EDGES of the dark forest

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

Anoma Ganguly

Infosys Fellow

with Rishi Khatri and Tuhin S. Roy

tifr

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Quy Nhon, Vietnam

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EDGES of the dark forest

(arXiv: 2301.03624)

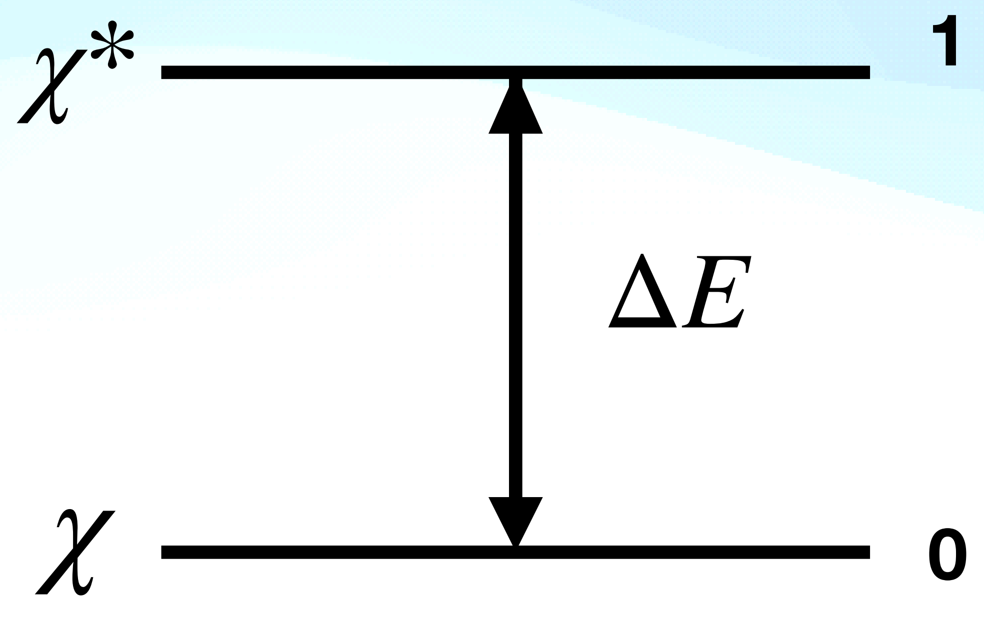
- Indirect DM searches have mostly focussed on emission signatures of dark matter
- Absorption signatures of dark matter is a promising and less-studied territory
- A huge parameter space is waiting to be explored!

Absorption of light by dark matter can create an absorption line in the source spectrum

Dark matter as a 2-level system

- Energy splitting

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

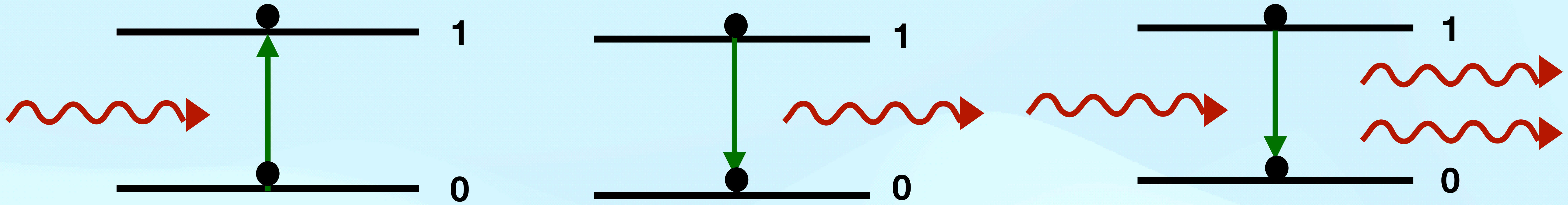


- Excitation temperature (T_{ex}) characterises the DM population in two states

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

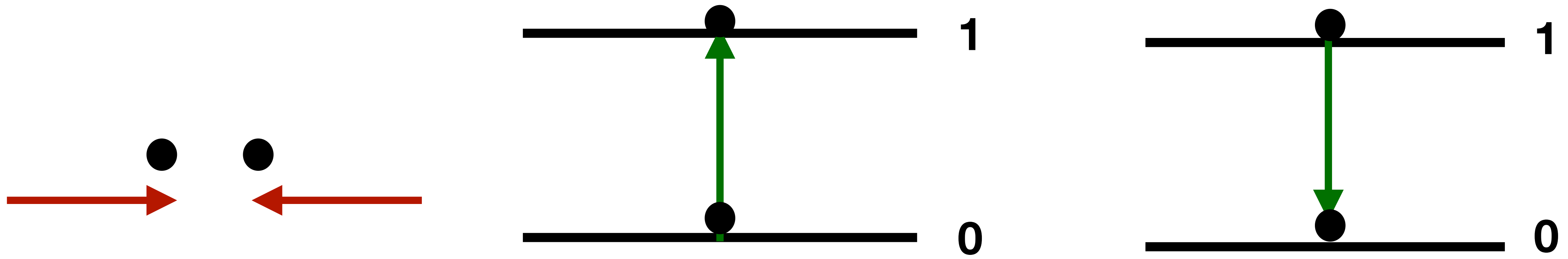
Transitions in 2-state dark matter

Electromagnetic transitions



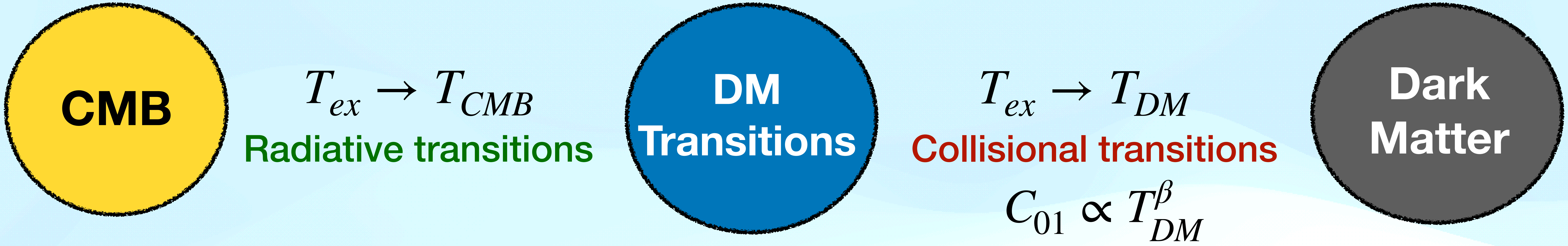
Absorption	Spontaneous Emission	Stimulated Emission
$n_0 B_{01} \bar{J}$	$n_1 A_{10}$	$n_1 B_{10} \bar{J}$

Inelastic collisional transitions



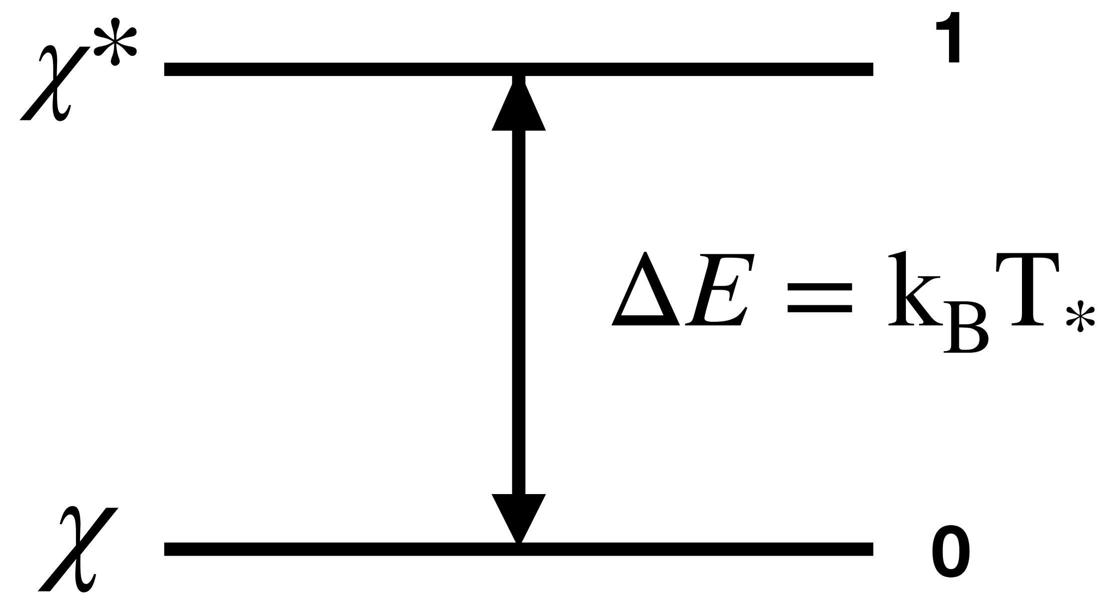
Excitation	De-excitation
$n_0 C_{01}$	$n_1 C_{10}$

Global absorption feature due to DM in the CMB spectrum

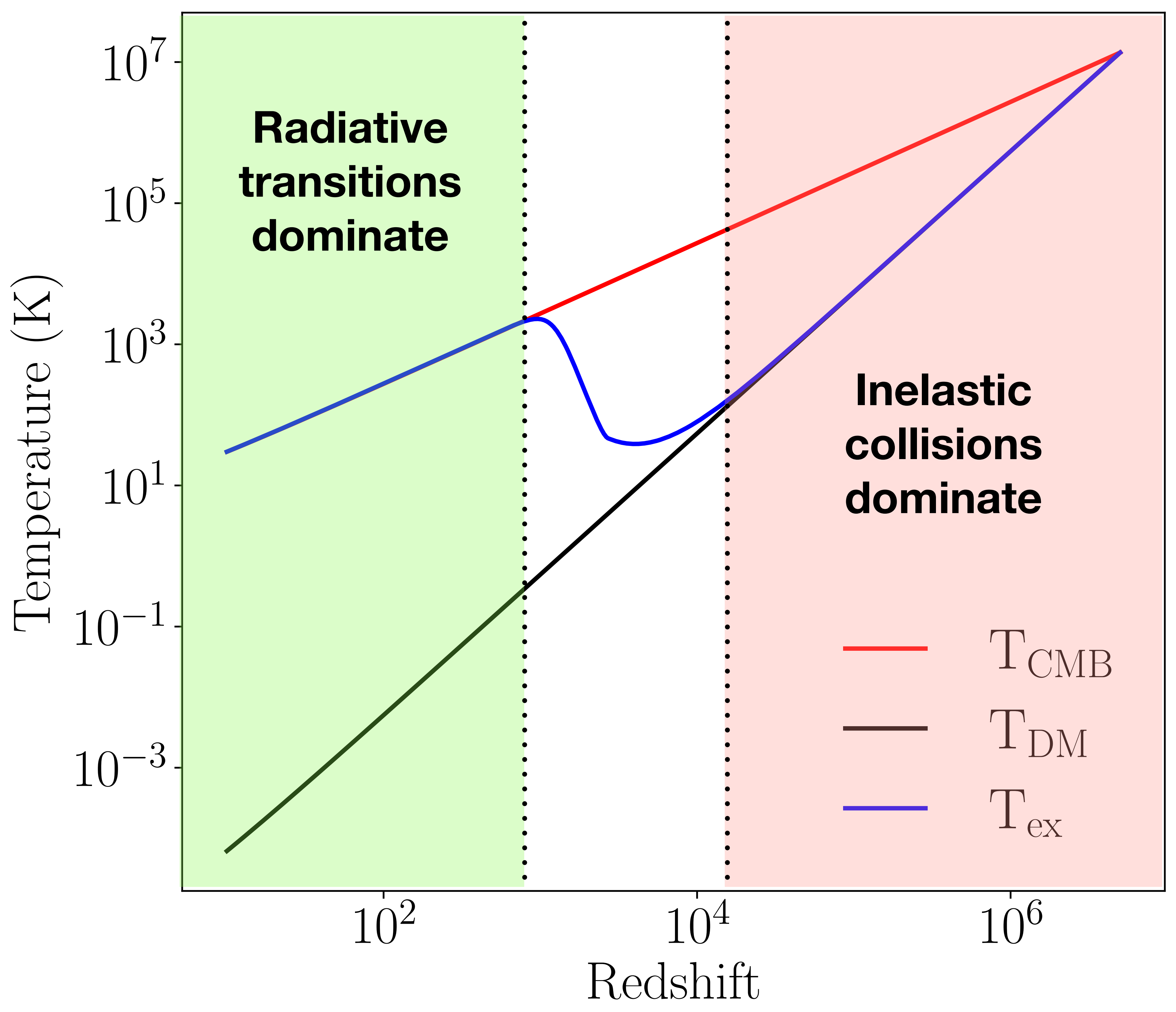


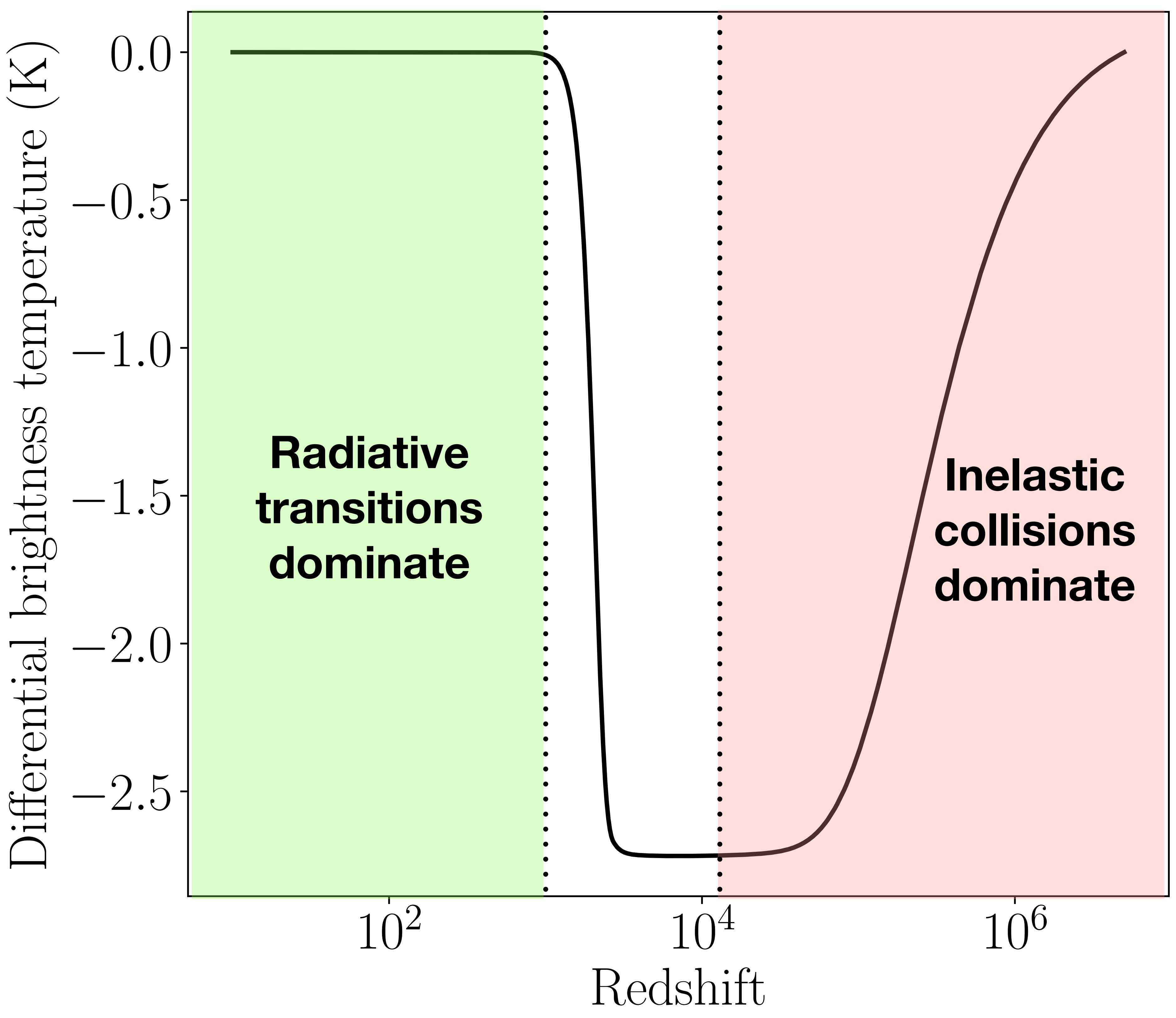
$T_{\rm ex}$ decides the population of dark matter in the ground state and the excited state

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



Global absorption feature due to DM in the CMB spectrum

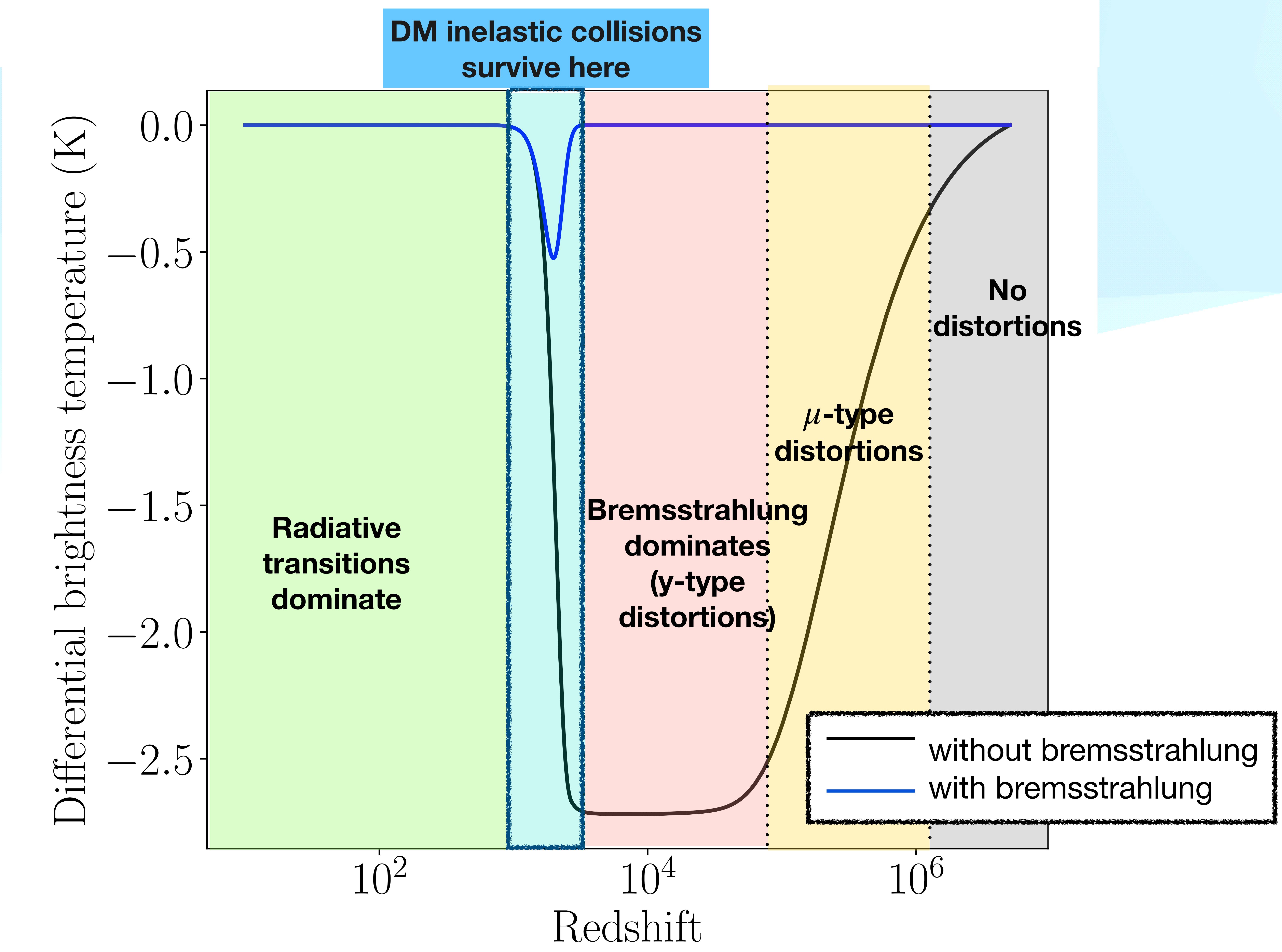




- At high redshifts, collisions dominate, $T_{ex} = T_\chi \ll T_{\rm CMB}$ and absorption begins
- As DM number density falls, radiative transitions take over and the absorption signal vanishes

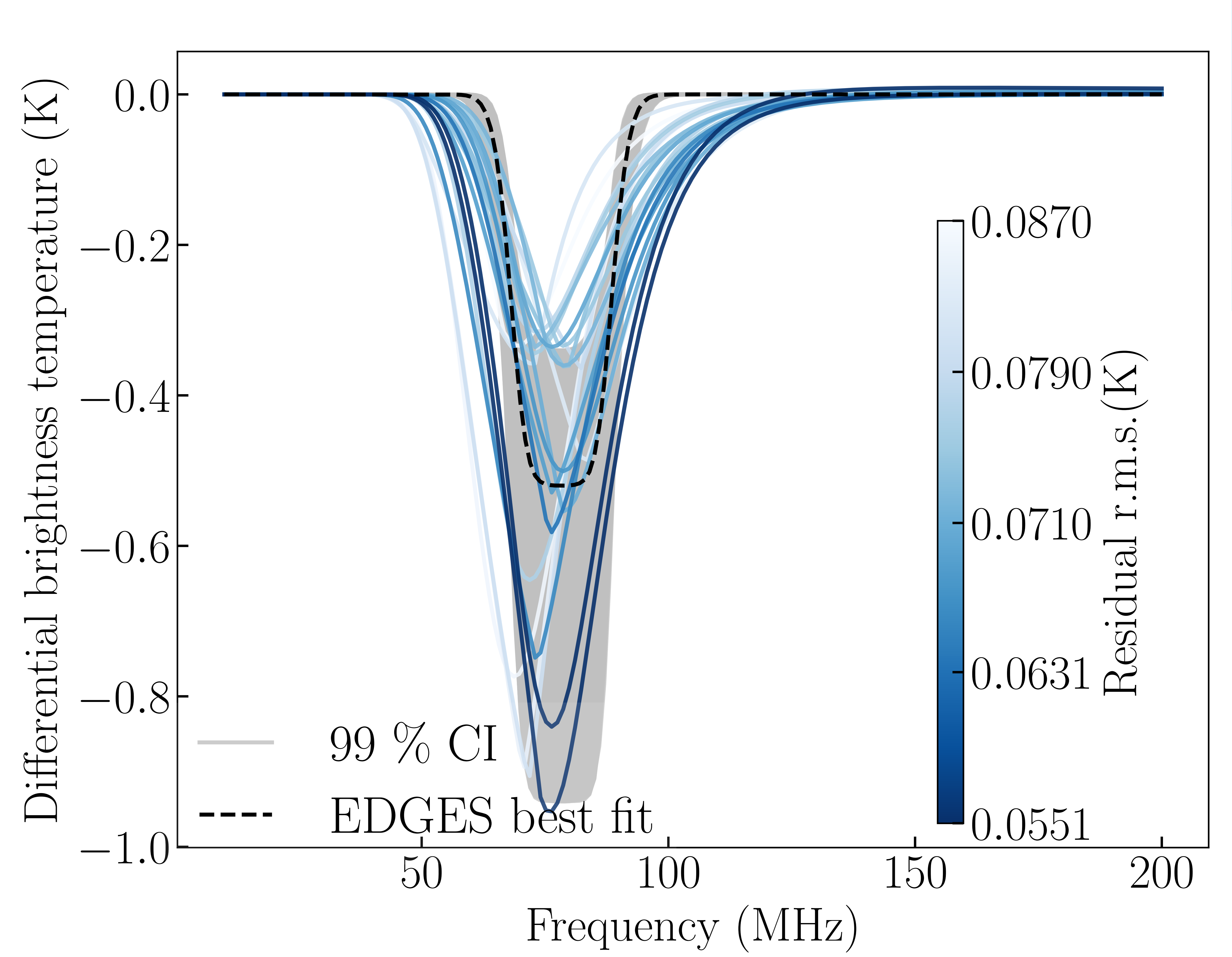
Dark matter creates distortions in the CMB

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

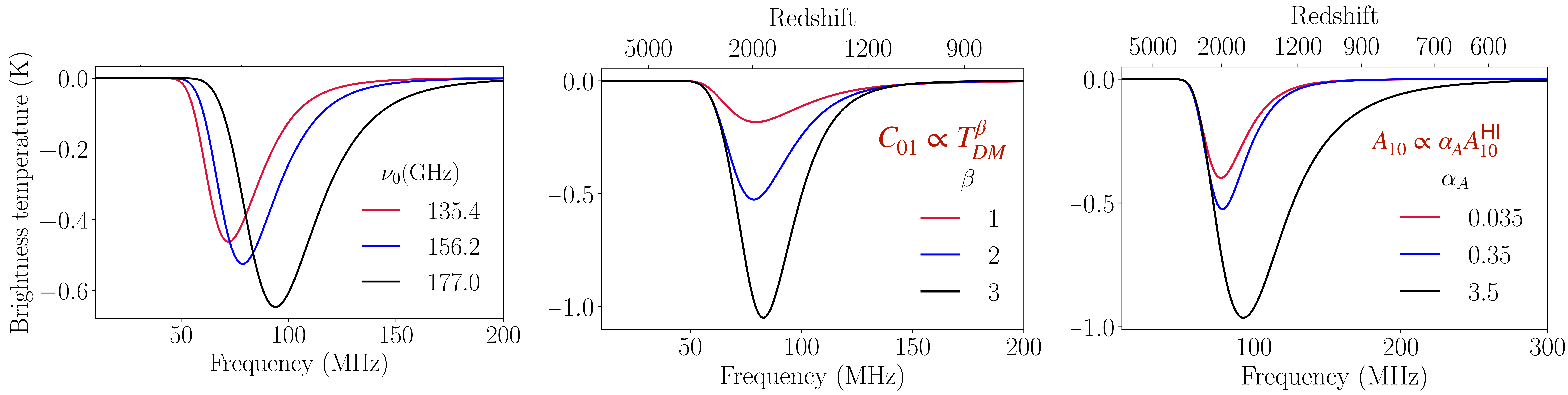


A wide parameter space of our DM model is consistent with the EDGES data

- DM with a 100-200 GHz transition frequency can produce signals with strong amplitudes and narrow shapes.
- These signals have residual r.m.s. values (< 0.087 K) consistent with EDGES observations.



Global absorption feature is sensitive to dark matter self-interactions



The global signal shifts with the shift in energy splitting

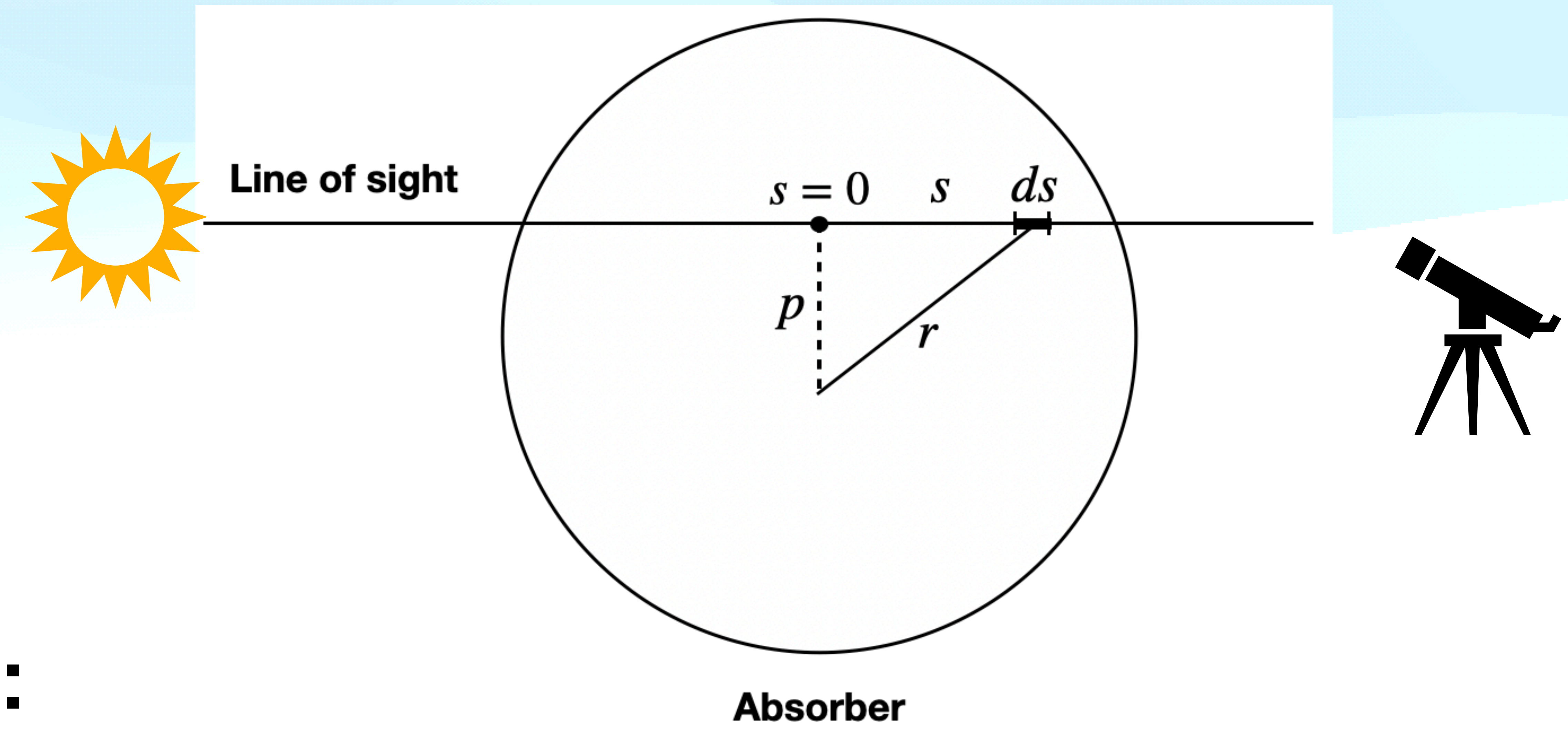
The signal has a steeper rise for stronger temperature dependence of collisional cross-section

The signal is stronger for larger radiative coupling

Absorption line created by a dark matter halo

Optical depth :

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

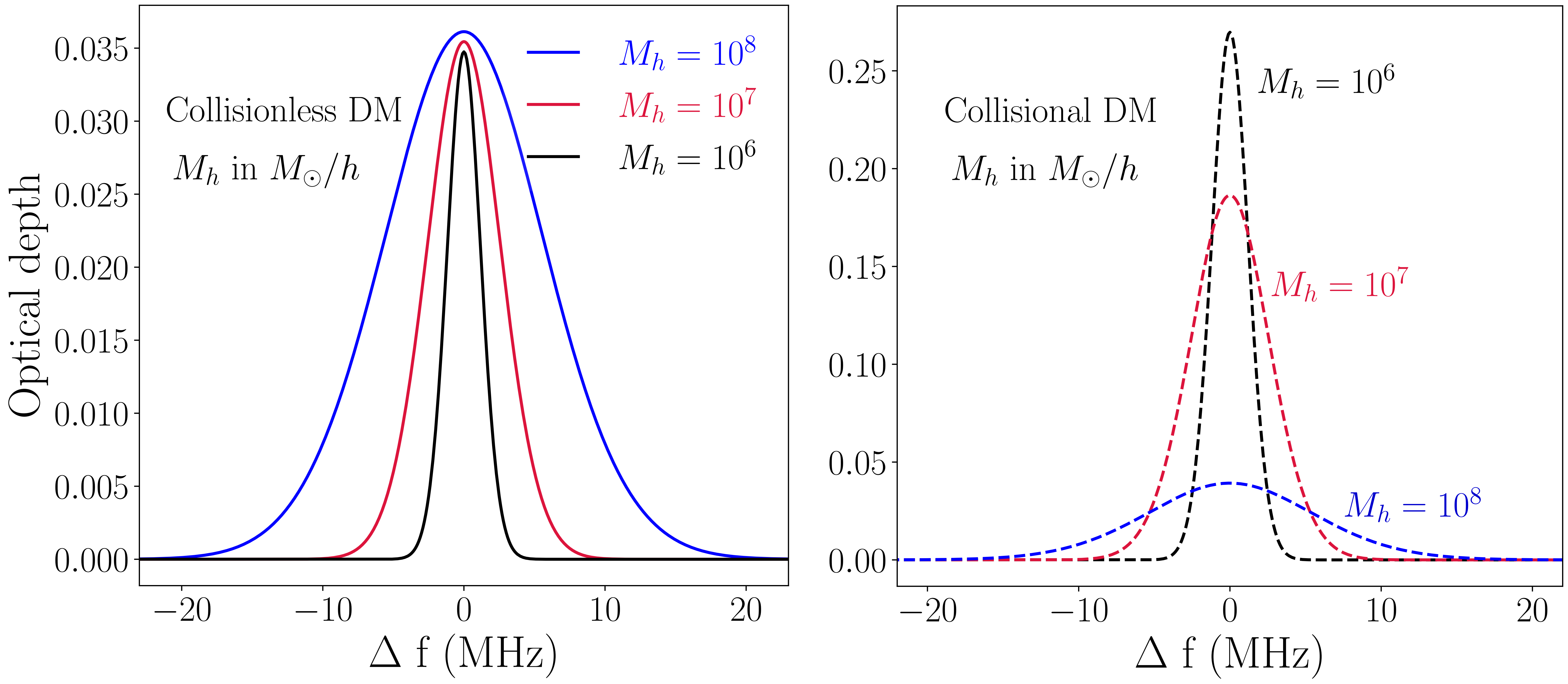


- Doppler line profile is decided by the halo temperature
- Two extreme cases for DM self-interactions:
  - Collisionless : $T_{ex} = T_{CMB}$
  - Collisional : $T_{ex} = T_{halo}$

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

Dark line is extremely sensitive to the dark matter self-interactions

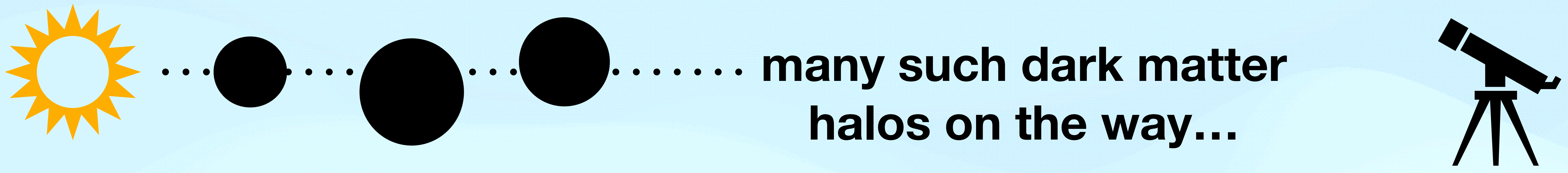
- **Amplitude** of the line is decided by $T_{\rm ex}$
- **Width** of the line is decided by $T_{\rm halo}$
- **Collisional DM** has **stronger absorption** compared to **collisionless DM**

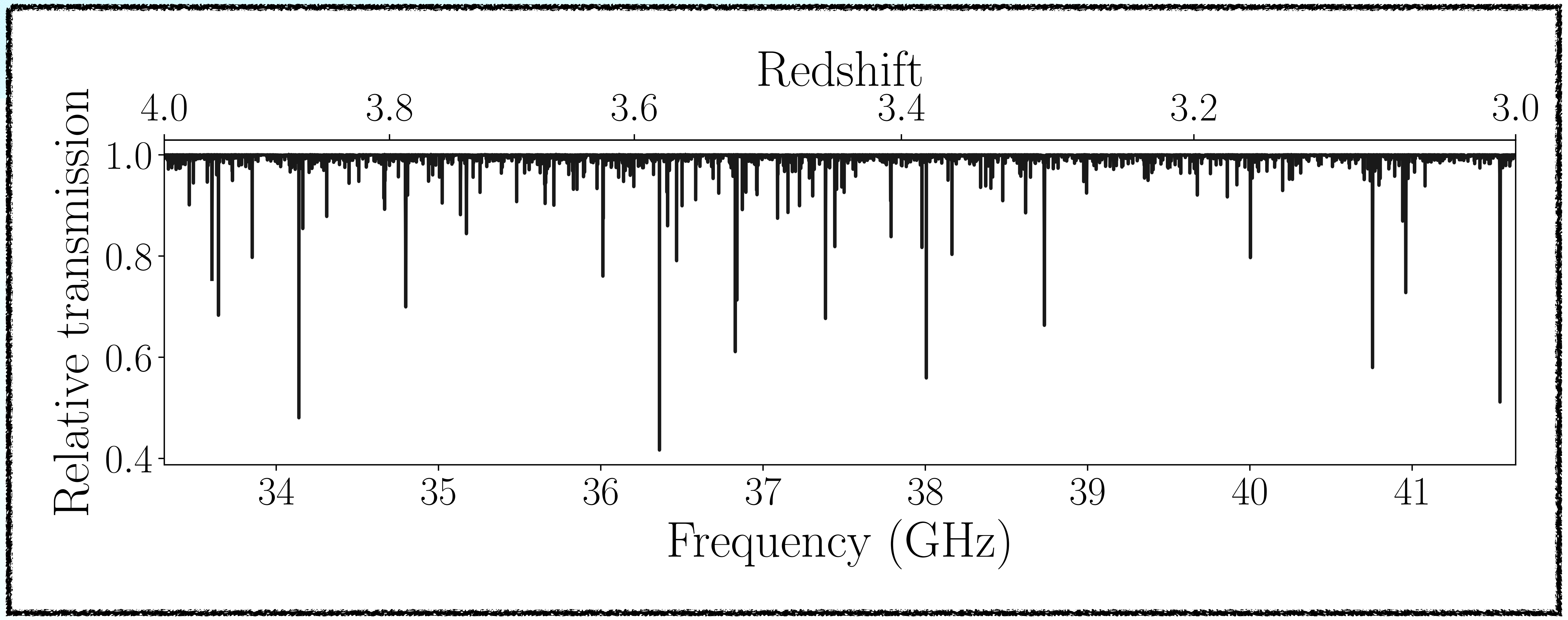


Redshift z = 5

Impact parameter : 0.5 r_{vir}

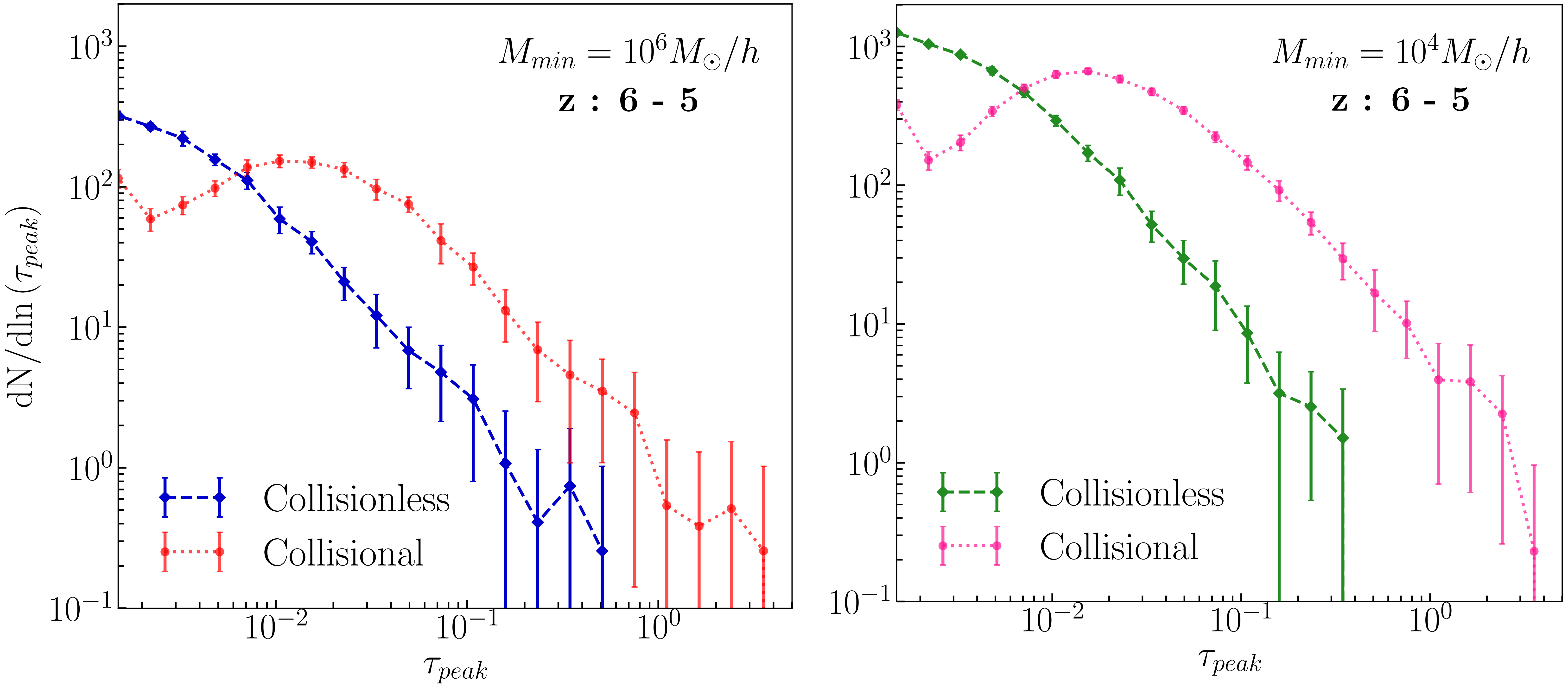
Dark forest - absorption by multiple dark matter halos





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

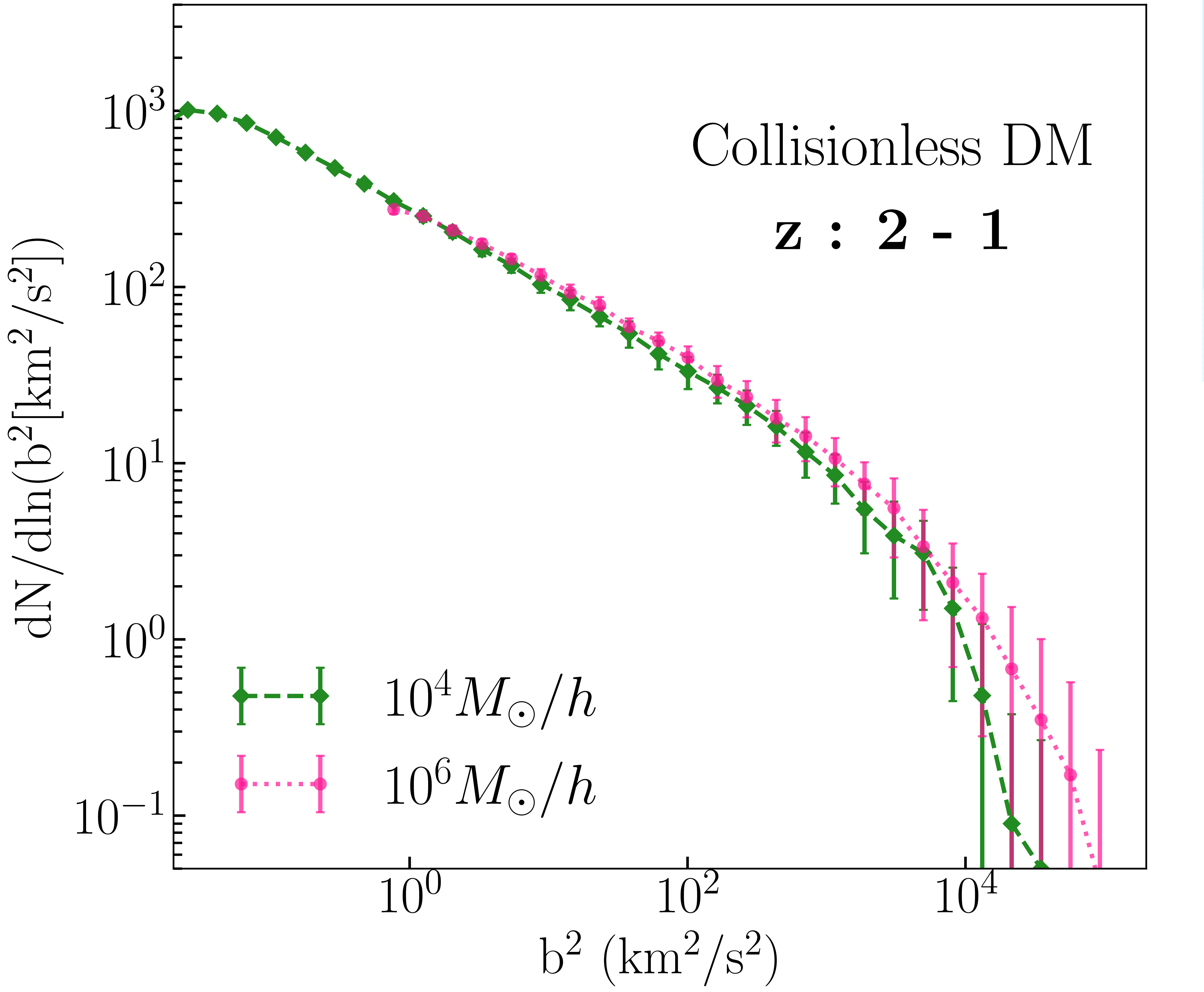


Distribution function for optical depth peaks

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

- Low mass halos give narrow lines in the dark forest

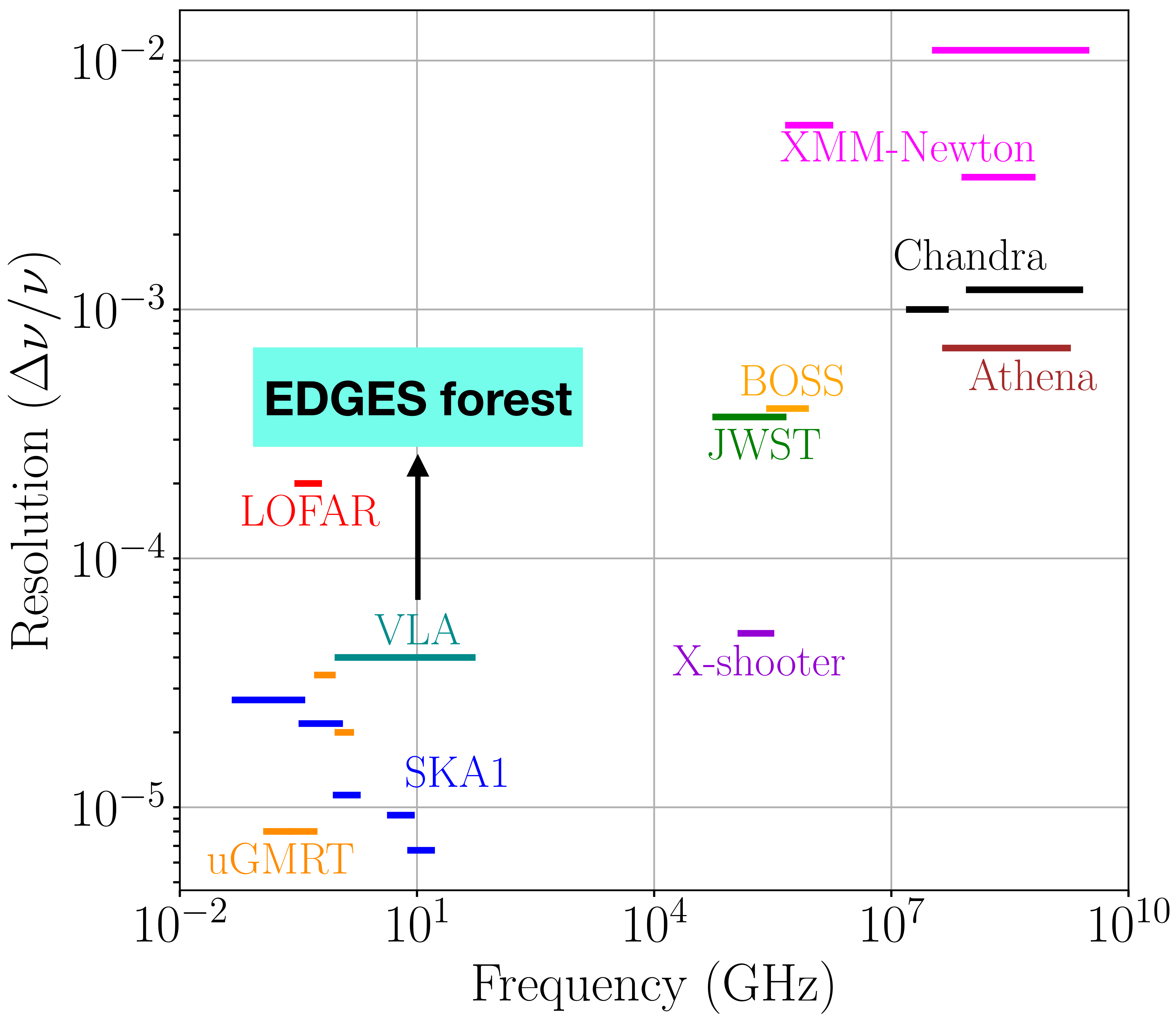
- Line width is independent of DM self interactions



Distribution function for line widths

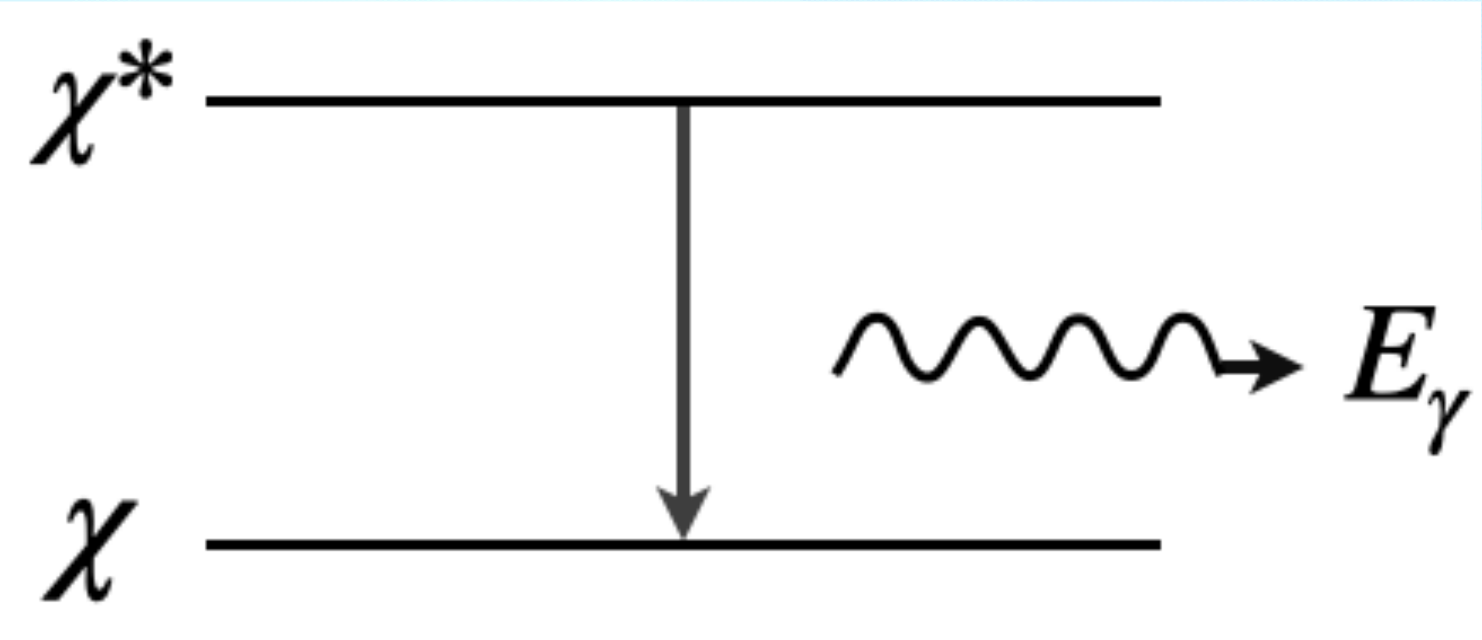
Detectability of dark forest

- 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



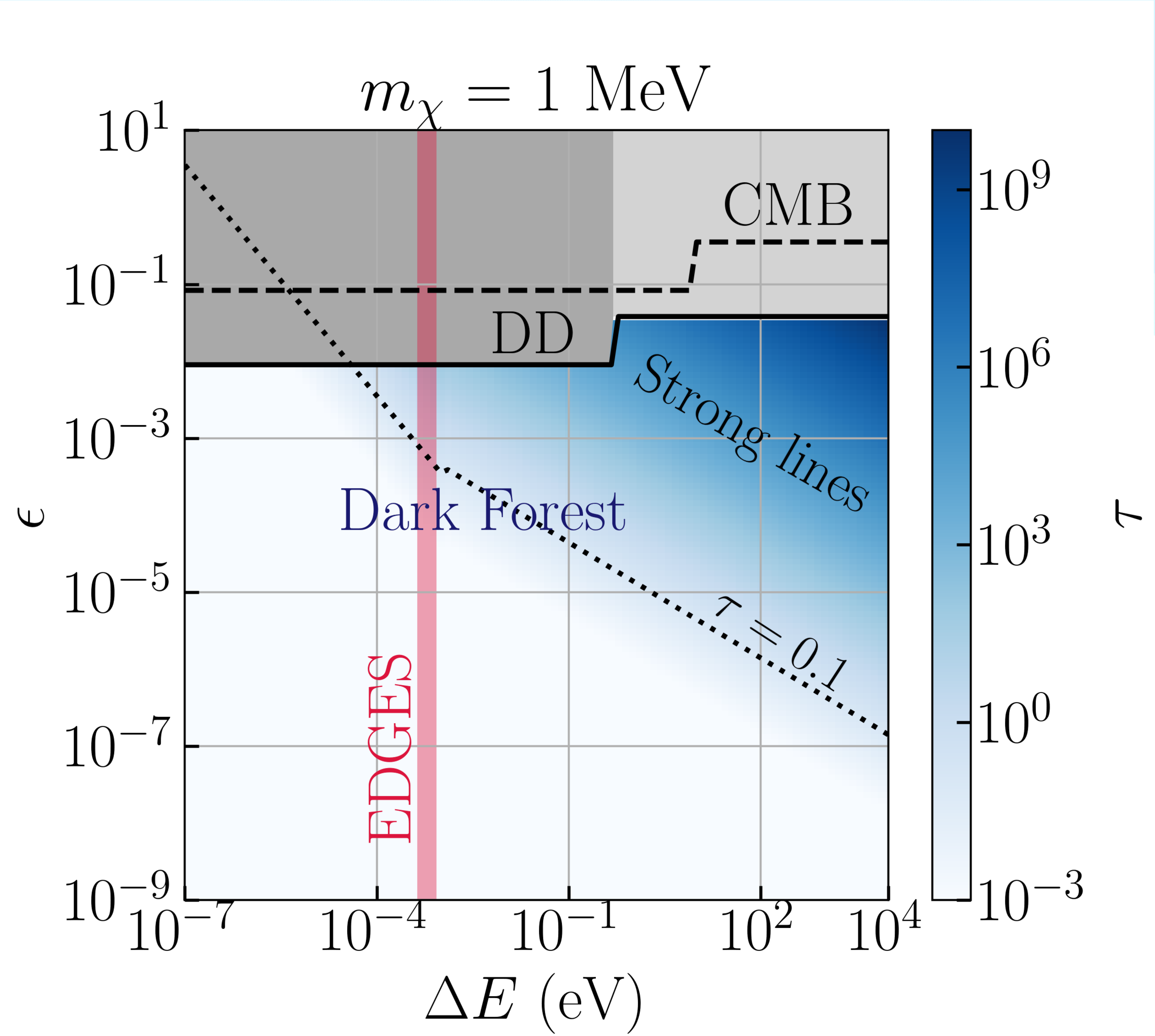
Dark forest is a more sensitive probe of composite DM compared to direct detection searches

- **Inelastic scattering:**

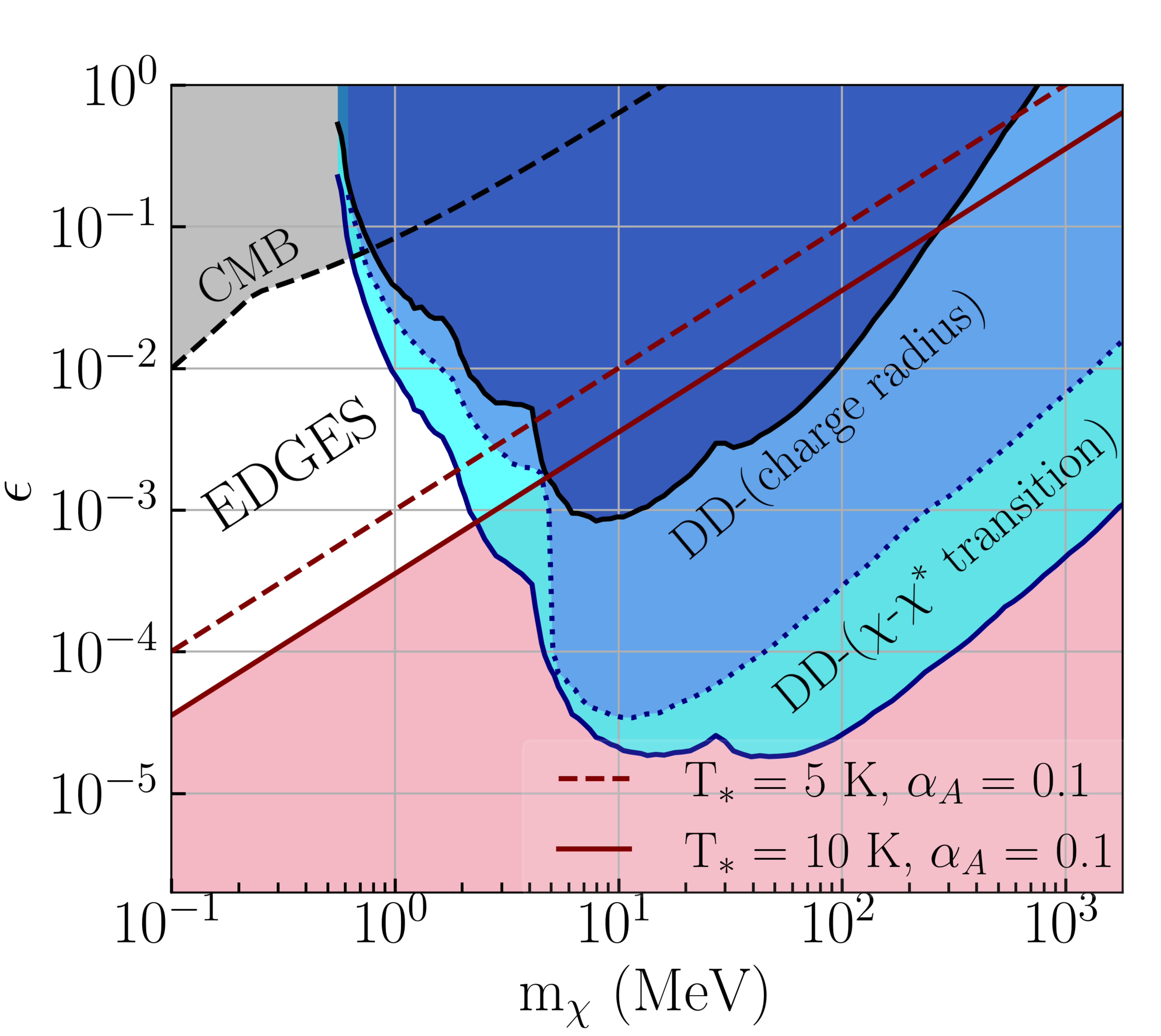
Magnetic moment of DM interacts with the magnetic field of electron causing $\chi - \chi^*$ transition

- **Elastic scattering:**

Charge radius of dark matter interacts with the electric field of electron



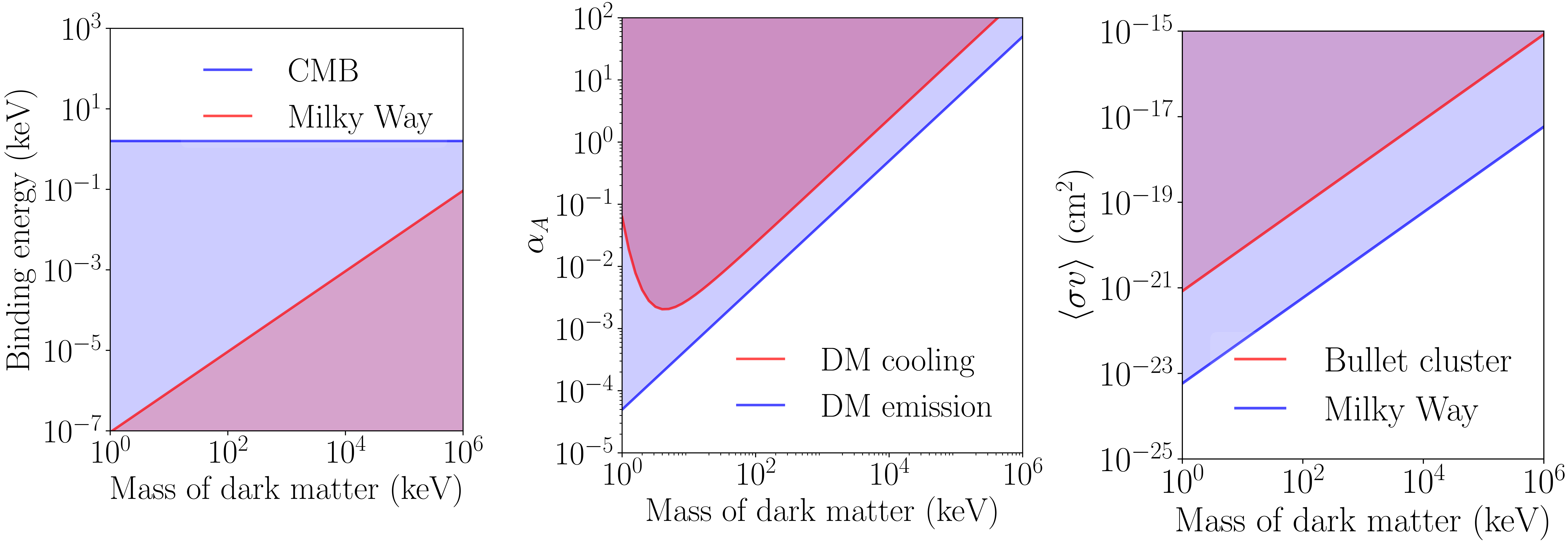
Direct detection and **CMB limits** allow $m_\chi < 3$ **MeV** as a possible explanation for **EDGES**



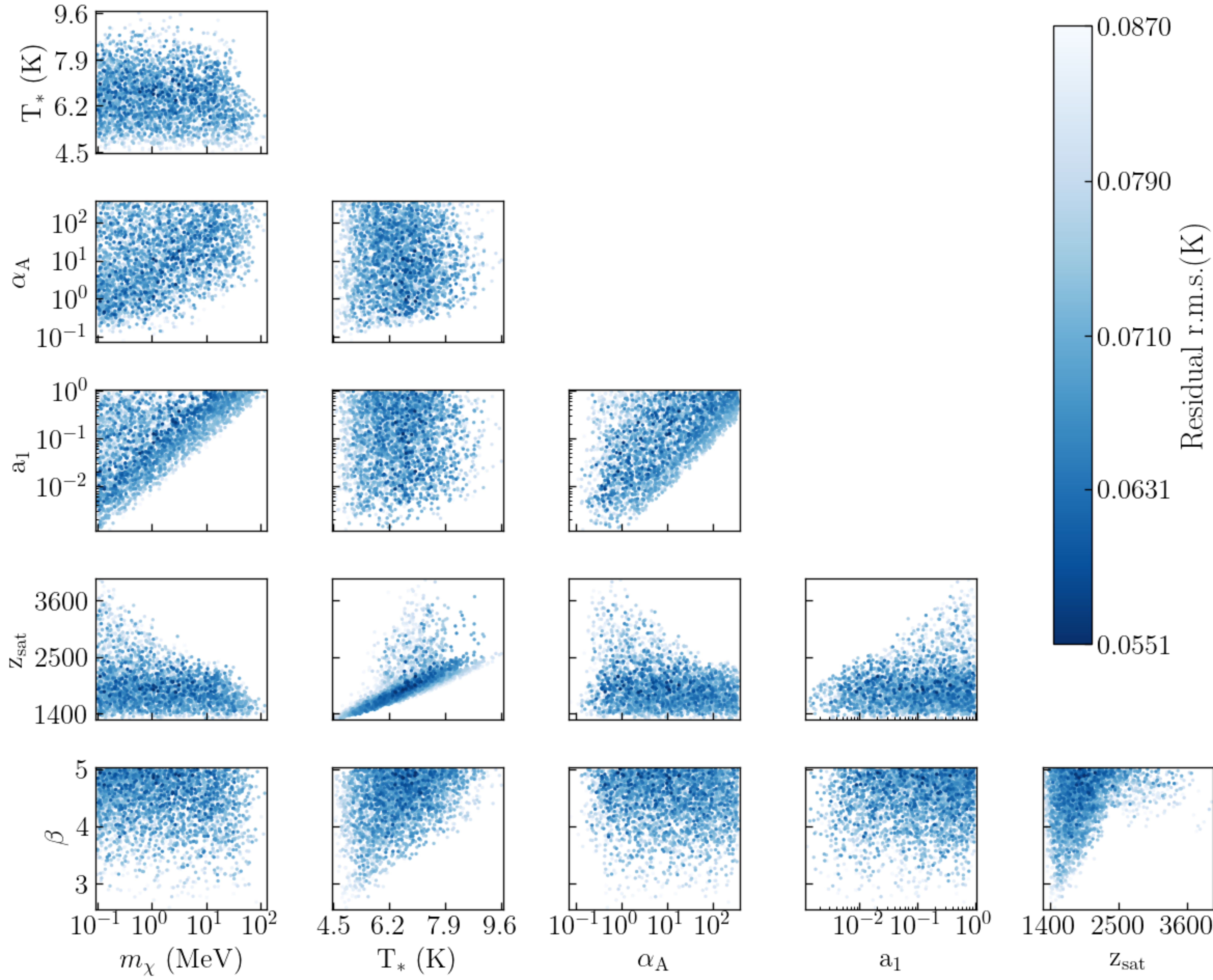
Key points

- 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!
- A large volume of parameter space exists where dark forest is a better probe of composite dark matter than the current and planned direct detection experiments.

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

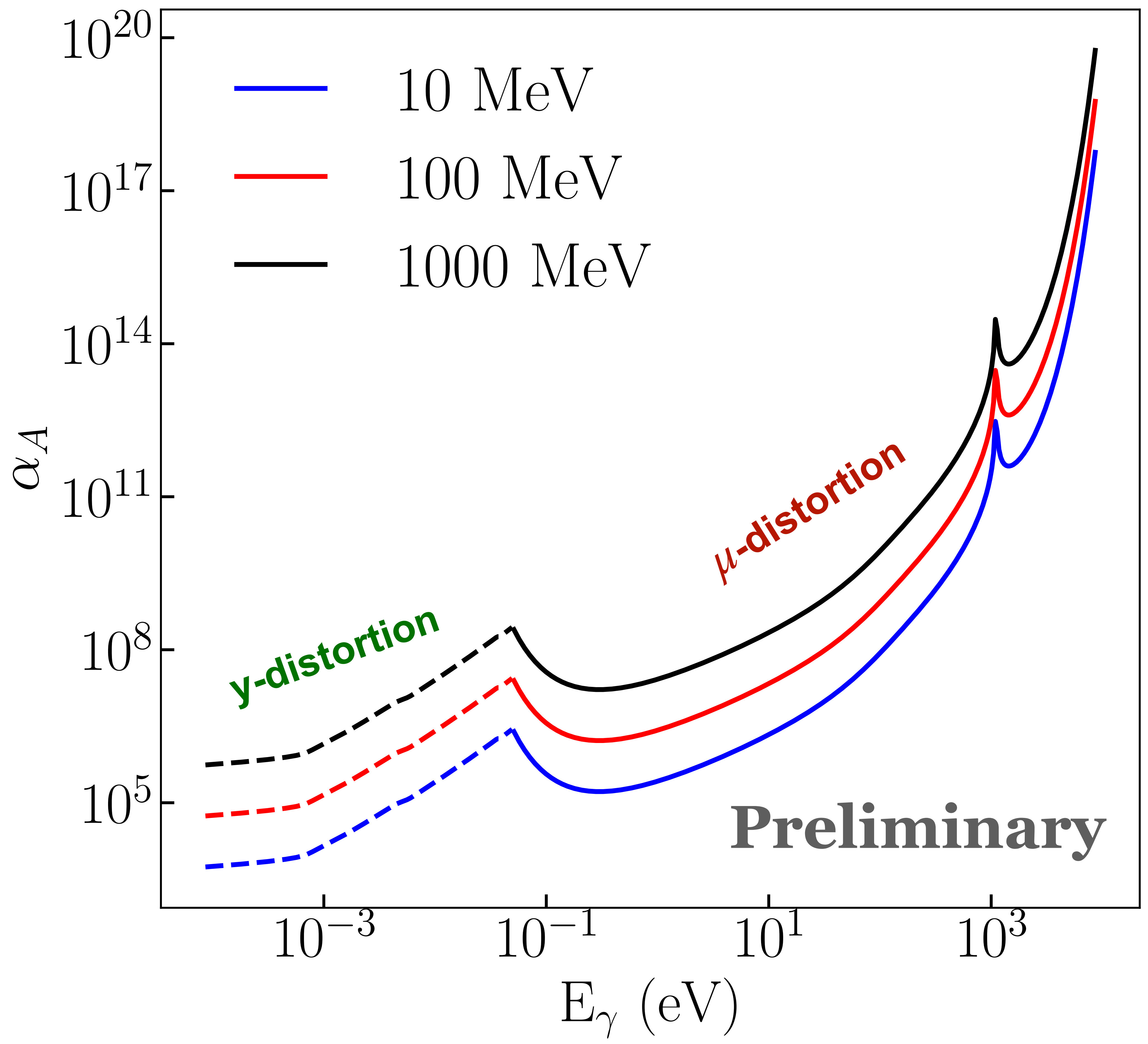


A wide parameter space is consistent with EDGES data



Spectral distortion limit from COBE constrains the electromagnetic coupling of dark matter

- Absorption of CMB by DM at redshifts $2 \times 10^6 > z > 10^5$ creates $\mu-$distortion.
- Absorption of CMB by DM at redshifts $z \leq 10^5$ creates $y-$distortion.

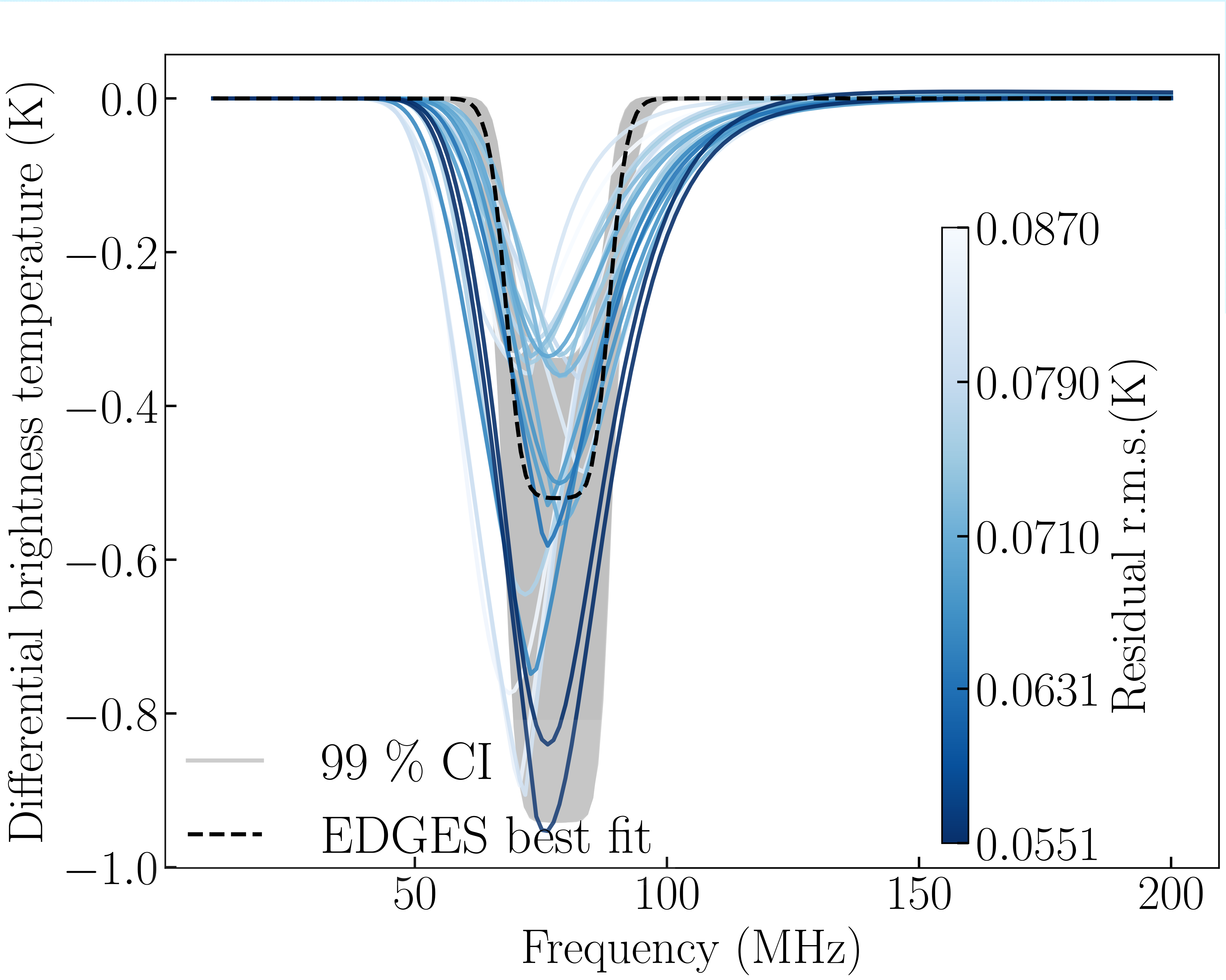


EDGES anomaly: absorption signature of collisional dark matter in the CMB

- **Mass m_χ** : 10 MeV - 1 GeV
- **Transition frequency ν_0** : 100 - 200 GHz
- **Radiative coupling** $A_{10} = \alpha_A A_{10}^{\mathrm{HI}}$ α_A: 0.1-100
- **Collisional coupling**

$$C_{10} = \begin{cases} a_1 \langle \sigma v \rangle_{\mathrm{bullet}} & , z > z_{\mathrm{sat}} \\ a_1 \langle \sigma v \rangle_{\mathrm{bullet}} \left(\dfrac{T_\chi}{T_\chi(z_{\mathrm{zsat}})} \right)^\beta & , z \leq z_{\mathrm{sat}} \end{cases}$$

a_1: 0.01-1, β : 2 - 5, z_{sat}:1500-4000



Spectral distortions

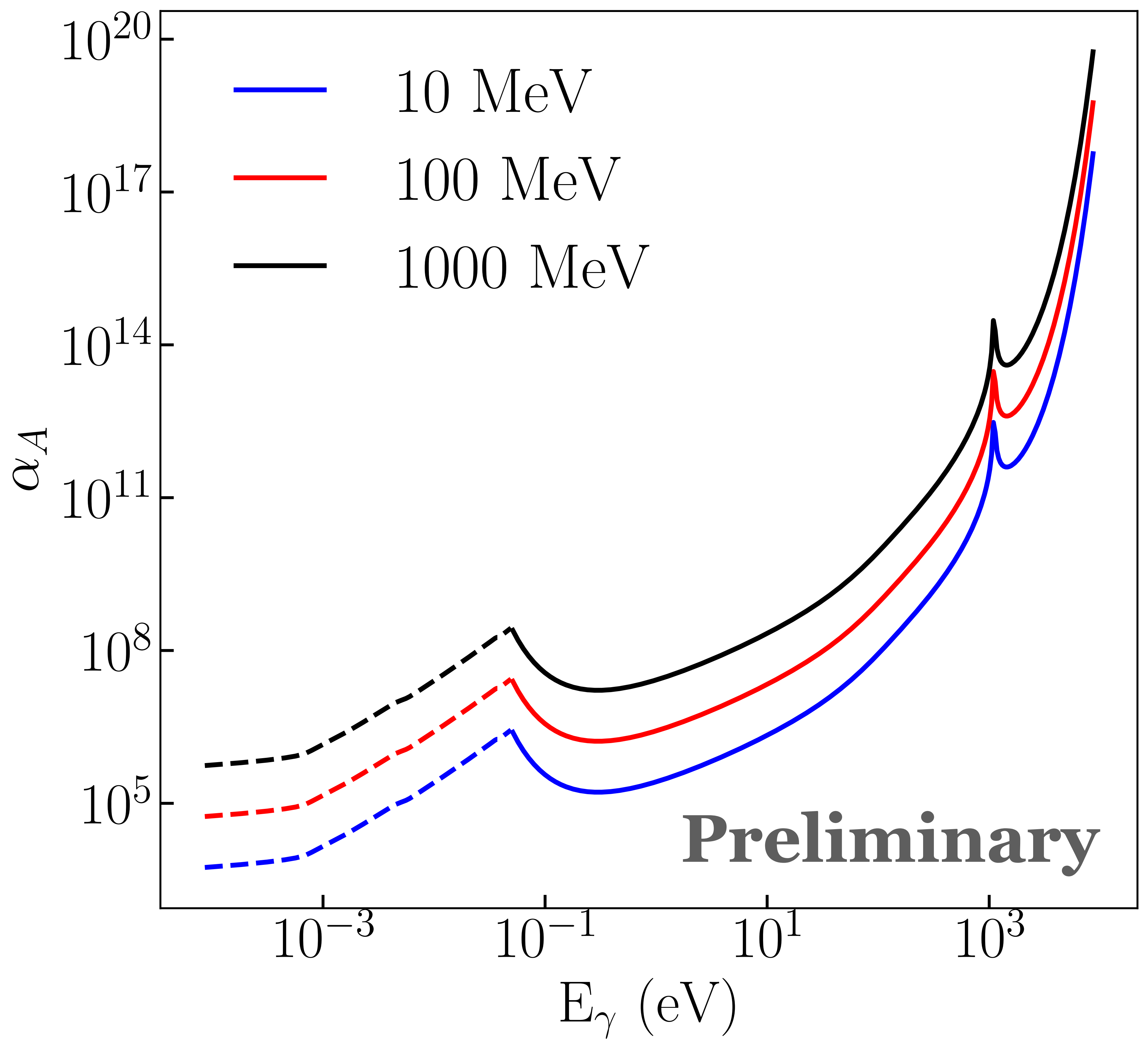
- Absorption of CMB by DM at redshifts $2 \times 10^6 > z > 10^5$ creates $\mu-$distortion.

$$\mu = 1.4 \left(\frac{\Delta \mathcal{E}}{\mathcal{E}_{pl}} - \frac{4}{3} \left(e^{x_c} e^{-x_c/x_*} \right) \frac{\Delta \mathcal{N}}{\mathcal{N}_{pl}} \right)$$

- Absorption of CMB by DM at redshifts $z \leq 10^5$ creates $y-$distortion. $y = \frac{1}{4} \frac{\Delta \mathcal{E}}{\mathcal{E}_{pl}}$

$$x_c = \sqrt{(K_{dc} + K_{br})/K_c}$$

$$x_* = \frac{T_*}{T_e(z)}$$

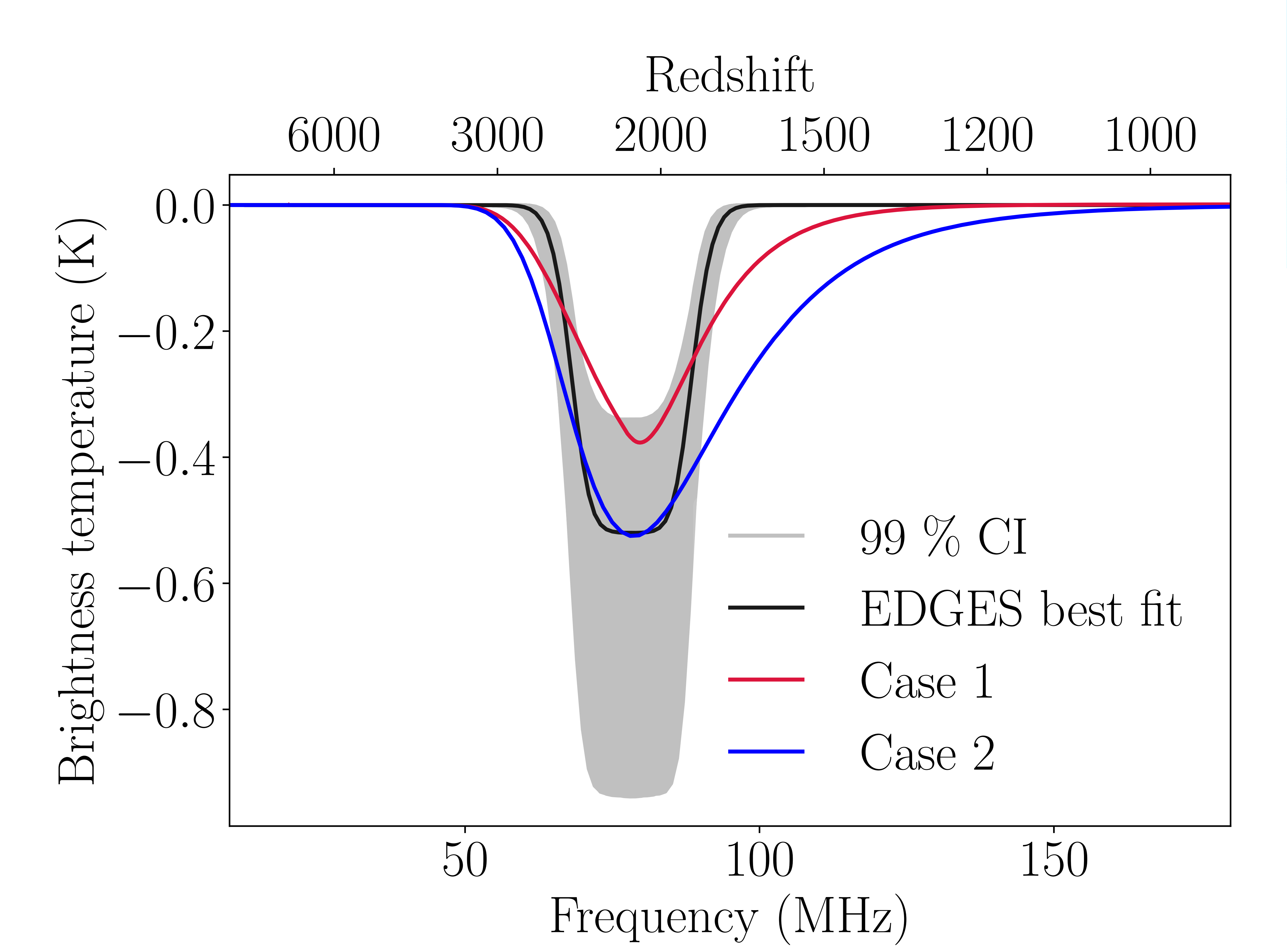


EDGES anomaly: absorption signature of dark matter in the CMB

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 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

Absorption of photons from a quasar by a halo

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

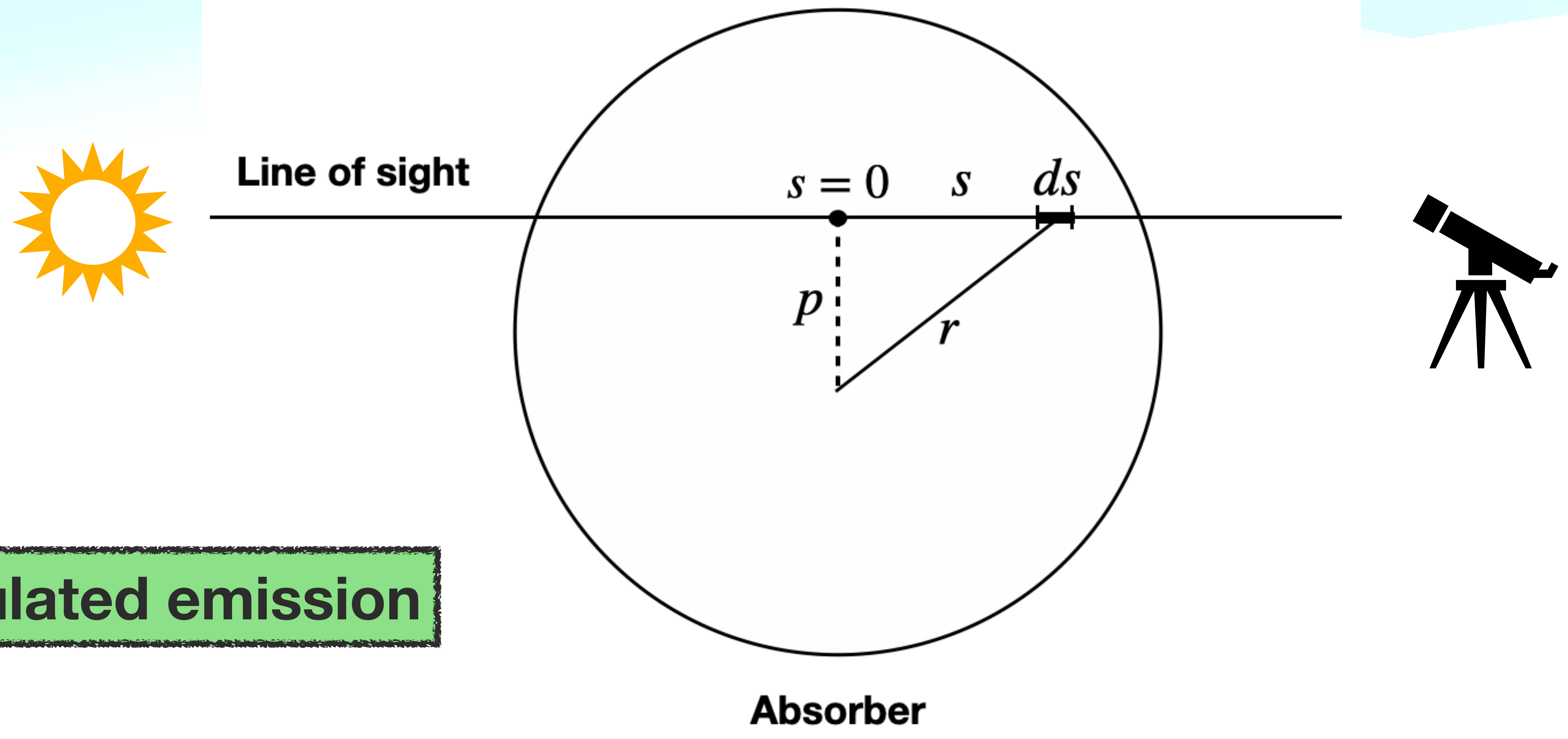
$$F_\nu = F_\nu^0 \exp(-\tau_\nu)$$

- **Optical depth :**

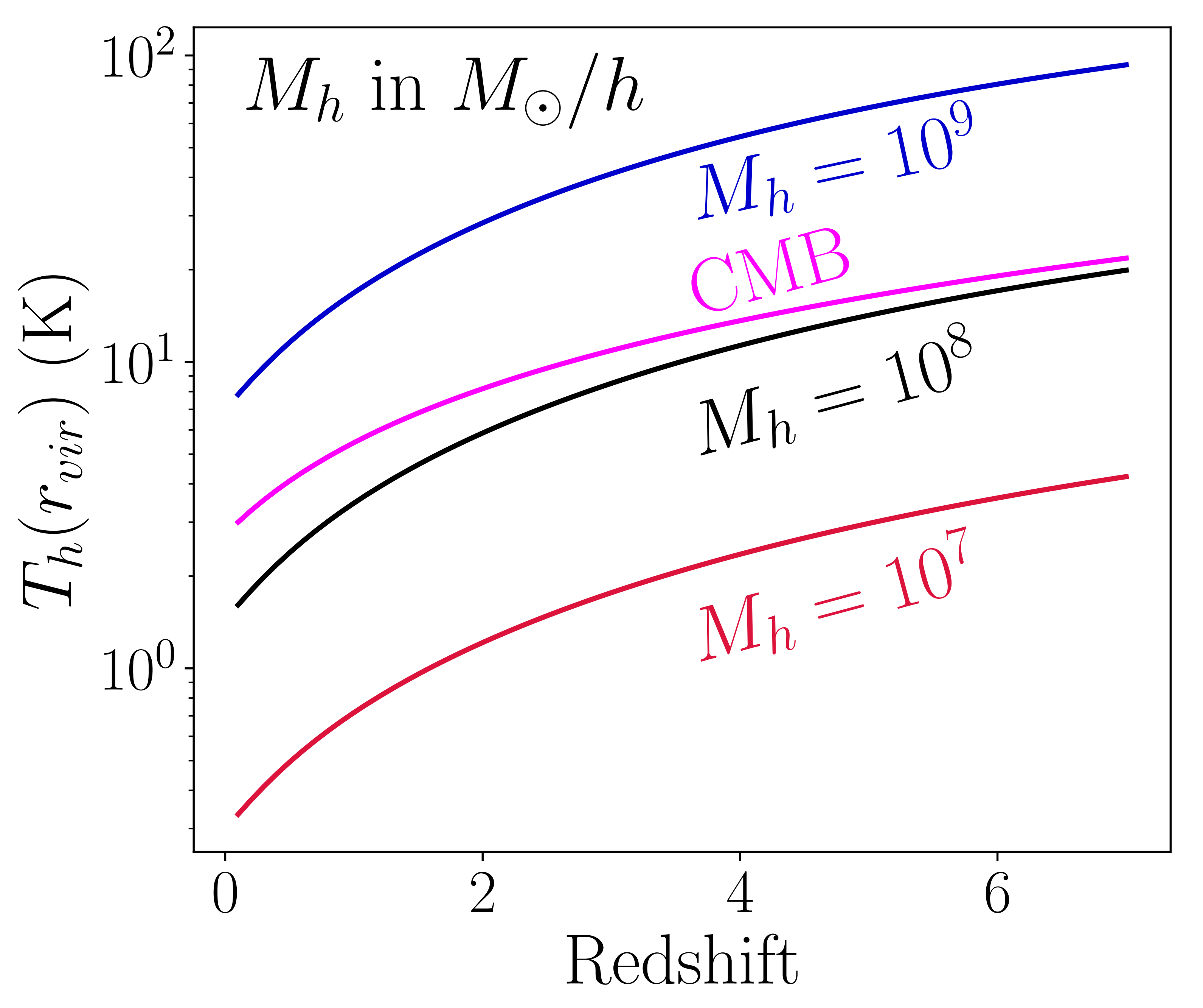
$$\tau_\nu(p) = \int ds \frac{h\nu_0}{4\pi} \phi_\nu \left(n_0 B_{01} - n_1 B_{10}\right)$$

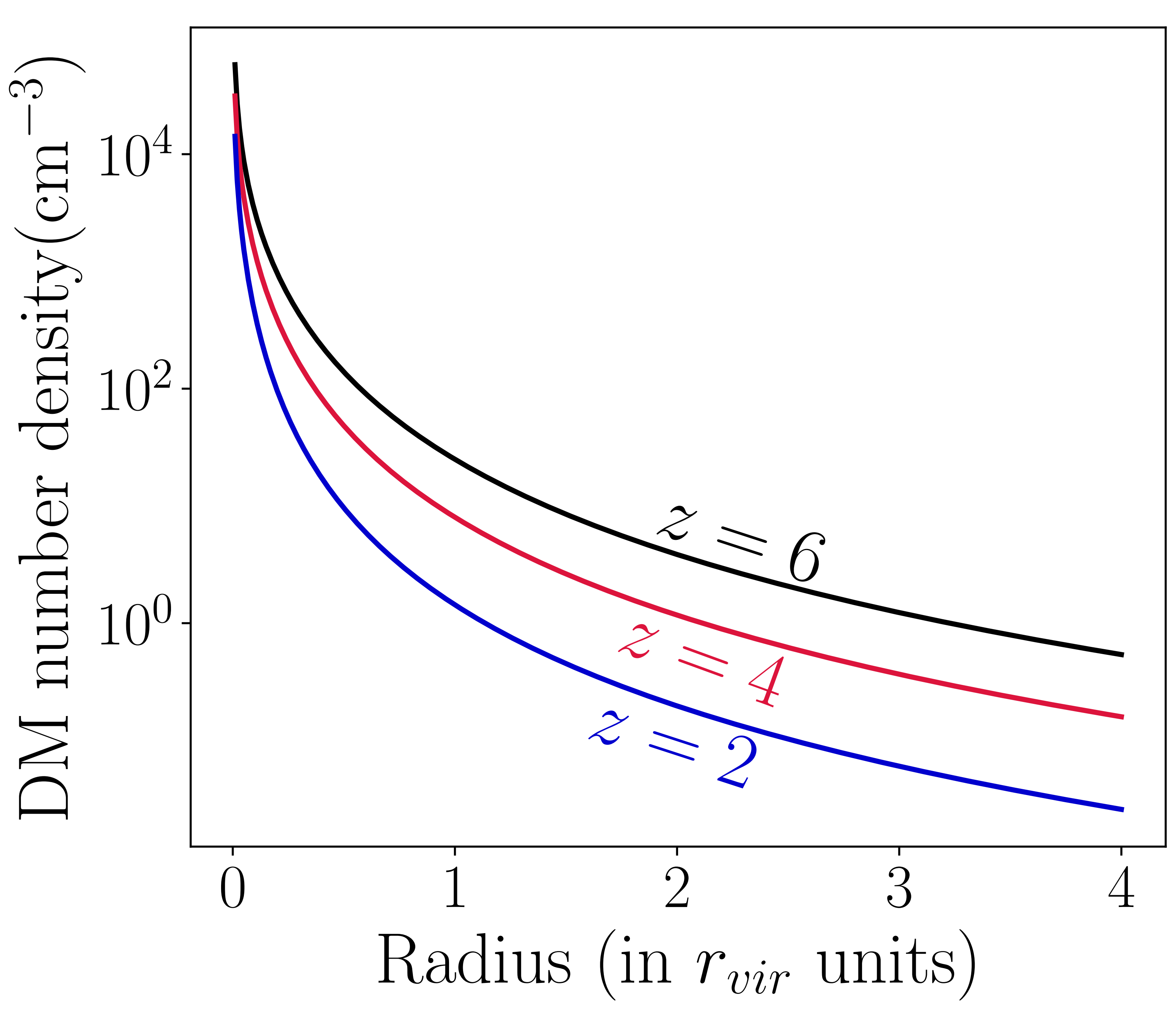
Doppler line profile (ϕ_ν)

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



Properties of the halo decide the shape of the absorption line





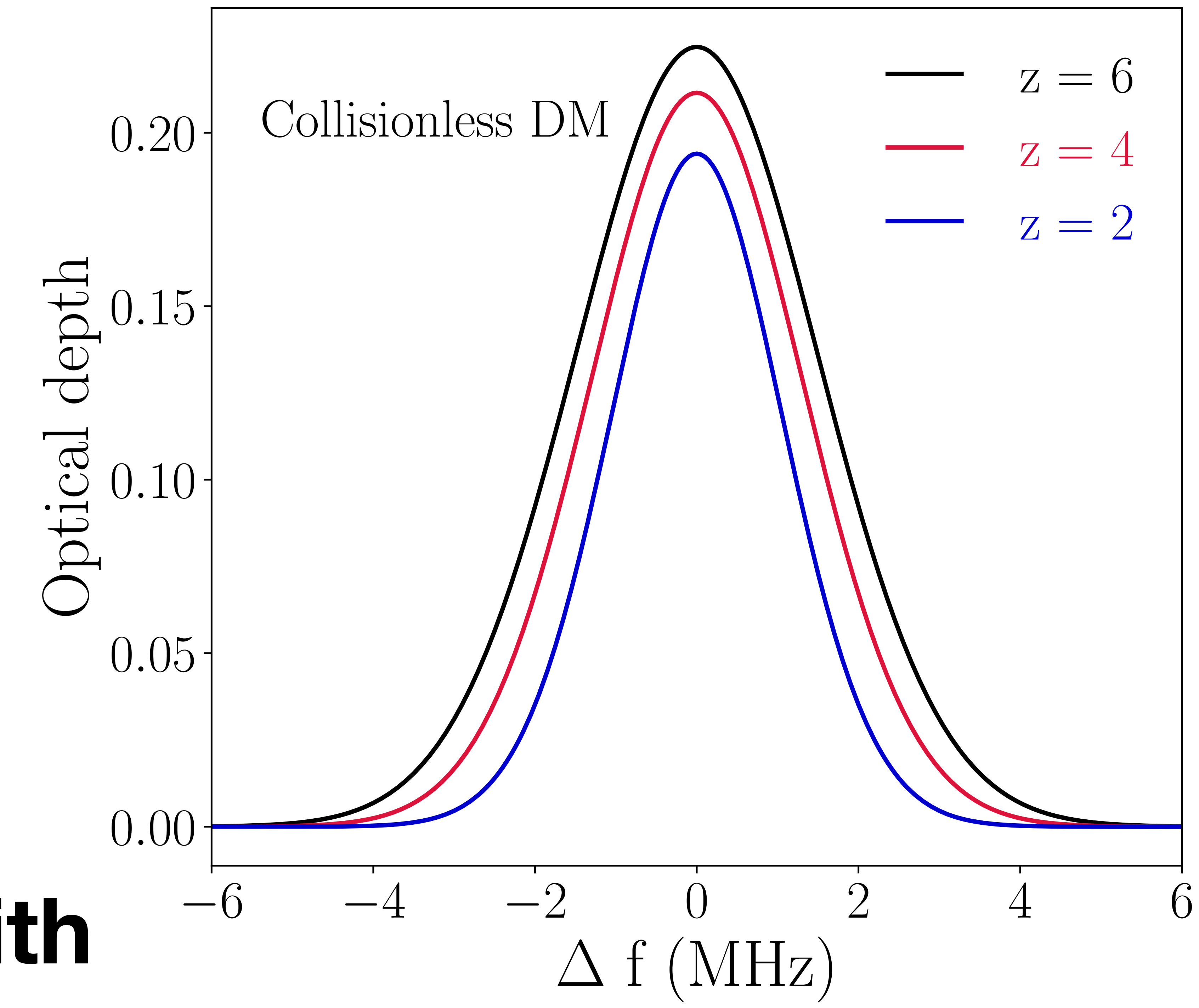
For halo masses <$10^8 M_\odot/h$,

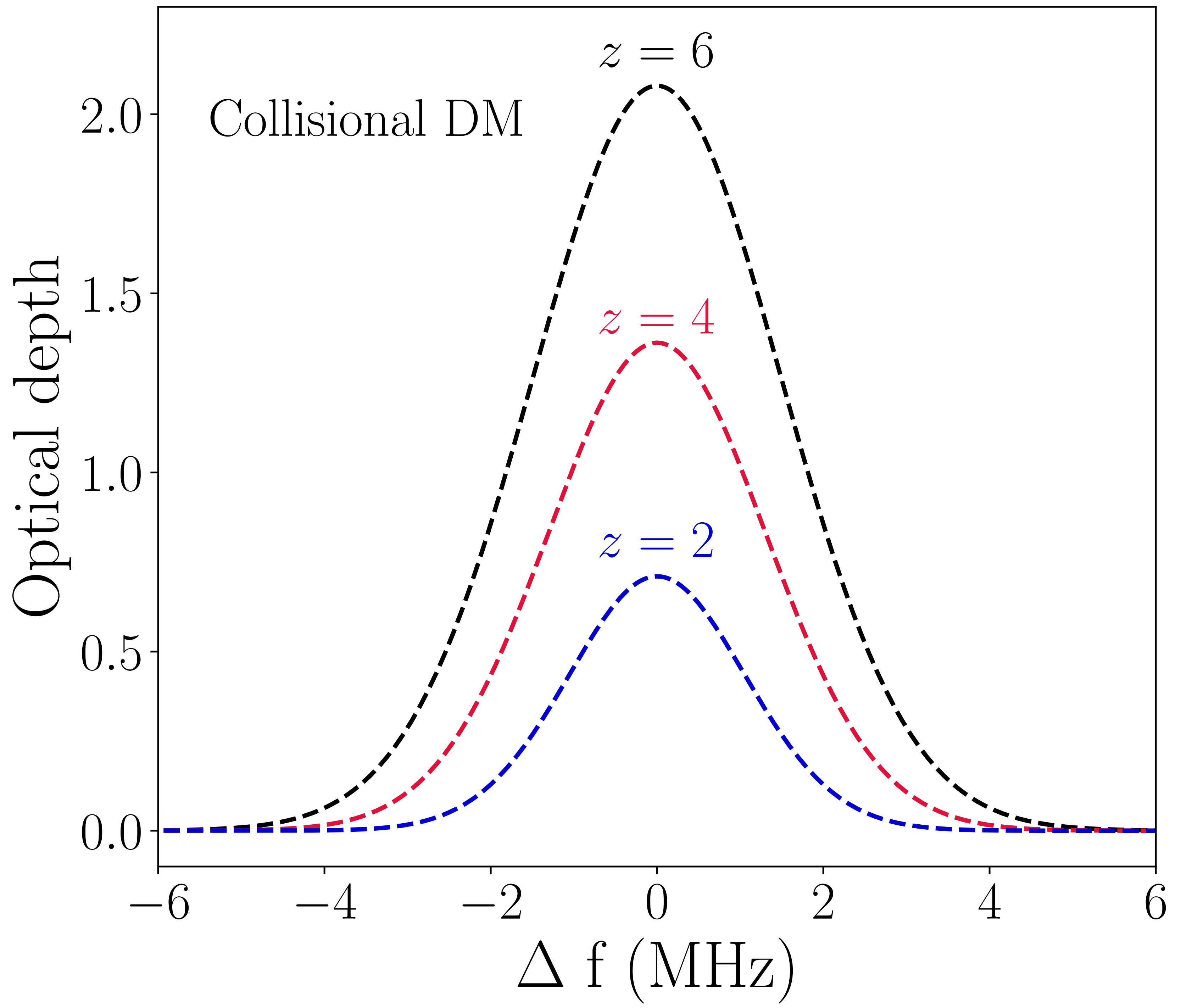
$T_{CMB} > T_{halo}$

Dark matter number density increases with redshift

Dark line - absorption by a single DM halo

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

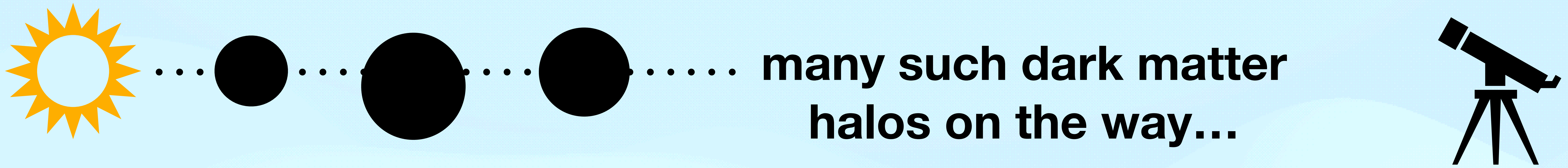




Halo mass: $10^6\ M_\odot/h$

Impact parameter : 0.5 r_{vir}

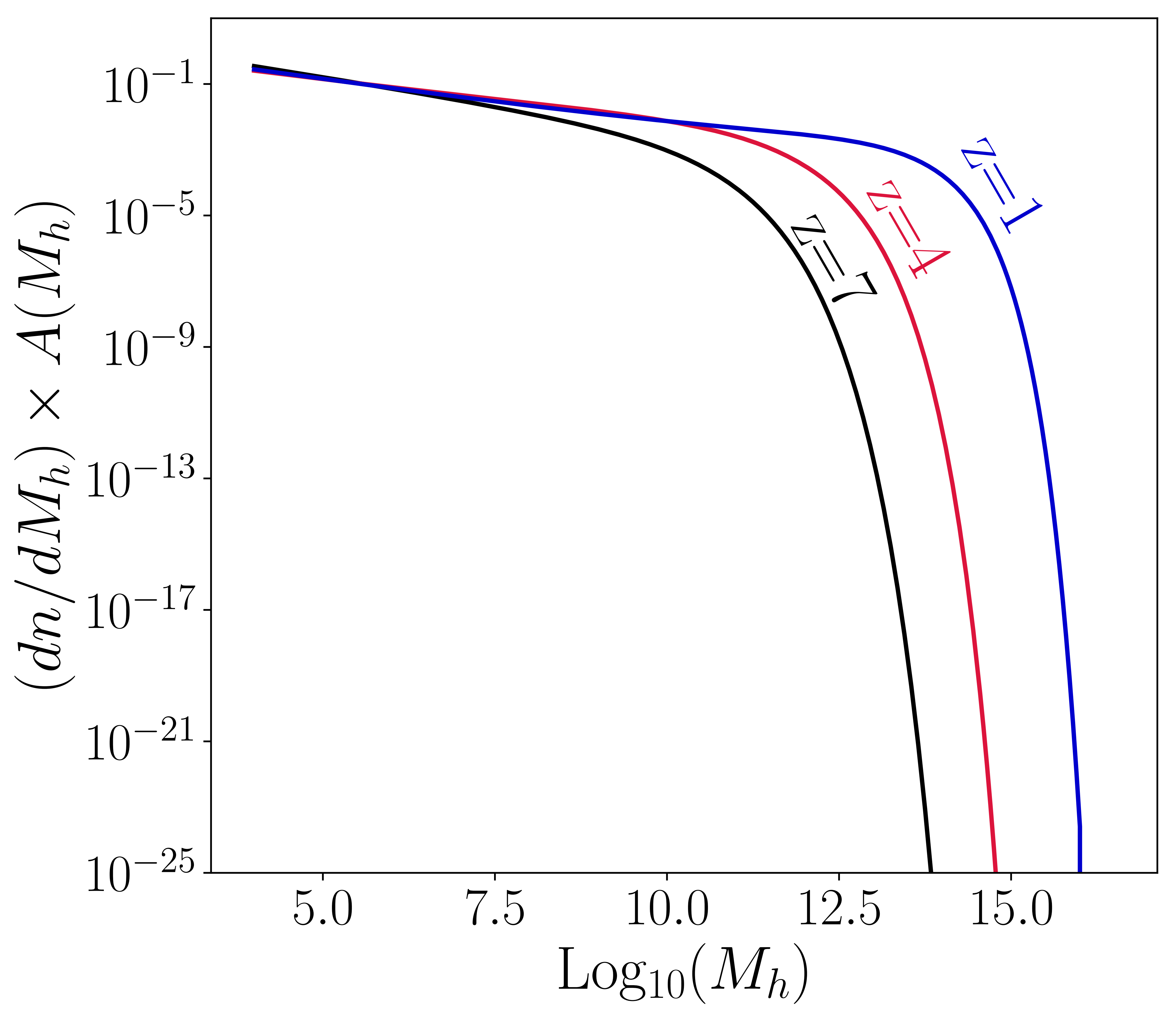
Dark forest - absorption by multiple dark matter halos



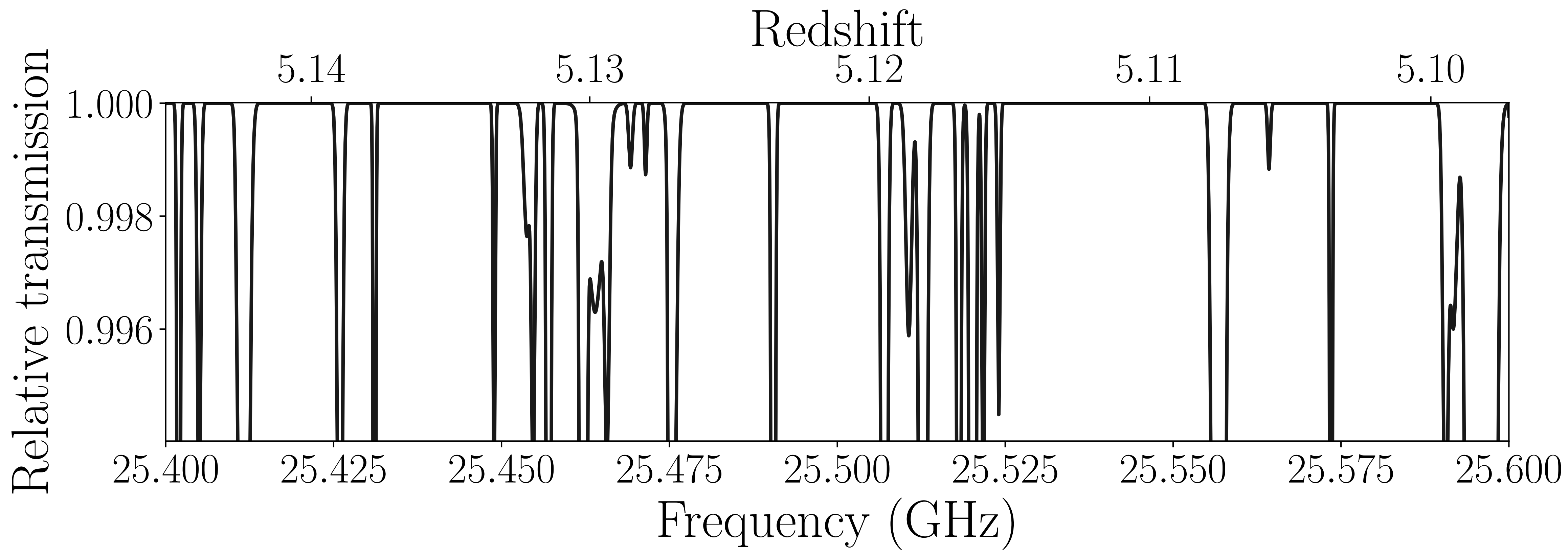
- Probability of intersecting a halo = fraction of the total area occupied by the halo
- Randomly sample halo masses
- Randomly impact parameter from uniform probability over the cross-sectional area

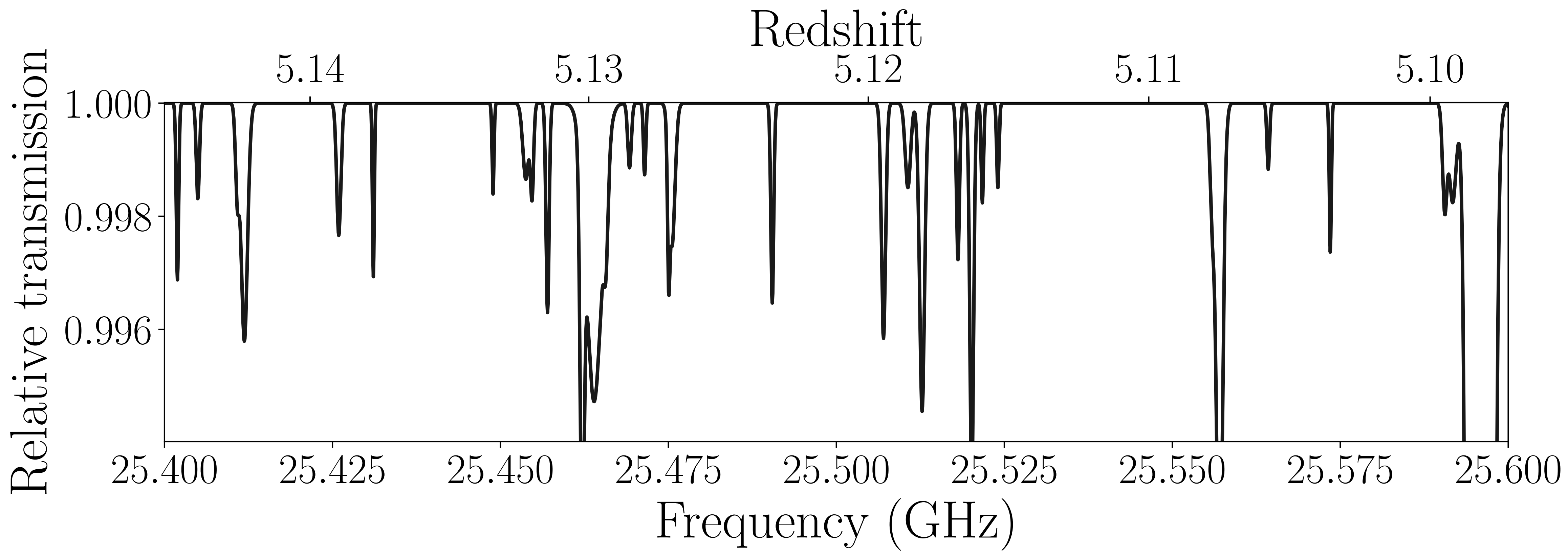
Furlanetto & Loeb 2002, Xu et al. 2011

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

	$SU(N)$	$SU(2)^D_L$	$SU(2)^D_R$	$U(1)_D$	$U(1)_{\text{em}}$
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 the 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: $A_{10}^{\rm DM} \approx \epsilon^2 \left(\frac{\Delta E_{\rm hf}^{\rm DM}}{\Delta E_{\rm hf}^{\rm HI}}\right)^3 \left(\frac{m_e}{m_q}\right)^2 A_{10}^{\rm HI}$

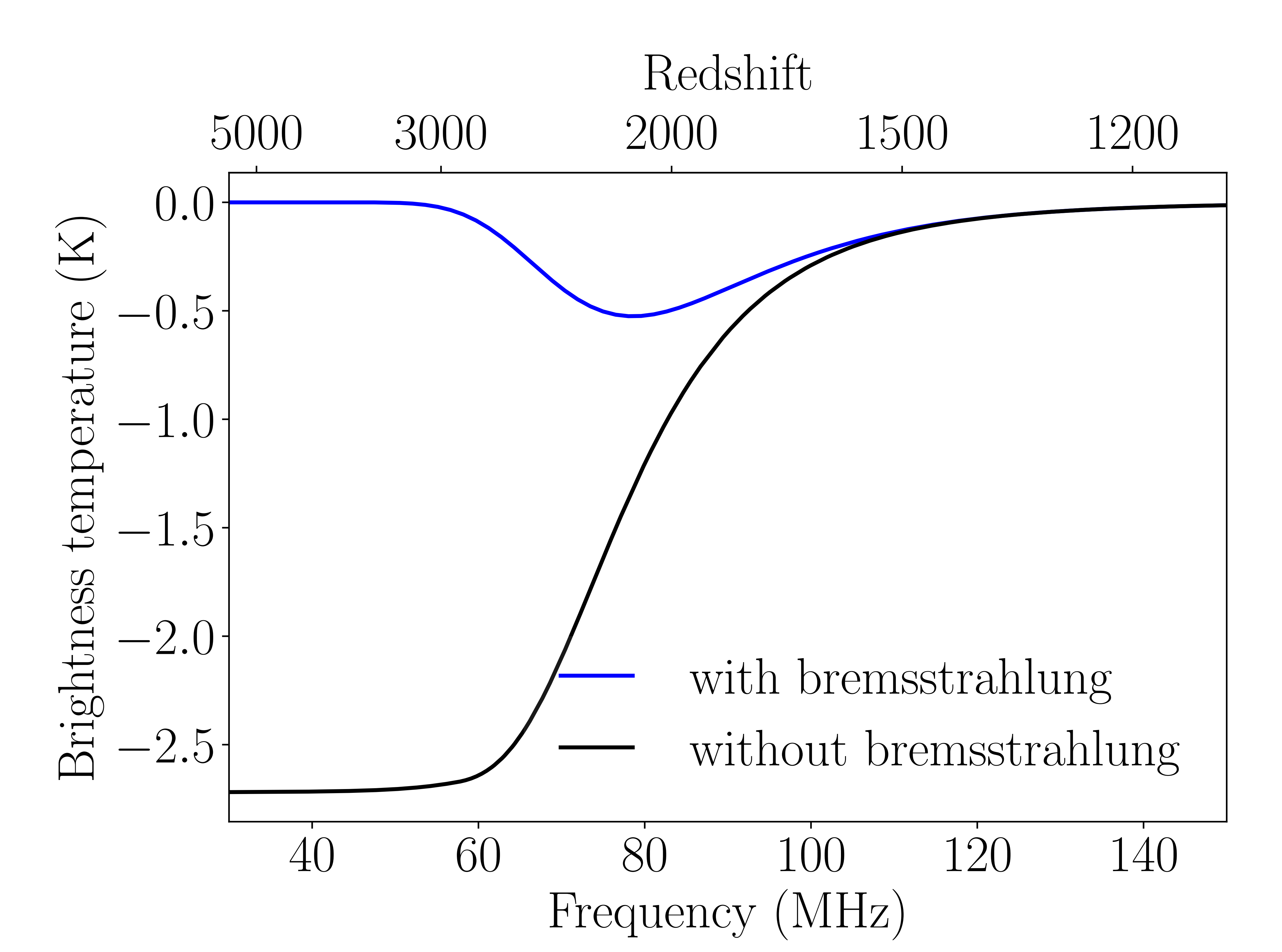
Bohr radius: $r_{\rm HI} = \frac{\alpha}{E_{\rm binding}^{\rm HI}}$

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

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**



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