Baryon-DM interactions and magnetic fields during the dark ages

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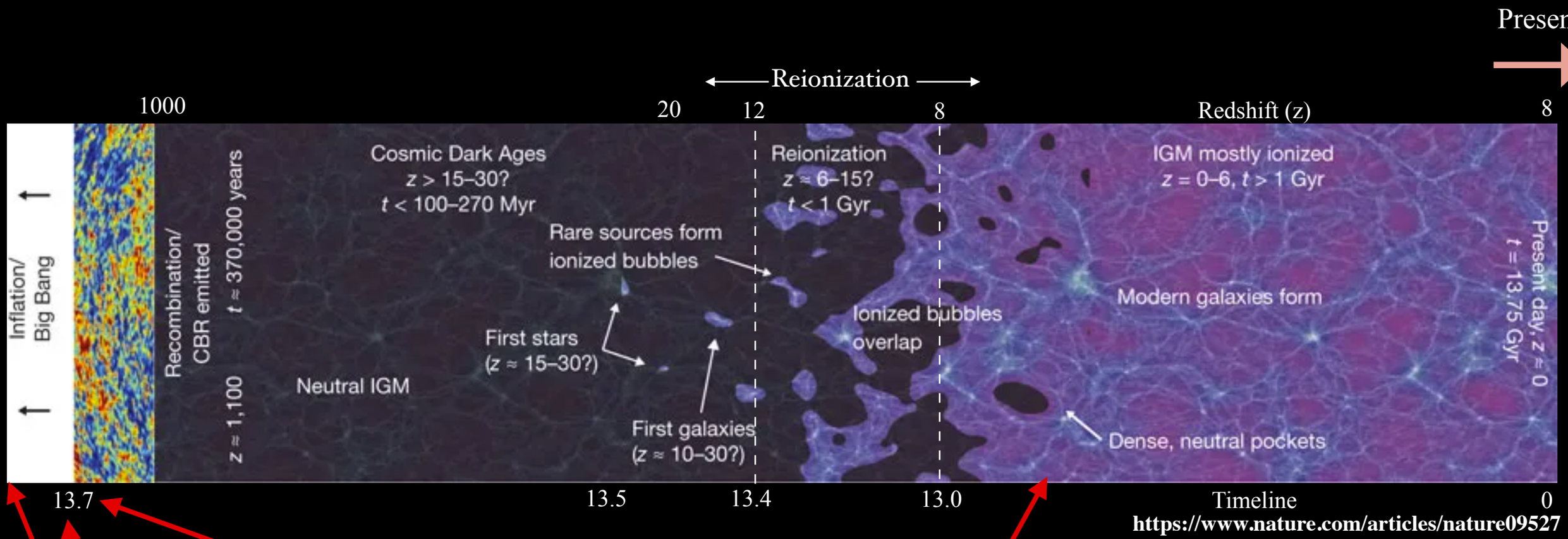
Plan of the talk

- Brief summary to thermal and ionization history of our universe
- Various process of interest
- Magnetic fields and their role
- Baryon-DM interaction
- Dark matter decay or annihilation
- Results and Discussion

Cosmic history

Cosmic history

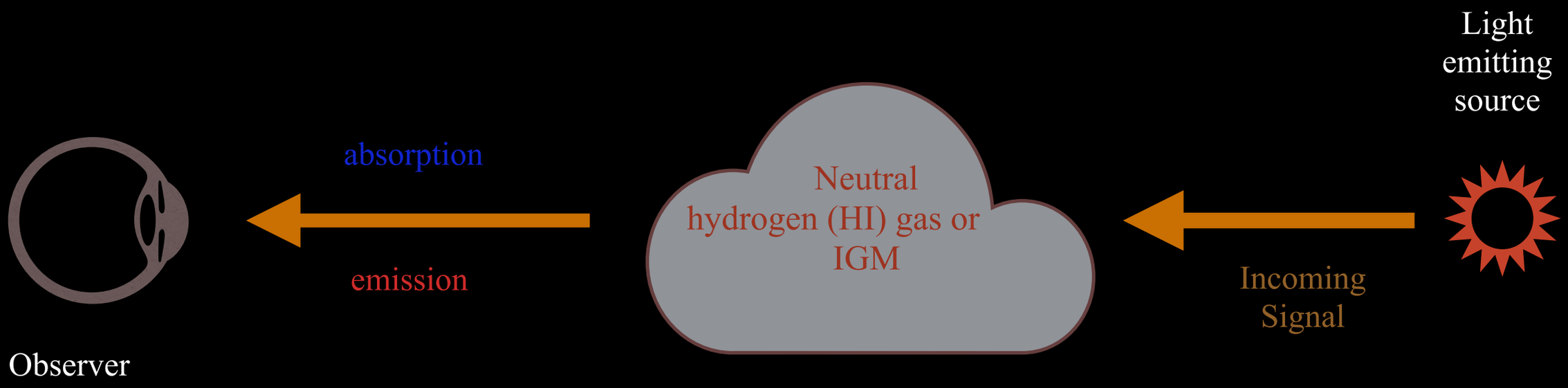


https://www.nature.com/articles/nature09527

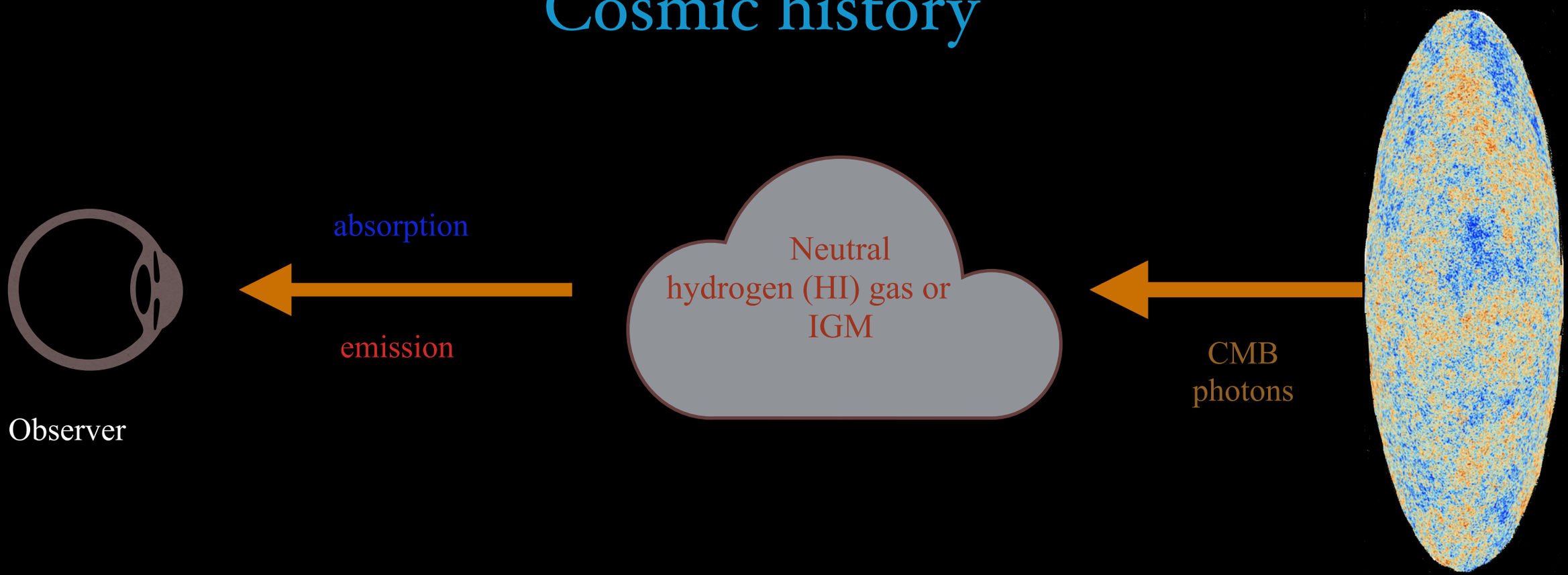
- Inflation
- GUT phase transition
- EW phase transition
- QCD scale
- Matter-radiation equality

- Recombination epoch
- Dark ages
- Reionization and formation of stars and galaxies

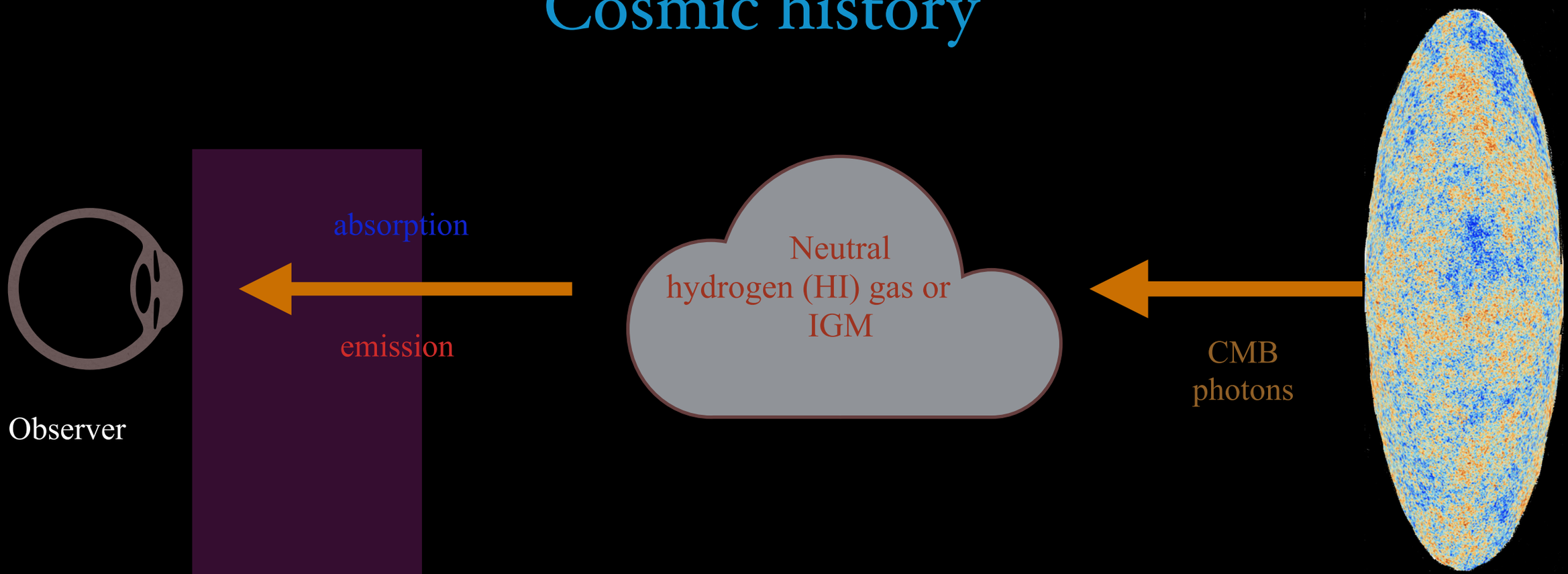
Cosmic history

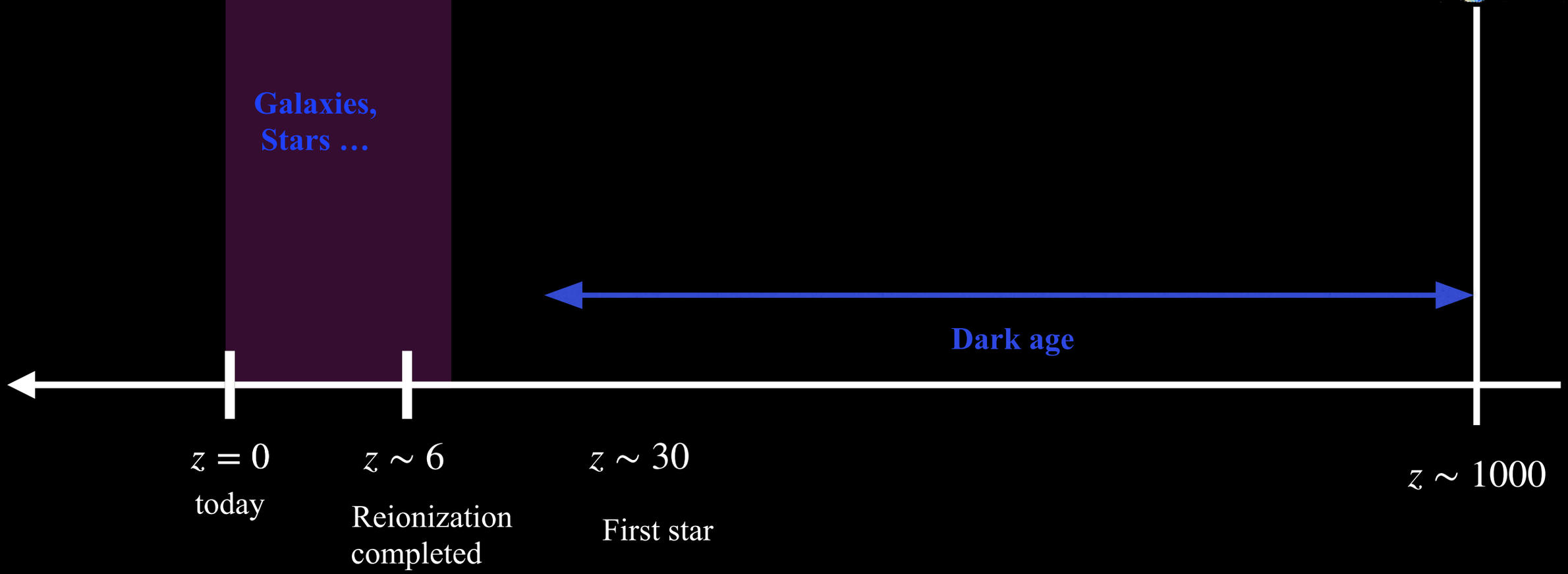


Cosmic history

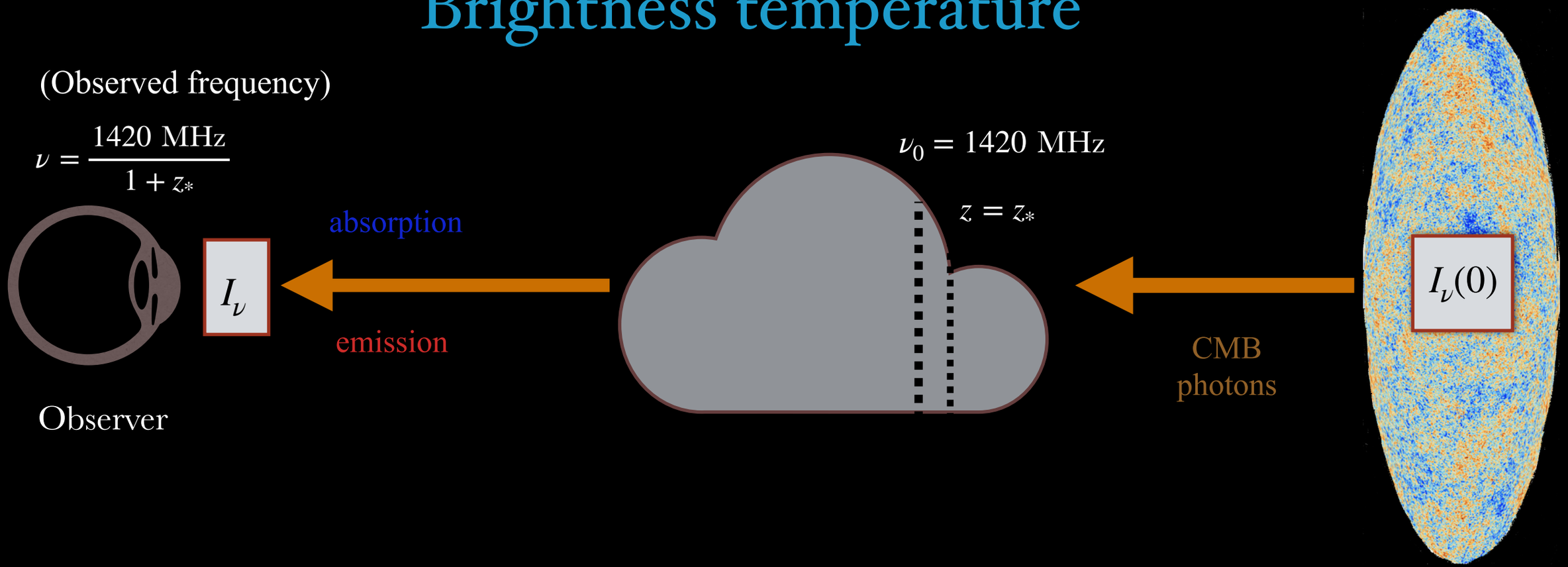


Cosmic history





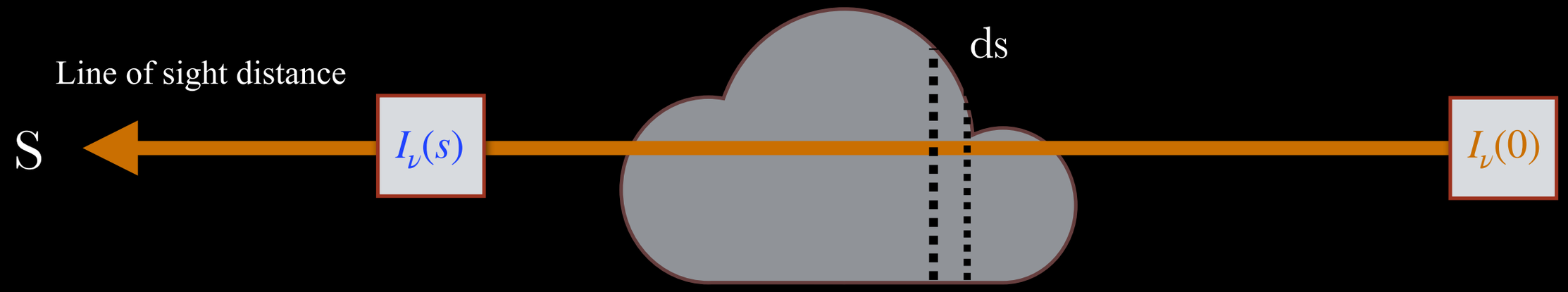
Brightness temperature



I_ν = Specific intensity per unit frequency in the absence of scattering long a path described by coordinate s

Brightness temperature

The detailed signal depends upon the radiative transfer through gas along the line of sight, which is defined in terms of I_ν.



$$\frac{d I_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

Absorption coefficient

Emission coefficient

$$\frac{d I_\nu}{d\tau_\nu} = -I_\nu + \frac{j_\nu}{\alpha_\nu}$$

Optical depth is defined as:

$$d\tau_\nu = \alpha_\nu \, ds$$

$$\frac{d I_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

Source function

Absorption and emission coefficients are determined by microscopic processes.

Brightness temperature

- When emission = absorption

$$\frac{d I_\nu}{d\tau_\nu} = 0 \longrightarrow I_\nu = S_\nu$$

- When S_ν = constant over line of sight

$$I_\nu(s) = I_\nu(0)\, e^{-\tau_\nu(s)} + S_\nu(1 - e^{-\tau_\nu(s)})$$

- For $\tau_\nu \ll 1$

$$I_\nu(s) - I_\nu(0) \simeq [S_\nu - I_\nu(0)]\, \tau_\nu(s)$$

If,

$I_\nu(s) - I_\nu(0) < 0 \longrightarrow$ Absorption

$I_\nu(s) - I_\nu(0) > 0 \longrightarrow$ Emission

Brightness temperature

- Intensity is often represented by an "effective" temperature called "Brightness temperature" T_b

Definition: $I_\nu \equiv B_{bb}(\nu, T_b)$ ← Black Body distribution

- In Rayleigh-Jeans (low frequency) region,

$$B_{bb}(\nu, T_b) \simeq 2k_B\nu^2\, T/c^2 \longrightarrow I_\nu \simeq 2k_B\nu^2\, T/c^2 \longrightarrow T_b = \frac{I_\nu c^2}{2\nu^2 k_B}$$

- Thus radiative transfer equation

$$T_b(s) - T_b(0) = [T - T_b(0)]\,\tau_\nu(s)$$

↑ Temperature of the medium (from S_ν)

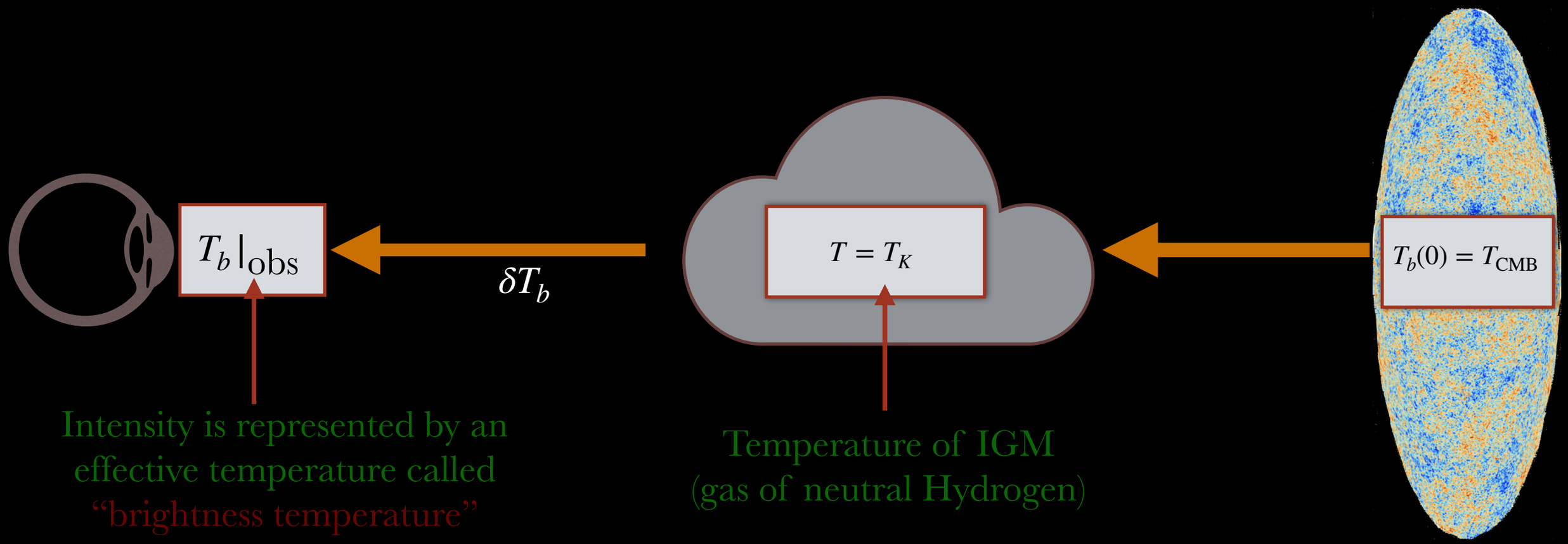
$$\begin{cases} T > T_b(0) \longrightarrow \text{Emission} \\ T = T_b(0) \longrightarrow \text{No signal} \\ T < T_b(0) \longrightarrow \text{Absorption} \end{cases}$$

Thus the evolution of T is very important.

Spin temperature

The excitation temperature of the 21 cm line is known as the spin temperature and is defined as ratio of the number densities of hydrogen atoms in the two hyperfine levels.

$$\frac{n_1}{n_0} = \left(\frac{g_1}{g_0}\right) \exp\left(-\frac{\Delta E}{k_b T_S}\right) = \left(\frac{g_1}{g_0}\right) \exp\left(-\frac{T_*}{T_S}\right) \qquad g_1/g_0 = 3 \quad \text{and} \quad T_* = \frac{hc}{k\lambda_{21}} = 0.068 \text{ K}$$



21cm signal (absorption, emission) depends on the spin temperature (relative to the CMB).

$$\delta T_b = T_b - T_R$$
$$= (T_S - T_R)\tau_\nu$$

Spin temperature

- Three process determine the spin temperature

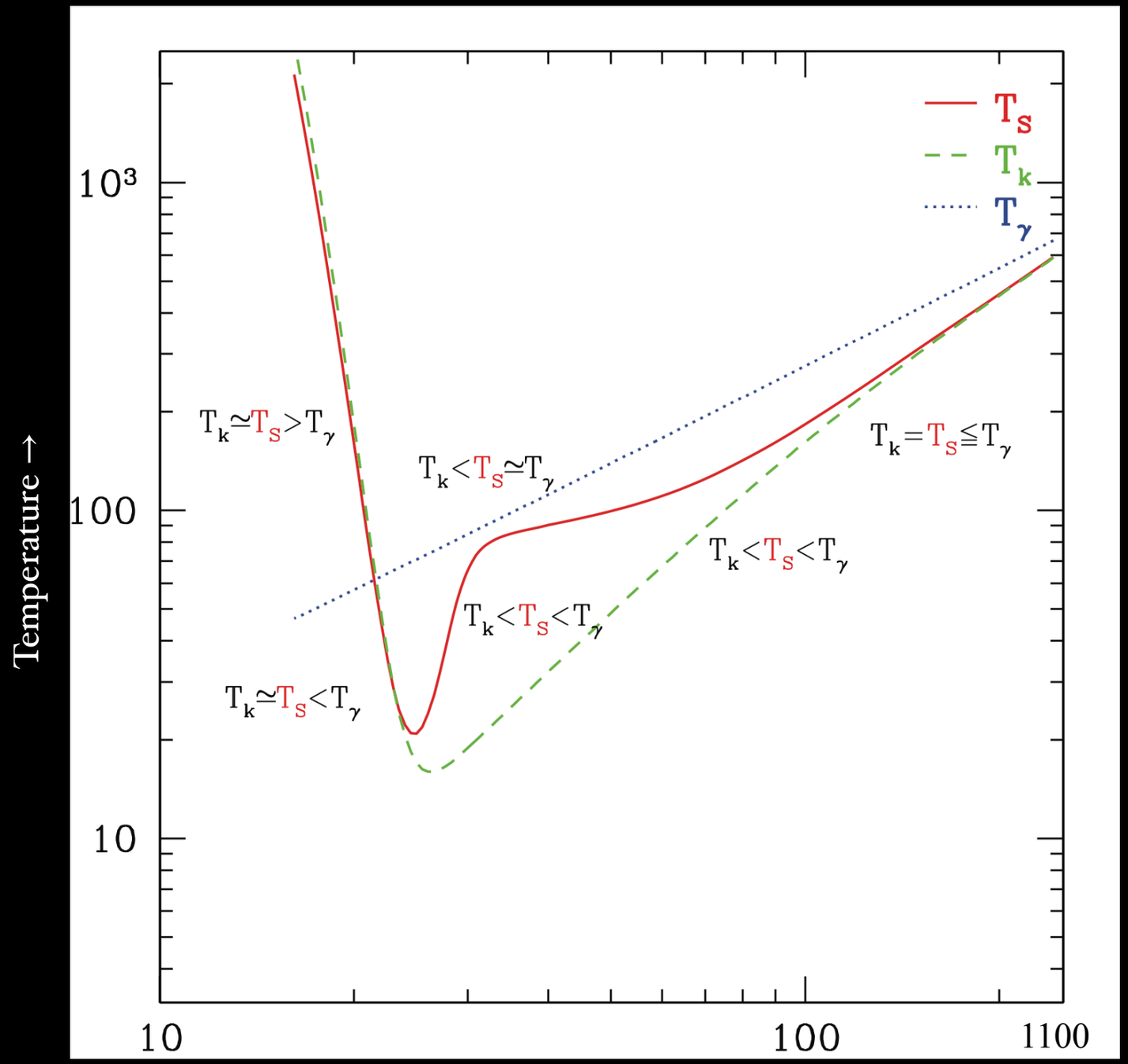
1. Resonant scattering of *Lyα* photons that cause a spin–flip via an intermediate excited state: T_α
2. Absorption/emission of 21 cm photons from/to the radio background, primarily the CMB: $T_\gamma = T_{\rm CMB}$
3. Collisions with other hydrogen atoms and with electrons: T_c

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_c^{-1}}{1 + x_\alpha + x_c}$$

x_c and x_α are the coupling coefficients due to atomic collisions and scattering of *Lyα* photons

- T_γ is the temperature of the surrounding bath of radio photons, typically set by the CMB so that $T_\gamma = T_{\rm CMB}$

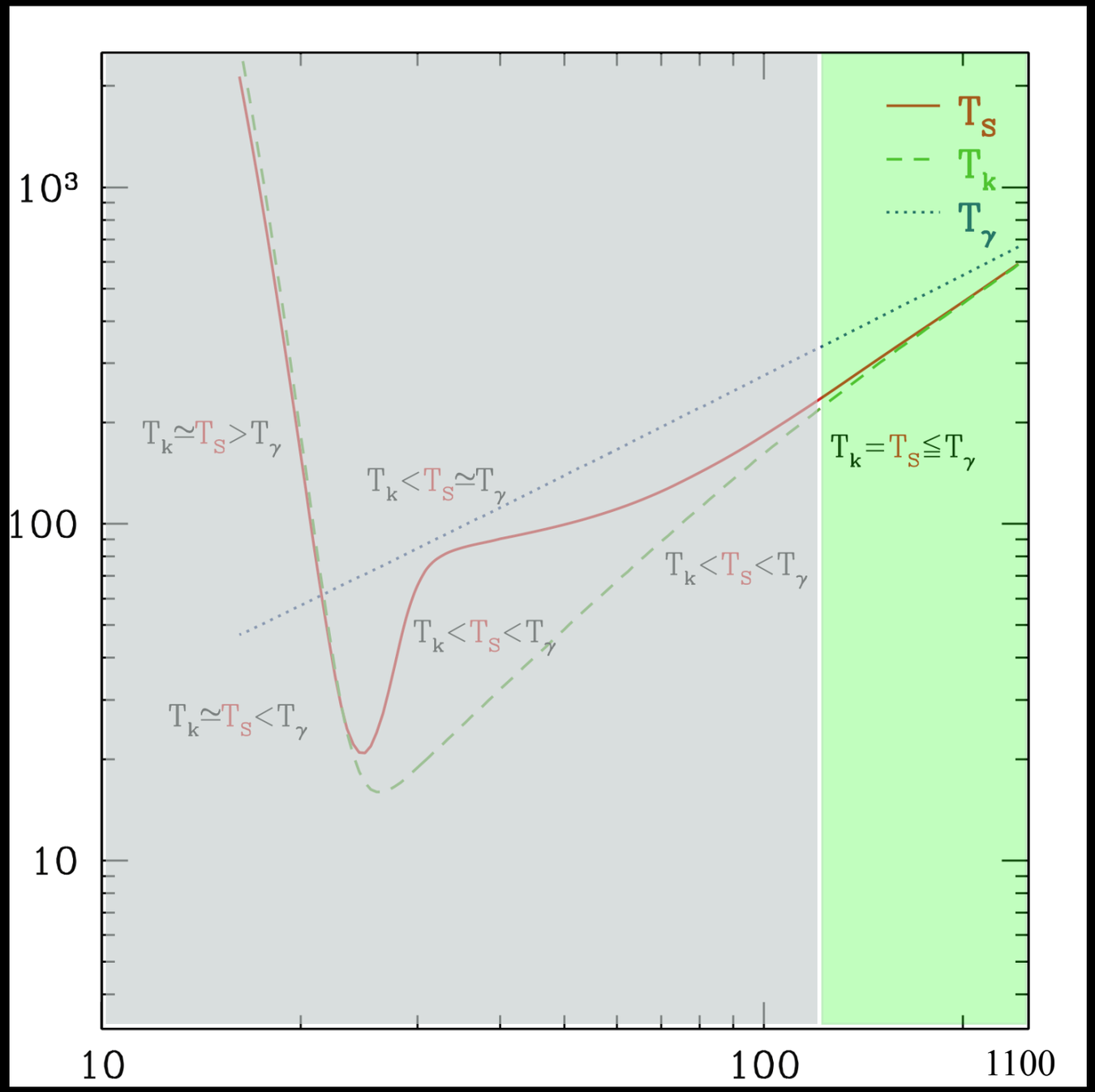
Spin temperature



Mon. Not. R. Astron. Soc. 411, 955–972 (2011)

Spin temperature

- Absorption
- De-excitation
- Collision



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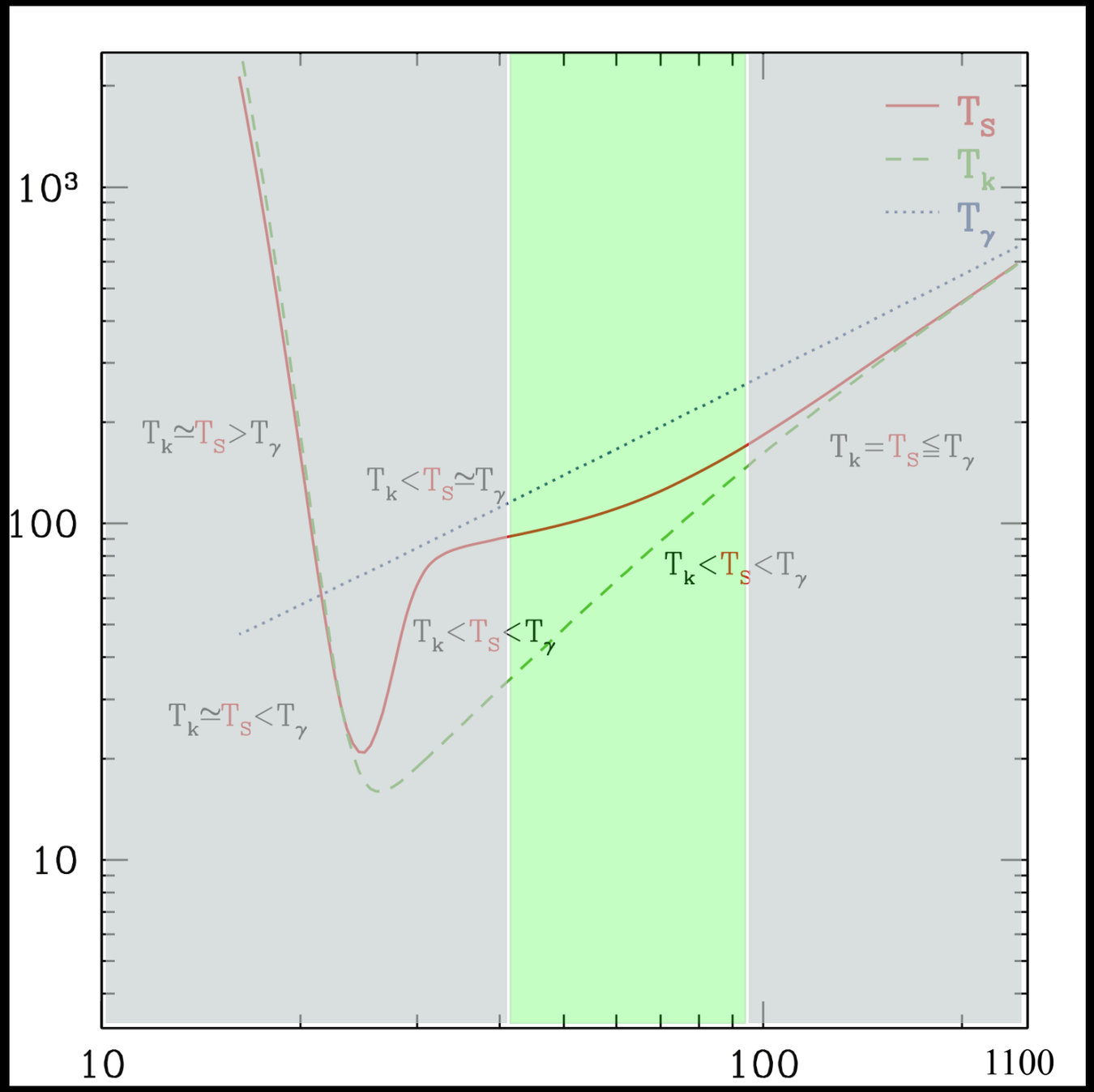
Spin temperature

- Absorption
- De-excitation
- Collision ↓



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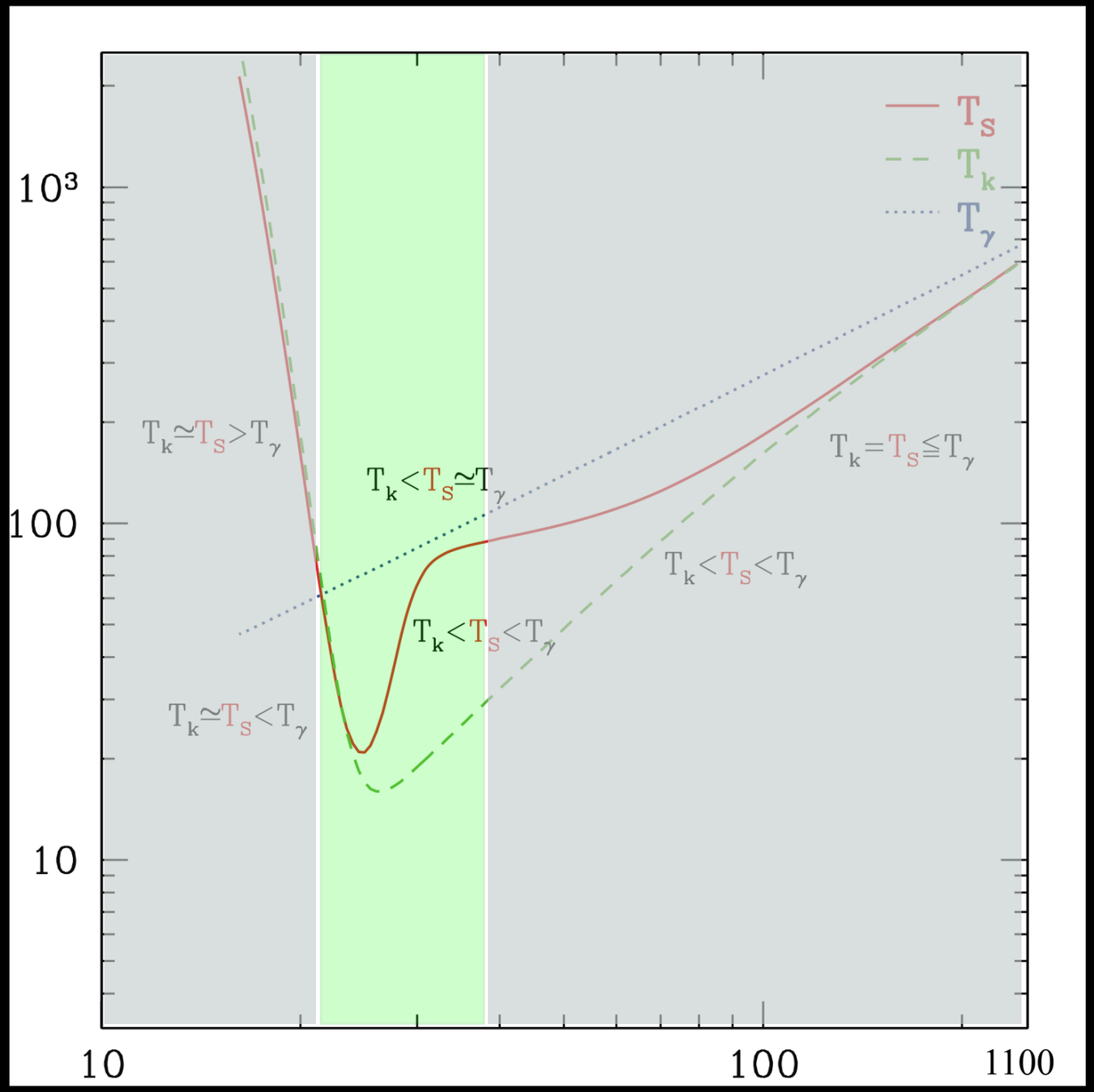
Spin temperature

- Absorption
- De-excitation
- Collision
- Lyα-WF effect



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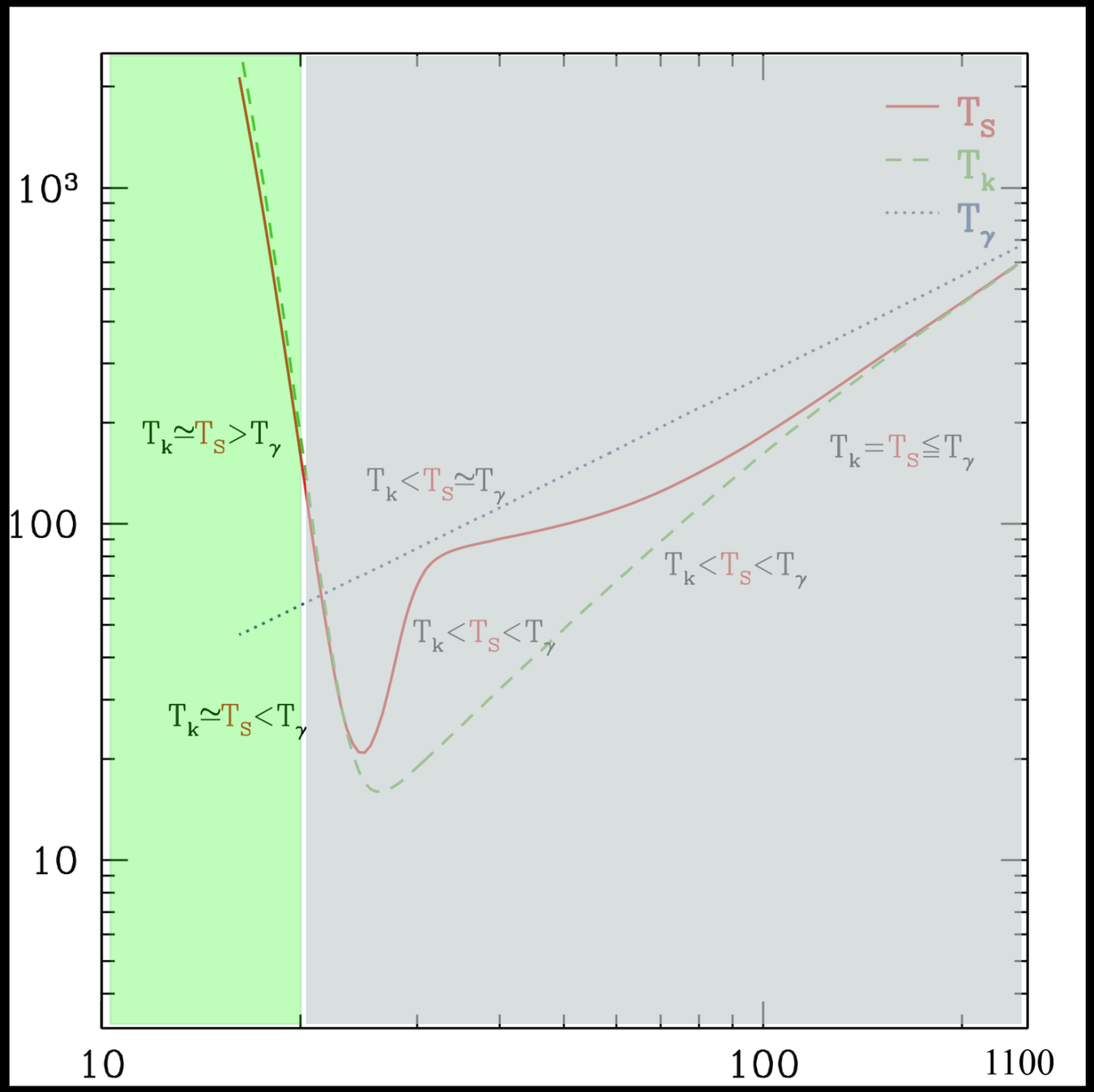
Spin temperature

- Absorption
- De-excitation
- Collision
- Lyα-WF effect
- X-ray sources



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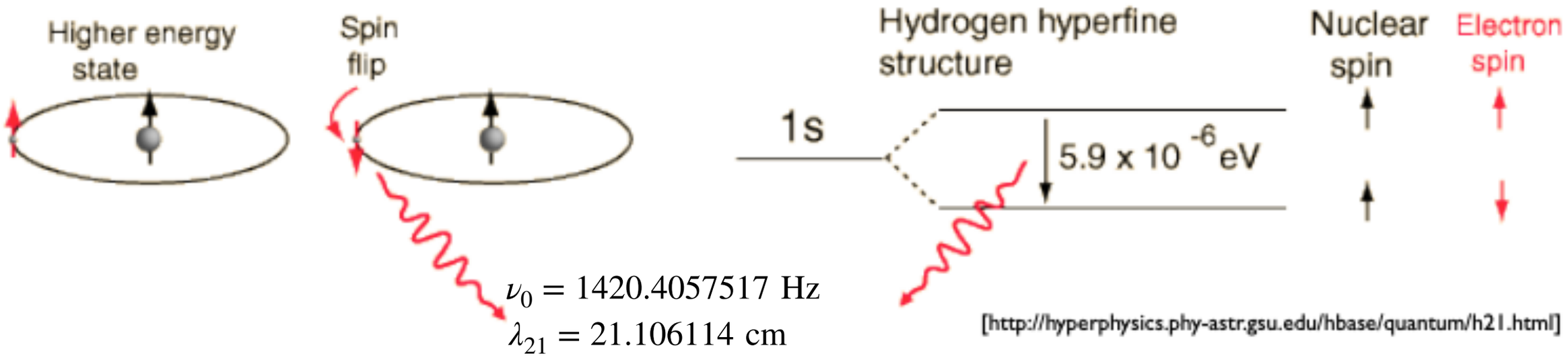
What is 21 cm Signal?

A 21cm line can probe dark ages

(which cannot be probed with other observations.)

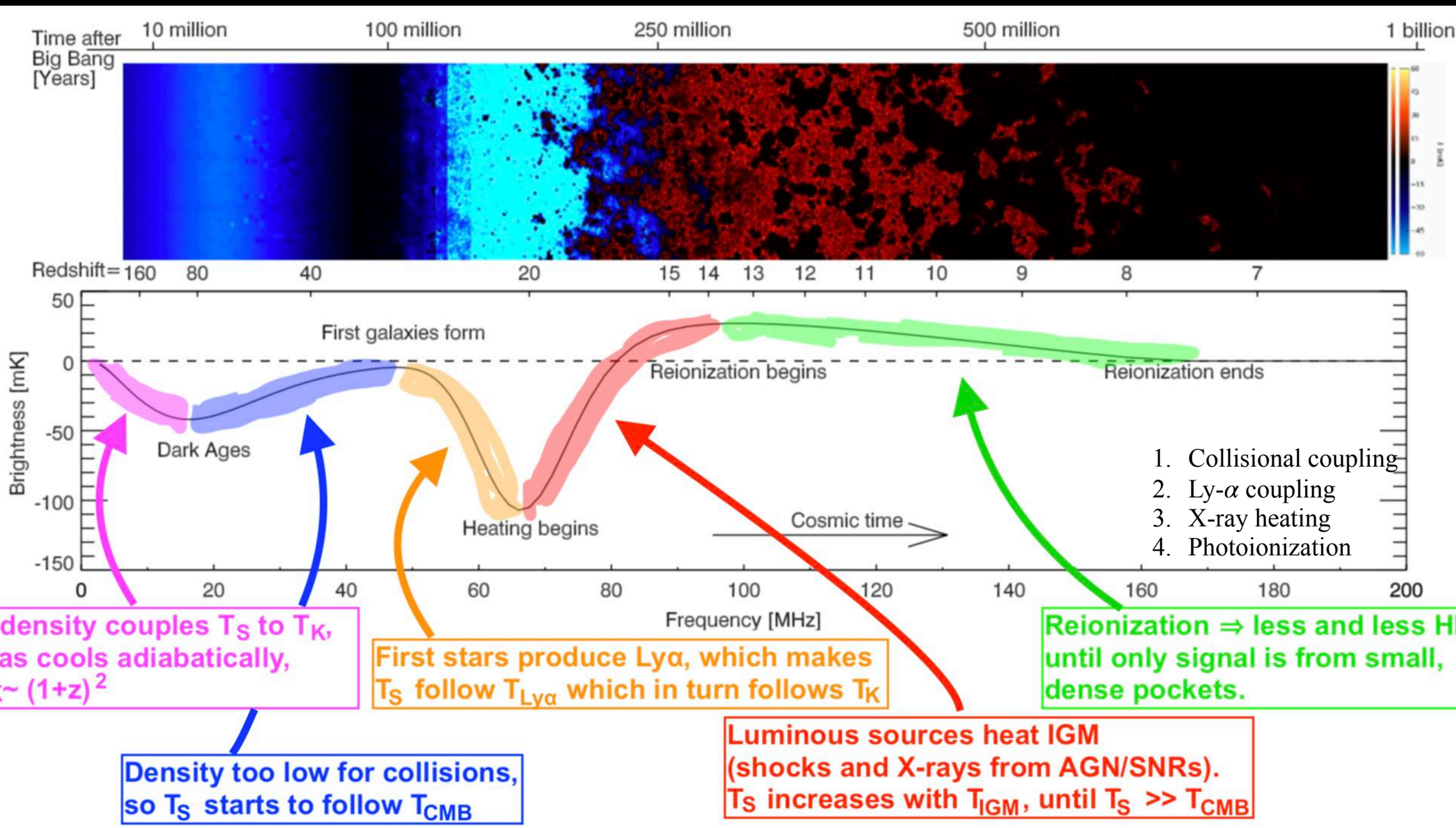
What is 21 cm Signal?



- The brightness temperature of the 21-cm hydrogen absorption line relative to the background radiation

$$\delta T_b \approx 27 x_{\rm HI} \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_R}{T_S}\right) \ \text{mK}$$

Spin temperature

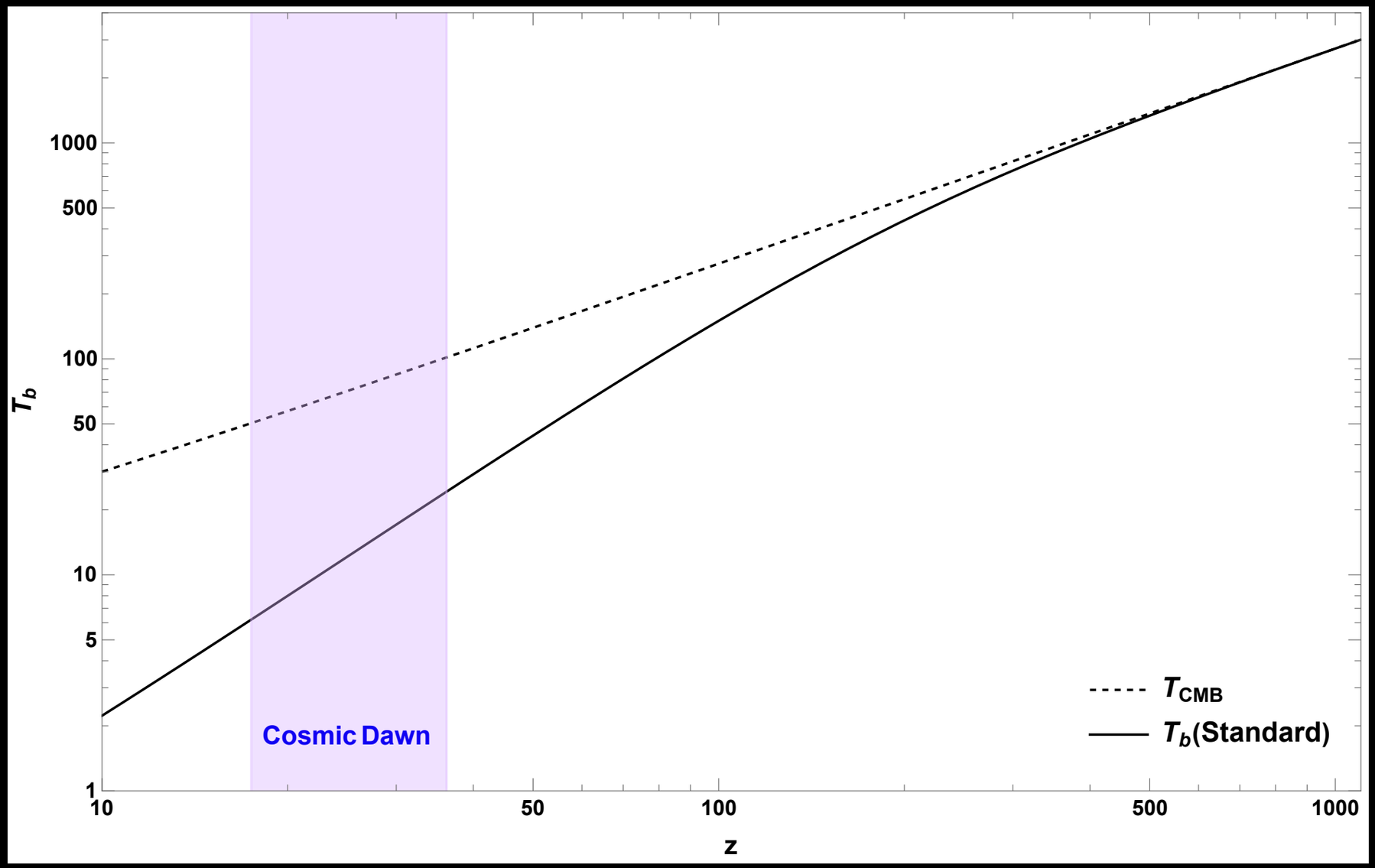


Possible sources and impact on IGM thermal and ionization history

Effects of interests

Following effects are important:

- Standard evolution
- Magnetic fields
- Baryon-Dark matter interactions
- Dark matter decay or annihilation



Hubble term | Compton scattering term | Heat exchange between the Baryon-DM | Heating and cooling | DM decay/annihilation

$$\frac{dT_{\rm gas}}{dz} = \frac{2T_{\rm gas}}{(1+z)} + \frac{\Gamma_C}{(1+z)H}(T_{\rm gas} - T_{\rm CMB}) + \frac{2}{3(1+z)H}\frac{dQ_{gas}}{dt} - \frac{2(\Gamma_{\rm heat} - \Gamma_{\rm cooling})}{3(1+z)H} - \frac{2\mathcal{F}(z)}{3k_B n_H(1+z)H}\frac{dE}{dVdt}\bigg|_{\rm inj}$$

$$\frac{dT_d}{dz} = \underbrace{\frac{2T_d}{(1+z)}}_{\text{Hubble term}} + \underbrace{\frac{2}{3(1+z)H}\frac{dQ_d}{dt}}_{\text{Heat exchange between the Baryon-DM}}$$

$$\frac{dQ_{gas}}{dt} = \frac{2m_H\rho_d\hat{\sigma}e^{-r^2/2}}{\sqrt{2\pi}(m_H+m_d)^2u_{\rm th}^3}\left(T_{\rm d} - T_{gas}\right) + \underbrace{\frac{\mu\rho_d}{\rho_M}\nu D(\nu)}_{\text{Drag term}}$$

$$\frac{d\nu}{dz} = \frac{\nu}{(1+z)} + \frac{D(\nu)}{(1+z)H}$$

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H}\left[\left(n_H x_e^2\alpha_B - (1-x_e)\beta_B e^{-E_{21}/T_{\rm CMB}}\right)D\right] + \boxed{\frac{1}{H(z)(1+z)}\left[\frac{f_i(z)}{E_i n_H} + \frac{(1-\mathscr{C})f_\alpha(z)}{E_\alpha n_H}\right]\frac{dE}{dVdt}\bigg|_{\rm inj}}$$

DM decay/annihilation

DM decay

$$\frac{dE}{dVdt}\bigg|_{\rm inj} = \begin{cases} (1+z)^3 f_{\chi,\rm dec}\,\Omega_{\chi,0}c^2\rho_c\dfrac{1}{\tau}, \\ (1+z)^6 f_{\chi,\rm ann}^2\,\Omega_{\chi,0}^2c^2\rho_c^2\dfrac{\langle\sigma v\rangle}{m_\chi}. \end{cases}$$

DM annihilation

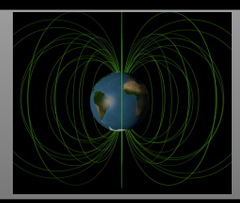
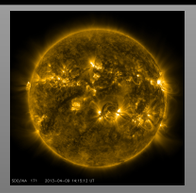
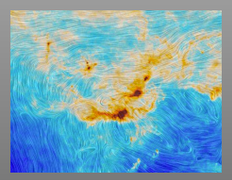
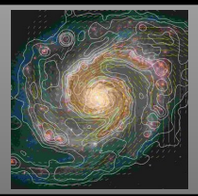
❋ E_{21} cm is the energy of the *Lyα* wavelength photons. $\lambda_{\rm Ly\alpha}$ is the wavelength corresponding to the *Lyα* photons. $\Lambda_{2s,1s} = 8.22\ \sec^{-1}$ is the hydrogen two photon decay rate.

$$D = \frac{\frac{3}{4}R_{Ly\alpha} + \frac{1}{4}\Lambda_{2s,1s}}{\beta_B + \frac{3}{4}R_{Ly\alpha} + \frac{1}{4}\Lambda_{2s,1s}} \qquad R_{Ly\alpha} = \frac{8\pi H}{3n_H(1-x_e)\lambda_{Ly\alpha}^3}$$

Magnetic fields and contributions

Magnetic field contribution

$B \approx 0.5\,G$ | $B \approx 1 - 10^3\,G$ | $B \approx 10^{-5}\,G$ | $B \approx 10^{-5}\,G$ | $B \approx 10^{-8} - 10^{-7}\,G$


Inter Galactic Medium

Planets: [here: Earth credit: Science Picture company]

Stars: [here:Sun **credit:** NASA/SDO]

Interstellar medium: [here: Molecular cloud **credit**: SESA and Planck collaboration]

Galaxies: [here: M51 **credit**: Beck 2011]

Galaxies Clusters: [here: credit: NRAO and NASA]

Magnetic fields are everywhere

Generally: Small scale → Large scale; Strong fields ← Weak fields

There are two important processes:

1). Ambipolar decay

2). Turbulent decay

(Sethi S. K., Subramanian K., 2005)

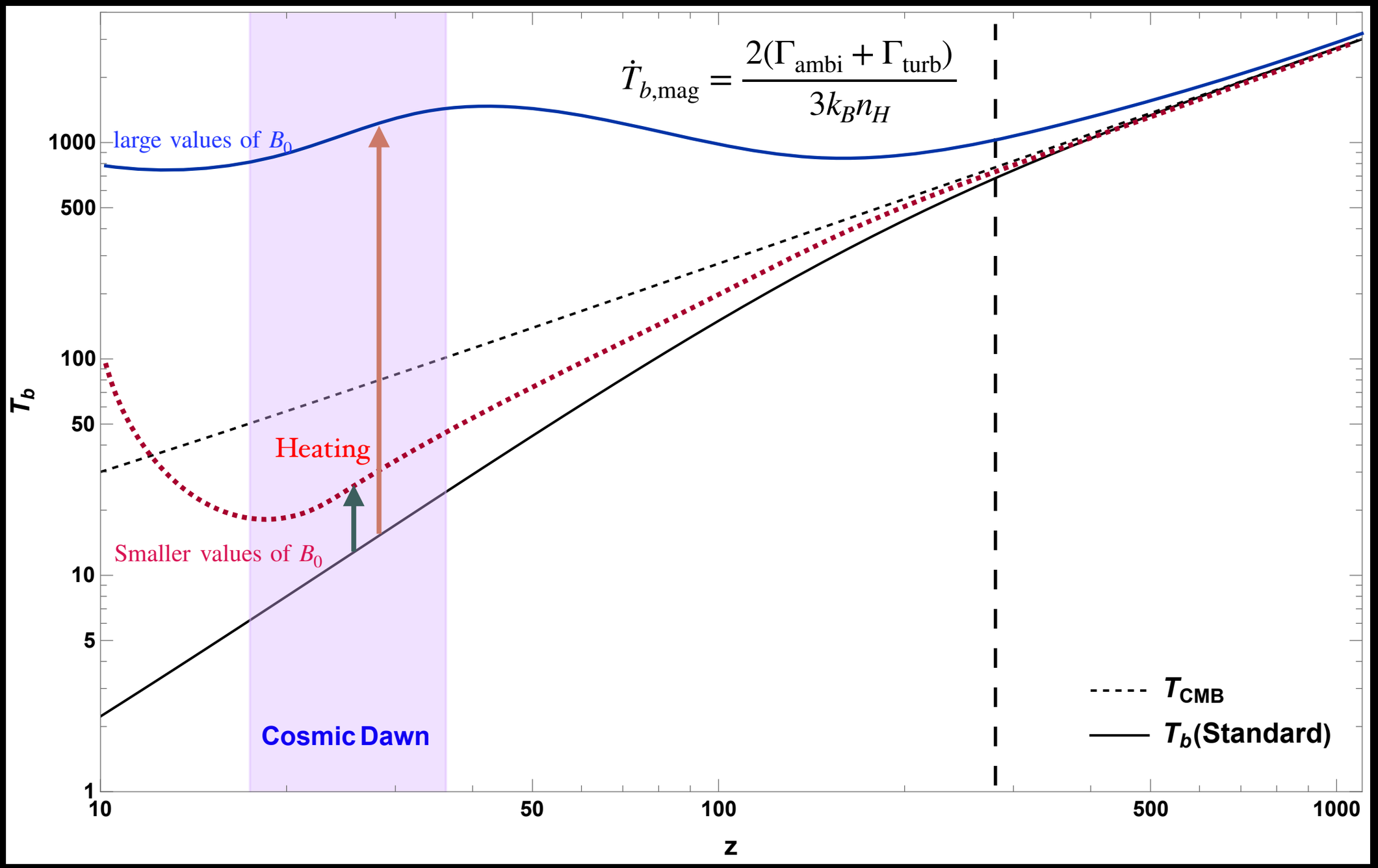
$$\frac{d}{dt}\left(\frac{|\mathbf{B}|^2}{8\pi}\right) = -4H(t)\left(\frac{|\mathbf{B}|^2}{8\pi}\right) - \Gamma_{\rm ambi} - \Gamma_{\rm decay}$$

Hubble expansion

$$\Gamma_{\rm ambi} = \frac{\rho_n}{16\pi^2\gamma\rho_b^2\rho_i}\,|(\nabla\times\vec{\mathbf{B}})\times\vec{\mathbf{B}}\,|^2$$

$$\Gamma_{\rm decay} = \frac{B_0^2(t)}{8\pi}\,\frac{3m}{2}\,\frac{\left[\ln\left(1+t_{\rm eddy}/t_i\right)\right]^m H(t)}{\left[\ln\left(1+t_{\rm eddy}/t_i\right)+\ln(t/t_i)\right]^{m+1}}$$

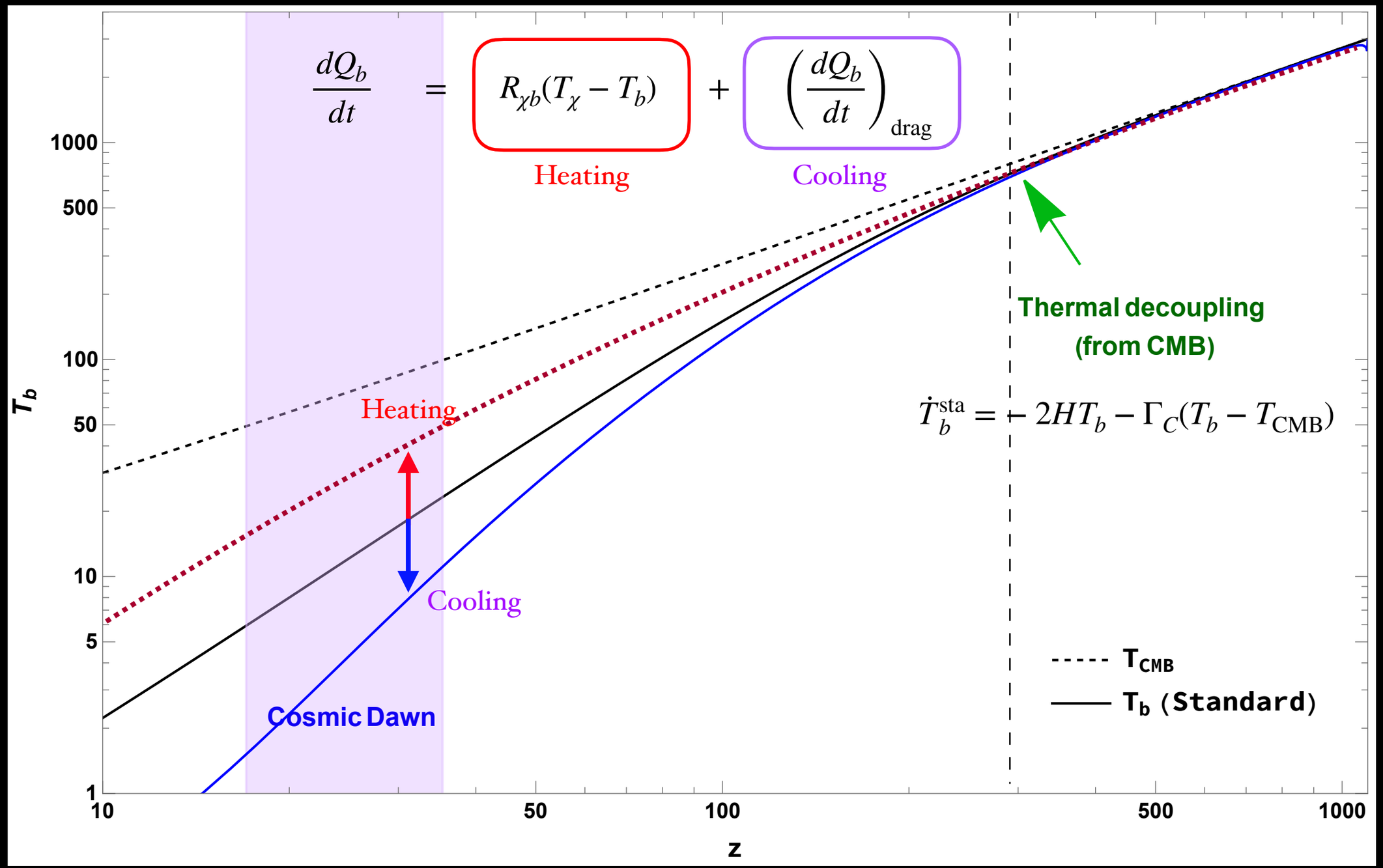
Cosmic History: Standard+Magnetic heating



$$\dot{T}_b = -2HT_b - \Gamma_C(T_b - T_{\mathrm{CMB}}) + \frac{2}{3k_B}\frac{dQ_b}{dt} + \frac{2\Gamma_{\mathrm{heat}}}{3k_B n_H}$$

Baryon-DM interactions

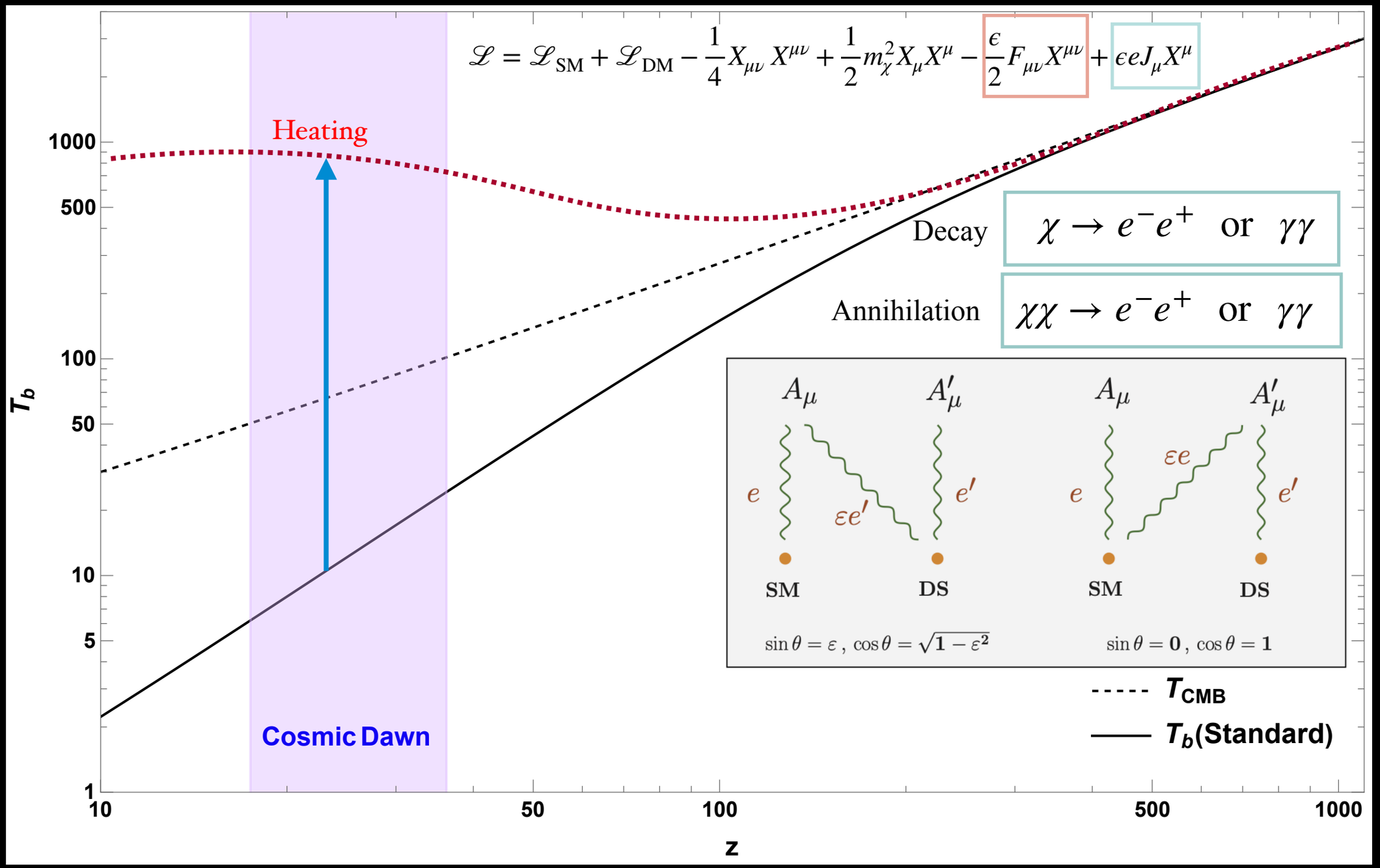
Cosmic History: Standard+BDM



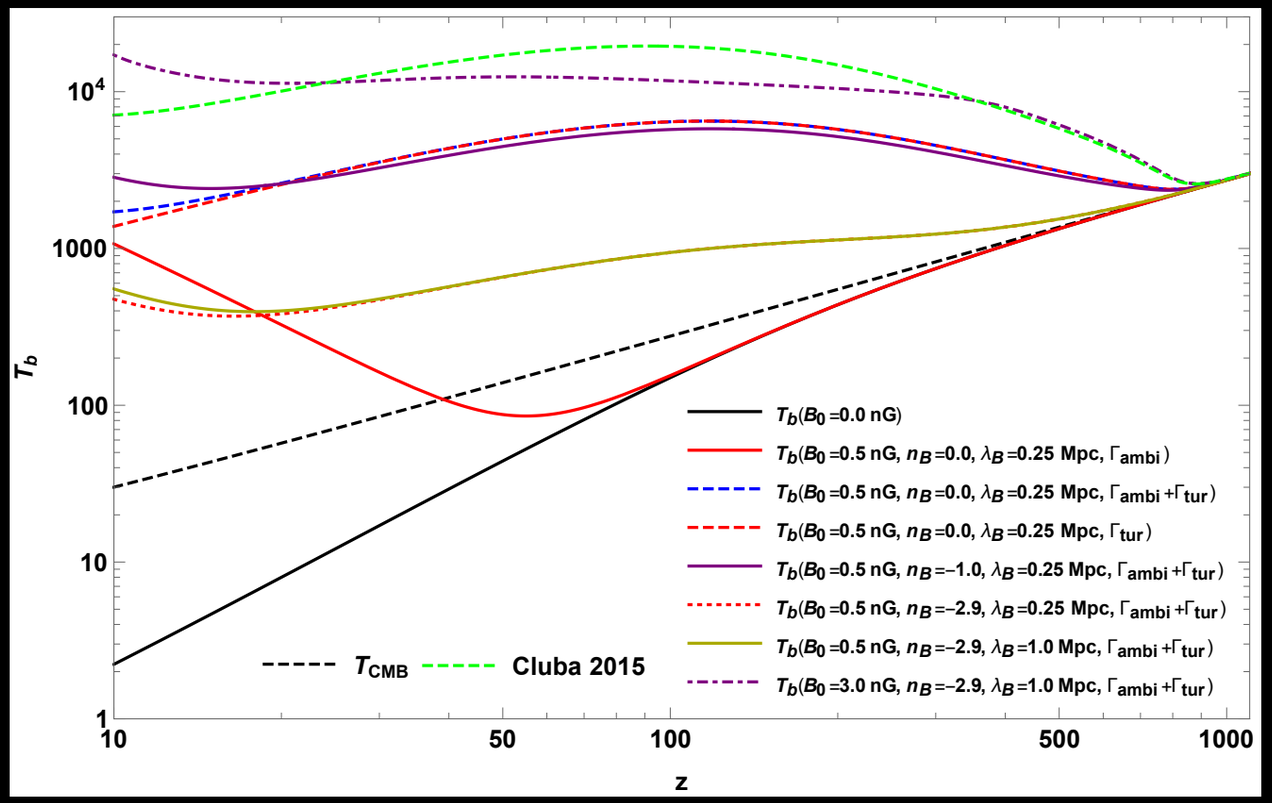
$$\dot{T}_b = -2HT_b - \Gamma_C(T_b - T_{\rm CMB}) + \frac{2}{3k_B}\frac{dQ_b}{dt}$$

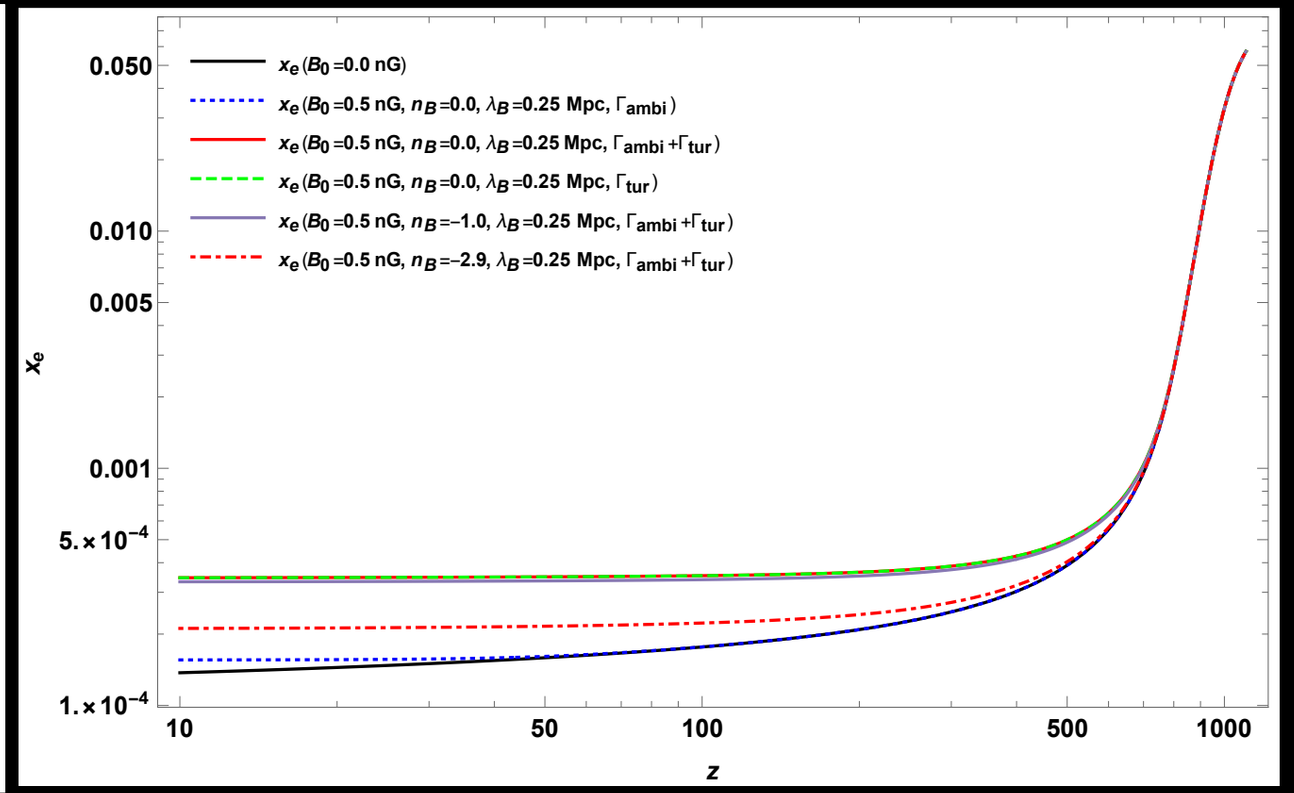
DM decay/annihilations

DM decay or annihilation

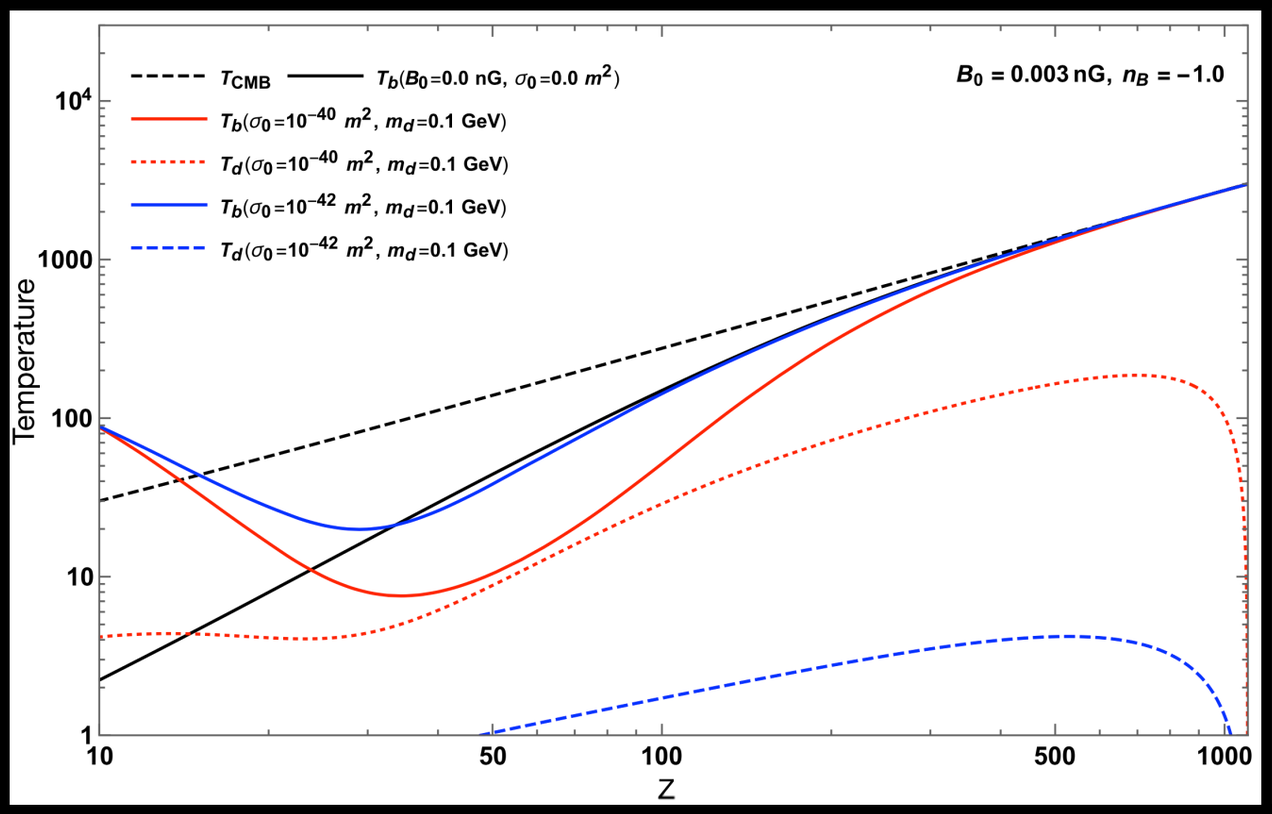


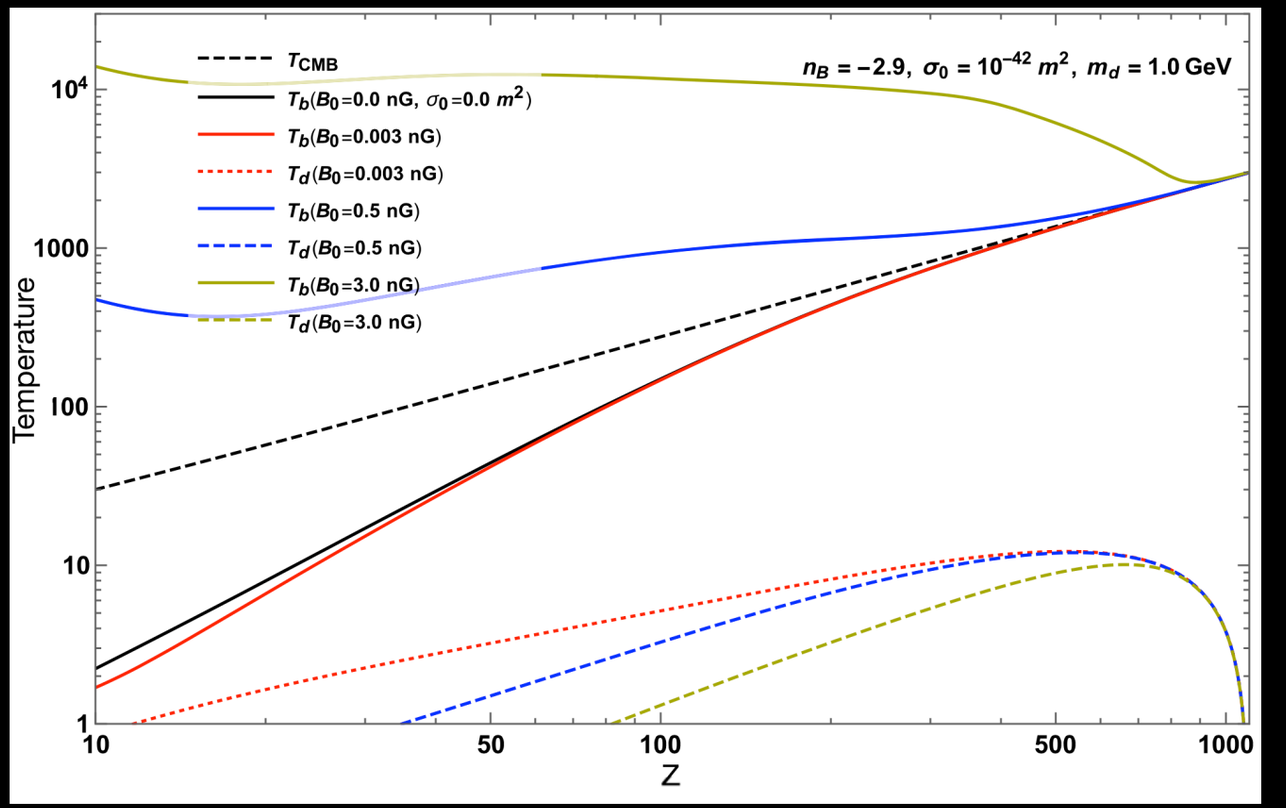
Result and Discussion





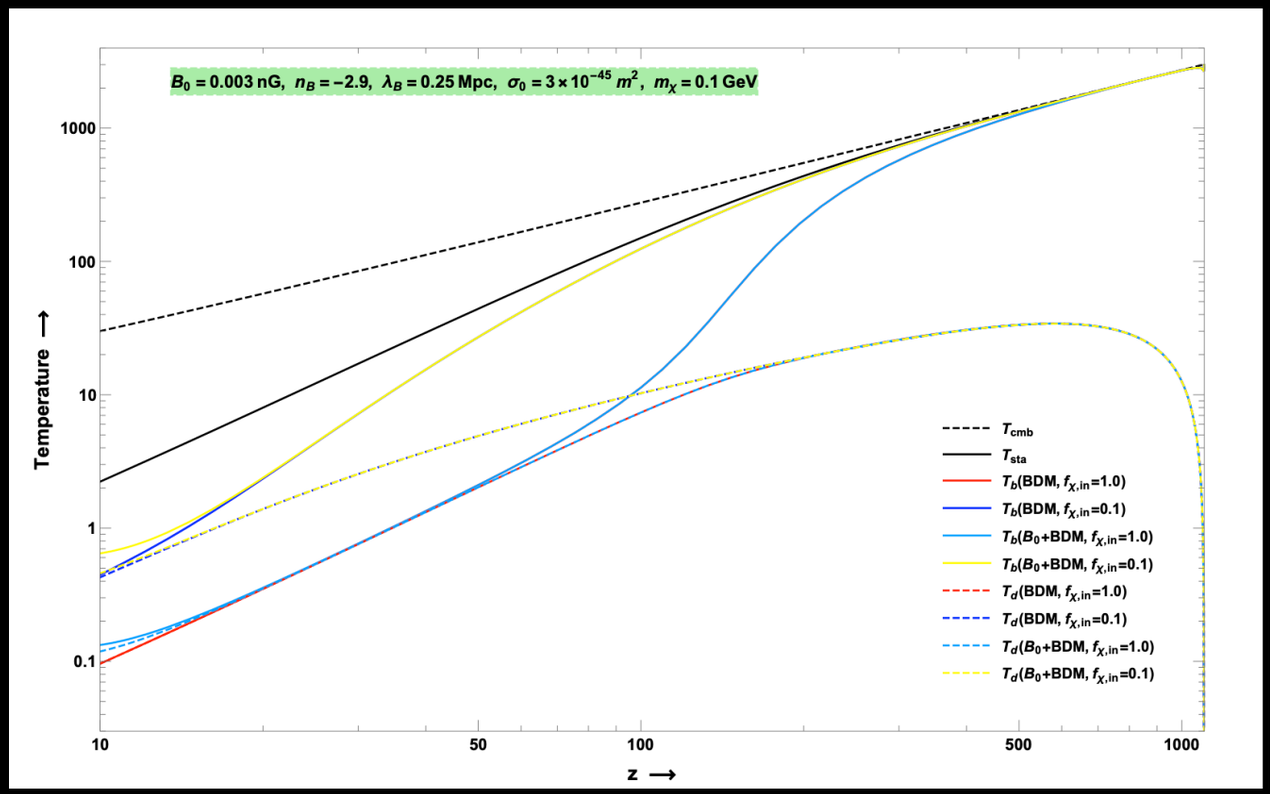
Standard+Magnetic fields

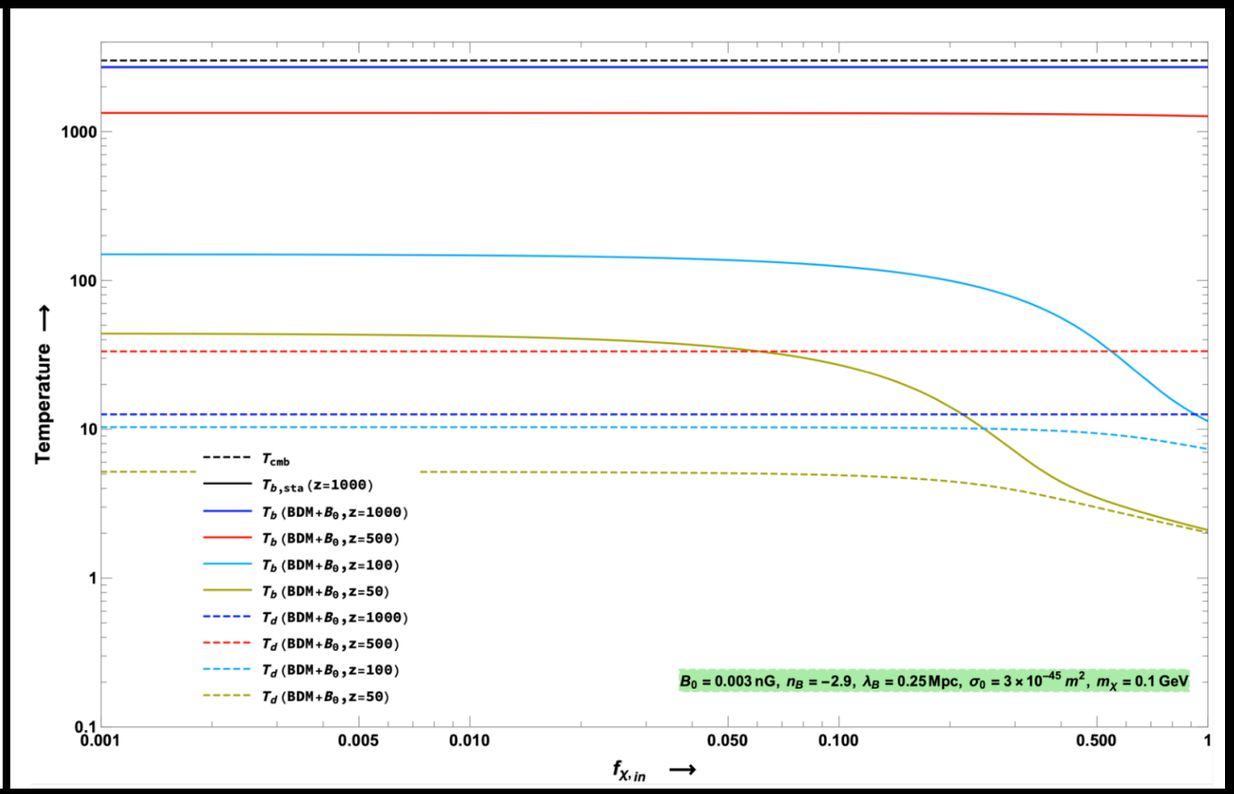




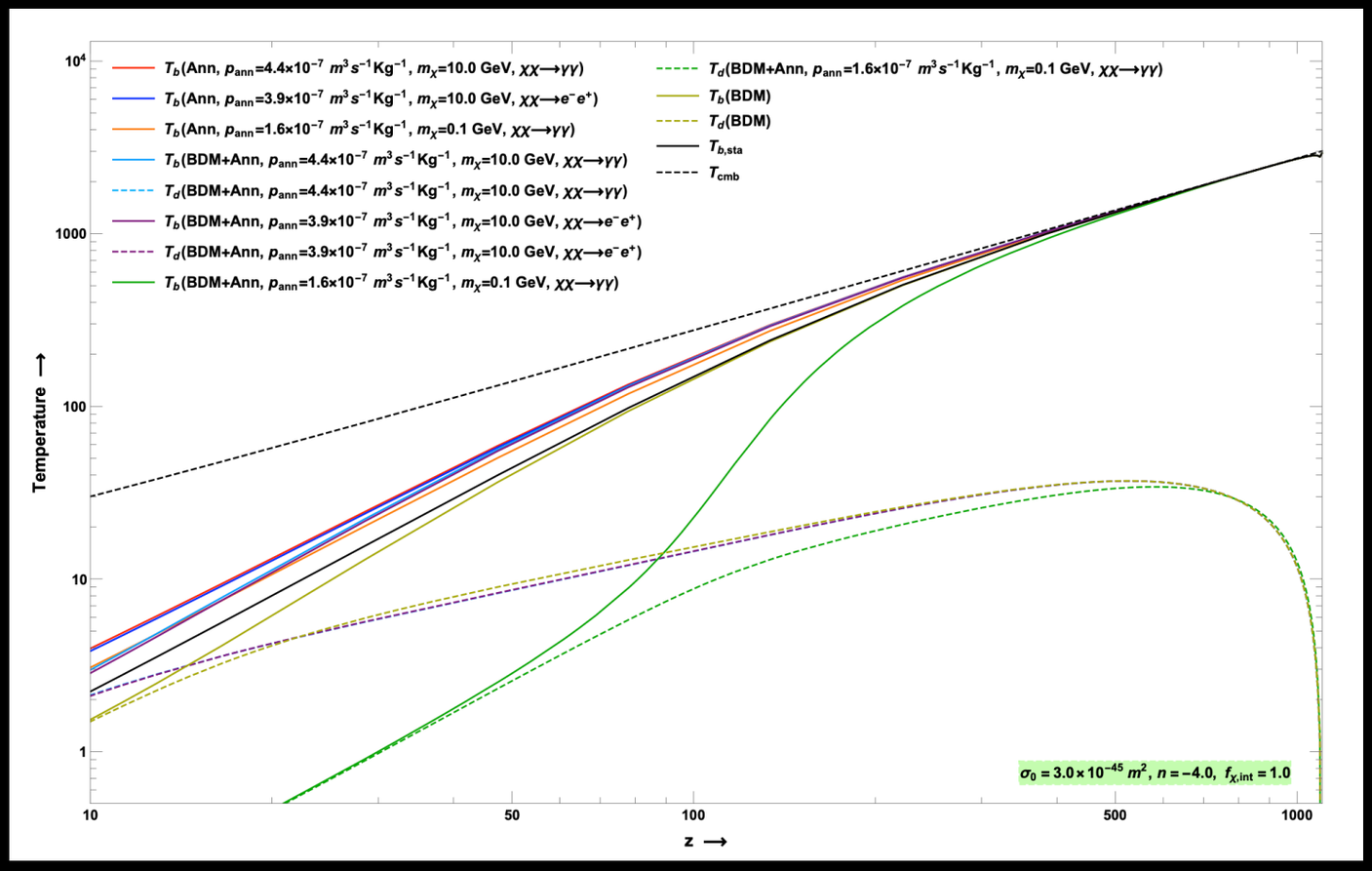
Standard+Magnetic fields+BDM interactions

Pandey et al., MNRAS 500 (2020) 1, 643-654

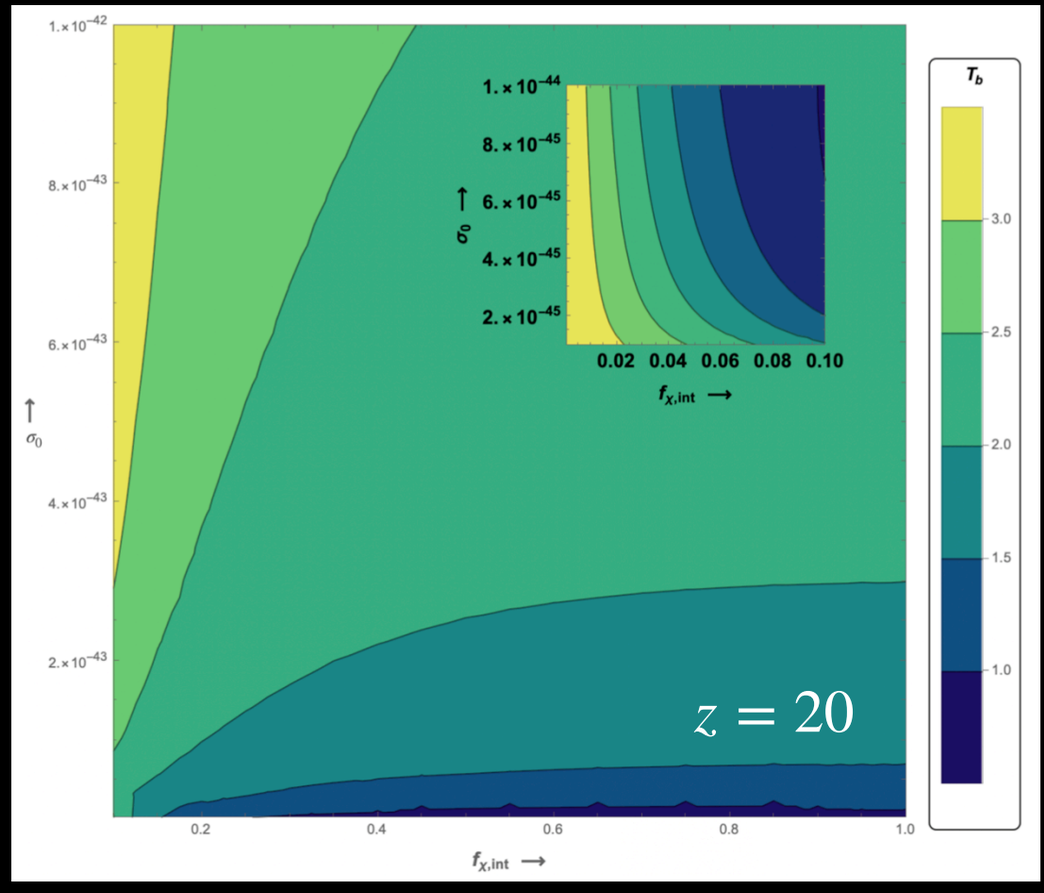




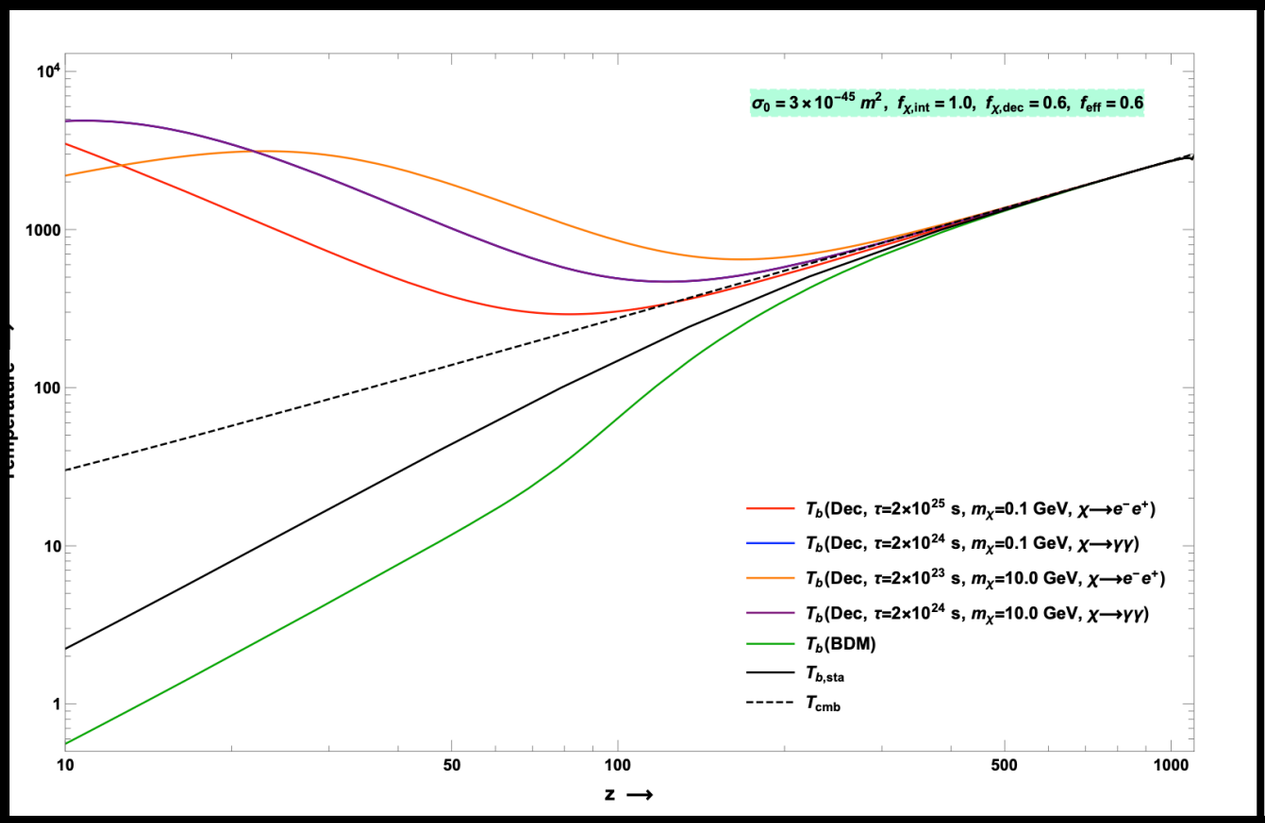
Standard+Magnetic fields+BDM interactions ($\Omega_\chi = f_{\chi,\mathrm{int}}\Omega_{\mathrm{DM}}$)

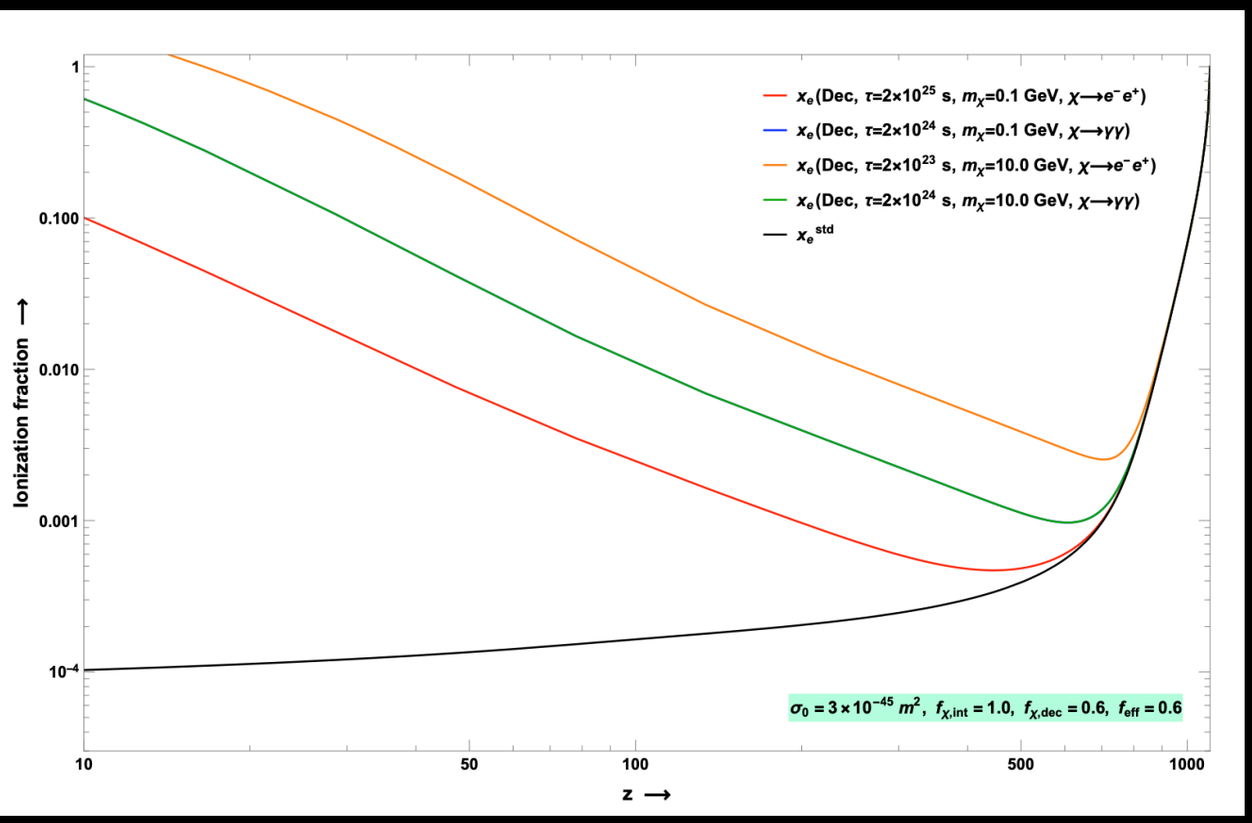


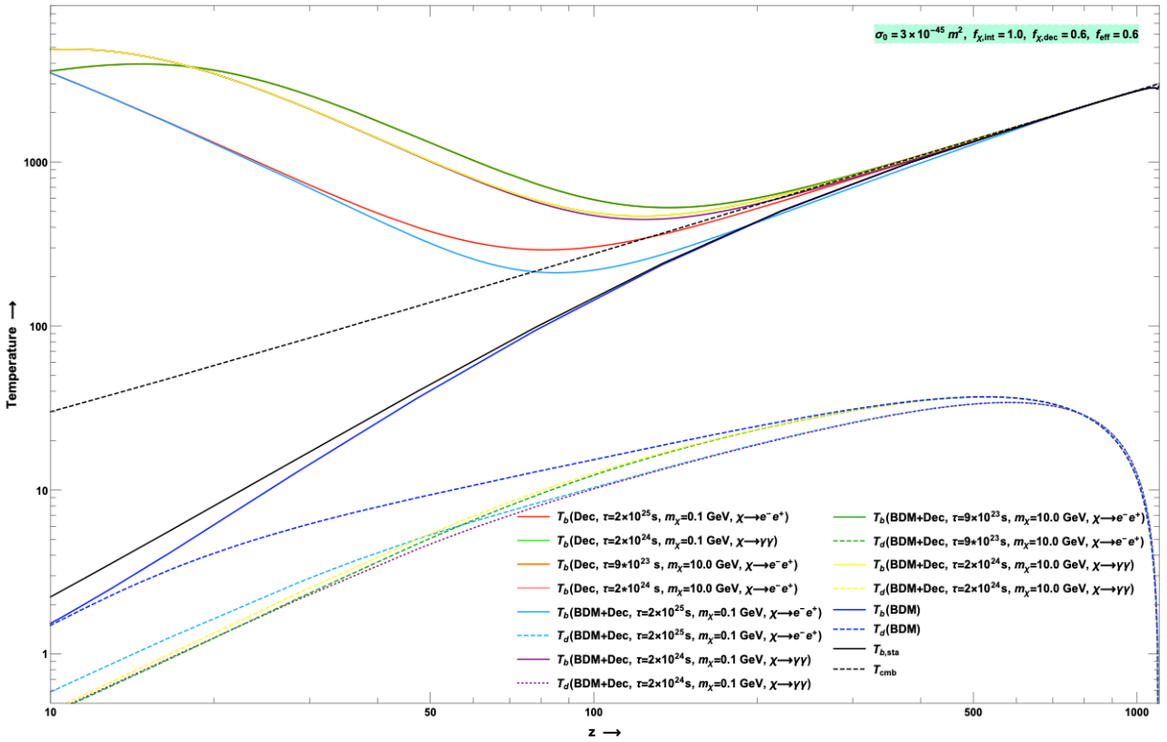
DM annihilation+ BDM interactions

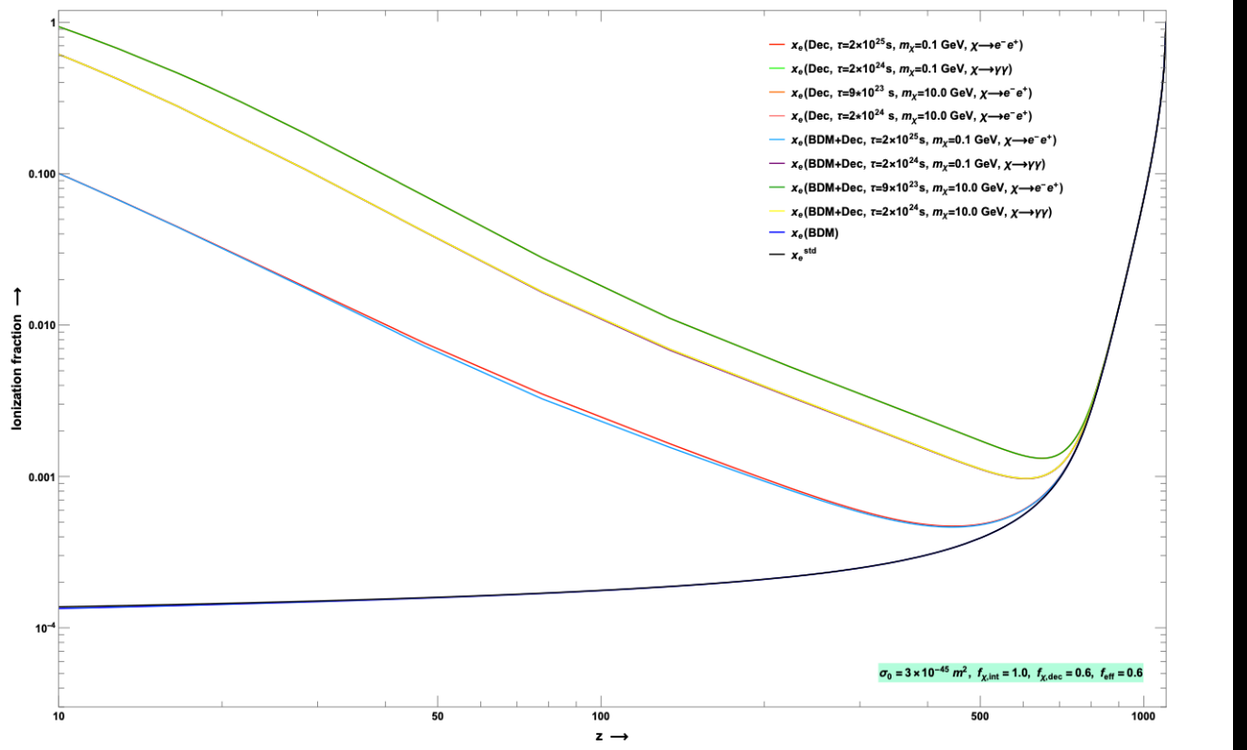


Pandey et al. (2022) 2204.08088 [astro-ph.CO]



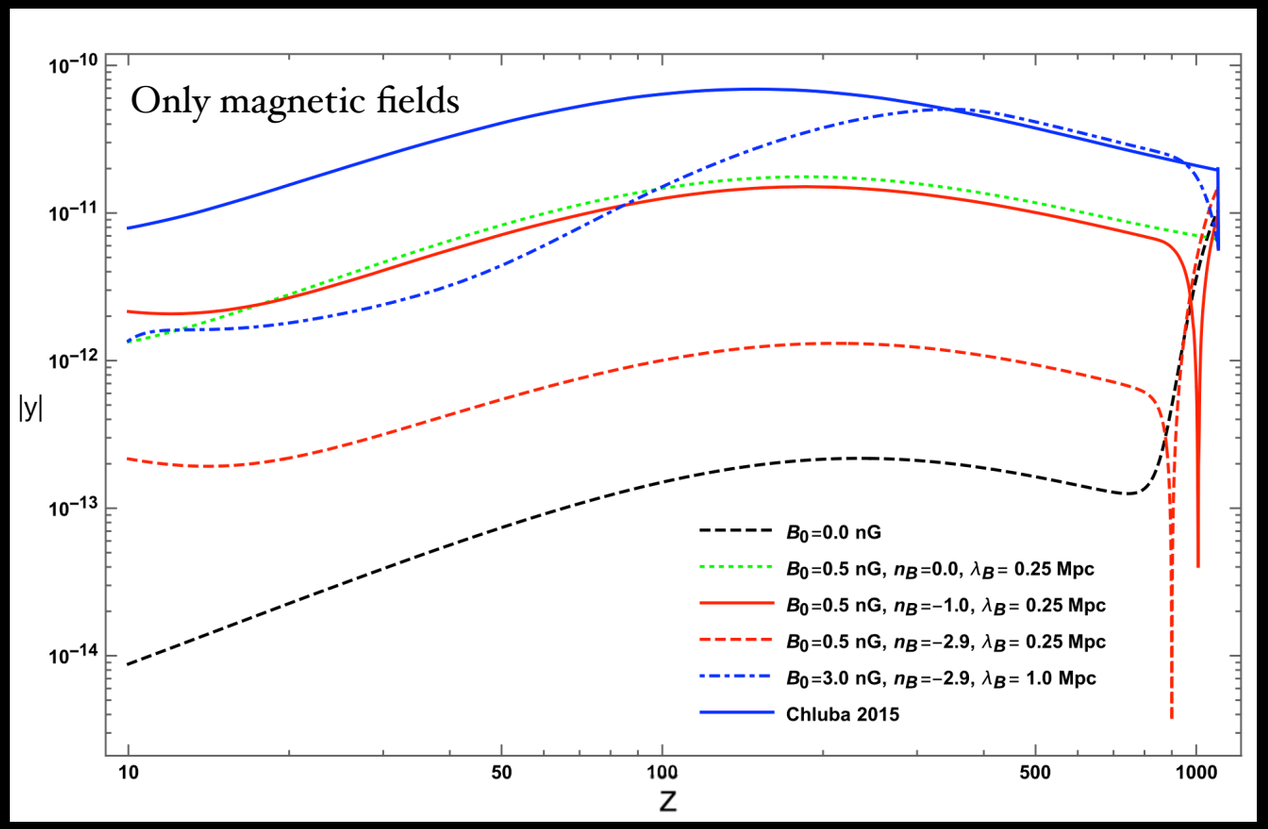






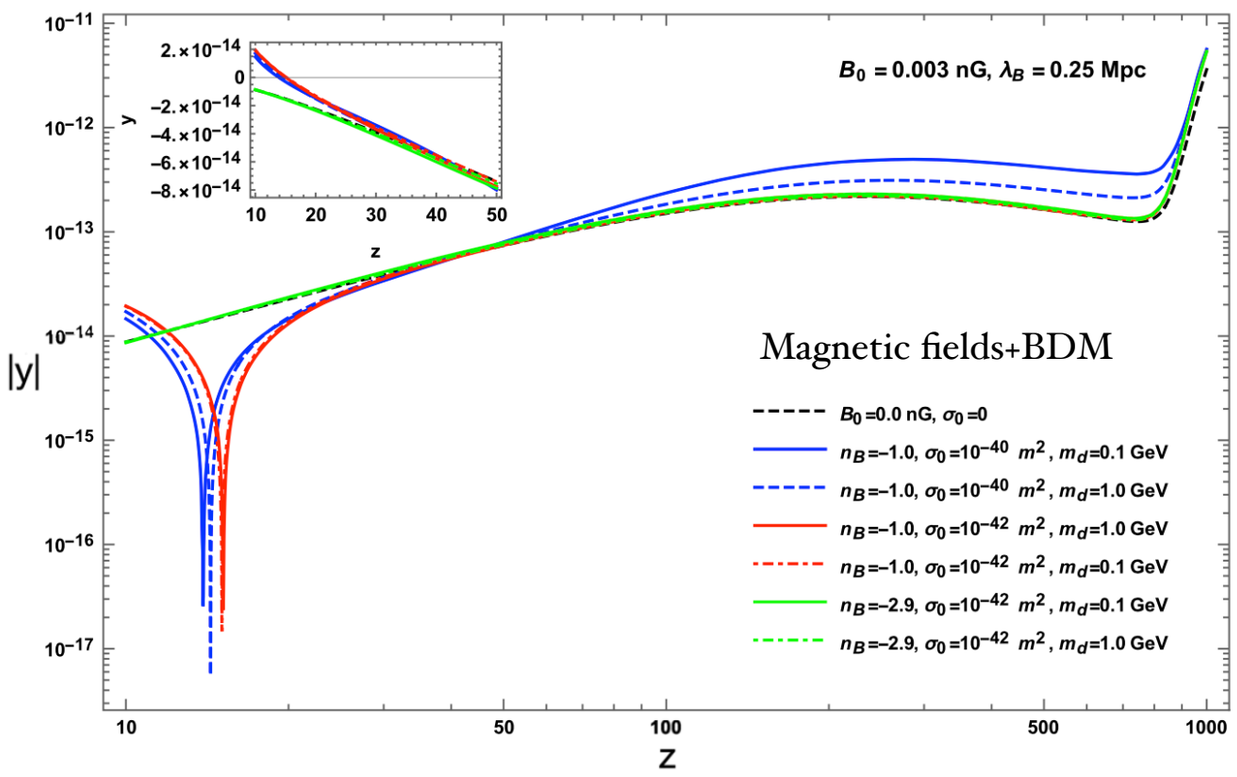
DM decay+ BDM interactions

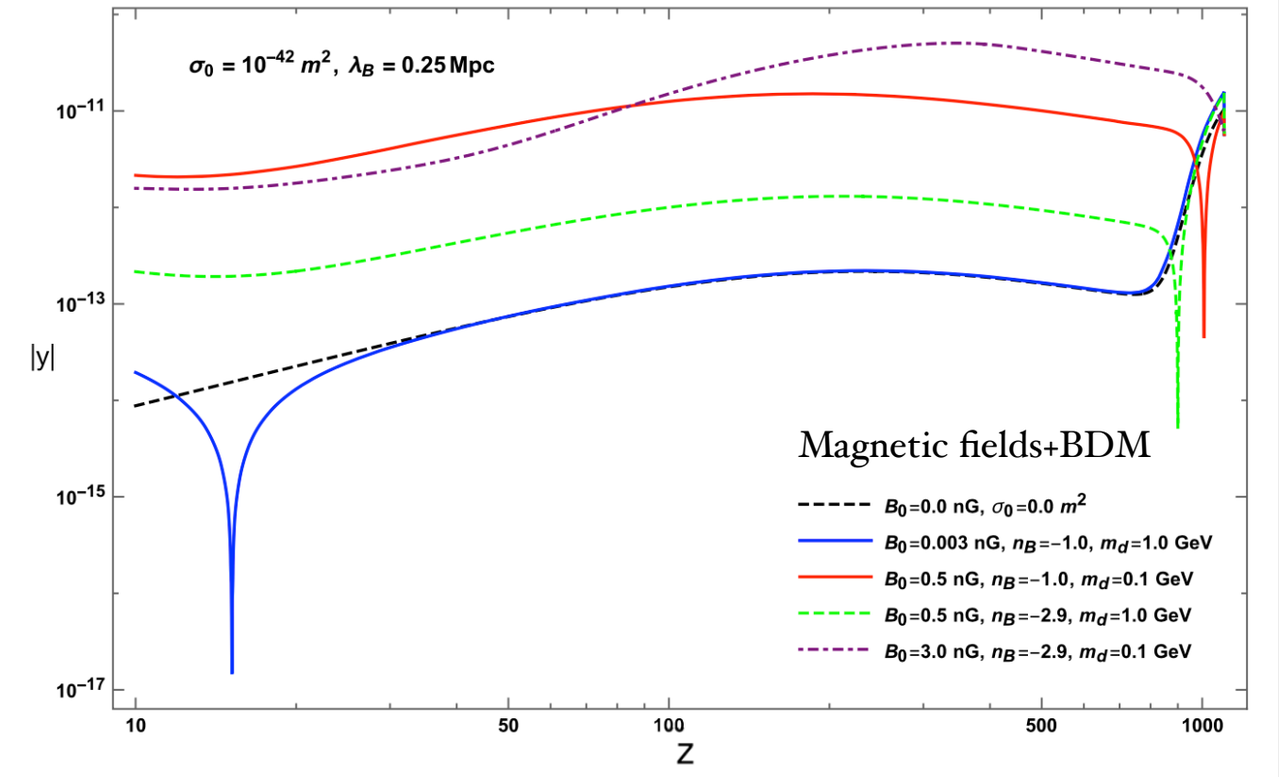
Pandey et al. (2022) 2204.08088 [astro-ph.CO]



The $y-$parameter on the sky plane in direction $\hat{n}$:

$$y(\hat{n}) = \int dz \frac{k_B \sigma_T}{m_e c} \frac{\left[x_e n_H (T_b - T_{\rm CMB})\right]|_{\hat{n},z}}{(1+z)H(z)}$$





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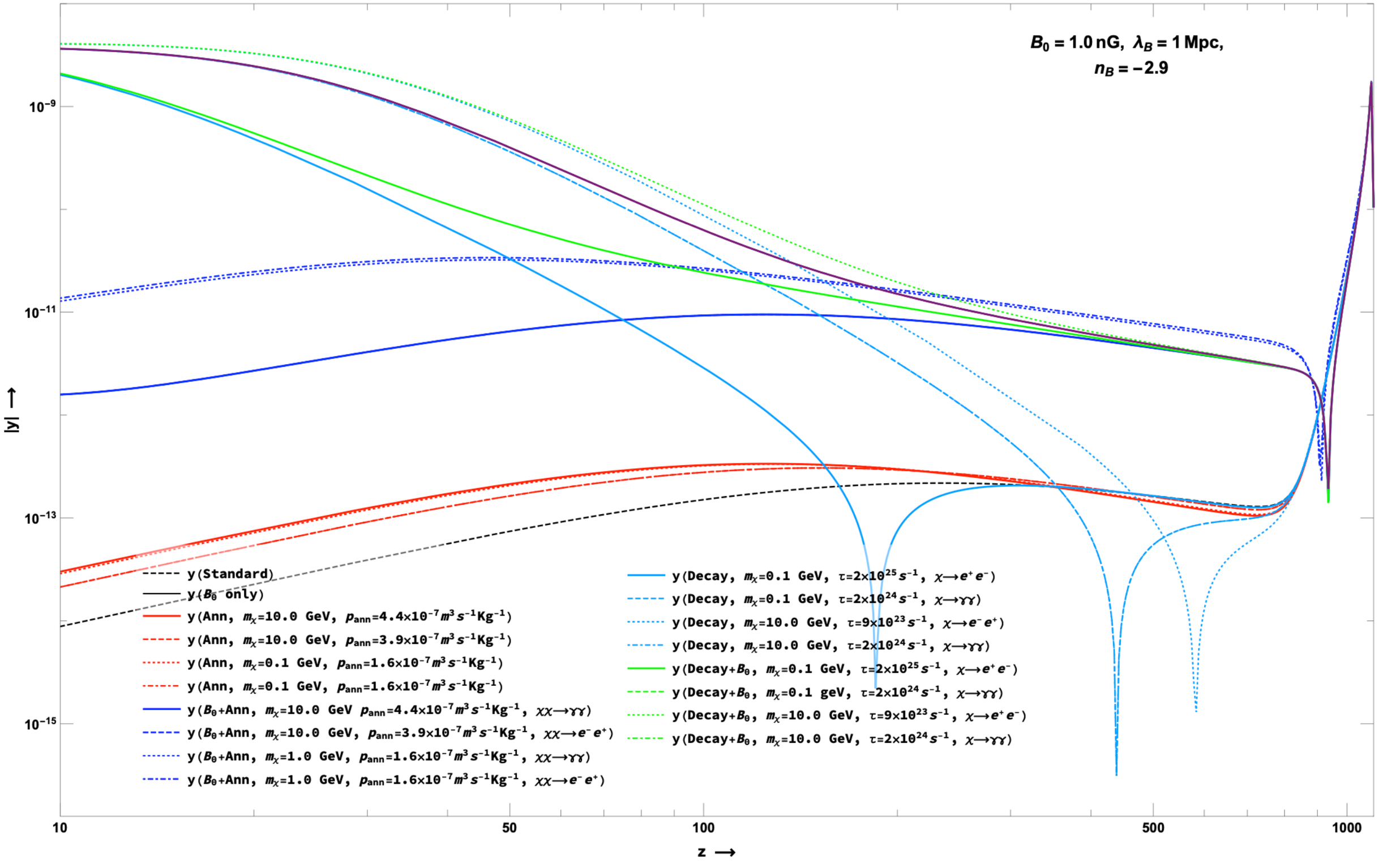

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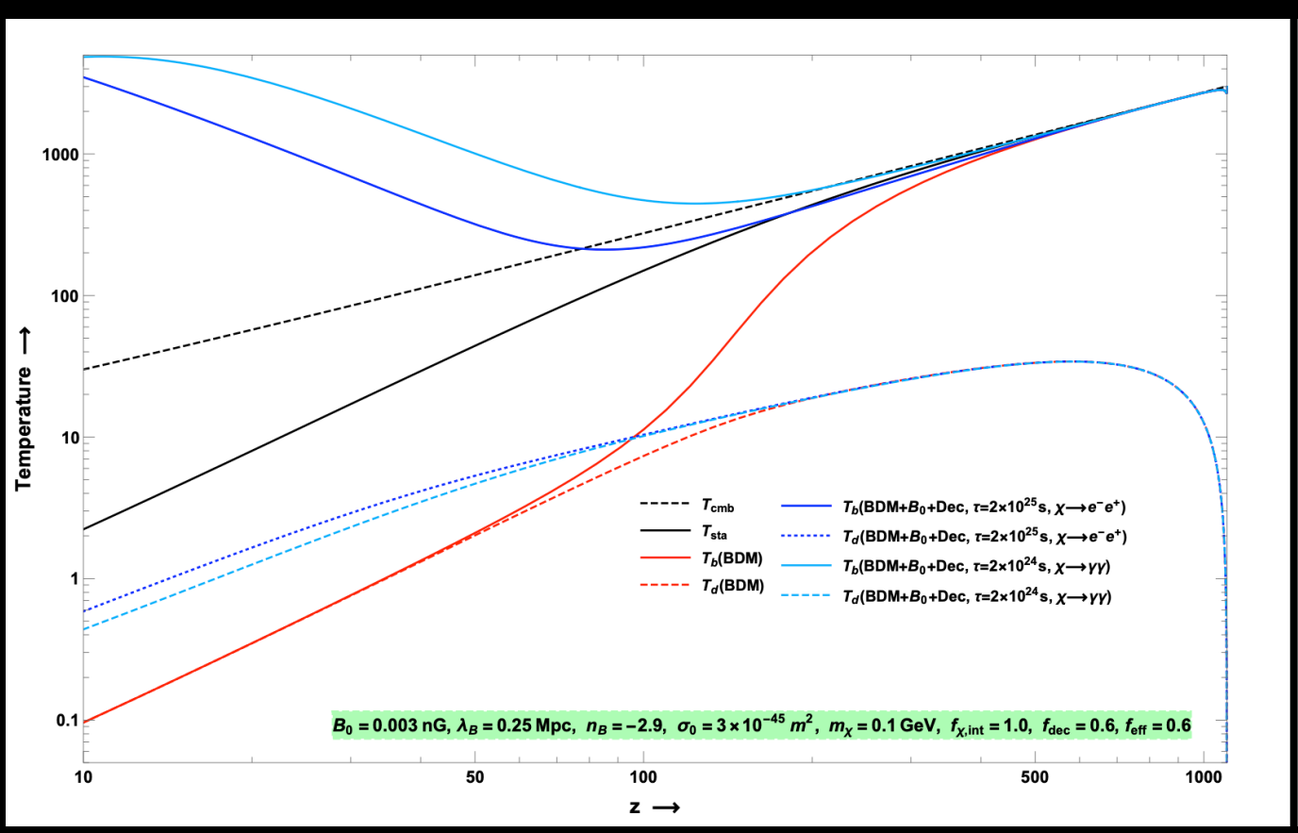
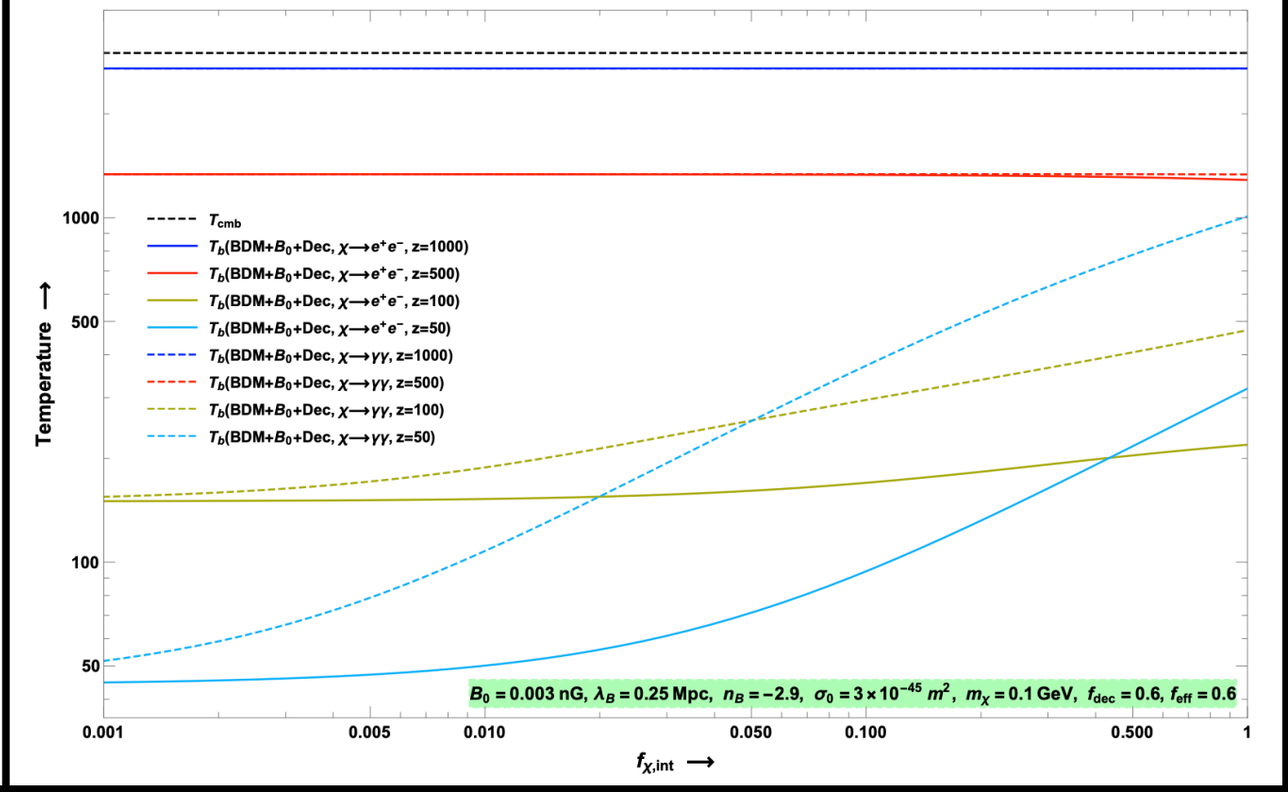
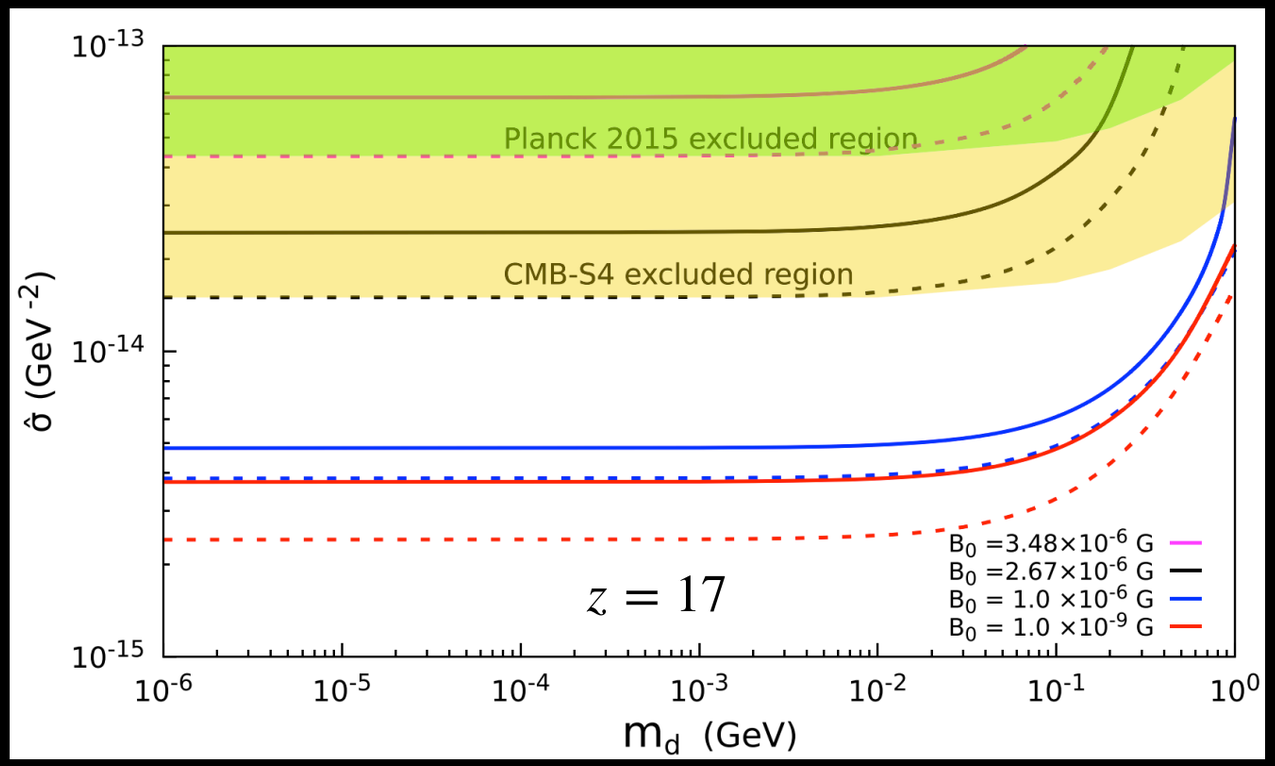
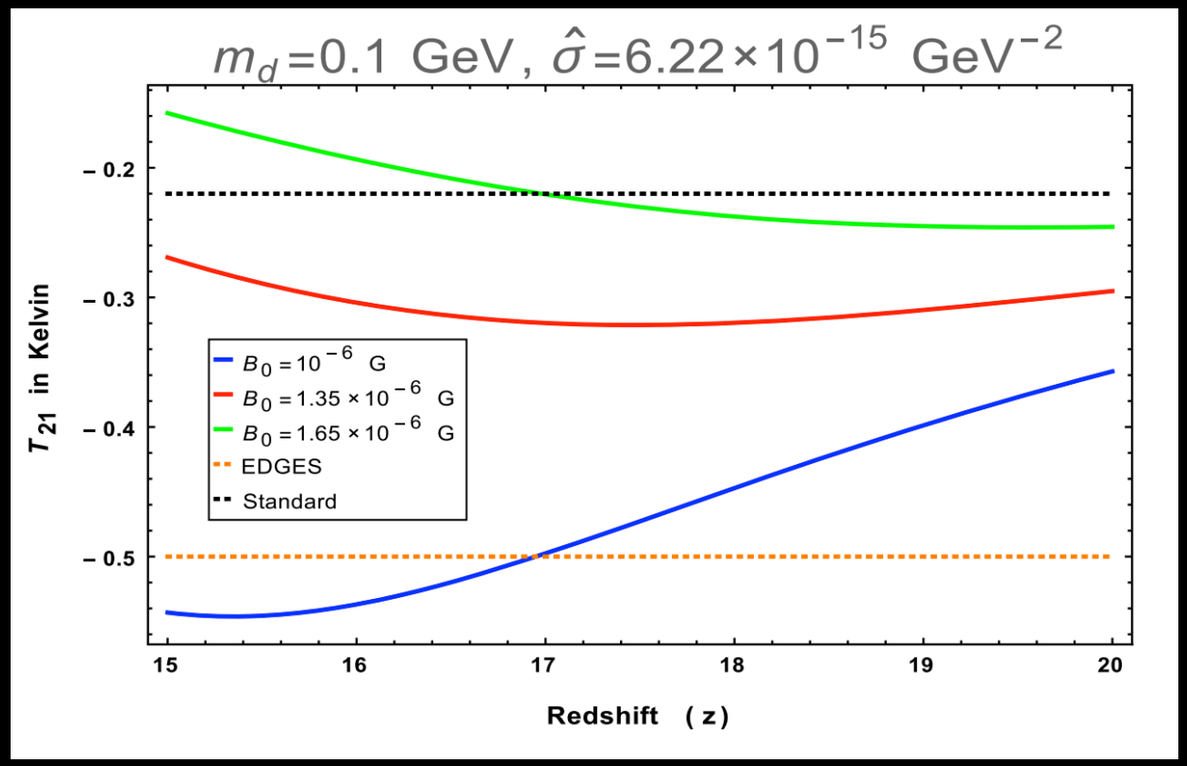




DM decay+ BDM interactions +B_0





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Thank You