EDGES of the dark forest

A new absorption window into the composite dark matter and large scale structure (arXiv: 2301.03624)

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EDGES of the dark forest

- Absorption signatures of dark matter is a promising and less-studied territory

- A huge parameter space is waiting to be explored!

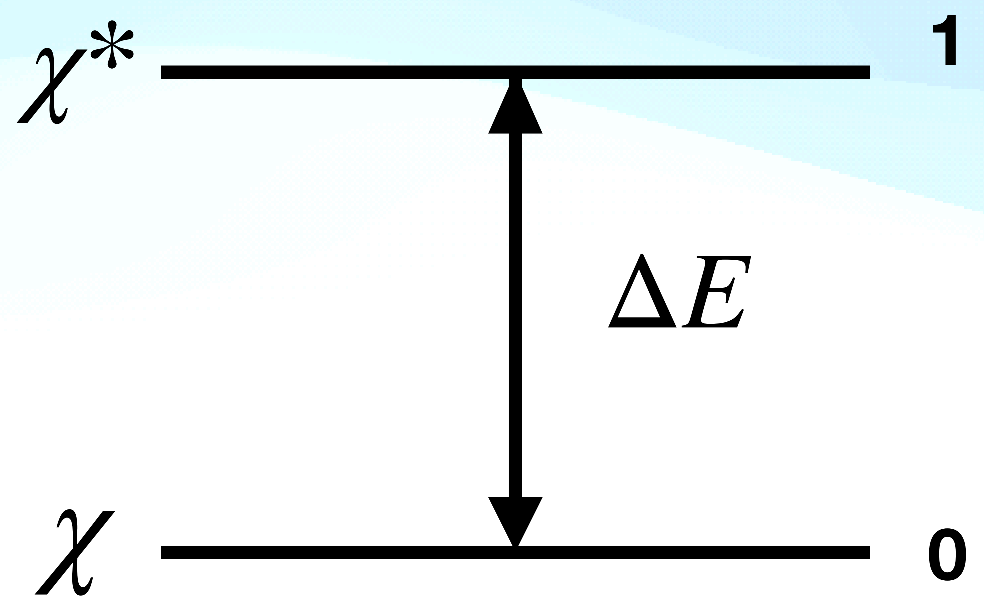
Dark matter as a 2-level system

- **Energy splitting**

$$\Delta E = h\nu_0 = k_B T_\star$$

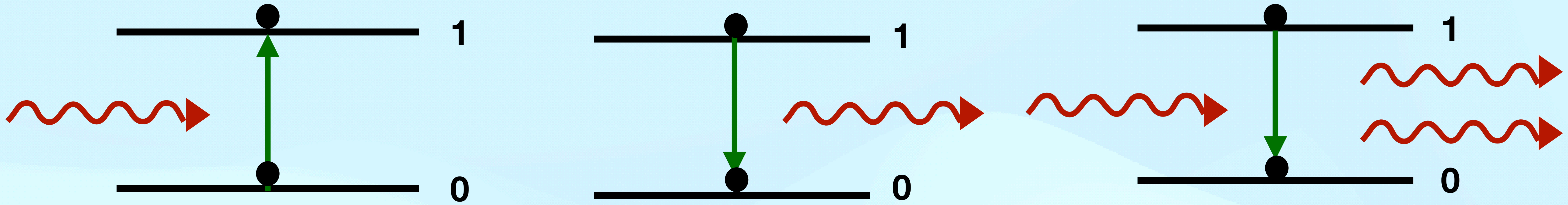
- **Excitation temperature** $\left(T_{ex}\right)$ **characterises the DM population in two states**

$$\frac{n_0}{n_1} \equiv \frac{g_0}{g_1} \exp\left(\frac{T_\star}{T_{ex}}\right)$$



Transitions in 2-state dark matter

1. Electromagnetic Transitions

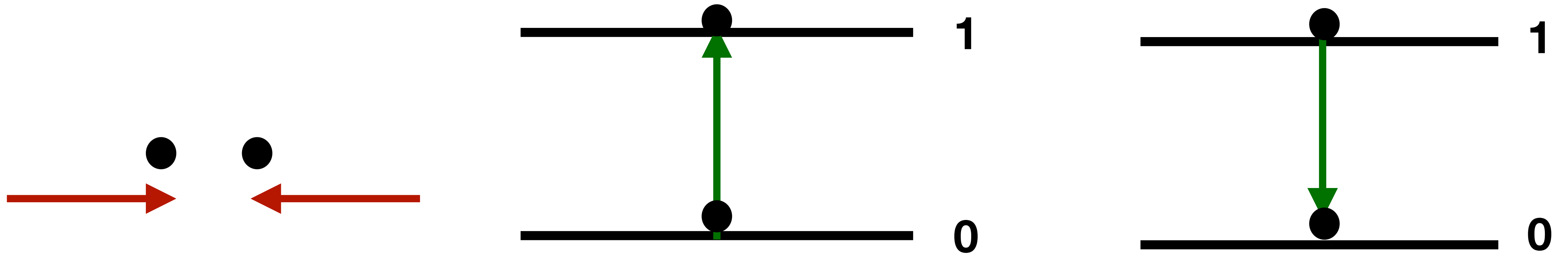


Absorption — $n_0 B_{01} \bar{J}$

Spontaneous Emission — $n_1 A_{10}$

Stimulated Emission — $n_1 B_{10} \bar{J}$

2. Collisional transitions



Excitation — $n_0 C_{01}$

De-excitation — $n_1 C_{10}$

Global absorption feature due to DM in the CMB spectrum

CMB

$T_{ex} \rightarrow T_{CMB}$

Radiative transitions

DM Transitions

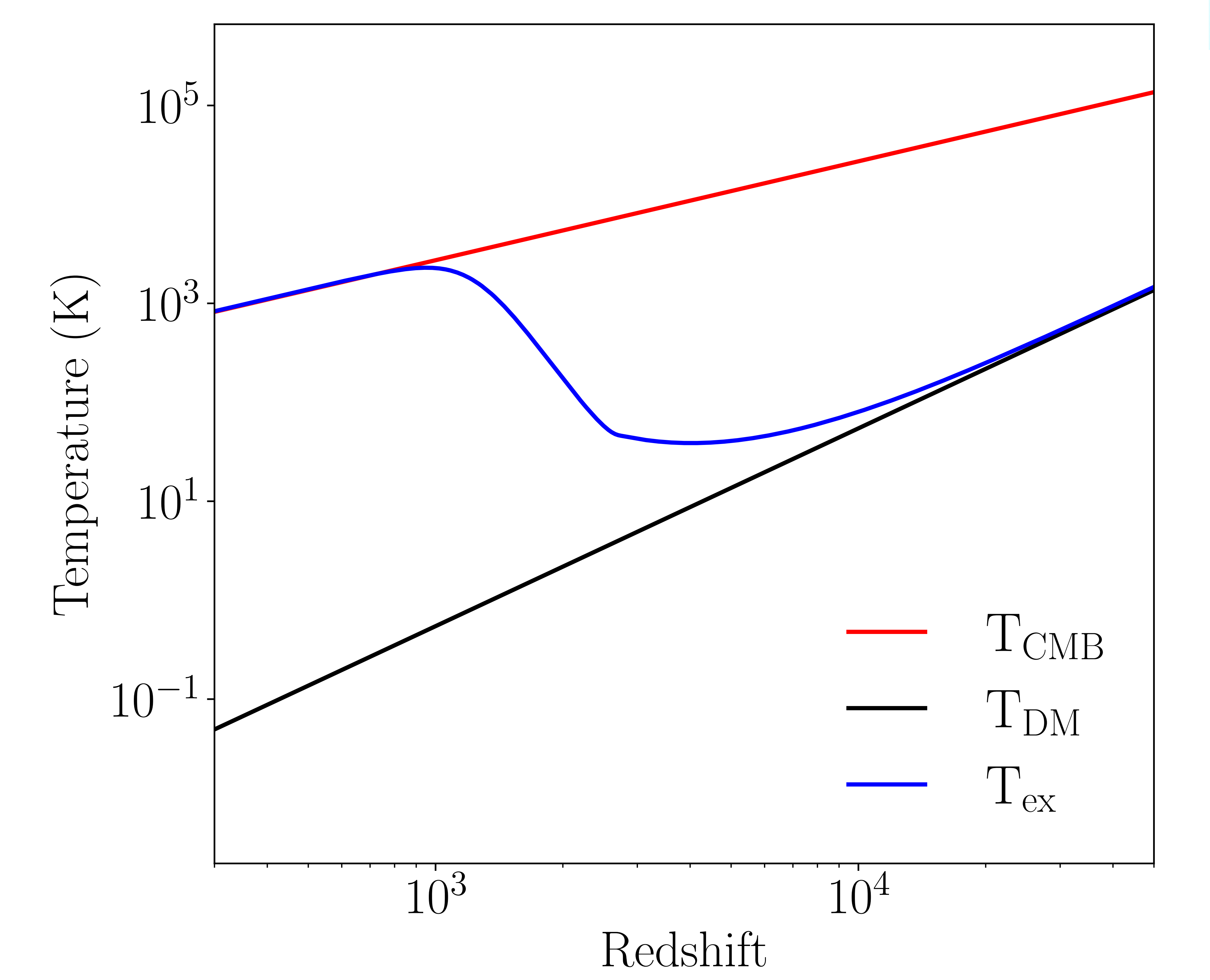
$T_{ex} \rightarrow T_{\chi}$

Collisional transitions

$C_{01} \propto T_{DM}^{\beta}$

Dark Matter

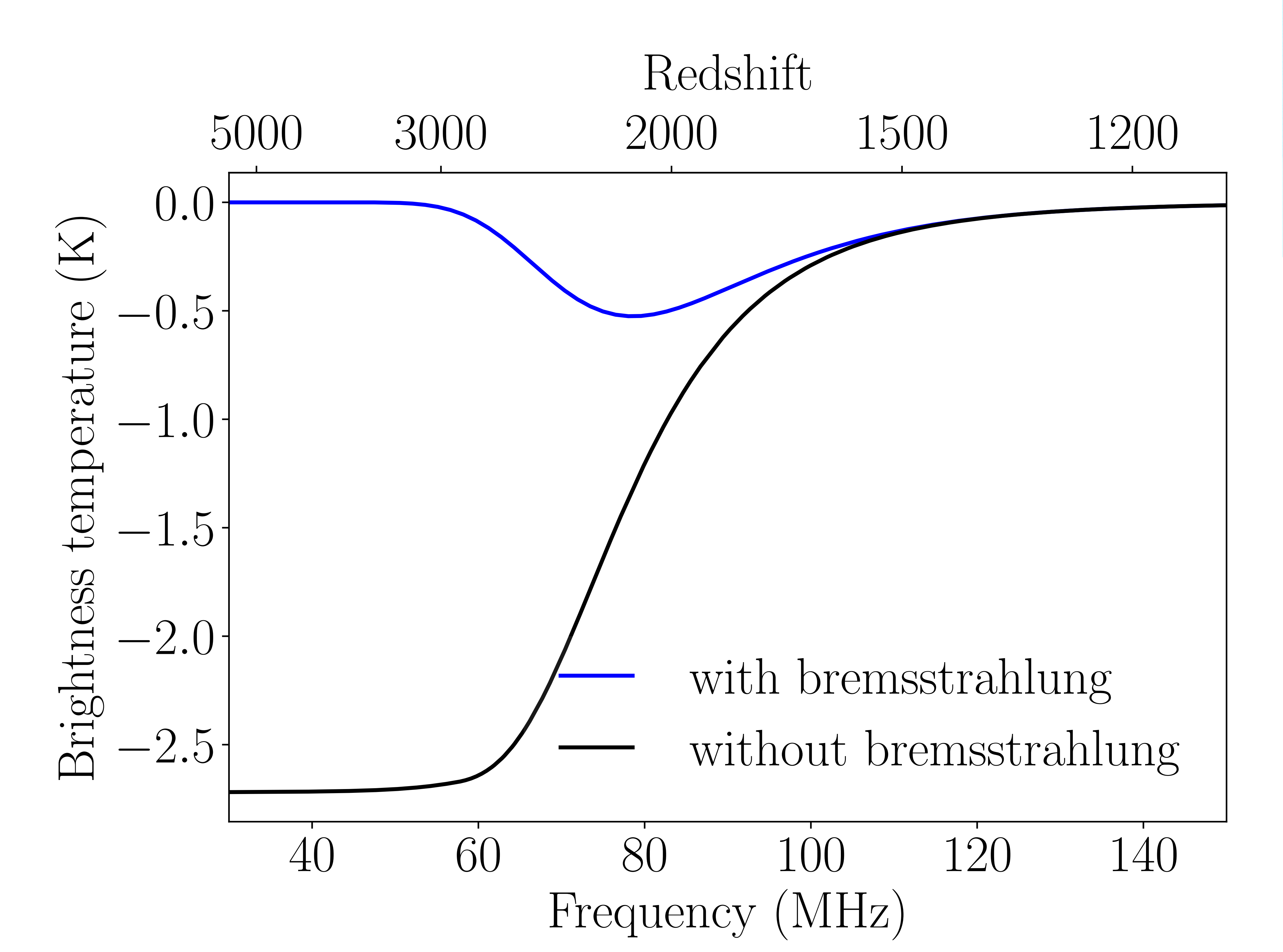
- At high redshifts, collisions dominate and absorption begins
- As DM number density falls, radiative transitions take over and the absorption signal vanishes



Bremsstrahlung decides the high redshift shape of the absorption feature

- Prior to recombination, bremsstrahlung is important in establishing a black body spectrum at low frequencies

- It brings the CMB temperature in equilibrium with the baryonic temperature



Global absorption feature gets contribution from dark matter + bremsstrahlung

- **Specific intensity into brightness temperature**

$$T_b = \frac{c^2}{2\nu^2 k_B} I_\nu$$

$$\frac{dT_b(\nu)}{dz} - \frac{T_b(\nu)}{1+z} = \frac{d\tau_\chi}{dz}\left(-T_b(\nu) + \frac{h\nu}{k_B}\frac{1}{(e^{h\nu/k_B T_{ex}(z)} - 1)}\right) + \frac{d\tau_{br}(x)}{dz}\left(-T_b(\nu) + T_g\right)$$

Redshifting — **DM transitions** — **Bremsstrahlung**

No approximation made between $T_\star, T_{ex}$ and T_{CMB}

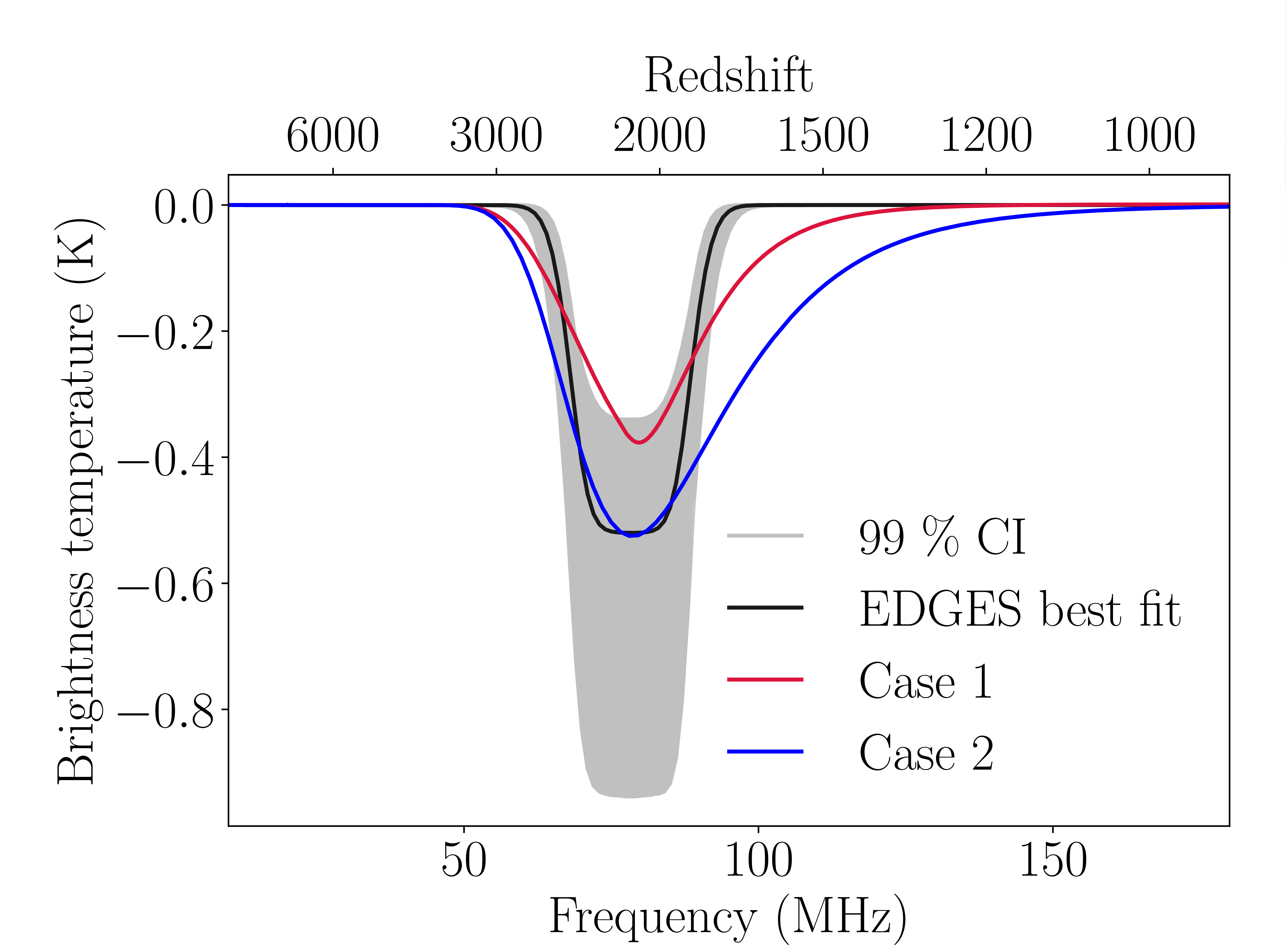
New term not present in the standard 21 cm cosmology

EDGES anomaly: absorption signature of dark matter in the CMB

- **DM transition frequency** $\nu_0 = 100 \times \nu_{21}$ **as absorption happens at z ~ 2000**

Model parameters

- m_χ = 1 MeV
- ν_0 = 156 GHz
- $A_{10} = \alpha_A A_{10}^{HI}$, α_A = 0.35
- $C_{10} \propto T_\chi^\beta$, β = 2, 4



Global absorption feature is sensitive to dark matter self-interactions

Absorption of background photons by a halo

- **Absorption is quantified in terms of optical depth**

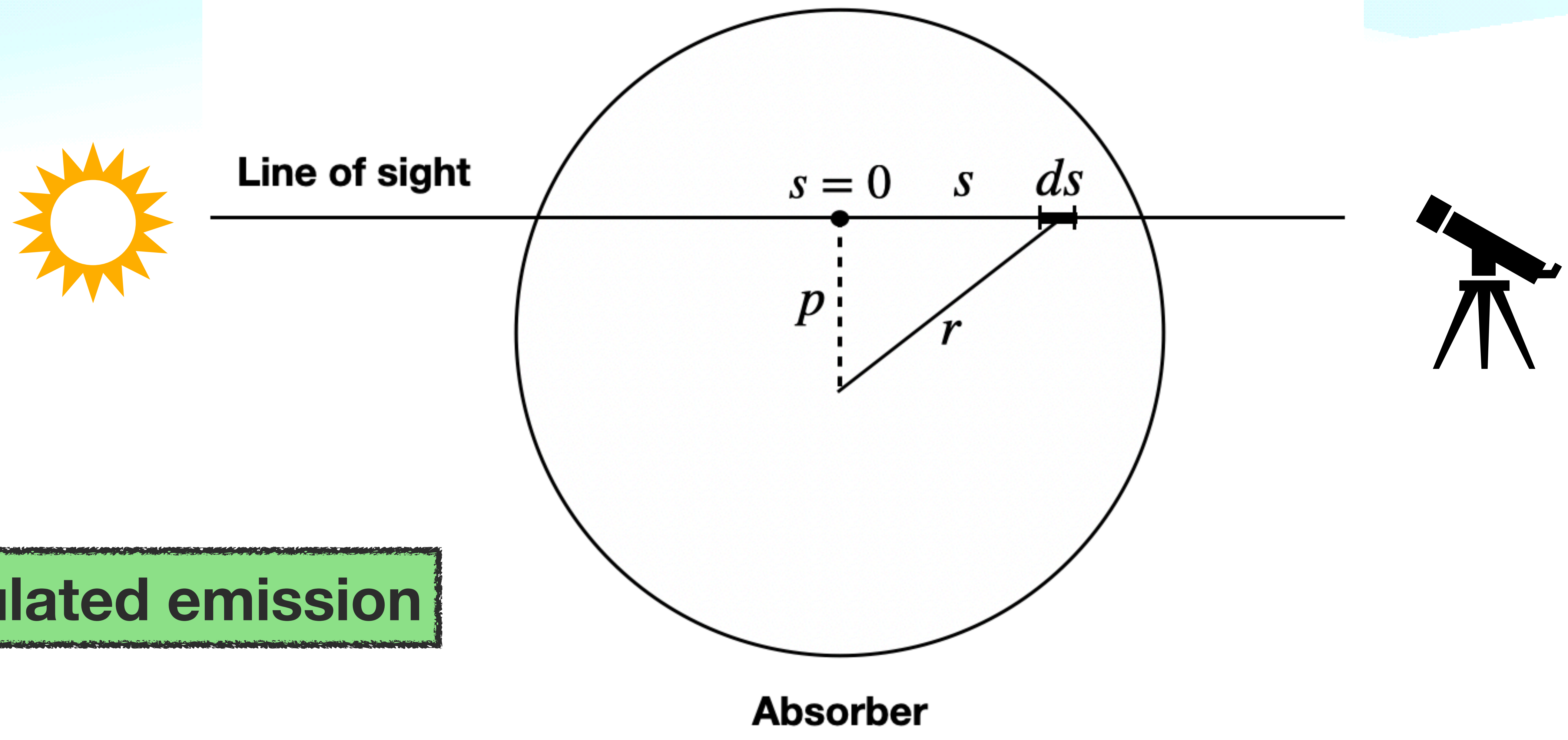
$$F_\nu = F_\nu^0 \exp(-\tau_\nu)$$

- **Optical depth :**

$$\tau_\nu(p) = \int ds \, \frac{h\nu_0}{4\pi} \phi_\nu \left(n_0 B_{01} - n_1 B_{10}\right)$$

Doppler line profile (ϕ_ν)

Absorption - Stimulated emission ($n_0 B_{01} - n_1 B_{10}$)



Absorption by a background photons by a halo

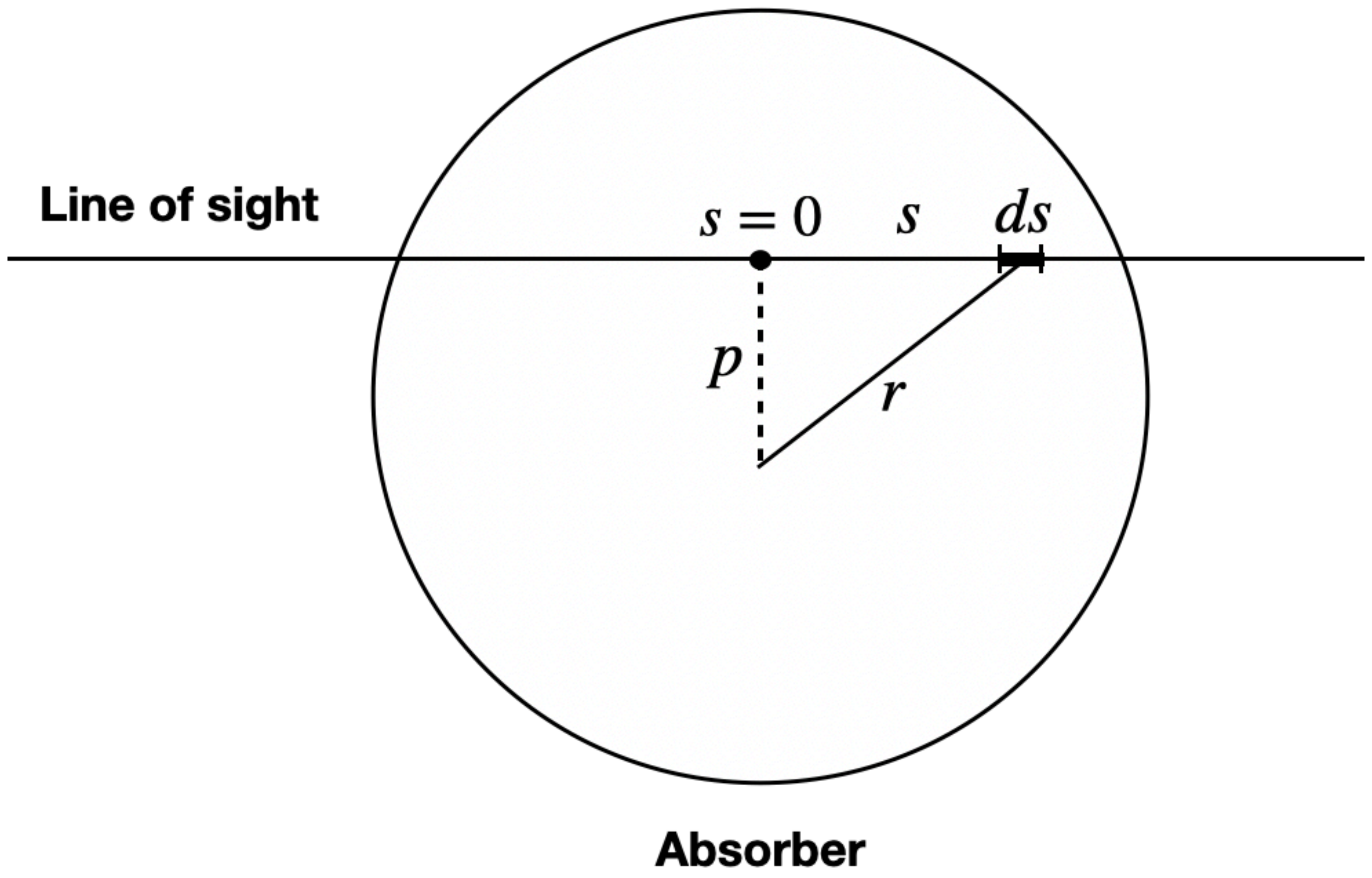
- **Optical depth :**

$$\tau_\nu(p) = \int ds\, \frac{g_1}{g_0} \frac{A_{10} c^2}{8\pi\nu_0^2} \frac{\rho_{DM}}{m_\chi} \phi_\nu \left(\frac{1 - e^{-T_\star/T_{ex}}}{1 + (g_1/g_0)\, e^{-T_\star/T_{ex}}} \right)$$

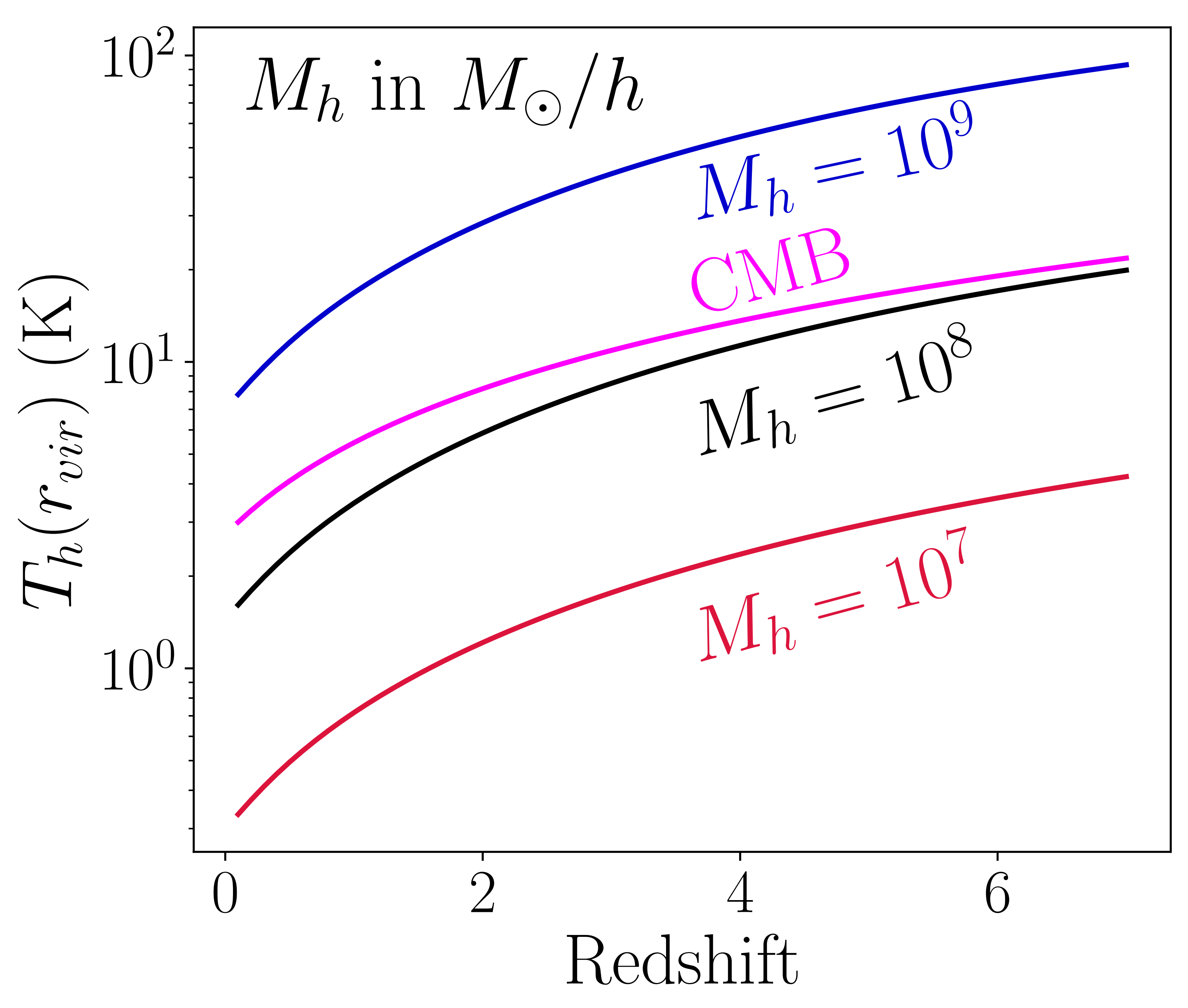
- **Doppler line profile is decided by the halo temperature**

- **Two extreme cases for DM self-interactions:**

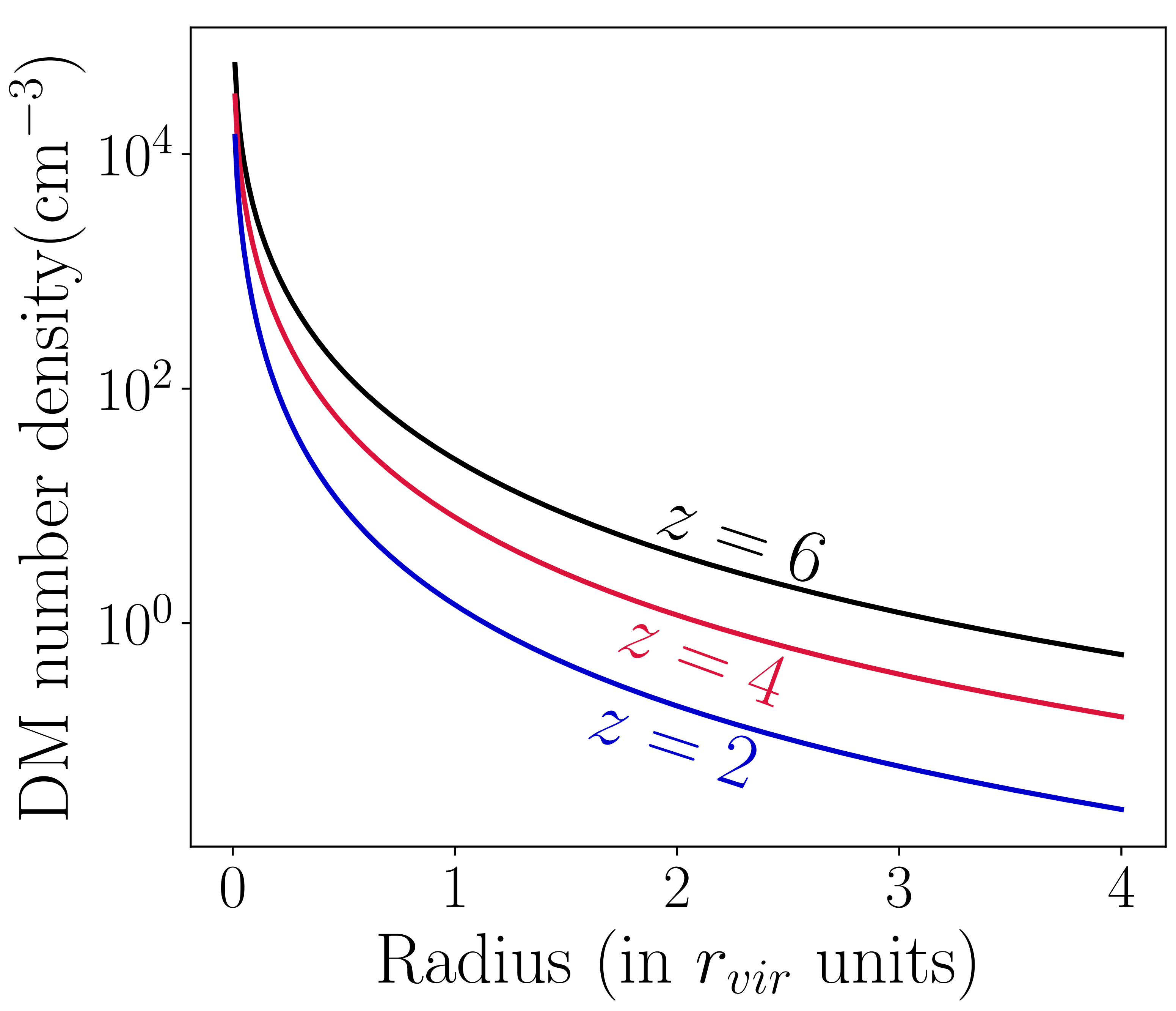
  1. **Collisionless :** $T_{ex} = T_{CMB}$
  2. **Collisional :** $T_{ex} = T_{halo}$



Properties of the halo decide the shape of the absorption line



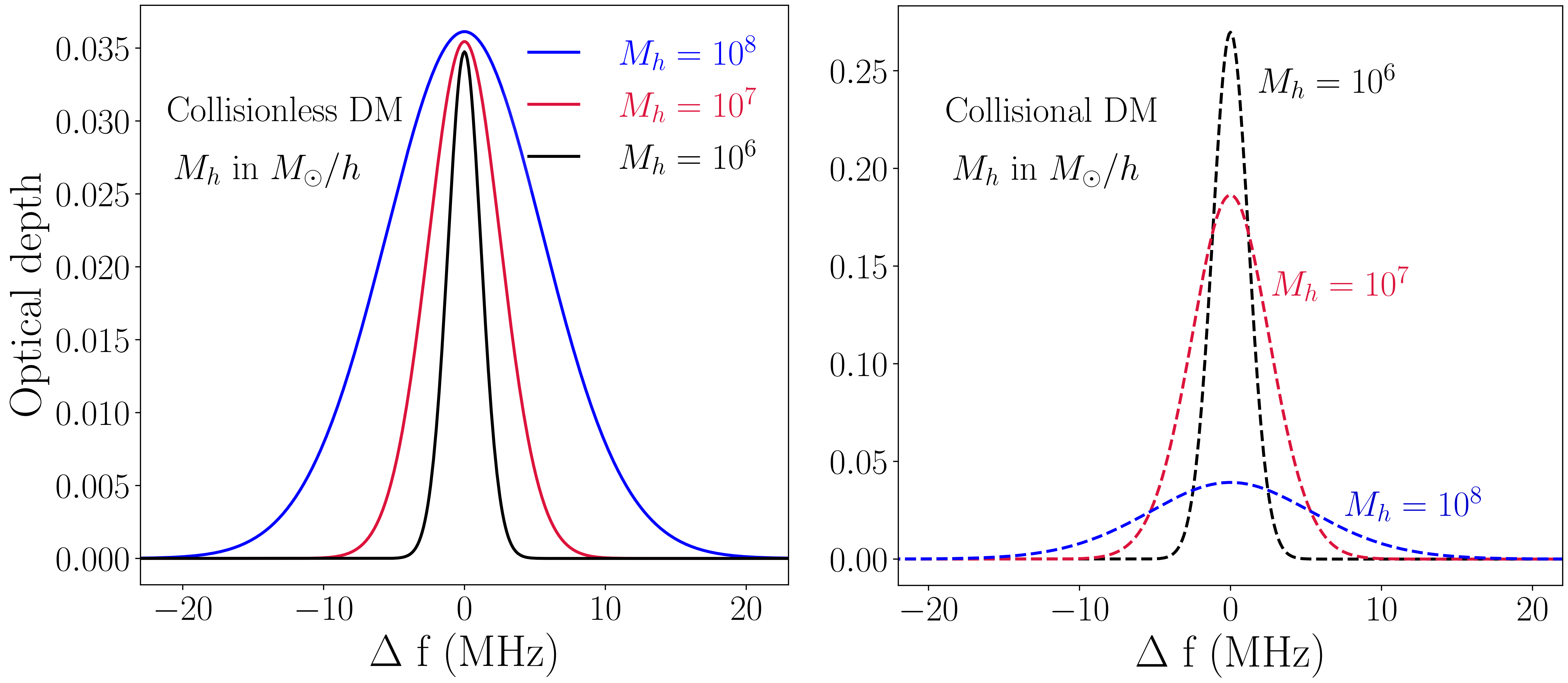
For halo masses > $10^8 M_\odot/h$,
$T_{CMB} > T_{halo}$



Dark matter number density increases with redshift

Dark line is extremely sensitive to dark matter self-interactions

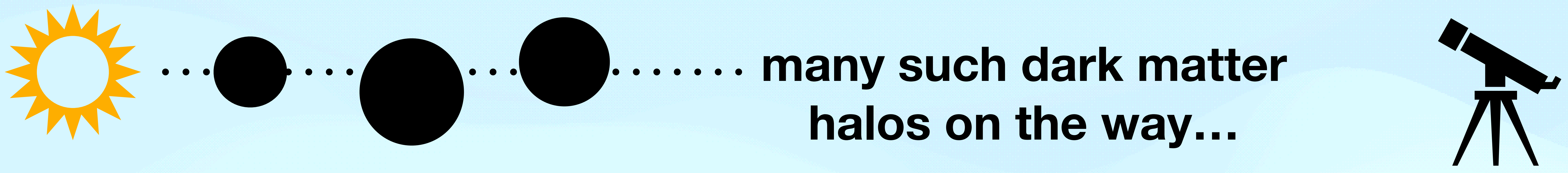
- **Amplitude** of the line is decided by $T_{\rm ex}$
- **Width** of the line is decided by $T_{\rm h}$
- **Collisional DM** has **stronger absorption** compared to **collision less DM**

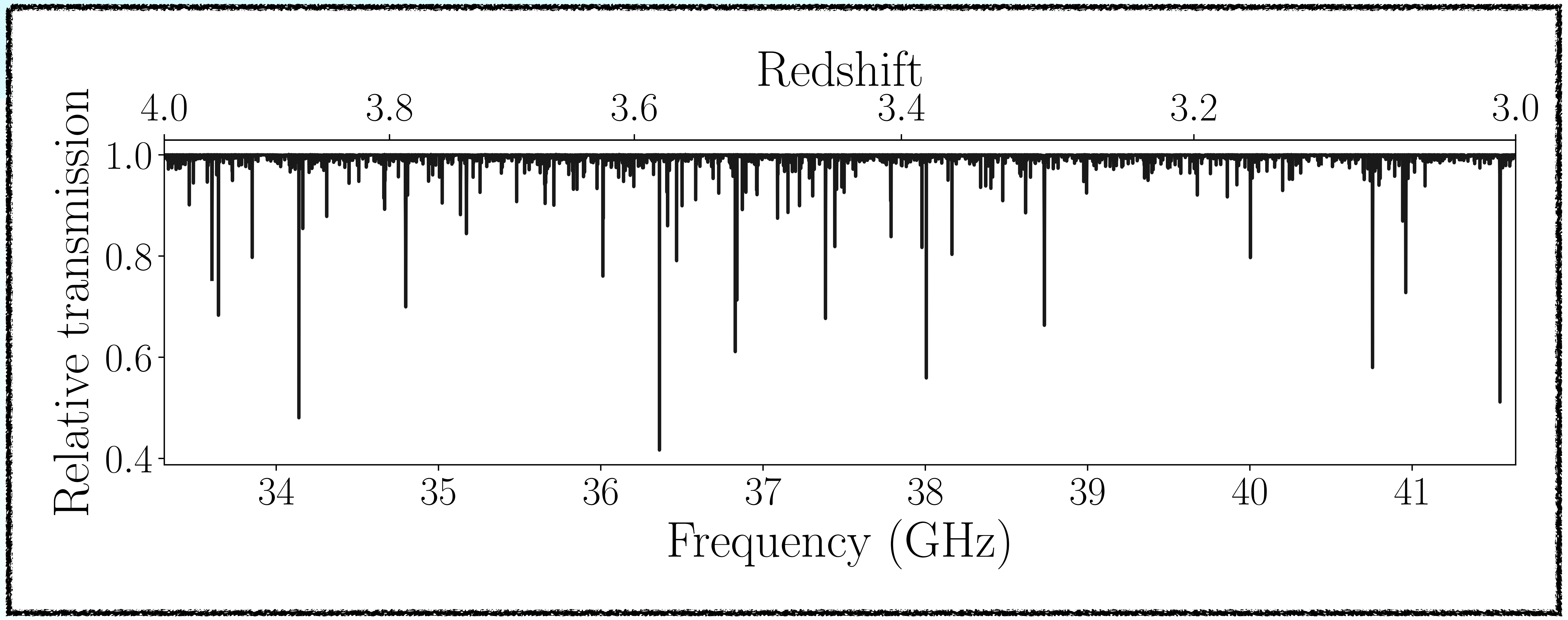


Redshift z = 5

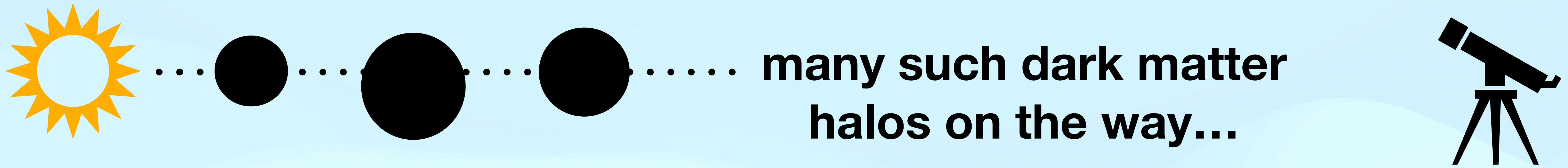
Impact parameter : 0.5 r_{vir}

Dark forest - absorption by multiple dark matter halos





Dark forest - absorption by multiple dark matter halos

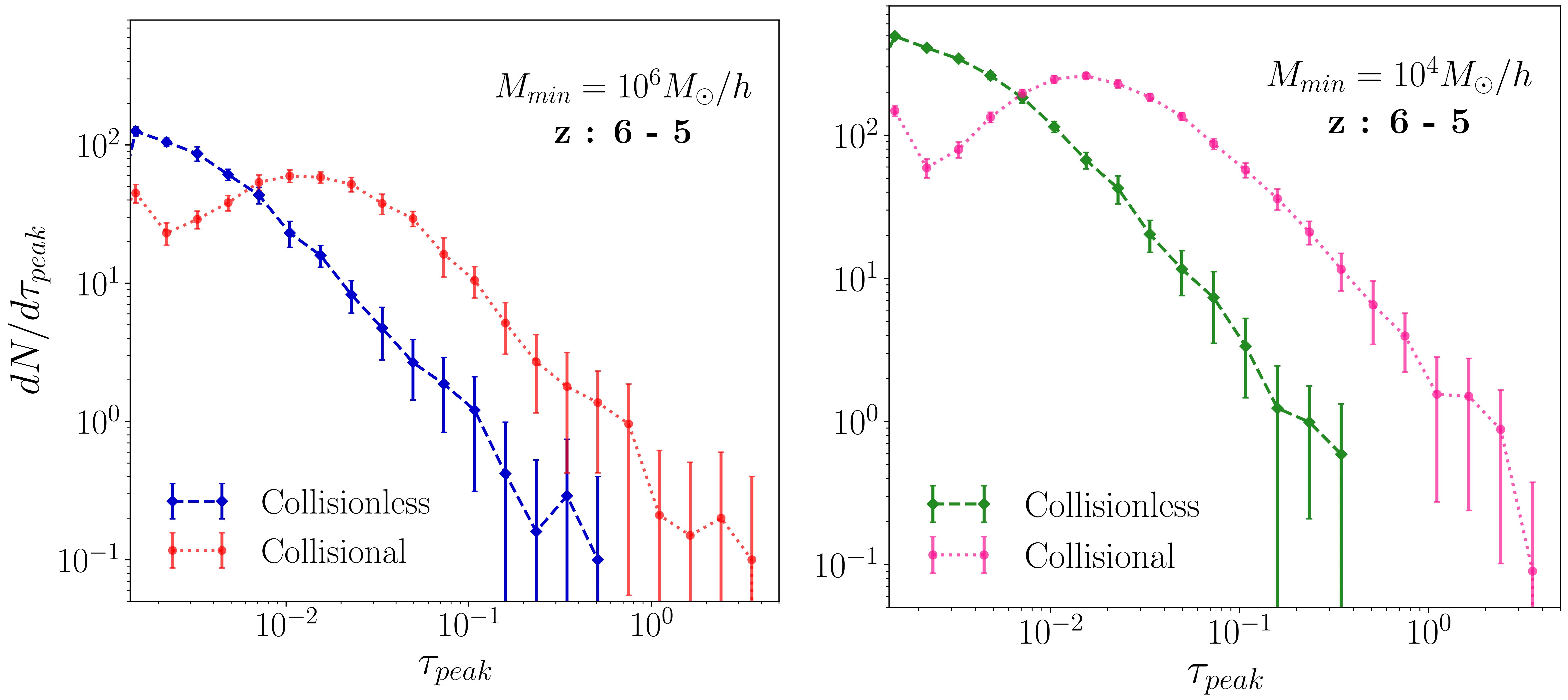


- Probability of intersecting a halo = fraction of the total area occupied by the halo
- Randomly sample halo masses
- Randomly impact parameter from uniform probability over the cross-sectional area

Furlanetto & Loeb 2002, Xu et al. 2011

Absorption amplitude is sensitive to dark matter self-interactions

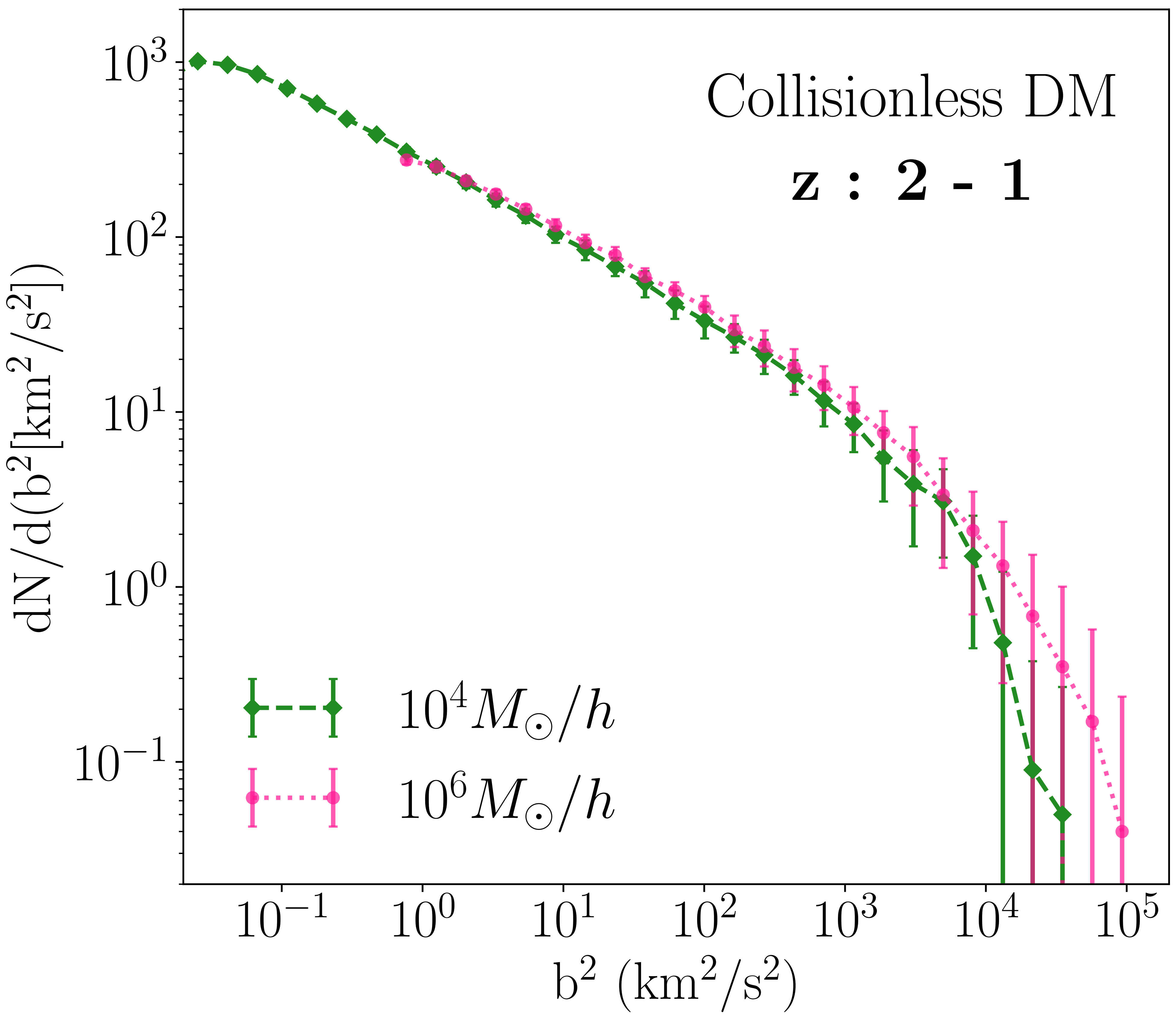
- **Collisional DM** has **stronger absorption** compared to **collisionless DM**
- **Number of halos intersected increases as we decrease the minimum halo mass**



Distribution function for optical depth peaks

Line width is sensitive to the low mass end of the halo mass function

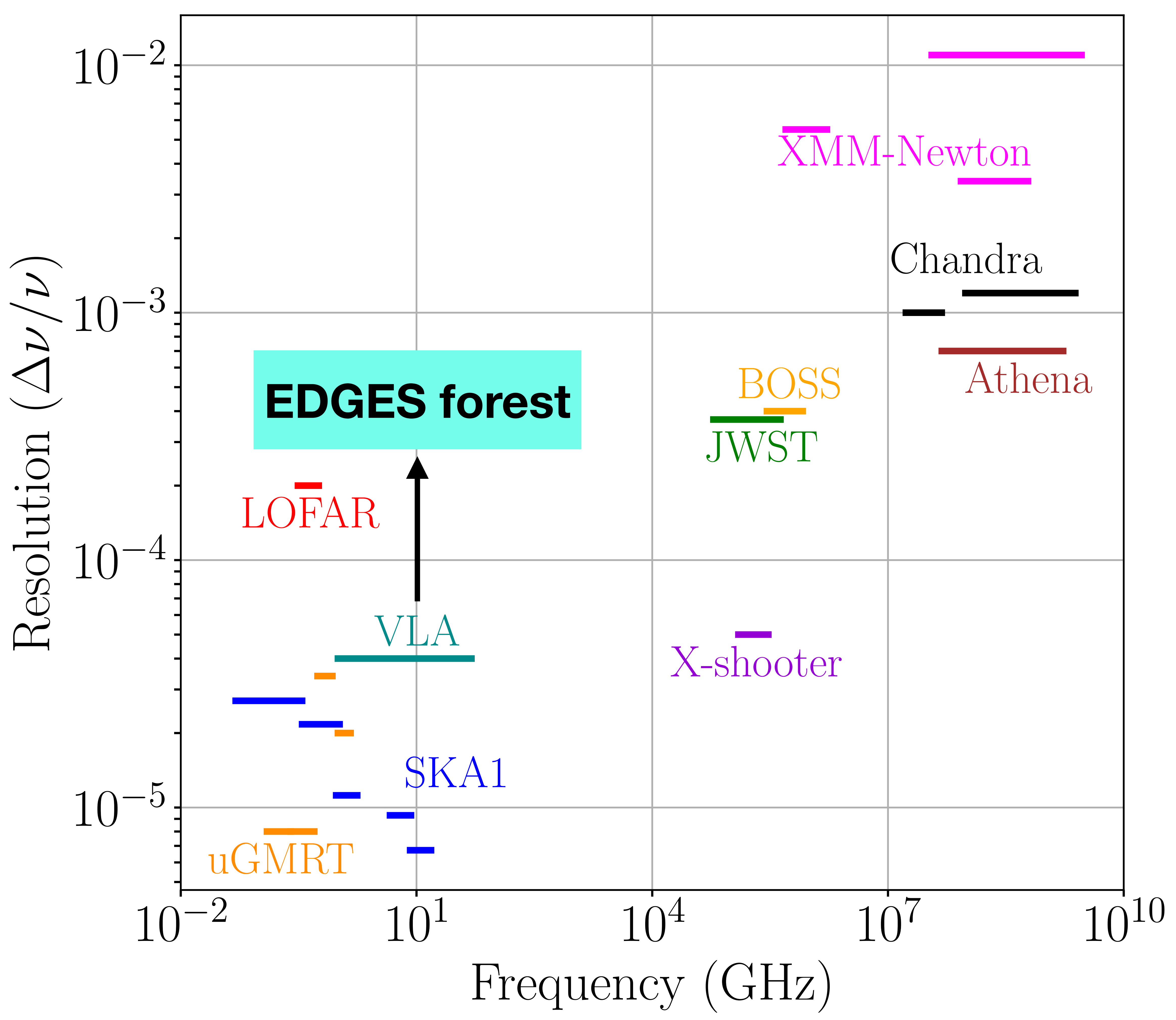
- Low mass halos give narrow lines in the dark forest
- Line width is independent of DM self interactions



Distribution function for line widths

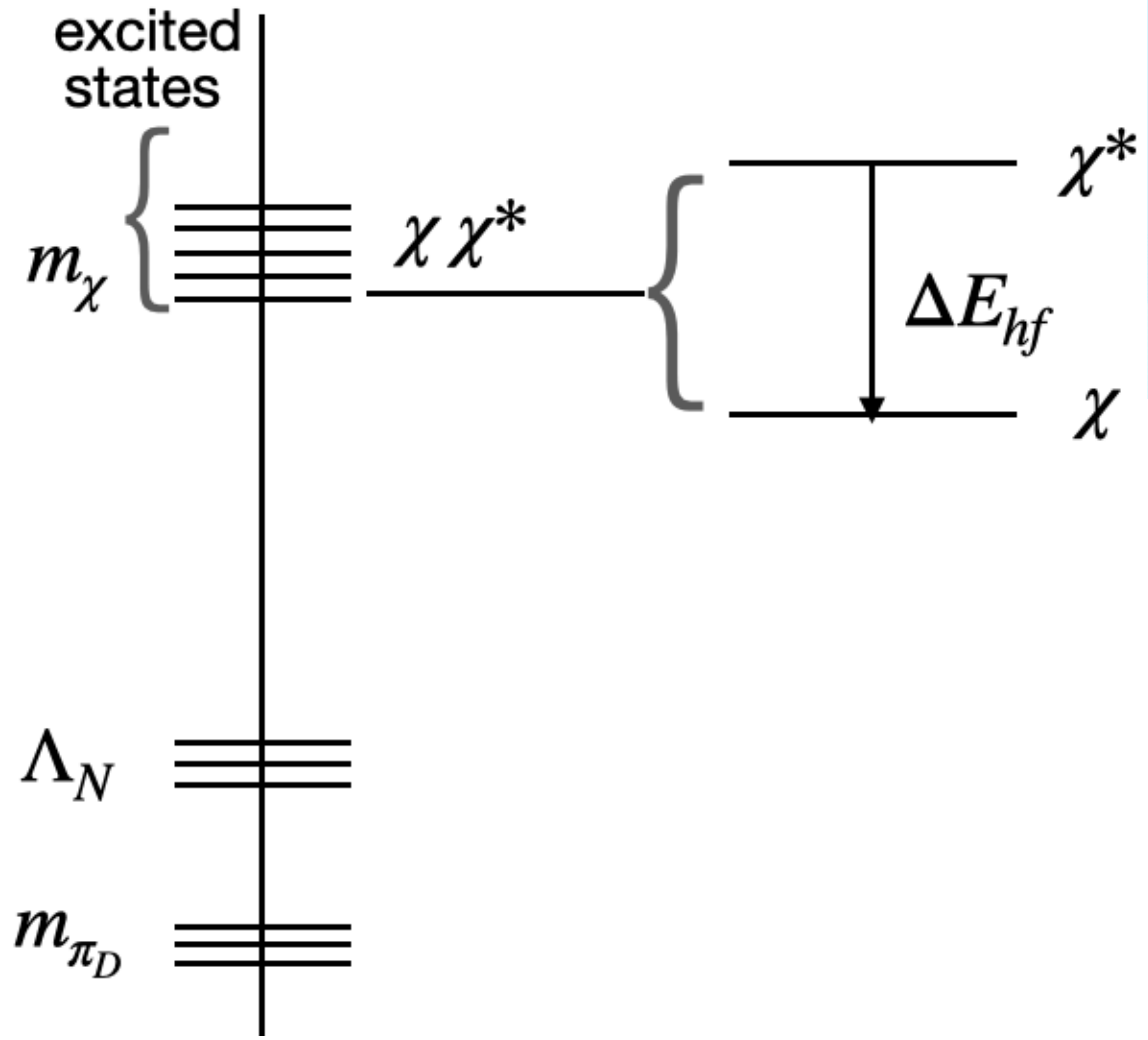
Detectability of dark forest

- Spectroscopic experiments in optical and radiowave band can detect dark forest !
- 20-40 GHz band of VLA falls in the EDGES forest band for a quasar at redshift ~ 4

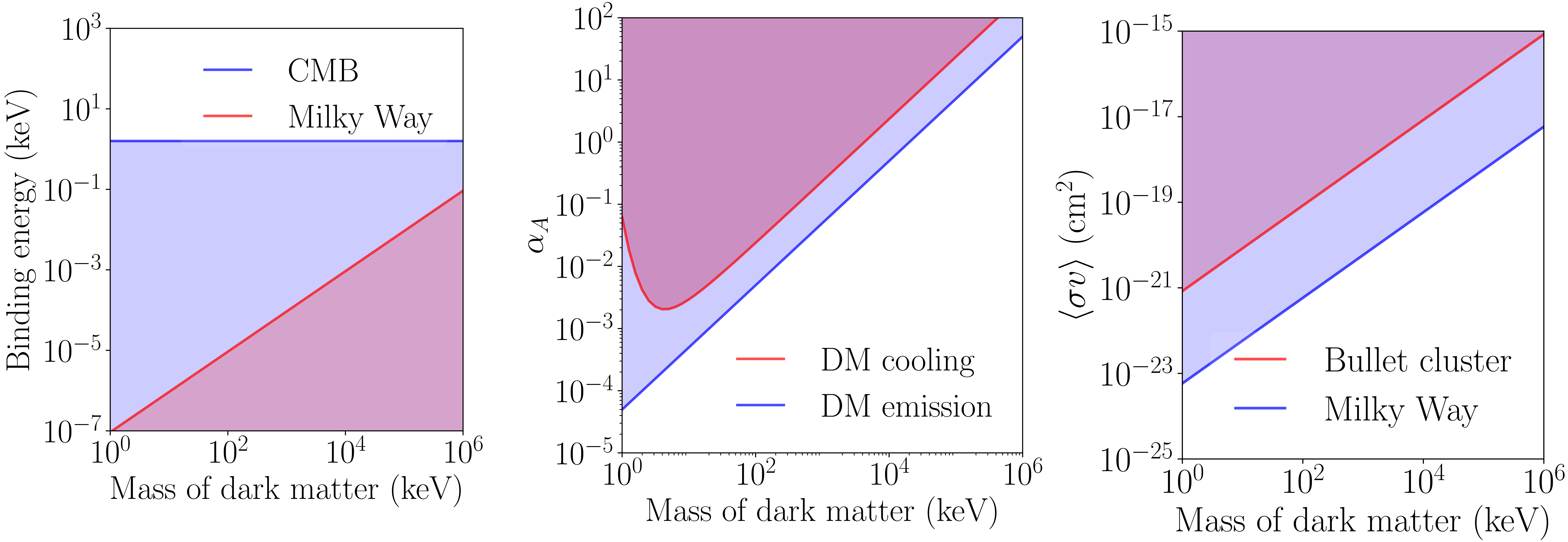


Dark matter as a composite particle

- Dark matter is a heavy-light bound state composed of two elementary particles (dark quarks) of the dark sector
- Dark quarks have $+\epsilon$ and $-\epsilon$ electric charge
- Strong interactions between dark quarks make the dark matter stable
- The hyperfine splitting of the ground state gets corrections from dark pions



First constraints from CMB and Milky Way for $\nu_0 = 156$ GHz

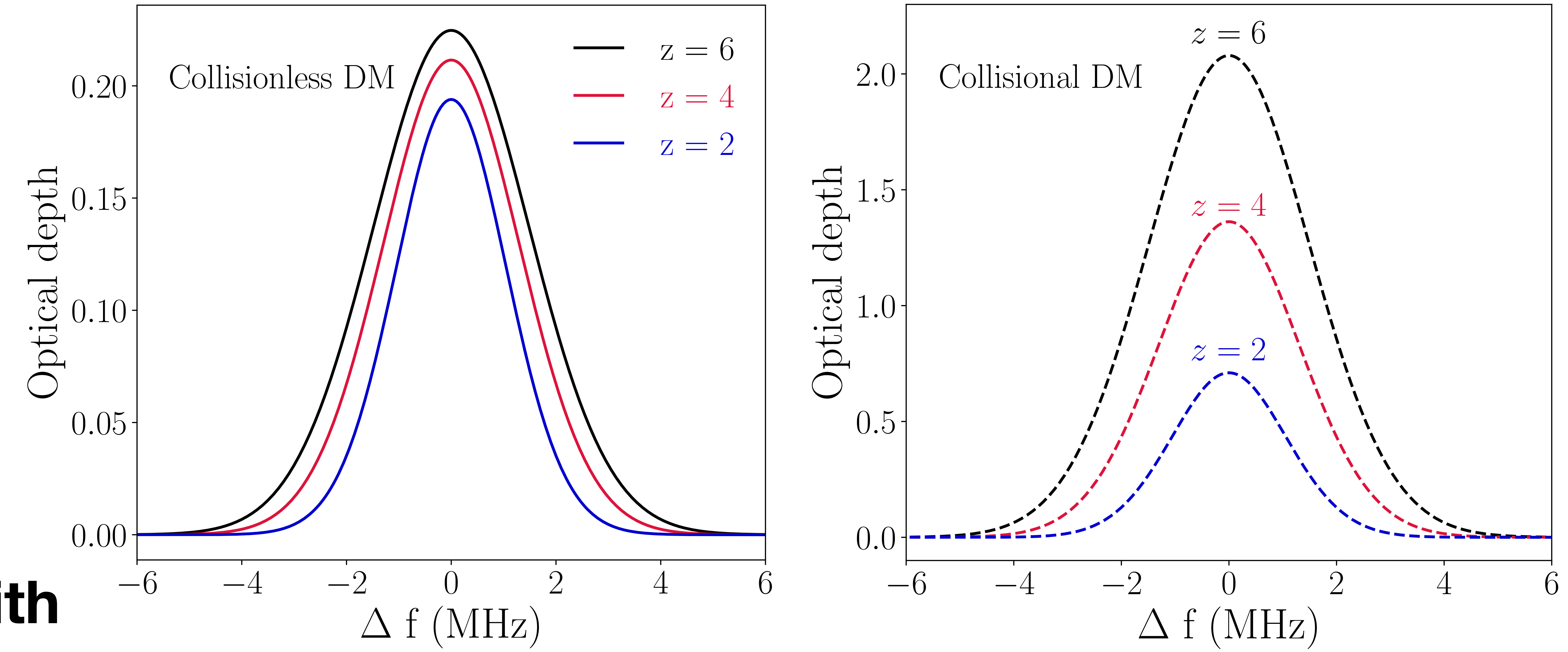


Key points

- We propose unique experimental signatures for a class of composite DM models having electromagnetic transitions: absorption lines in the spectrum of a background source.
- Such absorption signatures can occur as global absorption feature in CMB which can explain the anomalous signal measured by the EDGES collaboration.
- Such absorption signatures can also occur as a “dark forest” in the spectrum of a quasar and reveal the history of dark matter substructures.
- One can already look for such signatures in the existing data!

Dark line - absorption by a single DM halo

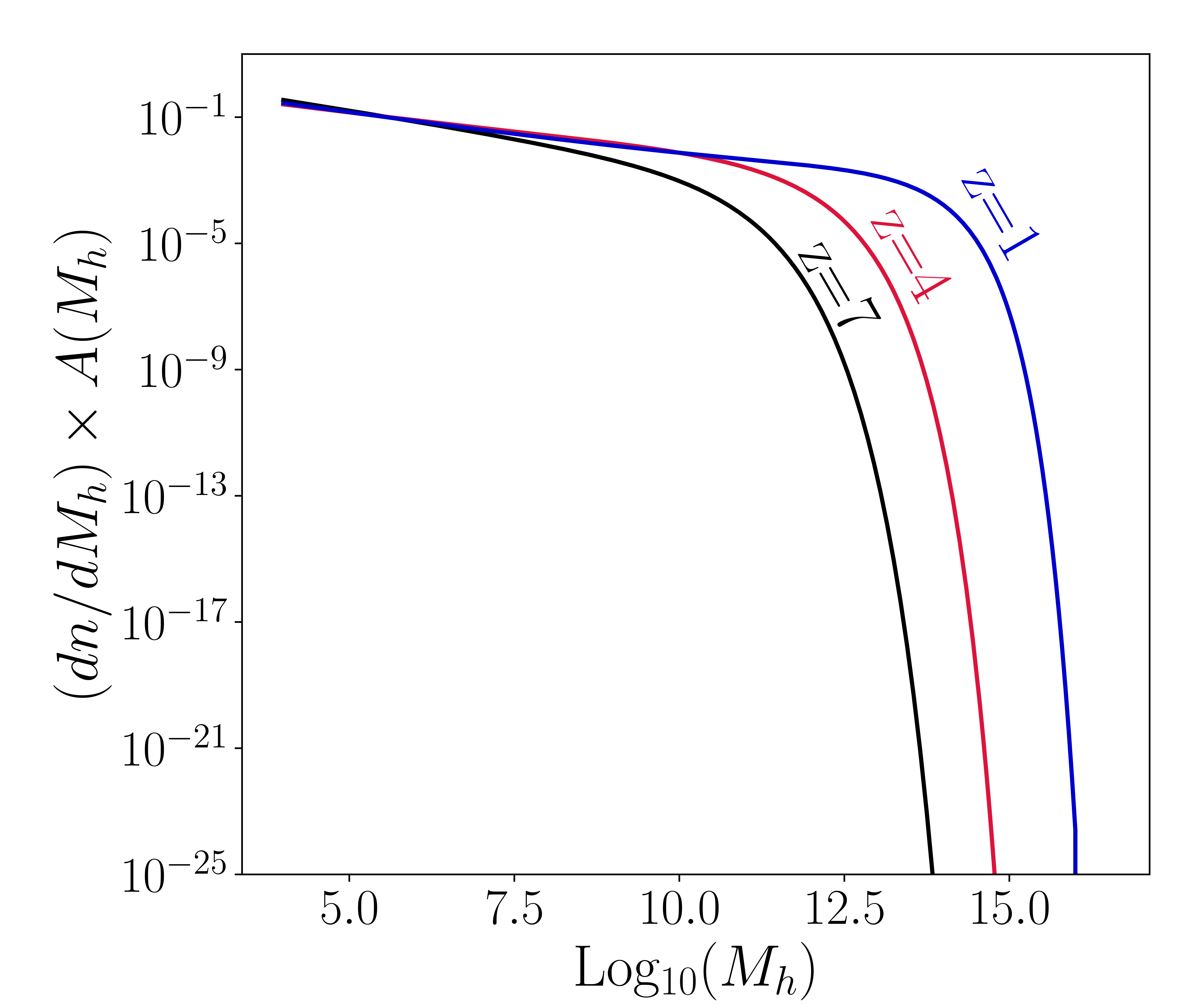
- **Stronger absorption in collisional case compared to collisionless case**
- **Absorption increases with redshift**
- **Line width increases with redshift**



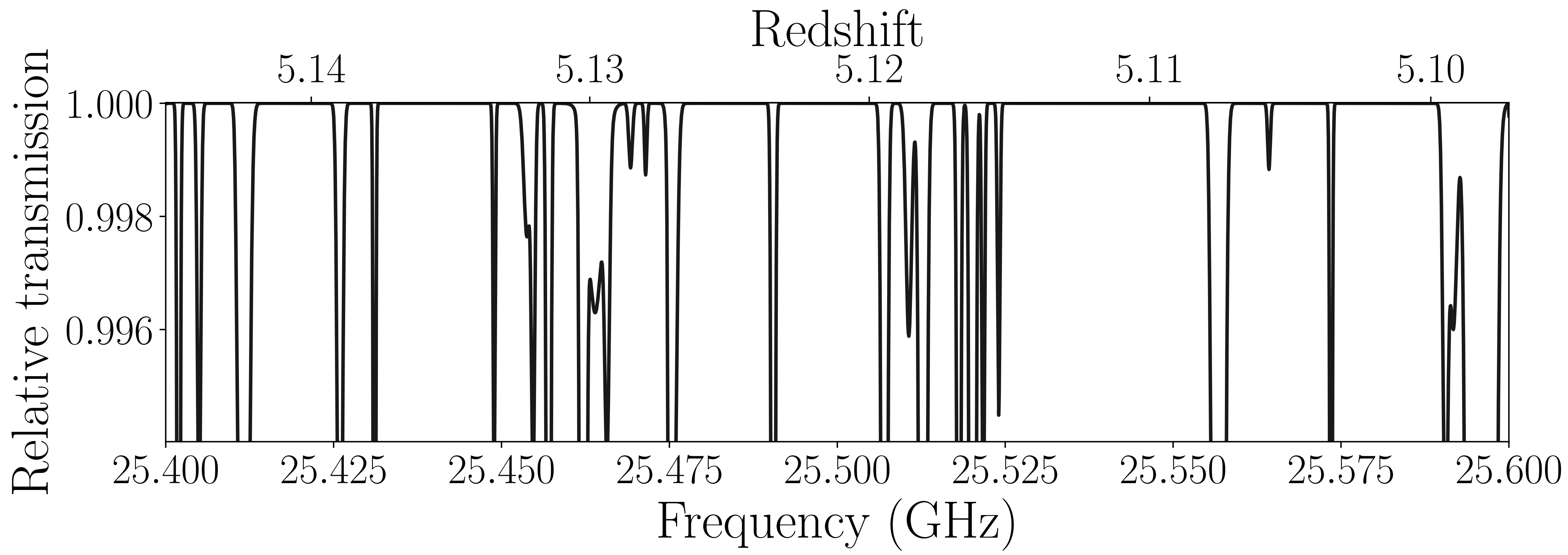
Halo mass: 10^6 $M_\odot$/h

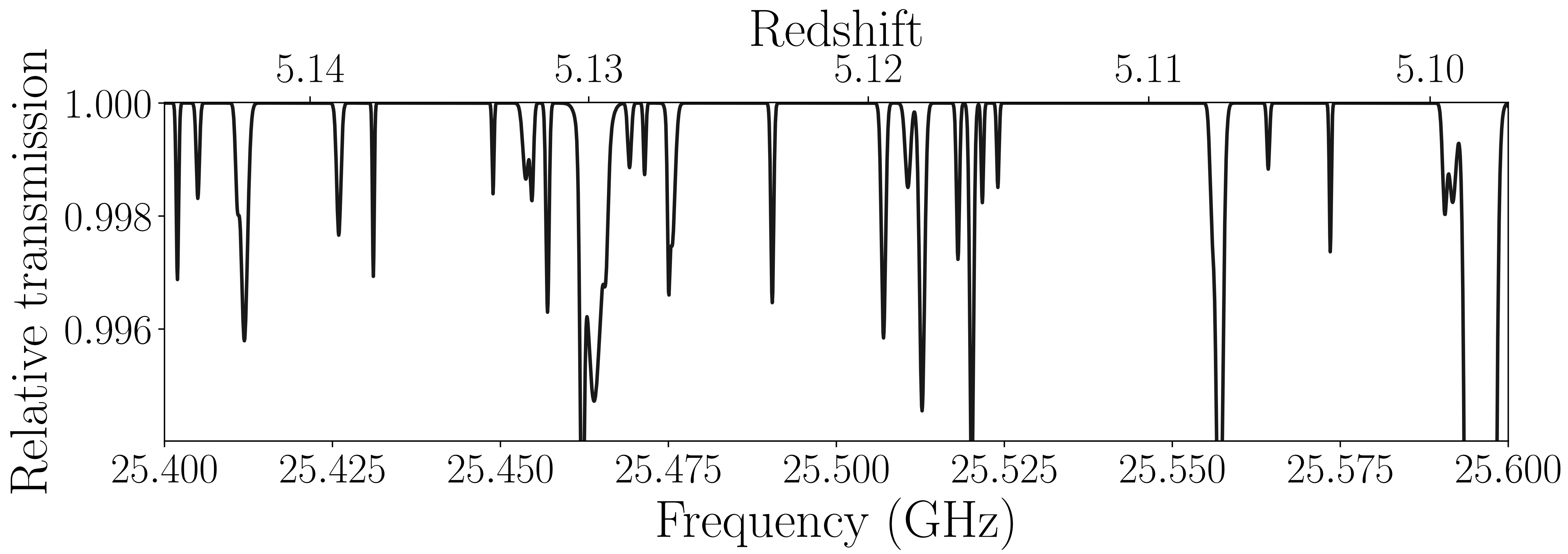
Impact parameter : 0.5 r_{vir}

Probability of intersecting a halo



Overlap between absorption lines





Halo temperature (Ascasibar et al. 2004)

$$\frac{\rho}{\sigma^3}(r) = 10^{1.46}\left(\frac{\rho_c(z)}{v_{\rm vir}^3}\right)\left(\frac{r}{r_{\rm vir}}\right)^{-1.9}$$

$$T_h(r) = \frac{m_\chi}{3k}\left(\frac{10^{1.46}}{\rho(r)}\left(\frac{\rho_c(z)}{v_{\rm vir}^3}\right)\left(\frac{r}{r_{\rm vir}}\right)^{-1.9}\right)^{-2/3}$$

Dark matter model

	$SU(N)$	$SU(2)^D_L$	$SU(2)^D_R$	$U(1)_D$	$U(1)_{\rm em}$
q_D	N	2	1	0	$+\epsilon$
q^c_D	$\bar{N}$	1	$\bar{2}$	0	$-\epsilon$
Q_D	N	1	1	$+1$	$+\epsilon$
Q^c_D	$\bar{N}$	1	1	-1	$-\epsilon$

Table 1: The dark quarks in Weyl representation and their charges under gauge and global symmetries.

- **Weakly coupled dark quarks in the UV**
- **At low energies, the theory is strongly coupled and is described in terms of bound states**
- **Strong interactions generate quark condensate which breaks the flavour symmetry resulting in 3 dark pions**
- **Hyper-fine splitting gets correction from pions**

Scaling the hydrogen atom parameters

Radiative coupling: $A_{10}^{\rm DM} \approx \epsilon^2 \left(\frac{\Delta E_{\rm hf}^{\rm DM}}{\Delta E_{\rm hf}^{\rm HI}}\right)^3 \left(\frac{m_e}{m_q}\right)^2 A_{10}^{\rm HI}$

Bohr radius: $r_{\rm HI} = \frac{\alpha}{E_{\rm binding}^{\rm HI}}$

Geometric cross-section: $\sigma_{\rm DM} \approx r_{\rm DM}^2 \approx \left(\frac{\alpha_s(m_\chi)}{\alpha}\right)^2 \left(\frac{E_{\rm binding}^{\rm HI}}{E_{\rm binding}^{\rm DM}}\right)^2 r_{\rm HI}^2$

Outline

- Basic ingredients for photon absorption by DM
- A formalism for quantifying absorption by DM
- Dark forest in the quasar spectrum
- Global absorption feature in the CMB spectrum
- A proof of principle DM model
- Existing constraints on DM model parameters