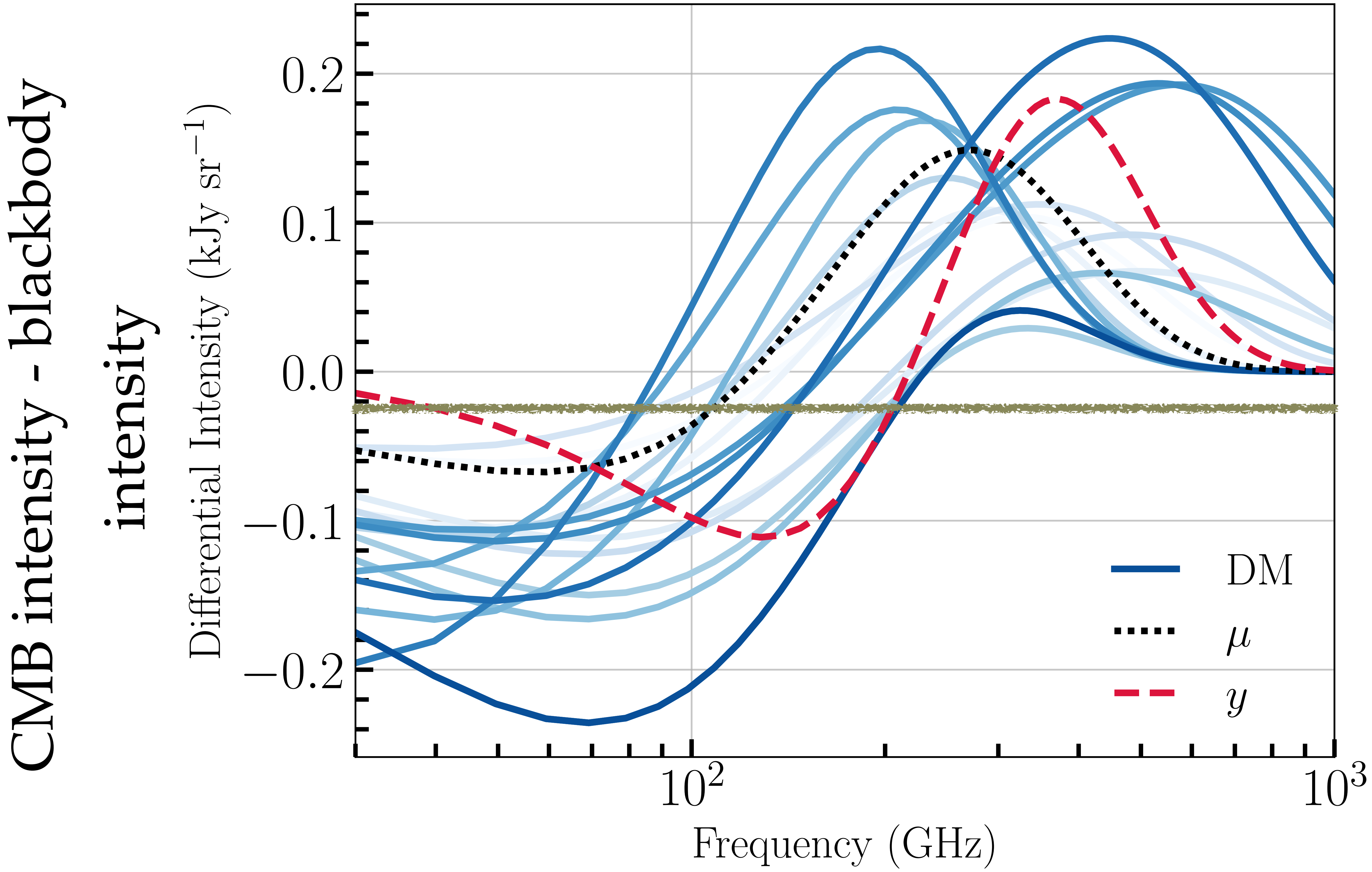
Signatures of composite dark matter in the CMB spectral distortions



Anoma Ganguly

(with Rishi Khatri and Tuhin S. Roy)

(arXiv: 2301.03624, 2407.14480)

THE UNIVERSITY OF ARIZONA

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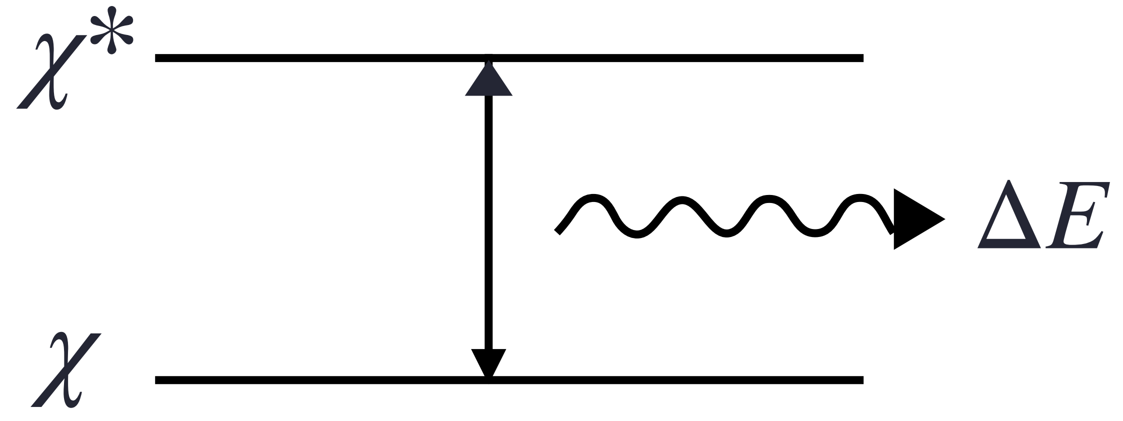
Les Houches' 25

Dark matter signatures as new features in the source spectrum

Searching dark matter through new lines/features in the spectrum of a background source (CMB and quasar/galaxy) across the full electromagnetic spectrum

Multiple states
+
Weak electromagnetic interactions

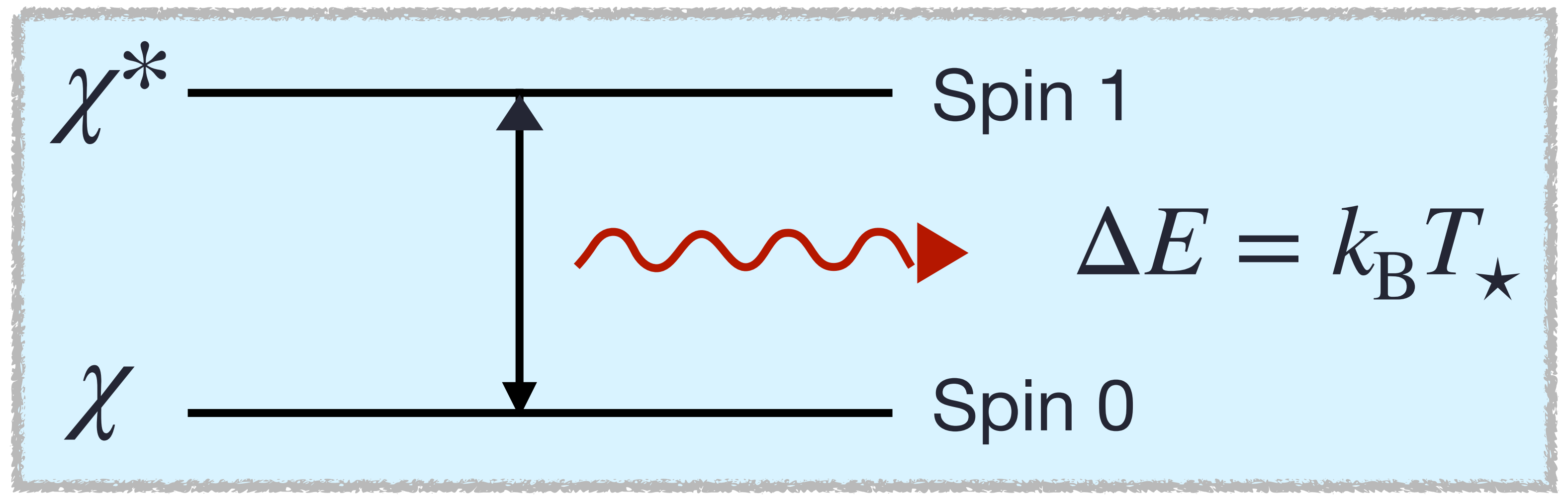
Absorption and (or) emission signal



Dark matter model setup

Dark matter as a two-state system

Dark matter comprises of two states which can transition by emitting/absorbing a photon of energy ΔE:



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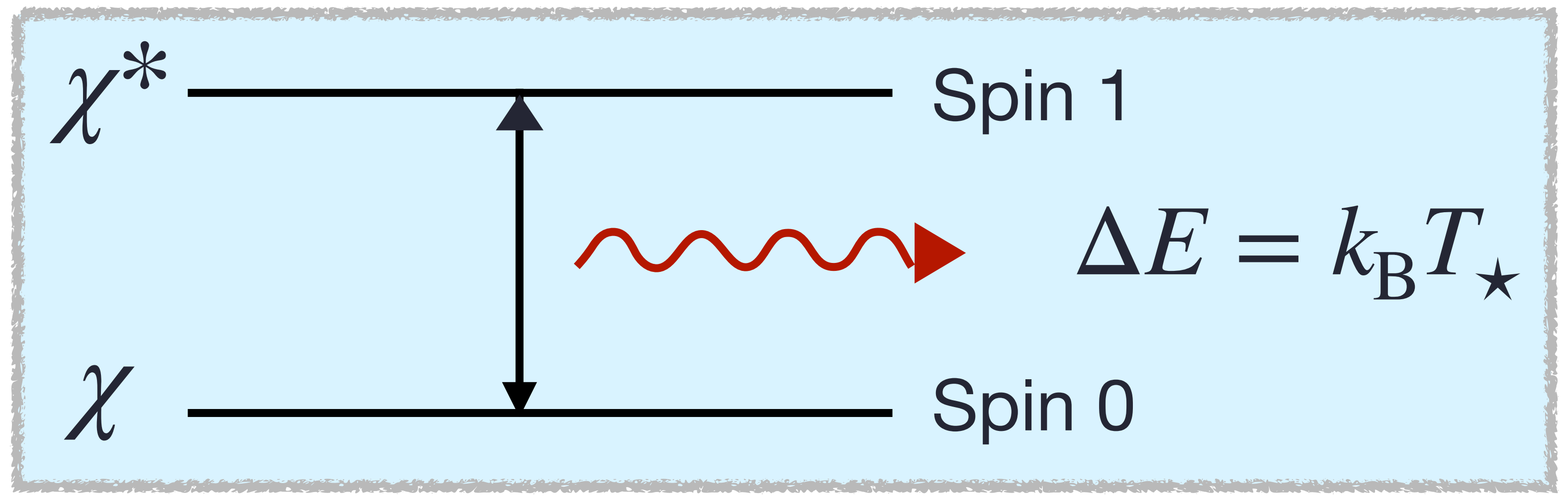

The excitation temperature T_{ex} characterizes the population of dark matter particles in the two states:

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

Transitions in the two-state dark matter

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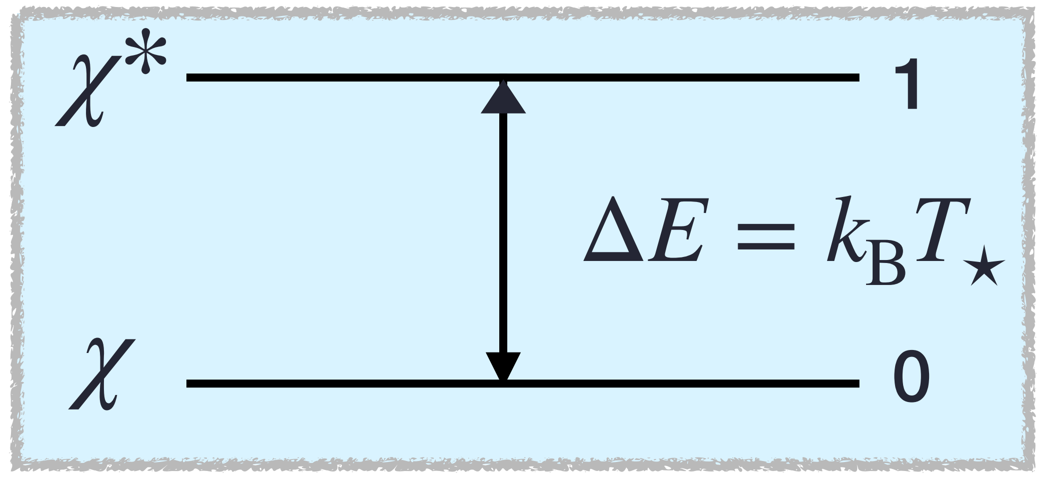


The transitions between the two states happens due to:

Collisional transitions

$T_{ex} \to T_{DM}$

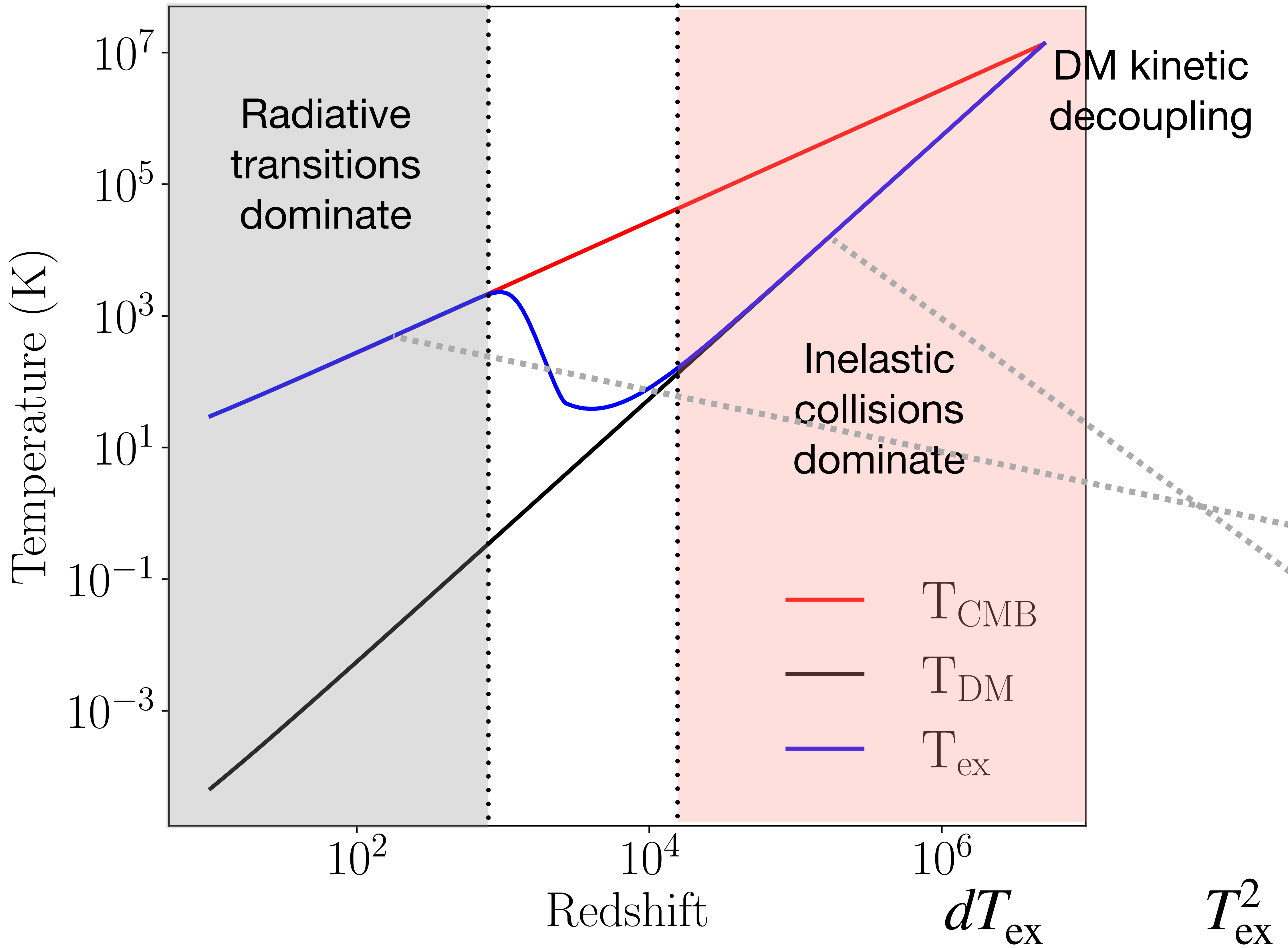
Radiative transitions

$T_{ex} \to T_{CMB}$

$$\frac{dT_{\rm ex}}{dz} = \frac{T_{\rm ex}^2}{T_*(1+z)}\left(\frac{\tilde{C}_{10}}{H}\left(1 - e^{-T_*\left(\frac{1}{T_{\rm DM}} - \frac{1}{T_{\rm ex}}\right)}\right) + \frac{\tilde{A}_{10}}{H}\left(1 - e^{-T_*\left(\frac{1}{T_\gamma} - \frac{1}{T_{\rm ex}}\right)}\right)\right)$$

Interactions between CMB and dark matter

Absorption feature in the CMB spectrum is created when $T_{ex} < T_{CMB}$



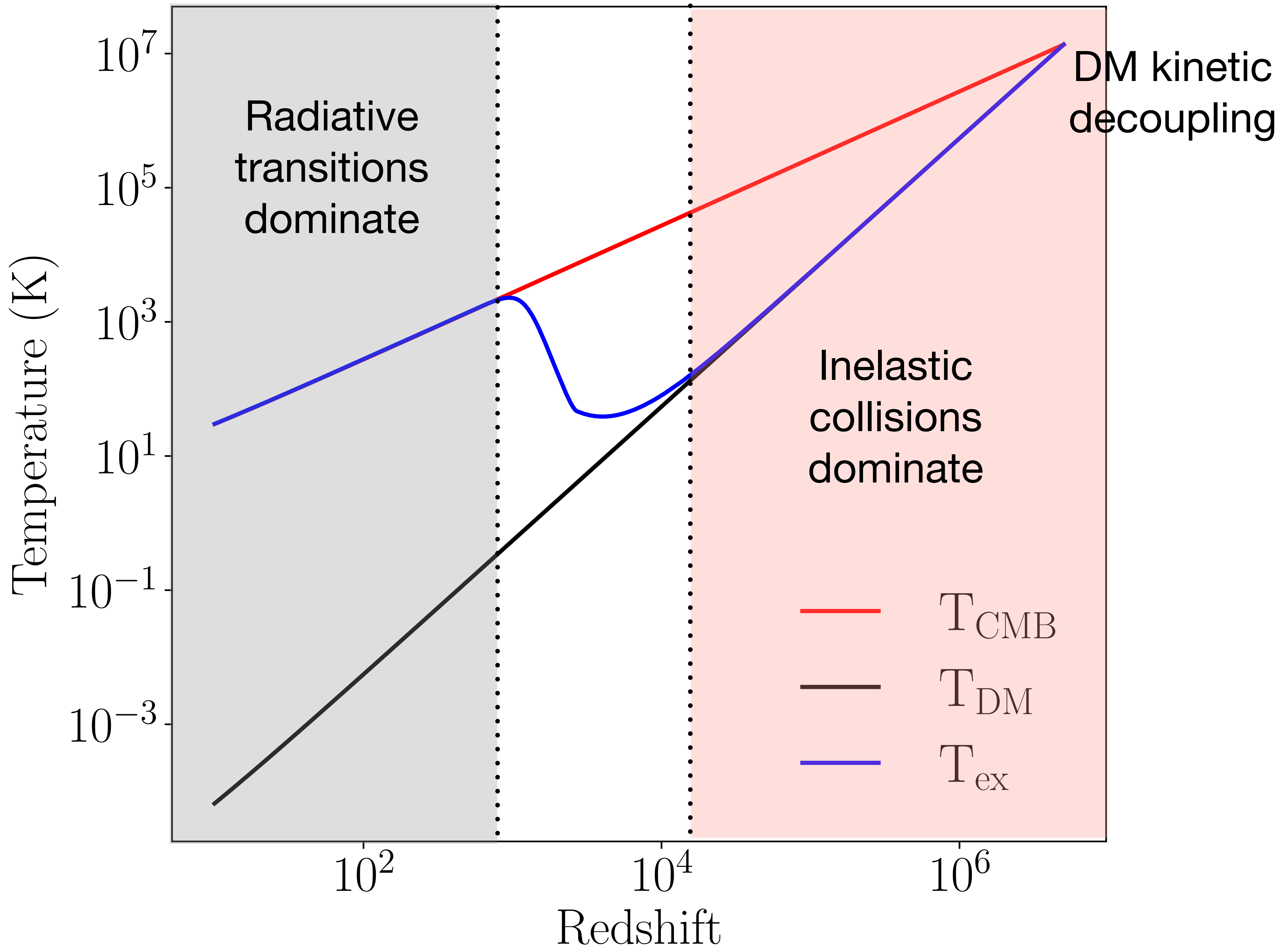
$$\frac{n_0}{n_1} \equiv \frac{g_0}{g_1}\exp\left(\frac{T_\star}{T_{ex}}\right)$$

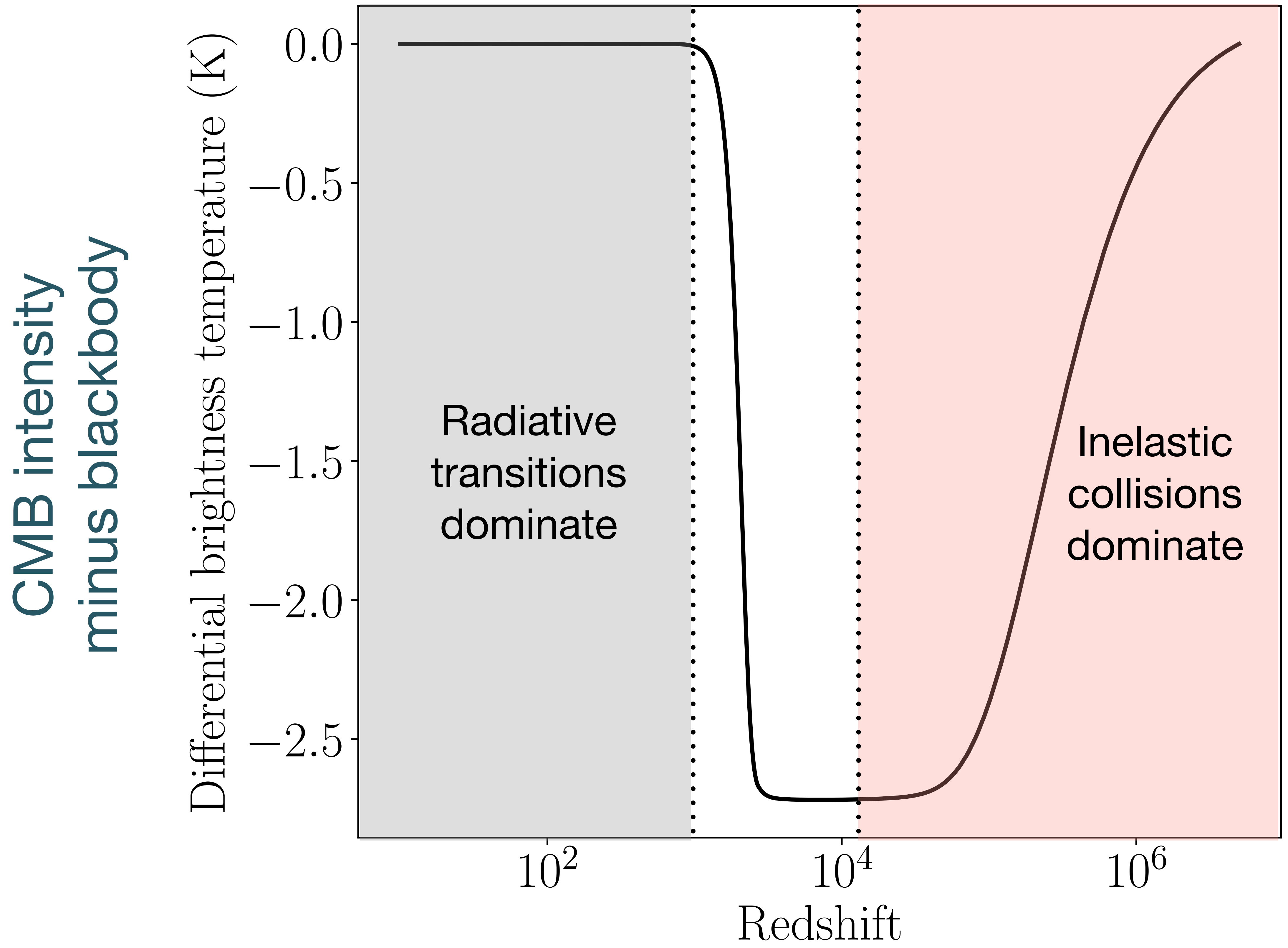
Collisional transitions — Radiative transitions

$$\frac{dT_{\rm ex}}{dz} = \frac{T_{\rm ex}^2}{T_*(1+z)}\left(\frac{\tilde{C}_{10}}{H}\left(1-e^{-T_*\left(\frac{1}{T_{\rm DM}}-\frac{1}{T_{\rm ex}}\right)}\right)+\frac{\tilde{A}_{10}}{H}\left(1-e^{-T_*\left(\frac{1}{T_{\rm CMB}}-\frac{1}{T_{\rm ex}}\right)}\right)\right)$$

$T_{ex} \to T_{DM}$ — $T_{ex} \to T_{\rm CMB}$

Absorption feature in the CMB spectrum is created when $T_{ex} < T_{CMB}$



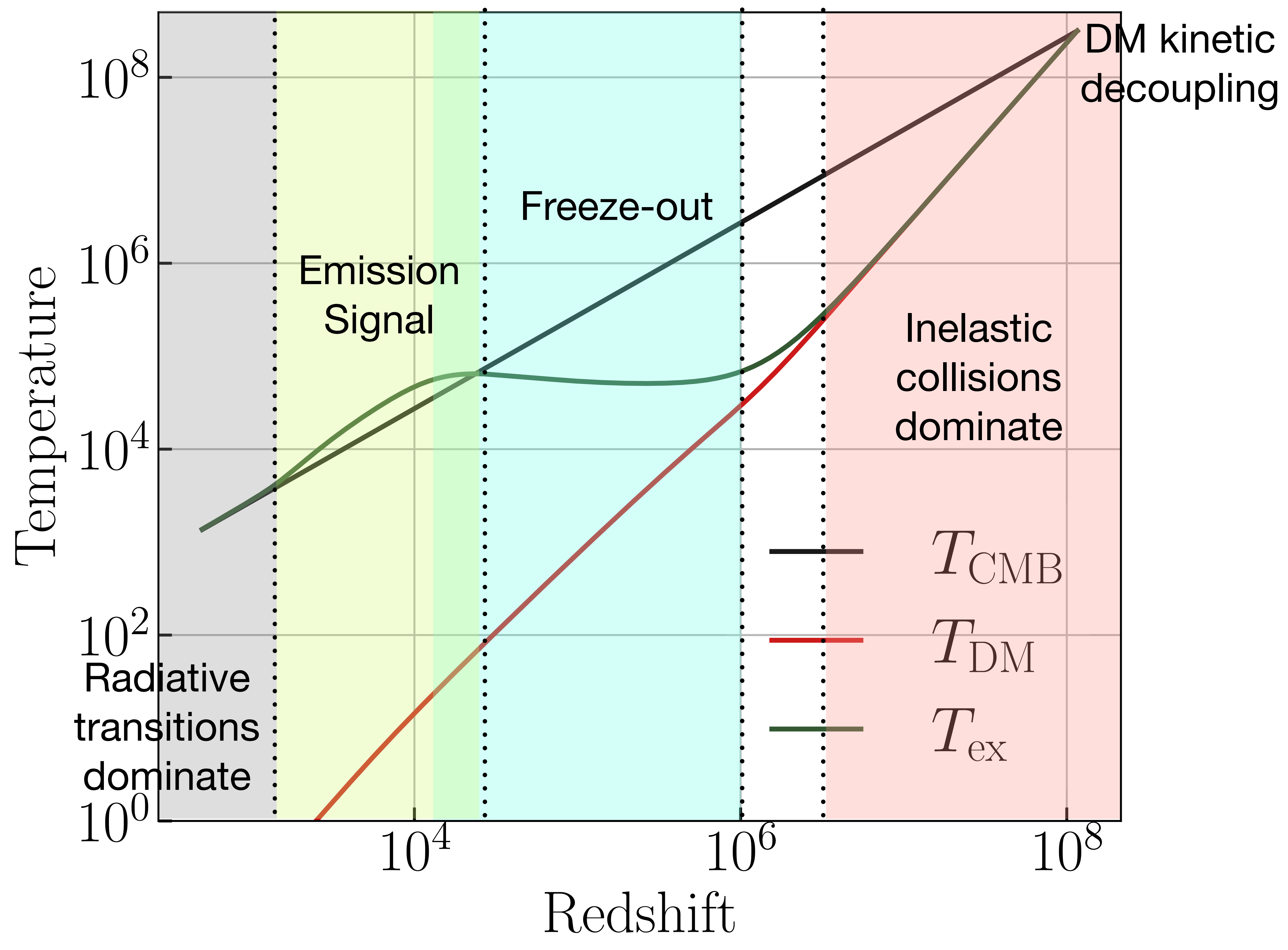


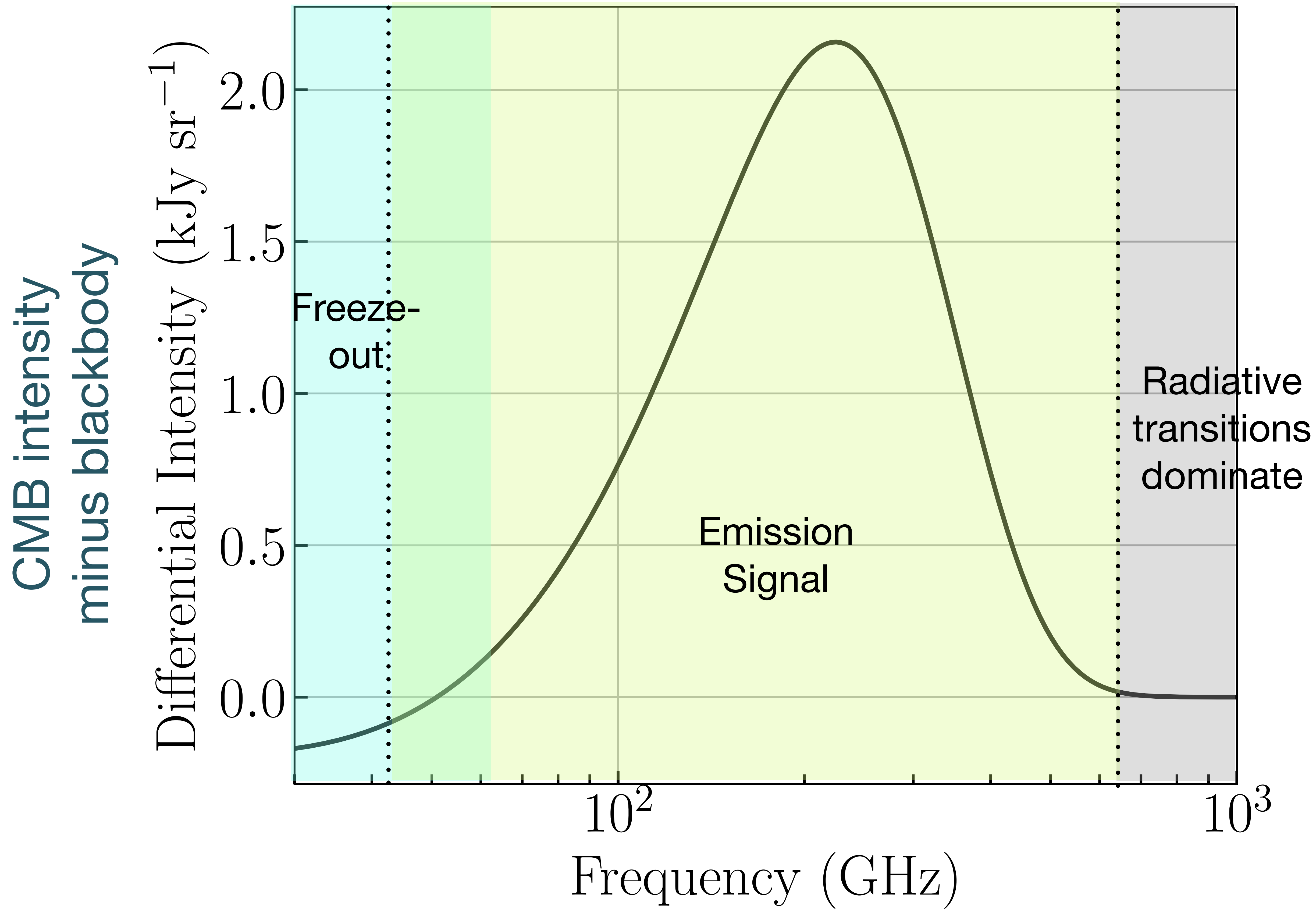
- When collisional transitions >> radiative transitions and Hubble expansion rate:

$T_{ex} \approx T_{DM} < T_{CMB} \rightarrow$ Dark matter absorbs CMB photons

- As DM number density falls, radiative transitions take over and the absorption signal vanishes

Emission feature in the CMB spectrum is created when $T_{ex} > T_{\gamma}$





- When collisional transition and radiative transition rates << Hubble expansion rate ⟶ T_{ex} freezes out,

$T_{ex} > T_{CMB}$ → Dark matter emits CMB photons

Interactions between CMB, dark matter, baryons, and electrons

Leading interactions between CMB, baryons, and electrons

Only photon energy changing process (independent of x):

Compton scattering: $e^- + \gamma \longleftrightarrow e^- + \gamma$

Maintains $T_{\text{electron}} \approx T_{\text{CMB}} \propto (1+z)$ till $z \sim 150$

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Maintains $T_{\rm electron} \approx T_{\rm CMB} \propto (1+z)$ till $z \sim 150$

$+$

Photon number and energy changing processes $\propto 1/x^2$:

Double Compton scattering : $e^- + \gamma \longleftrightarrow e^- + \gamma + \gamma$

Bremsstrahlung: $e^- + {\rm H}^+/{\rm He}^+/{\rm He}^{++} \longleftrightarrow e^- + {\rm H}^+/{\rm He}^+ + \gamma$

Important only in the low frequency tail
$(x \ll 1)$

$$x \equiv \frac{h\nu}{k_{\rm B} T_{\rm CMB}}$$

Kompaneets equation modified in the presence of a monochromatic source

The photon distribution function $n(x_e, t)$ is described by the modified Kompaneets equation:

$$\frac{\partial n(x_e,t)}{\partial t} = K_C \frac{1}{x_e^2}\frac{\partial}{\partial x_e} x_e^4 \left(n + n^2 + \frac{\partial n}{\partial x_e} \right) + \left(K_{br} + K_{dC}\right) \frac{e^{-x_e}}{x_e^3}\left[1 - n(e^{x_e} - 1)\right] + \frac{I_2}{b_R}\frac{1}{x_e^2 T_e^3}\dot{N}_{\chi\gamma}\delta(x_e - x_0(t))$$

$$x_e = \frac{h\nu}{k_B T_{electron}}$$

Compton scattering

$$n_{eq} \to \frac{1}{e^{x_e+\mu} - 1}$$

Double Compton scattering + bremsstrahlung

$$n_{eq} \to \frac{1}{e^{x_e} - 1}$$

Dark matter transitions at ν_0

$$x_0 = \frac{h\nu_0}{k_B T_{electron}}$$

Timeline of CMB spectral distortions caused by dark matter transitions

← Redshift (z)

$z \gtrsim 2 \times 10^6$	$2 \times 10^6 \gtrsim z \gtrsim 10^5$	$z \lesssim 10^5$
Compton scattering + Bremsstrahlung + double Compton scattering **active** Planck spectrum → No distortions		

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Timeline of CMB spectral distortions caused by dark matter transitions

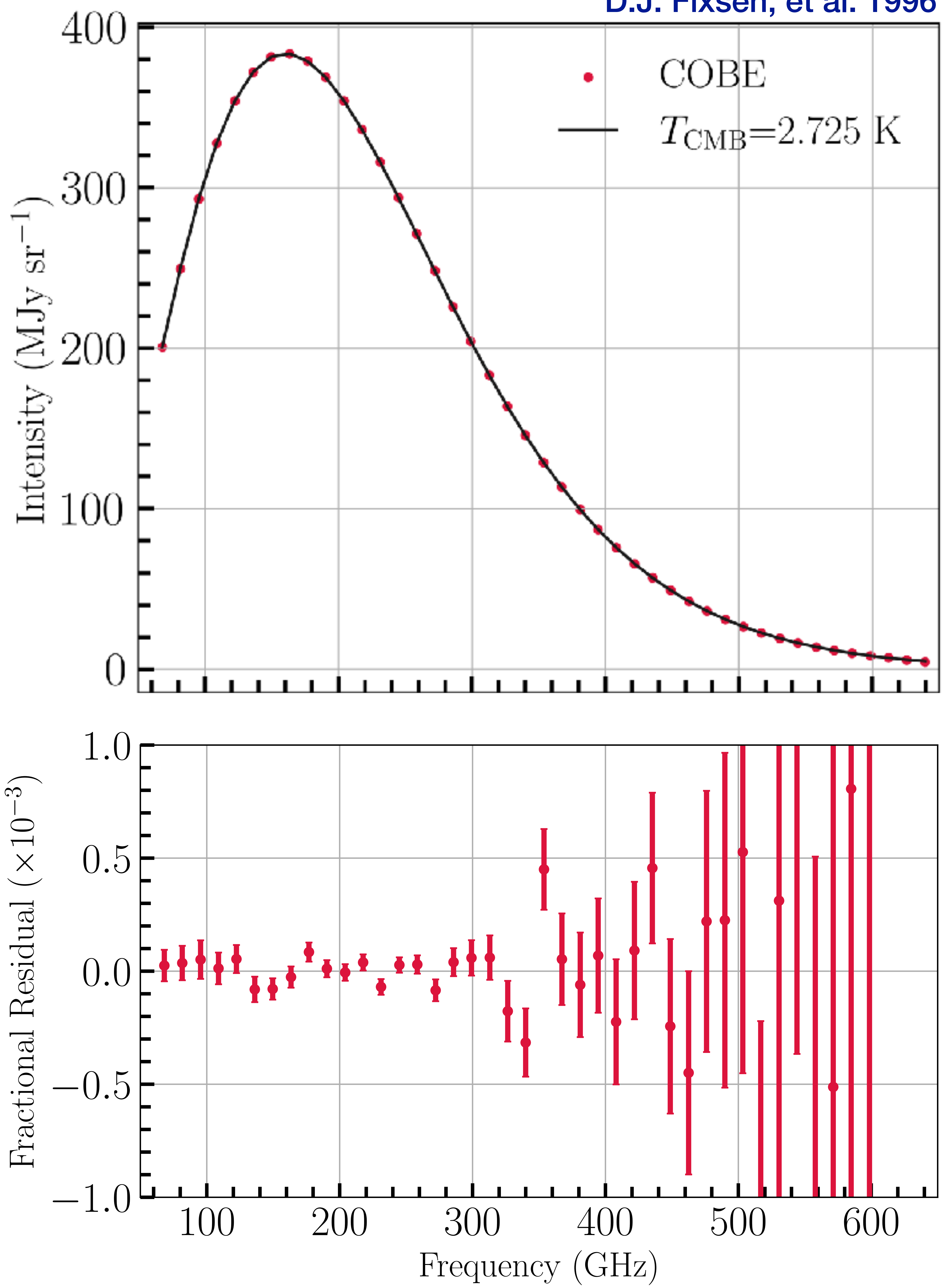
← Redshift (z)

$z \gtrsim 2 \times 10^6$	$2 \times 10^6 \gtrsim z \gtrsim 10^5$	$z \lesssim 10^5$	
		Low frequency transition $h\nu_0 \ll k_B T_{CMB}$	High frequency transition $h\nu_0 \gtrsim k_B T_{CMB}$
Compton scattering + Bremsstrahlung + double Compton scattering **active** Planck spectrum → No distortions	Only Compton scattering **active** Bose-Einstein spectrum → μ-distortions	Bremsstrahlung + Inefficient Compton scattering with thermal electrons y-distortions Upto $z \gtrsim 10^3$	All standard thermal processes **inactive** Non-thermal distortions Final spectrum obtained by solving the radiative transfer equation

The microwave band of the CMB spectrum

COBE has established CMB to be a perfect blackbody at the level of ~ 1 part in 10^4

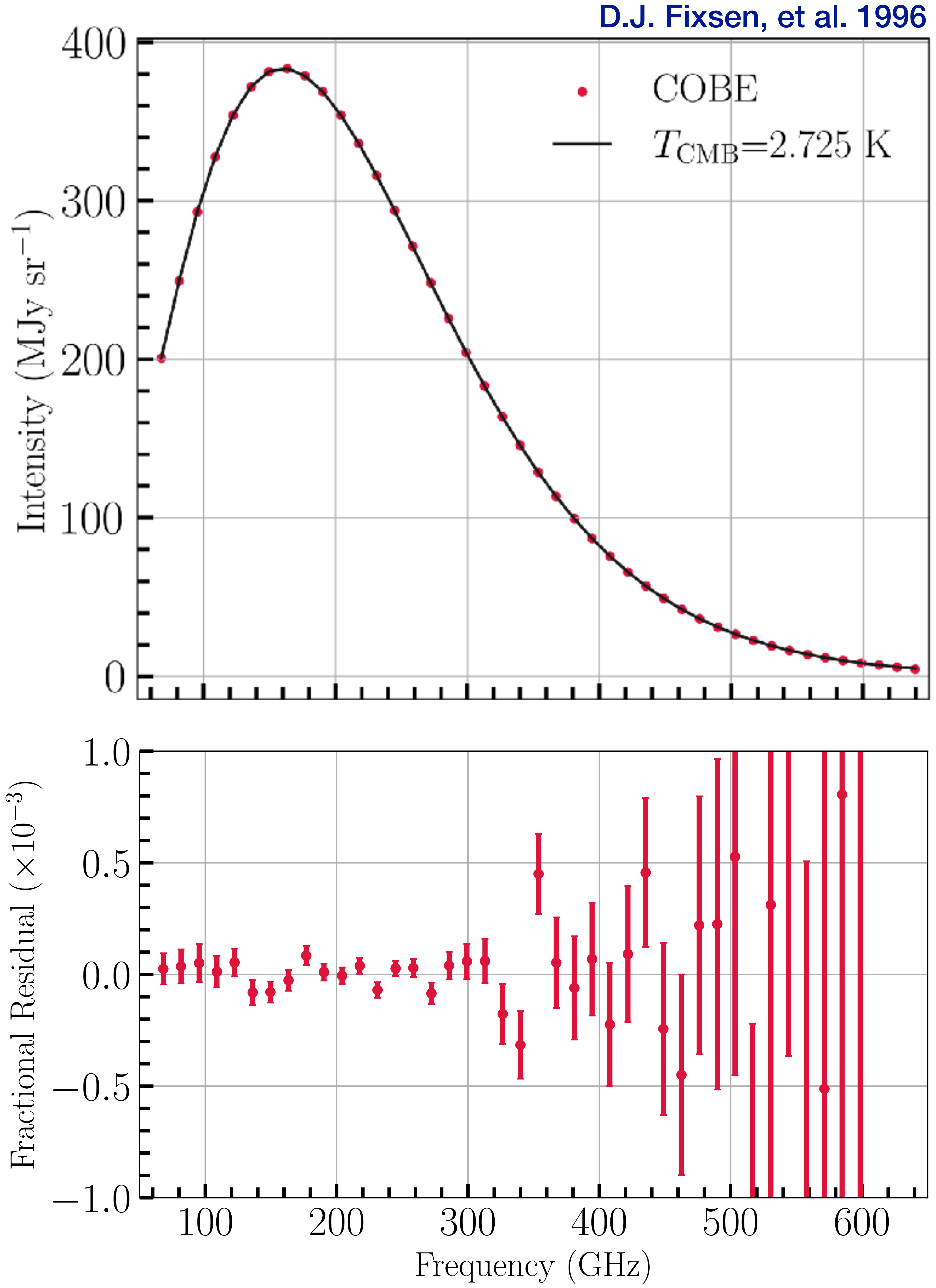
D.J. Fixsen, et al. 1996



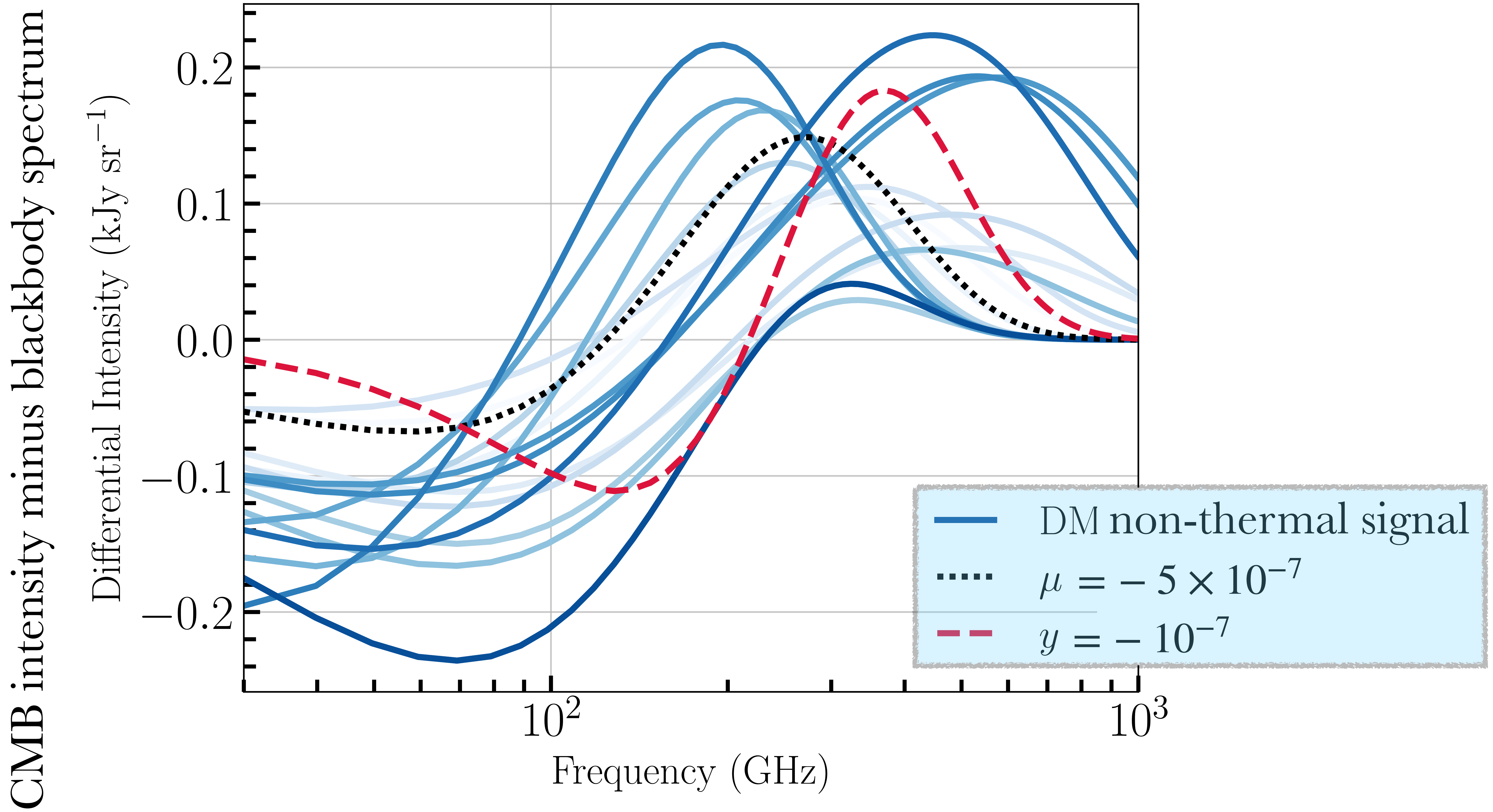
The microwave band of the CMB spectrum

COBE has established CMB to be a perfect blackbody at the level of ~ 1 part in 10^4

In future, PIXIE will probe the deviations from a blackbody at the level of ~ 1 part in 10^8 !



Spectral distortion features in the microwave band will be detectable by PIXIE



Non-thermal distortions in the CMB have distinct shapes from the thermal μ and y distortions.

More accurate constraints using the universal distortion parameter u

COBE constrains μ and y distortions independently

$\mu < 9 \times 10^{-5}$ and $y < 1.5 \times 10^{-5}$

Universal distortion measure

$$u \equiv \frac{\mu}{1.4} + 4y$$

$$\mu = 1.4\left(\frac{\Delta\mathscr{E}}{\mathscr{E}} - \frac{4}{3}\frac{\Delta\mathscr{N}}{\mathscr{N}}\right)$$

$$y = \frac{1}{4}\frac{\Delta\mathscr{E}}{\mathscr{E}}$$

Fractional change in the energy density of CMB photons

Fractional change in the number density of CMB photons

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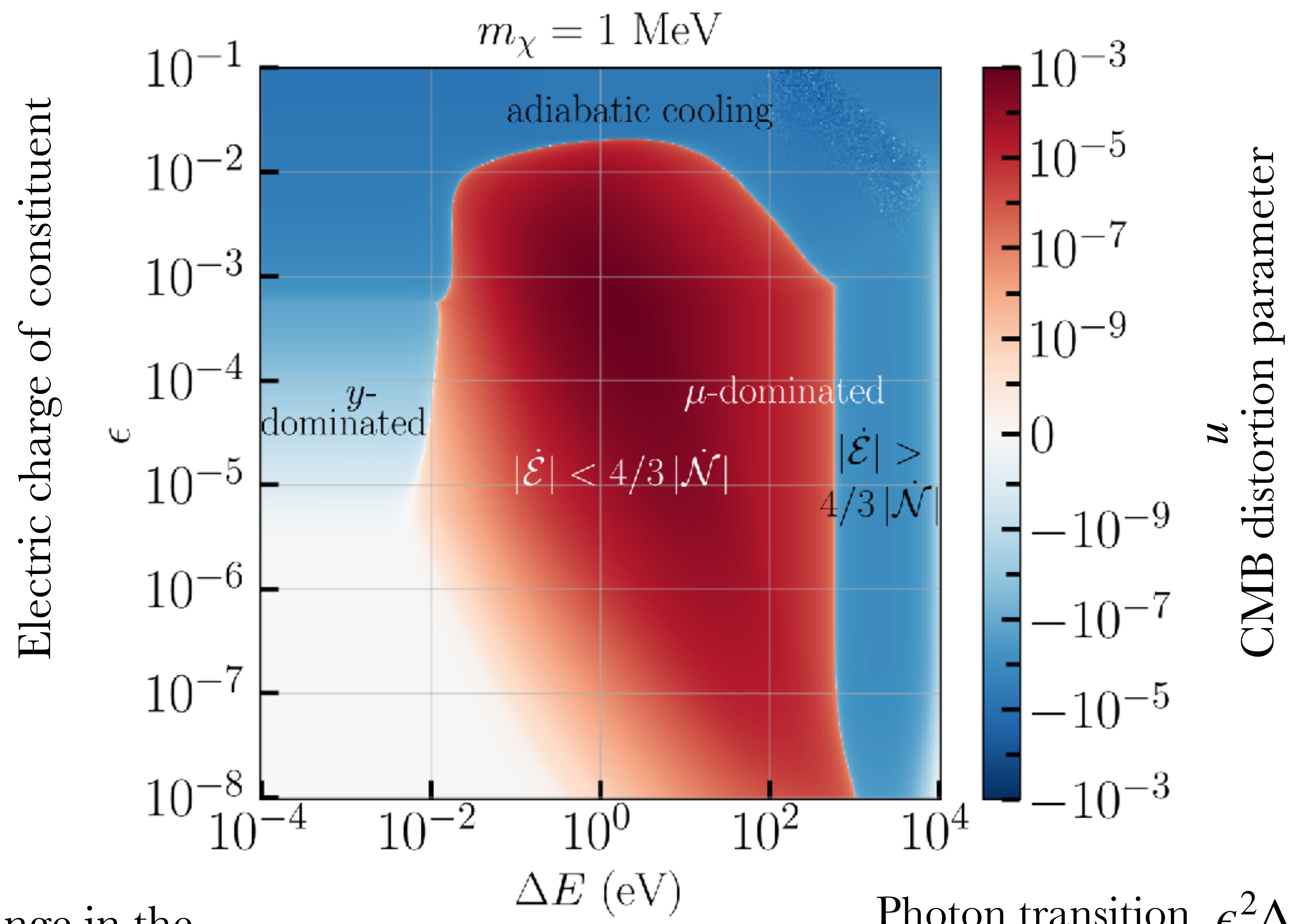
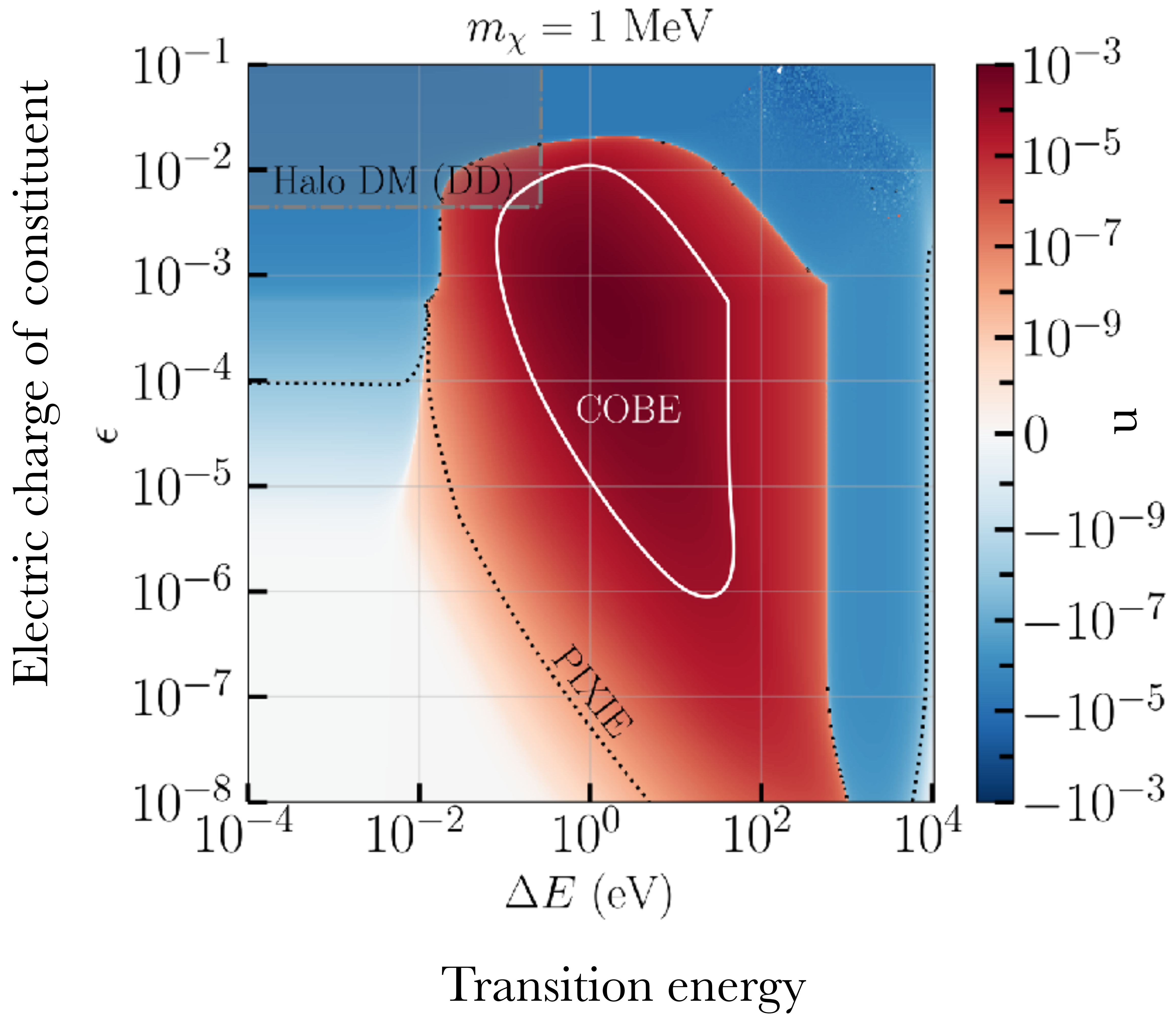


Transition energy

Photon transition rate $\propto \dfrac{\epsilon^2 \Delta E^3}{m_\chi^2}$

Spectral distortion constraints are stronger than the direct detection bounds

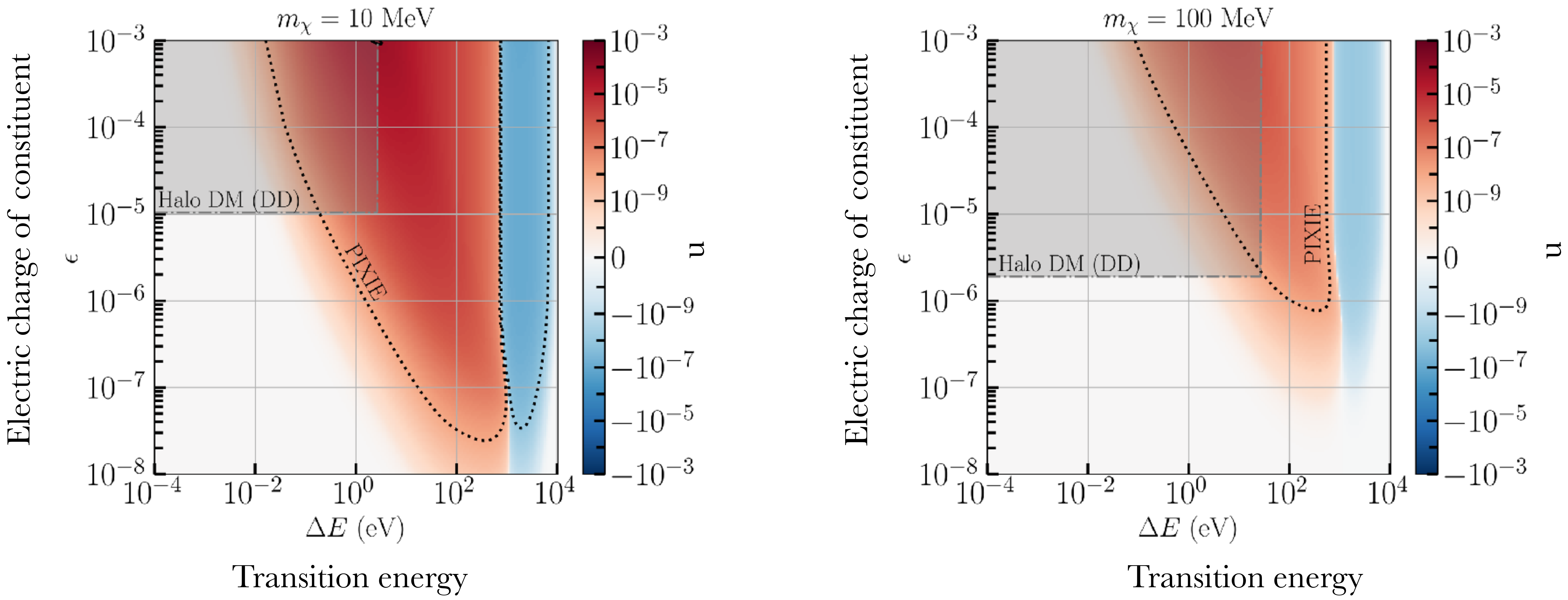


$$u \equiv \frac{\mu}{1.4} + 4y$$

2-σ limit from COBE: $u \leq 6 \times 10^{-5}$

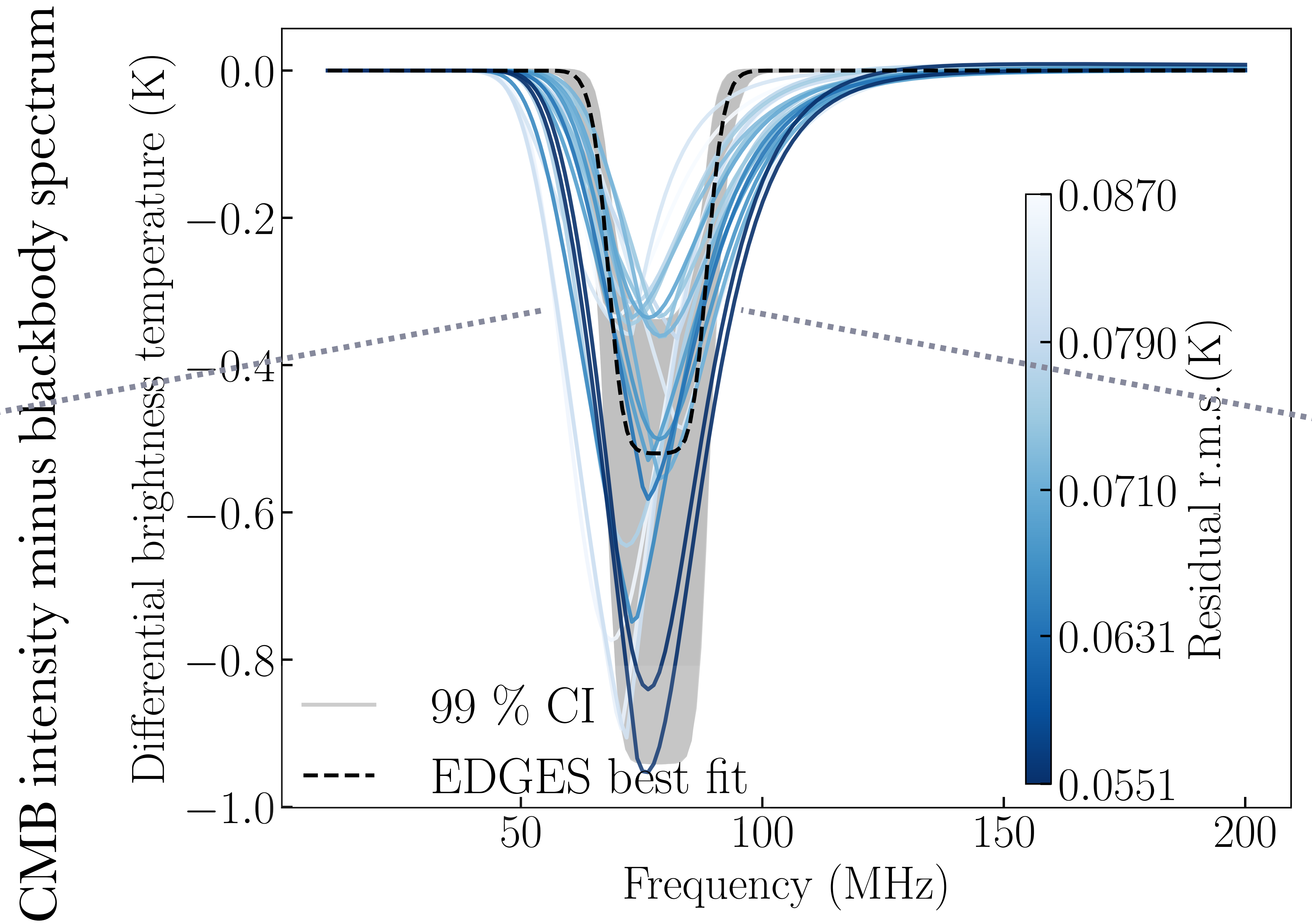
2-σ limit from PIXIE: $u \leq 10^{-8}$

Spectral distortion constraints weaker for larger dark matter mass



Non-thermal spectral distortions detectable in 21-cm experiments

Efficiency of bremsstrahlung at high z



Collision rate vs. radiative transition rate

Our dark matter model can produce absorption signals consistent with EDGES for $\Delta E \sim 100$ GHz at z ~ 1000 in observed frequency band of 50-100 MHz.

Conclusions

- We propose new indirect probes to detect dark matter through lines/ features in the spectrum of a background source.
- Dark matter can give rise to both thermal and non-thermal spectral distortions in the CMB which will be detectable in the next-generation PIXIE-like experiments in 30-600 GHz band.
- The radio frequency (50-100 MHz) experiments aiming to measure the 21 cm global signal would be sensitive to the non-thermal spectral distortion signatures of dark matter.
- The current limits on our model from COBE are much stronger than the current limits from direct detection experiments.

Thank you!