

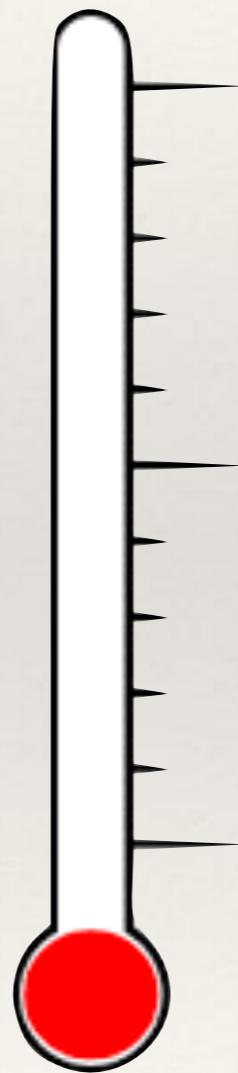
21-cm Implications for Dark Matter Part I: Introduction

Gregory Ridgway

based on work by Hongwan Liu and Tracy Slatyer, 1803.09739
and by Hongwan Liu and GR, in preparation

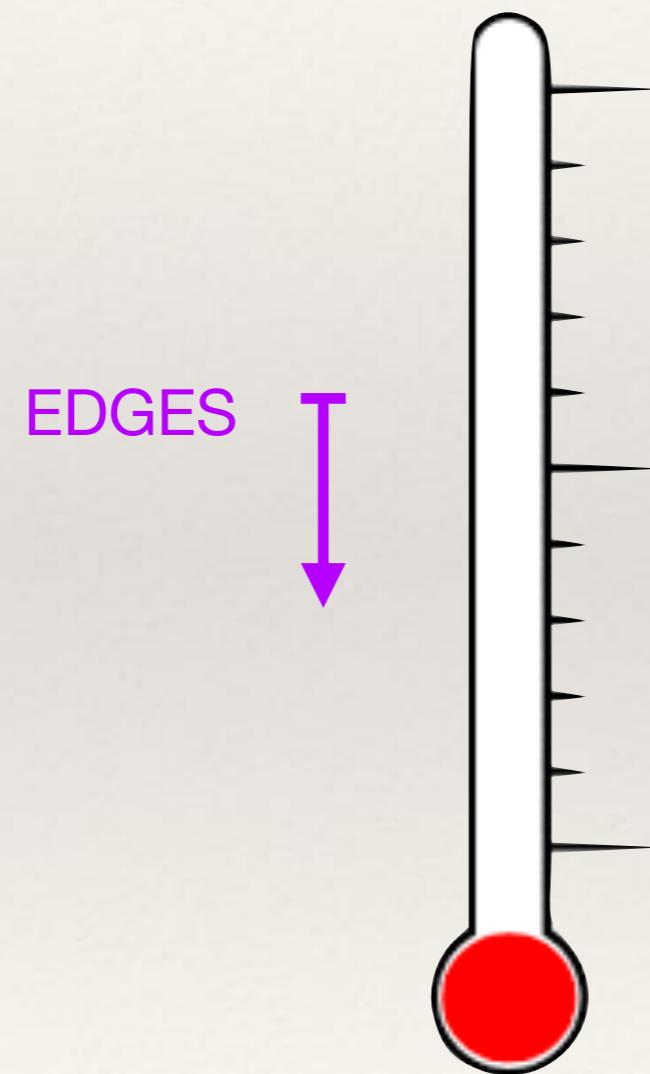
The Main Point

$T_m(z \approx 17.2)$



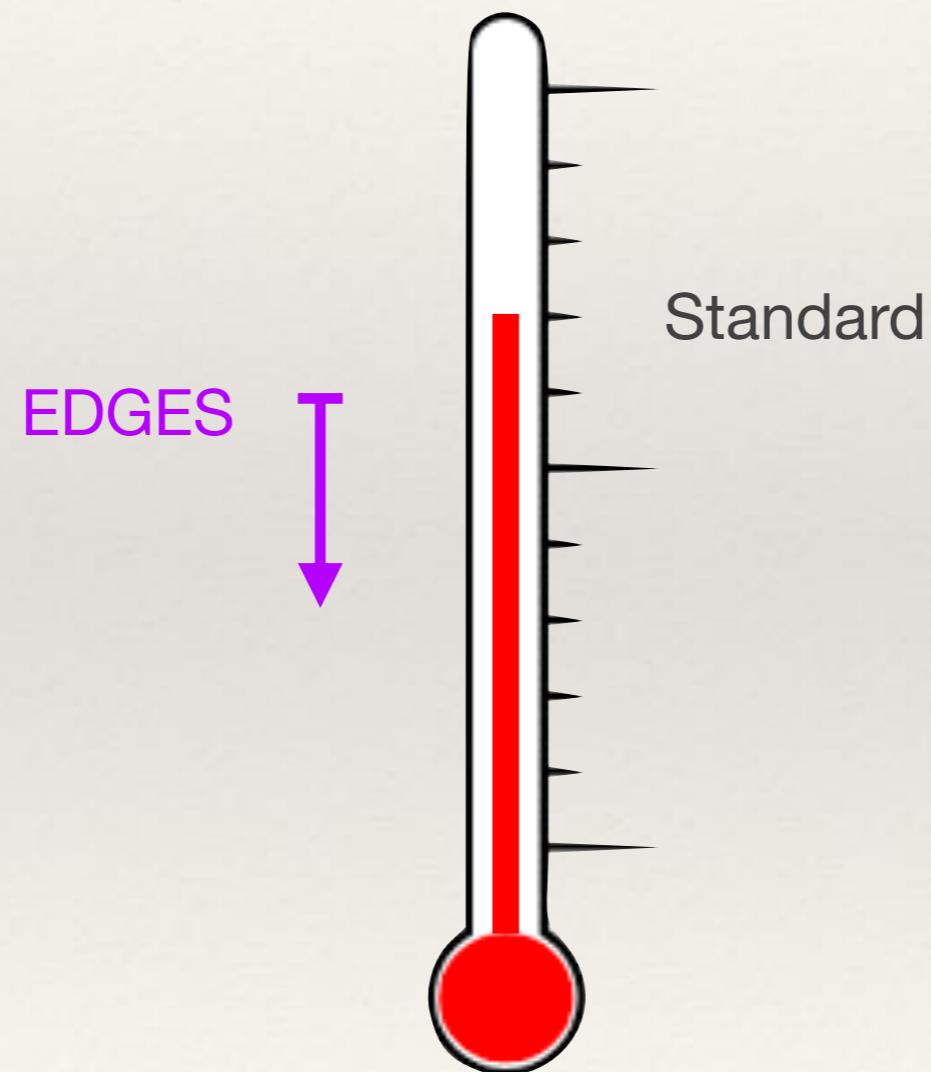
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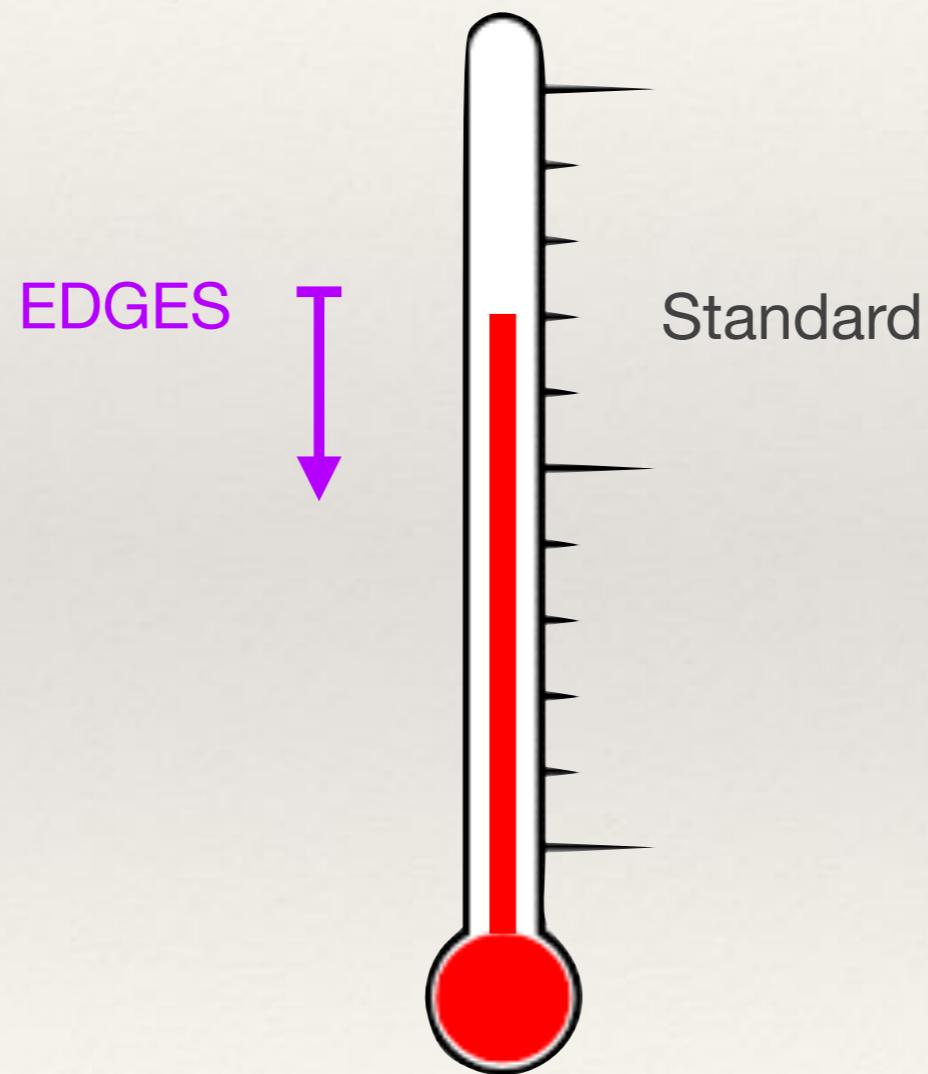
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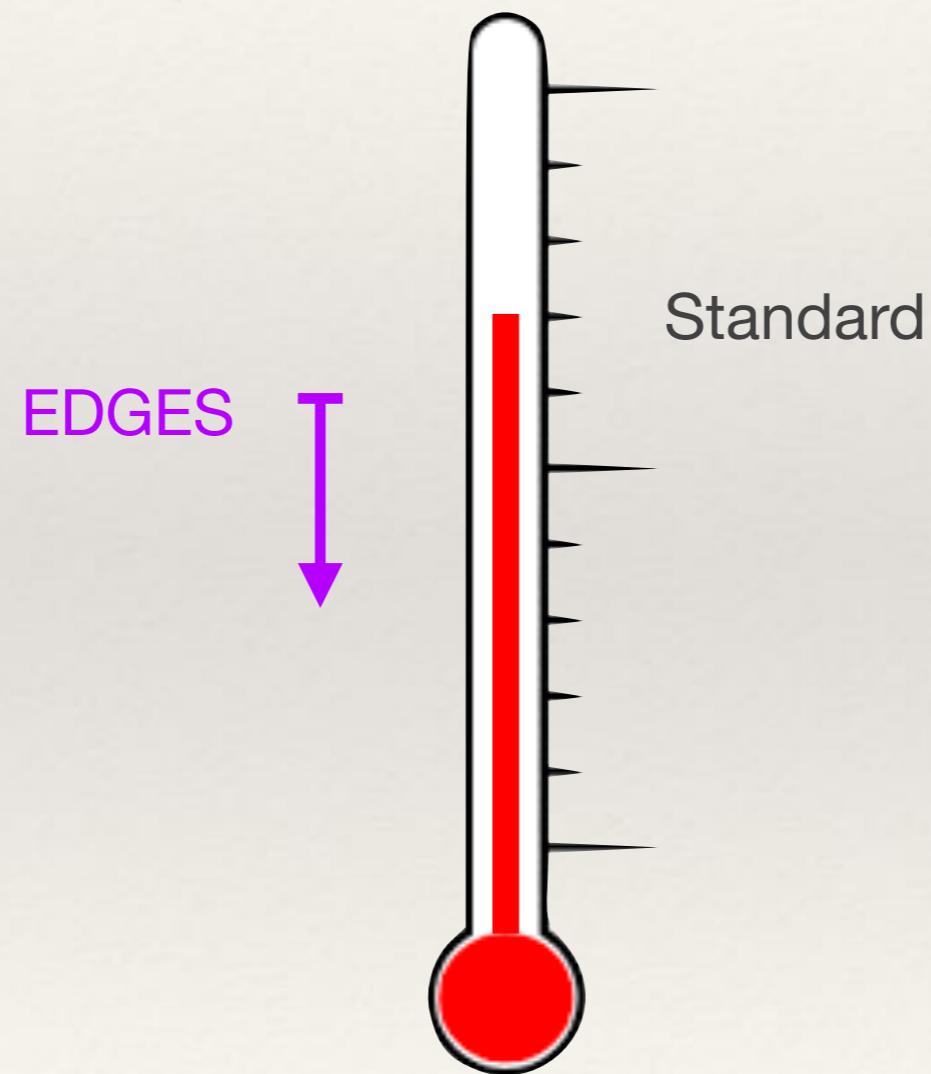
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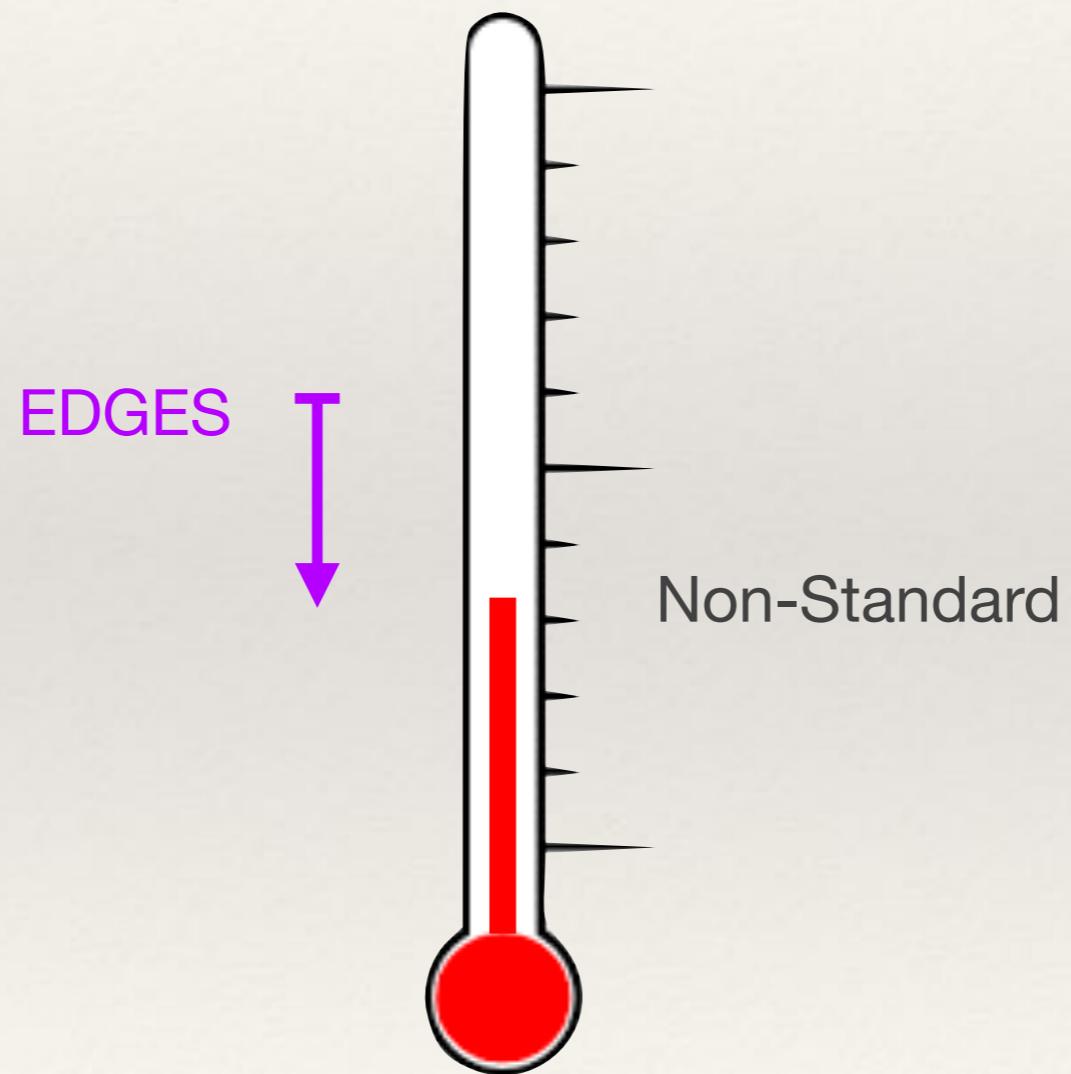
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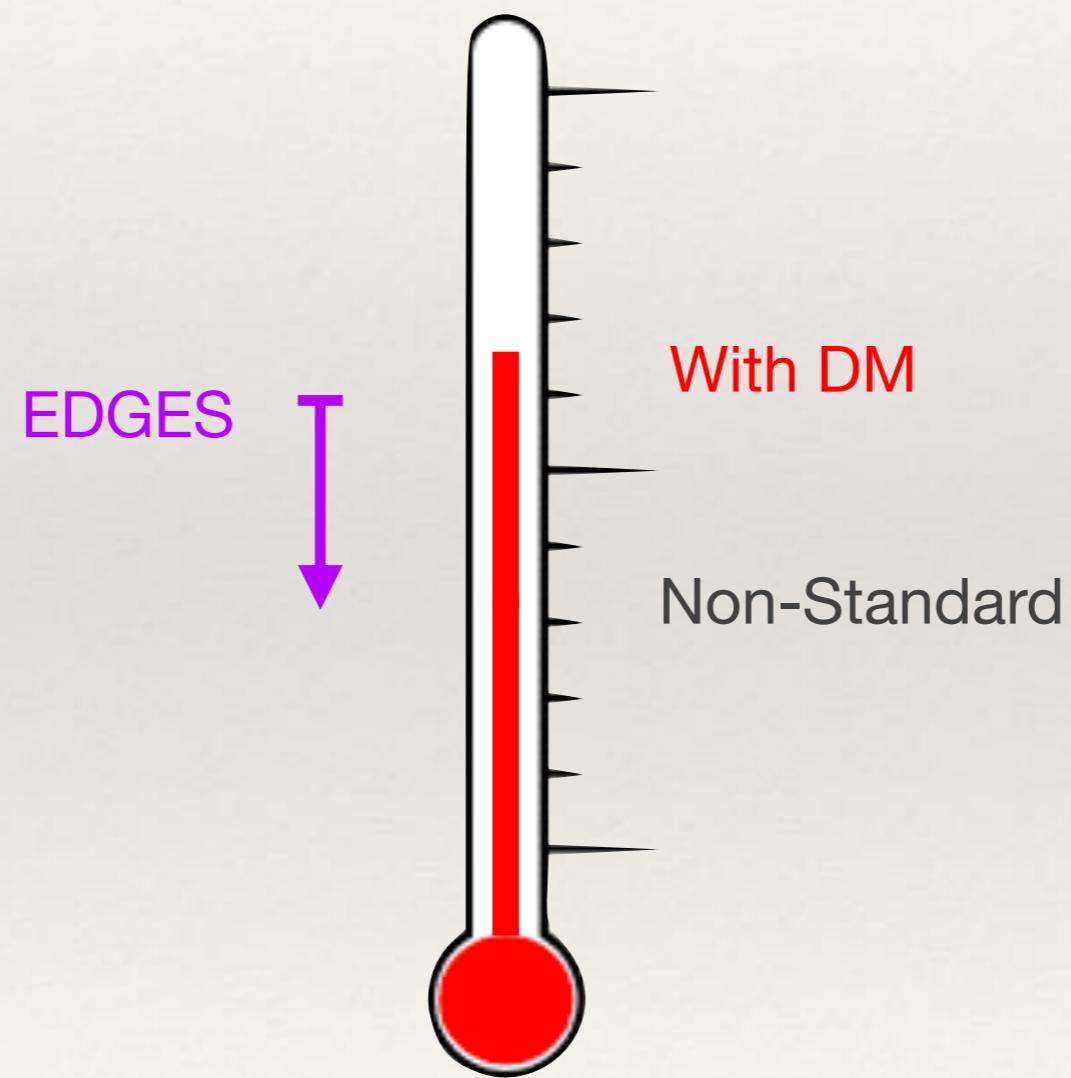
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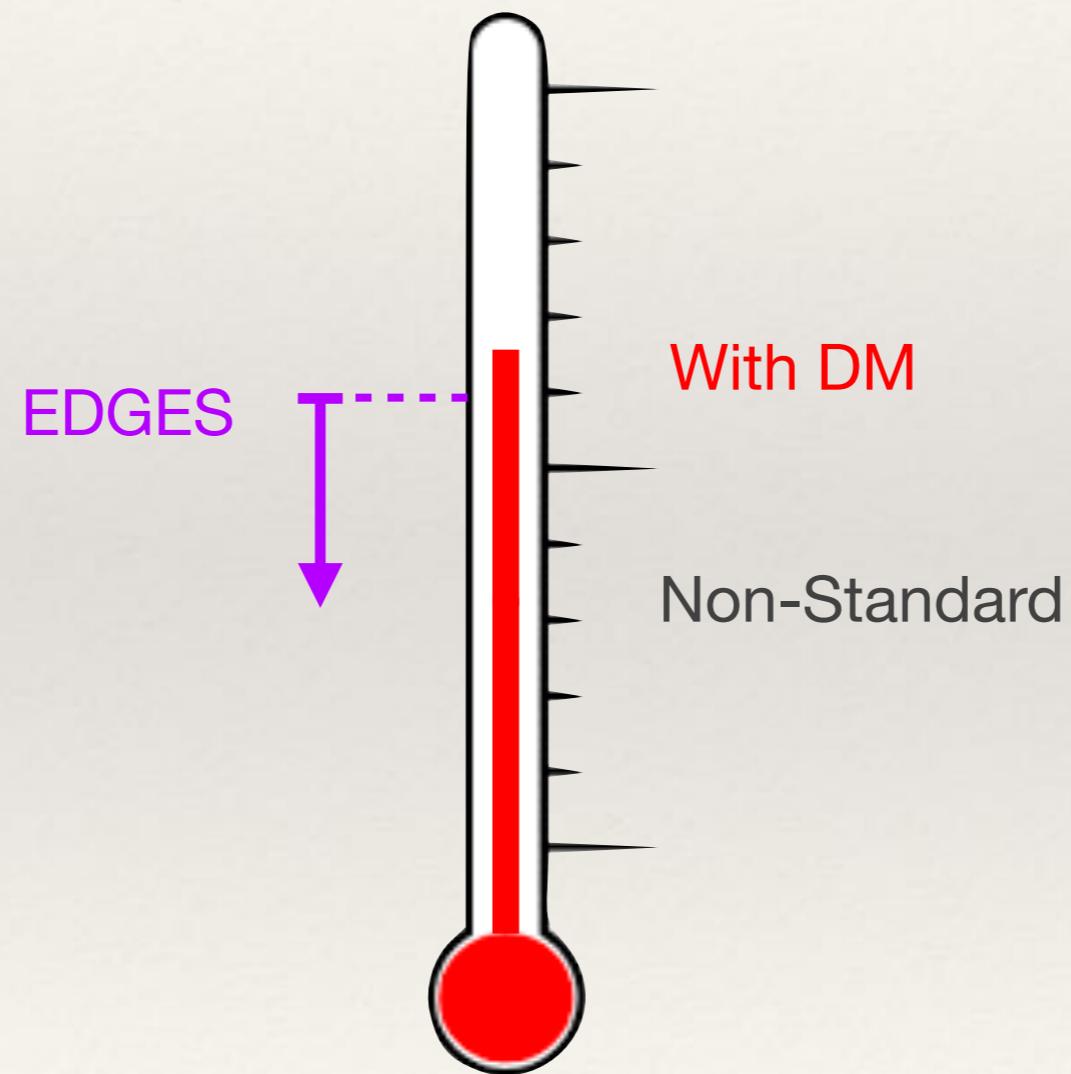
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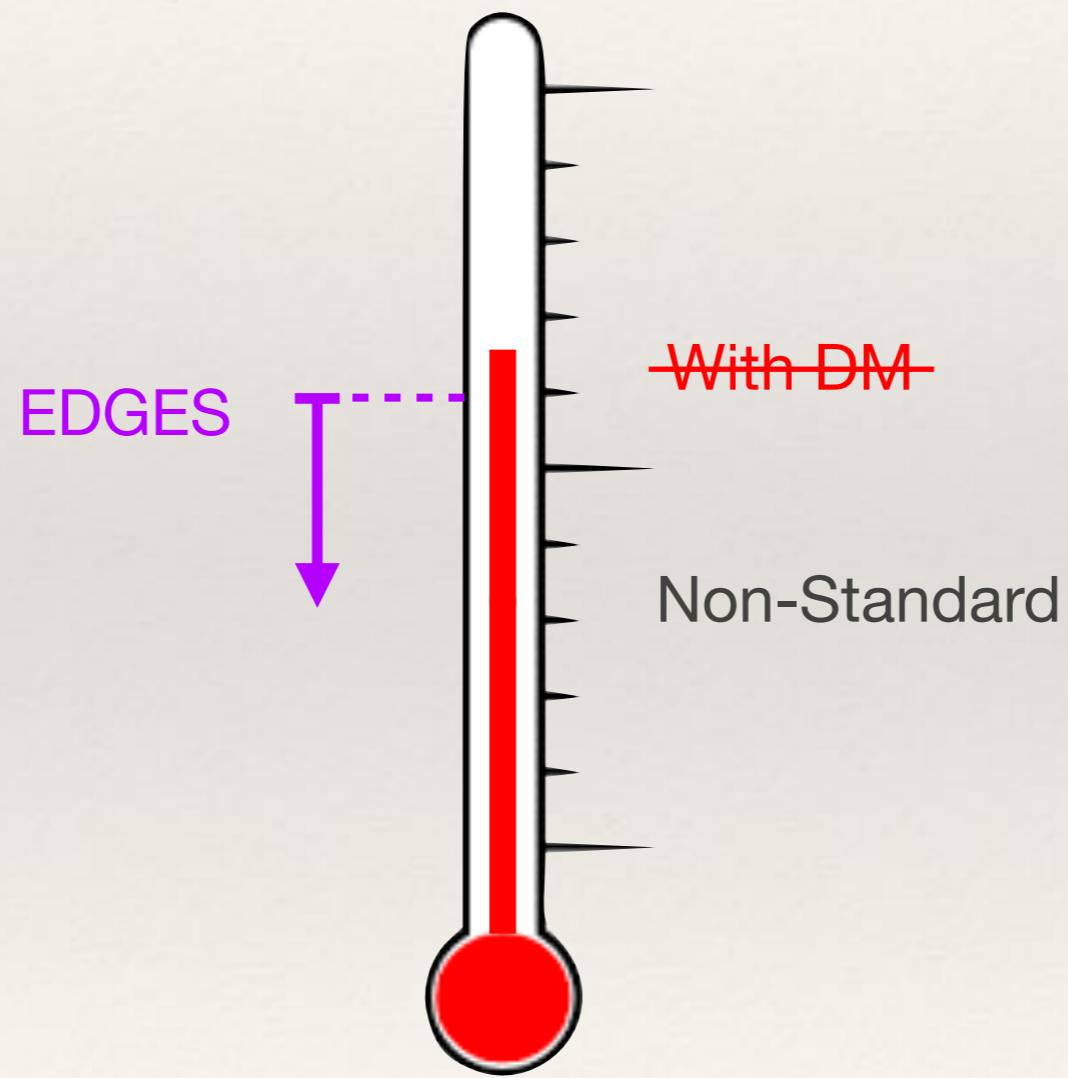
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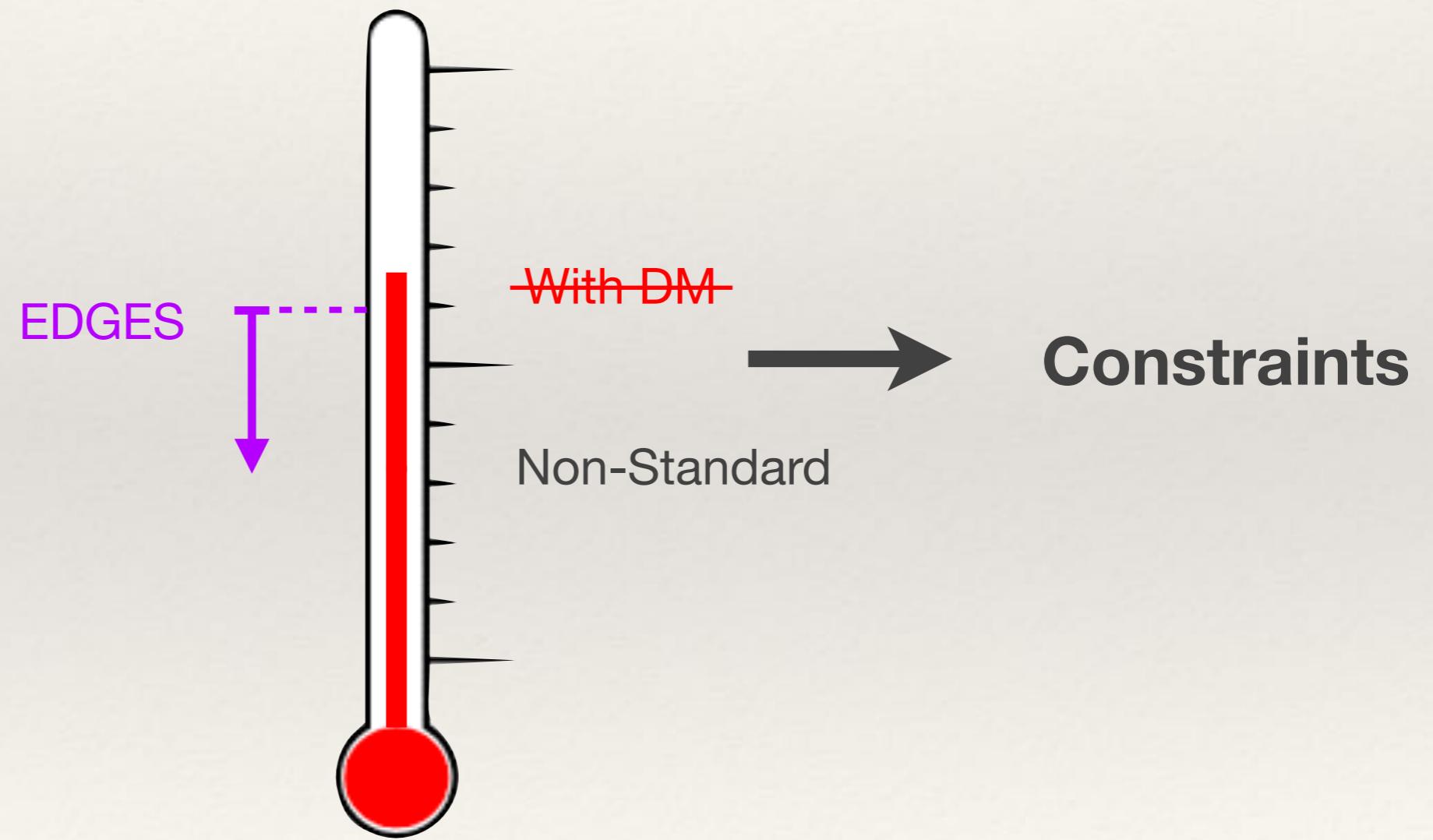
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The Main Point

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What Did EDGES Measure?

The Global 21-cm Signal

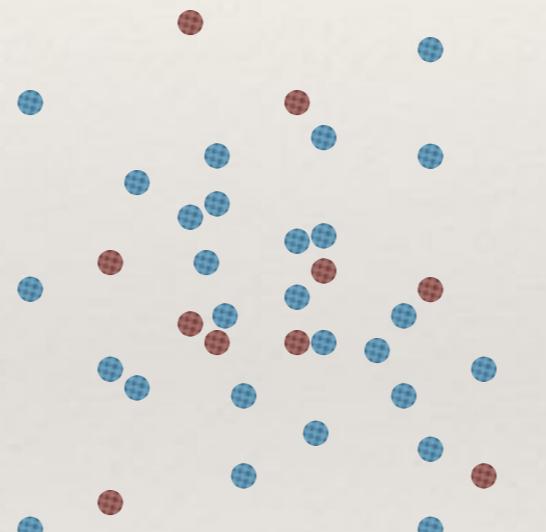
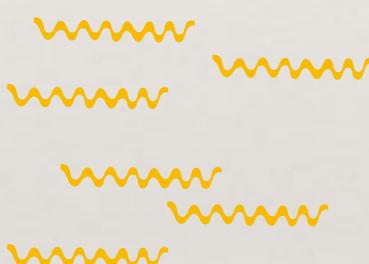
The Global 21-cm Signal

wavy - 21cm radiation



- Observer

- - Hydrogen, 1s, singlet
- - Hydrogen, 1s, triplet



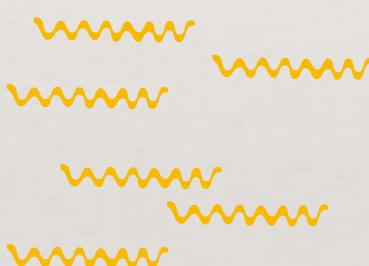
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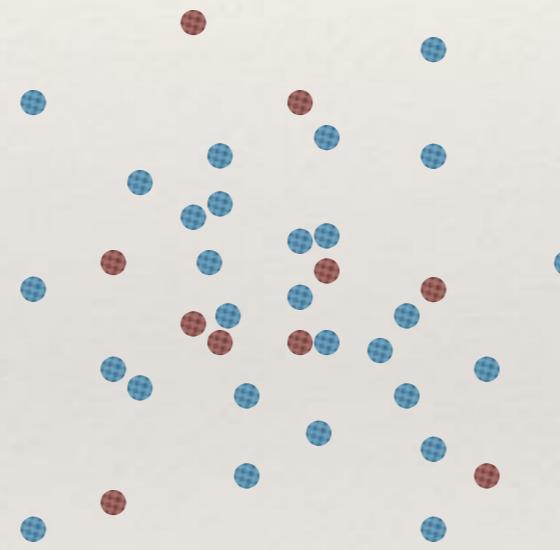
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T_R

Controls the **intensity** of the
21cm background radiation



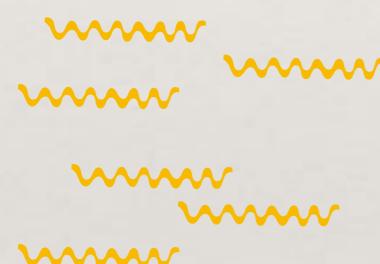
The Global 21-cm Signal

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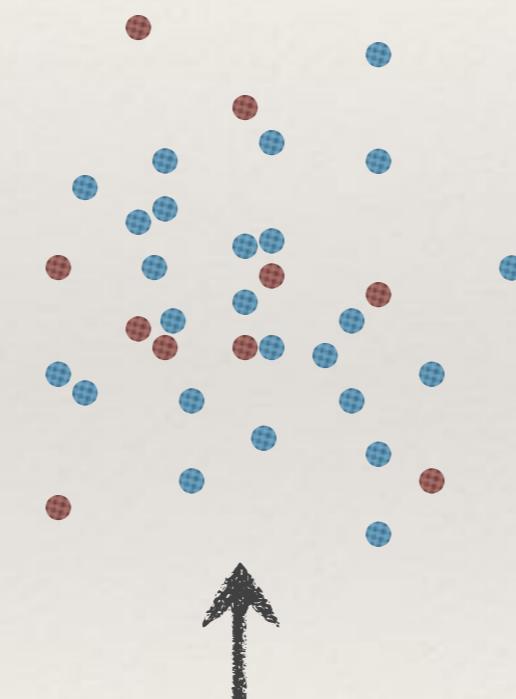
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T_R

Controls the **intensity** of the
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T_S

Controls $\frac{N(\text{triplet})}{N(\text{singlet})}$



*Images drawn to scale

The Global 21-cm Signal

wavy - 21cm radiation



- Observer

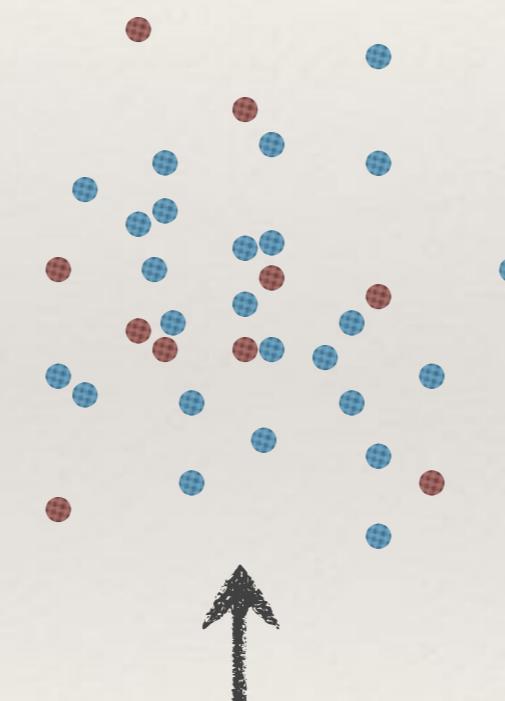
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wavy
wavy
wavy
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Measures

ΔT_{21}

differential brightness temperature of the 21cm line

The Global 21-cm Signal

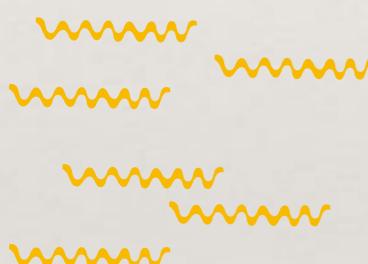
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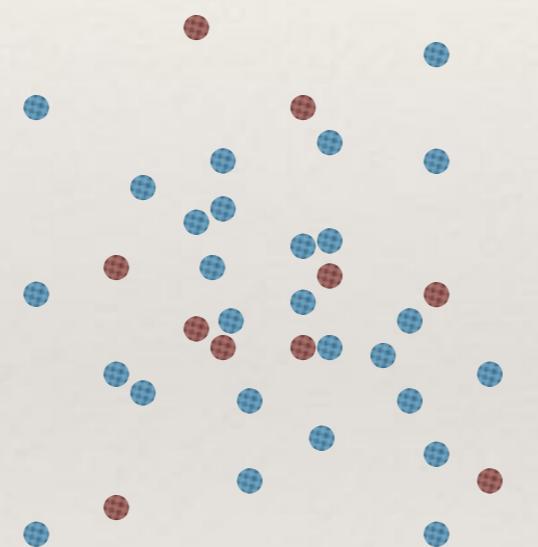
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$$\Delta T_{21} \propto \left[1 - \frac{T_R}{T_S} \right]$$



T_R



T_S

Controls $\frac{N(\text{triplet})}{N(\text{singlet})}$



ΔT_{21}

differential brightness
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Controls the **intensity** of the
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The Global 21-cm Signal: Example

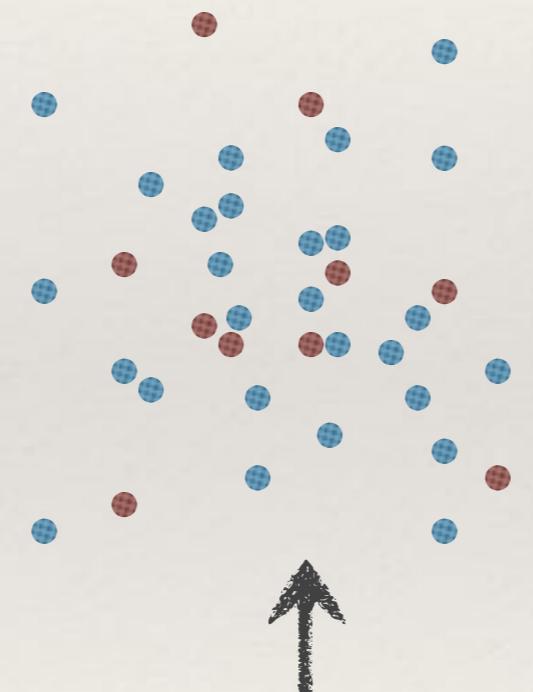
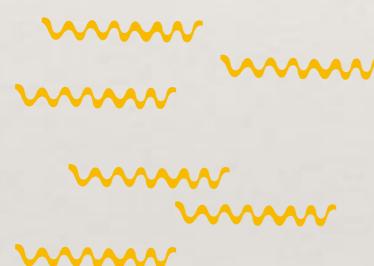
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T_R

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T_S

ΔT_{21}



Measures

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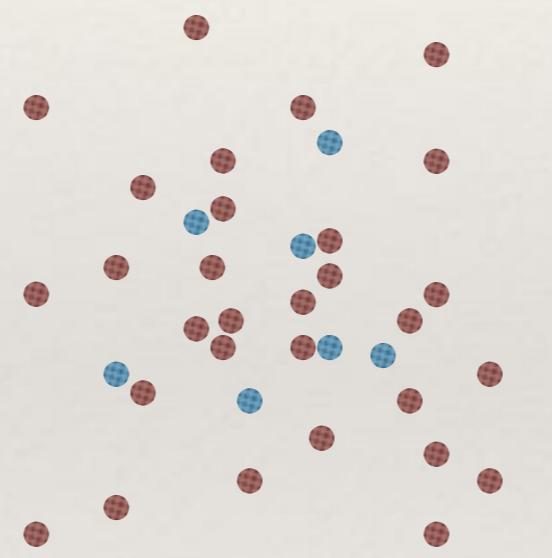
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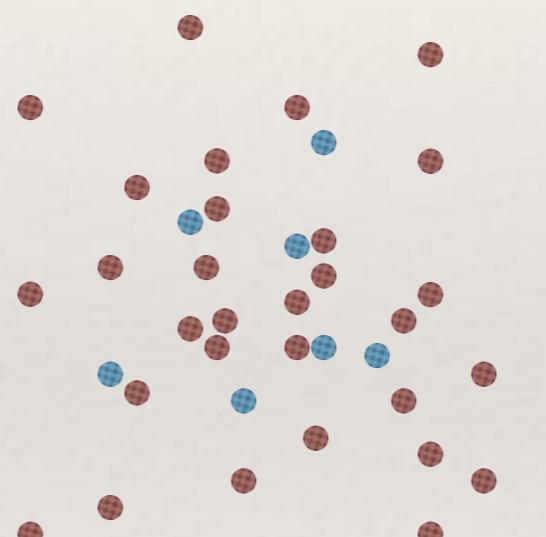
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T_S

T_R

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$\Delta T_{21} < 0$

Measures



The Global 21-cm Signal: Example

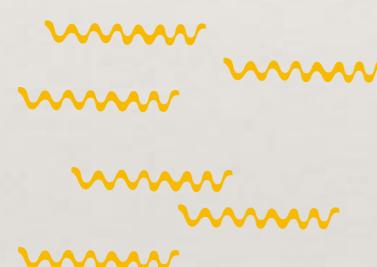
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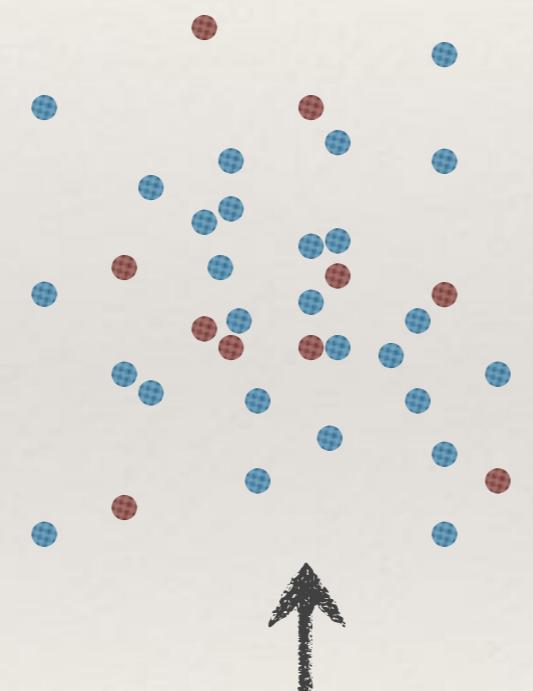


T_R

<

T_S

ΔT_{21}



The Global 21-cm Signal: Example

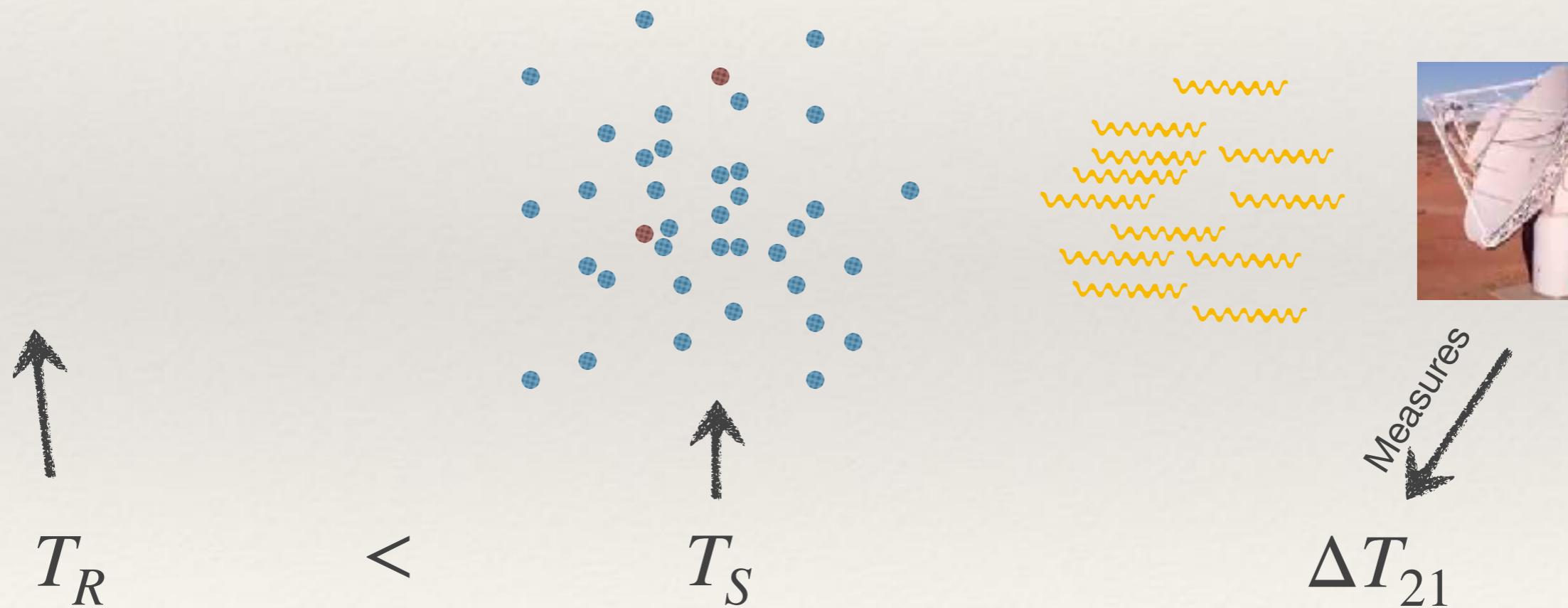
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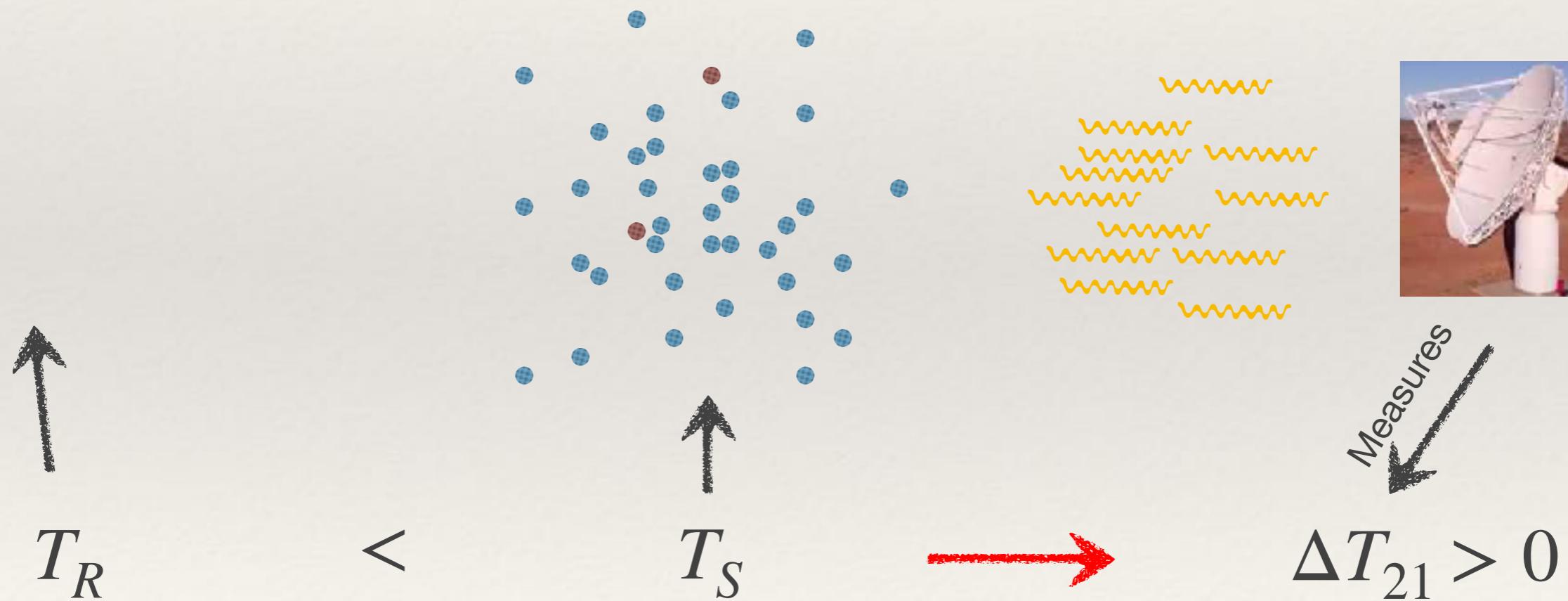
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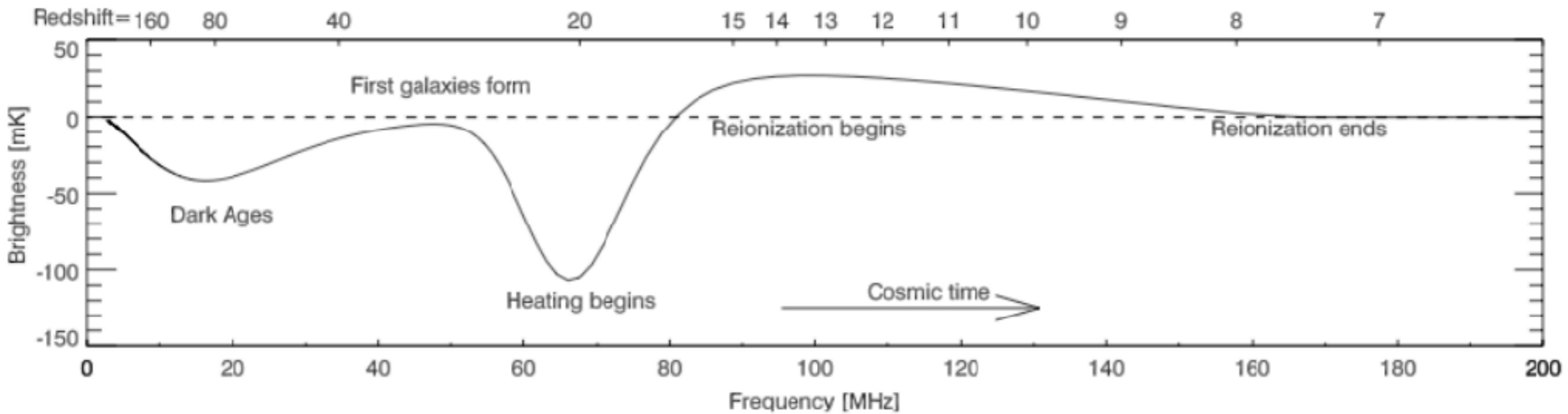
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The Global 21-cm signal

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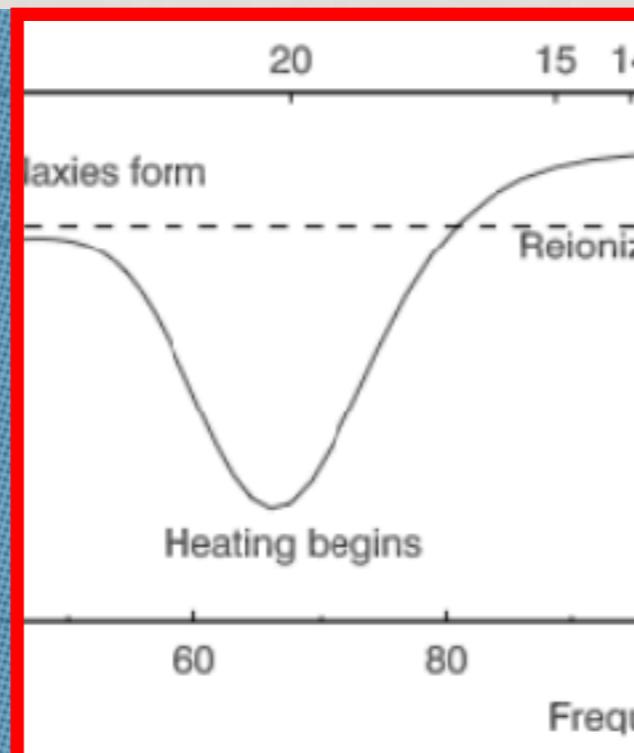
Pritchard & Loeb, 1109.6012



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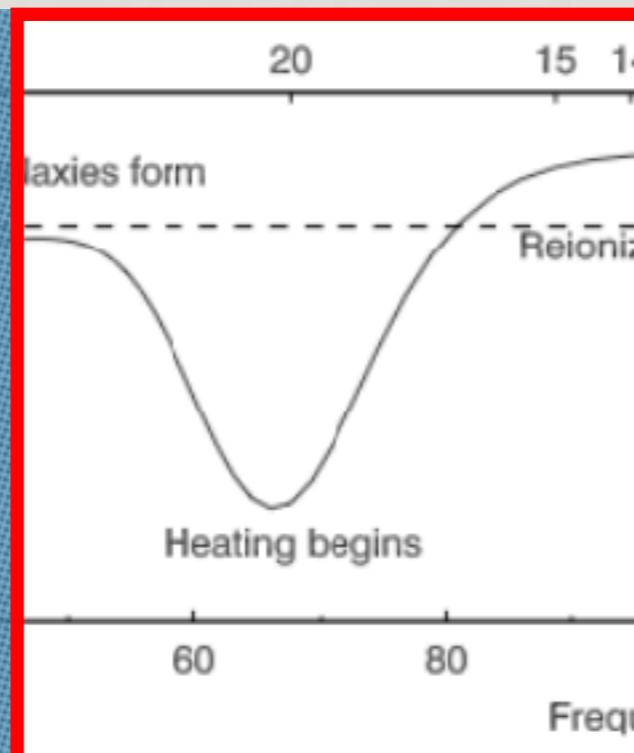


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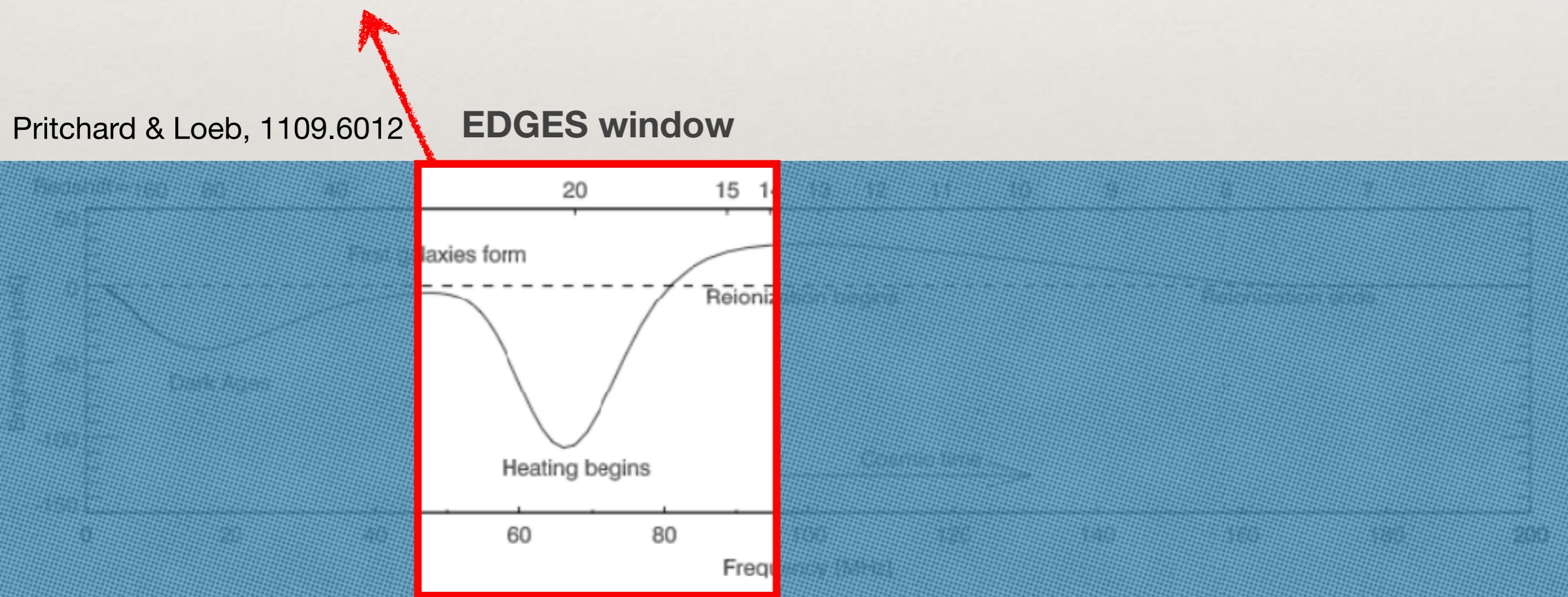
EDGES window



The Global 21-cm signal

$$\Delta T_{21} \propto \left[1 - \frac{T_R}{T_S} \right]$$

$T_m \leq T_S \leq T_R$ within this window.



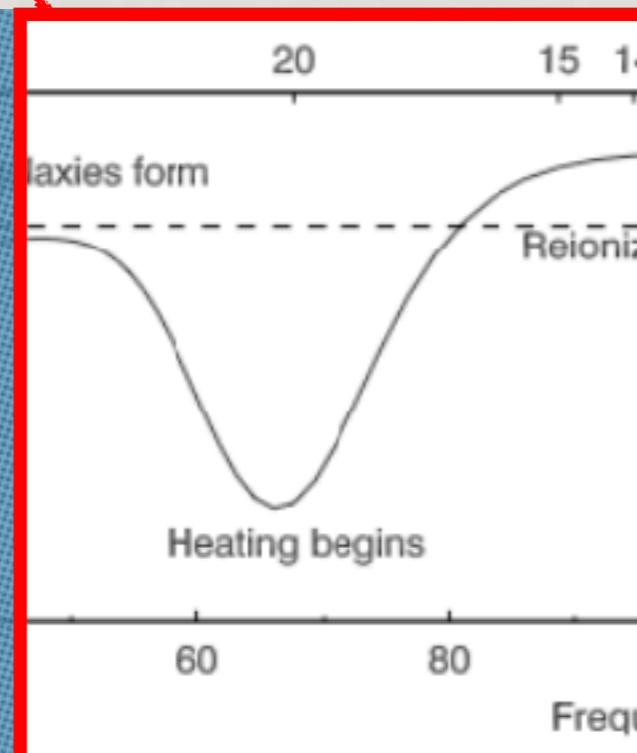
The Global 21-cm signal

$$\Delta T_{21} \propto \left[1 - \frac{T_R}{T_S} \right]$$

$T_m \leq T_S \leq T_R$ within this window. Additionally, star formation **drives** T_S down to T_m via the Wouthuysen-Field effect.

Pritchard & Loeb, 1109.6012

EDGES window

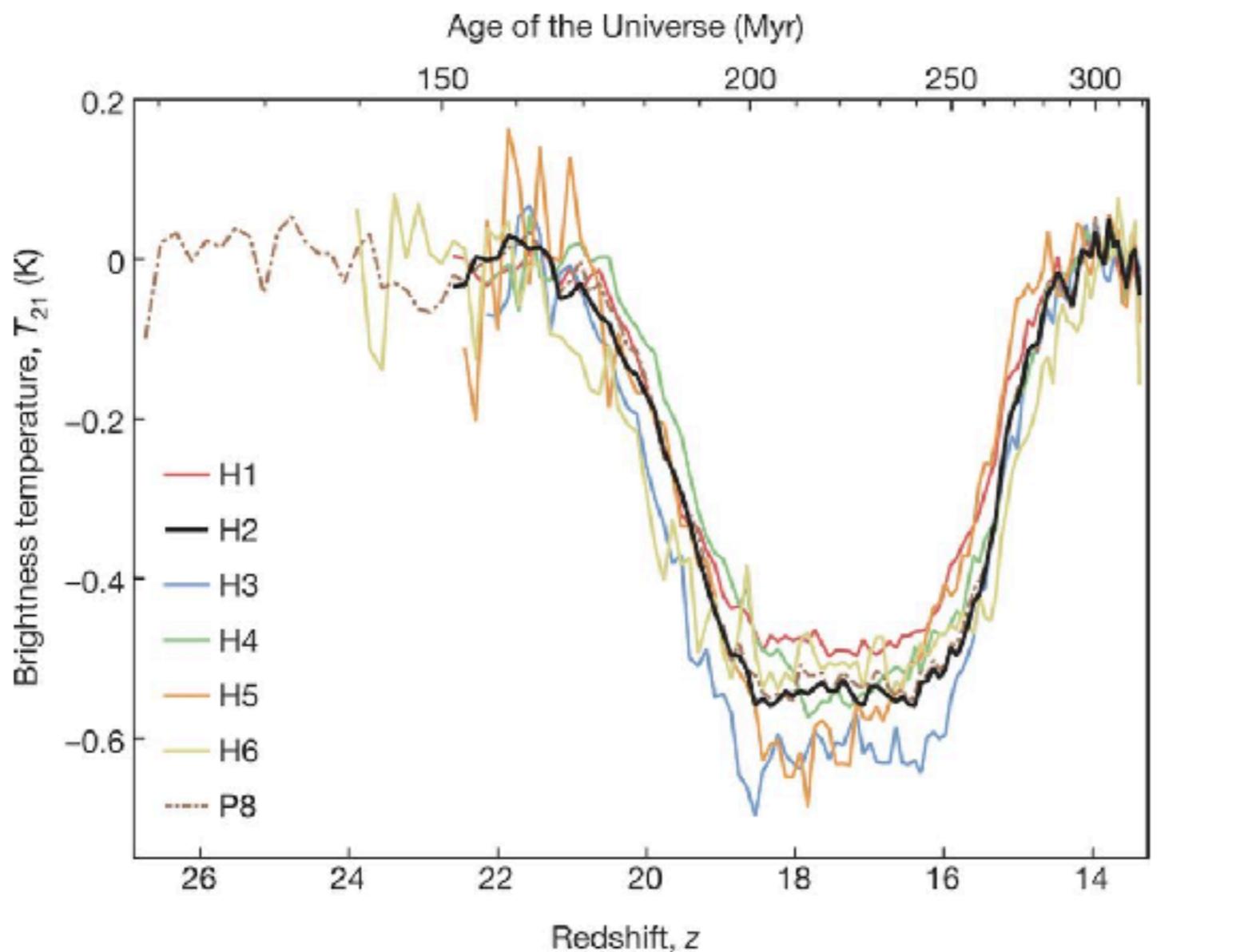


The EDGES signal

The Experiment to Detect the Global Epoch of Reionization Signature

$$\Delta T_{21} \propto \left[1 - \frac{T_R}{T_S} \right]$$

Bowman et. al: Nature 555, 67 (2018)

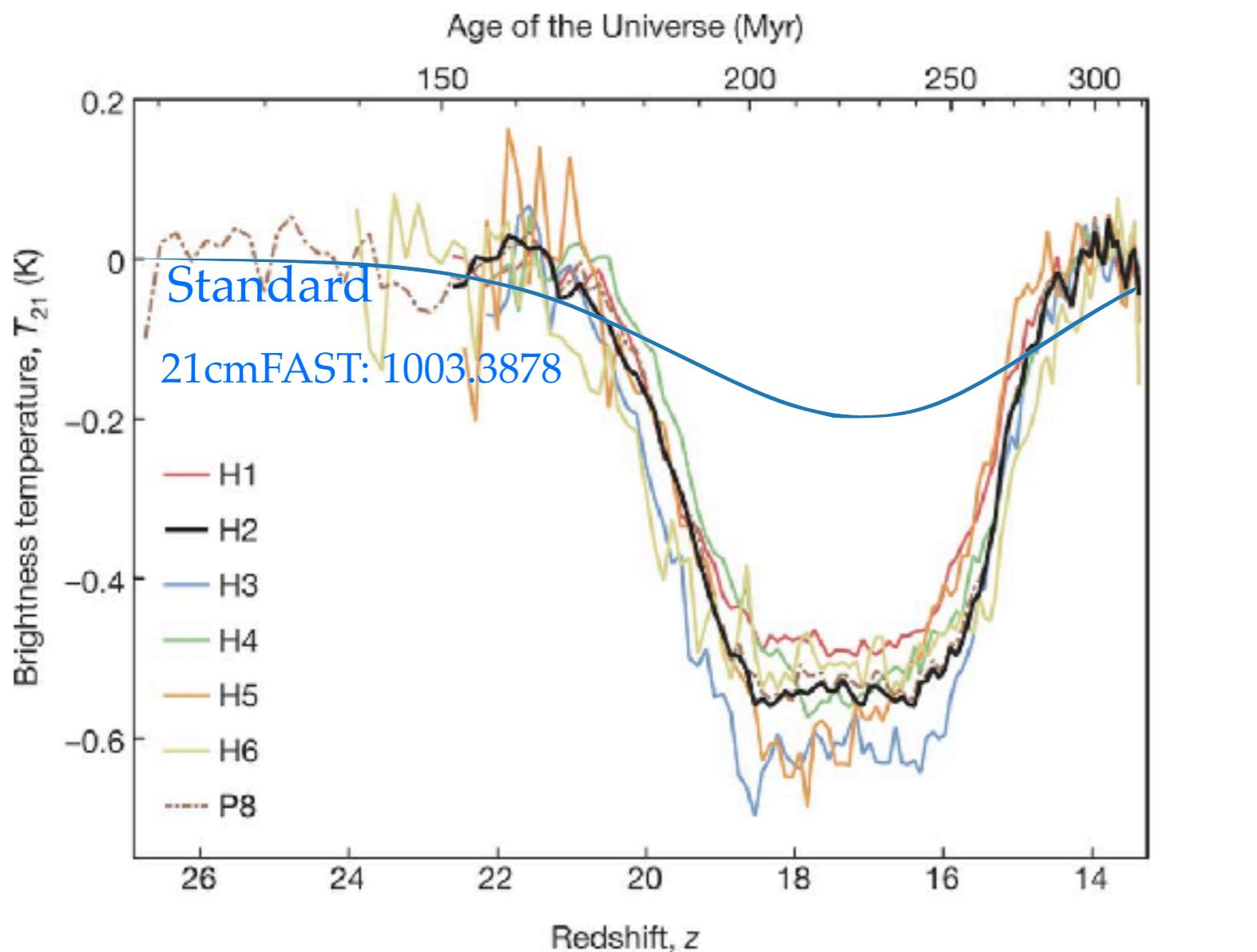


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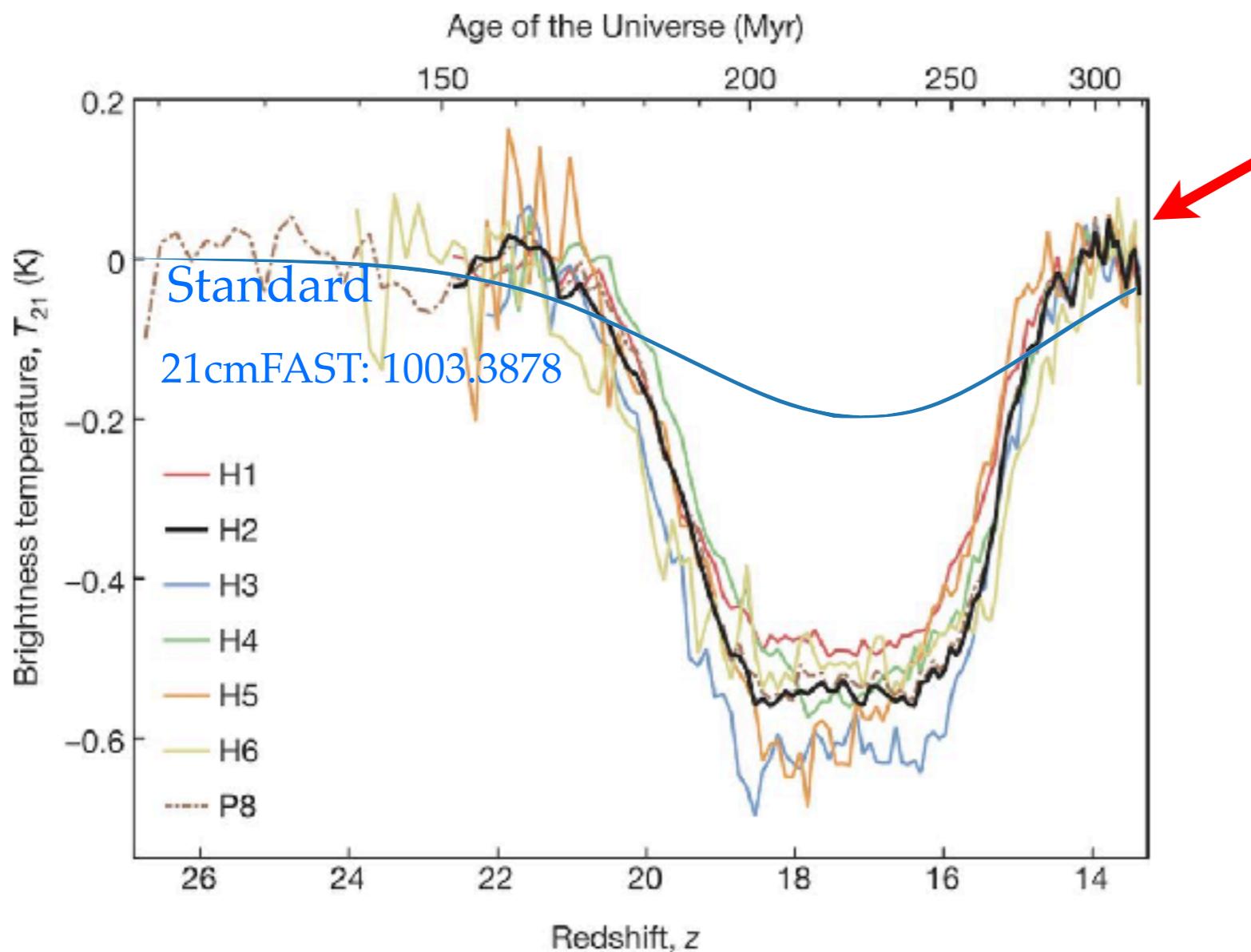


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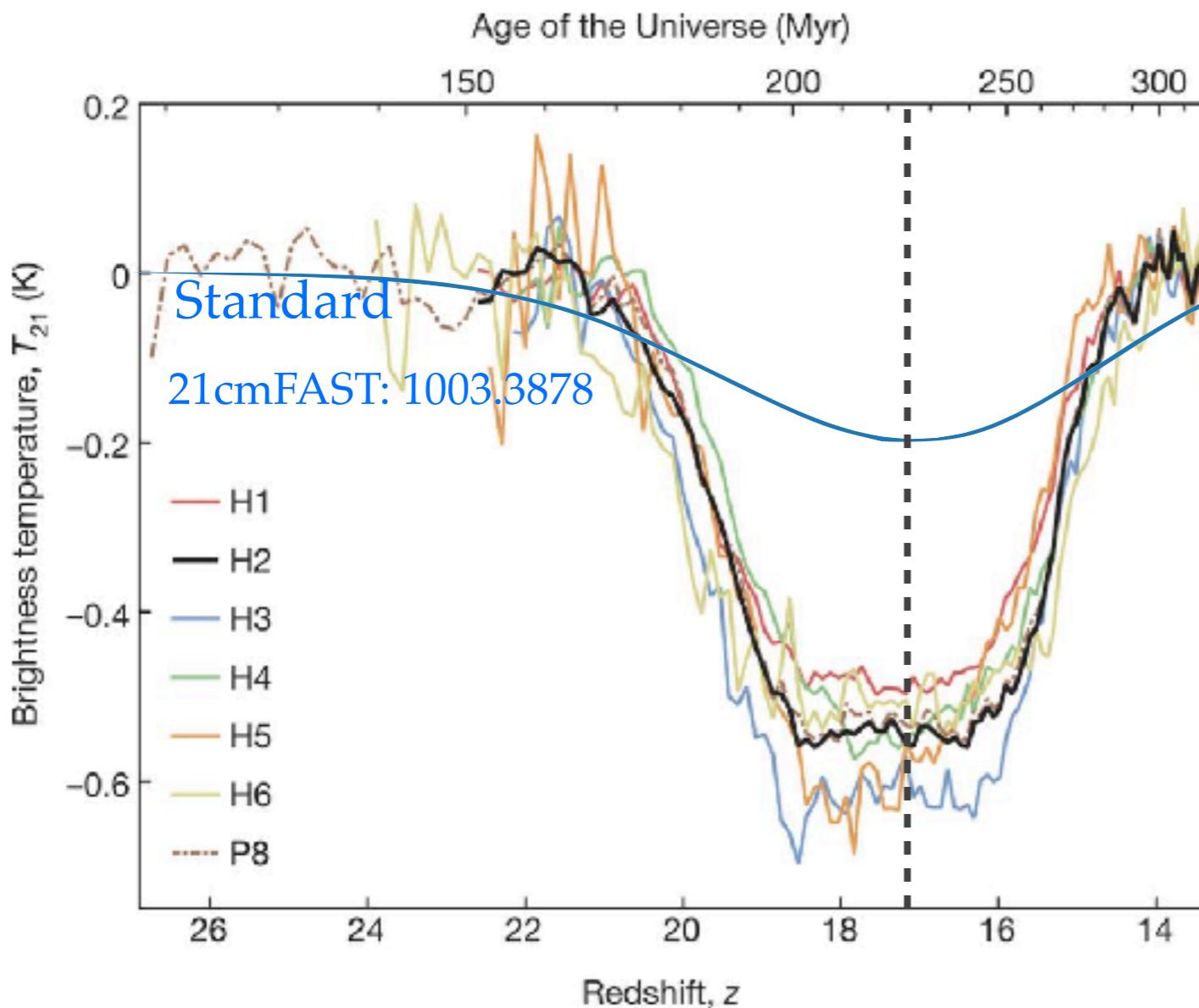
Will mainly focus on the depth.

The EDGES signal

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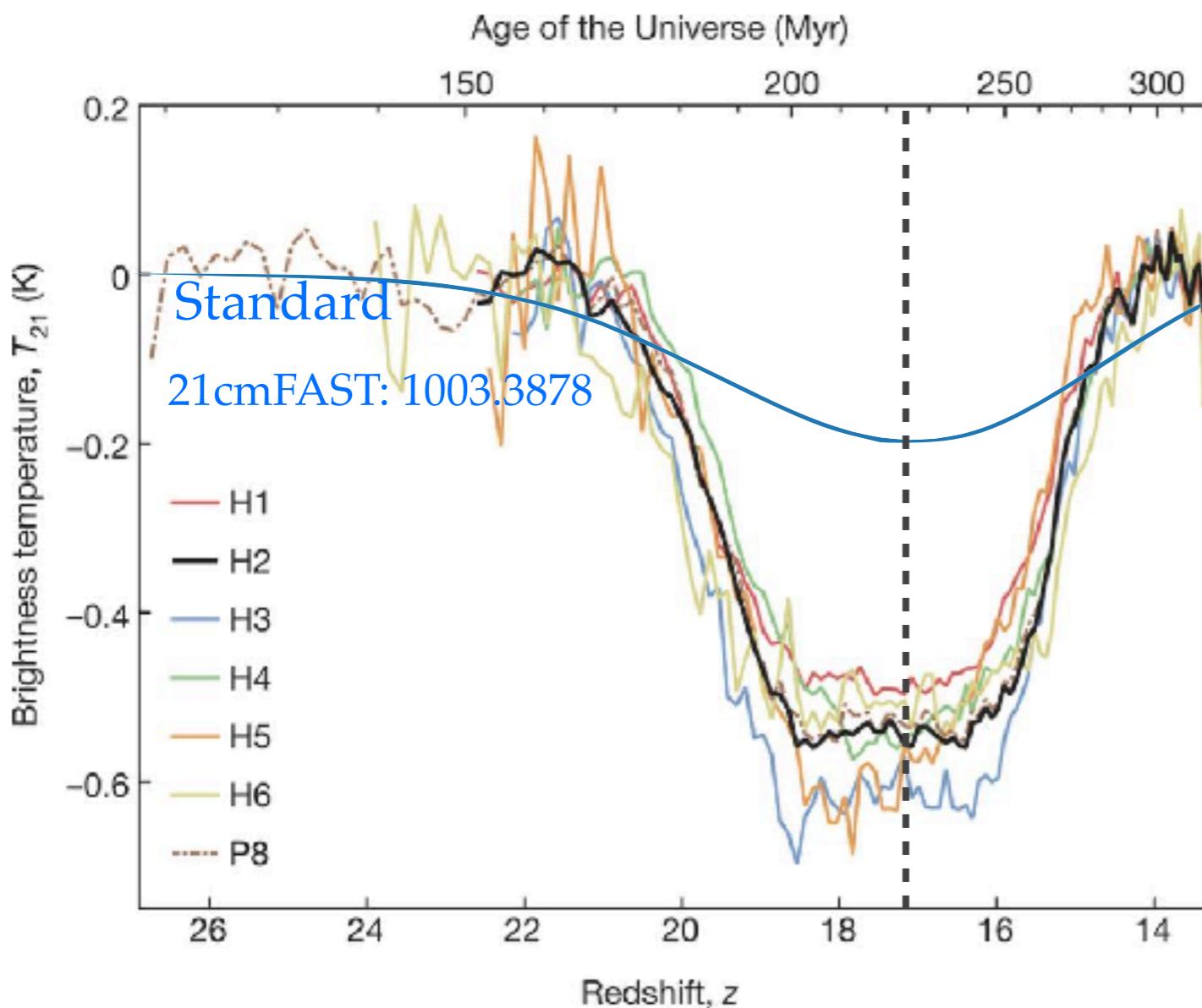
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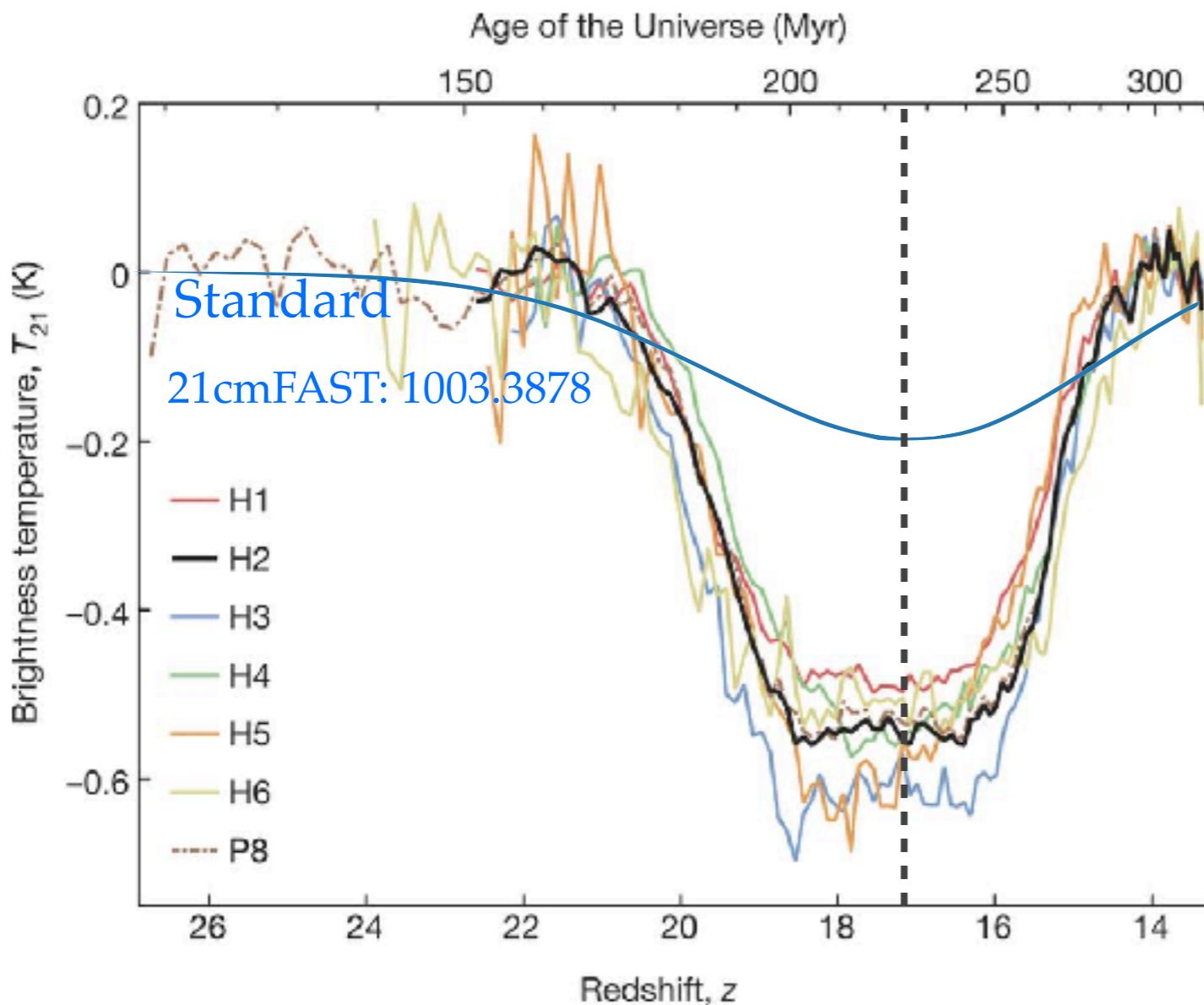
Will mainly focus on the depth.
 $\Delta T_{21}(z \approx 17.2) = -500^{+200}_{-500}$ mK

The EDGES signal

The Experiment to Detect the Global Epoch of Reionization Signature

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Will mainly focus on the depth.

$$\Delta T_{21}(z \approx 17.2) = -500^{+200}_{-500} \text{ mK}$$

$$(T_m \leq T_S)$$

$$\boxed{\frac{T_m}{T_R}(z = 17.2) \leq 0.105}$$

The EDGES signal

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We will consider 3 alternative cosmological scenarios in which:

The EDGES signal

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- ❖ T_R hotter

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- ❖ T_R hotter
- ❖ T_m colder

1. There was an additional source(s) of 21cm radiation

The EDGES signal

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We will consider 3 alternative cosmological scenarios in which:

- ❖ T_R hotter
- ❖ T_m colder

1. There was an additional source(s) of 21cm radiation
2. T_m decoupled from T_{CMB} earlier than is typically assumed

The EDGES signal

$$\frac{T_m}{T_R}(z = 17.2) \leq 0.105$$

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We will consider 3 alternative cosmological scenarios in which:

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1. There was an additional source(s) of 21cm radiation
2. T_m decoupled from T_{CMB} earlier than is typically assumed
3. There is a DM component that cools T_m through its interactions

The EDGES signal

$$\frac{T_m}{T_R}(z = 17.2) \leq 0.105$$

Cannot have $T_R = T_{CMB}$ and standard T_m

We will consider 3 alternative cosmological scenarios in which:

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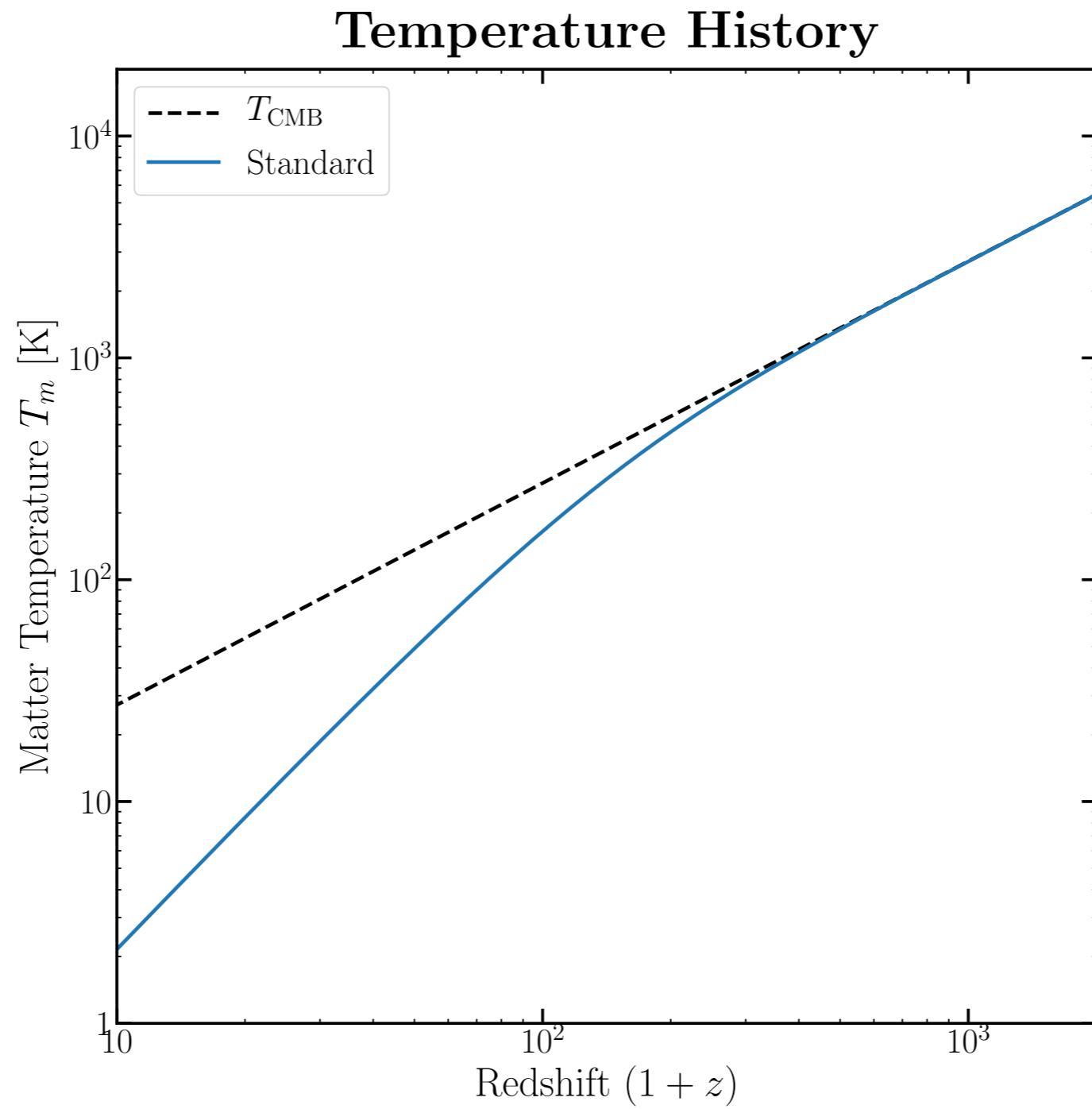
Assuming any of these scenarios, we ask our main question...

The Main Question:

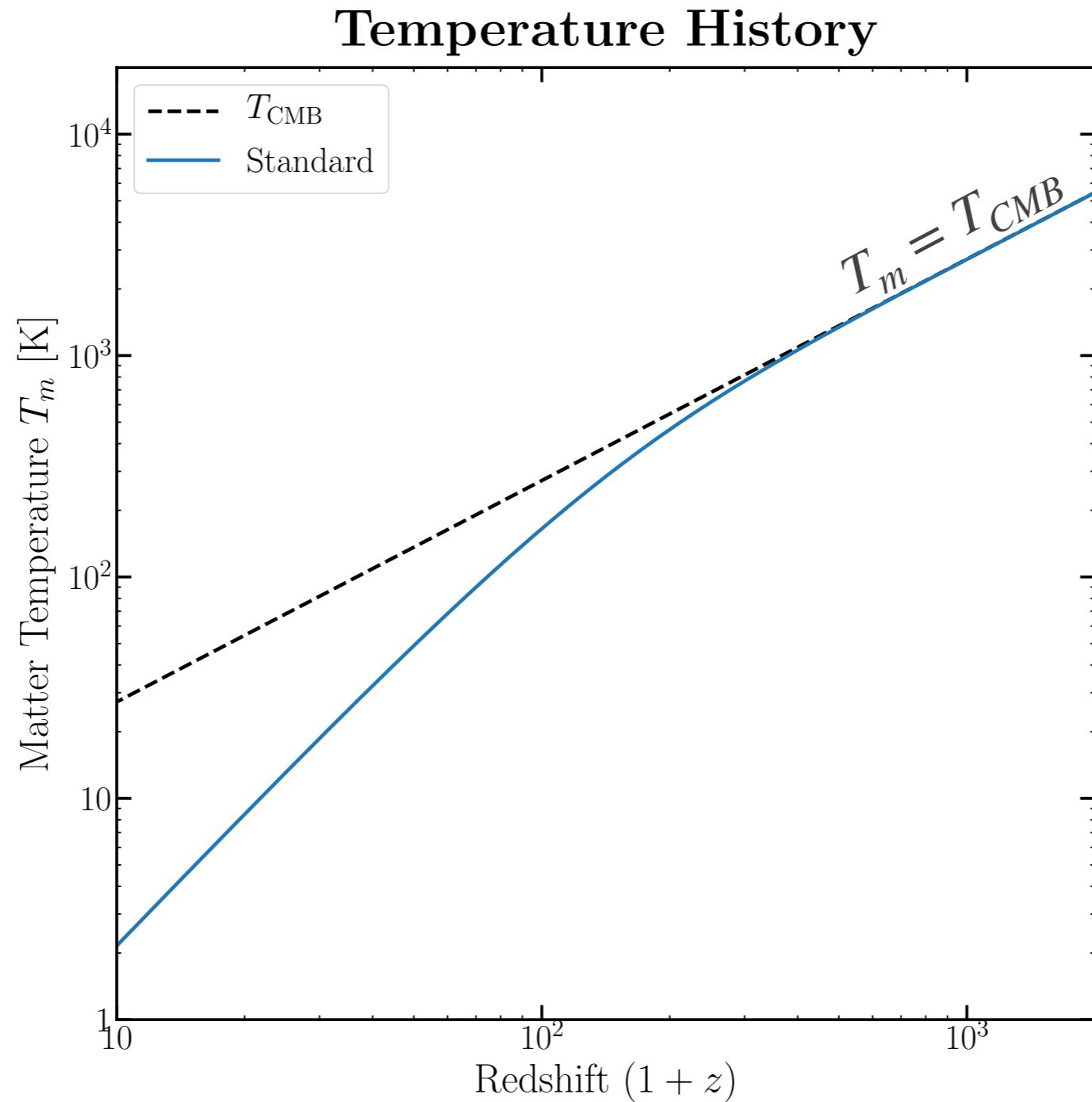
How does the EDGES signal (or an EDGES-like signal) constrain decaying/annihilating DM models?

Temperature Histories

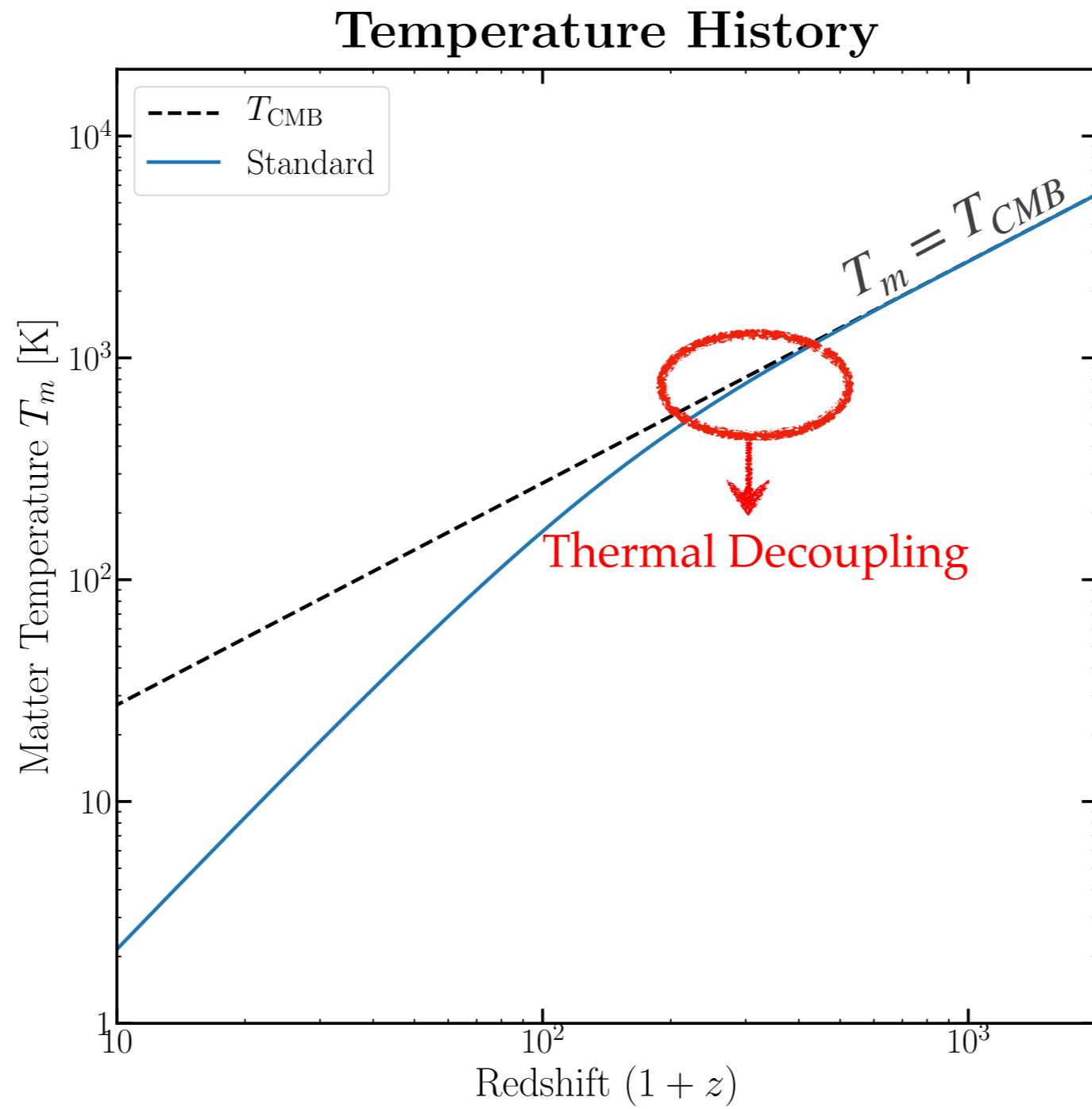
Temperature Histories



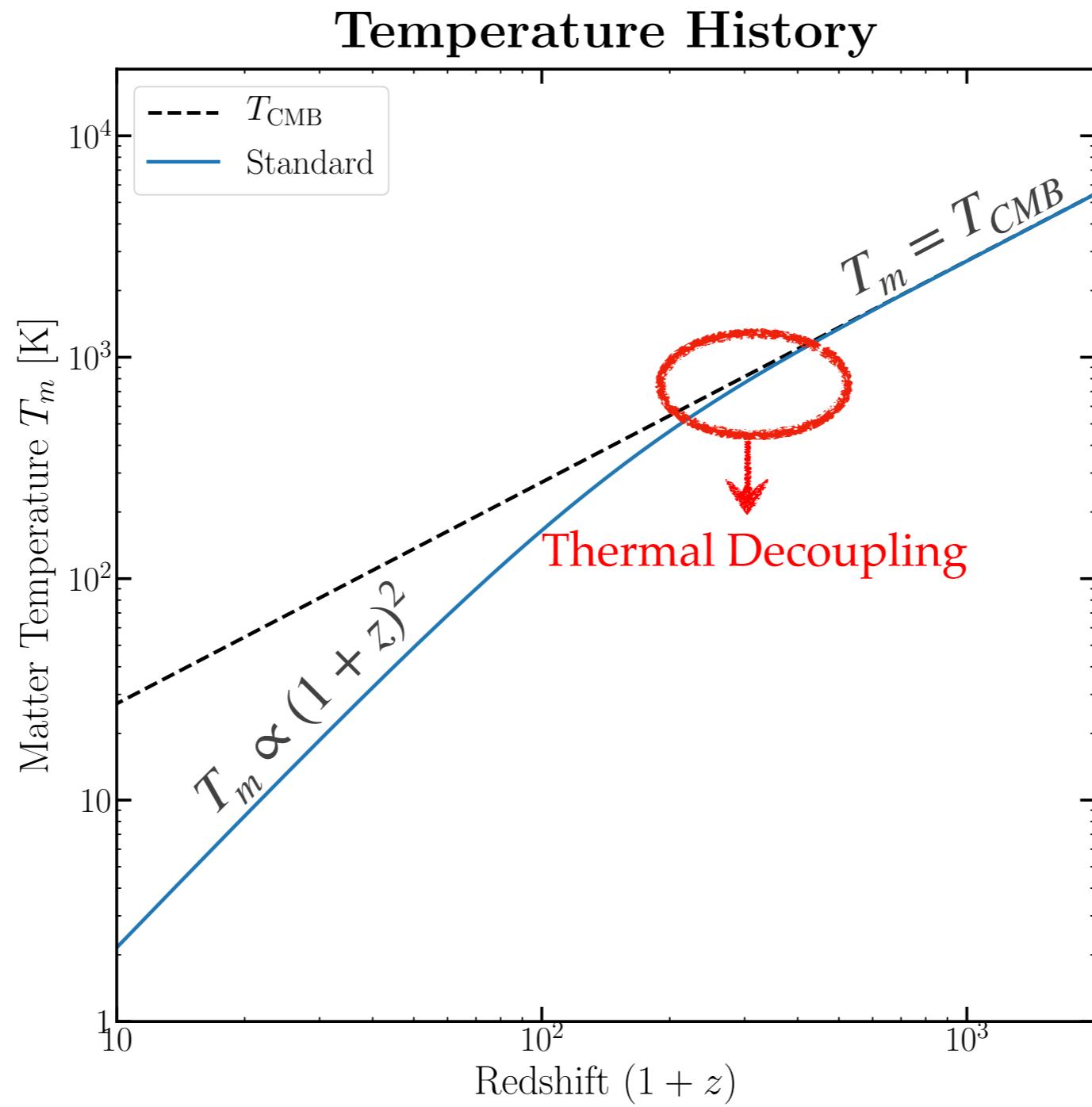
Temperature Histories



Temperature Histories

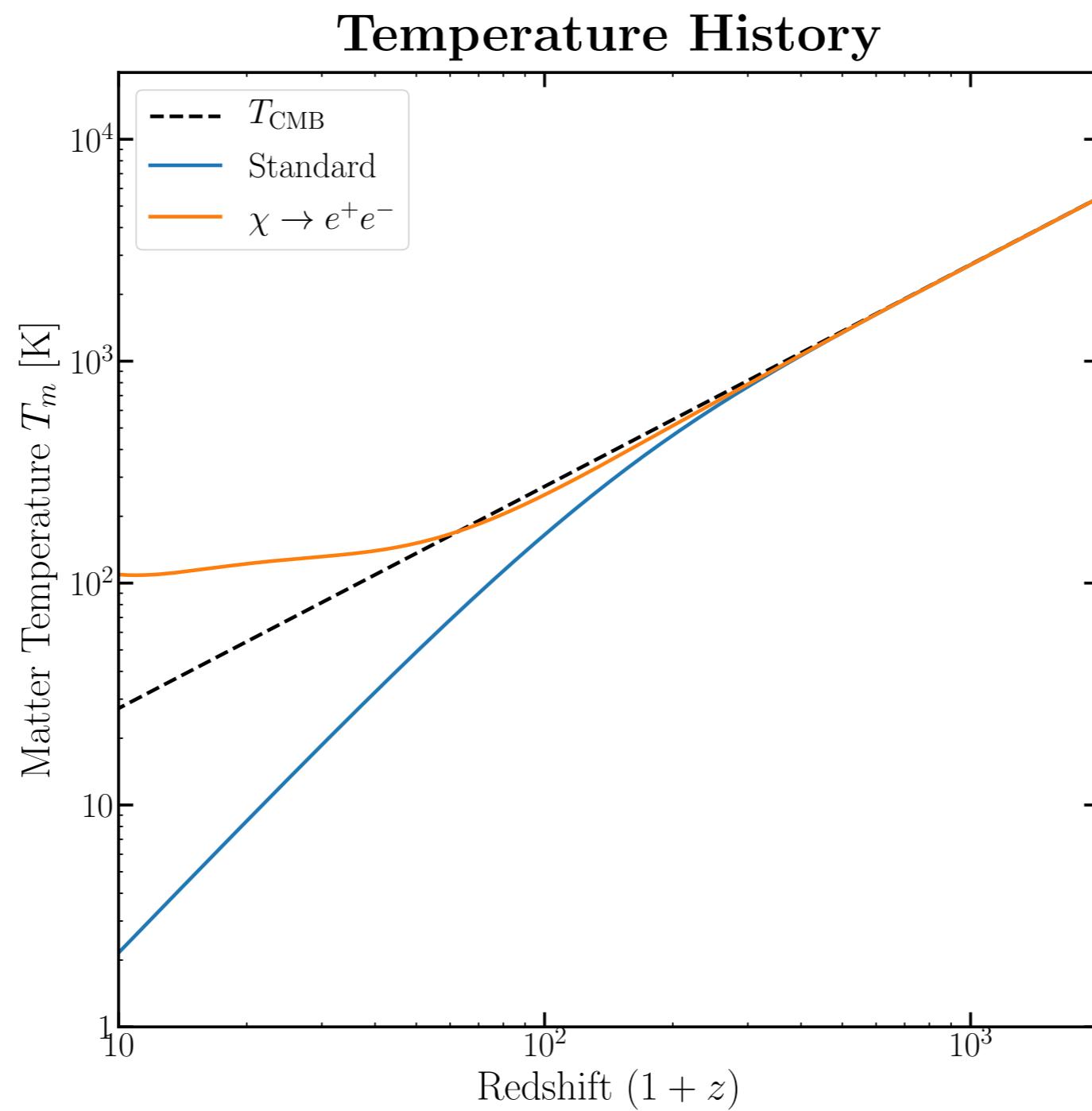


Temperature Histories



Temperature Histories with DM

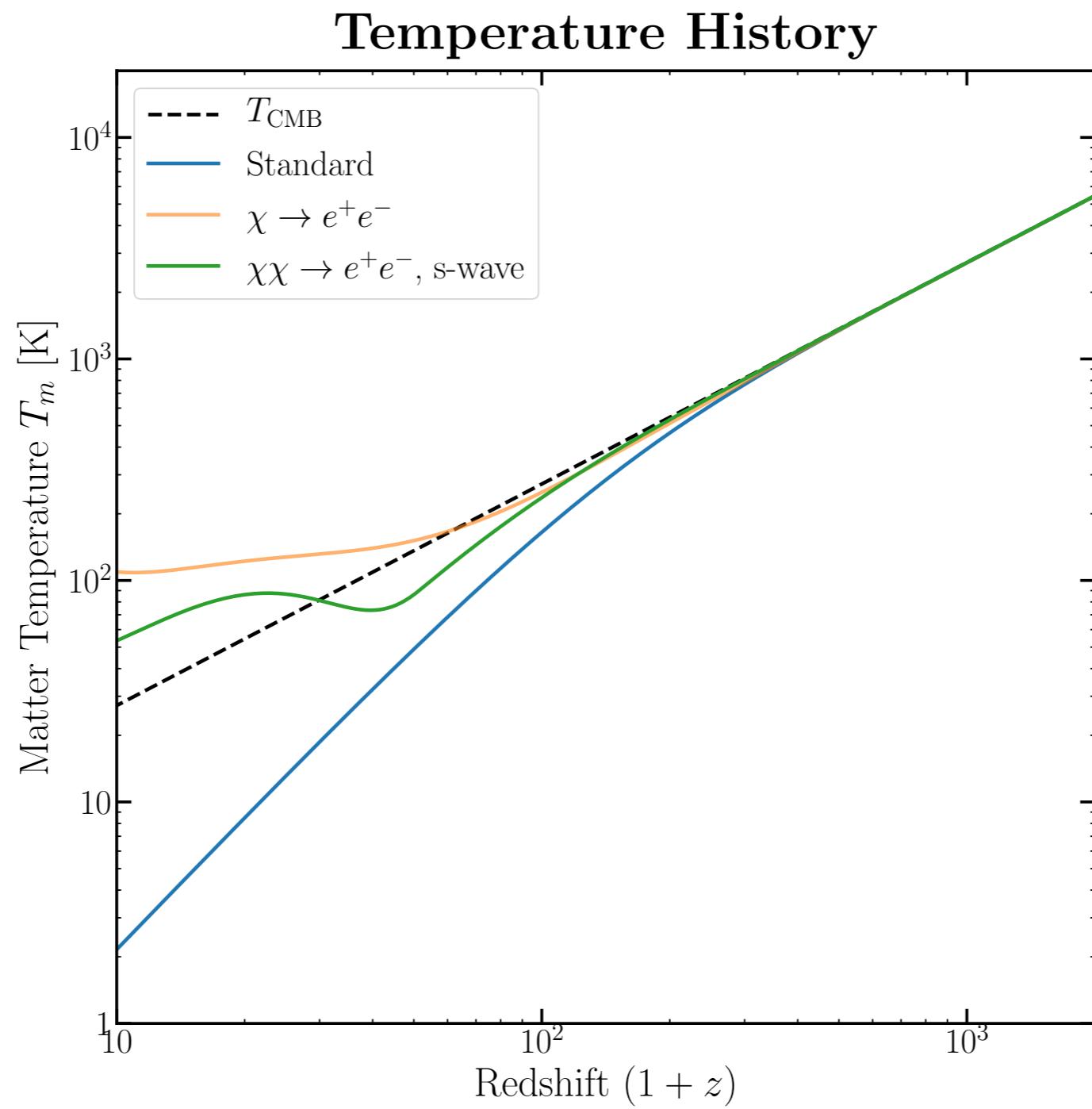
Add a **decaying**
DM component



$$\chi \rightarrow e^+e^-$$
$$\left(\frac{dE}{dVdt} \right)_{\text{inj}} \propto \rho$$

Temperature Histories with DM

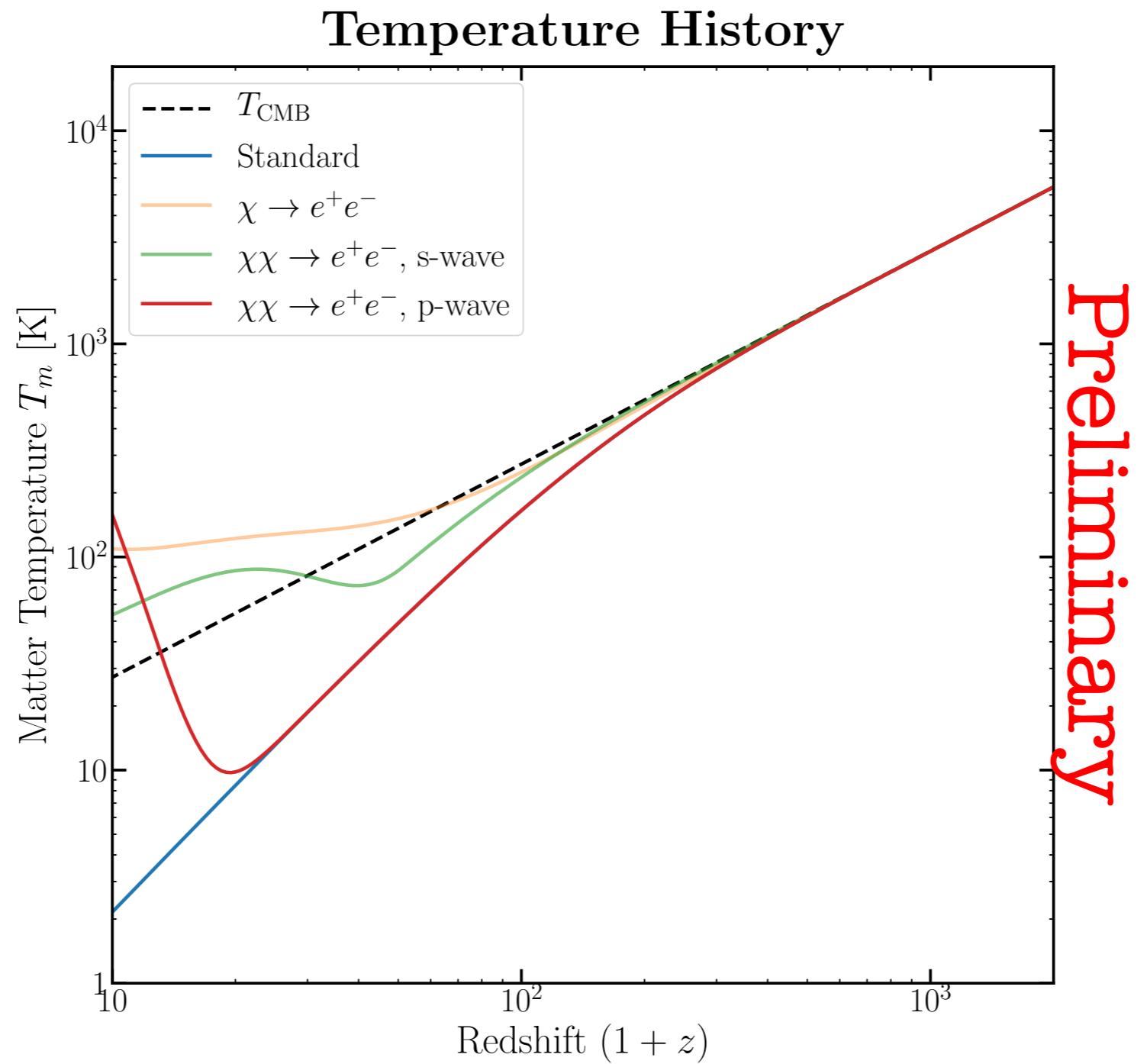
or s-wave
annihilating
DM component



$$\chi\chi \rightarrow e^+e^-$$
$$\left(\frac{dE}{dVdt} \right)_{\text{inj}} \propto \rho^2$$

Temperature Histories with DM

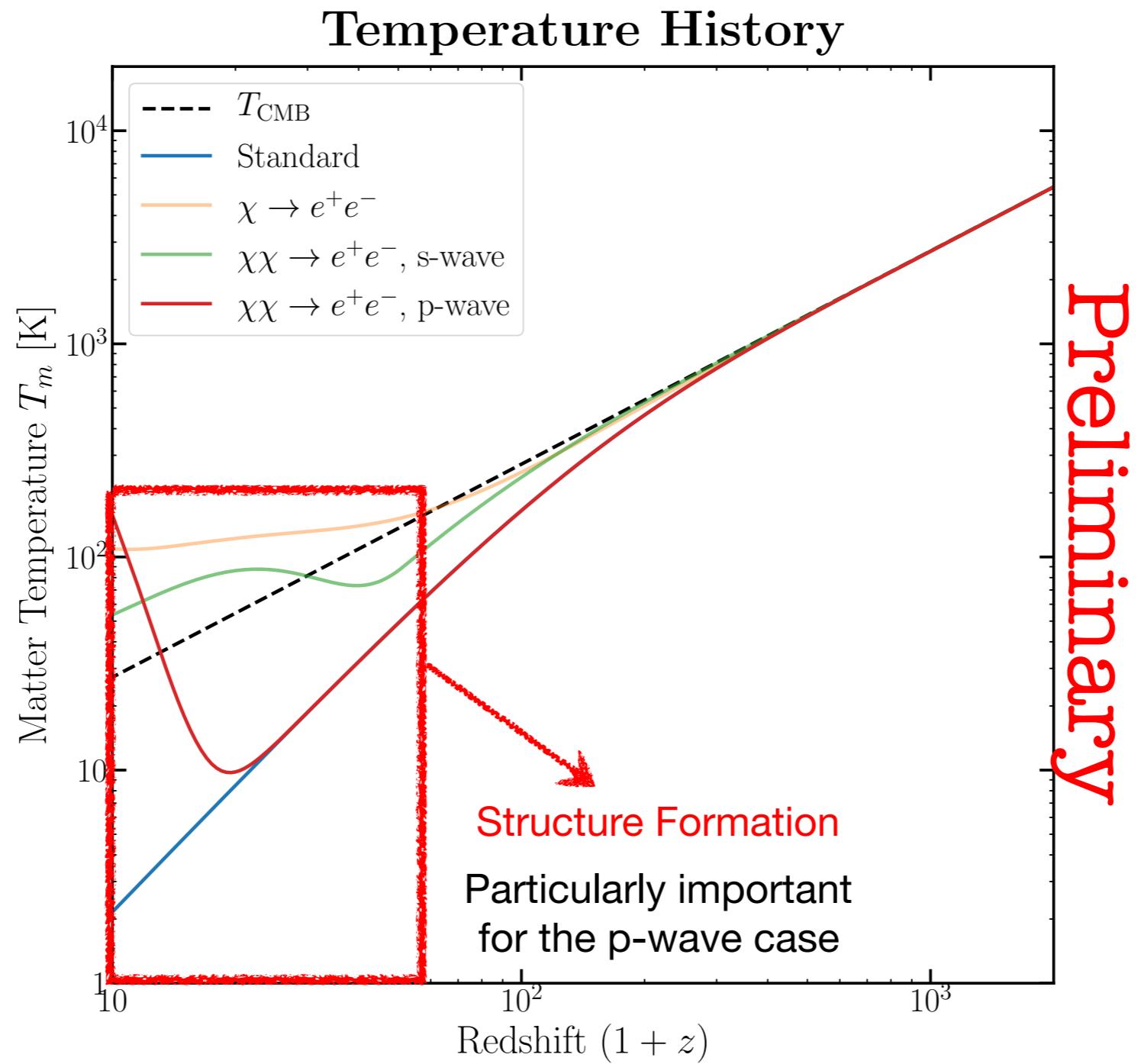
or p-wave
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Temperature Histories with DM

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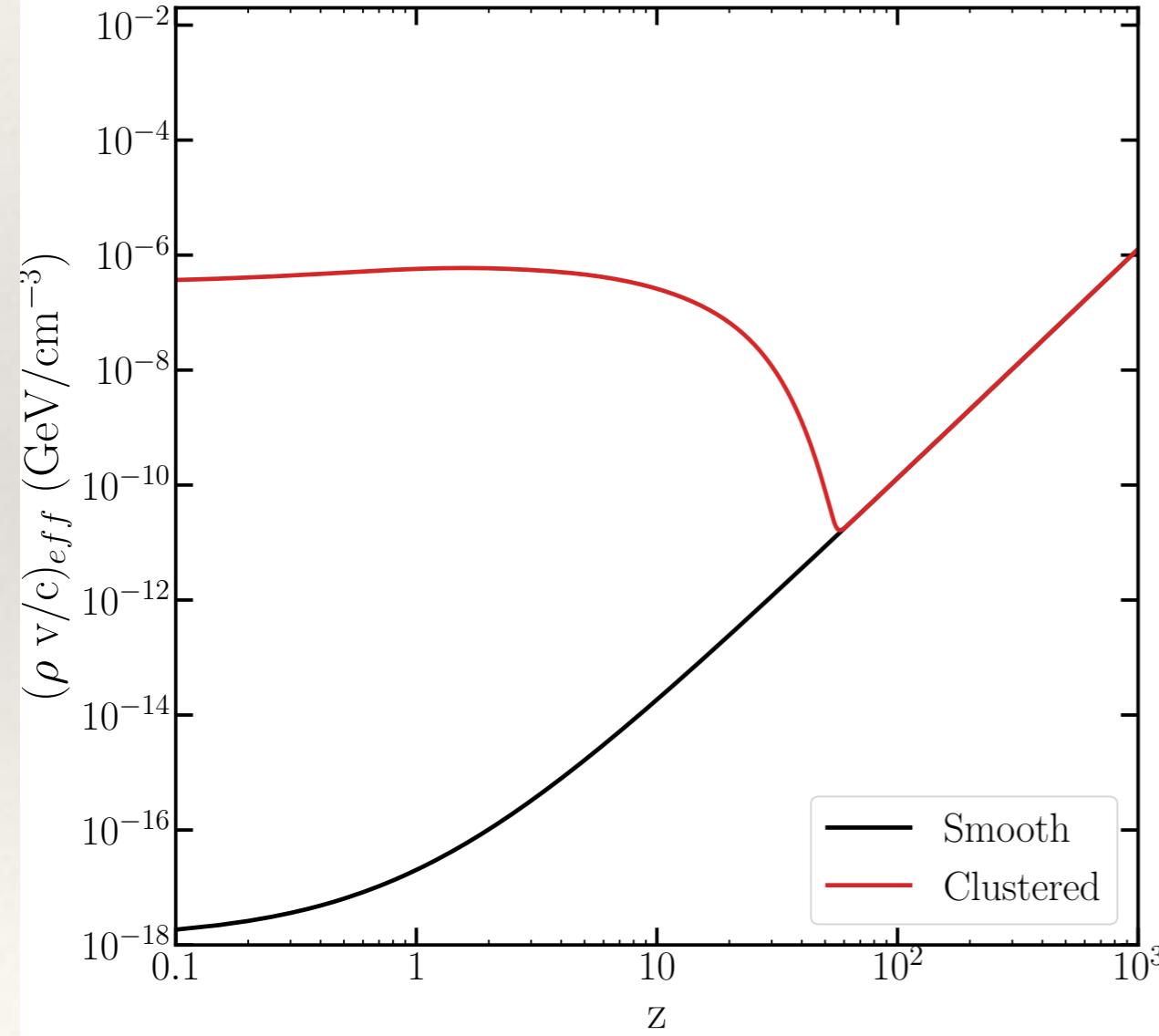
Structure Formation

p-wave case: Density boost + Velocity boost, $\rho v/c \rightarrow (\rho v/c)_{\text{eff}}$

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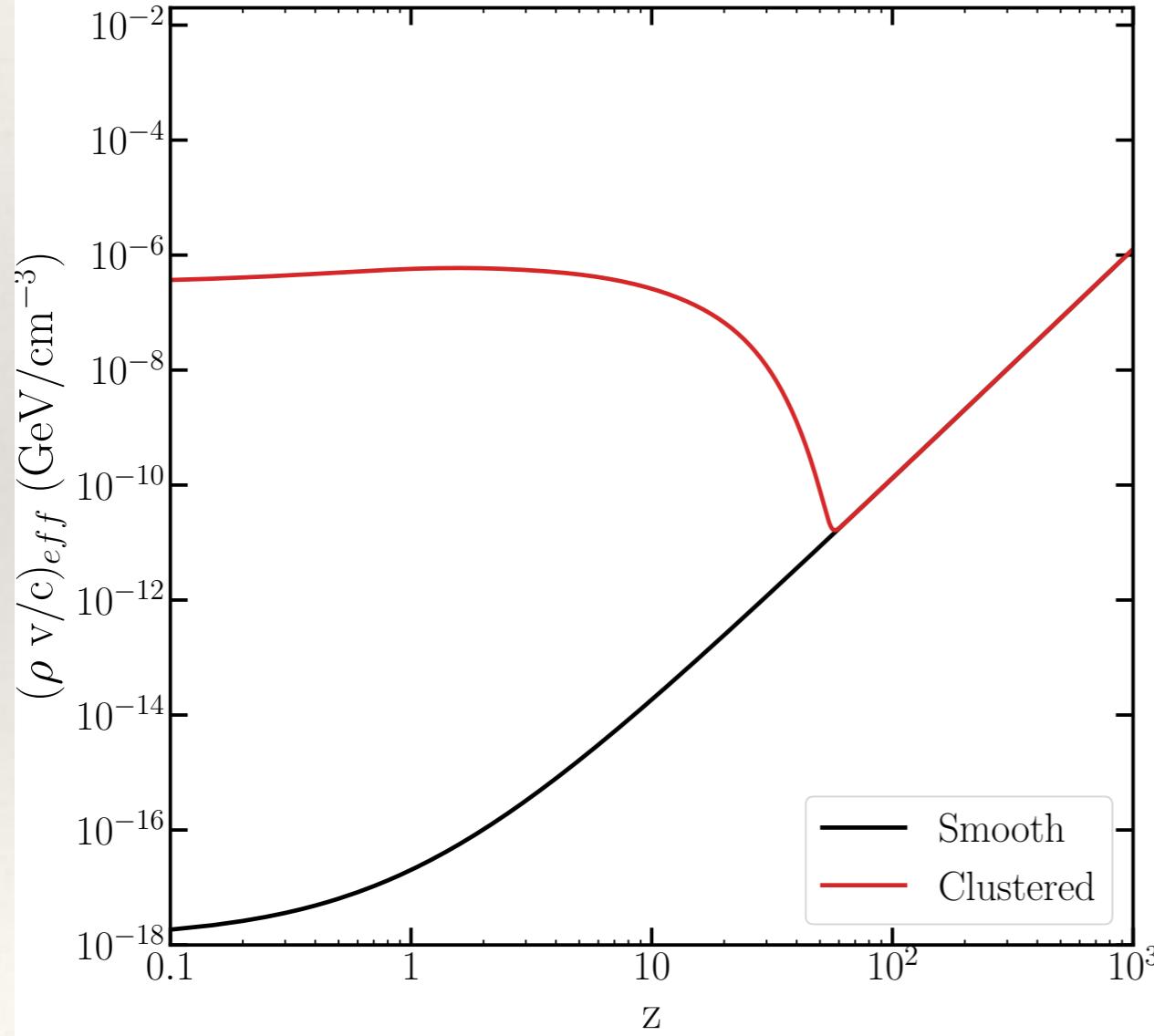
Preliminary



Structure Formation

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Preliminary

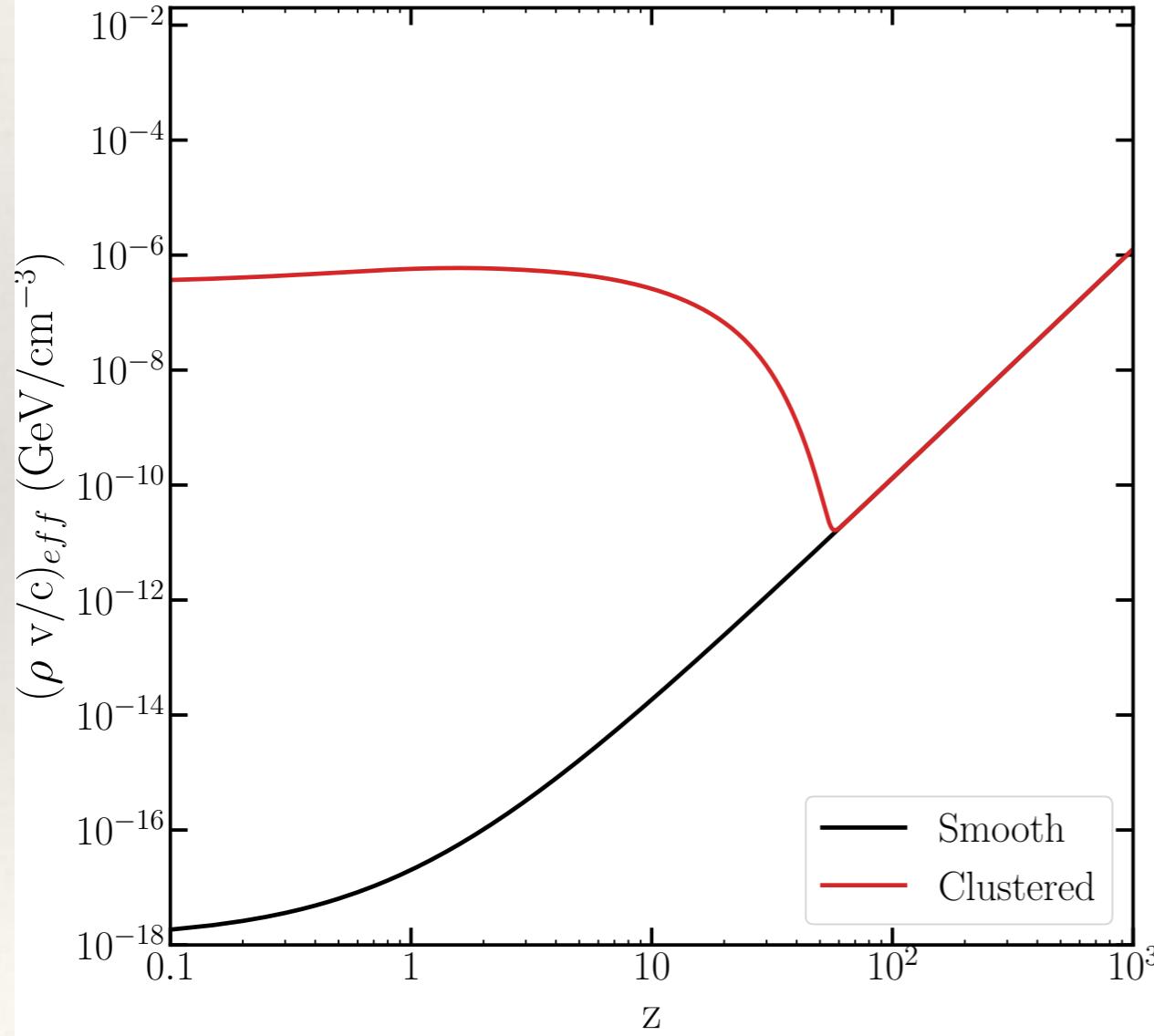


$$\left(\frac{dE}{dVdt} \right)_{\text{inj}} \propto \rho^2 v^2$$

Structure Formation

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Preliminary



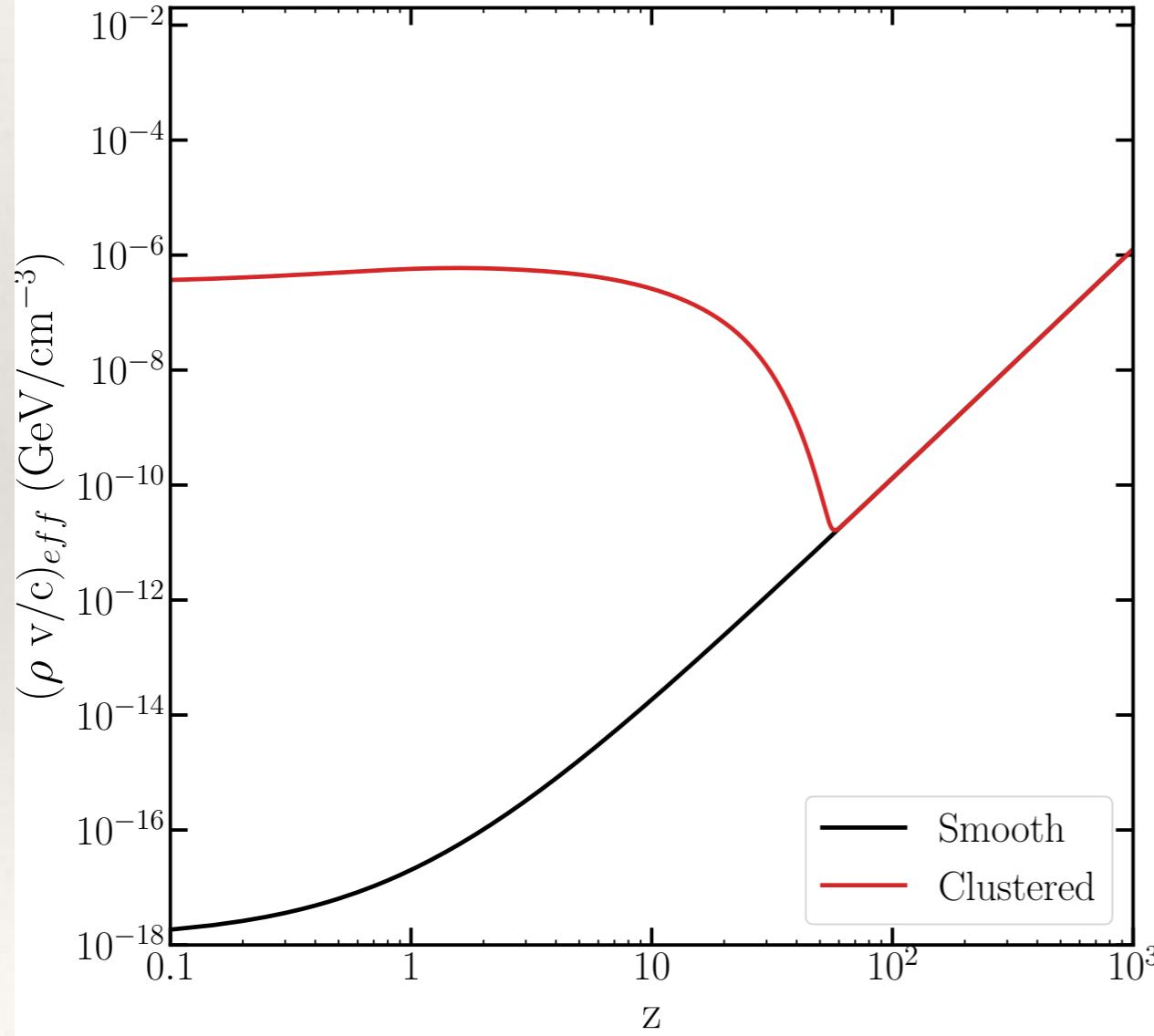
$$\left(\frac{dE}{dVdt} \right)_{\text{inj}} \propto \rho^2 v^2$$

Leads to an **energy injection boost**
by **many orders of magnitude**:

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Preliminary



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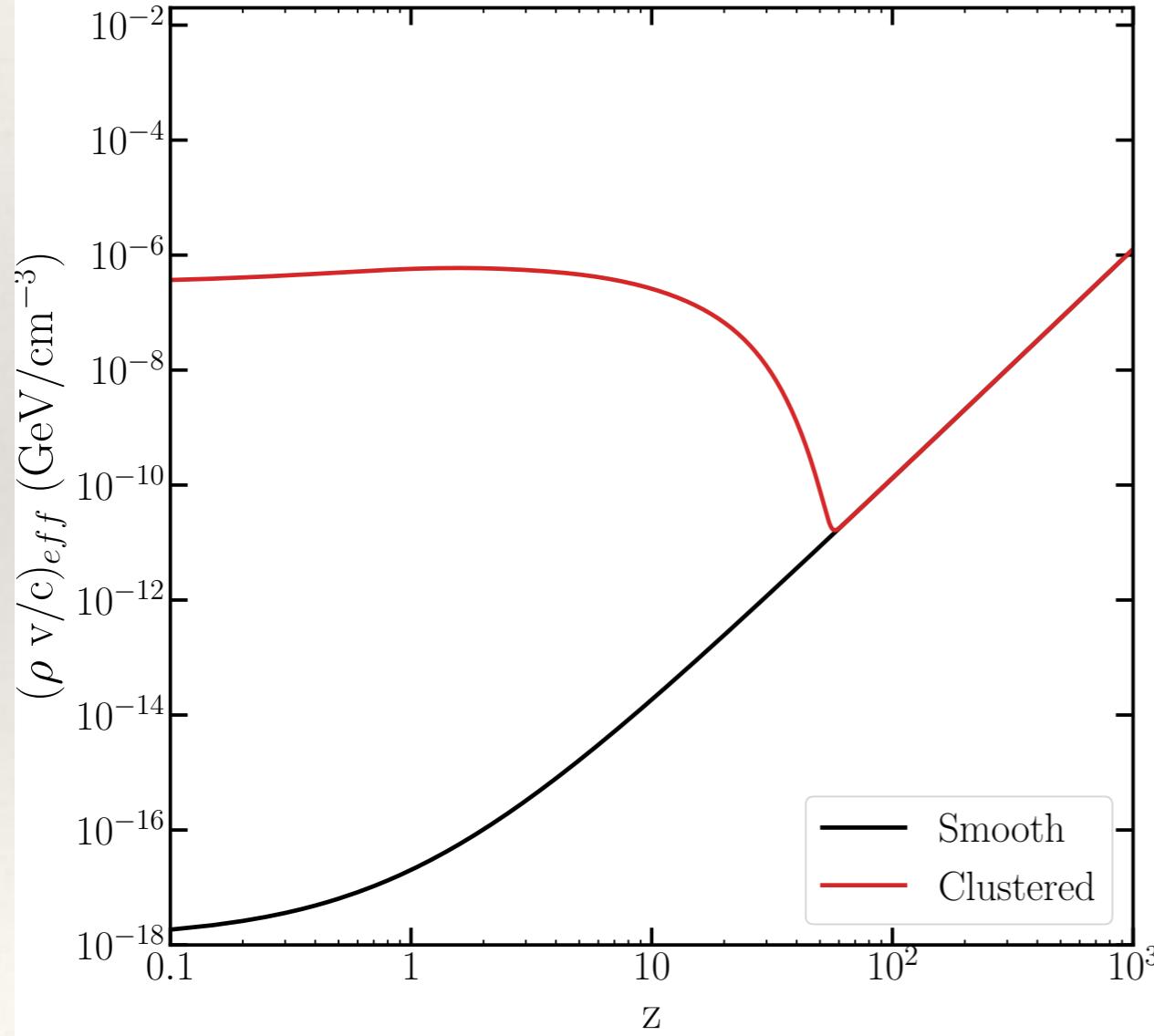
Leads to an **energy injection boost**
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$$\text{boost} \sim \left(\frac{(\rho v)_{\text{eff}}}{\rho v} \right)^2$$

Structure Formation

p-wave case: Density boost + Velocity boost, $\rho v/c \rightarrow (\rho v/c)_{\text{eff}}$

Preliminary



$$\left(\frac{dE}{dVdt} \right)_{\text{inj}} \propto \rho^2 v^2$$

Leads to an **energy injection boost**
by **many orders of magnitude**:

$$\text{boost} \sim \left(\frac{(\rho v)_{\text{eff}}}{\rho v} \right)^2 \sim 10^{12} - 10^{24}$$

Structure Formation

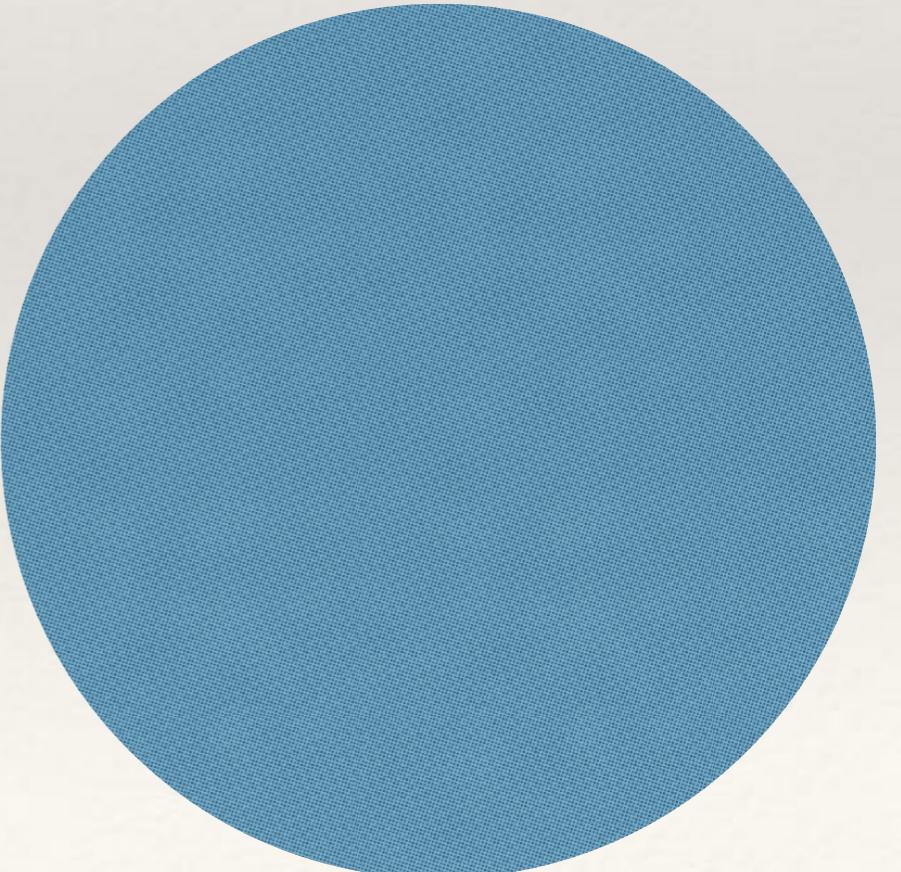
$$\text{boost} \propto \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$

Structure Formation

$$\text{boost} \propto \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{\text{Halo}}^2(r)$$

Boost from Single Halo

Halo



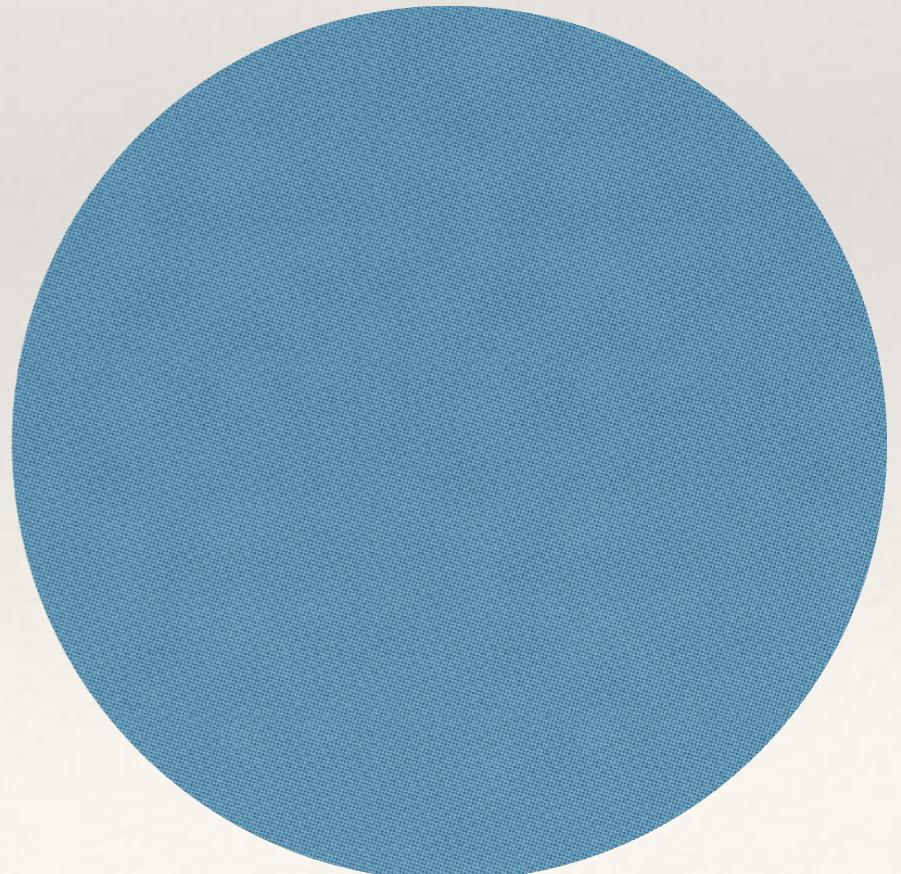
Structure Formation

$$\text{boost} \propto \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{\text{Halo}}^2(r)$$

Boost from Single Halo

- ❖ Assume an **NFW** profile

$$\rho_{\text{Halo}} = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$



Structure Formation

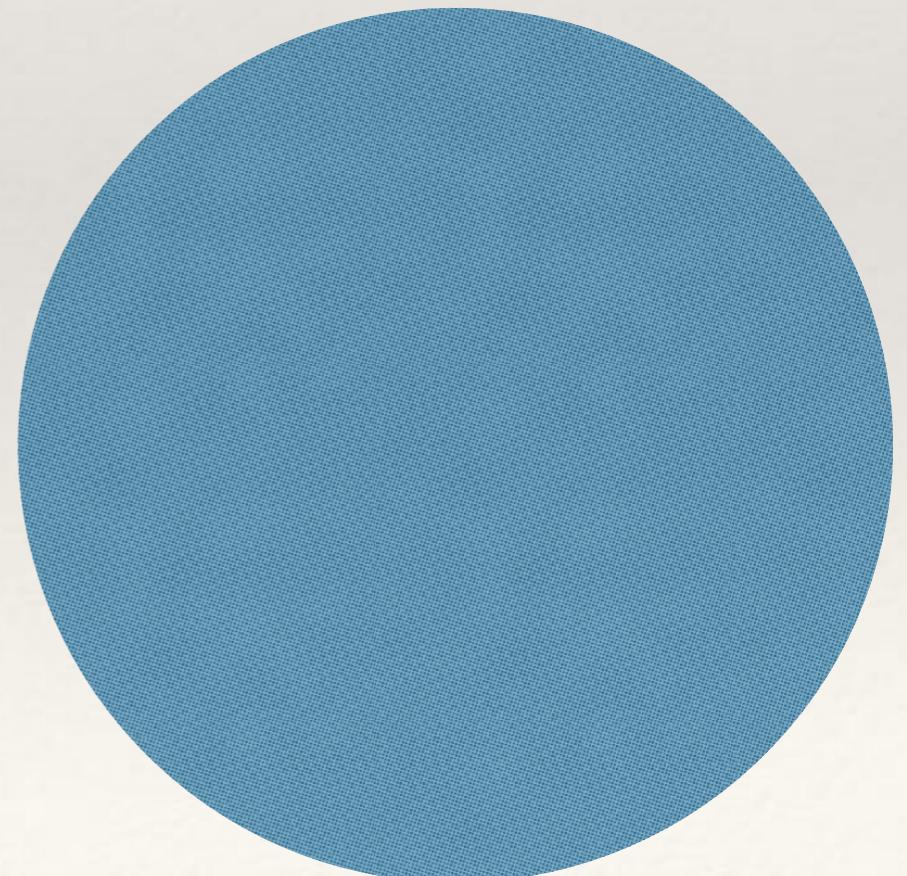
$$\text{boost} \propto \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{\text{Halo}}^2(r)$$

Boost from Single Halo

- ❖ Assume an **NFW** profile
- ❖ Both NFW parameters fixed in part by N-Body simulations

Halo

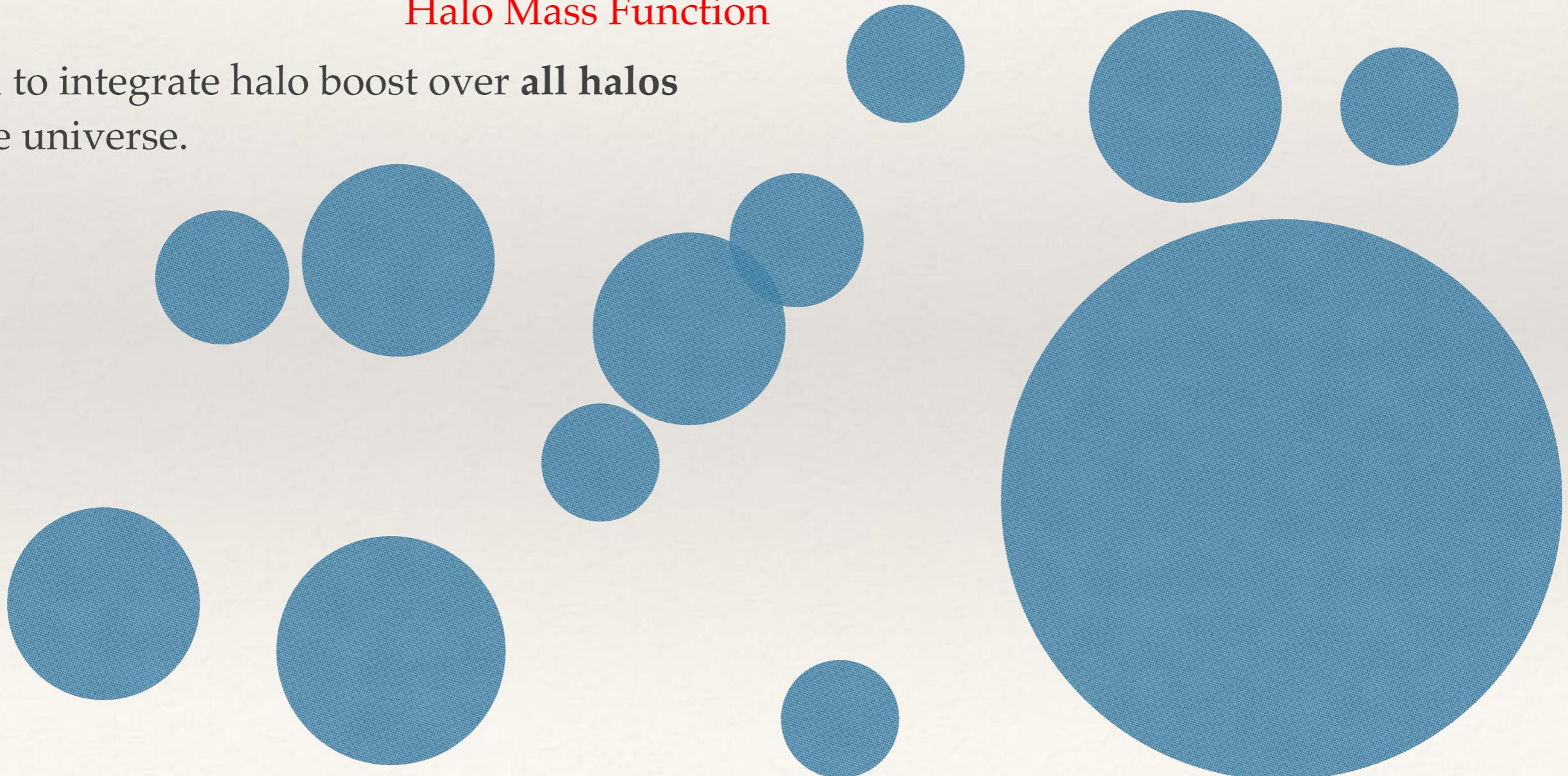
$$\rho_{\text{Halo}} = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$



Structure Formation

$$\text{boost} \propto \underbrace{\int dM \frac{dn}{dM}(M, z)}_{\text{Halo Mass Function}} \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$

Used to integrate halo boost over all halos
in the universe.

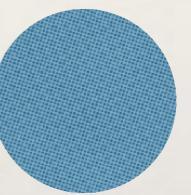
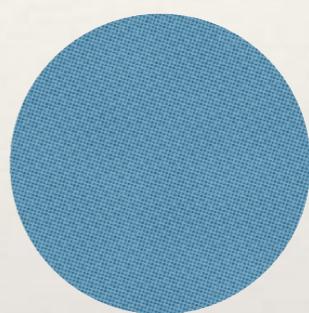
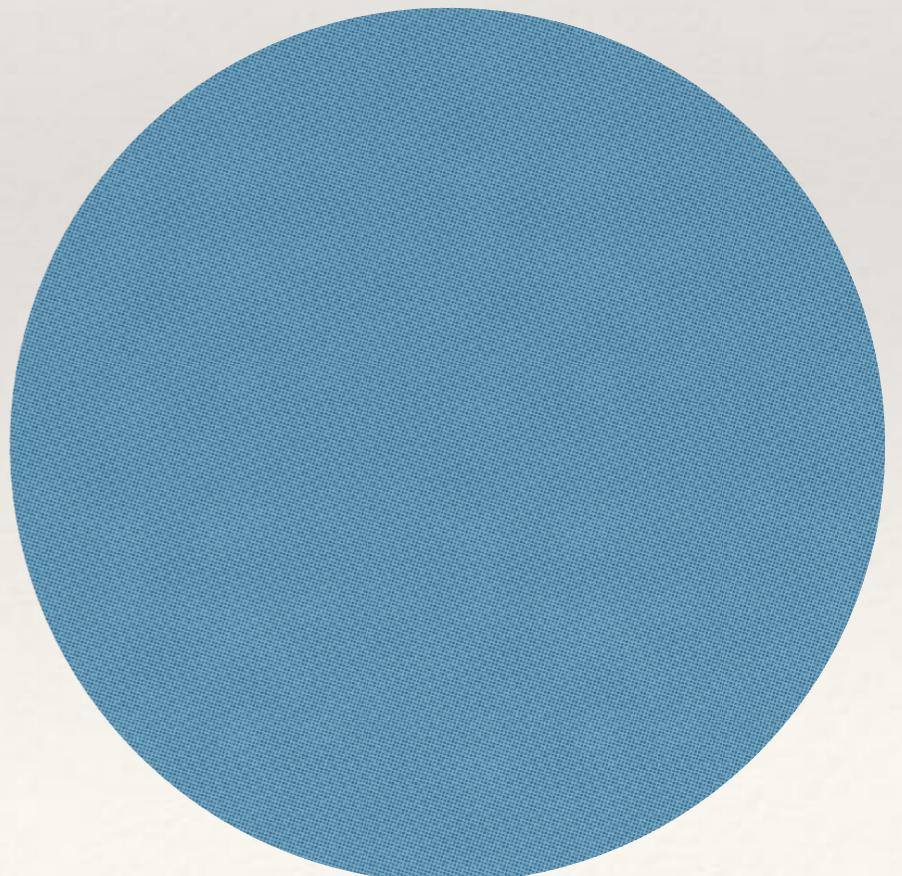
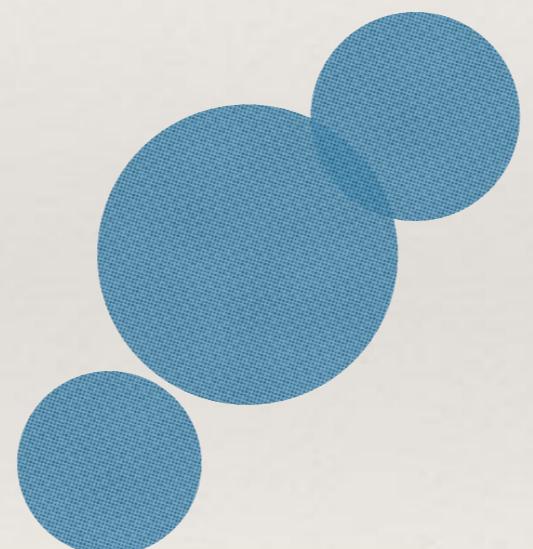
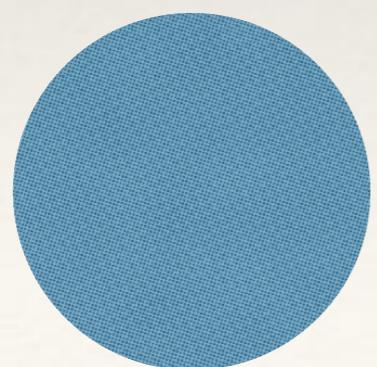
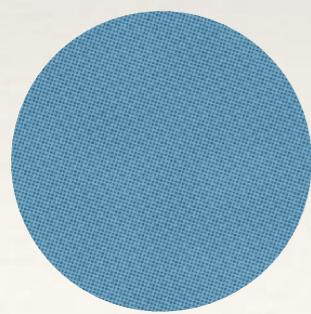


Structure Formation

$$\text{boost} \propto \underbrace{\int dM \frac{dn}{dM}(M, z)}_{\text{Halo Mass Function}} \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$

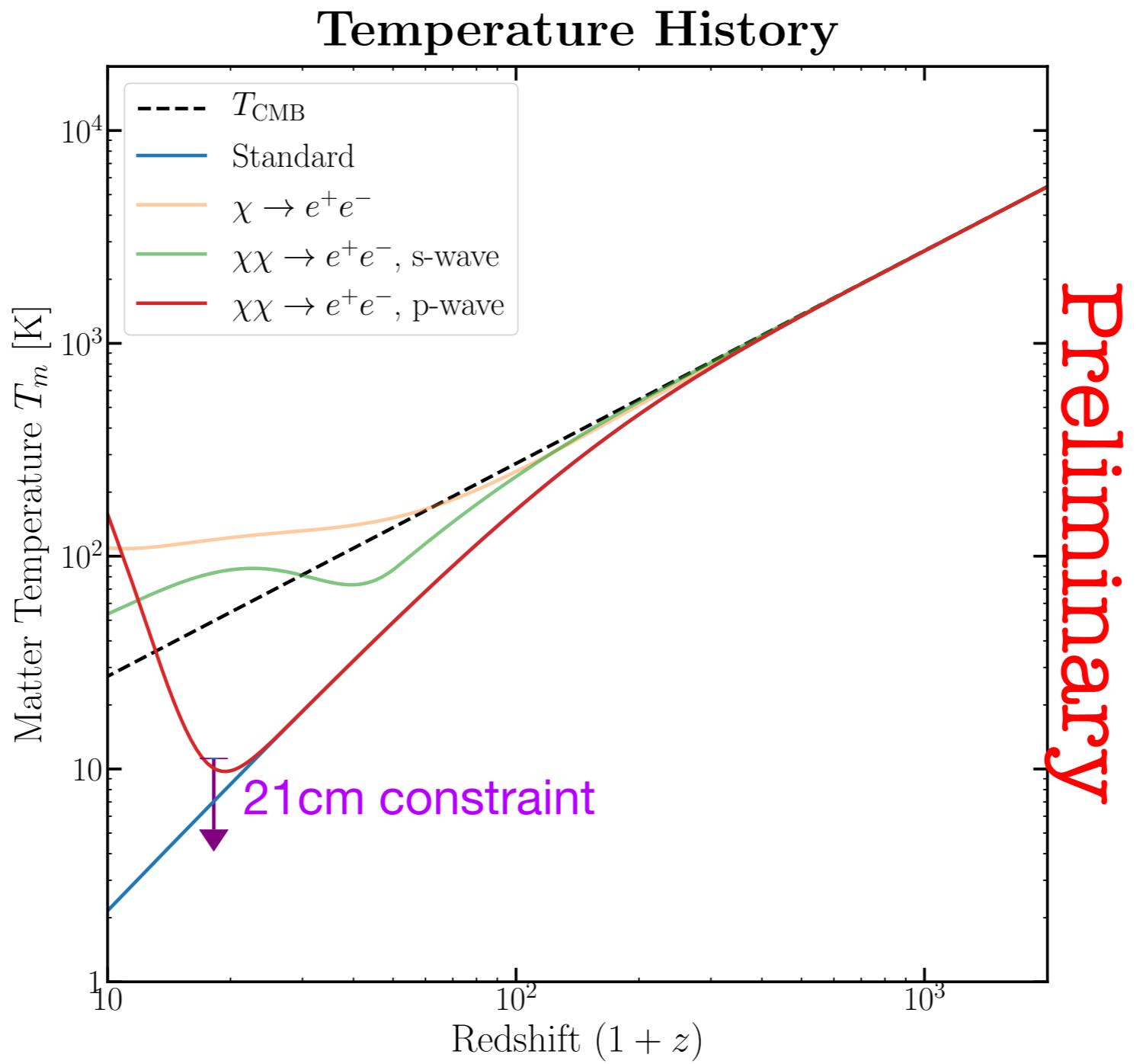
Used to integrate halo boost over all halos in the universe.

Again, uses input from N-Body simulations



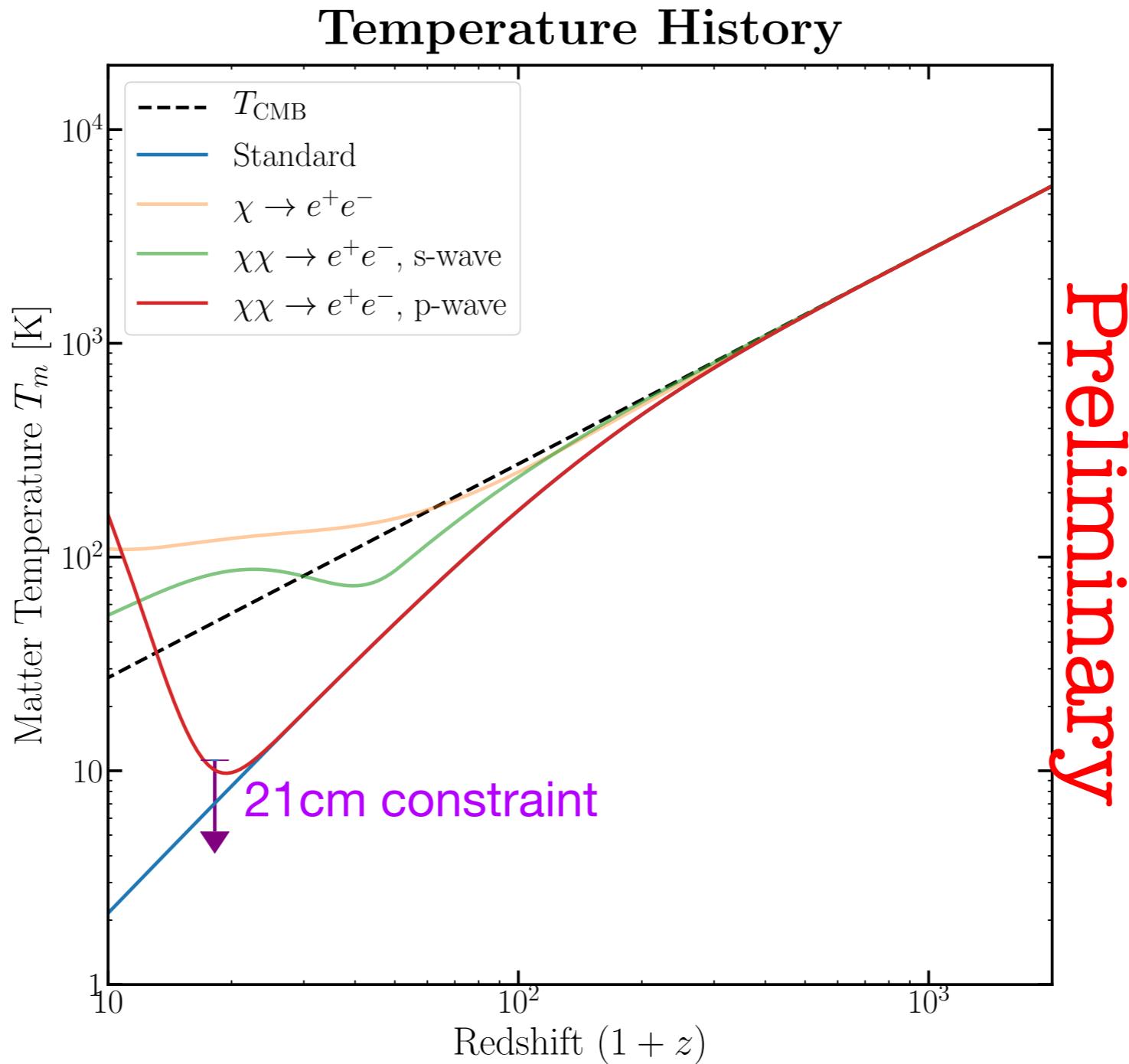
Constraints

$$\frac{T_m}{T_R}(z = 17.2) \leq 0.105$$



Constraints

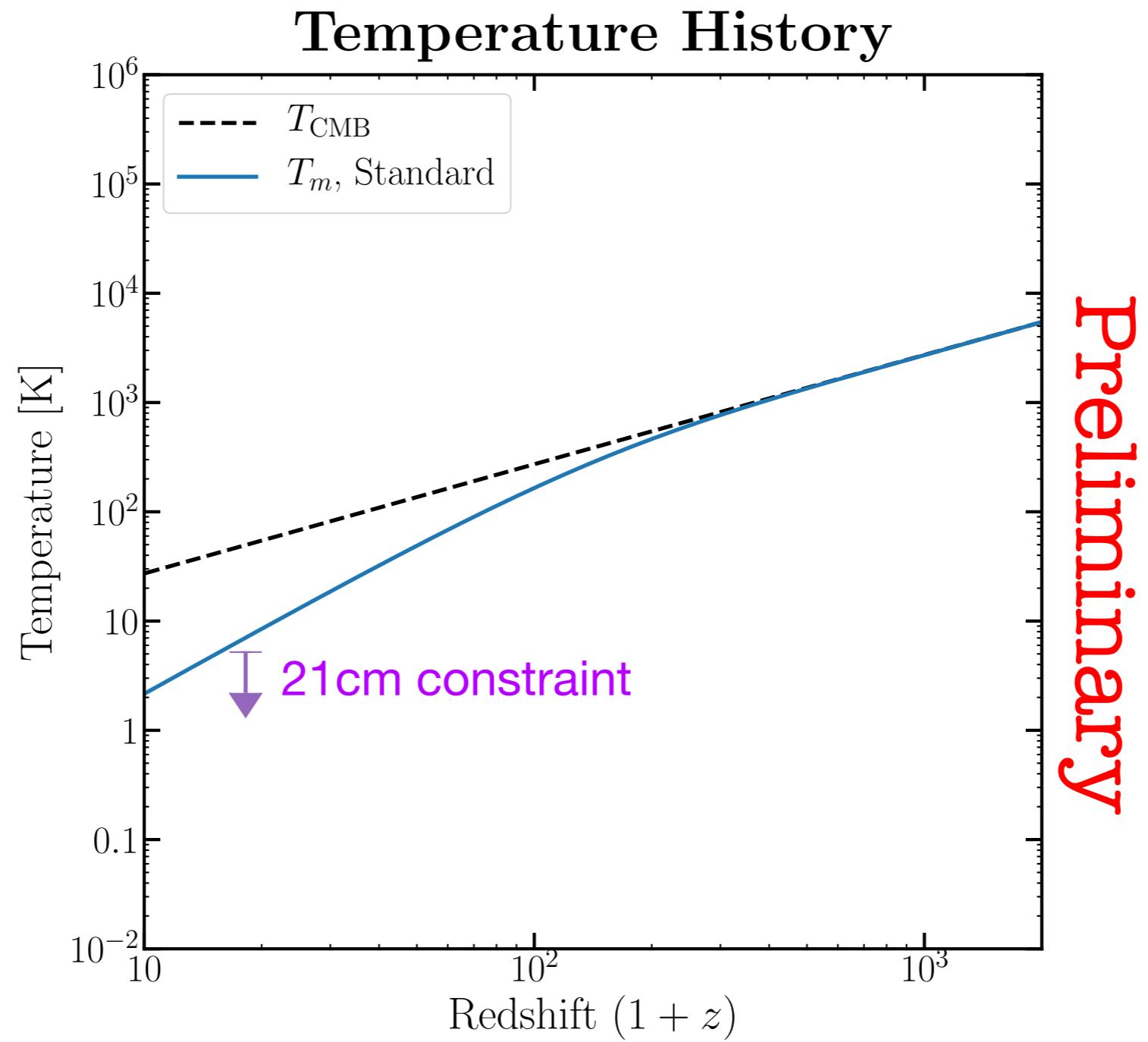
$$\frac{T_m}{T_R}(z = 17.2) \leq 0.105$$



p-wave constraints
determined mainly
by structure formation

Constraints

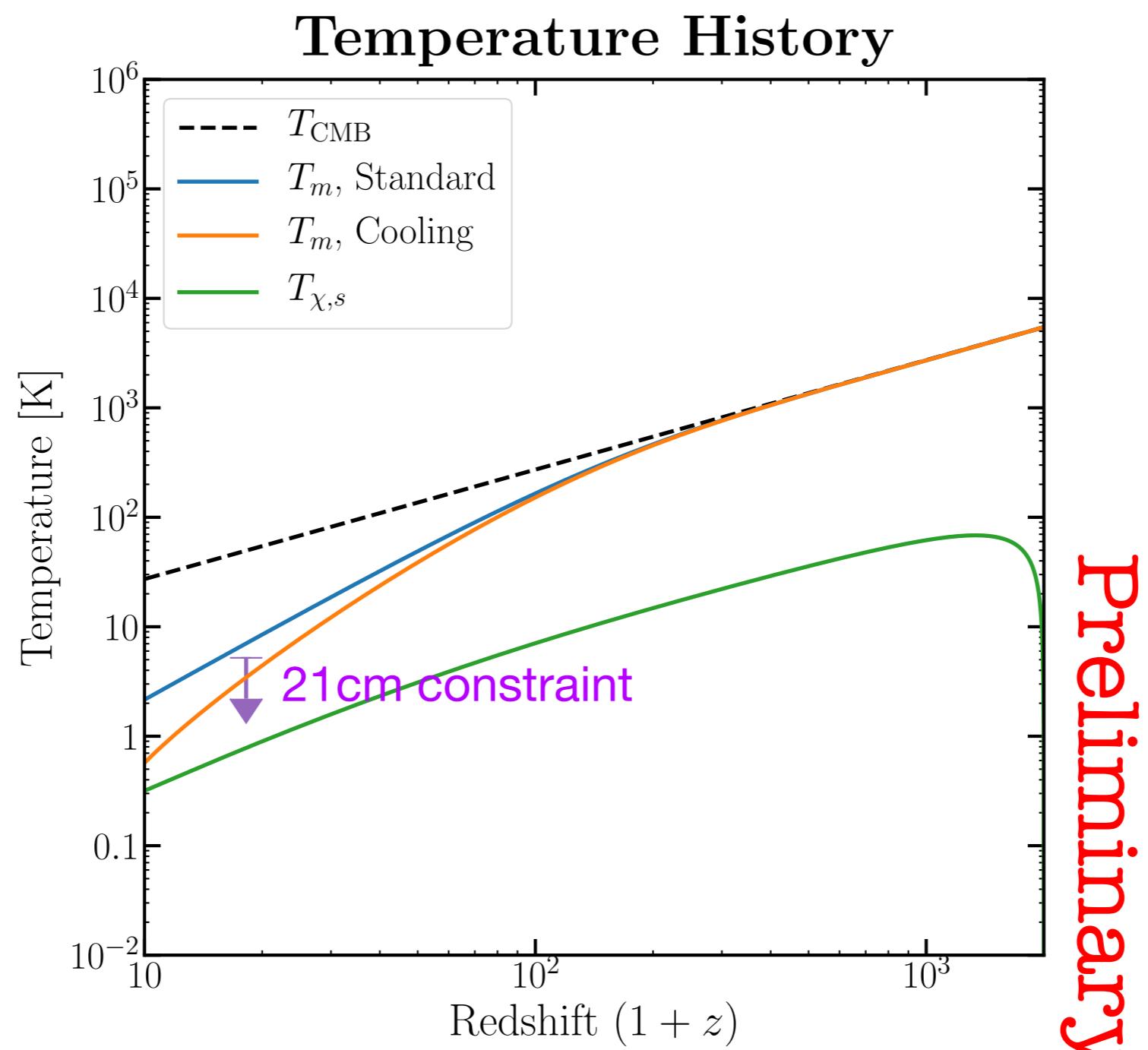
Now assume
 $T_R = T_{CMB}$



Constraints

$$\chi e^- \rightarrow \chi e^-$$

Introduce a small component of DM that **cools** visible matter via scattering



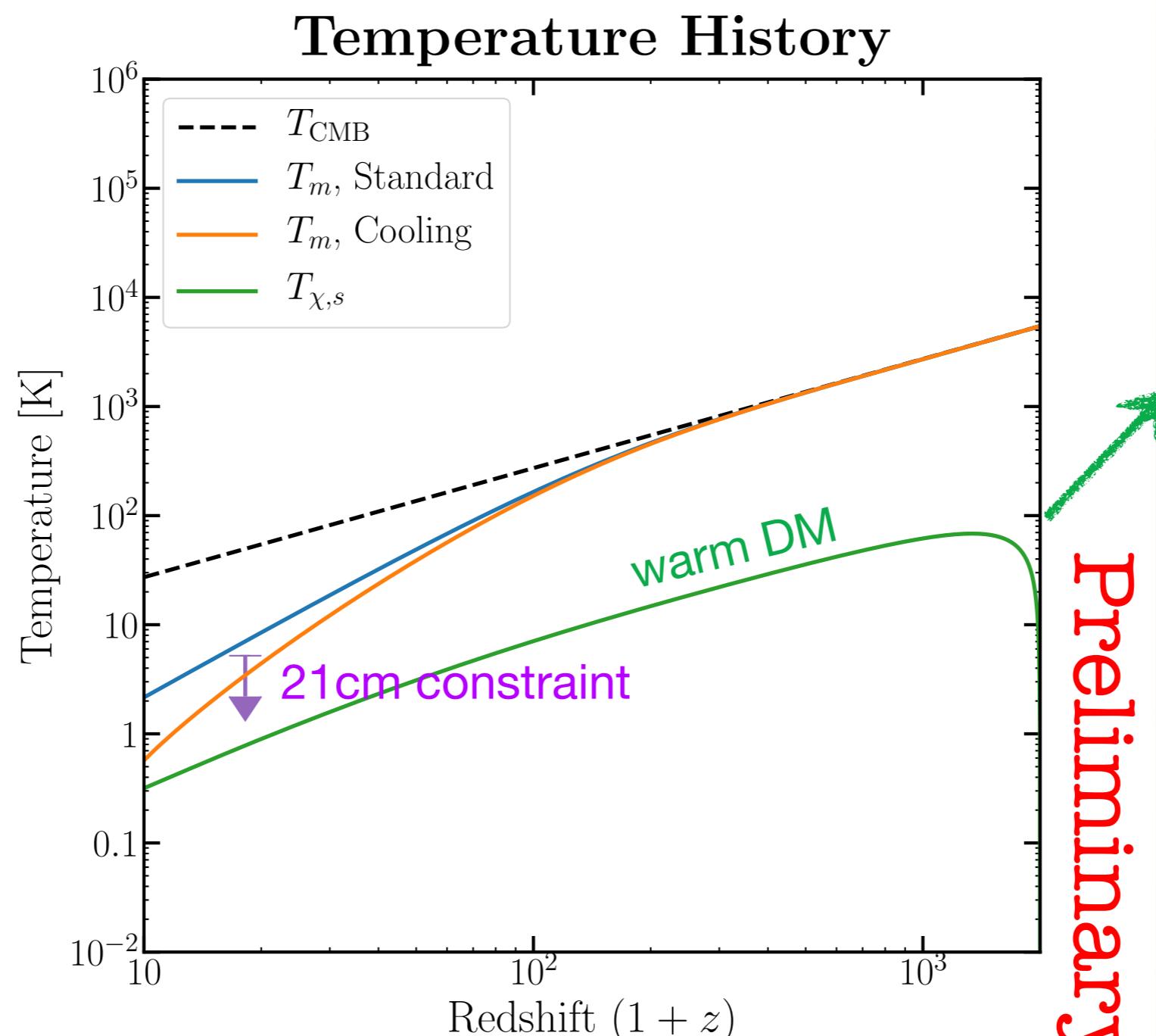
Constraints

$$\chi e^- \rightarrow \chi e^-$$

Introduce a small component of DM that **cools** visible matter via scattering

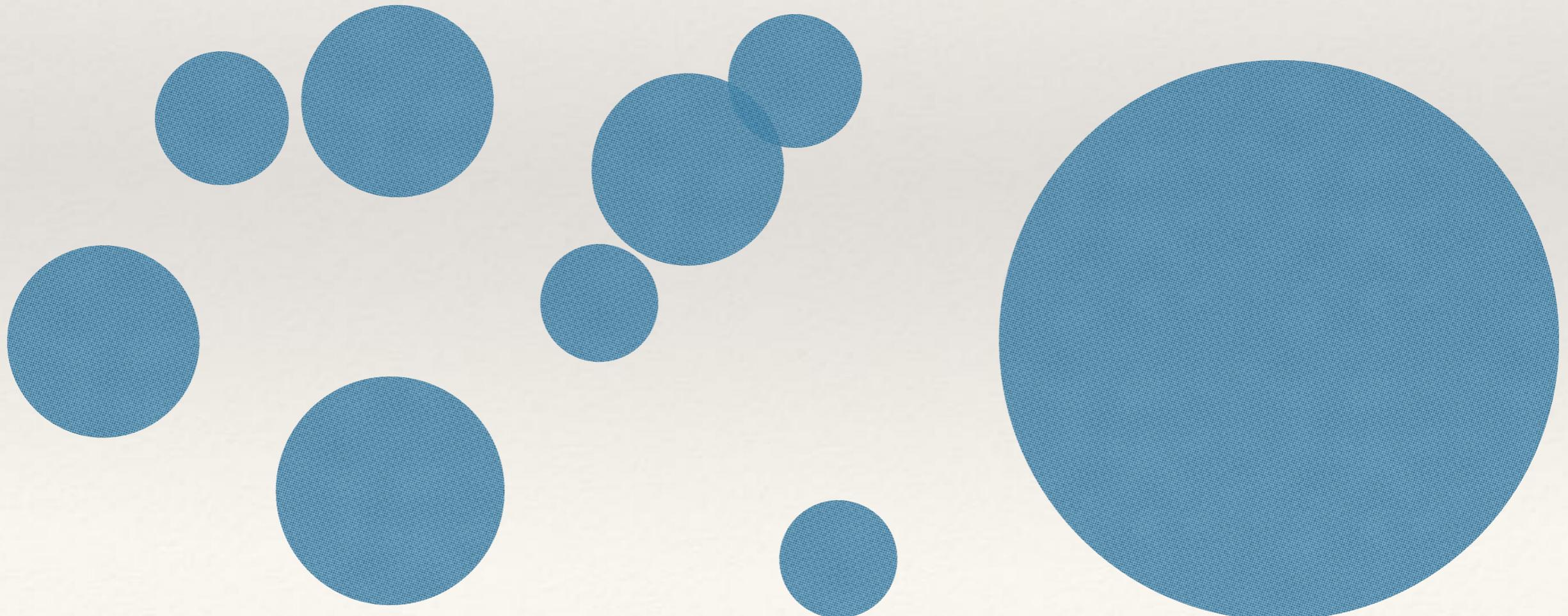
$$\chi\chi \rightarrow e^+e^-$$

A non-zero thermal velocity for DM **impedes structure formation** and contributes **extra energy injection**



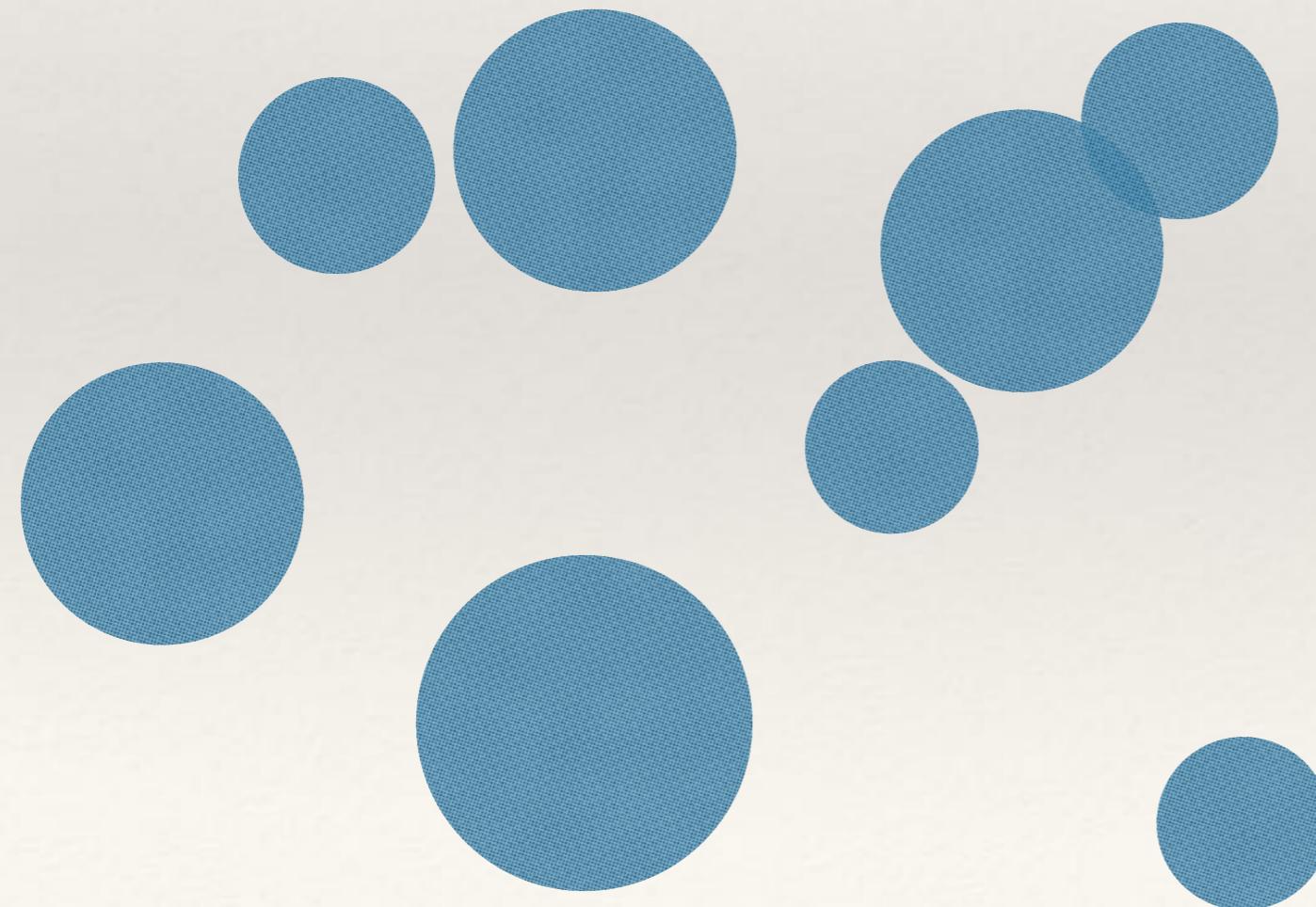
Warm Component of DM: Halo Mass Cut-Off

$$\text{boost} \sim \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \ 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$



Warm Component of DM: Halo Mass Cut-Off

$$\text{boost} \sim \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \ 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$



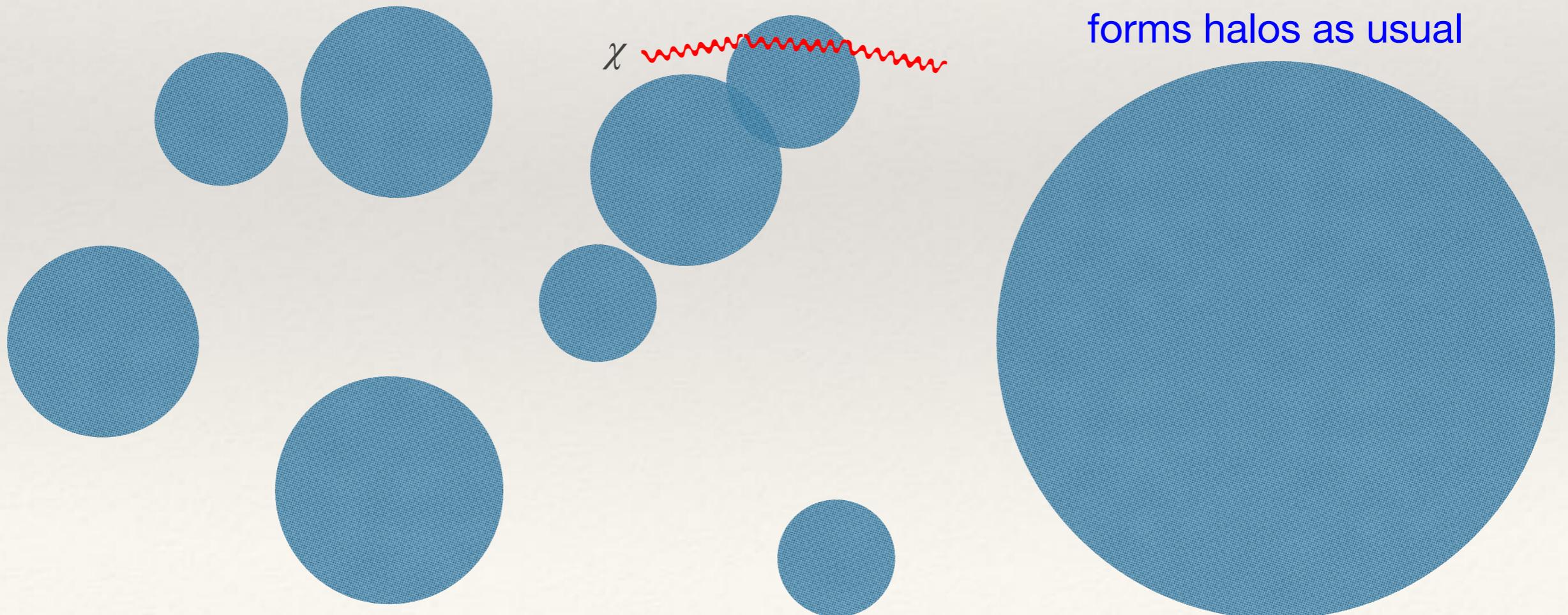
Assume cold, non-interacting
DM is dominant —
forms halos as usual

Warm Component of DM: Halo Mass Cut-Off

$$\text{boost} \sim \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \ 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$

Warm, interacting component
cannot be bound to small halos

Assume cold, non-interacting
DM is dominant —
forms halos as usual

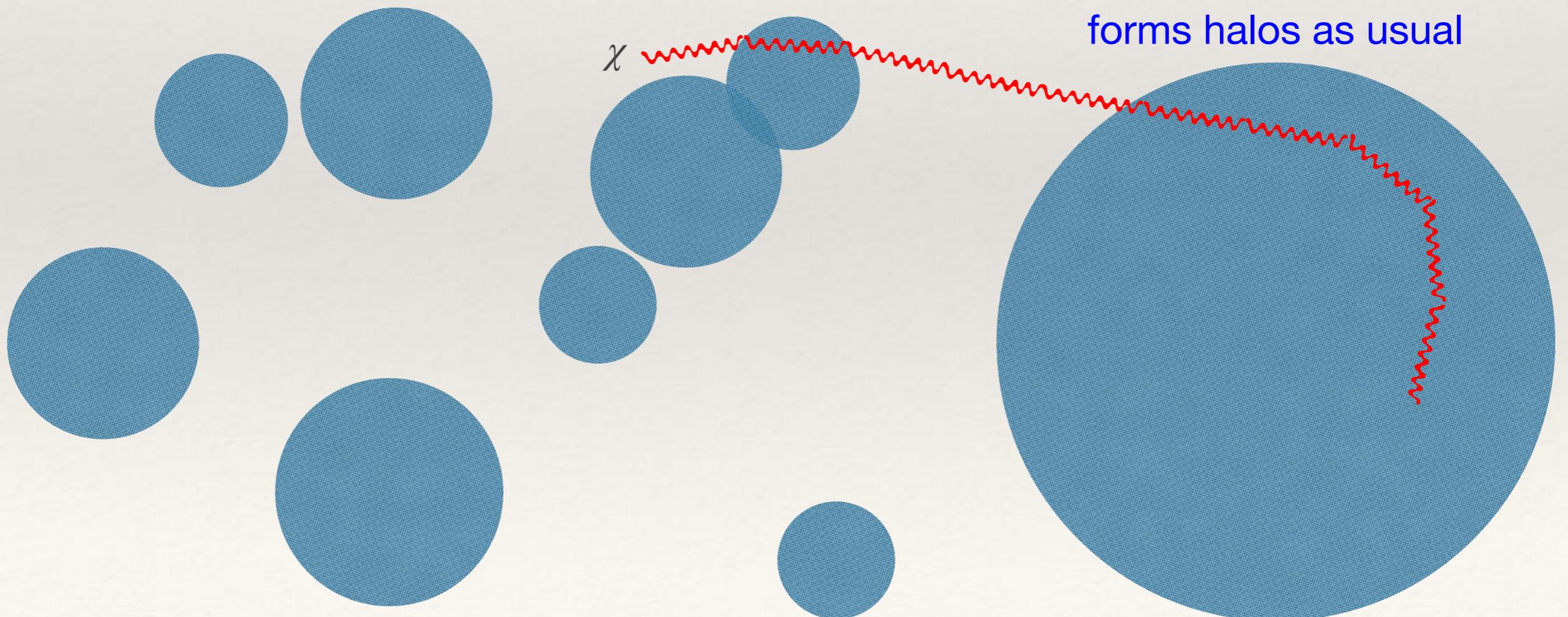


Warm Component of DM: Halo Mass Cut-Off

$$\text{boost} \sim \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$

Warm, interacting component
cannot be bound to small halos,
but can to large halos

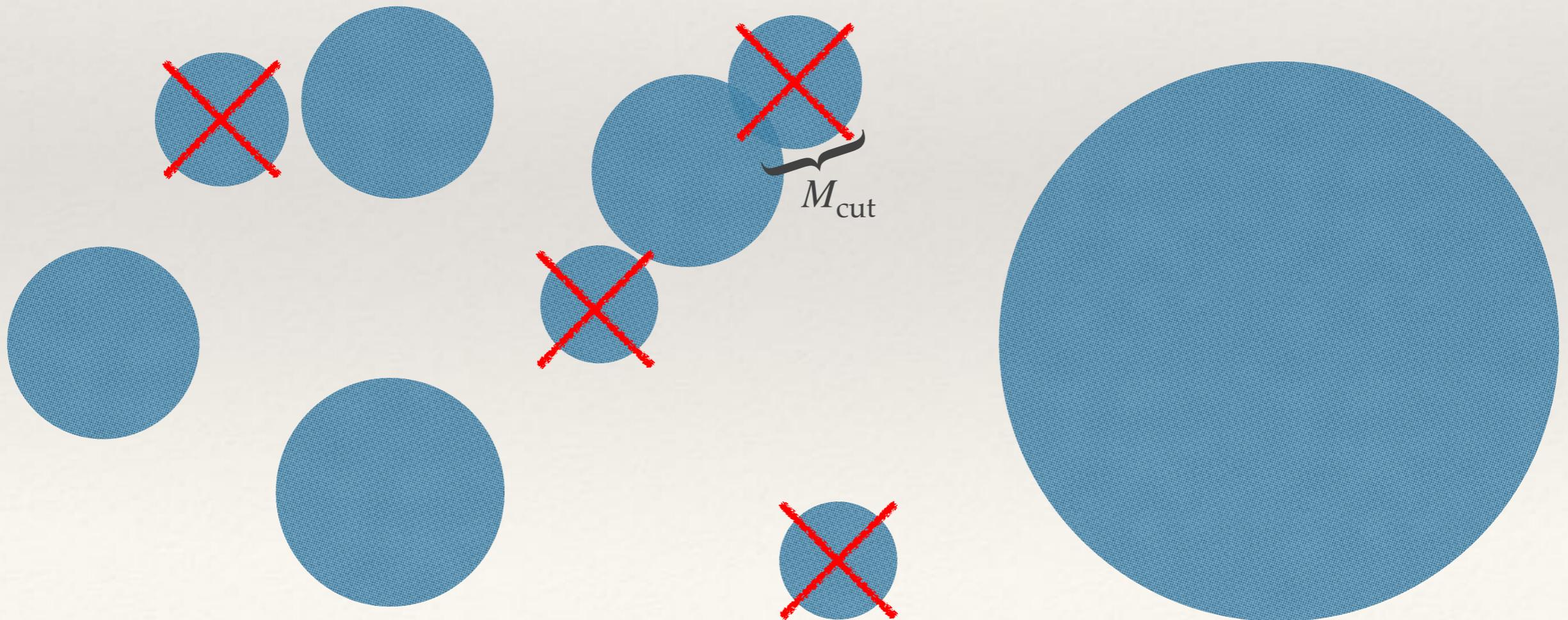
Assume cold, non-interacting
DM is dominant —
forms halos as usual



Warm Component of DM: Halo Mass Cut-Off

$$\text{boost} \sim \int dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \ 4\pi r^2 \langle v^2(r) \rangle \rho_{Halo}^2(r)$$

This results in a lower bound on the halo mass integral



Warm Component of DM: Thermal Velocity Boost

$$\text{boost} \sim \int_{M_{\text{cut}}} dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr \, 4\pi r^2 \langle v^2(r) \rangle \rho_{\text{Halo}}^2(r) + \left(\frac{v_{\text{warm}}}{v_{\text{cold}}} \right)^2$$

with $v_{\text{warm}}^2 \sim \frac{3k_B T_\chi}{m_\chi}$

$$v_{\text{cold}}^2 \sim v_0^2 (1+z)^2$$

Warm Component of DM: Thermal Velocity Boost

$$\text{boost} \sim \int_{M_{\text{cut}}} dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr 4\pi r^2 \langle v^2(r) \rangle \rho_{\text{Halo}}^2(r) + \left(\frac{v_{\text{warm}}}{v_{\text{cold}}} \right)^2$$

with $v_{\text{warm}}^2 \sim \frac{3k_B T_\chi}{m_\chi}$

$$v_{\text{cold}}^2 \sim v_0^2 (1+z)^2$$

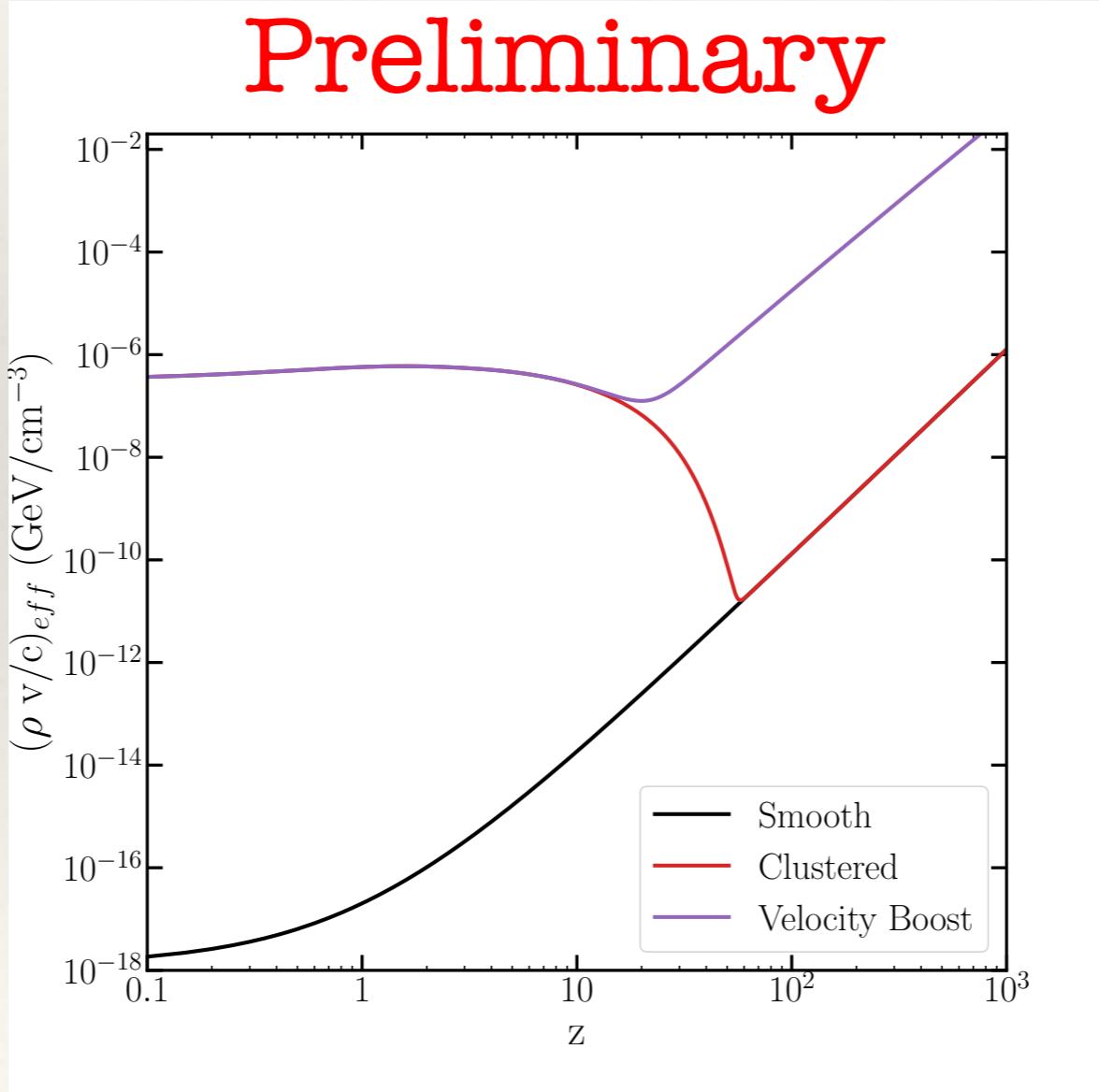
This is the dominant effect at $z \sim 17.2$

Warm Component of DM: Thermal Velocity Boost

$$\text{boost} \sim \int_{M_{\text{cut}}} dM \frac{dn}{dM}(M, z) \int_0^{r_\Delta} dr 4\pi r^2 \langle v^2(r) \rangle \rho_{\text{Halo}}^2(r)$$

$$+ \left(\frac{v_{\text{warm}}}{v_{\text{cold}}} \right)^2$$

Leads to:

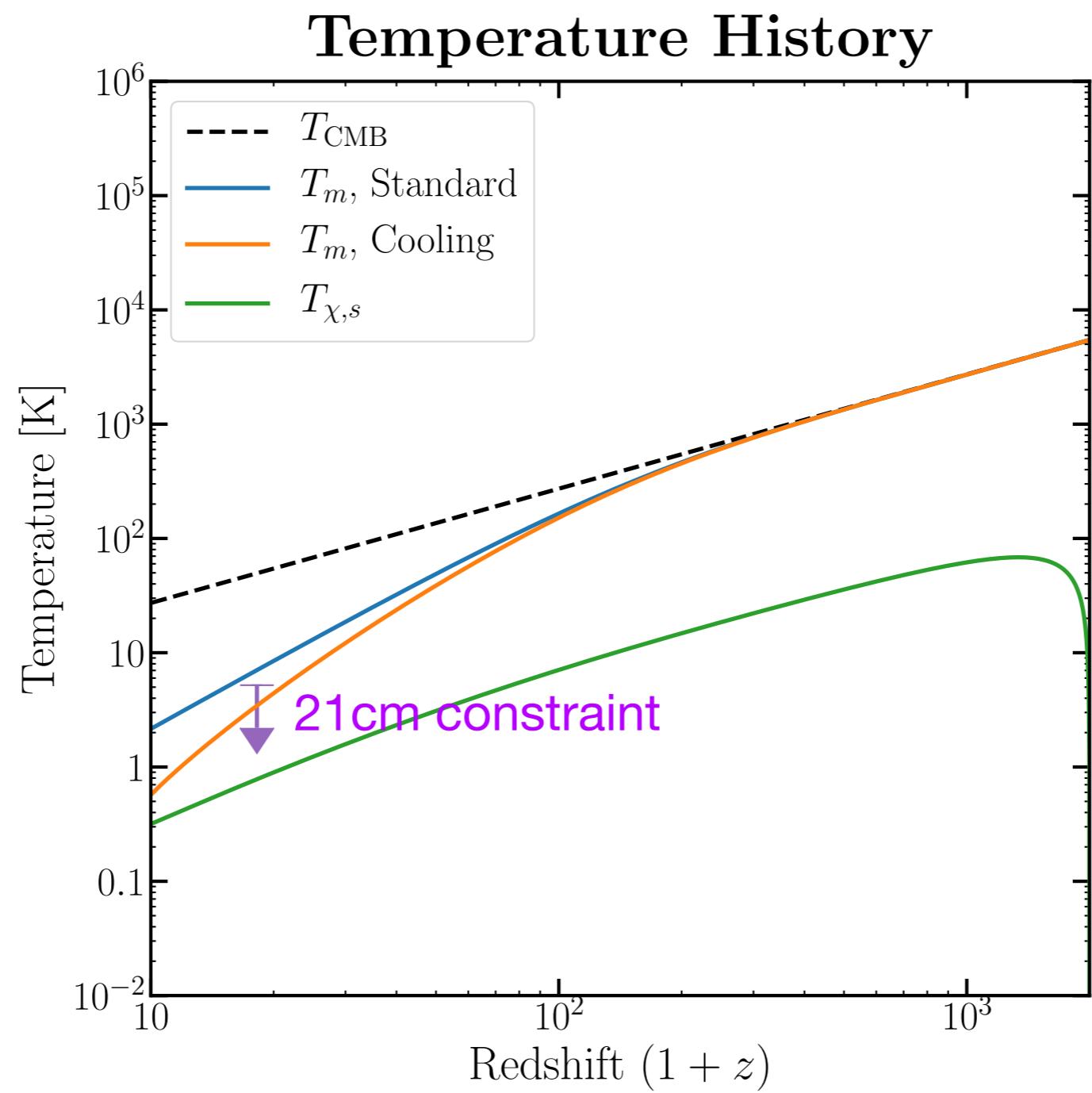


Constraints

$\chi e^- \rightarrow \chi e^-$

$\chi\chi \rightarrow e^+e^-$

Preliminary

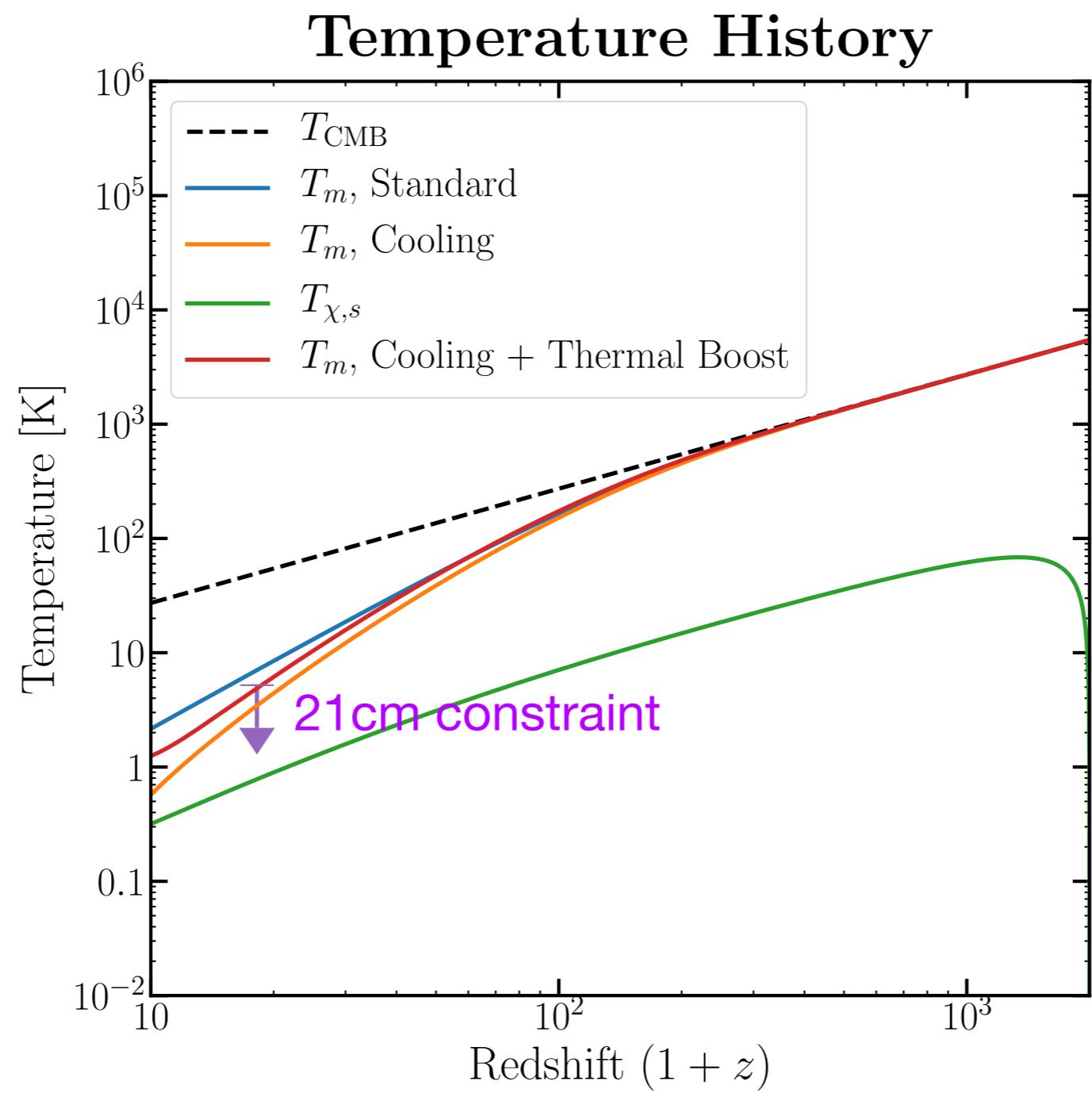


Constraints

$\chi e^- \rightarrow \chi e^-$

$\chi\chi \rightarrow e^+e^-$

Preliminary



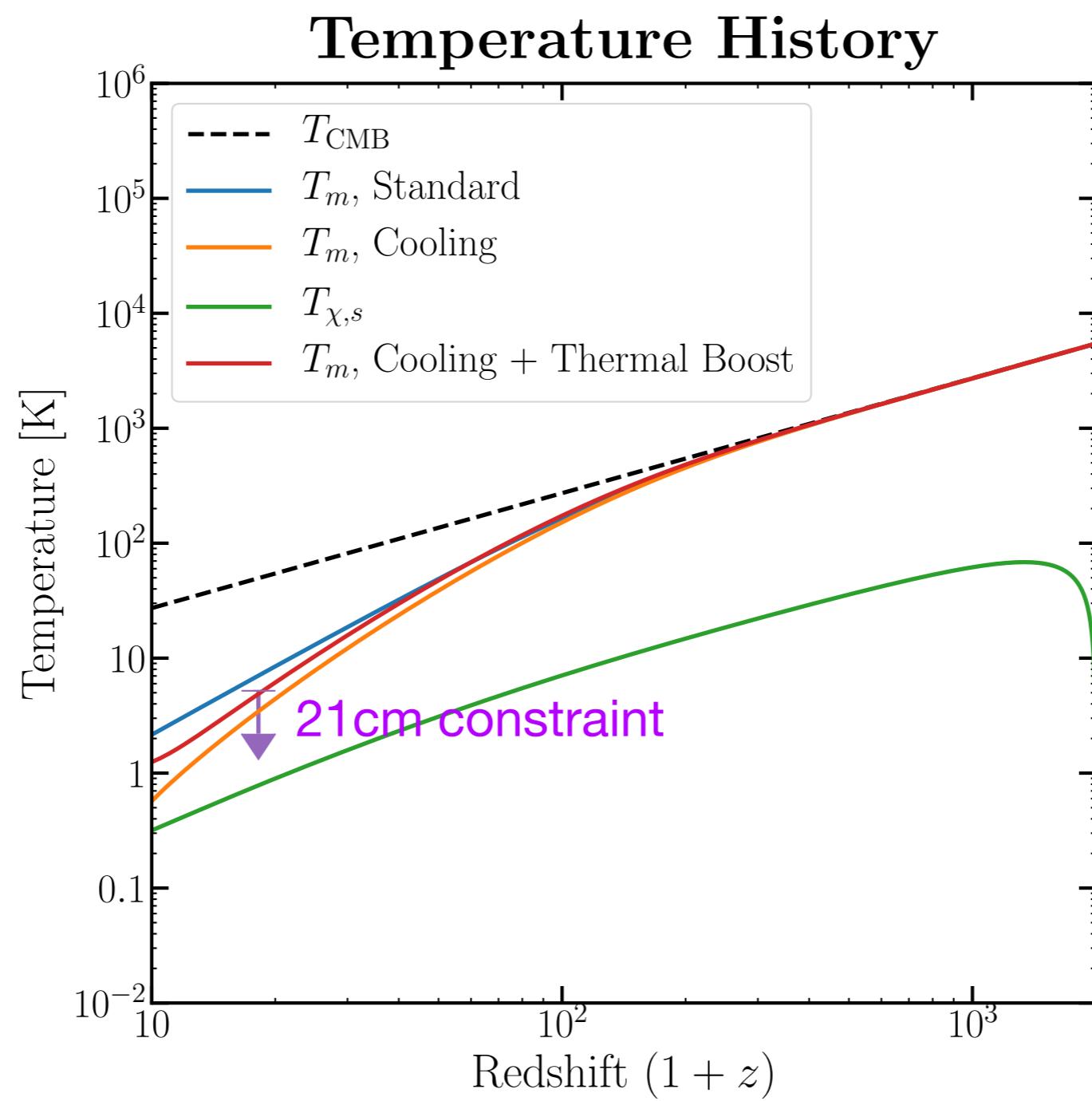
Constraints

$\chi e^- \rightarrow \chi e^-$

p-wave constraints
determined mainly
by non-zero
thermal velocity

$\chi\chi \rightarrow e^+e^-$

Preliminary



Recap

- ❖ The global 21cm signal puts an **upper bound** on T_m at $z \sim 17.2$
- ❖ If EDGES is verified, we are forced to consider **non-standard** temperature histories, or background 21cm radiation sources
- ❖ Either way, the global 21cm signal can **constrain** decaying/annihilating DM models by bounding how much energy can be injected into the universe
- ❖ **Structure Formation** must be treated carefully for the p-wave annihilation case, as well as any **non-zero DM thermal velocity**. These two effects are the main contributions to the p-wave constraints.

Thank You