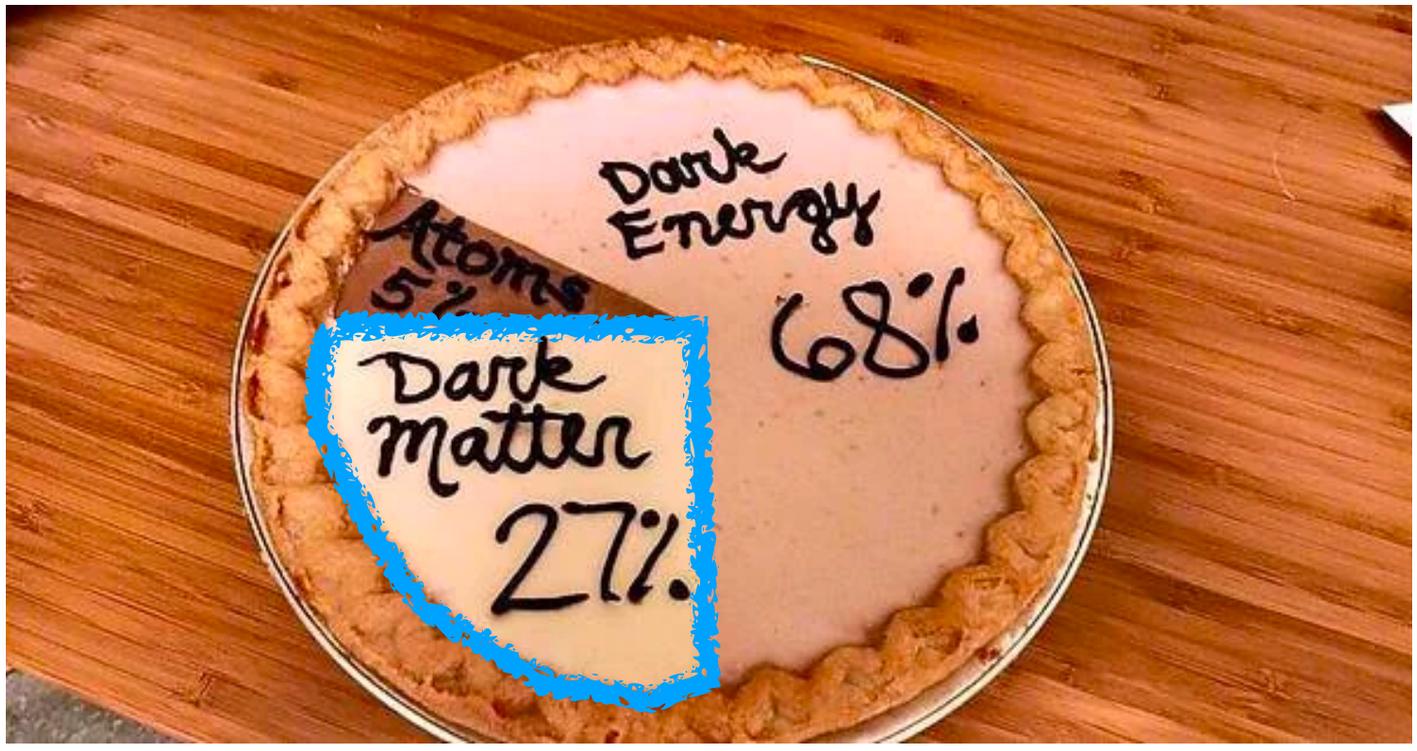



•Recent cosmological observations support “Cold Dark Matter (CDM)” scenario.

•However, we have room to consider other dark matter scenarios called “Warm Dark Matter (WDM)”

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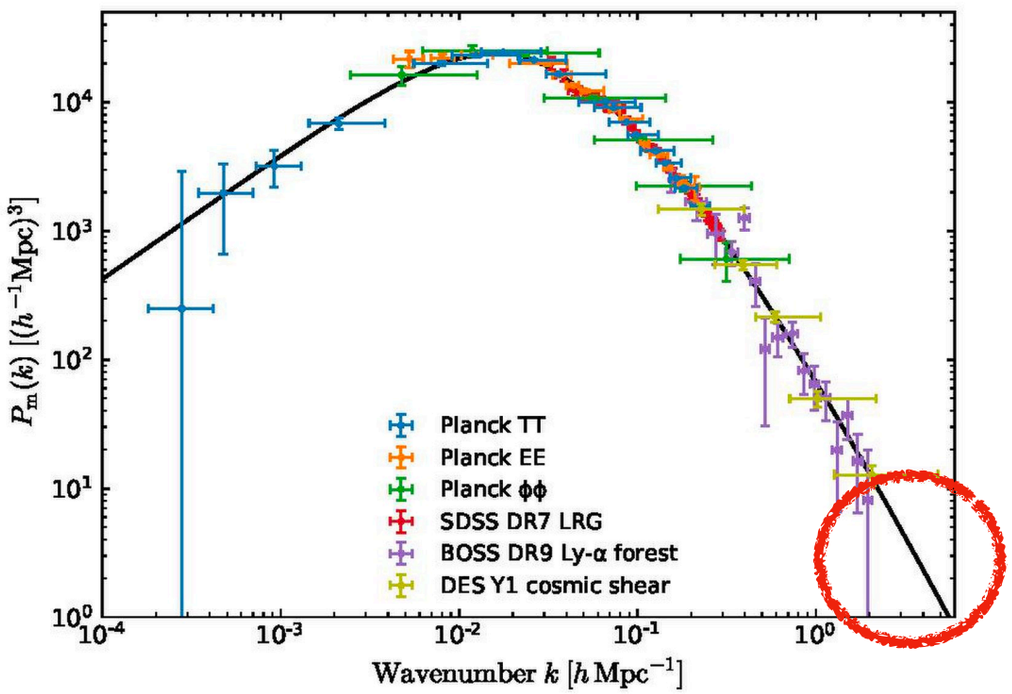


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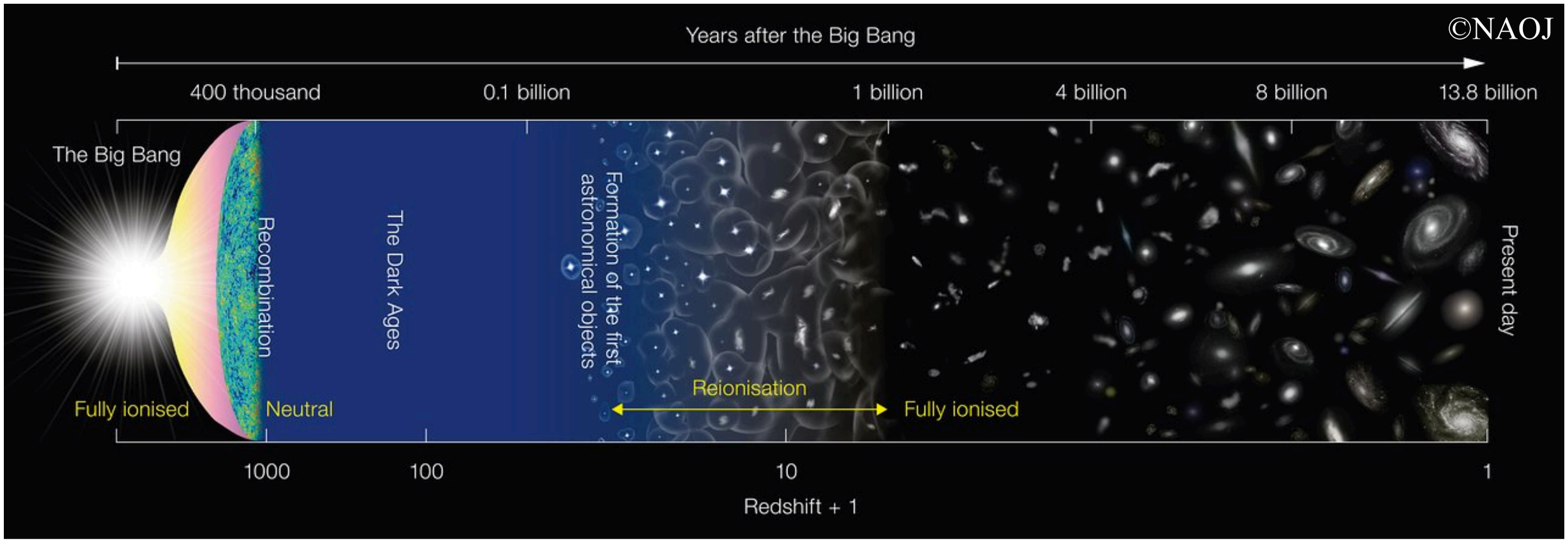
$$m_{\mathrm{WDM}} \sim \mathrm{keV}$$

# The history of the universe

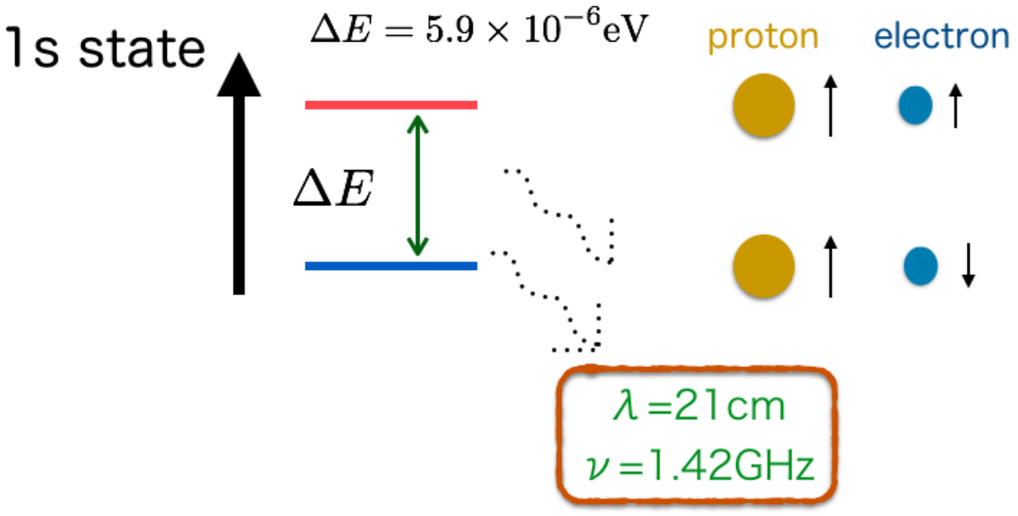



***Dark Ages*** ・・・No luminous object exists.

***Cosmic Dawn*** ・・・First stars and galaxies form ($z \sim 20 - 30$).

***Epoch of Reionization(EoR)*** ・・・UV photons by luminous objects ionize neutral hydrogen in the IGM ($z \sim 6 - 15$).

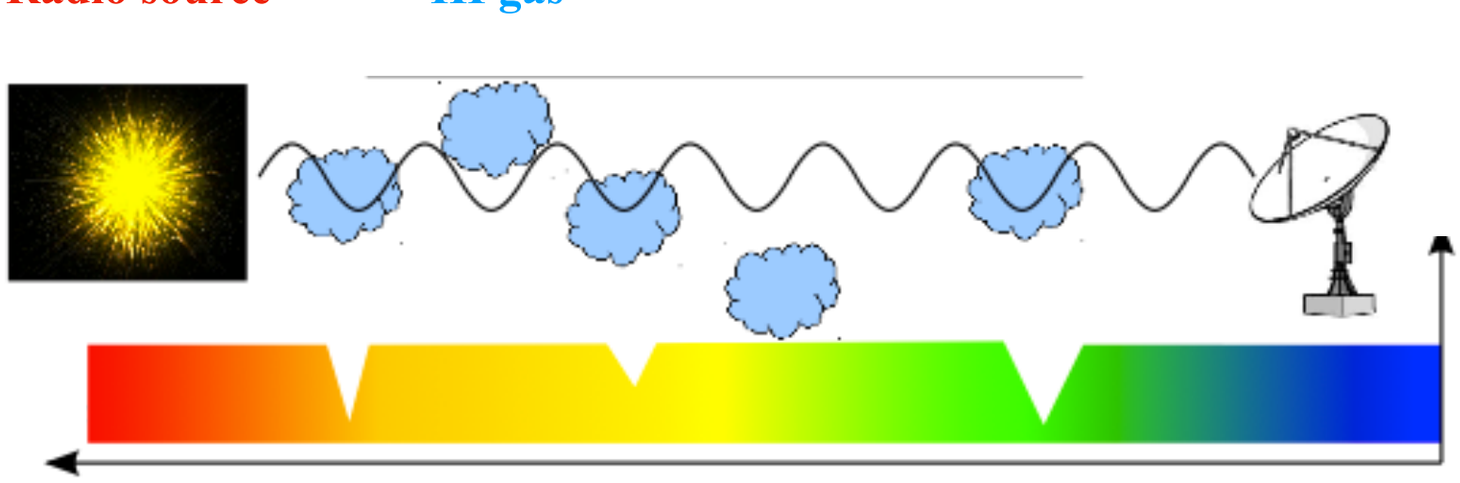
## 21cm line




•Neutral hydrogen(HI) atoms in intergalactic medium(IGM) emit or absorb 21cm wavelength radiation

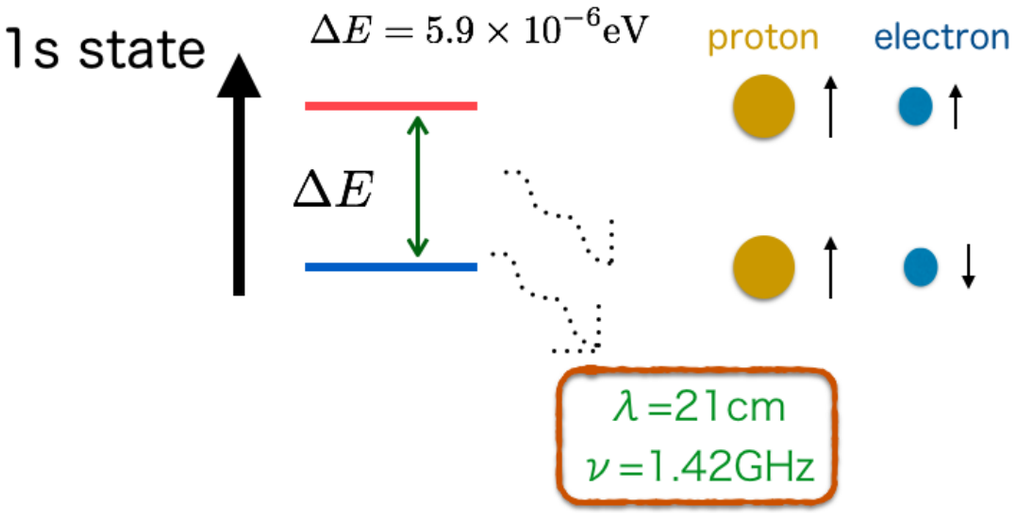
•We often focus on 21cm emission line to probe dark ages and epoch of reionization (EoR), but this paper focuses on 21cm absorption lines.

## 21cm forest




•The continuum emitted by radio sources produces 21cm absorption lines due to intervened HI gas. This 21cm absorption line is called **21cm forest**

## 21cm line

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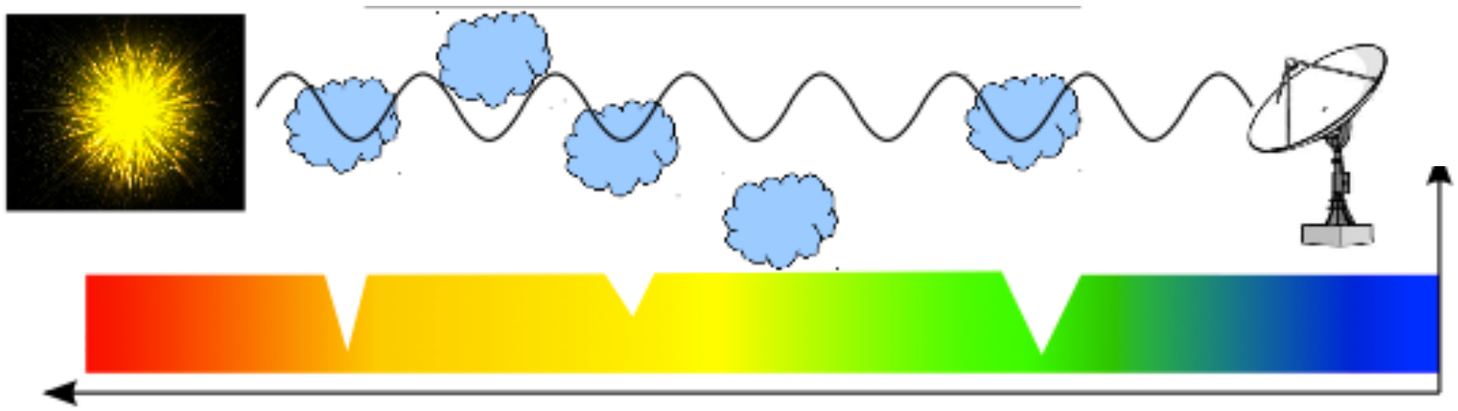
## 21cm forest

**Radio source** **HI gas**



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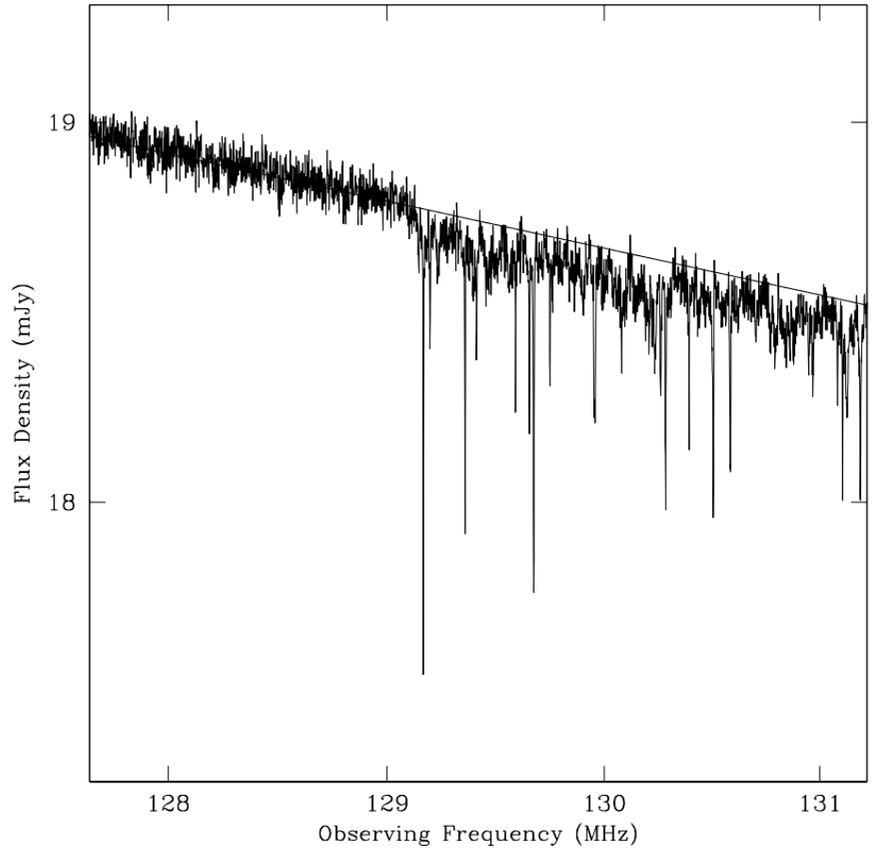
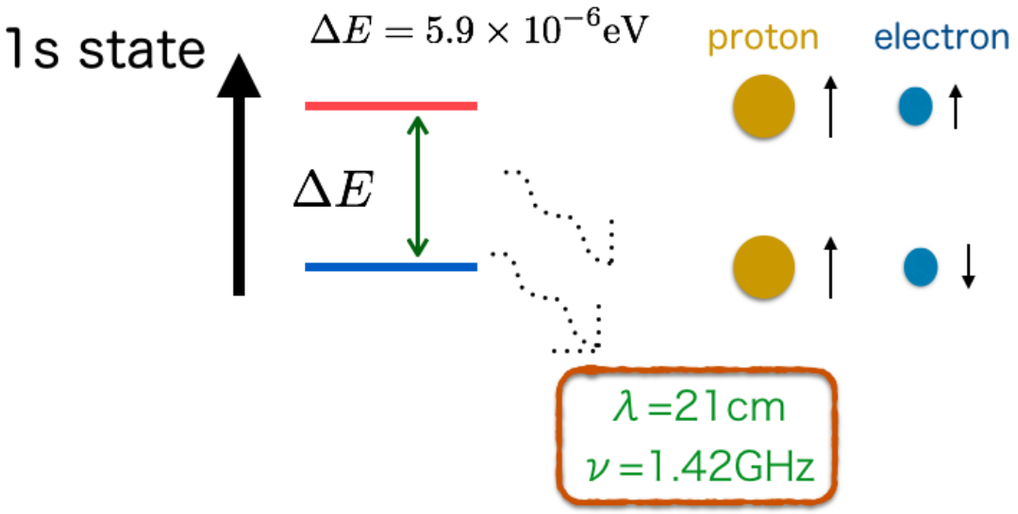



Carilli+ 2002

## 21cm line

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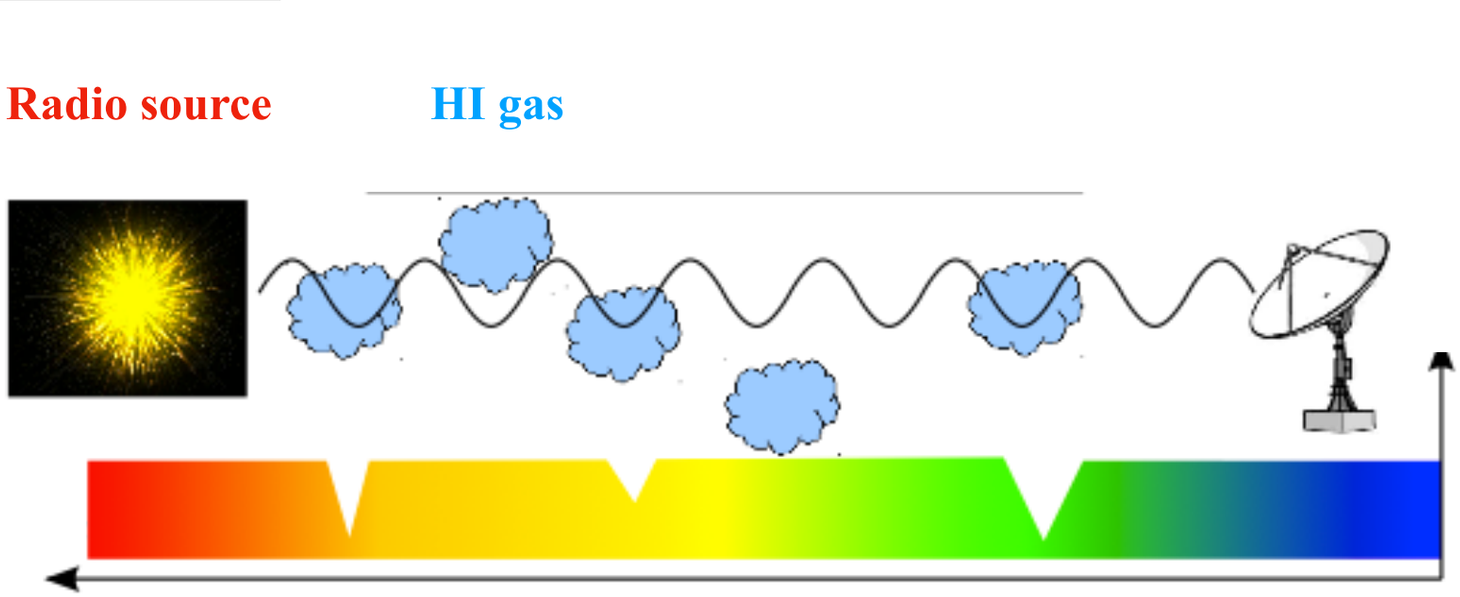


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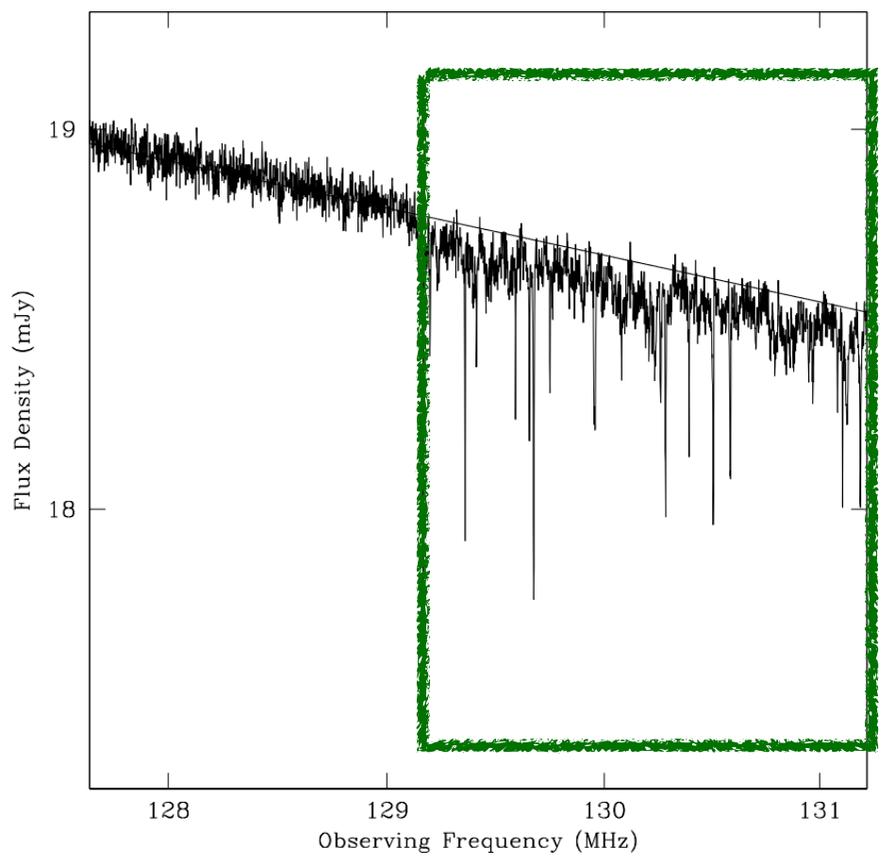
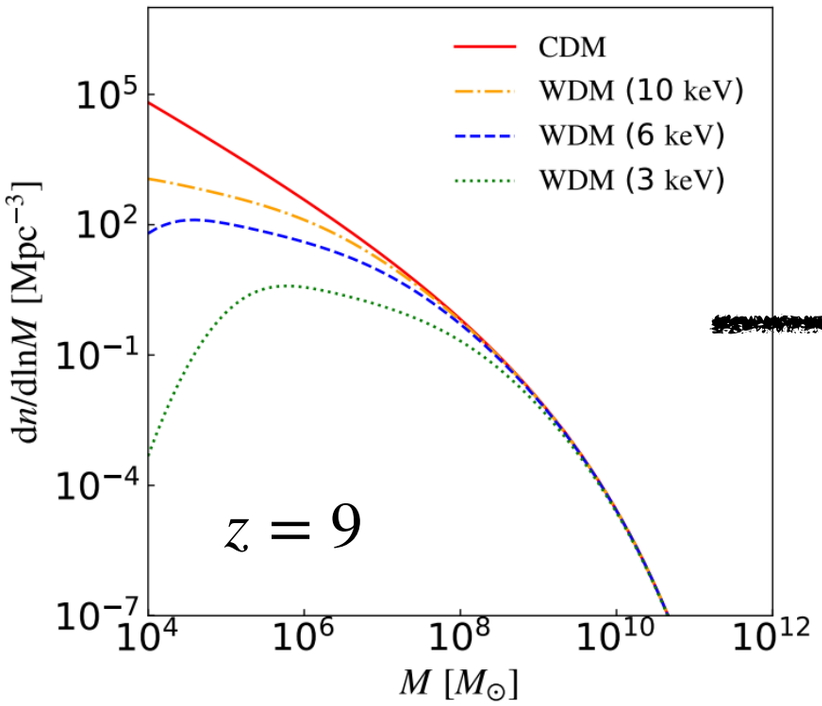



Carilli+ 2002

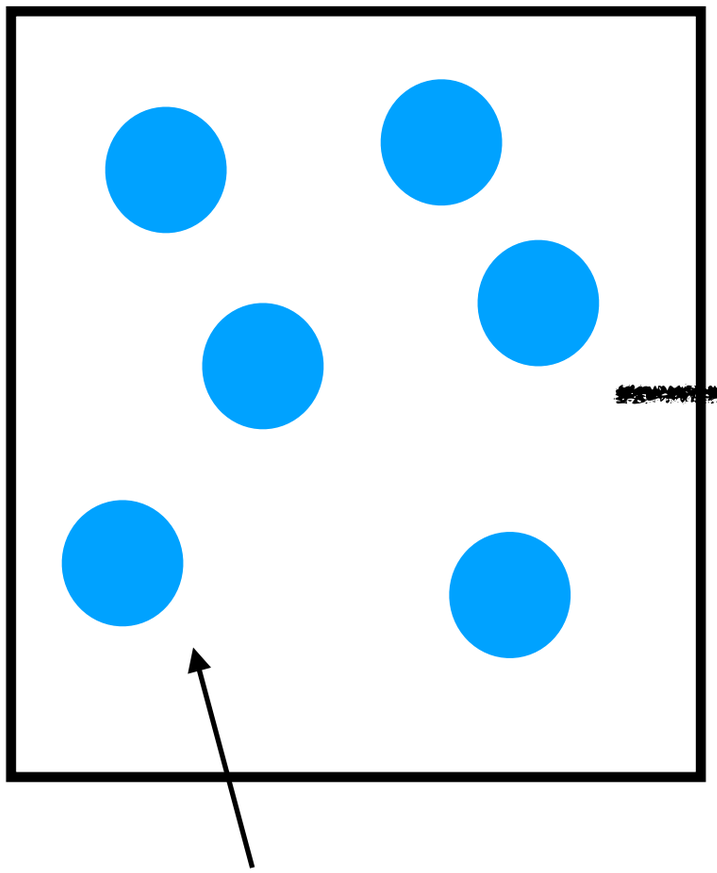
# Why can we evaluate the effect of WDM by 21cm forest?

**The effect of WDM on halo mass function**



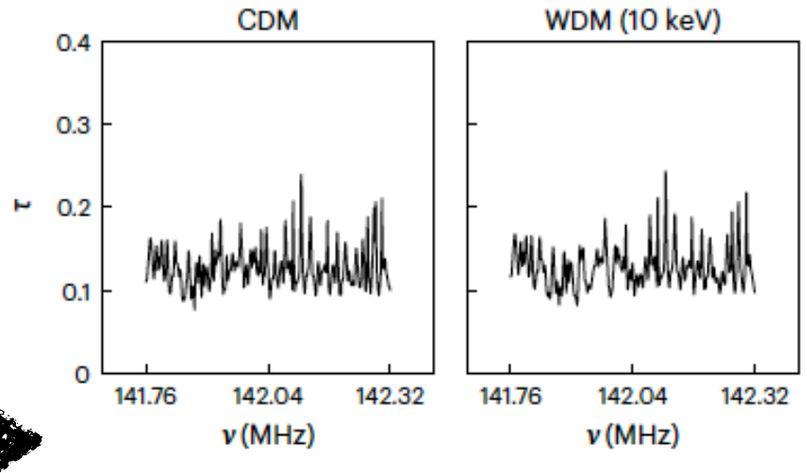

**Lower WDM mass suppresses mass function at a lower halo mass range.**

**The number of HI regions is suppressed**

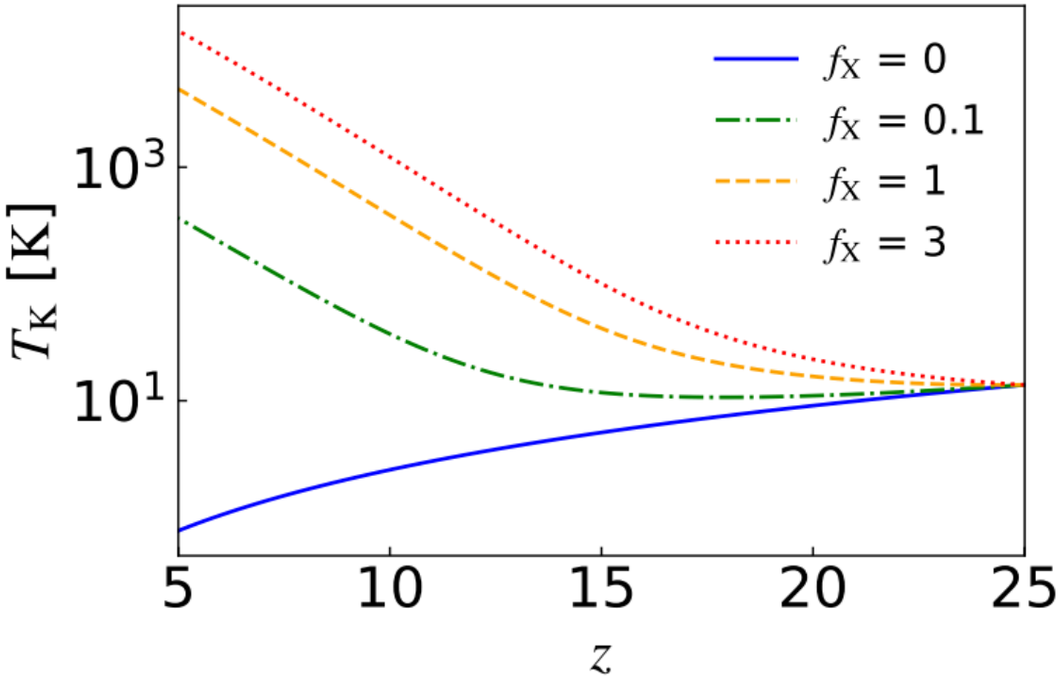


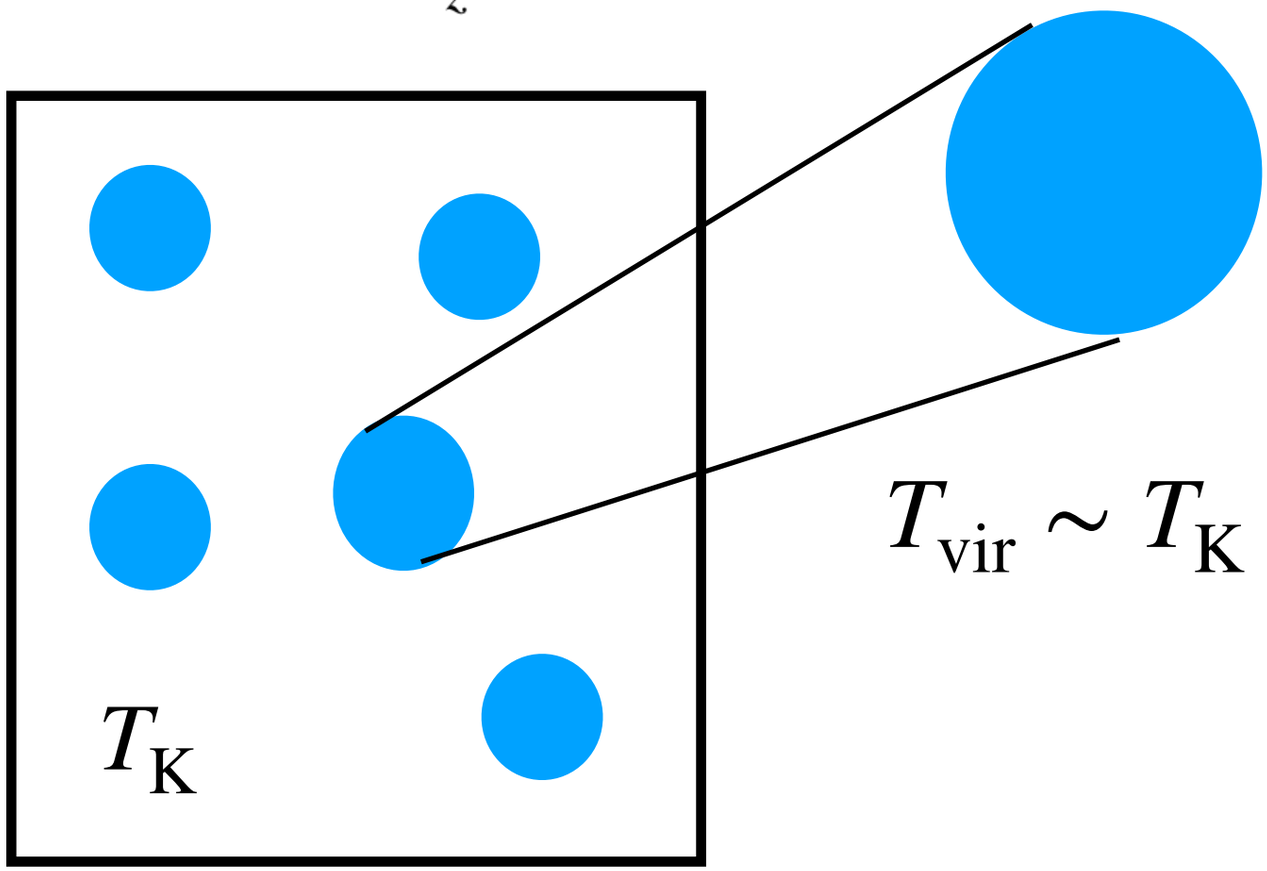
**HI gas inside the halo.**

**21cm absorption lines are also suppressed.**



# The effect of X-ray heating on halos




•When X-ray heating is more effective, the kinetic temperature of the gas is more heated.

$$\tau \propto \frac{1}{T_S} \sim \frac{1}{T_{vir}} \sim \frac{1}{T_K}$$

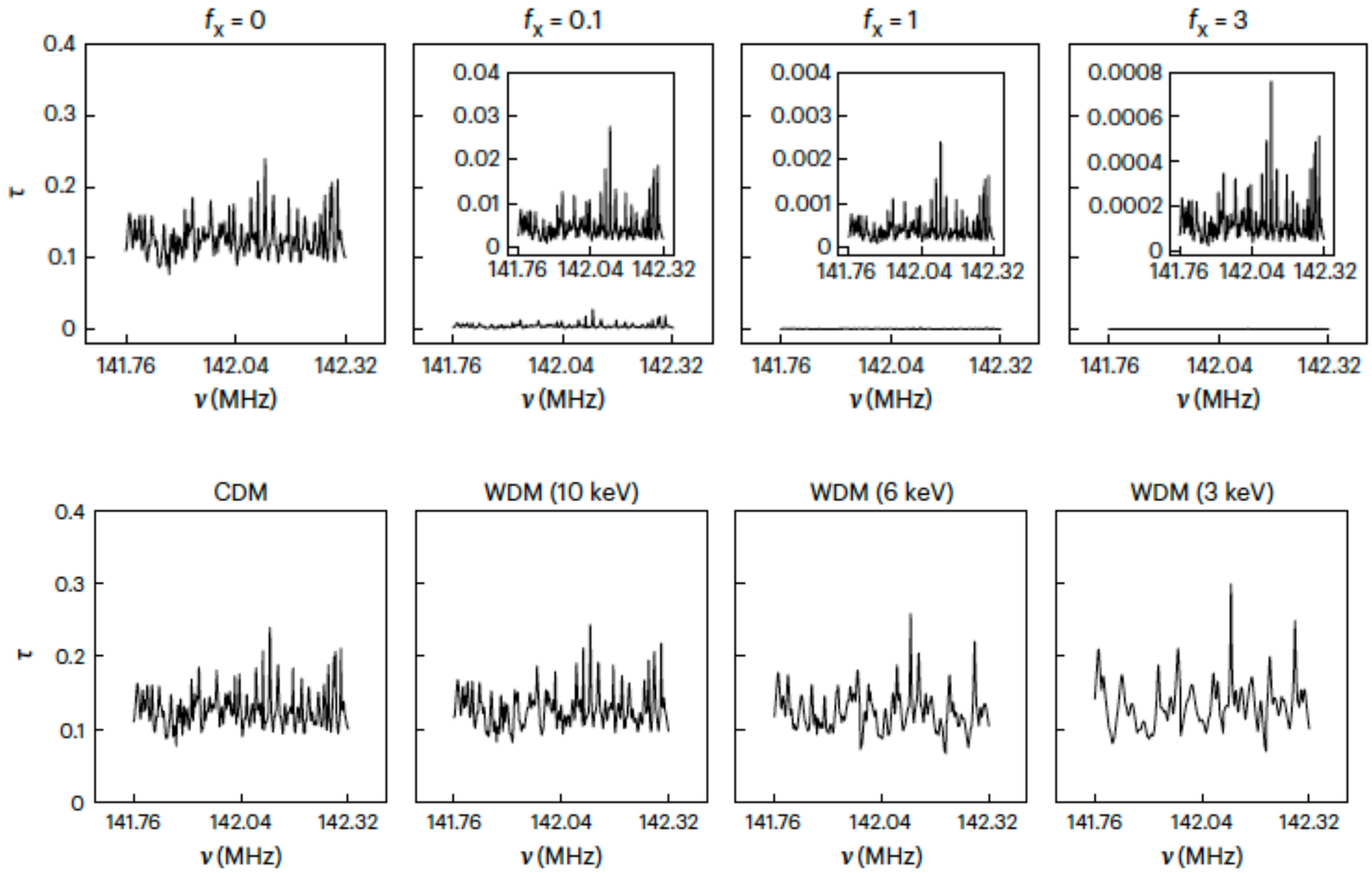
Inside the halo, the optical depth is determined by kinetic temperature

↓

**If X-ray heating is effective (higher $f_X$), 21cm forest is suppressed.**

(**Important !**)

## Both lower WDM and higher X-ray heating suppress the 21cm forest

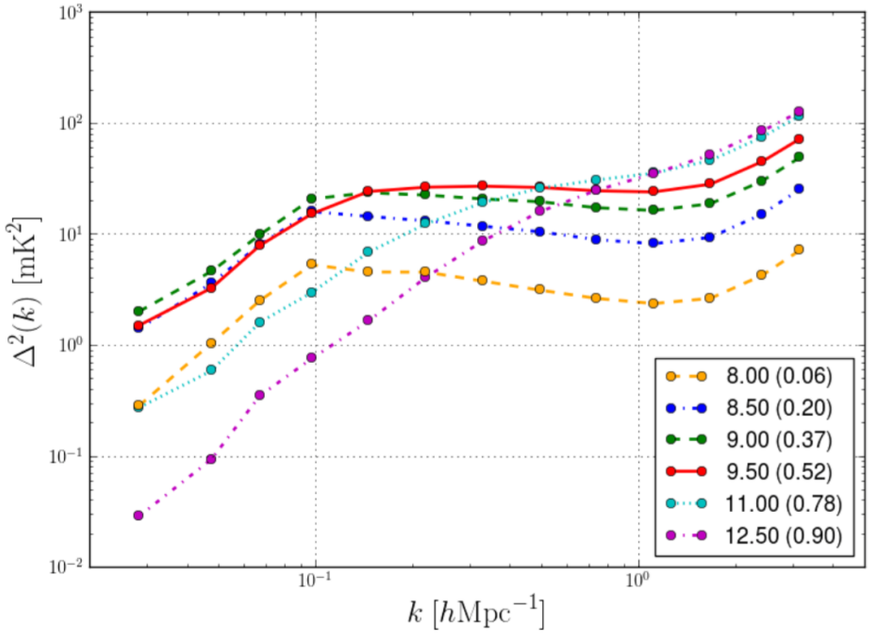


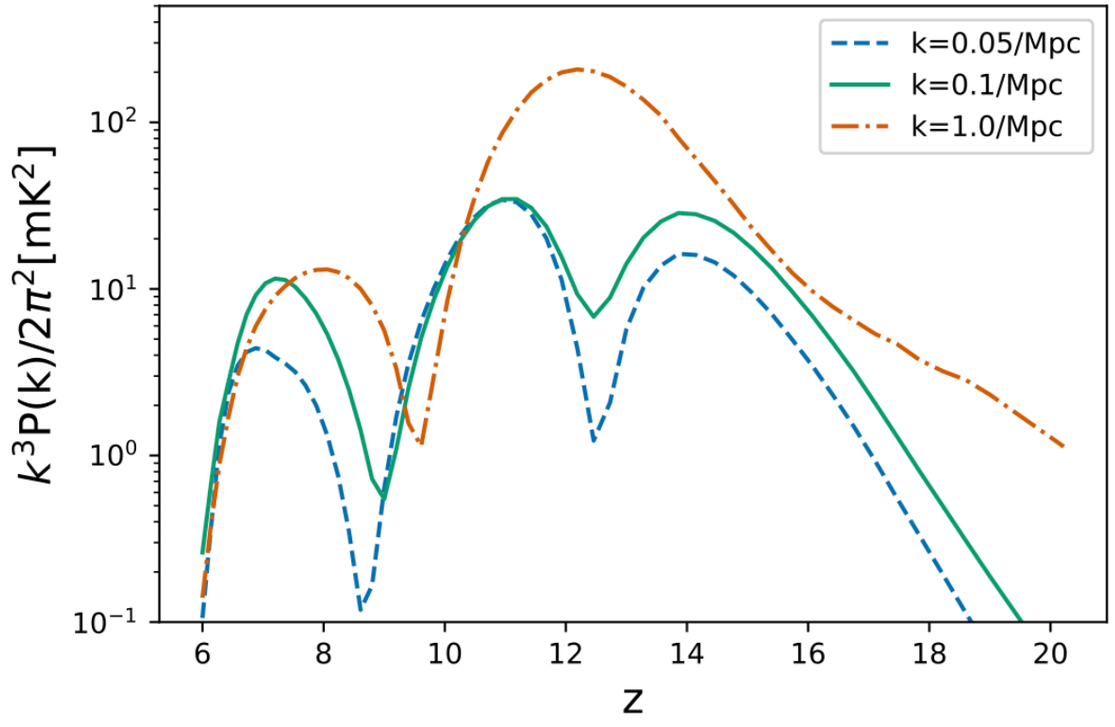
# Original view of this paper

•In this paper, they introduce **1-D power spectrum of 21cm forest** to evaluate the 21cm forest.

For 21cm emission lines, we usually use 1-D power spectrum. But, we have not used 1-D power spectrum to describe 21cm forest.

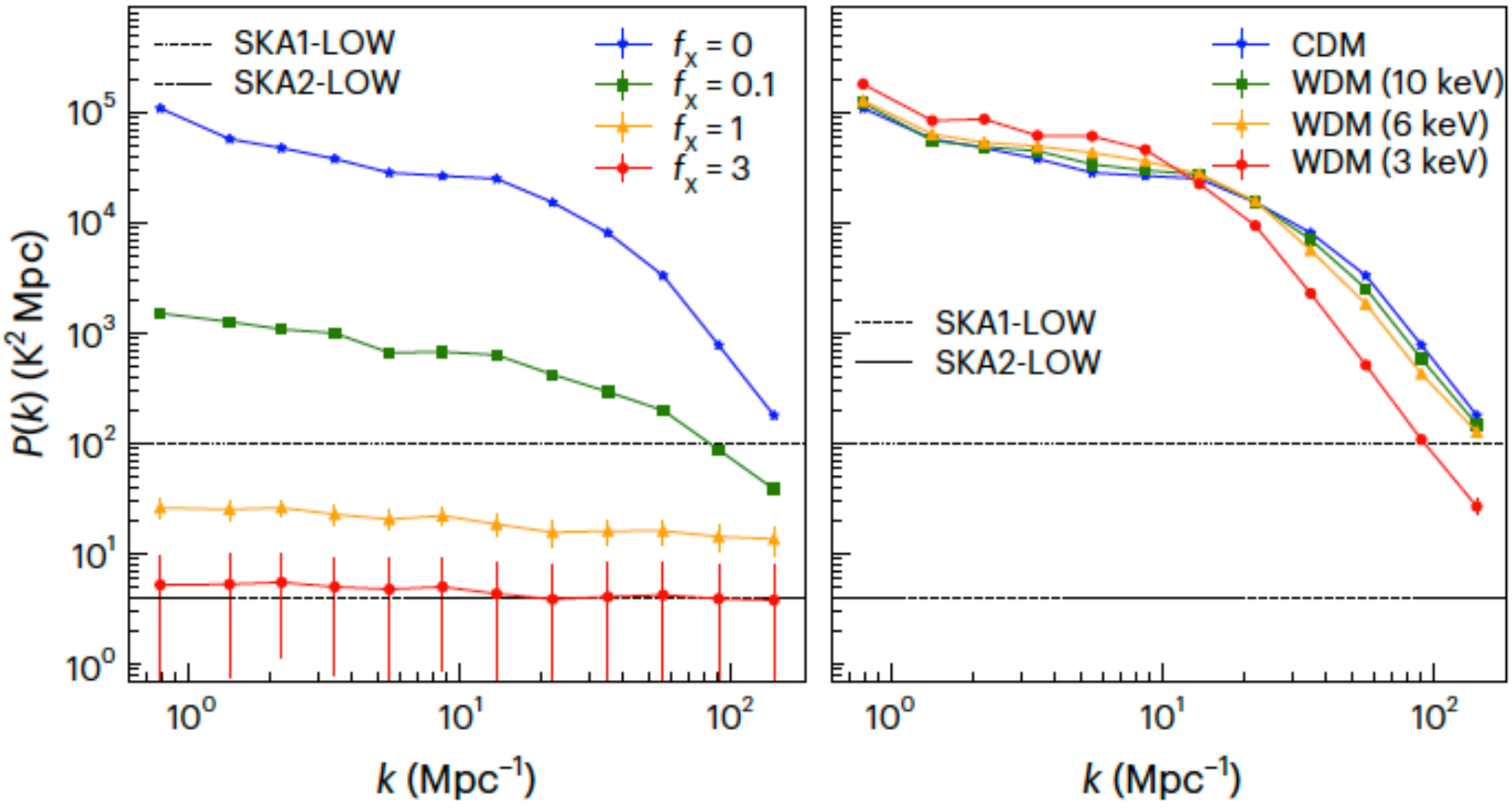
(e.g) 21cm power spectrum in the case of 21cm emission lines



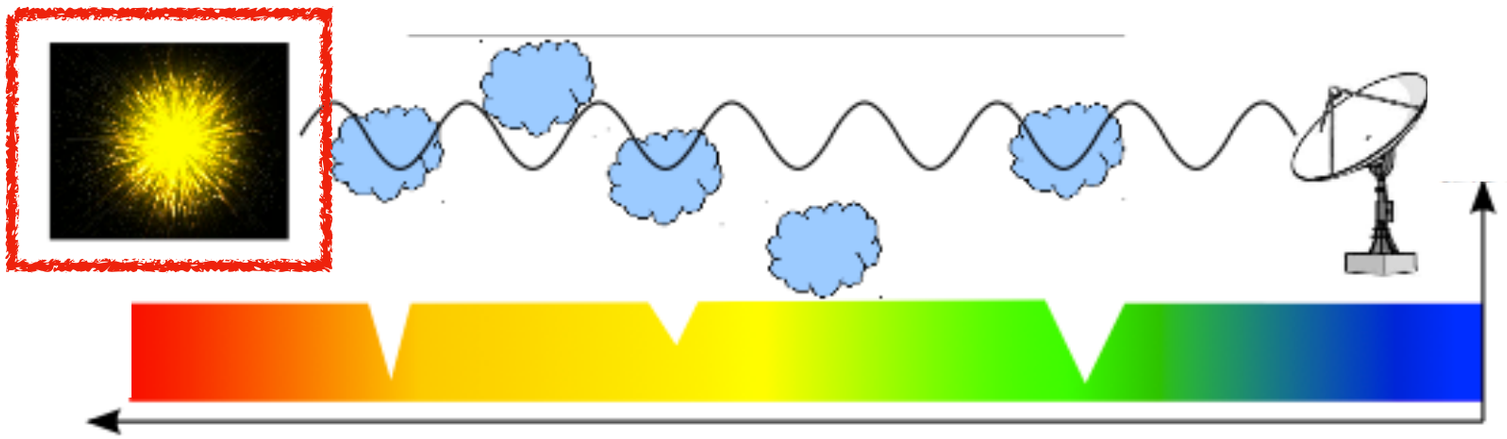



•As we expected, higher X-ray hearing and lower WDM mass suppress 21cm forest power spectrum

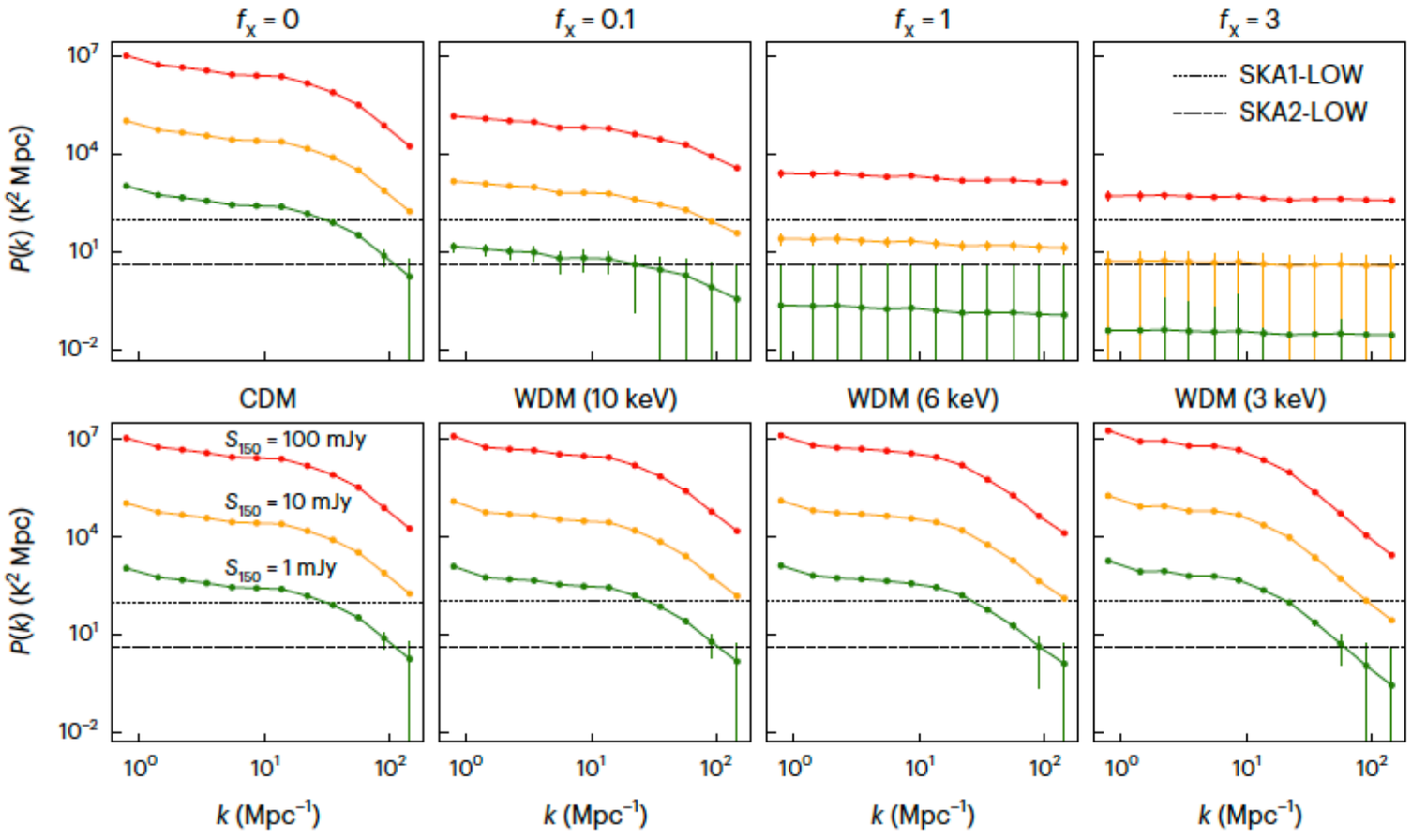
•The dependency is different between X-ray hearing and WDM (WDM suppresses 21cm forest power spectrum at higher wave-numbers)



•Remember that 21cm forest depends on the **brightness of radio sources**



•If the radio source are brighter, it is easier to detect 21cm forest.




•If we found radio sources brighter than **100mJy**, we can detect 21cm power spectrum even if $f_X = 3$ and $m_{\mathrm{WDM}} = 3\mathrm{keV}$

LETTER TO THE EDITOR

Belladitta et al (2020)

# The first blazar observed at z>6

S.Belladitta[1,2], A. Moretti[1], A. Caccianiga[1], C. Spingola[3,4], P. Severgnini[1], R. Della Ceca[1], G. Ghisellini[5], D. Dallacasa[3,4], T. Sbarrato[5,6], C. Cicone[7], L. P. Cassarà[8], and M. Pedani[9]

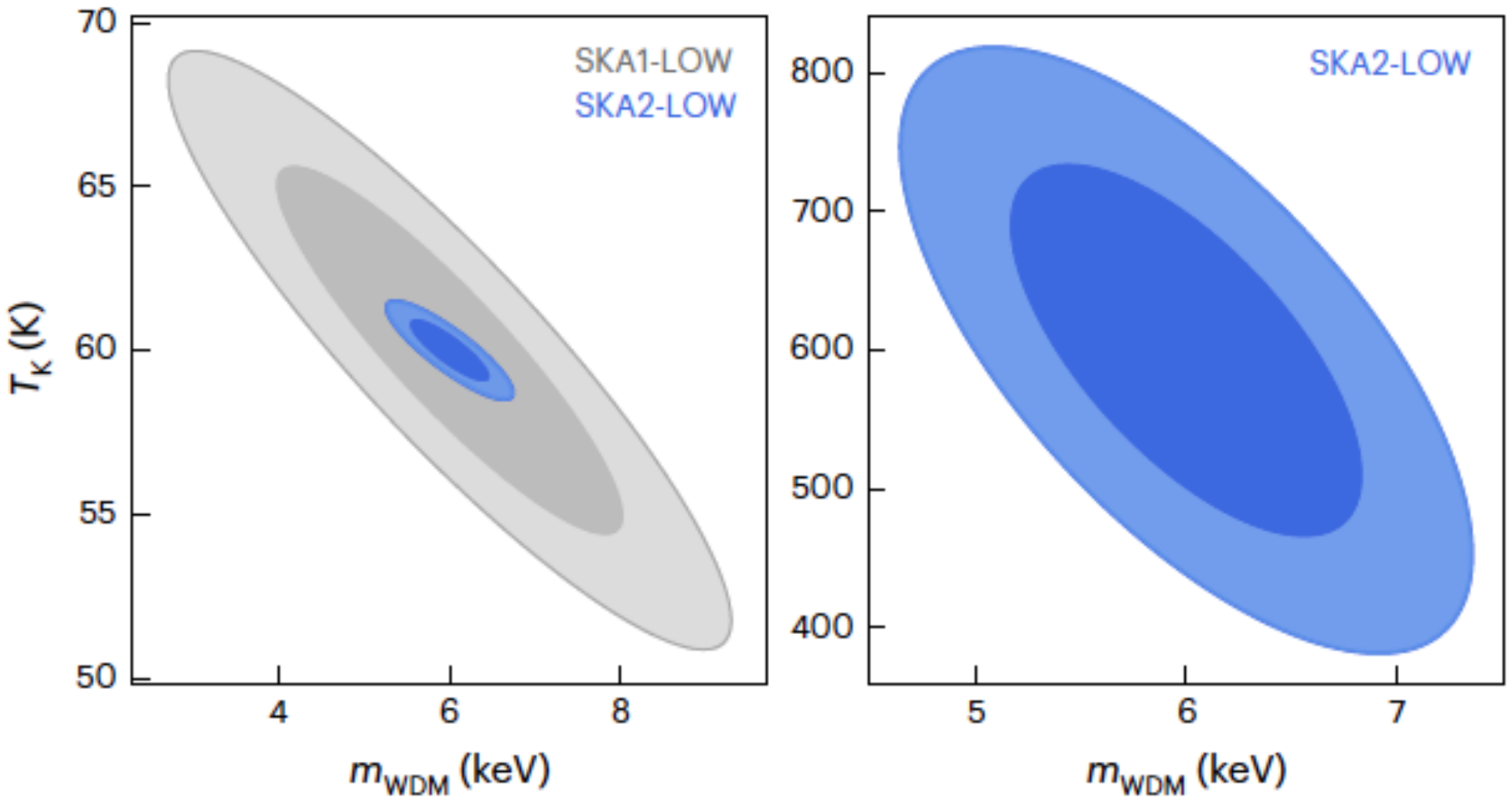
Table A.2: Multiwavelength properties of PSO J0309+27 (RA: 03:09:47.49 ; dec: +27:17:57.31)

| redshift (1) | $i$ (2) | $z$ (3) | $Y$ (4) | $S_{1.4GHz}$ (5) | $S_{147MHz}$ (6) | $\alpha_{vr}$ (7) | R (8) | $\Gamma_X$ (9) | $F_X$ (10) | $L_X$ (11) | $\tilde{\alpha_{ox}}$ (12) | $L_{2500Å}$ (13) | $M_{1450Å}$ (14) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.10±0.03 | >23.1 | 21.37±0.08 | 20.98±0.13 | 23.89±0.8 | 64.2±6.2 | 0.44±0.11 | 2500±500 | 1.5 | $3.6^{+2.5}_{-1.8}$ | $4.0^{+2.8}_{-1.9}$ | $1.09^{+0.07}_{-0.04}$ | 6.1±0.9 | -25.1 |

**They reported radio brightest AGN at $z \sim 6$ with $S_{147\mathrm{MHz}} \sim 64$mJy.**

**It is good target for 21cm forest.**

•Fisher forecast for 21cm forest power spectrum assuming 10mJy radio source.



# Summary & future work

- This paper proposed 1-D 21cm forest power spectrum to evaluate 21cm absorption lines

- They explore the effects of WDM and X-ray heating with 21cm forest power spectrum

- I expect this method can be applied to explore other dark matter scenarios such as axion dark matter and primordial black holes or enhancement by isocurvature perturbations.