Title: Dark Matter Annihilation in 21cm Signal at Cosmic Dawn

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Collection: Dark Matter, First Light

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Abstract: We will present our study of the interaction of dark matter (DM) annihilation with primordial gas during cosmic dawn, emphasizing its impact on the thermal environment of nearby dark matter halos. Utilizing a semi-analytic model, we analyze DM annihilation across redshifts $z=20 to 40$, uncovering its role in altering baryon history and impeding gas collapse and cooling in mini-halos, which affects PopIII star formation.

Our study also integrates streaming velocity effects to simulate the 21-cm hydrogen line signal using the 21cmvFAST code. This approach offers a detailed view of astrophysical processes in the early universe. We will present findings demonstrating DM annihilation's significant influence on early star formation and the observable characteristics of the neutral hydrogen line. Our presentation aims to enhance our understanding of baryon physics in the cosmic dawn and provide insights into dark matter models and early galactic and stellar formation.

Dark matter annihilation in 21cm signal at cosmic dawn

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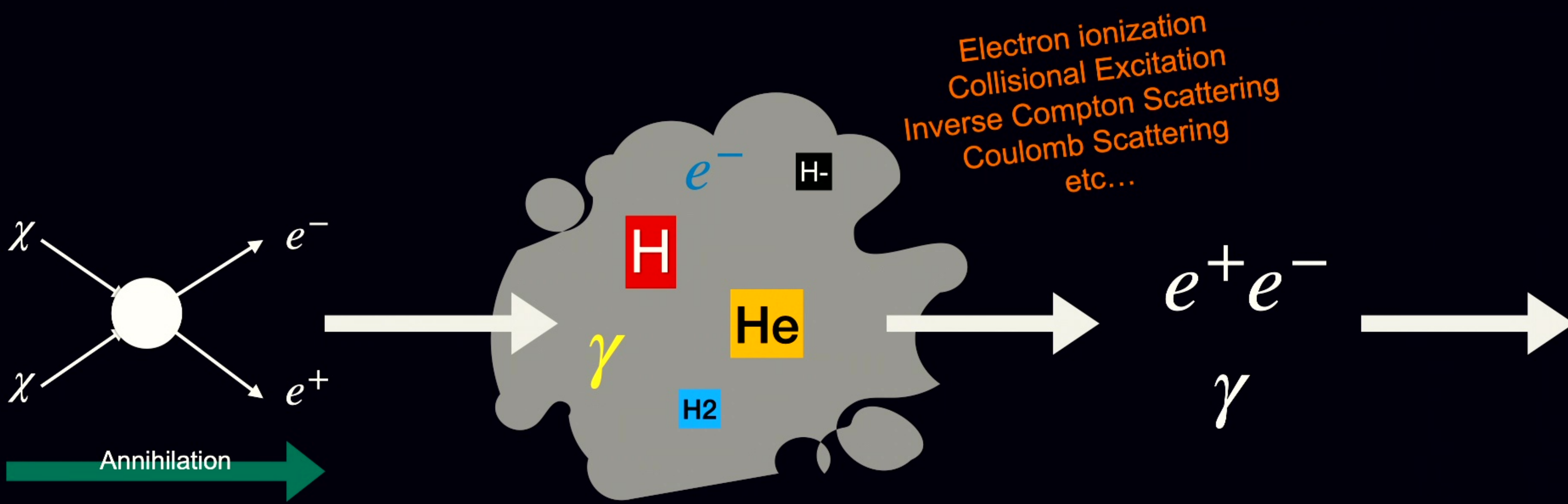
Dark Matter, First Light
PI Feb 27, 2024

Problem

- How does dark matter annihilation influence *early structure formation* and the *formation of the first stars*?
- How do those effects manifest in the *21cm signal*?
- How do those effects interact with or compare to: **molecular cooling, streaming velocity and some local halo effects…?**

Dark Matter Annihilation in Gas Context



Heat, ionize

3

Energy deposition

$$\frac{dE}{dVdt} = \frac{\langle \sigma v \rangle}{m_{\rm DM}} \rho_{\rm DM}^2 f_c (1 + B)$$

Heating

$$\left.\frac{dT_K}{dz}\right|_{\rm DM} = \frac{dt}{dz} \frac{2}{3k_B\left(1 + x_e\right)} \epsilon_{\rm heat}^{\rm DM}$$

Ionization

$$\left.\Lambda_{\rm ion}\right|_{\rm DM} = \mathfrak{f}_{\rm H} \frac{\epsilon_{\rm HI}^{\rm DM}}{E_{\rm HI}} + \mathfrak{f}_{\rm He} \frac{\epsilon_{\rm HeI}^{\rm DM}}{E_{\rm HeI}}$$

Lyman-α

$$J_{\alpha,\rm DM} = \frac{c n_b}{4\pi} \frac{\epsilon_{\rm Ly\alpha}^{\rm DM}}{h\nu_\alpha} \frac{1}{H(z)\nu_\alpha}$$

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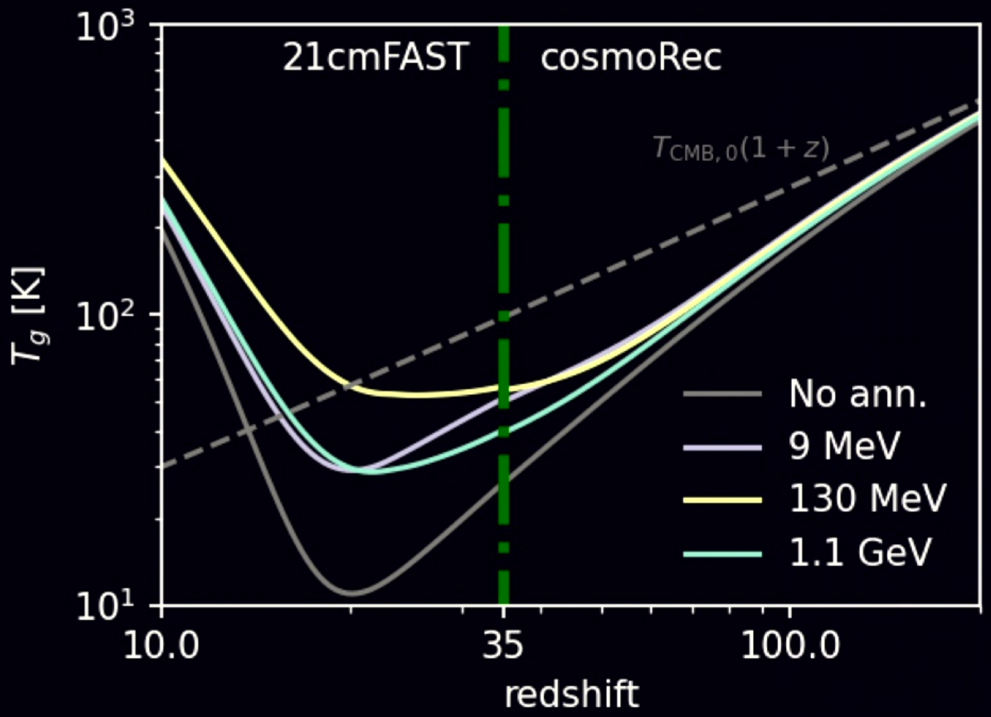
Thermal history

Evolving the Gas temperature with DM annihilation {Heating, Ionization}

DM Model

$$\chi\chi \to e^+e^-$$

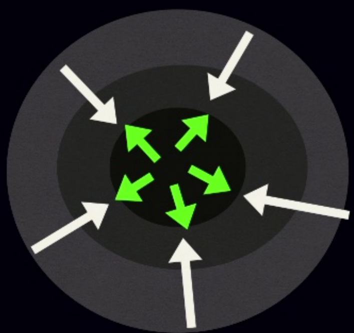
$$\langle\sigma v\rangle/m_{DM} = 10^{-27}\ \mathrm{cm^3/s/GeV}$$

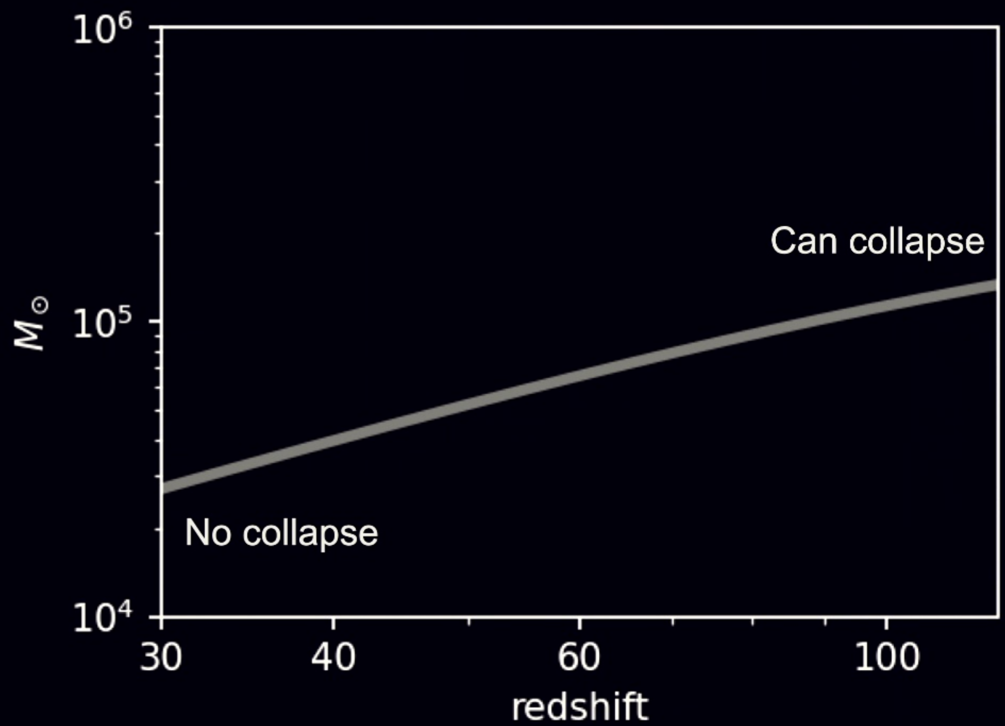


How does dark matter annihilation change the gas collapsing?

Jeans Mass

Gas Pressure v.s DM Gravity





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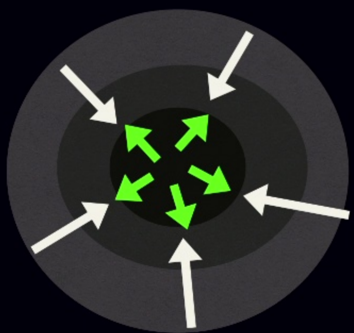

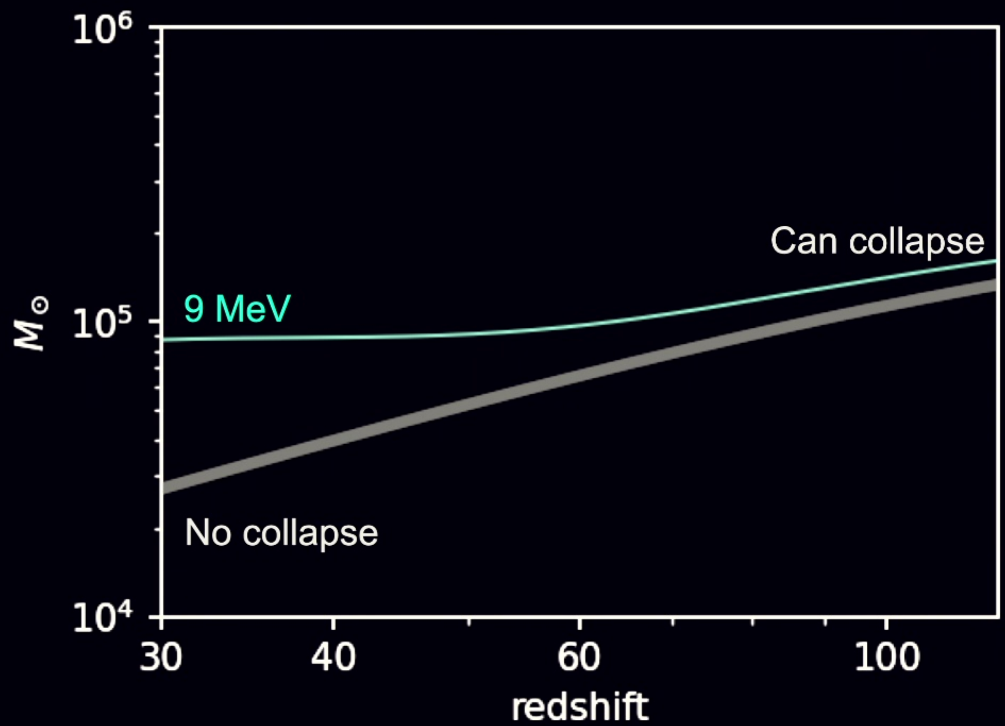

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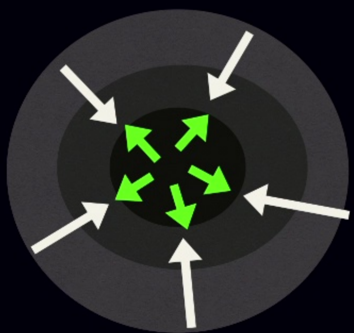
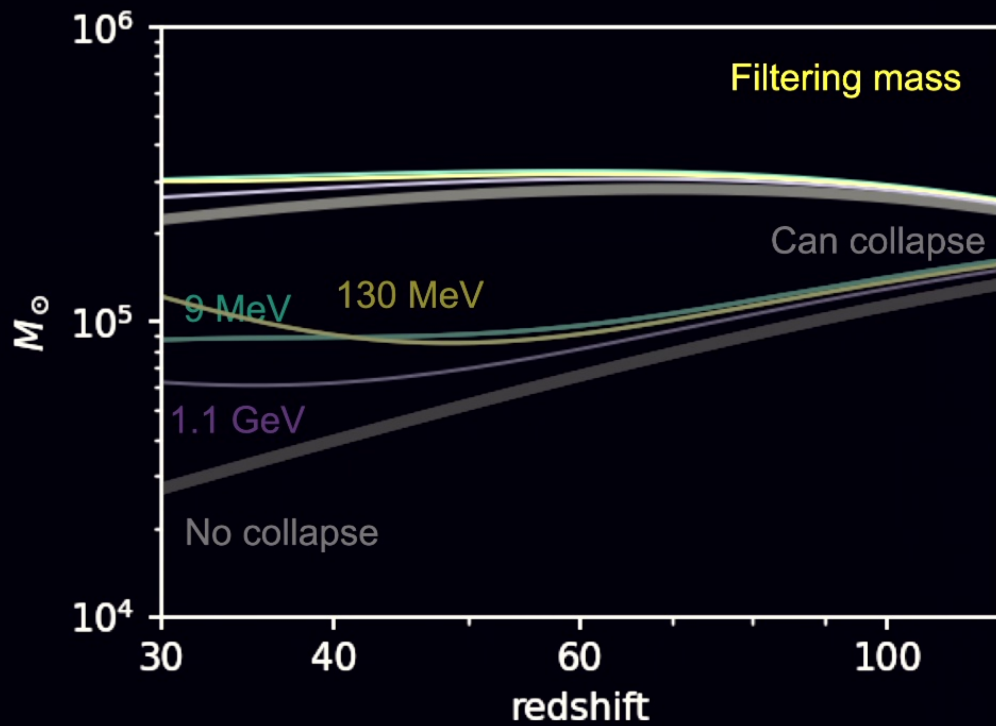
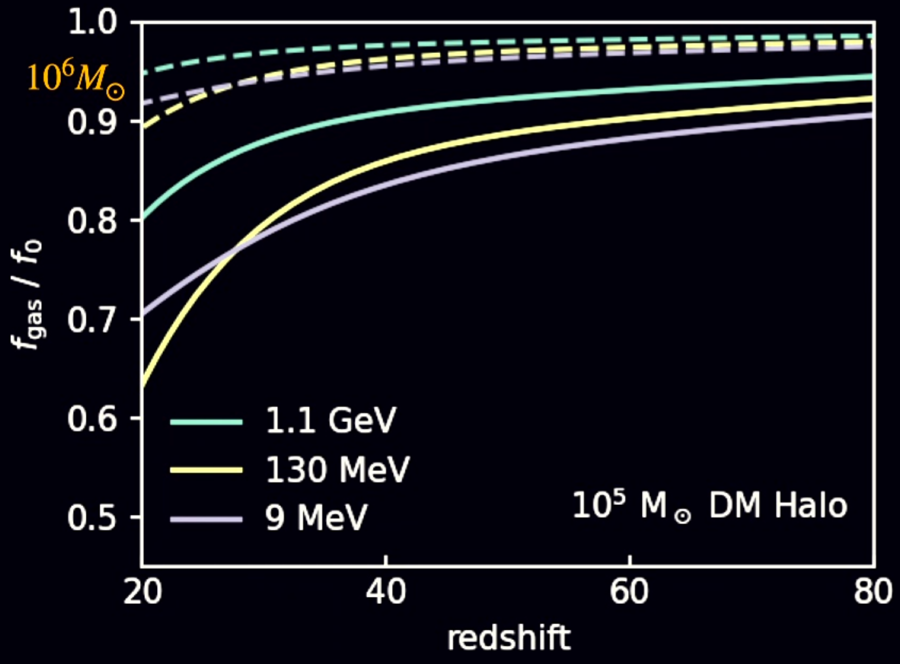
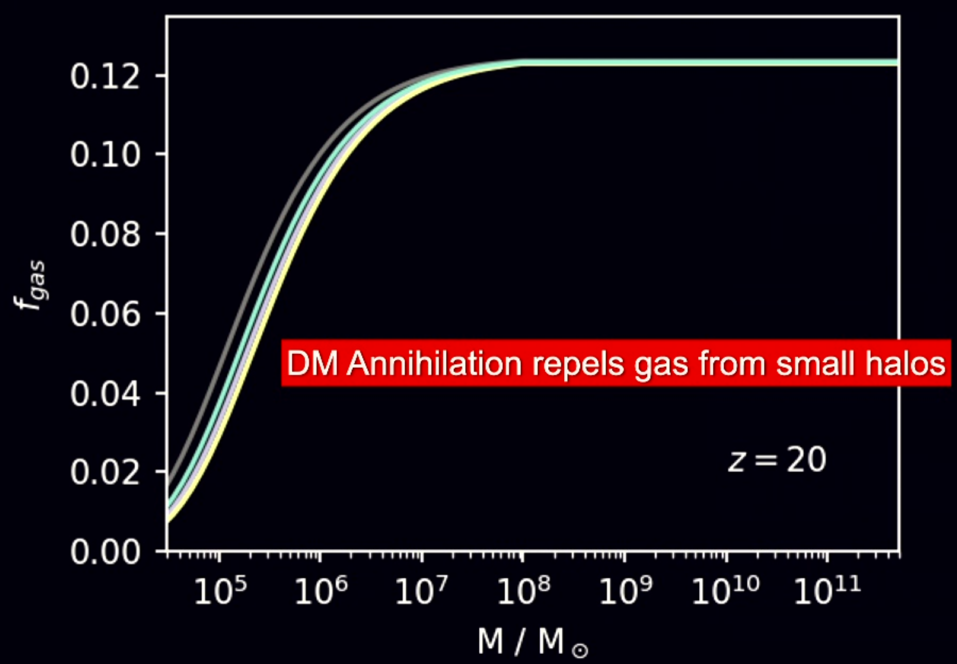




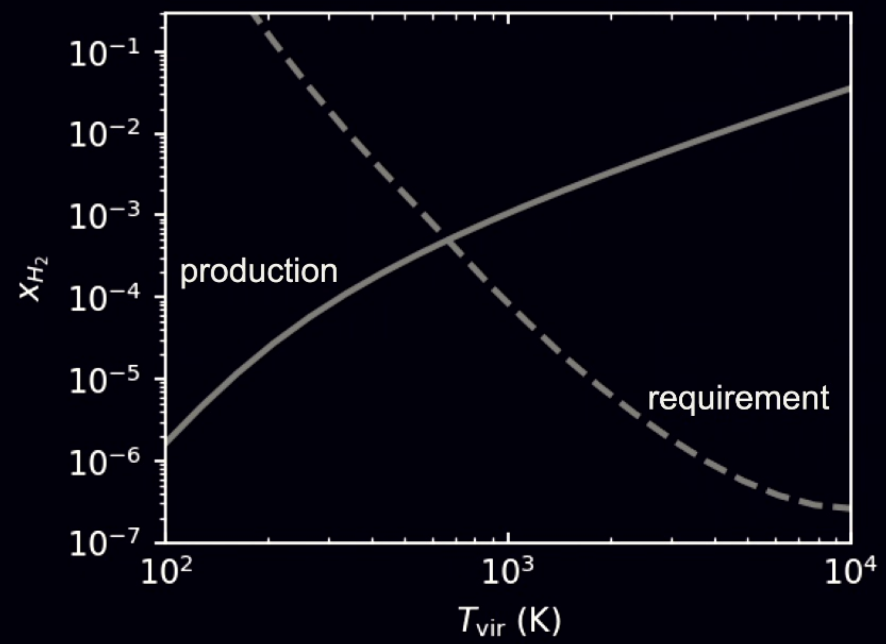
How does dark matter annihilation change the gas collapsing?





Molecular Cooling

- For first stars, molecular hydrogen production is predominantly driven by the H^- mechanism [Glover et al. (2008, 2009)]
- The requirement condition for molecular cooling is given by the cooling time $t_{cool} < 0.2 t_H$ [Machacek et al. (2001), Glover (2012)]



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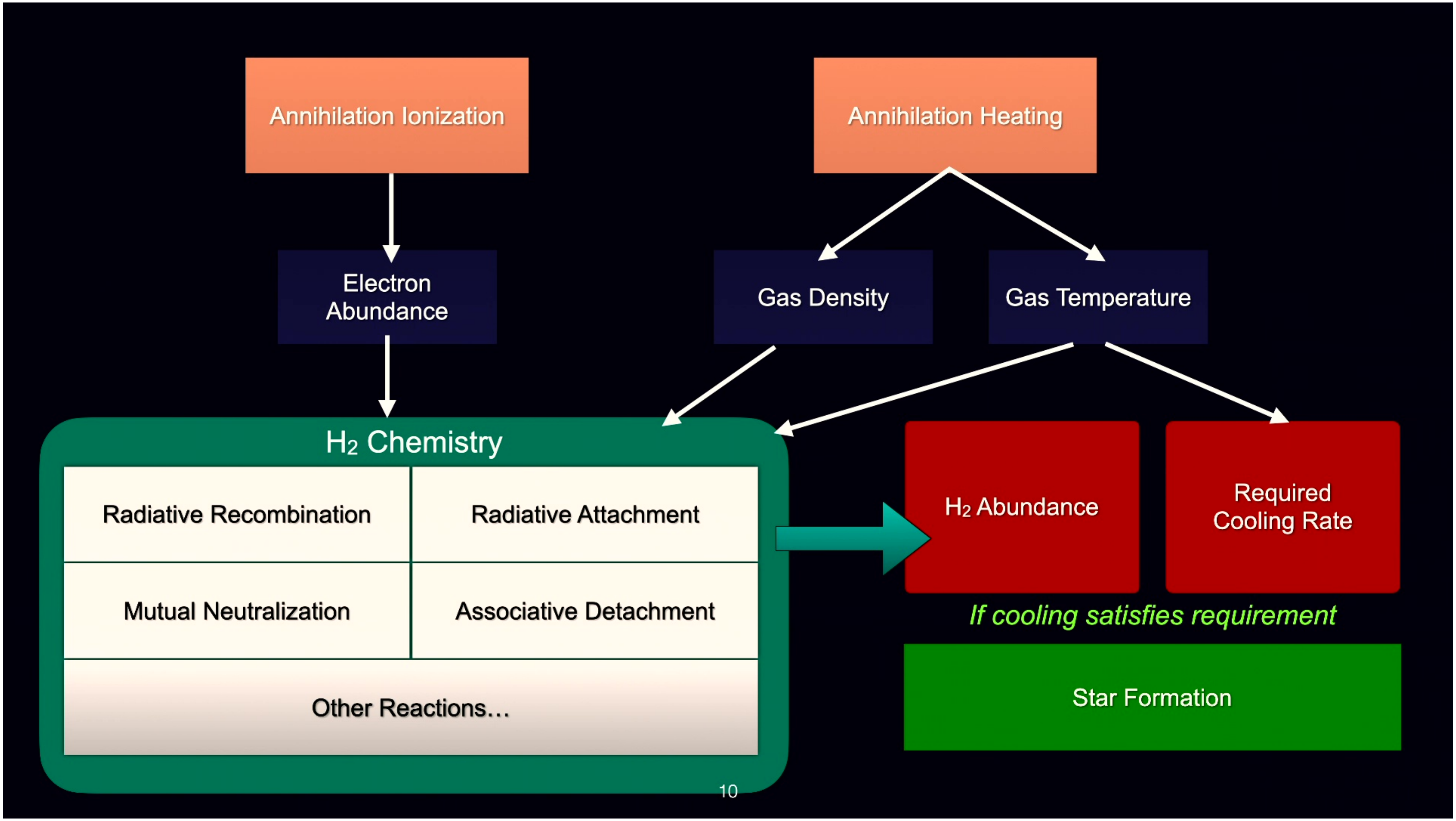
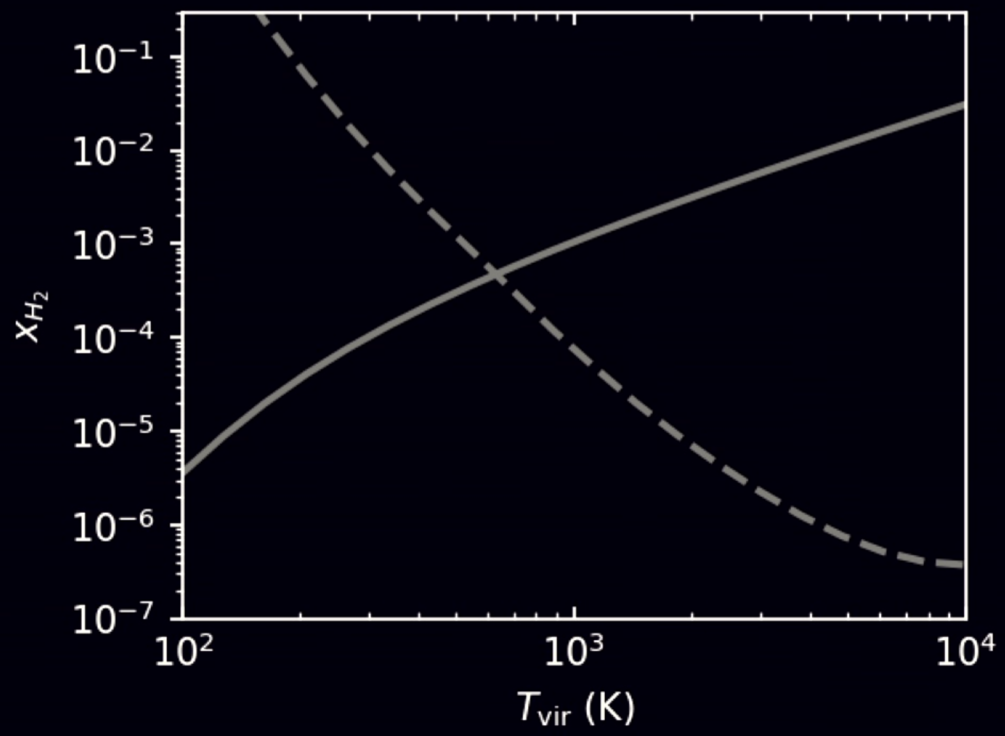


Annihilation Ionization
Annihilation Heating
Electron Abundance
Gas Density
Gas Temperature
H2 Chemistry
Radiative Recombination
Radiative Attachment
Mutual Neutralization
Associative Detachment
Other Reactions…
H2 Abundance
Required Cooling Rate
If cooling satisfies requirement
Star Formation
10

Molecular Cooling Threshold

Let's add the effect of DM heating, ionization



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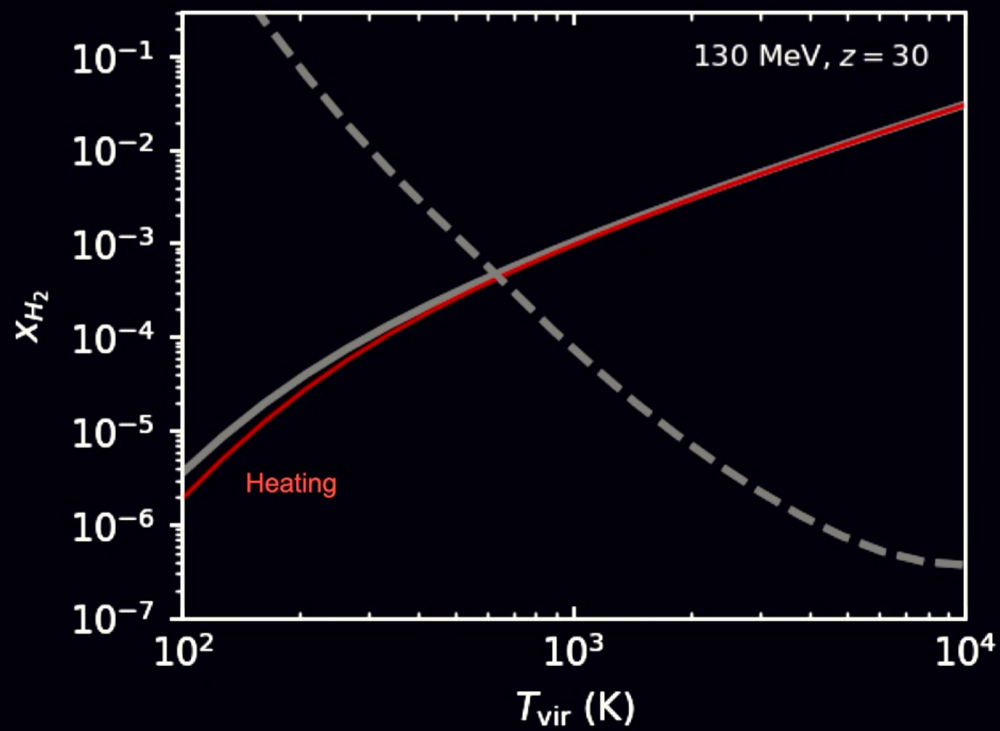

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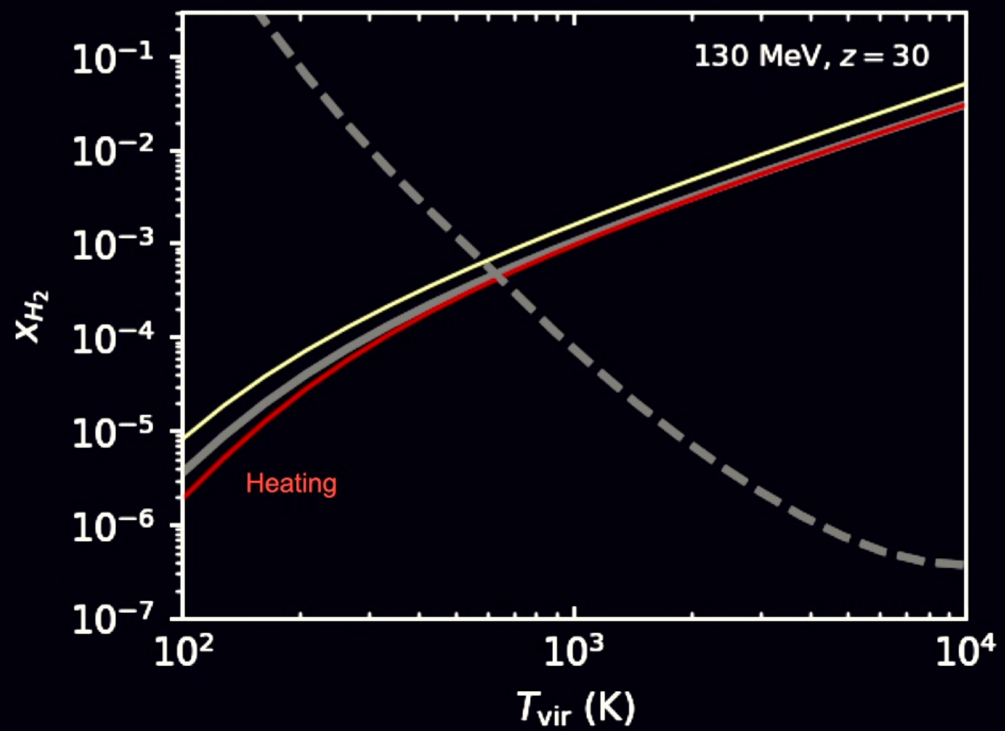

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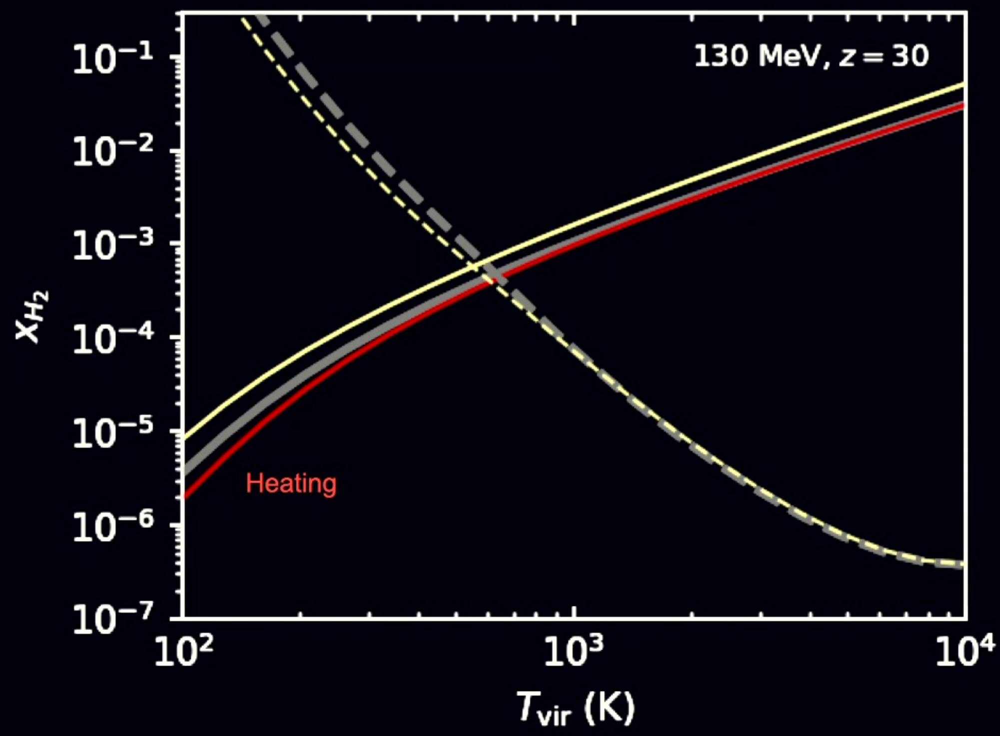

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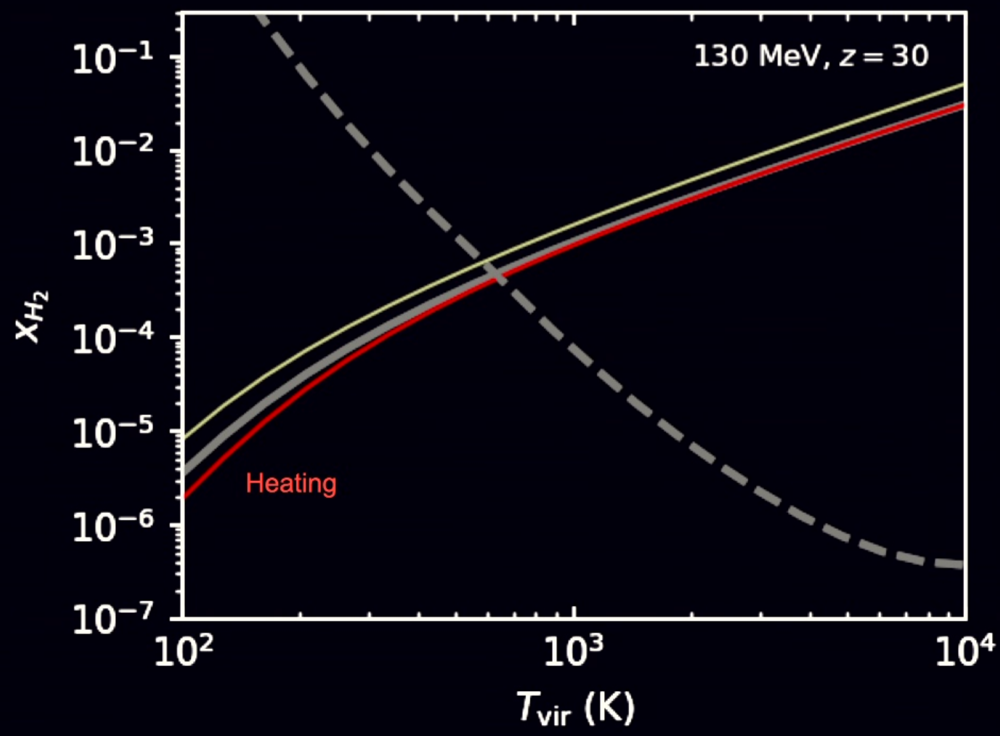
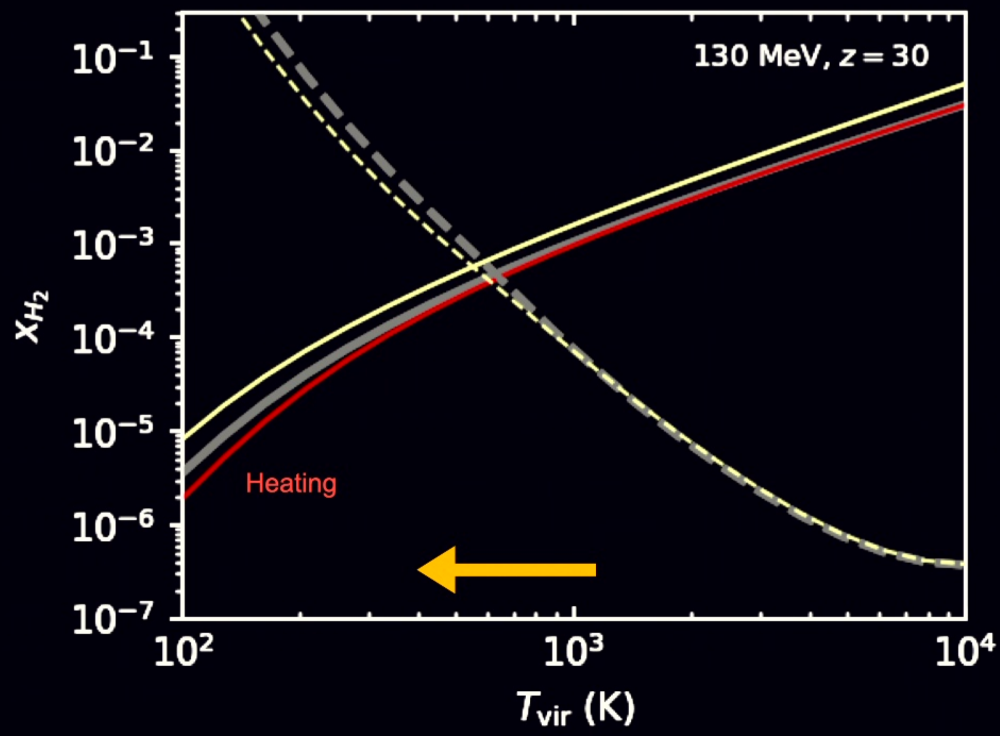


Molecular Cooling Threshold

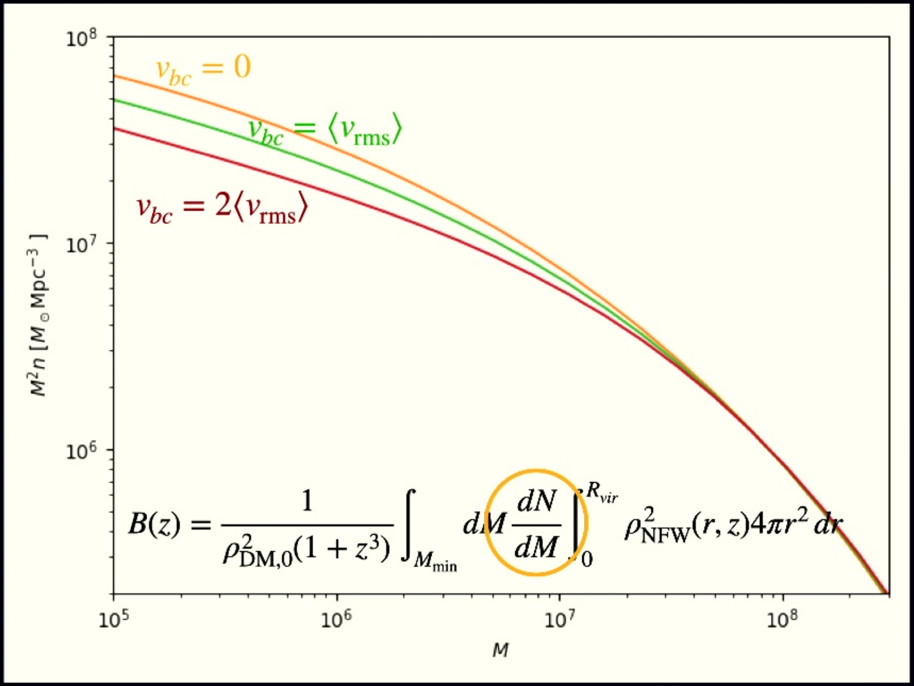
Let's add the effect of DM heating, ionization



Streaming Velocity

- streaming velocity can **suppress the average background dark matter annihilation power** by suppressing the mini-halo numbers [Tseliakhovich and Hirata. (2010)]

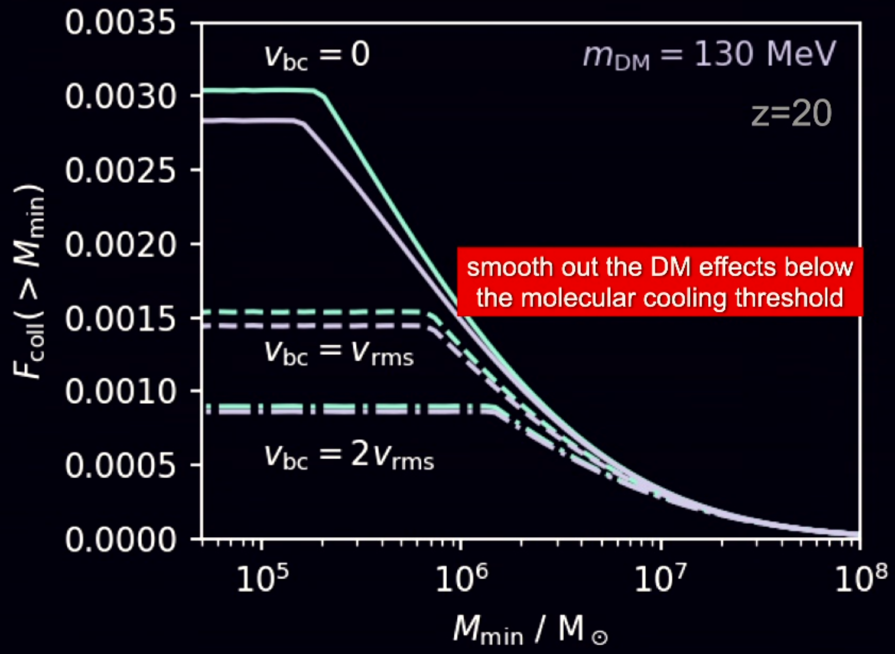
- For $M_{min} = 10^{-9} M_{\odot}$, the annihilation power (boost factor) is ~17% lower at z=40; ~6% lower at z=20.



Streaming Velocity

- Streaming velocity **reduce the first stars formation** by increasing the molecular cooling mass [Fialkov et al. (2012)]

- In regions with high streaming velocity, the effects of dark matter annihilation on star formation are subdominant.



21cm Signal at Cosmic Dawn

Spin Temperature

dark matter annihilation heating, ionization directly
star formation, Lyman-alpha coupling

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_k^{-1}}{1 + x_c + x_\alpha}$$

WF coupling coefficient

Collisional coupling coefficient

Star Formation

baryon collapse
streaming velocity

$$F_{\rm coll}(m_{DM}, v_{bc}) = \int_{M_{\rm min}} M \frac{dn}{dM} \frac{f_{gas}}{\rho_b} f_* \, dM$$

molecular cooling

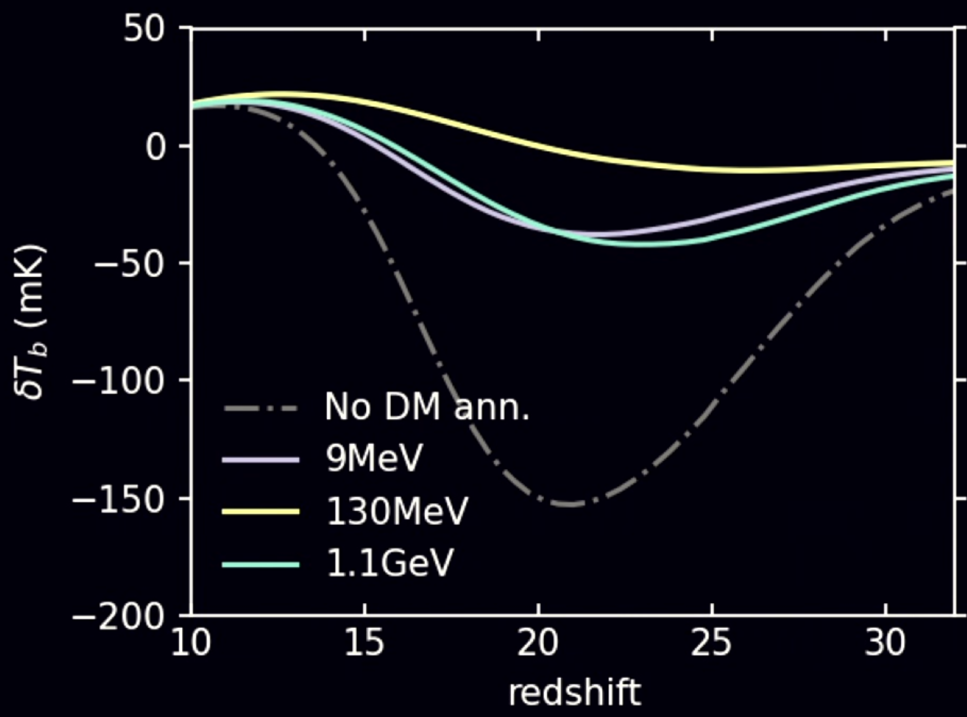
Results

Calculate in *21cmvFAST* code

Semi-Numerical Simulation

Include Molecular Cooling Halos

With dark matter annihilation {heating, ionization}



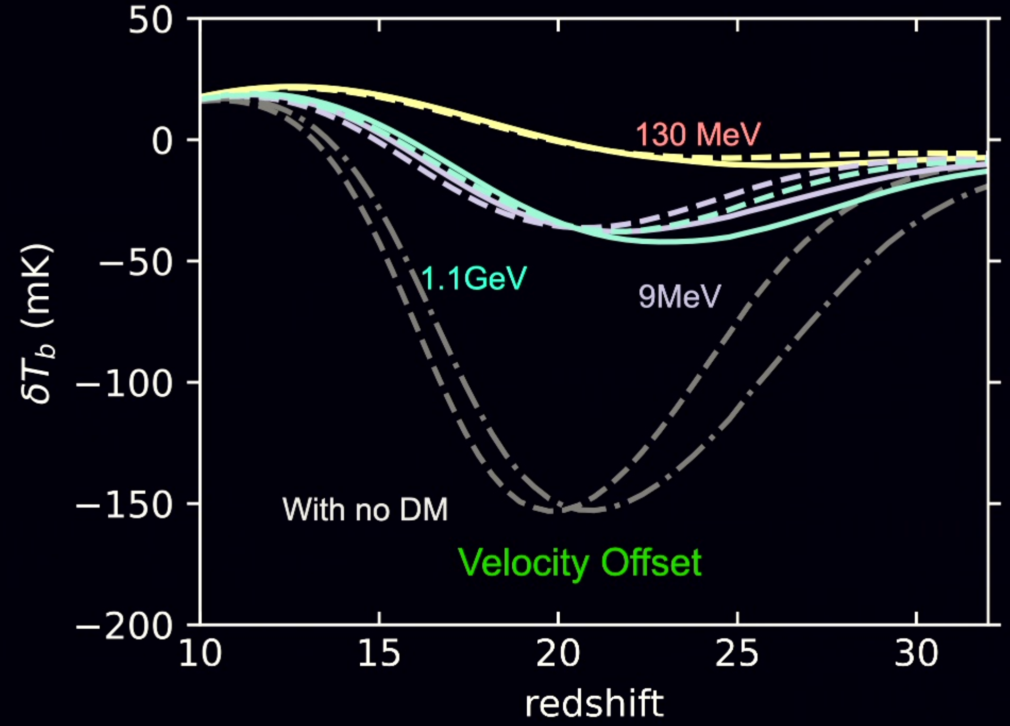
Results

Calculate in *21cmvFAST* code

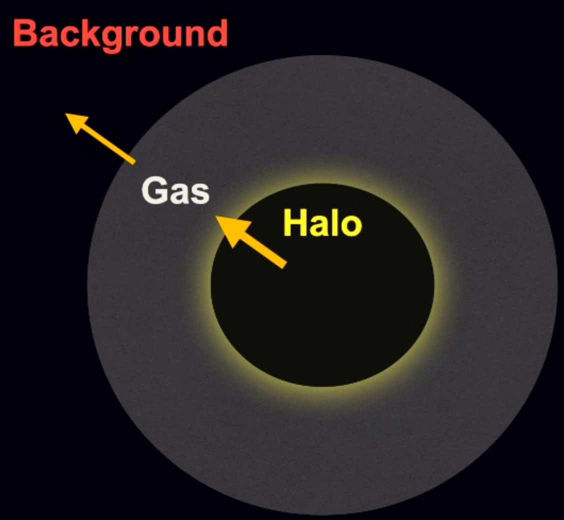
Semi-Numerical Simulation

Include Molecular Cooling Halos

With dark matter annihilation {heating, ionization}, adjusted for molecular cooling and streaming velocity



Local Halo Effect



- DM feedback does alters the gas properties and the chemical cooling [Ripamonti et al. (2010)]
- DM annihilation deposits sufficient energy into gas before it escapes, which can influence structure formation in high-redshift, small halos. [Schon et al. (2015, 2017)]

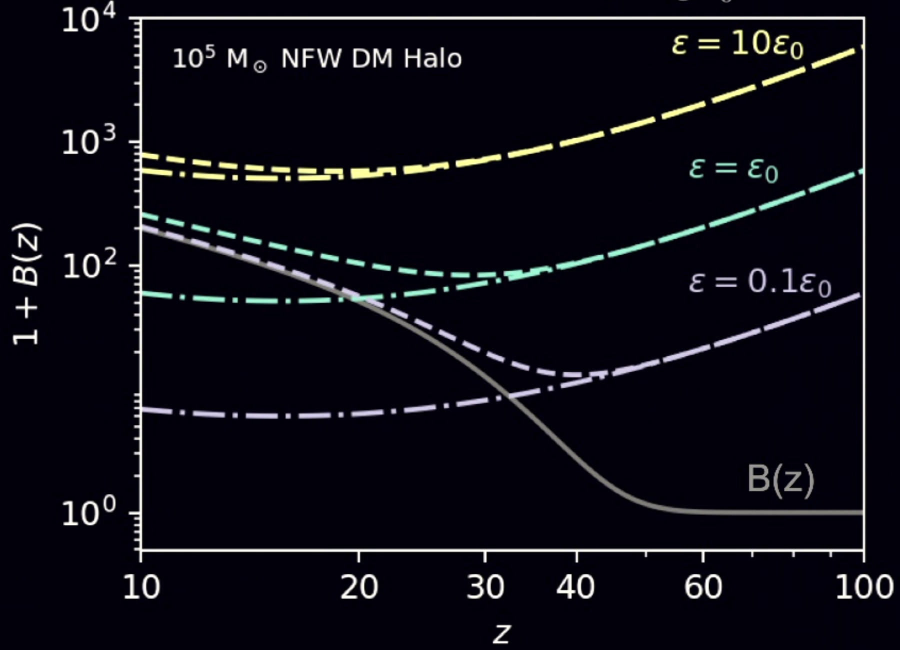
Local Halo Effect

- Local Boost Factor

$$\left.\frac{dE}{dVdt}\right|_{struct} = B(z)\left.\frac{dE}{dVdt}\right|_{smooth}$$

$$\left.\frac{dE}{dVdt}\right|_{local} = \boxed{B_{local}(z)}\left.\frac{dE}{dVdt}\right|_{smooth}$$

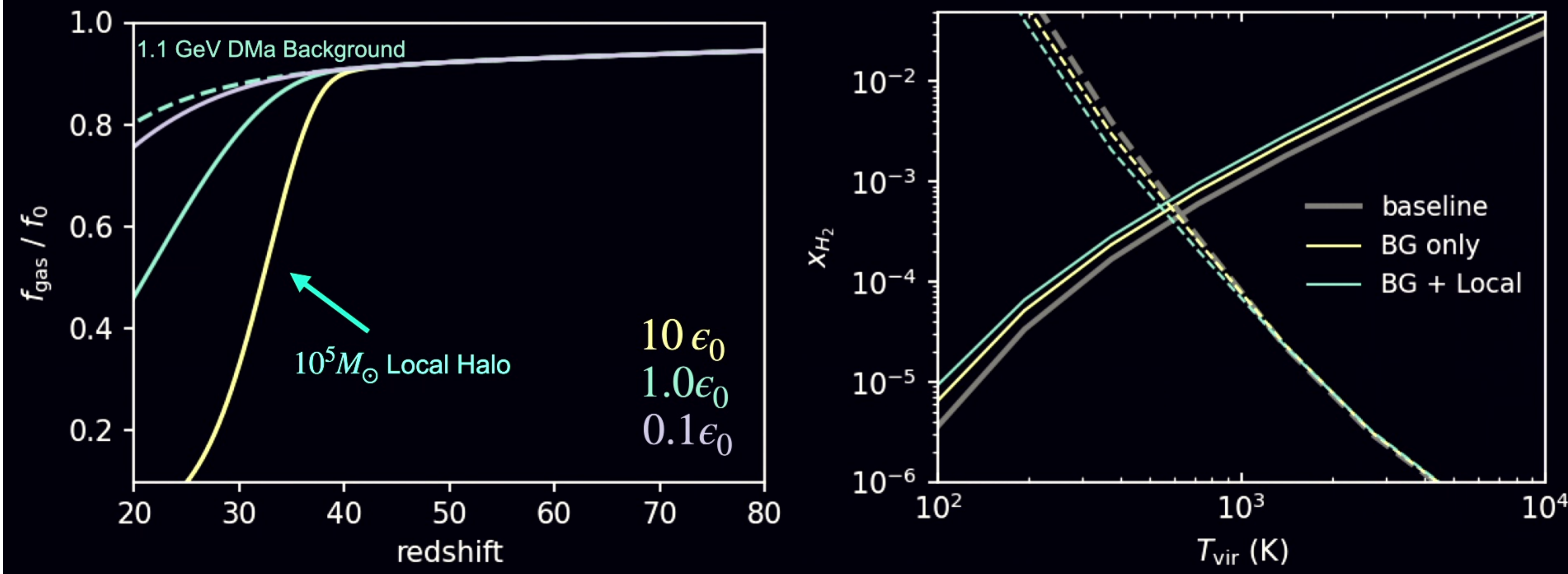
"Halo efficiency" $\log \epsilon_0 = -64$



Local Halo Effect

on baryon collapse

on cooling chemistry



Summary

- We simulate the 21cm signal to assess the effects of dark matter (DM) annihilation on first stars formation, incorporating baryon collapse, molecular cooling, and streaming velocity.
  - DM annihilation can alter the universe's thermal history at cosmic dawn.
  - It could impact the formation of the first stars by affecting baryon collapse and molecular cooling in early, small halos.
- Furthermore, annihilation in local halo have the potential to suppress the local star formation history, leading to further fluctuations in the 21cm signal.