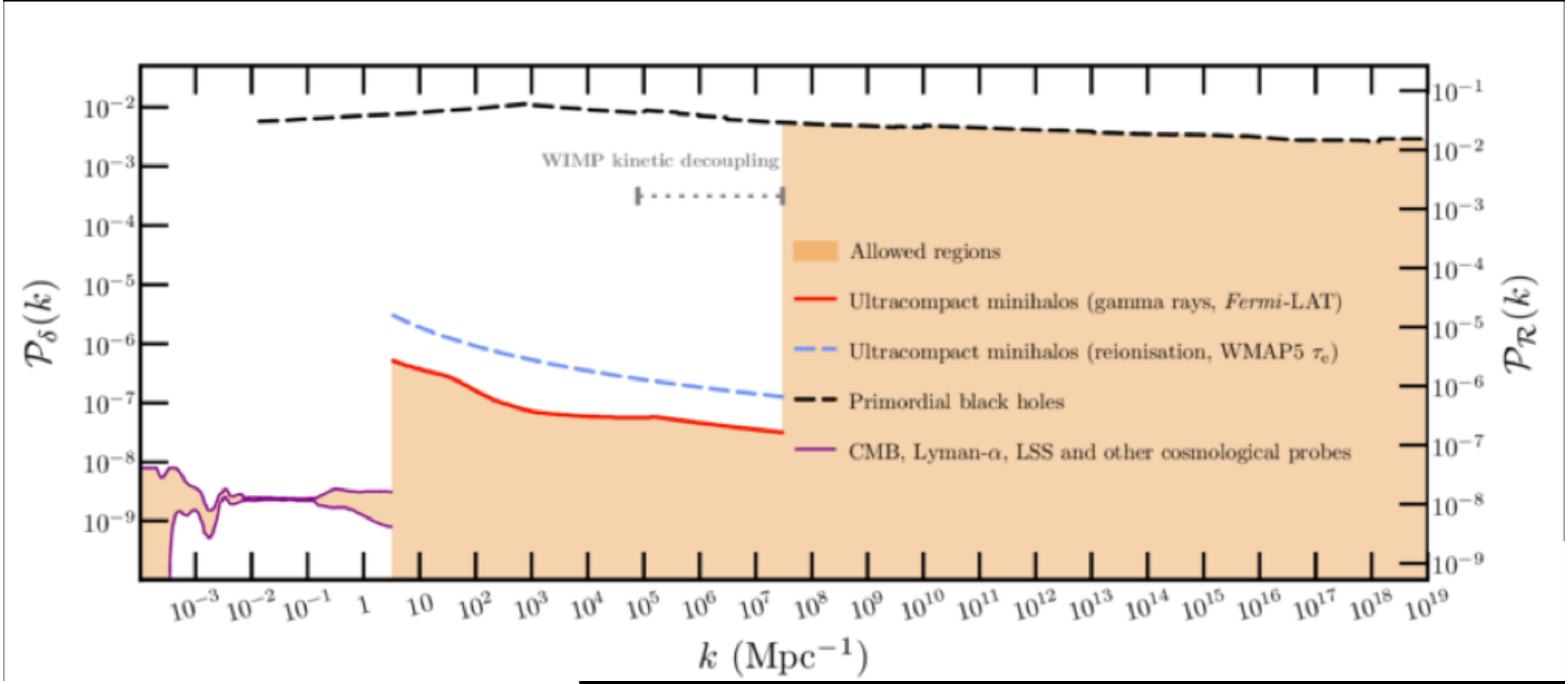
第8回観測的宇宙論ワークショップ

UCMHの個数と21-cm線グローバルシグナルについて



箕田鉄兵, 田代寛之 (名古屋大学)

Ultracompact minihalo (UCMH)?

The density profiles of ultracompact minihalos: implications for constraining the primordial power spectrum

M. Sten Delos,[1,*] Adrienne L. Erickcek,[1,†] Avery P. Bailey,[2,1] and Marcelo A. Alvarez[3]

UCMHs:

A dark matter structure hypothesized to possess $\rho \propto r^{-9/4}$ density profile due to its formation at z ≥ 1000.

(Filmore+ 1984, Bertschinger 1985)

Their purpose:
Confirming the UCMH density profile with N-body simulation

(Delos et al., 1806.07389)

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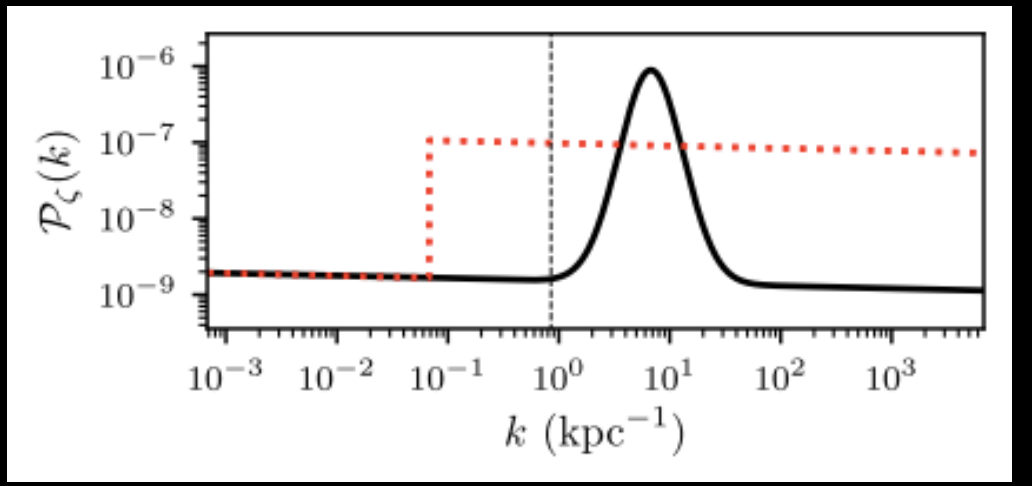
Setup:

- spiked power spectrum on small scale ~ 1 kpc
- initial redshift: $z = 8\times10^6$
- box size: $\mathrm{L} = 7.4$ ckpc
- particle number: $\mathrm{N} = 512^3$
- GADGET-2 with radiation
- ROCKSTAR halo finder



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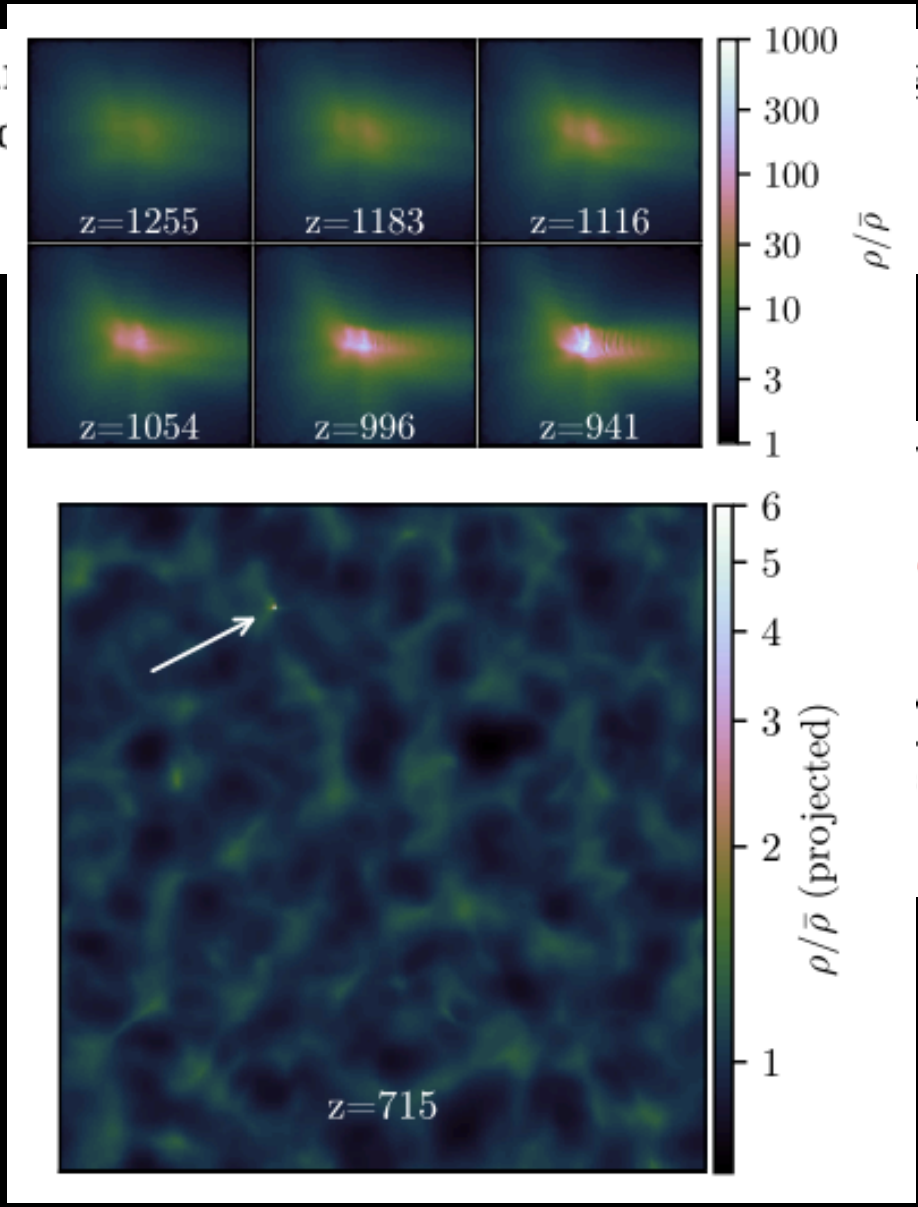

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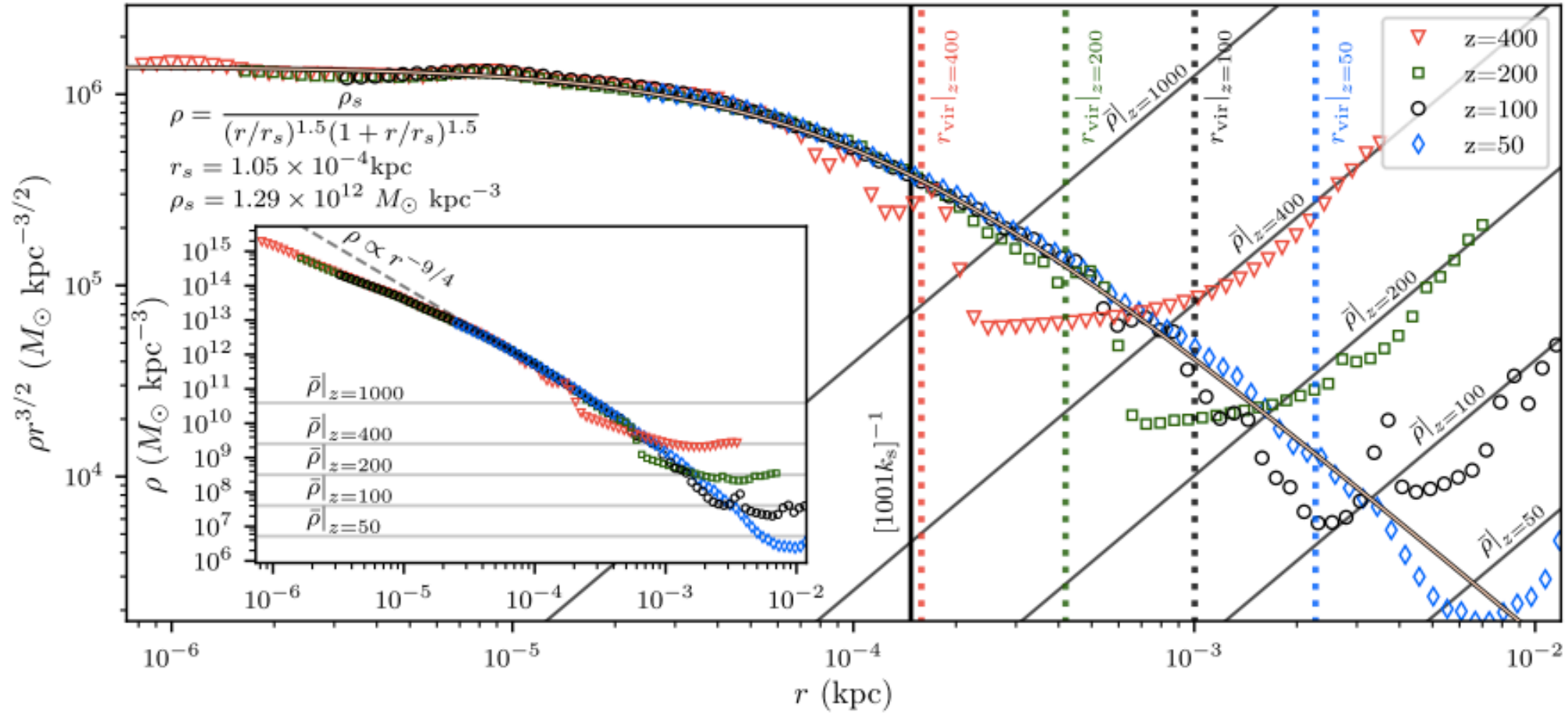
UCMH density profile

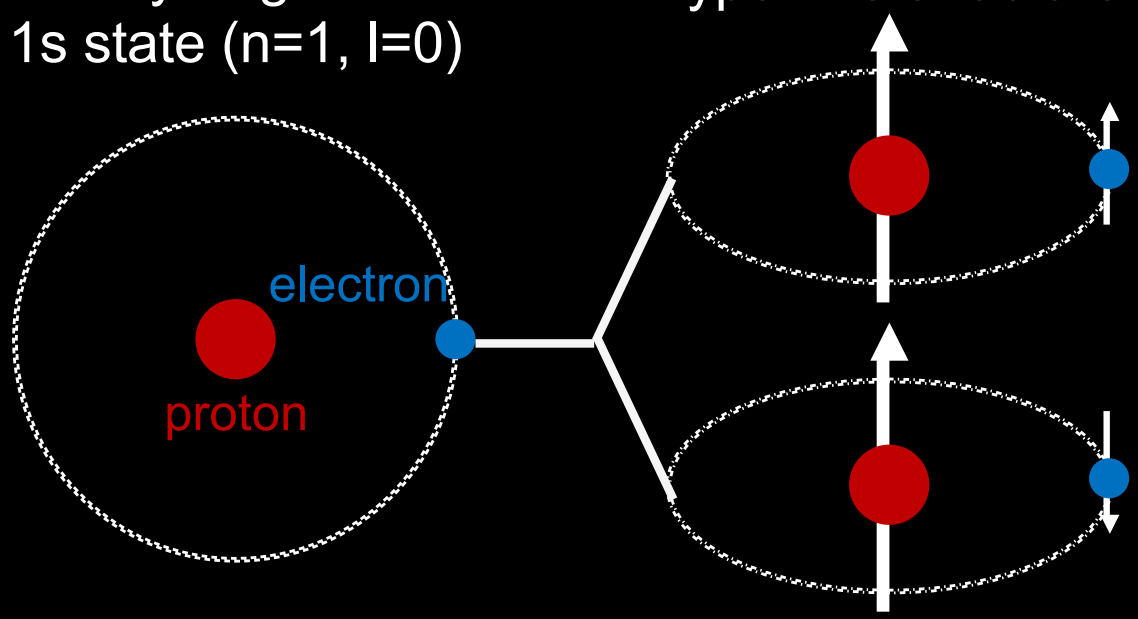


Steeper inner profile than NFW!!! ($\rho \neq r^{-9/4}$)

(Delos et al., 1806.07389)

What is 21-cm line?

EM wave due to neutral hydrogen hyperfine structure



$\Delta E = 5.9\times10^{-6}$ eV,
$\nu \approx 1.4$ GHz, $\lambda \approx 21$ cm

21-cm line

spin temperature $T_{\rm spin}$ ($\neq T_{\rm K}$)

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{\Delta E}{k_{\rm B}T_{\rm spin}}\right)$$

observation of redshifted 21-cm line
=> physical history of HI at the redshift
(matter clustering, IGM thermal history, details of EoR, …)

21-cm global signal

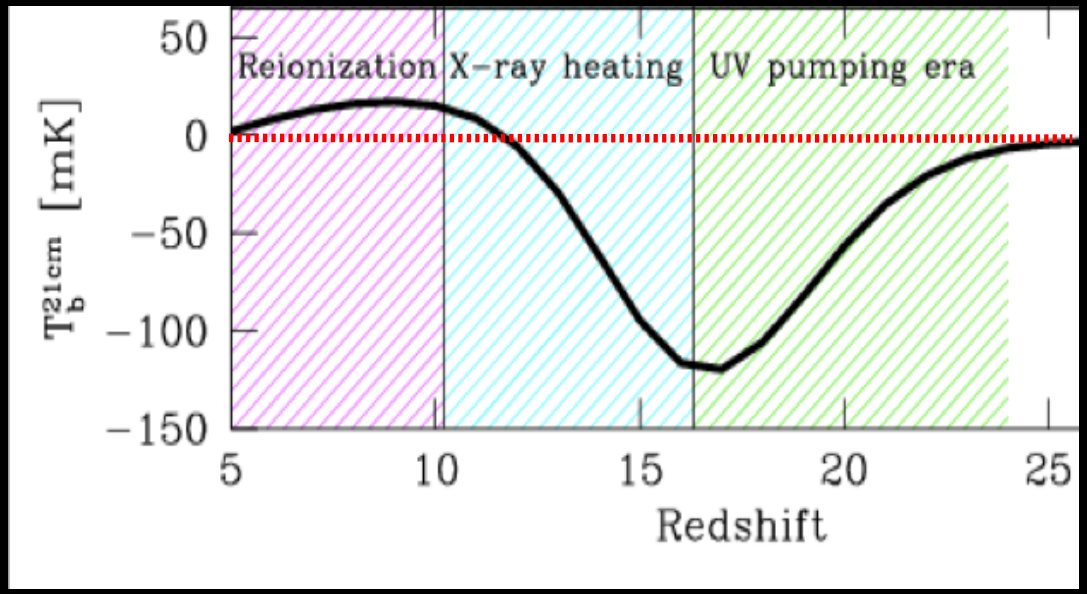
Observable → physical state of HI

Roughly speaking,
emission for

$$T_{\mathrm{K}} \geq T_{\mathrm{spin}} \geq T_{\gamma}\ ,$$

and absorption for

$$T_{\mathrm{K}} \leq T_{\mathrm{spin}} \leq T_{\gamma}$$



Theoretical prediction for 21-cm global signal
McQuinn & O'Leary, 2012 (arXiv:1204.1345)

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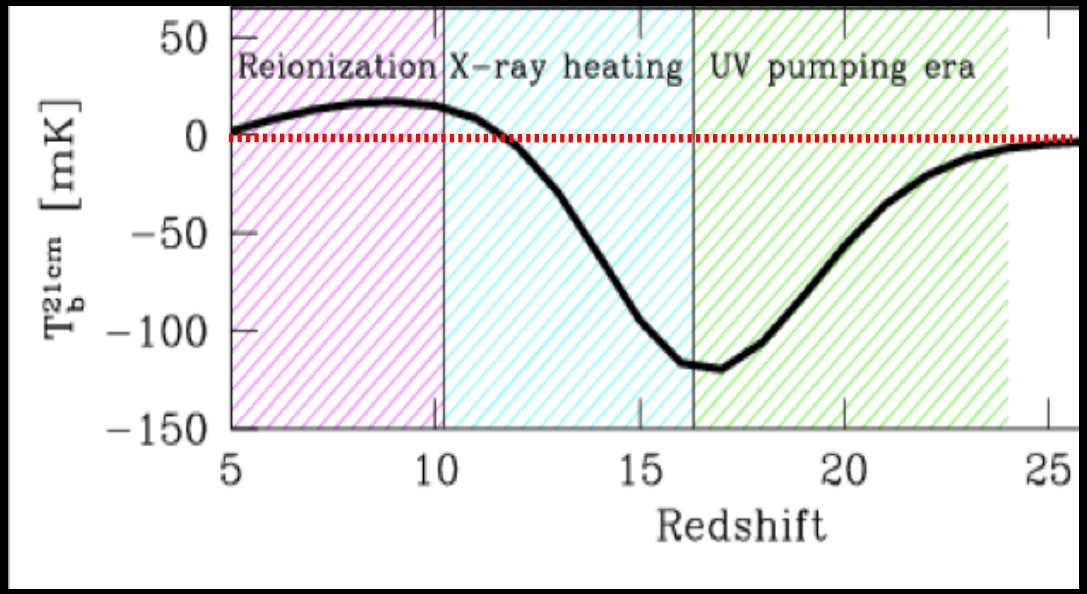

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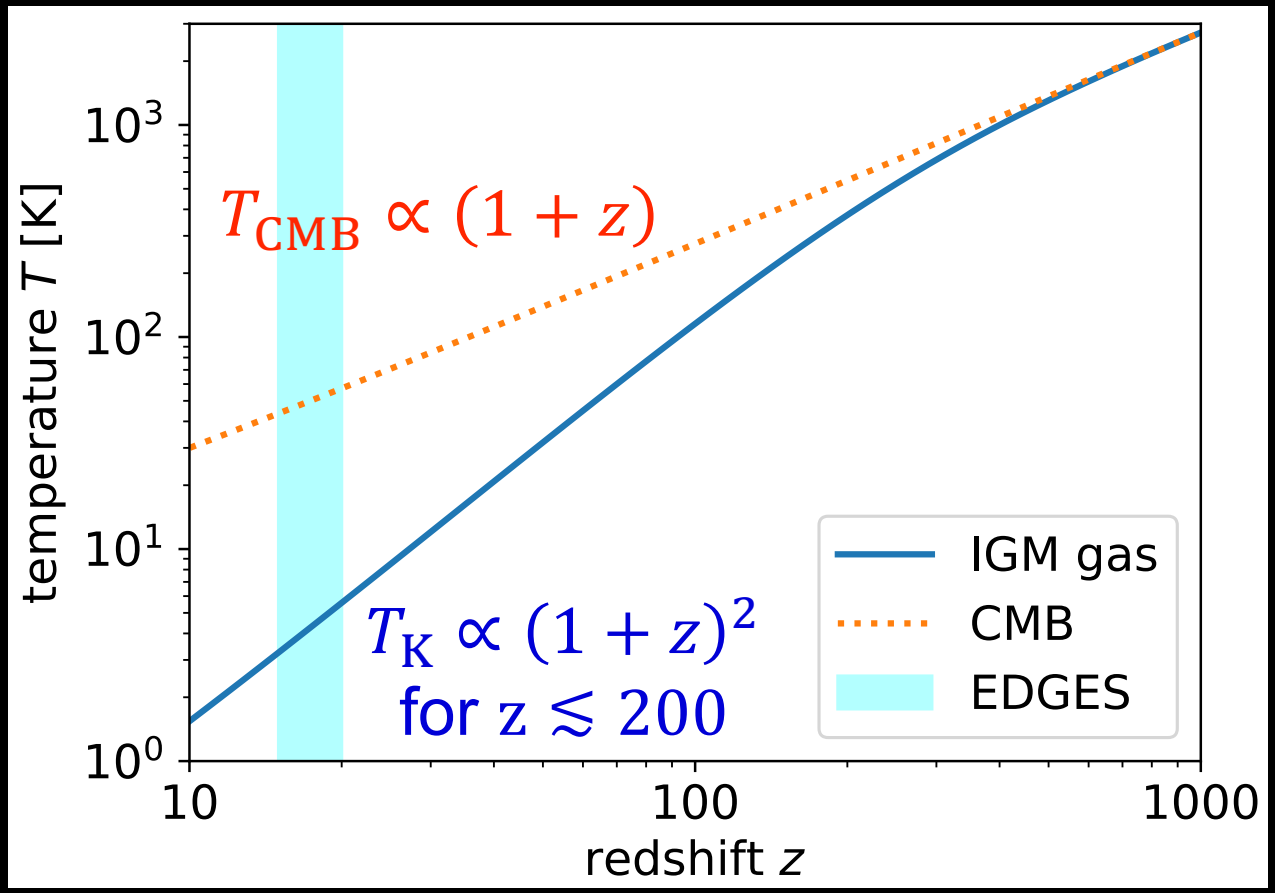
We focus on absorption signal during Dark Age (z~17)

IGM thermal history

Adiabatic calculation => $T_{\rm CMB} > T_{\rm K}$ (absorption) around z~17



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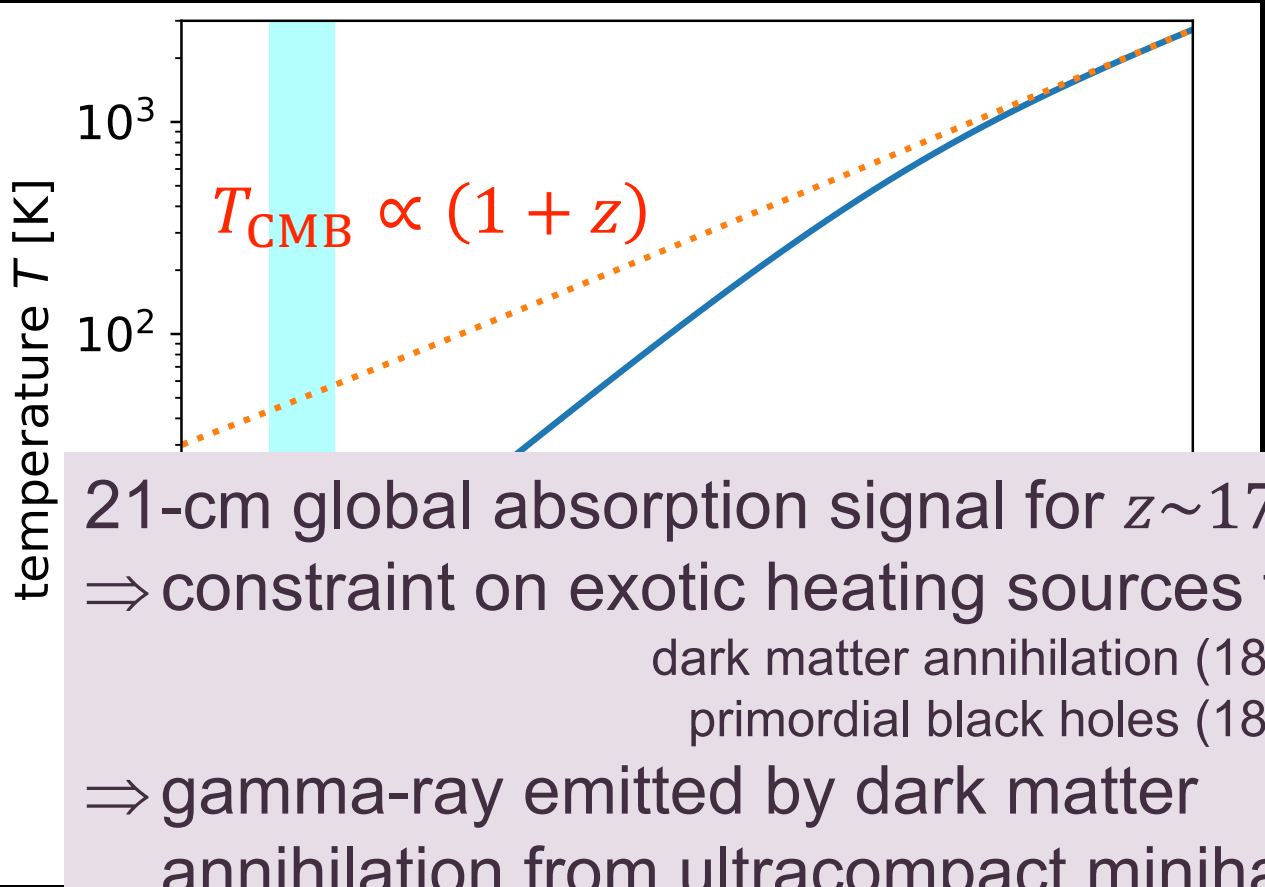


21-cm global absorption signal for z~17

⇒ constraint on exotic heating sources for IGM

dark matter annihilation (1803.03629)

primordial black holes (1803.09390)

⇒ gamma-ray emitted by dark matter annihilation from ultracompact minihalos

Gamma-ray emission due to DM annihilation from UCMH

Gamma-ray luminosity

dark matter mass: $m_x = 1$ (TeV)

annihilation rate: $\langle \sigma v \rangle = 3\times10^{-26}\ (\mathrm{cm}^3/\mathrm{s})$

$$L_{\mathrm{UCMH}} = \int E \frac{dN}{dE} dE \times \int_0^R 4\pi r^2 \frac{\rho^2}{2m_x^2} \langle \sigma v \rangle dr$$

Gamma-ray total energy from one DM annihilation

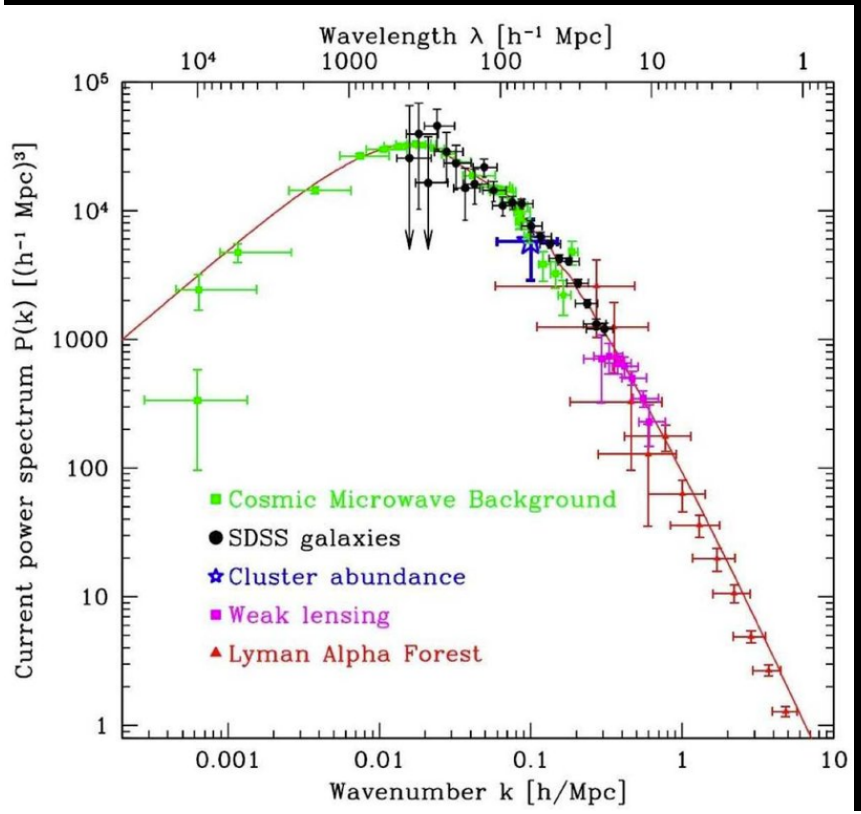
How many DM annihilates inside one UCMH per unit time

UCMH abundance

- UCMH number density from peak theory

$$\frac{dn_{\rm UCMH}}{da} = \frac{k_s^3}{(2\pi)^2 3^{3/2}} \frac{\nu}{a} \mathrm{e}^{-\nu^2} f(\nu)$$

(Bardeen et al., 1986)



peak height: $\nu \equiv \frac{\delta_c}{\sqrt{A_{\rm mat} a}}$

wave-number of spike: k_s

Amplitude of spike: $A_{\rm mat}$

overdensity threshold: $\delta_c = 1.686$

UCMH abundance

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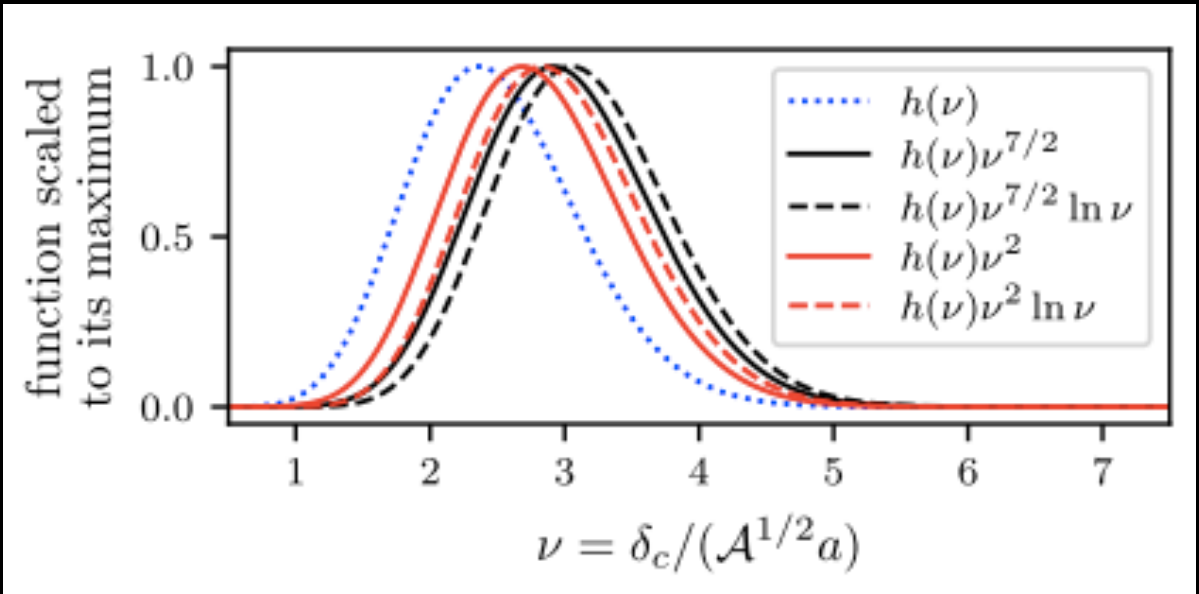


peak height: $\nu \equiv \dfrac{\delta_c}{\sqrt{A_{\rm mat}}a}$

wave-number of spike: k_s

IGM thermal history with UCMH

$$\frac{dT_{\rm gas}}{dt} = \frac{x_e}{1+x_e}\frac{8\rho_{\rm CMB}\sigma_{\rm T}}{3m_e c}\left(T_{\rm CMB} - T_{\rm gas}\right) - 2HT_{\rm gas}$$

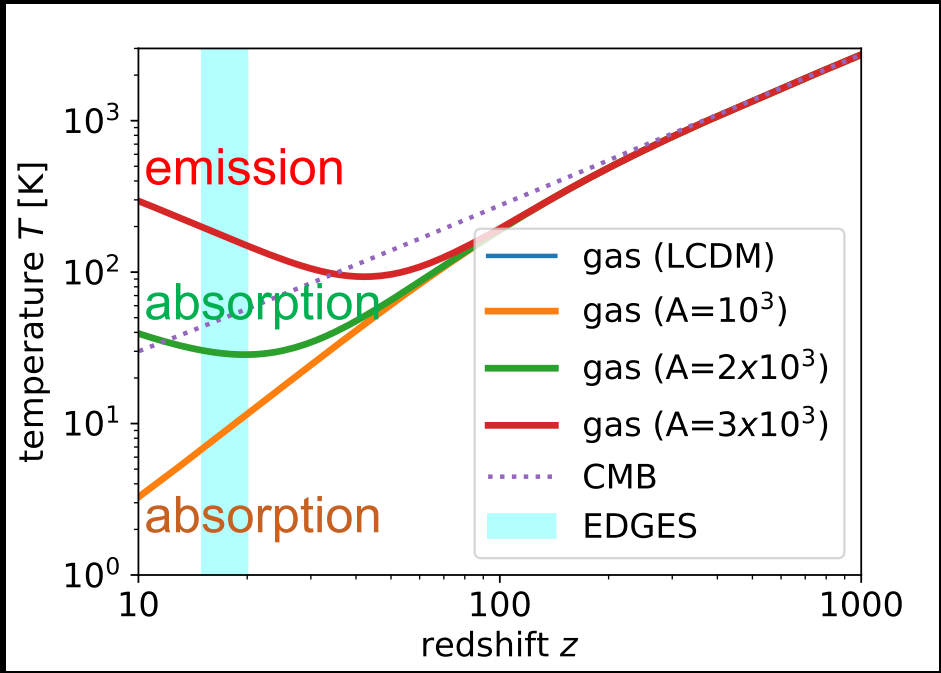
Compton scattering with CMB

cosmic expansion

$$+ \frac{\chi_{\rm heat}}{1.5 n_{\rm b} k_{\rm B}} \int L \frac{dn}{da} da$$

DM annihilation from UCMHs

(+ recombination history)



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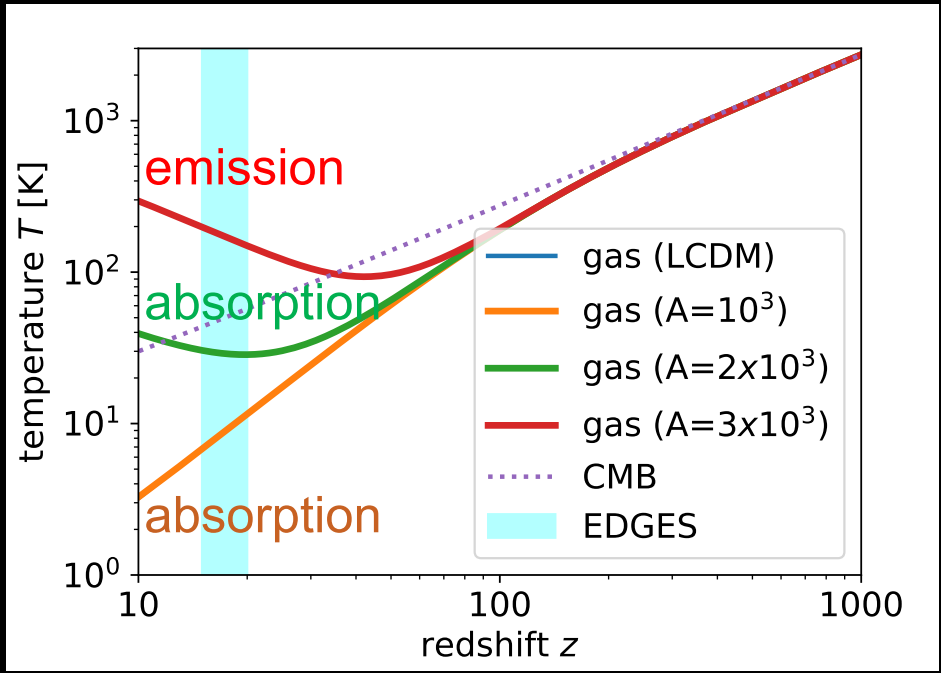
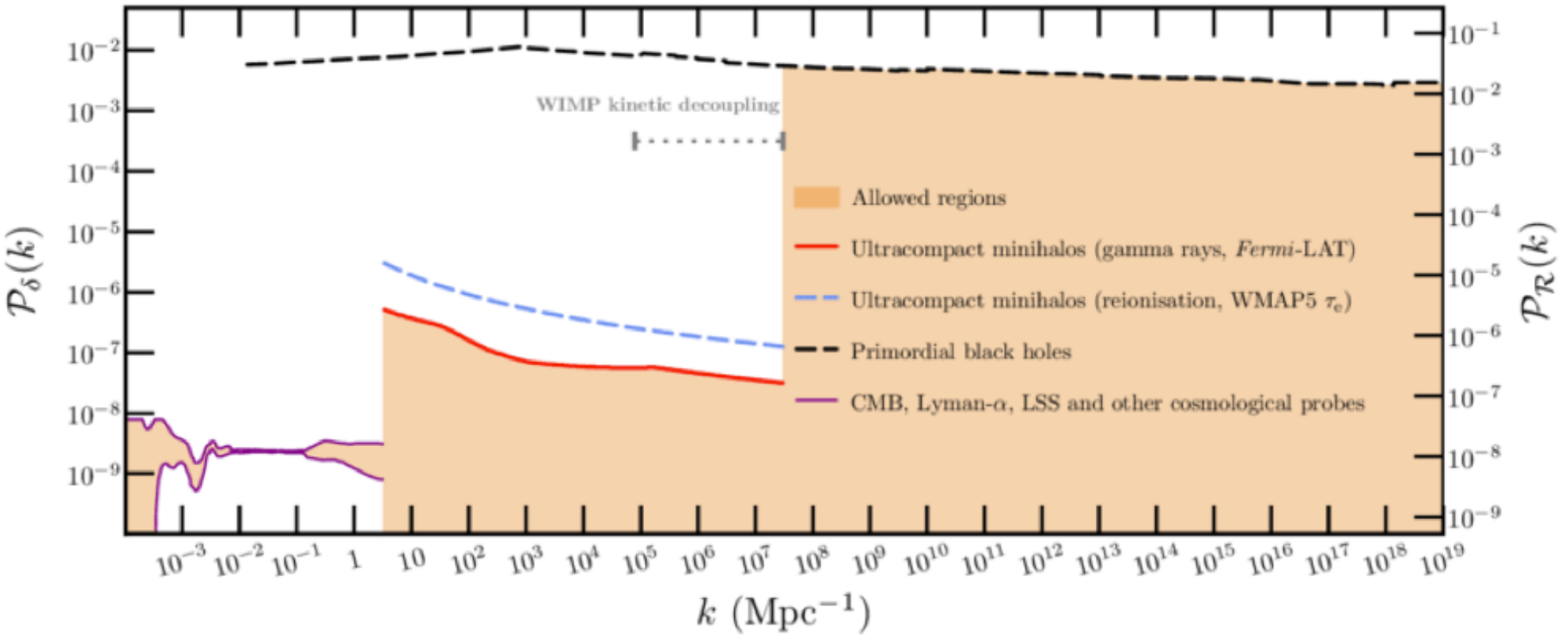
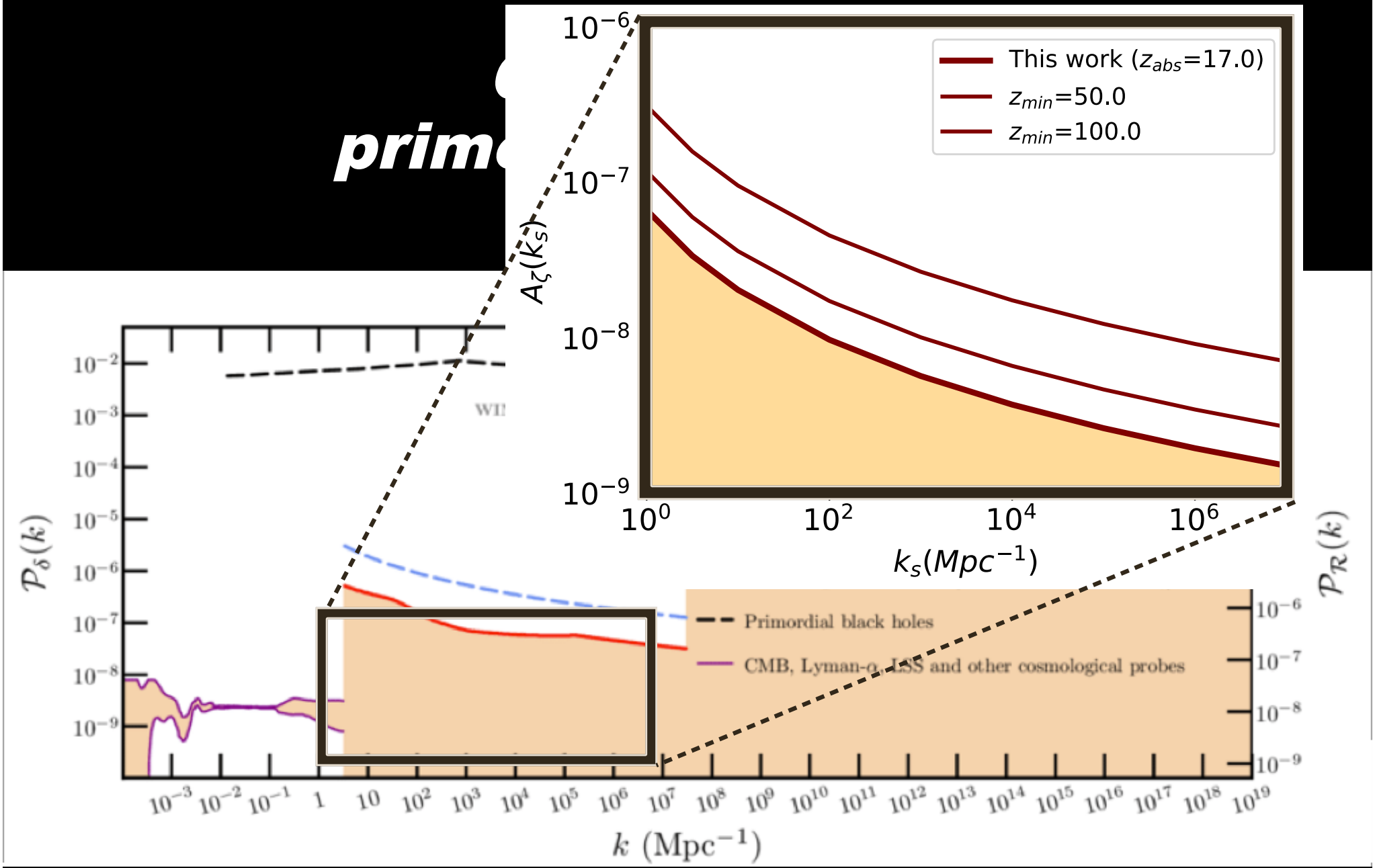


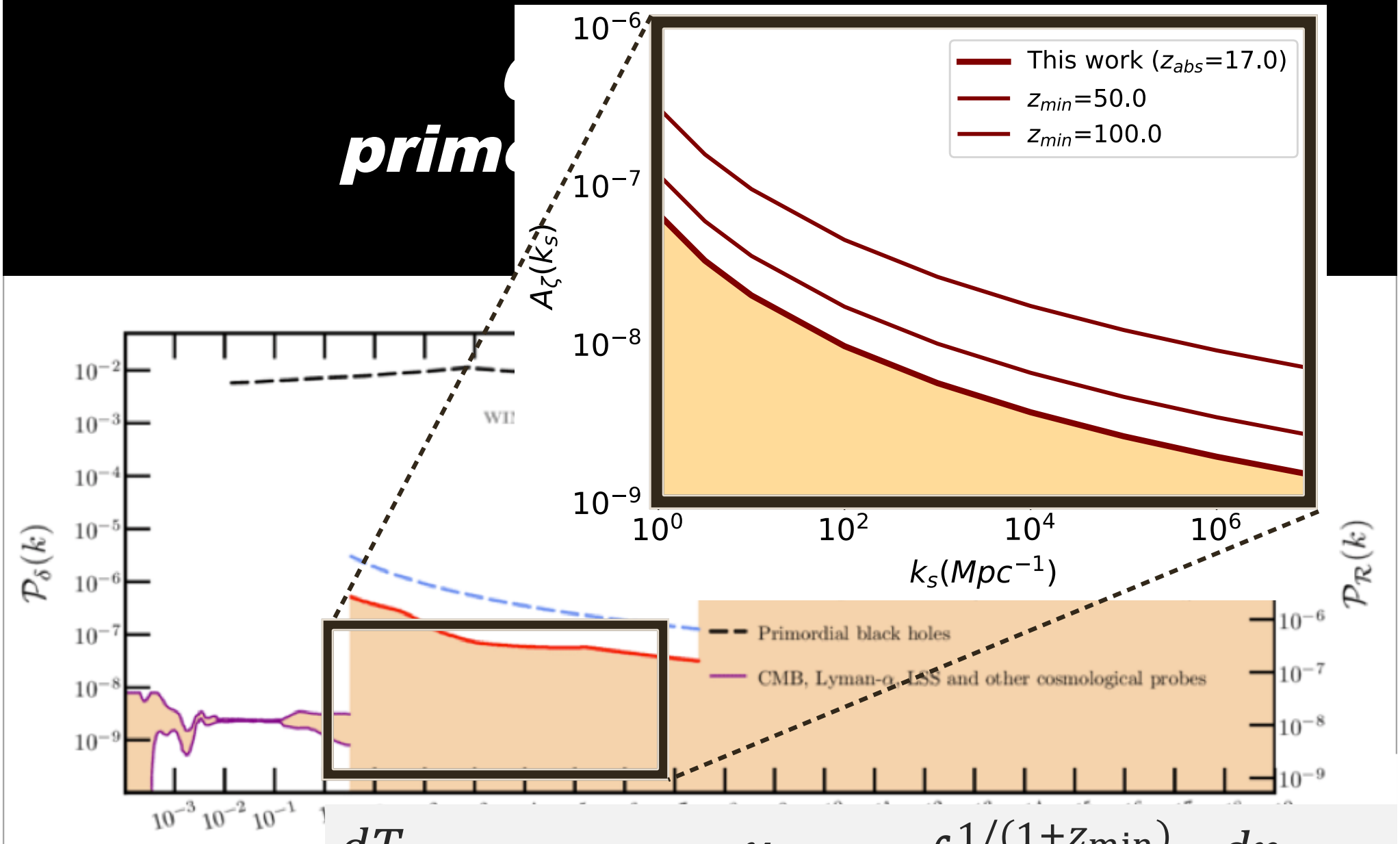
absorption signal for $z\sim17$
$\Rightarrow A_{\rm mat} \lesssim 2.3\times10^3$

Current constraints on primordial power spectrum




This work (z_{abs}=17.0)
z_{min}=50.0
z_{min}=100.0
$A_\zeta(k_s)$
$k_s(Mpc^{-1})$
$\mathcal{P}_\delta(k)$
$\mathcal{P}_\mathcal{R}(k)$
Primordial black holes
CMB, Lyman-α, LSS and other cosmological probes
k (Mpc^{-1})

prim



$$\frac{dT_{\rm gas}}{dt} = (\ldots) + \frac{\chi_{\rm heat}}{1.5 n_{\rm b} k_{\rm B}} \int_0^{1/(1+z_{\rm min})} L \frac{dn}{da} da$$

Summary

- ✓ Constrained primordial power spectrum on small-scales from 21-cm global absorption signal
- ✓ Calculated IGM thermal history during Dark Ages with DM annihilation from UCMHs
- ✓ absorption signal at redshift $z \sim 17$

=> $P_\zeta < 10^{-7}$ at $k_s < 10^0$ Mpc^{-1} ,

$P_\zeta < 10^{-9}$ at $k_s < 10^7$ Mpc^{-1} .