

Physik-Institut, University of Zurich

02/10/2018

Bounds of DM annihilations from 21-cm data



PAOLO PANCI



Based on D'Amico, PP, Strumia [arXiv:1803.03629](https://arxiv.org/abs/1803.03629)
Published on Phys.Rev.Lett. **121** (2018) no.1, 011103

Plan of the Talk

What EDGES has observed

Quick physics of the 21-cm line

A short history of the IGM properties

Bounds on Dark Matter properties

Outlook

LETTER

doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

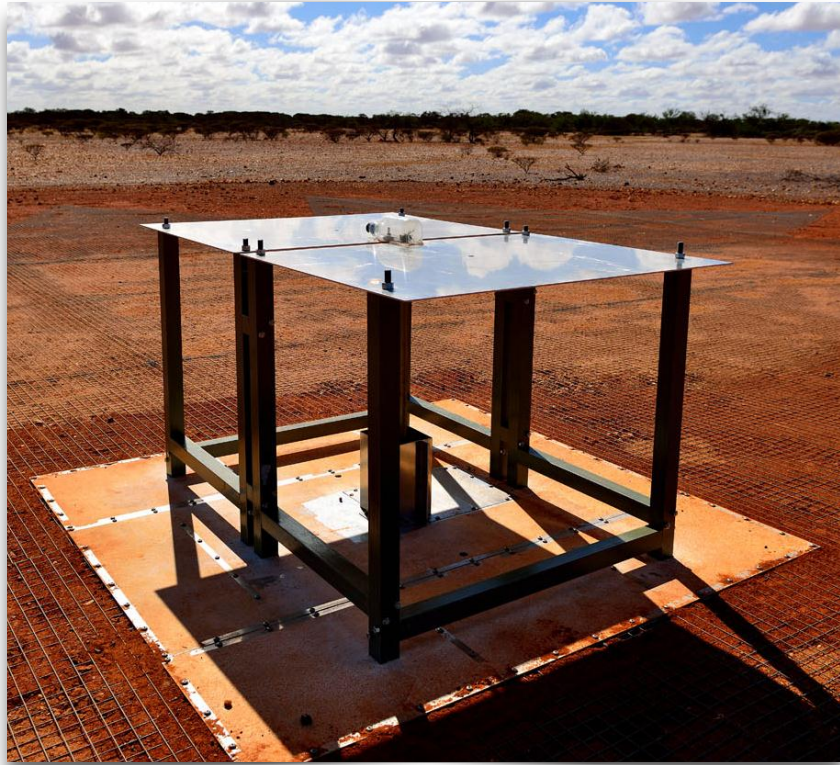
Judd D. Bowman¹, Alan E. E. Rogers², Raul A. Monsalve^{1,3,4}, Thomas J. Mozdzen¹ & Nivedita Mahesh¹

A **21-cm signal** in *absorption*

Between redshifts **~20 and 15**

Amplitude *twice* as large as predicted (**~500 mK** vs. ~200mK)

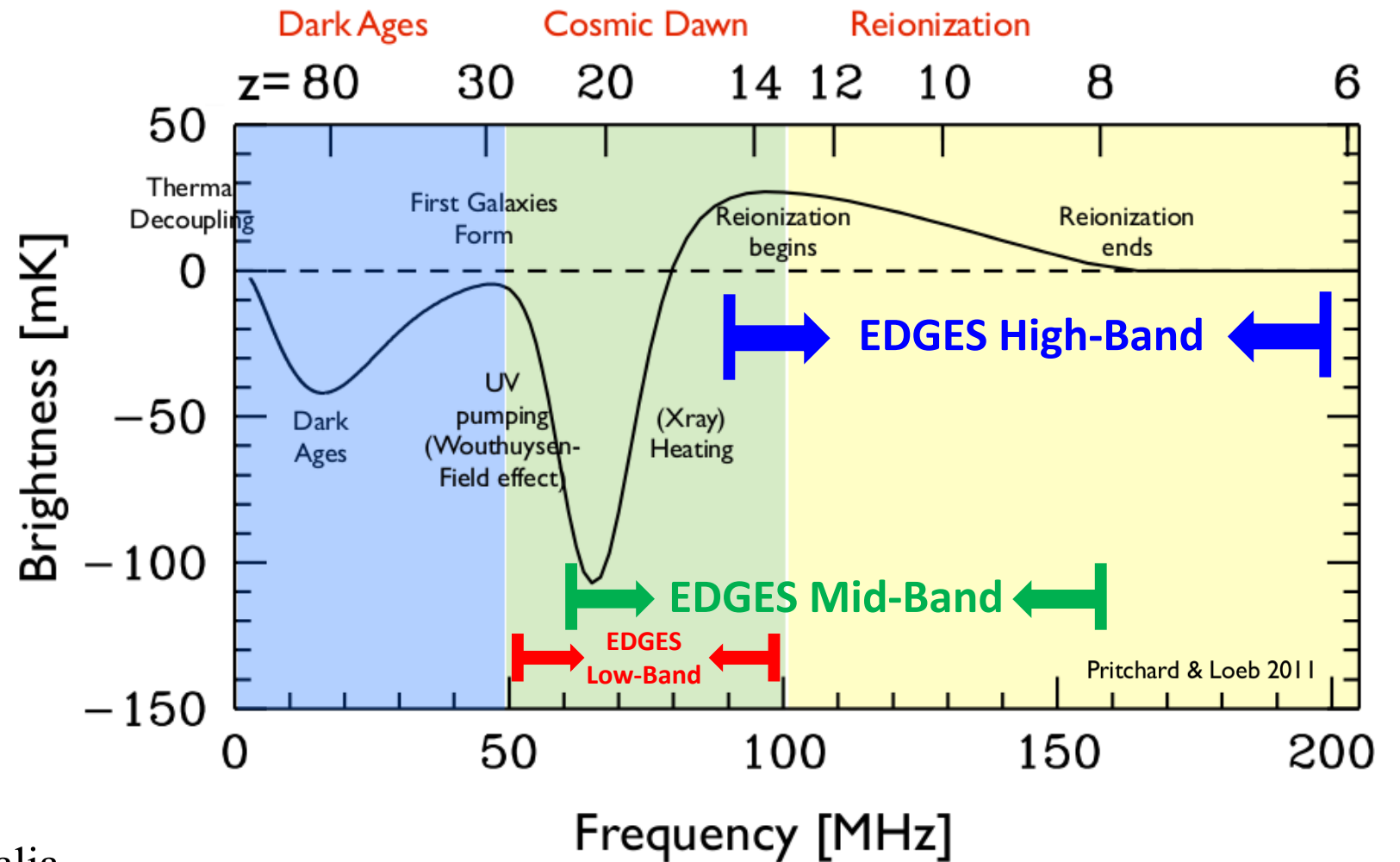
The EDGES experiment



Antenna size: 2m long and 1m meter high

Location: radio quiet zone in western Australia

Energy range: from 50 to 150 Mhz

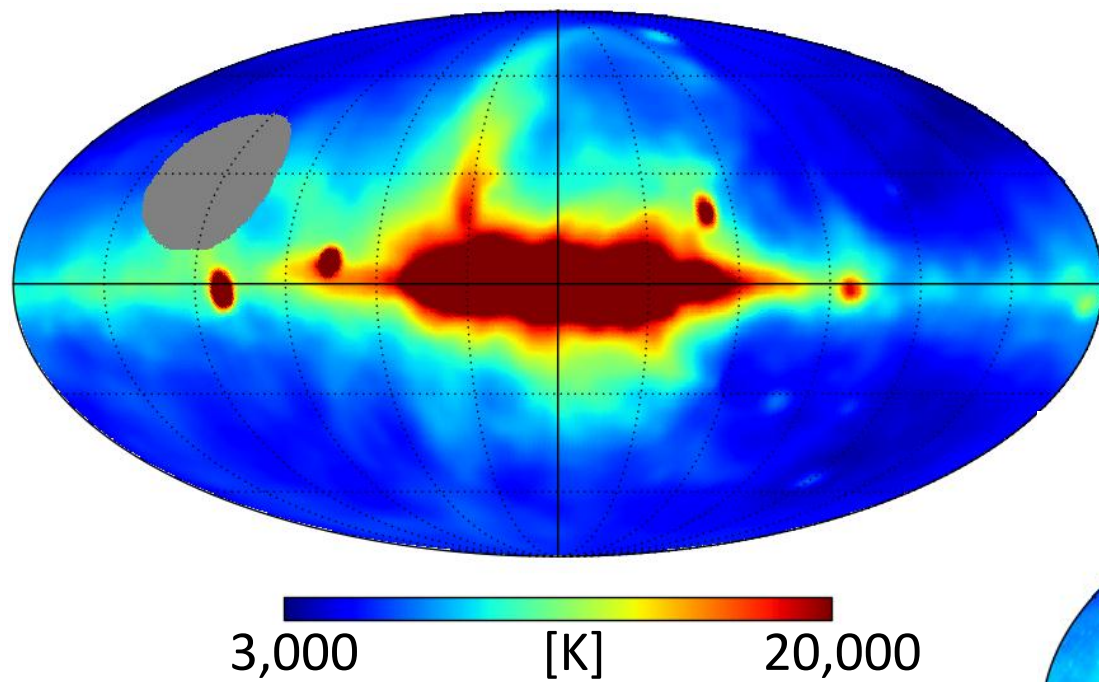


Low-band antenna: Designed to observe a spectral distortion in the 21-cm energy band at $z \sim 20$ due to the absorption of CMB photons by the IGM

Diffuse Foregrounds

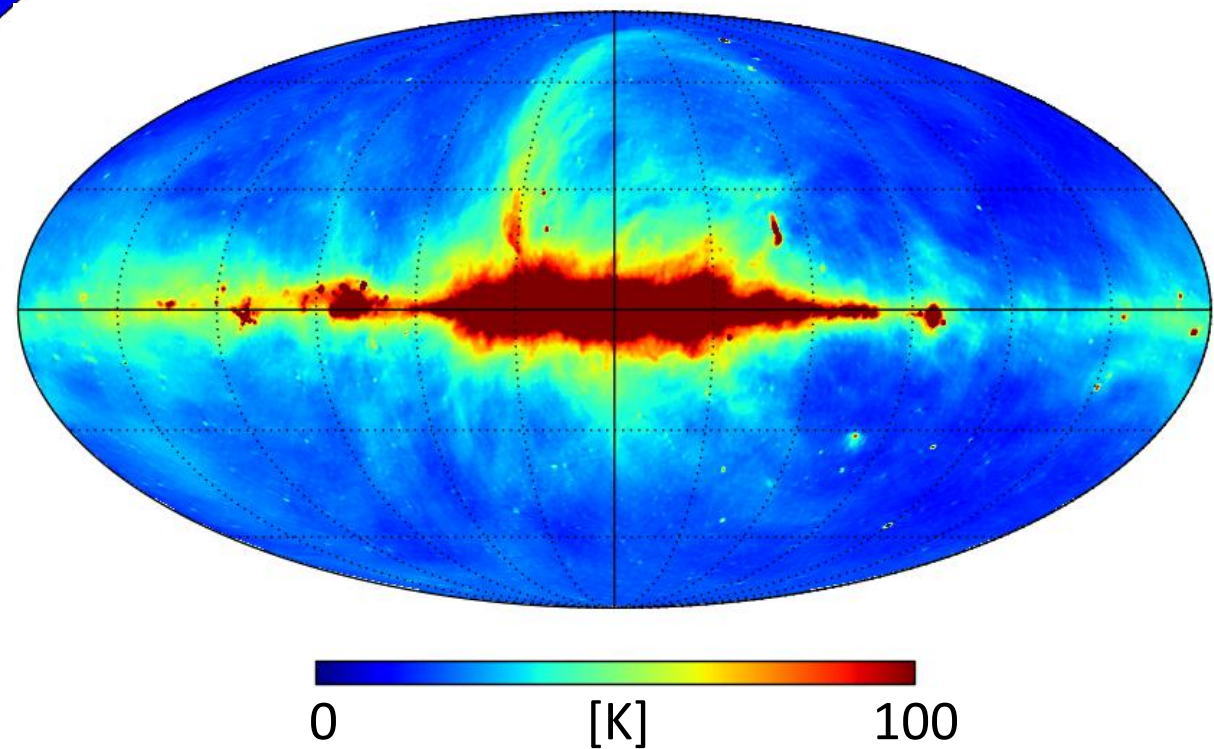
45-MHz Map

Guzmán et al. (2011)



408-MHz Map

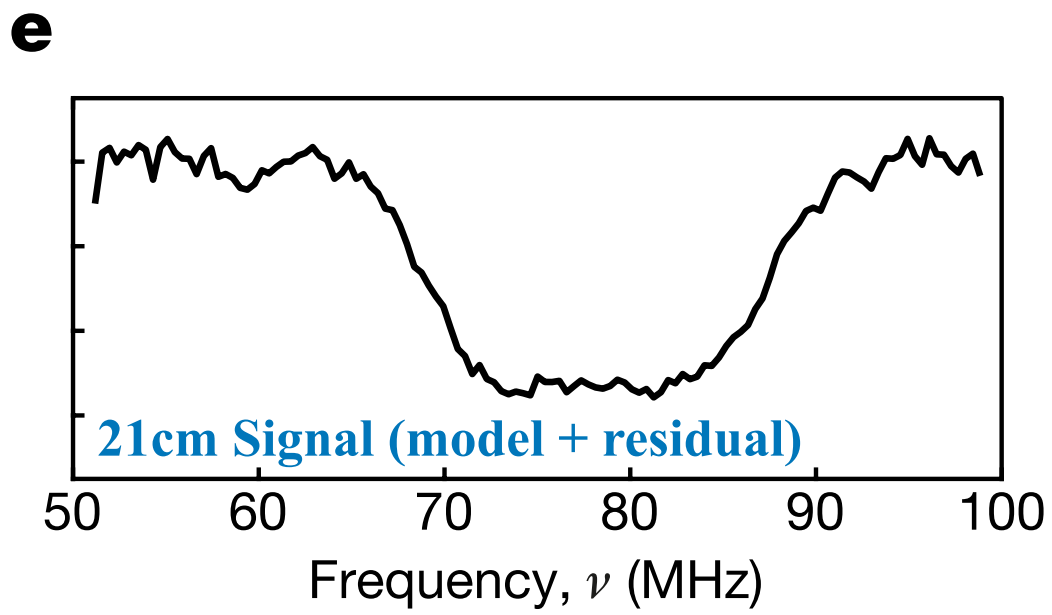
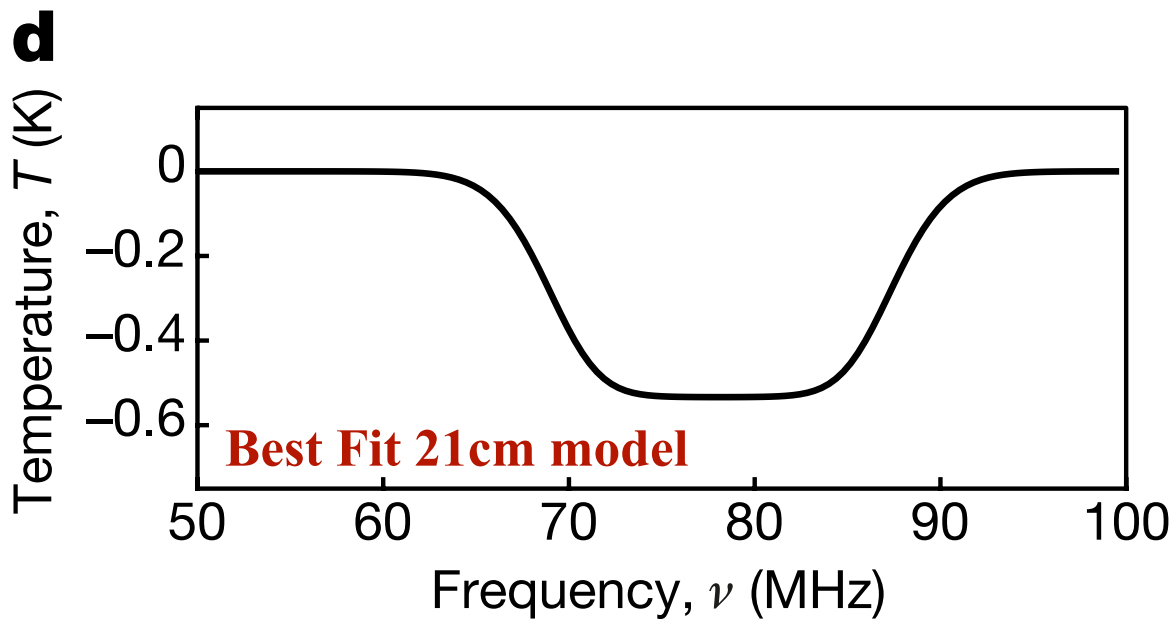
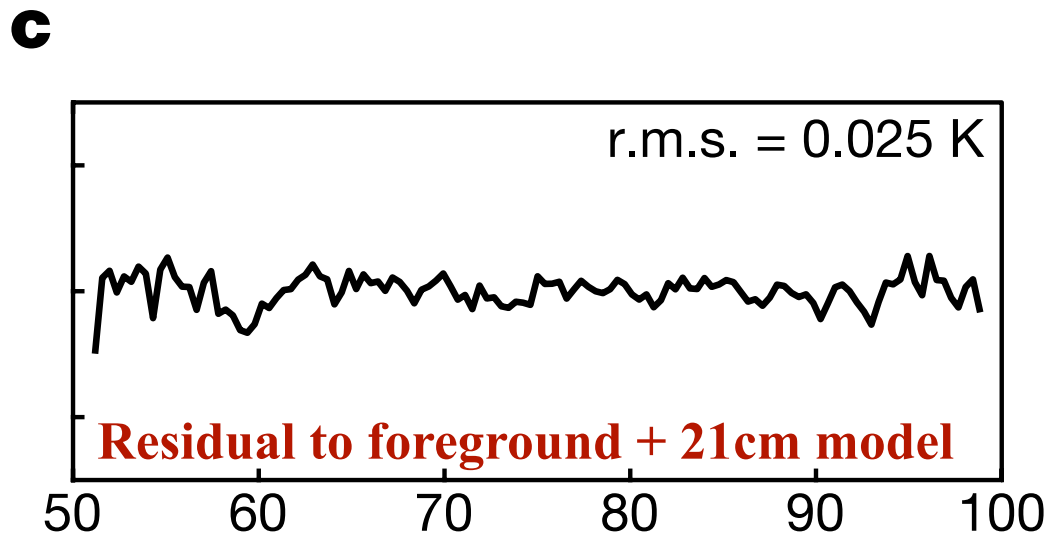
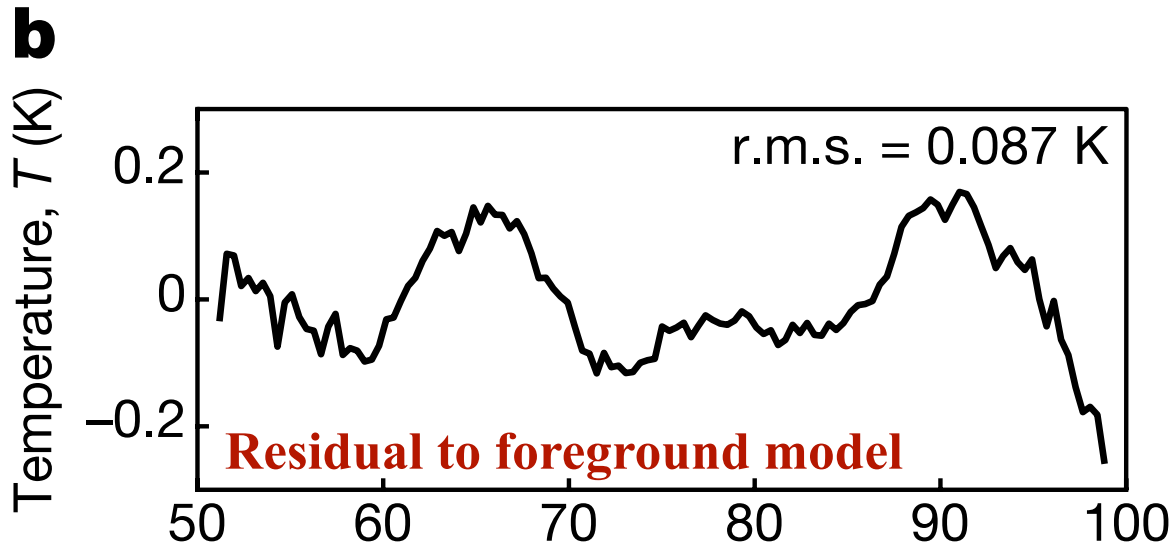
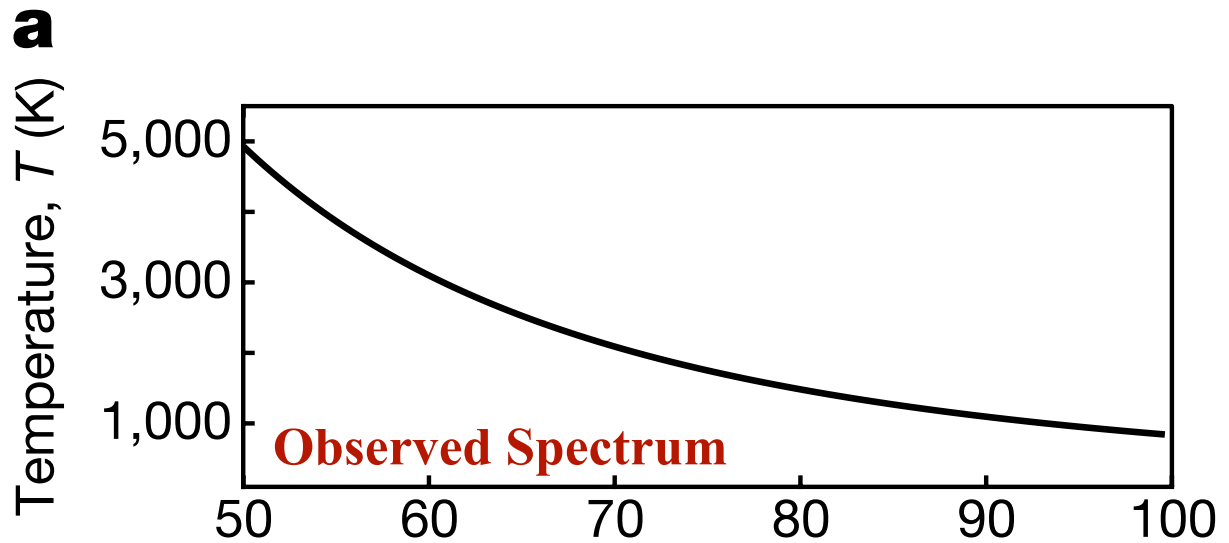
Haslam et al. (1982)



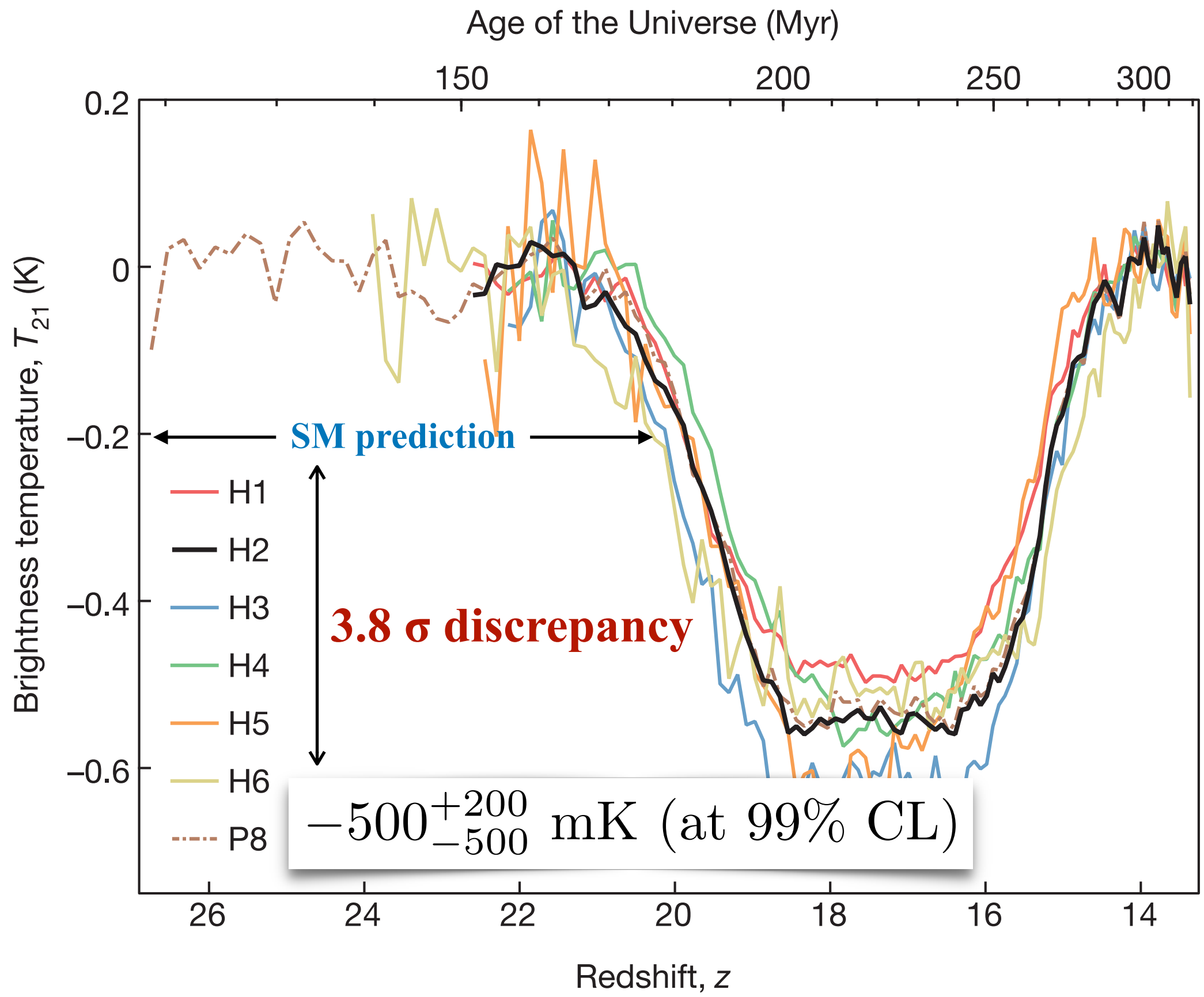
Main features of the Diffuse Foregrounds:

- 1) **Brightness temperature:** always more than 100 K
- 2) **Spectrally smooth** but might need **several terms** to model (see e.g. Bernardi et al. 2015)
- 3) **Large spatial gradient** (in particular close to the GC)

What did EDGES see?



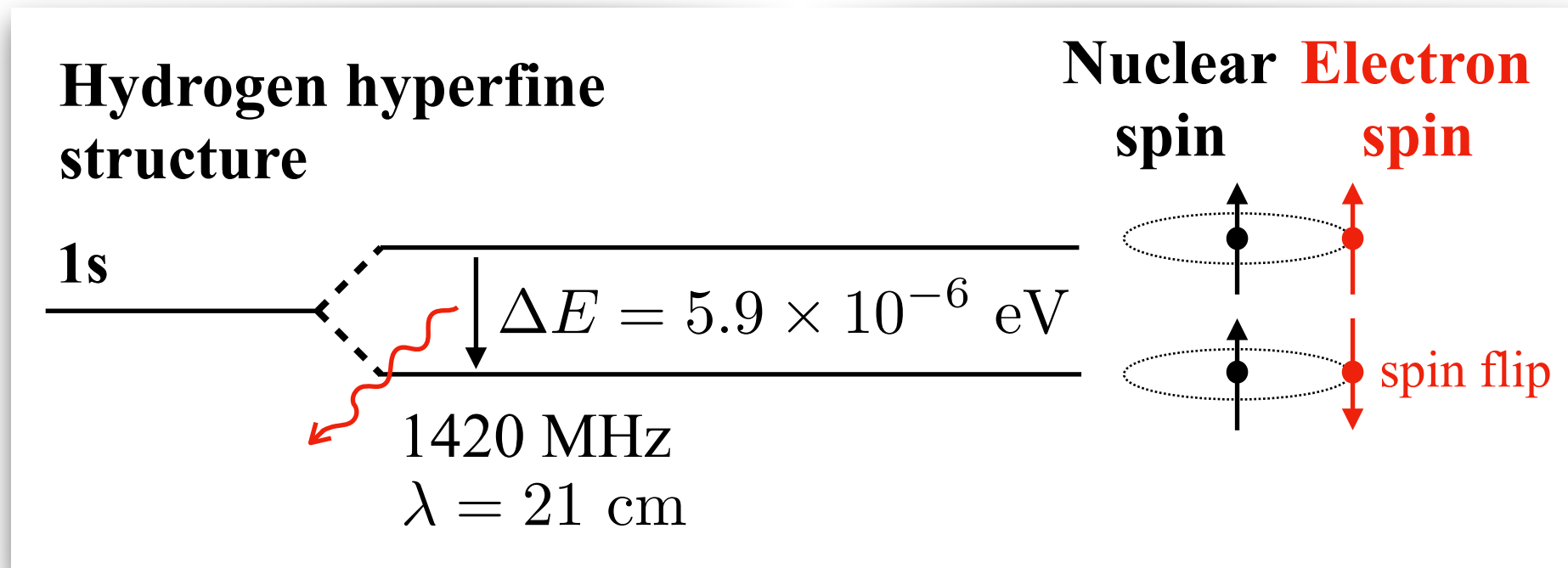
Some analysis of systematics



II PART

Physics of the 21-cm line

What is the 21-cm line?



Triplet-to-singlet transition of the atomic hydrogen 1s level

Define the **Spin temperature** by

$$\frac{n_{\uparrow\uparrow}}{n_{\uparrow\downarrow}} \equiv 3 e^{-\Delta E/T_S}$$

What sets the relative occupation?

Excited by what?

Excited by what?

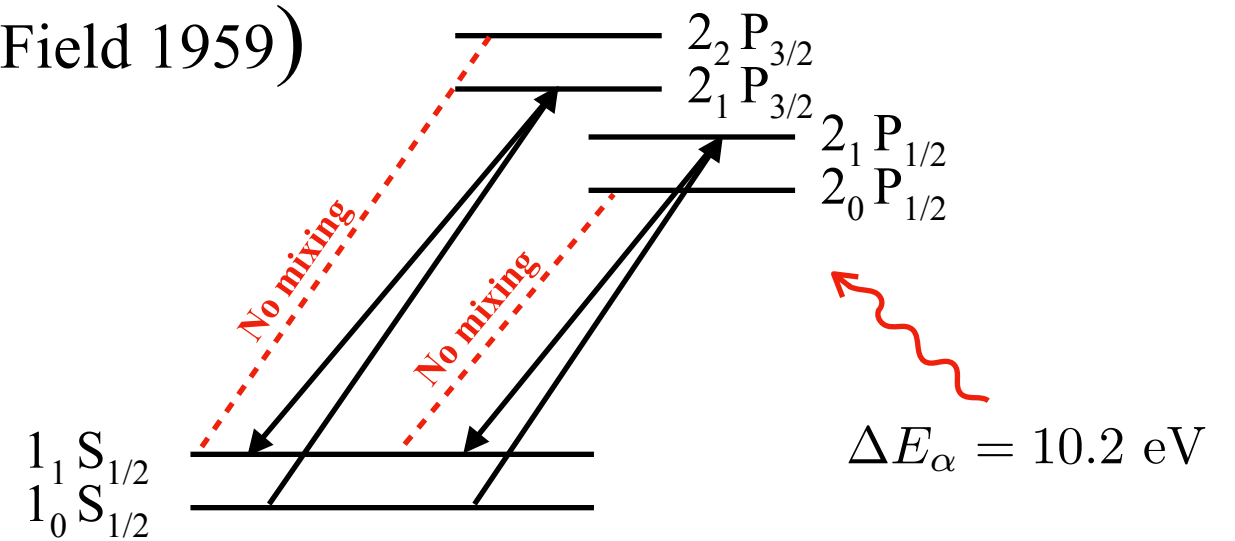
➔ **Absorption** of background CMB photon

Excited by what?

- ➔ **Absorption** of background CMB photon
- ➔ **Collisions**: important when density is high

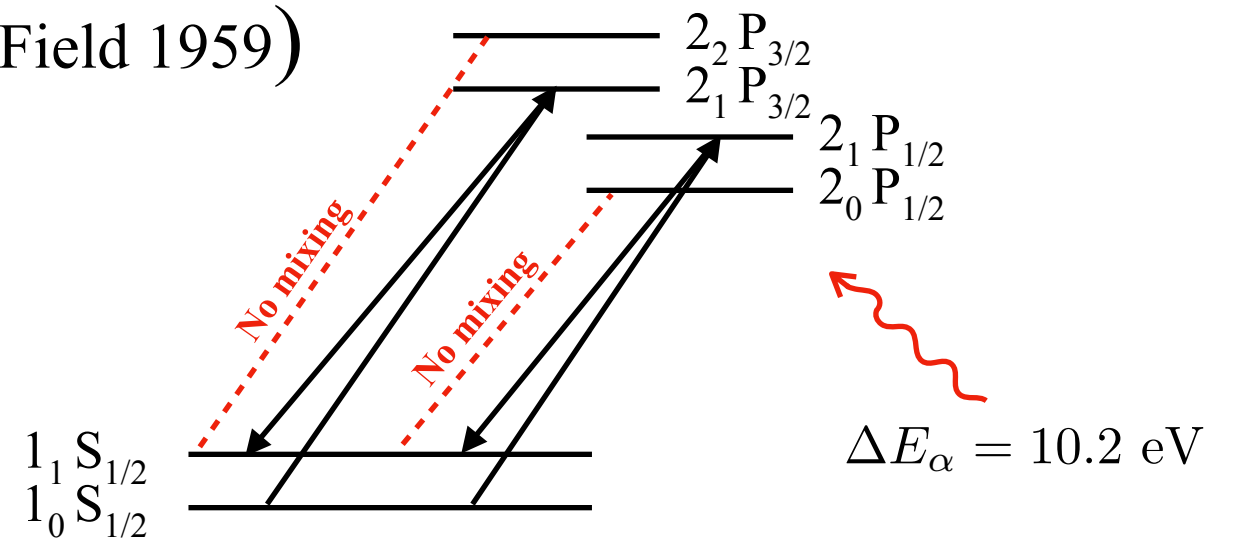
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- ➔ **Absorption** of background CMB photon
- ➔ **Collisions**: important when density is high
- ➔ **Ly- α pumping** (Wouthuysen 1952, Field 1959)



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Equilibrium implies:

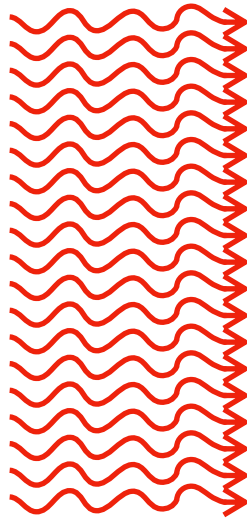
$$n_{\uparrow\uparrow}(C_{10} + \mathcal{P}_{10} + \mathcal{A}_{10} + \mathcal{B}_{10}I_{\gamma}) = n_{\uparrow\downarrow}(C_{01} + \mathcal{P}_{01} + \mathcal{B}_{01}I_{\gamma})$$

In terms of temperature:

$$T_S^{-1} = \frac{T_{\text{CMB}}^{-1} + y_C T_{\text{gas}}^{-1} + y_{\alpha} T_{\alpha}^{-1}}{1 + y_C + y_{\alpha}}$$

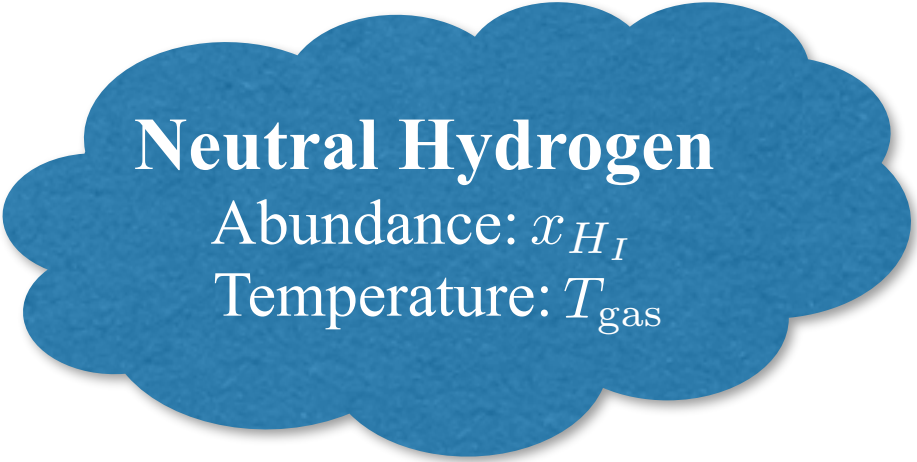
What we see

CMB



$$I_\gamma$$

Cloud of Hydrogen

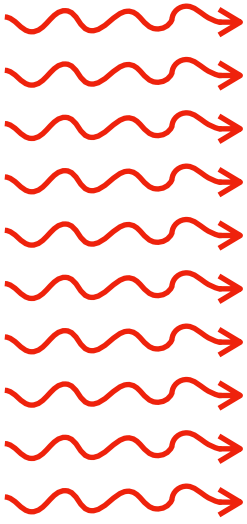


Neutral Hydrogen

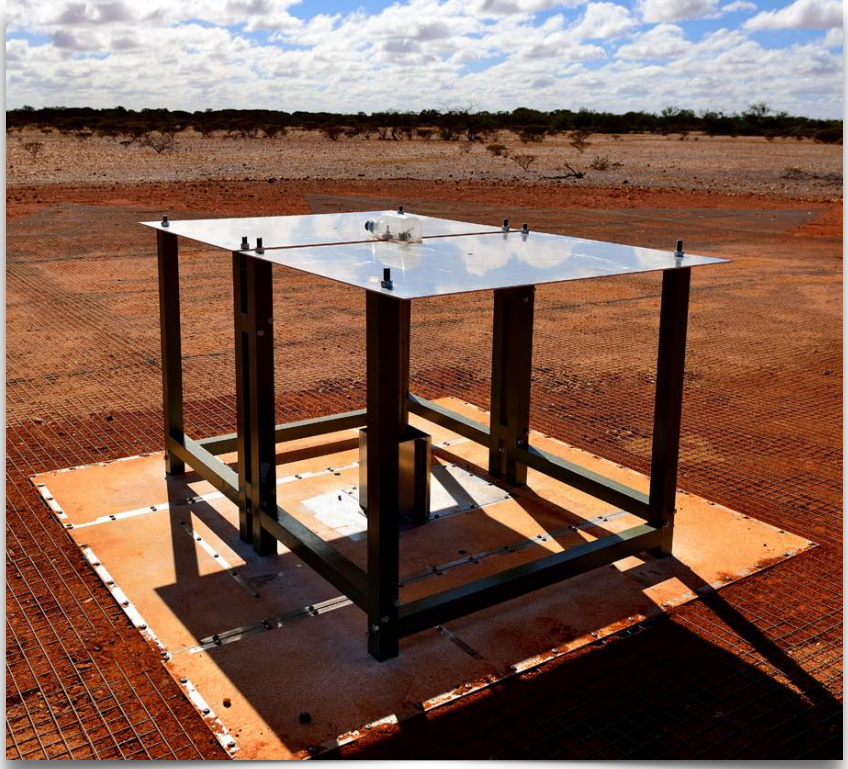
Abundance: x_{H_I}

Temperature: T_{gas}

CMB



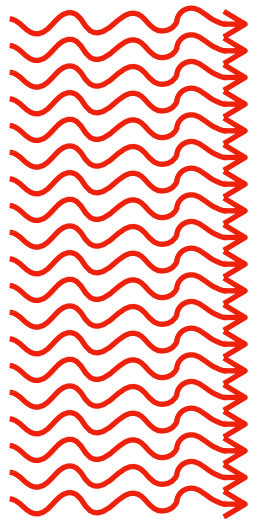
$$I_\gamma e^{-\tau}$$



$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

What we see

CMB



\mathcal{I}_γ

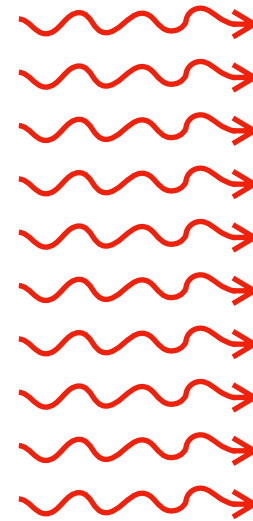
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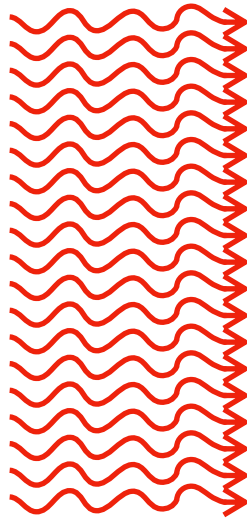
$$T_{21} \propto \mathcal{I}_\gamma (1 - e^{-\tau}) \approx \mathcal{I}_\gamma \tau \approx 21 \text{ mK } x_{H_I} \left(1 - \frac{T_{\text{CMB}}}{T_S} \right) \sqrt{\frac{1+z}{10}}$$

$T_S = T_{\text{CMB}}$: **NO** 21-cm signal

$T_S \neq T_{\text{CMB}}$: 21-cm signal in absorption/emission

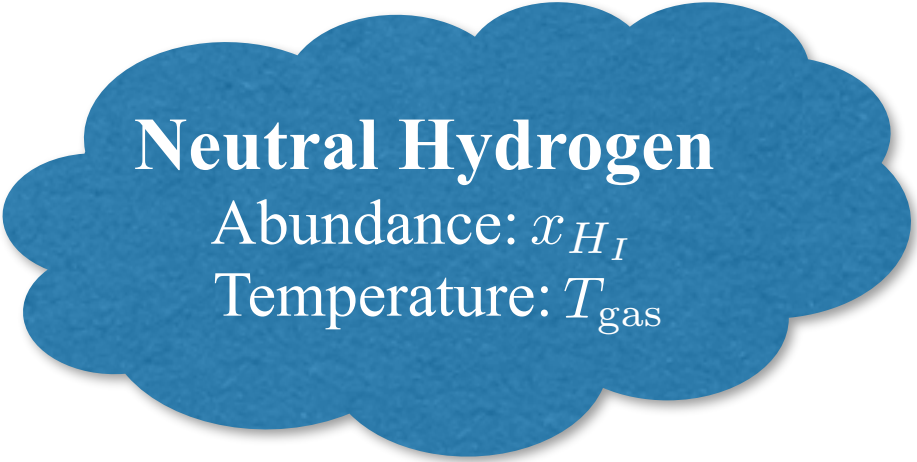
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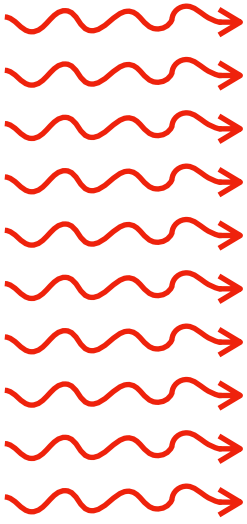


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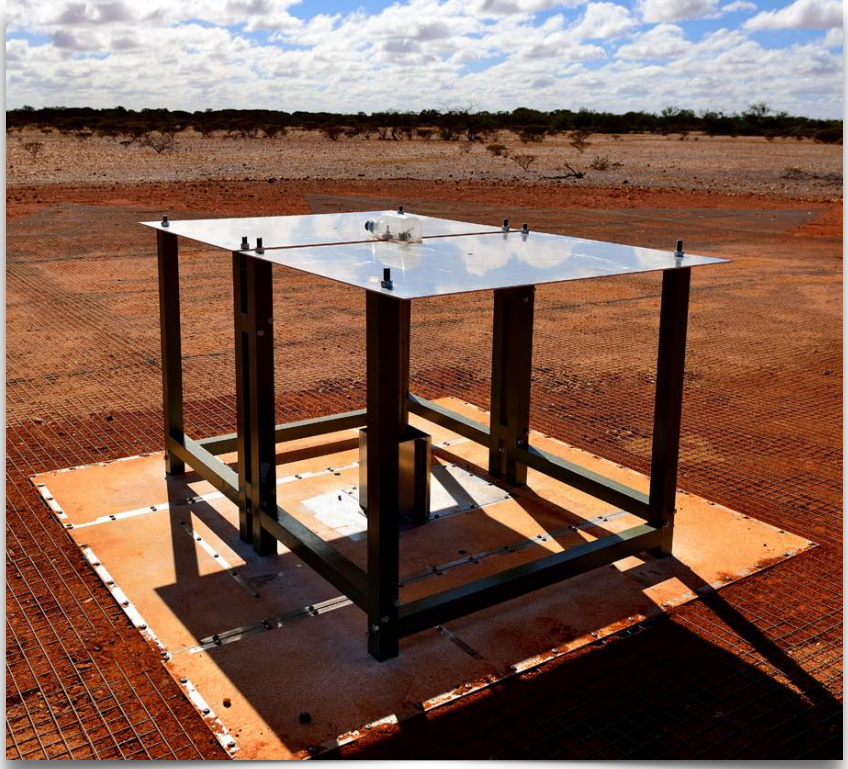
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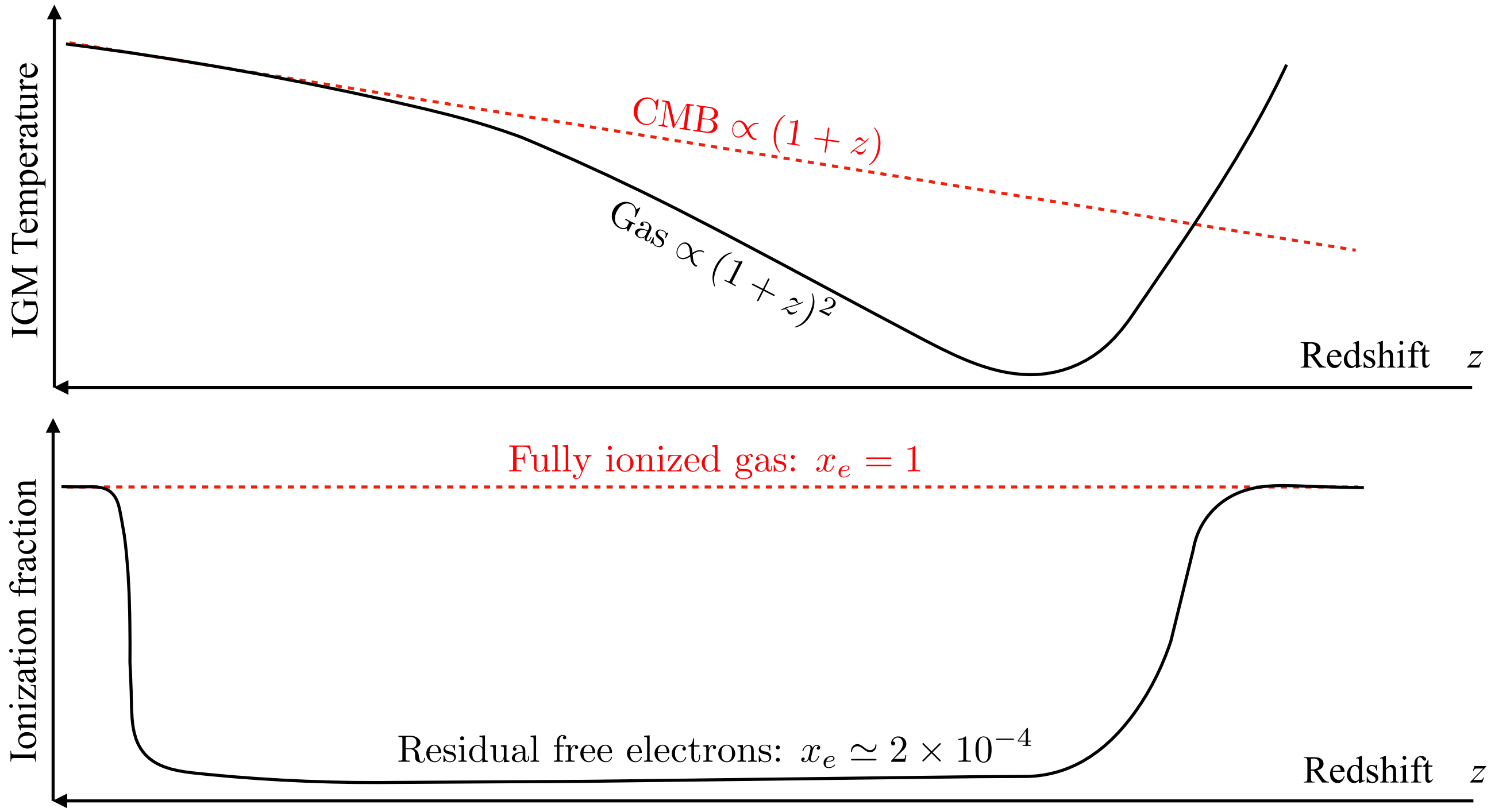


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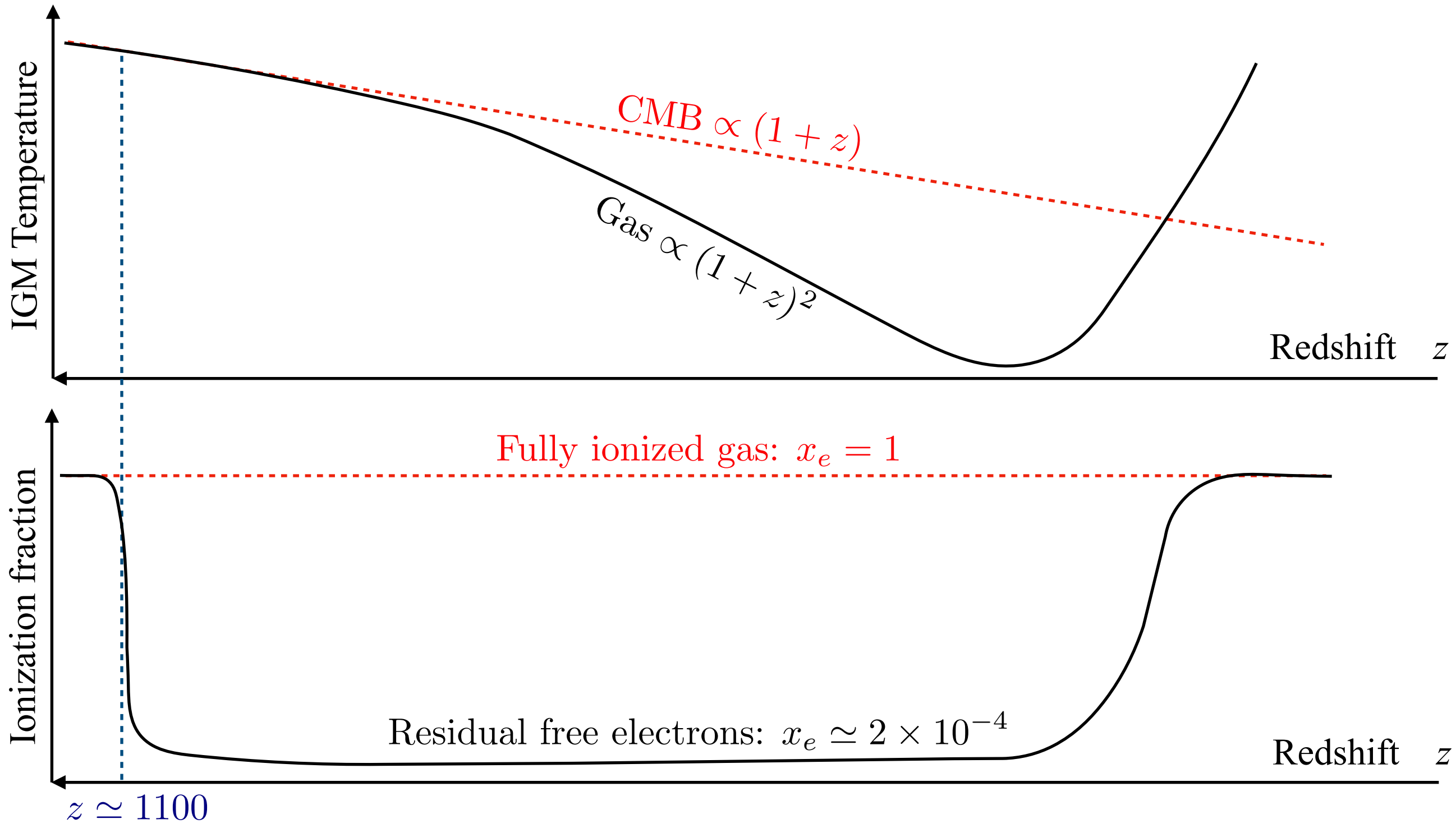
EDGES measurement implies
 $T_{\text{CMB}}/T_S \simeq 19$ at $z = 17$
 $T_S \simeq 3 \text{ K}$

A short history of the IGM



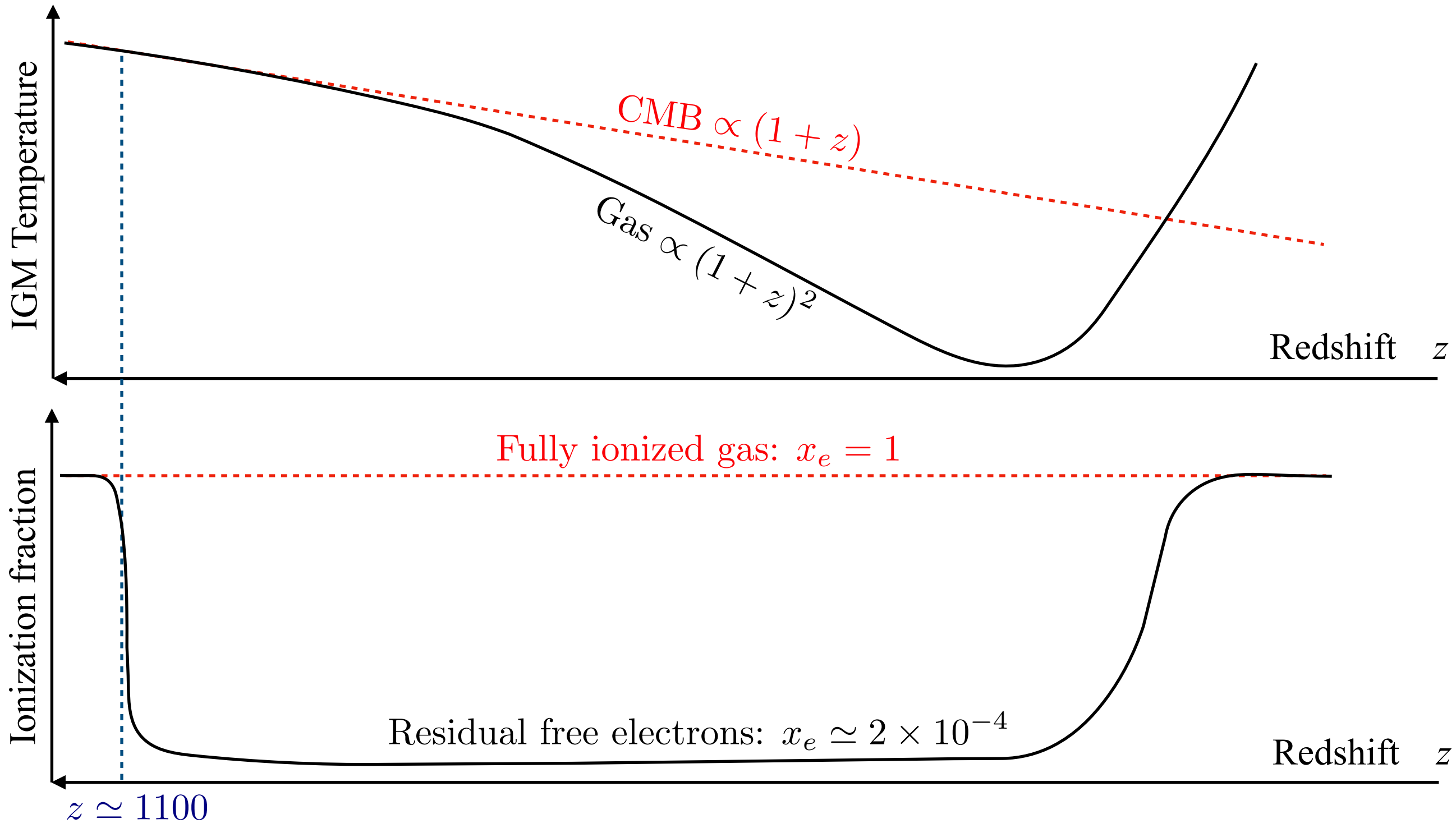
A short history of the IGM

→ At $z \sim 1100$, CMB and IGM kinetically decouple:
the Universe becomes neutral



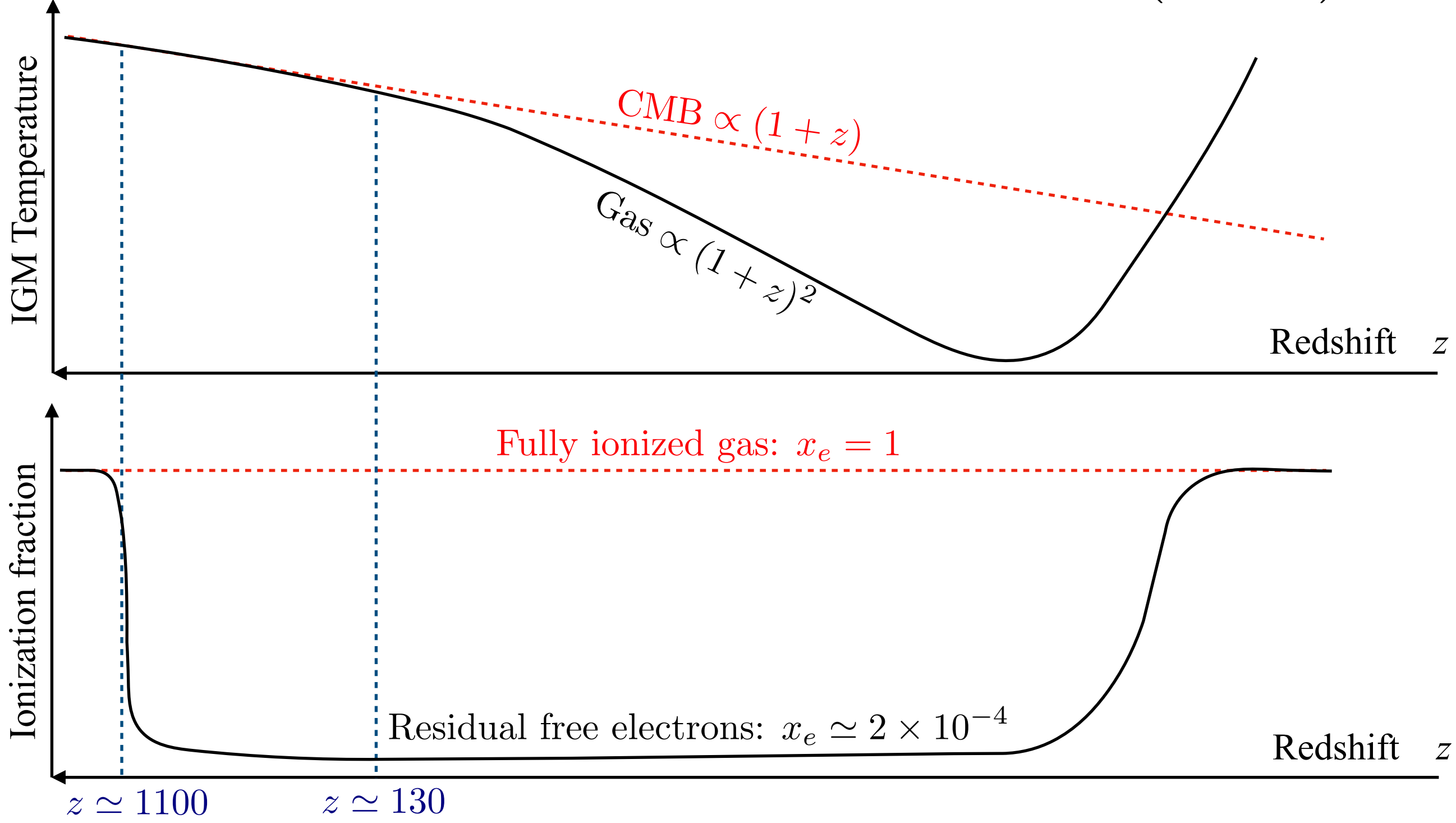
A short history of the IGM

→ However, the gas & CMB temperatures are still the same, because of efficient Compton scattering



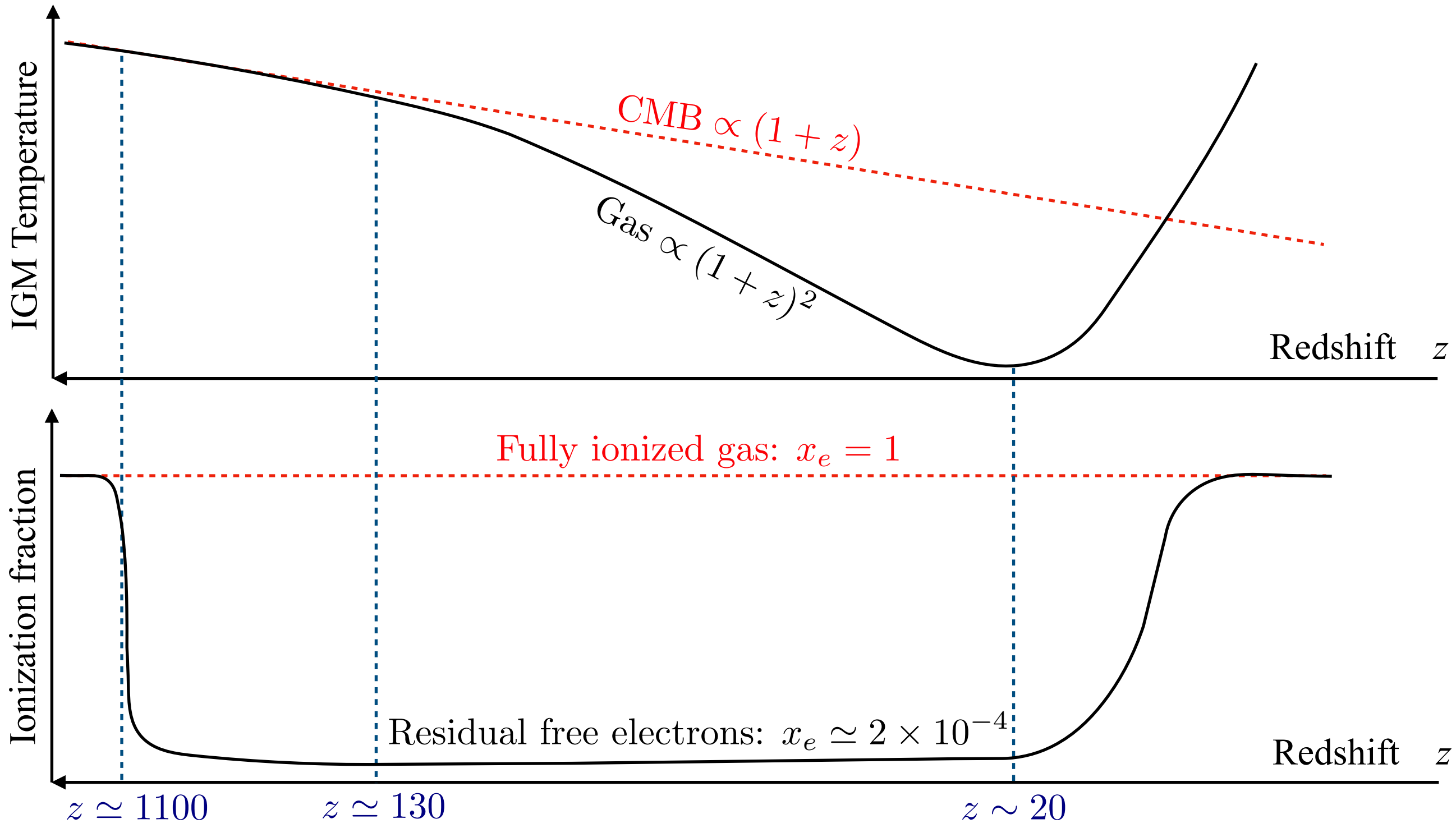
A short history of the IGM

➔ Finally, around $z \sim 130$, IGM thermally decouples:
it thereafter cools down adiabatically as: $T_{\text{gas}} \simeq T_{\text{CMB}}^{z=130} \left(\frac{1+z}{1+130} \right)^2$



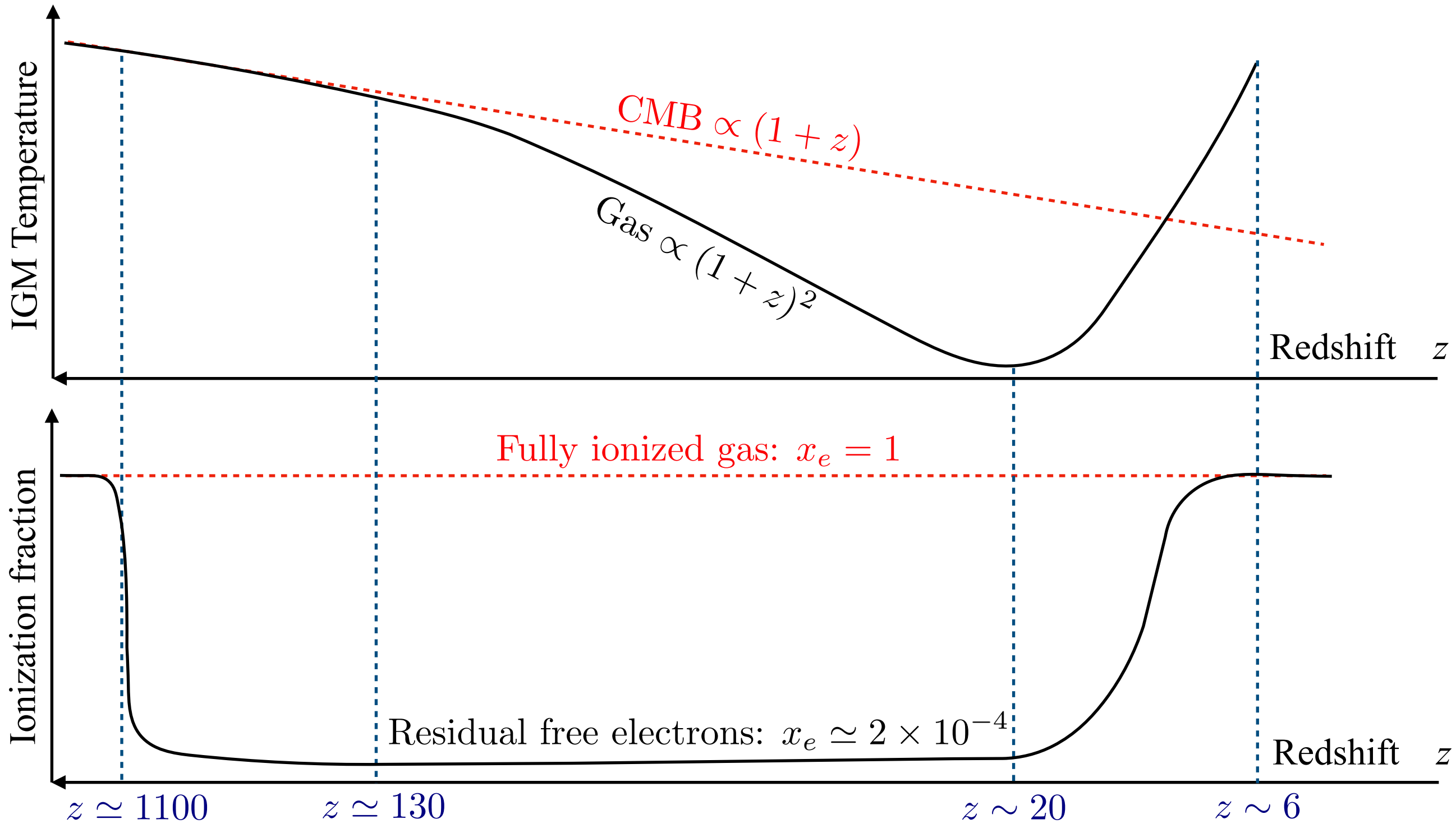
A short history of the IGM

➔ At some point, lights turn on: X-rays and Ly- α photons go around the Universe, heat the IGM, finally reaching



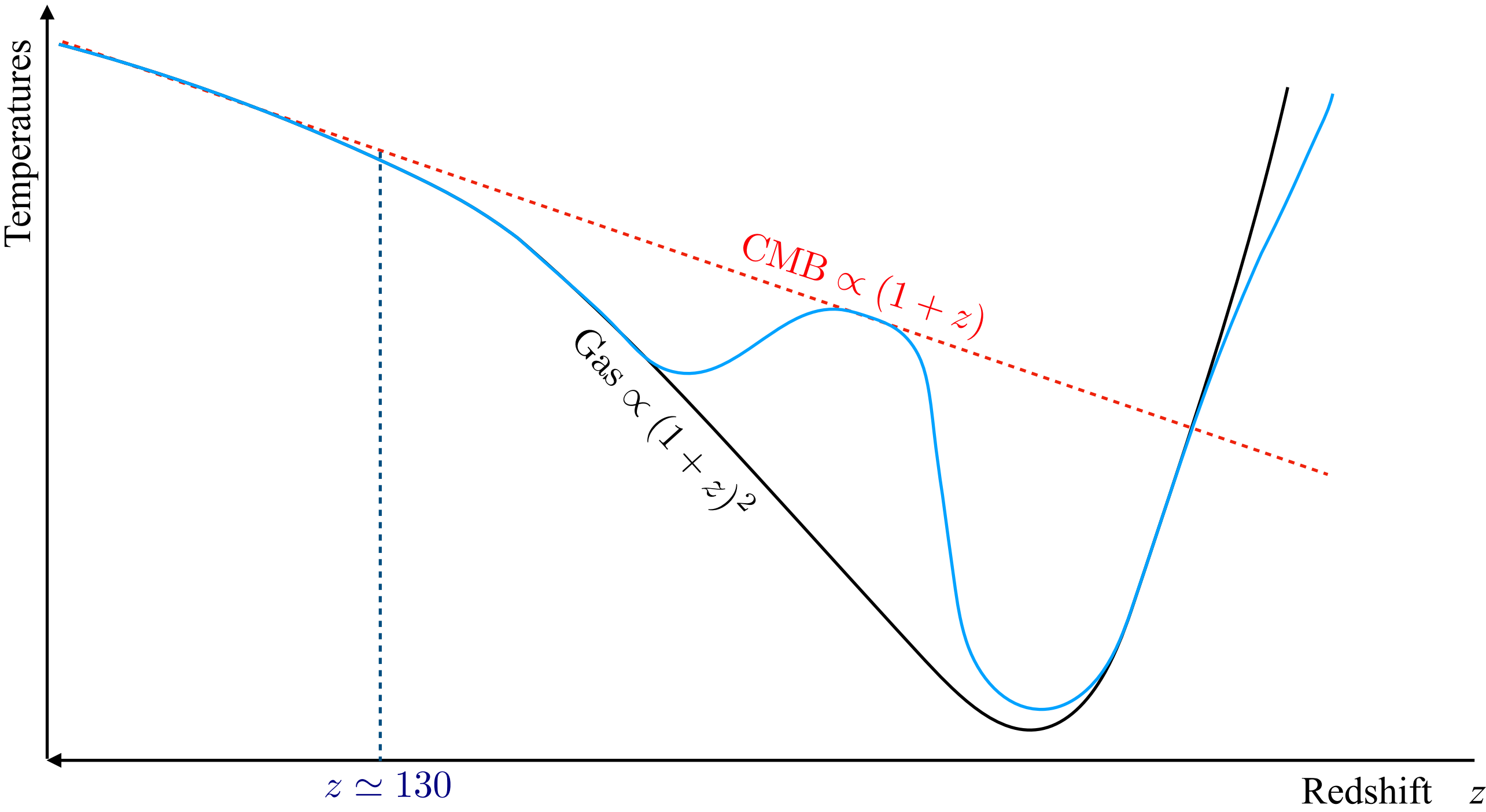
A short history of the IGM

→ **Reionization**: the Universe becomes ionized again, no neutral atomic hydrogen anymore



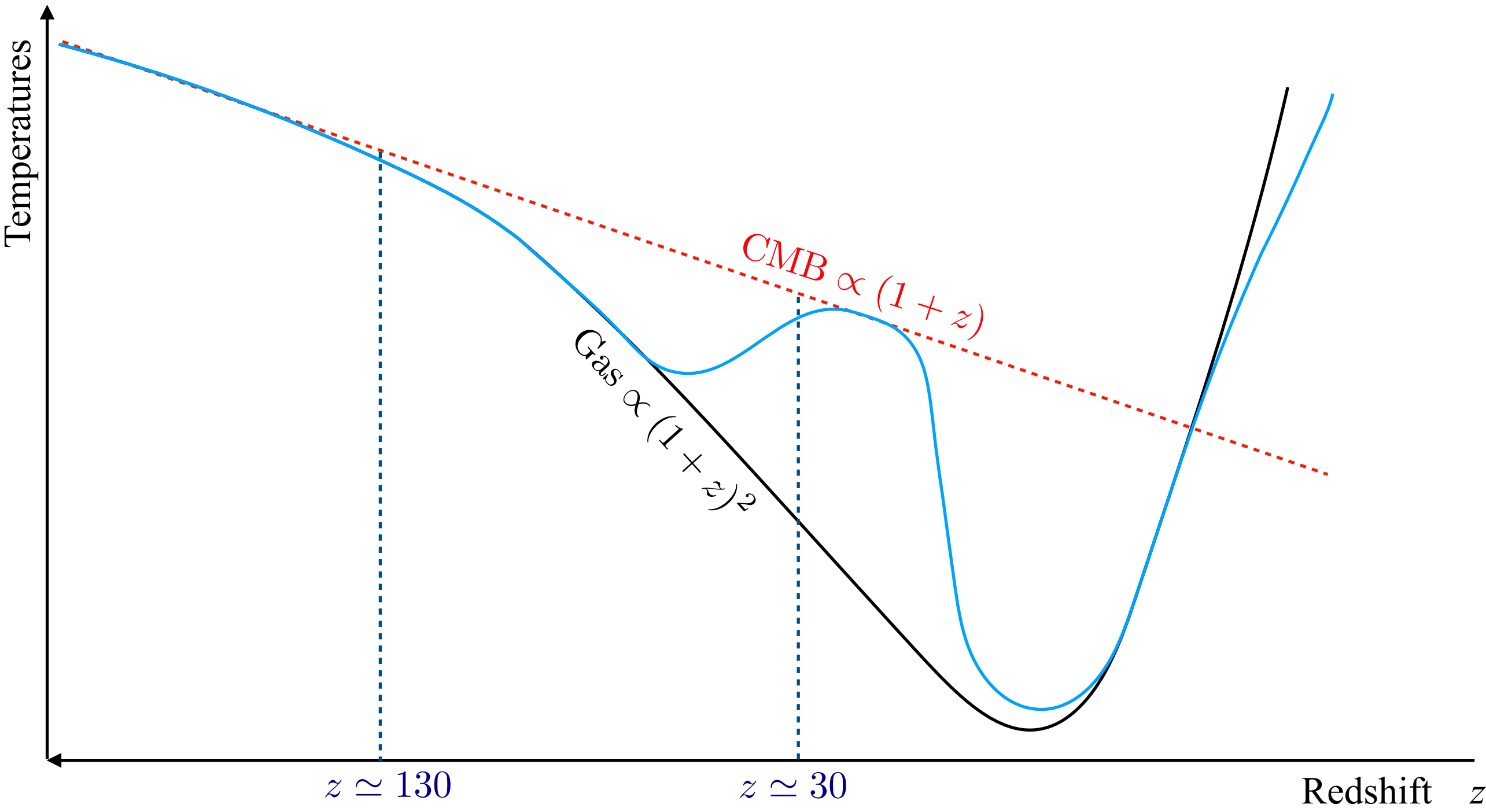
A short history of T_S

→ Nothing happens until IGM thermally decouple, temperatures are all the same, zero signal



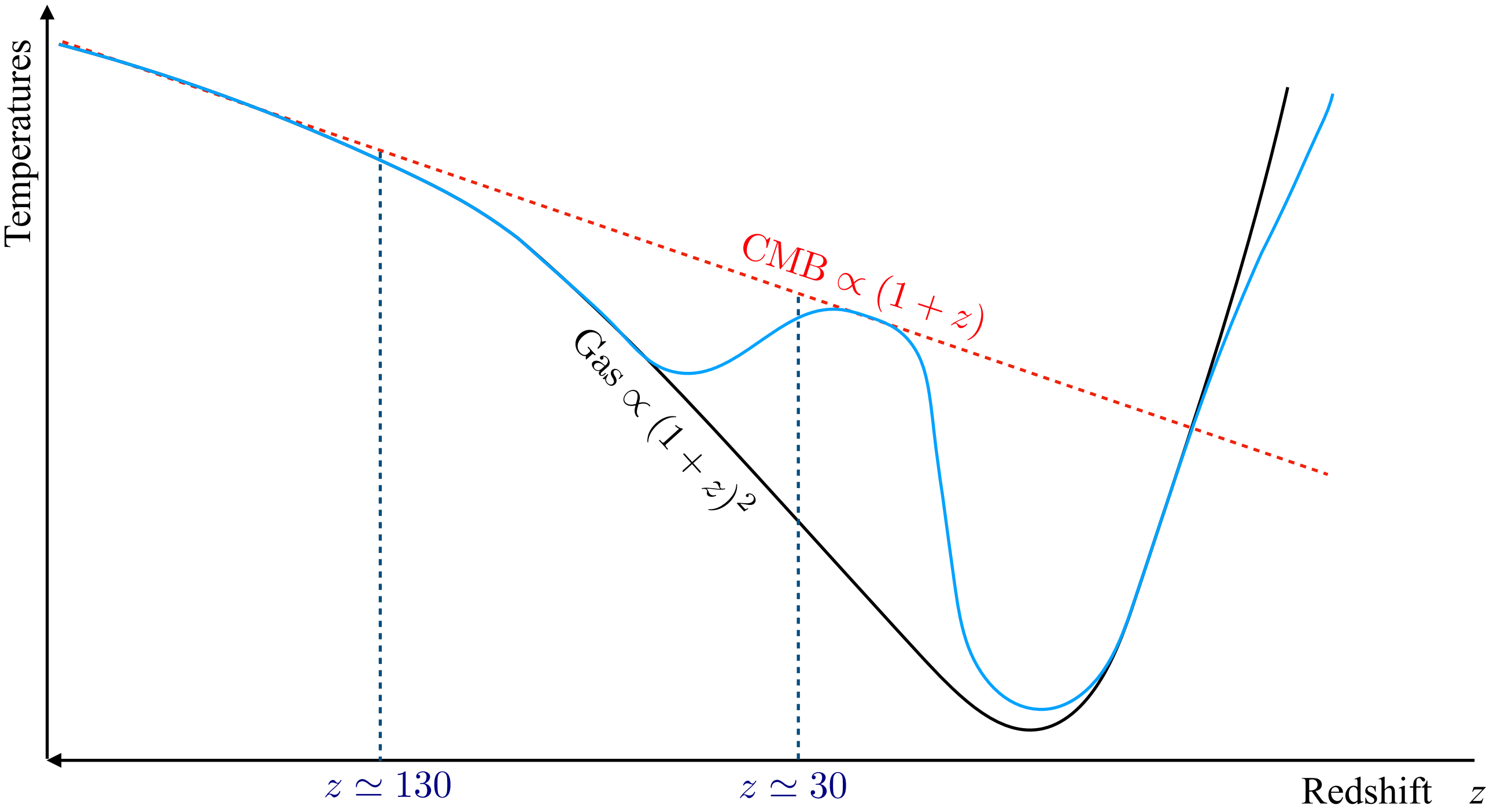
A short history of T_s

➔ After $z \sim 200$ until $z \sim 30$, collisions keep since the IGM is colder, I have a signal *in absorption*



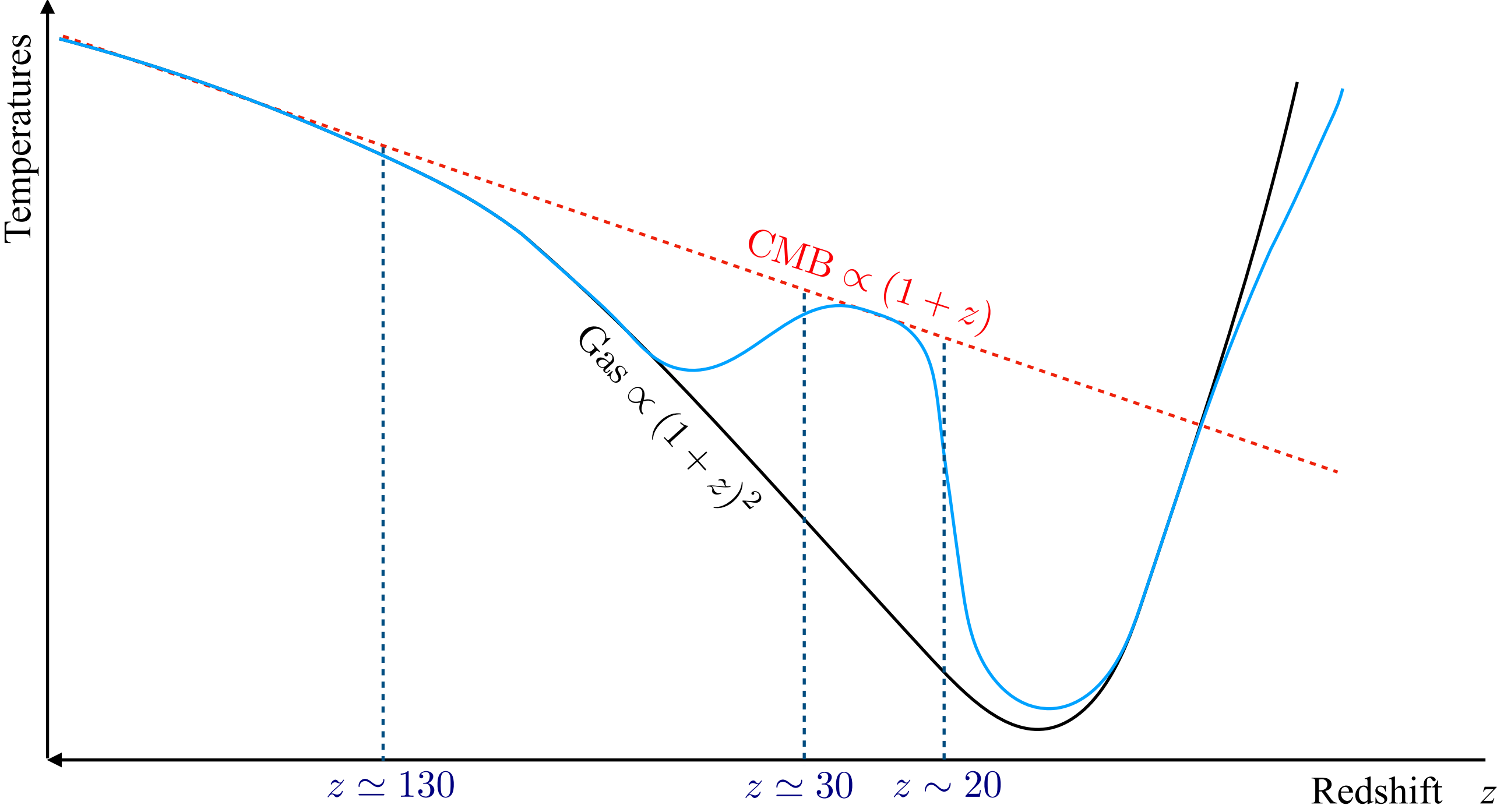
A short history of T_S

➔ After, no collisions, no other radiation:
and I have zero signal



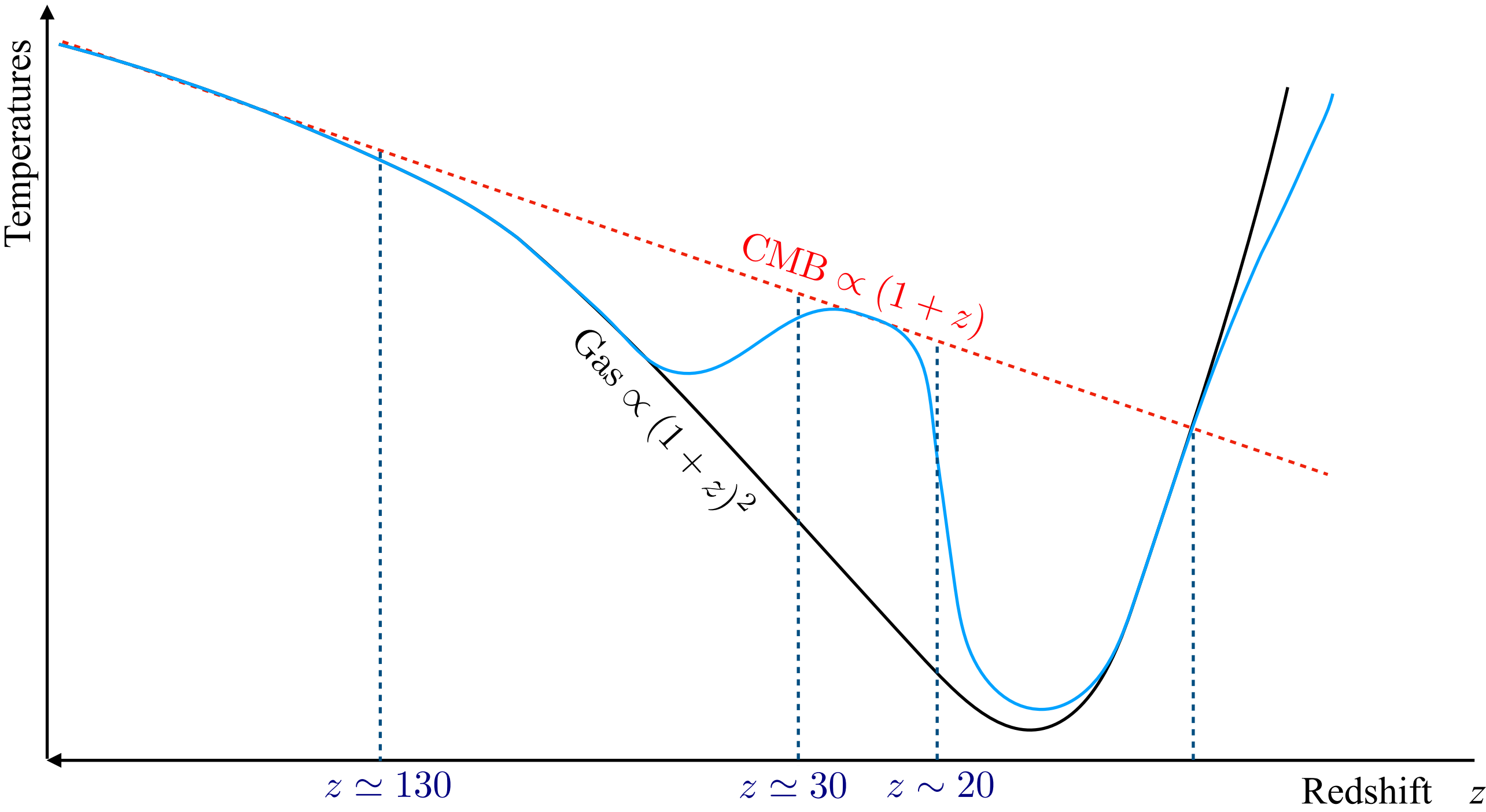
A short history of T_S

➔ And then? **At some point, Ly- α photons recouple,**
so I start decreasing and I get absorption

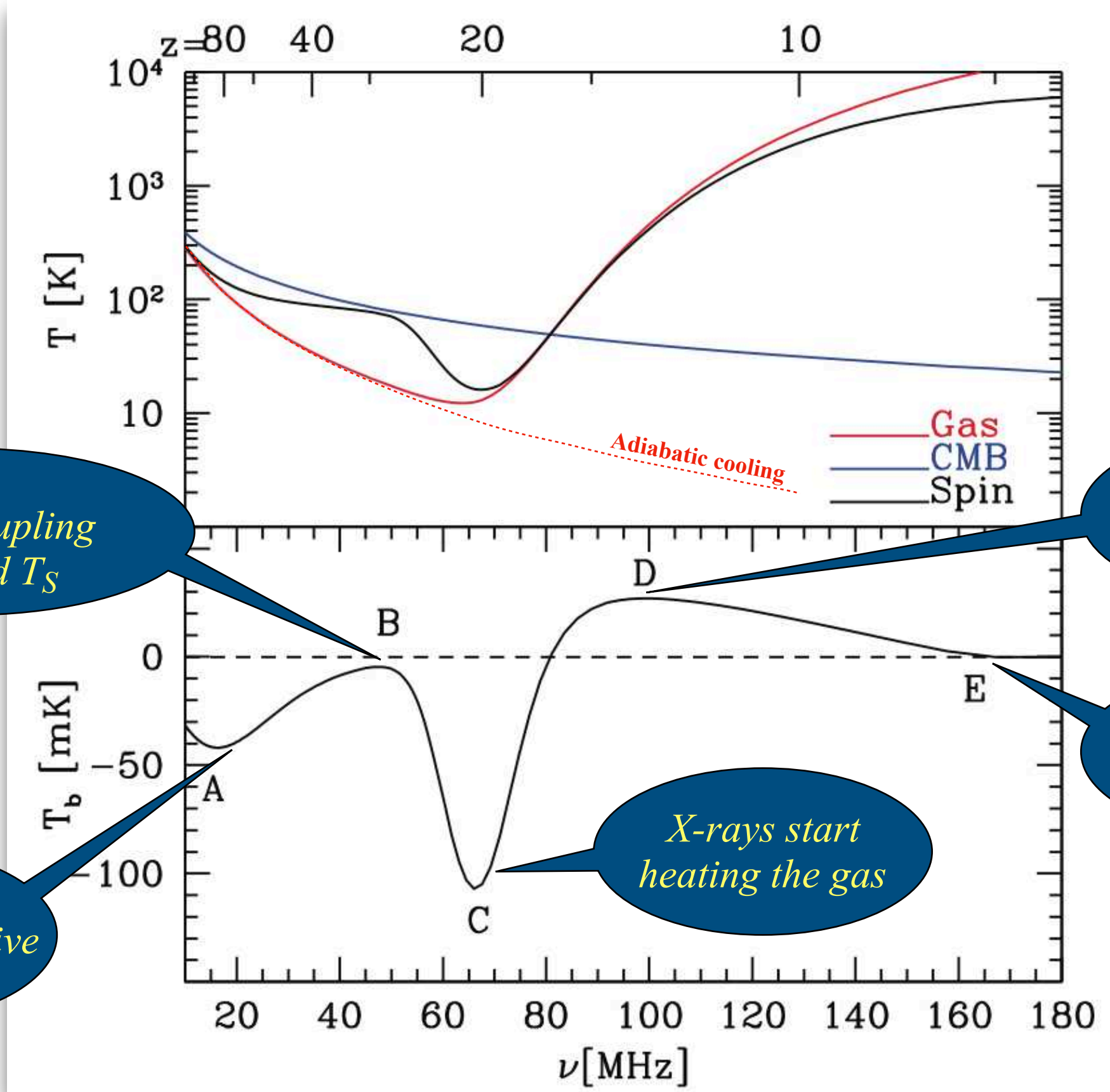


A short history of T_S

→ Finally, as I goes up, I increase and get an emission until 21-cm signal dies after full reionization



21-cm signal history



Lya start recoupling T_{gas} and T_S

From absorption to emission

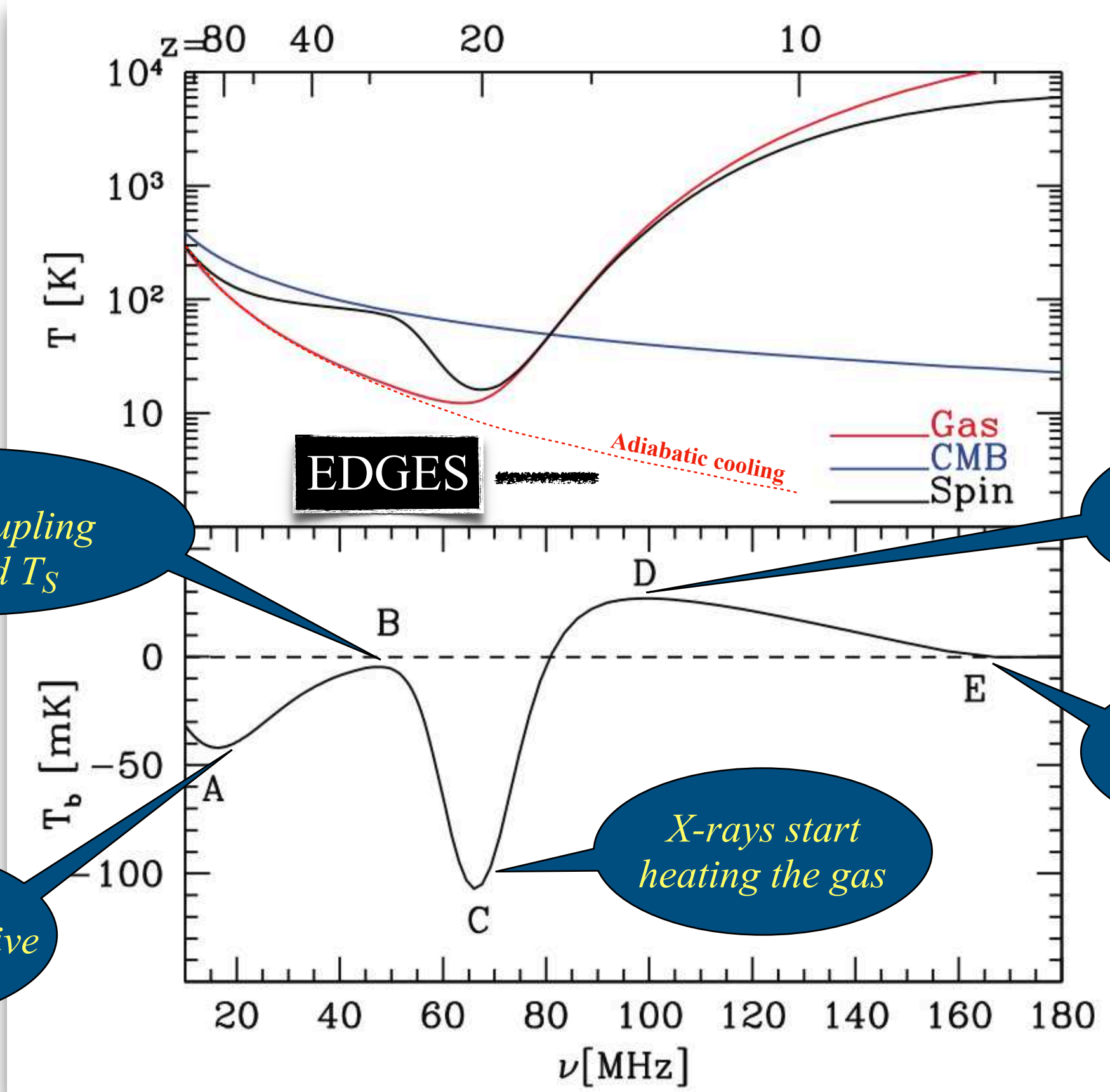
Collisions become ineffective

X-rays start heating the gas

Reionization kills the signal

Taylor et al. 2012
(1206.6733)

21-cm signal history



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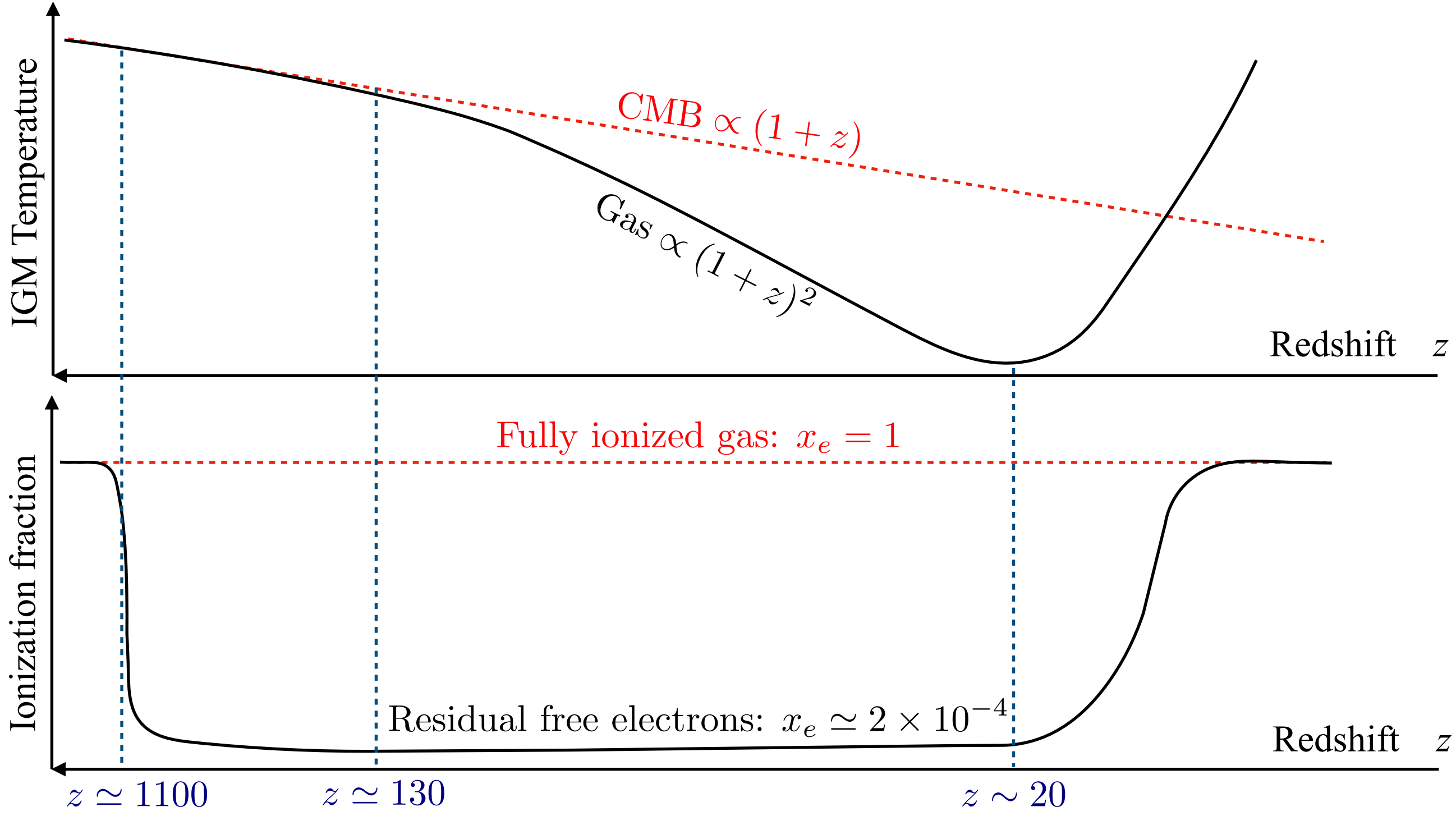
III PART

Constraints on DM annihilations

Where does DM enter?

DM can (and will if thermal) annihilate into SM.

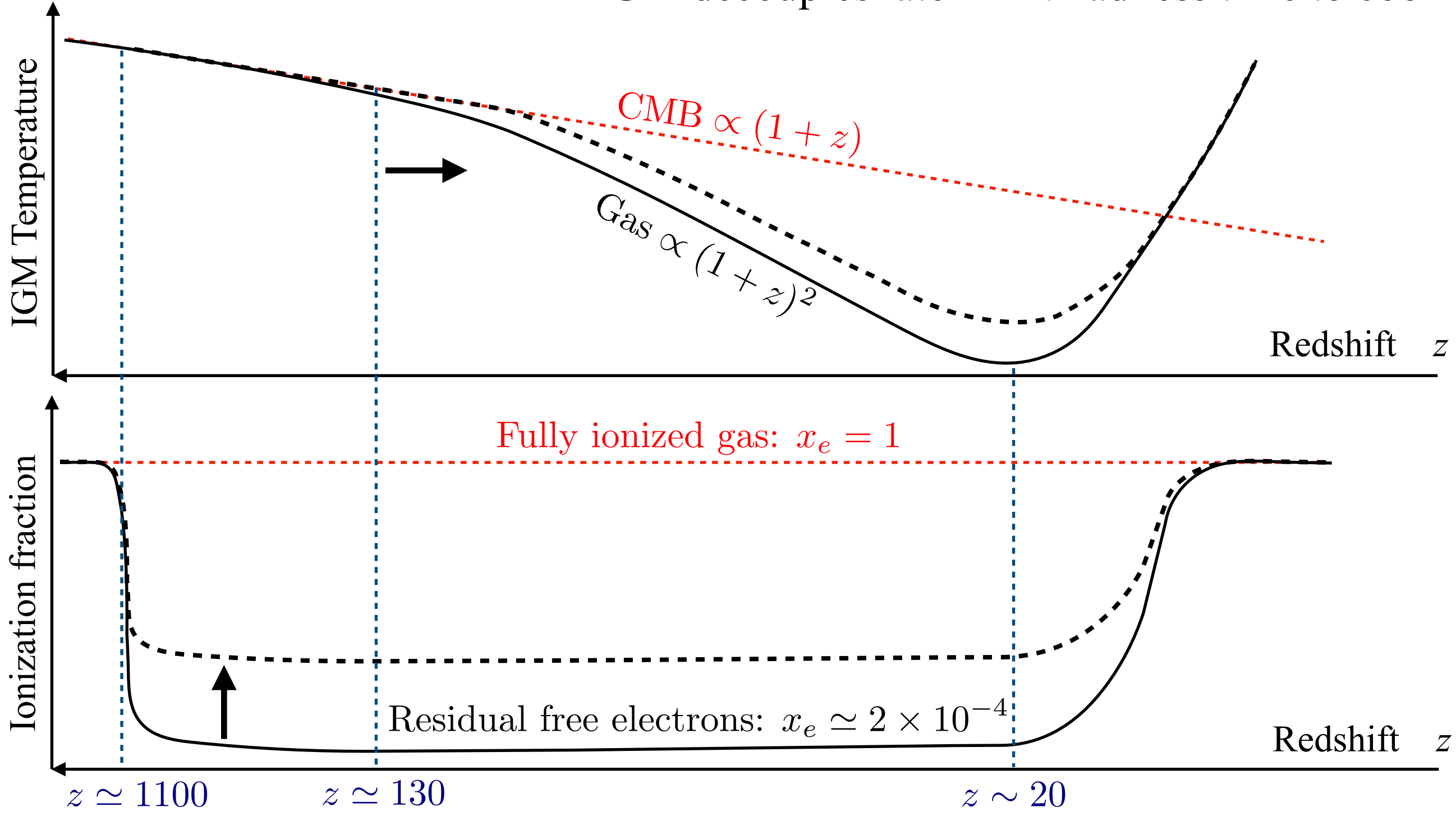
Will heat the IGM in 2 ways:



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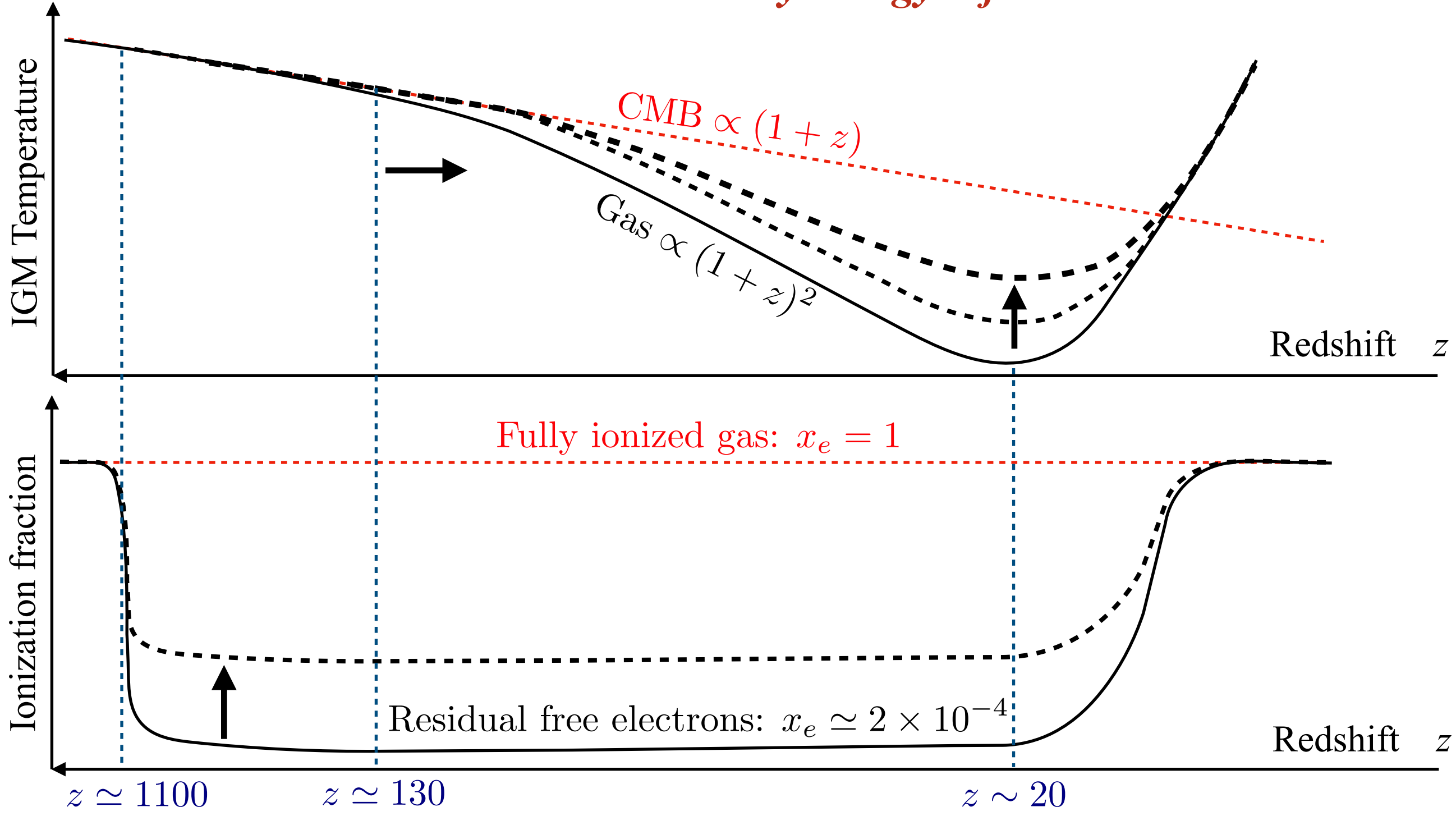
Will heat the IGM in 2 ways: → Annihilations *increase ionization fraction*
IGM decouples later ⇒ it had less time to cool



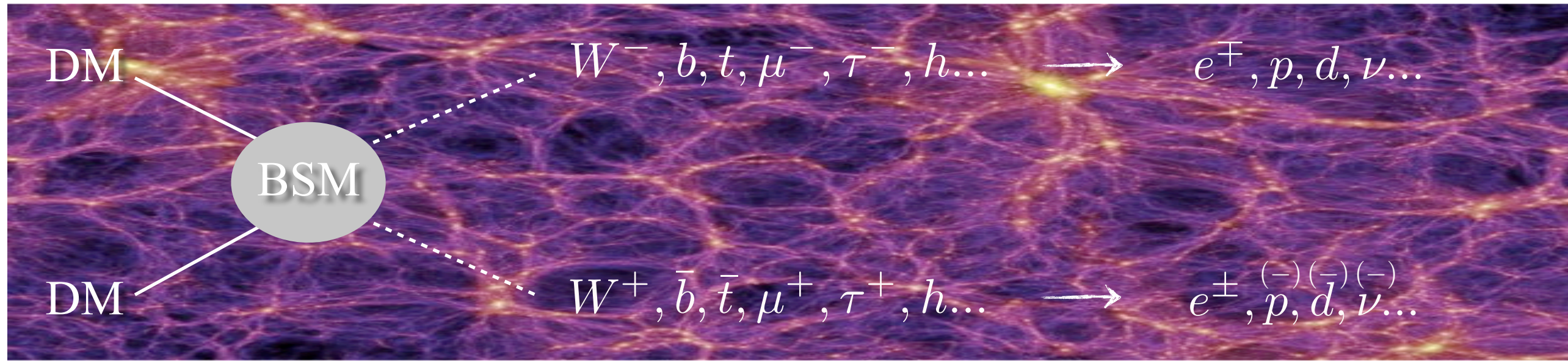
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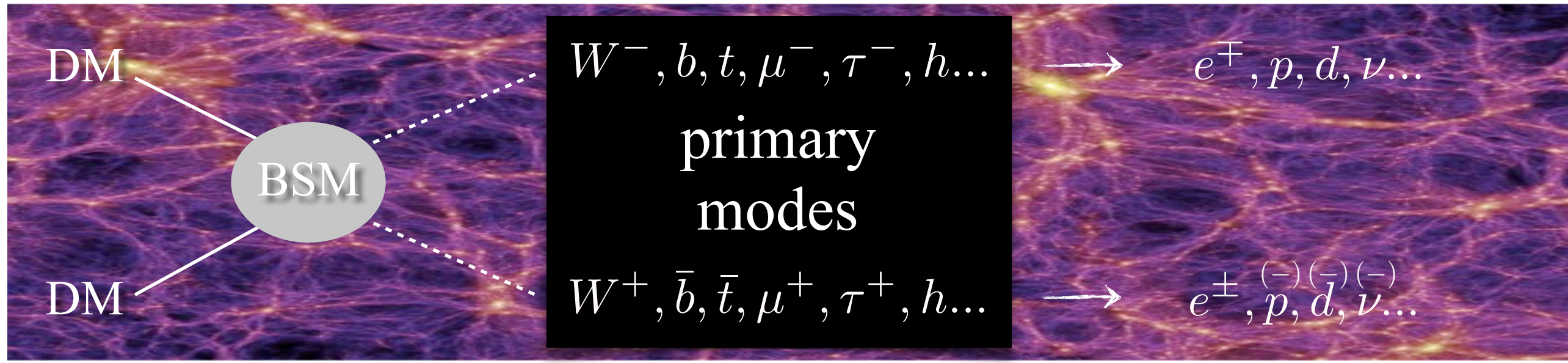
Will heat the IGM in 2 ways: \rightarrow More importantly, annihilations directly heat the IGM *by energy injection*



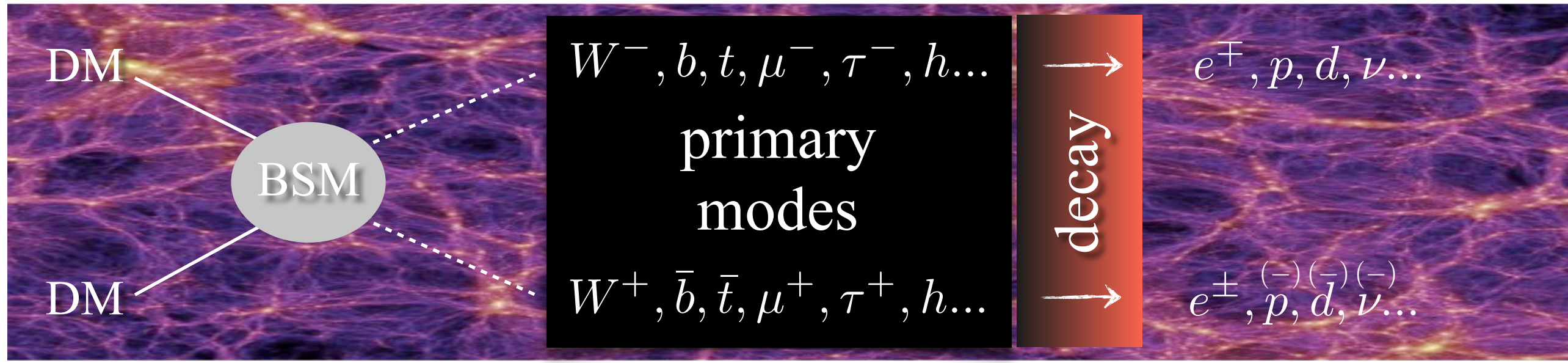
DM Annihilation: Basics



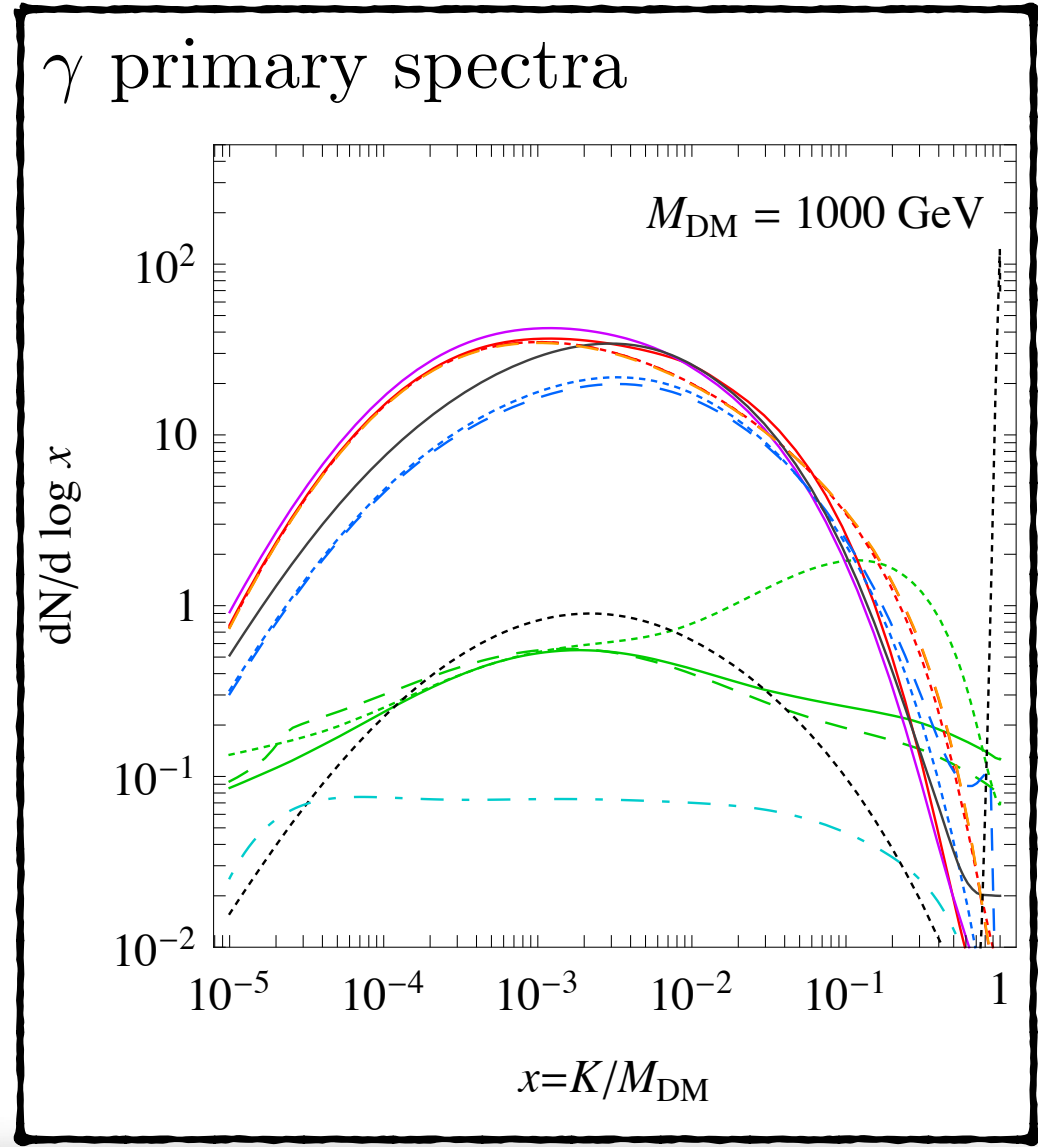
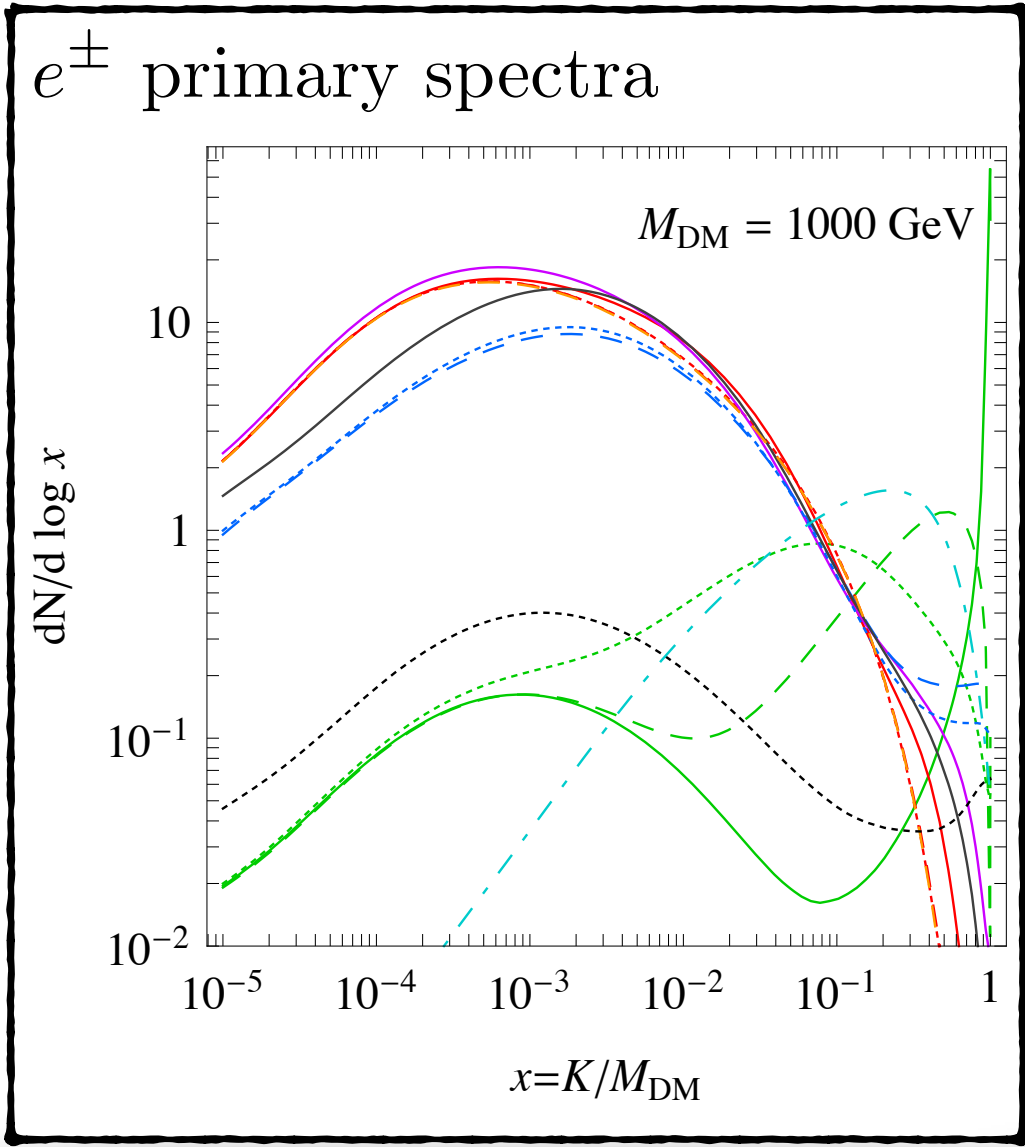
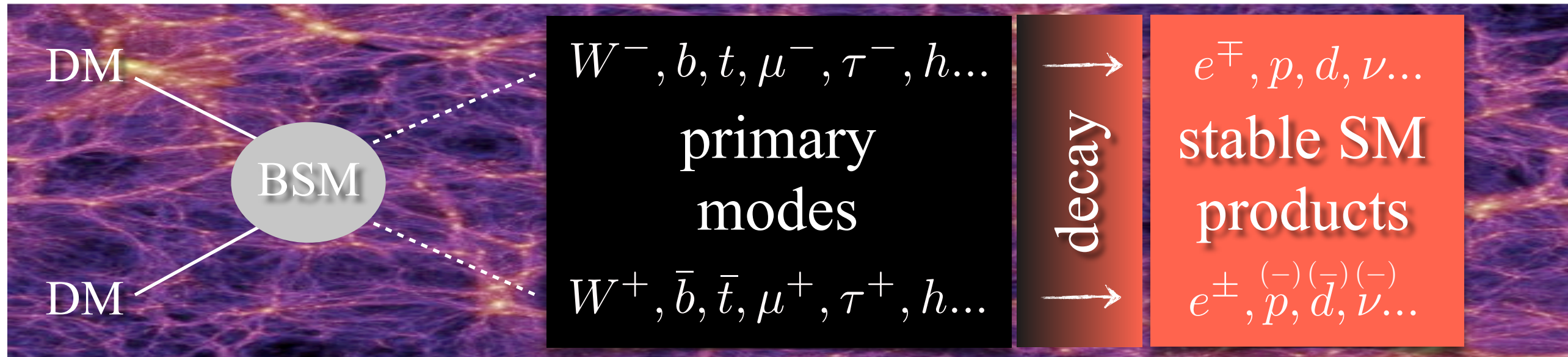
DM Annihilation: Basics



DM Annihilation: Basics



DM Annihilation: Basics



—	e
- - -	μ
⋯	τ
- · - ·	q
- · - ·	c
—	b
—	t
- - -	W
- · - ·	Z
—	h_{115}
- · - ·	g
- - -	γ
- · - ·	$V \rightarrow \mu$

Energy injection

Total number of stable SM products per (dV , dE and dt) at a given z :

$$\frac{d\mathcal{N}}{dV dE_f dt} = \langle \rho_{\text{DM}}^2 \rangle \frac{\langle \sigma v \rangle}{M_{\text{DM}}^2} \frac{dN}{dE_f}$$

Total Energy injected into the IGM per (dV and dt) at a given z :

$$\left. \frac{d\mathcal{E}}{dV dt} \right|_{\text{inj}} = \int \sum_f \frac{d\mathcal{N}}{dV dE_f dt} E_f dE_f \equiv \langle \rho_{\text{DM}}^2 \rangle \frac{\langle \sigma v \rangle}{M_{\text{DM}}}$$

Energy injection

Total number of stable SM products per (dV , dE and dt) at a given z :

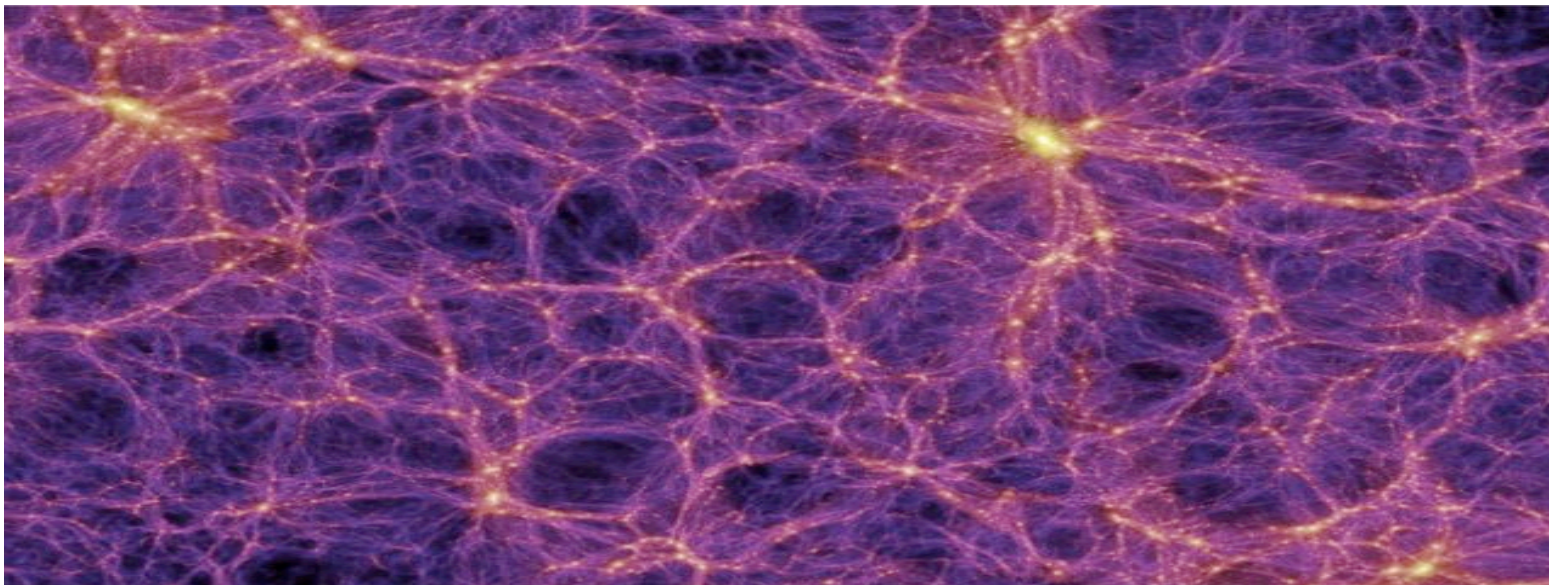
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Boosted Annihilation due to structure formation:

$$\langle \rho_{\text{DM}}^2 \rangle \equiv \langle \rho_{\text{DM}} \rangle^2 B(z) = \rho_c^2 \Omega_{\text{DM}}^2 (1+z)^6 B(z)$$



Energy injection

Total number of stable SM products per (dV , dE and dt) at a given z :

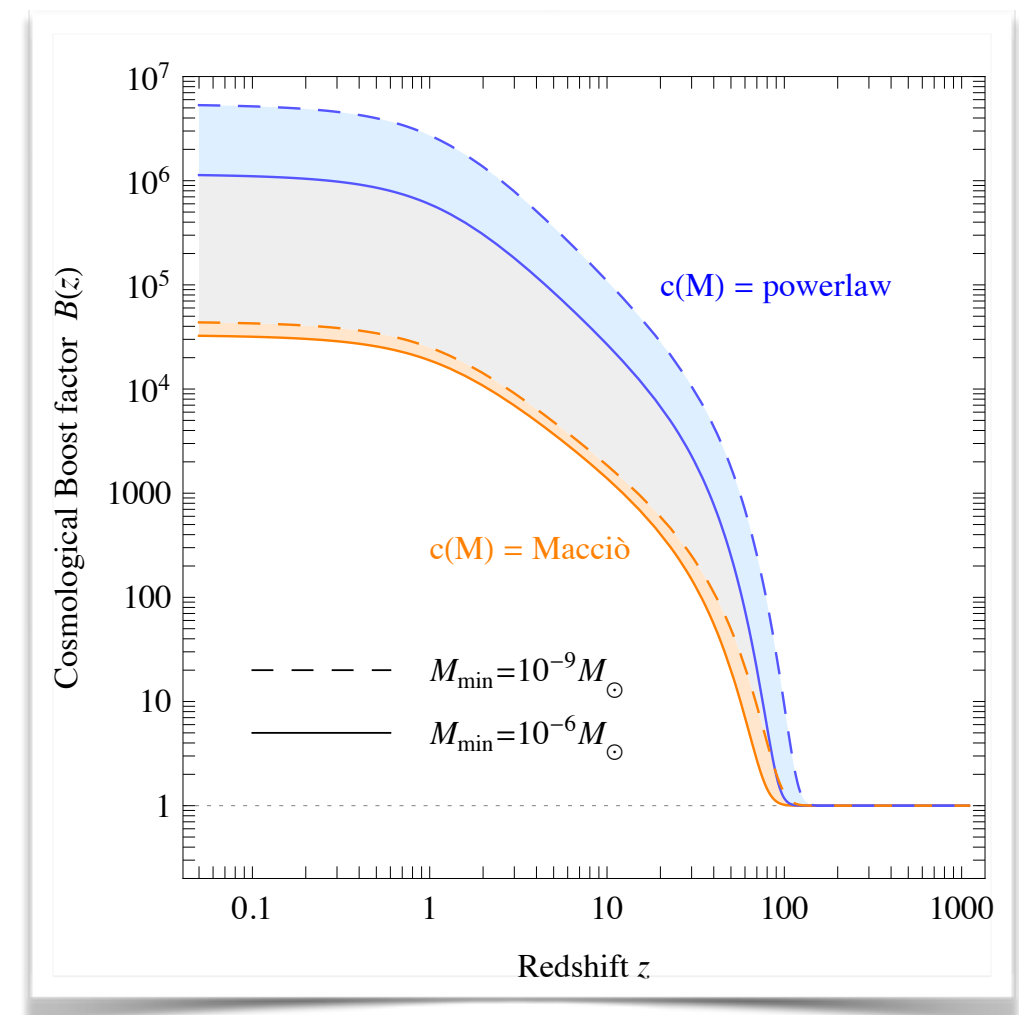
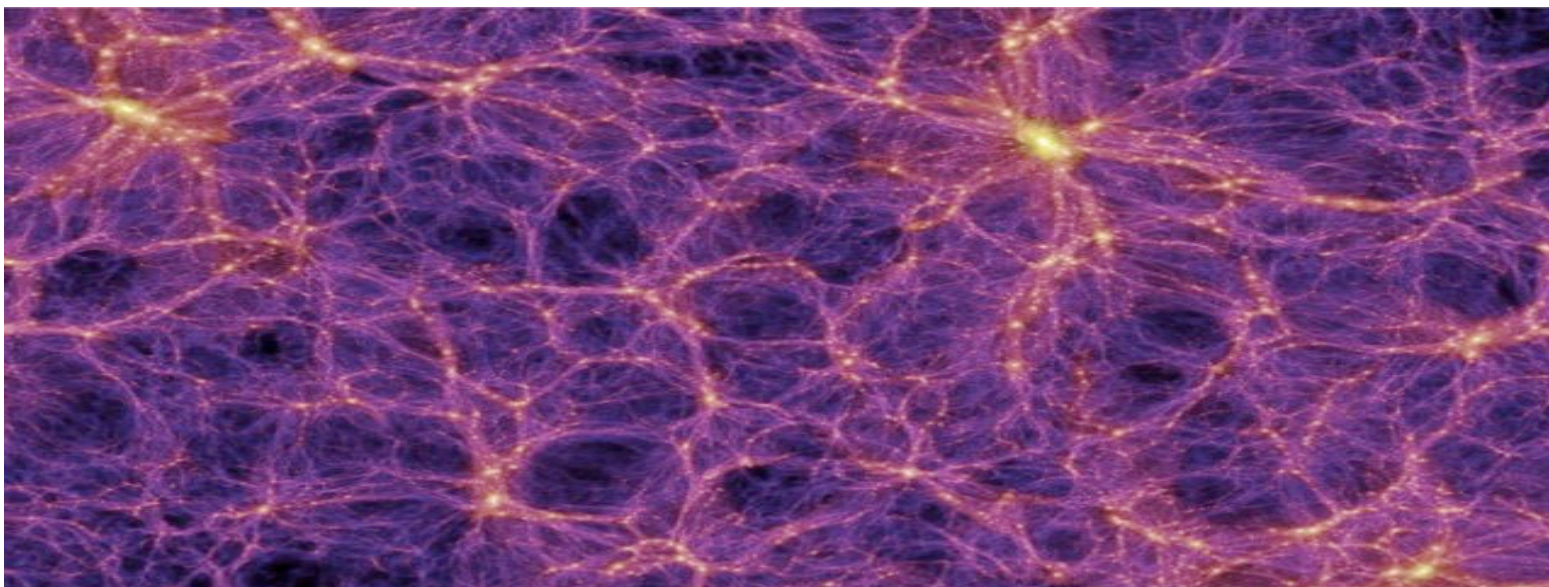
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Energy deposition

Energy deposited into the IGM in *3 main channels*:

$$\left. \frac{d\mathcal{E}}{dV dt} \right|_{\text{dep}} \equiv \left. \frac{d\mathcal{E}}{dV dt} \right|_{\text{inj}} f_c(z) \begin{cases} \rightarrow \text{Ionize } H_{\text{I}} \\ \rightarrow \text{Excite } H_{\text{I}} \\ \rightarrow \text{Heat the IGM} \end{cases}$$

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INSTANTANEOUS DEPOSITION: only valid at high redshift

$$f_{\text{ion}}^{z \gtrsim 100} = f_{\text{exc}}^{z \gtrsim 100} = \frac{f_{\text{eff}}}{3} (1 - x_e), \quad f_{\text{heat}}^{z \gtrsim 100} = \frac{f_{\text{eff}}}{3} (1 + 2x_e)$$

Energy deposition

Energy deposited into the IGM in *3 main channels*:

$$\left. \frac{d\mathcal{E}}{dV dt} \right|_{\text{dep}} \equiv \left. \frac{d\mathcal{E}}{dV dt} \right|_{\text{inj}} f_c(z)$$

- Ionize H_I
- Excite H_I
- Heat the IGM

DELAYED DEPOSITION: important at low redshift (EDGES from 20 to 15)

$$f_c(z) = \frac{\int dz' \frac{H(z)(1+z)^3}{H(z')(1+z')^4} \int dE E \mathcal{T}_c(E, z, z') \frac{d\mathcal{N}}{dV dE dt}(E, z')}{\left. \frac{d\mathcal{E}}{dV dt} \right|_{\text{inj}}}$$

Deposition redshift

Hubble Rate


Injection redshift

Accounts for EM shower

Slatyer
1506.03811,
1506.03812

Evolution of the **free electrons abundance**:


$$\frac{dx_e}{dz} = \frac{\mathcal{P}_2}{(1+z)H(z)} \left[\alpha_H(T_{\text{gas}})n_H x_e^2 - \beta_H(T_{\text{gas}}) e^{-E_\alpha/T_{\text{gas}}} (1 - x_e) \right]$$



Recombination of H_I Ionization of H_I

Evolution of the **gas Temperature**:

$$\frac{dT_{\text{gas}}}{dz} = \frac{1}{1+z} \{ 2T_{\text{gas}}(z) - \gamma_C [T_{\text{CMB}}(z) - T_{\text{gas}}(z)] \}$$



Adiabatic cooling term Compton heating term

Evolution of the **free electrons abundance**:

$$\frac{dx_e}{dz} = \frac{\mathcal{P}_2}{(1+z)H(z)} \left[\alpha_H(T_{\text{gas}})n_H x_e^2 - \beta_H(T_{\text{gas}}) e^{-E_\alpha/T_{\text{gas}}} (1 - x_e) \right]$$

$$- \frac{1}{(1+z)H(z)} \frac{d\mathcal{E}}{dV dt} \Big|_{\text{inj}} \frac{1}{n_H} \left(\frac{f_{\text{ion}}(z)}{E_0} + \frac{(1 - \mathcal{P}_2)f_{\text{exc}}(z)}{E_\alpha} \right),$$

Energy deposited: **IONIZATION** and **EXCITATION**

Evolution of the **gas Temperature**:

$$\frac{dT_{\text{gas}}}{dz} = \frac{1}{1+z} \{ 2T_{\text{gas}}(z) - \gamma_C [T_{\text{CMB}}(z) - T_{\text{gas}}(z)] \}$$

$$- \frac{1}{(1+z)H(z)} \frac{d\mathcal{E}}{dV dt} \Big|_{\text{inj}} \frac{1}{n_H} \frac{2f_{\text{heat}}(z)}{3(1 + x_e + f_{He})}.$$

Energy deposited: **HEATING**

How do we put bounds?

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- Signal is lower than expected (and maybe not even cosmological?).
We do not try to explain it!

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- Signal is lower than expected (and maybe not even cosmological?).
We do not try to explain it!
- Annihilation increases T_{gas} : **tends to erase the 21-cm signal**

How do we put bounds?

- Signal is lower than expected (and maybe not even cosmological?).
We do not try to explain it!
- Annihilation increases T_{gas} : **tends to erase the 21-cm signal**
- Hence, we can infer bounds. But we cannot use the observed signal:
already the SM is out at 3.8σ

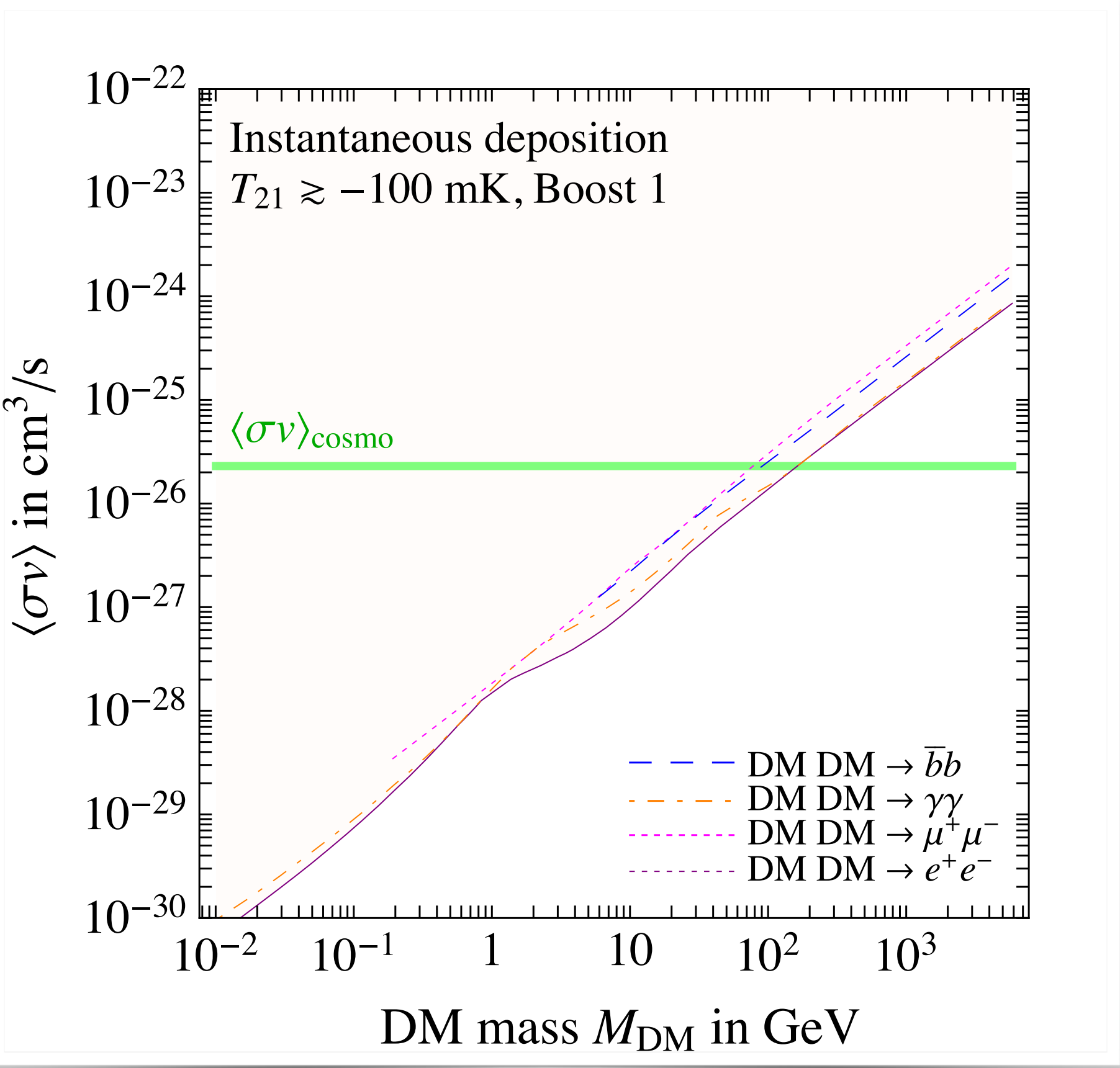
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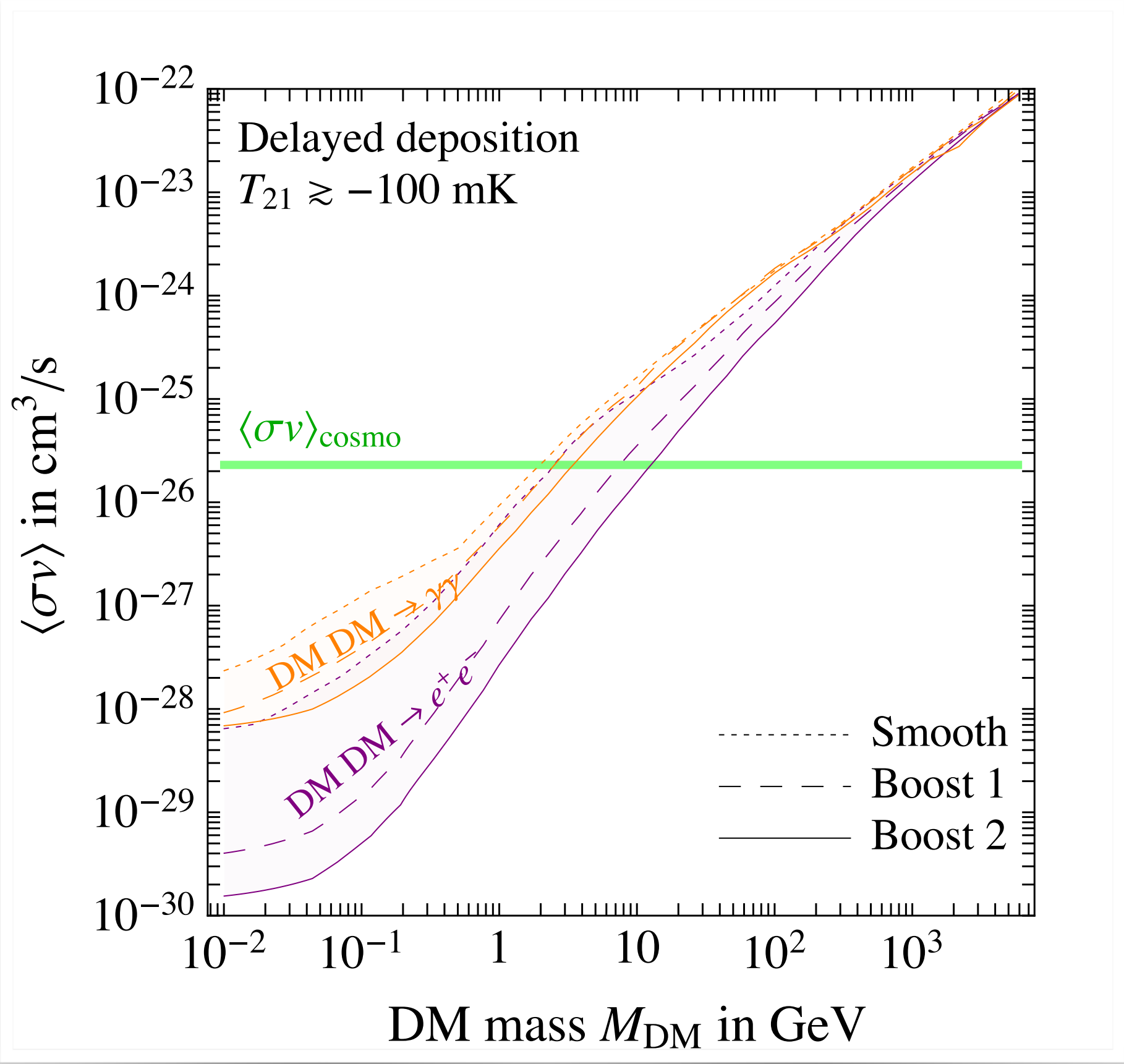
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- We require that DM annihilations do not erase the 21-cm signal above **-100 mK !!**

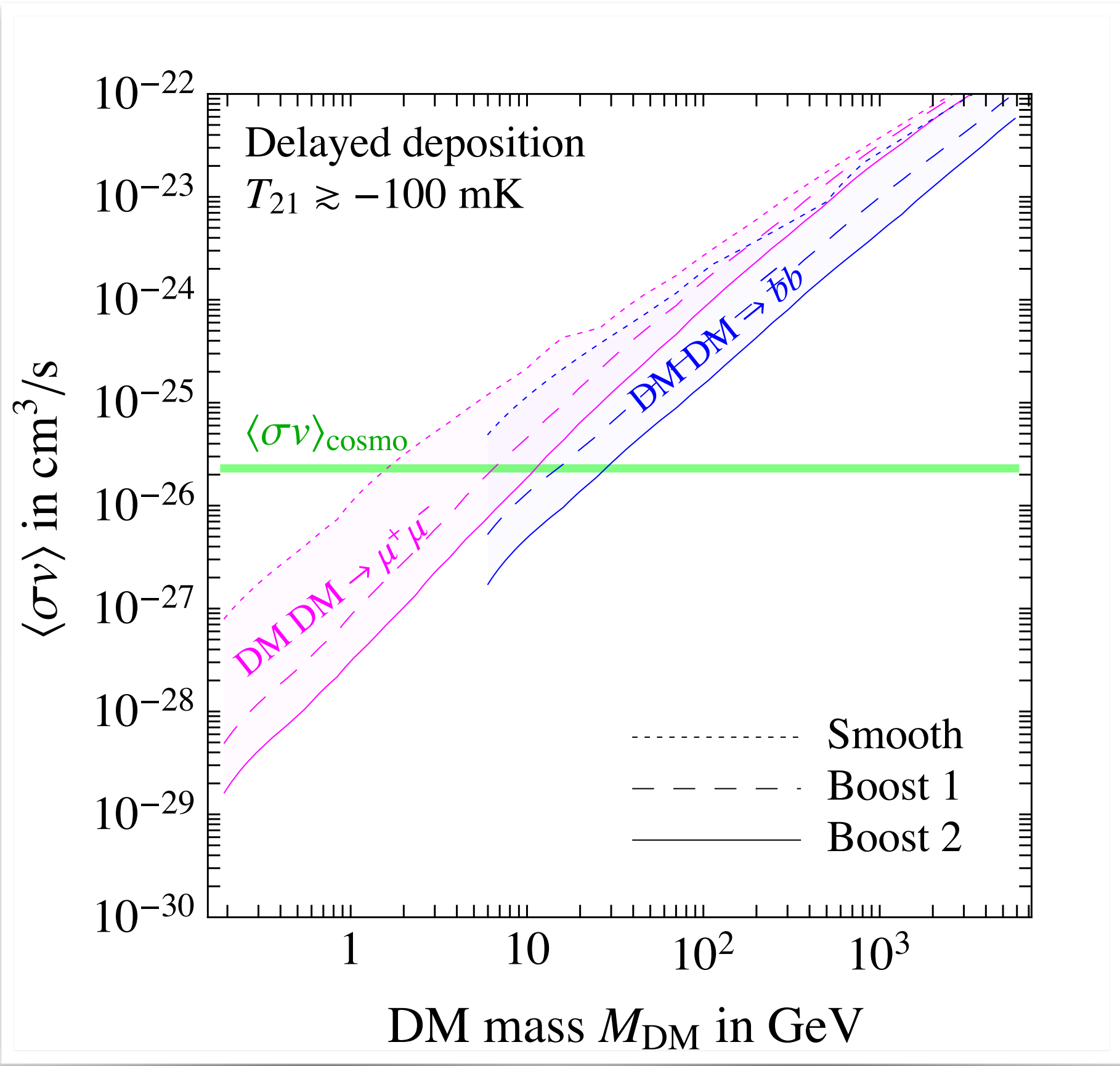
Instantaneous deposition



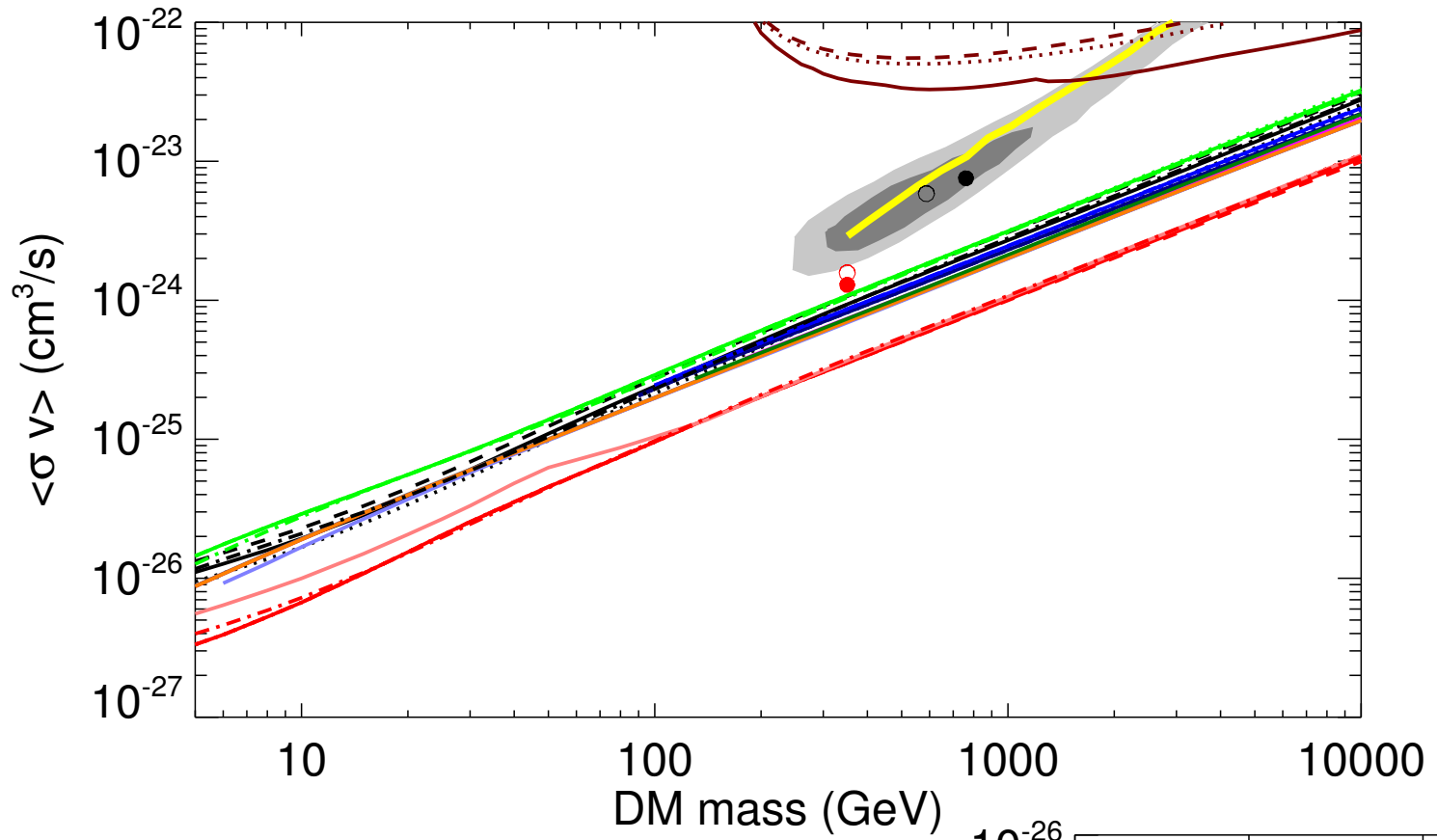
Some limits: $\gamma\gamma$ & e^+e^-



Some limits: $b\bar{b}$ & $\mu^+\mu^-$

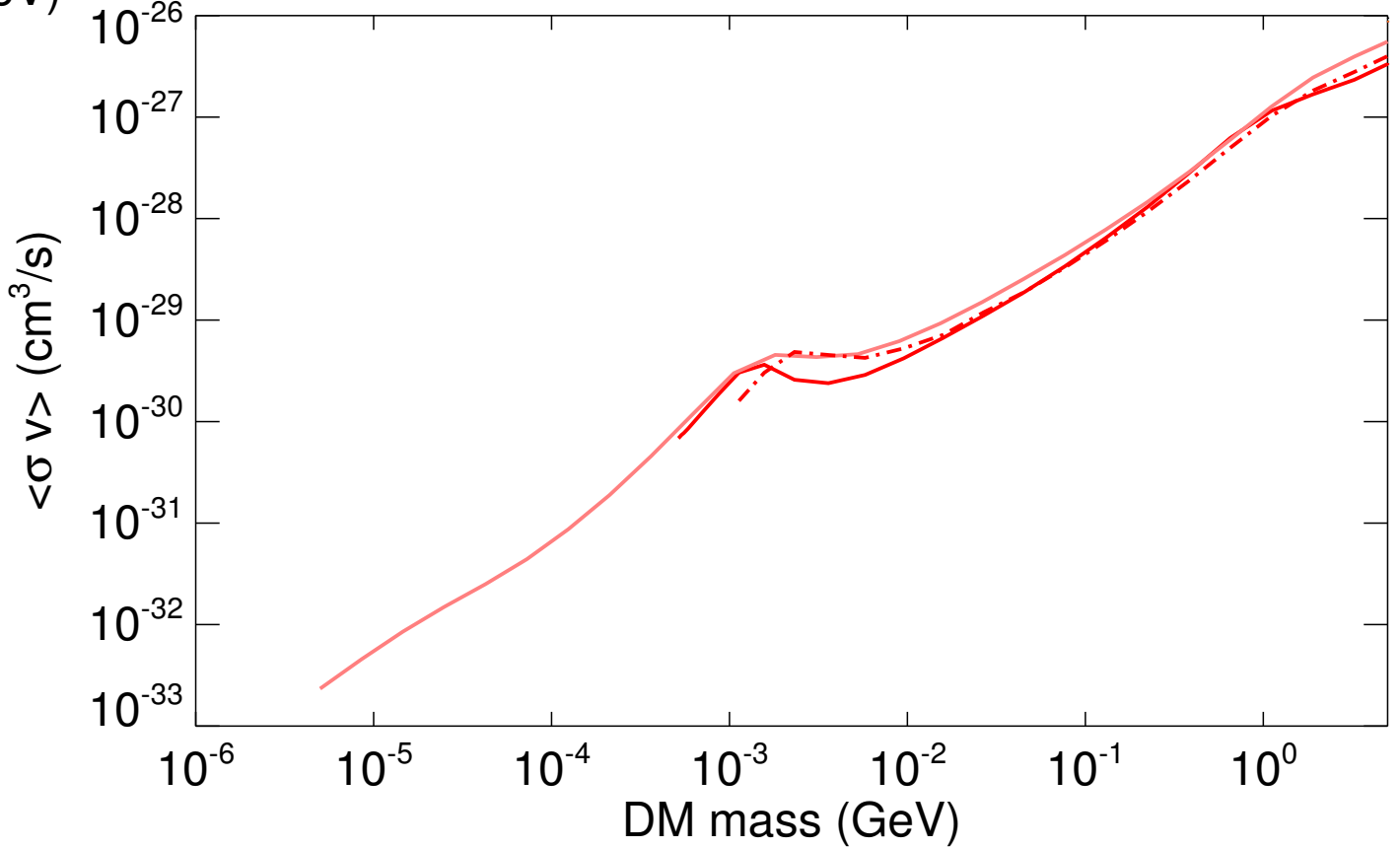


Comparison: PLANCK

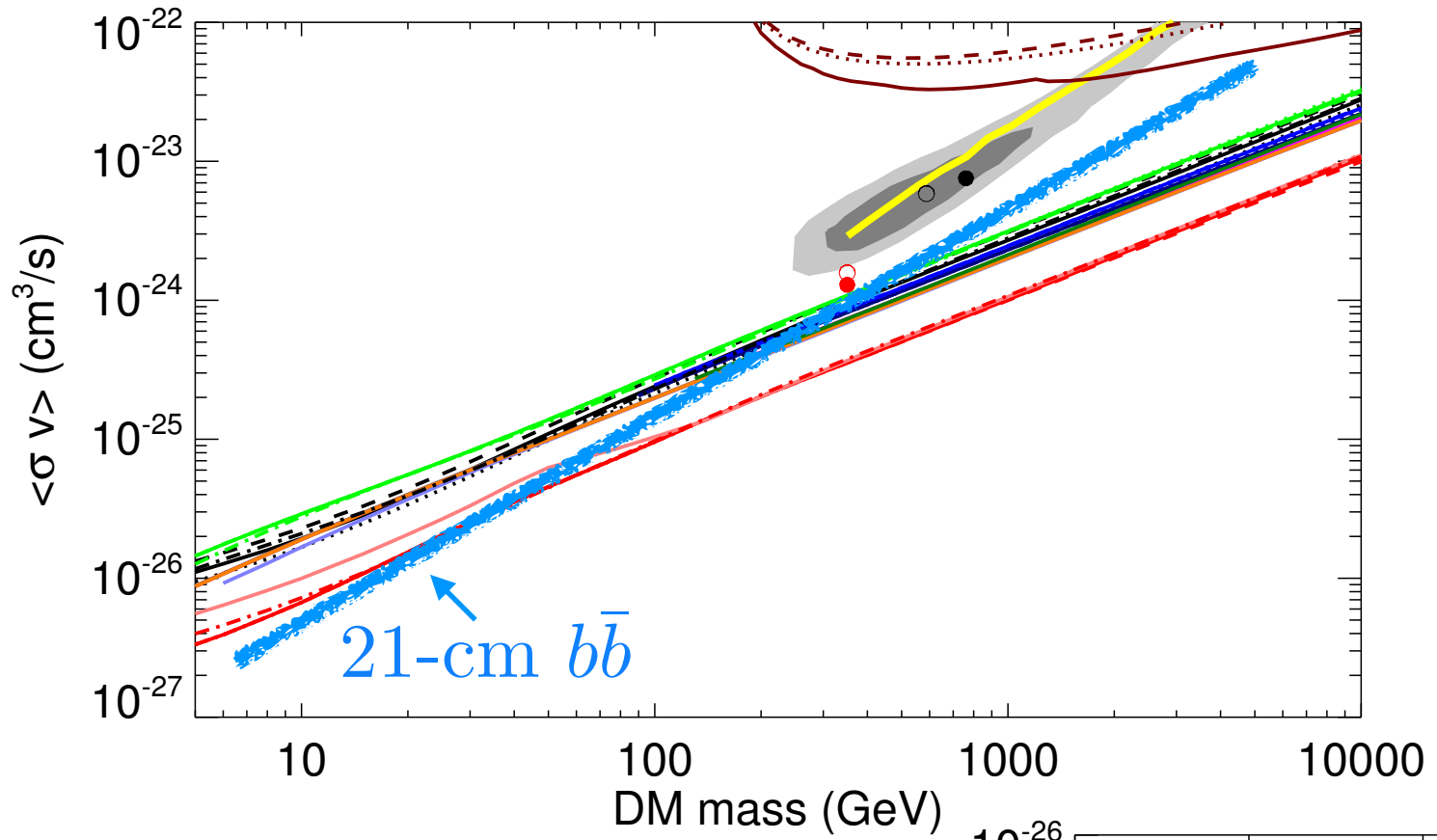


Annihilation channels:	
$e_L^+ e_L^-$	$W_L^+ W_L^-$
$e_R^+ e_R^-$	$W_T^+ W_T^-$
$e^+ e^-$	$W^+ W^-$
$\mu_L^+ \mu_L^-$	$Z_L^+ Z_L^-$
$\mu_R^+ \mu_R^-$	$Z_T^+ Z_T^-$
$\mu^+ \mu^-$	$Z^0 Z^0$
$\tau_L^+ \tau_L^-$	gg
$\tau_R^+ \tau_R^-$	$\gamma \gamma$
$\tau^+ \tau^-$	$h h$
$q\bar{q}$	$\nu_e \bar{\nu}_e$
$c\bar{c}$	$\nu_\mu \bar{\nu}_\mu$
$b\bar{b}$	$\nu_\tau \bar{\nu}_\tau$
$t\bar{t}$	$VV \rightarrow 4e$
	$VV \rightarrow 4\mu$
	$VV \rightarrow 4\tau$

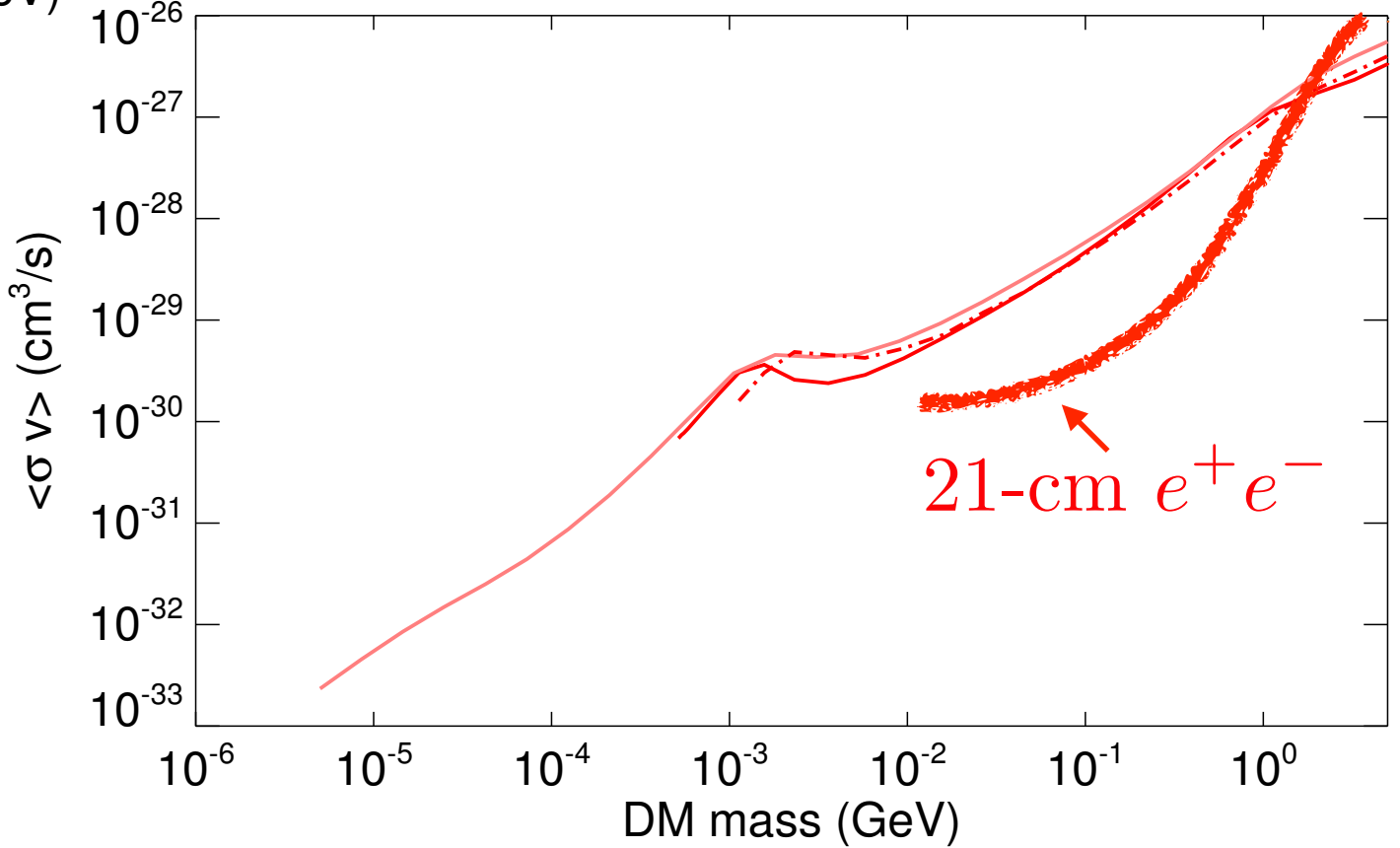
Slatyer 1506.03811



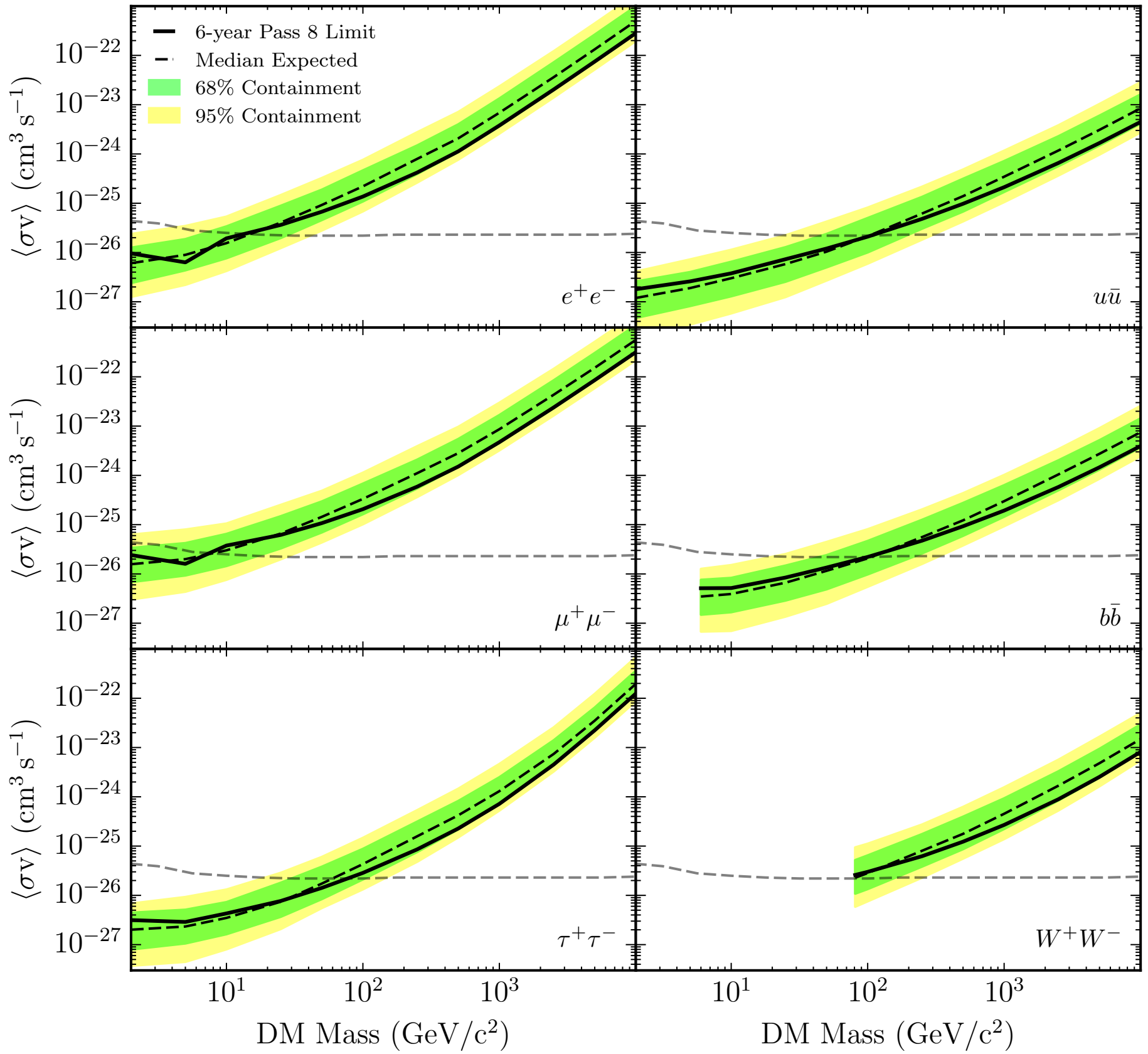
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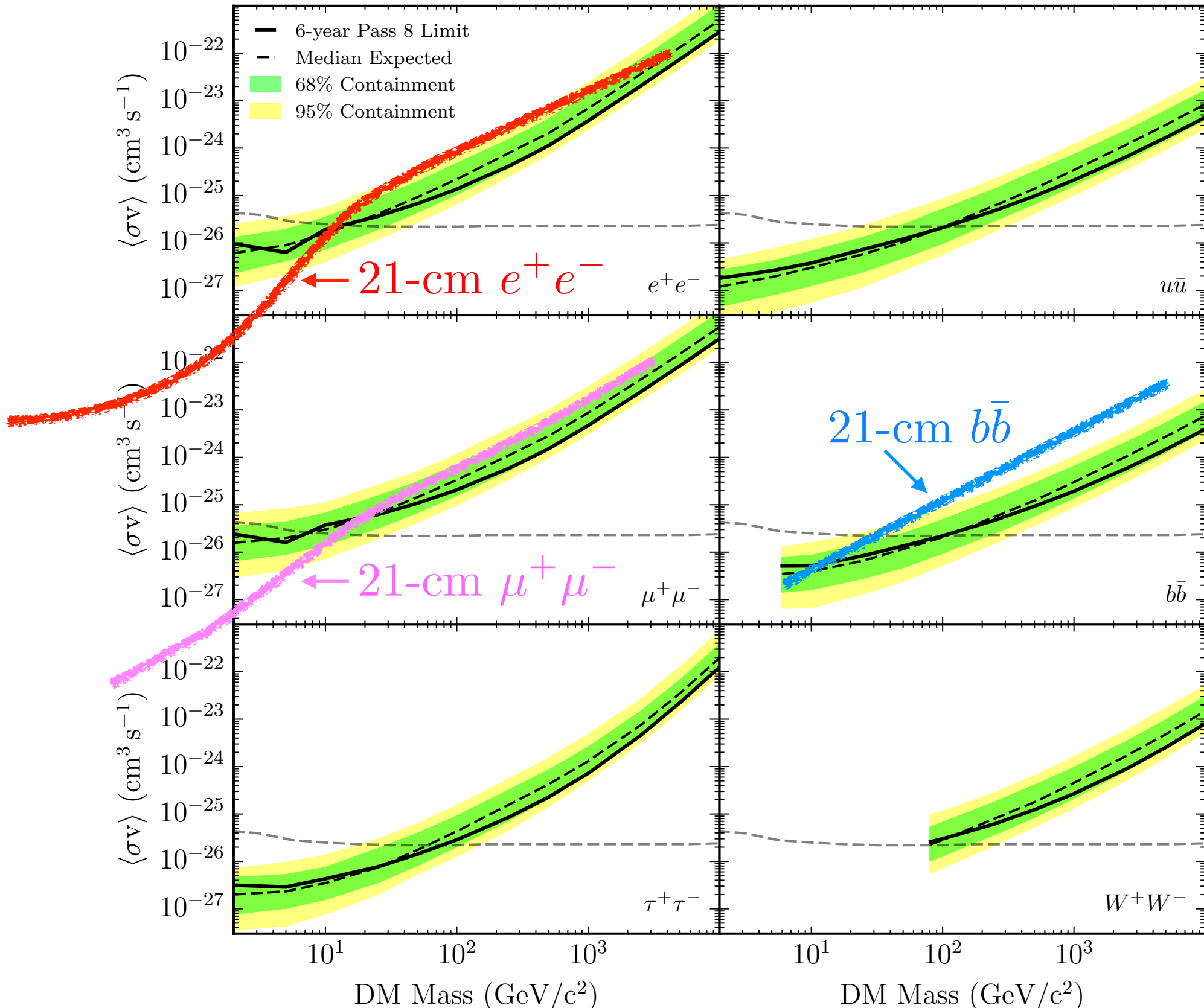
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Comparison: FERMI dSphs



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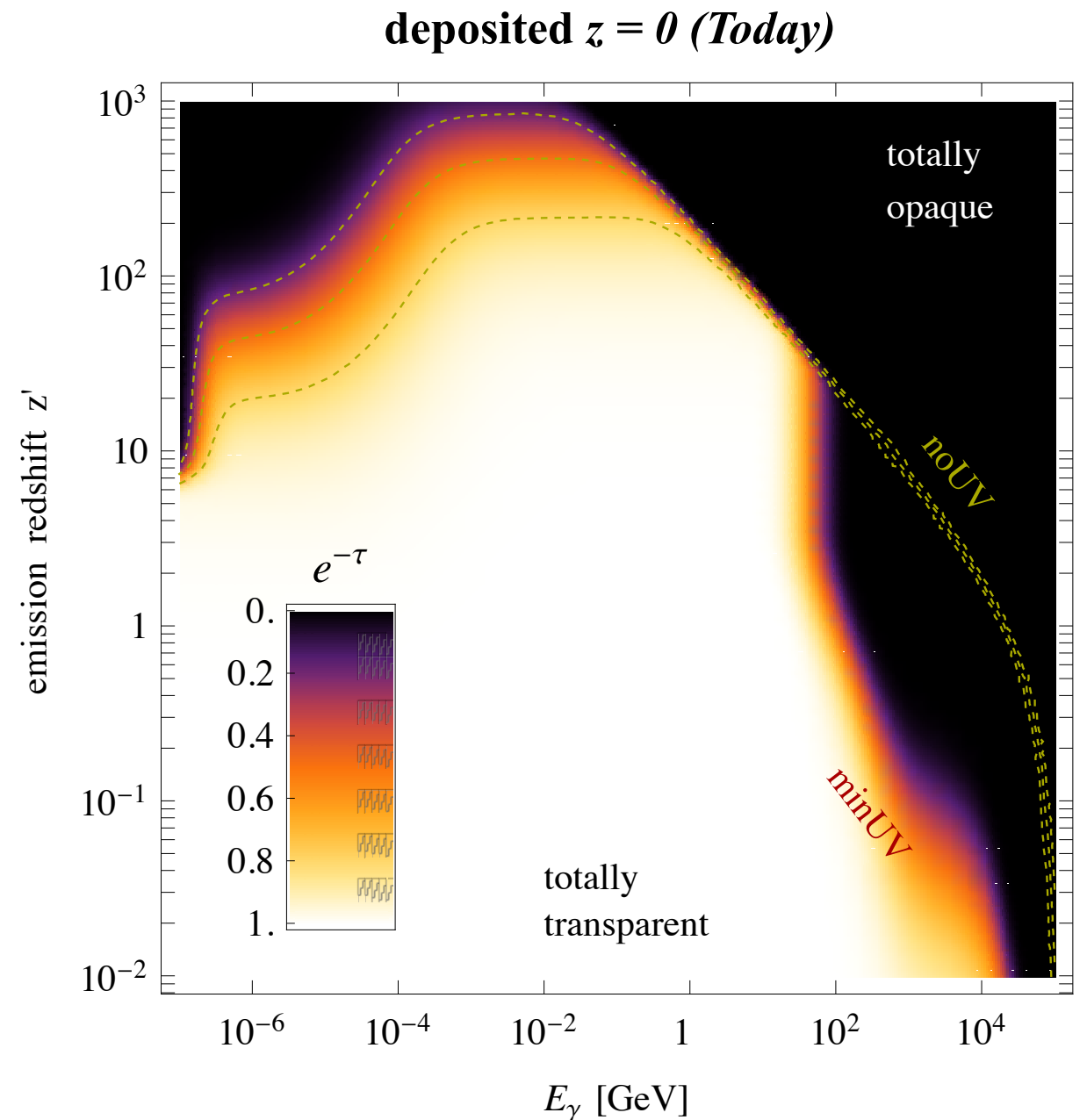
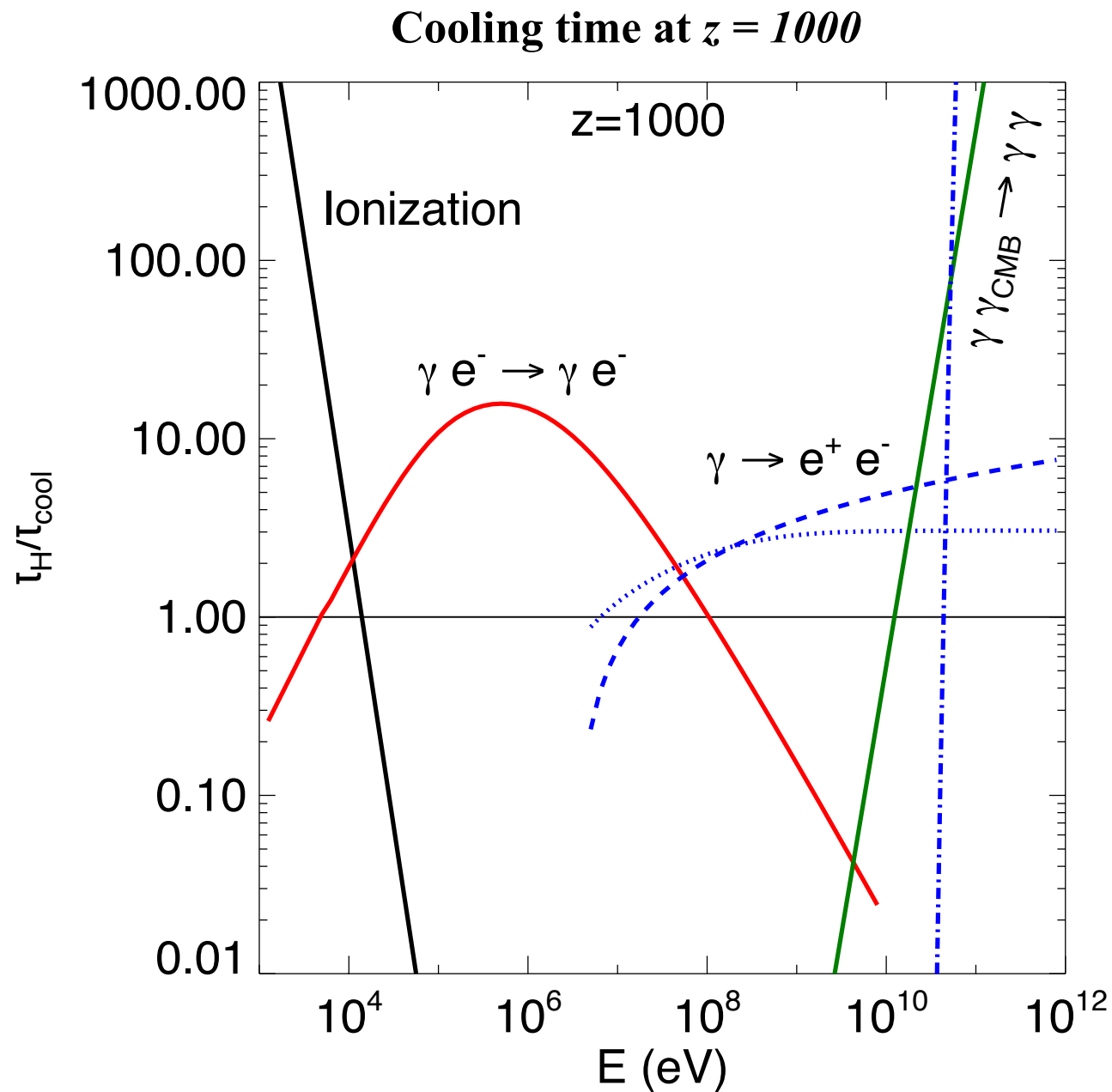
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- **The bounds on DM annihilations** are *competitive* and in some cases *more stringent* than any other limit in the literature
- This is just the beginning: Stay tuned for further developments!
Can the monopole 21cm alone shed light on dark matter?

Backup slides

The *delayed transfer function* encodes the physics of the EM shower

- ★ Mean free path of the electrons/positrons at a given redshift z
- ★ Absorption of photons in the IGM



World Wide 21cm

PRI^ZM
(Kwazulu-Natal, Sievers et al.)



SARAS 2
(RRI, Subrahmanyan et al.)



LEDA
(Harvard, Greenhill et al.)



SCI-HI
(Carnegie Mellon, Peterson et al.)



HYPERION
(Berkeley, Parsons et al.)



CTP
(NRAO, Bradley et al.)



EDGES Fitting procedure

Linearized version of Physically-Motivated foreground model

$$m_{\text{fg}}(\mathbf{a}_i) = \mathbf{a}_0 \left(\frac{\nu}{\nu_n}\right)^{-2.5} + \mathbf{a}_1 \left(\frac{\nu}{\nu_n}\right)^{-2.5} \left[\log\left(\frac{\nu}{\nu_n}\right)\right] + \mathbf{a}_2 \left(\frac{\nu}{\nu_n}\right)^{-2.5} \left[\log\left(\frac{\nu}{\nu_n}\right)\right]^2 \\ + \mathbf{a}_3 \left(\frac{\nu}{\nu_n}\right)^{-4.5} + \mathbf{a}_4 \left(\frac{\nu}{\nu_n}\right)^{-2}$$

Alternative Polynomial Model

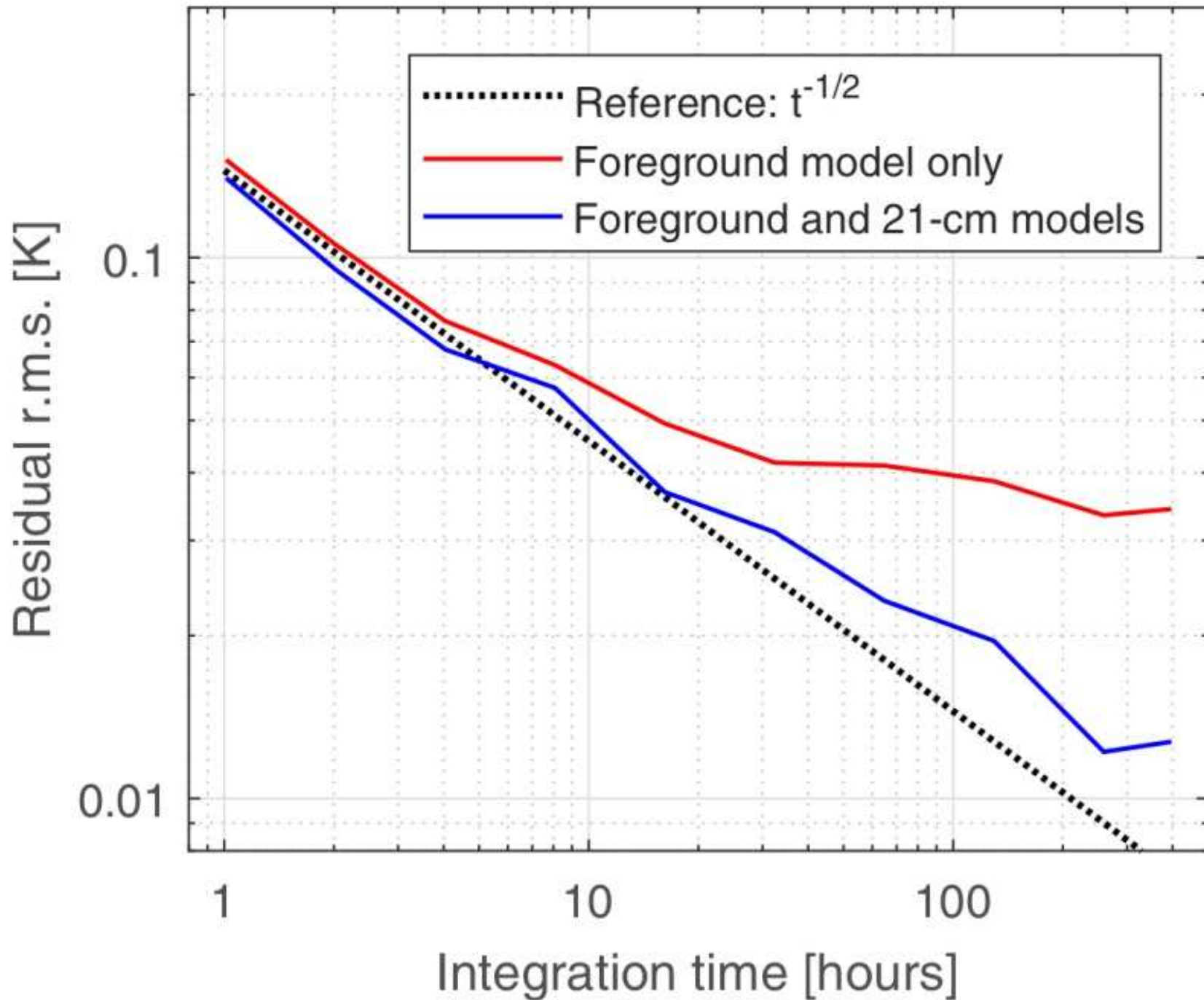
$$m_{\text{fg}}(\mathbf{a}_i) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \sum_{i=0}^{N_{\text{fg}}-1} \mathbf{a}_i \left(\frac{\nu}{\nu_n}\right)^i$$

Smooth sets of basis functions that model well, with few terms, the spectrum over wide frequency ranges.

Linear fit coefficients **not intended to be assigned physical interpretation**.

Slide from Monsalve's talk @ CERN

EDGES Residuals r.m.s.



Explain the Anomaly

Could DM do it? Yes, **BUT** it cannot be “normal” WIMP or axion with the interactions that are too weak !!

$$T_{21} \approx 21 \text{ mK } x_{H_I} \left(1 - \frac{T_\gamma}{T_S} \right) \sqrt{\frac{1+z}{10}}$$

$T_\gamma > T_{\text{CMB}}$: Increase the CMB Rayleigh-Jeans tail

$T_S \simeq T_{\text{gas}} < T_{\text{gas}}^{\text{ad}}$: Cool the gas even more

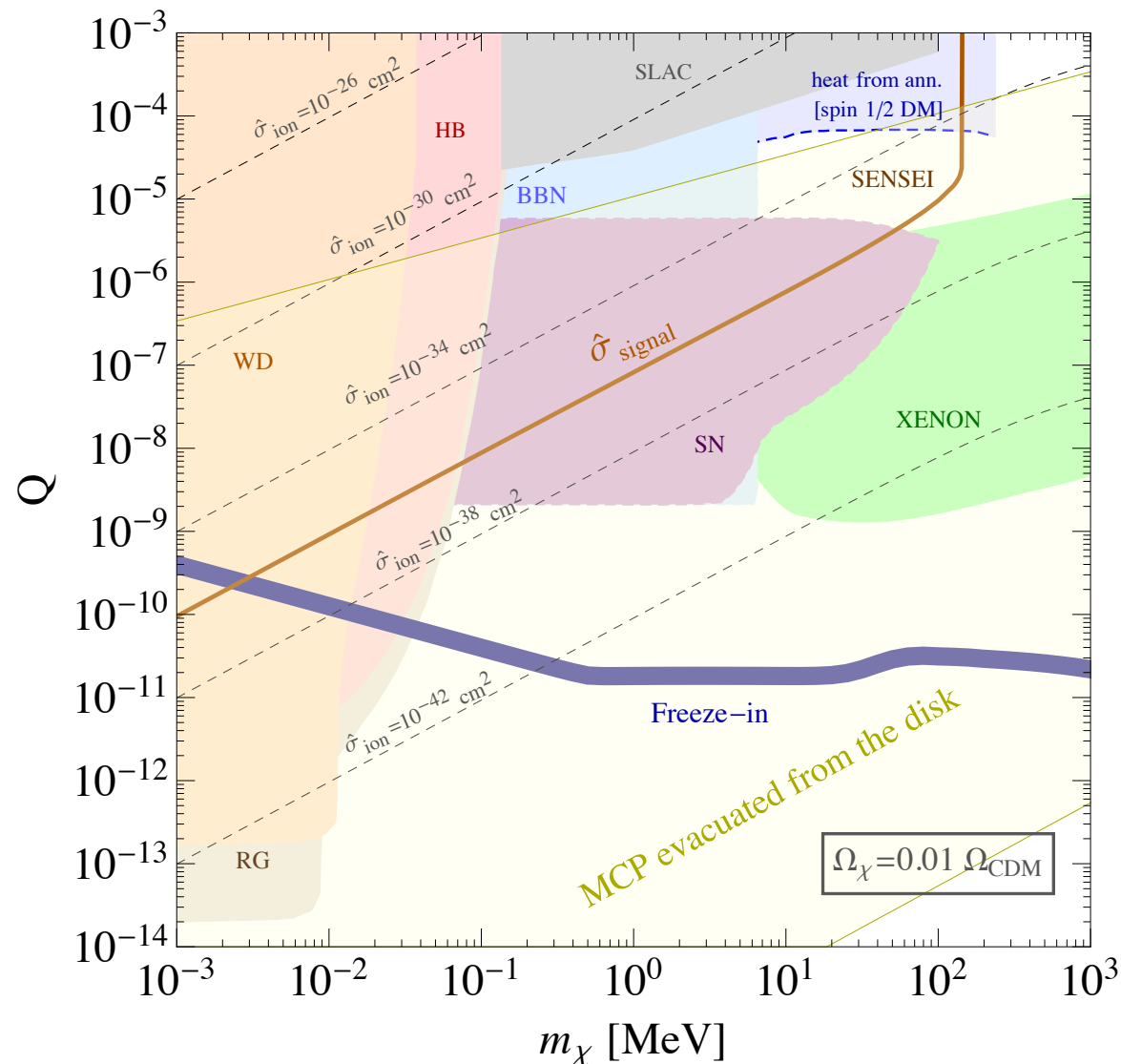
- ➔ Approach 1: *Cool the baryonic kinetic temperature even more* (90% of attempts: see e.g. **Barkana et al.**; **Munoz, Loeb**;)
- ➔ Approach 2: *Make more photons* that can mediate the 21-cm transition prior $z \sim 20$ (**Pospelov, Pradler, Ruderman, Urbano**)
- ➔ Approach 3: *Decouple protons from the CMB earlier* (**Falkowski & Petraki**)

1: Cool the IGM even more

Entropy transfer from the baryonic to the Dark sector

Milli-charged DM could work: DM-atom cross section is enhanced as $d\sigma/d\Omega \propto \sigma_0 v^{-4}$, which is Coulomb-like dependence

Implication: a significant fraction of DM has a milli-charge
Not clear if the model survives all the constraints



$$m_\chi \simeq (10 - 80) \text{ MeV} ,$$

$$Q \simeq (10^{-6} - 10^{-4}) ,$$

$$f_{\text{DM}} \simeq (0.1 - 2)\%$$

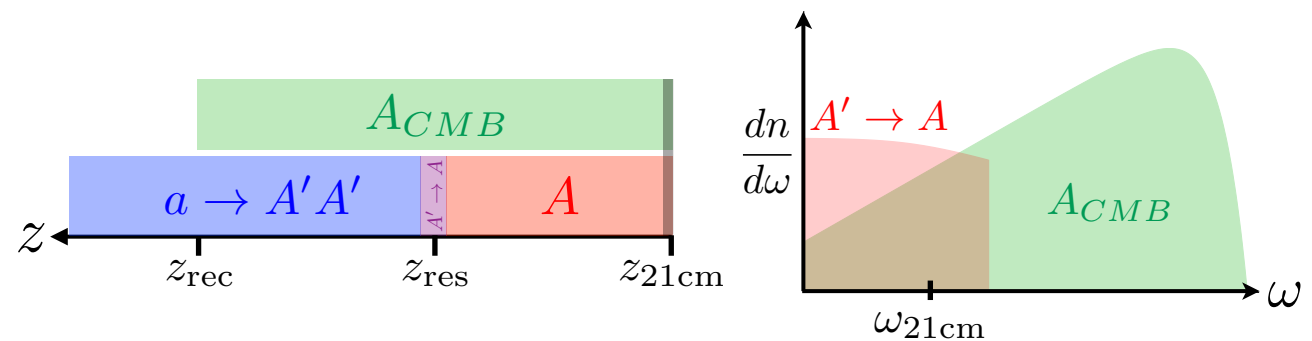
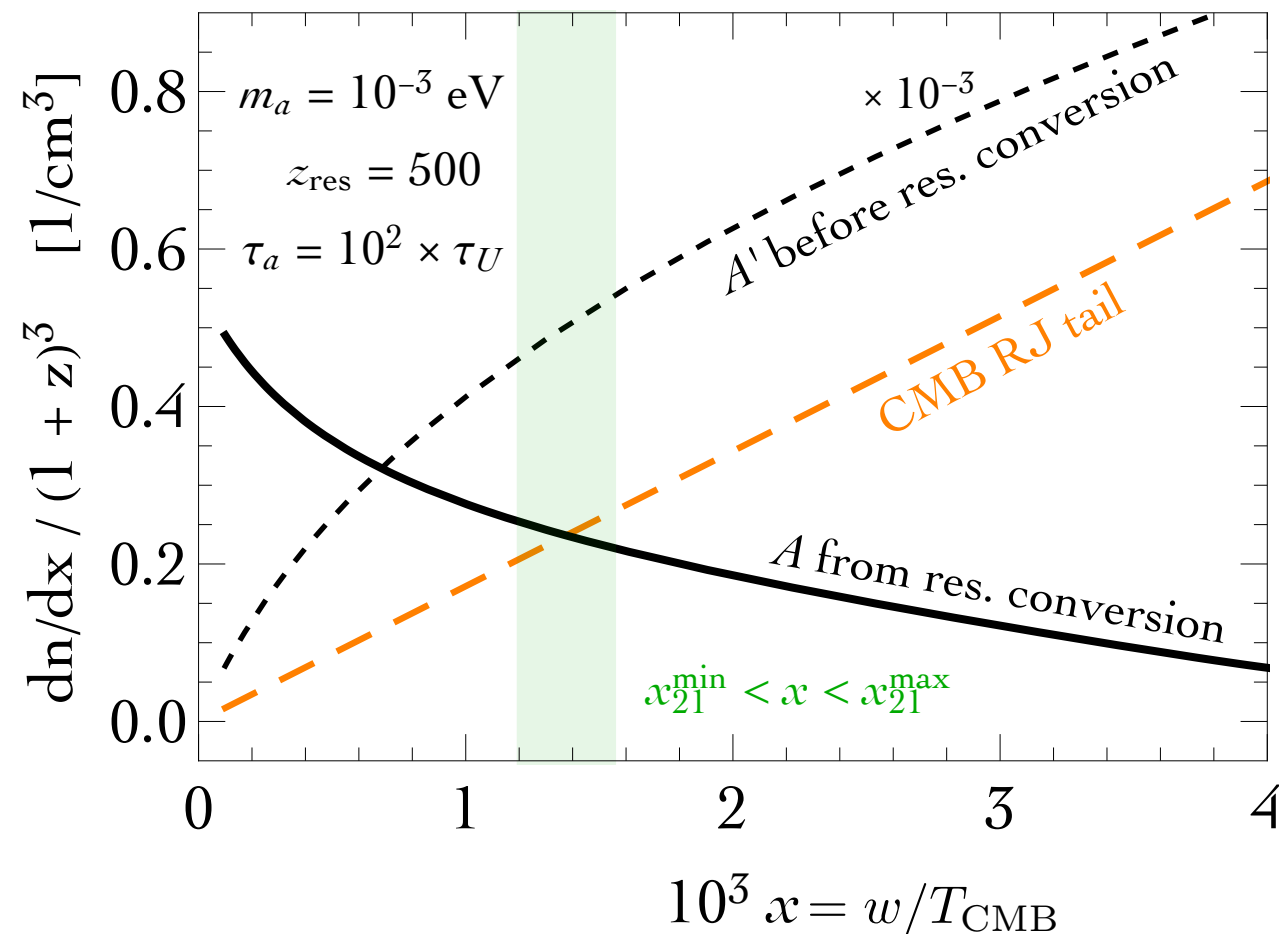
Barkana *et al.*
1803.03091

2: Increase the CMB RJ tail

Early ($z > 20$) decays (either DM or of DR species) create a non-thermal population of DR dark photon A' . Typical multiplicity is larger than n_{RJ}

Dark photons can oscillate to normal photons. At some redshift z_{res} a resonant oscillation of A' into A . This happens when the plasma frequency is $m_{A'}$

Enhanced number of RJ quanta are available in the $z = (15-20)$ window, making a deeper than expected absorption signal



Pospelov *et al.*
1803.07048

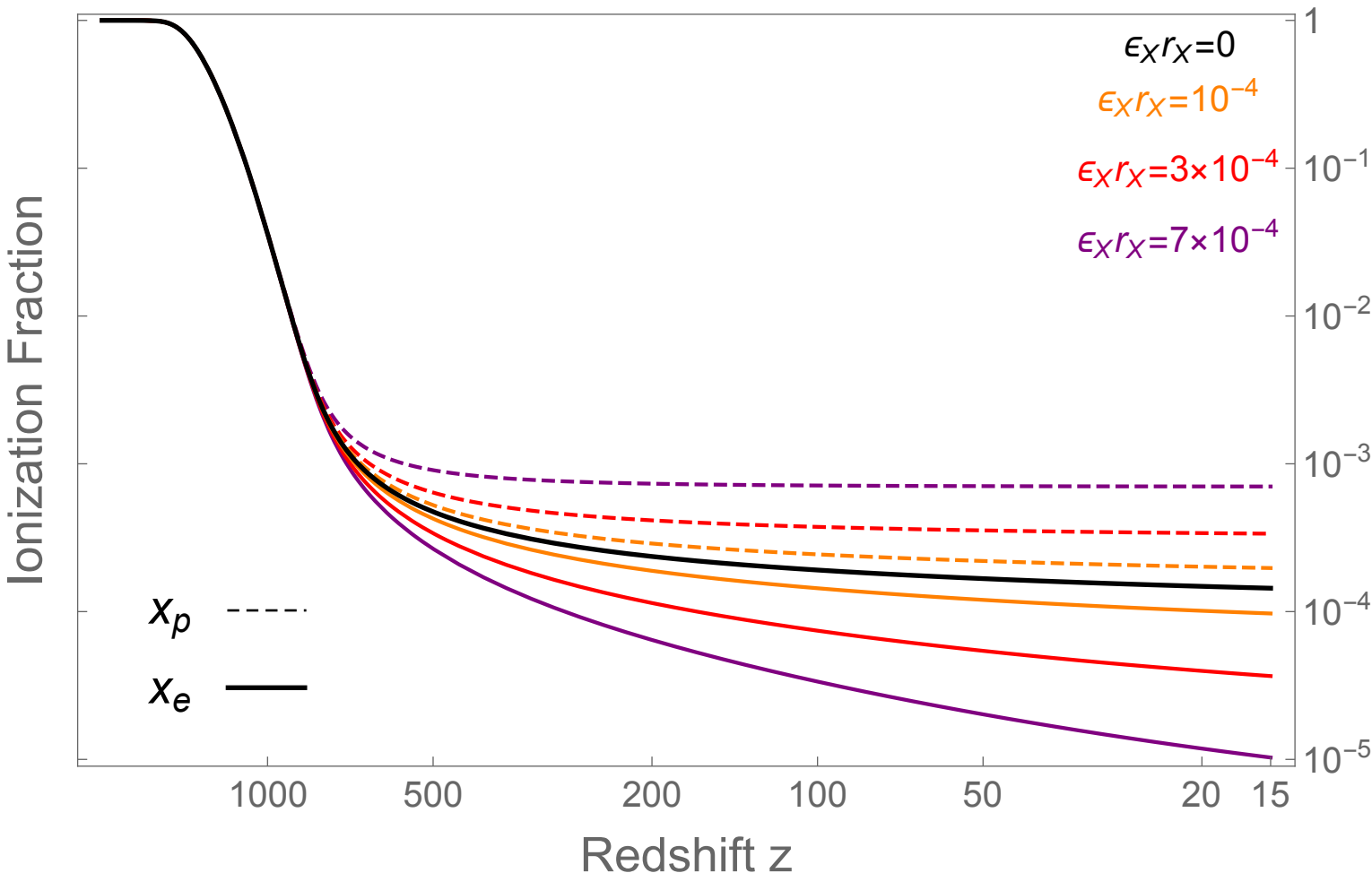
3: Charge sequestration

Postulate that there is a *mismatch between proton and electron numbers* in the Universe, such that $n_e < n_p$

The Universe is not charge neutral: *A clear disaster!!*

Thus one can introduce a *stable particle with negative charge and non-zero abundance* in the Universe. **The Universe is neutral again!!**

Charge neutrality imposes the relation: $x_p = x_e + \epsilon_\chi r_\chi$ with $r_\chi = n_\chi/n_b$



Falkowski, Petraki
1803.10096