Exotic Energy Injection in the Early Universe

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Fermilab Theory Seminar
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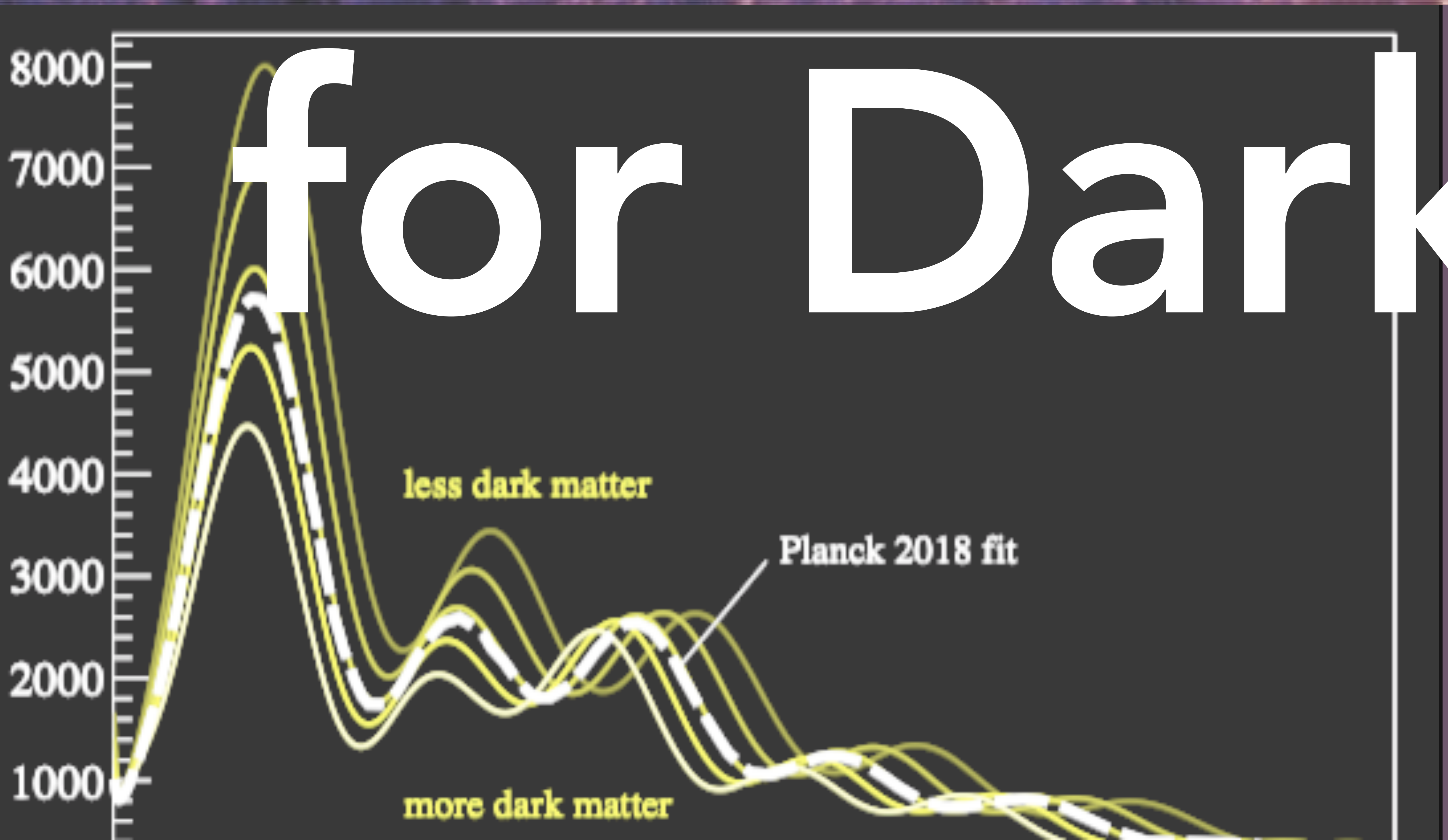
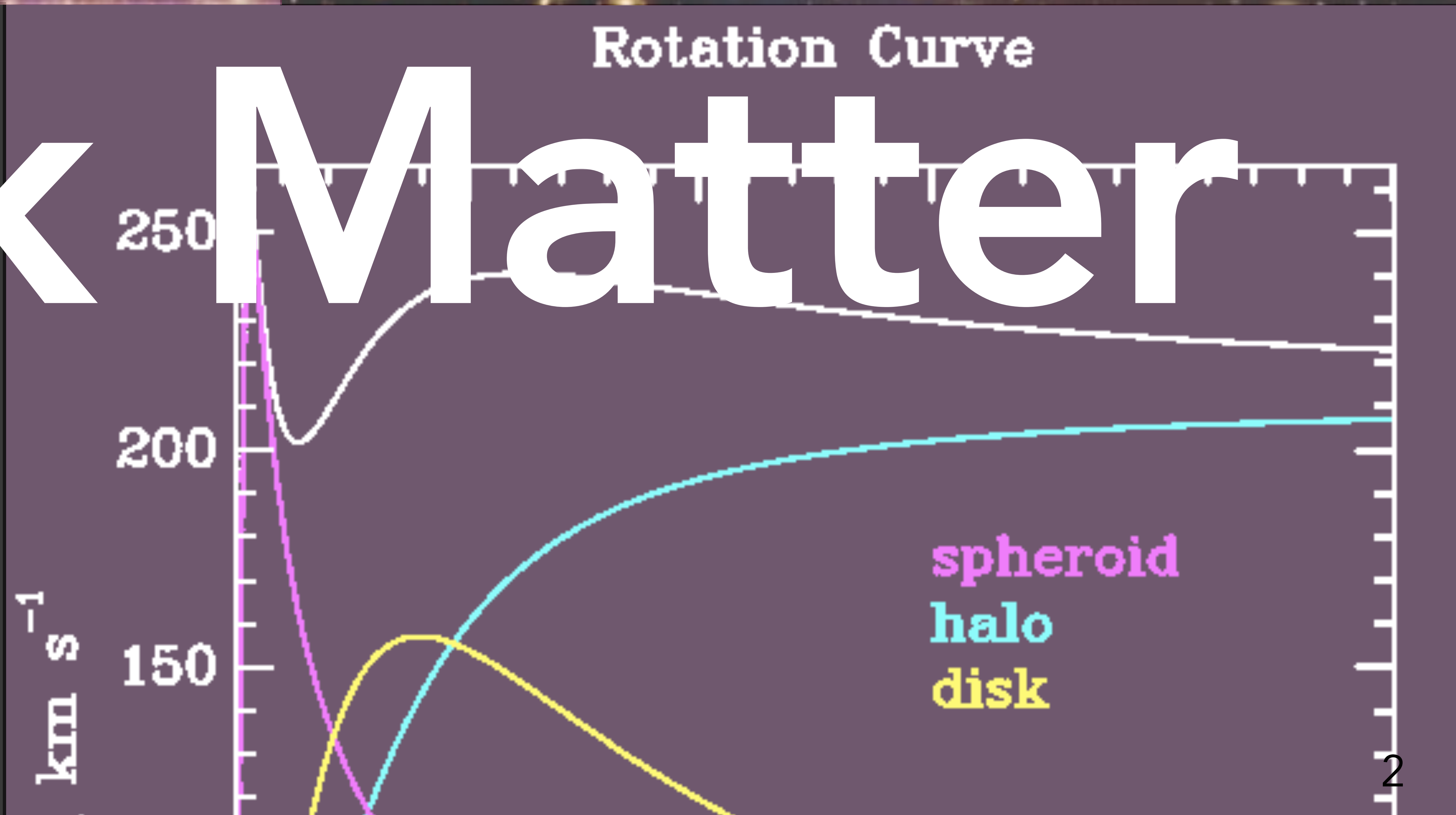
Lots of Evidence for Dark Matter





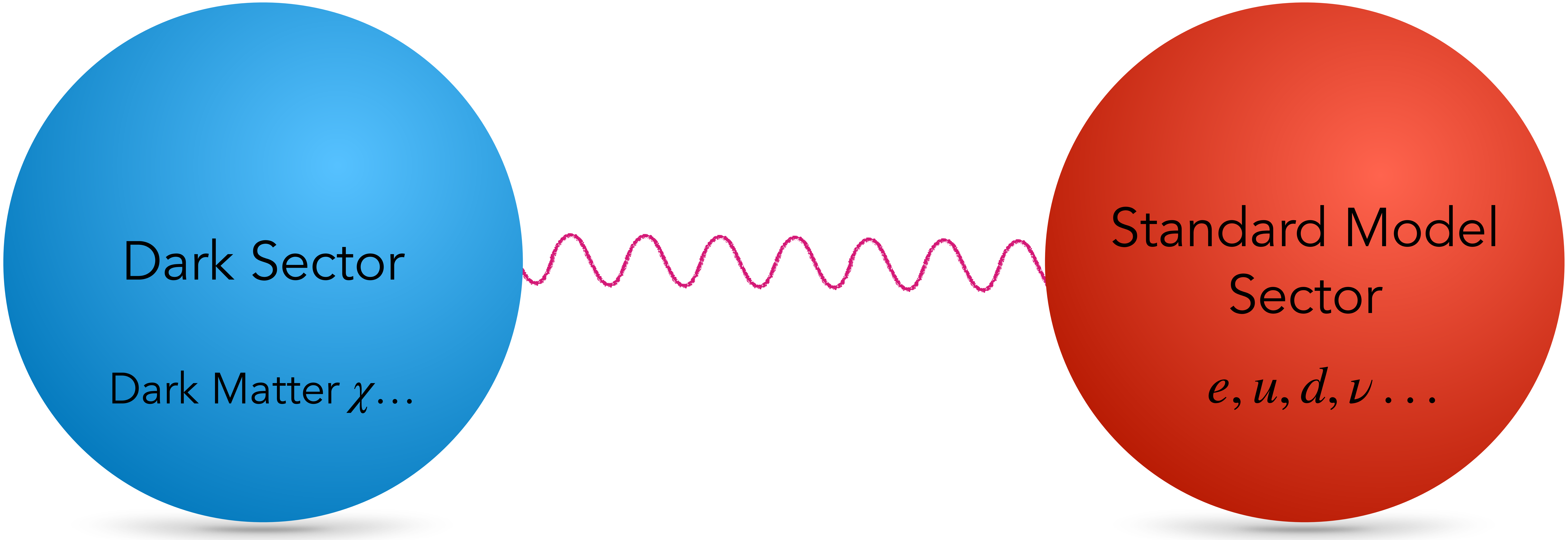
... but what is it?

image credit: Sandbox Studio, Chicago

Can we be agnostic, and still learn something about DM?

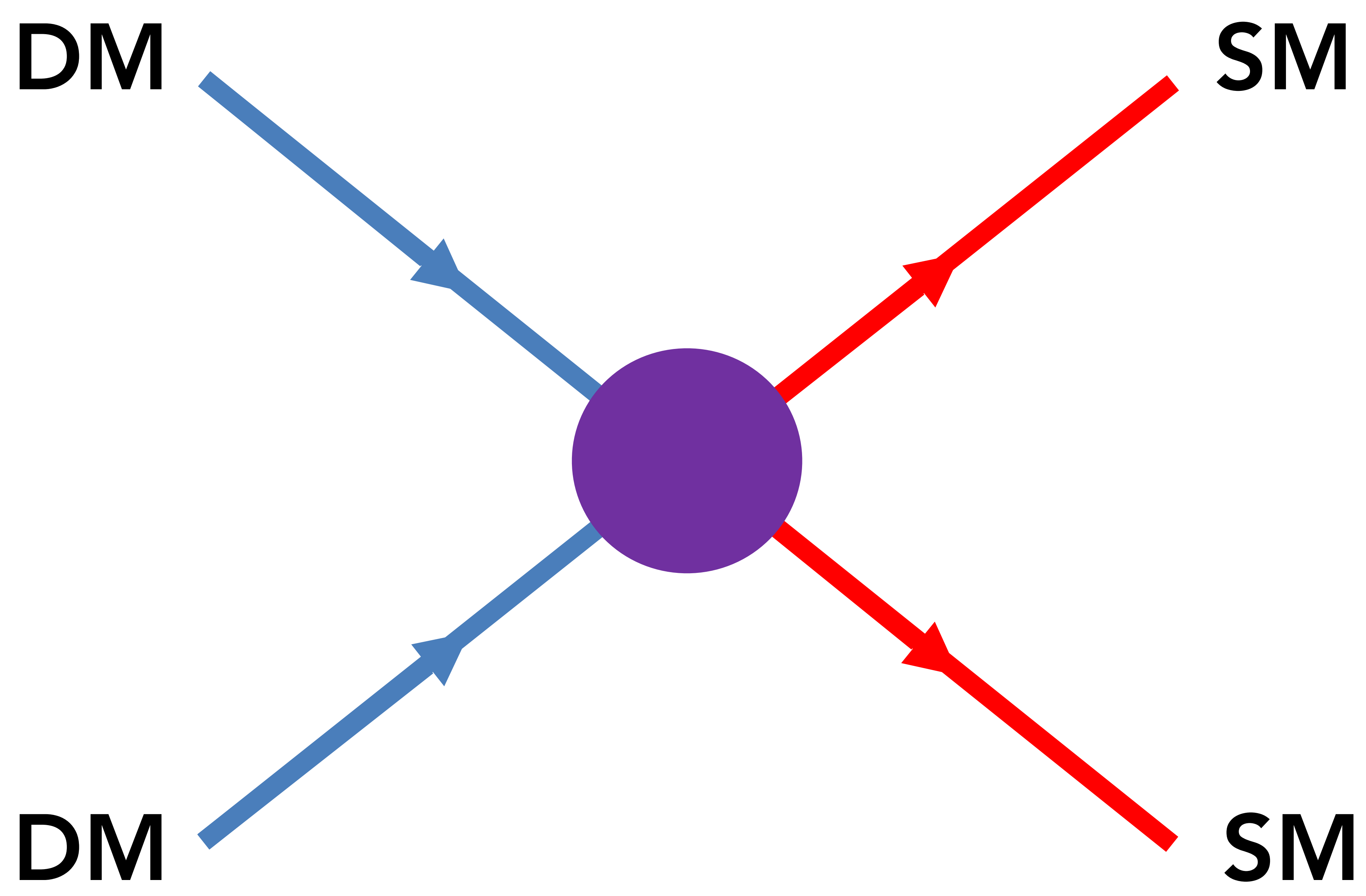
image credit: Sandbox Studio, Chicago

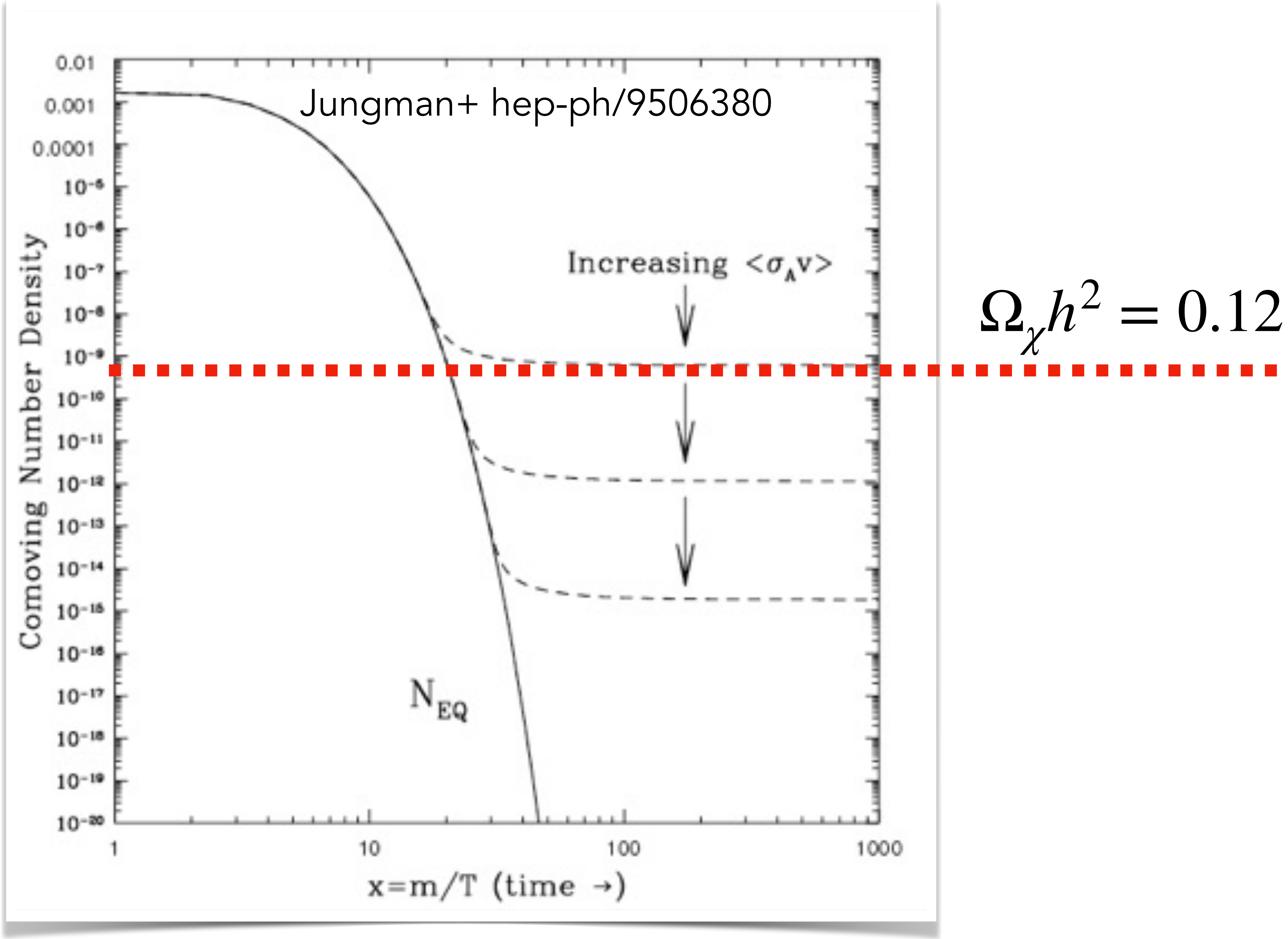
Dark Matter and the Standard Model



Nongravitational interaction between Standard Model and DM: **experimentally testable** and **theoretically well-motivated**.

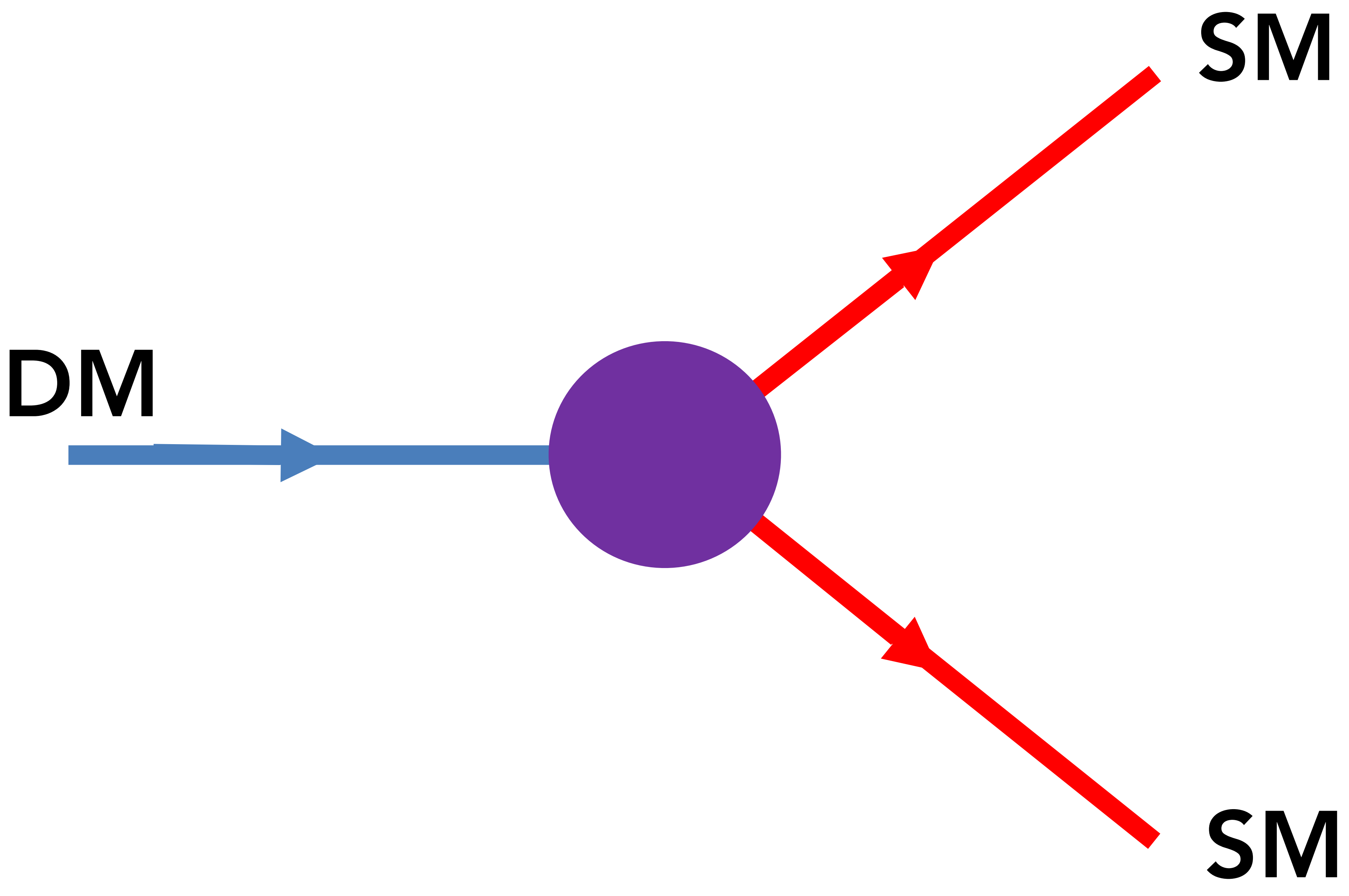
Dark Matter Annihilation

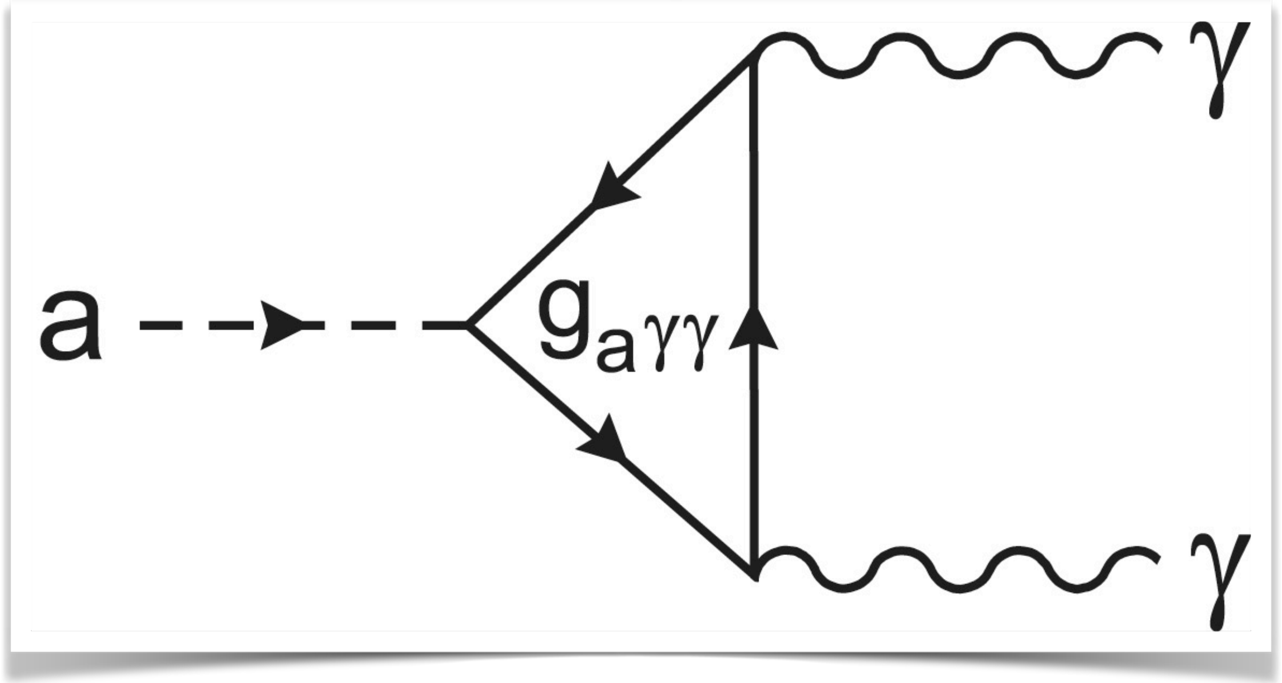




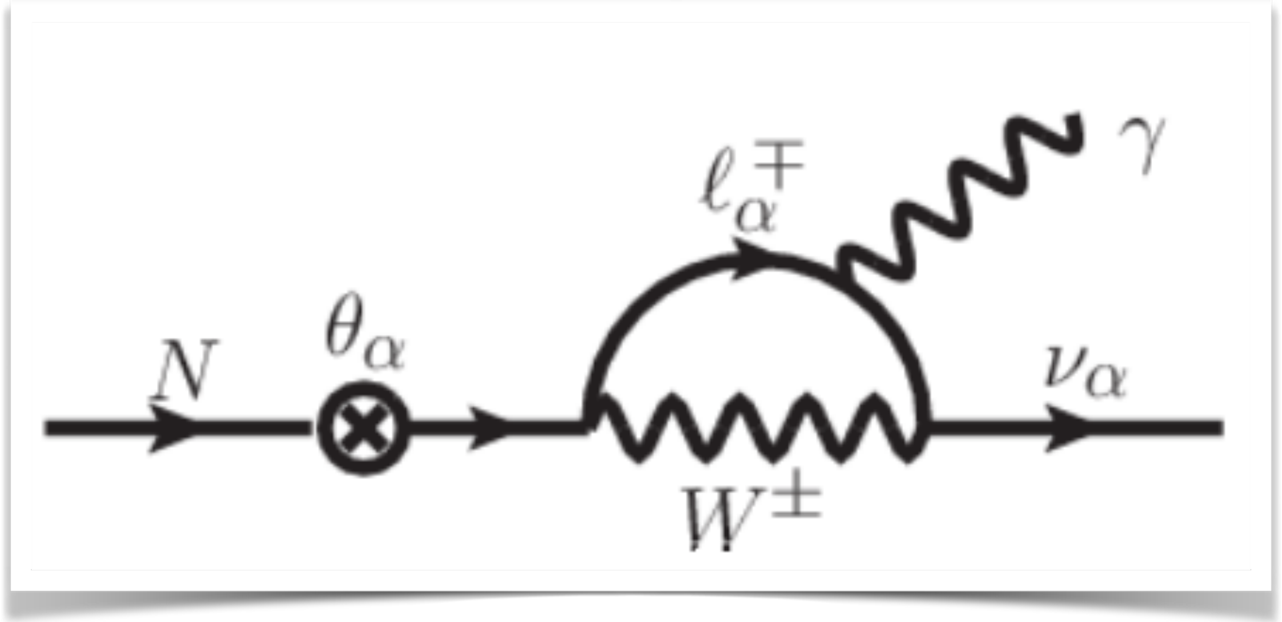
Motivated by ideas for **dark matter production** in the early universe.

Dark Matter Decay





QCD Axion
Axion-like Particles



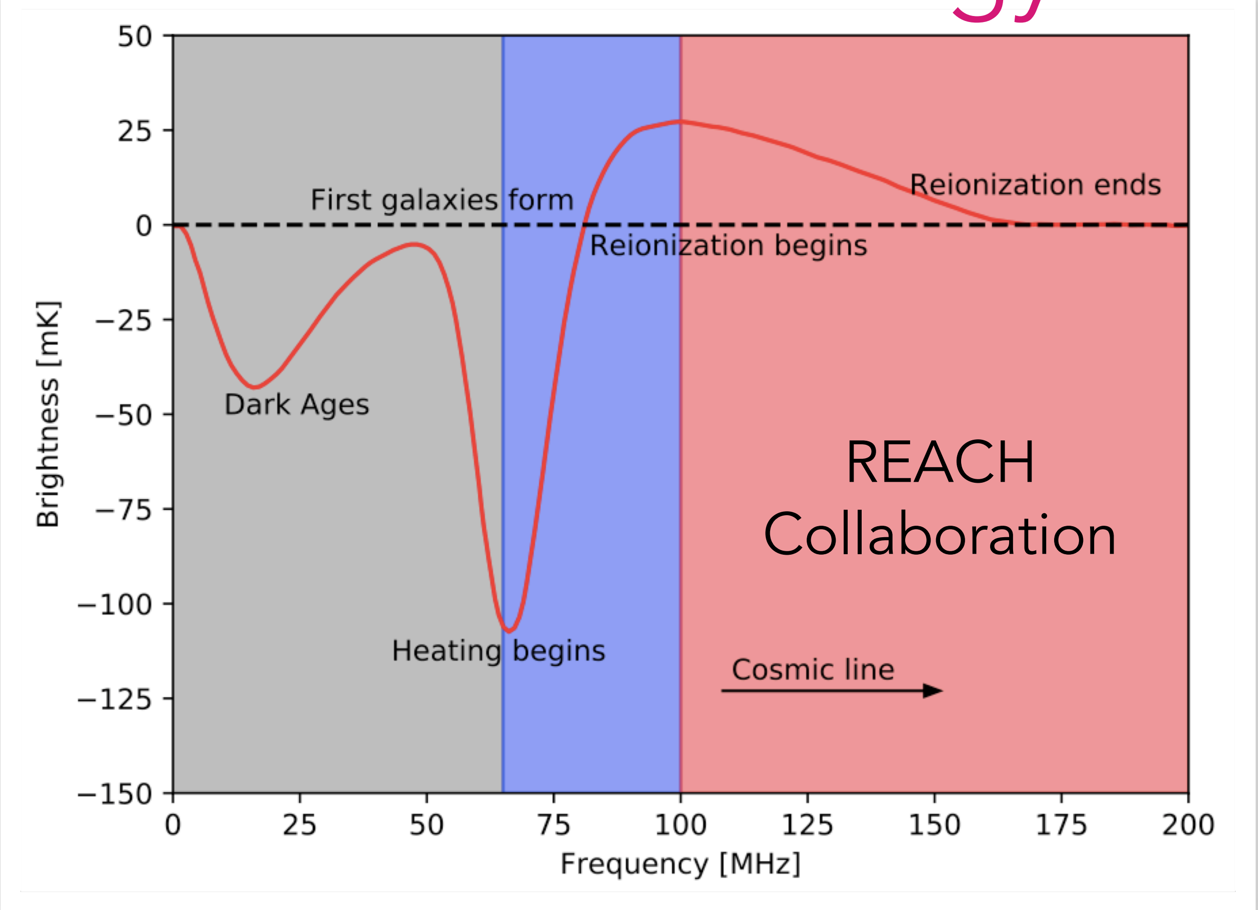
Sterile Neutrinos

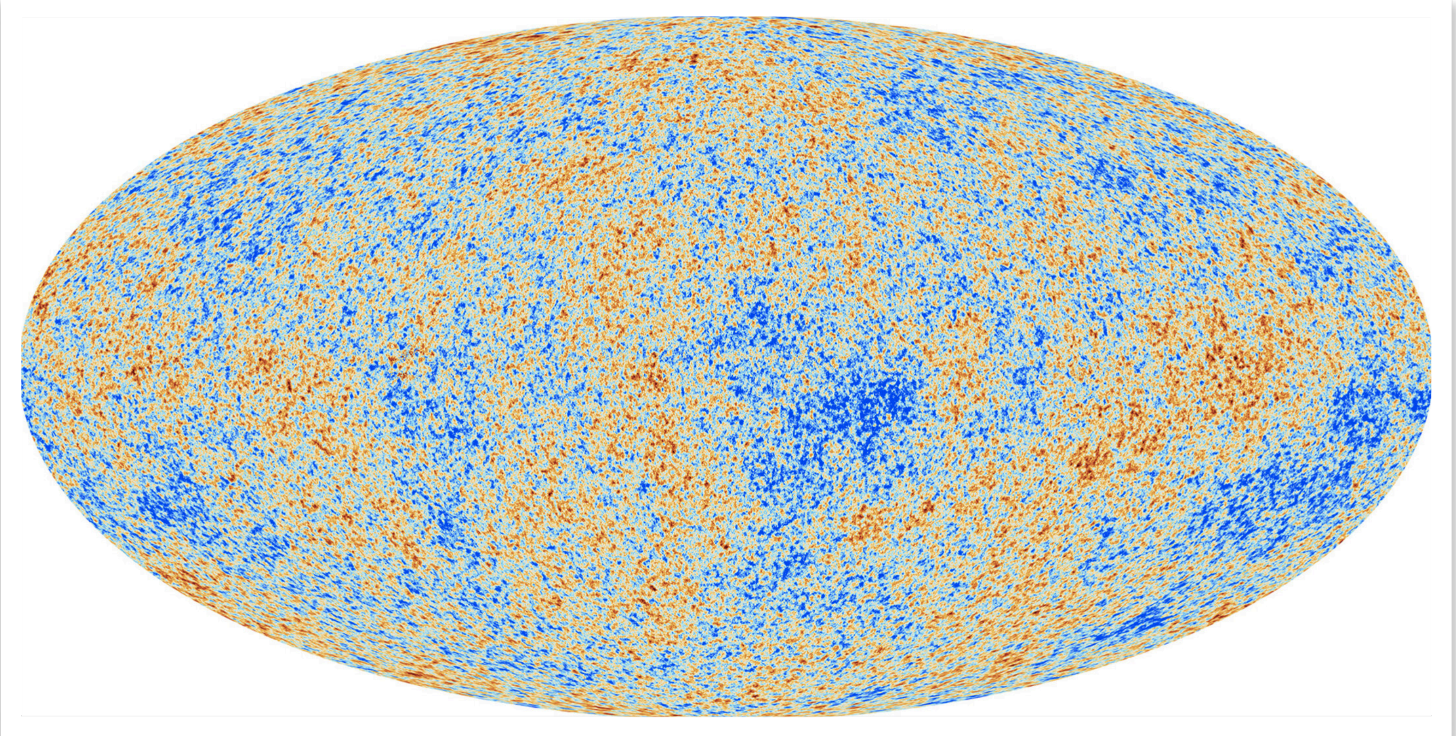
DM is *cosmologically* stable, but **small couplings to the SM** can lead to decays if DM not protected by symmetry.

How do we look for the SM products?

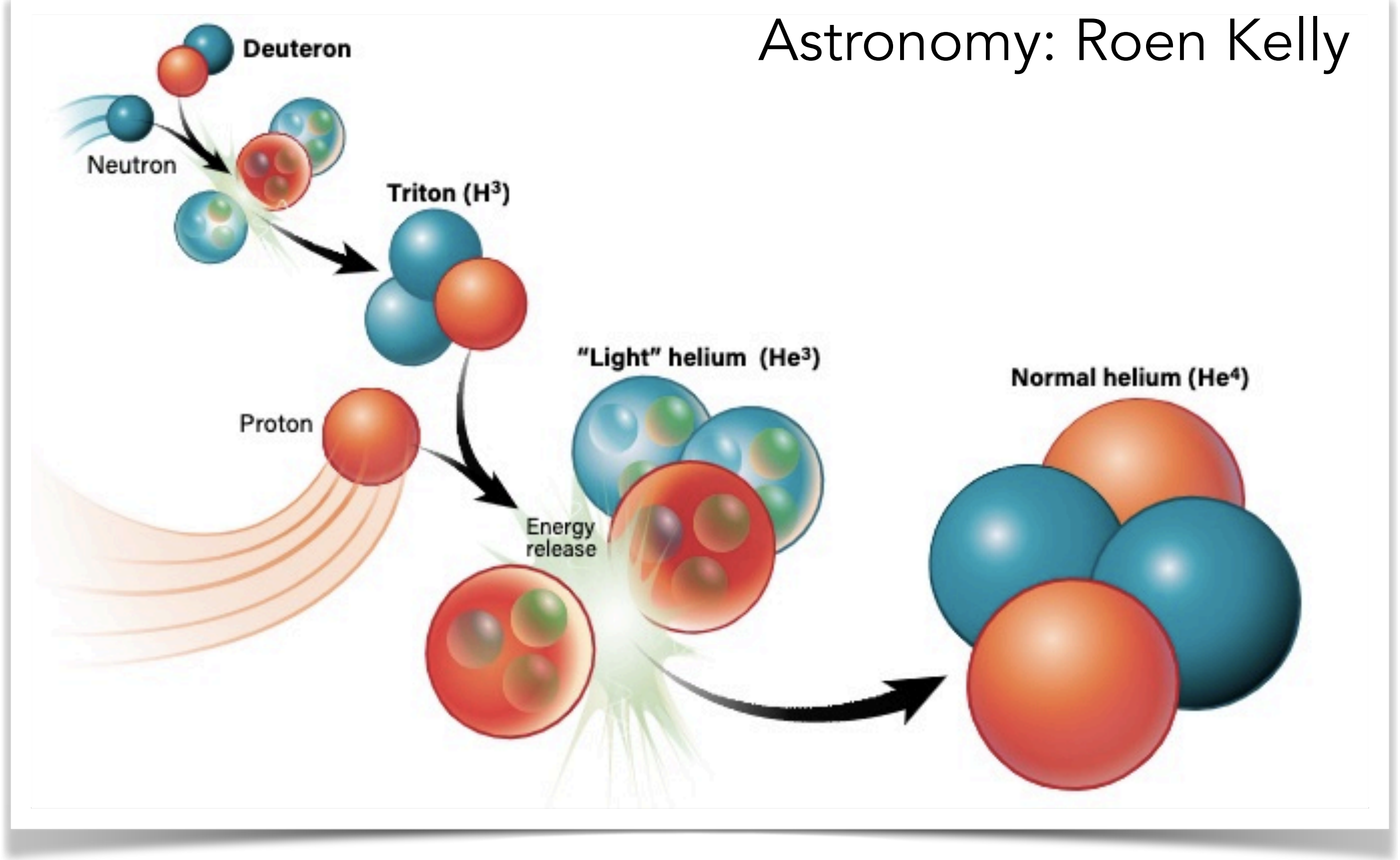
Cosmology

21-cm Cosmology



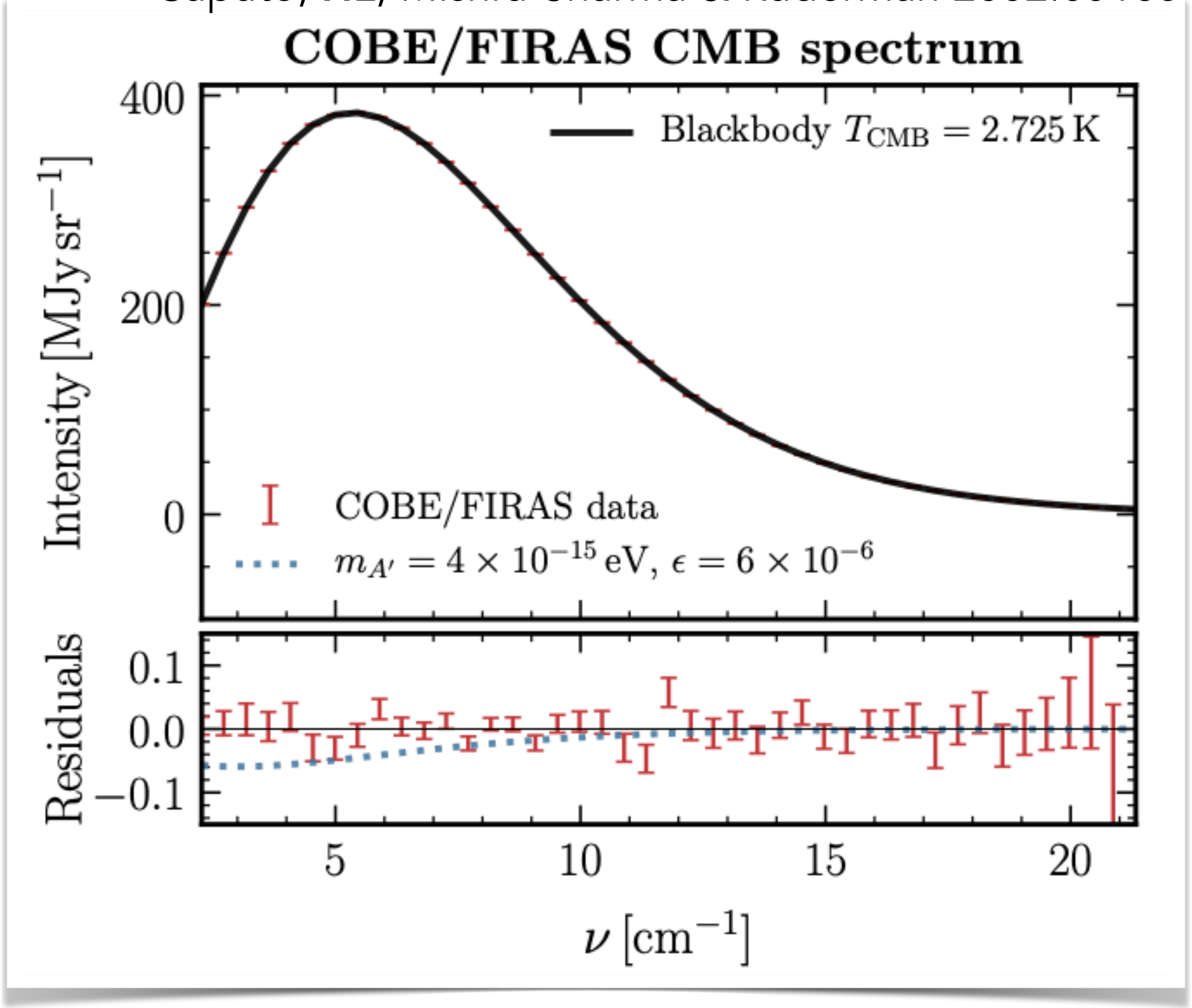


Cosmic Microwave Background (CMB) Power Spectrum



Big Bang Nucleosynthesis

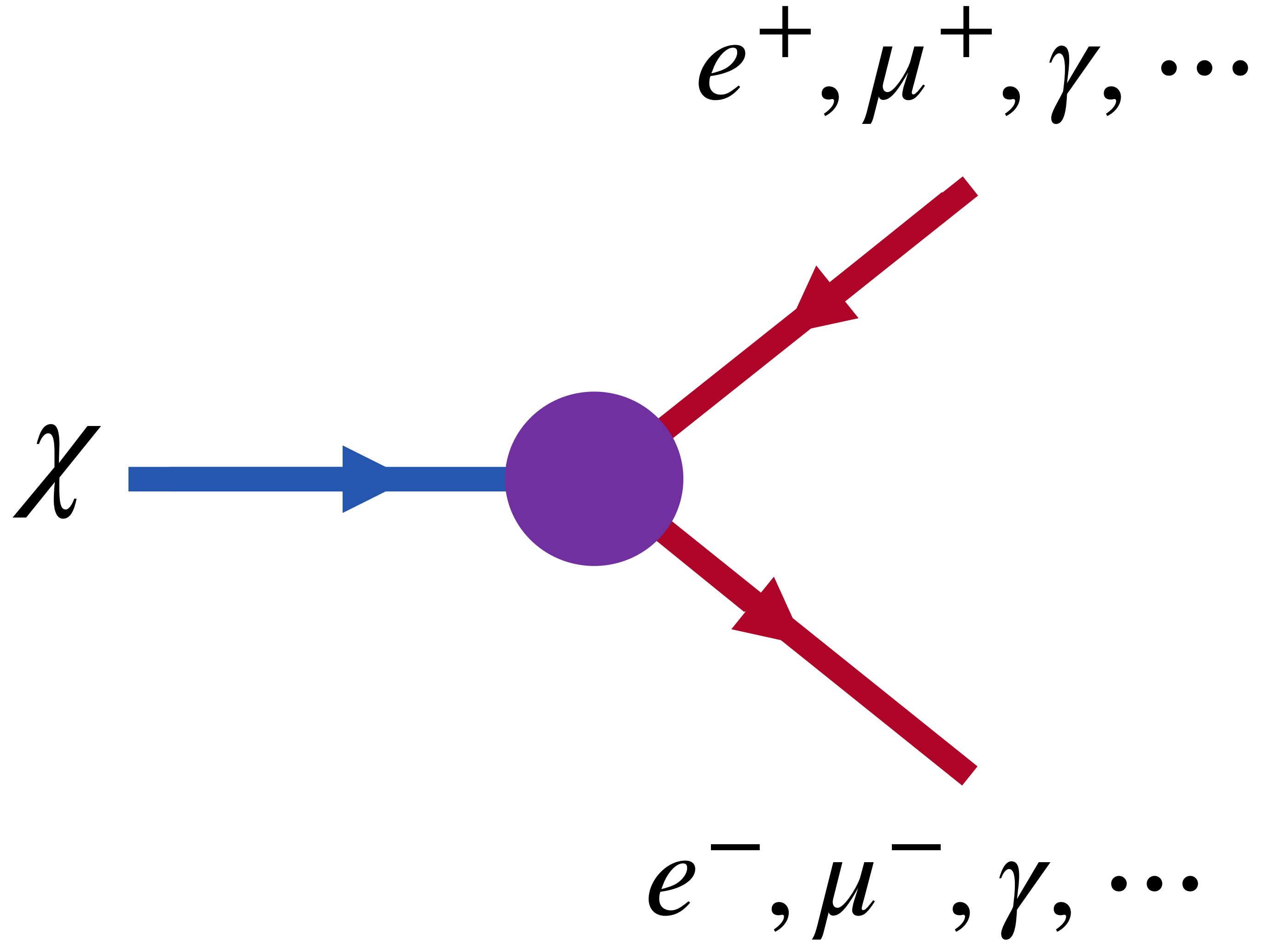
Caputo, **HL**, Mishra-Sharma & Ruderman 2002.05165



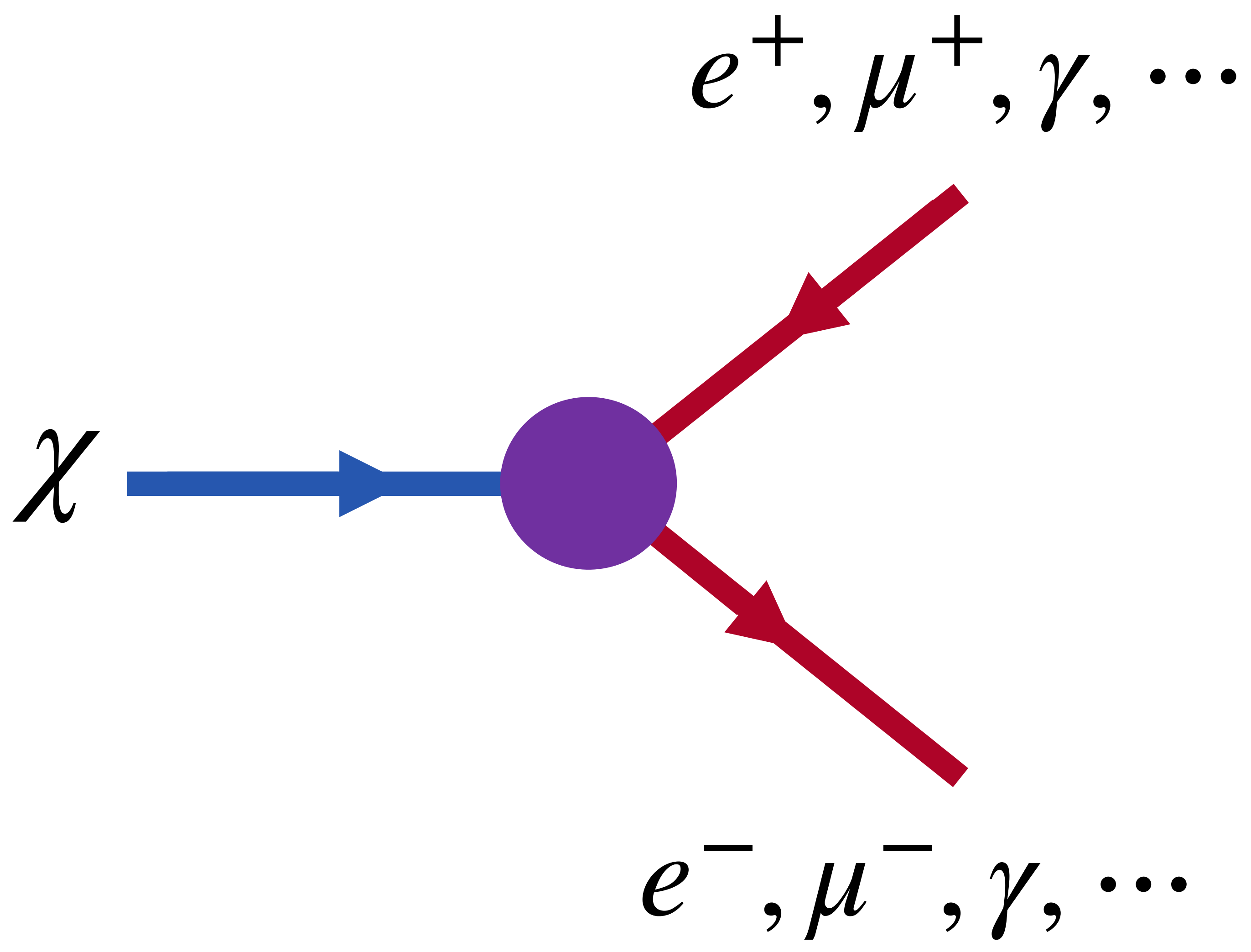
CMB Blackbody Spectrum

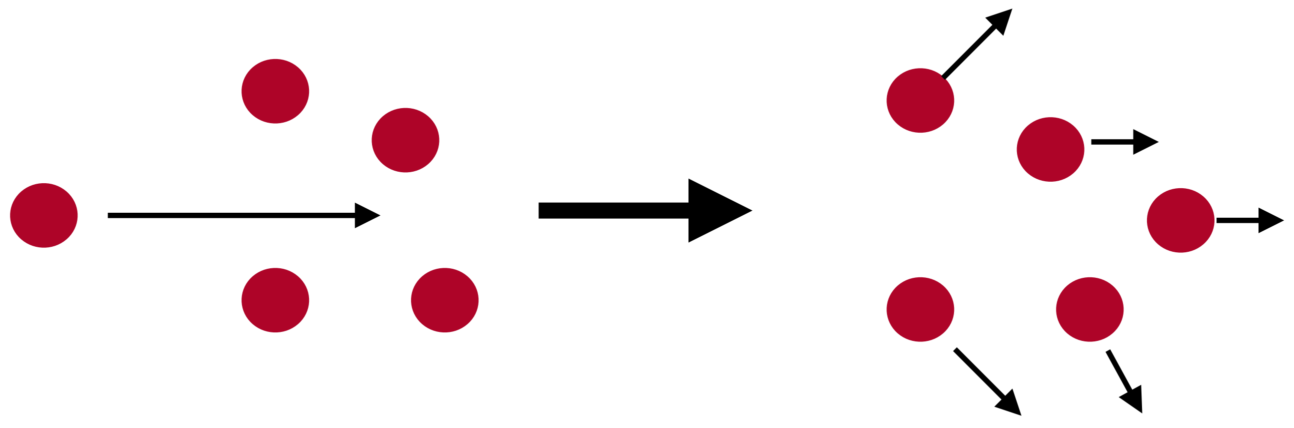
Cosmological probes highly effective: **high densities**, **long duration**, **pristine** environments, **precision** measurements.

Energy Injection

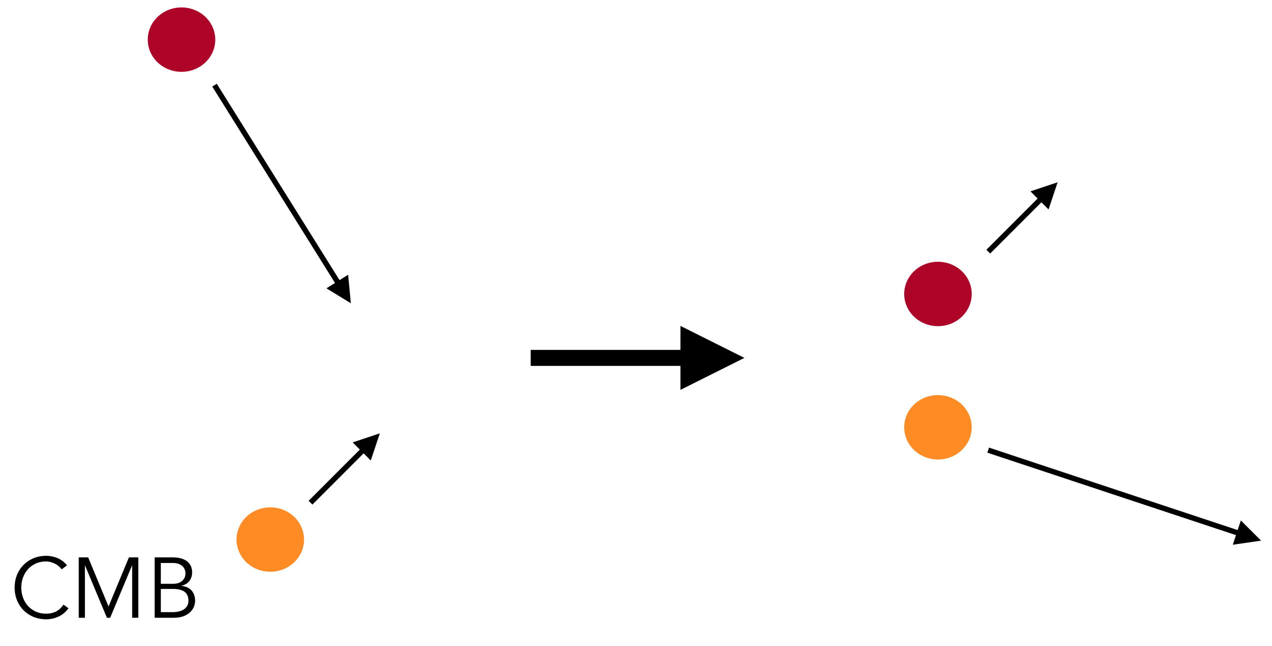


Energy Deposition

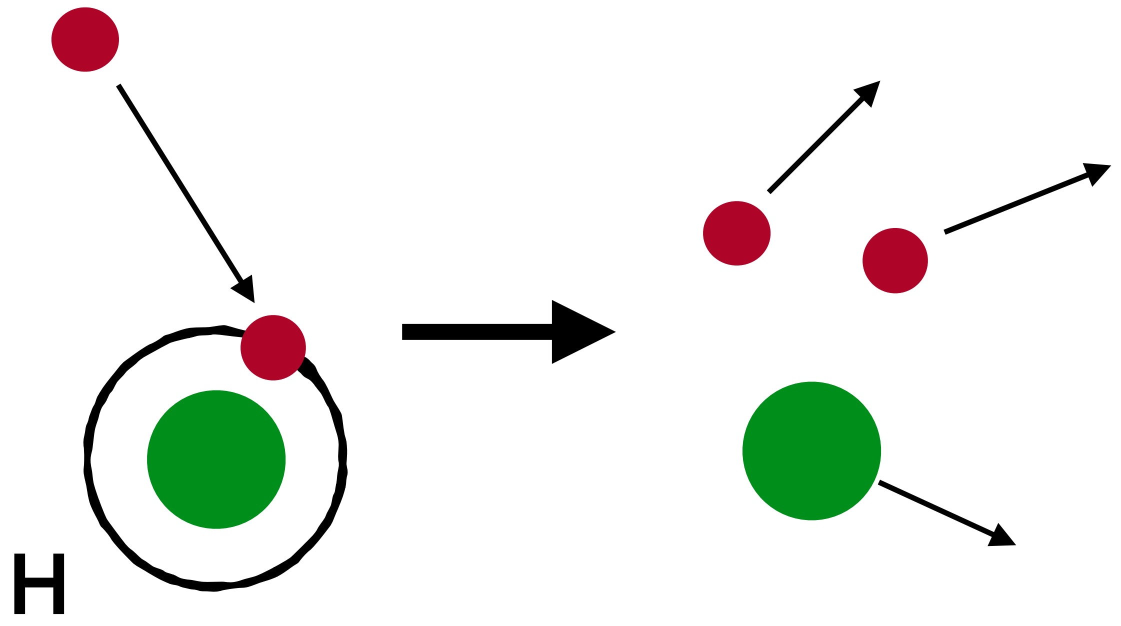




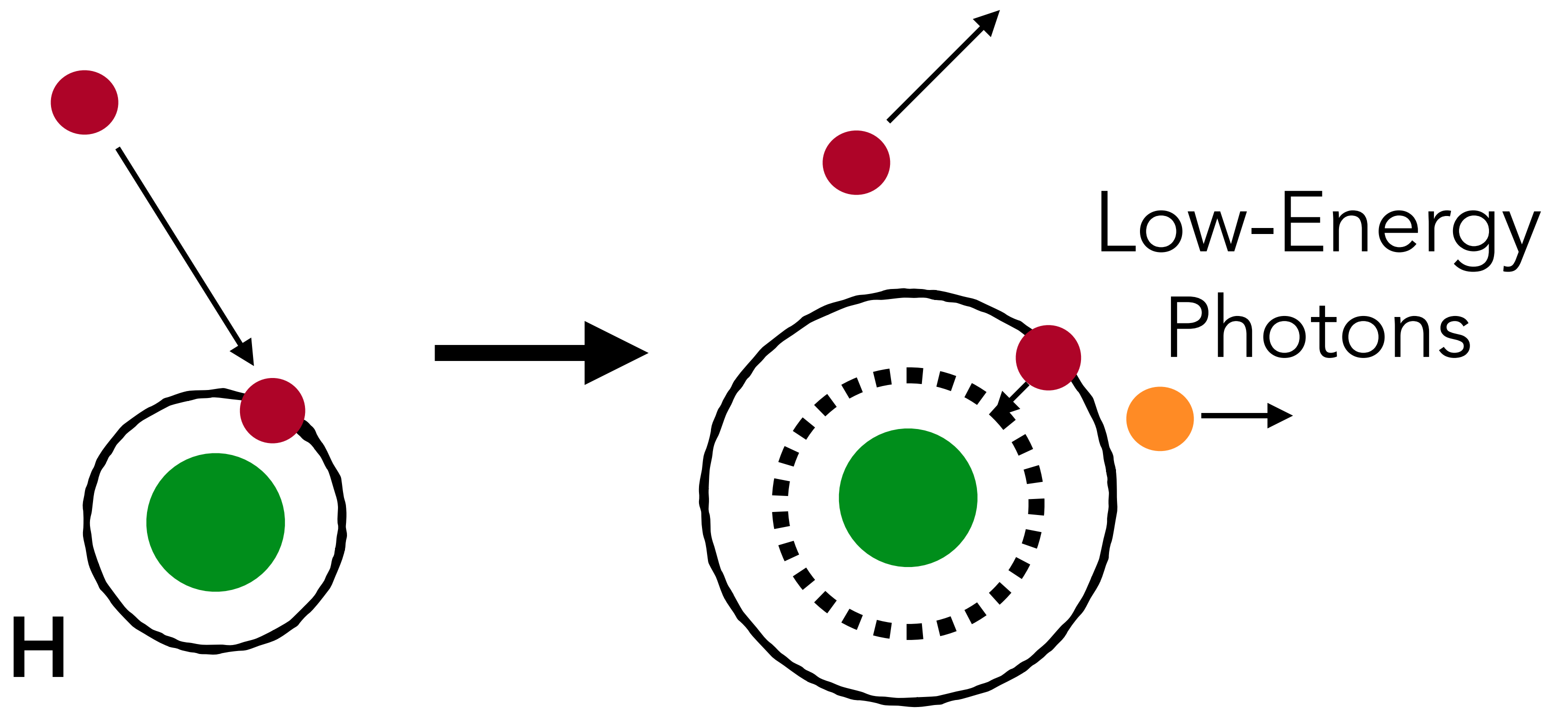
Heating



Inverse Compton Scattering



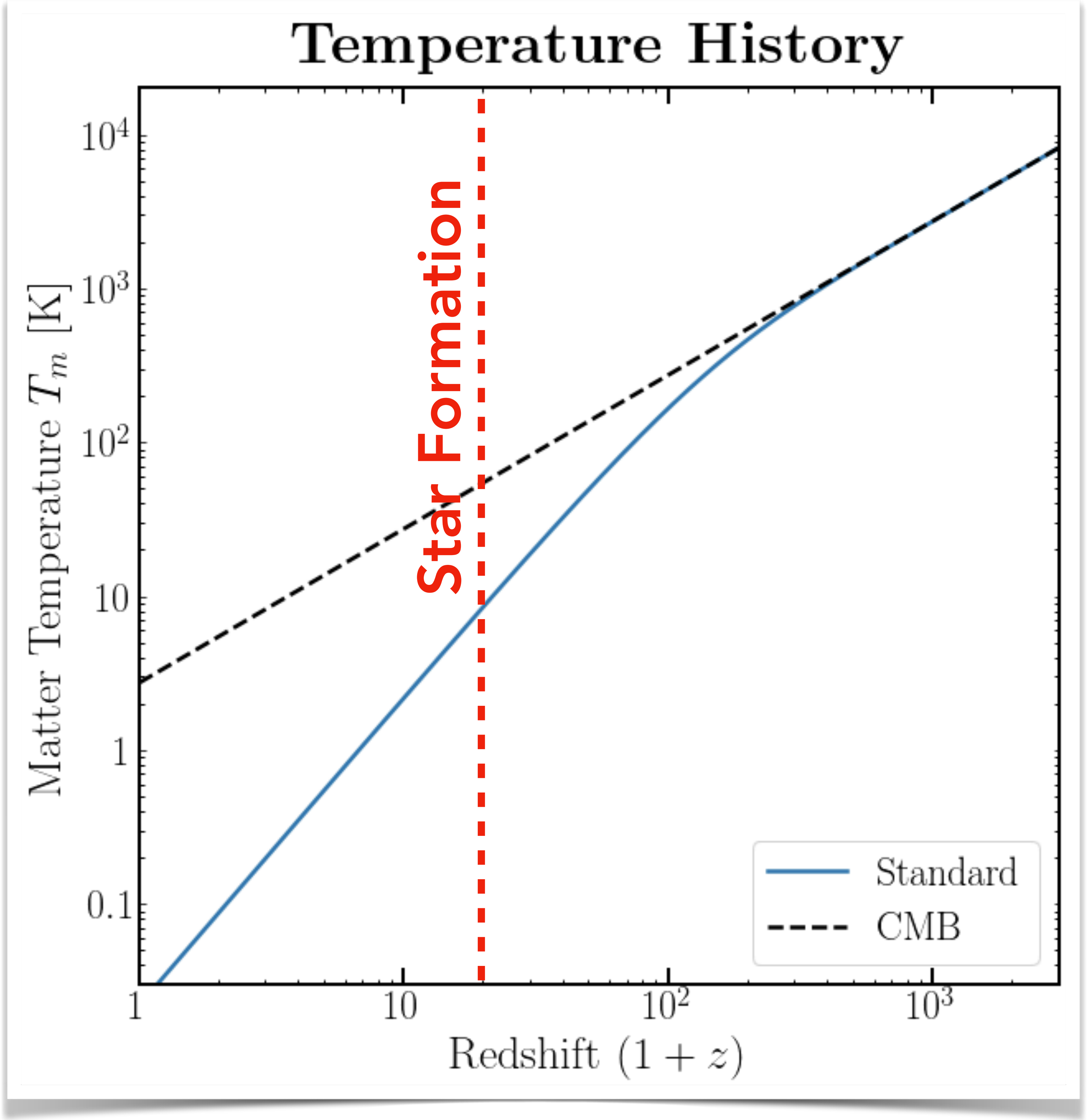
Ionization

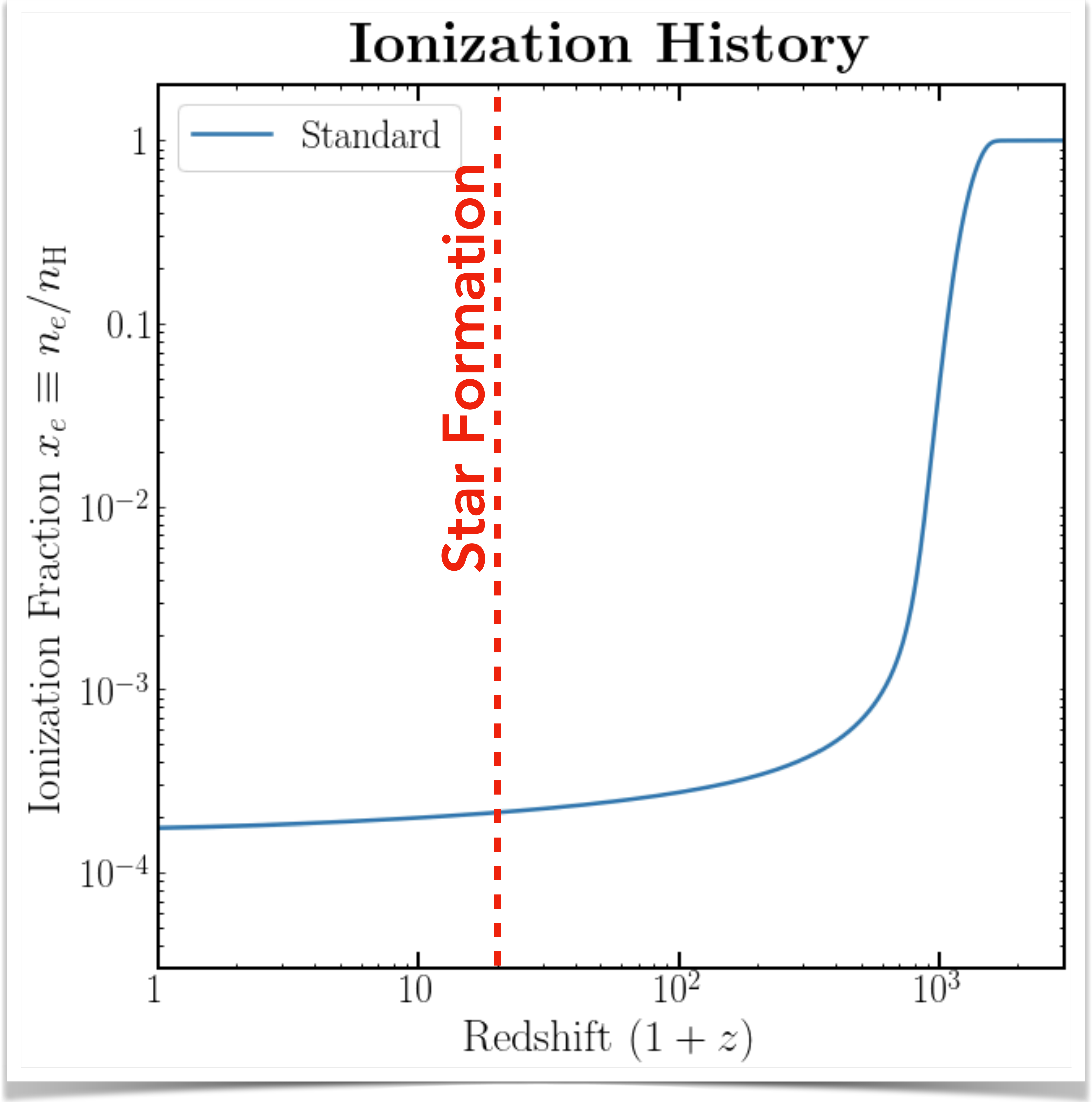


Excitation

How does this affect the Universe after recombination?

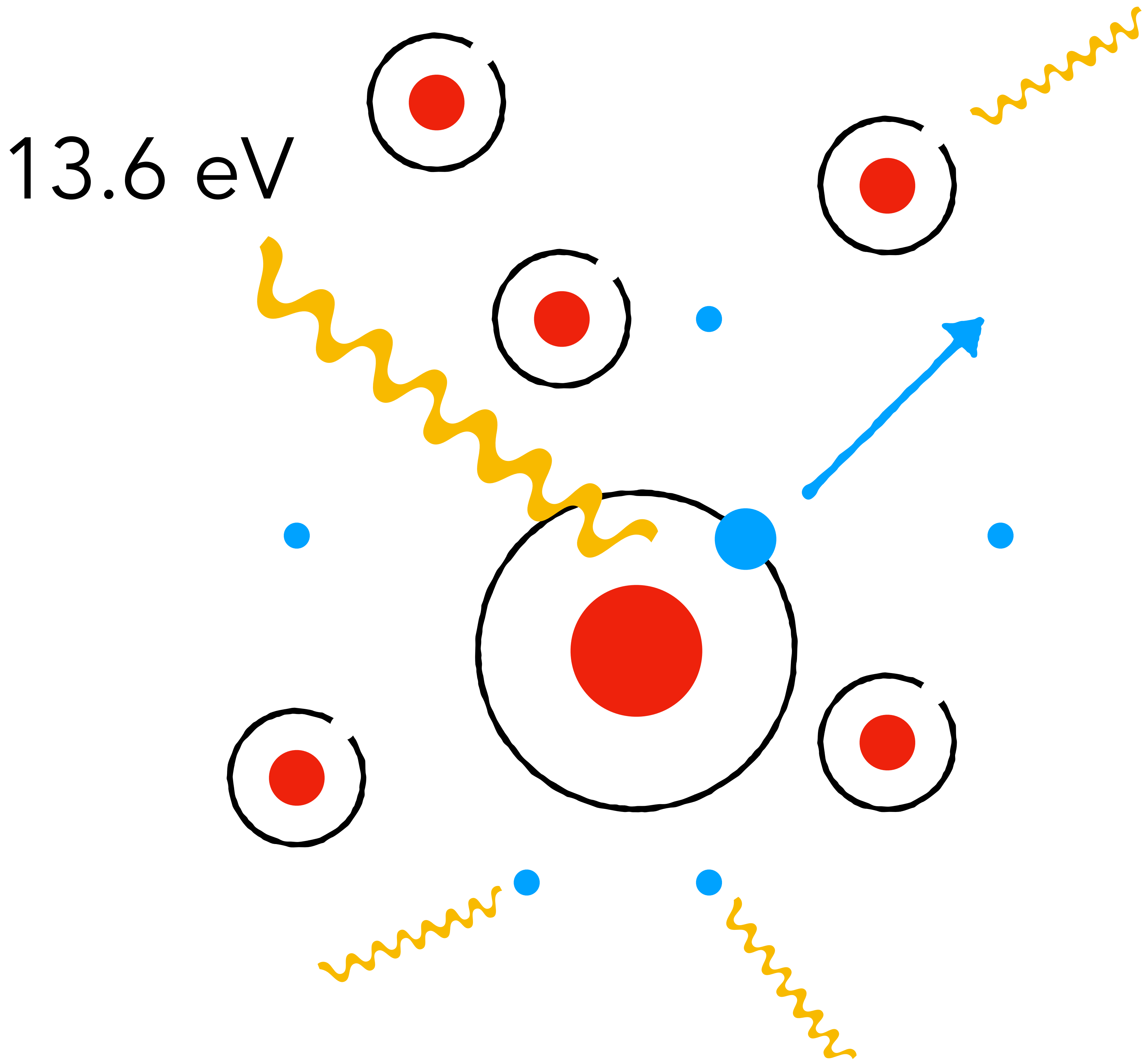
Standard Histories

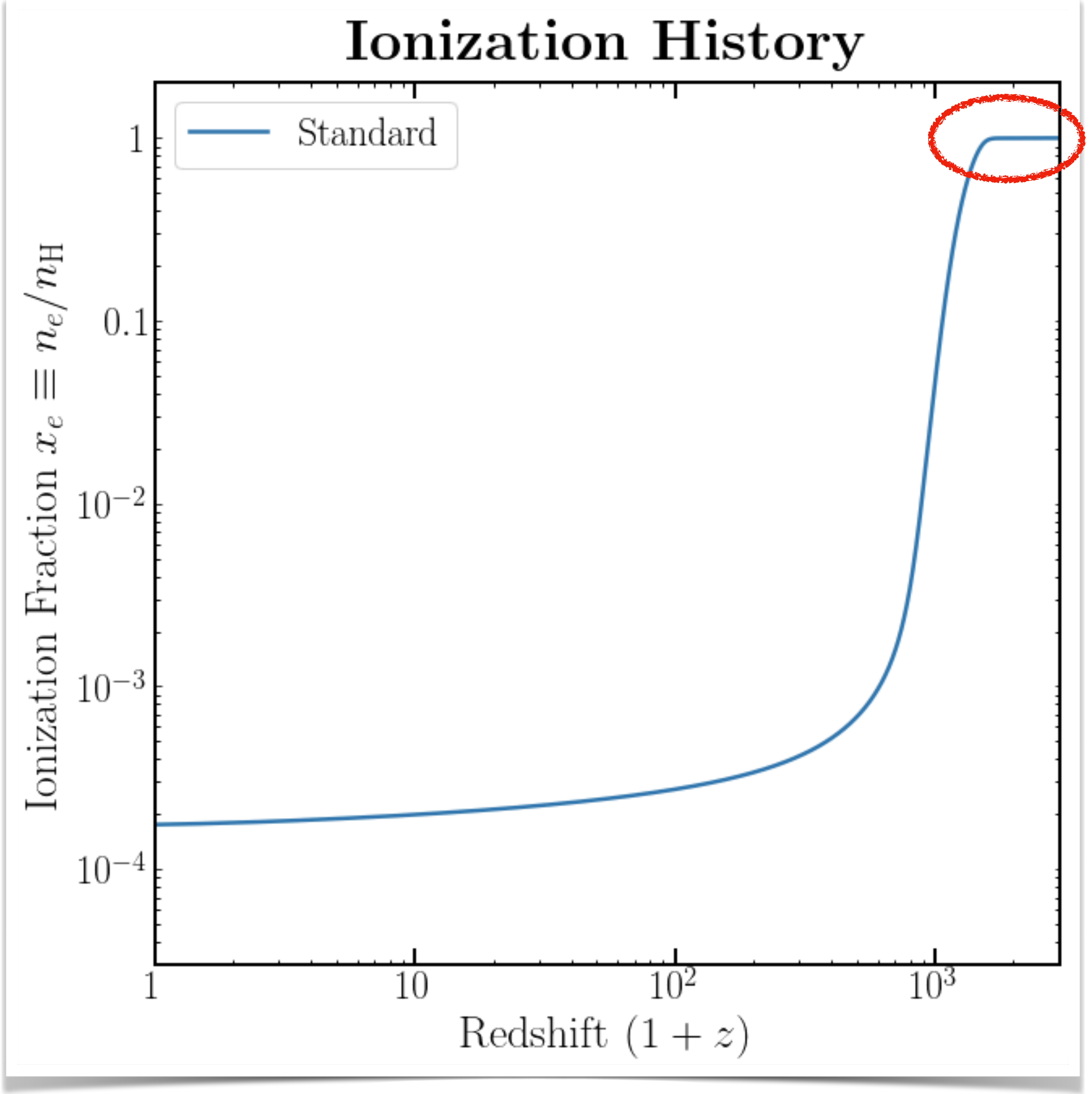




Standard histories very well-understood before star formation:
Believed to be understood at **0.1% precision**.

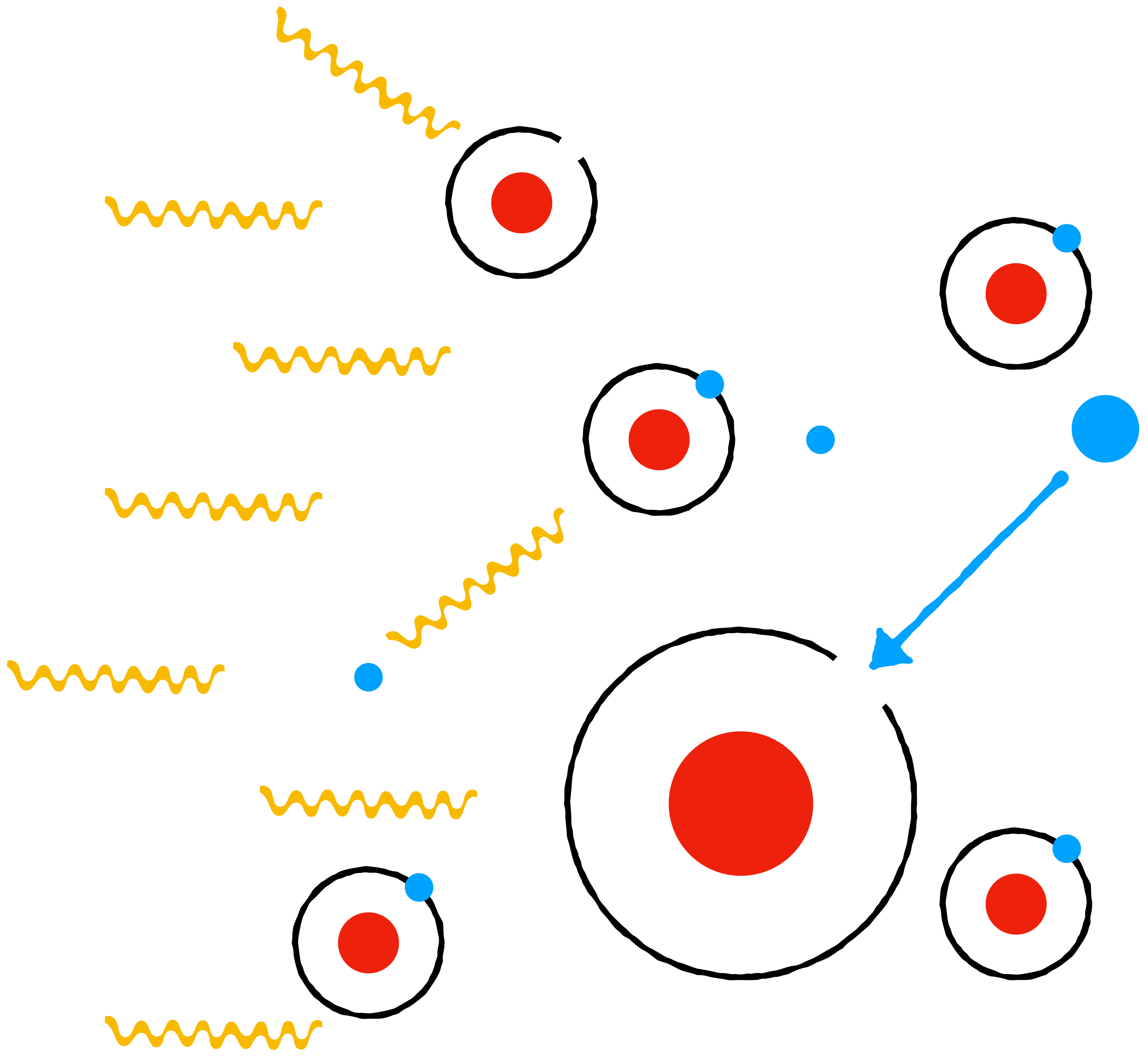
Recombination

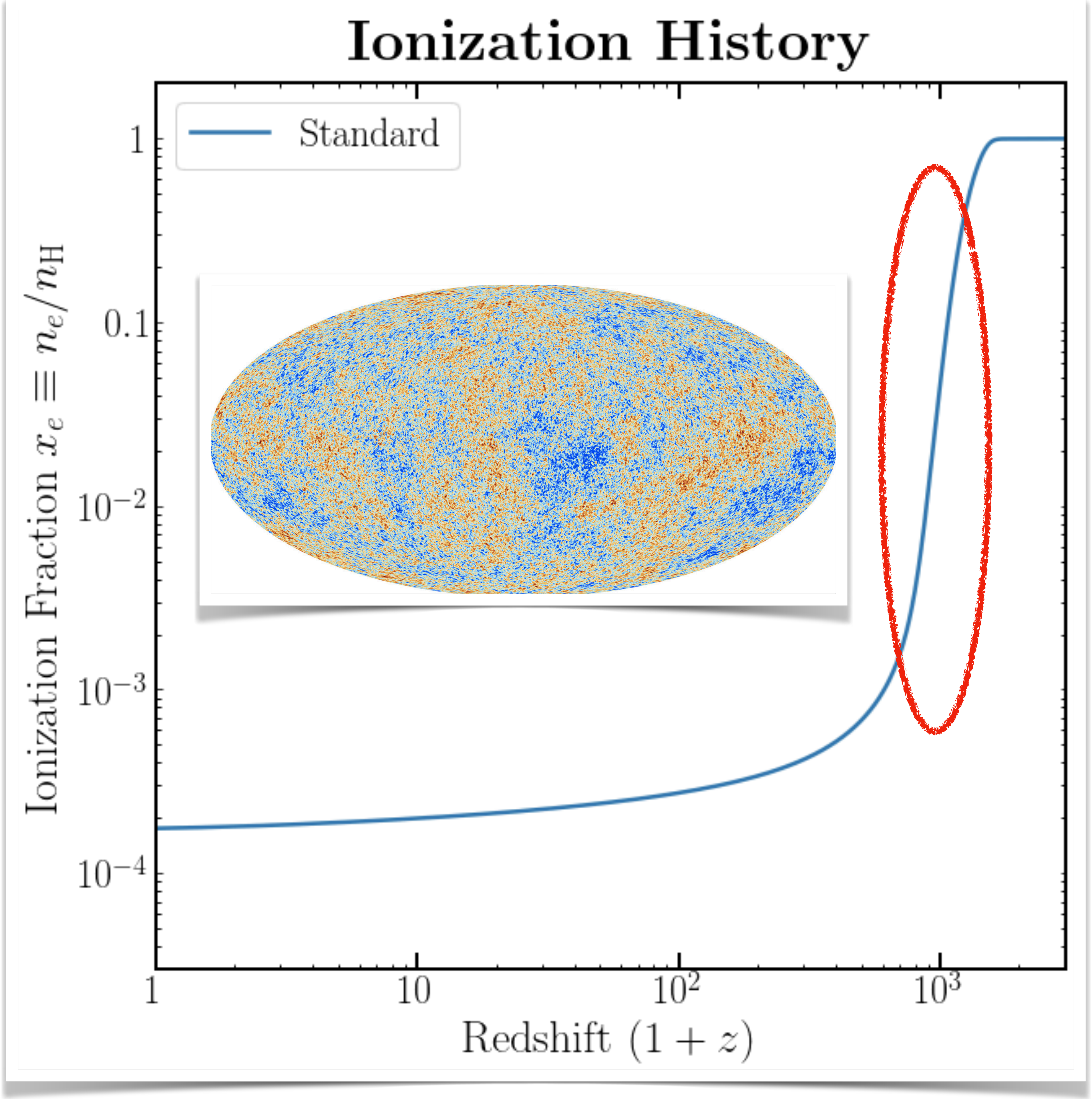




Photons with energy > 13.6 eV are **abundant**:
hydrogen atoms are **ionized**.

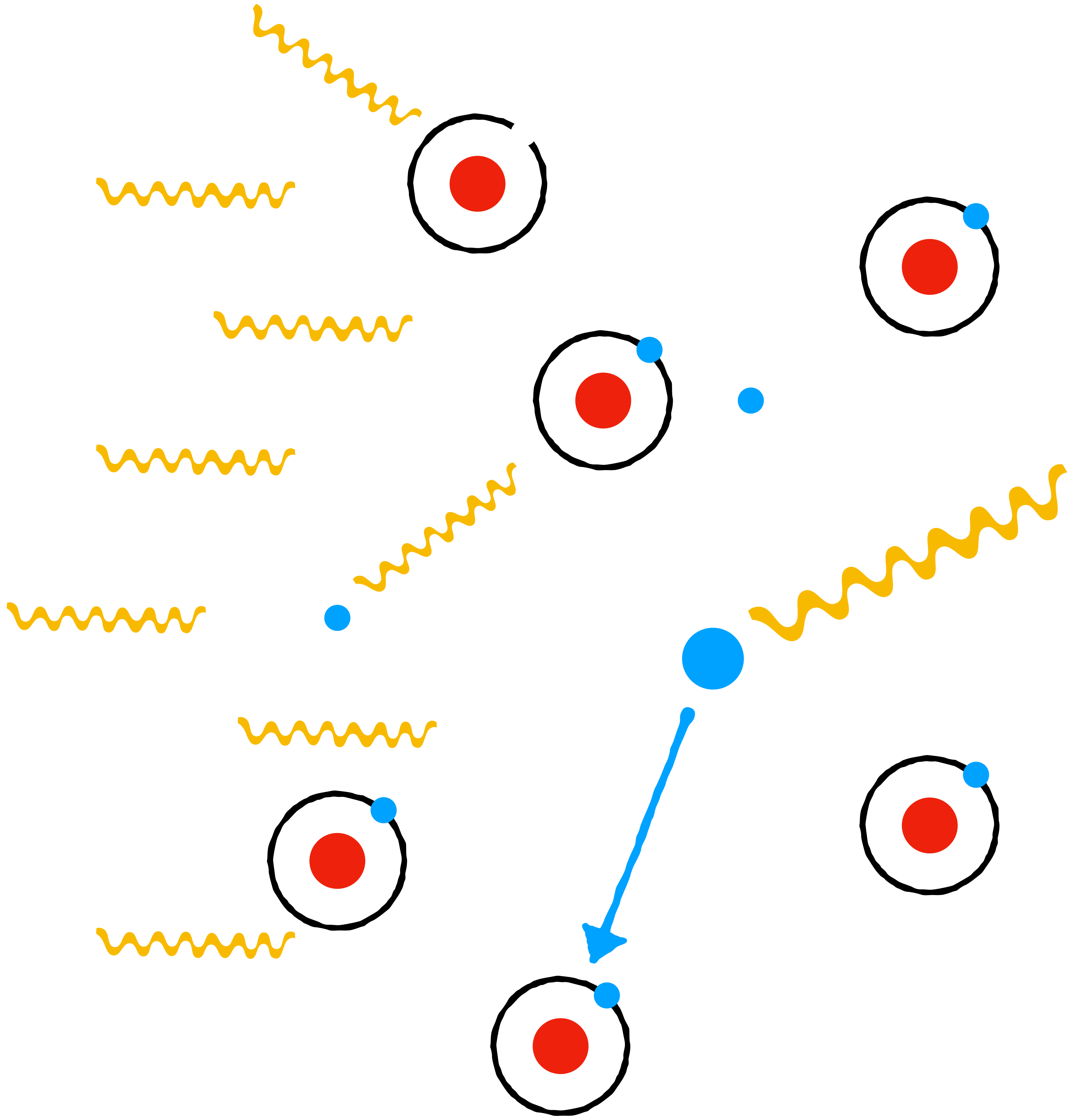
Recombination

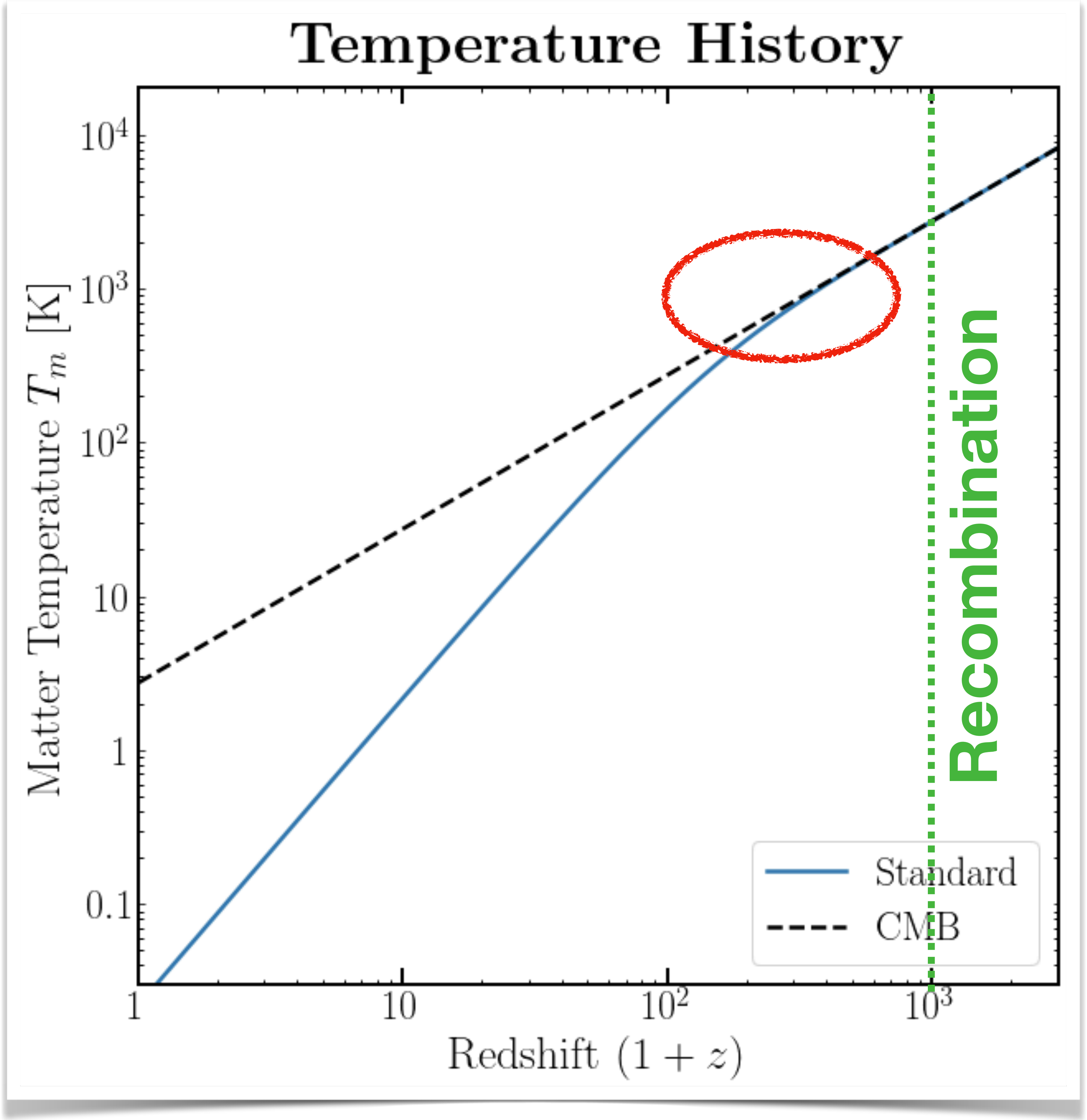




Universe expands, cools: protons and electrons **recombines**, Universe becomes **neutral** and **transparent**.

Compton Scattering



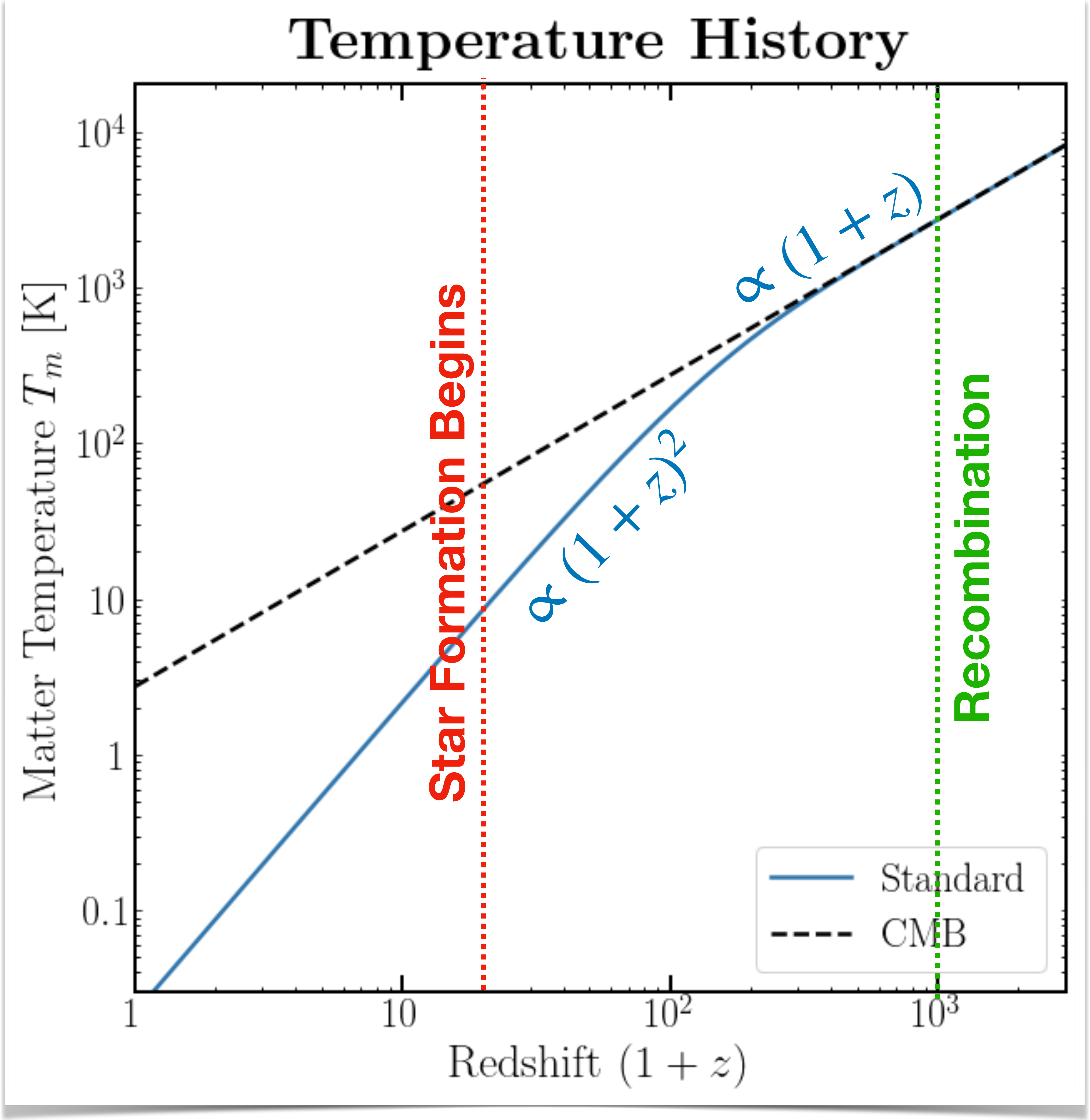


Compton scattering between free electrons and CMB photons keep matter and the CMB **in thermal contact** until $z \sim 150$.

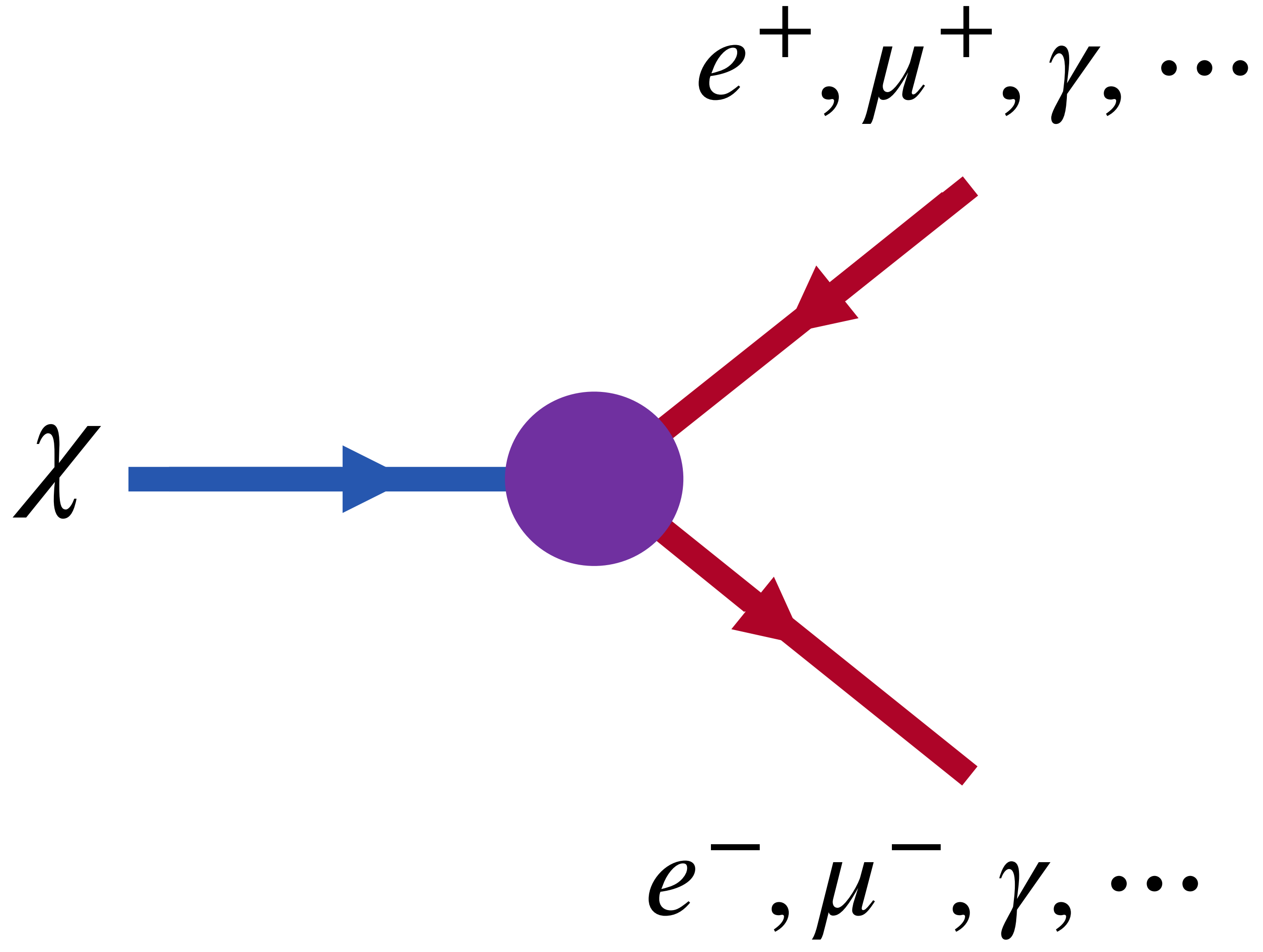
Redshifting

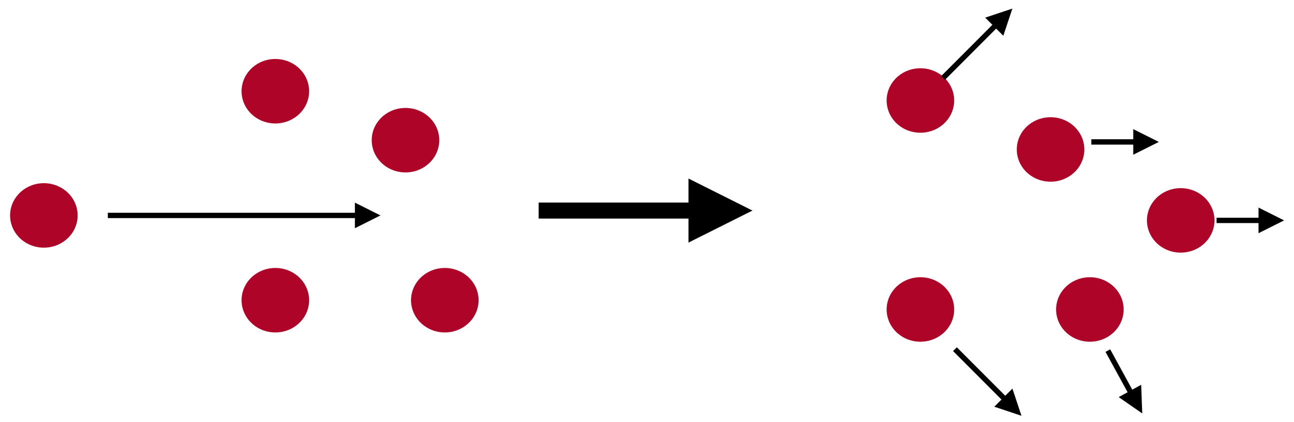
After decoupling from photons, redshifts as nonrelativistic matter until star formation.

Simple evolution!

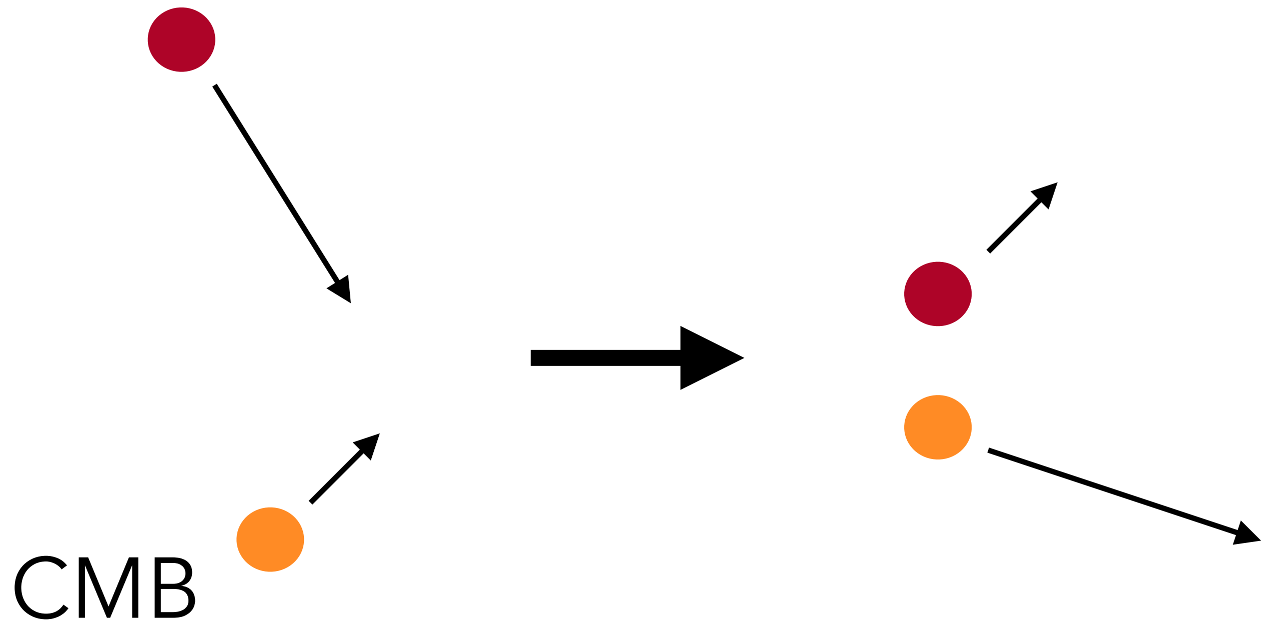


What Does Energy Deposition do?

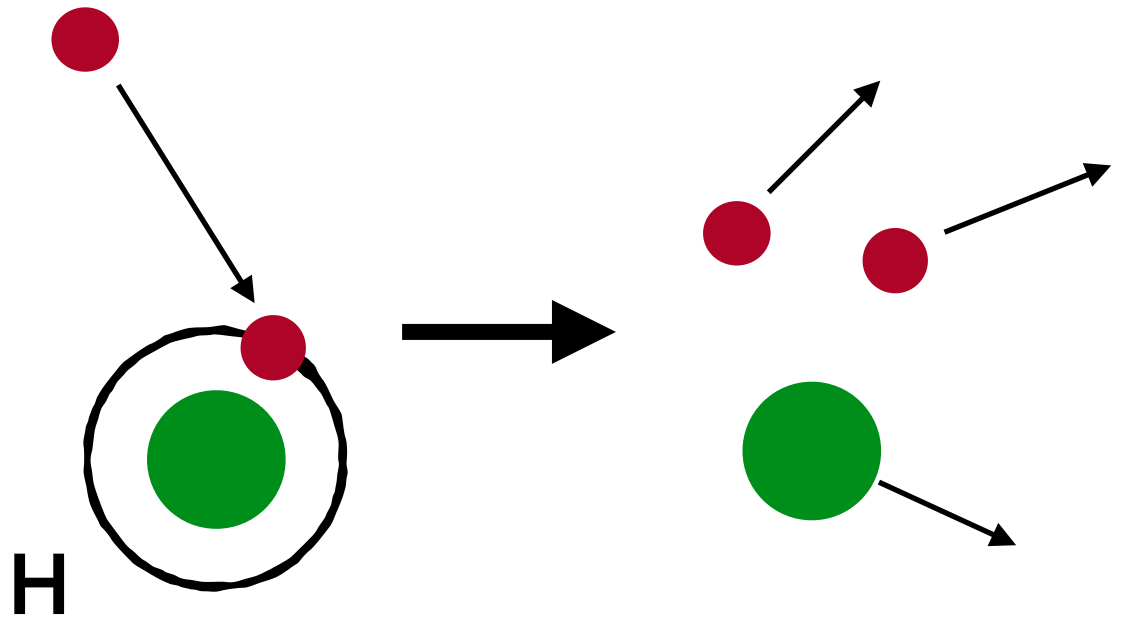




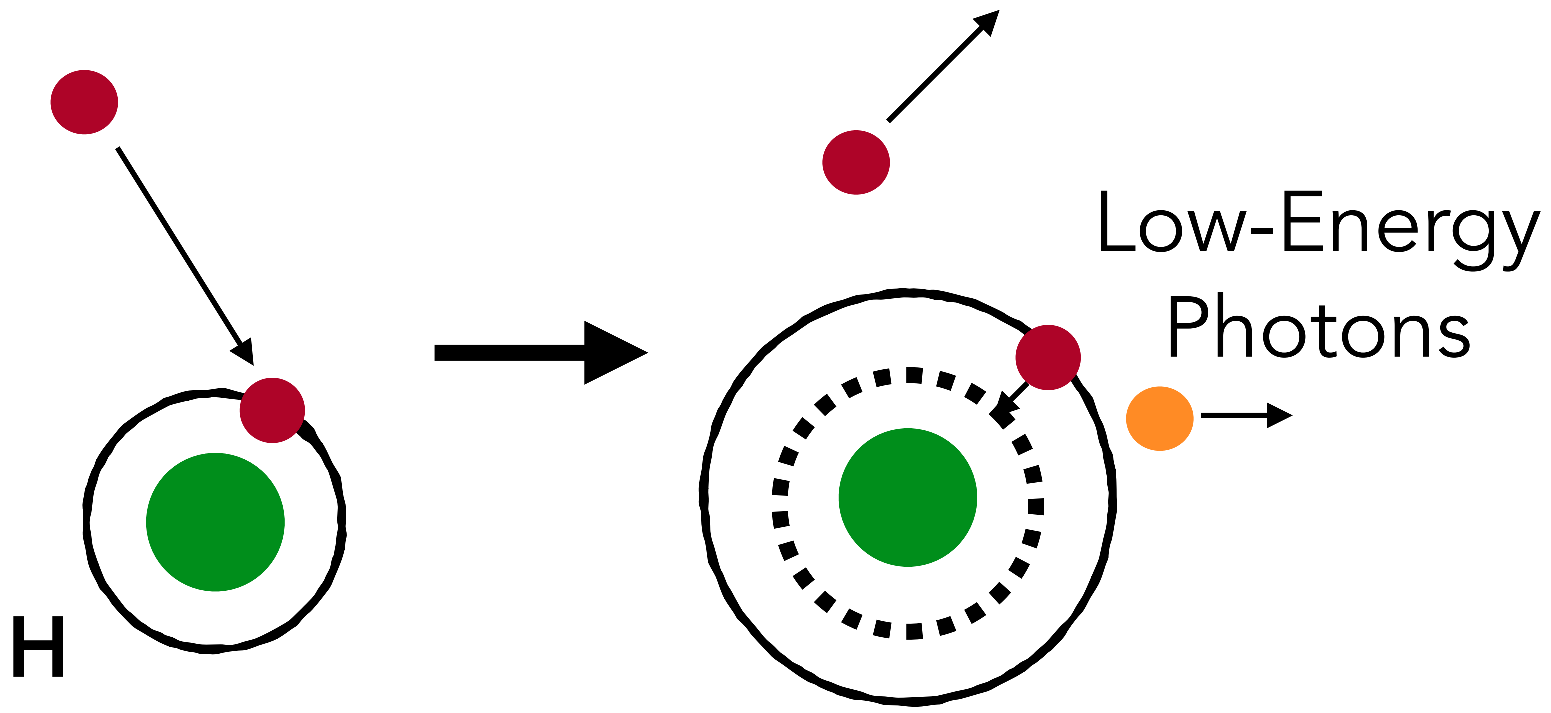
Heating



Inverse Compton Scattering



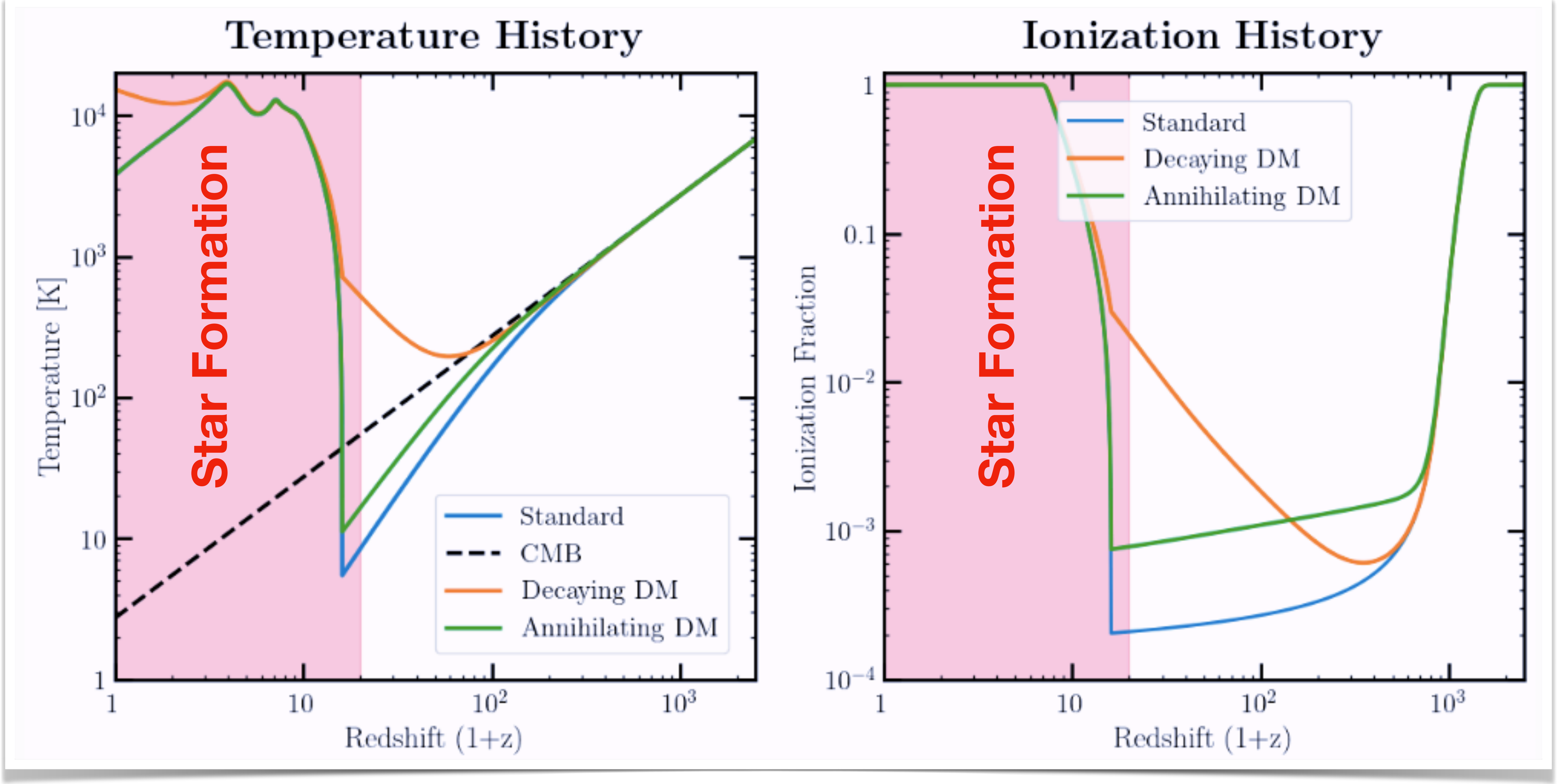
Ionization

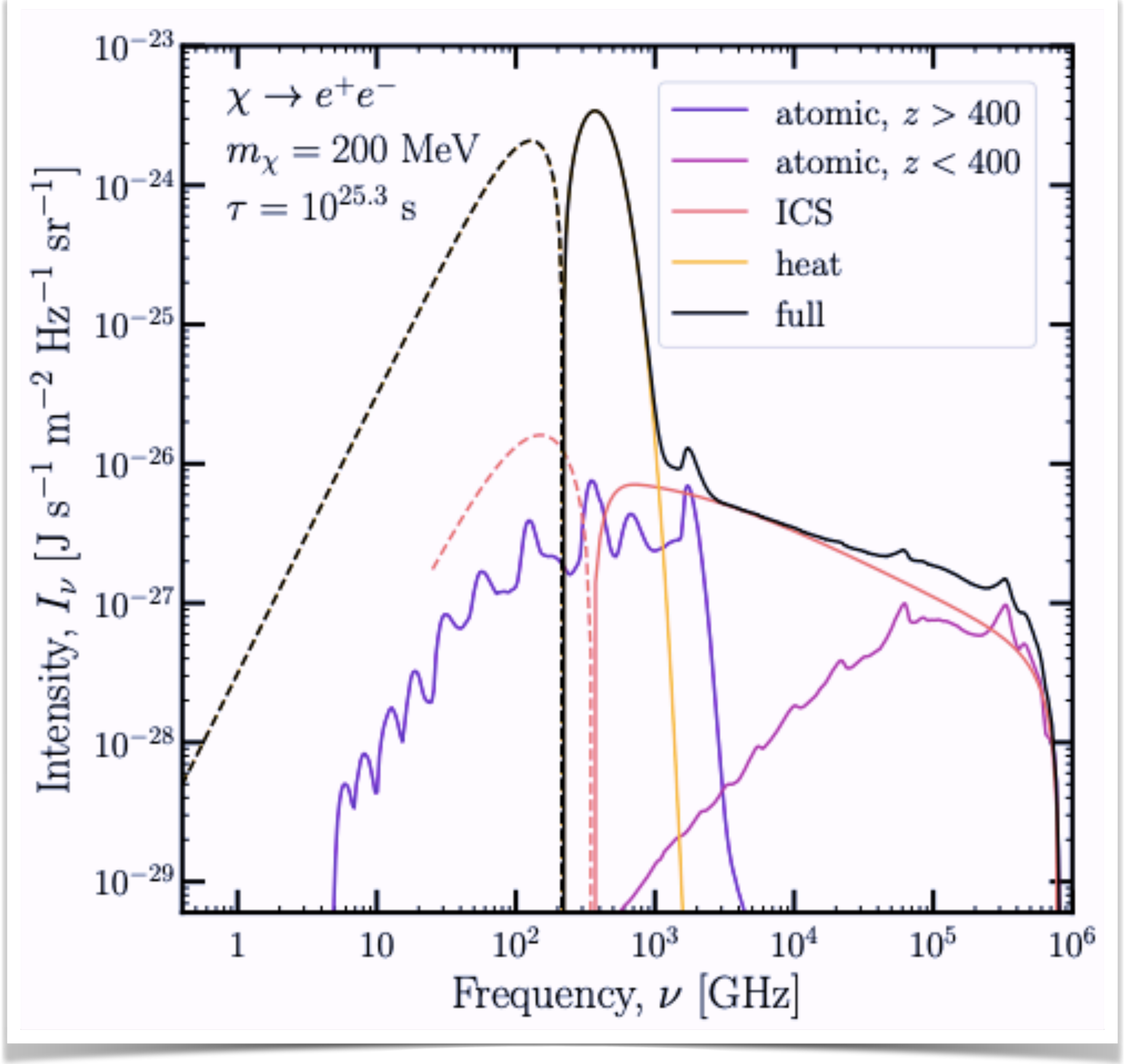


Excitation

github.com/hongwanliu/DarkHistory

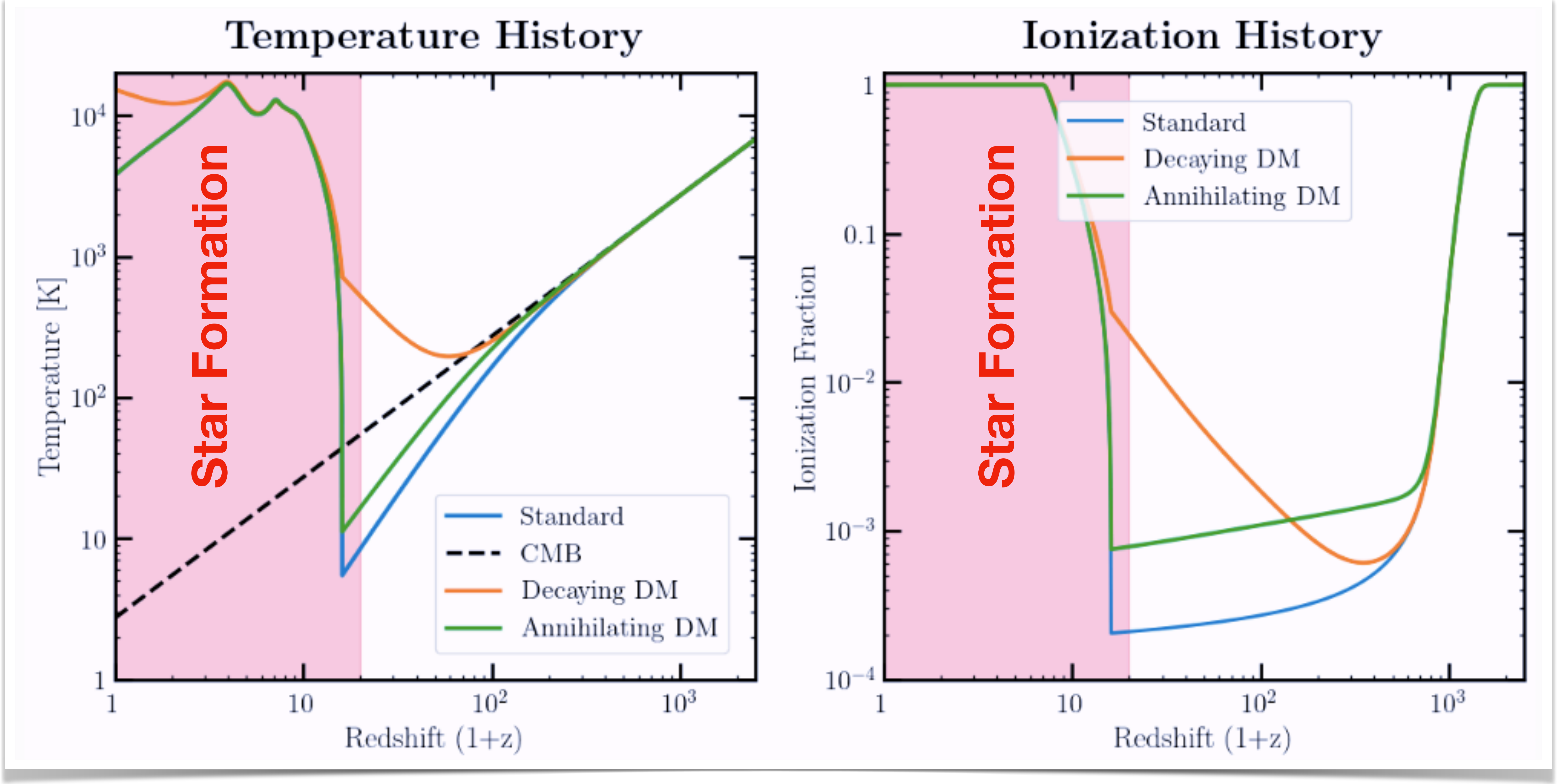
DarkHistory

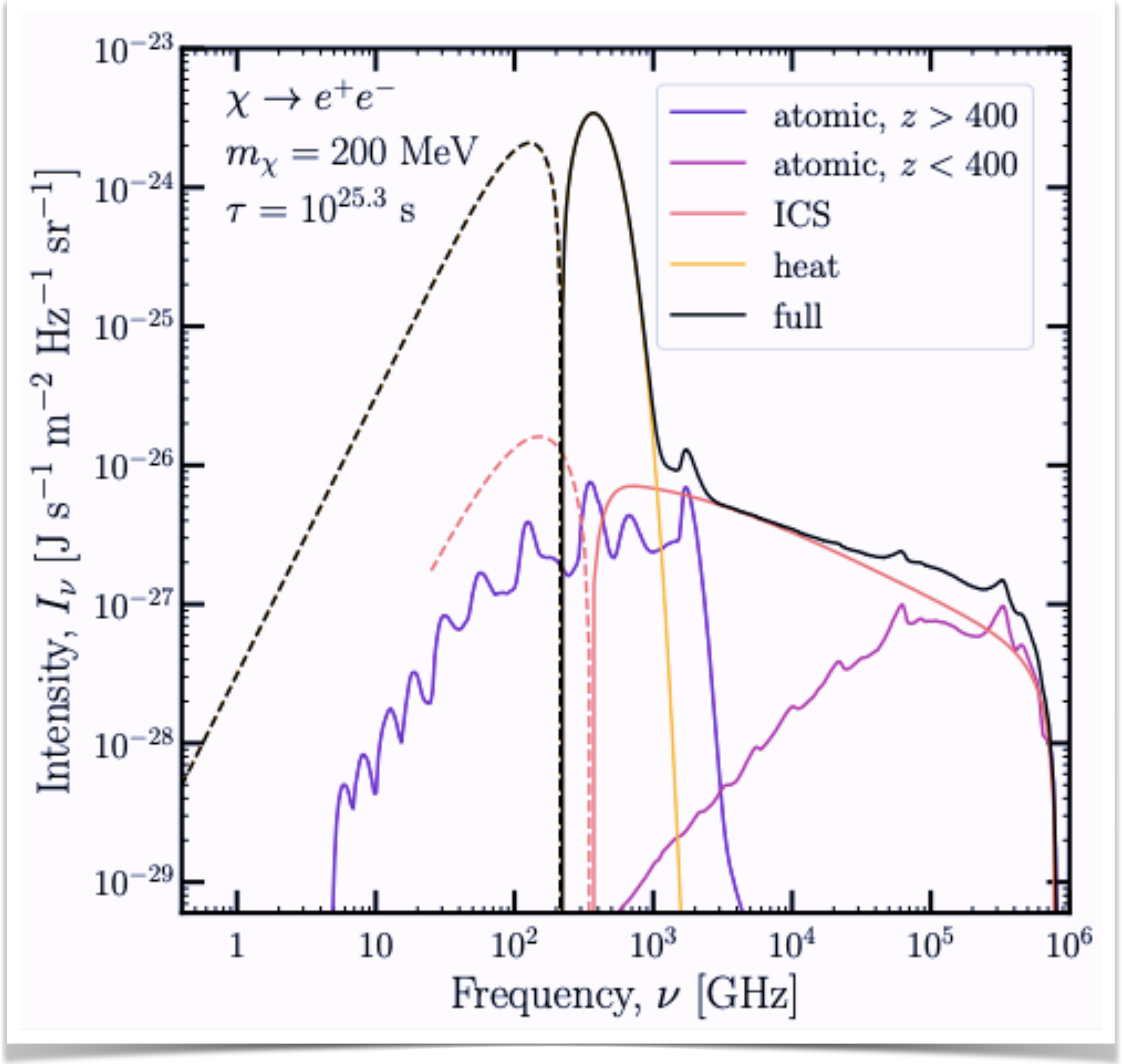




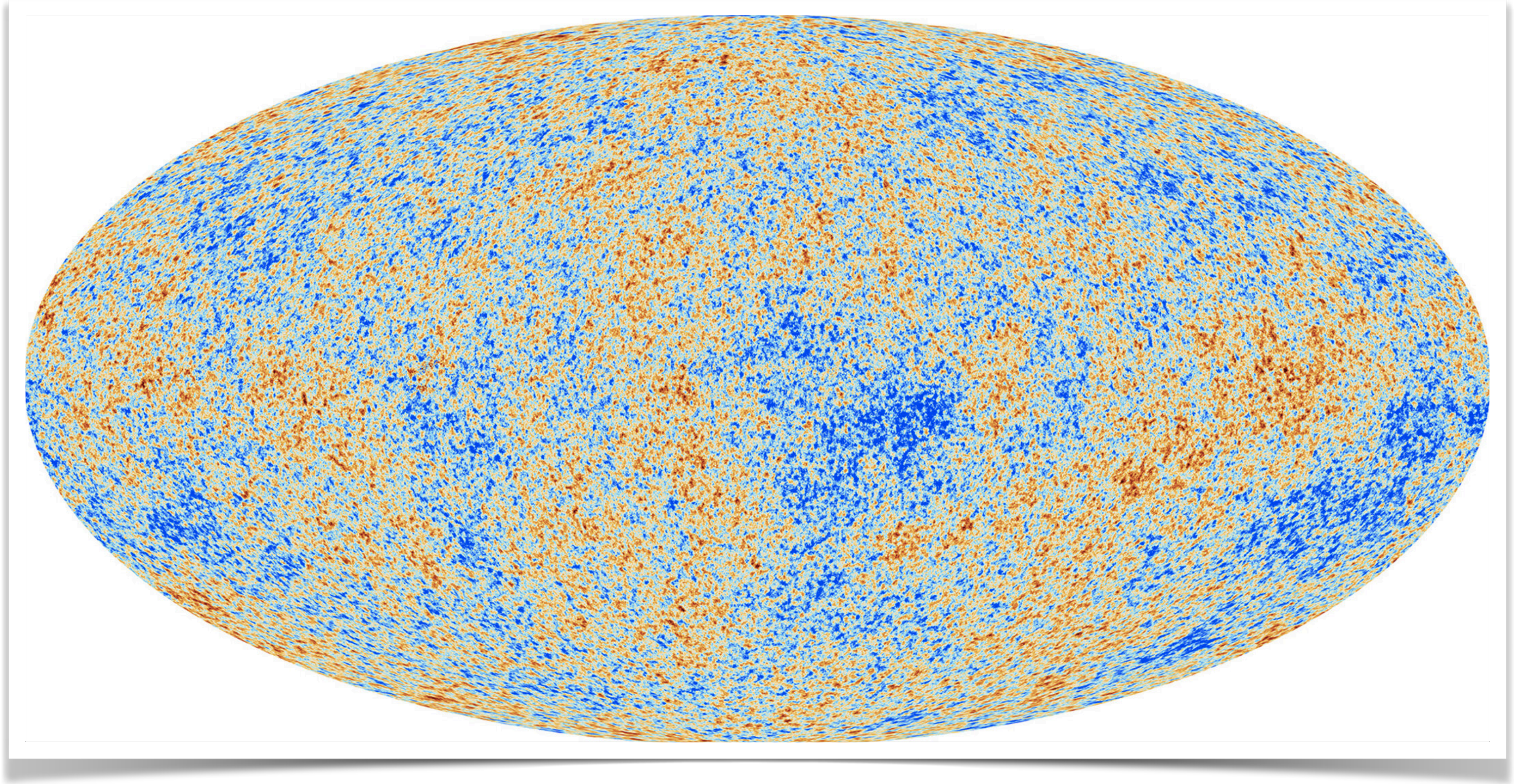
Calculates **ionization history**, **temperature history** and **photon spectrum** given an exotic source.

Signals in Data?

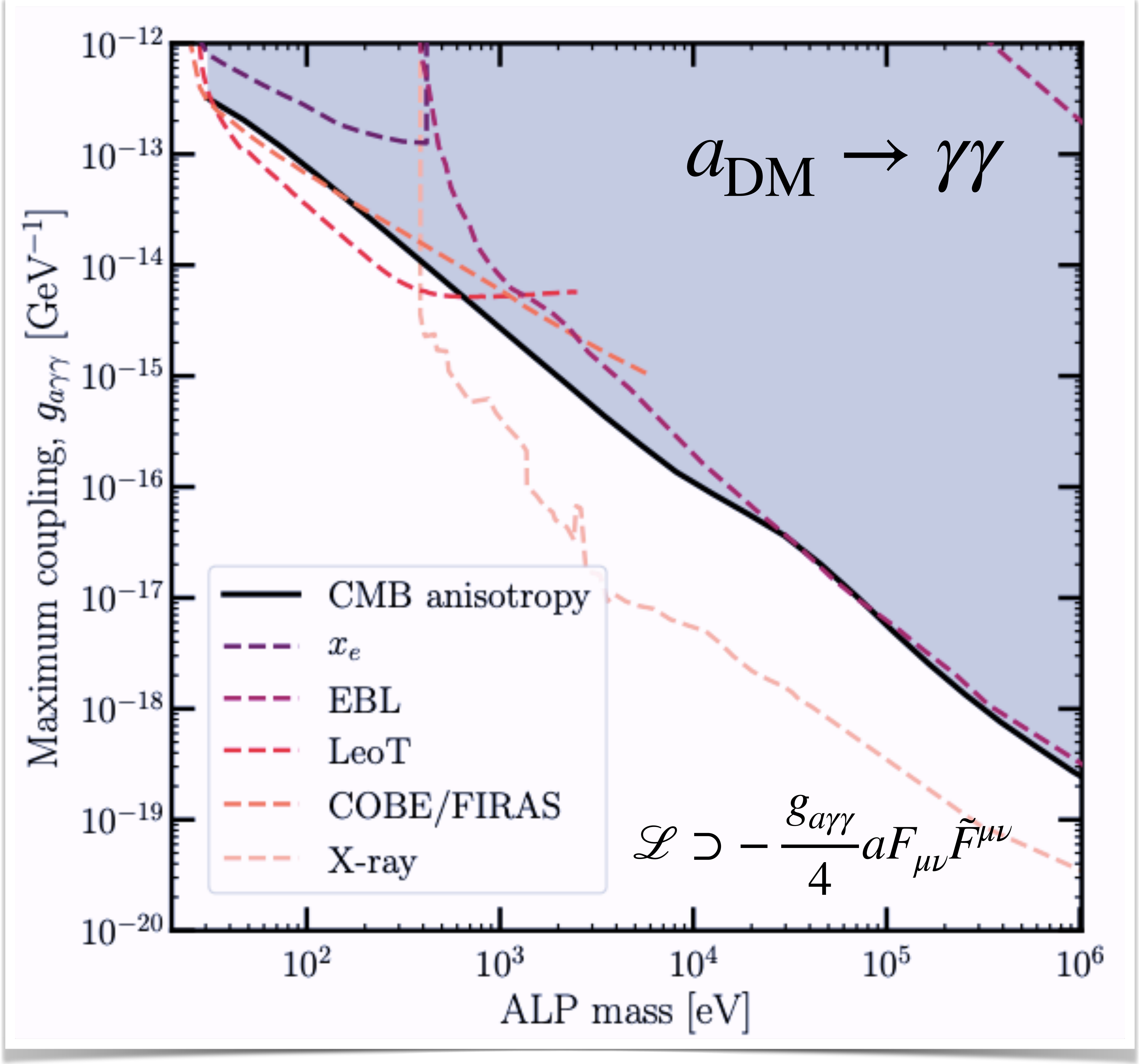




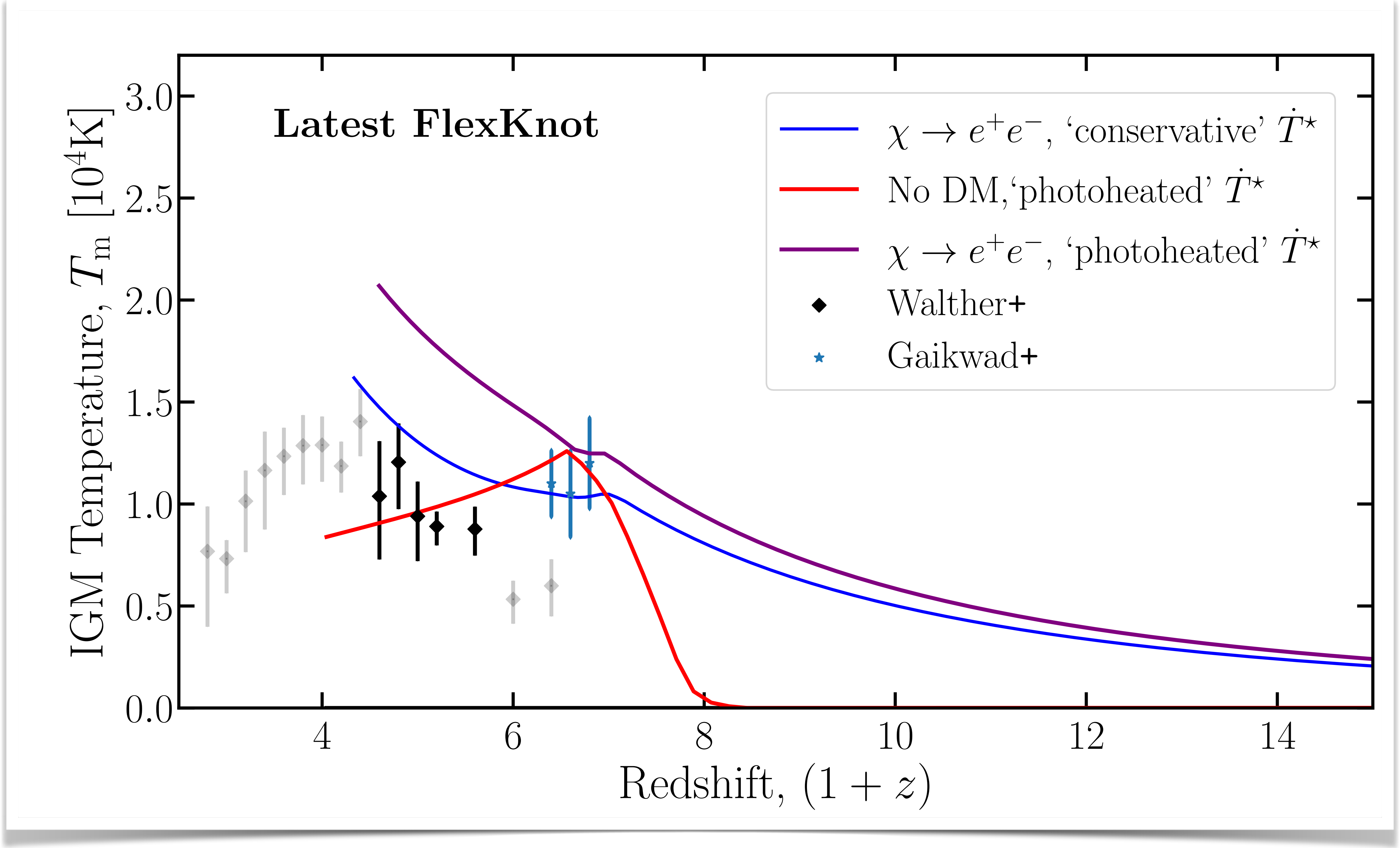
Increased Ionization

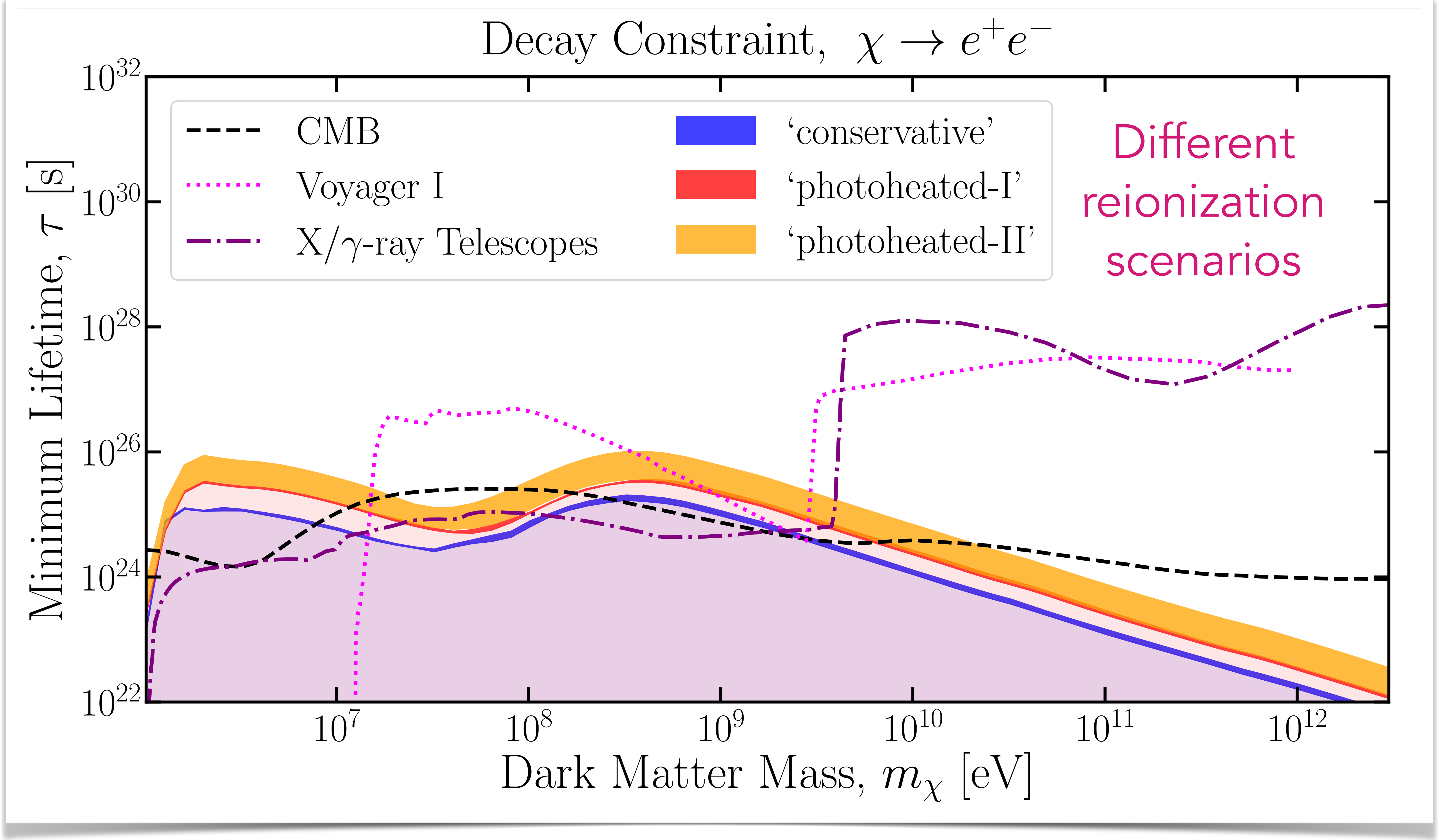


More free electrons means **photons scatter more**, affecting the CMB **power spectrum**.



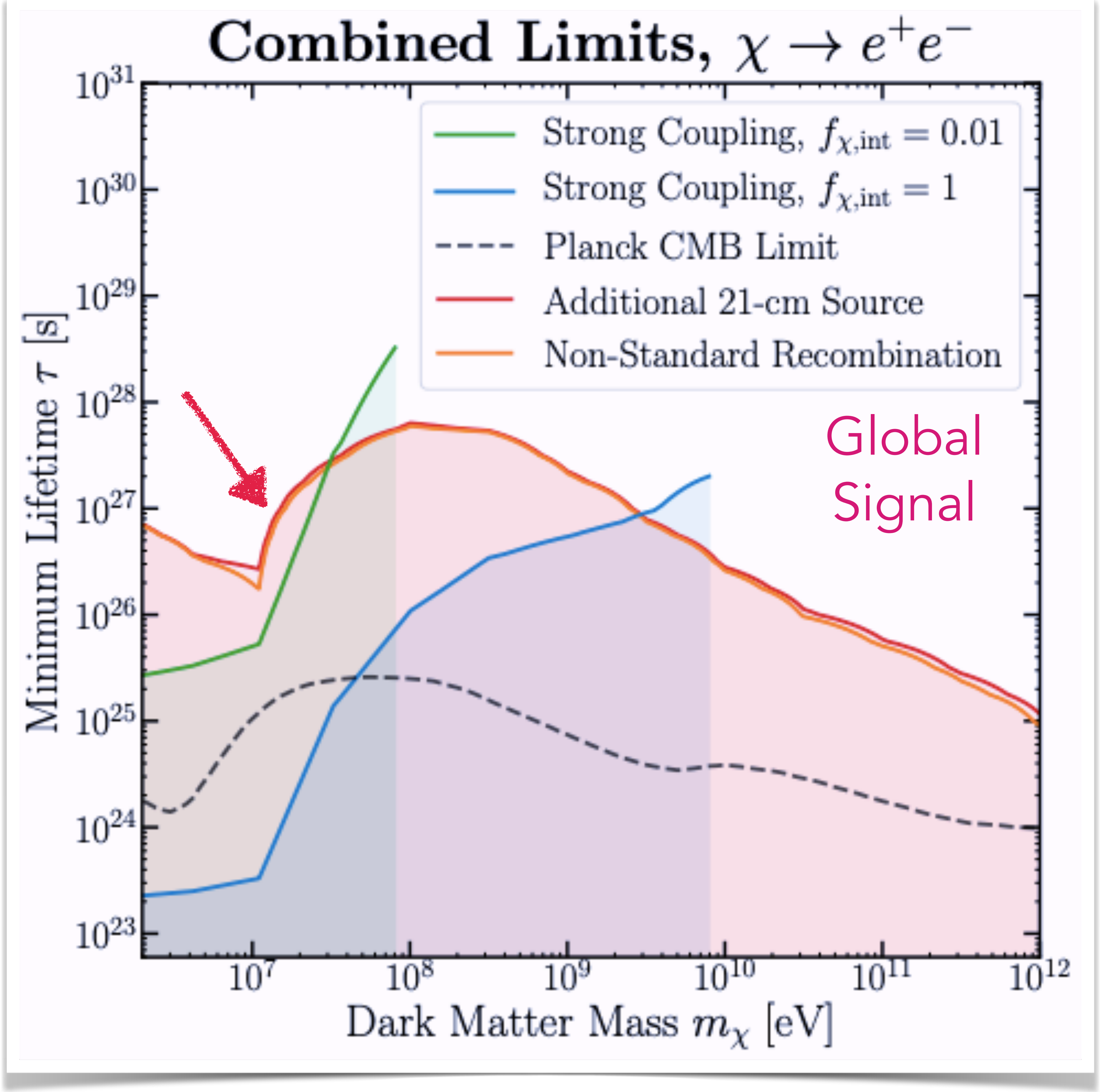
Increased Heating - Lyα

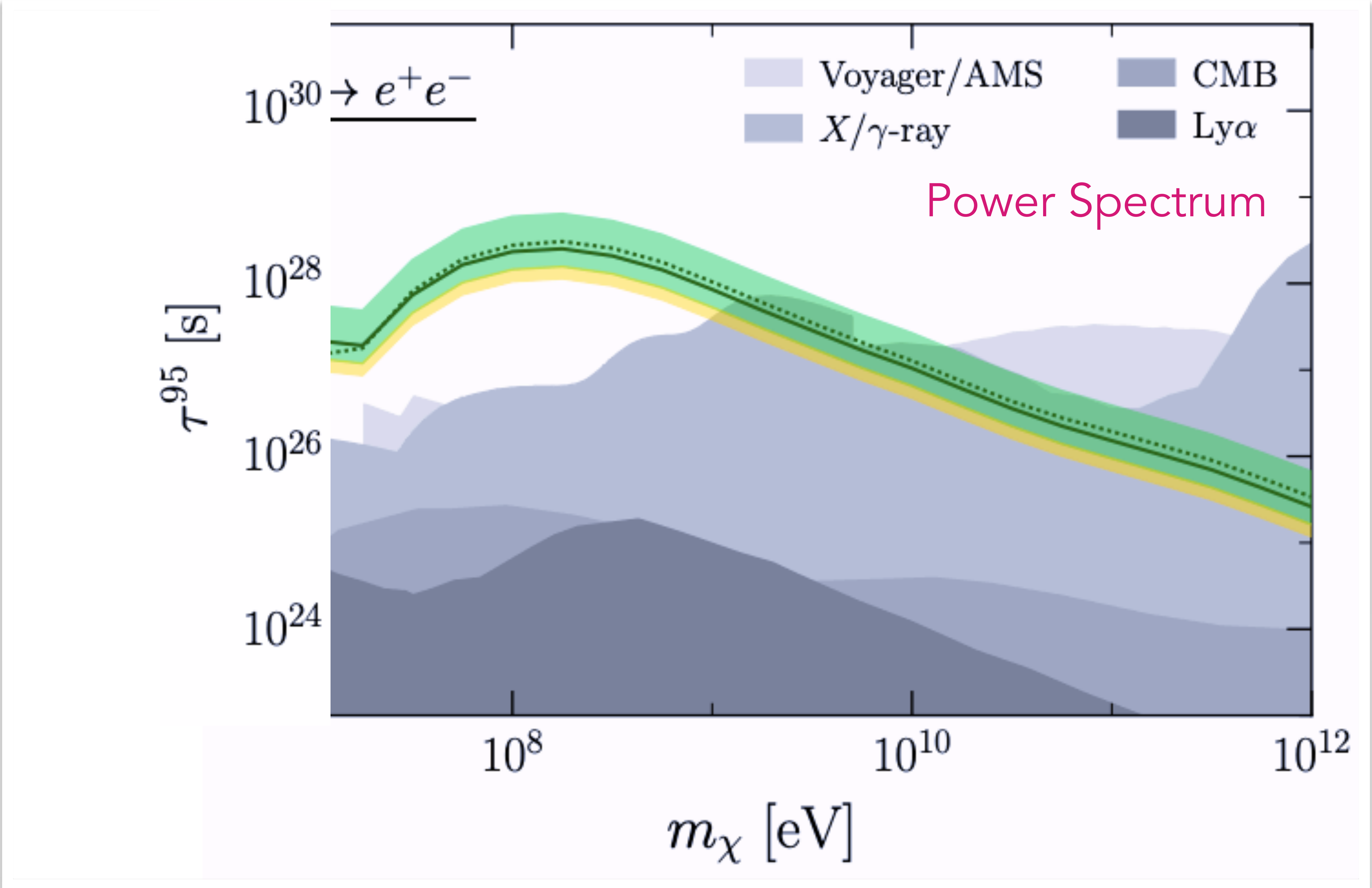




Intergalactic medium temperature known through **Lyman-α forest** data. Strong constraints on sub-GeV DM decay.

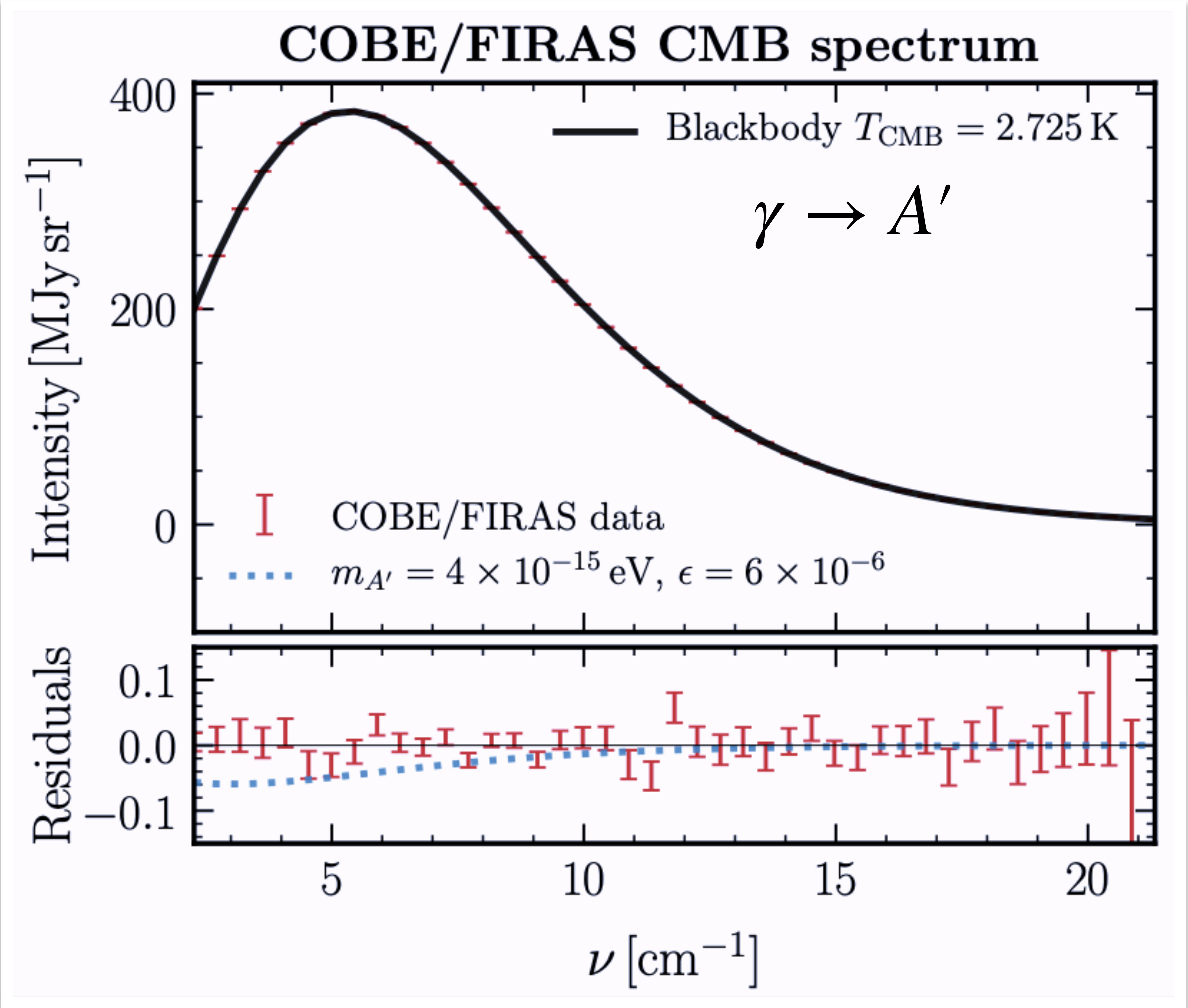
Increased Heating - 21cm

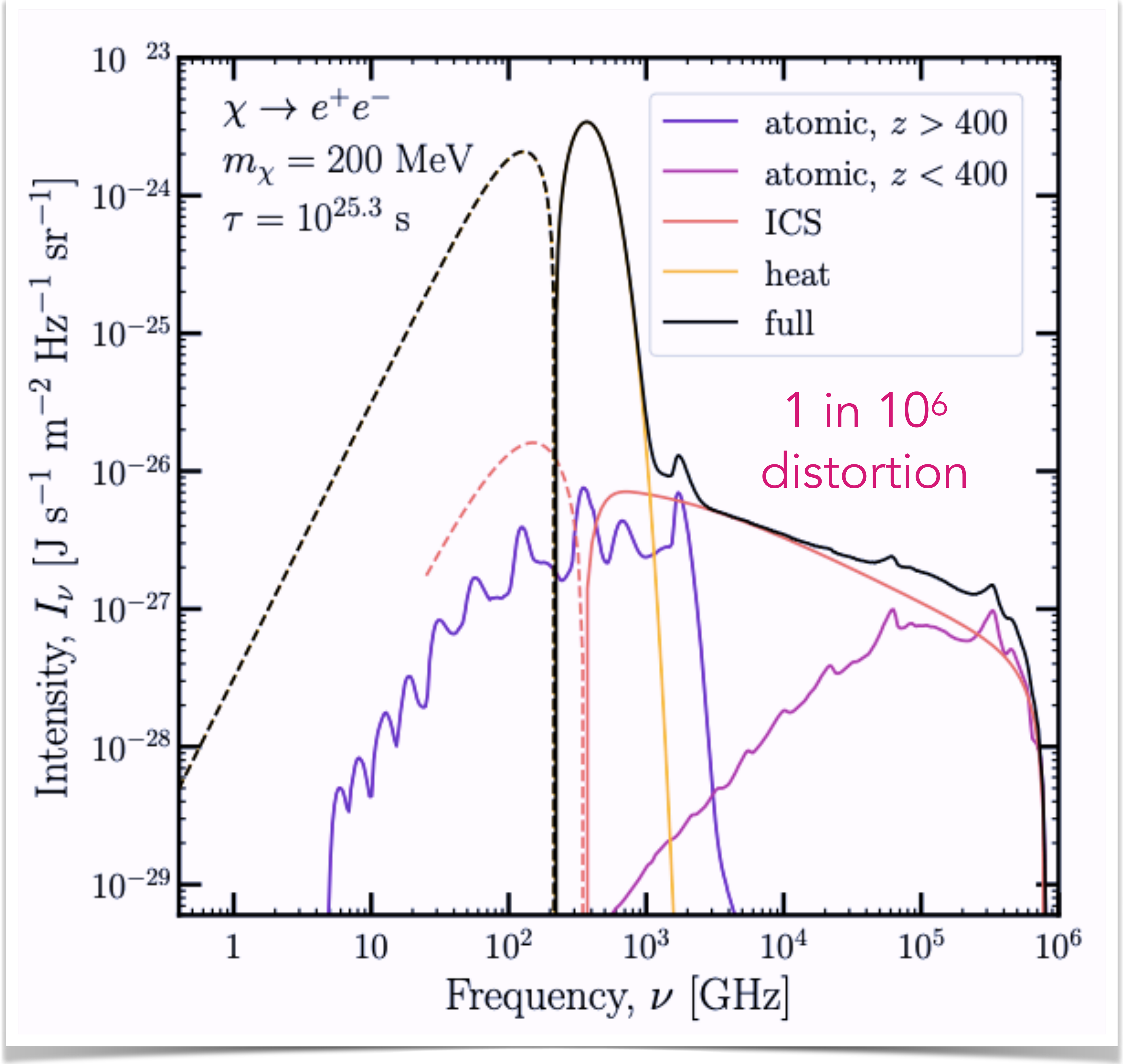




21-cm will be very sensitive to heating of baryons during the **cosmic dark ages** $(6 \lesssim z \lesssim 30)$.

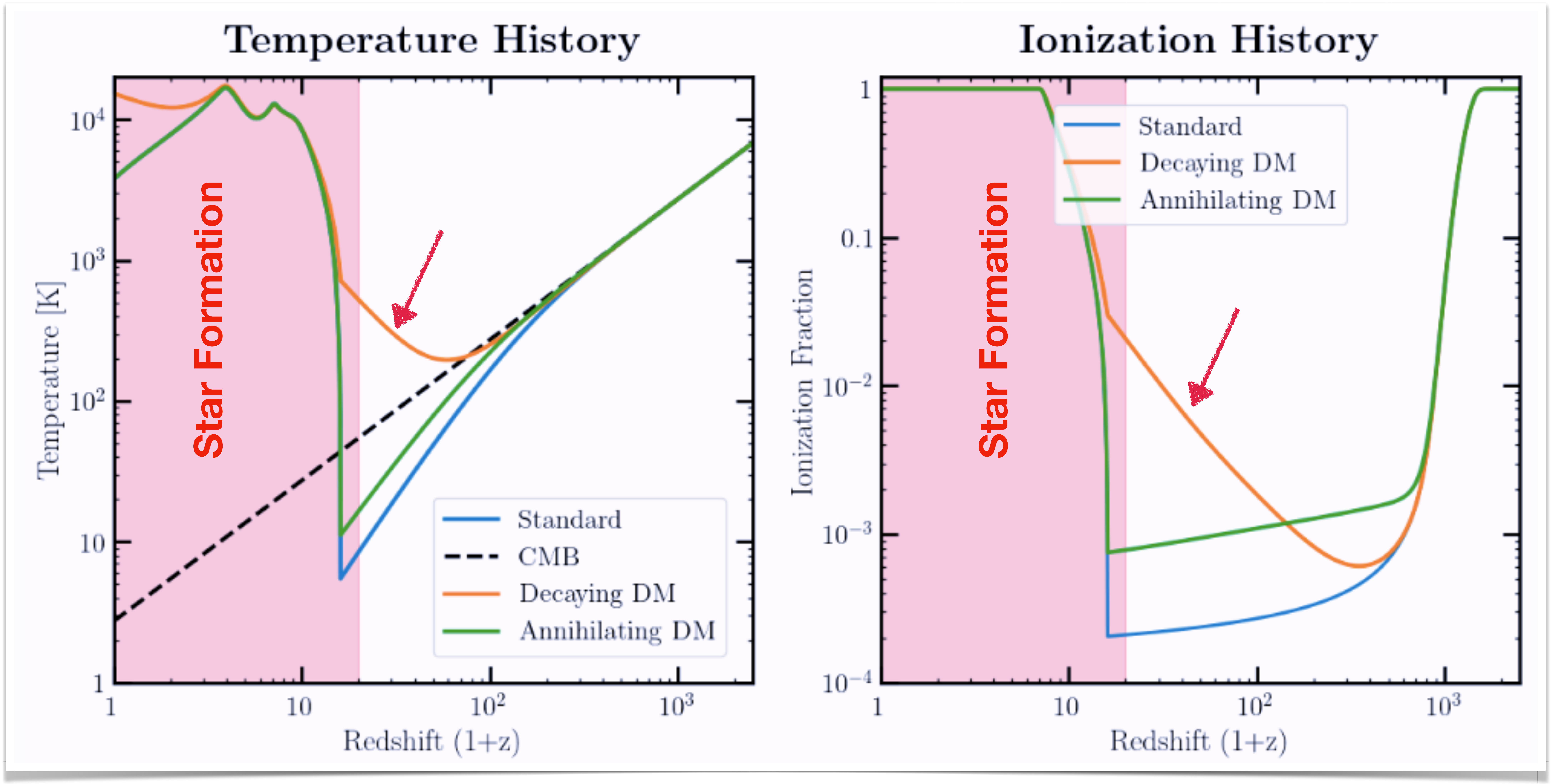
CMB Blackbody Distortions





Powerful probe for photons **oscillating** into other states.
Useful for DM decay with next generation experiments (**PIXIE**).

Big Shift in Temperature & Ionization

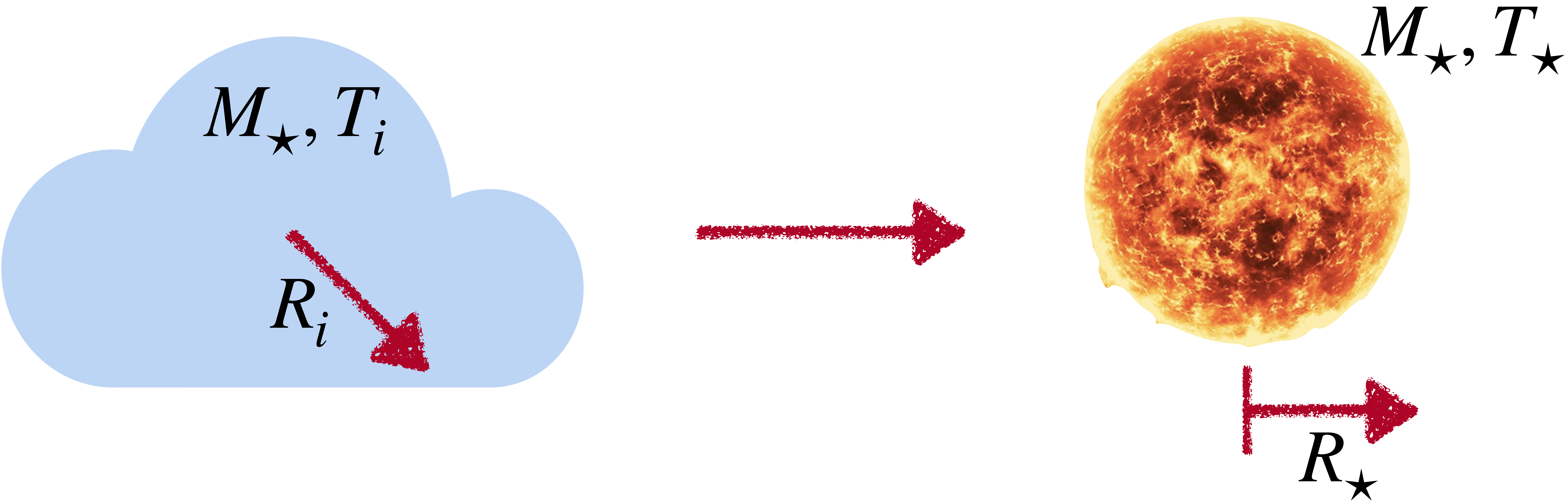


Does an orders-of-magnitude shift affect how the first stars form?

Dark matter can delay or accelerate star formation.

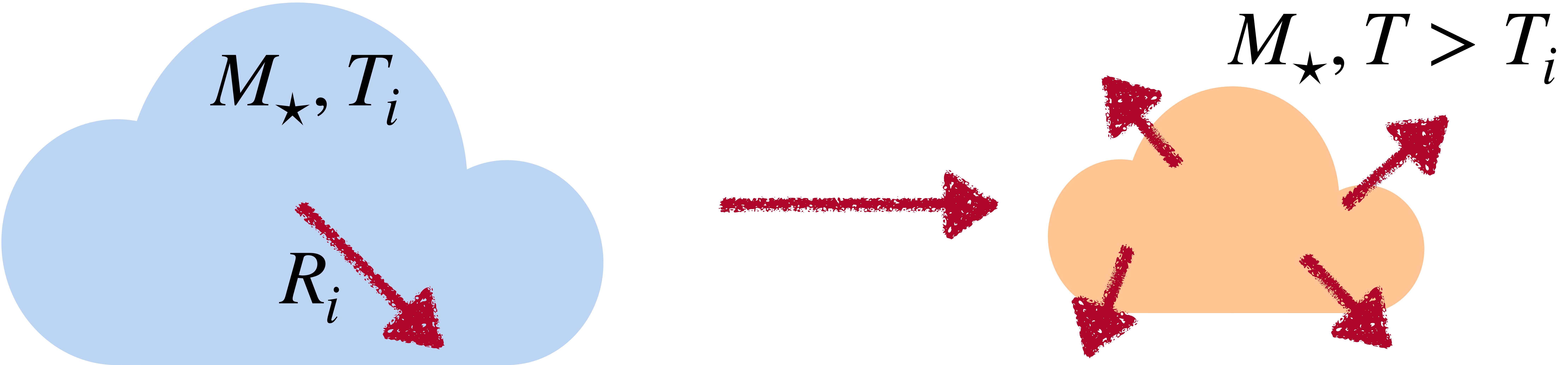
W. Qin, J. Muñoz, **HL** & T. Slatyer, 2308.12992

Star Formation



Schematically, stars form if a stellar mass, low density gas cloud can **gravitationally collapse** successfully.

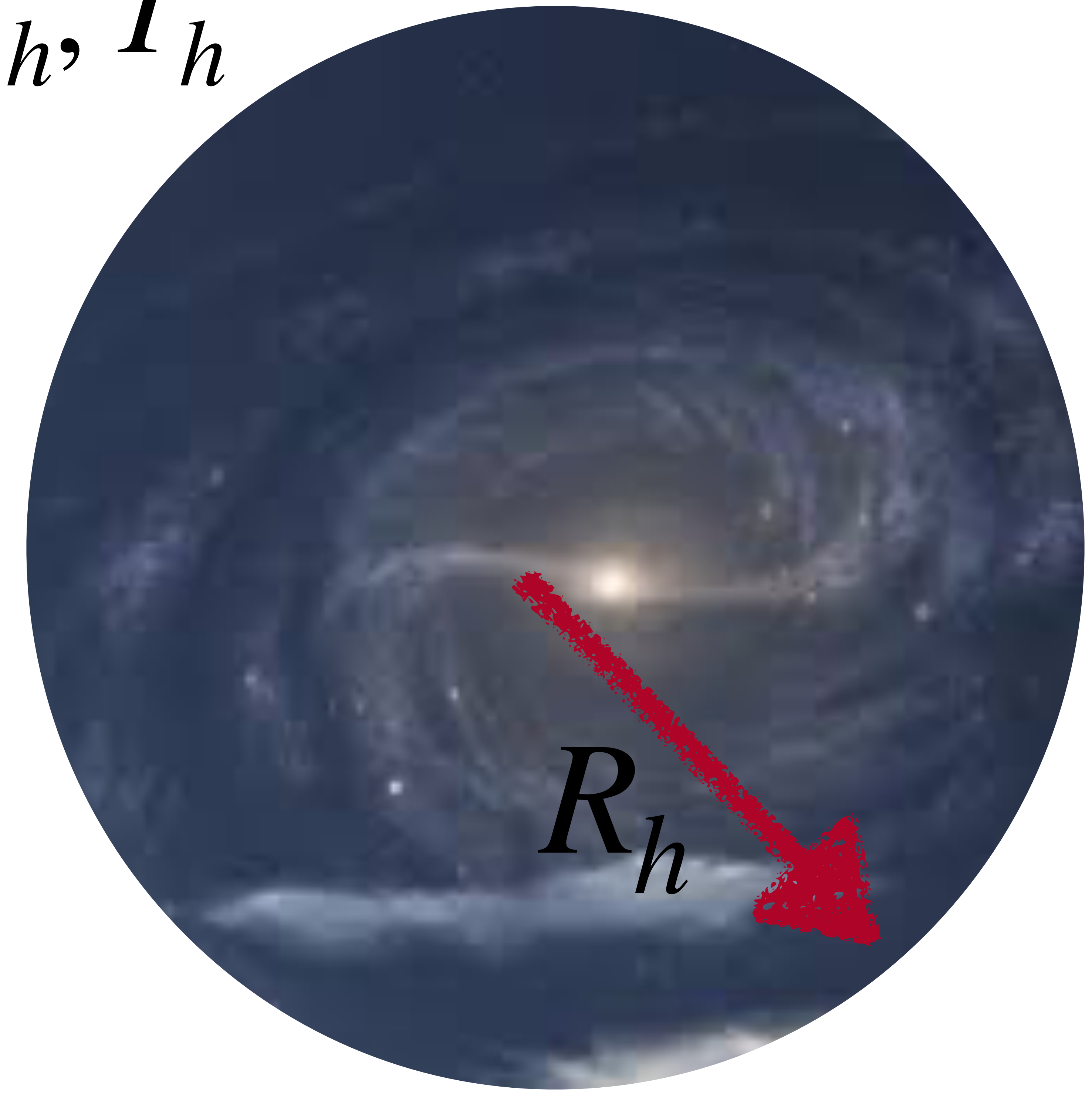
Gravity vs. Pressure



But the **pressure** in a gas cloud counteracts gravity.
Gas cloud must be **sufficiently cold**.

Gas Temperature in a Halo

M_h, T_h



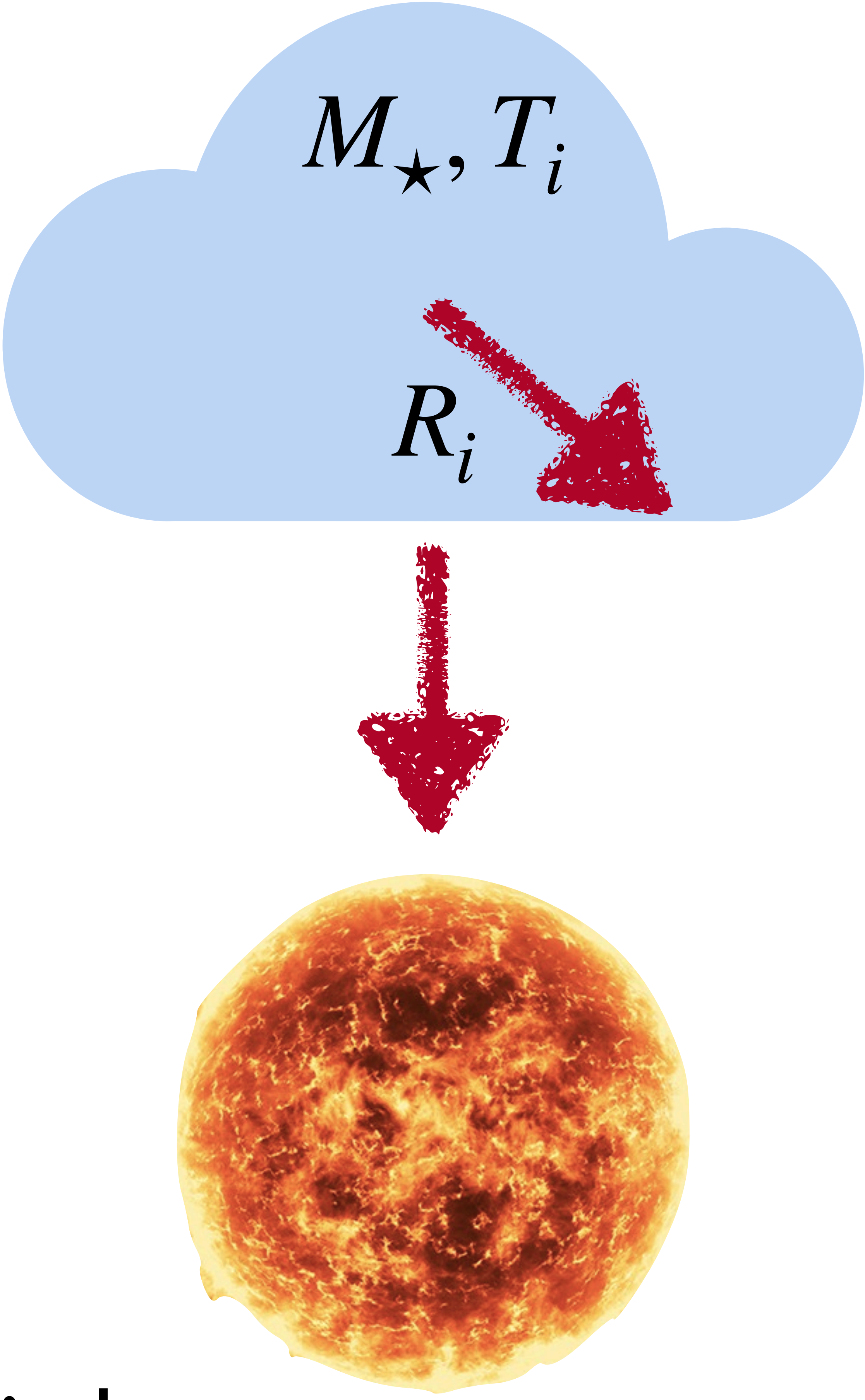
potential energy ~ kinetic energy

$$NT_h \sim \frac{GM_h^2}{R_h}, N \sim \frac{M_h}{m_{\mathrm{H}}}$$

$$T_h \sim 3 \times 10^3\,\mathrm{K} \left(\frac{M_h}{10^6 M_\odot} \right)^{2/3} \left(\frac{\rho_h}{200\rho_{\mathrm{crit}}(z=20)} \right)^{1/3}$$

Gas in halos expected to be roughly $\sim 10^3\,\mathrm{K}$.

Initial Temperature for Collapse



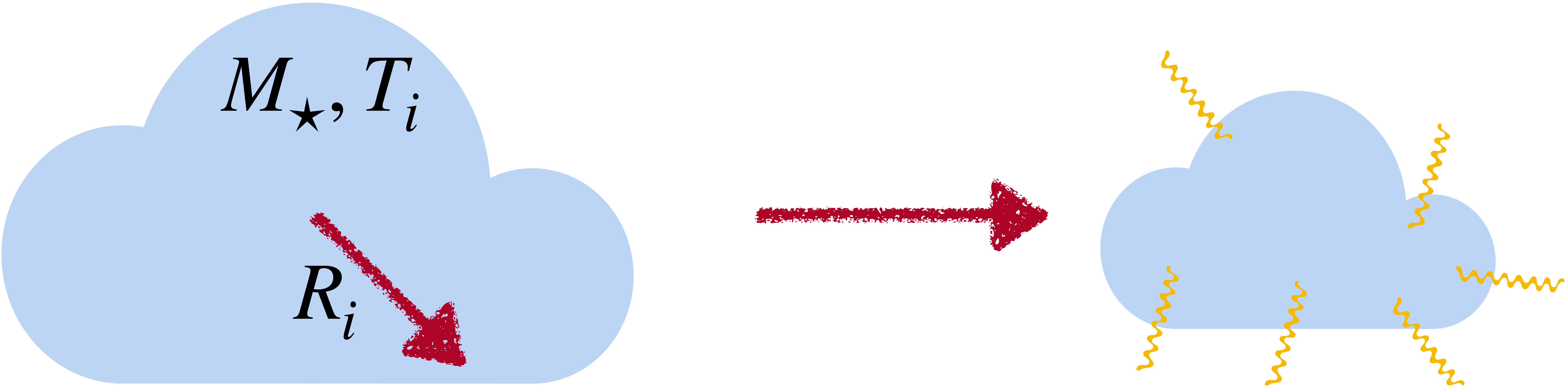
potential energy ~ kinetic energy
when stable

$$NT_i \ll \frac{GM_\star^2}{R_i}, N \sim \frac{M_\star}{m_\mathrm{H}}, R_i \sim (M_\star/\rho_h)^{1/3}$$

$$T_i \ll 30\,\mathrm{K} \left(\frac{M_\star}{10^3 M_\odot} \right)^{2/3} \left(\frac{\rho_h}{200 \rho_\mathrm{crit}(z=20)} \right)^{1/3}$$

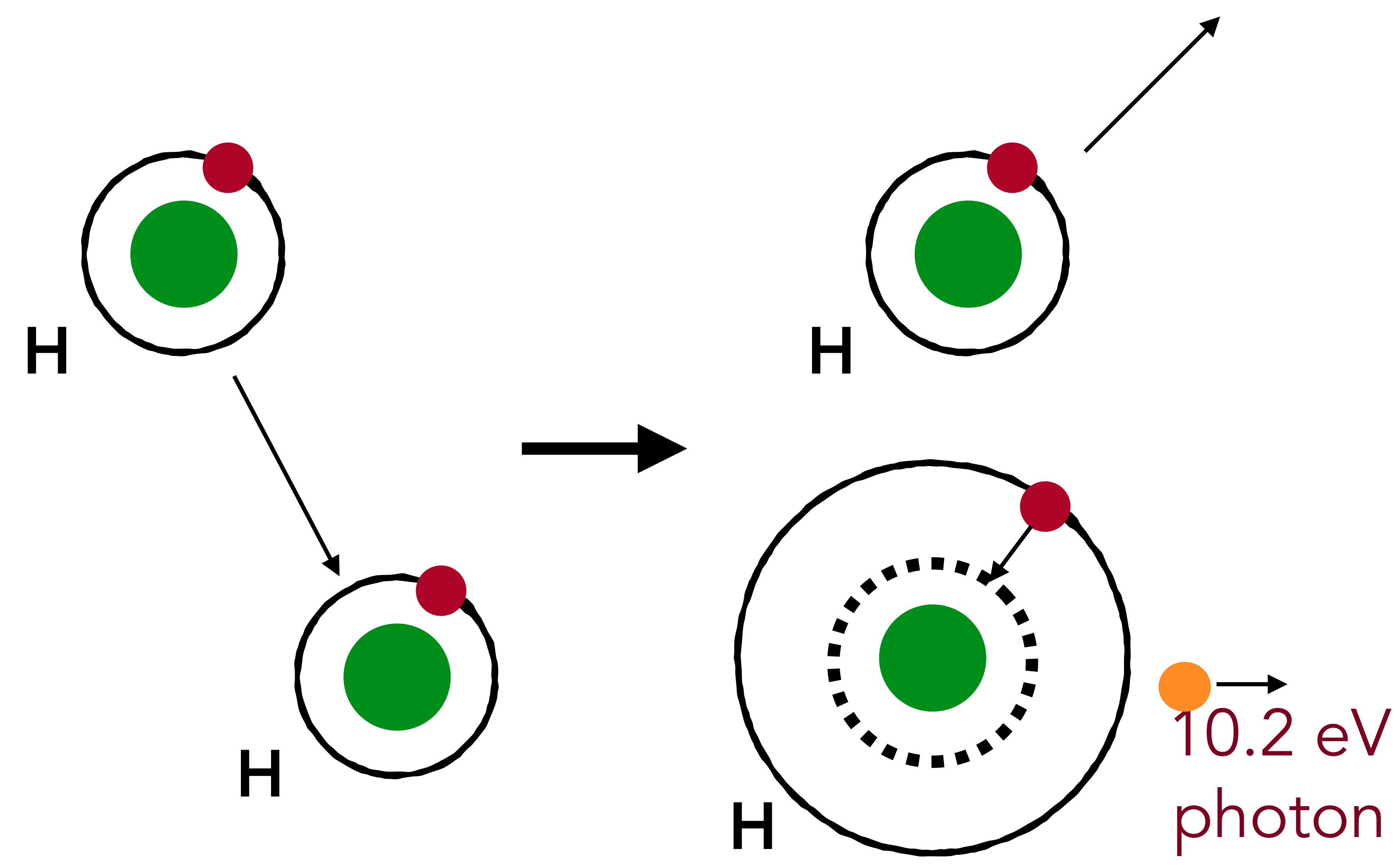
Initial temperature for successful collapse is **much smaller** than typical temperature in halo ($\sim 10^3\,\mathrm{K}$).

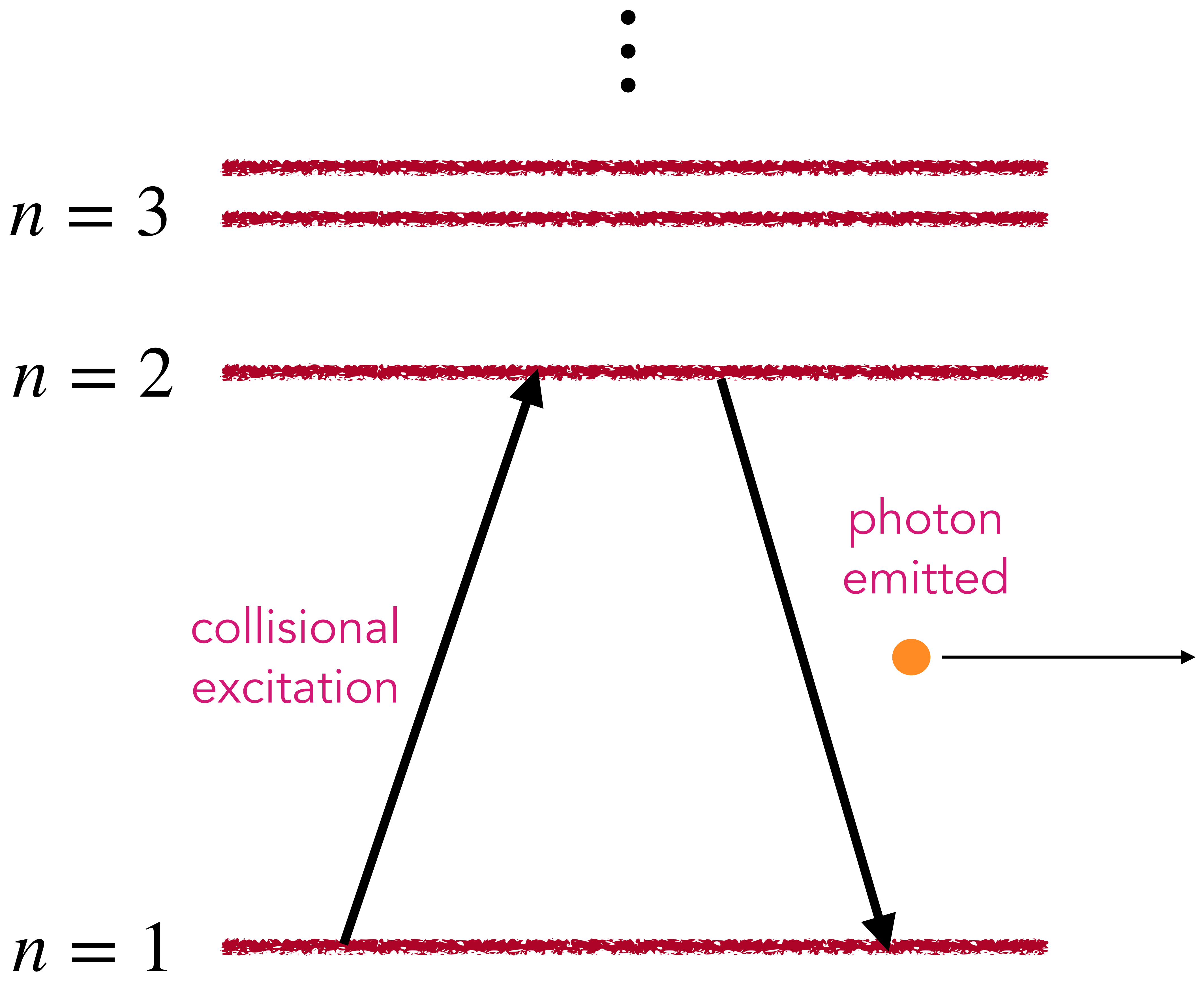
Cooling



… or the gas cloud must be able to **cool** by **emitting radiation**.

Atomic Cooling

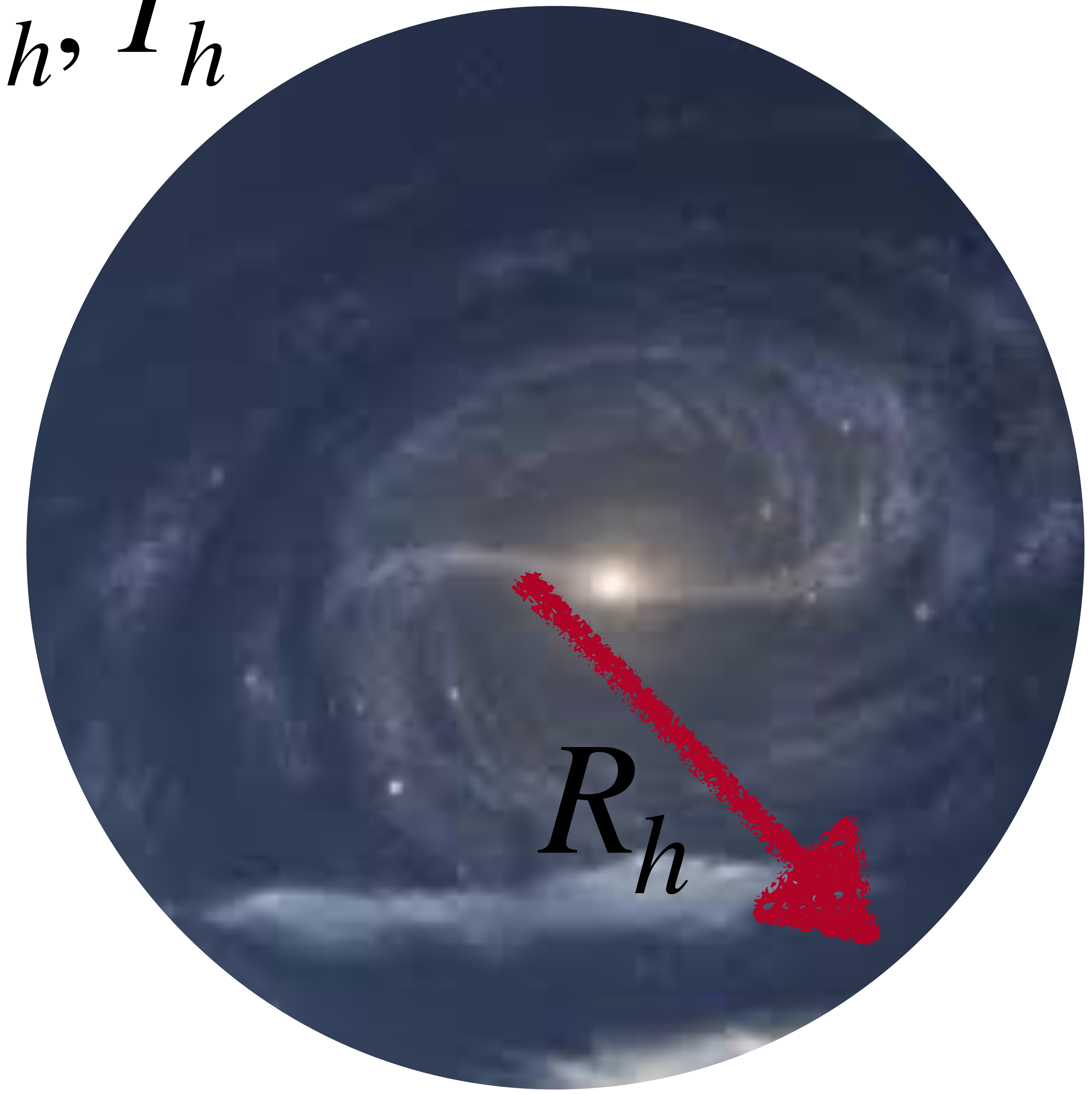




H atomic cooling **inefficient** well below $T \ll 10.2\,\mathrm{eV} = 10^5\,\mathrm{K}$ (no free electrons for bremsstrahlung).

Gas Temperature in a Halo

M_h, T_h



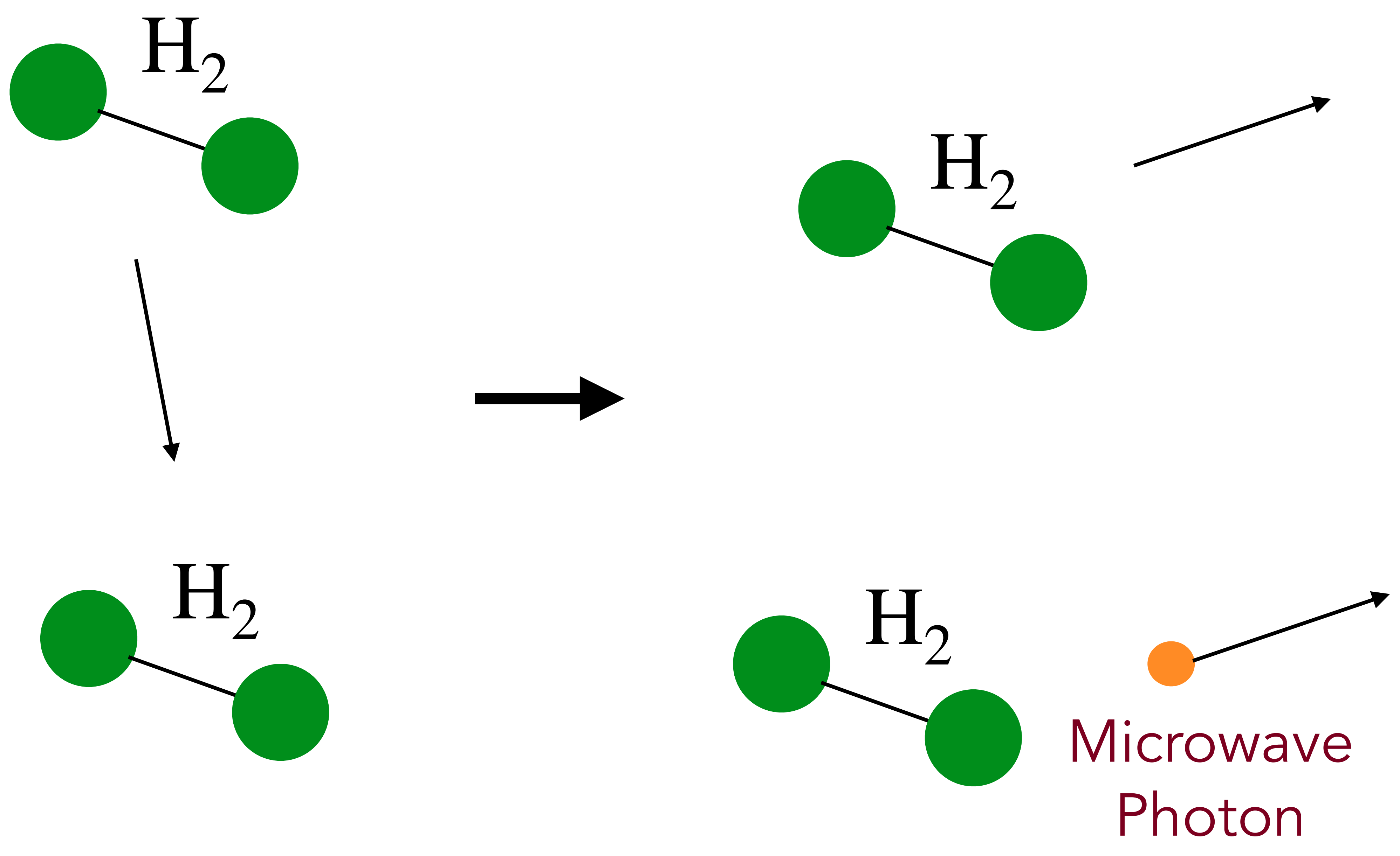
potential energy ~ kinetic energy

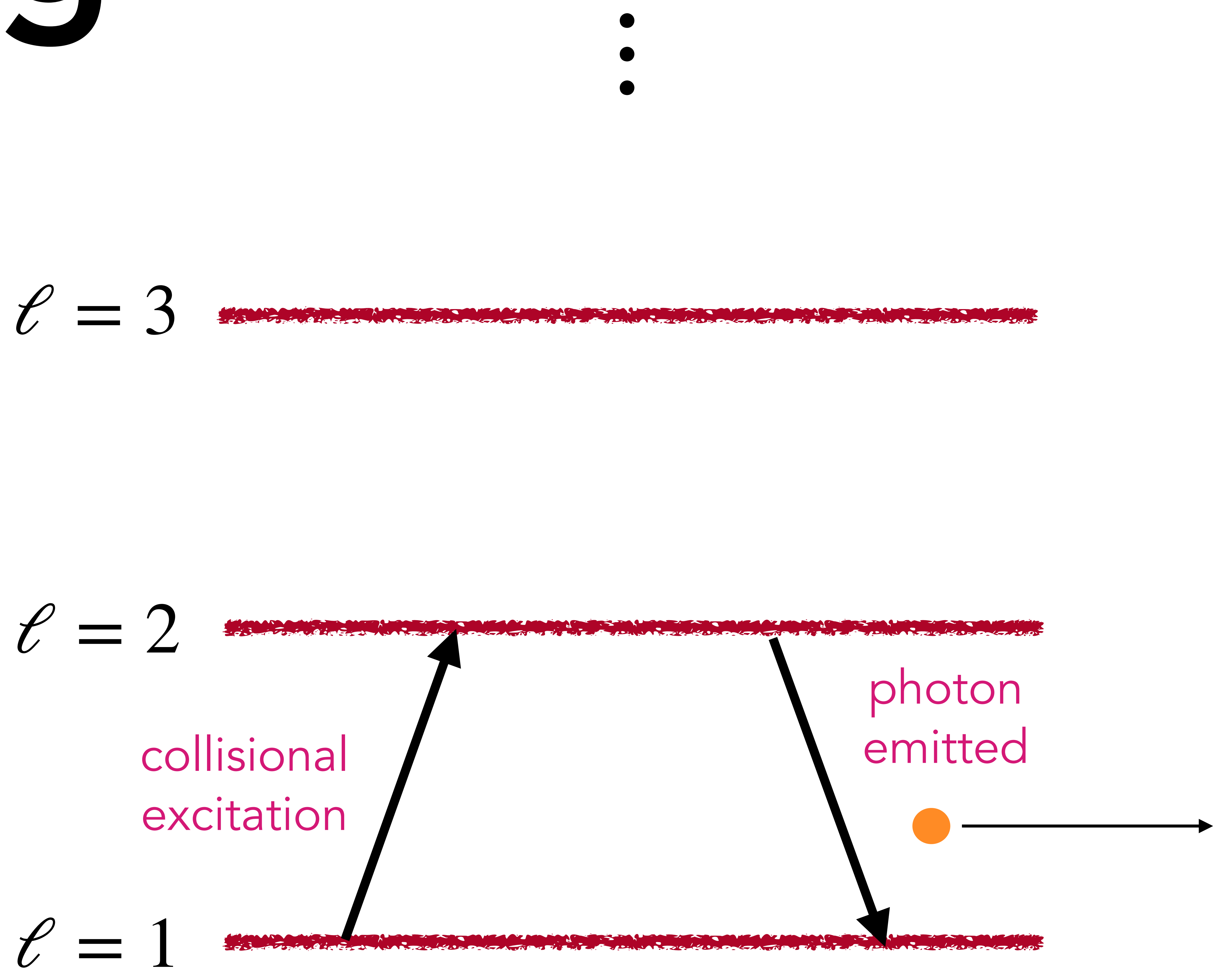
$$NT_h \sim \frac{GM_h^2}{R_h}, N \sim \frac{M_h}{m_{\rm H}}$$

$$T_h \sim 3 \times 10^3\,{\rm K} \left(\frac{M_h}{10^6 M_\odot} \right)^{2/3} \left(\frac{\rho_h}{200 \rho_{\rm crit}(z = 20)} \right)^{1/3}$$

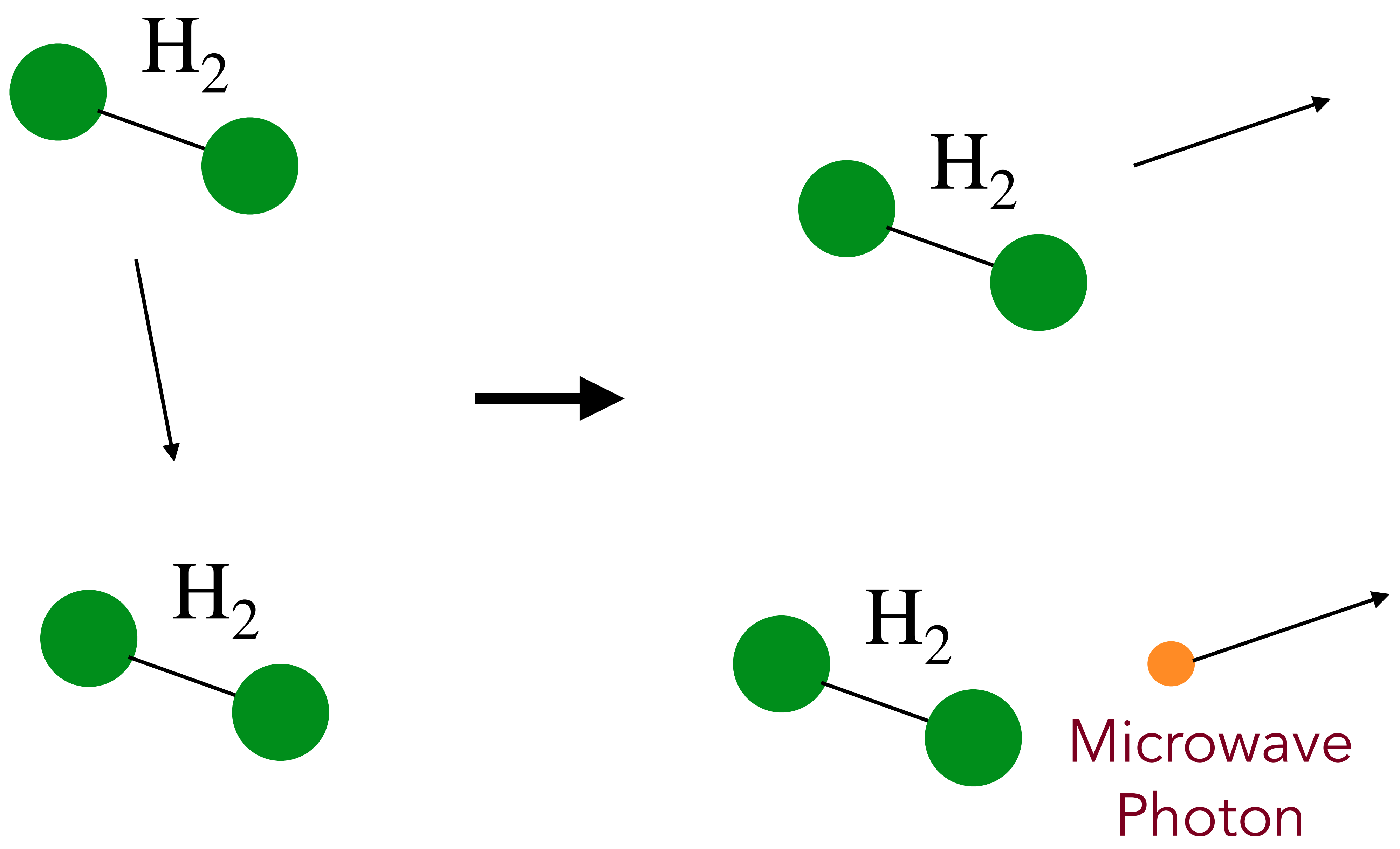
Atomic cooling (and bremsstrahlung) cannot cool gas below $\sim 10^3\,{\rm K}$ in typical halos.

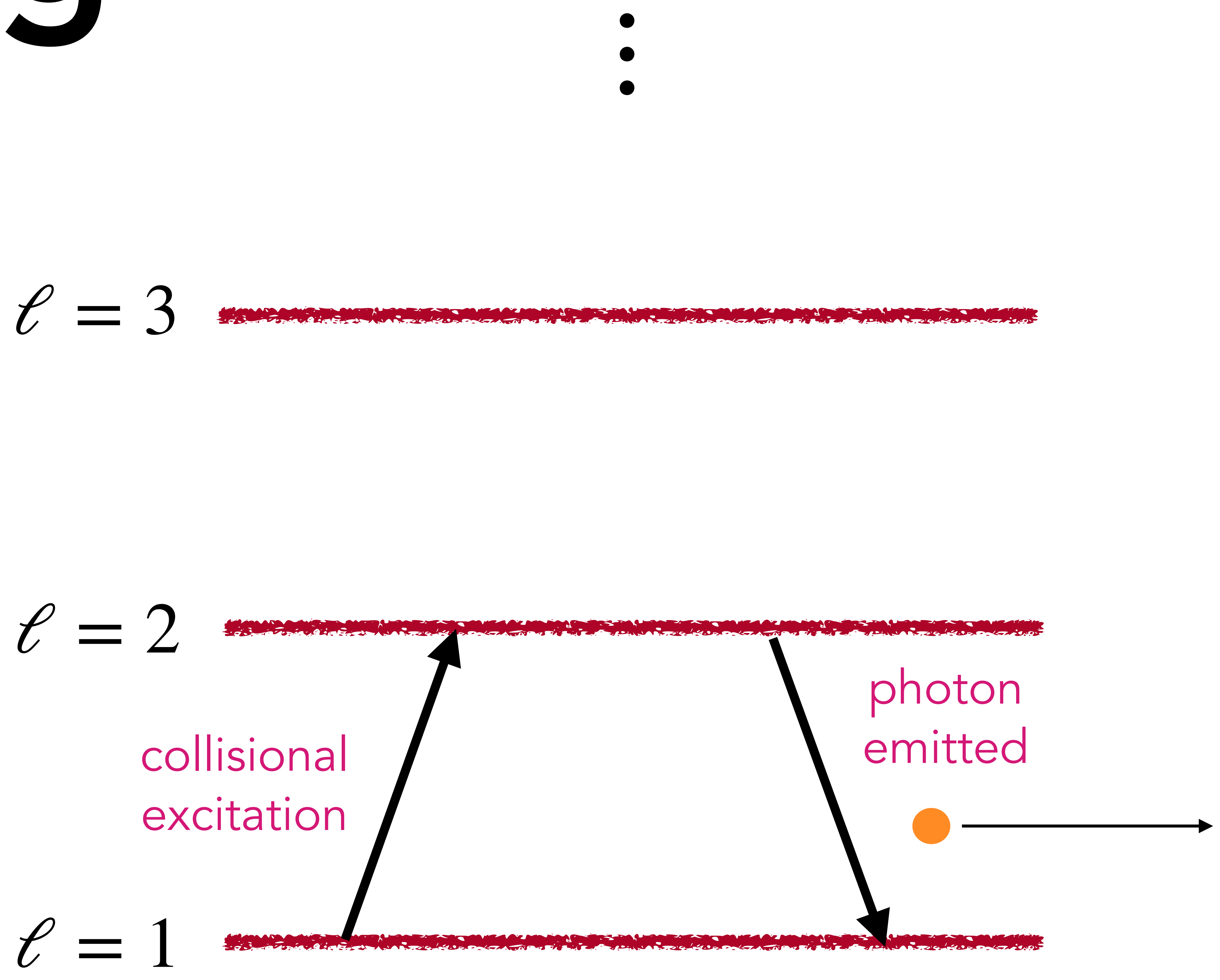
Molecular Cooling





Molecular Cooling





Cooling from collisional excitation of **hydrogen molecules crucial for star formation**. How does DM affect H_2 formation?

Molecular H_2 Formation

$$\mathrm{H} + e^- \leftrightarrow \mathrm{H}^- + \gamma$$

$$\mathrm{H} + \mathrm{H}^- \leftrightarrow \mathrm{H}_2 + e^-$$

$$\mathrm{H}^+ + \mathrm{H}^- \leftrightarrow 2\mathrm{H}$$

$$\mathrm{H}_2 + \gamma_{\mathrm{LW}} \leftrightarrow 2\mathrm{H}$$

Molecular hydrogen formation affected by changes in **ionization**, **heating** and **low-energy photons**.

Molecular H_2 Formation

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Molecular hydrogen formation affected by changes in **ionization**, **heating** and **low-energy photons**.

Dark Matter and H_2

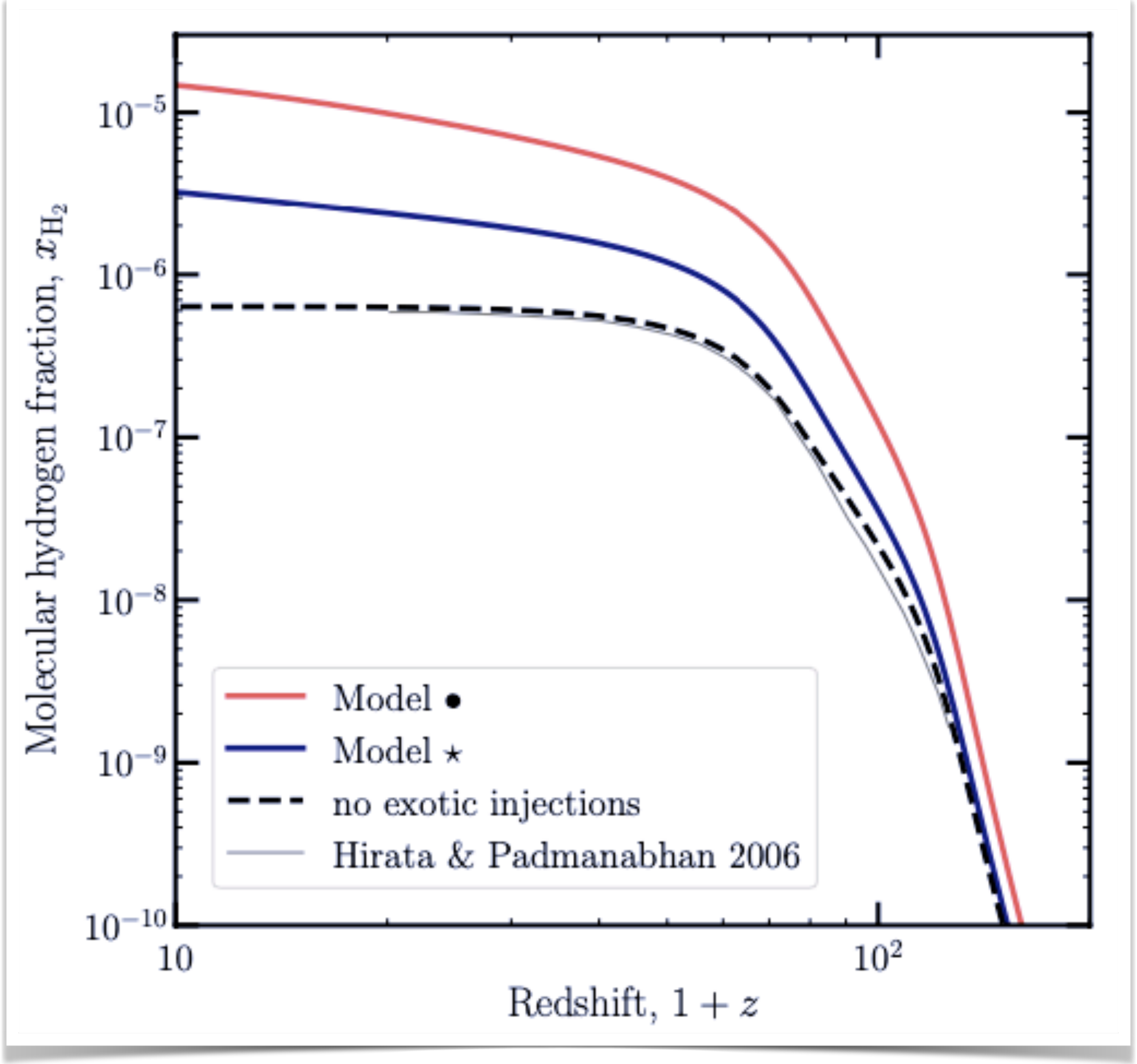
	Channel	Mass [MeV]	$\log_{10}(\tau/[s])$
Model •	$\chi \to e^+e^-$	185	25.6
Model ⋆	$\chi \to e^+e^-$	185	26.4

$$H + e^- \leftrightarrow H^- + \gamma$$

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

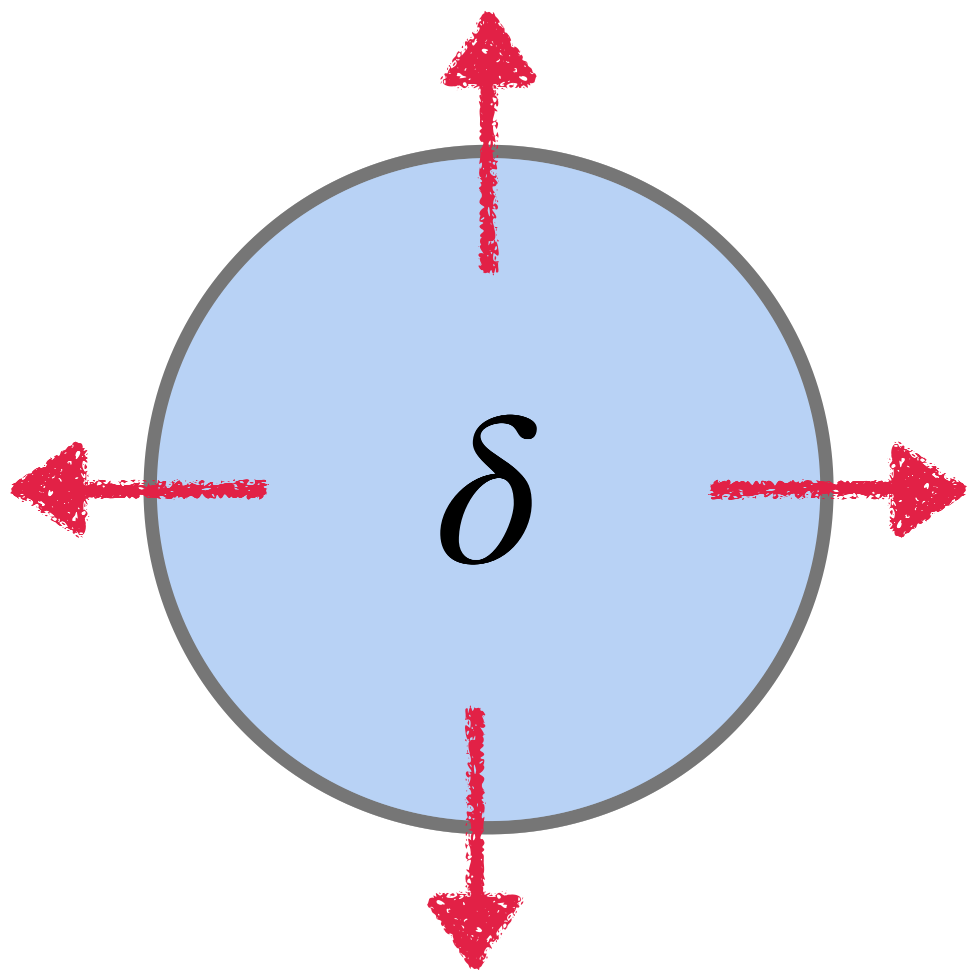
$$H^+ + H^- \leftrightarrow 2H$$

$$H_2 + \gamma_{LW} \leftrightarrow 2H$$

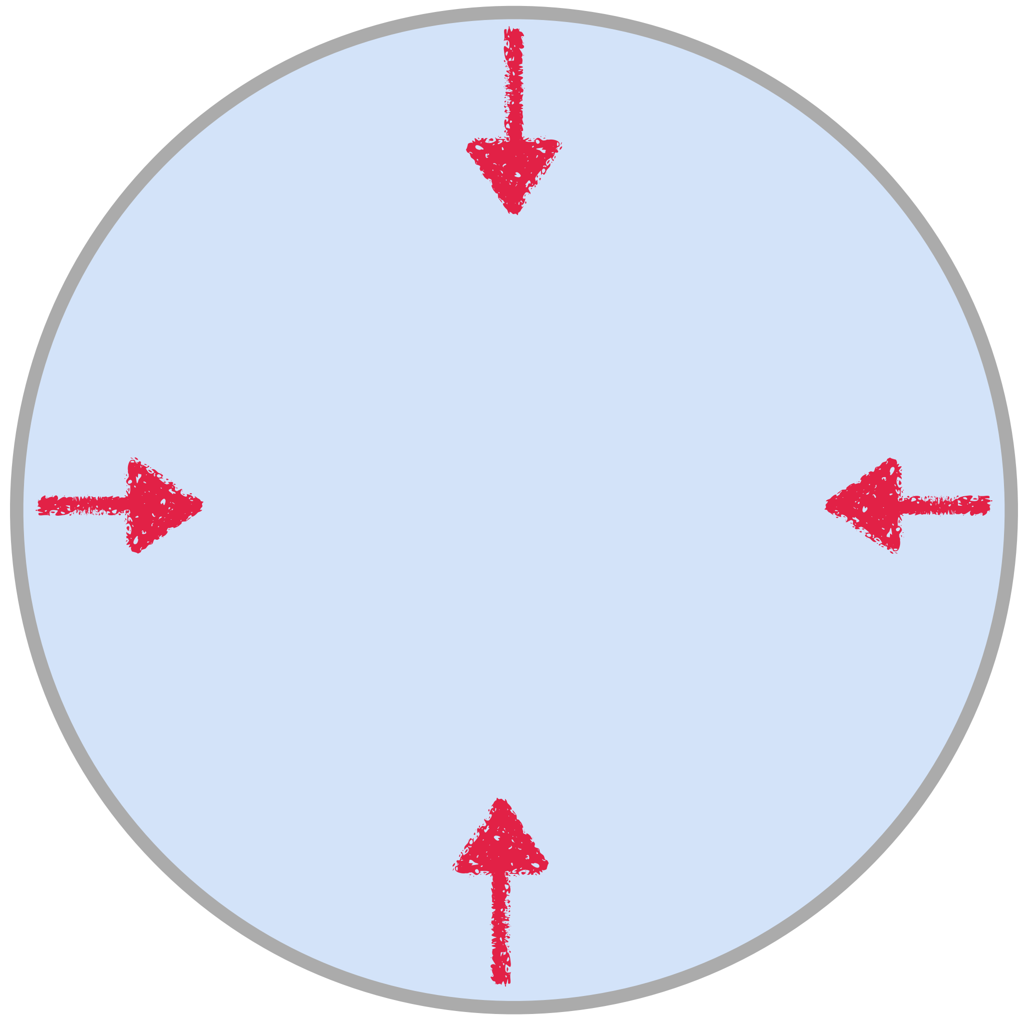


Molecular hydrogen formation affected by changes in **ionization**, **heating** and **low-energy photons**. **DM will change them all.**

Spherical Collapse



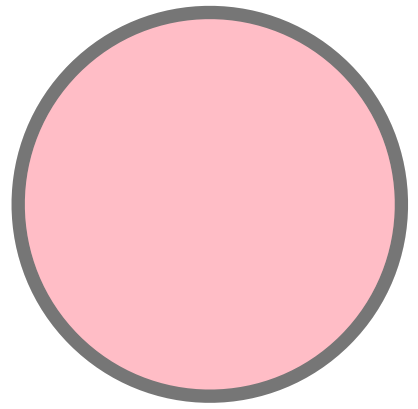
Overdensity initially undergoes Hubble expansion.



Gravitational pull counteracts expansion. Collapse begins.

$$NT_h \sim GM_h^2/R_h$$

$$\rho_h \sim 200\rho_{\text{crit}}$$

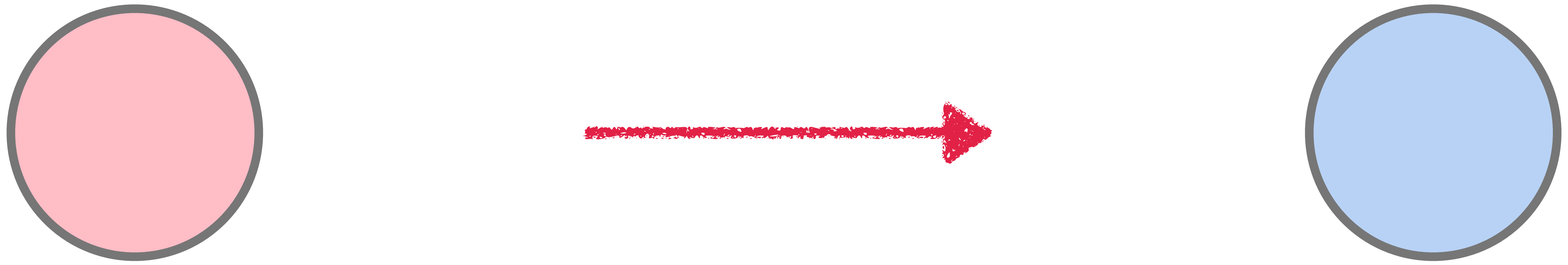


Collapse leads to virialization.

Really requires **simulation**. To get a sense of the effect, we adopt the **spherical collapse** model.

How Efficient is Cooling?

$$NT \sim GM_h^2/R_h$$
$$\rho_h \sim 200\rho_{\rm crit}$$



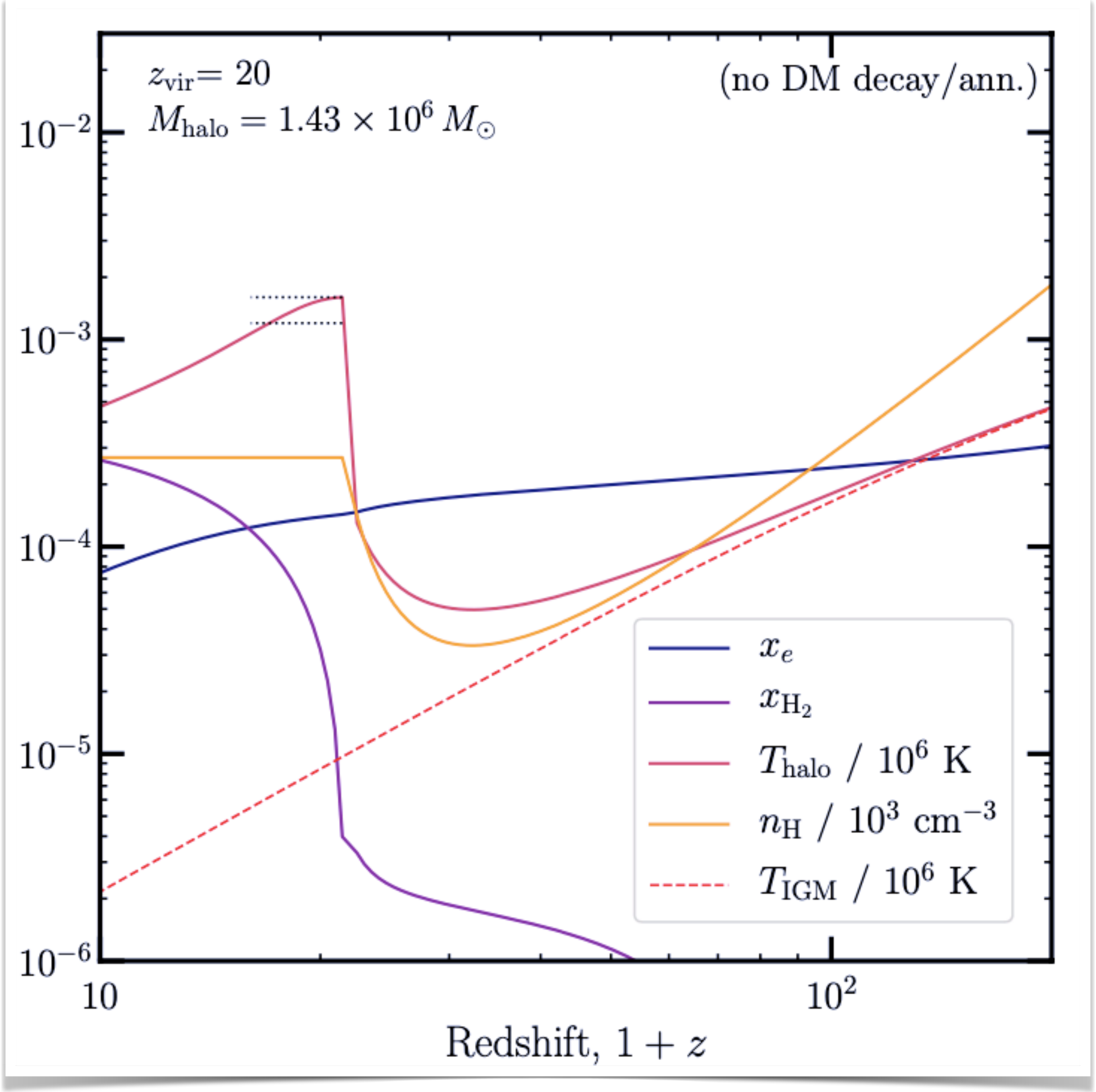
Molecular hydrogen formed during spherical collapse.

Molecular cooling occurs in the halo.

We consider cooling to be **efficient** if after virialization, $|\dot{T}_h| \gtrsim HT_h$. This is our **star formation criterion**.

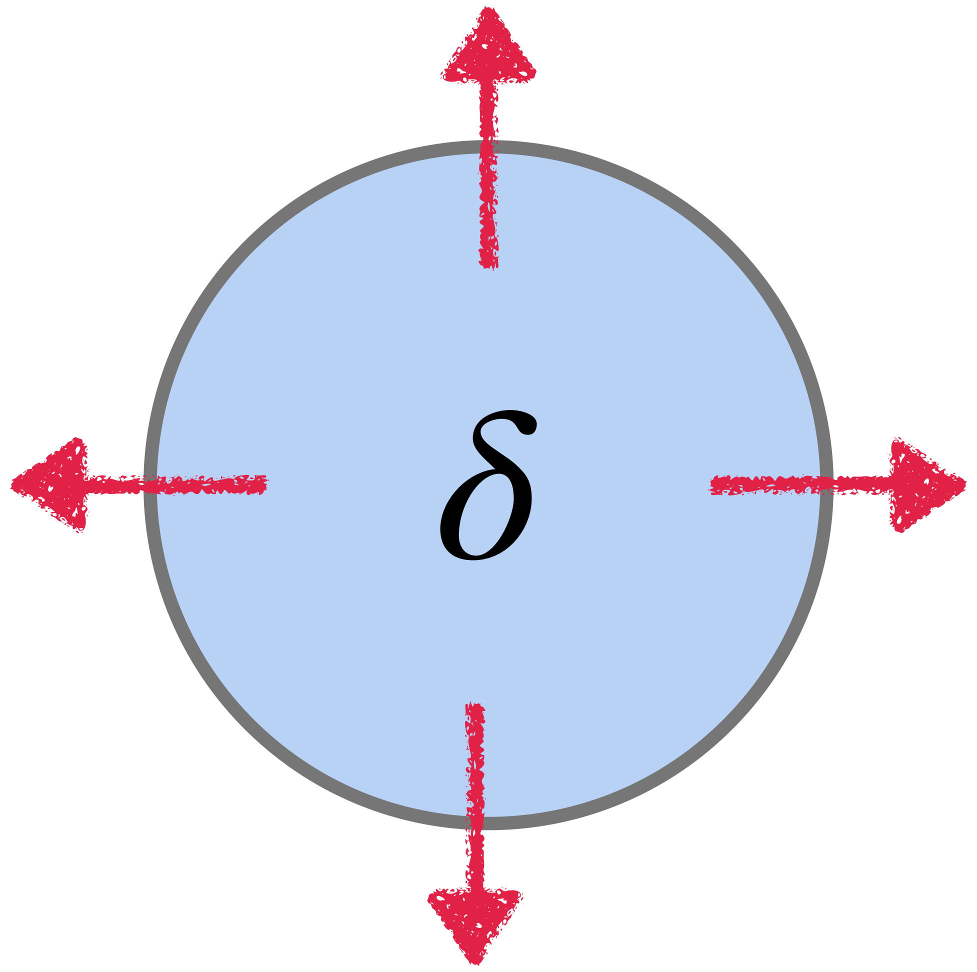
Evolution without DM

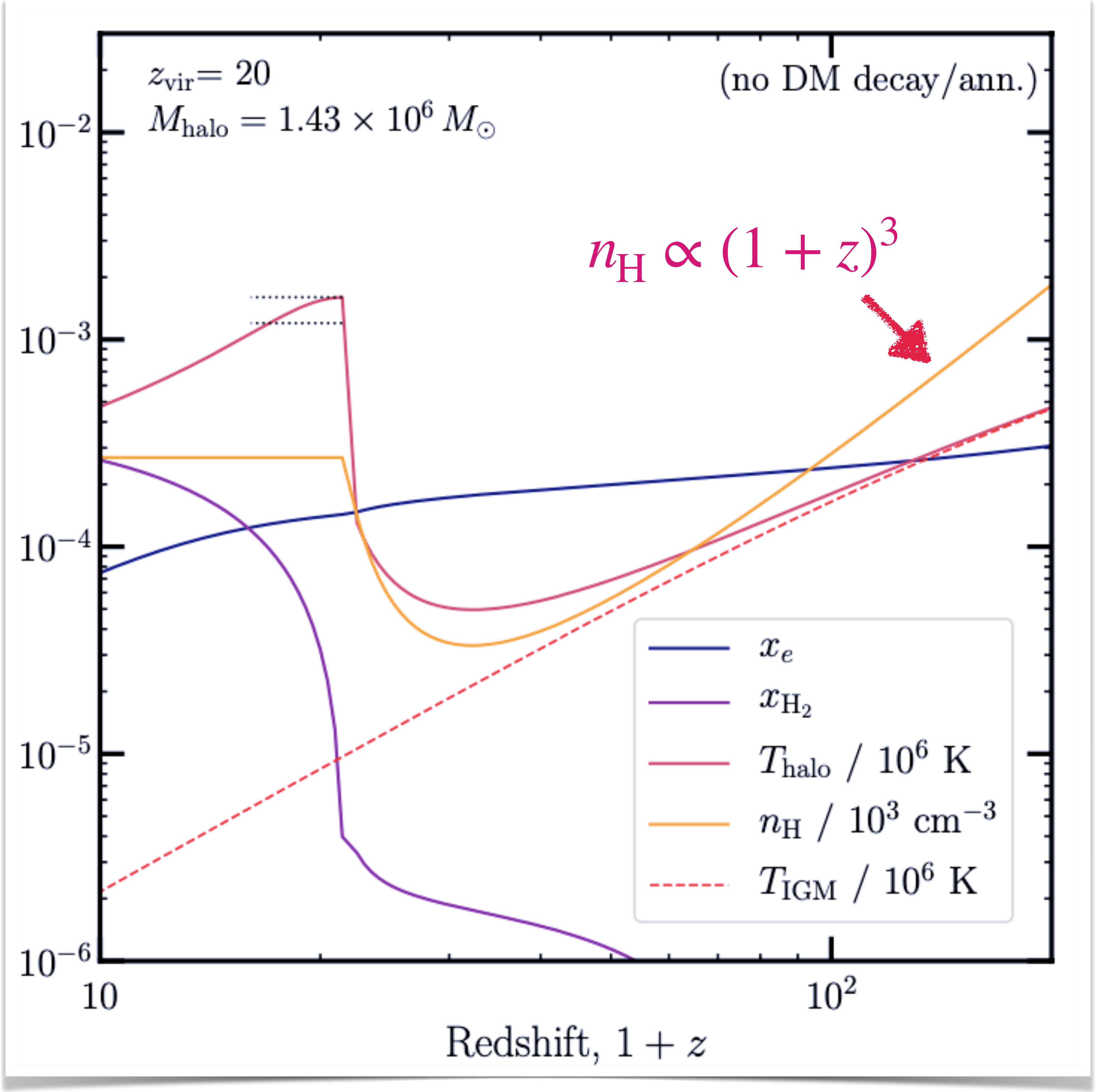
NO DM



Initial Hubble Expansion

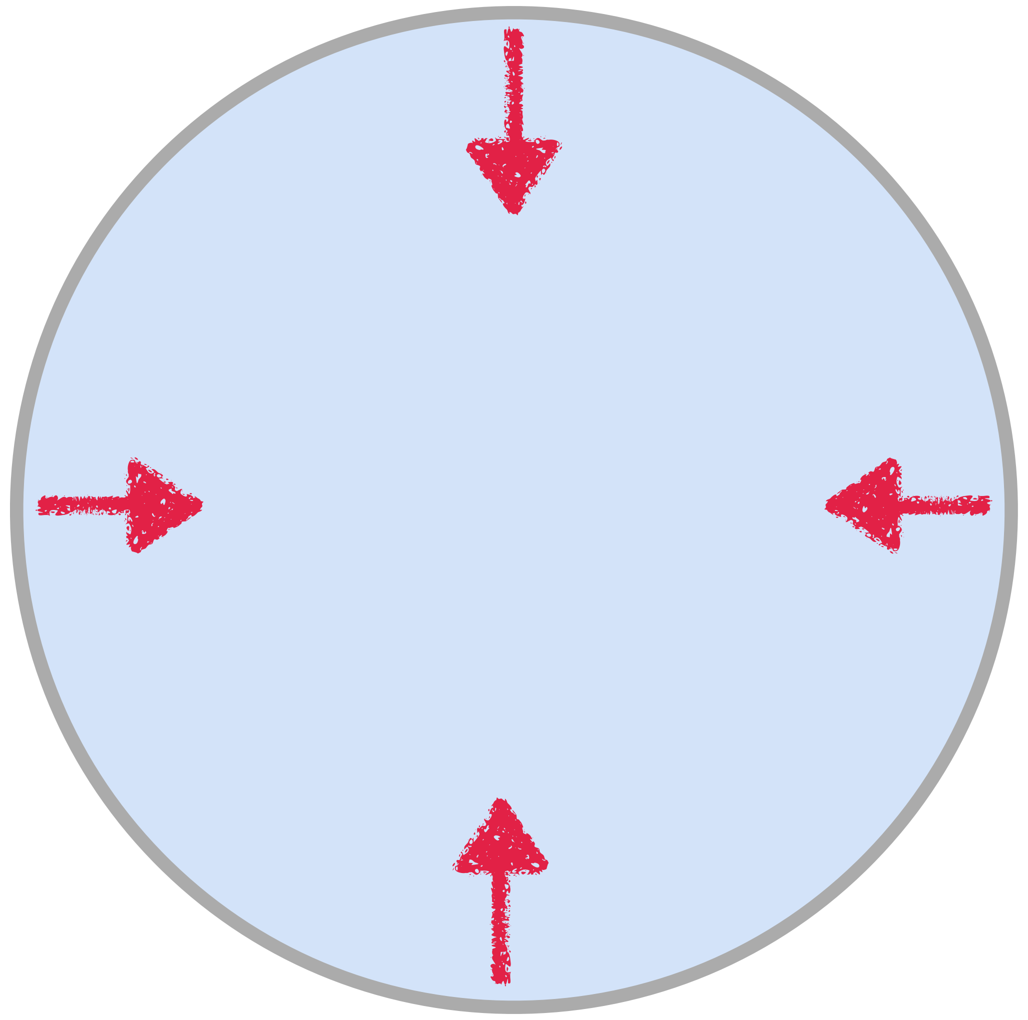
NO DM

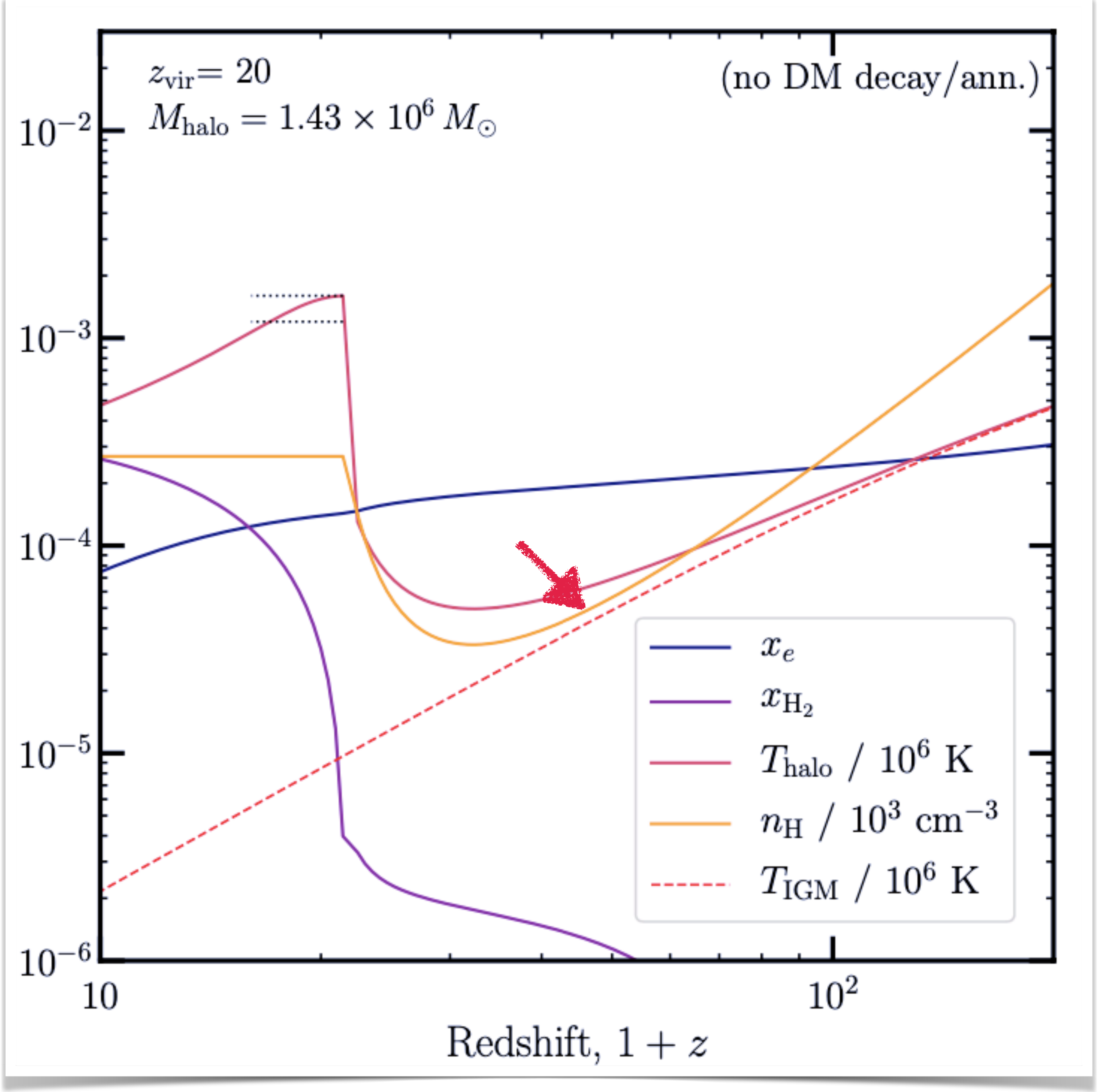




Spherical Collapse Begins

NO DM

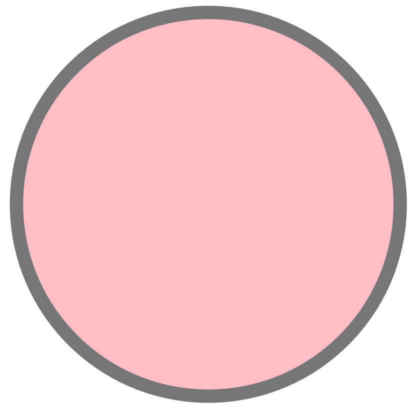


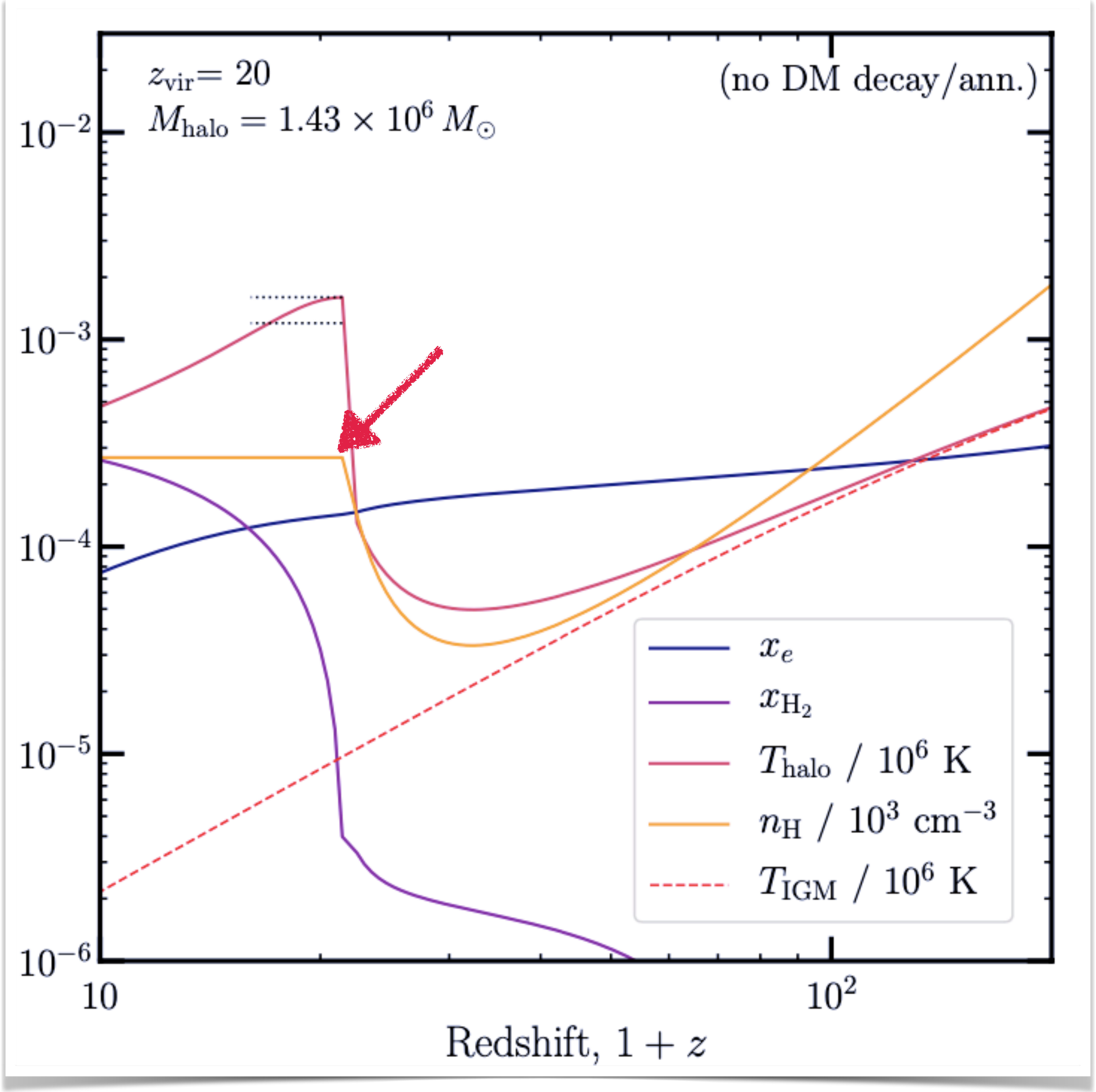


Virialization

NO DM

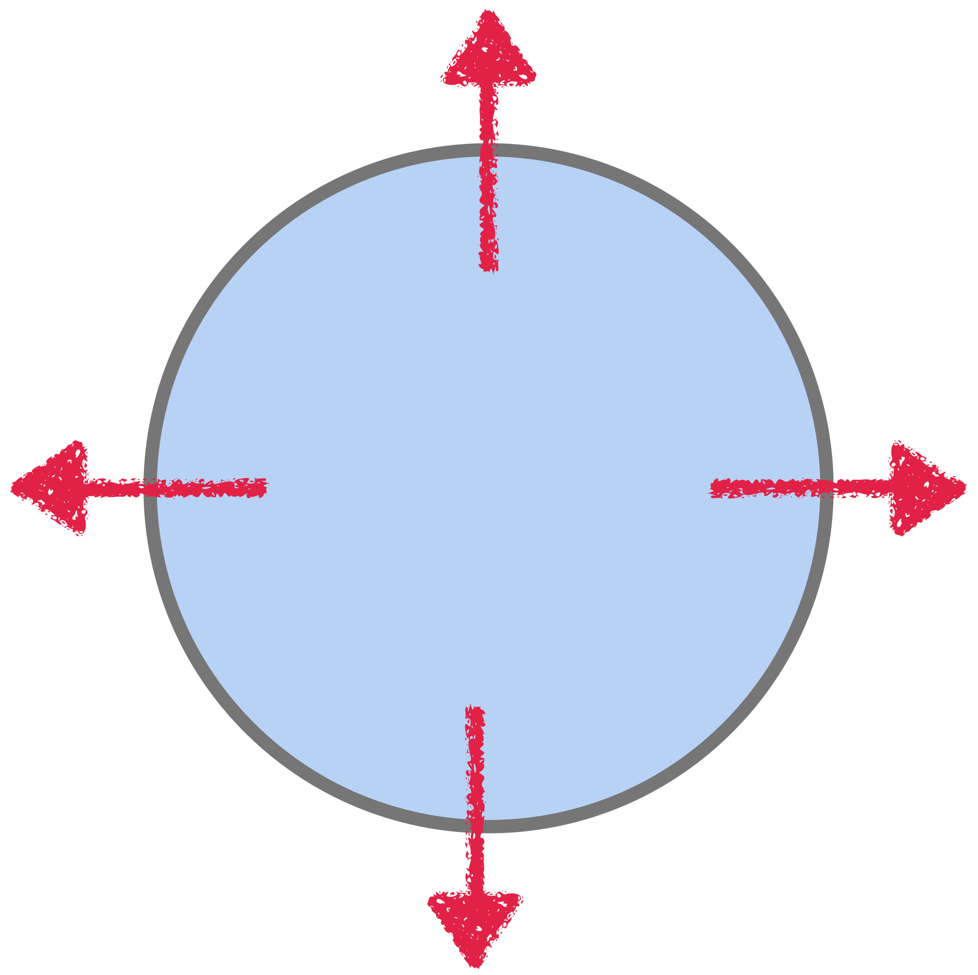
$$NT_h \sim GM_h^2/R_h$$
$$\rho_h \sim 200\rho_{\rm crit}$$

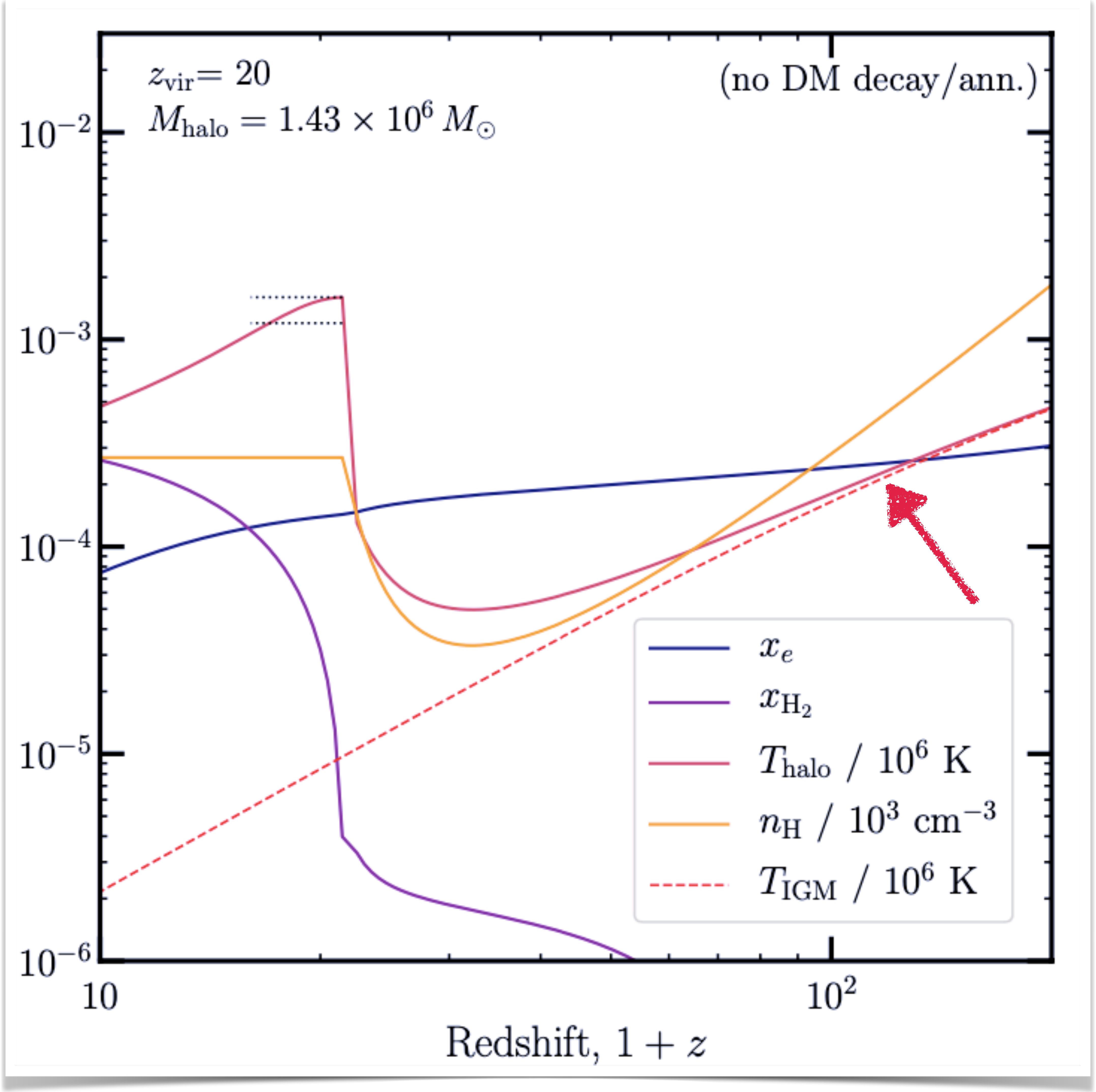




Intergalactic Medium (Mean) Evolution

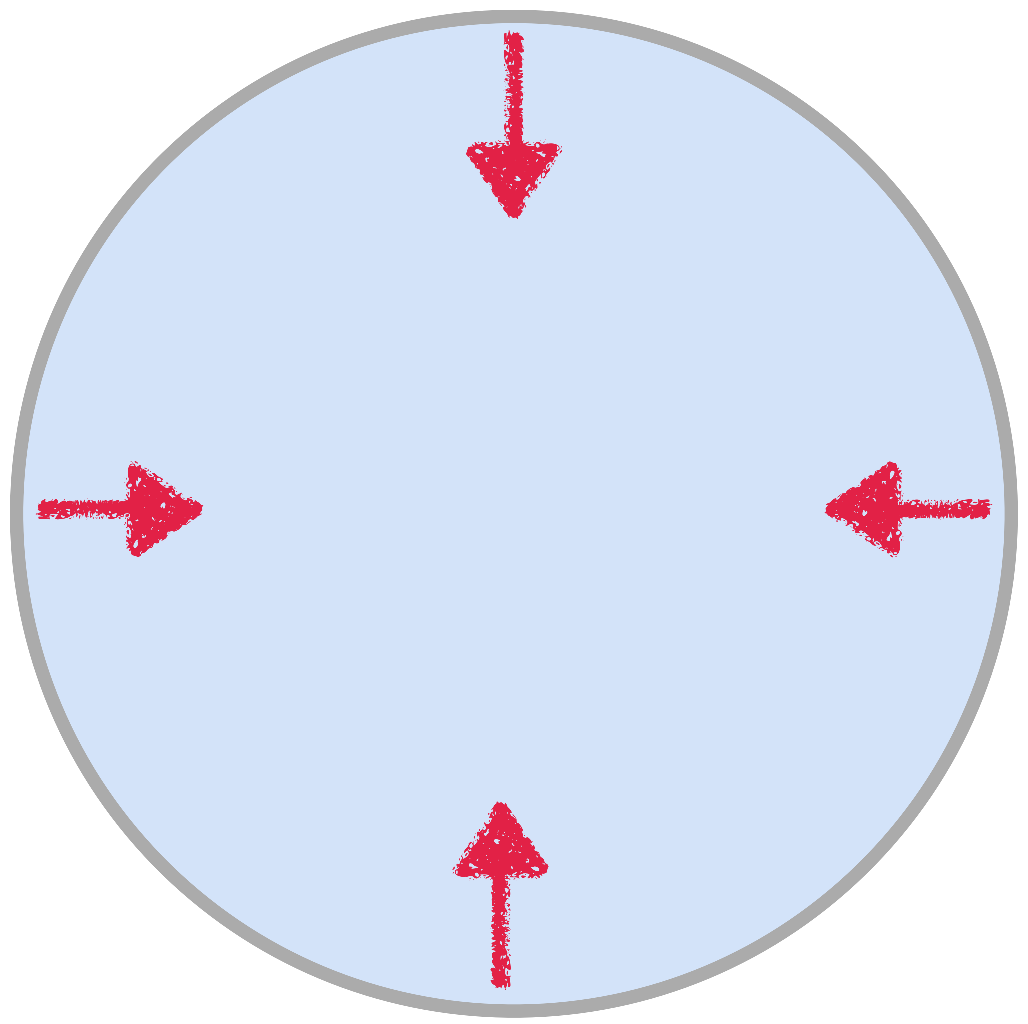
NO DM

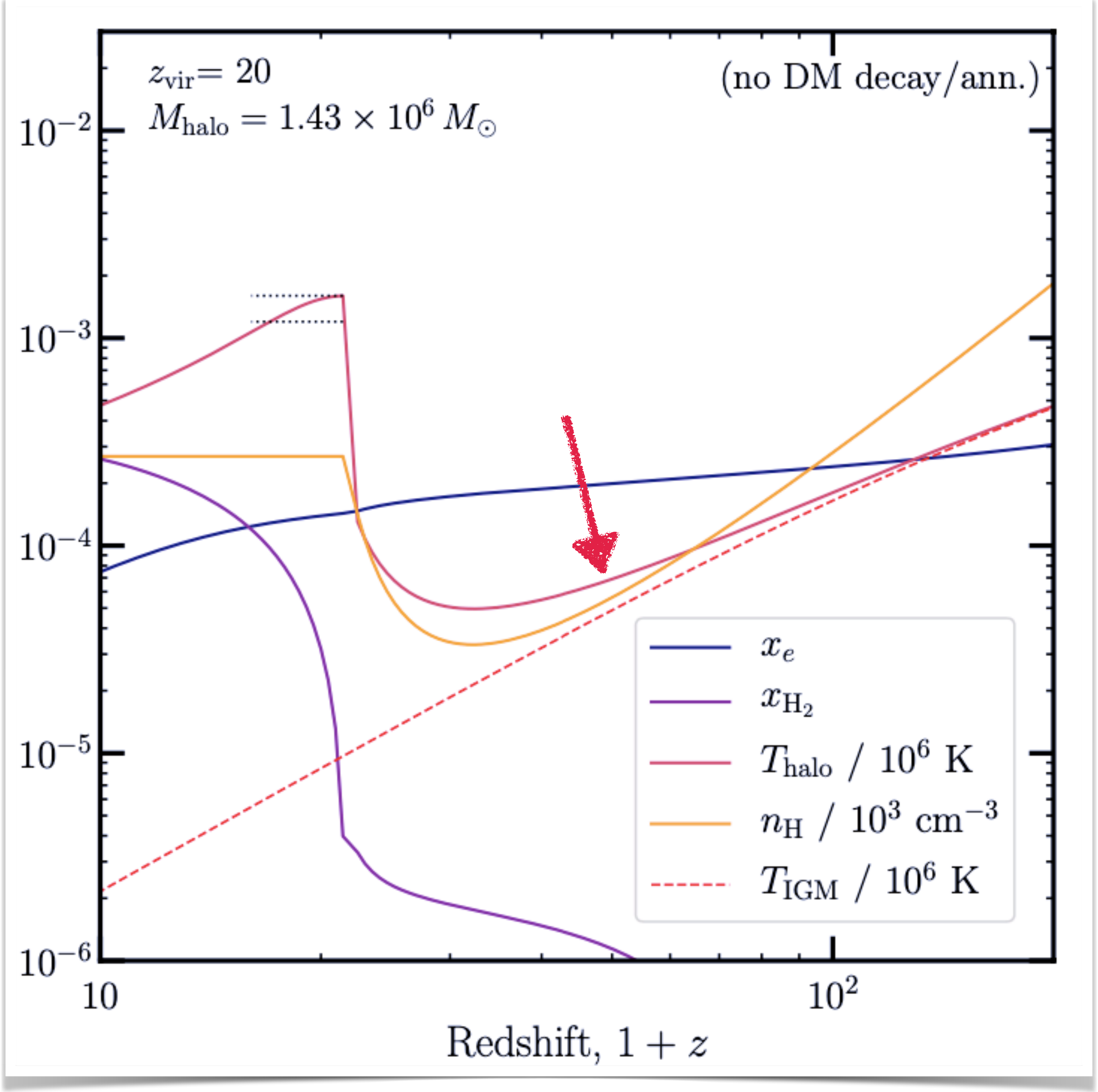




Heating due to Collapse

NO DM



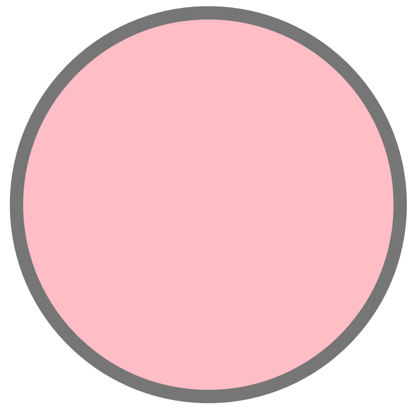


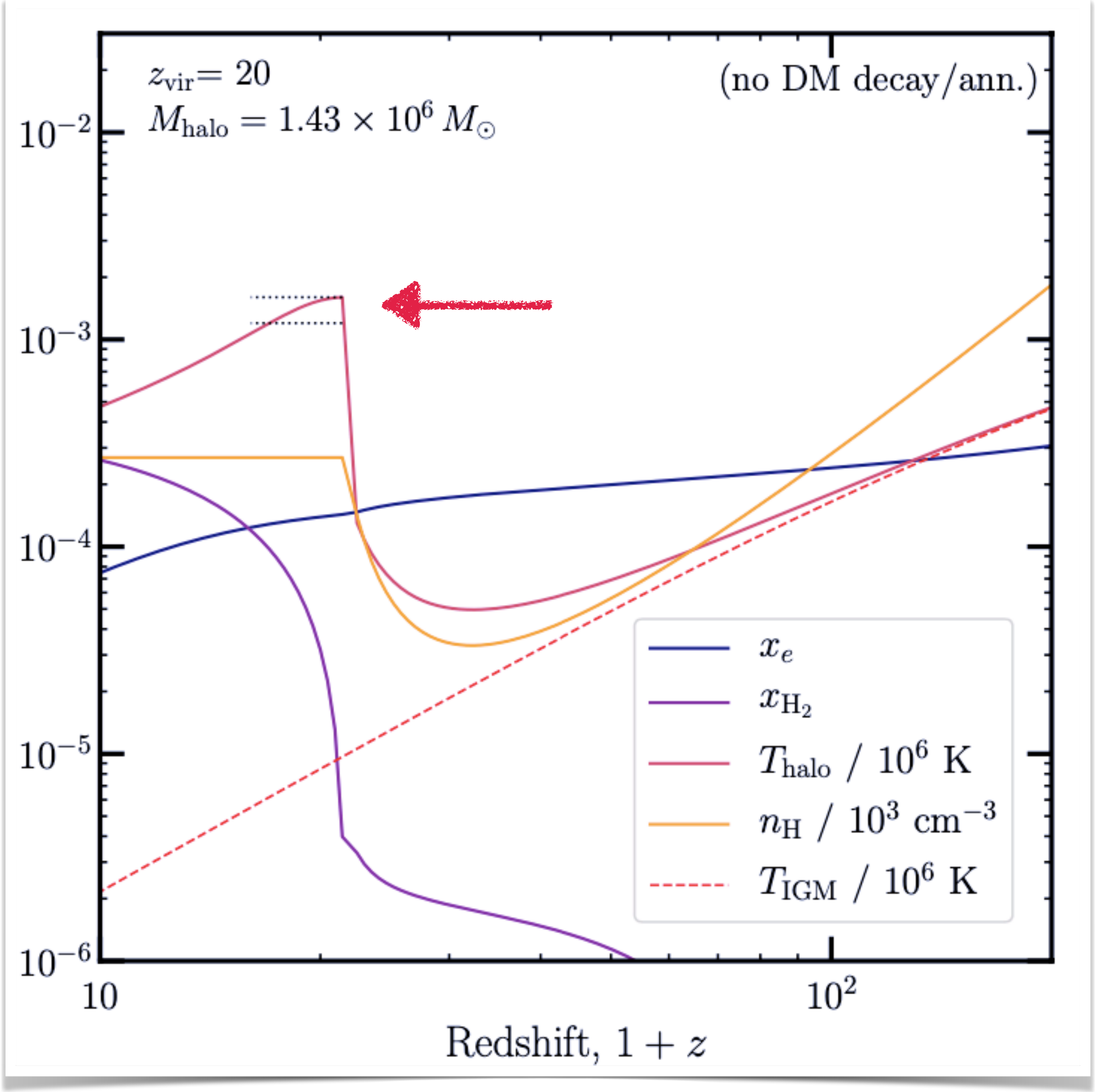
Virialization

NO DM

$NT_h \sim GM_h^2/R_h$

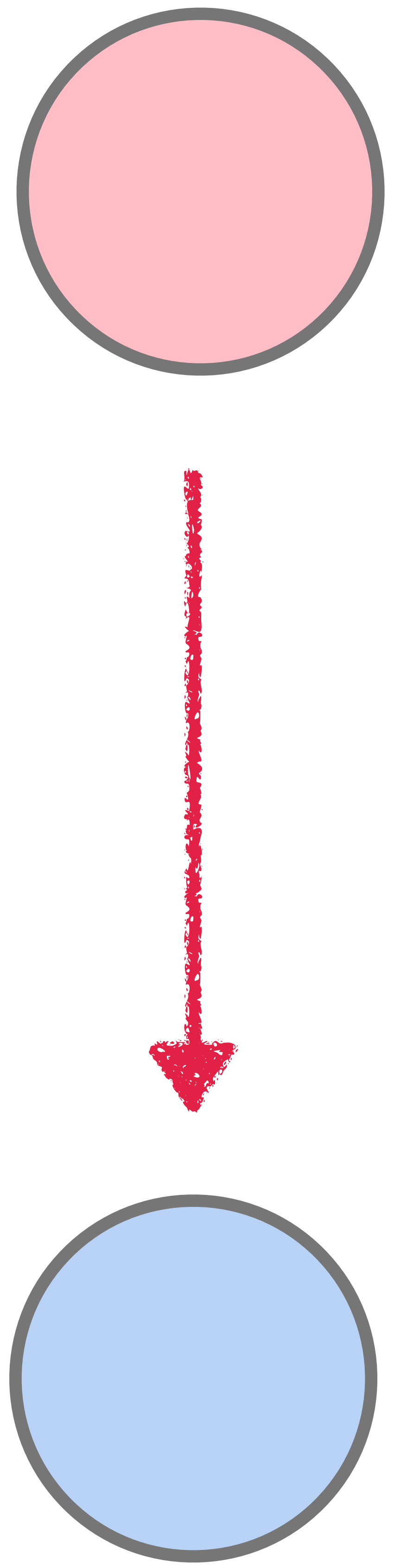
$\rho_h \sim 200\rho_{crit}$

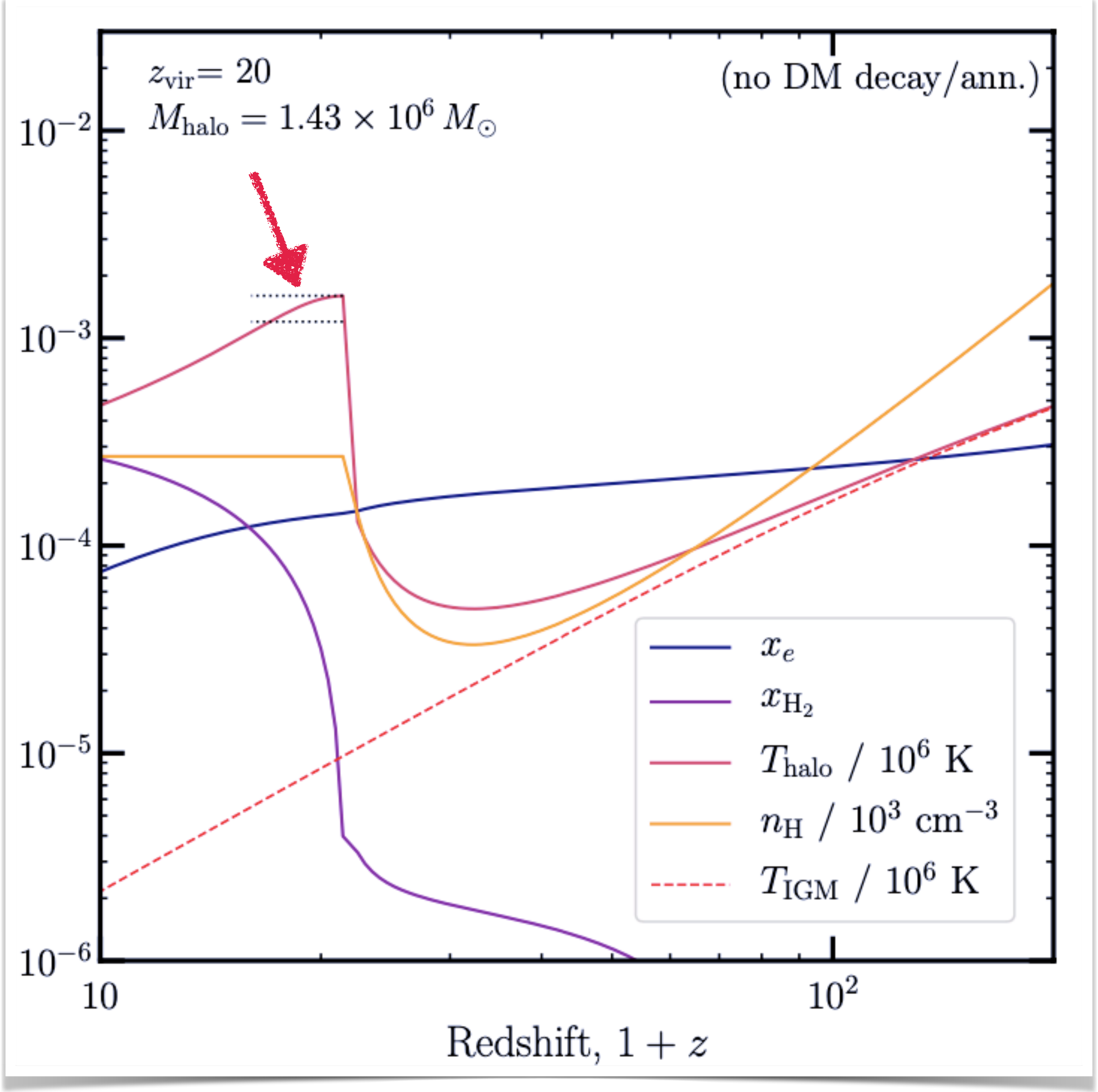




Cooling is Efficient!

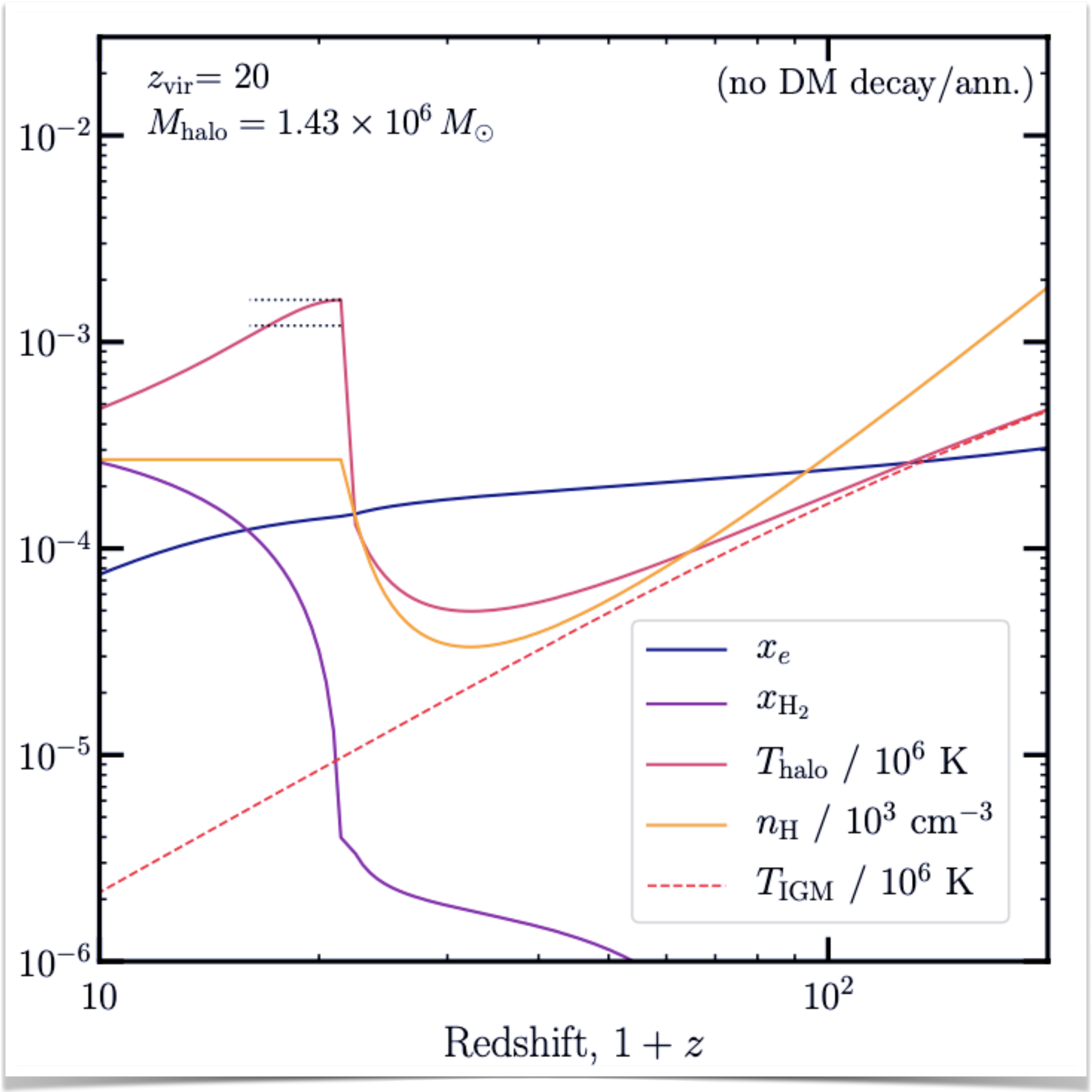
NO DM

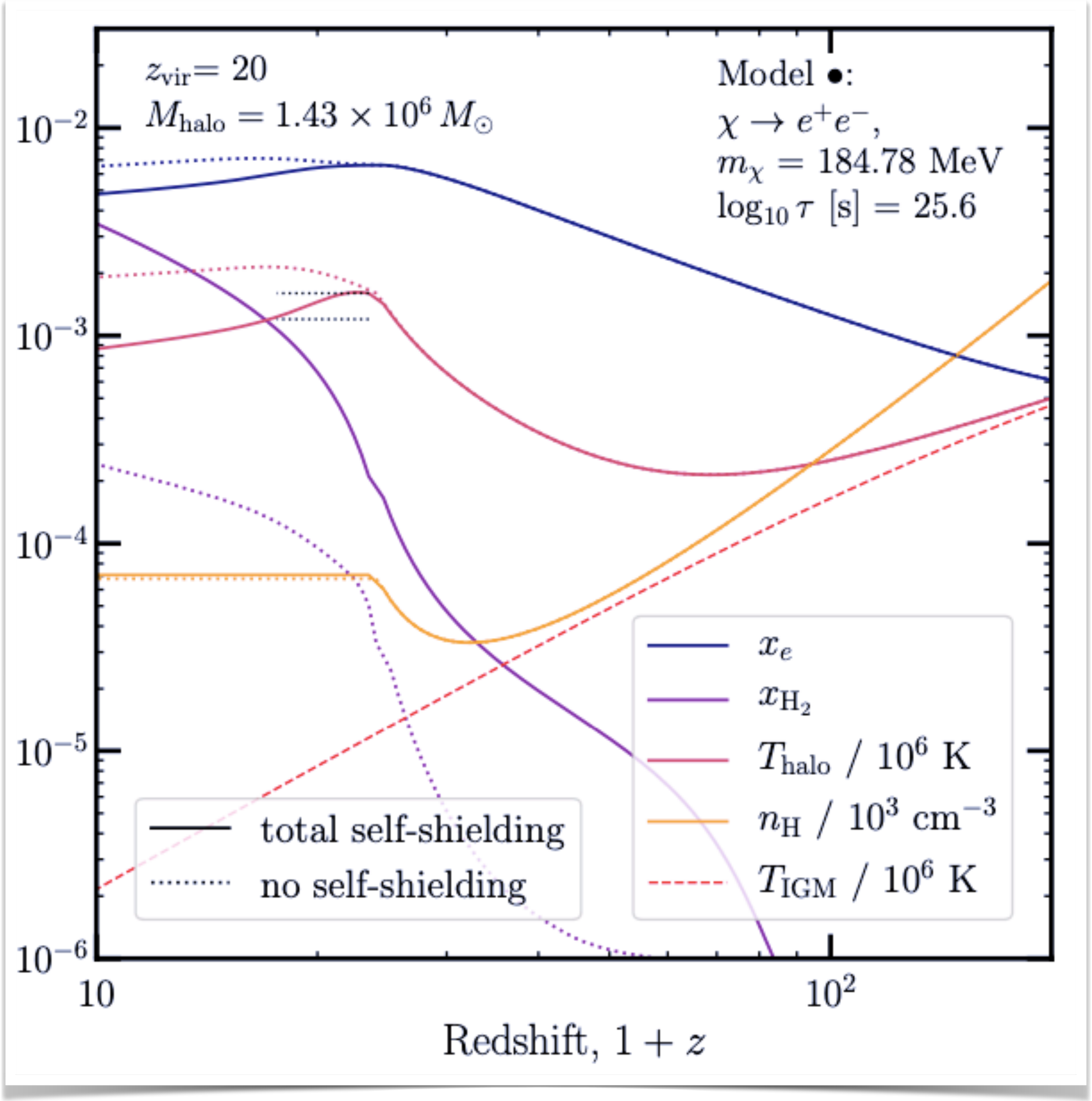




Comparison with Dark Matter

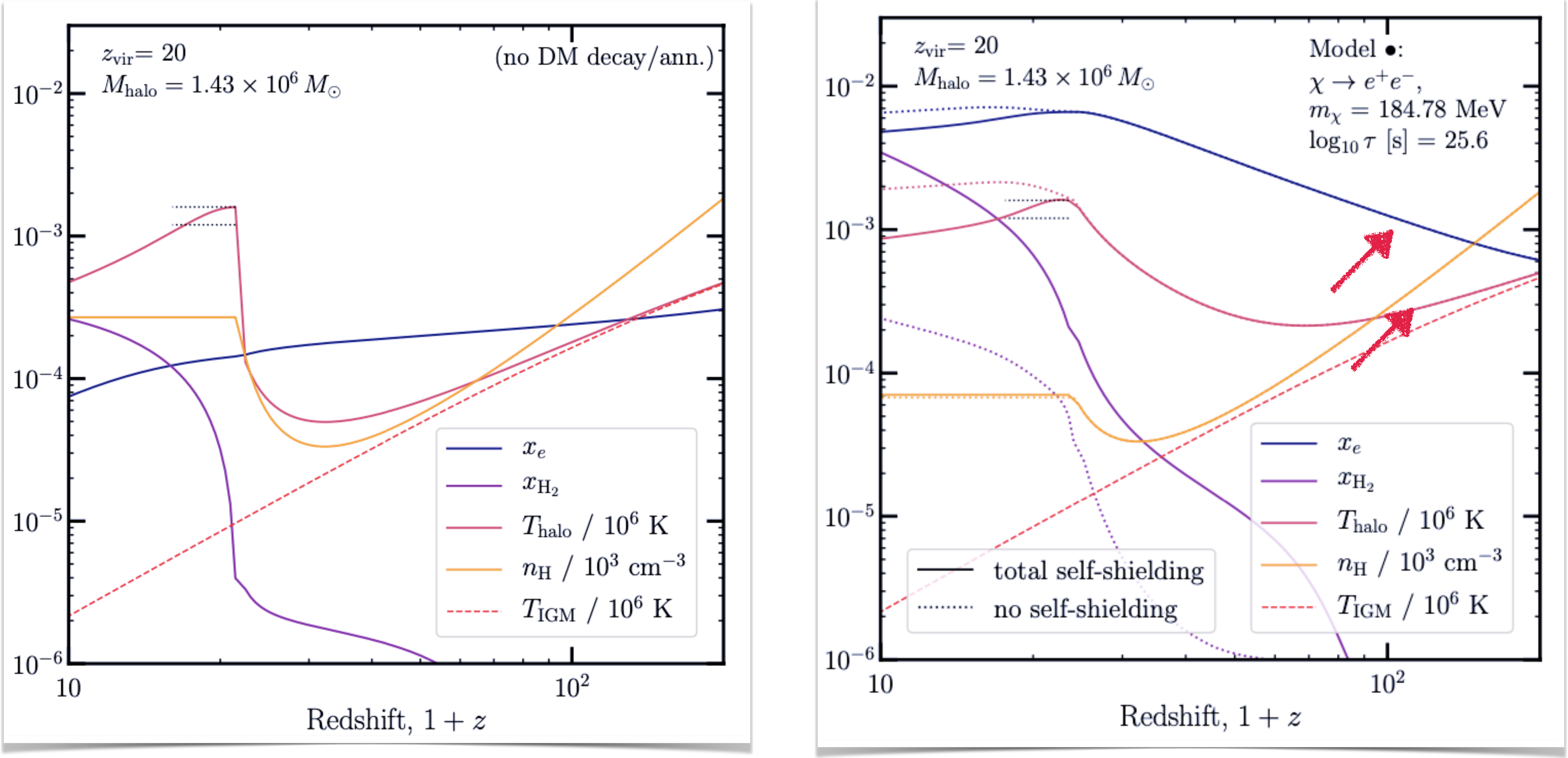
DM
Short τ





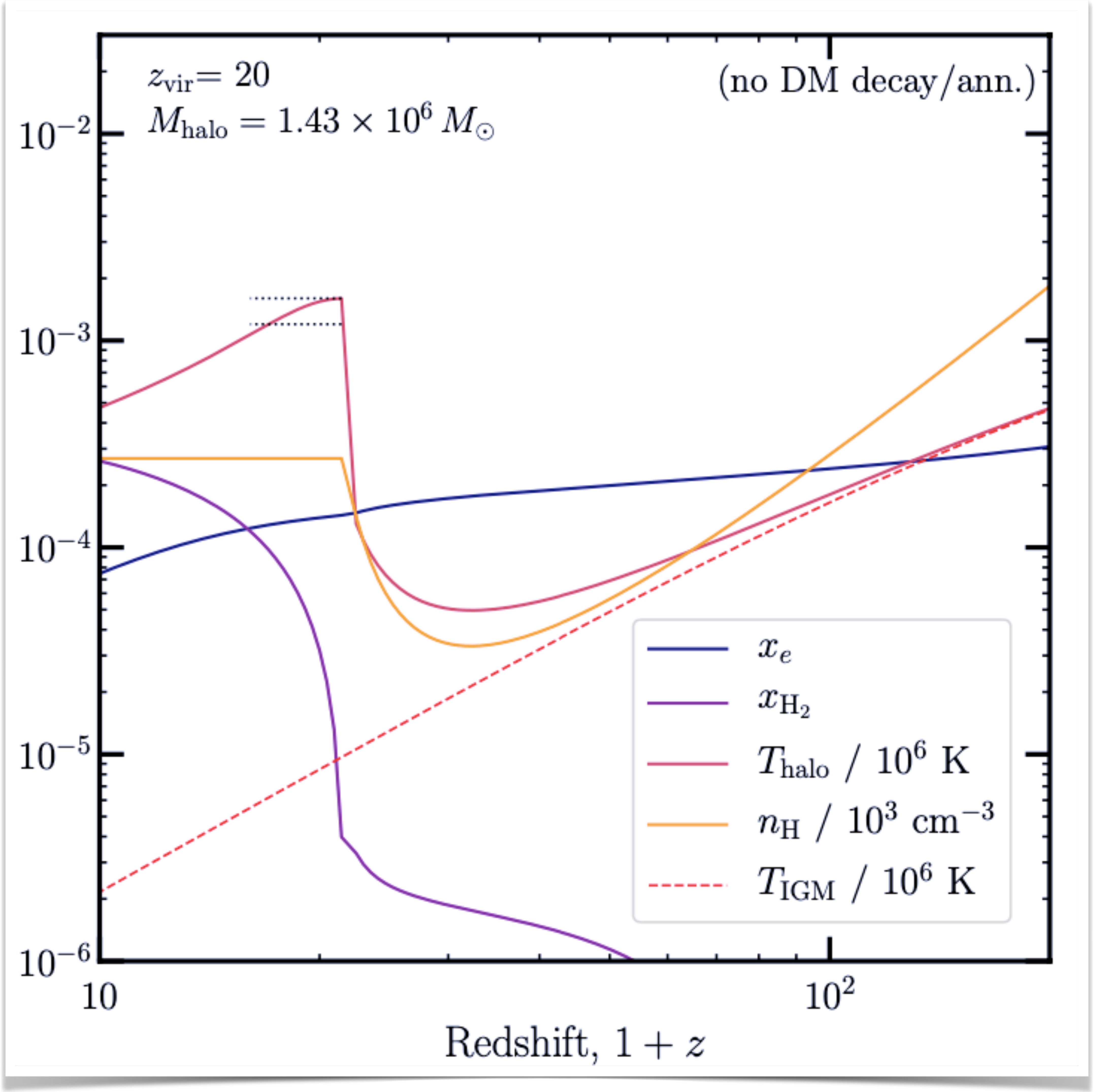
Additional Ionization and Heating

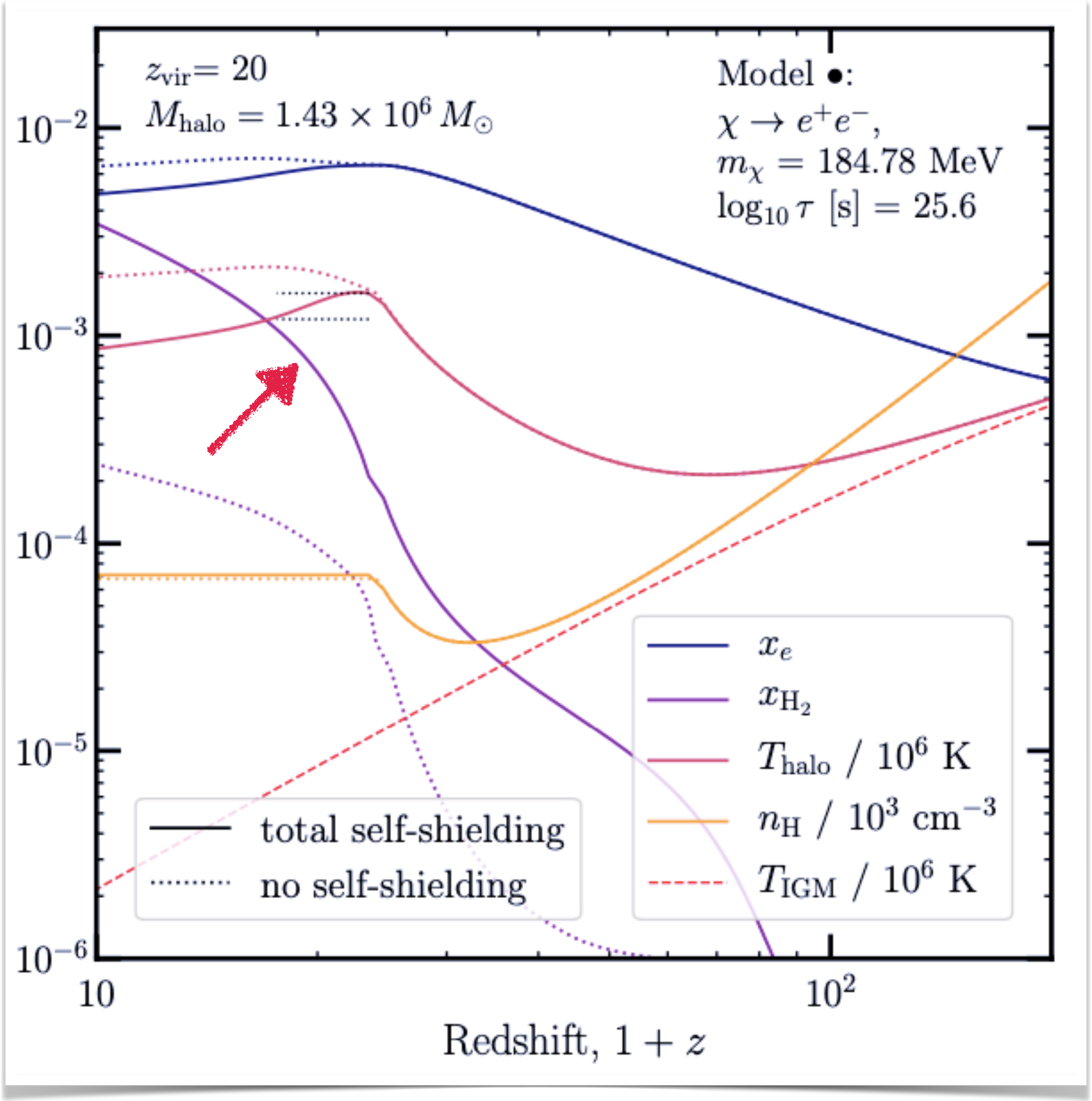
DM
Short τ



Increased Ionization by DM Boosts H_2

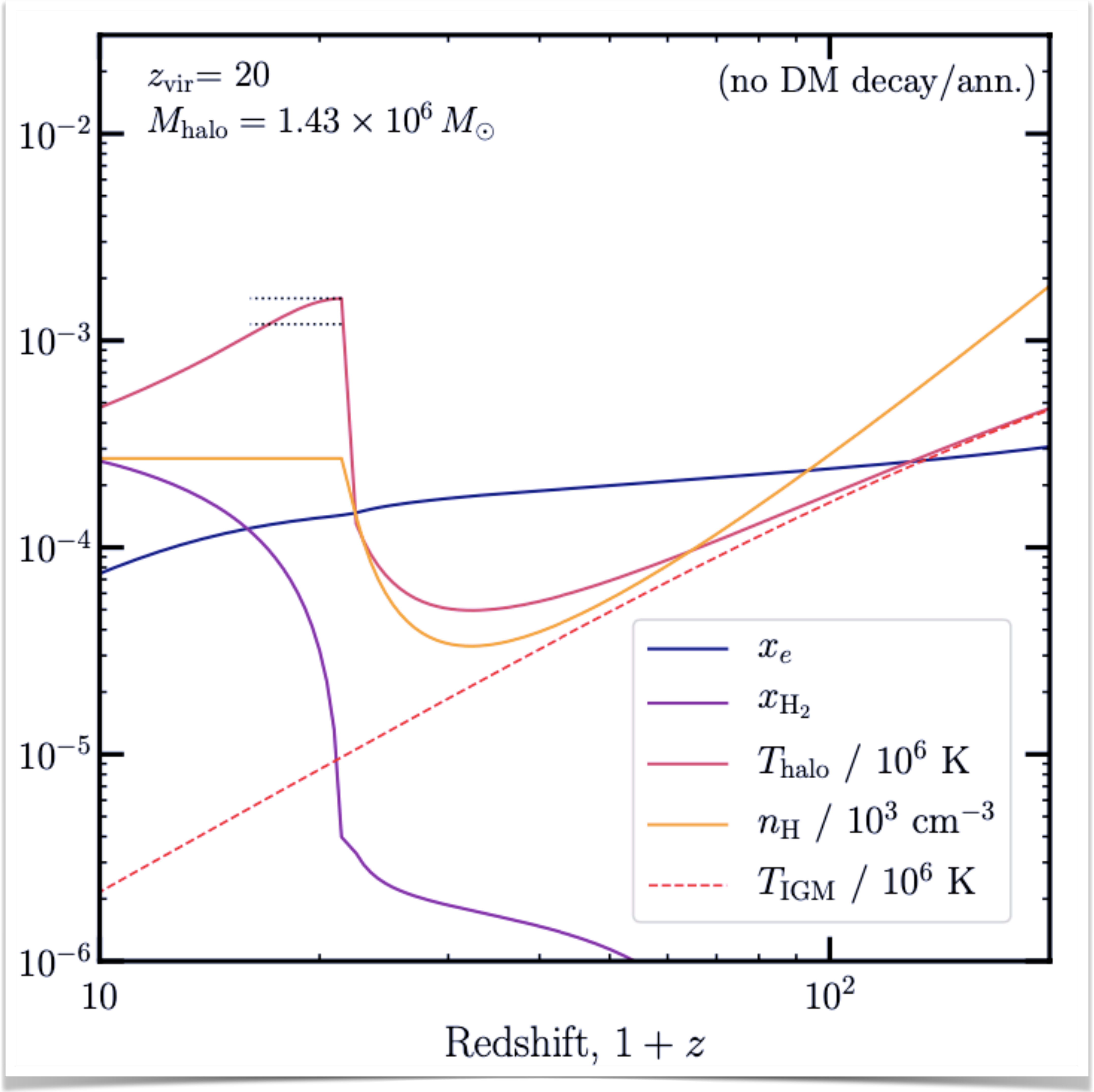
DM
Short τ

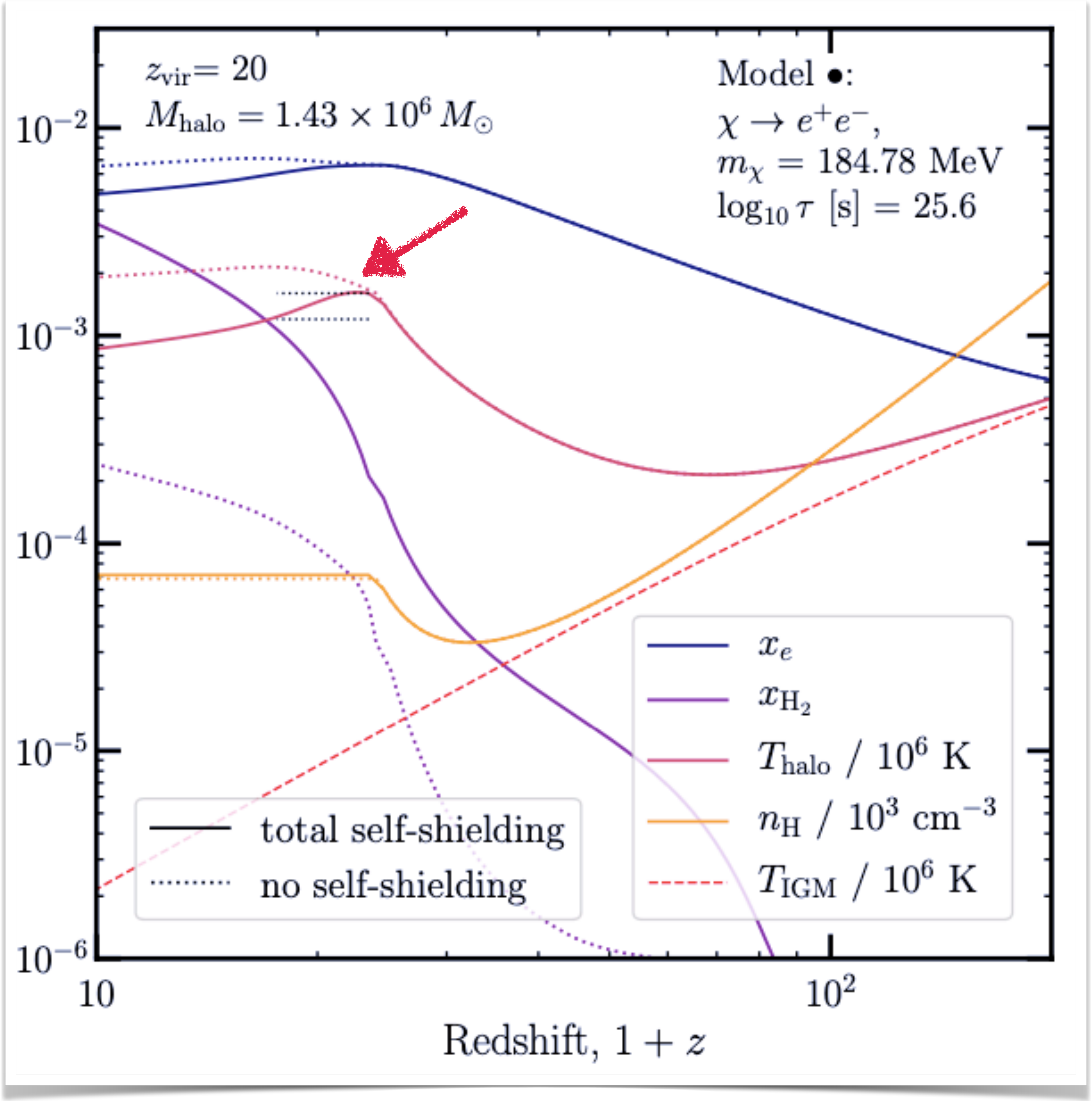




DM Heating Prevents Efficient Cooling

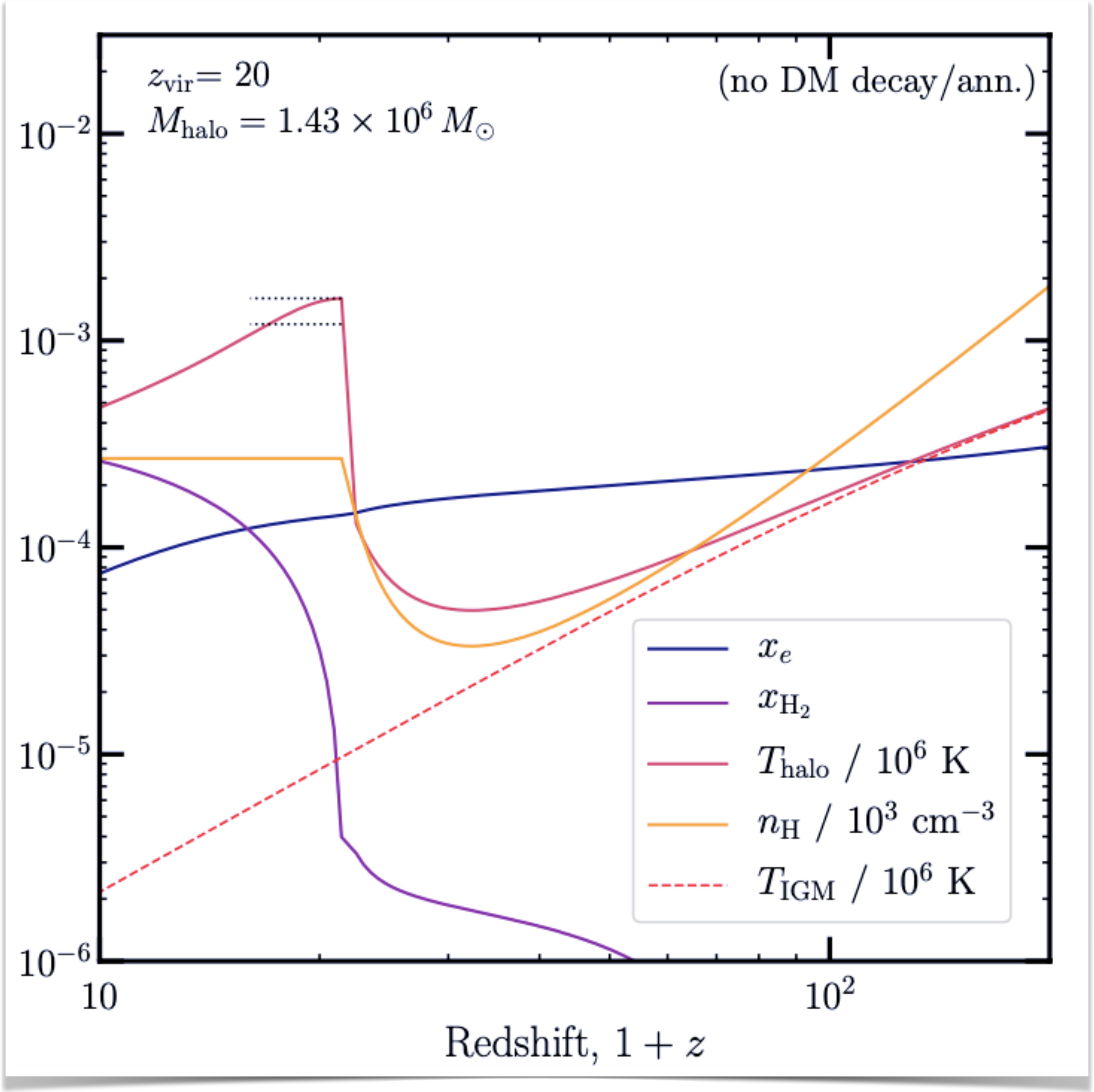
DM
Short τ

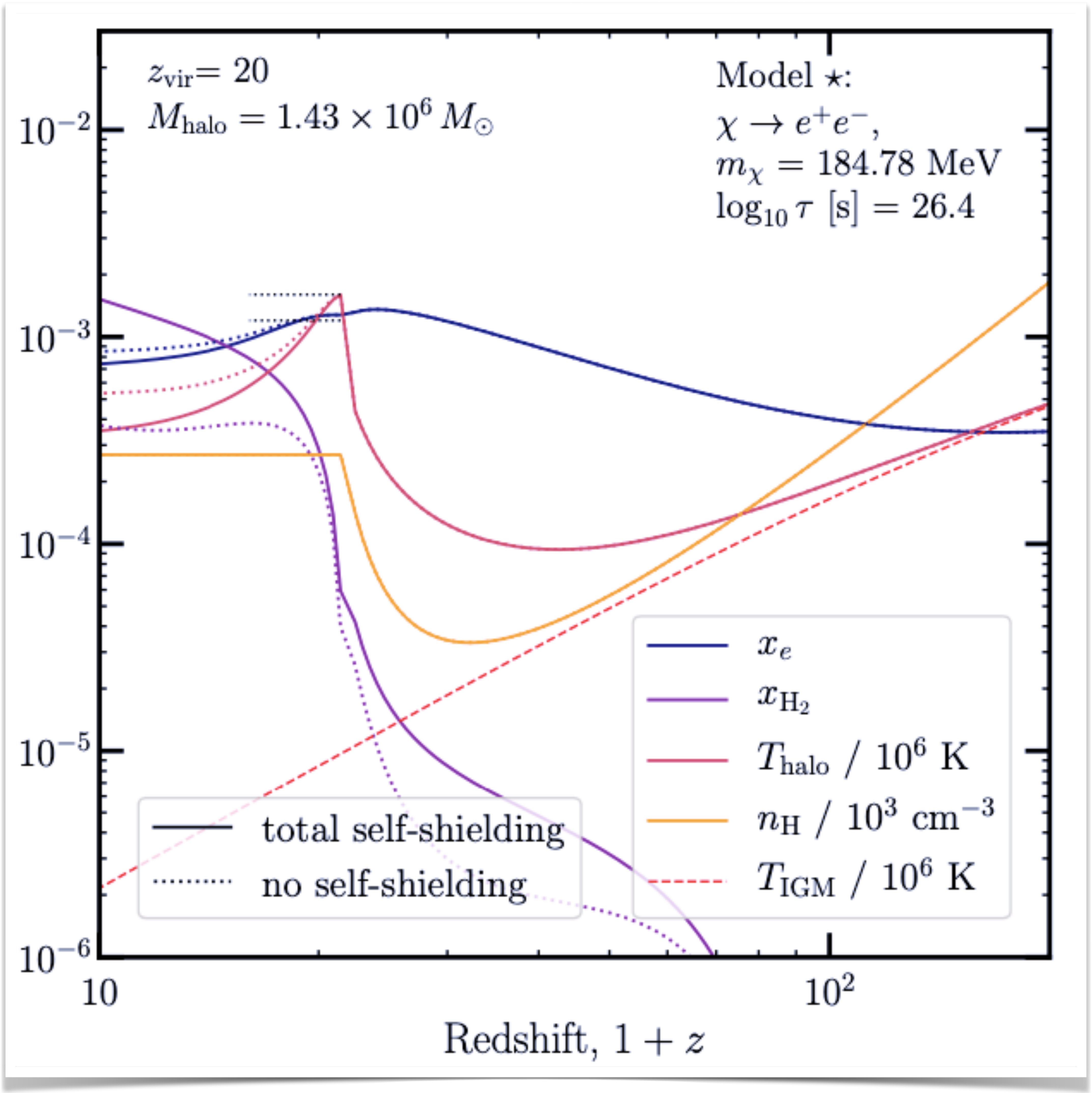




in another model...

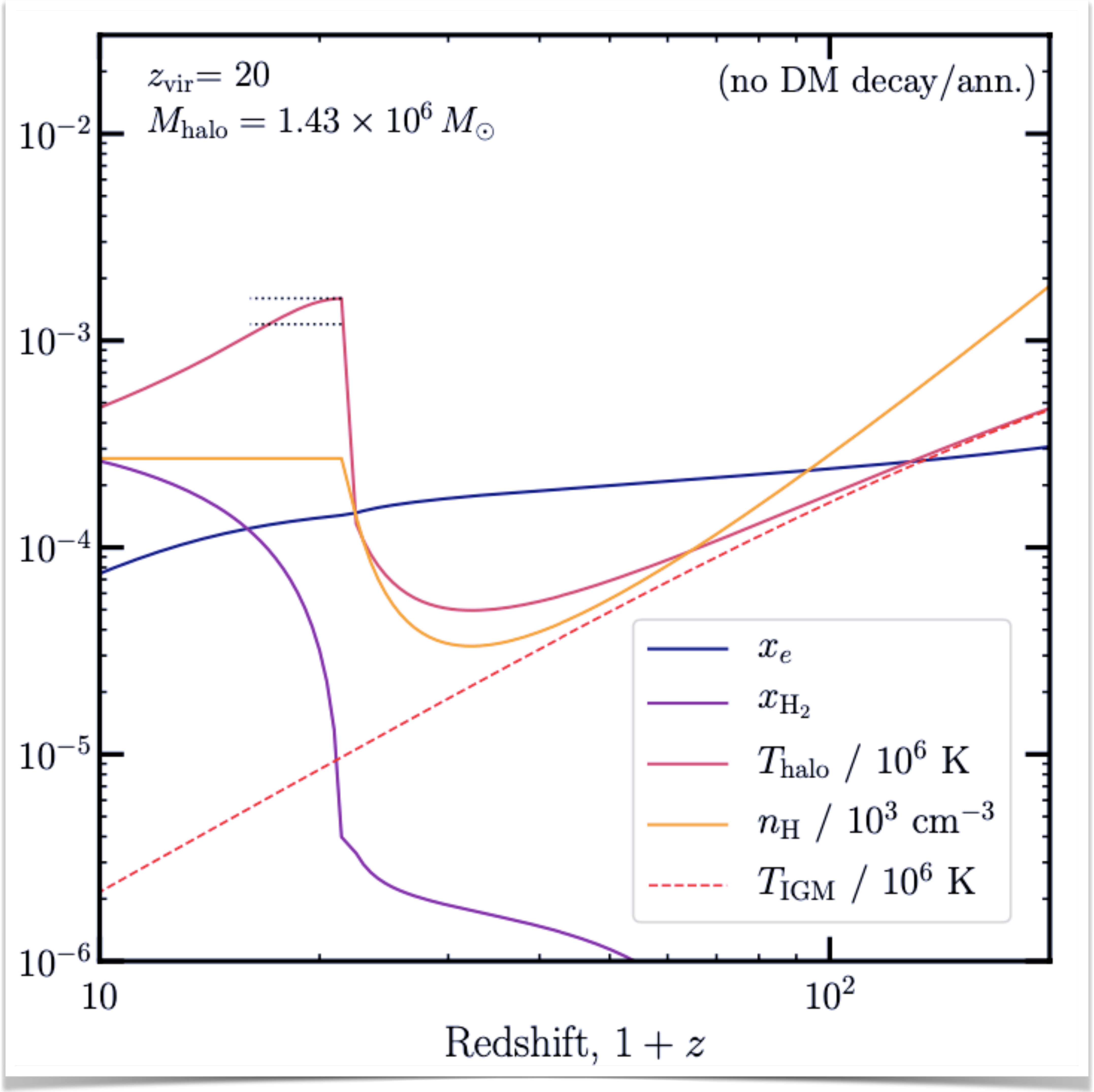
DM
Long τ

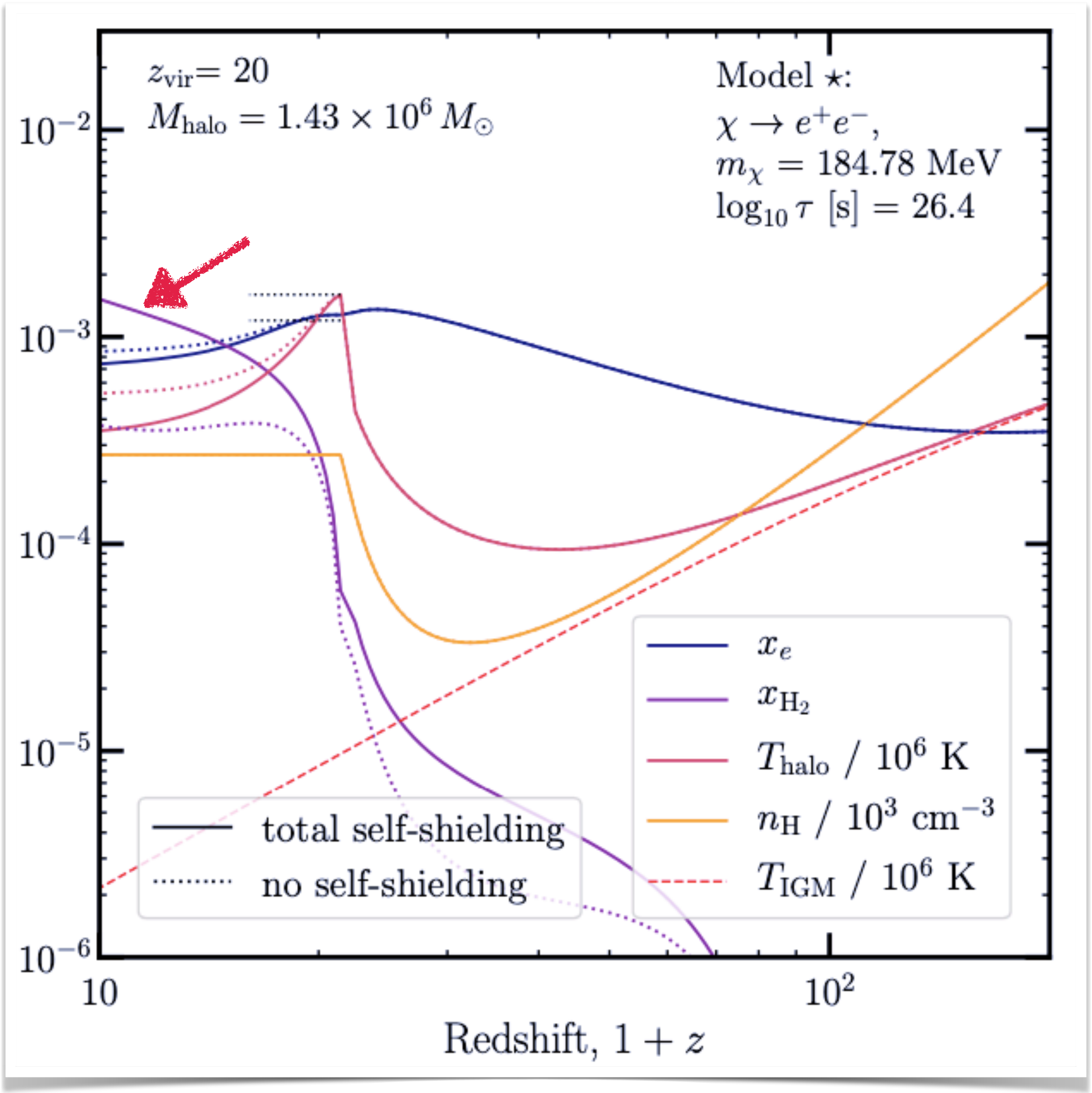




Increased Ionization Boosts H_2...

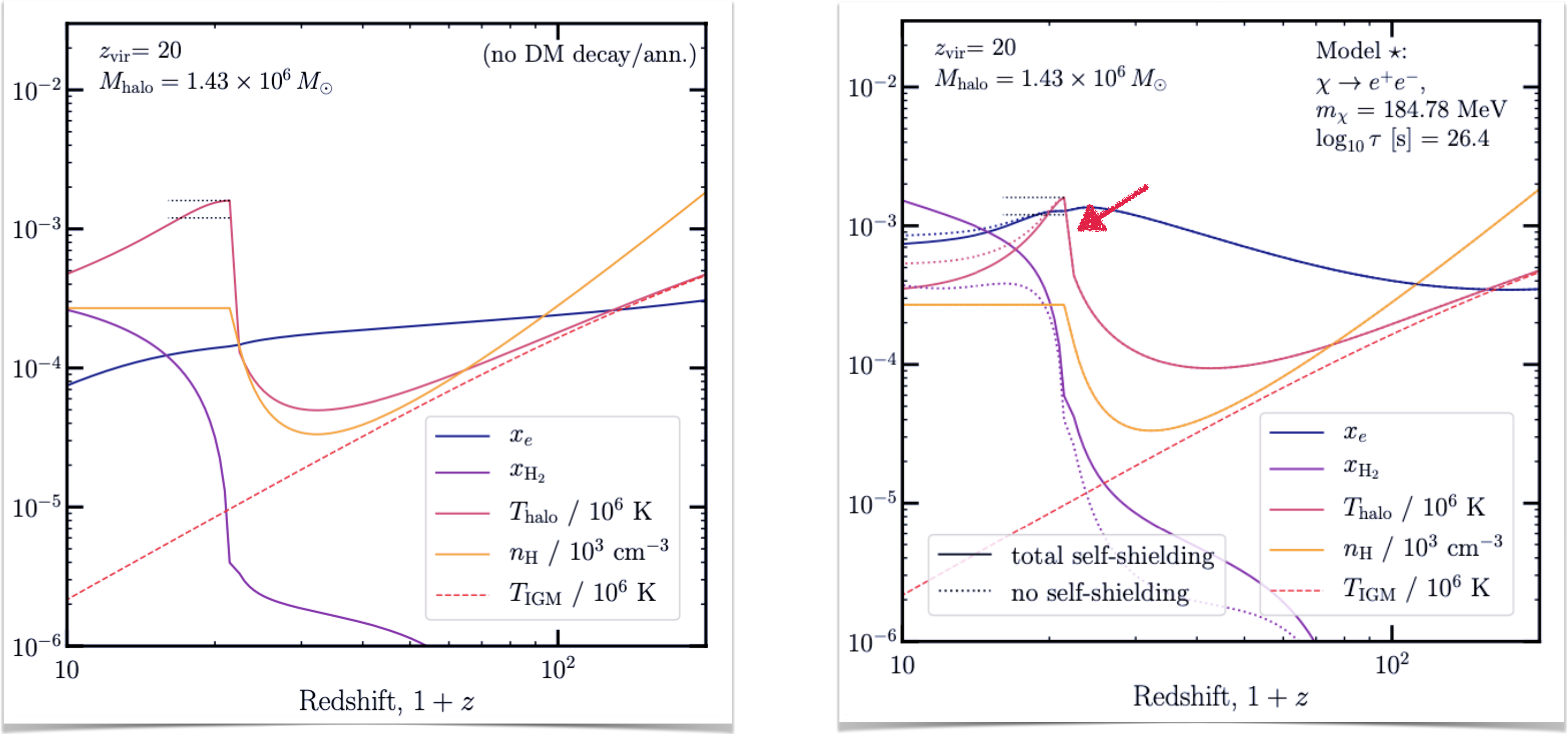
DM
Long τ





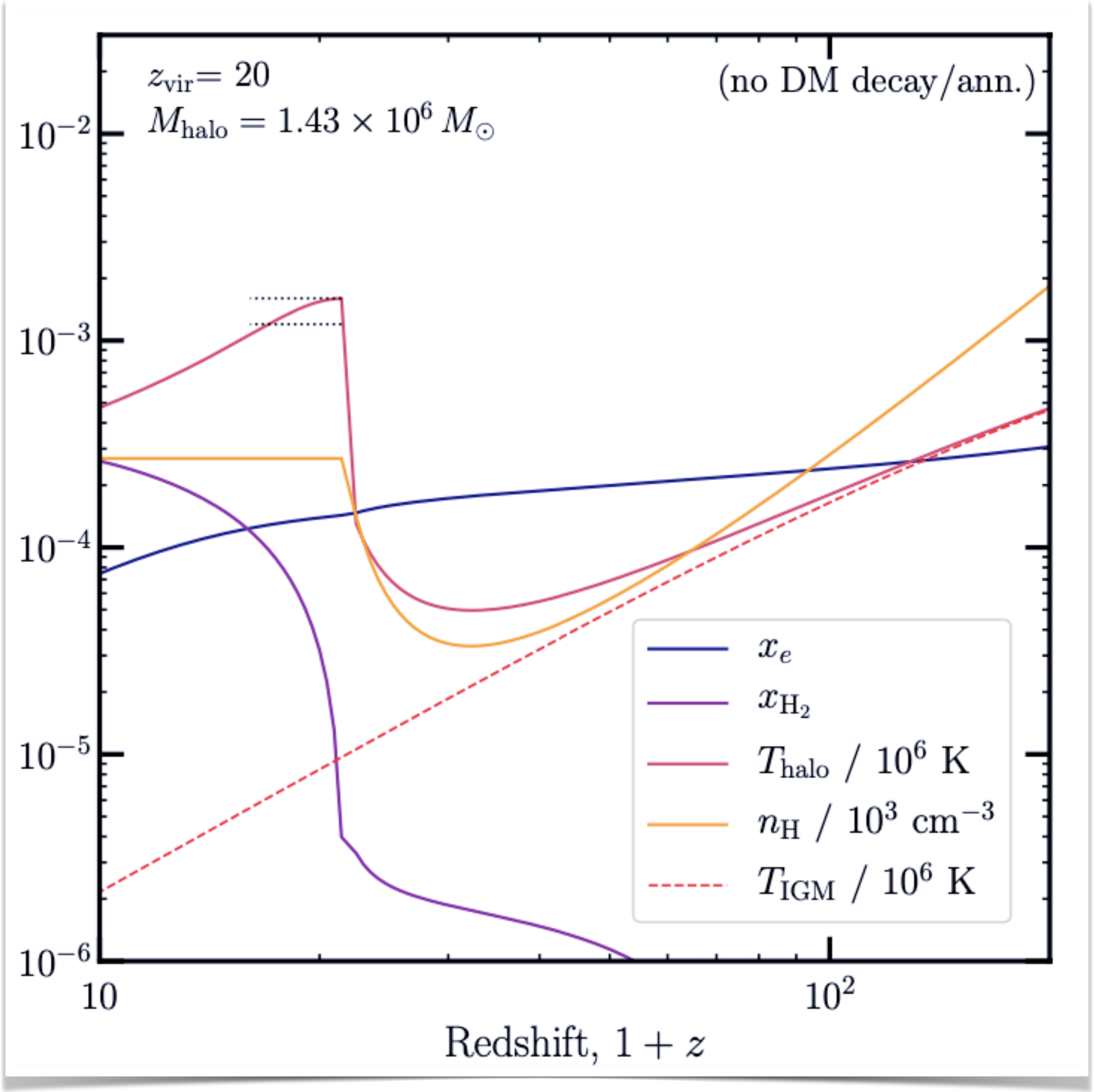
...but much less DM Heating

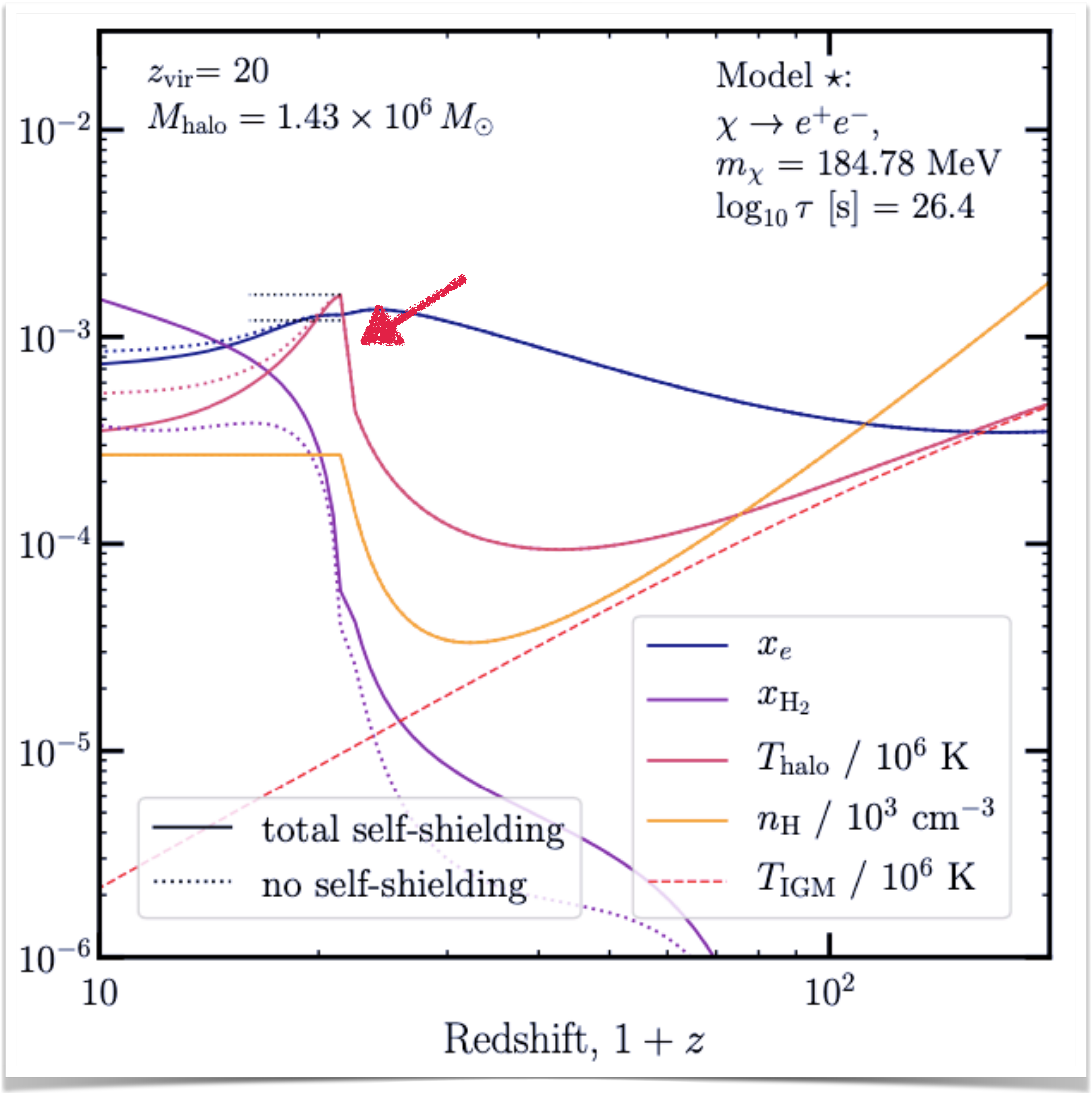
DM
Long τ



Cooling Efficiency Enhanced!

DM
Long τ



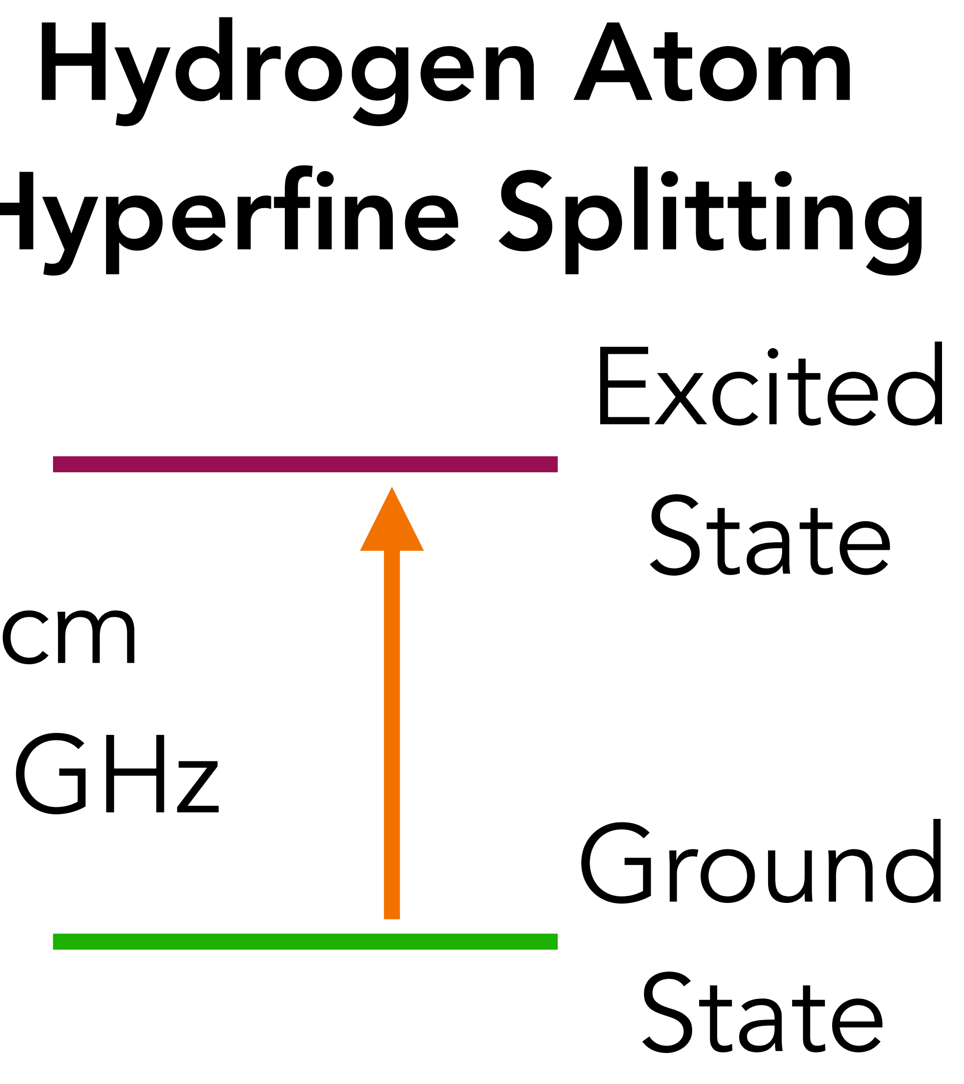


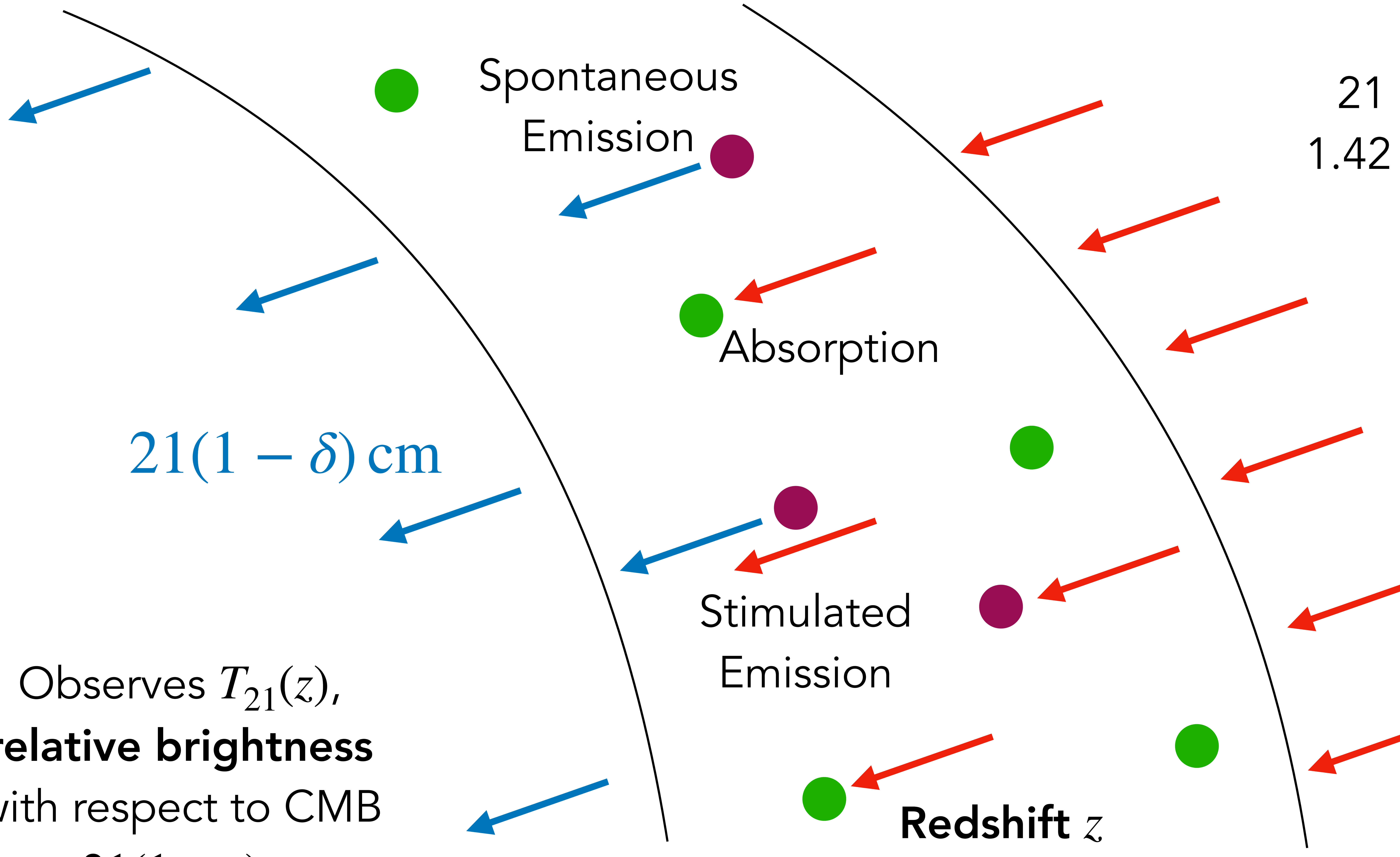
Dark matter can delay or accelerate star formation.

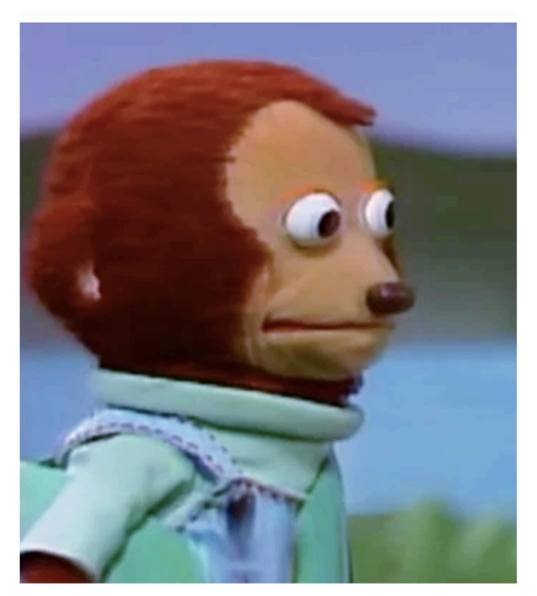
W. Qin, J. Muñoz, **HL** & T. Slatyer, 2308.12992


How do we
look for this?

21-cm Cosmology

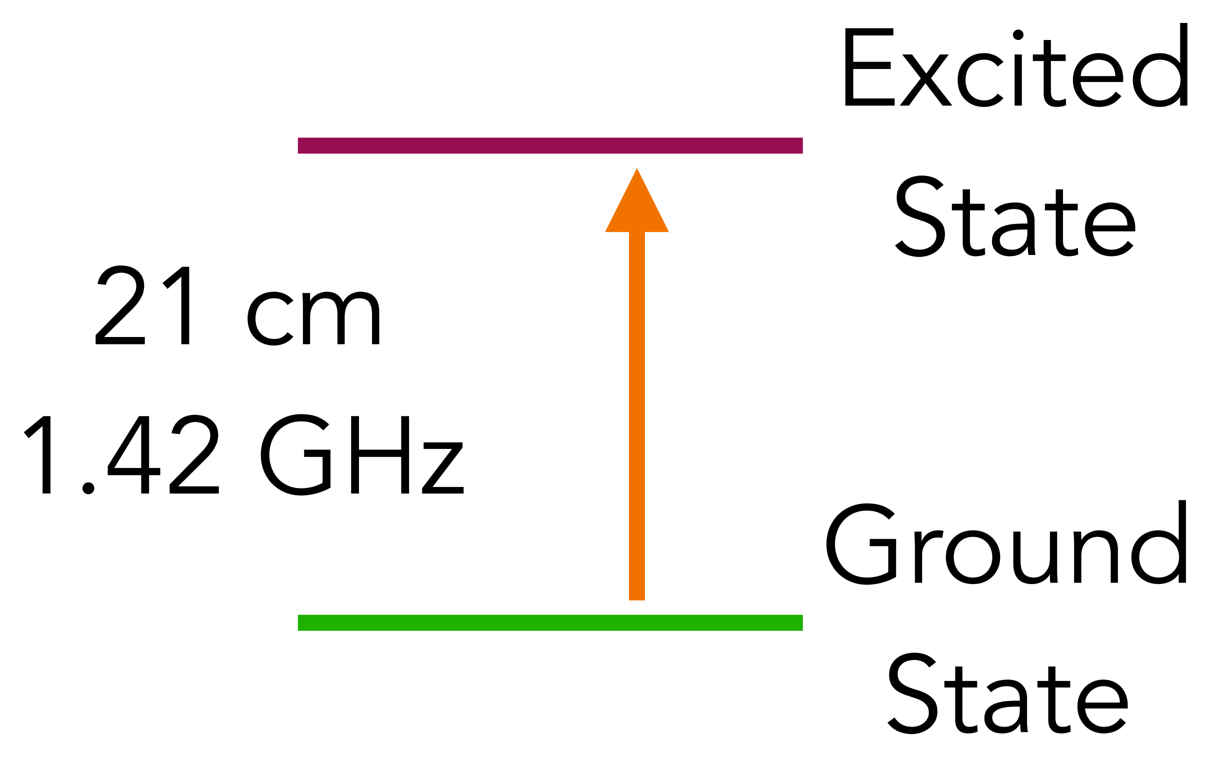






Observes $T_{21}(z)$, **relative brightness** with respect to CMB at $21(1+z)\,\mathrm{cm}$

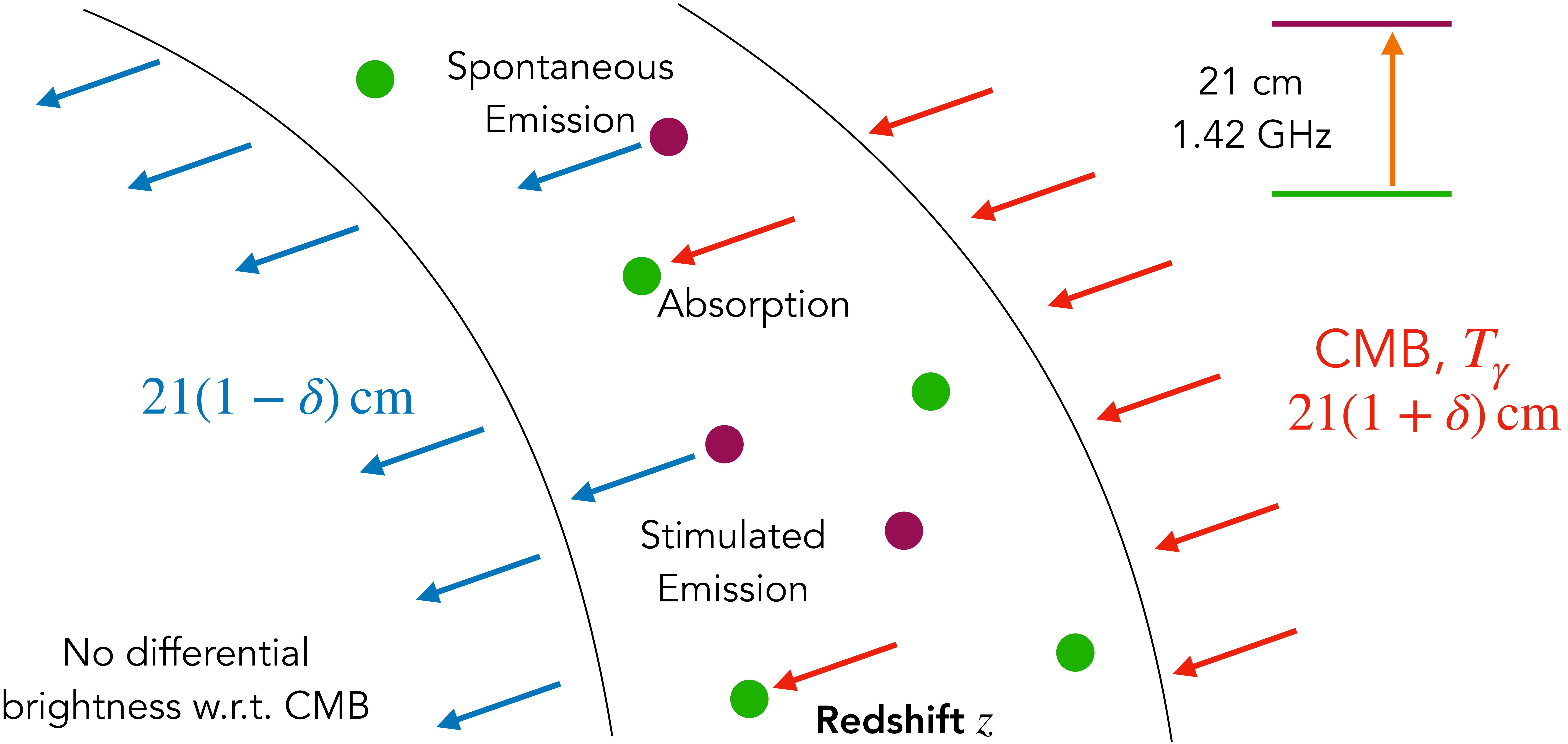
Spin Temperature

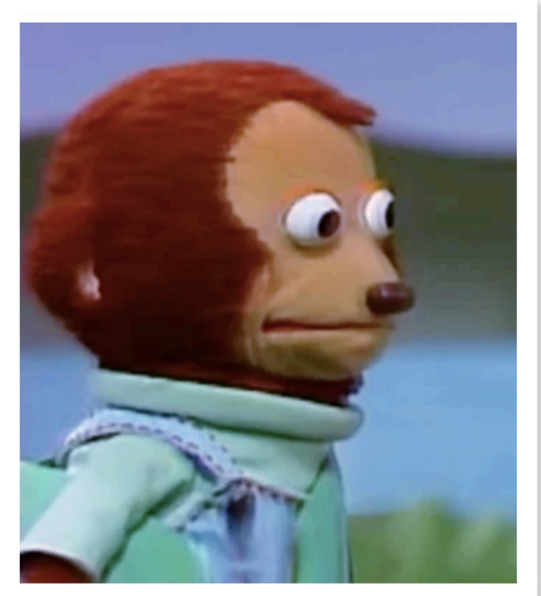


$$\frac{n_1}{n_0} = 3\exp\left(-\frac{E_{21}}{k_B T_S}\right)$$

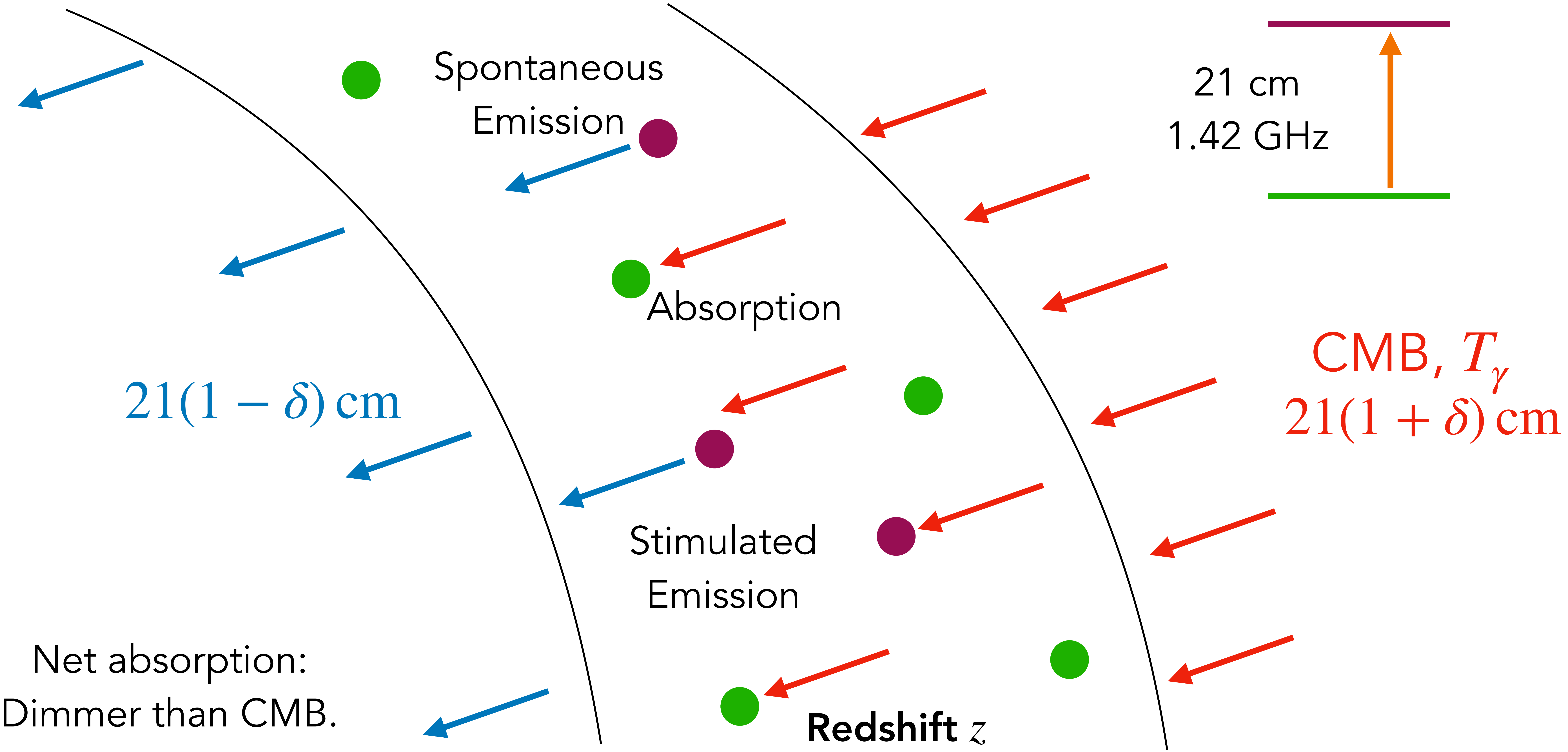
21-cm signal set by **spin temperature** (population in ground vs. excited state). Can be coupled to CMB ($T_S = T_\gamma$), or baryons ($T_S = T_b$).

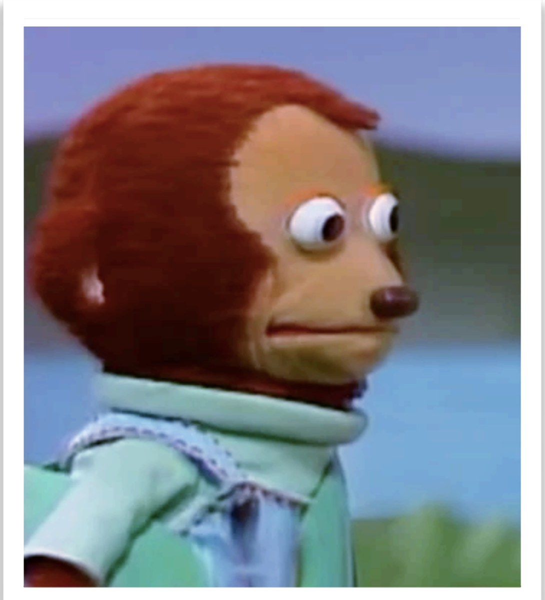
2-State System Coupled to CMB





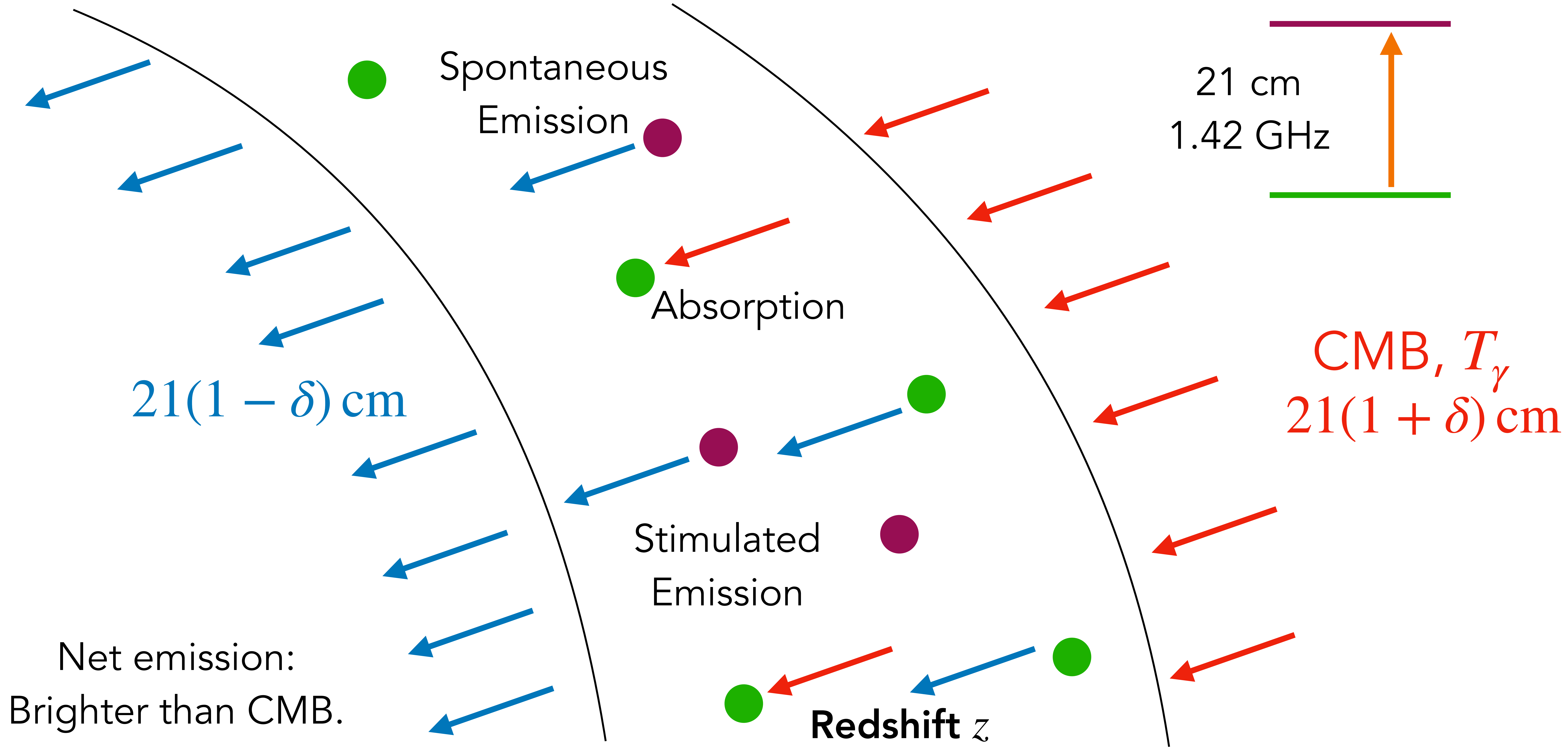
Coupled to Colder Baryons

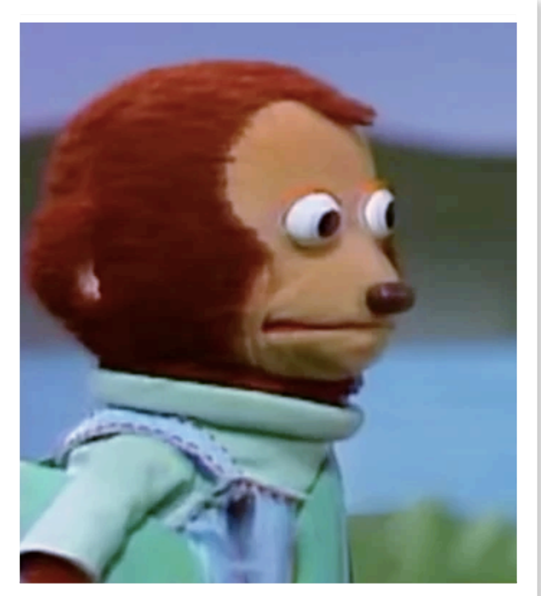




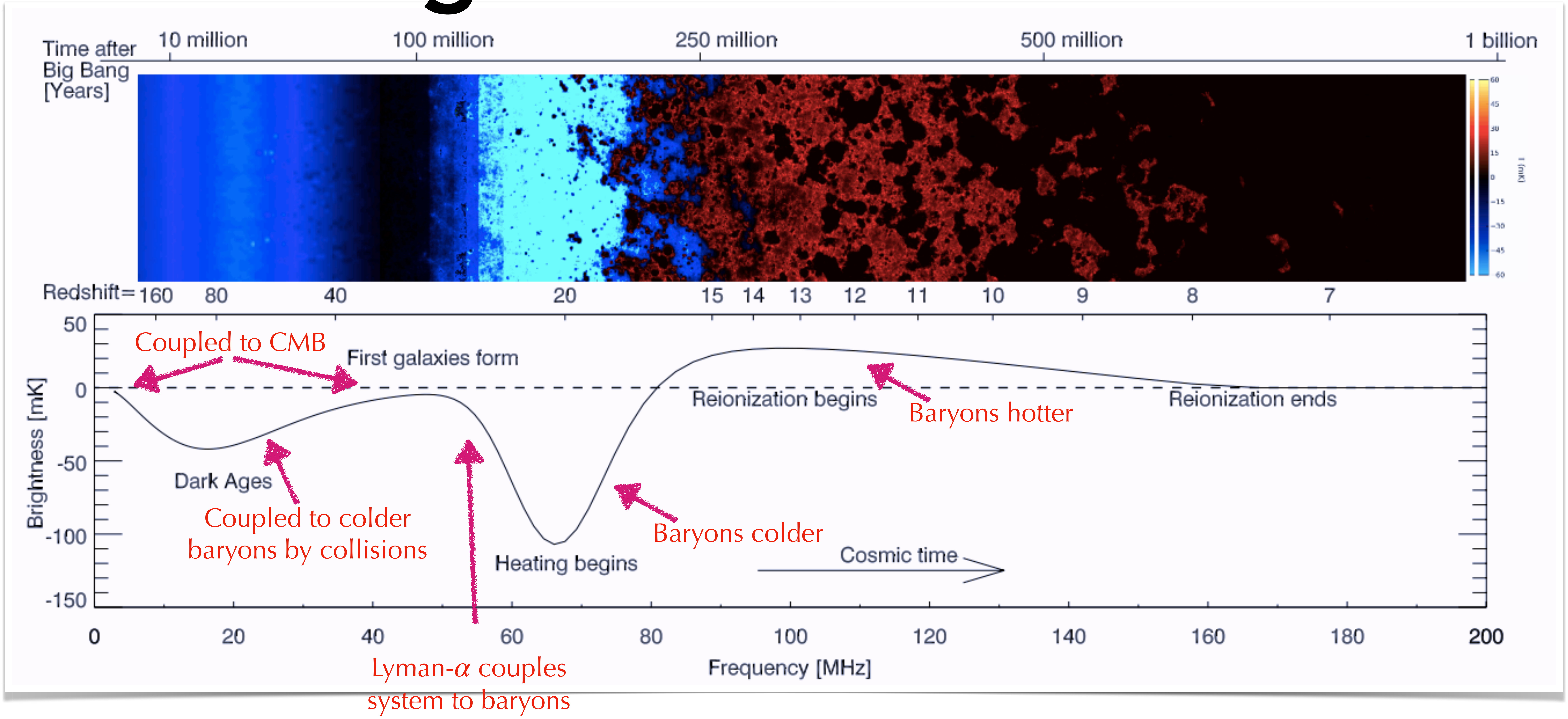
Net absorption:
Dimmer than CMB.

Coupled to Hotter Baryons

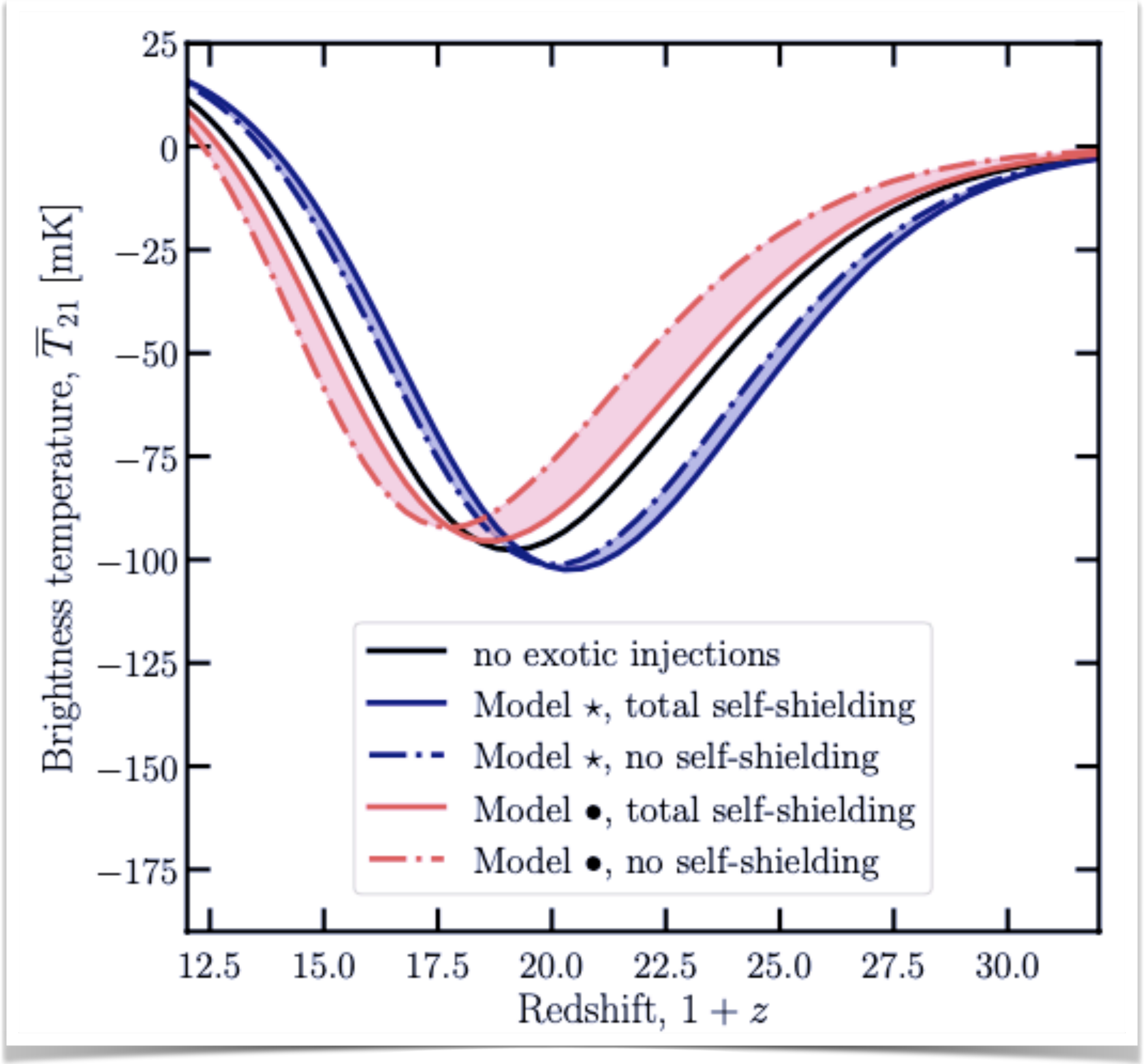


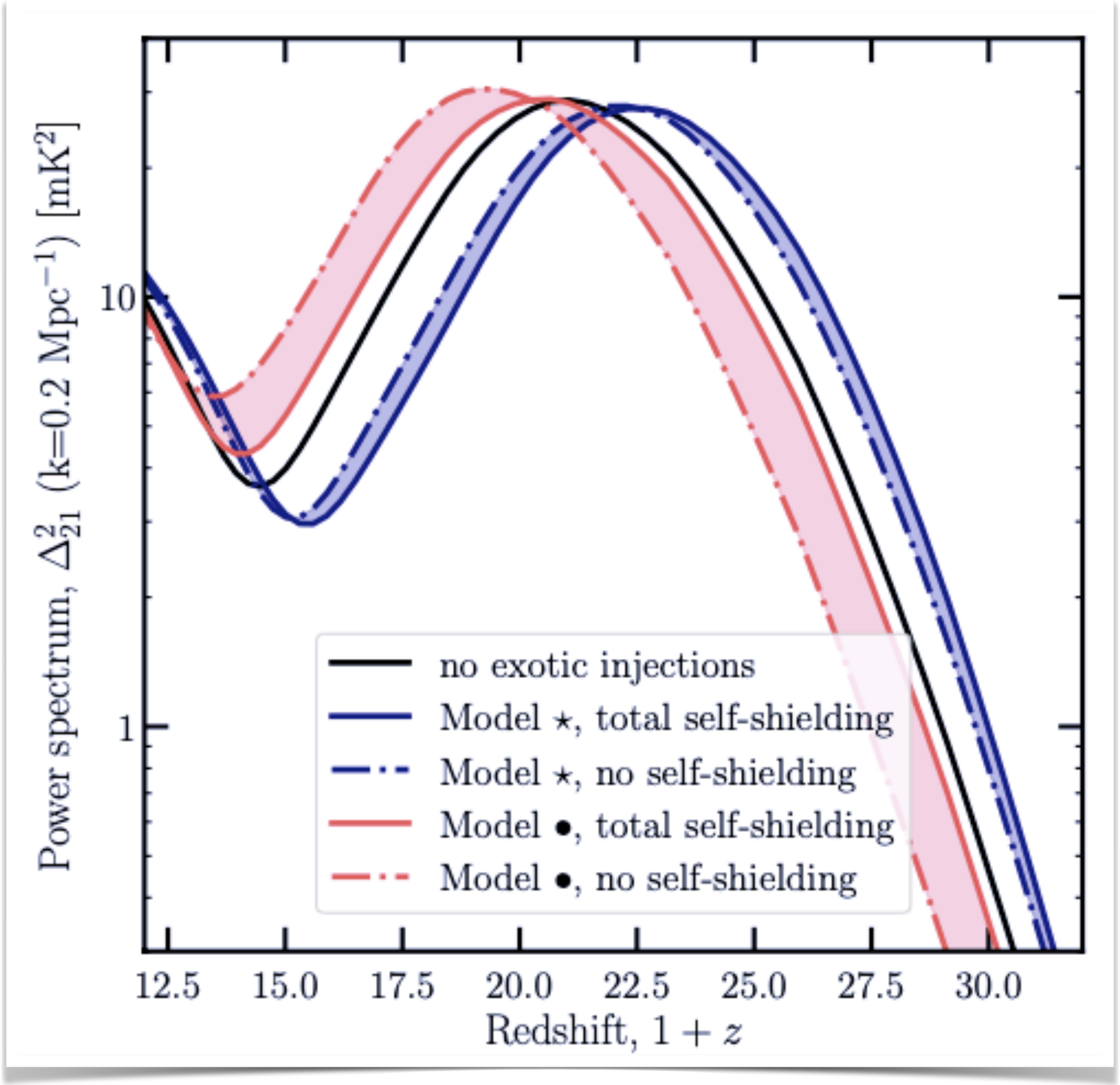


Global Signal



Global Signal Shift from DM





Observable in near-future with EDGES, SARAS etc. Also **power spectrum of fluctuations** by experiments like HERA.

Exotic energy injection in the early Universe leaves remarkable signals that can be detected in current and future cosmological datasets.