TAUP VIENNA 2023

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

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

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Ionisation and Thermal History

Parameters describing the evolution of the Universe after recombination:

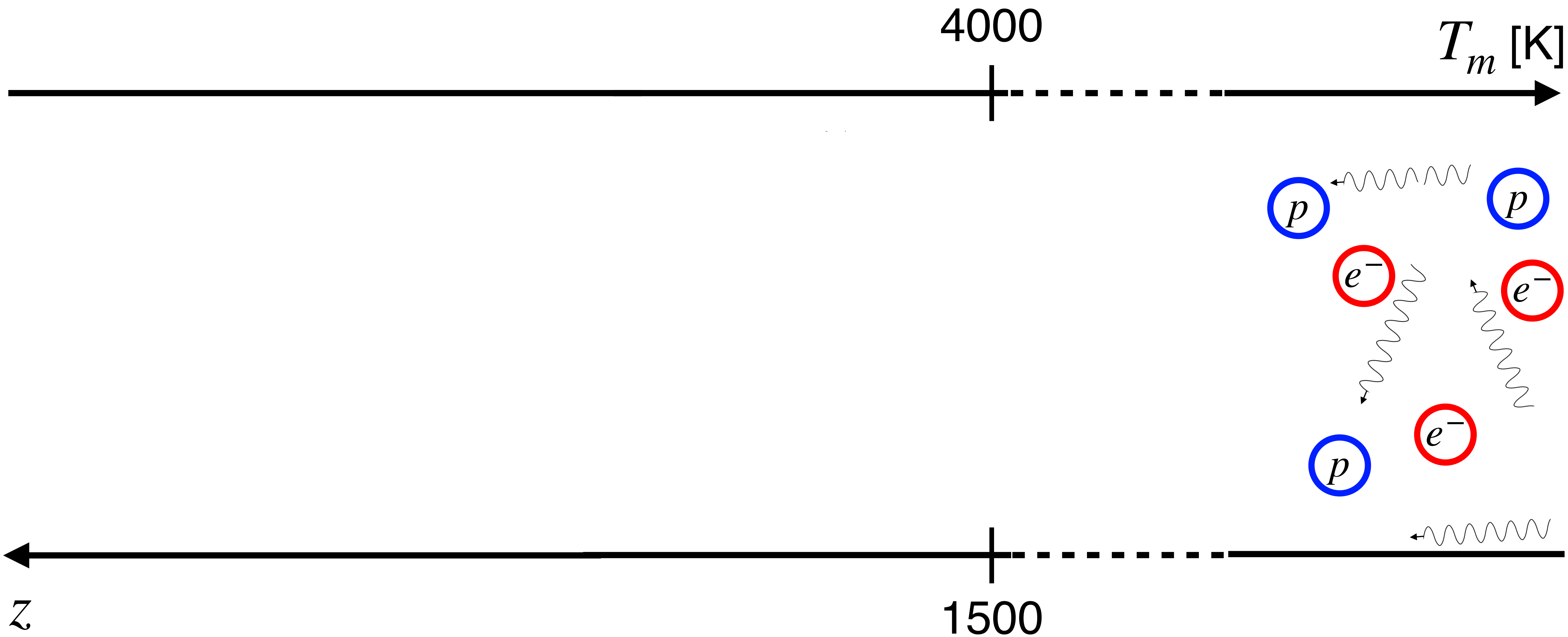
$$T_m(z) = \text{Temperature of matter}$$

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

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

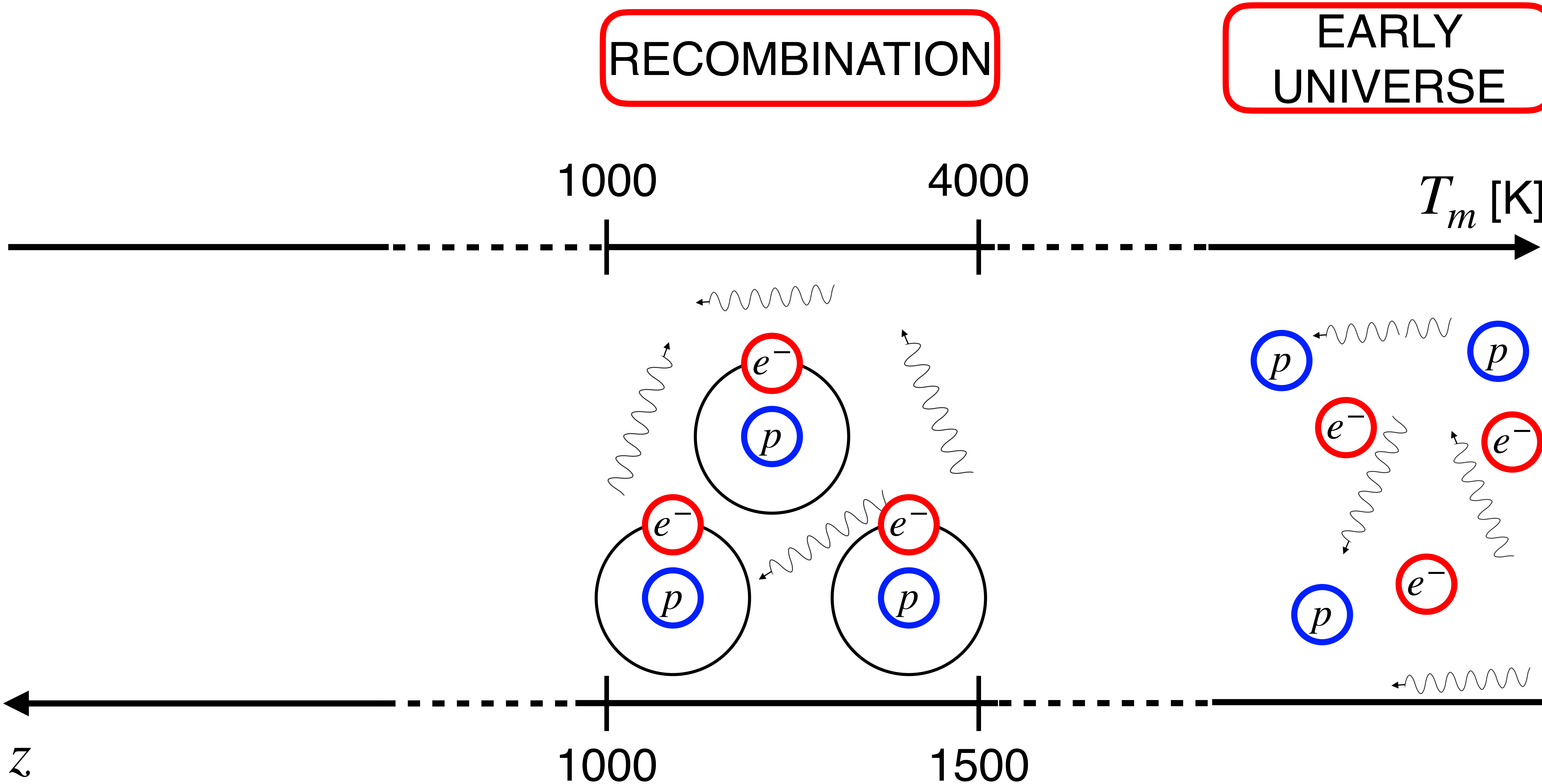
Ionisation and Thermal History

EARLY UNIVERSE



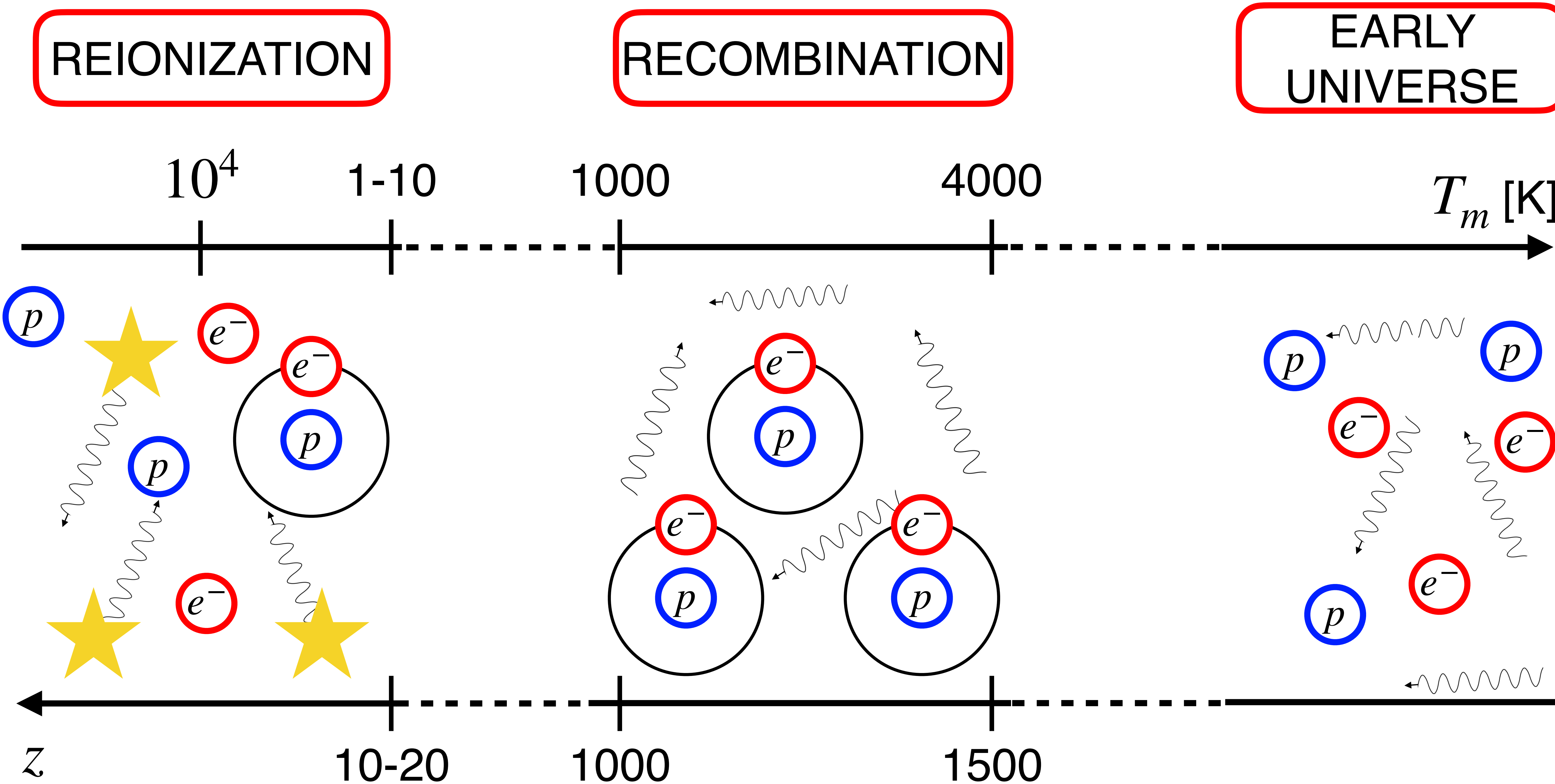
$z > 1500$: the universe is fully ionised and $T_m = T_{\rm CMB}$

Ionisation and Thermal History



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

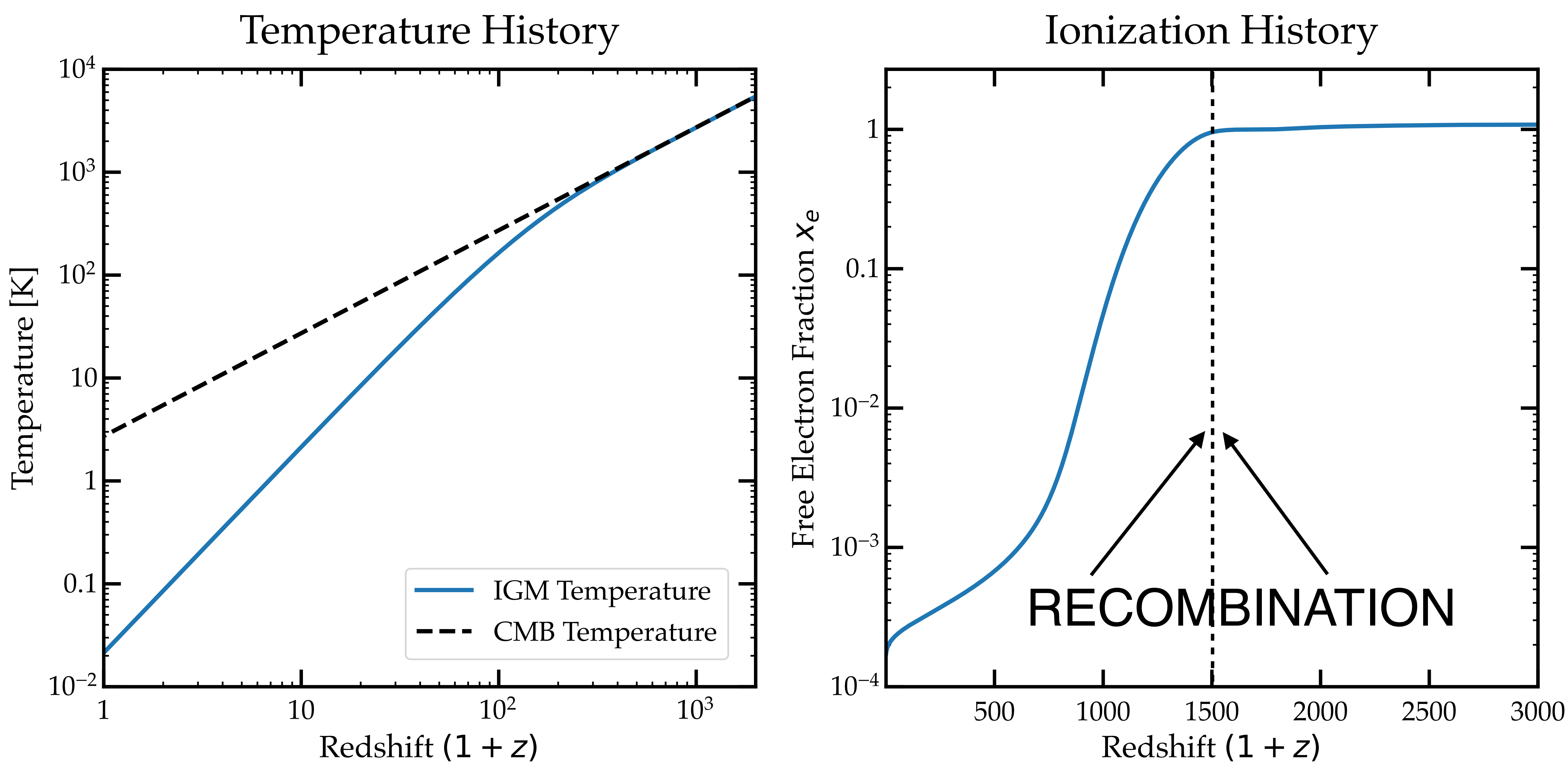
Ionisation and Thermal History



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

Ionisation and Thermal History

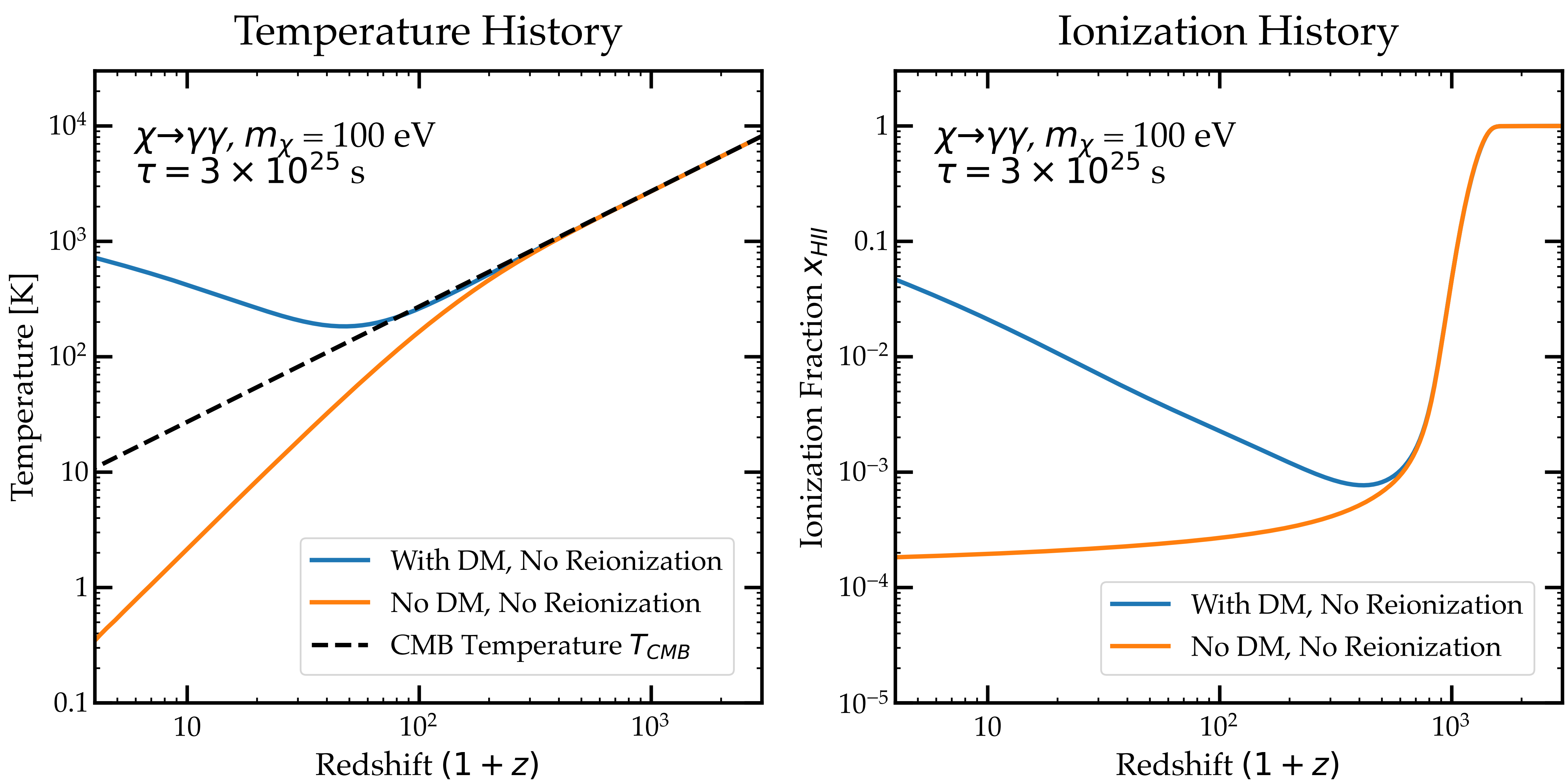
T_m and x_e redshift evolution: **NO dark matter, NO reionisation**



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

Ionisation and Thermal History

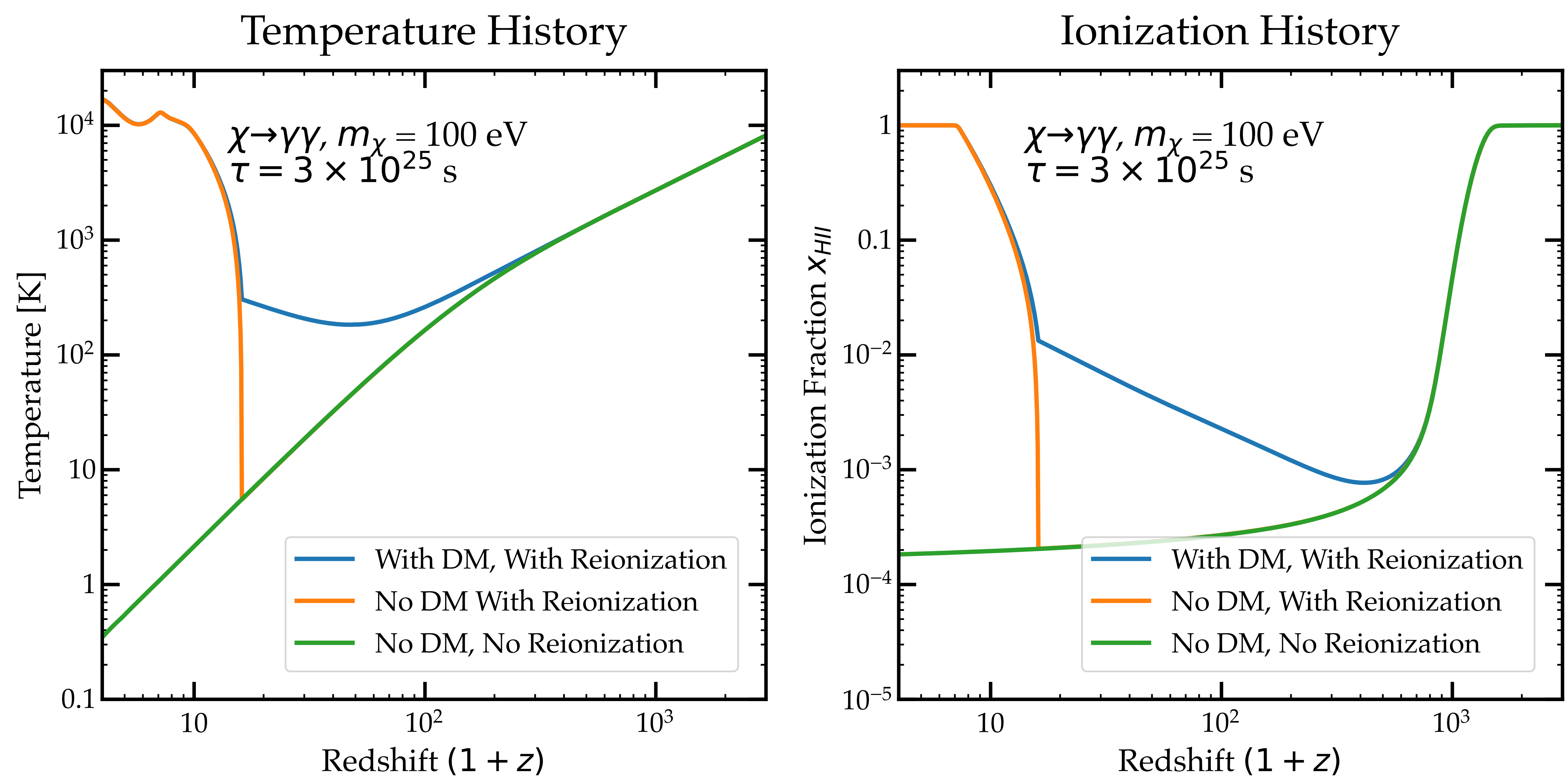
T_m and x_e redshift evolution: **WITH dark matter, NO reionisation**



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

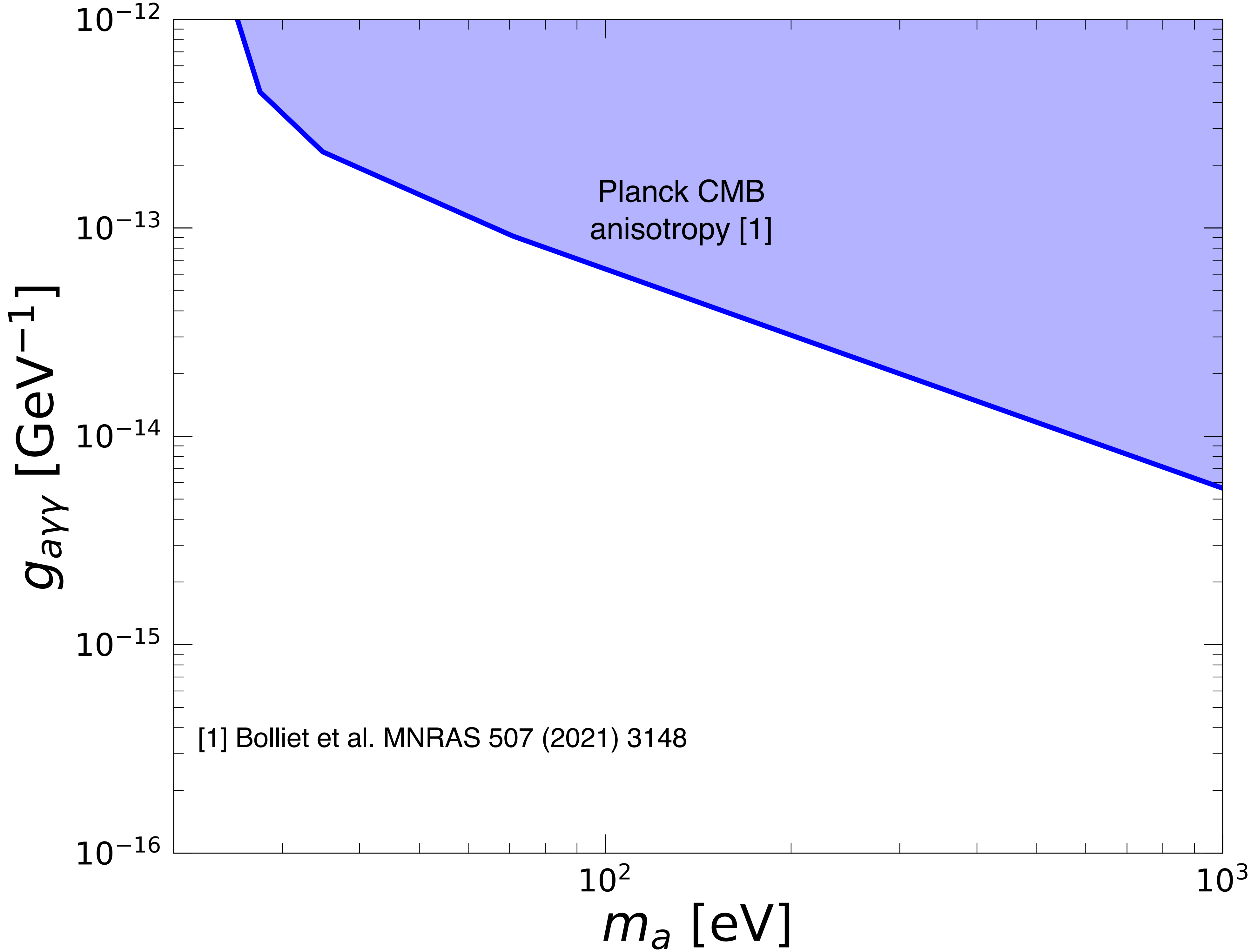
Ionisation and Thermal History

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

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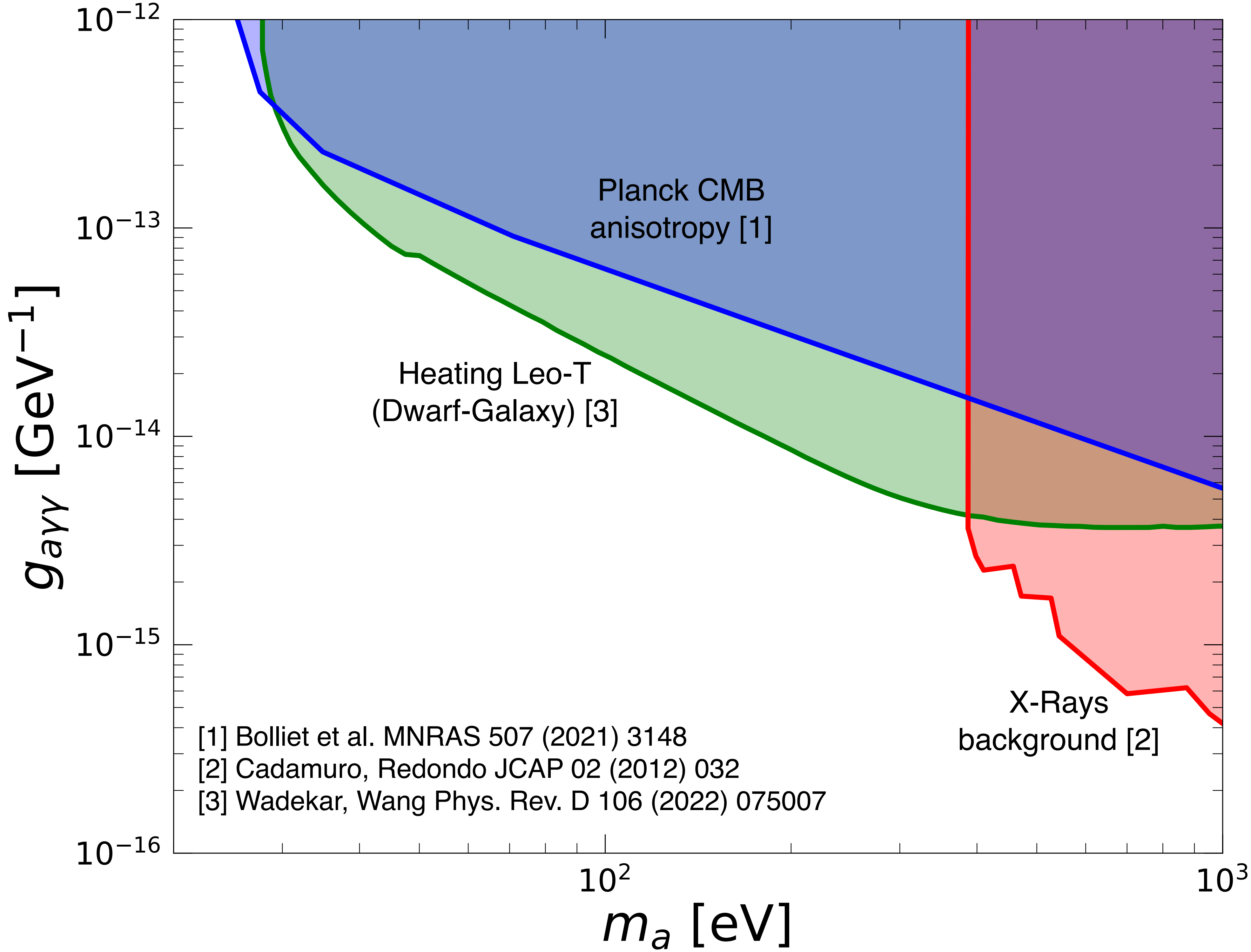
Full MCMC analysis of Planck data [4]
(we vary the fiducial cosmological parameters, as well as m_a, $g_{a\gamma\gamma}$)

[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

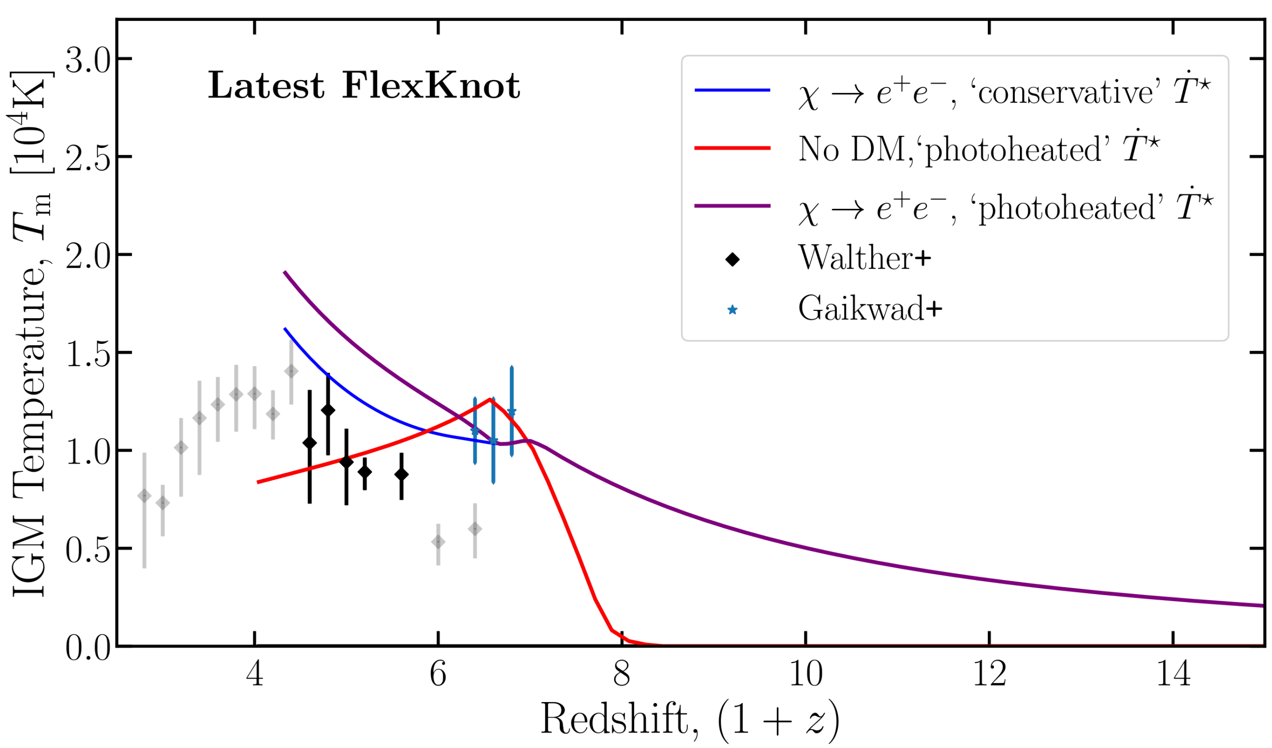


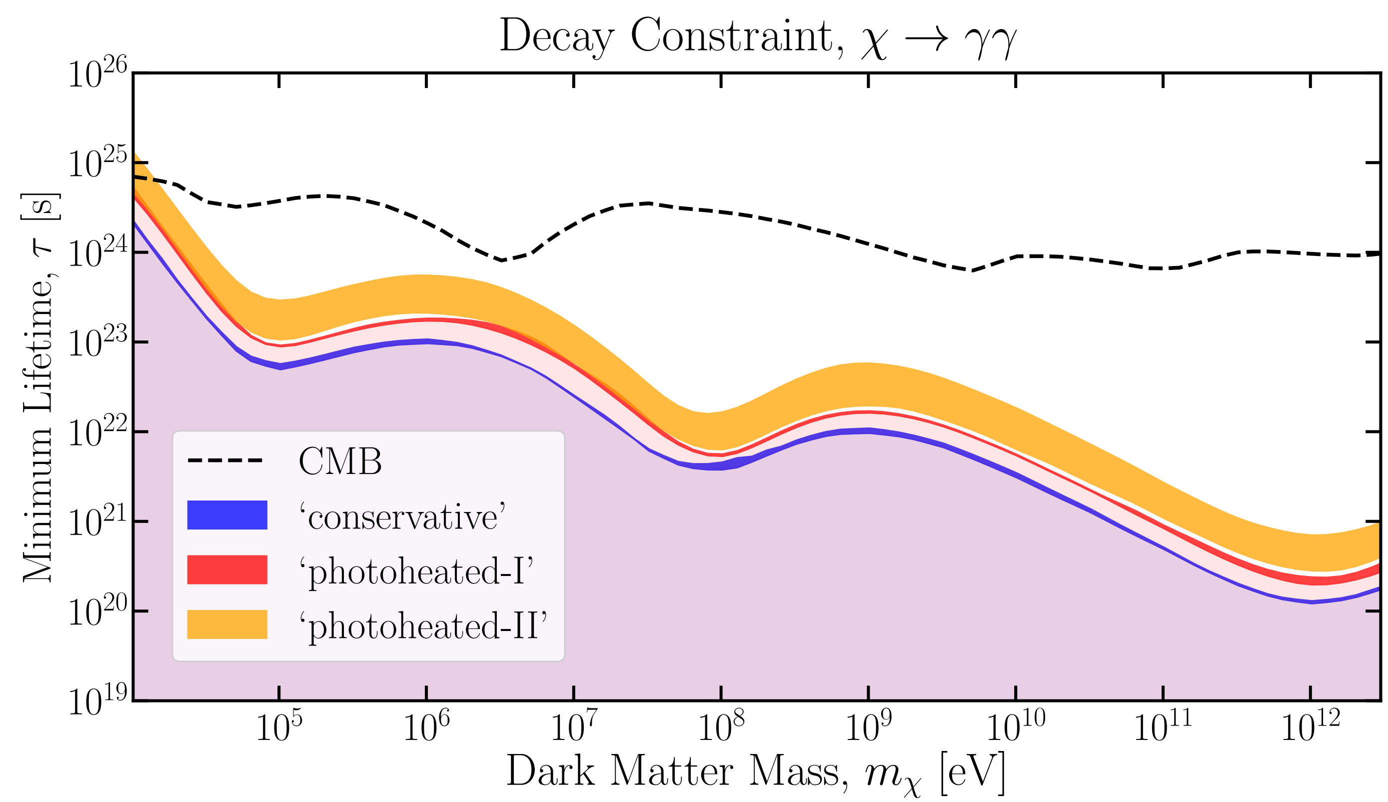
Dark matter decays can be constrained using astrophysical observables

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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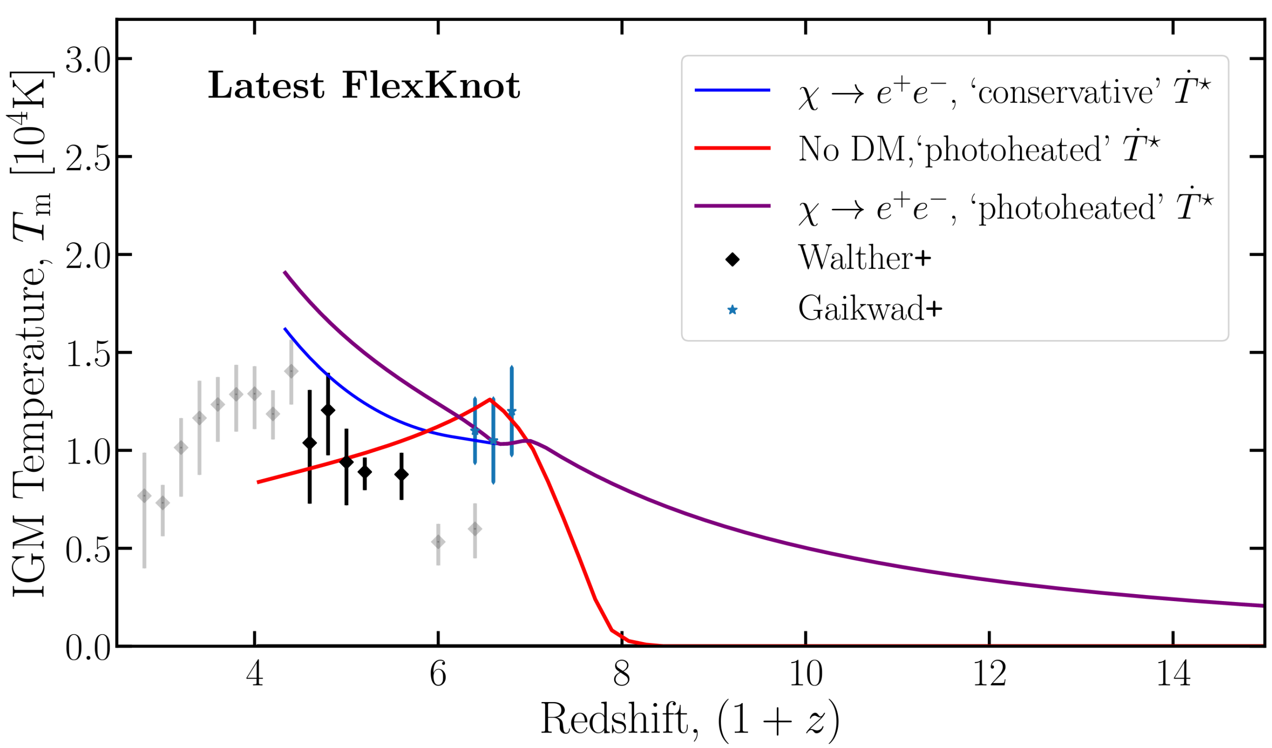

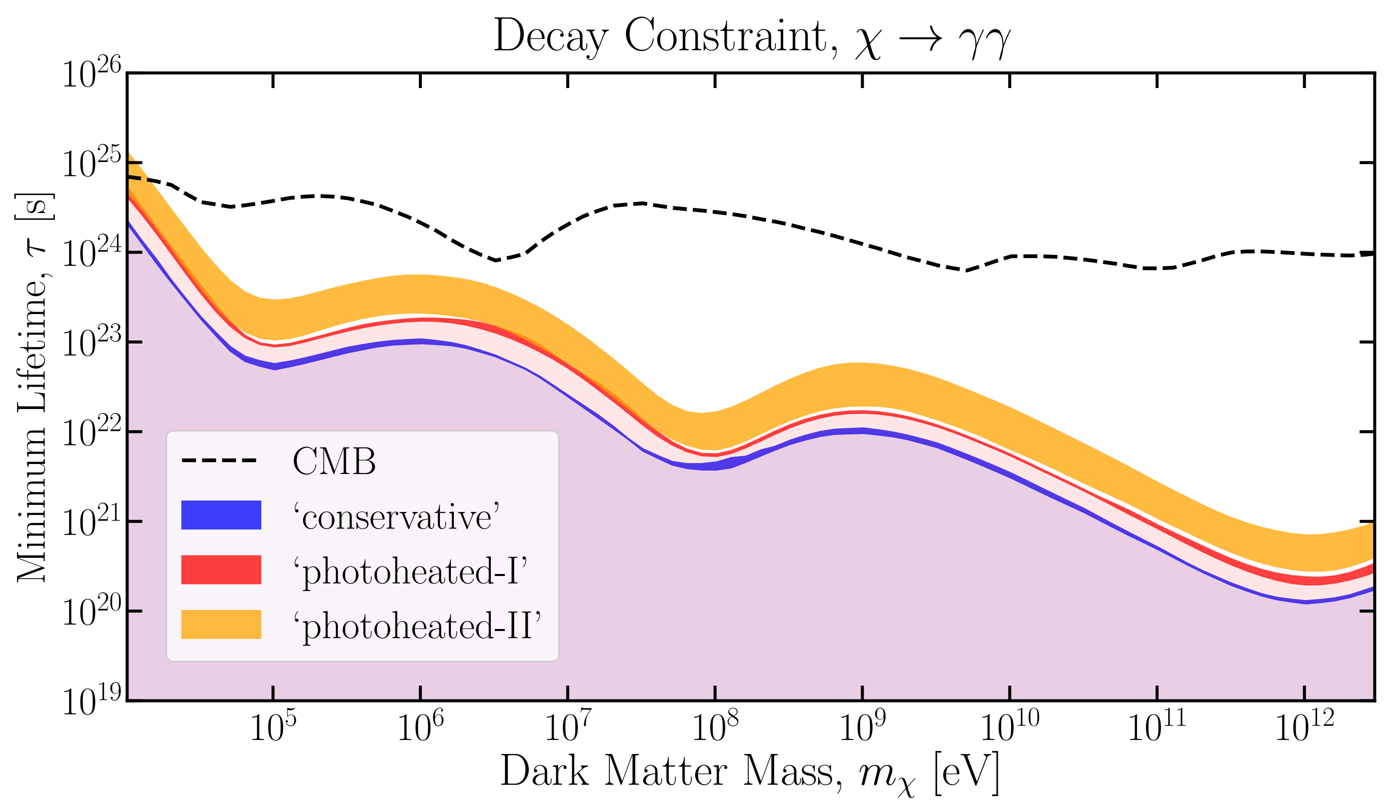

OUR IMPROVEMENT:

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

Analysis: CMB anistropy

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

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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 $x_e(z)$

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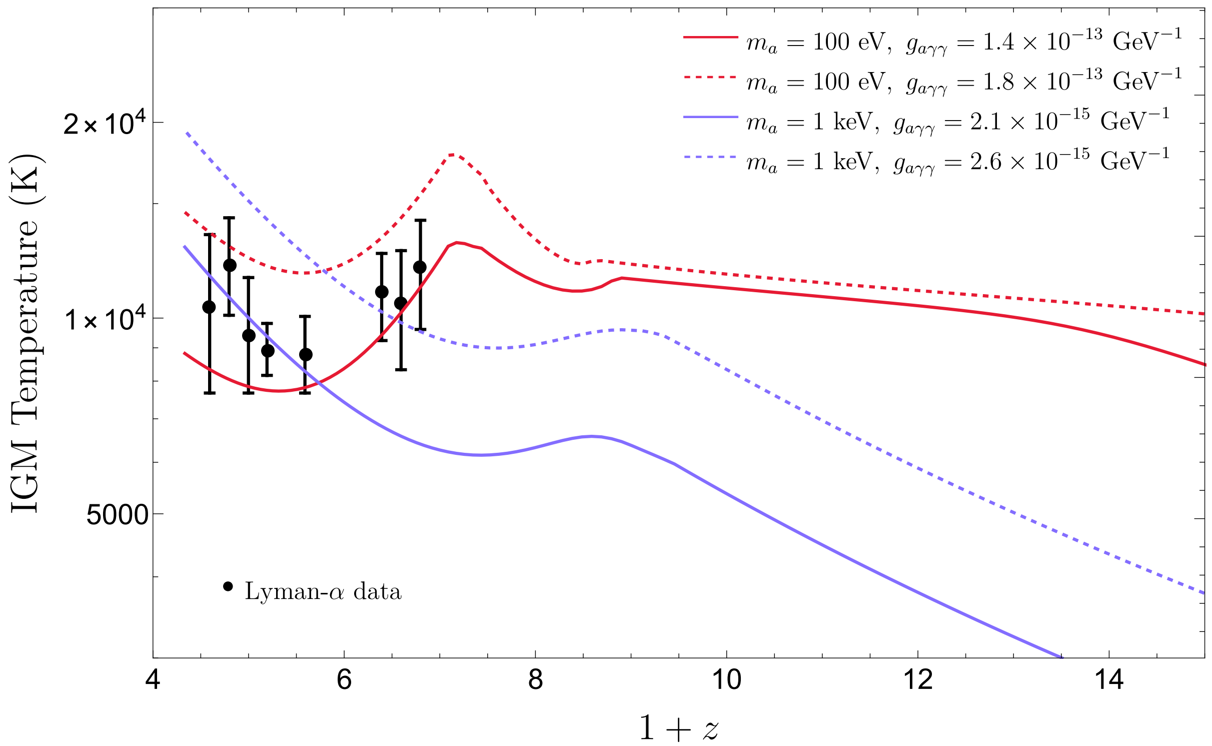
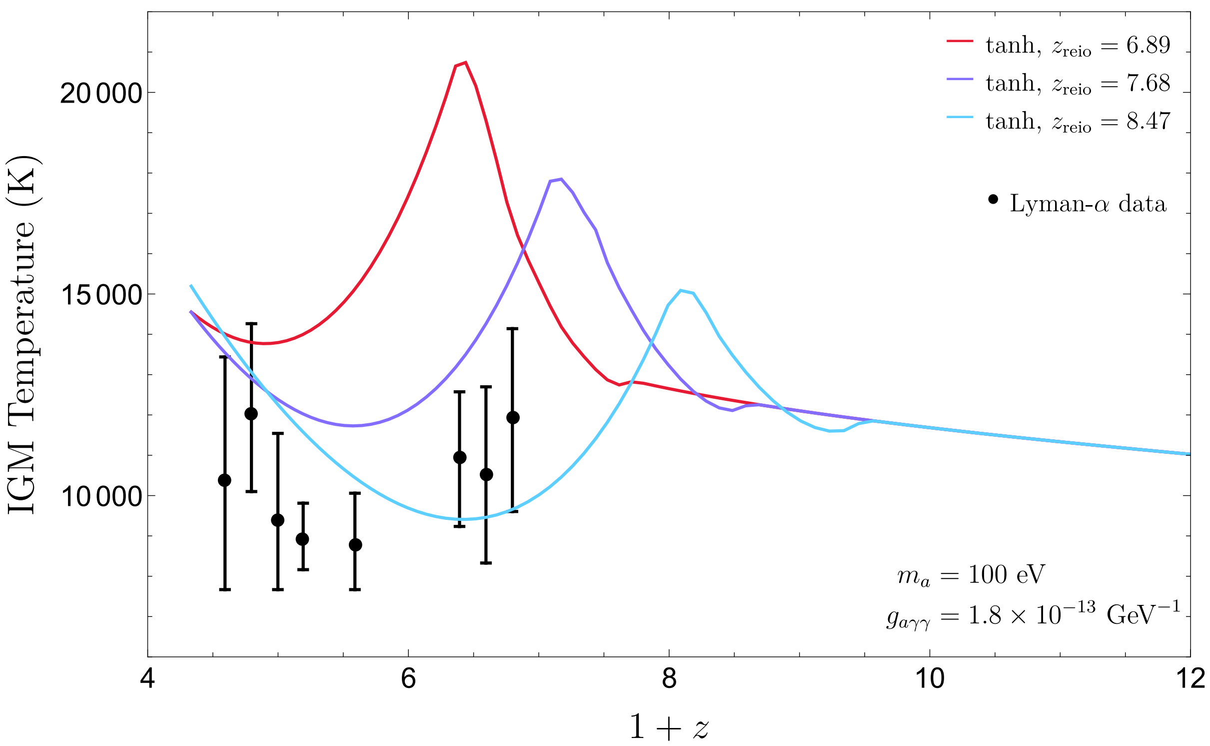
2) Modify CLASS Boltzmann solver implementing both $f_c(x_e, z)$ and $x_e(z)$

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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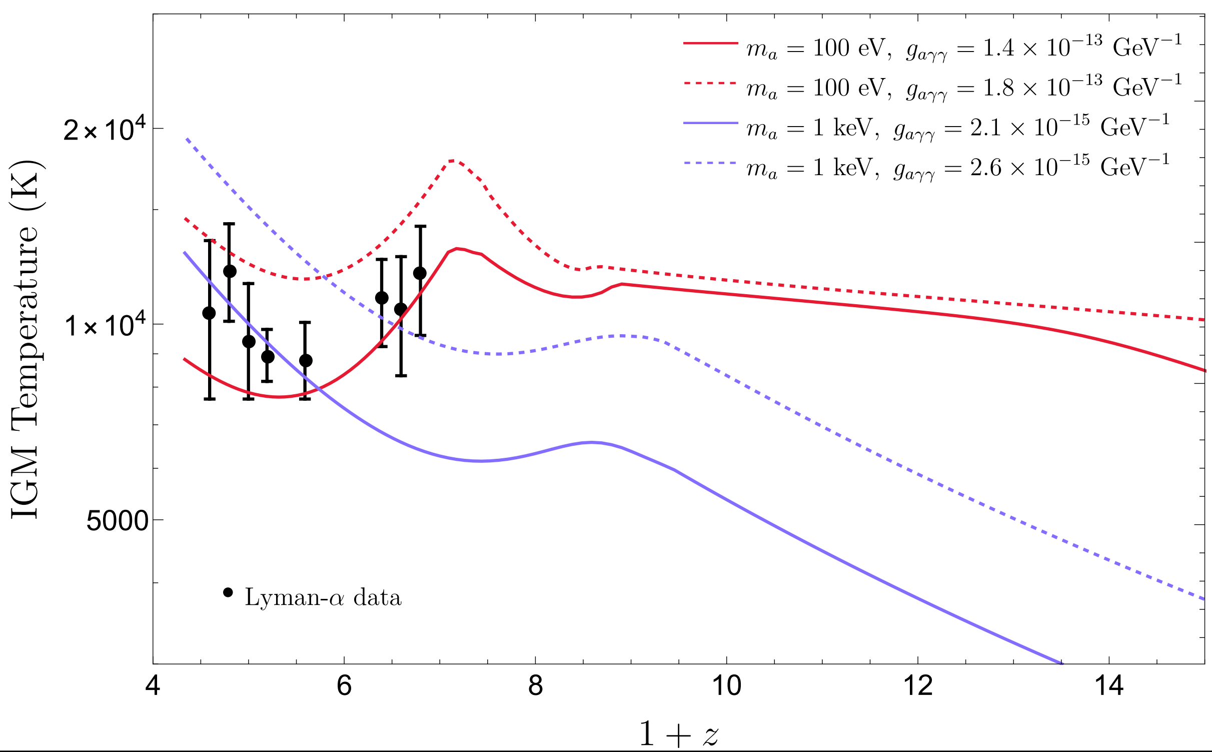
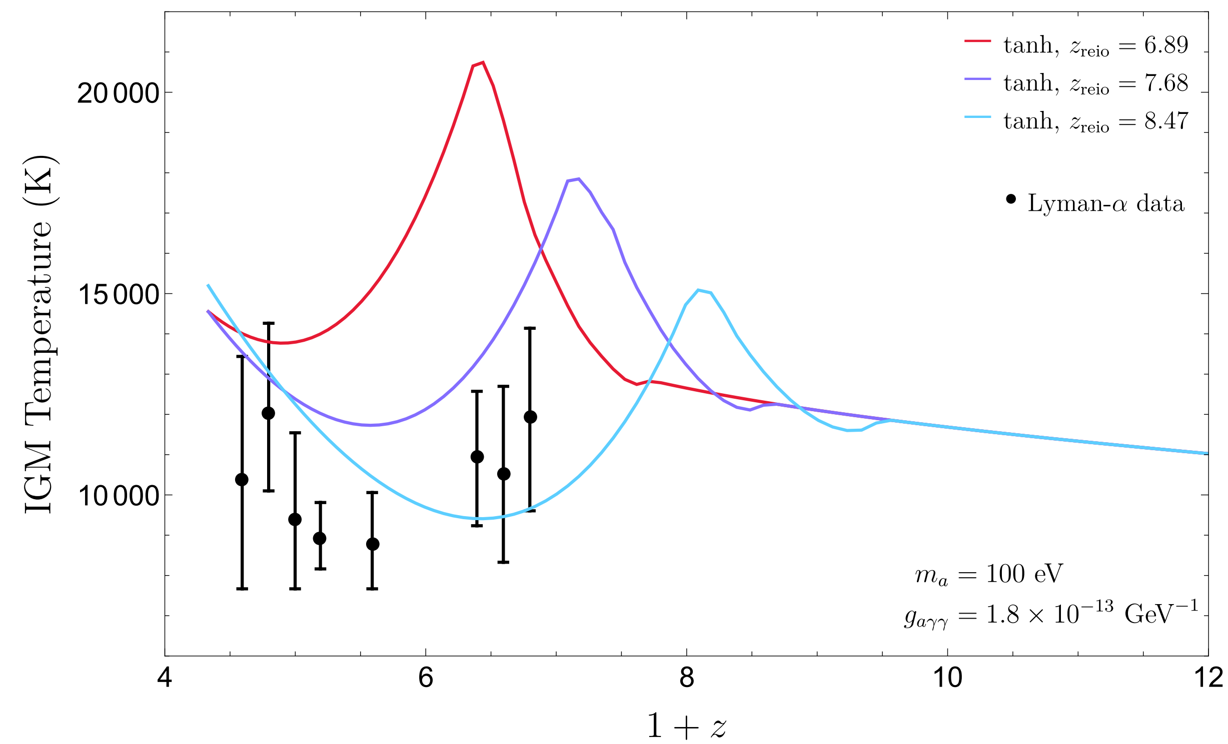
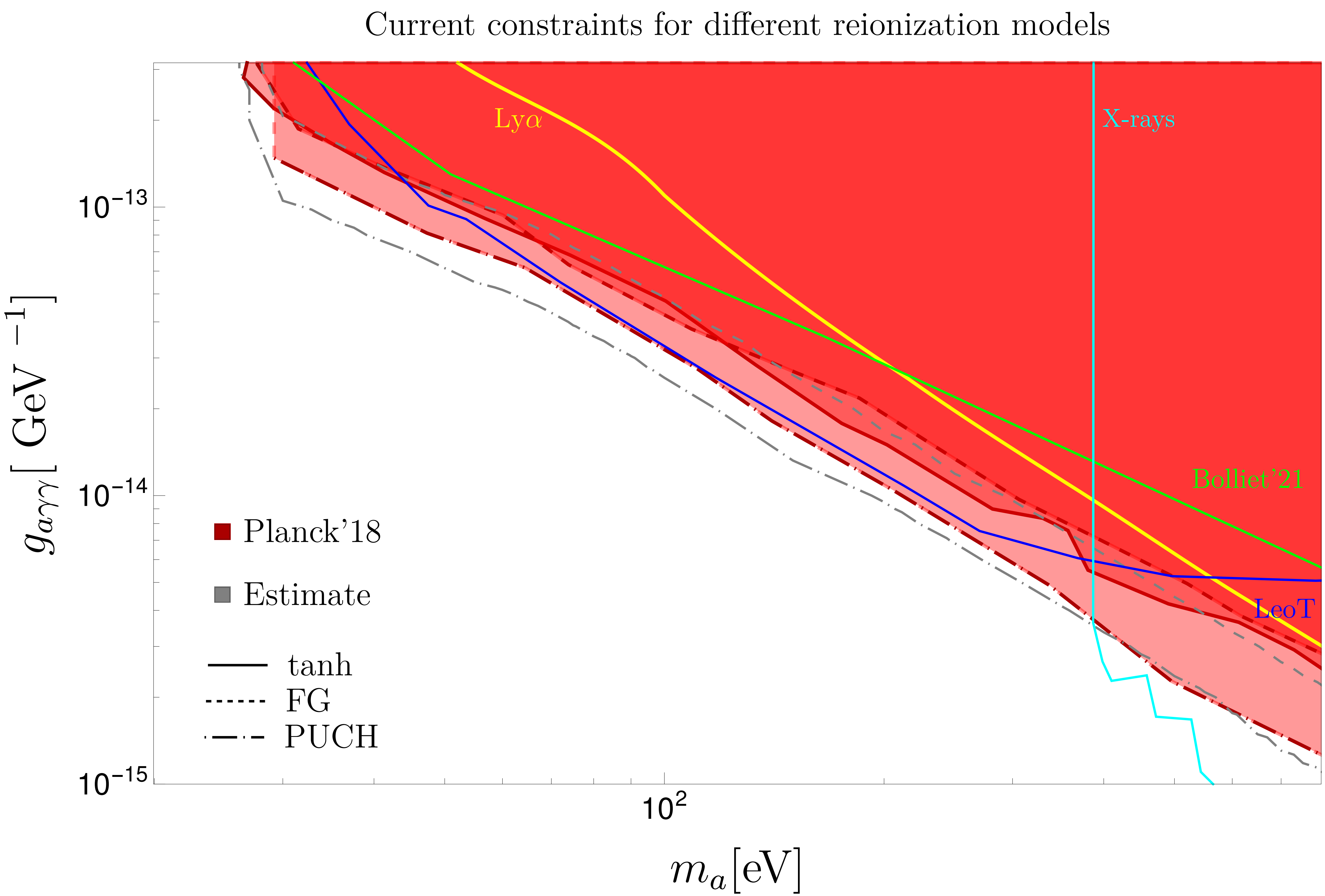


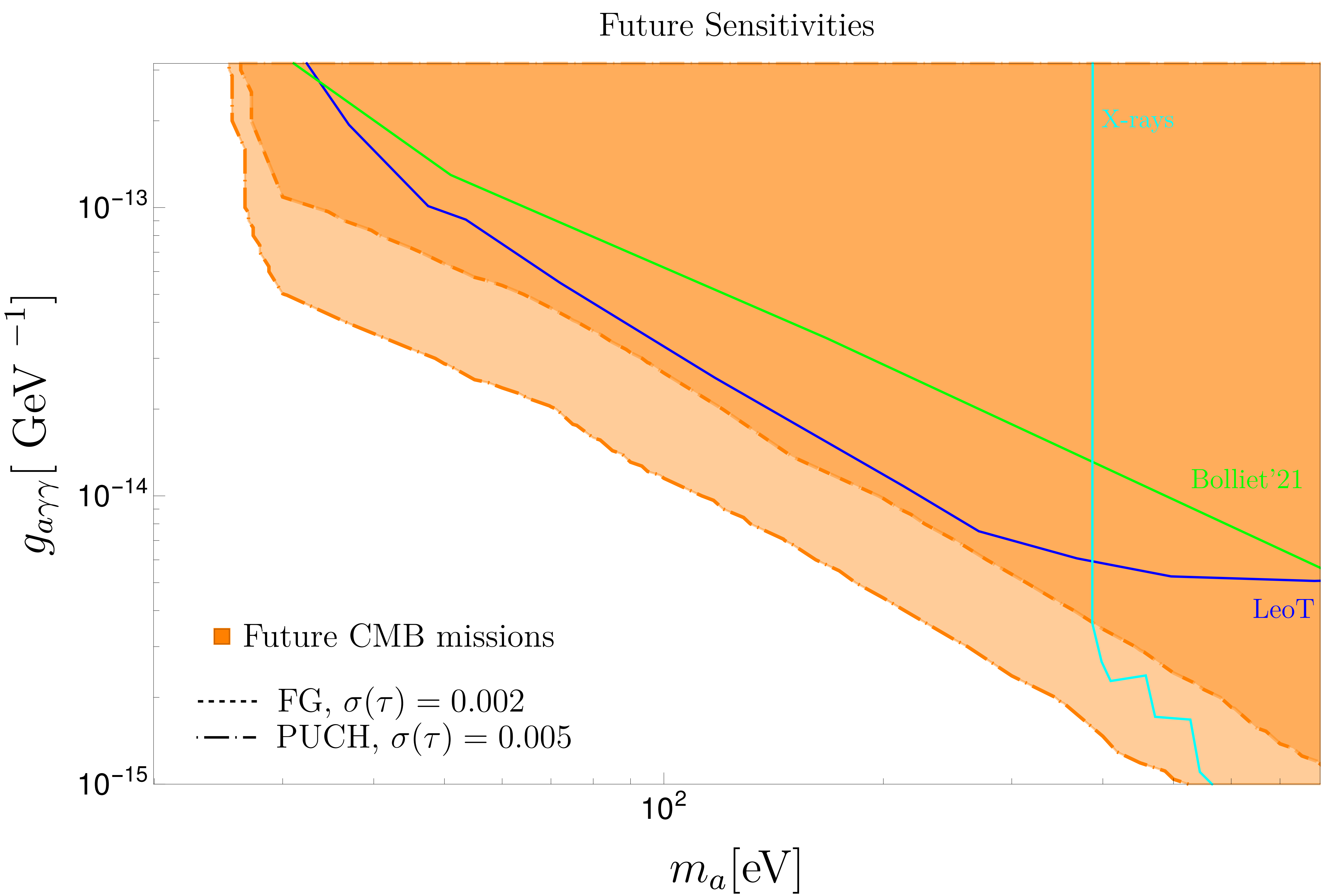


2) $$\chi_i^2 = \begin{cases} 0\,, & T_{m,i,\text{pred}} < T_{m,i,\text{data}} \\ \left(\dfrac{T_{m,i,\text{pred}} - T_{m,i,\text{data}}}{\sigma_{i,\text{data}}}\right)^2, & T_{m,i,\text{pred}} \geq T_{m,i,\text{data}} \end{cases}$$

Analysis: CMB anistropy



Analysis: CMB anistropy



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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

Ionisation and Thermal History: equation

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

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

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

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

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

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

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

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

Dark matter energy injection/deposition

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

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

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

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

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

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

Optical depth to reionization

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

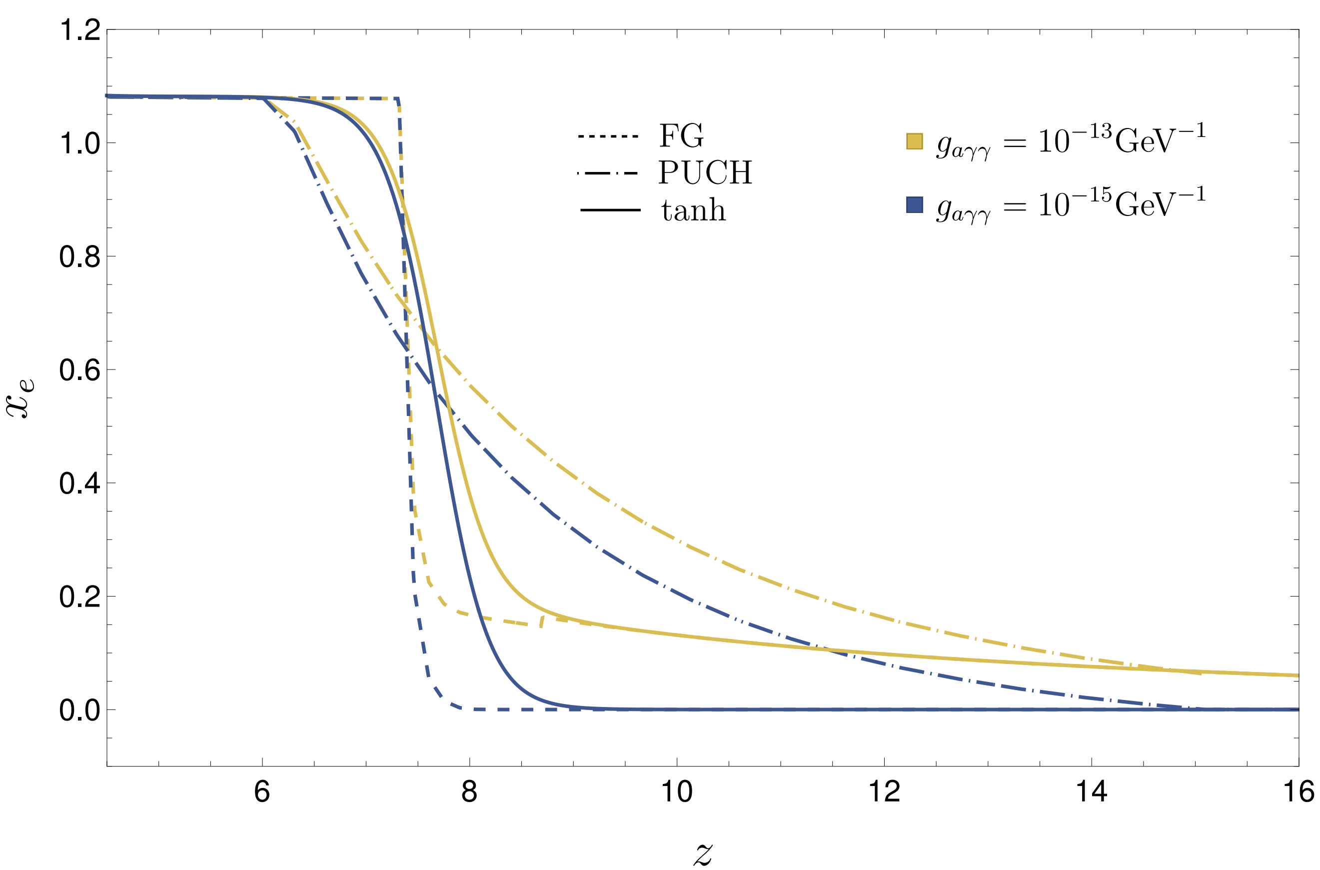
$\sigma_T \rightarrow$ Thomson scattering cross section

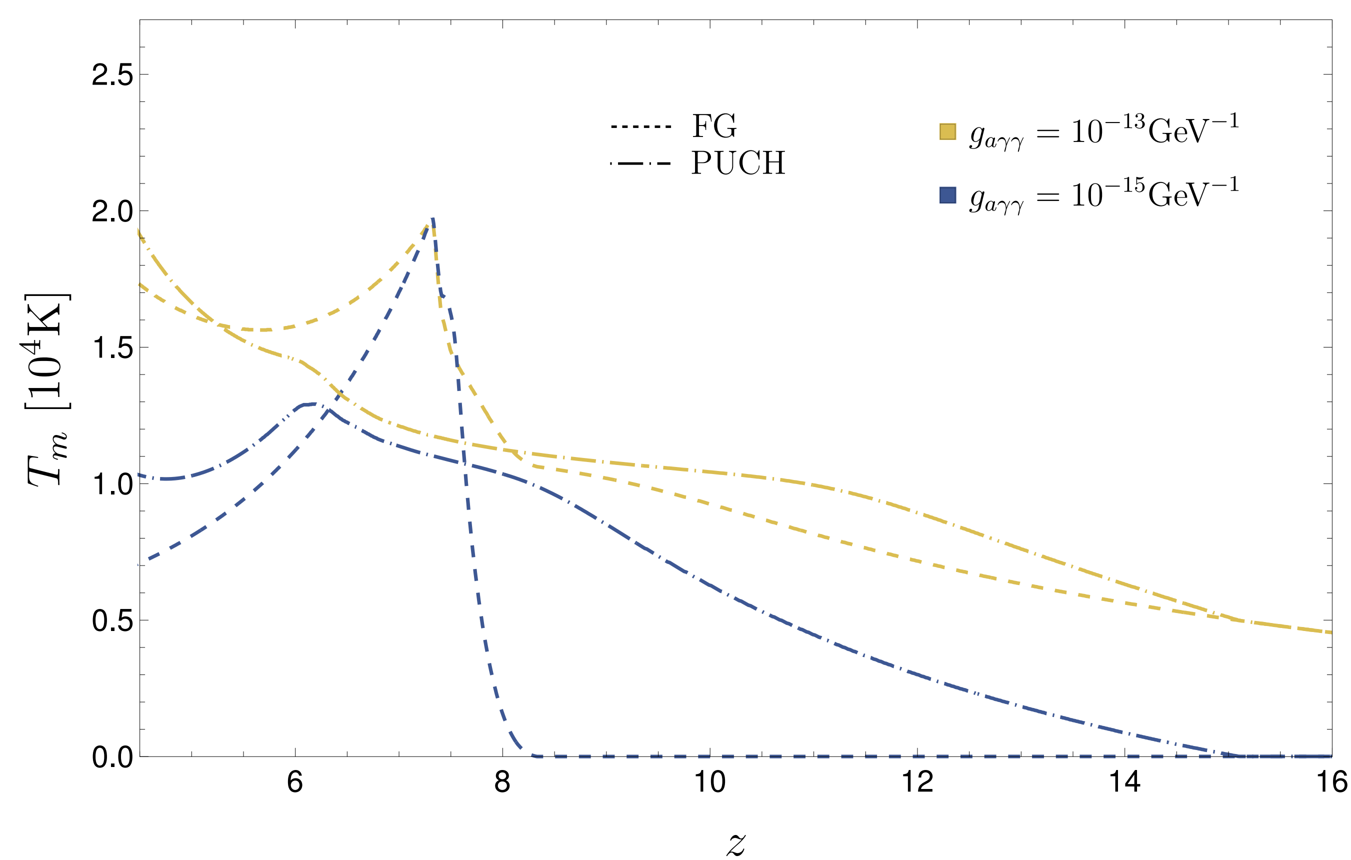
$\tau = 0.054 \pm 0.007$, measured by Planck

Reionisation from stars

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

X = HII, HeII, HeIII



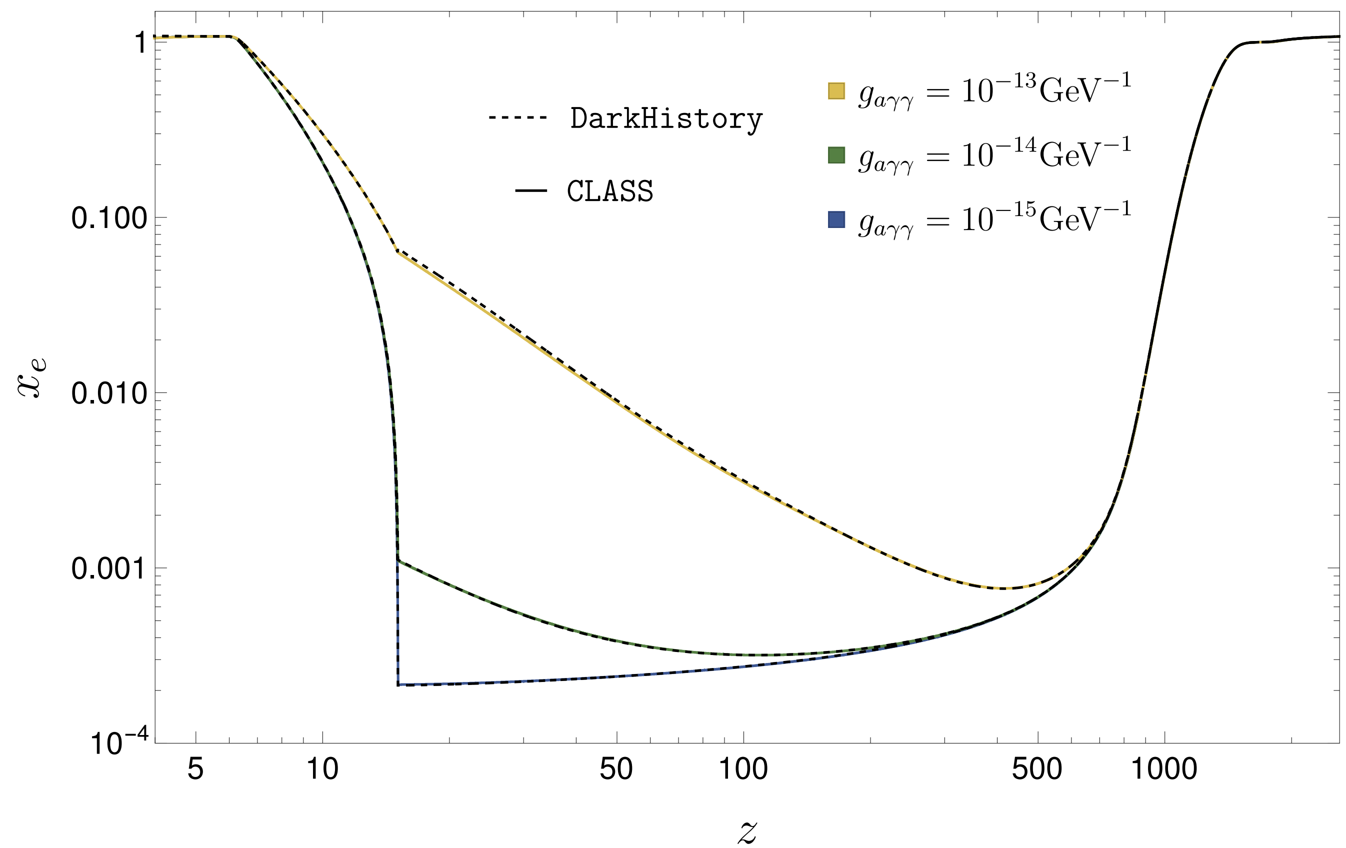


$\tau_{\rm PUCH} = 0.064$ $\tau_{\rm FG} = 0.052$

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

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

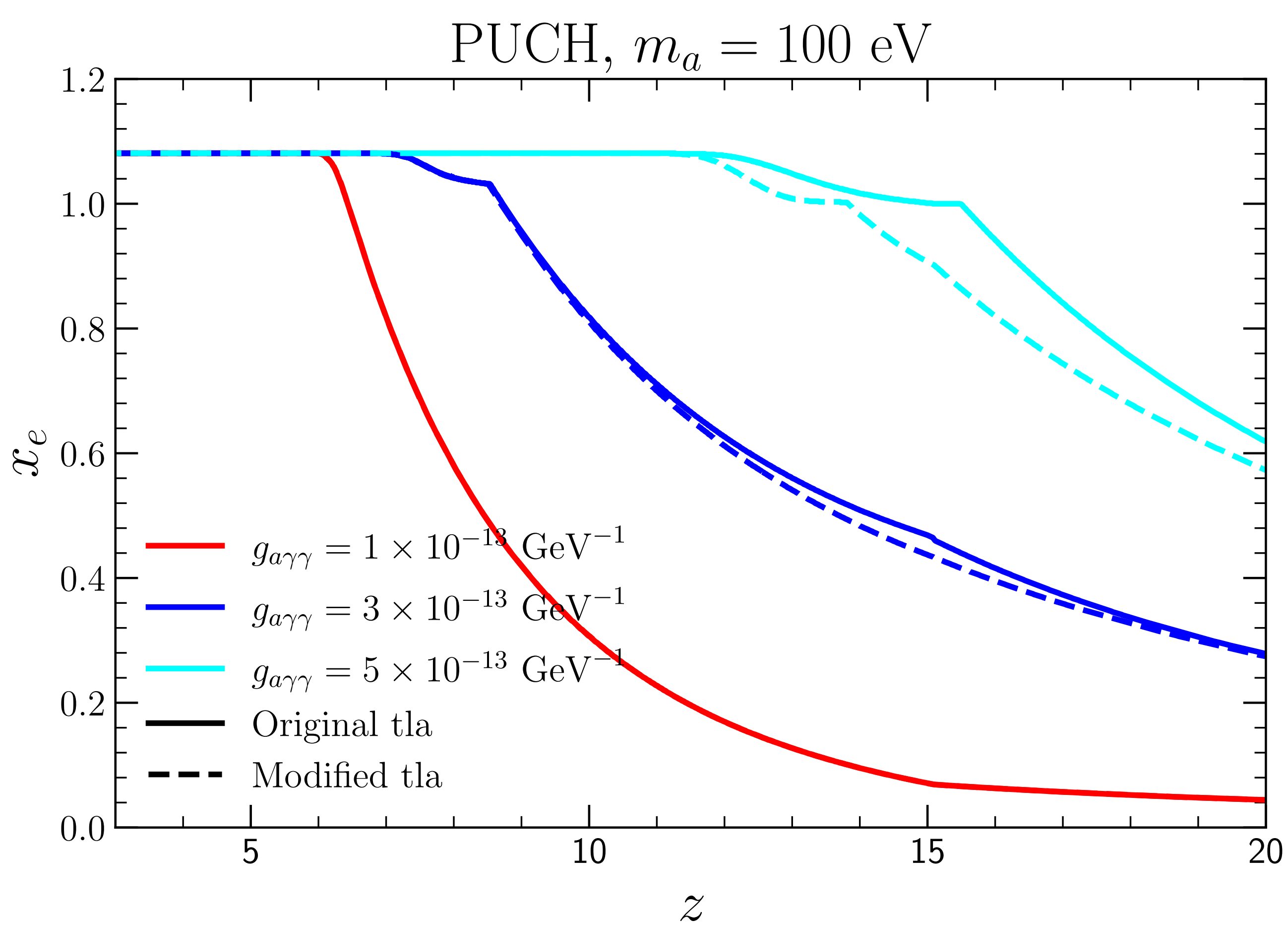
$$\mathcal{F}_{\rm He} = n_{\rm HeII}/n_{\rm H} \qquad y(z) = (1+z)^{\gamma} \qquad \Delta_y = \gamma(1+z_{\rm reio})^{\gamma-1}\Delta_z$$

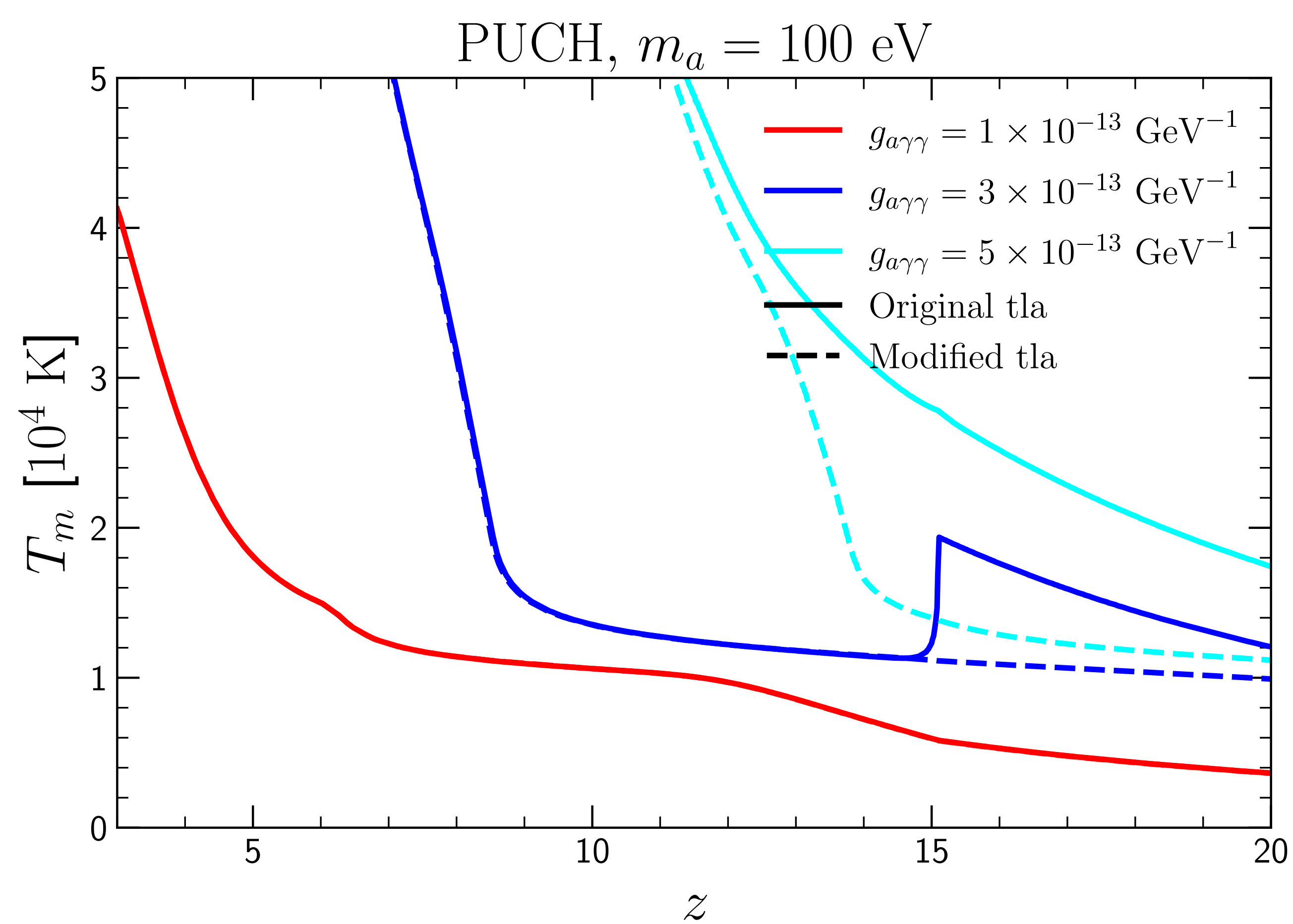
$$\Delta z = 0.5, \gamma = \frac{3}{2}, z_{\rm reio} = \text{free}$$

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

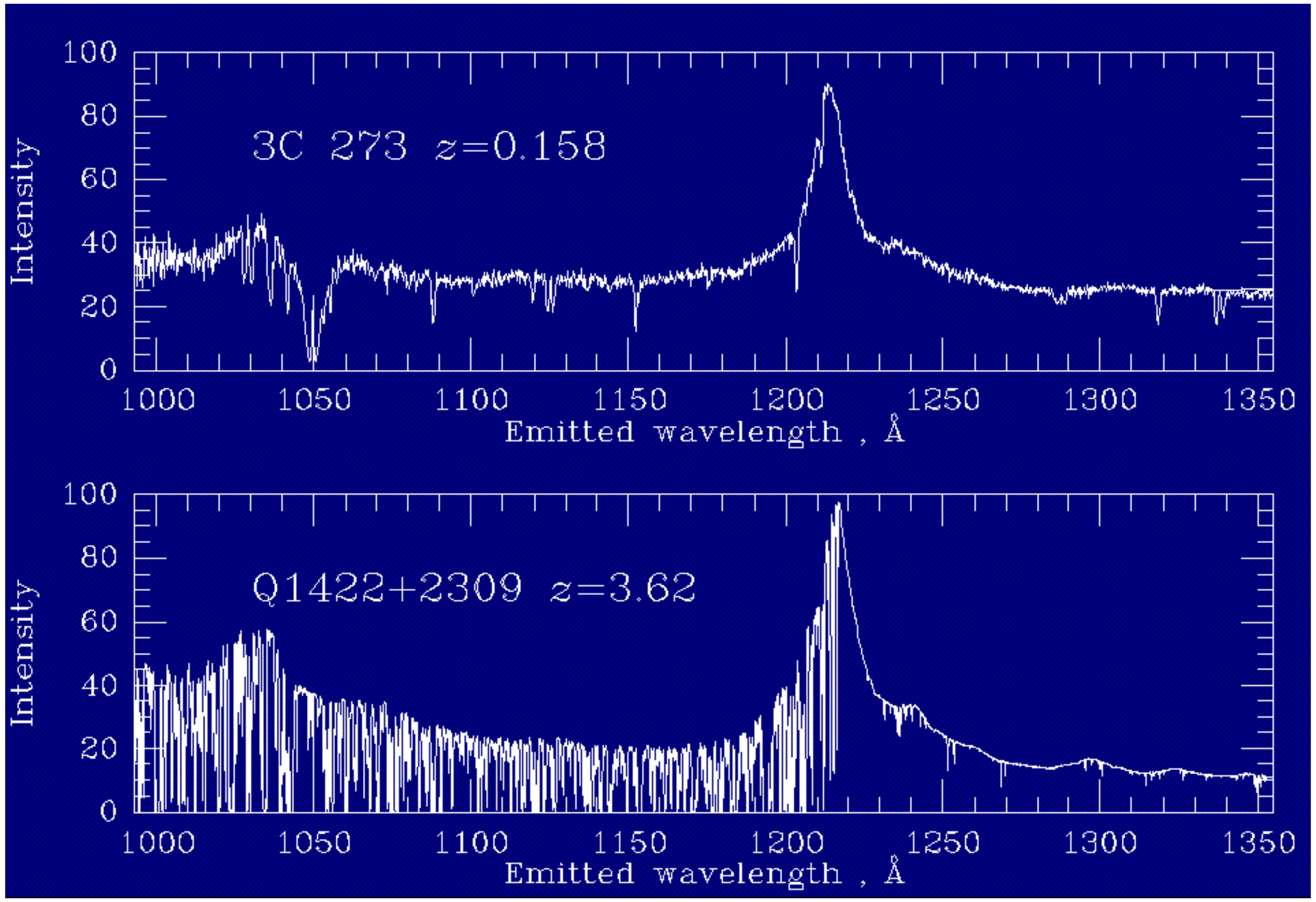




Lyman-α measurement of T_m

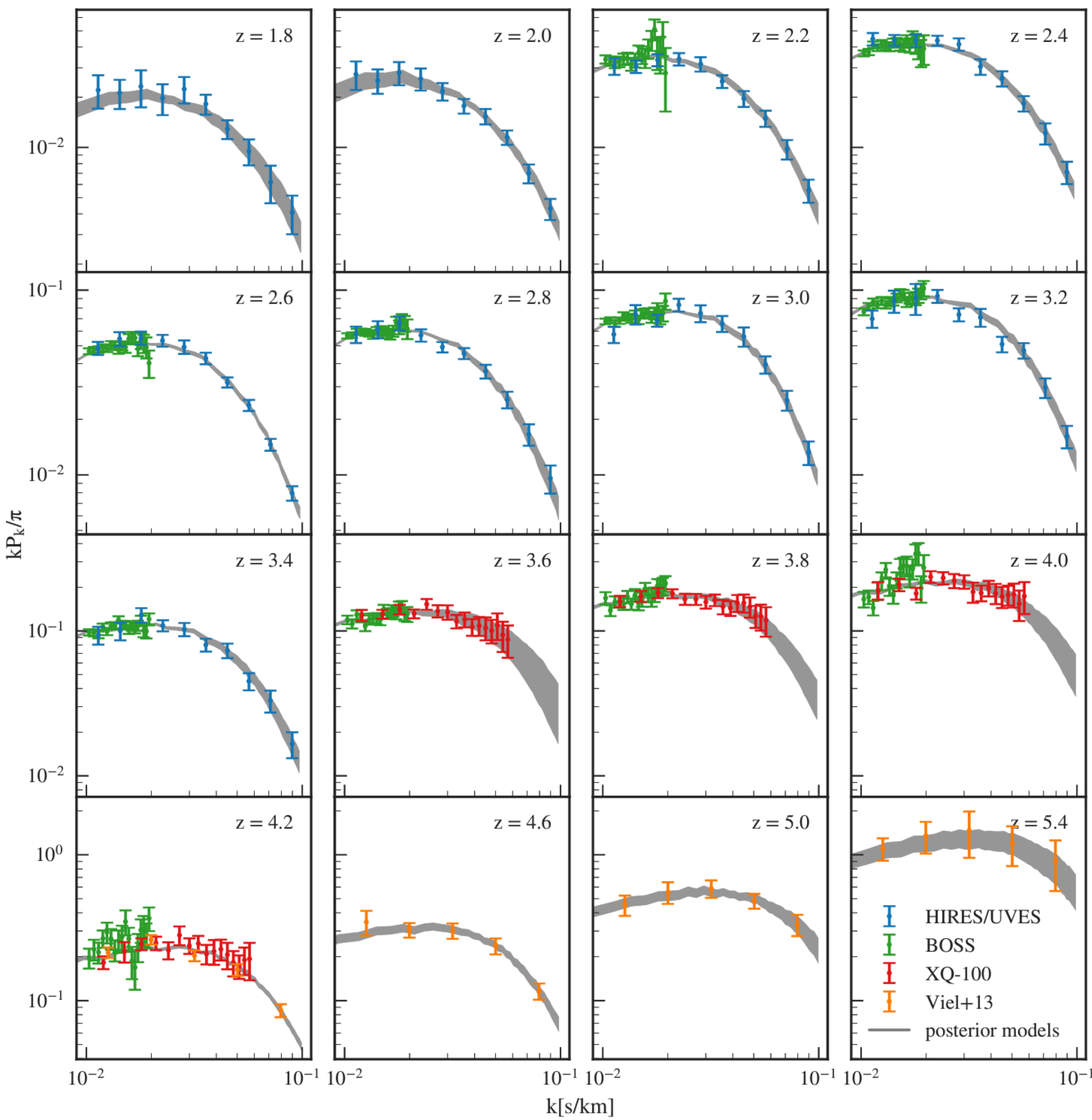
Emission from high-z quasars undergoes Lyman-α absorption by gas clouds

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



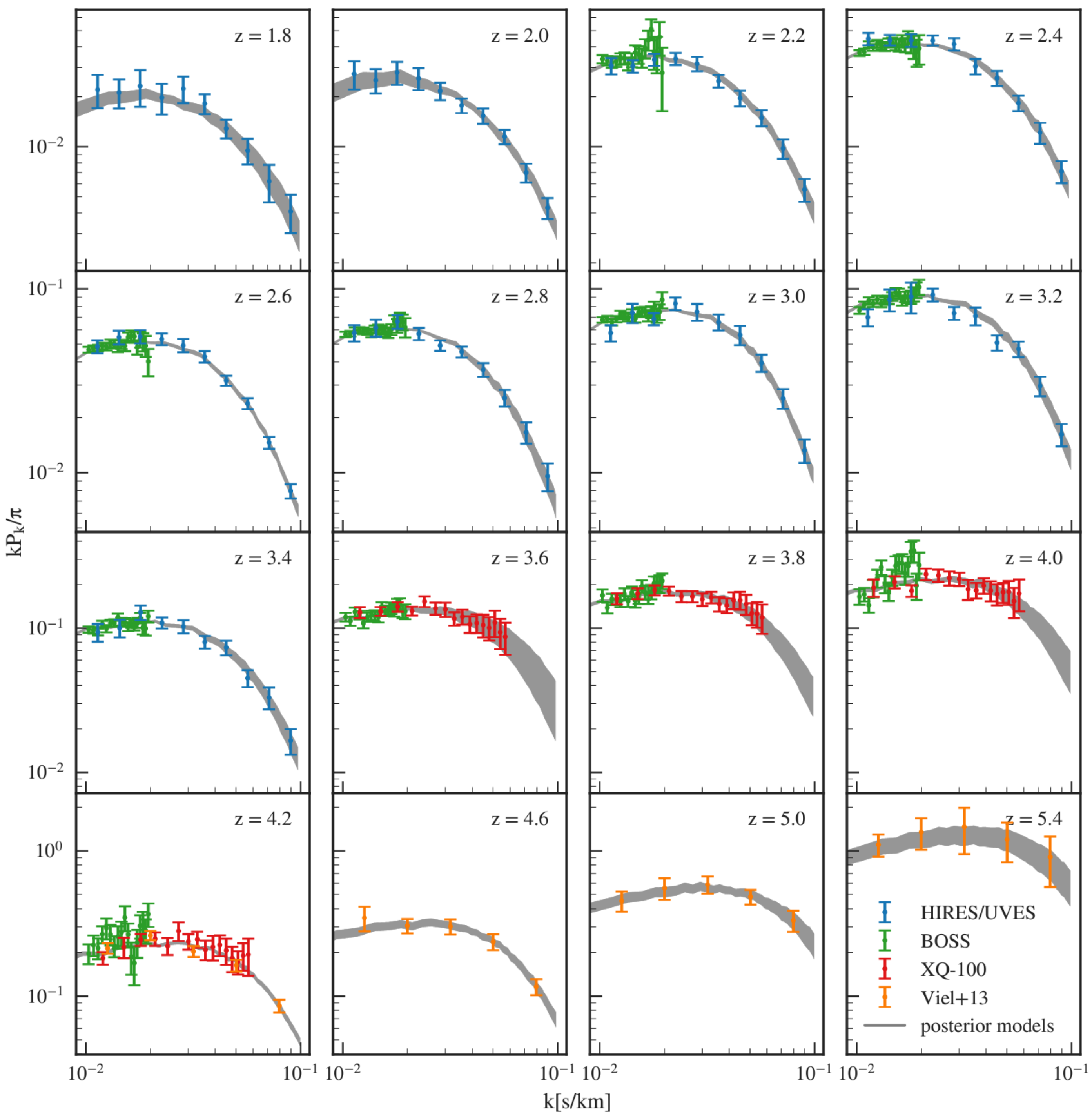
The higher the quasar redshift the more absorption lines there are

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_{eff}, $\sum m_\nu$.

Lyman-α measurement of T_m



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