TeVPA 2023

CMB and Lyman-α constraints on dark matter decays to photons

FRANCESCO CAPOZZI

based on JCAP 06 (2023) 060, in collaboration with R. Z. Ferreira, L. Lopez-Honorez and O. Mena

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DEL GRAN SASSO

Ionisation and Thermal History

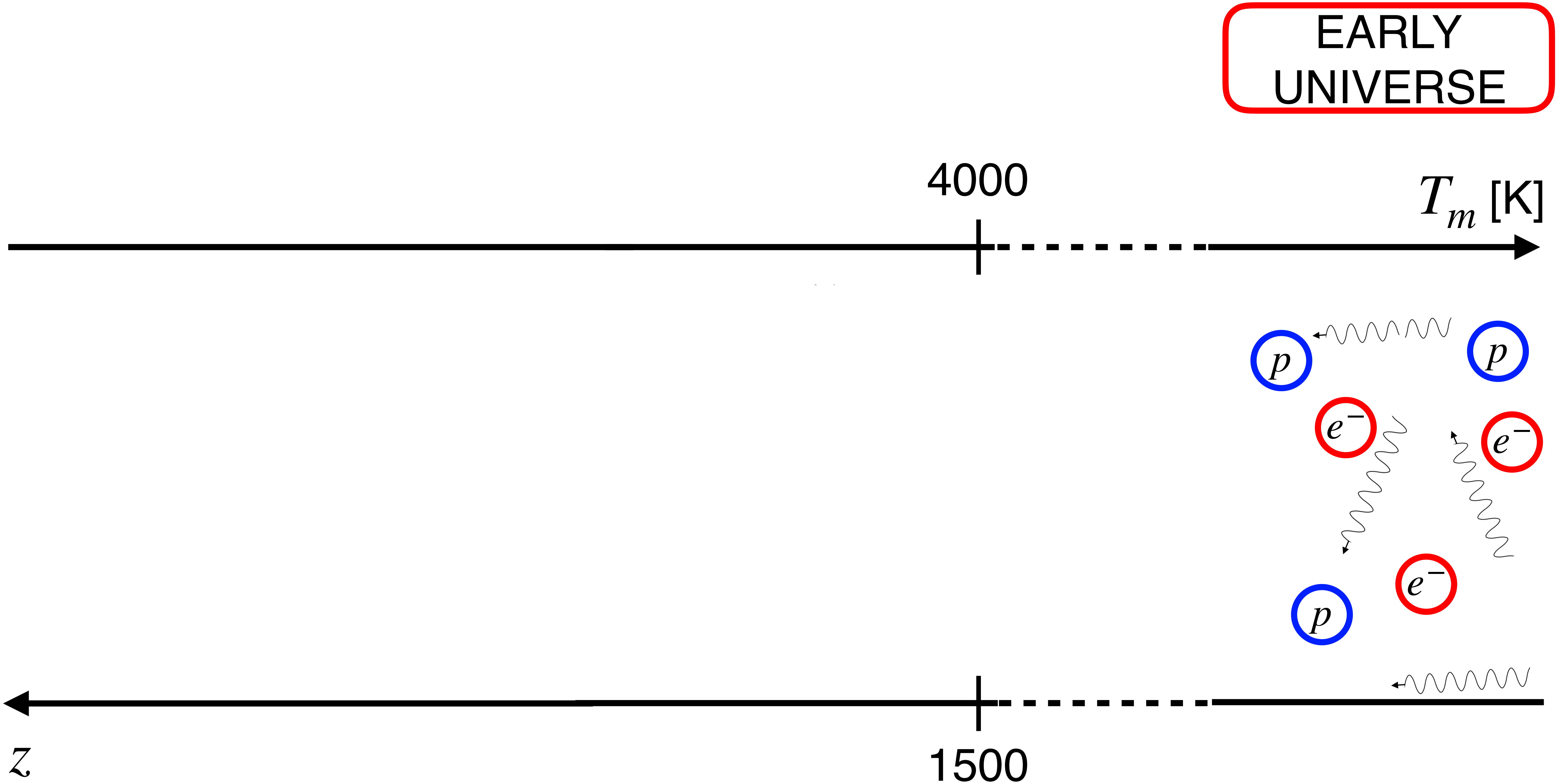
Parameters describing the evolution of the Universe after recombination:

$$T_m(z) = \text{Temperature of matter}$$

$$T_{\text{CMB}}(z) = \text{Temperature of cosmic microwave background}$$

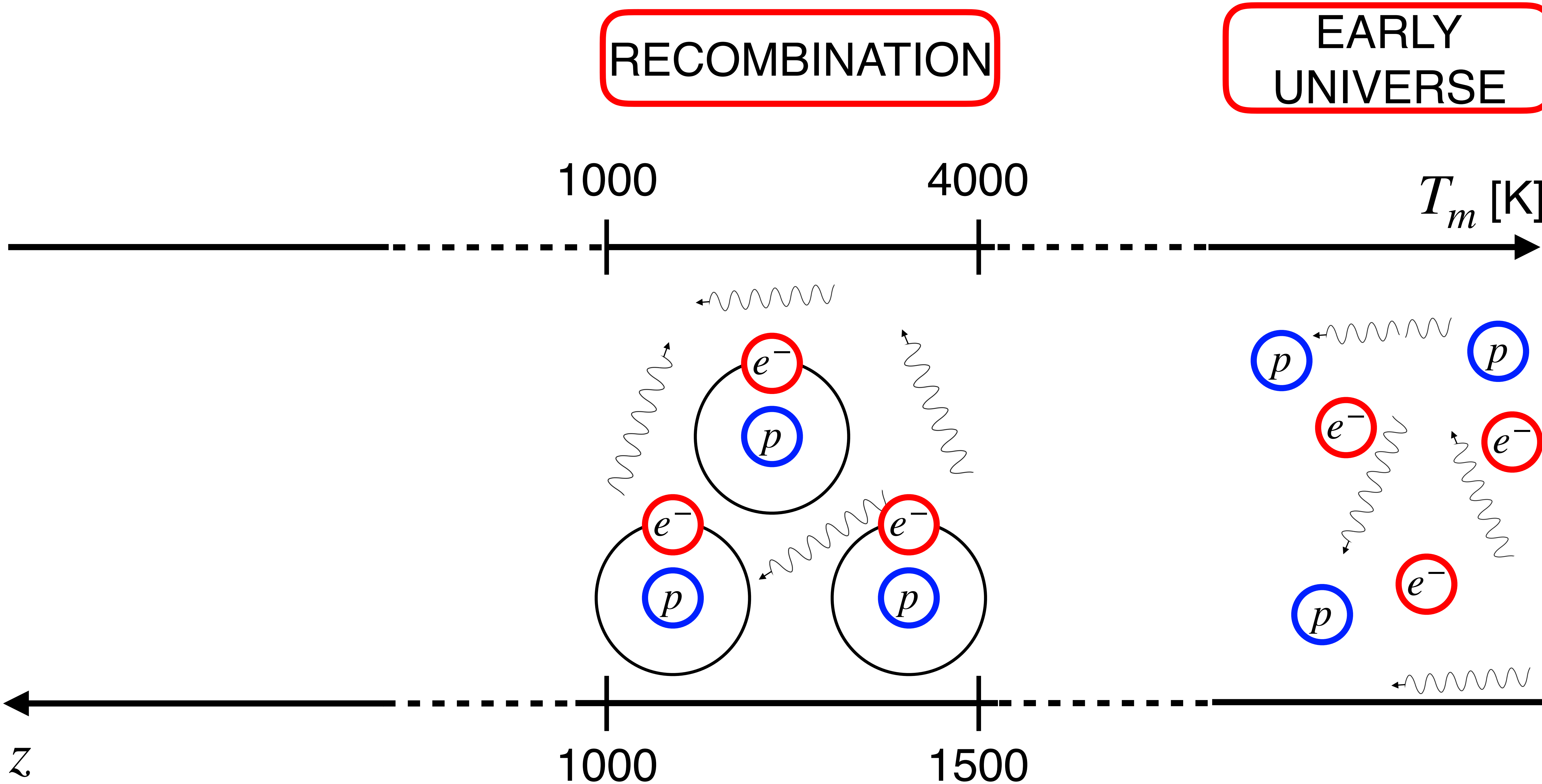
$$x_e(z) = \frac{\text{Number density of free electrons}}{\text{Number density of hydrogen nuclei}} = \frac{n_e^{\text{free}}}{n_H}$$

Ionisation and Thermal History



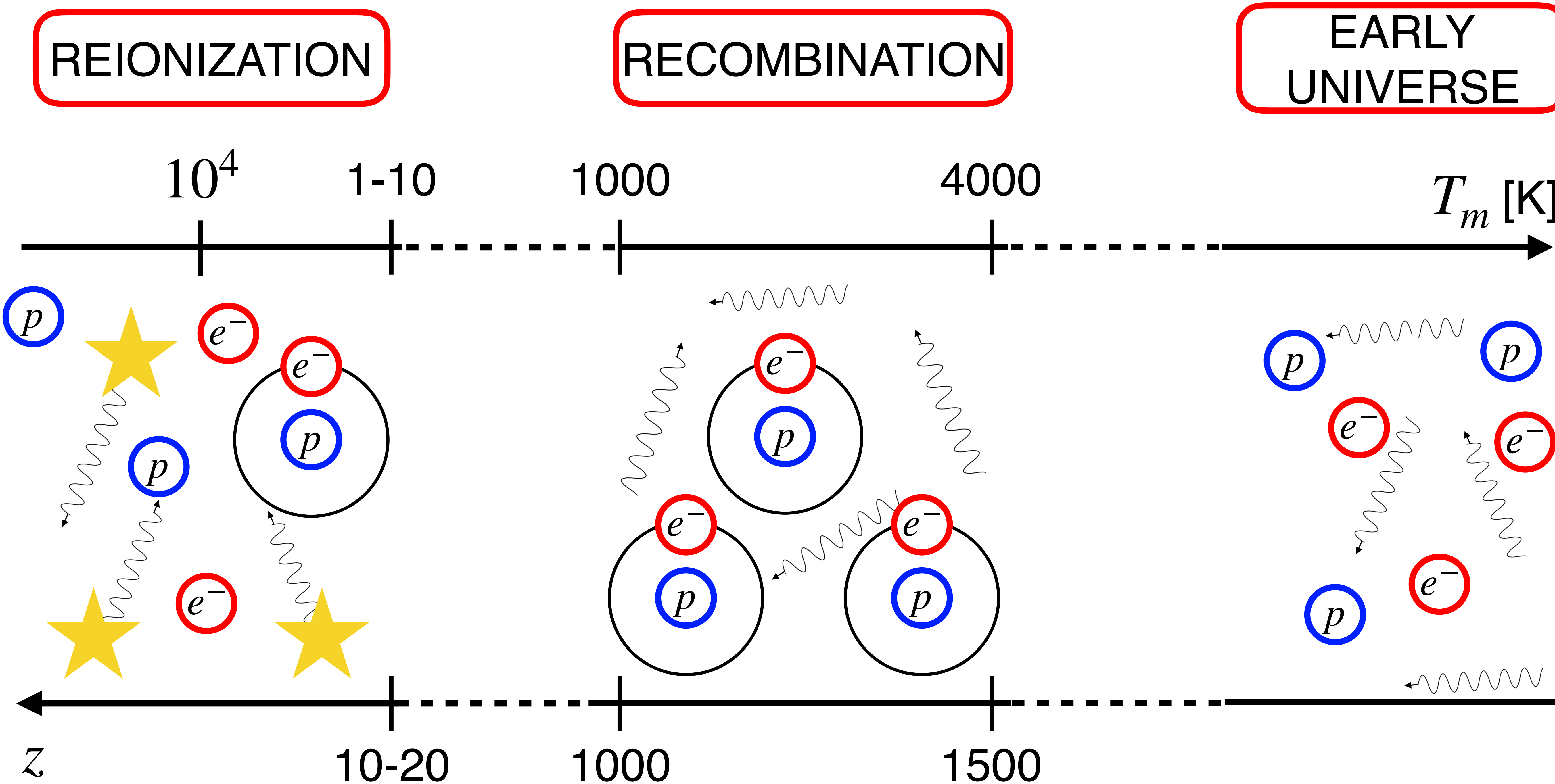
$z > 1500$: the universe is fully ionised and $T_m = T_{\rm CMB}$

Ionisation and Thermal History



$1000 < z < 1500$: cosmic recombination, formation of neutral hydrogen

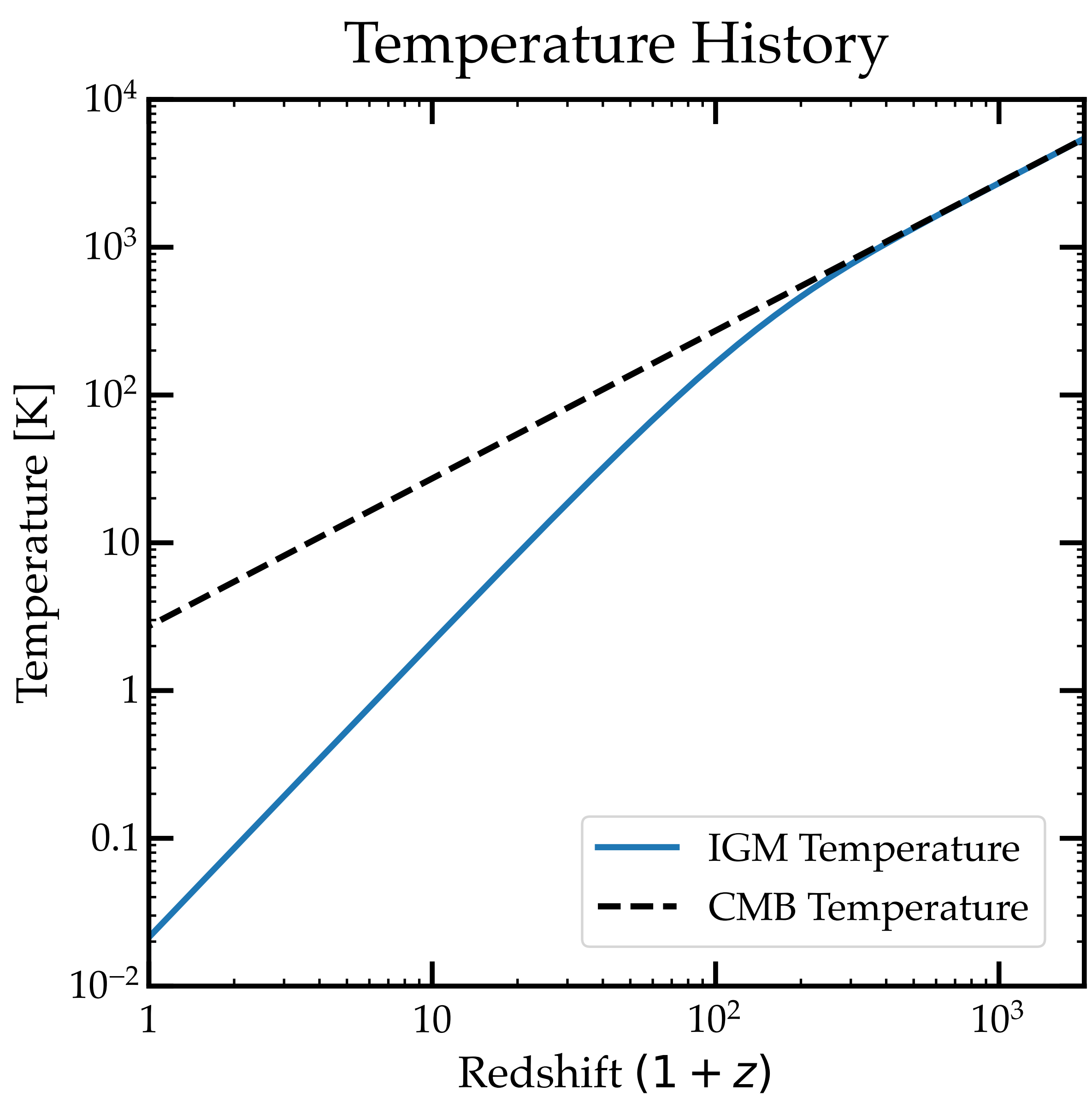
Ionisation and Thermal History

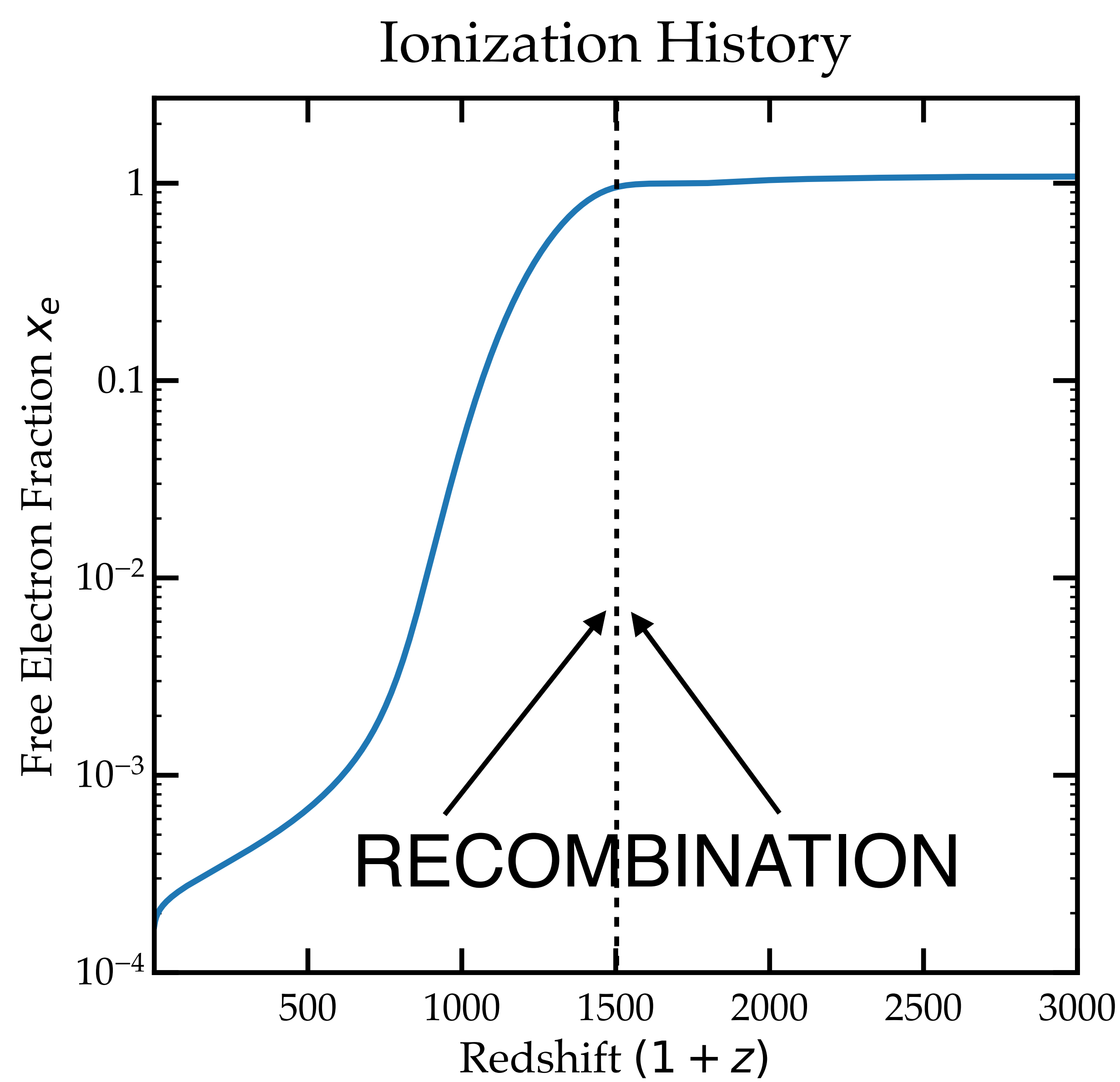


$z < 20$: starlight from first stars produces again ionisation (**reionisation**)

Ionisation and Thermal History

T_m and x_e redshift evolution: **NO dark matter, NO reionisation**

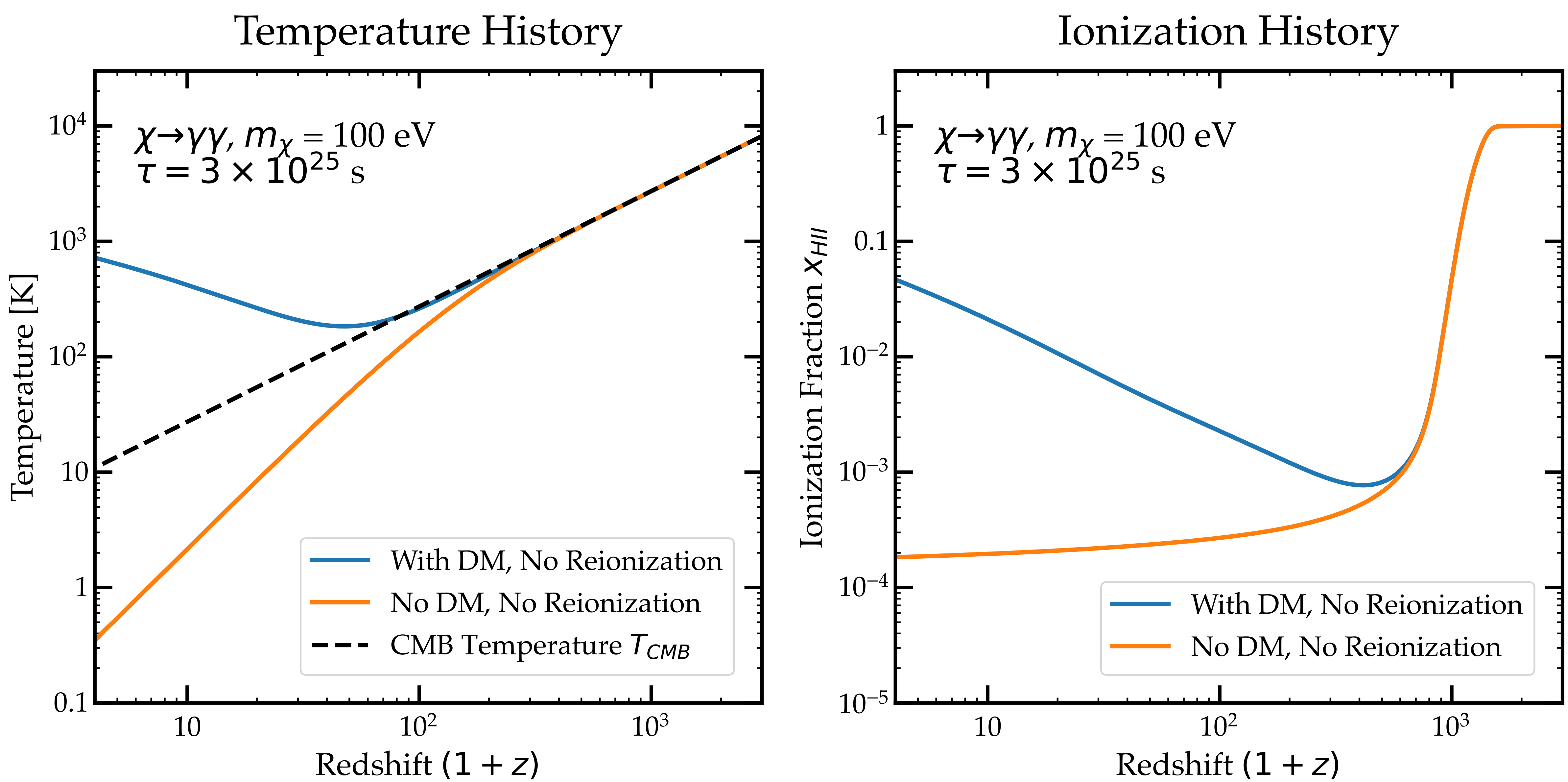




Recombination at z ~ 1500. CMB still in thermal equilibrium up to z ~ 200

Ionisation and Thermal History

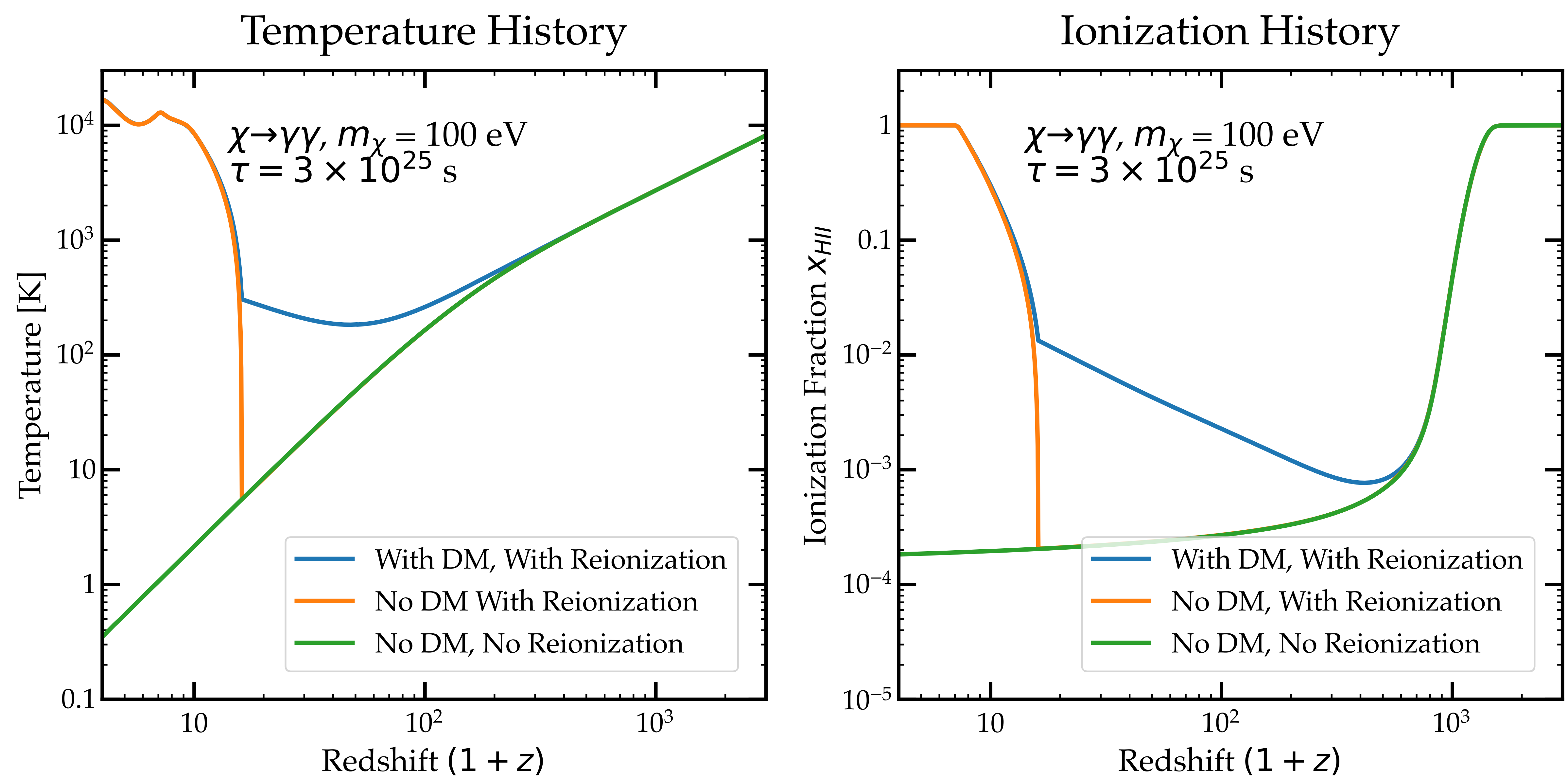
T_m and x_e redshift evolution: **WITH dark matter, NO reionisation**



Dark matter decays injects energy, which produces early ionisation and temperature increase

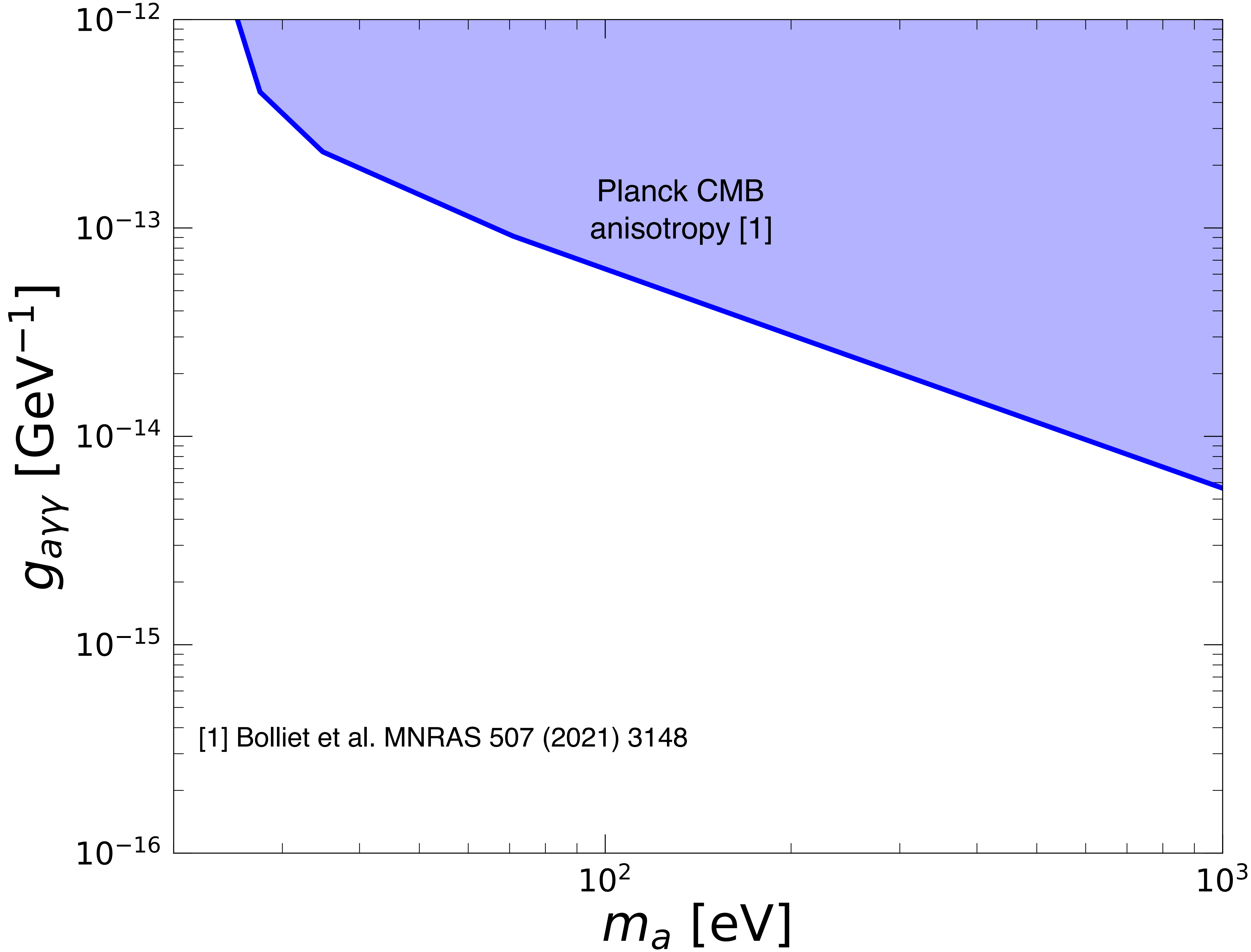
Ionisation and Thermal History

T_m and x_e redshift evolution: **WITH dark matter, WITH reionisation**



Reionisation modifies cosmic history below z ~ 20

Current Bounds: CMB anisotropy



Dark matter decays affect CMB anisotropies
(broader last scattering surface, larger optical depth to reionization)

CMB anisotropy: our improvements

Calculate the energy injection efficiencies with DarkHistory [1], which self consistently takes into account the feedback on T_m and x_e

[1] Liu, Ridgway, Slatyer, Phys. Rev. D 101 (2020) 023530 + arXiv:2303.07366 + arXiv:2303.07370

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which self consistently takes into account the feedback on T_m and x_e

$$\left(\frac{dE_c(x_e, z)}{dt\, dV}\right)_{\text{deposited}} = f_c(x_e, z) \left(\frac{dE(z)}{dt\, dV}\right)_{\text{injected}}$$

c = heat, H ionisation, Helium single/double ionization, atom excitation

Without backreaction there would be $f_c(x_{e,\,\text{std}}, z)$ instead of $f_c(x_e, z)$

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Multiple reionisation scenarios (Puchwein [2], Faucher-Giguere [3])

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[3] Faucher-Giguere, MNRAS 493 (2020) 1614

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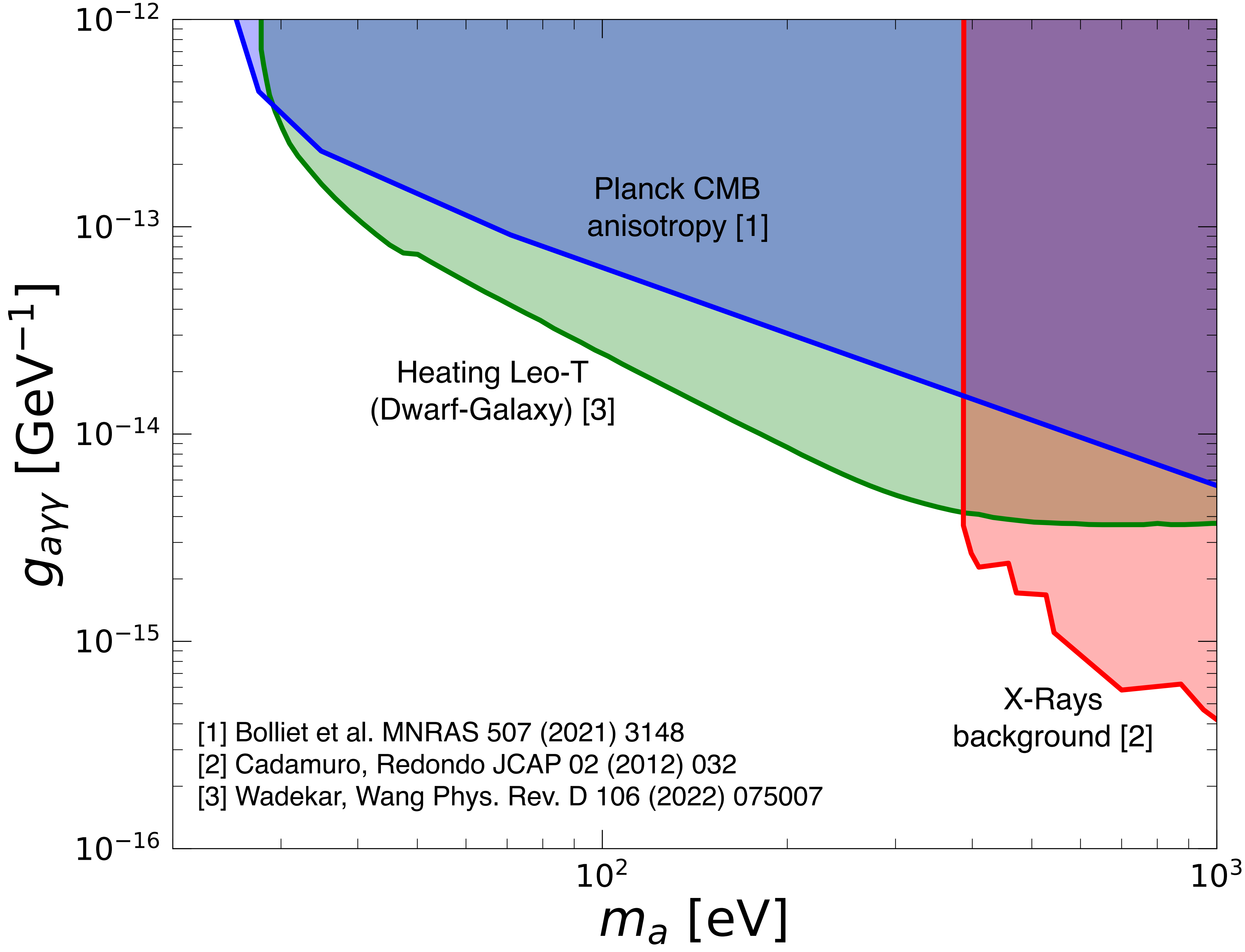
Multiple reionisation scenarios (Puchwein [2], Faucher-Giguere [3])

Full MCMC analysis of Planck data [4]
(we vary the fiducial cosmological parameters, as well as m_a, $g_{a\gamma\gamma}$)

[1] Liu, Ridgway, Slatyer, Phys. Rev. D 101 (2020) 023530 + arXiv:2303.07366 + arXiv:2303.07370
[2] Puchwein, et al. MNRAS 485 (2019) 47
[3] Faucher-Giguere, MNRAS 493 (2020) 1614
[4] Planck collaboration, Astron. Astrophys. 641 (2020) A6

Current Bounds: Astrophysical

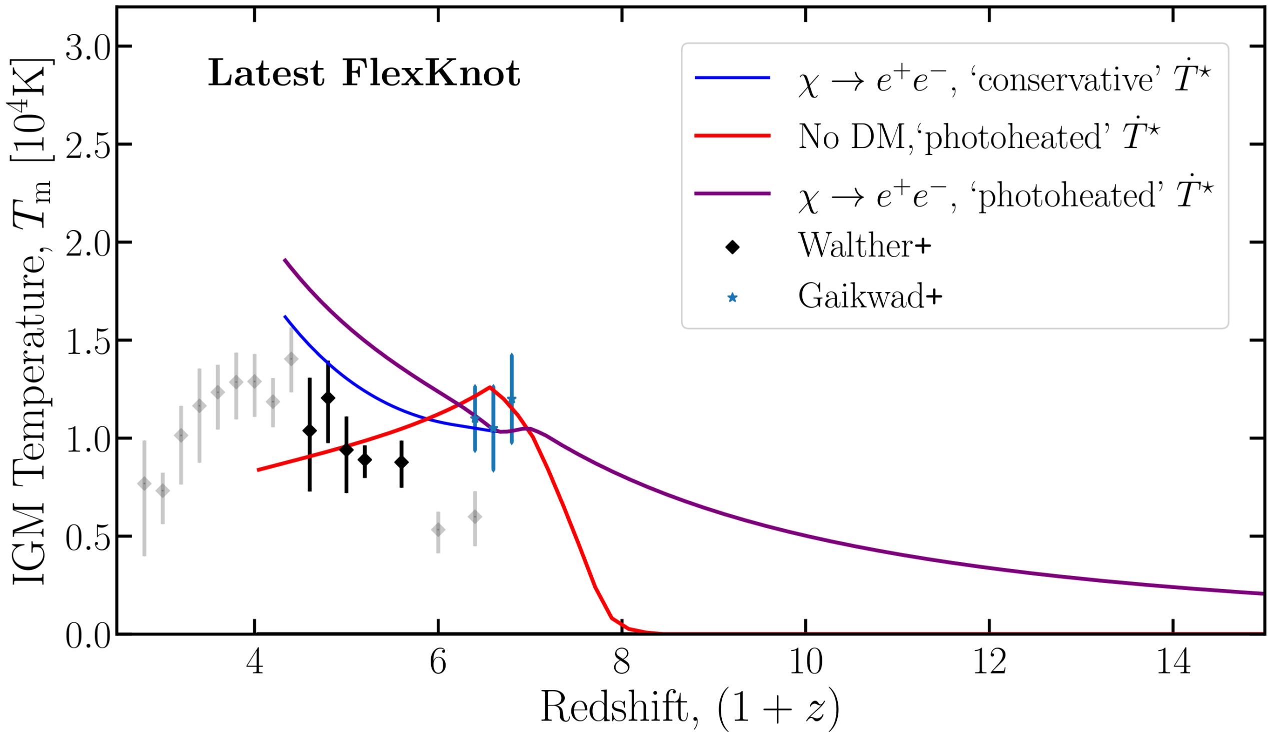


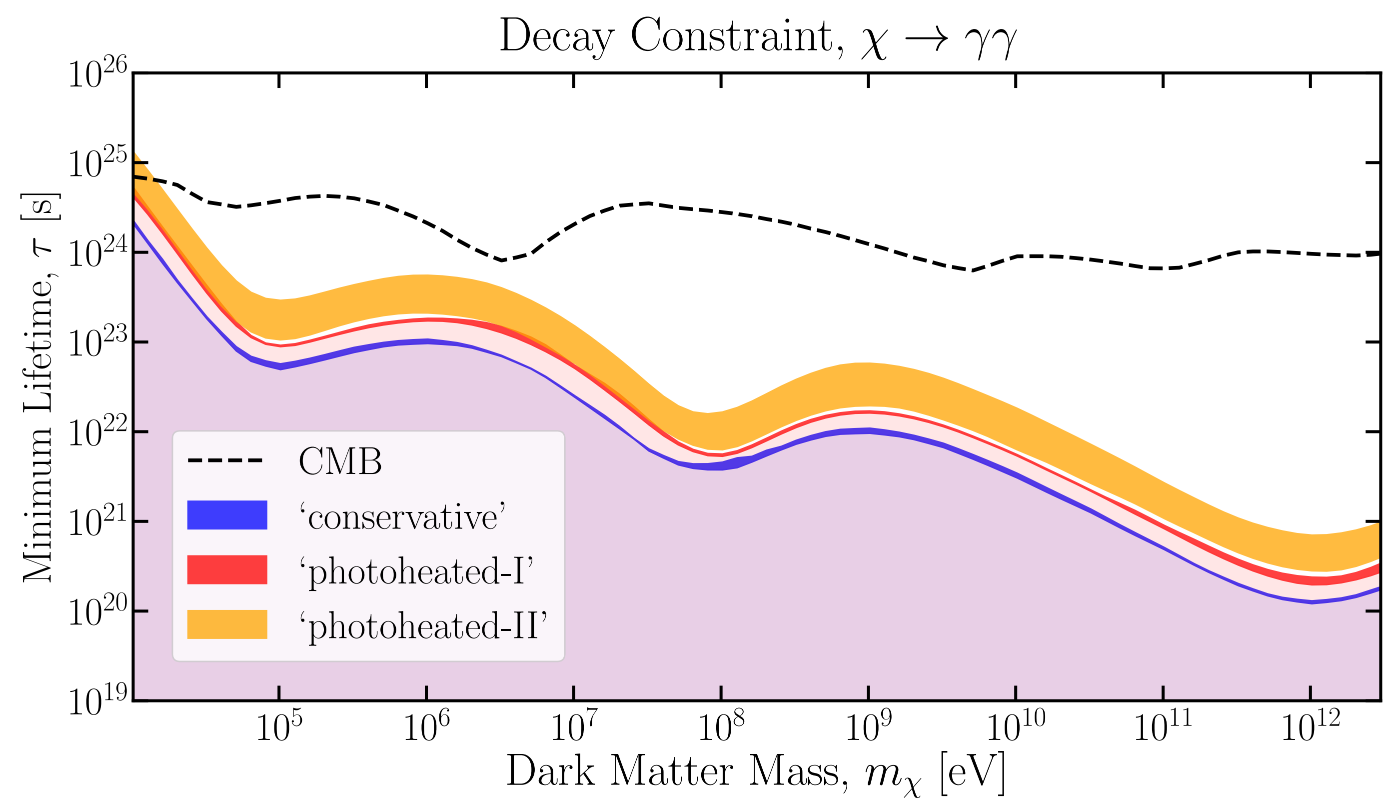
Dark matter decays can be constrained using astrophysical observables

Current Bounds: Lyman-α

Lyman-α observations can be used to measure T_m at low redshift

H. Liu, W. Qin, G. W. Ridgway and Slatyer, Phys. Rev. D 104 (2021) no.4, 043514





"Conservative" constraints can be obtained neglecting the photo-heating from astrophysical sources

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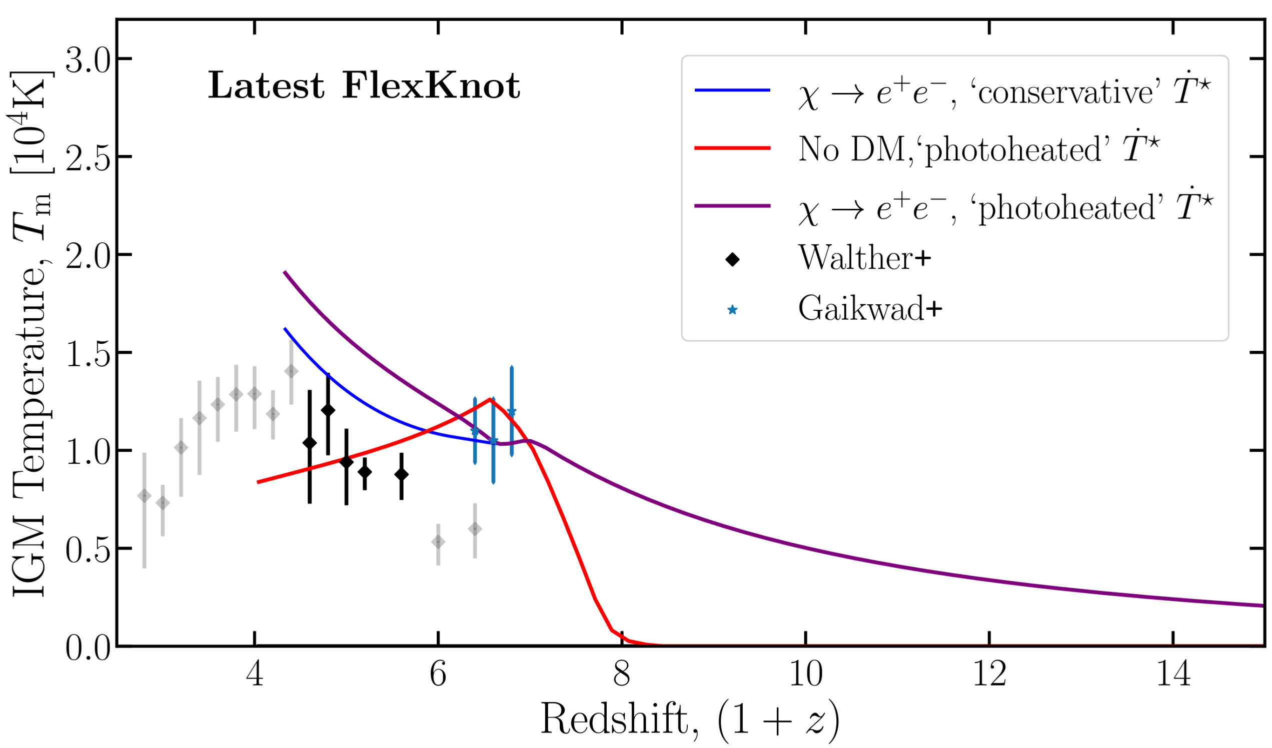
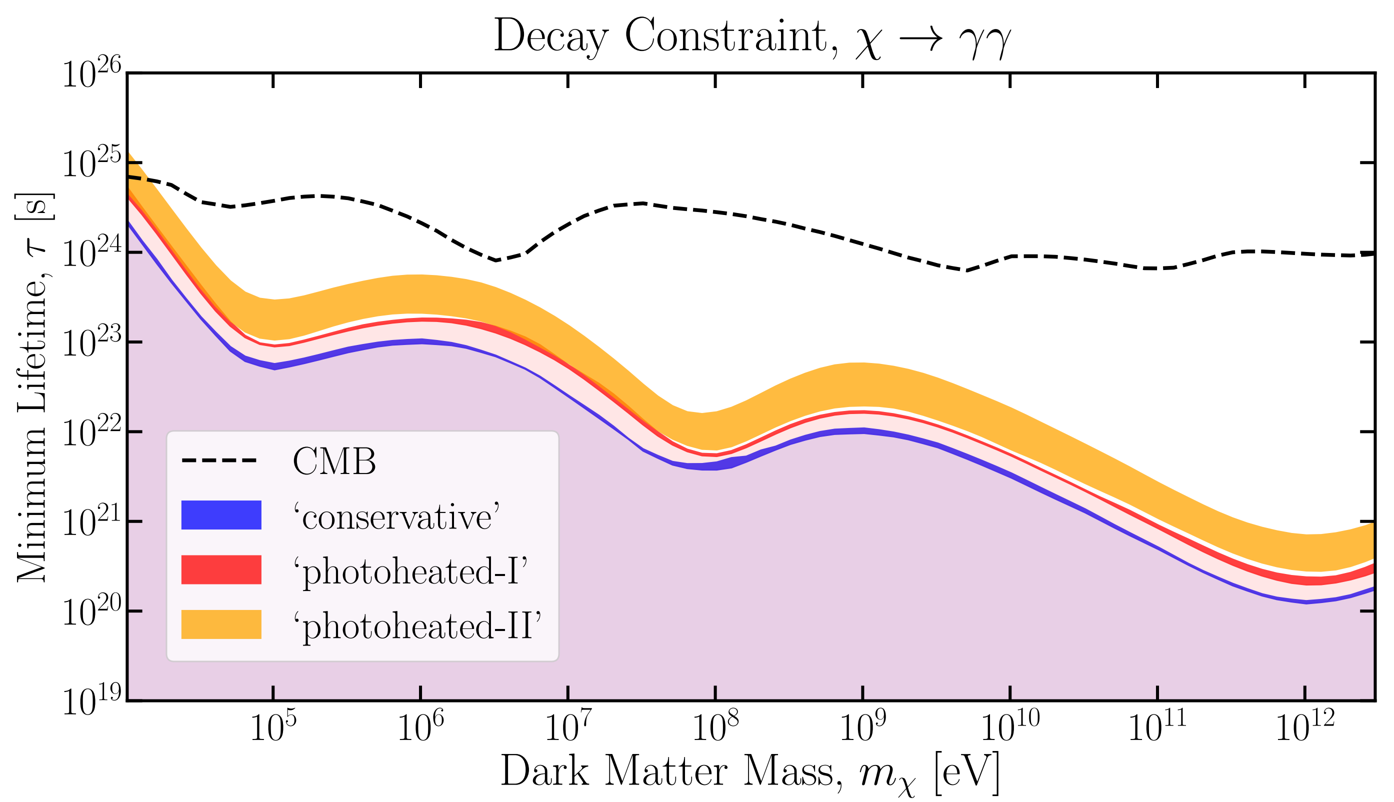
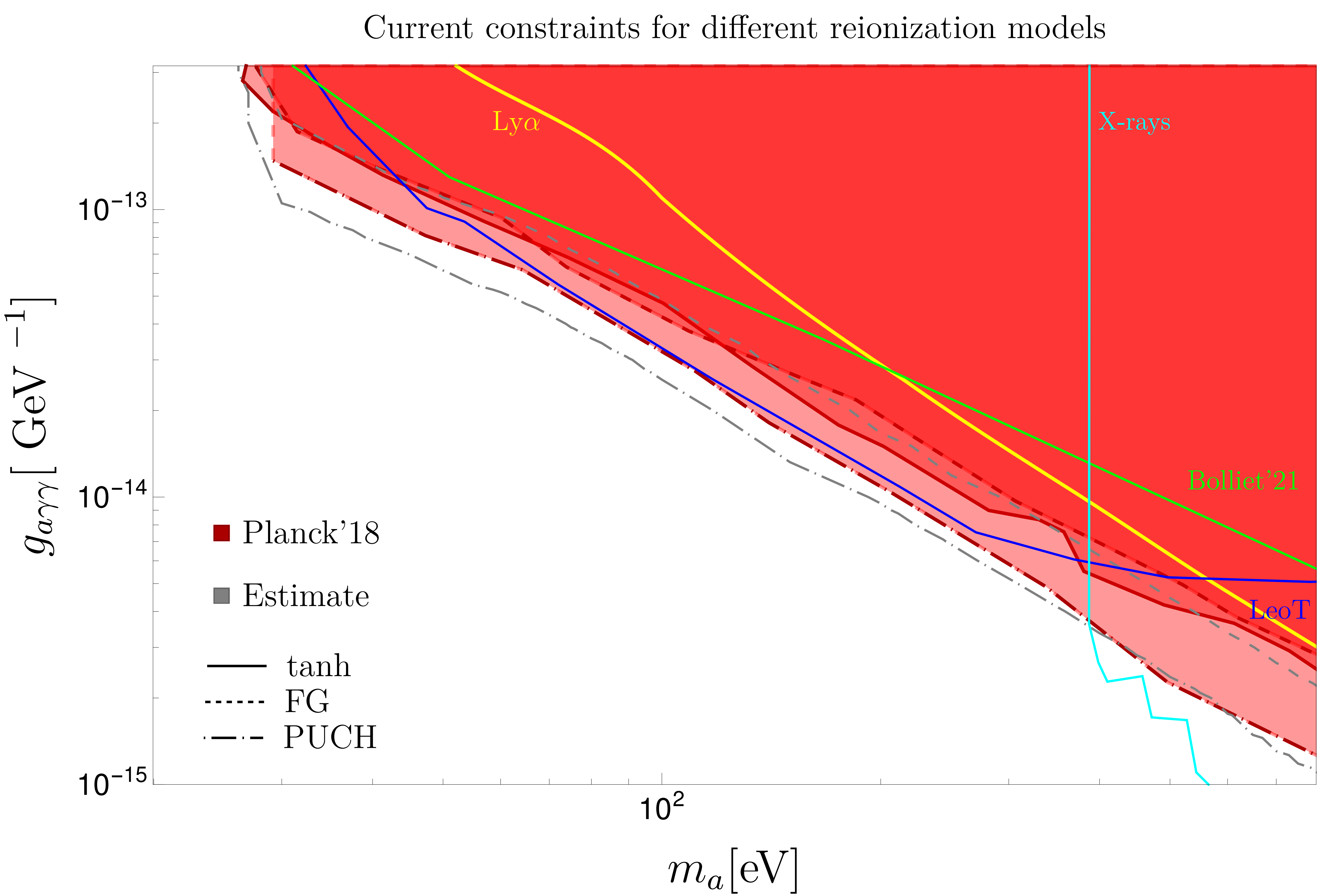




OUR IMPROVEMENT:

We extend the analysis to dark matter mass $20.4\,\mathrm{eV} < m_\chi < 10^3\,\mathrm{eV}$

Analysis: CMB anistropy



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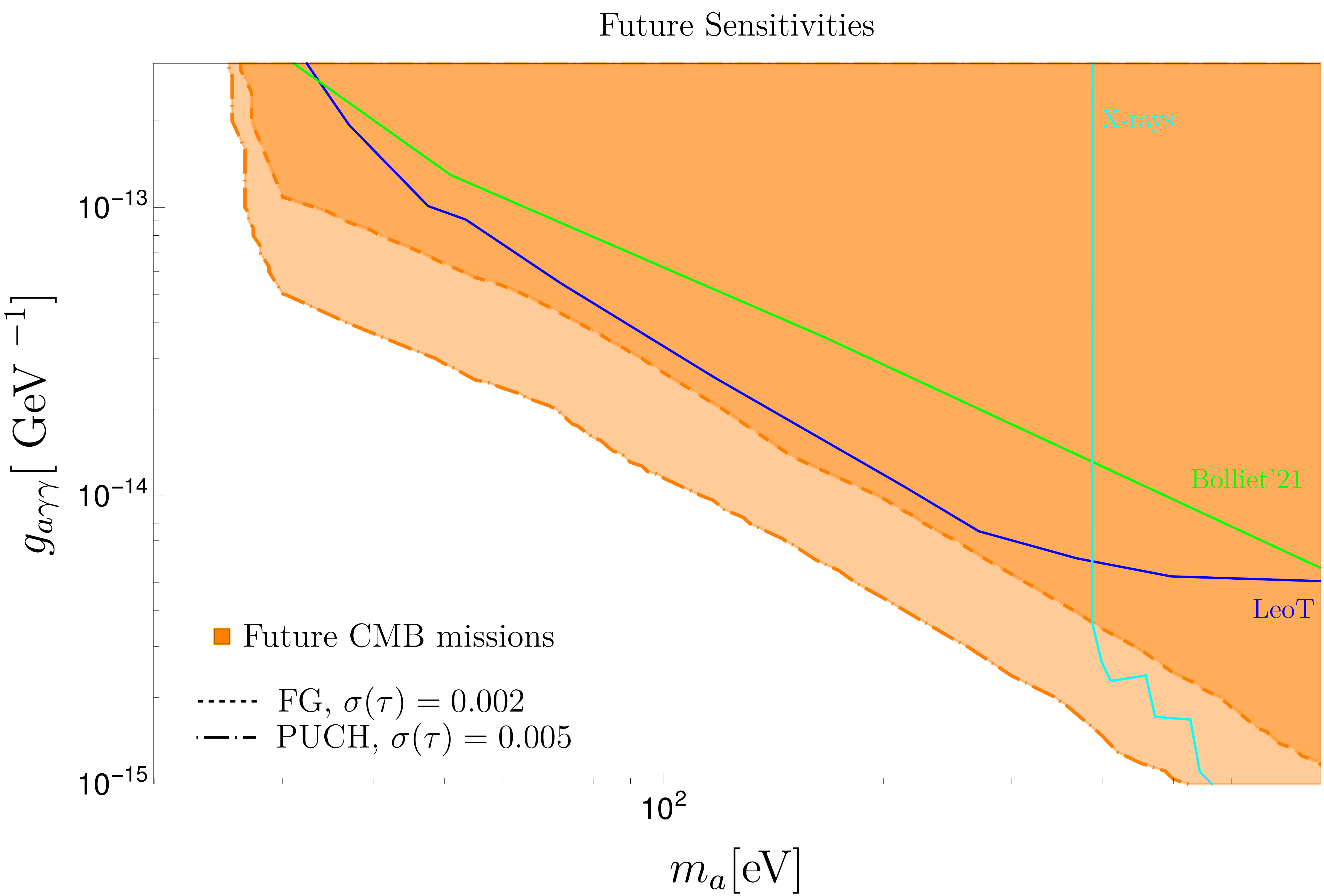

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a) we exploit the latest and full Planck anisotropy data release

b) we explore the dependence on the reionization model

c) we evaluate x_e and T_m taking into account backreaction

d) extend Lyman-α analysis in the range 20.4 eV - 1 keV

Conclusions

The bounds on dark matter decays are:

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h) complementary.
Lyman-α data provides tomographic constraints (at different redshifts).
CMB data relies on the linear evolution of cosmological perturbations.
Leo-T bounds depend on non-linear evolution (structure formation)

BACKUP

Analysis: CMB anistropy

1) Calculate energy injection efficiency $f_c(x_e, z)$ and $x_e(z)$ with DarkHistory

$$\left(\frac{dE_c(x_e, z)}{dt\, dV}\right)_{\text{deposited}} = f_c(x_e, z) \left(\frac{dE(z)}{dt\, dV}\right)_{\text{injected}}$$

c = heat, H ionisation, Helium single/double ionization, atom excitation

Analysis: CMB anistropy

1) Calculate energy injection efficiency $f_c(x_e, z)$ and $x_e(z)$ with DarkHistory

2) Modify CLASS Boltzmann solver implementing both $f_c(x_e, z)$ and $x_e(z)$

Analysis: CMB anistropy

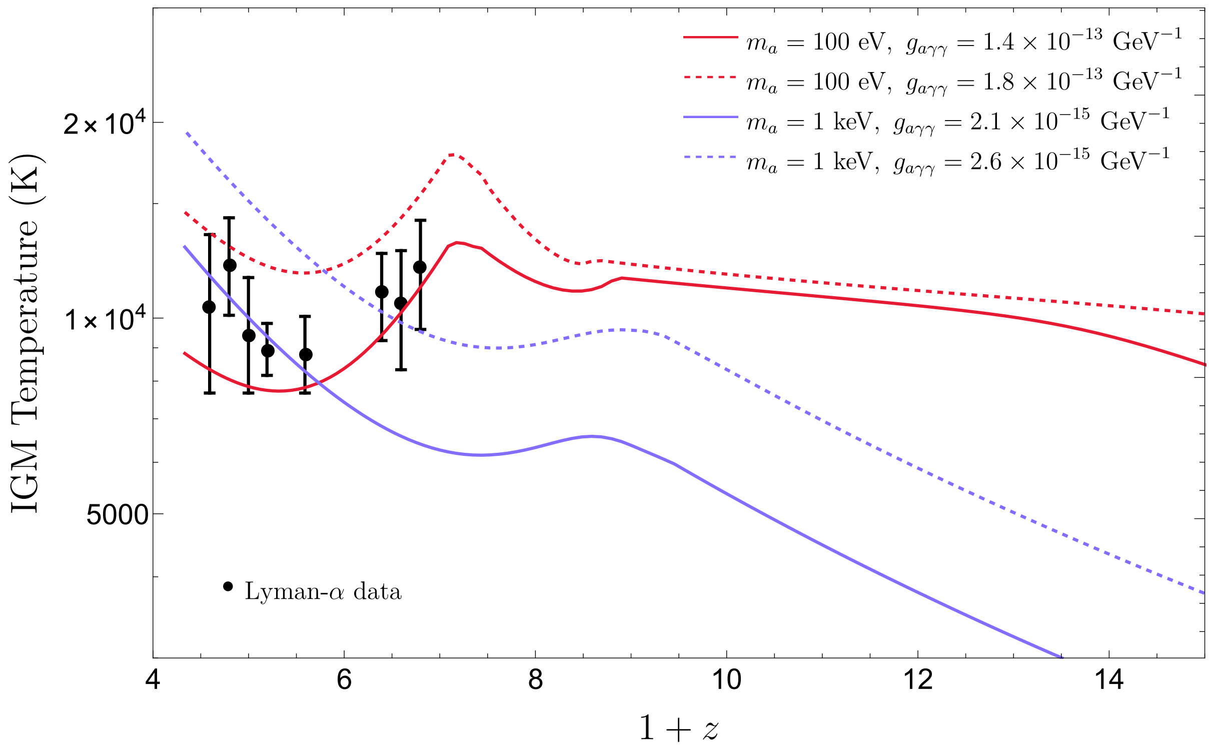
1) Calculate energy injection efficiency $f_c(x_e, z)$ and $x_e(z)$ with DarkHistory

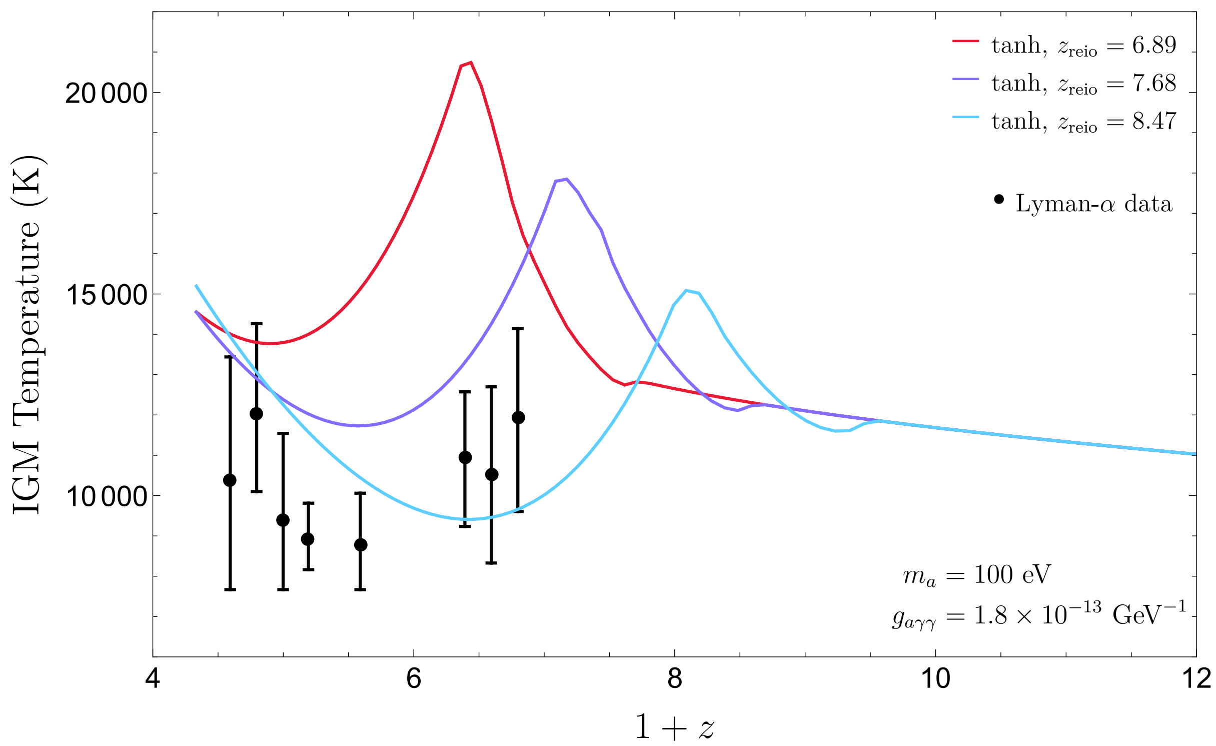
2) Modify CLASS Boltzmann solver implementing both $f_c(x_e, z)$ and $x_e(z)$

3) MCMC analysis using MontePython interfaced with CLASS and baseline TT, TE, EE + lowE Planck 2018 likelihoods

Analysis: Lyman-α

1) We compute $T_m(z)$ with DarkHistory, following [1]. Photo-heating from stars is set to zero. We also assume that all astrophysical contributions to $x_e(z)$ sum up to the tanh model at small z





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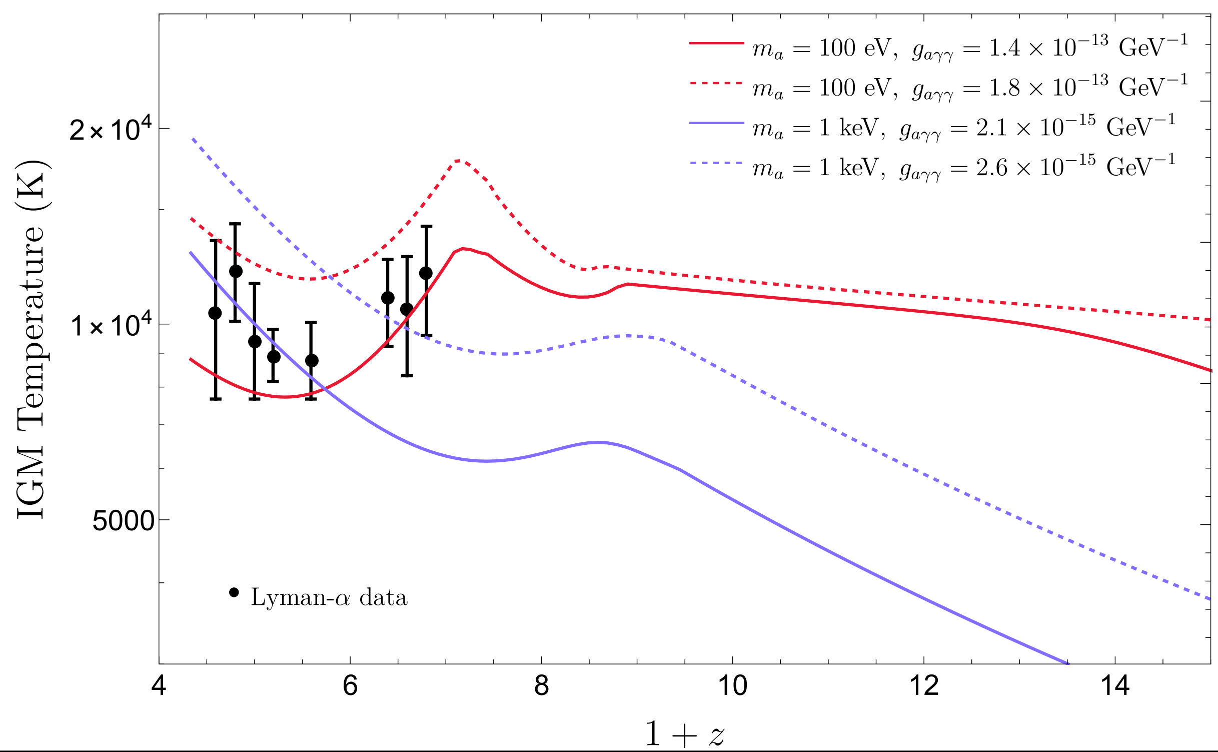
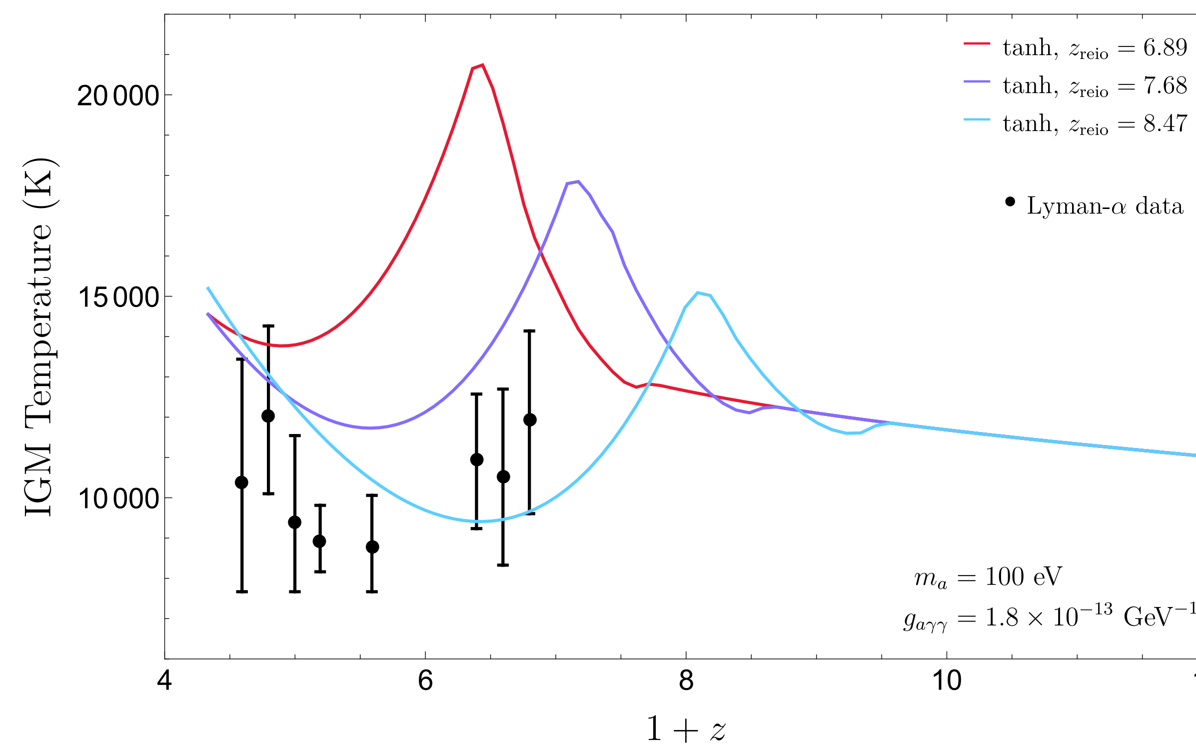




2)
$$\chi_i^2 = \begin{cases} 0\,, & T_{m,i,\mathrm{pred}} < T_{m,i,\mathrm{data}} \\ \left(\dfrac{T_{m,i,\mathrm{pred}} - T_{m,i,\mathrm{data}}}{\sigma_{i,\mathrm{data}}}\right)^2, & T_{m,i,\mathrm{pred}} \geq T_{m,i,\mathrm{data}} \end{cases}$$

Ionisation and Thermal History: equation

$$\dot{Y} = \dot{Y}^{(0)} + \dot{Y}^{\mathbf{DM}} + \dot{Y}^{\mathbf{astro}}, \qquad \text{where} \quad Y = \begin{pmatrix} T_m \\ x_{\mathbf{HII}} \\ x_{\mathbf{HeII}} \\ x_{\mathbf{HeIII}} \end{pmatrix}$$

$$x_X = \frac{n_X}{n_{\mathrm{H}}}$$

n_H is the total number density of hydrogen nuclei

n_X ($X =$ HII, HeII and HeIII) stands for ionised Hydrogen, singly ionised and doubly ionized Helium

Ionisation and Thermal History: equation

$$\dot{T}_m^{(0)} = -2HT_m + \Gamma_C \left(T_{\rm CMB} - T_m\right) + \dot{T}_m^{\rm atom}$$

$-2HT_m \rightarrow$ adiabatic cooling

$\Gamma_C(T_{\rm CMB} - T_m) \rightarrow$ Compton heating/cooling (Γ_C Compton scattering rate)

$\dot{T}_m^{\rm atom} \rightarrow$ atomic processes
(recombination, collisional ionisation/excitation and bremsstrahlung)

Ionisation and Thermal History: equation

$$\dot{x}_{\mathrm{X}}^{(0)} = \dot{x}_{\mathrm{X}}^{\mathrm{ion}} - \dot{x}_{\mathrm{X}}^{\mathrm{rec}}$$

$\dot{x}_{\mathrm{X}}^{\mathrm{ion}} \rightarrow$ ionisation processes

$\dot{x}_{\mathrm{X}}^{\mathrm{rec}} \rightarrow$ recombination processes

$z > z_A^{\mathrm{max}}$: the universe is optically thin (case-A), recombinations to the ground state are accounted for

$z \lesssim z_A^{\mathrm{max}}$: the universe is optically thick (case-B), recombinations to the ground state are **NOT** accounted for

Dark matter energy injection/deposition

$$\dot{Y}^{\rm DM} = A(f_c(x_e,z)) \times \frac{1}{n_H}\left(\frac{dE(z)}{dt\,dV}\right)_{\rm injected}$$

$$\left(\frac{dE(z)}{dt\,dV}\right)_{\rm injected} = \rho_a(1+z)^3\Gamma_{\rm dec}$$

$$\Gamma_{\rm dec} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$ for ALPs

$$\left(\frac{dE_c(x_e,z)}{dt\,dV}\right)_{\rm deposited} = f_c(x_e,z)\left(\frac{dE(z)}{dt\,dV}\right)_{\rm injected}$$

$f_c(x_e, z) \rightarrow$ dark matter energy deposition efficiencies

c = heat, H ionisation, He single or double ionisation, atom excitation

Optical depth to reionization

$$\tau = \int_0^{z_{e,\min}} dz\, n_e \sigma_T \frac{dt}{dz}$$

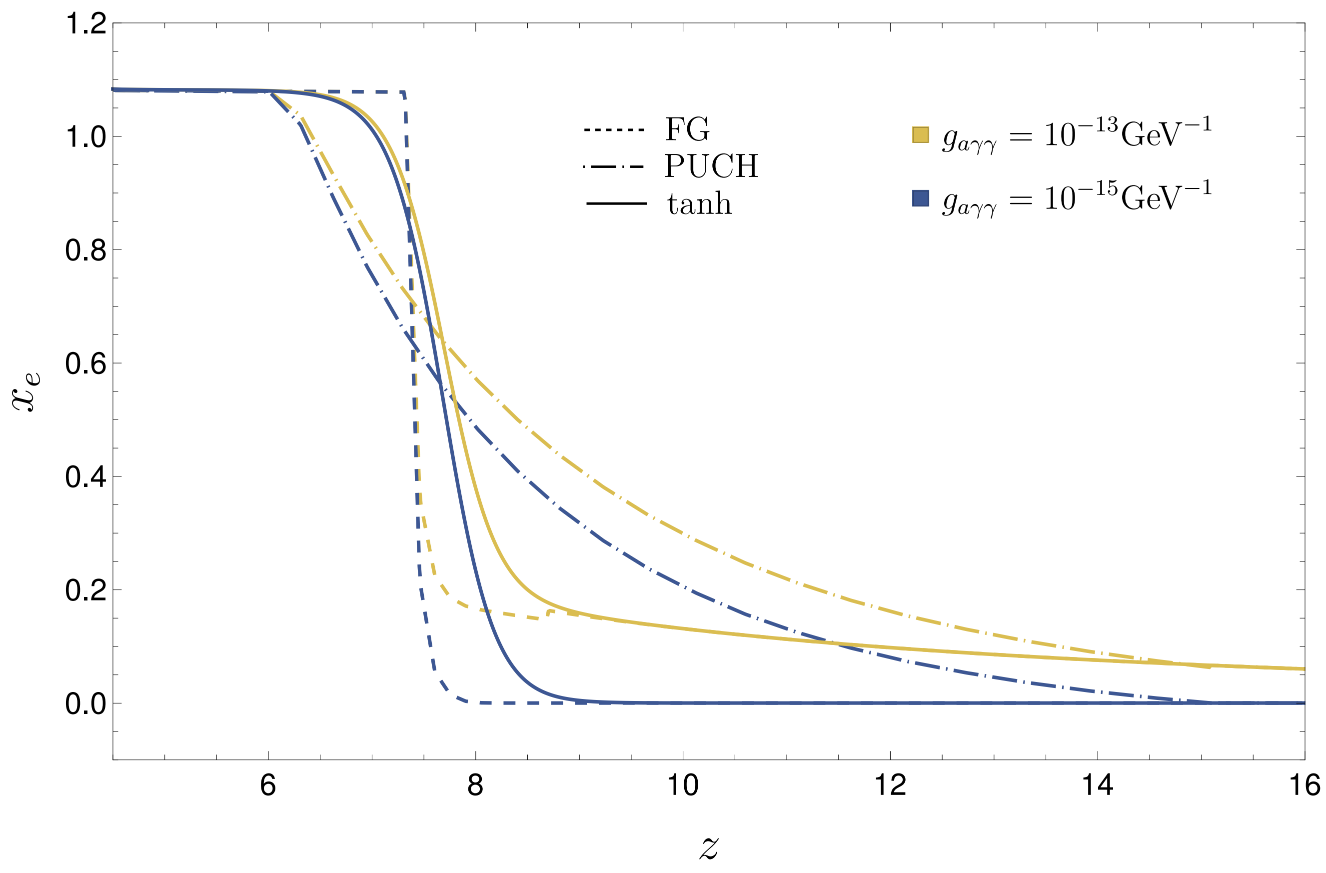
$\sigma_T \rightarrow$ Thomson scattering cross section

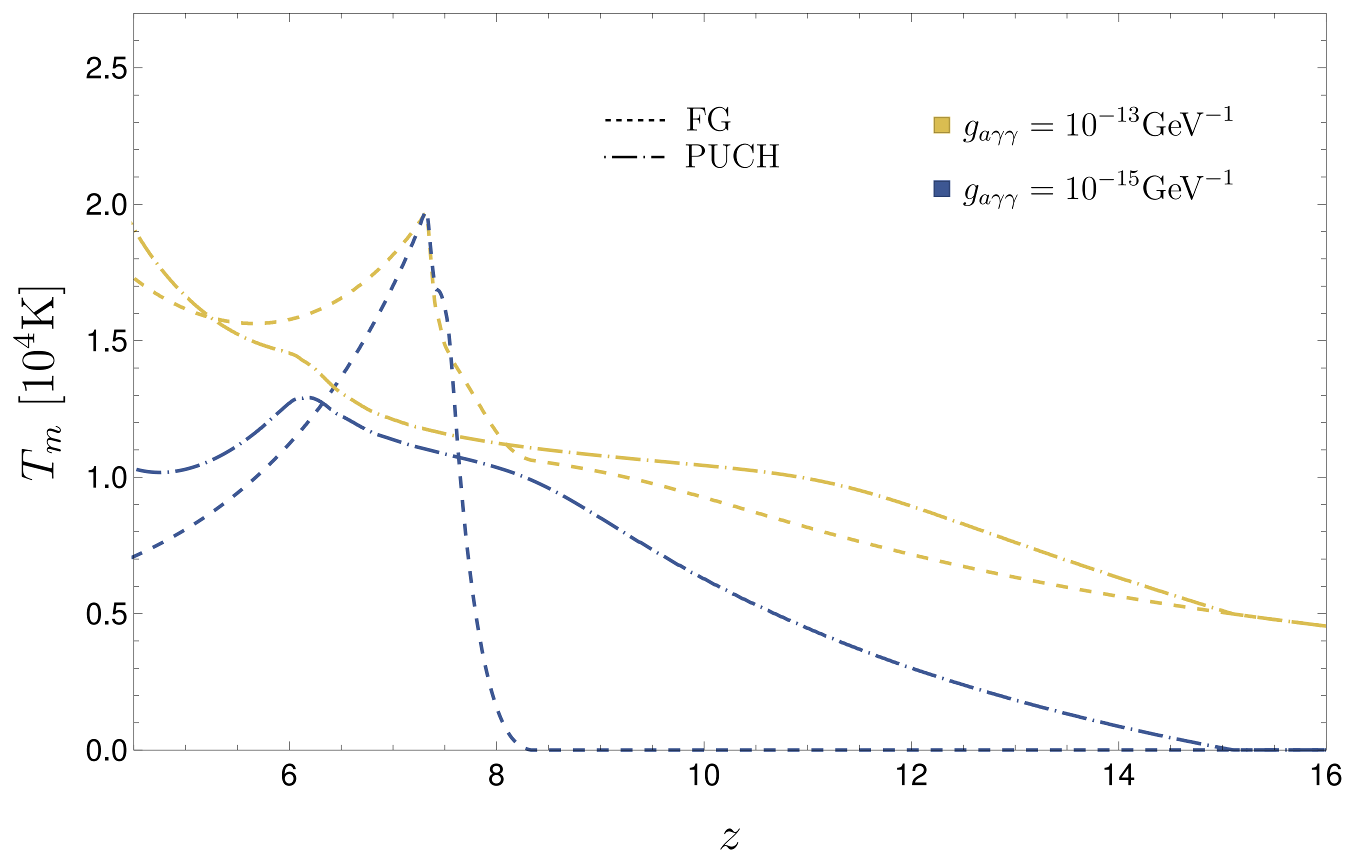
$\tau = 0.054 \pm 0.007$, measured by Planck

Reionisation from stars

$$\begin{pmatrix} \dot{T}_m^{\text{astro}} \\ \dot{x}_{\text{X}}^{\text{astro}} \end{pmatrix} = \begin{pmatrix} \frac{2}{3(1+\mathscr{F}_{\text{He}}+x_e)n_{\text{H}}} \sum_{\text{X}} \mathscr{H}_{\text{X}}^{\gamma-\text{heat}} \\ x_X \Gamma_{\text{X}}^{\gamma-\text{ion}} \end{pmatrix}$$

X = HII, HeII, HeIII



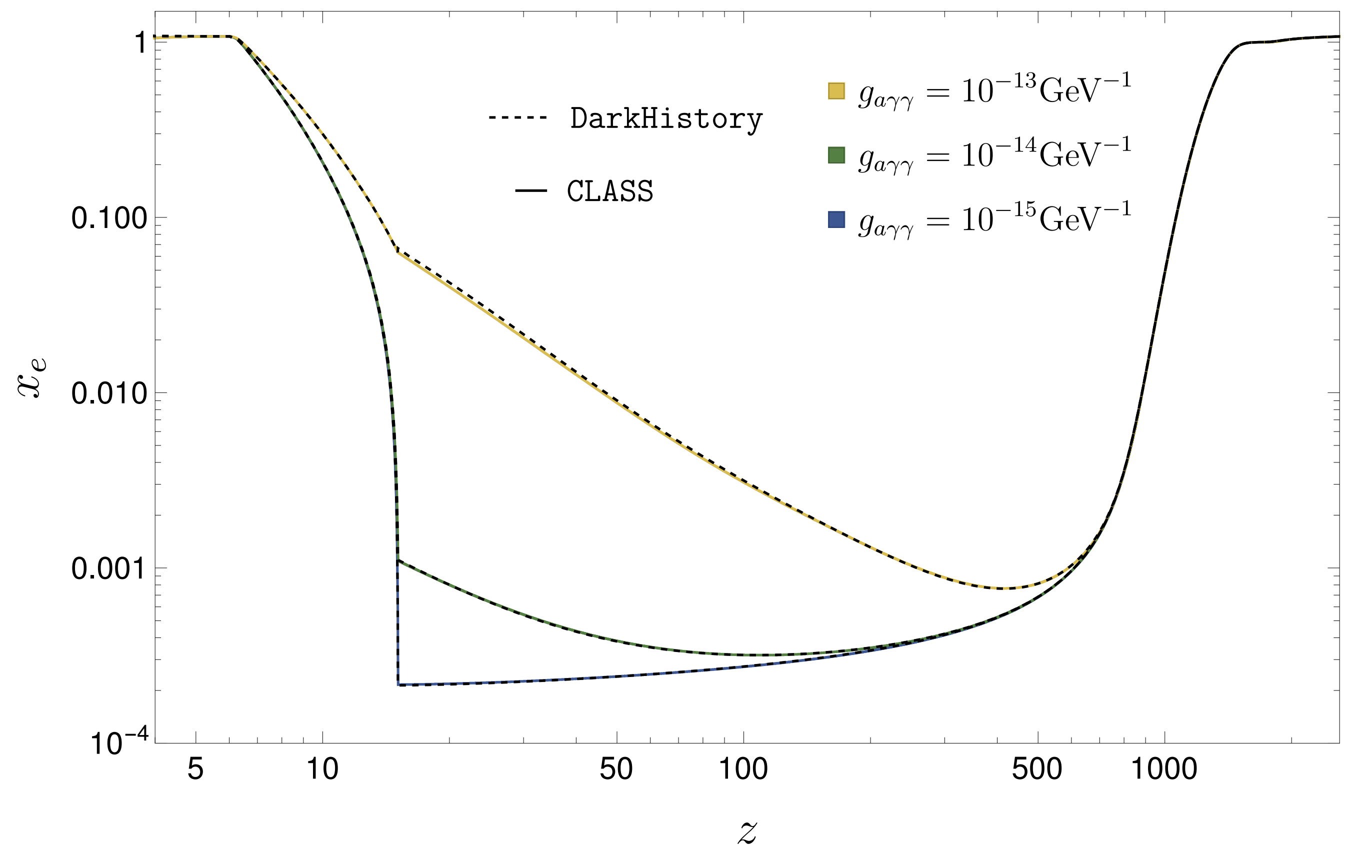


$\tau_{\text{PUCH}} = 0.064$ $\tau_{\text{FG}} = 0.052$

Modification of CLASS

$z \lesssim z_A^{\max}$: for each model we obtain from DarkHistory $x_e(z, m_a, g_{a\gamma\gamma})$. In the "thermodynamics" module of CLASS, we do an interpolation of $x_e(z)$ table.

$z > z_A^{\max}$: we first calculate $f_c(z, m_a, g_{a\gamma\gamma})$ with DarkHistory. Then, for a given $(m_a, g_{a\gamma\gamma})$ we do an interpolation at z=300 [Slatyer, Wu, Phys. Rev. D 95 (2017) 023010] and we have implemented it in the "injection" module of CLASS



Reionisation: Tanh model

$$x_e^{\tanh}(z) = \frac{1+\mathscr{F}_{\rm He}}{2}\left(1+\tanh\left[\frac{y(z_{\rm reio})-y(z)}{\Delta_y}\right]\right)$$

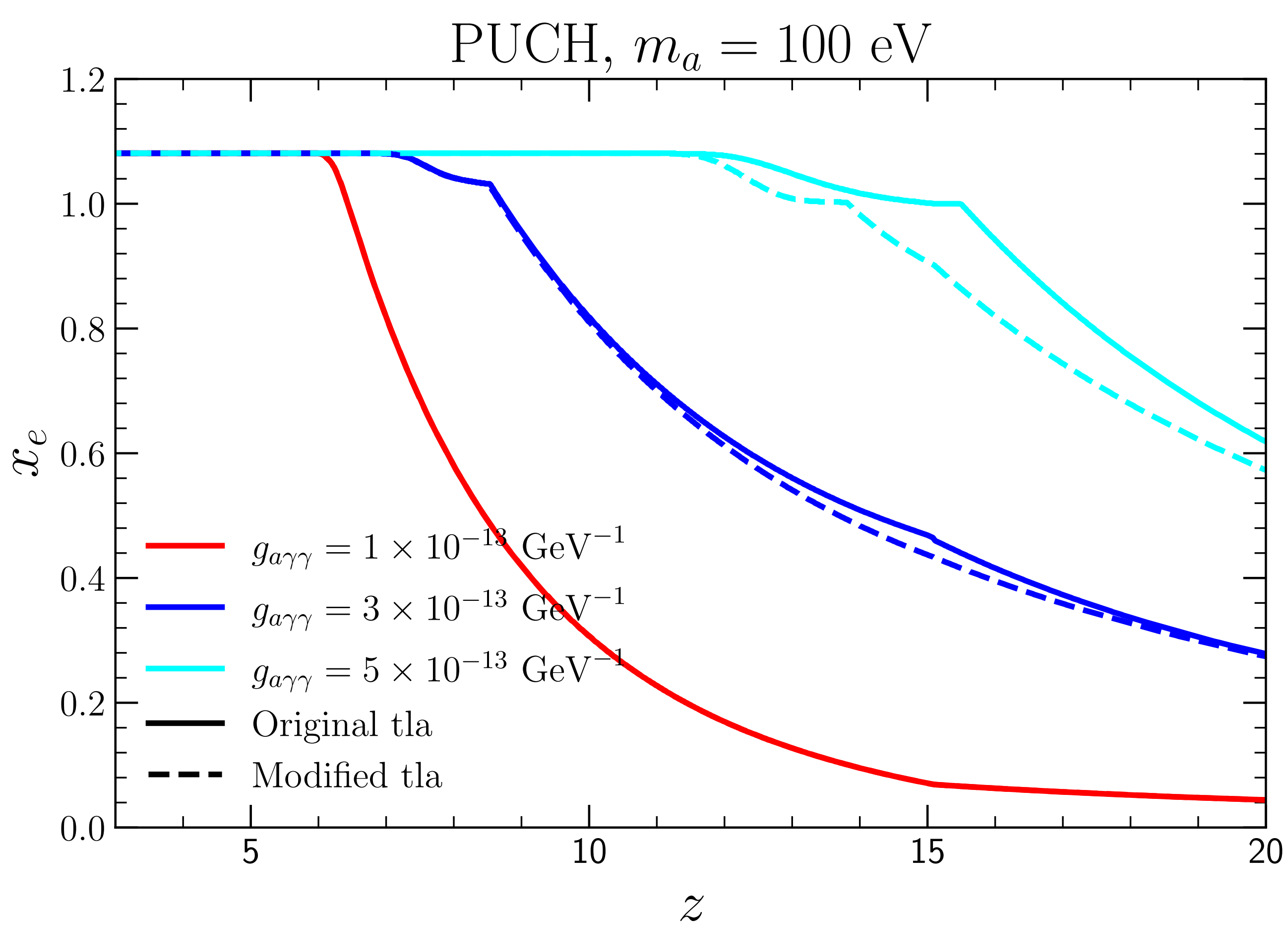
$\mathscr{F}_{\rm He} = n_{\rm HeII}/n_{\rm H}$ $\quad y(z) = (1+z)^{\gamma}$ $\quad \Delta_y = \gamma(1+z_{\rm reio})^{\gamma-1}\Delta_z$

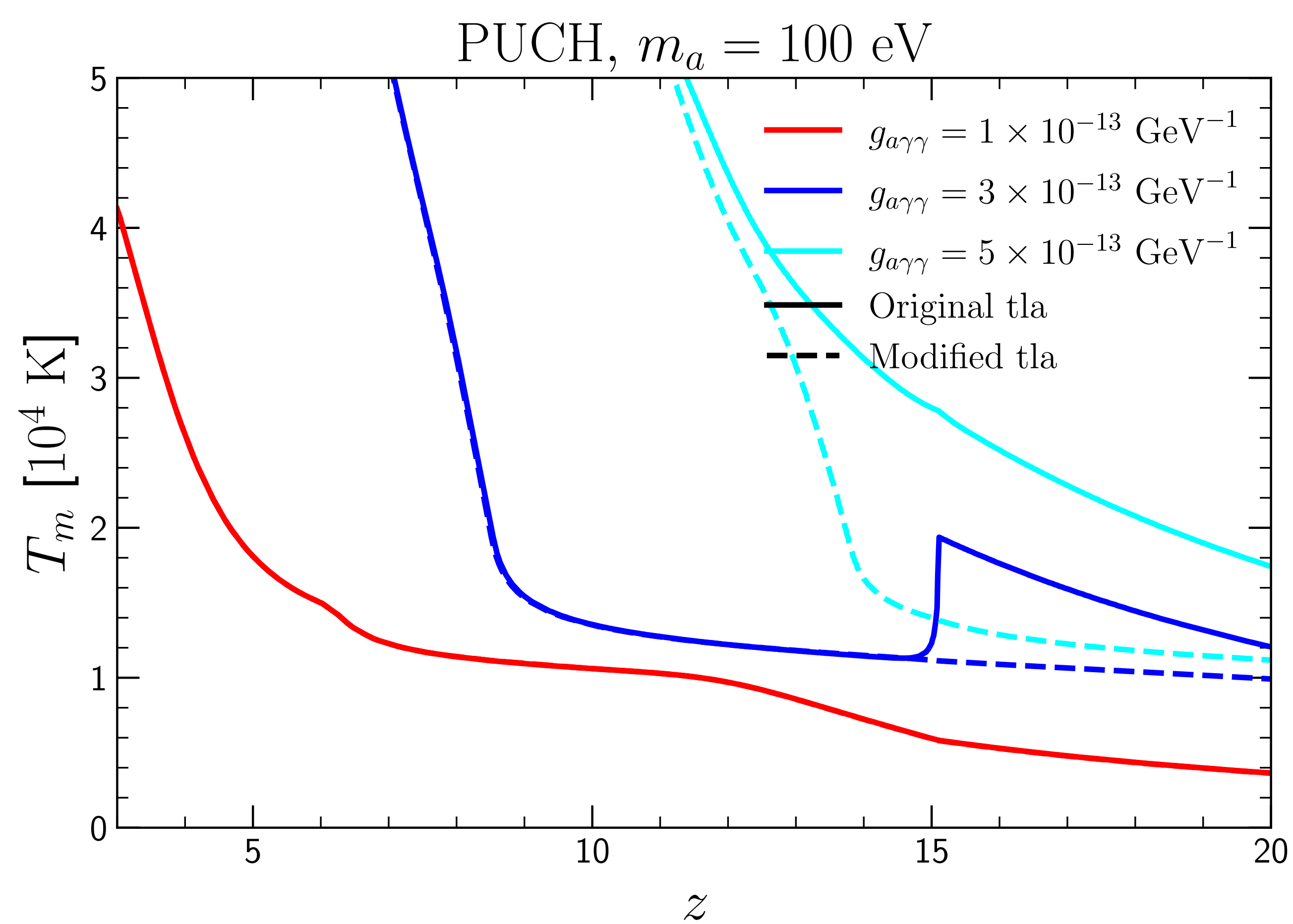
$$\Delta z = 0.5, \gamma = \frac{3}{2}, z_{\rm reio} = \text{free}$$

Modification of DarkHistory

While running DarkHistory for $m_a < 1\,\mathrm{keV}$ we observed a sudden drop of T_m at redshifts near the beginning of reionisation. The effect is stronger for $m_a \simeq 100\,\mathrm{eV}, g_{a\gamma\gamma} \gtrsim 10^{-13}\,\mathrm{GeV}^{-1}$.

The origin of this sudden drop is related to the (non-)inclusion of collisional excitations at redshifts around the onset of reionization

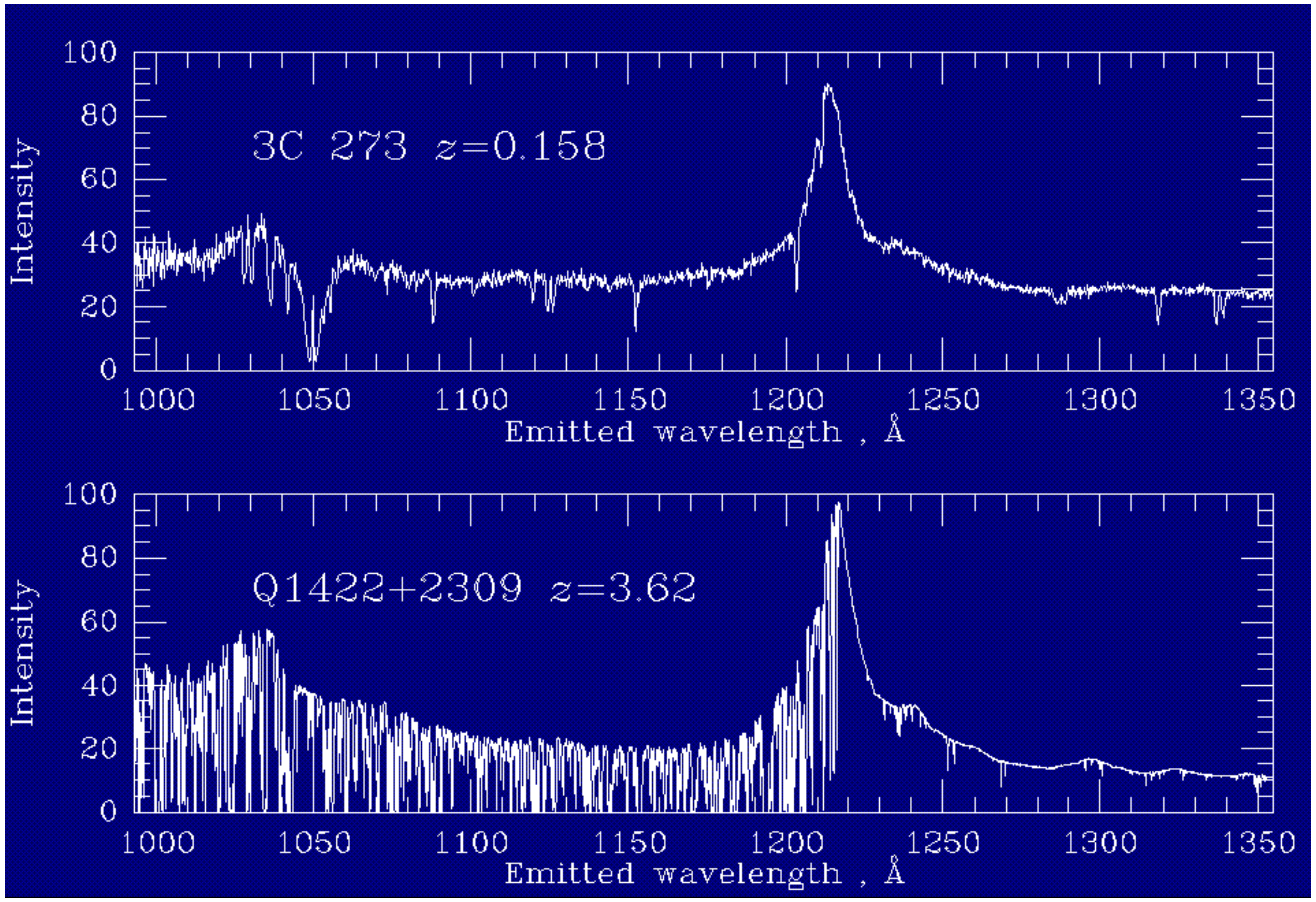




Lyman-α measurement of T_m

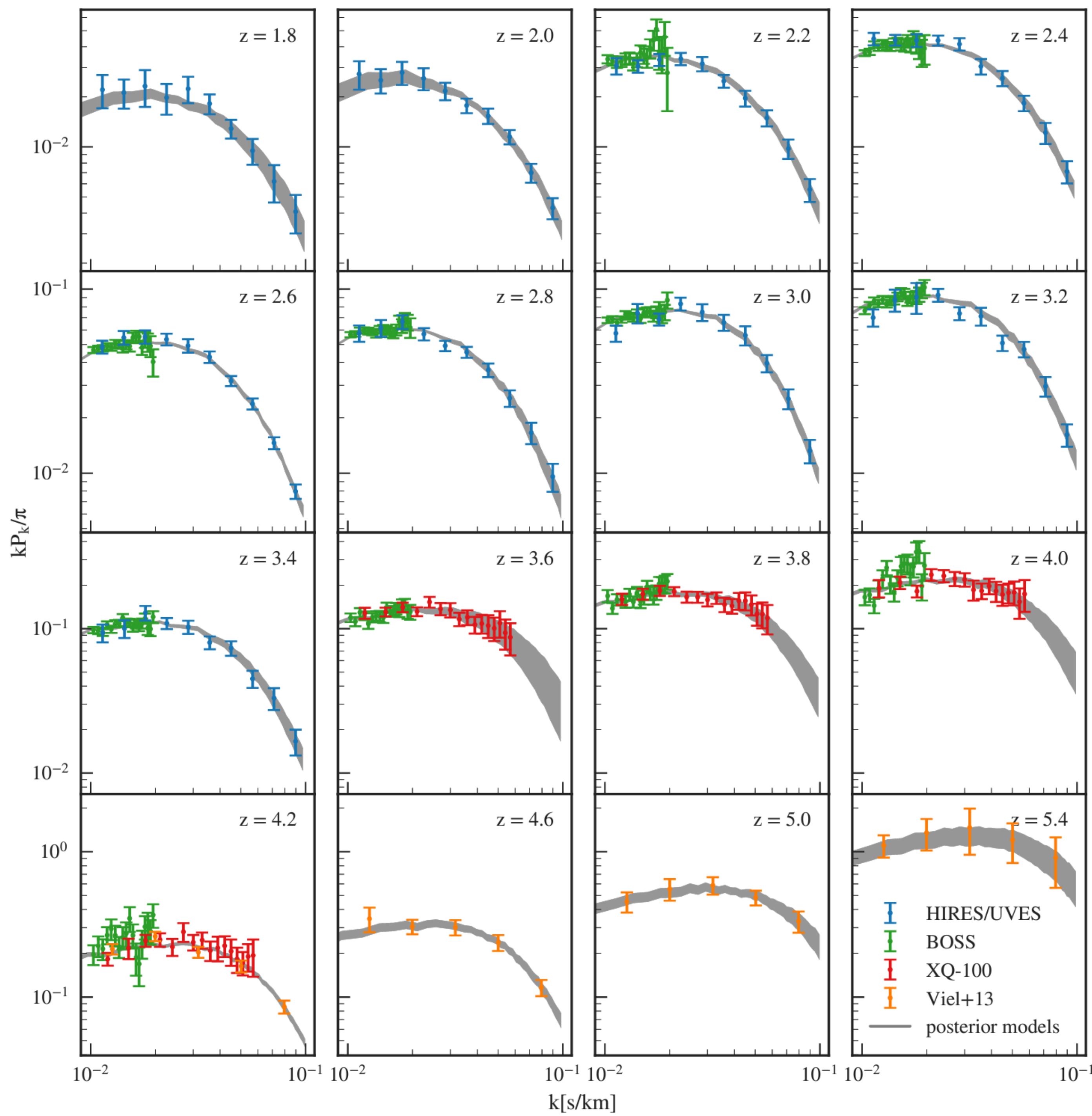
Emission from high-z quasars undergoes Lyman-α absorption by gas clouds

$$\lambda_{L-\alpha} = 1215.67\ \text{Å}$$



The higher the quasar redshift the more absorption lines there are

Lyman-α measurement of T_m



The Lyman-α power spectrum at large scales is sensitive to cosmological parameters, such as σ_8, primordial power spectrum, Ω_b, $N_{\rm eff}$, $\sum m_\nu$.

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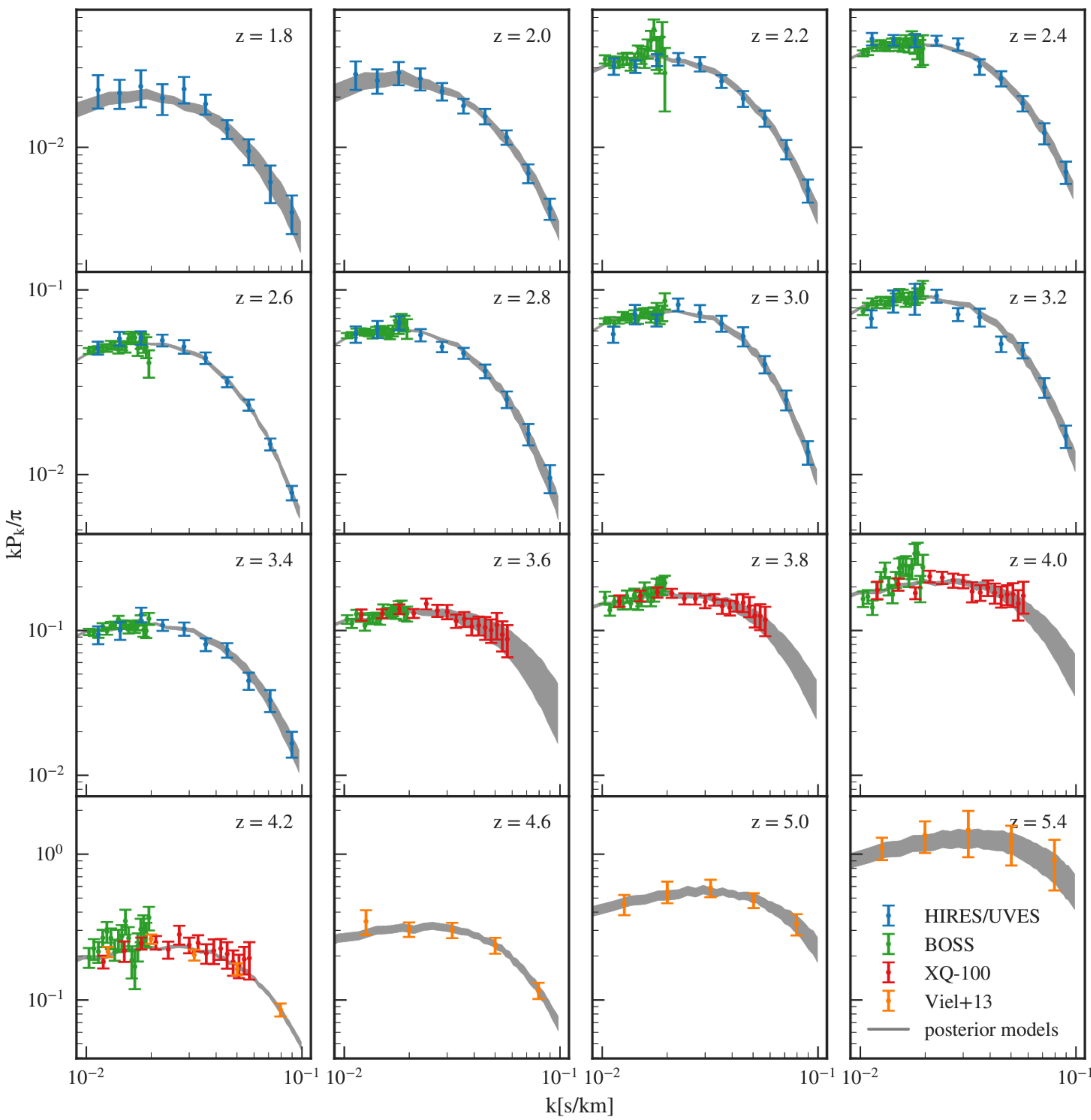

The Lyman-α power spectrum at small scales depends on T_m because of Doppler broadening of absorption features due to thermal motions