BIRTH OF THE FIRST STARS AMIDST DECAYING AND ANNIHILATING DARK MATTER

WENZER QIN

Aug 27th, 2024 | TeVPA

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

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High redshifts: 21cm cosmology, JWST, etc.

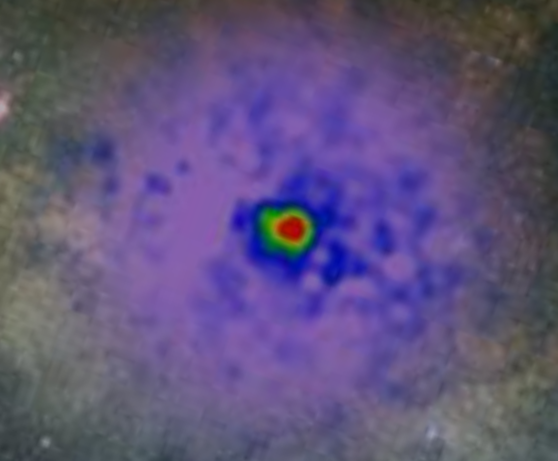
First look at the first stars and galaxies

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/positron

EFFECTS OF EXOTIC ENERGY INJECTION

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$$\chi \xrightarrow{\text{decay}} e^+e^-$$

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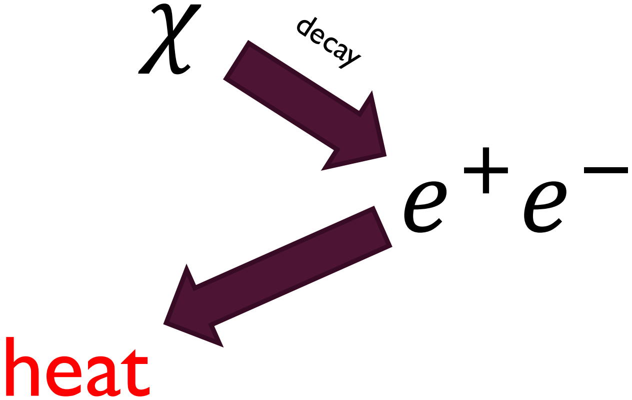

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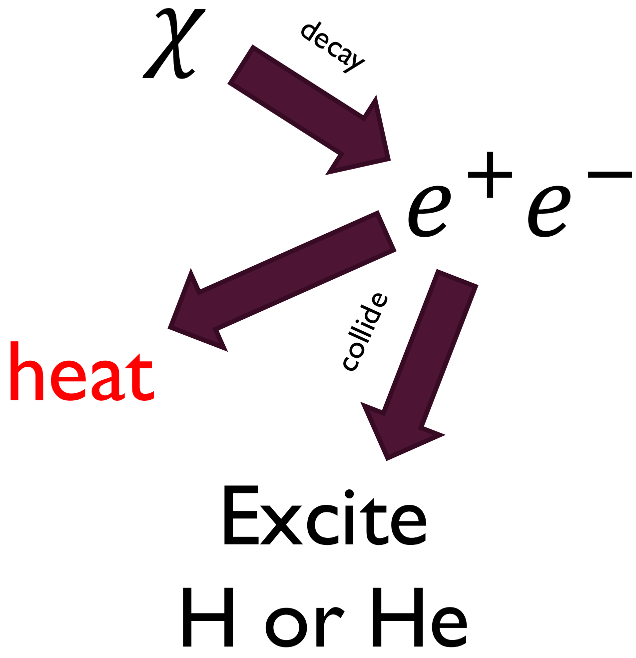

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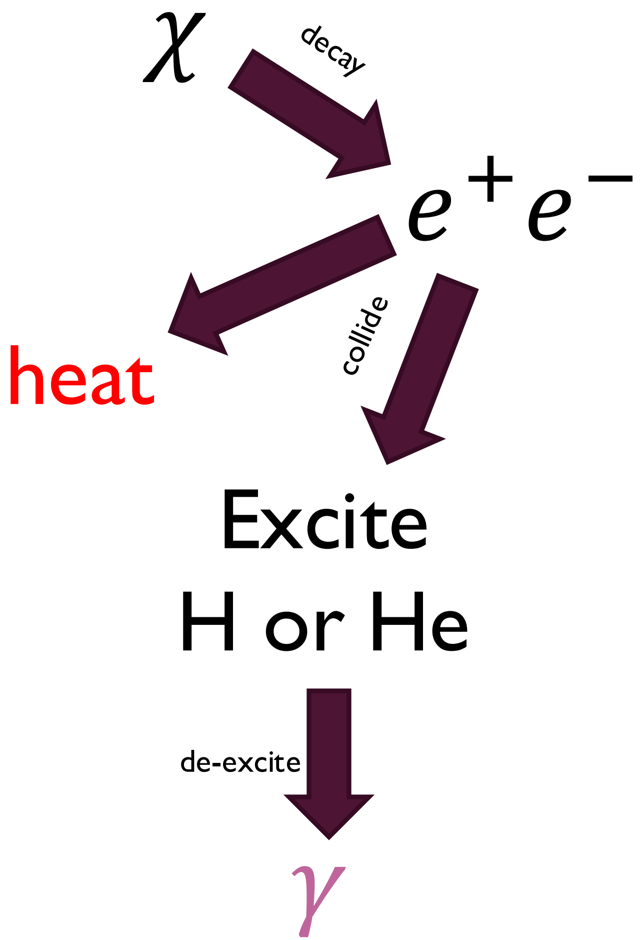

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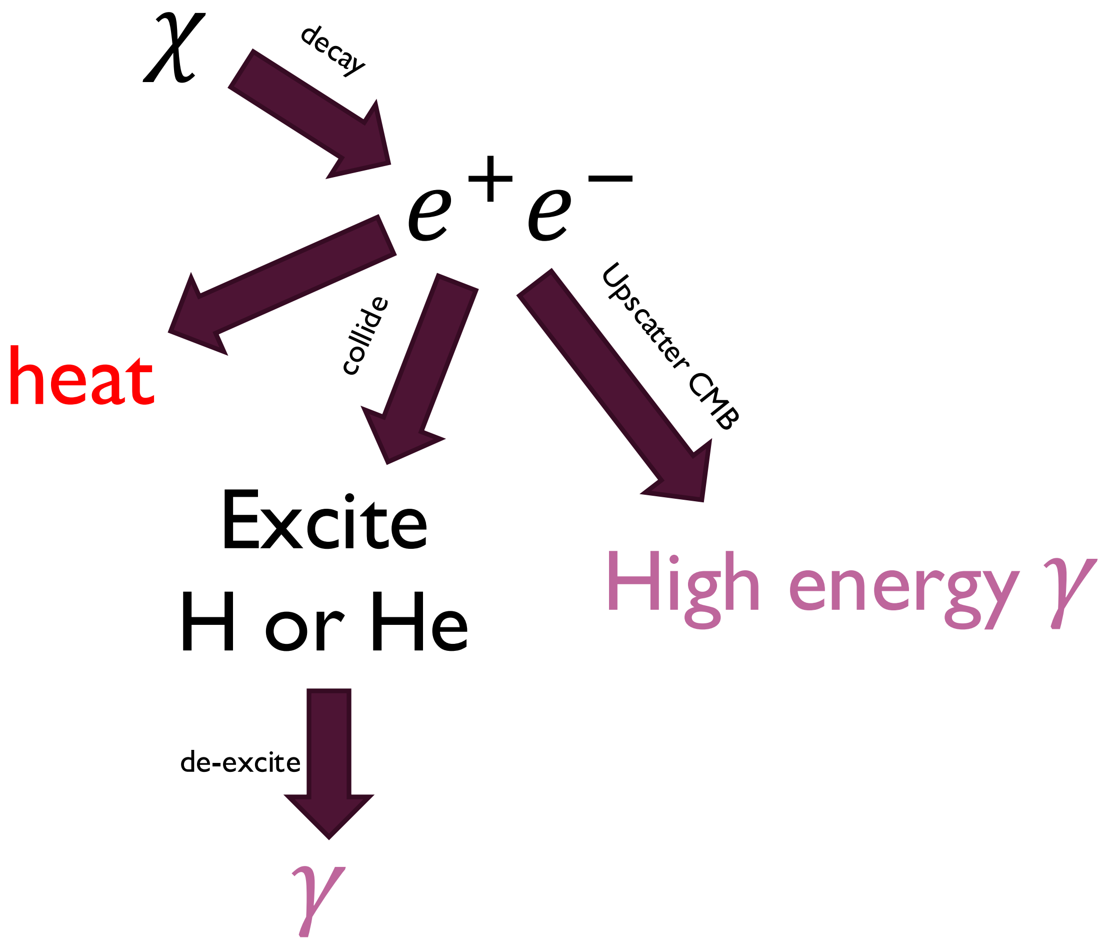

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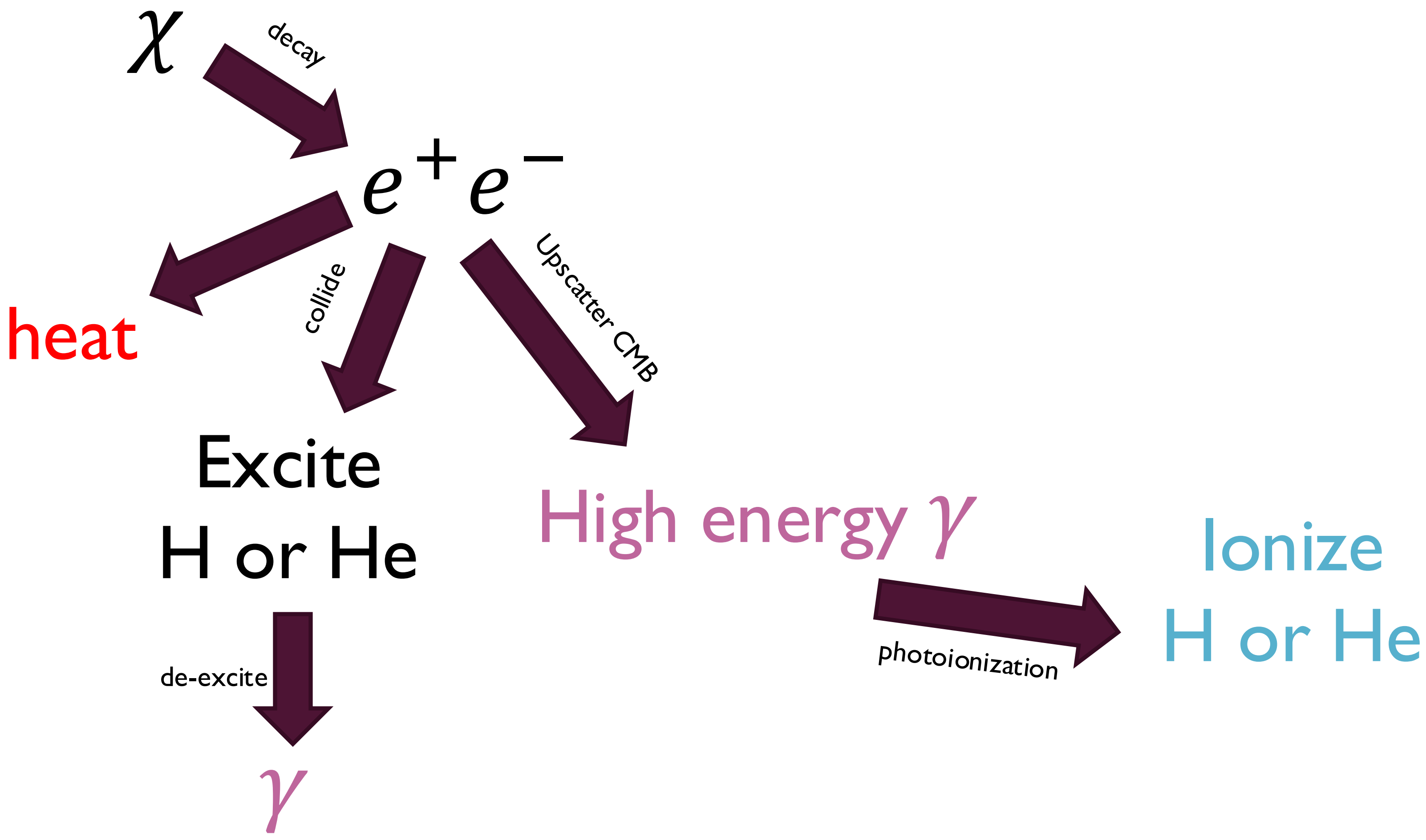

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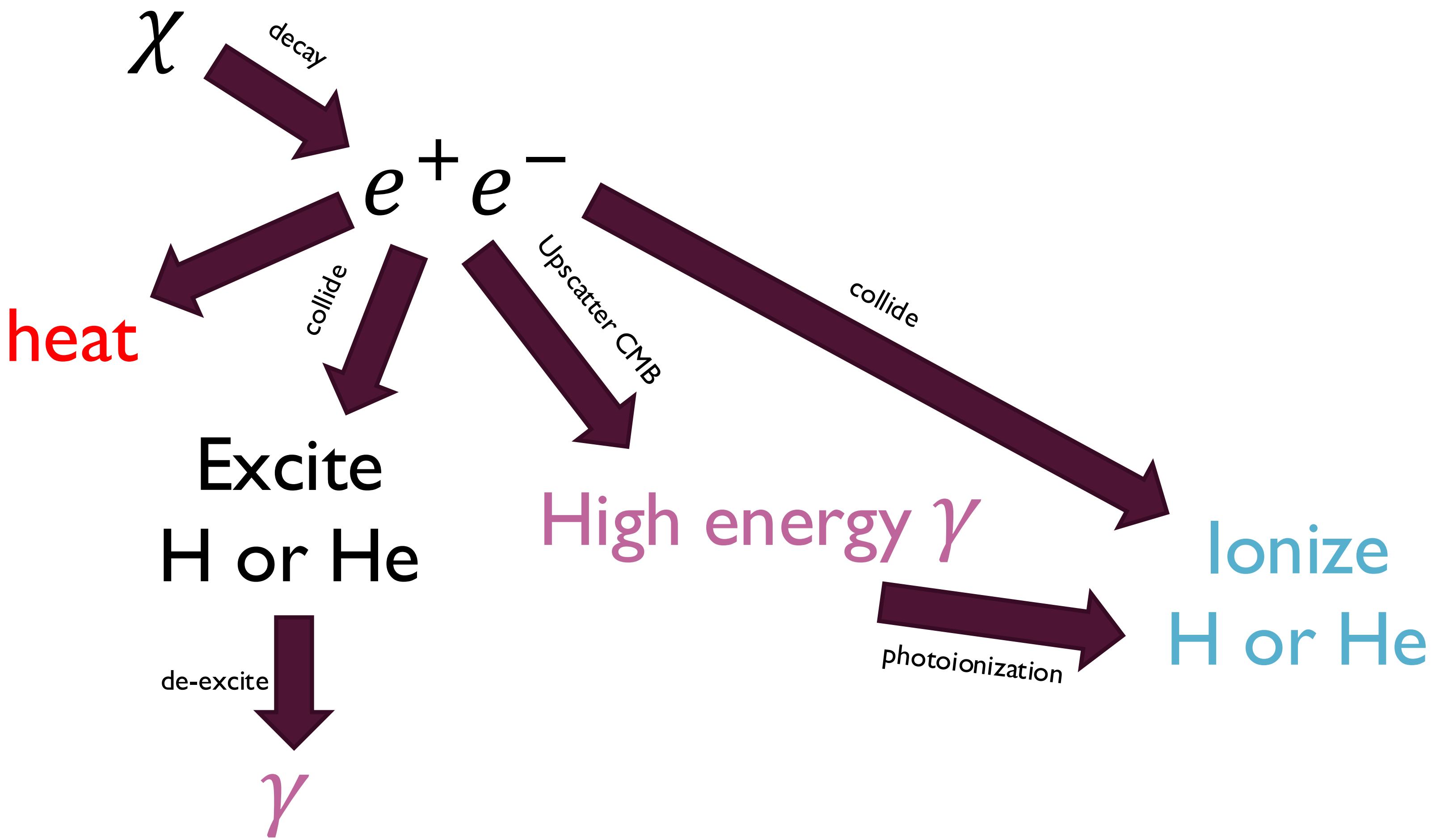

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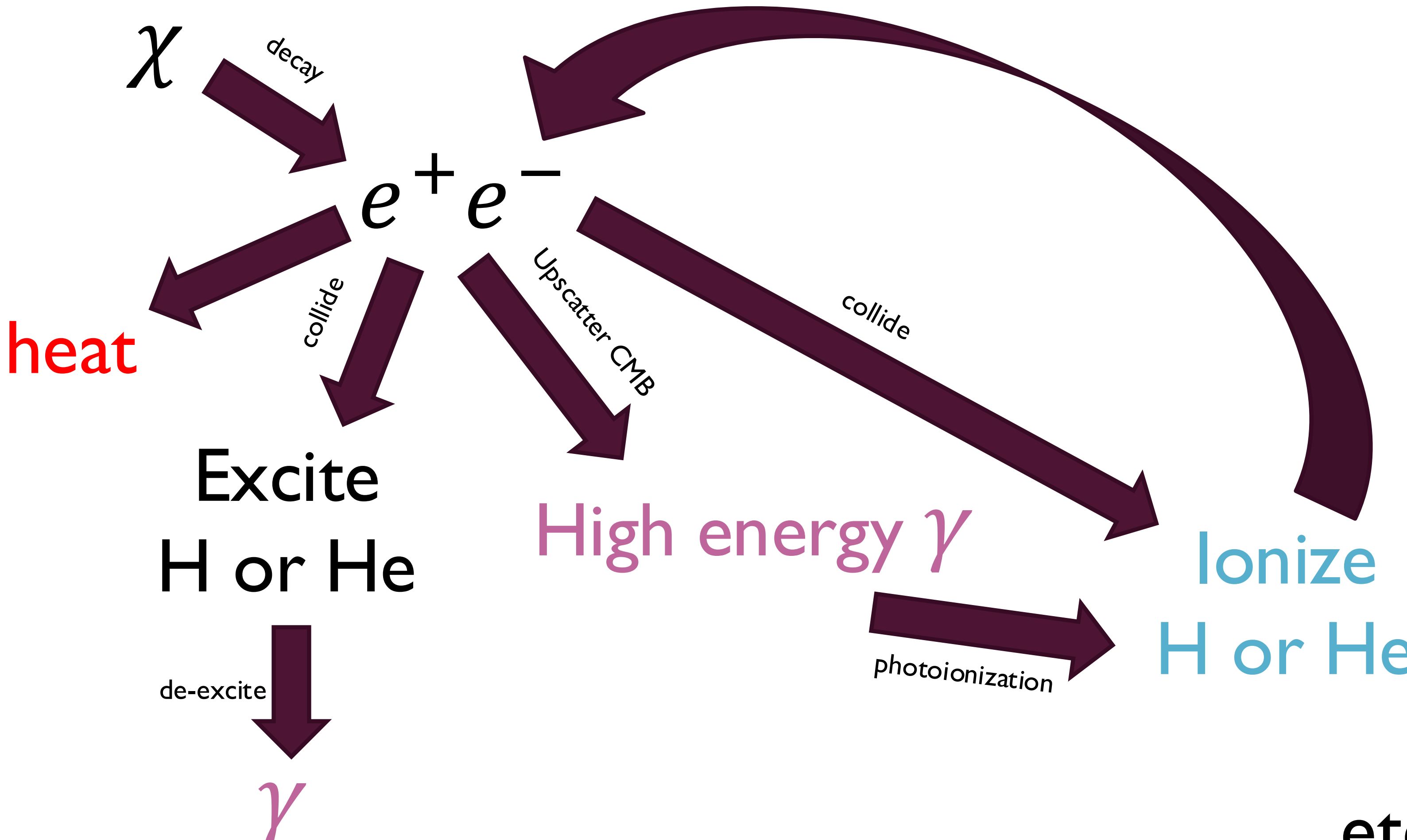
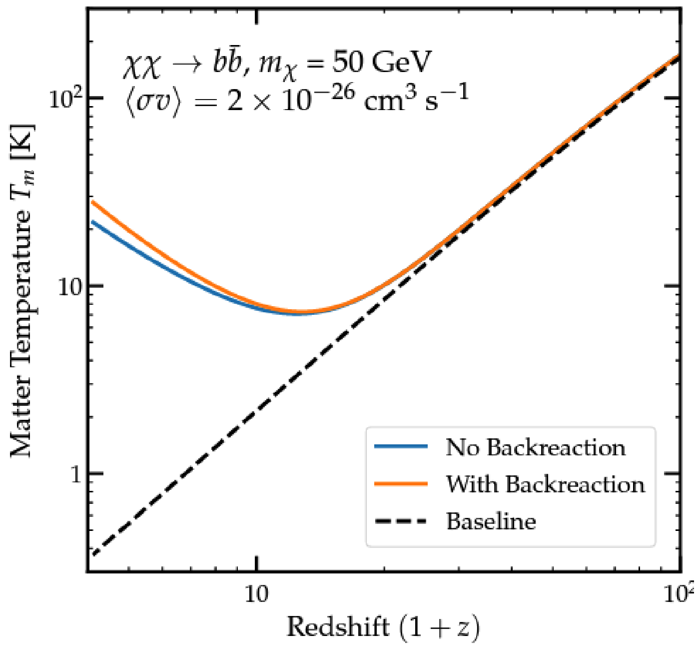
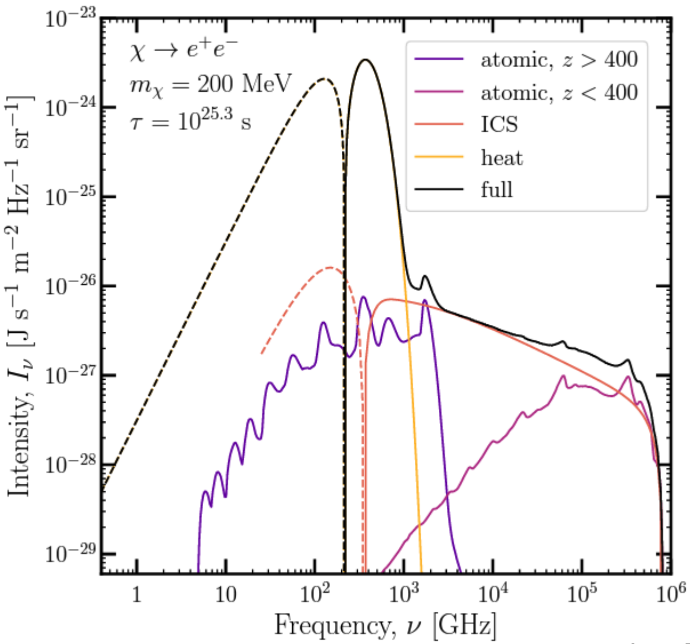


etc…

DarkHistory

- Download at https://github.com/hongwanliu/DarkHistory
- Calculates global temperature, ionization, and background radiation, while including models of exotic energy injection





Liu, Ridgway, & Slatyer 2020

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

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

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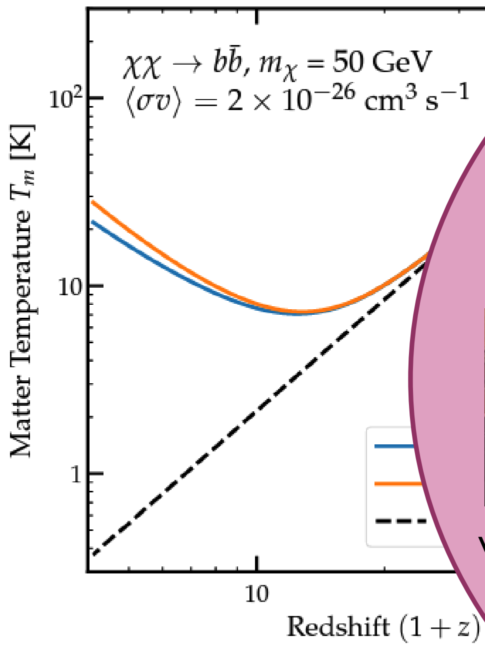
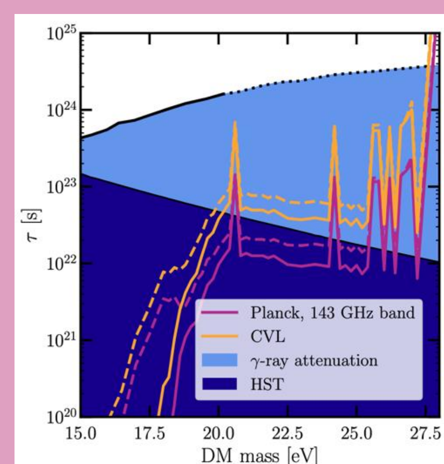
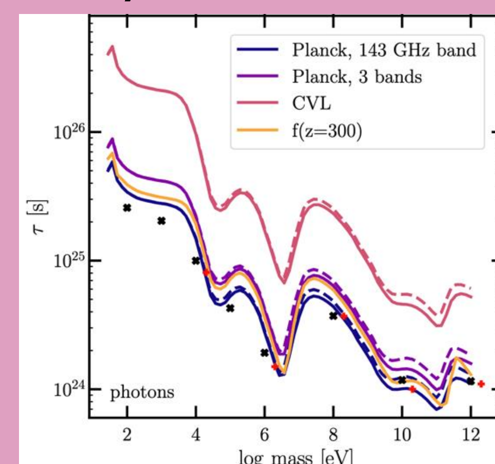


Fresh off the press!
arXiv:2408.13305

Used `DarkHistory v2.0` to calculate CMB power spectrum constraints on decaying dark matter from TeV all the way down to ~7 eV

w/Clara Xu





EARLY STAR FORMATION

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

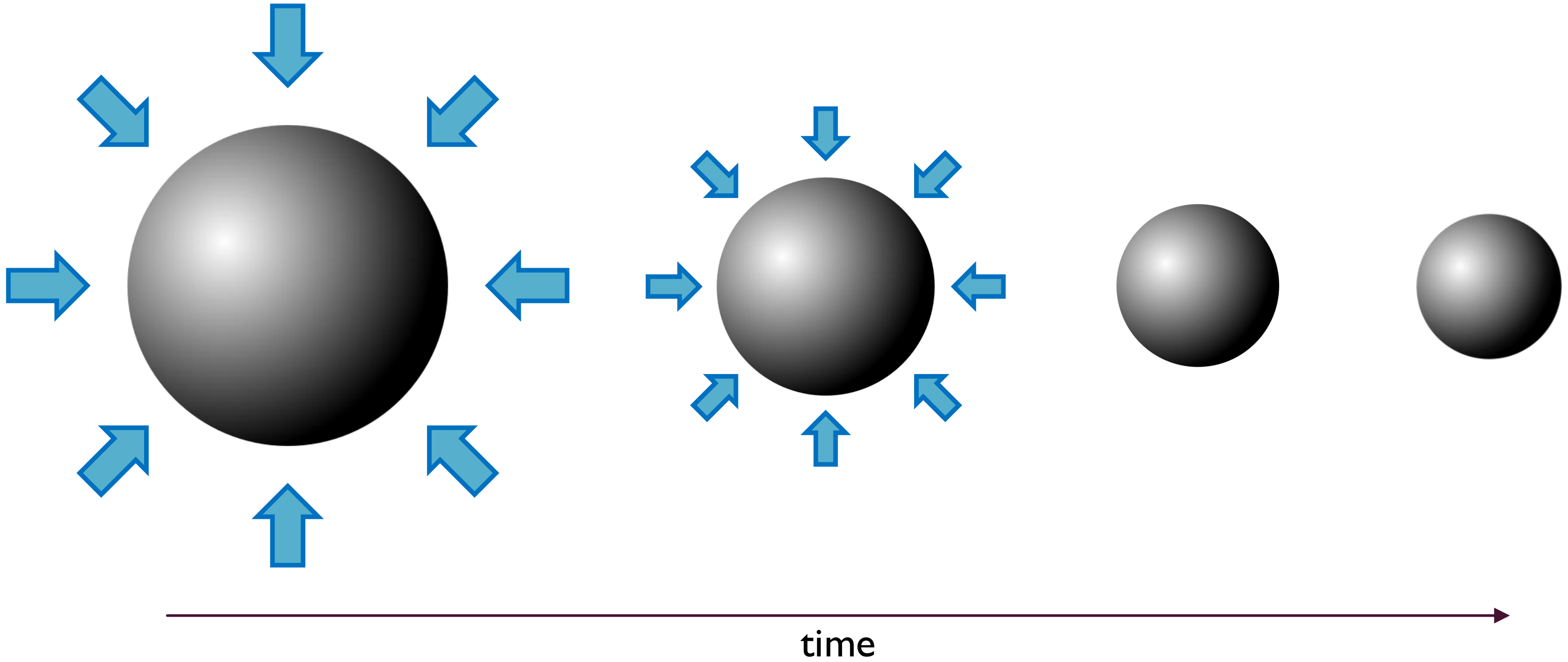
$$H + e^- \rightarrow H^- +$$
$$H + H^- \rightarrow H_2 + e^-$$

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

Greif et al. 2008

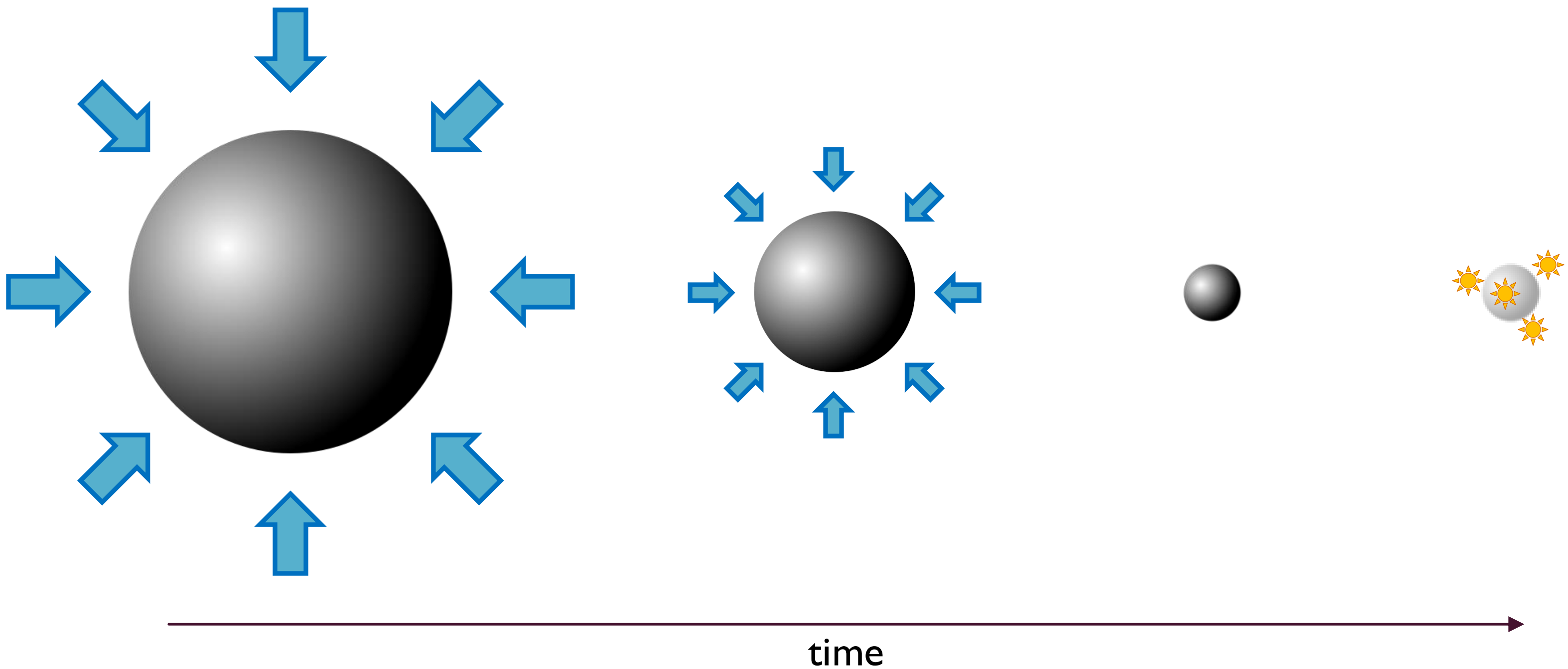
COLLAPSING HALOS

- Treat gas as spherical top-hat (uniform density)
- Smaller halos → less efficient at cooling, stay pressure-supported



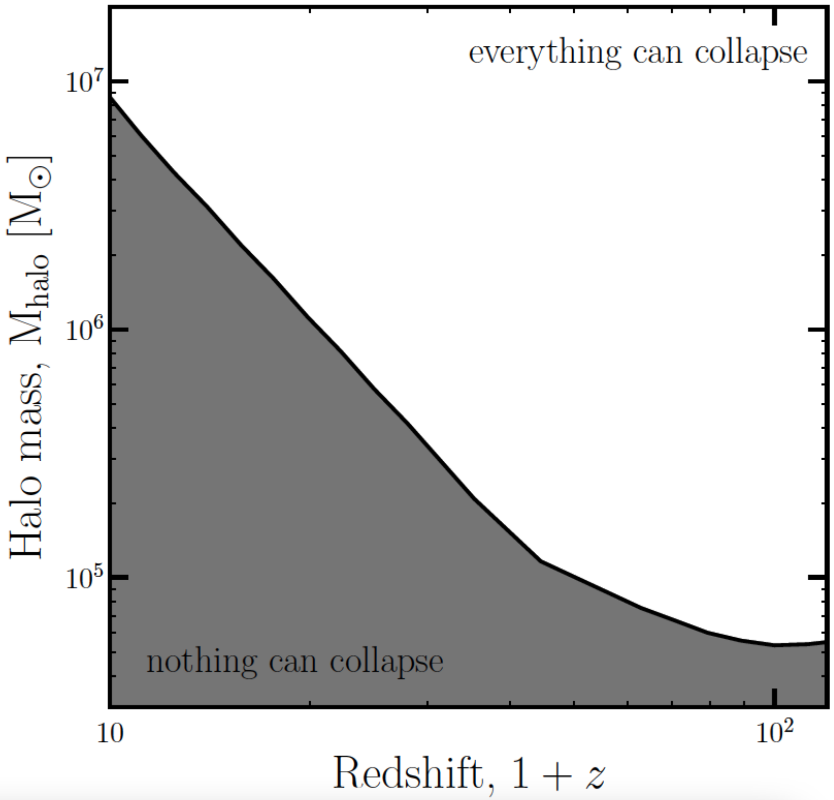
COLLAPSING HALOS

- Treat gas as spherical top-hat (uniform density)
- Smaller halos → less efficient at cooling, stay pressure-supported
- Larger halos → cooling wins, runaway collapse, form stars



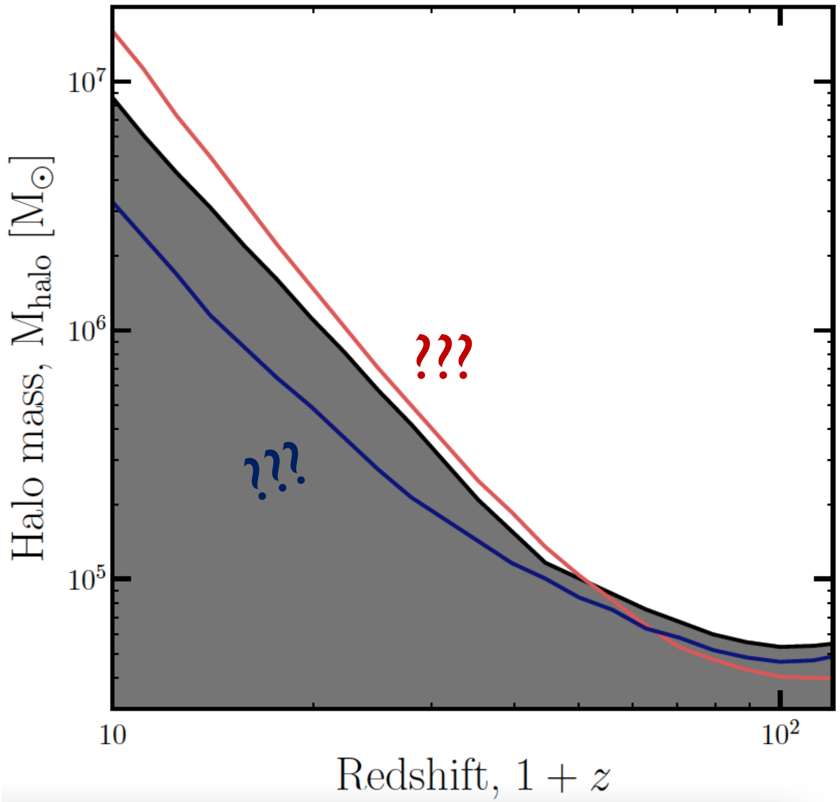
CRITICAL COLLAPSE

- Calculate the halo mass above which halos collapse

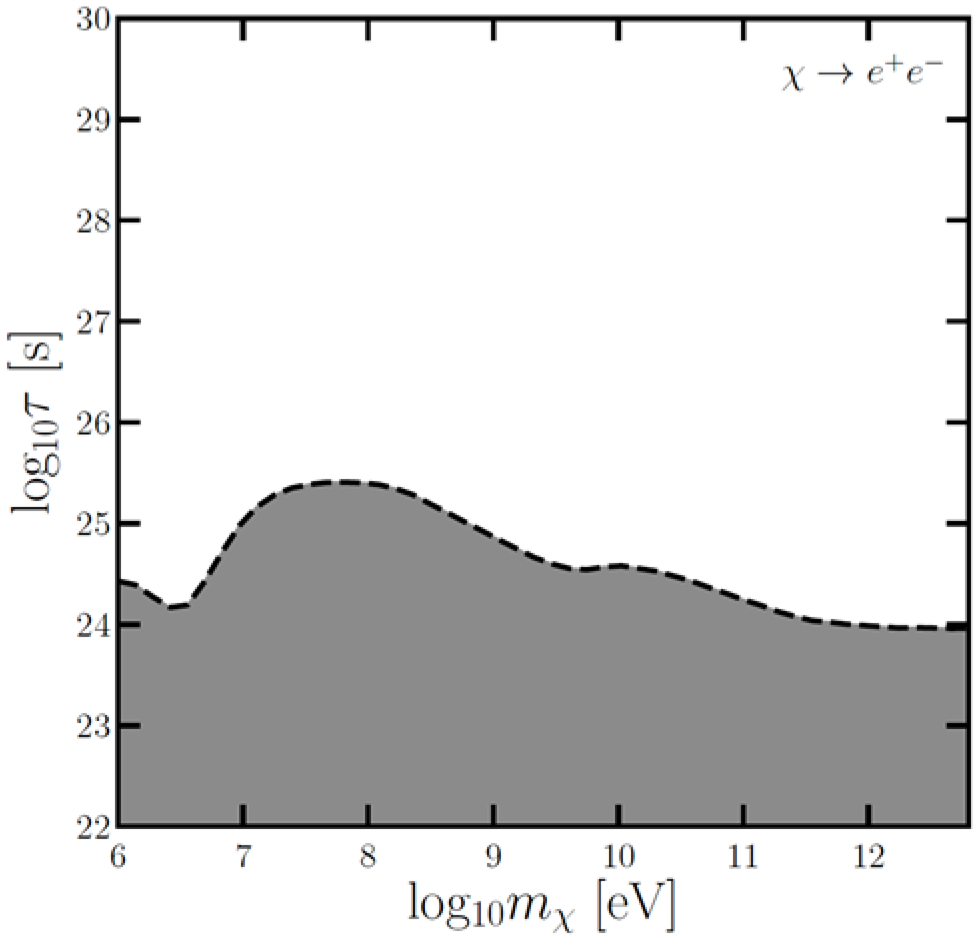


CRITICAL COLLAPSE

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



STAR FORMATION vs CMB CONSTRAINTS



WQ, Muñoz et al. 2023

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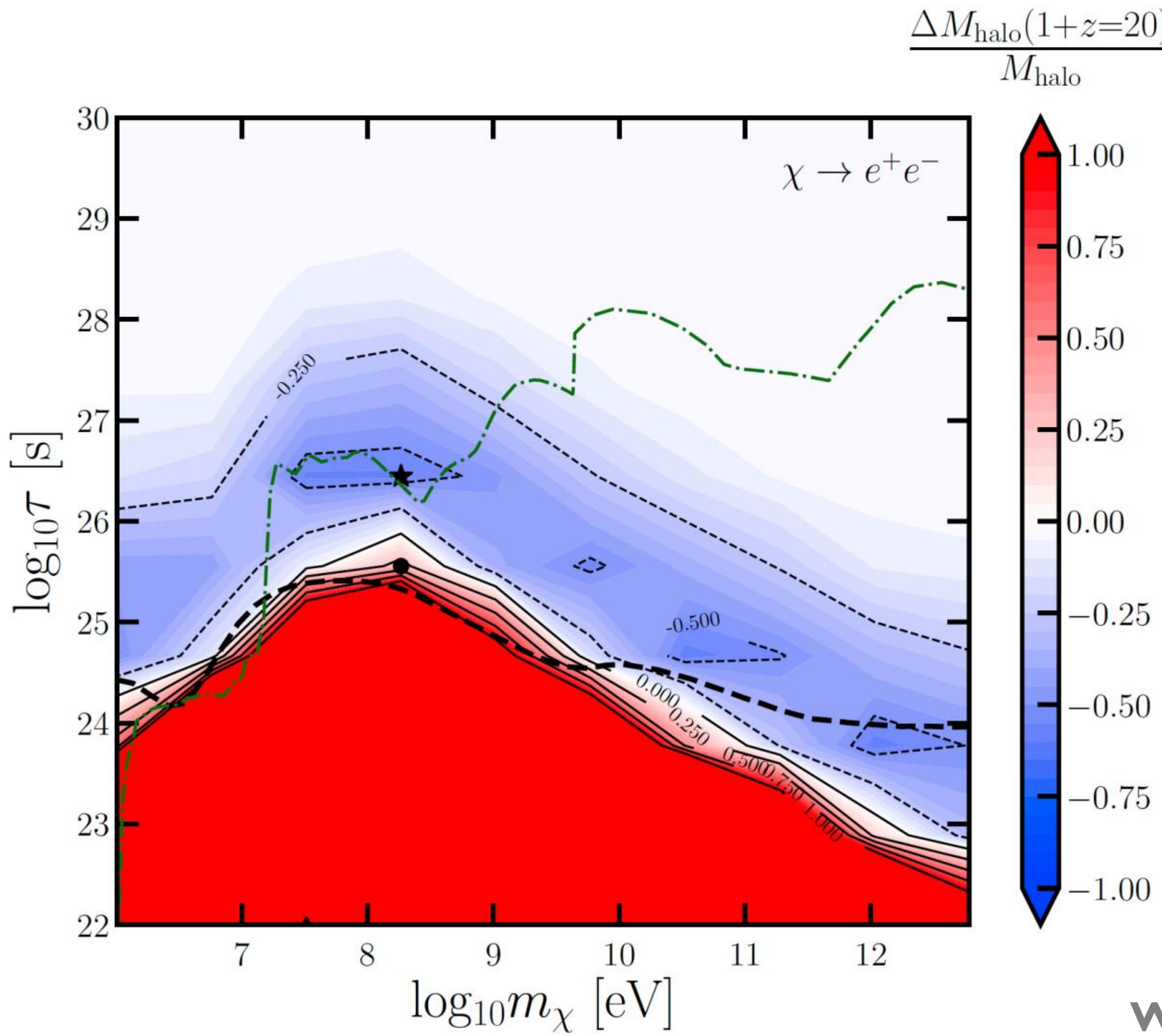

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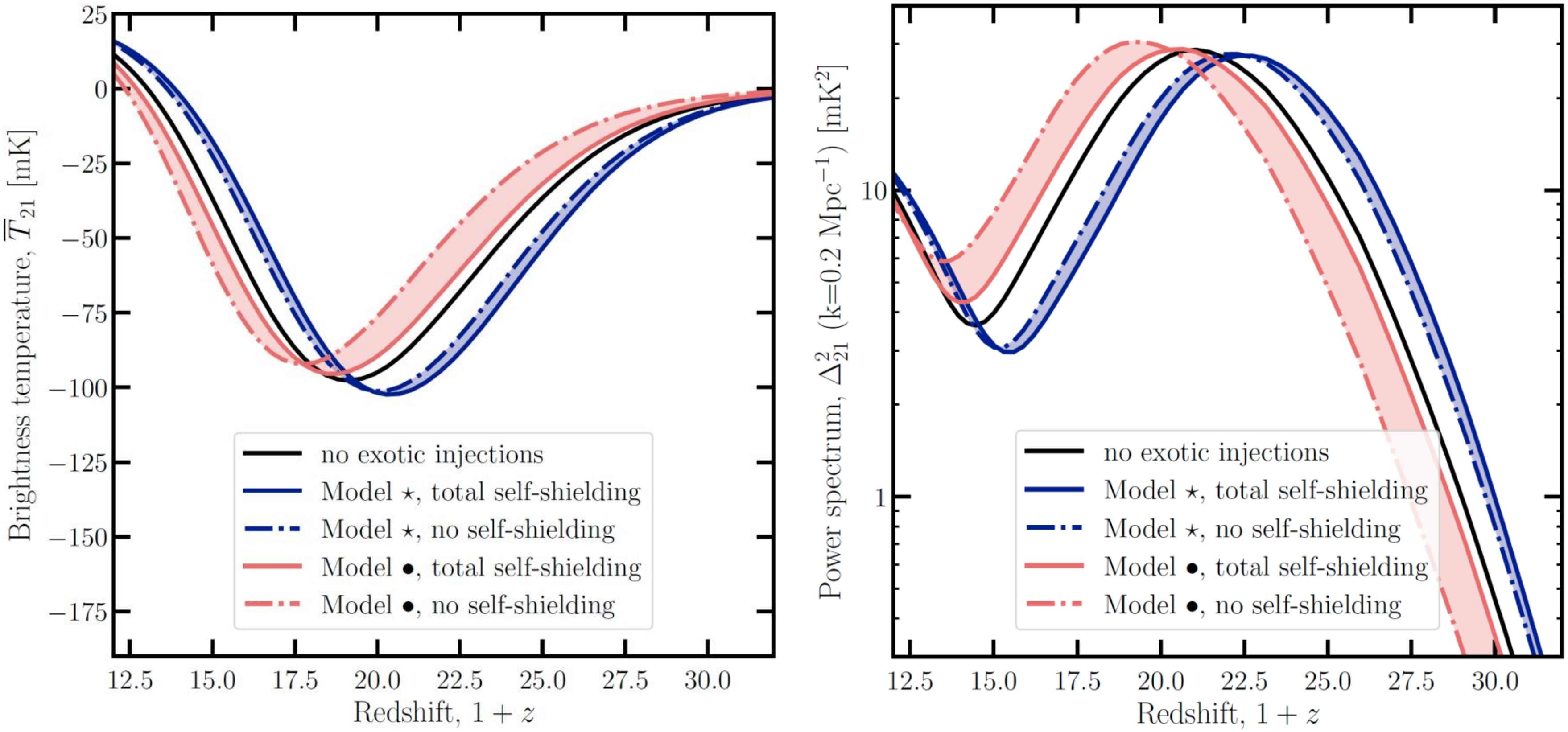
STAR FORMATION AFFECTS 21CM



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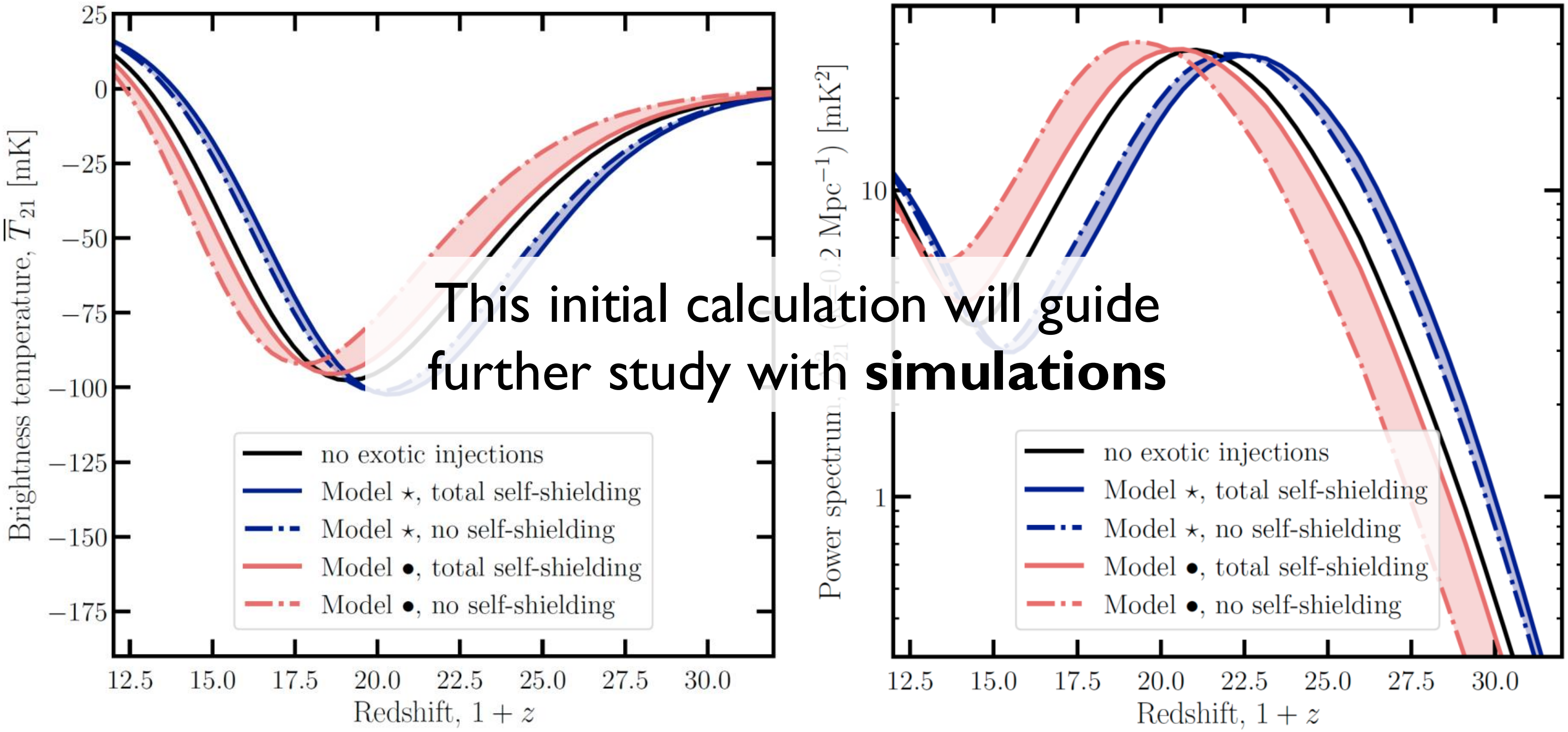


This initial calculation will guide further study with **simulations**

WQ, Muñoz et al. 2023

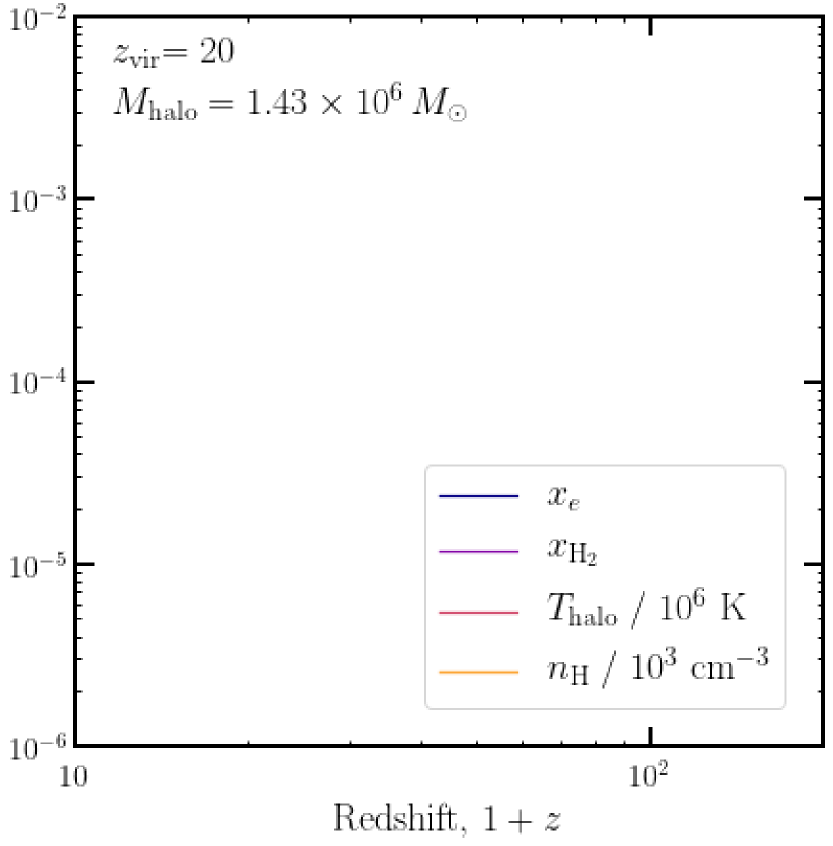
CONCLUSION

- 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
  - Detailed hydrodynamical simulations
  - Impact on first black hole formation

BACKUP SLIDES

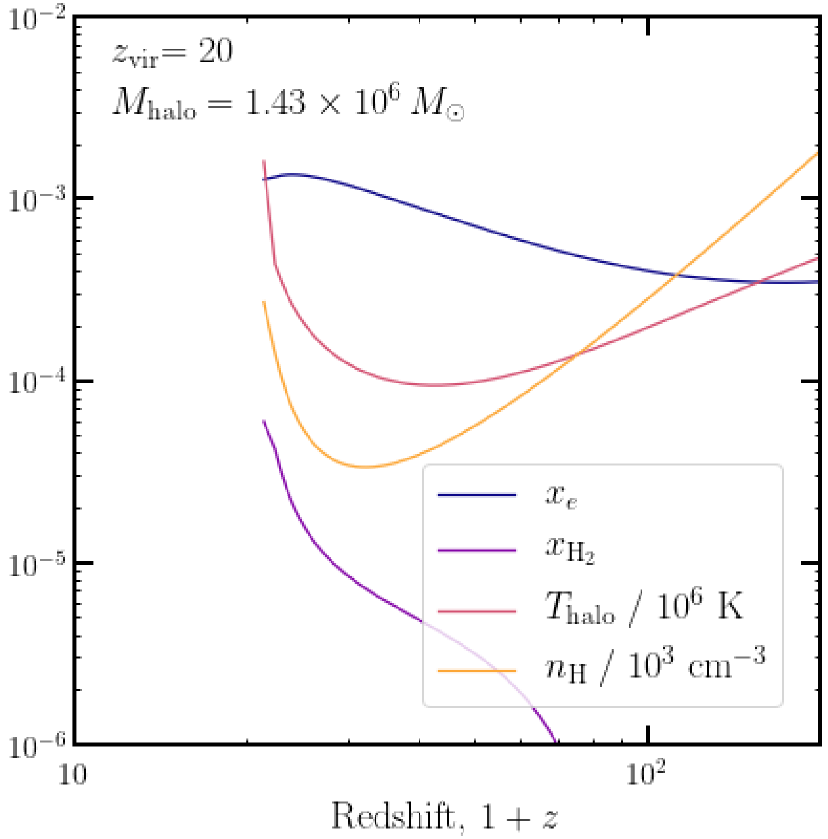
TRACKING HALO EVOLUTION

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



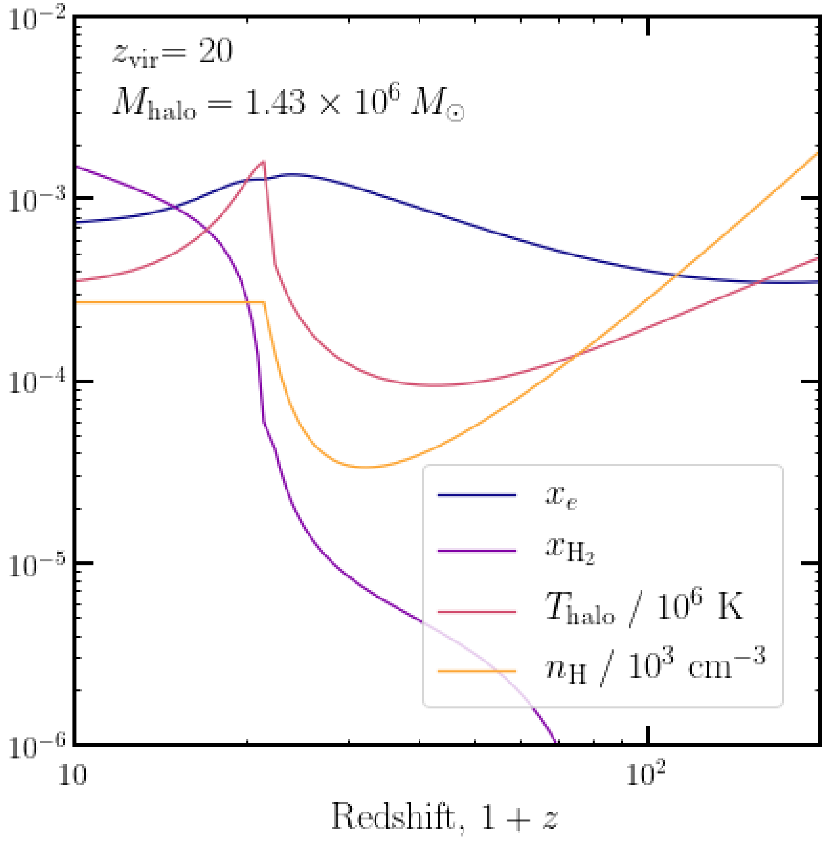
TRACKING HALO EVOLUTION

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



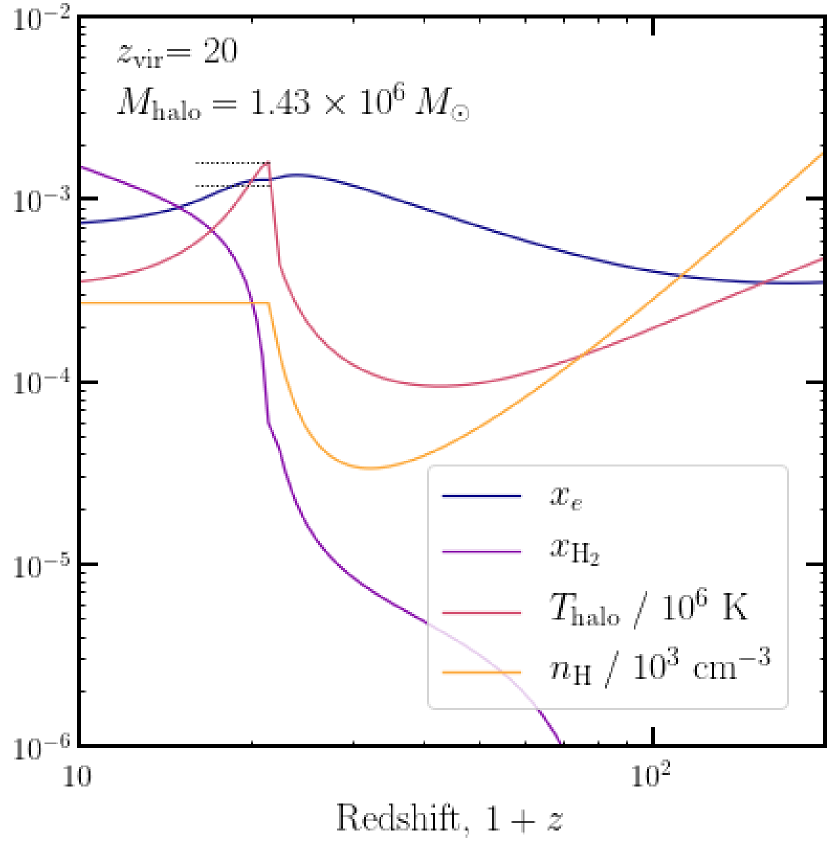
TRACKING HALO EVOLUTION

- After virialization
  - Hold density fixed and continue to evolve other quantities



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 $\eta \approx 2/3$

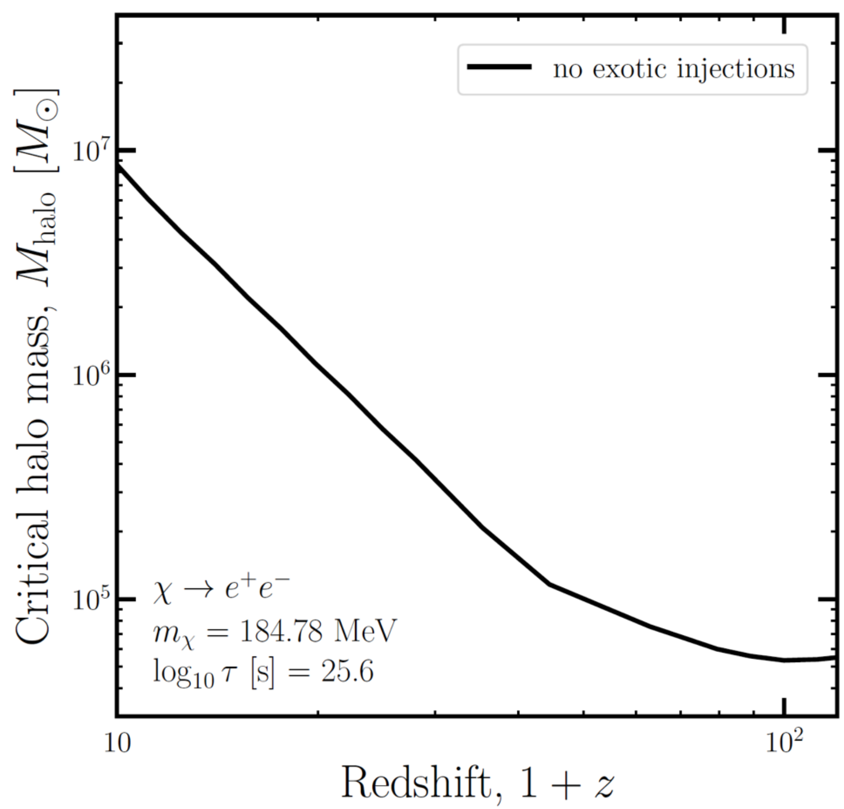


INCLUDING EXOTIC ENERGY INJECTION

- 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

EXAMPLE

- Let's examine effects one by one



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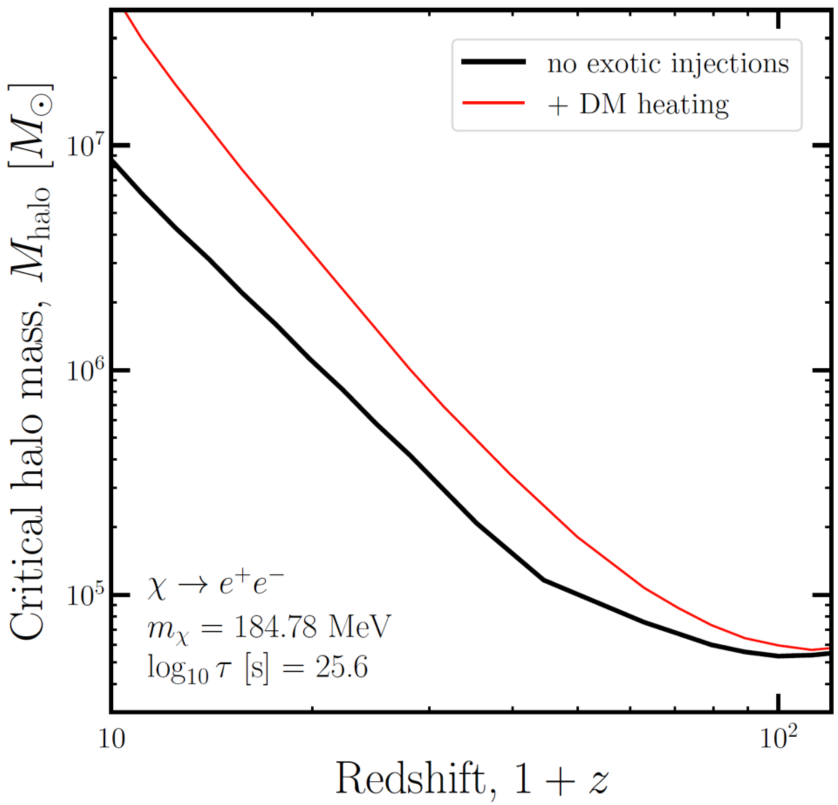
EXAMPLE

- Heating: counters molecular cooling, raises threshold for collapse



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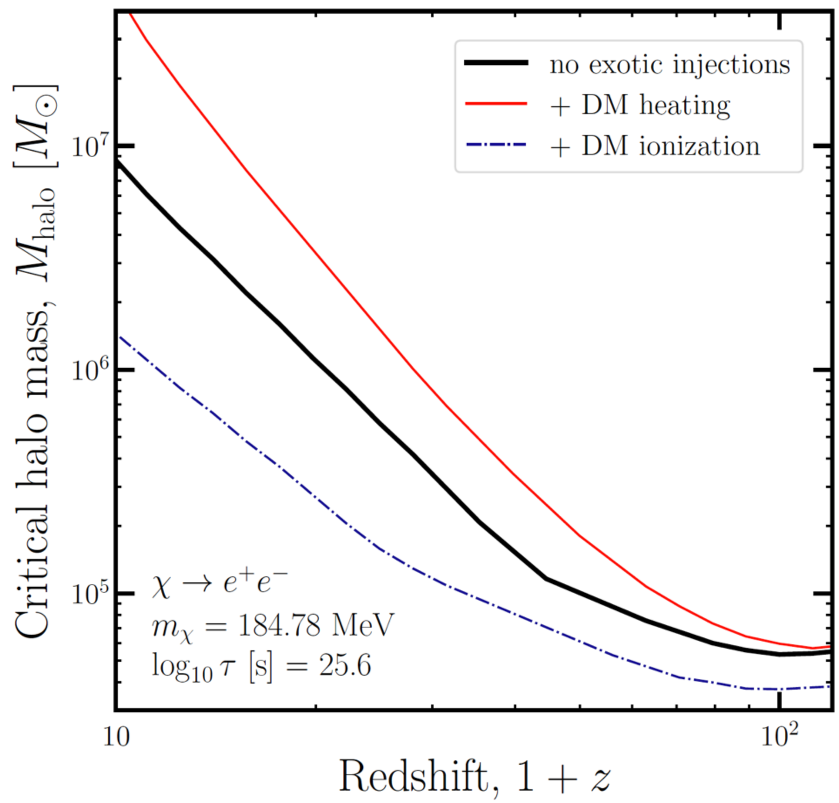
EXAMPLE

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



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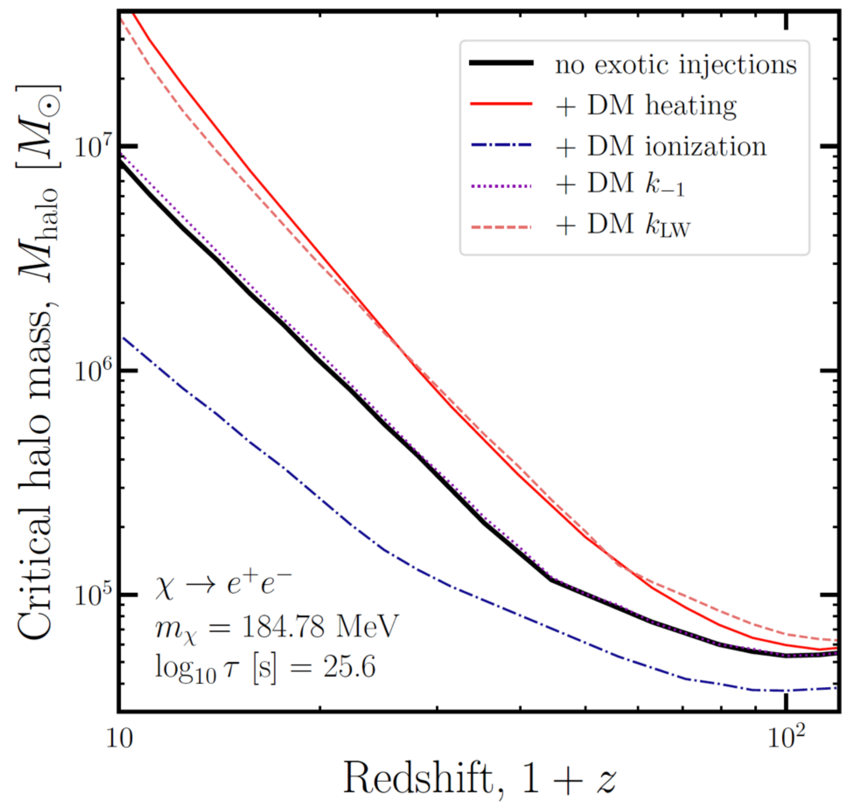
EXAMPLE

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



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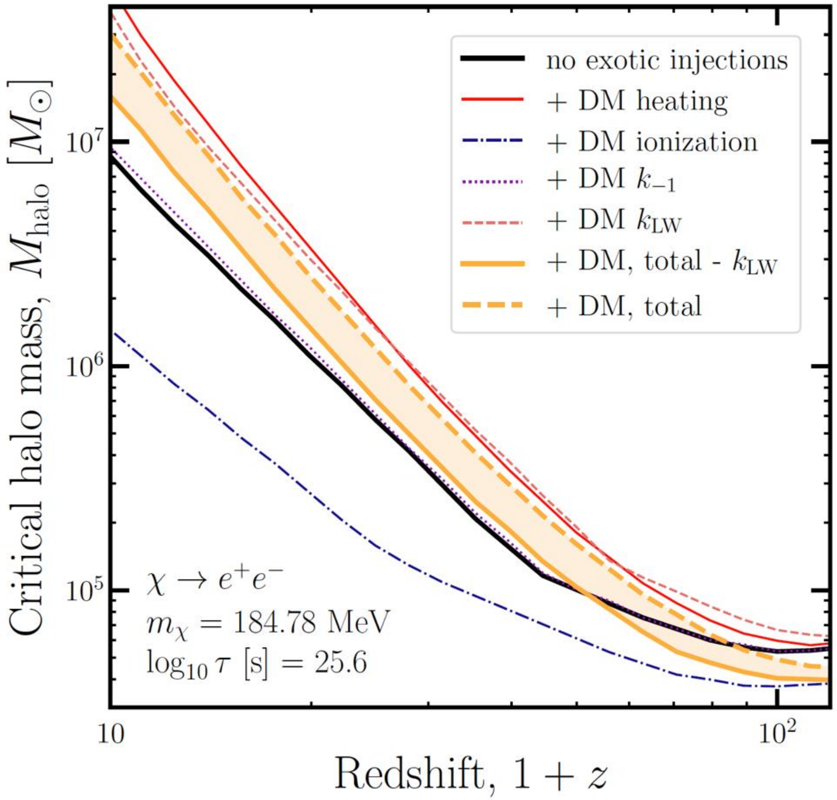
EXAMPLE

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



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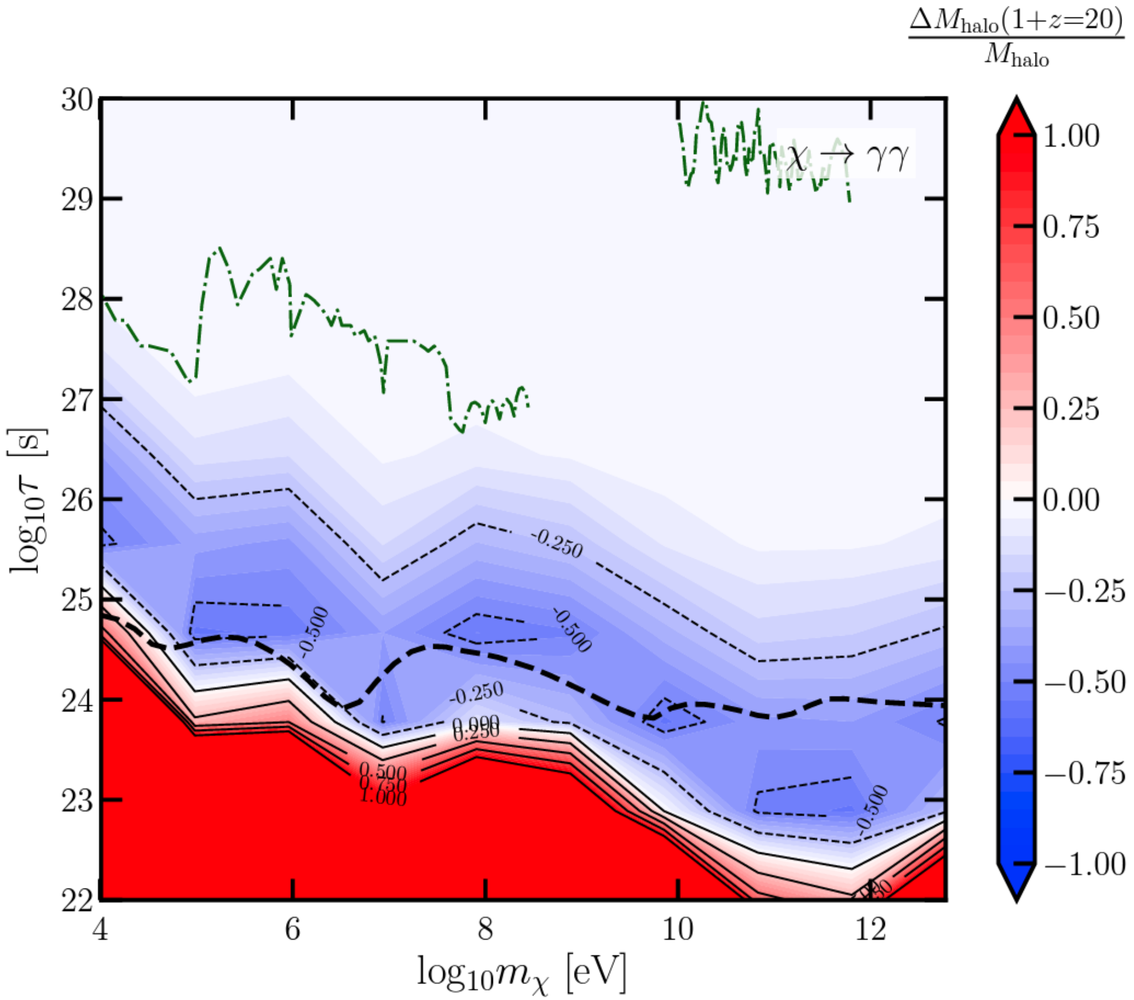
OTHER CHANNELS



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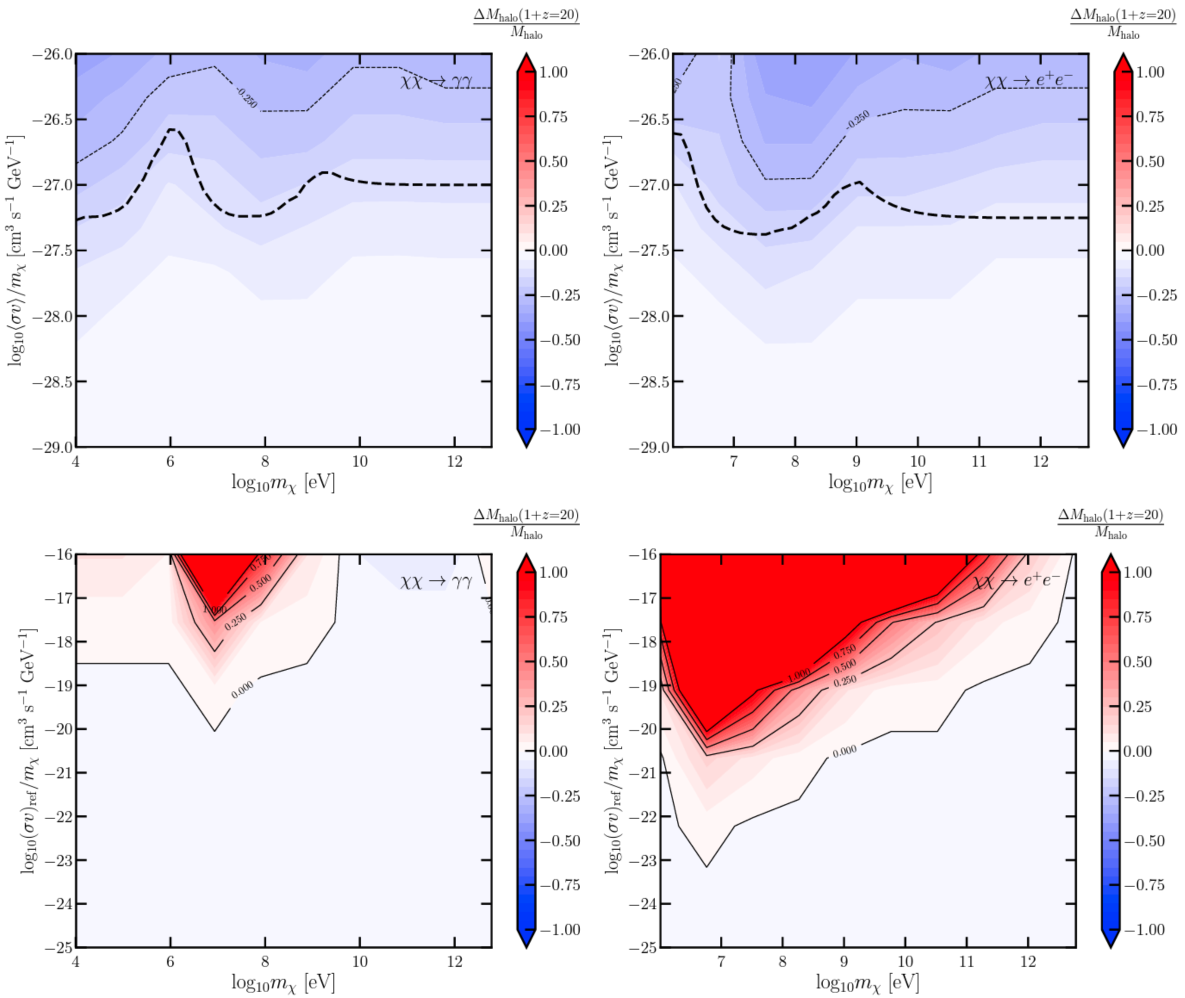

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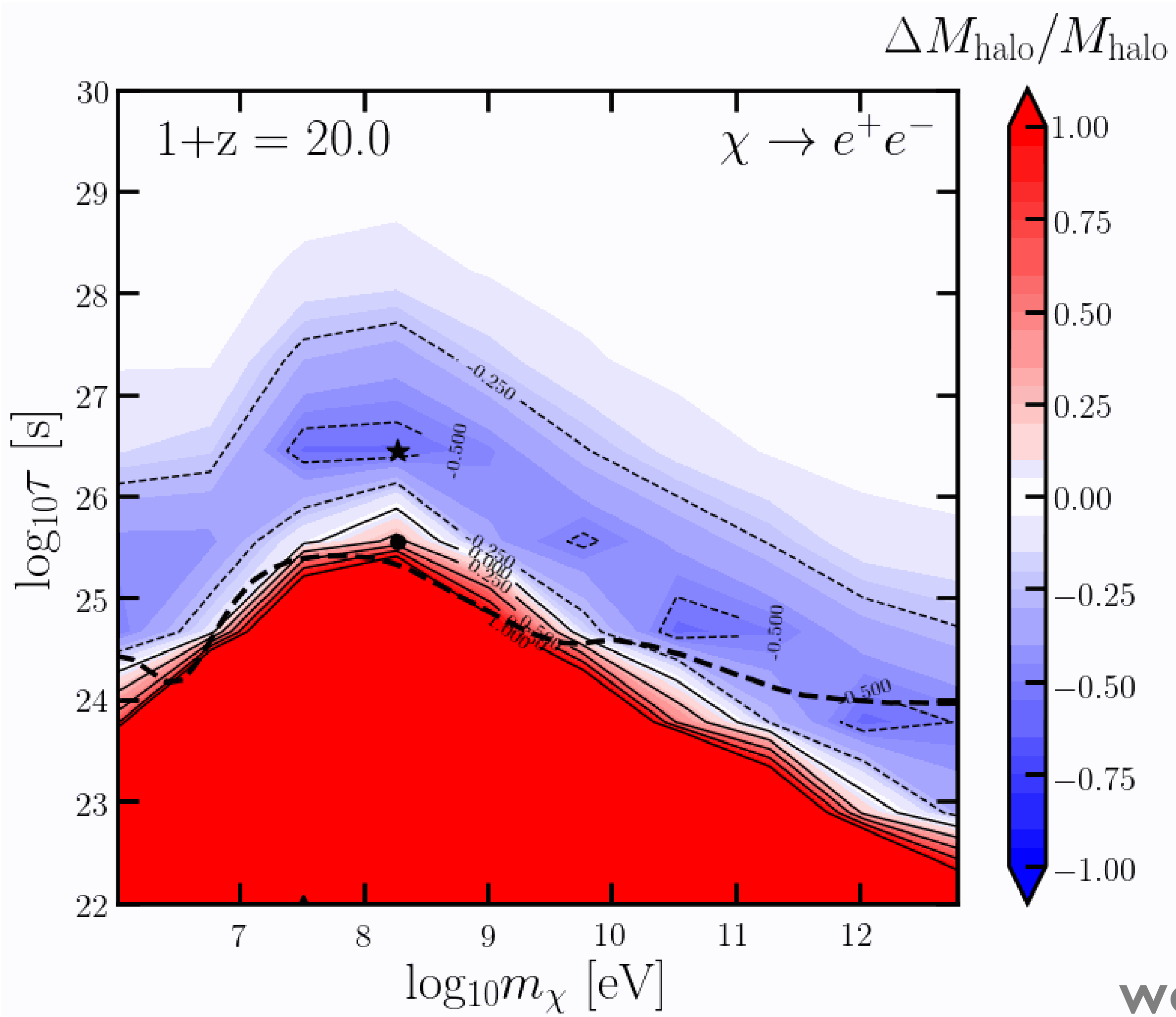

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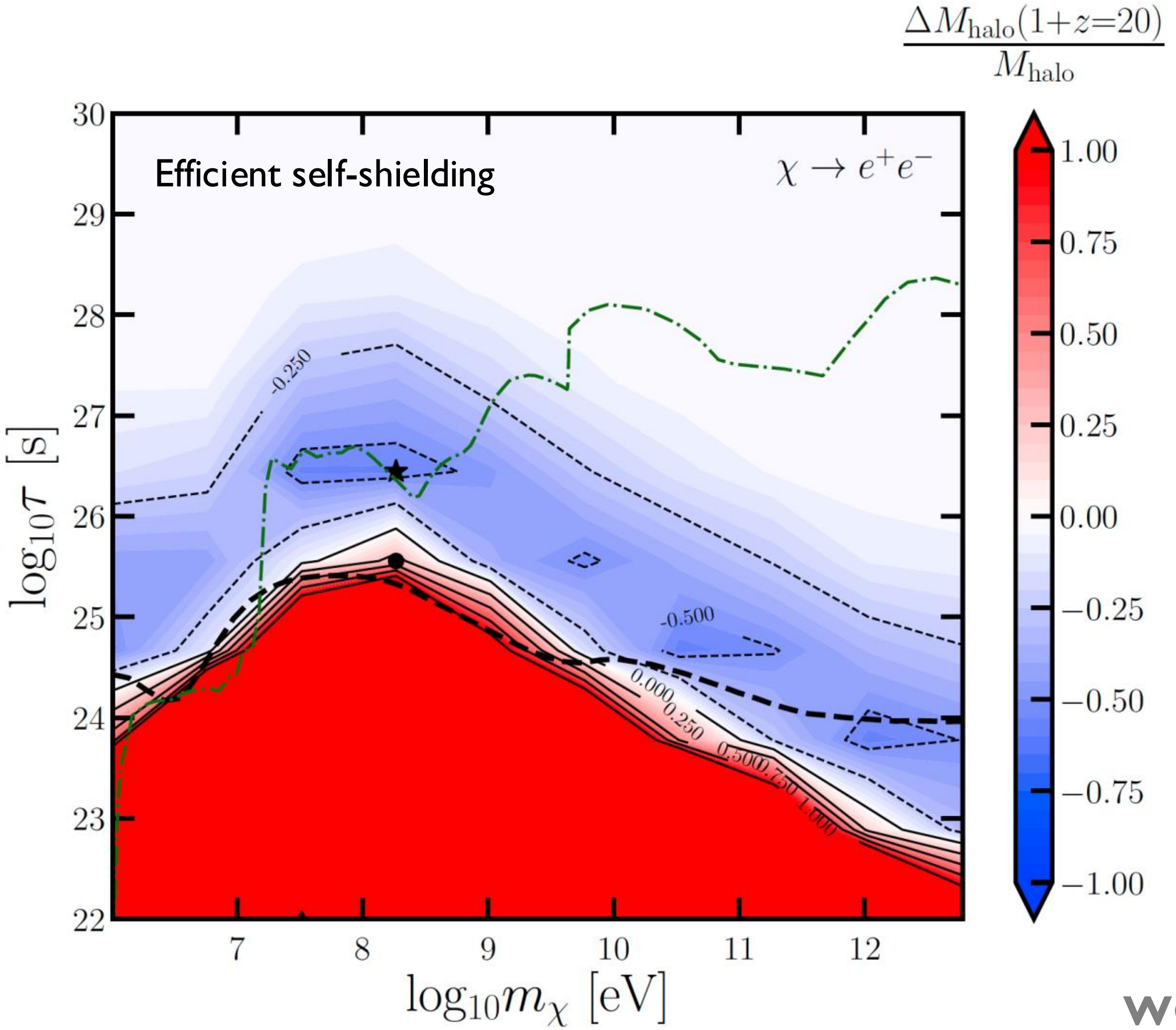

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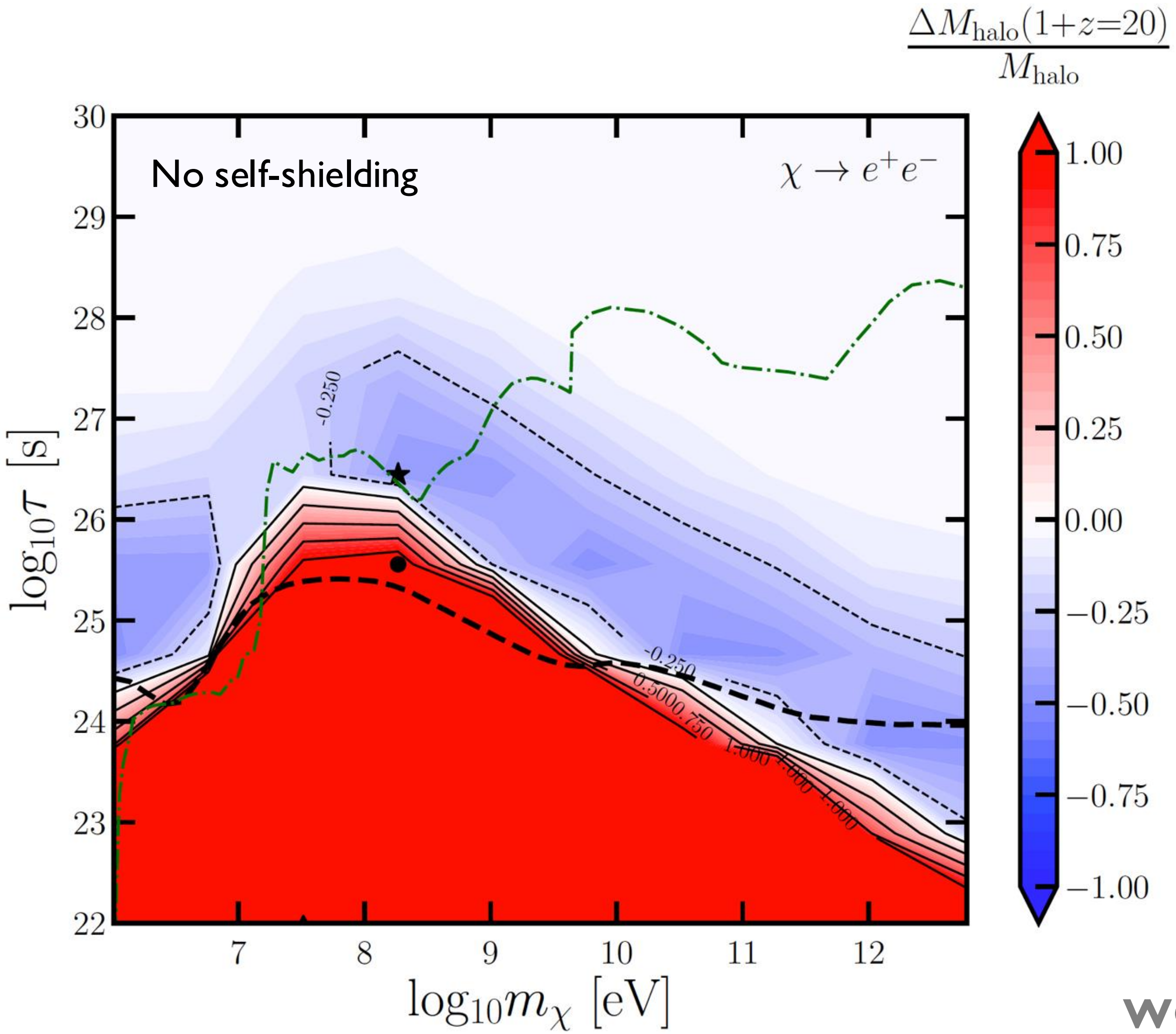

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HOW TO PROBE STAR FORMATION?

- 21cm cosmology:
  - Hyperfine transition of neutral hydrogen → 21cm line photons
  - Lots of neutral hydrogen before stars form/reionization

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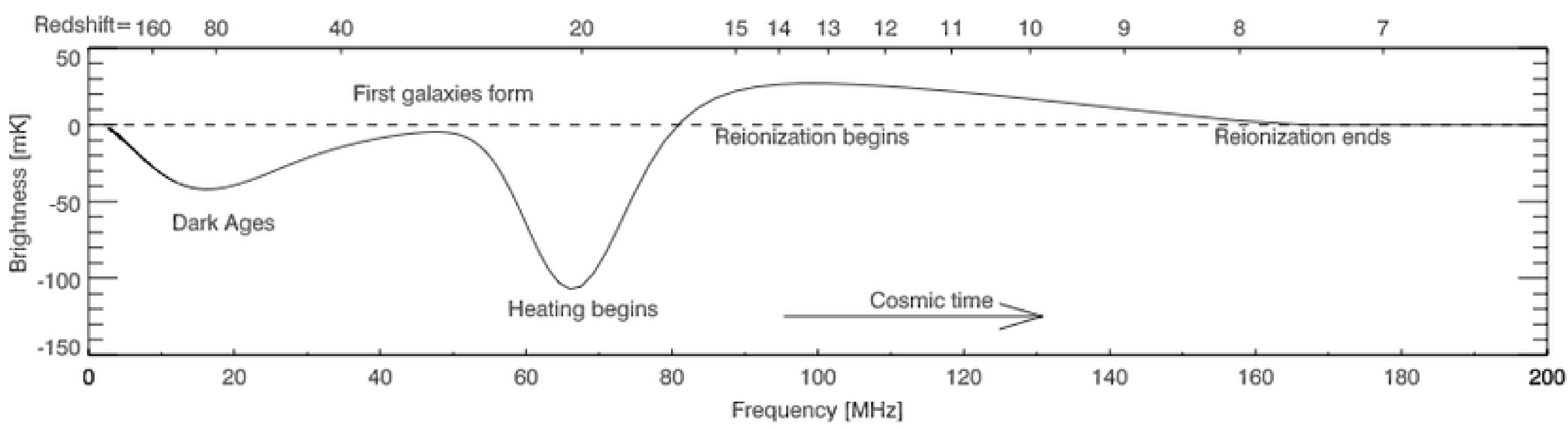
- 21cm cosmology:
  - Hyperfine transition of neutral hydrogen → 21cm line photons
  - Lots of neutral hydrogen before stars form/reionization
- Predicted signals depend on timing of star formation



SIMPLIFIED CASCADE

Electron Kinetic Energy	$1 \to 2$	2	$2 \to 3$	3	$3 \to 4$	4	$4 \to 5$
1–14 MeV	ICS	$< 13.6\,\mathrm{eV}\ \gamma$ (ICS,2)	**No Ionization /Heating**	–	–	–	–
14–60 MeV	ICS	$13.6\text{–}230\,\mathrm{eV}\ \gamma$	Photoionization	$0\text{–}215\,\mathrm{eV}\ e^-$ (ICS,3)	e^- **Atomic**	–	–
60–350 MeV	ICS	$0.23\text{–}8\,\mathrm{keV}\ \gamma$	Photoionization	$0.215\text{–}8\,\mathrm{keV}\ e^-$ (ICS,3)	e^- **Atomic**	–	–
0.35–1.37 GeV	ICS	$8\text{–}120\,\mathrm{keV}\ \gamma$	Compton	$0.125\text{–}30\,\mathrm{keV}\ e^-$ (ICS,3)	e^- **Atomic**	–	–
1.37–10 GeV	ICS	$0.12\text{–}6.4\,\mathrm{MeV}\ \gamma$ (ICS,2)	Compton	$0.03\text{–}1.8\,\mathrm{MeV}\ e^-$	ICS	$< 13.6\,\mathrm{eV}\ \gamma$ (γ,t)	**No Ionization /Heating**

SIMPLIFIED CASCADE

Photon Energy	$1 \to 2$	2	$2 \to 3$	3	$3 \to 4$	4	$4 \to 5$	5	$5 \to 6$
10–120 keV	Compton	0.125–30 keV e^- $(\gamma,2)$	e^- **Atomic**	–	–	–	–		
0.12–14 MeV	Compton	0.03–14 MeV e^-	ICS	<13.6 eV γ $(\gamma,3)$	**No Ionization /Heating**	–	–		
14–60 MeV	Compton	14–60 MeV e^- $(\gamma,2)$	ICS	13.6–230 eV γ	Photo-ionization	0–215 eV e^- (ICS,t)	e^- **Atomic**		
60–120 MeV	H Pair Production	30–60 MeV e^- $(\gamma,2)$	ICS	58–230 eV γ	Photo-ionization	43–215 eV e^- (ICS,t)	e^- **Atomic**		
120–700 MeV	H Pair Production	60–350 MeV e^-	ICS	0.145–8 keV γ $(\gamma,3)$	Photo-ionization	0.13–8 keV e^- (γ,s)	e^- **Atomic**		
0.7–2.8 GeV	H Pair Production	0.35–1.4 GeV e^-	ICS	8–120 keV γ $(\gamma,3)$	Compton	0.125–30 keV e^- (γ,s)	e^- **Atomic**		
2.8–10 GeV	H Pair Production	1.4–5 GeV e^-	ICS	120–450 keV γ $(\gamma,3)$	Compton	30–400 keV e^-	ICS	$<$ 10.2 eV γ (γ,t)	**No Ionization /Heating**