Constraints from Cosmology

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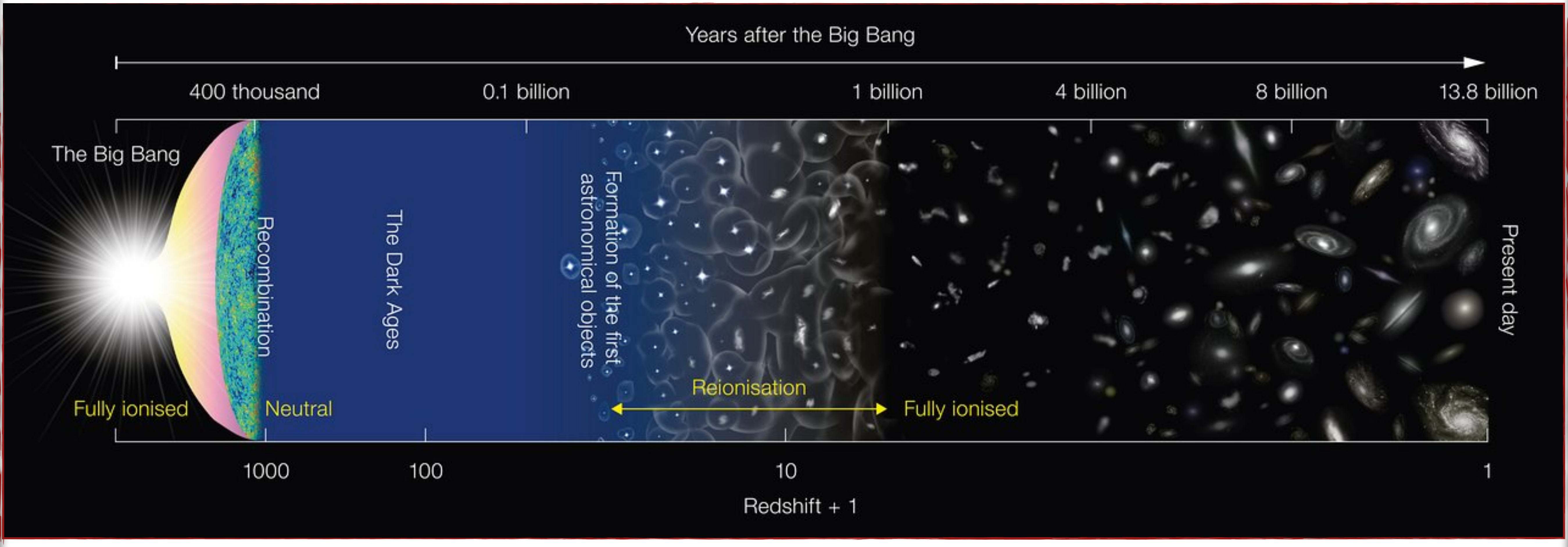
Constraints from Cosmology

A *partial* view

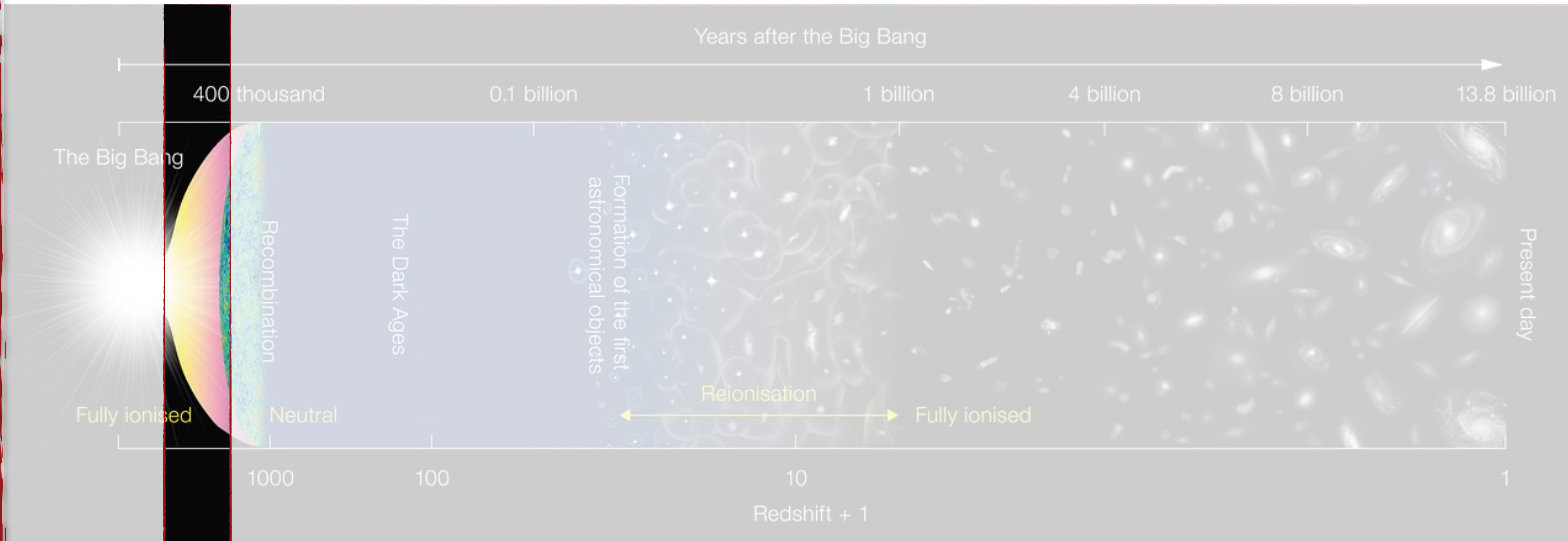
$$\textit{partial} = \begin{cases} \text{Not complete} \\ \text{Biased} \end{cases}$$

Constraints from Cosmology



Constraints from Cosmology

The very early Universe



Constraints from Cosmology

The very early Universe

What is the dark matter production mechanism?

Constraints from Cosmology

The very early Universe

What is the dark matter production mechanism?

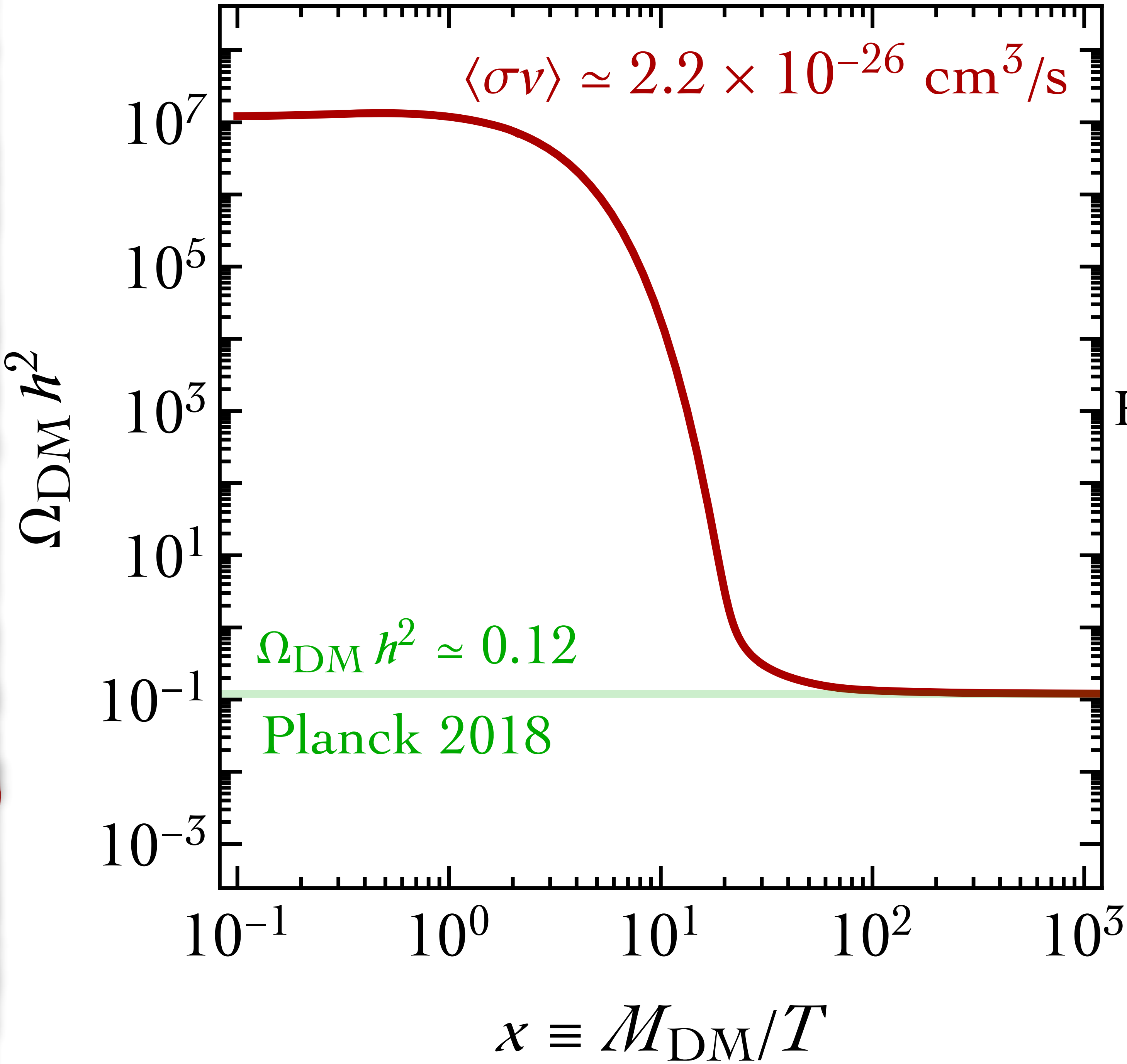
Thermal (WIMP)

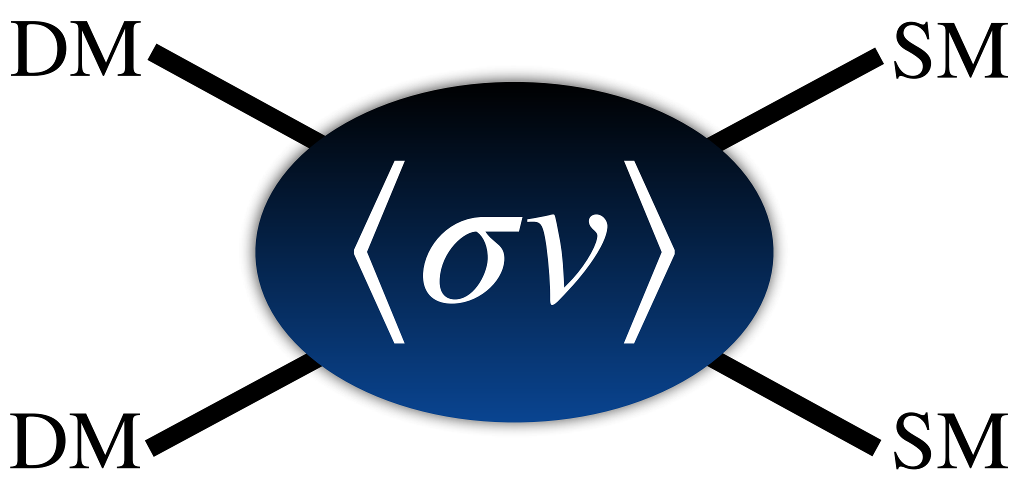
Non-thermal (ALPs)

Constraints from Cosmology

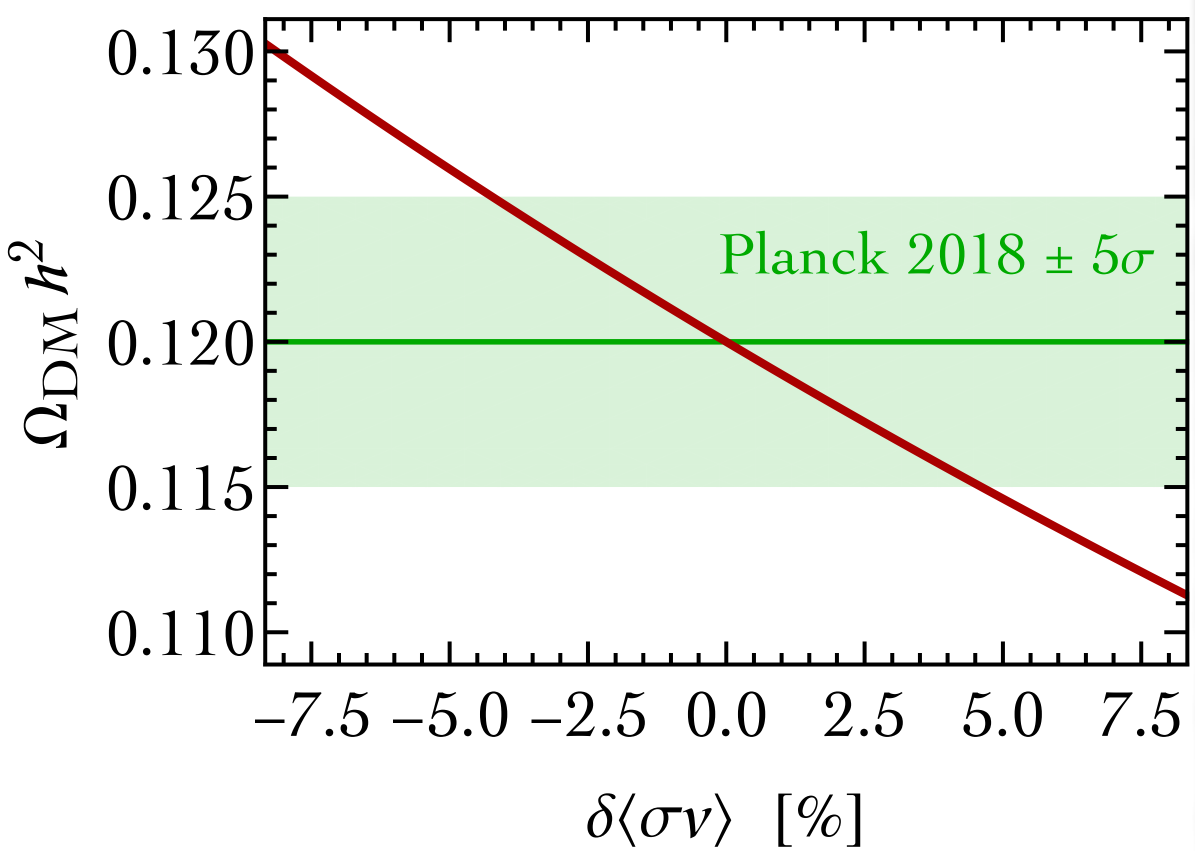
The very early Universe

Thermal (WIMP)





Higher annihilation $\langle\sigma v\rangle$ = lower relic density



Constraints from Cosmology

The very early Universe **Thermal (WIMP)**

PRO

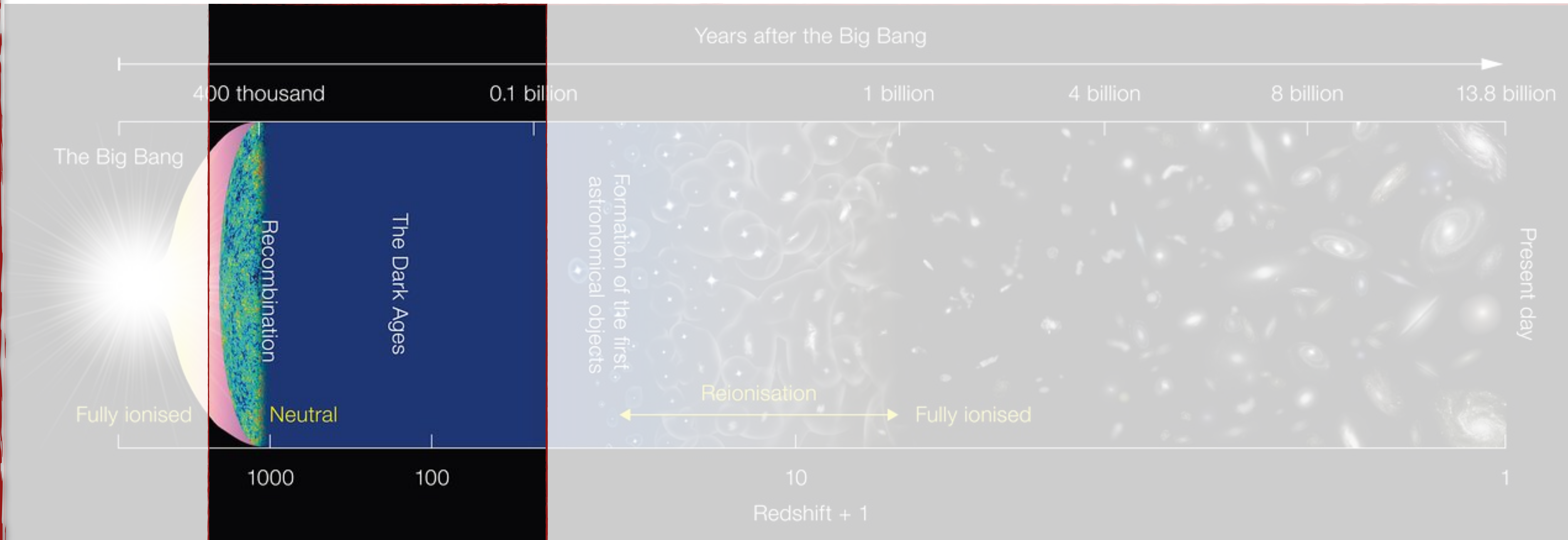
- No initial conditions.
- "Easy" to detect: The same interactions with SM particles that set the relic abundance control possible signatures (direct, indirect, collider).

CONTRO

- Tension with experiments (?)

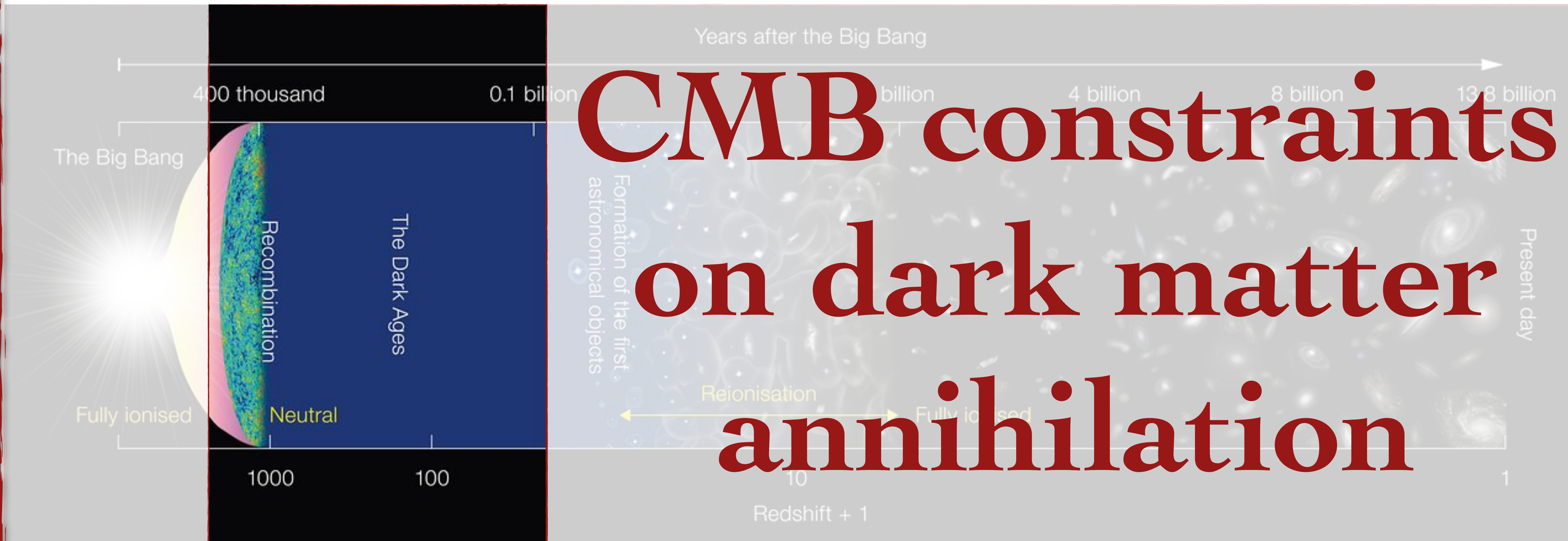
Constraints from Cosmology

The early Universe



Constraints from Cosmology

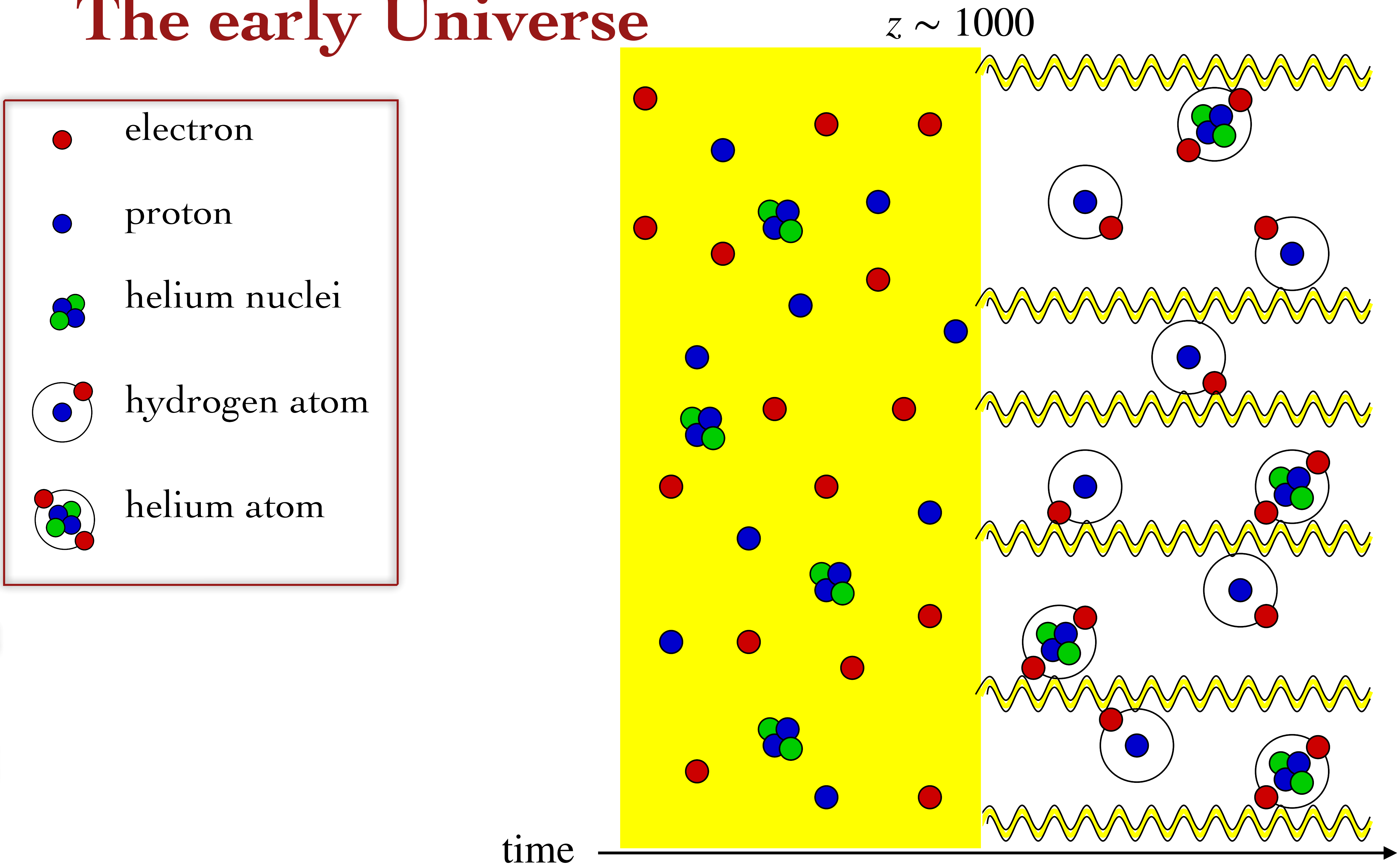
The early Universe



CMB constraints on dark matter annihilation

Constraints from Cosmology

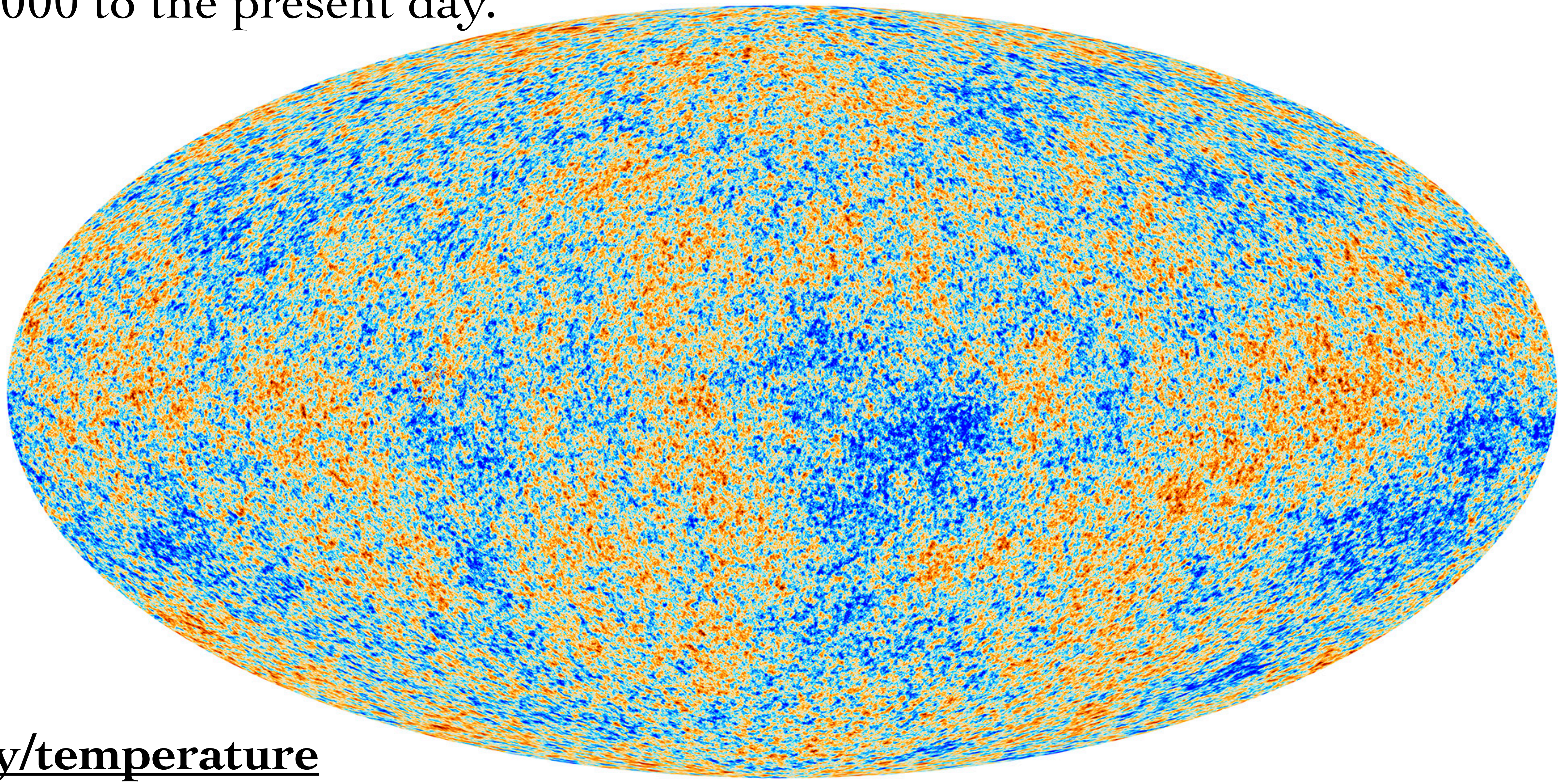
The early Universe



Constraints from Cosmology

The early Universe

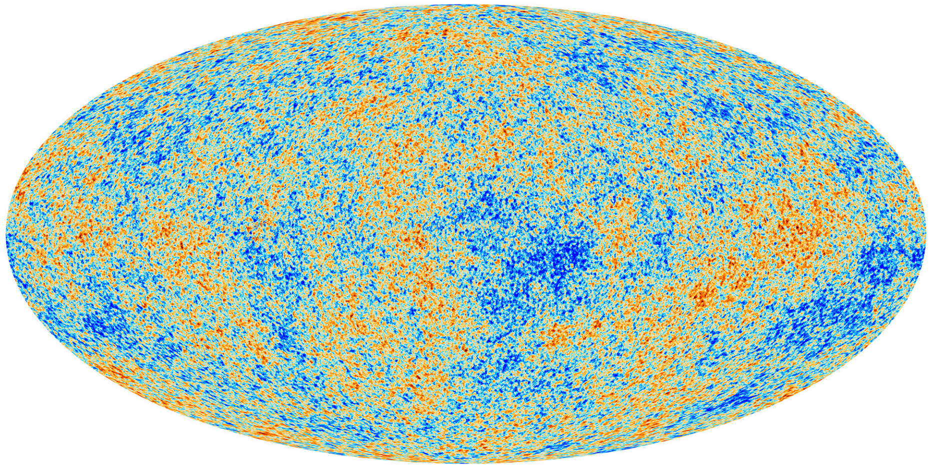
CMB photons propagate freely from the "last scattering surface" at z ~ 1000 to the present day.



Density/temperature fluctuations in the plasma at the time of last scattering are therefore imprinted on the CMB.

Constraints from Cosmology

The early Universe



The injection of secondary particles produced by dark matter annihilation around redshift $z \sim 1000$ affects the process of recombination, <u>leaving an imprint on CMB angular power spectra</u>

Constraints from Cosmology

The early Universe

The effective parameter constrained by CMB anisotropies

$$p_{\mathrm{ann}} \equiv \frac{f_{\mathrm{ann}} \langle \sigma v \rangle}{m_\chi}$$

Constraints from Cosmology

The early Universe

The effective parameter constrained by CMB anisotropies

$$p_{ann} \equiv \frac{f_{ann}\langle\sigma v\rangle}{m_\chi}$$

Slatyer, Padmanabhan and Finkbeiner, Phys.Rev.D **80**,043526 (2009)

Finkbeiner, Galli, Lin and Slatyer, Phys.Rev.D **85**,043522 (2012)

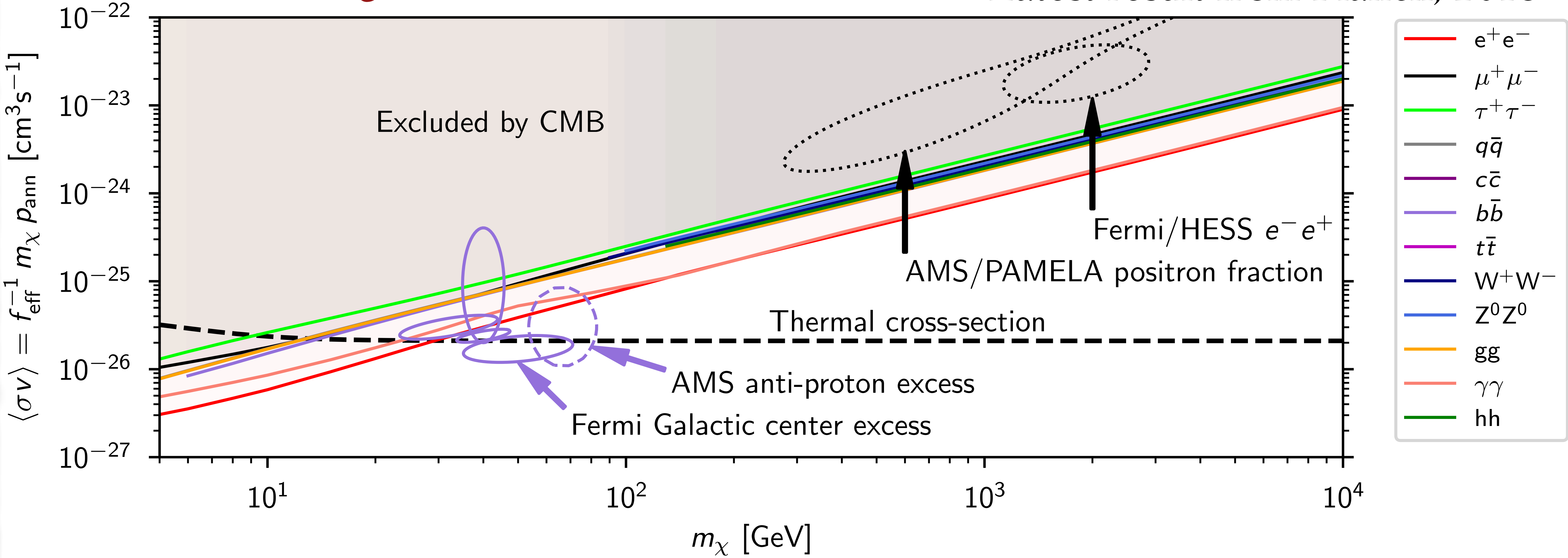
For any given annihilation final state, this factor can be calculated immediately from spectrum of photons/electrons/positrons produced per annihilation (assuming constant cross section during dark ages).

f_{ann} is the fraction of the energy released by the annihilation process that is transferred to the intergalactic medium

Constraints from Cosmology

The early Universe

Latest result from Planck, 2018



Thermal cross section excluded for all visible final states if mass is below ~10 GeV

Constraints from Cosmology

The early Universe

For sub-GeV DM that underwent thermal freeze-out, cross section should be suppressed today compared with freeze-out (or annihilation should have large invisible branching ratio).

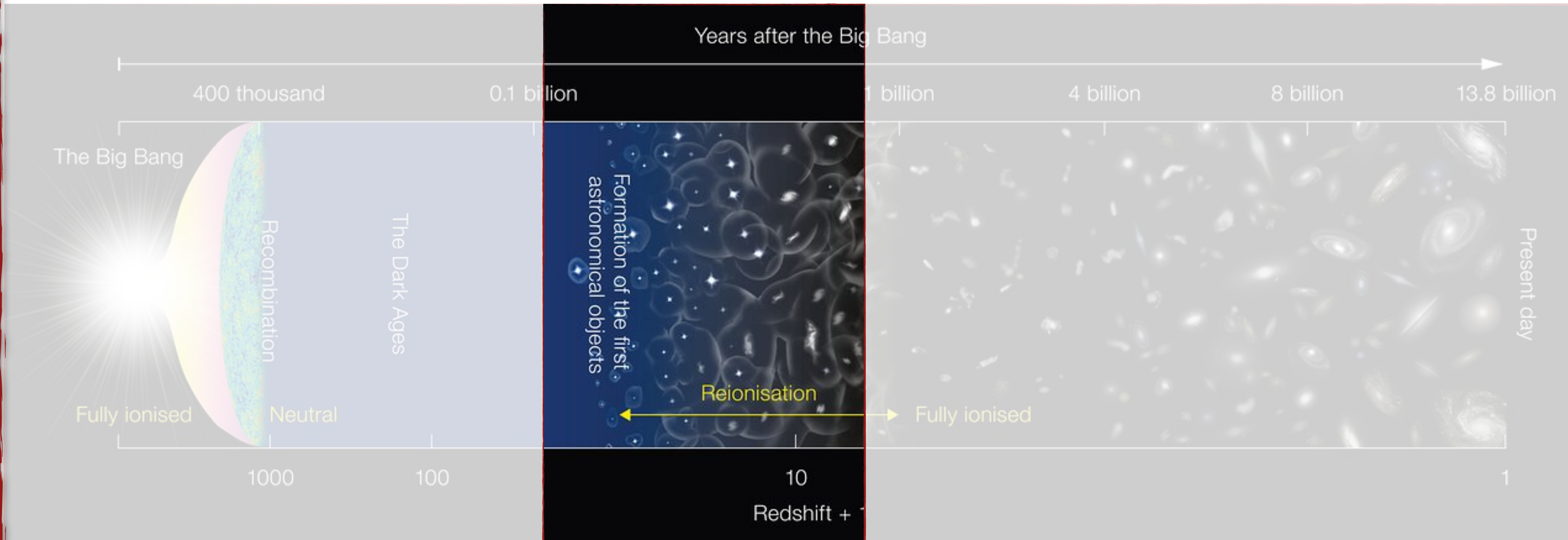
Some examples:

- Asymmetric dark matter
- Co-annihilation partner present in the early universe, absent today
- 3-body annihilation
- Velocity-suppressed annihilation

Dark sectors containing long-range forces can be particularly constrained (attractive interactions enhance low-velocity annihilation rate, a.k.a. the Sommerfeld enhancement)

Constraints from Cosmology

The late Universe



Constraints from Cosmology

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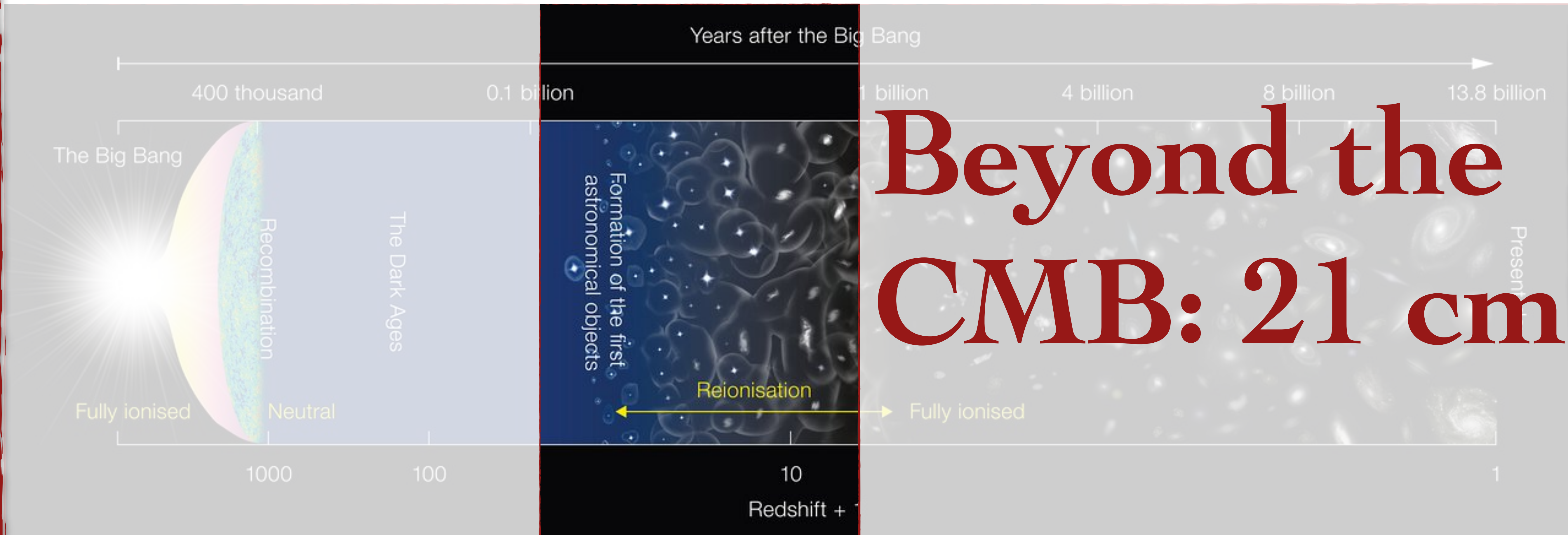
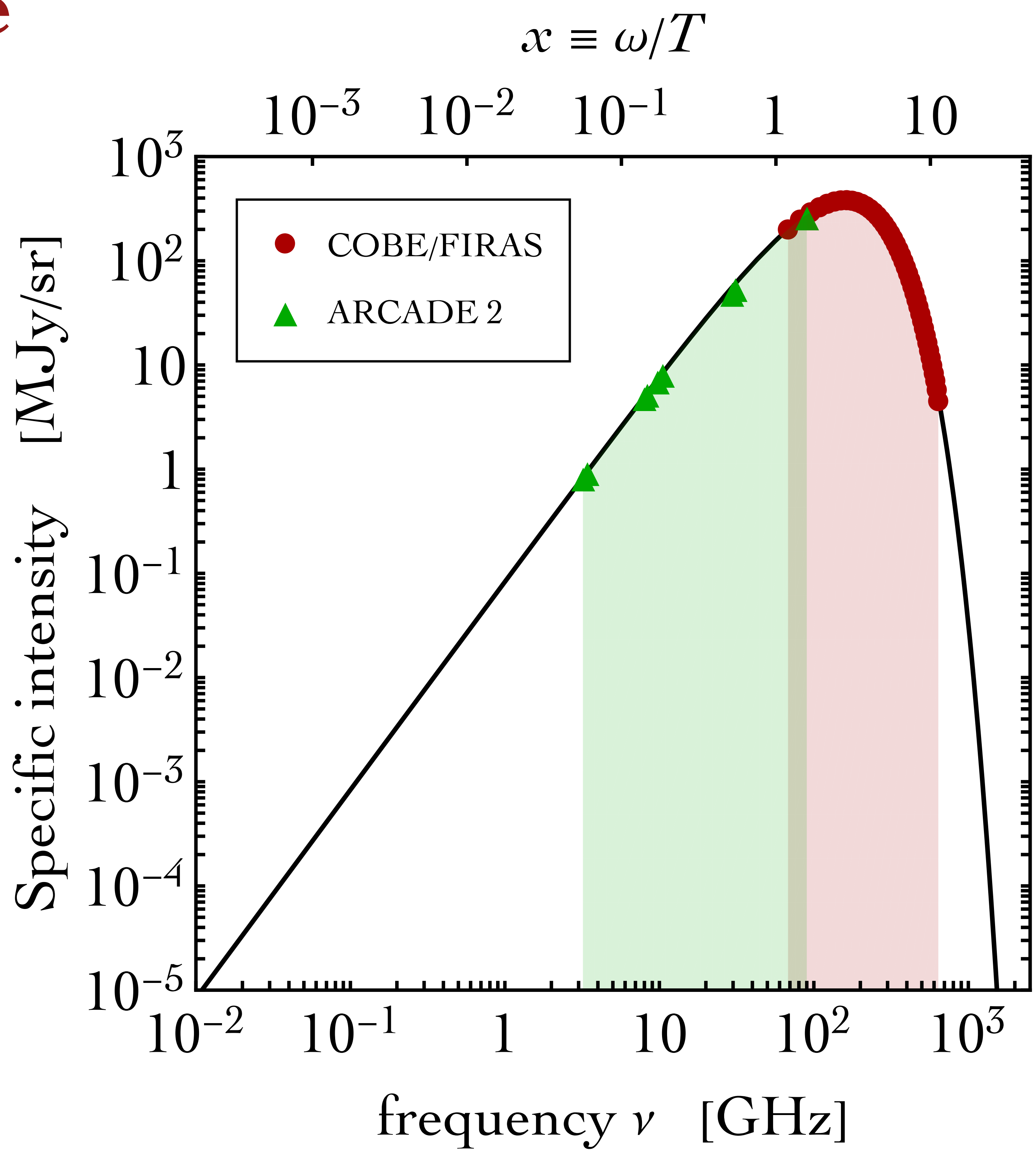


Beyond the CMB: 21 cm

Constraints from Cosmology

The late Universe

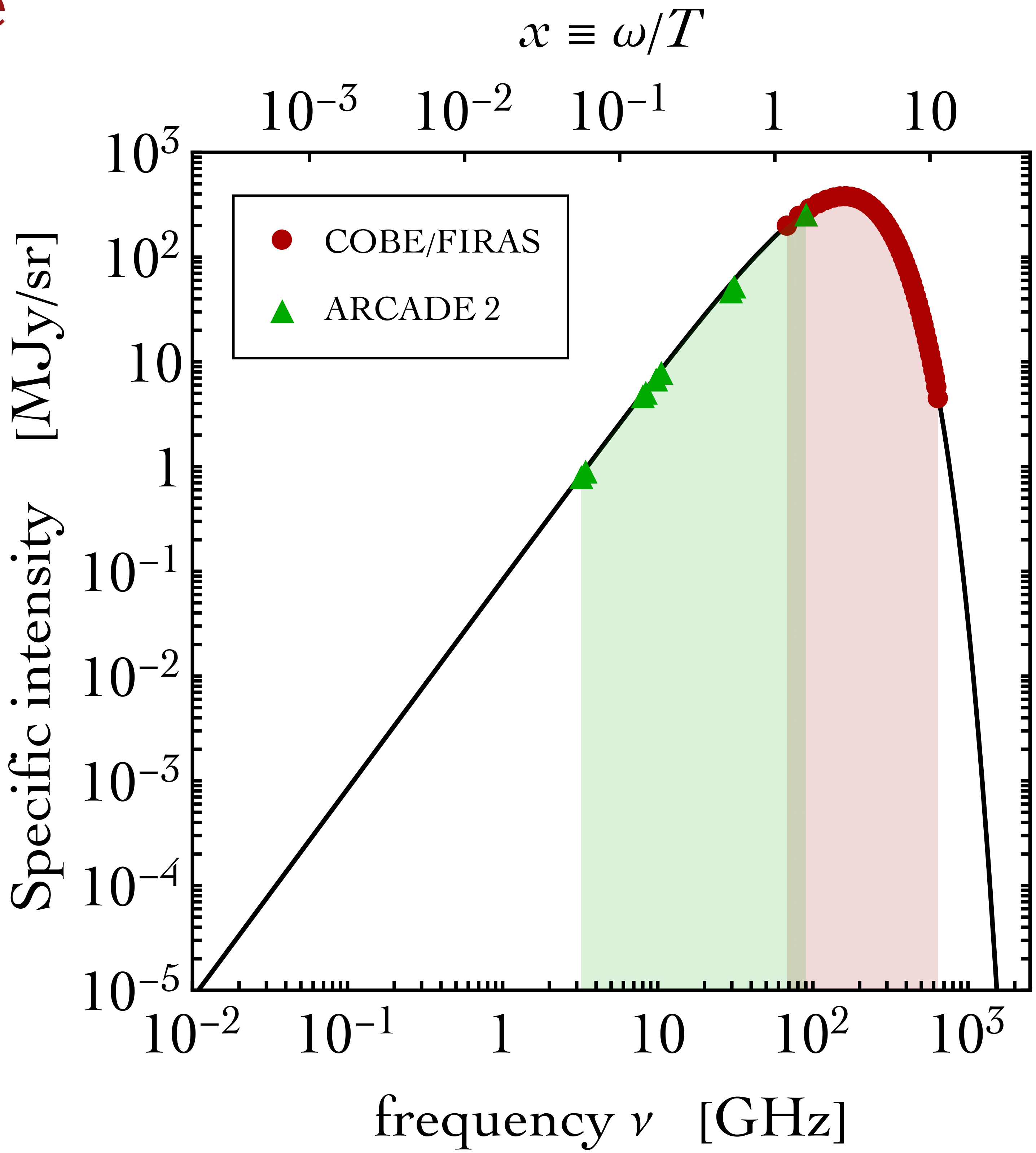
Intensity of the CMB compared to a perfect blackbody curve with $T_0 = 2.735$ K



$$\mathscr{I}(\nu, T) = \frac{2\pi\nu^3}{c^2}\frac{1}{\left[\exp\left(\frac{h\nu}{k_B T}\right) - 1\right]}$$

Constraints from Cosmology

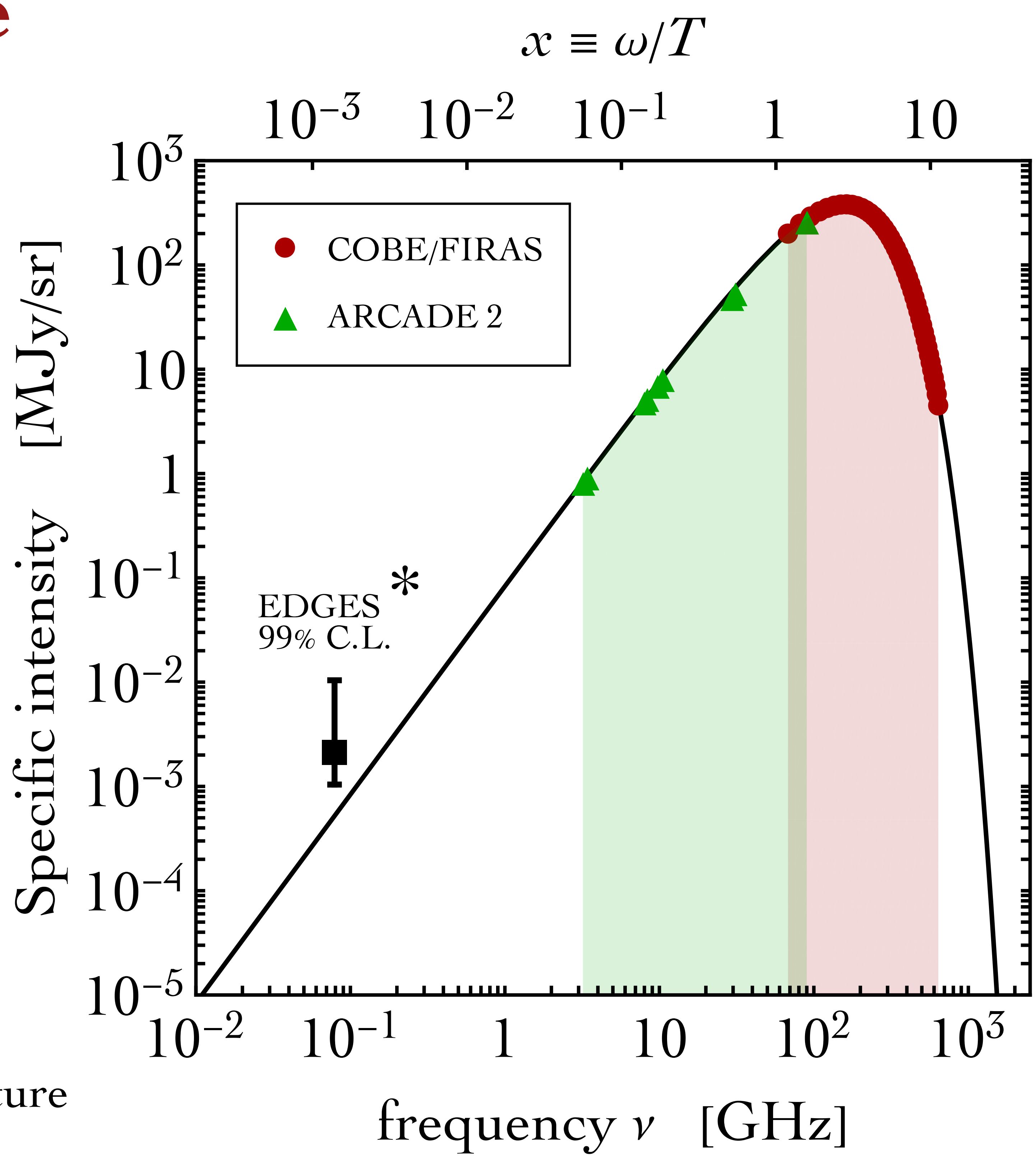
The late Universe



Constraints from Cosmology

The late Universe

Bowman *et. al.* Nature **555**, 67 (2018)

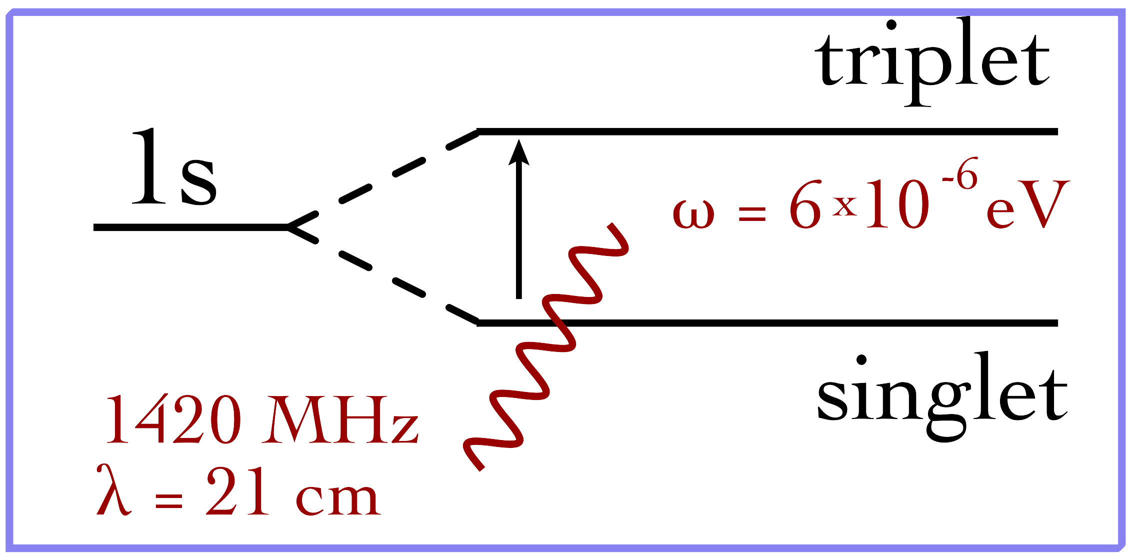


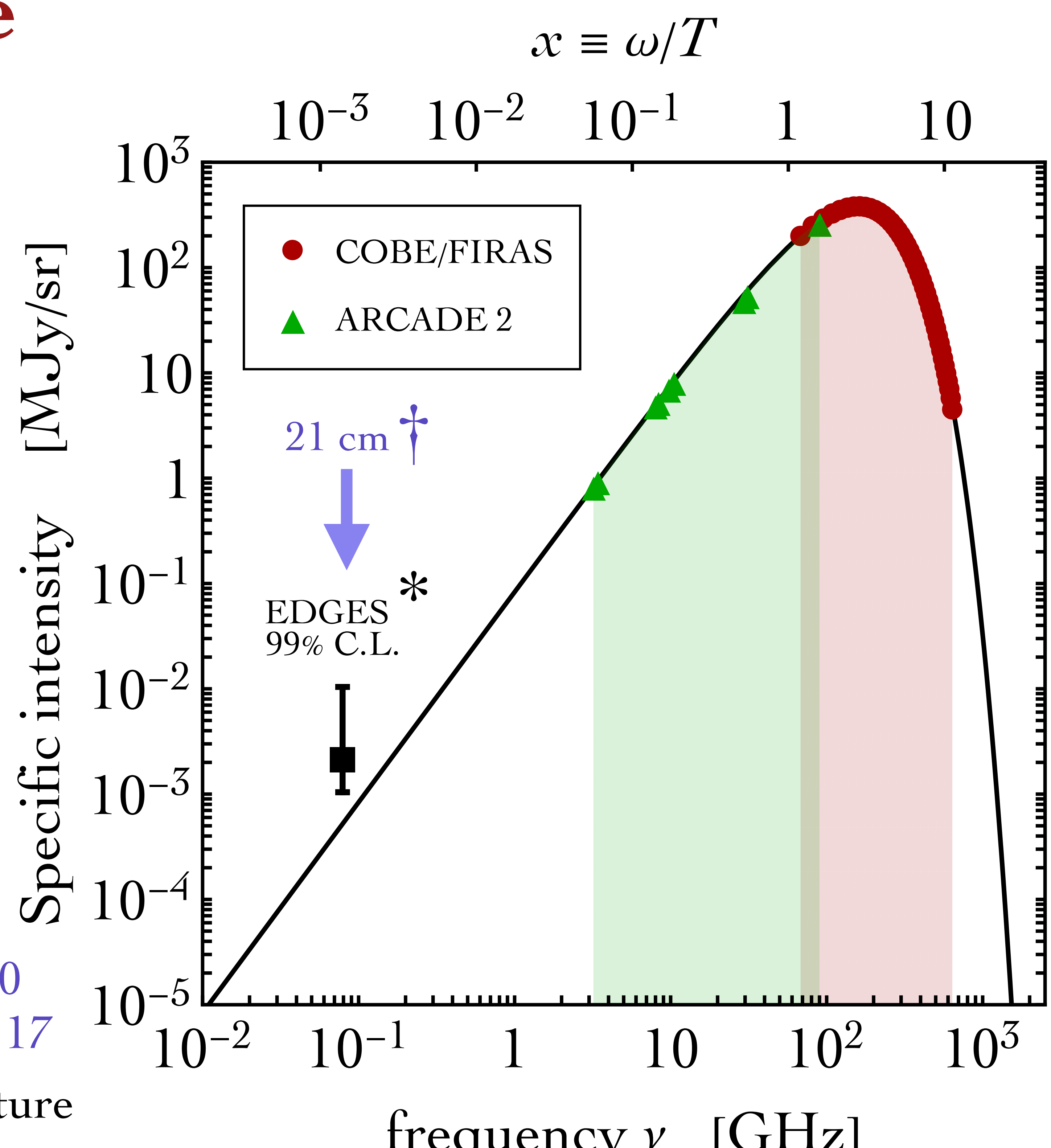
* Assuming a model for the gas temperature

Constraints from Cosmology

The late Universe

Bowman *et. al.* Nature **555**, *67* (2018)

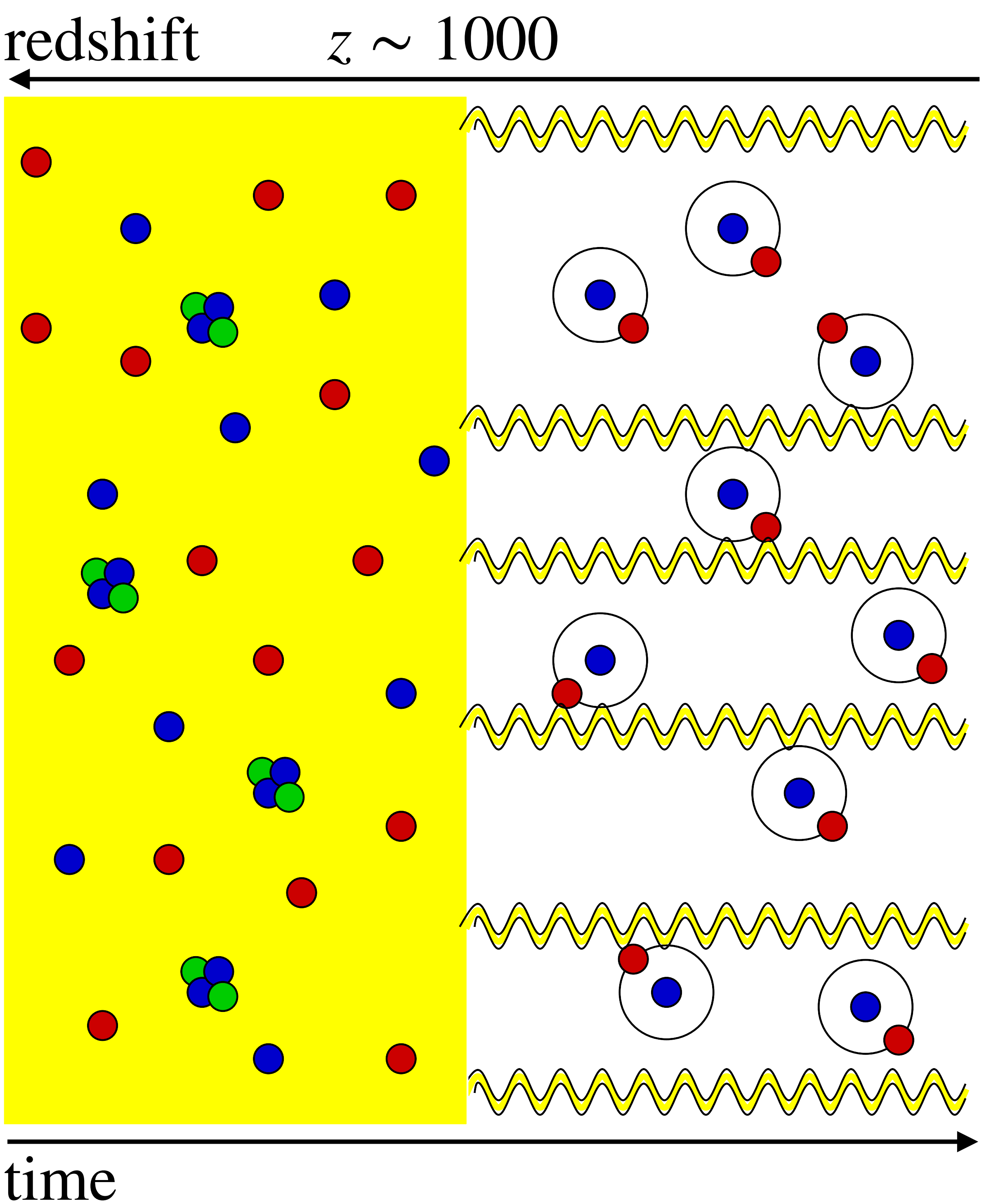




† Frequency of a photon at redshift z = 0 with wavelength 21 cm at redshift z = 17

* Assuming a model for the gas temperature

Constraints from Cosmology



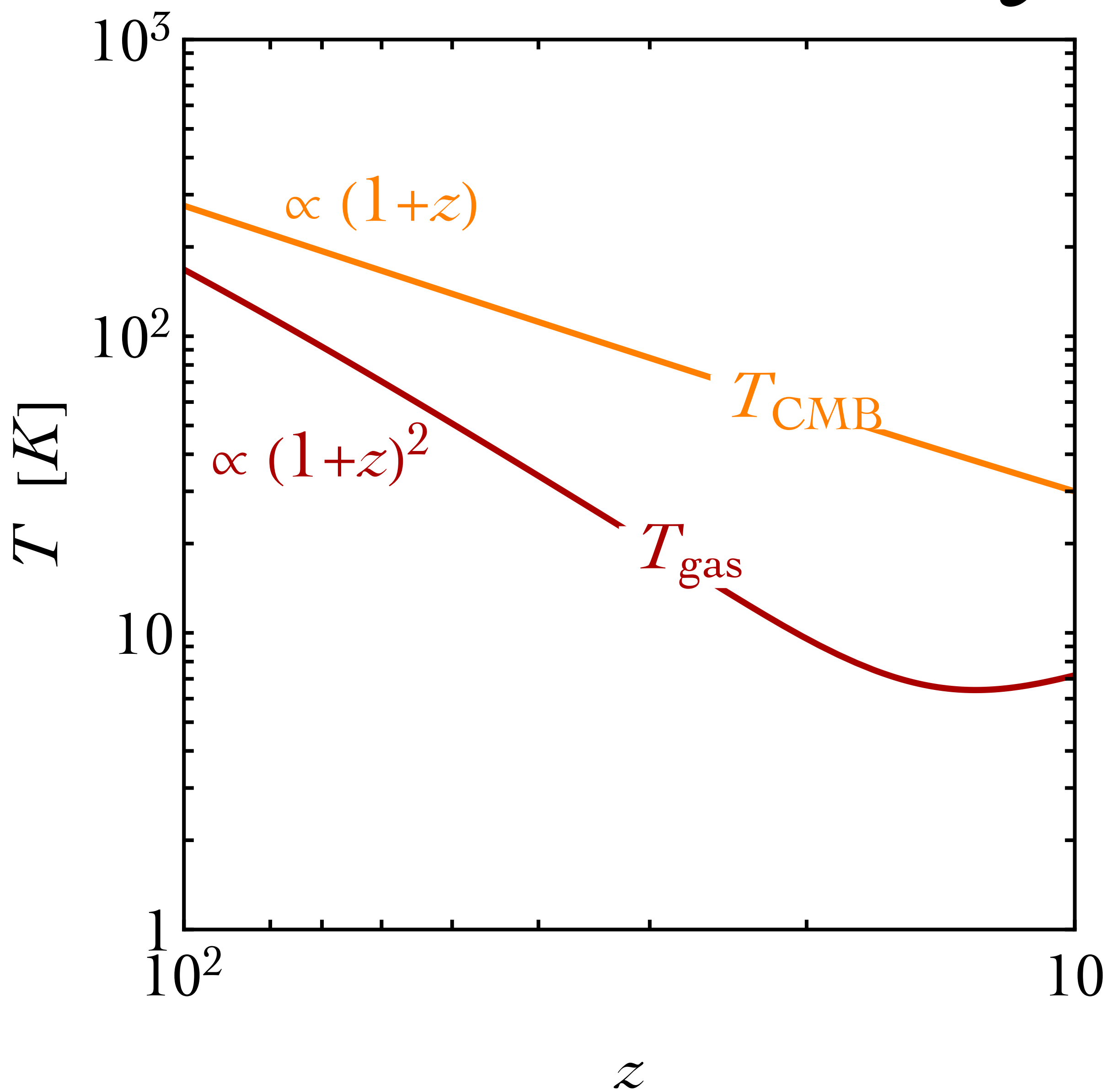
CMB photons

$$T_{\rm CMB}(z) = (1+z)T_0$$

Hydrogen atoms

$$T_{gas}(z) \neq T_{\rm CMB}$$

Constraints from Cosmology



CMB photons

$$T_{\rm CMB}(z) = (1+z)T_0$$

Hydrogen atoms

$$T_{gas}(z) \neq T_{\rm CMB}$$

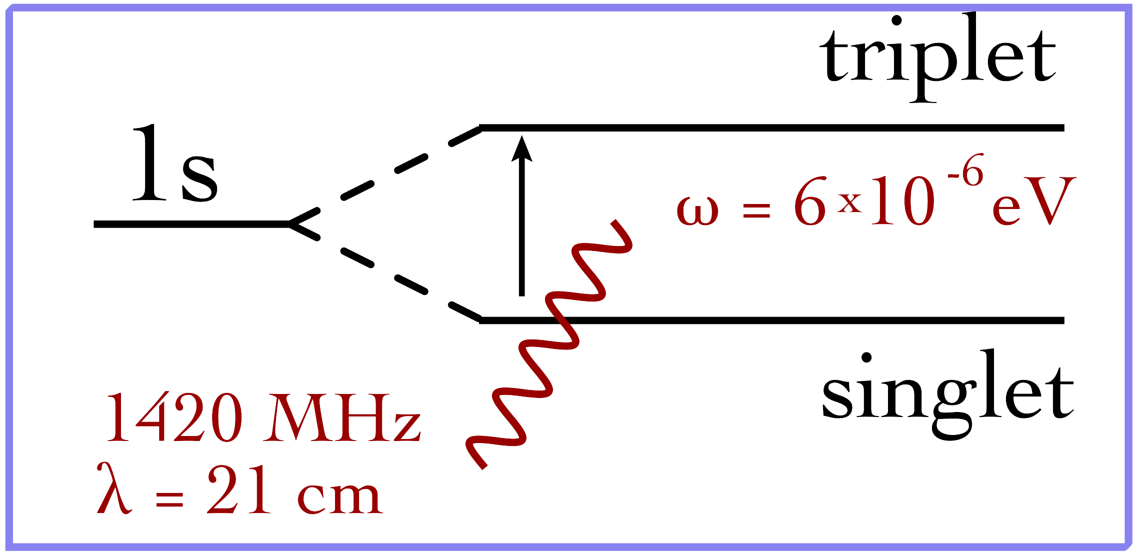
The gas thermally decouples from the CMB and *cools adiabatically* with the expansion of the Universe.

The particles of the gas are slowed down by the expansion of the Universe because their de Broglie wavelength $\lambda_{\rm dB} = 2\pi/p$ is redshifted as $\lambda_{\rm dB} \propto a$

Therefore the momentum of the particle goes as $p \propto a^{-1}$

Their kinetic energy goes as $E_{\rm kin} = \dfrac{p^2}{2m} \propto a^{-2}$

Constraints from Cosmology



CMB photons

$$T_{\rm CMB}(z) = (1+z)T_0$$

Hydrogen atoms

$$T_{gas}(z) \neq T_{\rm CMB}$$

$$T_s(z)$$

$\Delta E \simeq 0.068\,\mathrm{K}$
energy difference between the two state

$$\frac{n_1}{n_0} = 3e^{-\Delta E/T_s}$$

number densities of electrons in the triplet and singlet states of the hyperfine level

The spin temperature is merely a shorthand
for the ratio between the occupation number
of the two hyperfine levels.

Constraints from Cosmology

What sets the relative occupation?

CMB photons

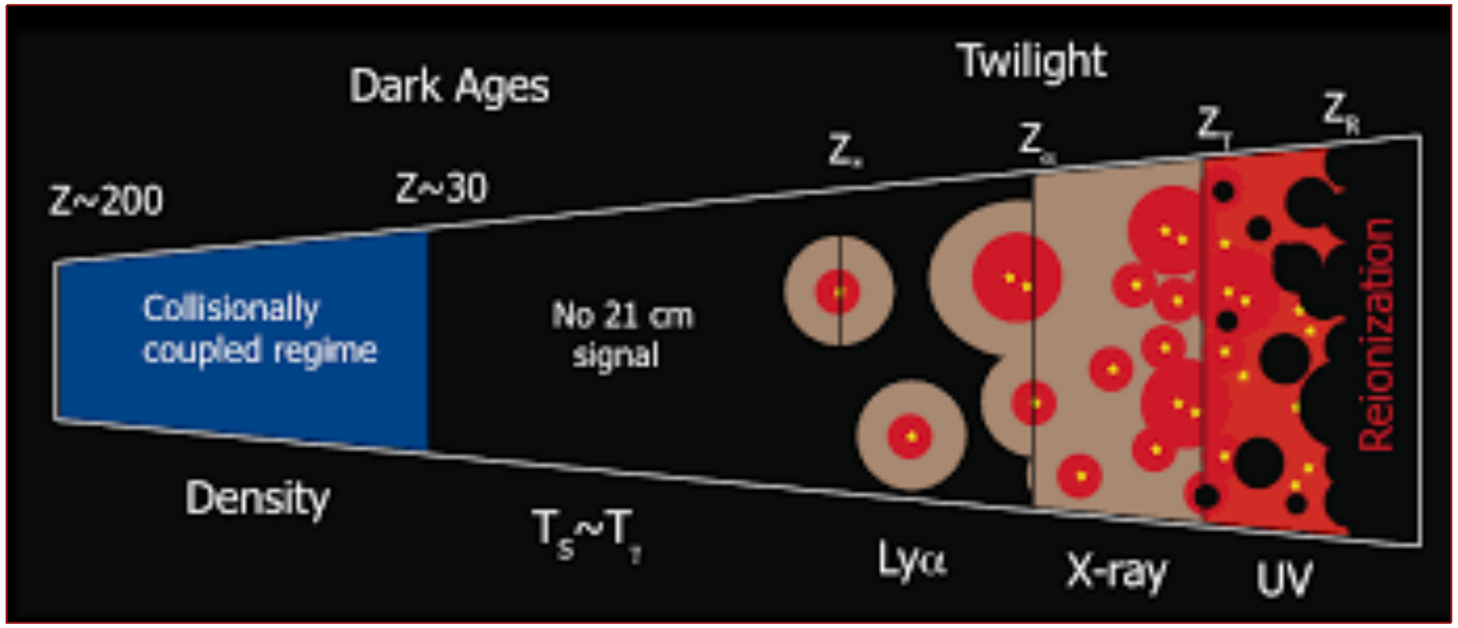
$$T_{\rm CMB}(z) = (1+z)T_0$$

Hydrogen atoms

$$T_{gas}(z) \neq T_{\rm CMB}$$

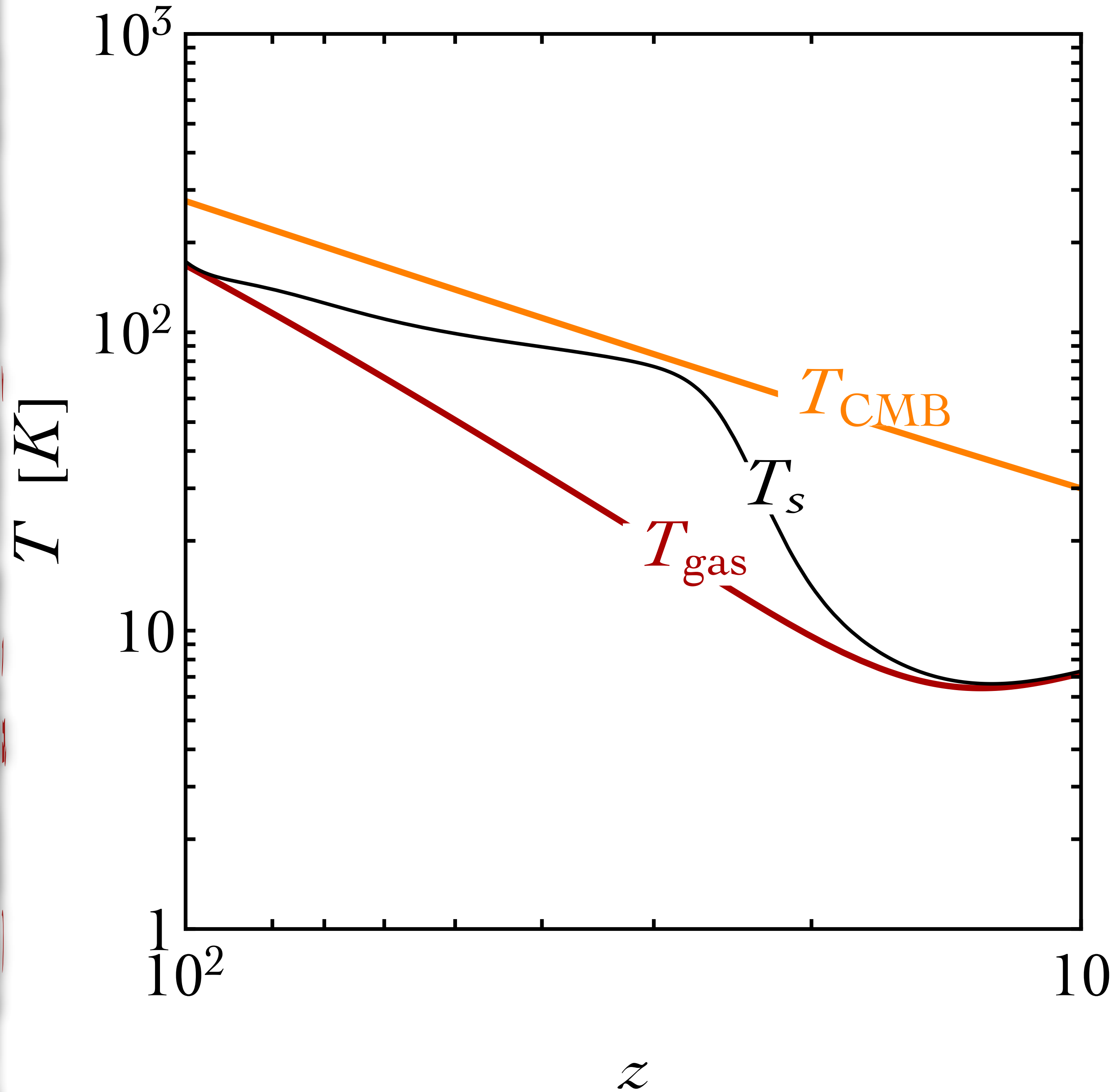
$$T_s(z)$$

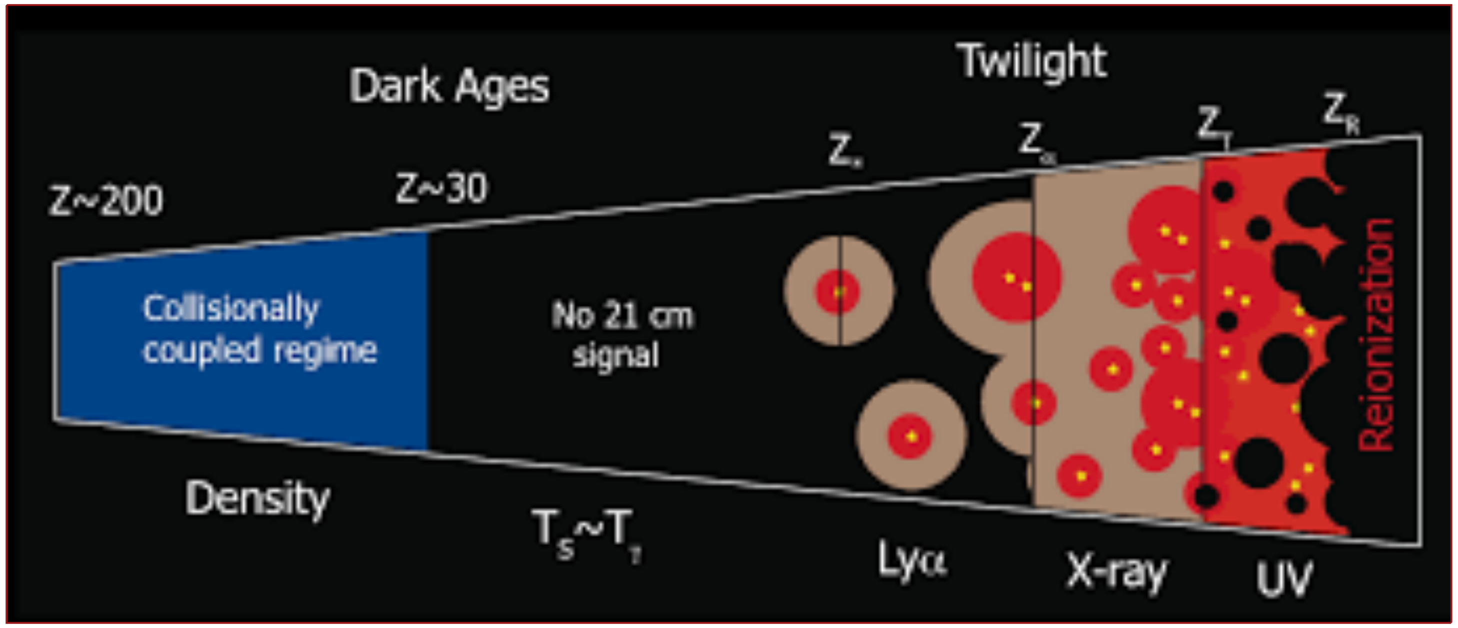
- **Absorption of background CMB light**
- **Collisions among gas atoms** (important when density is high)
- **Ly-alpha pumping** (the "Wouthuysen-Field effect" important after the formation of the firsts collapsed objects)



The solution of the radiative transfer problem gives

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_{gas}^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha}$$





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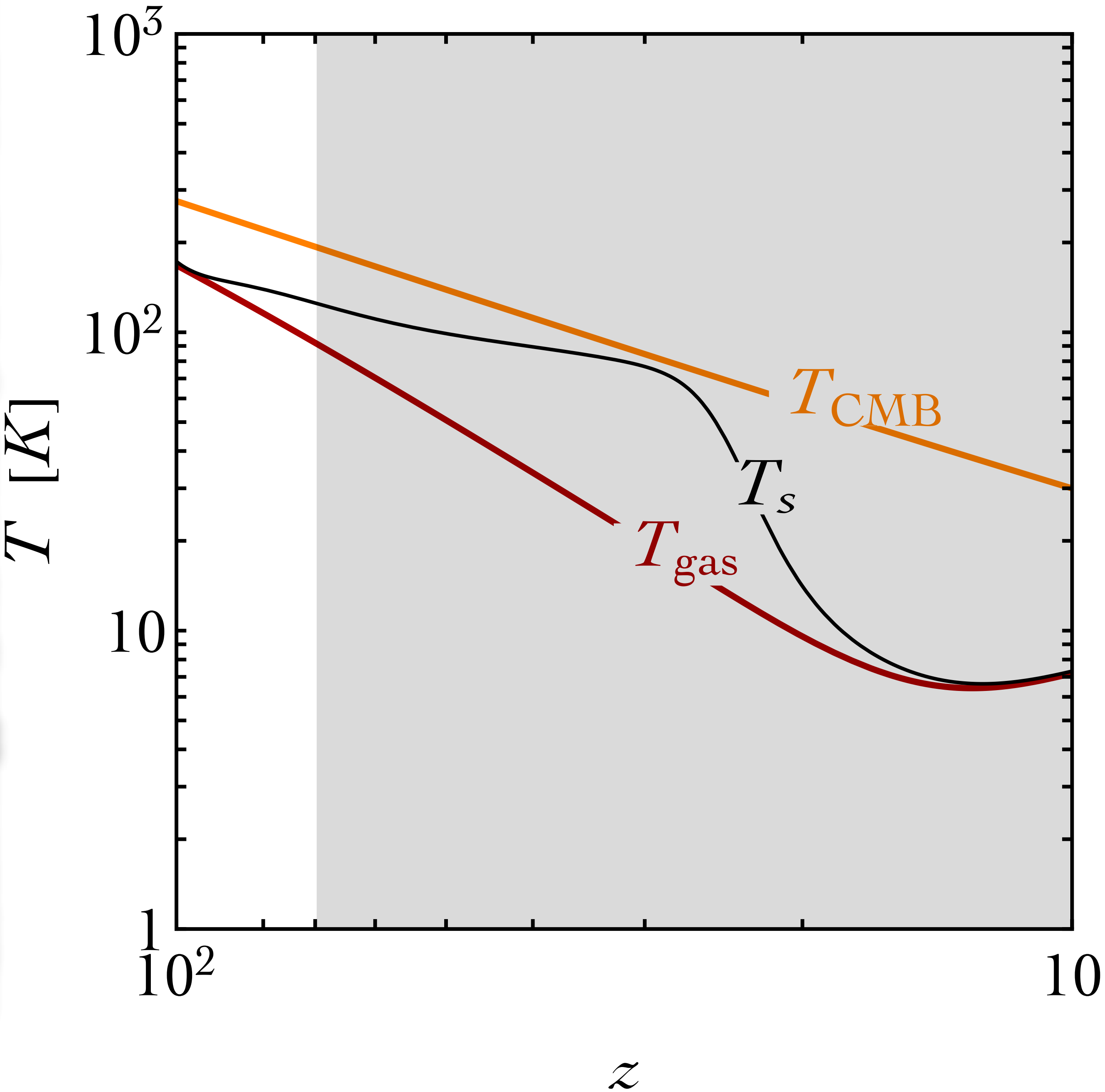

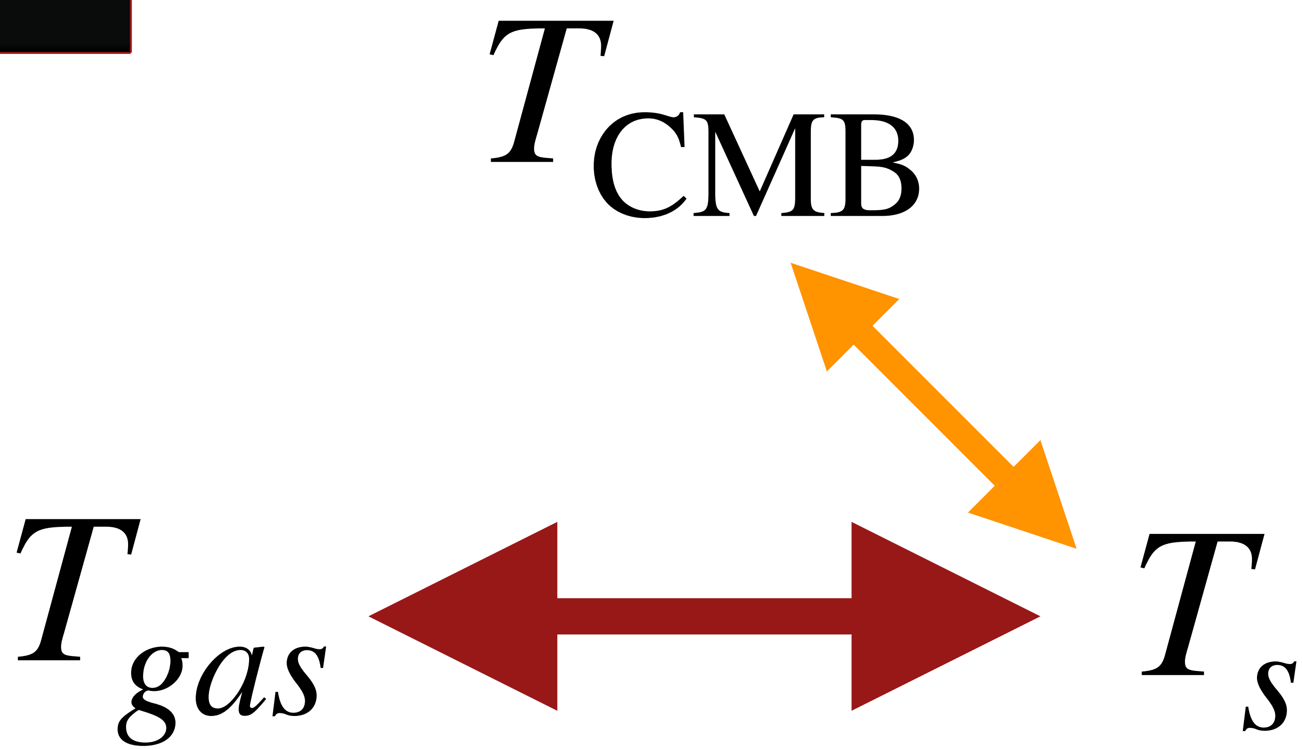

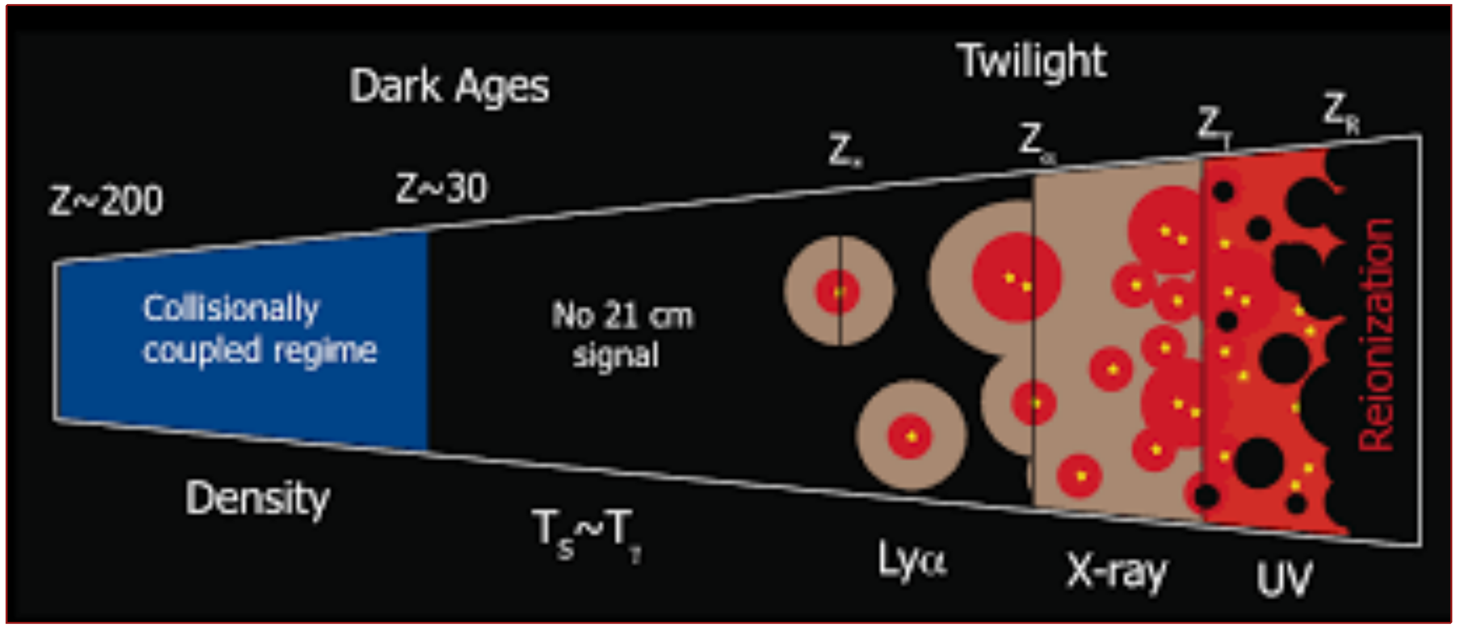

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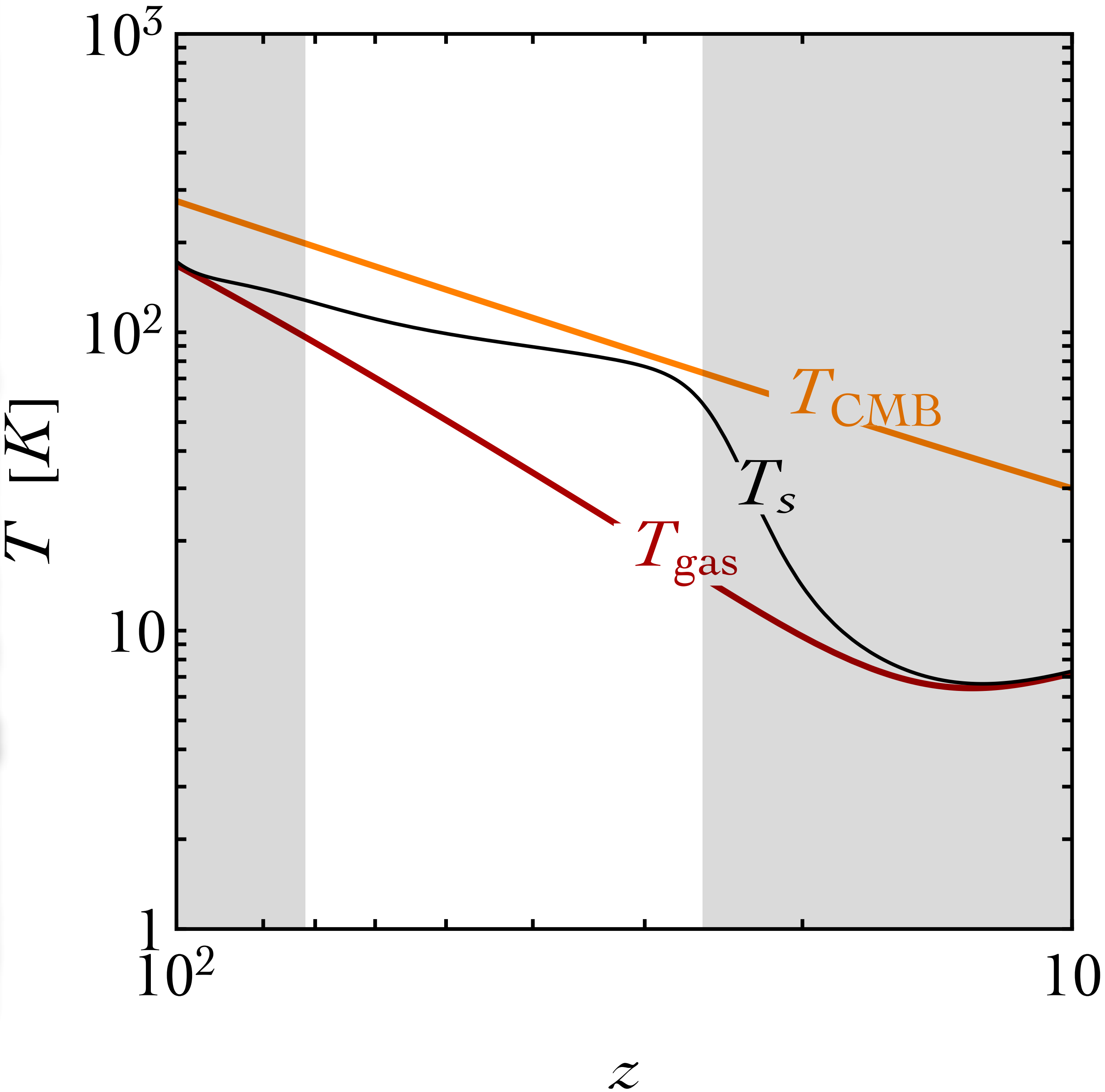

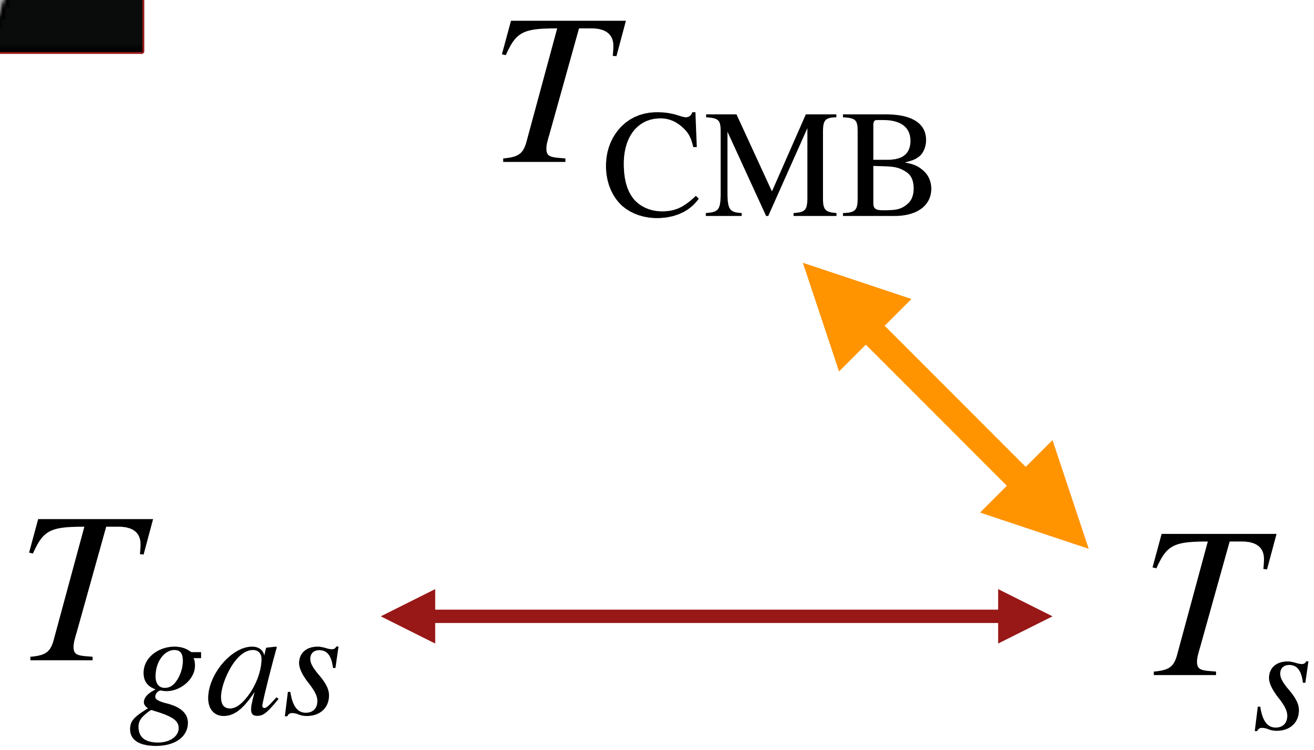

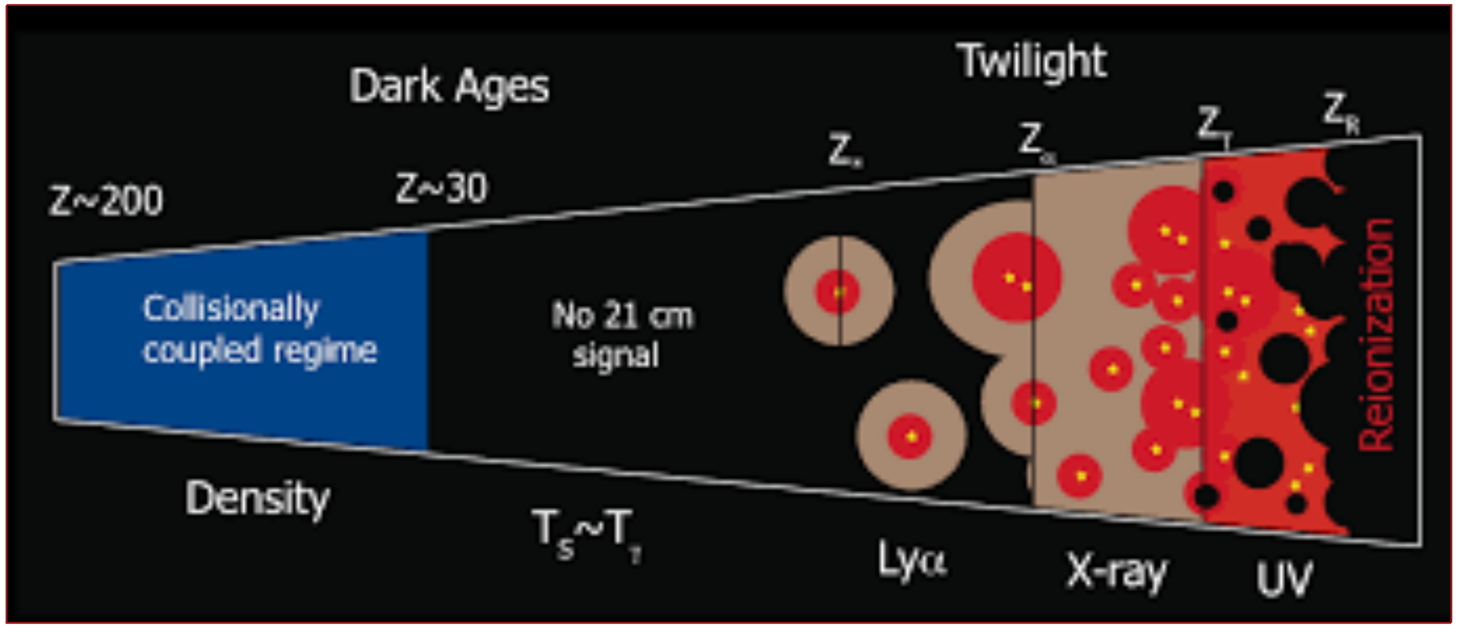

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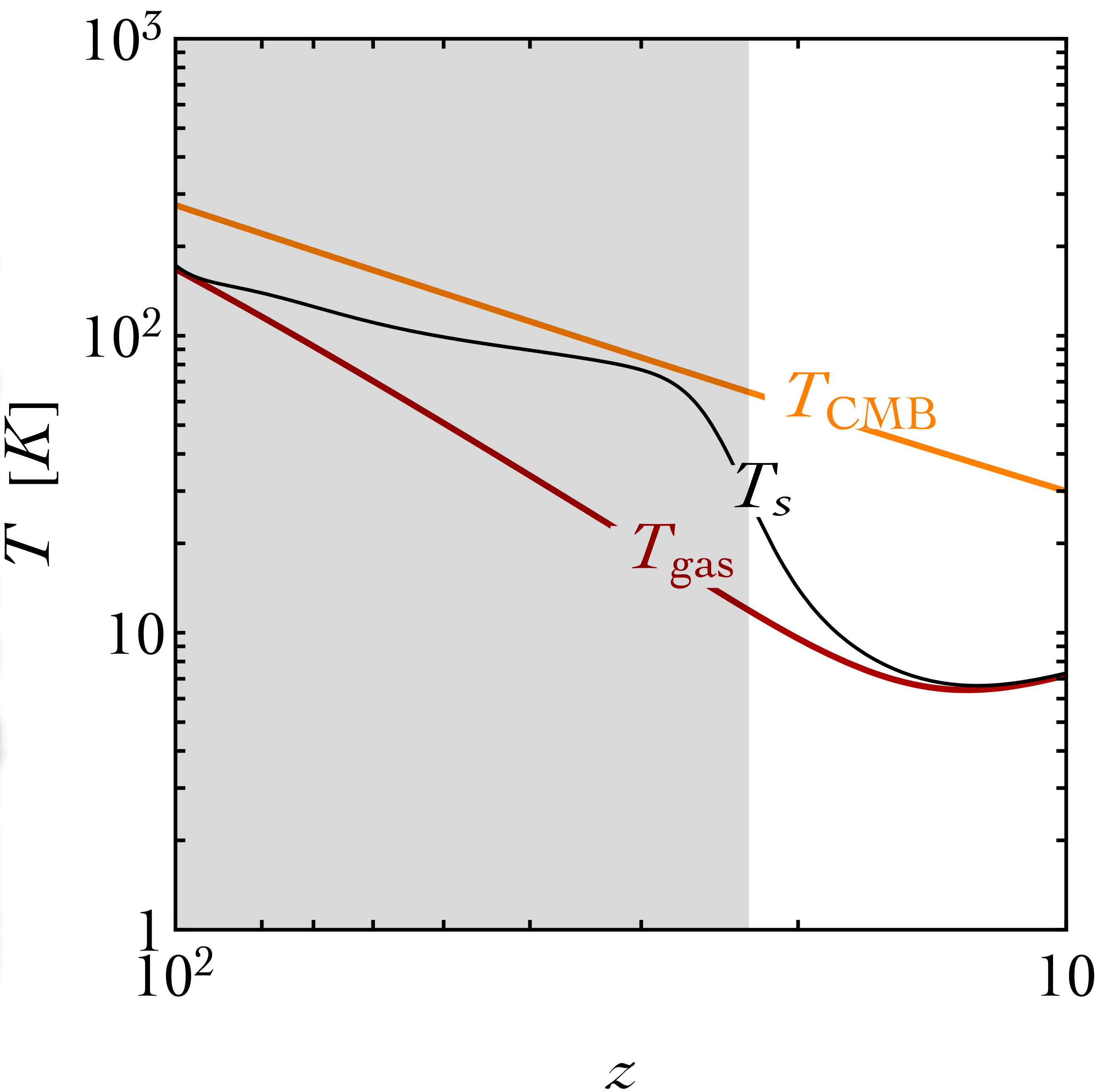
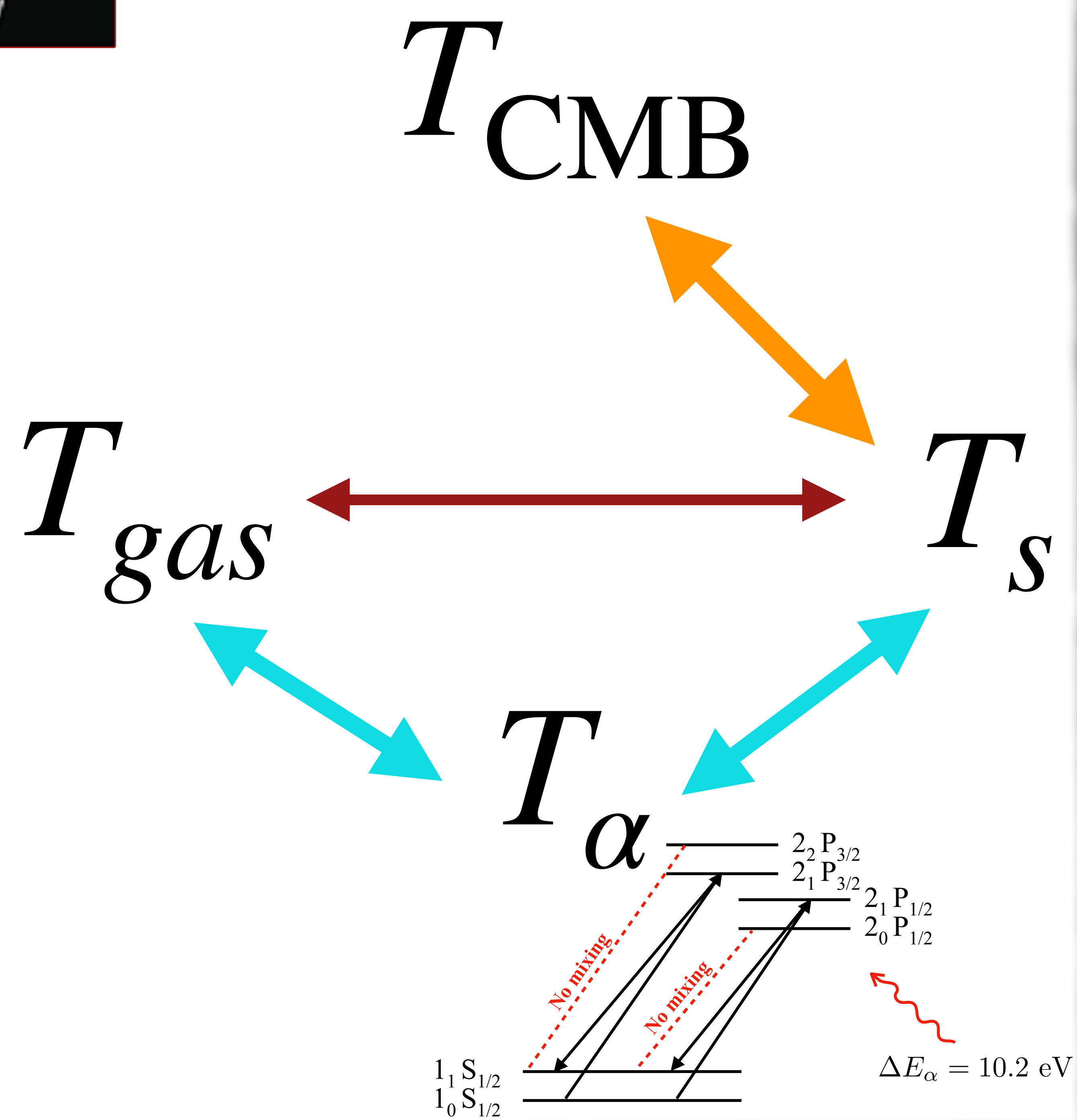
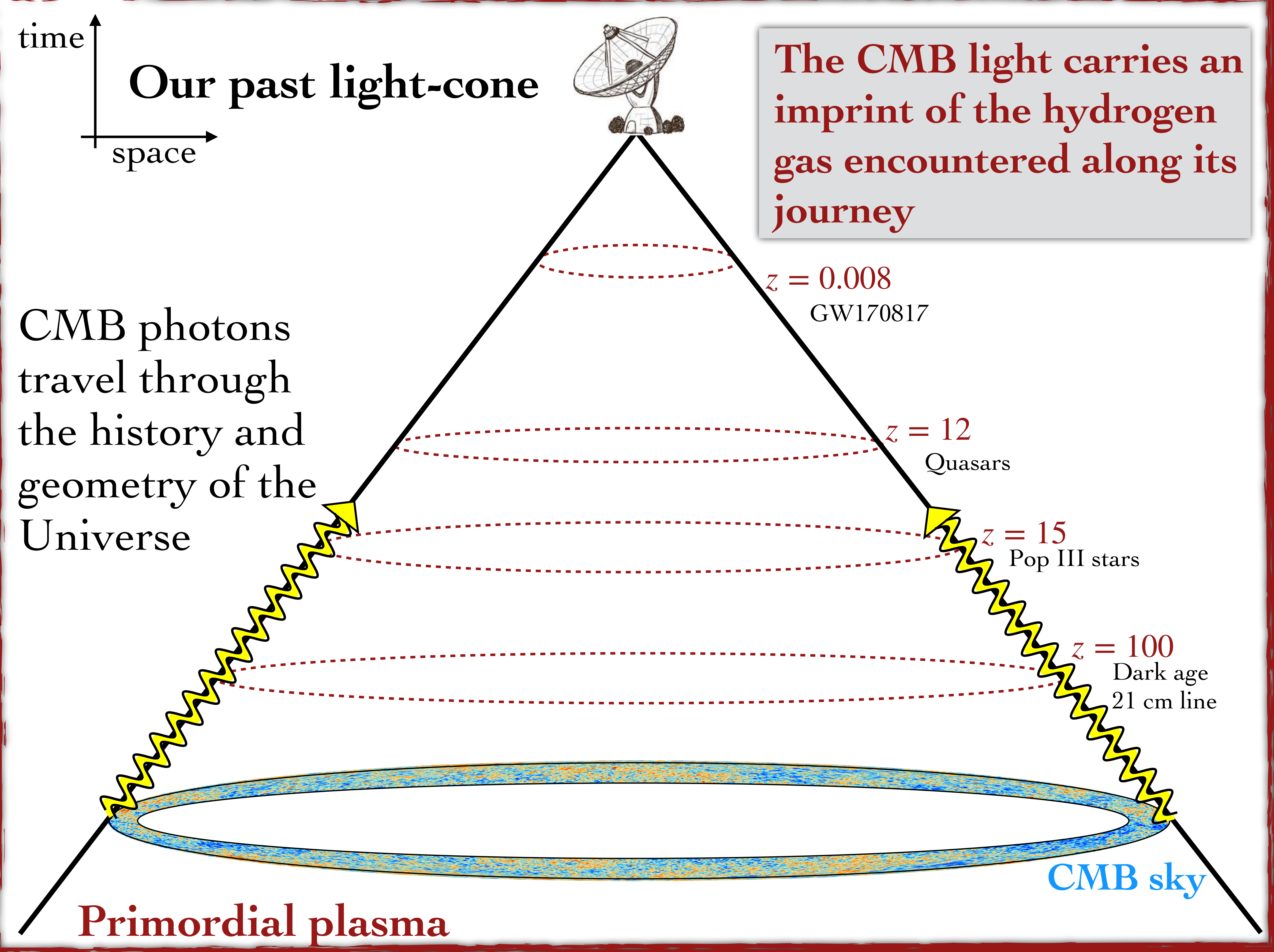
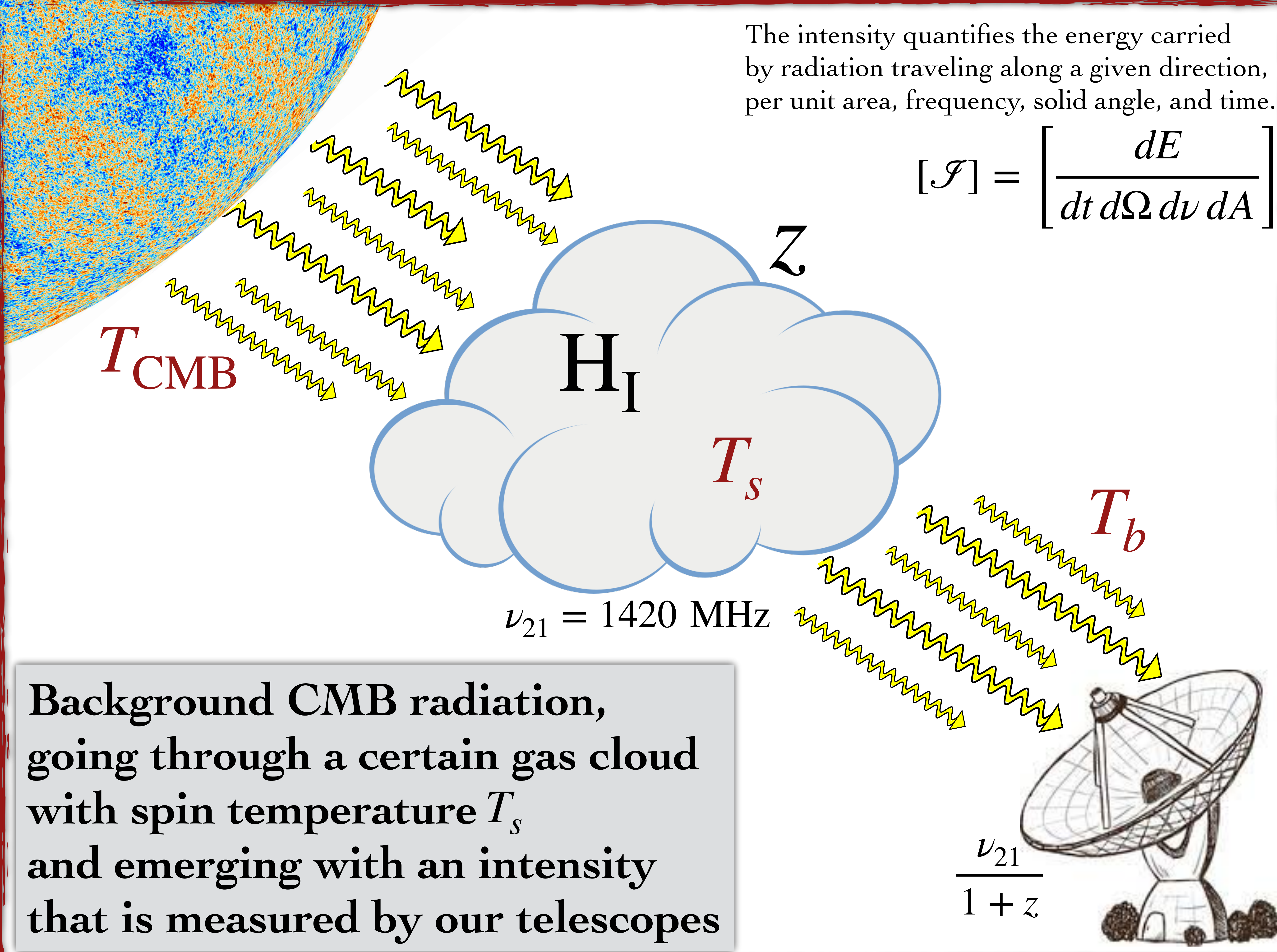




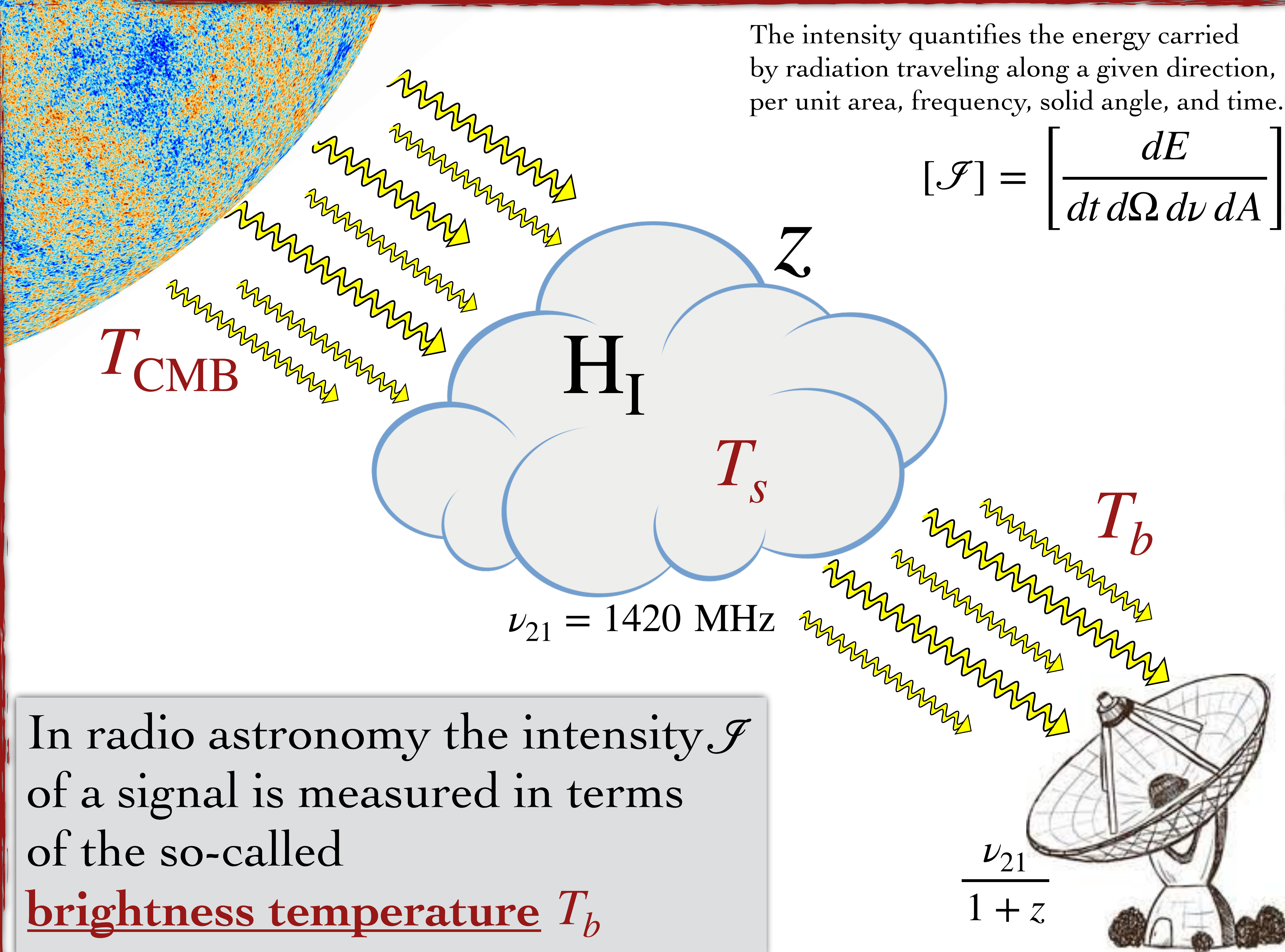

time
space
Our past light-cone
The CMB light carries an imprint of the hydrogen gas encountered along its journey
CMB photons travel through the history and geometry of the Universe
z = 0.008
GW170817
z = 12
Quasars
z = 15
Pop III stars
z = 100
Dark age
21 cm line
CMB sky
Primordial plasma

The intensity quantifies the energy carried by radiation traveling along a given direction, per unit area, frequency, solid angle, and time.

$$[\mathcal{I}] = \left[\frac{dE}{dt\, d\Omega\, d\nu\, dA}\right]$$



Background CMB radiation, going through a certain gas cloud with spin temperature T_s and emerging with an intensity that is measured by our telescopes


The intensity quantifies the energy carried
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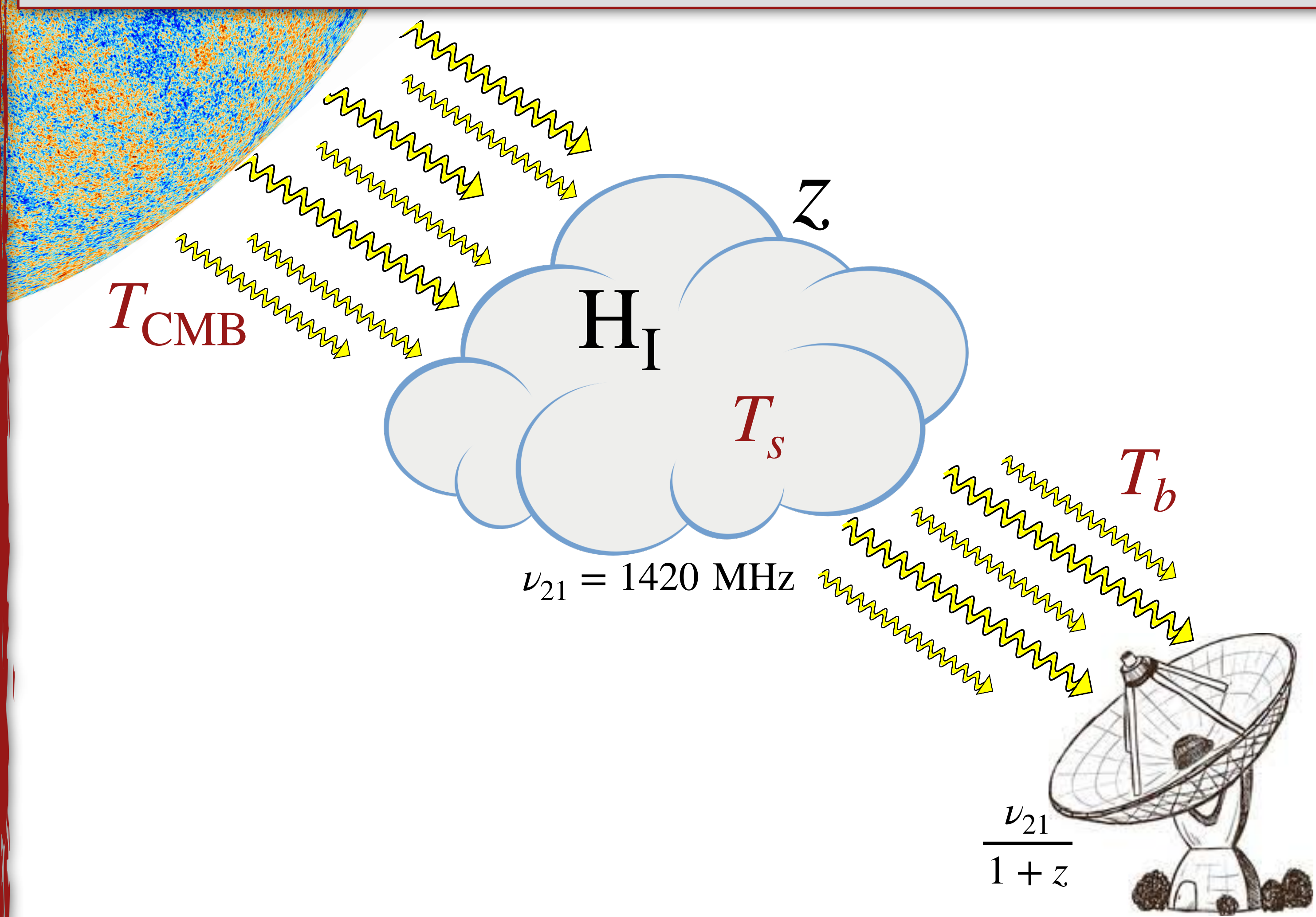
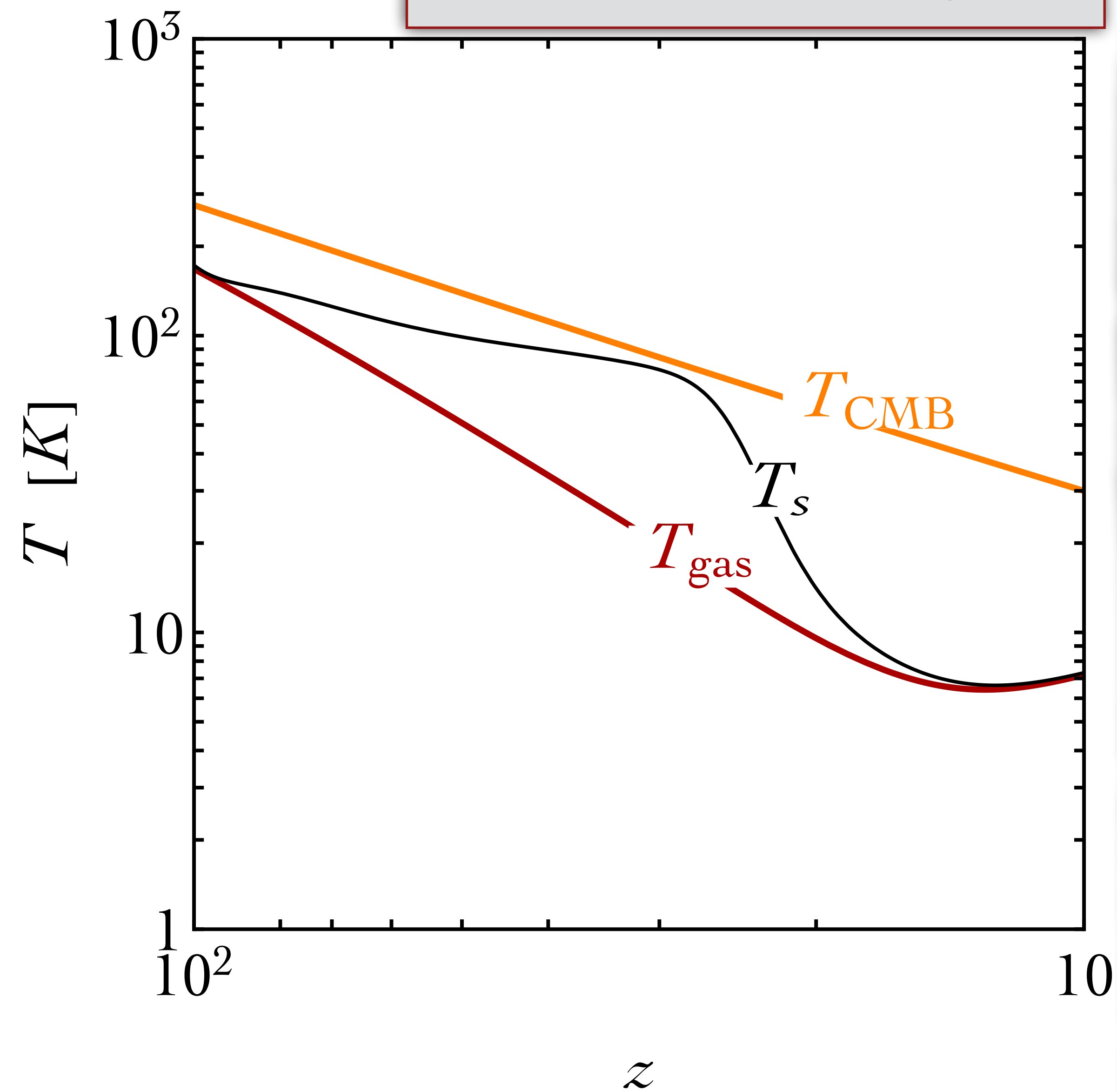
$[\mathcal{I}] = \left[\frac{dE}{dt\, d\Omega\, d\nu\, dA}\right]$
z
$T_{\rm CMB}$
$\rm H_I$
T_s
T_b
$\nu_{21} = 1420$ MHz
$\frac{\nu_{21}}{1+z}$
In radio astronomy the intensity $\mathcal{I}$
of a signal is measured in terms
of the so-called
brightness temperature T_b

$$\delta T_b \approx 23\, x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{\rm CMB}(z)}{T_s(z)}\right] \text{mK}$$

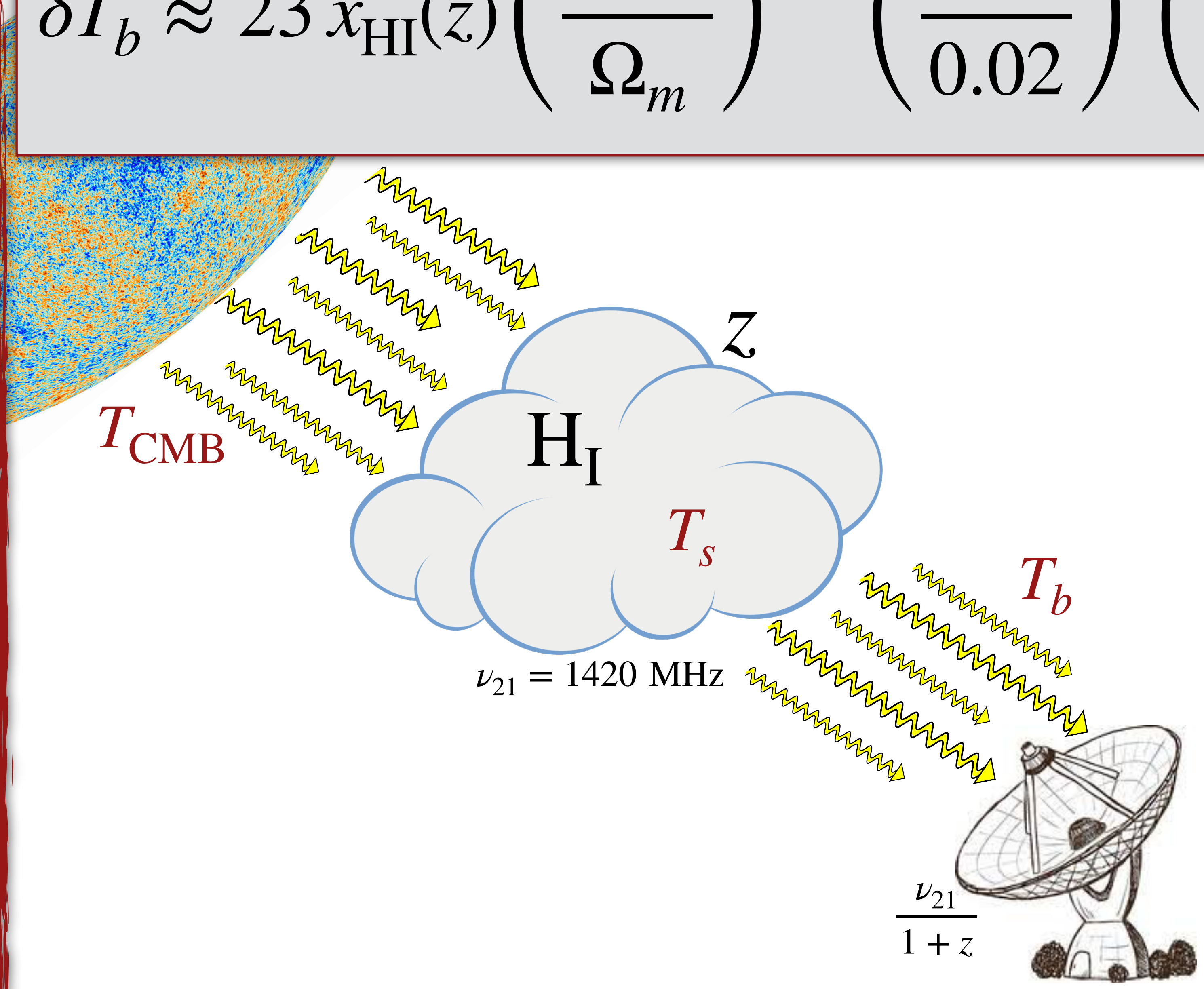
$$\delta T_b \equiv T_b - T_{\rm CMB}$$

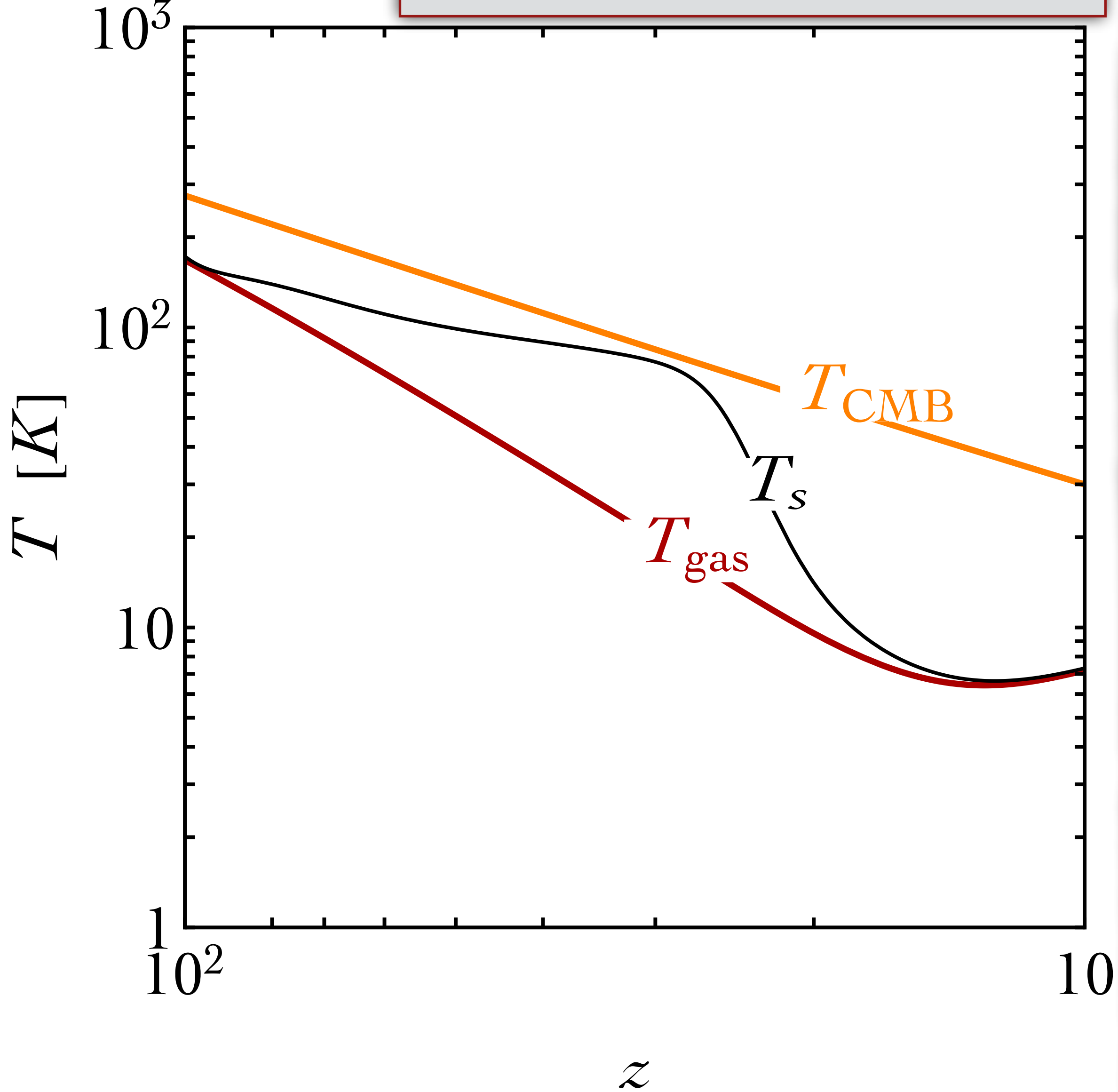




$$\delta T_b \approx 23\, x_{HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{CMB}(z)}{T_s(z)}\right] \mathrm{mK}$$

$$\delta T_b \equiv T_b - T_{CMB}$$





In the case in which $T_s \simeq T_{CMB}$ the brightness temperature gives exactly the CMB temperature (and the differential brightness temperature vanishes). This is simply because in such a case there is a prefect balance between the absorption and emission.

$$\delta T_b \approx 23\, x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{\rm CMB}(z)}{T_s(z)}\right] \mathrm{mK}$$

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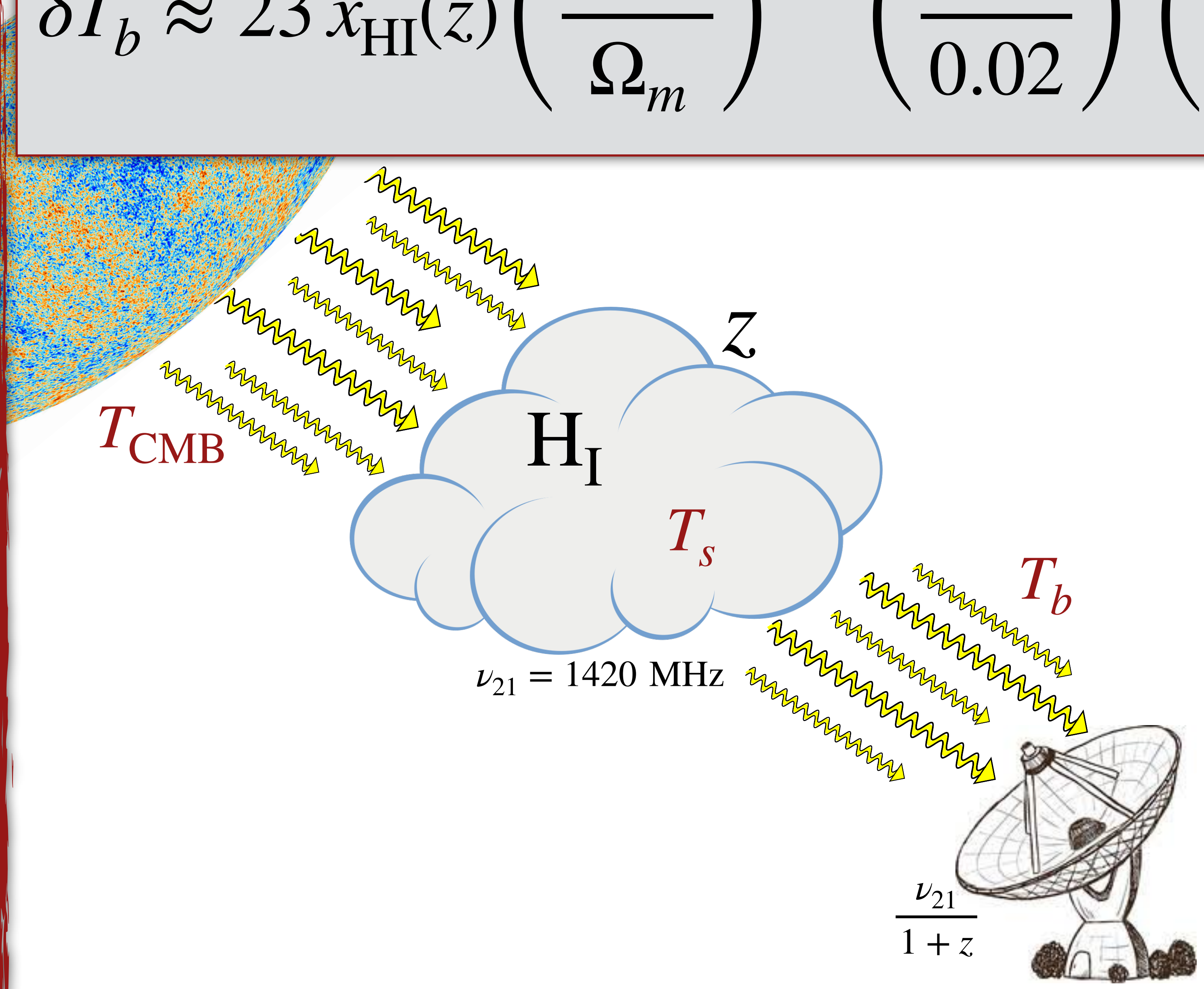
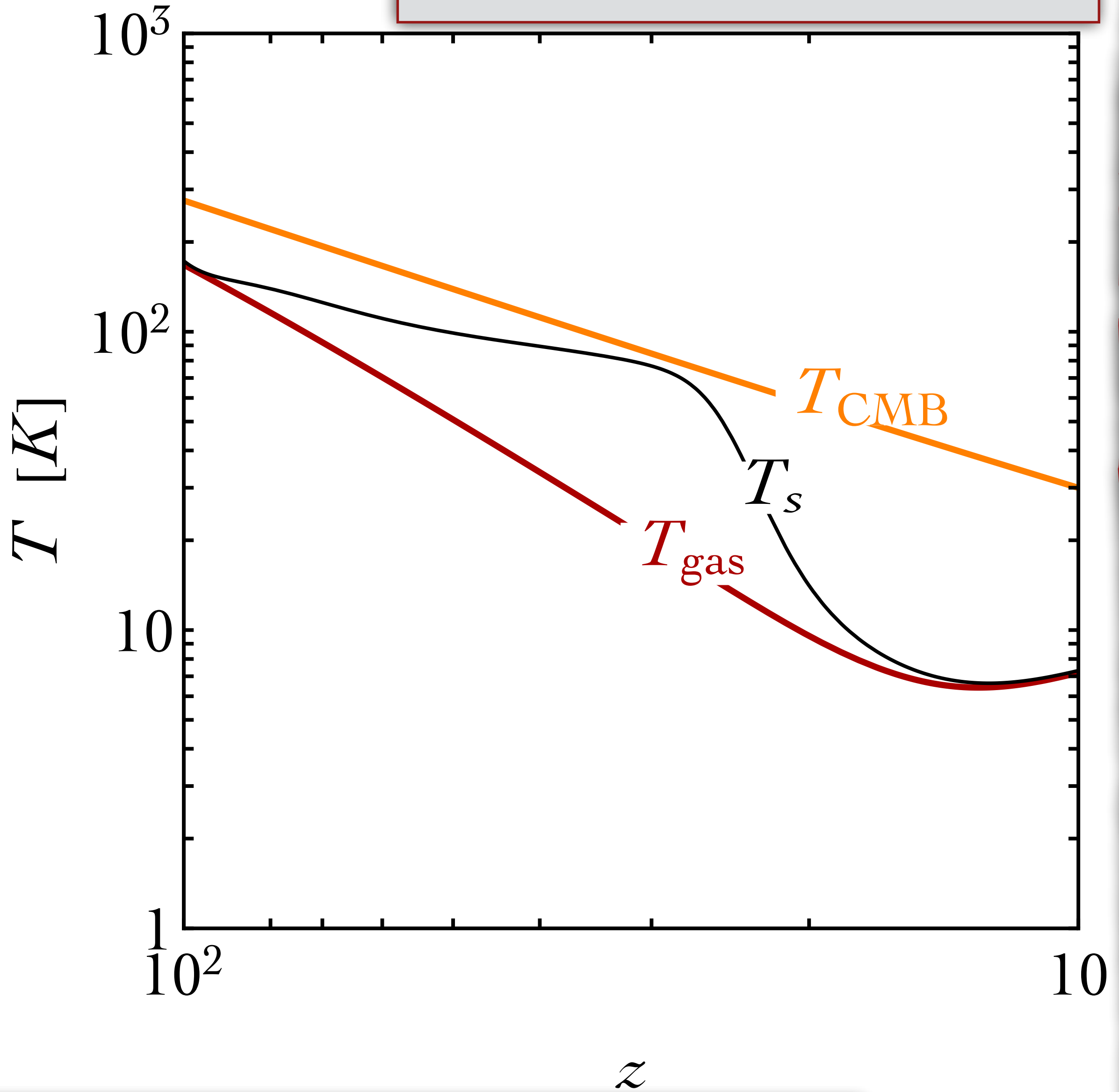
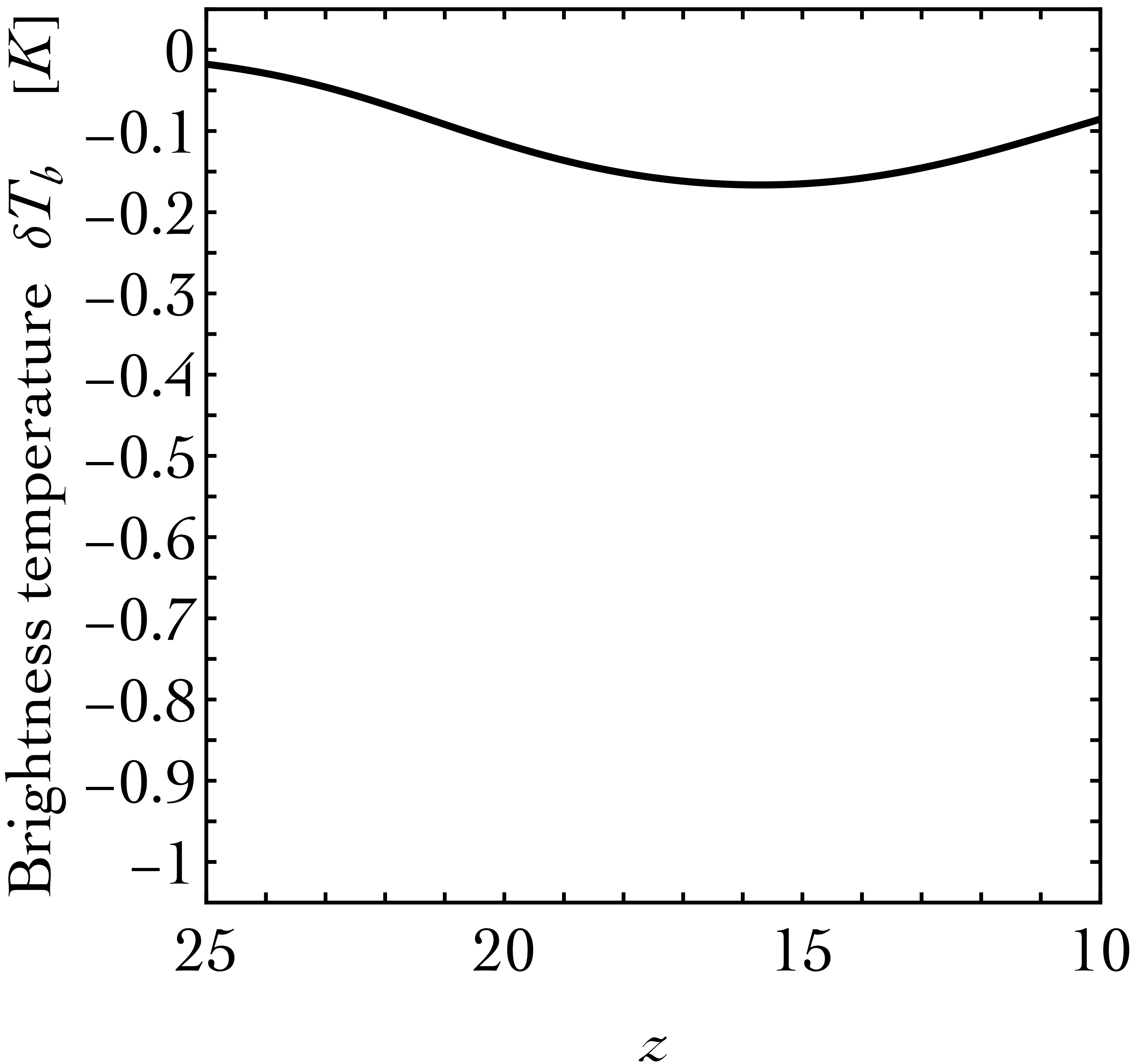




If $T_s < T_{\rm CMB}$ we have $\delta T_b < 0$

$$\delta T_b \approx 23\, x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{\rm CMB}(z)}{T_s(z)}\right] \,\rm mK$$



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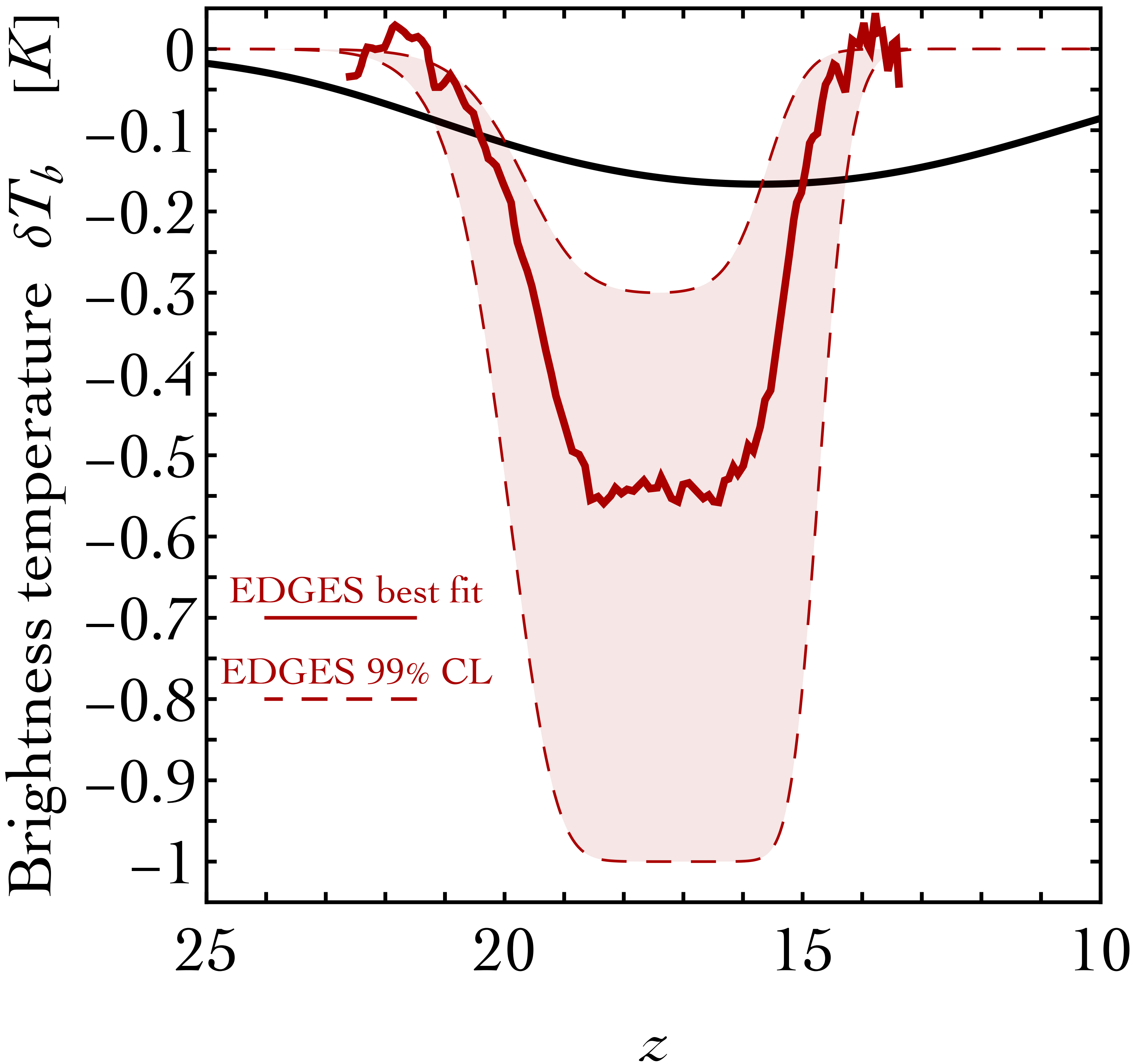
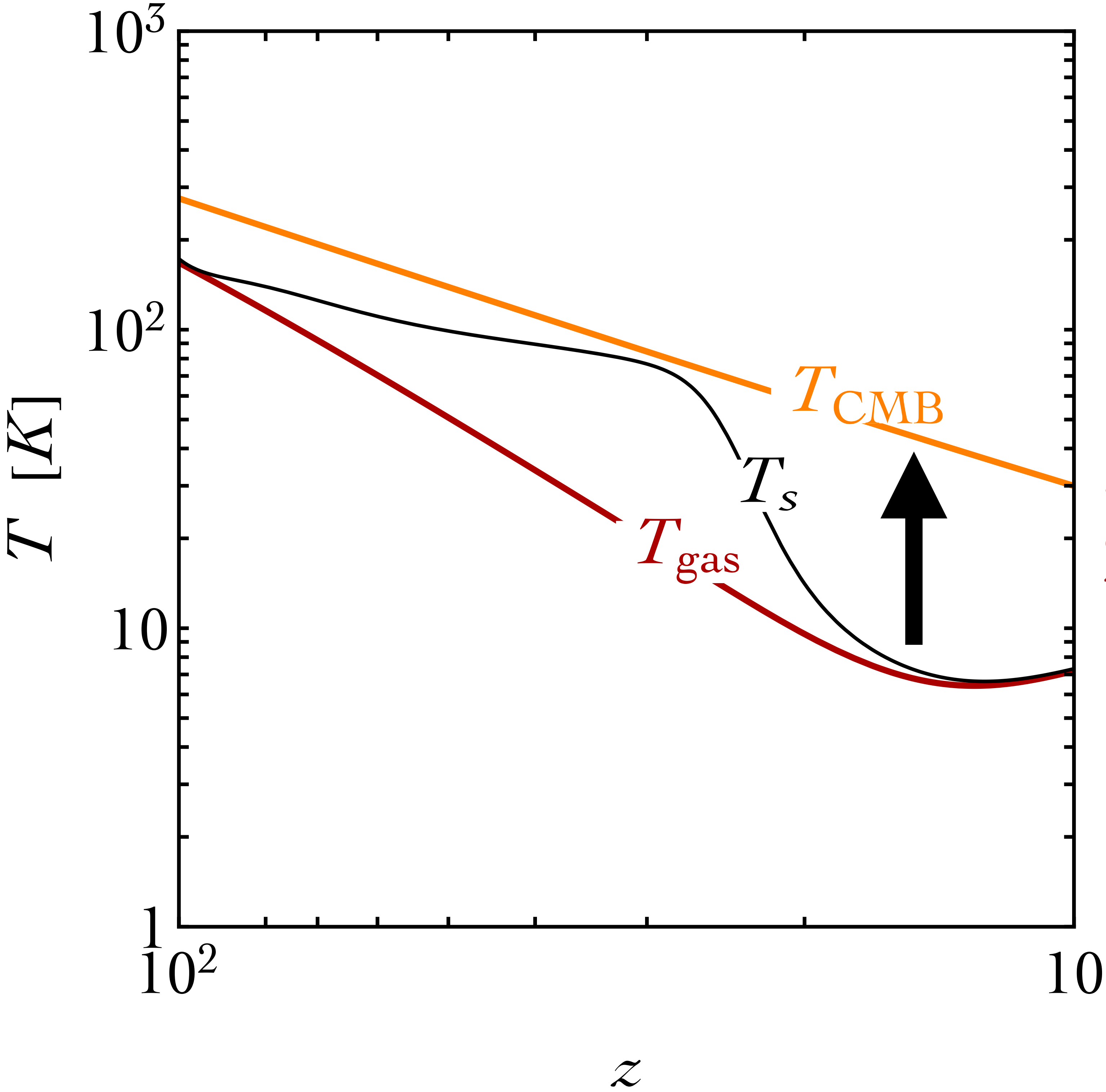


3.8 σ discrepancy

What can be learned from EDGES?

1. Bounds on dark matter annihilation

(WIMP)

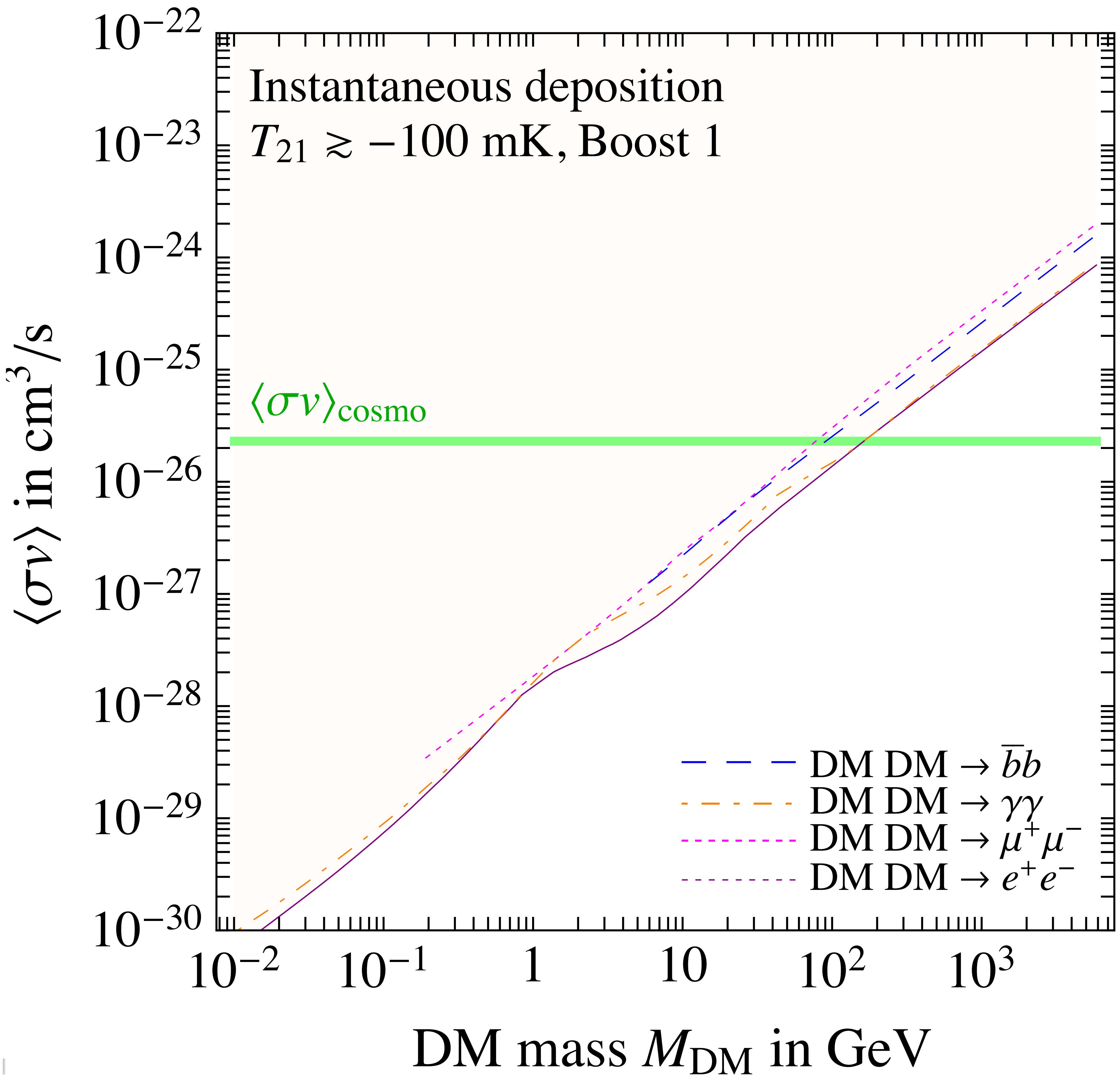


Dark matter annihilations directly heat the IGM by energy injection.

It tends to erase the 21-cm signal

1. Bounds on dark matter annihilation

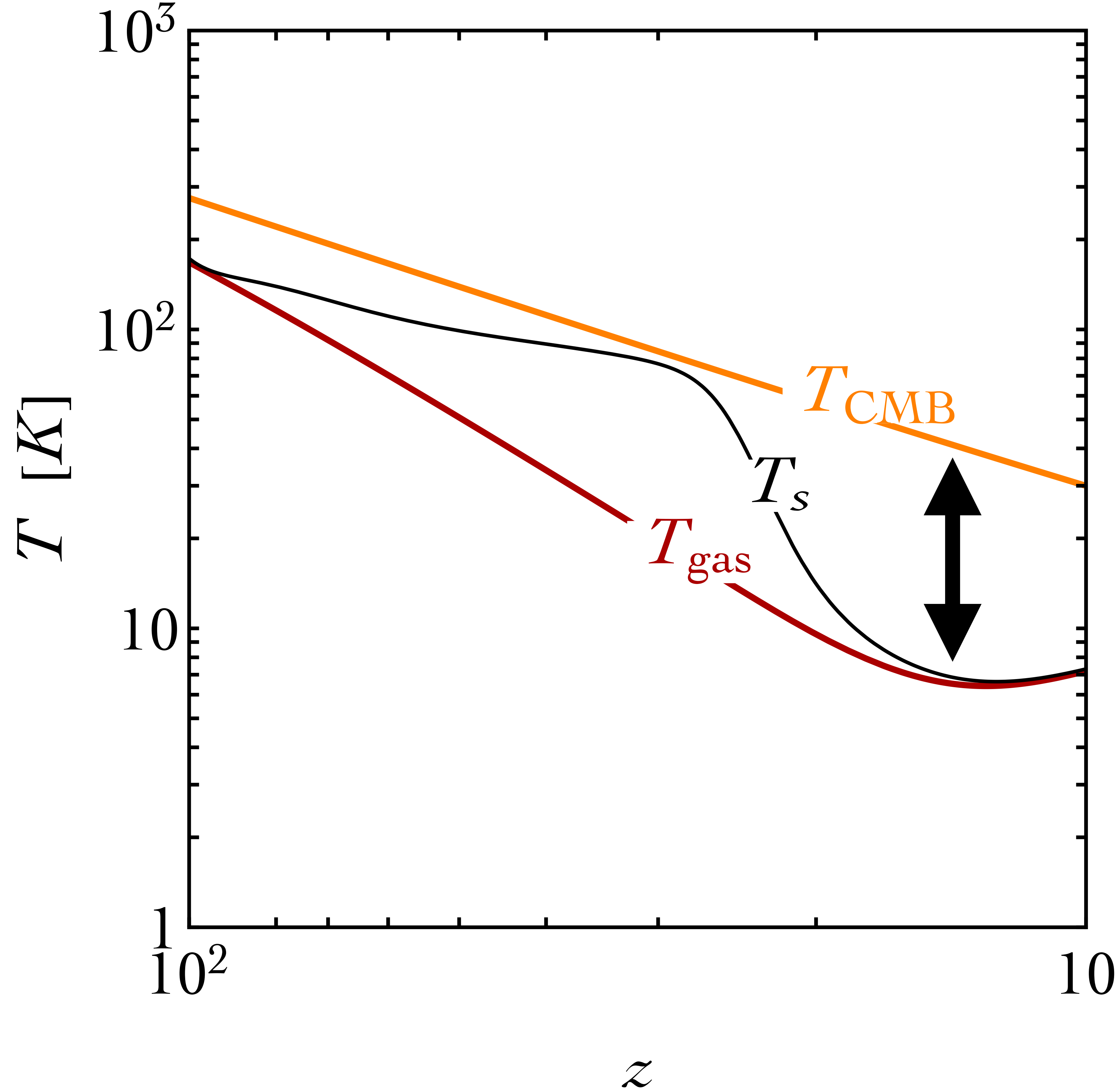
(WIMP)



D'Amico, Panci and Strumia, Phys.Rev.Lett. **121**, no. 1, 011103

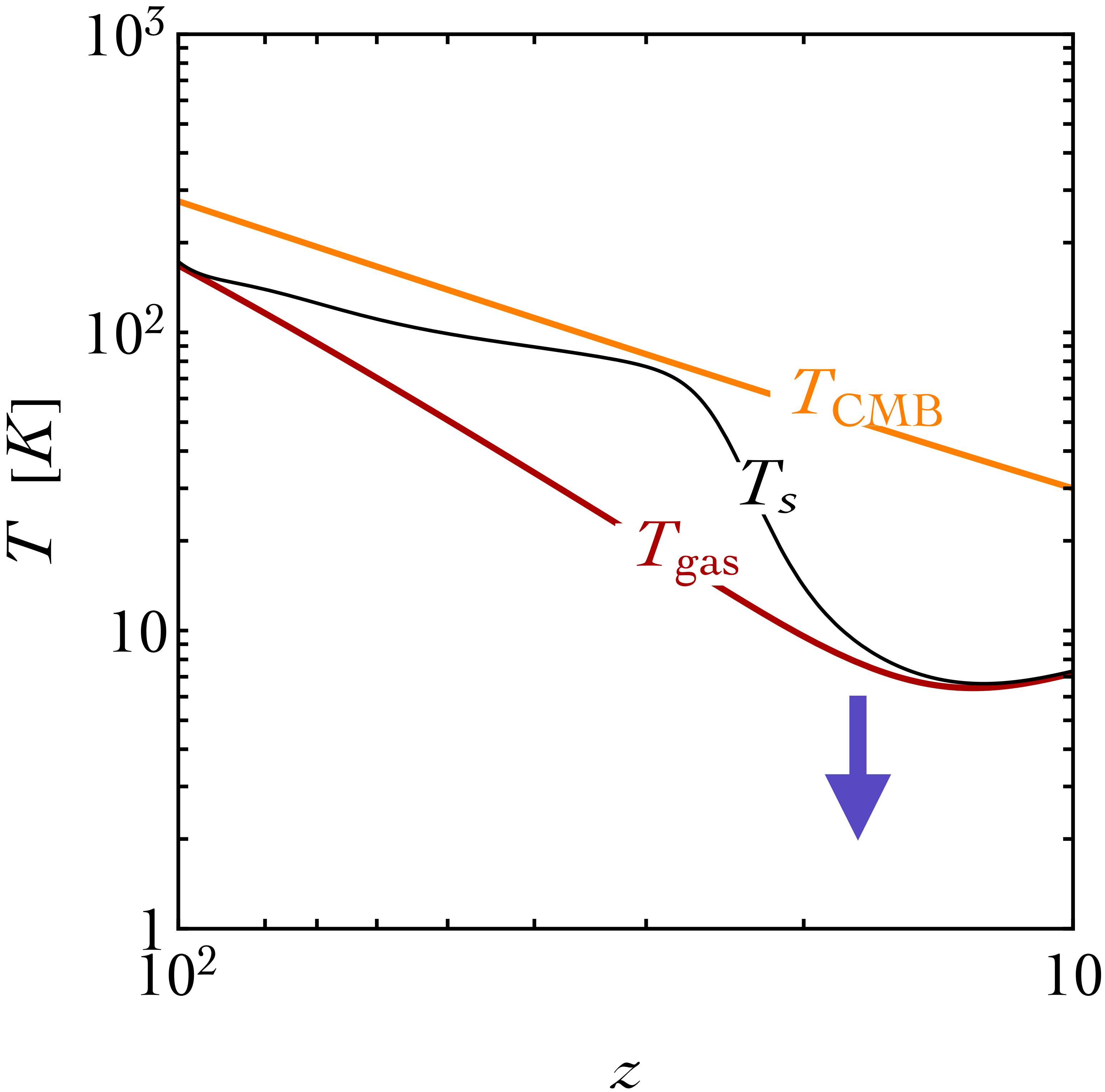
See also Liu and Slatyer, Phys.Rev.D **98**, no. 2, 023501

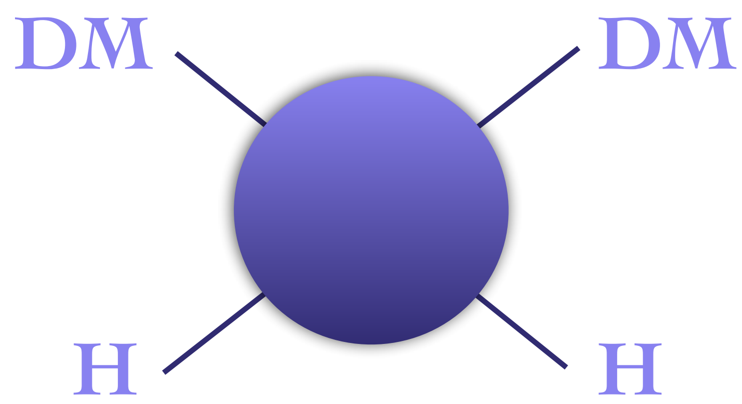
2. Try to explain the signal



2.1 Milli-charged dark matter

Cool baryons (very hard!)



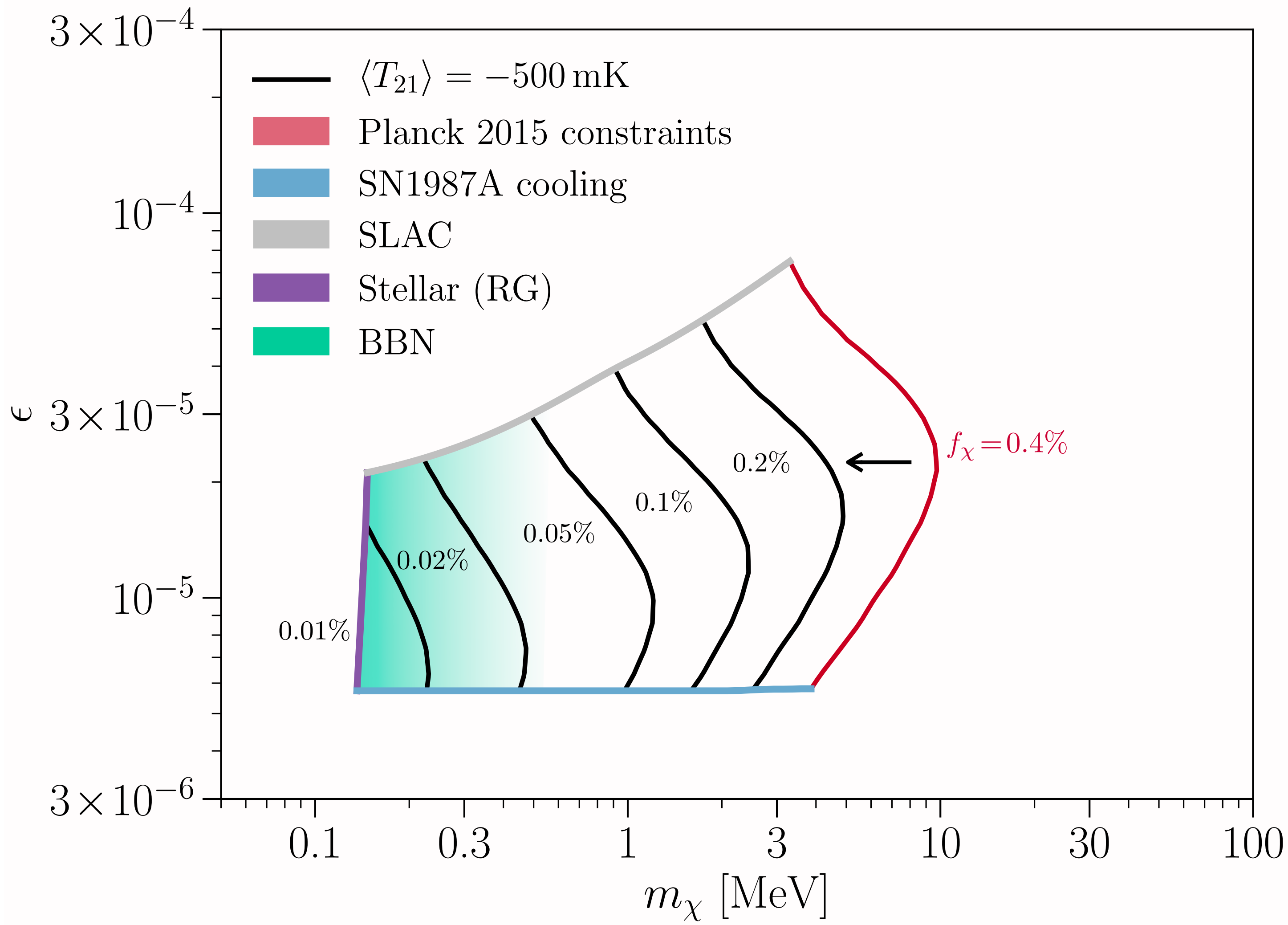


Dark matter is colder (it decouples much earlier), and **elastic scattering with baryons may cool down the gas**

2.1 Milli-charged dark matter

However, quite contrived in practice…

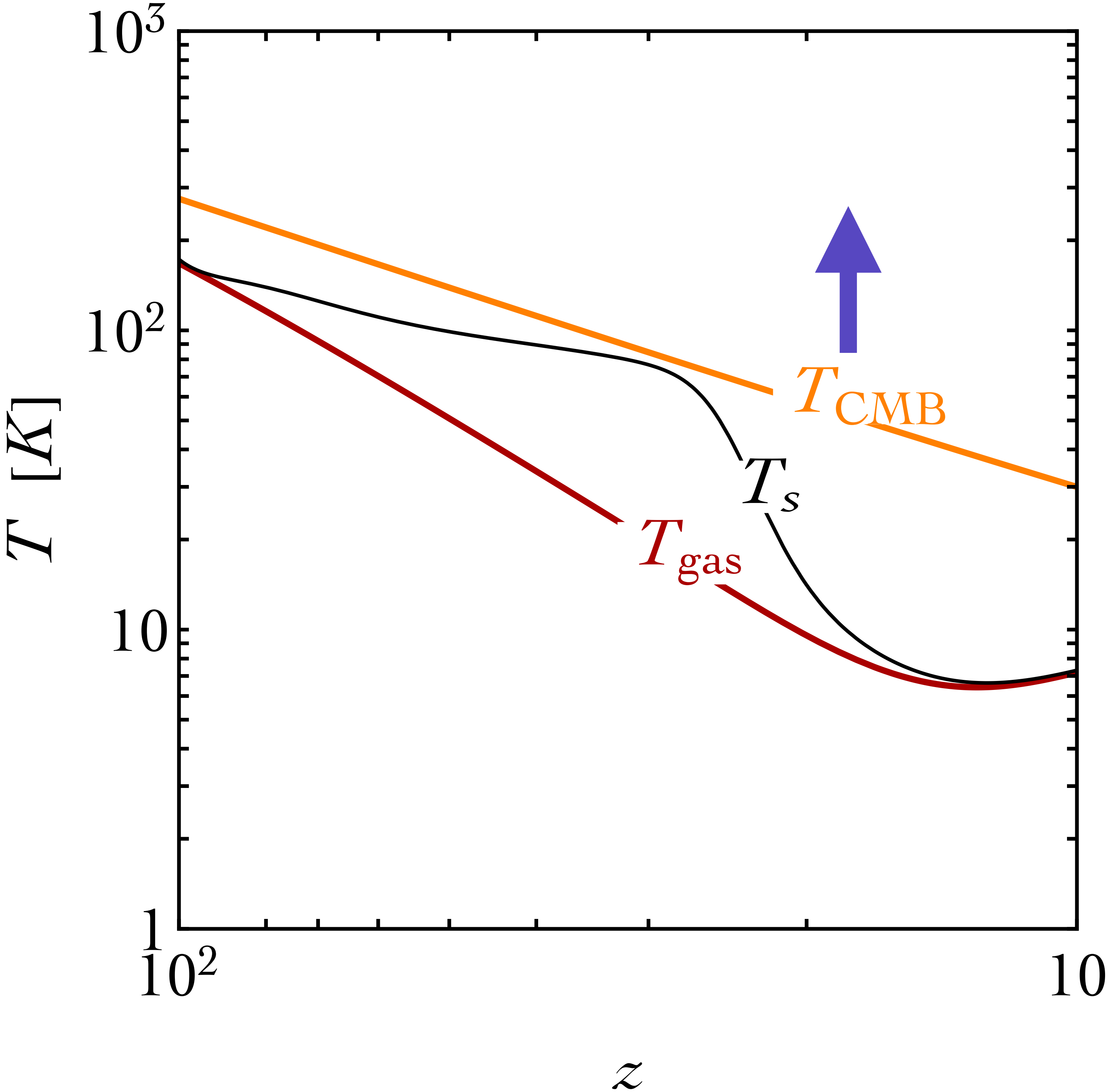
- Mechanism: a small fraction of DM carries a tiny electric charge, scattering of this component with baryons cools the gas.
- Scattering is Rutherford ($\sigma \propto v^{-4}$) enhanced in late dark ages.



Kovetz *et al.*,
Phys.Rev.D **98**, no. 10, 103529

See also Slatyer and Wu,
Phys.Rev.D **98**, no. 2, 023013

2.2 "Light out of the dark (sector)"



Add photons (very easy!)

$$T_\gamma > T_{\rm CMB}$$

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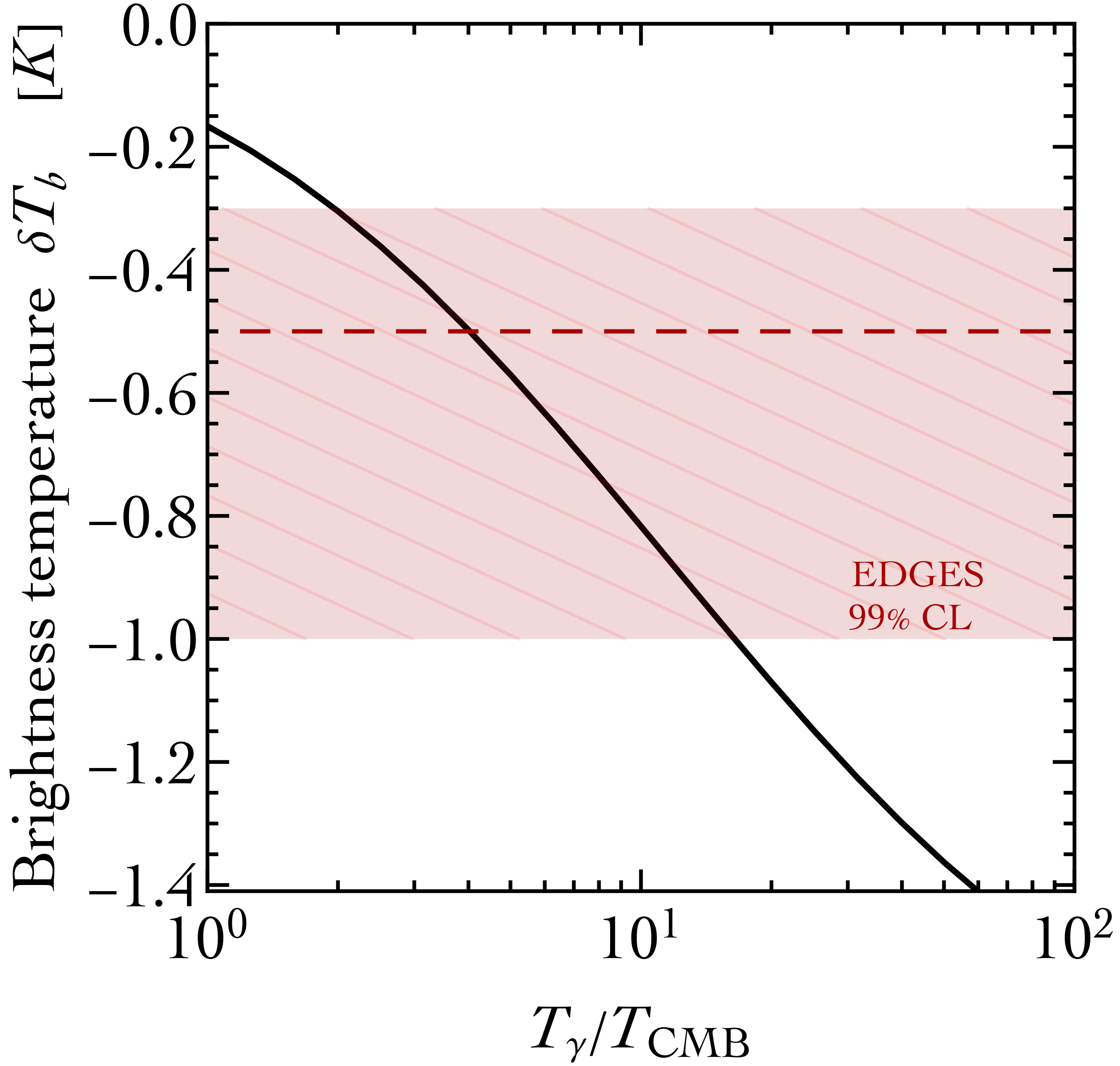
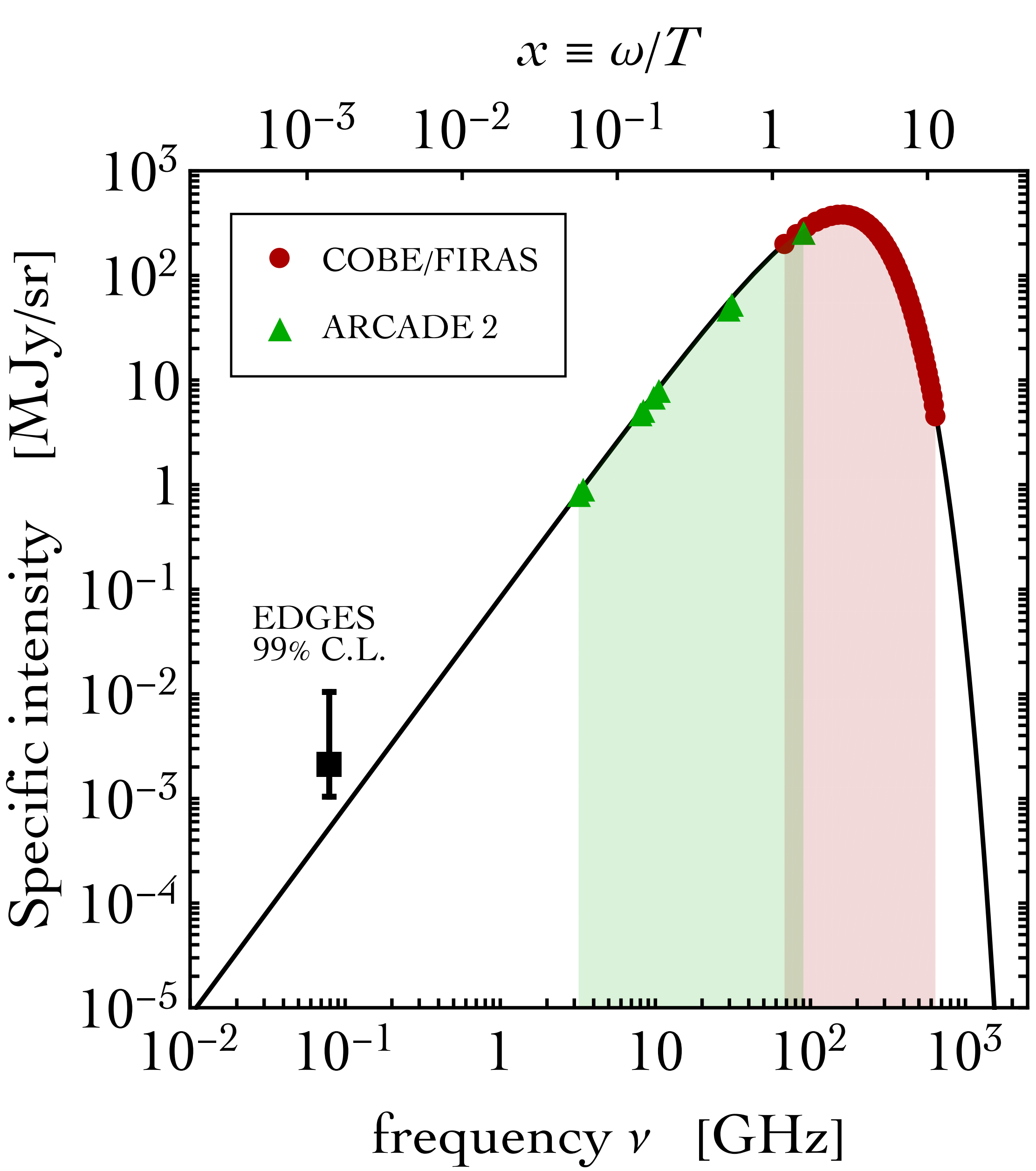
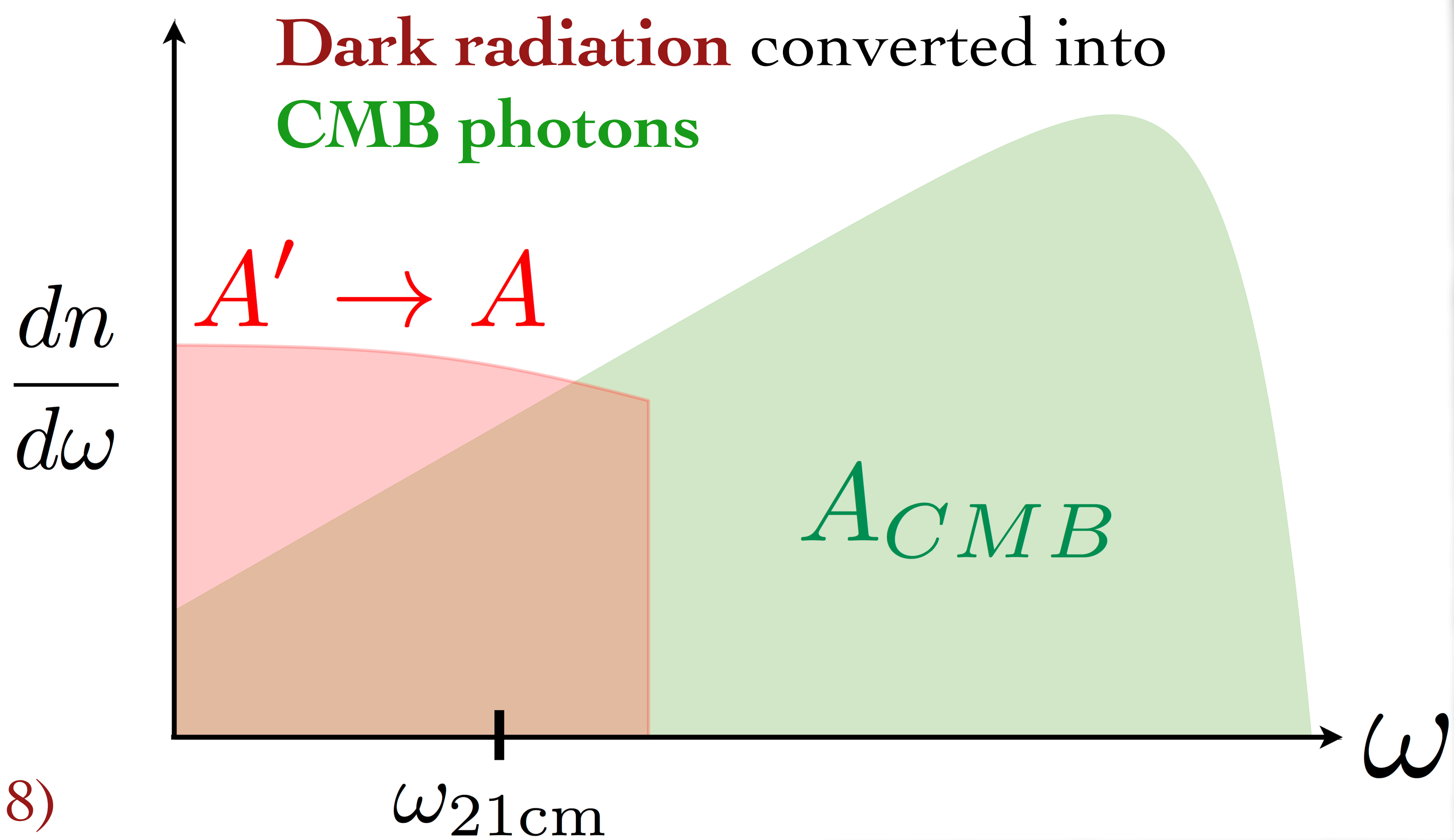




2.2 "Light out of the dark (sector)"

Dark matter ($10^{-5}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-3}\,\mathrm{eV}$)
is an axion-like particle, and it decays to light dark photons ($10^{-14}\,\mathrm{eV} \lesssim m_{A'} \lesssim 10^{-9}\,\mathrm{eV}$)
which are subsequently resonantly converted into visible photons when the plasma frequency passes through the dark photon mass

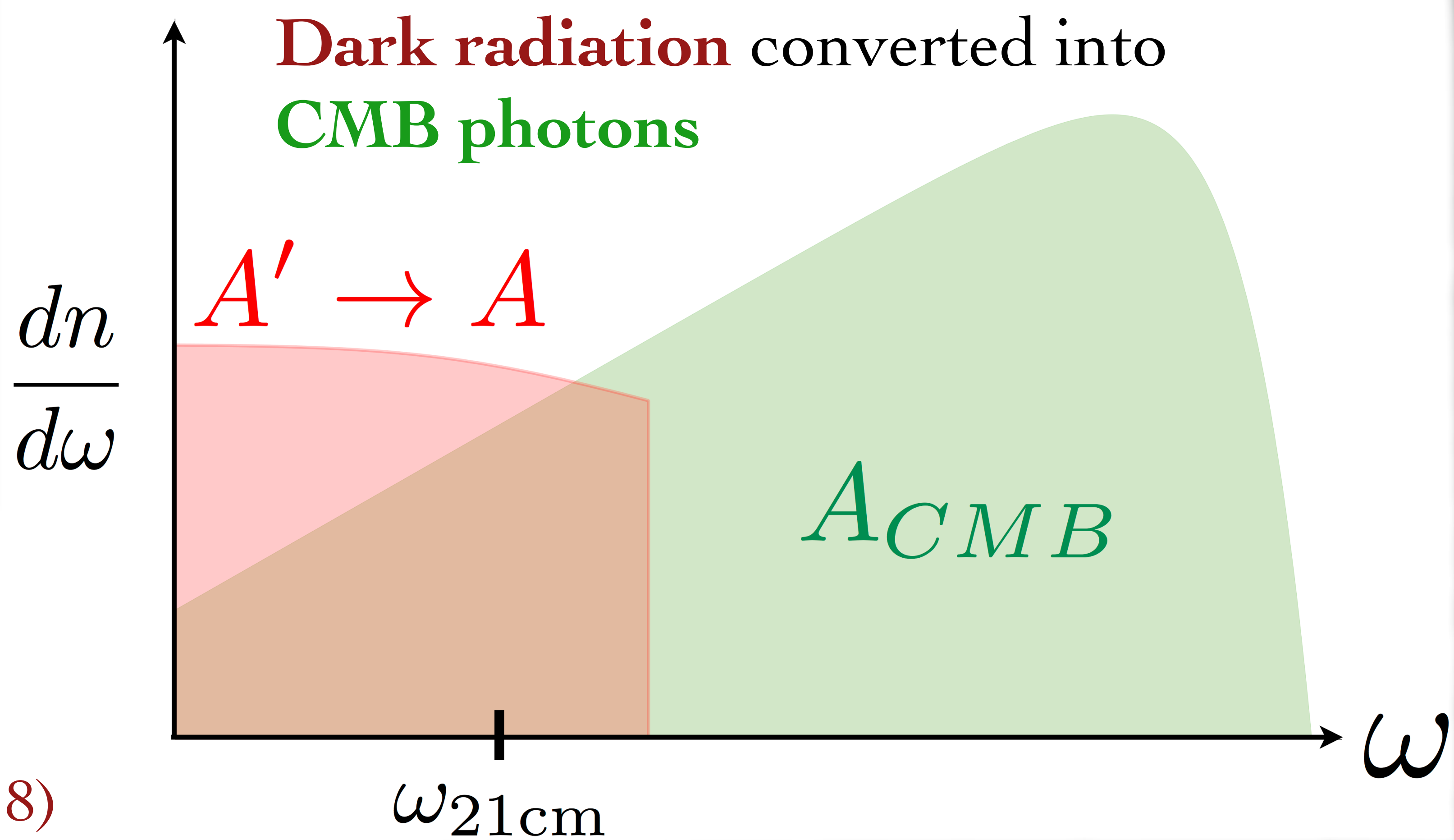


Pospelov, Pradler, Ruderman and AU,
Phys.Rev.Lett. **121**, no. 3, 031103 (2018)

2.2 "Light out of the dark (sector)"

The key point: not many constraints on new signals appearing in the very low-energy tail of the CMB - strong limits on spectral distortion are at higher wavelengths

The amount of dark radiation that is needed to sizably alter the CMB tail is easily consistent with Planck bound on $\Delta N_{\rm eff}$



Pospelov, Pradler, Ruderman and AU, Phys.Rev.Lett. **121**, no. 3, 031103 (2018)

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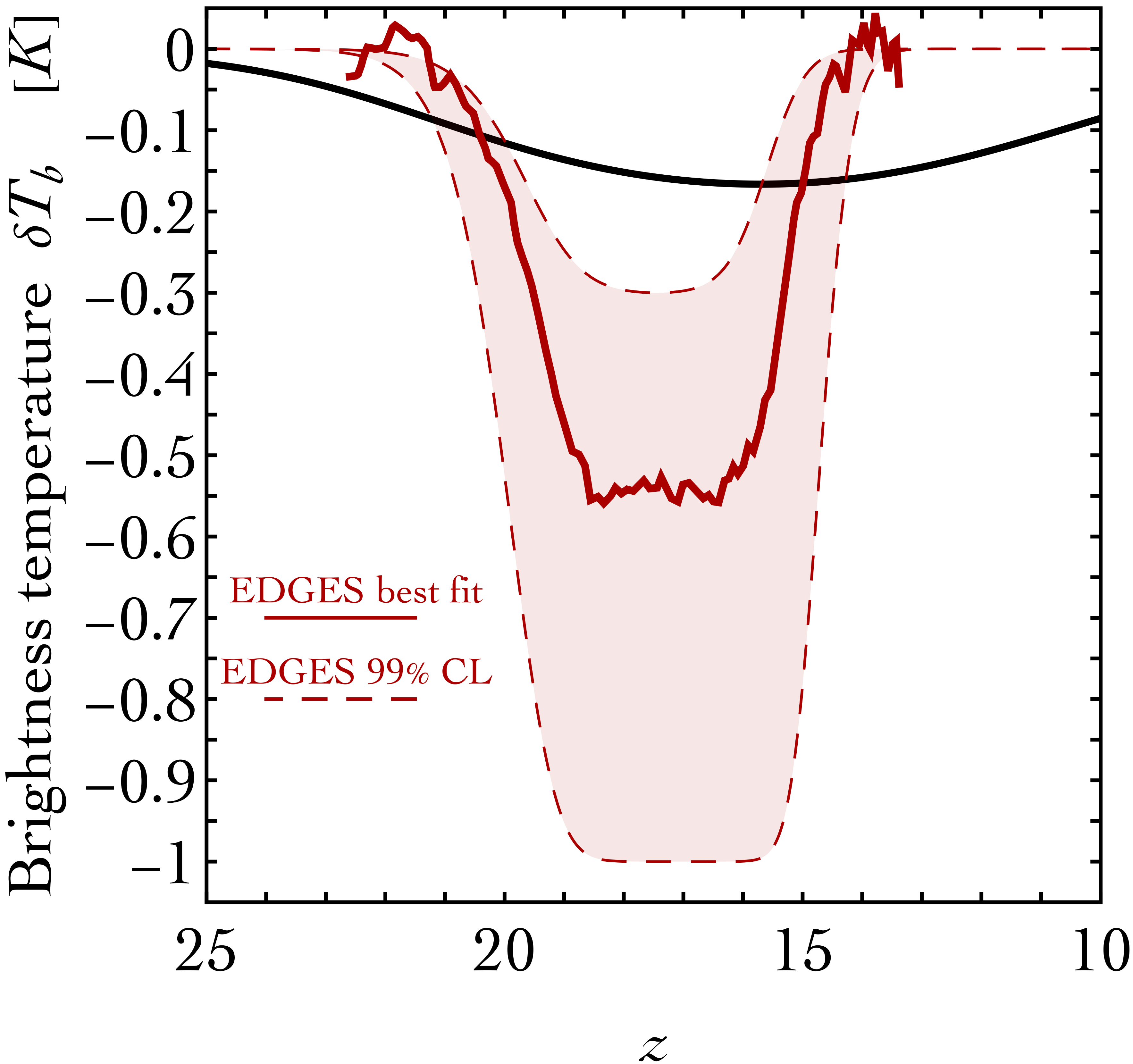

?

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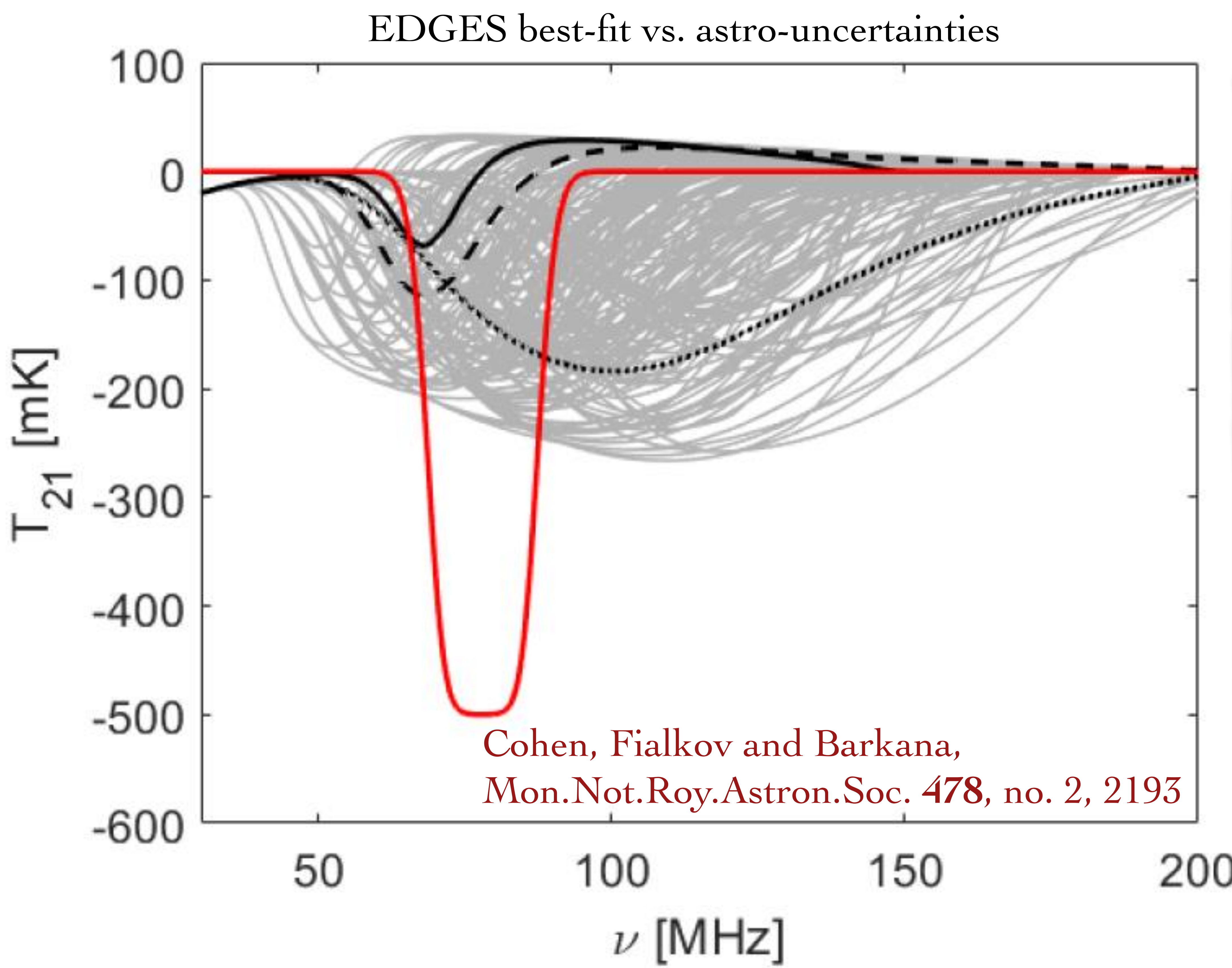

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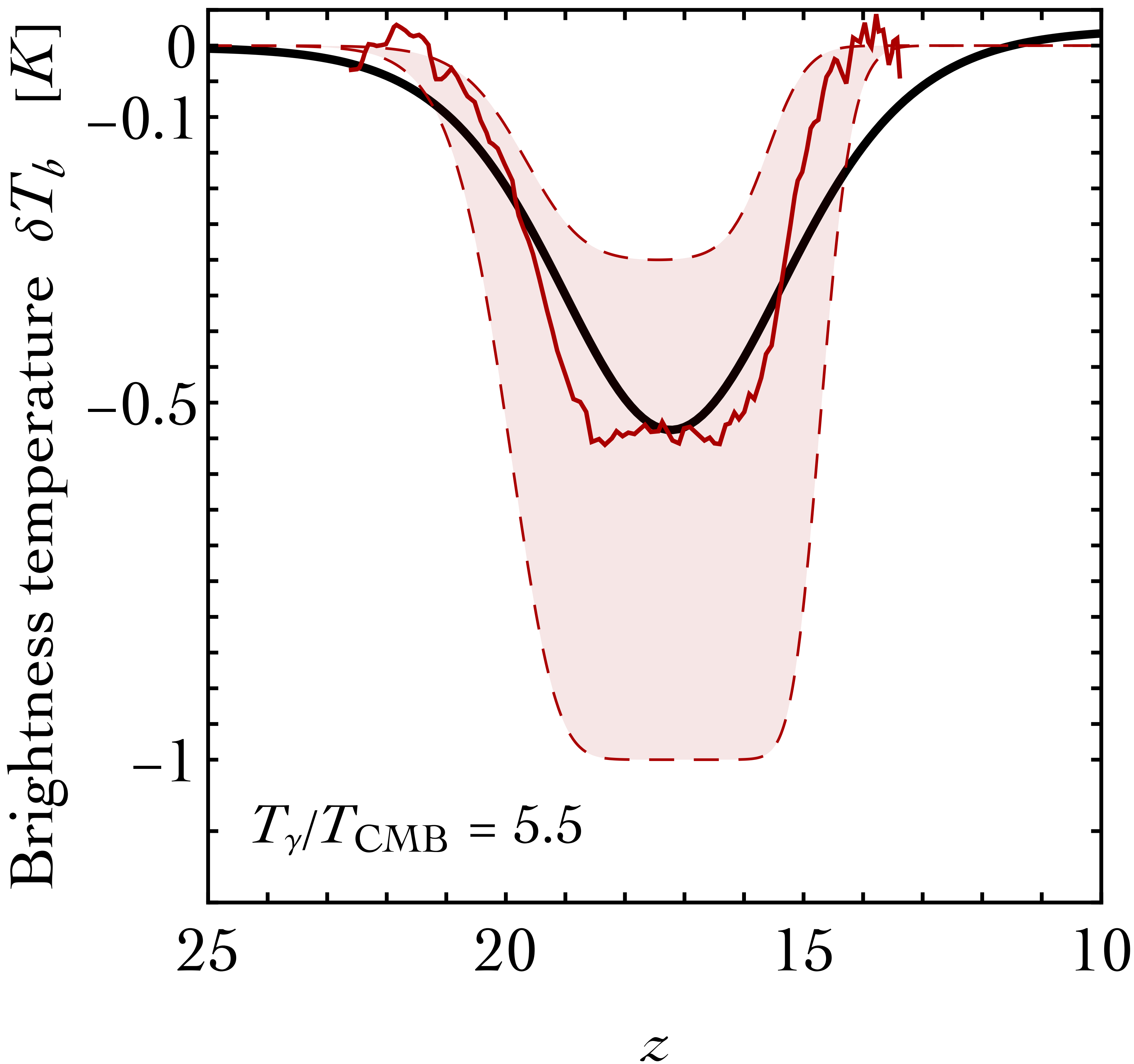


Constraints from Cosmology

CONCLUSIONS

Cosmology (CMB) places stringent constraints on thermal dark matter.

21-cm observations promise to place even more stringent constraints.

Claim of a first detection by EDGES could have striking implications for cosmology **if confirmed** *

Constraints from Cosmology

*Other global 21-cm experiments

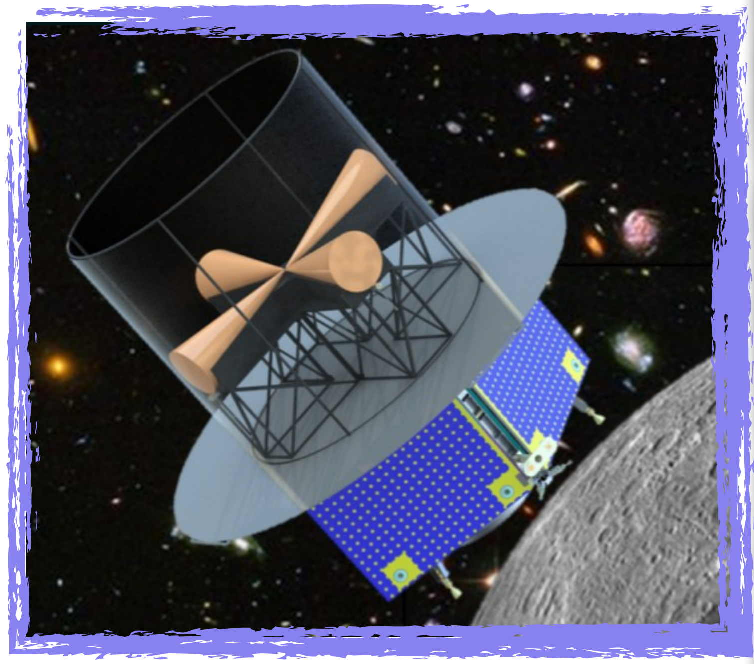
LEDA

SARAS

BIGHORNS

EDGES

PRI^{Z}M



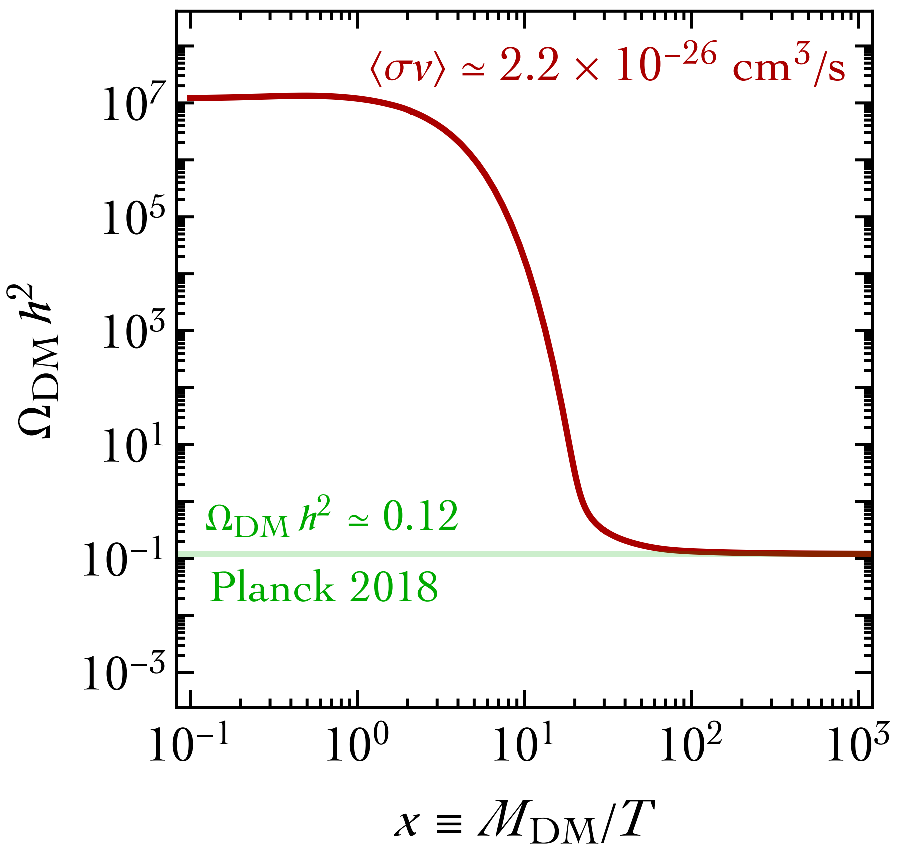
DARE

FAQ

Tension with experiments (?)

WIMP (thermal)

$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_{\rm DM}^2} \sim 10^{-26} \times \left(\frac{\alpha_W}{0.003}\right)^2 \times \left(\frac{100\,\text{GeV}}{M_{\rm DM}}\right)^2 \text{cm}^3/\text{s}$$



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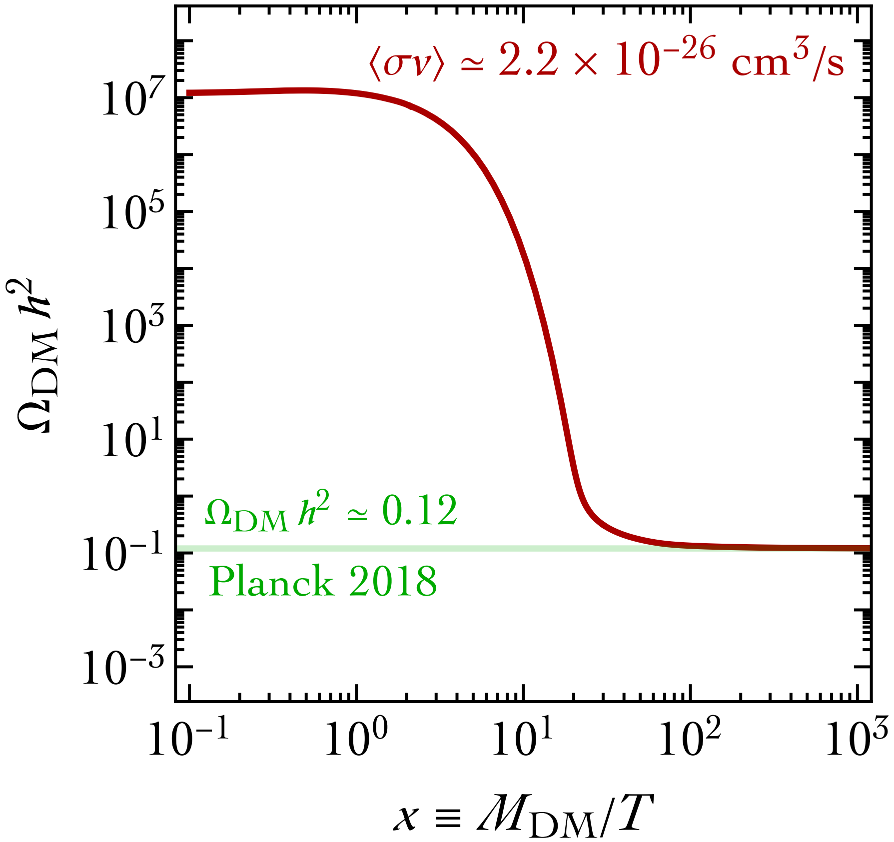

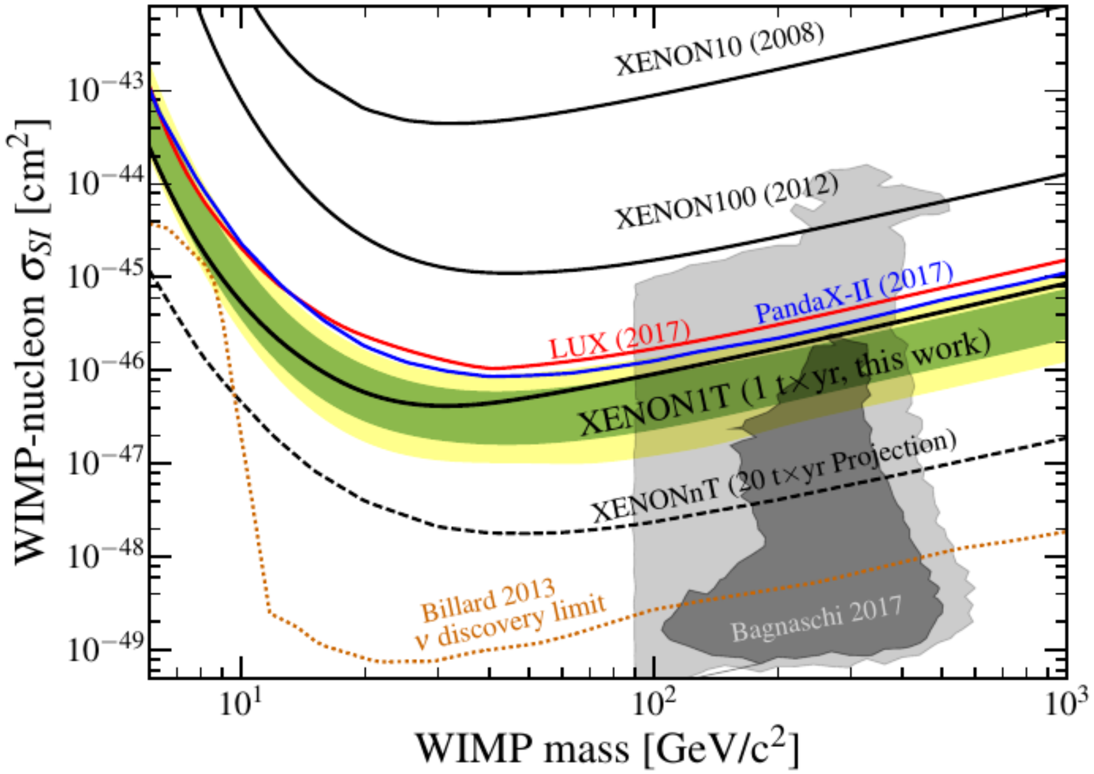

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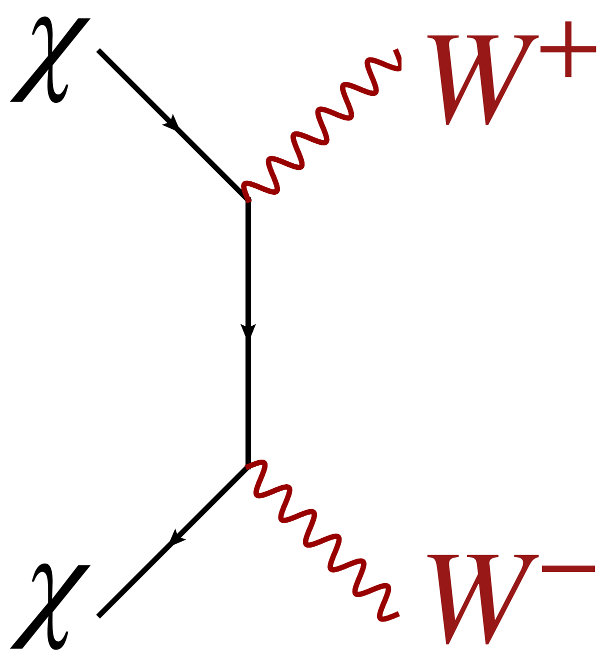

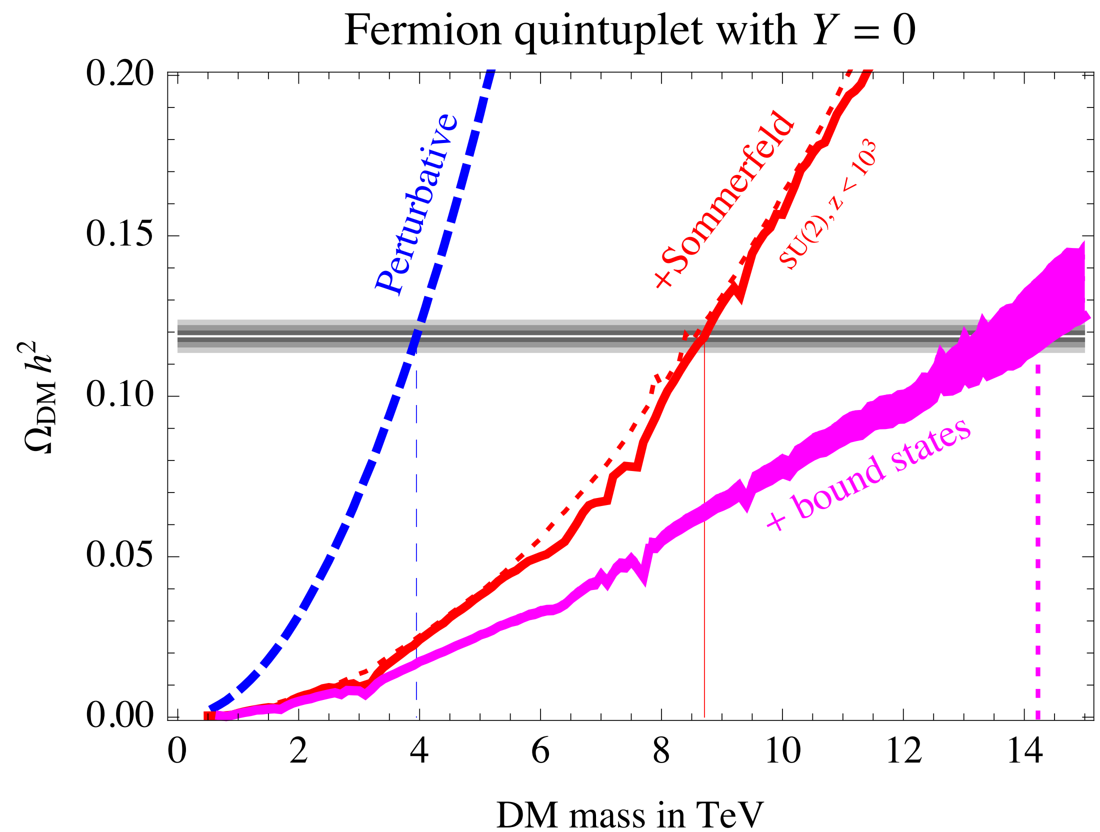

What is the bound on dark radiation?

$$N_{\text{eff}} = 3.04 \pm 0.33$$
$$(N_{\text{eff}}^{\text{SM}} = 3.046)$$

$$\rho_{\text{rad}}^{\text{tot}} = \rho_\gamma + \rho_\nu$$

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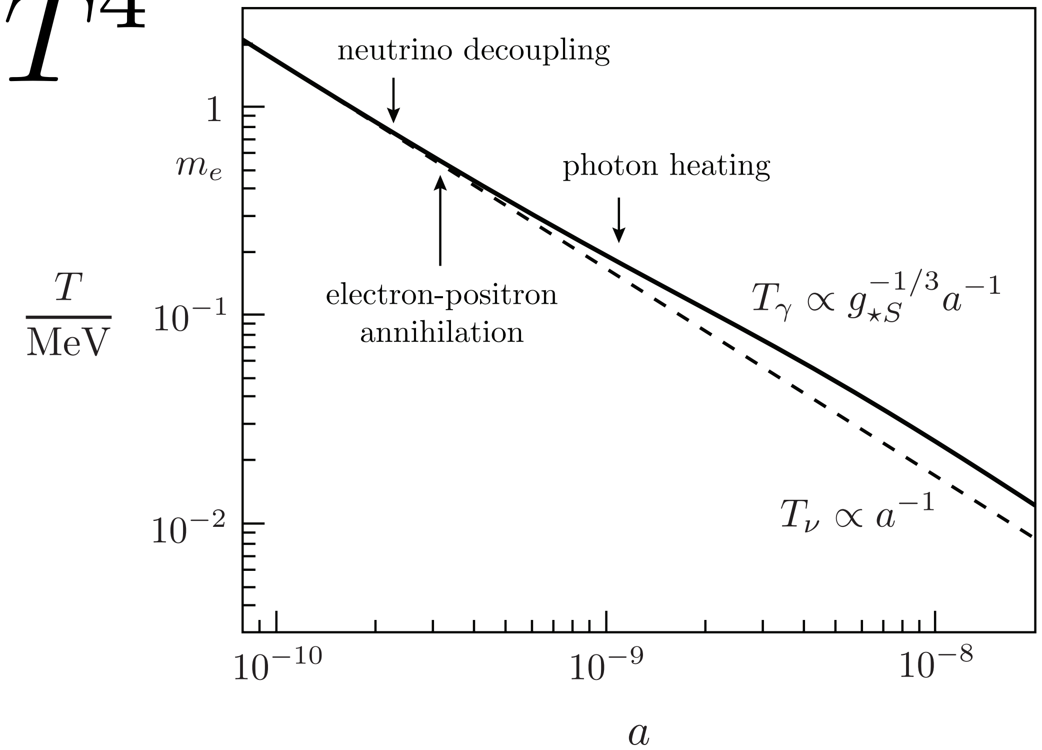

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Soft DR quanta with $x \simeq 10^{-3}$

$$\frac{n_{\text{DR}}}{n_{\text{CMB}}} \simeq 10^2 \left(\frac{\Delta N_{\text{eff}}}{0.5} \right)$$

What is the bound on dark radiation?

Soft DR quanta have a potential to outnumber the RJ CMB photons by up to 8 orders of magnitude while being consistent with the amount of DR allowed by cosmological observations!

$$\frac{n_{\rm DR}}{n_{\rm CMB}} \simeq 10^2 \left(\frac{\Delta N_{\rm eff}}{0.5} \right)$$

$$n_{\rm RJ}/n_{\rm CMB} \simeq 10^{-6}$$

Towards a concrete model

Pospelov, Pradler, Ruderman and AU,
Phys.Rev.Lett. **121**, no. 3, 031103 (2018)

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

An axion-like dark matter particle coupled to U(1)'

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

U(1)' massive dark photon mixed with U(1) e.m.

Towards a concrete model

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Towards a concrete model

$$\Gamma_a = \frac{m_a^3}{64\pi f_a^2}$$

$$\ldots - \frac{m_a^2}{2} a^2 + \frac{a}{4 f_a} F'_{\mu\nu} \tilde{F}'^{\,\mu\nu} + \mathcal{L}_{AA'}$$

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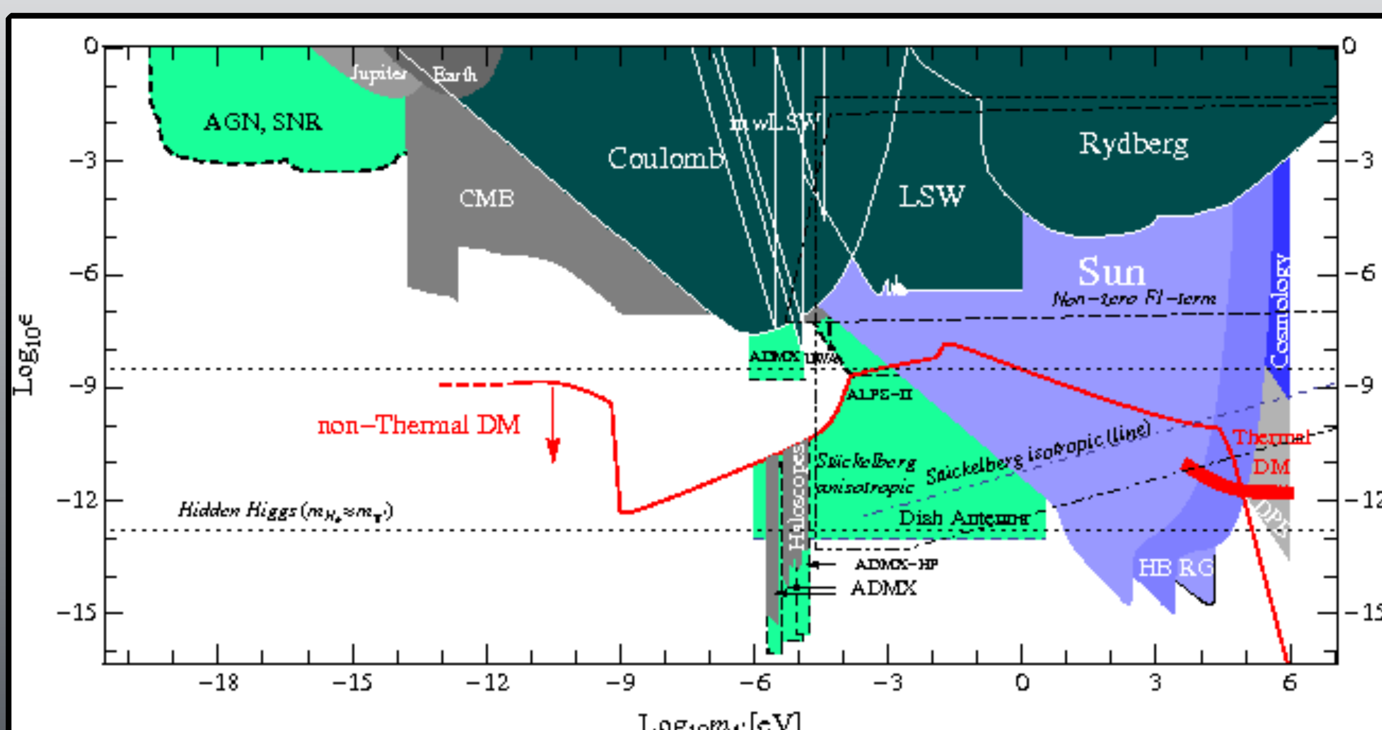

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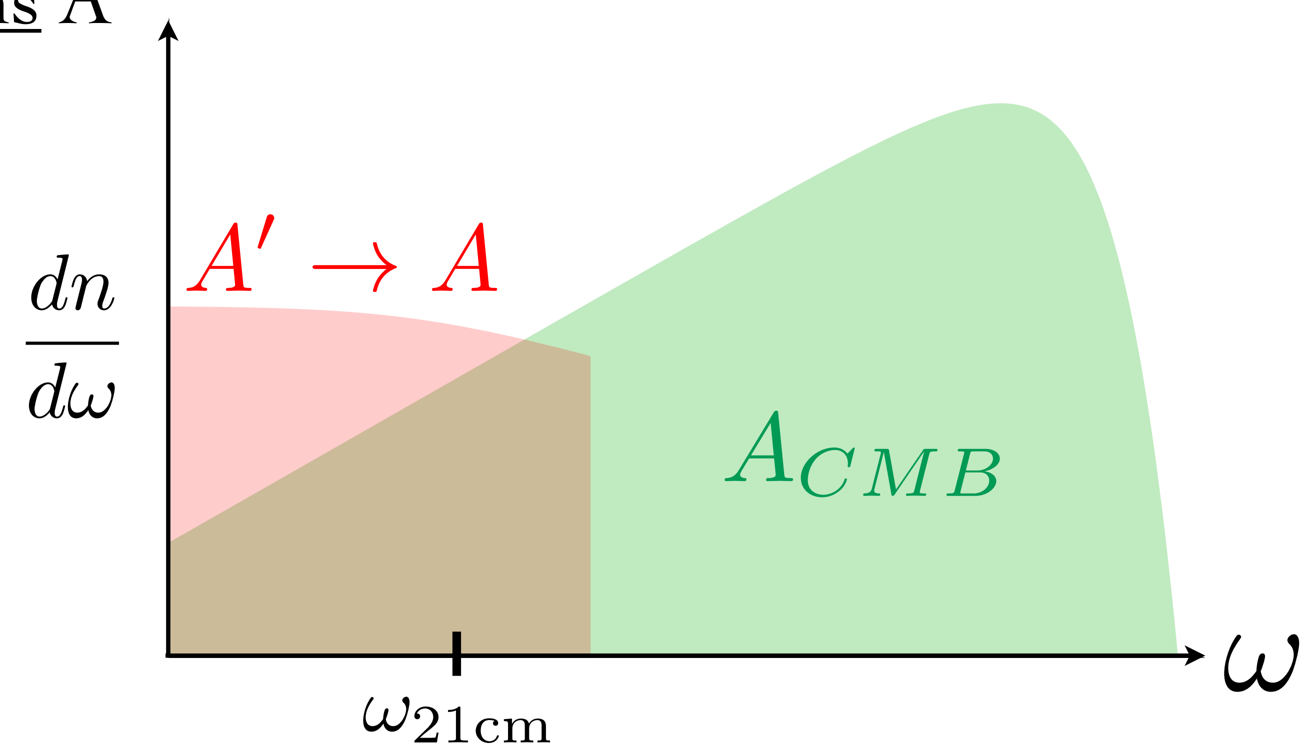
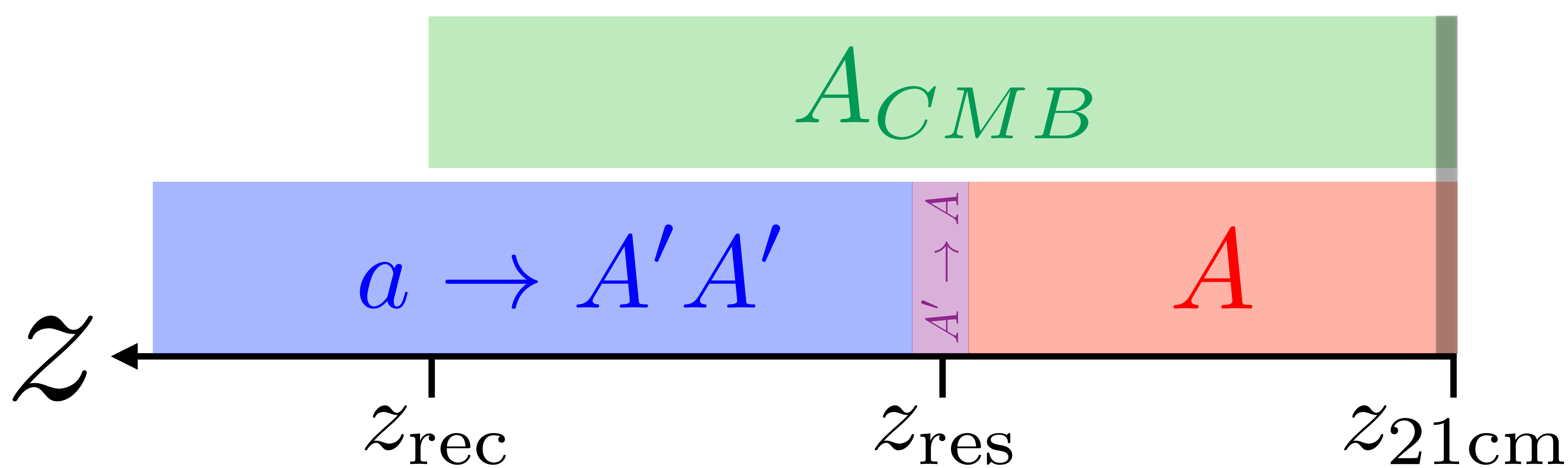
Towards a concrete model

The decays of an unstable relic, a, which may constitute dark matter, produce a population of soft massive dark photons A'

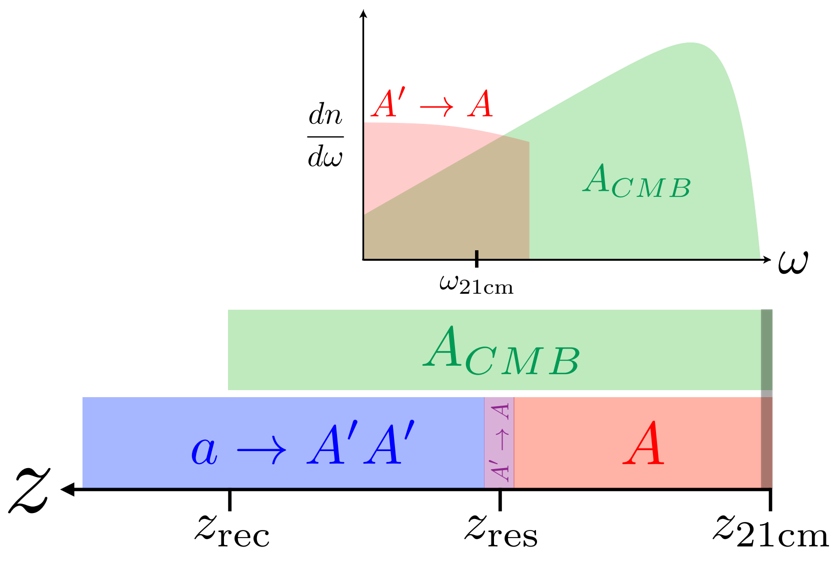


At some z, a fraction of these dark photons is resonantly converted into ordinary photons.
The latter add to the CMB photon count in the RJ tail, resulting in a more negative $1 - T_{\text{CMB}}/T_s$ temperature constrast.



Towards a concrete model

The resonant conversion of massive dark photons into ordinary photons due to the mixing is a crucial ingredient.



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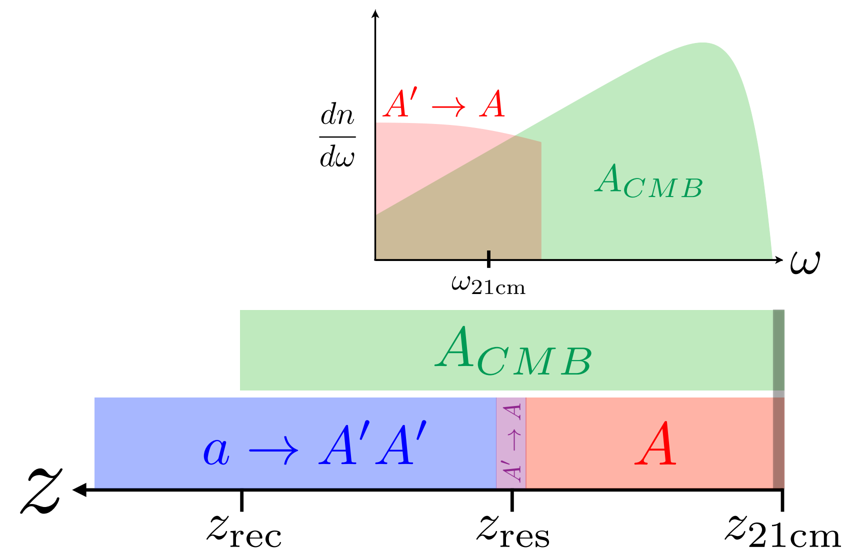

$$\mathcal{M}^2 = \begin{pmatrix} 0 & \epsilon m_{A'}^2 \\ \epsilon m_{A'}^2 & m_{A'}^2 \end{pmatrix}$$

In the "interaction basis" the kinetic term is diagonal but the mixing angle appears in an off-diagonal term in the mass-squared matrix

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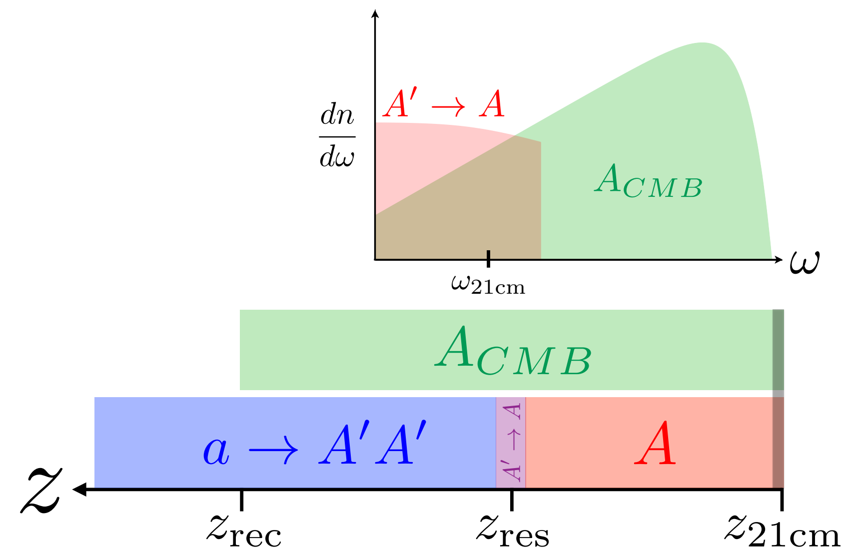

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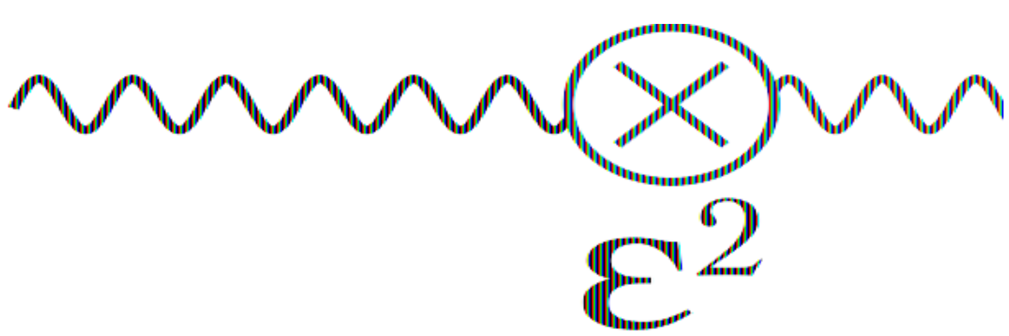
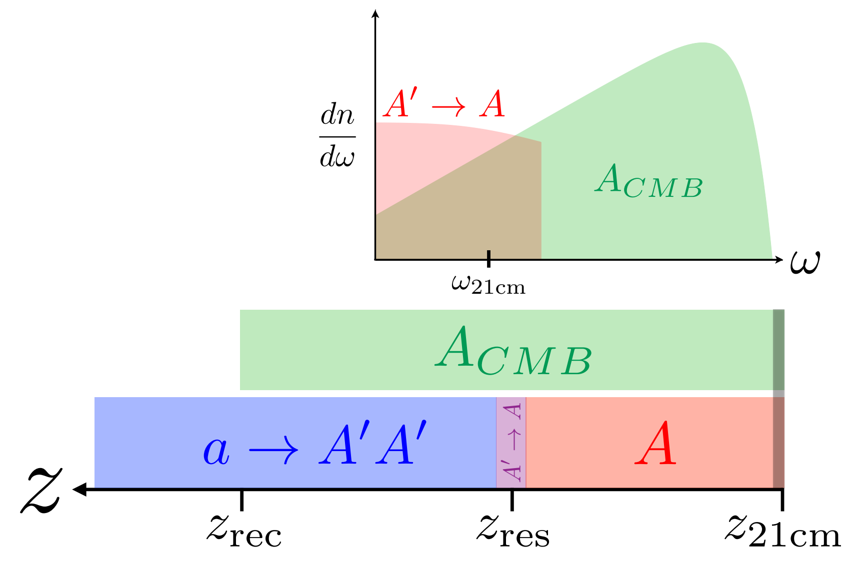
In the vacuum, the conversion is suppressed, and an efficient conversion mechanism hopeless.



Towards a concrete model

The resonant conversion of massive dark photons into ordinary photons due to the mixing is a crucial ingredient.



$$\mathcal{M}^2 = \begin{pmatrix} \omega_{\rm pl}^2(z) & \epsilon m_{A'}^2 \\ \epsilon m_{A'}^2 & m_{A'}^2 \end{pmatrix}$$

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However,
CMB photons do not propagate in the vacuum but in the primordial plasma (electrons). This leads to birefringence which can be effectively described by an effective mass term in their dispersion relation

Towards a concrete model

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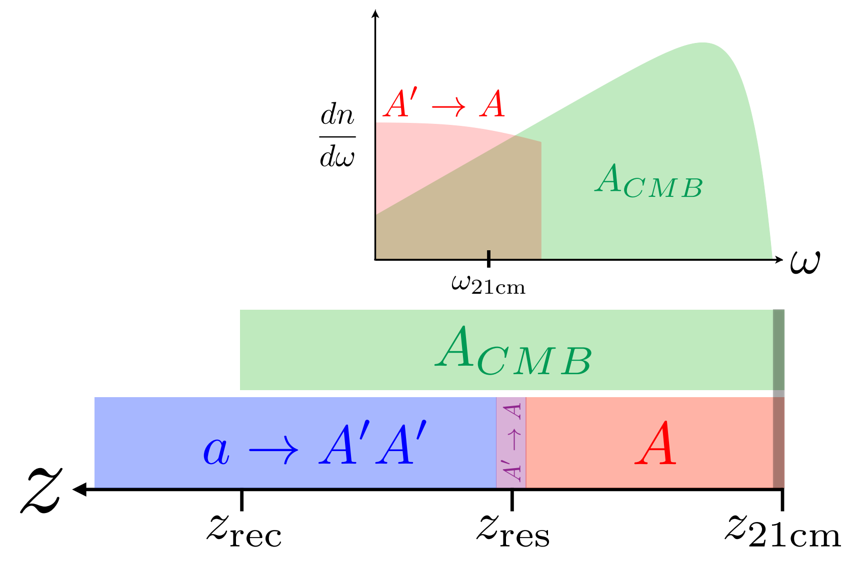

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$\omega_{\mathrm{pl}}^2 \ll m_{A'}^2$ Vacuum oscillation, $\mathscr{P}_{A\to A'} \sim \epsilon$

$\omega_{\mathrm{pl}}^2 \gg m_{A'}^2$ In-medium oscillation, $\mathscr{P}_{A\to A'} \sim \epsilon \times \frac{m_{A'}}{\omega_{\mathrm{pl}}^2}$

Towards a concrete model

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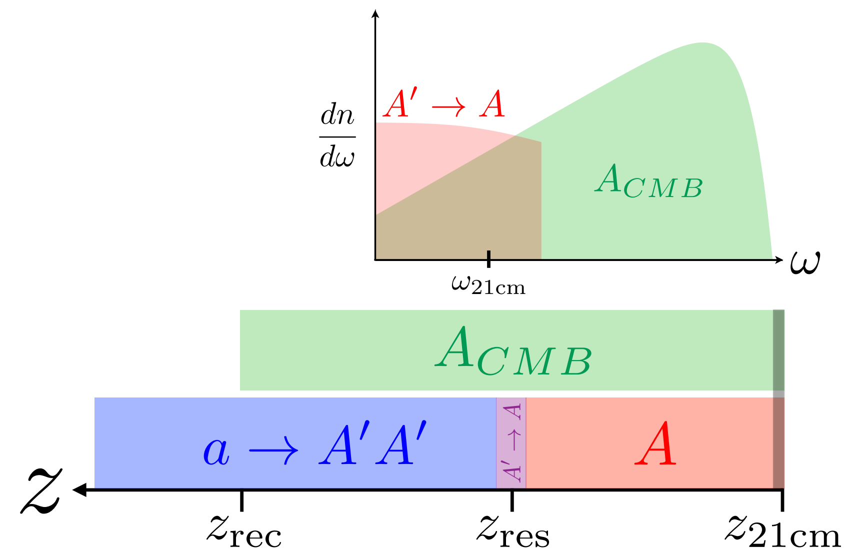

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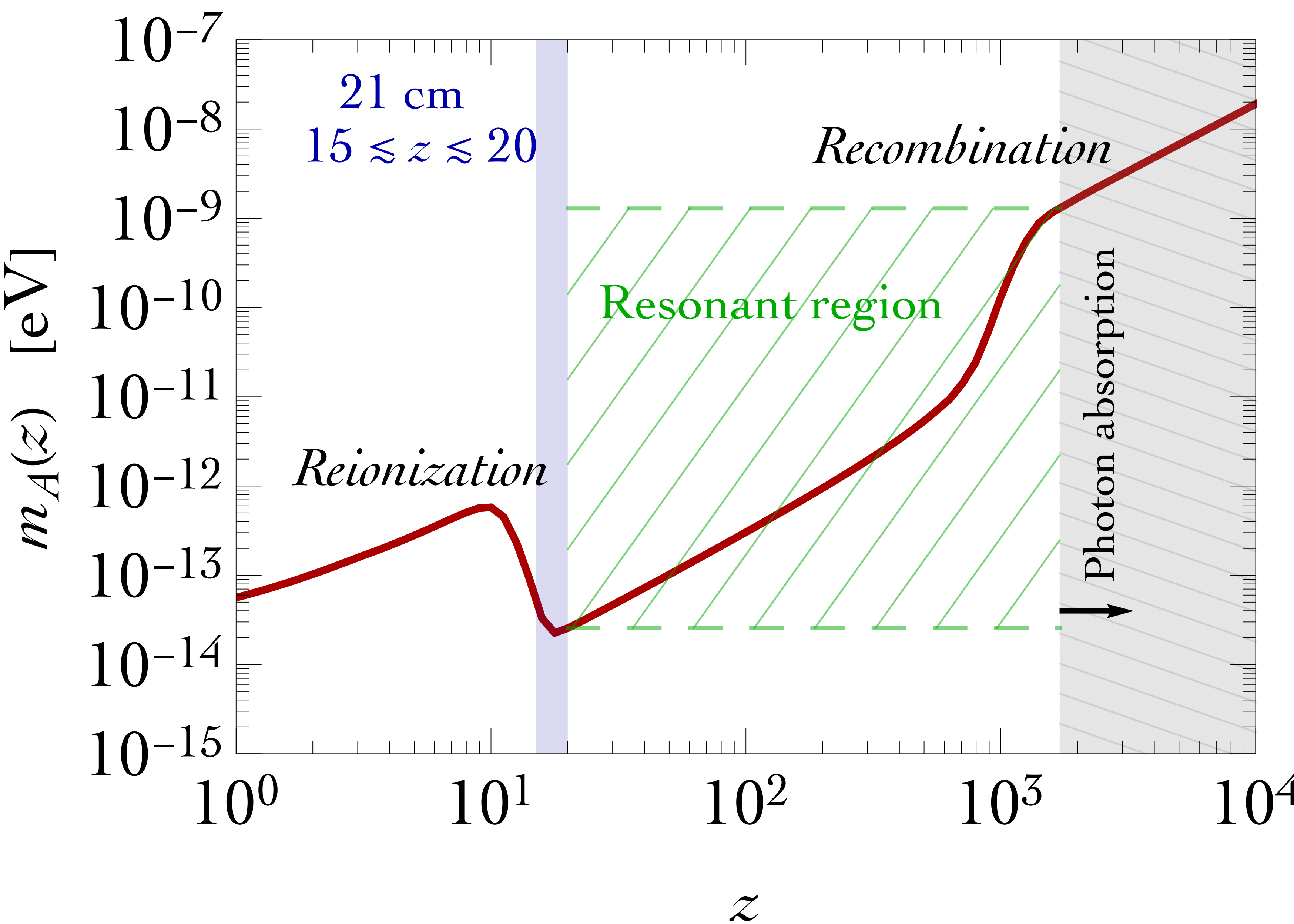
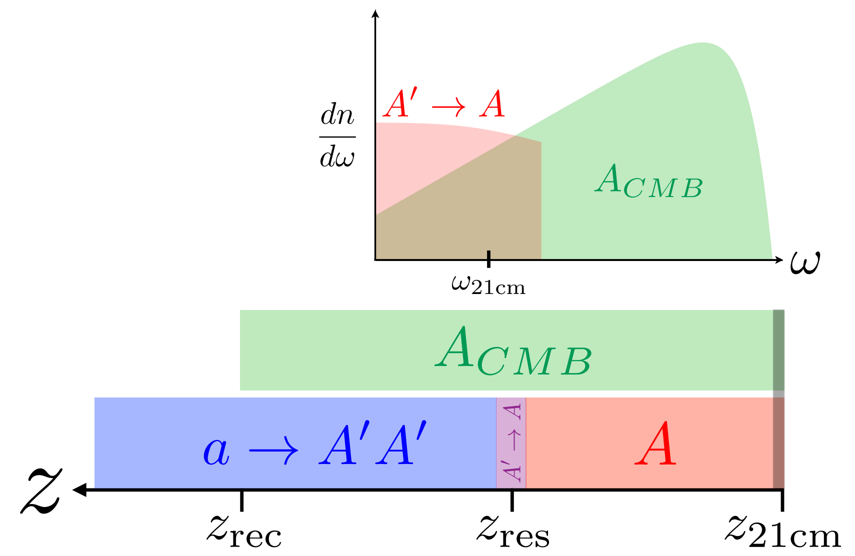
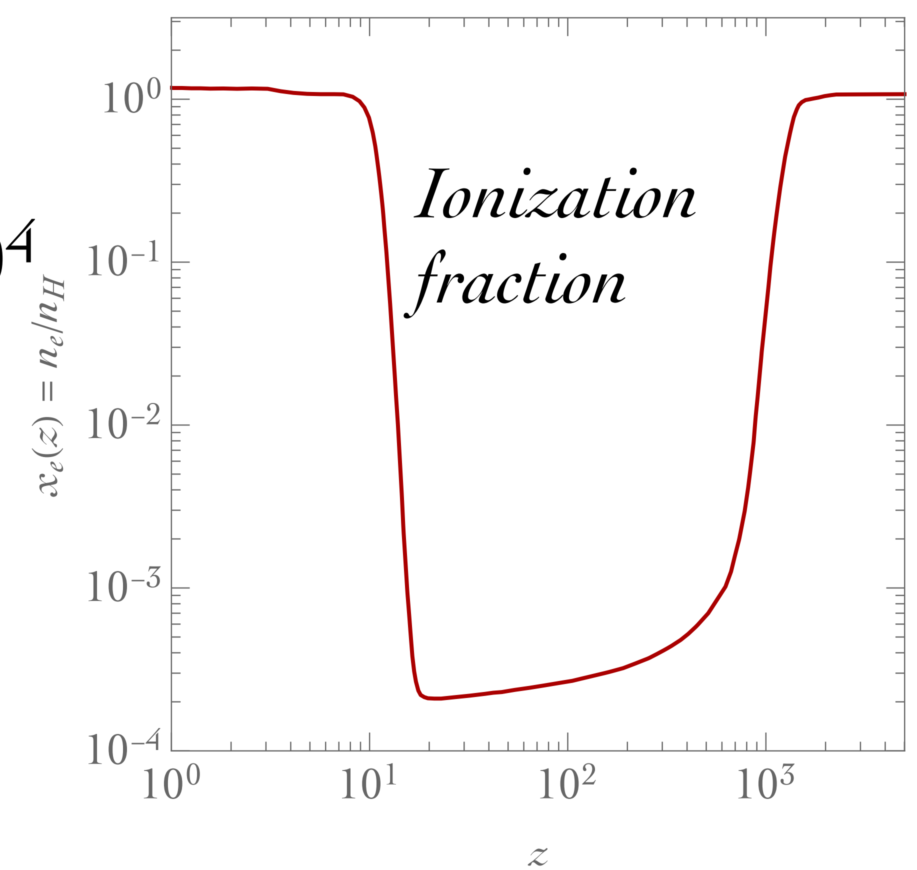
Resonant conversion when $\omega_{\mathrm{pl}}(z) = m_{A'}$

The probability of photon-hidden photon resonant conversions can be obtained using the Landau-Zener expression (similar for neutrinos, the "Mikheyev-Smirnov-Wolfenstein" effect)
Wolfenstein [Phys. Rev. D17(1978) 2369]
Mikheyev and Smirnov [Sov. J. Nucl. Phys. 42, 913 (1985)]

Towards a concrete model



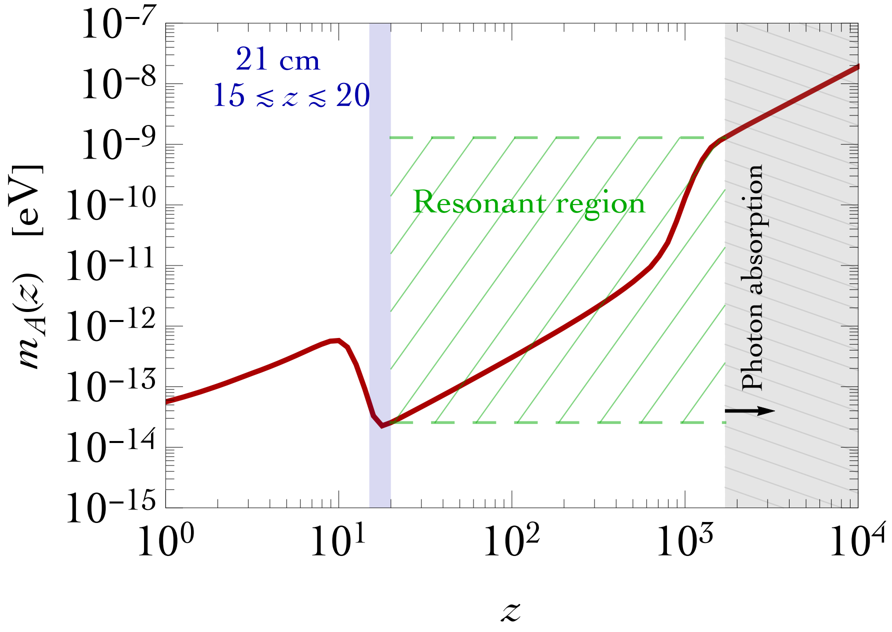




$$\omega_{\mathrm{pl}}^2(z) = \frac{4\pi\alpha n_e(z)}{m_e}$$

Towards a concrete model

Carving out the parameter space: the dark photon mass



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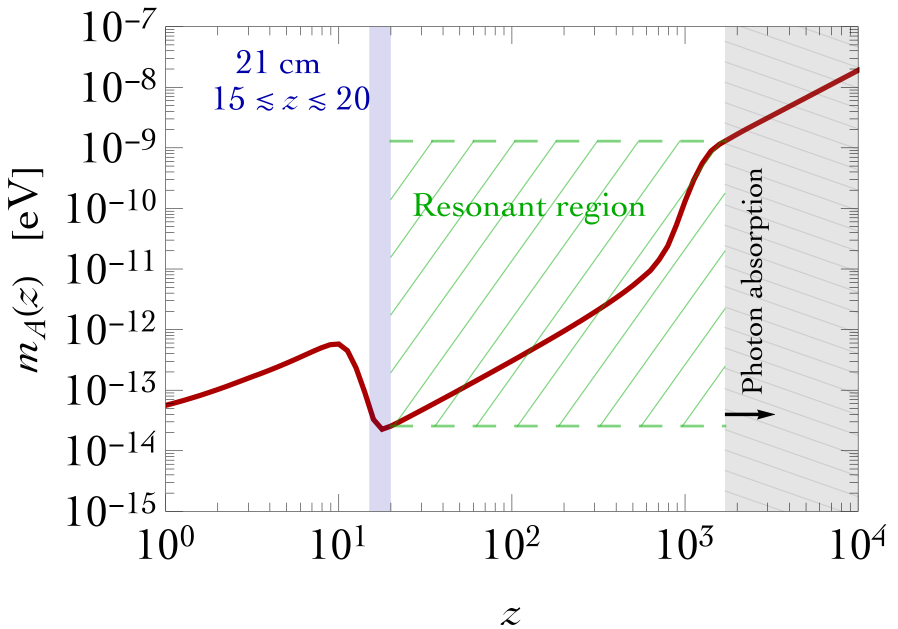

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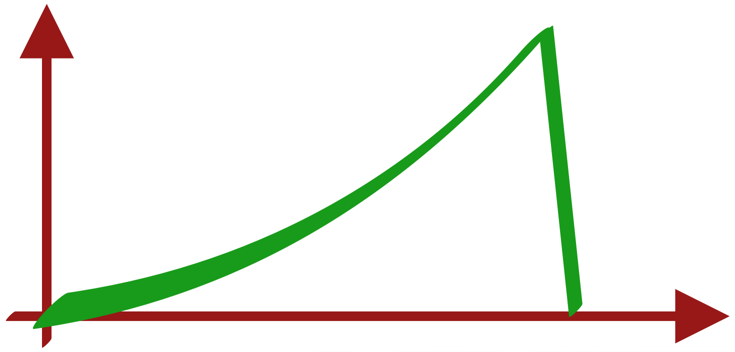
What about the mass of the decaying particle ?

If $m_a \gg m_{A'}$ the spectrum of the dark photons originated from the a decay is a distribution peaked at $E_{A'} = m_a/2$ (and broadened by redshift of mometum).



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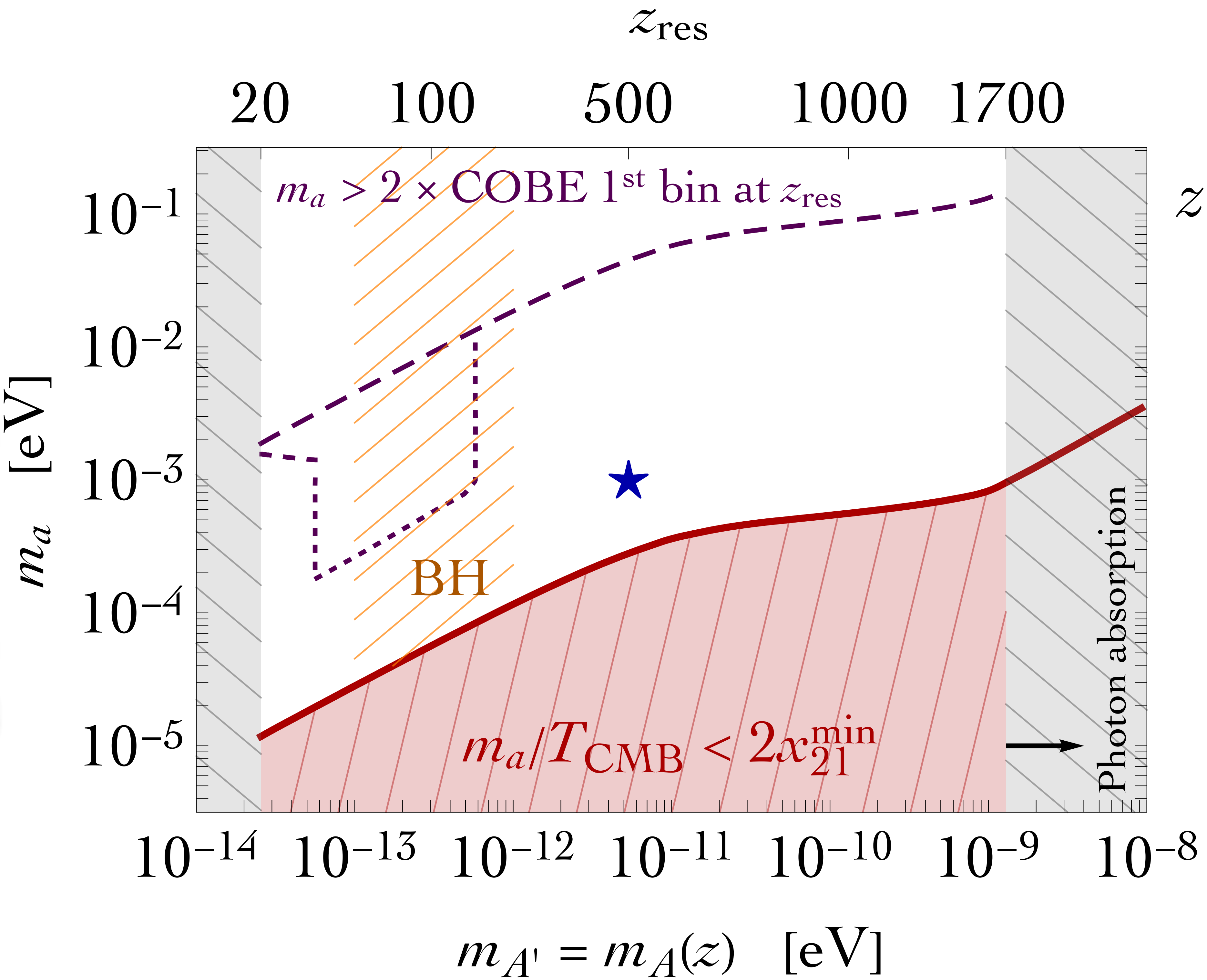

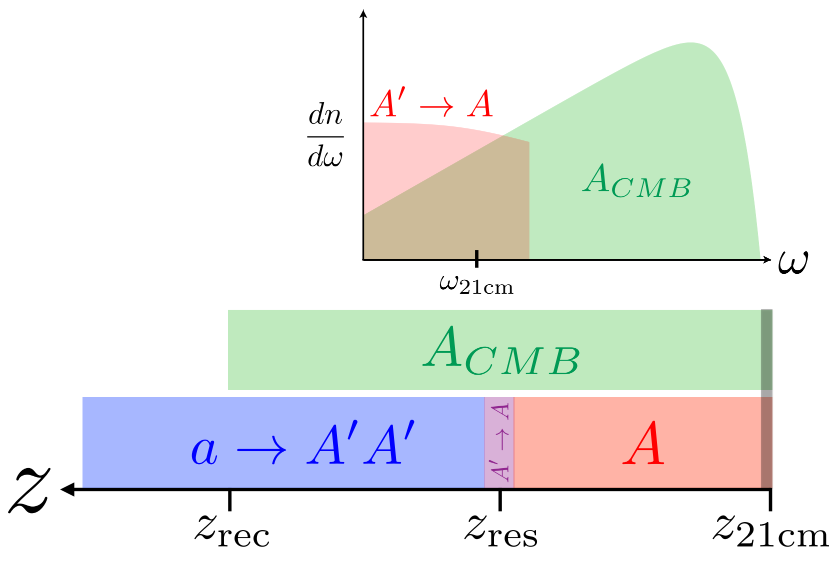

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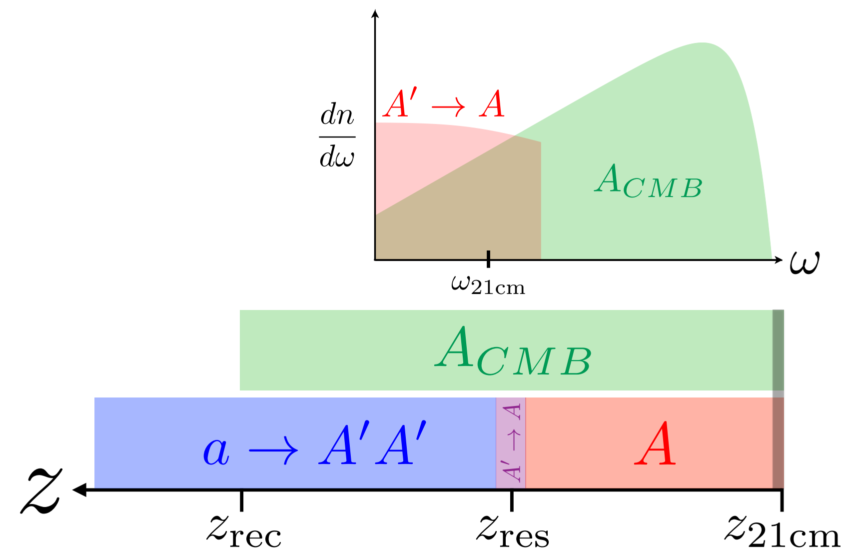

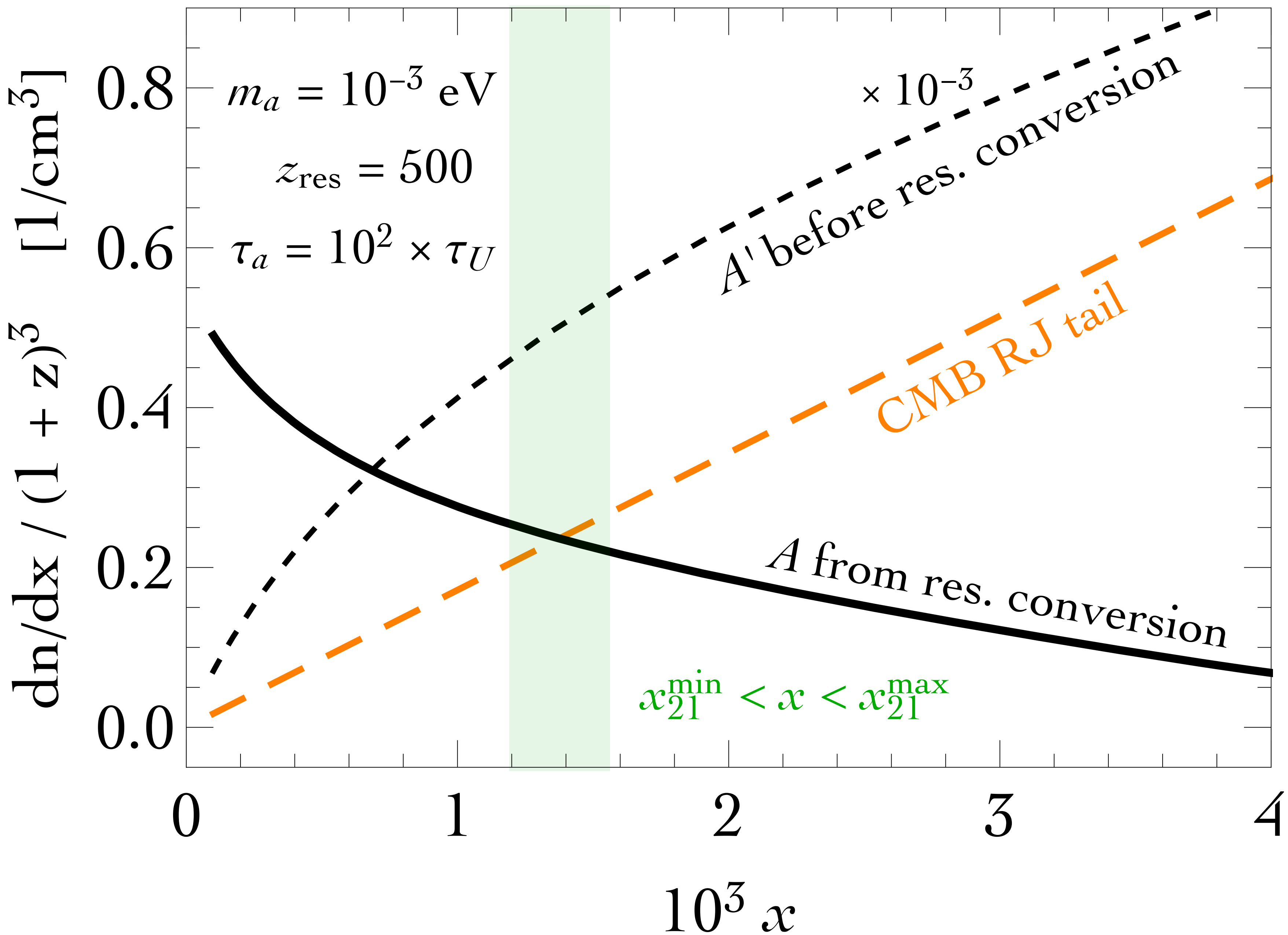

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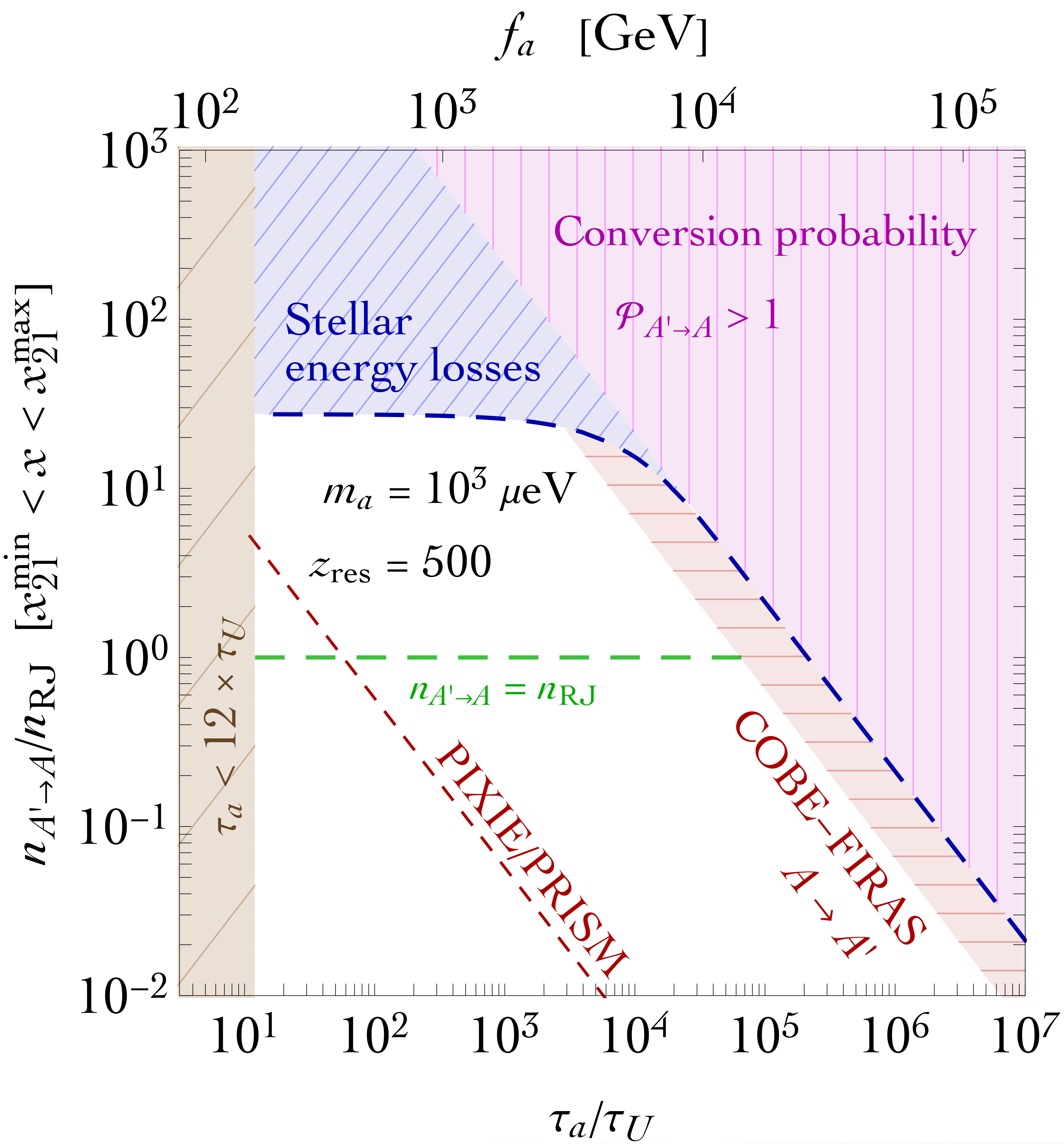
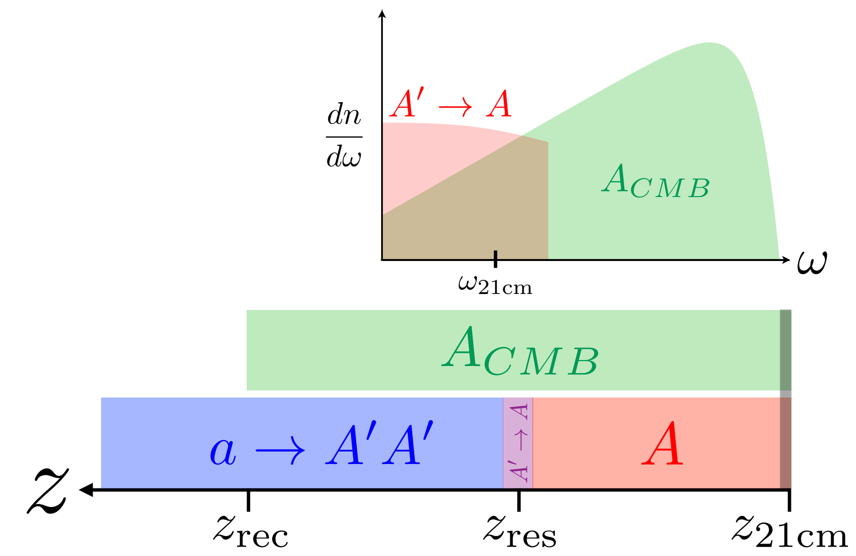
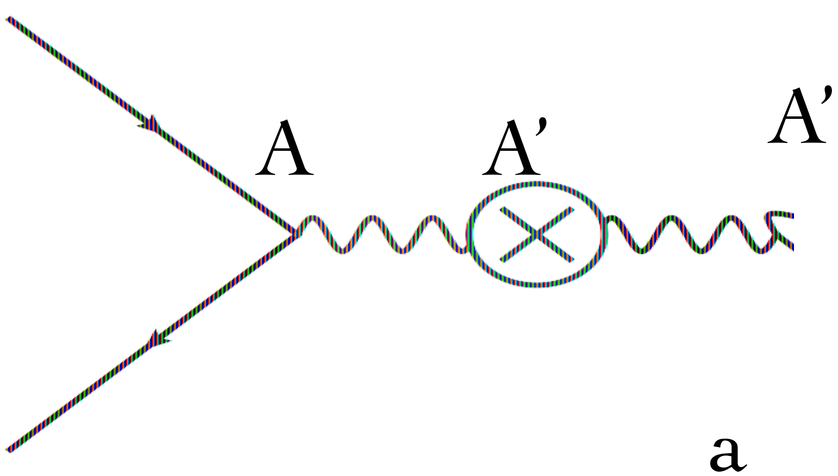




Cooling bound from:



Towards a concrete model