**7th Rome Joint Workshop: "Current Topics in Particle Physics"**
18/12/2018

# Bounds of DM annihilations from 21-cm data

**PAOLO PANCI**

Based on D'Amico, PP, Strumia arXiv:1803.03629
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# 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

# What happened in March



LETTER

doi:10.1038/nature25792

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

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

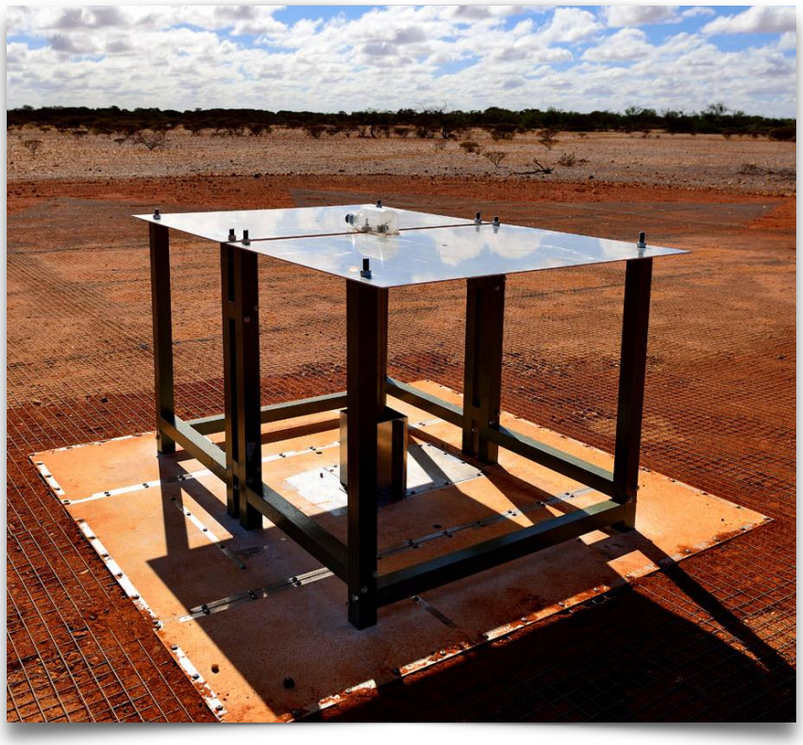
A 21-cm signal in *absorption*

Between redshifts ∼20 and 15

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

# The EDGES experiment

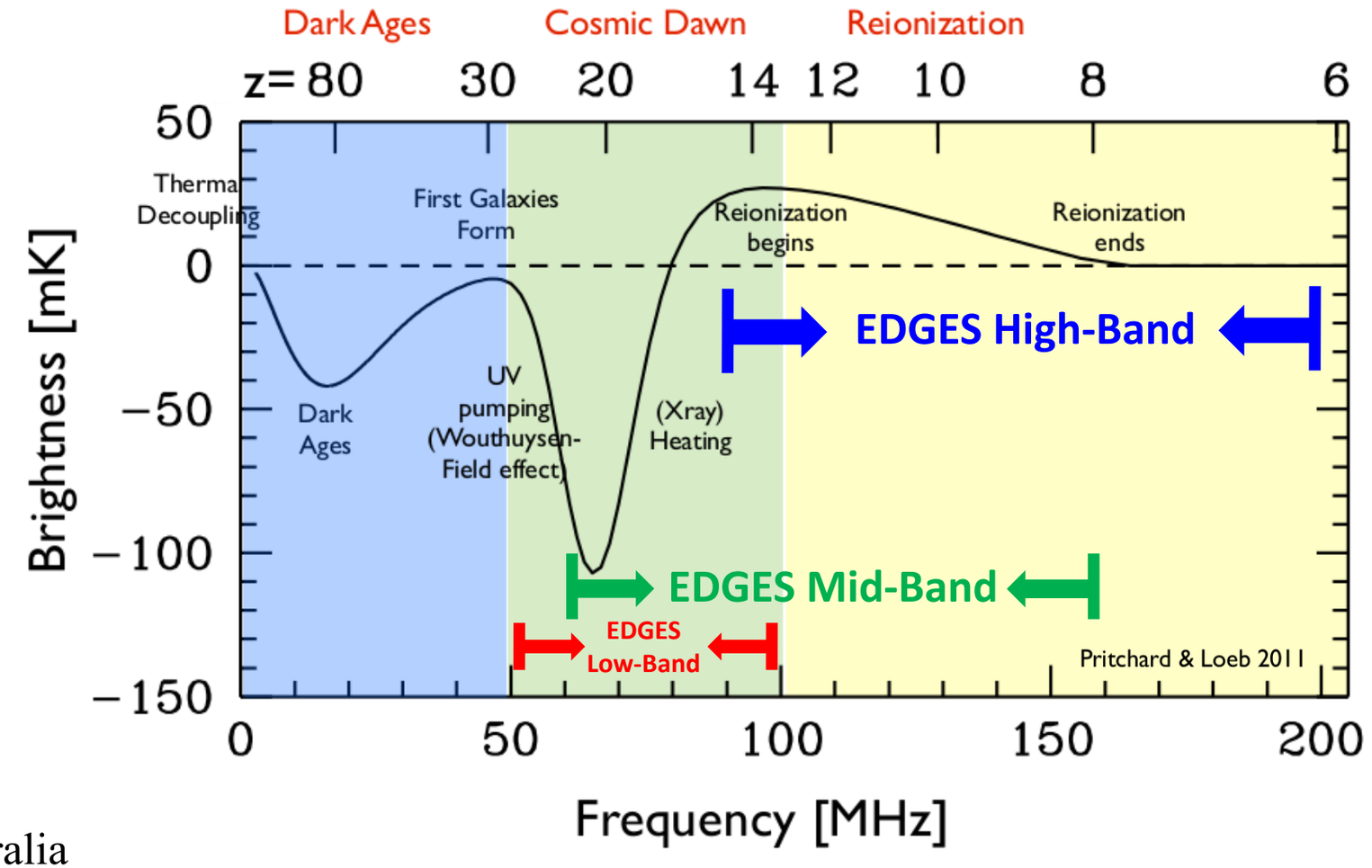




**Antenna size**: 2m long and 1m meter high

**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 $z\sim20$ due to the absorption of CMB photons by the IGM

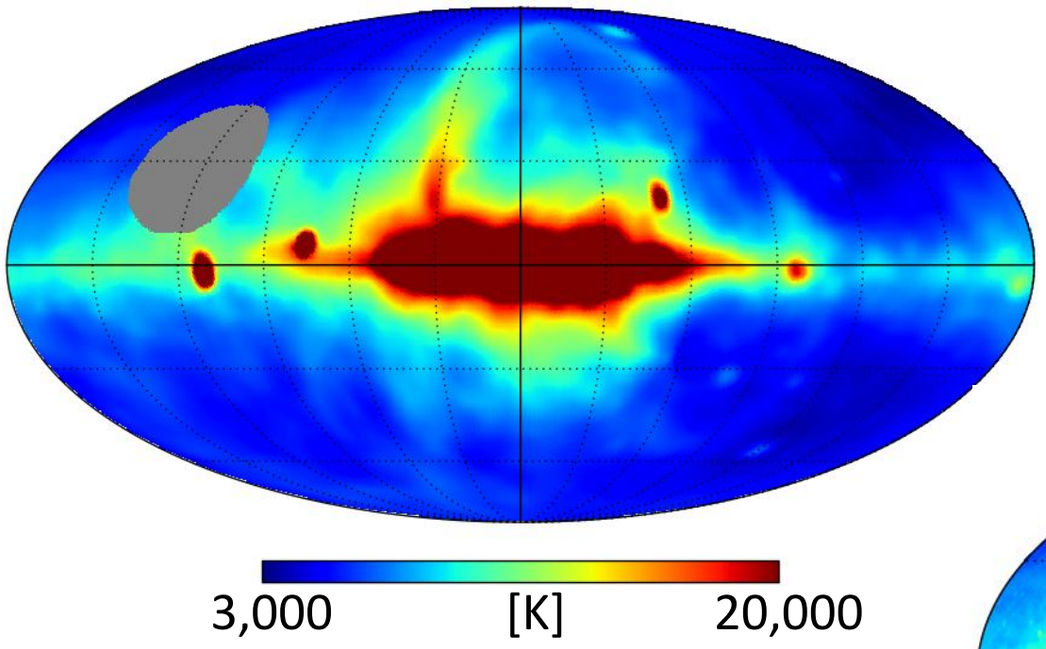
# Large synchrotron bkg.



## Diffuse Foregrounds

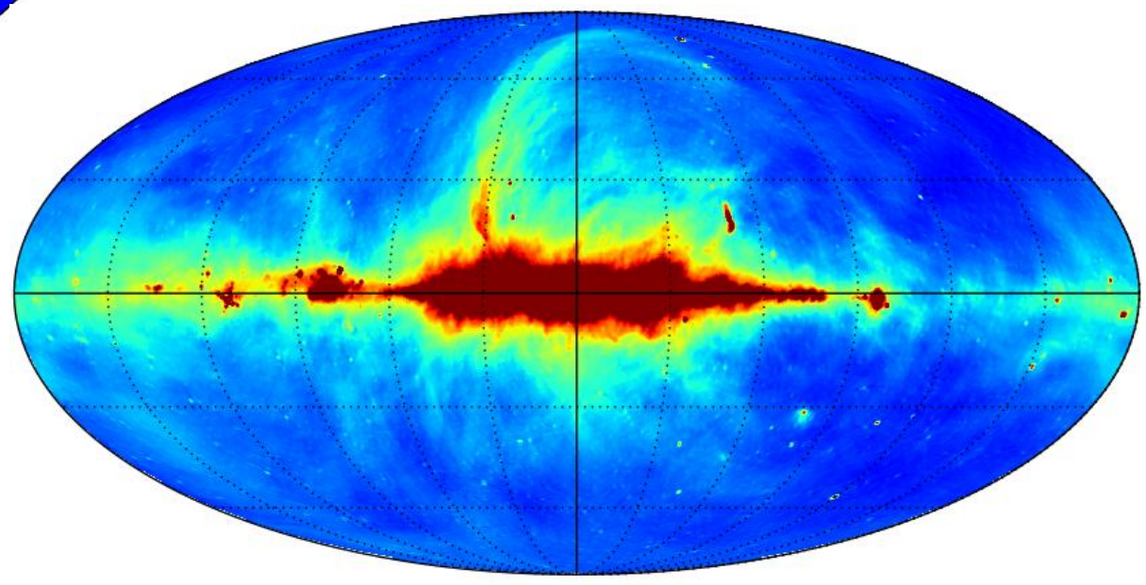
45-MHz Map

Guzmán et al. (2011)




408-MHz Map

Haslam et al. (1982)




**Main features of the Diffuse Foregrounds:**

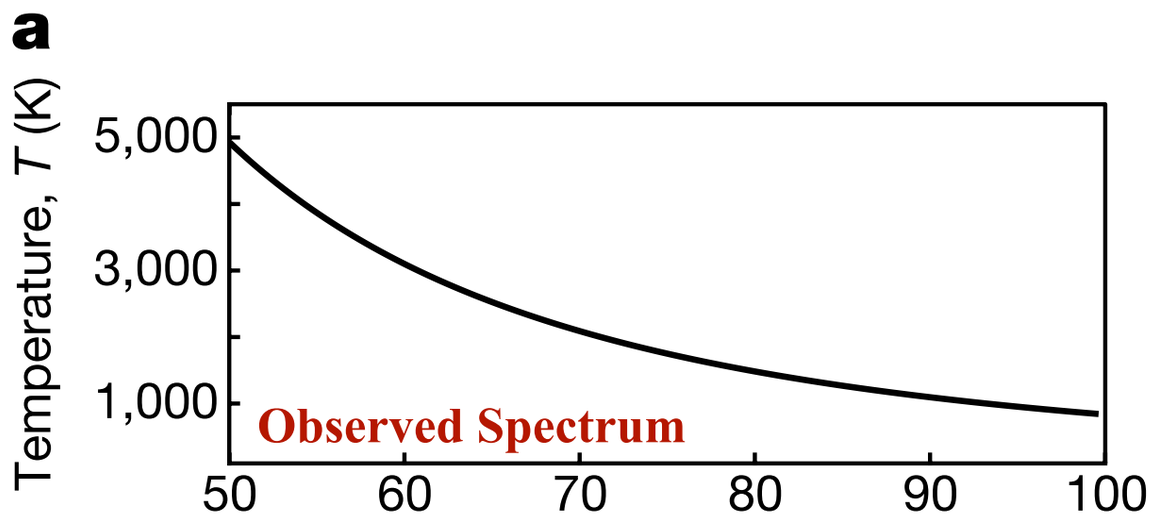
1) **Brightness temperature**: always more than 100 K

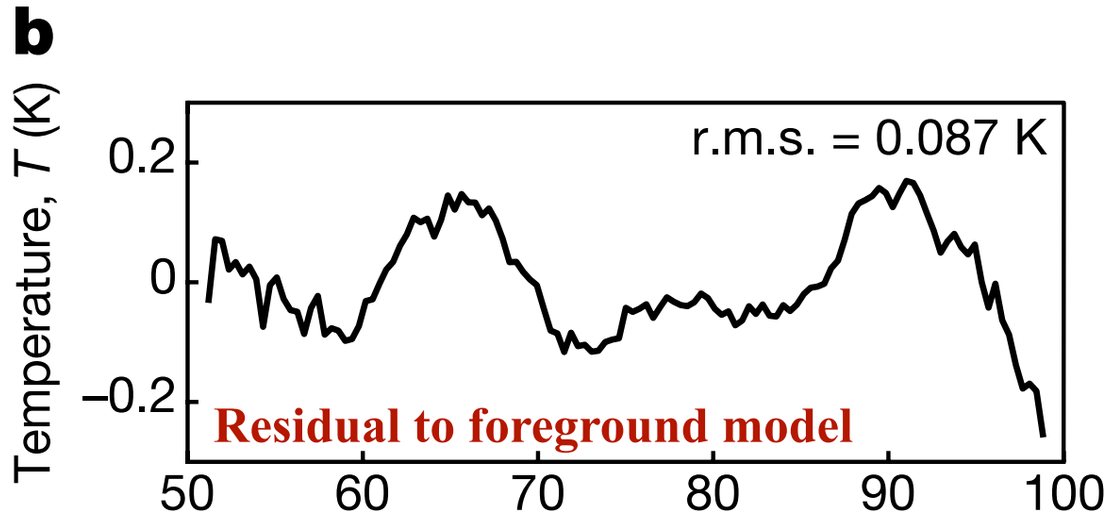
2) **Spectrally smooth** but might need **several terms** to model (see e.g. Bernardi et al. 2015)

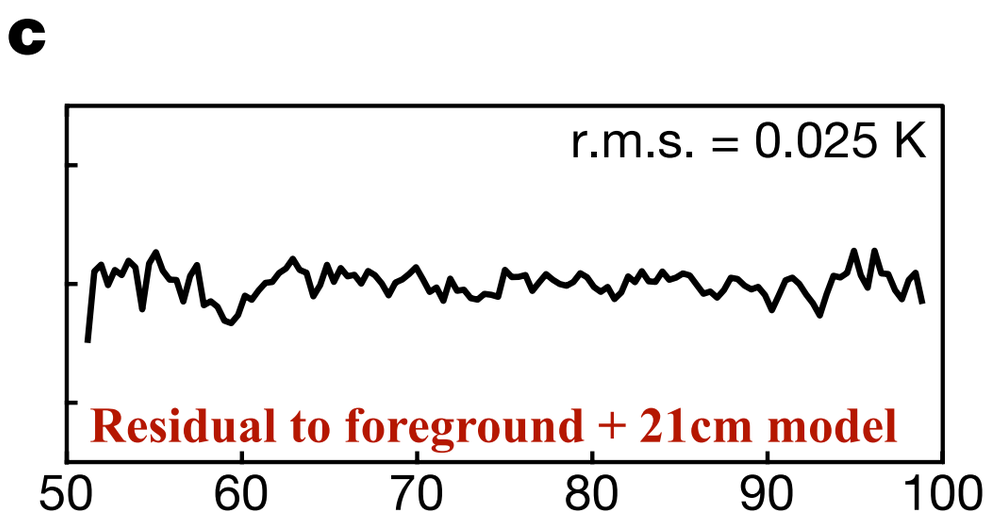
3) **Large spatial gradient** (in particular close to the GC)

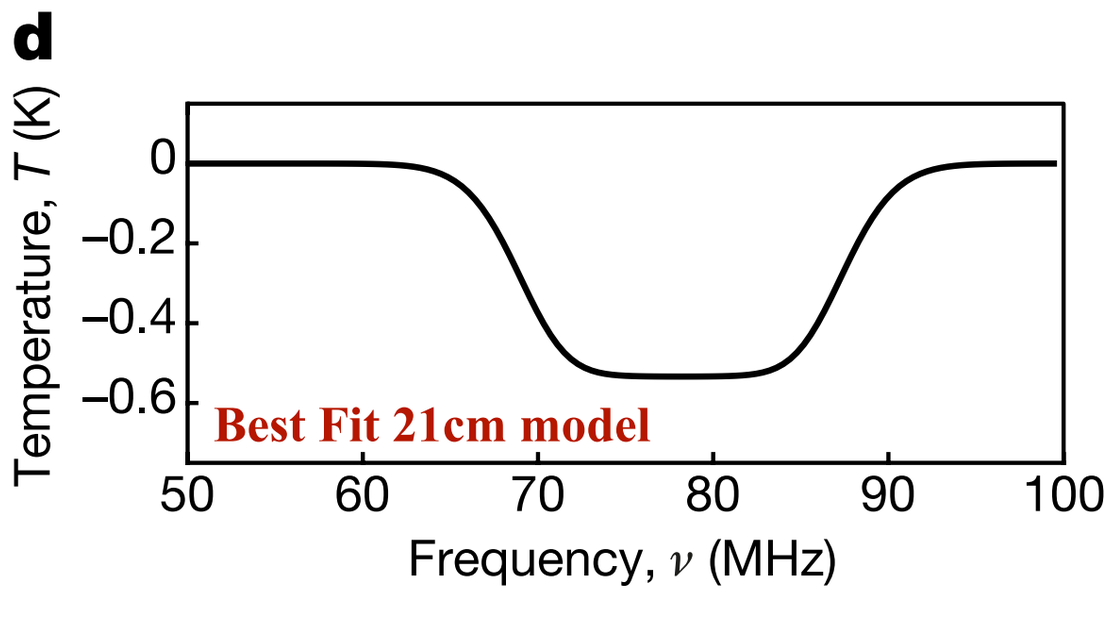
# What did EDGES see?

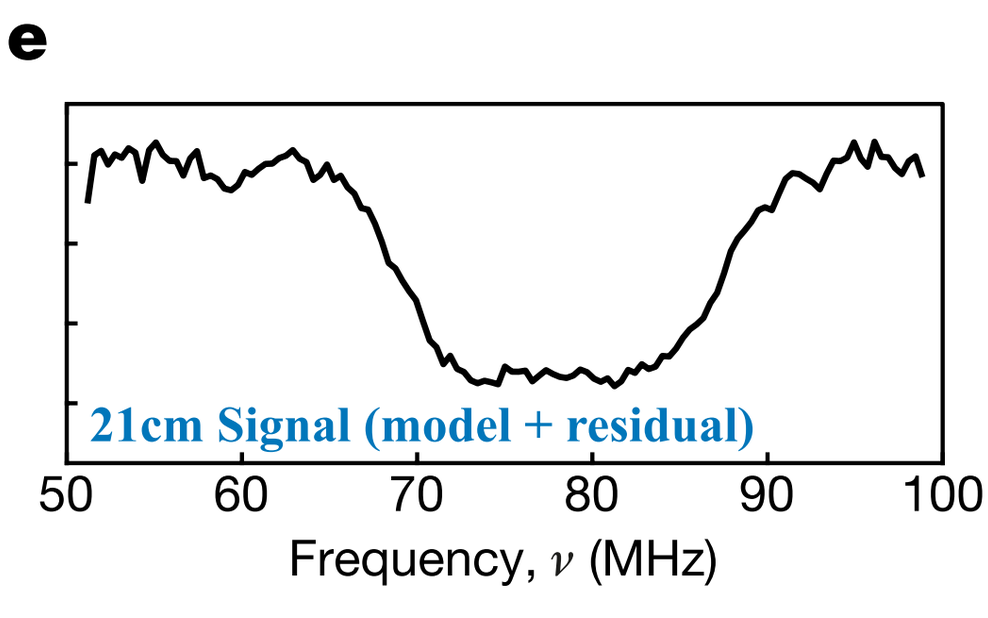




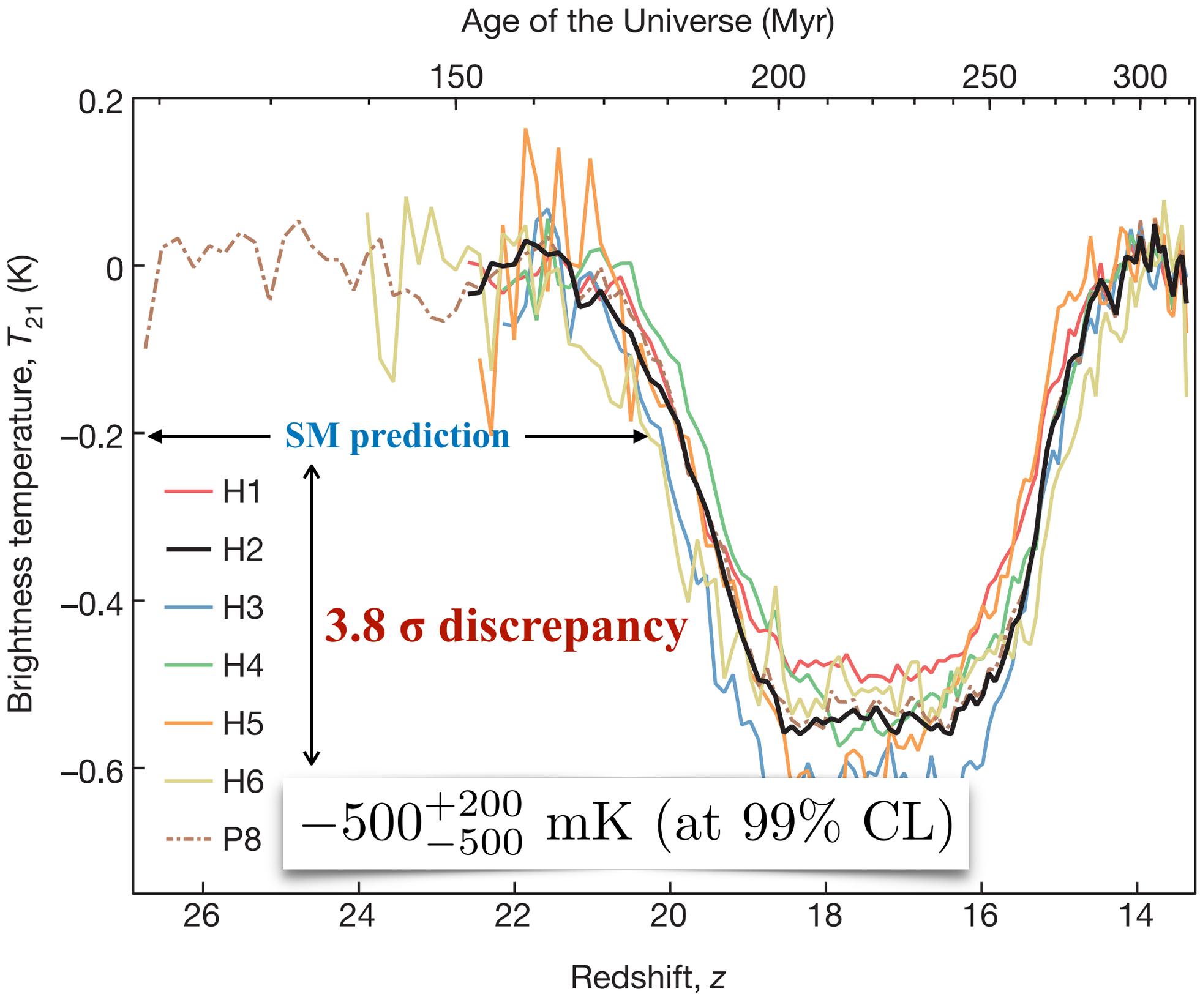



# Some analysis of systematics



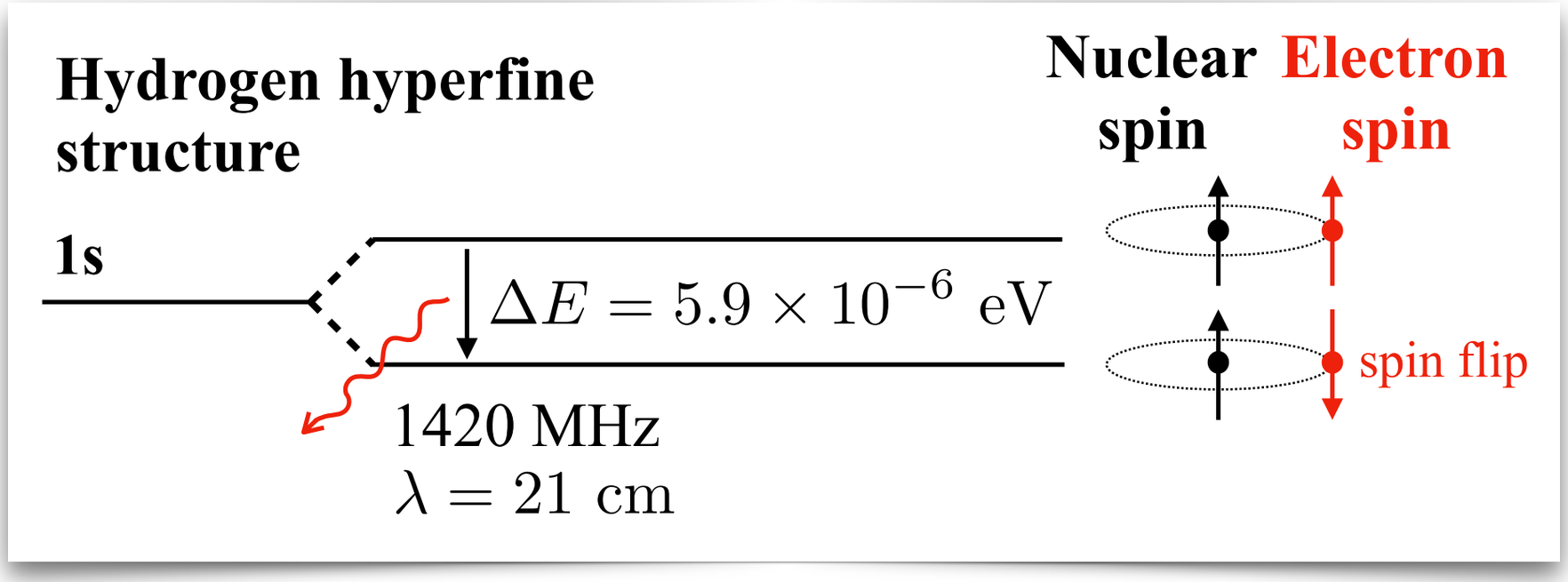


# II PART

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

What sets the relative occupation?

# Excited by what?

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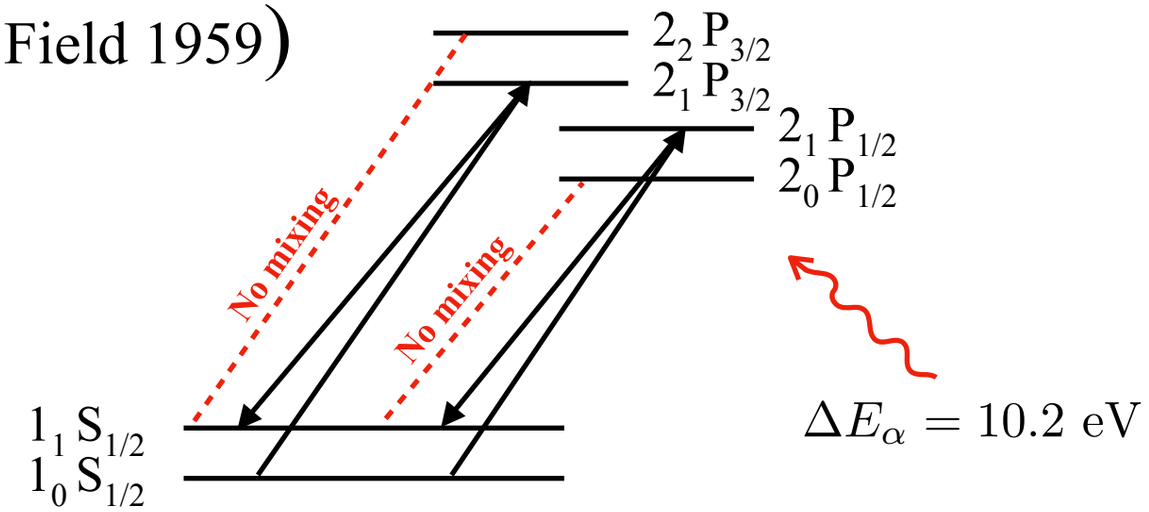

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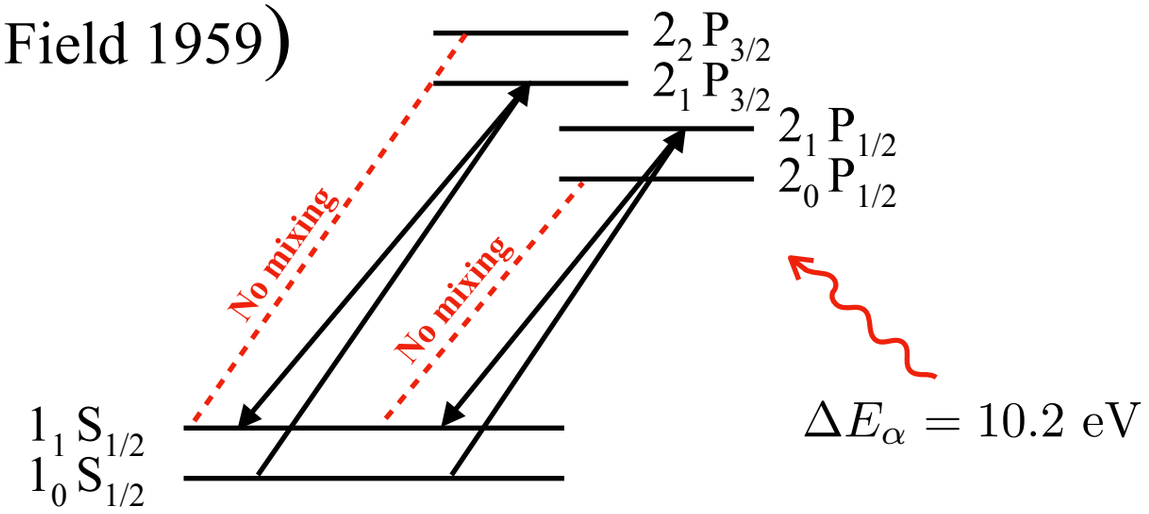



Equilibrium implies:

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

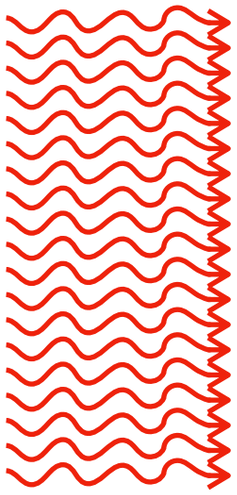
In terms of temperature:

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

# What we see



**CMB**



$\mathcal{I}_\gamma$

**Cloud of Hydrogen**

**Neutral Hydrogen**
Abundance: $x_{H_I}$
Temperature: $T_{\rm gas}$

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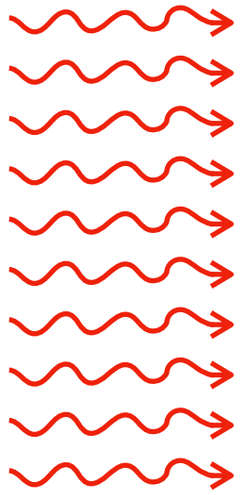
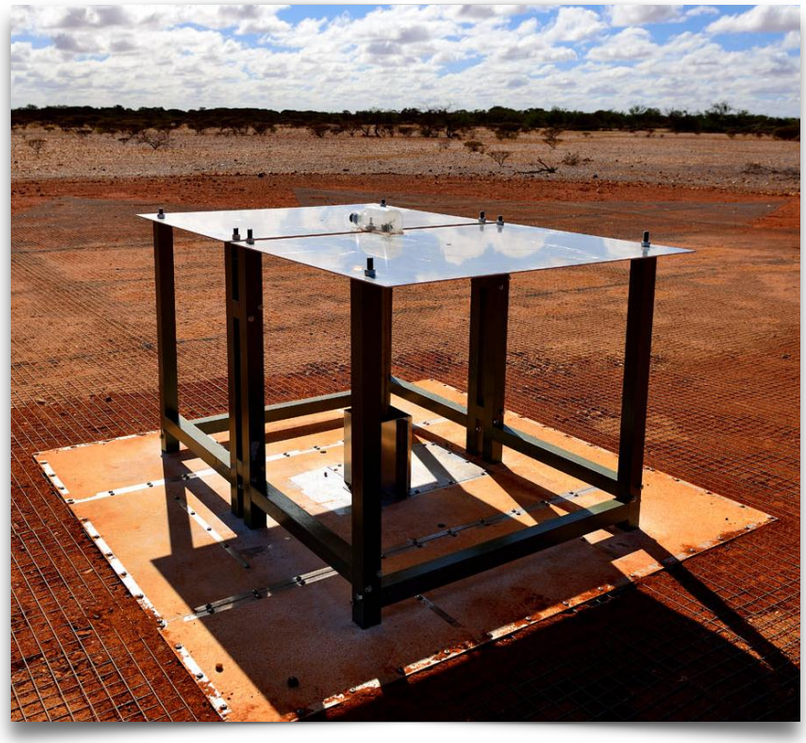


$\mathcal{I}_\gamma\, e^{-\tau}$



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

# What we see



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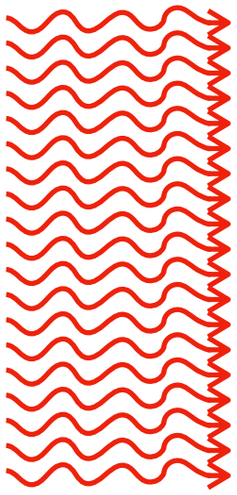

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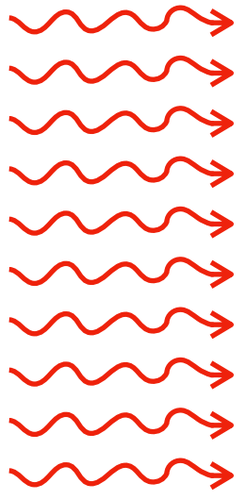

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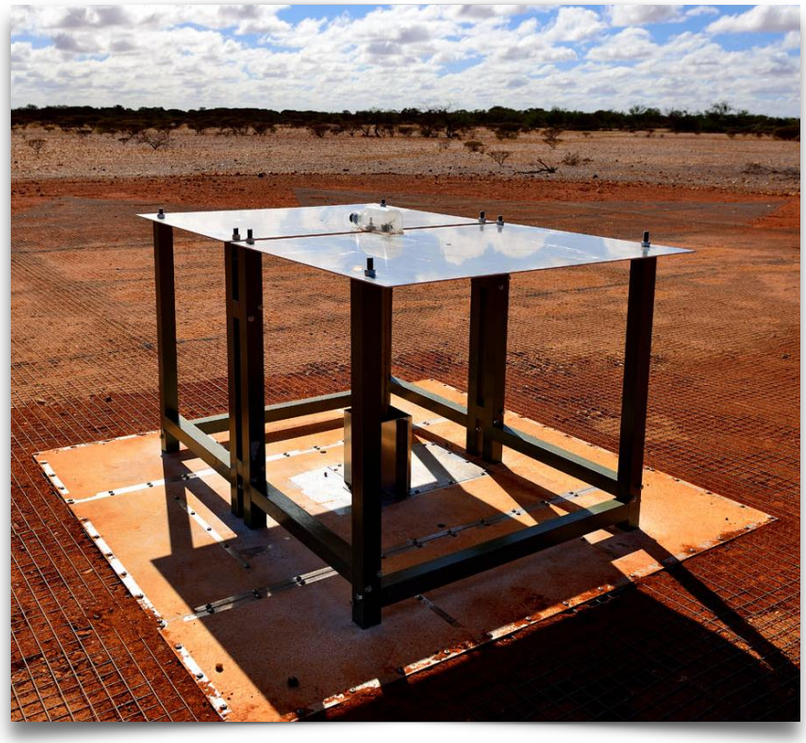


$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

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

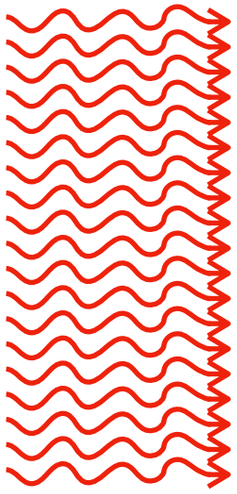
$T_S = T_{\rm CMB}$ : **NO** 21-cm signal

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

# What we see



**CMB**



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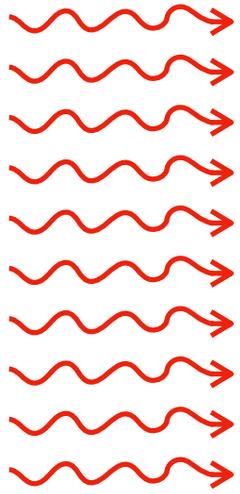

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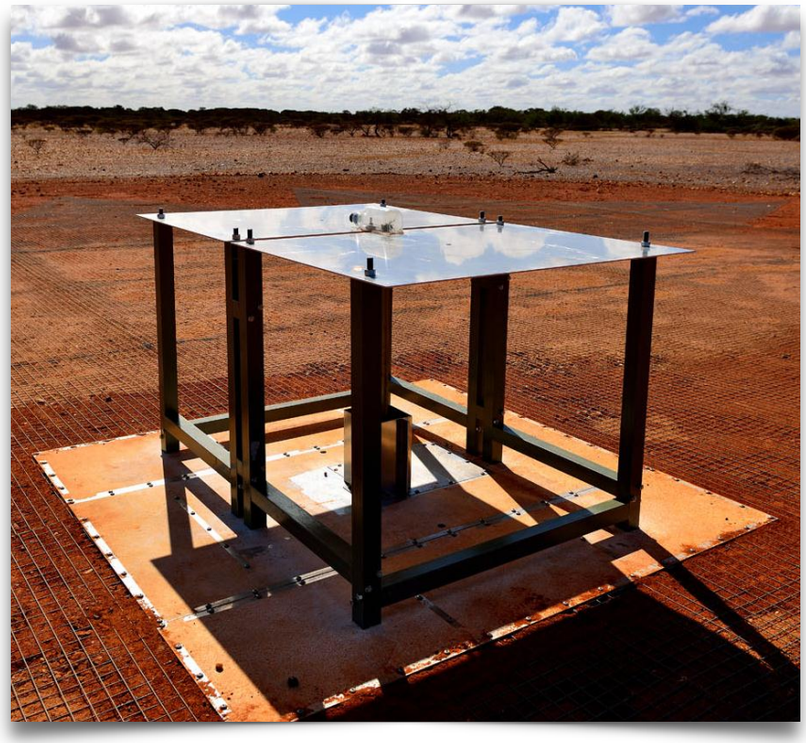

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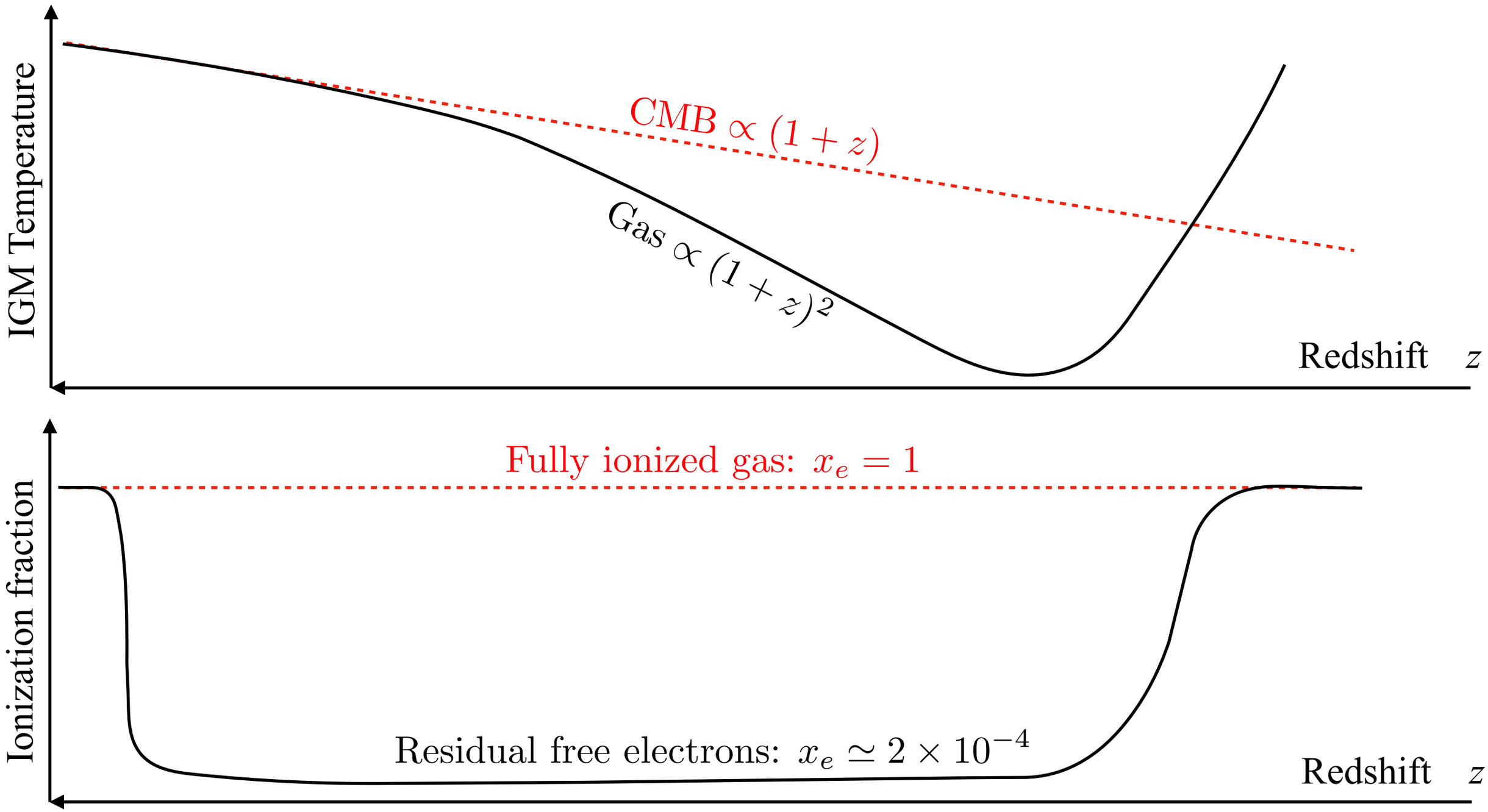
**EDGES measurement implies**
$T_{\rm CMB}/T_S \simeq 19$ at $z = 17$

$$T_S \simeq 3\ \mathrm{K}$$

# A short history of the IGM

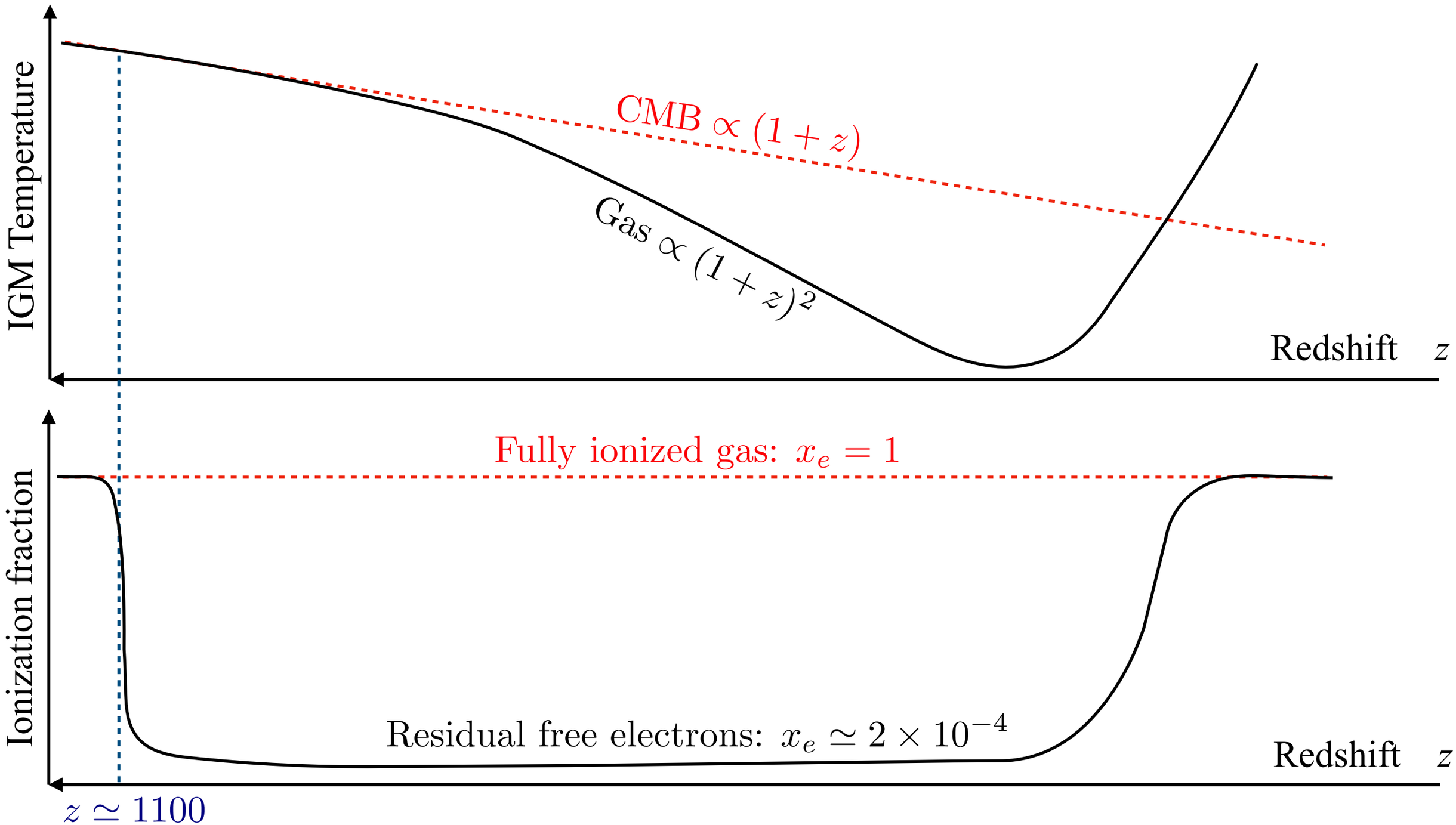




# A short history of the IGM



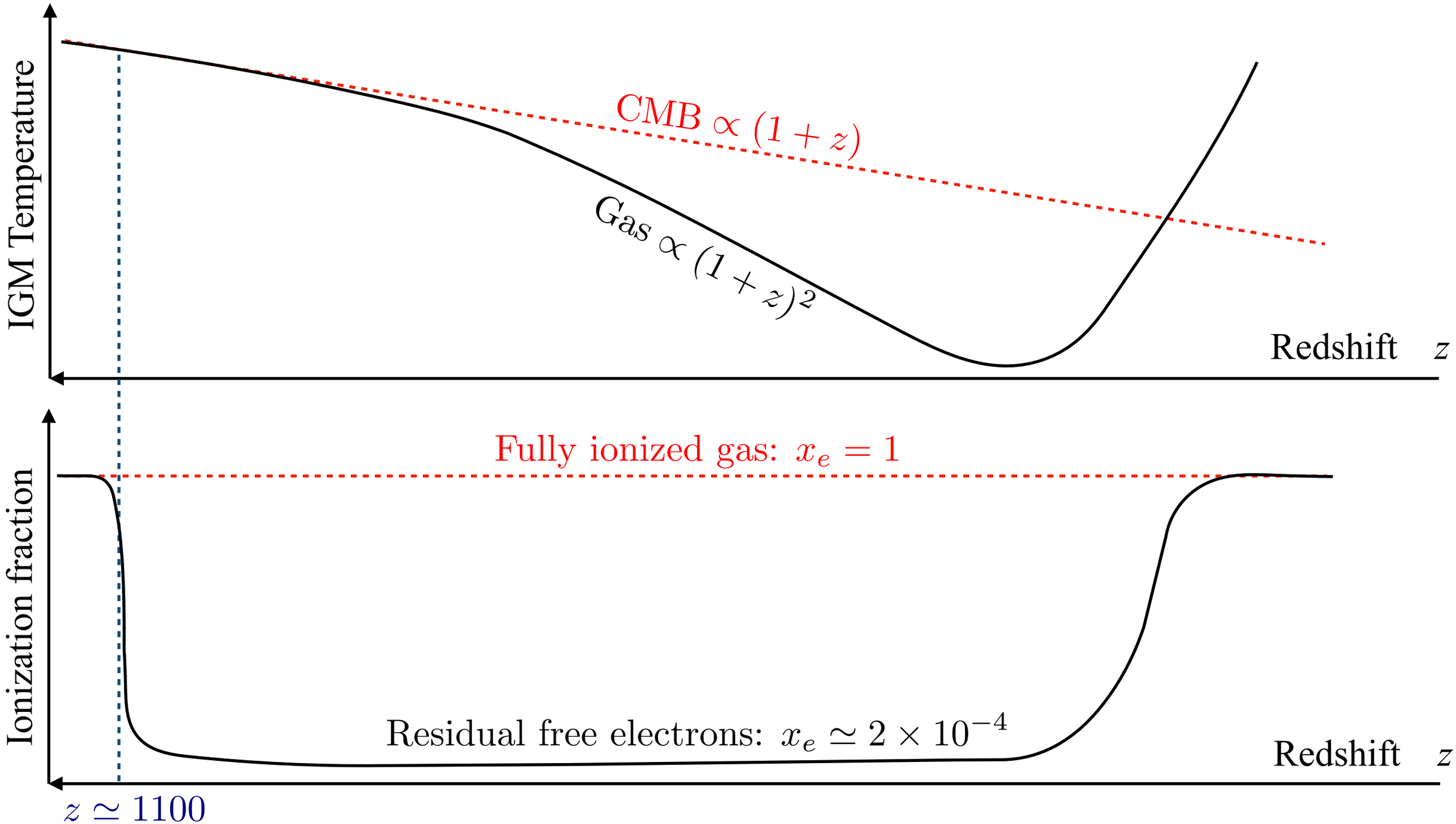
- At $z\sim1100$, CMB and IGM *kinetically decouple*:
  the Universe becomes neutral



# A short history of the IGM



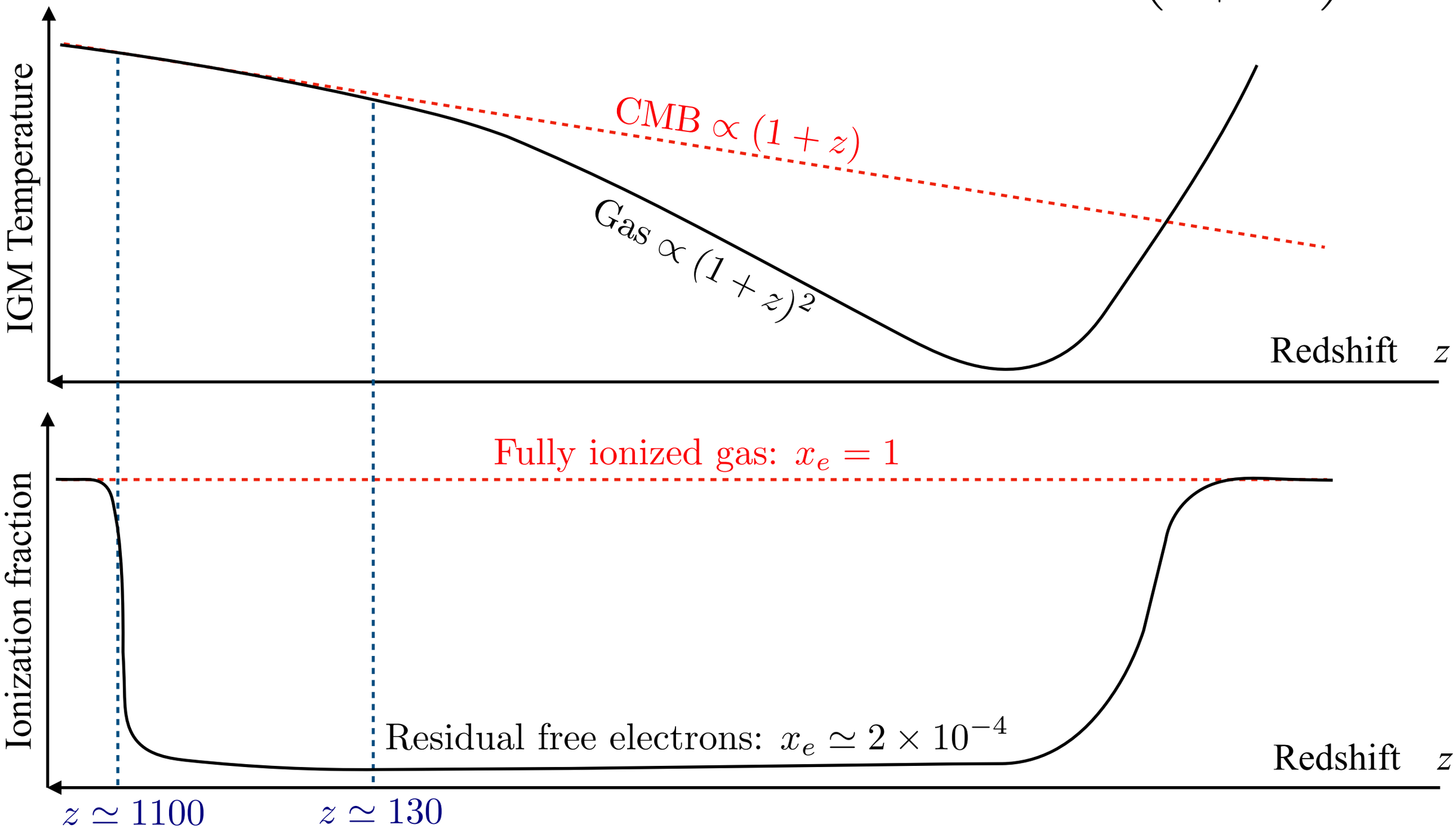
- However, the gas & CMB temperatures are still the same, because of efficient Compton scattering



# A short history of the IGM



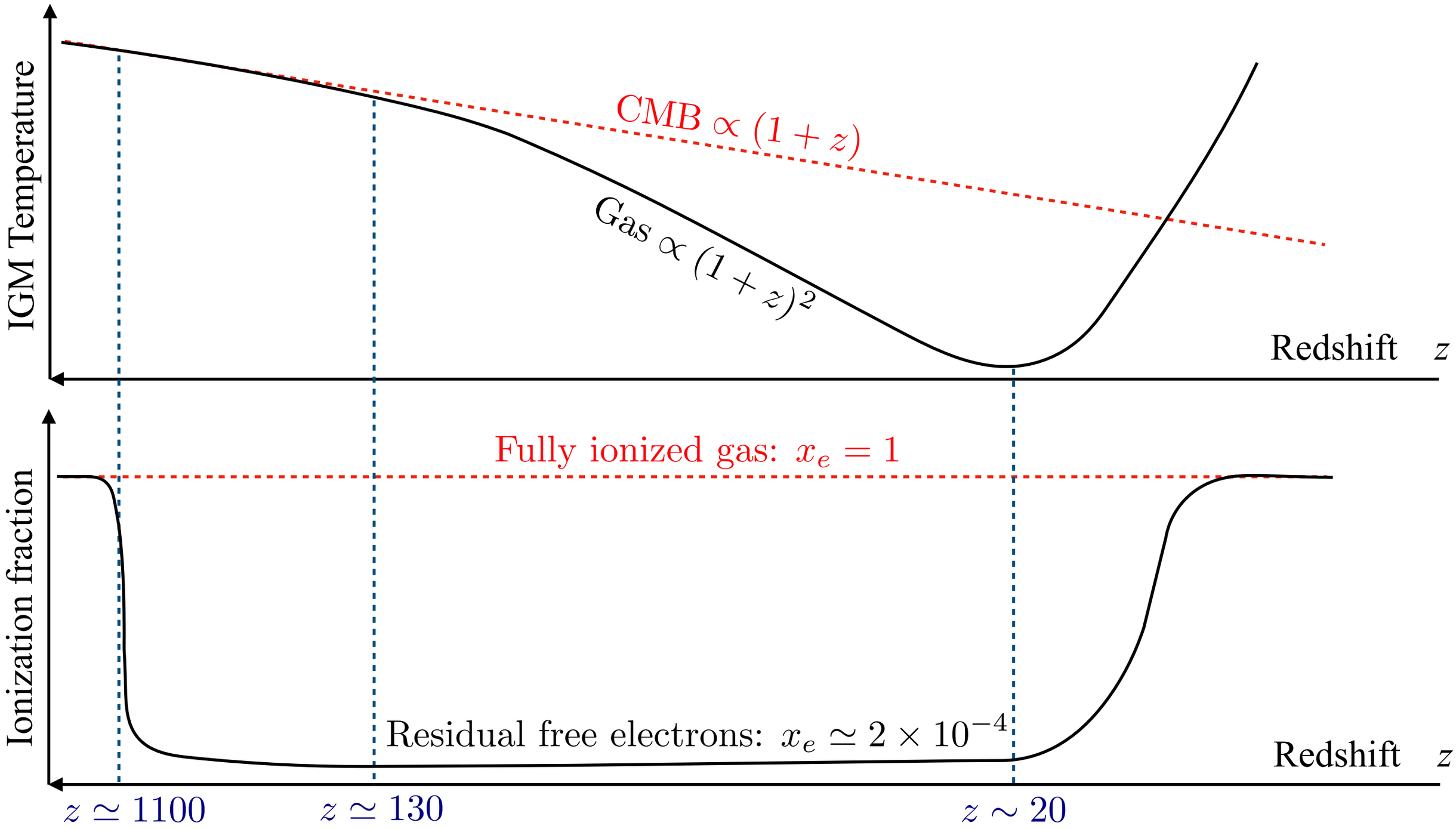
- Finally, around $z\sim130$, IGM *thermally decouples*:
  it thereafter cools down adiabatically as: $T_{\rm gas} \simeq T_{\rm CMB}^{z=130} \left(\dfrac{1+z}{1+130}\right)^2$



# A short history of the IGM



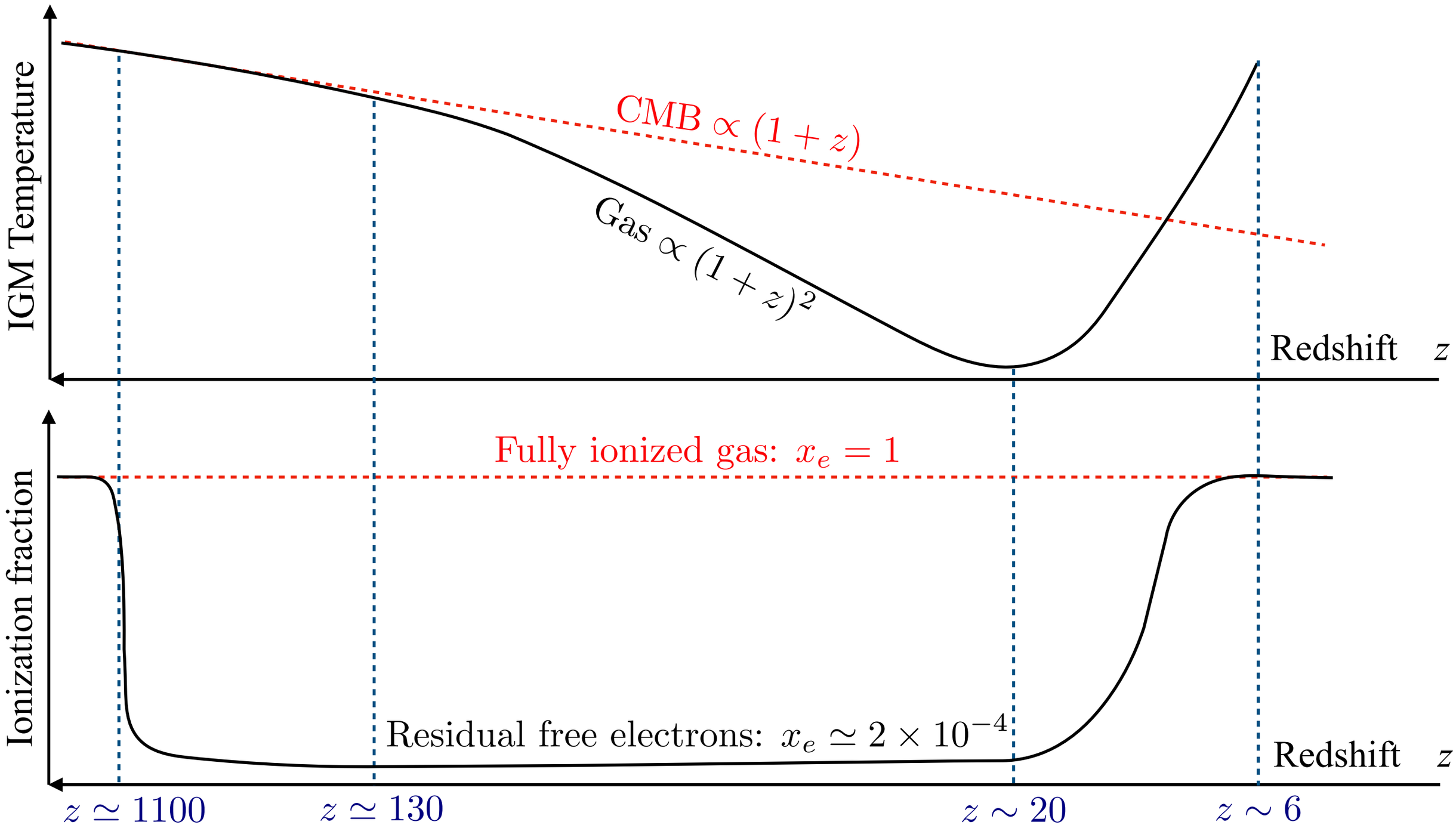
- At some point, lights turn on: *X*-rays and Ly-α photons go around the Universe, heat the IGM, finally reaching



# A short history of the IGM



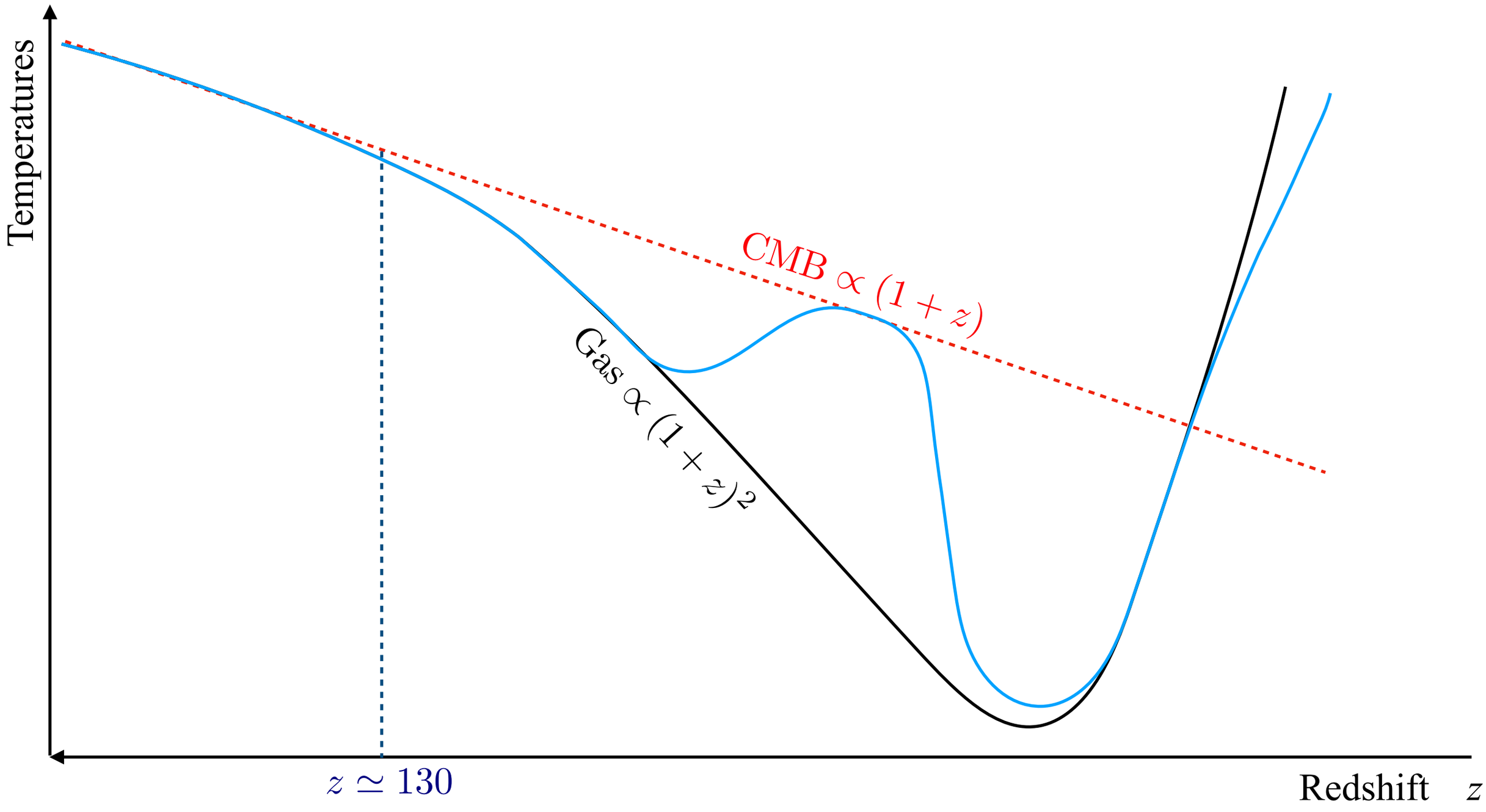
- Reionization: the Universe becomes ionized again, no neutral atomic hydrogen anymore



# A short history of $T_S$



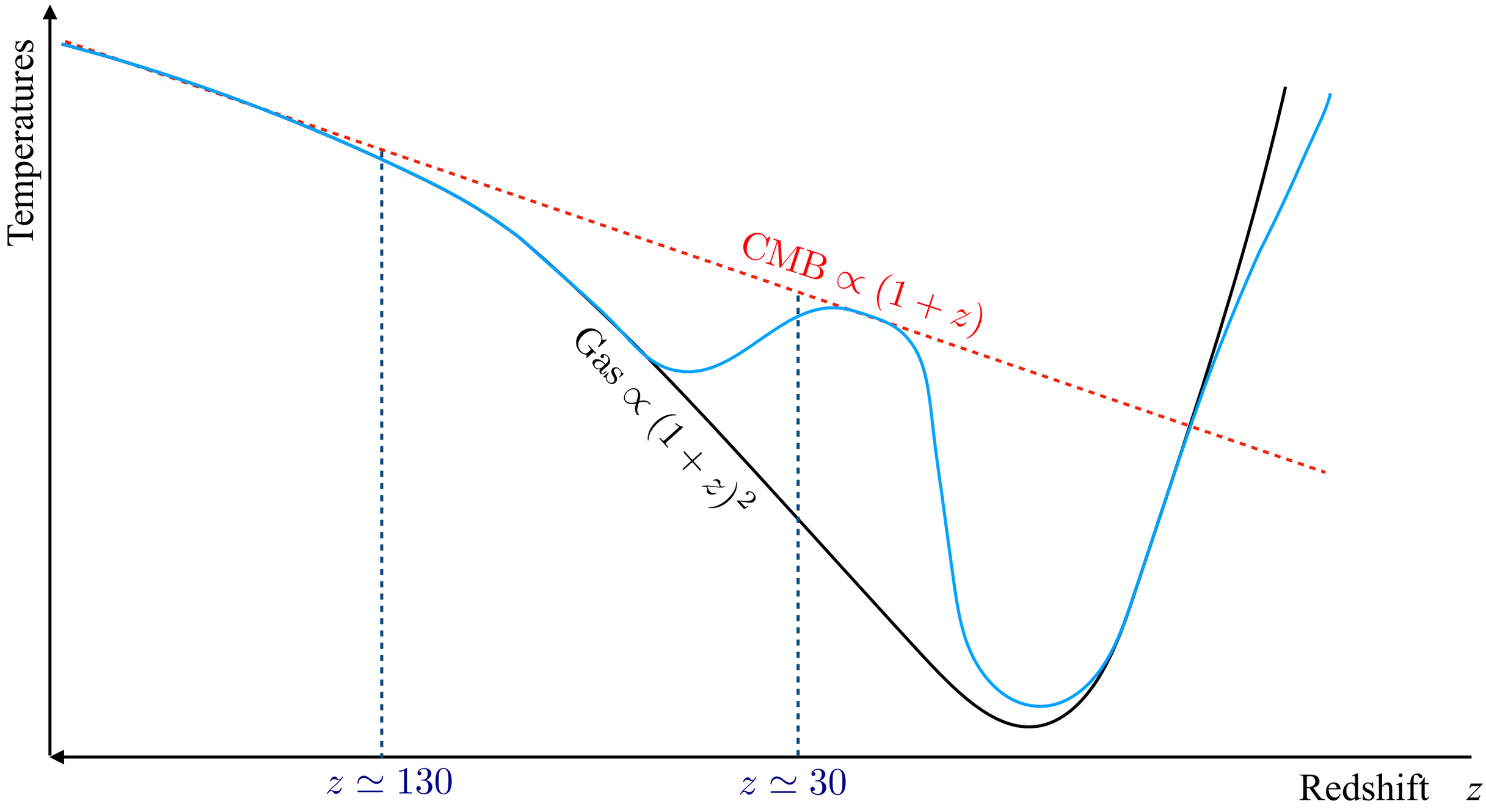
- Nothing happens until IGM thermally decouple,
  temperatures are all the same, zero signal



# A short history of $T_S$



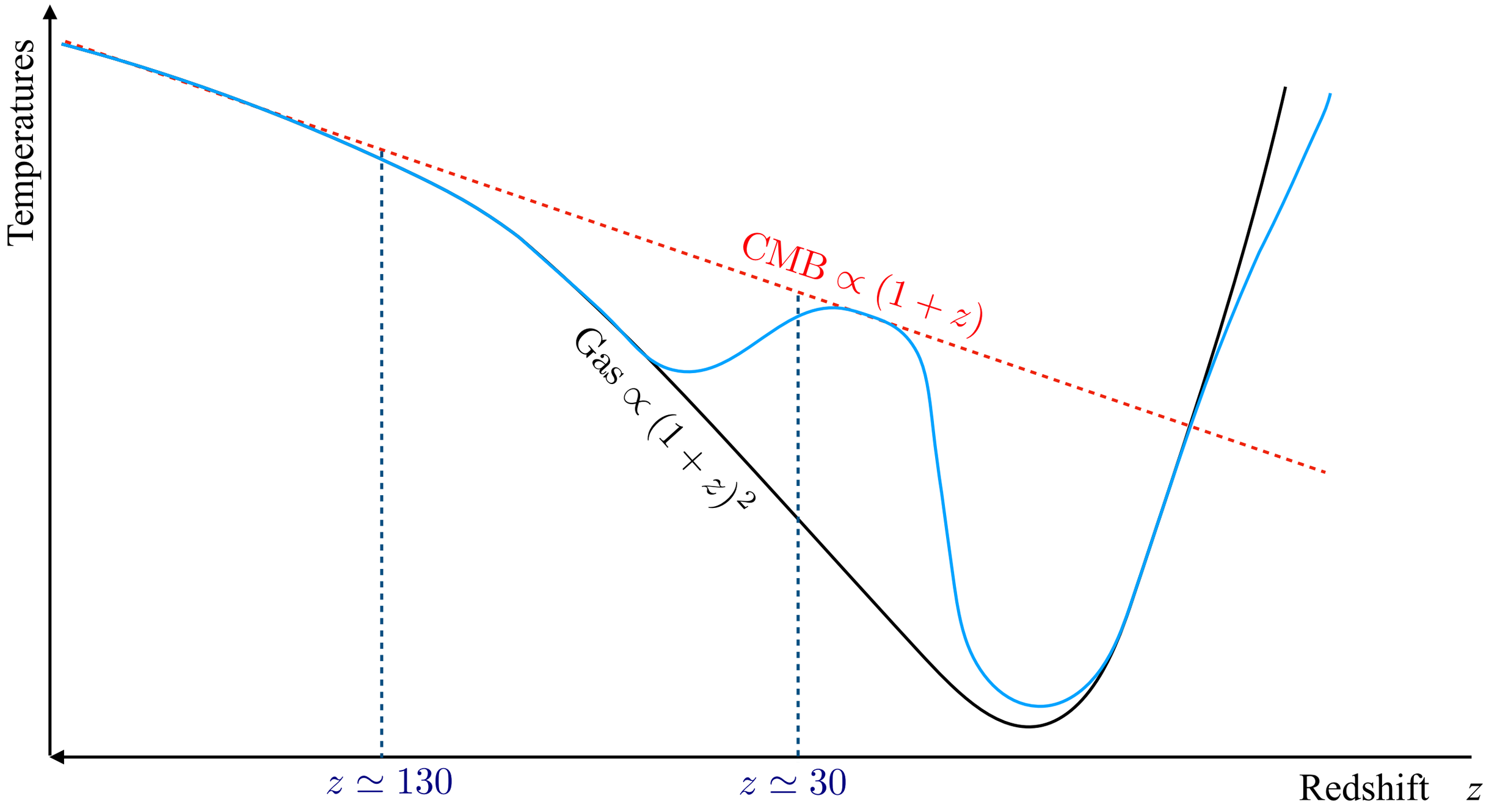
- After $z\sim200$ until $z\sim30$, collisions keep since the IGM is colder, I have a signal *in absorption*



# A short history of $T_S$



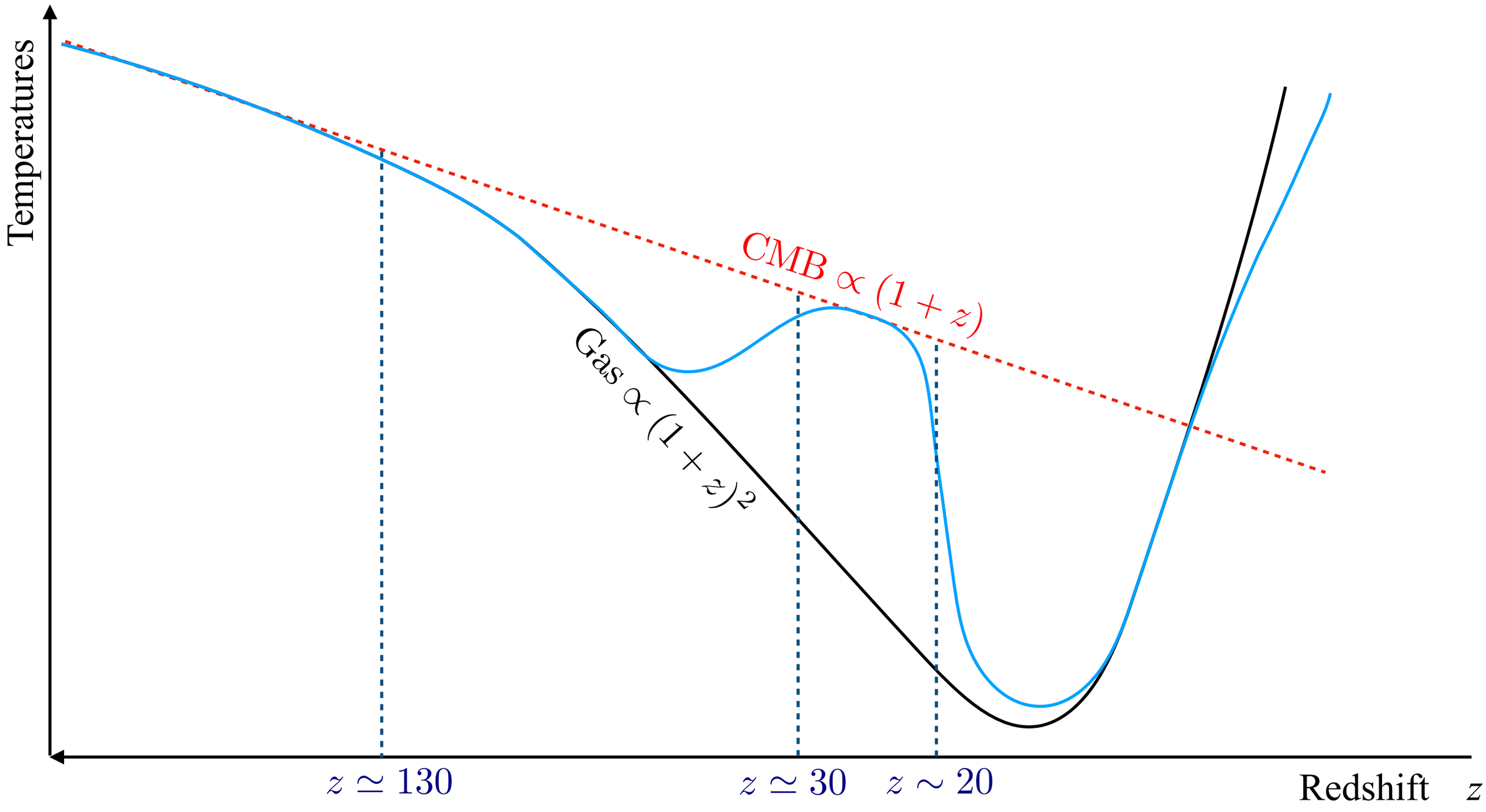
➡ After, no collisions, no other radiation:
and I have zero signal



# A short history of $T_S$



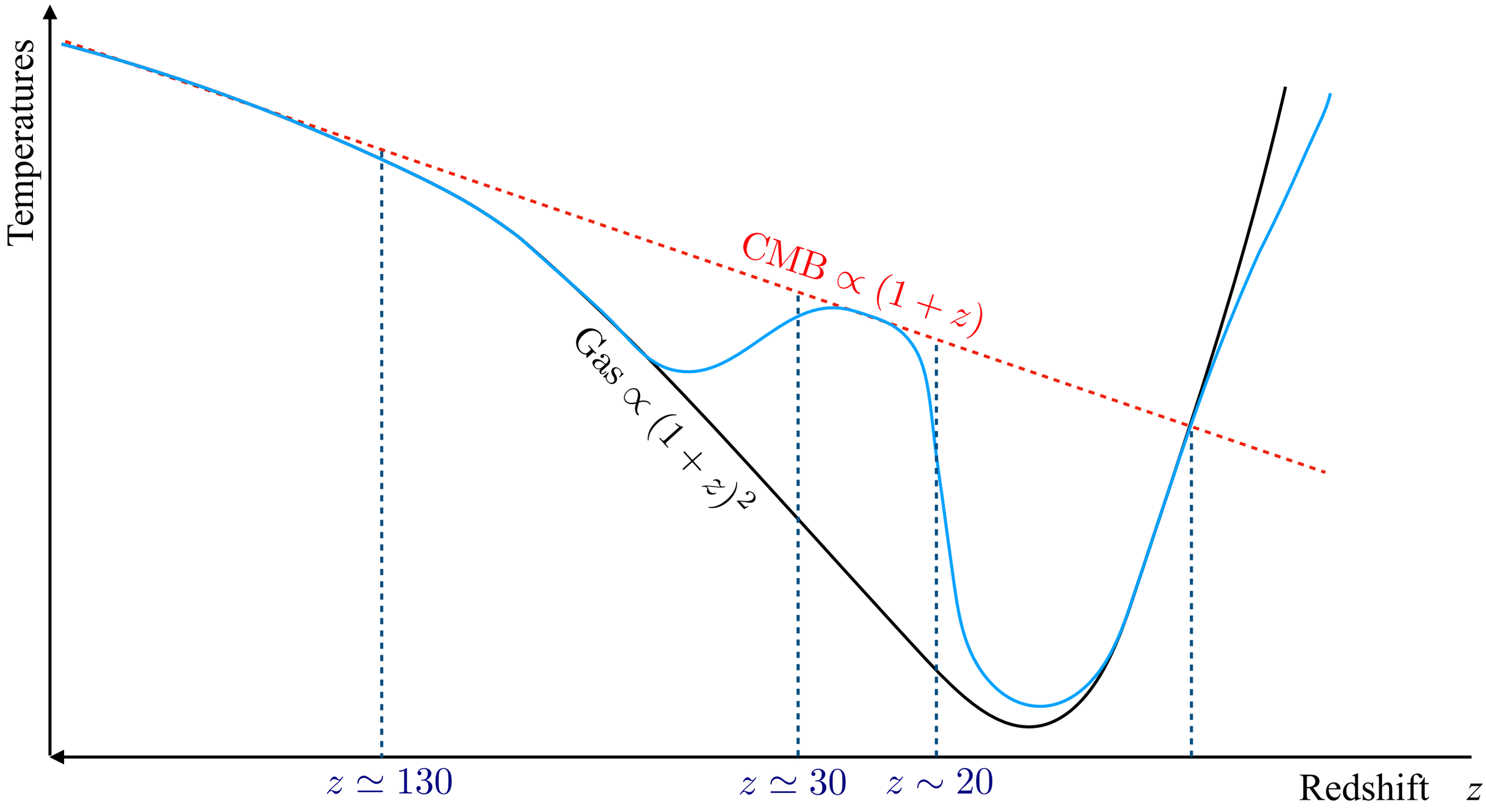
➡ And then? At some point, Ly-α photons recouple, so I start decreasing and I get absorption



# A short history of $T_S$

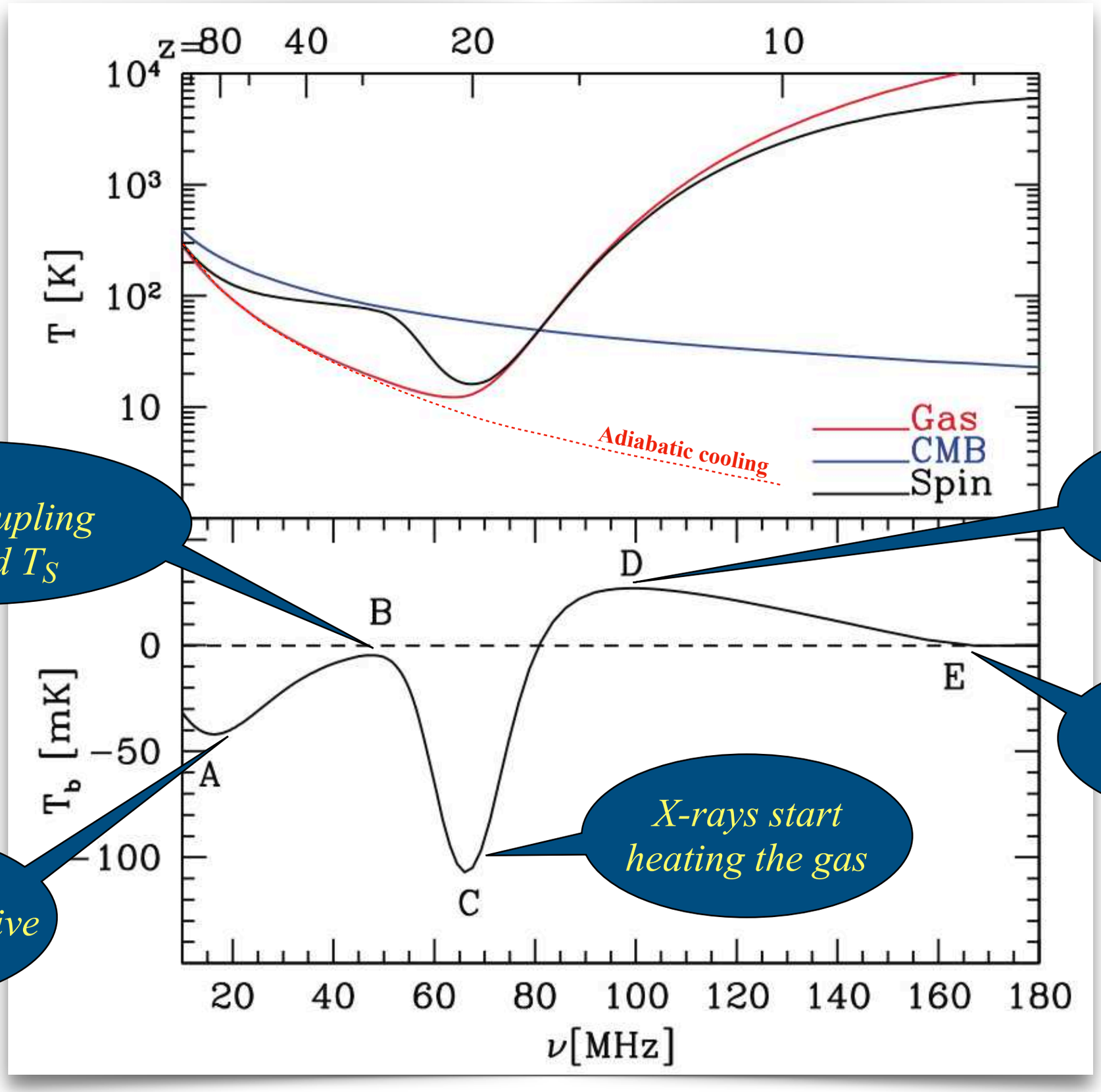


- Finally, as goes up, I increase and get an emission until 21-cm signal dies after full reionization



# 21-cm signal history






*Lyα start recoupling $T_{gas}$ and $T_S$*

*From absorption to emission*

*Reionization kills the signal*

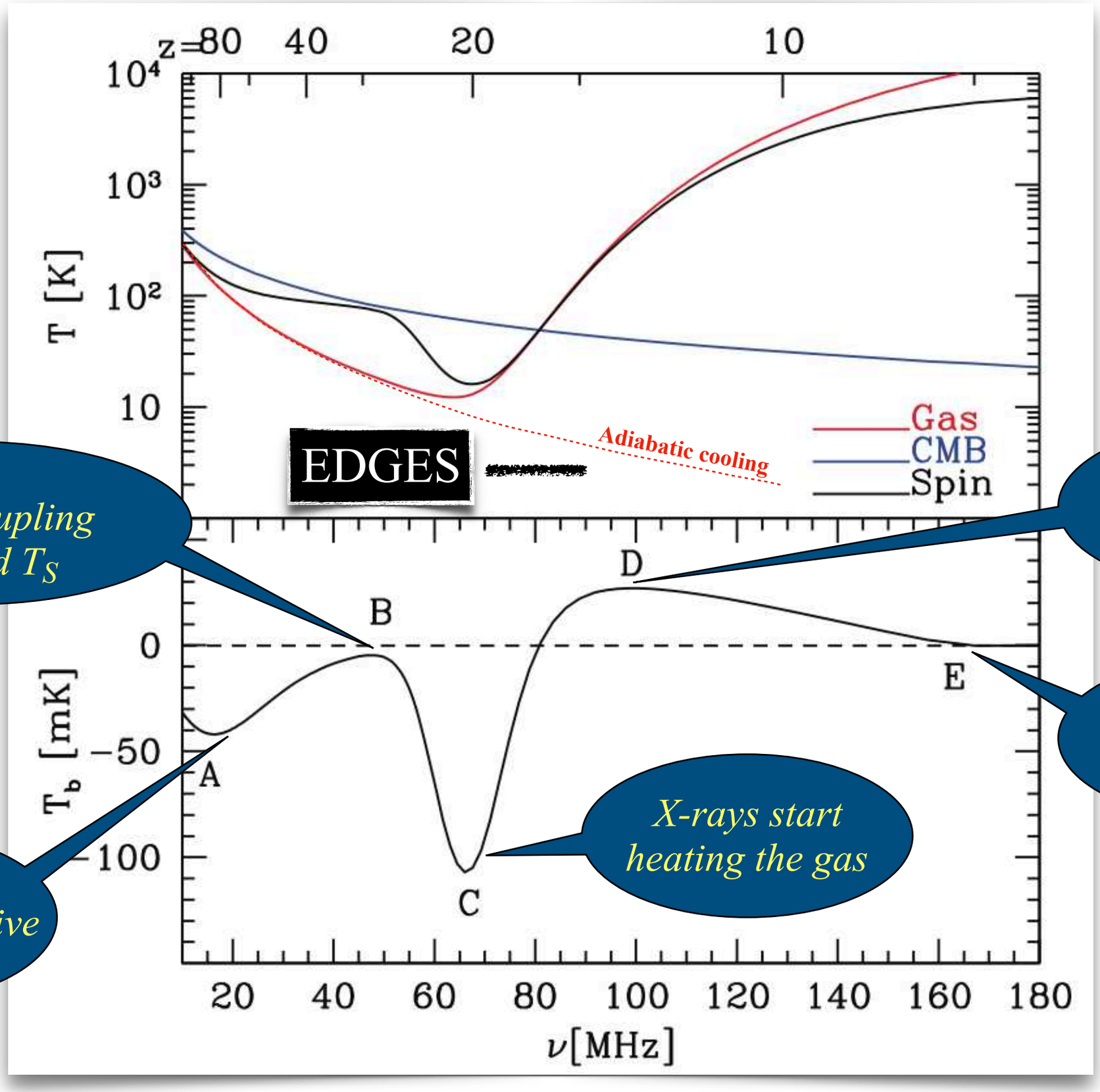
*X-rays start heating the gas*

*Collisions become ineffective*

Taylor et al. 2012 (1206.6733)

# 21-cm signal history



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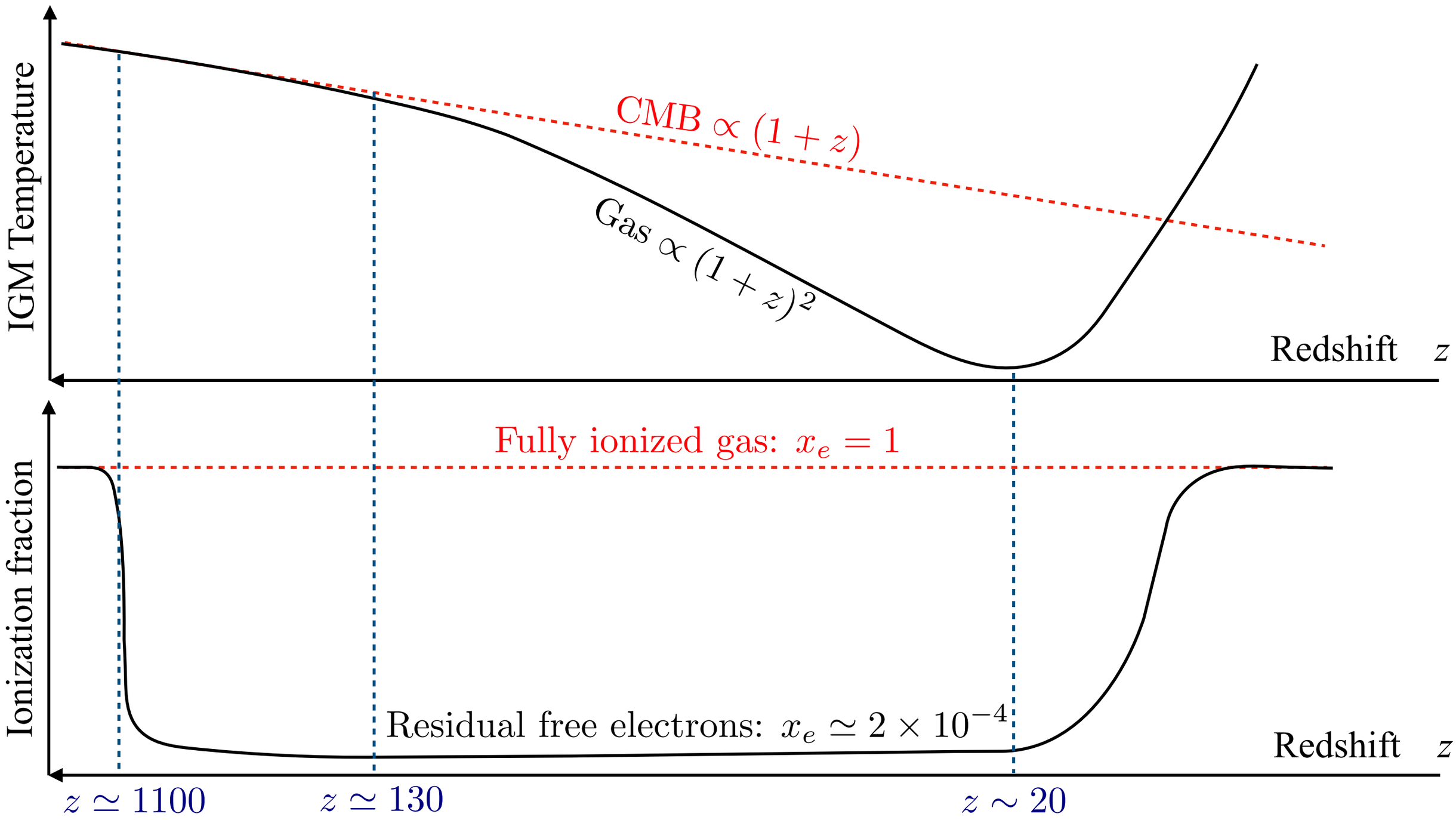
# III PART

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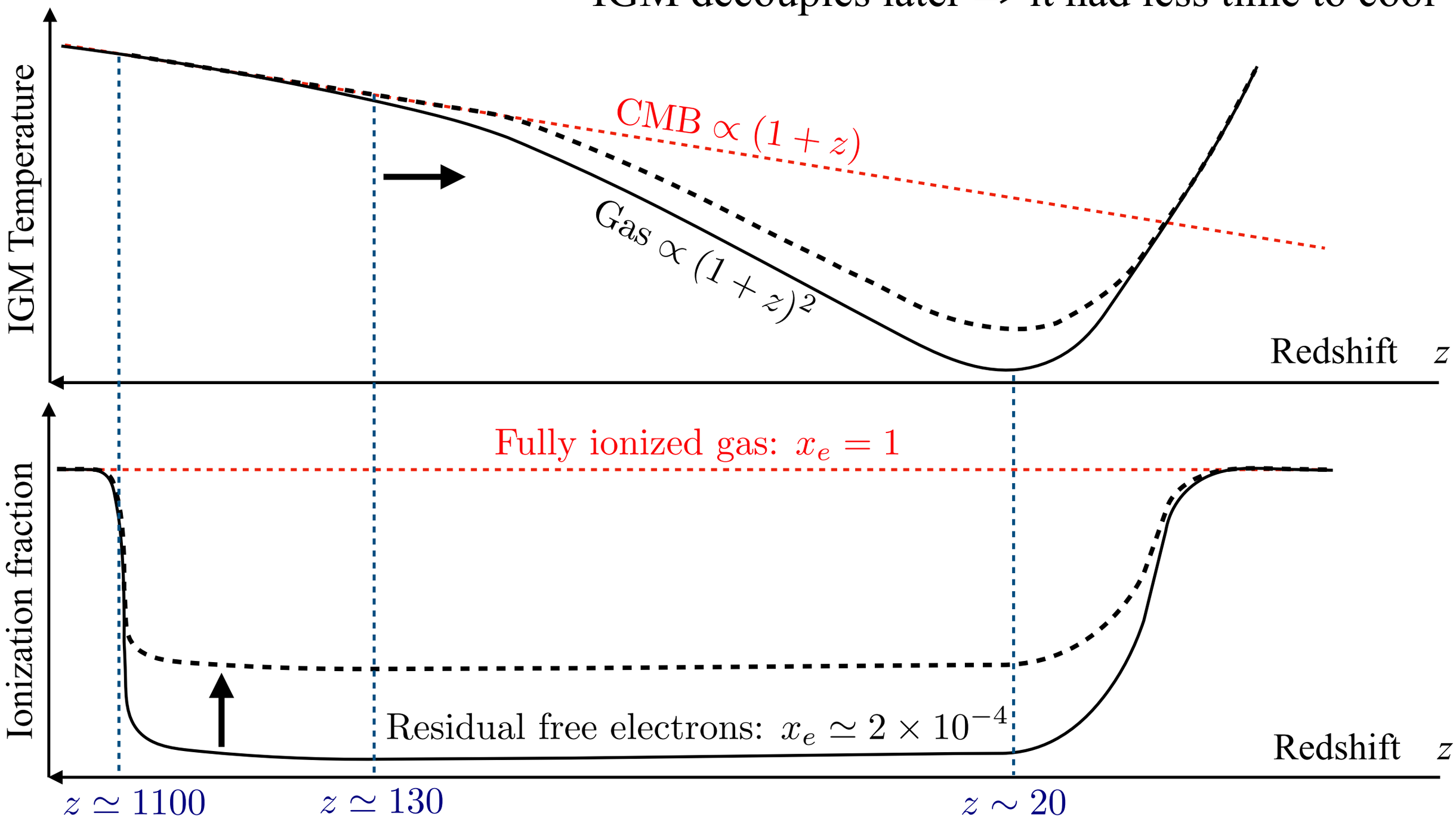
DM can (and will if thermal) annihilate into SM.

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



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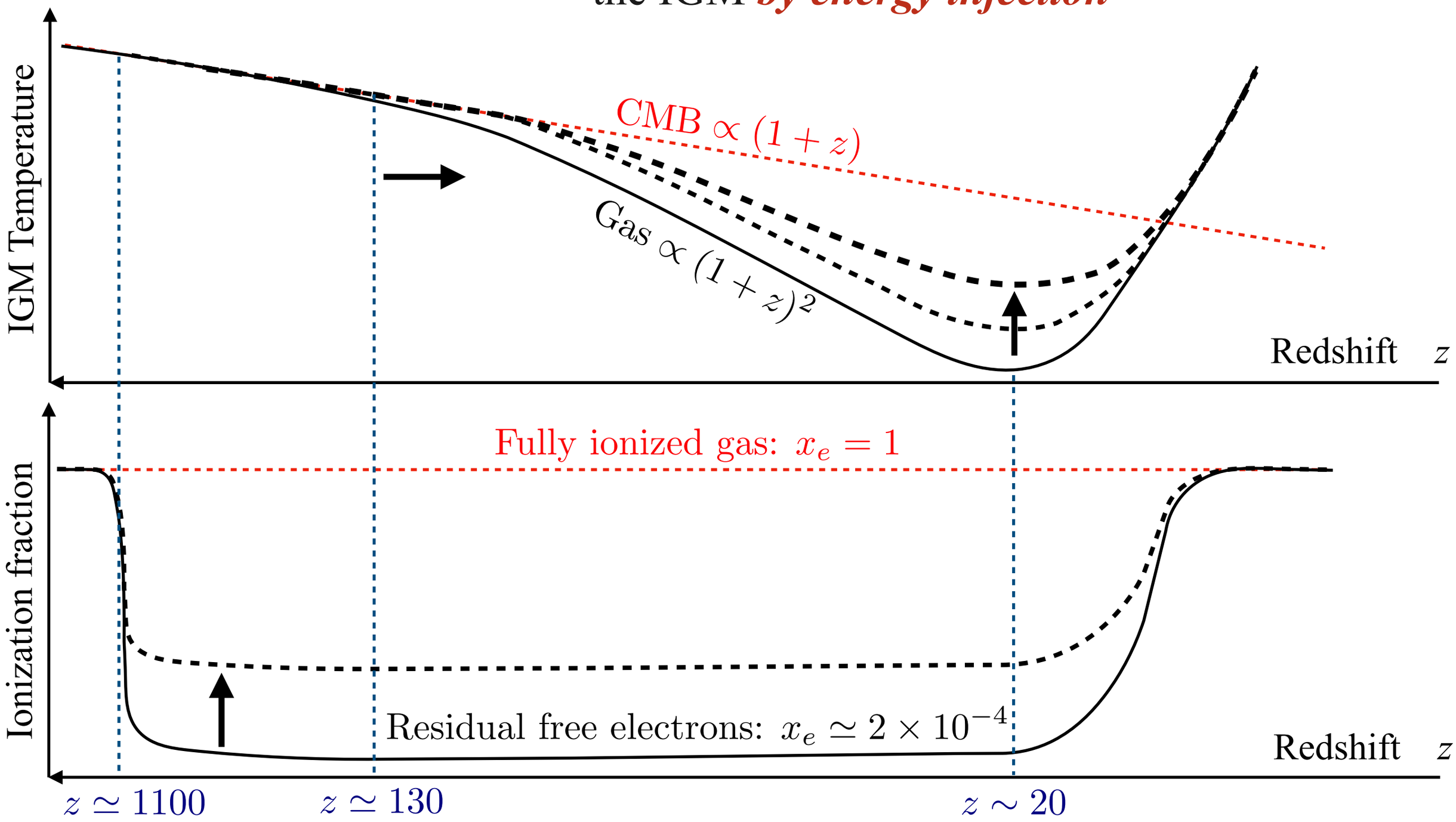
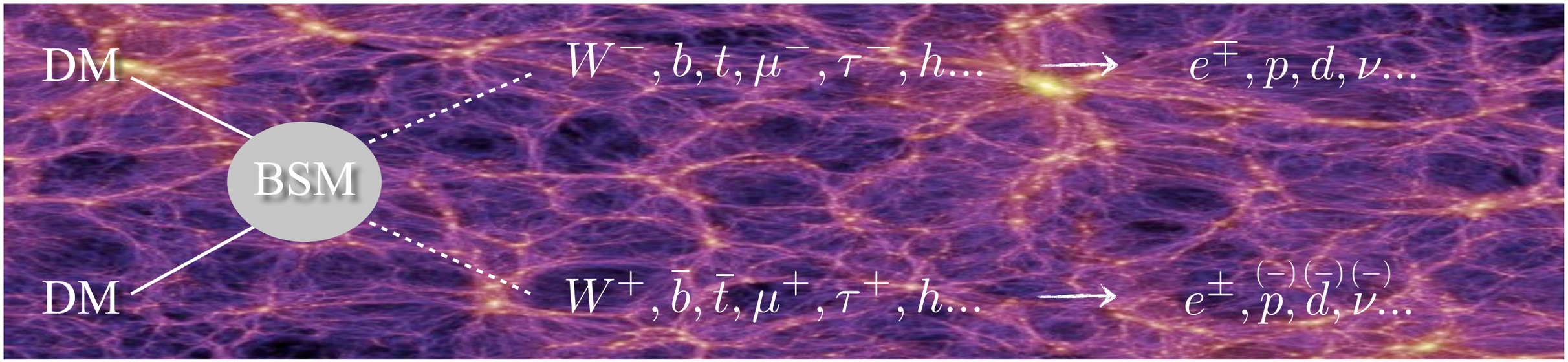
**Will heat the IGM** in 2 ways: ➡ More importantly, annihilations directly heat the IGM ***by energy injection***



# DM Annihilation: Basics





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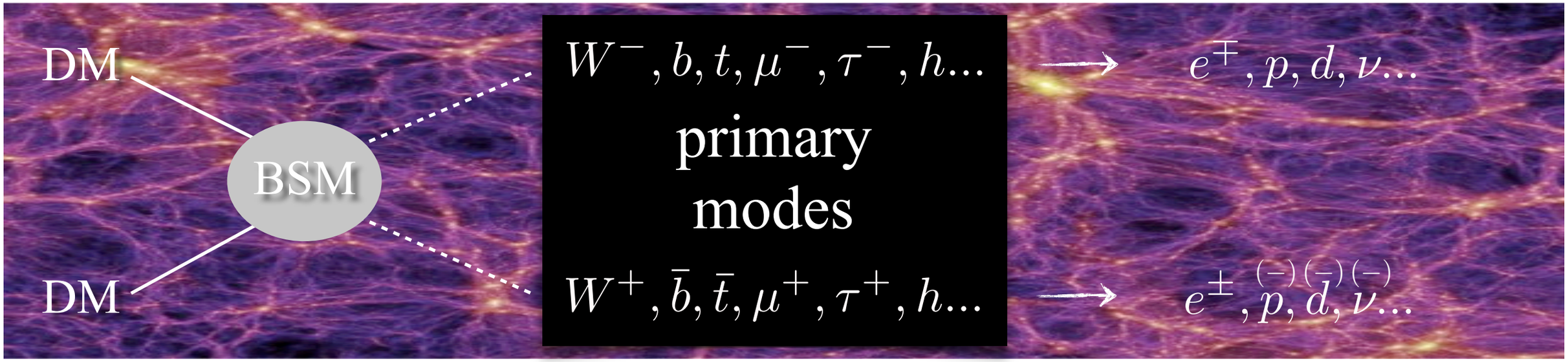

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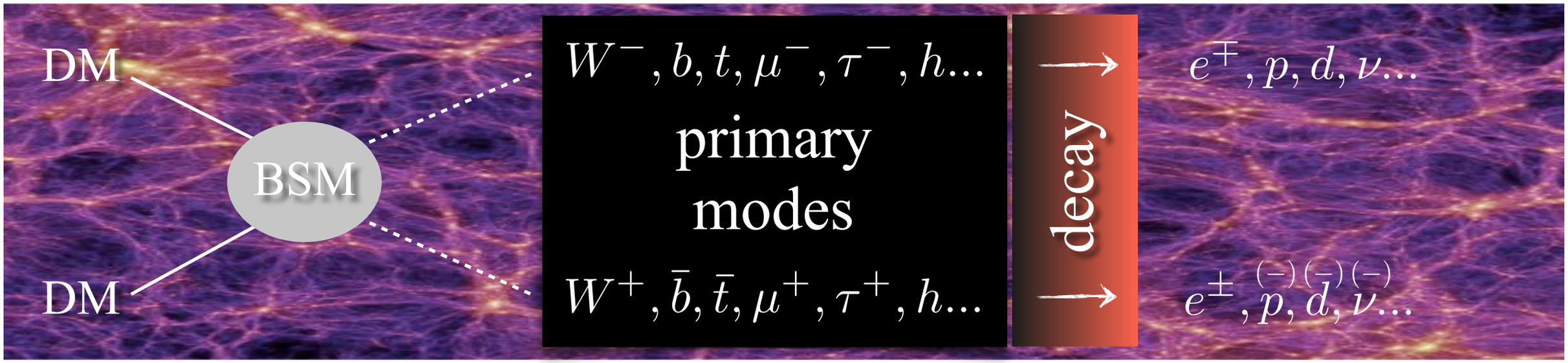
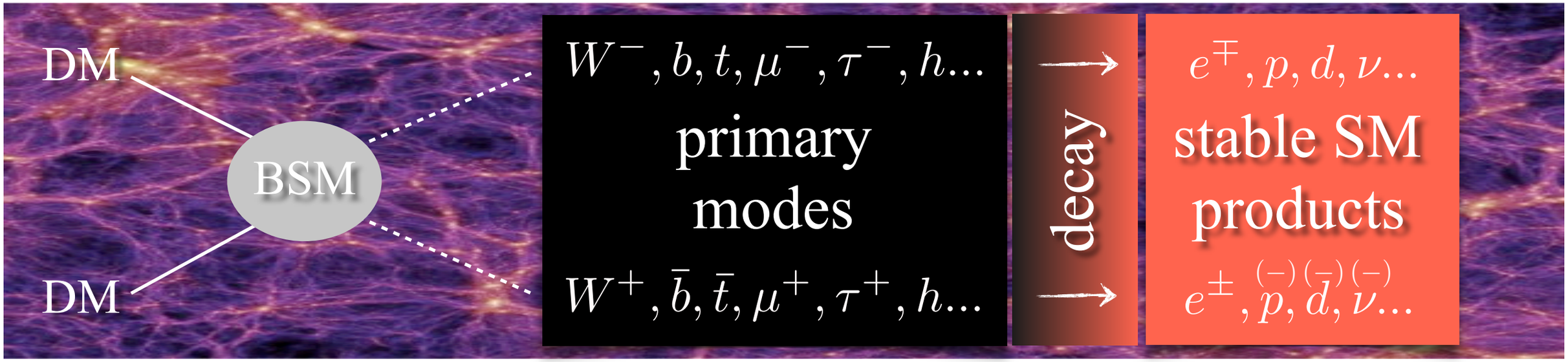
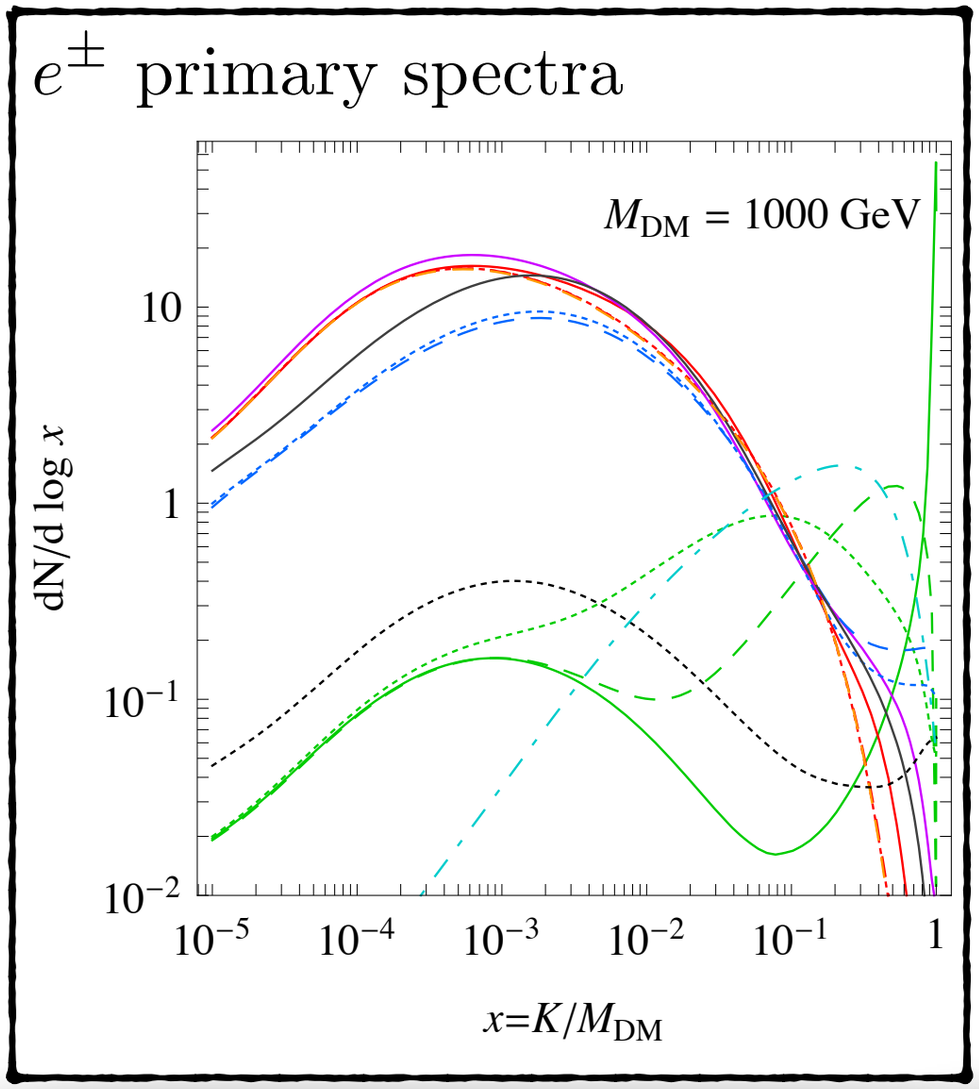
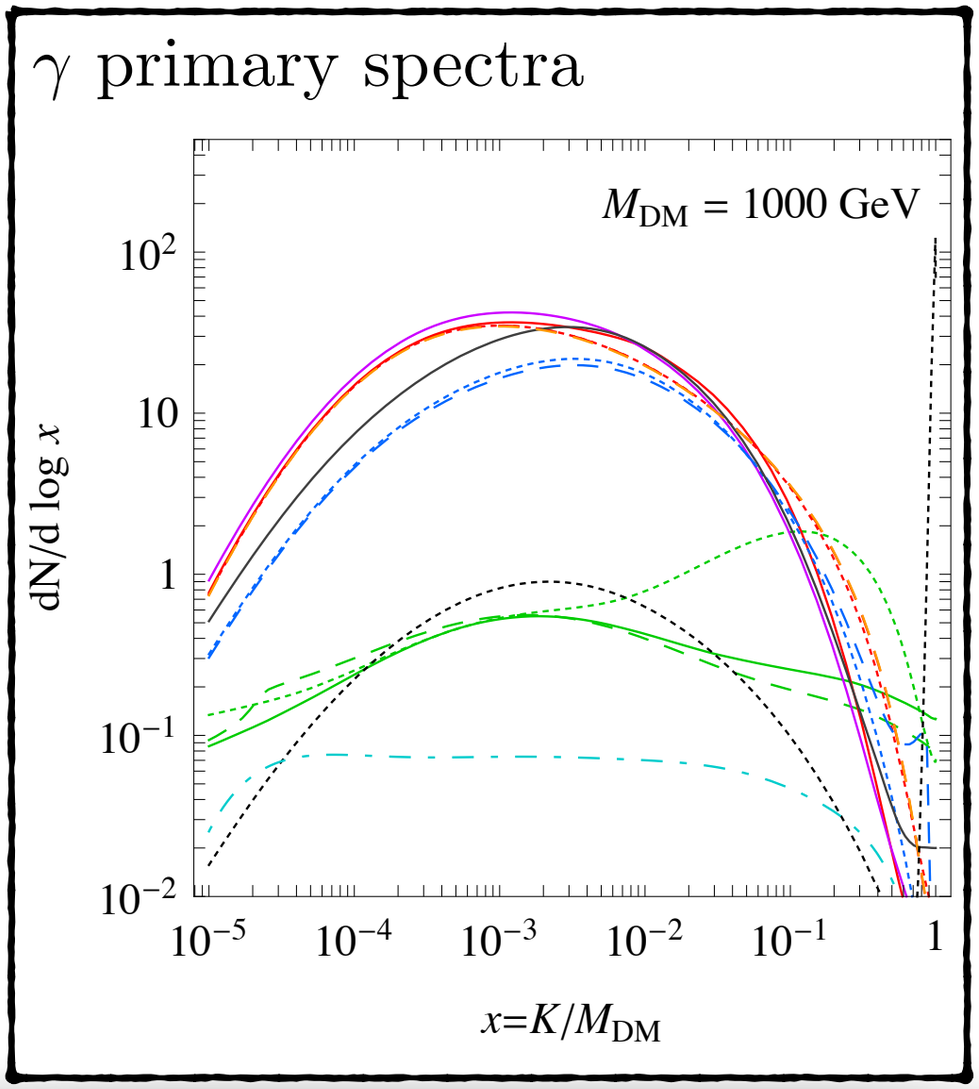


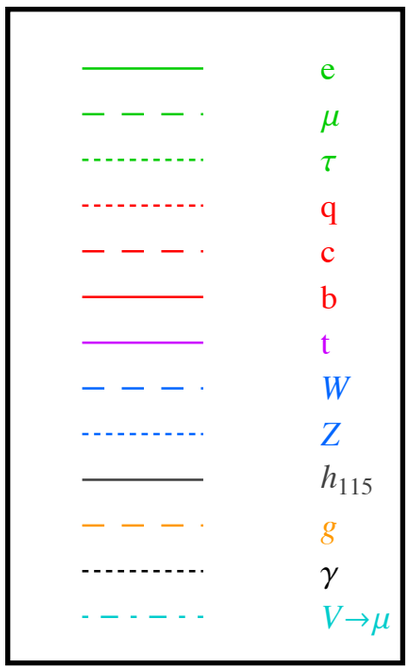
# DM Annihilation: Basics





# Energy injection



**Total number of stable SM products** per (d$V$, d$E$ and d$t$) at a given $z$:

$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}V\,\mathrm{d}E_f\,\mathrm{d}t} = \langle\rho^2_{\rm DM}\rangle\,\frac{\langle\sigma v\rangle}{M^2_{\rm DM}}\,\frac{\mathrm{d}N}{\mathrm{d}E_f}$$

**Total Energy injected** into the IGM per (d$V$ and d$t$) at a given $z$:

$$\left.\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}V\,\mathrm{d}t}\right|_{\rm inj} = \int\sum_f \frac{\mathrm{d}\mathcal{N}}{\mathrm{d}V\,\mathrm{d}E_f\,\mathrm{d}t}\,E_f\,\mathrm{d}E_f \equiv \langle\rho^2_{\rm DM}\rangle\,\frac{\langle\sigma v\rangle}{M_{\rm DM}}$$

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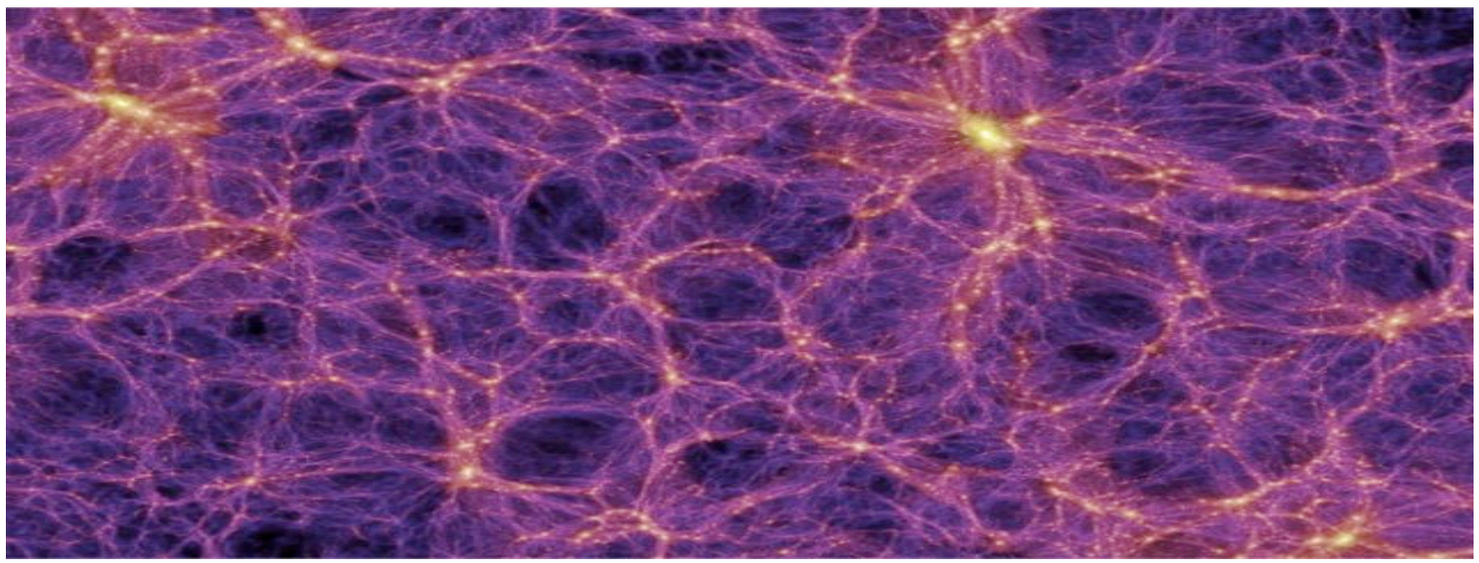
***Boosted Annihilation*** due to structure formation:

$$\langle\rho^2_{\rm DM}\rangle \equiv \langle\rho_{\rm DM}\rangle^2 B(z) = \rho_c^2 \Omega^2_{\rm DM} (1+z)^6 B(z)$$



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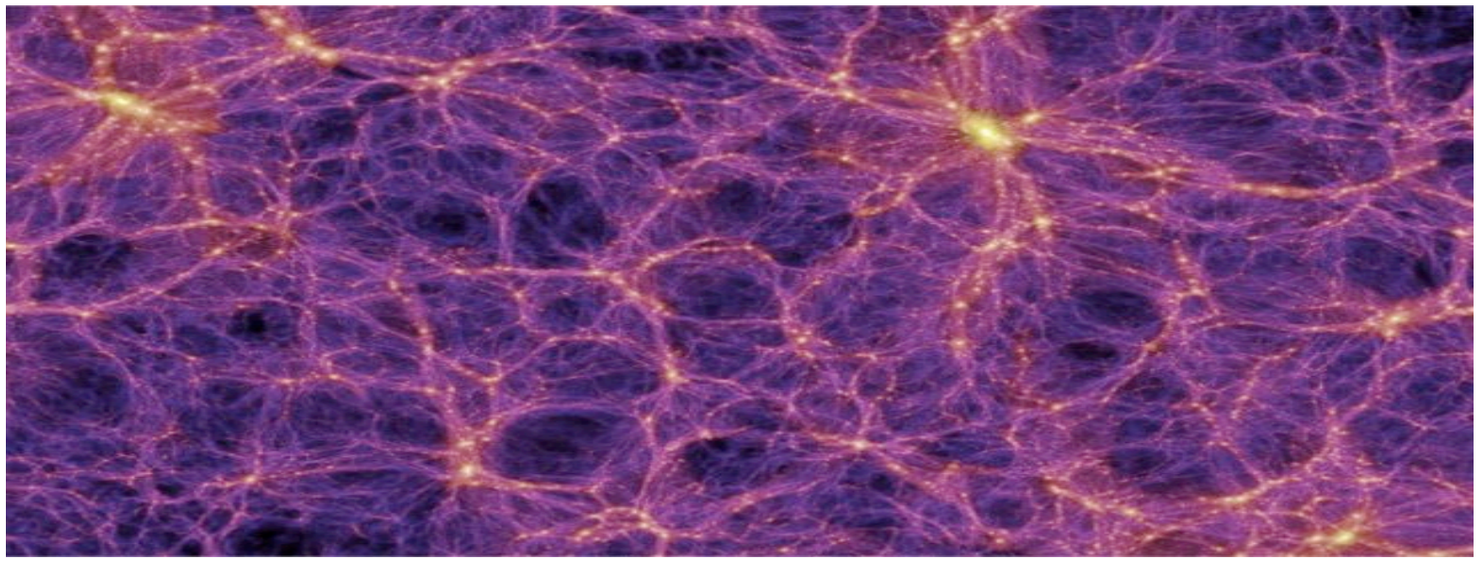

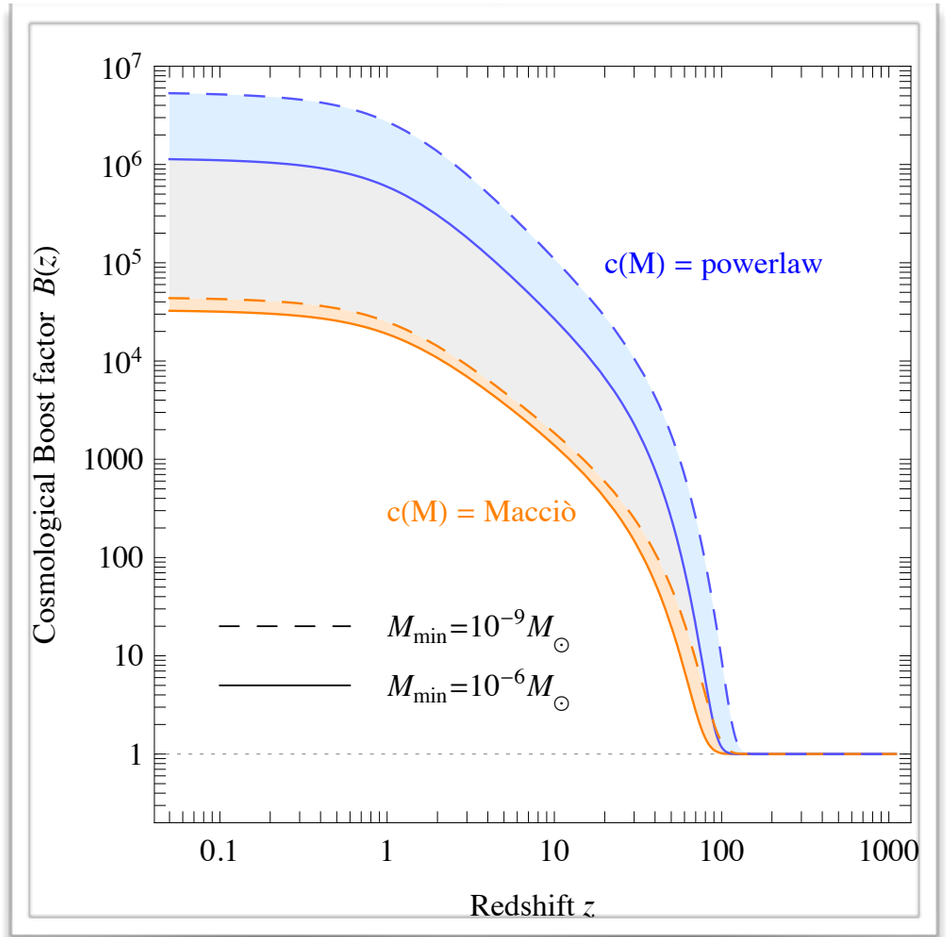

# Energy deposition



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

$$\left.\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}V\,\mathrm{d}t}\right|_{\rm dep} \equiv \left.\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}V\,\mathrm{d}t}\right|_{\rm inj} f_c(z)$$

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**INSTANTANEOUS DEPOSITION**: only valid at high redshift

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

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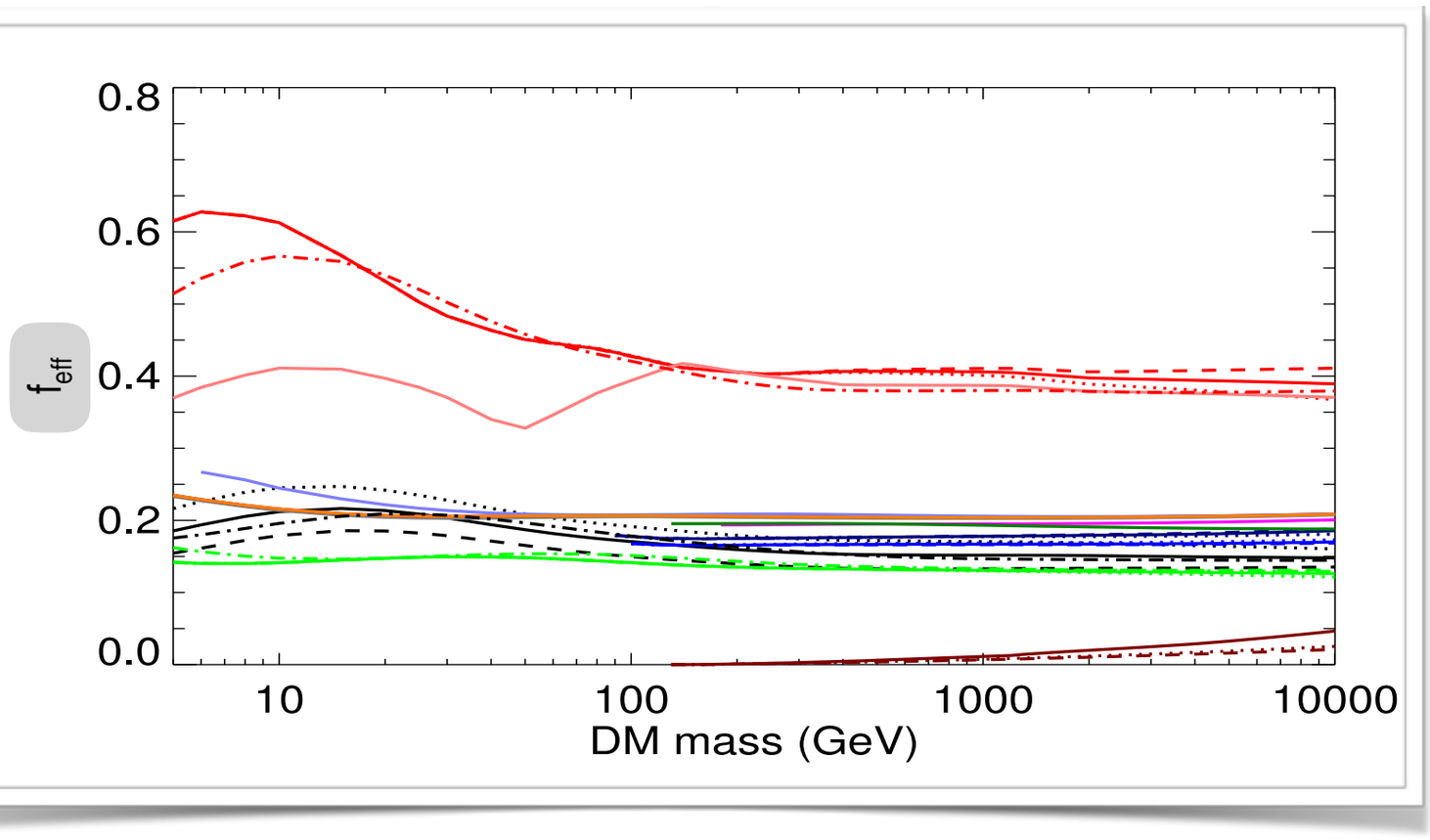


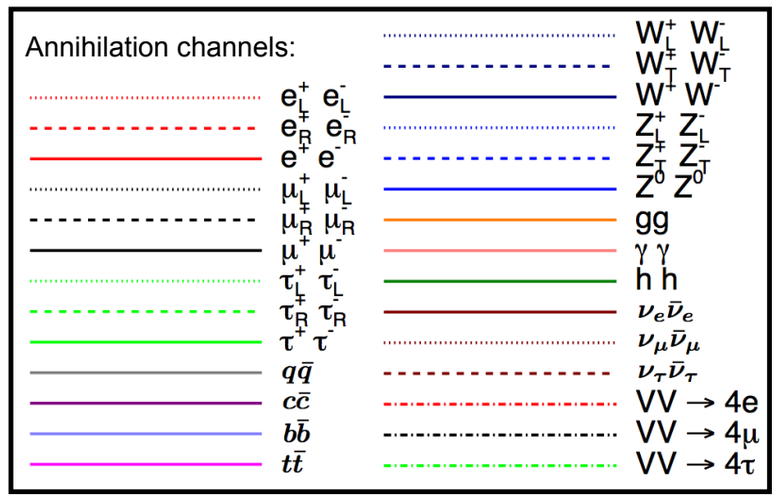


Slatyer
1506.03811,
1506.03812

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

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

- $f_c(z)$: **Deposition redshift**
- $H(z)$: **Hubble Rate**
- $\mathcal{T}_c(E,z,z')$: **Accounts for EM shower** → Slatyer 1506.03811, 1506.03812
- $\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}V\,\mathrm{d}E\mathrm{d}t}(E,z')$: **Injection redshift**

# Evolution w/o DM ann.



Evolution of the **free electrons abundance**:

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

Recombination of $H_{\rm I}$ — Ionization of $H_{\rm I}$

Evolution of the **gas Temperature**:

$$\frac{\mathrm{d}T_{\rm gas}}{\mathrm{d}z} = \frac{1}{1+z}\left\{2T_{\rm gas}(z) - \gamma_{\rm C}[T_{\rm CMB}(z) - T_{\rm gas}(z)]\right\}$$

Adiabatic cooling term — Compton heating term

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

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Energy deposited: **HEATING**

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*We do not try to explain it!*

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  - Assume standard evolution
  - Conservative scenario: Adiabatic cooling & efficient Lα-pumping
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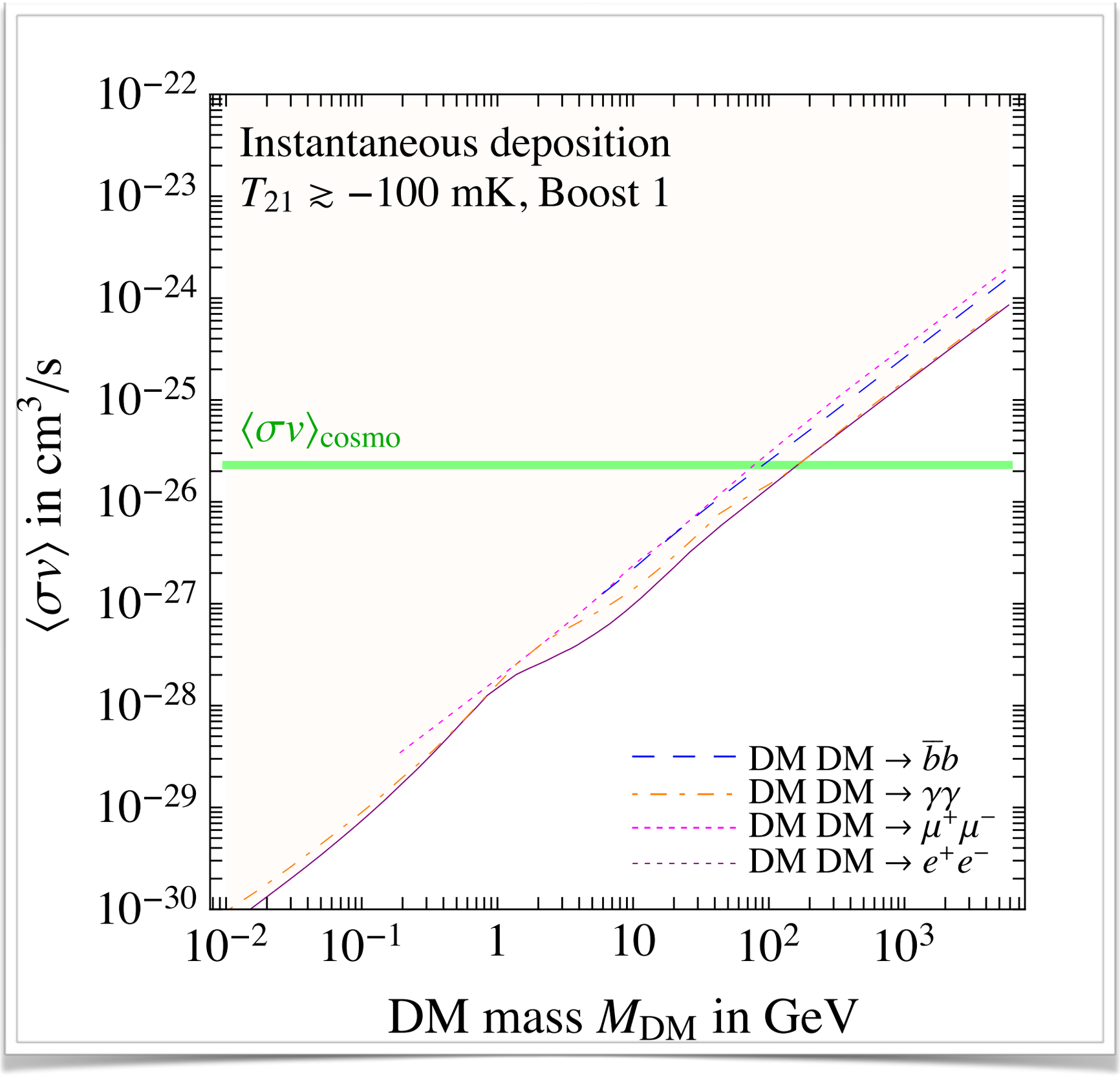
- We require that DM annihilations do not erase the 21-cm signal above **-100 mK** !!

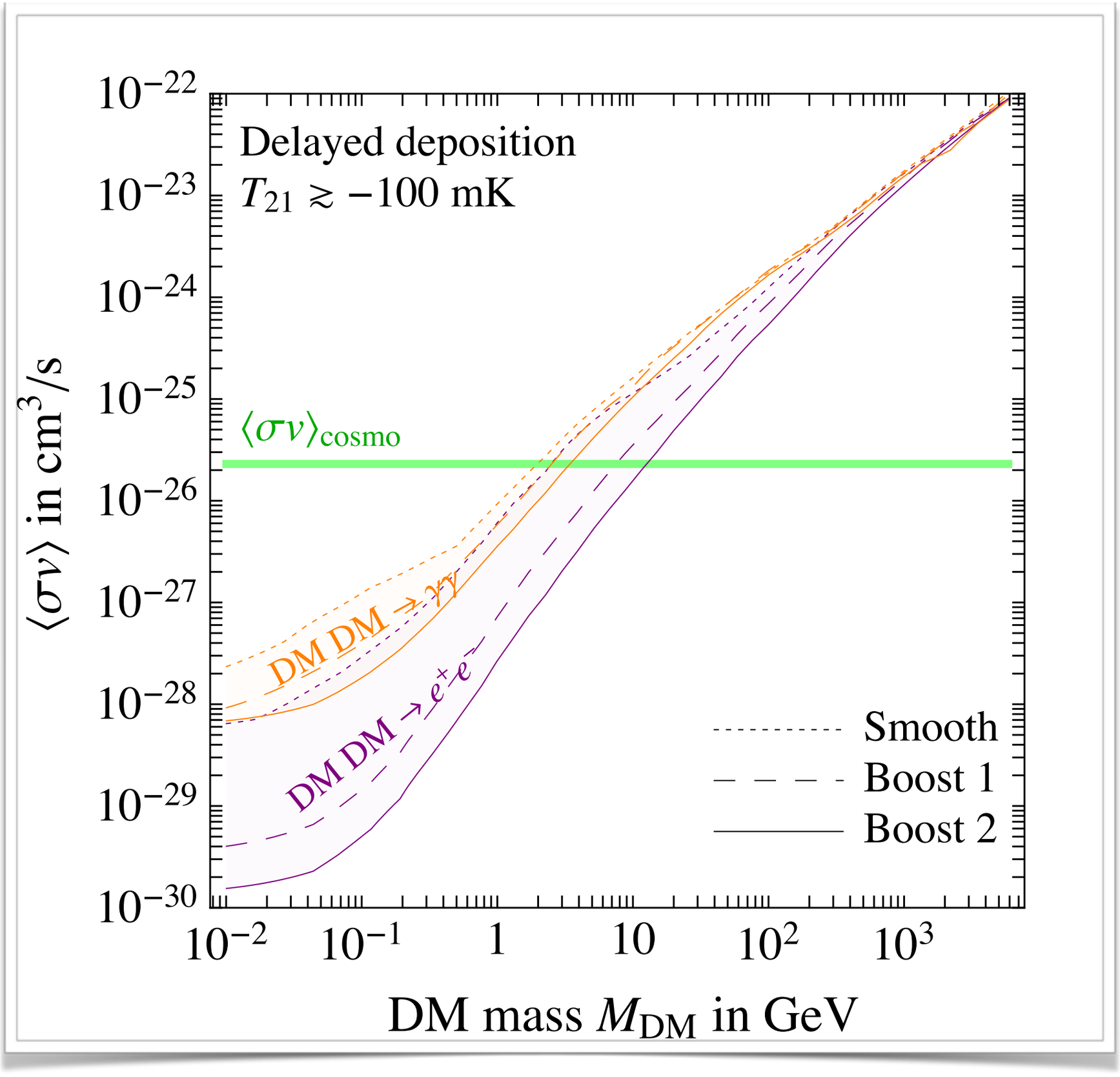
# Instantaneous deposition





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





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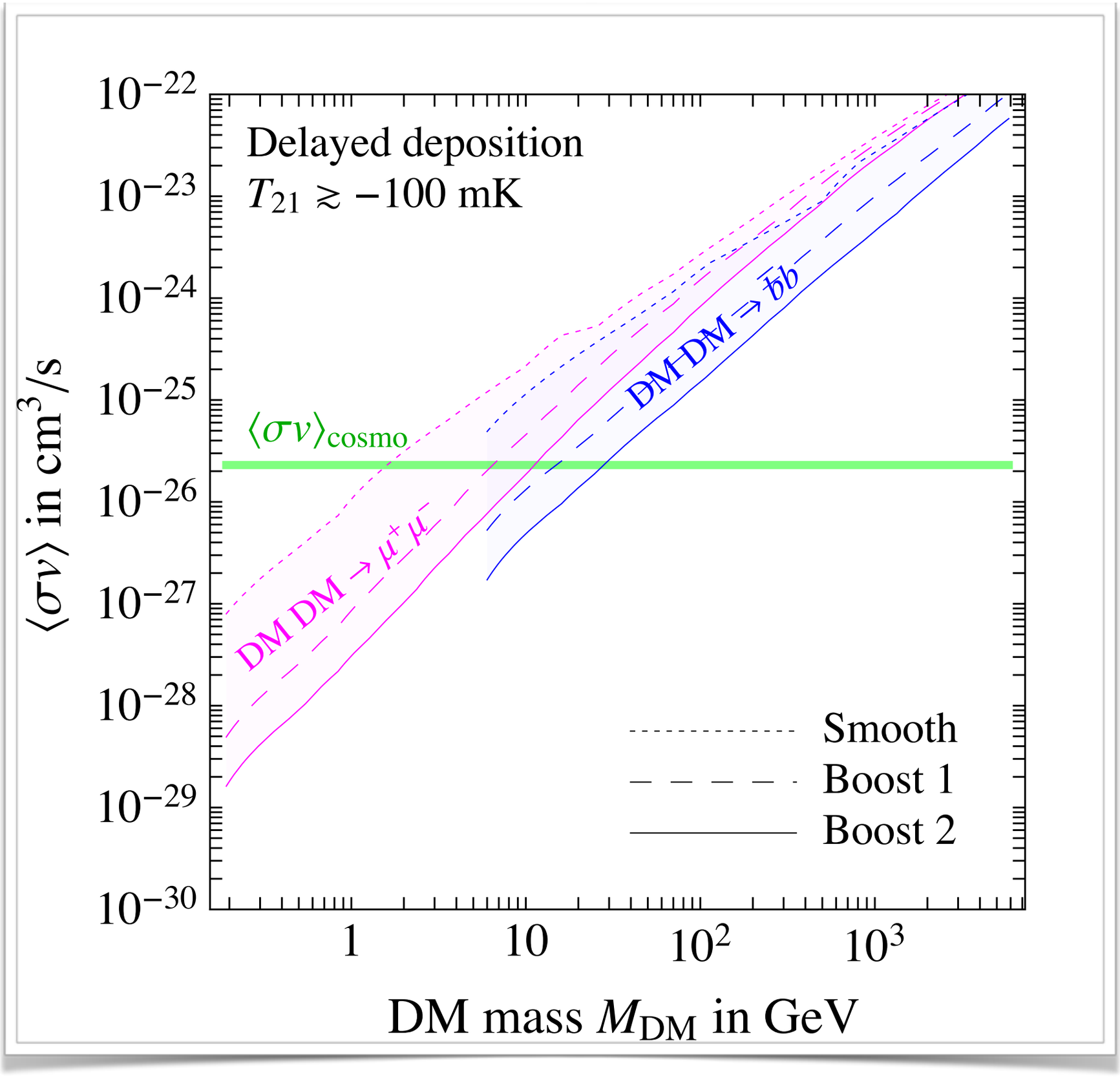
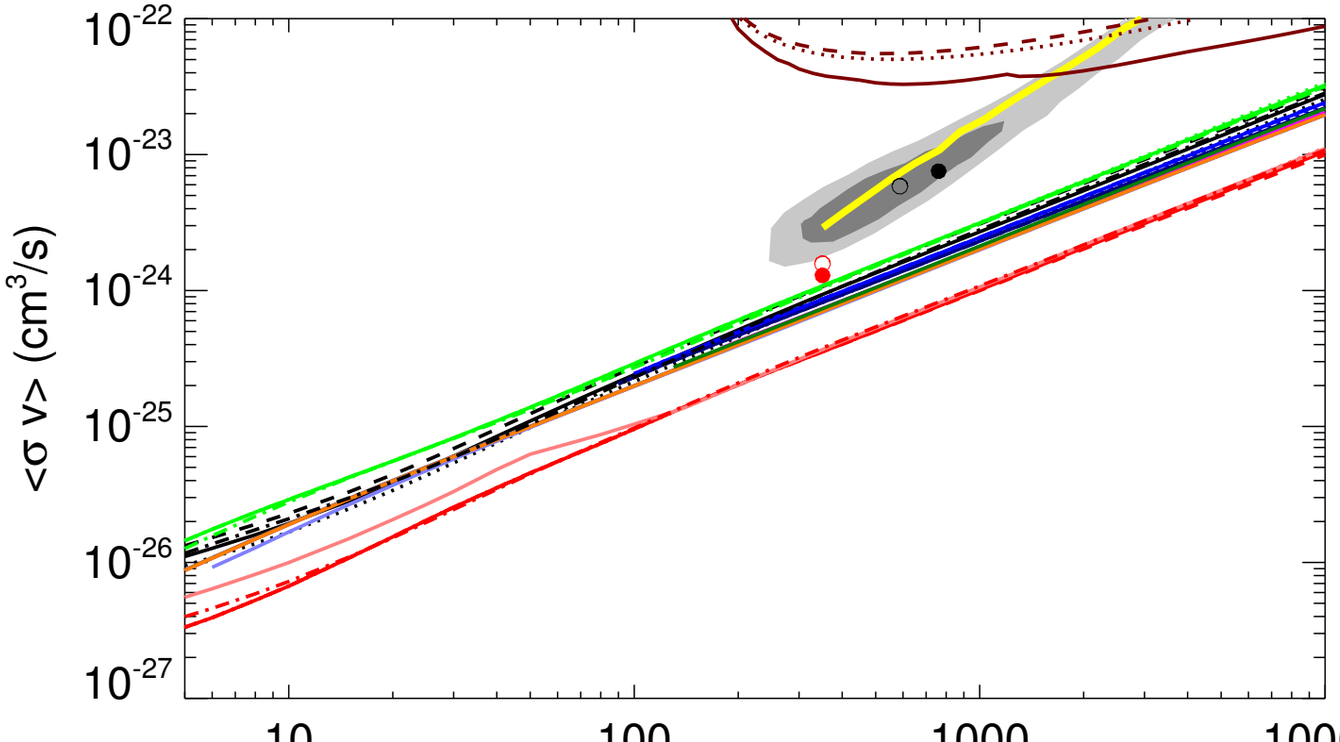
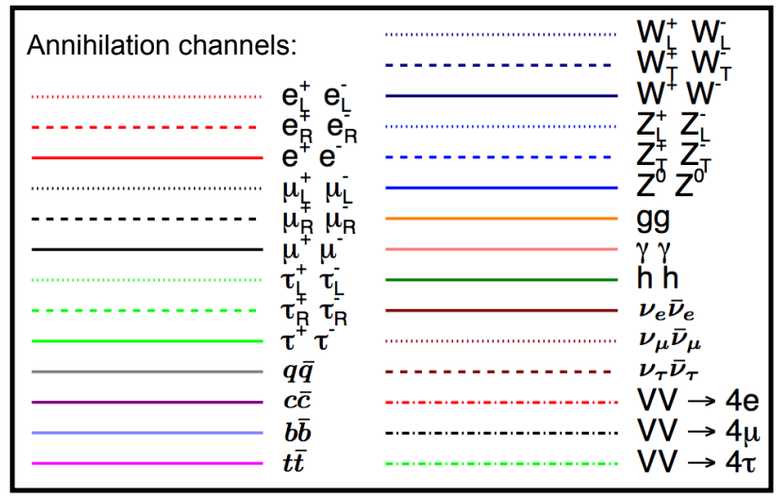


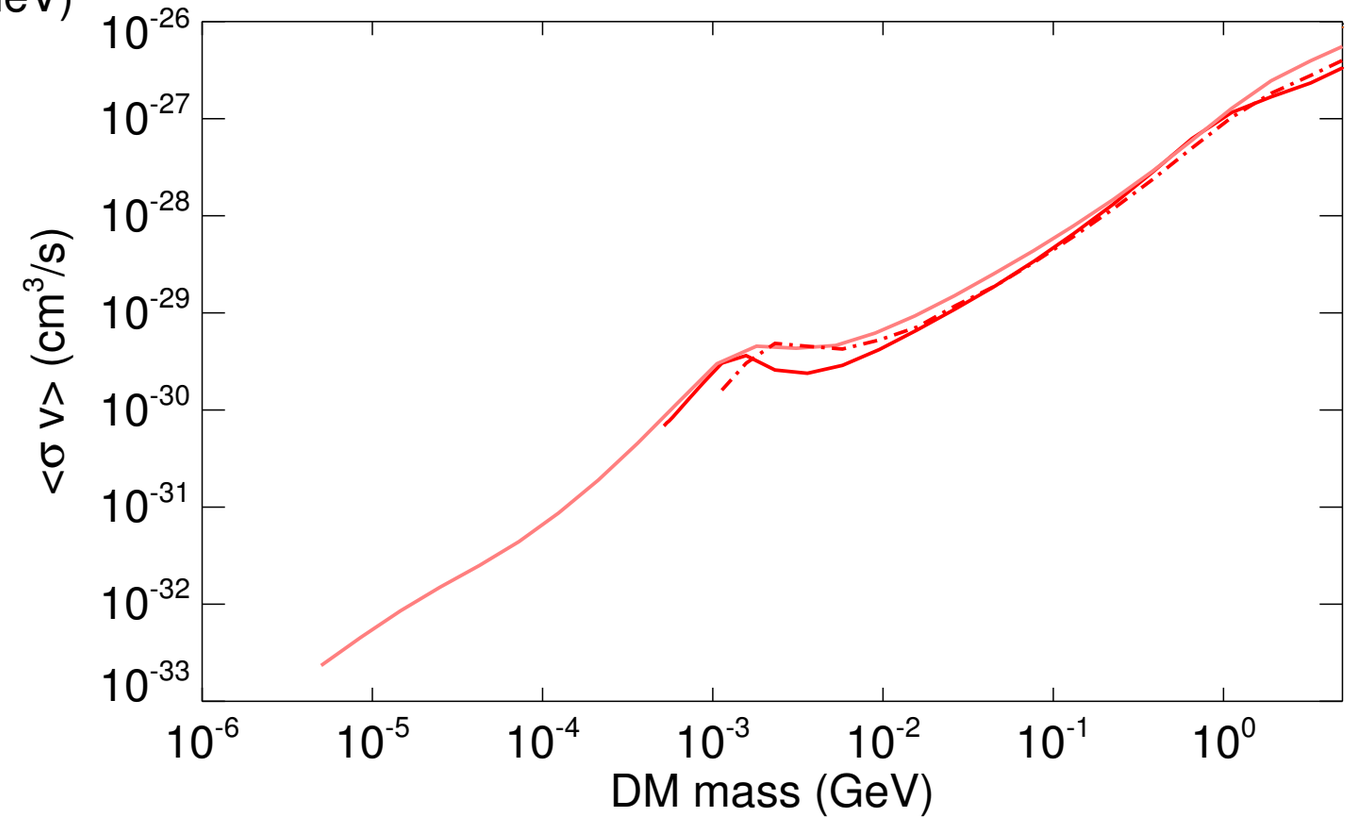
# Comparison: PLANCK






Slatyer 1506.03811



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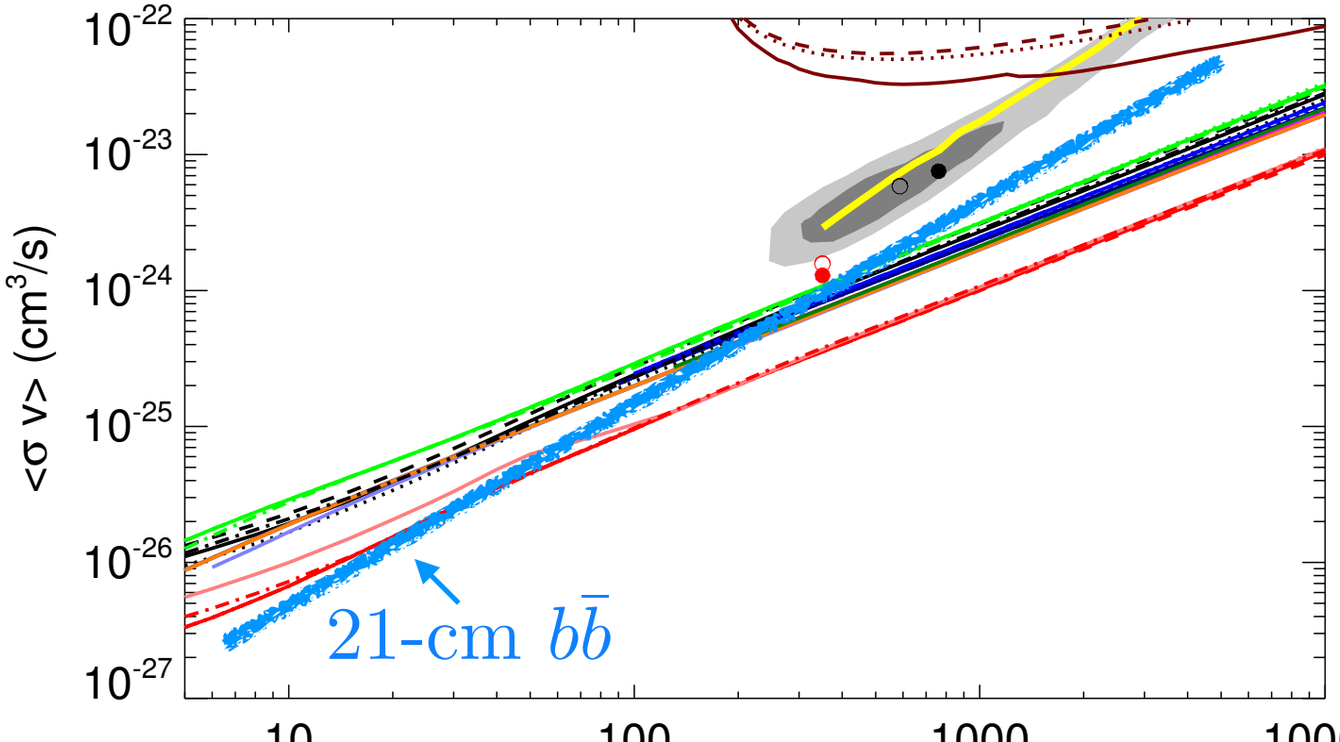


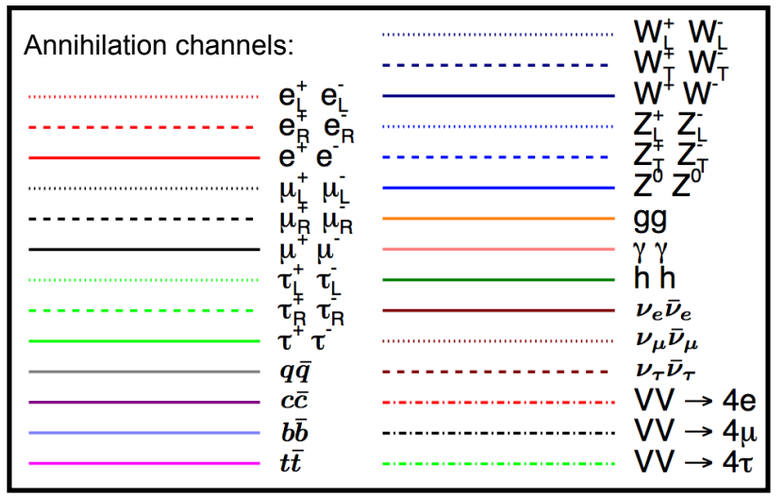


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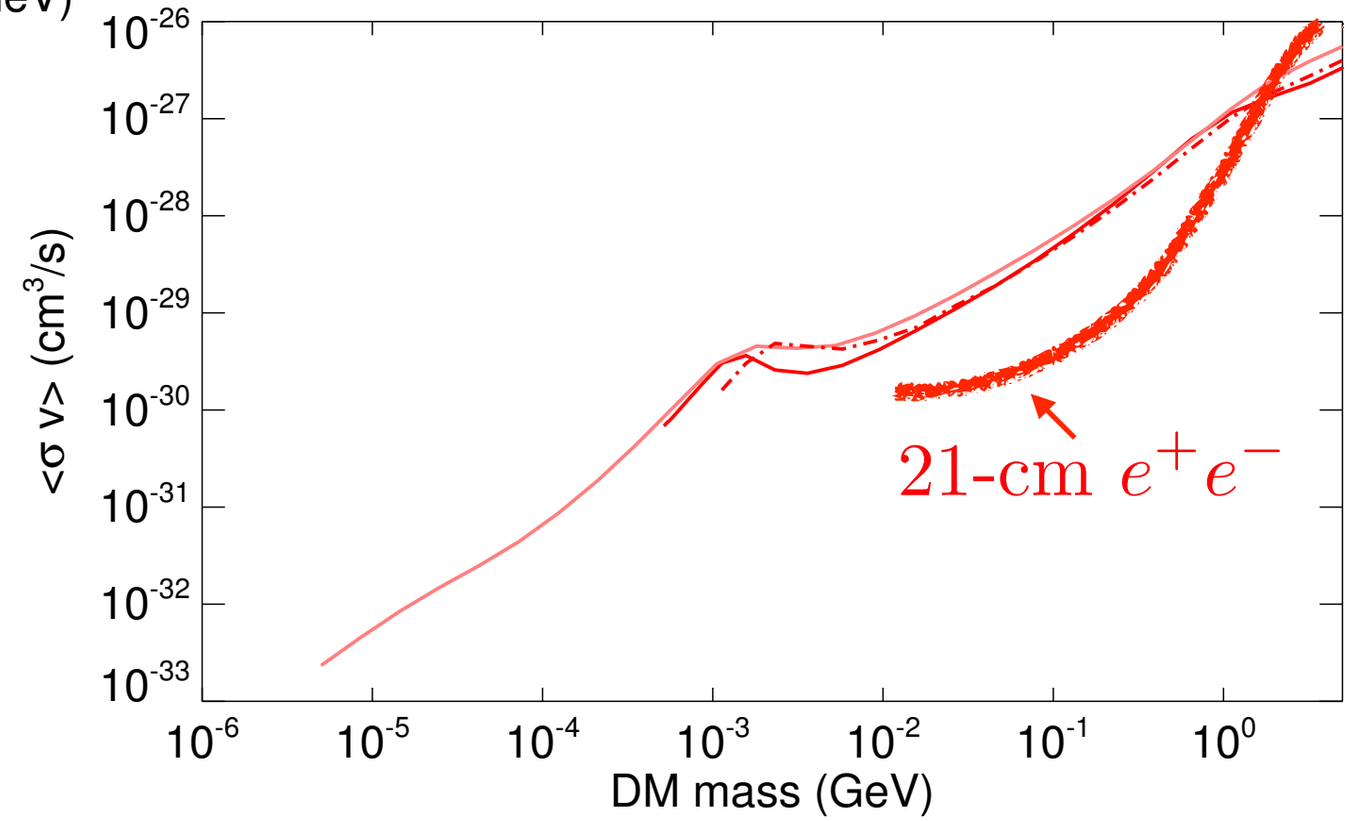
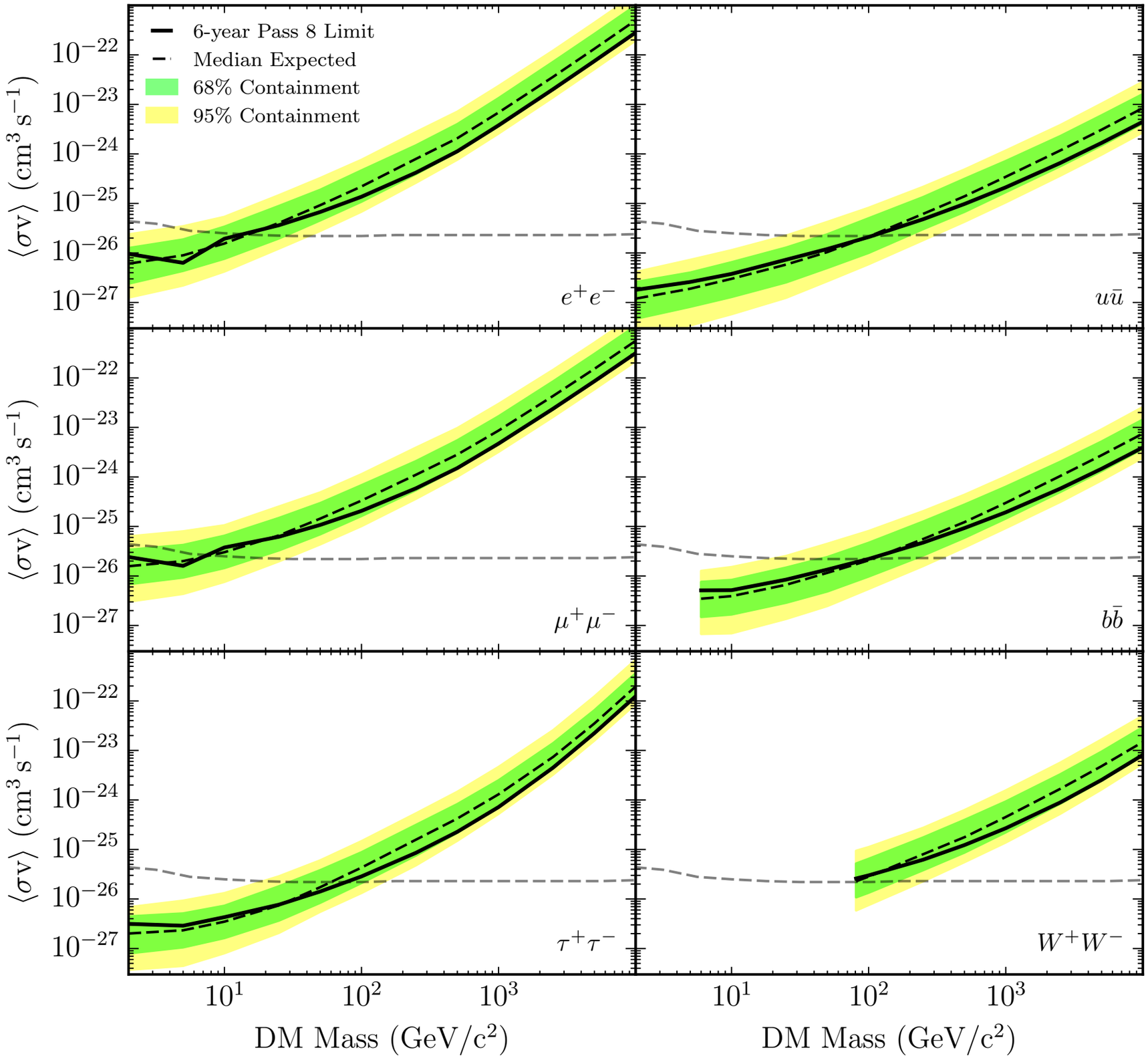


# Comparison: FERMI dSphs






FERMI coll.
1503.02641

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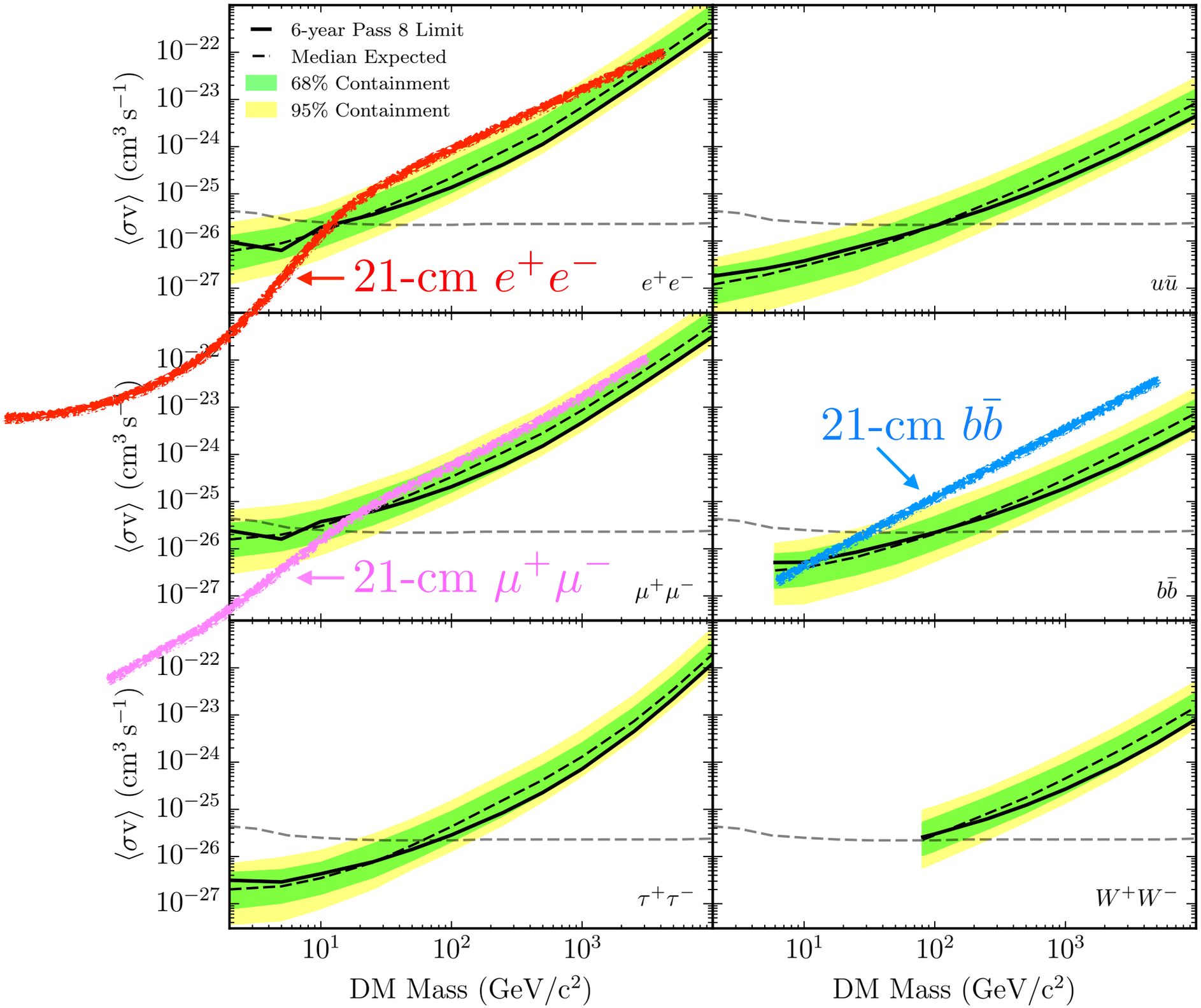


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- This is just the beginning: Stay tuned for further developments!
  Can the monopole 21cm alone shed light on dark matter?

# Backup slides

# EM shower in the IGM

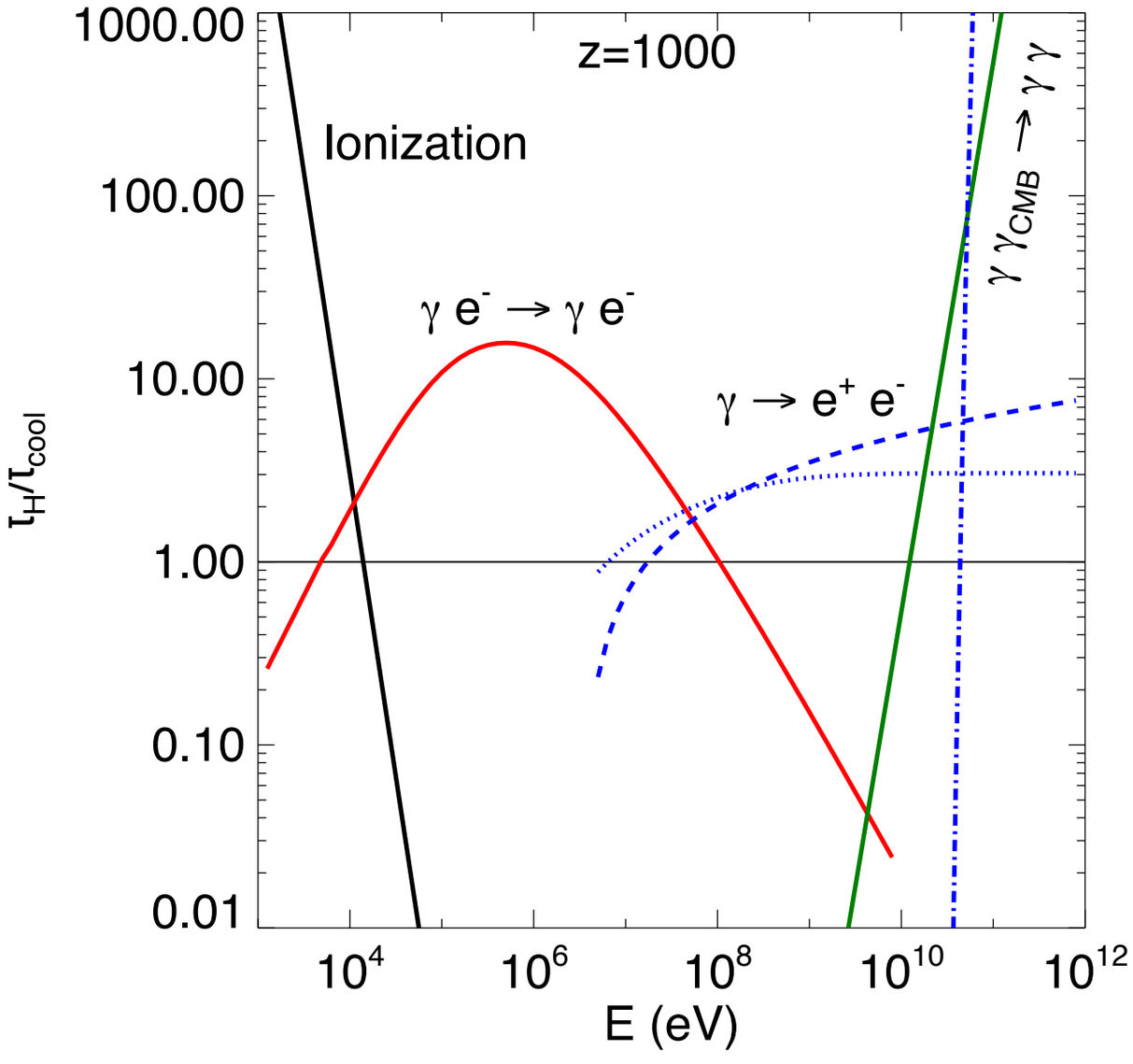


The ***delayed transfer function*** encodes the physics of the EM shower

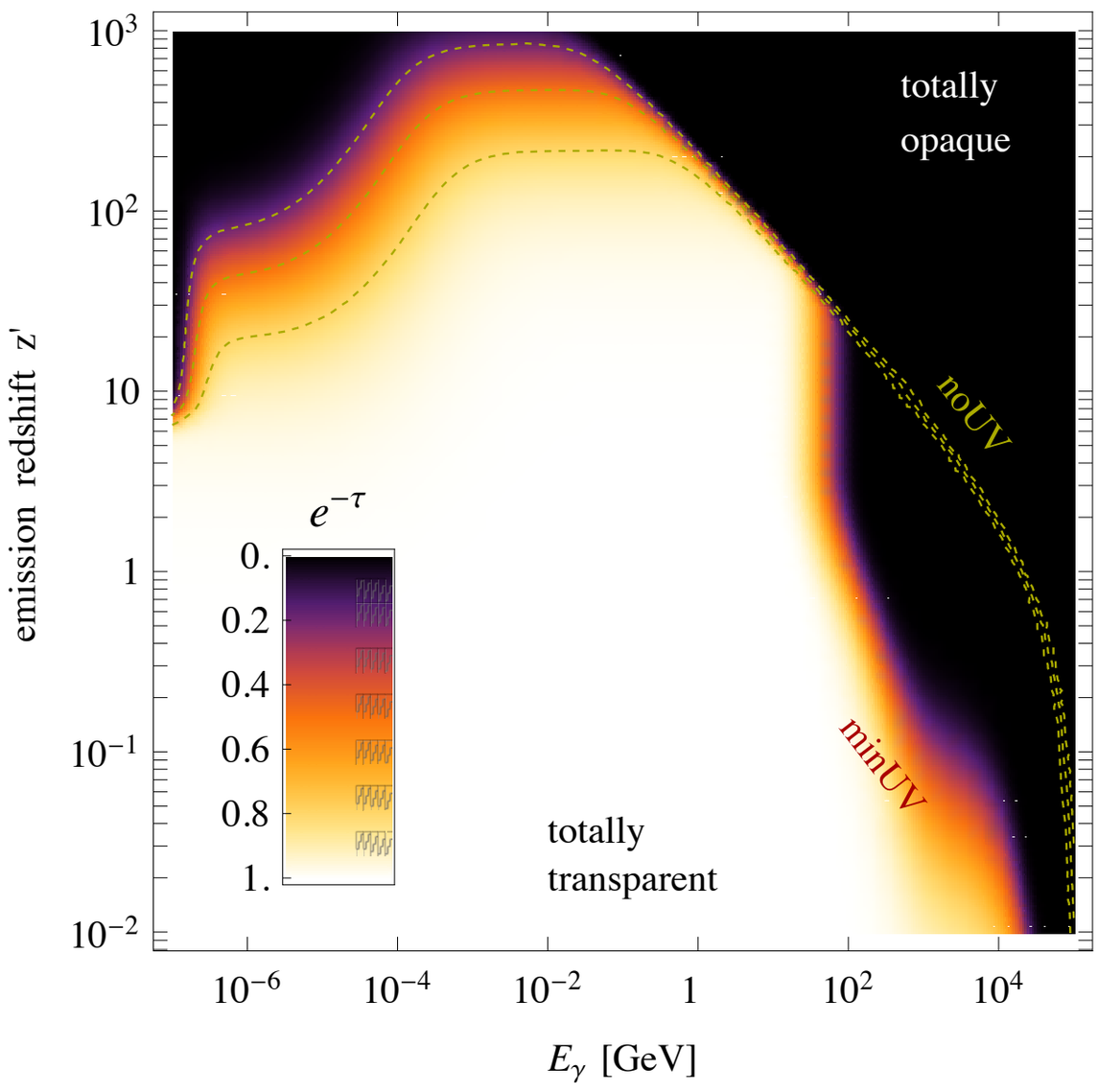
★ *Mean free path of the electrons/positrons* at a given redshift *z*

★ *Absorption of photons in the IGM*

**Cooling time at *z = 1000***



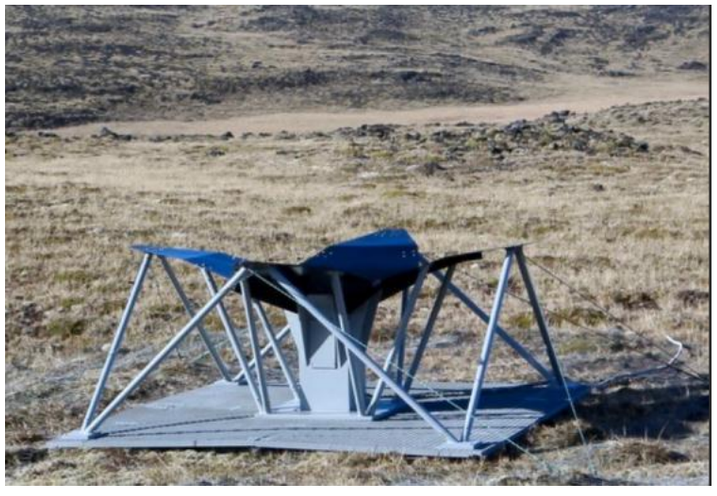

**deposited *z = 0 (Today)***



# World Wide 21cm



PRI$^Z$M
(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.)

Slide from Monsalve's talk @ CERN

# EDGES Fitting procedure



Linearized version of Physically-Motivated foreground model

$$m_{\mathrm{fg}}(\boldsymbol{a_i}) = \boldsymbol{a_0}\left(\frac{\nu}{\nu_n}\right)^{-2.5} + \boldsymbol{a_1}\left(\frac{\nu}{\nu_n}\right)^{-2.5}\left[\log\left(\frac{\nu}{\nu_n}\right)\right] + \boldsymbol{a_2}\left(\frac{\nu}{\nu_n}\right)^{-2.5}\left[\log\left(\frac{\nu}{\nu_n}\right)\right]^2 + \boldsymbol{a_3}\left(\frac{\nu}{\nu_n}\right)^{-4.5} + \boldsymbol{a_4}\left(\frac{\nu}{\nu_n}\right)^{-2}$$

Alternative Polynomial Model

$$m_{\mathrm{fg}}(\boldsymbol{a_i}) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \sum_{i=0}^{N_{\mathrm{fg}}-1} \boldsymbol{a_i}\left(\frac{\nu}{\nu_n}\right)^{i}$$

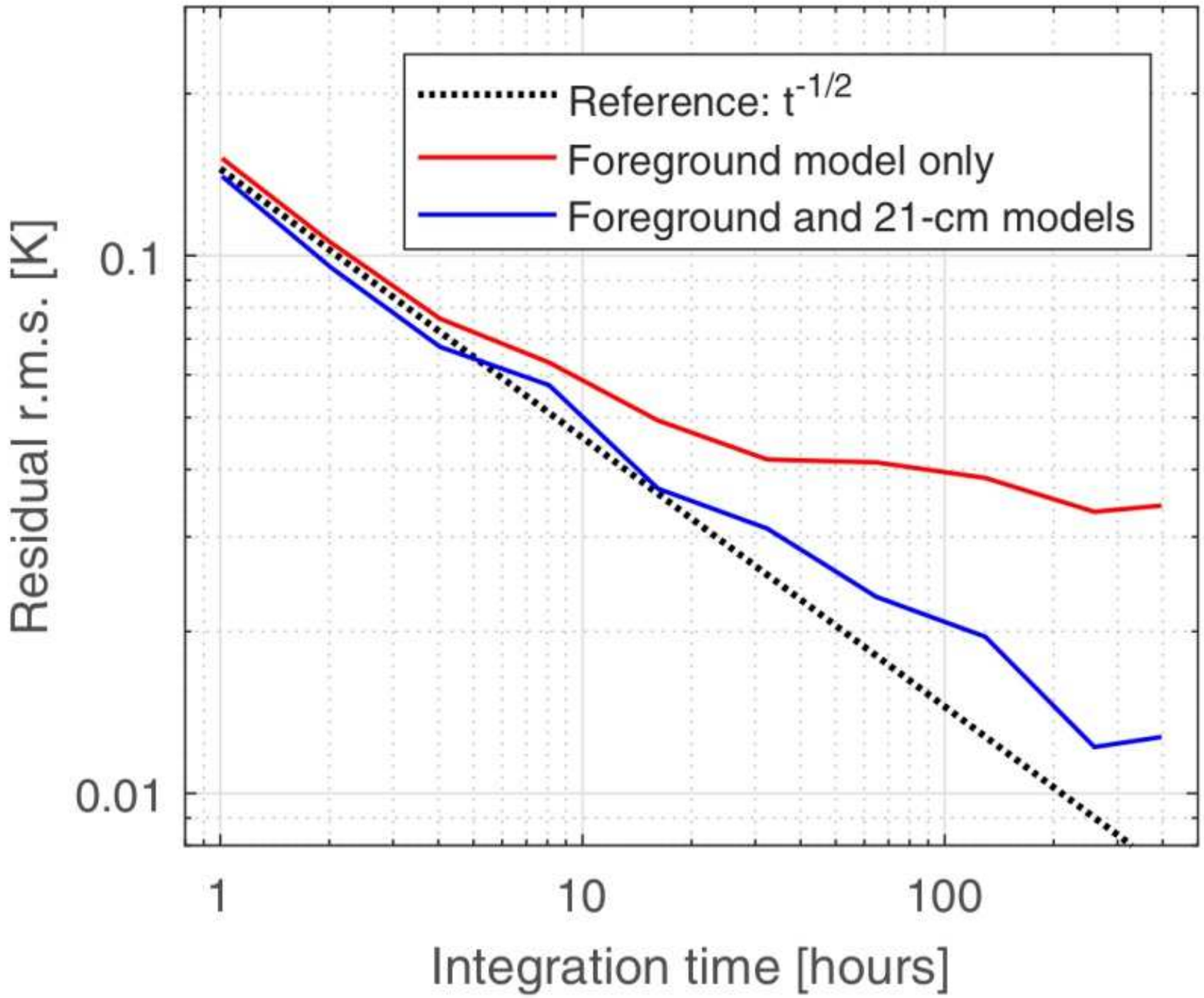
**Smooth sets of basis functions** that model well, with few terms, the spectrum over wide frequency ranges.

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

Slide from Monsalve's talk @ CERN

# EDGES Residuals r.m.s.






Slide from Monsalve's talk @ CERN

# Explain the Anomaly



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

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

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

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

- Approach 1: *Cool the baryonic kinetic temperature even more* (90% of attemps: see e.g. Barkana et al.; Munoz, Loeb; ….)
- Approach 2: *Make more photons* that can mediate the 21-cm transition prior $z\sim20$ (Pospelov, Pradler, Ruderman, Urbano)
- Approach 3: *Decouple protons from the CMB earlier* (Falkowski & Petraki)

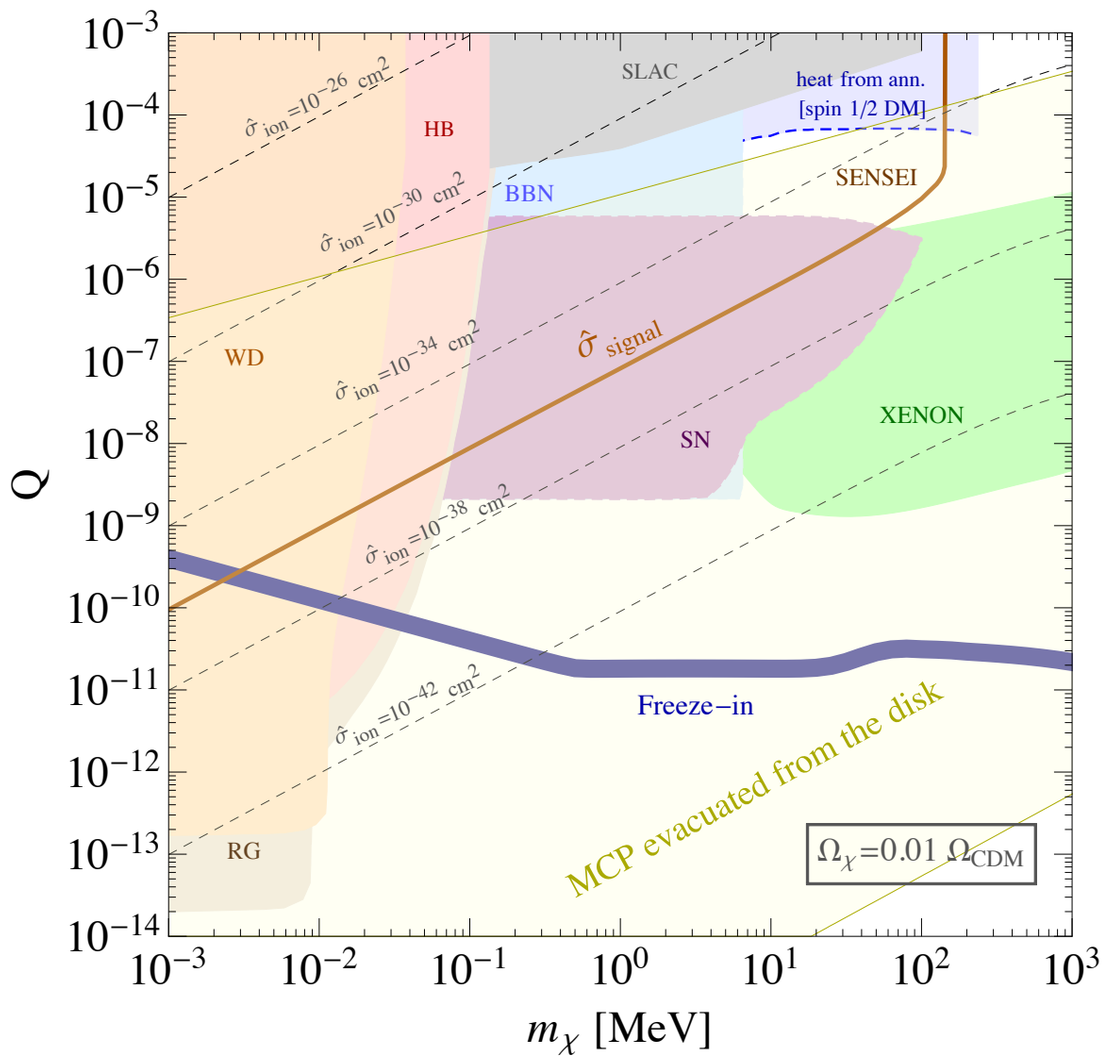
# 1: Cool the IGM even more



*Entropy transfer from the baryonic to the Dark sector*

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

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




$$m_\chi \simeq (10 - 80)\ \mathrm{MeV}\ ,$$
$$Q \simeq (10^{-6} - 10^{-4})\ ,$$
$$f_{\rm DM} \simeq (0.1 - 2)\%$$

Barkana *et al.*
1803.03091

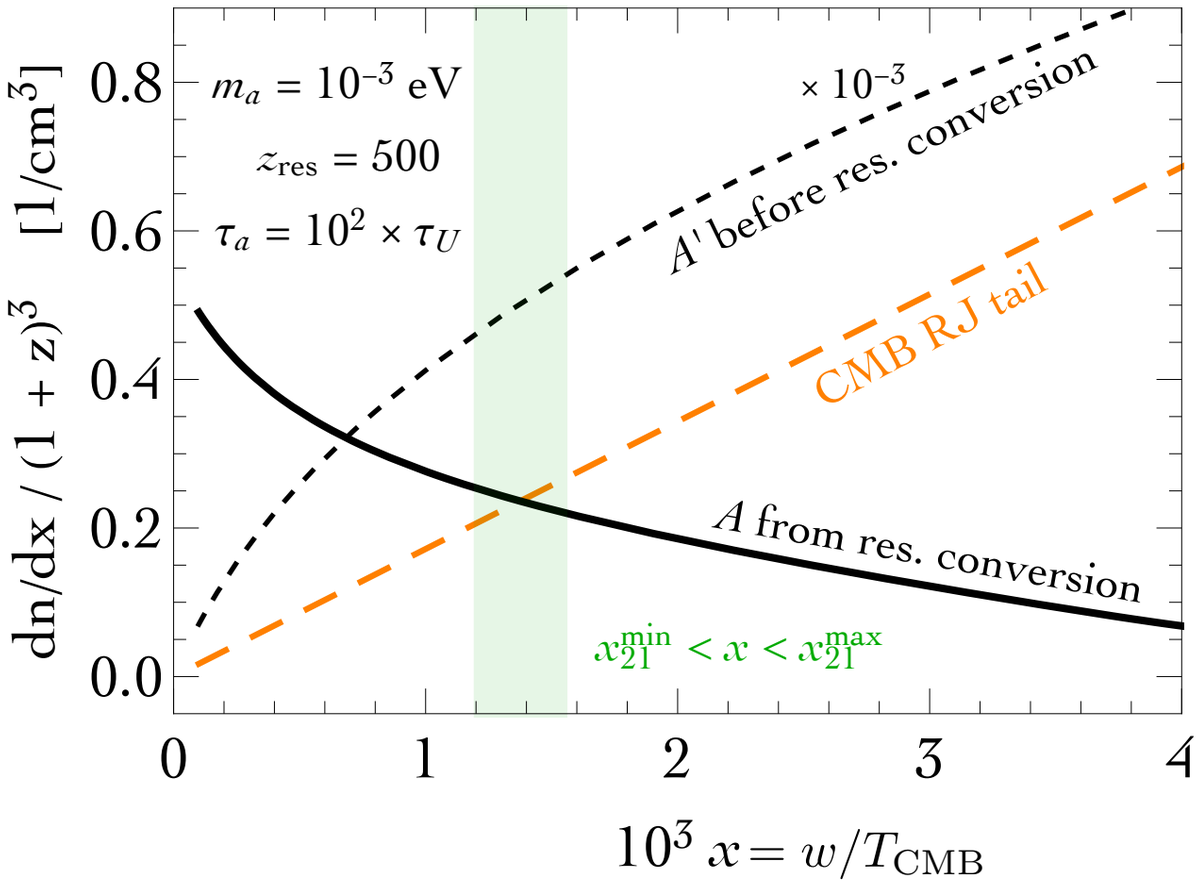
# 2: Increase the CMB RJ tail

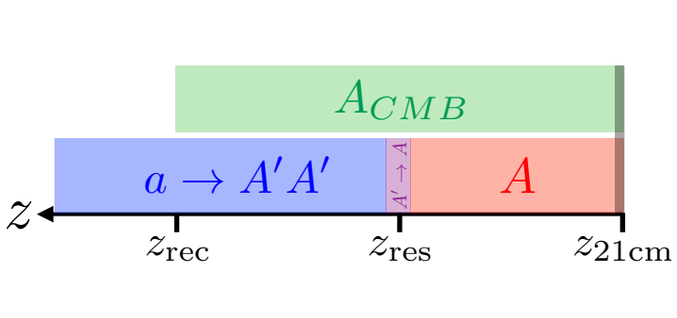


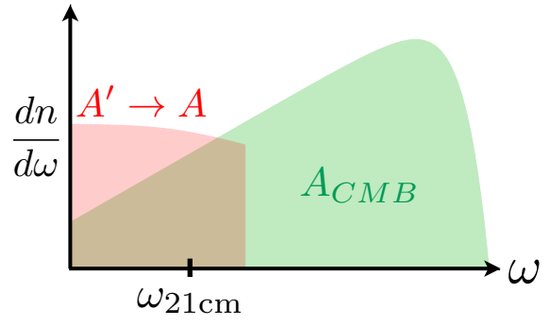
Early ($z > 20$) decays (either DM or of DR species) create a non-non-thermal ***population of DR dark photon A'***. Typical multiplicity is larger than $n_{\rm RJ}$

Dark photons can oscillate to normal photons. At some redshift $z_{\rm res}$ a resonant ***oscillation of A' into A.*** This happen 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

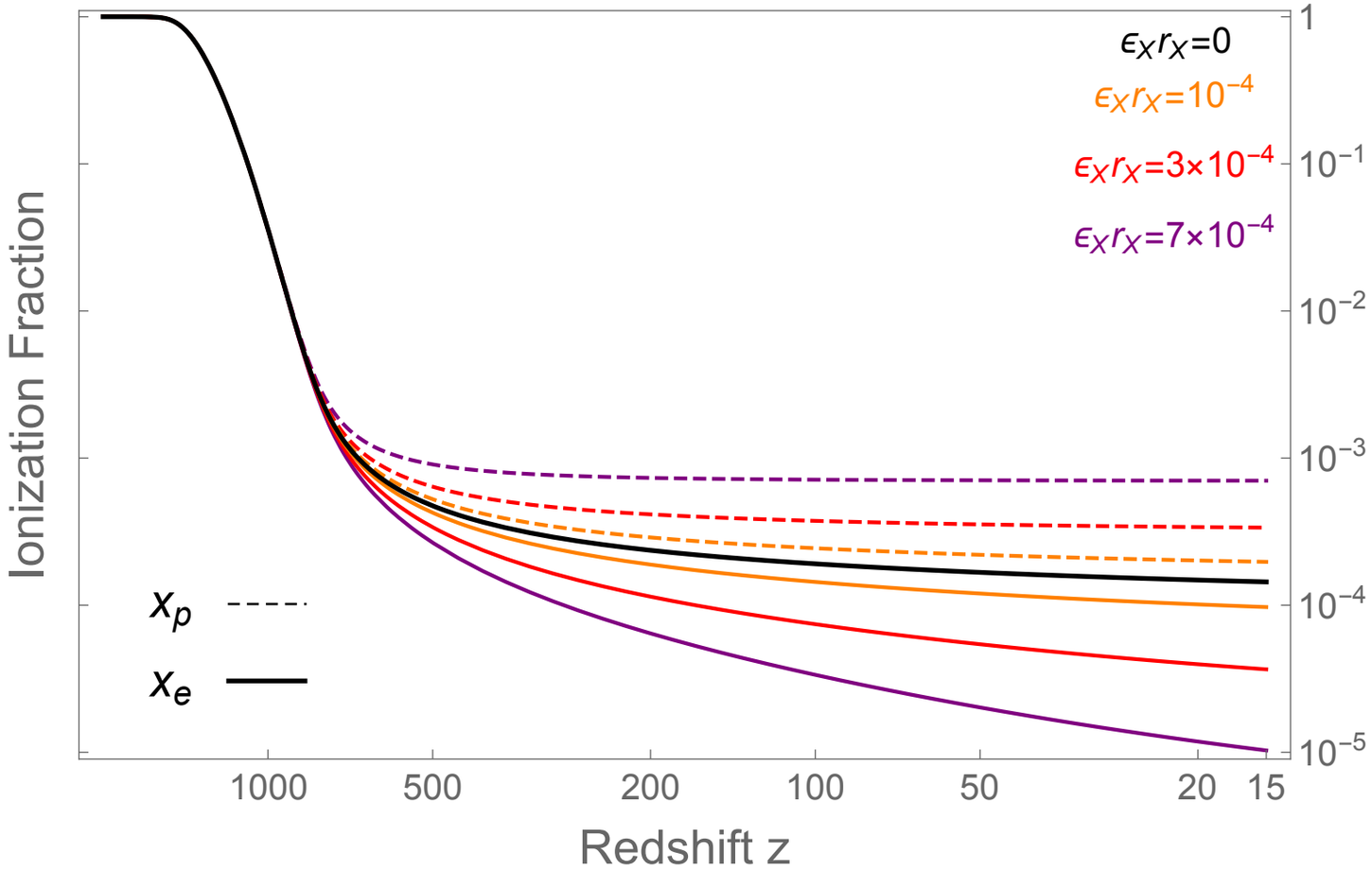


Postulate that there is a ***mismatch between proton and electron numbers*** in the Universe, such that $n_e < n_p$

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