Importance of soft photon heating for 21cm Cosmology

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21cm Cosmology

- 21 cm ($\approx$ 1.4 GHz) line arises from hyperfine splitting of ground state of hydrogen

- Observable - 21cm brightness temperature relative to background radiation at that frequency

$$\Delta T_b = \frac{(1 - e^{-\tau_{21}})}{1+z}(T_s - T_R)$$ (Furlanetto 2006)

Typically, $T_R = T_{\rm CMB}$ assuming this is the only background but it can have extra non-thermal contribution with $T_R = T_{\rm CMB} + \Delta T$

21cm Cosmology

- Spin temperature (T_s) is defined as the ratio of population of upper and lower hyperfine states,

$$\frac{n_1}{n_0} = 3e^{-T_*/T_s} \qquad T_* = h\nu_{21}/k_B$$

Spin temperature is determined by processes such as interaction of HI with radiation, collision with other hydrogen atoms, electrons and protons, resonant scattering of Lyman-alpha photons from stars and X-ray heating from energetic photon sources.

Spin temperature is given by a weighted sum of radiation temperature, matter temperature and colour temperature of Ly-alpha radiation field.

Tale of two radio excess
1. EDGES

- Strong 21 cm absorption signal reported by EDGES collaboration (Bowman et al 2018) with $\Delta T_b =$ -500 mK at $z \approx 18$. For just CMB as a background, $\Delta T_b \approx -(100-150)$ mK

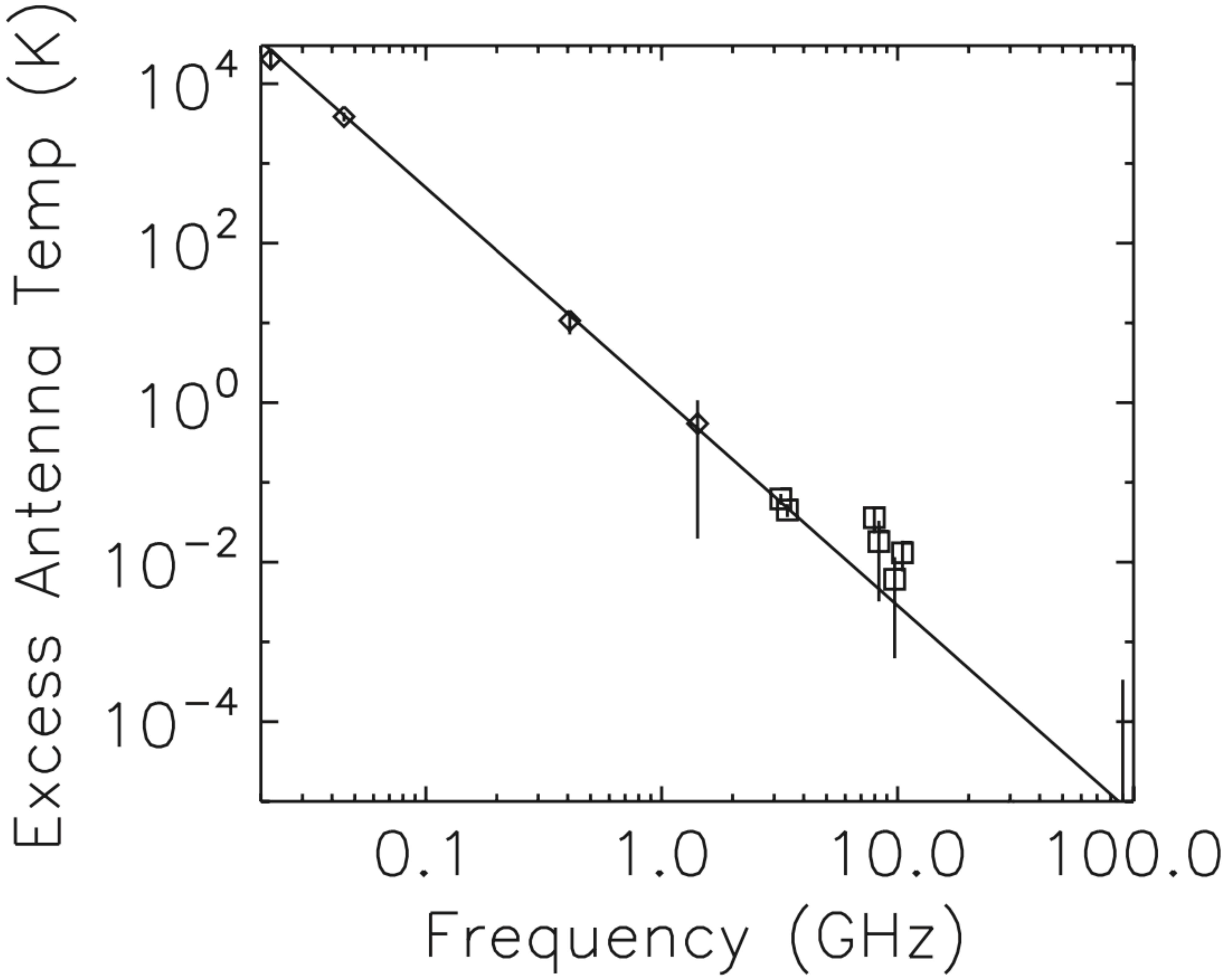
- Since $\Delta T_b \propto x_{\rm HI}\left(1-\frac{T_r}{T_s}\right)$, extra radio background on top of CMB can potentially explain the absorption depth given the spin temperature does not get affected by the radio background

- EDGES measurement could not be reproduced by SARAS 3 (Singh et al 2022). We use EDGES as a figure of merit in our work

Tale of two radio excess
2. ARCADE 2/LWA excess

Detected excess radio background, as seen today, on top of CMB within 20 MHz-10 GHz even after accounting for resolved discrete radio sources

Best fit power law spectrum with spectral index ≈ 2.6



Fixsen et al 2011, Dowell and Taylor 2018

Interplay between two excess

- If the ARCADE 2/LWA excess was already present at $z \approx 20$, the absorption depth would have been even deeper than the EDGES detection (Feng and Holder 2018)

- EDGES detection allows for about 5 percent of radio excess at $z \approx 18$

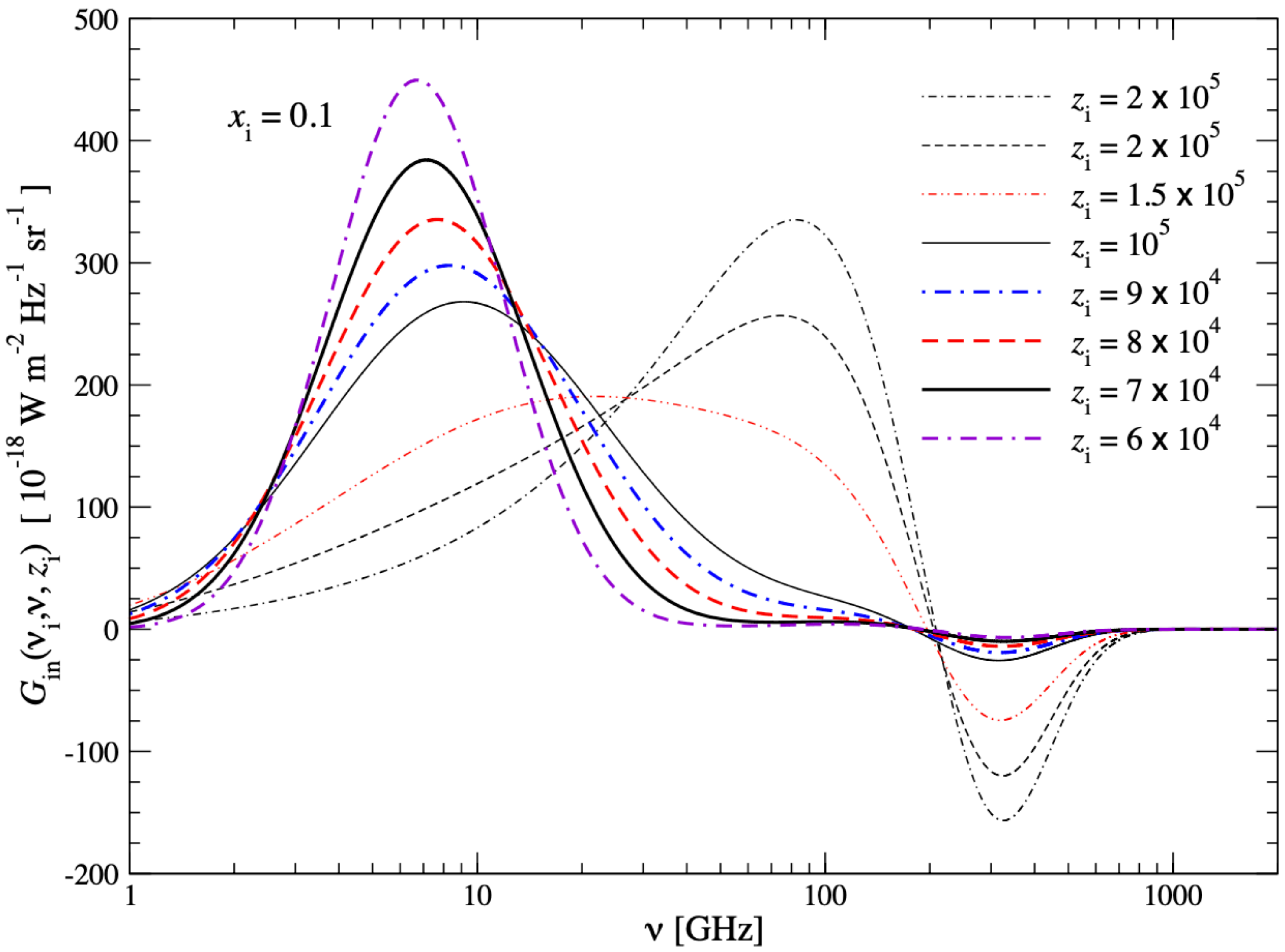
- 21 cm anisotropy measurements puts complementary constraints on allowed radio background at $z \approx 10$ (HERA collaboration 2022) though it does not allow or exclude EDGES measurements currently

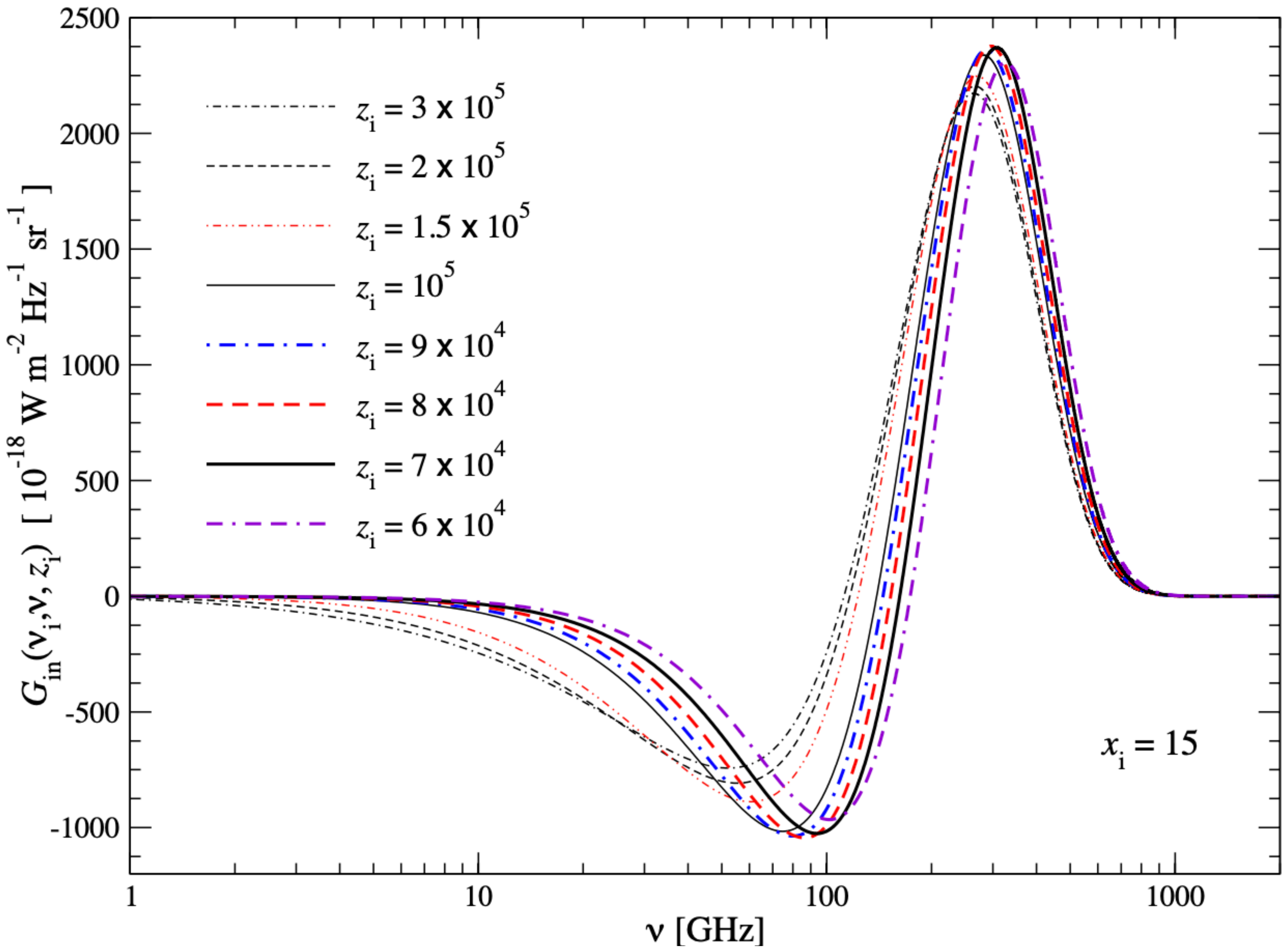
- These constraints are derived assuming that the radio photons, once injected, just redshift over time

Impact of photon injection on thermal history of universe

- Addition of photons disturbs the equilibrium between CMB photons and the electrons

CMB photons and the electrons evolve to establish the equilibrium but expansion of universe prohibits that giving rise to distortion from Planck spectrum





Consistent thermal history evolution with CosmoTherm

- We can consistently solve for evolution of thermal history of the universe using CosmoTherm (Chluba and Sunyaev 2012)

- Can compute CMB spectral distortion solutions, temperature evolution, ionization history and 21cm global distortion signal (thanks to Jiten Dhandha)

- Already present modules for analysing mono-energetic photons (Bolliet et al 2021), broad photon spectrum (Acharya et al 2023) and string decay (Cyr et al 2023)

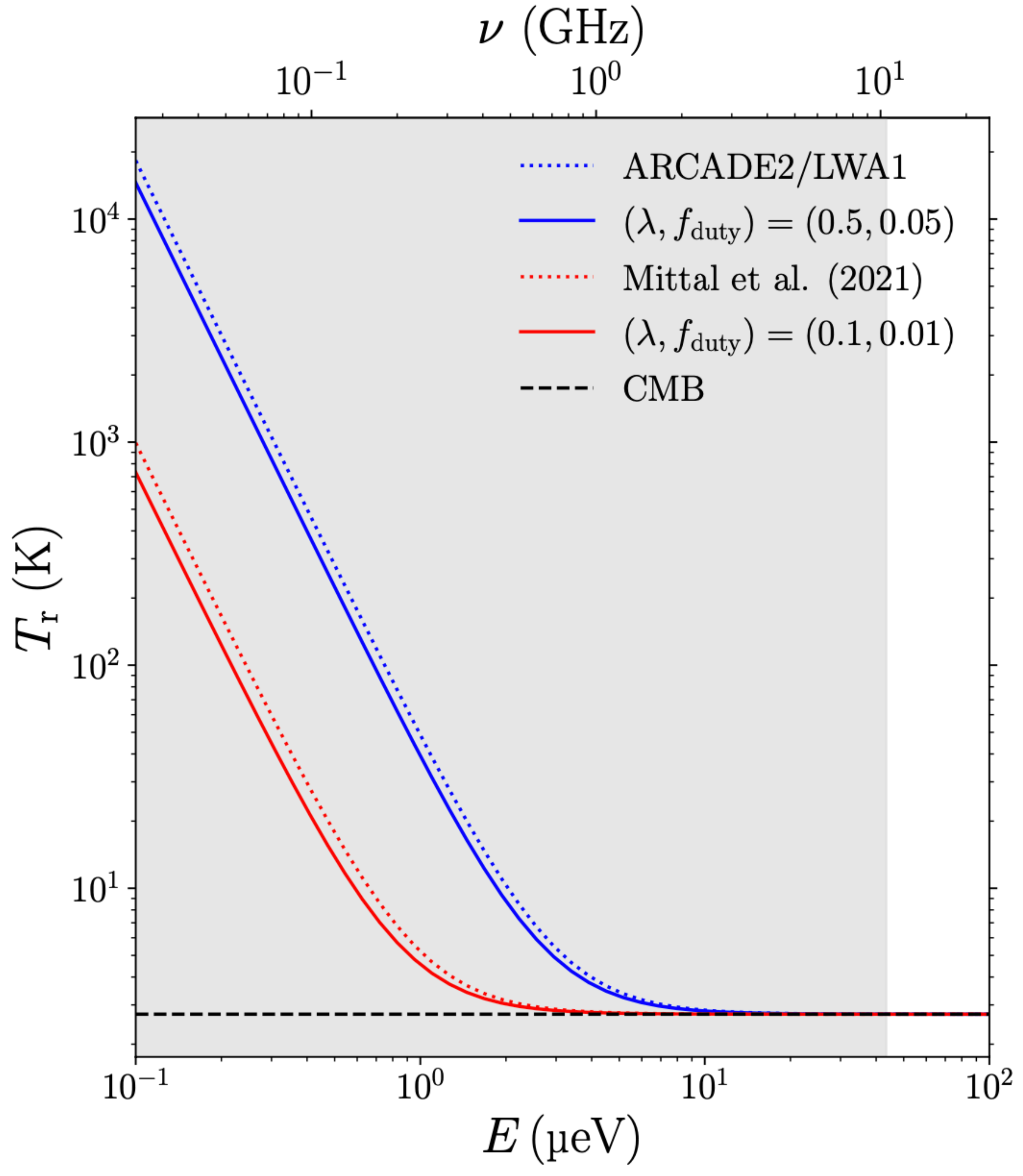
Soft photons vs hard photons

- Hard photons - photons with energy >13.6 eV. Can ionise neutral gas in post-recombination universe which changes ionization history drastically -> strong CMB anisotropy constraint

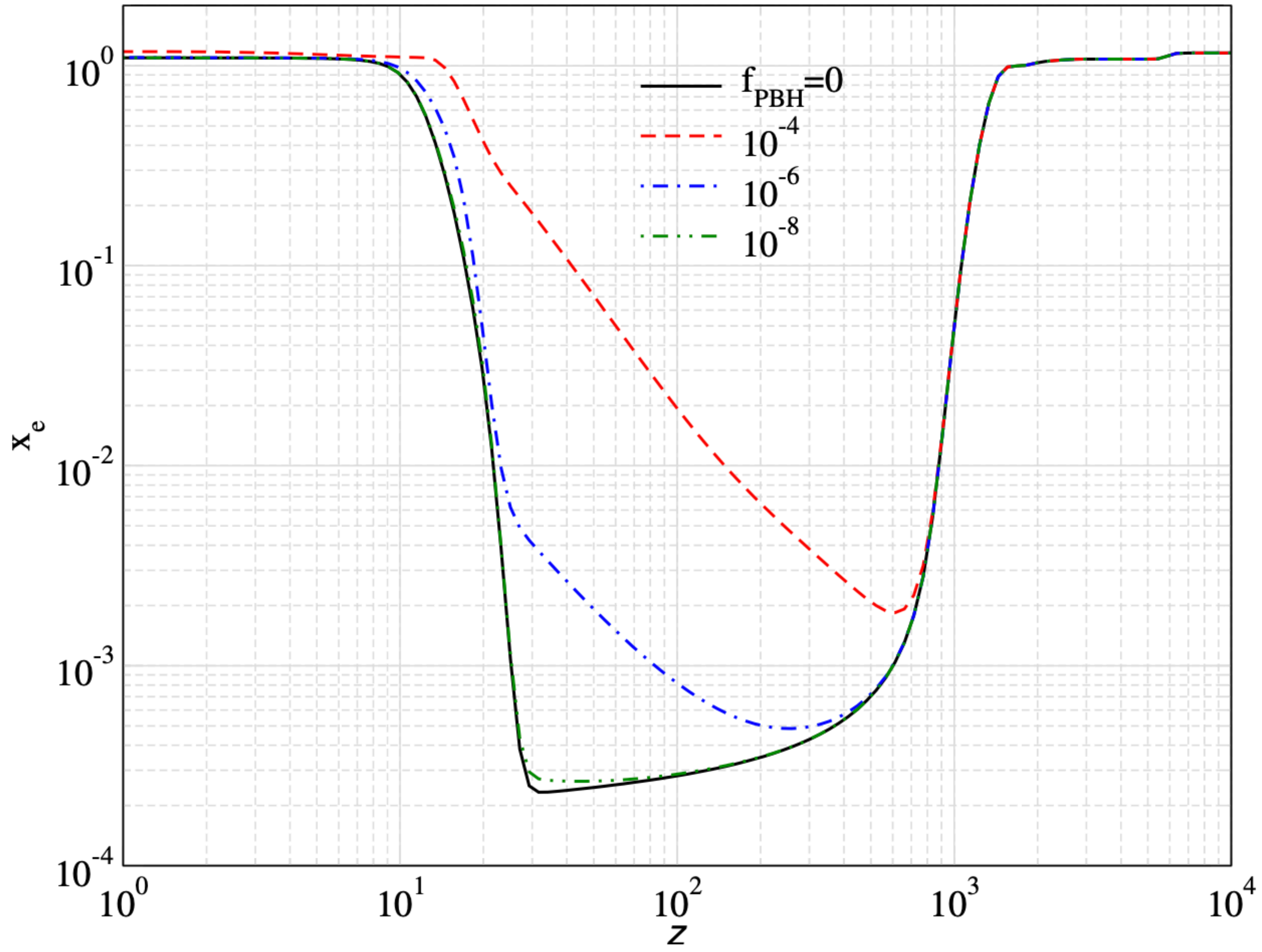
- Soft photons - Lower energy photons can't ionise neutral gas directly. Heating due to absorption of these soft photons by electrons -> rise in gas temperature and moderate change in post-recombination ionization history

Complementarity of CMB and 21cm observables for astrophysical emission process

- Typically, astrophysical emissions have broad emission spectrum
- For accreting primordial black holes, UV photon emission is strongly constrained by CMB anisotropies which then constraints amount of radio emission given there is a correlation between radio and UV flux



Mittal and Kulkarni 2022

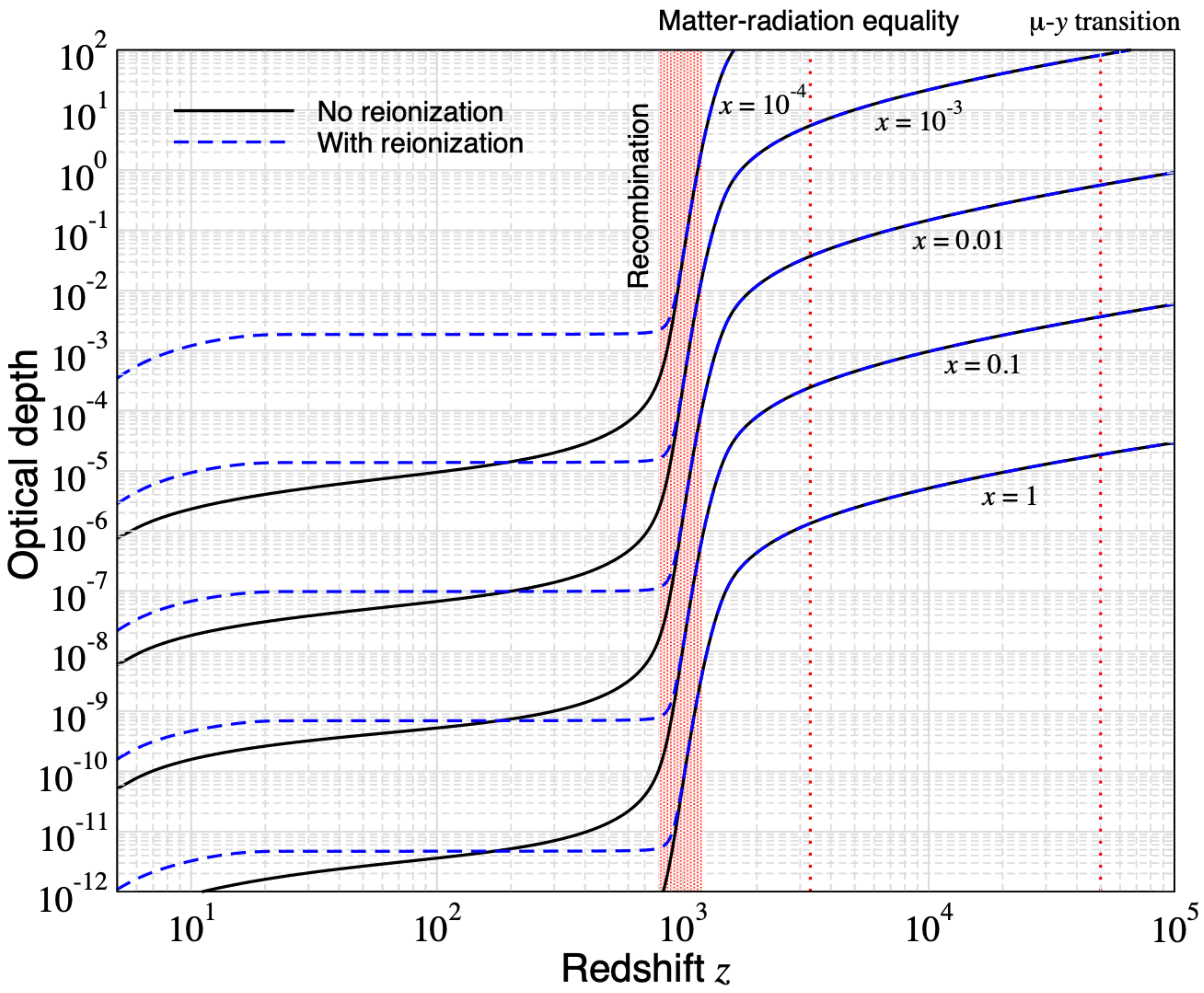


Acharya, Dhandha and Chluba 2022

Heating due to soft photons (SPH) at low redshifts

Low frequency photons are absorbed by electrons via Bremsstrahlung process which leads to heating

$$x = \frac{E_\gamma}{kT_{\rm CMB}}$$



Bolliet, Chluba and Battye 2021

Phenomenological model for soft photon injection

- We consider a phenomenological profile for photon injection,

$$\frac{d\rho_\gamma}{dt} = f_{dm}\Gamma\rho_{cdm}e^{-\Gamma t}$$

Γ = inverse lifetime

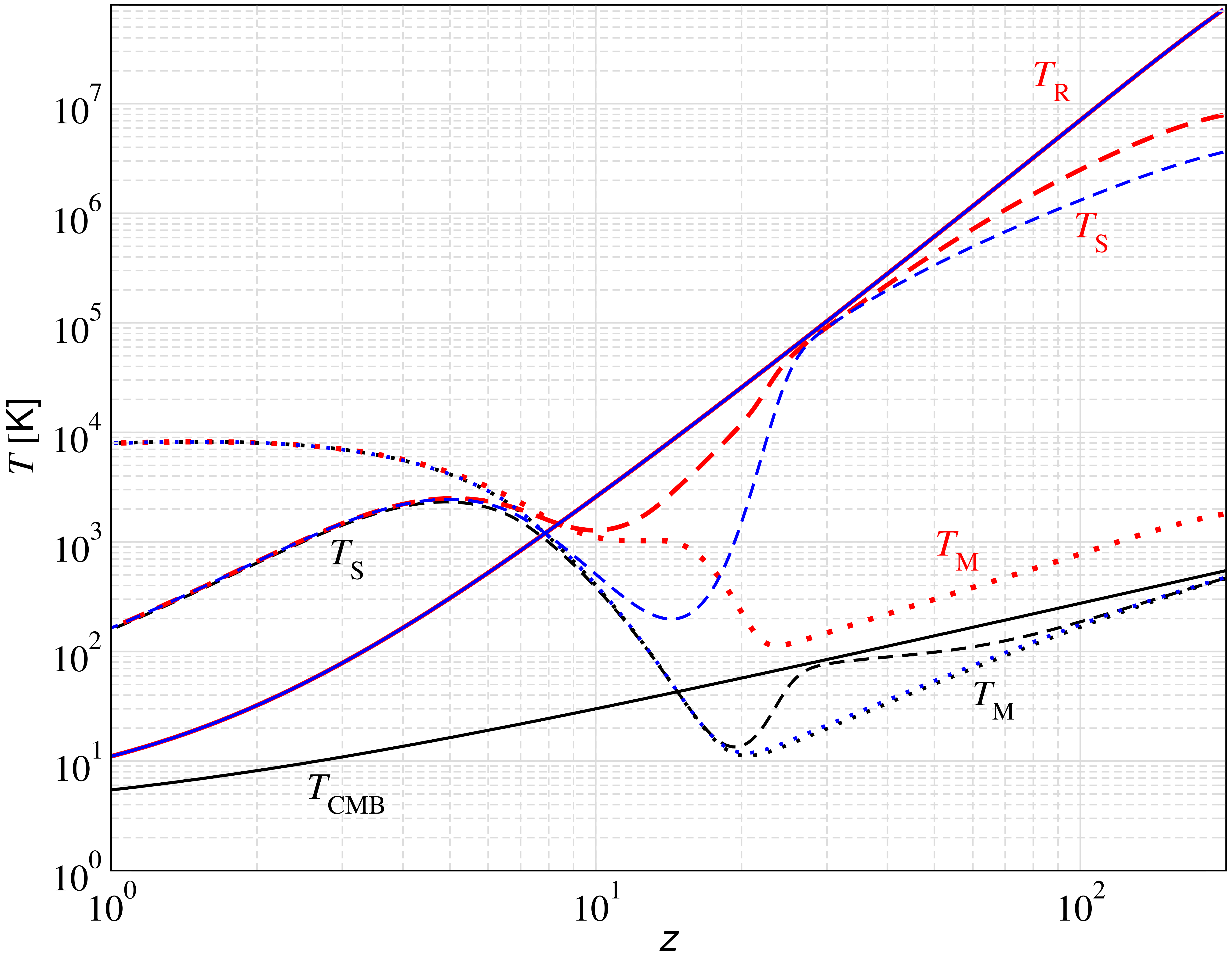
The injection spectrum is a broad power-law distribution,

$$\Delta I(x) \propto x^{-\gamma} e^{-\frac{x}{x_{\rm inj,0}}}$$

$$x = \frac{E_\gamma}{kT_{\rm CMB}}$$

We consider two cases with γ=0 and 0.6 which are free-free and synchrotron spectrum respectively.

Thermal history including SPH

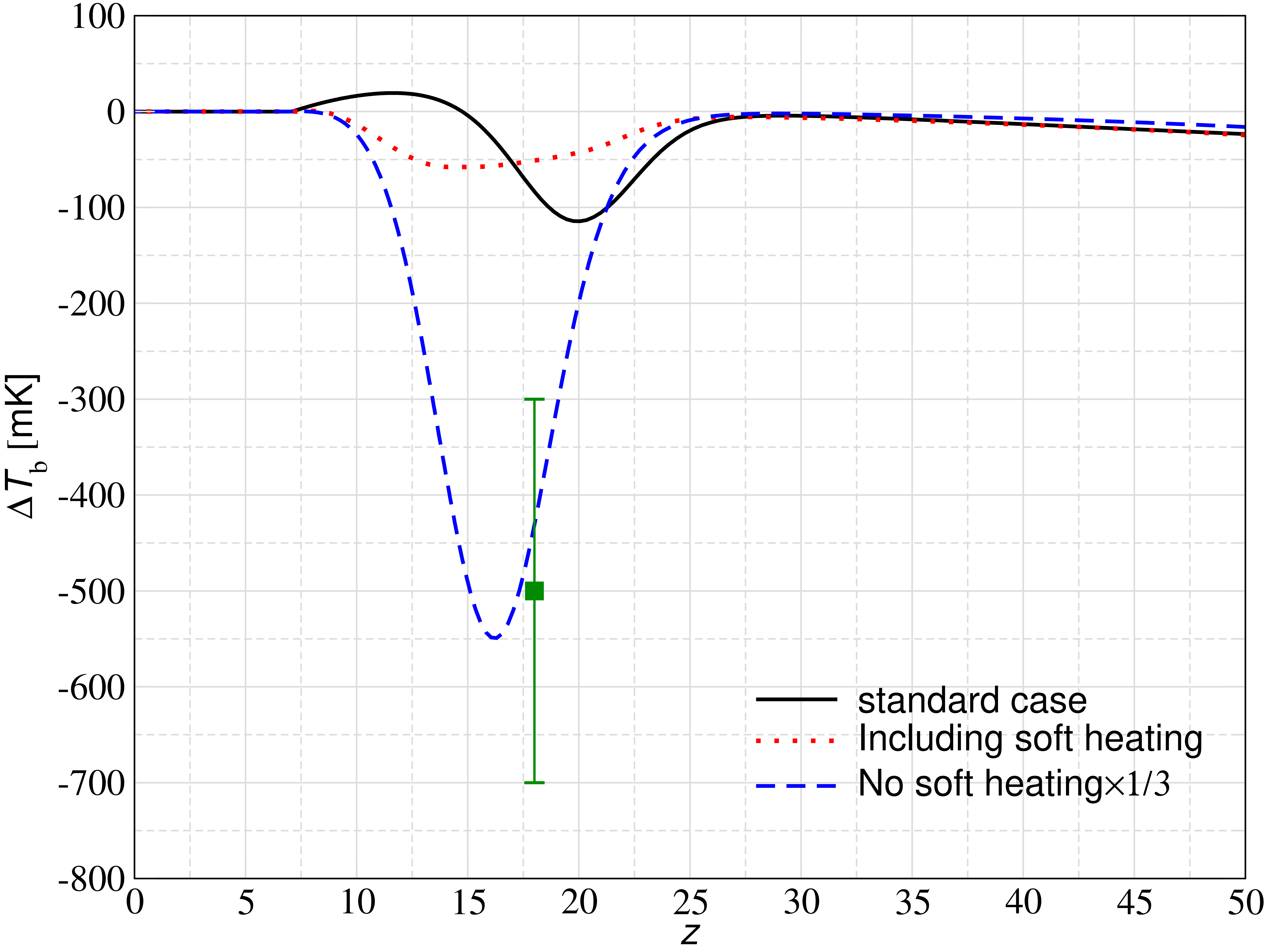


Acharya, Cyr and Chluba 2023

Black -standard cosmology
Red -with SPH
Blue - without SPH

Solid line- T_R
Dotted line- T_K
Dashed line- T_s

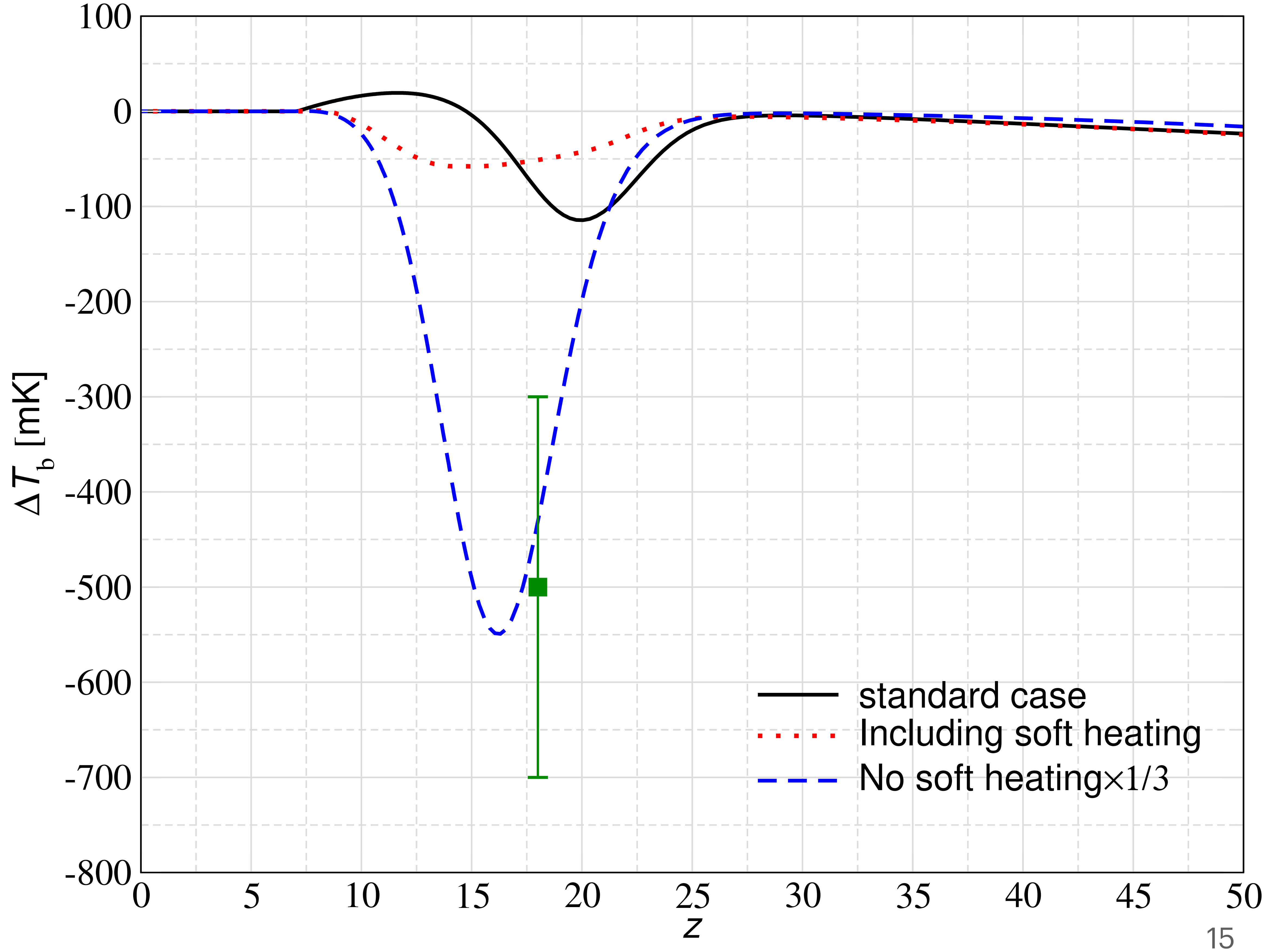
Implication for 21 cm global signal

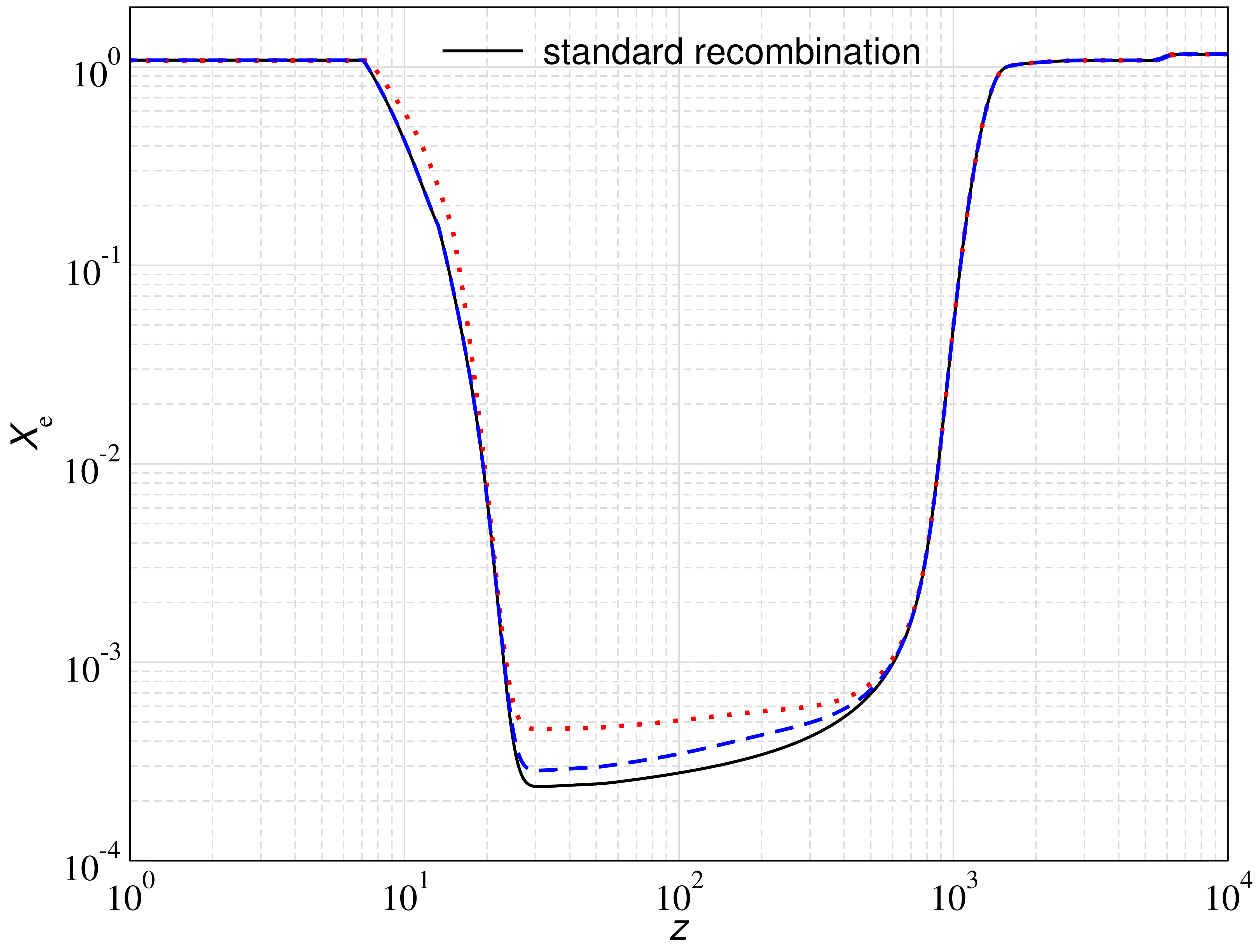


Parameter combination is chosen to have ARCADE excess at $z \approx 20$

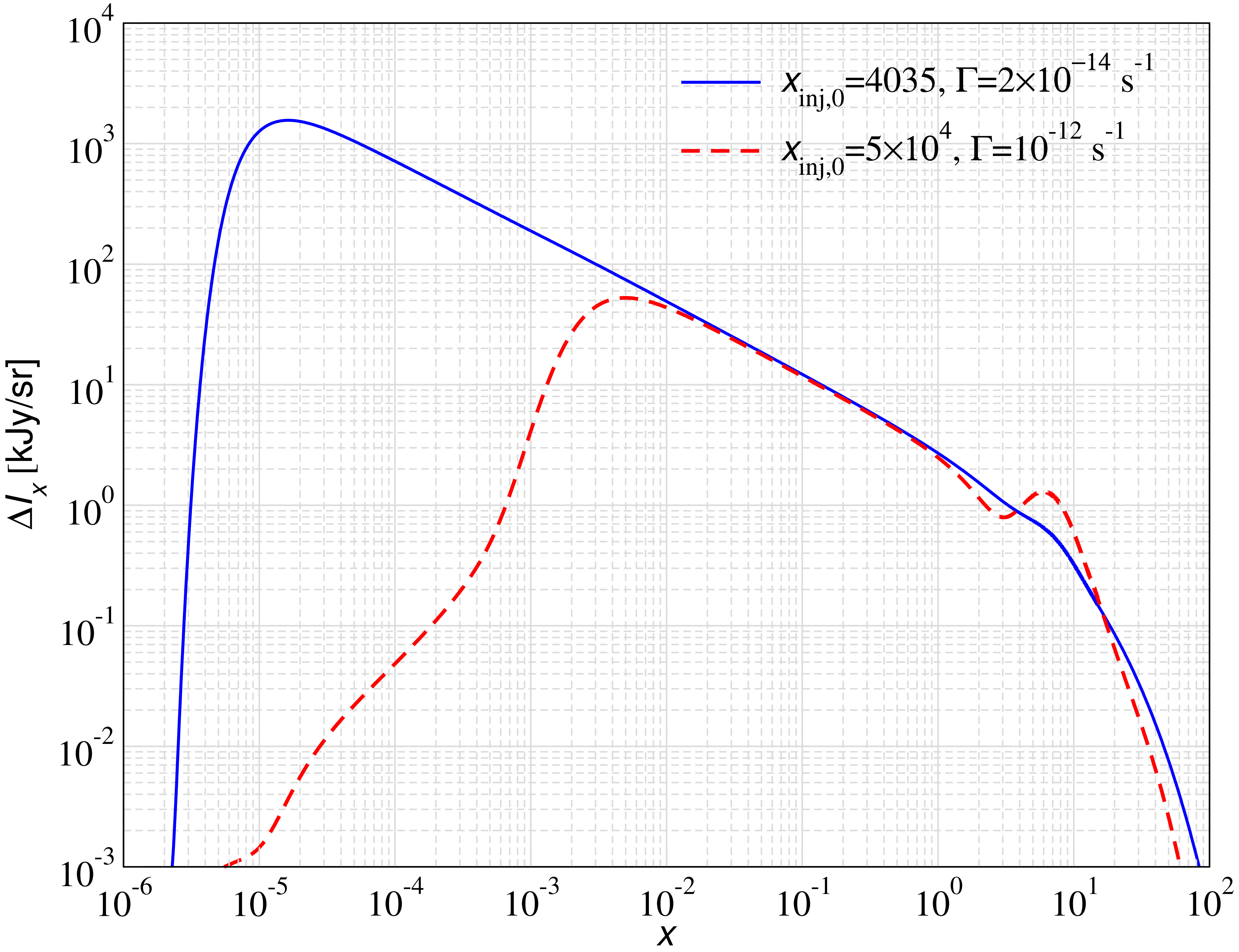
Complementarity with CMB observables

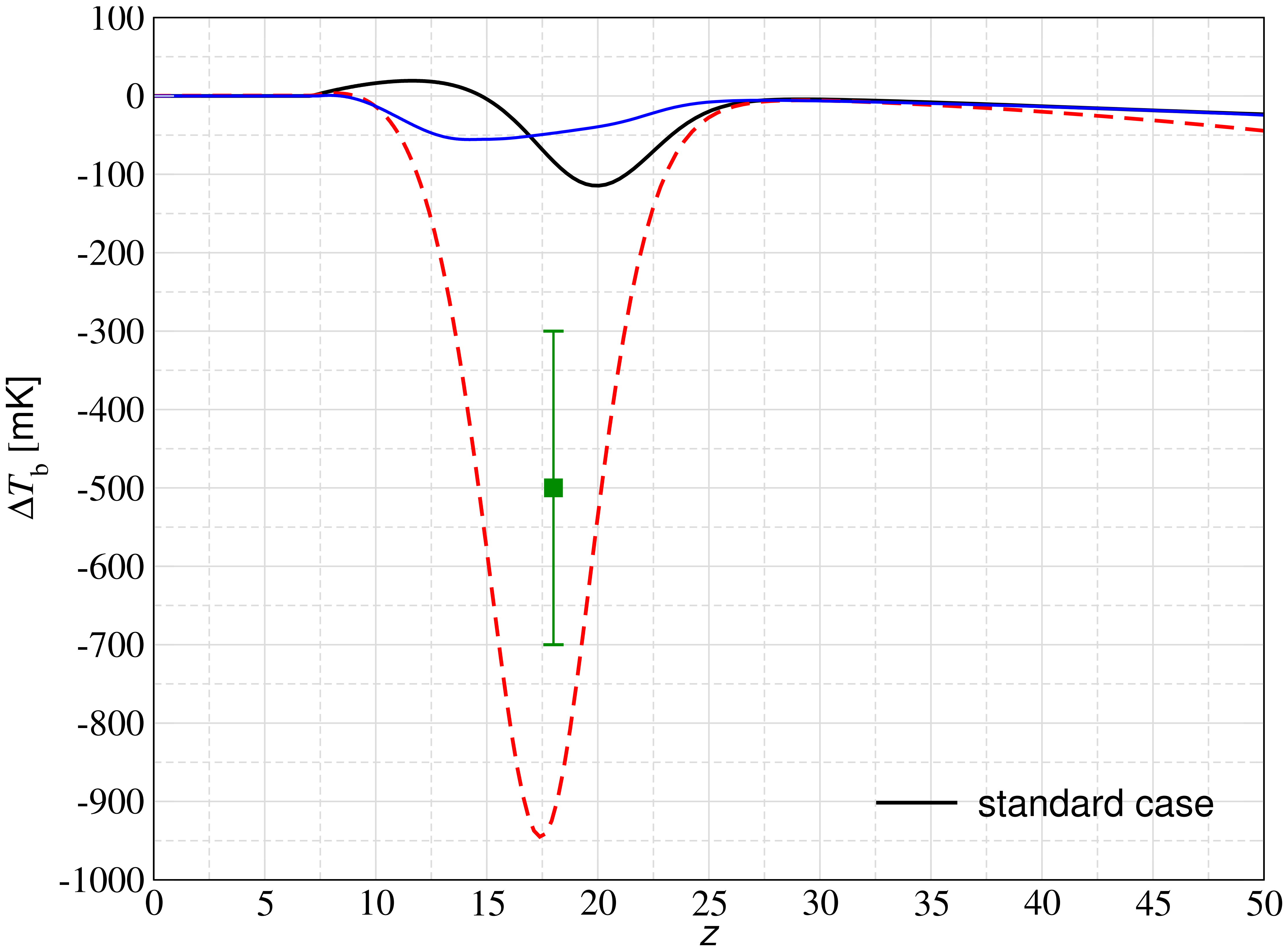
- Heated baryons lead to less recombinations which leads to increased residual electron ionization fraction -> modification to CMB anisotropies



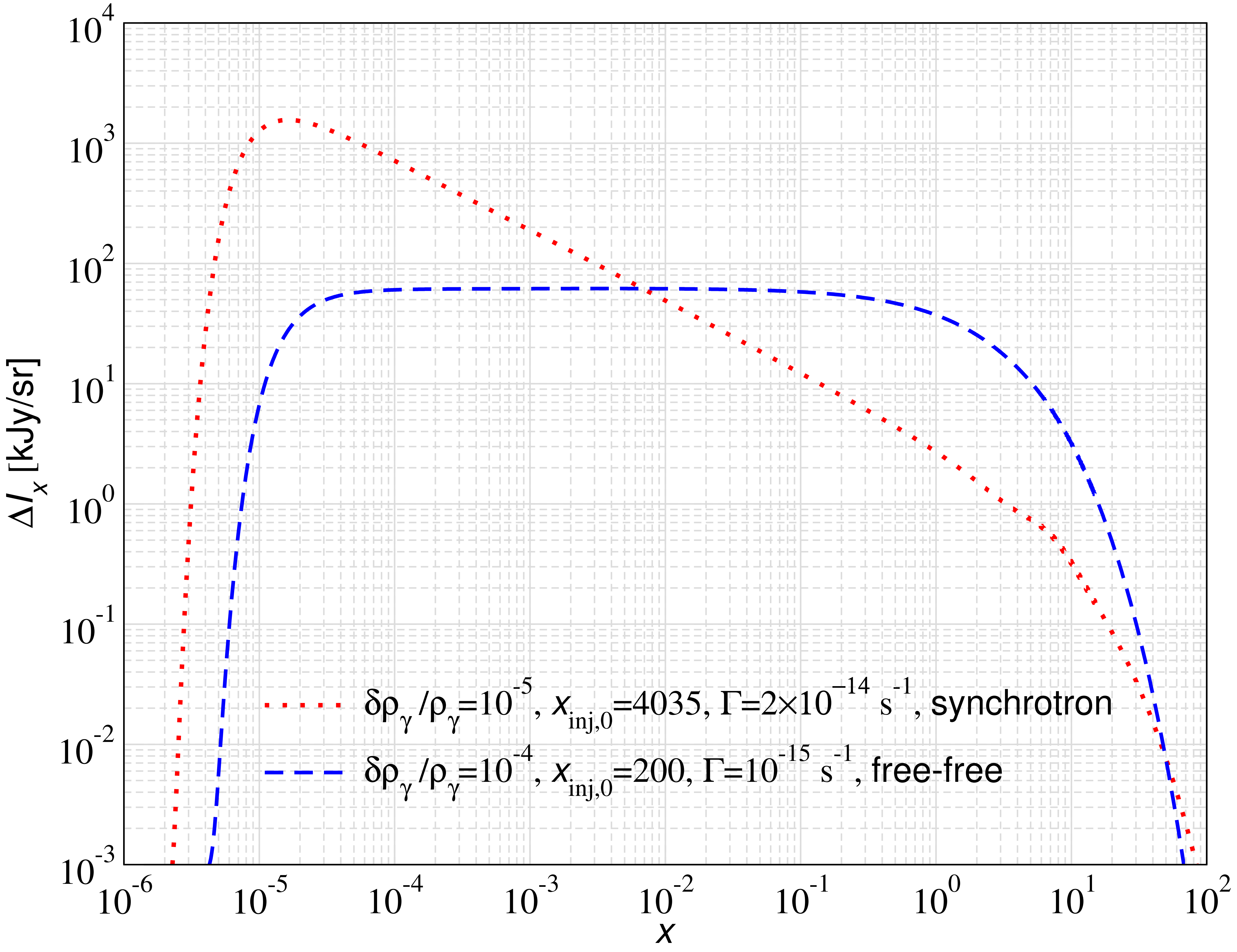


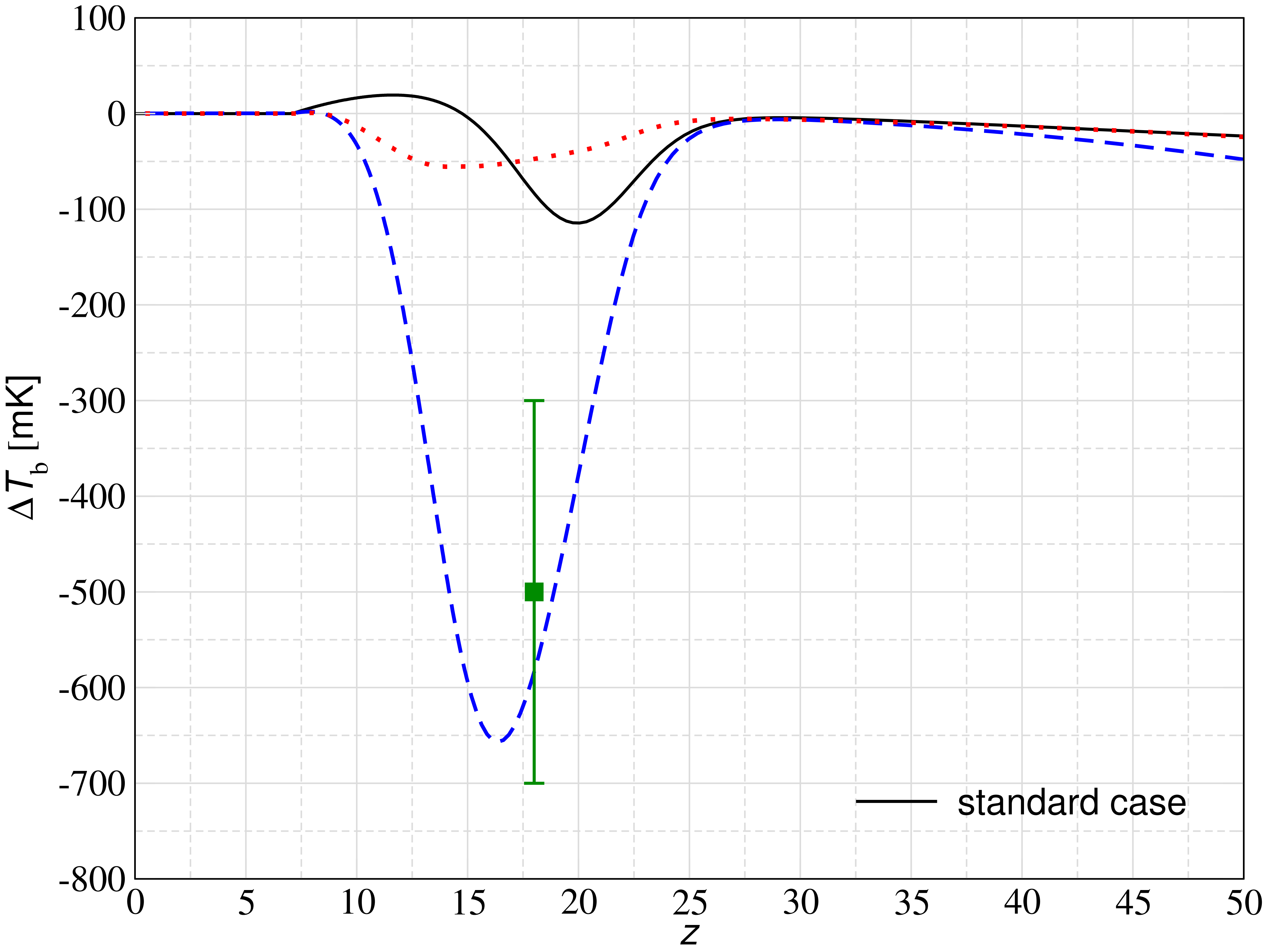
SPH mechanism only effective in post recombination universe



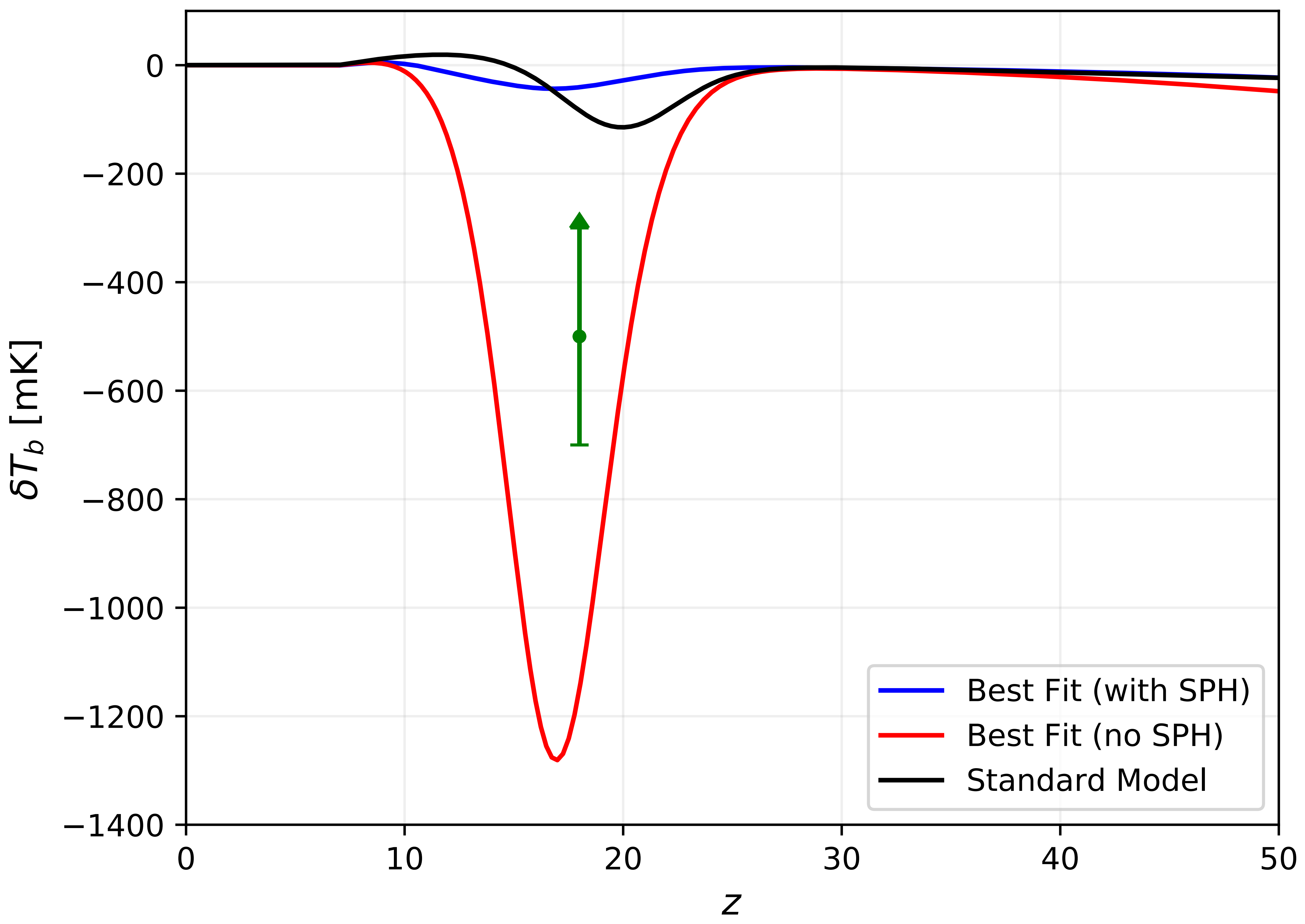


SPH mechanism is dependent on soft photon spectrum





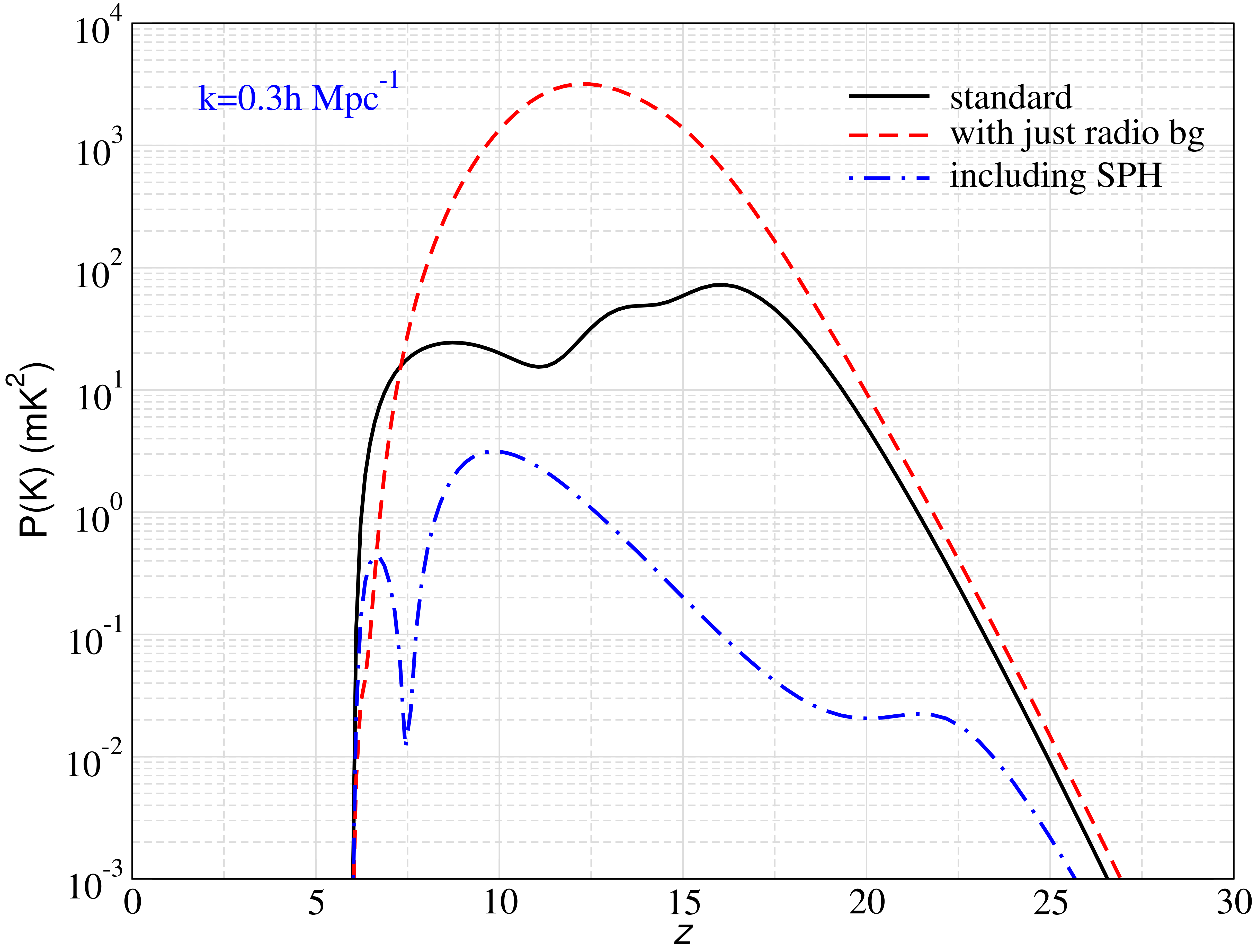
Implication of SPH for string loops decay



Cyr et al (in prep), Cyr et al 2305.09816

Importance of SPH for 21 cm anisotropy

SPH can drastically alter constraints on radio background from 21cm anisotropy measurements



Preliminary results

Conclusion

- We showed the importance of heating due to soft or radio photons for global 21cm signal
- Has implications for 21cm anisotropy signal too
- This effect can be computed using *CosmoTherm*