Title: Probing exotic energy injection with the CMB and early star formation

Speakers: Wenzer Qin

Series: Cosmology & Gravitation

Date: November 28, 2023 - 1:00 PM

URL: https://pirsa.org/23110080

Abstract: Dark matter interactions with Standard Model particles can inject energy at early times, altering the standard evolution of the early universe. In particular, this energy injection can perturb the spectrum of the cosmic microwave background (CMB) away from that of a perfect blackbody, alter the CMB anisotropy spectrum, and affect processes by which the first stars form. For this study, I will discuss recent work to upgrade the DarkHistory code package to more carefully track interactions among low energy electrons, hydrogen atoms, and radiation, in order to accurately compute the evolution of the CMB spectral distortion in the presence of Dark Matter energy injection. I will show results for the contribution to the spectral distortions from redshifts z < 3000 for arbitrary energy injection scenarios, new CMB anisotropy constraints on light dark matter, as well as the effect of exotic energy injection on early star formation.

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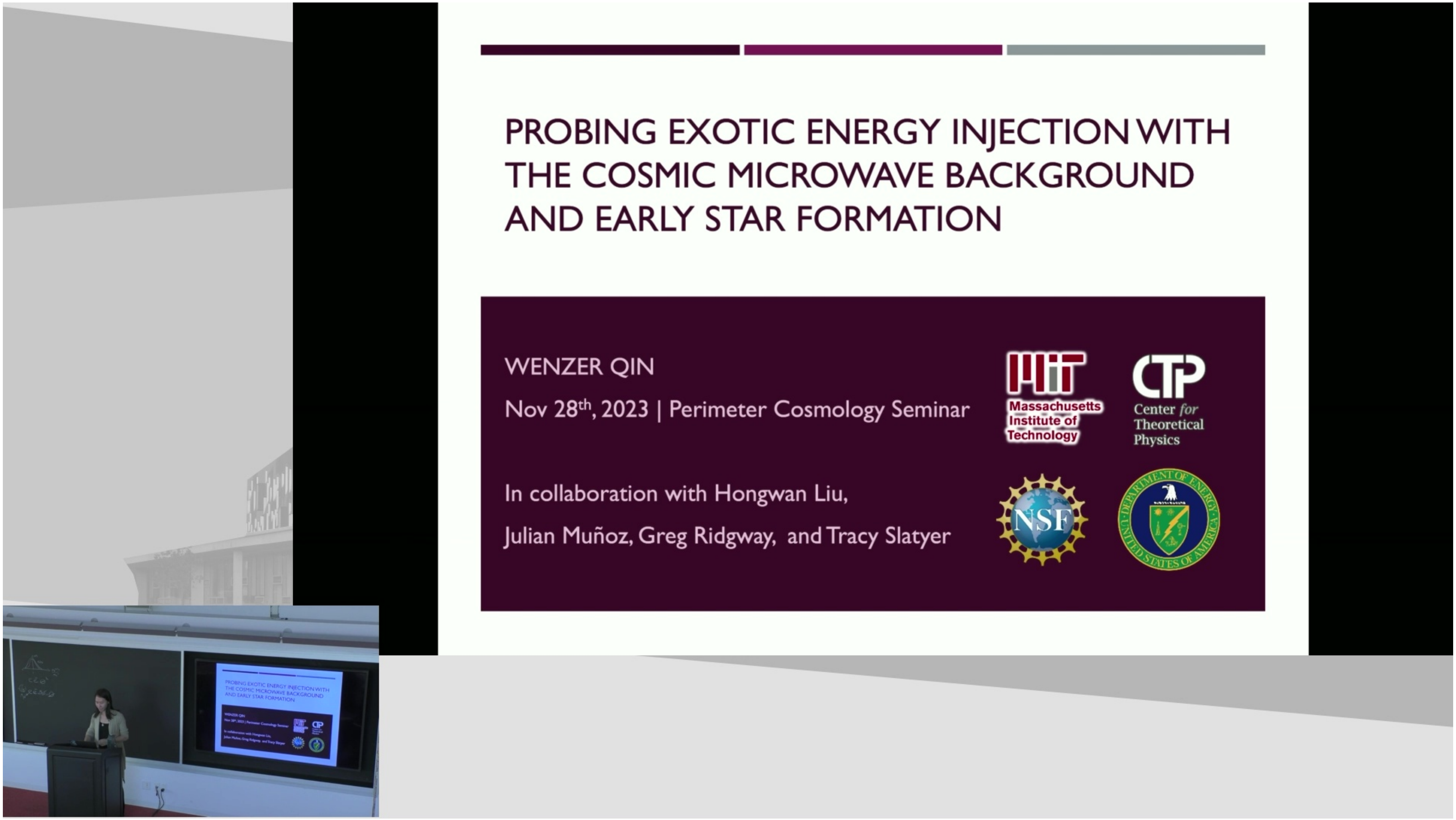
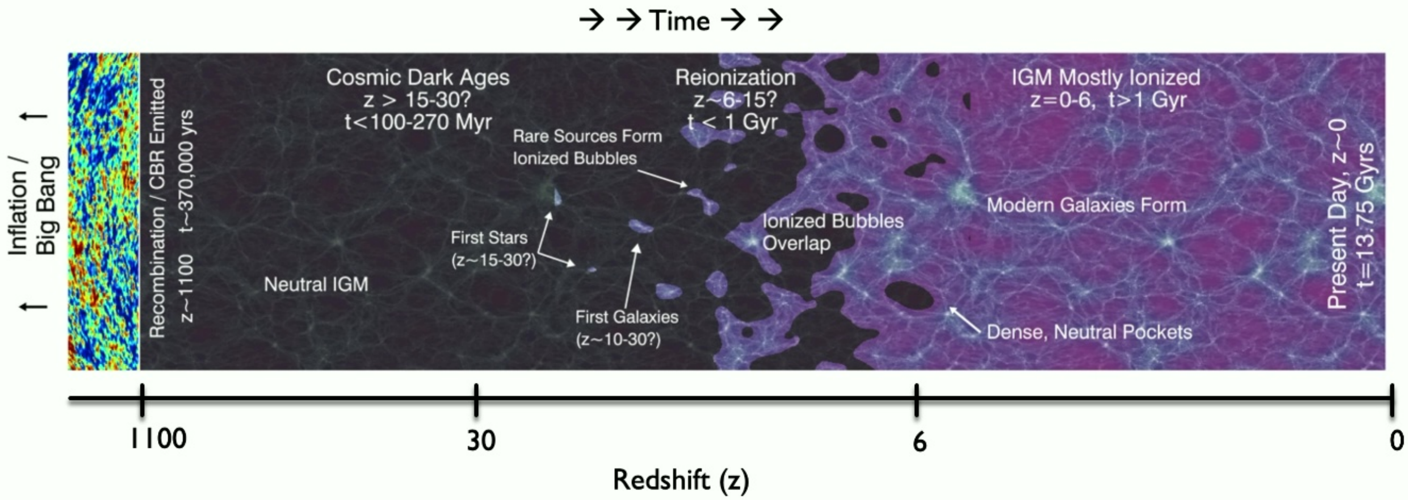
Zoom link https://pitp.zoom.us/j/99559611185?pwd=bDFVdmpyVE5CbXVXVHdEL29Md0FXUT09


PROBING EXOTIC ENERGY INJECTION WITH THE COSMIC MICROWAVE BACKGROUND AND EARLY STAR FORMATION
WENZER QIN
Nov 28th, 2023 | Perimeter Cosmology Seminar
In collaboration with Hongwan Liu,
Julian Muñoz, Greg Ridgway, and Tracy Slatyer
Massachusetts Institute of Technology
Center for Theoretical Physics
NSF

# OUTLINE

- Introduction
- `DarkHistory v2.0`
- Applications
  - CMB spectral distortions
  - CMB anisotropy constraints on light dark matter
  - Formation of the first stars
- Conclusion

# INTRODUCTION

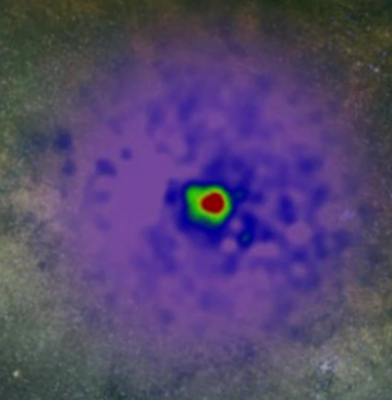



- What *exactly* is the DM in ΛCDM?
- How can dark matter microphysics imprint on observables?

Robertson et al. (2010)

# EXOTIC ENERGY INJECTION

- Energy injected into electromagnetic observables, not by processes in $\Lambda$CDM/Standard Model
- Focus on decaying dark matter
- Could generalize results to
  - Annihilating dark matter
  - Evaporating primordial black holes
  - Accreting primordial black holes



# WHAT IS YOUR MODEL/LAGRANGIAN?

- Do not require specific particle physics model; only need
  - Redshift dependence of energy injection rate
  - Spectrum of primary particles
- E.g. for decaying dark matter, we need to specify
  - Dark matter mass
  - Interaction rate/decay lifetime
  - Focus on decay to electrons/positrons or photons

# EFFECTS OF EXOTIC ENERGY INJECTION

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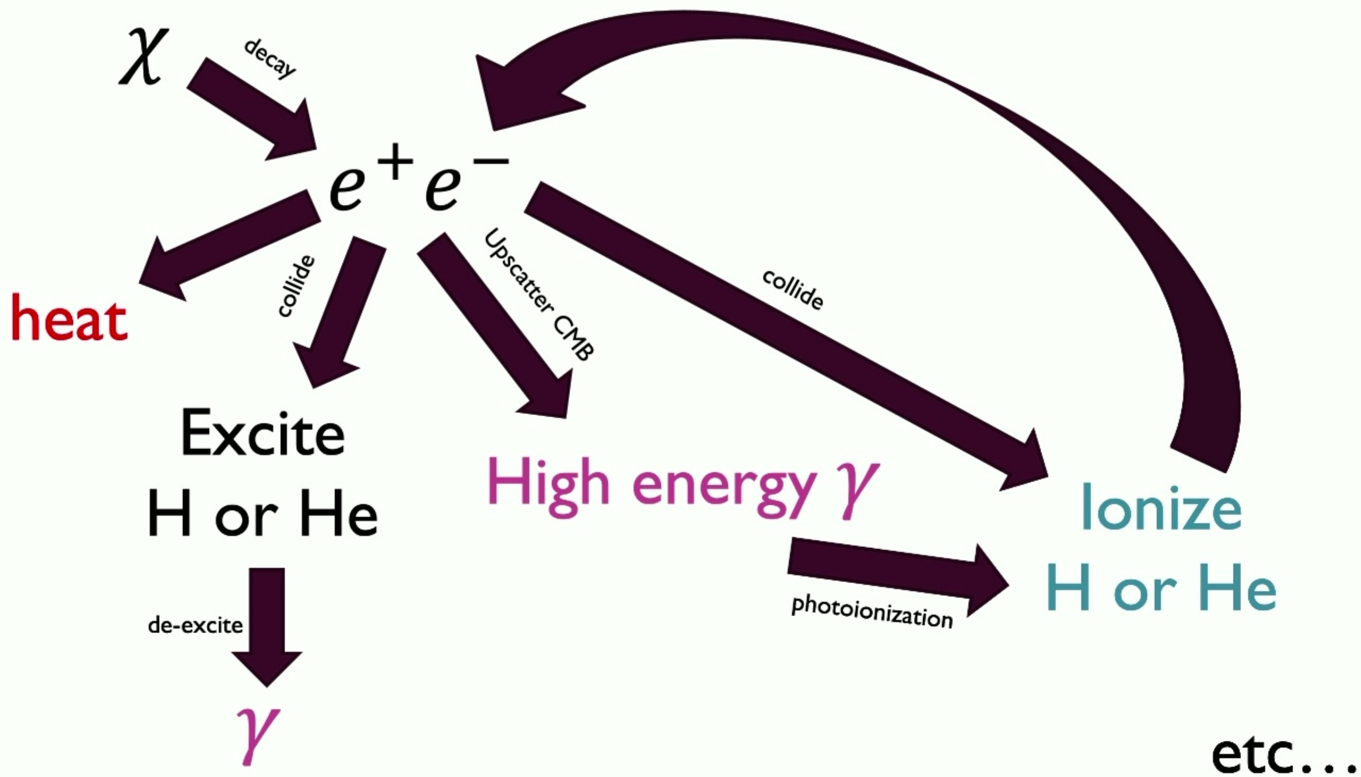


# DarkHistory

- Download at https://github.com/hongwanliu/DarkHistory
- Calculates global temperature and ionization histories, while self-consistently including models of exotic energy injection
- `DarkHistory v2.0:` major upgrades to also calculate evolution of radiation background
    - Improved treatment of low-energy electrons
    - New machinery to track more hydrogen levels

Liu, Ridgway, & Slatyer 2020

Liu, **WQ**, et al. 2023 (arXiv:2303.07366)

Liu, **WQ**, et al. 2023 (arXiv:2303.07370)

# PREVIOUS ELECTRON TREATMENT

## High energy (≥ 3 keV)

- Consider energy deposited into channel $c$ by electron with energy $E'$
  - In a short time step, promptly deposits some energy: $P_c(E)$
  - Produces spectrum of secondary electrons: $\frac{dN_{sec}}{dE}$
- Want to know energy deposited after electron cools completely: $R_c(E)$
- Solve for $R_c$ using

$$R_c(E') = P_c(E') + \int dE \, R_c(E) \frac{dN_{sec}}{dE}$$

## Low energy (< 3 keV)

- Used results of `MEDEA`
  - Monte Carlo method to track energy
  - Only had results for electrons at 14, 30, 60, 100, 300, and 3000 eV
  - No secondary photon spectra

428 C. Evoli et al.

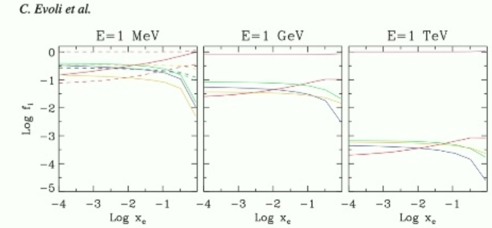



**Figure 4.** The energy deposition fractions for a single electron (solid line) and positron (dashed line) of different initial energies ($E = 10^6$, $10^9$ and $10^{12}$ eV at $z = 10$). The curves represent the energy fraction that goes into gas heating ($f_h$, red line), Lyα photons ($f_\alpha$, green line), ionizations ($f_{ion}$, blue line), photons with $E < 10.2$ eV ($f_c$, orange line) and photons with higher energy that free stream to the observer ($f_{HE}$, purple line). Note that in the middle and right-hand panels, the solid and dashed curves are indistinguishable.

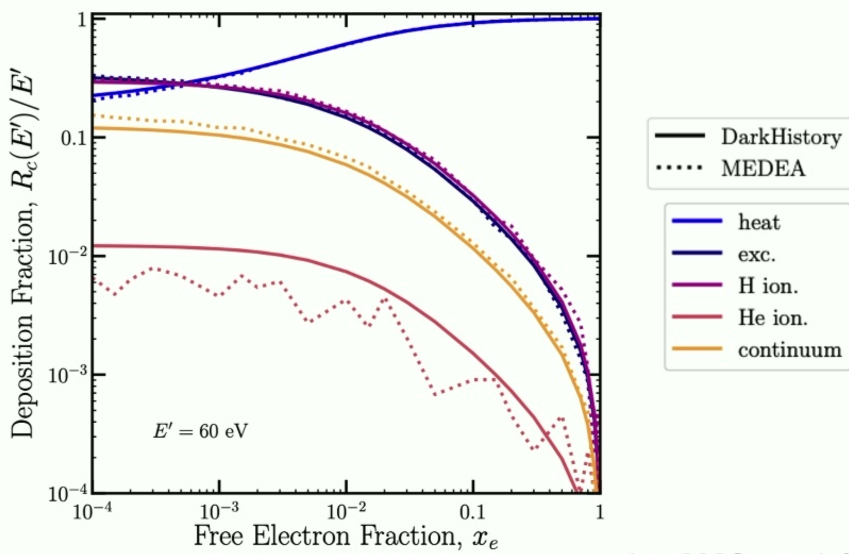
Evoli et al. 2012

# PREVIOUS ELECTRON TREATMENT

- In principle, our high-energy treatment should apply to *all* energies; however…
  - Made approximations in cross-sections that may not apply at low energies
  - Also allowed users to implement their own model for low energy cooling

# UPGRADED ELECTRON TREATMENT

- Upgraded cross-sections; can now extend high energy treatment
- Generally agree with MEDEA; Monte Carlo noisy for rare events




Liu, **WQ**, et al. 2023 (arXiv:2303.07366)

# PREVIOUS ELECTRON TREATMENT

## High energy ($\geq$ 3 keV)

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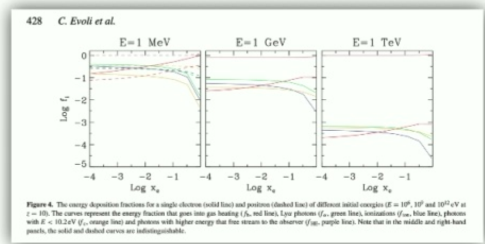


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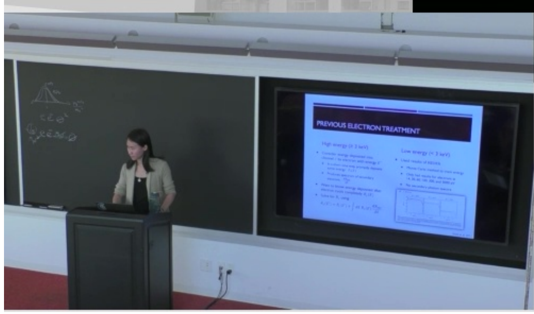

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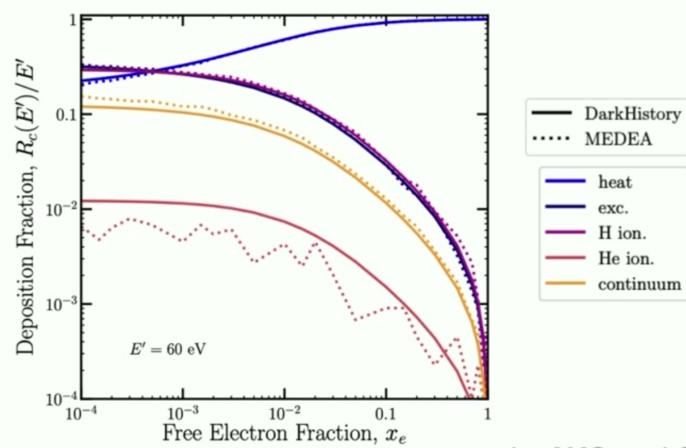


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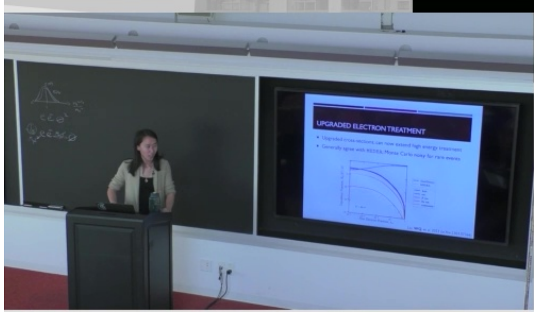
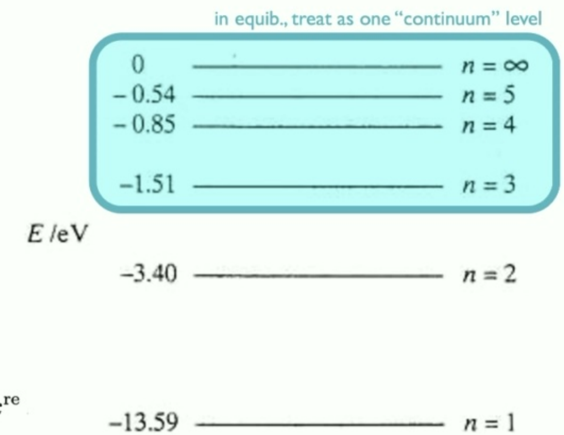


# PREVIOUS HYDROGEN TREATMENT

- Used Three-Level Atom (TLA) approximation
  - Assume background radiation is perfect blackbody
  - Assume all levels above n=2 are in thermal equilibrium
- Leads to coupled temperature and ionization equations




$$\dot{x}_e = \mathcal{C}\left(-x_e^2 n_{\rm H}\alpha_{\rm B} + 4\beta_{\rm B} e^{-(\omega_2-\omega_1)/T} x_{1s}\right) + \dot{x}_{\rm inj} + \dot{x}^{\rm re}$$

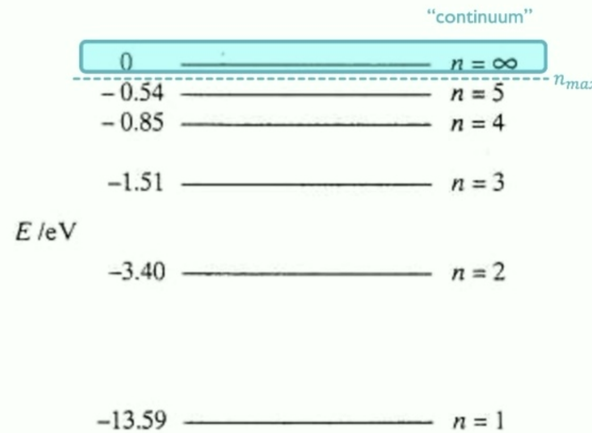
$$\dot{T}_m = -2HT_m + \Gamma_C(T_{\rm CMB} - T_m) + \dot{T}_m^{\rm inj} + \dot{T}_m^{\rm re}$$

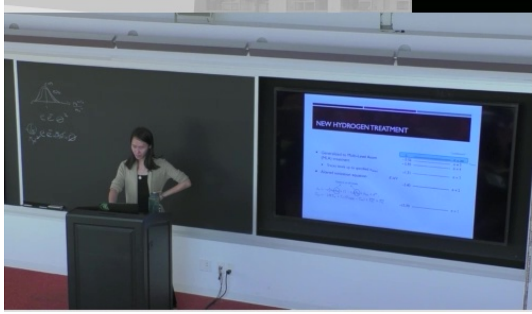
# NEW HYDROGEN TREATMENT

- Generalized to Multi-Level Atom (MLA) treatment
  - Tracks levels up to specified $n_{max}$
- Altered ionization equation

Depend on all levels

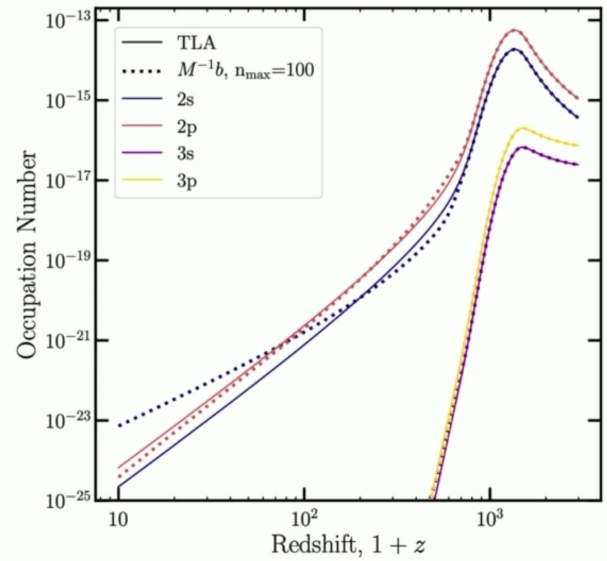
$$\dot{x}_e = -x_e^2 n_{\rm H} \tilde{\alpha}_{\rm B} + (1 - x_e) \tilde{\beta}_{\rm B} + \dot{x}_{\rm inj} + \dot{x}^{\rm re} \,,$$
$$\dot{T}_m = -2HT_m + \Gamma_C (T_{\rm CMB} - T_m) + \dot{T}_m^{\rm inj} + \dot{T}_m^{\rm re}$$



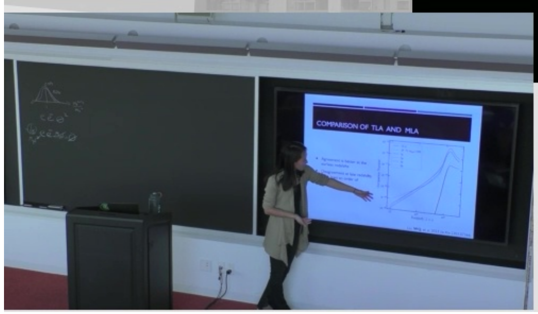



# COMPARISON OF TLA AND MLA

- Agreement is better at the earliest redshifts
- Disagreement at late redshifts by at least an order of magnitude

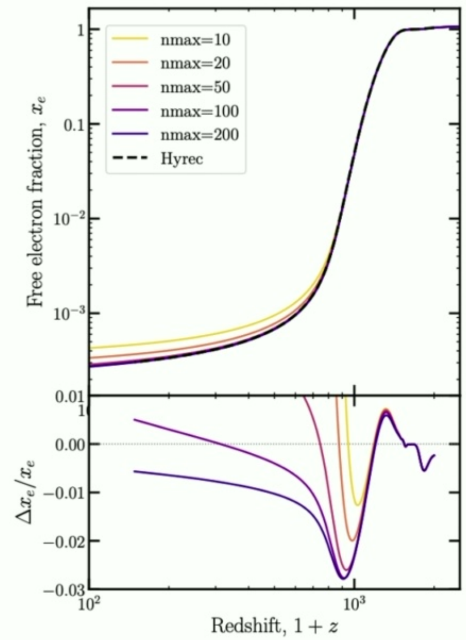



Liu, **WQ**, et al. 2023 (arXiv:2303.07366)



# INCLUDING MORE LEVELS

- Results converge as $n_{max}$ increases
- Also in reasonable agreement with other codes, e.g. Hyrec
- More levels requires more time to compute

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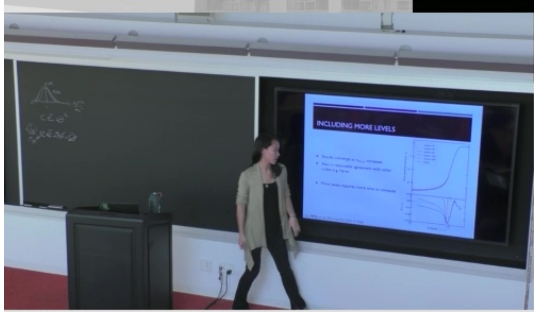

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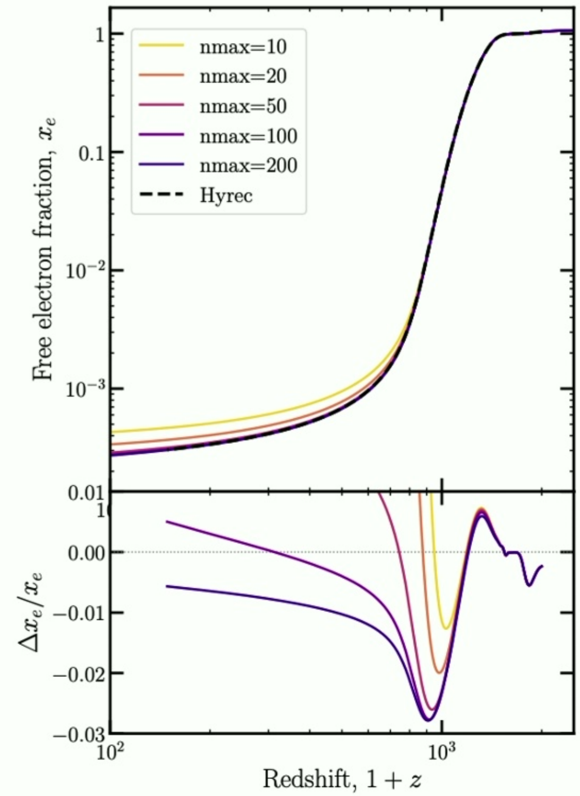


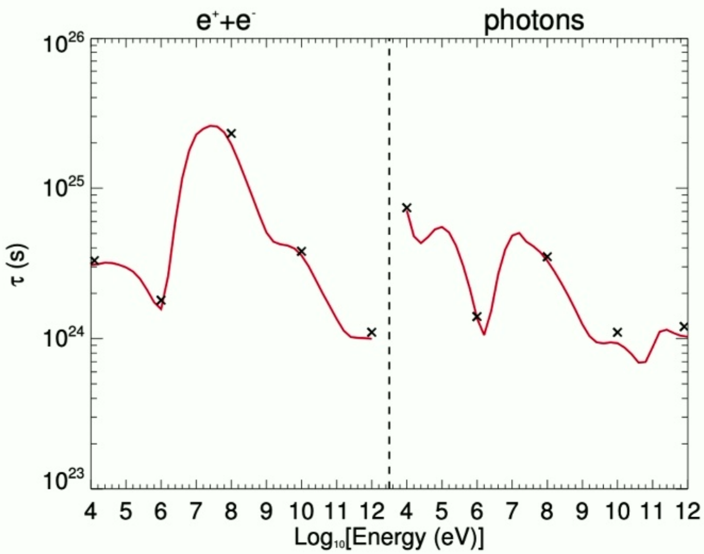

Liu, **WQ**, et al. 2023 (arXiv:2303.07366)

# APPLICATIONS

1) CMB blackbody 2) CMB anisotropies 3) early star formation

# PREVIOUS APPLICATIONS

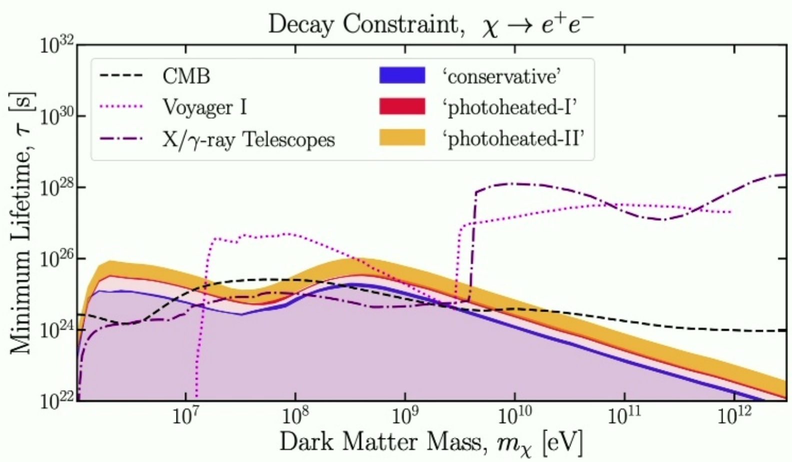
- Using `DarkHistory v1.0` and precursors…
- Ionization → constraints from CMB anisotropy spectrum




Slatyer and Wu (2016)

# PREVIOUS APPLICATIONS

- Using `DarkHistory v1.0` and precursors…
- Ionization → constraints from CMB anisotropy spectrum
- Heating → constraints from Lyman-α forest




Liu, **WQ**, et al. 2021 (arXiv:2008.01084)

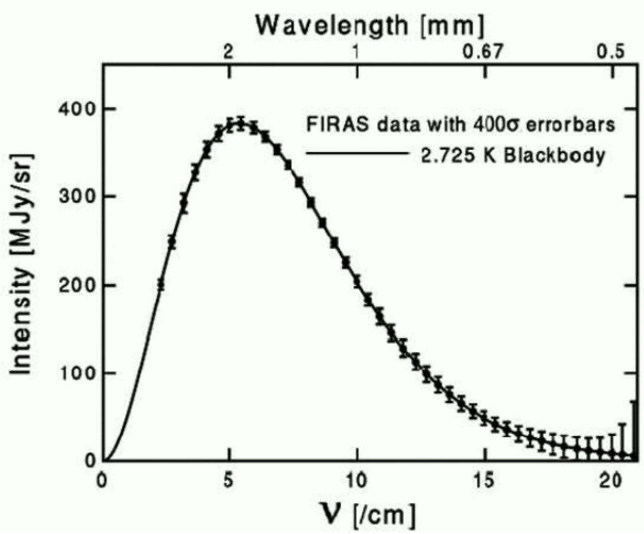
# PREVIOUS APPLICATIONS

- Using `DarkHistory v1.0` and precursors…
- Ionization → constraints from CMB anisotropy spectrum
- Heating → constraints from Lyman-$\alpha$ forest

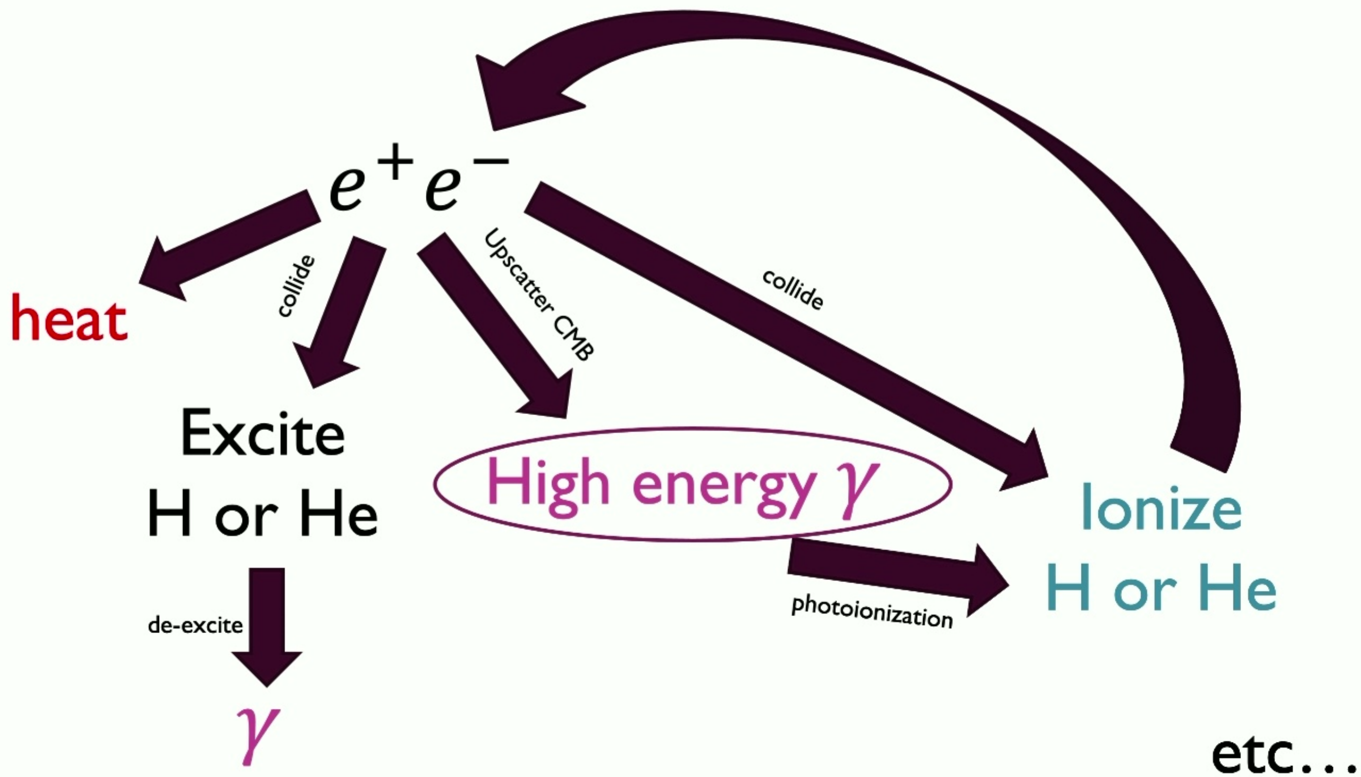
- Now have photon spectrum → CMB spectral distortions
- Completely new application of `DarkHistory`

# 1) CMB SPECTRAL DISTORTIONS

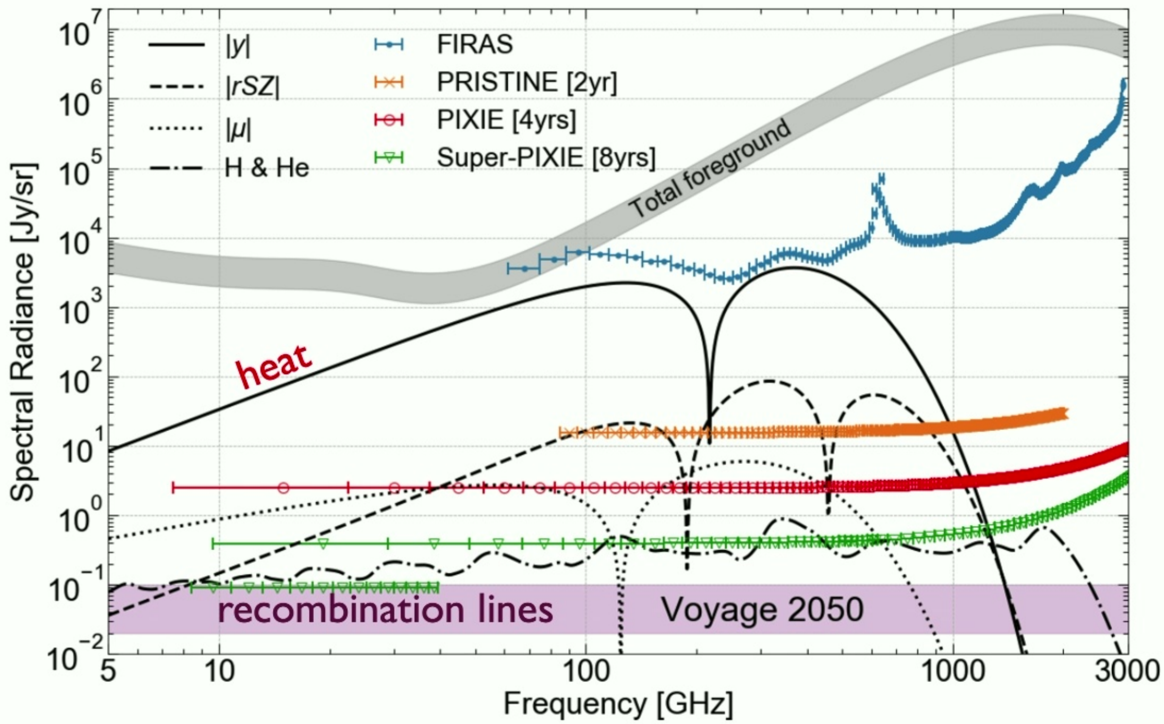
- COBE/FIRAS showed us the CMB is nearly a perfect blackbody
- If addition (or subtraction) of energy from photons **cannot fully thermalize**, the CMB spectrum will **no longer be blackbody**
- Distortions are known to be very small, $\Delta I/I < 10^{-4}$



# WAYS TO FORM A DISTORTION

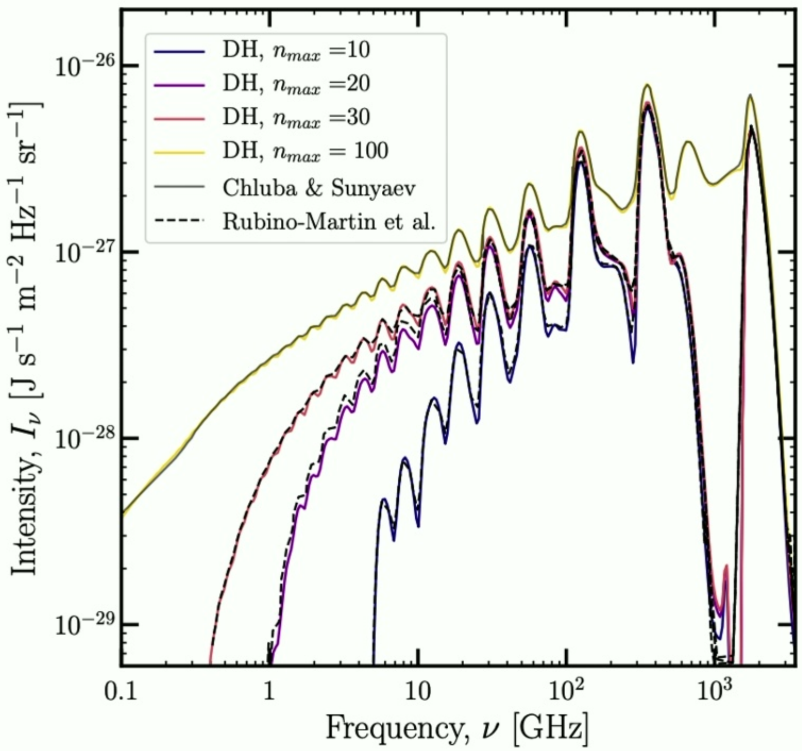


# EXPECTED SPECTRAL DISTORTIONS




ESA Voyage 2050 White Paper

# DarkHistory REPRODUCES EXPECTED DISTORTIONS




Liu, **WQ**, et al. 2023 (arXiv:2303.07366)

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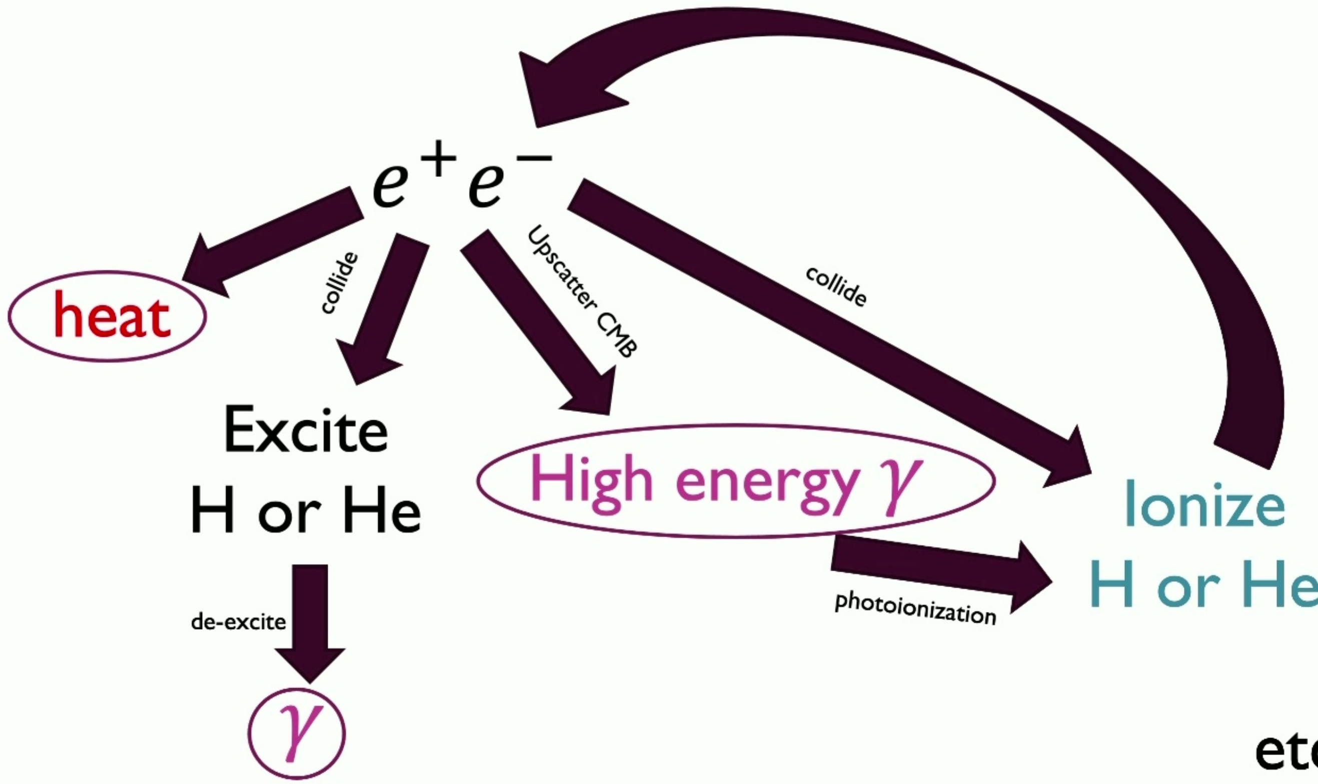
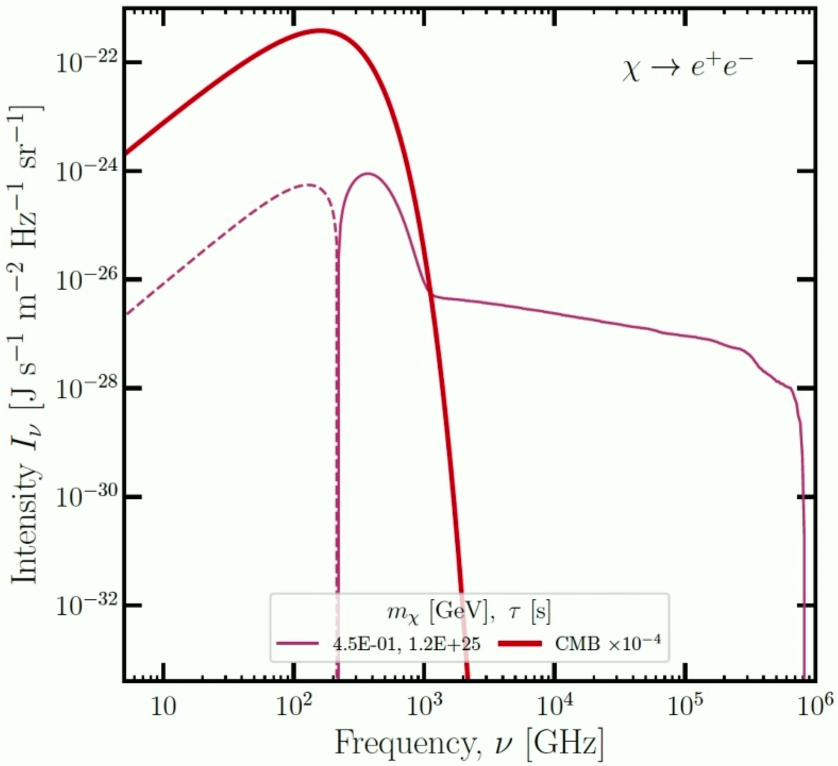



etc…

# EXOTIC SPECTRAL DISTORTIONS




*1 GeV = 1.8 x $10^{-24}$ grams

Liu, **WQ**, et al. 2023 (arXiv:2303.07370)

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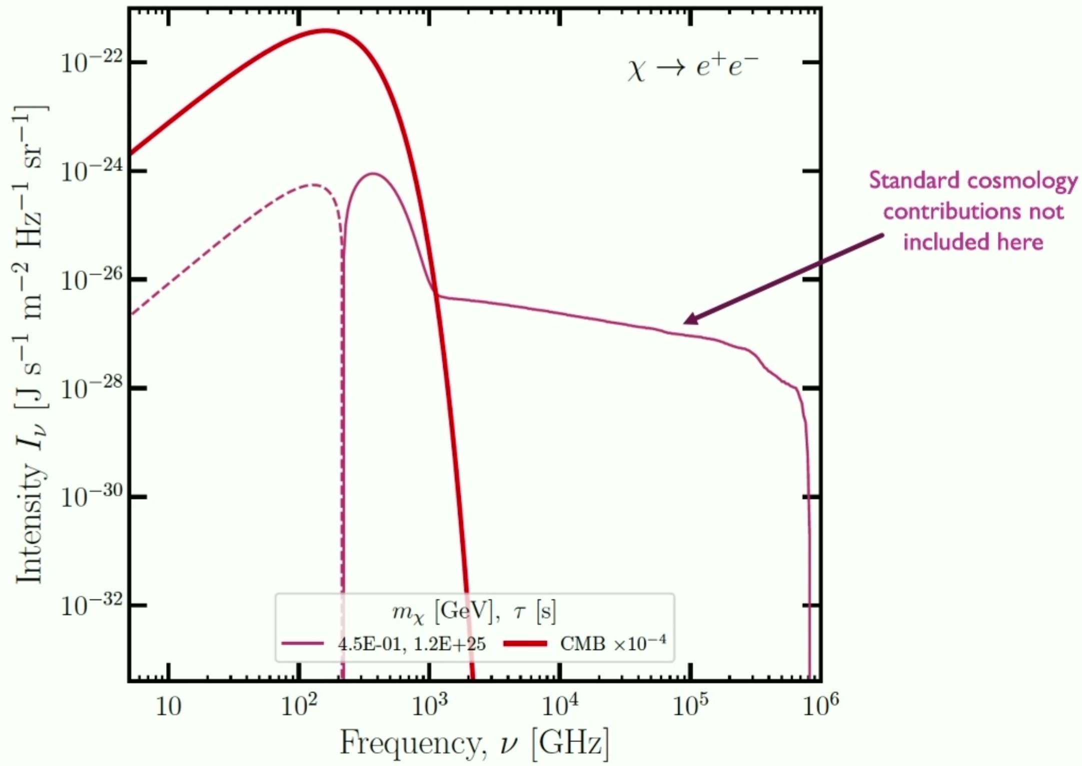


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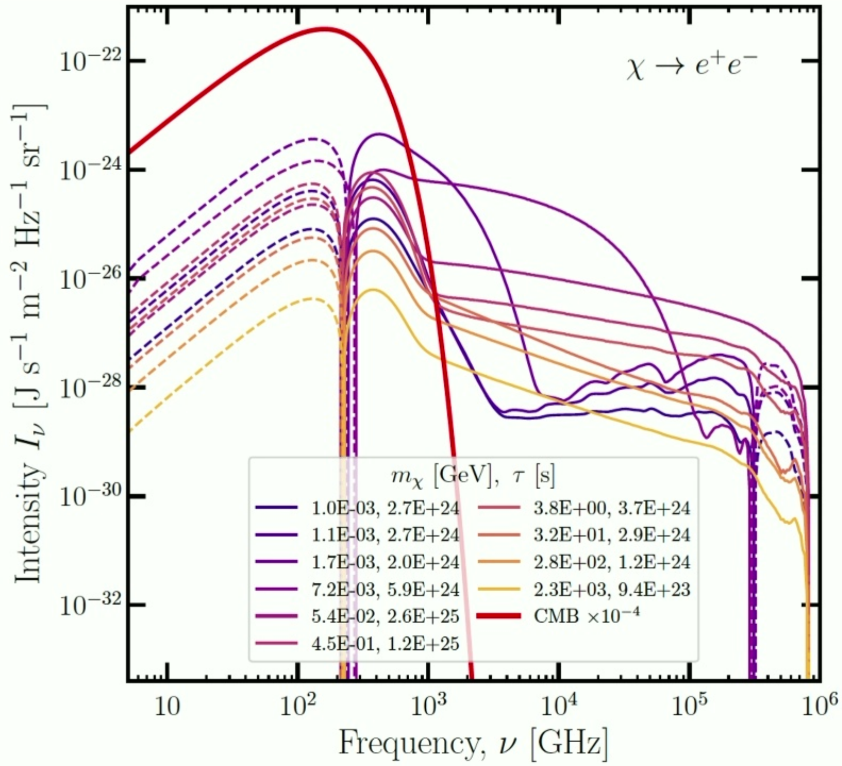


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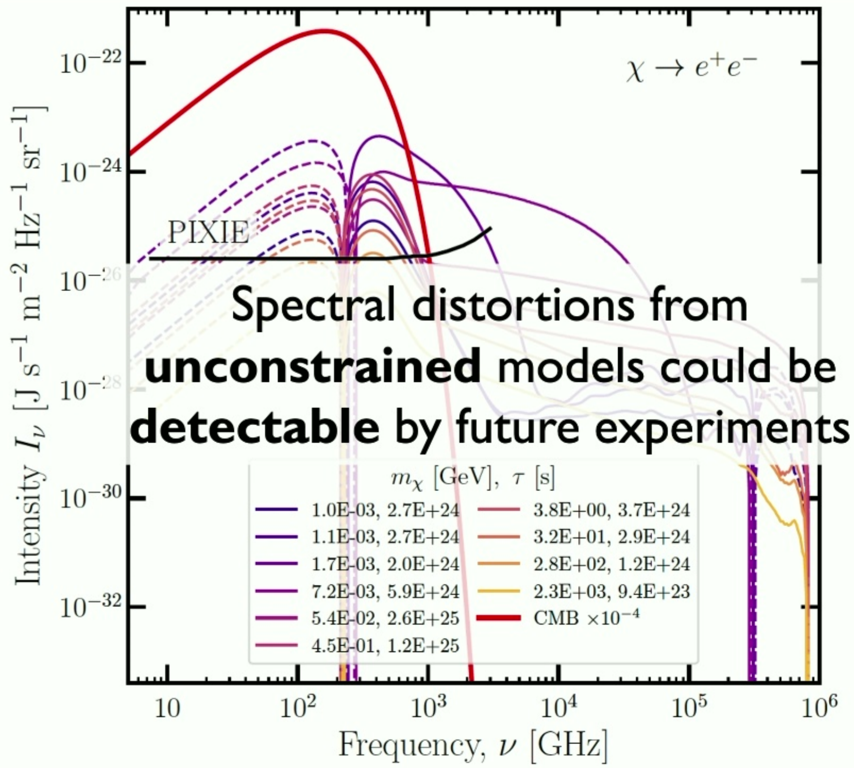


Spectral distortions from **unconstrained** models could be **detectable** by future experiments

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Liu, **WQ**, et al. 2023 (arXiv:2303.07370)

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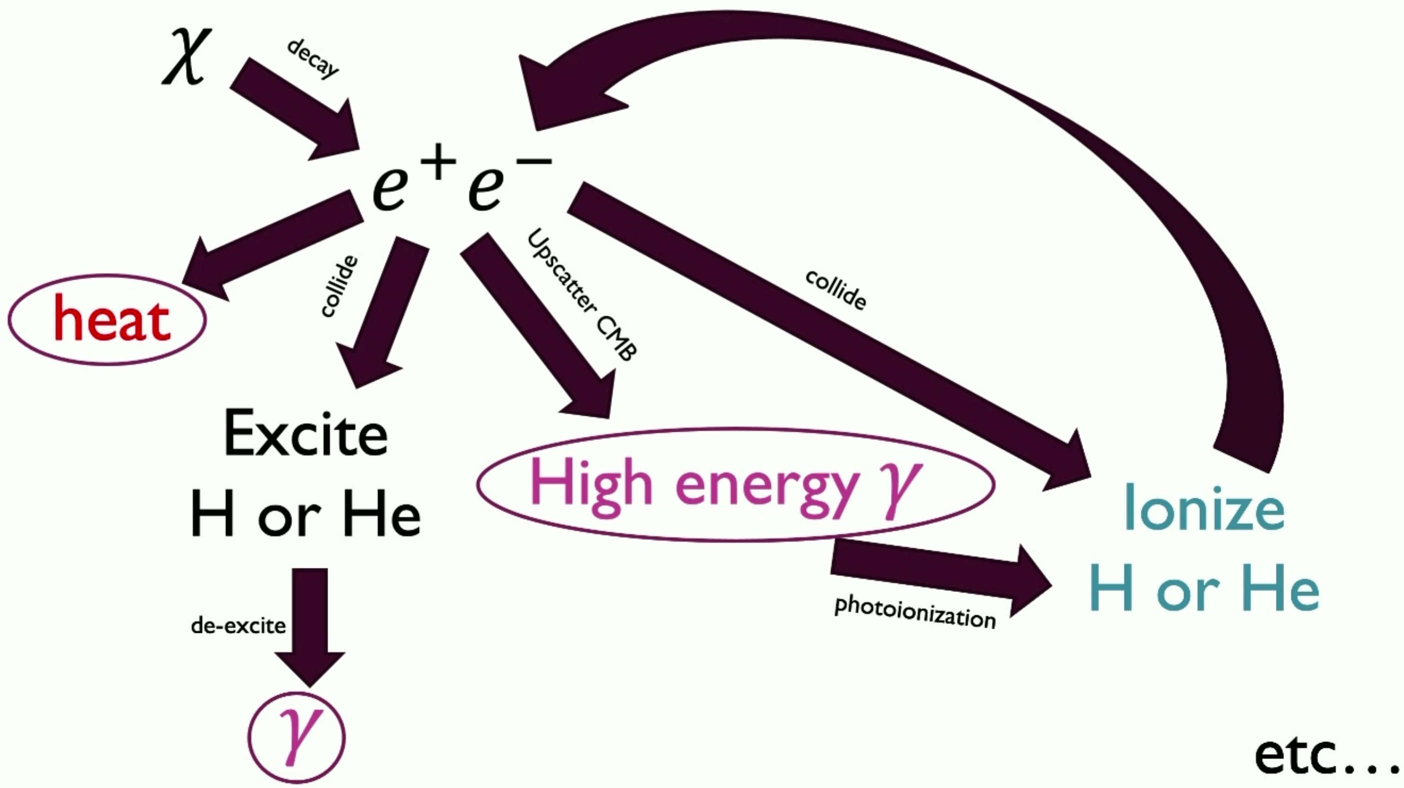

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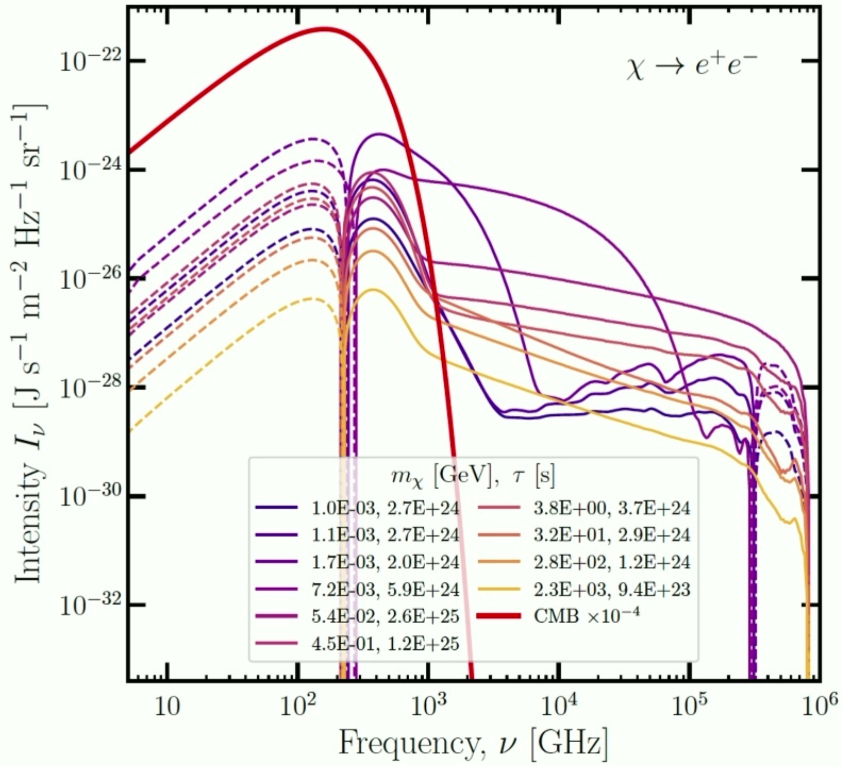


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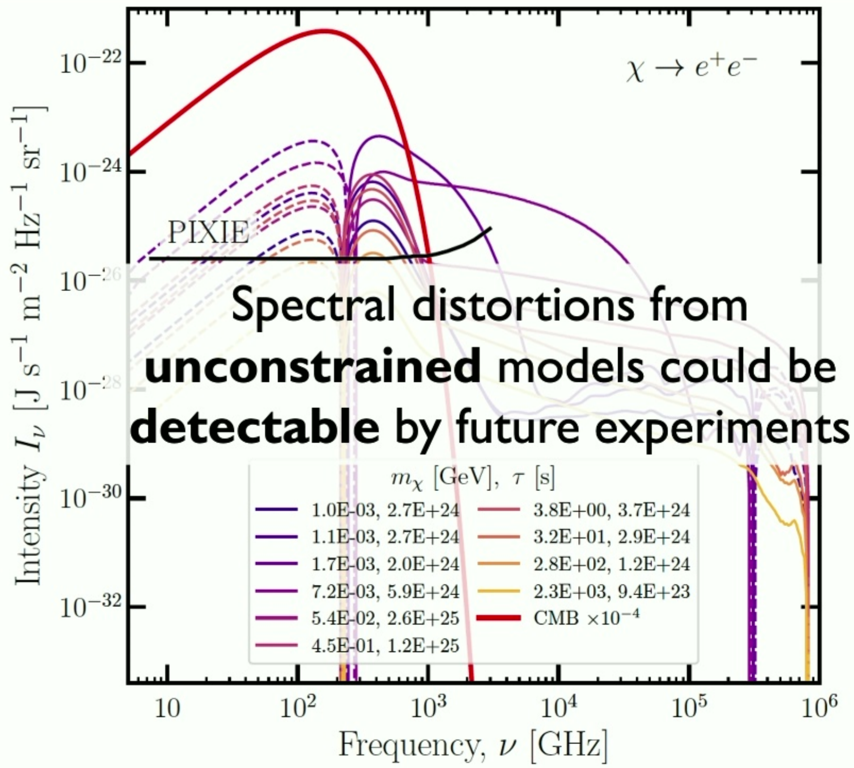


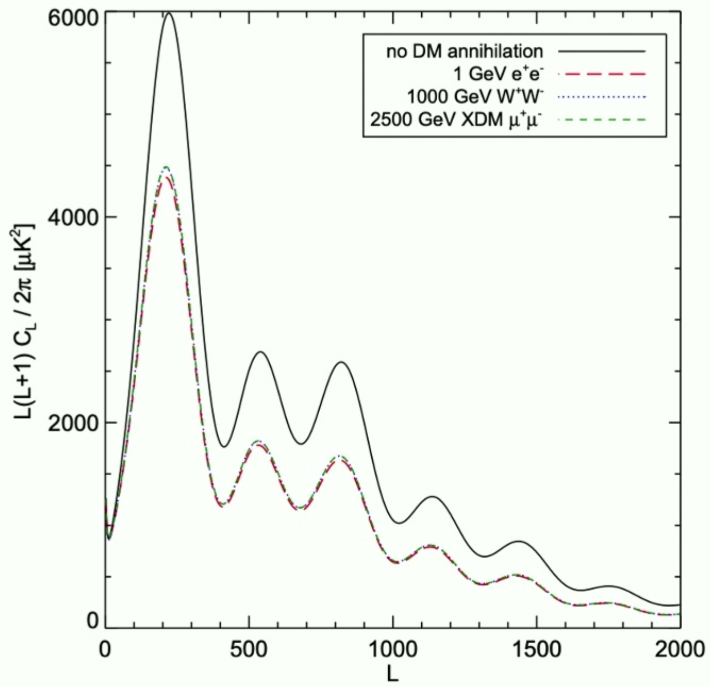

Spectral distortions from **unconstrained** models could be **detectable** by future experiments

*1 GeV = 1.8 x $10^{-24}$ grams

Liu, **WQ**, et al. 2023 (arXiv:2303.07370)

# 2) CMB ANISOTROPY CONSTRAINTS

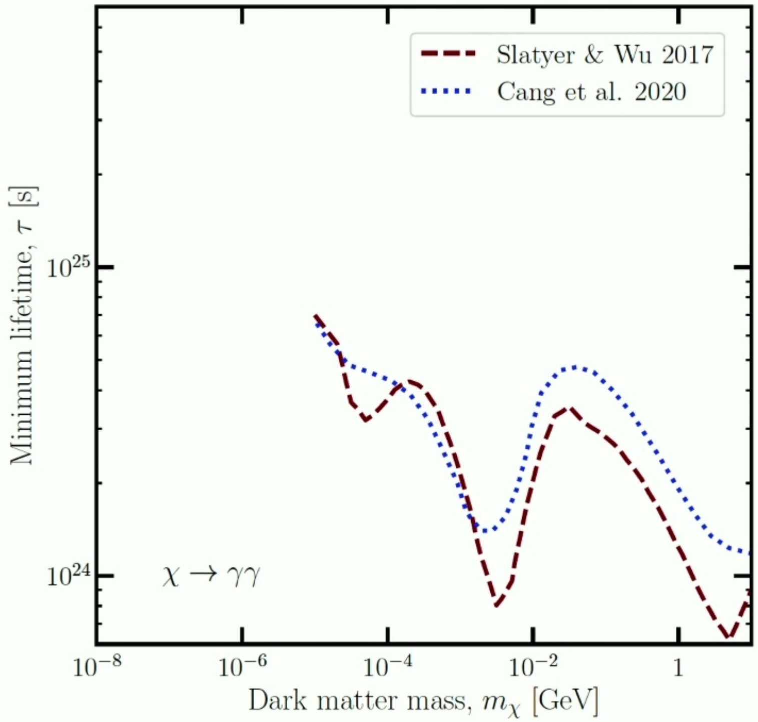
- Additional ionization damps CMB fluctuations
- Use this to constrain exotic energy injection by dark matter




Slatyer, Padmanabhan, & Finkbeiner (2009)

# CMB ANISOTROPY CONSTRAINTS

- **DarkHistory v1.0 :** theoretical uncertainties in low-energy treatment

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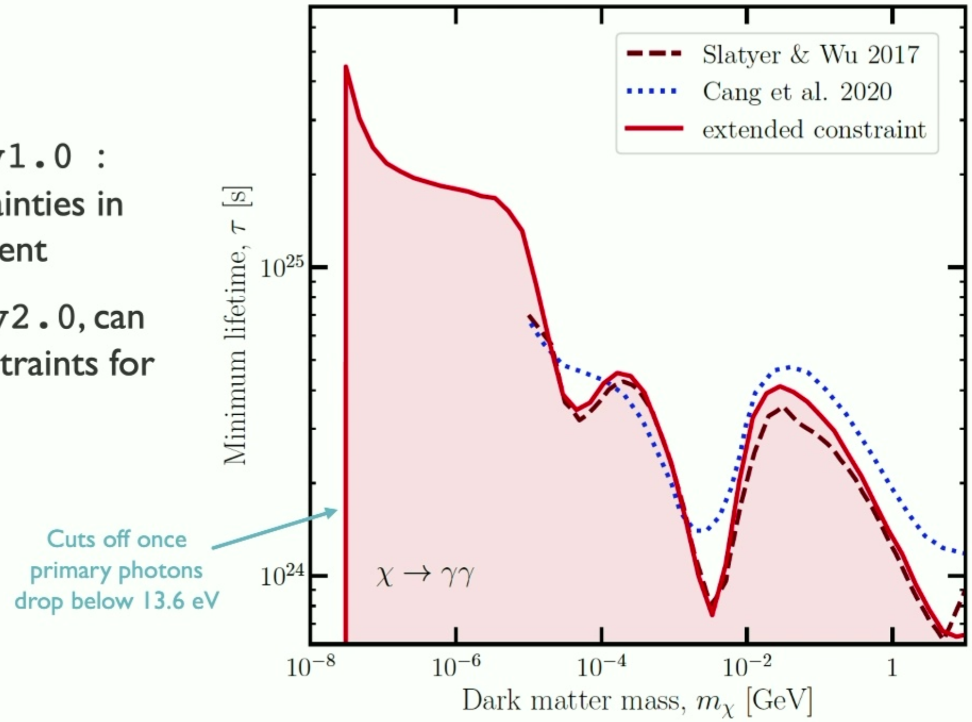
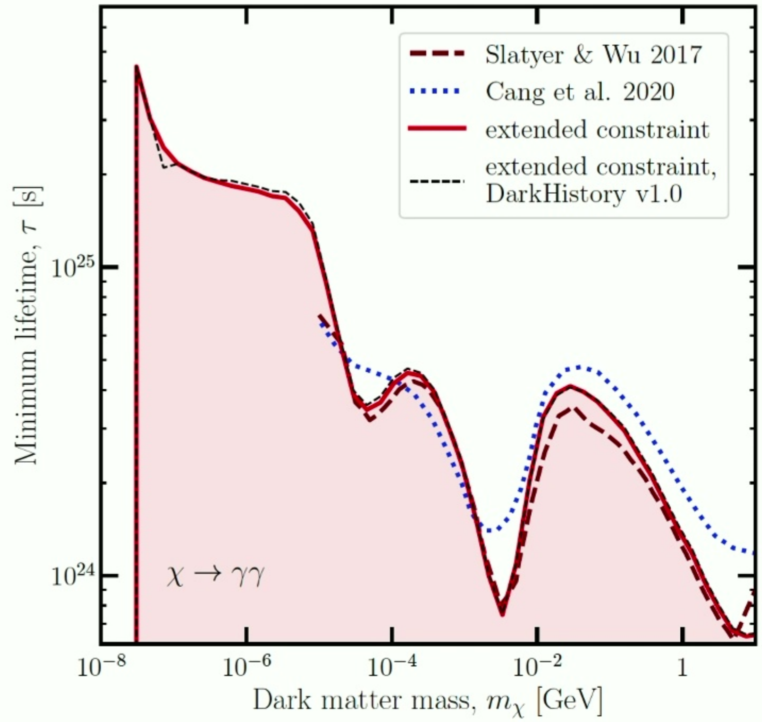
- `DarkHistory v1.0` : theoretical uncertainties in low-energy treatment
- With upgrades in `v2.0`, can now estimate constraints for light dark matter




Liu, **WQ**, et al. 2023 (arXiv:2303.07370)

# CMB ANISOTROPY CONSTRAINTS

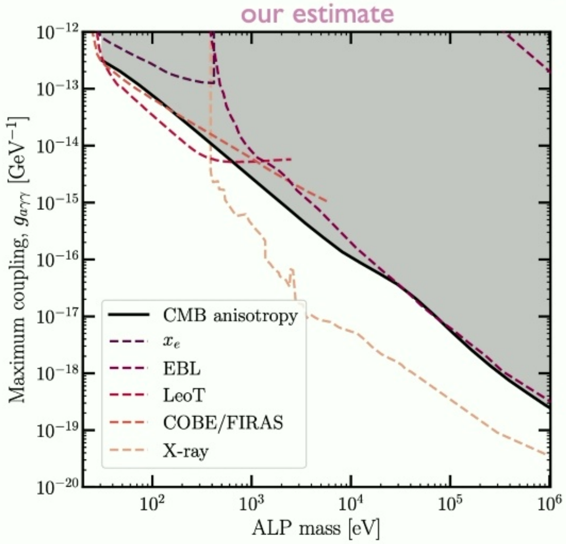
- `DarkHistory v1.0` : theoretical uncertainties in low-energy treatment
- With upgrades in `v2.0`, can now estimate constraints for light dark matter
- (old code actually very good!)




Liu, **WQ**, et al. 2023 (arXiv:2303.07370)

# CONSTRAINTS ON AXION-LIKE PARTICLES (ALPs)

Liu, **WQ,** et al. 2023 (arXiv:2303.07370), our estimate



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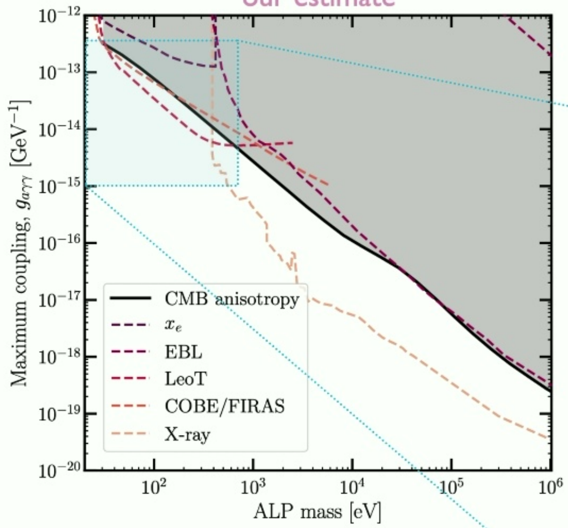
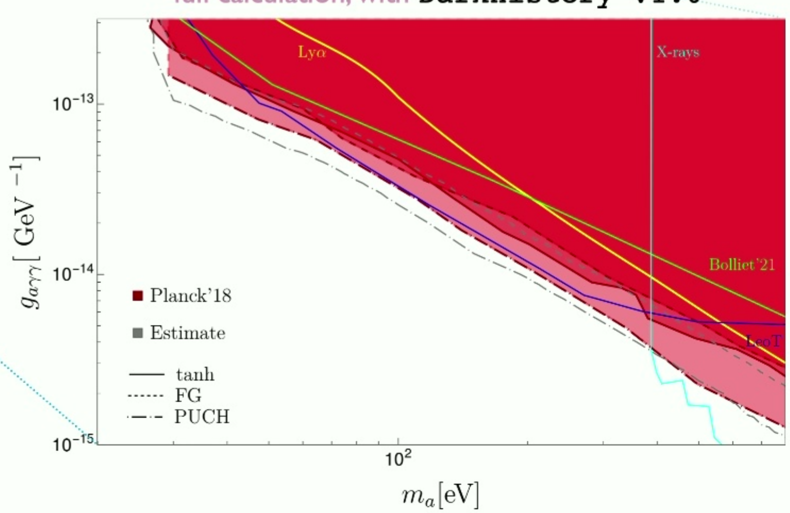



Capozzi et al. 2023 (arXiv:2303.07426), full calculation, with `DarkHistory v1.0`



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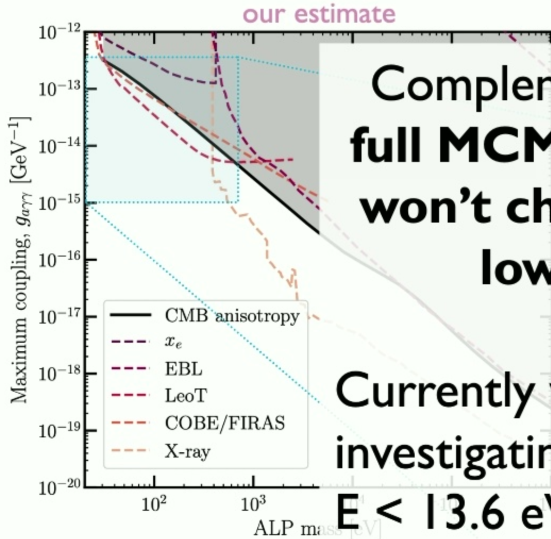
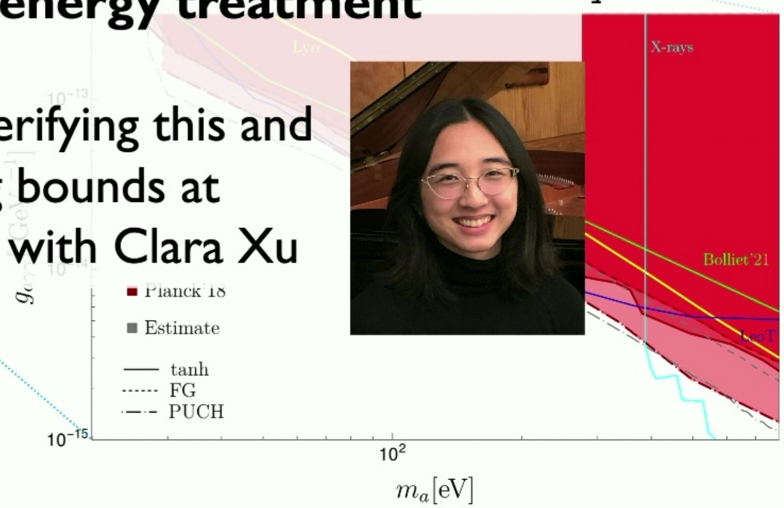



Complementary work! They did the **full MCMC**, we show the constraints **won't change with the improved low-energy treatment**

07426), full calculation with DarkHistory v1.0




Currently verifying this and investigating bounds at E < 13.6 eV with Clara Xu

# 3) EARLY STAR FORMATION

- First halos cool/collapse via molecular hydrogen ($H_2$)
- Heating, ionization, and background radiation all affect formation of $H_2$

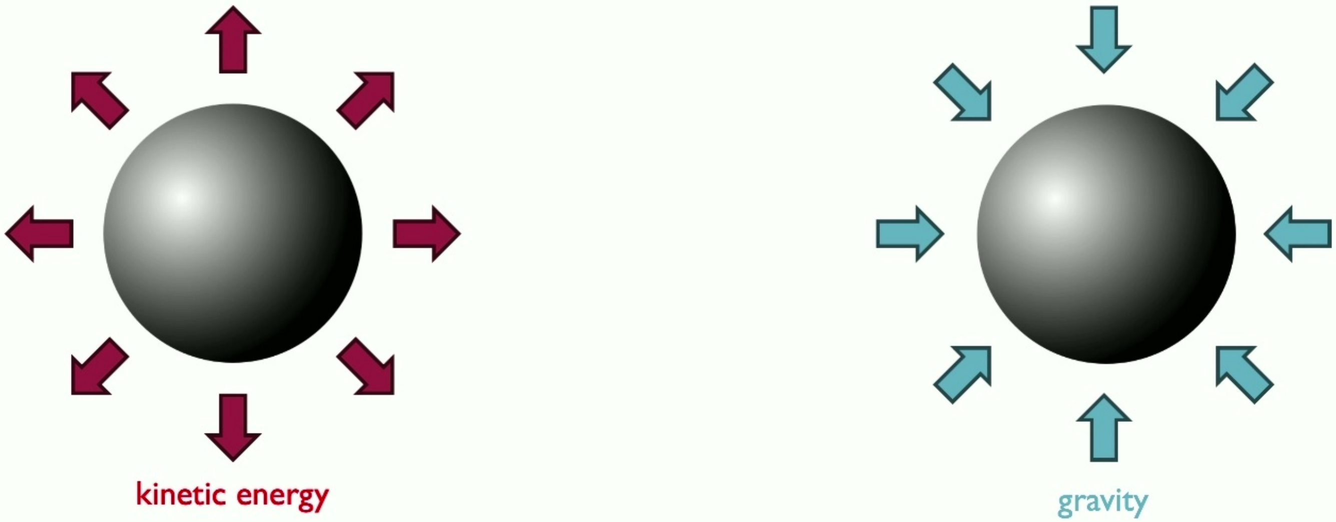
$$H + e^- \rightarrow H^- + \gamma$$
$$H + H^- \rightarrow H_2 + e^-$$

$$H^- + \gamma \rightarrow H + e^-$$
$$H_2 + \gamma \rightarrow H_2^* \rightarrow 2H$$

Greif et al. 2008

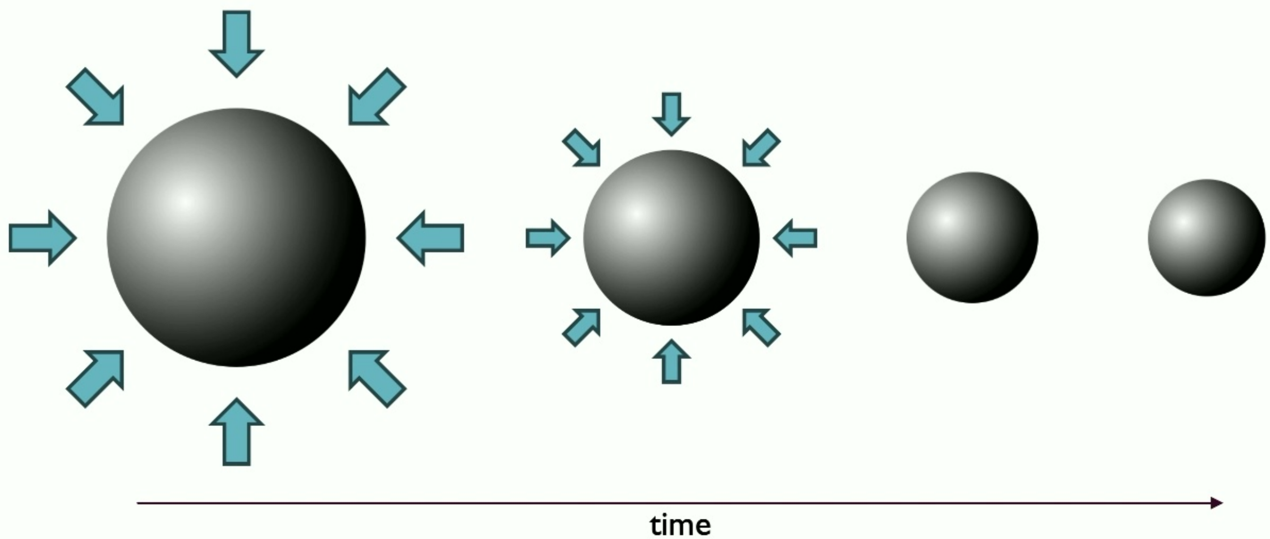
# COLLAPSING HALOS

- Treat gas as spherical top-hat (uniform density)
- First, overdensity must collapse and virialize to form a halo



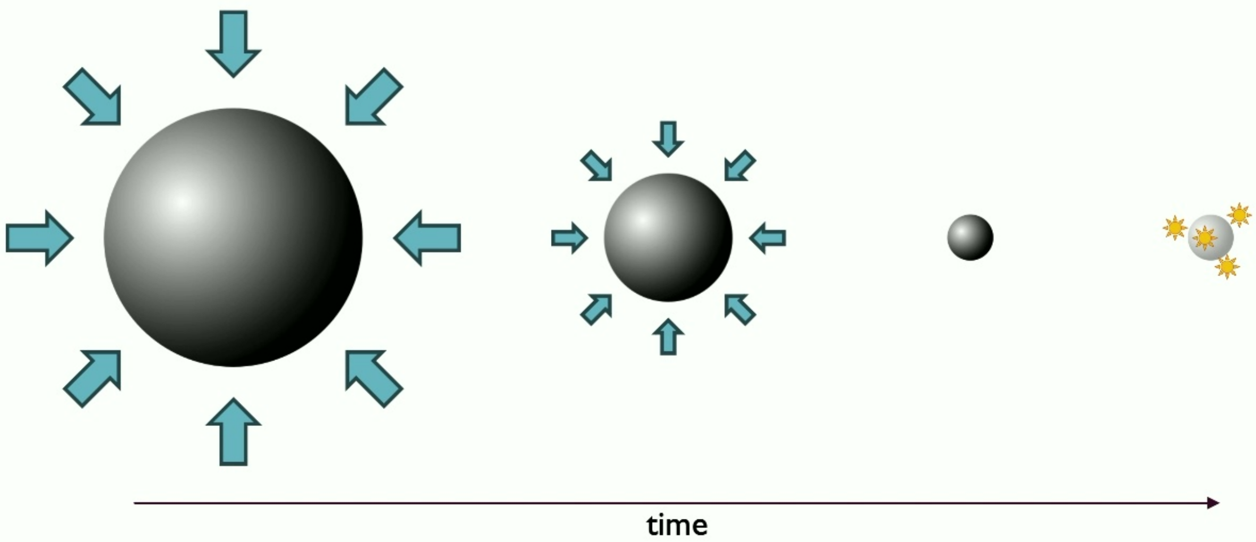
# COLLAPSING HALOS

- Smaller halos → pressure-supported, less efficient at cooling



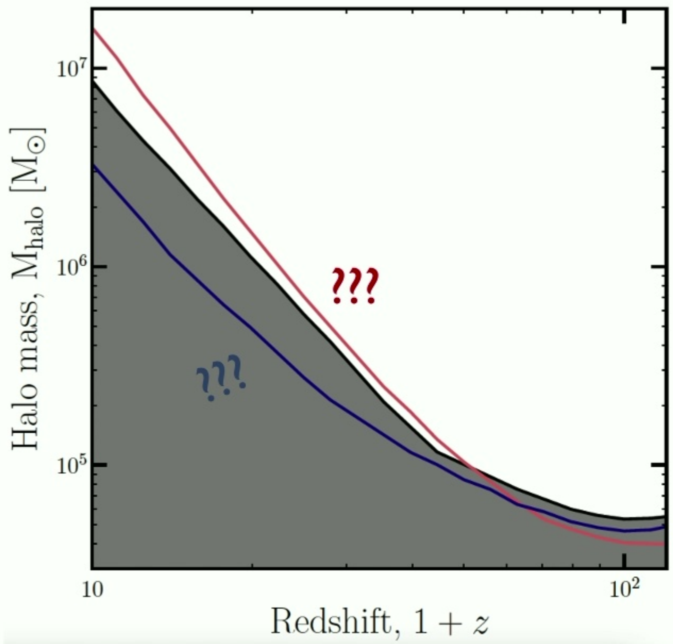
# COLLAPSING HALOS

- Smaller halos → pressure-supported, less efficient at cooling
- Larger halos → cooling wins, runaway collapse, form stars



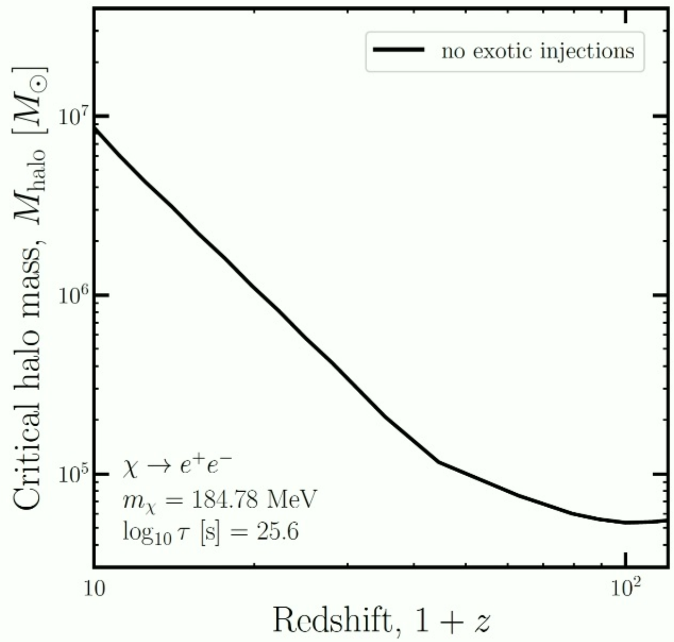
# CRITICAL COLLAPSE

- Calculate the halo mass above which halos collapse
- How does dark matter energy injection affect this value?



# EXAMPLE

- Let's examine effects one by one

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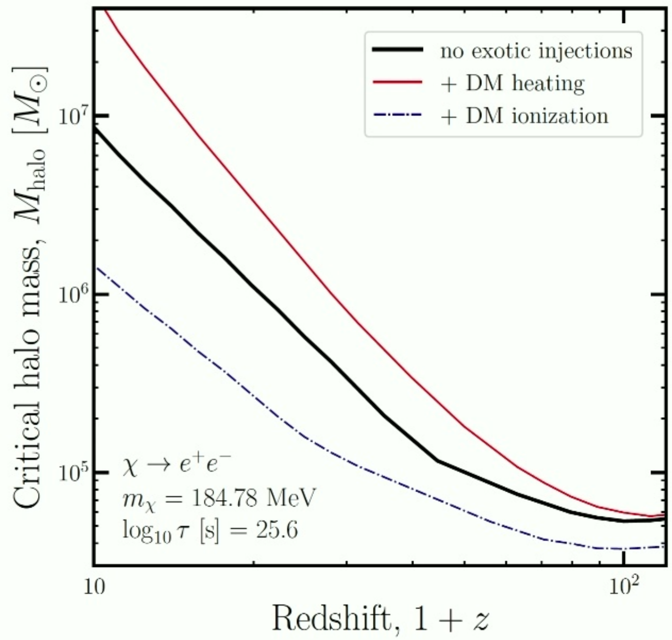
# EXAMPLE

- Ionization: more free $e^-$ catalyze $H_2$ formation, so more cooling

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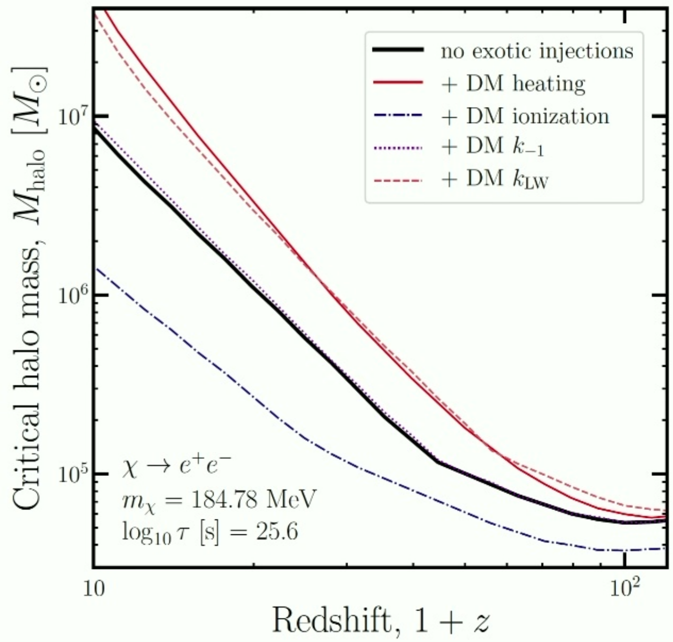
# EXAMPLE

- Small effect from $H^-$ detachment
- Lyman-Werner background raises threshold (uncertain astrophysics)

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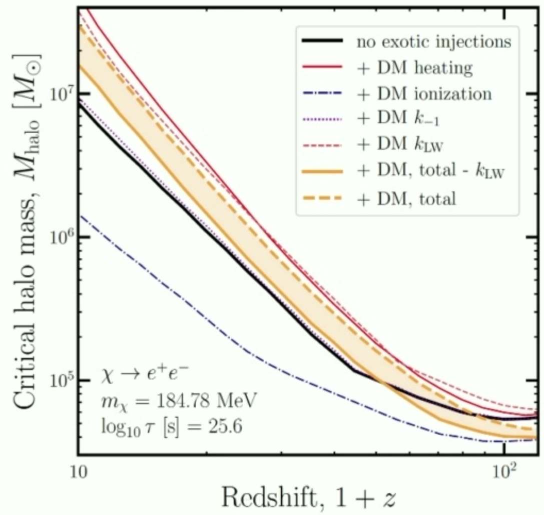
# EXAMPLE

- Adding them all up…net effect can be redshift dependent
- Bracket effects of LW radiation

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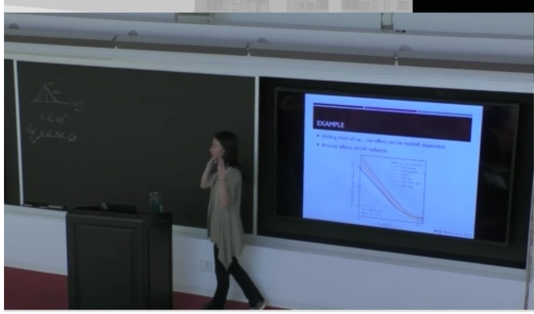
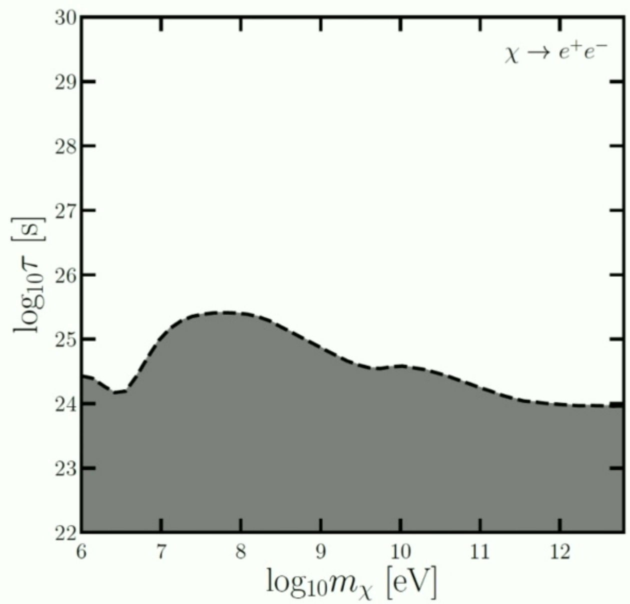


# STAR FORMATION vs CMB CONSTRAINTS

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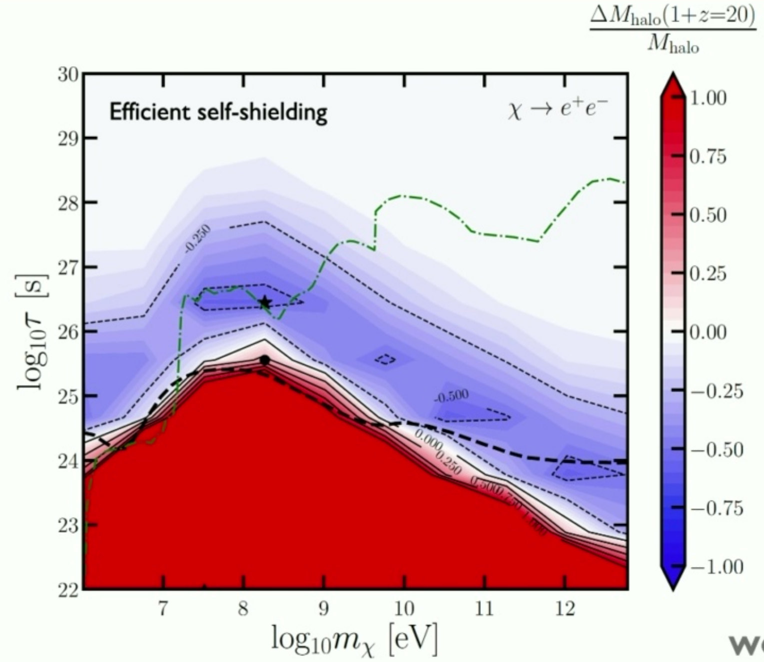


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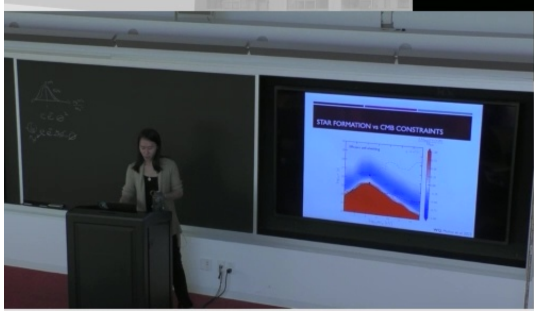

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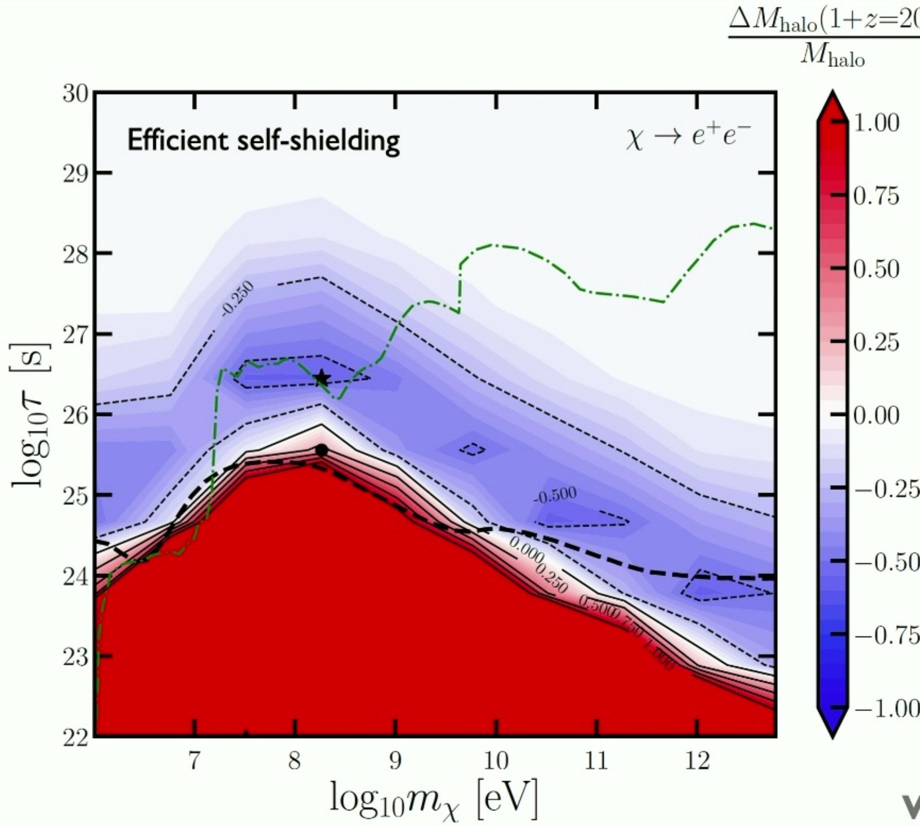


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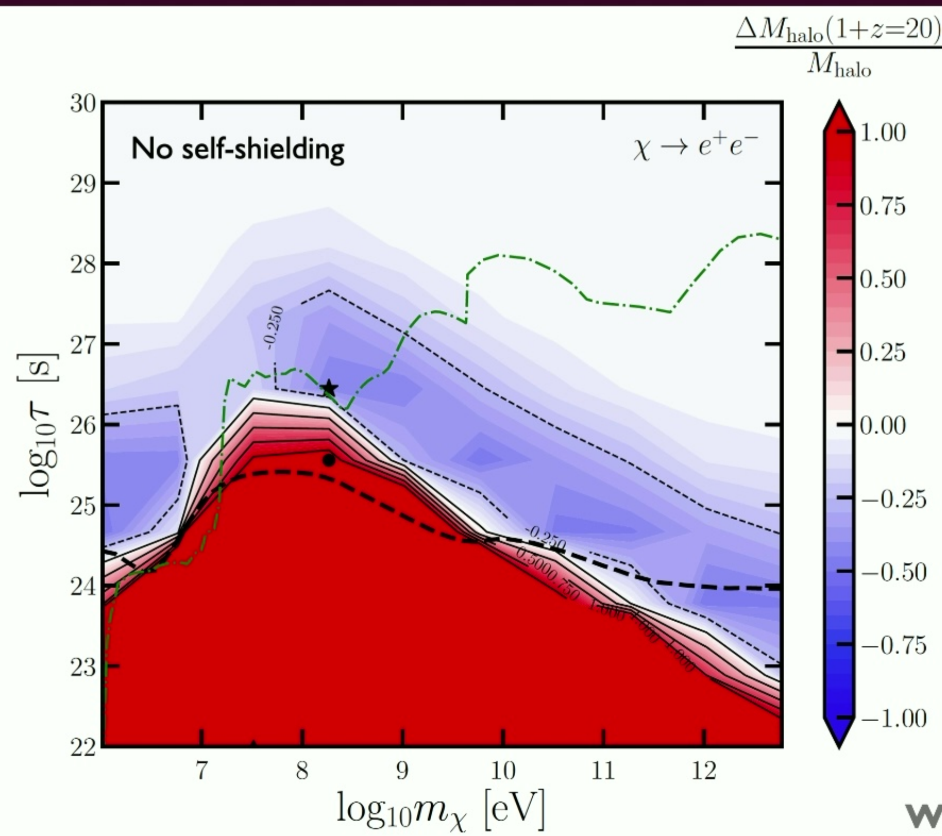


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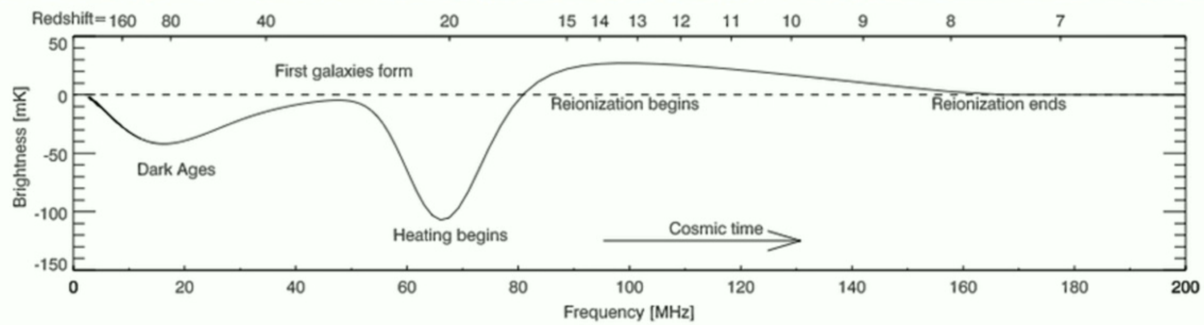
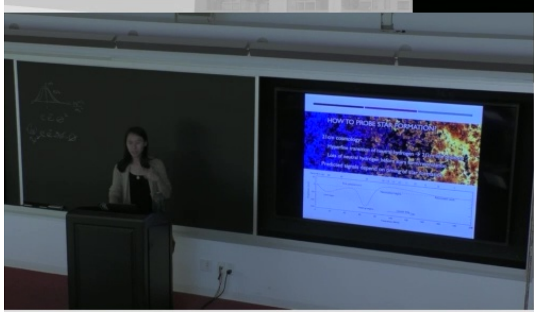
HOW TO PROBE STAR FORMATION?
21cm cosmology:
Hyperfine transition of neutral hydrogen → 21cm line photons
Lots of neutral hydrogen before stars form/reionization

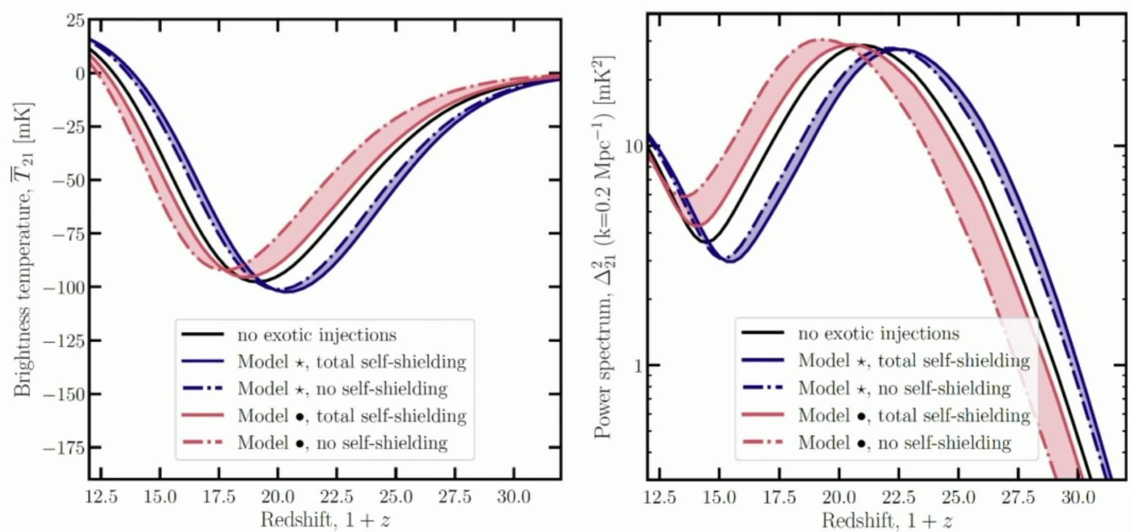
# HOW TO PROBE STAR FORMATION?

- 21cm cosmology:
  - Hyperfine transition of neutral hydrogen → 21cm line photons
  - Lots of neutral hydrogen before stars form/reionization
- Predicted signals depend on timing of star formation



# STAR FORMATION AFFECTS 21CM

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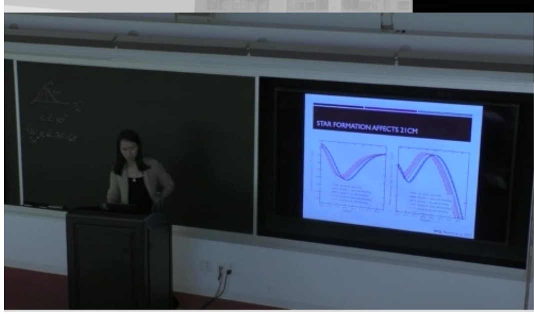

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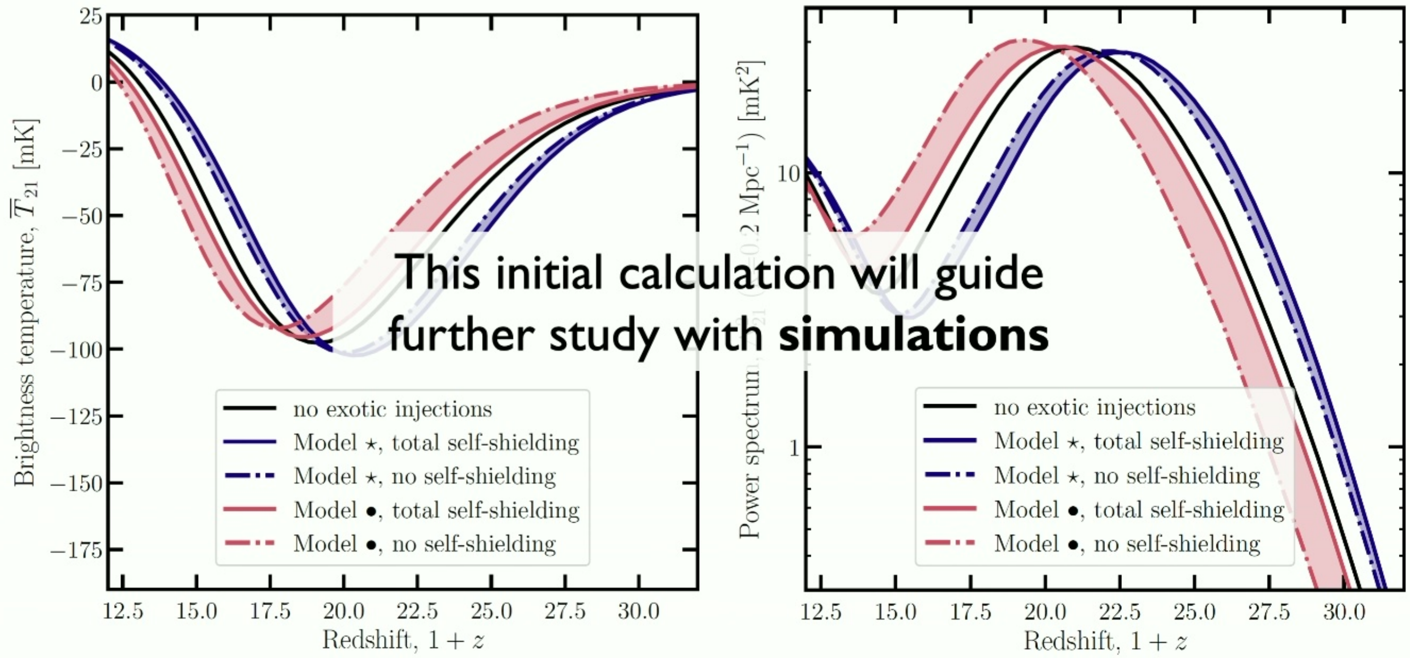


This initial calculation will guide further study with **simulations**

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# CONCLUSION

- Exotic energy injection can affect cosmological observables
- With `DarkHistory`, we can study these effects on…
  - CMB spectral distortions
  - CMB power spectrum constraints on light dark matter
  - First star formation and 21cm signals
- Other applications
  - First black hole formation

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- Other applications
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Also happy to chat about:

- Primordial black holes from inflation (2205.04471, 2303.02168)
- Effective field theory of 21cm signals (2205.06270)