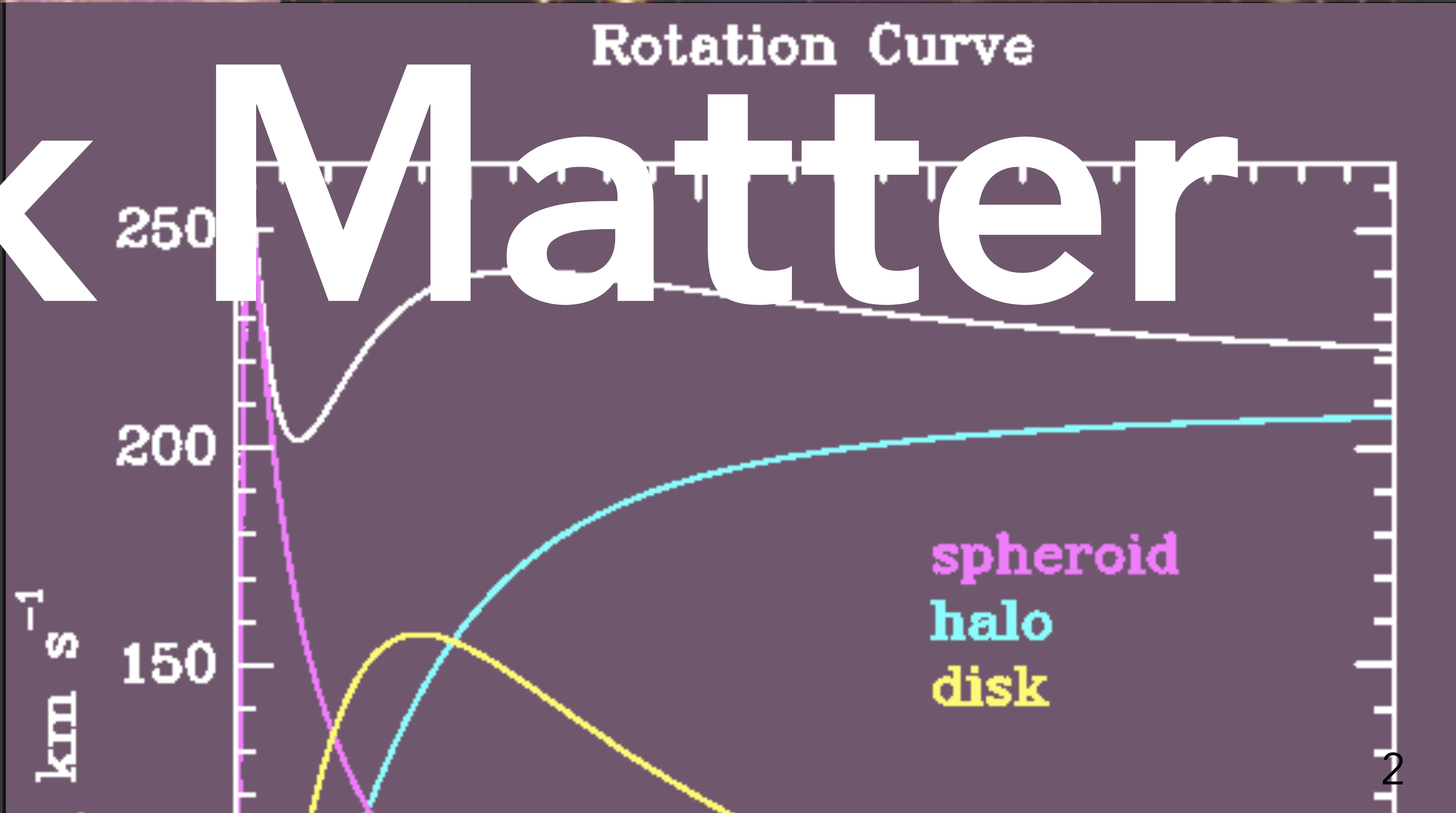
Cosmological Probes of Dark Matter Energy Deposition

Hongwan Liu

Lots of Evidence for Dark Matter



… but what is it?

image credit: Sandbox Studio, Chicago

Can we be agnostic, and still learn something about DM?

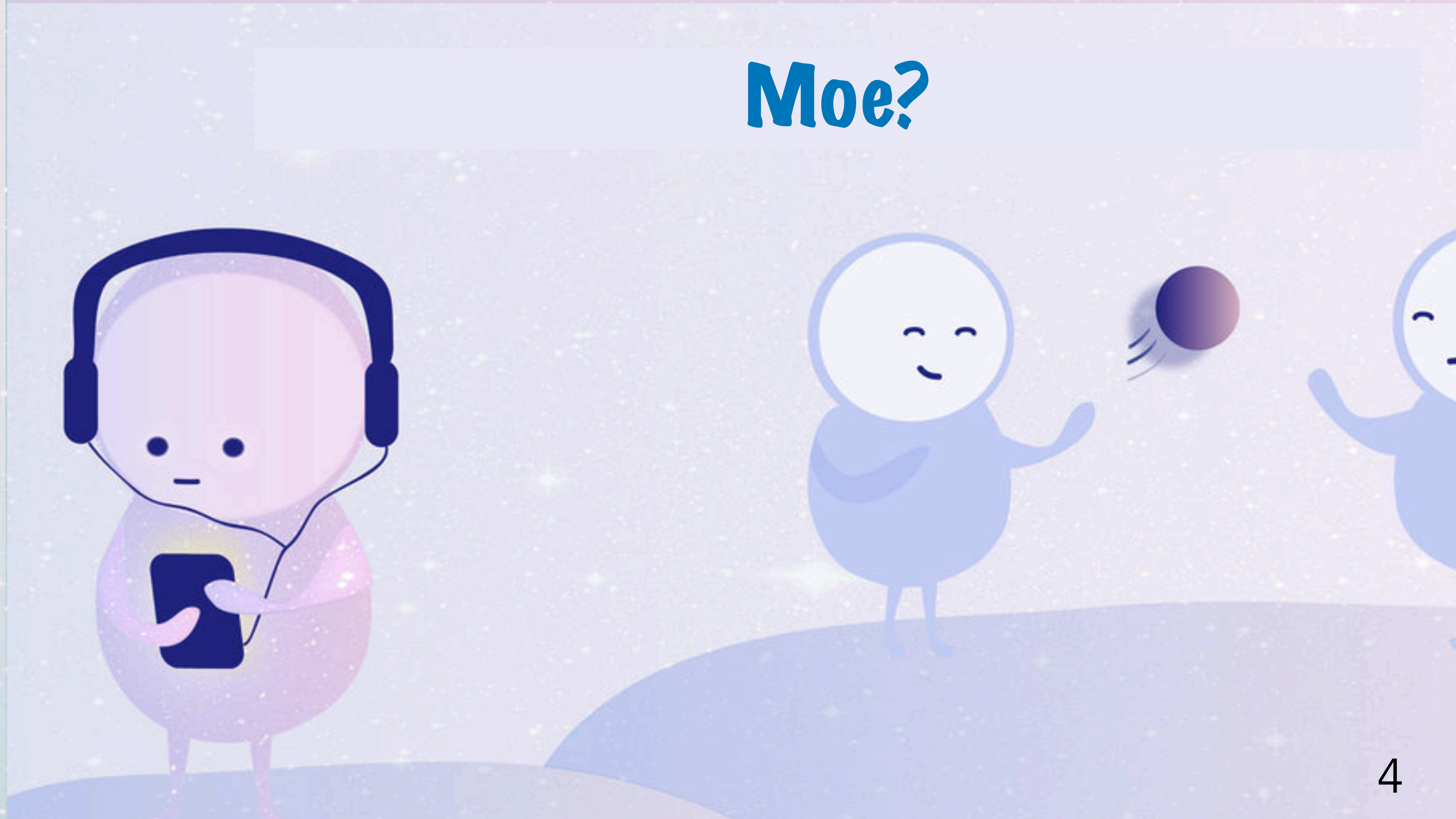
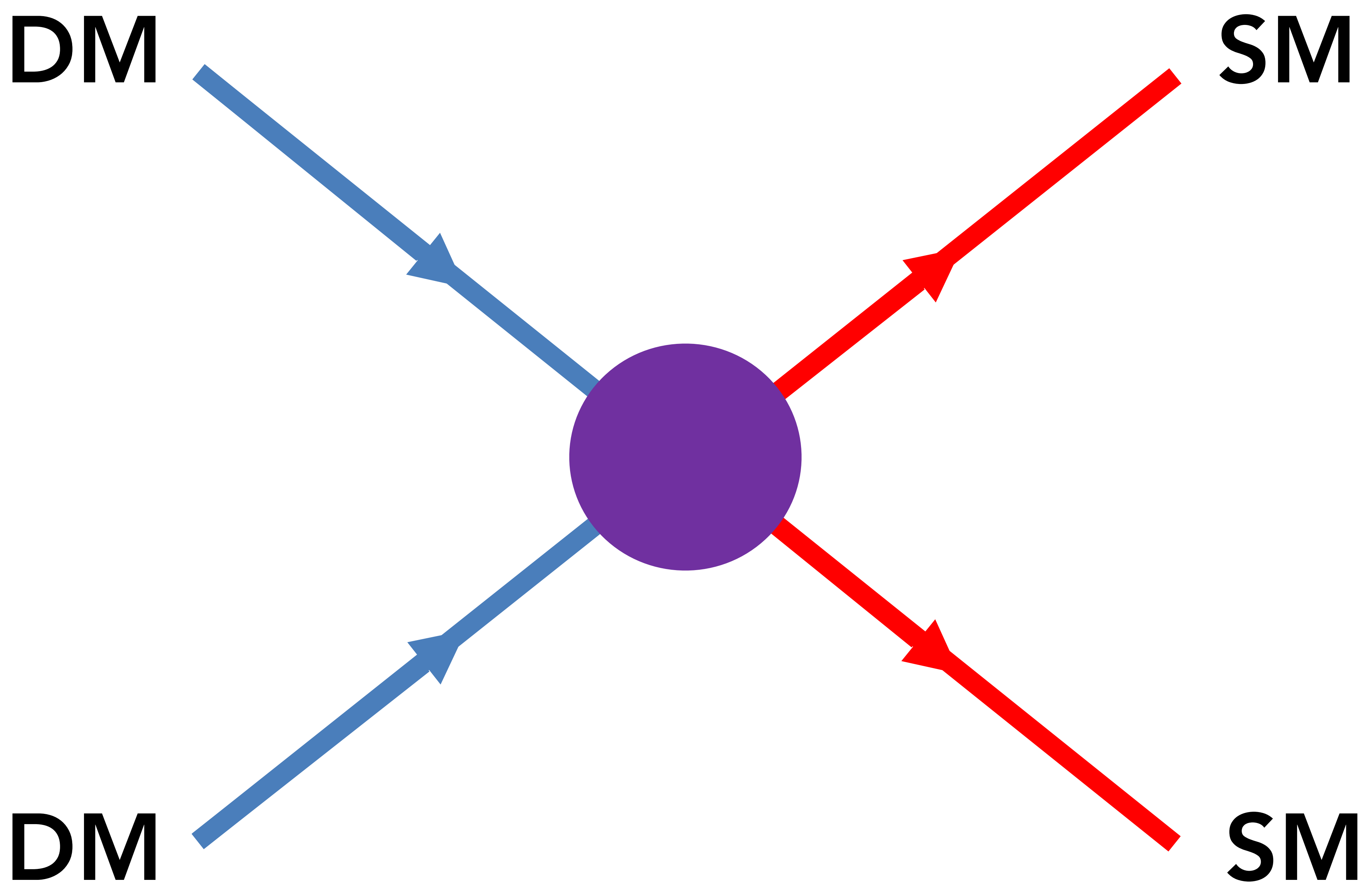
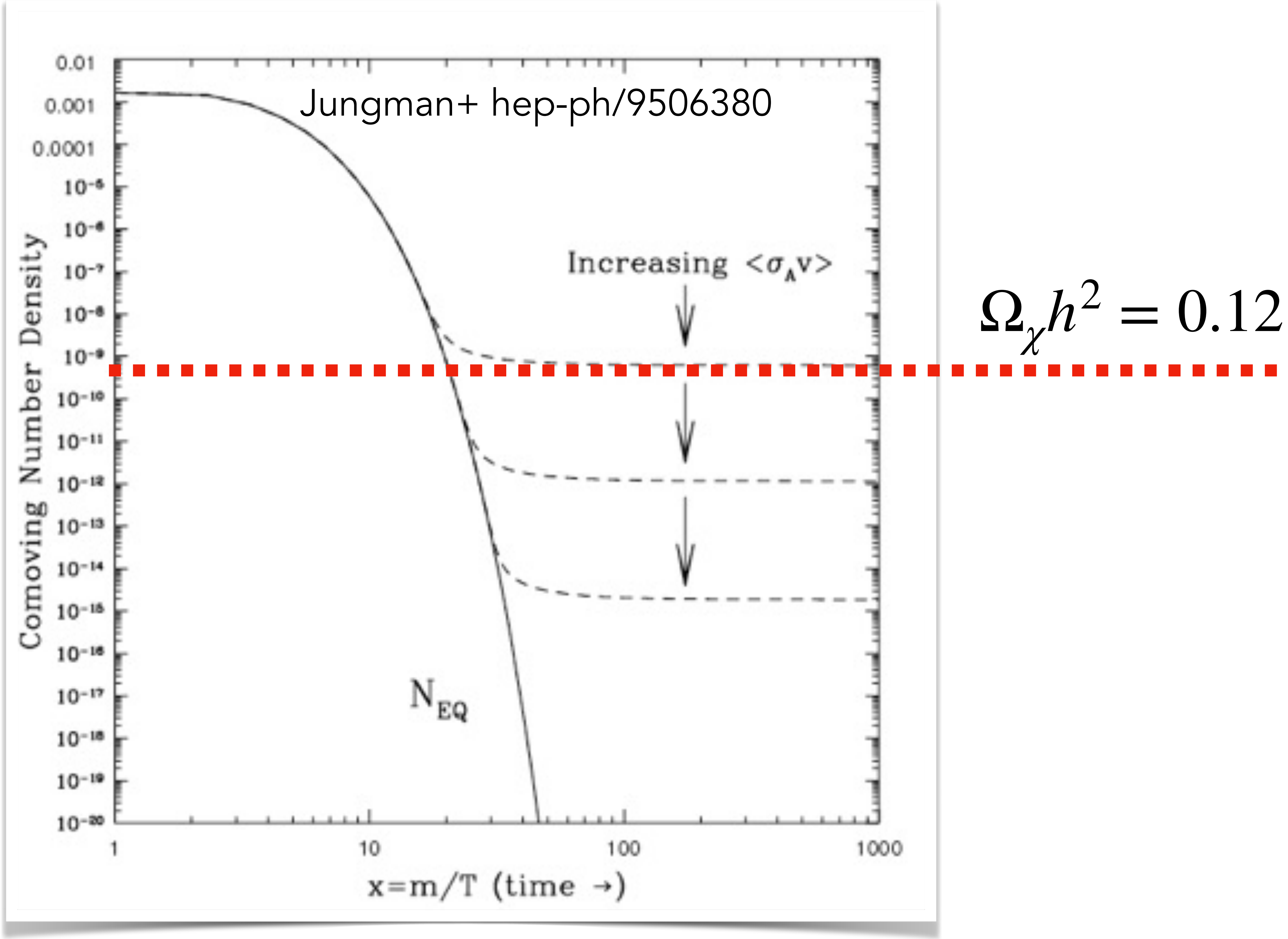


image credit: Sandbox Studio, Chicago

Dark Matter Annihilation

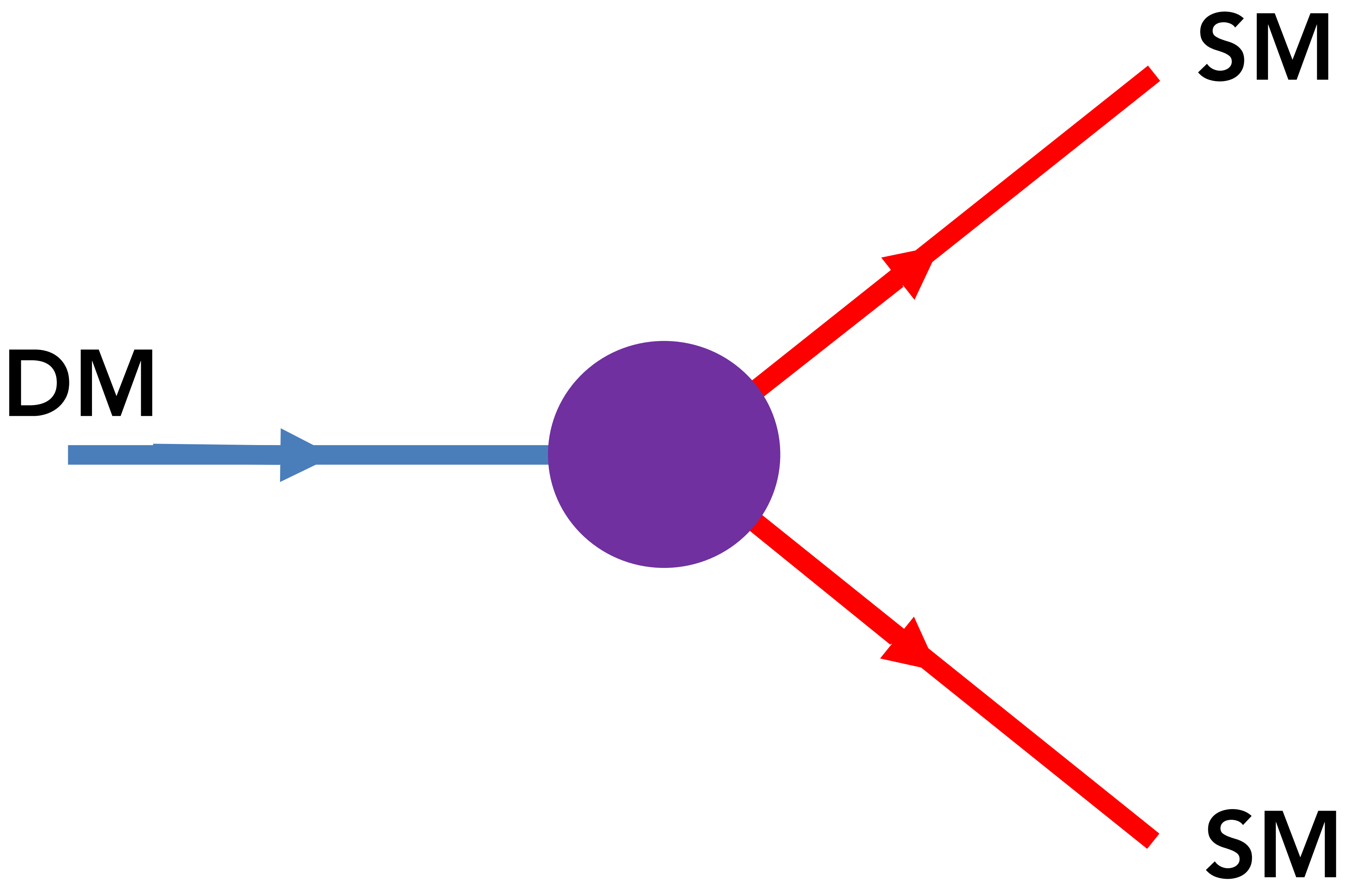


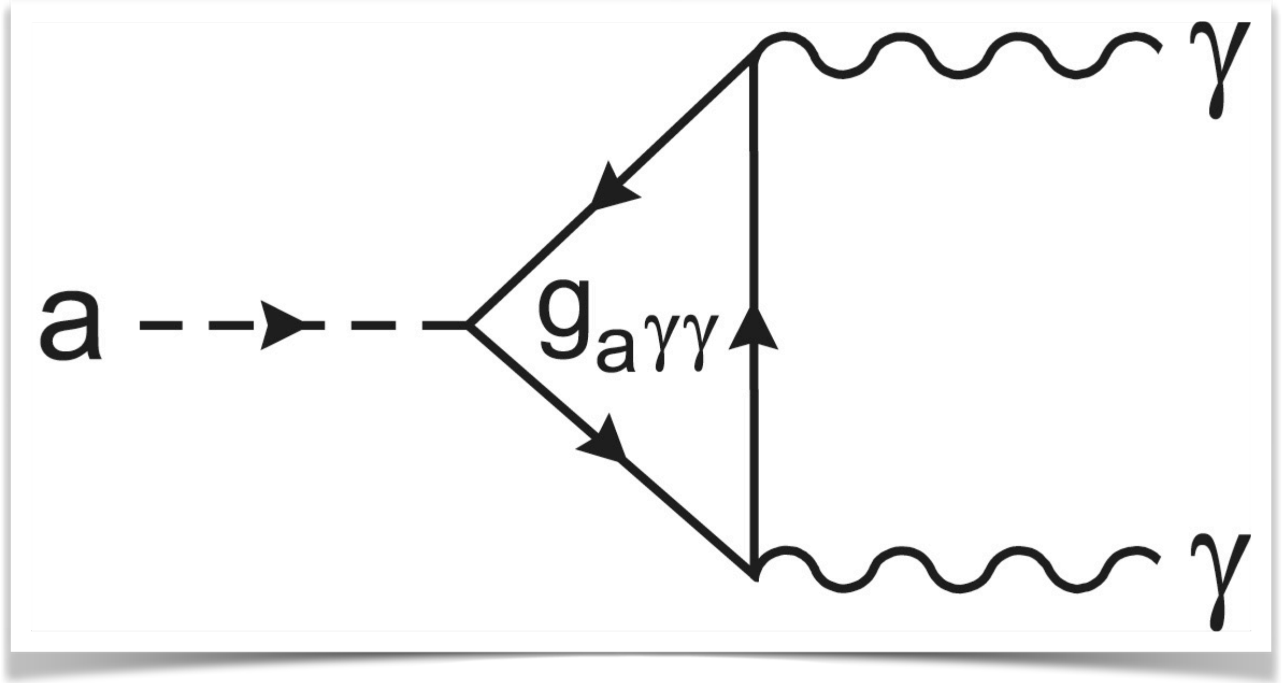
Katelin Schutz (22 Mar)
Miguel Sánchez-Conde (23 Mar)
Seyda Ipek (23 Mar)



Motivated by ideas for **dark matter production** in the early universe.

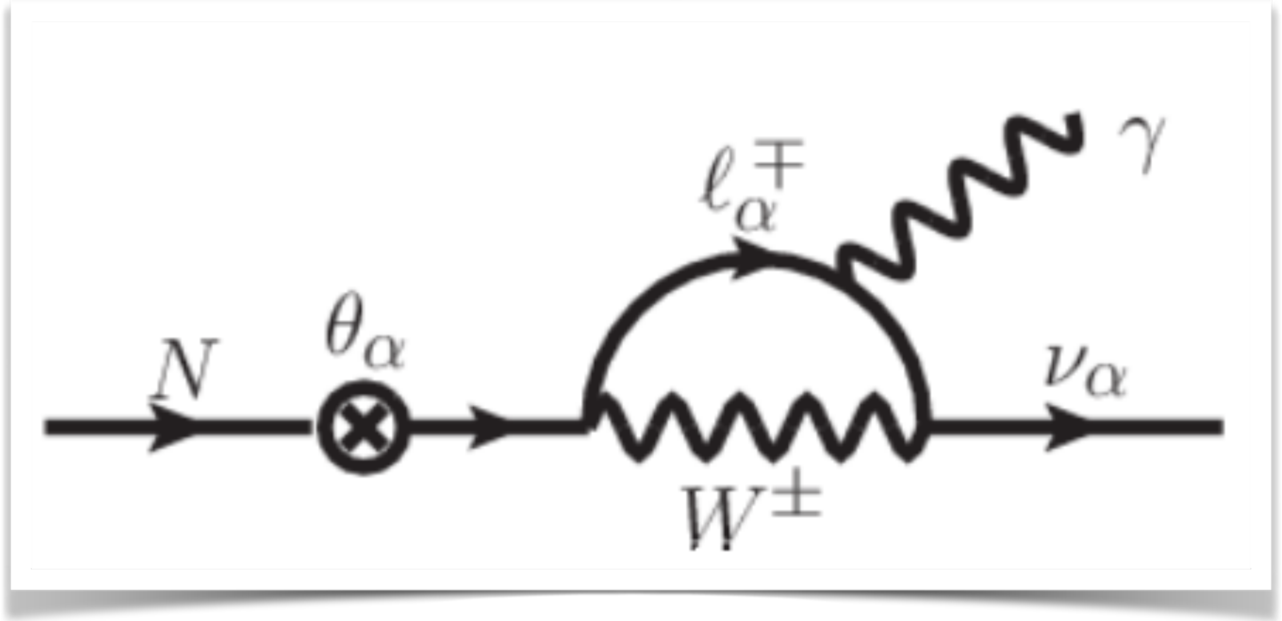
Dark Matter Decay





Axion-Like Particles

JiJi Fan, Kerstin Perez (22 Mar)
Lindley Winslow (23 Mar)



Sterile Neutrinos

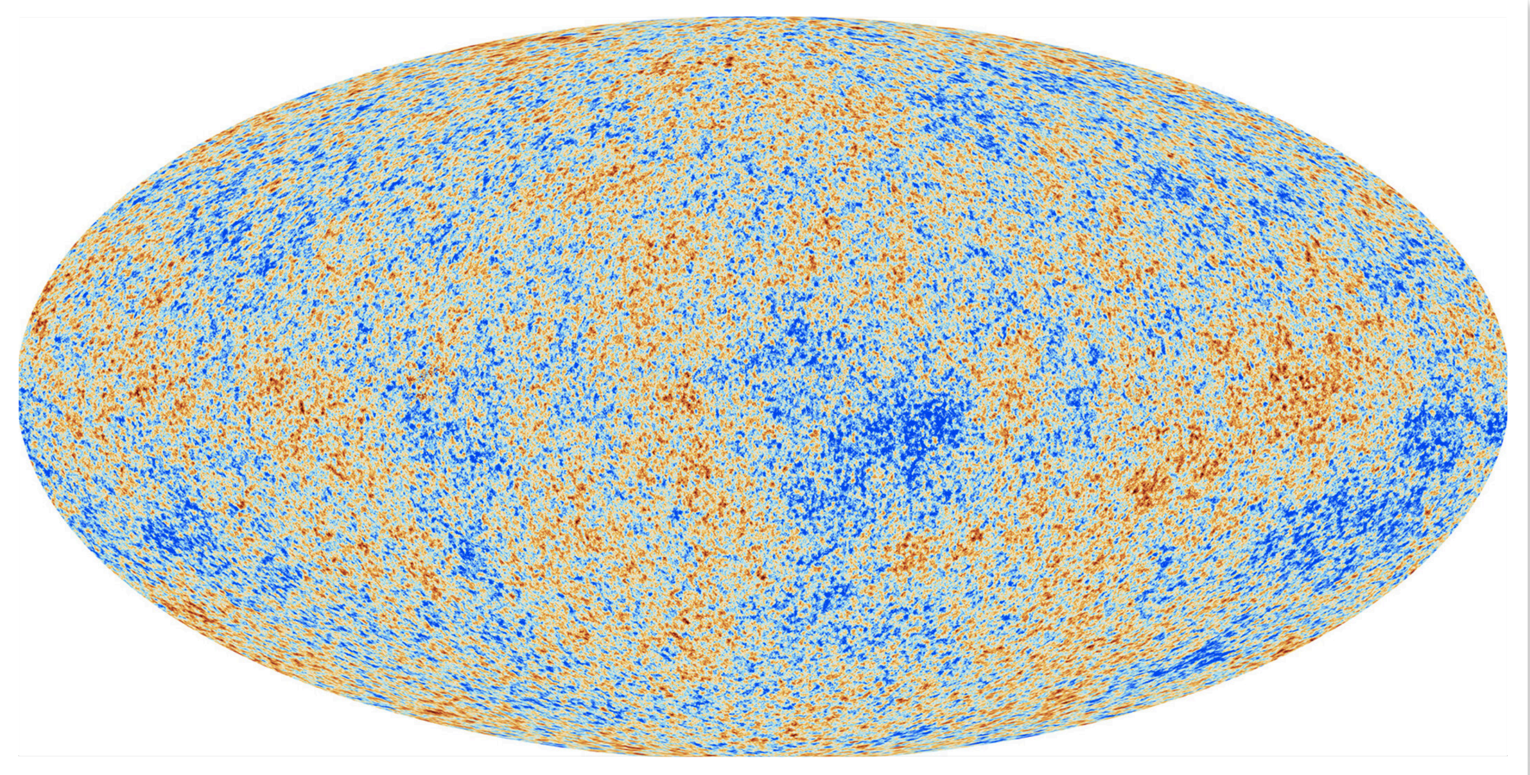
Kerstin Perez (22 Mar)

DM is *cosmologically* stable, but **small couplings to the SM** can lead to decays if DM not protected by symmetry.

Cosmological probes of high-energy particles are highly effective: **high densities**, **long duration** and **pristine systems**.

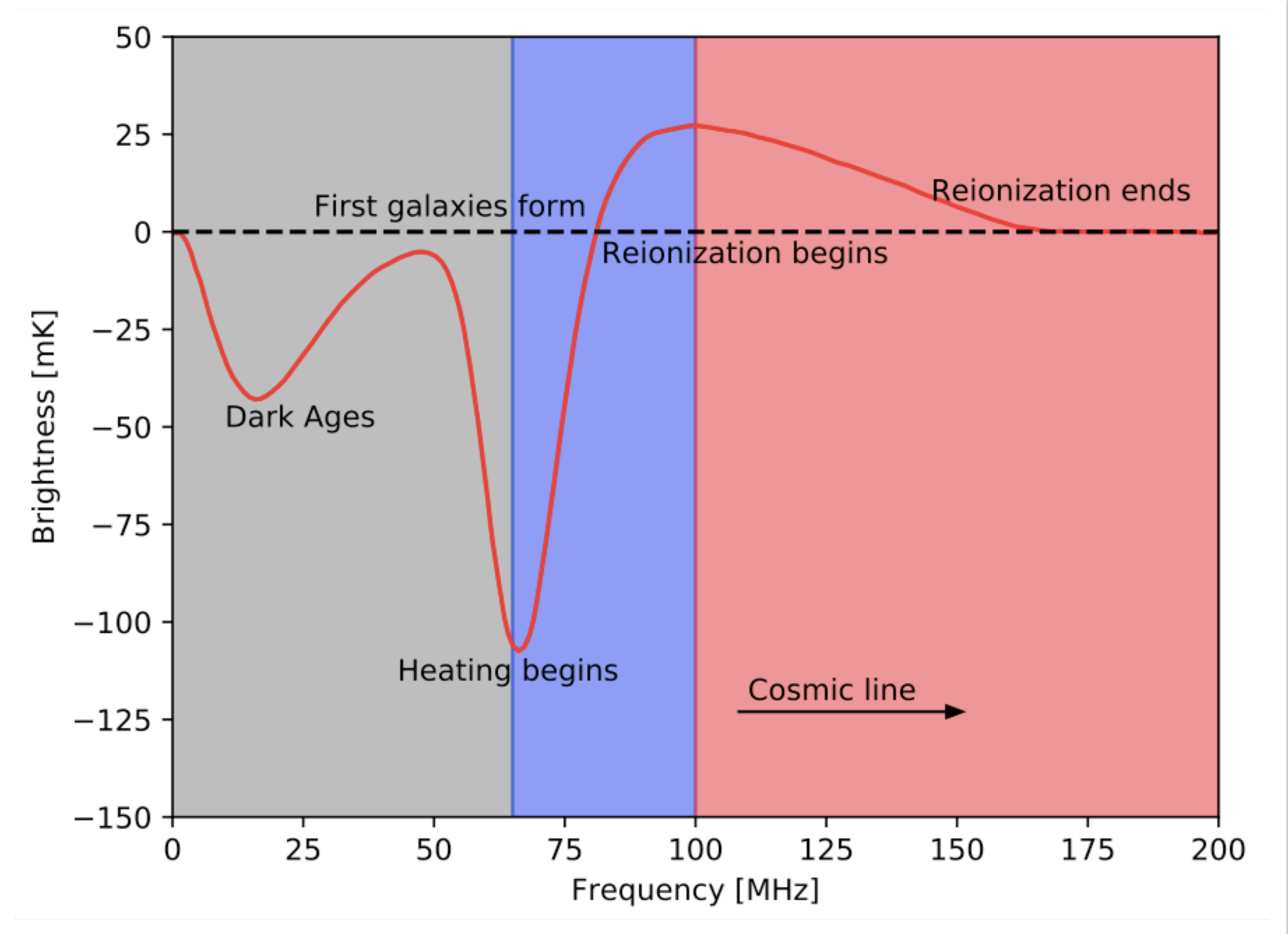
Cosmological Probes

Planck Collaboration



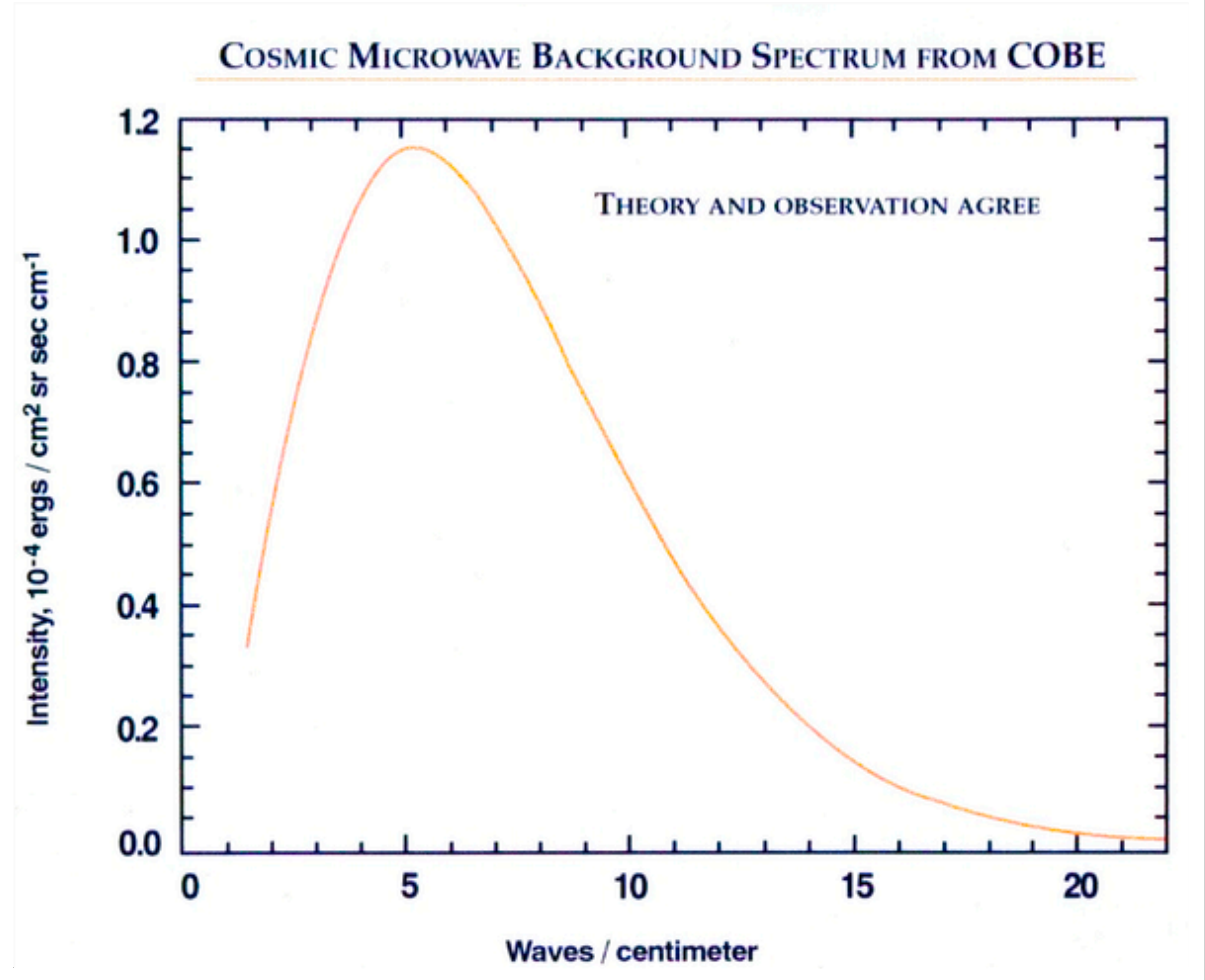
Cosmic Microwave Background (CMB) Power Spectrum

REACH Collaboration

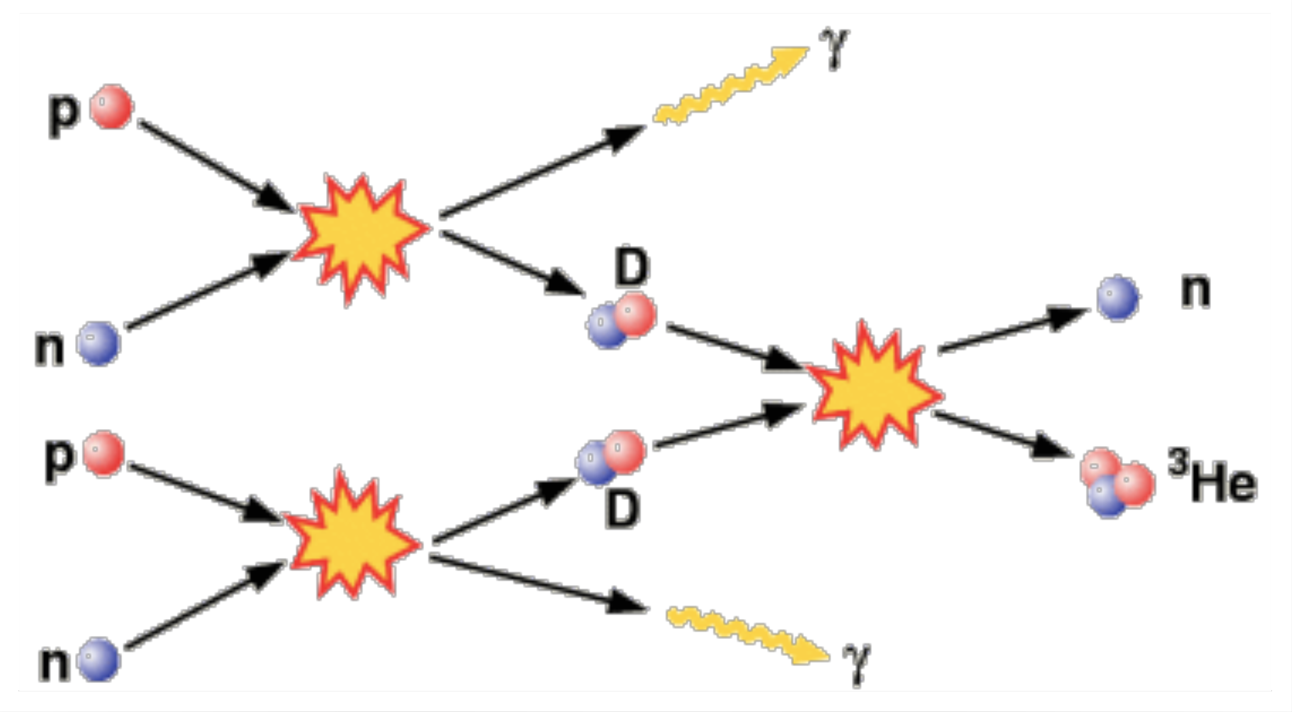


21-cm Global Signal

Mather+ ApJ **420**(439) 1994

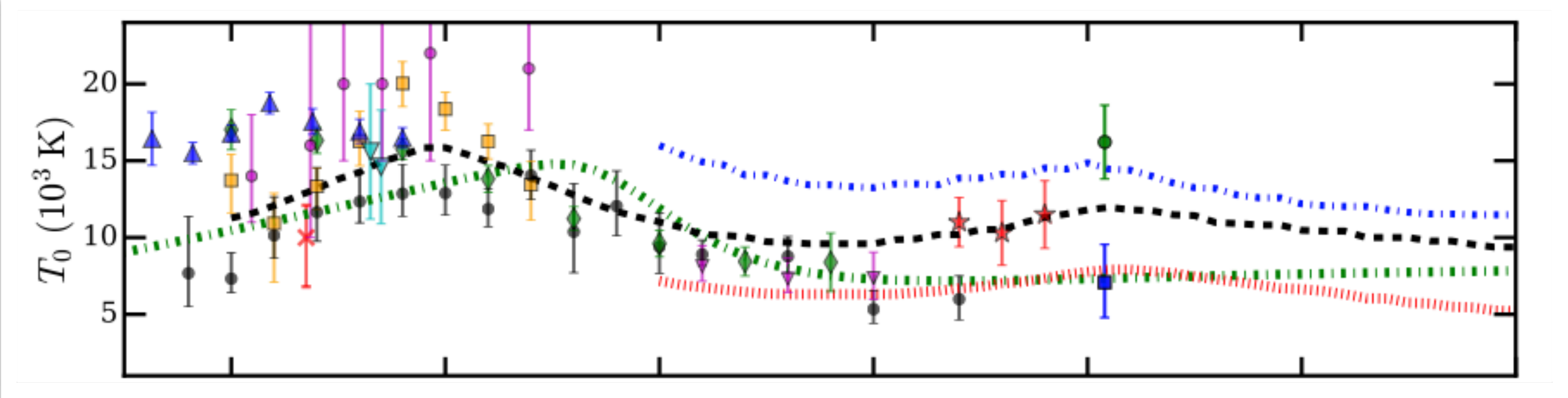


CMB Spectral Distortions

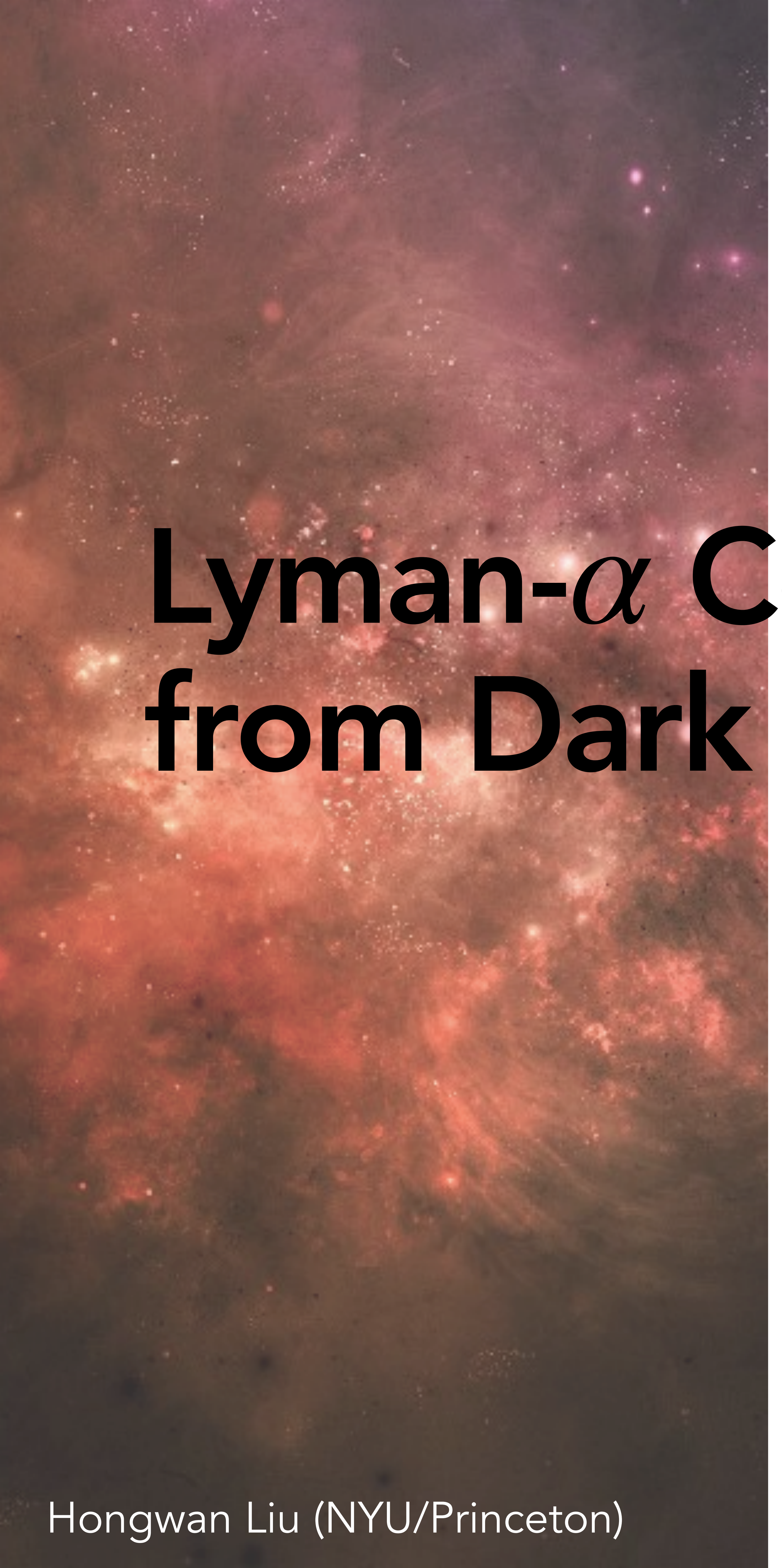


Big-Bang Nucleosynthesis

Gaikwad+ 2001.10018



Intergalactic Medium (IGM) Temperature from Lyman-α Forest



Lyman-α Constraints on Cosmic Heating from Dark Matter Annihilation and Decay

Gregory Ridgway

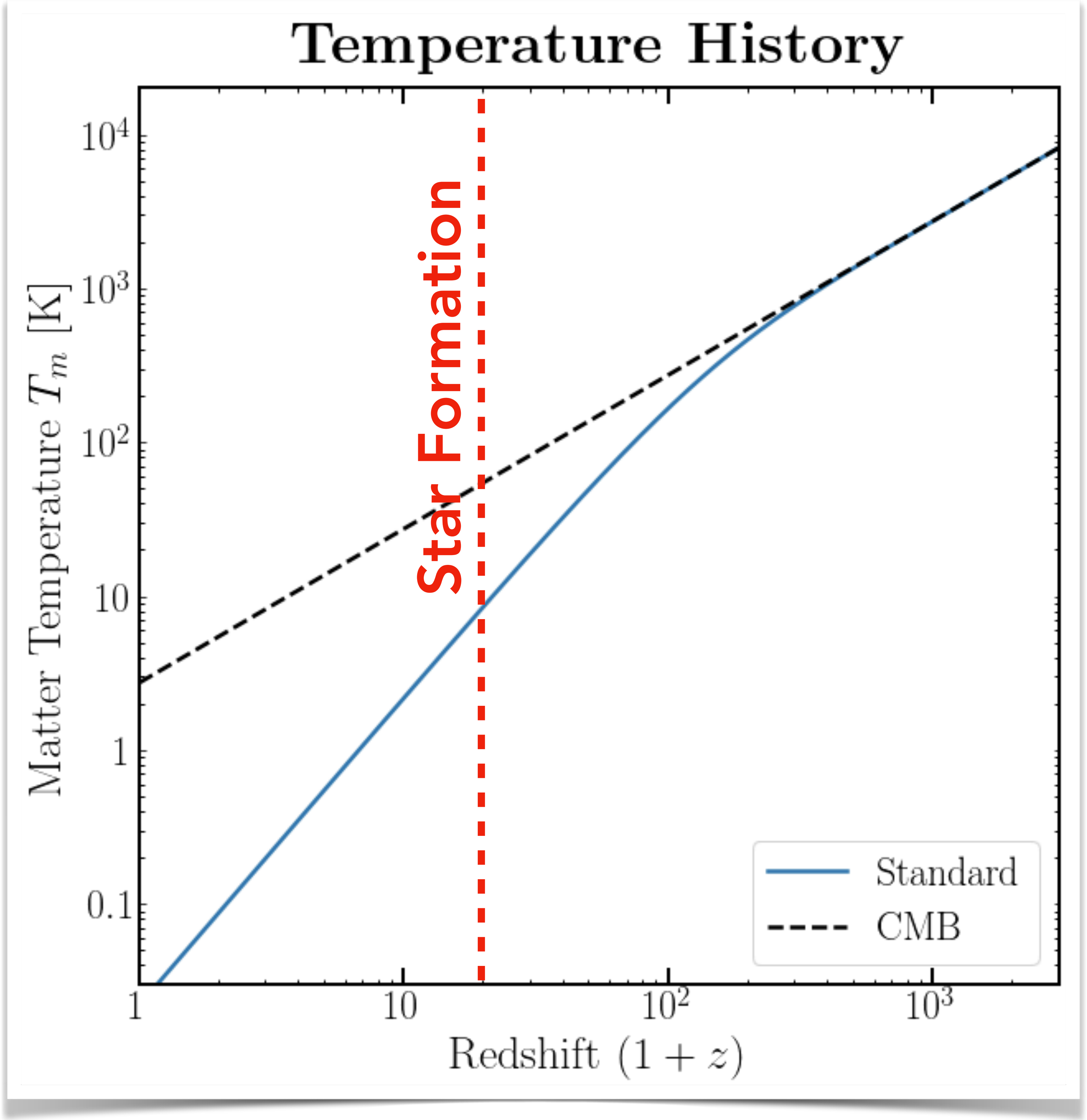
Wenzer Qin

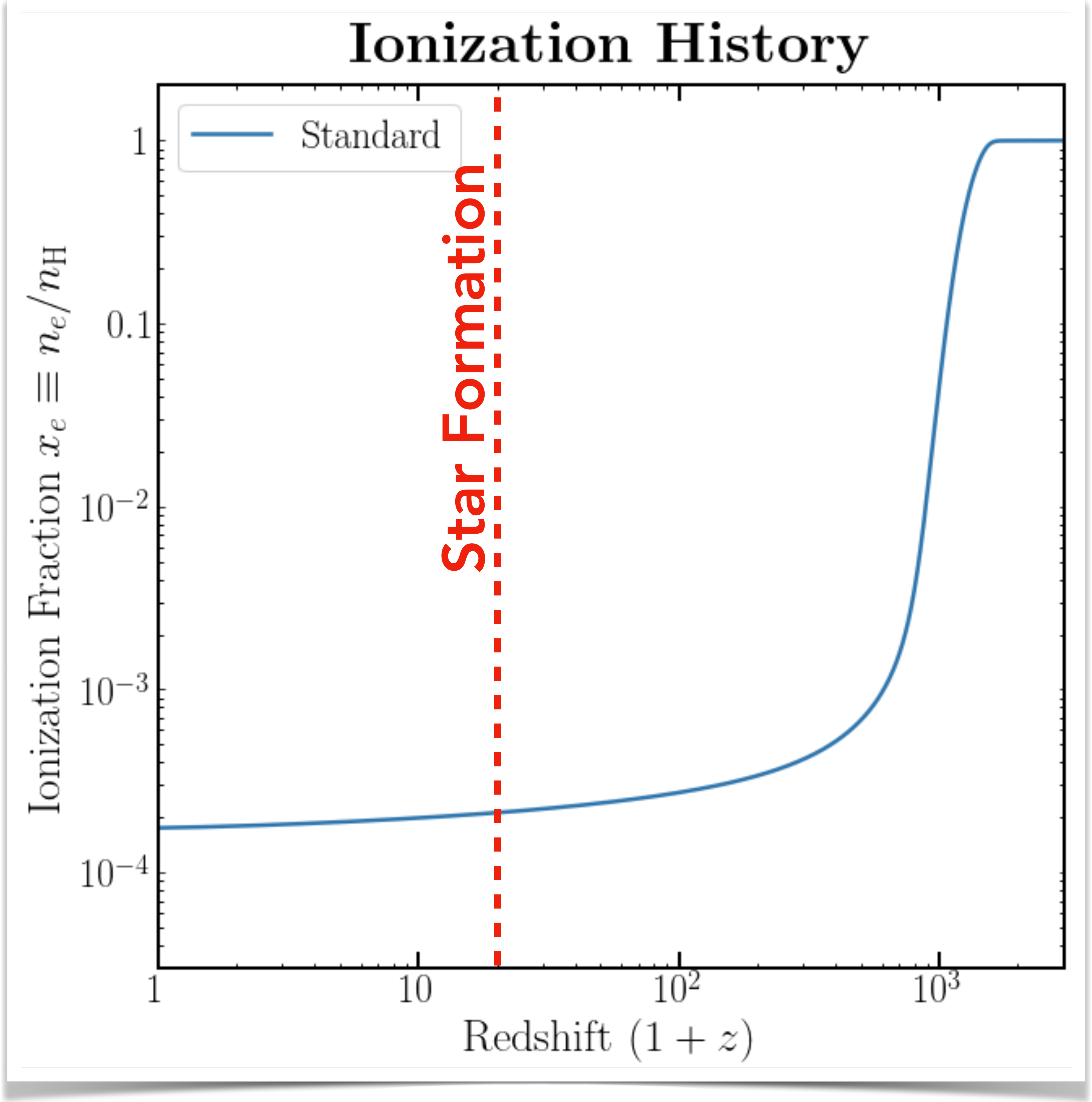
Tracy Slatyer

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

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

Histories without Exotic Energy Injection





Well-understood before star formation:
Precise calculations used in CMB analysis.

How Much Heat from DM?

1. Every decay releases m_χ worth of energy.
2. n_χ/τ decays per volume per time.
3. n_B is the number density of baryons.

Energy per baryon $\sim m_\chi \times \dfrac{n_\chi}{\tau} \times \dfrac{1}{n_B} \times$ Age of the universe

$$\sim 2.5 \times 10^6\,\mathrm{K}\left(\frac{10^{25}\,\mathrm{s}}{\tau}\right)$$

$T_m \sim 10\,\mathrm{K}$ at star formation
$T_m \sim 10^4\,\mathrm{K}$ after reionization

Dark Matter Injection

Matter Temperature

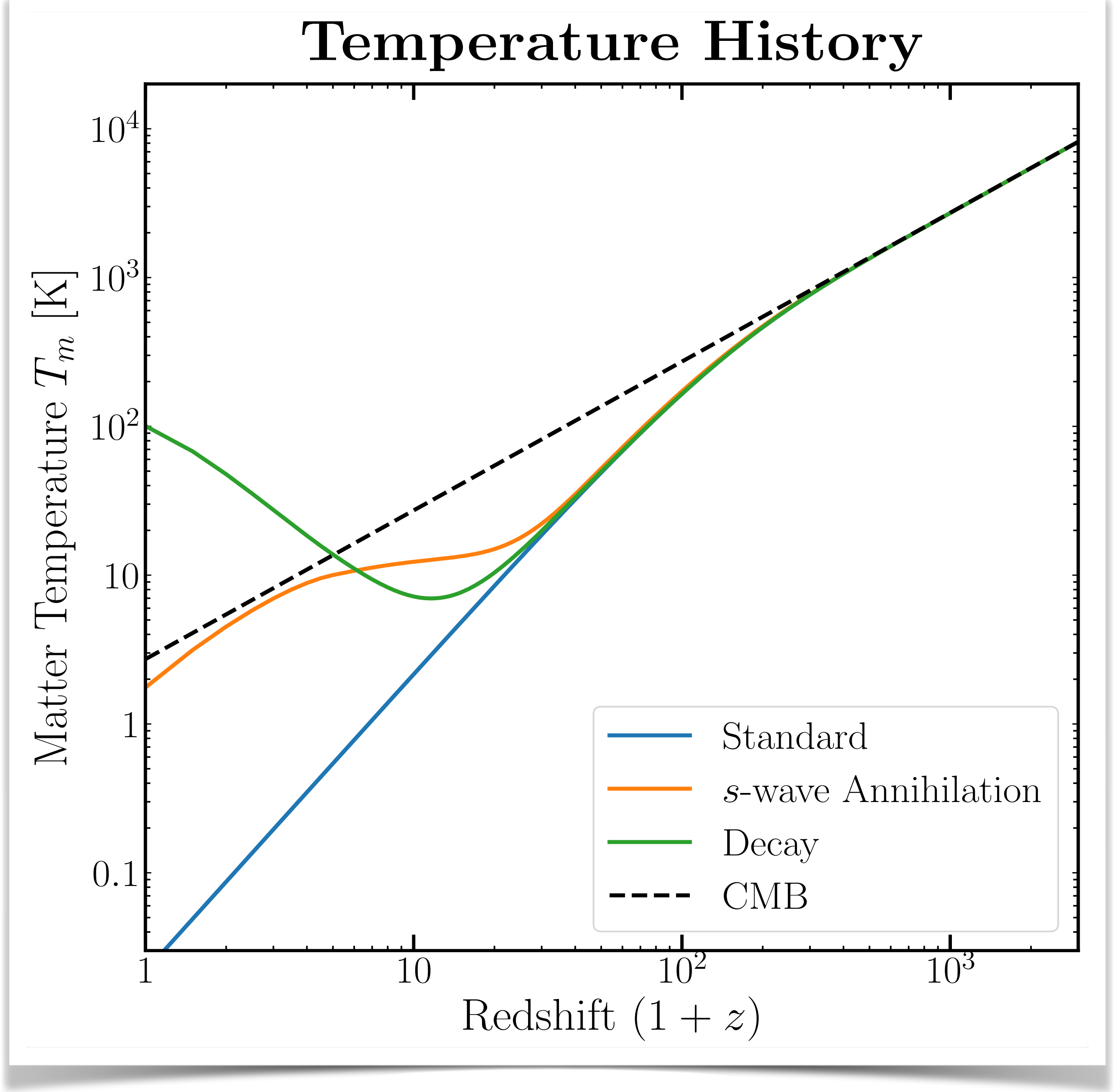
$$\dot{T}_m = \cdots + \frac{2f_{\text{heat}}(z, \mathbf{x}_\mathbf{e})}{3(1 + f_{\text{He}} + x_e)n_{\text{H}}} \left(\frac{dE}{dV\,dt} \right)_{\text{inj}}$$

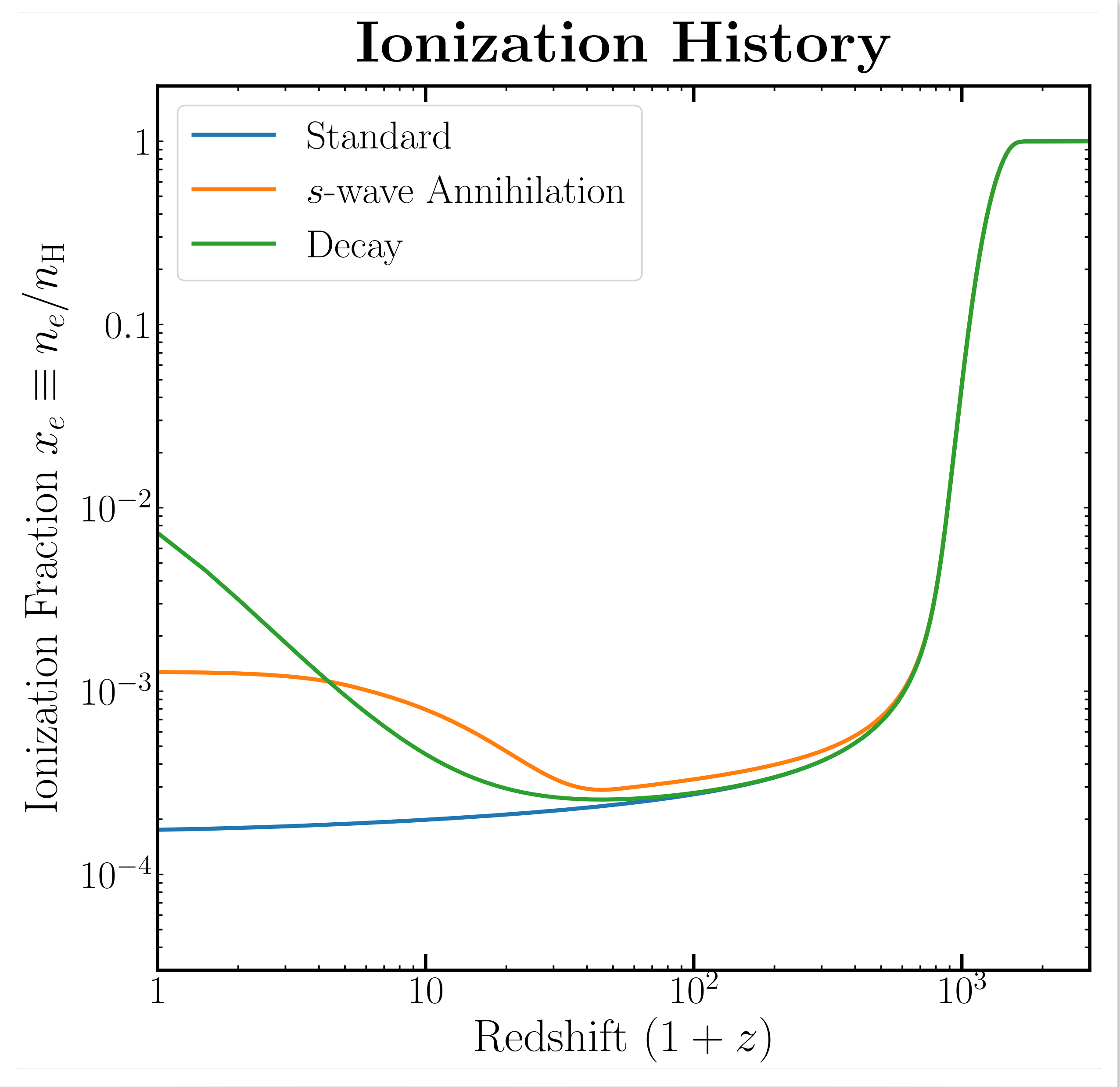
Dark matter energy injection **heats IGM**, deposition parametrized by **efficiency factor**. Nontrivial to calculate.

Ionization

$$\dot{x}_e = \cdots + \left[\frac{f_{\text{ion}}(z, \mathbf{x}_\mathbf{e})}{\mathcal{R} n_{\text{H}}} + \frac{(1 - \mathscr{C})f_{\text{exc}}(z, \mathbf{x}_\mathbf{e})}{0.75 \mathcal{R} n_{\text{H}}} \right] \left(\frac{dE}{dV\,dt} \right)_{\text{inj}}$$

HL, Ridgway & Slatyer 1904.09296
github.com/hongwanliu/DarkHistory

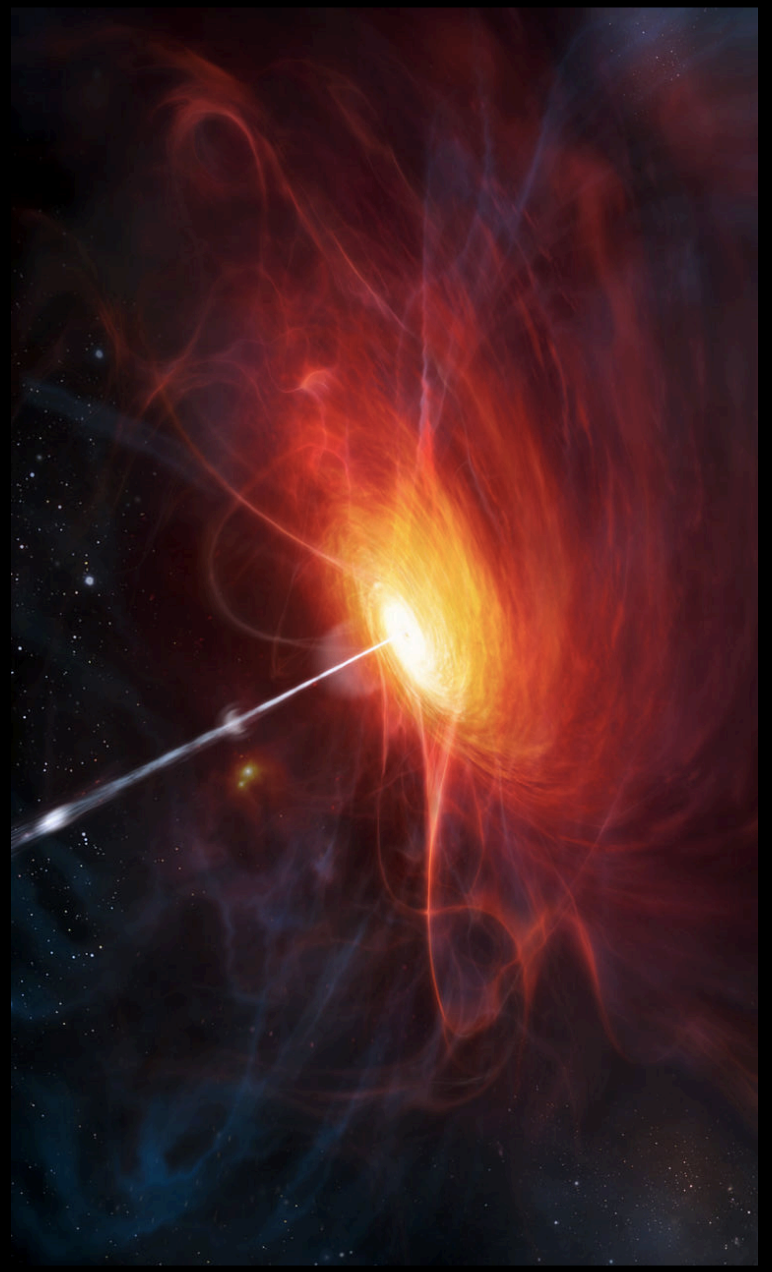




Lyman-α Forest

HI Gas

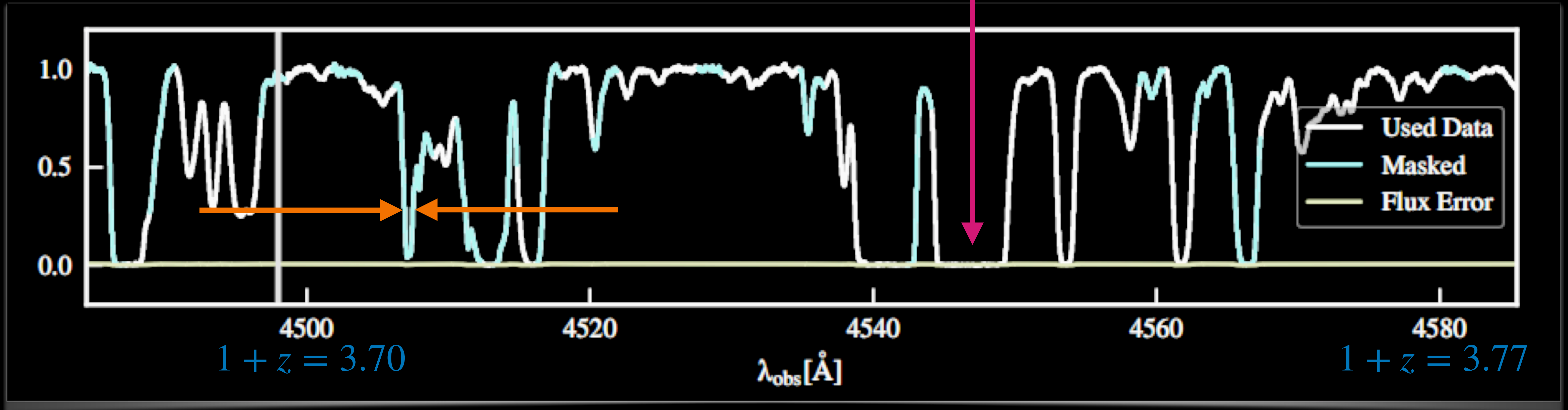
Quasar



$1 + z = 3.89$

Doppler broadening

Walther+ 1709.07354



$1 + z = 3.70$

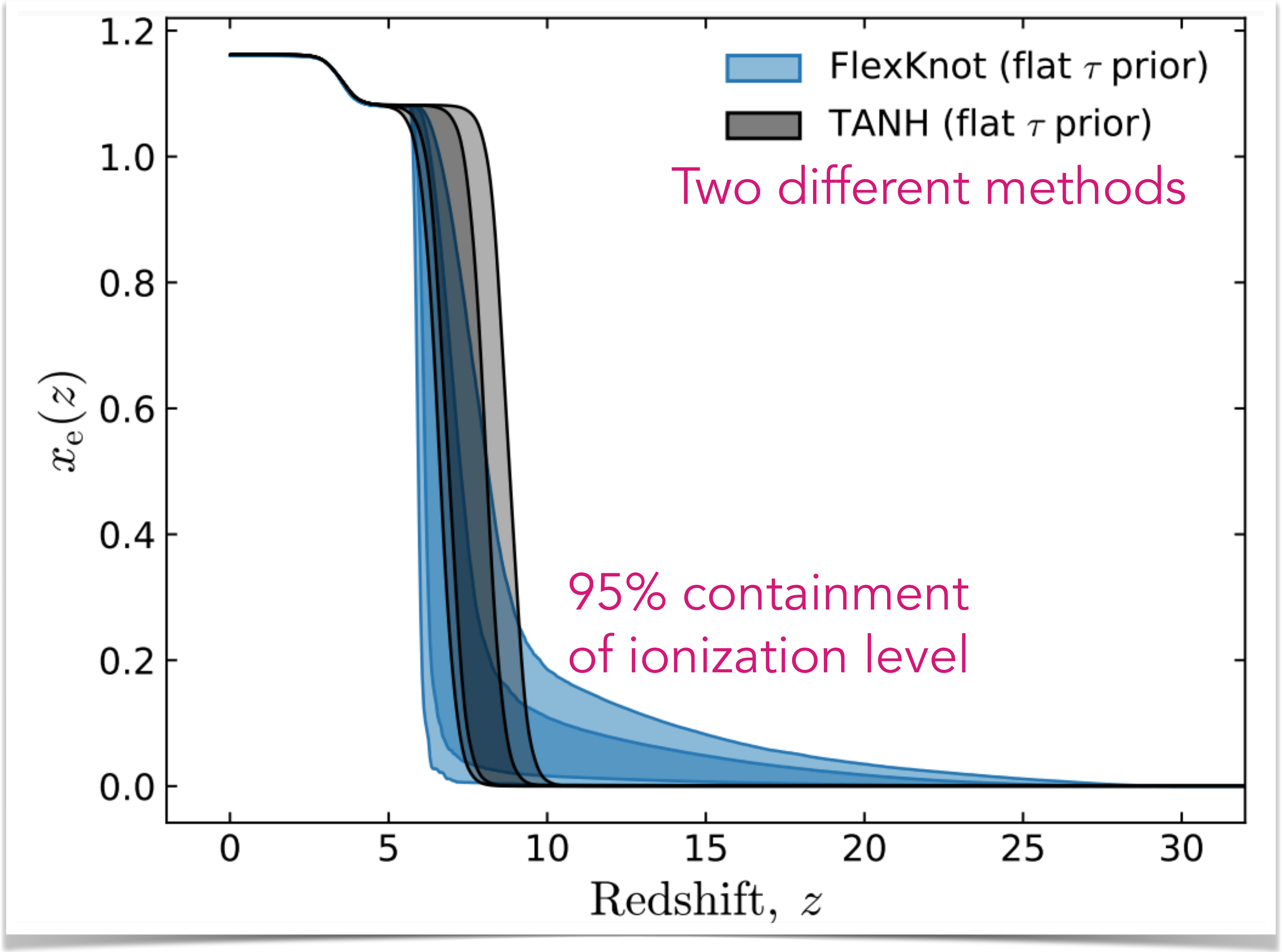
$1 + z = 3.77$

Jeans broadening

Intergalactic medium (IGM) temperature can be deduced from Lyman-α forest measurements.

Data

Planck Collab. 1807.06209

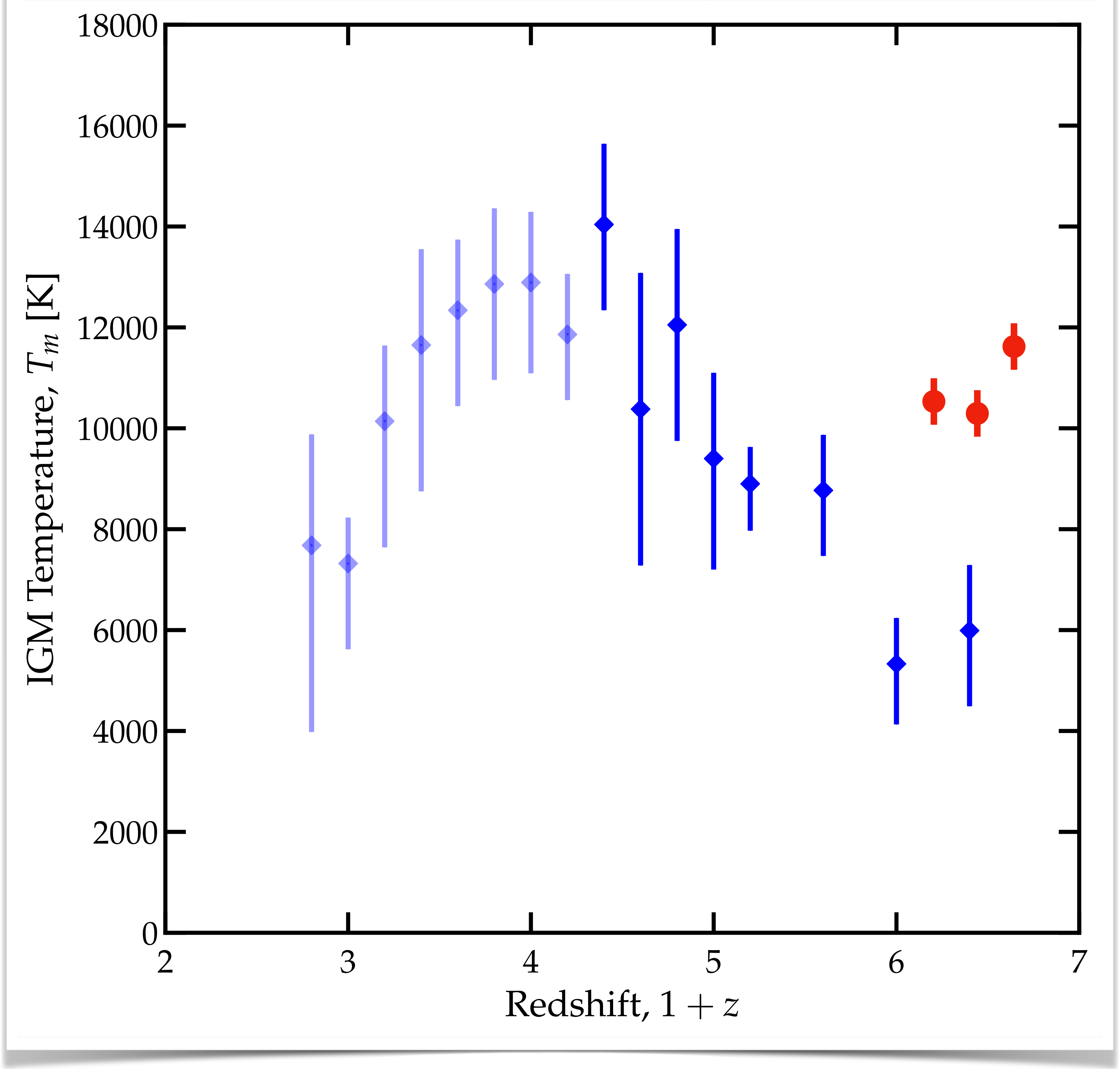


Two different methods

95% containment of ionization level

Walther+ 1808.04367

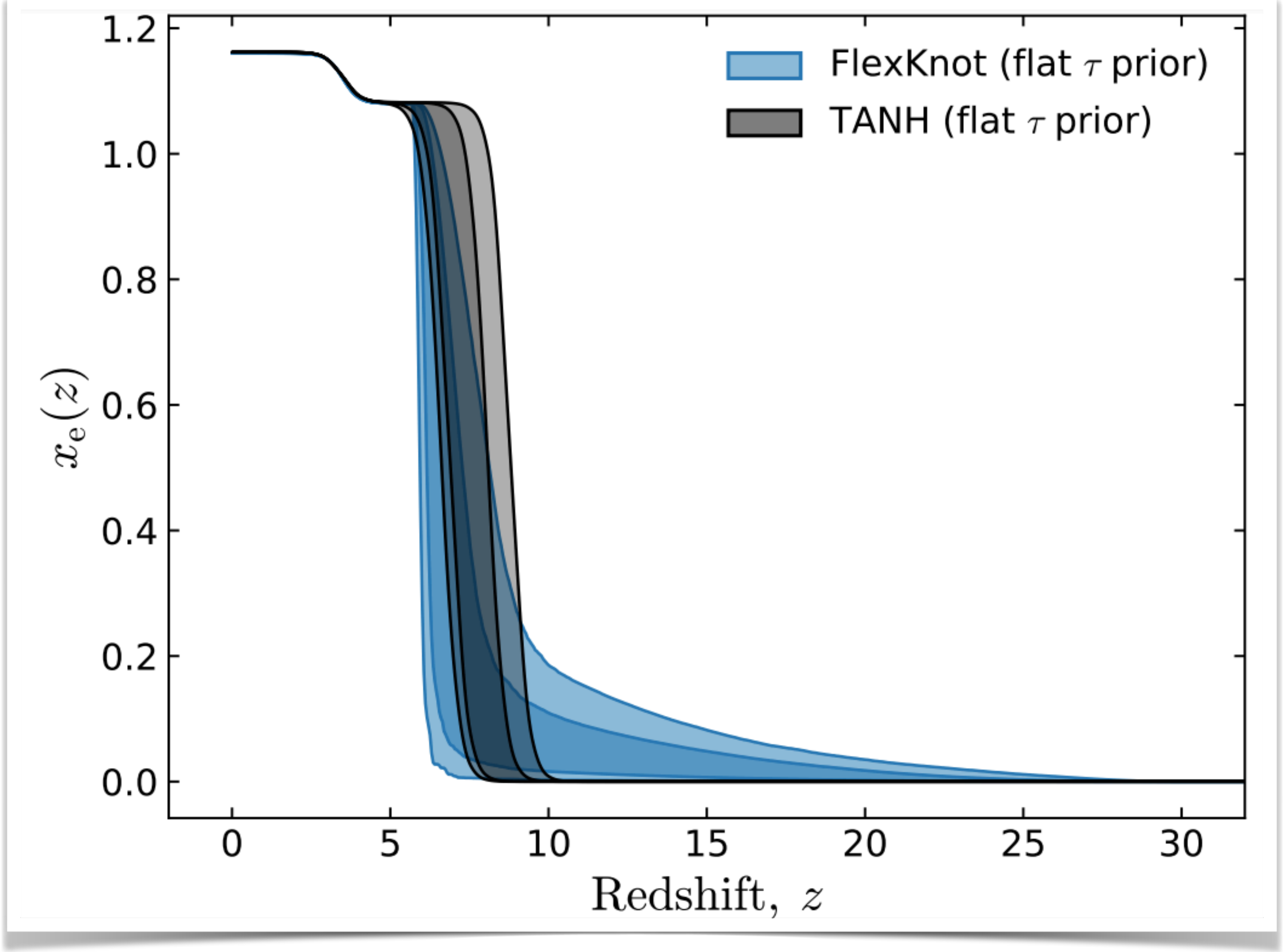
Gaikwad+ 2001.10018



Both **ionization** and **thermal histories** are becoming well-measured.

Ionization History

Planck Collab. 1807.06209



Avoid direct modelling of reionization, which is **highly uncertain**.

For each DM decay/annihilation model, **scan over ionization histories.**

Excess assigned to photoionization (i.e. caused by star formation and reionization).

set by DM model (DarkHistory)

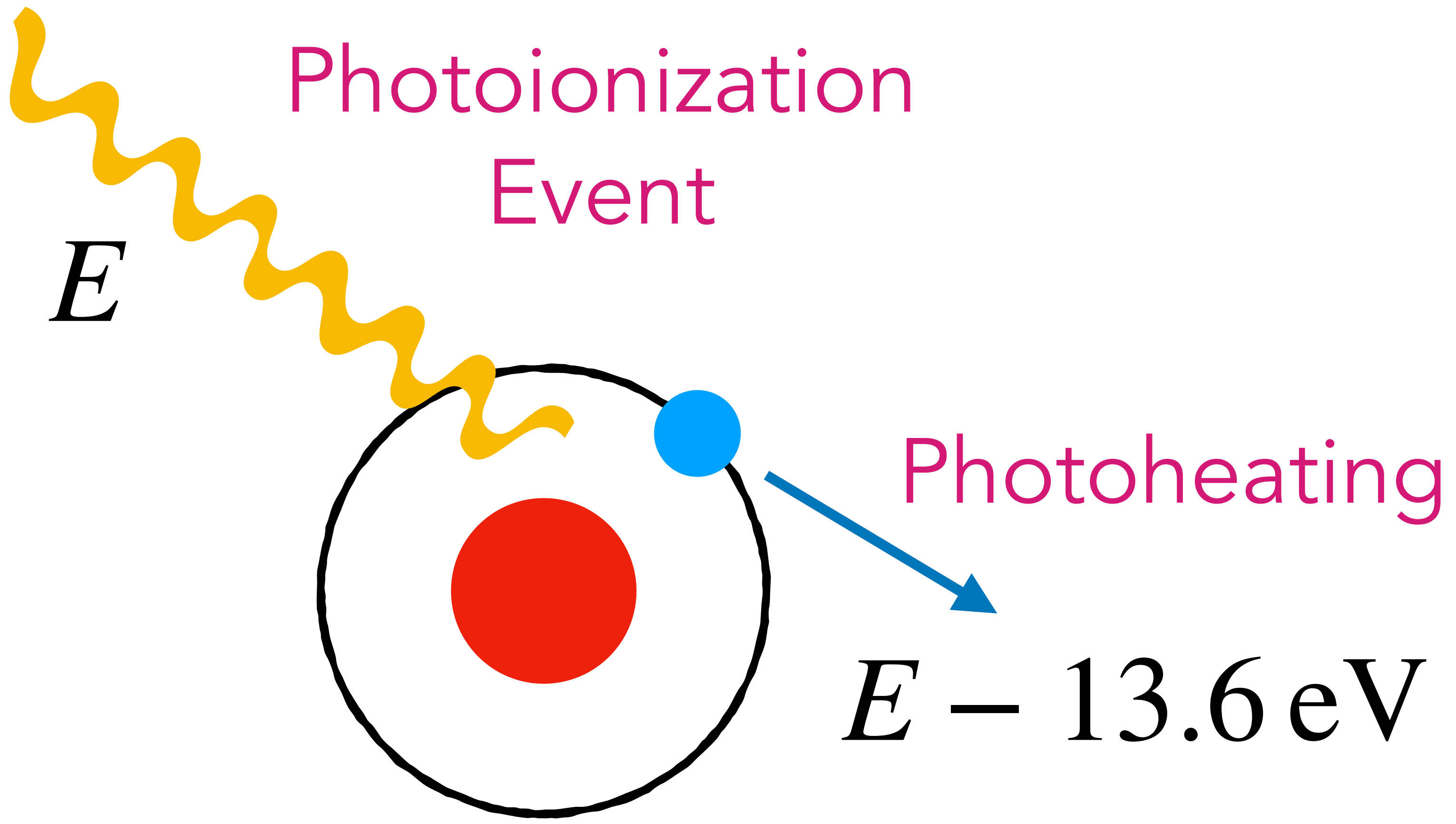
collisional ionization, recombination…

photoionization from stars (only unknown)

constrained by Planck

$$\dot{x}_e^{\rm Pl} = \dot{x}_e^{\rm DM}(m_\chi, \Gamma, x_e) + \dot{x}_e^{\rm atom}(T_{\rm m}, x_e) + \dot{x}_e^{\star}$$

Temperature History



$$\dot{x}_e^{\mathrm{Pl}} = \dot{x}_e^{\mathrm{DM}}(m_\chi, \Gamma, x_e) + \dot{x}_e^{\mathrm{atom}}(T_{\mathrm{m}}, x_e) + \dot{x}_e^\star$$

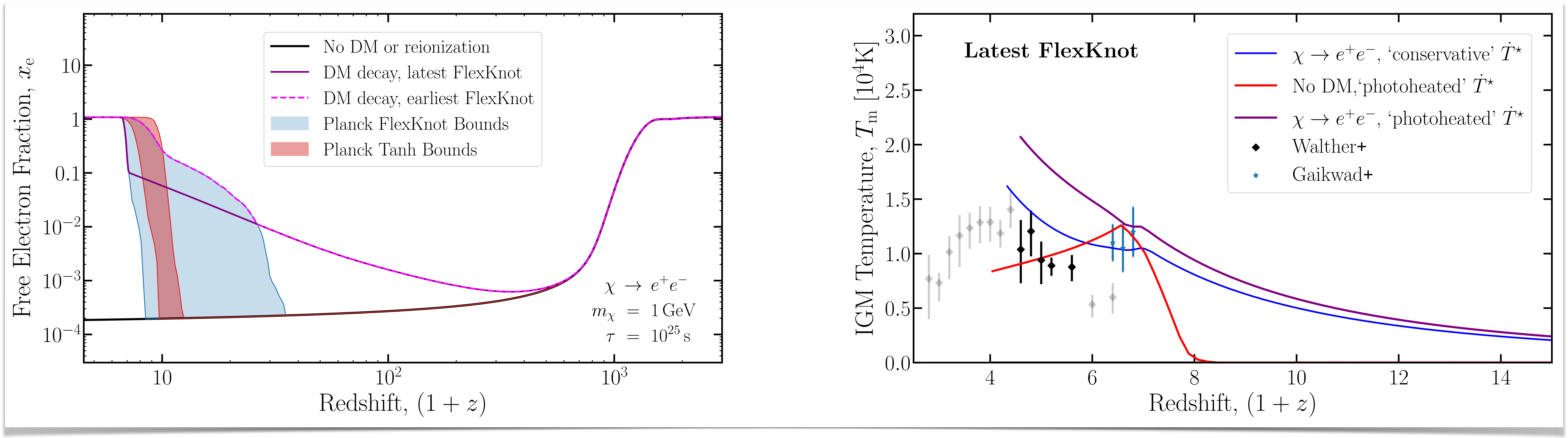
$$\dot{T}_m = \dot{T}_{\mathrm{expansion}} + \dot{T}_{\mathrm{Compton}} + \dot{T}_{\mathrm{DM}} + \dot{T}_{\mathrm{atom}} + \dot{T}^\star$$

- $\dot{T}_m$: To Calculate!
- $\dot{T}_{\mathrm{expansion}}$: Adiabatic Expansion Cooling
- $\dot{T}_{\mathrm{Compton}}$: Compton Heating
- $\dot{T}_{\mathrm{DM}}$: DM Heating
- $\dot{T}_{\mathrm{atom}}$: Recombination Cooling, …
- $\dot{T}^\star$: Photoheating from Photoionization

Photoionization causes heating, $\dot{T}^\star$.

i) **Conservative:** $\dot{T}^\star = 0$. ii) **Photoheating Model:** $\dot{T}^\star = \dot{x}_e^\star \Delta T$.

Histories



Conservative:

$$\dot{T}^\star = 0$$

Photoheating I:

$$\dot{T}^\star = \dot{x}_e^\star \Delta T$$

$$0\,\mathrm{K} < \Delta T < 3 \times 10^4\,\mathrm{K}$$

(+ model after full ionization)

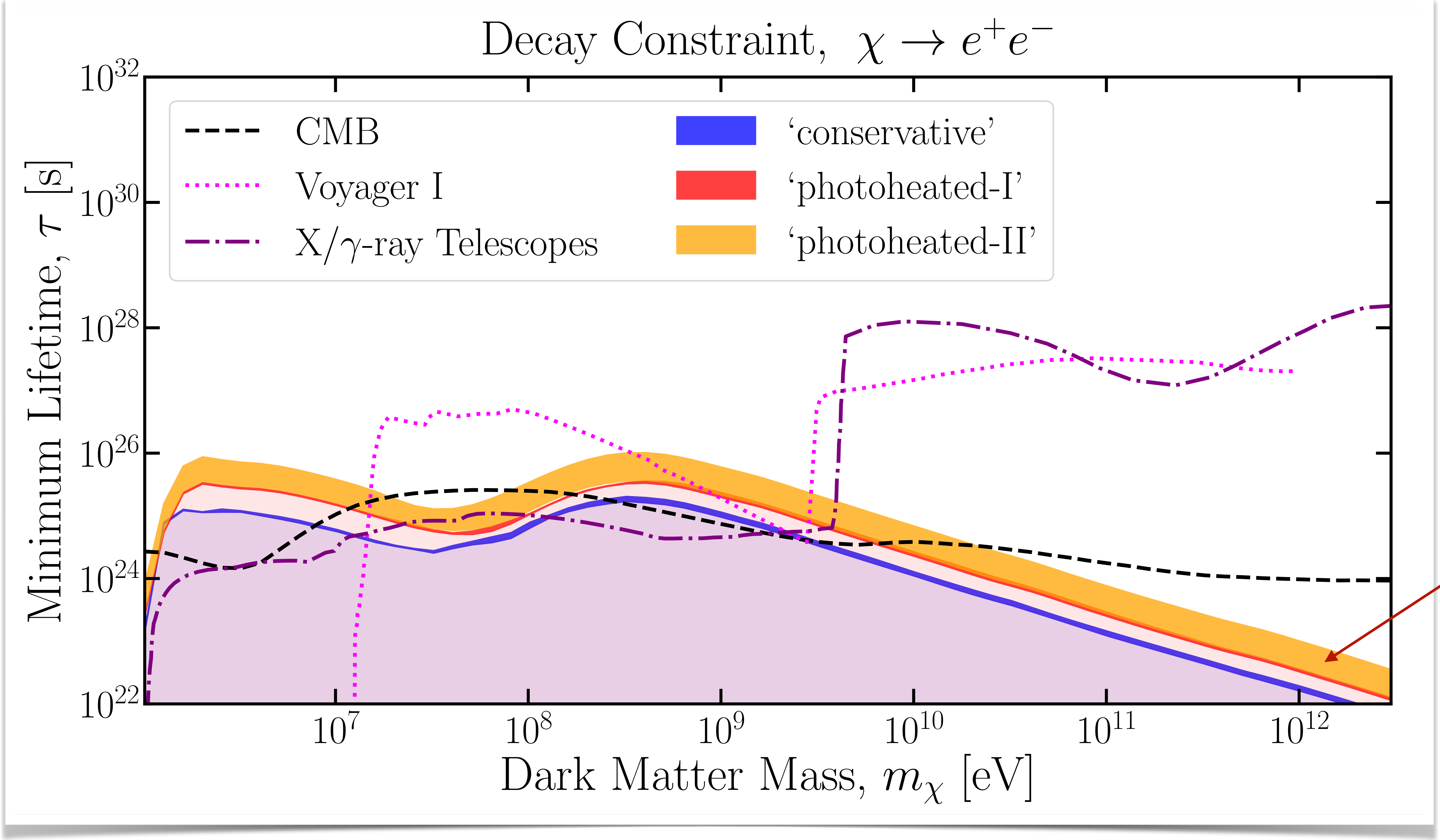
Photoheating II:

$$\dot{T}^\star = \dot{x}_e^\star \Delta T$$

$$2 \times 10^4\,\mathrm{K} < \Delta T < 3 \times 10^4\,\mathrm{K}$$

(+ model after full ionization)

Constraints — Decay



Band from scanning over different ionization histories

Competitive with other constraints for dark matter decay into electron/positron pairs.

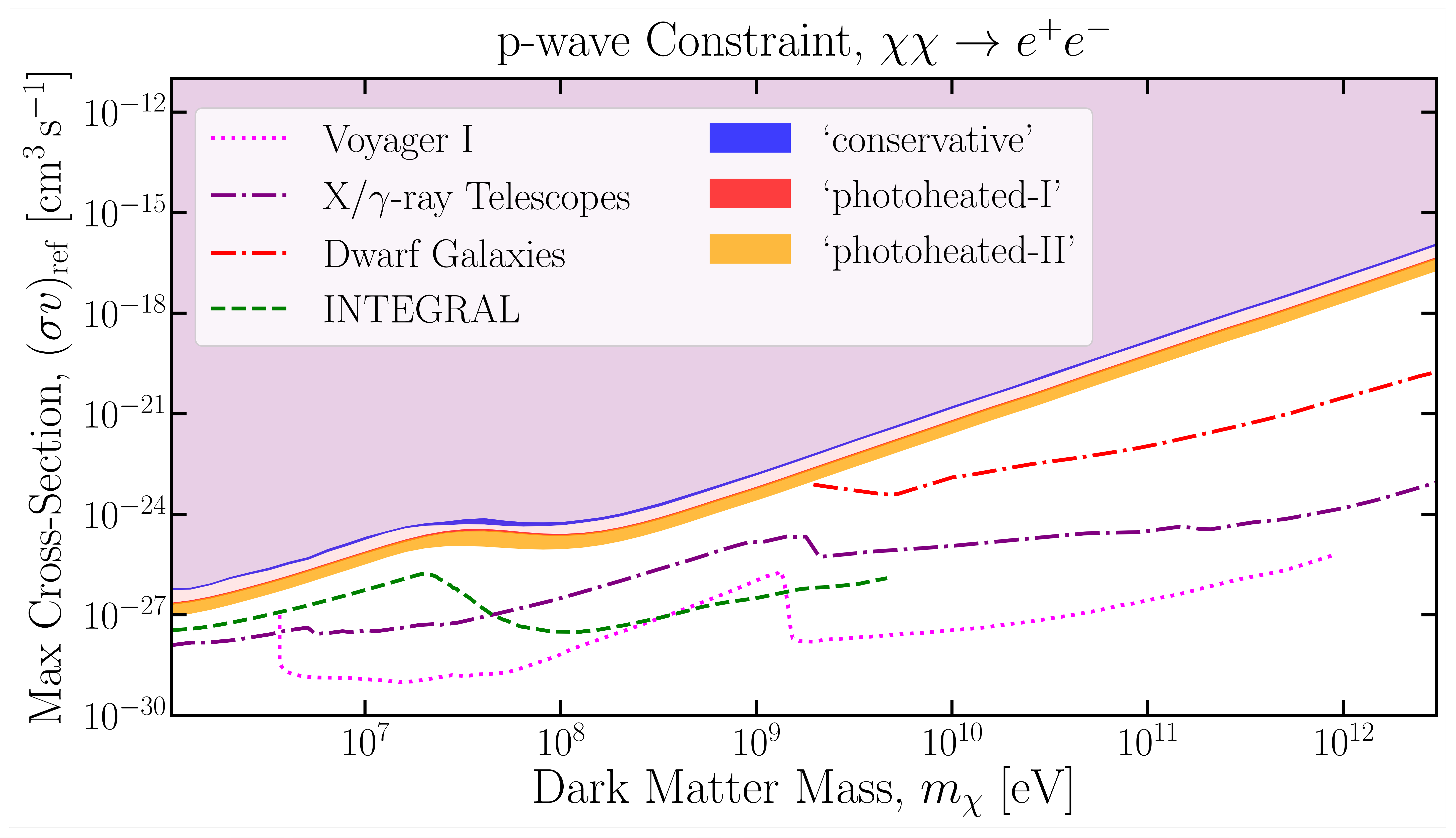
Constraints — *p*-wave Annihilation

p-wave annihilation, $\langle \sigma v \rangle \propto v^2$

$$\langle \sigma v \rangle = (\sigma v)_\text{ref} \frac{v^2}{v_\text{ref}^2}, \; v_\text{ref} = 100\,\text{km/s}$$

Boost from structure included, both density and dispersion.

HL, Slatyer and Zavala 1604.02457

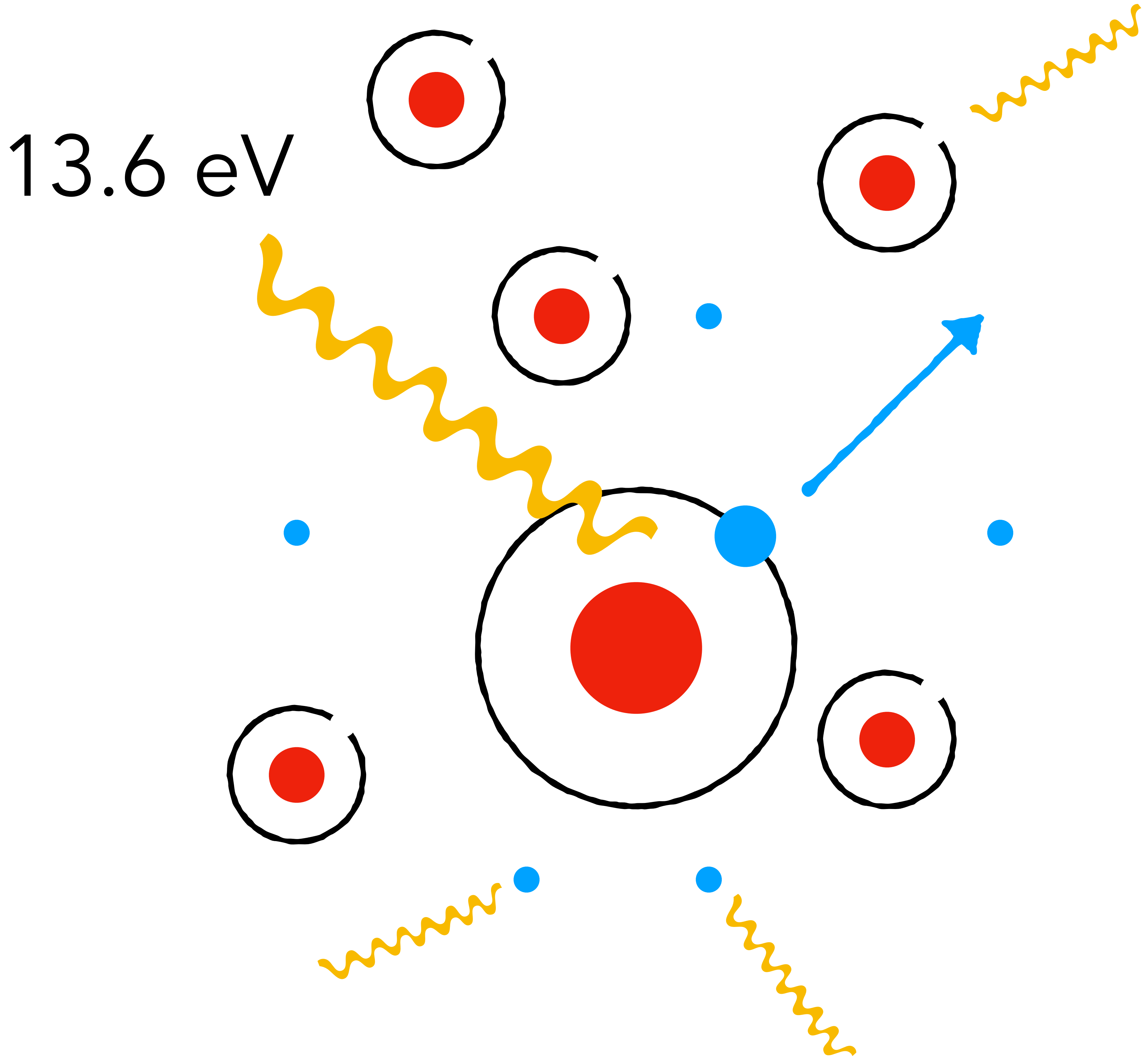


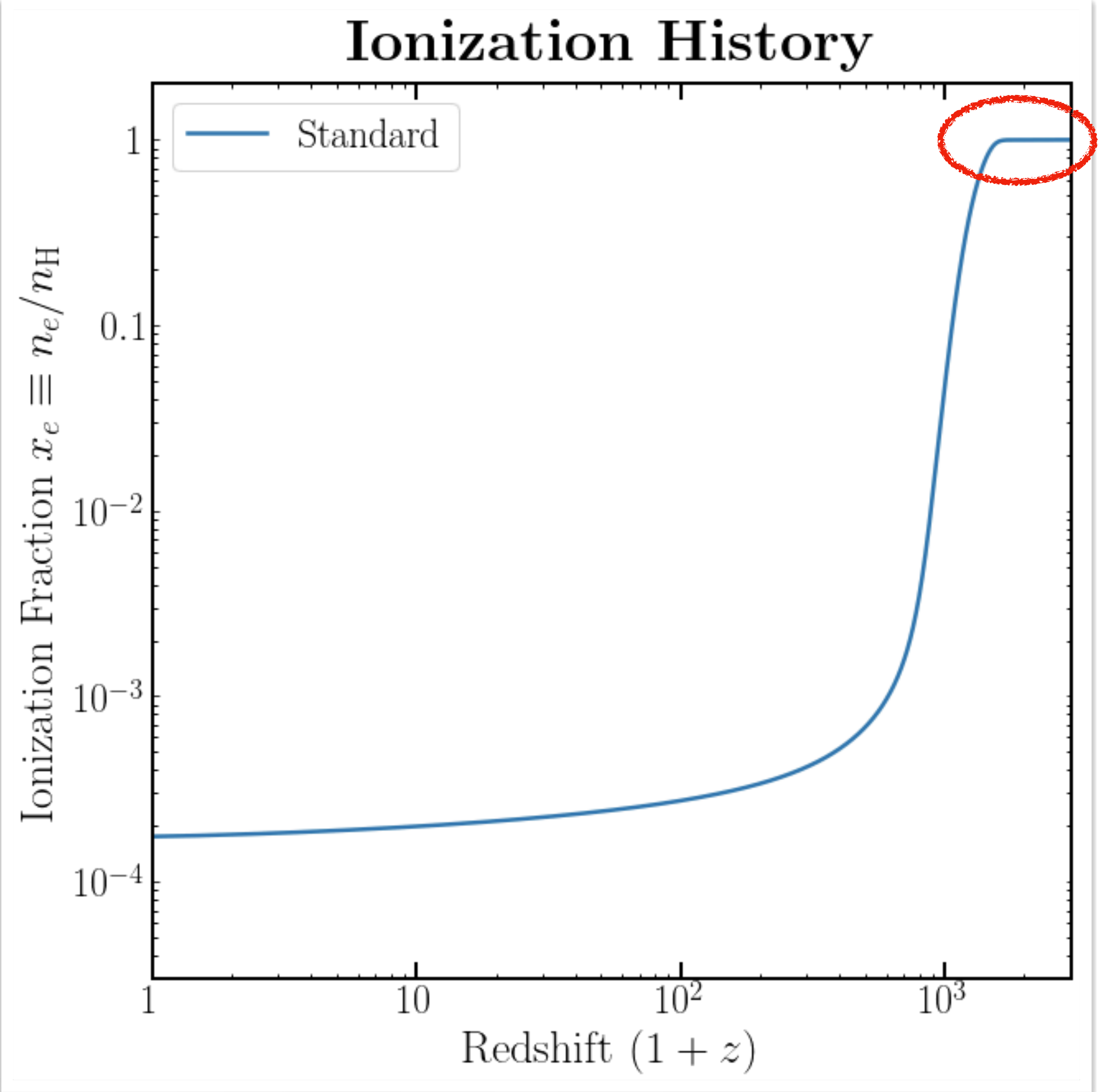
Complementary with other probes: much less dependent on Milky Way DM distribution/cosmic ray transport.

Dark matter energy injection can be constrained through cosmological probes, including IGM temperature measurements.

Backup Slides

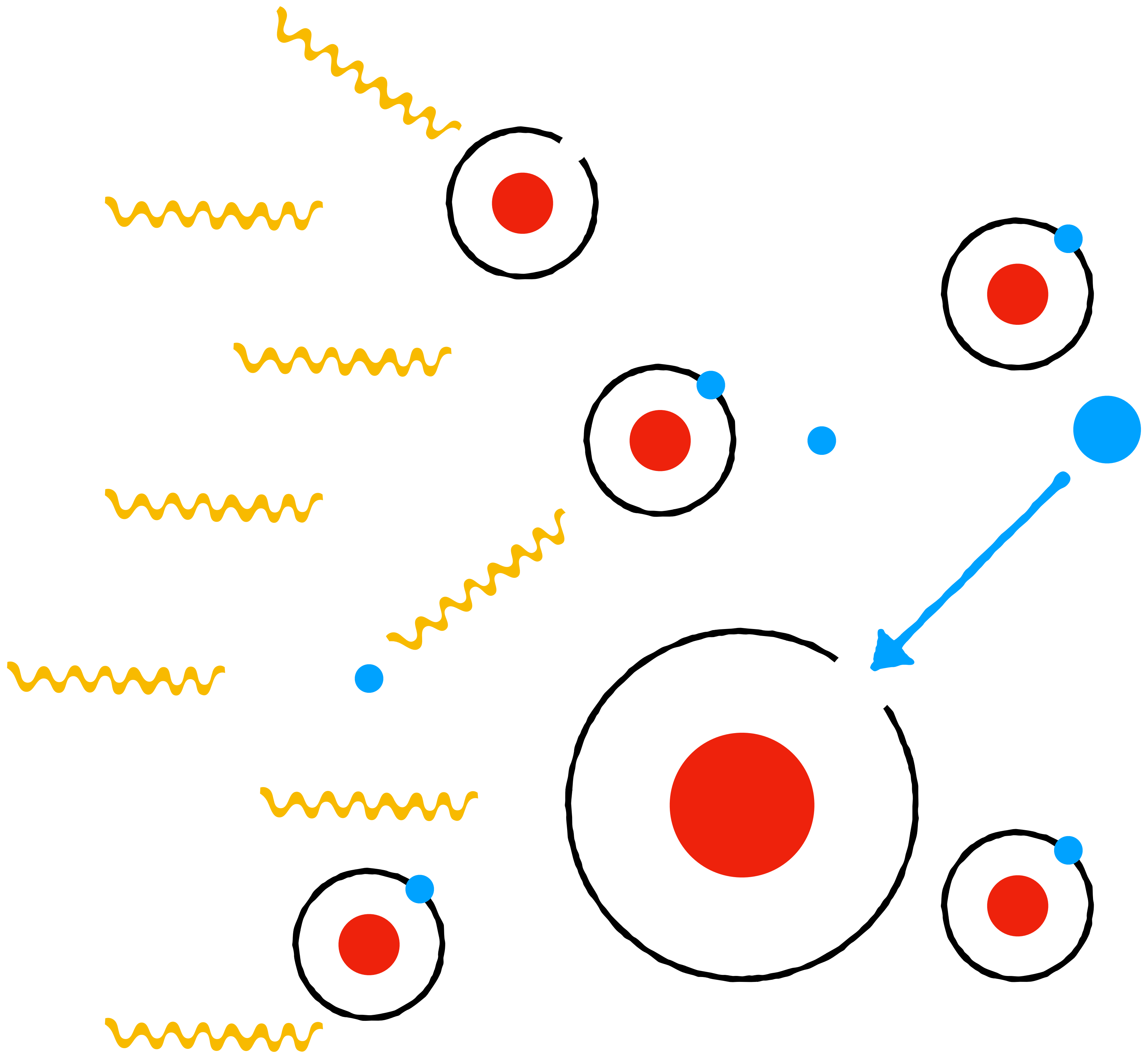
Recombination

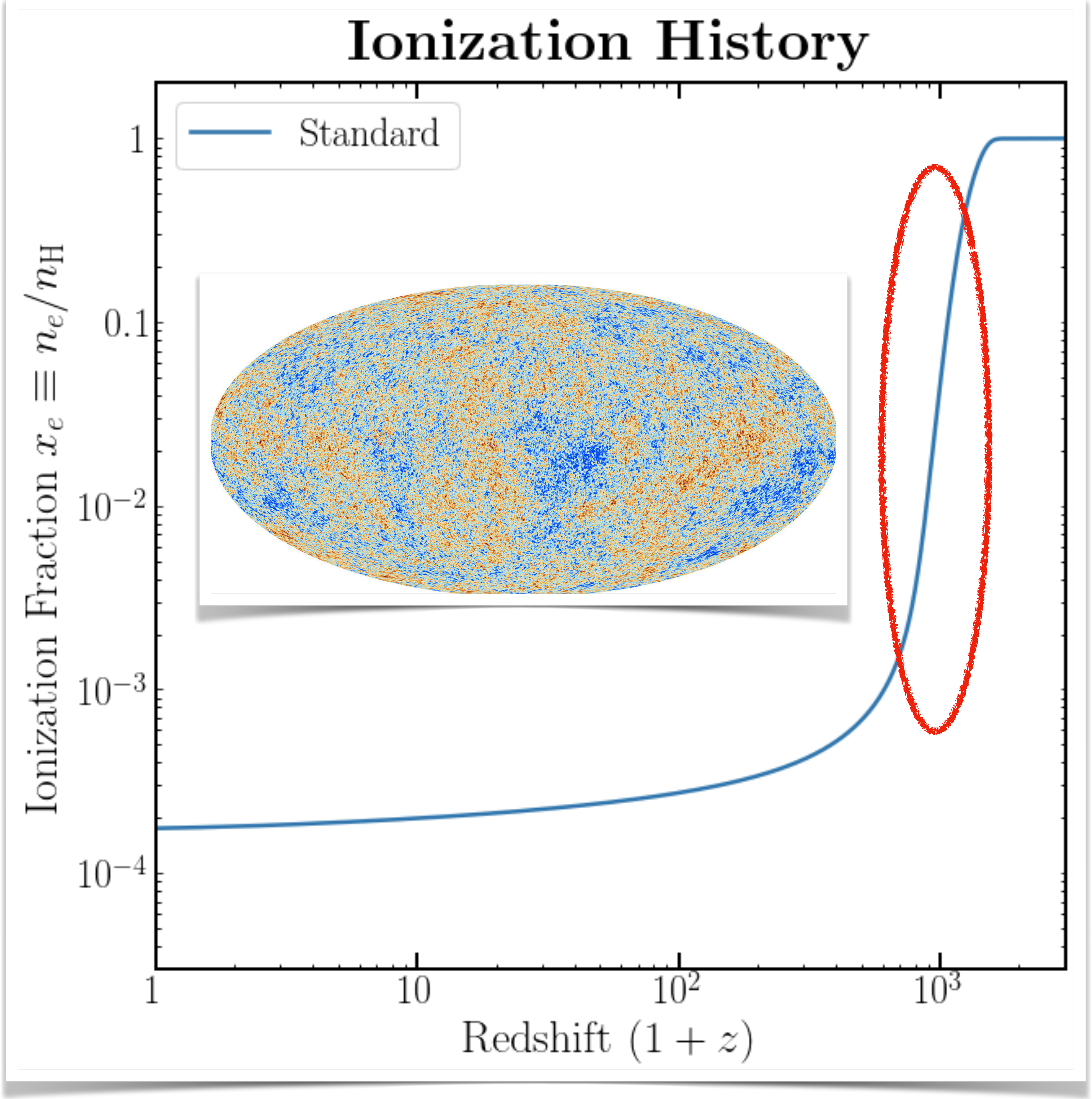




Photons with energy > 13.6 eV are **abundant**:
hydrogen atoms are **ionized**.

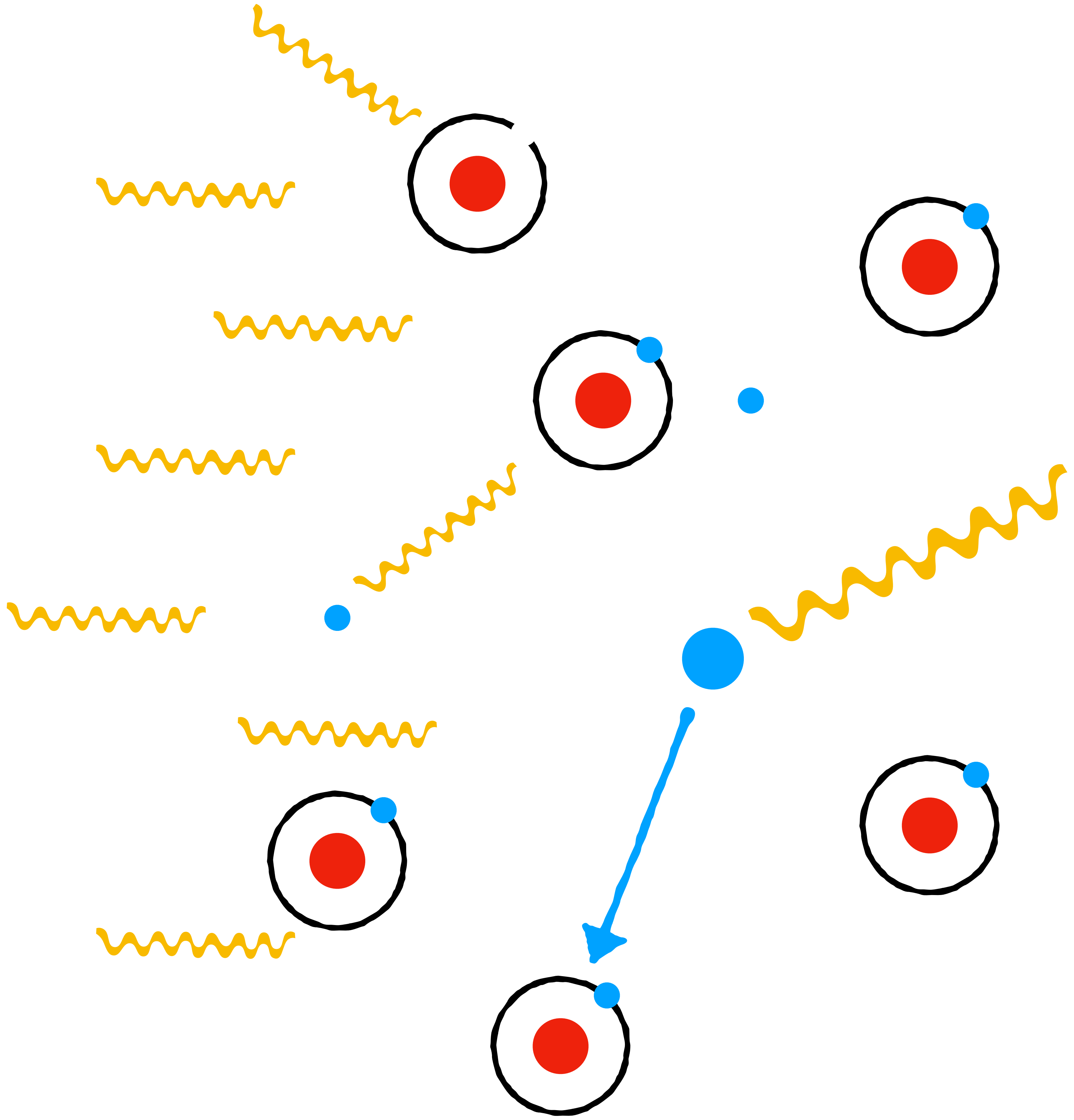
Recombination

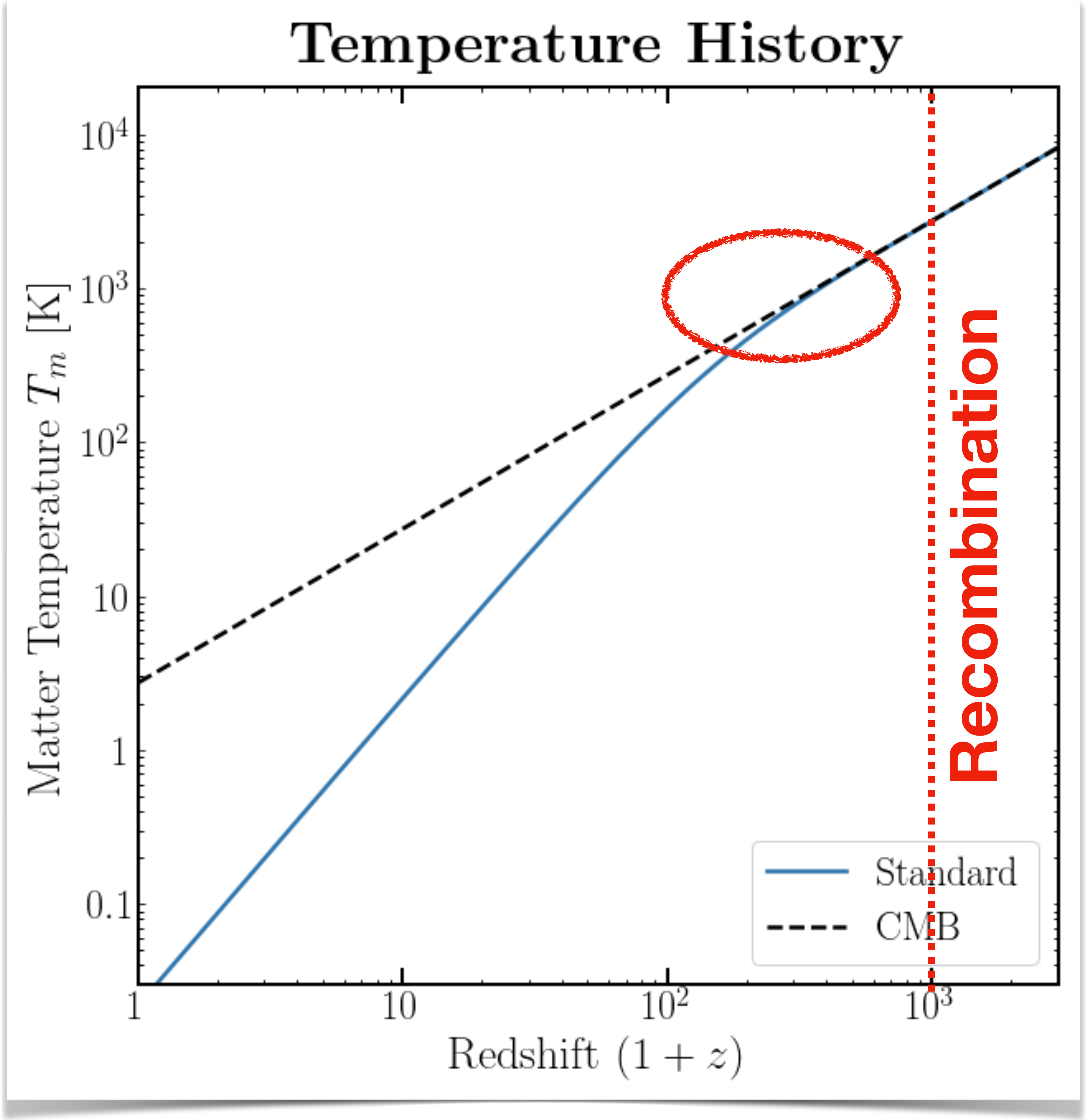




Universe expands, cools: protons and electrons **recombines**, Universe becomes **neutral** and **transparent**.

Thermal Decoupling

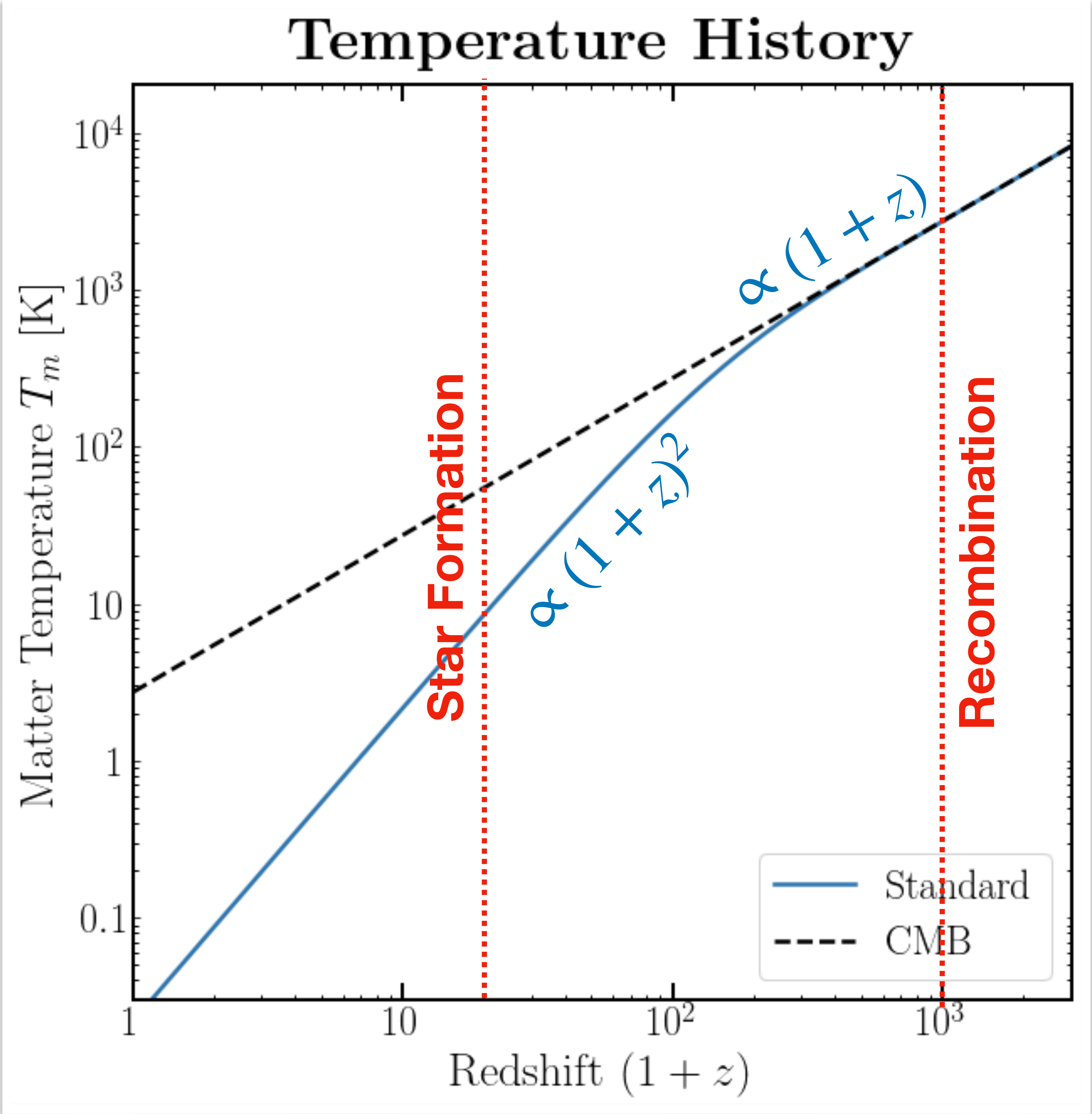




Compton scattering between free electrons and CMB photons keep matter and the CMB **in thermal contact** until $z \sim 150$.

Redshifting

Simple thermal history
between recombination and
star formation.



Three-Level Atom

Matter Temperature

Compton heating

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

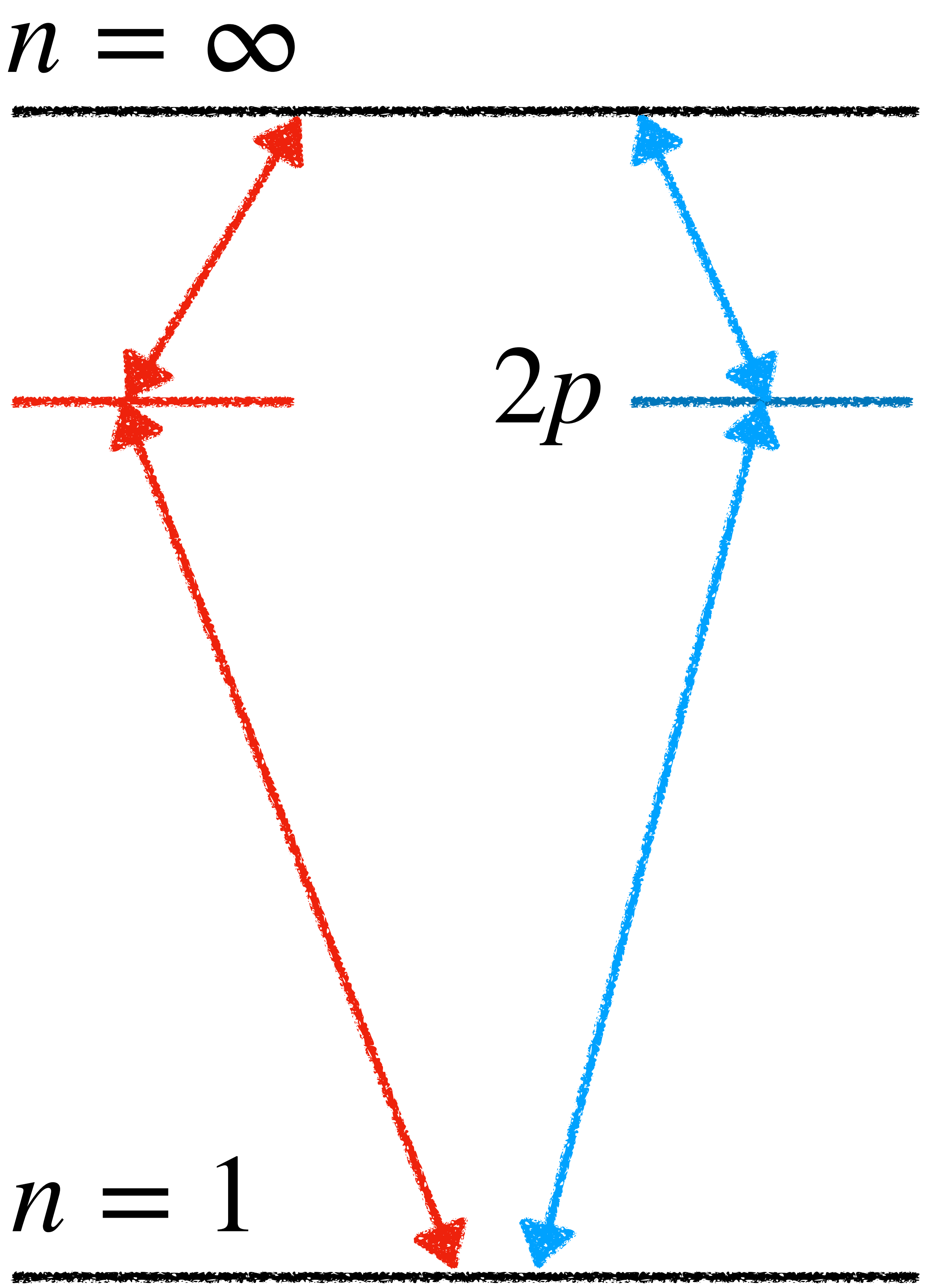
Adiabatic cooling

Ionization

Photoionization

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

Recombination



Peebles Astrophys. J 153, 1968
Zel'dovich+ Soviet Physics JETP 28, 1969

Simple model captures most of the physics of the cosmic ionization and thermal histories.

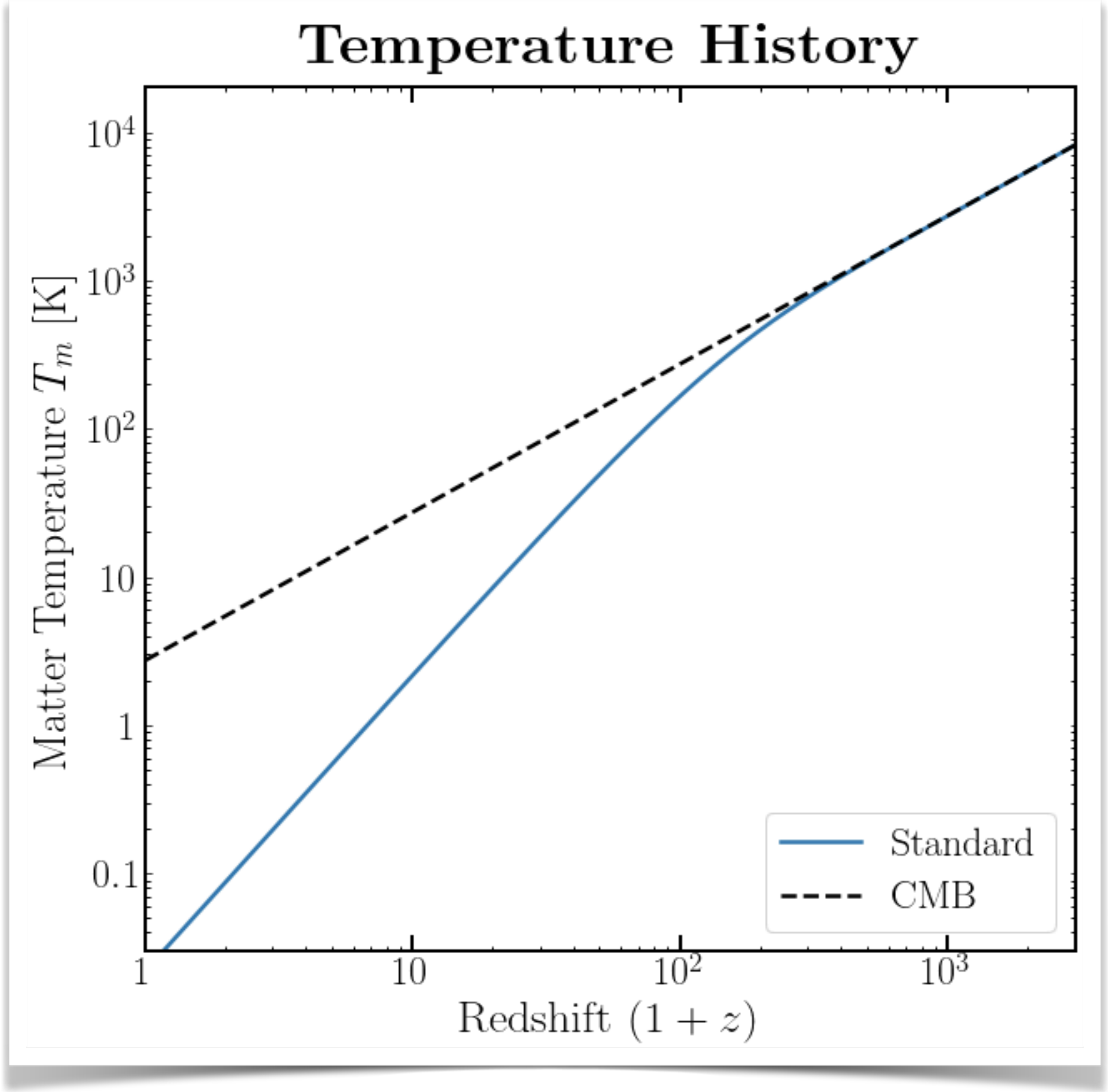
Three-Level Atom

Matter Temperature

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

Adiabatic cooling

Compton heating

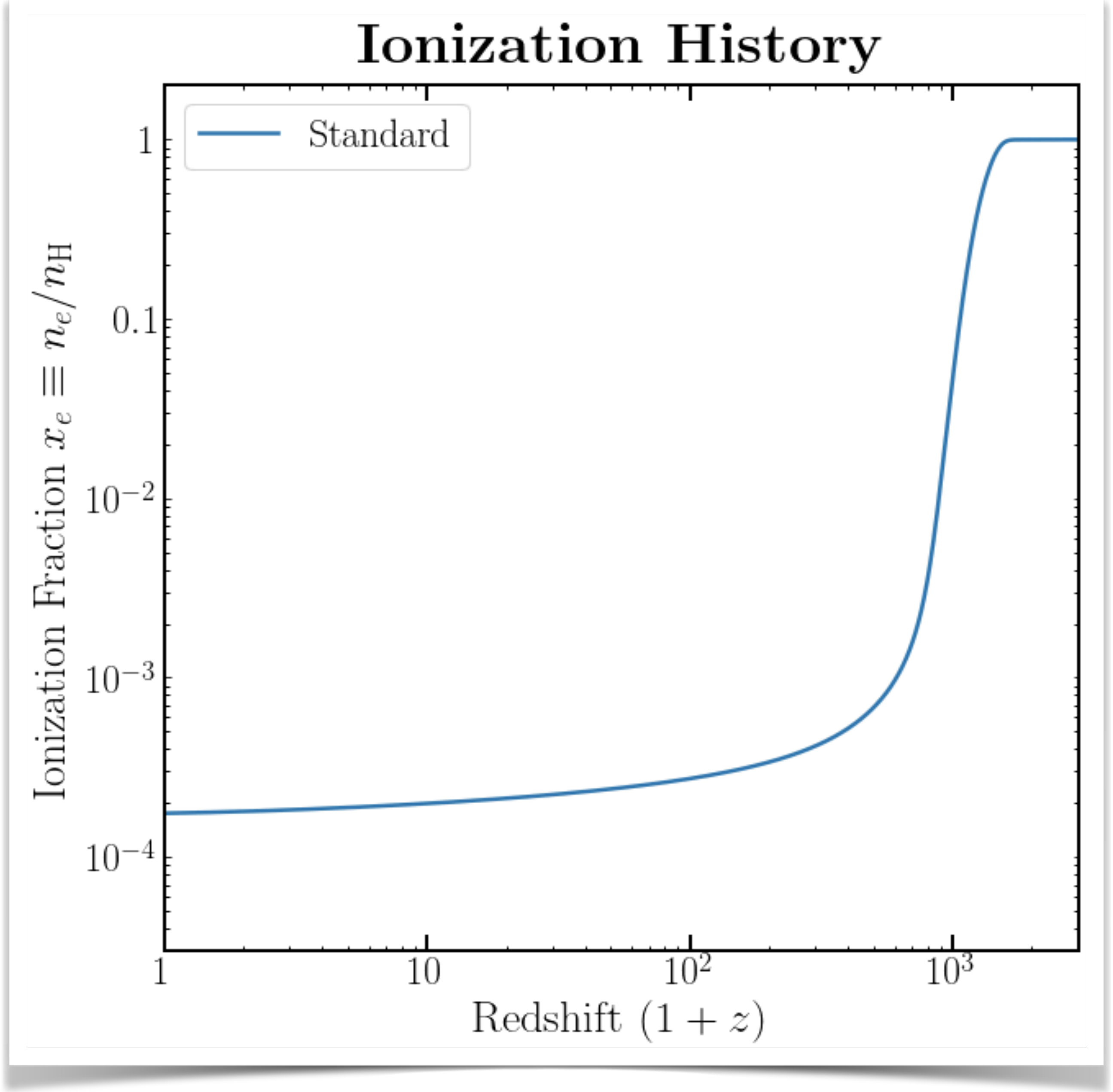


Ionization

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

Recombination

Photoionization



Dark Matter Effects

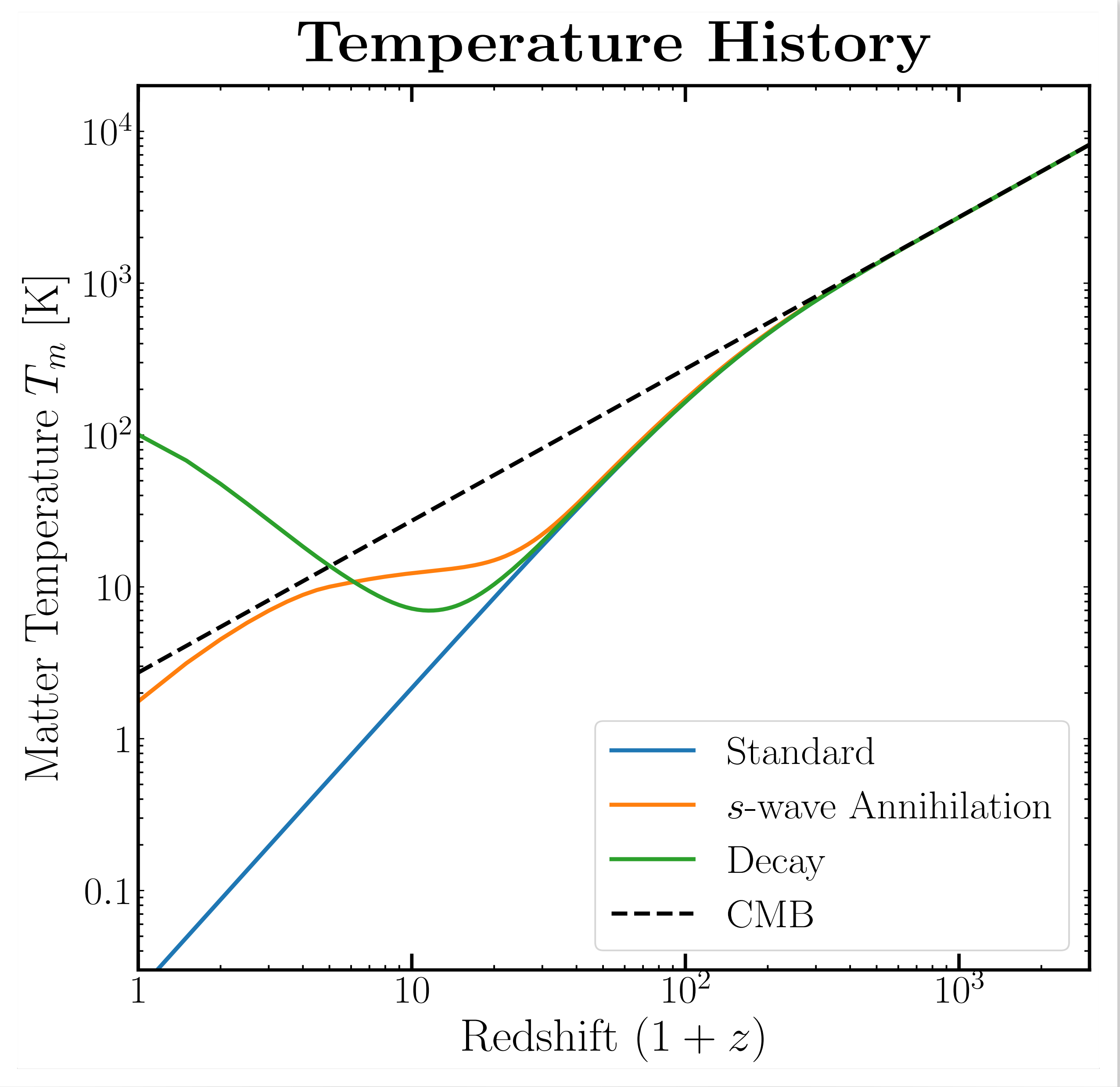
Matter Temperature

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

Adiabatic cooling

Compton heating

DM heating


Temperature History

Additional ionization from DM excitation

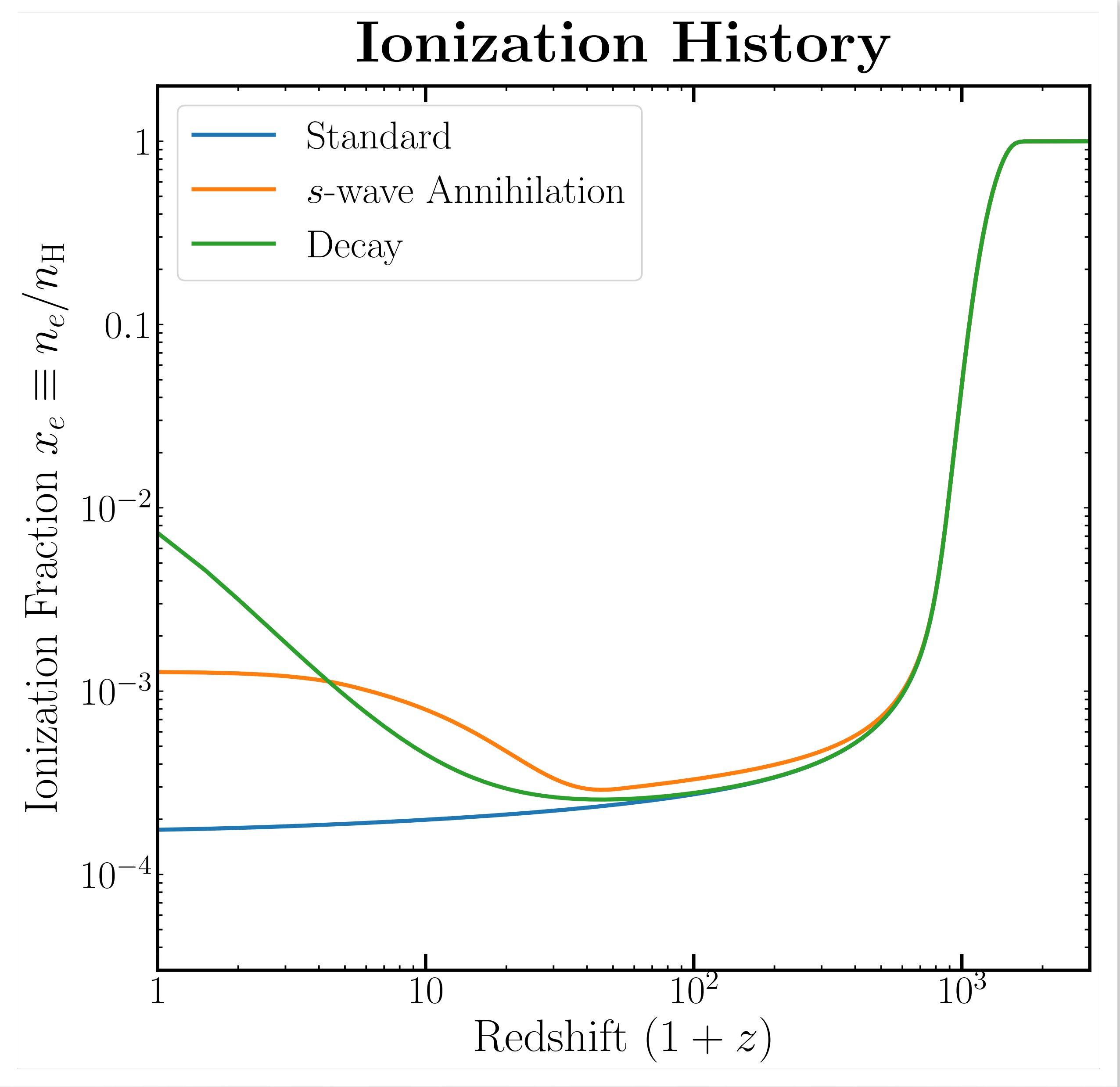
DM ionization

Ionization

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

Recombination

Photoionization


Ionization History

Calculating Deposition Efficiency with DarkHistory

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

Deposition Efficiency

Matter Temperature

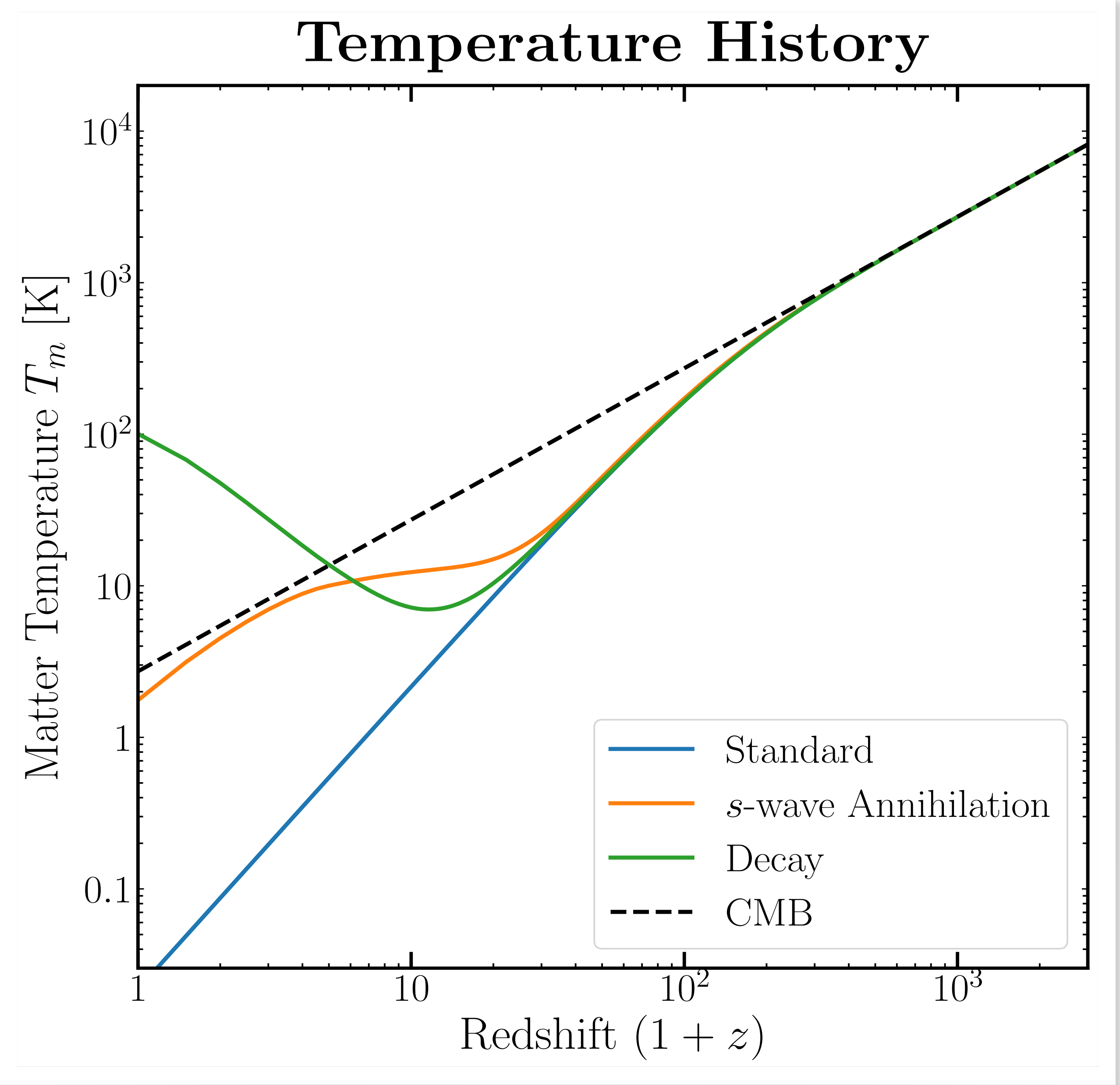
$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \frac{2f_{\rm heat}(z)}{3(1+f_{\rm He}+x_e)n_{\rm H}}\left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

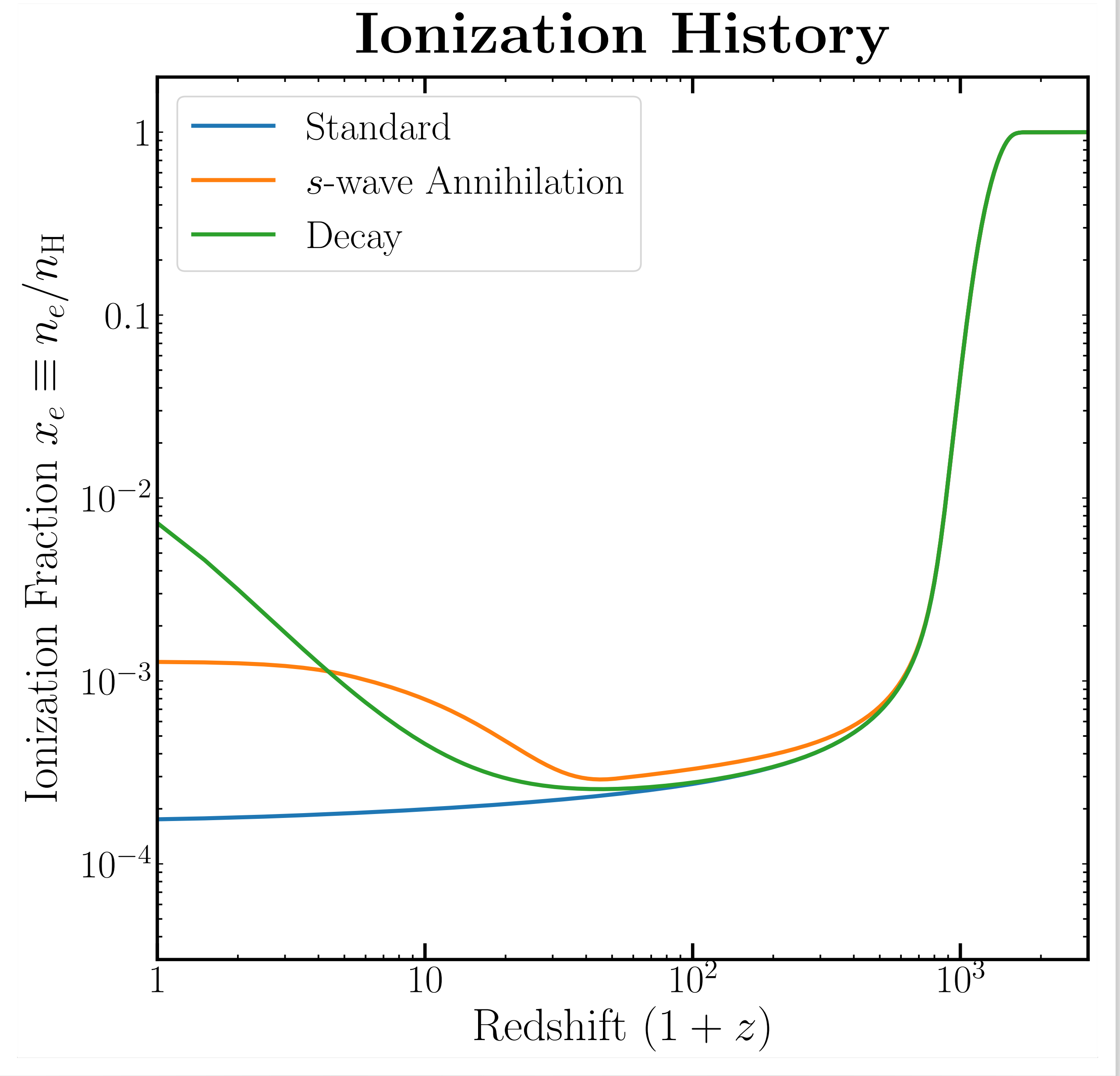
Deposition efficiencies are **nontrivial to calculate**.

Valdes+ 0911.1125
Galli+ 1306.0563
Slatyer 1506.03812
…

Ionization

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





Deposition Efficiency

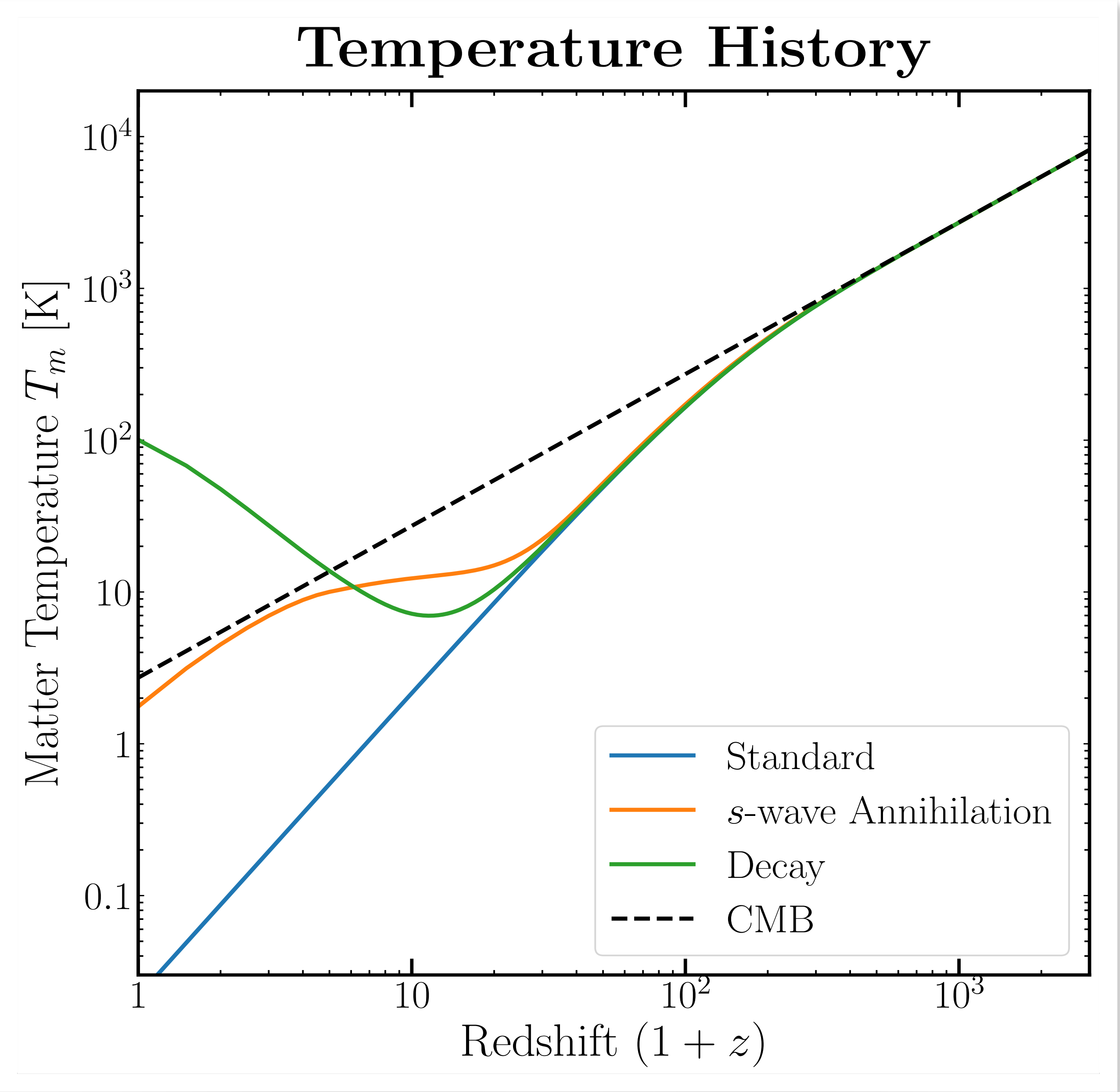
Matter Temperature

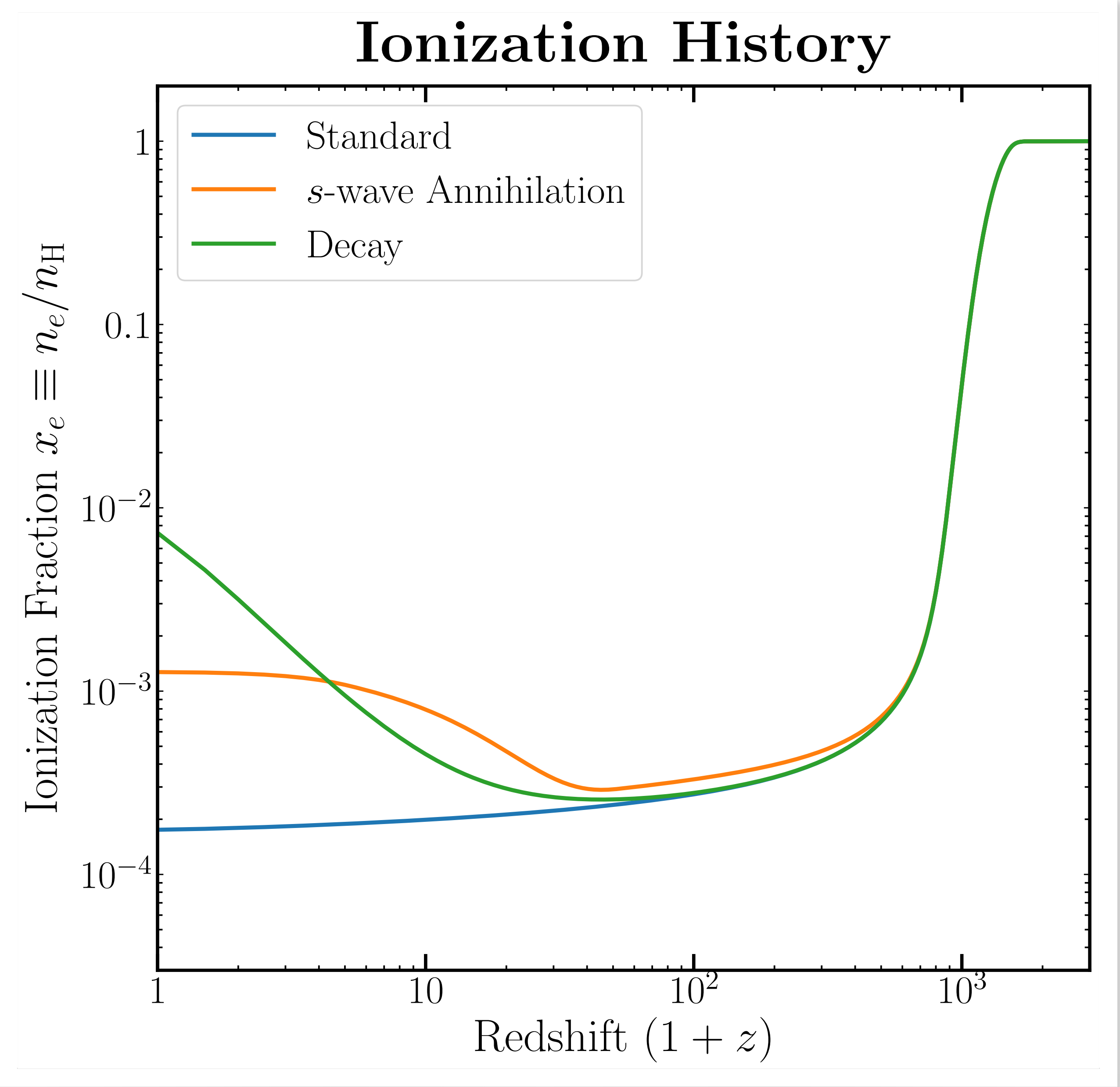
$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \frac{2f_{\rm heat}(z, \mathbf{x_e})}{3(1+f_{\rm He}+x_e)n_{\rm H}} \left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

Strongly dependent on **ionization**: previous calculations **assumed standard cosmic history**.

Ionization

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





Backreaction

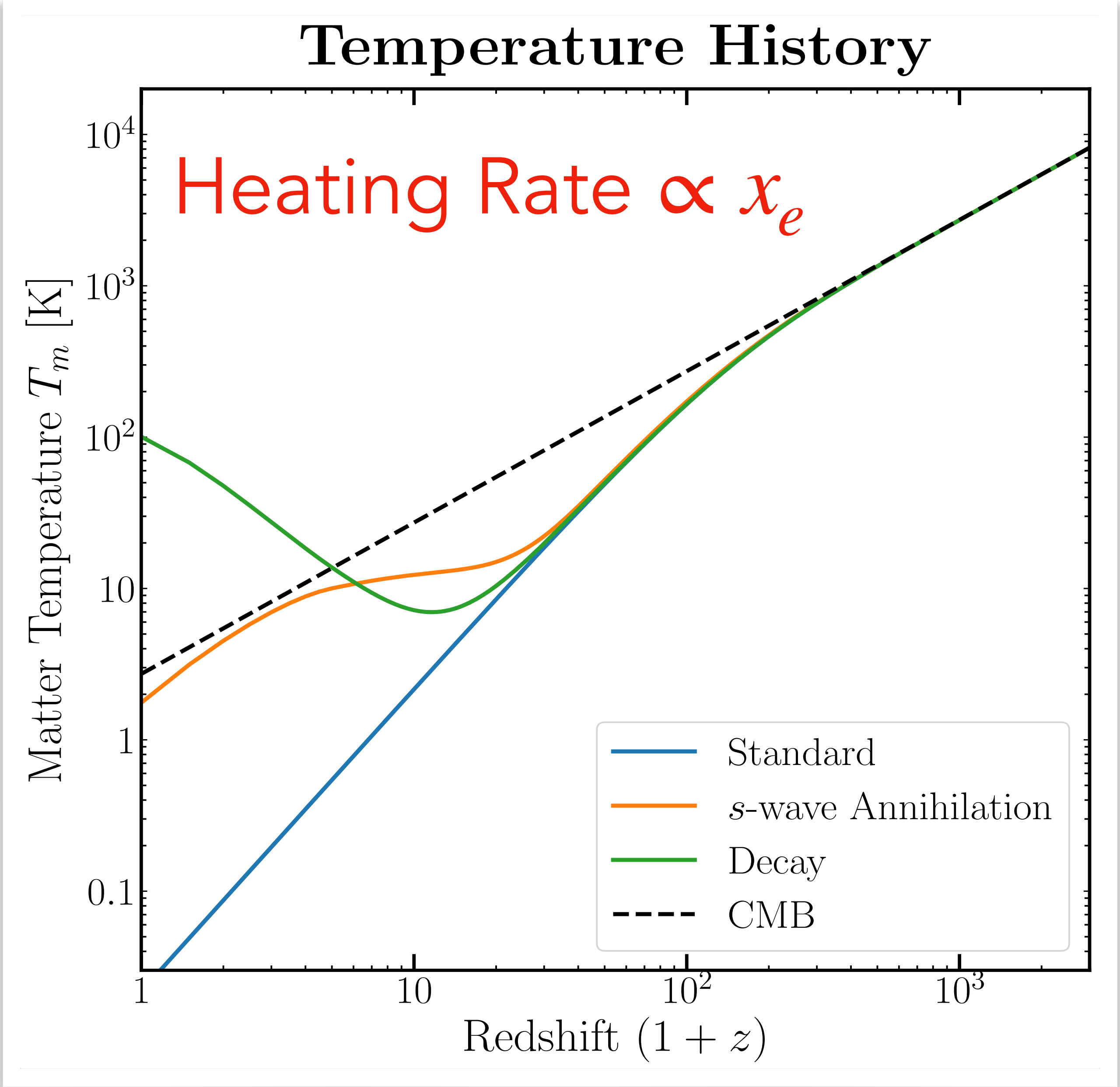
Matter Temperature

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

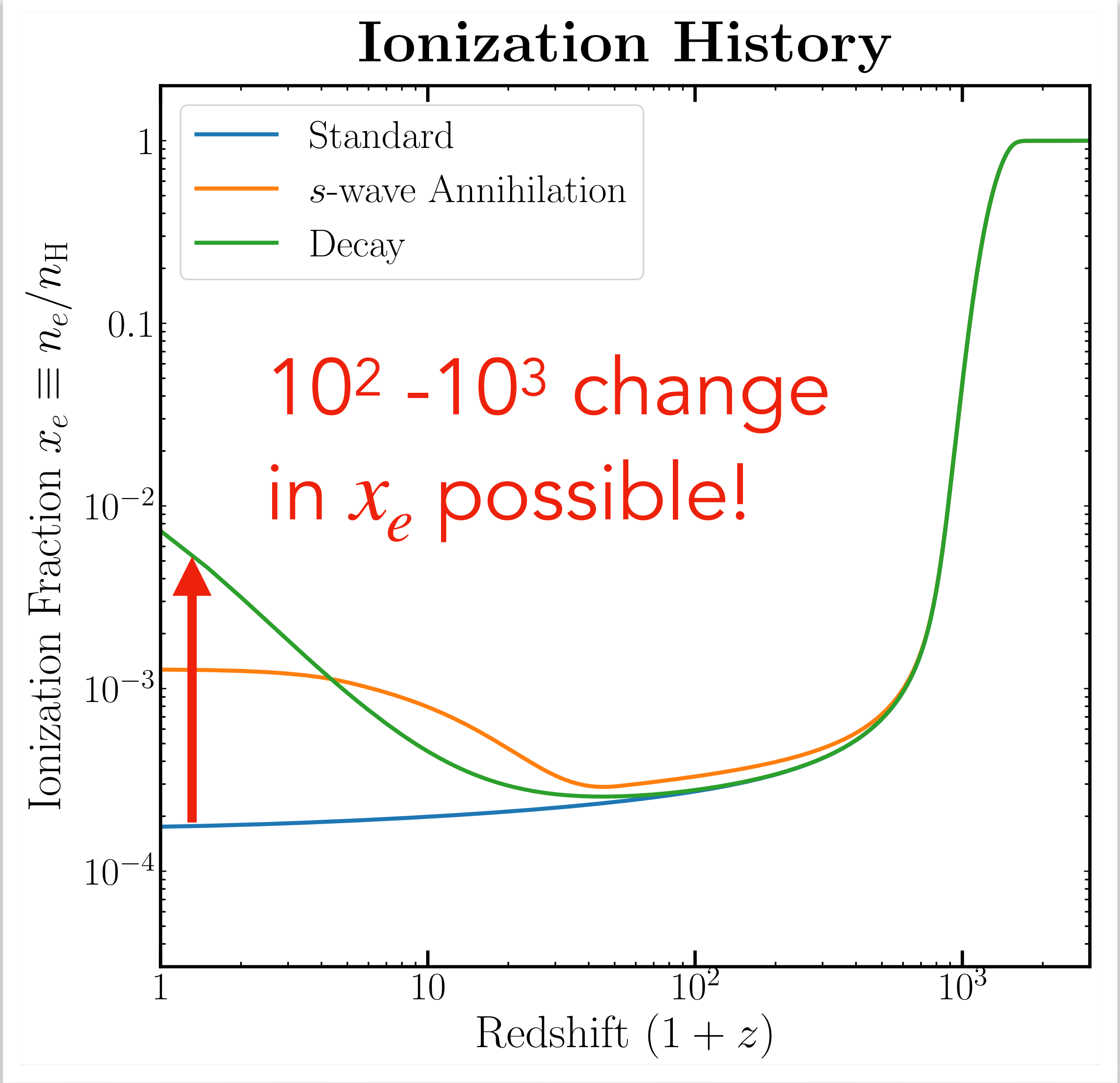
Increased ionization leads to **increased heating efficiency**: accounting for **backreaction** important for accurate temperature histories.

Ionization

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

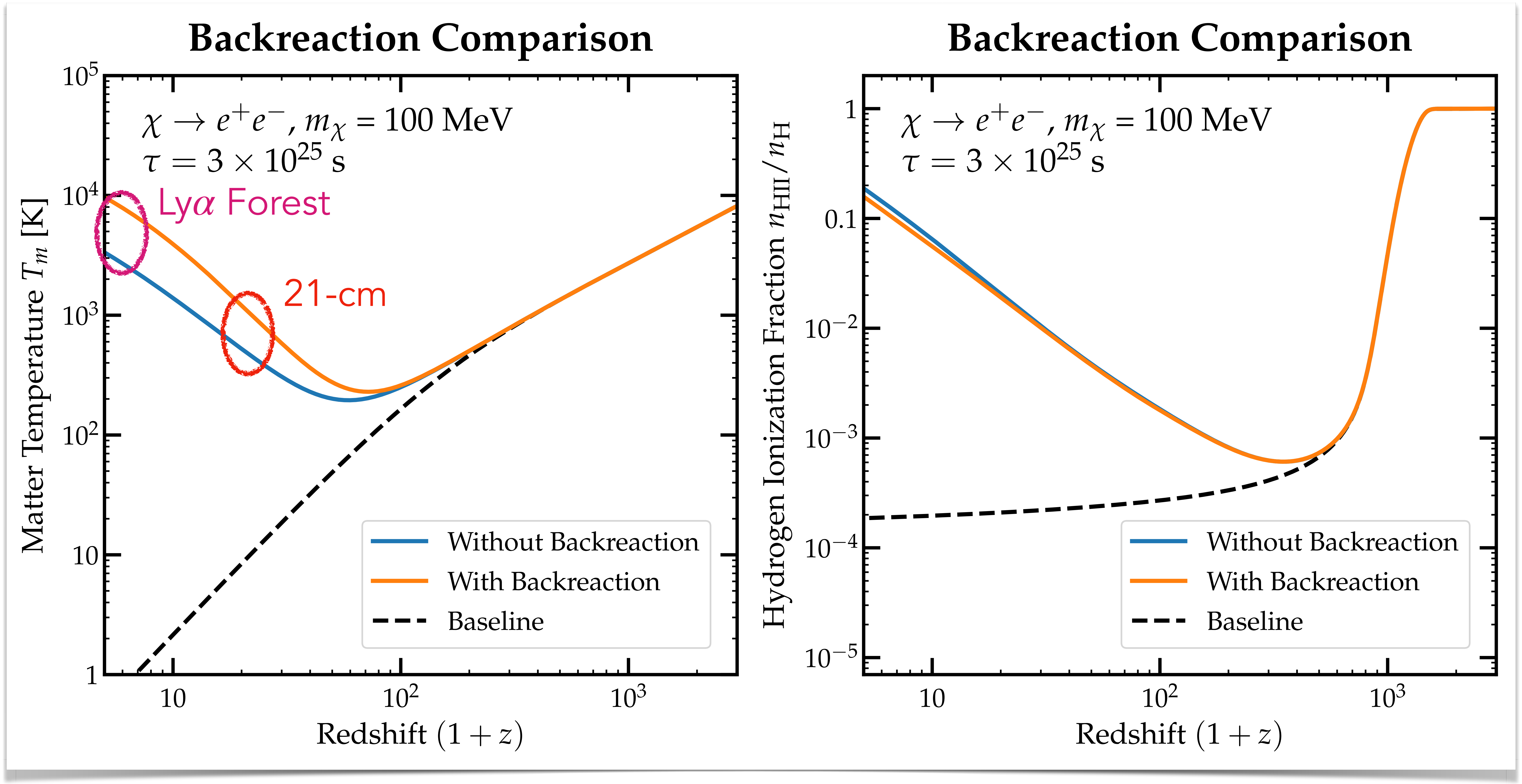


Heating Rate ∝ x_e



10^2 -10^3 change in x_e possible!

Backreaction



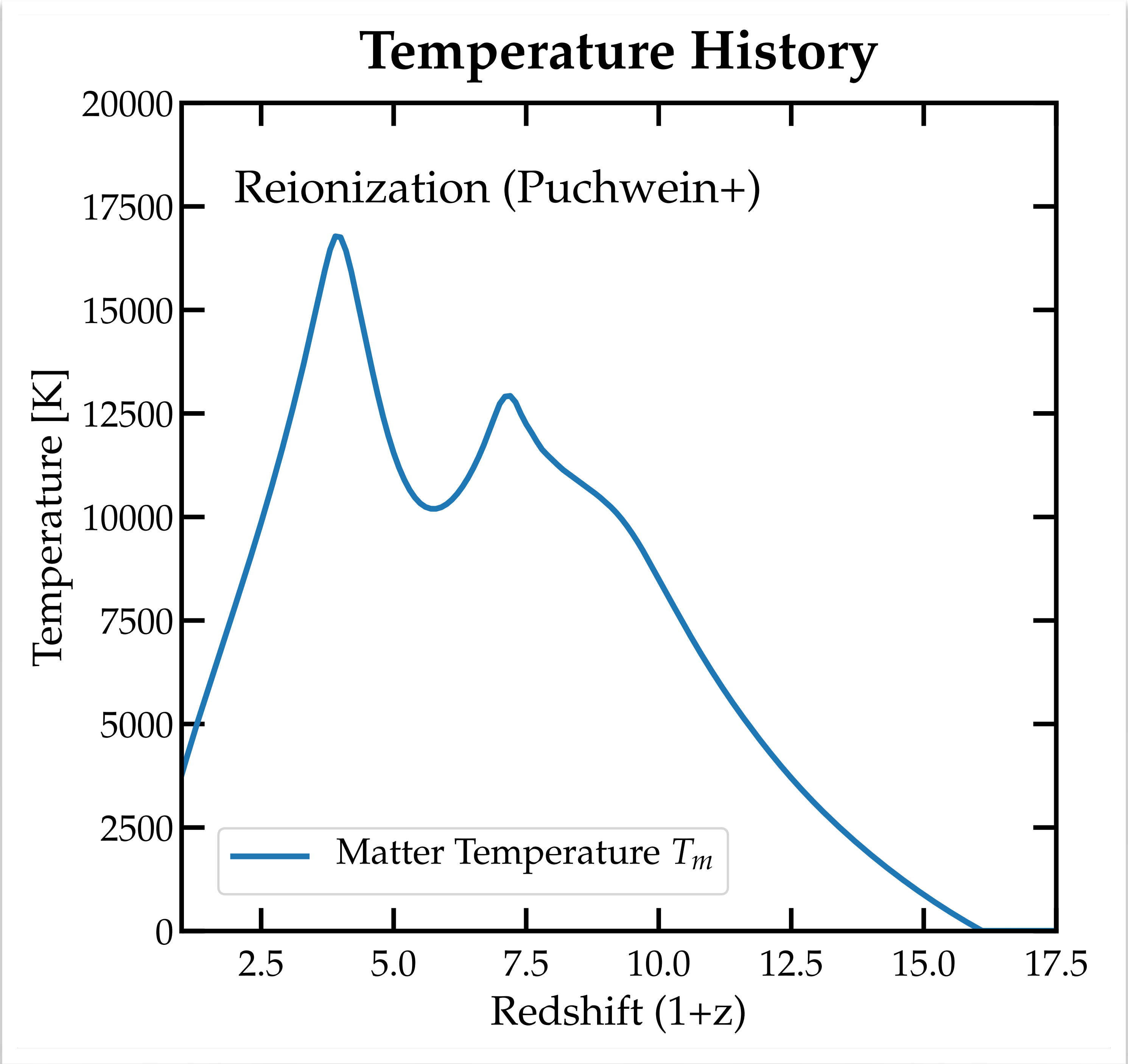
Important for accurate temperature calculations.

Reionization

Matter Temperature

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

Photoionization rate, photoheating rate,
recombination cooling, bremsstrahlung cooling…



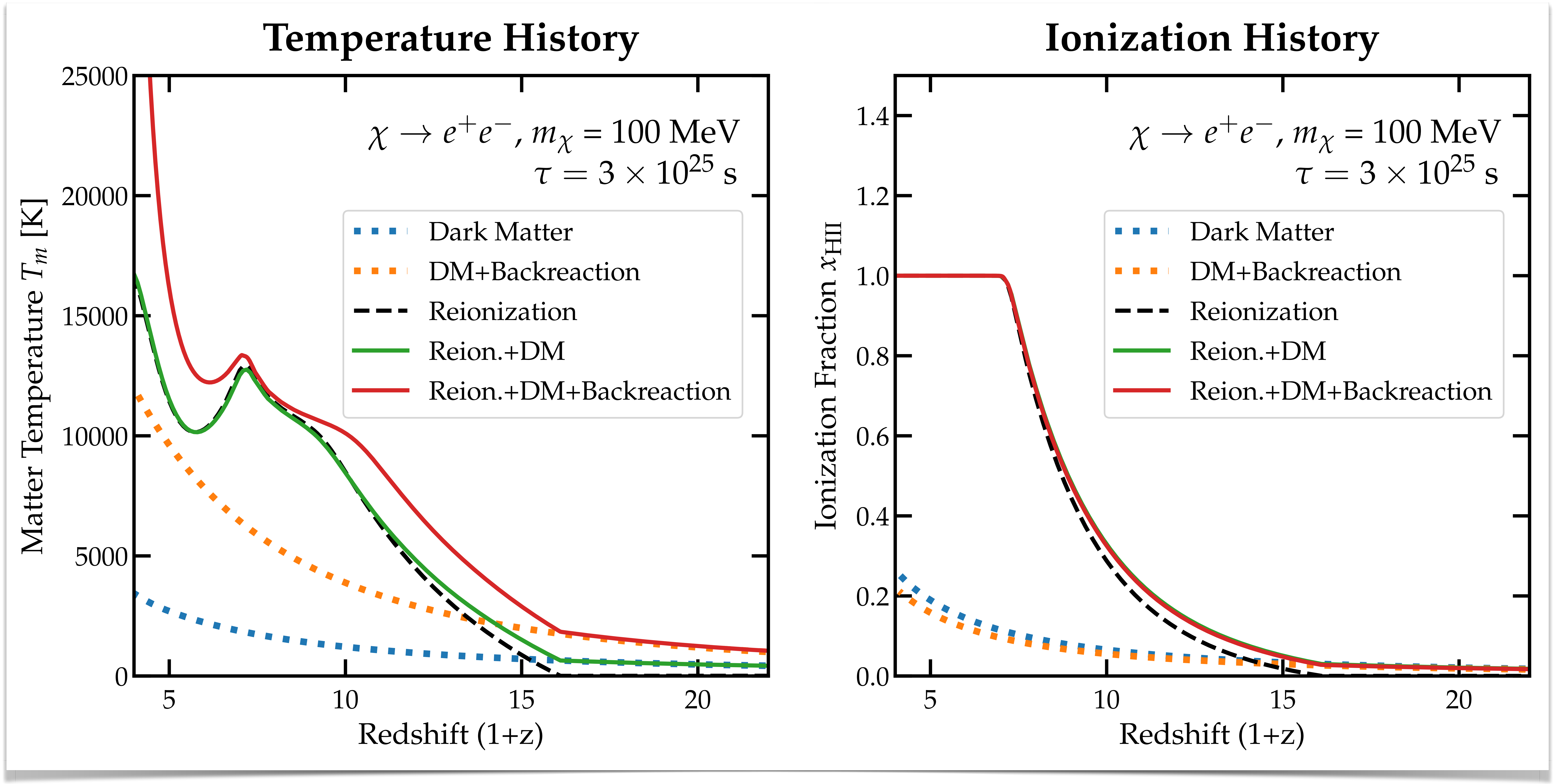
Puchwein+ 1801.04931

Ionization

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

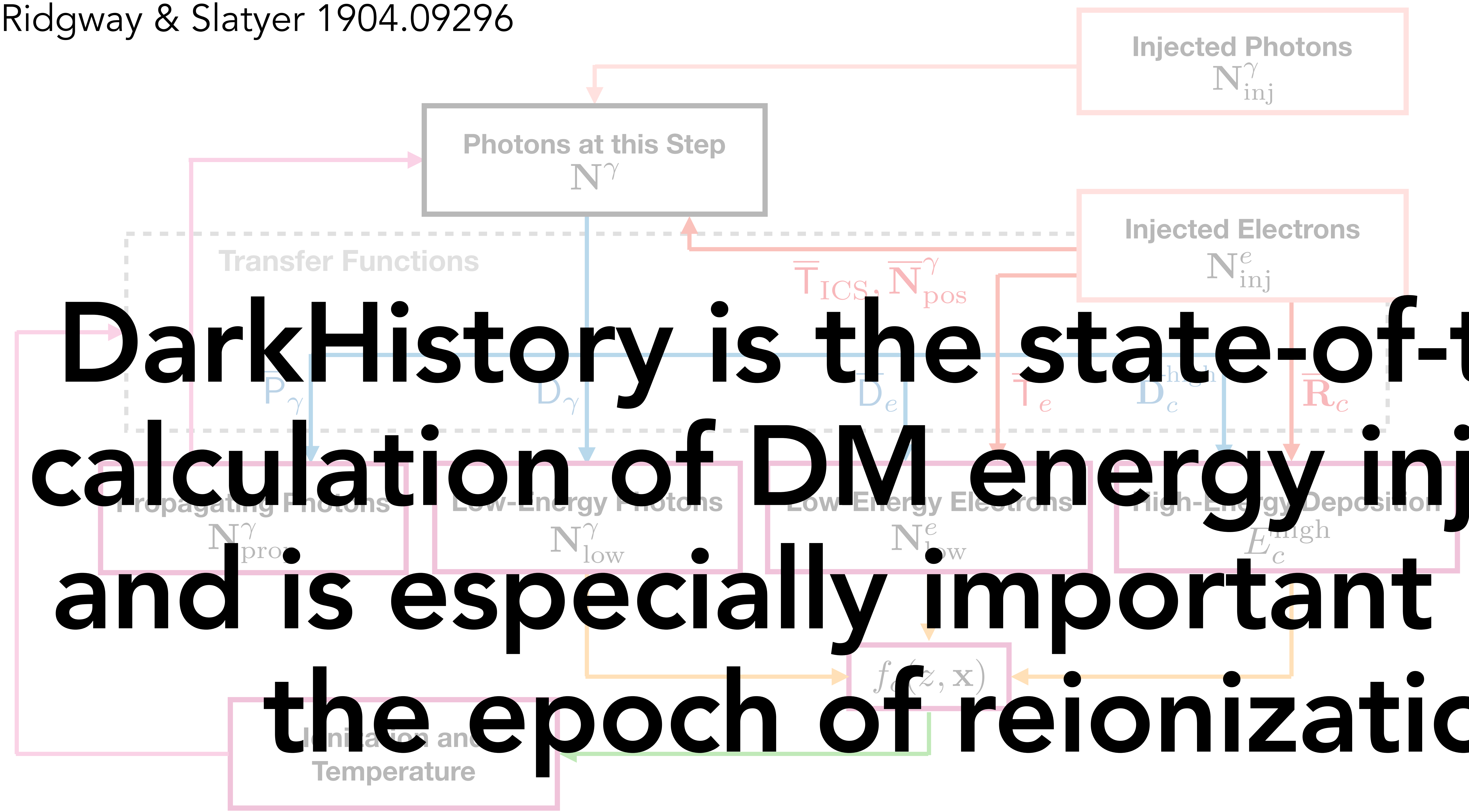
Given a model for reionization, we can now track **dark matter and reionization** self-consistently.

Reionization + Dark Matter



HL, Ridgway & Slatyer 1904.09296

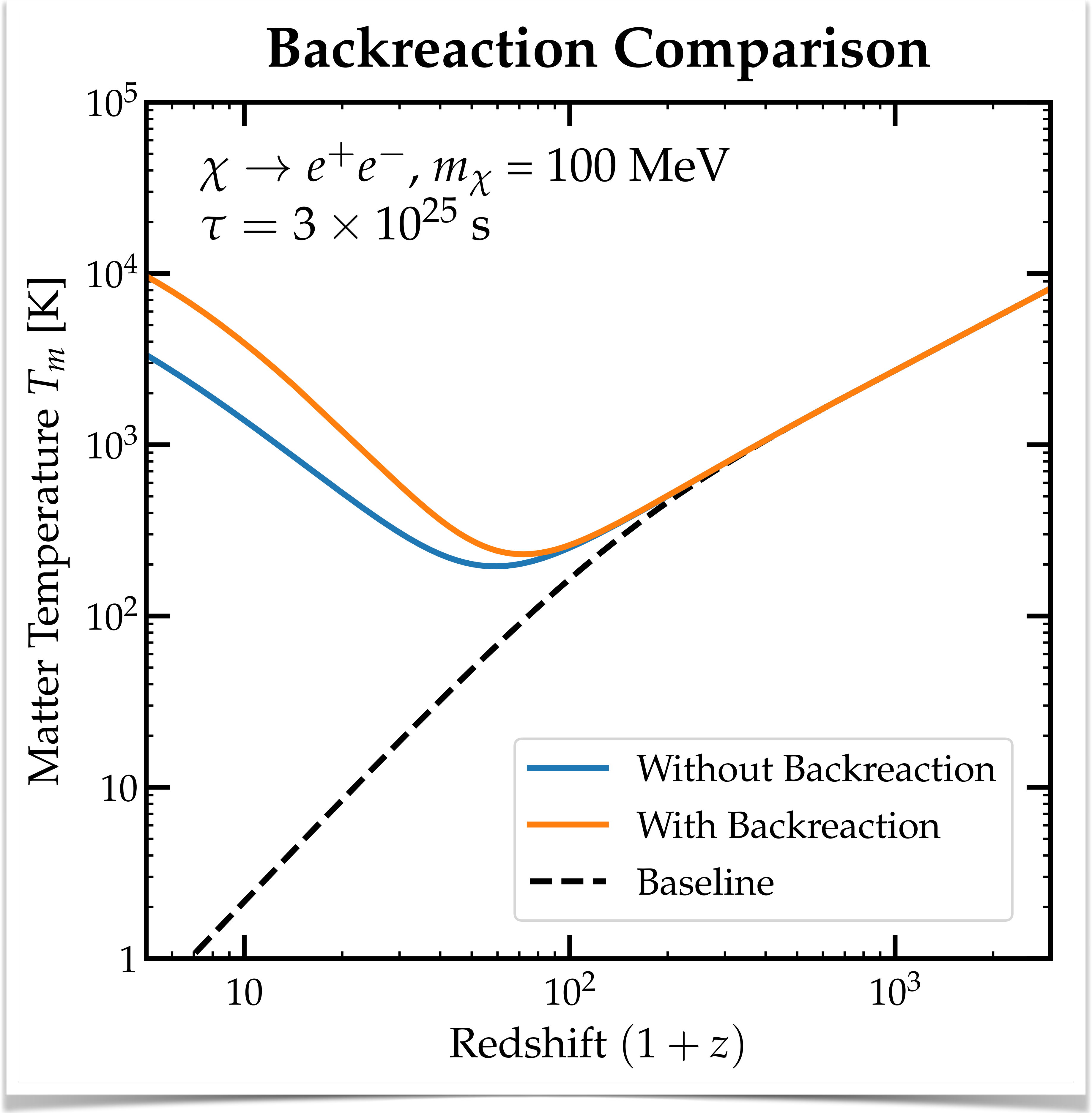
DarkHistory is the state-of-the-art calculation of DM energy injection, and is especially important during the epoch of reionization.



STEPS	RELEVANT MODULES
1. Input	1. `main`
2. Electron Cooling	2. `darkhistory.electrons`
3. Photon Propagation and Deposition	3. `main`
4. Calculating $f_c(z, \mathbf{x})$	4. `darkhistory.low_energy`
5. TLA Integration and Reionization	5. `darkhistory.history`
6. Next Step	6. `main`

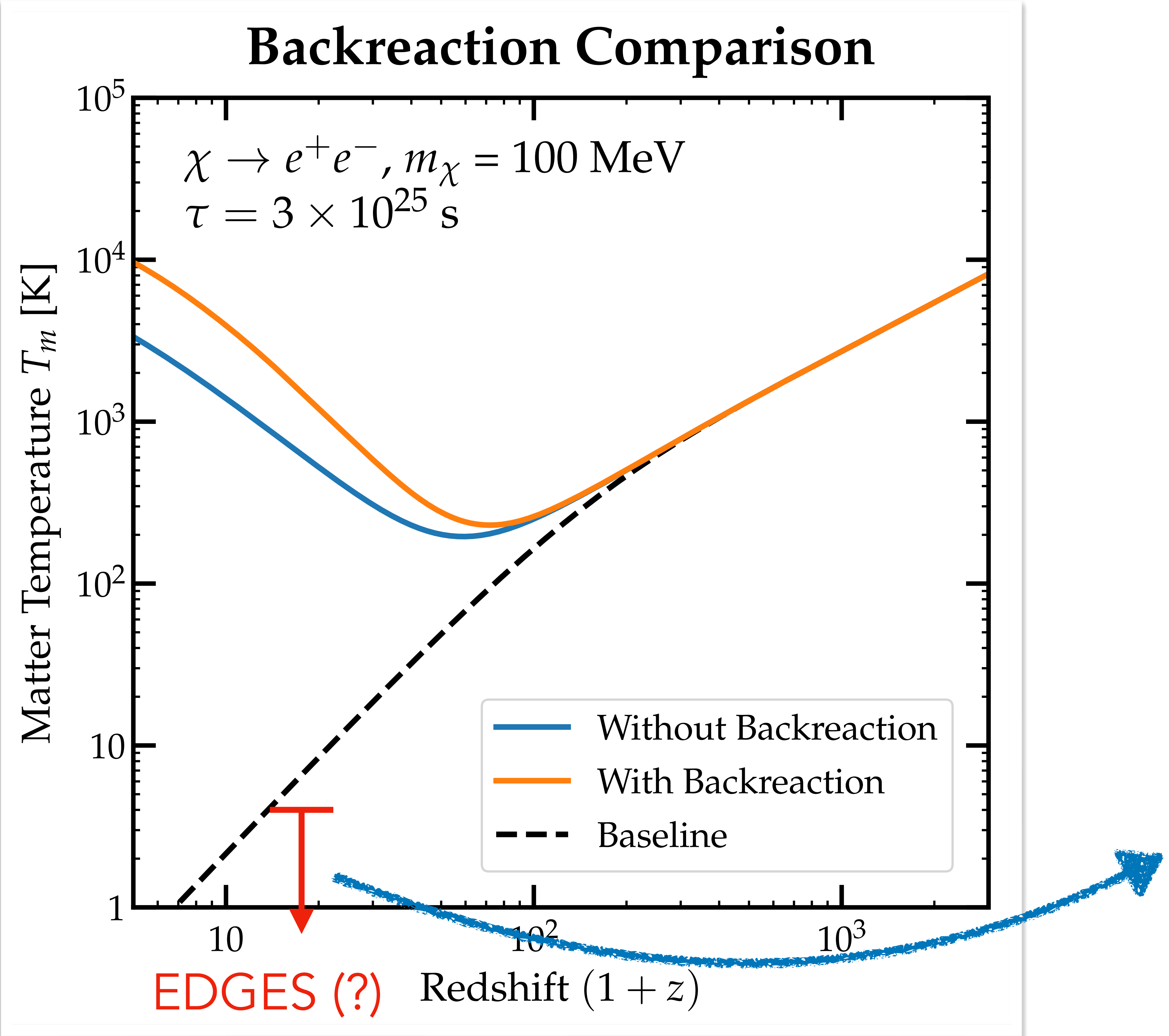
github.com/hongwanliu/DarkHistory

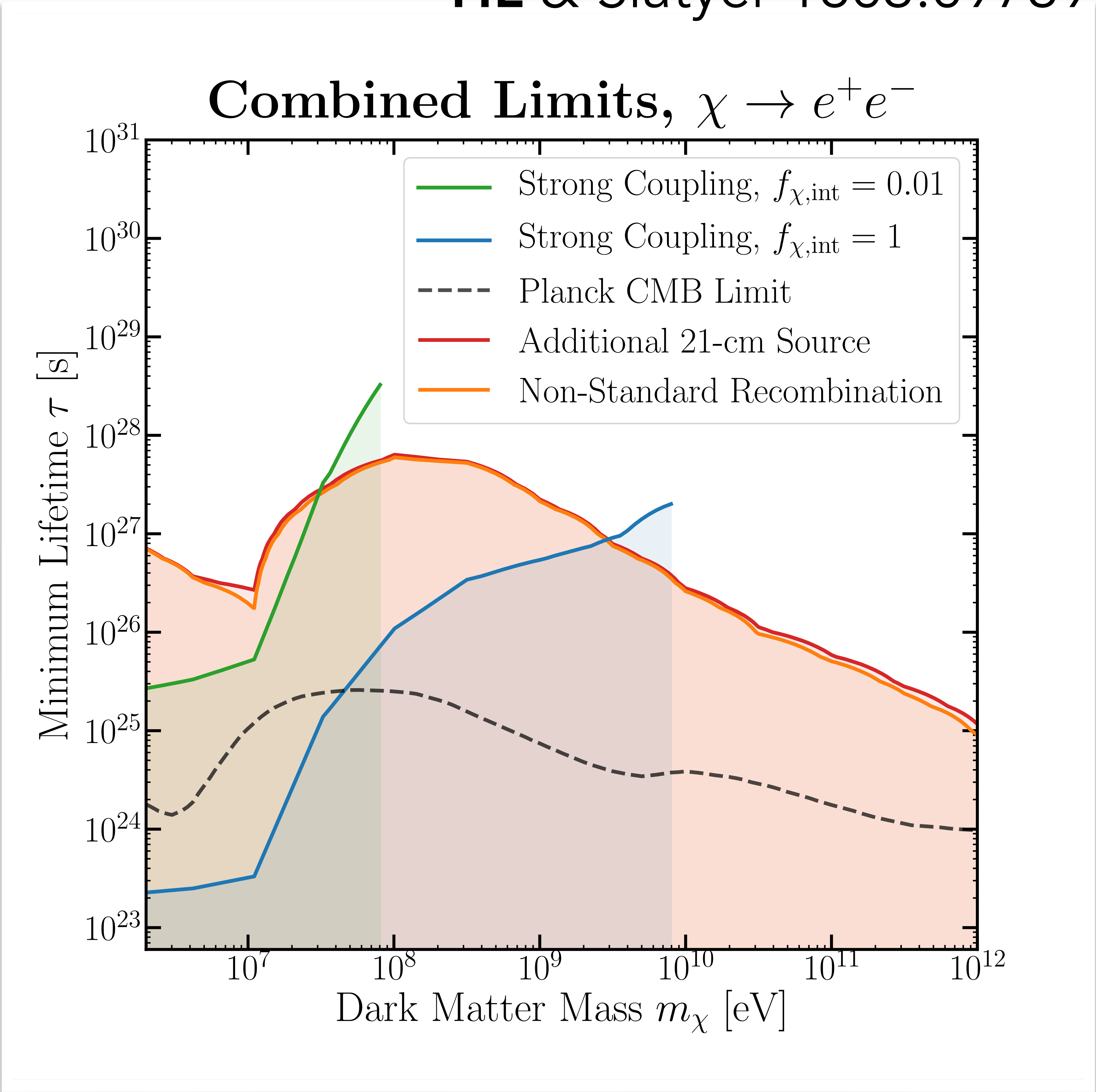
Temperature Probes



Temperature Probes

HL & Slatyer 1803.09739





21-cm is potentially very **sensitive** to DM energy injection.

many other relevant results, including Lopez-Honorez, Vincent+ 1603.06795 …

Temperature History

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

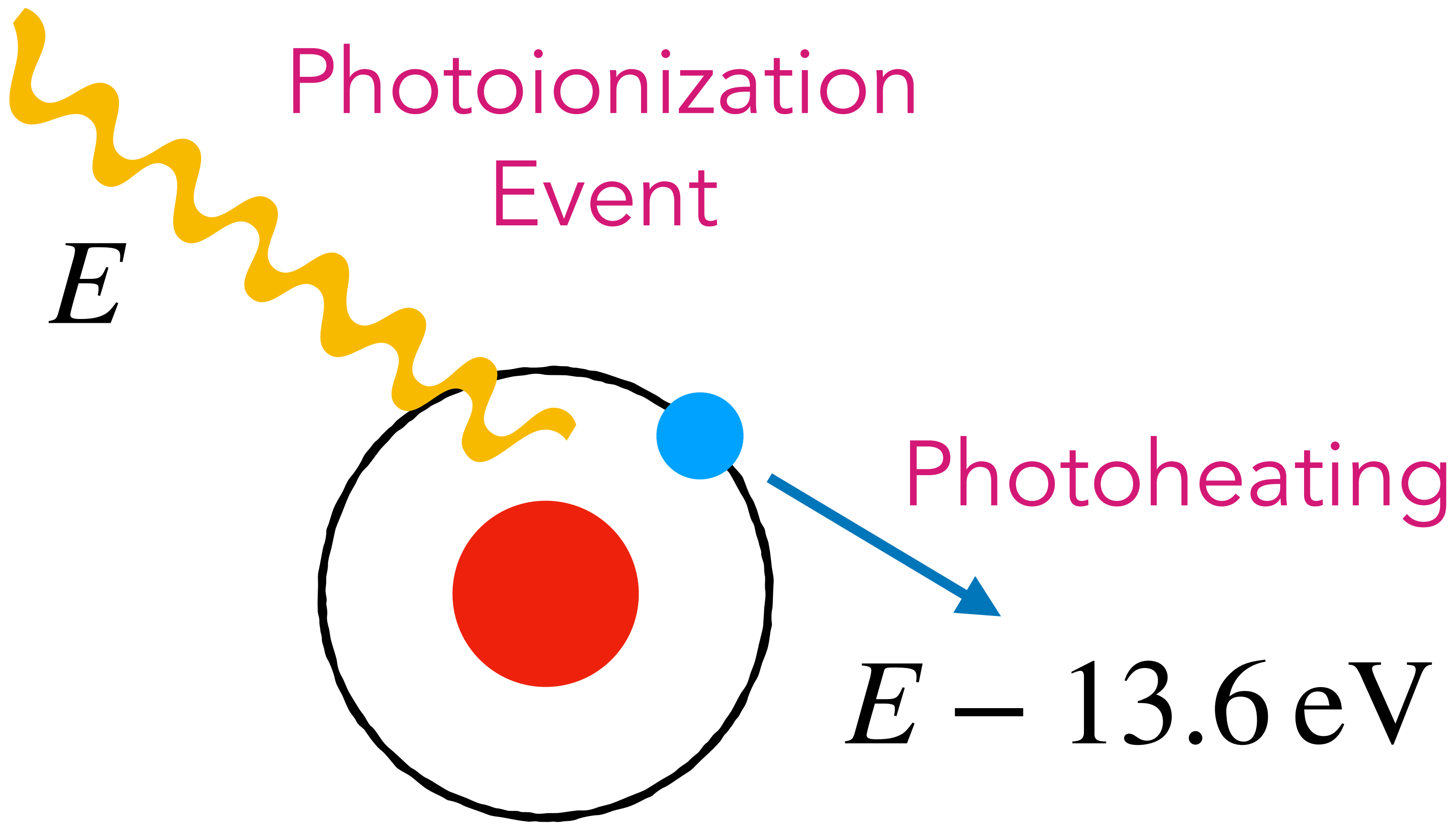
Adiabatic cooling

Compton heating

DM heating

Atomic cooling

Photoheating



Photoionization Event

E

Photoheating

$E - 13.6\,\mathrm{eV}$

Case-A recombination coefficient

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

Upton Sanderbeck+ 1511.05992

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

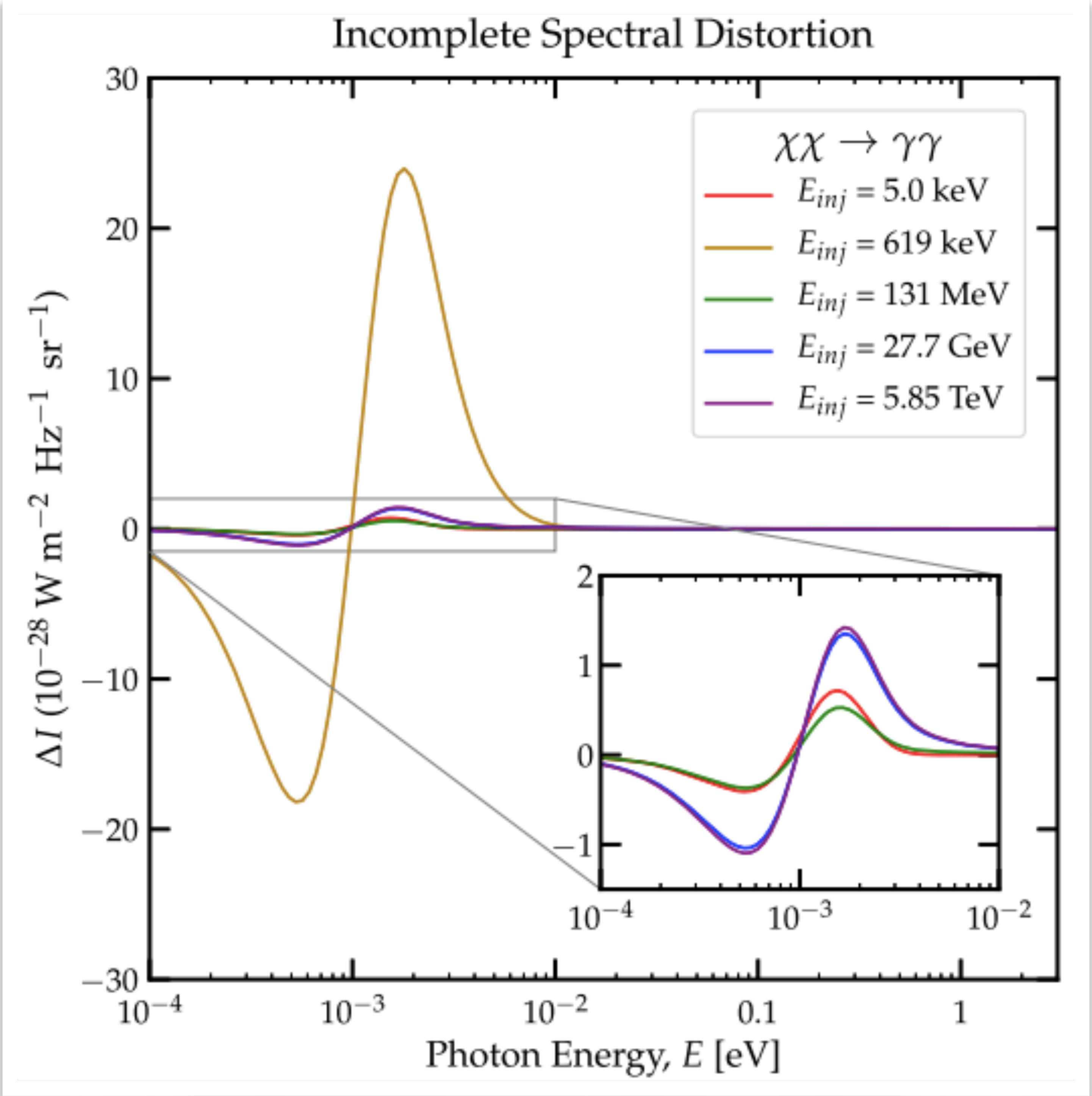
Spectral index near ionization threshold, $J_\nu \propto \nu^{-\alpha_{\rm bk}}$

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

Future Work

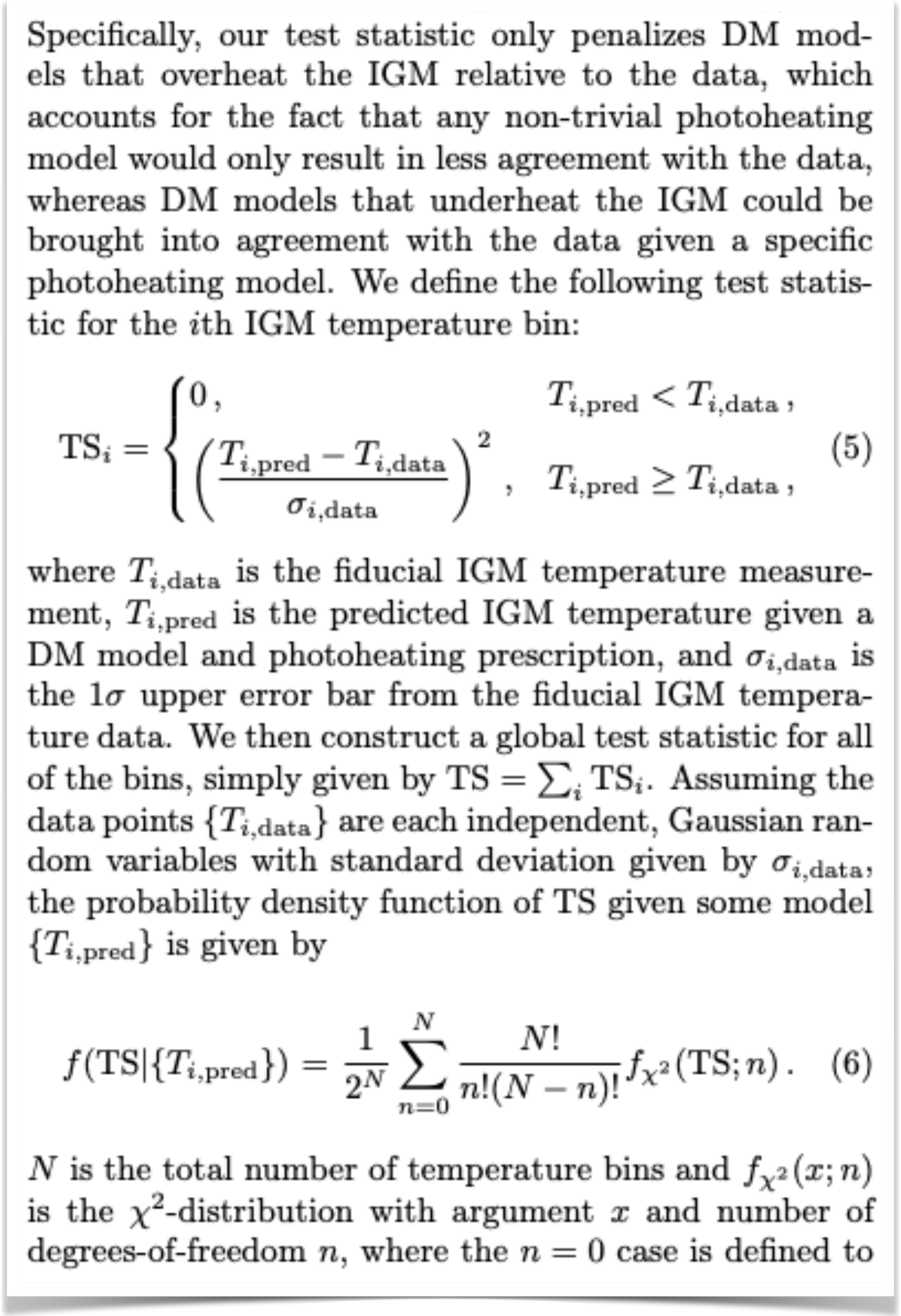
1. Computing **spectral distortions** from DM energy injection in full.
2. **Improved calculation** of energy injection: many spectral distortion effects neglected so far.
3. Energy injection in **haloes**: how to particles escape the halo into the IGM? Schön+ 1706.04327

HL, Ridgway & Slatyer 1904.09296



Incomplete Spectral Distortion

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:

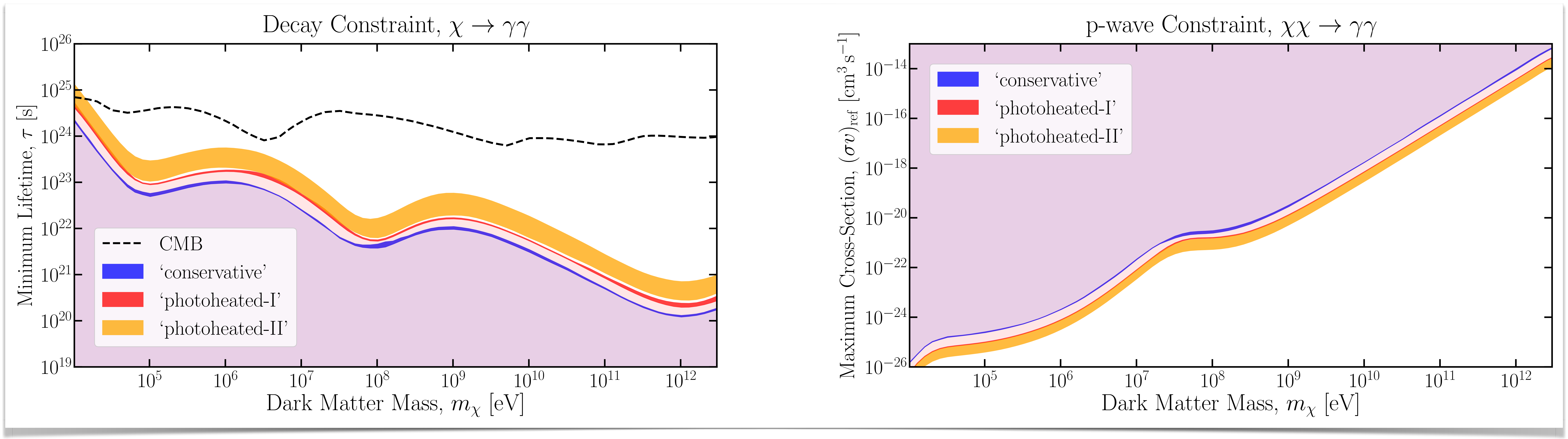
$$\mathrm{TS}_i = \begin{cases} 0\,, & T_{i,\mathrm{pred}} < T_{i,\mathrm{data}}\,, \\ \left(\dfrac{T_{i,\mathrm{pred}} - T_{i,\mathrm{data}}}{\sigma_{i,\mathrm{data}}}\right)^2 , & T_{i,\mathrm{pred}} \geq T_{i,\mathrm{data}}\,, \end{cases} \tag{5}$$

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

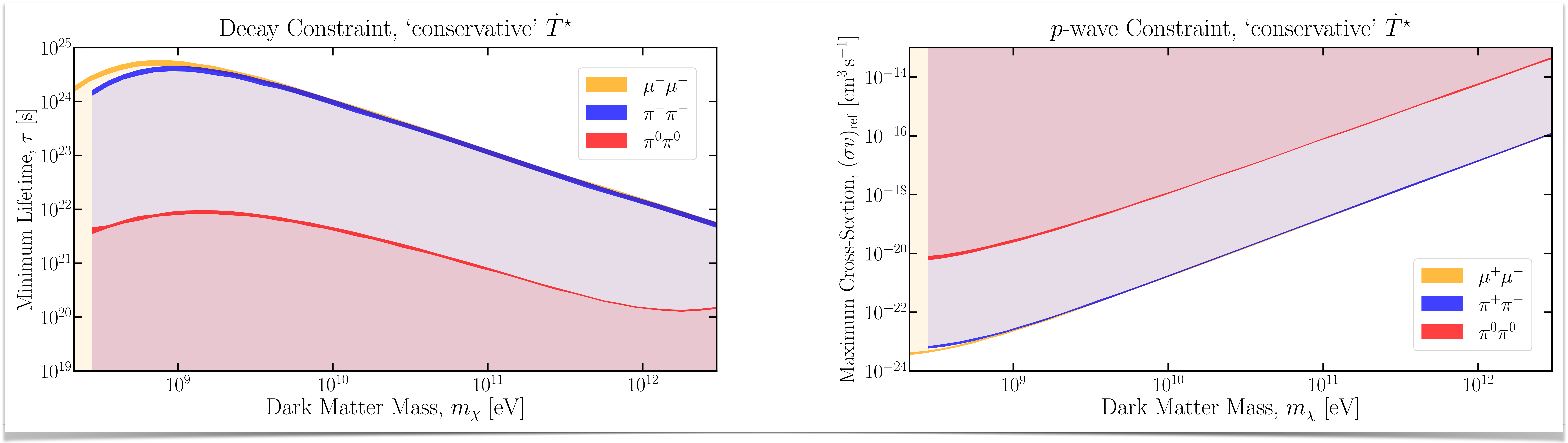
$$f(\mathrm{TS}|\{T_{i,\mathrm{pred}}\}) = \frac{1}{2^N} \sum_{n=0}^{N} \frac{N!}{n!(N-n)!} f_{\chi^2}(\mathrm{TS}; n)\,. \tag{6}$$

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

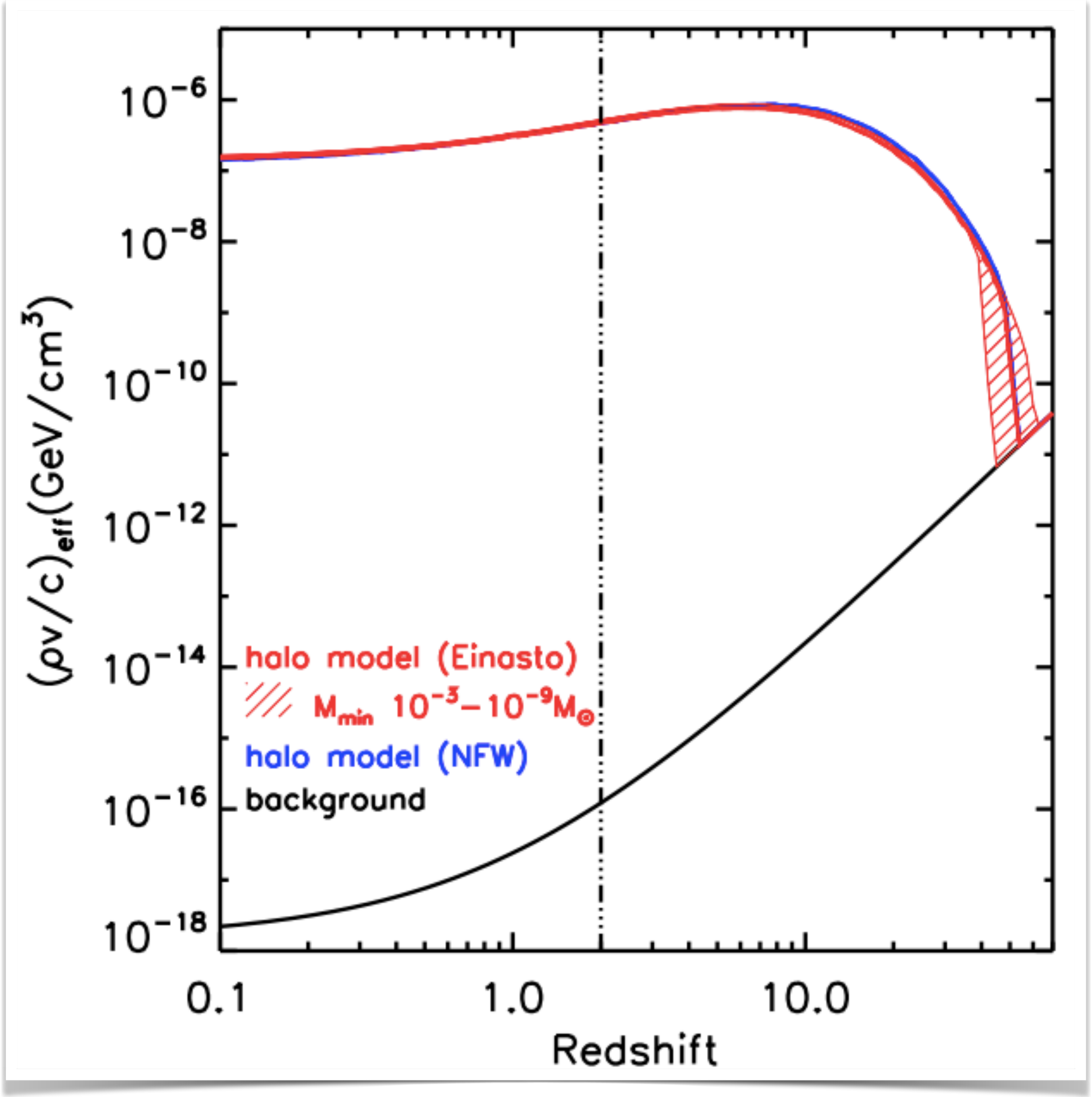
Photons


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

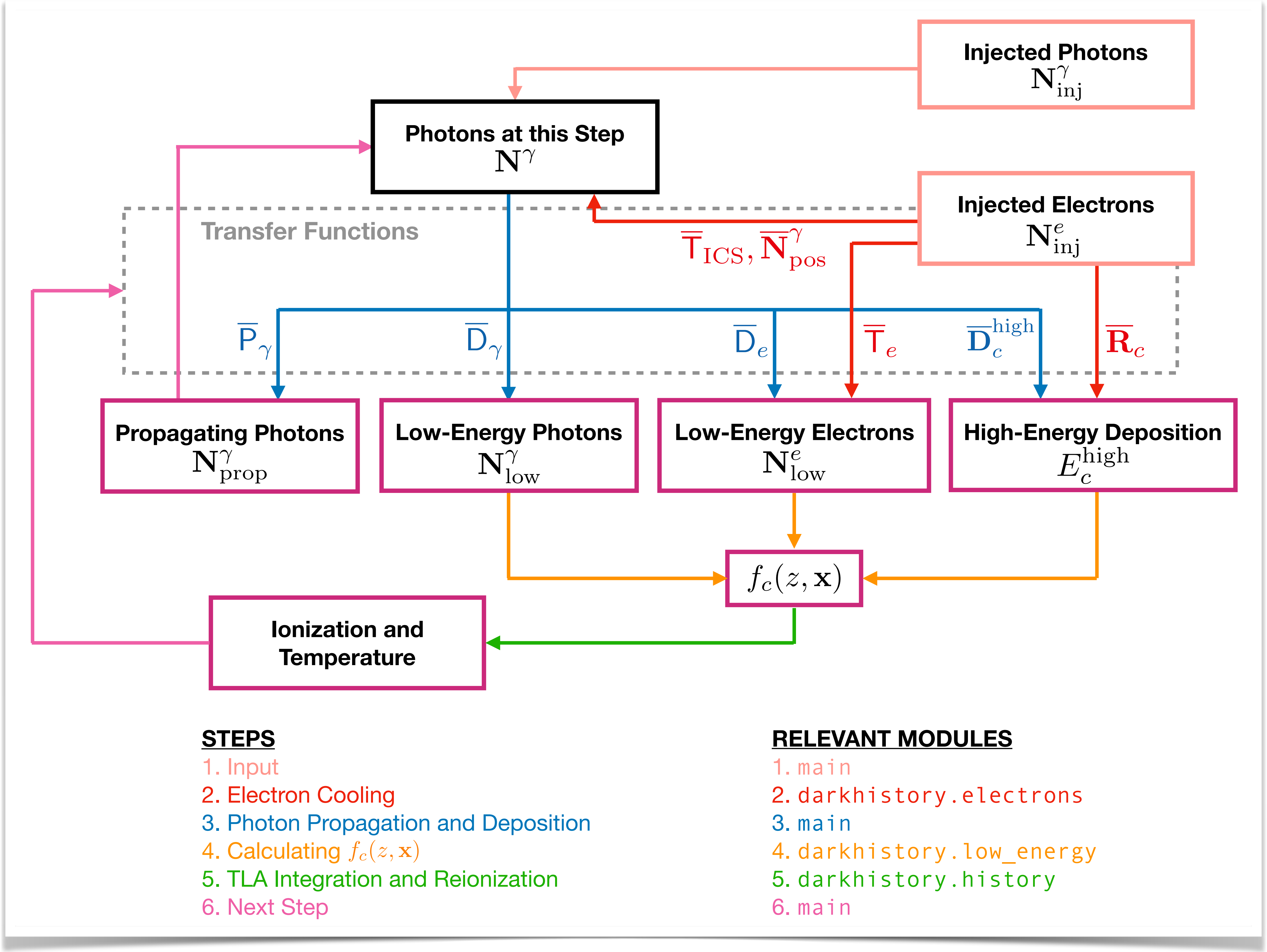
Muons and Pions



p-wave Boost Factor



DarkHistory Code



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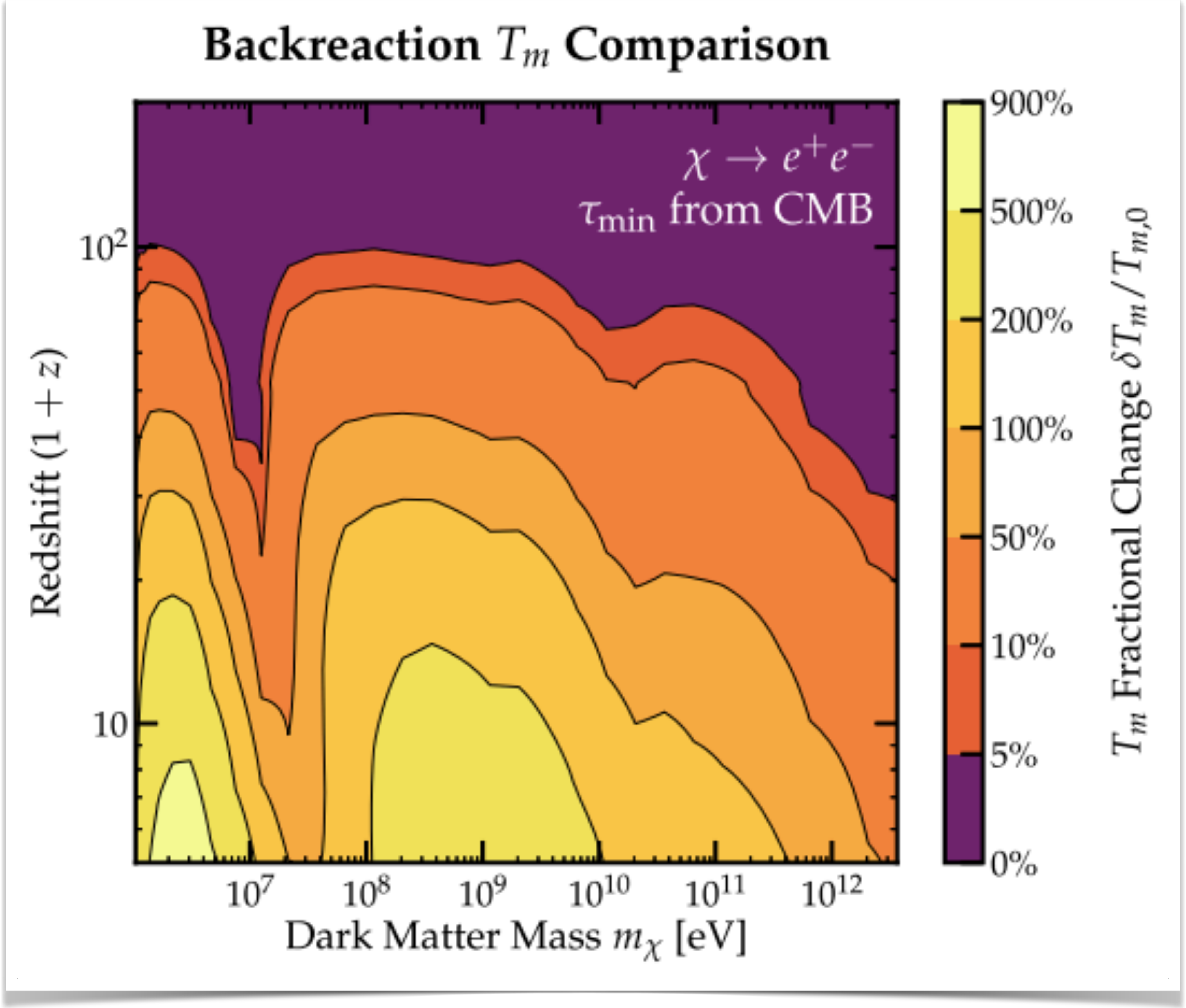
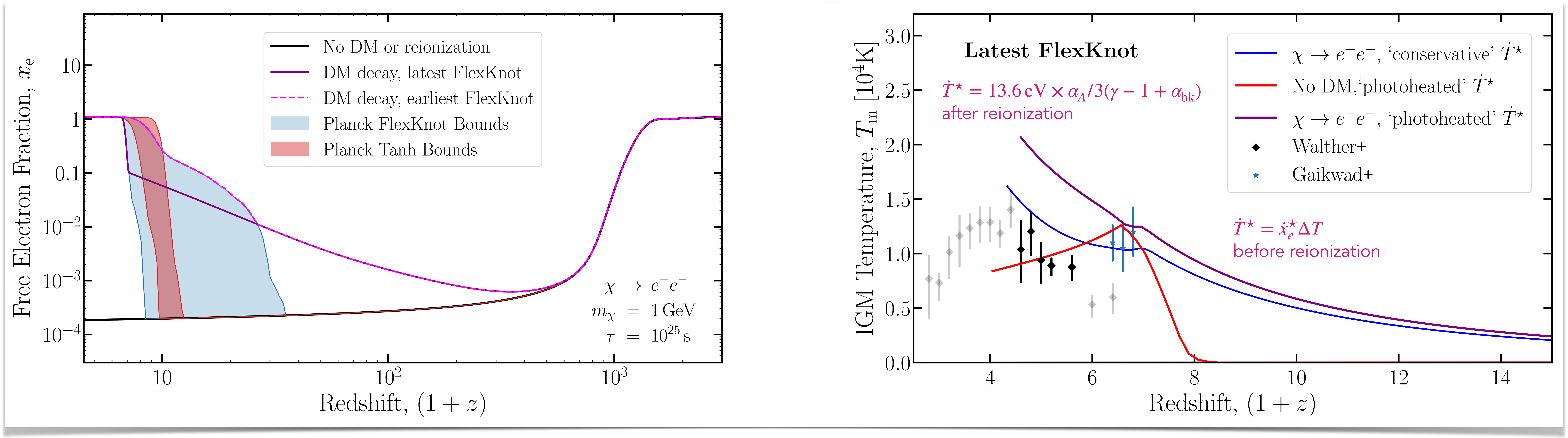
Change in Temperature due to Backreaction



Histories



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

$\dot{T}^\star = \dot{x}_e^\star \Delta T$
before reionization

Conservative:

$$\dot{T}^\star = 0$$

Photoheating I:

$$0\,\mathrm{K} < \Delta T < 3 \times 10^4\,\mathrm{K}$$

$$-0.5 < \alpha_\mathrm{bk} < 1.5$$

Photoheating II:

$$2 \times 10^4\,\mathrm{K} < \Delta T < 3 \times 10^4\,\mathrm{K}$$

$$-0.5 < \alpha_\mathrm{bk} < 1.5$$

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HL, Ridgway & Slatyer 1904.09296