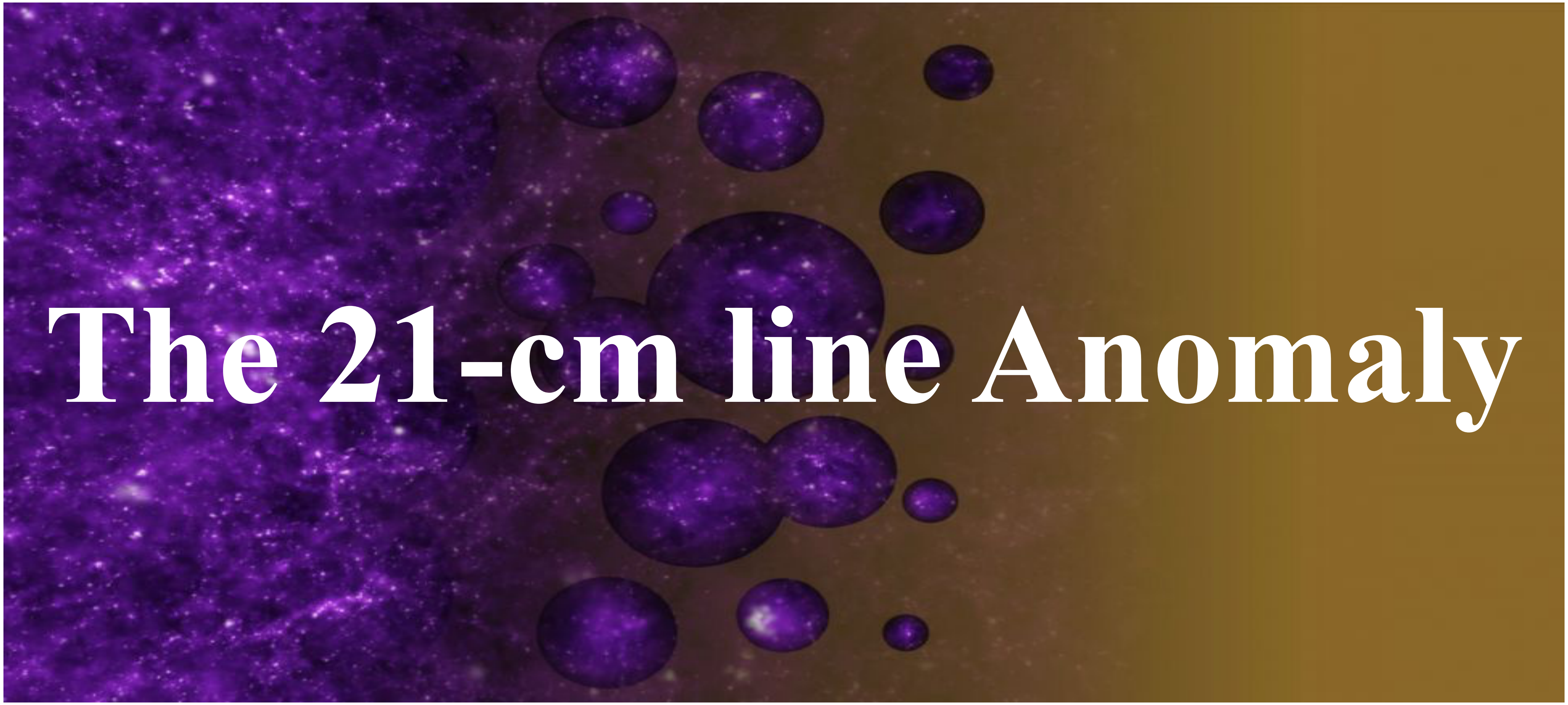
La Thuile 2019: “Les Rencontres de physique de la vallée d'Aoste"
11/03/2019



The 21-cm line Anomaly

PAOLO PANCI

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

CERN

Plan of the Talk

What EDGES has observed

Quick physics of the 21-cm line

- A short history of the IGM properties
- Why the amplitude of the signal is anomalous

BSM Implications from the EDGES anomaly

Outlook & Discussions

What happened in March

LETTER

doi:10.1038/nature25792

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

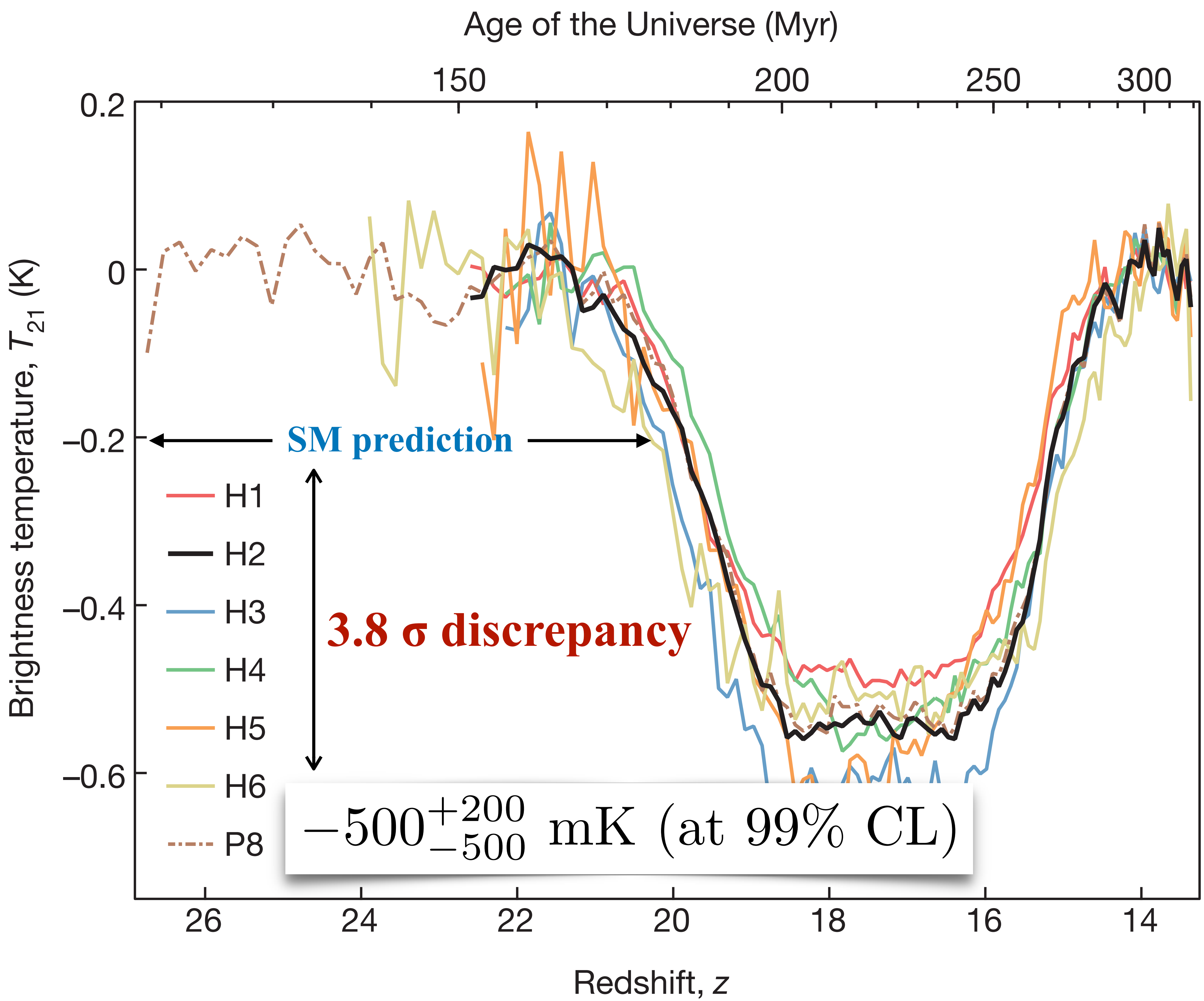
Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

A 21-cm signal in *absorption*

Between redshifts ∼20 and 15

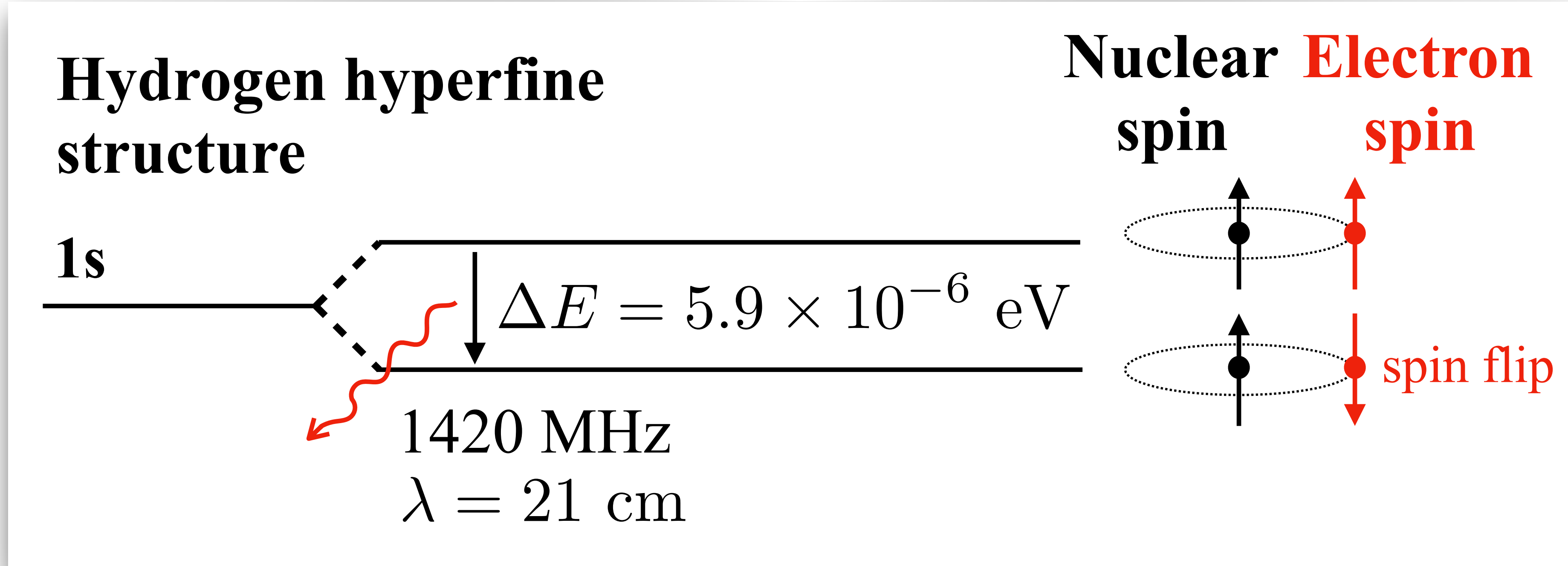
Amplitude *twice* as large as predicted (∼500 mK vs. ∼200mK)

What did EDGES see?



$$-500^{+200}_{-500} \text{ mK (at 99\% CL)}$$

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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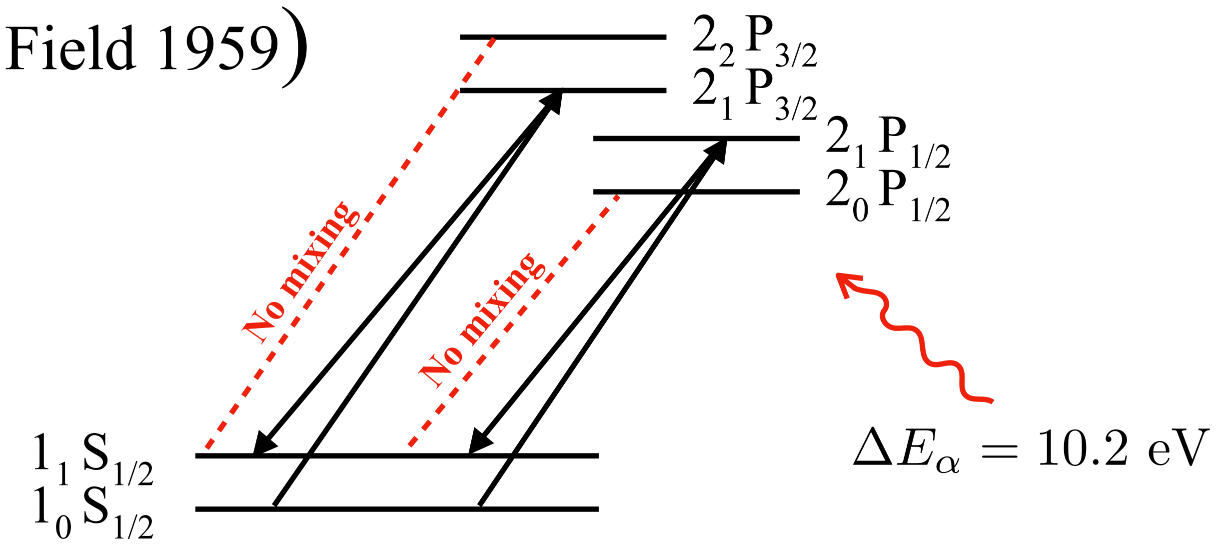

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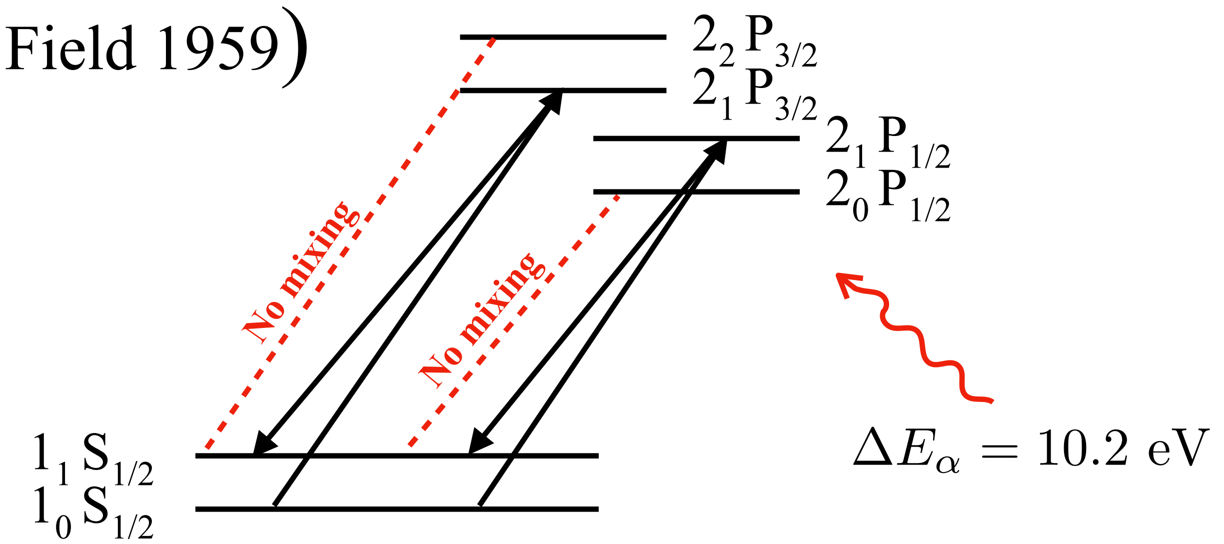


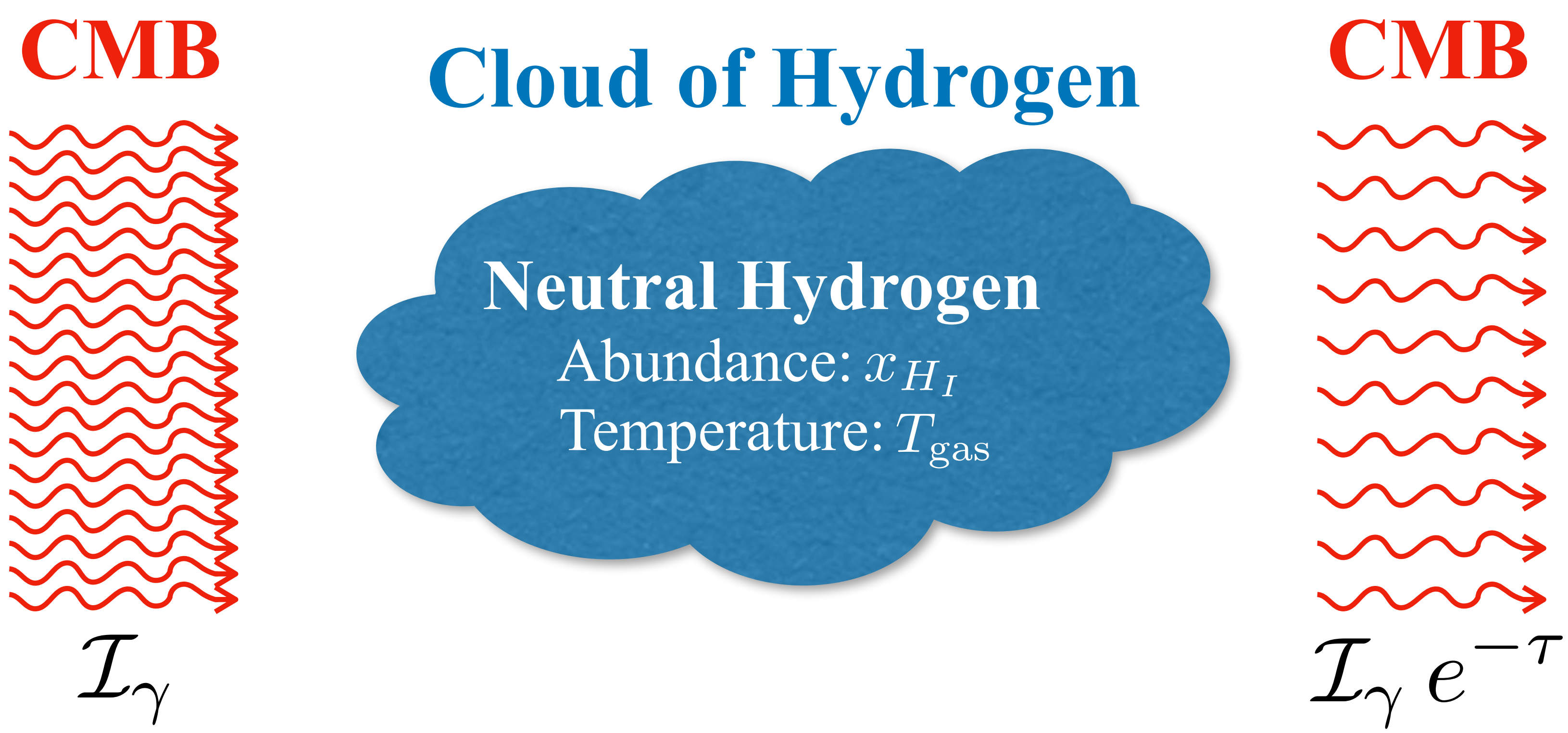
Equilibrium implies:

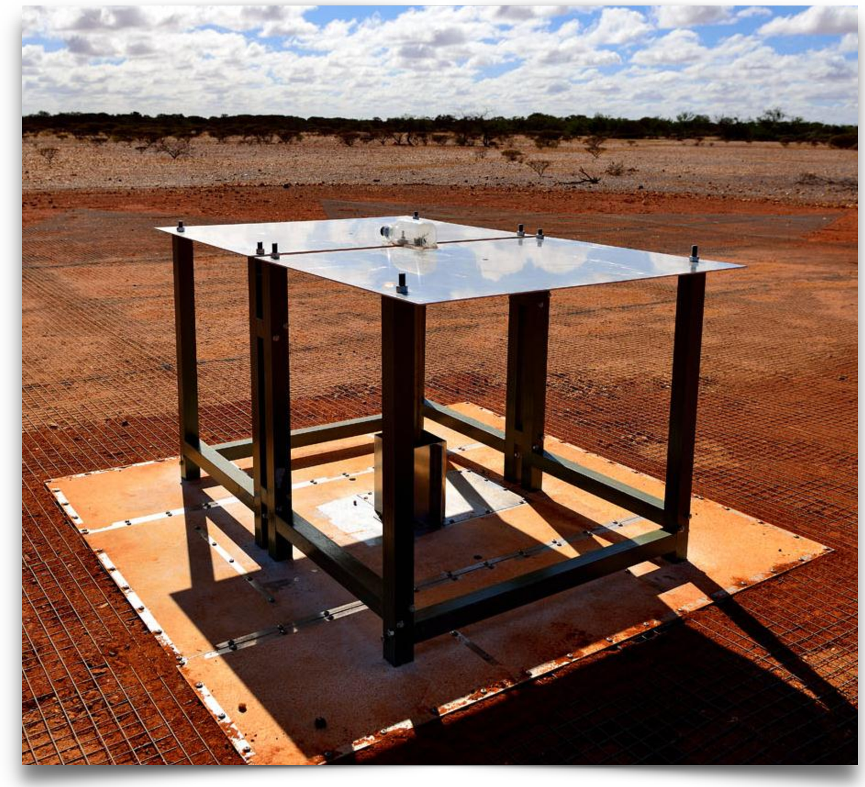
$$n_{\uparrow\uparrow}(\mathcal{C}_{10} + \mathcal{P}_{10} + \mathcal{A}_{10} + \mathcal{B}_{10} I_\gamma) = n_{\uparrow\downarrow}(\mathcal{C}_{01} + \mathcal{P}_{01} + \mathcal{B}_{01} I_\gamma)$$

In terms of temperature:

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

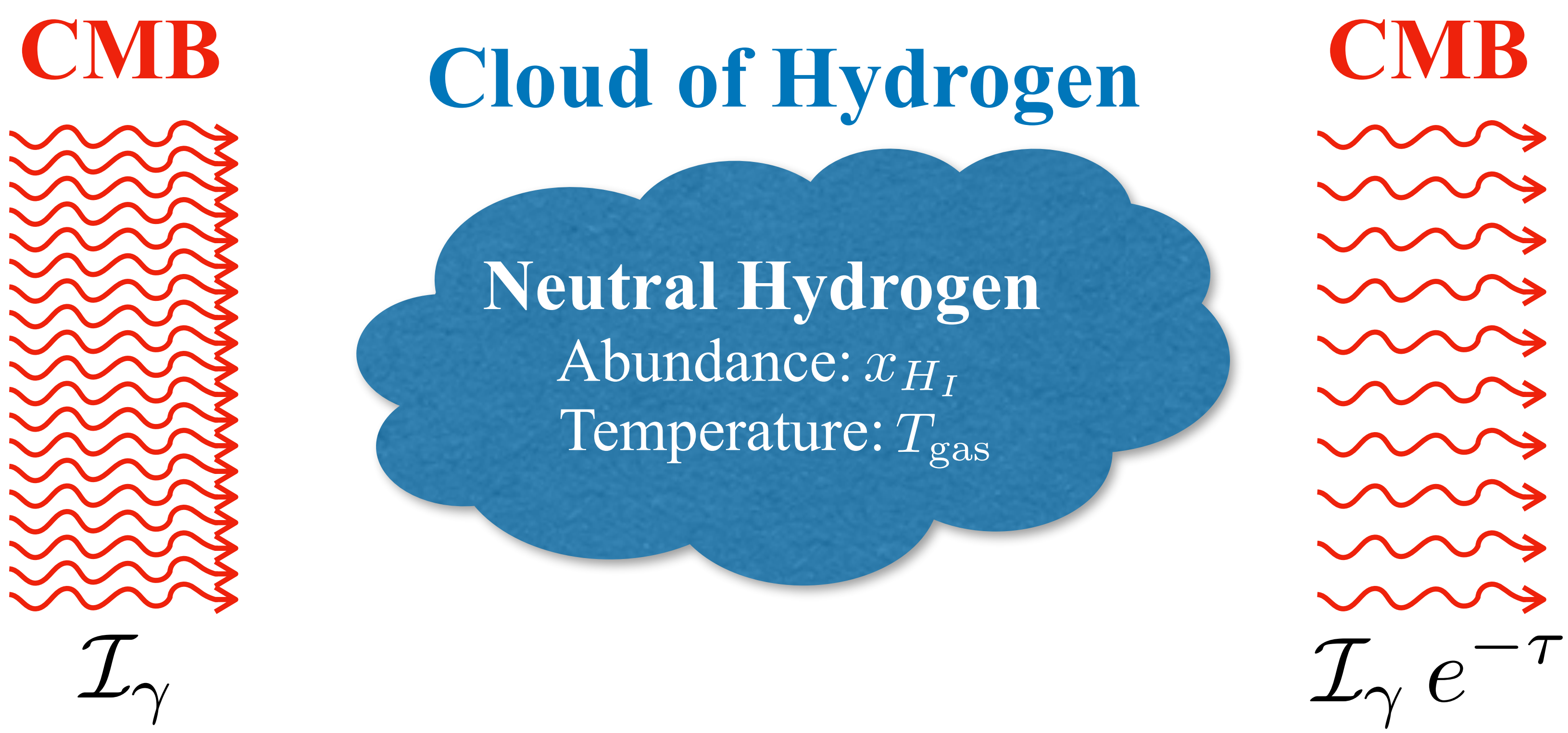
What we see

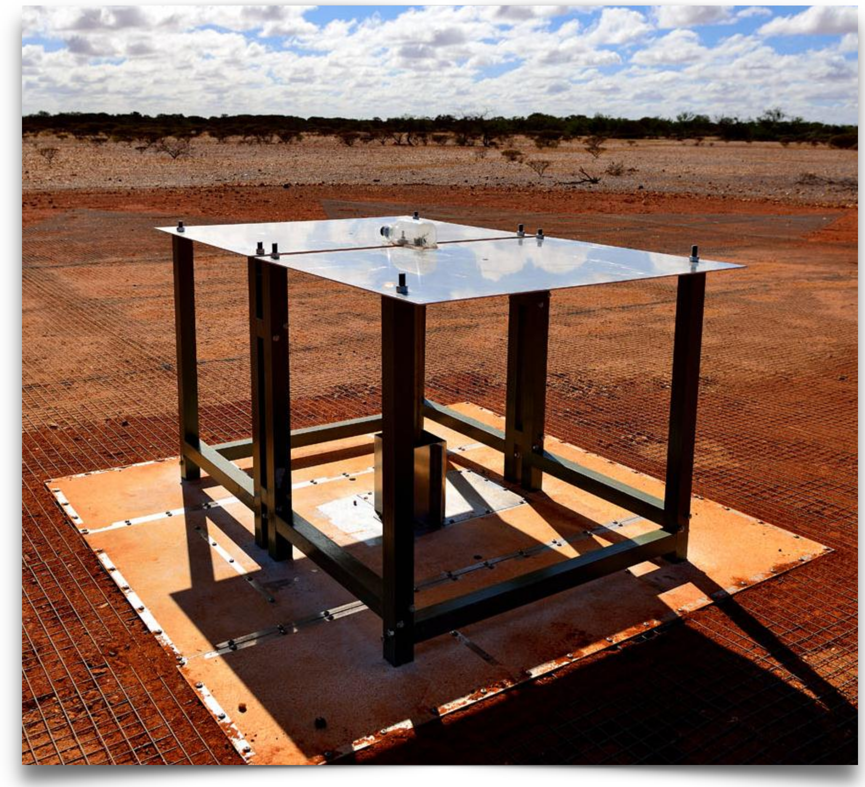




$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

What we see





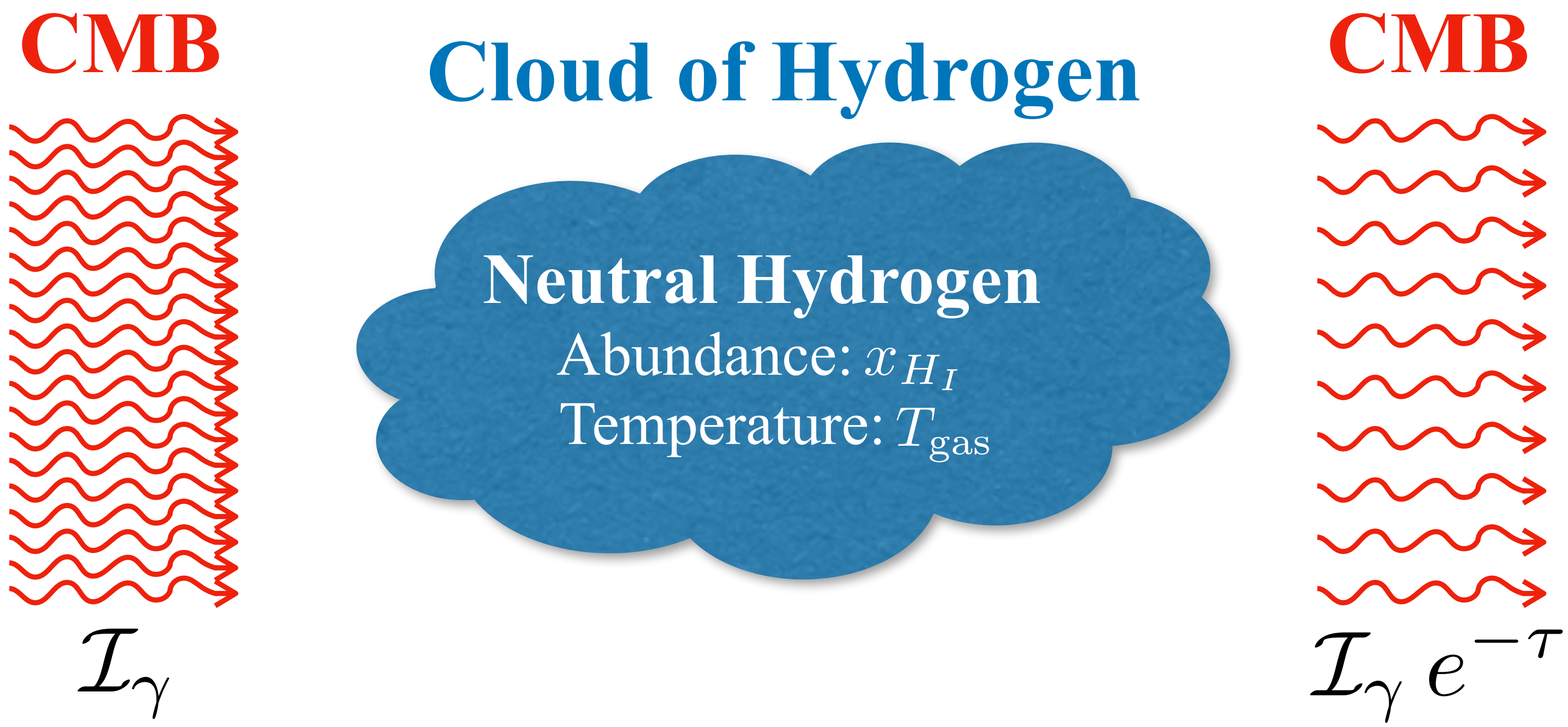
$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

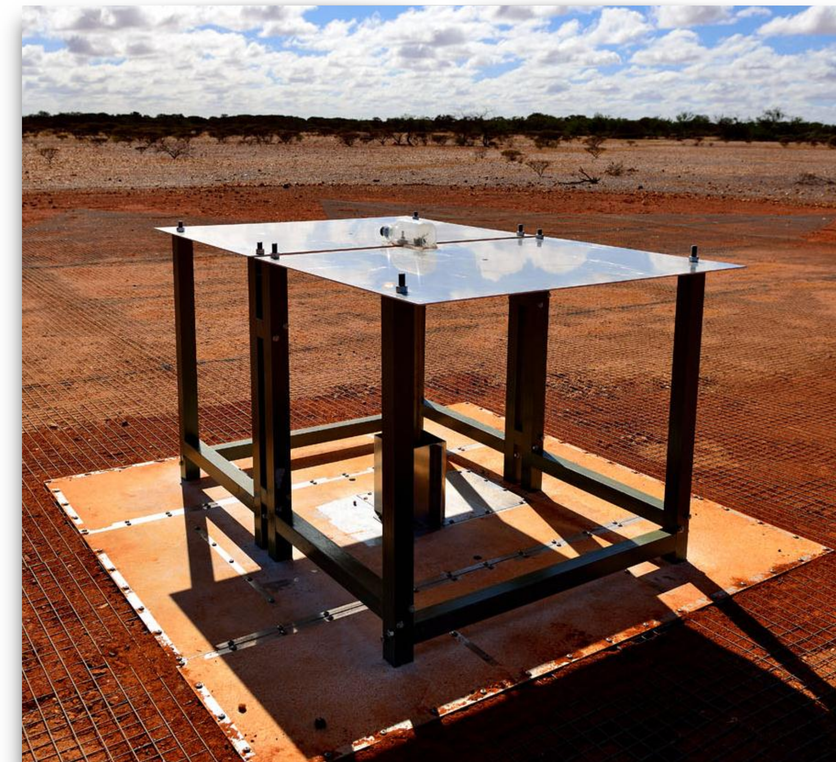
$$T_{21} \propto \mathcal{I}_\gamma(1-e^{-\tau}) \approx I_\gamma \tau \approx 21\,\mathrm{mK}\, x_{H_I}\left(1-\frac{T_{\mathrm{CMB}}}{T_S}\right)\sqrt{\frac{1+z}{10}}$$

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

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

What we see





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

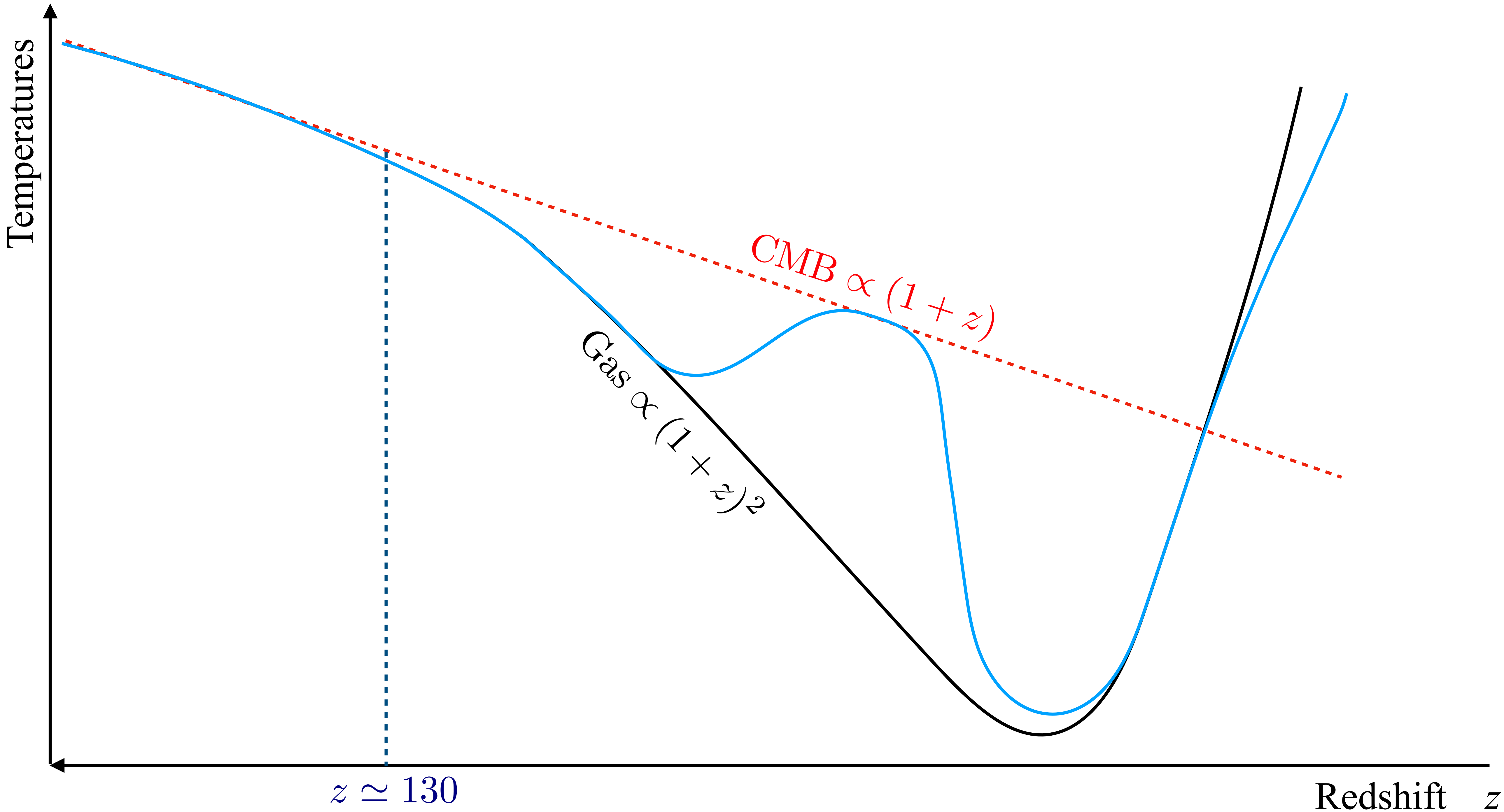
EDGES measurement implies

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

$T_S \simeq 3$ K

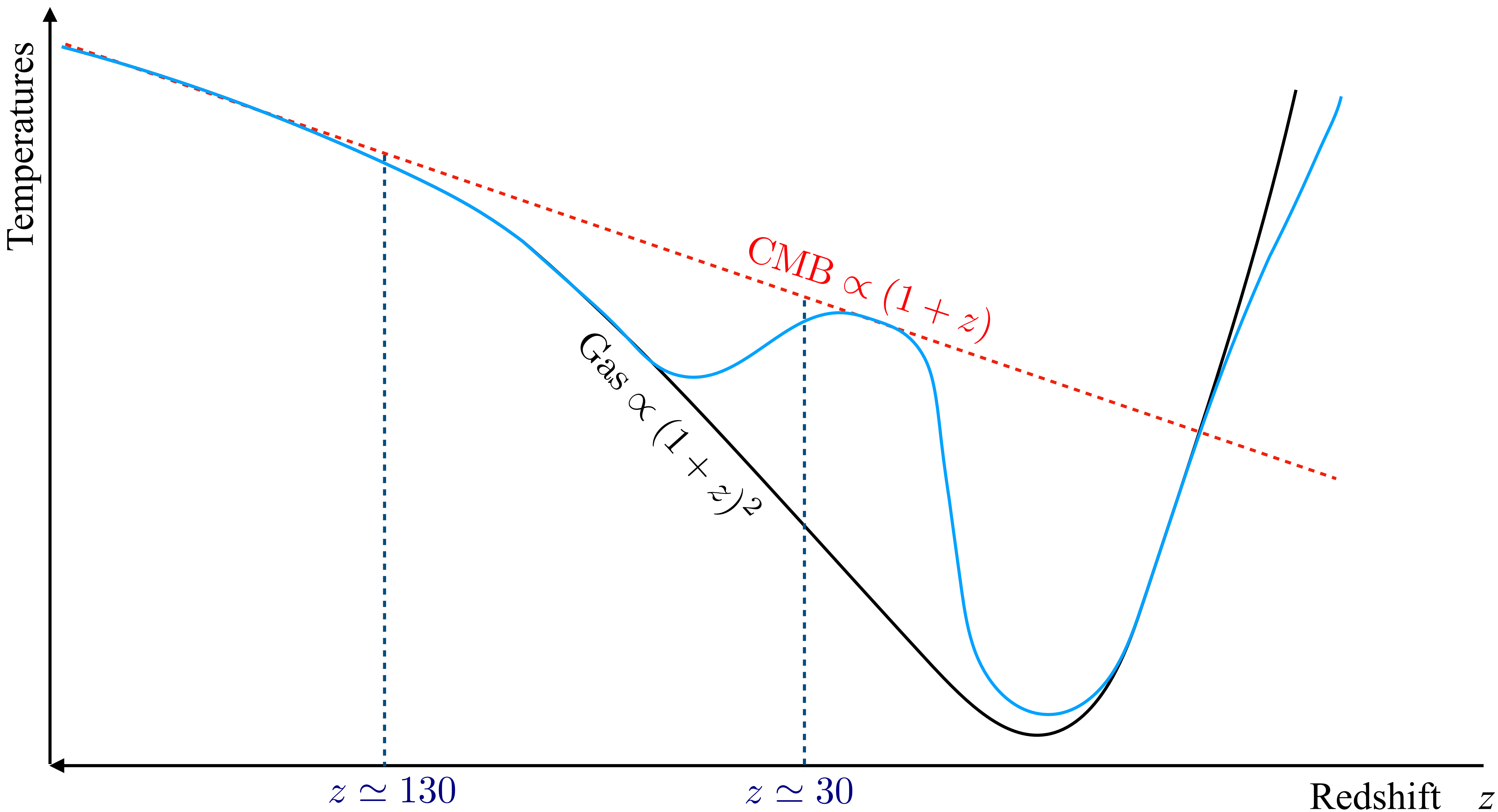
A short history of T_S

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



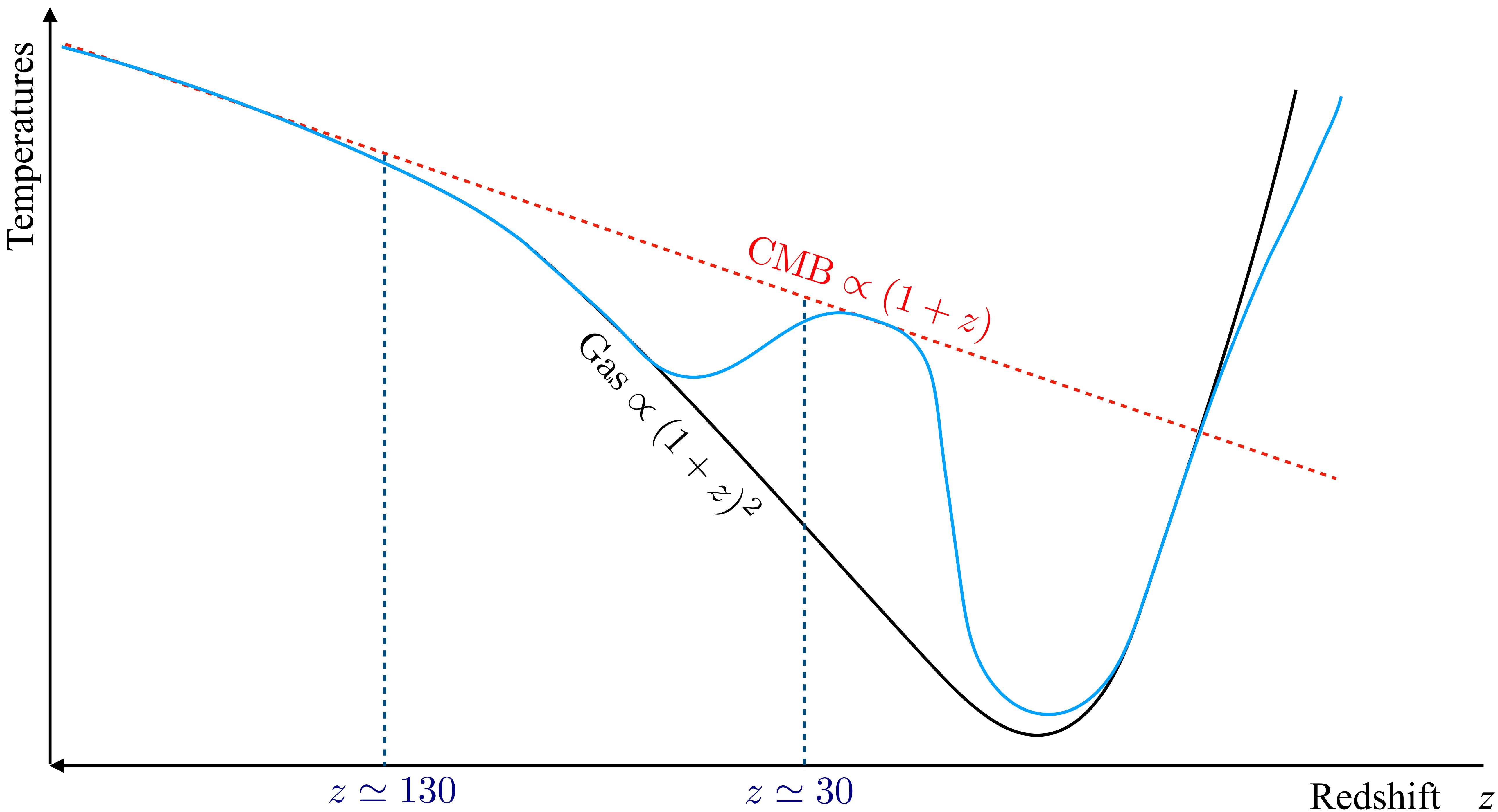
A short history of T_S

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



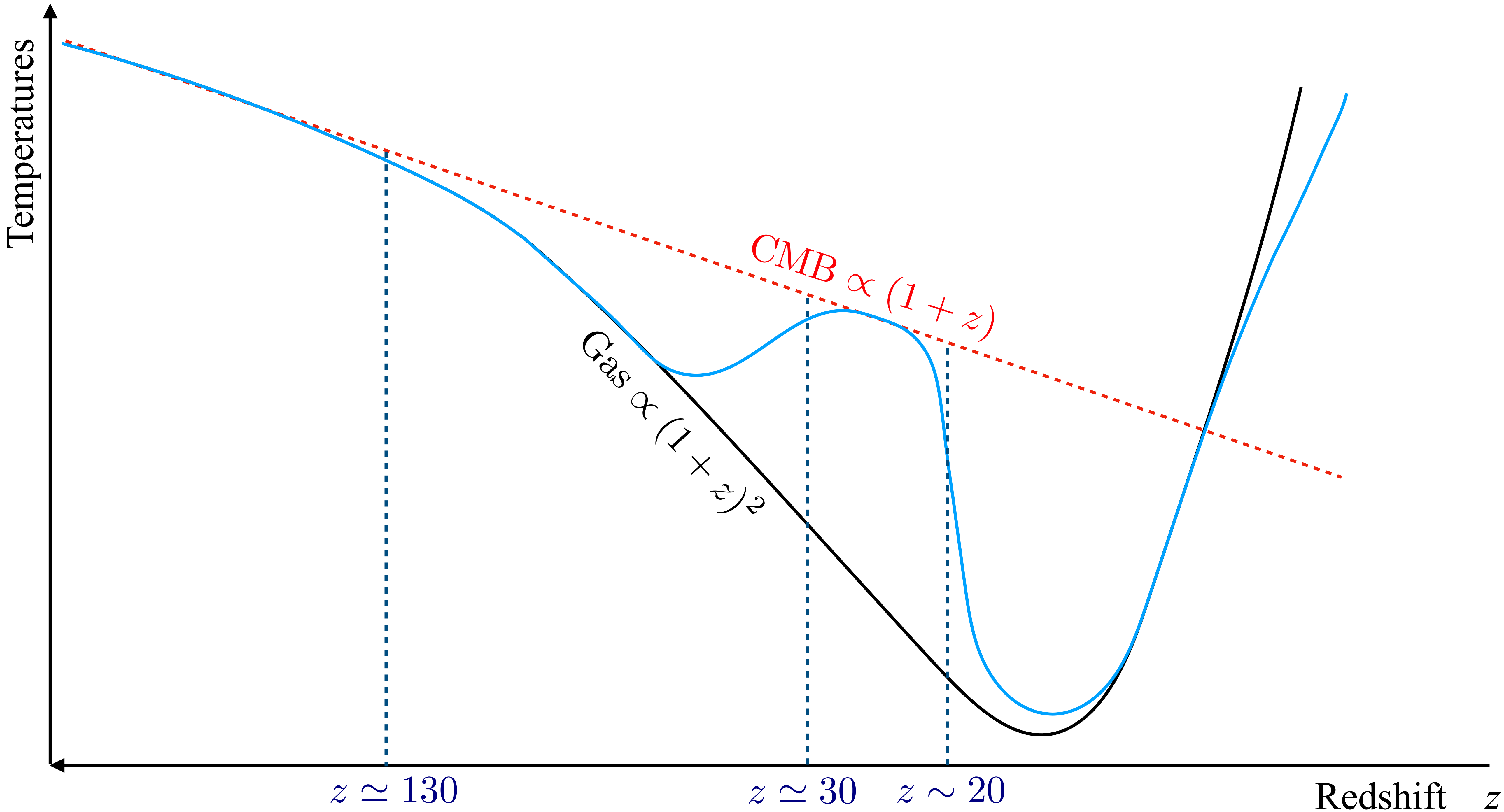
A short history of T_S

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



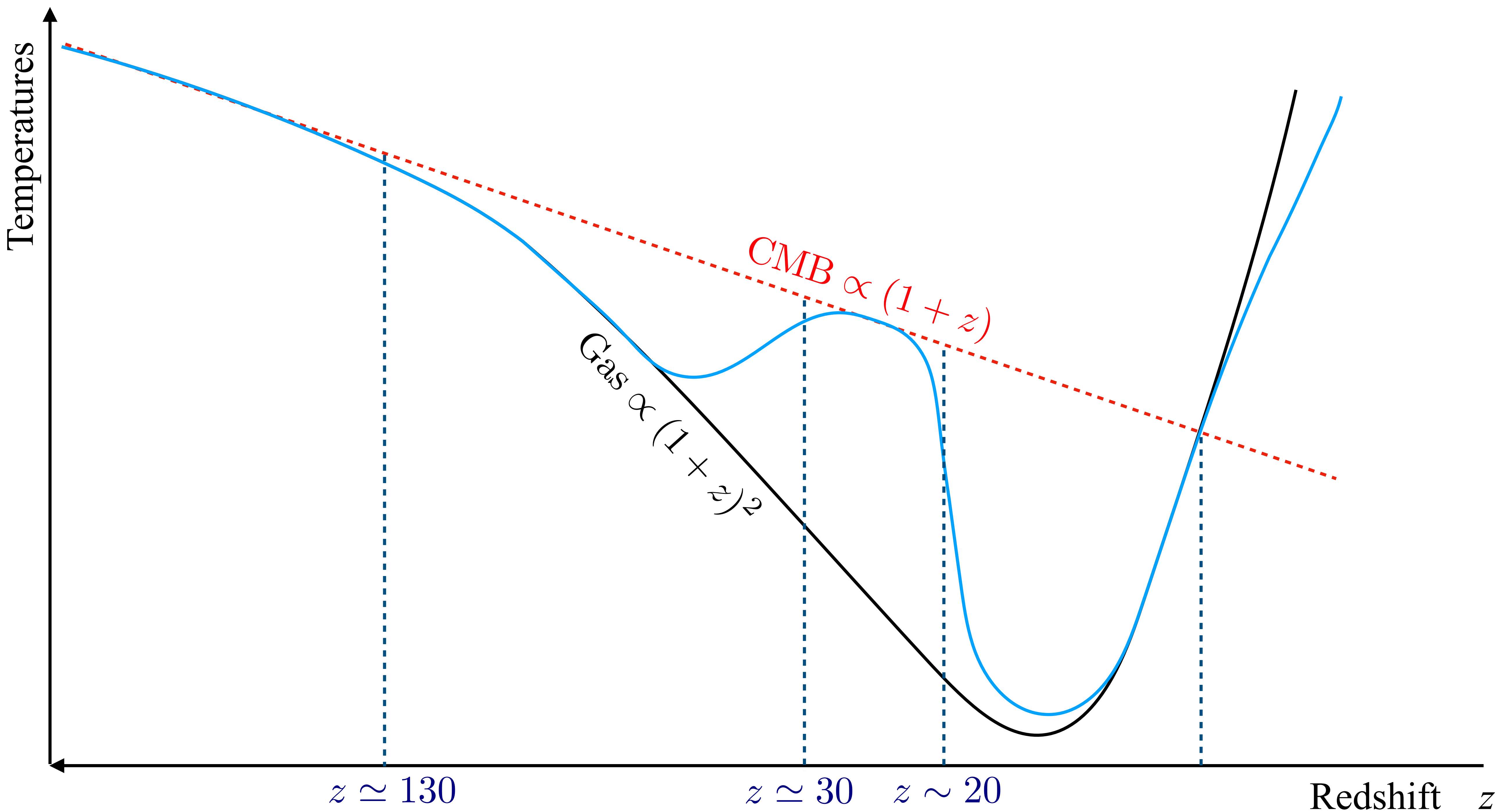
A short history of T_S

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

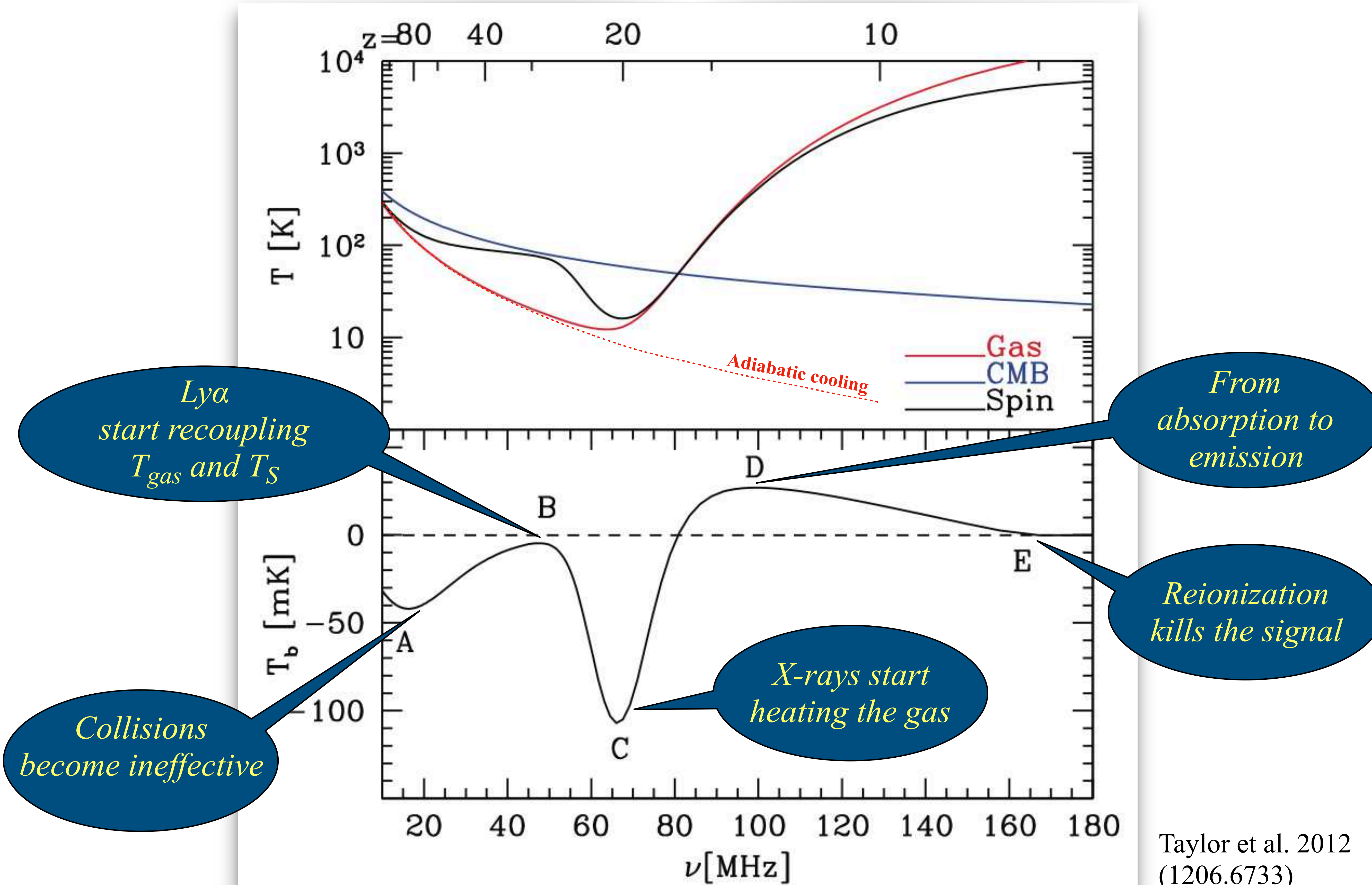


A short history of T_S

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

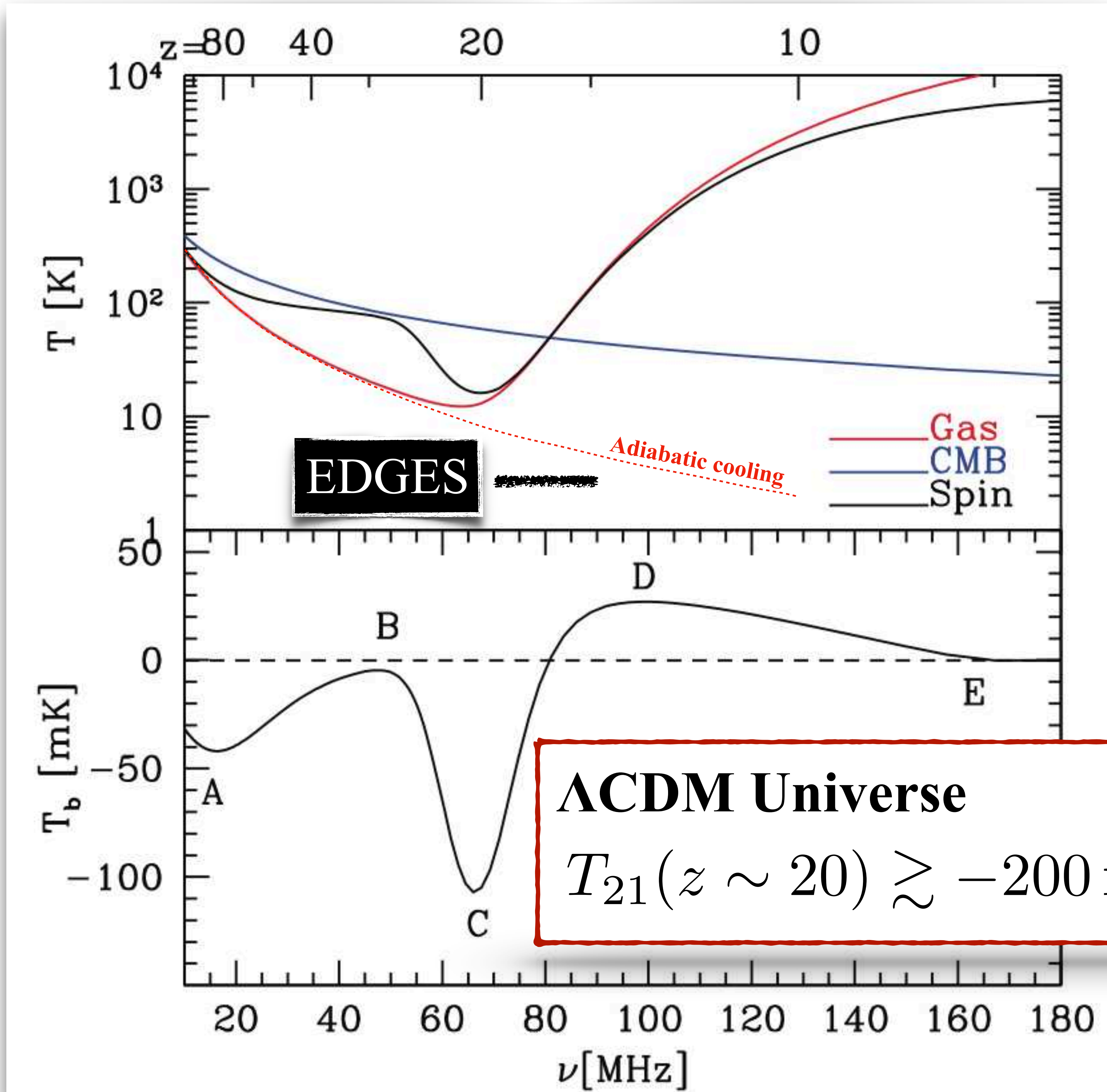


21-cm signal history



Taylor et al. 2012 (1206.6733)

21-cm signal history



ΛCDM Universe

$$T_{21}(z \sim 20) \gtrsim -200\,\mathrm{mK}$$

Taylor et al. 2012
(1206.6733)

Explain the Anomaly

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

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

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

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

- 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)

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- Large DM-baryons interactions to exchange energy very efficiently
  ***Coulomb-like interactions enhanced** as* $\mathrm{d}\sigma/\mathrm{d}\Omega \propto \hat{\sigma}\, v^{-4}$

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What DM models?

DM Models with **large long-range interactions**
& not excluded by **5th force experiments**

- Models with light **hidden photon that mixes with SM photons**
- Models under which **DM is millicharged**

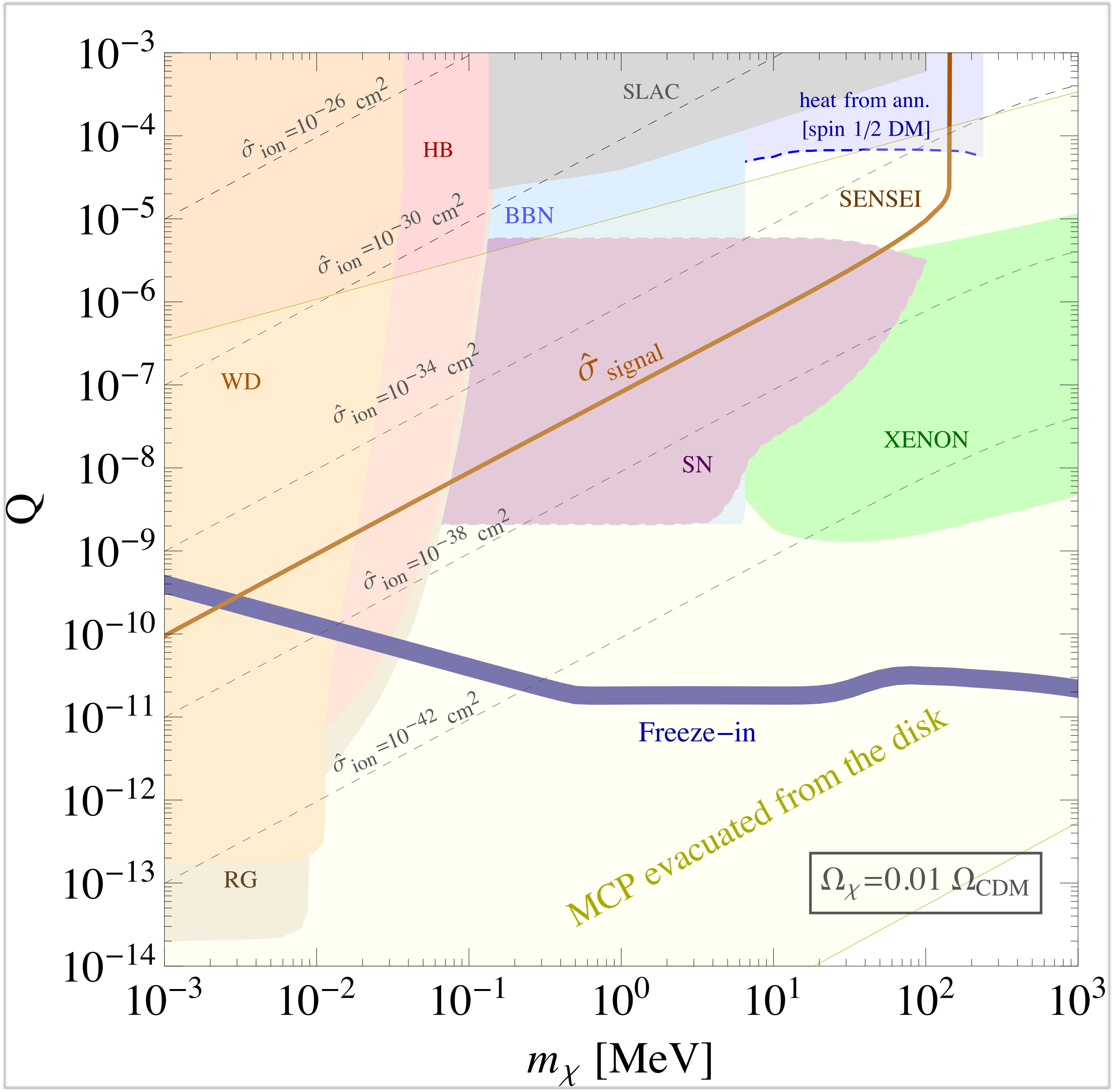
see e.g. Barkana et al.

1: Cool the IGM even more

Milli-charged DM could work: DM-baryon XS enhanced as $\mathrm{d}\sigma/\mathrm{d}\Omega \propto \hat{\sigma}\, v^{-4}$

Implication: a subdominant 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.*
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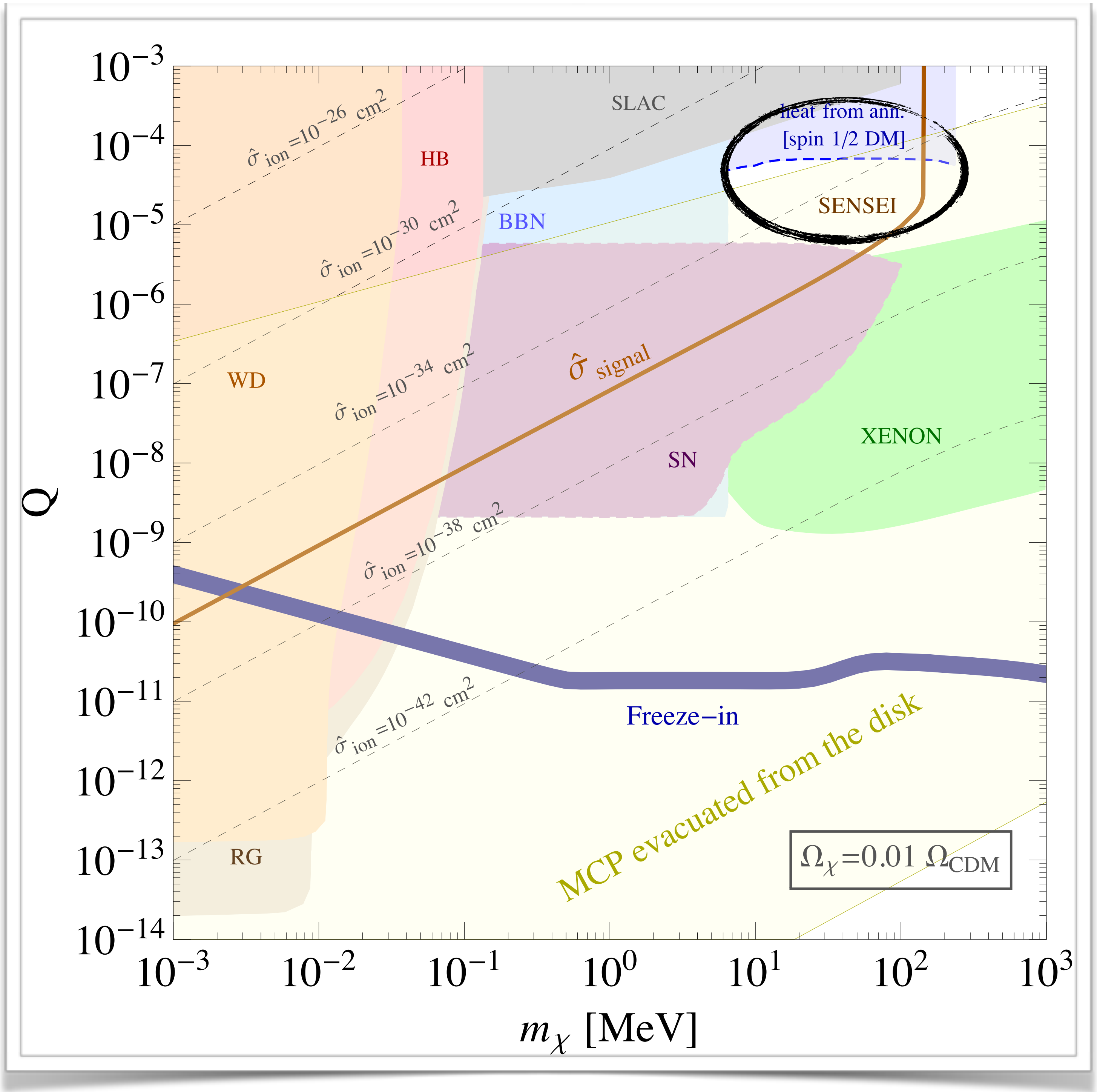

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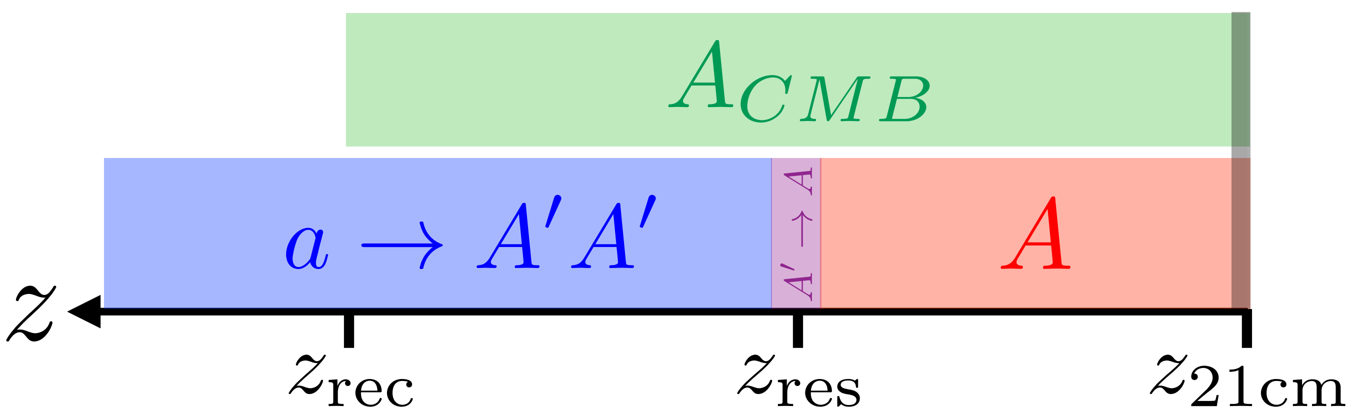
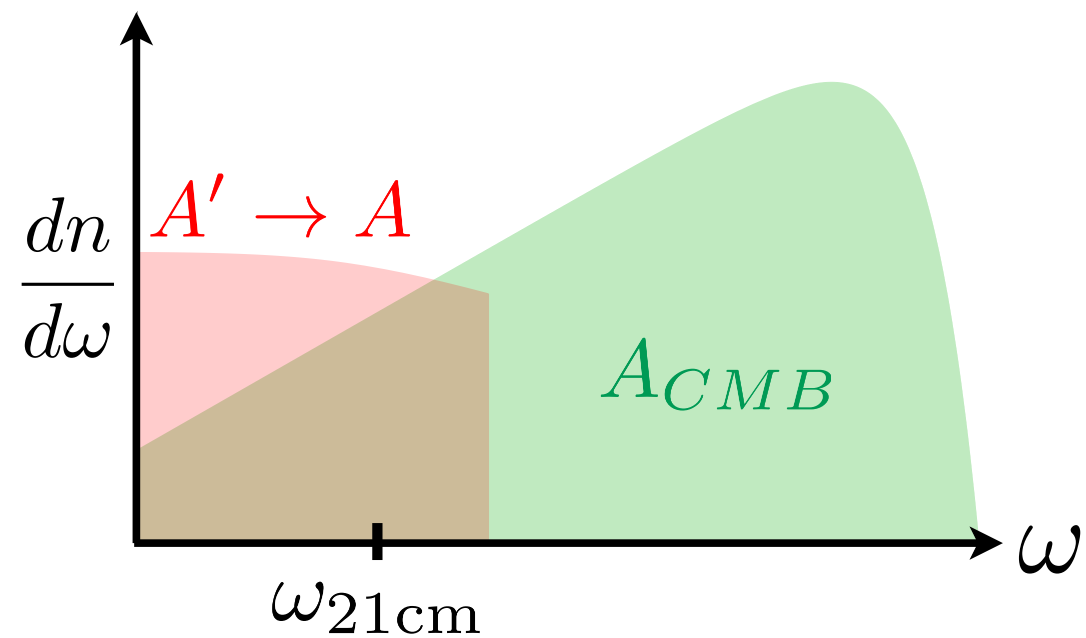
What DM model can do that?

see Pospelov, Pradler, Ruderman, Urbano





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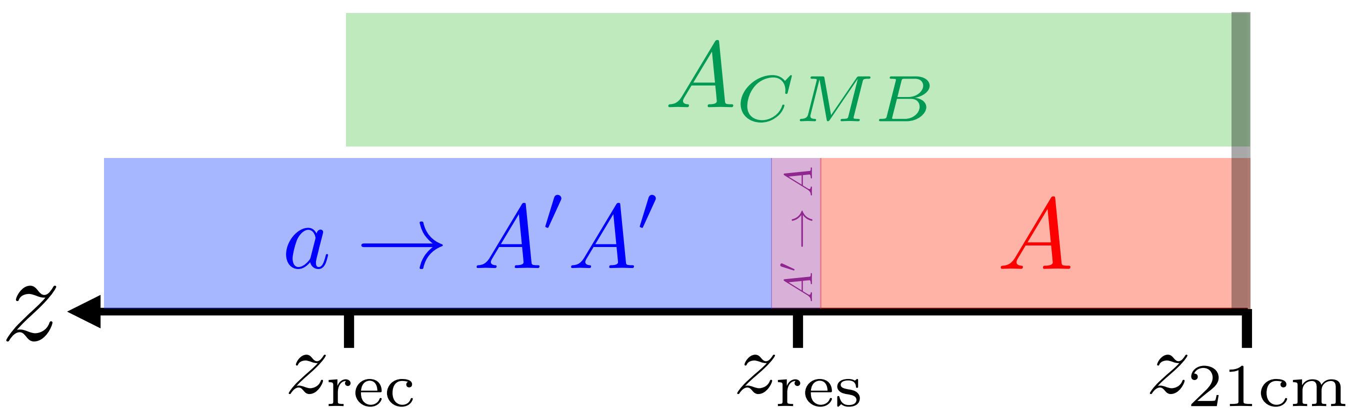

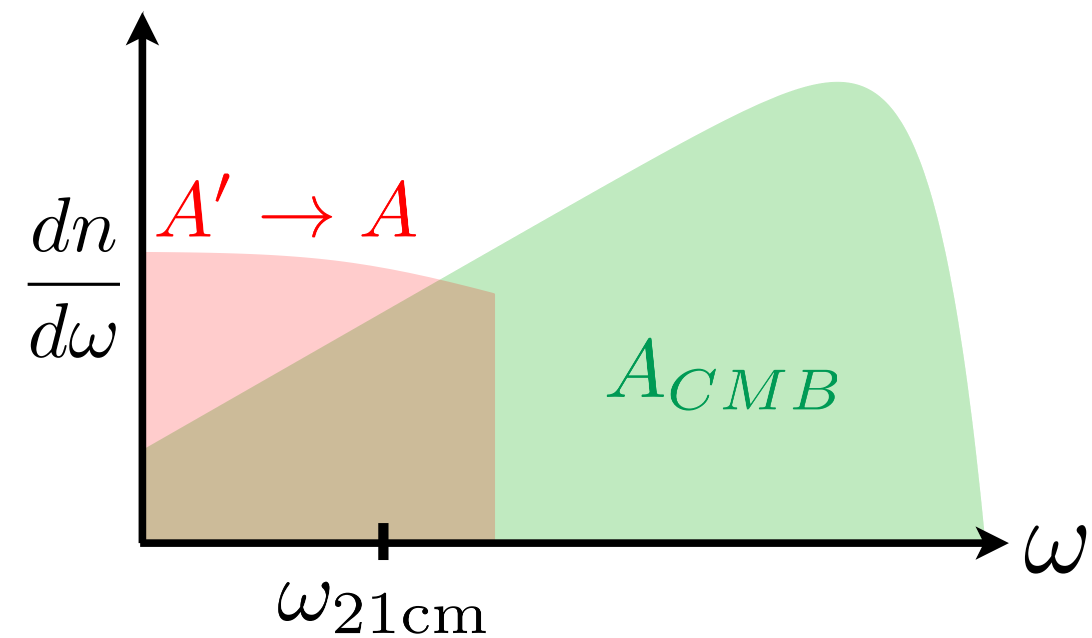

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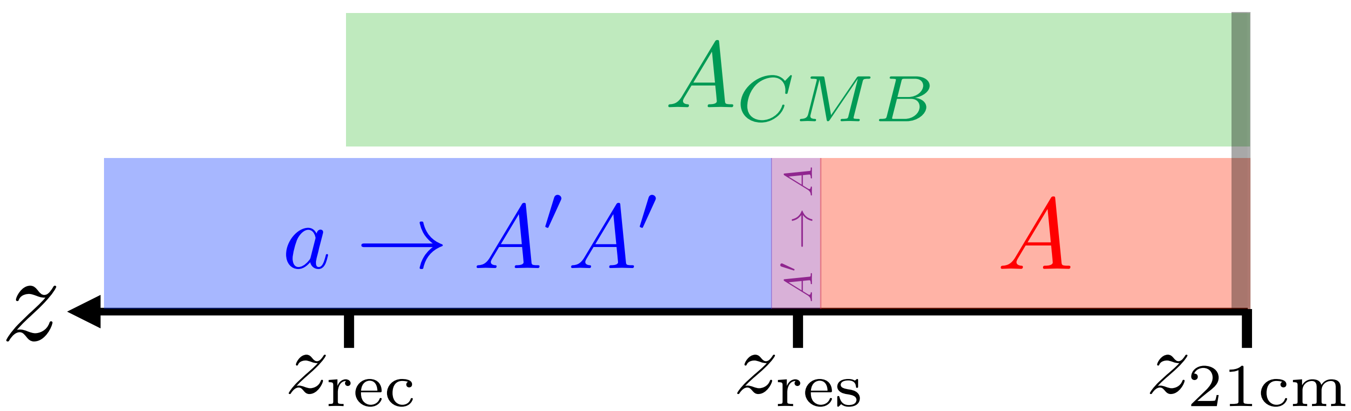

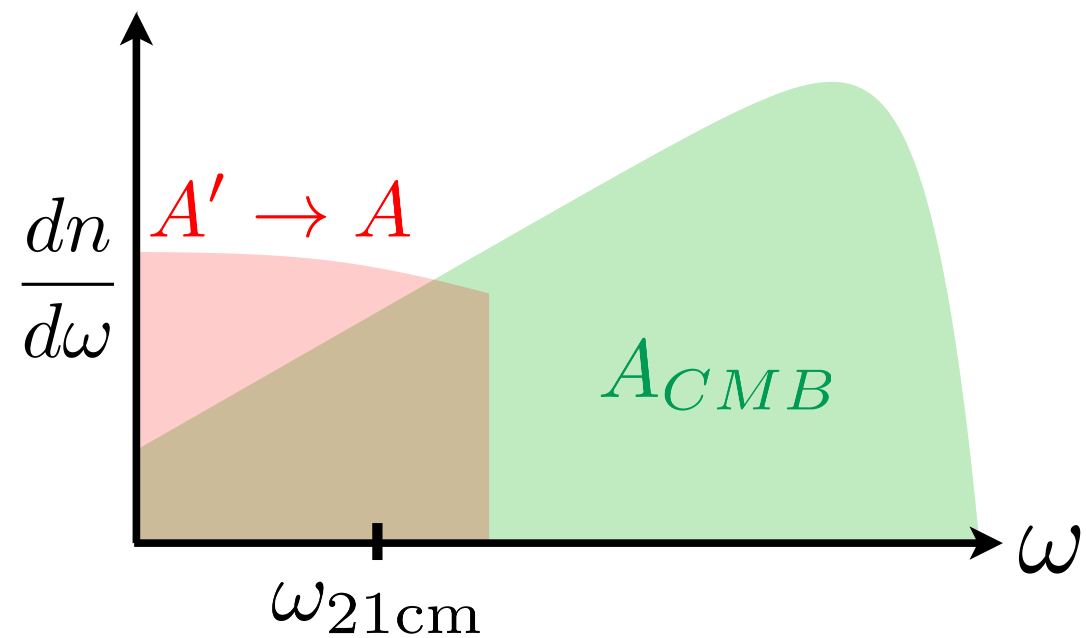

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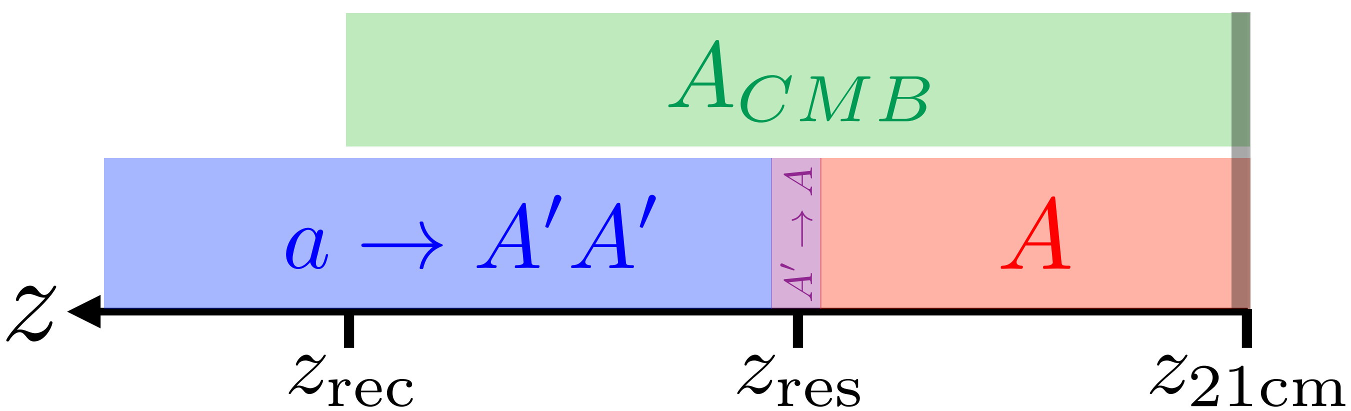

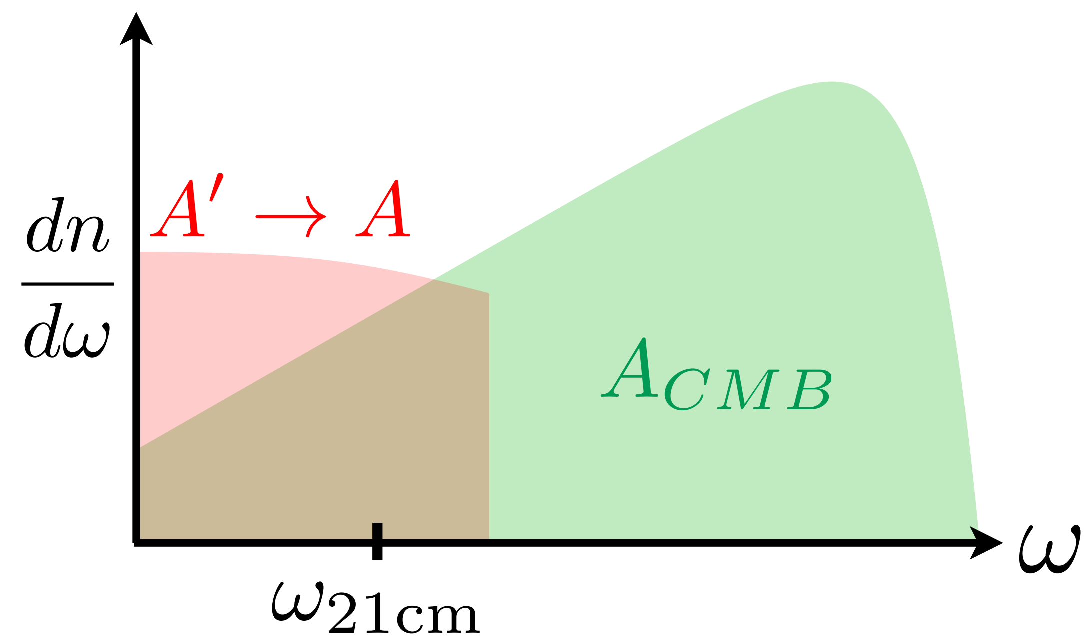

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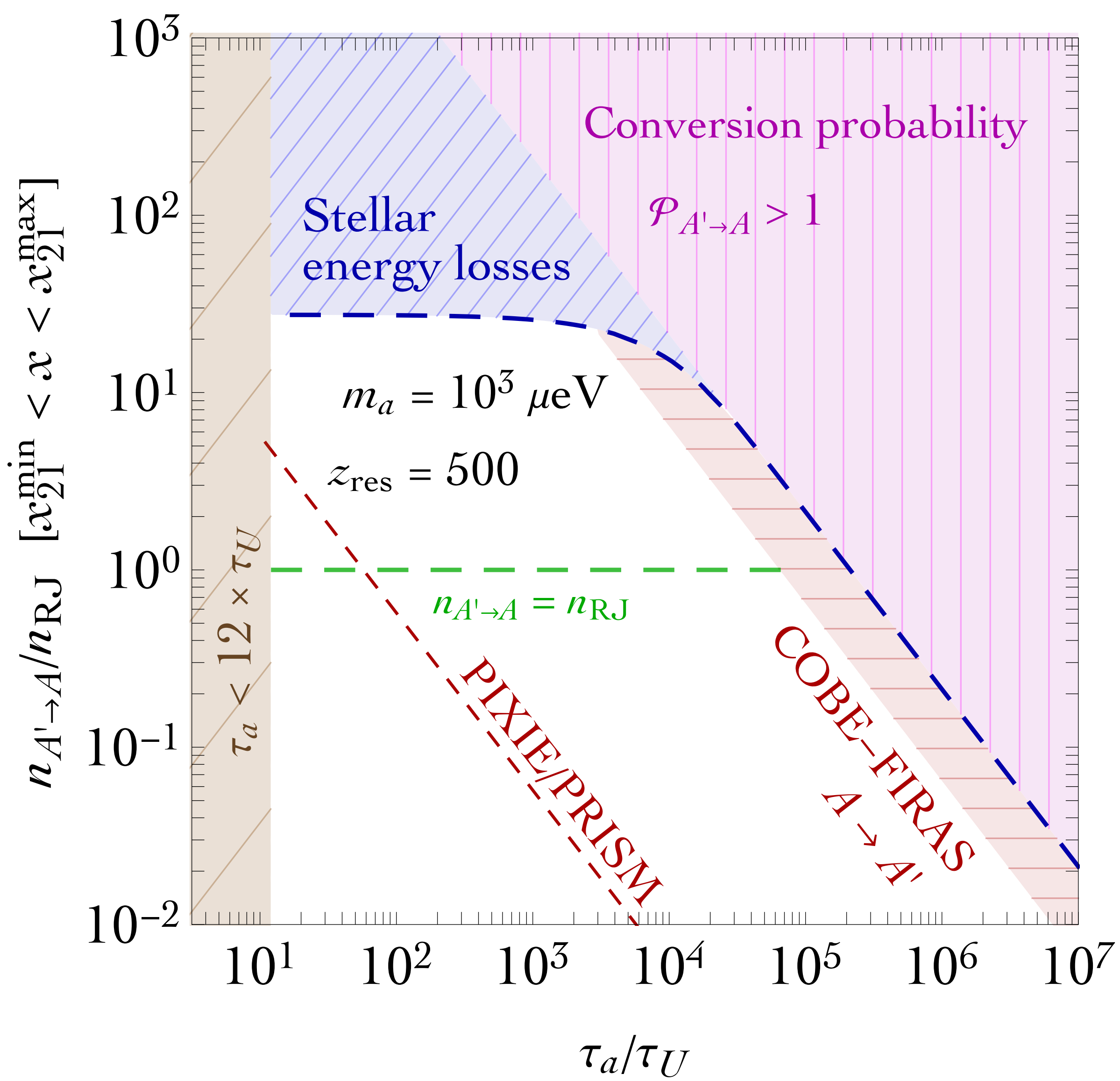
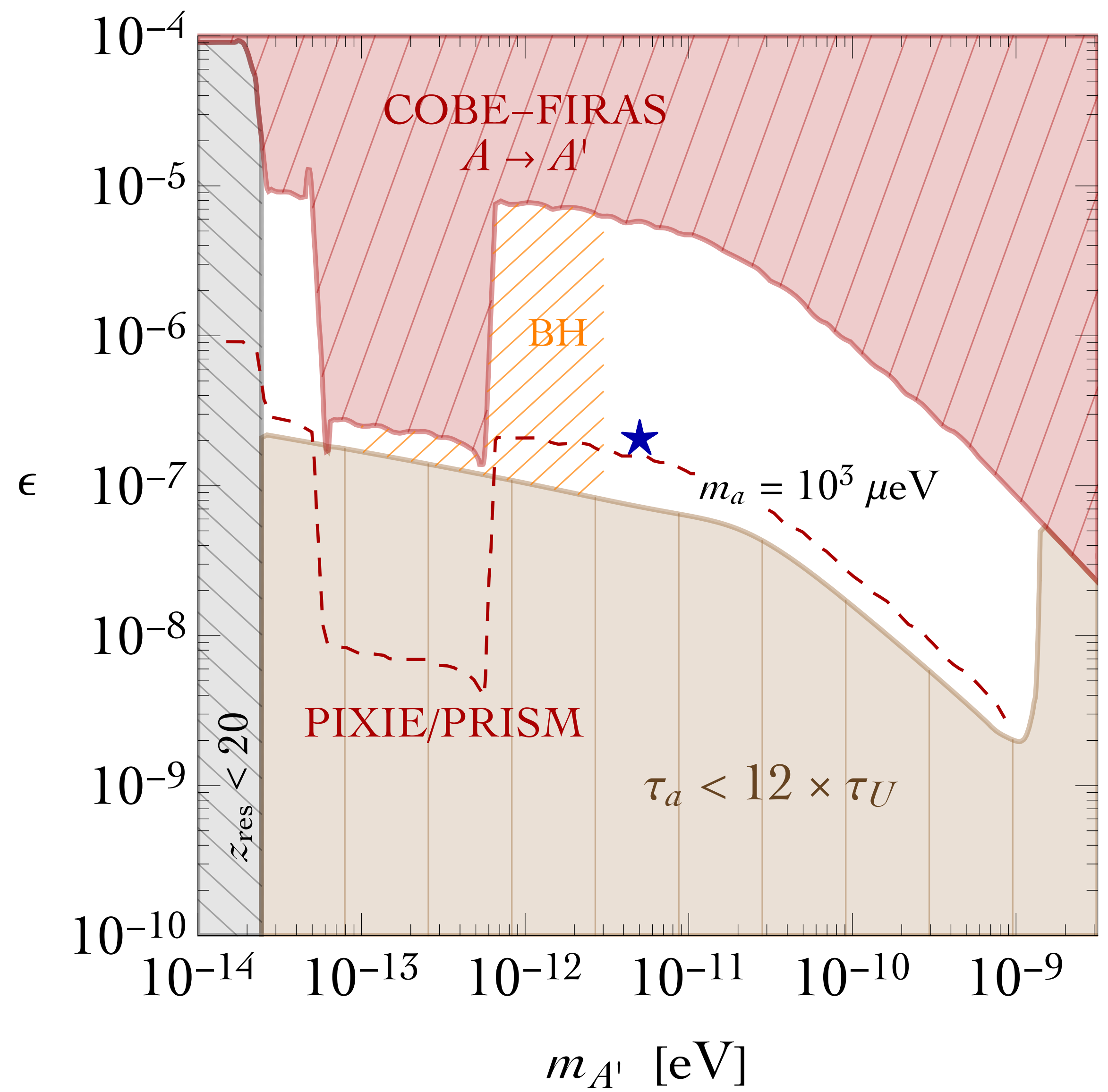
Enhanced number of RJ quanta are available in the z = (15-20) window, making a deeper than expected absorption signal

2: Increase the CMB RJ tail

Axion-like particles decaying into **very light soft DR** could work

Implication: considerable room for the modification of the CMB RJ tail
The model can be probed by the proposed PIXIE/PRISM experiments





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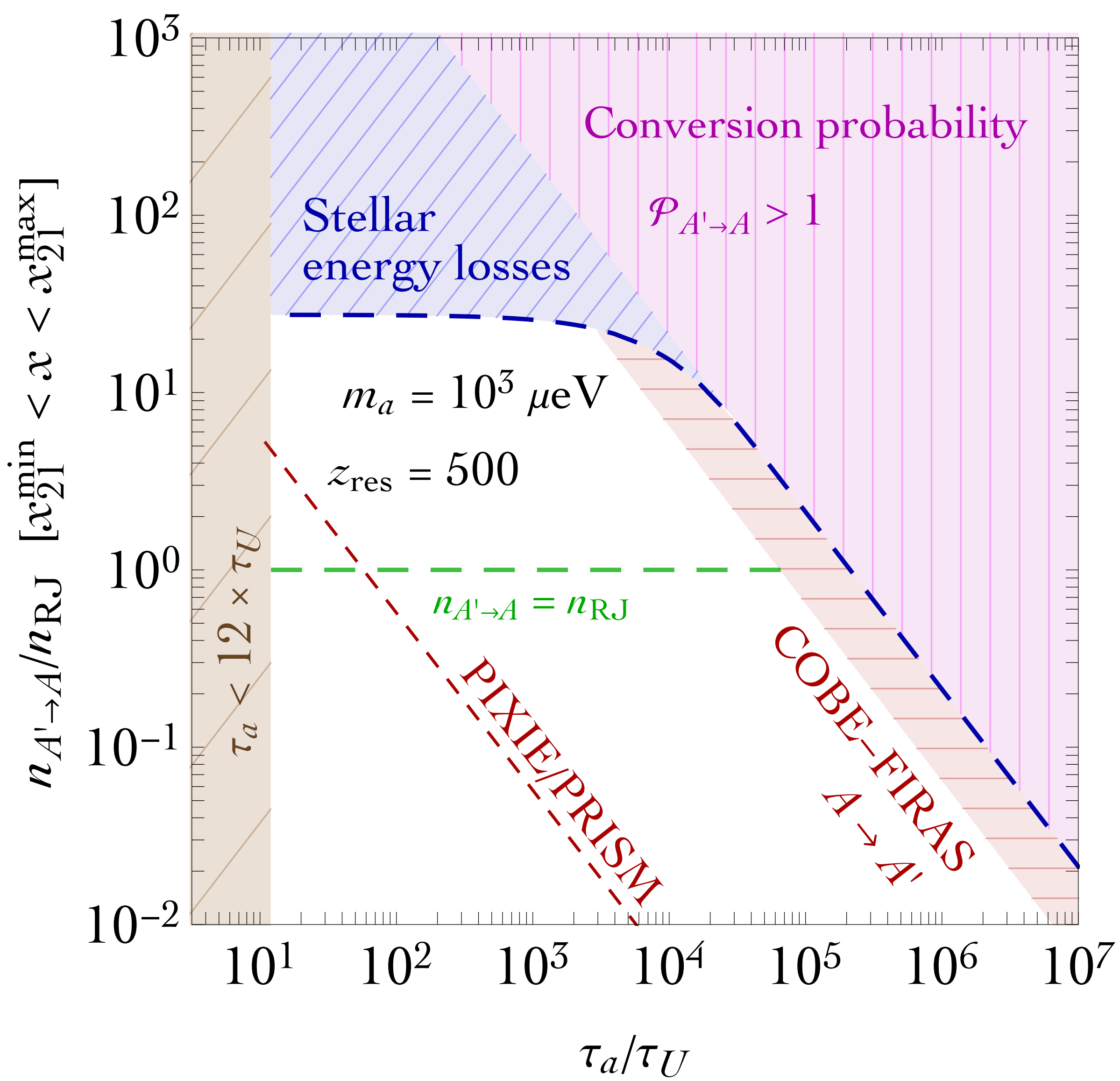
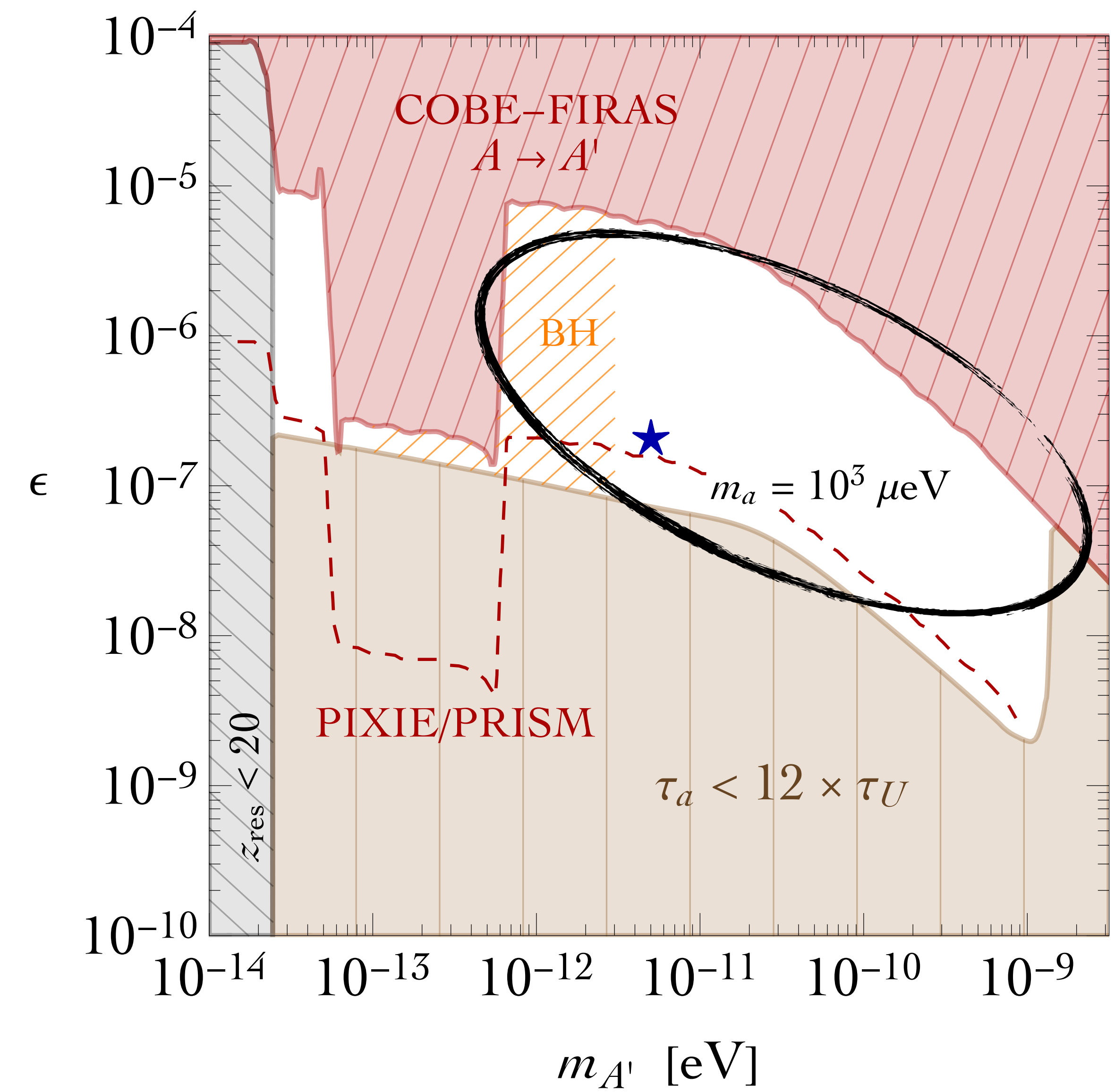


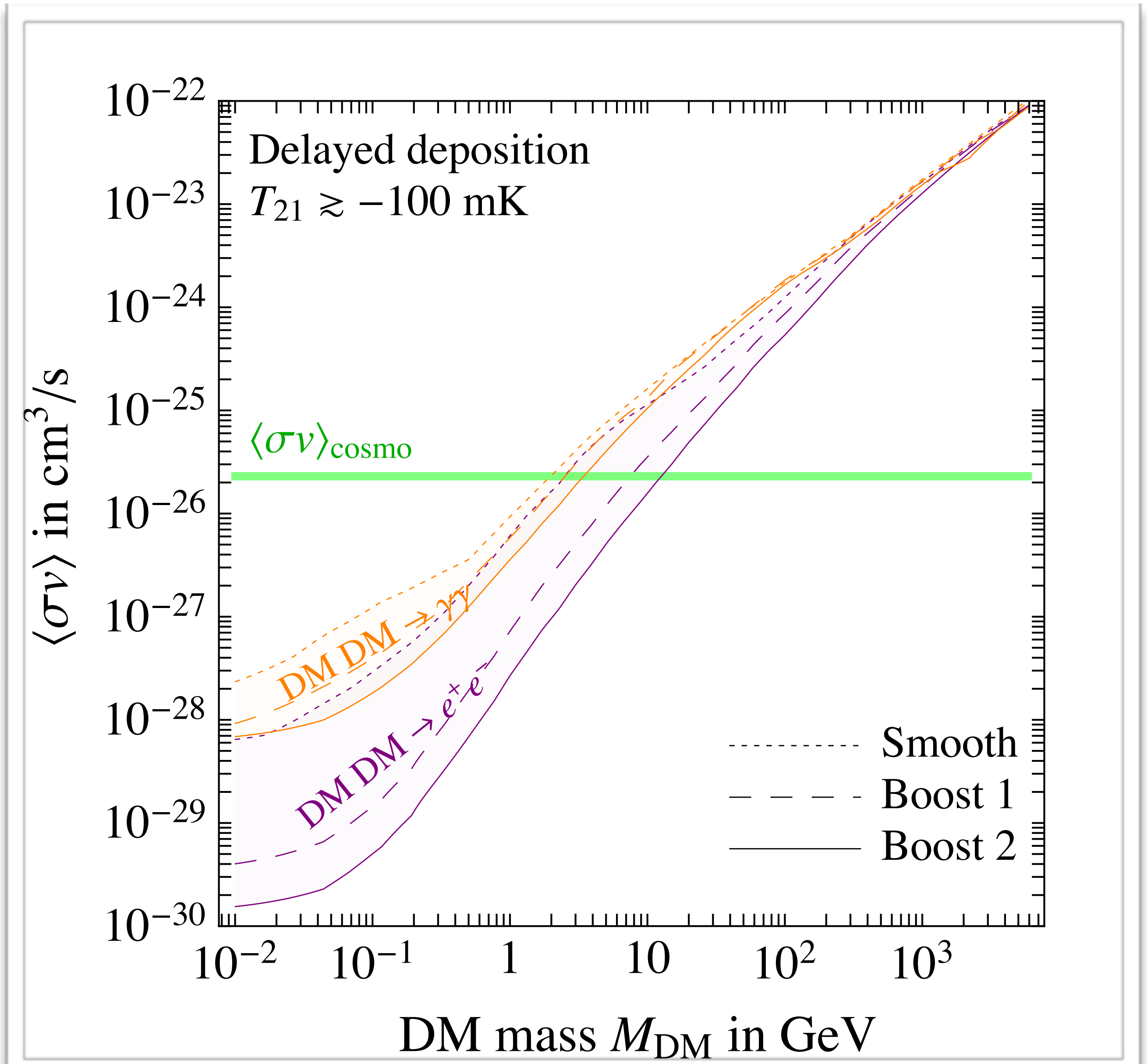


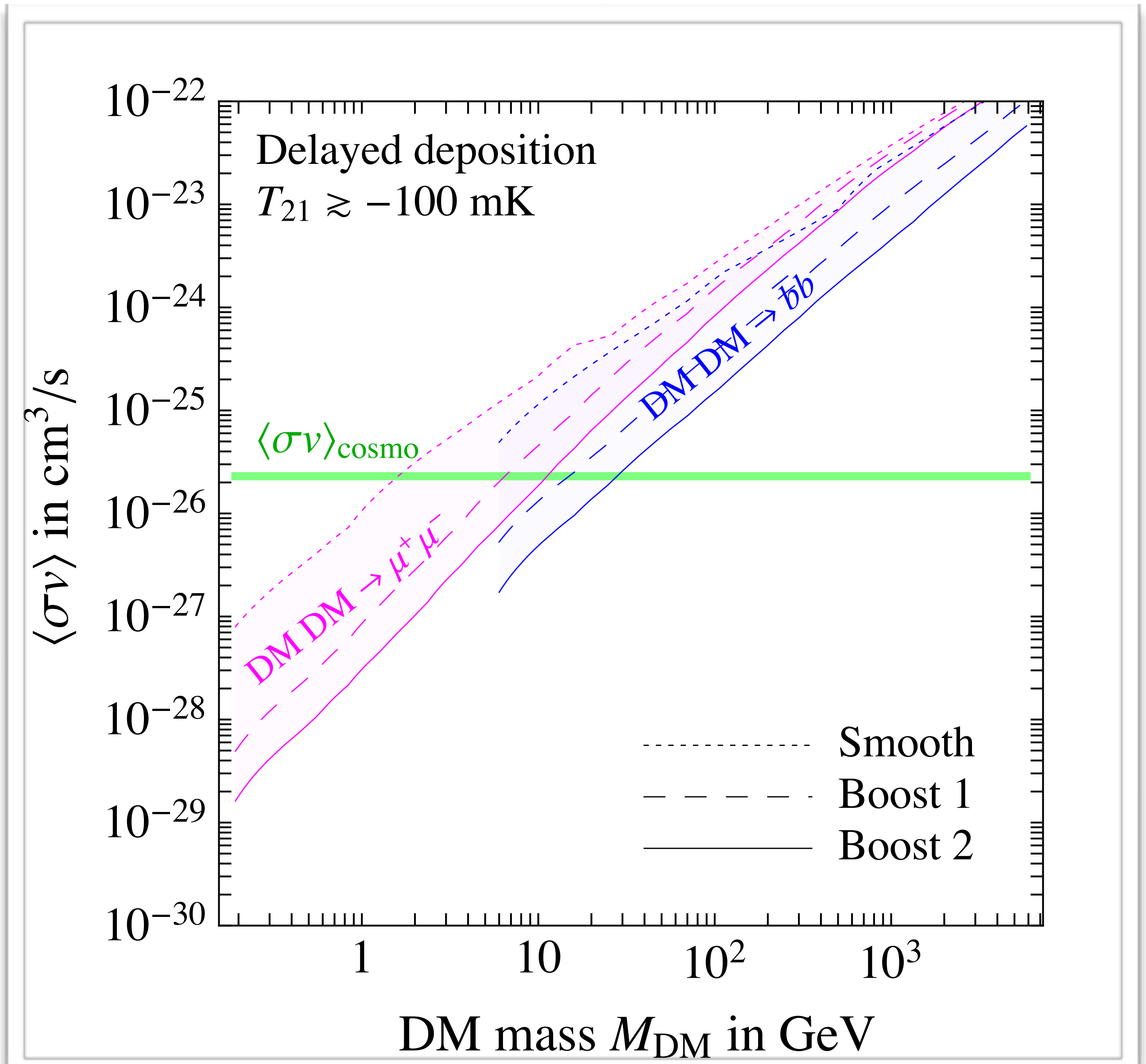
Other implications for BSM

The inferred spin temperature by EDGES is very small:
great opportunity to set limits on the properties of any ***extra source of heating***

Limits on DM annihilation!

see D'Amico, PP, Strumia, Phys.Rev.Lett. **121** (2018) no.1, 011103





Outlook & Conclusions

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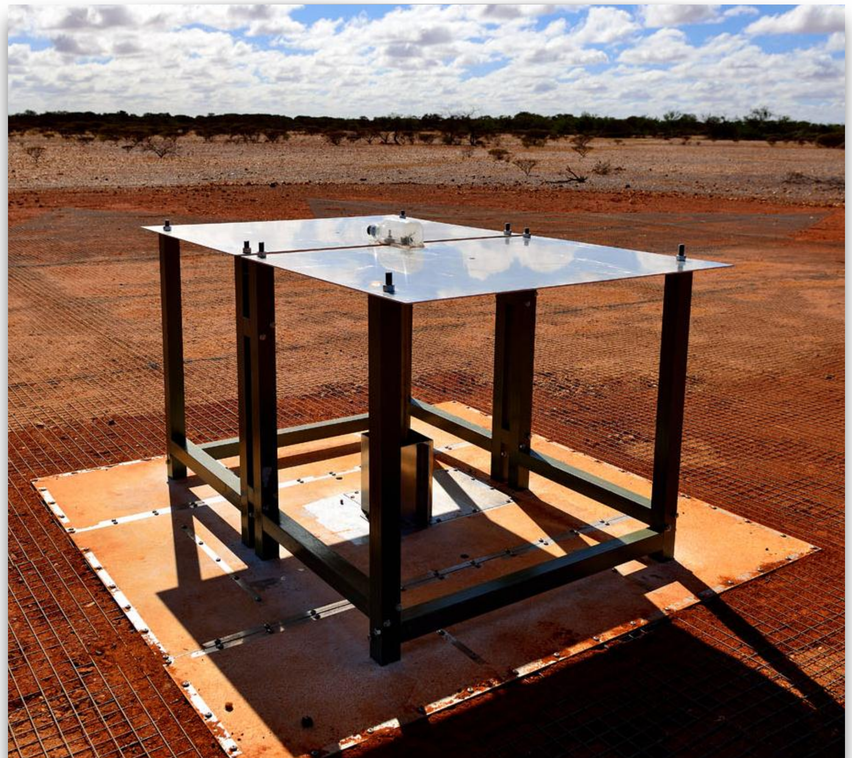
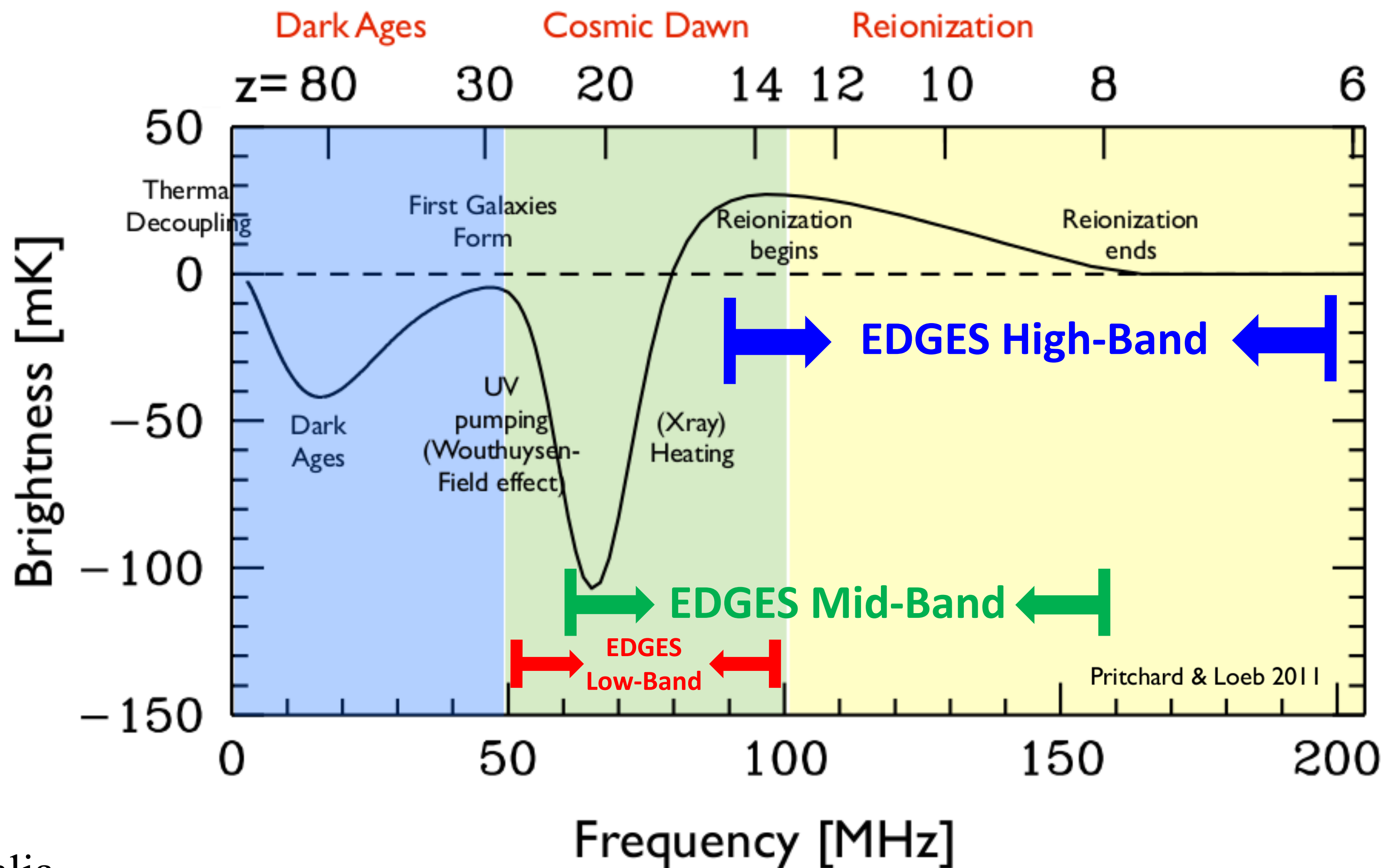
- *This is just the beginning: Stay tuned for further developments!*
  Can the monopole 21-cm alone shed light on dark matter?

Backup slides

The EDGES experiment





Antenna size: 2m long and 1m meter high

Location: radio quiet zone in western Australia

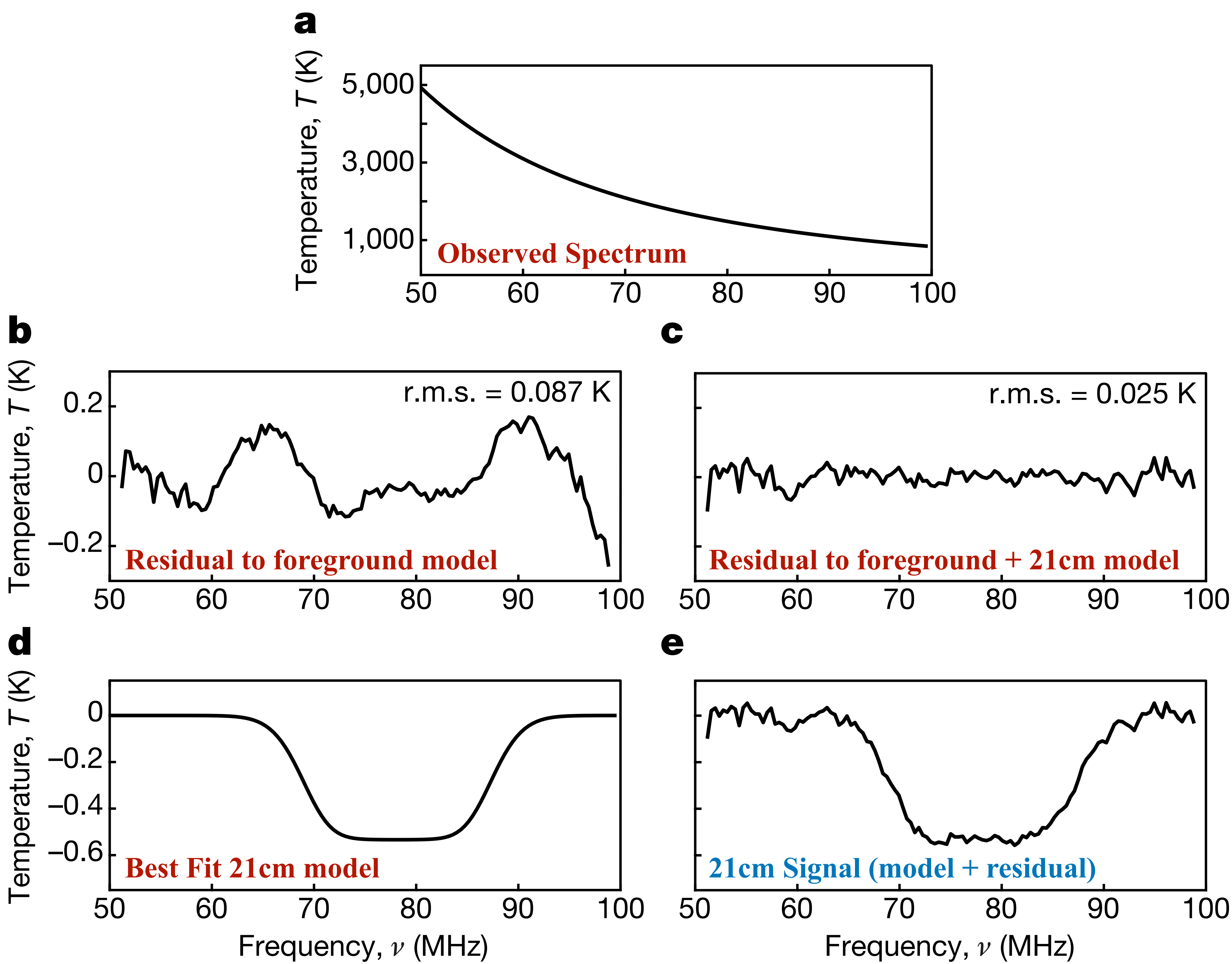
Energy range: from 50 to 150 Mhz

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

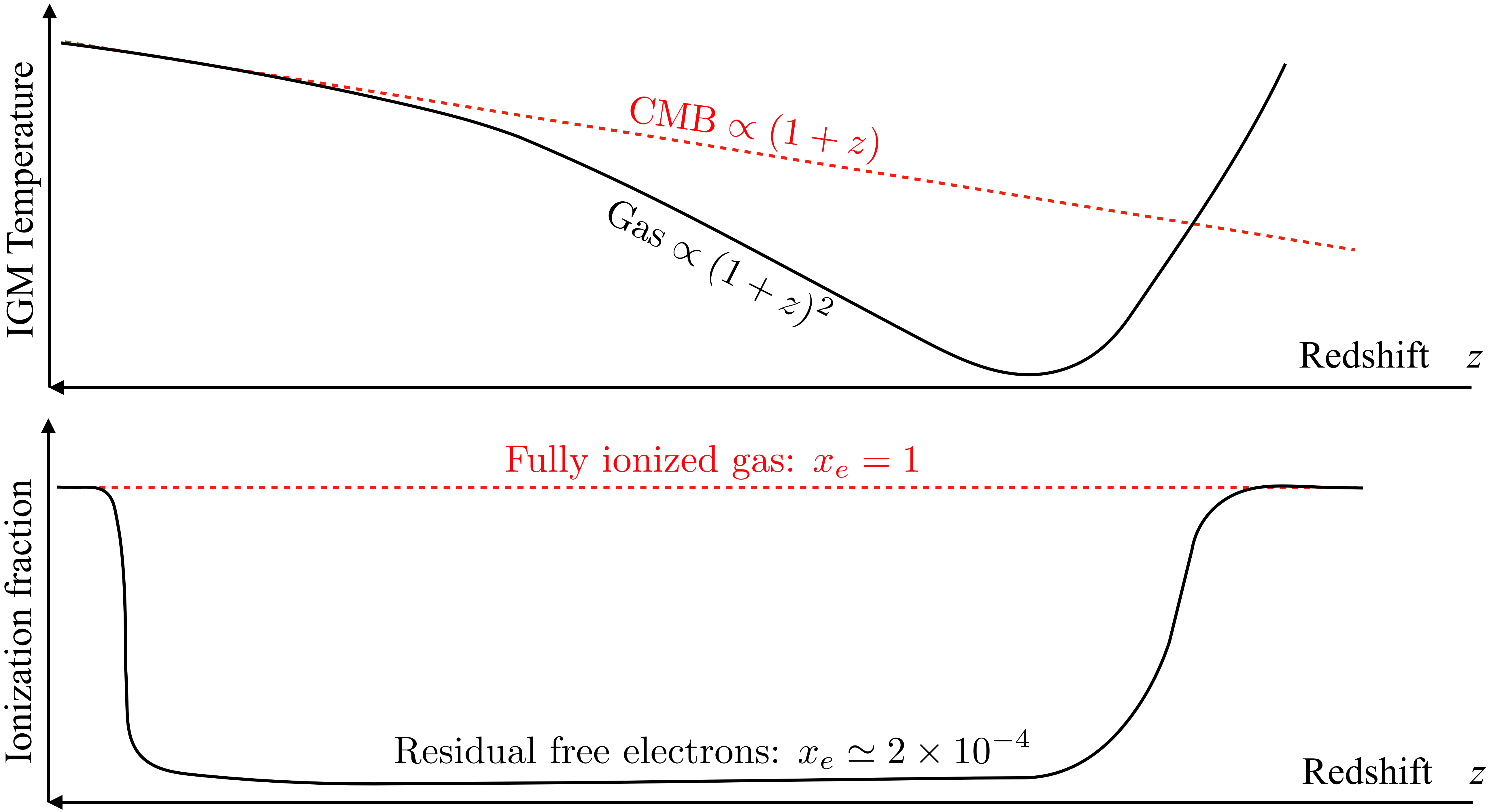
backup
slide 2/15

What did EDGES see?

La Thuile 2019
11/03/2019

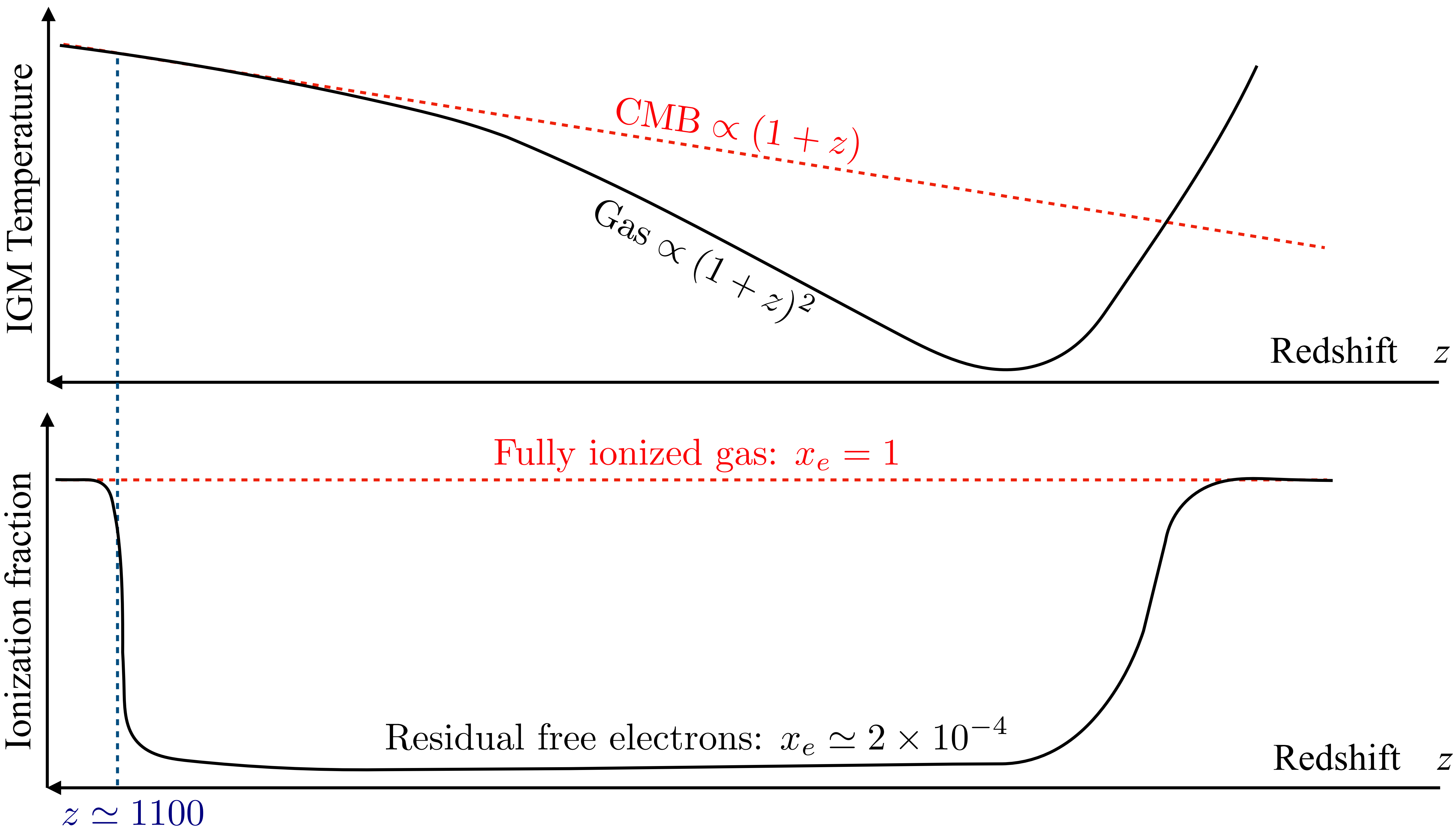


A short history of the IGM



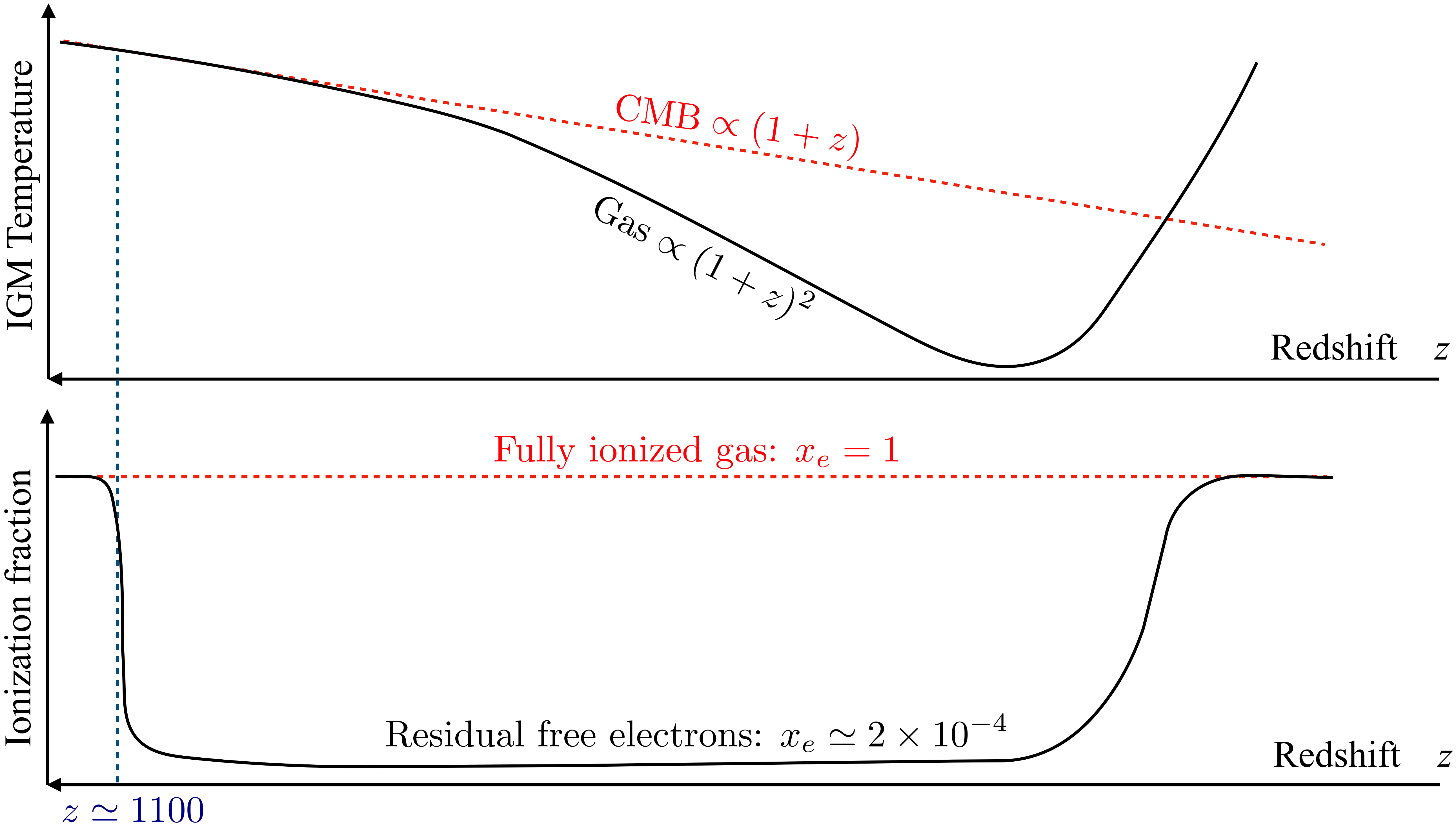
A short history of the IGM

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



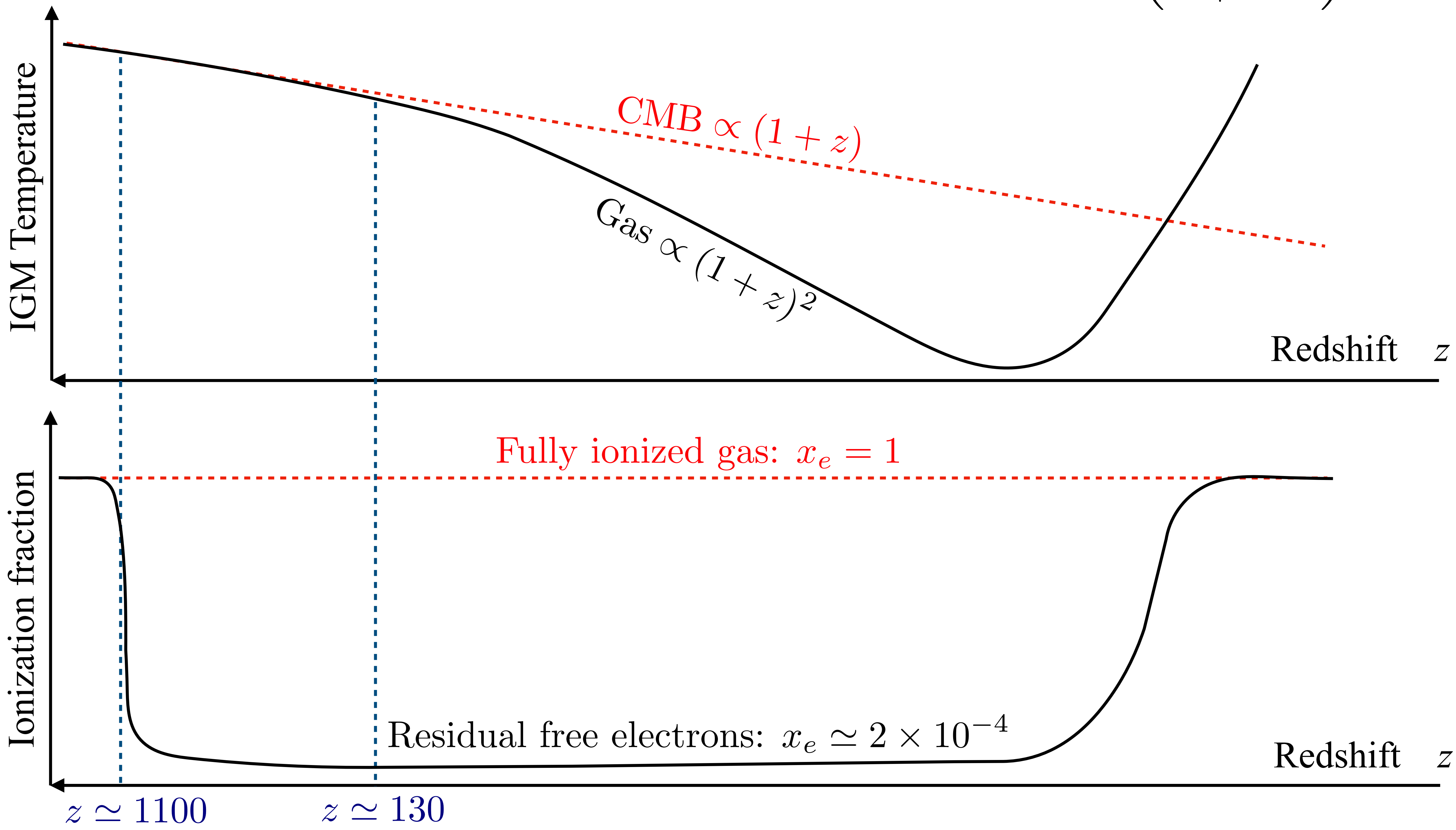
A short history of the IGM

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



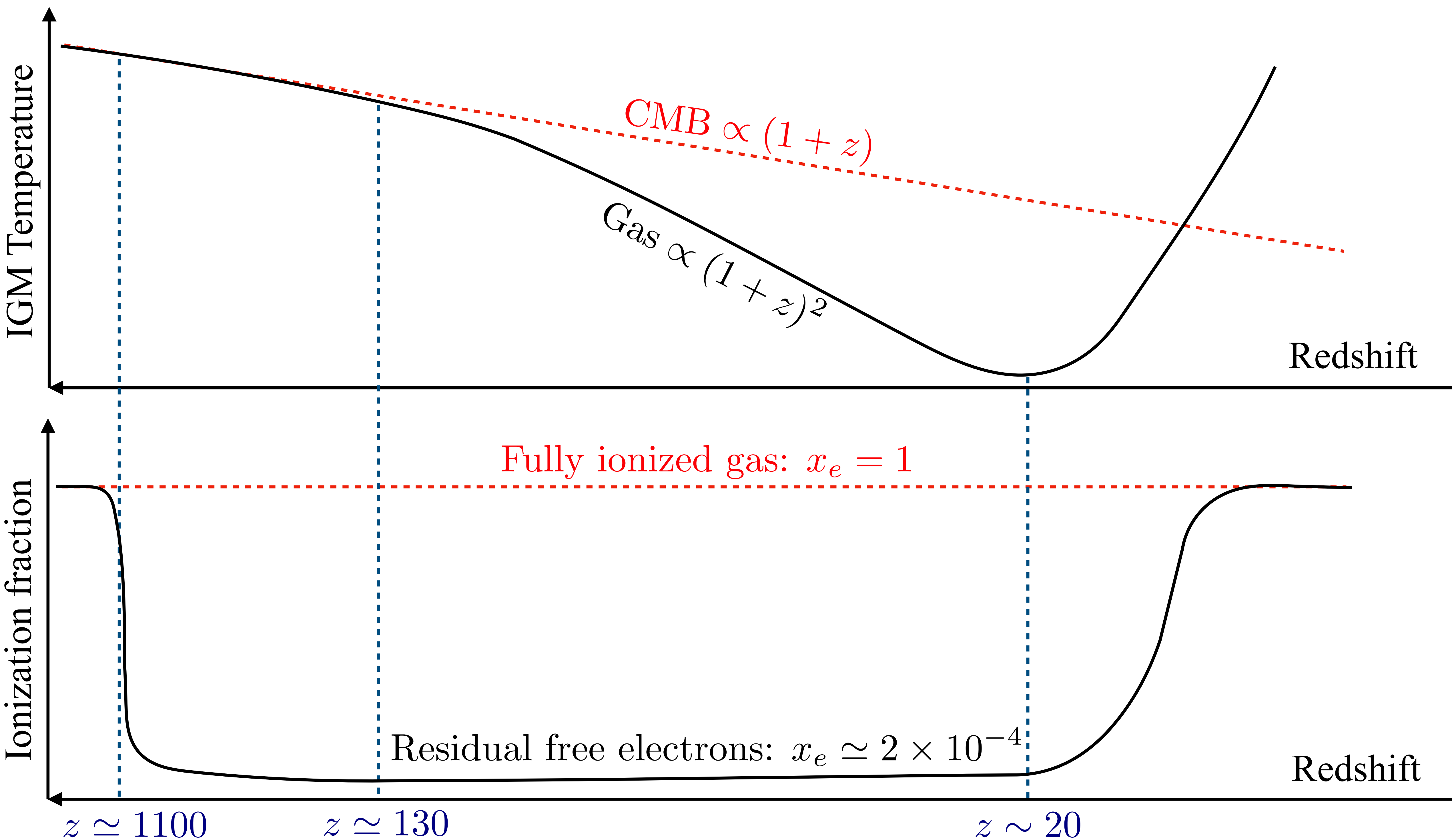
A short history of the IGM

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



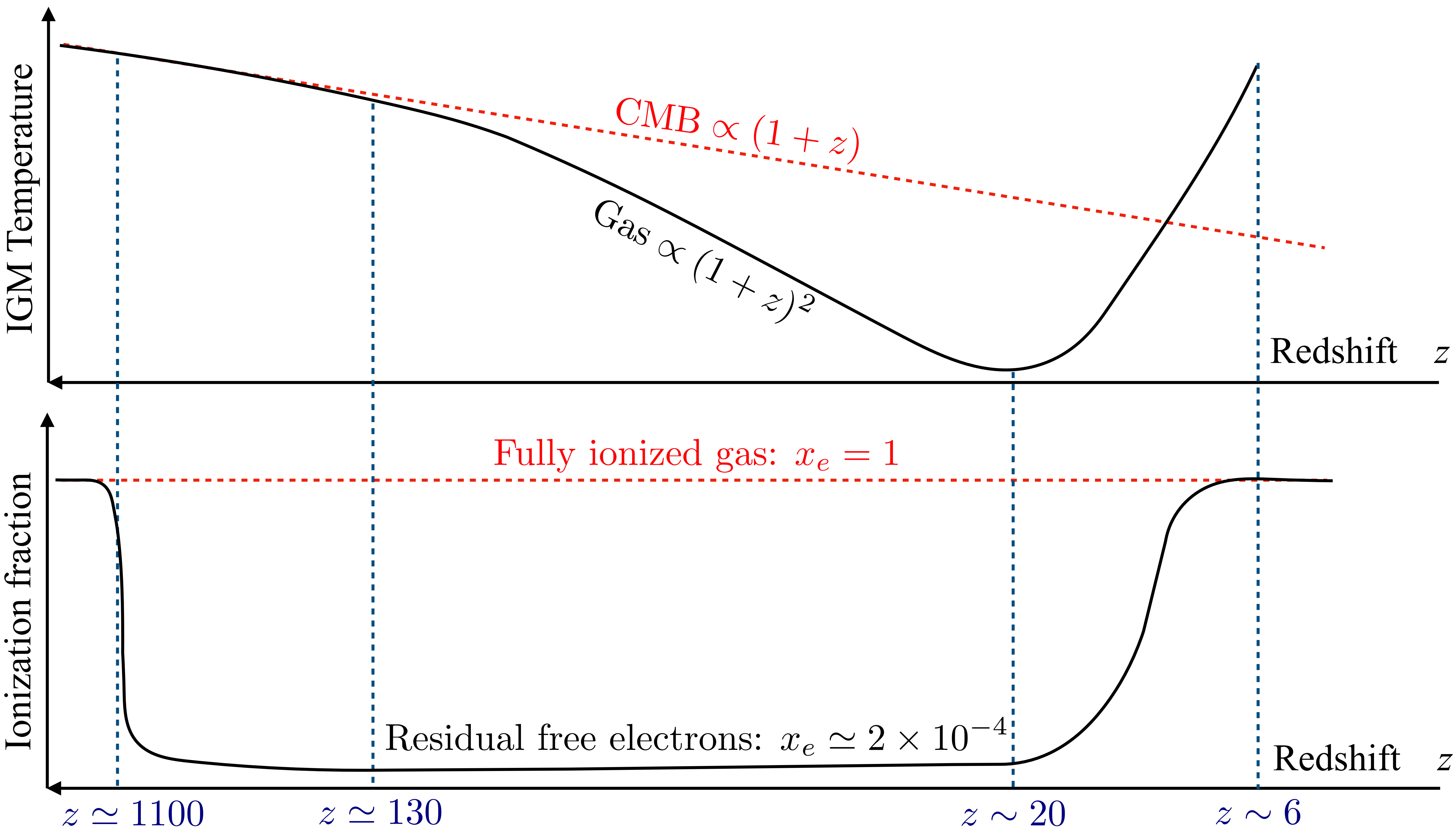
A short history of the IGM

➡ 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

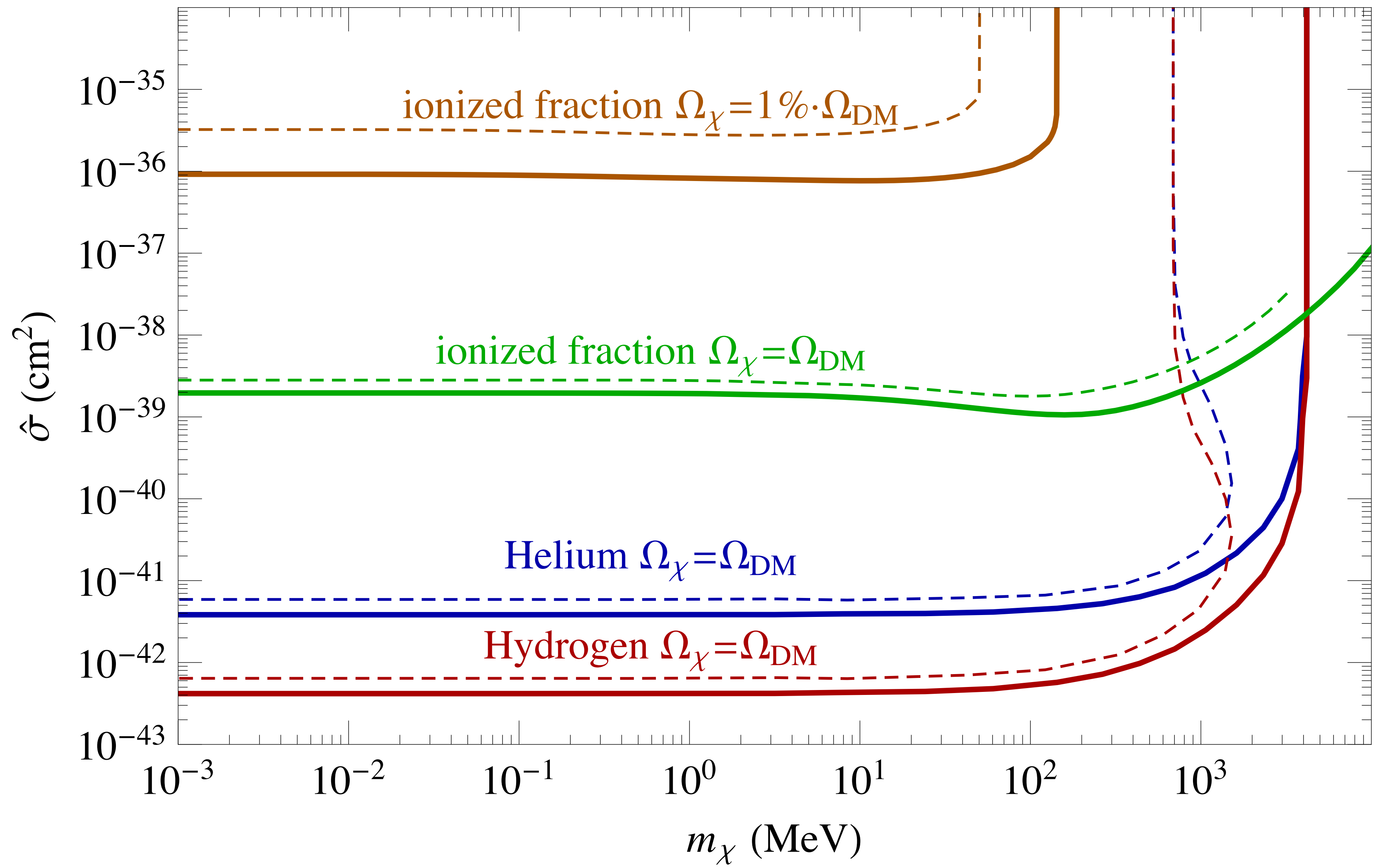


1: Cool the IGM even more

DM-baryons interactions enhanced as

$d\sigma/d\Omega \propto \hat{\sigma}\, v^{-4}$ with $v = 29\ \mathrm{km/s}\,(1+z)/(1+z_{\mathrm{rec}})$

Required cross sections to fit the EDGES signal



Barkana *et al.* 1803.03091

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1: Cool the IGM even more

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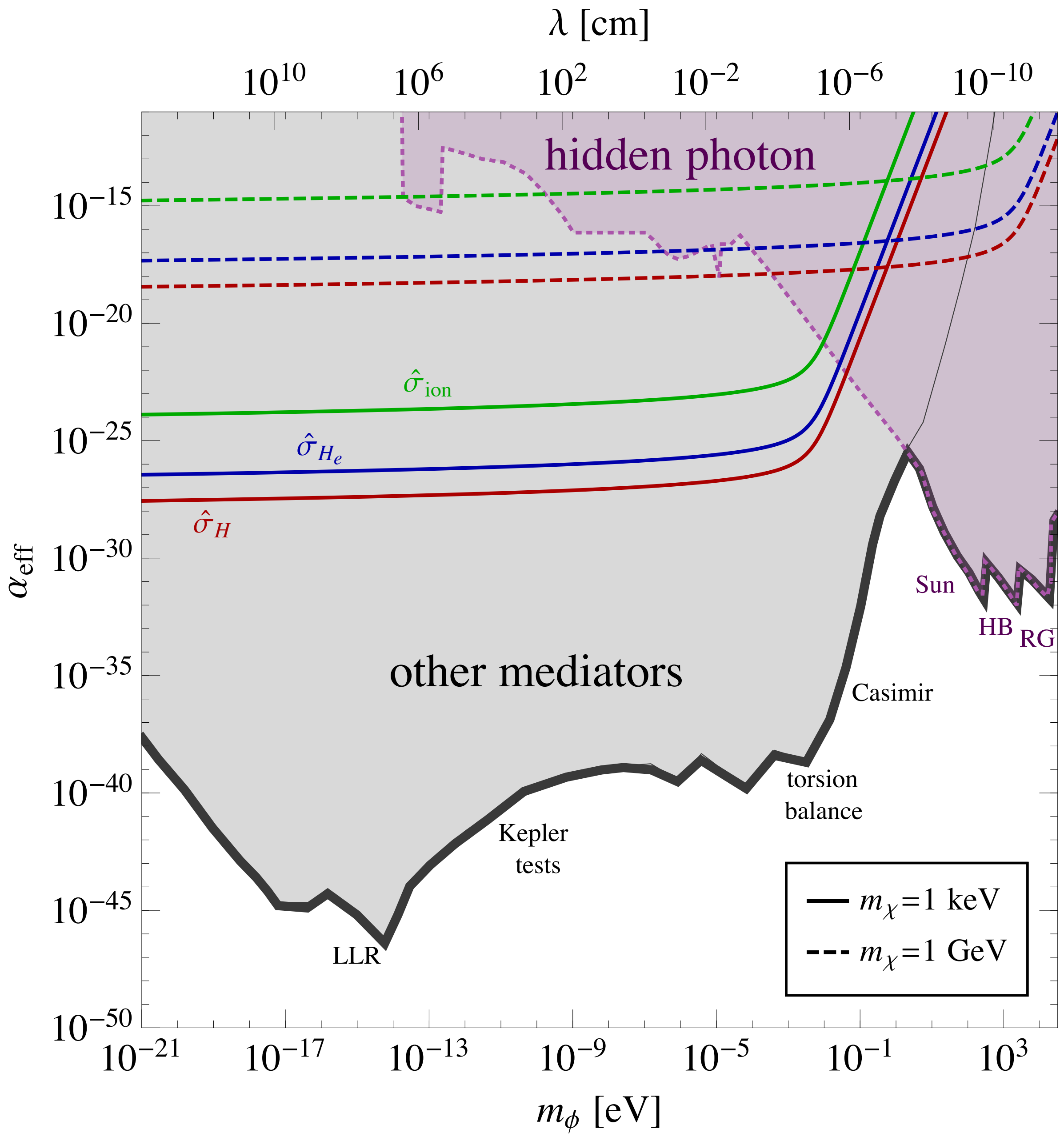
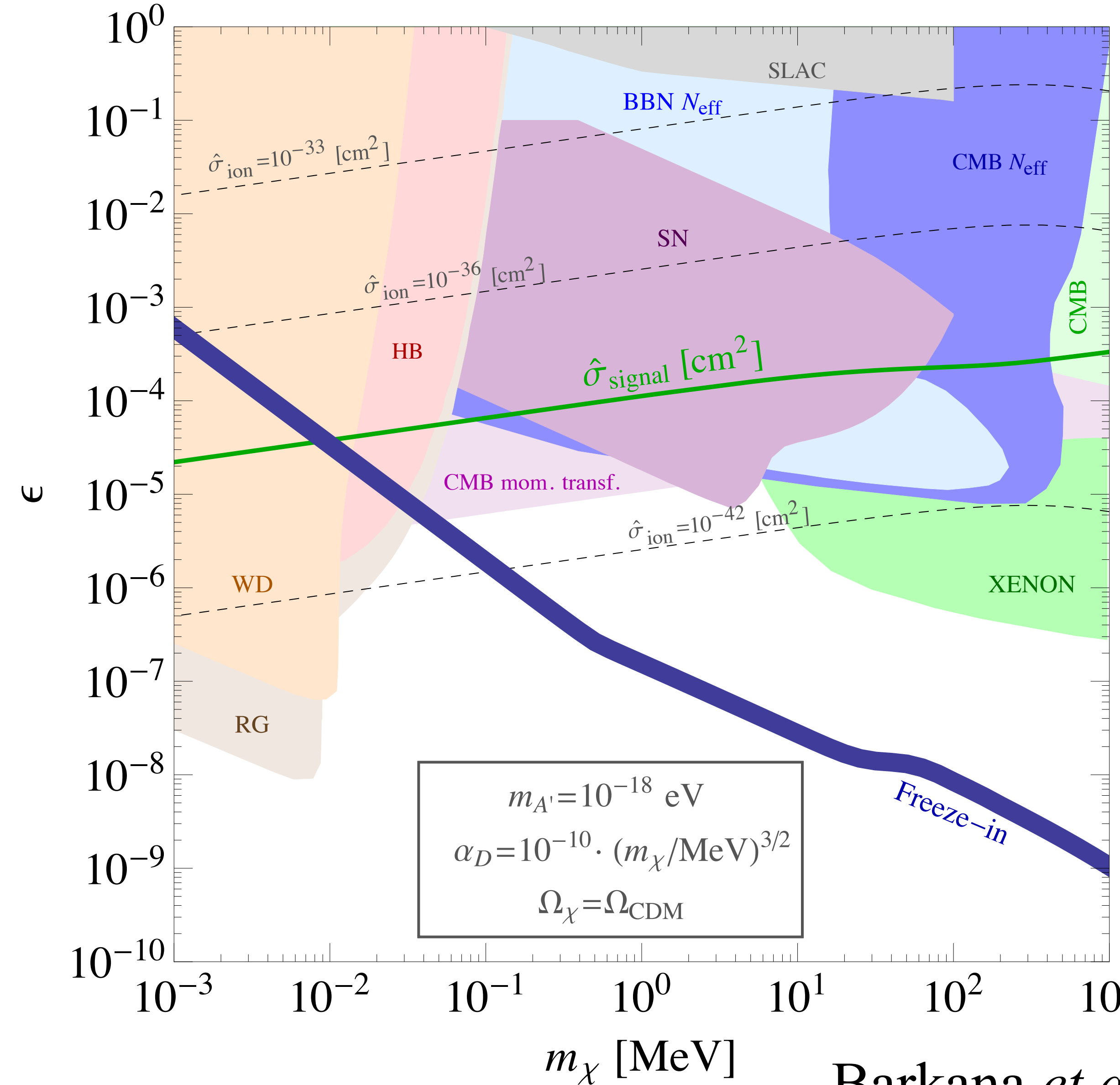
Other mediators: *Coulomb-like interactions are fully screened only for dark photons that kinetically mixes with the visible photon*

$$\mathcal{L} \supset -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \qquad \textit{for dark photon:} \;\; \alpha_{\rm eff} = \epsilon^2 \alpha$$



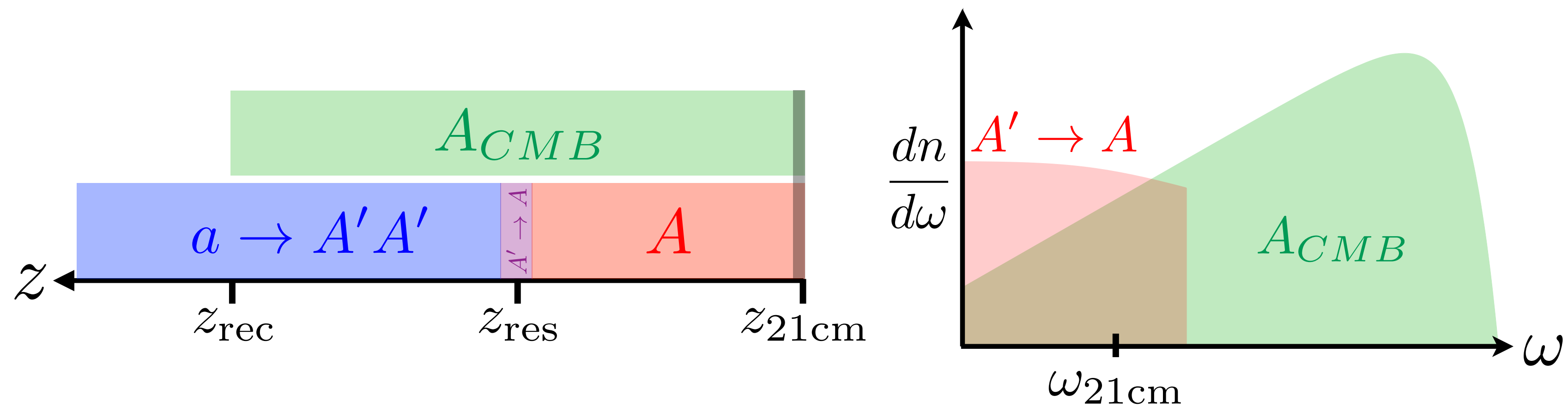
Dark photon case



Barkana *et al.* 1803.03091

2: Increase the CMB RJ tail

What DM model can do that?



$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{a}{4f_a}F'_{\mu\nu}\tilde{F}'^{\mu\nu} + \mathcal{L}_{AA'}$$

Decay Rate: $\Gamma_a = \frac{m_a^3}{64\pi f_a^2} = \frac{3\times 10^{-4}}{\tau_{\rm U}}\left(\frac{m_a}{10^{-4}\,{\rm eV}}\right)^3\left(\frac{100\,{\rm GeV}}{f_a}\right)^2.$

$$\mathcal{L}_{AA'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2$$

Resonant mass: $m_A(z) \simeq 1.7\times 10^{-14}\,{\rm eV}\times(1+z)^{3/2}X_e^{1/2}(z)$

Pospelov *et al.*
1803.07048

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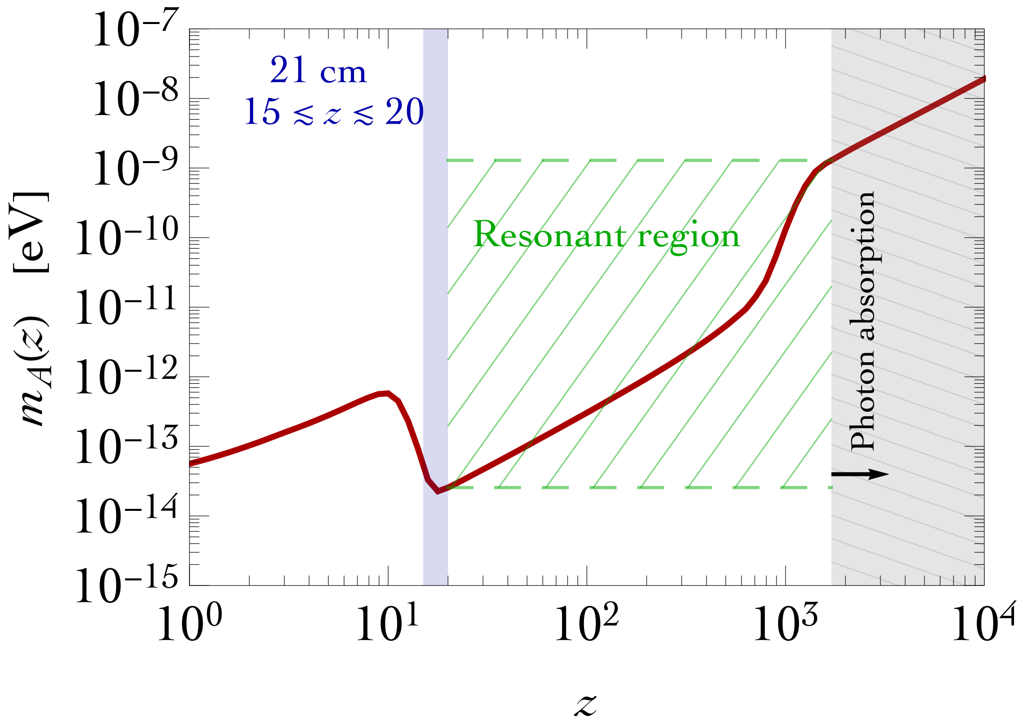
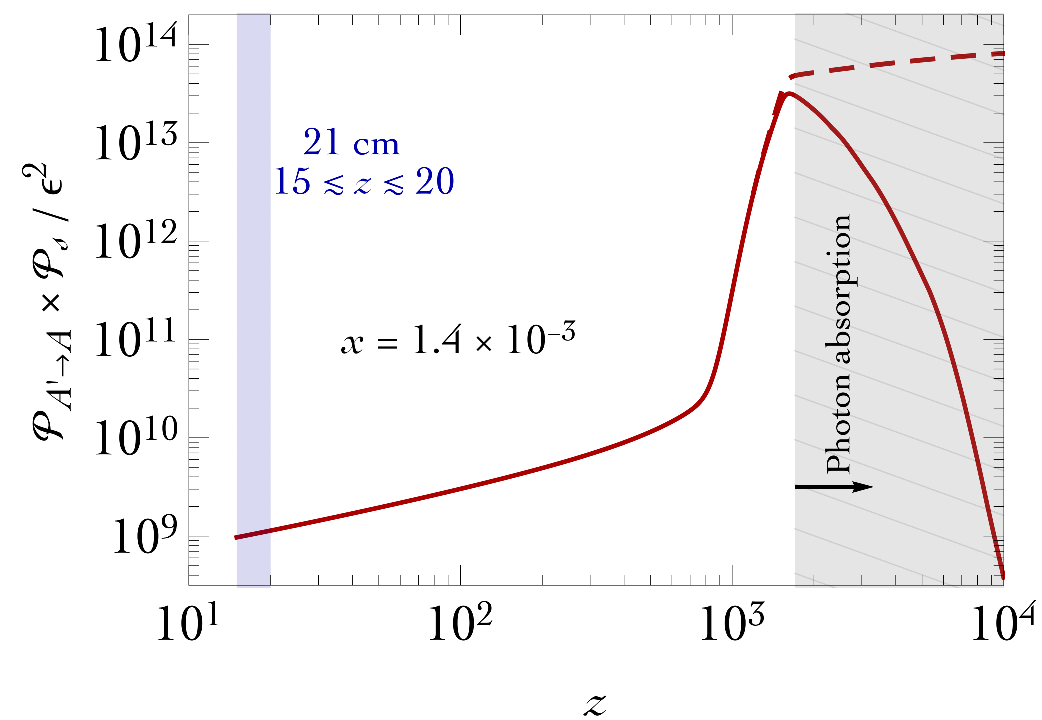
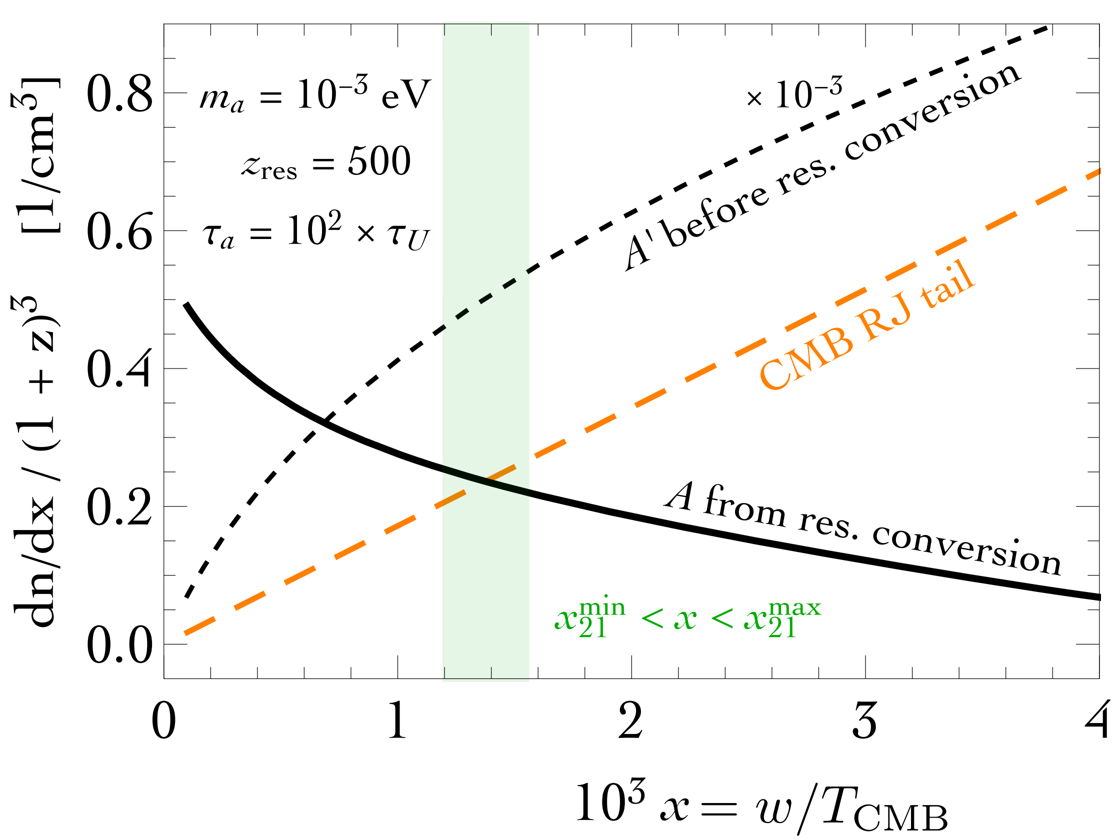
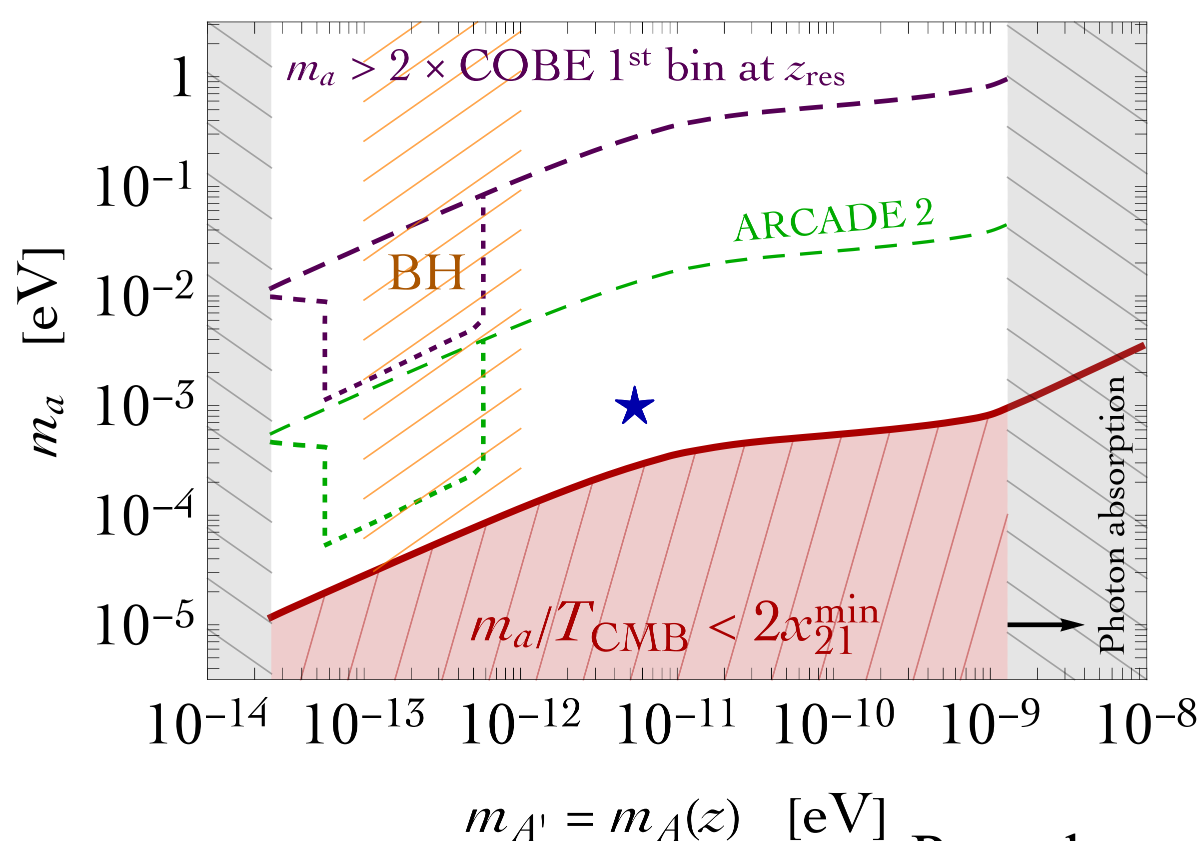








Pospelov *et al.*
1803.07048

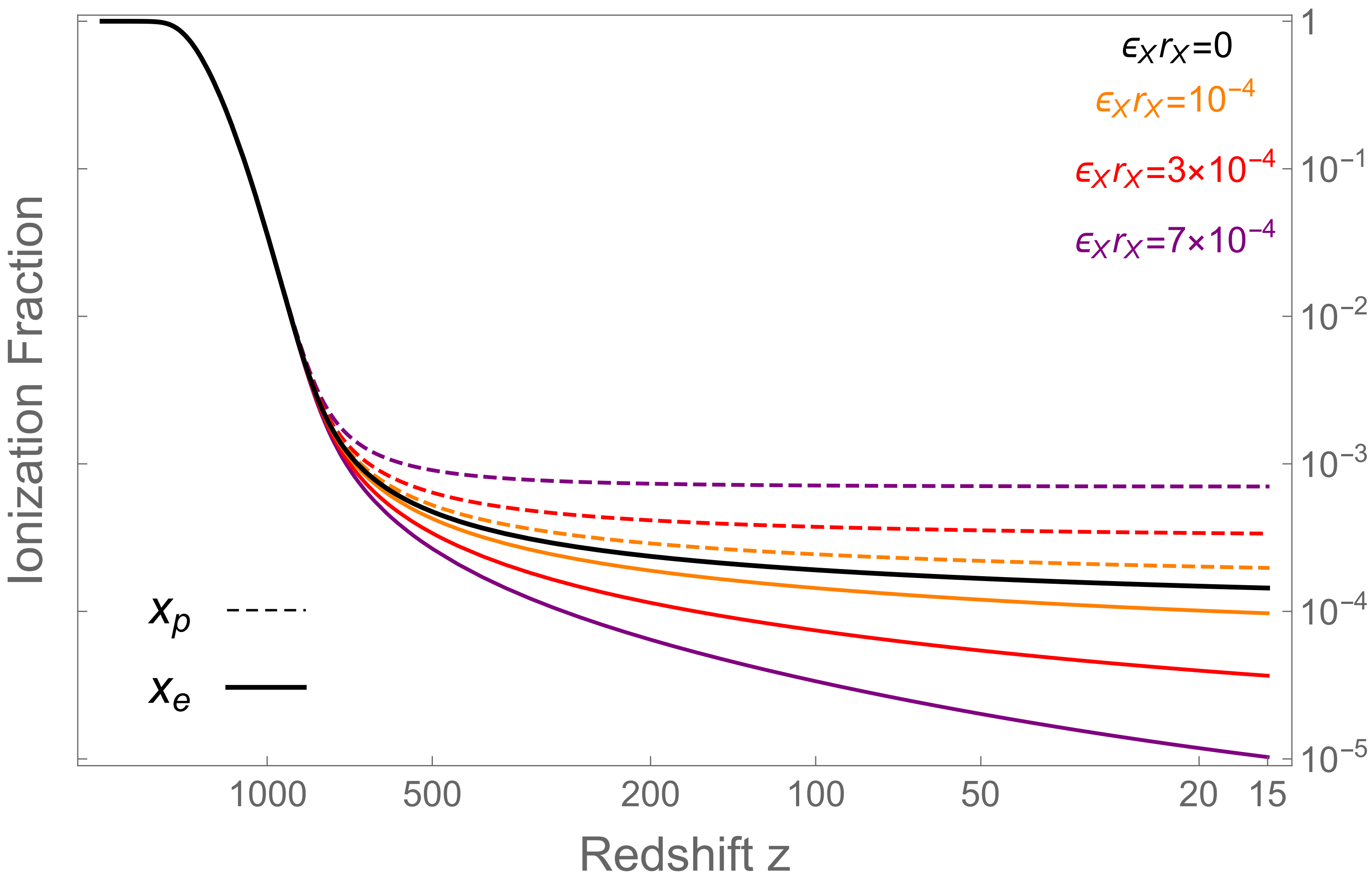
3: Charge sequestration?

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 $r_\chi = n_\chi / n_b$



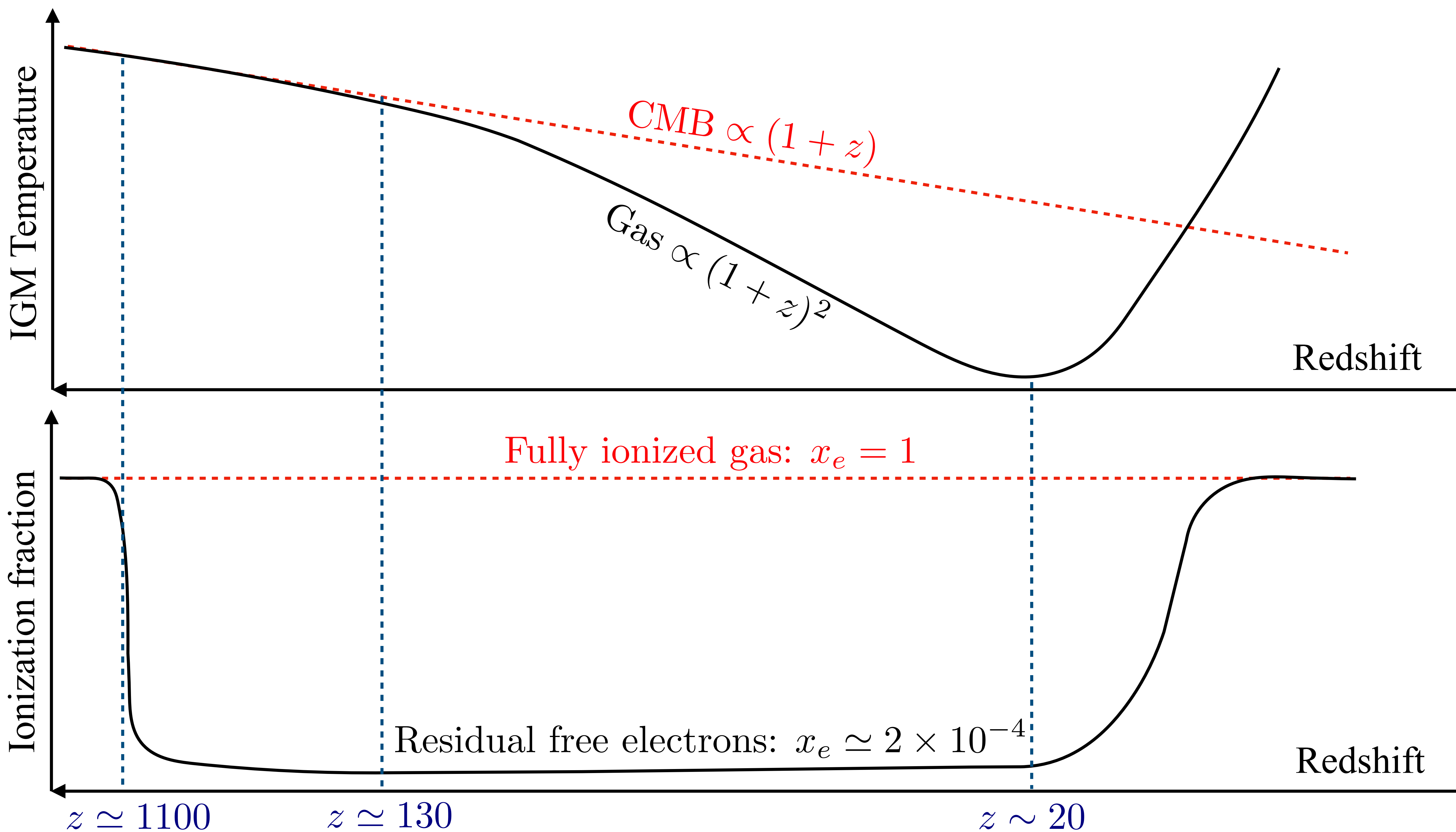
Falkowski, Petraki
1803.10096

DM annihilations limits

see D'Amico, PP, Strumia, Phys.Rev.Lett. **121** (2018) no.1, 011103

Where does DM Ann. enter?

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



Where does DM Ann. enter?

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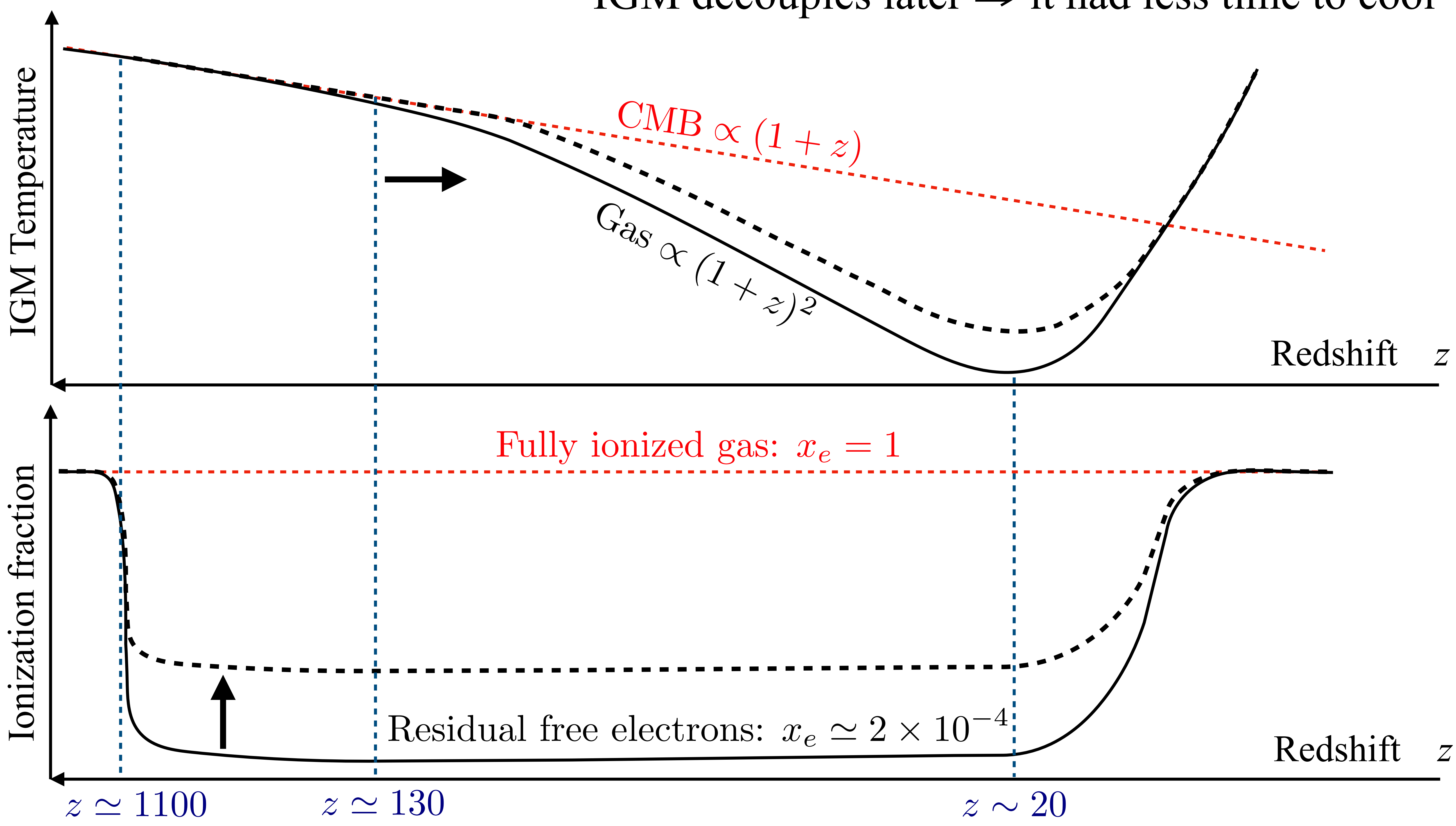
Will heat the IGM in 2 ways: ➡ Annihilations ***increase ionization fraction***
IGM decouples later $\Rightarrow$ it had less time to cool



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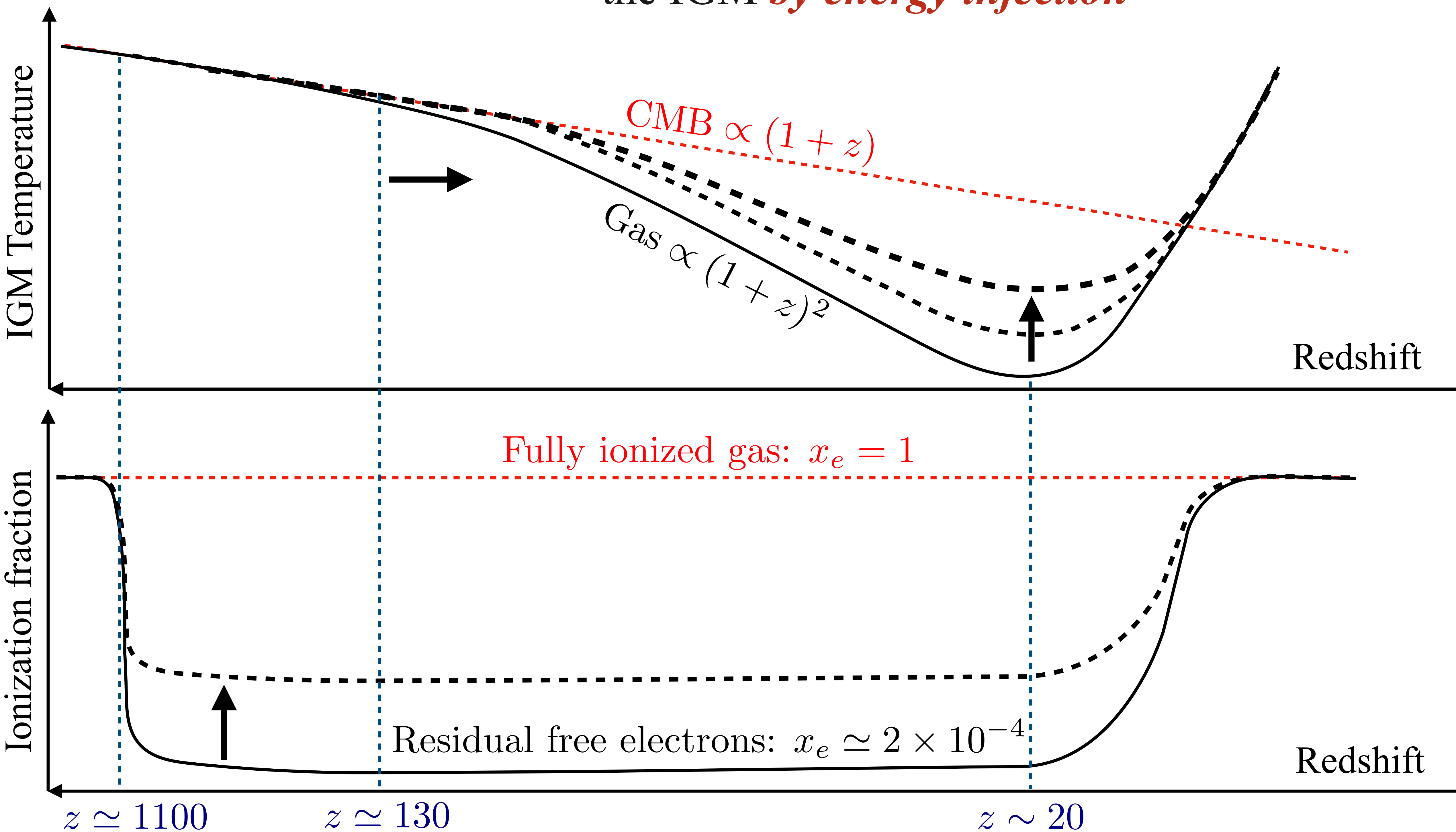
DM can (and will if thermal) annihilate into SM.

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

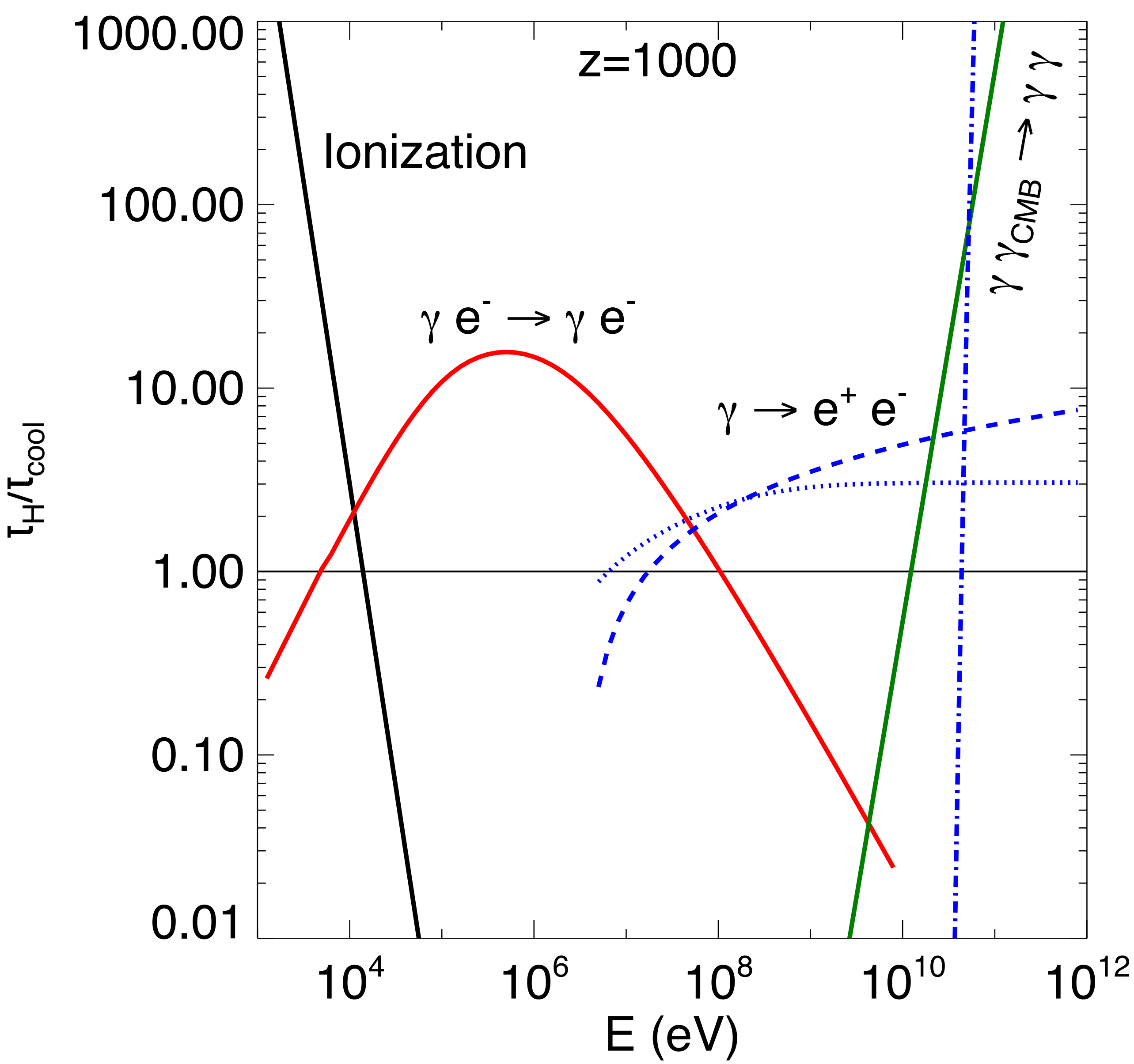


EM shower in the IGM

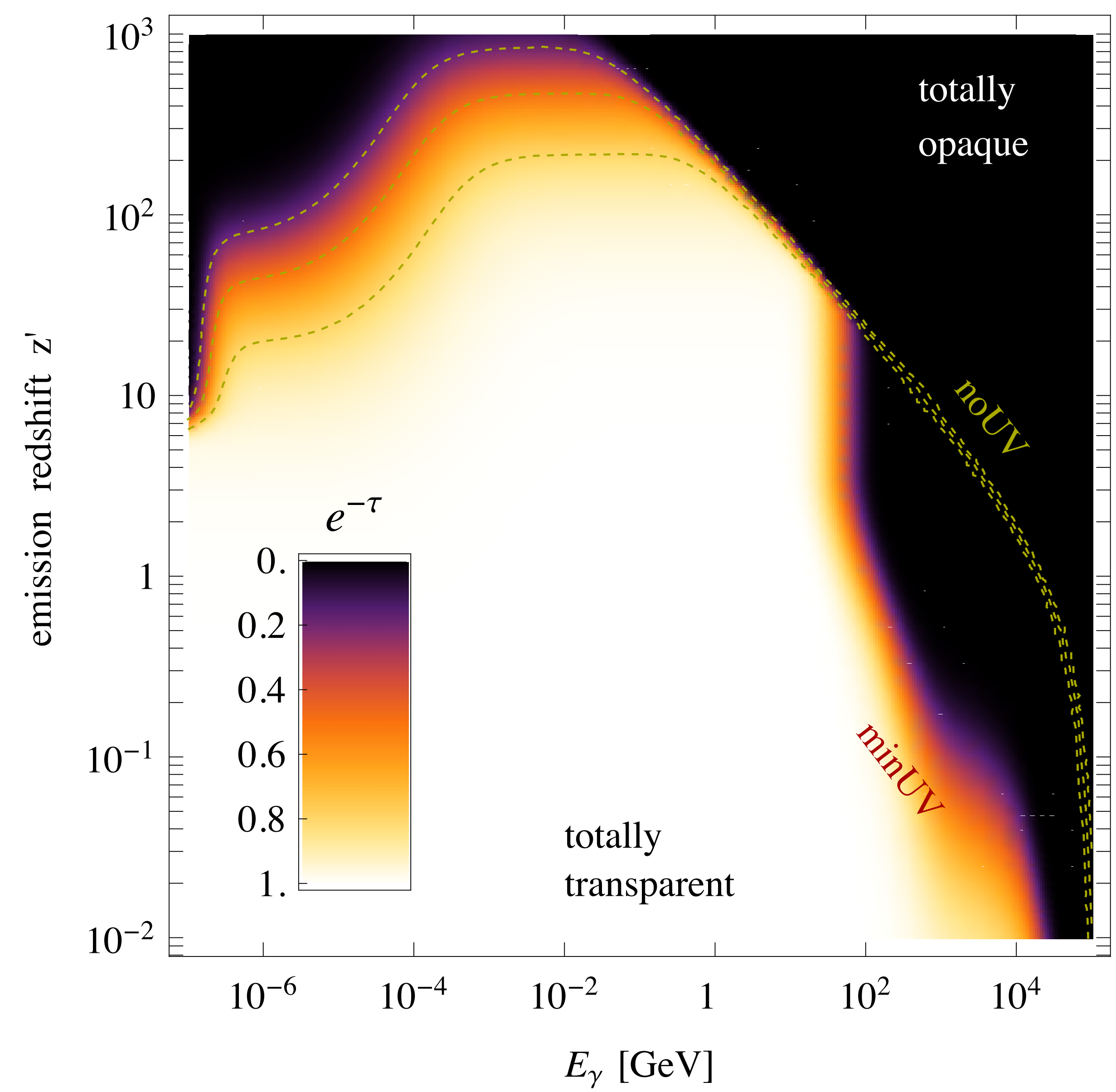
The ***delayed transfer function*** encodes the physics of the EM shower

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

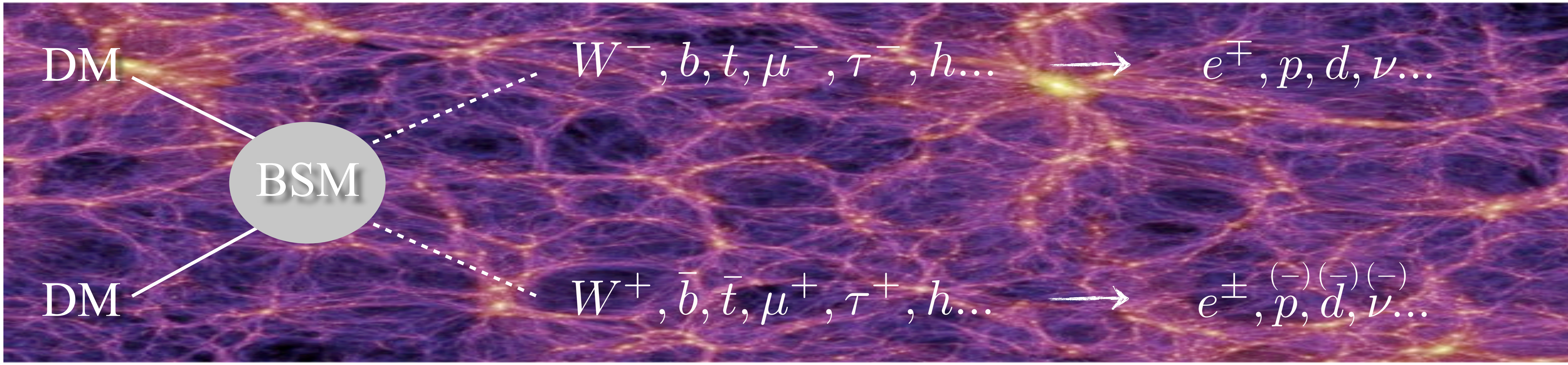
Cooling time at $z = 1000$



deposited $z = 0$ (Today)



DM Annihilation: Basics



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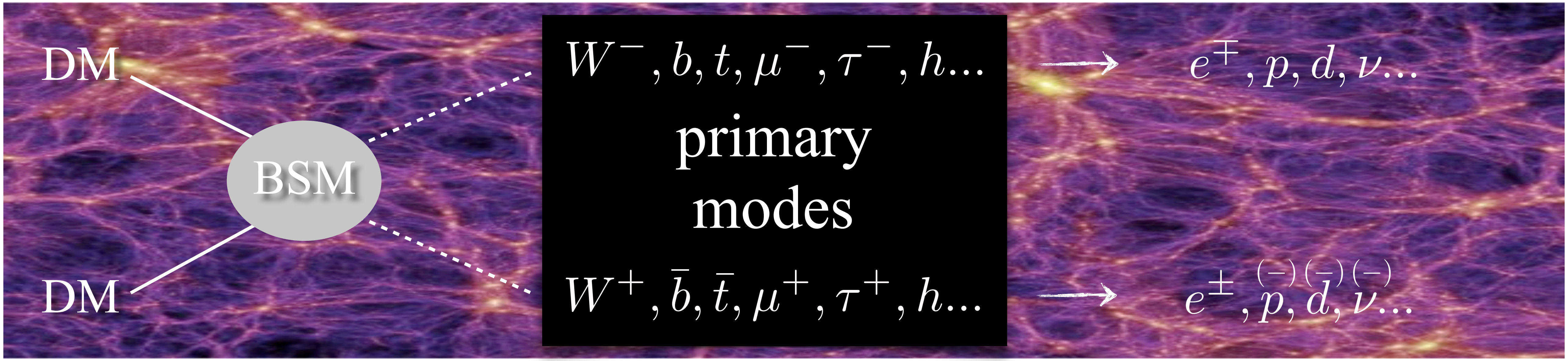

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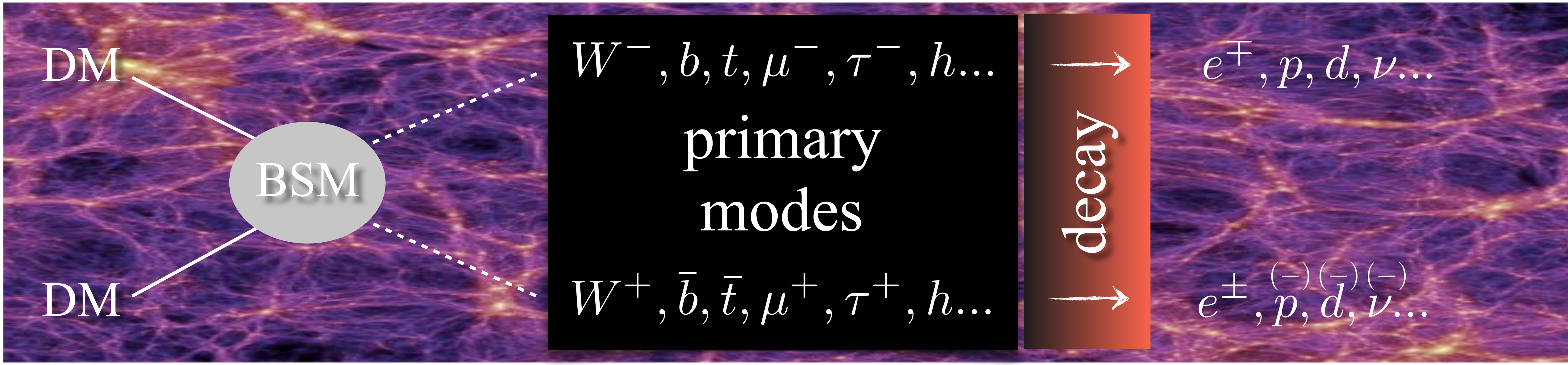

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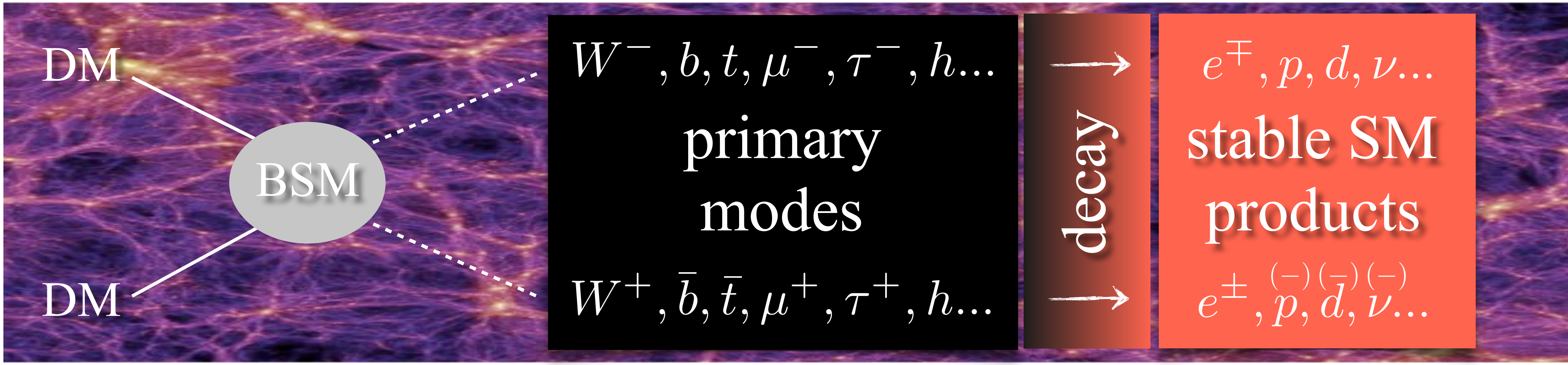

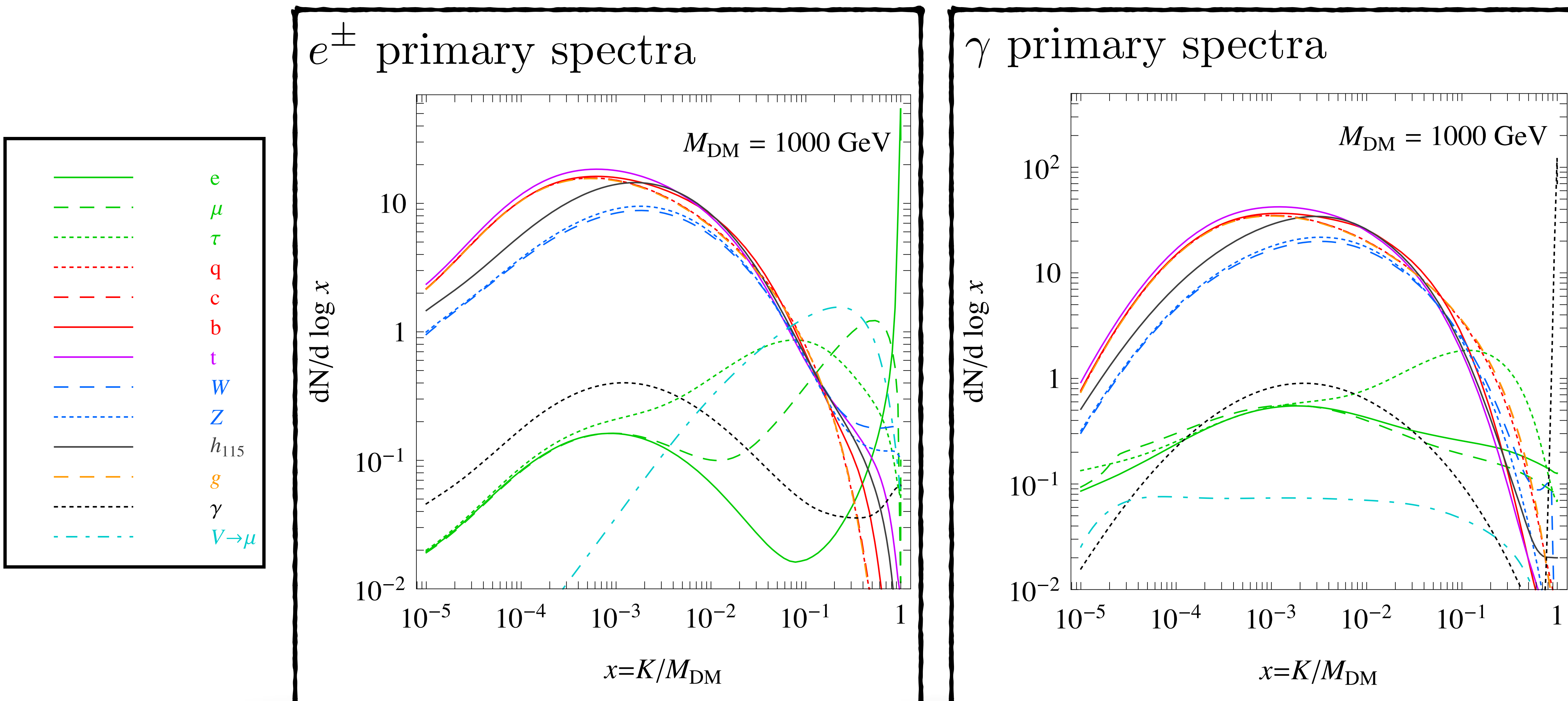

Energy injection

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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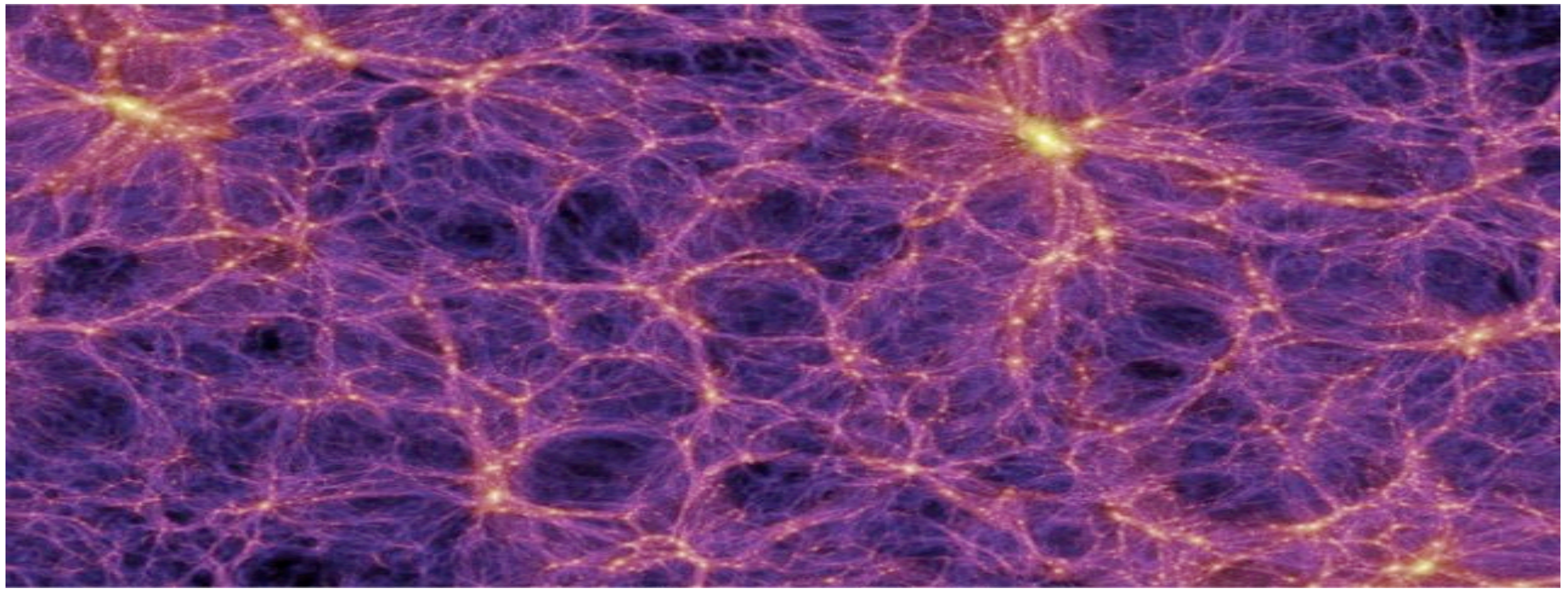
Boosted Annihilation due to structure formation:

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



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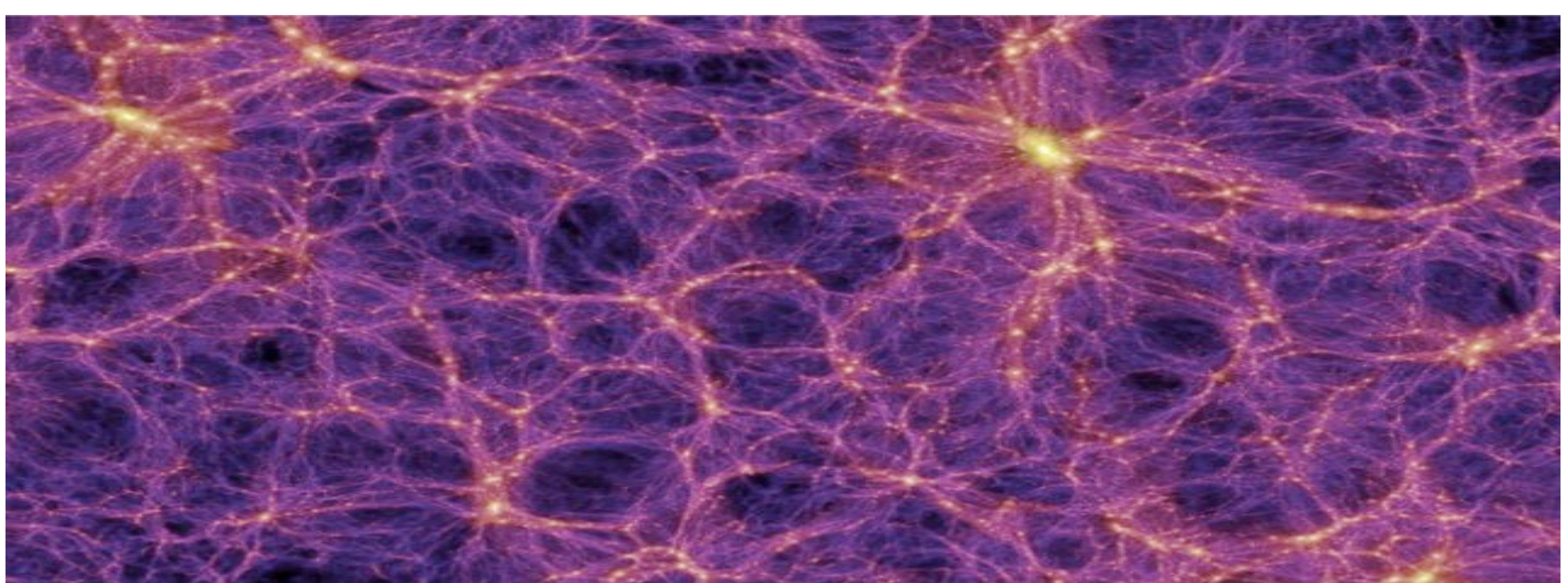

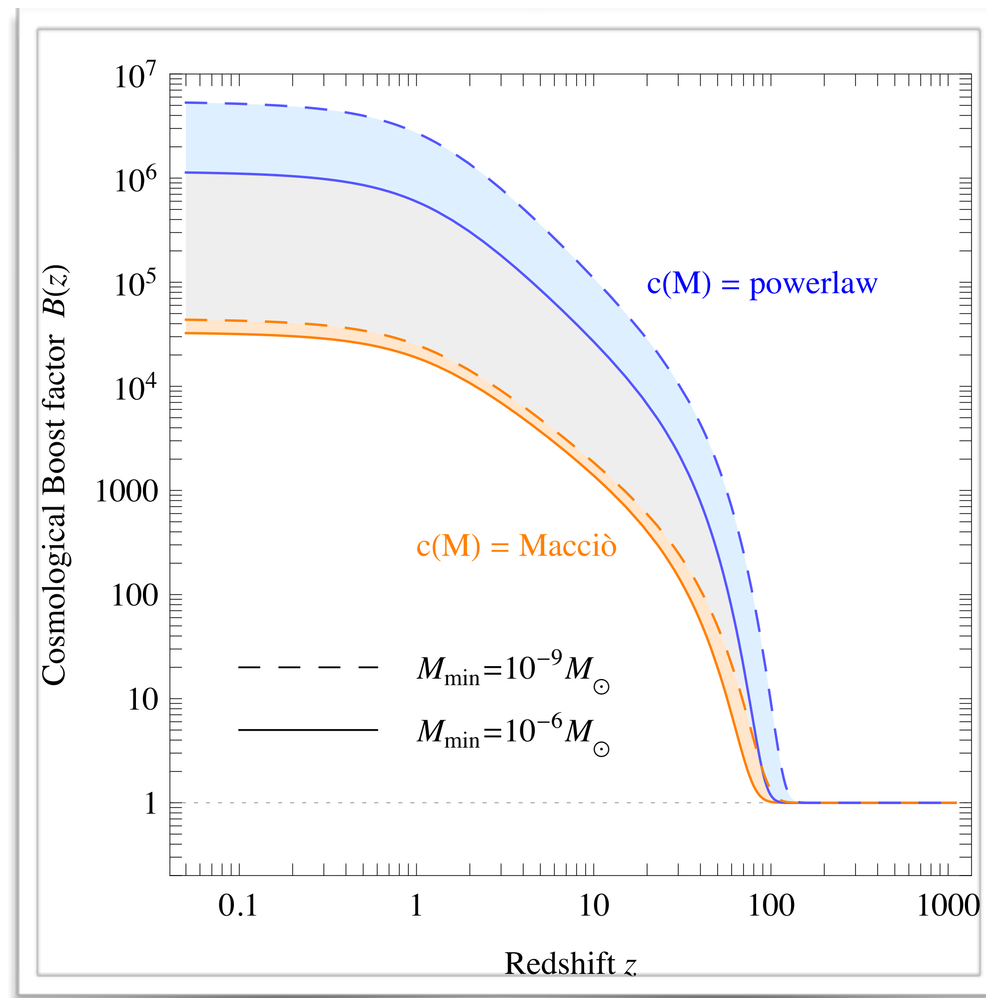

Energy deposition

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

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

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

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INSTANTANEOUS DEPOSITION: only valid at high redshift

$$f_{\mathrm{ion}}^{z\gtrsim100} = f_{\mathrm{exc}}^{z\gtrsim100} = \frac{f_{\mathrm{eff}}}{3}(1-x_e)\,, \qquad f_{\mathrm{heat}}^{z\gtrsim100} = \frac{f_{\mathrm{eff}}}{3}(1+2x_e)$$

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Energy deposition

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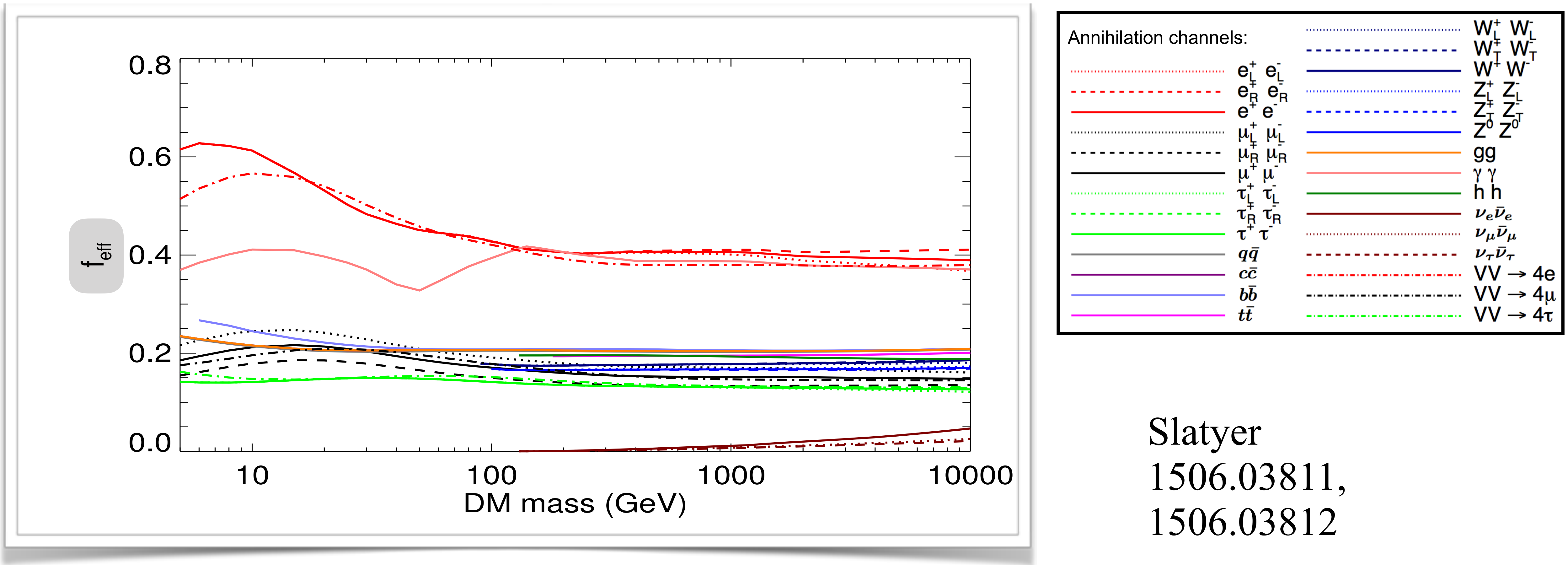

Slatyer
1506.03811,
1506.03812

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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**
- $\frac{H(z)(1+z)^3}{H(z')(1+z')^4}$: **Hubble Rate**
- $\mathcal{T}_c(E,z,z')$: *Accounts for EM shower* → Slatyer 1506.03811, 1506.03812
- 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

Evolution w/ DM ann.

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

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

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

Energy deposited: **HEATING**

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- **Our strategy**:
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  - **Strongest absorption**: $T_S^{z=17} \sim T_{\rm gas}^{\rm ad} = 6.5\ {\rm K} \implies T_{21}^{z=17} \simeq -200\ {\rm mK}$

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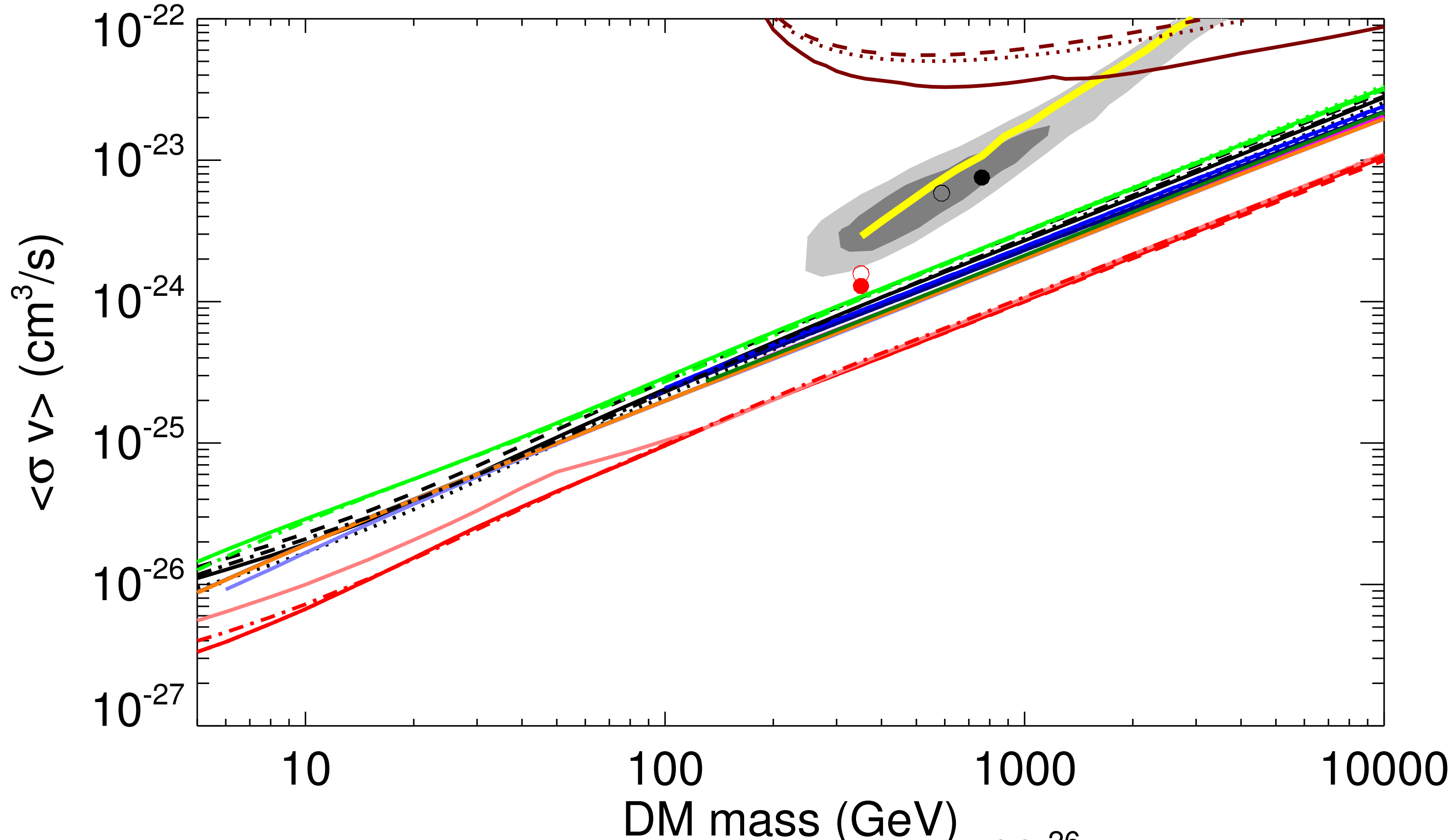
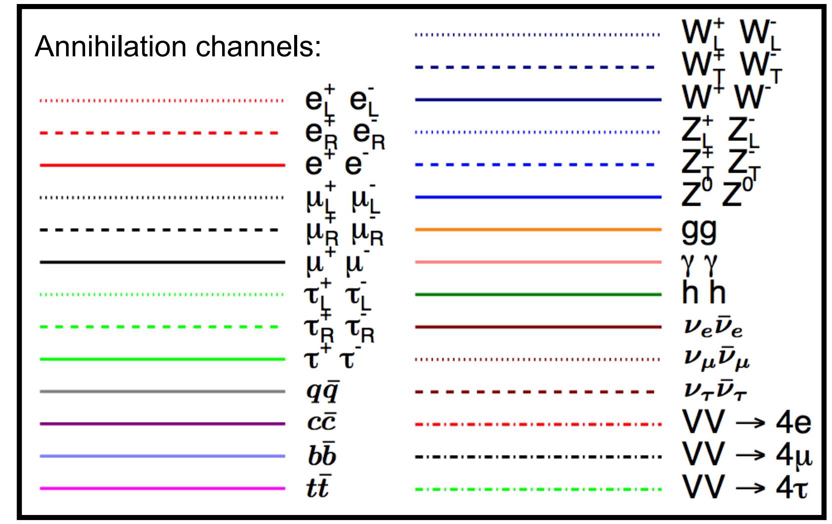
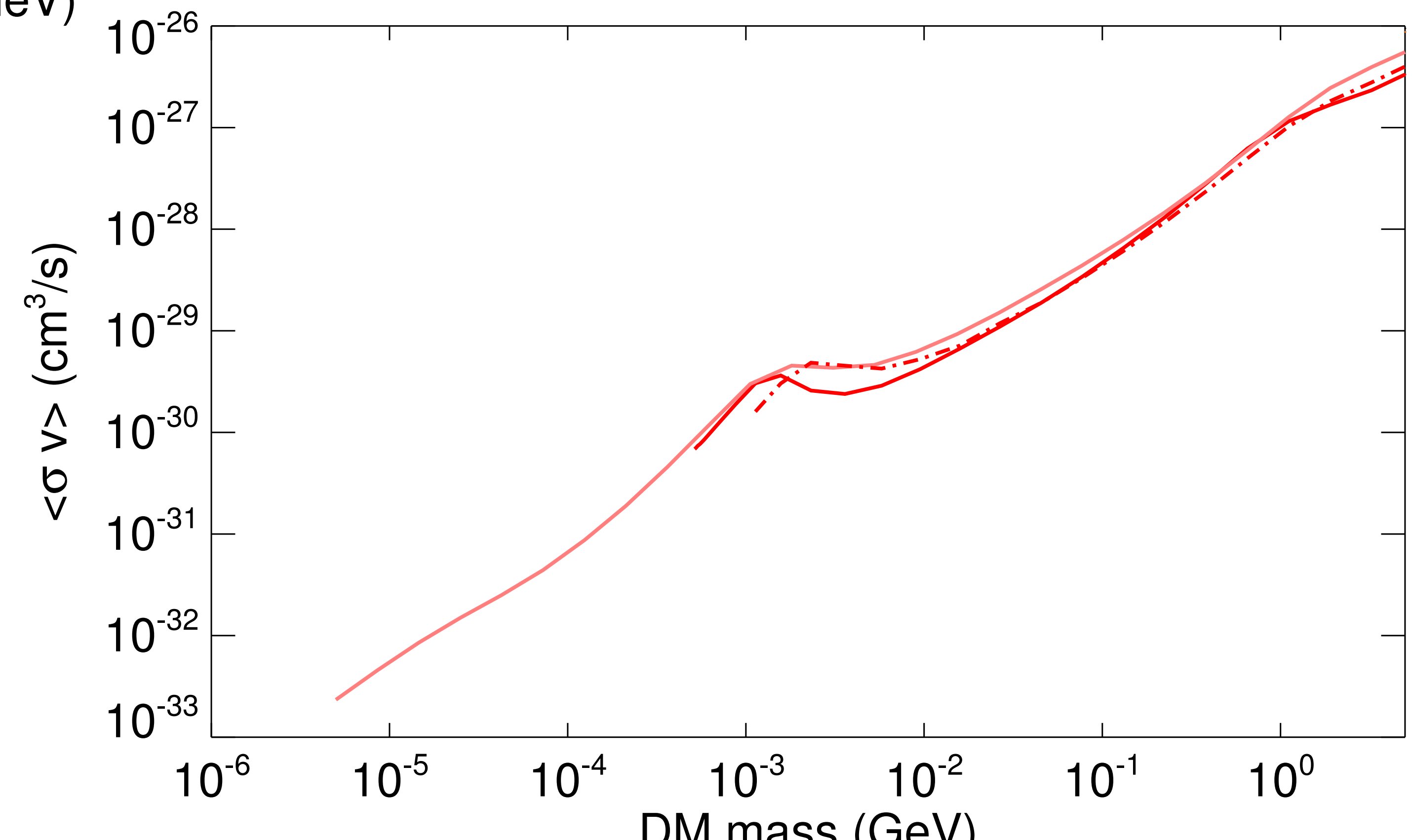
- We require that DM annihilations do not erase the 21-cm signal above **-100 mK** !!

Comparison: PLANCK





Slatyer 1506.03811



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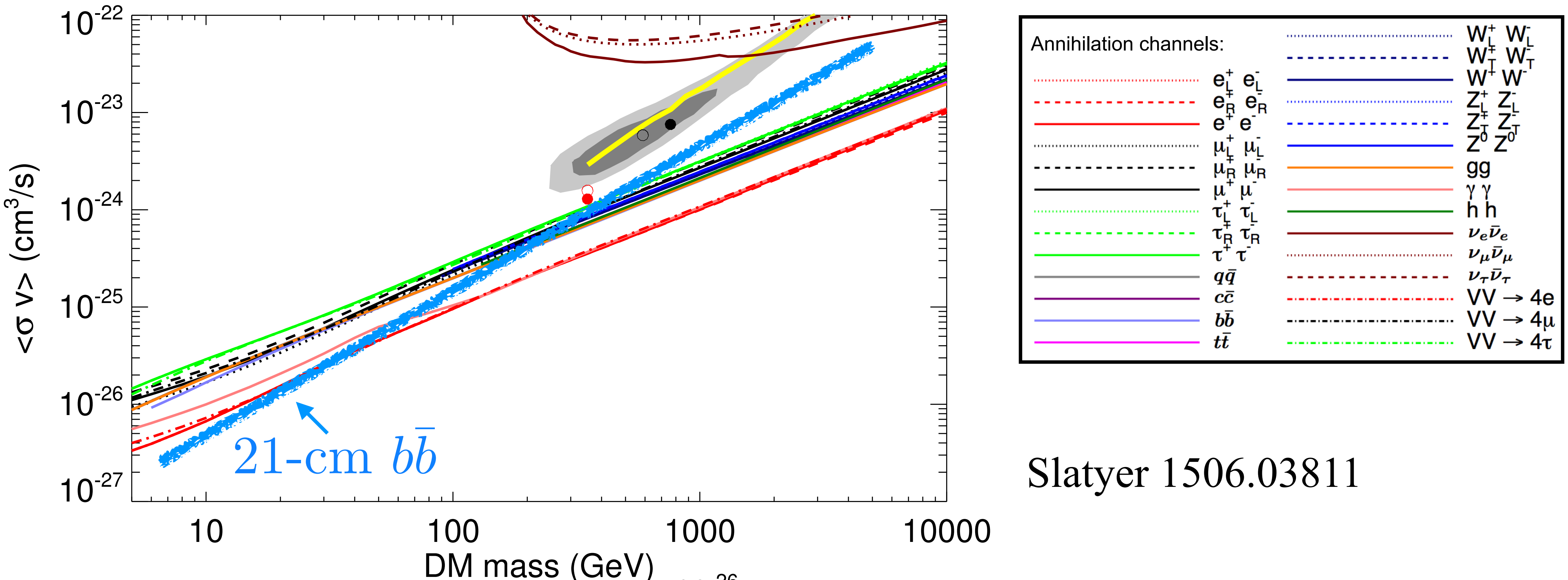
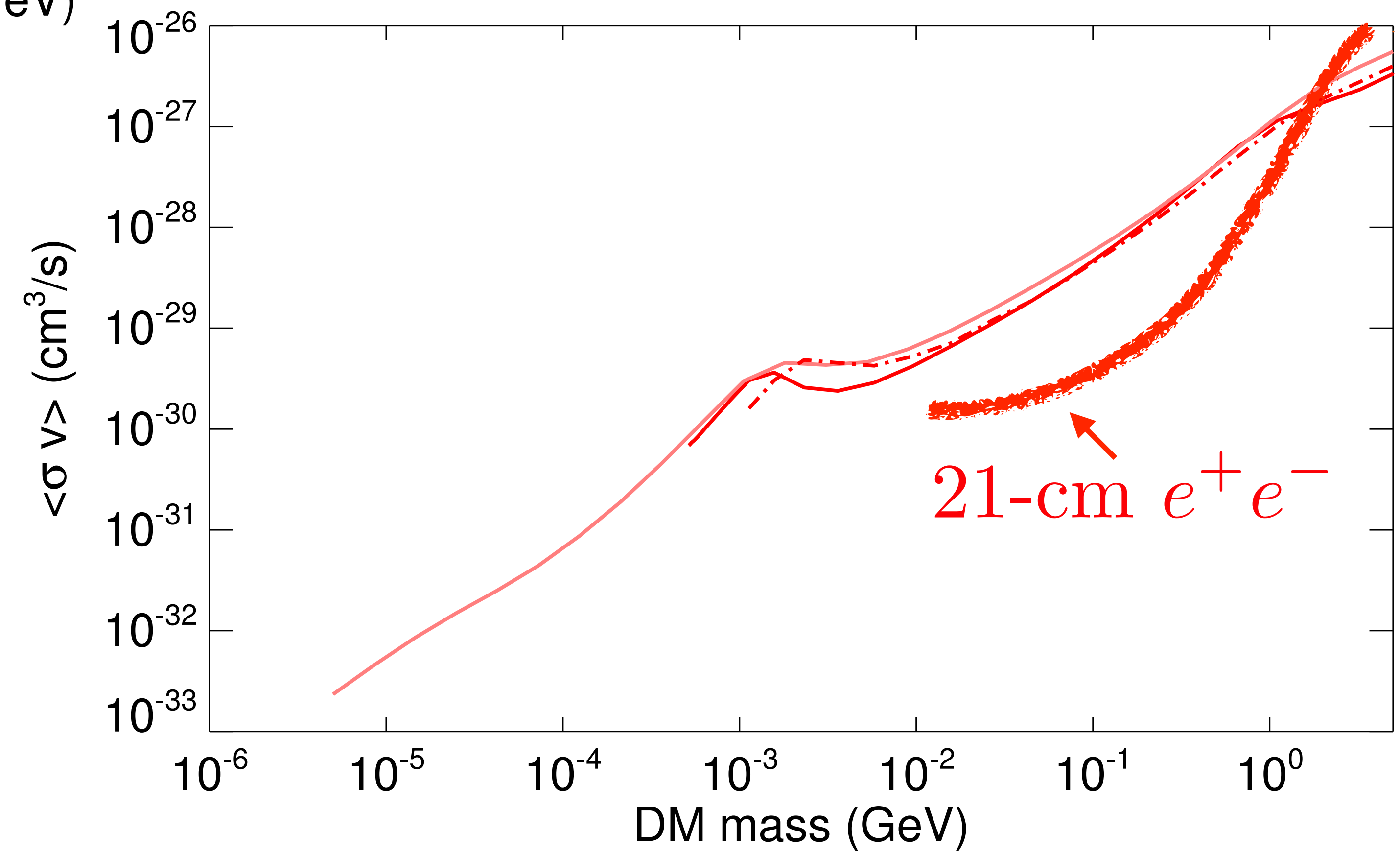


Slatyer 1506.03811



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Comparison: FERMI dSphs

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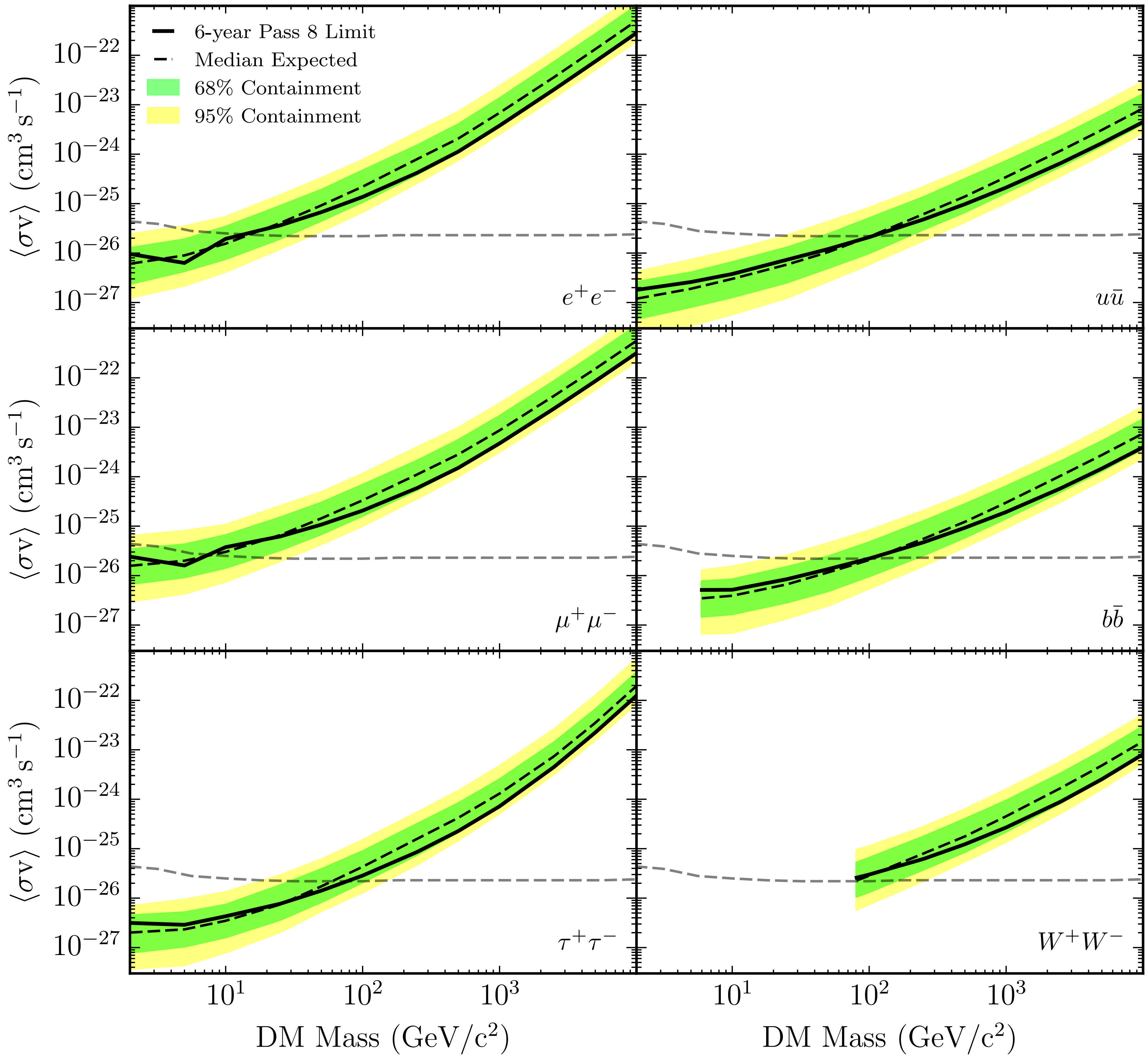

FERMI coll.
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Comparison: FERMI dSphs

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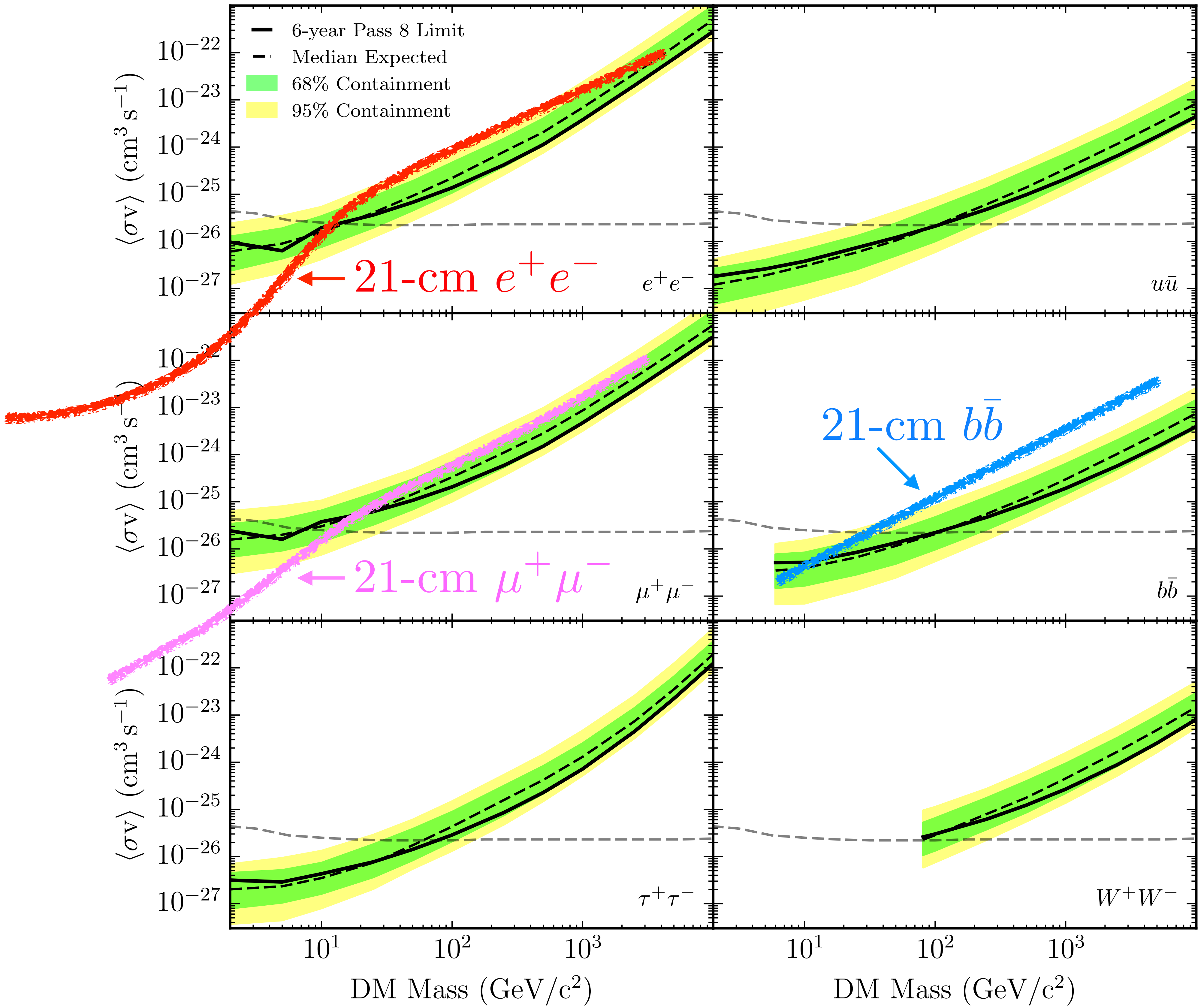

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