LYMAN-α CONSTRAINTS on COSMIC HEATING from DARK MATTER ANNIHILATION and DECAY

Wenzer Qin
with Greg Ridgway, Hongwan Liu, and Tracy Slatyer

Massachusetts Institute of Technology
Center for Theoretical Physics

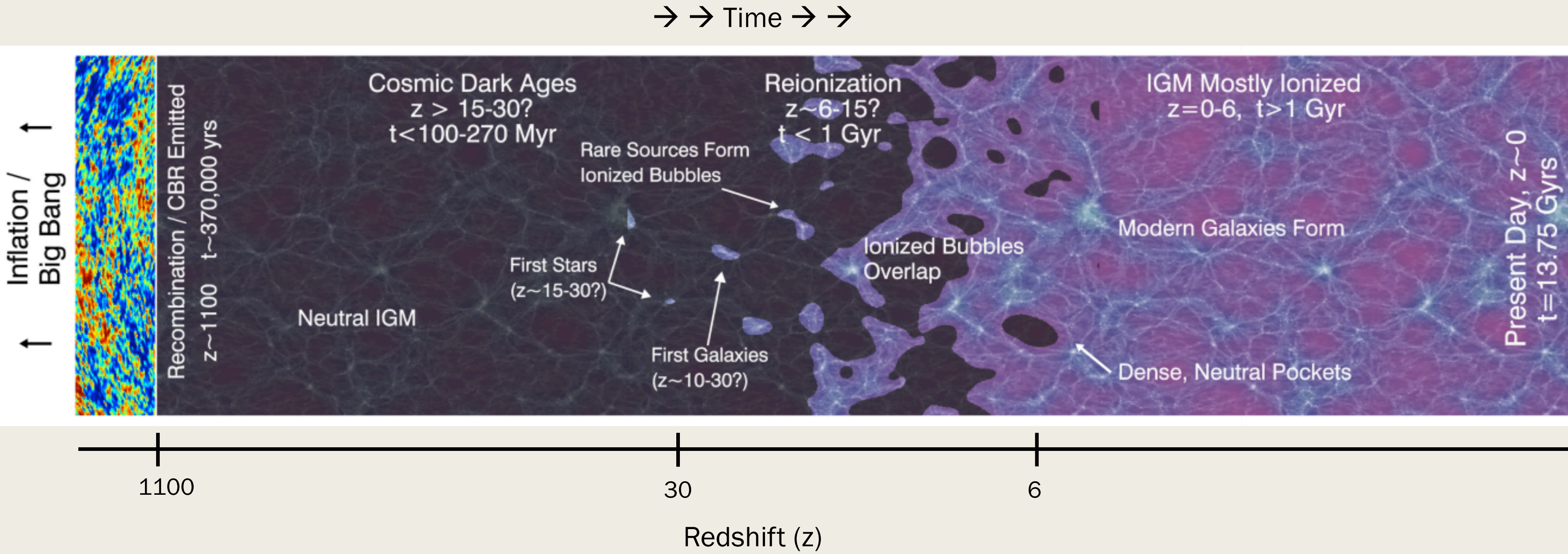
based on [2008.01084]

MIT Center for Theoretical Physics, BSM Journal Club
August 14th, 2020

Outline

- Early universe
- Effect of dark matter (DM) on ionization and temperature
- **`DarkHistory`** code package
  - *Choosing a reionization model*
- Data
  - *Reionization histories from Planck 2018*
  - *IGM temperature measurements from Lyα*
- New constraints
- Conclusion

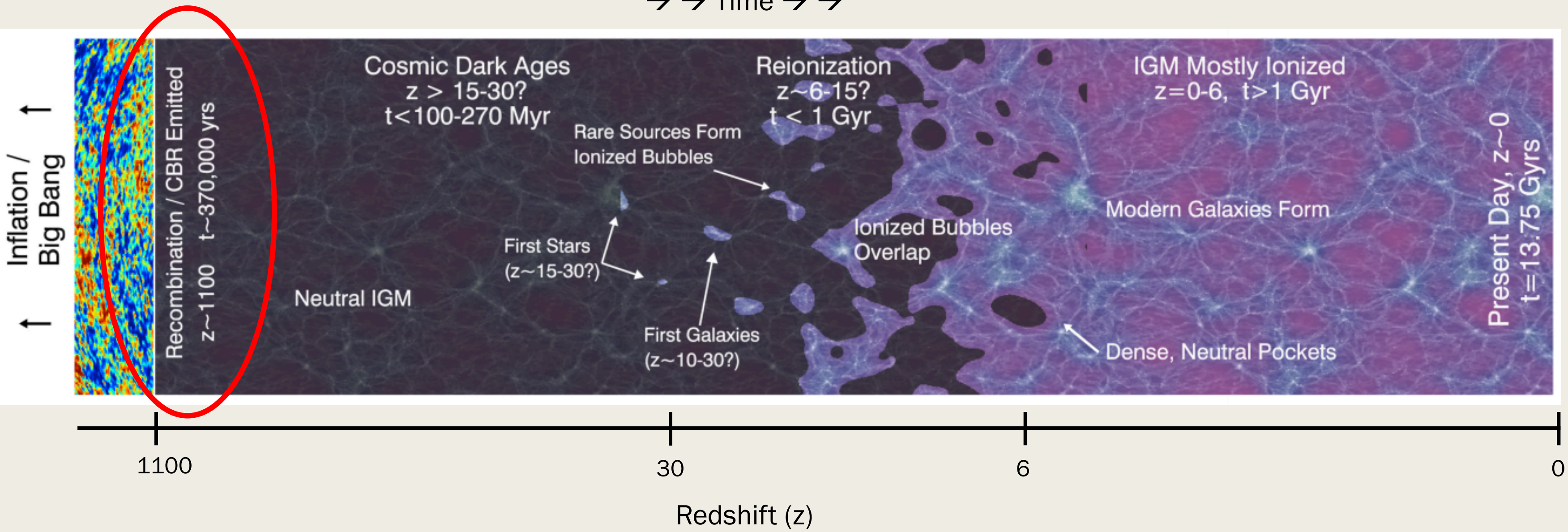
Timeline of the early universe



Robertson et al. (2010)

Timeline of the early universe

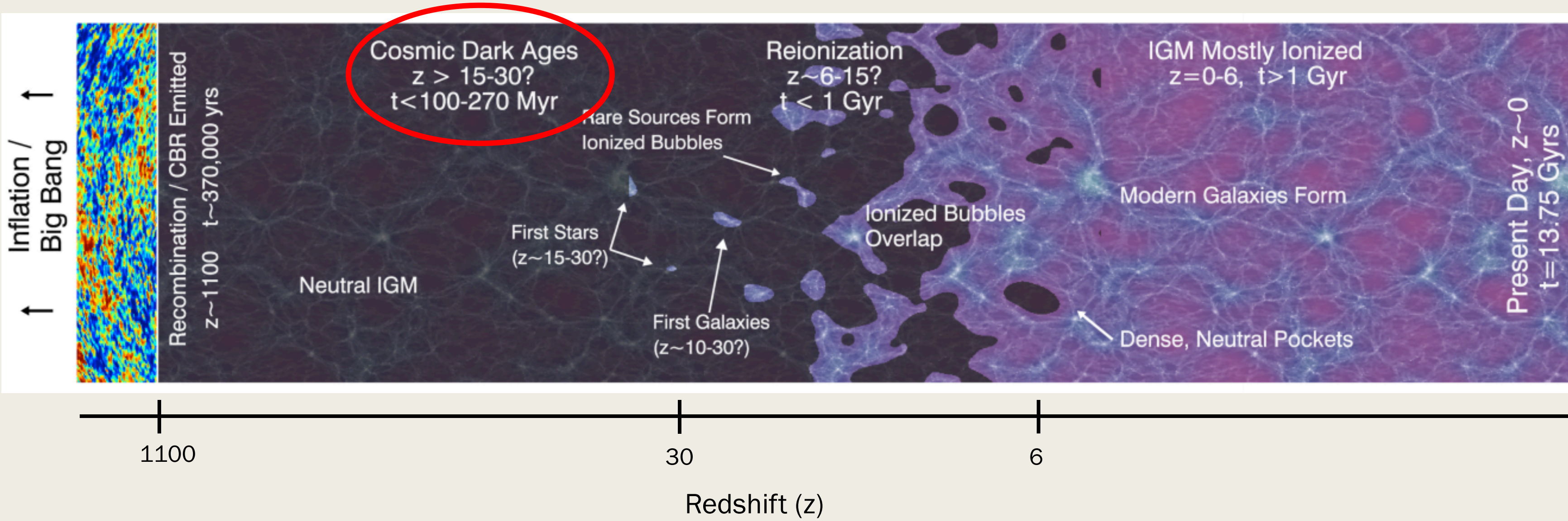
→ → Time → →



Robertson et al. (2010)

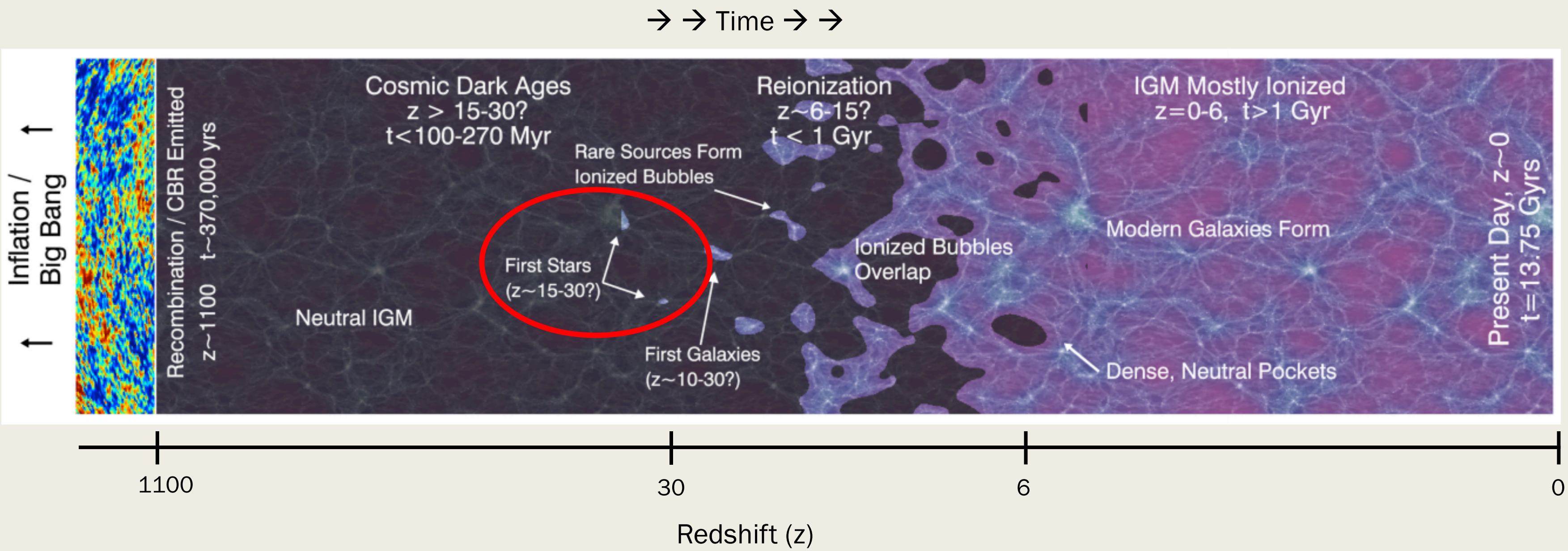
Timeline of the early universe

→ → Time → →



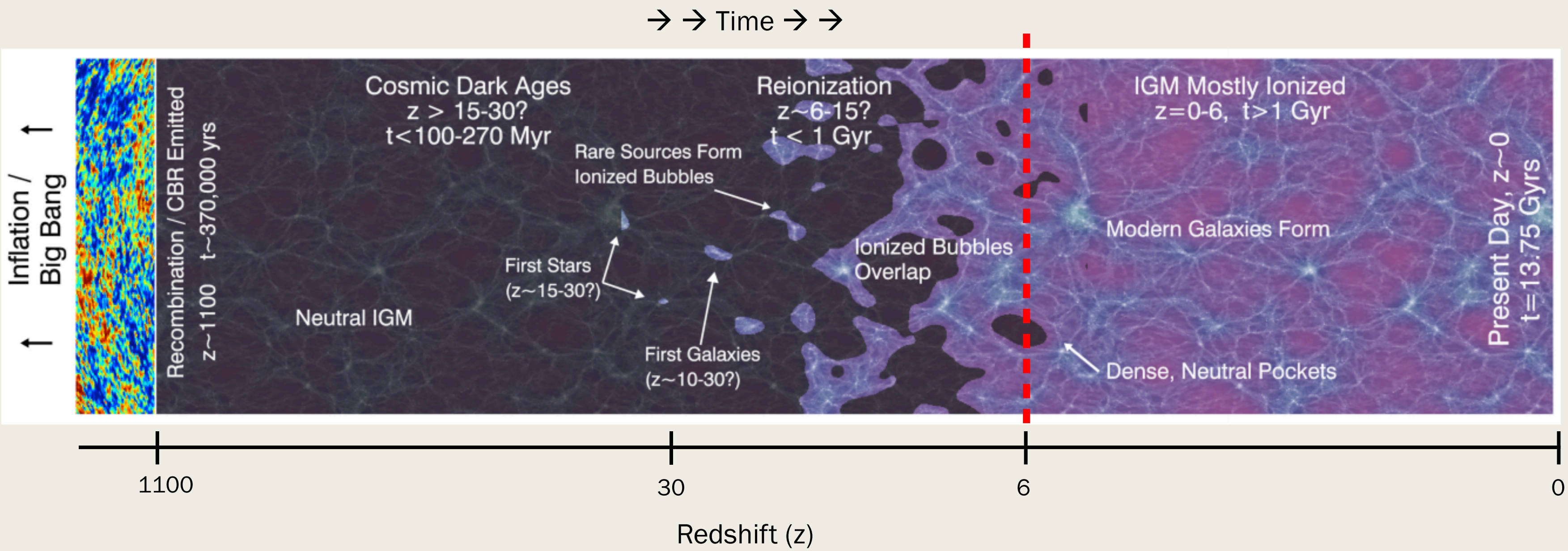
Robertson et al. (2010)

Timeline of the early universe



Robertson et al. (2010)

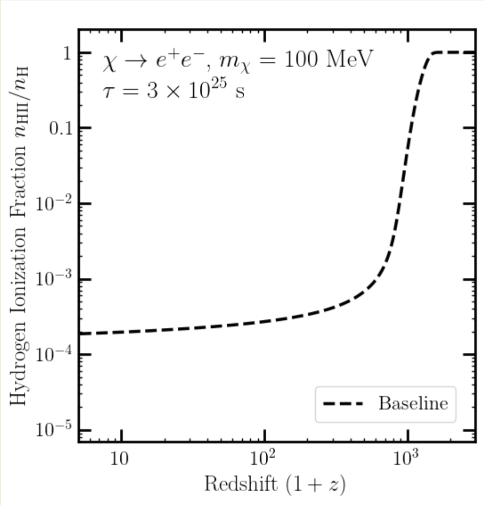
Timeline of the early universe

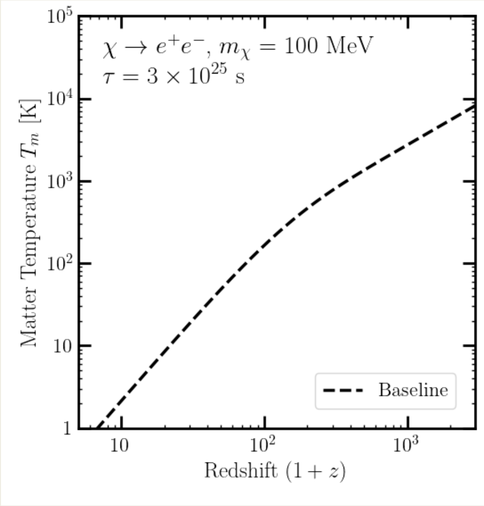


Robertson et al. (2010)

Cosmic heating and ionization

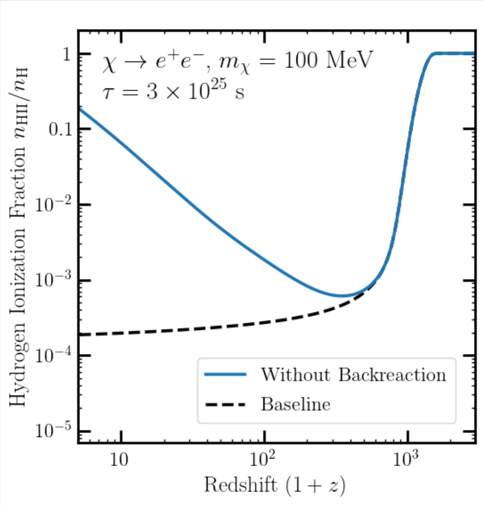
- If DM interacts with Standard Model particles, then decays/annihilations can inject energy into the IGM at early times
- Extra energy causes
  1. *Extra ionization: Detectable in the CMB power spectrum*
  2. *Extra heating: can probe with Lyman-α forest measurements*

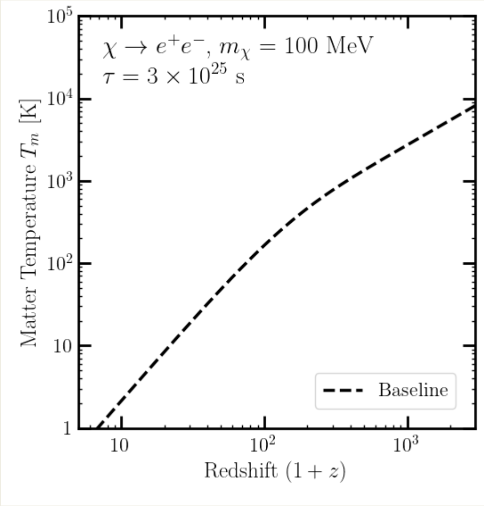




Cosmic heating and ionization

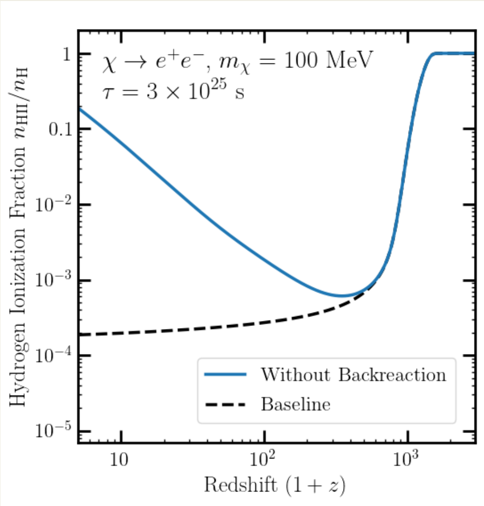
- If DM interacts with Standard Model particles, then decays/annihilations can inject energy into the IGM at early times
- Extra energy causes
  1. *Extra ionization: Detectable in the CMB power spectrum*
  2. *Extra heating: can probe with Lyman-α forest measurements*

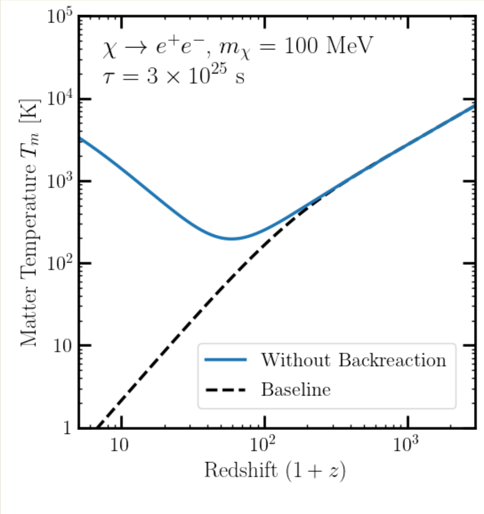




Cosmic heating and ionization

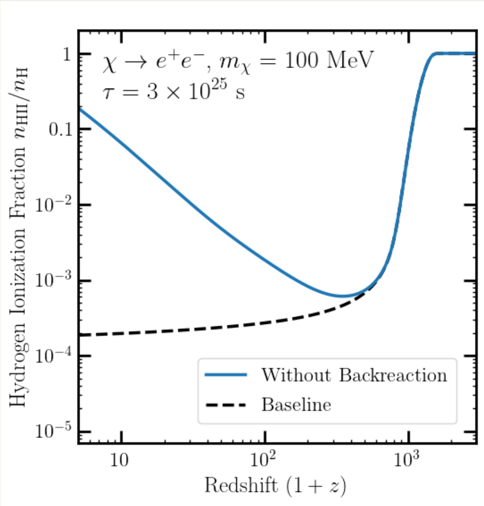
- If DM interacts with Standard Model particles, then decays/annihilations can inject energy into the IGM at early times
- Extra energy causes
  1. *Extra ionization: Detectable in the CMB power spectrum*
  2. *Extra heating: can probe with Lyman-α forest measurements*

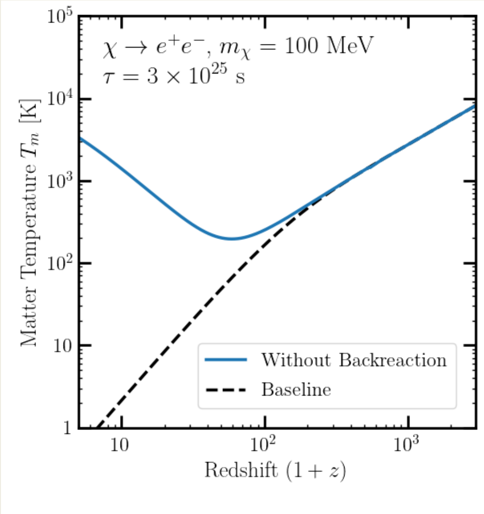




DarkHistory

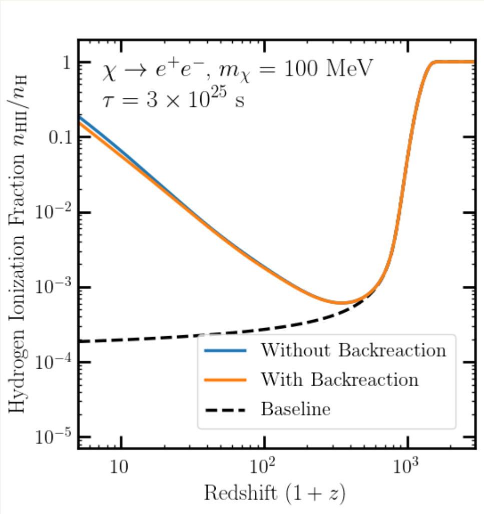
- Python code package
  - *Download at https://github.com/hongwanliu/DarkHistory/*
- Simultaneously solves for evolution of free electron fraction and gas temperature, including exotic sources of energy injection
- Accounts for 'backreaction', where changes in ionization/temperature modify subsequent energy-loss processes
- Model-independent

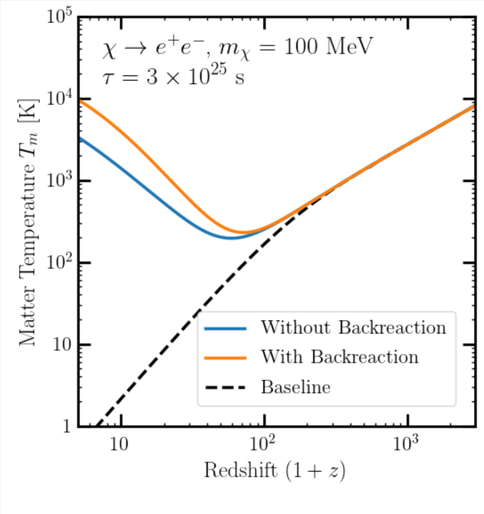




DarkHistory

- Python code package
  - *Download at https://github.com/hongwanliu/DarkHistory/*
- Simultaneously solves for evolution of free electron fraction and gas temperature, including exotic sources of energy injection
- Accounts for ‘backreaction’, where changes in ionization/temperature modify subsequent energy-loss processes
- Model-independent





Evolution of H ionization

$$\dot{x}_{\rm HII} = \dot{x}_{\rm HII}^{\rm atom} + \dot{x}_{\rm HII}^{\rm DM} + \dot{x}_{\rm HII}^{\star}$$

Recombination,
collisional ionization

DM energy injection

Astrophysical sources,
use Planck constraints

Evolution of He ionization

$$\dot{x}_{\mathrm{HeII}} = \dot{x}_{\mathrm{HeII}}^{\mathrm{atom}} + \dot{x}_{\mathrm{HeII}}^{\mathrm{DM}} + \dot{x}_{\mathrm{HeII}}^{\star}$$
$$x_{\mathrm{HeIII}} = 0$$

- Analogous equation for HeII
- Assume there is no HeIII, which is a good approximation before HeII reionization

Evolution of temperature

$$\dot{T}_{\rm m} = \dot{T}_{\rm adia} + \dot{T}_{\rm C} + \dot{T}_{\rm DM} + \dot{T}_{\rm atom} + \dot{T}^{\star}$$

Hubble expansion

Compton scattering off the CMB

DM energy injection

Recombination, collisions, etc.

Photoheating from reionization (x*)

Photoheating model

How to treat photoheating rate?

- ‘Conservative’: Include no photoheating at all.
- ‘Photoheated’: Use a two-stage reionization model
    1. *Before reionization is complete, assume photoheating rate is proportional to photoionization rate $\dot{x}^*$; parametrized by ΔT*
        - Restrict $\Delta T > 0$ K (‘photoheated-I’)
        - Restrict $\Delta T > 2\times10^4$ K (‘photoheated-II’), based on analytical arguments + simulations [1]
    2. *After reionization, assume IGM is in photoionization equilibrium → gives calculable heating rate* [2]

[1] Miralda-Escudé and Rees (1994), McQuinn (2012)
[2] Sanderbeck, D’Aloisio, and McQuinn (2016)

Photoheating model

How to treat photoheating rate?

- 'Conservative': Include no photoheating at all.
- 'Photoheated': Use a two-stage reionization model
  1. *Before reionization is complete, assume photoheating rate is proportional to photoionization rate $\dot{x}^*$; parametrized by ΔT*
     - Restrict $\Delta T > 0$ K ('photoheated-I')
     - Restrict $\Delta T > 2\times10^4$ K ('photoheated-II'), based on analytical arguments + simulations [1]
  2. *After reionization, assume IGM is in photoionization equilibrium → gives calculable heating rate* [2]

[1] Miralda-Escudé and Rees (1994), McQuinn (2012)
[2] Sanderbeck, D'Aloisio, and McQuinn (2016)

Photoheating model

How to treat photoheating rate?

- 'Conservative': Include no photoheating at all.
- 'Photoheated': Use a two-stage reionization model
  1. *Before reionization is complete, assume photoheating rate is proportional to photoionization rate $\dot{x}^*$; parametrized by ΔT*
     - Restrict $\Delta T > 0$ K ('photoheated-I')
     - Restrict $\Delta T > 2\times10^4$ K ('photoheated-II'), based on analytical arguments + simulations [1]
  2. *After reionization, assume IGM is in photoionization equilibrium → gives calculable heating rate* [2]

[1] Miralda-Escudé and Rees (1994), McQuinn (2012)
[2] Sanderbeck, D'Aloisio, and McQuinn (2016)

Photoheating model

How to treat photoheating rate?

- ‘Conservative’: Include no photoheating at all.
- ‘Photoheated’: Use a two-stage reionization model
  1. *Before reionization is complete, assume photoheating rate is proportional to photoionization rate $\dot{x}^*$; parametrized by ΔT*
     - Restrict ΔT > 0 K (‘photoheated-I’)
     - Restrict ΔT > $2{\times}10^4$ K (‘photoheated-II’), based on analytical arguments + simulations [1]
  2. *After reionization, assume IGM is in photoionization equilibrium → gives calculable heating rate* [2]

[1] Miralda-Escudé and Rees (1994), McQuinn (2012)
[2] Sanderbeck, D’Aloisio, and McQuinn (2016)

Photoheating model

How to treat photoheating rate?

- 'Conservative': Include no photoheating at all.
- 'Photoheated': Use a two-stage reionization model
  1. *Before reionization is complete, assume photoheating rate is proportional to photoionization rate $\dot{x}^*$; parametrized by ΔT*
     - Restrict $\Delta T > 0$ K ('photoheated-I')
     - Restrict $\Delta T > 2\times10^4$ K ('photoheated-II'), based on analytical arguments + simulations [1]
  2. *After reionization, assume IGM is in photoionization equilibrium → gives calculable heating rate* [2]

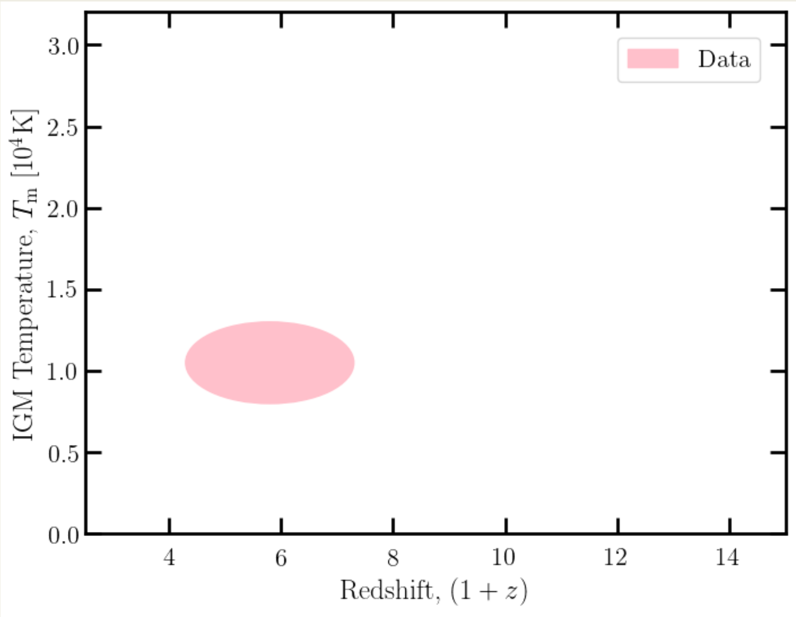
[1] Miralda-Escudé and Rees (1994), McQuinn (2012)
[2] Sanderbeck, D'Aloisio, and McQuinn (2016)

Example histories

- For ‘conservative’ method, use modified chi-squared
  - *Only penalize model where overheats*
  - *Most robust because adding photoheating will only increase IGM temperature, producing stronger constraints*
- For ‘photoheated’ methods, use standard chi-squared

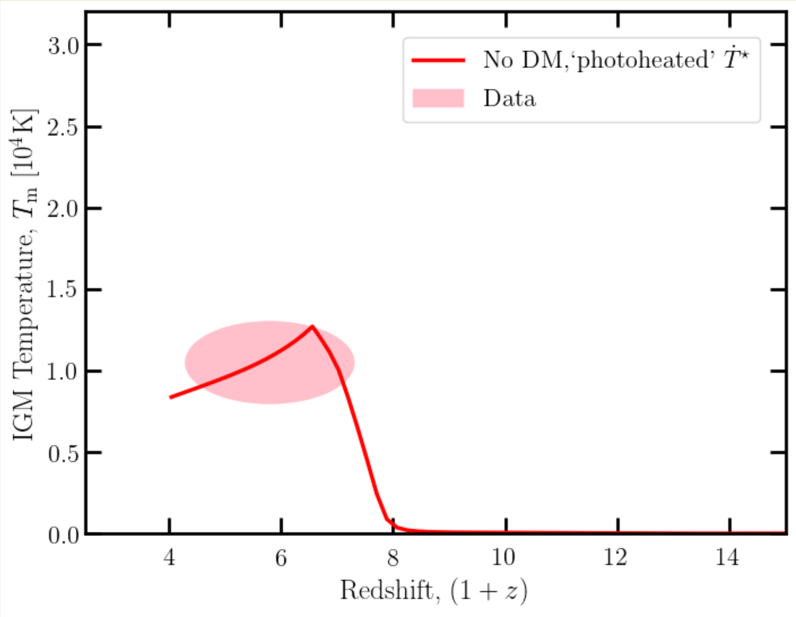
Example histories

- For 'conservative' method, use modified chi-squared
  - *Only penalize model where overheats*
  - *Most robust because adding photoheating will only increase IGM temperature, producing stronger constraints*
- For 'photoheated' methods, use standard chi-squared



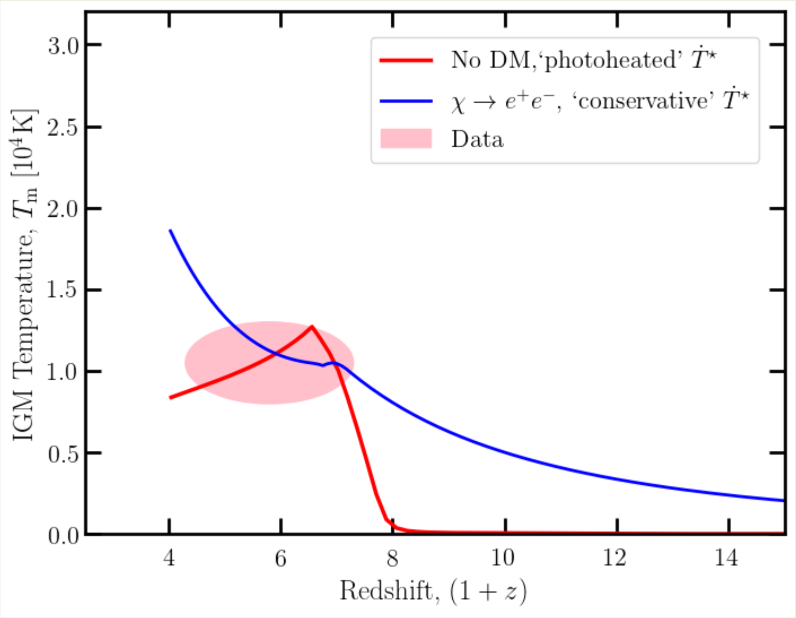
Example histories

- For ‘conservative’ method, use modified chi-squared
  - *Only penalize model where overheats*
  - *Most robust because adding photoheating will only increase IGM temperature, producing stronger constraints*
- For ‘photoheated’ methods, use standard chi-squared



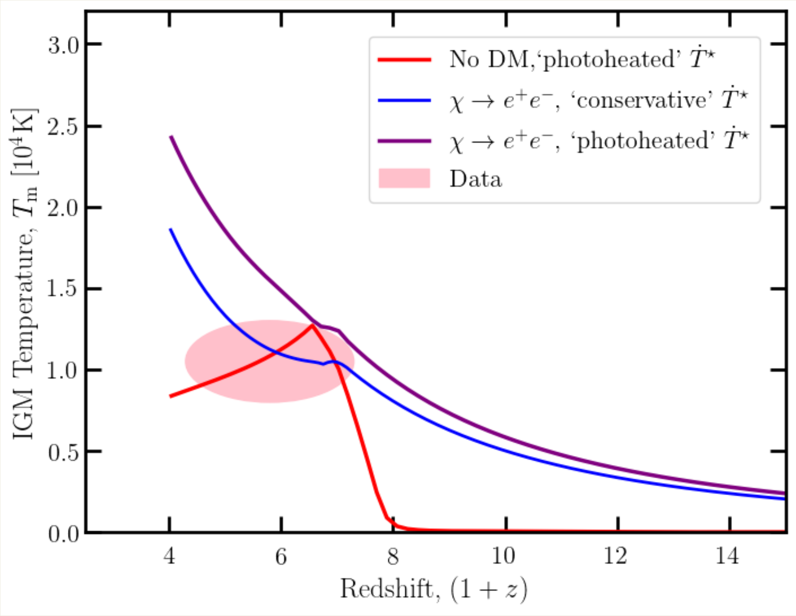
Example histories

- For 'conservative' method, use modified chi-squared
  - *Only penalize model where overheats*
  - *Most robust because adding photoheating will only increase IGM temperature, producing stronger constraints*
- For 'photoheated' methods, use standard chi-squared



Example histories

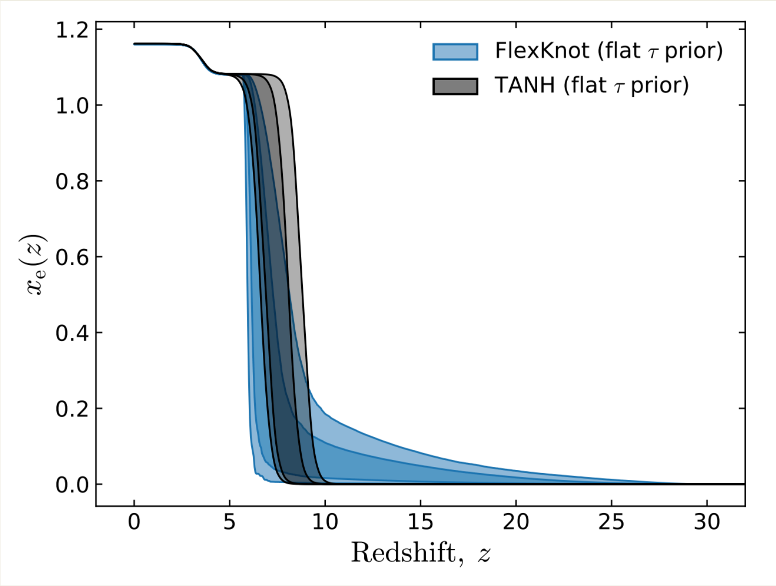
- For ‘conservative’ method, use modified chi-squared
  - *Only penalize model where overheats*
  - *Most robust because adding photoheating will only increase IGM temperature, producing stronger constraints*
- For ‘photoheated’ methods, use standard chi-squared



DATA

Reionization sources

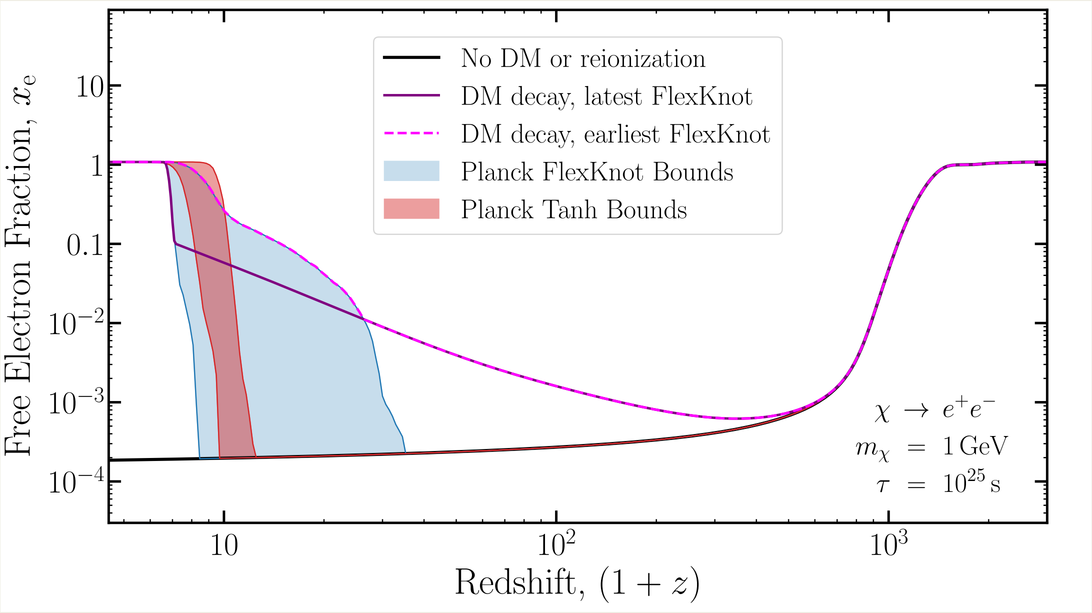
- Planck 2018: Constrains free electron fraction using either a ‘Tanh’ or ‘FlexKnot’ model
- DM produces extra ionization at early times, too little at late times---need astrophysical sources *
- Instead of modeling the astrophysics, match the ionization due to DM at early times onto the Planck reionization histories at later times



Planck (2018)

Reionization sources

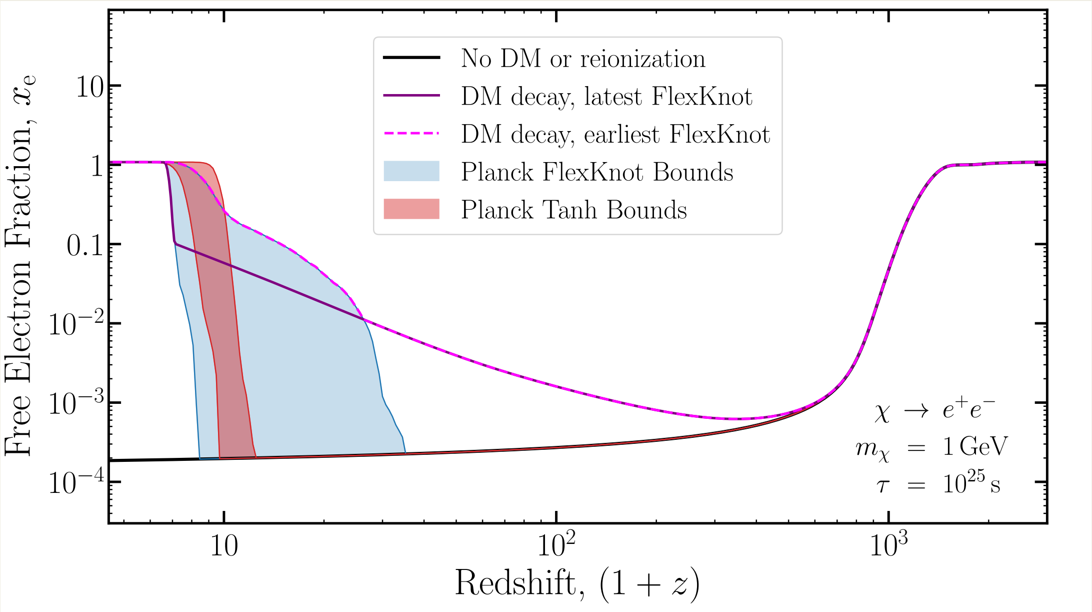
- Planck 2018: Constrains free electron fraction using either a 'Tanh' or 'FlexKnot' model
- DM produces extra ionization at early times, too little at late times---need astrophysical sources *
- Instead of modeling the astrophysics, match the ionization due to DM at early times onto the Planck reionization histories at later times



*Liu, Slatyer, and Zavala (2016)

Reionization sources

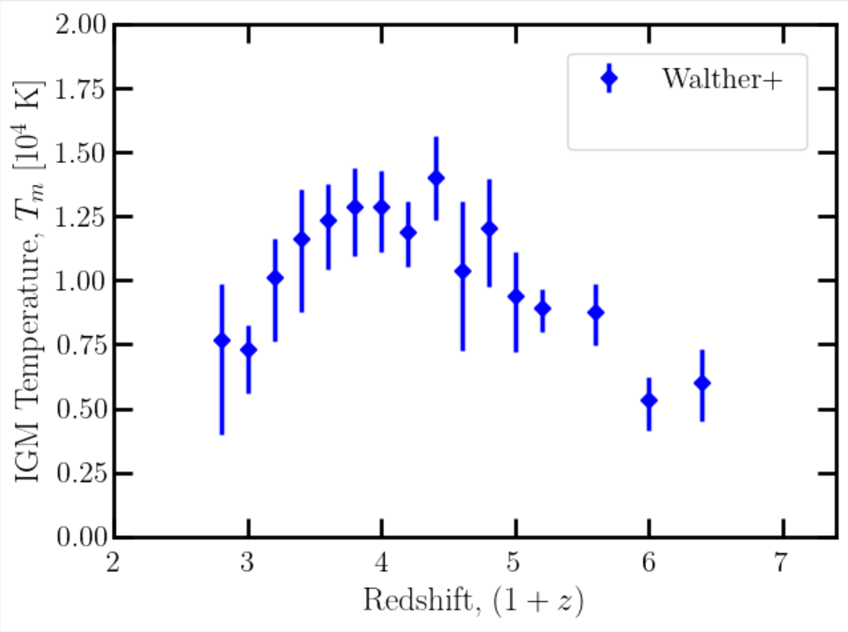
- Planck 2018: Constrains free electron fraction using either a ‘Tanh’ or ‘FlexKnot’ model
- DM produces extra ionization at early times, too little at late times---need astrophysical sources *
- Instead of modeling the astrophysics, match the ionization due to DM at early times onto the Planck reionization histories at later times



*Liu, Slatyer, and Zavala (2016)

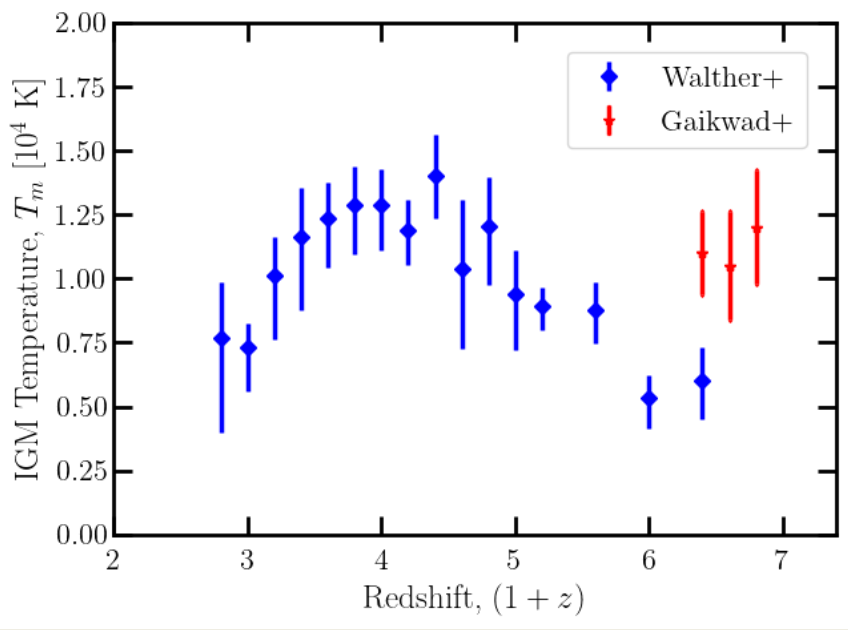
Temperature measurements

- Walther et al. (2019): Compared measured Lyα forest power spectra to hydrodynamical simulations to infer thermal evolution of IGM
- Gaikwad et al. (2020): Fit Lyα transmission spikes to simulations results



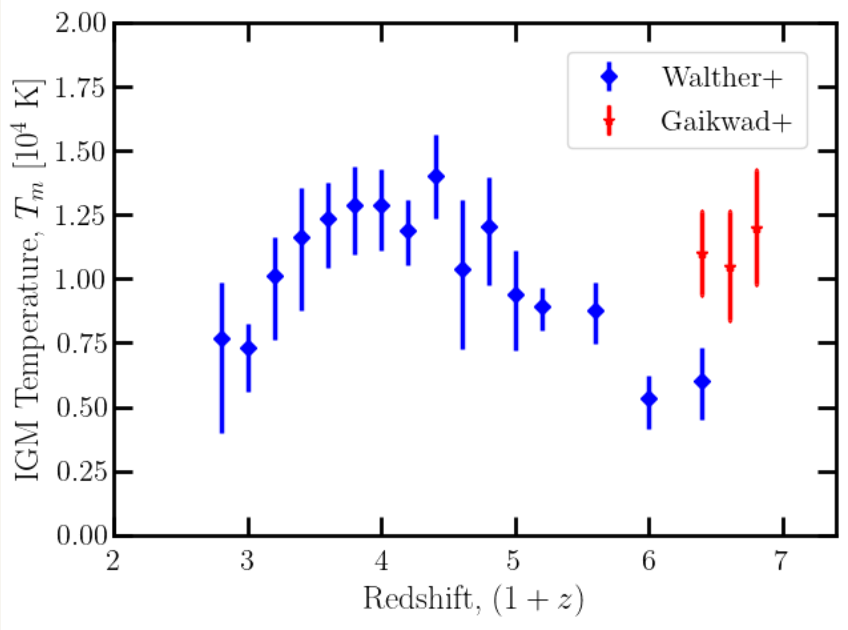
Temperature measurements

- Walther et al. (2019): Compared measured Lyα forest power spectra to hydrodynamical simulations to infer thermal evolution of IGM
- Gaikwad et al. (2020): Fit Lyα transmission spikes to simulations results



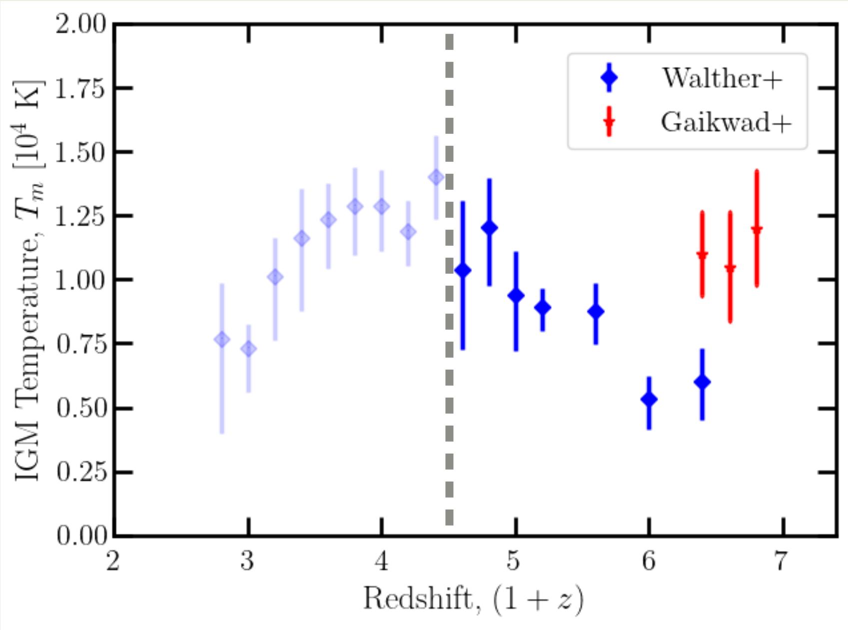
Temperature measurements

- Combined datasets:
  - *`DarkHistory` is not yet equipped to deal with HeII reionization so we only consider data points at 1+z > 4.6*
  - *At 1+z ~ 6-7, the two data sets are in tension; we discard the Walther+ results which could artificially strengthen our constraints*



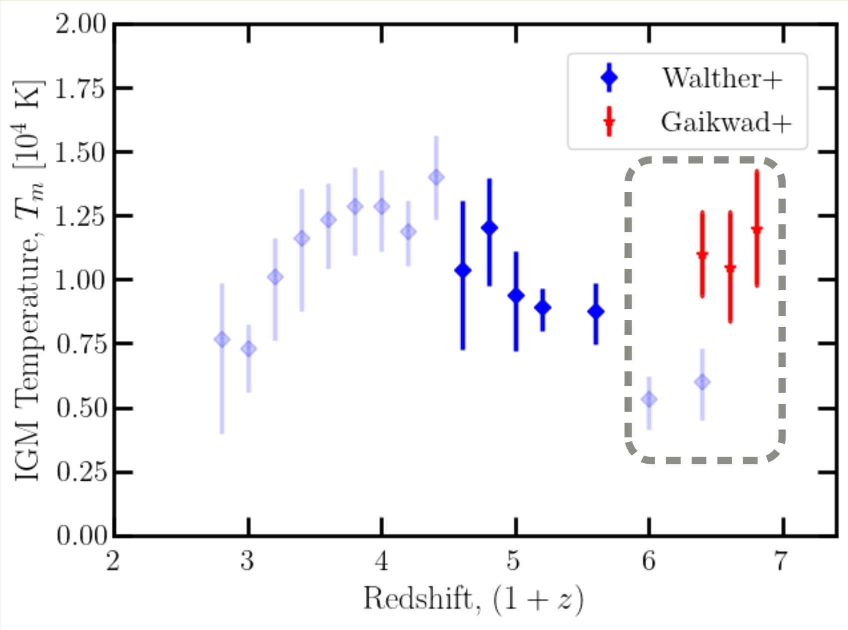
Temperature measurements

- Combined datasets:
  - *`DarkHistory` is not yet equipped to deal with HeII reionization so we only consider data points at 1+z > 4.6*
  - *At 1+z ~ 6-7, the two data sets are in tension; we discard the Walther+ results which could artificially strengthen our constraints*



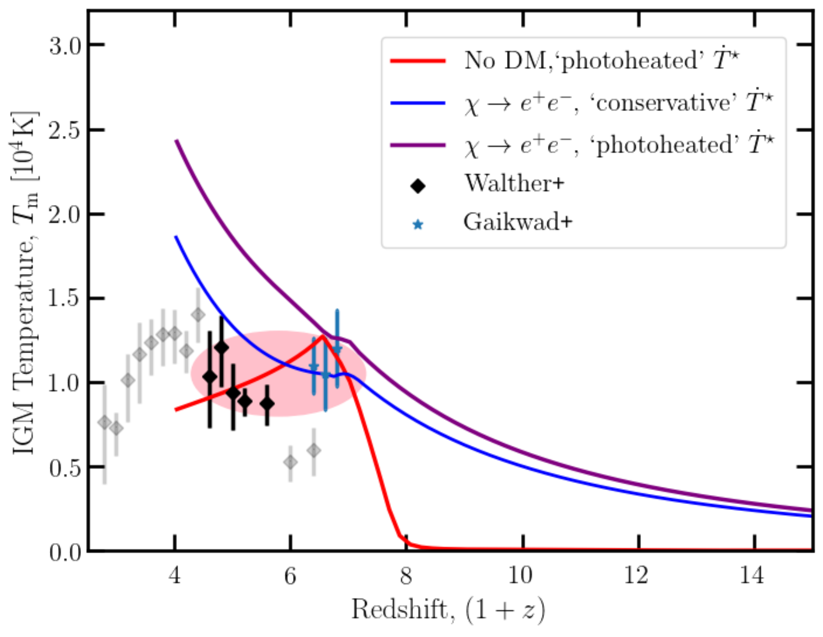
Temperature measurements

- Combined datasets:
  - *`DarkHistory` is not yet equipped to deal with HeII reionization so we only consider data points at 1+z > 4.6*
  - *At 1+z ~ 6-7, the two data sets are in tension; we discard the Walther+ results which could artificially strengthen our constraints*



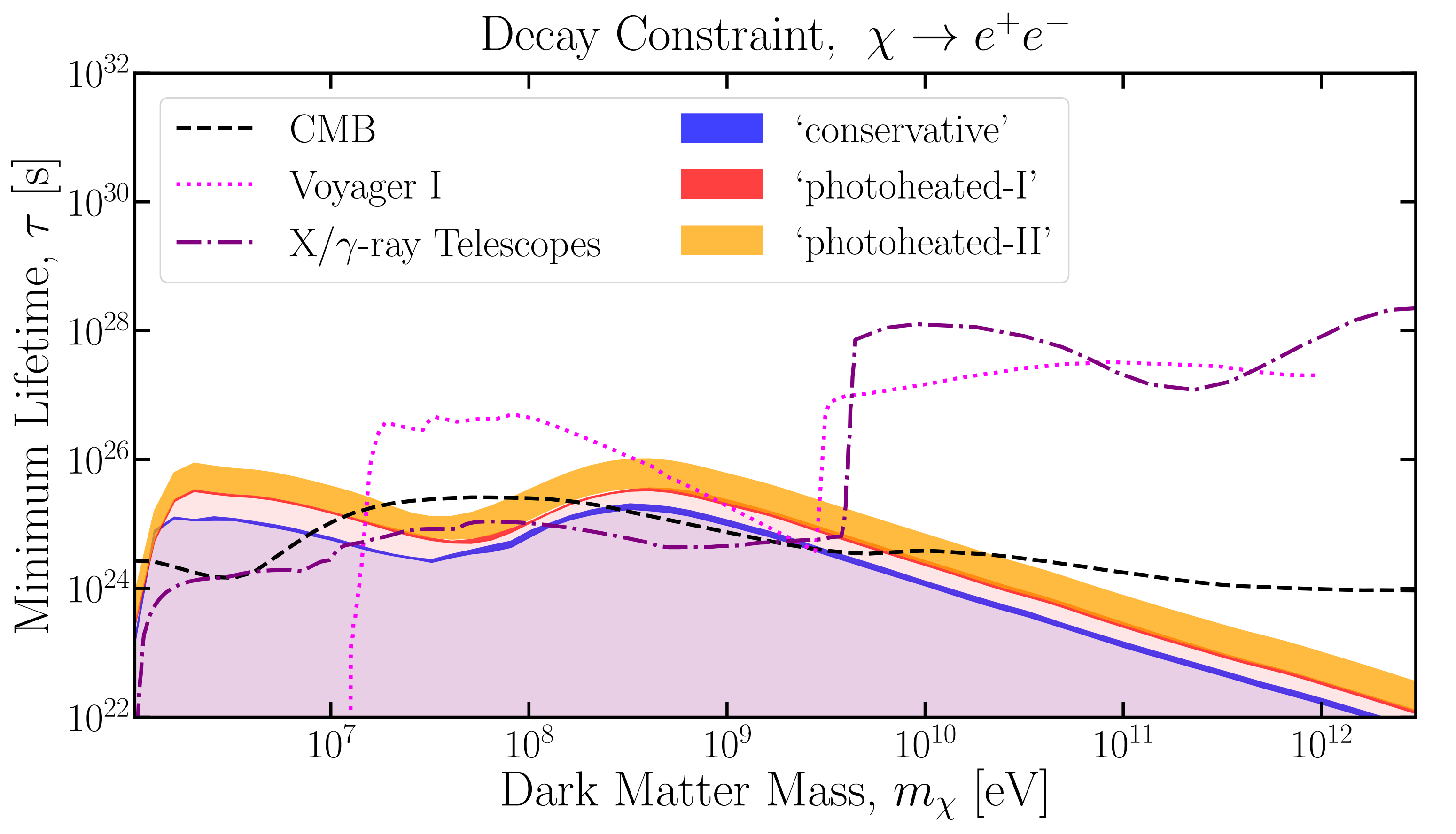
Temperature measurements

- Combined datasets:
  - *`DarkHistory` is not yet equipped to deal with HeII reionization so we only consider data points at 1+z > 4.6*
  - *At 1+z ~ 6-7, the two data sets are in tension; we discard the Walther+ results which could artificially strengthen our constraints*



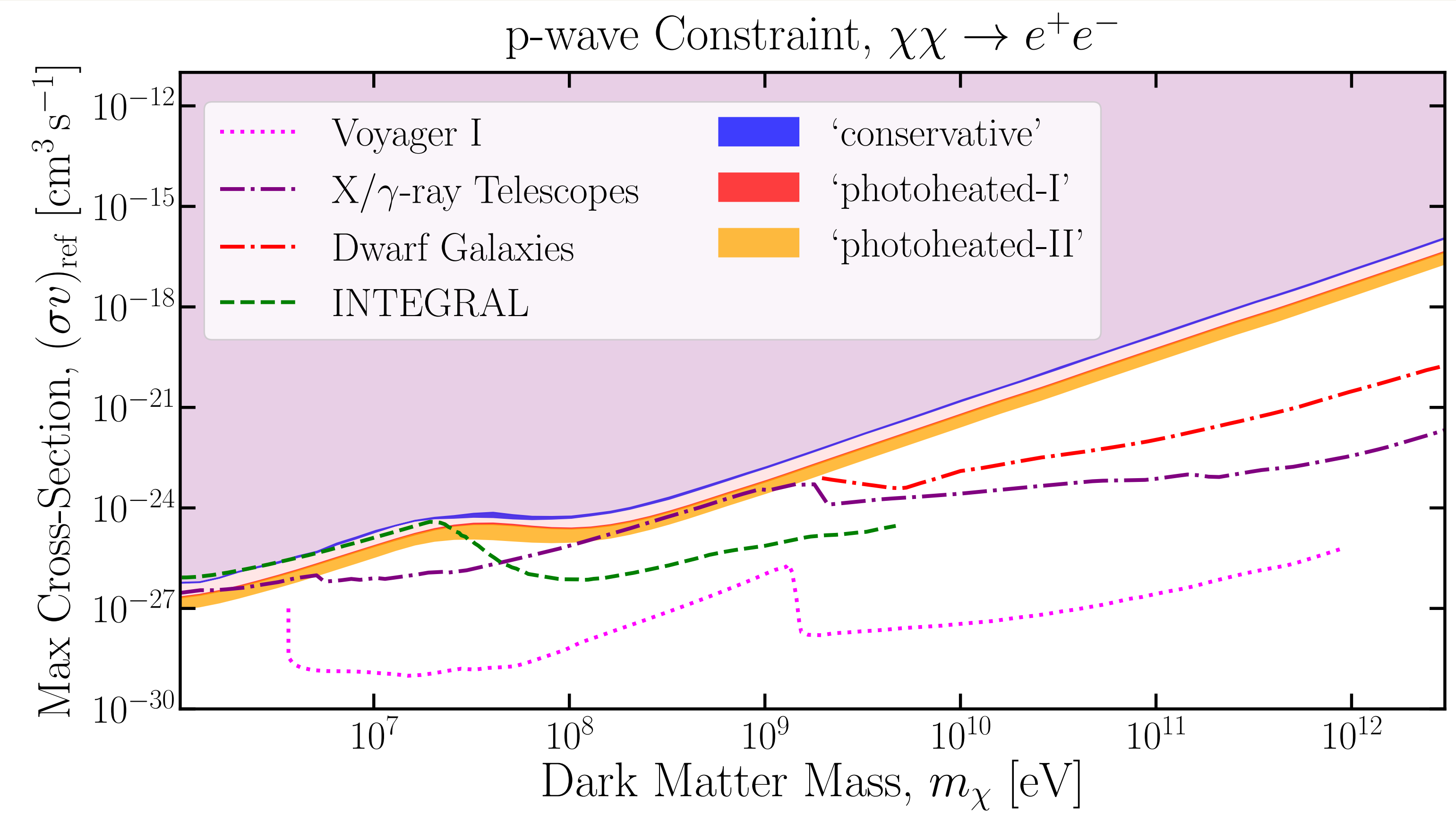
RESULTS

Decay to e^+e^-



Decay Constraint, $\chi \to e^+e^-$
Minimum Lifetime, τ [s]
Dark Matter Mass, m_χ [eV]
CMB
Voyager I
X/γ-ray Telescopes
'conservative'
'photoheated-I'
'photoheated-II'
10^{22}
10^{24}
10^{26}
10^{28}
10^{30}
10^{32}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}

p-wave annihilation to e^+e^-

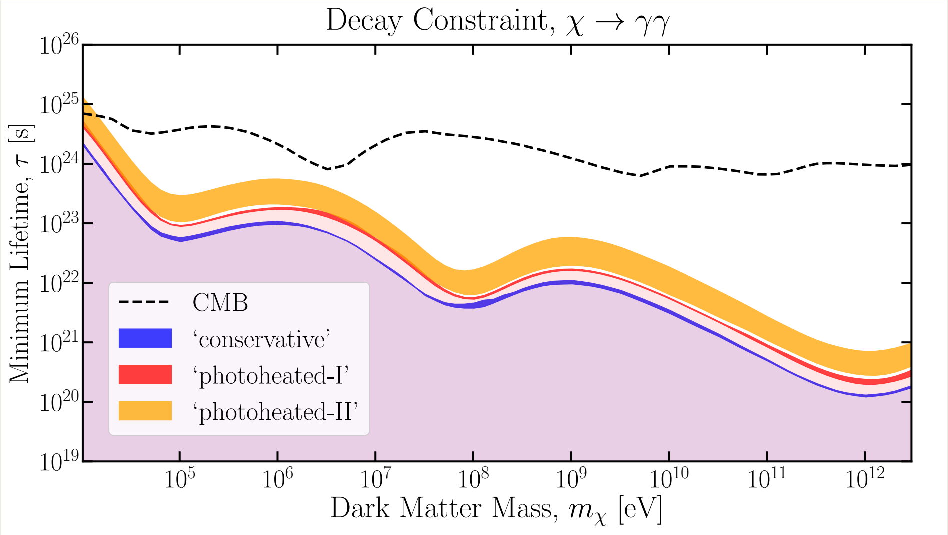


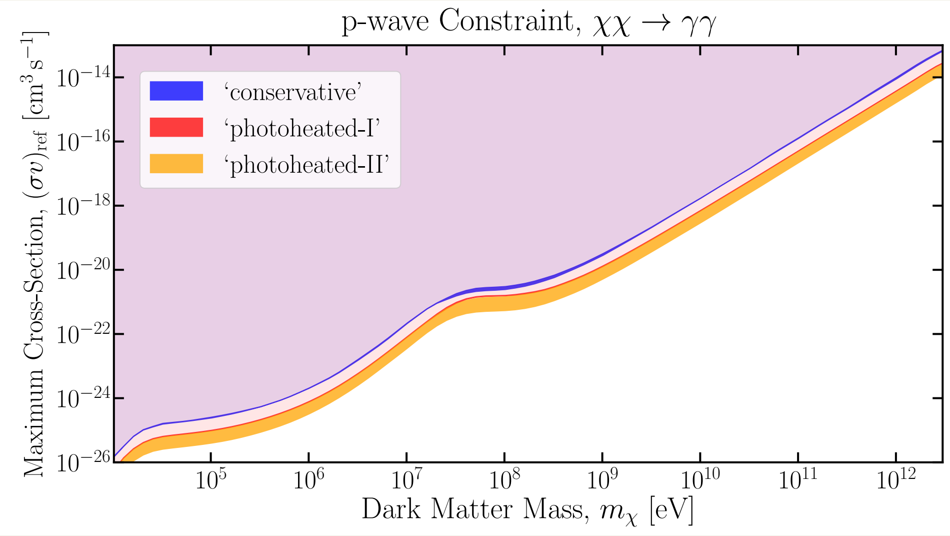
Summary

- We can self-consistently construct ionization and IGM temperature histories…
  - *in the presence of DM energy injection by using* `DarkHistory` *to solve evolution equations*
  - *in the presence of reionization sources by using Planck measurements*
- We use Lyα measurements of IGM temperature to constrain DM decay and p-wave annihilation
  - *'Conservative' constraints assume no photoheating*
  - *'Photoheated' constraints use two-stage model that strengthens limits by factor of 2-8*
- Could similarly use future 21cm observations for z~20
- As uncertainties on IGM temperature measurements shrink, and reionization and photoheating models become more constrained, limits could strengthen considerably

BACKUP SLIDES

Photon constraints





Photoheating model: Stage 2

- ‘Photoheated’: Use a two-stage reionization model
  1. *Before reionization is complete, assume photoheating is proportional to photoionization; parametrized by ΔT*
  2. *After reionization, assume IGM is in photoionization equilibrium*
     - Parametrized by α_{bk} (defined by $J_{\upsilon} \propto \upsilon^{-\alpha_{bk}}$)
     - Restrict $-0.5 < \alpha_{bk} < 1.5$

$$\dot{T}^{\star} = \begin{cases} \dot{x}^{\star}_{\rm HII}(1+\chi)\Delta T\,, & x_{\rm HII} < 0.99 \\ \sum_i \dfrac{E_i x_i}{3(\gamma_i - 1 + \alpha_{\rm bk})}\alpha_{{\rm A},i} n_{\rm H}\,, & x_{\rm HII} \geq 0.99 \end{cases}$$

Sum is over HI and HeI (not HeII).
E_i is the ionization potential,
γ_i is the power-law index for photoionization cross section at threshold,
α_{Ai} is the case-A recombination coefficient.

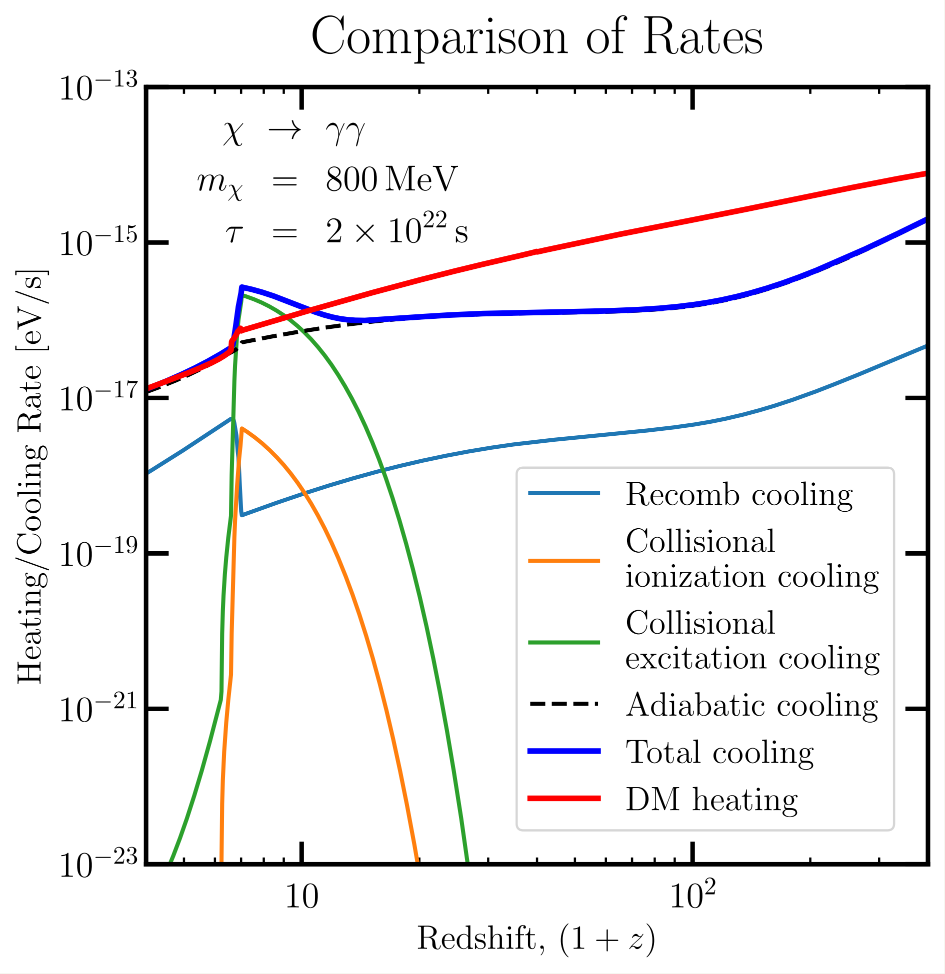
Heating/cooling terms

$$\dot{T}_{\rm adia} = -2HT_{\rm m}$$

$$\dot{T}_{\rm C} = -\Gamma_C(T_{\rm CMB} - T_{\rm m})$$

$$\Gamma_C = \frac{x_{\rm e}}{1+\chi+x_{\rm e}} \frac{8\sigma_T a_r T_{\rm CMB}^4}{3m_{\rm e}}$$

$$\dot{T}_{\rm DM} = \frac{2 f_{\rm heat}(z, \mathbf{x})}{3(1+\chi+x_{\rm e})n_{\rm H}} \left(\frac{dE}{dV\,dt}\right)^{\rm inj}$$



Ionization terms

- Atomic processes
  - *Before z*, case-B scenario*

$$\dot{x}_{\rm HII}^{\rm atom} = 4\,\mathcal{C}_{\rm H}\,\left[(1-x_{\rm HII})\,\beta_{\rm H}^{B}\,e^{-E_{\rm H}/T_{\rm CMB}} - n_{\rm H}\,x_{\rm e}\,x_{\rm HII}\,\alpha_{\rm H}^{B}\right]$$

$$\dot{x}_{\rm HeII}^{\rm atom} = 4\sum_{s}\mathcal{C}_{{\rm HeII},s}\,\left[g_s(\chi - x_{\rm HeI})\,\beta_{{\rm HeI},s}^{B}e^{-E_{{\rm HeI},s}/T_{\rm CMB}} - n_{\rm H}\,x_{\rm e}\,x_{\rm HeII}\,\alpha_{{\rm HeI},s}^{B}\right]$$

  - *After z < z*, case-A scenario*

$$\dot{x}_{\rm HII}^{\rm atom} = n_{\rm H}\,(1-x_{\rm HII})\,x_{\rm e}\,\Gamma_{\rm eHI} - n_{\rm H}\,x_{\rm e}\,x_{\rm HII}\,\alpha_{\rm HII}^{A}$$

- Dark matter energy injection

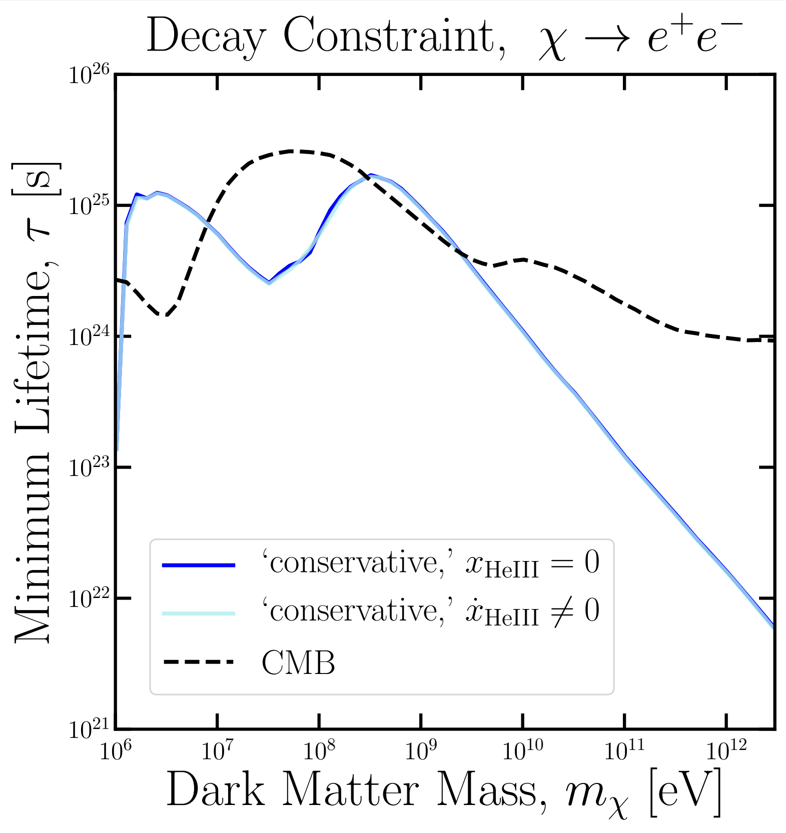
$$\dot{x}_{\rm HII}^{\rm DM} = \left[\frac{f_{\rm H\ ion}(z,\mathbf{x})}{E_{\rm H}n_{\rm H}} + \frac{(1-\mathcal{C}_{\rm H})f_{\rm exc}(z,\mathbf{x})}{0.75E_{\rm H}n_{\rm H}}\right]\left(\frac{dE}{dV\,dt}\right)^{\rm inj}$$

$$\dot{x}_{\rm HeII}^{\rm DM} = \frac{f_{\rm He\ ion}(z,\mathbf{x})}{E_{\rm HeI}n_{\rm He}}\left(\frac{dE}{dV\,dt}\right)^{\rm inj}$$

$$\dot{x}_{\rm HeIII}^{\rm DM} = 0$$

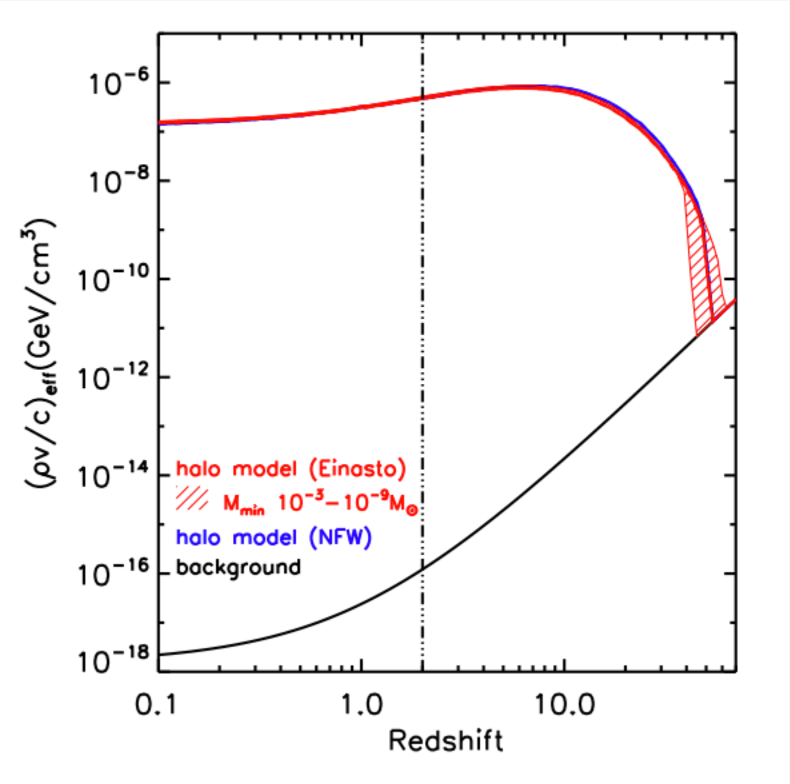
Effects of including HeIII

- Currently, `DarkHistory` assumes there is never HeIII
- However, still allows energy to be deposited into the IGM by
  1. *Photoionization of HeII → HeIII + e-*
  2. *Resulting electron thermalizes with IGM*
  3. *Does NOT keep track of change to HeII and HeIII fractions*
- This treatment is not self-consistent; however, the effect is small



Uncertainty from p-wave boost factor

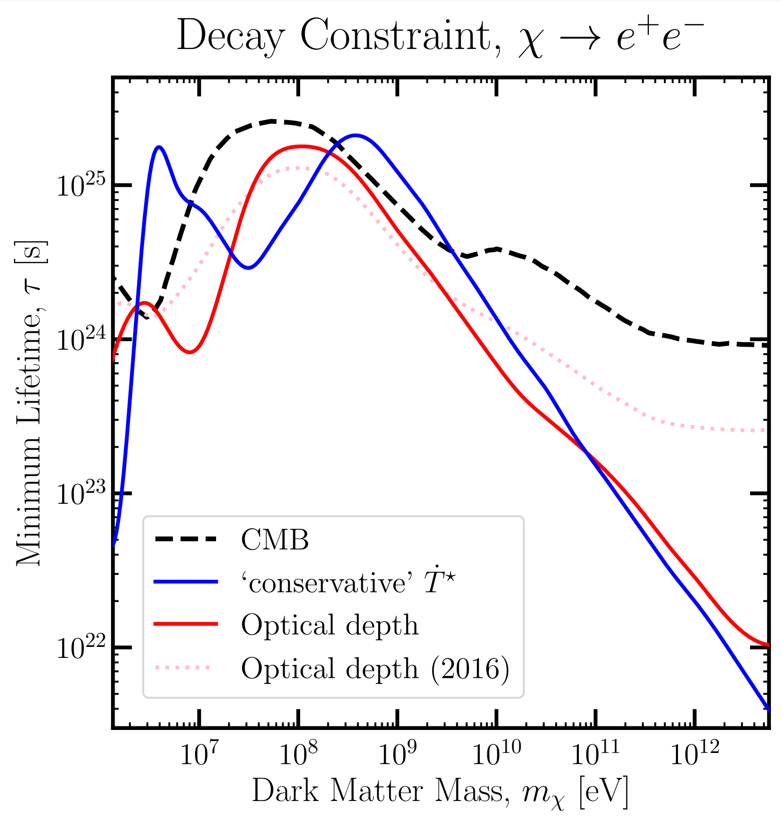
- For p-wave, main contribution to boost factor is from largest halos
  - *Well studied by N-body simulations*
- Uncertainty on boost factor is small, hence uncertainty on our constraints is small,
  - *Results in < 0.5% variation in our results*



Liu et al. (2016)

Comparison to optical depth constraints

- Are the histories along our constraints excluded by their contribution to the optical depth?
  - *Planck 2018: For tanh function reionization,* $\tau = 0.0519^{+0.0030}_{-0.0079}$
- Temperature constraints are comparable to ionization constraints, and stronger in many places



Test statistics

- For the ‘conservative’ method, we use a modified chi-squared that only penalizes data points that overheat the IGM
- Can also think of this as a standard chi-squared test with a flexible background heating model
  - *Model contributes a non-negative amount to the temperature at each measured redshift*
    - In bins where contribution from DM is under measurement, model is set to match data exactly
    - In bins where contribution from DM exceeds measurement, model is fixed to 0
  - *# of model parameters = # of bins where DM is under is under measurement*
  - *Hence, degrees of freedom = # of bins where DM exceeds measurement*