Title: Forming the first stars amidst decaying and annihilating dark matter

Speakers: Wenzer Qin

Collection: Dark Matter, First Light

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Abstract: The first stars are expected to form through molecular-hydrogen (H2) cooling, a channel that is especially sensitive to the thermal and ionization state of gas, and can thus act as a probe of exotic energy injection from decaying or annihilating dark matter (DM). I will discuss using a toy halo model to study the impact of DM-sourced energy injection on the H2 content of the first galaxies, and thus estimate the threshold mass required for a halo to form stars at high redshifts. I will show that currently allowed DM models can significantly change this threshold, producing both positive and negative feedback and estimate how this can impact the timing of 21cm signals at cosmic dawn.

Forming the First Stars amidst Decaying and Annihilating Dark Matter

WENZER QIN

Feb 27th, 2024 | Dark Matter First Light

Massachusetts Institute of Technology

Center for Theoretical Physics

In collaboration with Hongwan Liu, Julian Muñoz, and Tracy Slatyer

INTRODUCTION

Two considerations in searching for dark matter

- What are the most *model-independent* signatures of dark matter we can look for?

E.g., exotic energy injection

- What *new data* is coming out that we can leverage?

High redshifts: 21cm cosmology, JWST, etc.

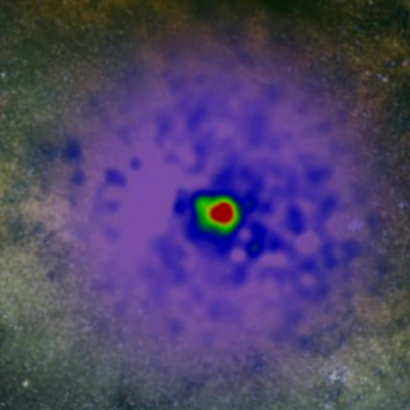
First look at the first stars and galaxies

INTRODUCTION

- The collapse of a halo into stars becomes a complicated and highly nonlinear process → requires simulations
- We will pave the way for simulations by identifying the most interesting models for study

EXOTIC ENERGY INJECTION

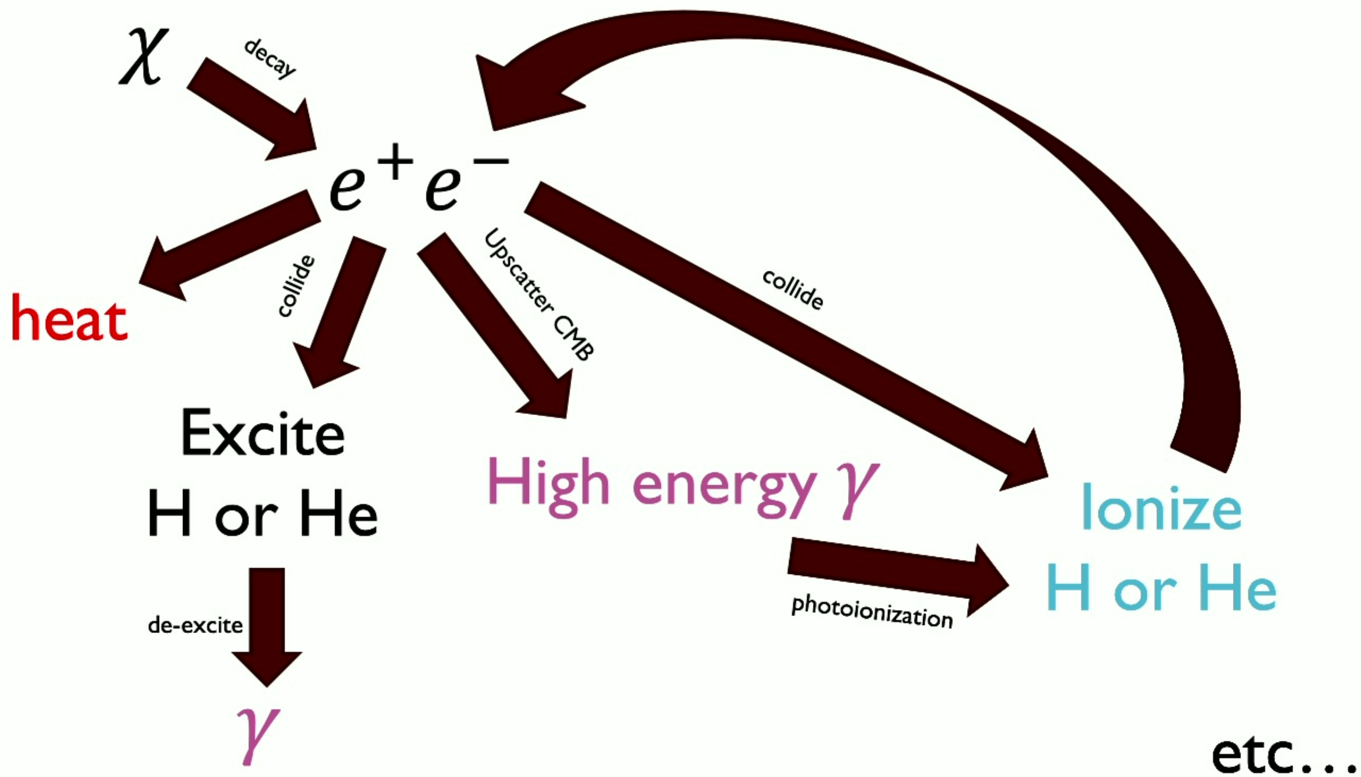
- Energy injected into electromagnetic observables, not by processes in ΛCDM/Standard Model
- Focus on decaying dark matter
- Could generalize results to
  - Annihilating dark matter
  - Evaporating primordial black holes
  - Accreting primordial black holes



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



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)

EARLY STAR FORMATION

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

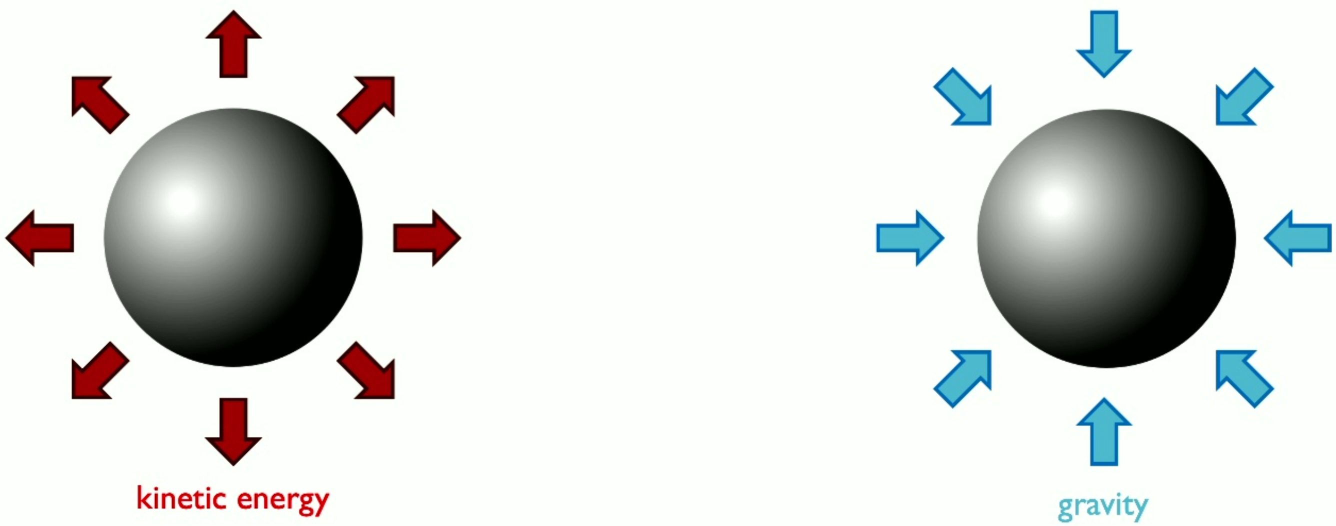
$$H + e^- \rightarrow H^- +$$
$$H + H^- \rightarrow H_2 + e^-$$

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

Greif et al. 2008

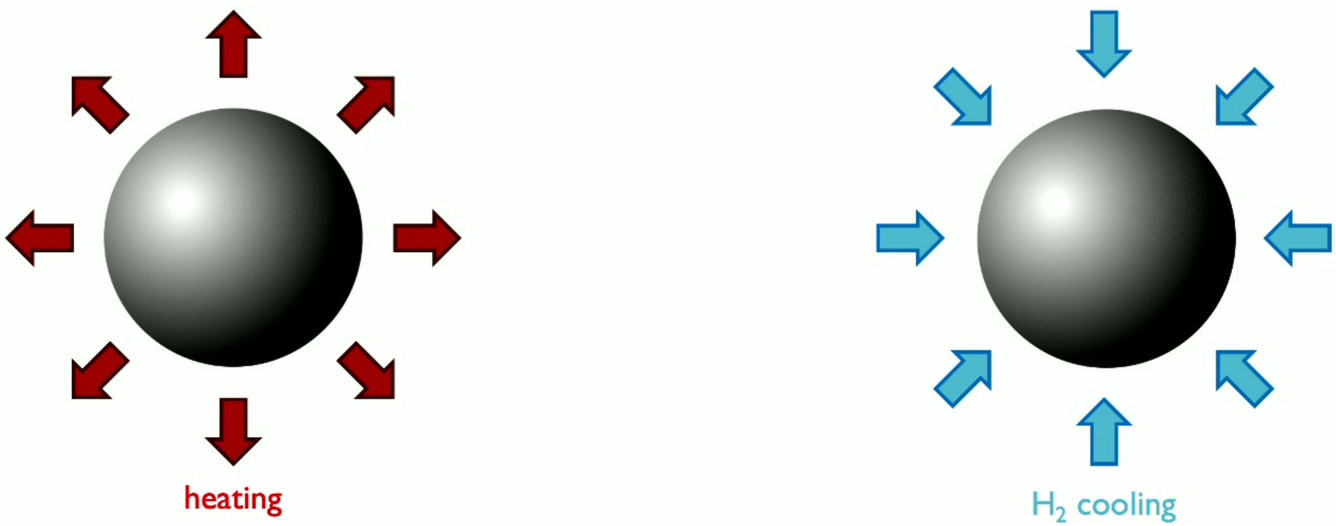
COLLAPSING HALOS

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



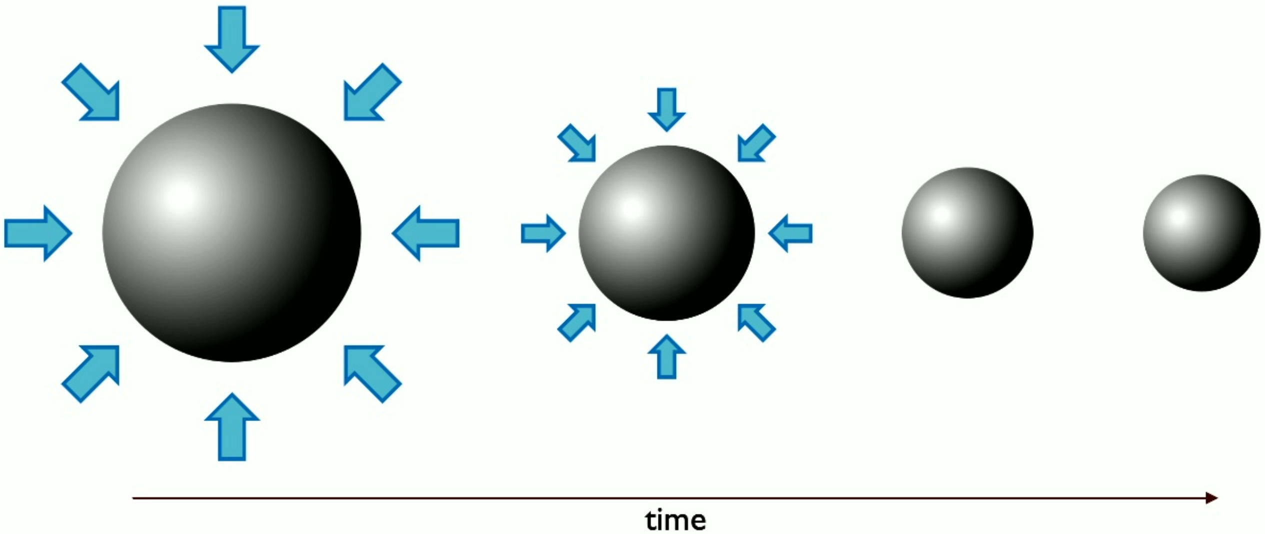
COLLAPSING HALOS

- Treat gas as spherical top-hat (uniform density)
- First, overdensity must collapse and virialize to form a halo
- For baryons to continue collapsing, must dissipate kinetic energy



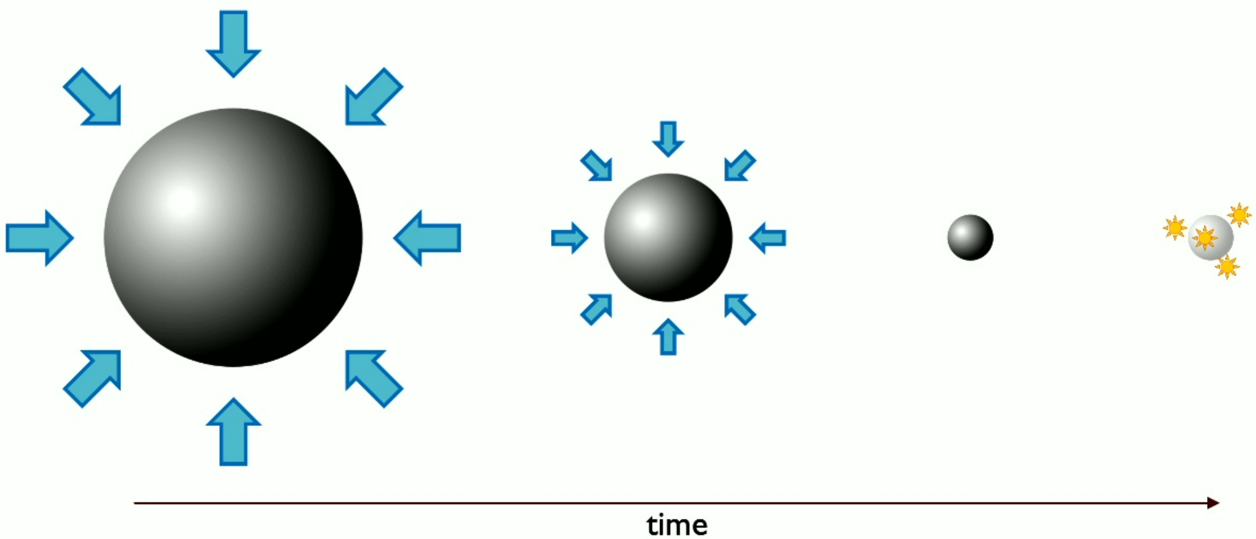
COLLAPSING HALOS

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



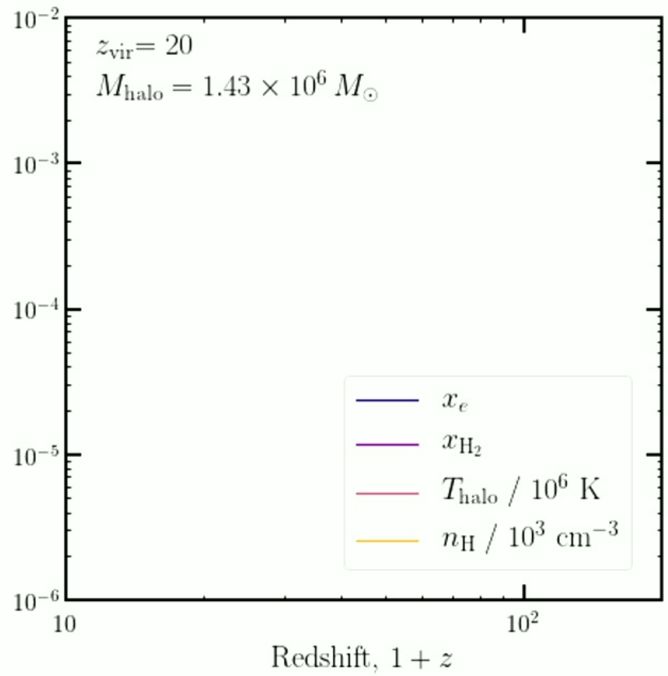
COLLAPSING HALOS

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



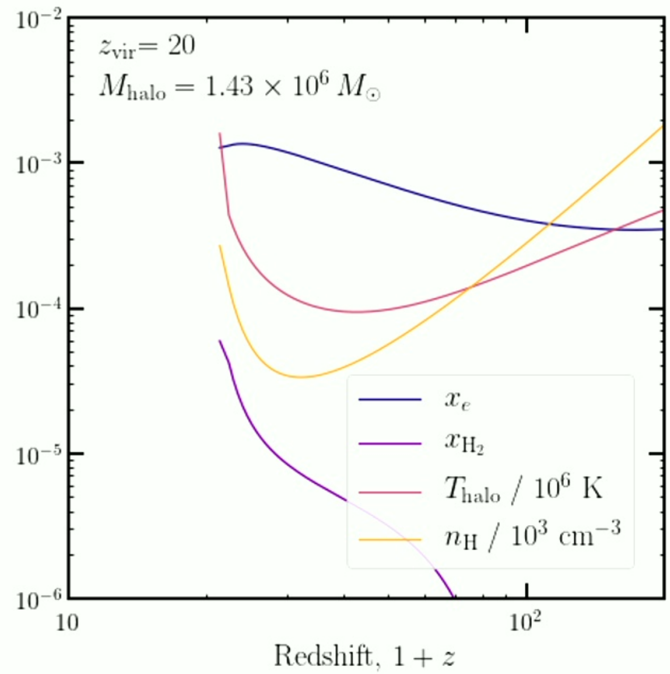
TRACKING HALO EVOLUTION

- Quantities that we evolve simultaneously:
  - Free electron fraction
  - H_2 abundance
  - Gas temperature
  - Density



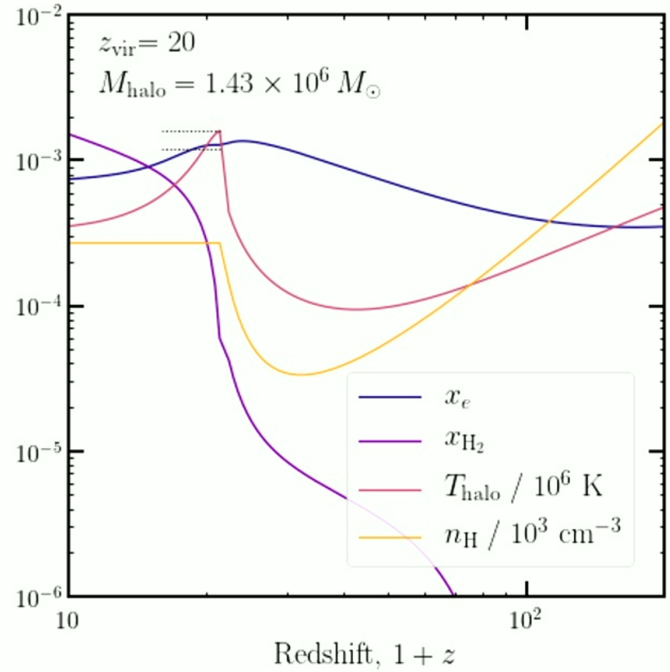
TRACKING HALO EVOLUTION

- Evolve halo until virialized
  - Either density reaches $\rho_{\rm vir} = 18\pi^2\rho_0(1+z)^3$
  - Or temperature reaches virial temperature



TRACKING HALO EVOLUTION

- After virialization
  - Hold density fixed and continue to evolve other quantities
- Halo cools fast enough to collapse if temperature drops substantially within a Hubble time
  - $T_{\rm halo}(\eta z_{\rm vir}) \leq \eta T_{\rm halo}(z_{\rm vir})$ with $\eta \approx 2/3$

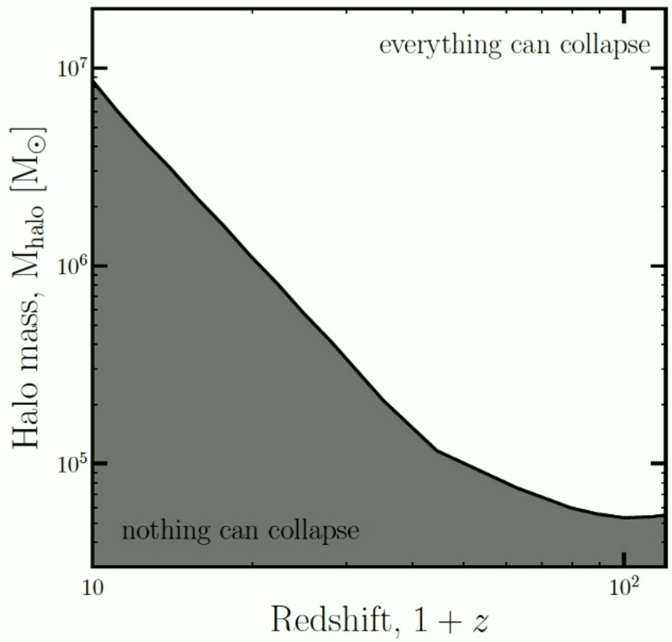


INCLUDING EXOTIC ENERGY INJECTION

- DarkHistory tracks how energy is deposited into heat, ionization, and radiation globally
- We assume the energy deposition *per baryon* is the same in the halo and include this in the halo evolution
  - Justified by following simplified cascades
  - Assumption is valid for most decaying dark matter models

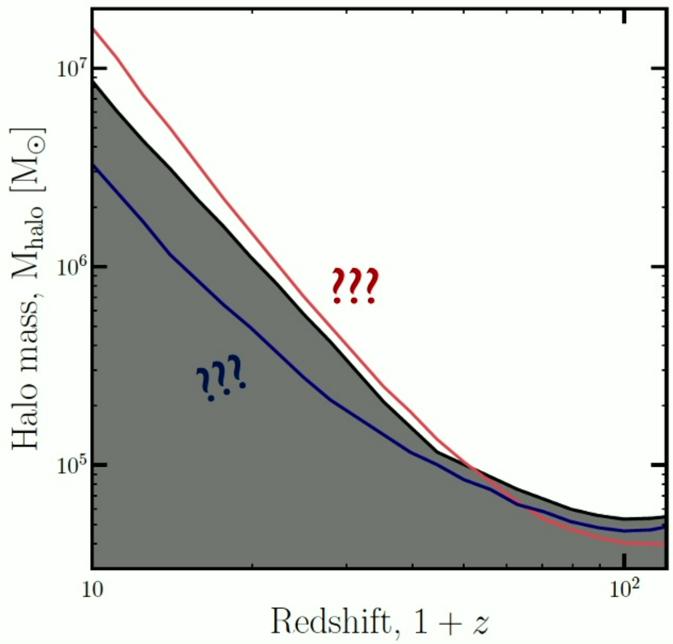
CRITICAL COLLAPSE

- Calculate the halo mass above which halos collapse



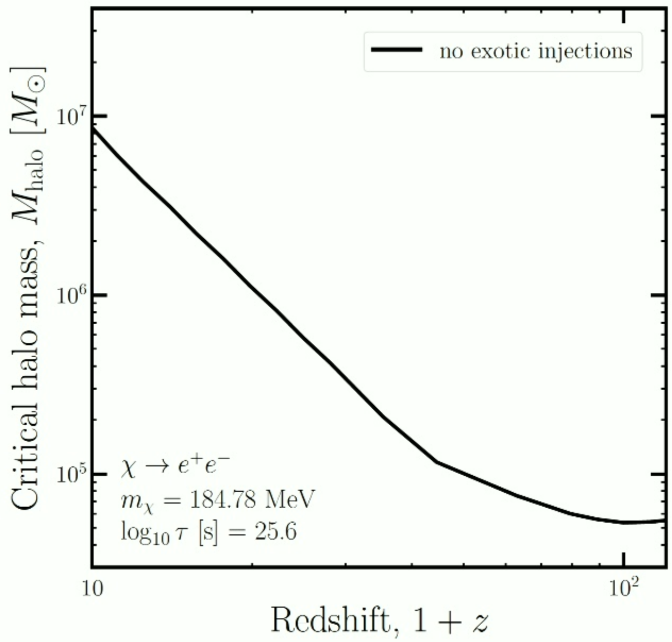
CRITICAL COLLAPSE

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



EXAMPLE

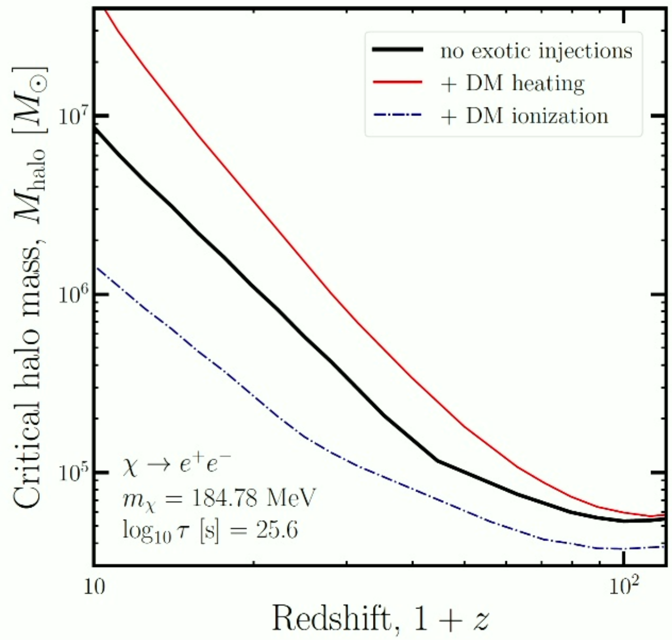
- Let's examine effects one by one



WQ, Muñoz et al. 2023

EXAMPLE

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



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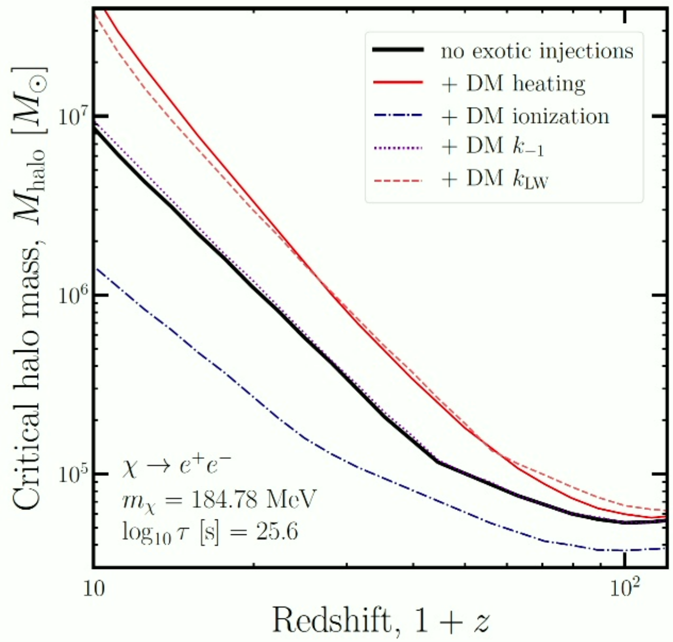
EXAMPLE

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



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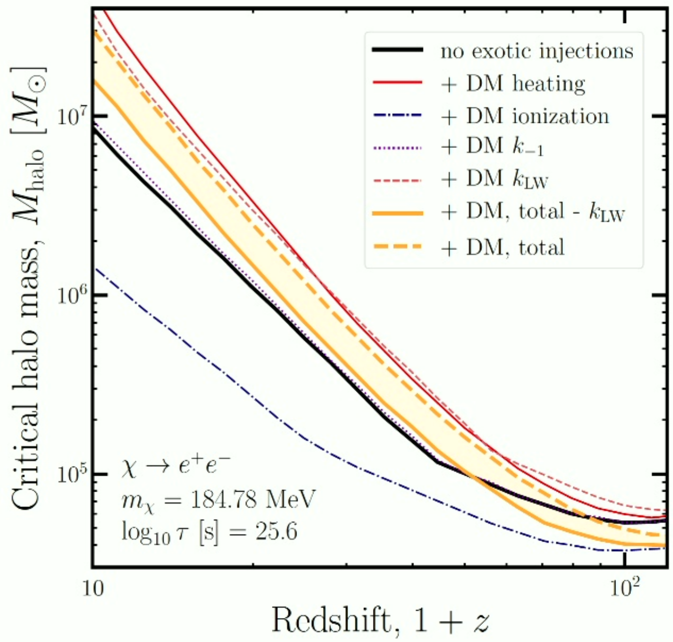
EXAMPLE

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



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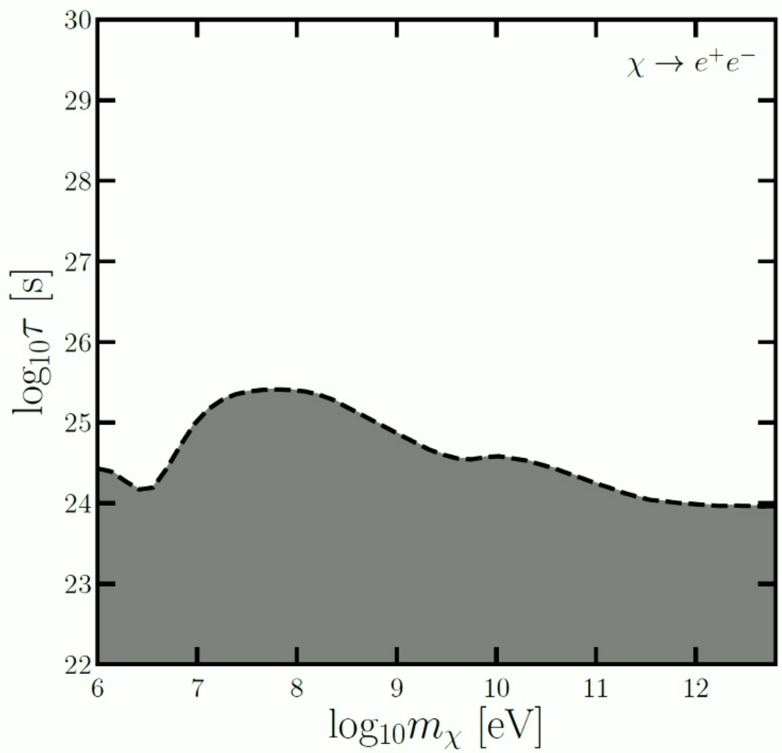
STAR FORMATION vs CMB CONSTRAINTS



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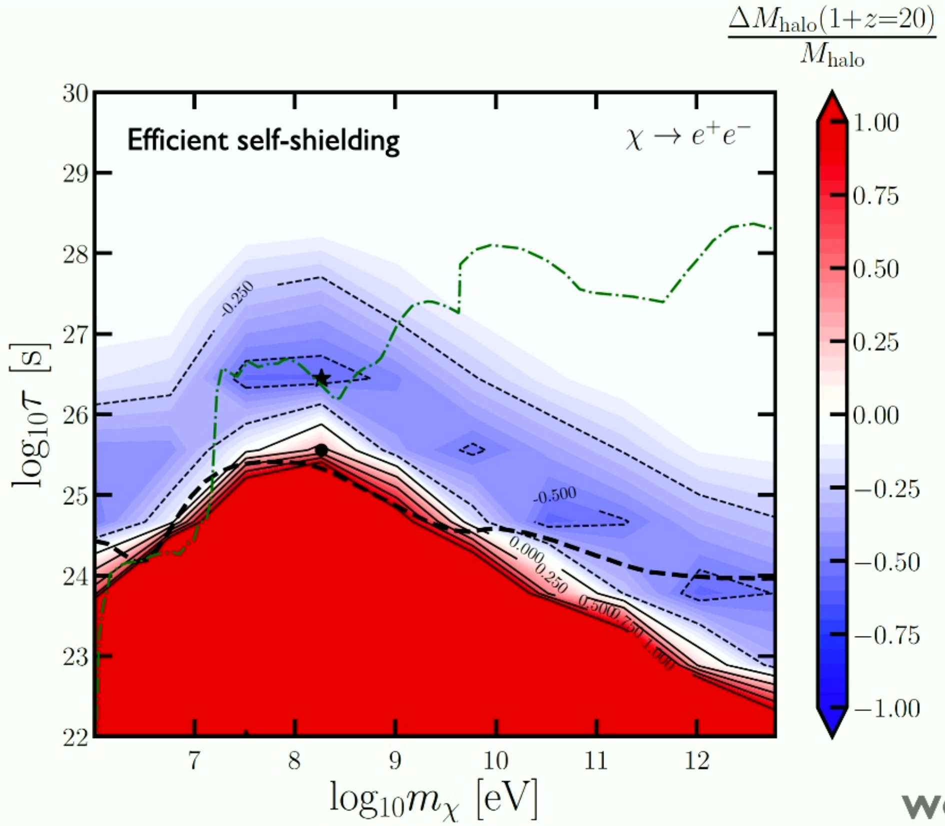

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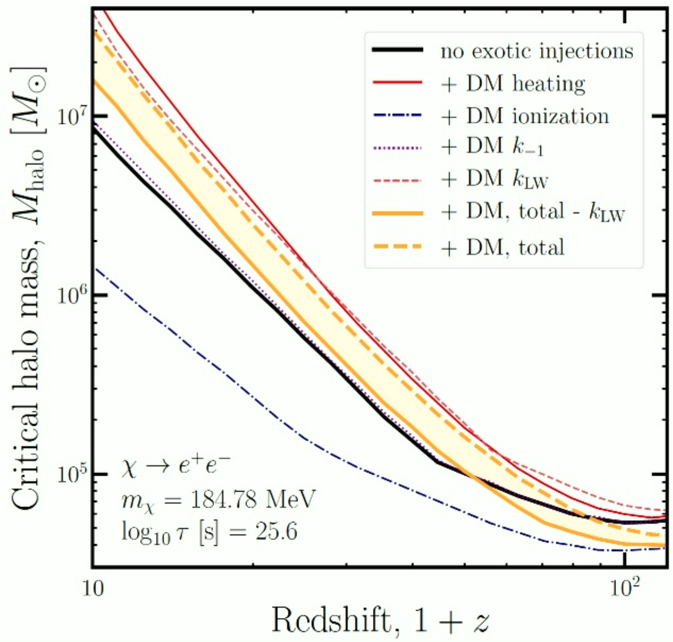

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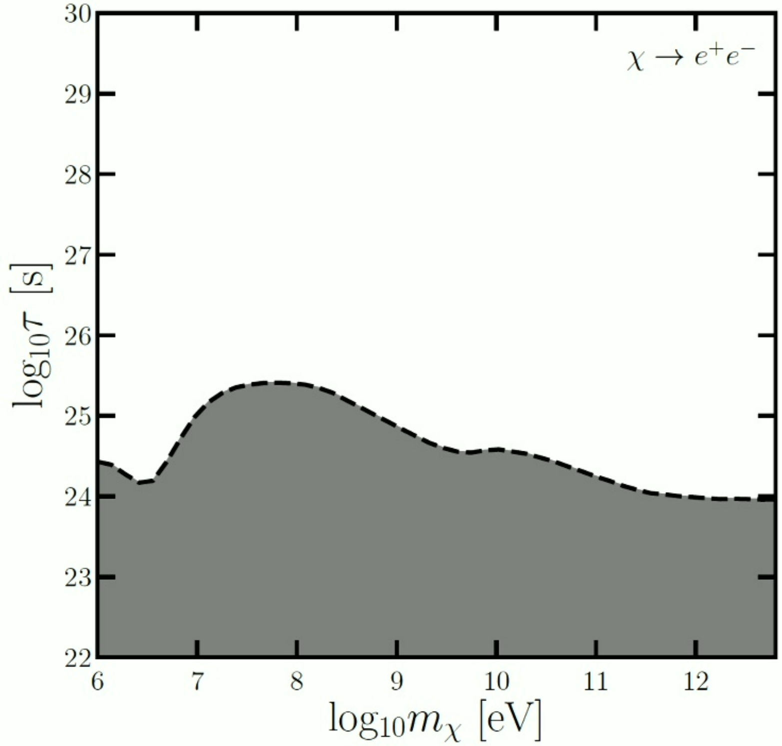

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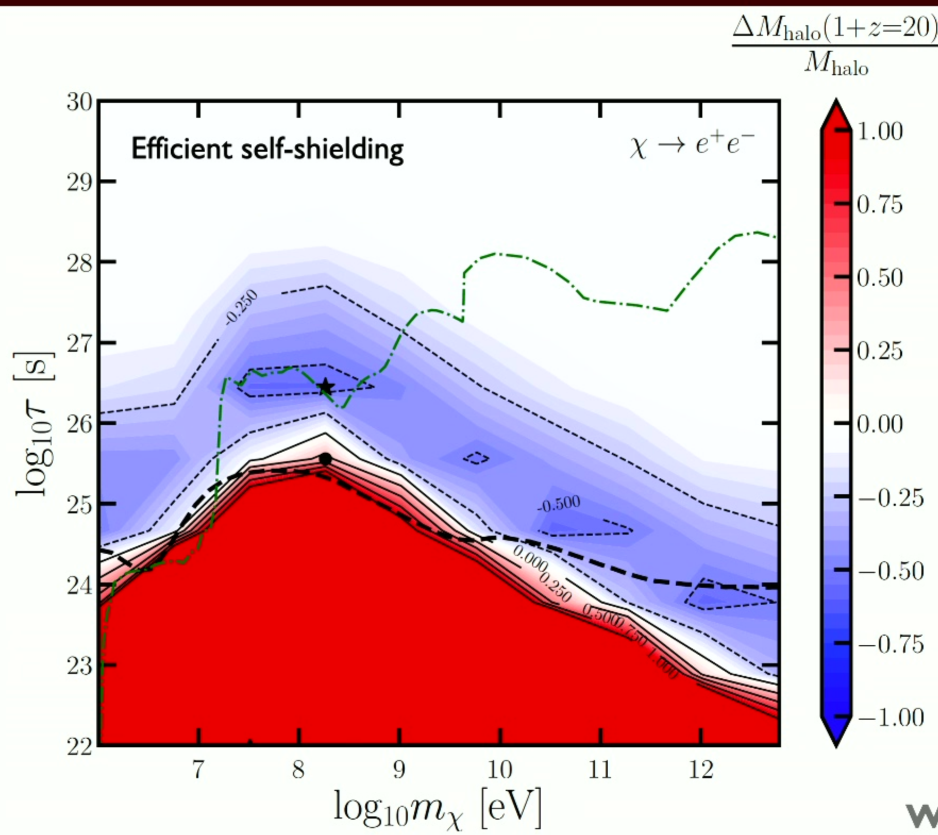
STAR FORMATION vs CMB CONSTRAINTS



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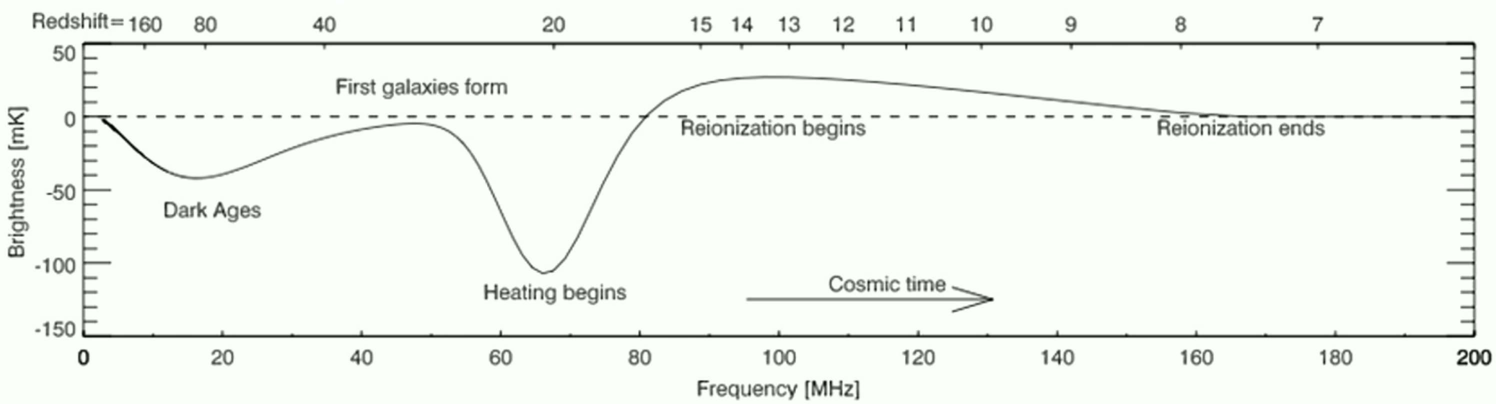
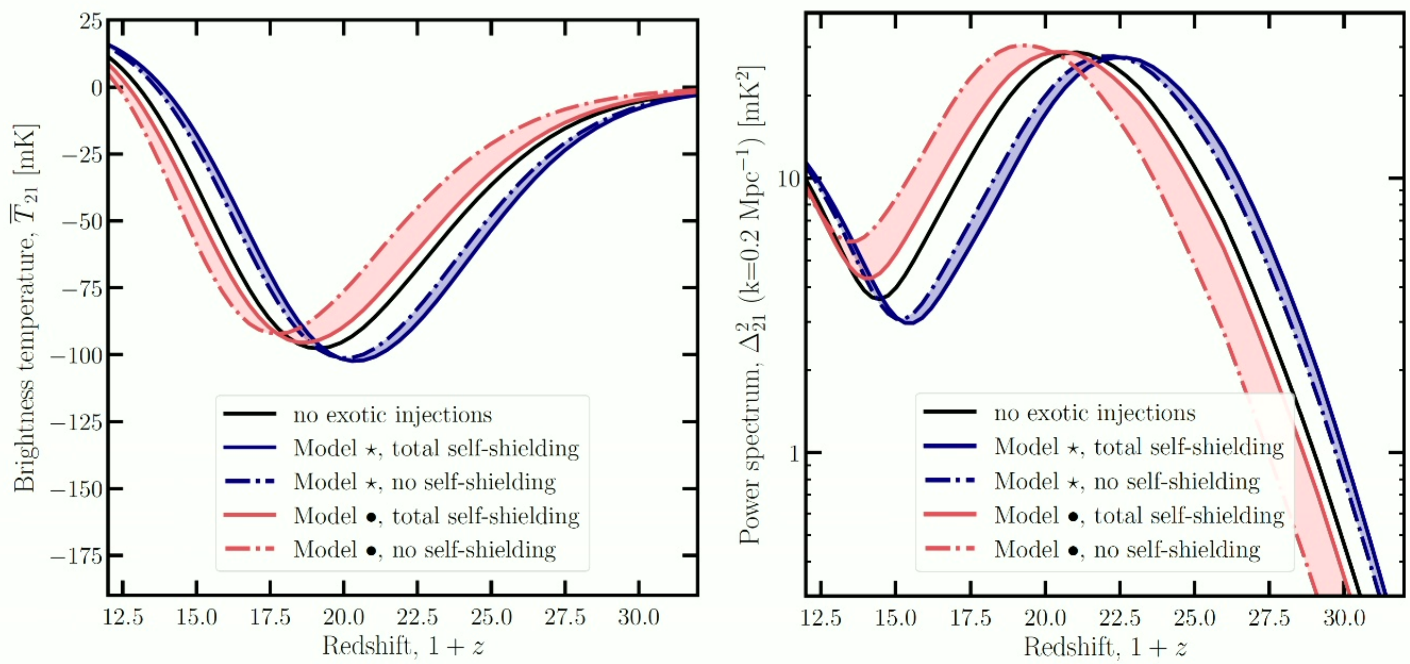
HOW TO PROBE STAR FORMATION?

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



STAR FORMATION AFFECTS 21CM



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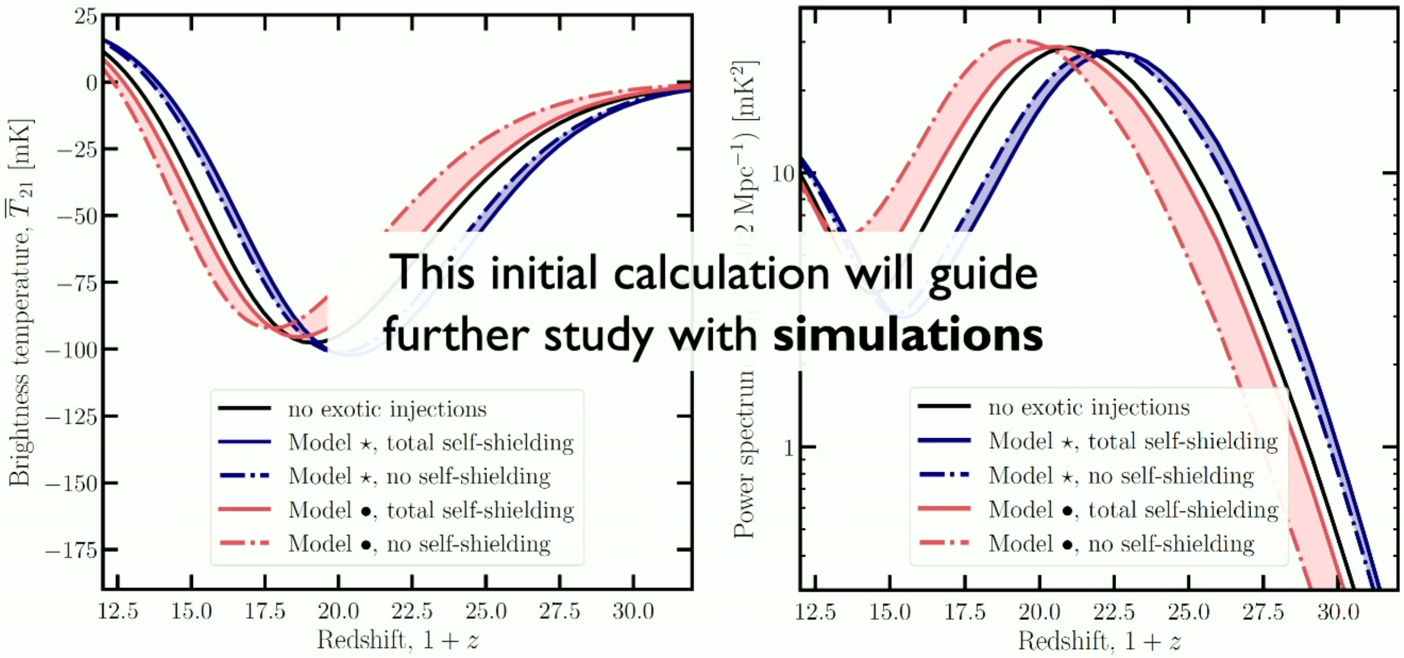
STAR FORMATION AFFECTS 21CM



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

WQ, Muñoz et al. 2023

CONCLUSION

- Exotic energy injection is a relatively general feature of many dark matter models
- Exotic heating/ionization/radiation have competing effects on star formation: models can both accelerate/delay star formation
- Potentially detectable in upcoming 21cm data
- Future directions
  - Investigate degeneracy with other astrophysical parameters
  - Detailed hydrodynamical simulations
  - Impact on first black hole formation