Gran Sasso Science Institute
13/02/2019

The 21-cm signal seen by EDGES

PAOLO PANCI

Based on G. D'Amico, PP, A. Strumia arXiv: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 & Discussions

What happened in March

LETTER

doi:10.1038/nature25792

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

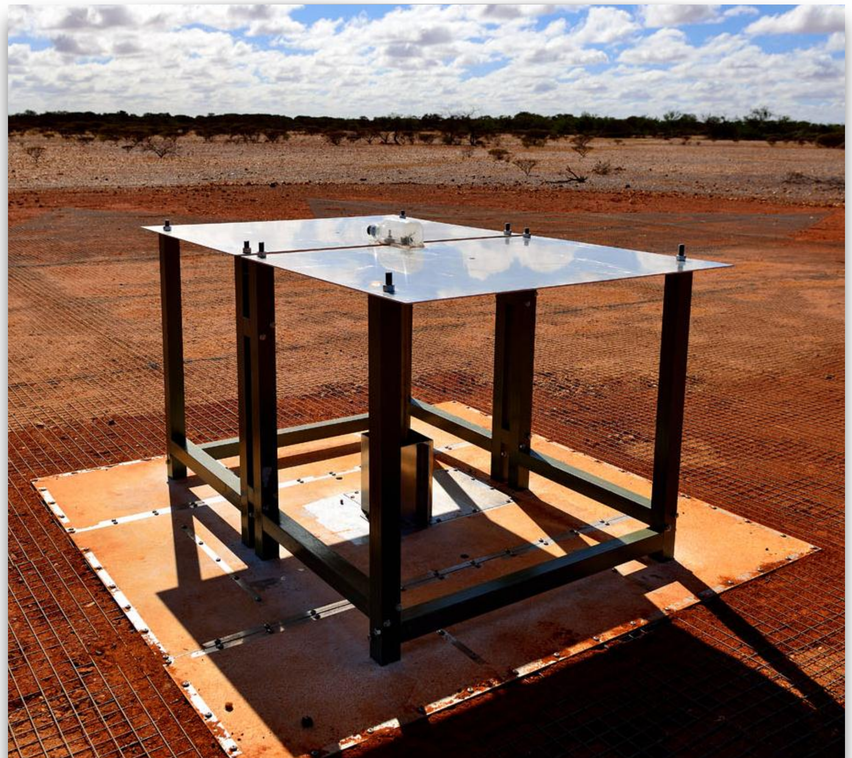
Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

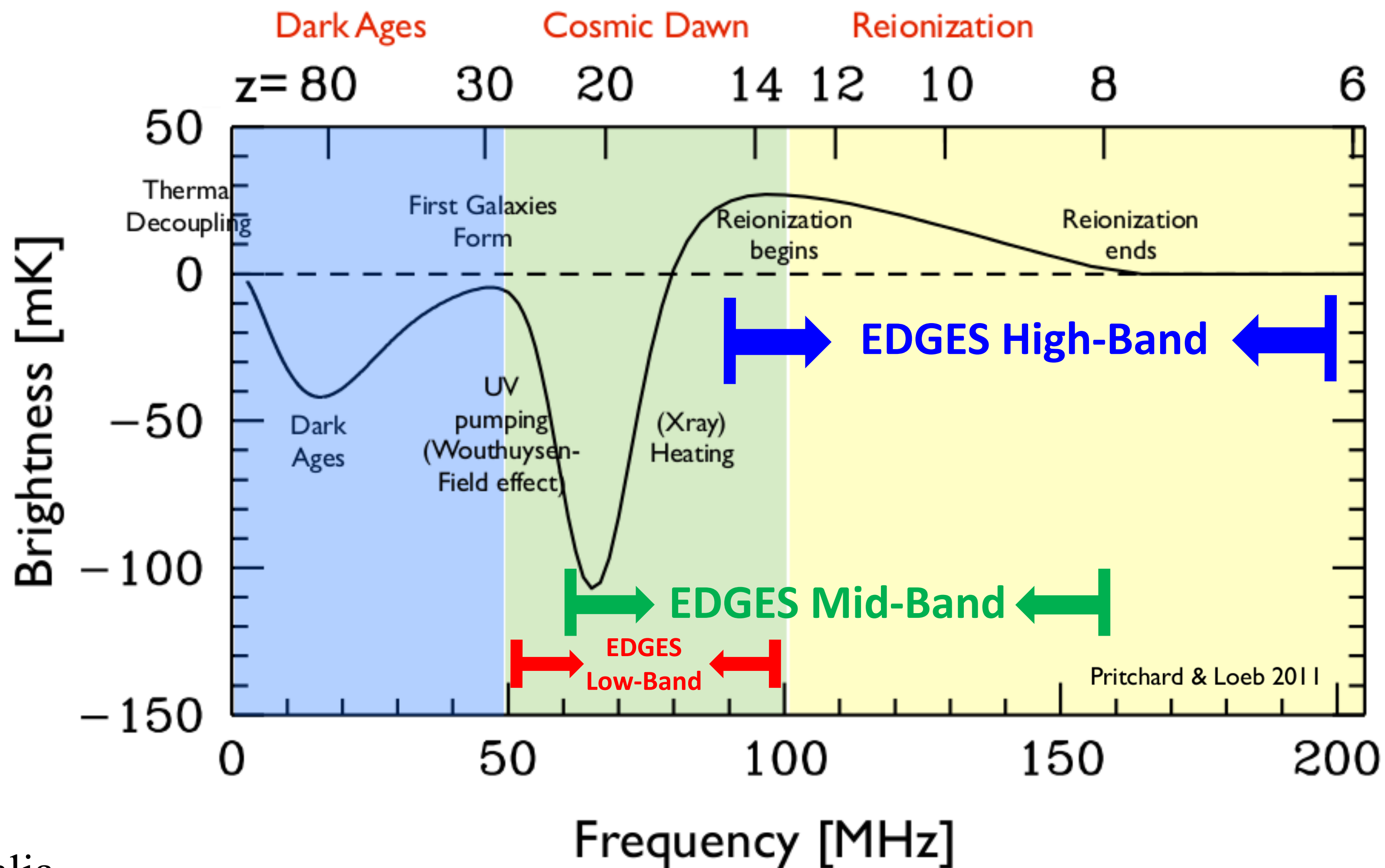
A 21-cm signal in *absorption*

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

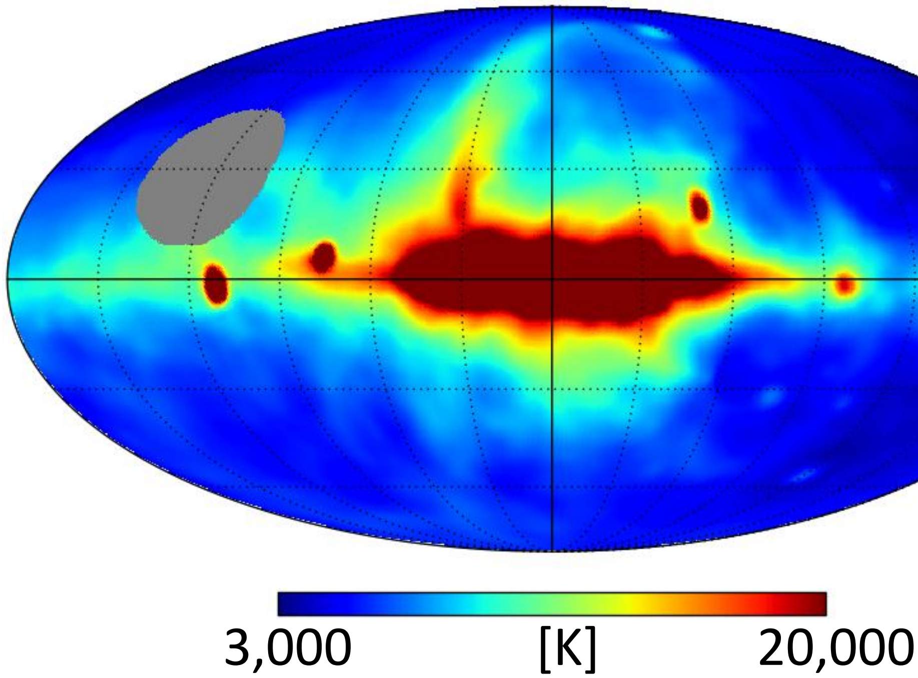
Low-band antenna: Designed to observe a spectral distortion in the 21-cm energy band at $z \sim 20$ due to the absorption of CMB photons by the IGM

Large synchrotron bkg.

Diffuse Foregrounds

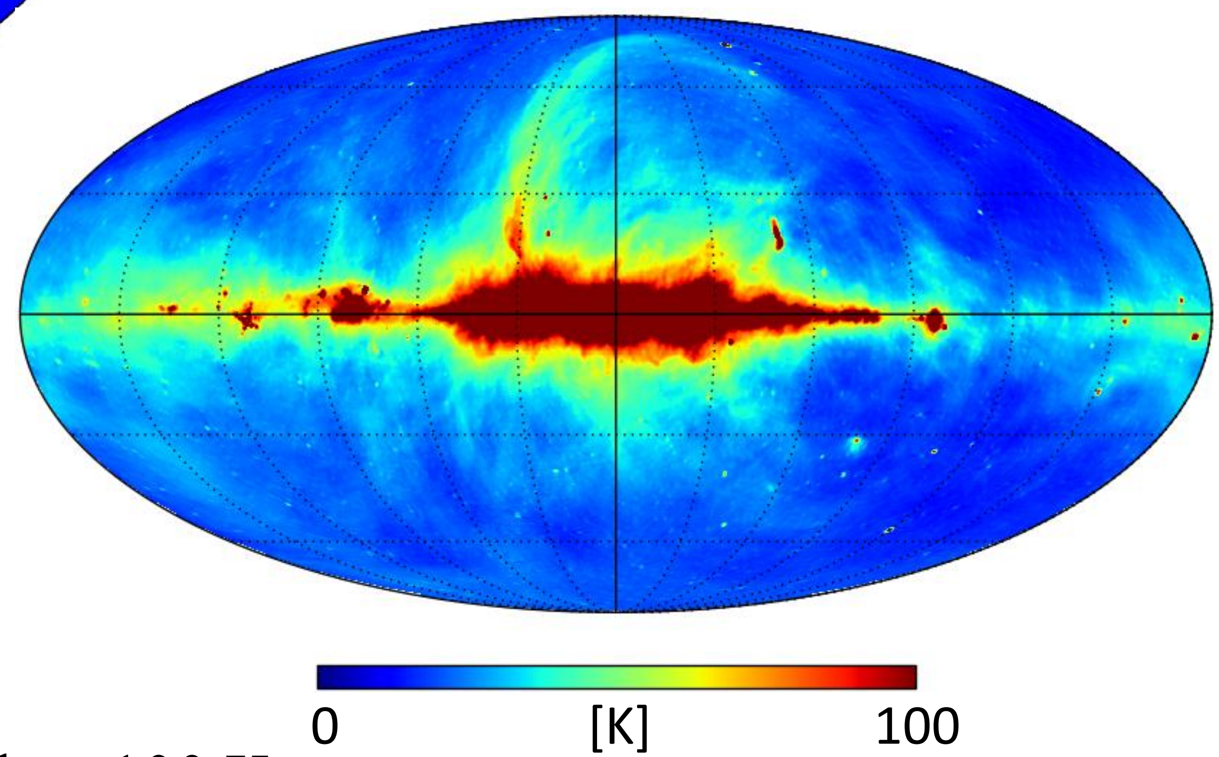
45-MHz Map

Guzmán et al. (2011)



408-MHz Map

Haslam et al. (1982)



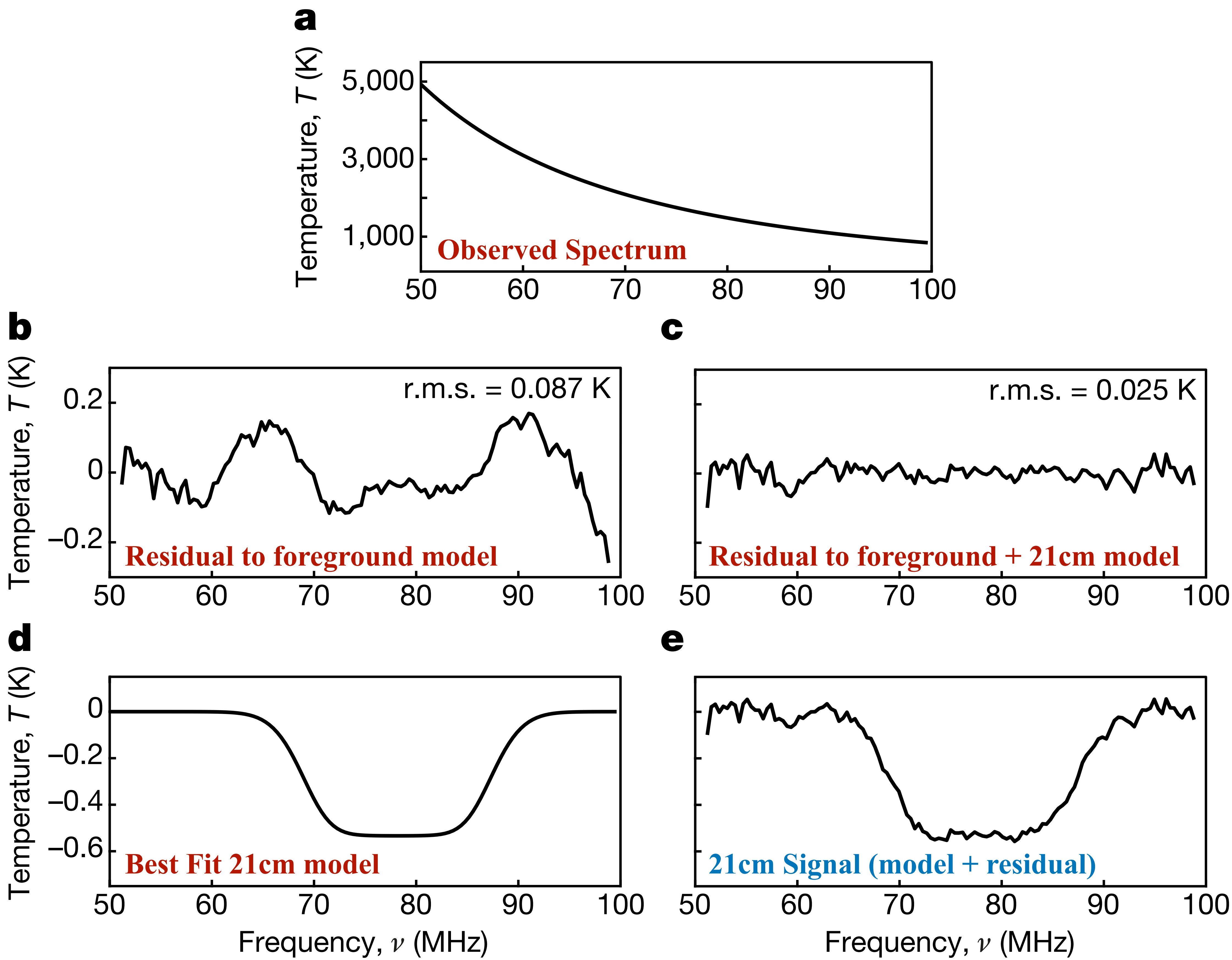
Main features of the Diffuse Foregrounds:

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

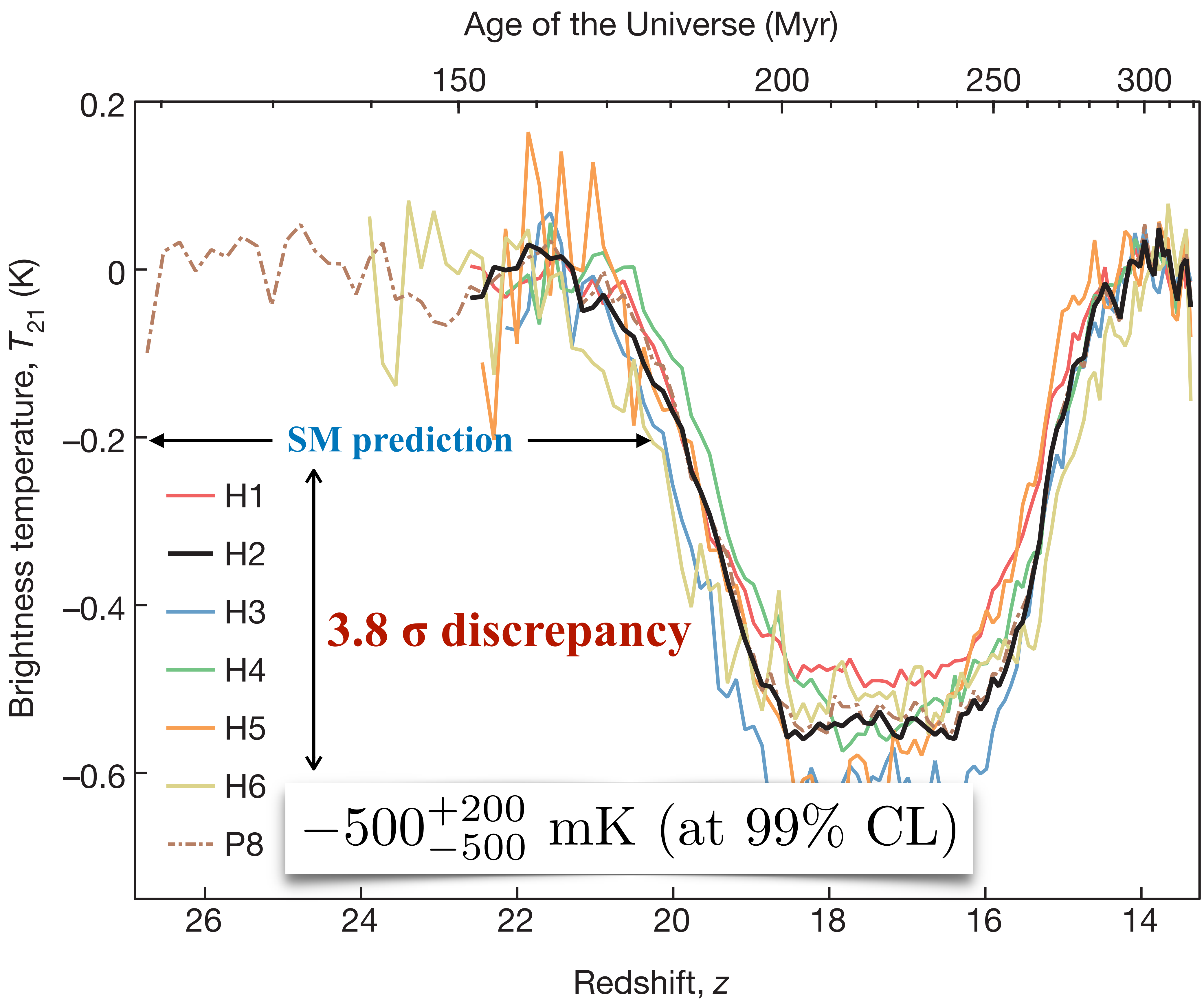
2) **Spectrally smooth** but might need **several terms** to model (see e.g. Bernardi et al. 2015)

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

What did EDGES see?



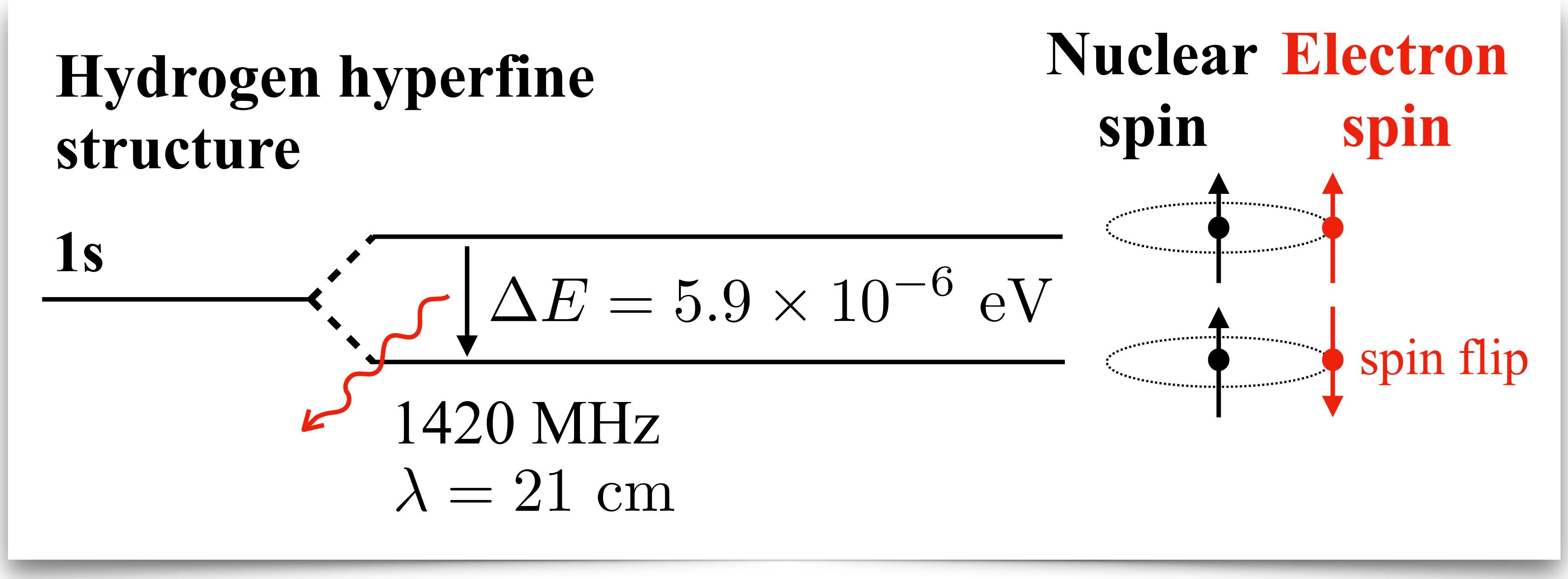
Some analysis of systematics



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

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

What sets the relative occupation?

Excited by what?

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➡ **Absorption** of background CMB photon

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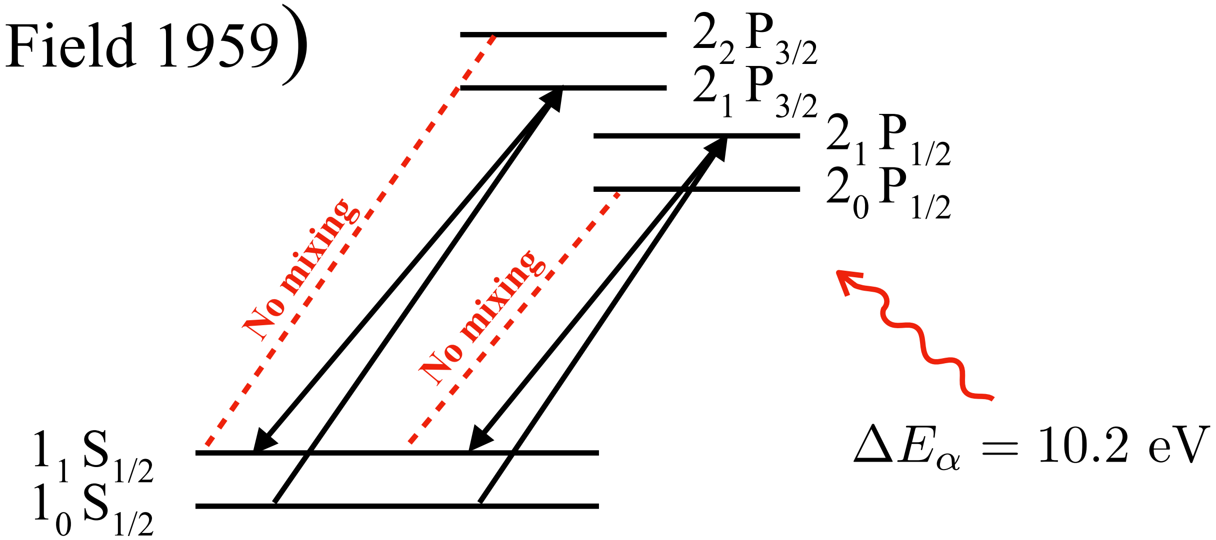
- ➡ **Ly-α pumping** (Wouthuysen 1952, Field 1959)



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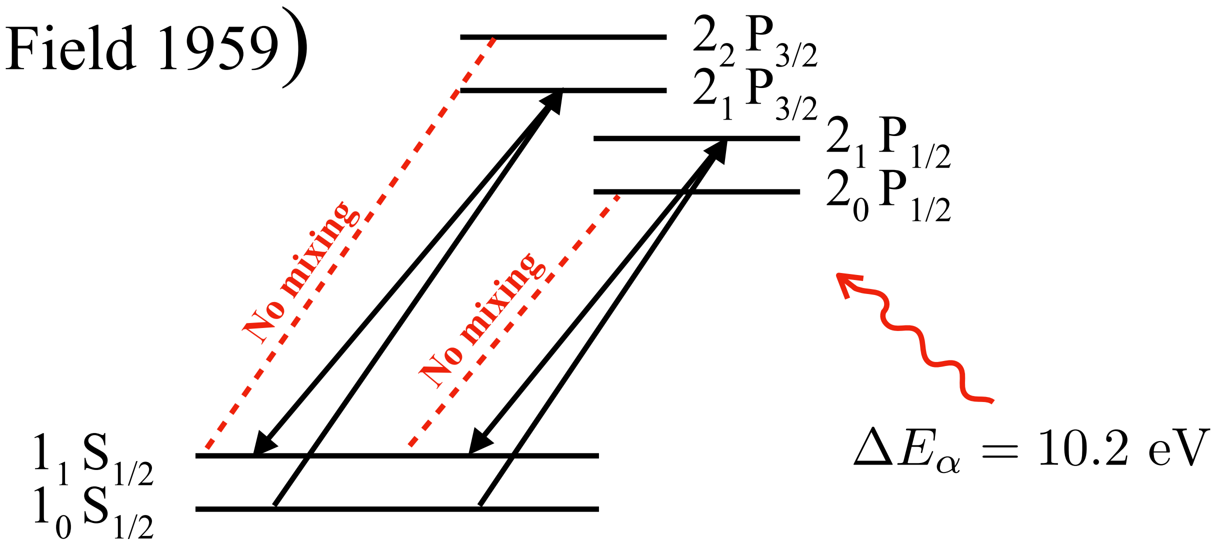
- **Absorption** of background CMB photon
- **Collisions**: important when density is high
- **Ly-α pumping** (Wouthuysen 1952, Field 1959)



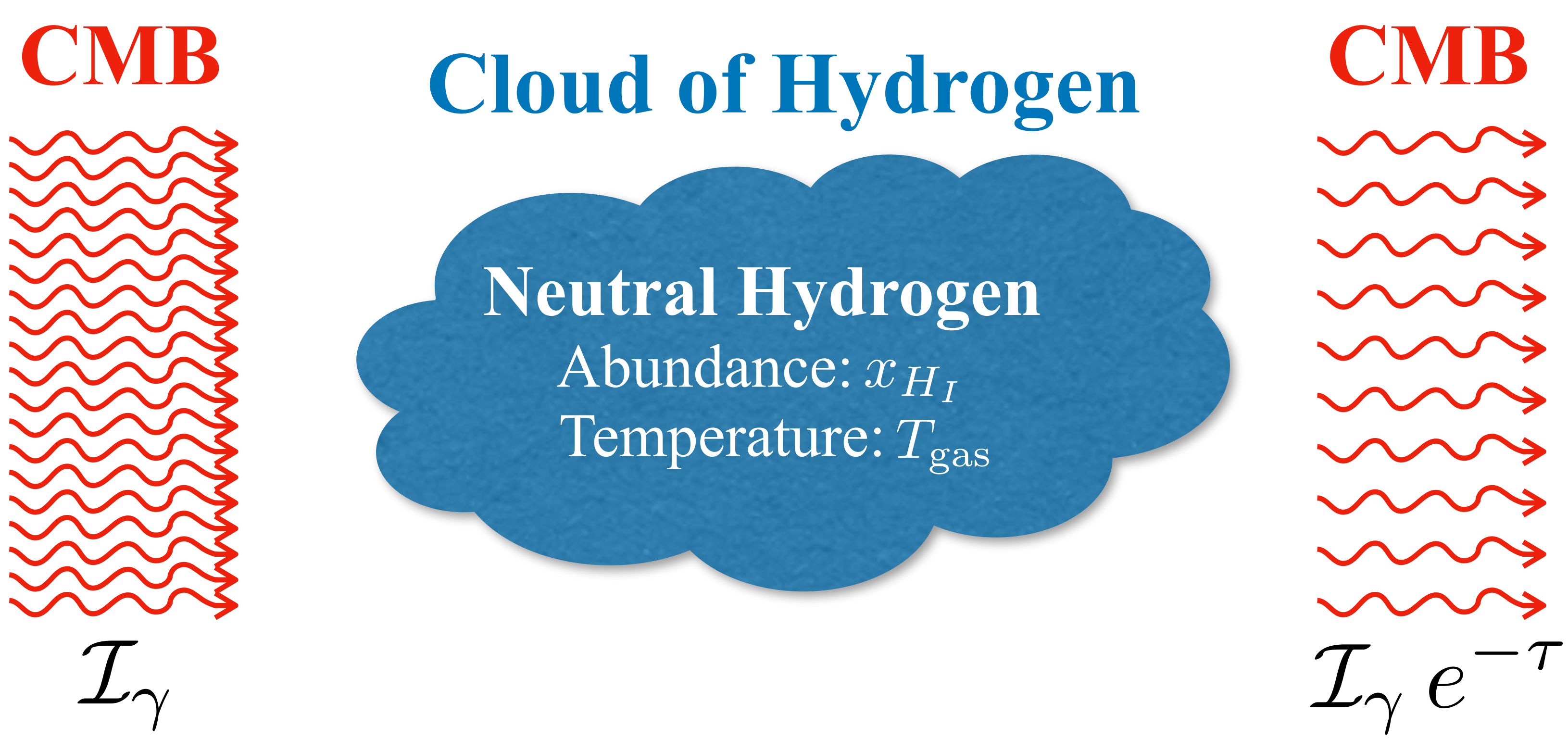
Equilibrium implies:

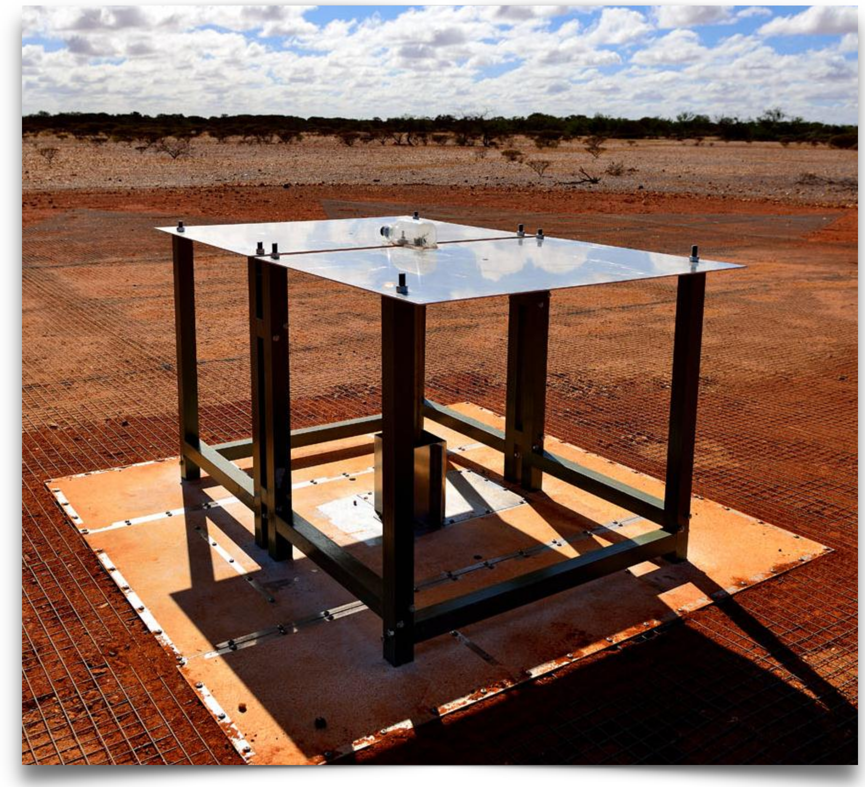
$$n_{\uparrow\uparrow}(\mathcal{C}_{10} + \mathcal{P}_{10} + \mathcal{A}_{10} + \mathcal{B}_{10} I_\gamma) = n_{\uparrow\downarrow}(\mathcal{C}_{01} + \mathcal{P}_{01} + \mathcal{B}_{01} I_\gamma)$$

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





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

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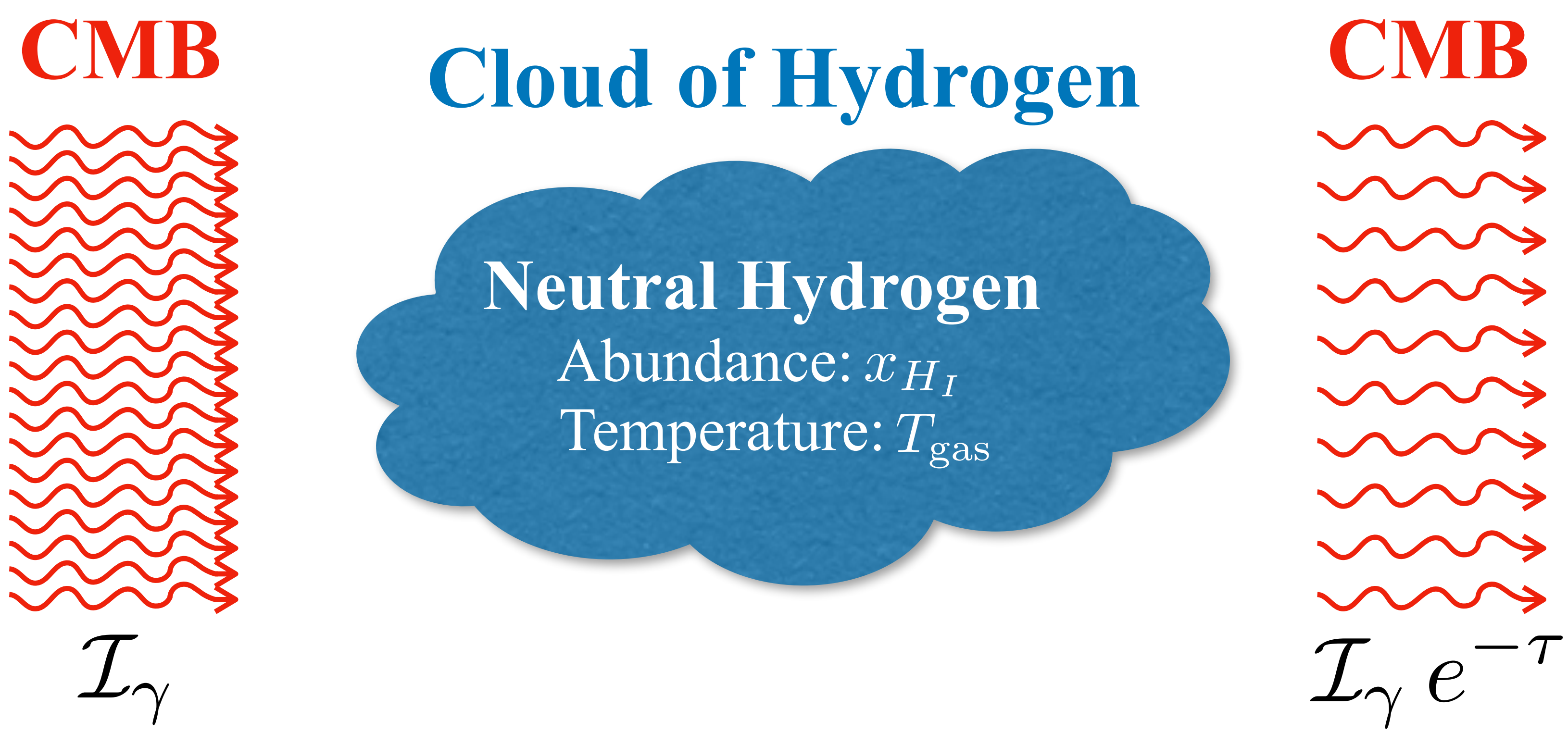
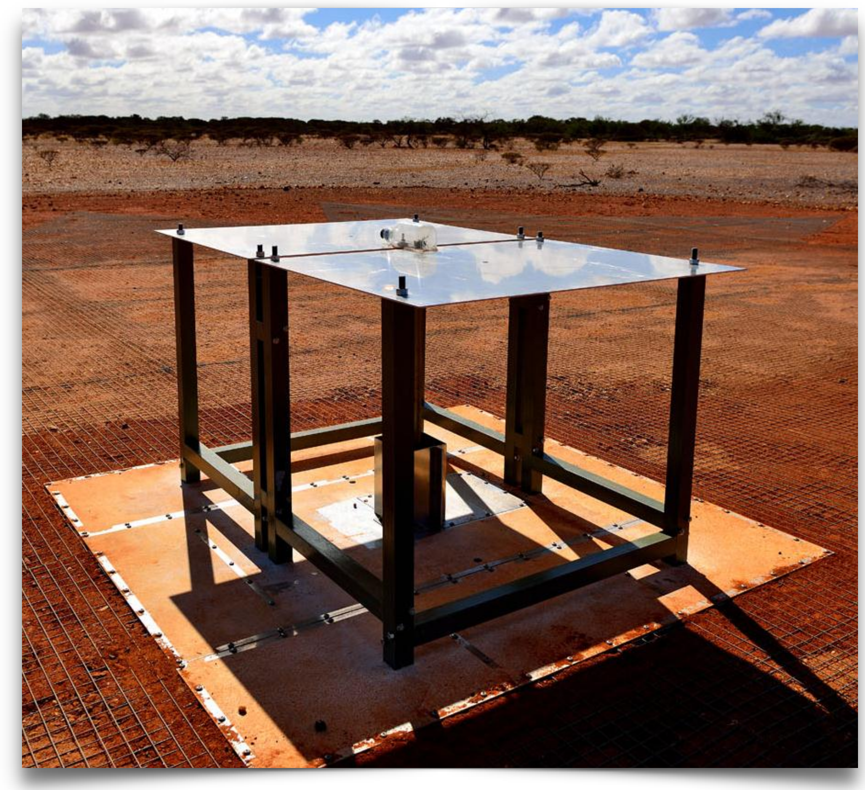




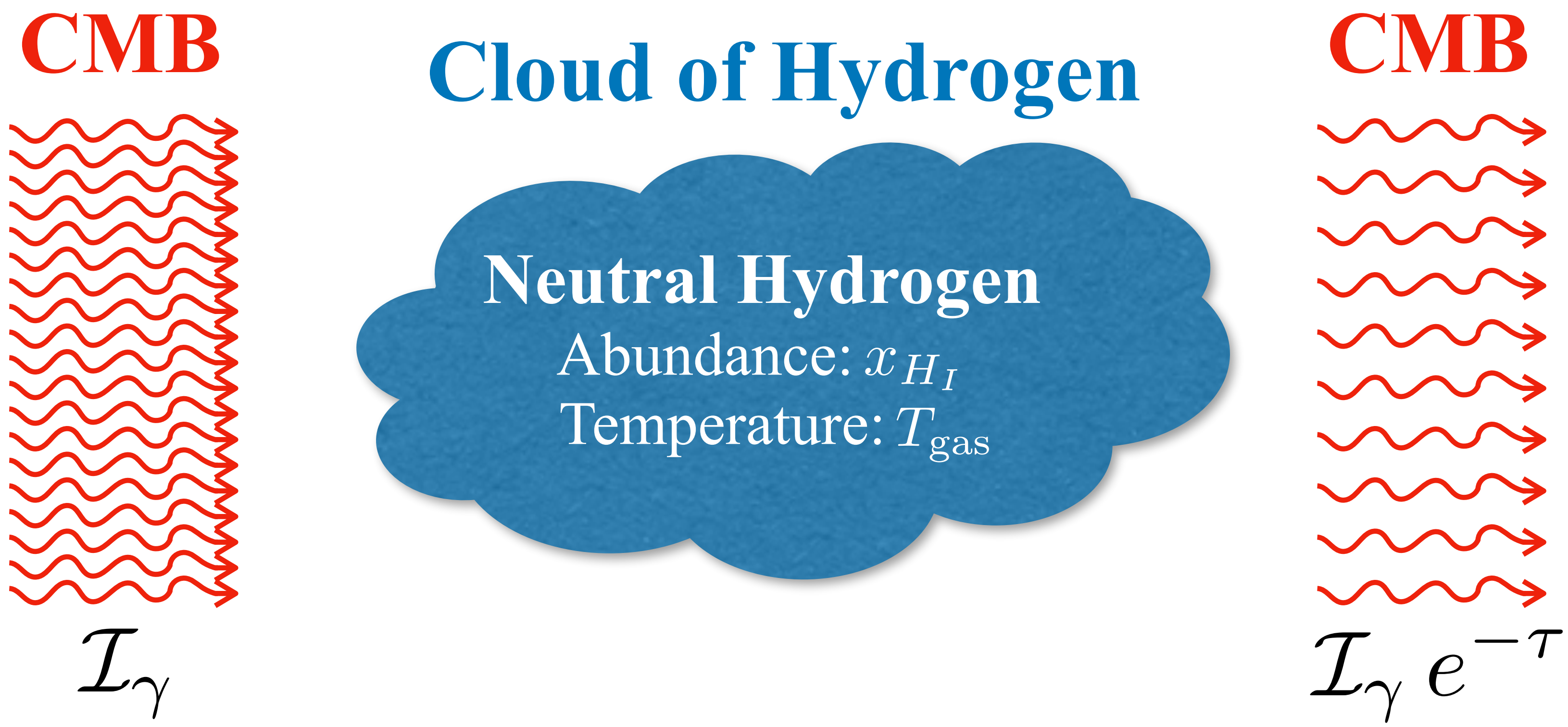
$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

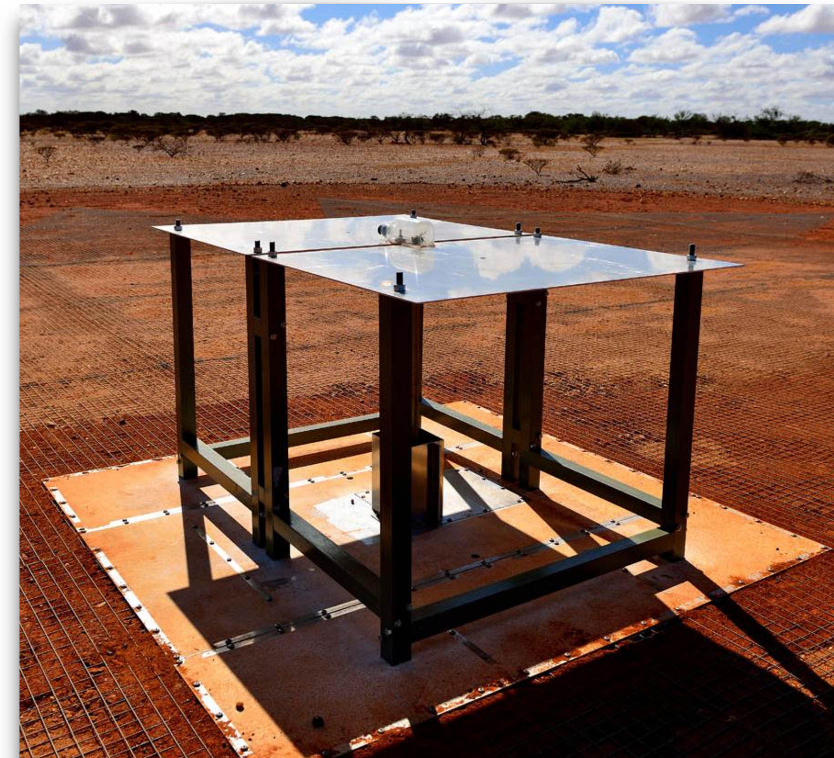
$$T_{21} \propto \mathcal{I}_\gamma (1 - e^{-\tau}) \approx I_\gamma \tau \approx 21\,\mathrm{mK}\, x_{H_I} \left(1 - \frac{T_{\rm CMB}}{T_S}\right) \sqrt{\frac{1+z}{10}}$$

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

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

What we see





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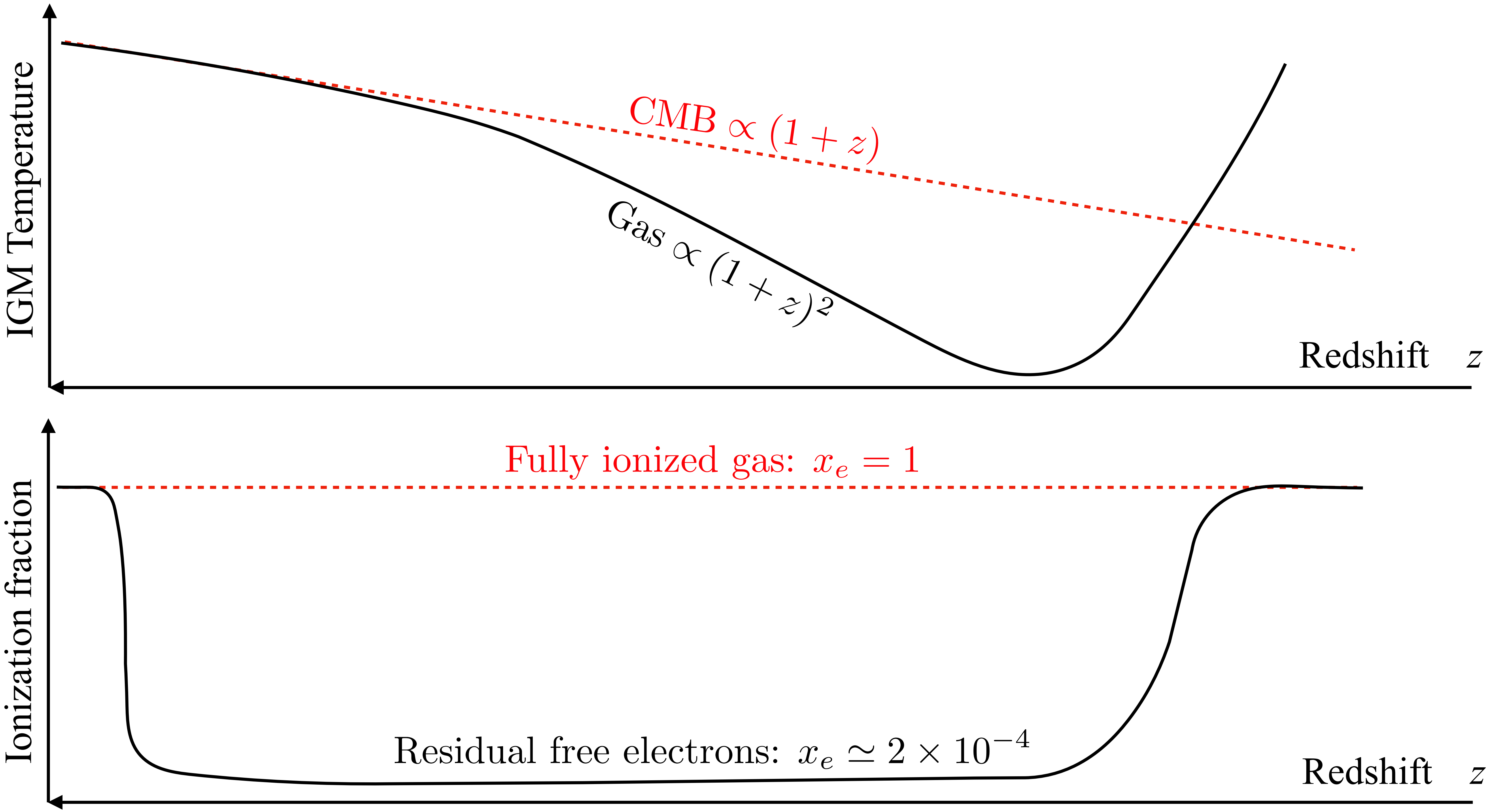
EDGES measurement implies

$T_{\rm CMB}/T_S \simeq 19$ at $z = 17$

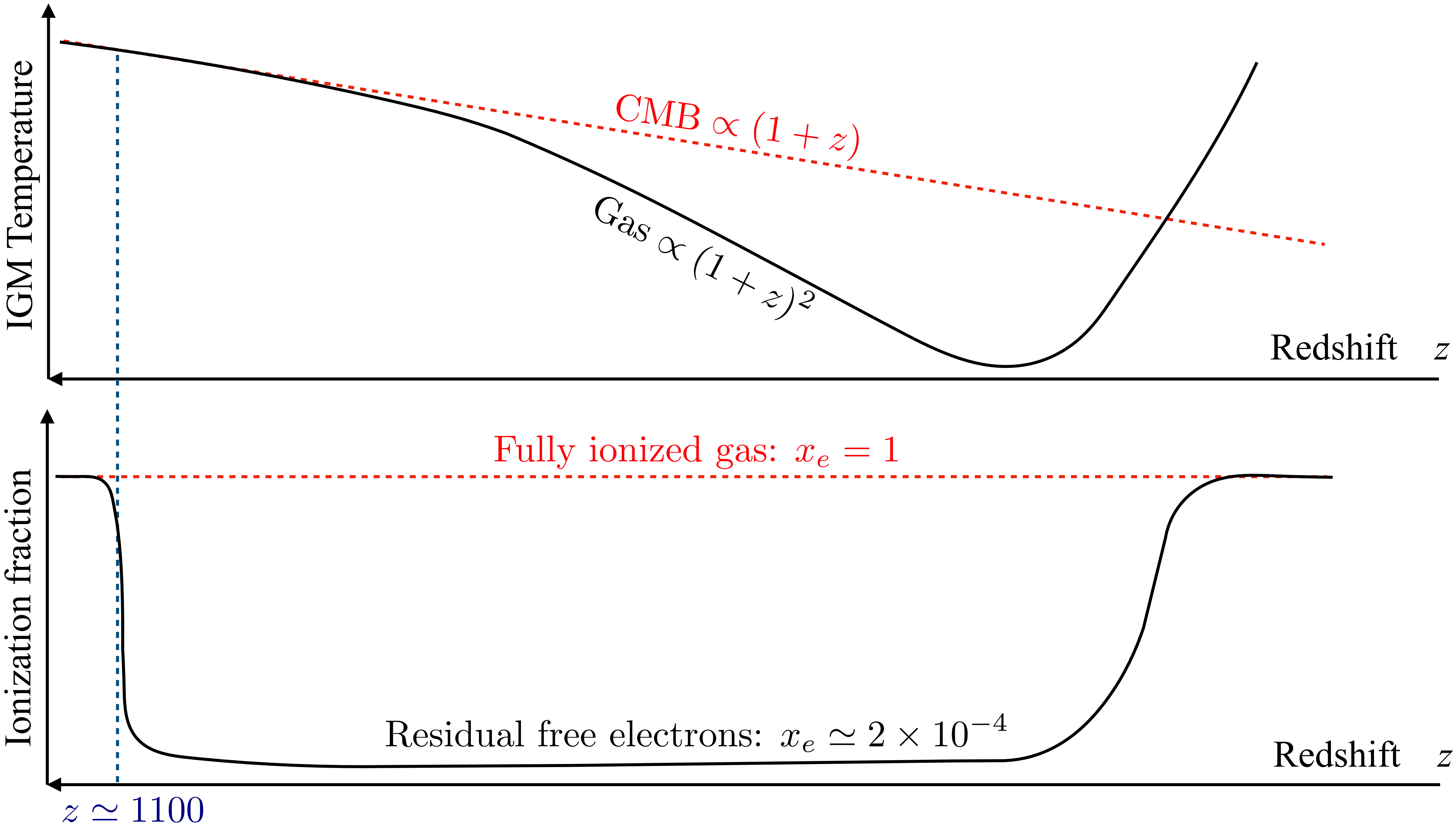
$T_S \simeq 3$ K

A short history of the IGM



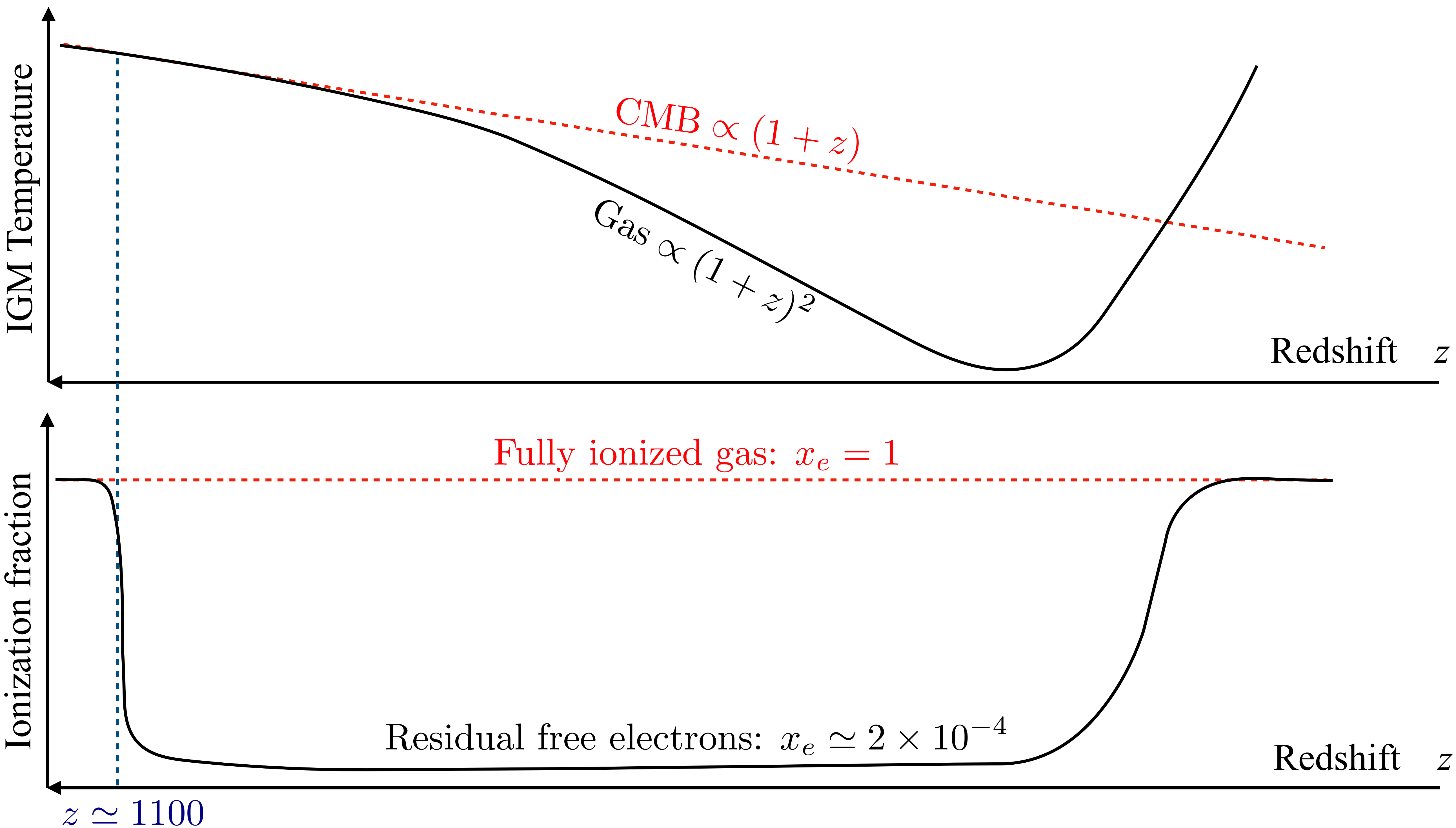
A short history of the IGM

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



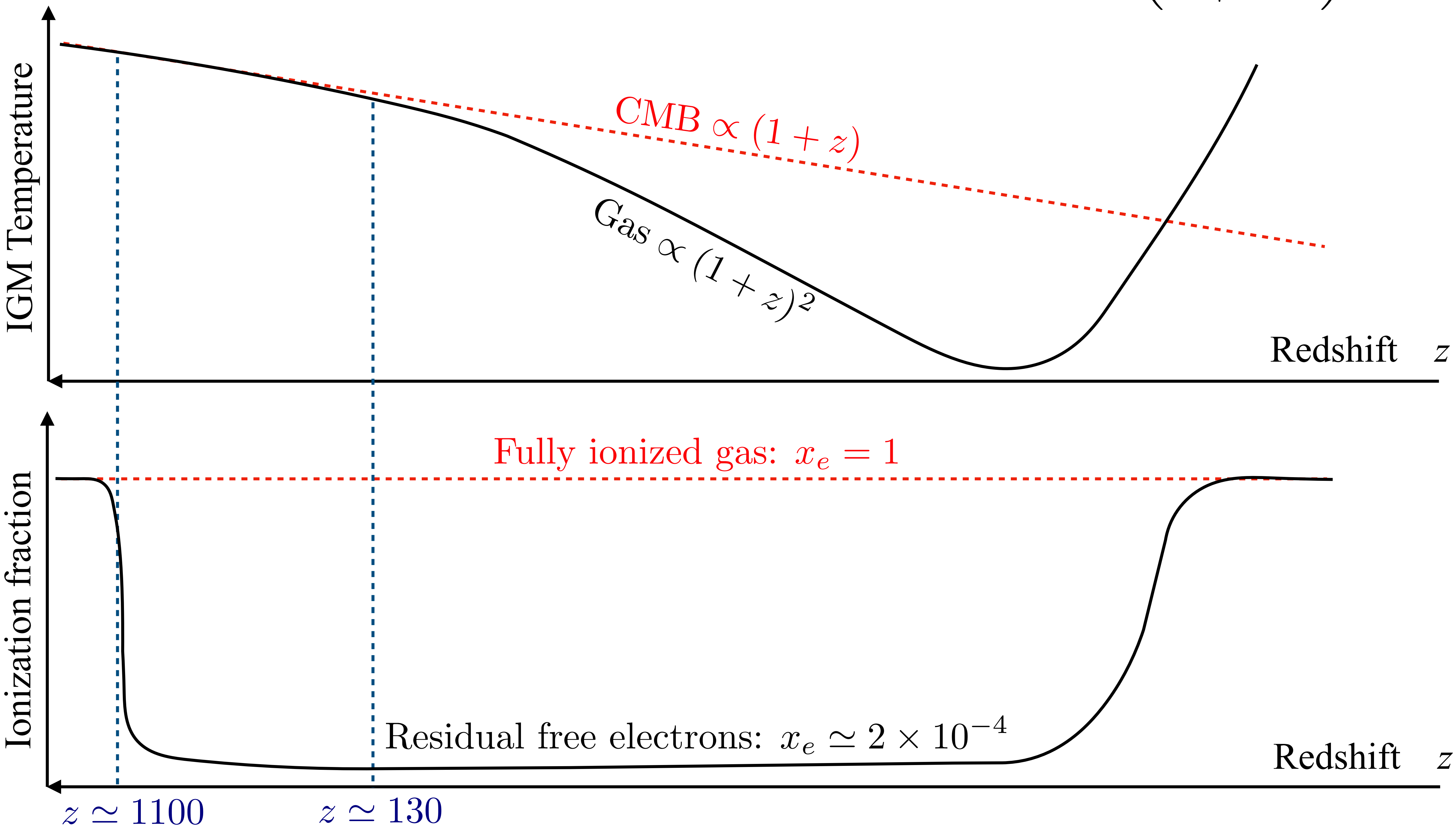
A short history of the IGM

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



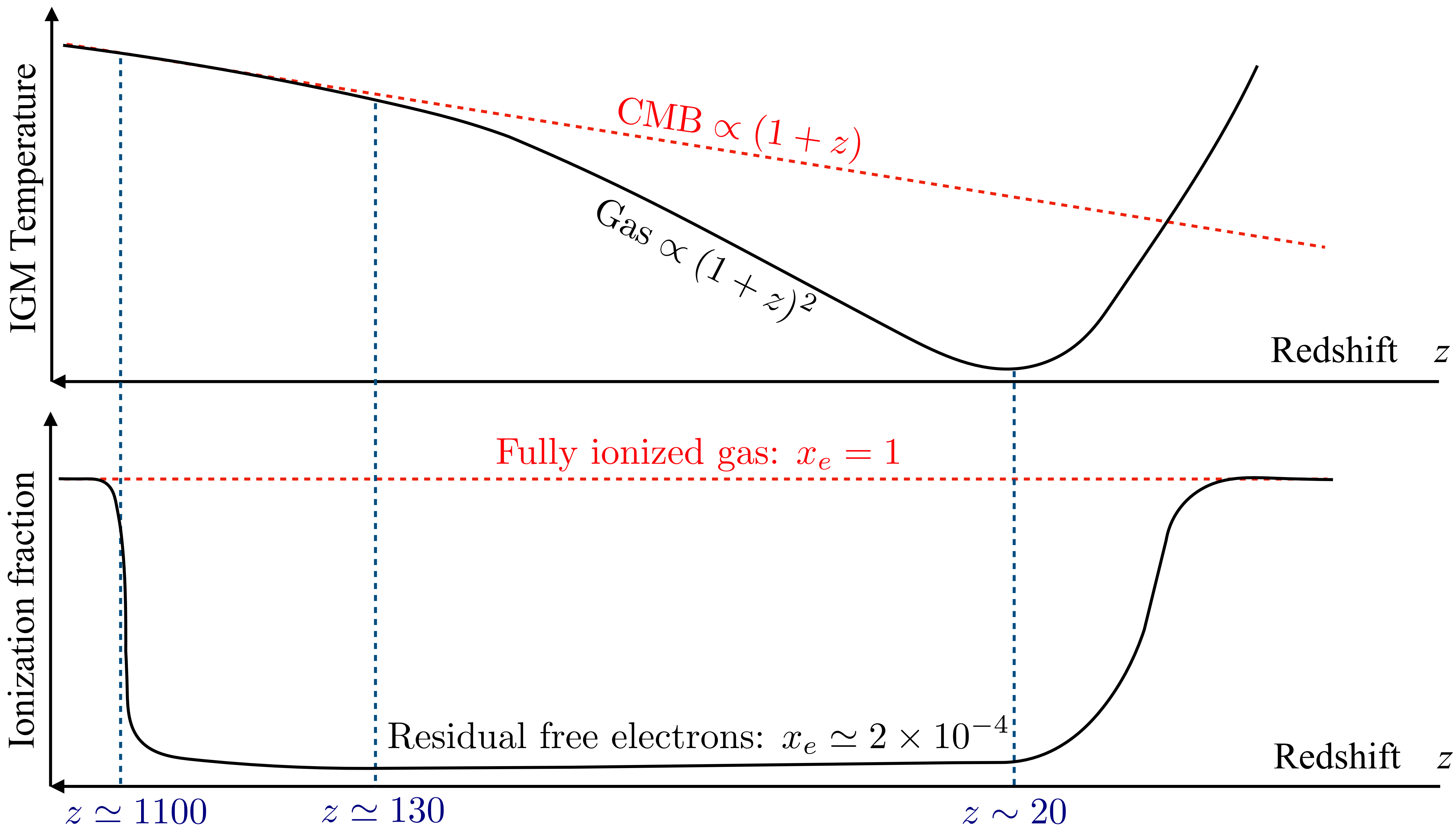
A short history of the IGM

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



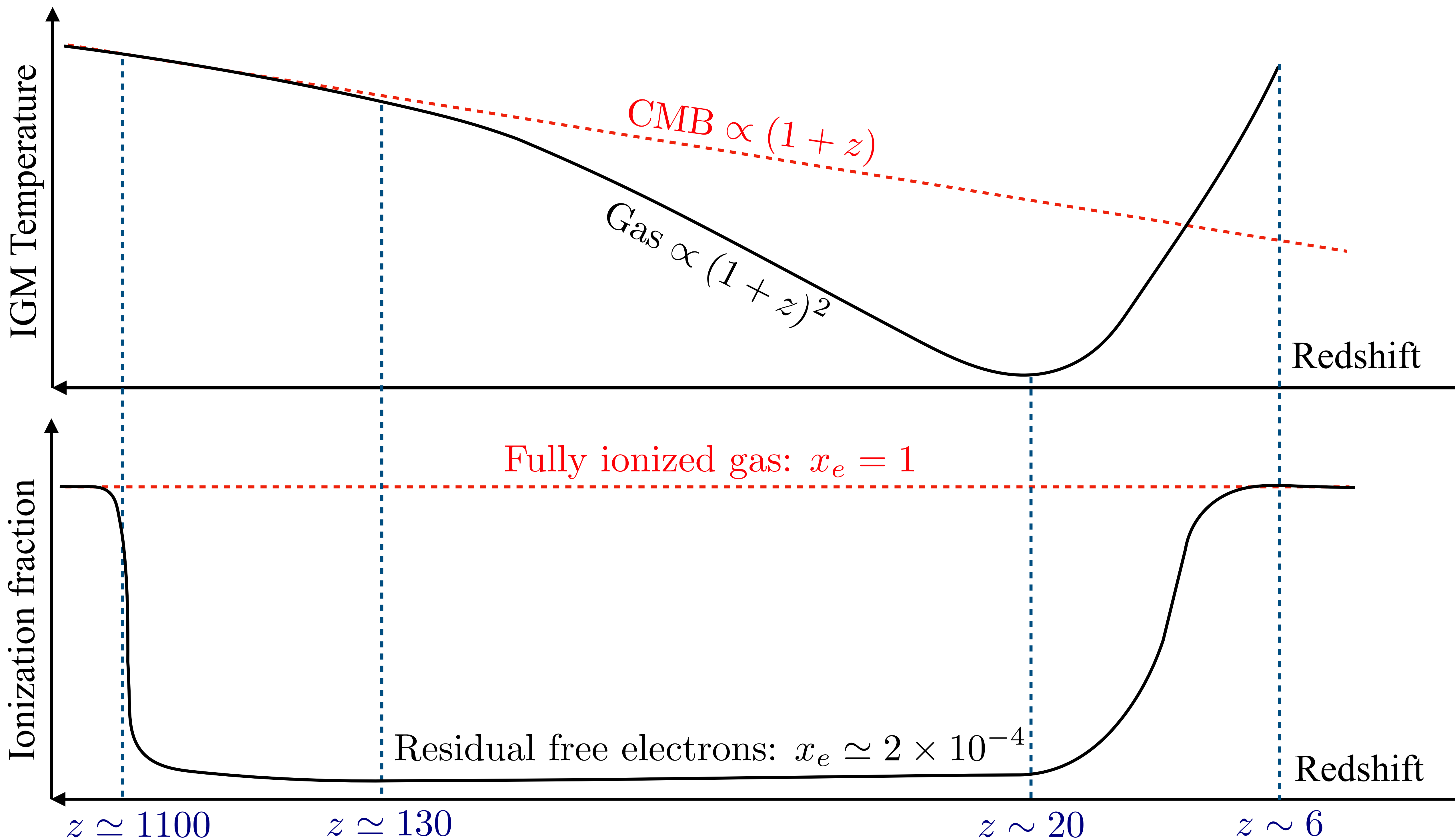
A short history of the IGM

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



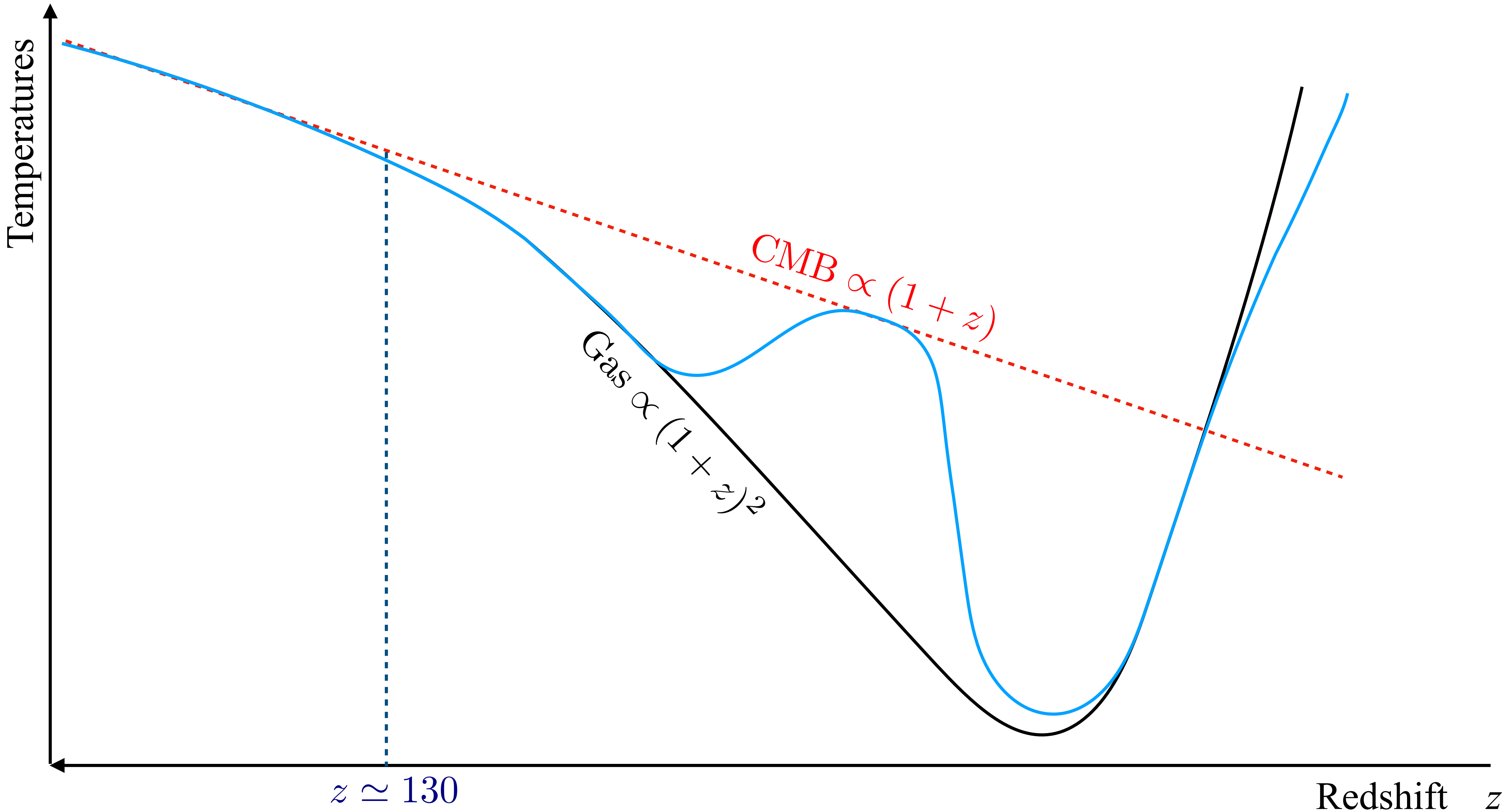
A short history of the IGM

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



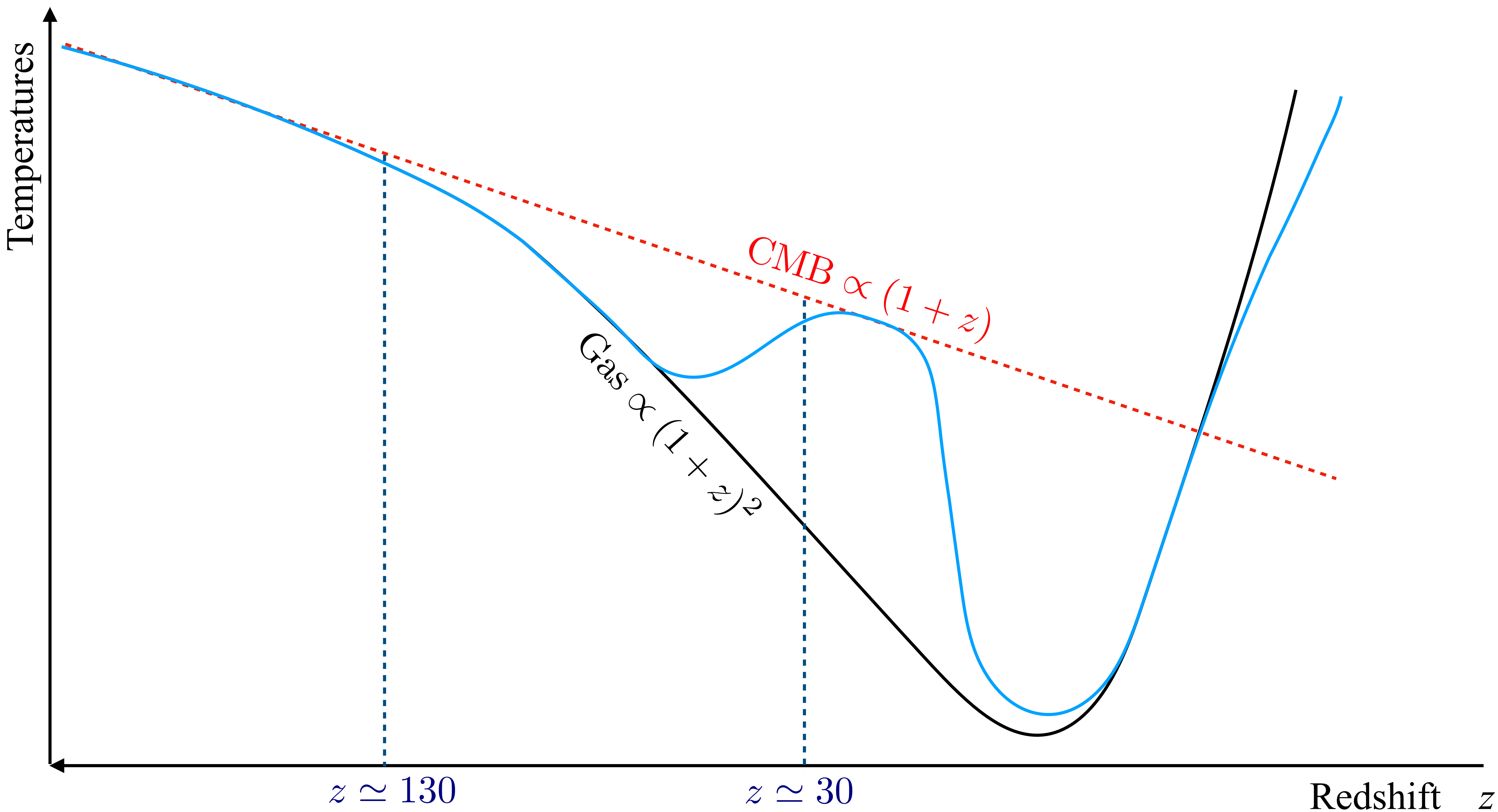
A short history of T_S

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



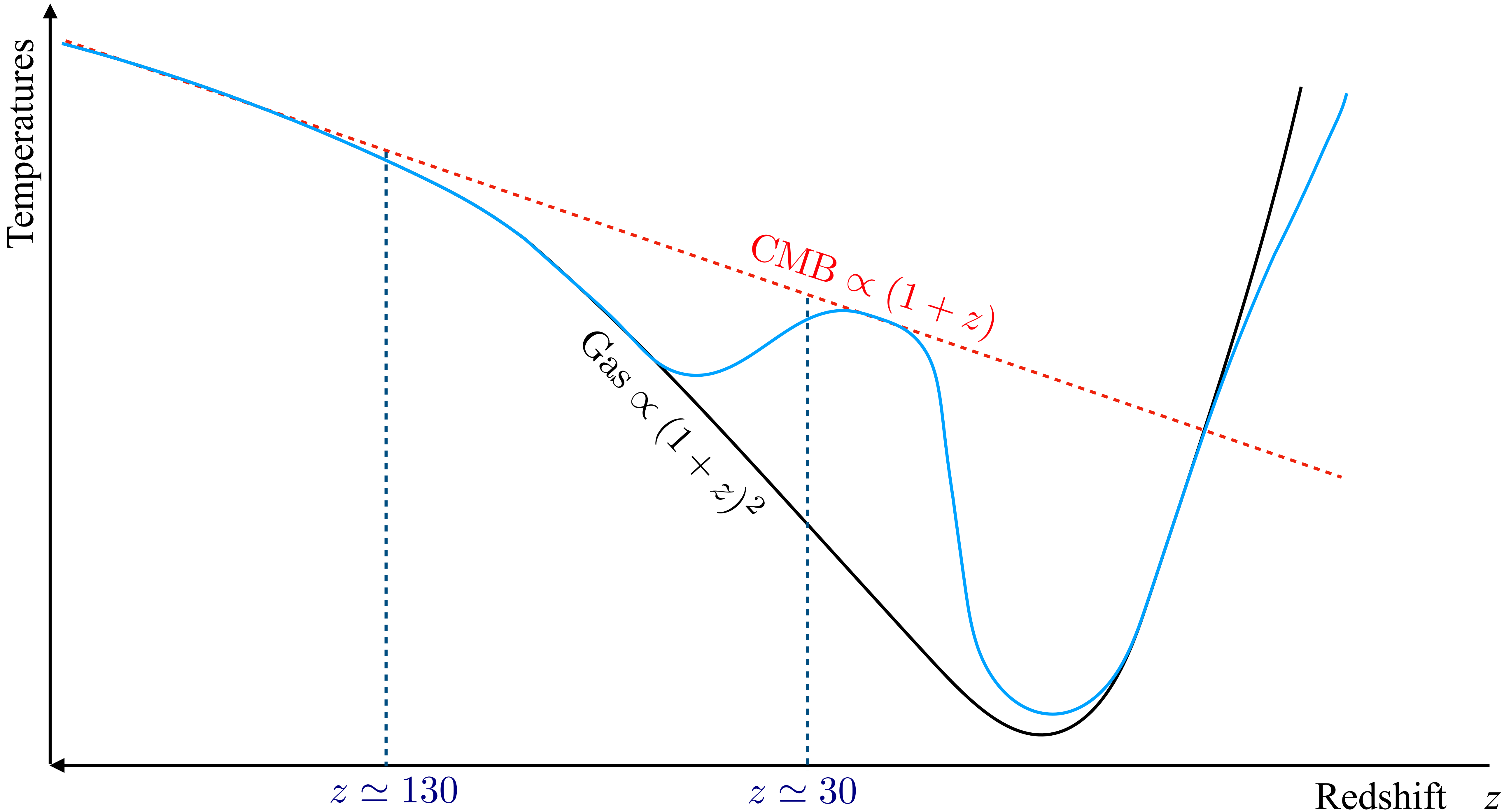
A short history of T_S

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



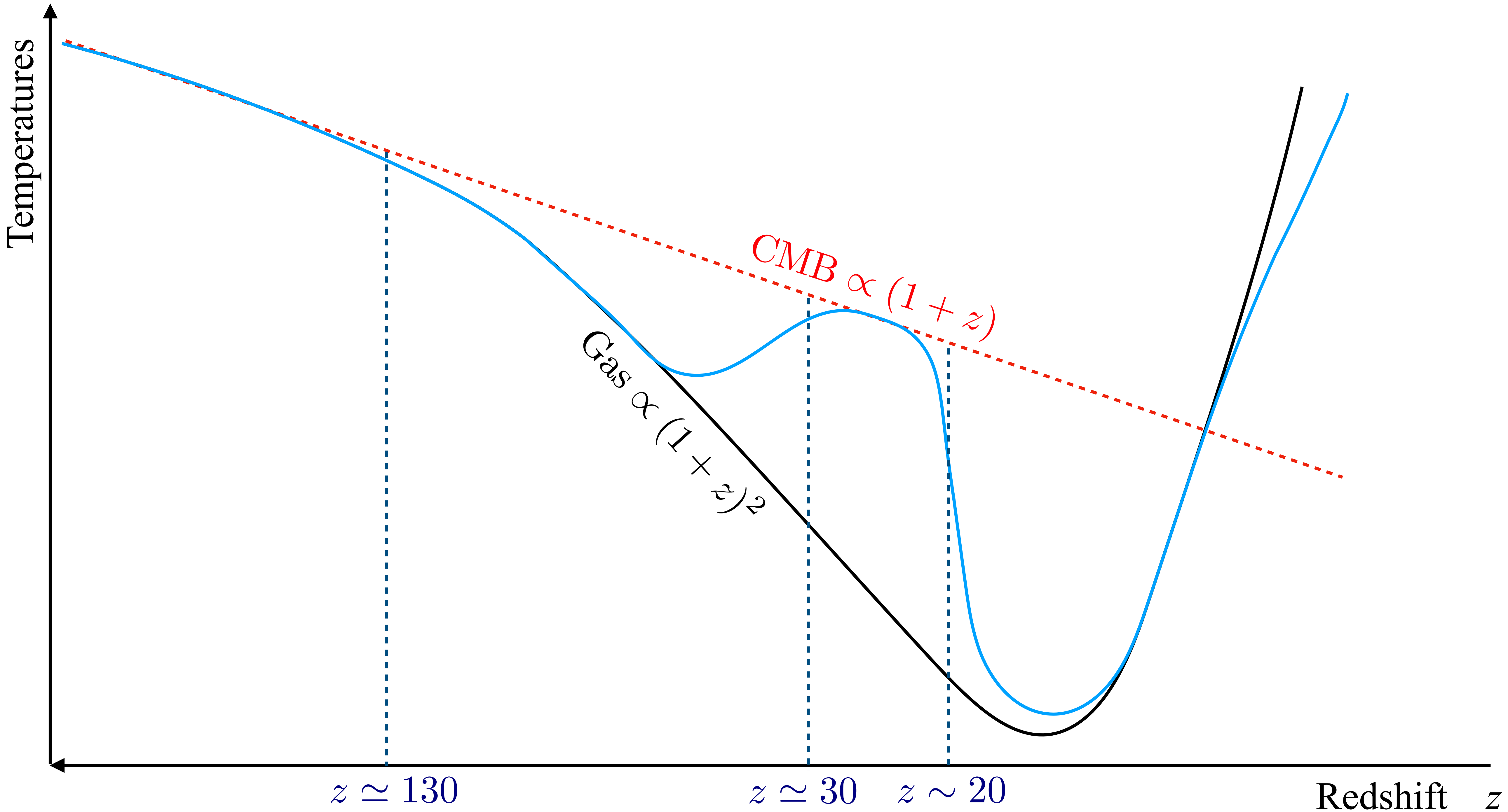
A short history of T_S

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



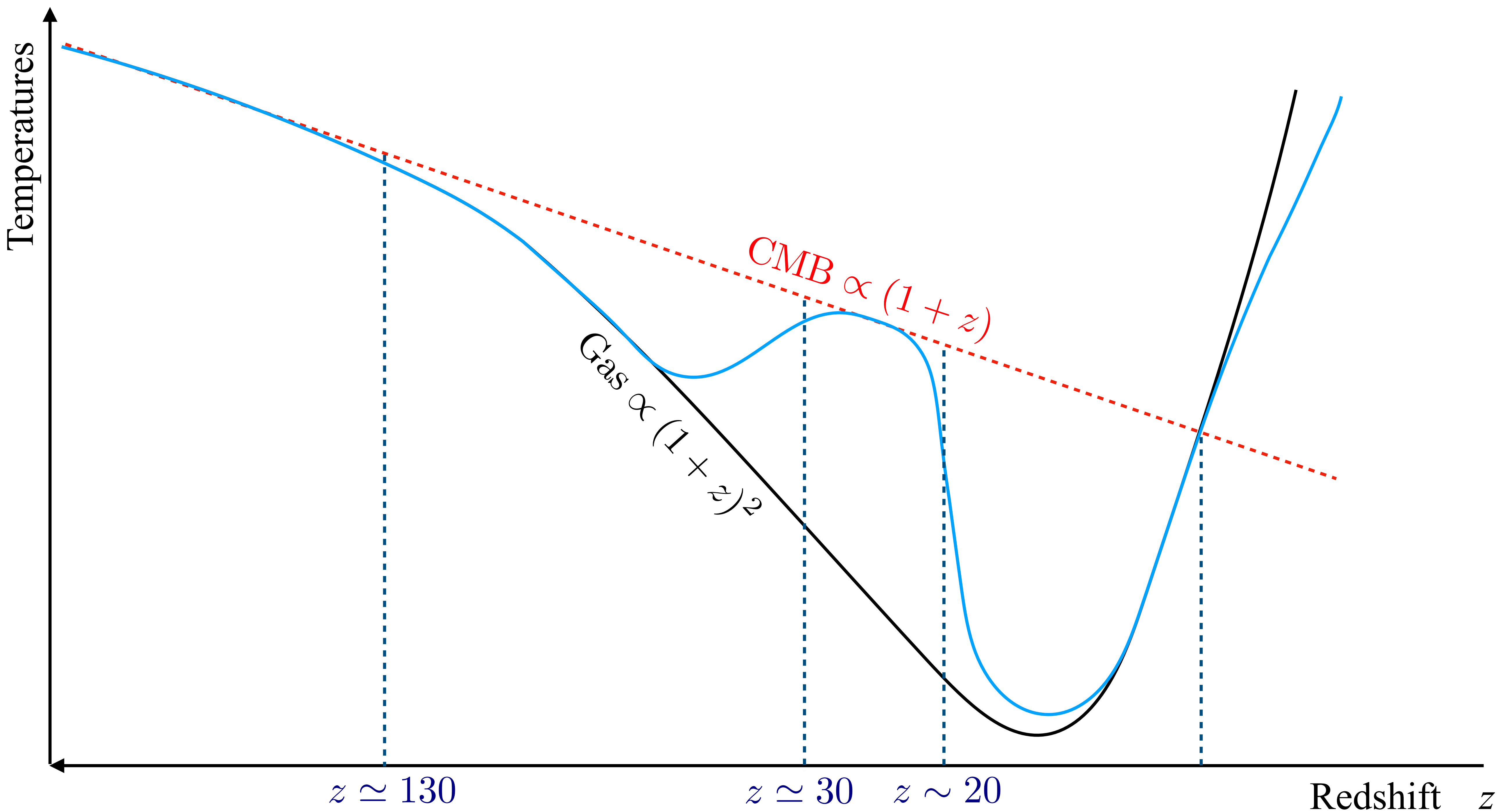
A short history of T_S

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

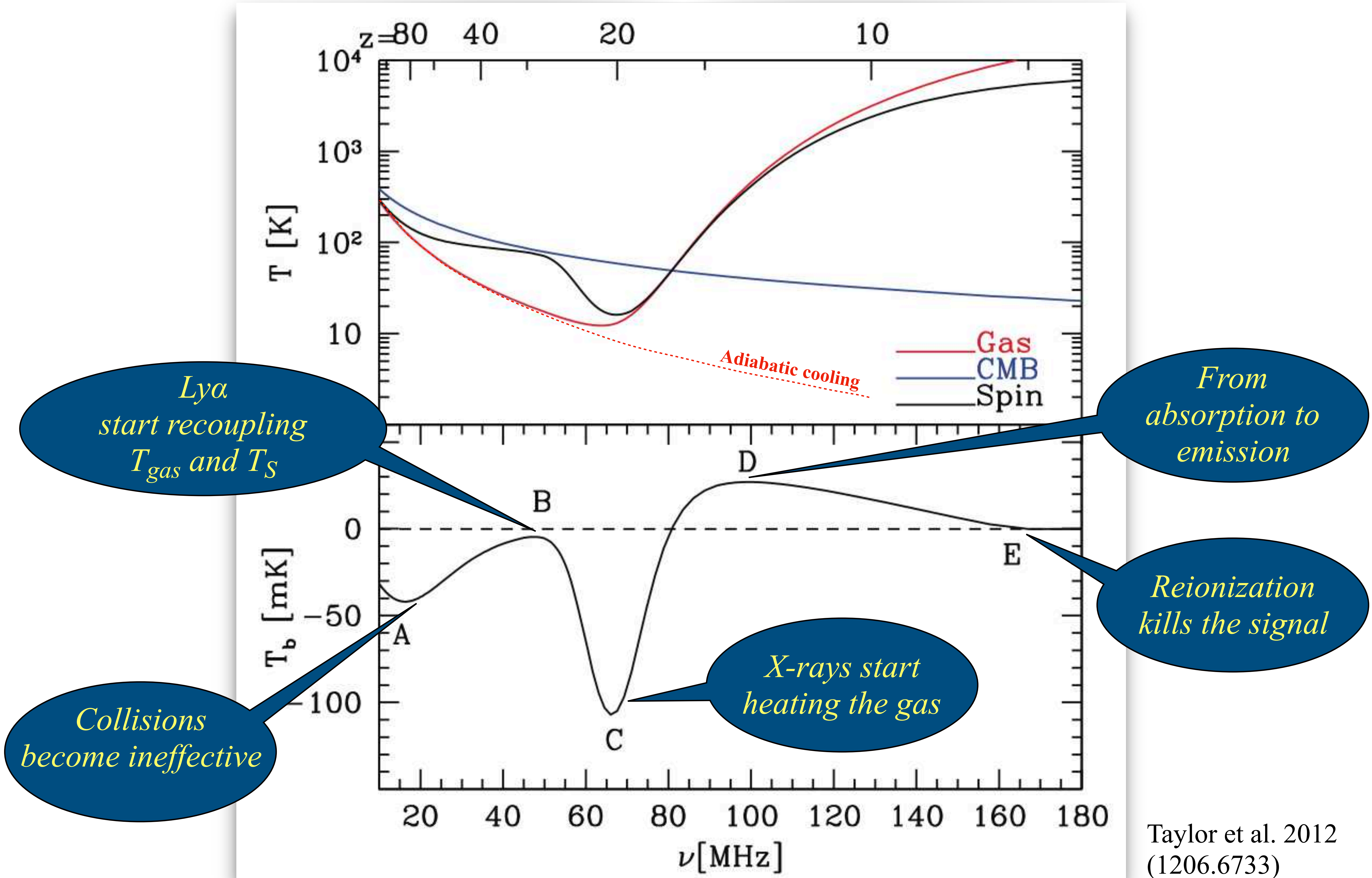


A short history of T_S

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

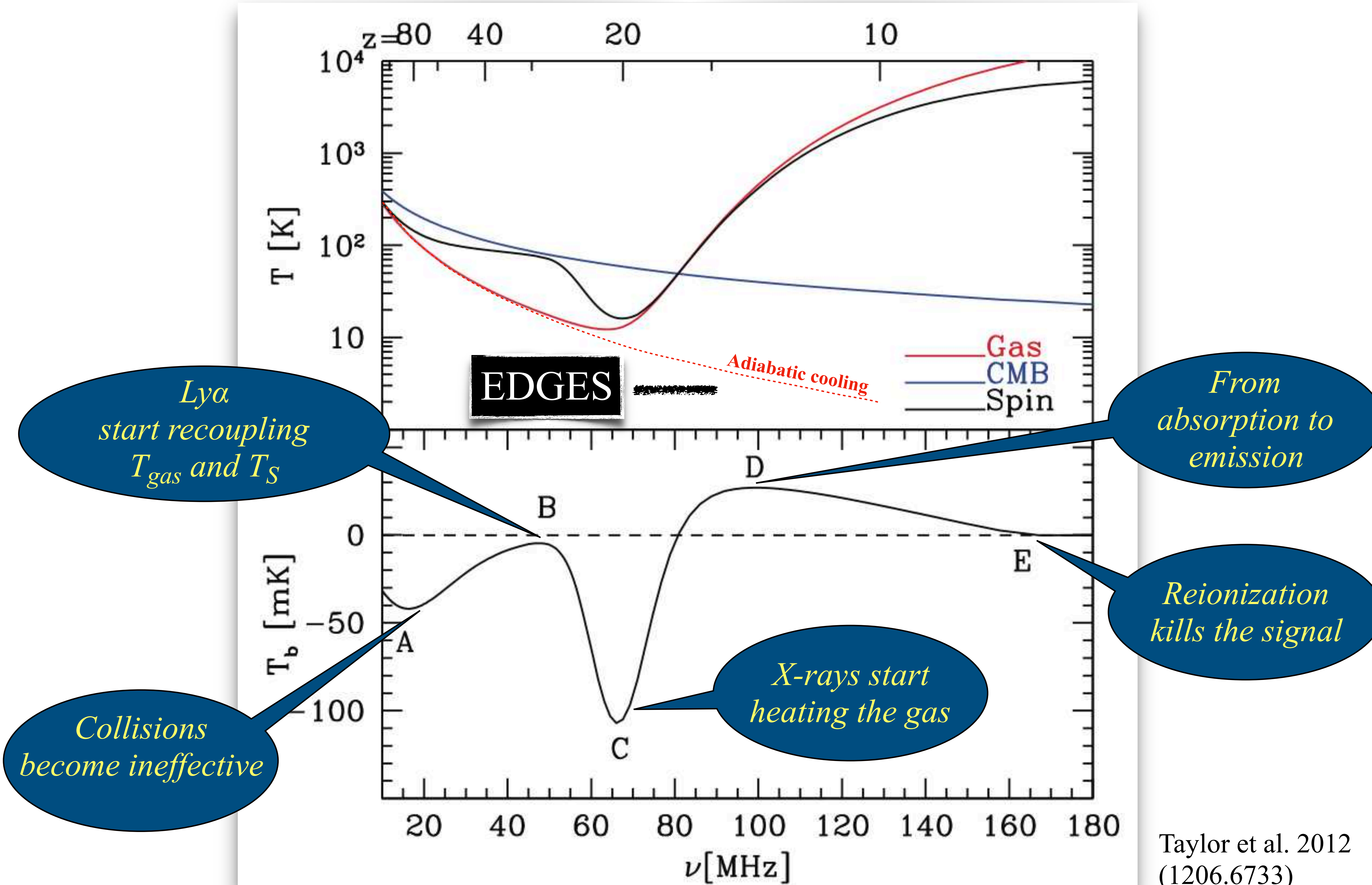


21-cm signal history



Taylor et al. 2012
(1206.6733)

21-cm signal history



Taylor et al. 2012
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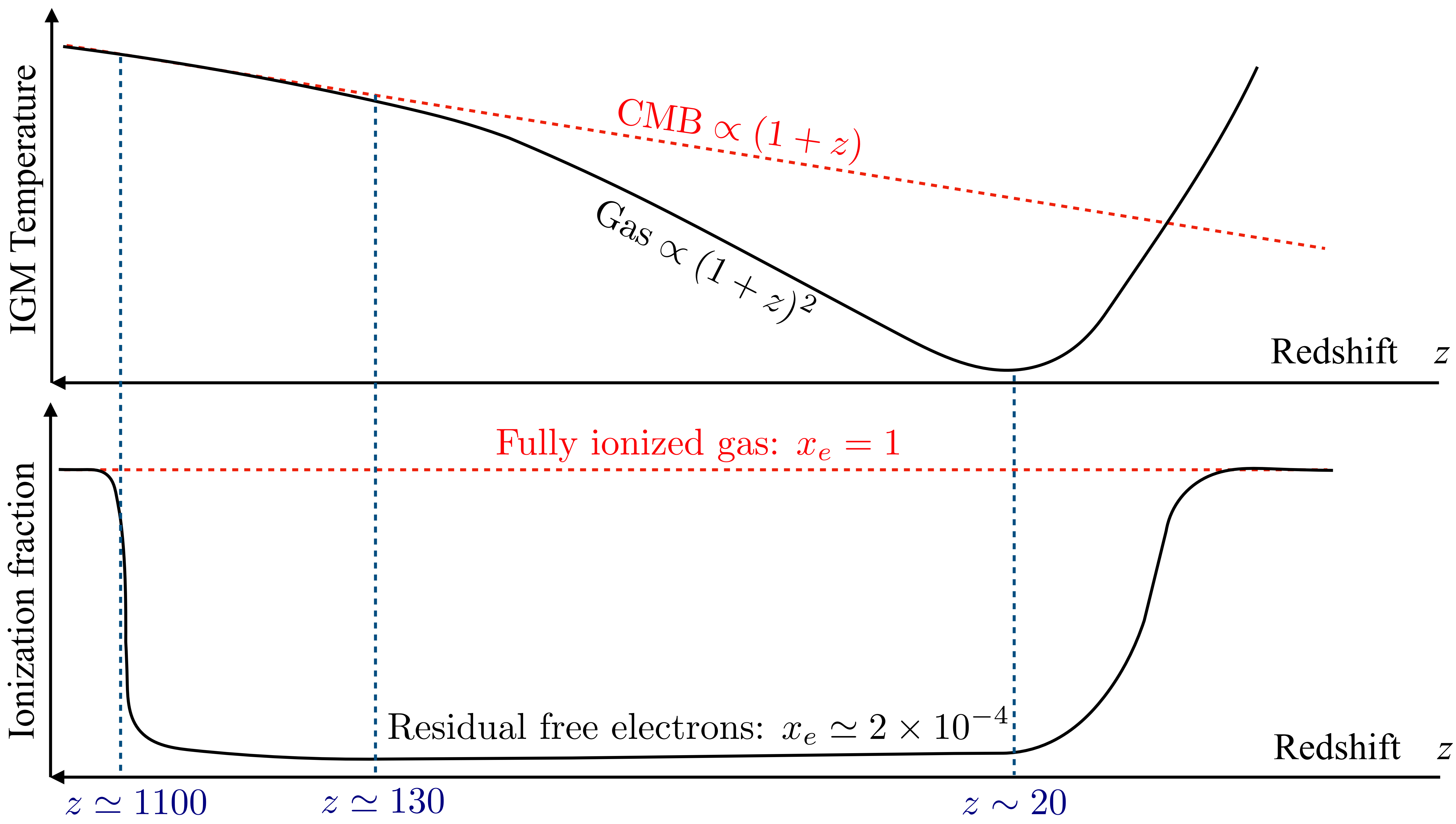
III PART

Constraints on DM annihilations

Where does DM enter?

DM can (and will if thermal) annihilate into SM.
Will heat the IGM in 2 ways:

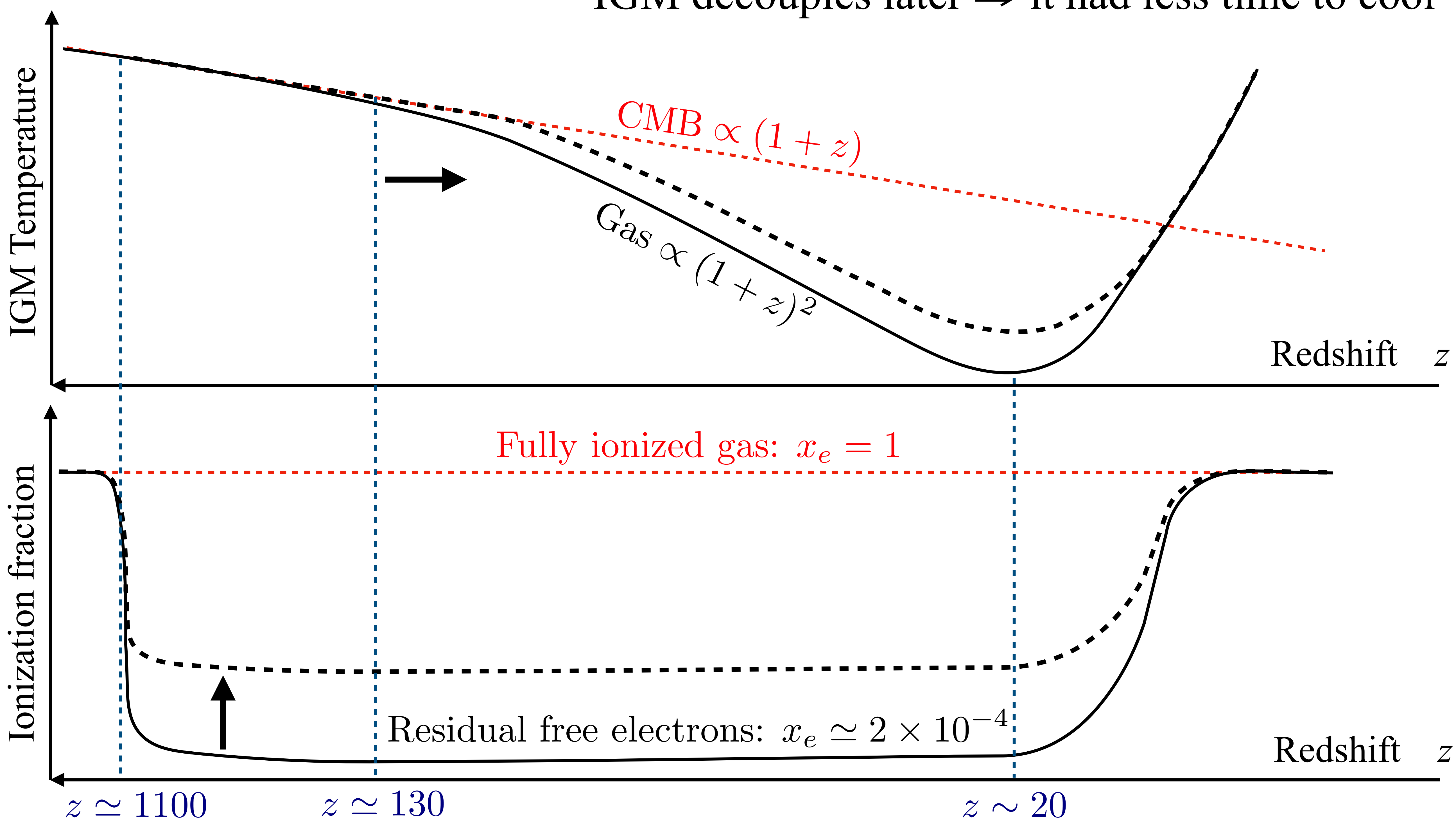


Where does DM enter?

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

Will heat the IGM in 2 ways: ➡ Annihilations ***increase ionization fraction***

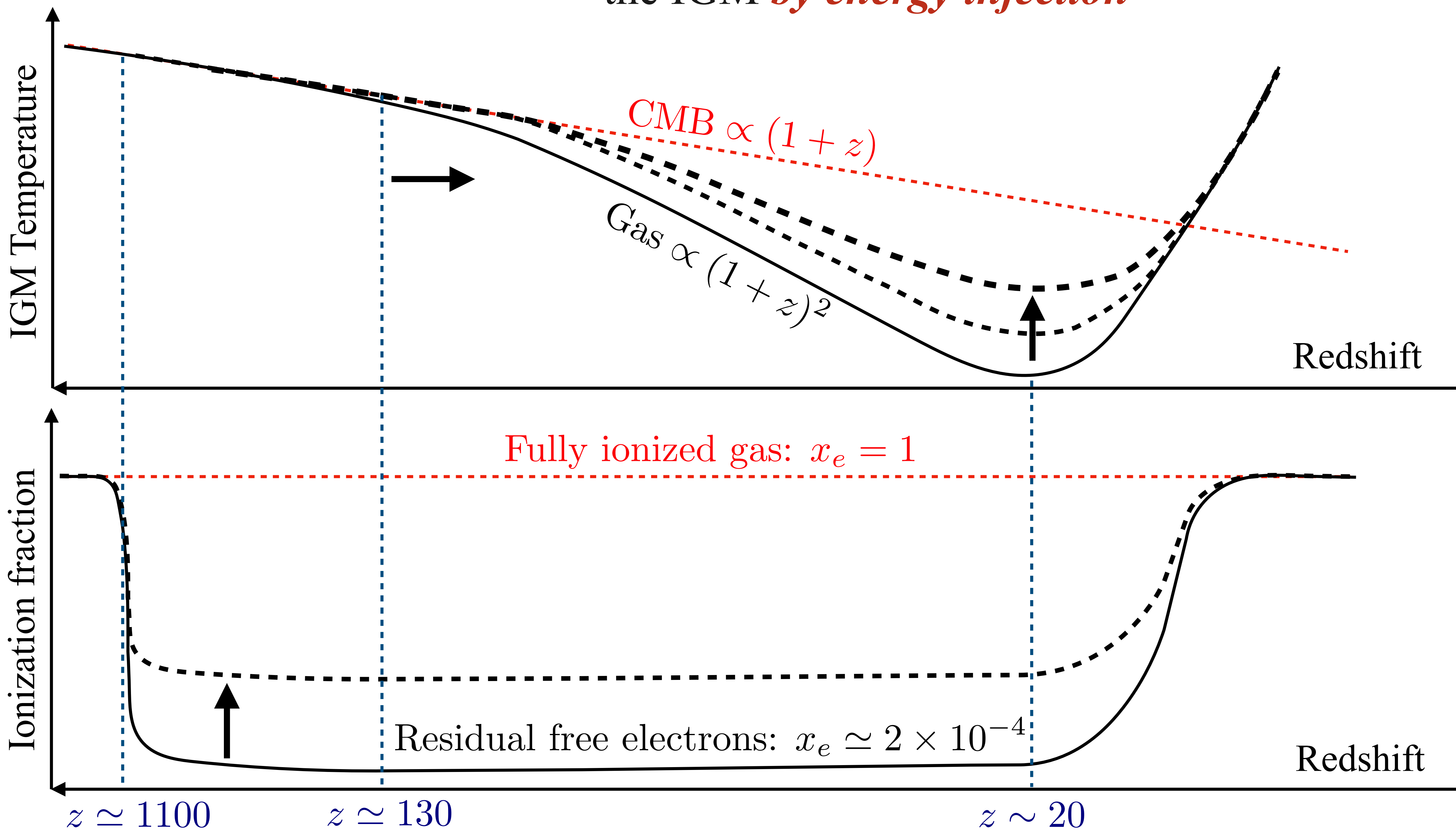
IGM decouples later ⇒ it had less time to cool



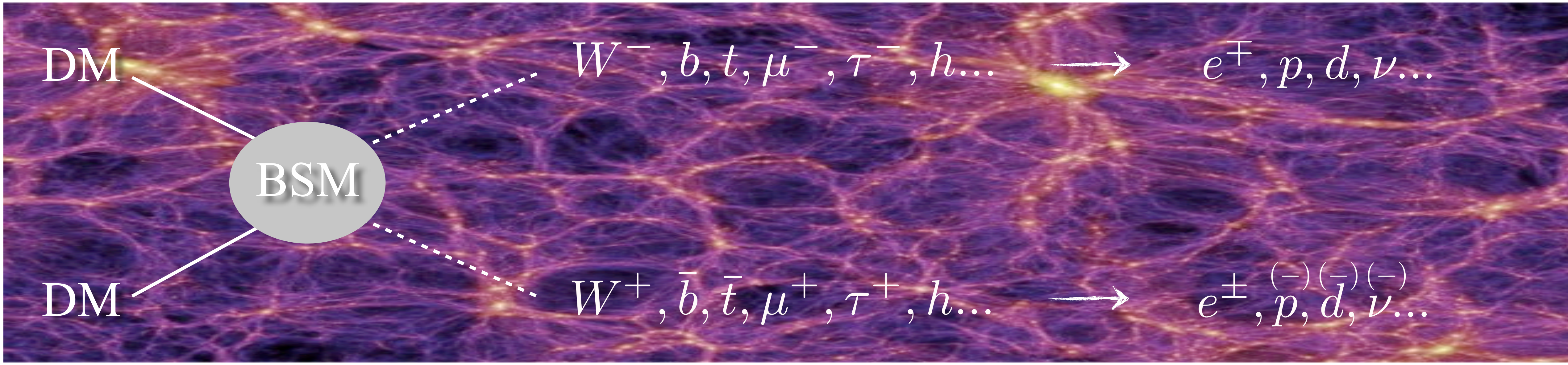
Where does DM enter?

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

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



DM Annihilation: Basics



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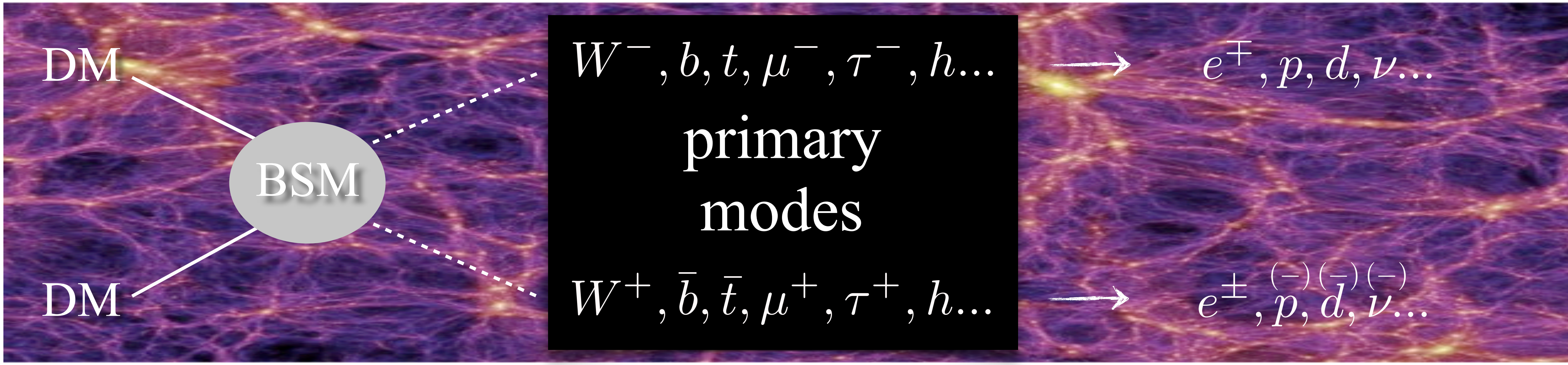

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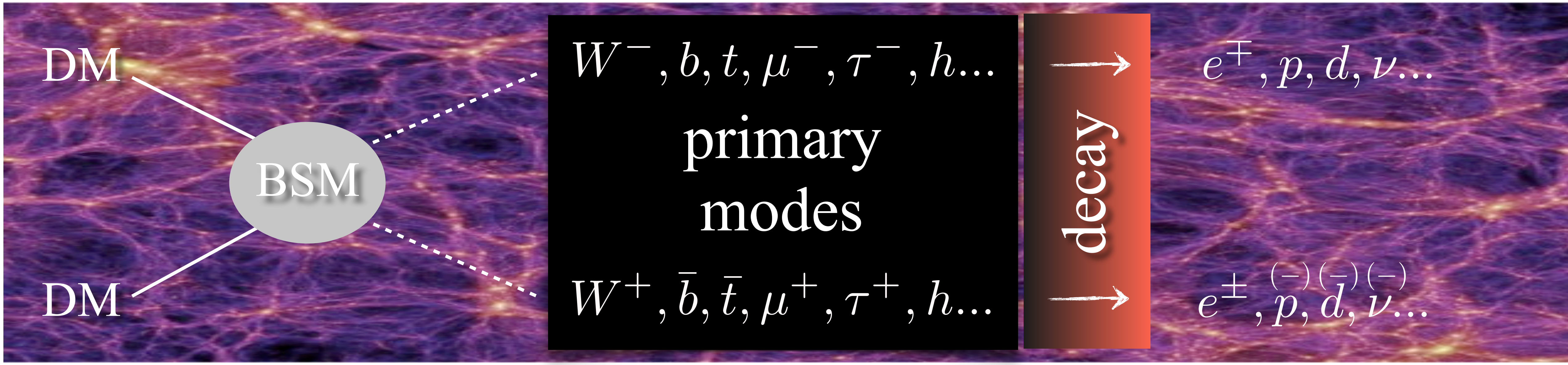

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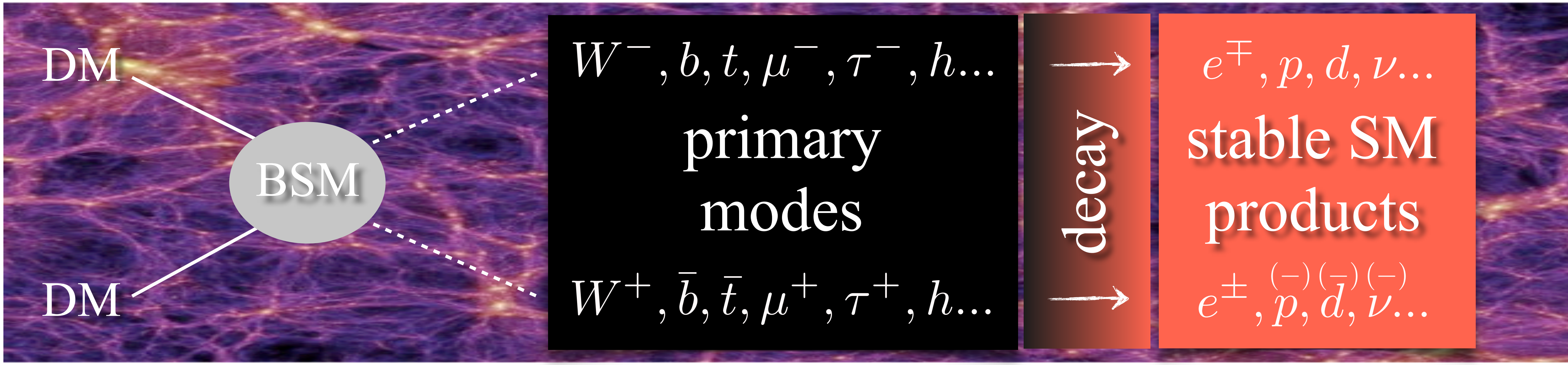

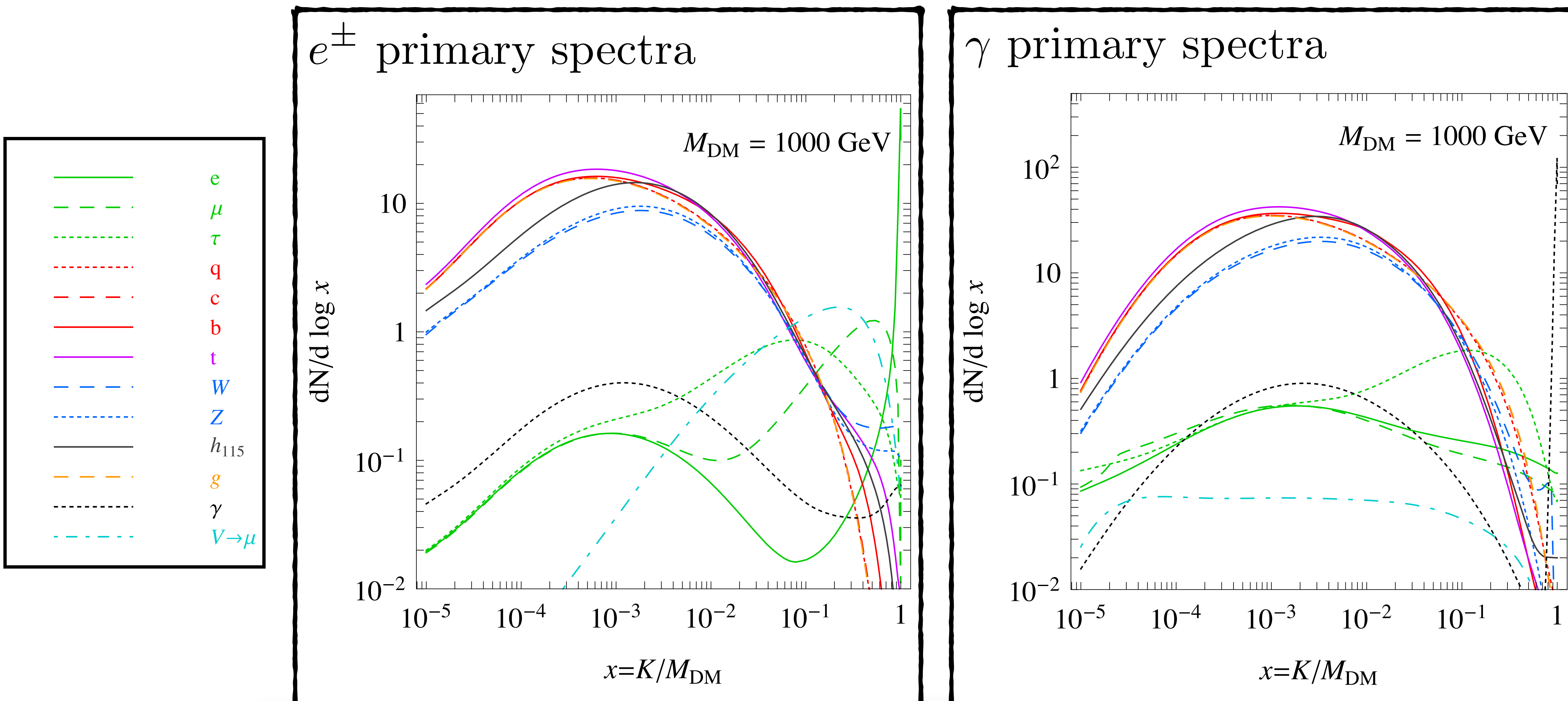

Energy injection

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

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

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

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

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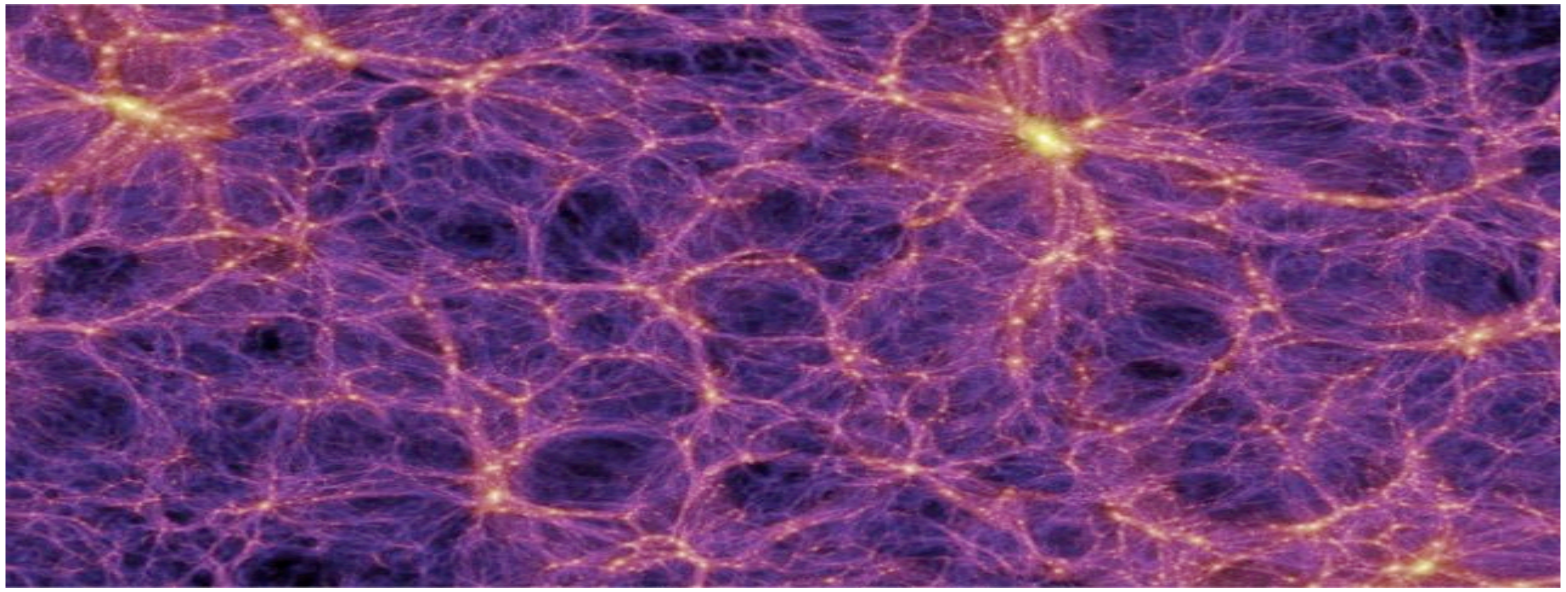
Boosted Annihilation due to structure formation:

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



Energy injection

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

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

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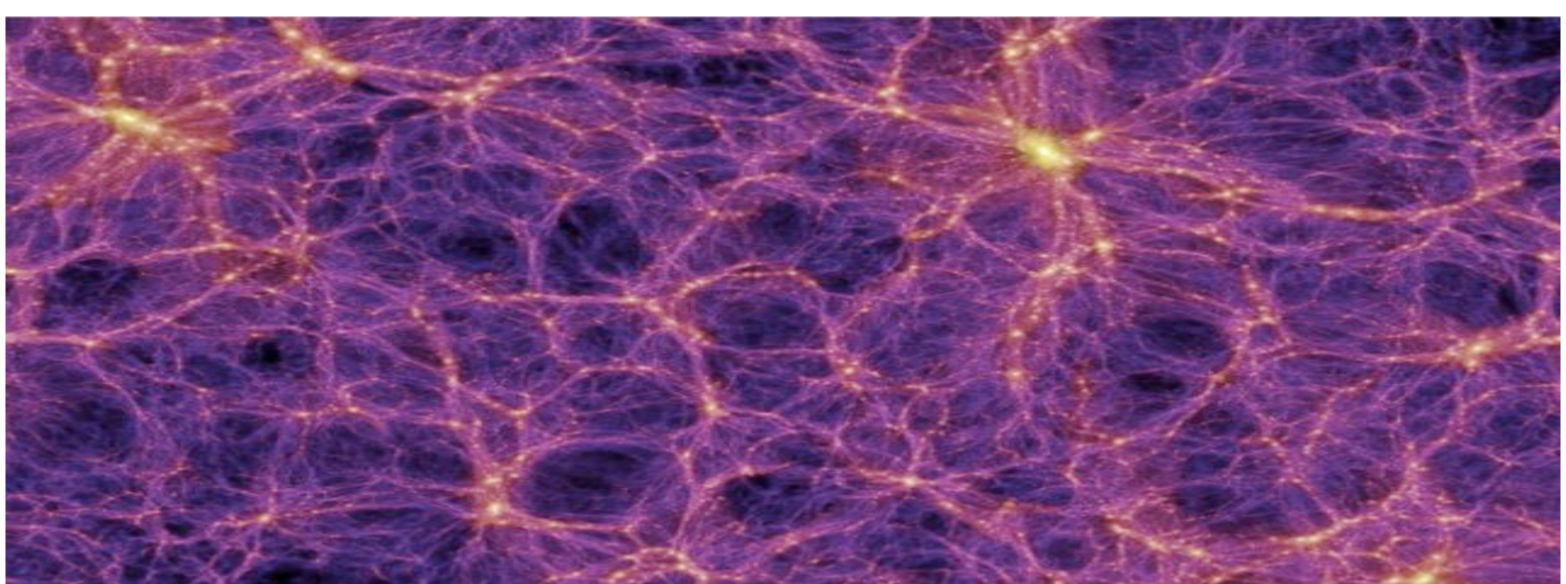

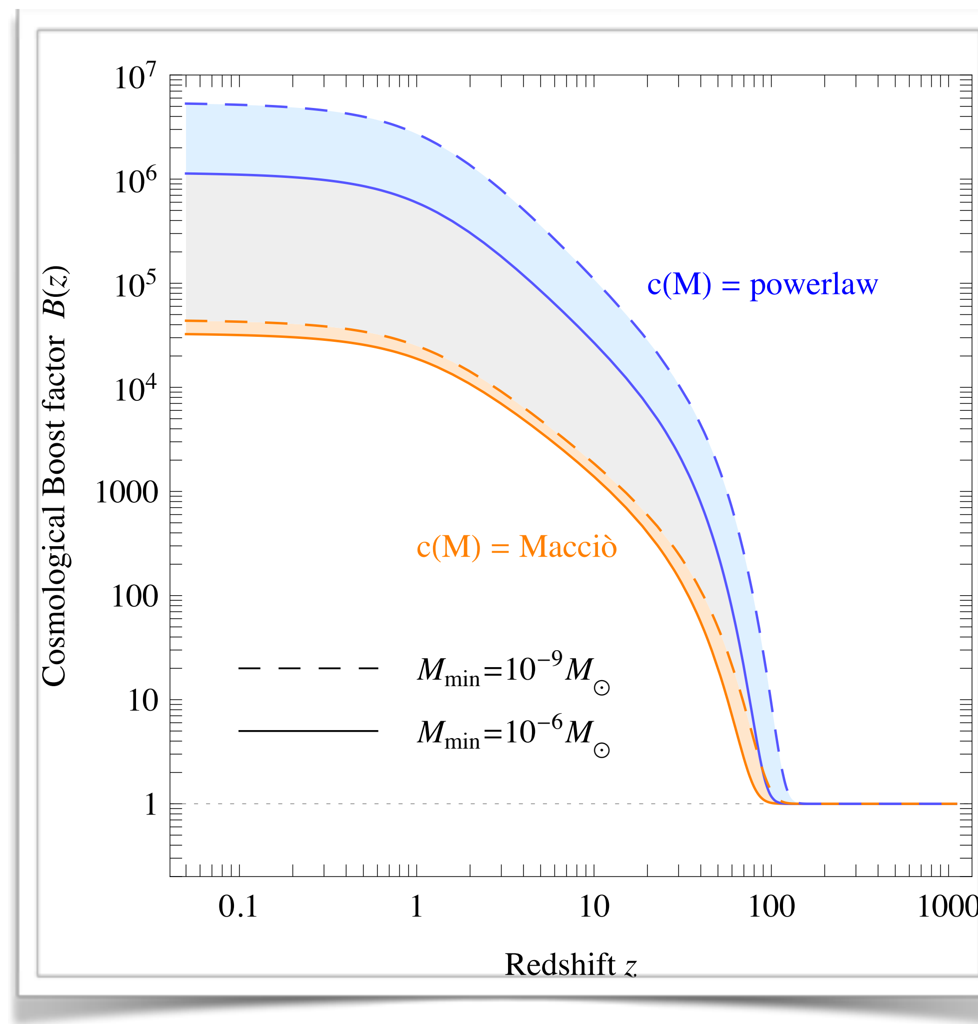

Energy deposition

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

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

→ Ionize H_{I}
→ Excite H_{I}
→ Heat the IGM

Energy deposition

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→ Ionize $H_{\rm I}$
→ Excite $H_{\rm I}$
→ Heat the IGM

INSTANTANEOUS DEPOSITION: only valid at high redshift

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

Energy deposition

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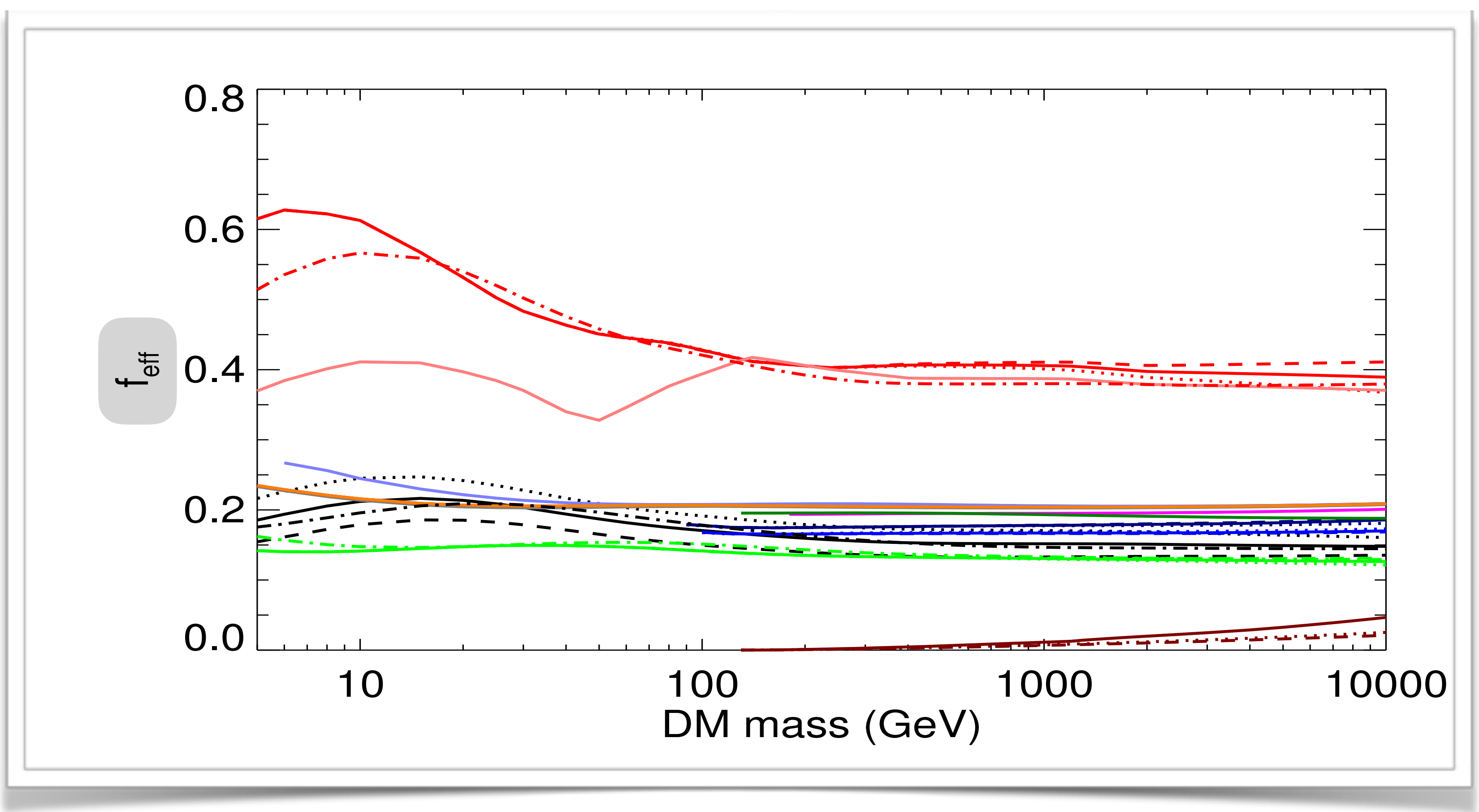

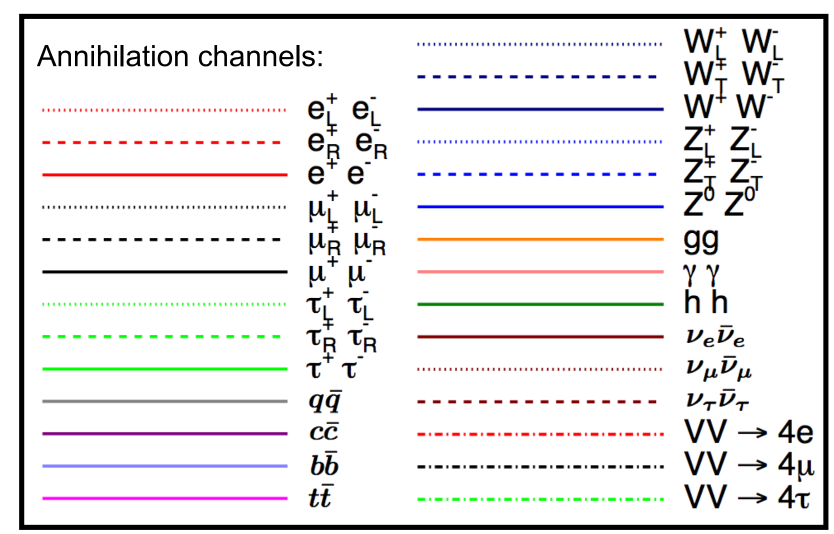

Slatyer
1506.03811,
1506.03812

Energy deposition

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- Ionize H_{I}
- Excite H_{I}
- Heat the IGM

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

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

Deposition redshift ($f_c(z)$)

Hubble Rate ($H(z)$, $H(z')$)

Accounts for EM shower ($\mathcal{T}_c(E,z,z')$): Slatyer 1506.03811, 1506.03812

Injection redshift (z')

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

Evolution w/ DM ann.

Evolution of the **free electrons abundance**:

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

$$- \frac{1}{(1+z)H(z)} \left.\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}V\mathrm{d}t}\right|_{\rm inj} \frac{1}{n_H} \left(\frac{f_{\rm ion}(z)}{E_0} + \frac{(1-\mathcal{P}_2) f_{\rm exc}(z)}{E_\alpha} \right),$$

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

Evolution of the **gas Temperature**:

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

$$- \frac{1}{(1+z)H(z)} \left.\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}V\mathrm{d}t}\right|_{\rm inj} \frac{1}{n_H} \frac{2 f_{\rm heat}(z)}{3(1+x_e+f_{He})}.$$

Energy deposited: **HEATING**

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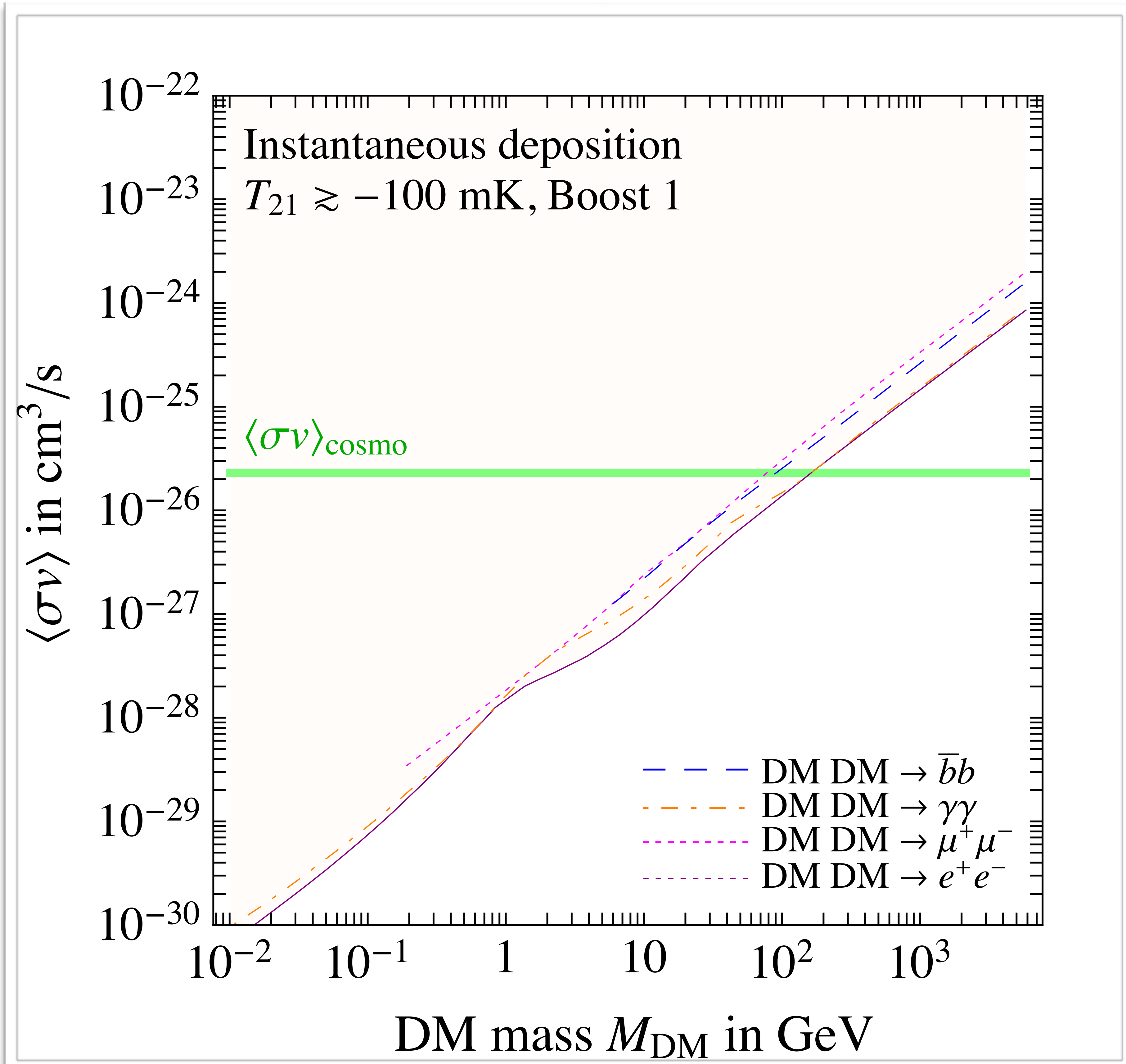
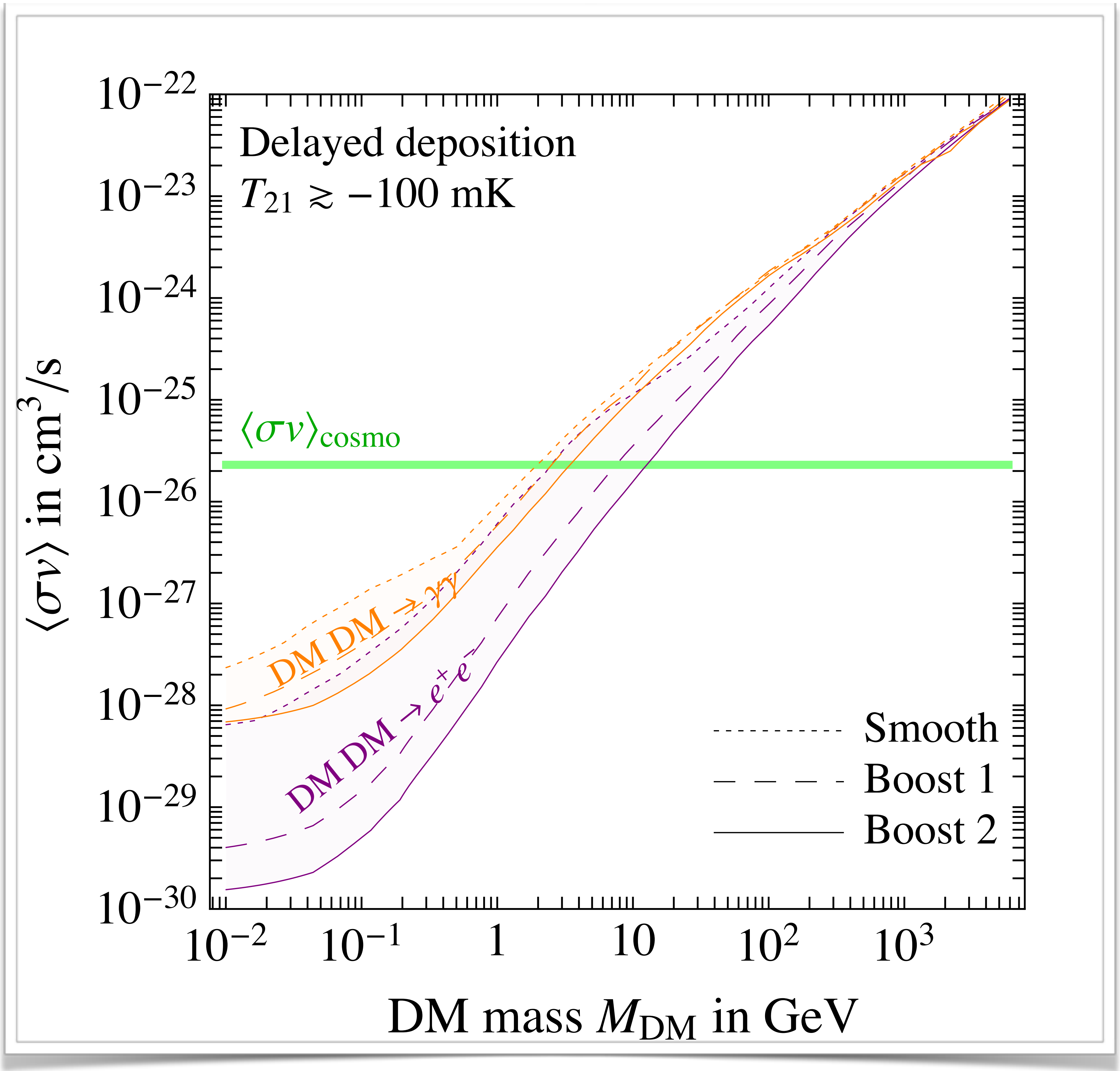
- We require that DM annihilations do not erase the 21-cm signal above **-100 mK** !!

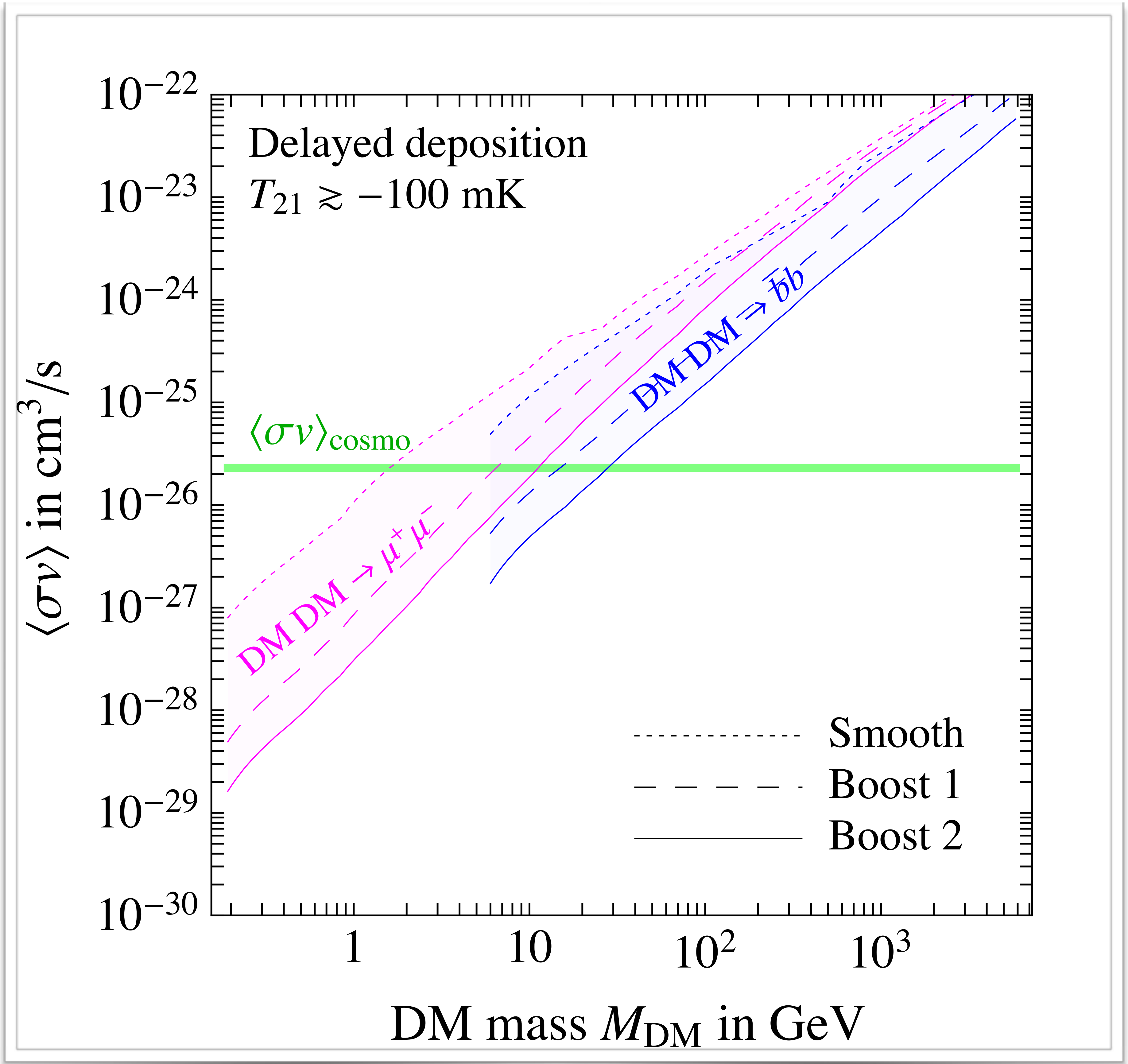
Instantaneous deposition



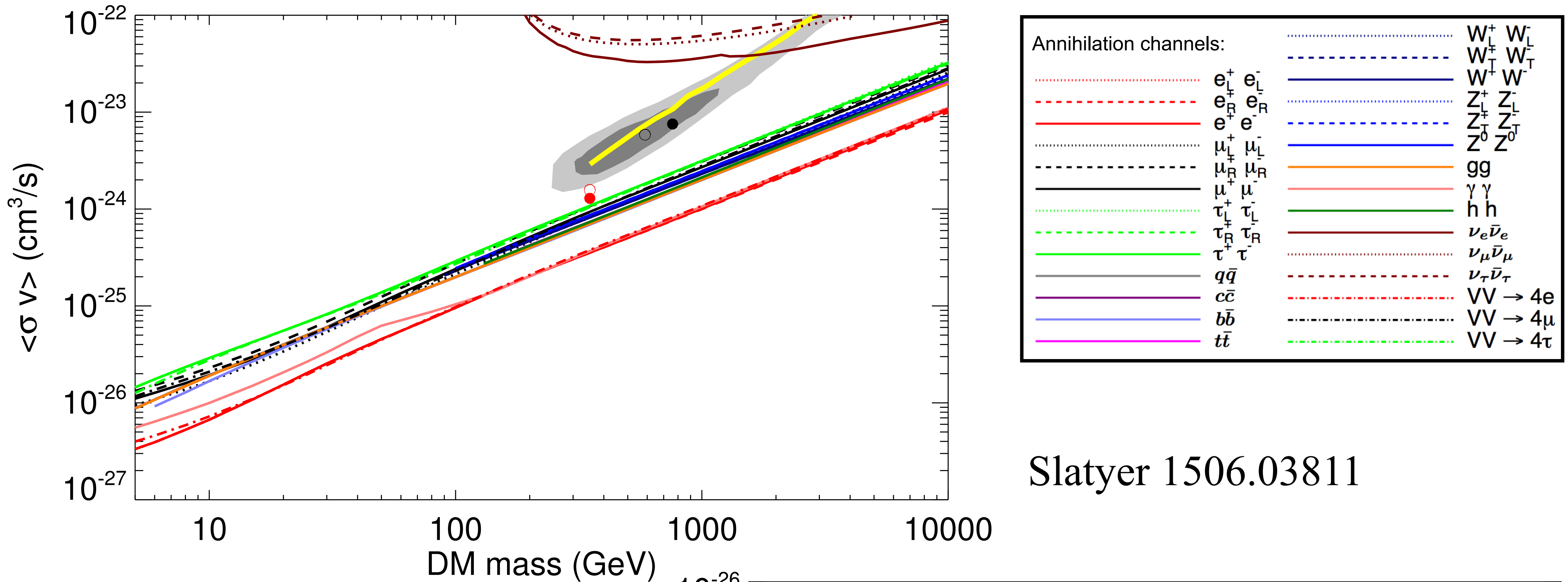
Some limits: $\gamma\gamma$ & e^+e^-



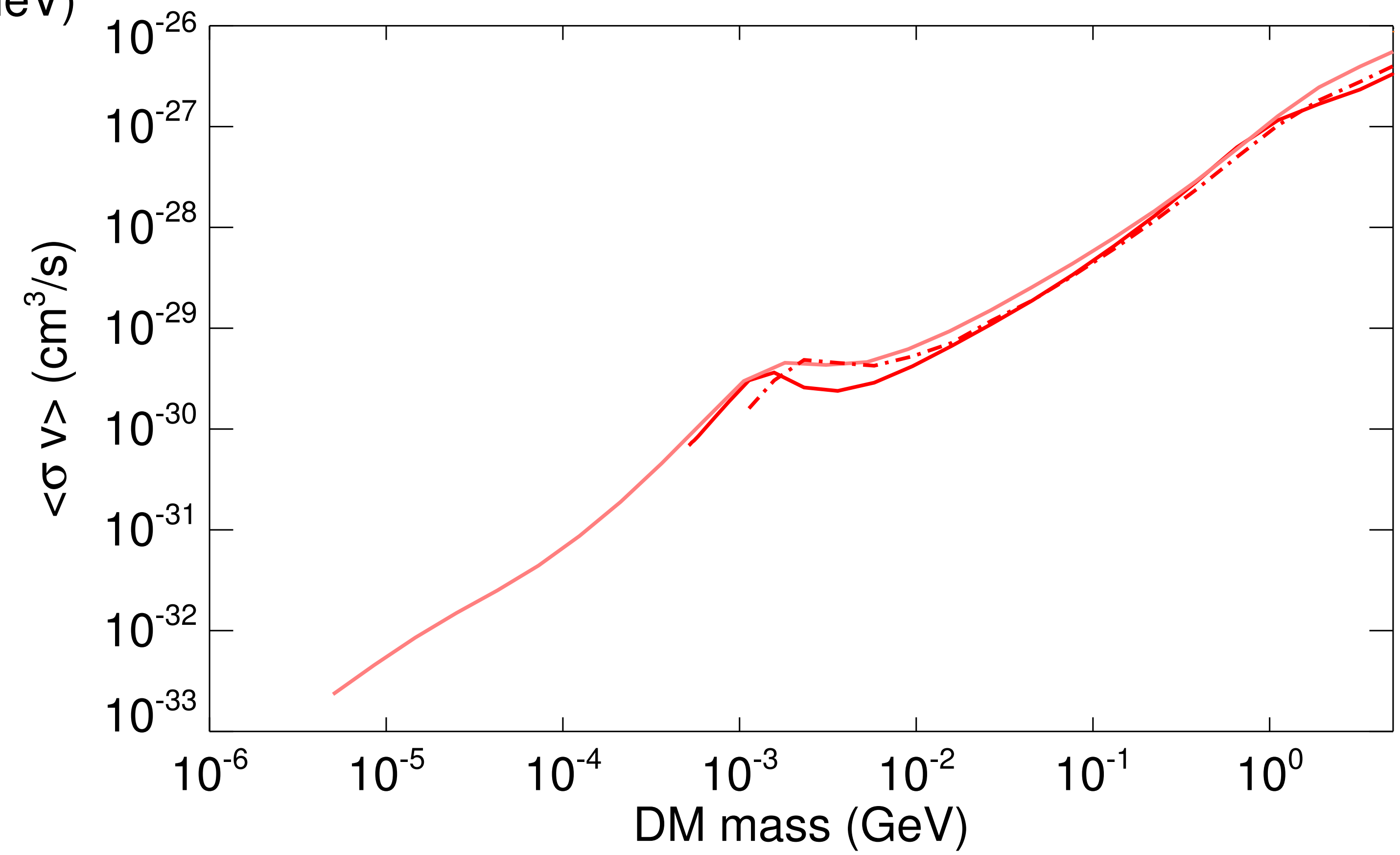
Some limits: $b\bar{b}$ & $\mu^+\mu^-$.



Comparison: PLANCK



Slatyer 1506.03811



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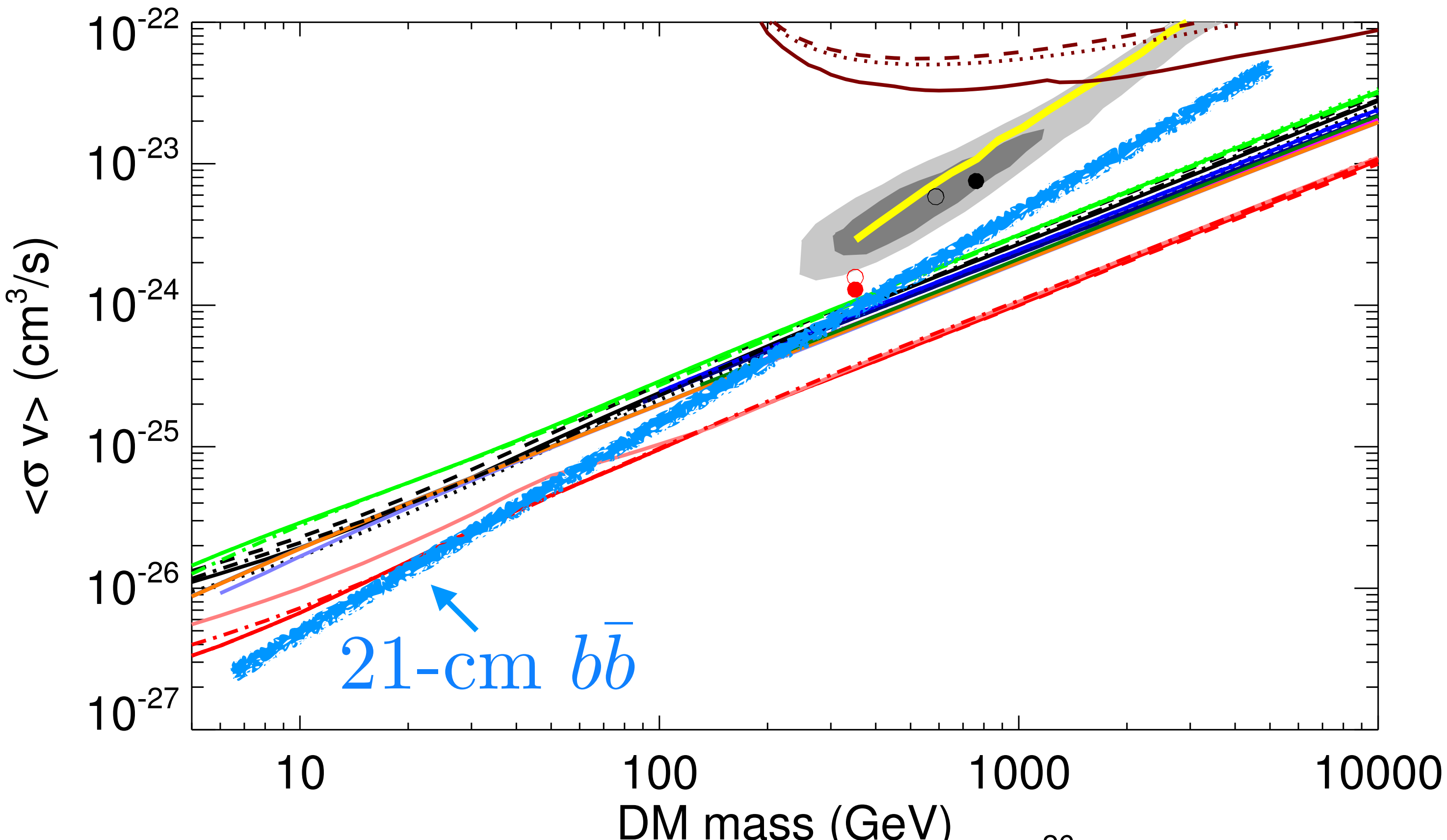

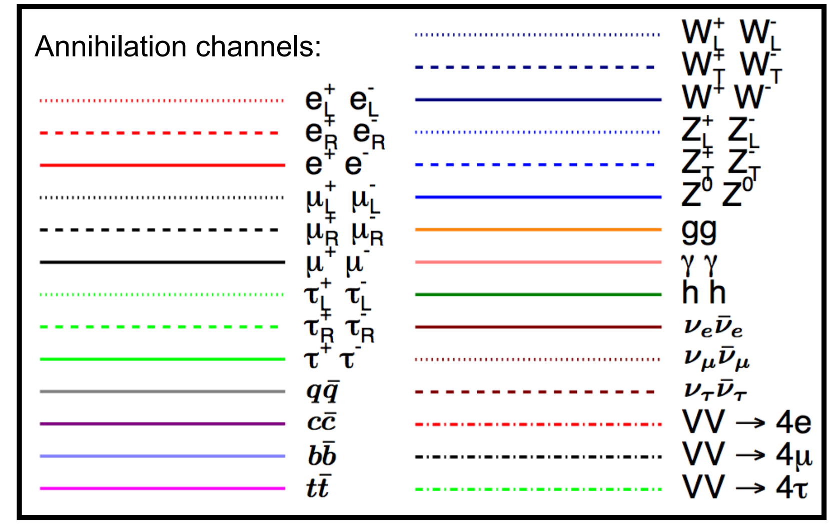

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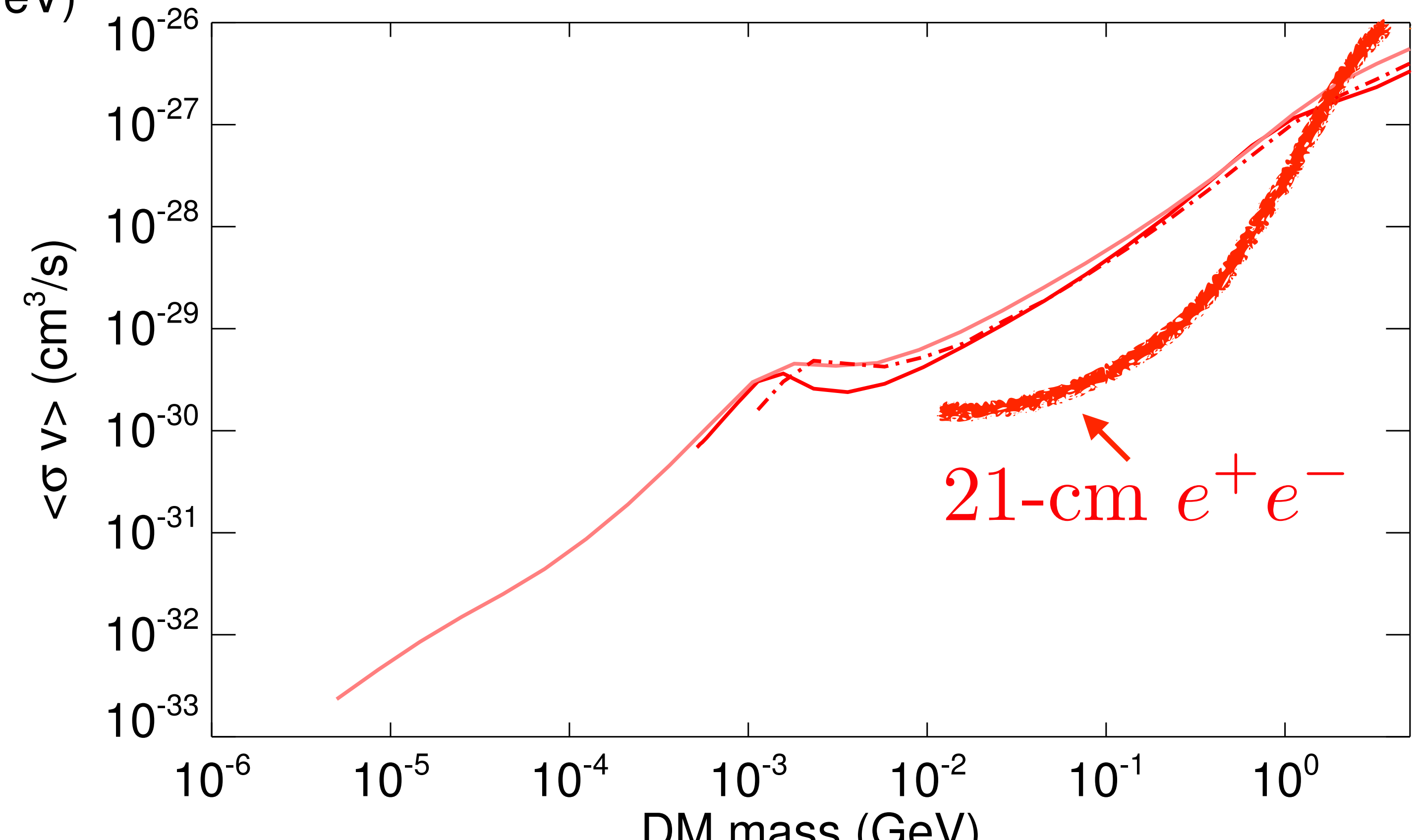
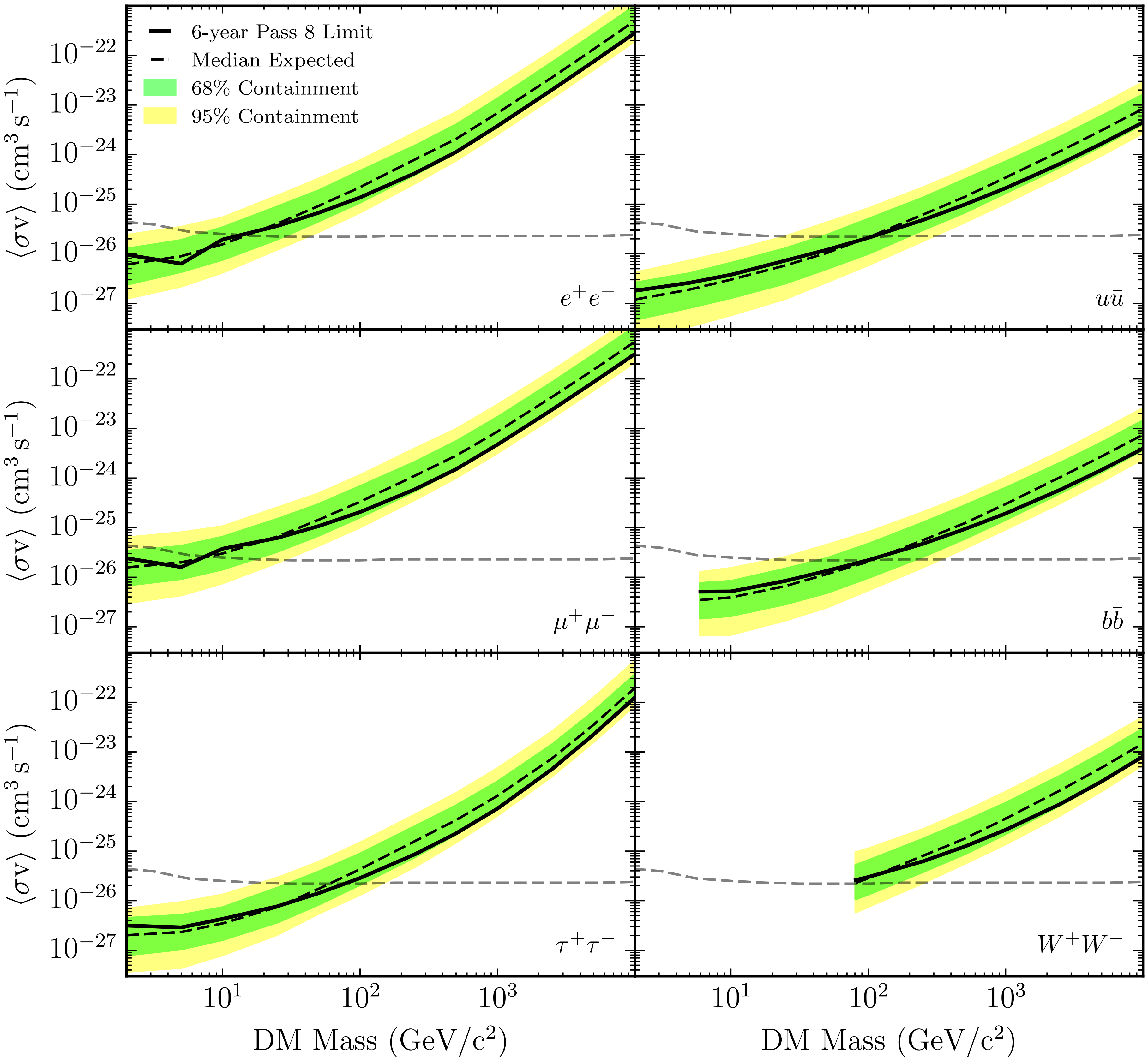


Comparison: FERMI dSphs

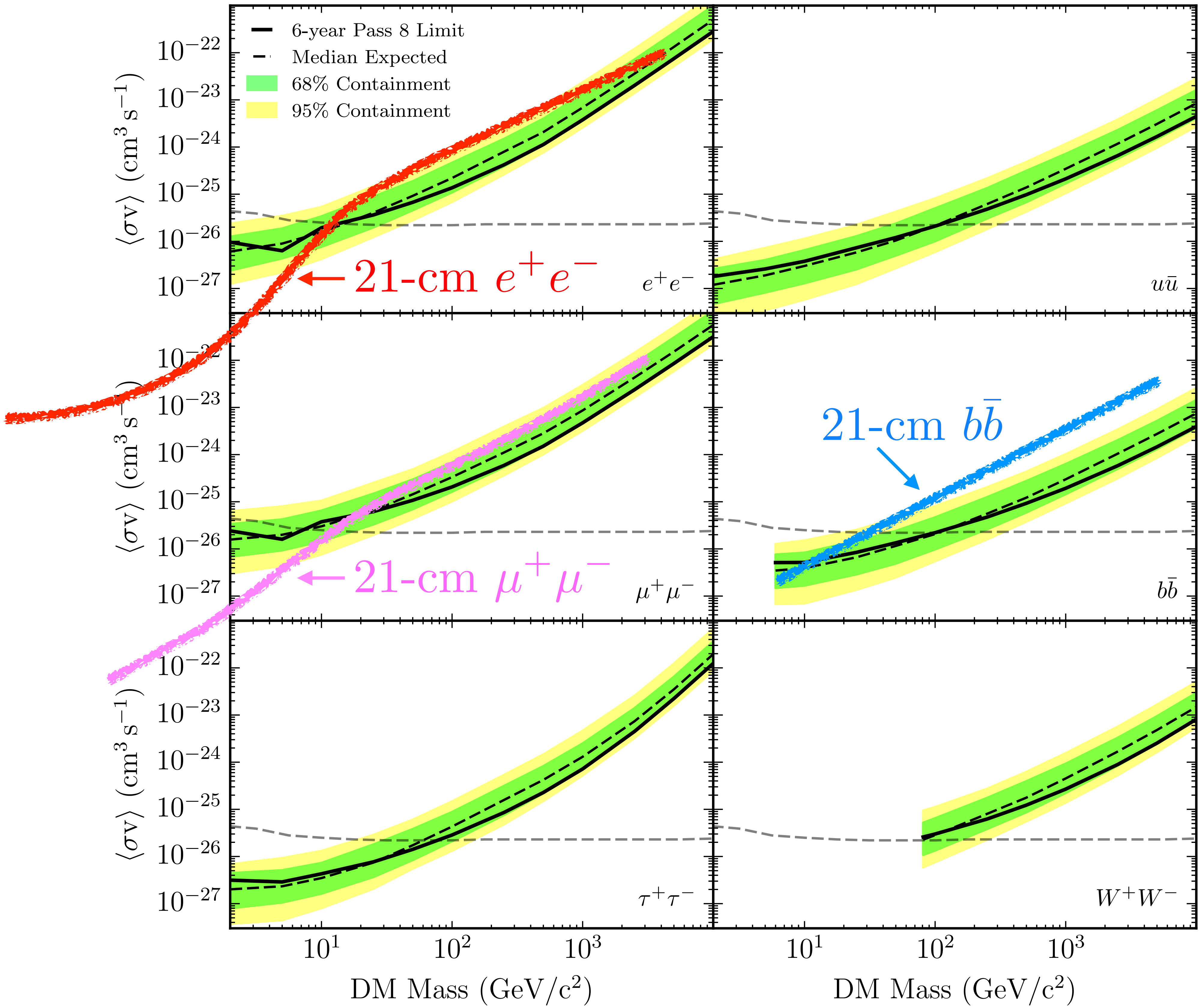


FERMI coll.
1503.02641

PAOLO PANCI
slide 25/26

Comparison: FERMI dSphs

GSSI
13/02/2019



FERMI coll.
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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

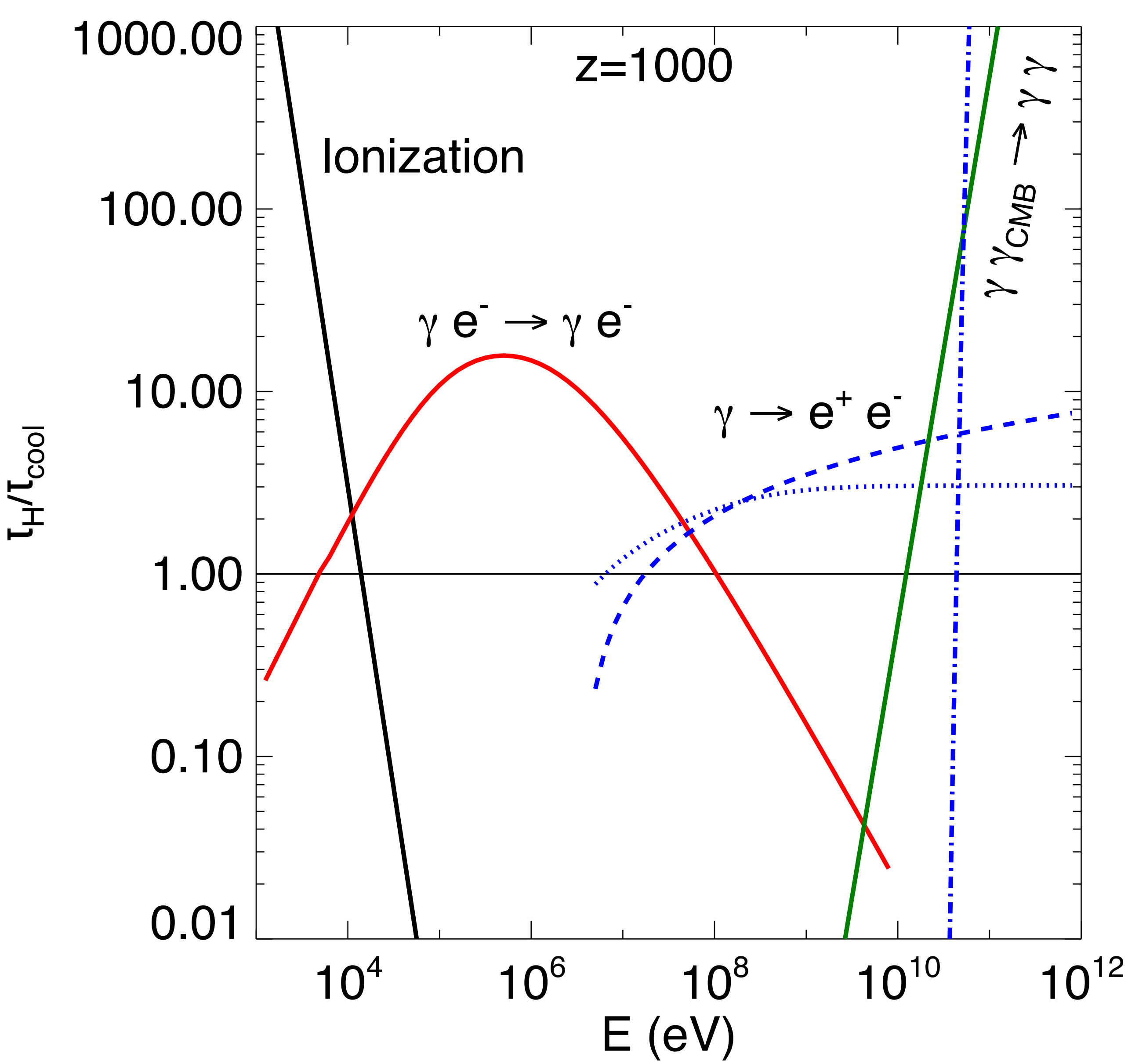
EM shower in the IGM

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

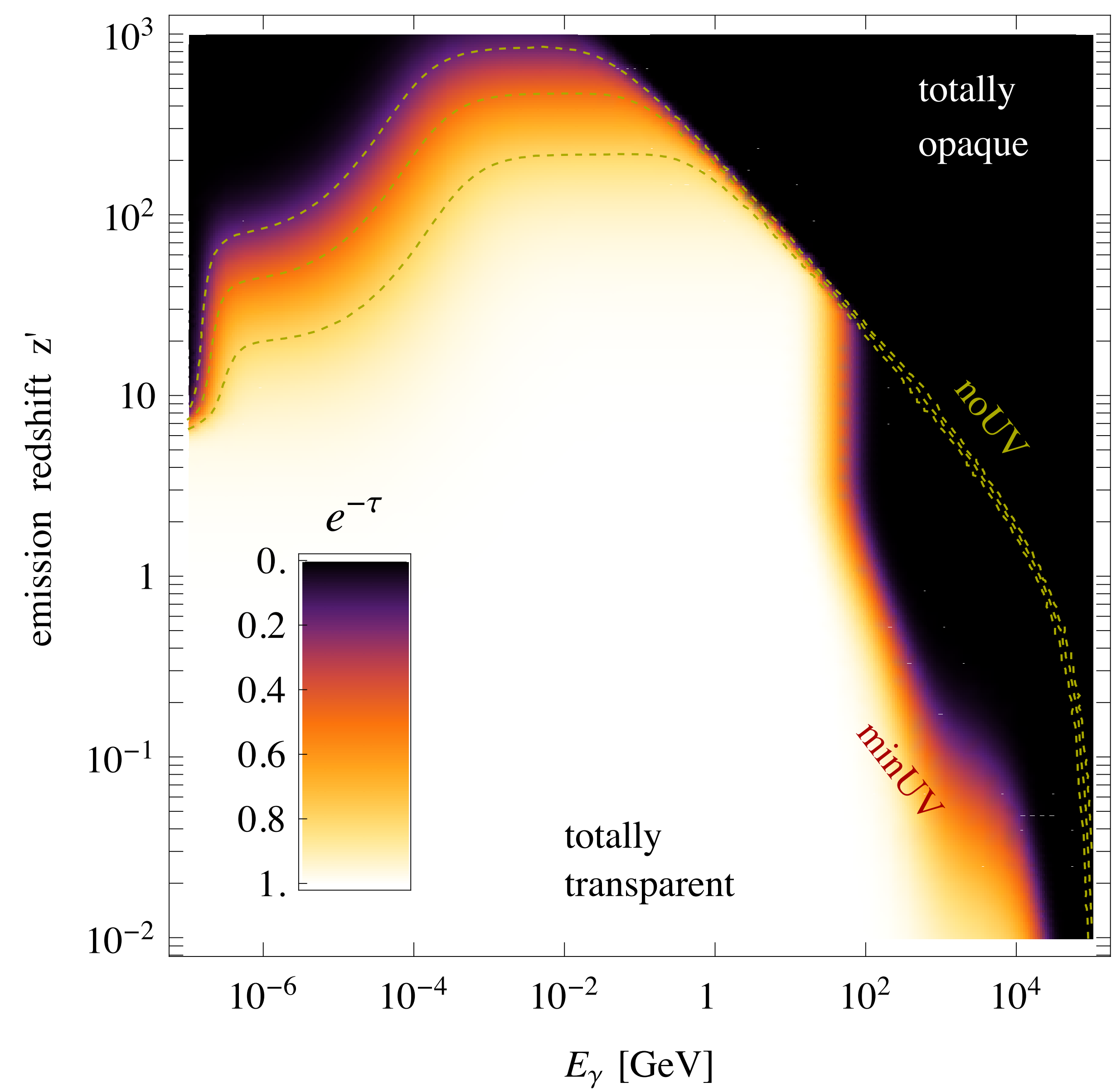
★ *Mean free path of the electrons/positrons* at a given redshift z

★ *Absorption of photons in the IGM*

Cooling time at z = *1000*

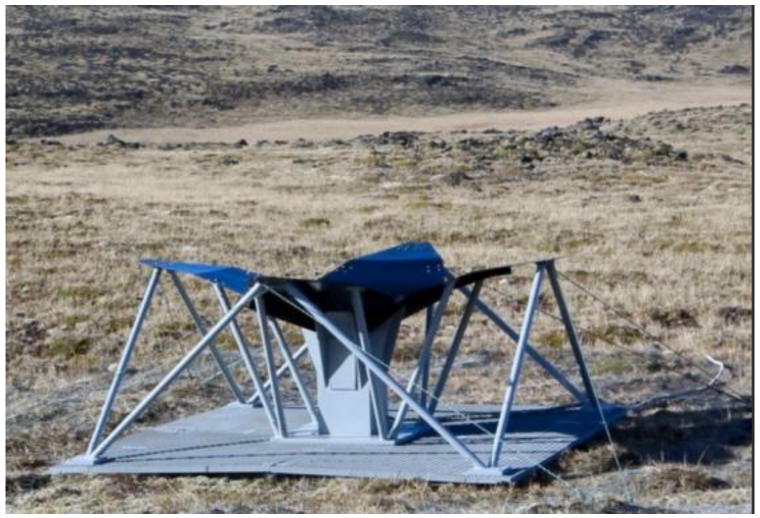


deposited z = *0 (Today)*

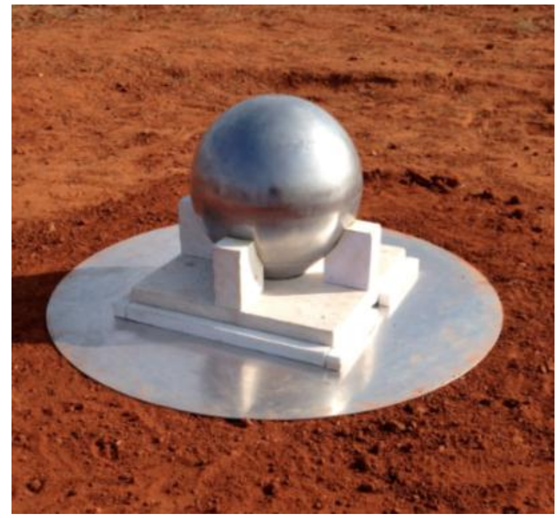


World Wide 21cm

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

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

Alternative Polynomial Model

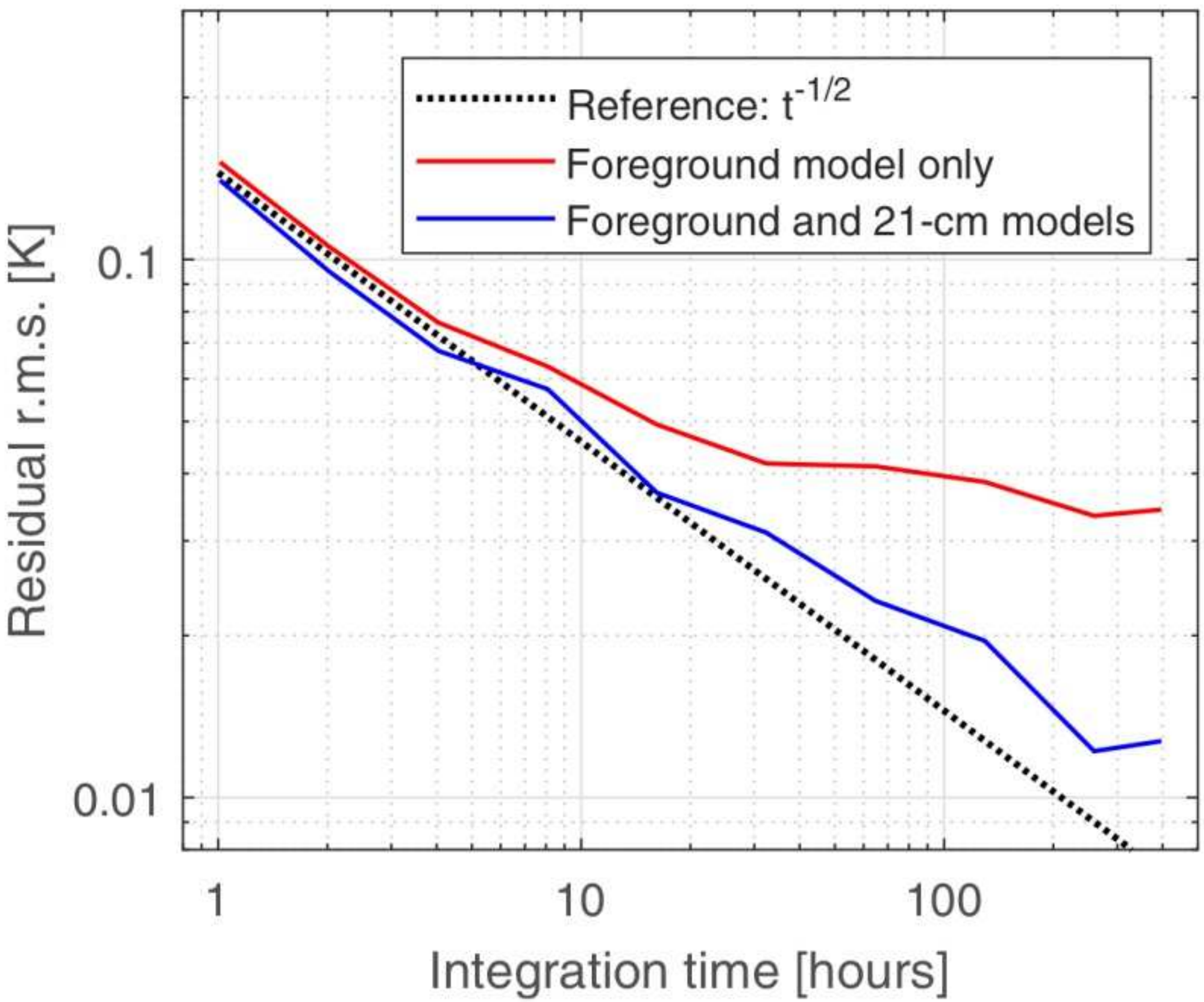
$$m_{\text{fg}}(\boldsymbol{a_i}) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \sum_{i=0}^{N_{\text{fg}}-1} \boldsymbol{a_i}\left(\frac{\nu}{\nu_n}\right)^{i}$$

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 !!

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

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

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

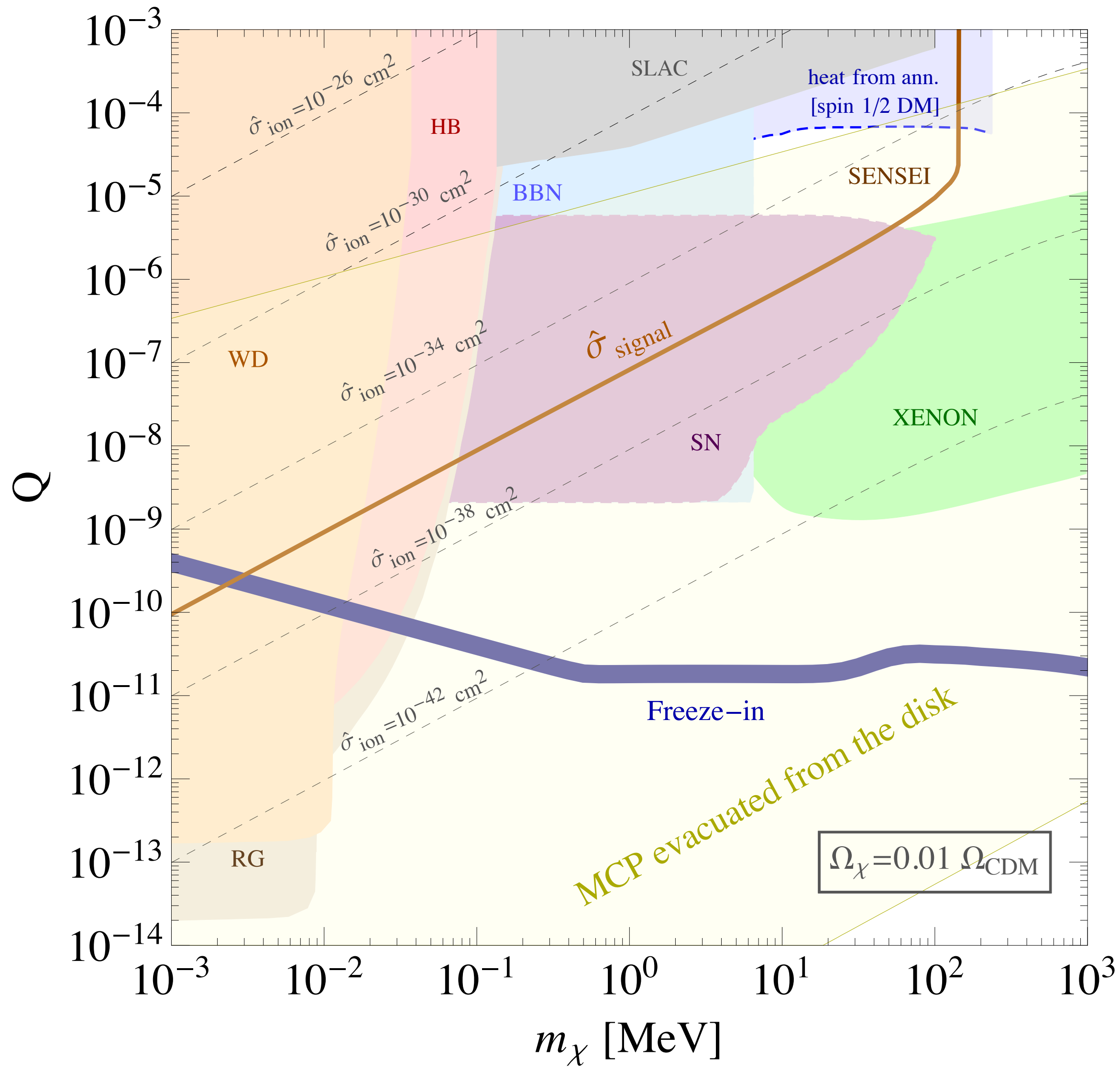
- Approach 1: *Cool the baryonic kinetic temperature even more* (90% of attemps: see e.g. Barkana et al.; Munoz, Loeb; ….)
- Approach 2: *Make more photons* that can mediate the 21-cm transition prior $z \sim 20$ (Pospelov, Pradler, Ruderman, Urbano)
- Approach 3: *Decouple protons from the CMB earlier*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



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

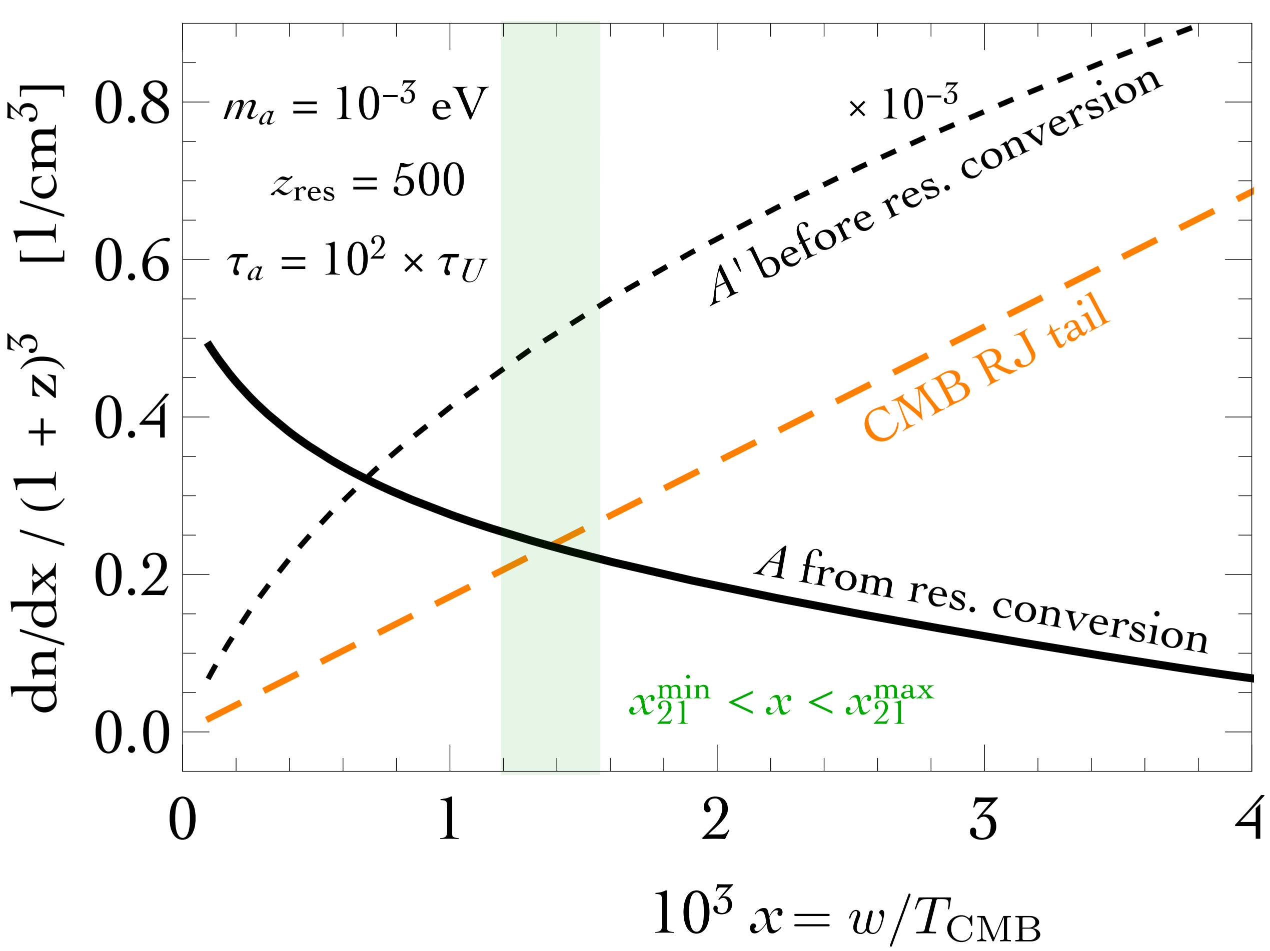
Barkana *et al.*
1803.03091

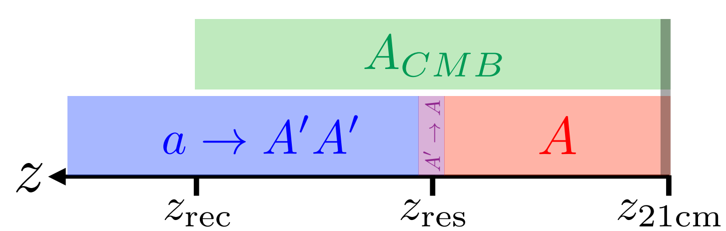
2: Increase the CMB RJ tail

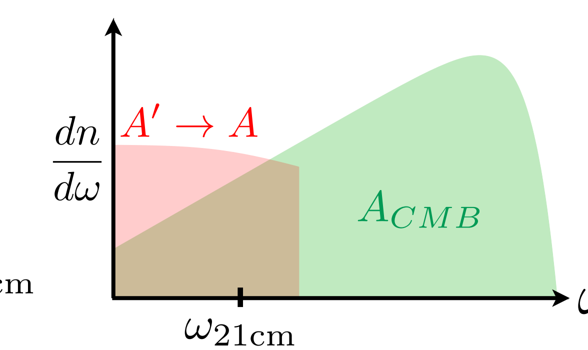
Early ($z > 20$) decays (either DM or of DR species) create a non-non-thermal ***population of DR dark photon A'***. Typical multiplicity is larger than $n_{\rm RJ}$

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

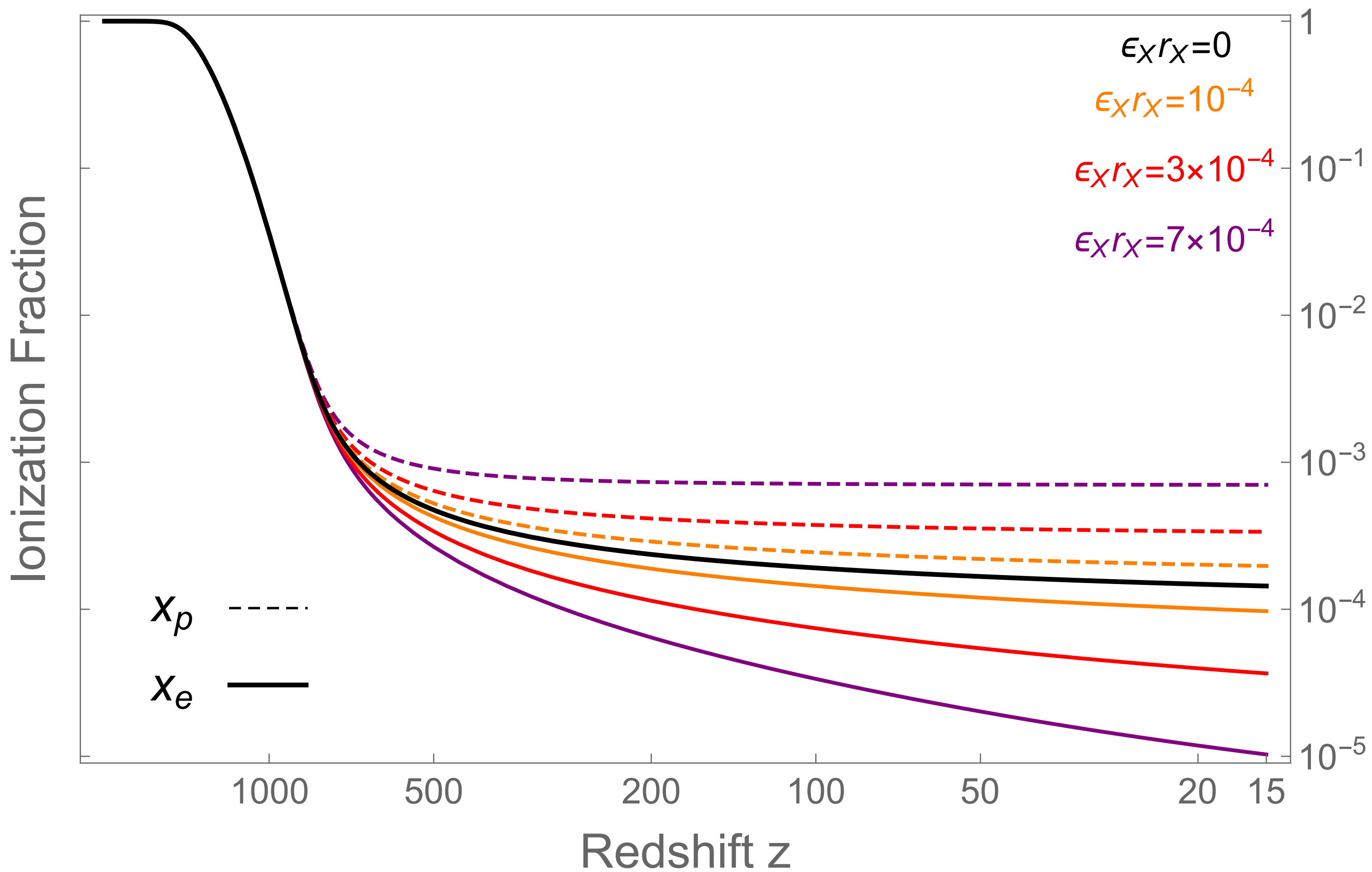
3: Charge sequestration

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