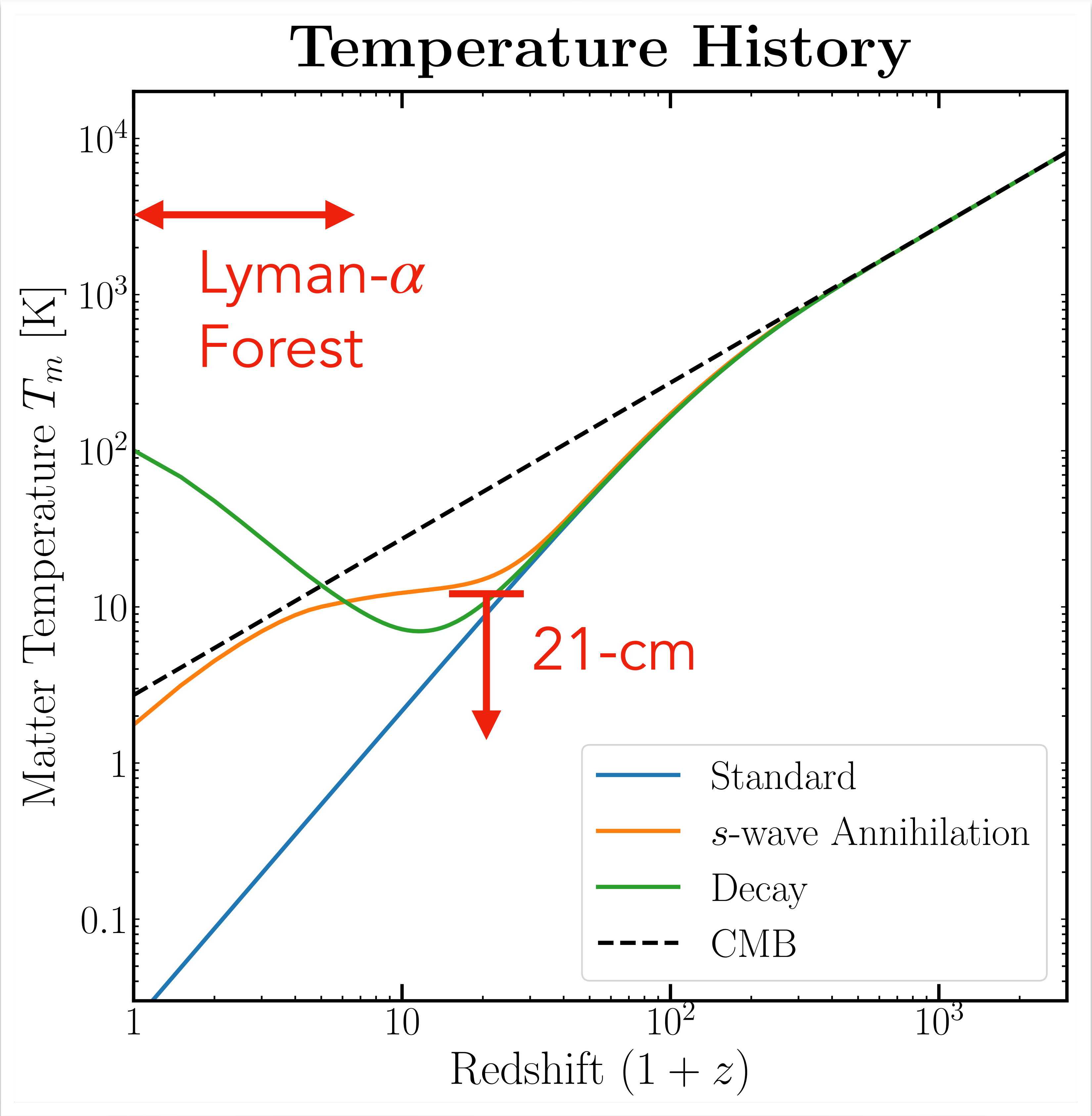
DarkHistory

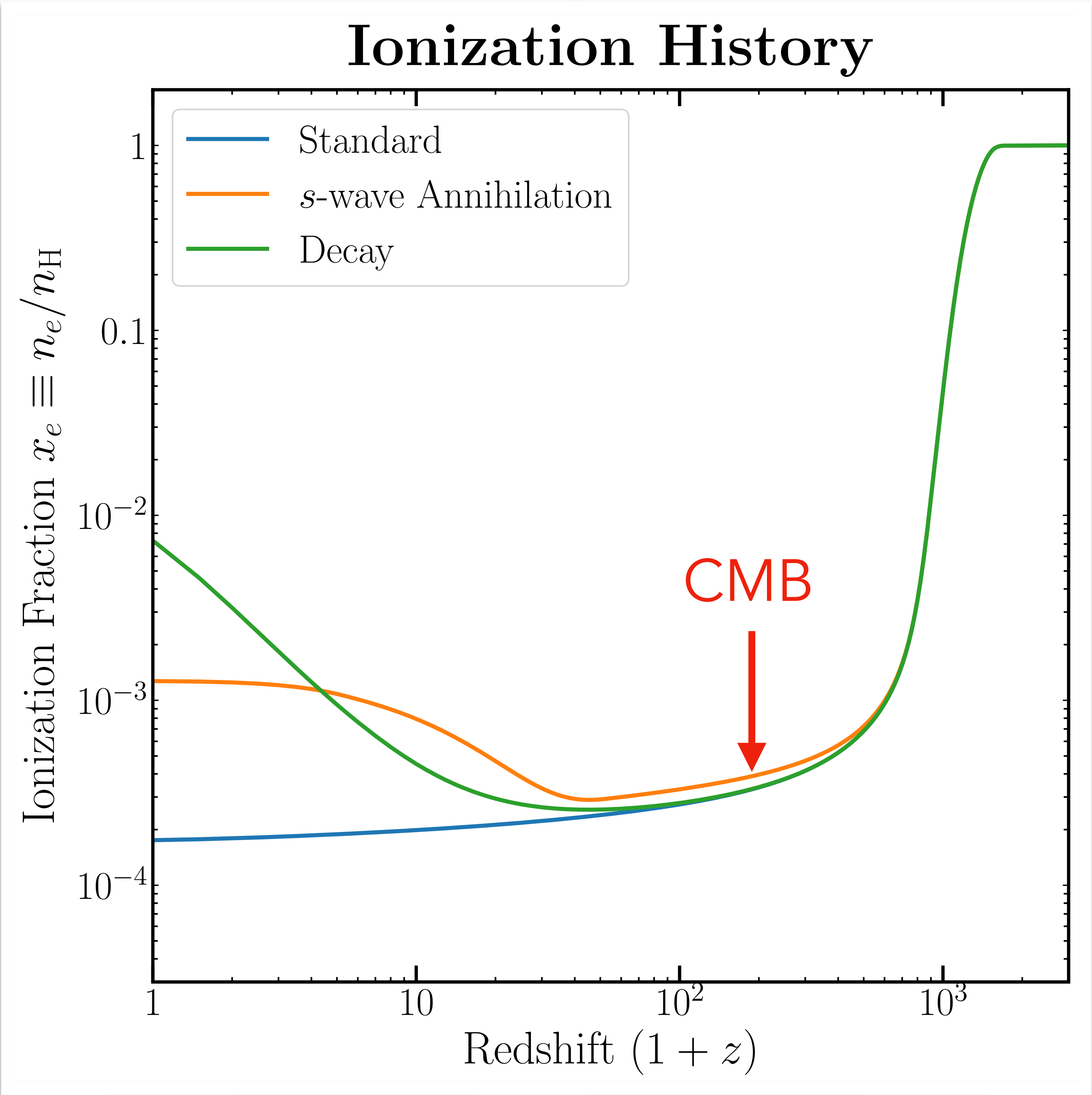
Accurate Ionization and Thermal Histories with Exotic Energy Injection

Hongwan Liu

HL, Gregory W. Ridgway and Tracy Slatyer arXiv:1904.09296
HL, Wenzer Qin, Gregory W. Ridgway and Tracy Slatyer arXiv:2008.01084

Why DarkHistory?



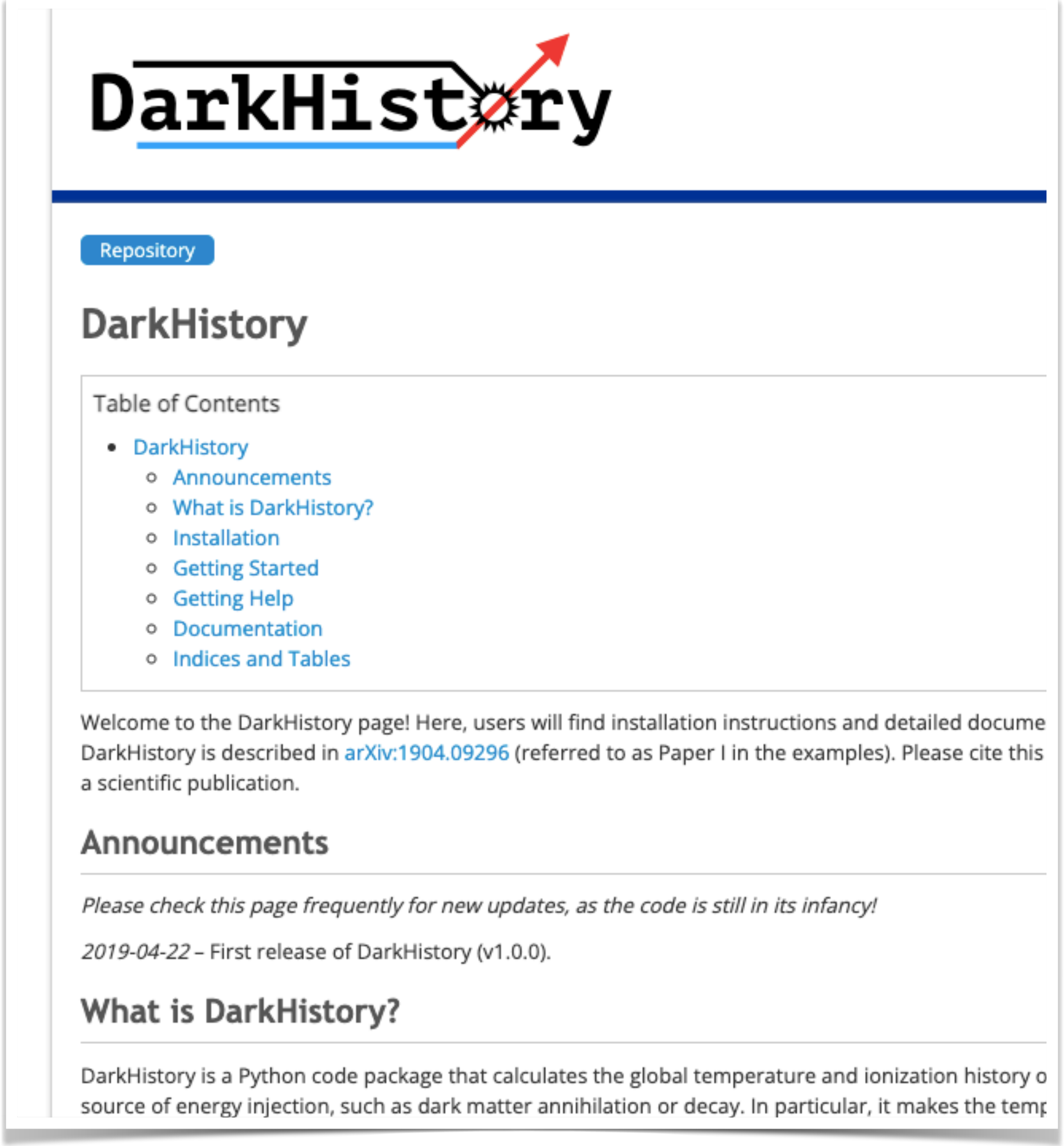


Powerful cosmological probes of exotic energy injection,
if we can compute the effects correctly!

DarkHistory Highlights

Open source code in **Python** with **documentation** and **Jupyter** notebook examples.

https://github.com/hongwanliu/DarkHistory/
https://darkhistory.readthedocs.io/


DarkHistory

Repository

DarkHistory

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  - What is DarkHistory?
  - Installation
  - Getting Started
  - Getting Help
  - Documentation
  - Indices and Tables

Welcome to the DarkHistory page! Here, users will find installation instructions and detailed docume
DarkHistory is described in arXiv:1904.09296 (referred to as Paper I in the examples). Please cite this
a scientific publication.

Announcements

Please check this page frequently for new updates, as the code is still in its infancy!

2019-04-22 – First release of DarkHistory (v1.0.0).

What is DarkHistory?

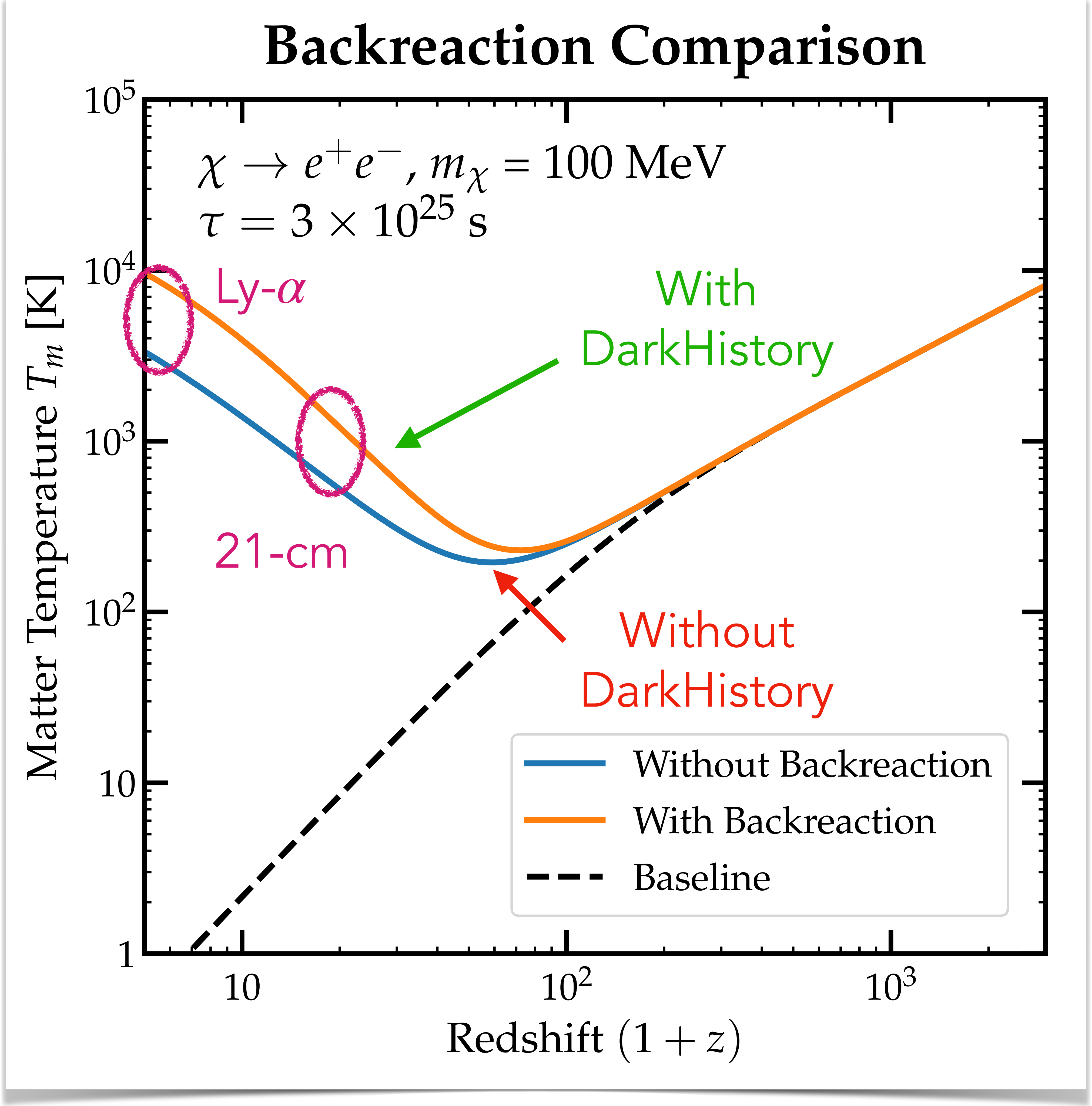
DarkHistory is a Python code package that calculates the global temperature and ionization history o
source of energy injection, such as dark matter annihilation or decay. In particular, it makes the temp

DarkHistory Highlights

Implements **important corrections** to **temperature** calculation.

Self-consistent treatment of **exotic energy injection and reionization**.

Critical for **21-cm** and **Lyman-α forest** comparison.



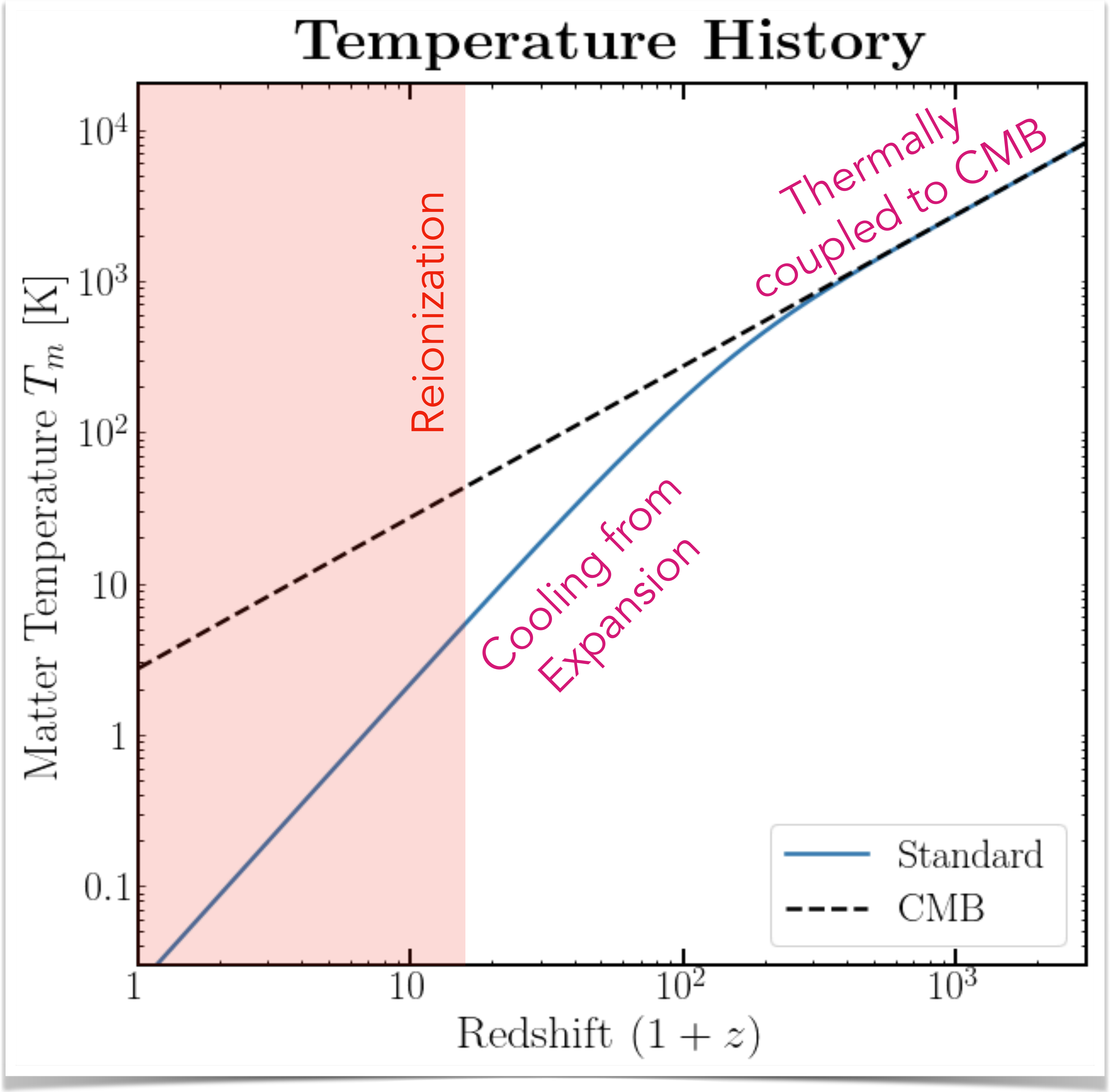
Temperature History

Matter Temperature

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\mathrm{CMB}} - T_m)$$

Cooling from Expansion

Heating from CMB



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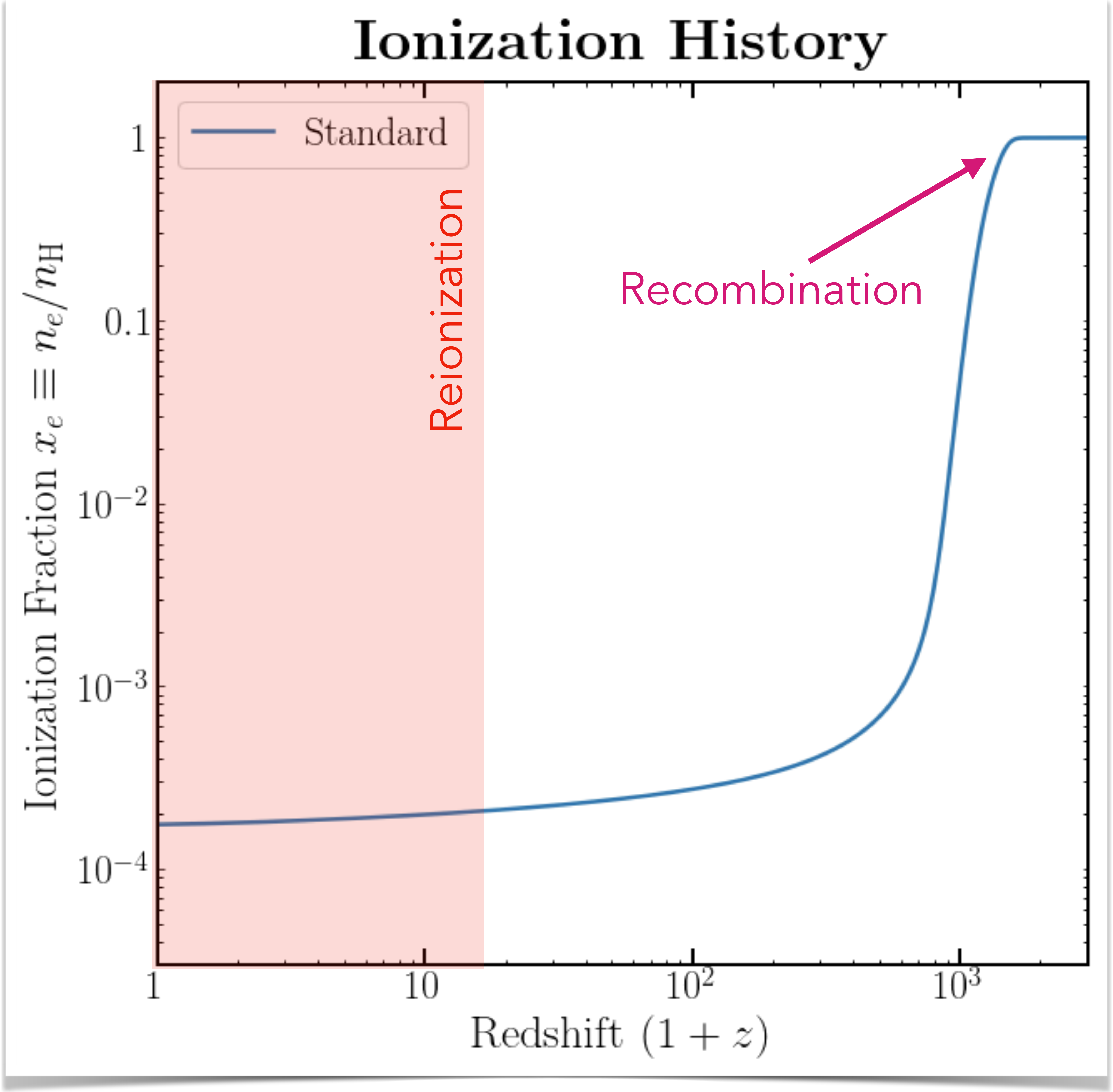


Ionization

$$\dot{x}_e = -\mathscr{C}\left[n_H x_e^2 \alpha_B - 4(1-x_e)\beta_B e^{-E_{21}/T_{\text{CMB}}}\right]$$

Recombination

Photoionization

Exotic Injection

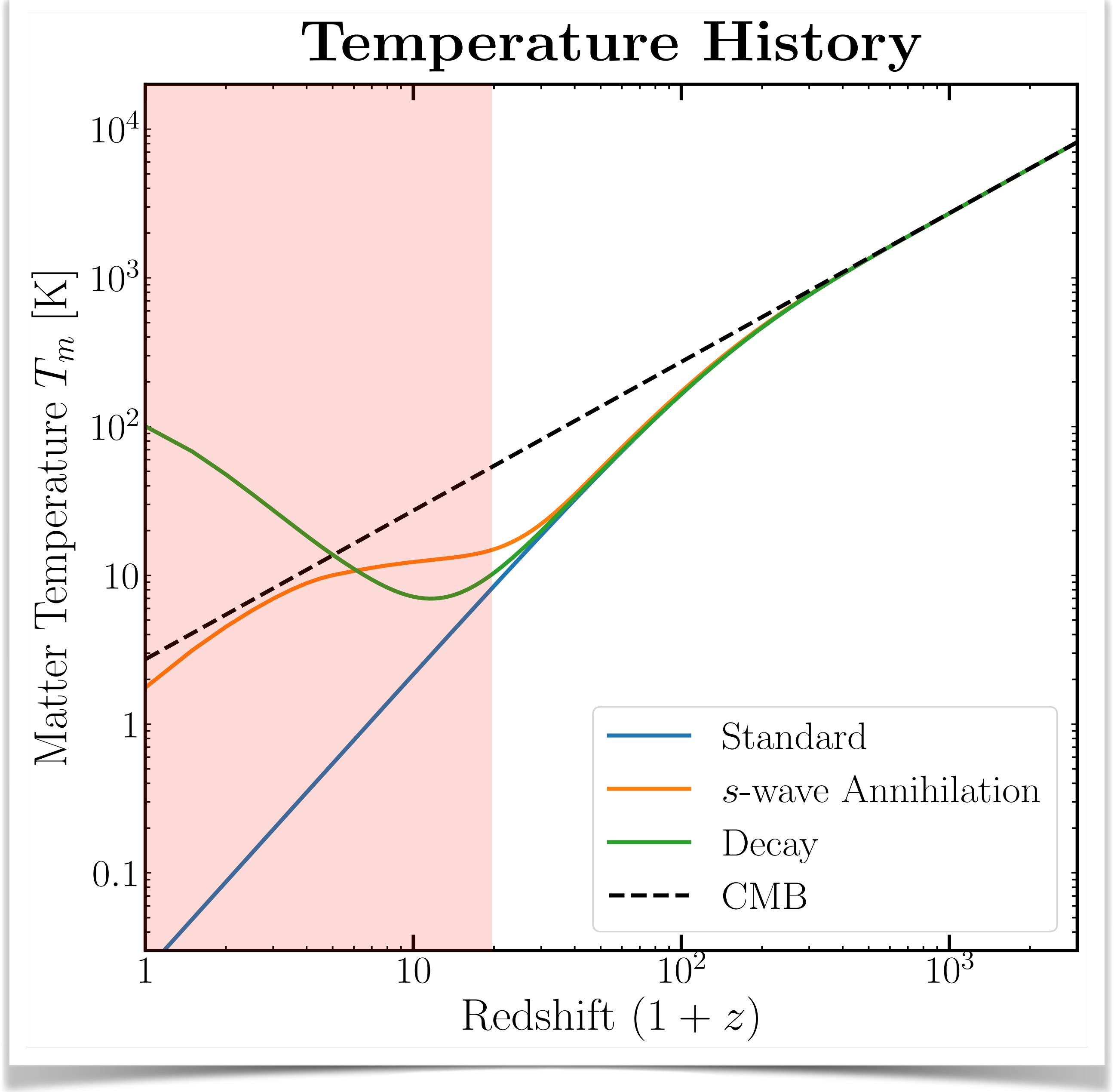
Matter Temperature

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \frac{2f_{\rm heat}(z, \mathbf{x_e})}{3(1 + f_{\rm He} + x_e)n_{\rm H}}\left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

Cooling from Expansion

Heating from CMB

Exotic heating



Ionization

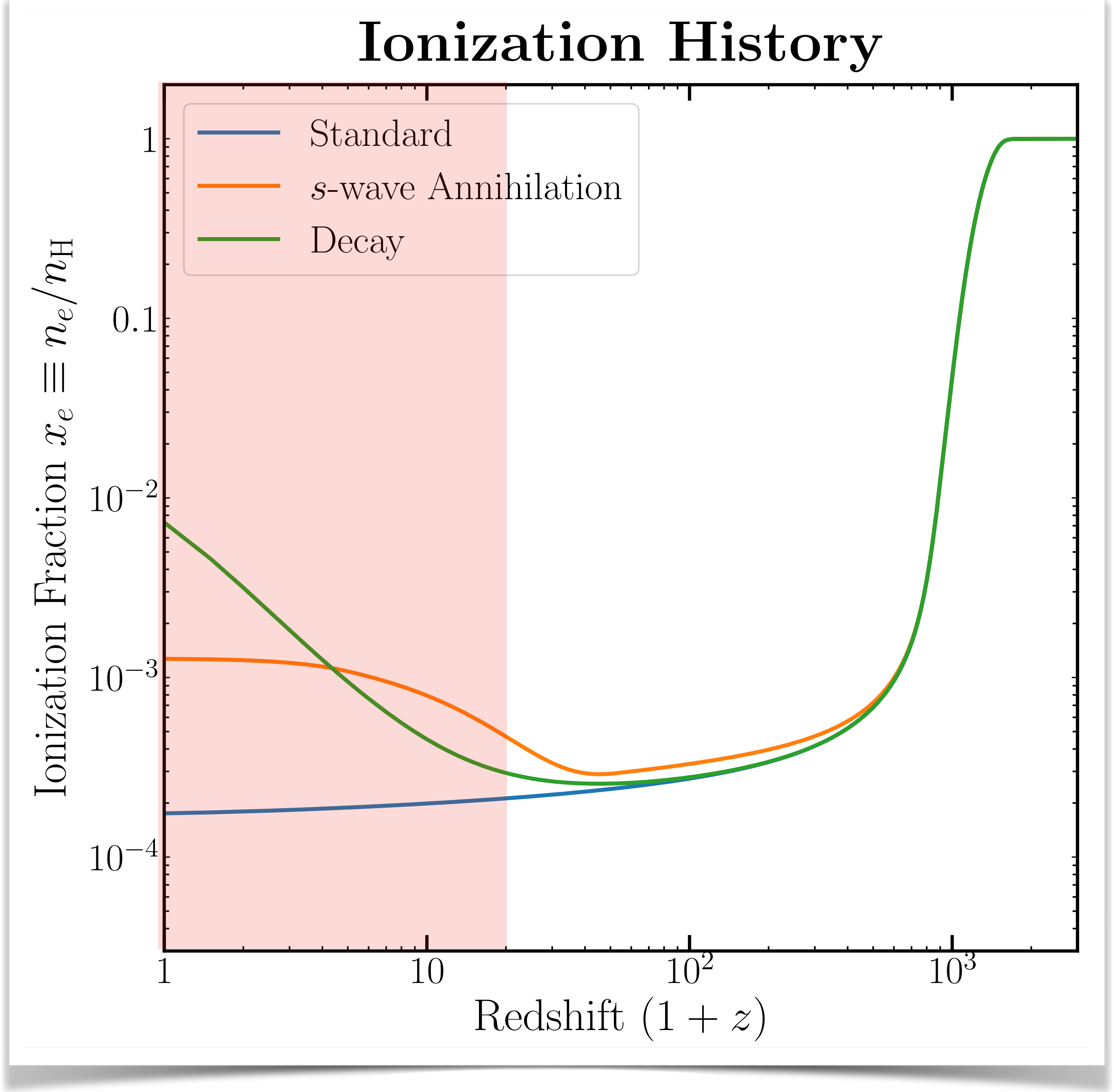
$$\dot{x}_e = -\mathscr{C}\left[n_H x_e^2 \alpha_B - 4(1 - x_e)\beta_B e^{-E_{21}/T_{\rm CMB}}\right] + \left[\frac{f_{\rm ion}(z, \mathbf{x_e})}{\mathscr{R} n_{\rm H}} + \frac{(1-\mathscr{C})f_{\rm exc}(z, \mathbf{x_e})}{0.75\mathscr{R} n_{\rm H}}\right]\left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

Recombination

Photoionization

Exotic ionization

Additional ionization from exotic excitation



Deposition Efficiency and Ionization

Matter Temperature

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \frac{f_{\rm heat}(z, \mathbf{x_e})}{3(1 + f_{\rm He} + x_e)n_{\rm H}} \left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

Cooling from Expans

Heating from CMB

exotic heating

l ionization

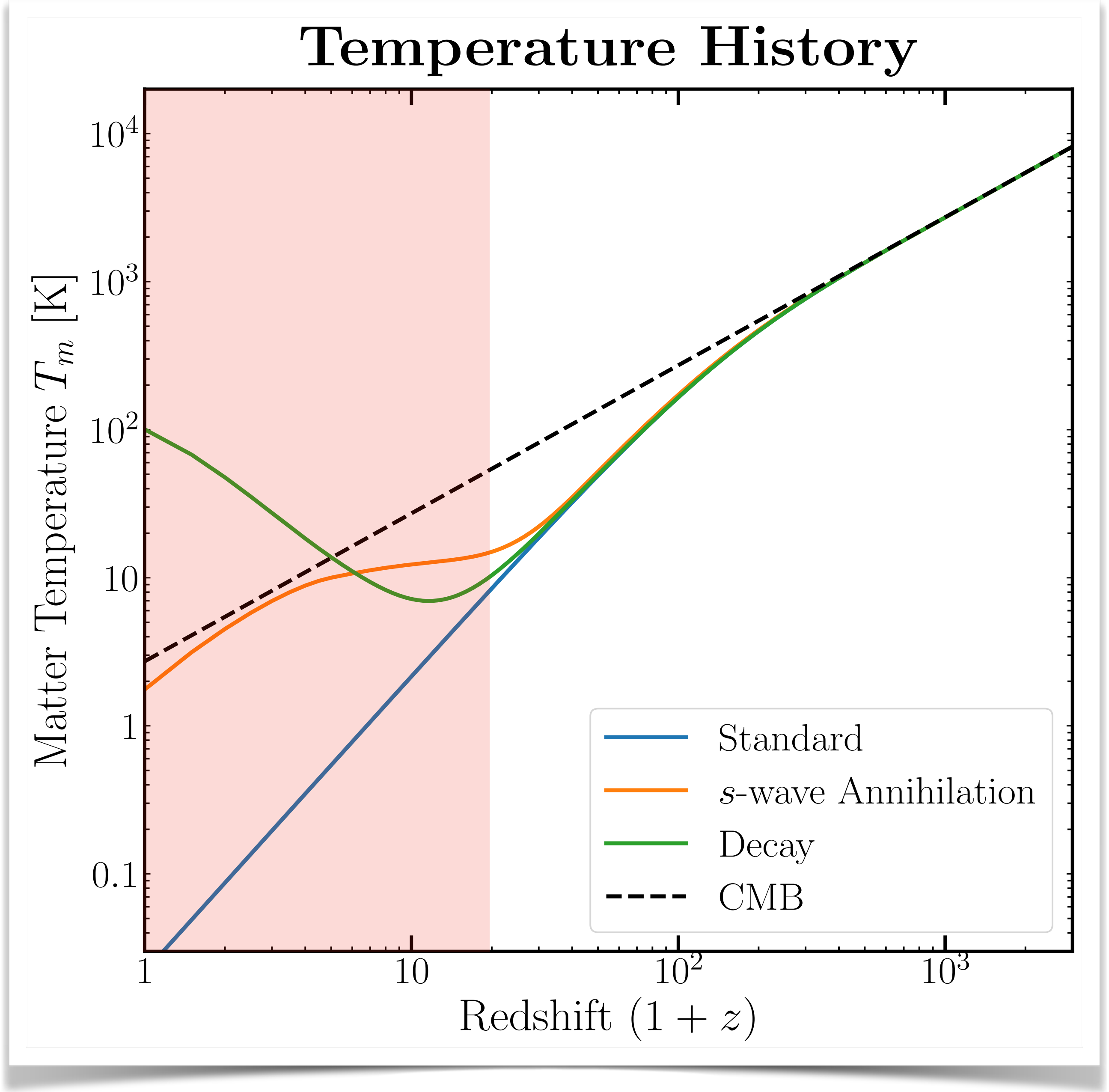
excitation

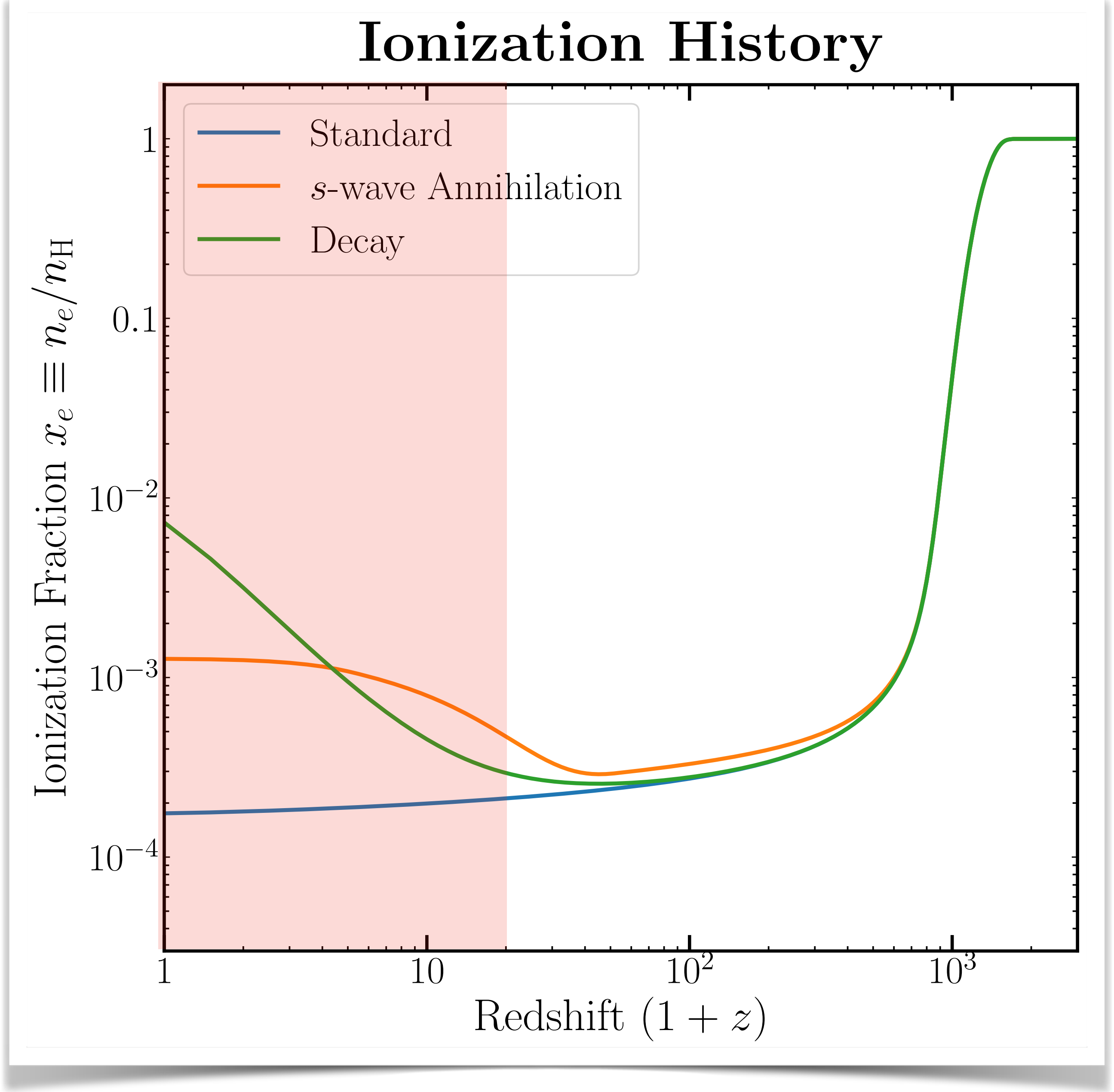
Ionization

$$\dot{x}_e = -\mathscr{C}\left[n_H x_e^2 \alpha_B - 4(1 - x_e)\beta_B e^{-E_{21}/T_{\rm CMB}}\right] + \left[\frac{f_{\rm ion}(z, \mathbf{x_e})}{\mathcal{R} n_{\rm H}} + \frac{(1 - \mathscr{C}) f_{\rm exc}(z, \mathbf{x_e})}{0.75 \mathcal{R} n_{\rm H}}\right] \left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

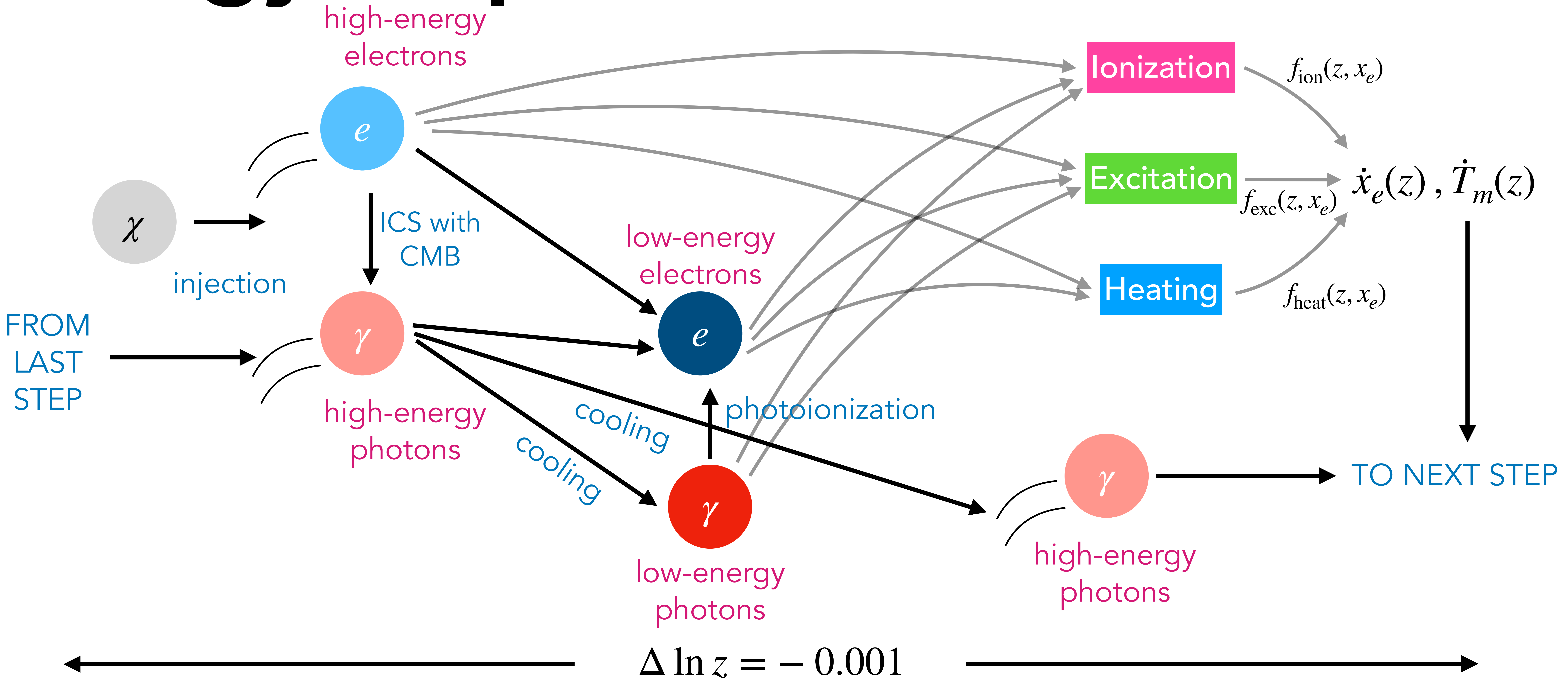
Recombination

Photoionization





Energy Deposition



Transfer Functions

Obtained by interpolating over a large grid of precomputed transfer functions

Dark Matter Effects

Matter Temperature

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\text{CMB}} - T_m) + \frac{2f_{\text{heat}}(z, \mathbf{x_e})}{3(1 + f_{\text{He}} + x_e)n_{\text{H}}} \left(\frac{dE}{dV\,dt} \right)_{\text{inj}}$$ + reionization terms

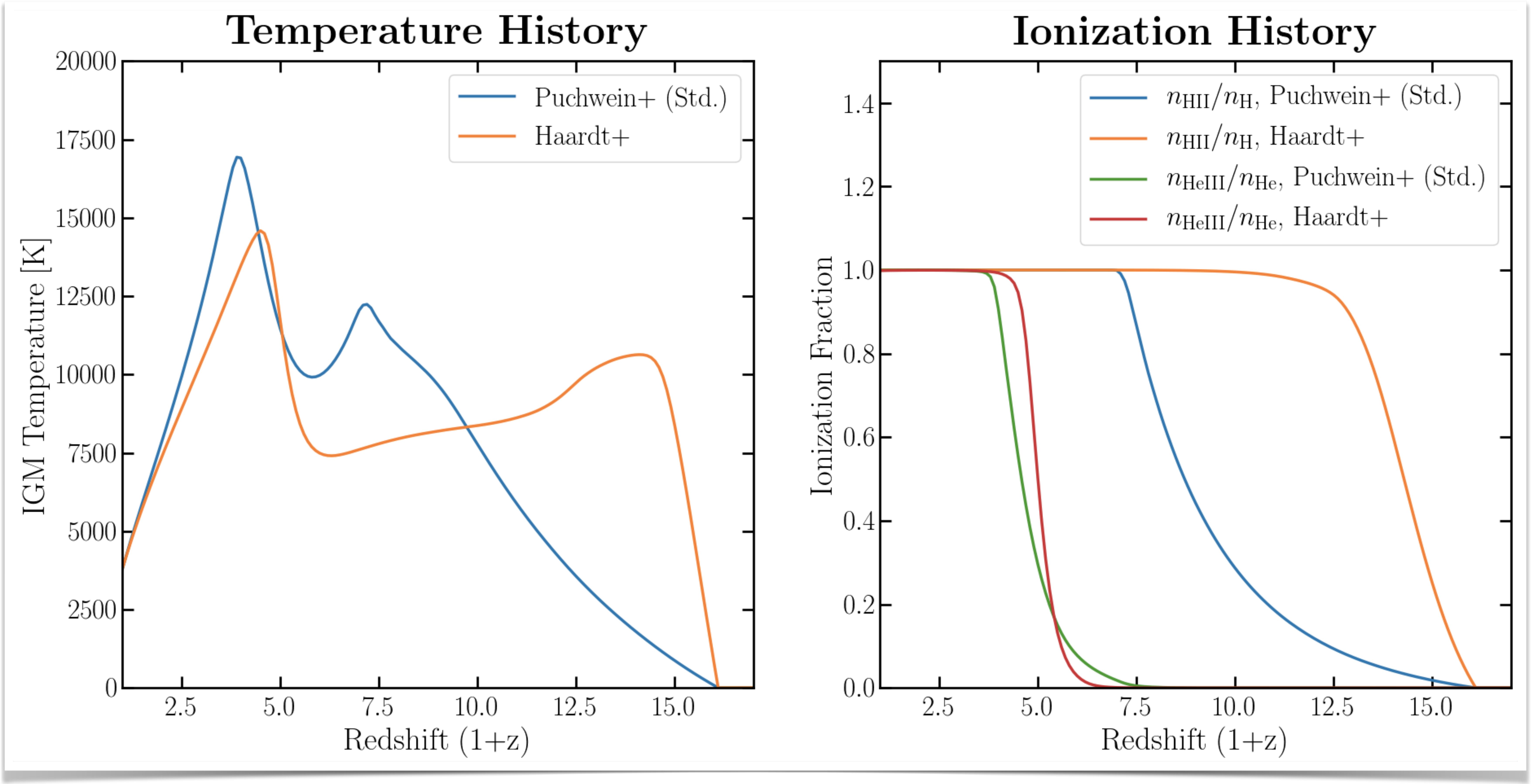
Ionization

$$\dot{x}_e = -\mathscr{C} \left[n_H x_e^2 \alpha_B - 4(1 - x_e)\beta_B e^{-E_{21}/T_{\text{CMB}}} \right] + \left[\frac{f_{\text{ion}}(z, \mathbf{x_e})}{\mathscr{R} n_{\text{H}}} + \frac{(1 - \mathscr{C}) f_{\text{exc}}(z, \mathbf{x_e})}{0.75 \mathscr{R} n_{\text{H}}} \right] \left(\frac{dE}{dV\,dt} \right)_{\text{inj}}$$

+ reionization terms

Accurate calculation of $f(z, \mathbf{x_e})$ allows **self-consistent treatment** of **exotic energy injection and reionization**.

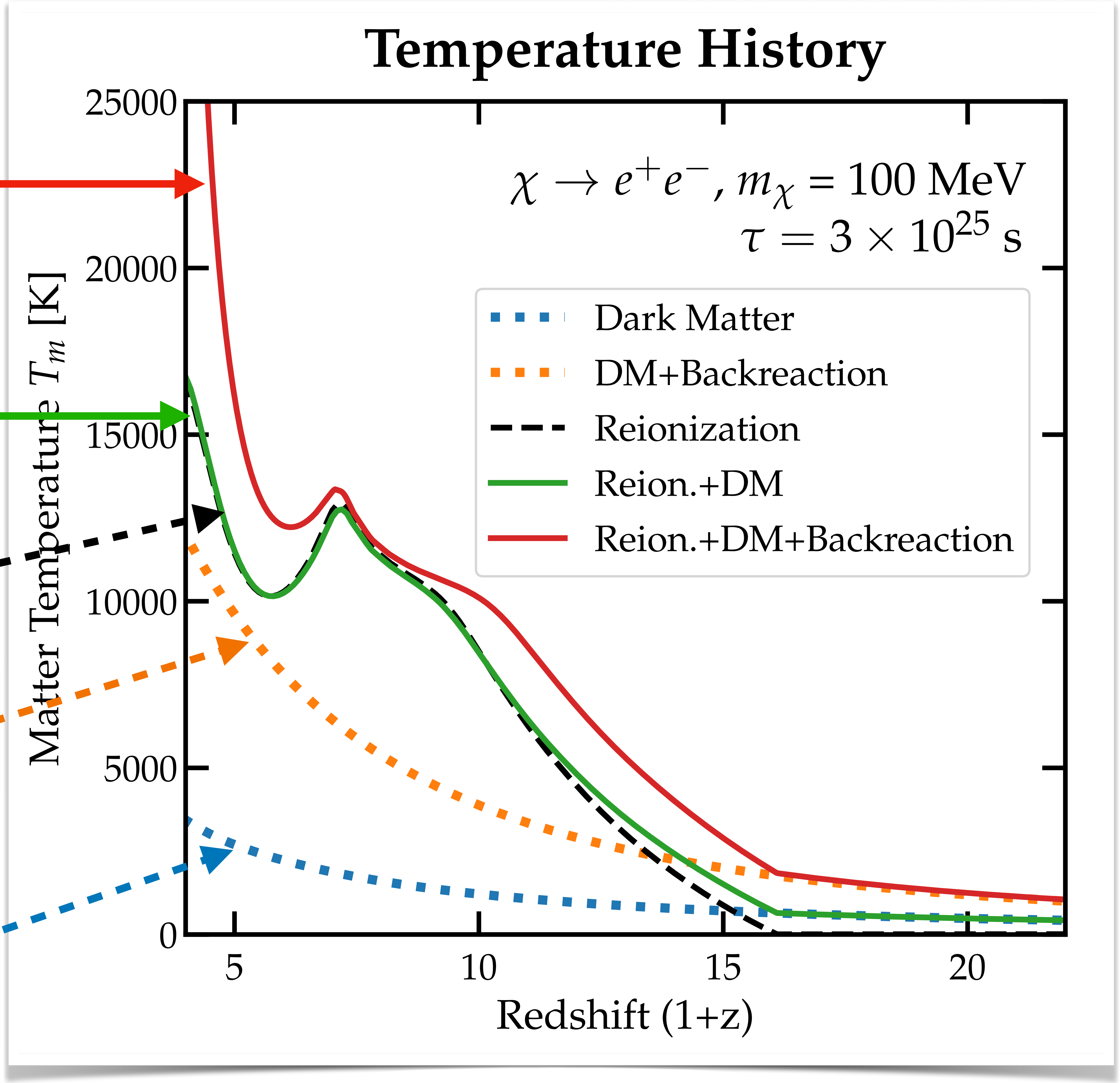
Reionization



Easily include **photoionization**, **photoheating** and **atomic processes** to model reionization.

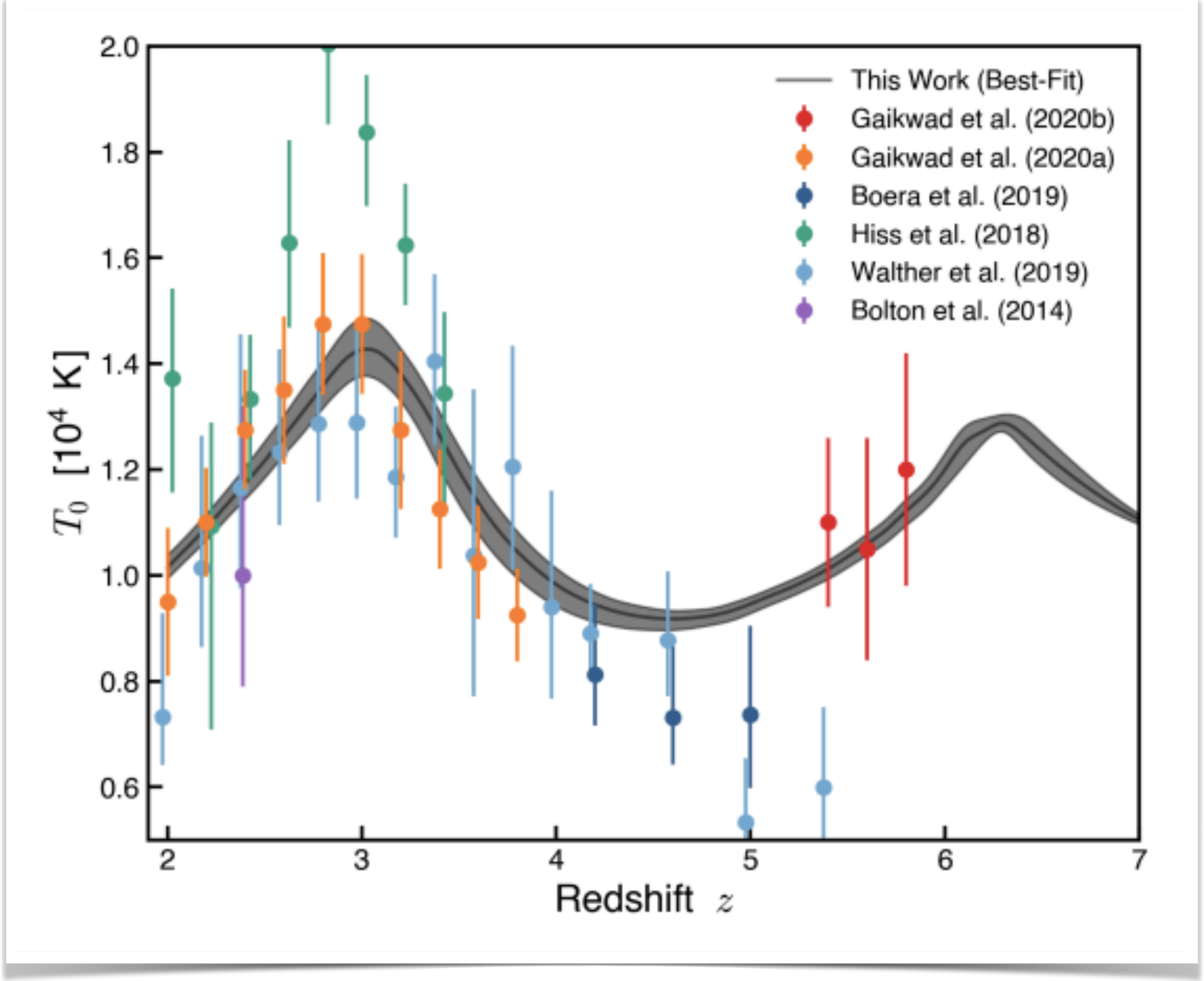
Reionization + Dark Matter

DM Effects	Using DarkHistory	Reionization Effects
✓	✓	✓
✓	✗	✓
✗	✗	✓
✓	✓	✗
✓	✗	✗



Intergalactic Medium Temperature

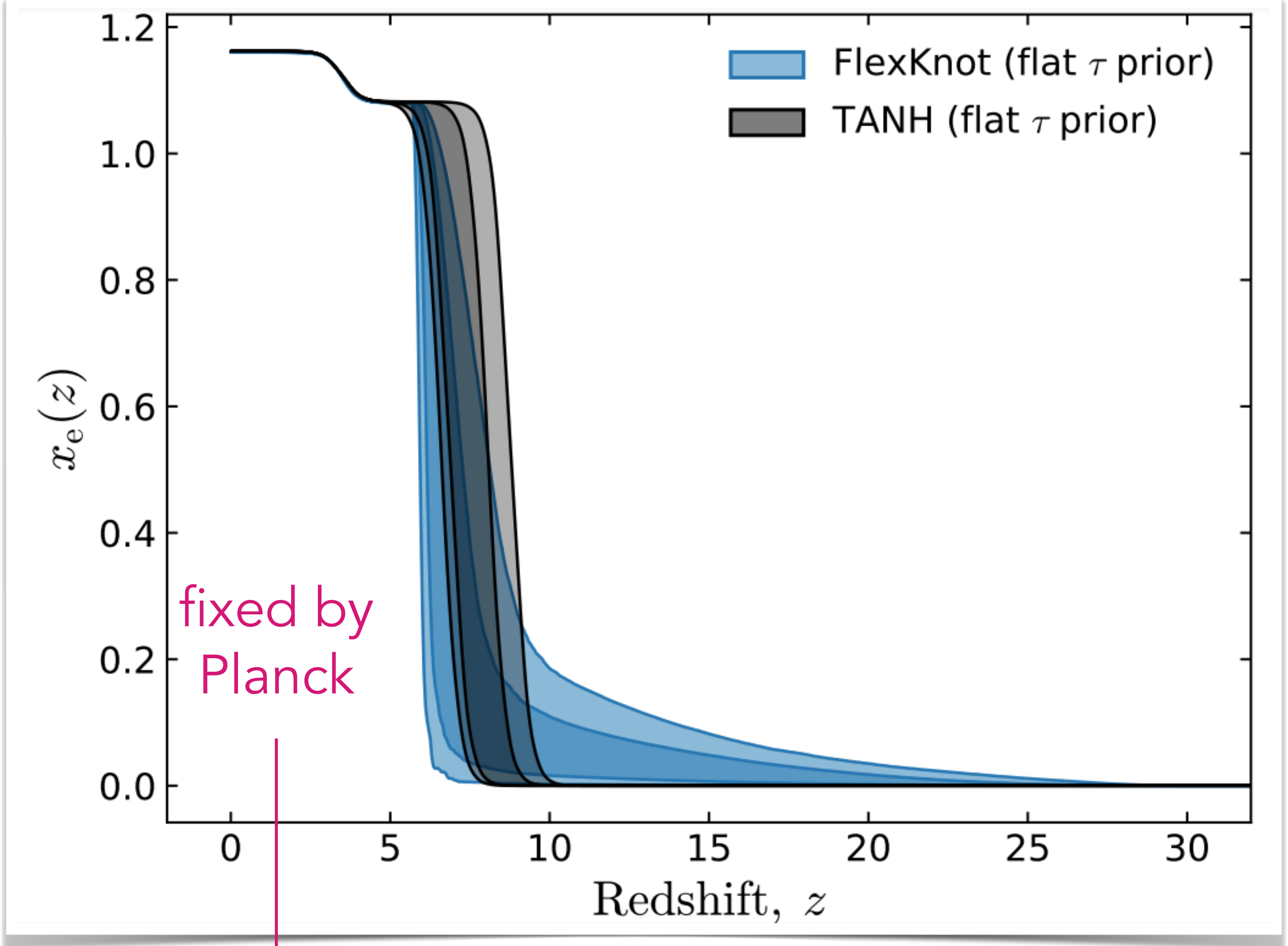
Villasenor+ 2111.00019



Intergalactic medium temperature measured by **Lyman-α forest** observations can constrain DM processes.

Ionization History

Planck Collab. 1807.06209

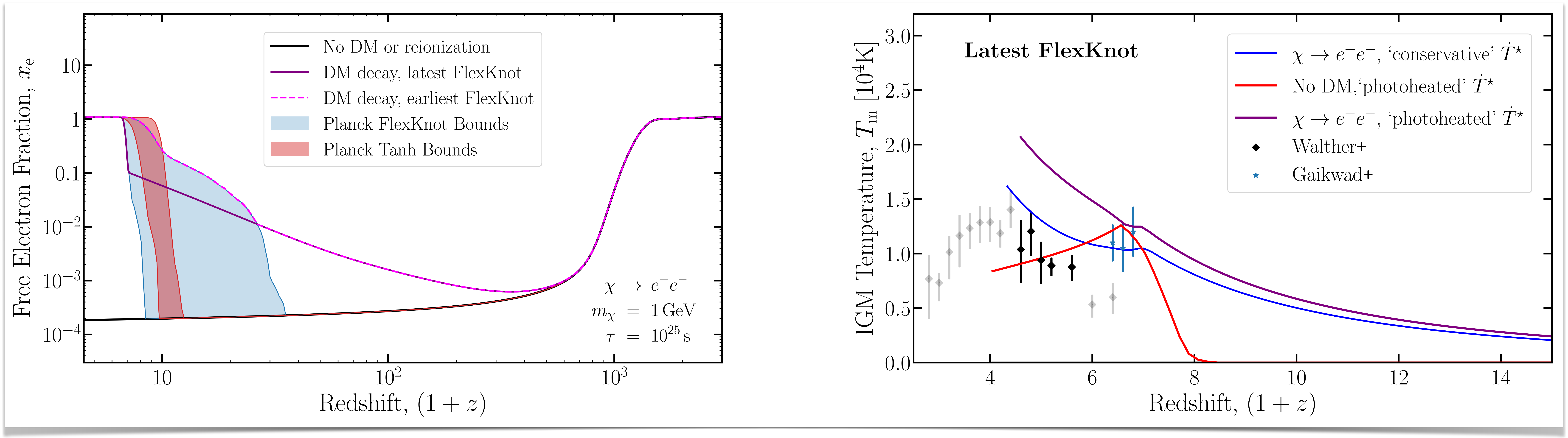


1. Pick a history within Planck 95% containment, call it $\dot{x}_e^{\rm Pl}$.
2. Given this ionization history, we can compute $f_c(z, x_e)$.
3. For a given DM model, DM energy injection makes up $\dot{x}_e^{\rm DM}$.
4. Reionization responsible for the rest through photoionization, $\dot{x}_e^\star$.

$$\dot{x}_e^{\rm Pl} = -\mathscr{C}\left[n_H x_e^2 \alpha_B - 4(1-x_e)\beta_B e^{-E_{21}/T_{\rm CMB}}\right] + \left[\frac{f_{\rm ion}(z,x_e)}{\mathscr{R} n_{\rm H}} + \frac{(1-\mathscr{C}) f_{\rm exc}(z,x_e)}{0.75 \mathscr{R} n_{\rm H}}\right]\left(\frac{dE}{dV\,dt}\right)_{\rm inj} + \dot{x}_e^\star$$

HL, W. Qin, Ridgway & Slatyer
2008.01084

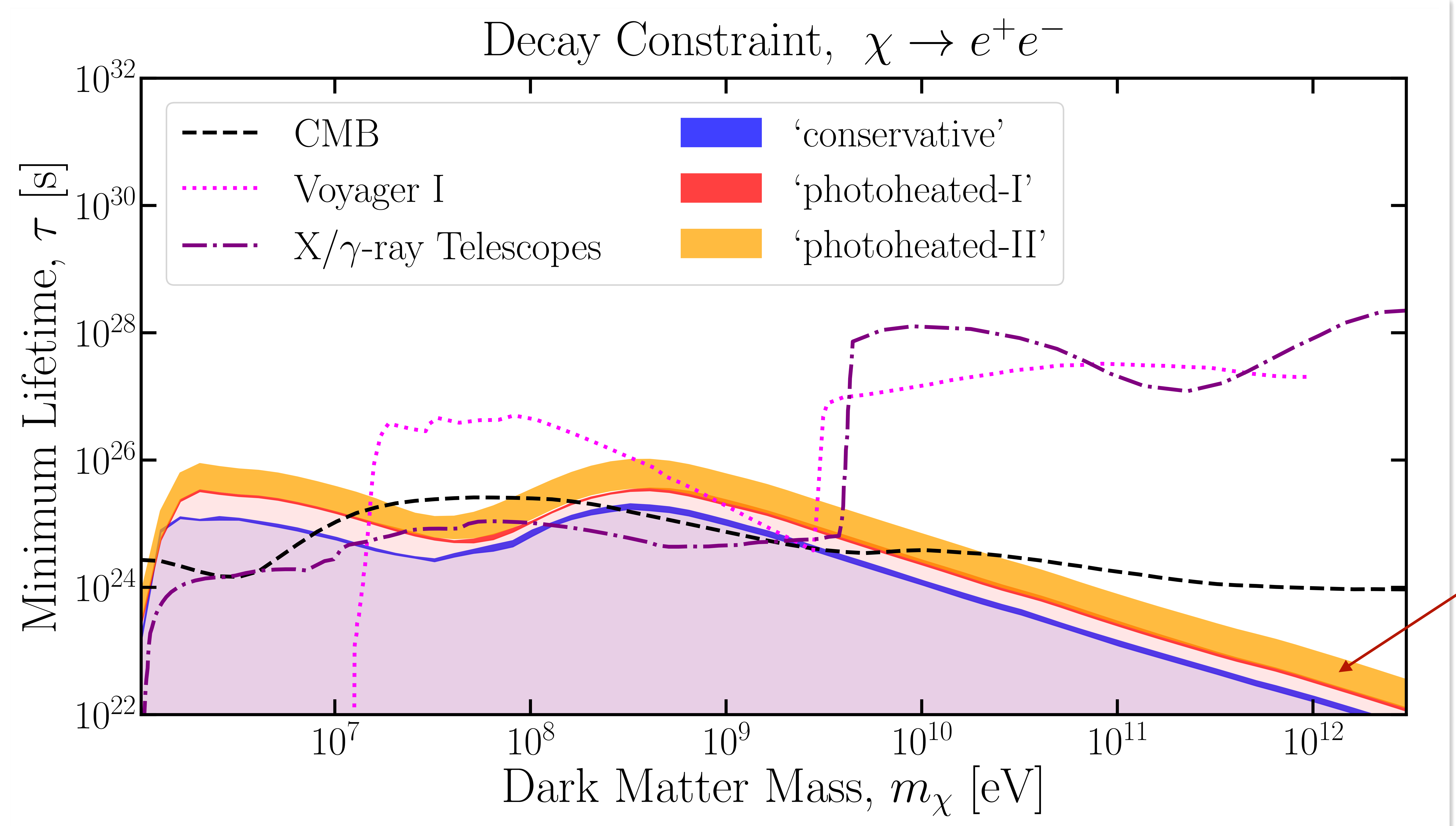
Dark Matter Constraints



Scan over ionization histories and photoionization rates. Adopt **different parametrizations** for photoheating **as a function of photoionization**, including **no photoheating**.

HL, W. Qin, Ridgway & Slatyer
2008.01084

Constraints — Decay



Band from scanning over different ionization histories

Competitive with other constraints for **dark matter decay** into e^+e^- pairs.

Other Uses

1. Spinning black holes and global 21cm signal, *Natwariya+ 2107.12358*

2. Primordial black holes constraints with 21-cm signal, X-ray heating and radio background, *Mittal+ 2107.02190*

3. Millicharged dark matter and 21-cm signal, ***HL****+ 1908.06986*

4. *more upcoming!*

Tidbit: **fast evaluation** of integrals over **Bose-Einstein** and **Fermi-Dirac distributions**.

DarkHistory

Open source code in **Python** for calculating **ionization** and **thermal histories** with **exotic energy injection**.

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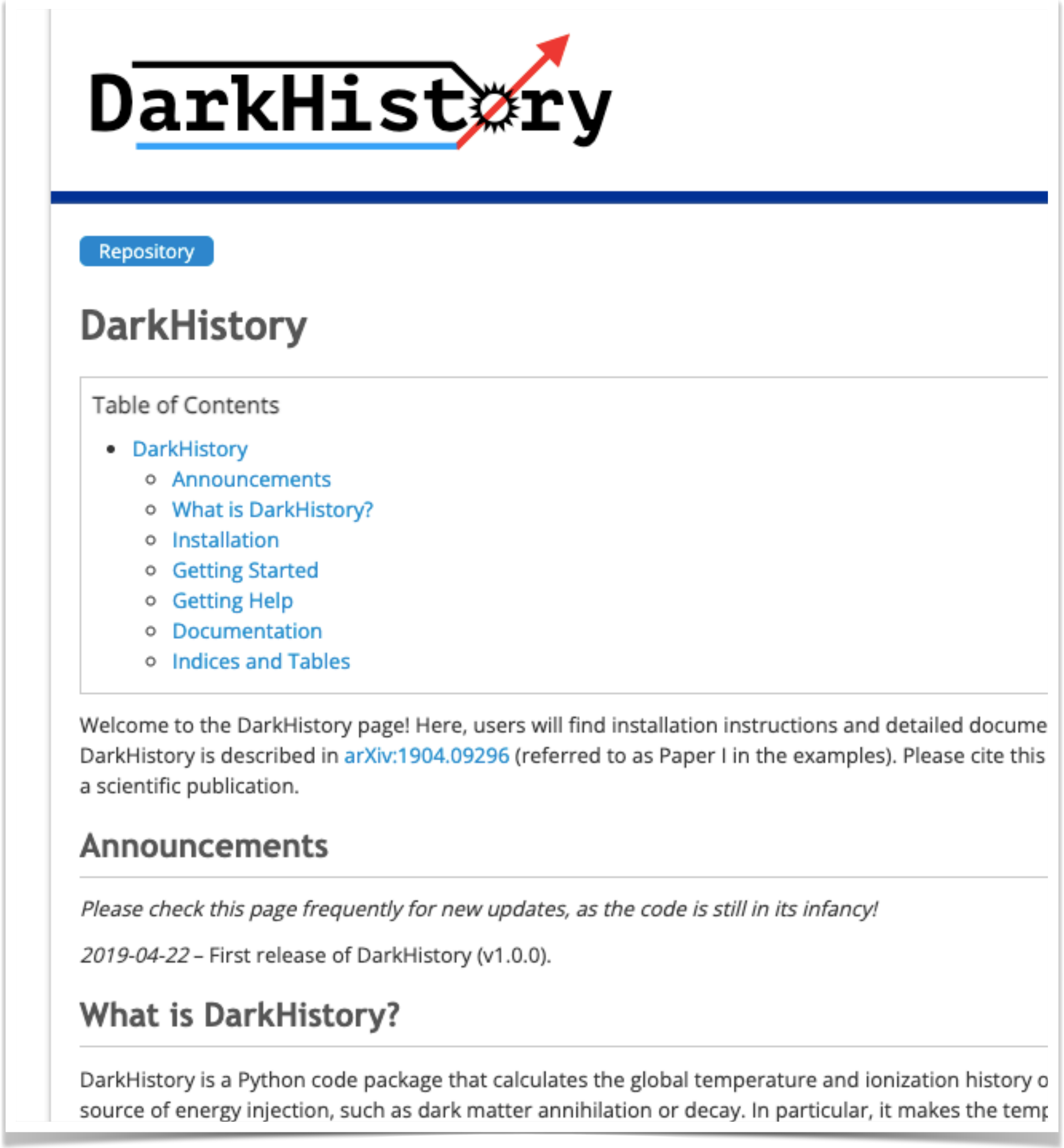
https://darkhistory.readthedocs.io/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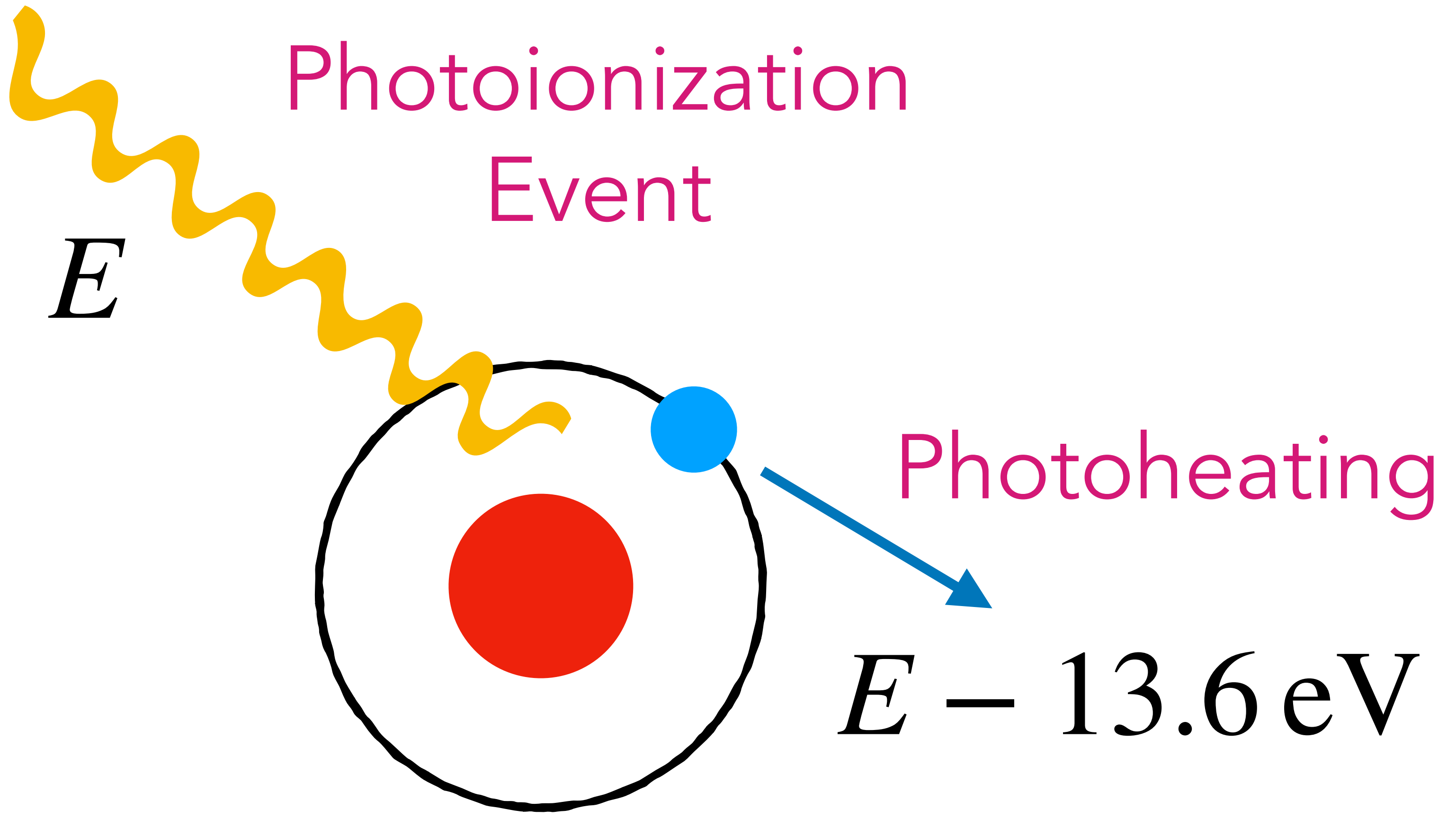
Backup Slides

Temperature History



Ionization History

$$\dot{x}_e^{\mathrm{Pl}} = -\mathscr{C}\left[n_H x_e^2 \alpha_B - 4(1-x_e)\beta_B e^{-E_{21}/T_{\mathrm{CMB}}}\right] + \left[\frac{f_{\mathrm{ion}}(z, x_e)}{\mathscr{R} n_{\mathrm{H}}} + \frac{(1-\mathscr{C}) f_{\mathrm{exc}}(z, x_e)}{0.75 \mathscr{R} n_{\mathrm{H}}}\right]\left(\frac{dE}{dV\,dt}\right)_{\mathrm{inj}} + \dot{x}_e^{\star}$$

Fixed by Planck

Fixed by DM Injection Rate

Photoionization

leads to

Temperature History

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\mathrm{CMB}} - T_m) + \dot{T}_{\mathrm{atom}} + \frac{2 f_{\mathrm{heat}}(z)}{3(1 + f_{\mathrm{He}} + x_e) n_{\mathrm{H}}}\left(\frac{dE}{dV\,dt}\right)_{\mathrm{inj}} + \dot{T}^{\star}$$

Expansion

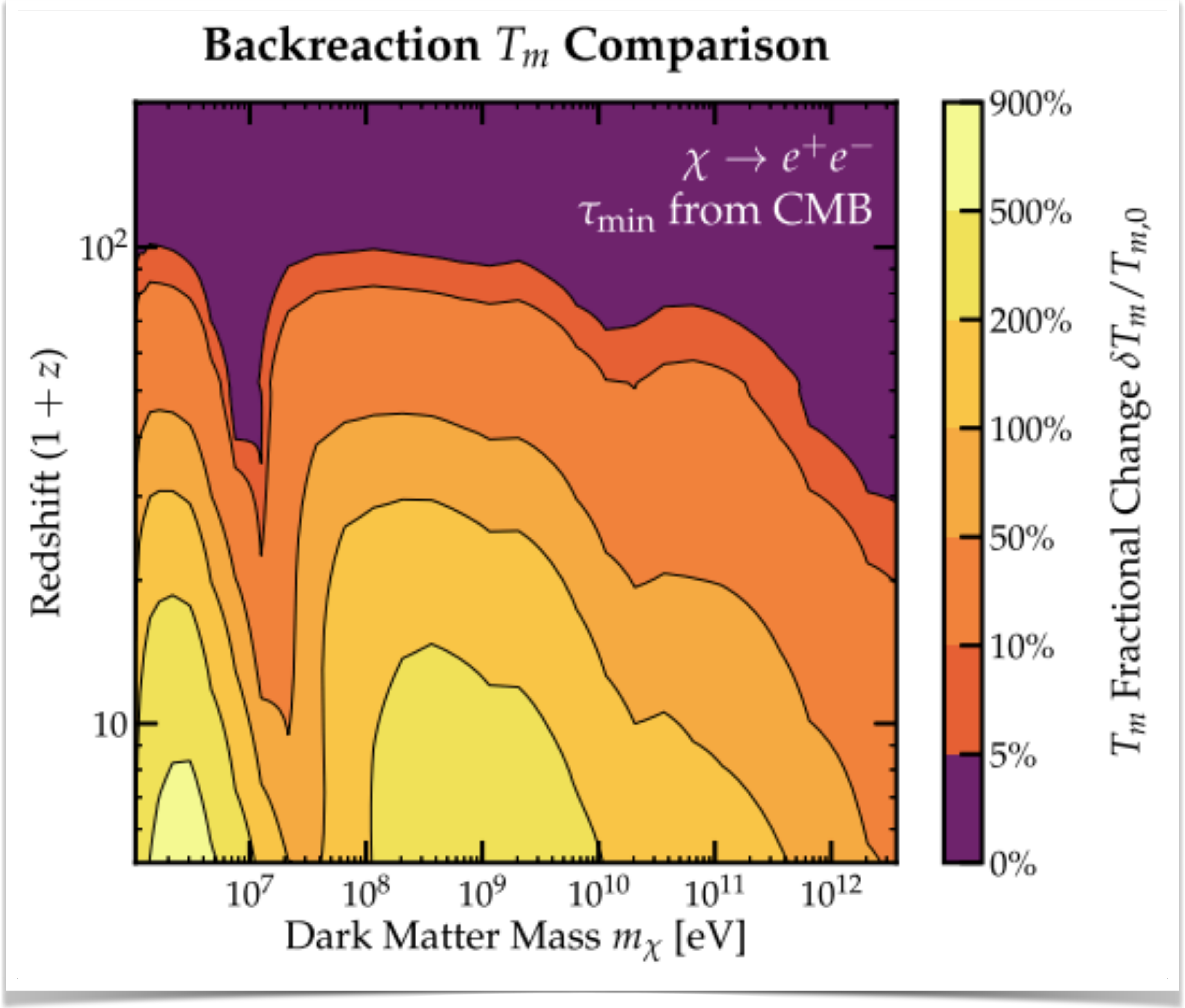
Compton with CMB

Atomic Cooling Processes

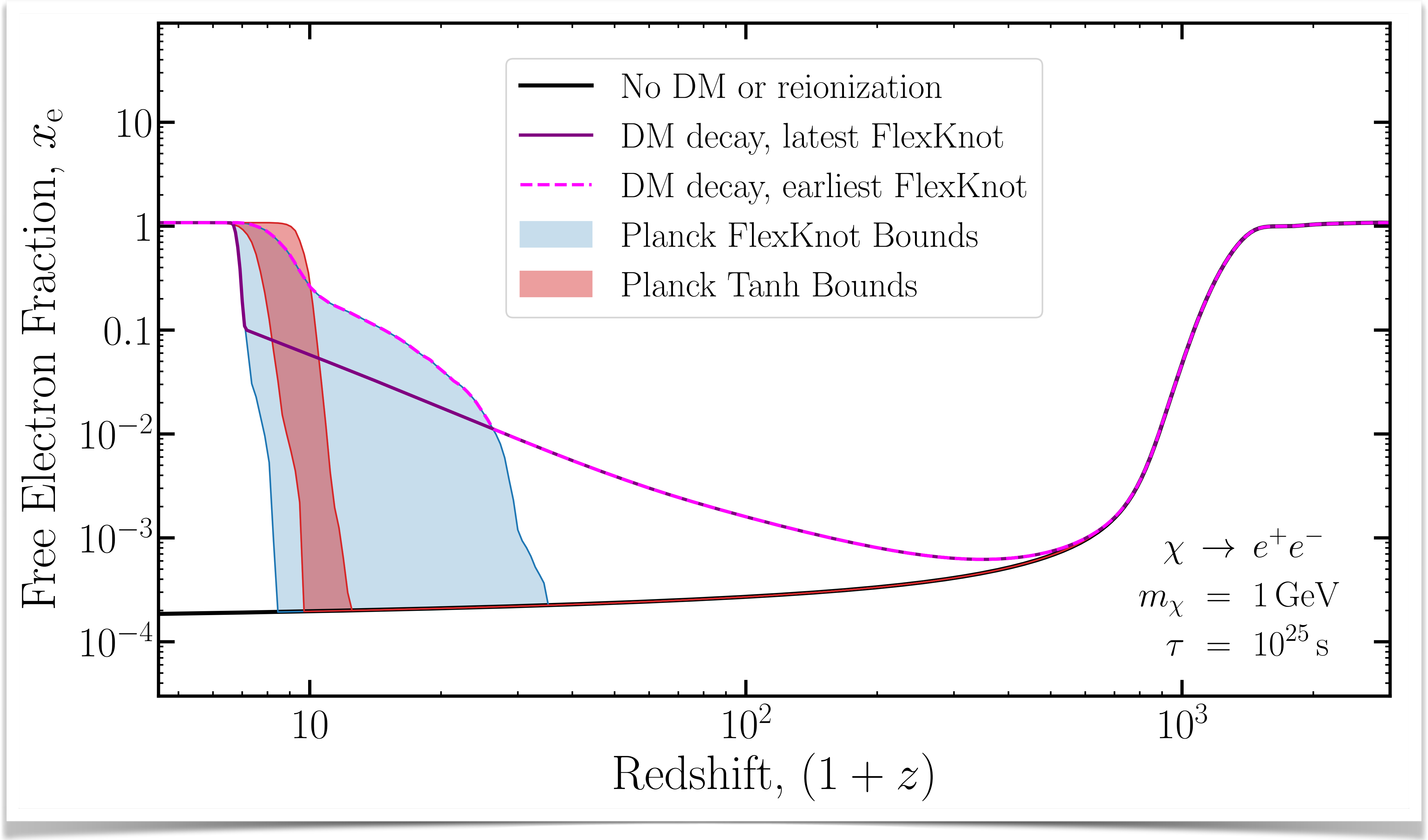
Fixed by DM Injection Rate

Photoheating

Change in Temperature due to Backreaction



Ionization History



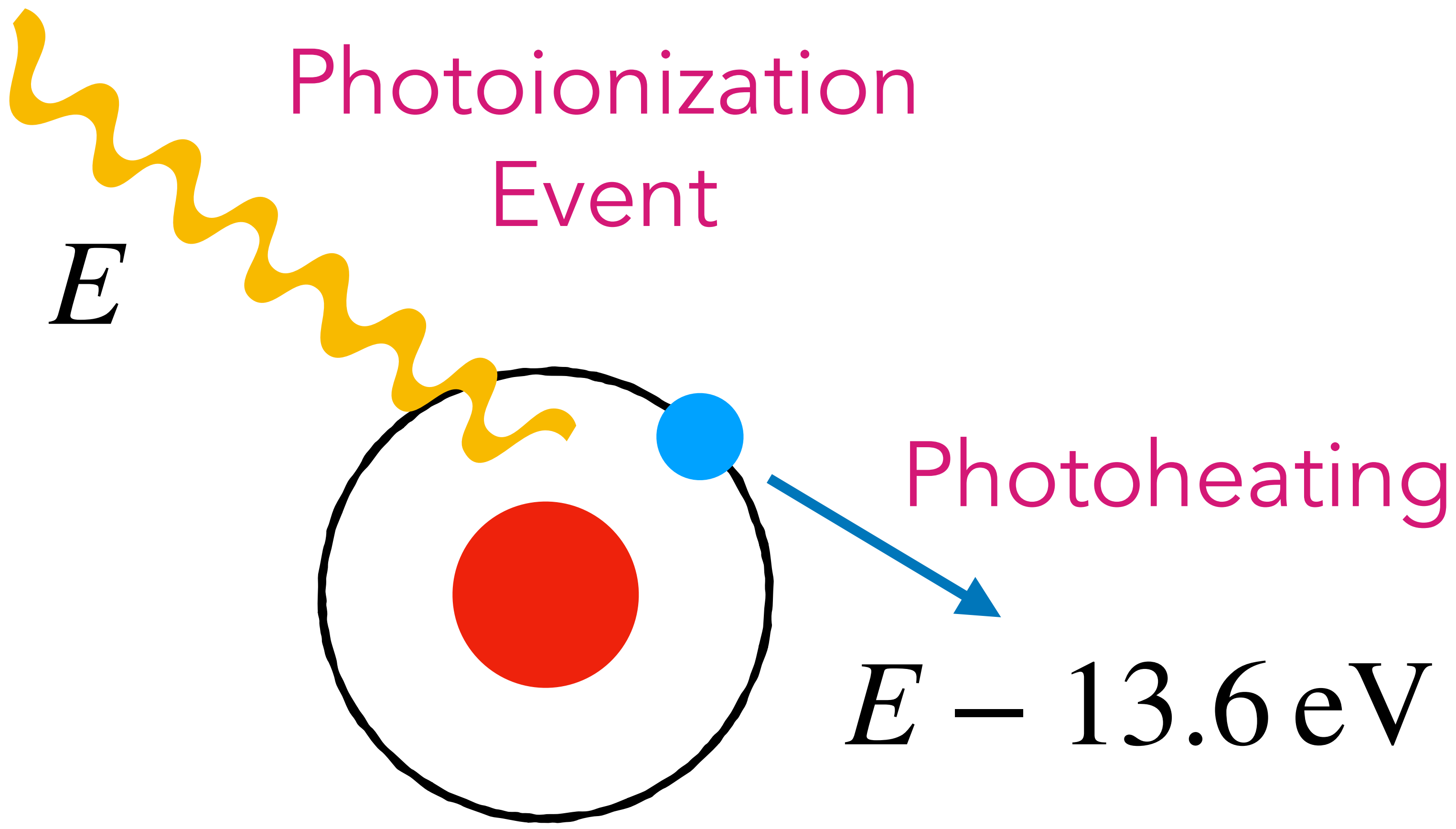
$$\dot{x}_e^{\mathrm{Pl}} = -\mathscr{C}\left[n_H x_e^2 \alpha_B - 4(1-x_e)\beta_B e^{-E_{21}/T_{\mathrm{CMB}}}\right] + \left[\frac{f_{\mathrm{ion}}(z,x_e)}{\mathscr{R} n_{\mathrm{H}}} + \frac{(1-\mathscr{C}) f_{\mathrm{exc}}(z,x_e)}{0.75 \mathscr{R} n_{\mathrm{H}}}\right]\left(\frac{dE}{dV\,dt}\right)_{\mathrm{inj}} + \dot{x}_e^{\star}$$

Temperature History

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \frac{2f_{\rm heat}(z)}{3(1+f_{\rm He}+x_e)n_{\rm H}}\left(\frac{dE}{dV\,dt}\right)_{\rm inj} + \dot{T}_{\rm atom} + \dot{T}^\star$$

Photoheating

Adiabatic cooling Compton heating DM heating Atomic cooling



$\dot{T}^\star = \dot{x}_e^\star \Delta T$. $\Delta T \sim 2.5 \times 10^4\,\mathrm{K}$ without DM is a good fit.

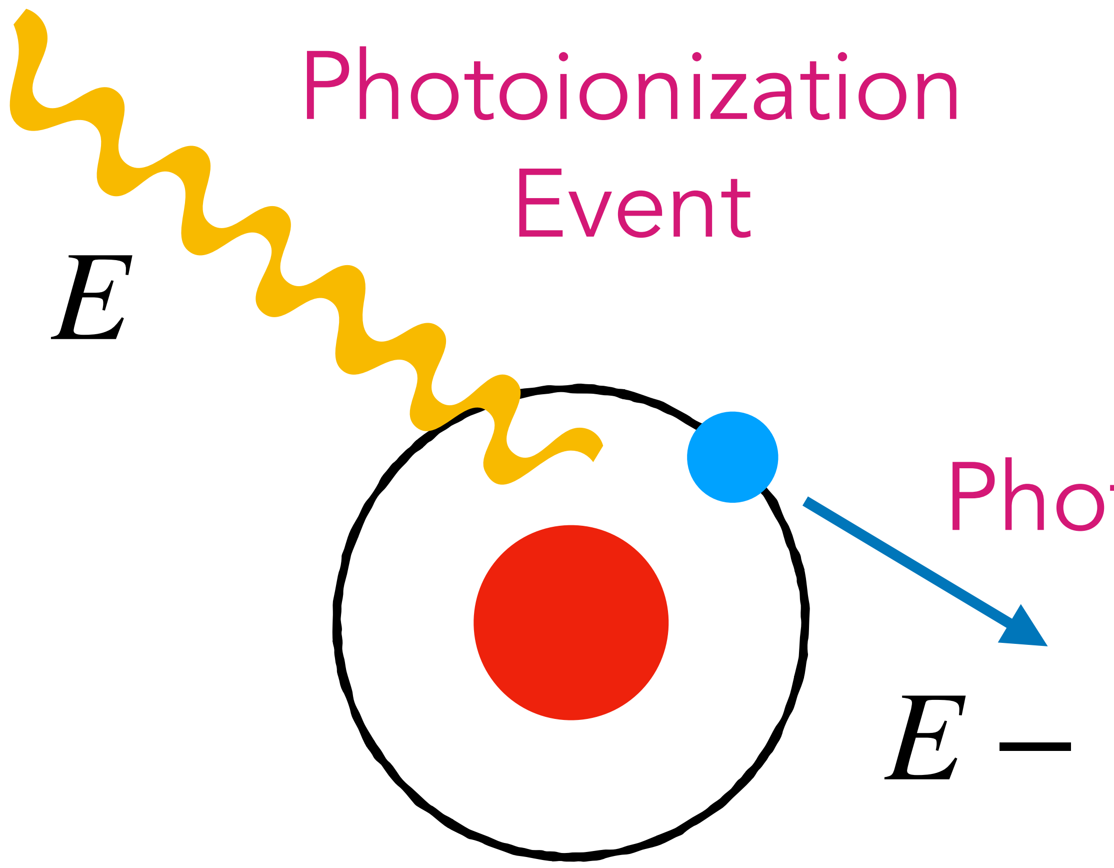
Oñorbe+ 1607.04218

Before reionization, we use a common, well-motivated **parametrization** photoheating.

Temperature History

$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \frac{2f_{\rm heat}(z)}{3(1+f_{\rm He}+x_e)n_{\rm H}}\left(\frac{dE}{dV\,dt}\right)_{\rm inj} + \dot{T}_{\rm atom} + \dot{T}^\star$$

Adiabatic cooling — Compton heating — DM heating — Atomic cooling — Photoheating



$$\dot{T}^\star = \frac{13.6\,\mathrm{eV} \times \alpha_A}{3(\gamma - 1 + \alpha_{\rm bk})}$$

Upton Sanderbeck+ 1511.05992

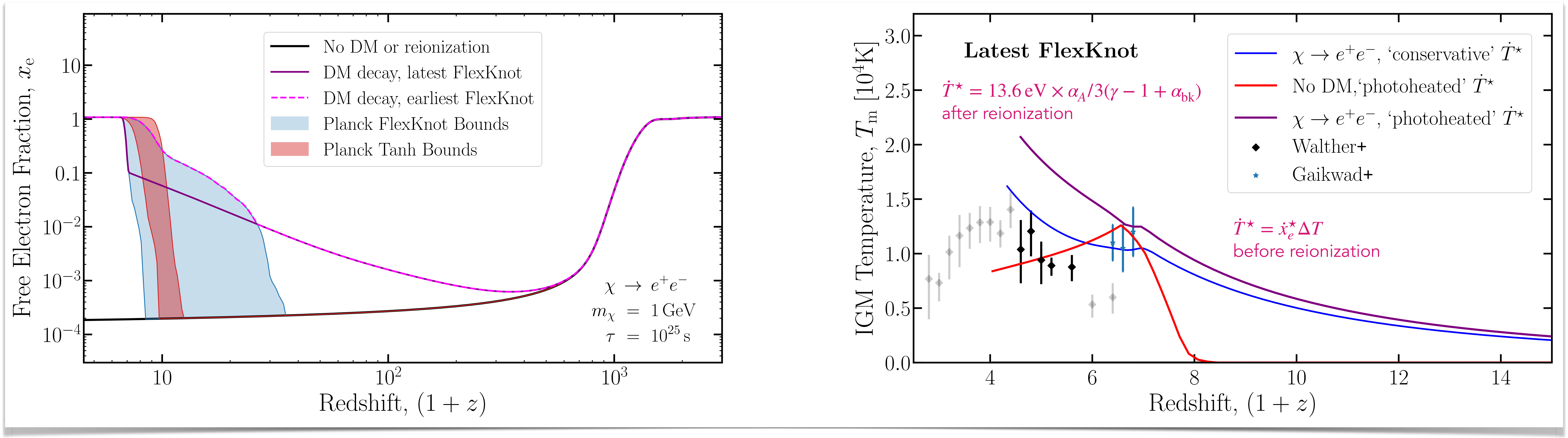
Case-A recombination coefficient (α_A)

$\sigma_{\rm PH} \propto \nu^{-\gamma}$

Spectral index near ionization threshold, $J_\nu \propto \nu^{-\alpha_{\rm bk}}$

After reionization, simple relation between **UV spectrum at threshold** and **temperature evolution**.

Histories



For each DM model (mass, injection parameter), do a **goodness-of-fit** test, marginalizing over ΔT, α_{bk} for "photoheated" cases.

Statistical Test

Specifically, our test statistic only penalizes DM models that overheat the IGM relative to the data, which accounts for the fact that any non-trivial photoheating model would only result in less agreement with the data, whereas DM models that underheat the IGM could be brought into agreement with the data given a specific photoheating model. We define the following test statistic for the ith IGM temperature bin:

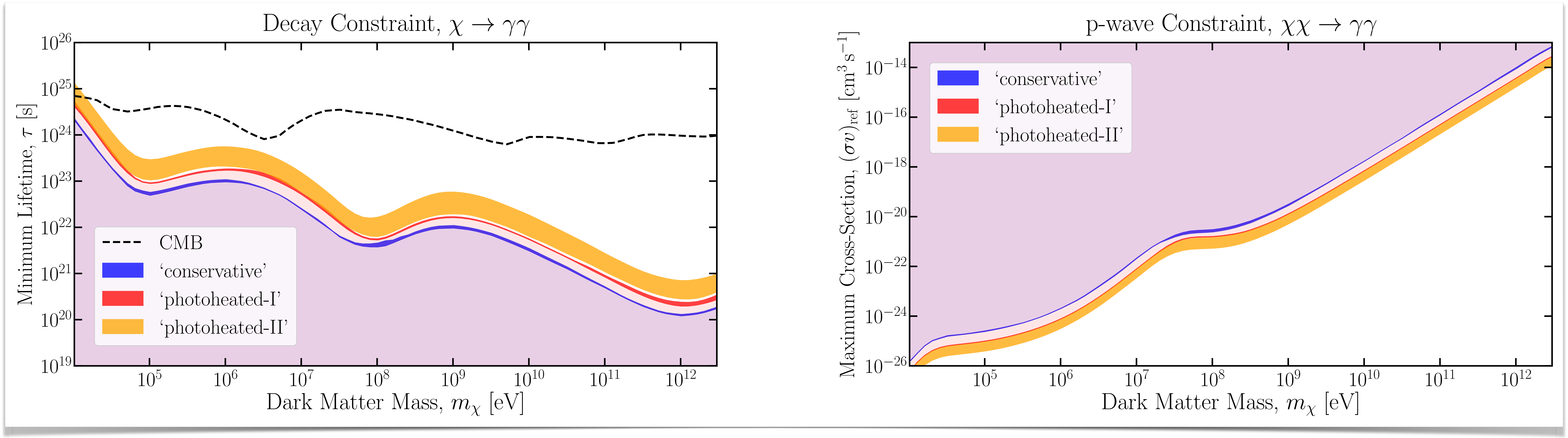
$$\mathrm{TS}_i = \begin{cases} 0\,, & T_{i,\mathrm{pred}} < T_{i,\mathrm{data}}\,, \\ \left(\dfrac{T_{i,\mathrm{pred}} - T_{i,\mathrm{data}}}{\sigma_{i,\mathrm{data}}}\right)^2\,, & T_{i,\mathrm{pred}} \geq T_{i,\mathrm{data}}\,, \end{cases} \quad (5)$$

where $T_{i,\mathrm{data}}$ is the fiducial IGM temperature measurement, $T_{i,\mathrm{pred}}$ is the predicted IGM temperature given a DM model and photoheating prescription, and $\sigma_{i,\mathrm{data}}$ is the 1σ upper error bar from the fiducial IGM temperature data. We then construct a global test statistic for all of the bins, simply given by $\mathrm{TS} = \sum_i \mathrm{TS}_i$. Assuming the data points $\{T_{i,\mathrm{data}}\}$ are each independent, Gaussian random variables with standard deviation given by $\sigma_{i,\mathrm{data}}$, the probability density function of TS given some model $\{T_{i,\mathrm{pred}}\}$ is given by

$$f(\mathrm{TS}|\{T_{i,\mathrm{pred}}\}) = \frac{1}{2^N} \sum_{n=0}^{N} \frac{N!}{n!(N-n)!} f_{\chi^2}(\mathrm{TS}; n)\,. \quad (6)$$

N is the total number of temperature bins and $f_{\chi^2}(x; n)$ is the χ^2-distribution with argument x and number of degrees-of-freedom n, where the $n = 0$ case is defined to

Photons



Decay Constraint, $\chi \to \gamma\gamma$
Minimum Lifetime, τ [s]
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
10^{26}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
Dark Matter Mass, m_χ [eV]
CMB
'conservative'
'photoheated-I'
'photoheated-II'
p-wave Constraint, $\chi\chi \to \gamma\gamma$
Maximum Cross-Section, $(\sigma v)_{\text{ref}}$ [cm^{3}s^{-1}]
10^{-26}
10^{-24}
10^{-22}
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
Dark Matter Mass, m_χ [eV]
'conservative'
'photoheated-I'
'photoheated-II'

Muons and Pions