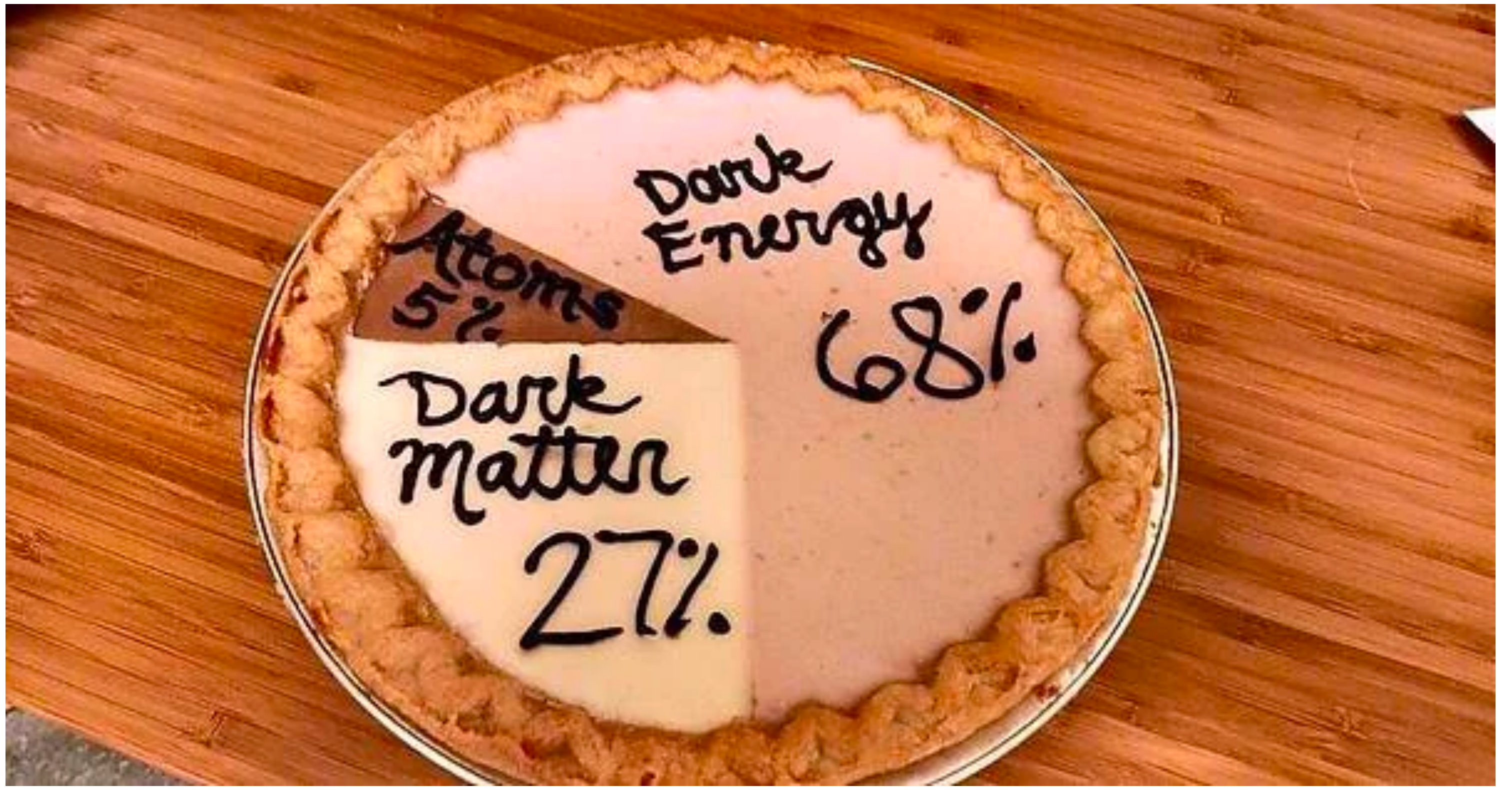
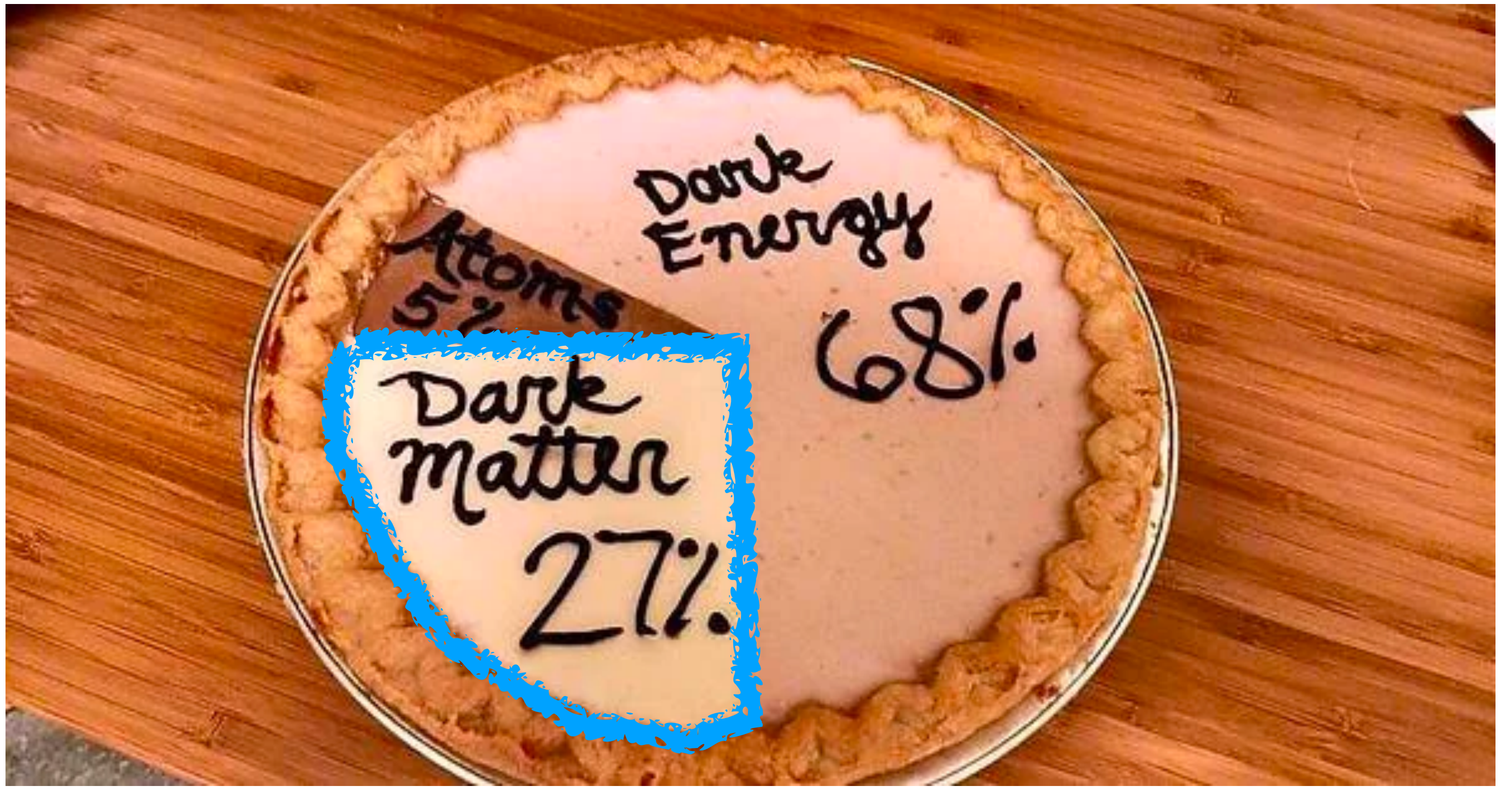
Hongo-21cm workshop（2024/10/3-10/4）

# Exploring small-scale cosmological fluctuations with 21cm forest

Hayato Shimabukuro (Yunnan university, SWIFAR)




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

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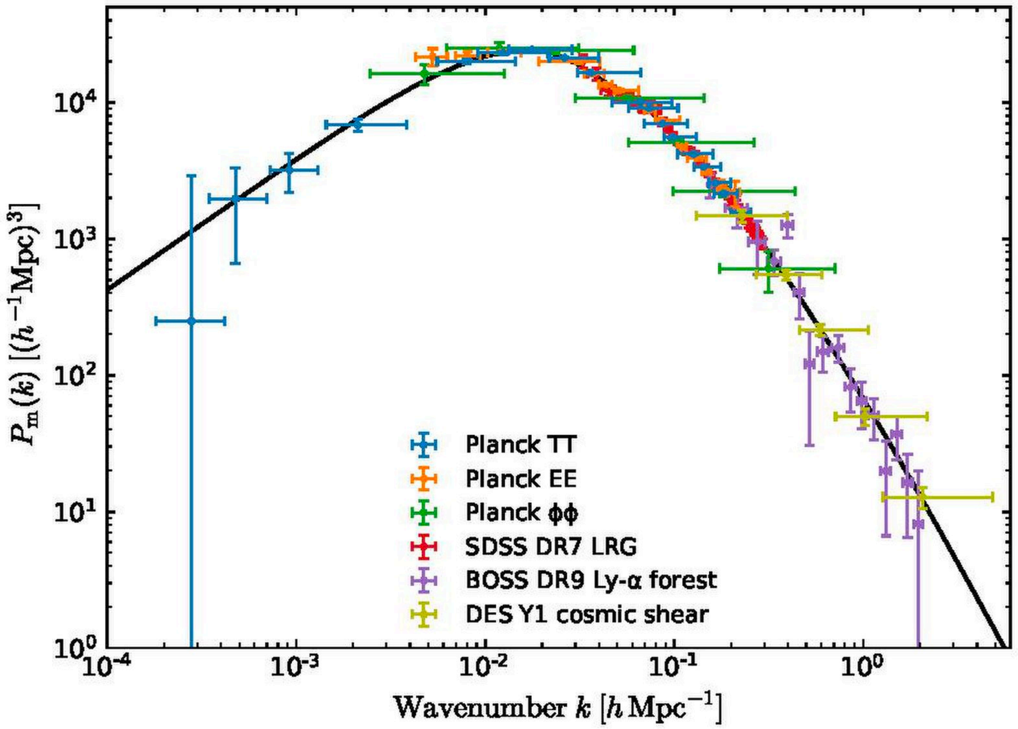
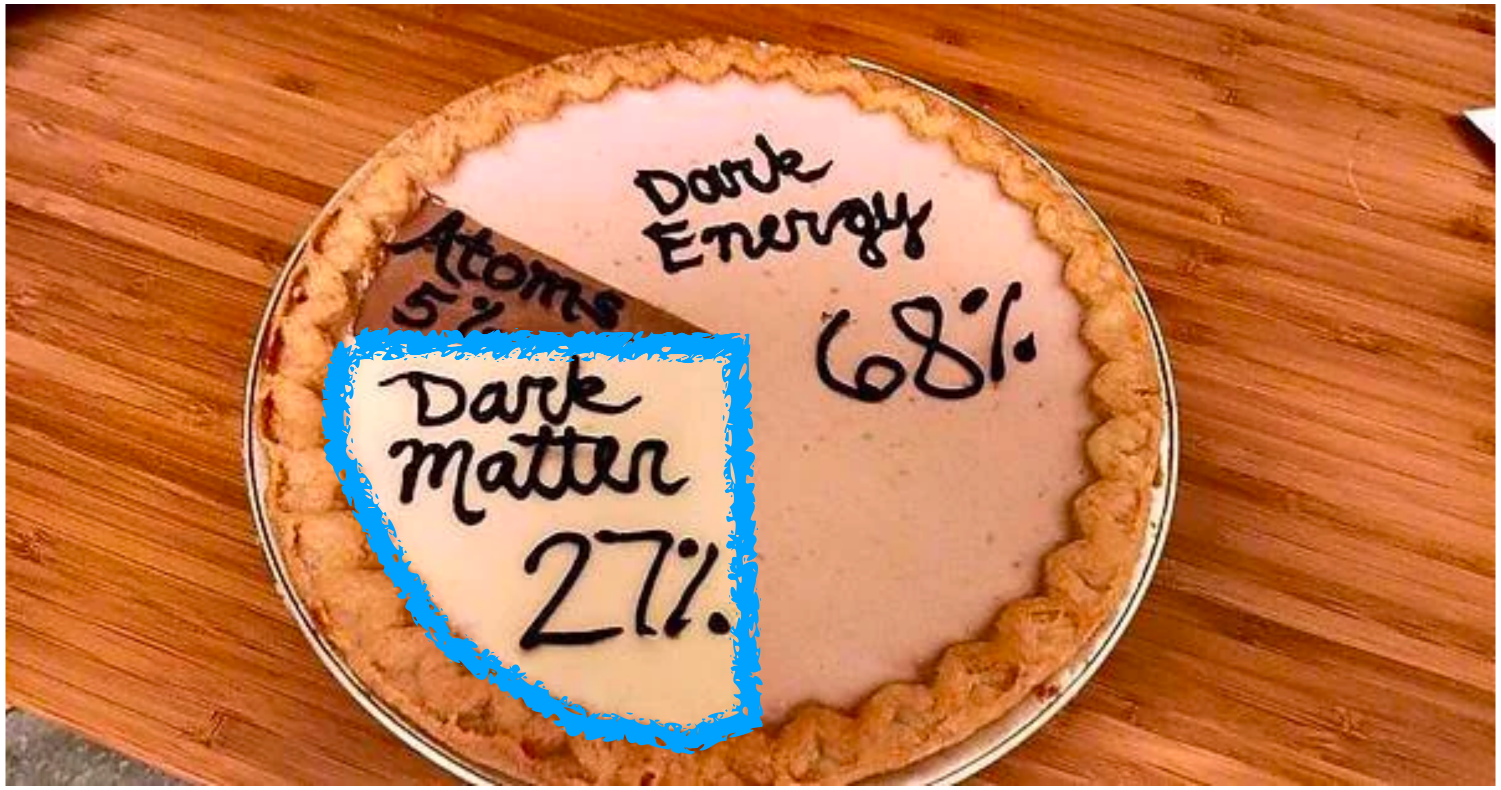



•Recent cosmological observations support "Cold Dark Matter (CDM)" scenario.

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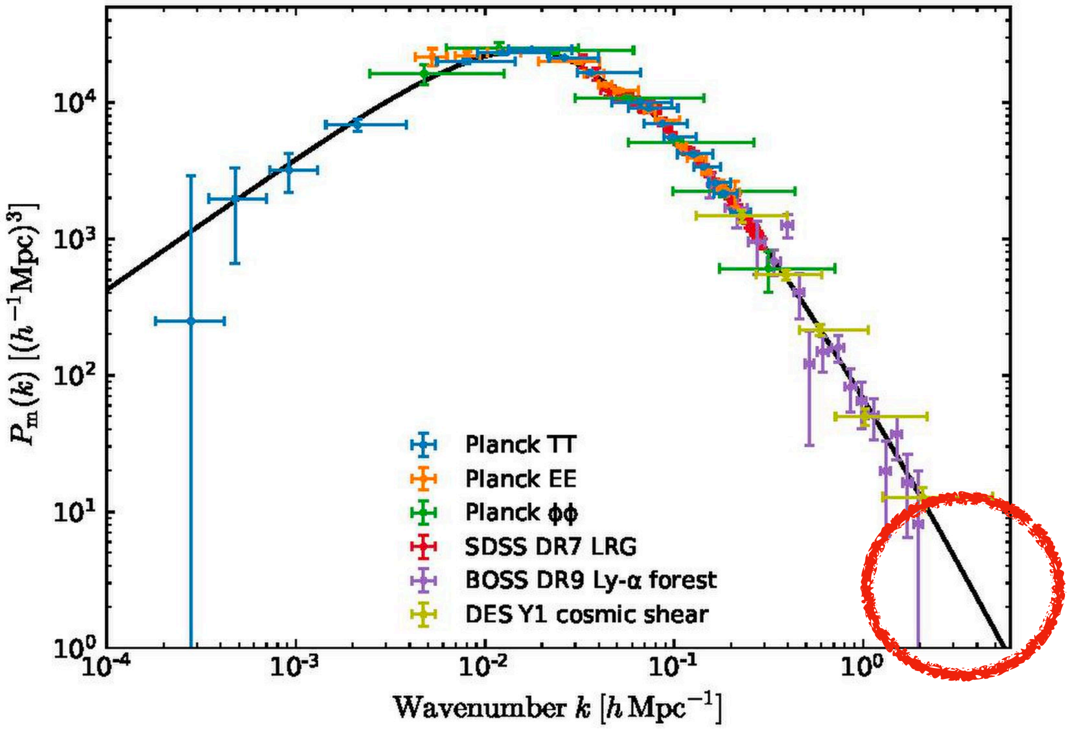



•Recent cosmological observations support "Cold Dark Matter (CDM)" scenario.

•However, we have room to consider other dark matter scenarios such as axion-like ultralight dark matter, warm dark matter, etc

•They have an impact on small scale fluctuations.

# Axion particles

In QCD(Quantum ChoromoDynamics) 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 ***conserves*** **CP symmetry**.

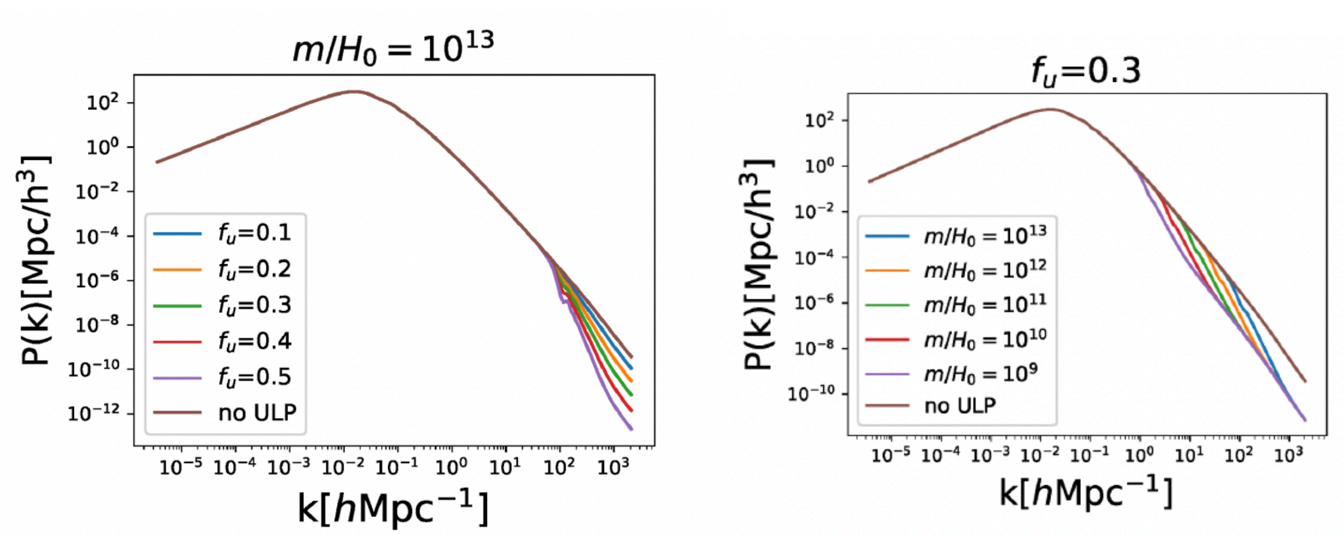
To conserve CP symmetry, **Peccei-Quinn(PQ) symmetry** was introduced (Peccei &Quinn(1977)).

As the result of breaking PQ symmetry, axion particles are generated (Wilczek(1978), Weinberg(1978))). **Axionlike ultralight particle (ULP) is one of the candidates of dark matter.**

# When did PQ symmetry break?

If PQ symmetry breaks **during** inflation

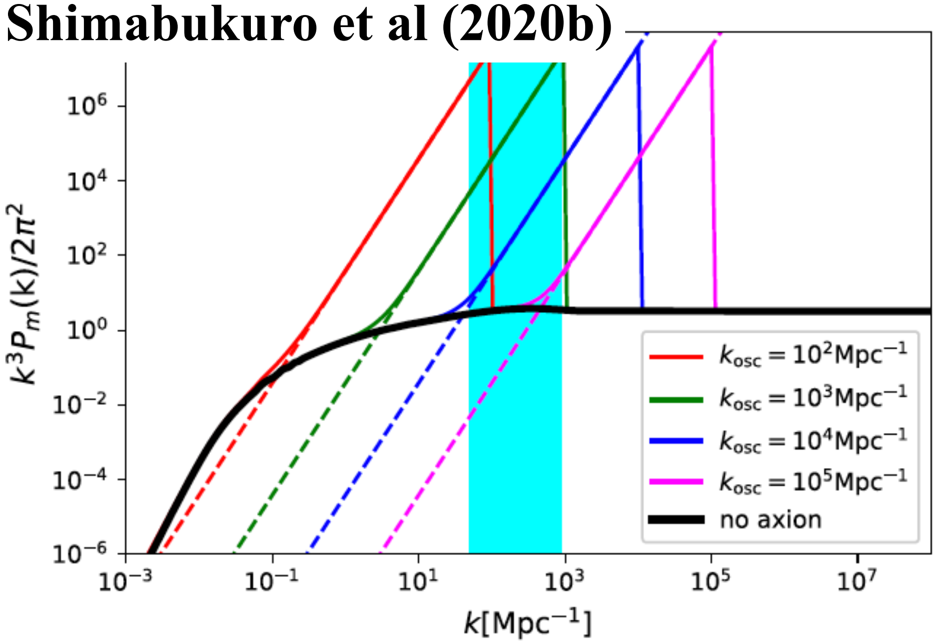
**Shimabukuro et al (2020a)**




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

If PQ symmetry breaks **after** inflation

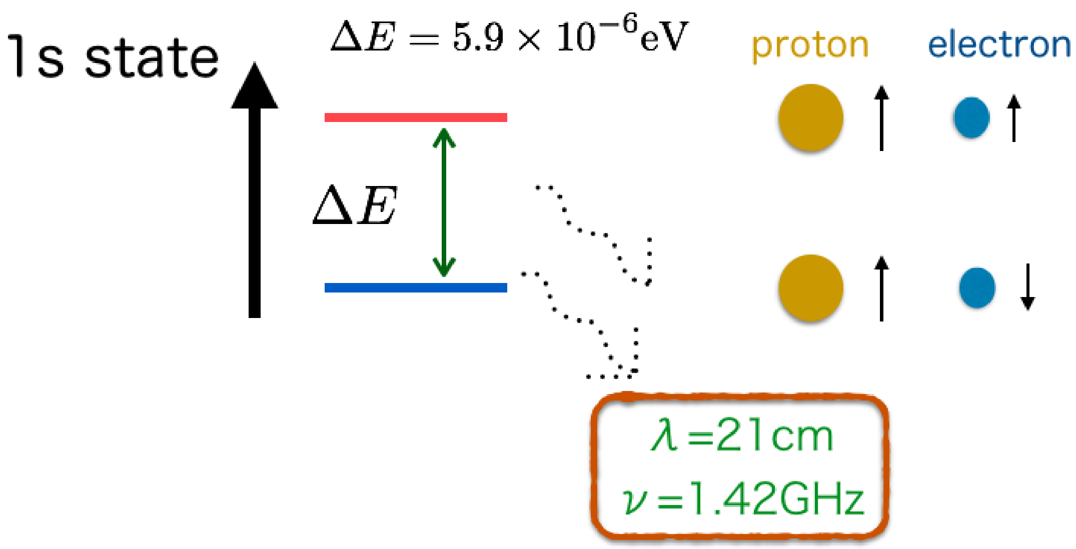
**Shimabukuro et al (2020b)**




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

→ *The formation of small-scale structures (**minihalo**) is also enhanced.*

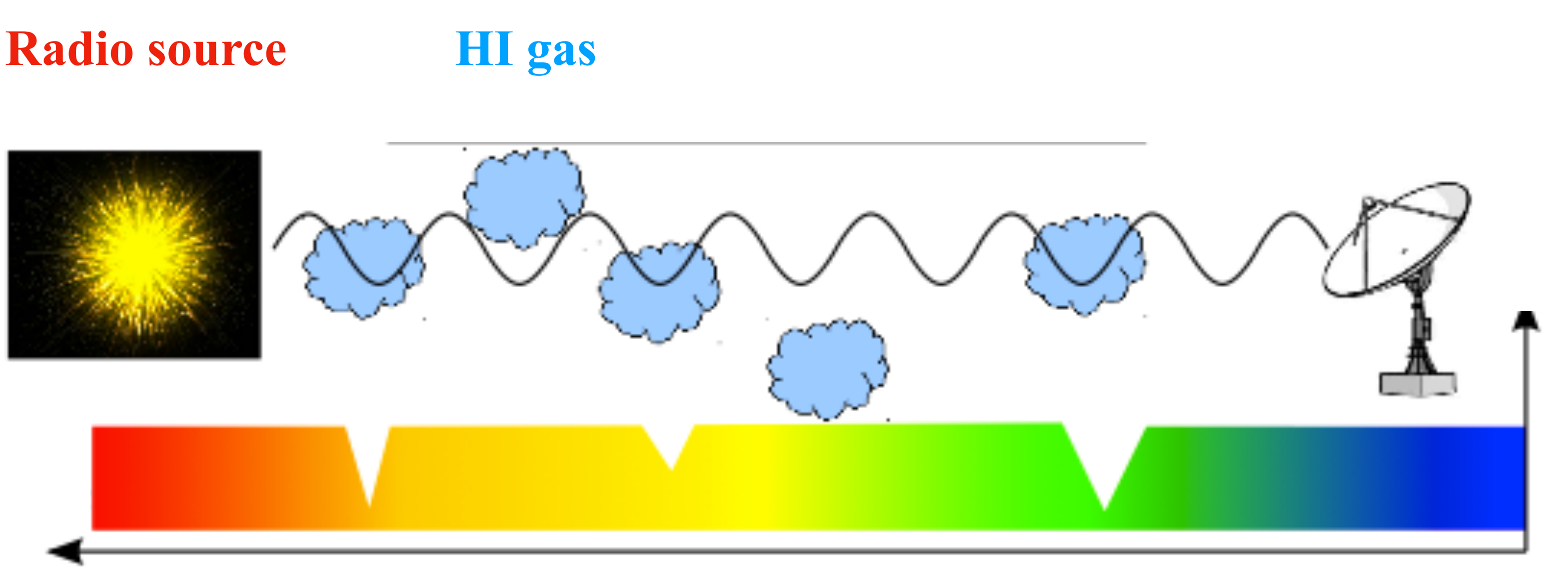
## 21cm line




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

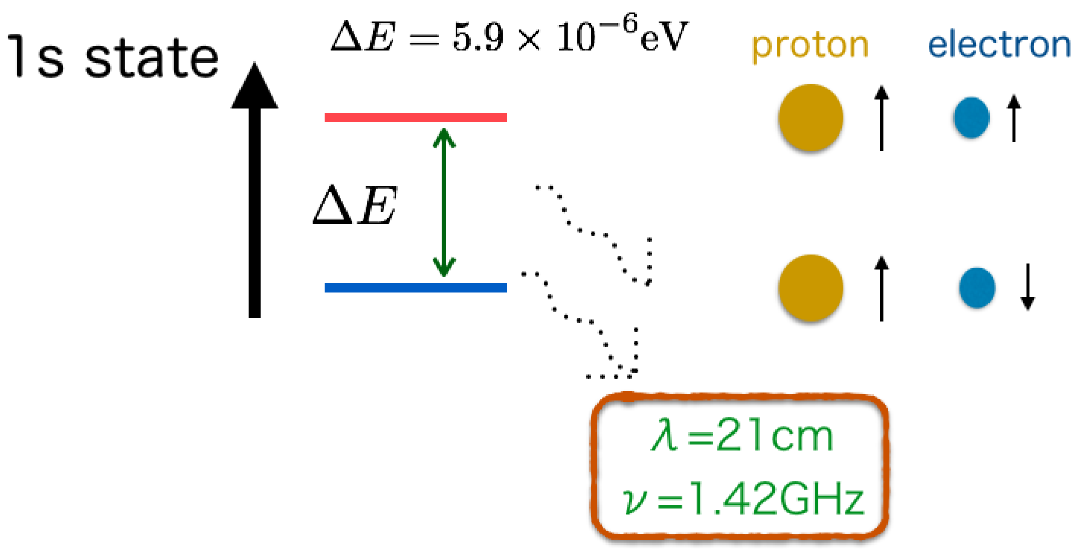
- We often focus on 21cm emission line to probe dark ages and epoch of reionization (EoR), but this talk focuses on 21cm absorption lines.

## 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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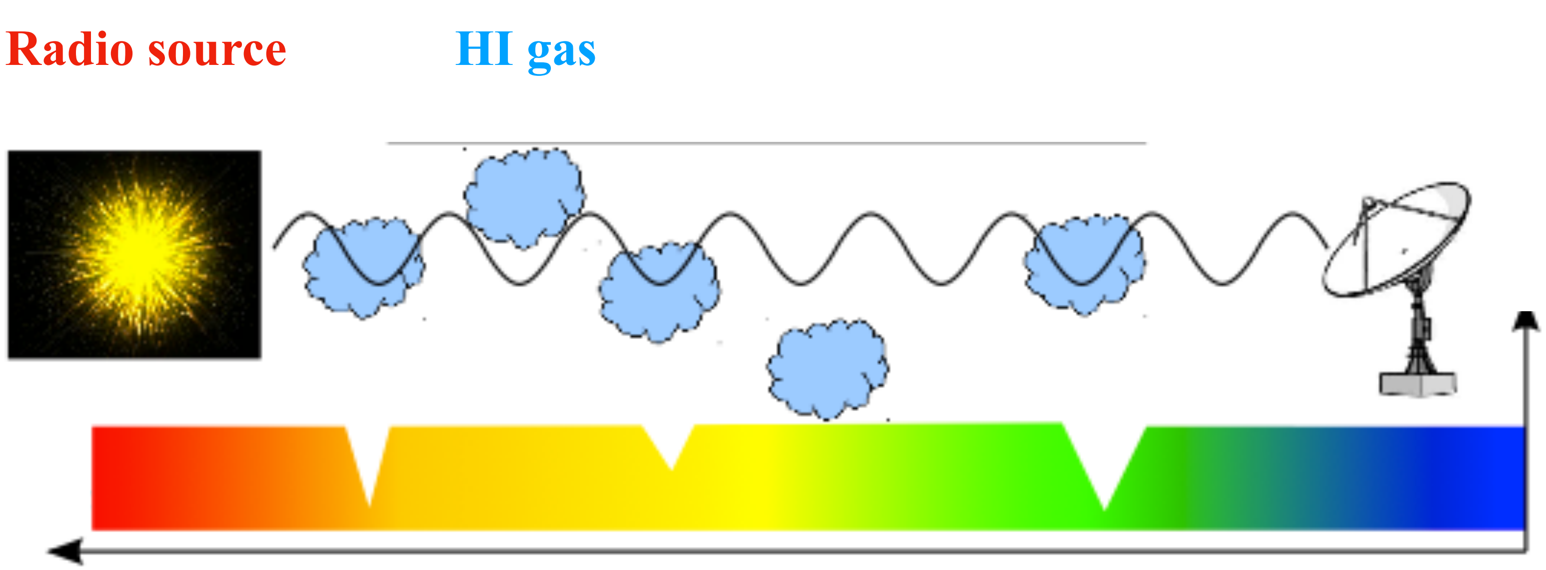


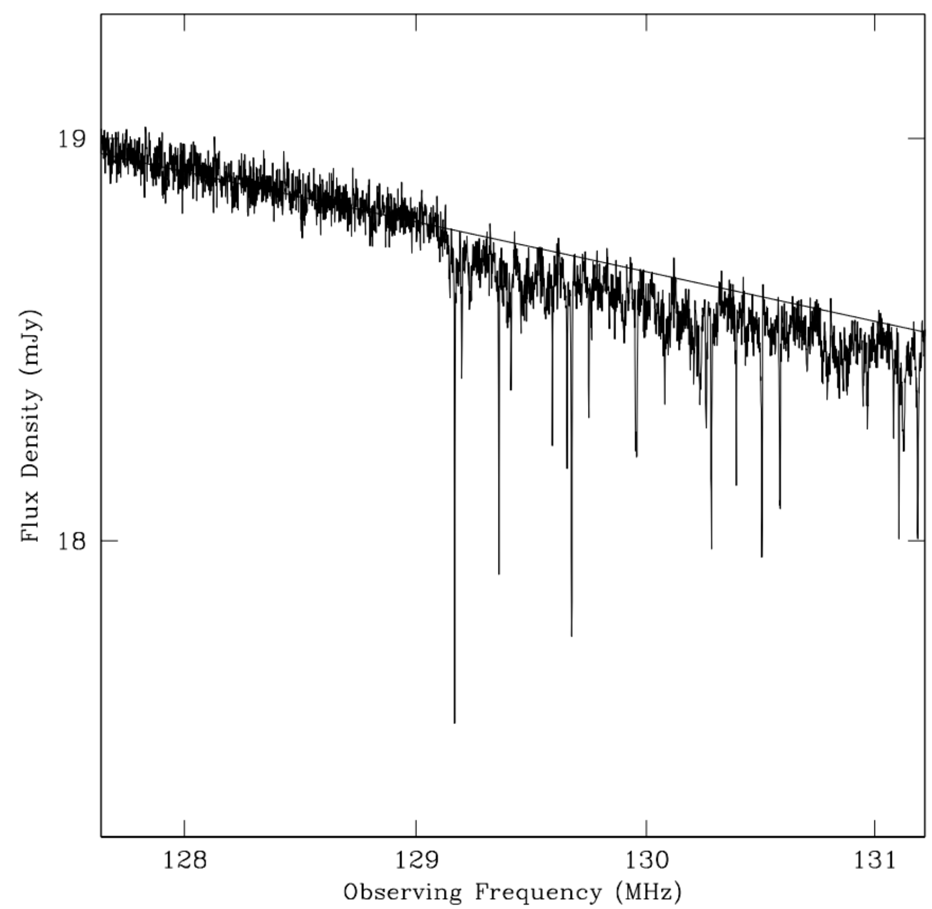


Carilli+ 2002

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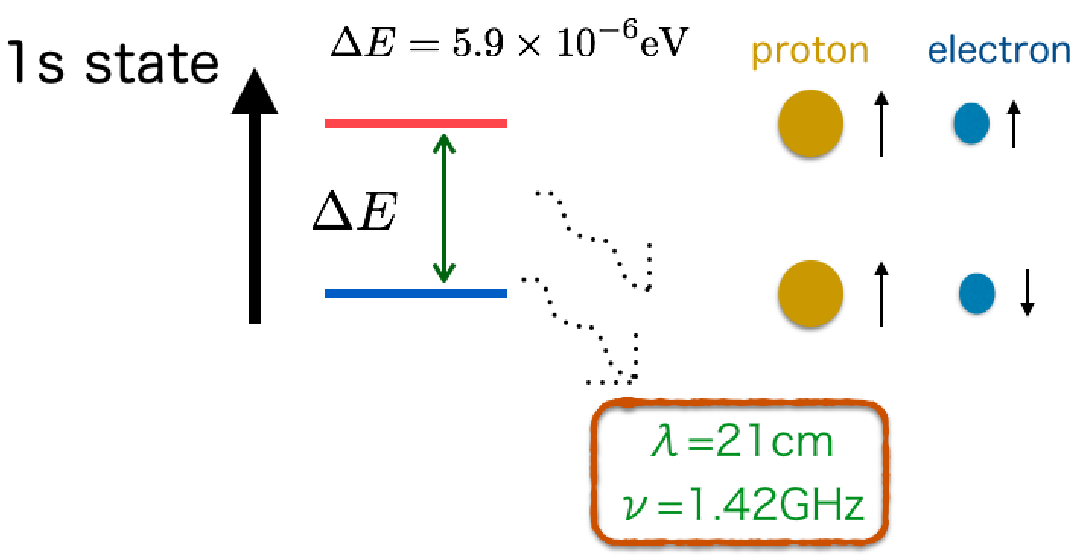


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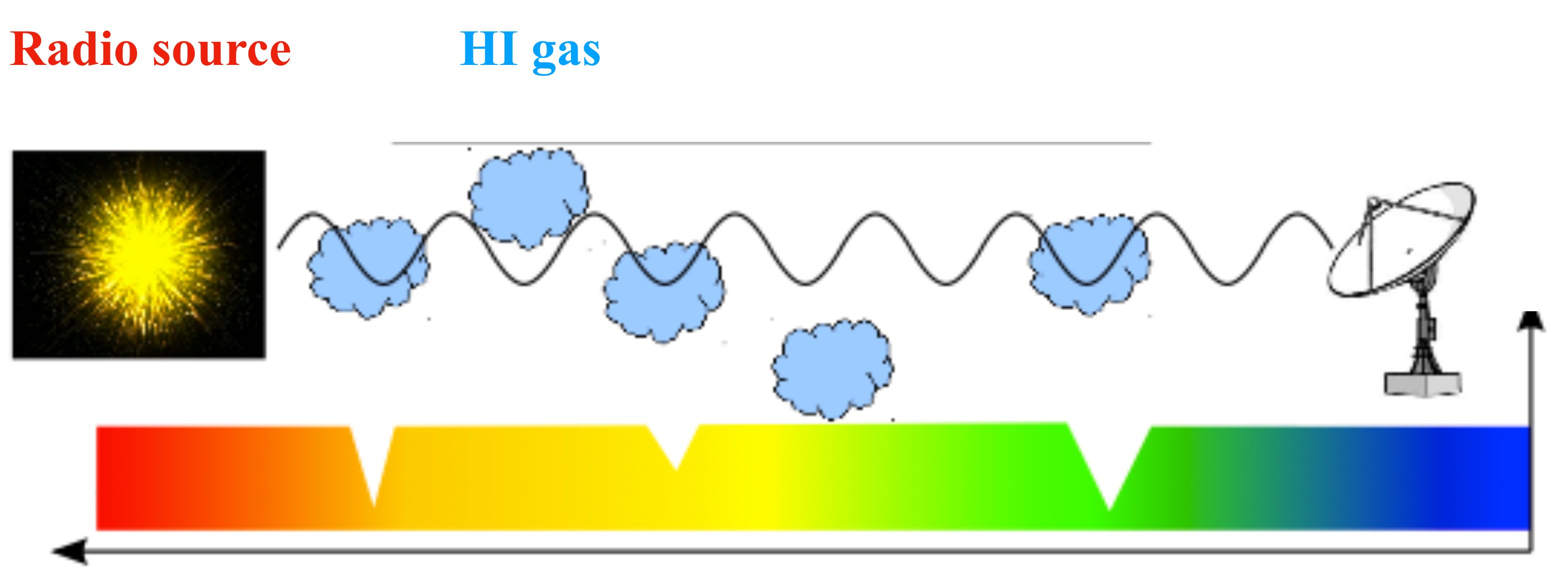


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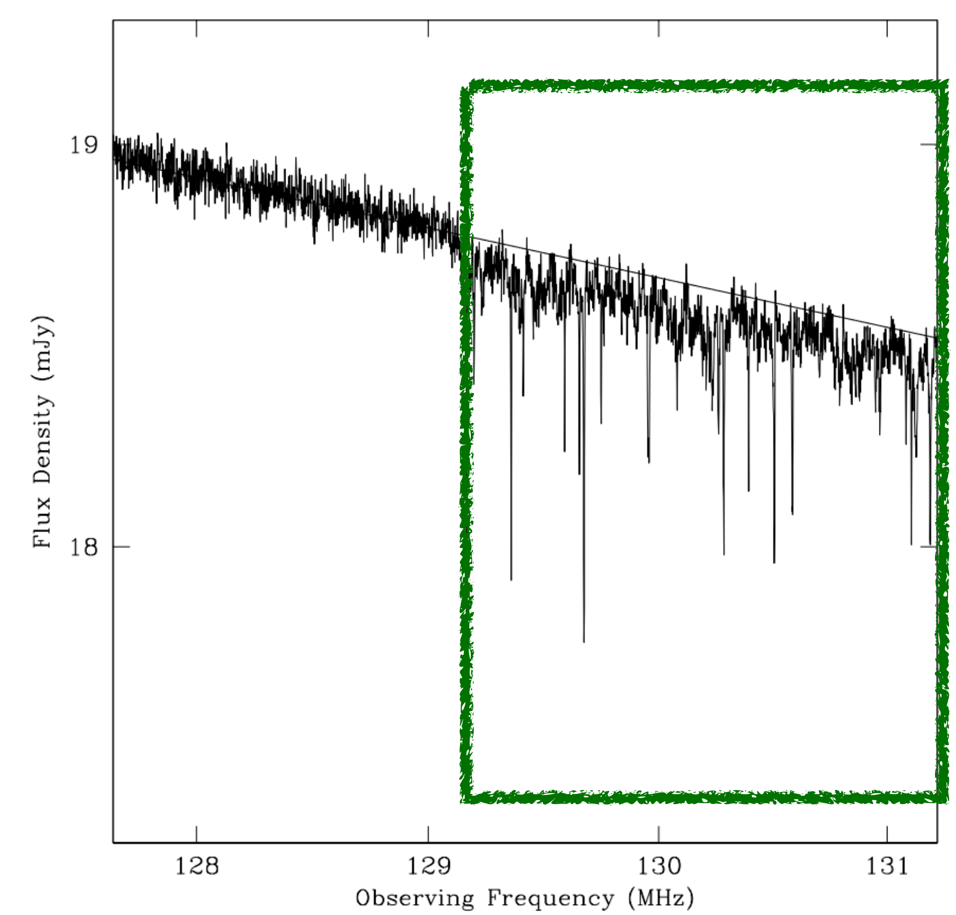



Carilli+ 2002

# The key quantities in the 21cm forest

## Optical depth

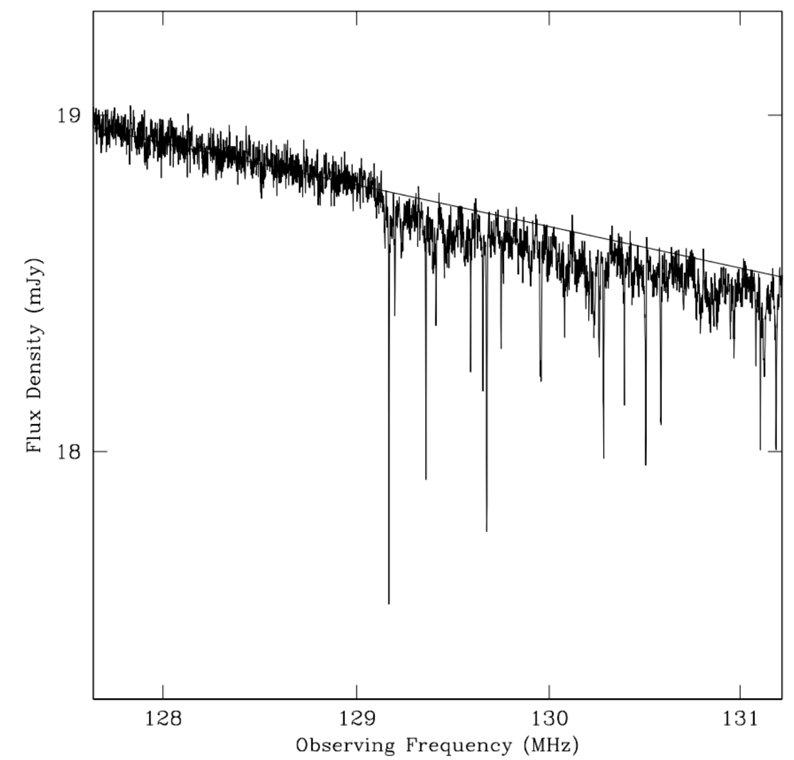
For the **IGM**

$$\tau_\nu = \frac{3c^3 h_P A_{10} n_{HI}(z)}{32\pi k \nu_0^2 T_S H(z)}$$

$$\approx 10^{-2}\left[\frac{T_{CMB}(z)}{T_S}\right]\left(\frac{\Omega_b h}{0.035}\right)\left[\left(\frac{0.3}{\Omega_m}\right)\left(\frac{1+z}{10}\right)\right]^{1/2} x_{HI}\,.$$

For the **minihalo**

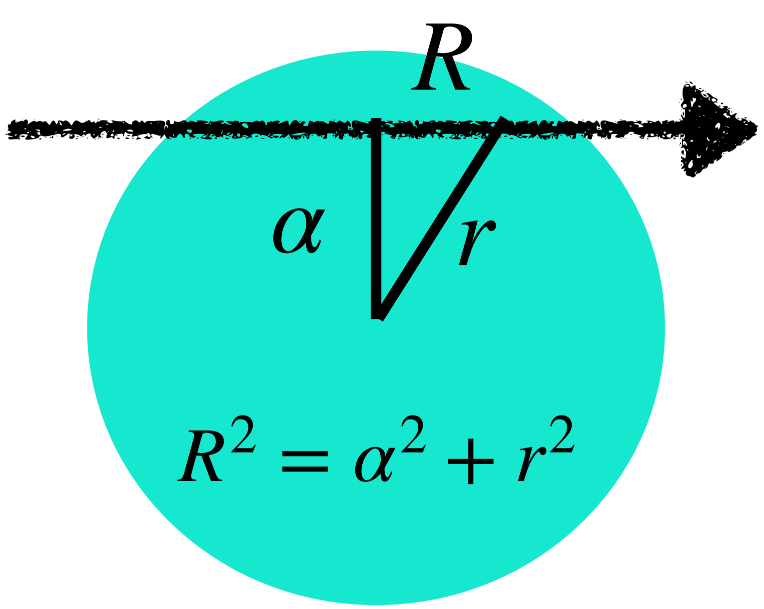
$$\tau(\nu, M, \alpha) = \frac{3h_p c^3 A_{10}}{32\pi k_B \nu_{21}^2}\int_{-R_{max}(\alpha)}^{R_{max}(\alpha)} dR \frac{n_{HI}(r)}{T_S(r)\sqrt{\pi} b}\exp\left(-\frac{v^2(\nu)}{b^2}\right),$$




Carilli+ 2002

## The number count of absorption lines caused by minihalo

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



# Cosmological applications of the 21cm forest

PHYSICAL REVIEW D **90**, 083003 (2014)

**Probing small-scale cosmological fluctuations with the 21 cm forest: Effects of neutrino mass, running spectral index, and warm dark matter**

Hayato Shimabukuro,[1,*] Kiyotomo Ichiki,[2] Susumu Inoue,[3,4] and Shuichiro Yokoyama[4]

[1]*Department of Physics, Graduate School of Science, Nagoya University, Aichi 464-8602, Japan*
[2]*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Aichi 464-8602, Japan*
[3]*Max-Planck-Institut für Physik, 80805 München, Germany*
[4]*Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*

(Received 6 March 2014; published 14 October 2014)

**Shimabukuro et al (2014)**

•Exploring the small scale structure **cosmological fluctuations** by the 21cm forest.

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***Neutrino mass, running spectral index and warm dark mater***

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**Shimabukuro et al (2014)**

•Exploring the small scale structure **cosmological fluctuations** by the 21cm forest.

***Neutrino mass, running spectral index and warm dark mater***

•We also explore the impacts of ultra light particles on the 21cm forest (See also Kawasaki et al 2021, Kadota et al 2021)

**Constraining the nature of ultra light dark matter particles with the 21 cm forest**

Hayato Shimabukuro*
*epartment of Astronomy, Tsinghua Center for Astrophysics, Tsinghua University, Beijing 100084, Ch*
*d Yunnan University, SWIFAR, No. 2 North Green Lake Road, Kunming, Yunnan Province 650500, Ch*

Kiyotomo Ichiki
*Graduate School of Science, Division of Particle and Astrophysical Science, Nagoya University, Chikusa-ku, Nagoya, 464-8602, Japan and Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan*

Kenji Kadota

**Shimabukuro et al (2020a)**

**21 cm forest probes on axion dark matter in postinflationary Peccei-Quinn symmetry breaking scenarios**

Hayato Shimabukuro*
*Yunnan University, SWIFAR, No. 2 North Green Lake Road, Kunming, Yunnan Province 650500, China*

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*Graduate School of Science, Division of Particle and Astrophysical Science, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan and Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan*

Kenji Kadota‡
*Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon 34051, Korea*

(Received 12 May 2020; accepted 25 June 2020; published 13 July 2020)

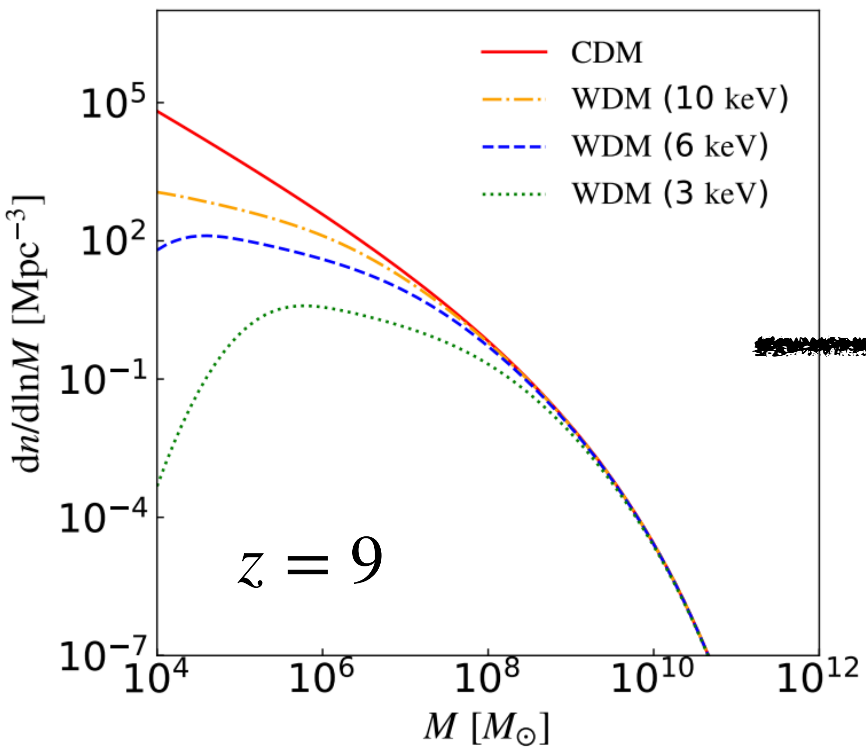
**Shimabukuro et al (2020b)**

# Why can we explore the small scale fluctuations by the 21cm forest?

(Example)

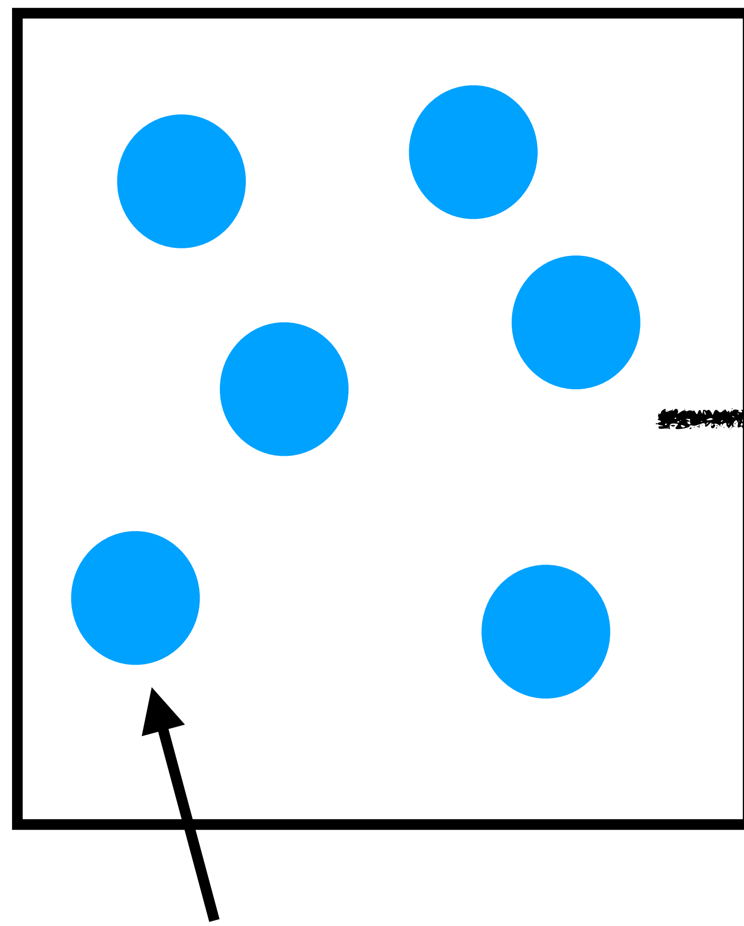
**Warm dark matter (WDM)**

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



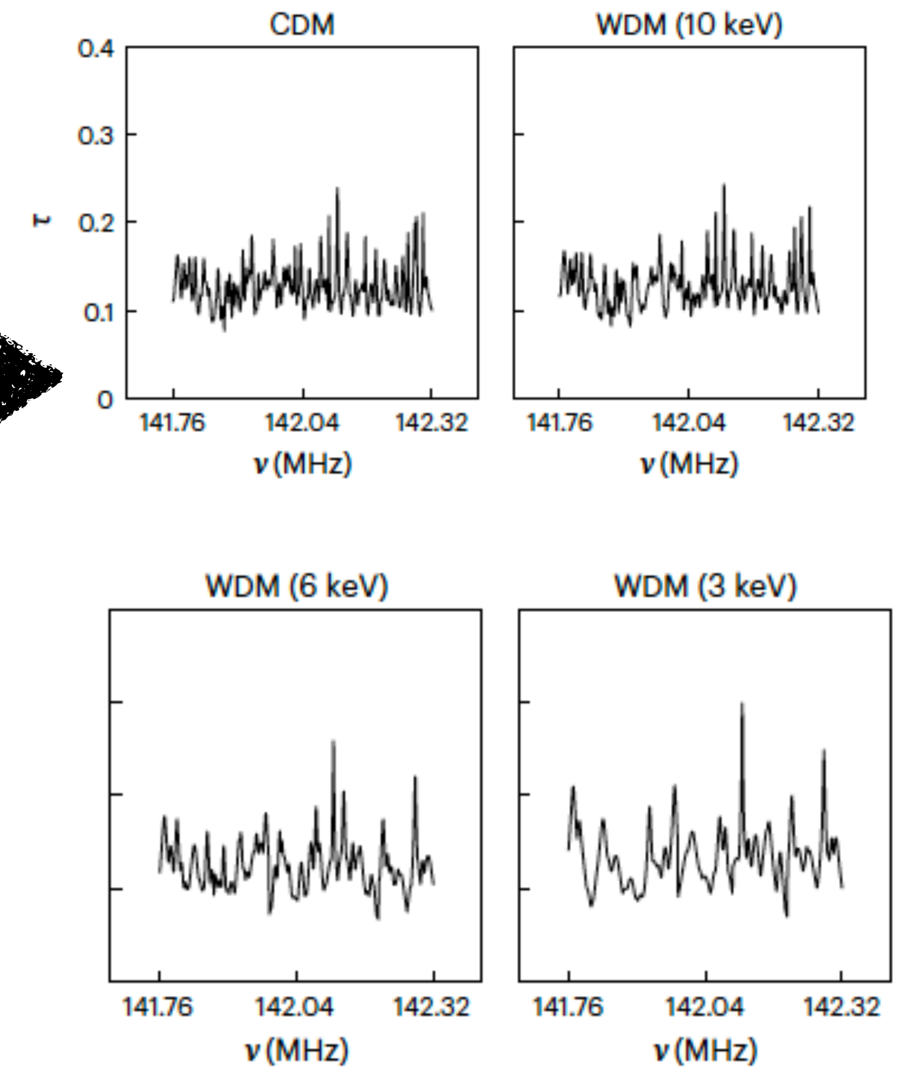

**Lower WDM mass suppresses mass function at a lower halo mass range.**

**The number of minihalo is suppressed**



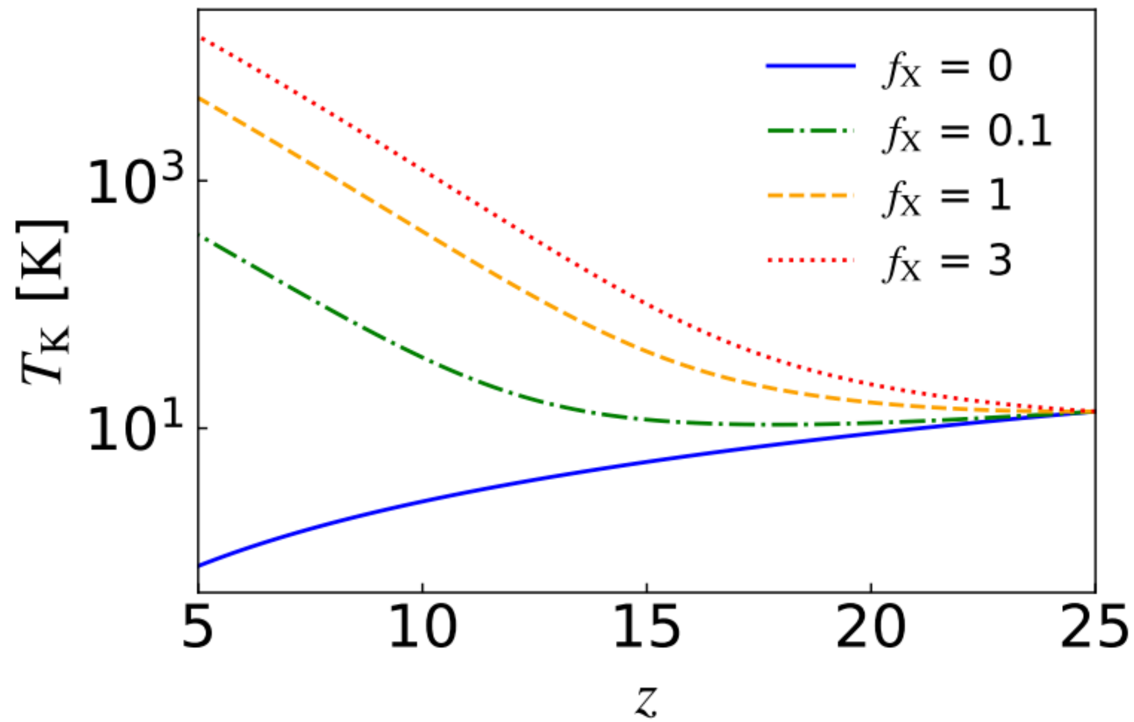
**HI gas inside the halo.**

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



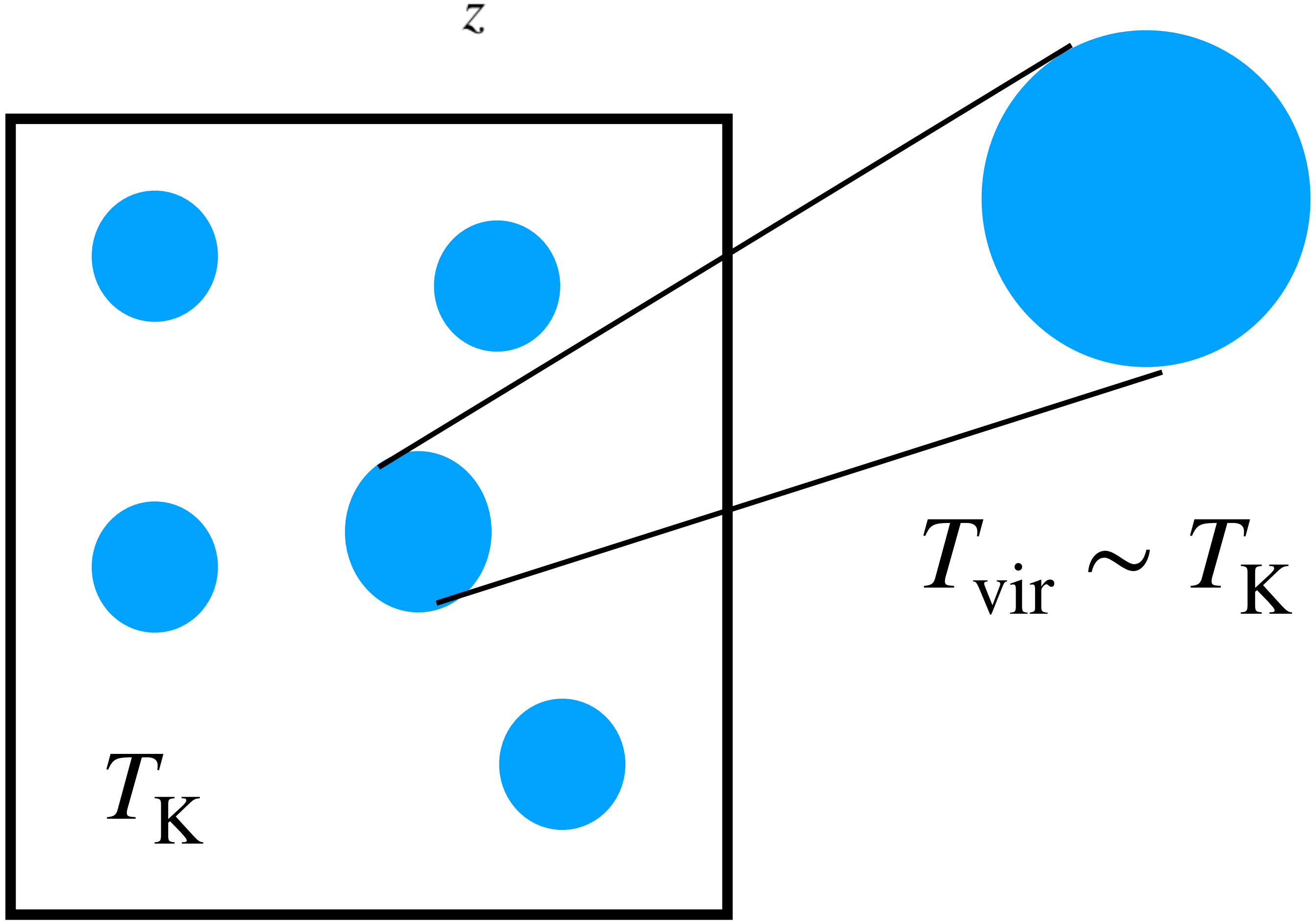

**Shao et al (2023)**

## 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

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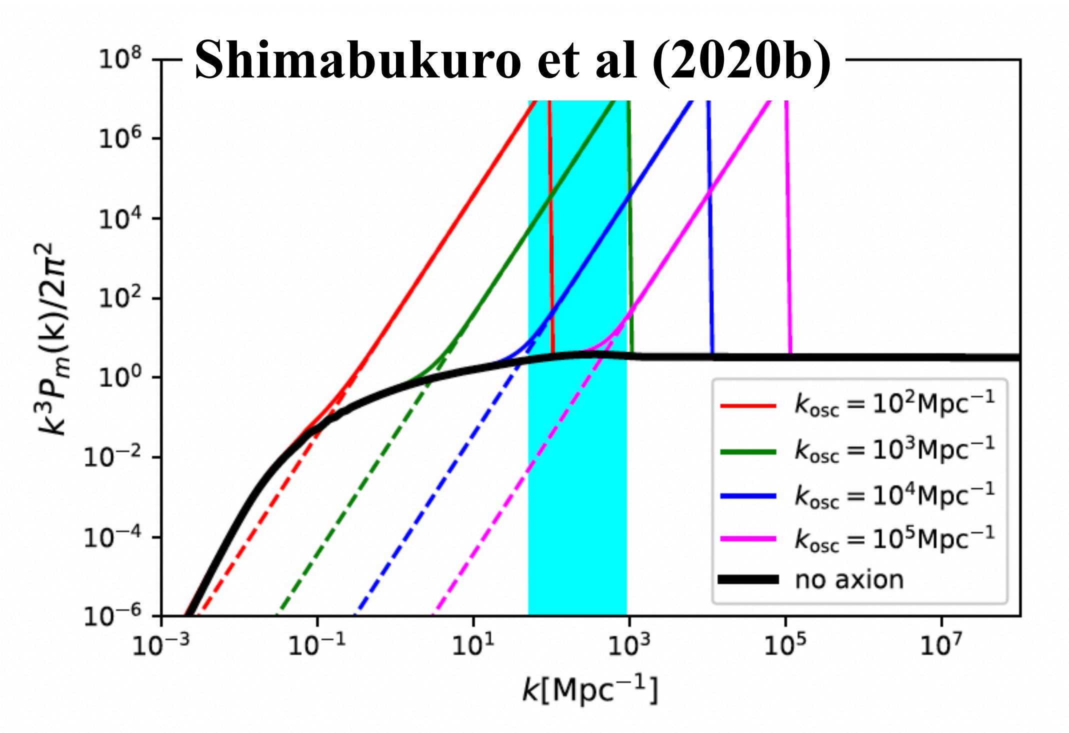
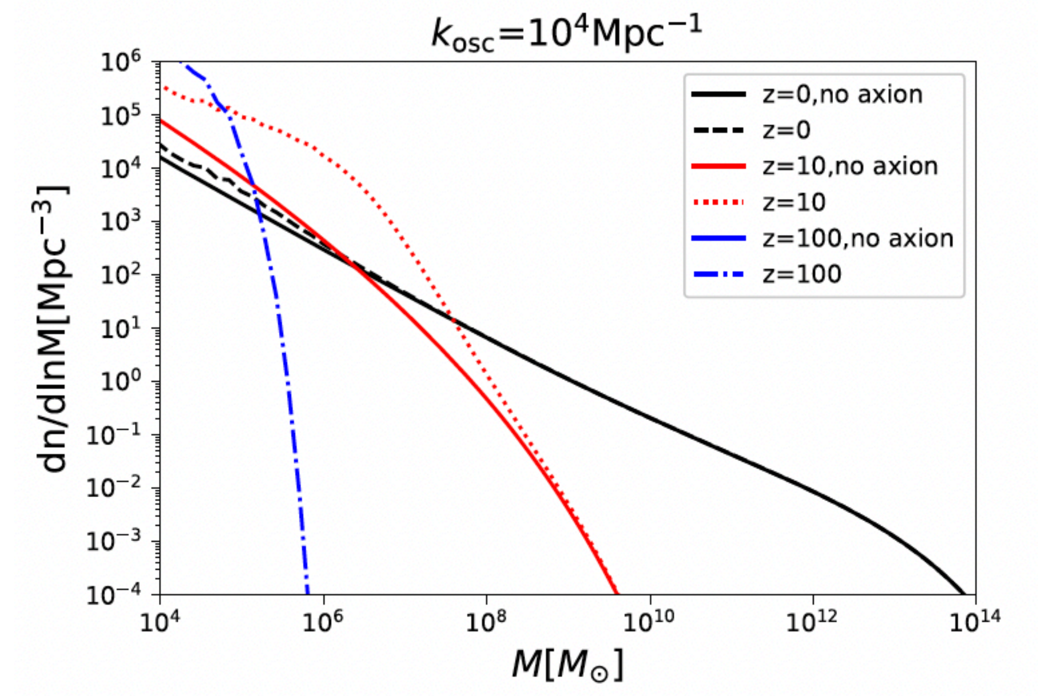
**If X-ray heating is effective (higher $f_X$), 21cm forest is suppressed.**

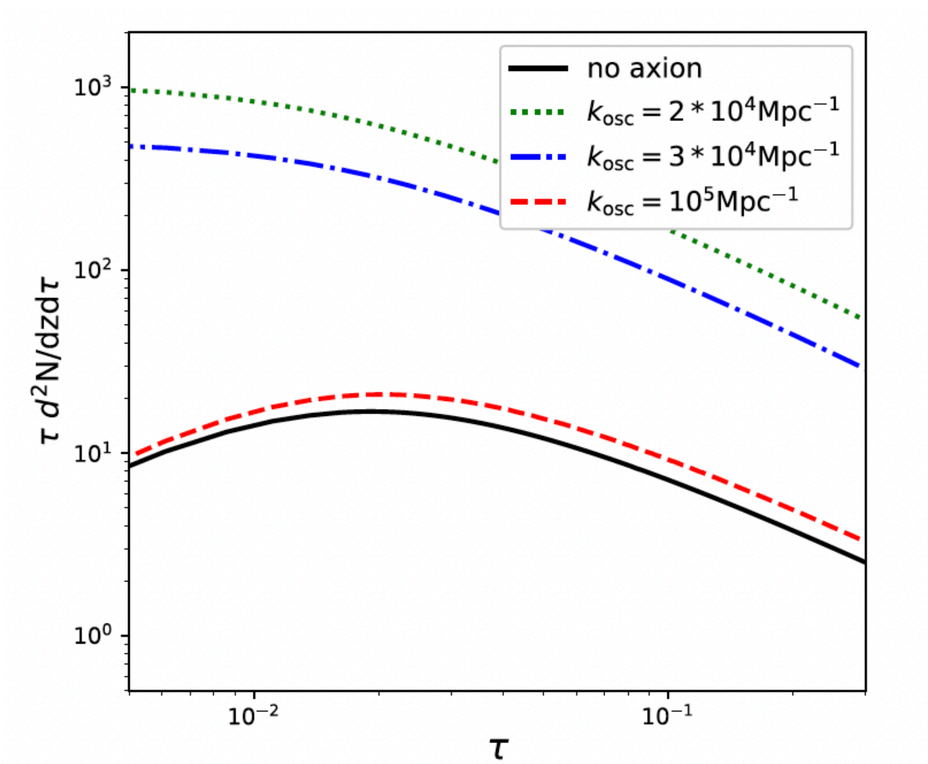
# How do we evaluate the cosmological effects on the 21cm forest?

•matter power spectrum




•Halo mass function



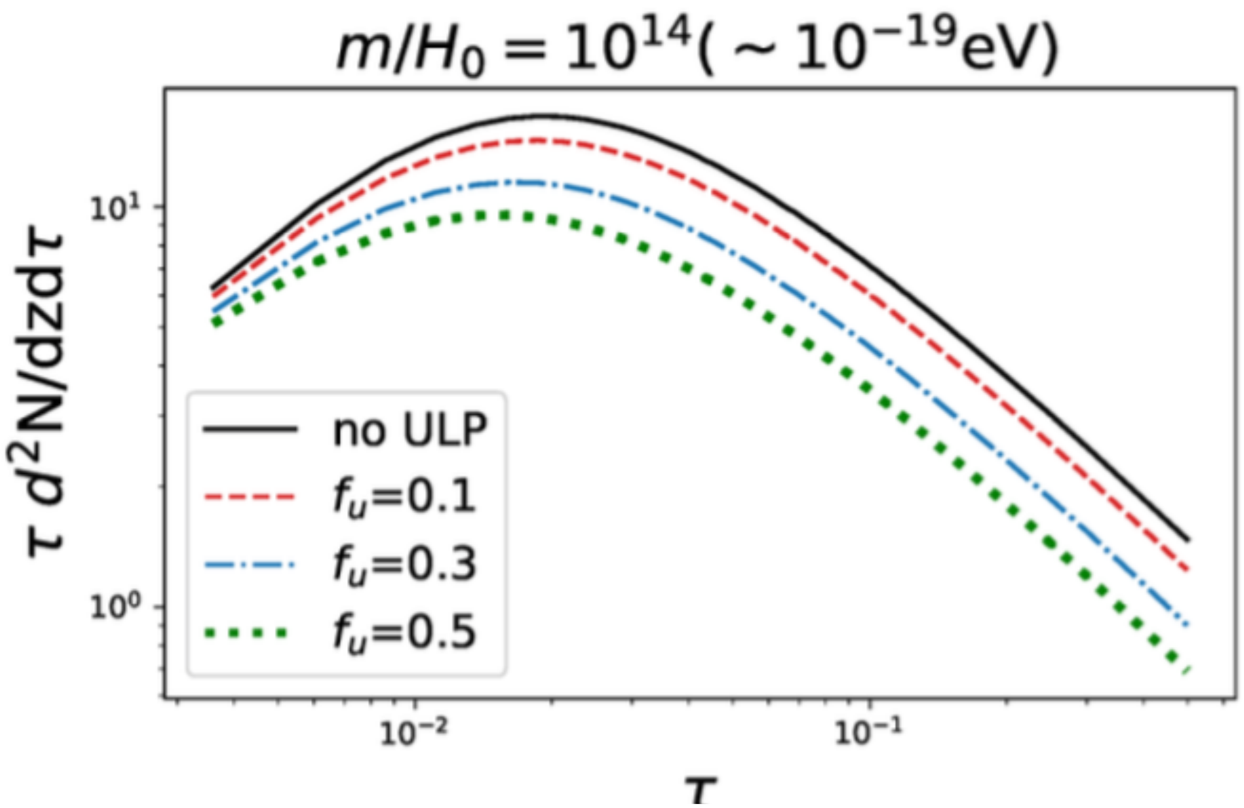

•The number counts of 21cm absorption lines

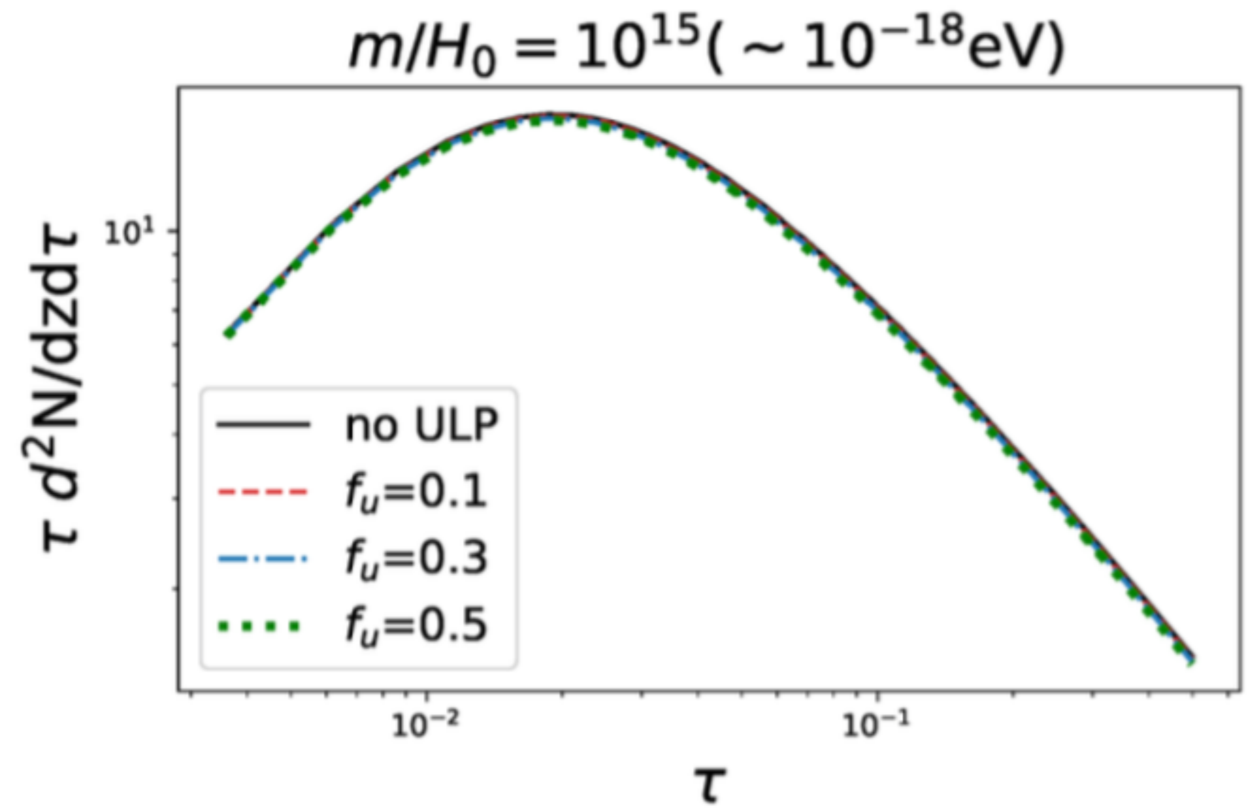
$$\frac{dN(>\tau)}{dz} = \frac{dr}{dz}\int_{M_{\rm min}}^{M_{\rm max}} dM\,\frac{dN}{dM}\pi r_\tau^2(M,\tau),$$

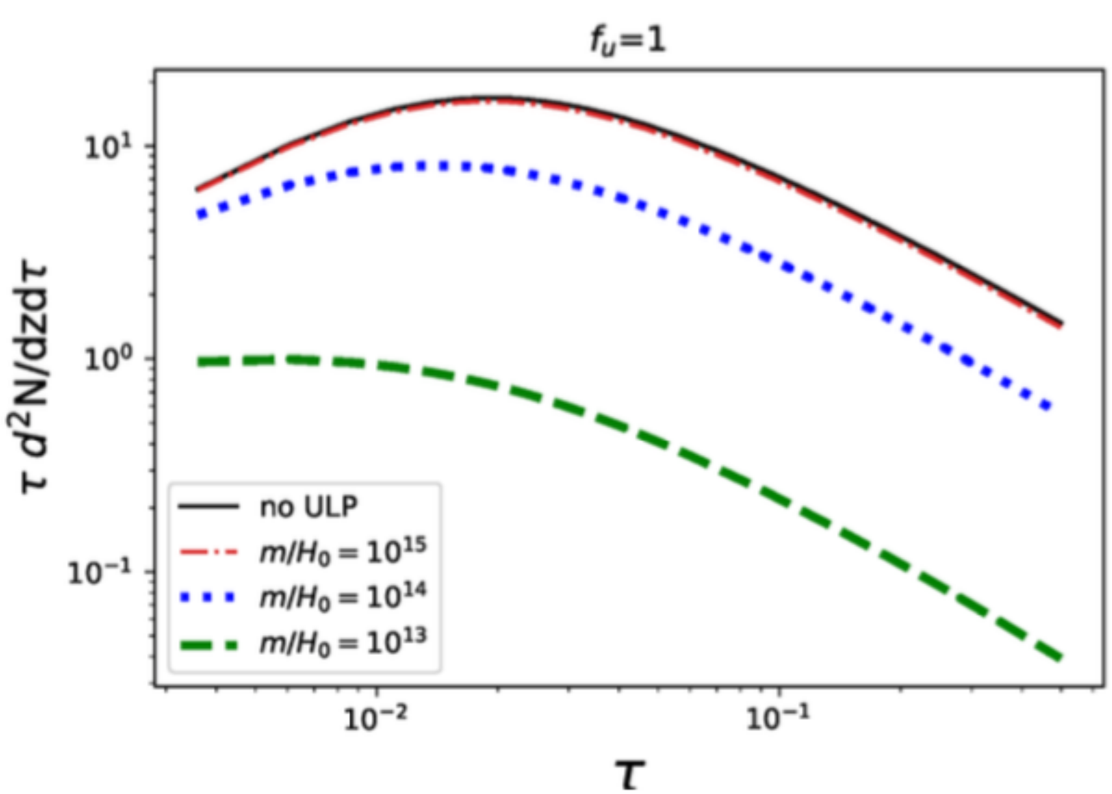
(Note) This is the case that the PQ symmetry breaks after inflation (i.e. isocurvature perturbation enhances matter fluctuaions)

# How large mass can we explore with 21cm forest?

Shimabukuro et al (2020a)



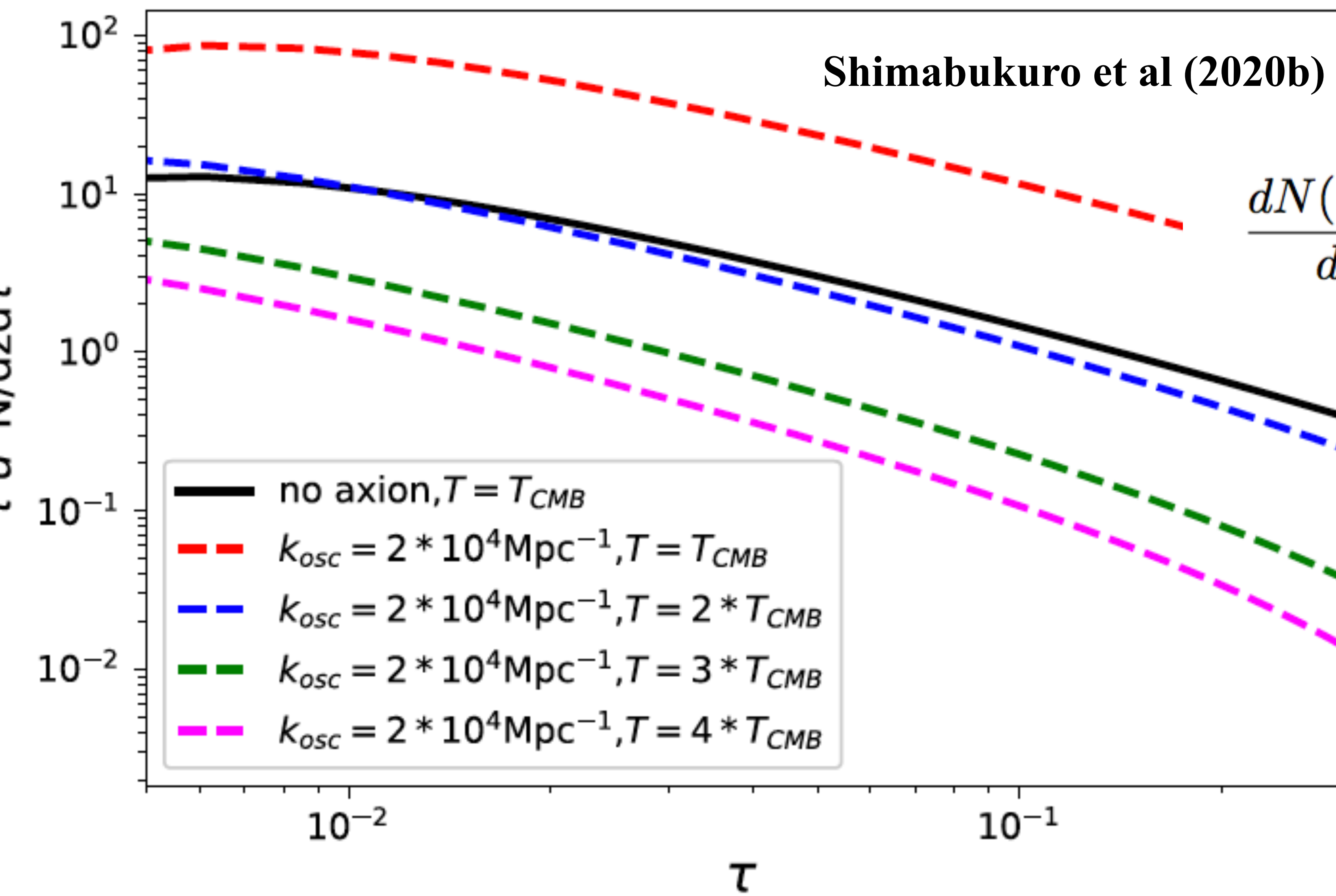

- We can probe ULP mass up to $m_u \sim 10^{-18}$eV for $f_u \leq 0.5$

- If $f_u = 1$, we can probe ULP mass up to $m_u \sim 10^{-18}$eV

**With 21cm foreset, we can explore 3 orders of magnitude higher ULP mass than the Lya forest.**

How does the 21cm forest depends on IGM temperature?

→ We test 21cm forest by varying IGM temperature (Jeans mass)




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

$$M_{\min} = M_{\mathrm{Jeans}}$$

Below $4 \times T_{CMB}$, the number of 21cm absorption lines is still O(1) at a small optical depth

# Other approaches for the evaluation of the 21cm forest??

nature astronomy

Article https://doi.org/10.1038/s41550-023-02024-7

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

Received: 16 May 2022

Accepted: 6 June 2023

Published online: 06 July 2023

Check for updates

Yue Shao[1], Yidong Xu[2,3], Yougang Wang[2,3], Wenxiu Yang[2,4], Ran Li[2,4,5], Xin Zhang[1,6,7] & Xuelei Chen[1,2,3,4,8]

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

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

**Observed differential brightness temperature of the 21cm absorption signal**

$$\delta T_{\mathrm{b}}(\hat{\mathbf{s}}, \nu) \approx \frac{T_{\mathrm{S}}(\hat{\mathbf{s}}, z) - T_{\gamma}\left(\hat{\mathbf{s}}, \nu_0, z\right)}{1+z} \tau_{\nu_0}(\hat{\mathbf{s}}, z)$$

**Depending on gas profile inside halo**

$$\tau_{\nu_0}(\hat{\mathbf{s}}, z) \approx 0.0085[1+\delta(\hat{\mathbf{s}}, z)](1+z)^{3/2}\left[\frac{x_{\mathrm{H}}(\hat{\mathbf{s}}, z)}{T_S(\hat{\mathbf{s}}, z)}\right]\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\|}/\mathrm{d}r_{\|}}\right] \left(\frac{\Omega_{\mathrm{b}} h^2}{0.022}\right)\left(\frac{0.14}{\Omega_{\mathrm{m}} h^2}\right)$$

**1D power spectrum of 21cm forest**

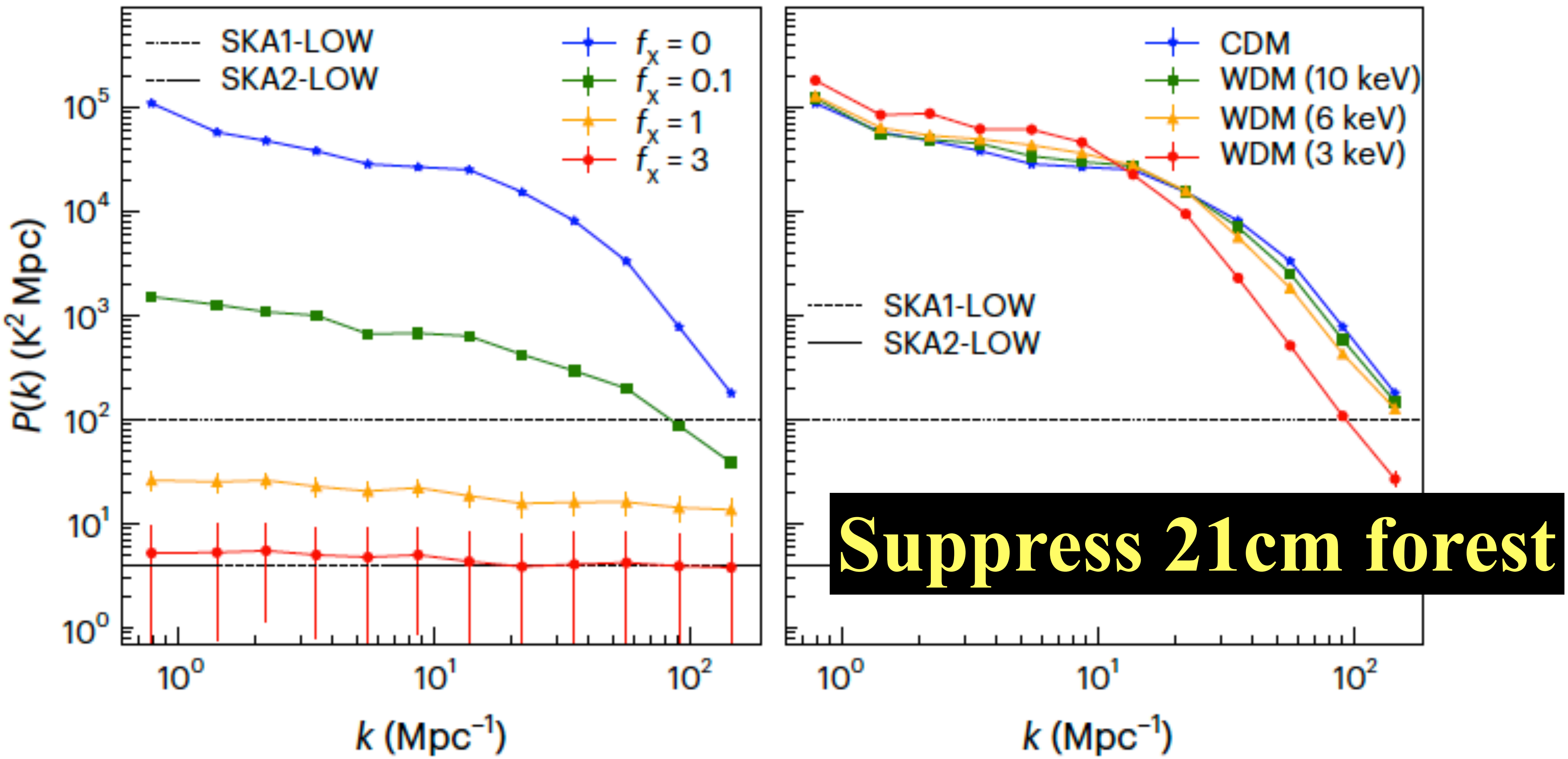
$$\delta \widetilde{T}'\left(\hat{\mathbf{s}}, k_{\|}\right) = \int \delta T_{\mathrm{b}}'\left(\hat{\mathbf{s}}, r_z\right) \mathrm{e}^{-\mathrm{i} k_{\|} r_z}\, \mathrm{d} r_z \longrightarrow P\left(\hat{\mathbf{s}}, k_{\|}\right) = \left|\delta \widetilde{T}\left(\hat{\mathbf{s}}, k_{\|}\right)\right|^2\left(\frac{1}{\Delta r_z}\right).$$

Fourier transformation

(Left) The impact of the X-ray heating on the 21cm forest

(Right) The impact of the WDM on the 21cm forest

**Shao et al (2023)**




*How about applying this method to other cosmological effects (e.g.* ***axion dark matter, primordial blackhole, magnetic field****)? Does anyone try it ??*

# Summary

- 21cm forest is a complementary approach to 21cm emission line.
- 21cm forest can explore small-scale fluctuations
- How do we evaluate the 21cm forest?
- What cosmological information can we subtract from 21cm forest?