“Next Frontiers in the Search of Dark Matter"

Galileo Galilei Institute, 13/09/2019

21-cm line anomaly: A brief Status

PAOLO PANCI

Università di Pisa
Dipartimento di Fisica

Istituto Nazionale di Fisica Nucleare
Sezione di PISA

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

- Explain the anomaly with new physics
- Bounds on DM annihilations

Outlook & Discussions

PAOLO PANCI
slide 2/30

What happened in March 2018

LETTER

doi:10.1038/nature25792

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

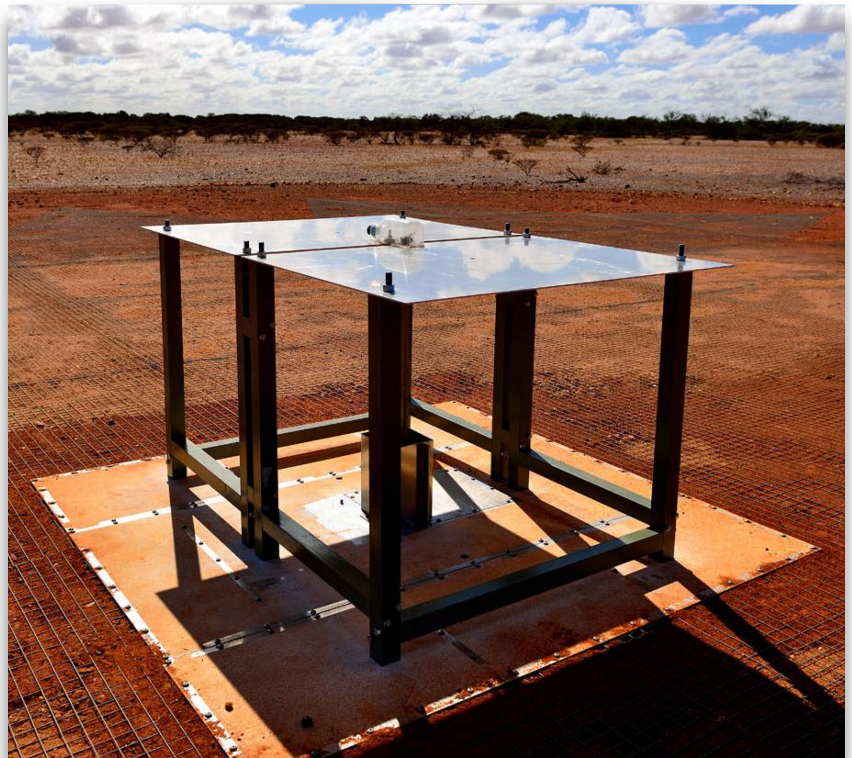
Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

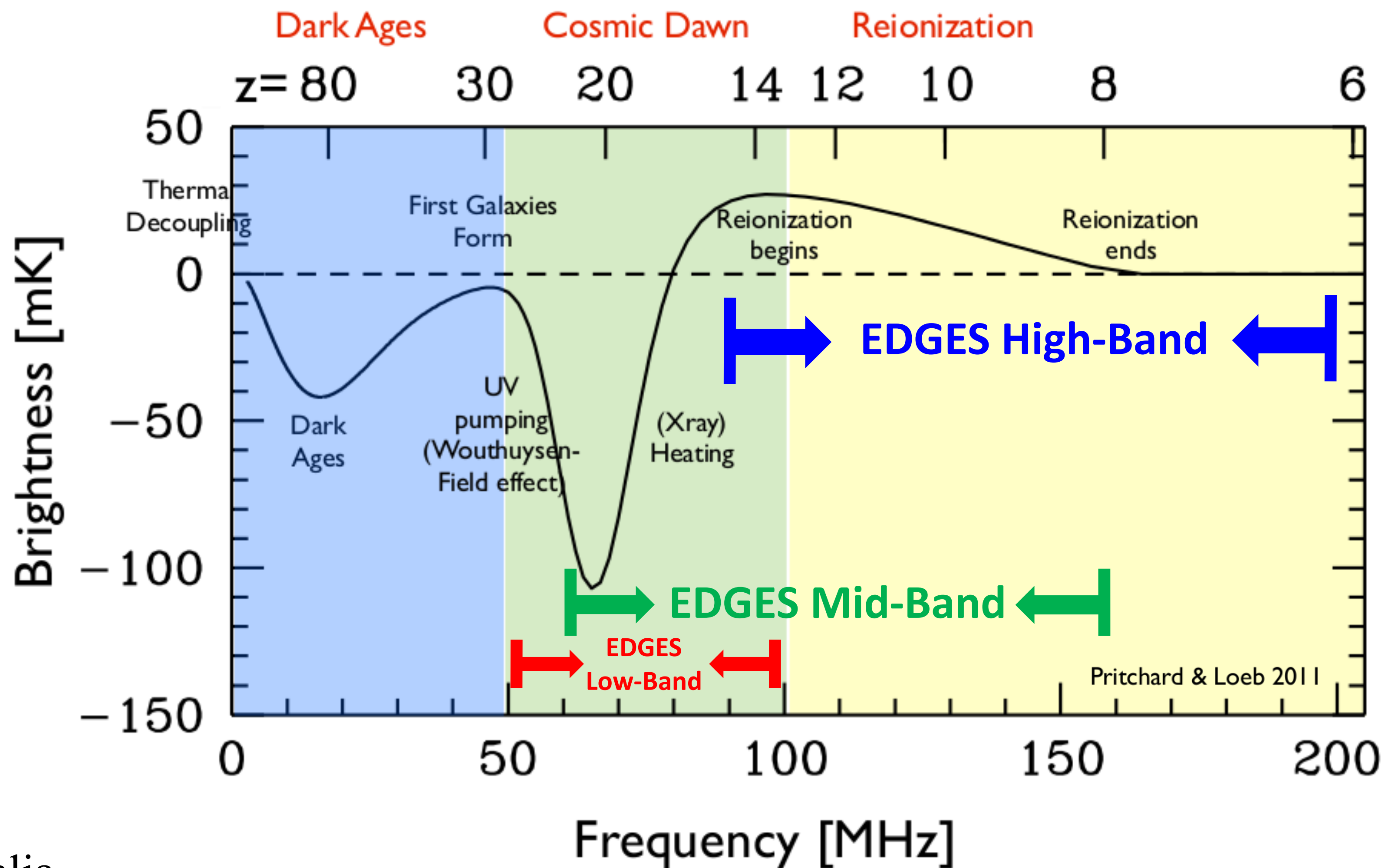
A 21-cm signal in *absorption*

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

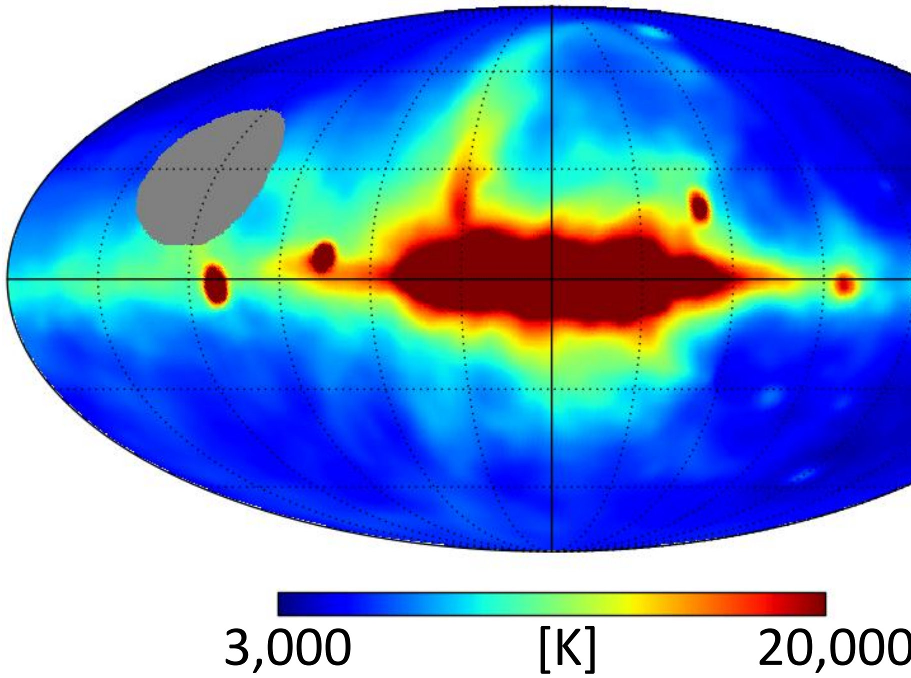
Low-band antenna: Designed to observe a spectral distortion in the 21-cm energy band at $z \sim 20$ due to the absorption of CMB photons by the IGM

PAOLO PANCI
slide 4/30

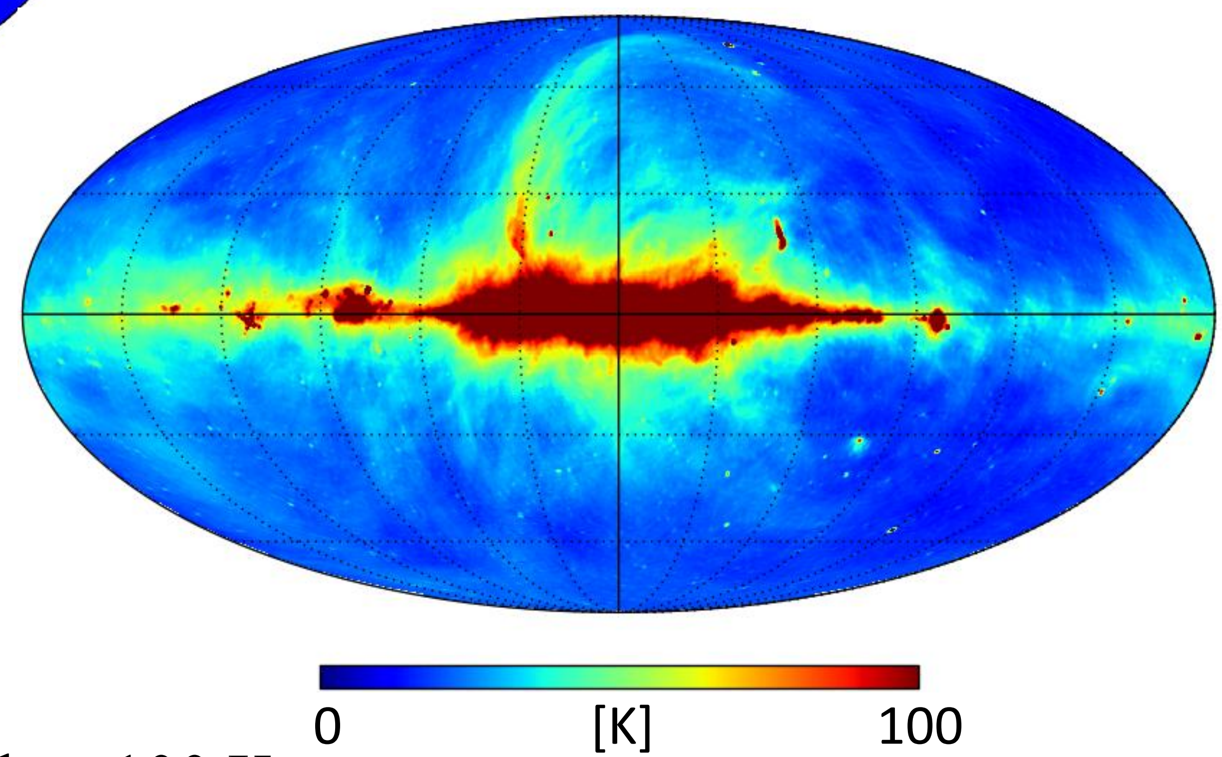
Large synchrotron bkg.

Diffuse Foregrounds

45-MHz Map
Guzmán et al. (2011)



408-MHz Map
Haslam et al. (1982)



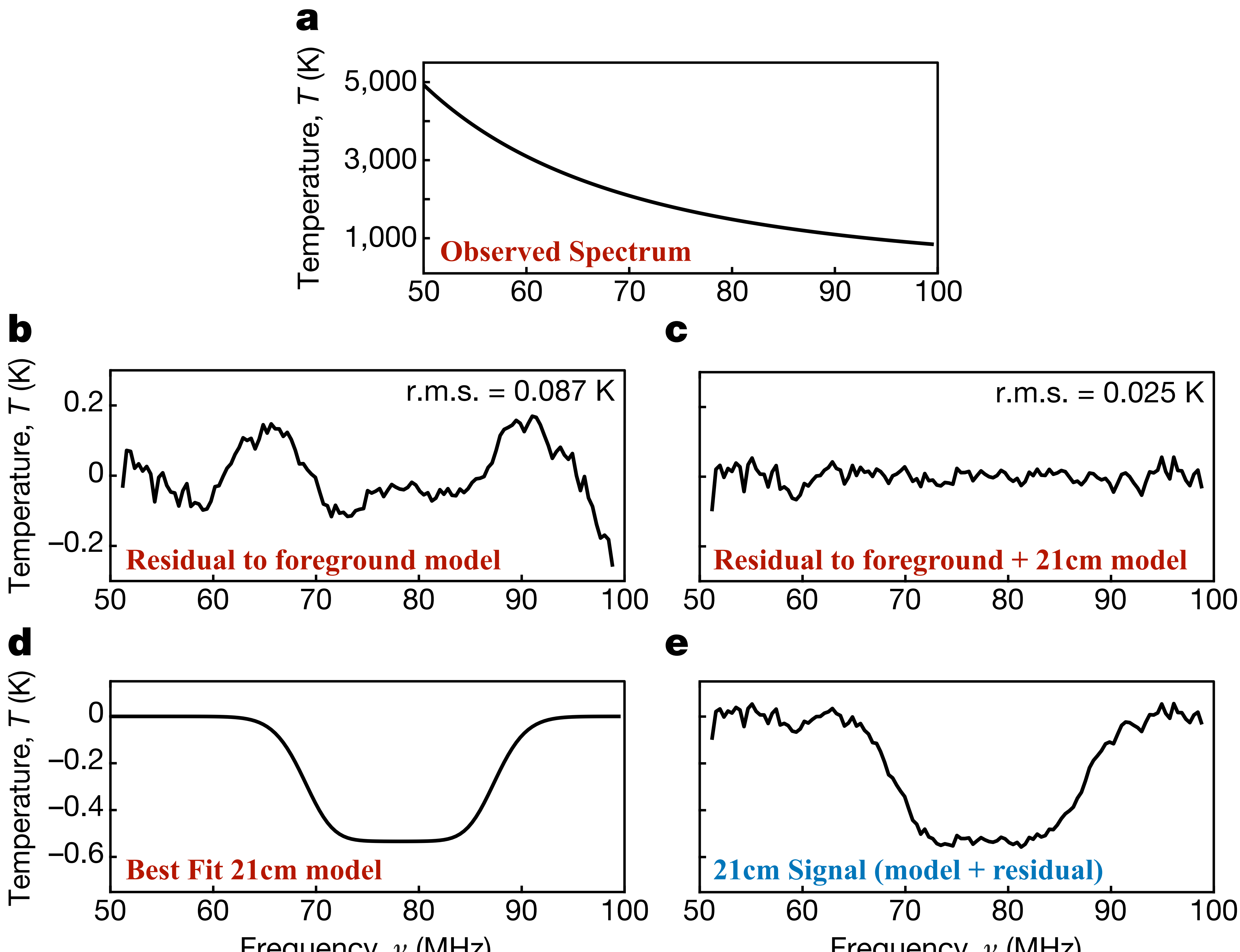
Main features of the Diffuse Foregrounds:

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

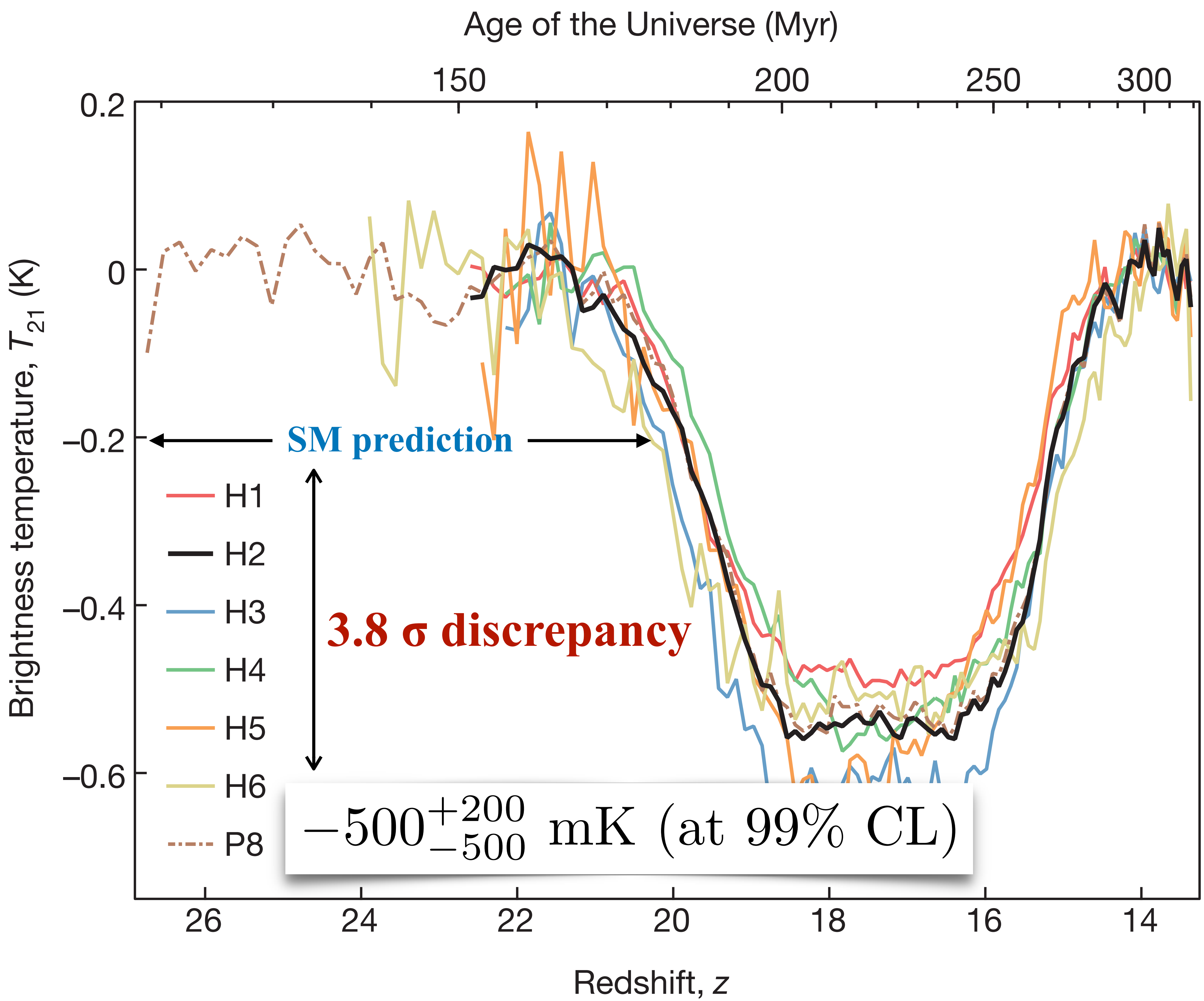
2) **Spectrally smooth** but might need **several terms** to model (see e.g. Bernardi et al. 2015)

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

What did EDGES see?



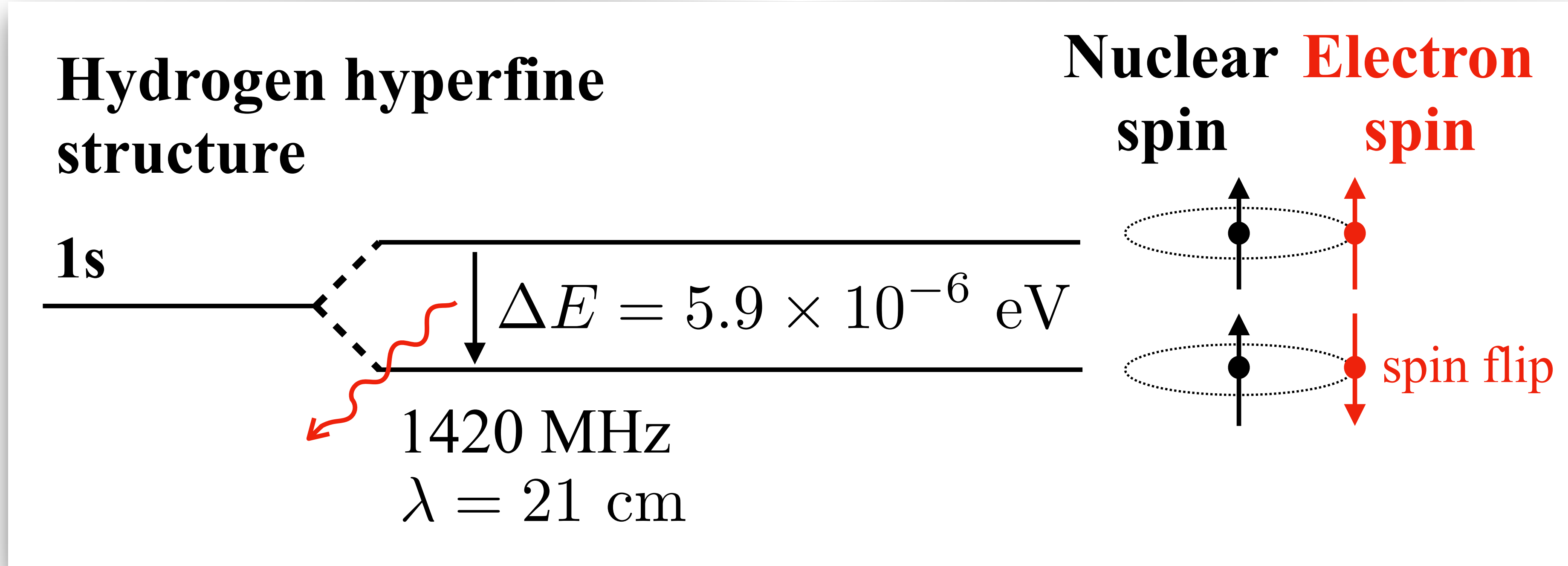
Some analysis of systematics



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?

Excited by what?

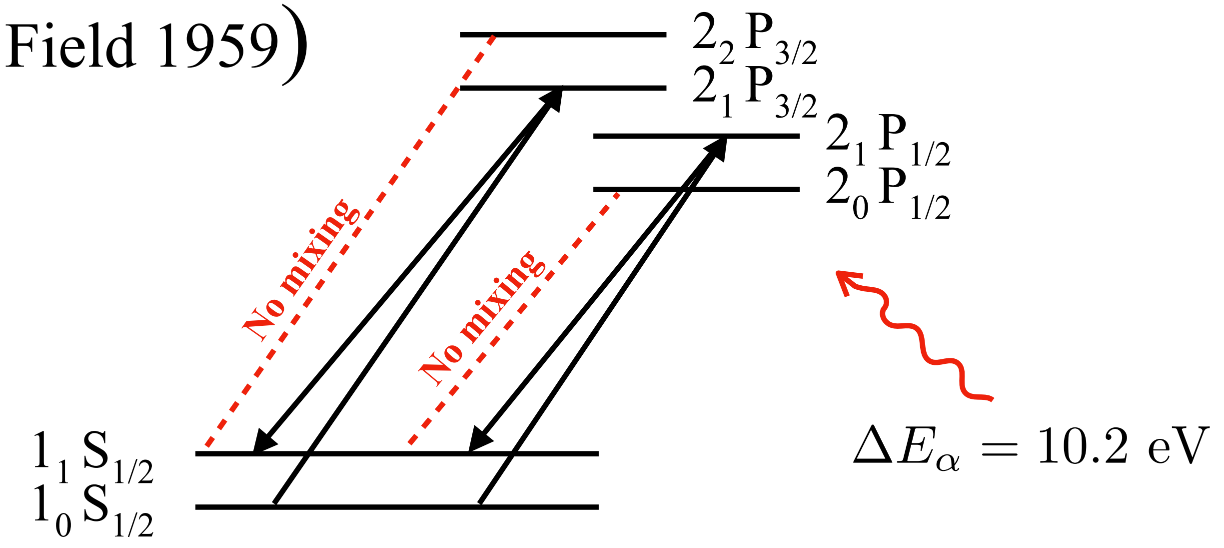
➡ **Absorption** of background CMB photon

Excited by what?

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

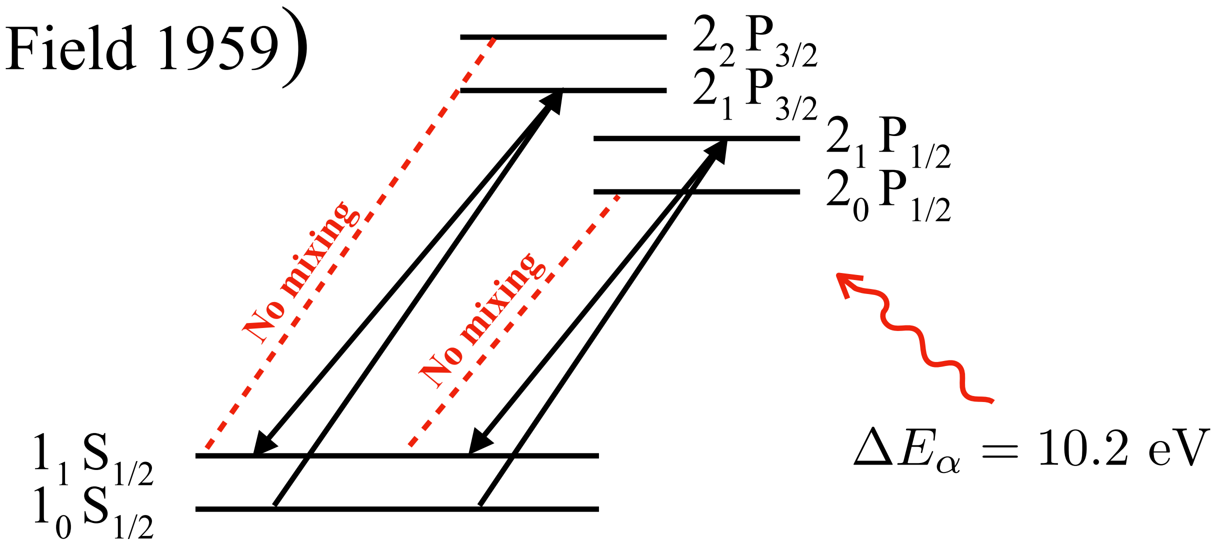
Excited by what?

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



Excited by what?

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



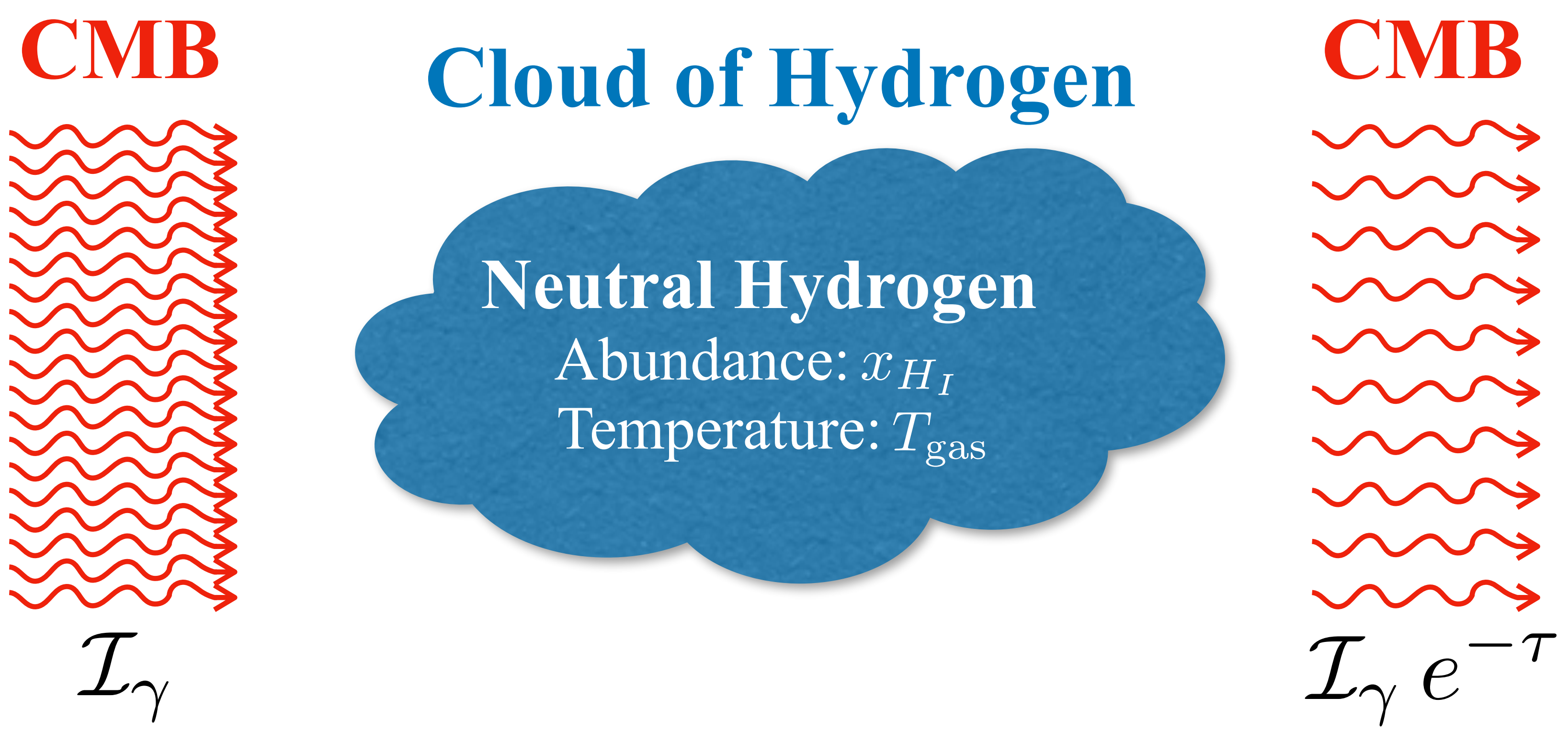
Equilibrium implies:

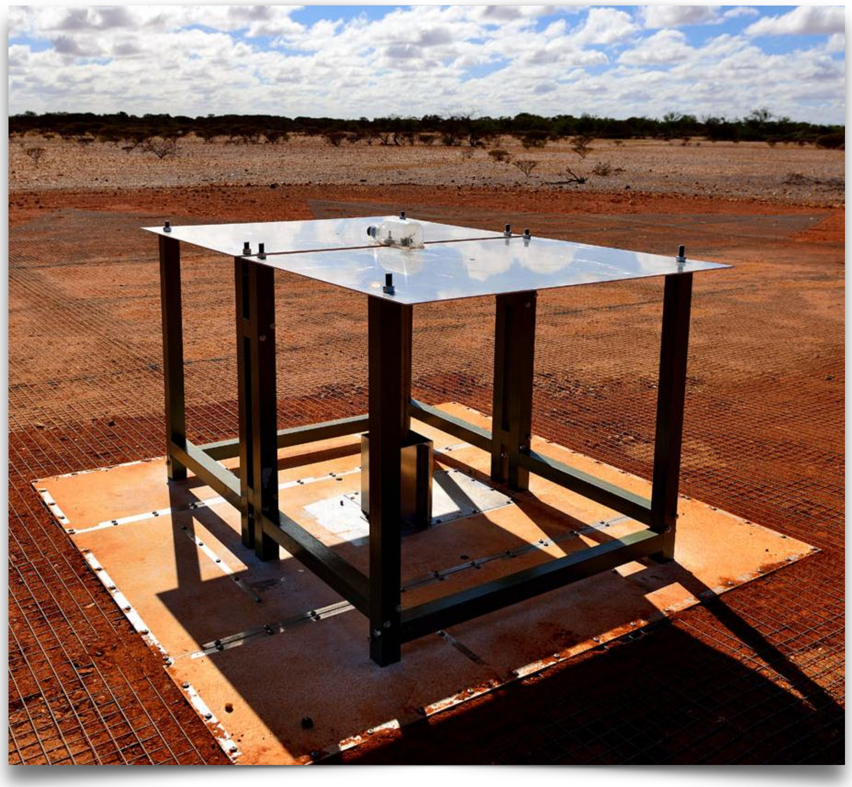
$$n_{\uparrow\uparrow}(\mathcal{C}_{10} + \mathcal{P}_{10} + \mathcal{A}_{10} + \mathcal{B}_{10} I_\gamma) = n_{\uparrow\downarrow}(\mathcal{C}_{01} + \mathcal{P}_{01} + \mathcal{B}_{01} I_\gamma)$$

In terms of temperature:

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

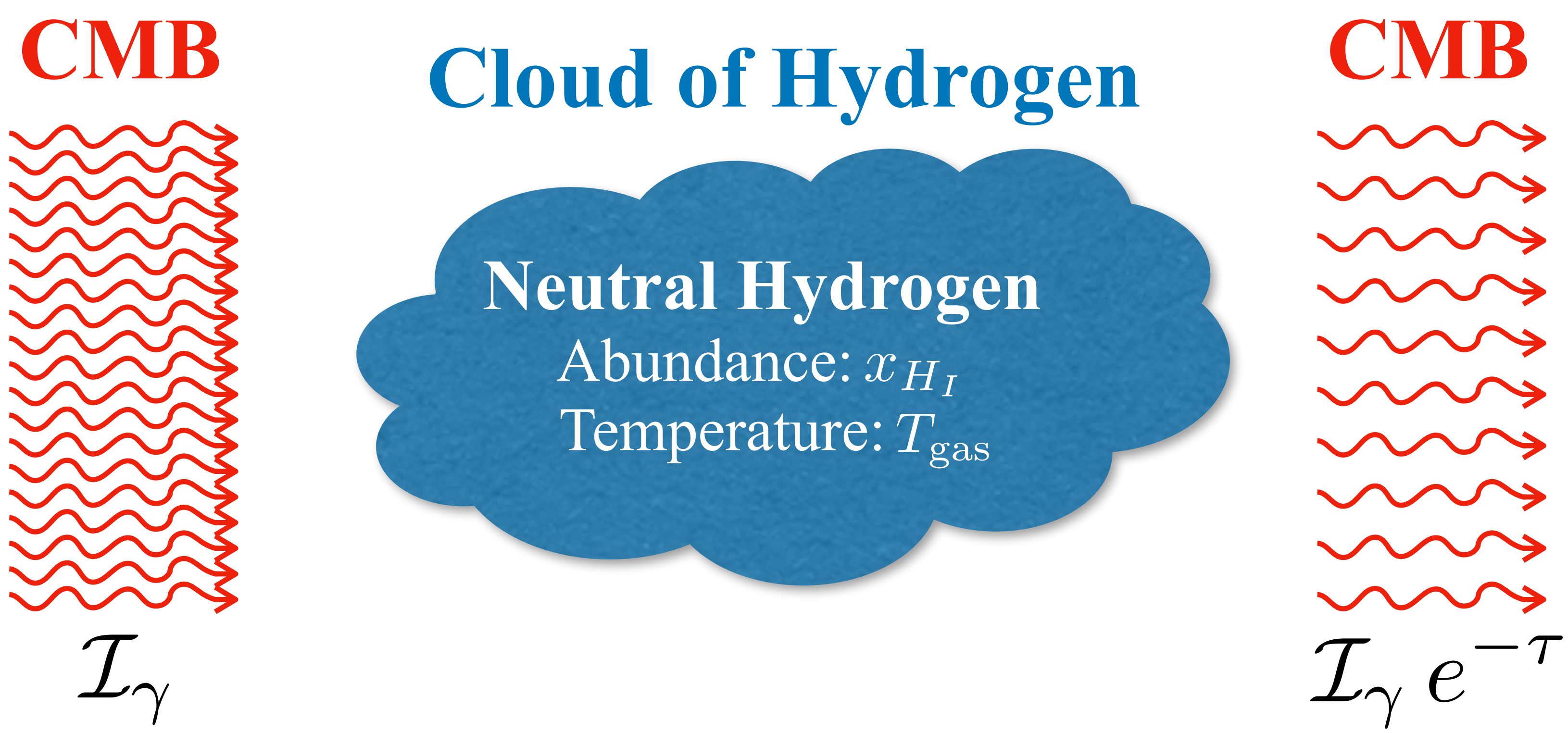
What we see

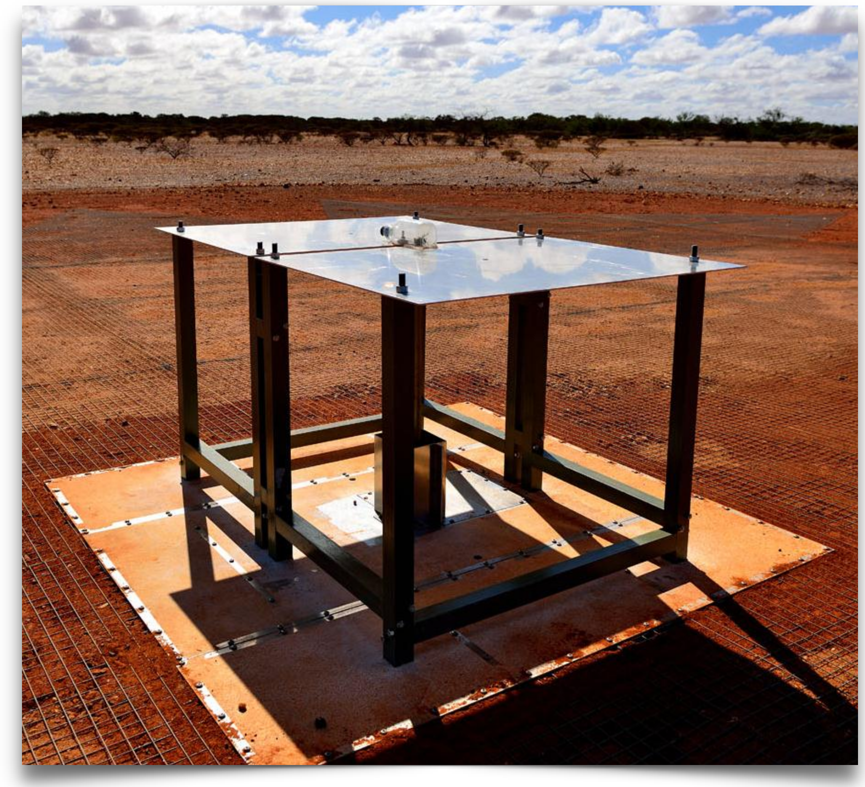




$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

What we see





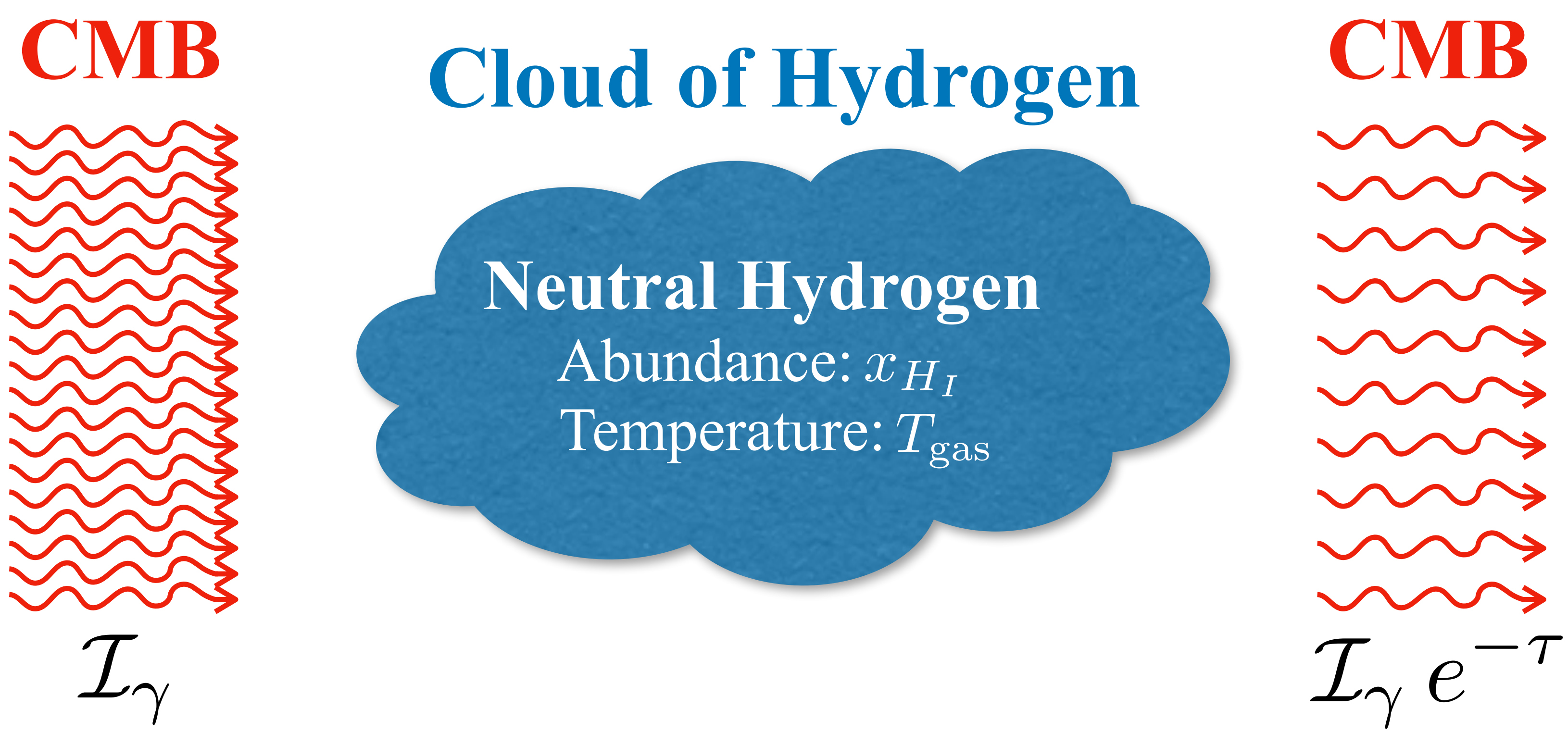
$\tau \ll 1$: The Universe is **mostly transparent** to 21-cm photons

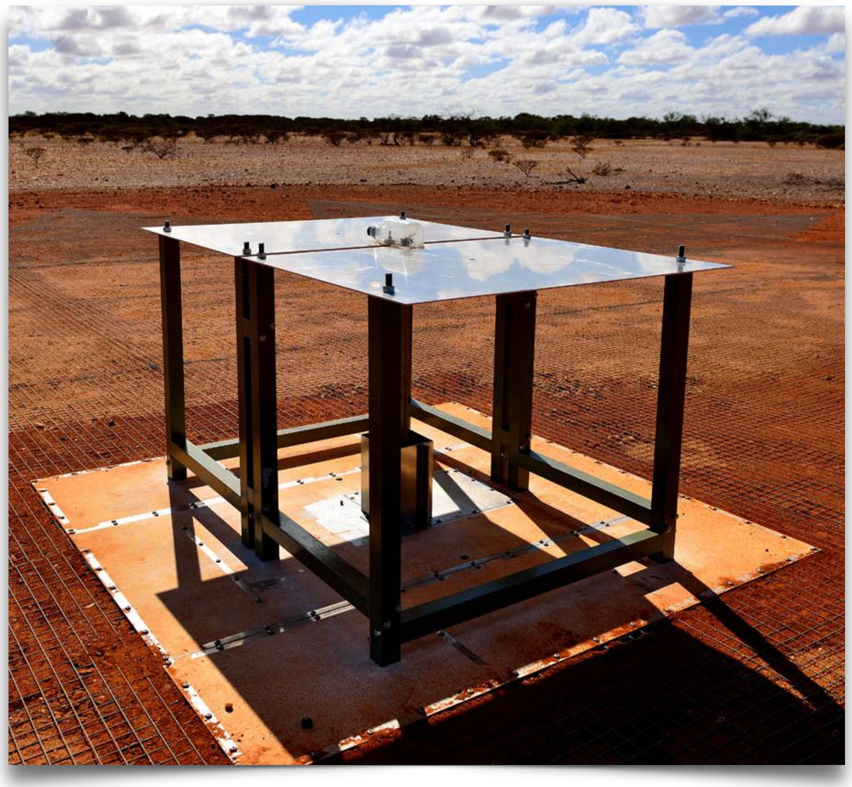
$$T_{21} \propto \mathcal{I}_\gamma (1 - e^{-\tau}) \approx I_\gamma \tau \approx 21\,\text{mK}\, x_{H_I} \left(1 - \frac{T_{\rm CMB}}{T_S}\right) \sqrt{\frac{1+z}{10}}$$

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

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

What we see





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

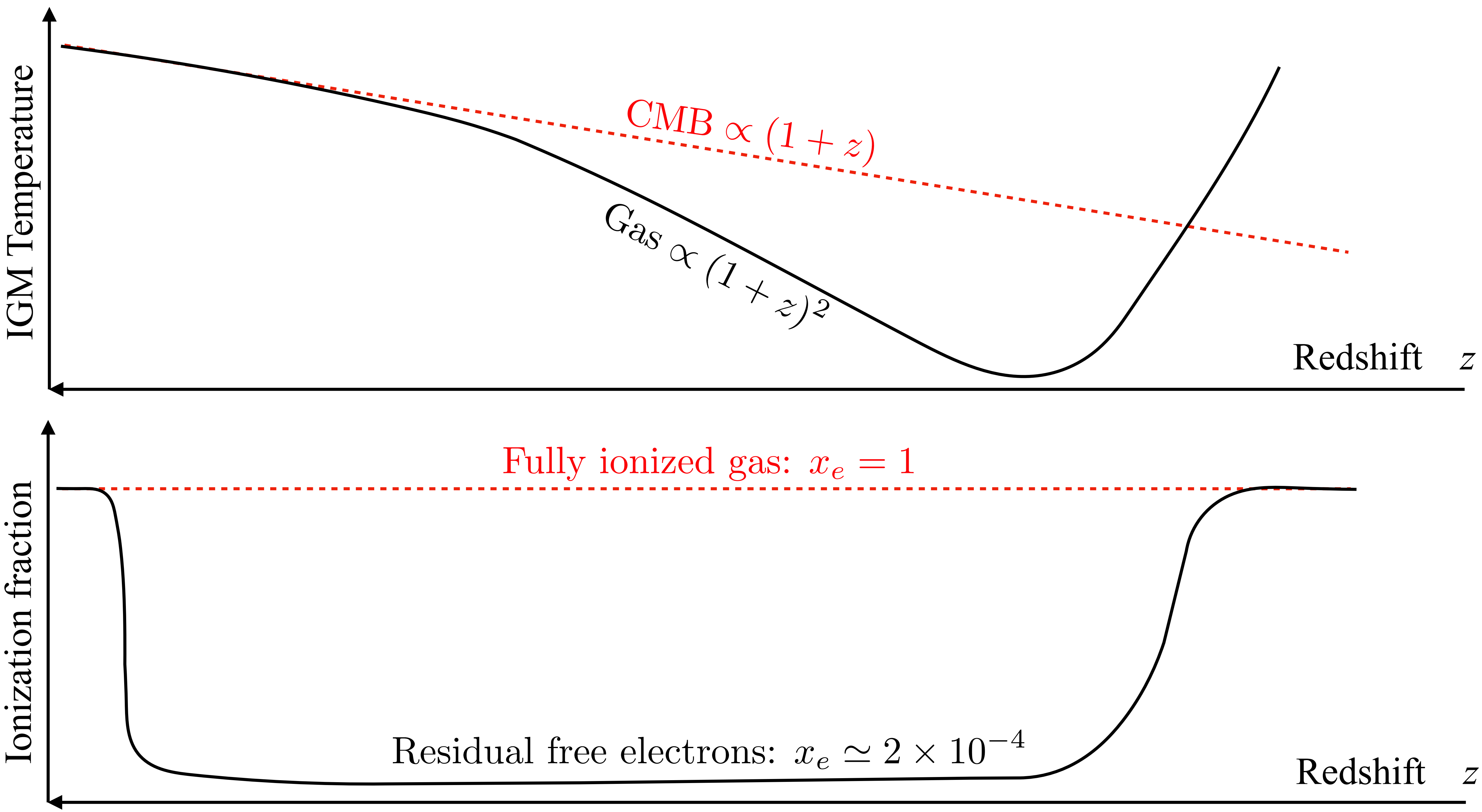
$$T_{21} \propto \mathcal{I}_\gamma (1 - e^{-\tau}) \approx I_\gamma \tau \approx 21\,\mathrm{mK}\, x_{H_I} \left(1 - \frac{T_{\rm CMB}}{T_S}\right) \sqrt{\frac{1+z}{10}}$$

EDGES measurement implies

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

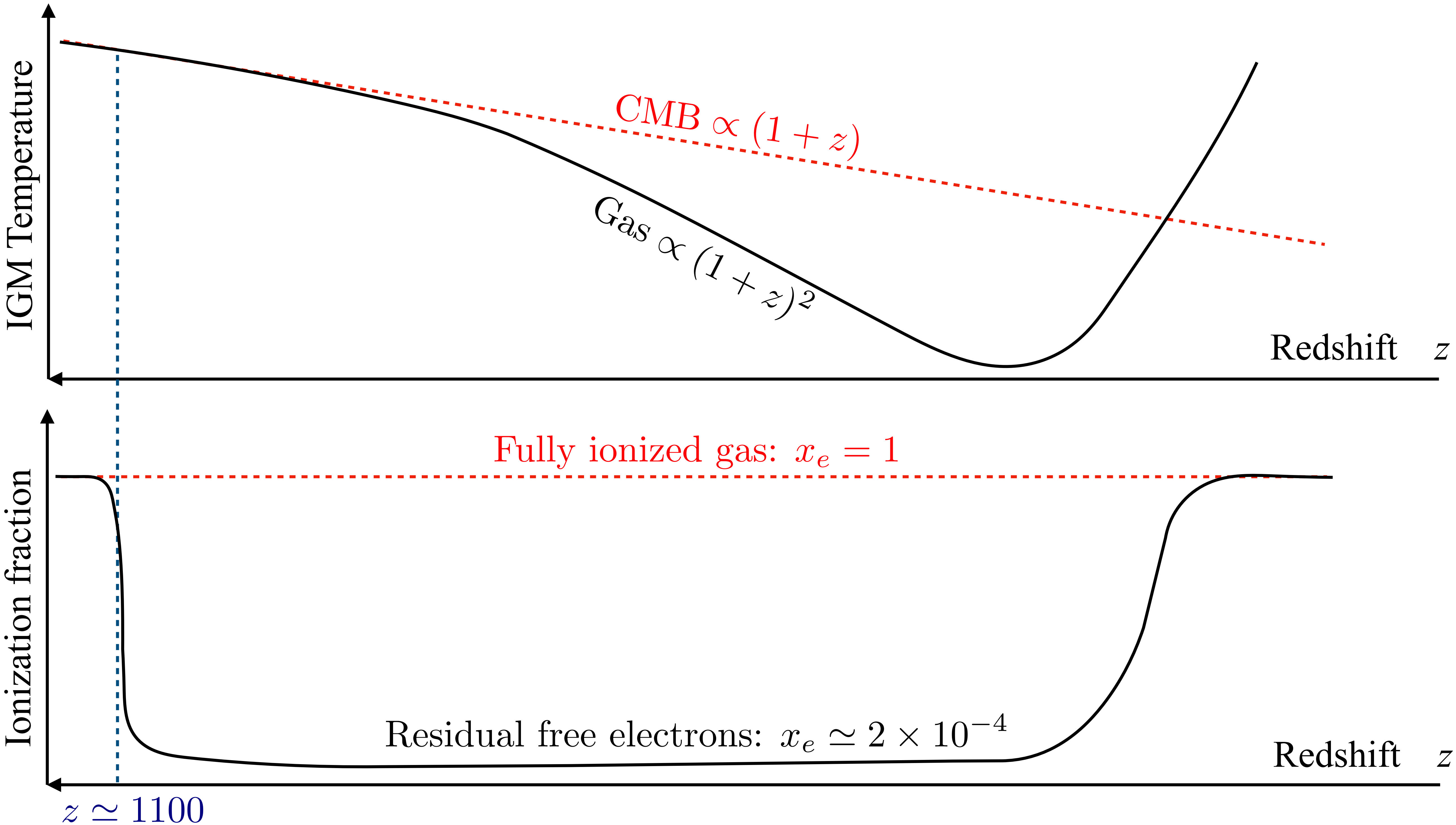
$T_S \simeq 3$ K

A short history of the IGM



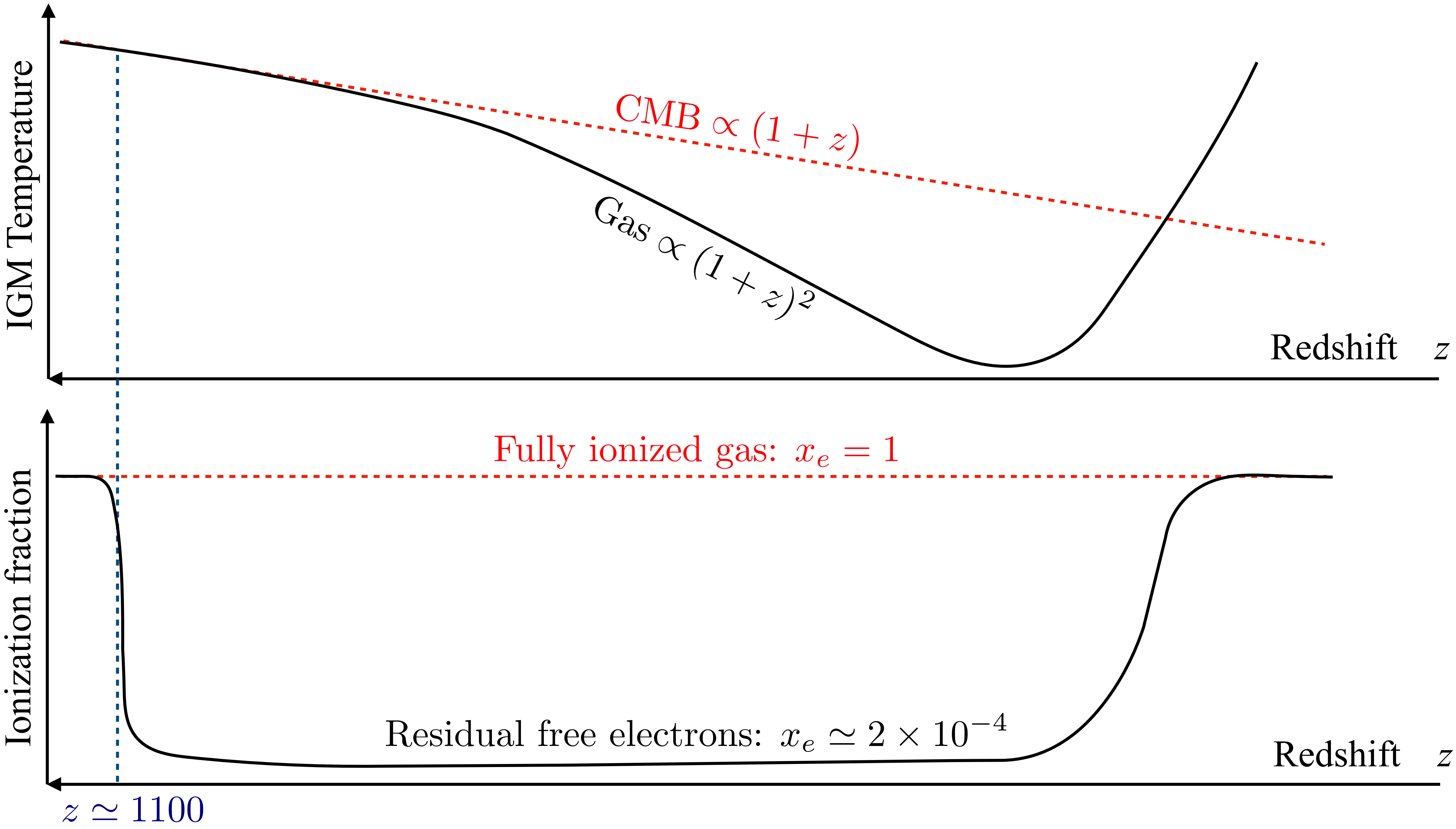
A short history of the IGM

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



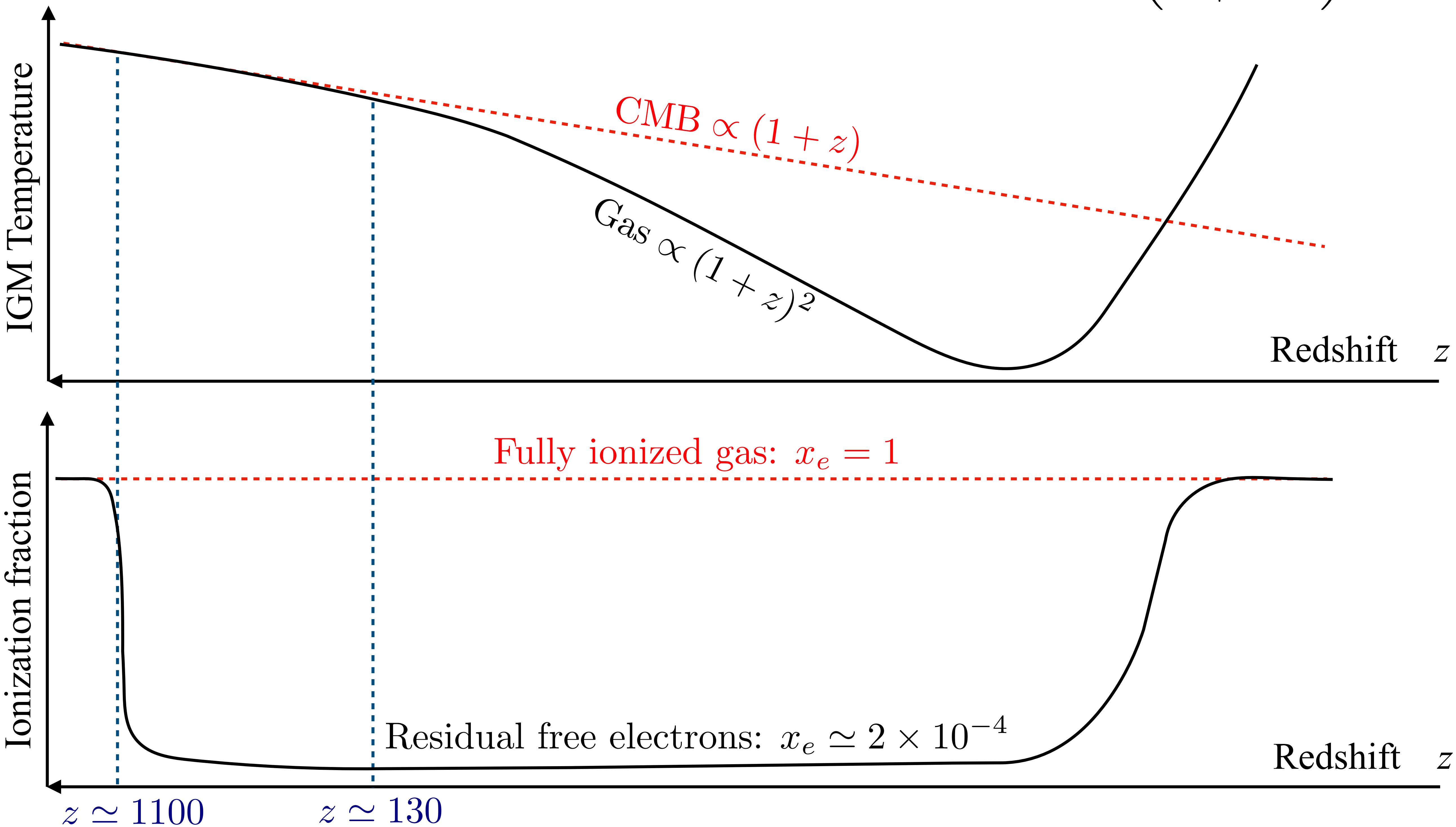
A short history of the IGM

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



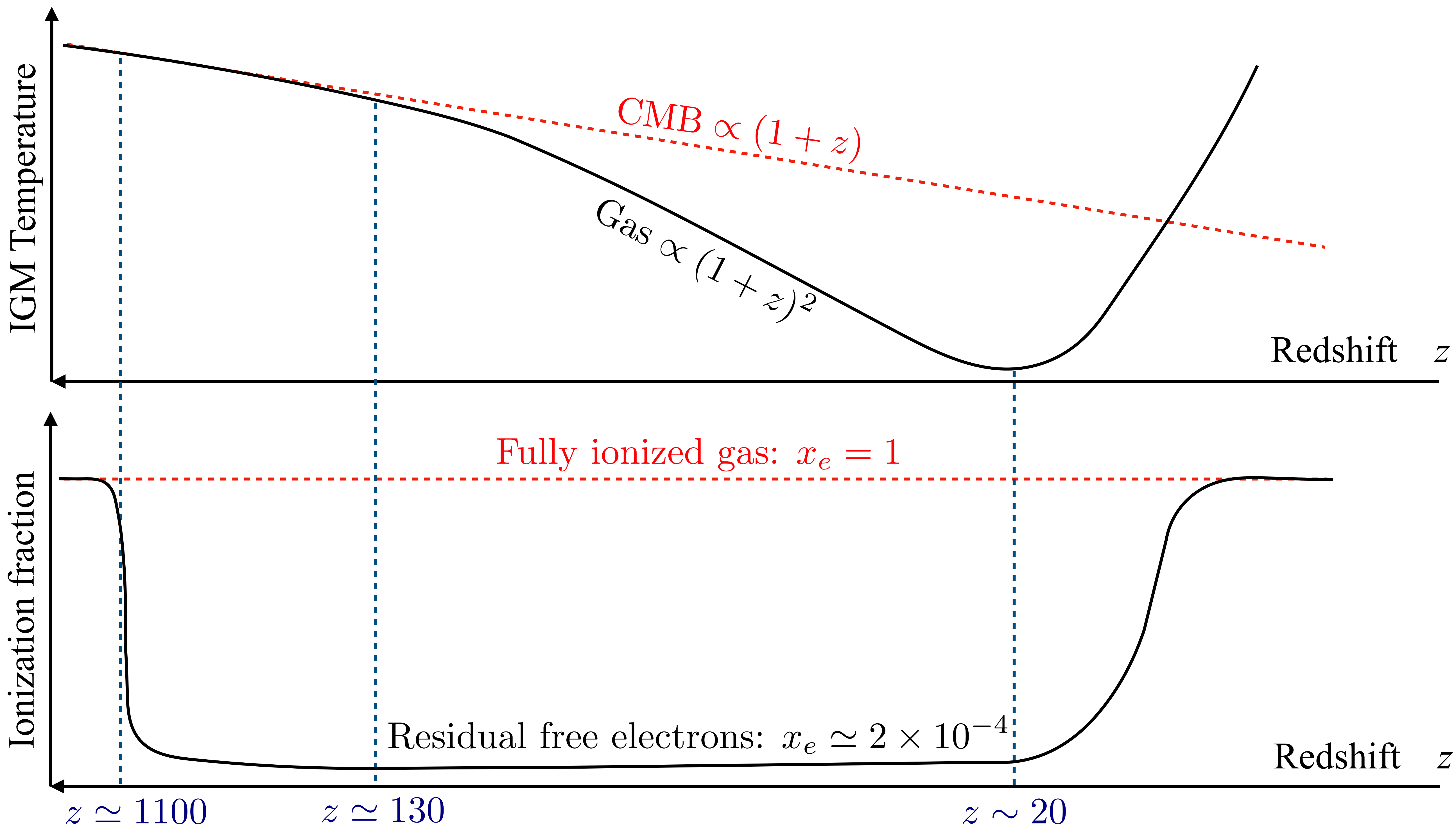
A short history of the IGM

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



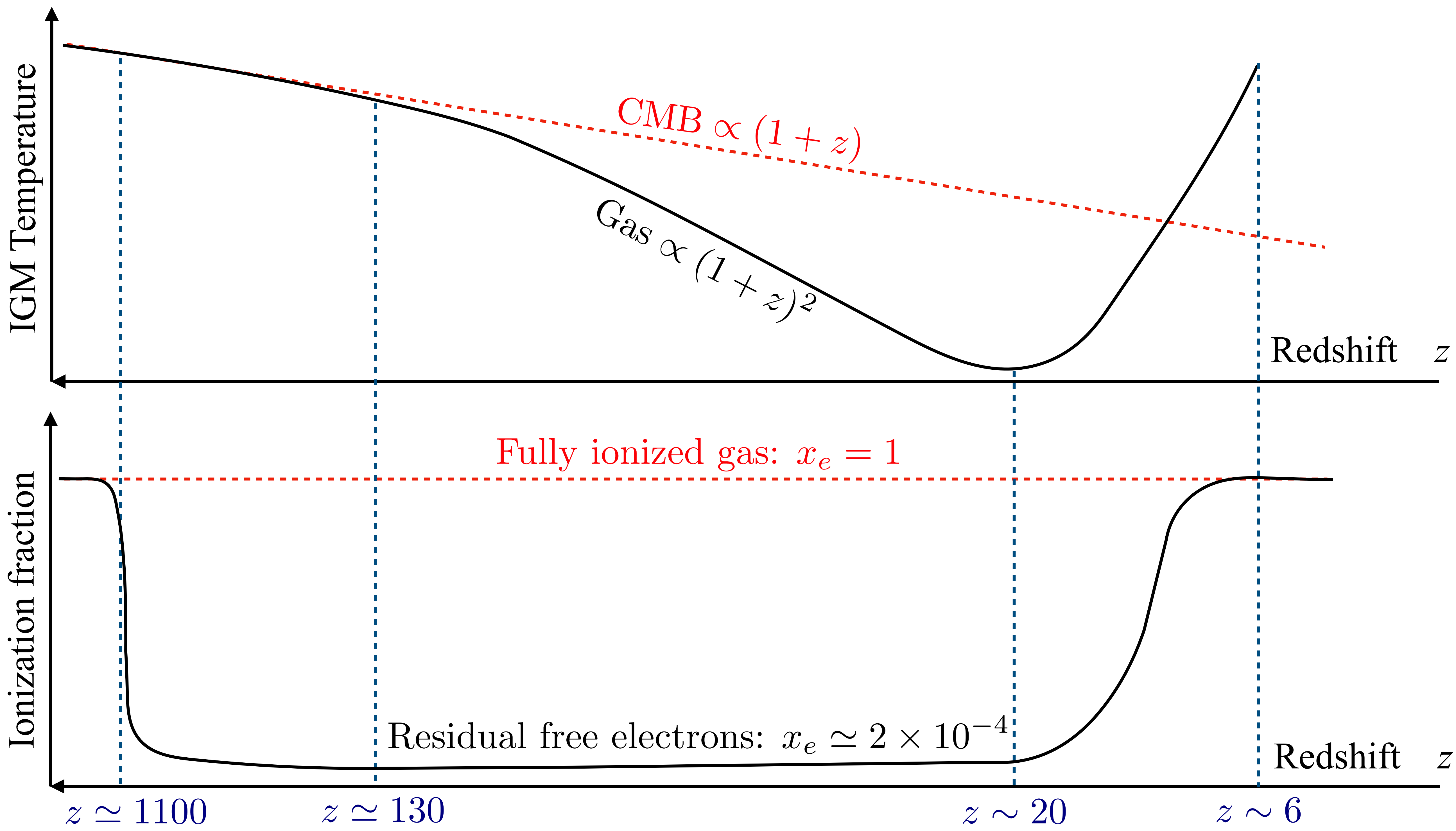
A short history of the IGM

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



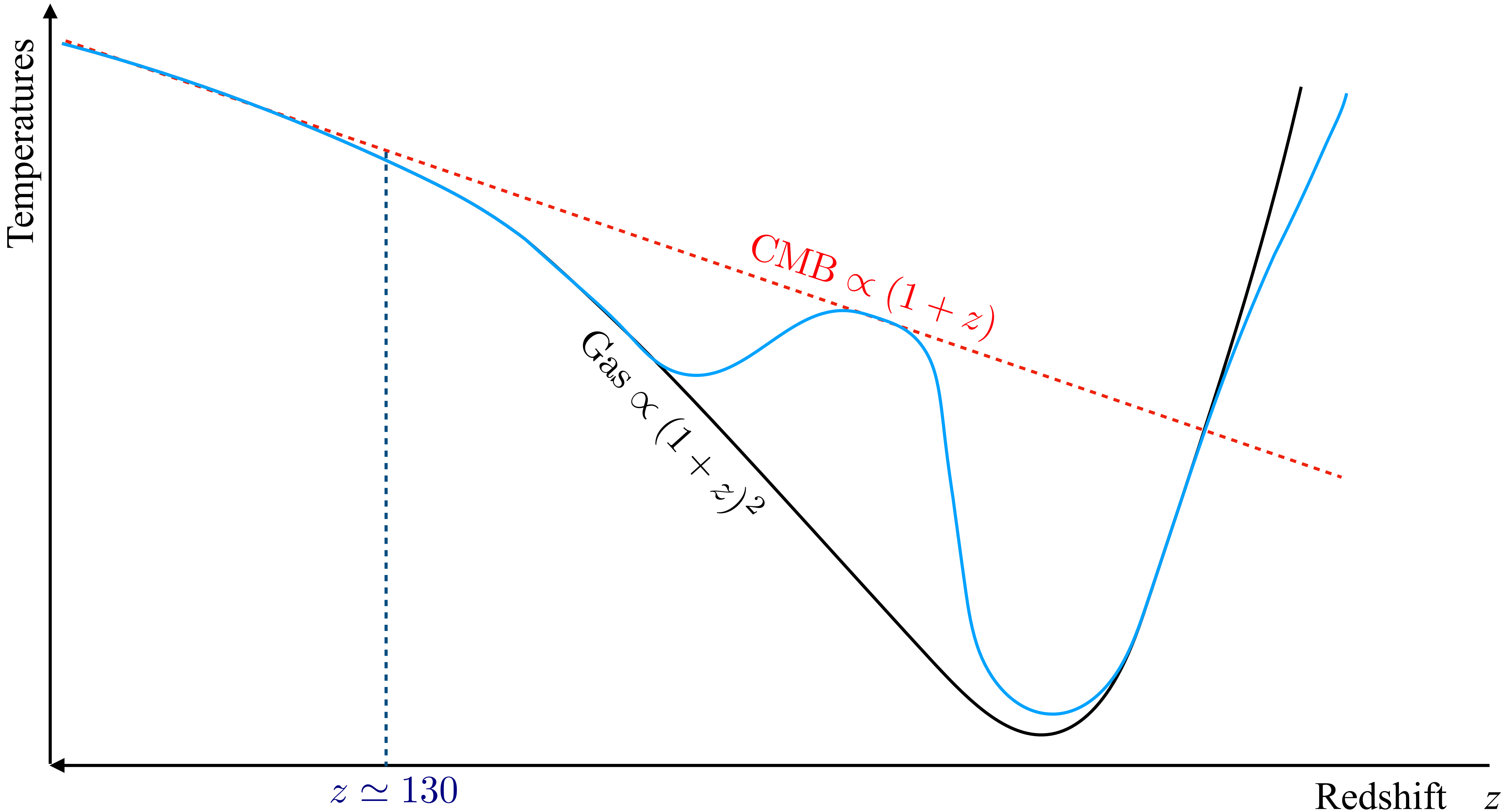
A short history of the IGM

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



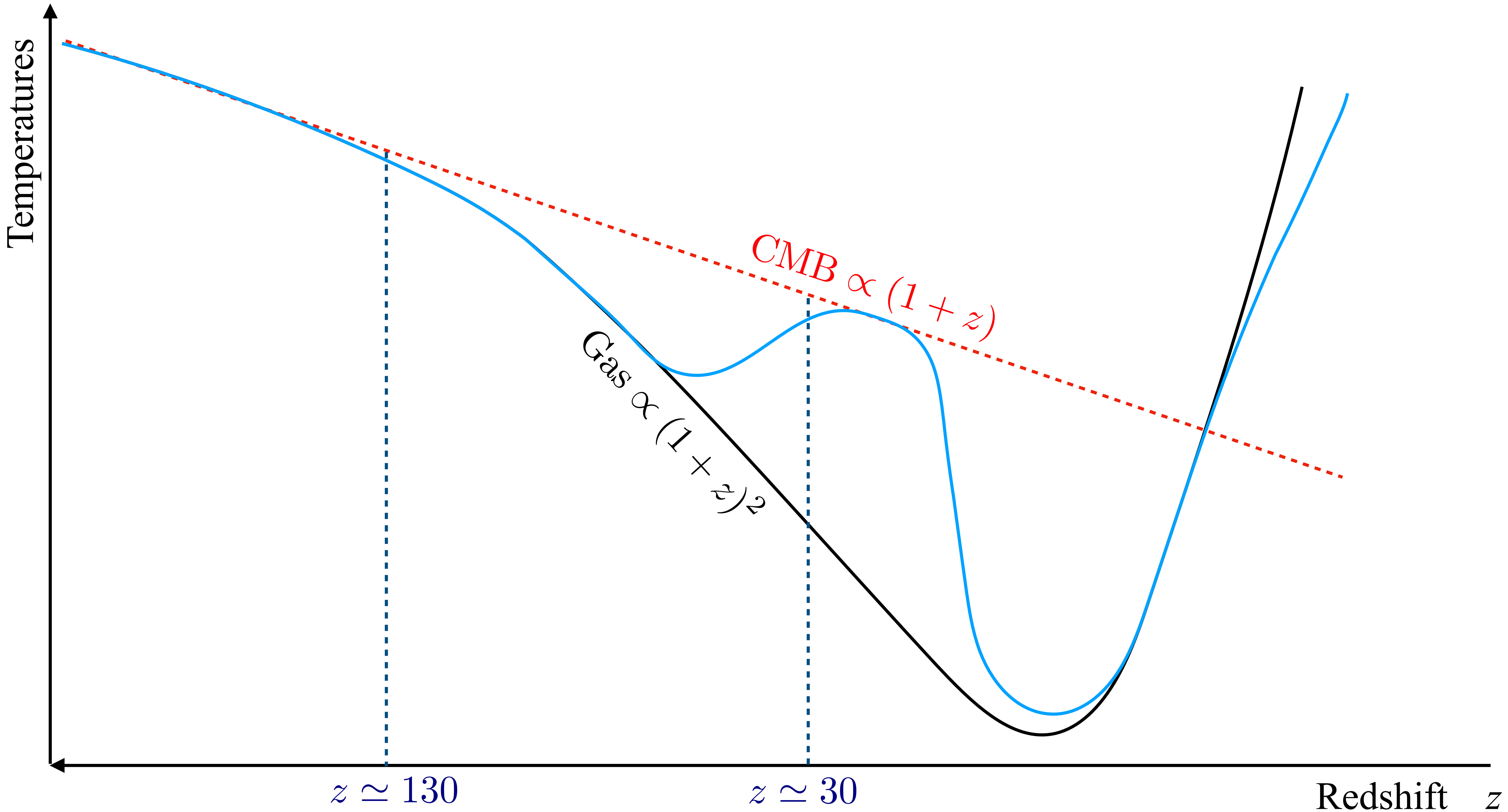
A short history of T_S

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



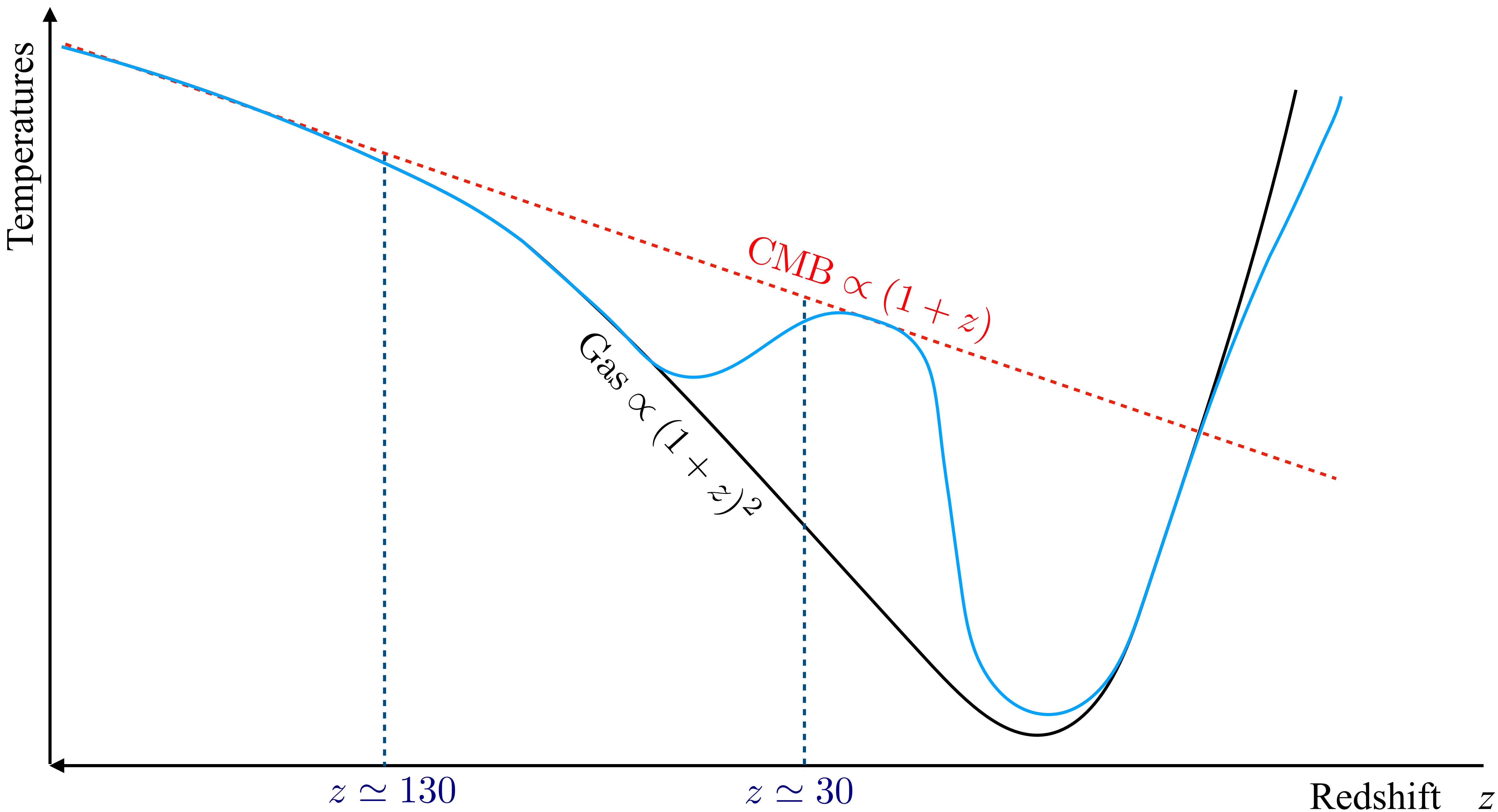
A short history of T_S

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



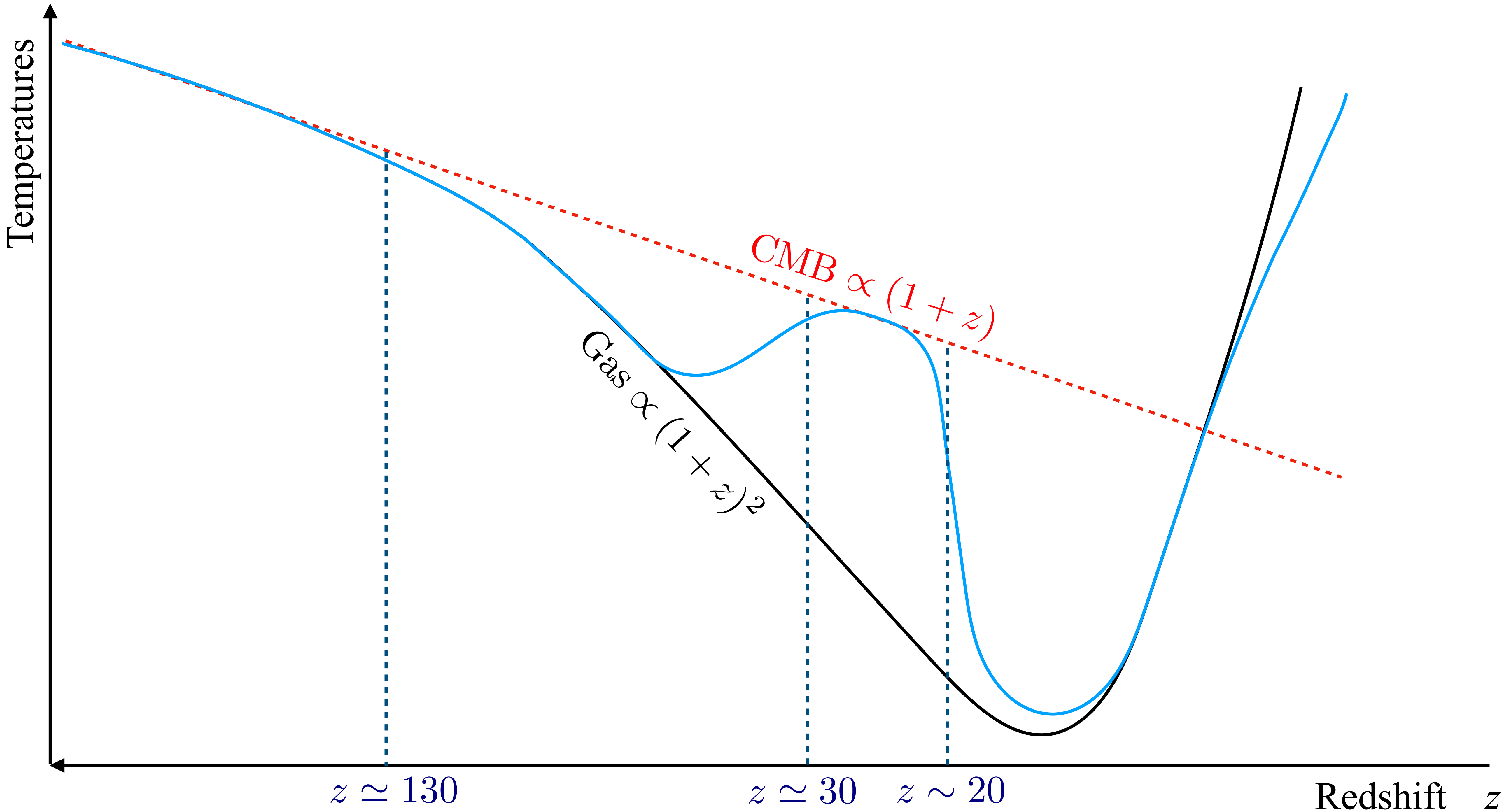
A short history of T_S

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



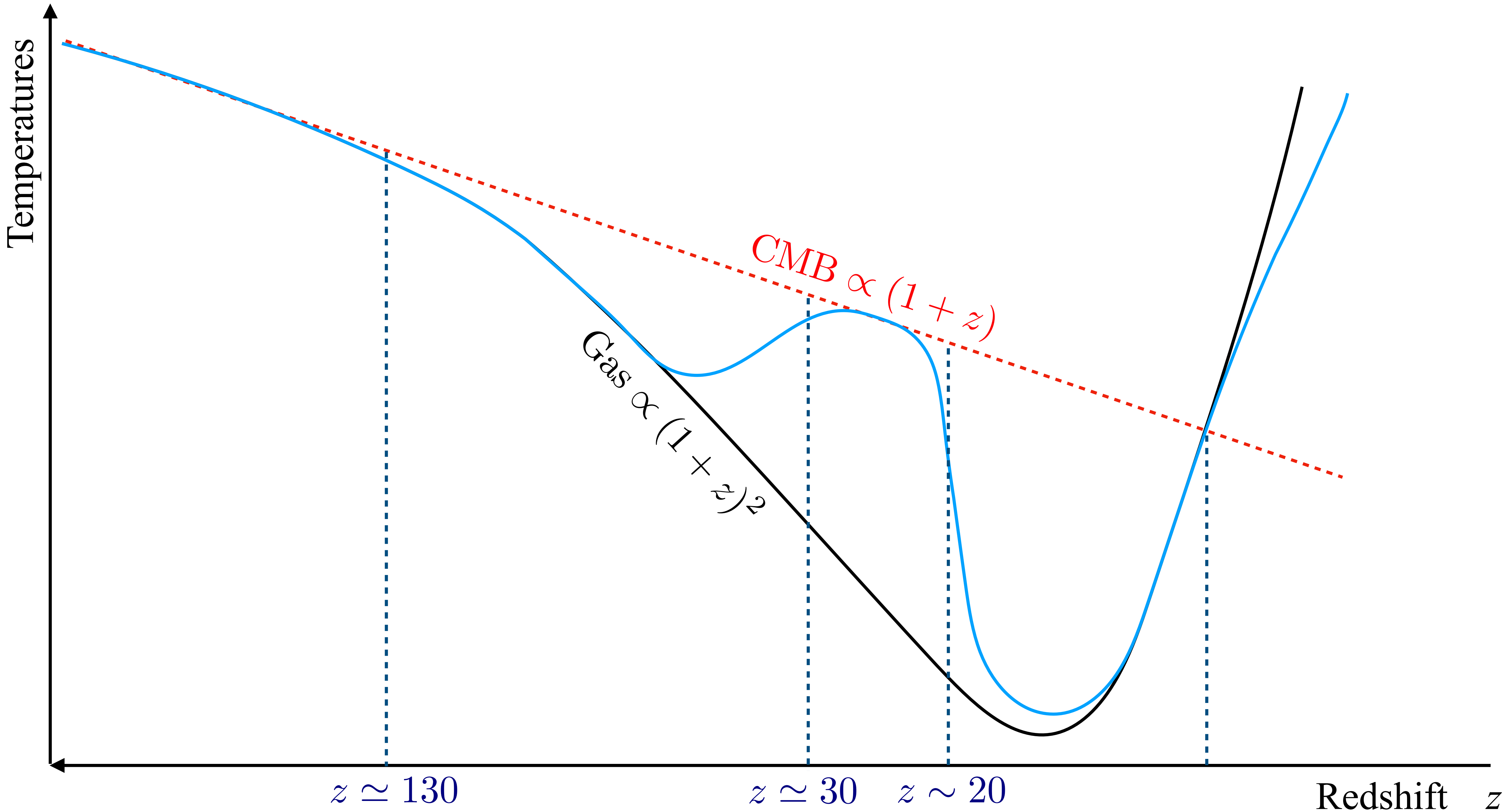
A short history of T_S

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



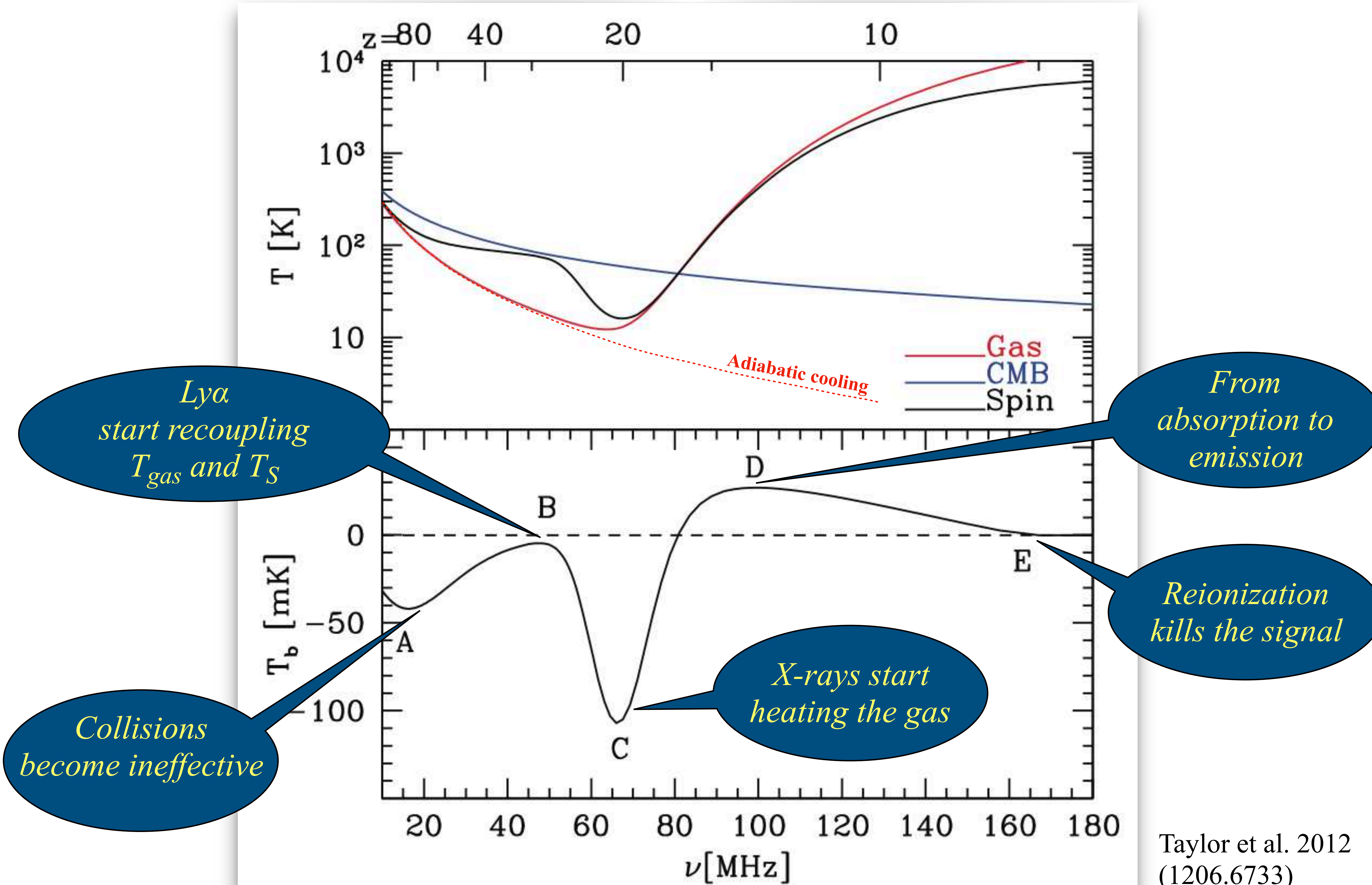
A short history of T_S

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



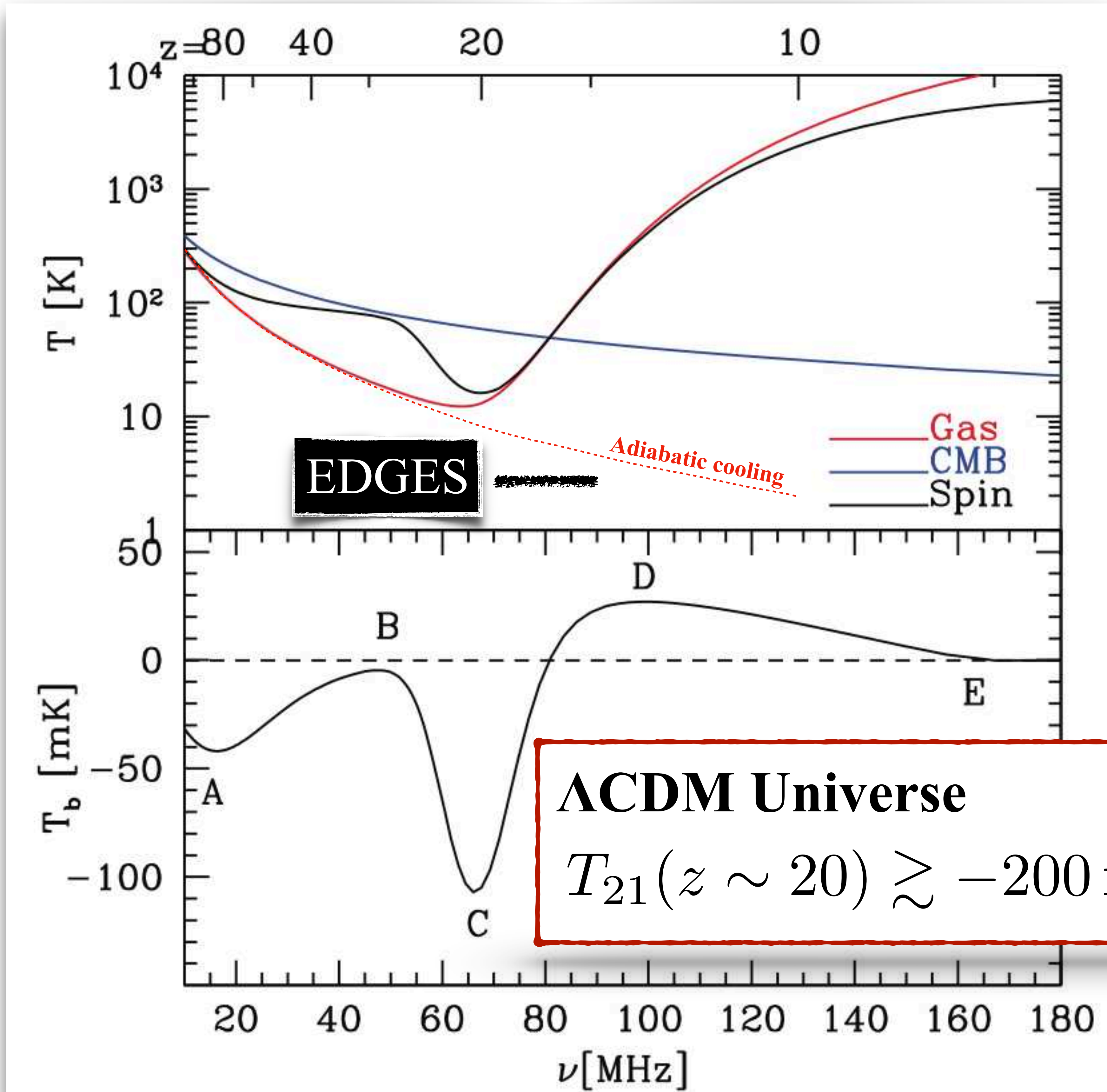
PAOLO PANCI
slide 13/30

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)

III PART

Implications for BSM

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**

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**

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 $z \sim 20$ (Pospelov, Pradler, Ruderman, Urbano)

1: Cool the IGM even more

1: Cool the IGM even more

➡ Another sector of particles in the early Universe to transfer the entropy
*The **Dark Matter** is **abundant** and very **cold***

1: Cool the IGM even more

- ➡ Another sector of particles in the early Universe to transfer the entropy
  *The **Dark Matter** is **abundant** and very **cold***

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

see e.g. Barkana et al.; Munoz, Loeb; ….

1: Cool the IGM even more

- Another sector of particles in the early Universe to transfer the entropy
  *The **Dark Matter** is **abundant** and very **cold***

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

see e.g. Barkana et al.; Munoz, Loeb; ….

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**

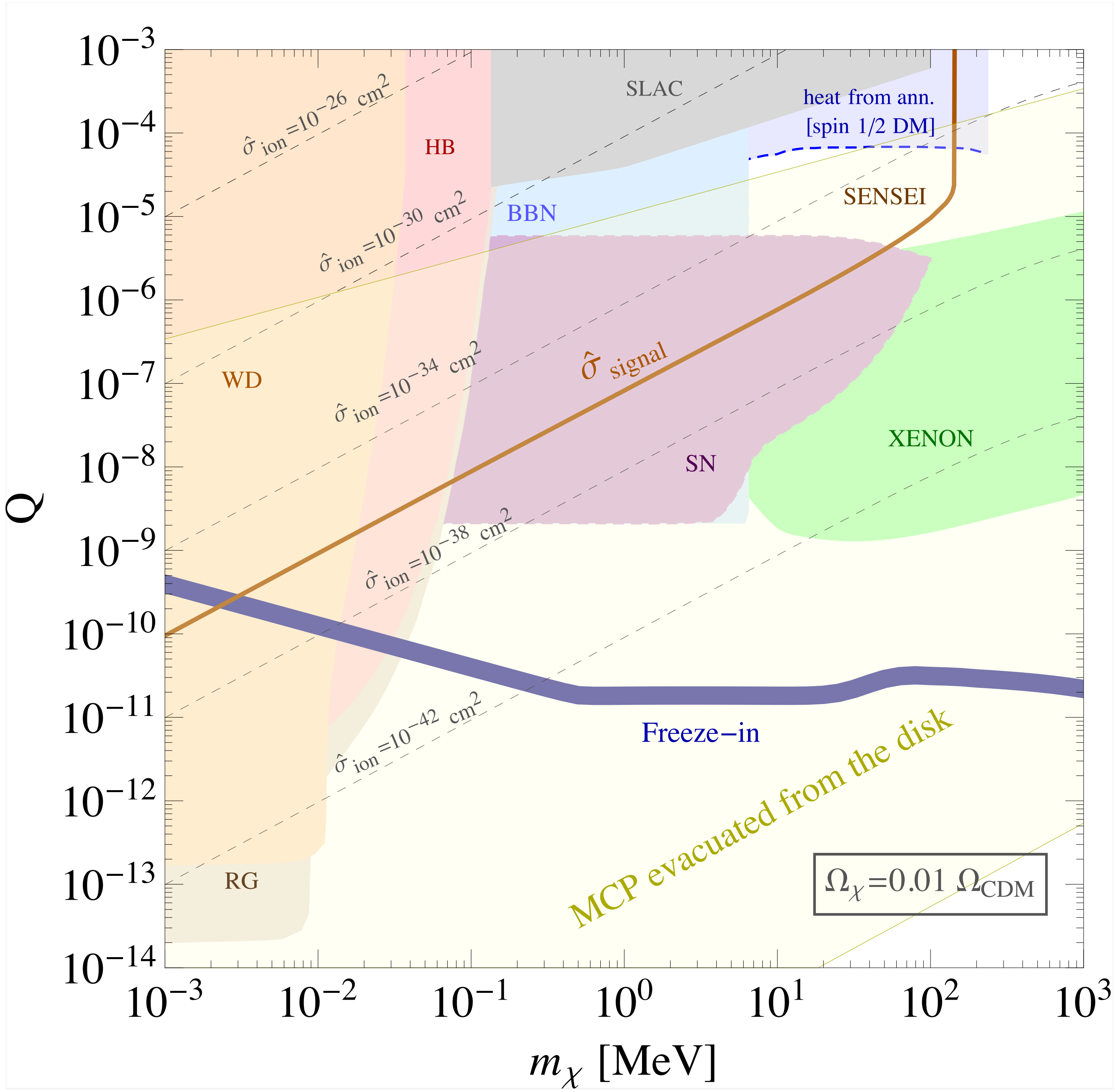
see e.g. Barkana et al.

PAOLO PANCI
slide 16/30

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



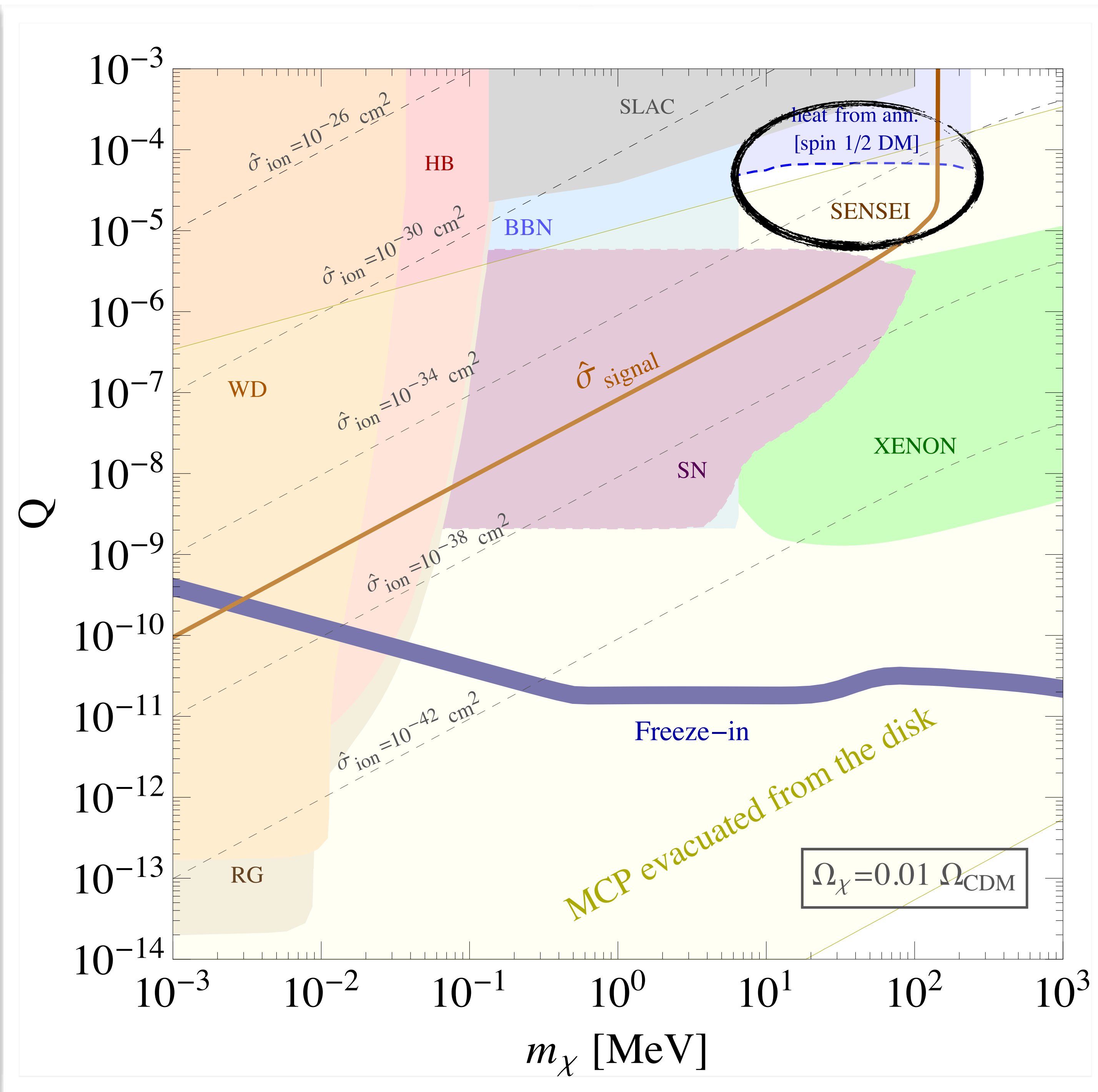
$$m_\chi \simeq (10 - 80)\ \mathrm{MeV}\ ,$$
$$Q \simeq (10^{-6} - 10^{-4})\ ,$$
$$f_{\mathrm{DM}} \simeq (0.1 - 2)\%$$

Barkana *et al.*
1803.03091

1: Cool the IGM even more

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

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



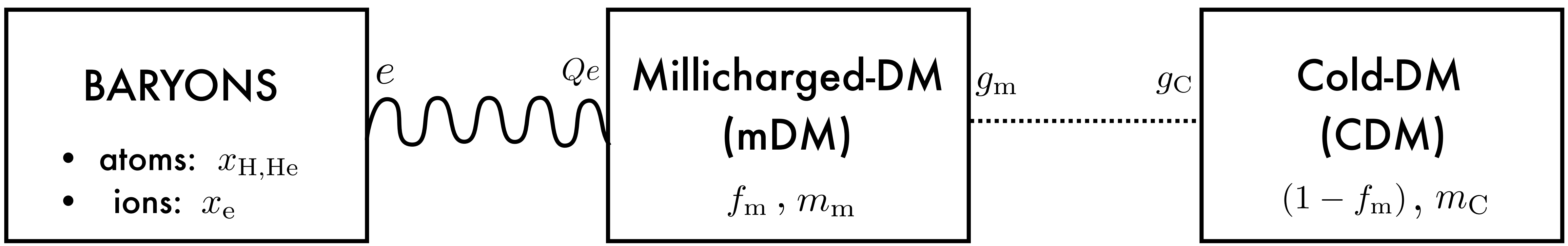
$$m_\chi \simeq (10 - 80)\ \text{MeV}\ ,$$
$$Q \simeq (10^{-6} - 10^{-4})\ ,$$
$$f_{\rm DM} \simeq (0.1 - 2)\%$$

Barkana *et al.*
1803.03091

1: Cool the IGM even more

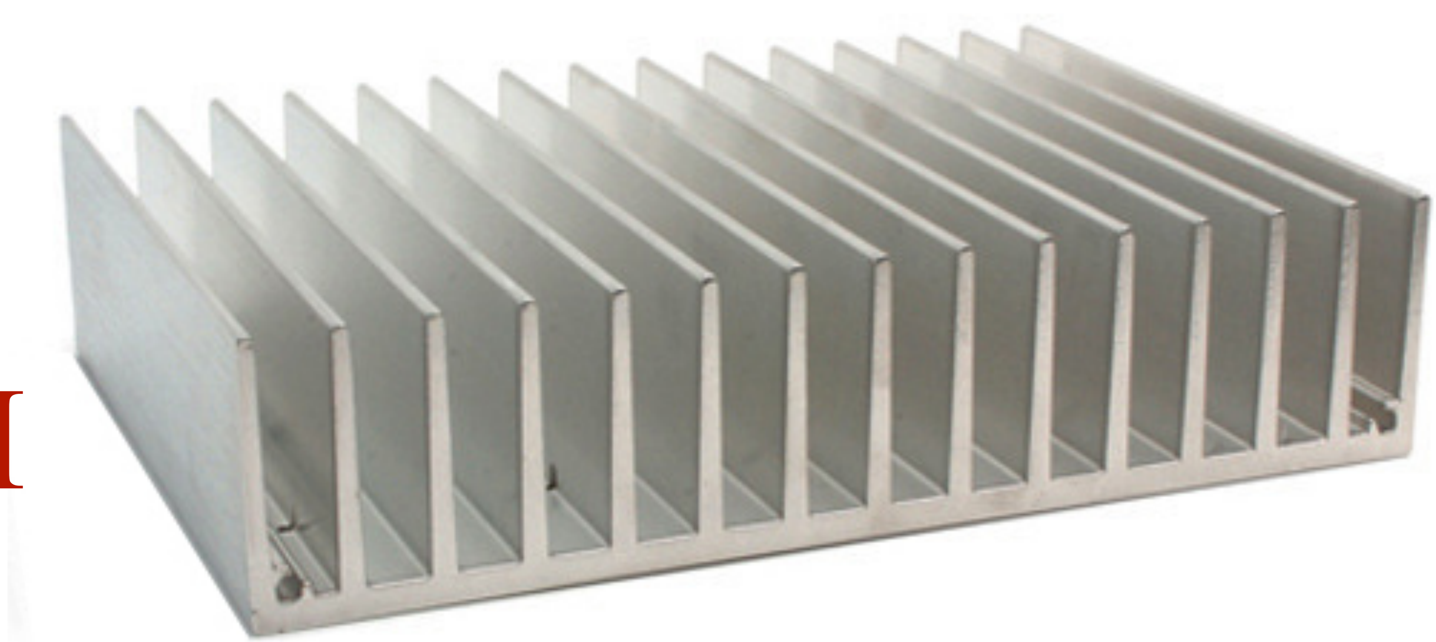
Reviving milliDM for 21-cm cosmology

see Liu, Outmezguine, Redigolo, Volansky, **(or Outmezguine's TALK)**



CDM & mDM have a
<u>new long-range dark force</u>

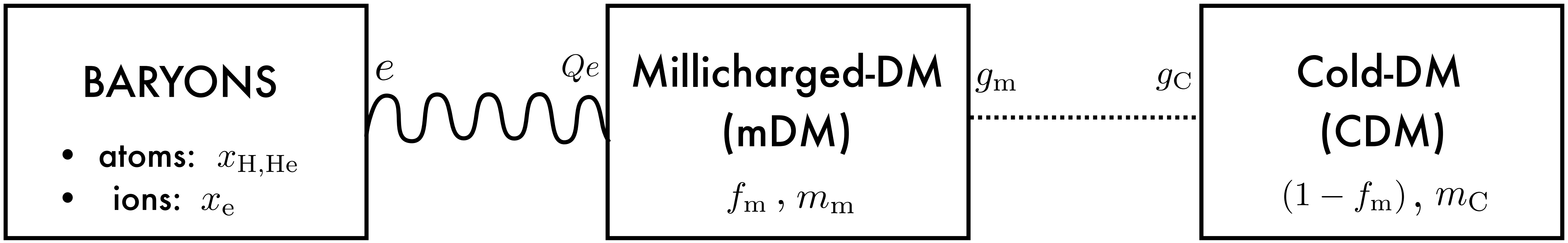
CDM acts as a
heat sink for **mDM**

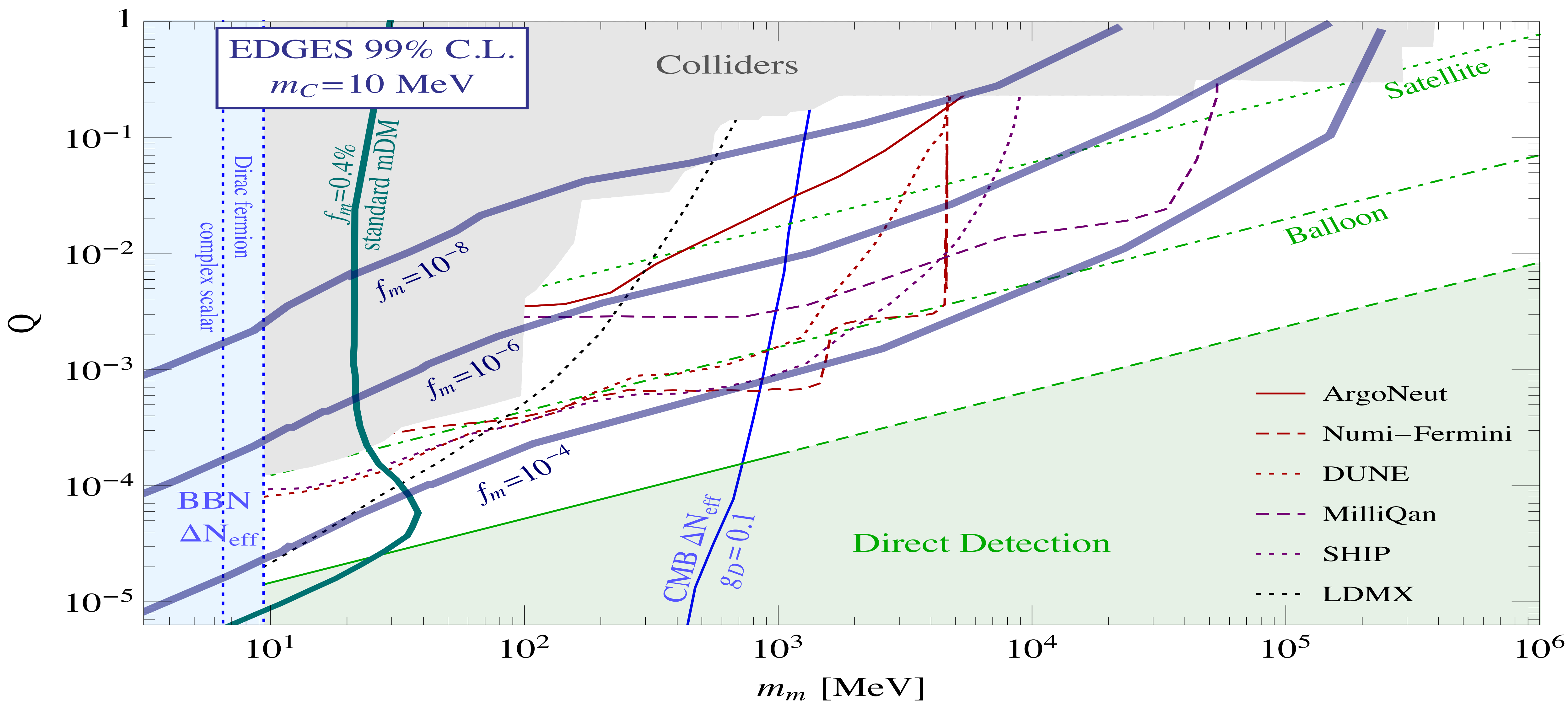


1: Cool the IGM even more

Reviving milliDM for 21-cm cosmology

see Liu, Outmezguine, Redigolo, Volansky, **(or Outmezguine's TALK)**

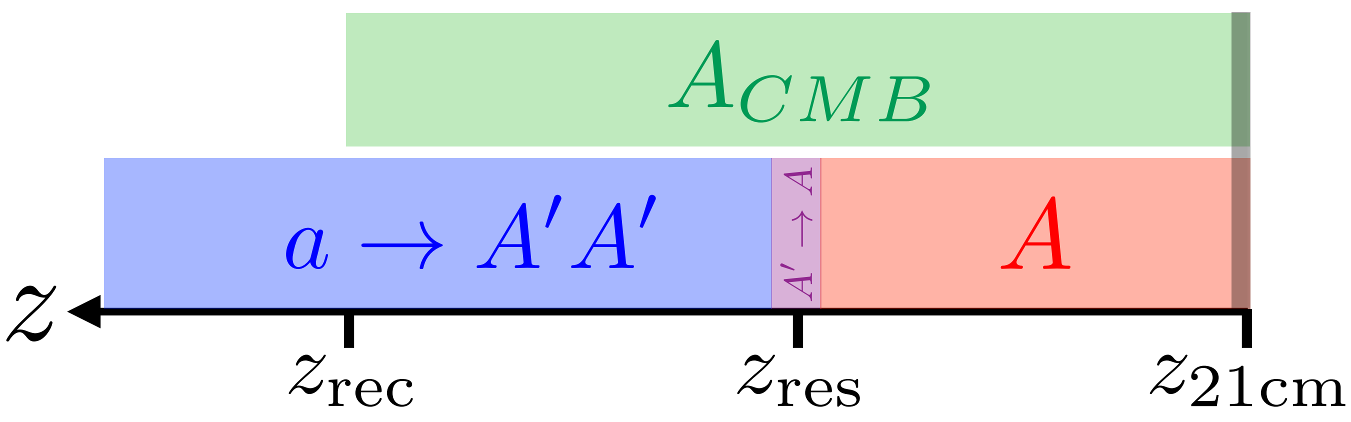


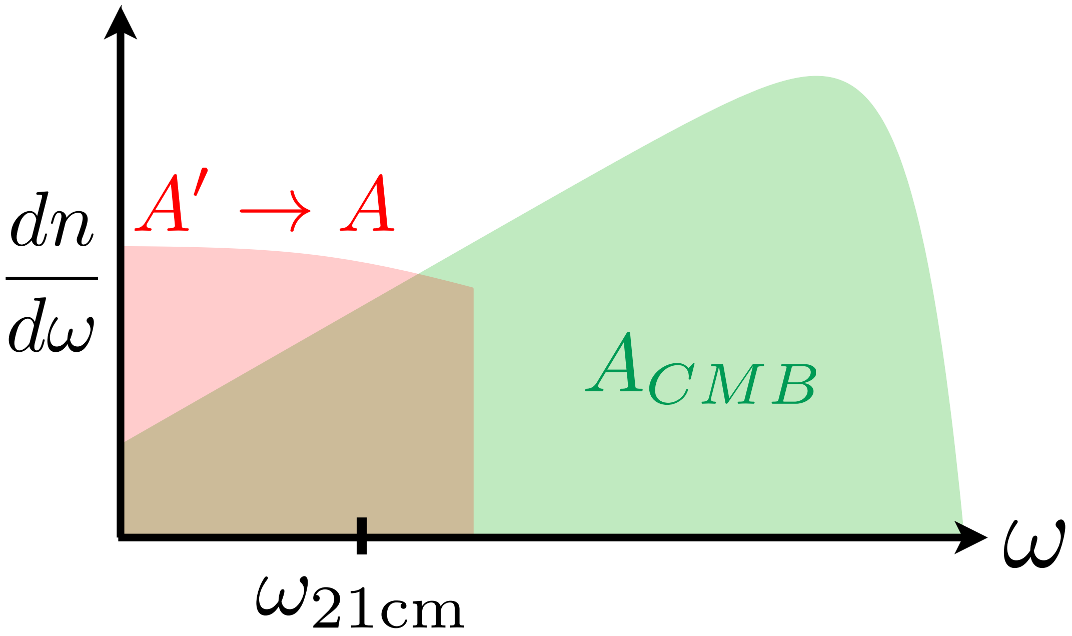


2: Increase the CMB RJ tail

What DM model can do that?

see Pospelov, Pradler, Ruderman, Urbano

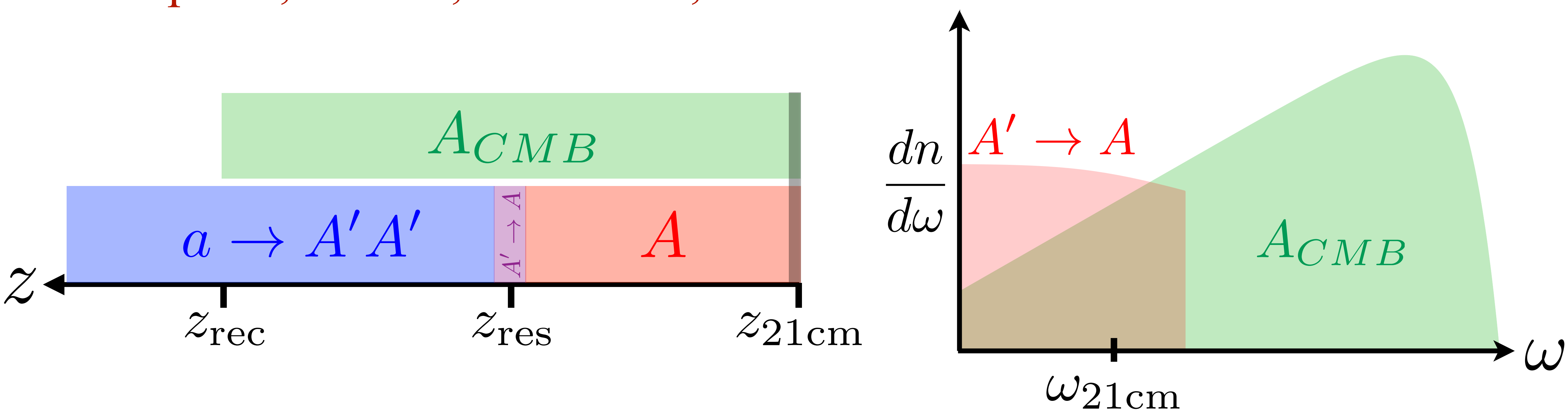




2: Increase the CMB RJ tail

What DM model can do that?

see Pospelov, Pradler, Ruderman, Urbano

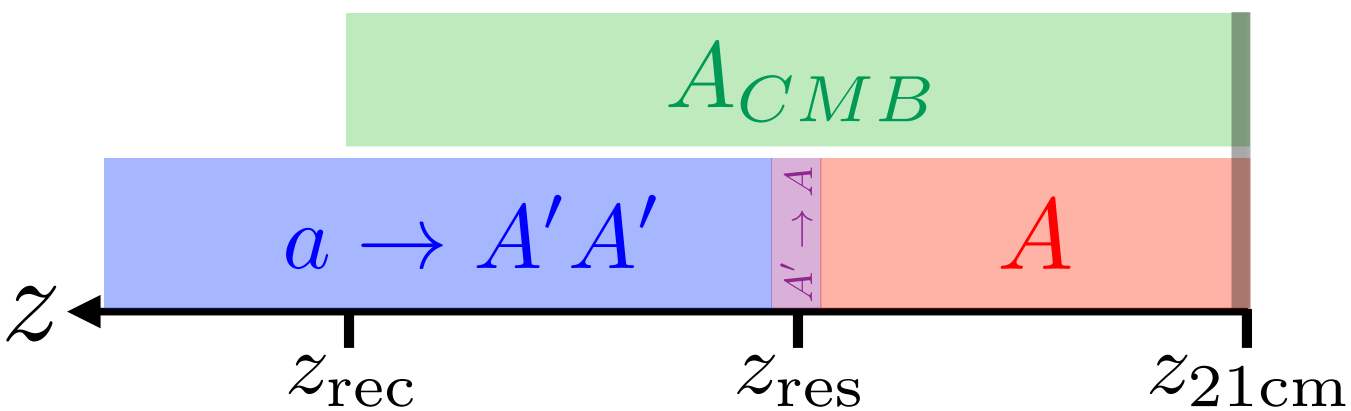


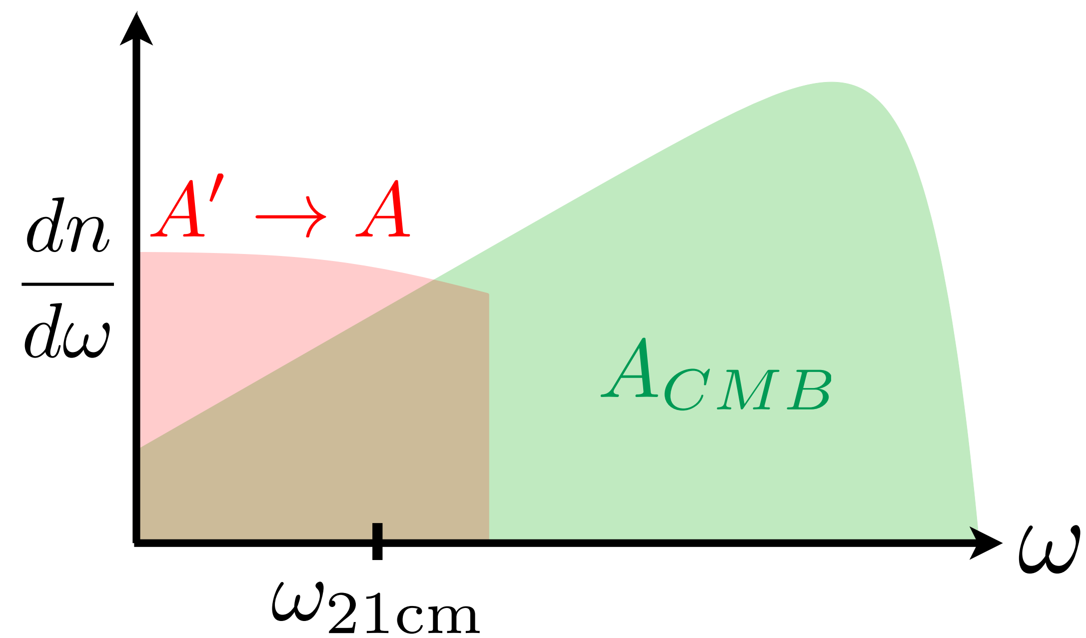
Early ($z > 20$) decays (either DM or of DR species) create a non-thermal ***population of DR dark photon A'***. Typical multiplicity is larger than $n_{\rm RJ}$

2: Increase the CMB RJ tail

What DM model can do that?

see Pospelov, Pradler, Ruderman, Urbano





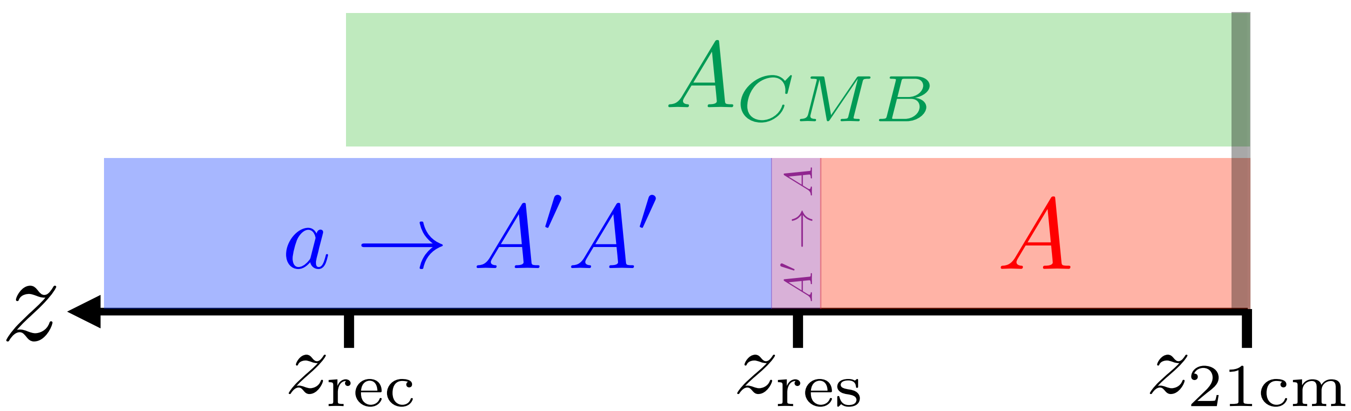
Early ($z > 20$) decays (either DM or of DR species) create a non-thermal ***population of DR dark photon A'***. Typical multiplicity is larger than $n_{\rm RJ}$

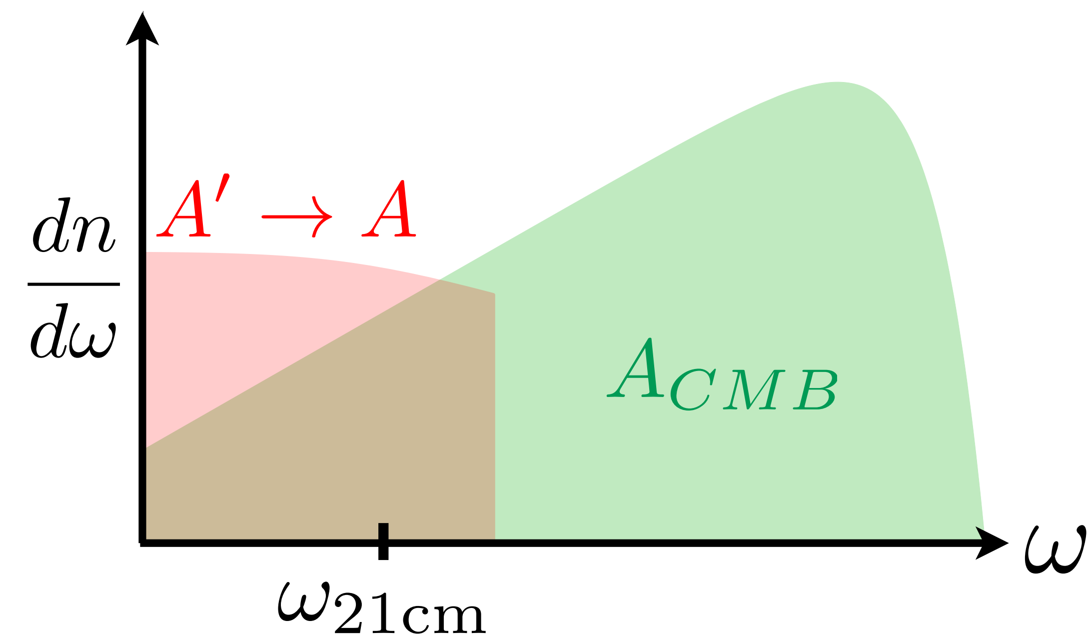
Dark photons can oscillate to normal photons. At some redshift $z_{\rm res}$ a resonant ***oscillation of A' into A.*** This happen when the plasma frequency is $m_{A'}$

2: Increase the CMB RJ tail

What DM model can do that?

see Pospelov, Pradler, Ruderman, Urbano





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 $n_{\rm RJ}$

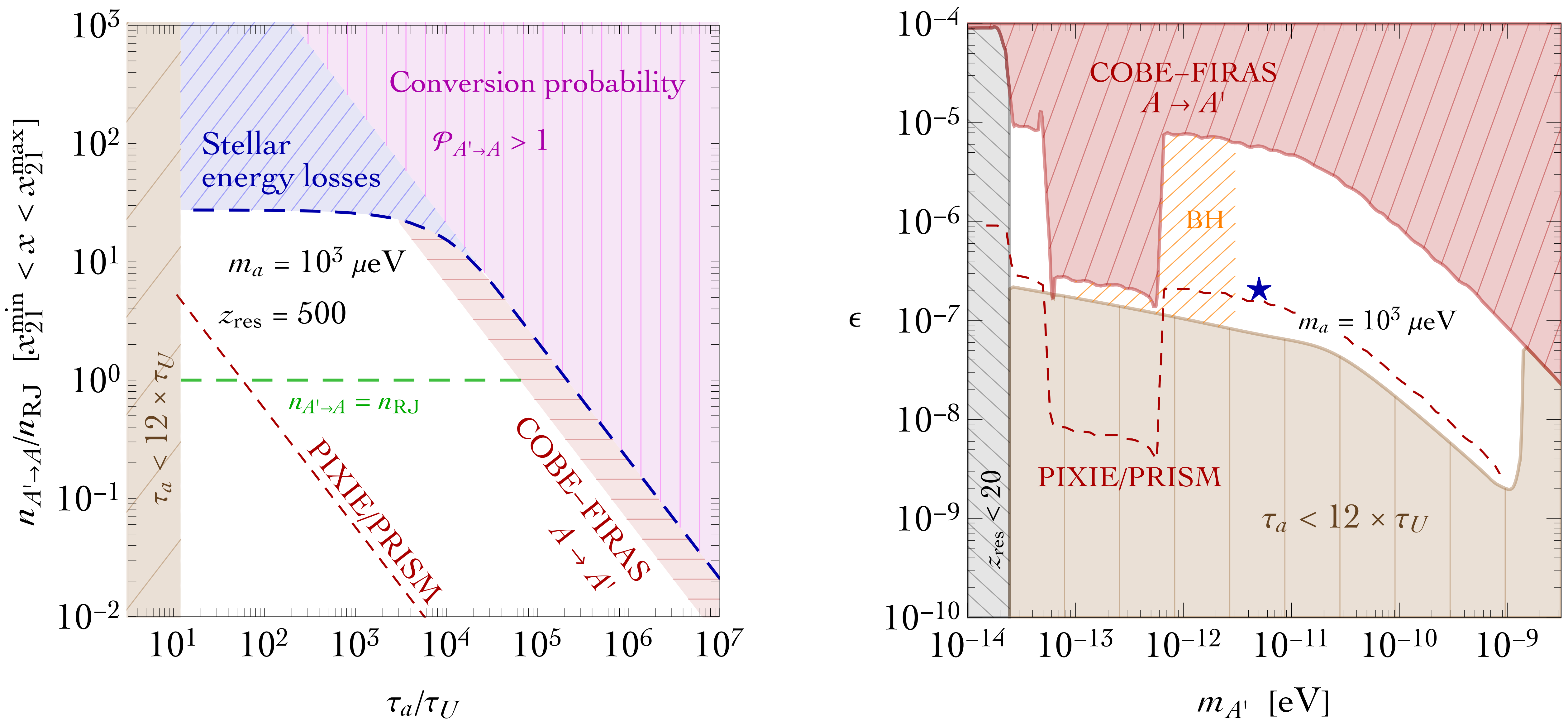
Dark photons can oscillate to normal photons. At some redshift $z_{\rm res}$ a resonant ***oscillation of A' into A.*** This happen when the plasma frequency is $m_{A'}$

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

2: Increase the CMB RJ tail

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

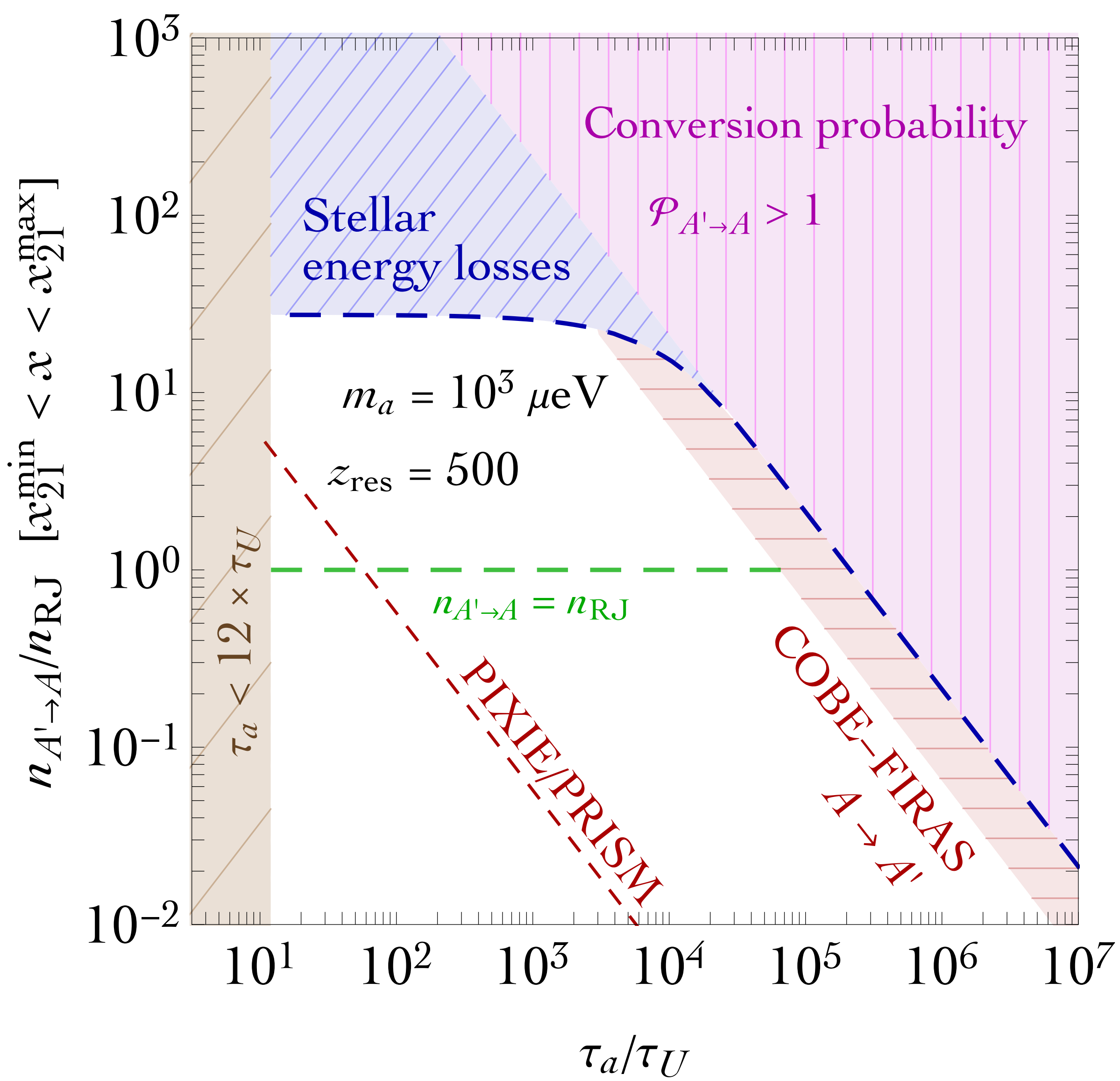
Implication: considerable room for the modification of the CMB RJ tail
The model can be probed by the proposed PIXIE/PRISM experiments

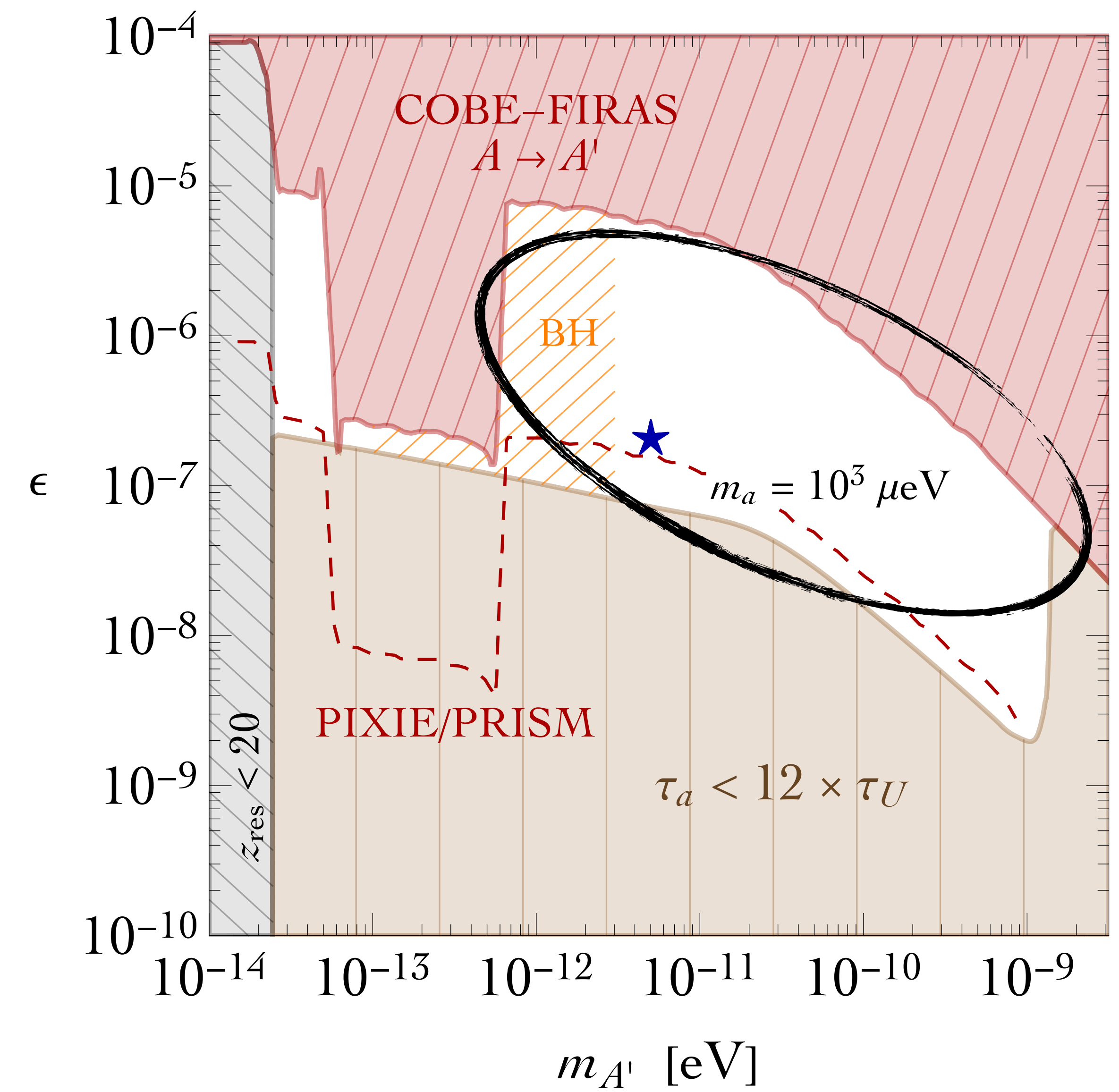


2: Increase the CMB RJ tail

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





Other implications for BSM

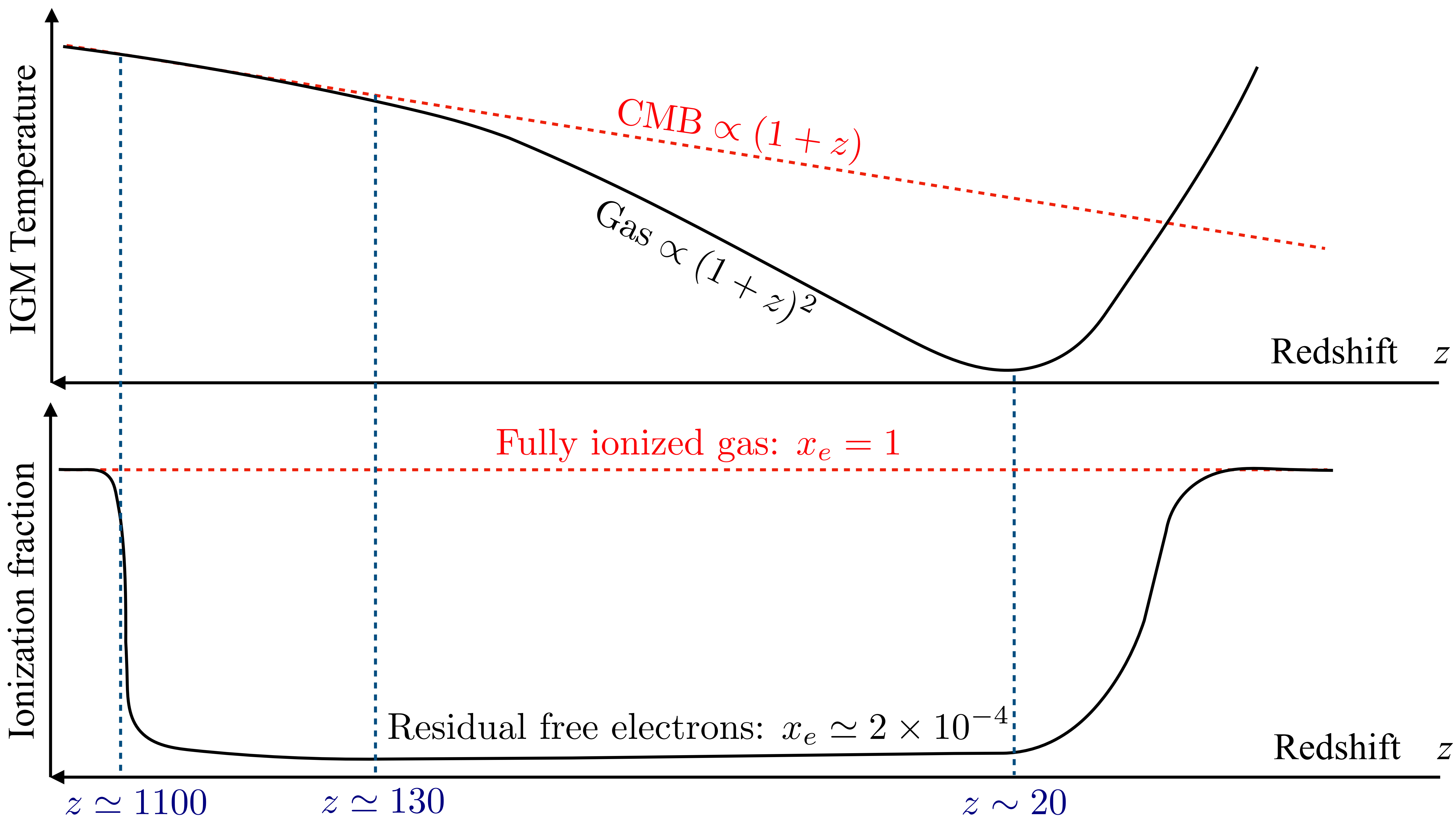
The inferred spin temperature by EDGES is very small:
great opportunity to set limits on the properties of any ***extra source of heating***

DM annihilations limits

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

Where does DM Ann. enter?

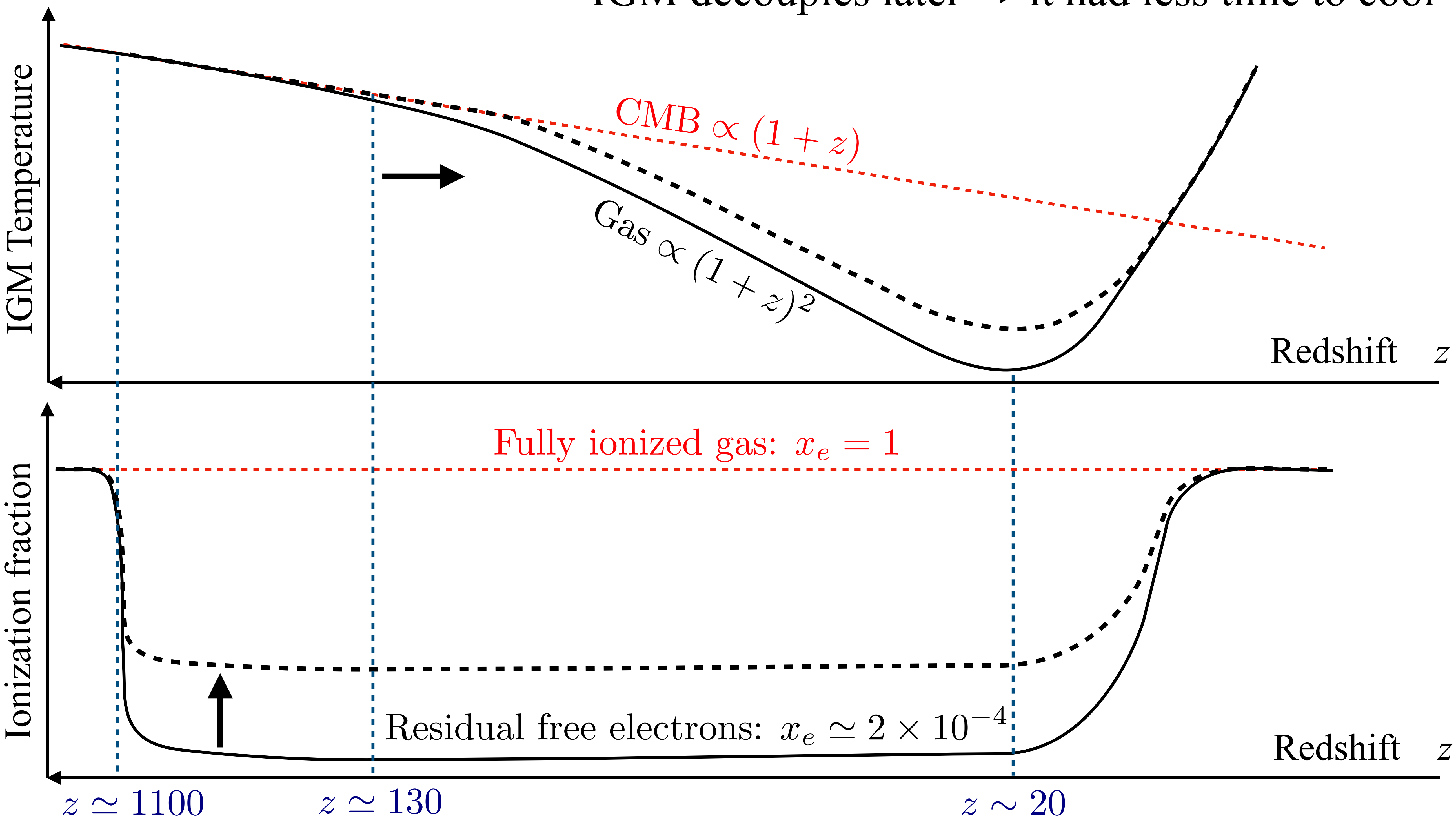
DM can (and will if thermal) annihilate into SM.
Will heat the IGM in 2 ways:



Where does DM Ann. enter?

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

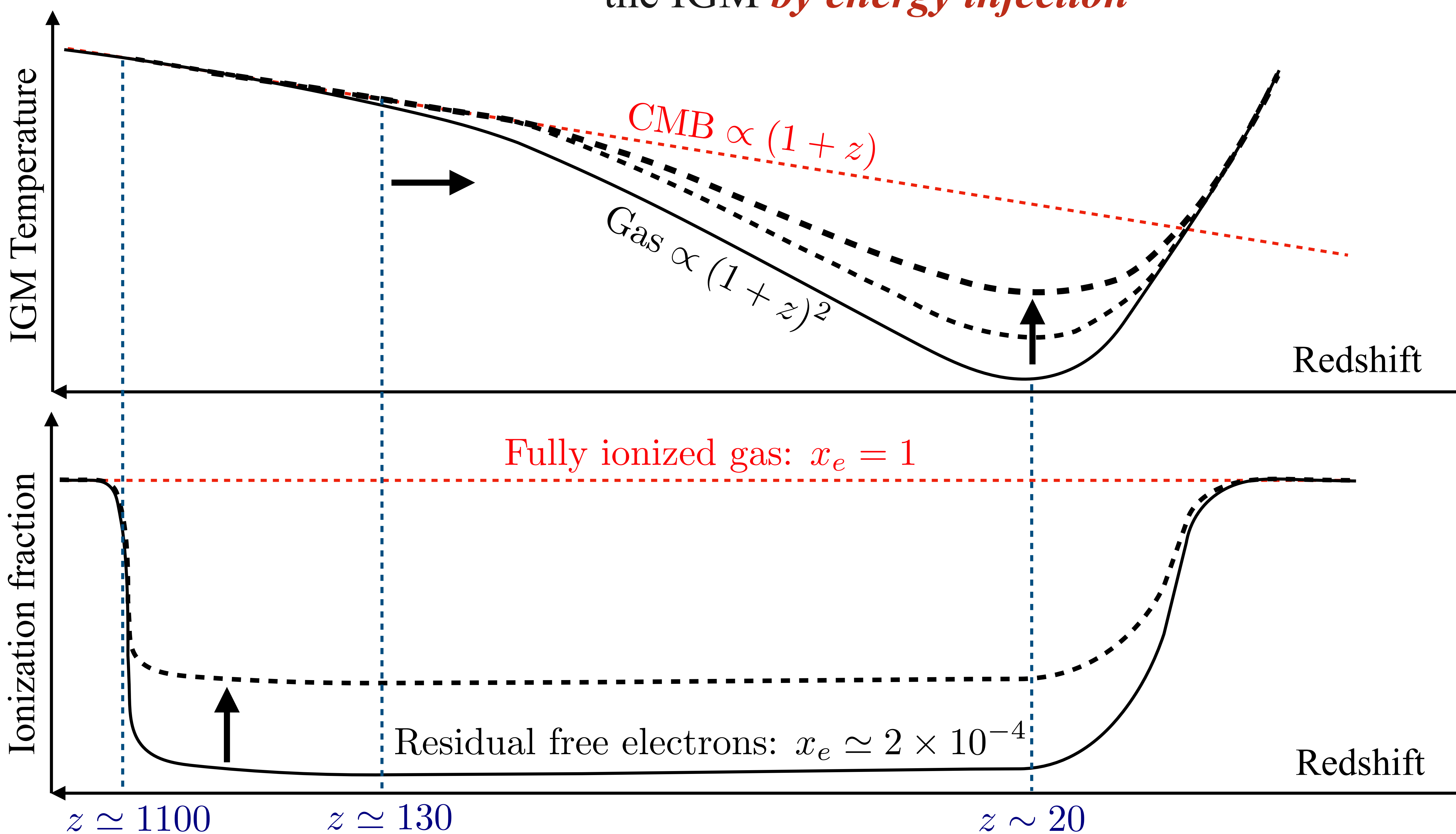
Will heat the IGM in 2 ways: ➡ Annihilations ***increase ionization fraction***
IGM decouples later ⇒ it had less time to cool



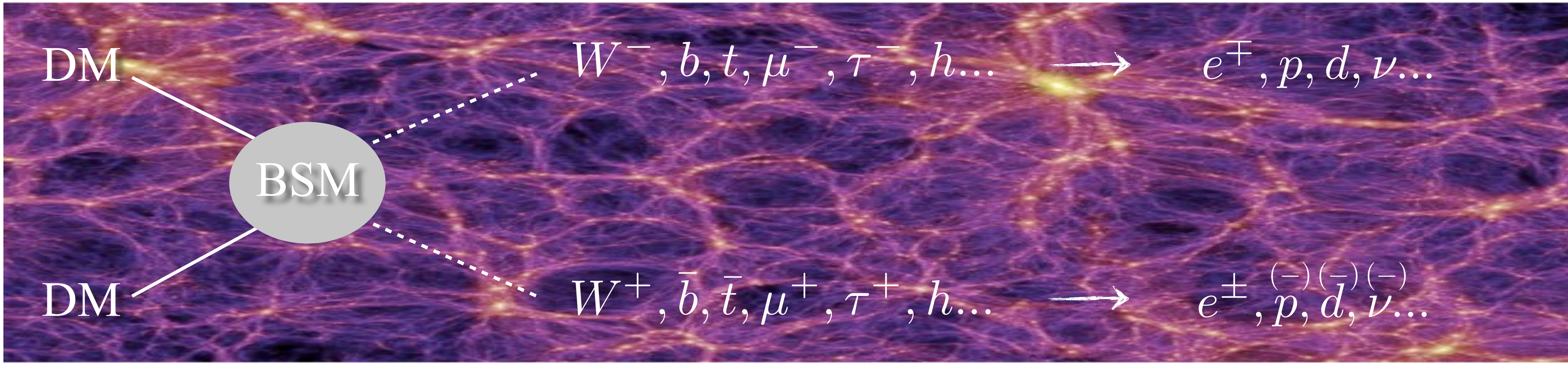
Where does DM Ann. enter?

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

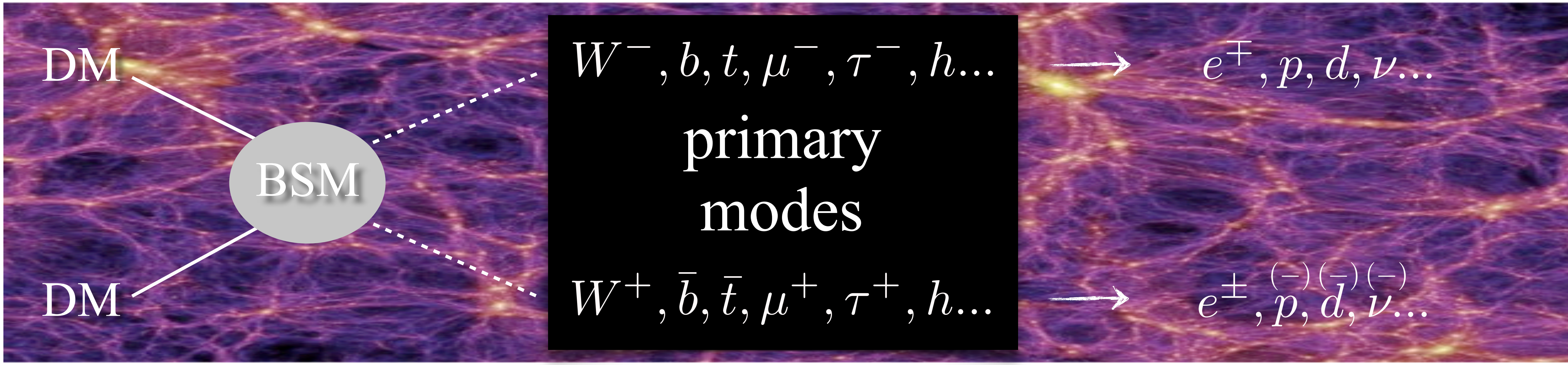
Will heat the IGM in 2 ways: ➡ More importantly, annihilations directly heat the IGM ***by energy injection***



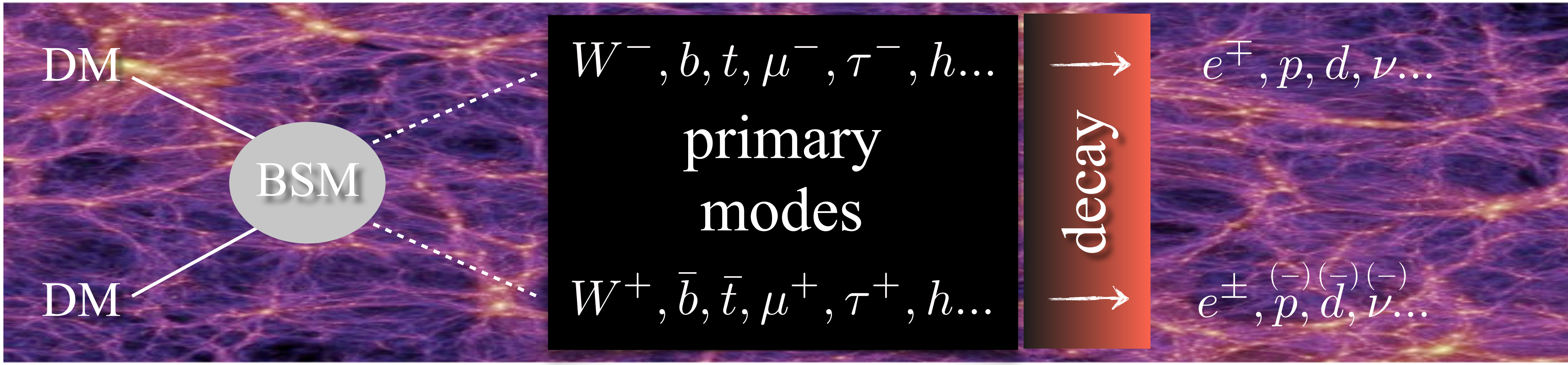
DM Annihilation: Basics



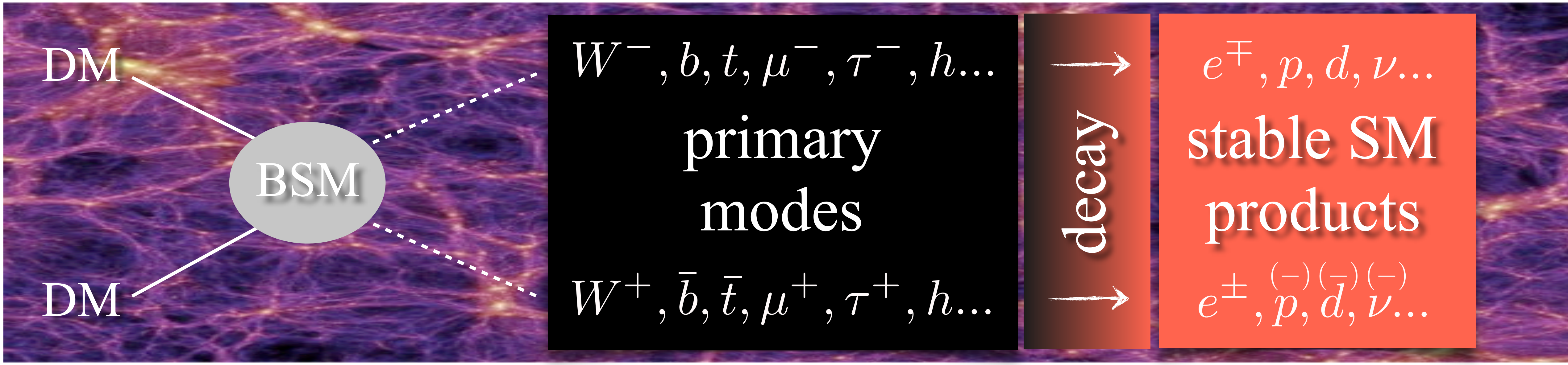
DM Annihilation: Basics

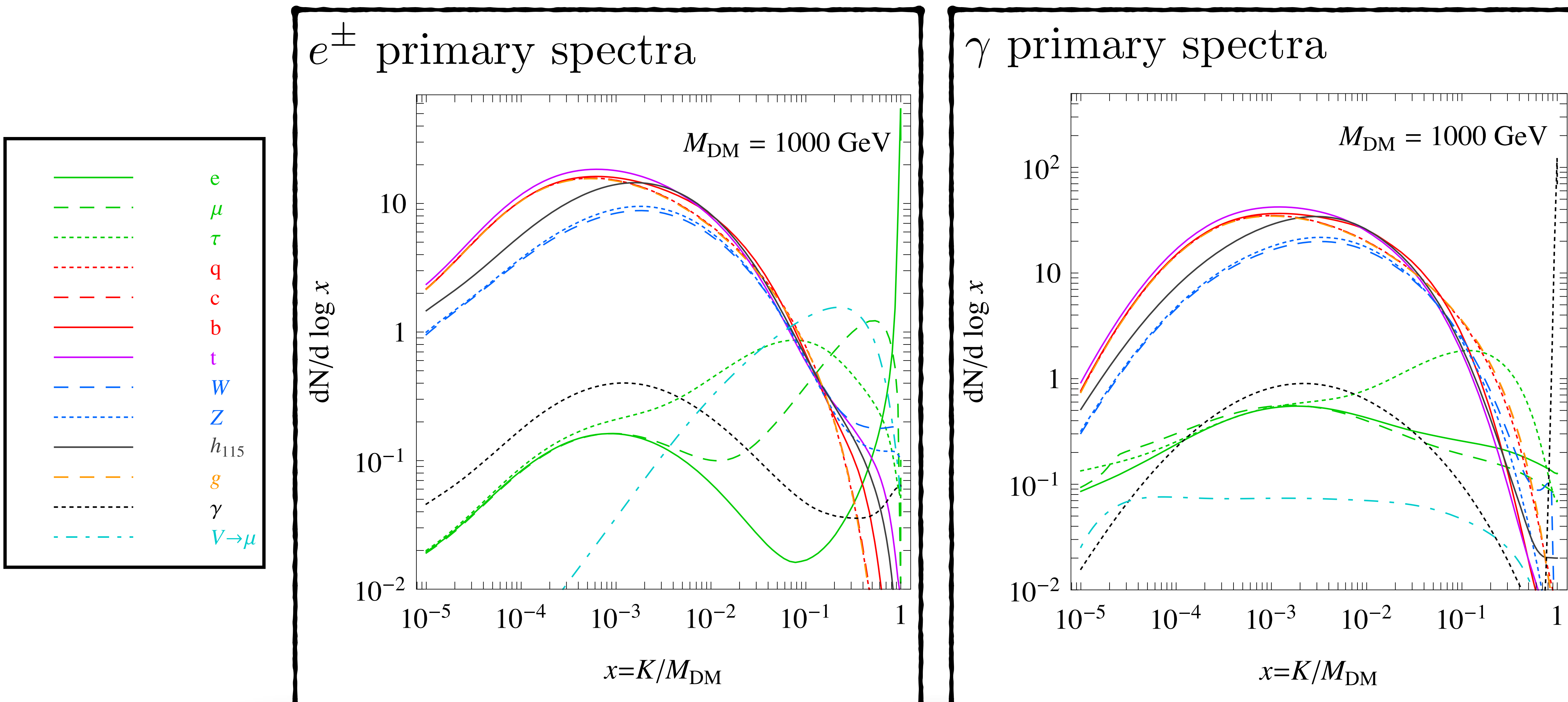


DM Annihilation: Basics



DM Annihilation: Basics





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:

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

Energy injection

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

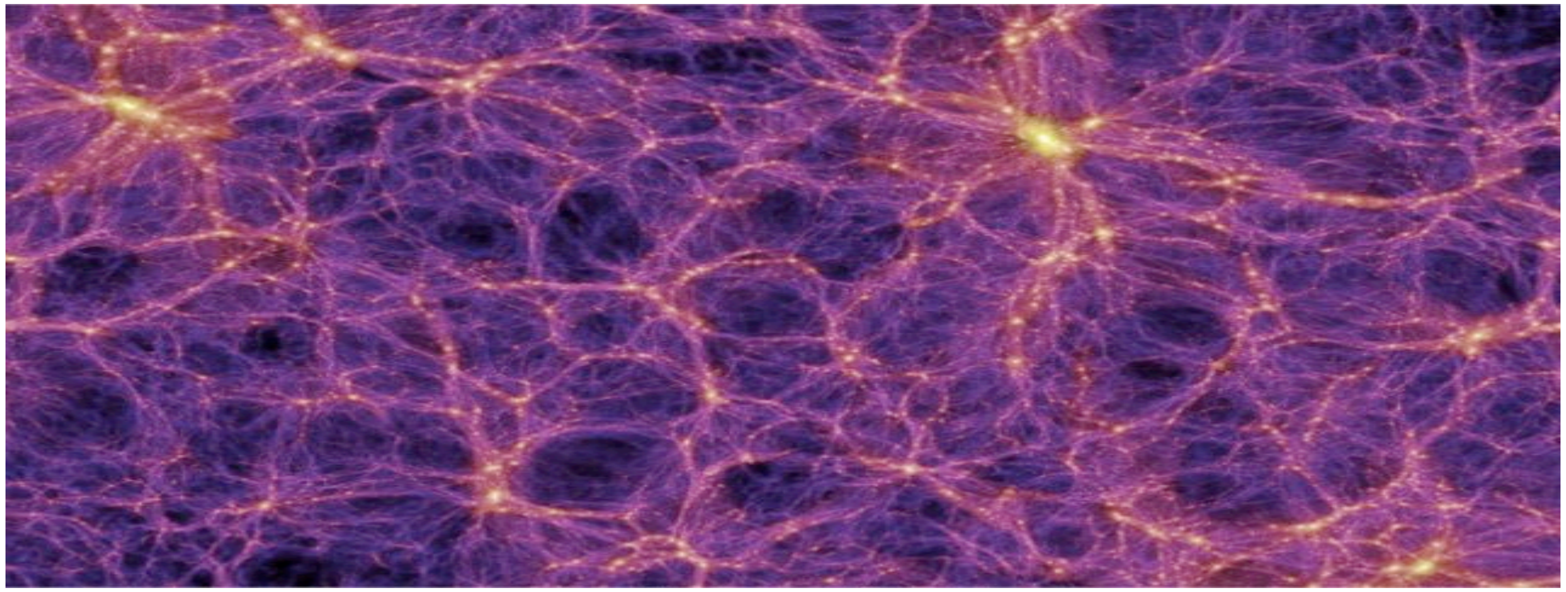
$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}V\,\mathrm{d}E_f\,\mathrm{d}t} = \langle\rho^2_{\mathrm{DM}}\rangle \frac{\langle\sigma v\rangle}{M^2_{\mathrm{DM}}} \frac{\mathrm{d}N}{\mathrm{d}E_f}$$

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

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

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:

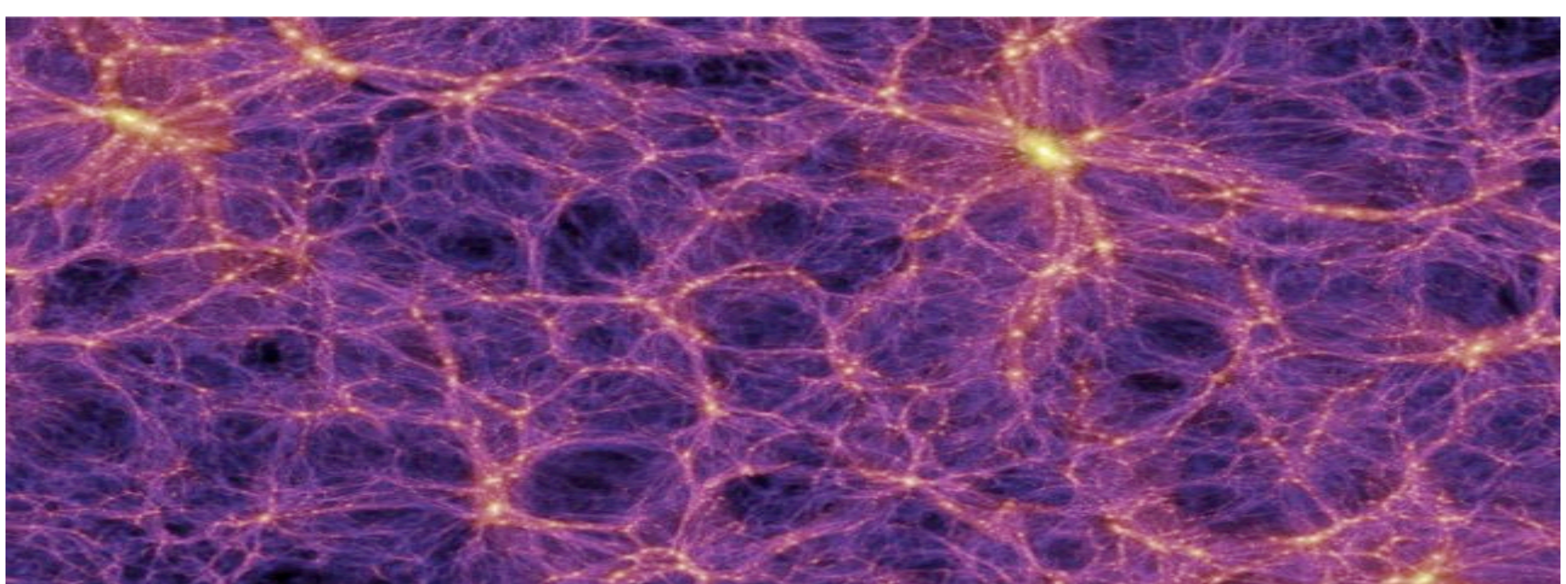
$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}V\,\mathrm{d}E_f\,\mathrm{d}t} = \langle\rho^2_{\rm DM}\rangle\frac{\langle\sigma v\rangle}{M^2_{\rm DM}}\frac{\mathrm{d}N}{\mathrm{d}E_f}$$

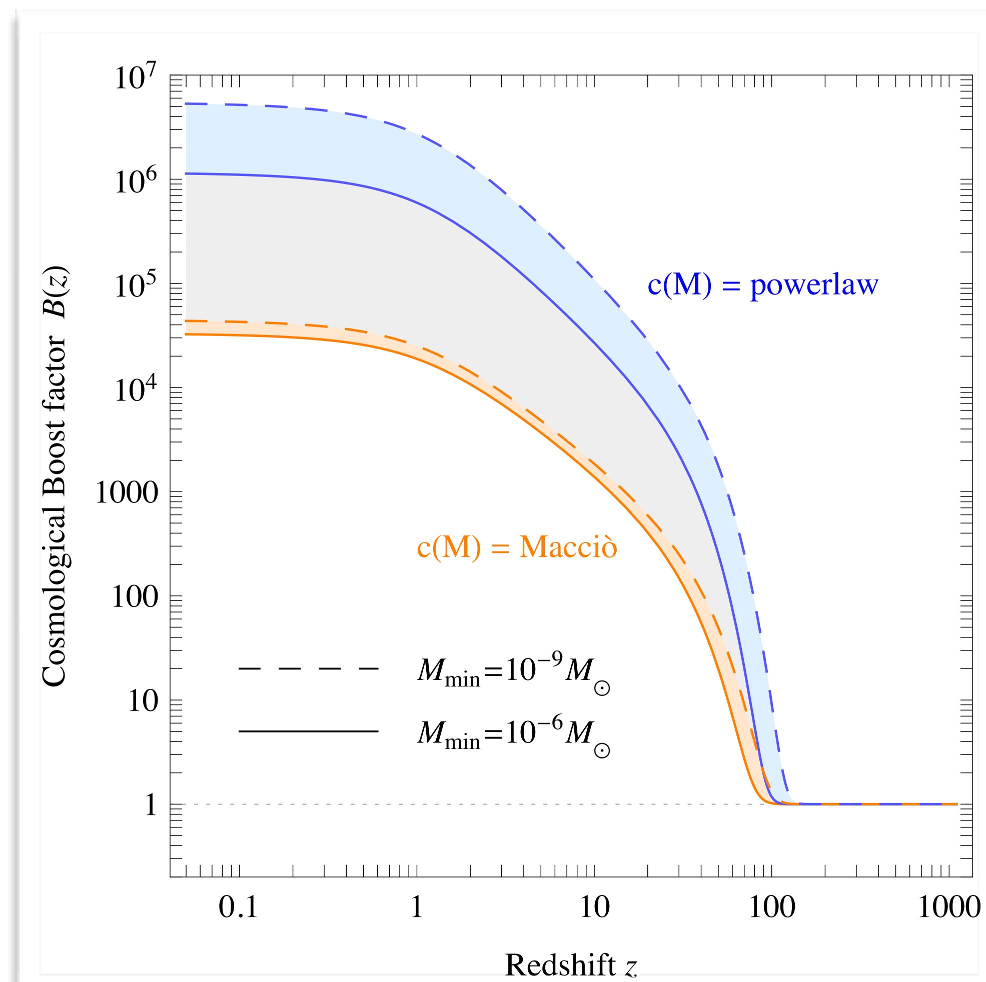
Total Energy injected into the IGM per (dV and dt) at a given z:

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

Boosted Annihilation due to structure formation:

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





Energy deposition

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

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

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

INSTANTANEOUS DEPOSITION: only valid at high redshift

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

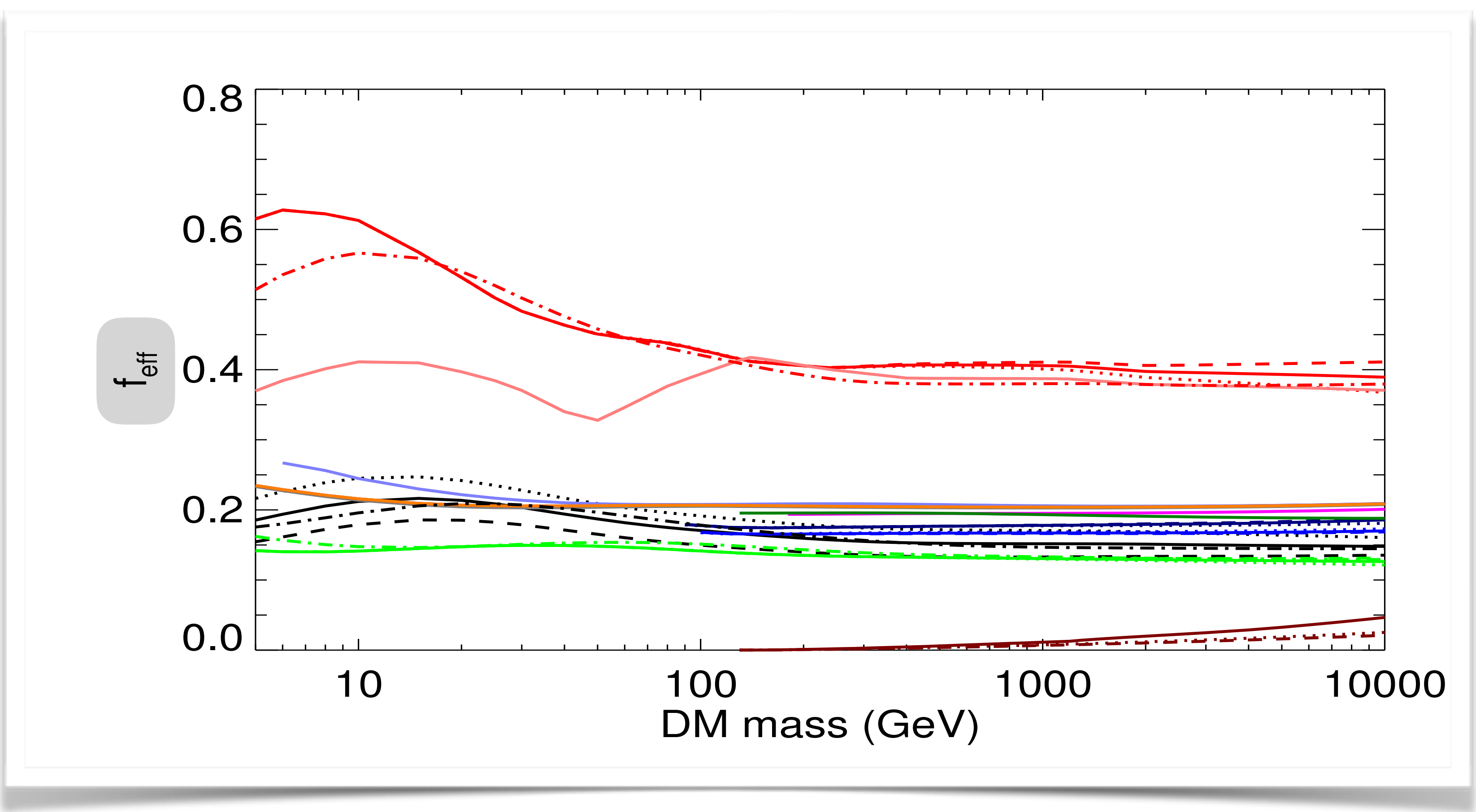
Energy deposition

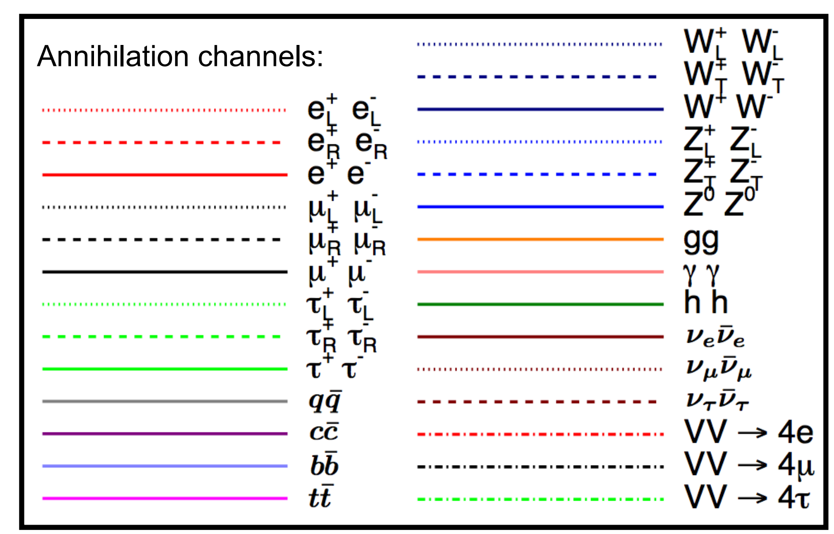
Energy deposited into the IGM in ***3 main channels***:

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

INSTANTANEOUS DEPOSITION: only valid at high redshift

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





Slatyer
1506.03811,
1506.03812

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

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**:

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

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

Evolution of the **gas Temperature**:

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

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**

How do we put bounds?

How do we put bounds?

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

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**

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….

How do we put bounds?

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

- Annihilation increases $T_{\rm gas}$: **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….

- **Our strategy**:
  - Assume standard evolution
  - Conservative scenario: Adiabatic cooling & efficient Lα-pumping
  - **Strongest absorption**: $T_S^{z=17} \sim T_{\rm gas}^{\rm ad} = 6.5\ \mathrm{K} \implies T_{21}^{z=17} \simeq -200\ \mathrm{mK}$

How do we put bounds?

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

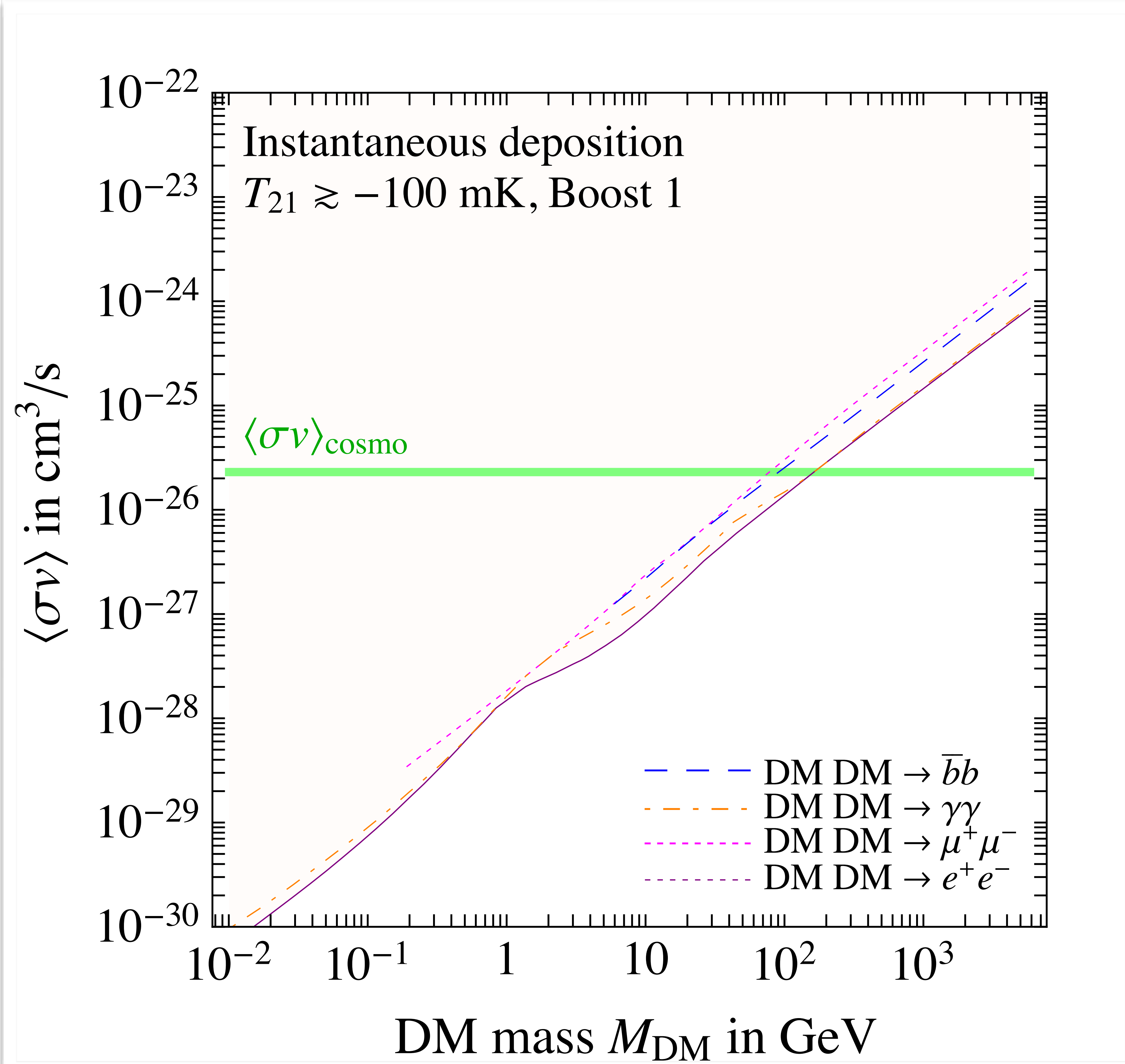
- Annihilation increases T_{gas}: **tends to erase the 21-cm signal**

- Hence, we can infer bounds. But we cannot use the observed signal: already the SM is out at 3.8σ….

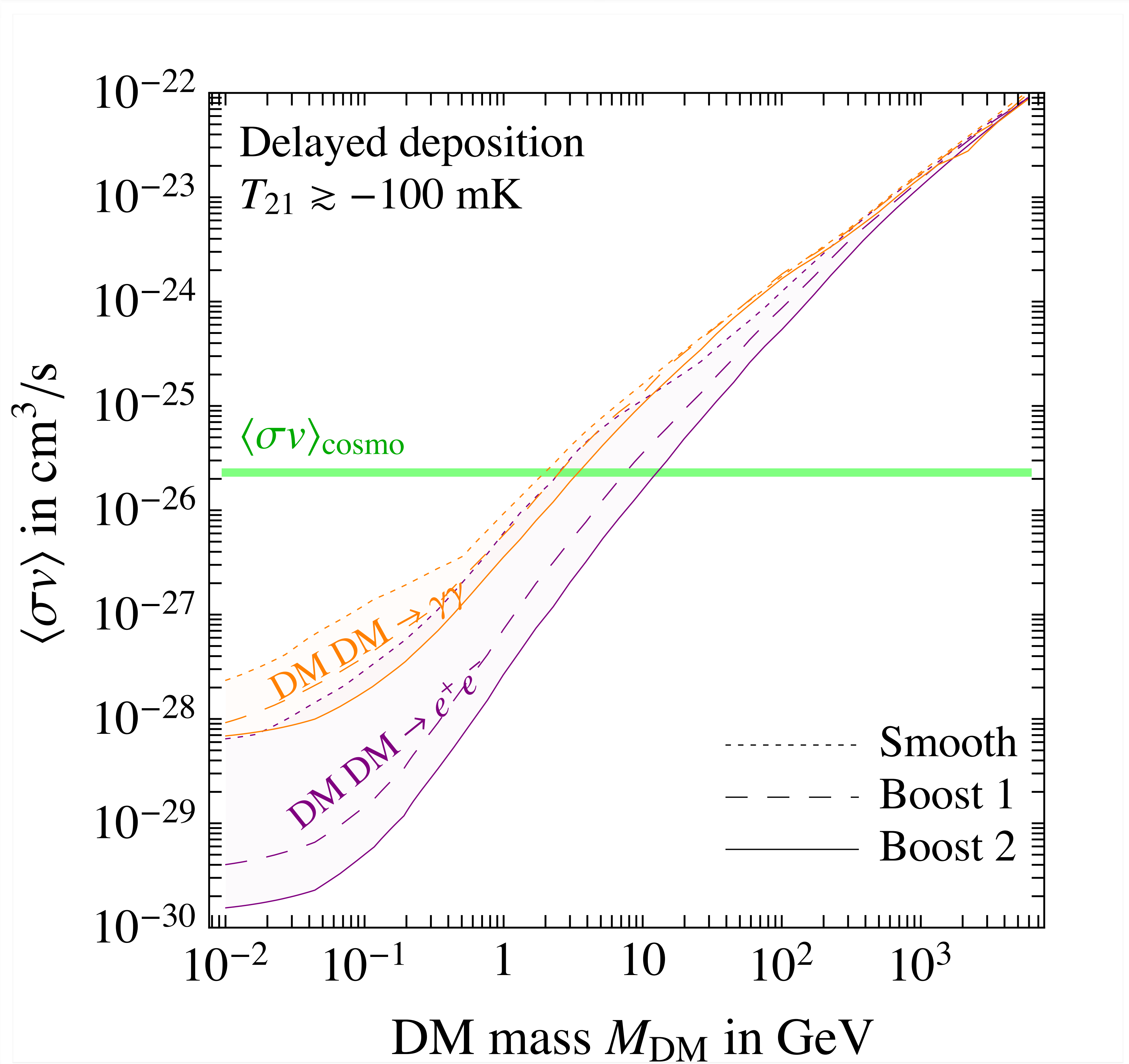
- **Our strategy**:
  - Assume standard evolution
  - Conservative scenario: Adiabatic cooling & efficient Lα-pumping
  - **Strongest absorption**: $T_S^{z=17} \sim T_{\text{gas}}^{\text{ad}} = 6.5\ \text{K} \implies T_{21}^{z=17} \simeq -200\ \text{mK}$

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

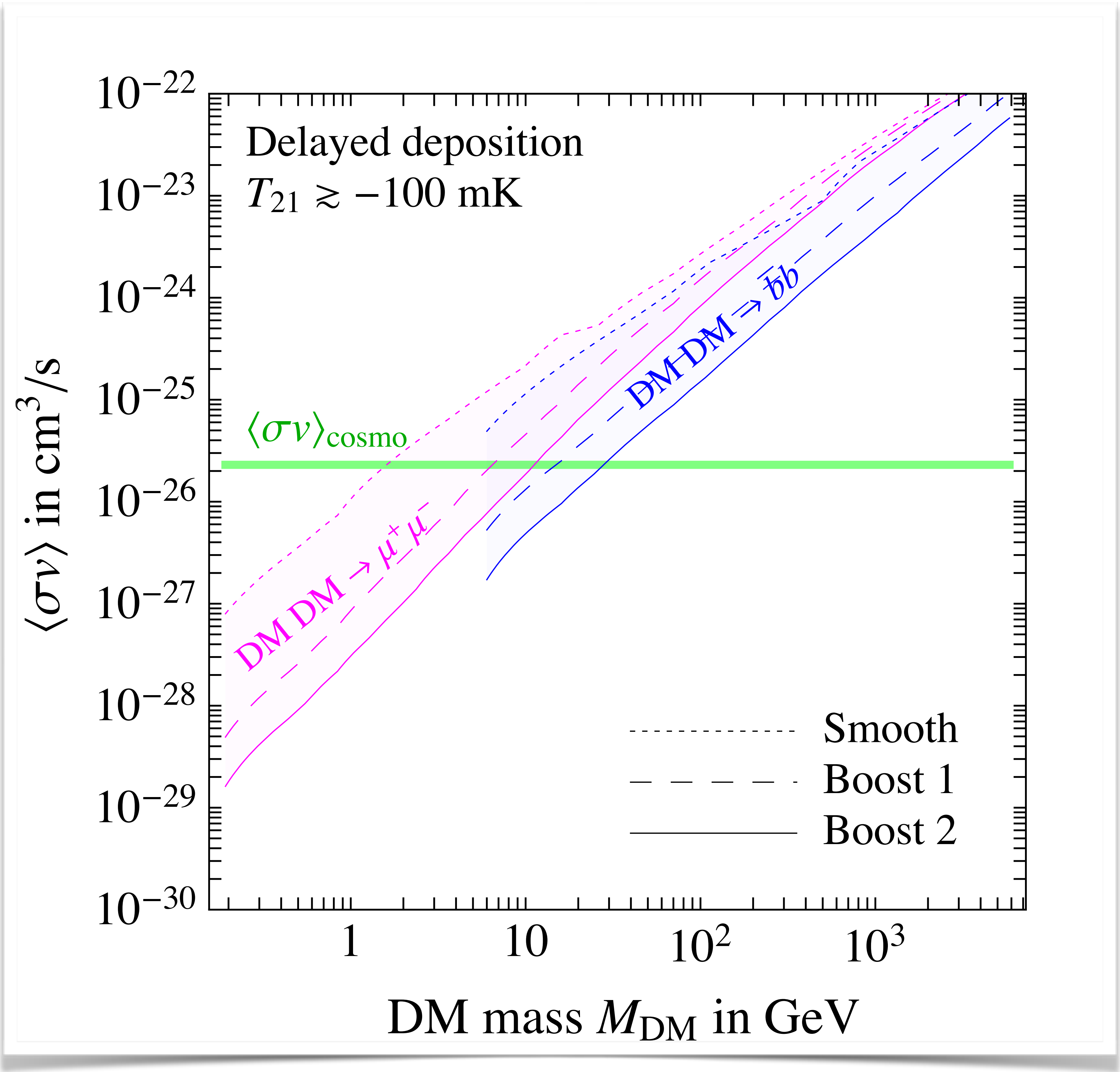
Instantaneous deposition



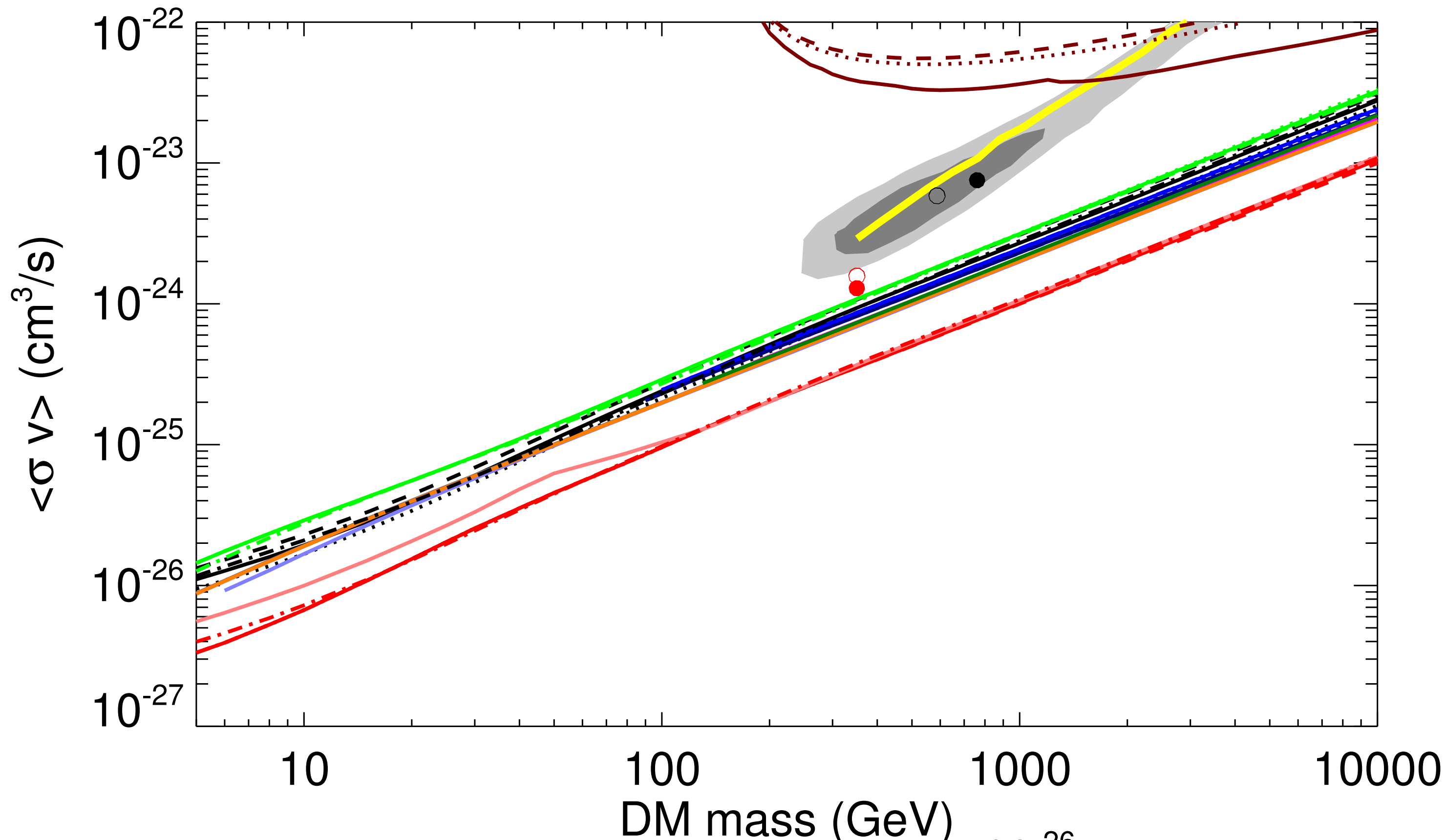
Some limits: $\gamma\gamma$ & e^+e^-

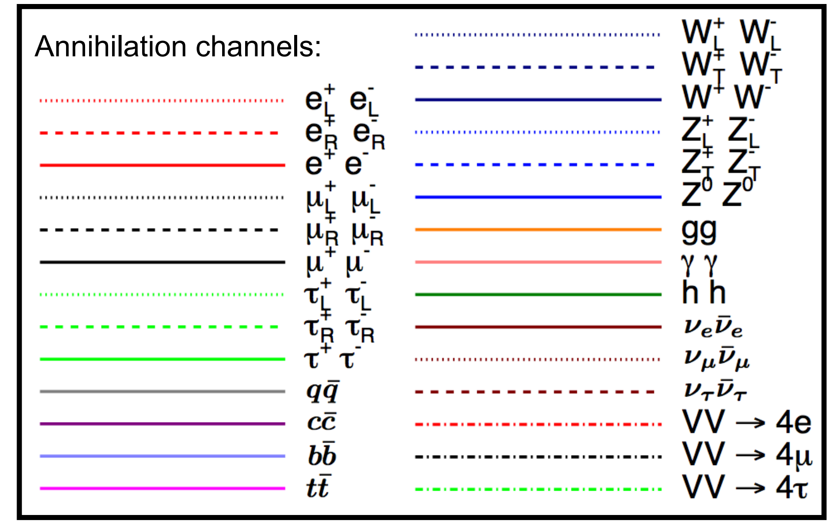


Some limits: $b\bar{b}$ & $\mu^+\mu^-$.

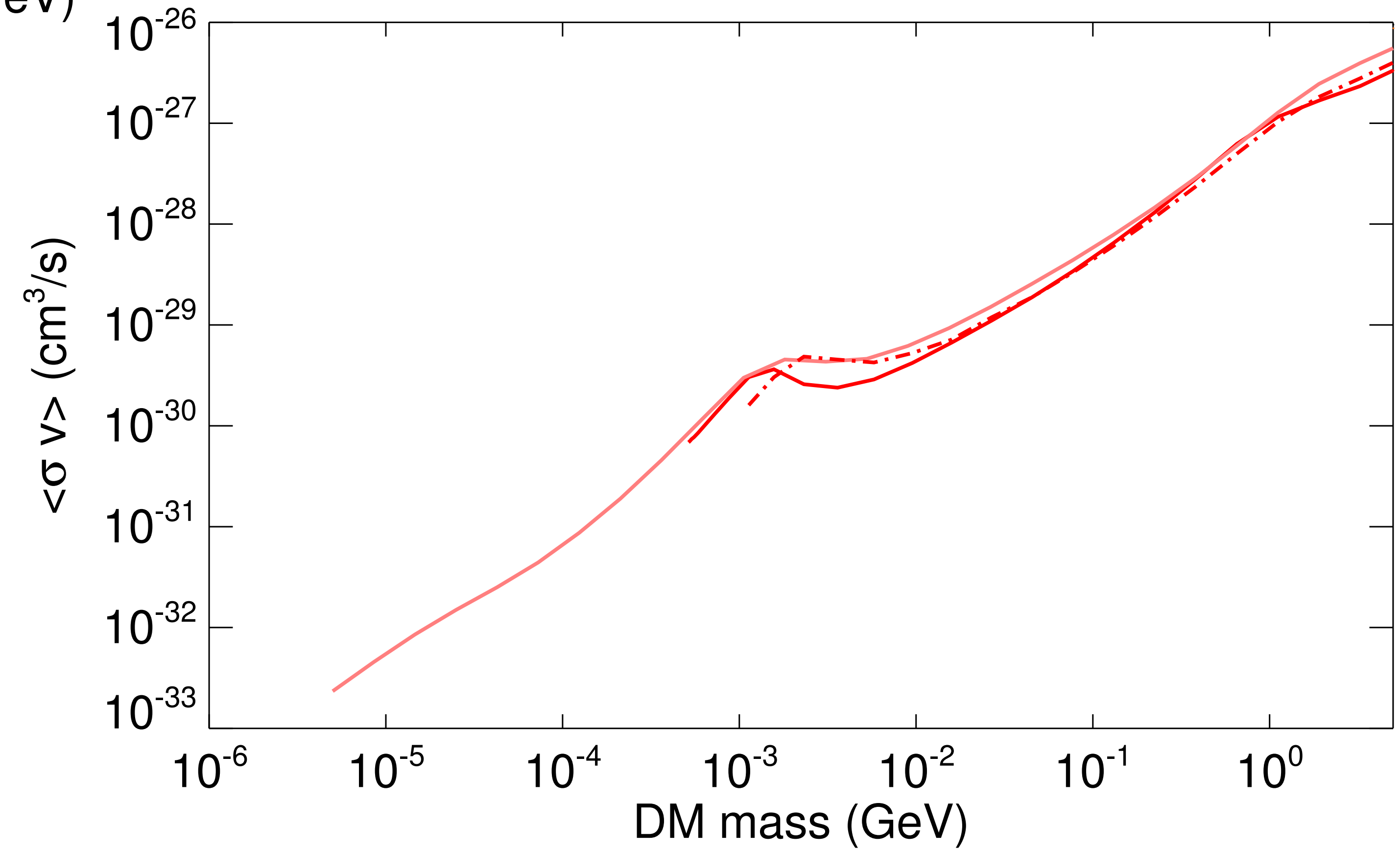


Comparison: PLANCK



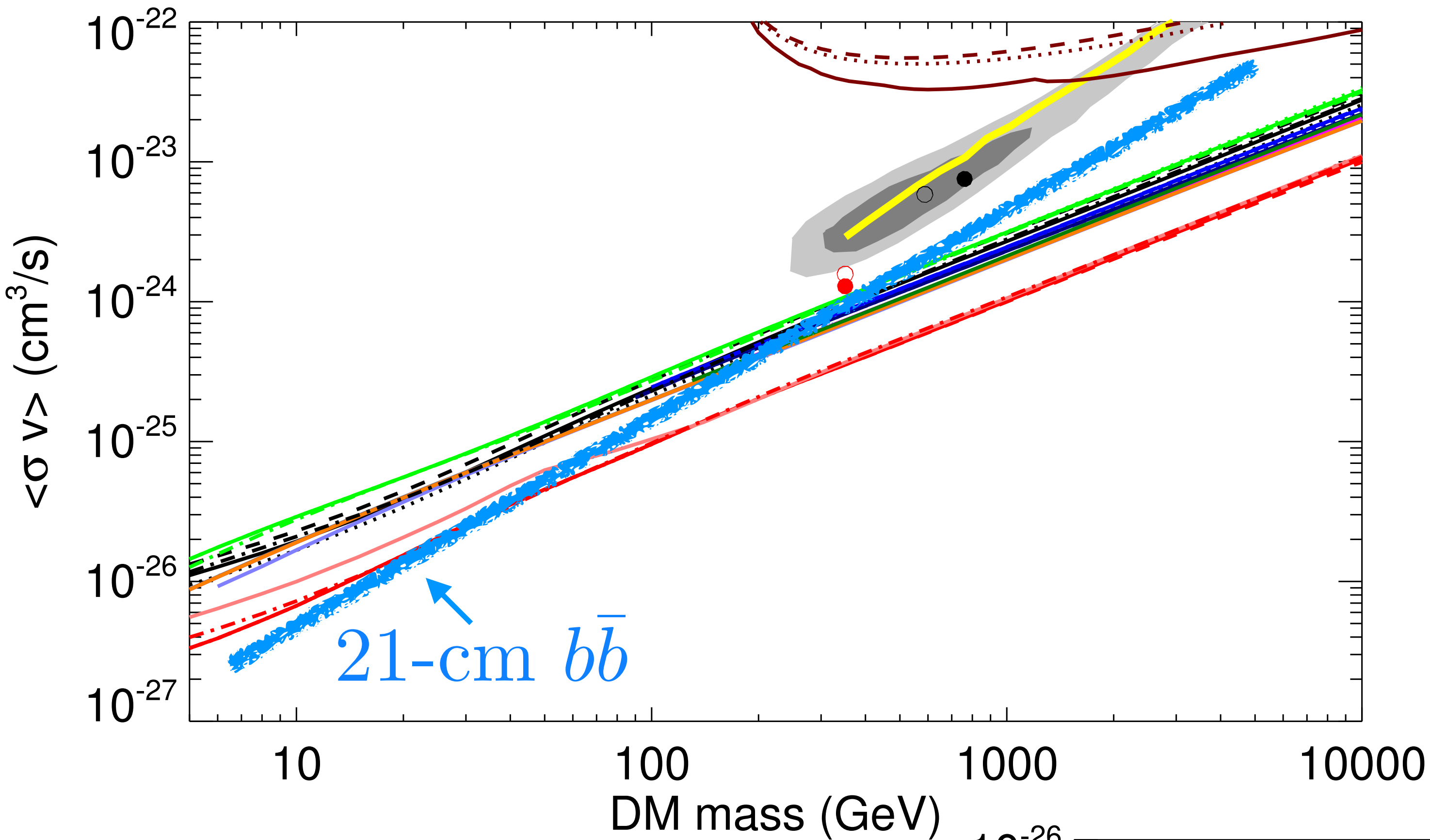


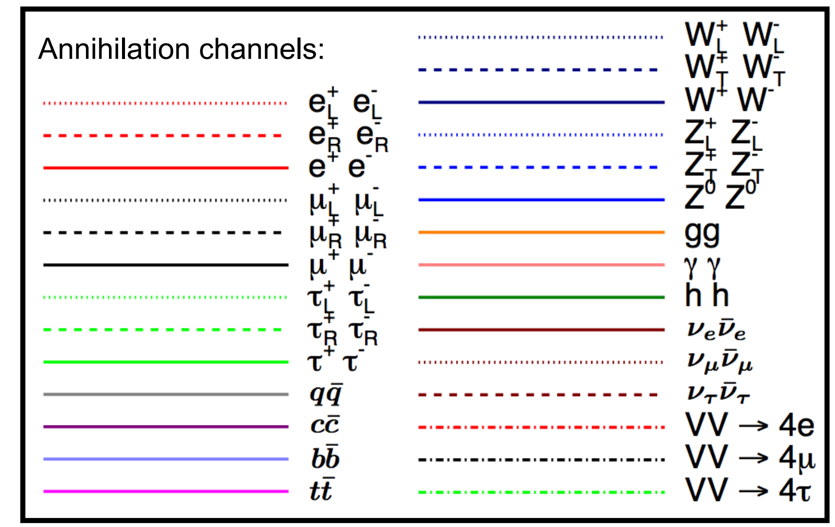
Slatyer 1506.03811



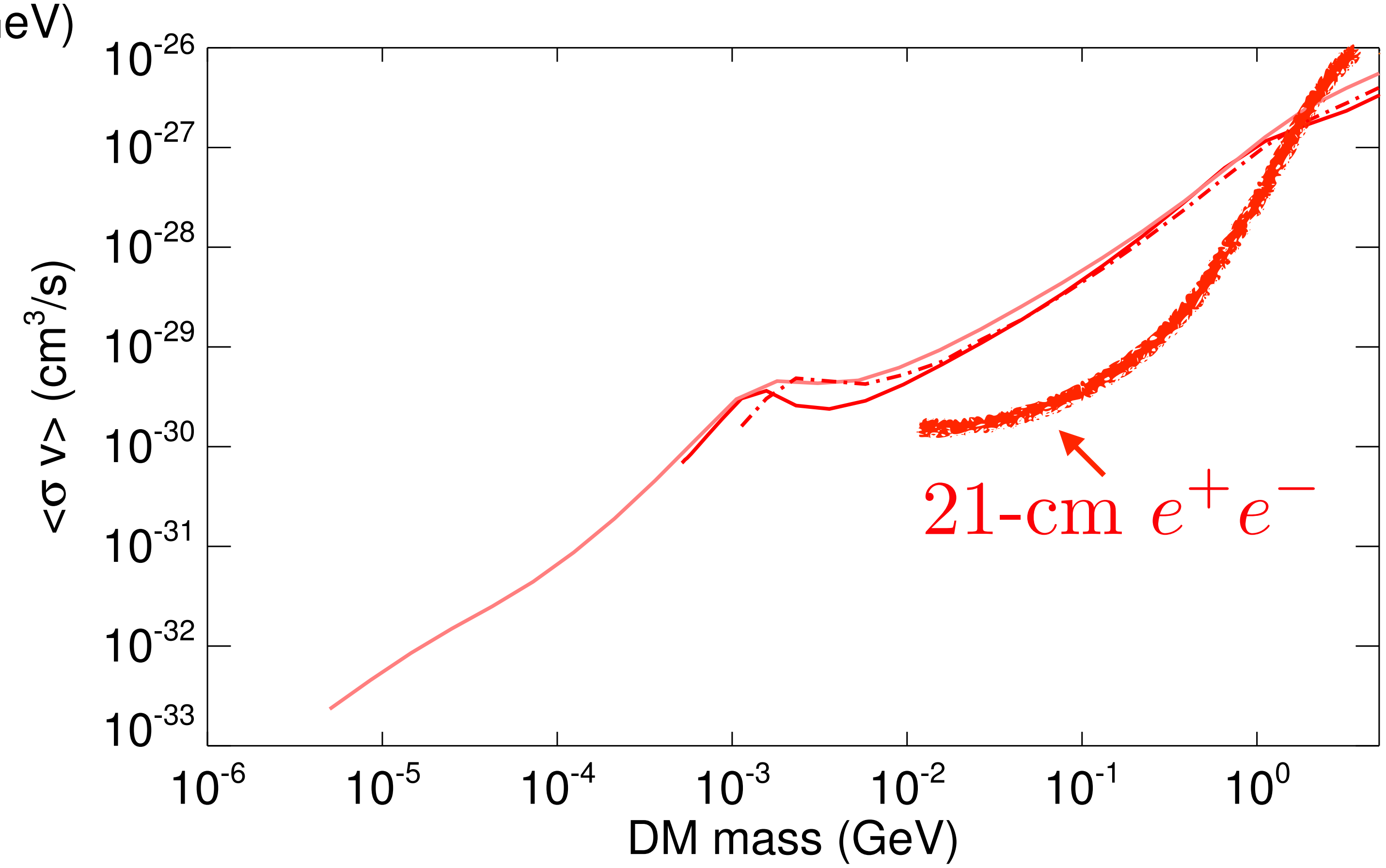
PAOLO PANCI
slide 28/30

Comparison: PLANCK



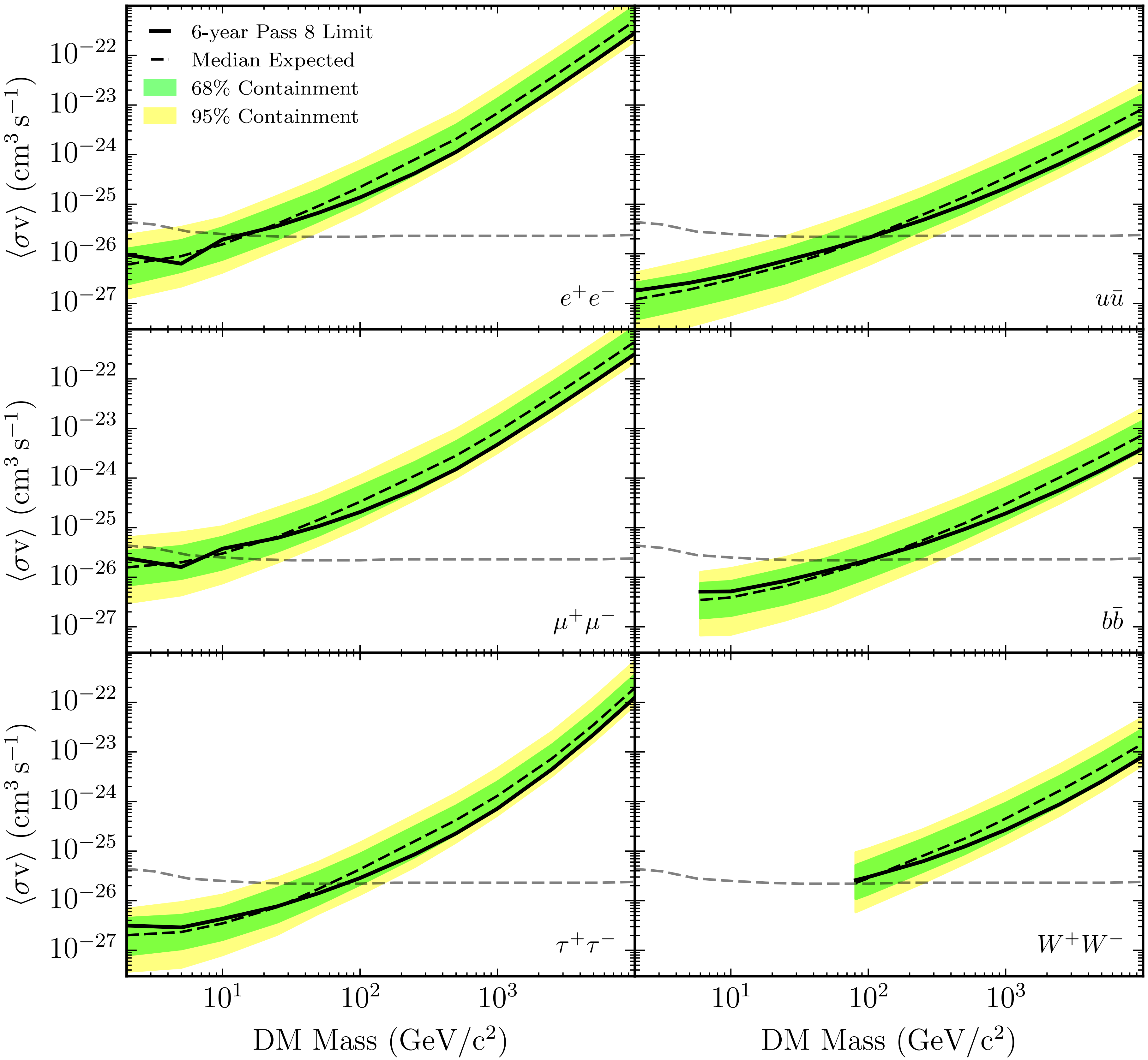


Slatyer 1506.03811



PAOLO PANCI
slide 29/30

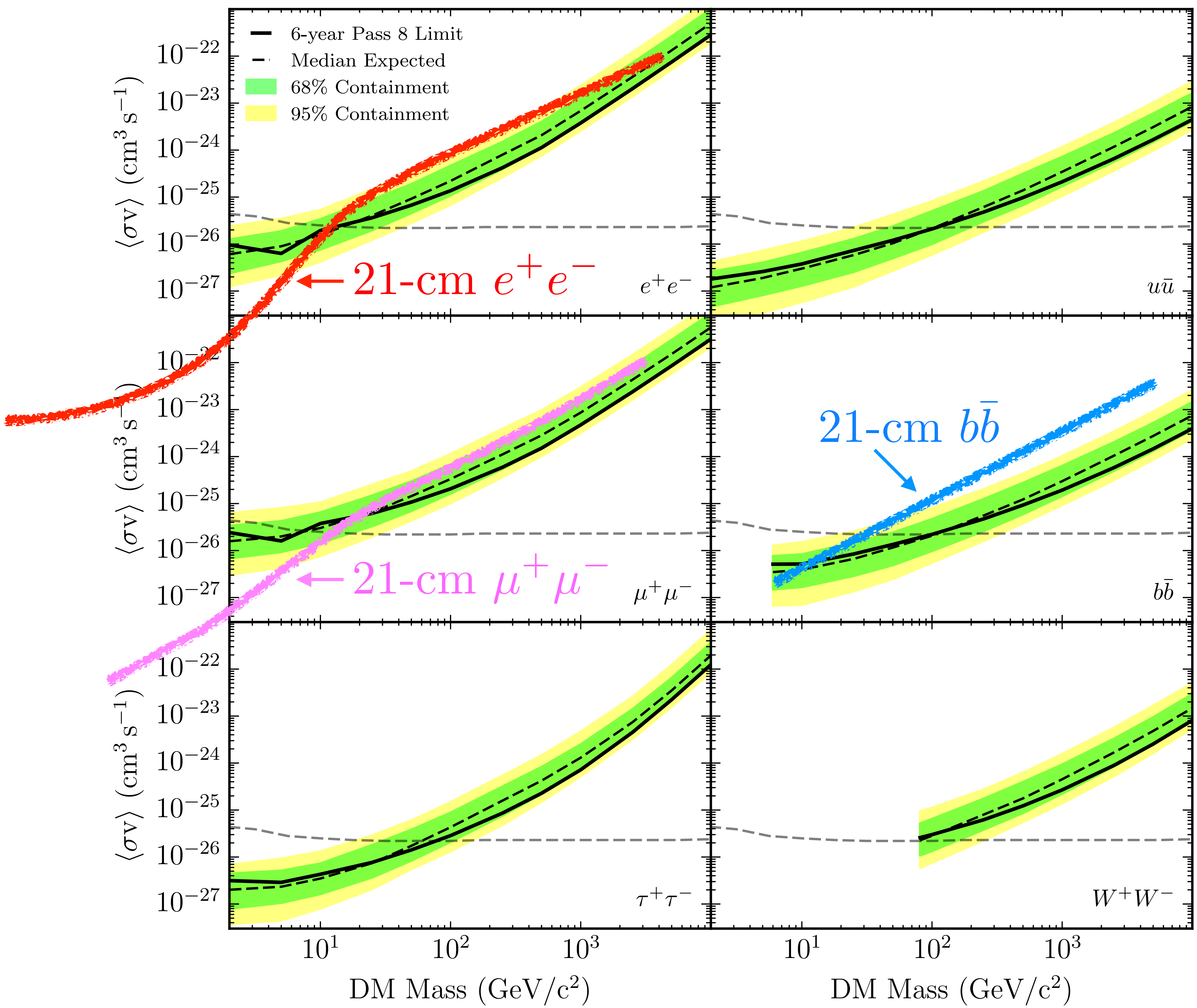
Comparison: FERMI dSphs



FERMI coll.
1503.02641

PAOLO PANCI
slide 29/30

Comparison: FERMI dSphs



FERMI coll.
1503.02641

Outlook & Conclusions

Outlook & Conclusions

- ➡ We (hopefully) have started probing the Universe in 21-cm

Outlook & Conclusions

➡ We (hopefully) have started probing the Universe in 21-cm

➡ **EDGES result is fundamental for astrophysics (and particle physics?)**: information about the *epoch of reionization* and indirectly about the *IGM temperature* soon after the formation of first stars and galaxies

Outlook & Conclusions

- We (hopefully) have started probing the Universe in 21-cm

- **EDGES result is fundamental for astrophysics (and particle physics?)**: information about the *epoch of reionization* and indirectly about the *IGM temperature* soon after the formation of first stars and galaxies

- **The amplitude of the 21-cm signal detected by EDGES is anomalous**: *two approaches* to explain the anomaly that *select few peculiar BSM models*

Outlook & Conclusions

- We (hopefully) have started probing the Universe in 21-cm

- **EDGES result is fundamental for astrophysics (and particle physics?)**: information about the *epoch of reionization* and indirectly about the *IGM temperature* soon after the formation of first stars and galaxies

- **The amplitude of the 21-cm signal detected by EDGES is anomalous**: *two approaches* to explain the anomaly that *select few peculiar BSM models*

- **The inferred spin temperature by EDGES is very small**: *great opportunity* to set severe and stringent bounds on the properties of any *extra source of heating (e.g. DM ann./dec., PBHs, etc…)*

Outlook & Conclusions

- We (hopefully) have started probing the Universe in 21-cm

- **EDGES result is fundamental for astrophysics (and particle physics?)**: information about the *epoch of reionization* and indirectly about the *IGM temperature* soon after the formation of first stars and galaxies

- **The amplitude of the 21-cm signal detected by EDGES is anomalous**: *two approaches* to explain the anomaly that *select few peculiar BSM models*

- **The inferred spin temperature by EDGES is very small**: *great opportunity* to set severe and stringent bounds on the properties of any *extra source of heating (e.g. DM ann./dec., PBHs, etc…)*

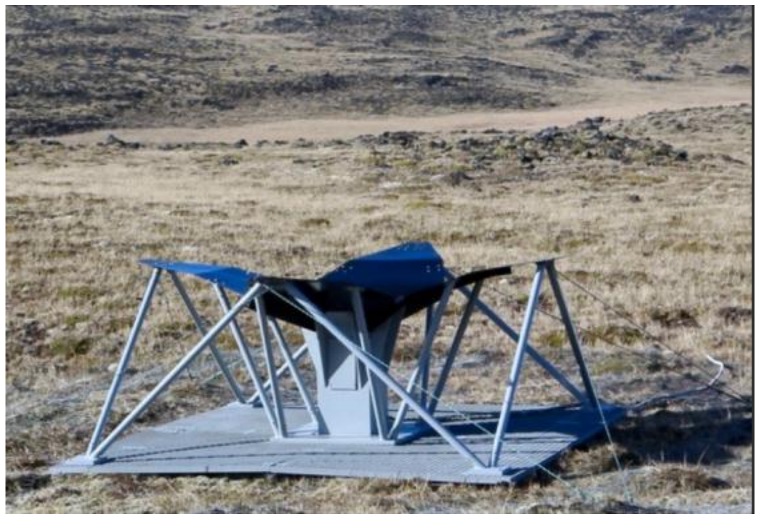
- *This is just the beginning: Stay tuned for further developments!*
  Can the monopole 21-cm alone shed light on dark matter?

Backup slides

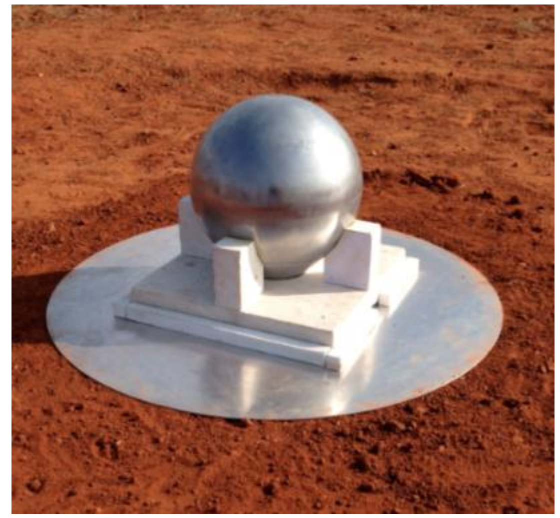
backup
slide 1/14

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

backup slide 2/14

EDGES Fitting procedure

Linearized version of Physically-Motivated foreground model

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

Alternative Polynomial Model

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

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

backup slide 3/14

Main concerns

A Ground Plane Artifact that Induces an Absorption Profile in Averaged Spectra from Global 21-cm Measurements - with Possible Application to EDGES

Richard F. Bradley, Keith Tauscher, David Rapetti, and Jack O. Burns

backup slide 4/14

Addressing concerns: Recent tests

Null Tests (**feature should not be found)**

1) Measuring noise sources that produce a **flat spectrum**.
2) Measuring noise sources that produce a spectrum **resembling the diffuse foregrounds**.

Tests Addressing Antenna Beam Effects (**feature should be found**)

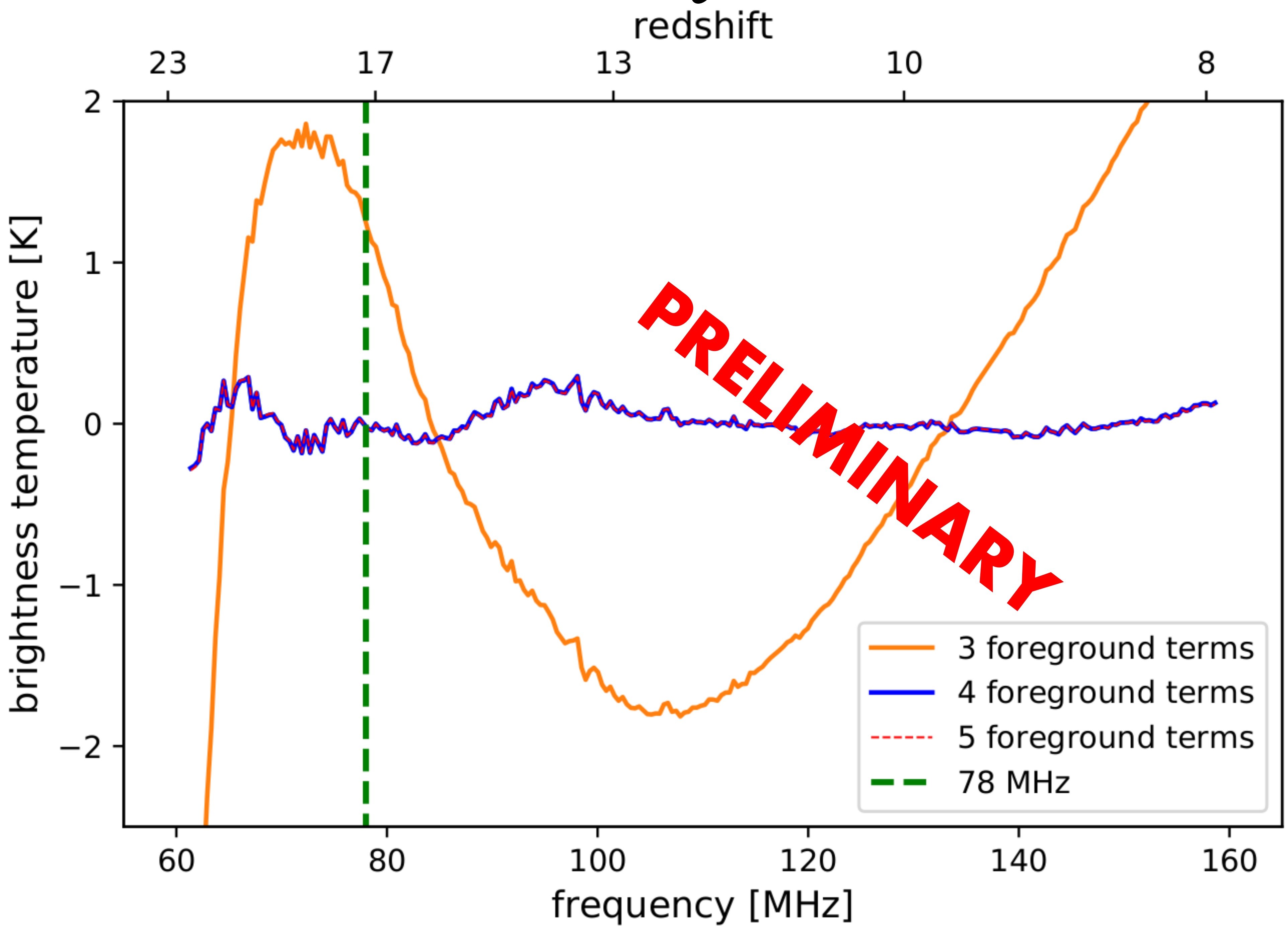
1) Using **smaller Mid-Band antenna** covering 60-160 MHz.
2) Using Low-Band antenna over a **smaller 9m x 9m ground plane**. We call this **Low-Band 3**.

These **tests have been passed successfully**. This supports a **spectral feature from the sky**.

Slide from Monsalve's talk @ La Thuile 2019

backup slide 5/14

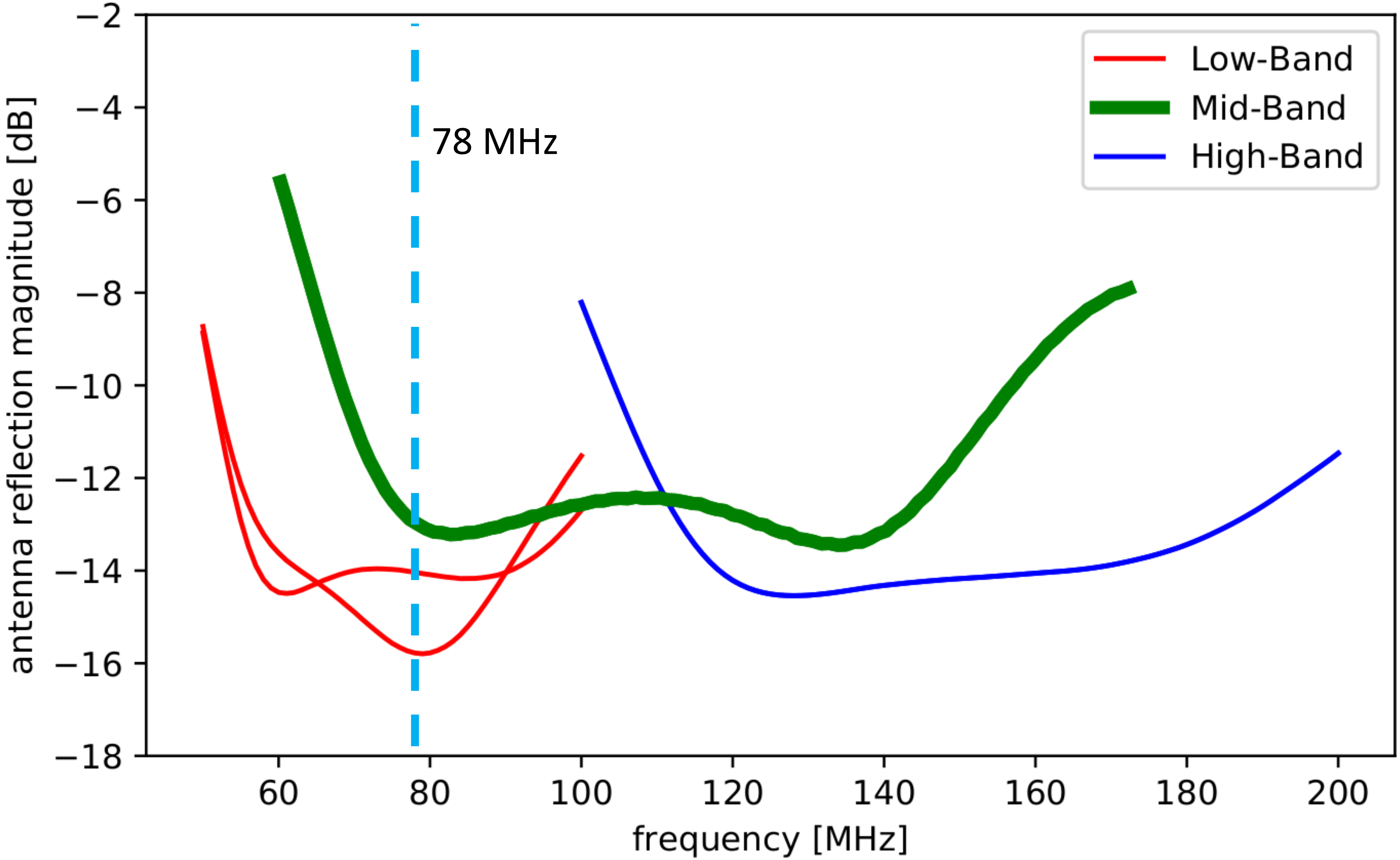
Preliminary: Mid-band results



1) Data from **May - August 2018.**
2) **Low foregrounds**.
3) Best-fit absorption **consistent with Bowman et al. (2018)**.
4) Some alternative models suggested **can be disfavored**.

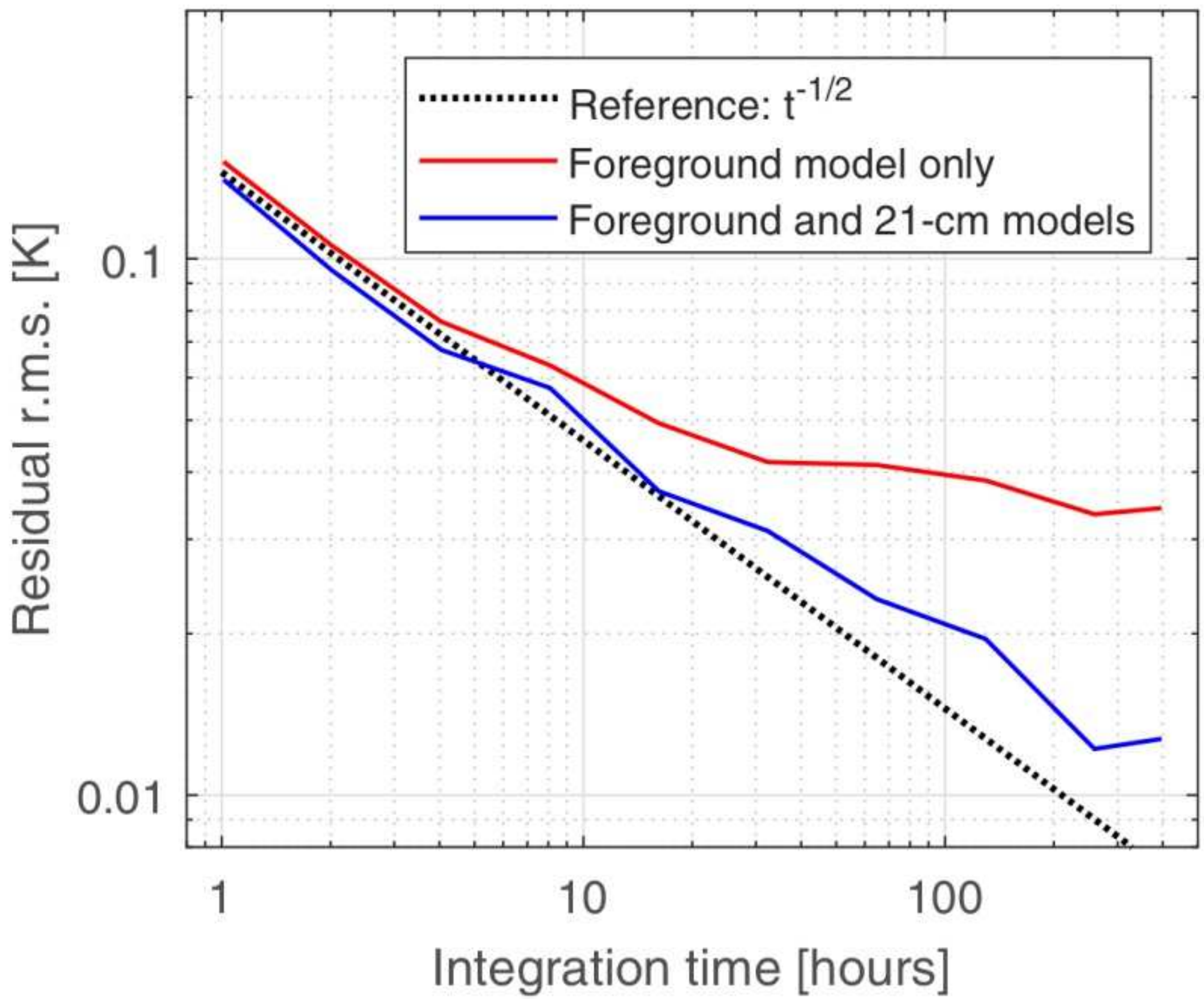
Slide from Monsalve's talk @ La Thuile 2019

Antenna reflection coefficients



Slide from Monsalve's talk @ La Thuile 2019

EDGES Residuals r.m.s.



Slide from Monsalve’s talk @ CERN

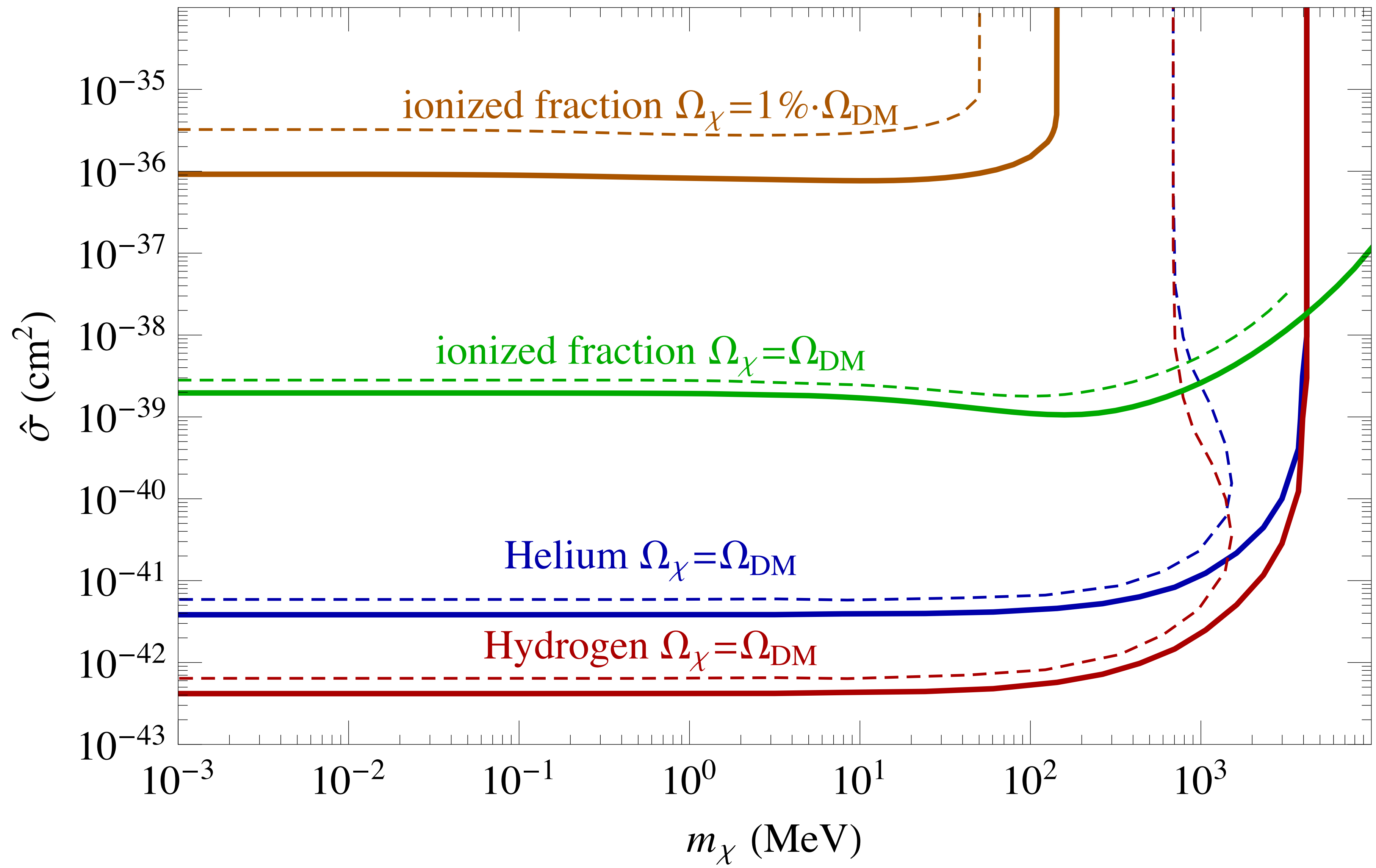
backup slide 8/14

1: Cool the IGM even more

DM-baryons interactions enhanced as

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

Required cross sections to fit the EDGES signal



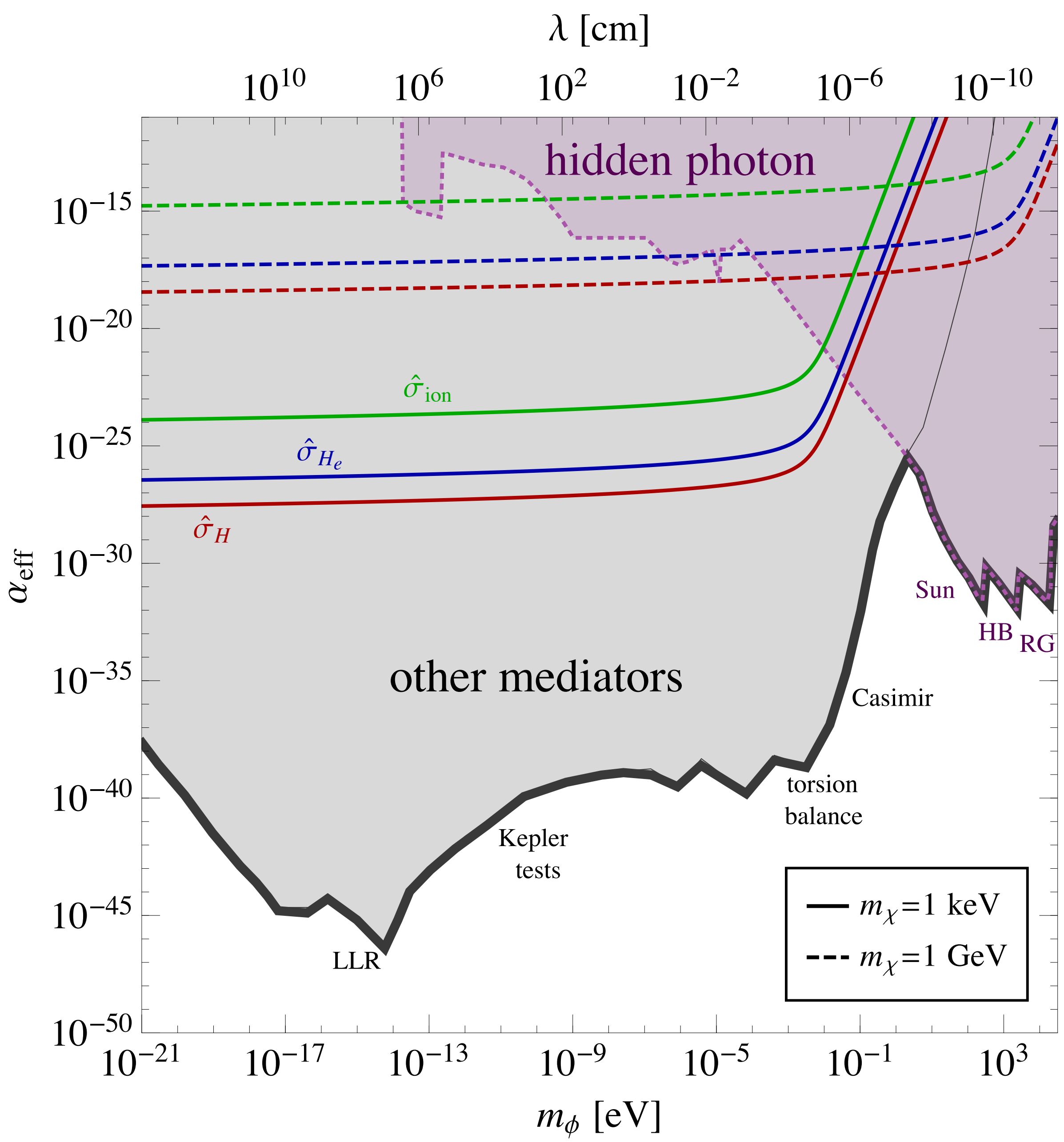
Barkana *et al.*
1803.03091

backup slide 9/14

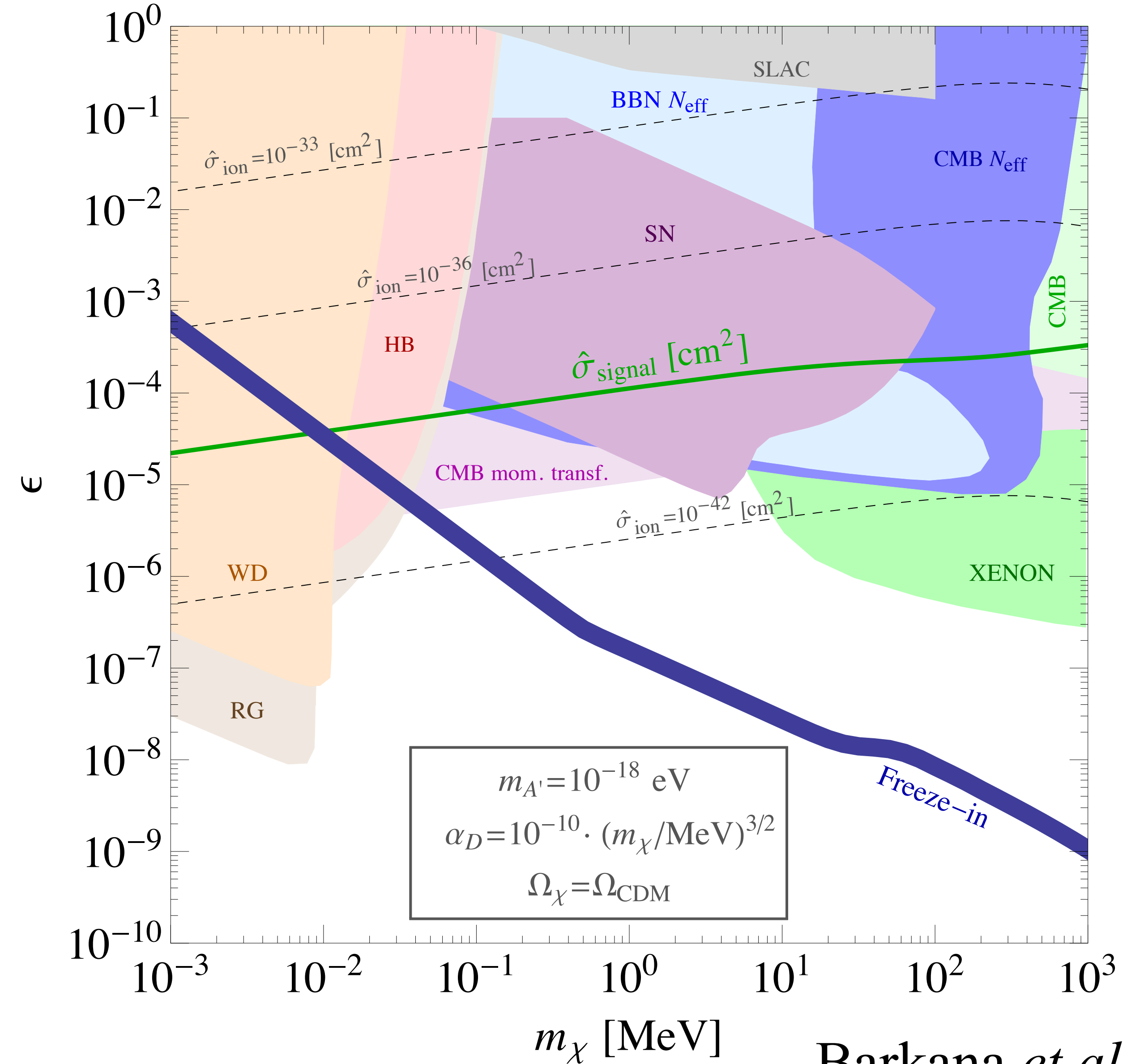
1: Cool the IGM even more

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

backup slide 10/14

1: Cool the IGM even more

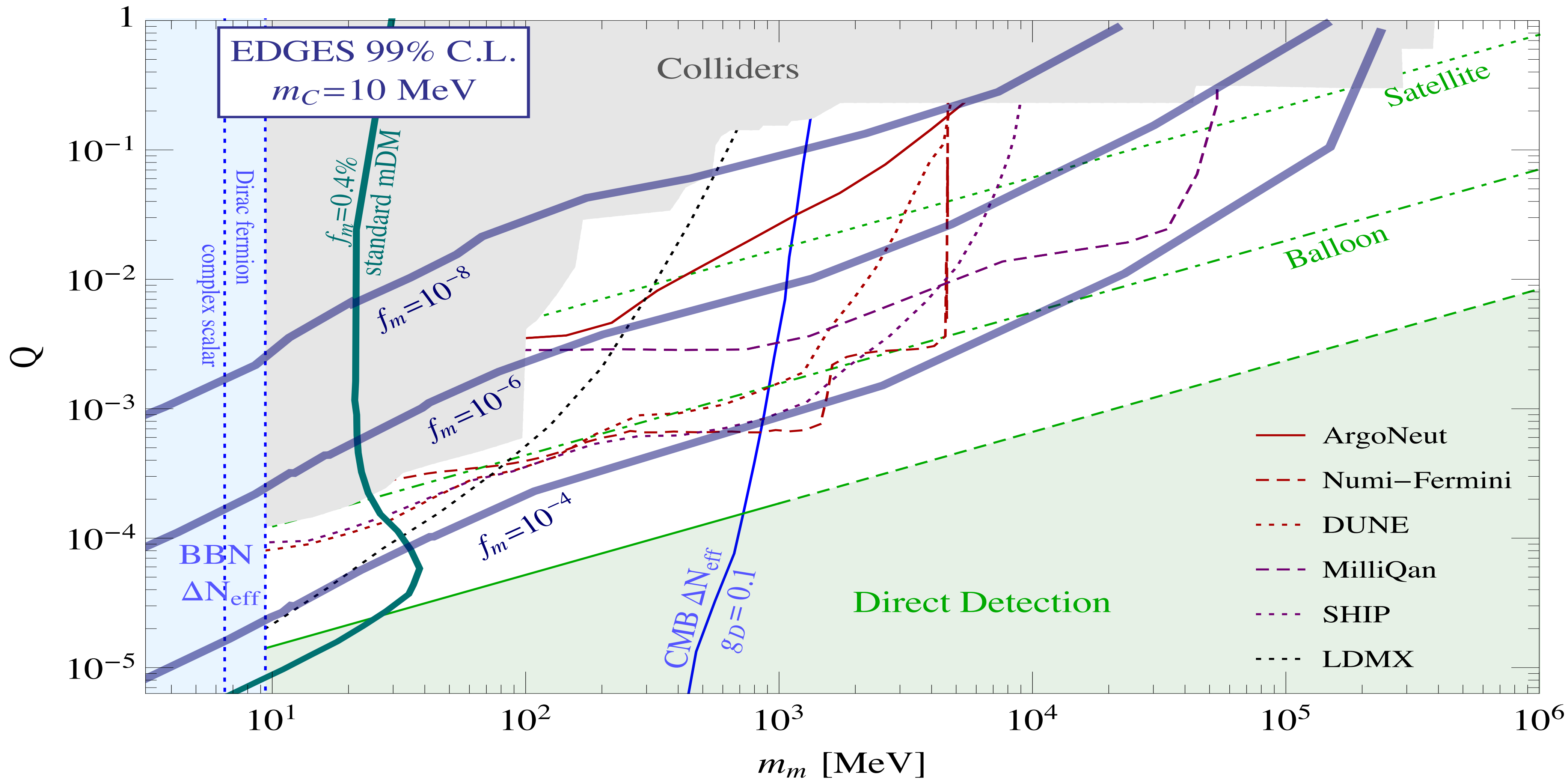
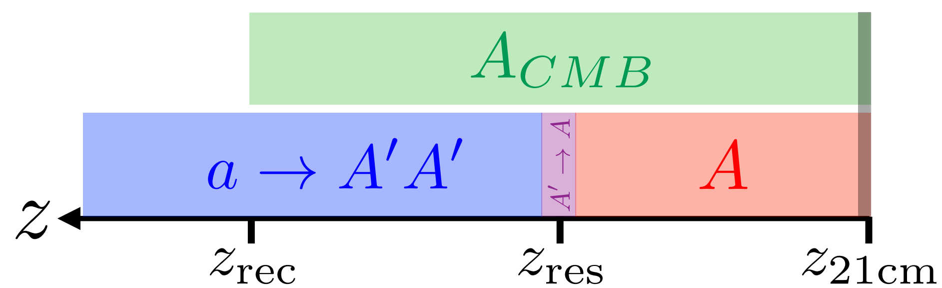


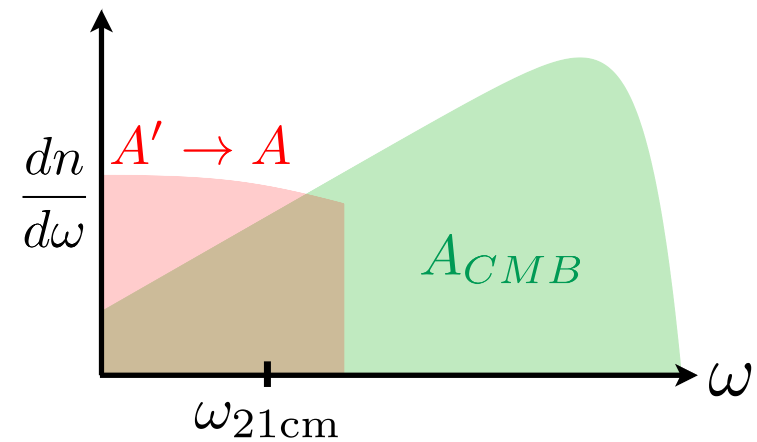
FIG. 2. Parameter space of the scenario described in Fig. 1 in the plane (m_m, Q) where we fix $m_C = 10$ MeV to maximize the heat capacity of the CDM bath and the maximal $\alpha_m\alpha_C$ allowed by CMB bounds [14–18]. The **dark blue** contours give the mDM fraction f_m required for a given (m_m, Q) point to fit the upper value of the 99% CL interval of the EDGES measurement in the setup of Fig. 1. For a fixed f_m the entire region above the dark blue contour can be probed by reducing $\alpha_m\alpha_C$ (see text for details). For comparison, the **dark green** contour shows the standard mDM case where 0.4% of mDM alone provides the baryonic cooling. The **light blue** region for $m_m < 10$ MeV is robustly excluded by BBN contraints on N_{eff} [7, 8, 10, 19], the two dotted lines distinguish between the case in which mDM is a scalar or a Dirac fermion. The **gray shaded** area is a collection of different constraints taken from Refs. [37, 87], plus limits on millicharge particles from milliQ at SLAC [35], searches for low ionizing particles in CMS at the LHC [88] and the new constraints from LSND and MiniBooNE derived in Ref. [40]. The region on the left of the **blue line** is excluded by CMB constraints on N_{eff} only when mDM couples to a dark photon with coupling $g_D = 0.1$. The **green region** is excluded by present direct detection experiments as shown in Ref. [47]. The **green dashed line** indicates our extrapolation of the results in Ref. [47] to higher masses (see discussion in the text). The **red/black/magenta lines** indicate the Fermilab/SLAC/CERN effort to probe mDM. **Solid/dashed/dotted lines** give a rough sense of the short/medium/long time scale of the proposal. **Solid red** is the ArgoNeut sensitivity derived in Ref. [43], **dashed red** is the sensitivity of the Fermini proposal at NuMI [42] (see Ref. [43] for a more conservative reach based on ArgoNeut at NuMI), **dotted red** is the DUNE reach [40] while **dotted black** is the LDMX reach [41]. **Dashed magenta** is the milliQan reach as [38] while **dotted magenta** is the SHiP sensitivity [40]. The **dash-dotted/dotted green lines** indicate the reach of a SENSEI-like dark matter detector on a balloon/satellite with 0.1 gram-month exposure [47].

backup slide 11/14

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

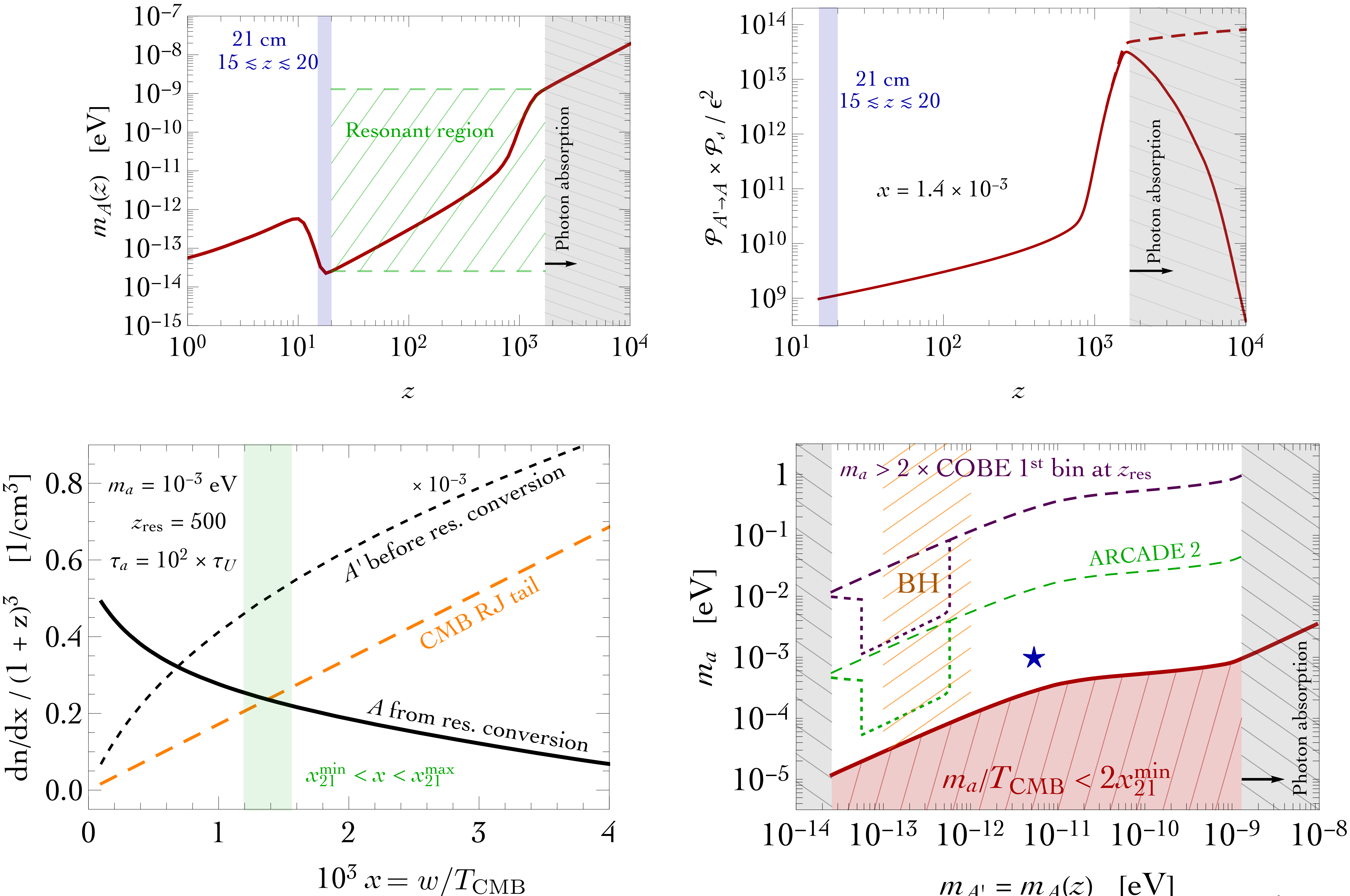
$$\mathcal{L}_{AA'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2$$

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

backup slide 12/14

2: Increase the CMB RJ tail



Pospelov *et al.* 1803.07048

backup slide 13/14

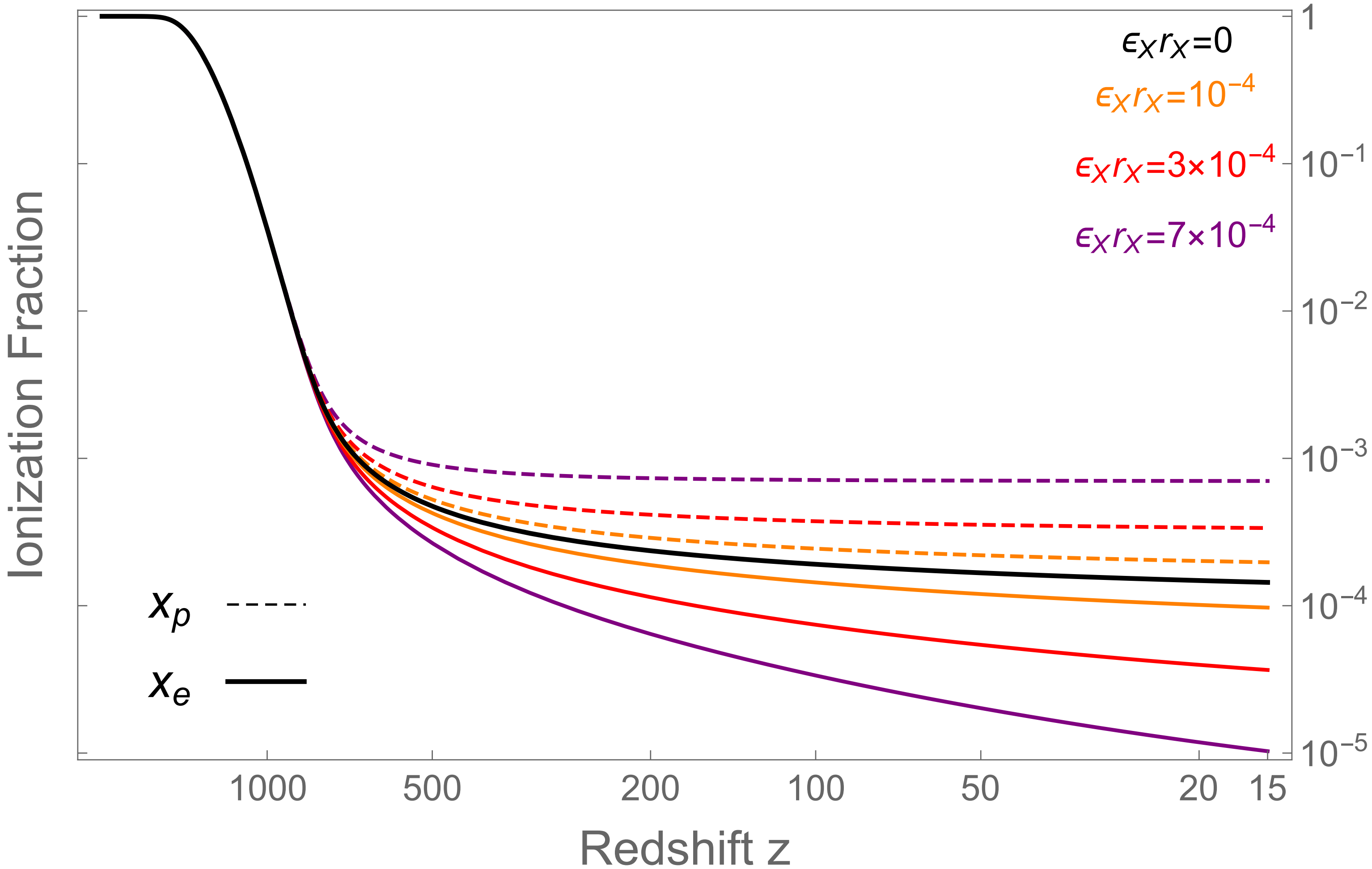
3: Charge sequestration?

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 $r_\chi = n_\chi / n_b$



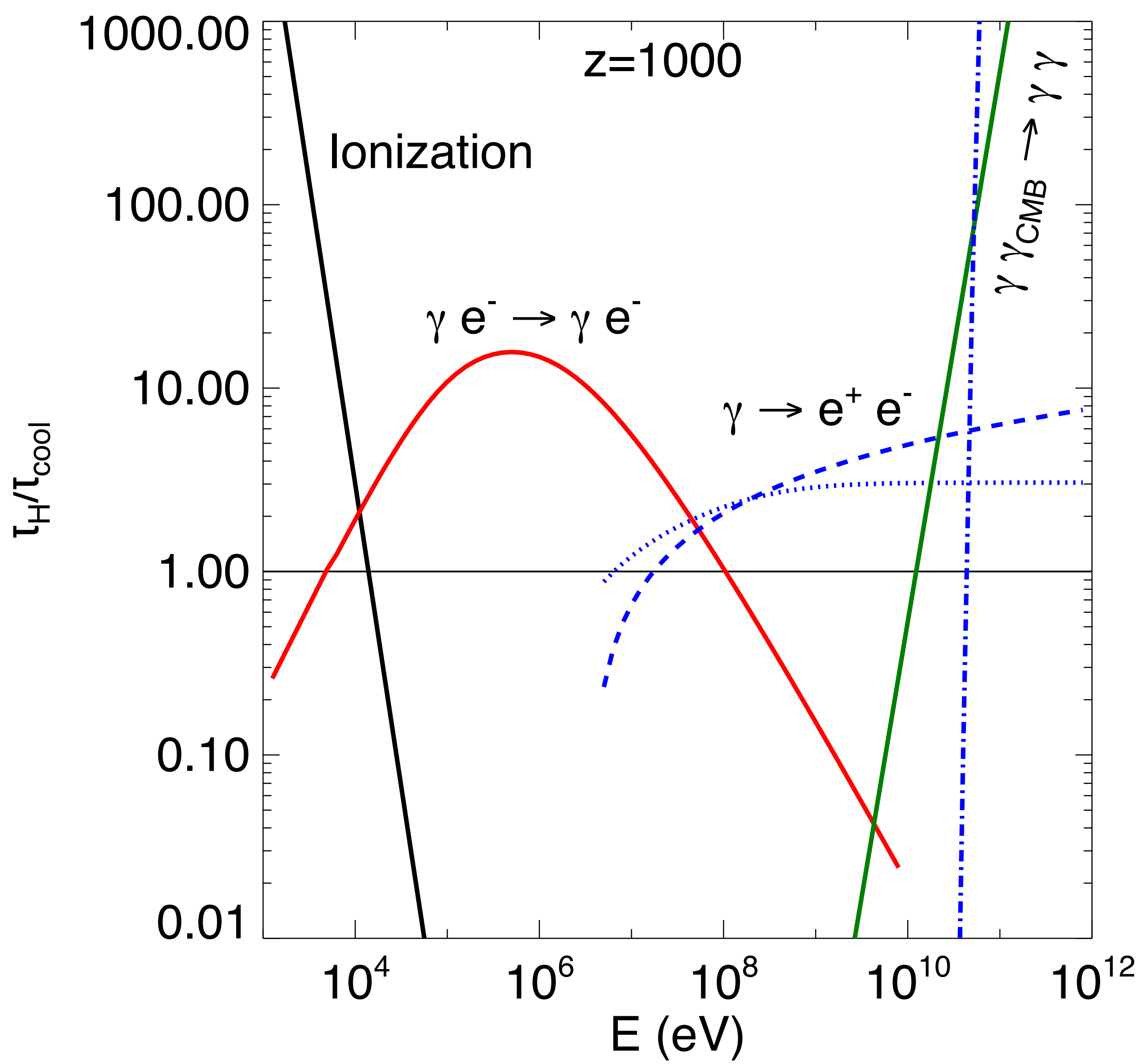
Falkowski, Petraki
1803.10096

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)*