

21-cm Constraints on Dark Matter

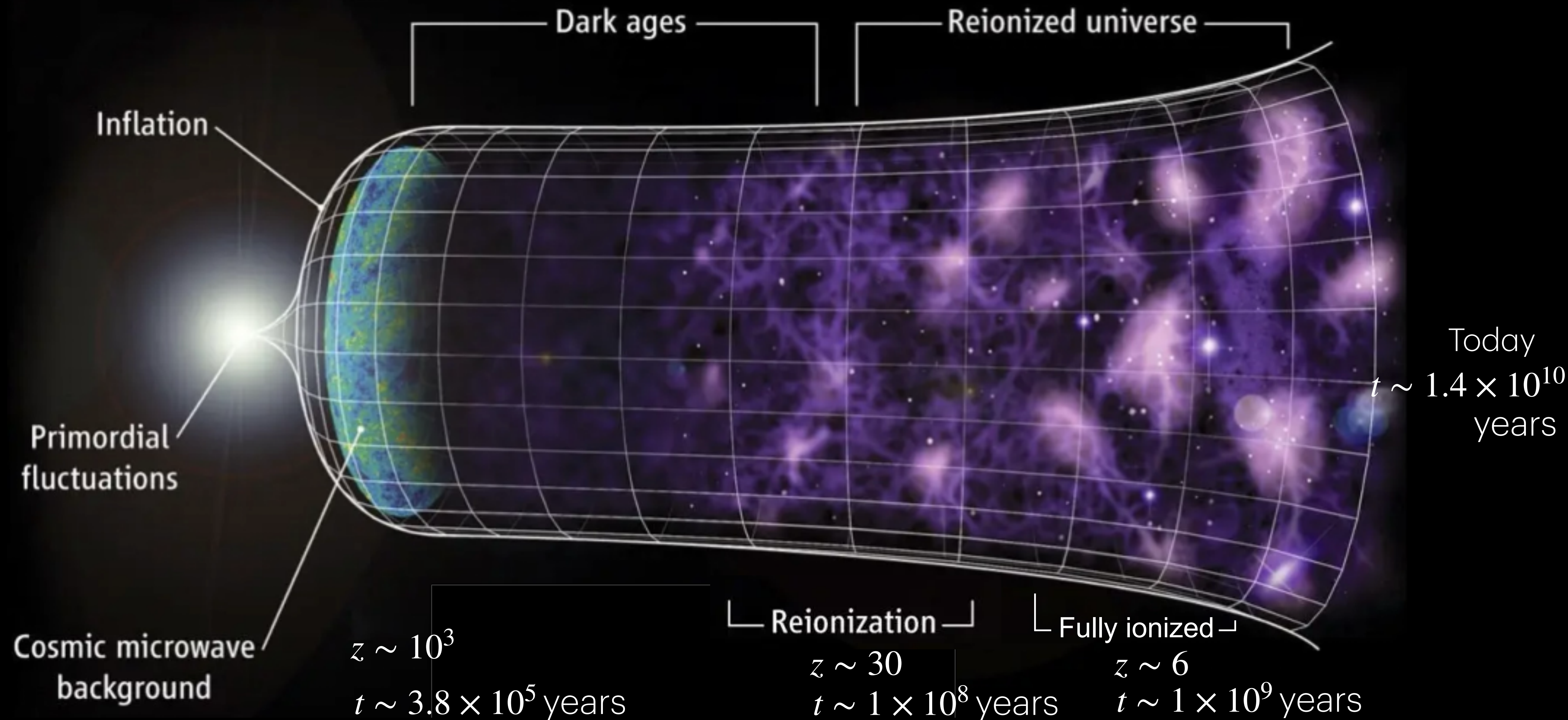
Based on 2510.14877 and 2510.26791.



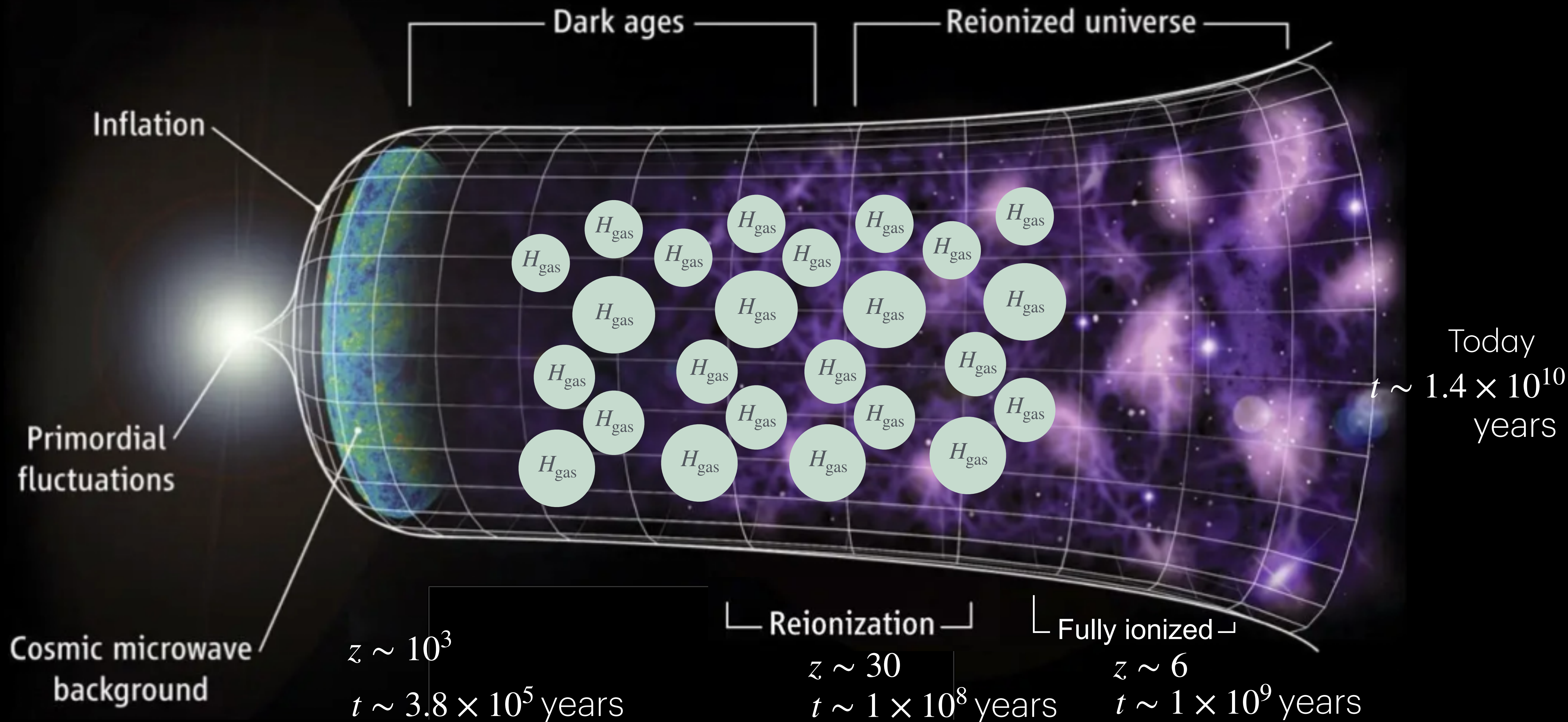
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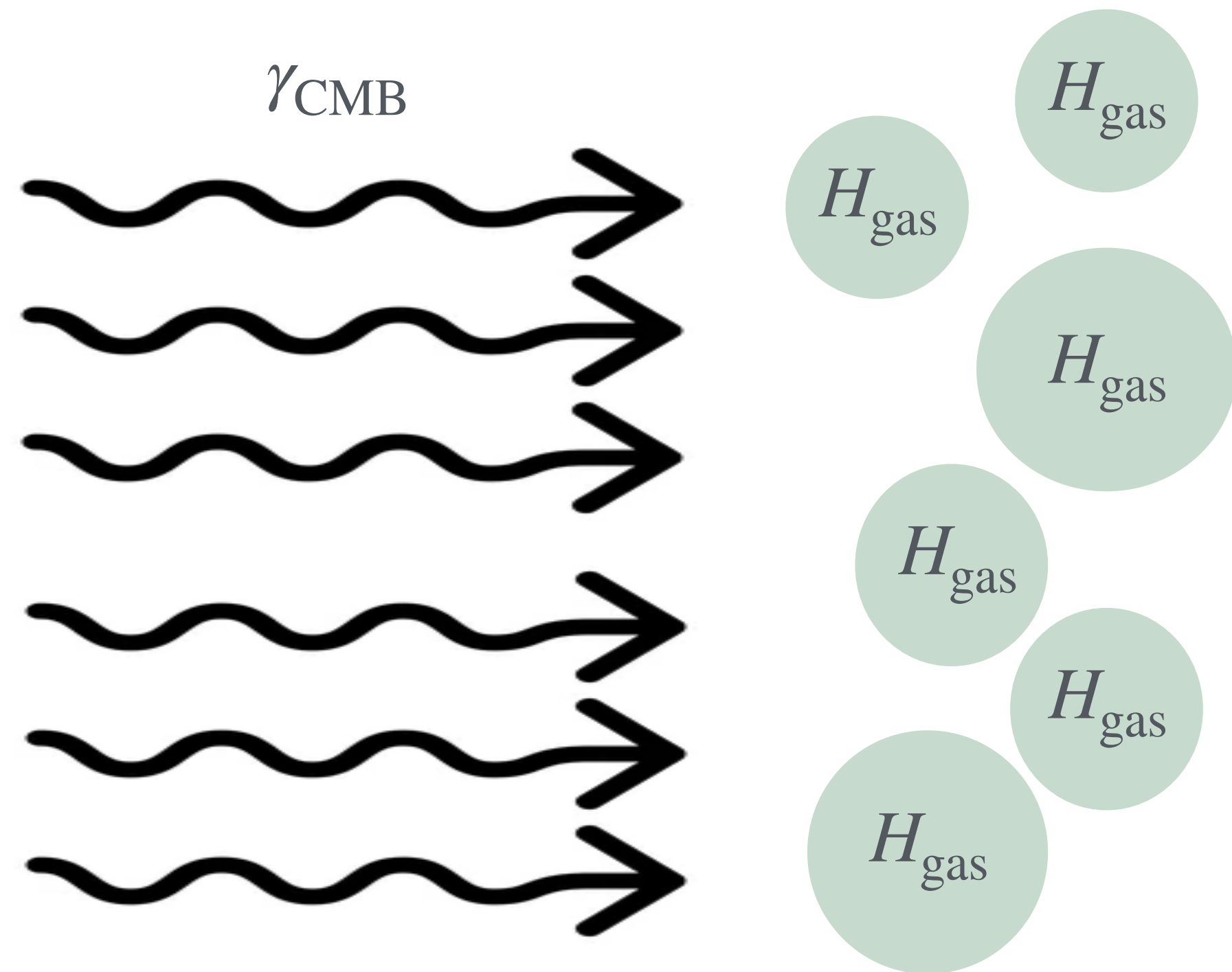
Setting the scene



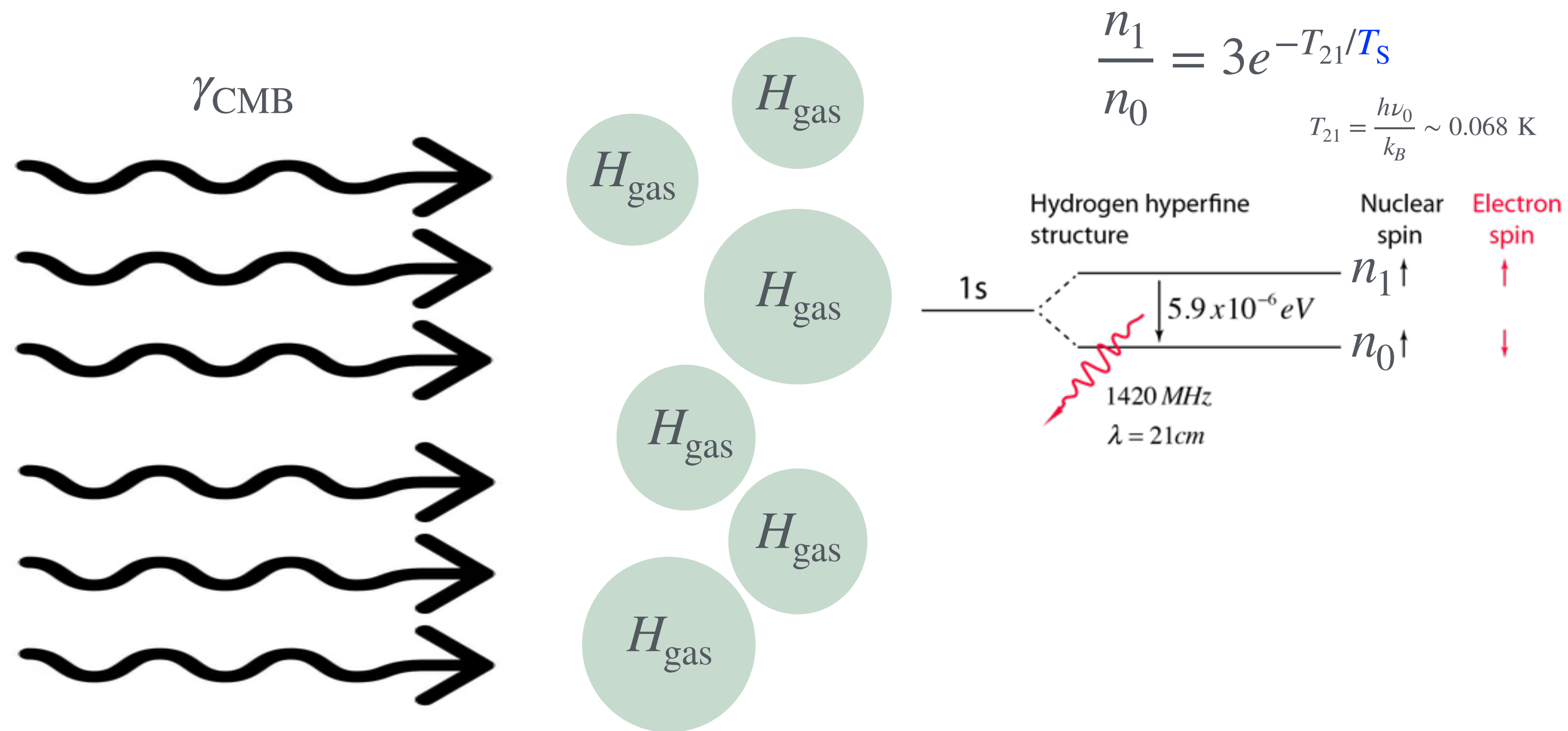
Setting the scene — Hydrogen as a tracer



The 21-cm signal

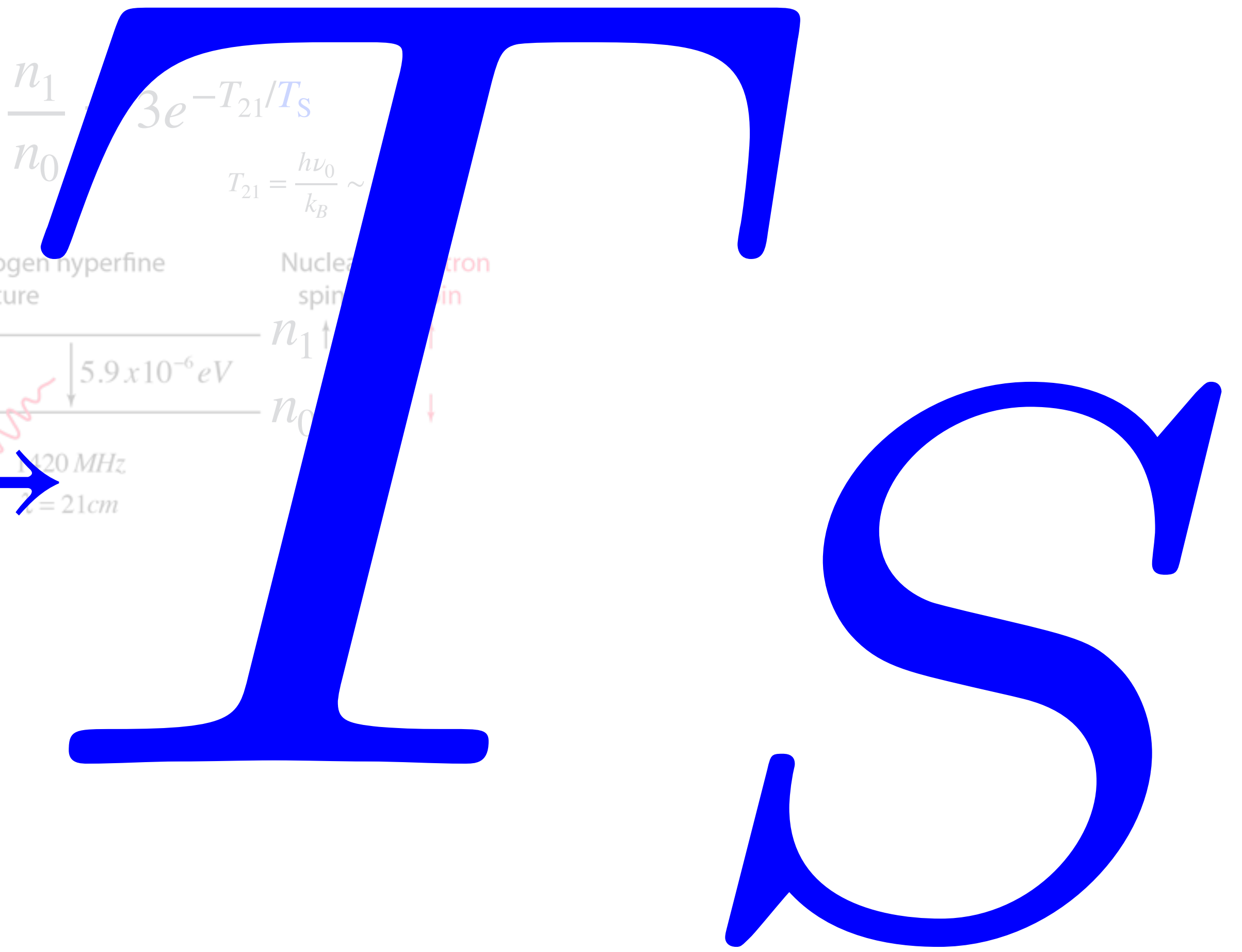
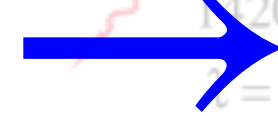


The 21-cm signal



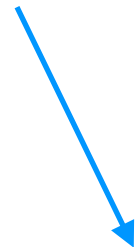
The 21-cm signal

Atomic Physics



The 21-cm signal

CMB temperature


$$T_S^{-1} = T_\gamma^{-1}$$

The spin temperature is dictated by its (de)coupling to T_γ and T_K . This is determined by:

1. Absorption and emission of 21cm photons from and to the CMB

The 21-cm signal

CMB temperature

Gas kinetic temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1}}{1 + x_k}$$

heating dependent

The spin temperature is dictated by its (de)coupling to T_γ and T_K . This is determined by:

1. Absorption and emission of 21cm photons from and to the CMB
2. Collisional coupling between H atoms

The 21-cm signal

CMB temperature

Gas kinetic temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

heating dependent
UV dependent

The spin temperature is dictated by its (de)coupling to T_γ and T_K . This is determined by:

1. Absorption and emission of 21cm photons from and to the CMB
2. Collisional coupling between H atoms
3. Wouthuysen-Field Effect (Lyman-alpha photons)

21cm physics (a primer)

Differential brightness temperature

CMB temperature

$$\delta T_b \propto x_{\text{HI}} \left(1 - \frac{T_\gamma}{T_S} \right) \left(\frac{1+z}{10} \right)^{1/2}$$

Fraction of neutral hydrogen

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

Spin temperature

21cm physics (a primer)

Differential brightness temperature

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Fraction of neutral hydrogen

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_k + x_\alpha}$$

Spin temperature

- $T_S = T_\gamma \rightarrow \delta T_b = 0$
- $T_S > T_\gamma \rightarrow \delta T_b > 0$
- $T_S < T_\gamma \rightarrow \delta T_b < 0$

21cm physics (a primer)

Differential brightness temperature

Fraction of neutral hydrogen

CMB temperature

Spin temperature

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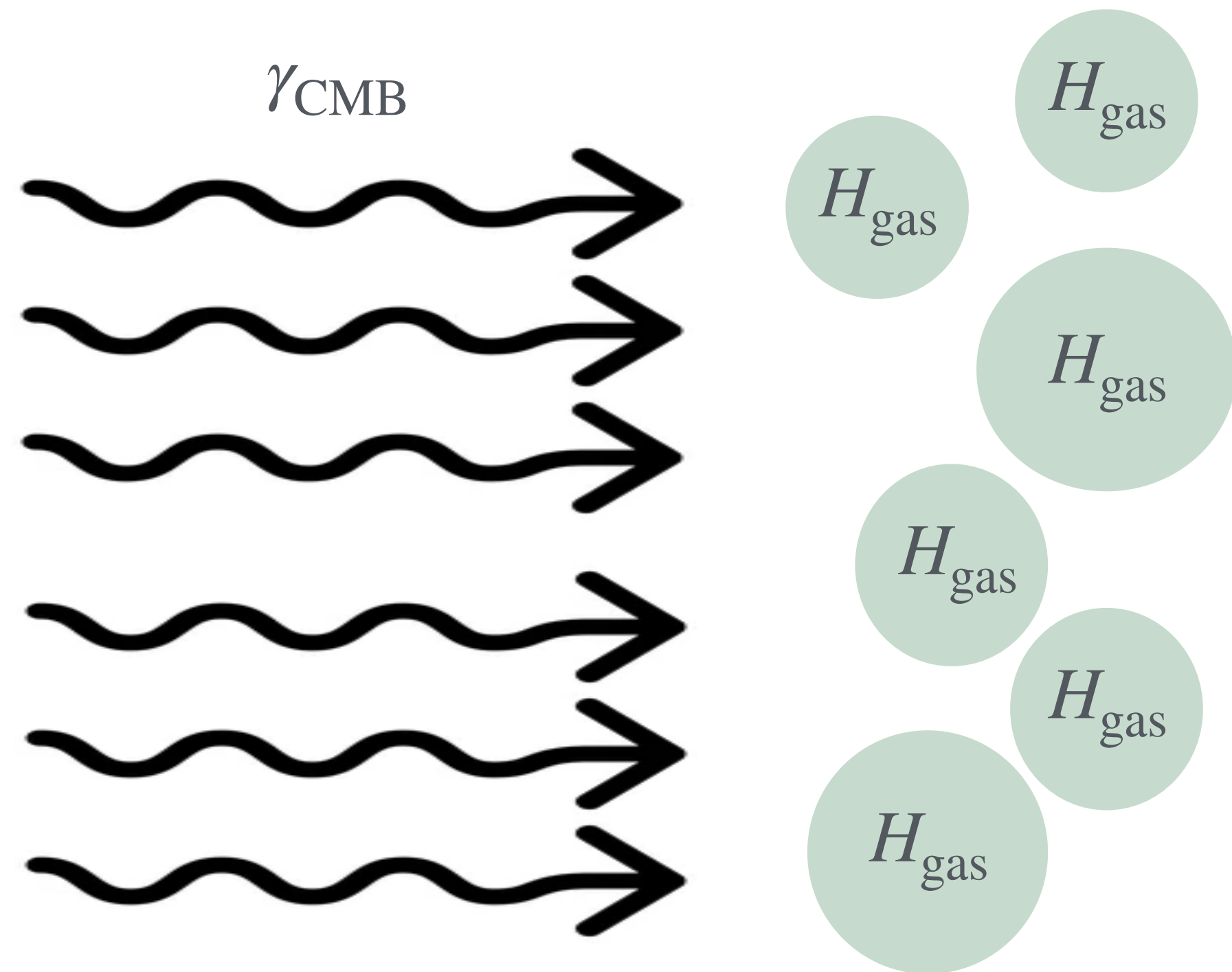
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- $T_S = T_\gamma \rightarrow \delta T_b = 0$
- $T_S > T_\gamma \rightarrow \delta T_b > 0$
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The signal is dictated by T_γ/T_S and x_{HI} !

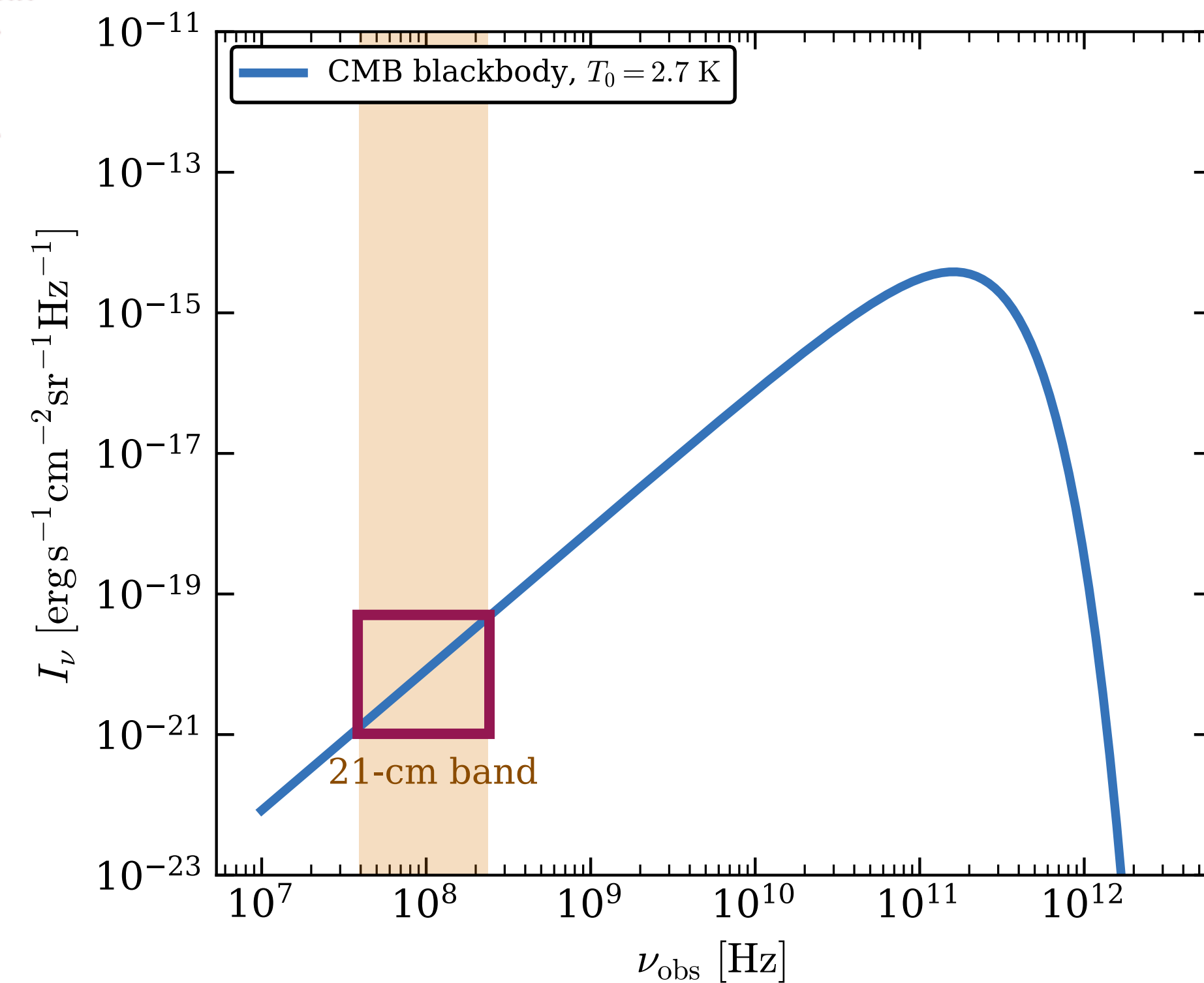
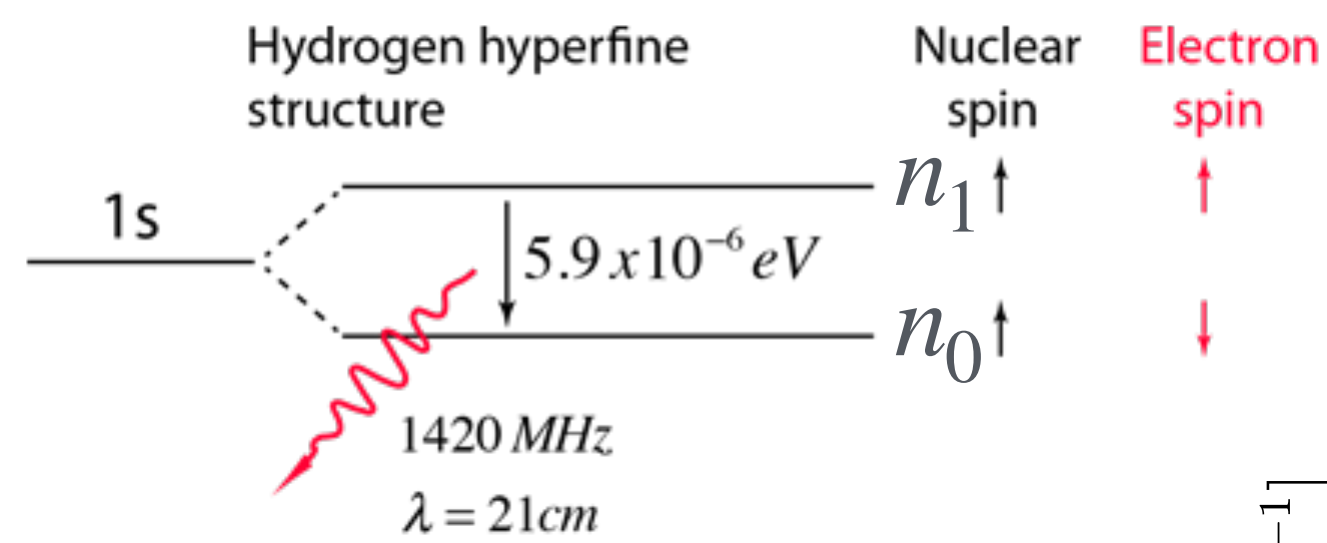
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The 21-cm signal

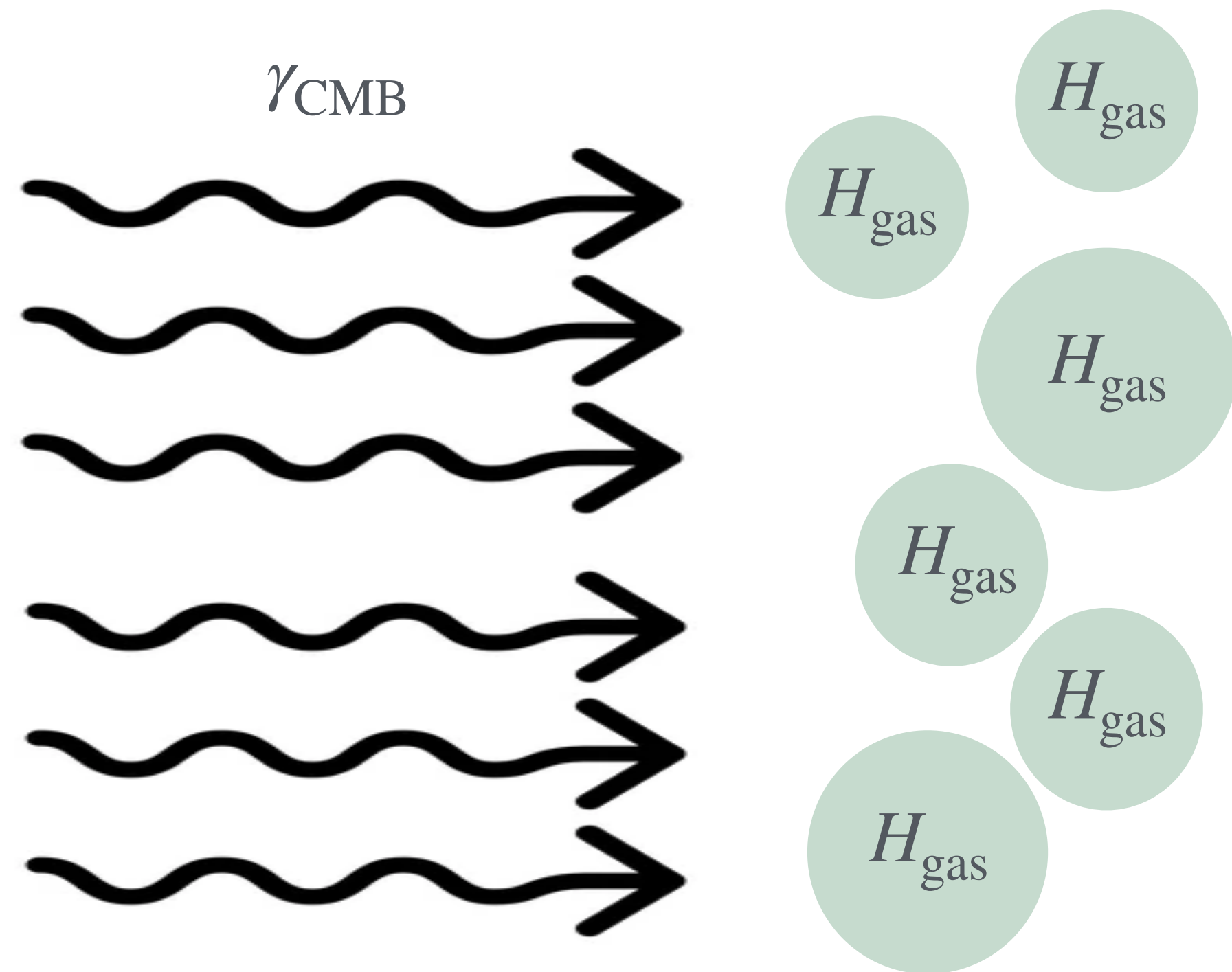


$$\frac{n_1}{n_0} = 3e^{-T_{21}/T_S}$$

$$T_{21} = \frac{h\nu_0}{k_B} \sim 0.068 \text{ K}$$

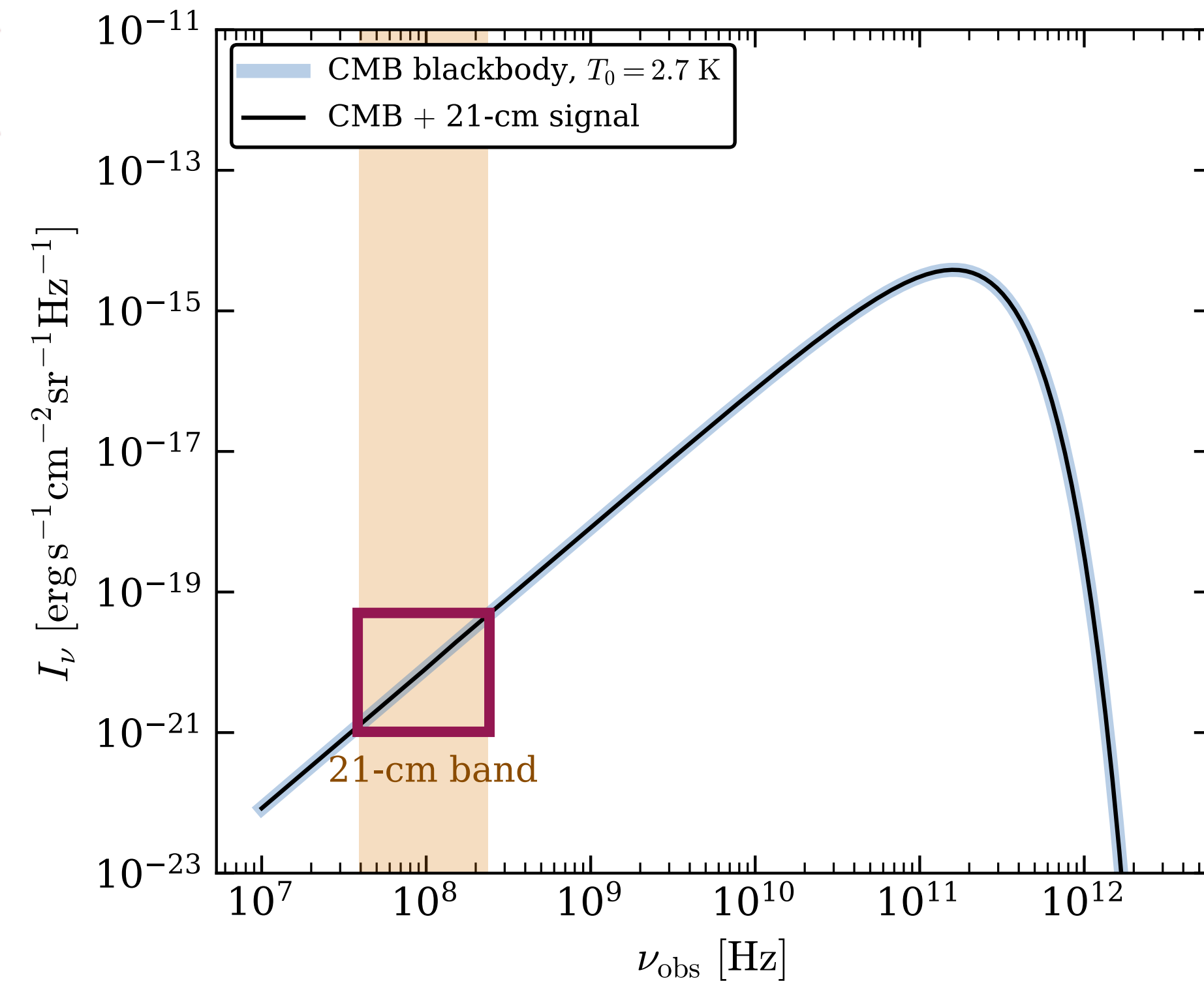
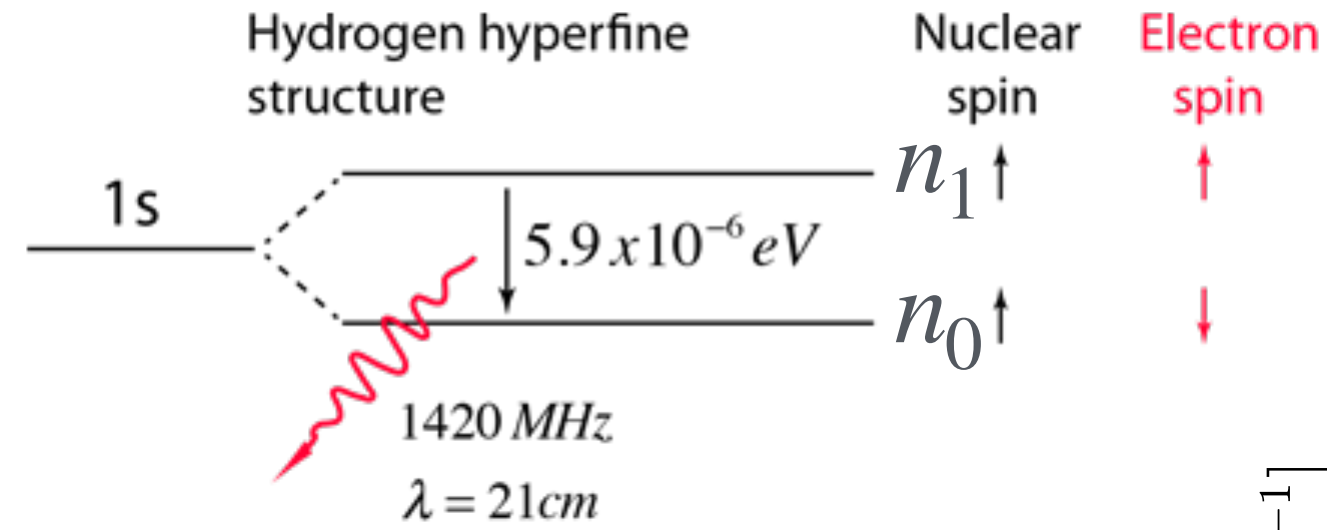


The 21-cm signal

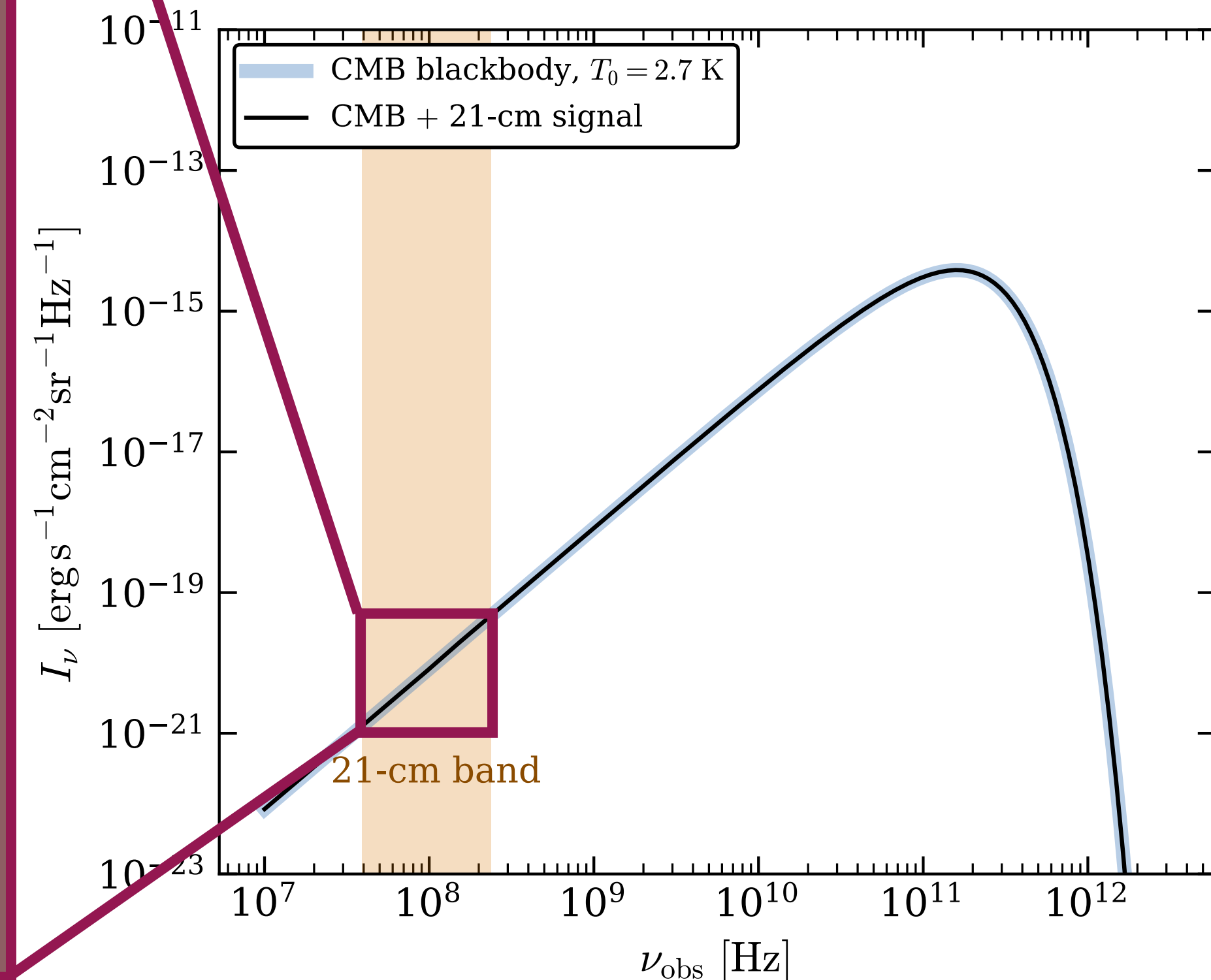
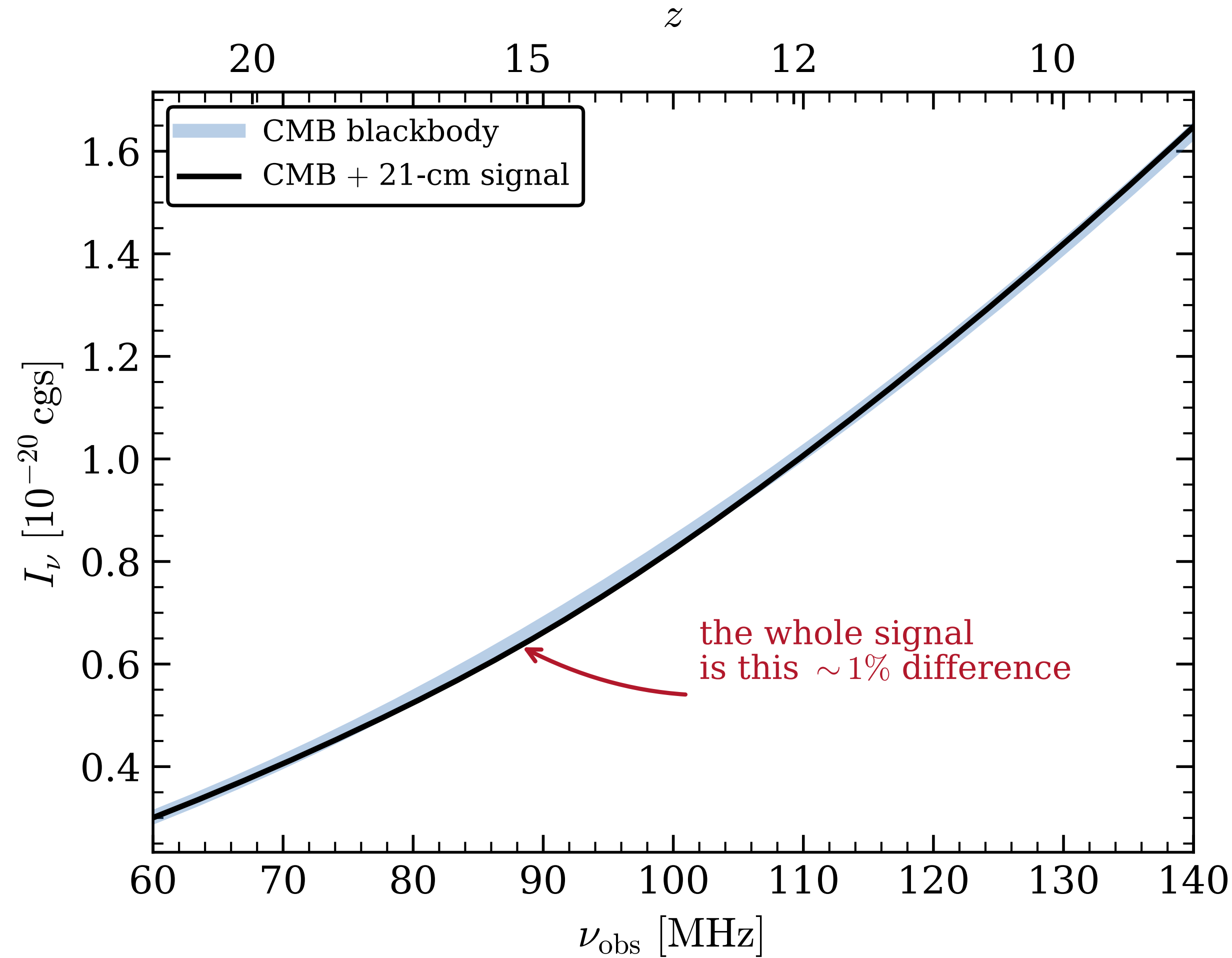


$$\frac{n_1}{n_0} = 3e^{-T_{21}/T_S}$$

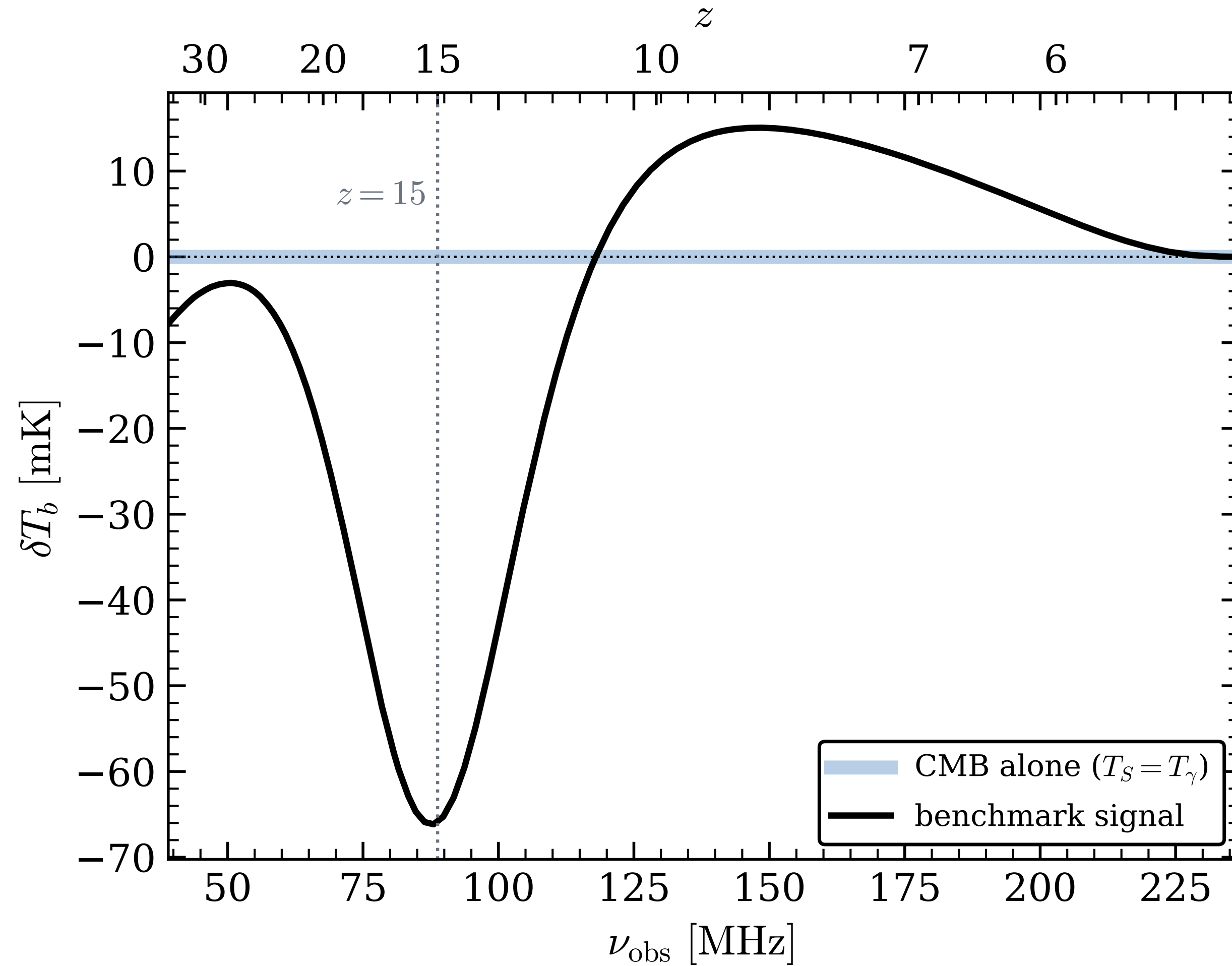
$$T_{21} = \frac{h\nu_0}{k_B} \sim 0.068 \text{ K}$$



The 21-cm signal — zoomed in



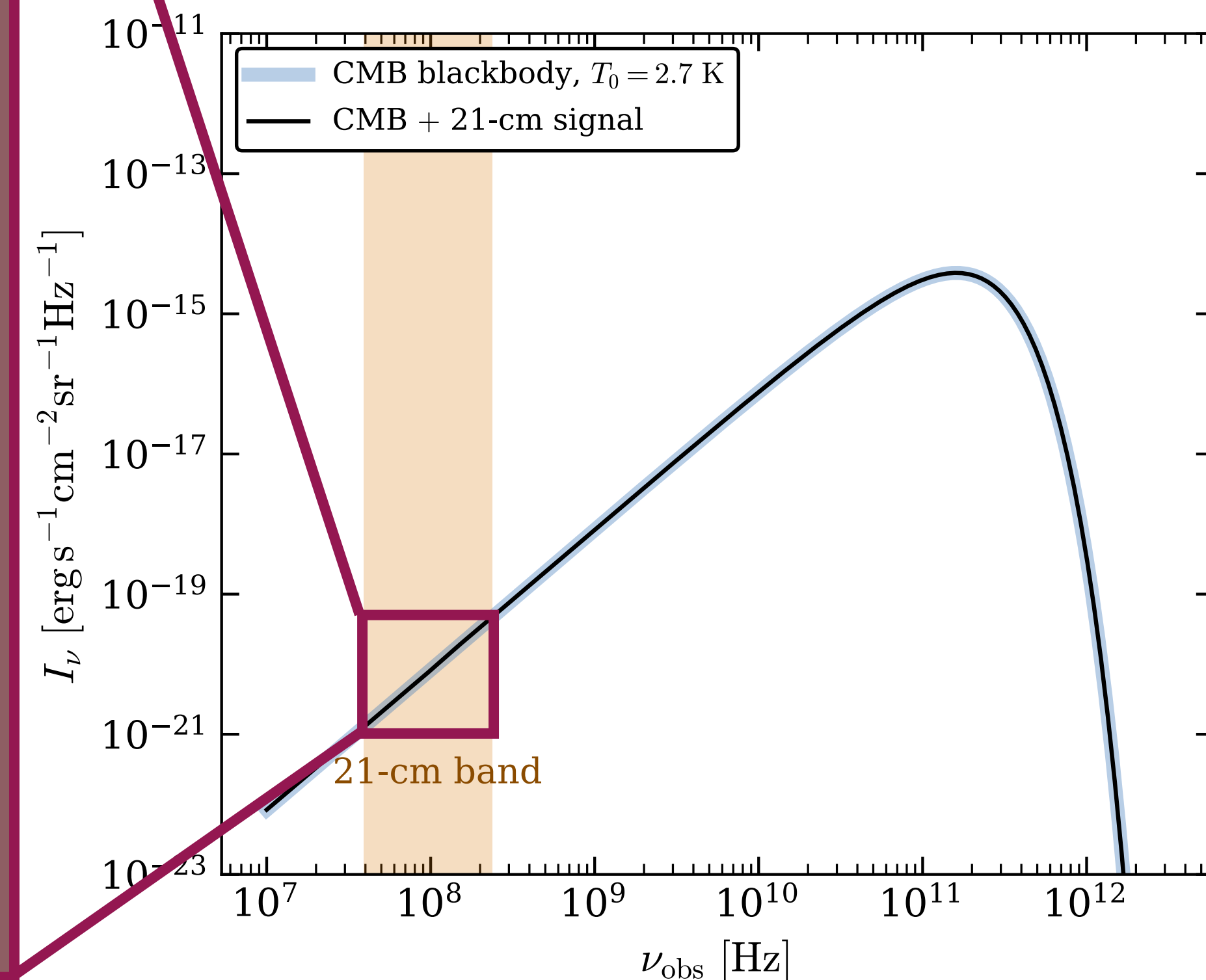
The 21-cm signal — convert to temperature



1. $I_\nu \rightarrow T_\nu$

2. Subtract T_{CMB}

$$\delta T_b \propto x_{\text{HI}} \left(1 - \frac{T_\gamma}{T_s} \right) \left(\frac{1+z}{10} \right)^{1/2}$$



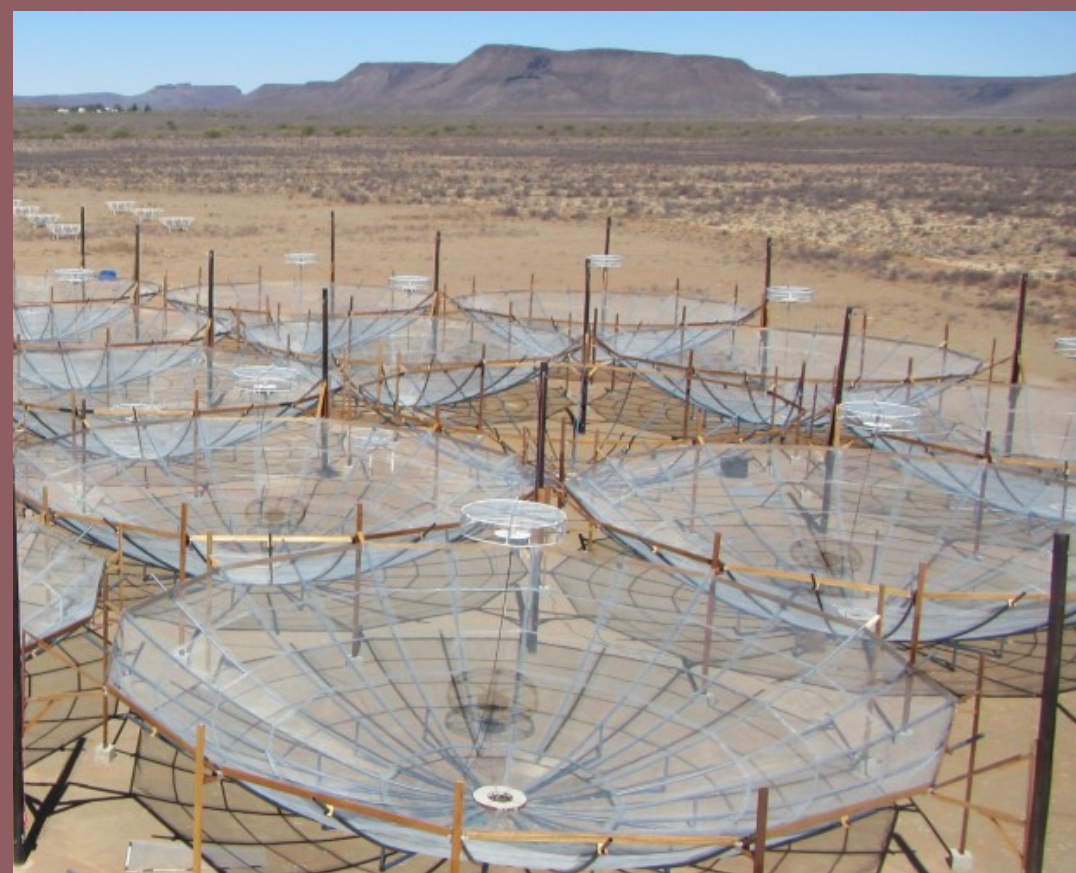
The 21-cm signal



EDGES



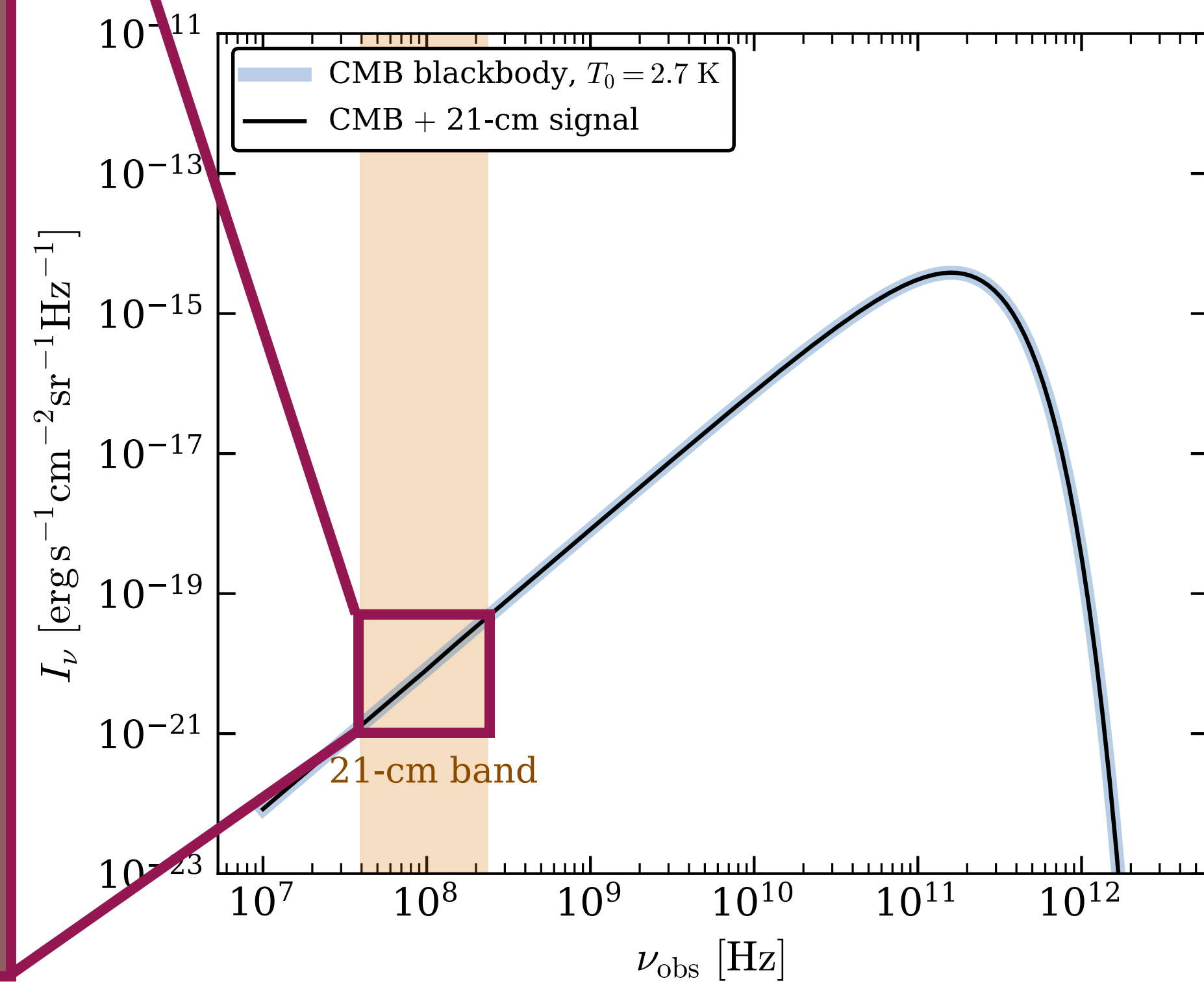
SARAS



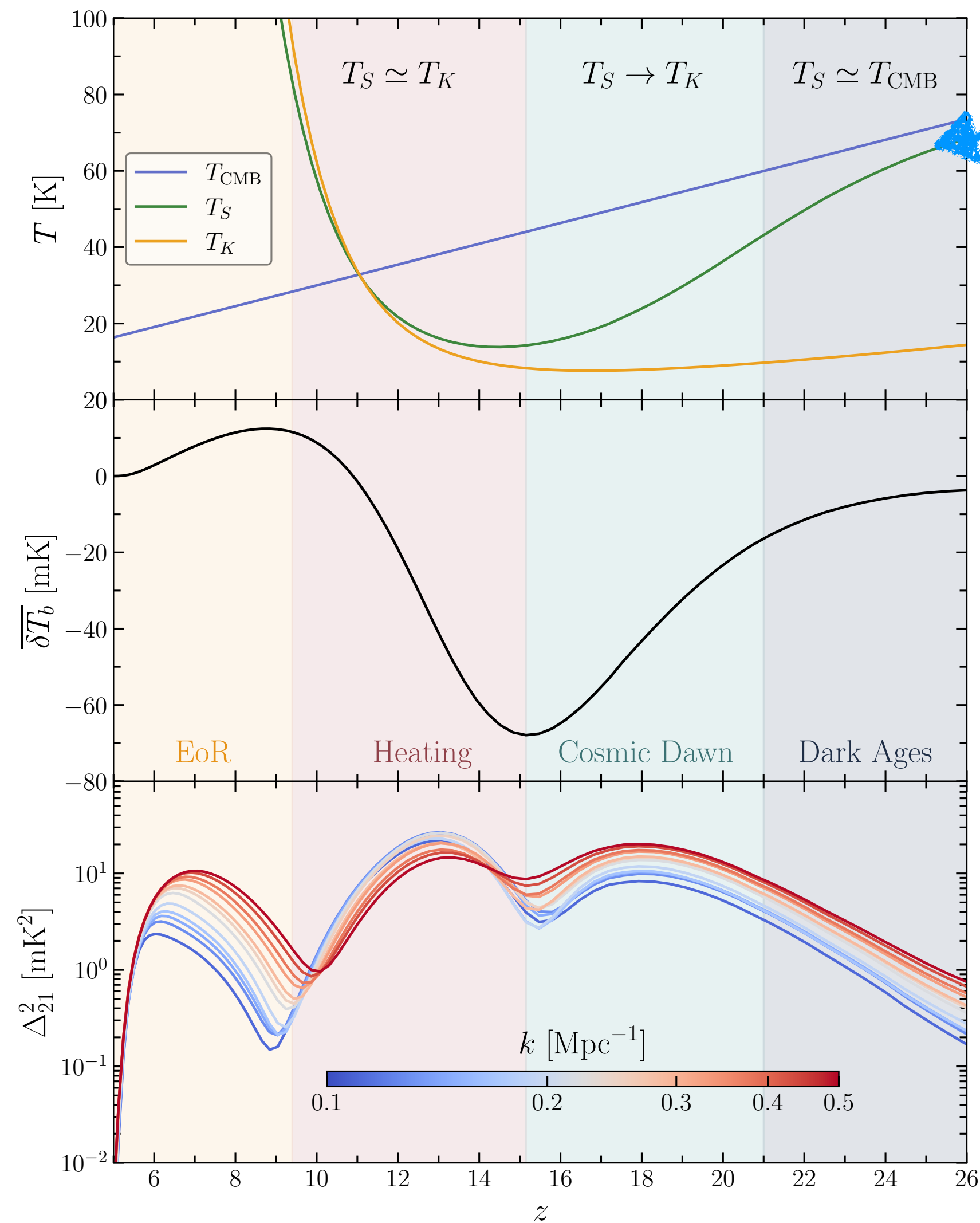
HERA



SKA



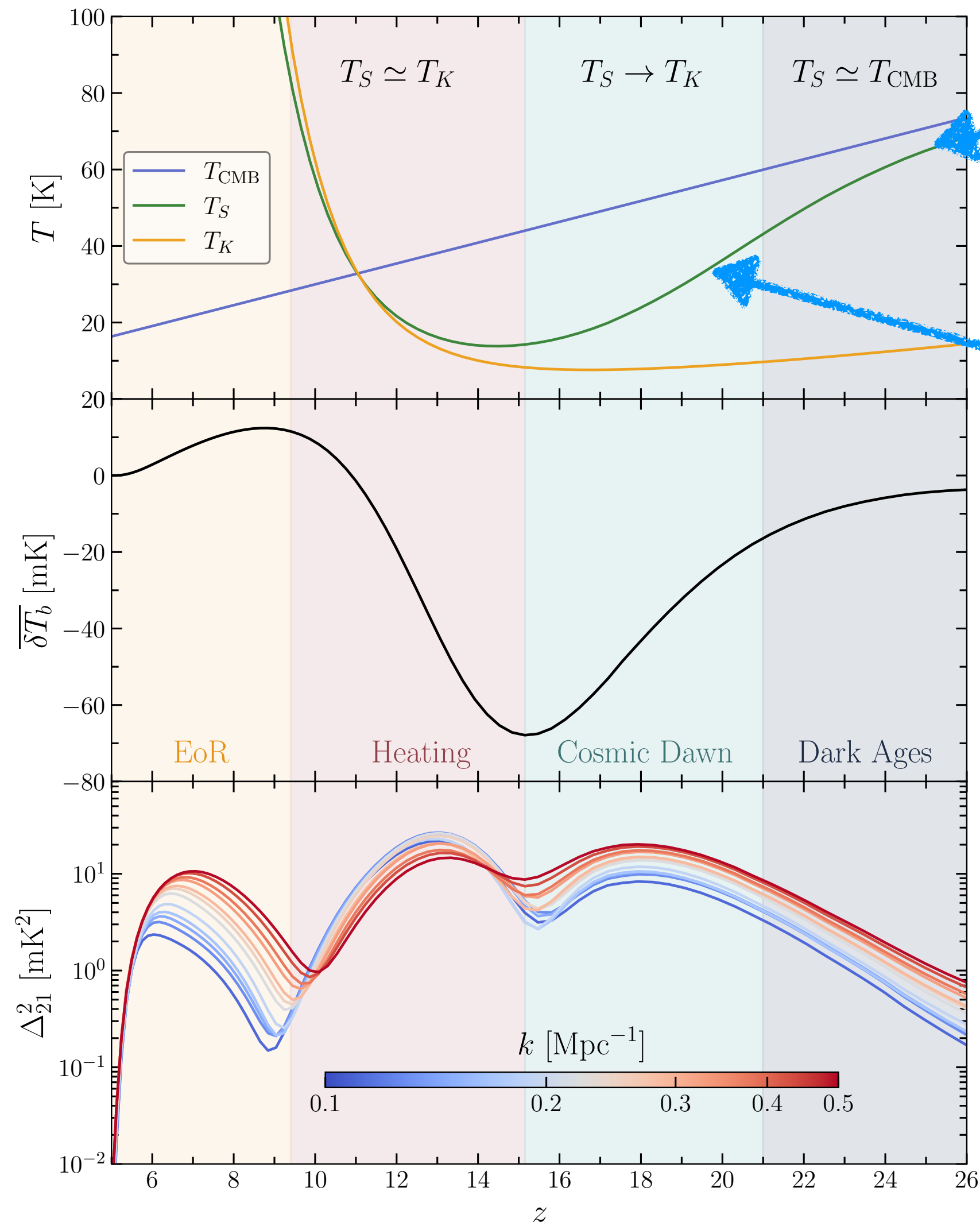
The standard story



Radiative coupling most efficient (too low densities for collisions) and $T_S \simeq T_\gamma$

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

The standard story

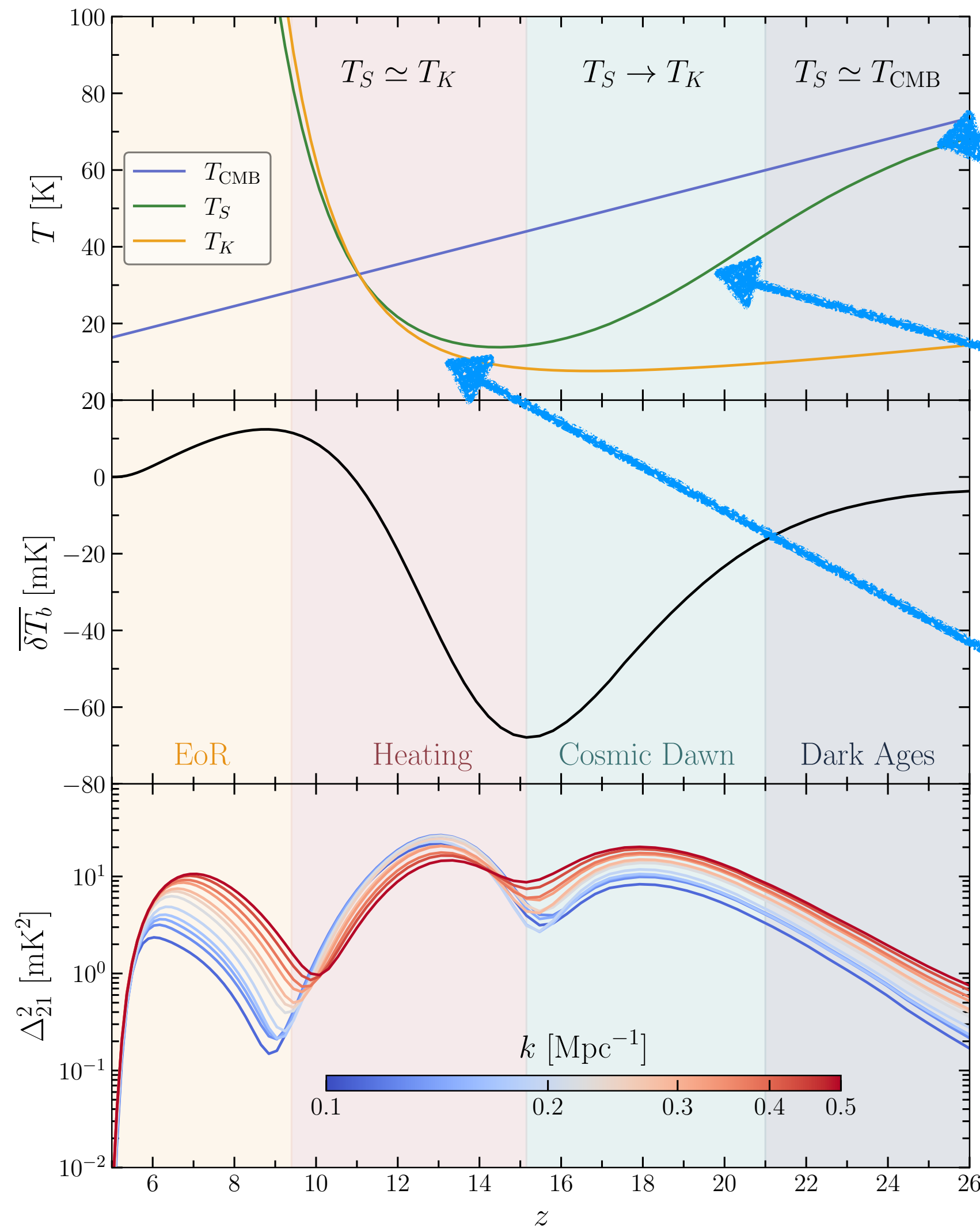


Radiative coupling most efficient (too low densities for collisions) and $T_S \simeq T_\gamma$

Lyman-alpha photons from first sources couples $T_S \rightarrow T_K$, through the WF effect

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The standard story



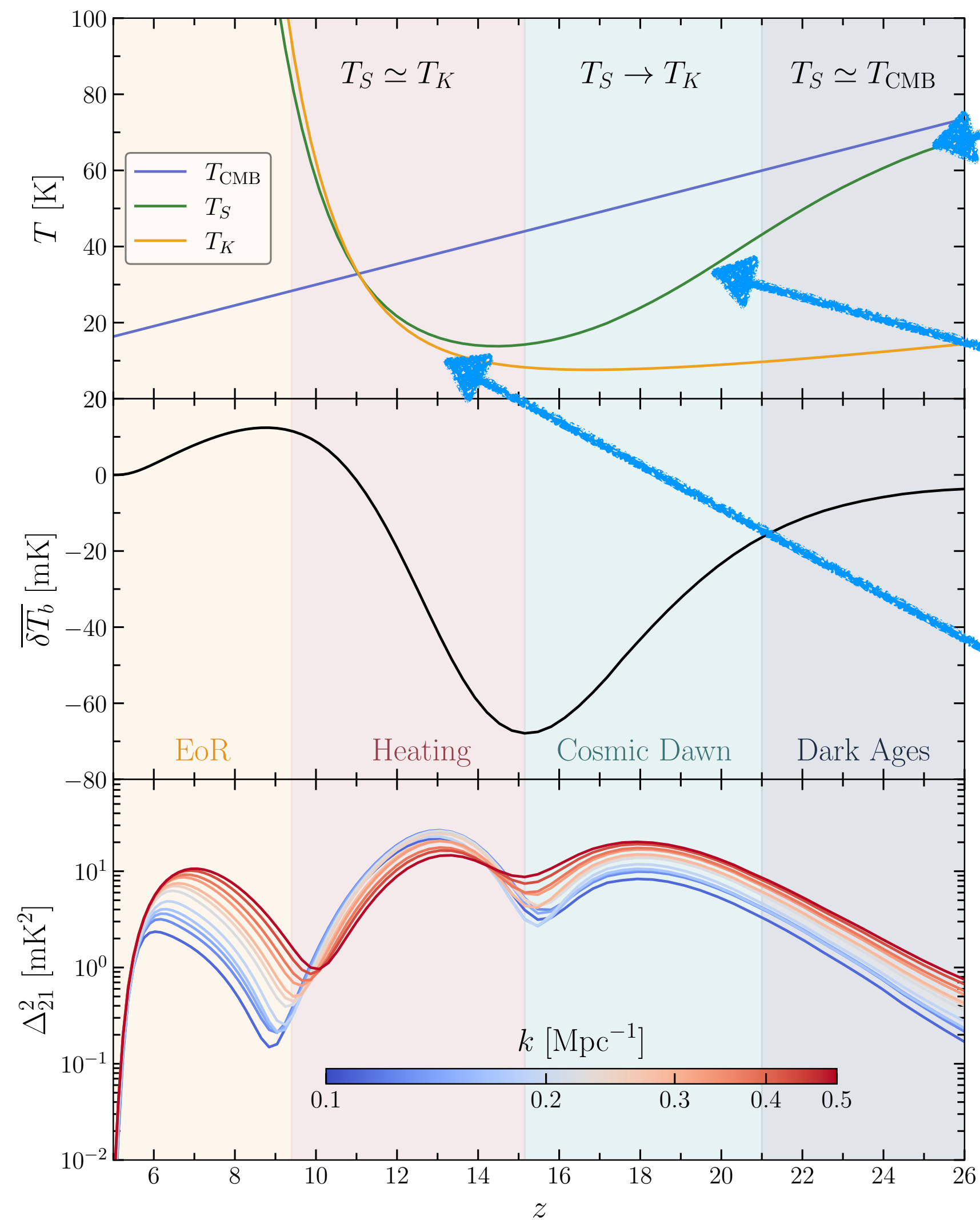
Radiative coupling most efficient (too low densities for collisions) and $T_S \simeq T_\gamma$

Lyman-alpha photons from first sources couples $T_S \rightarrow T_K$, through the WF effect

X-ray heating of the gas, where WF effect still couples $T_S \rightarrow T_K$. We see emission when $T_K > T_\gamma$

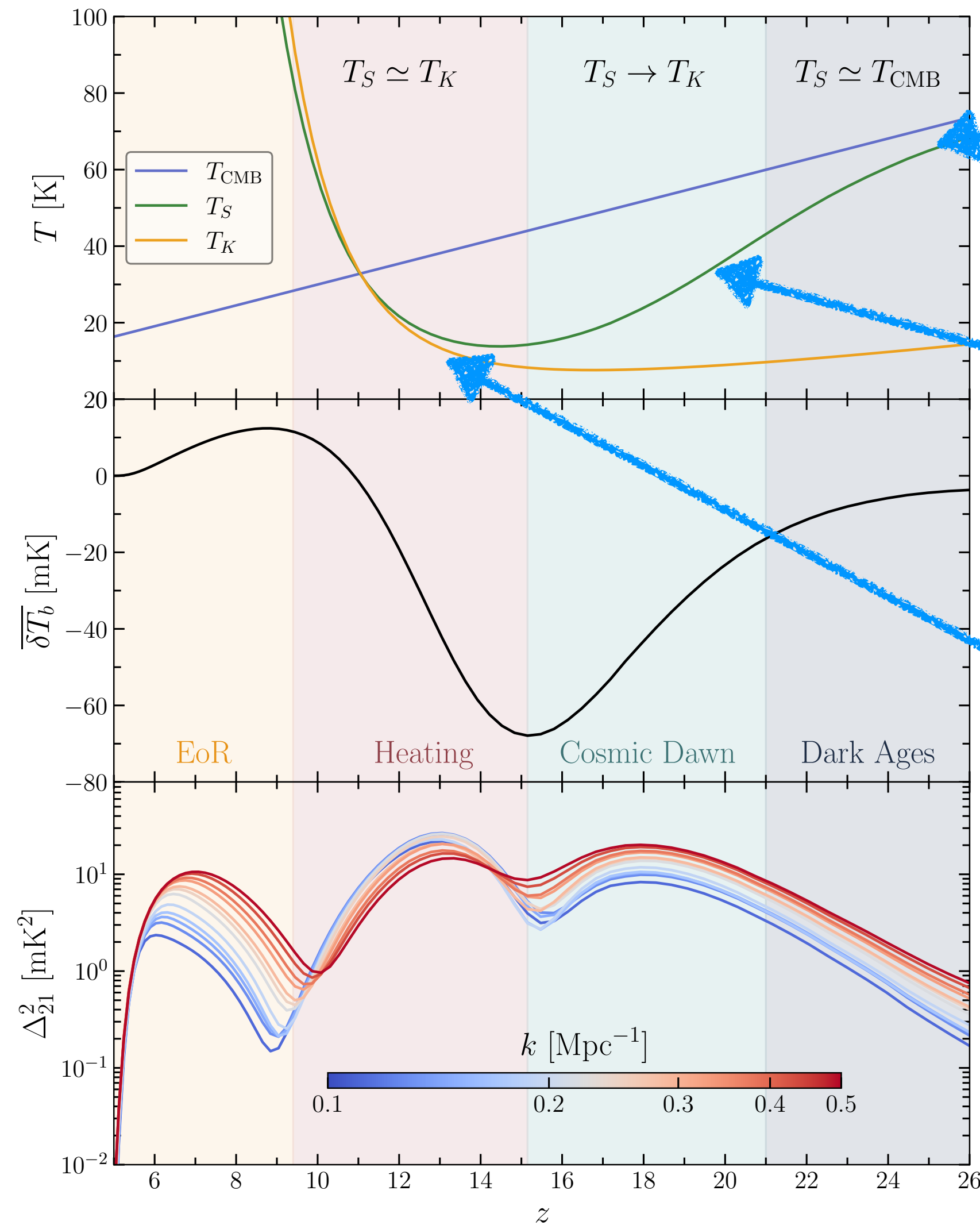
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

21cm physics (with exotica)



We study how Exotic Energy Injections change two (measurable) things:

21cm physics (with exotica)



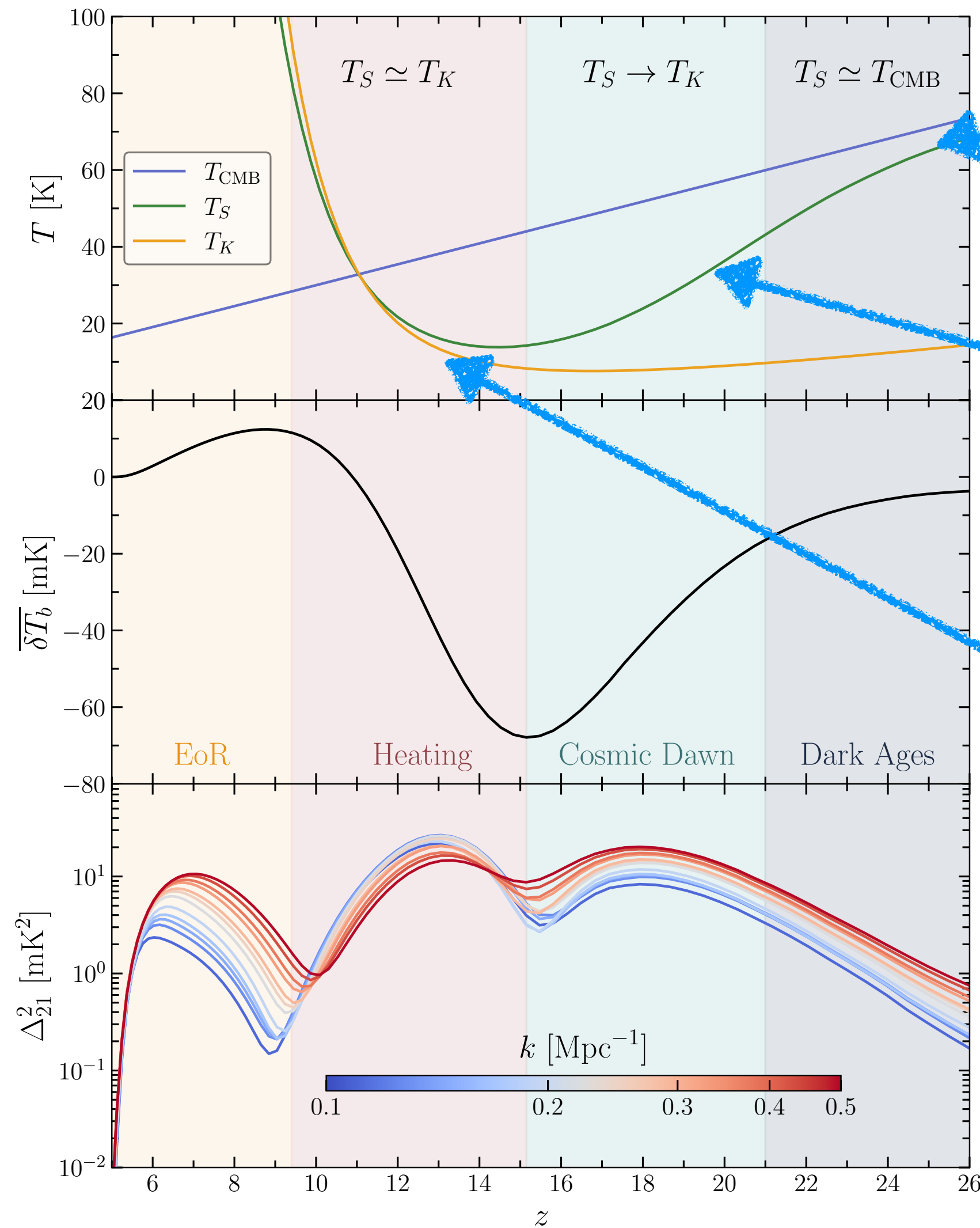
Radiative coupling most efficient (too low densities for collisions) and $T_S \simeq T_\gamma$

Lyman-alpha photons from first sources dark matter couples $T_S \rightarrow T_K$, through the WF effect

X-ray **heating** of the gas, where WF effect still couples $T_S \rightarrow T_K$. We see emission when $T_K > T_\gamma$

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

21cm physics (with exotica)



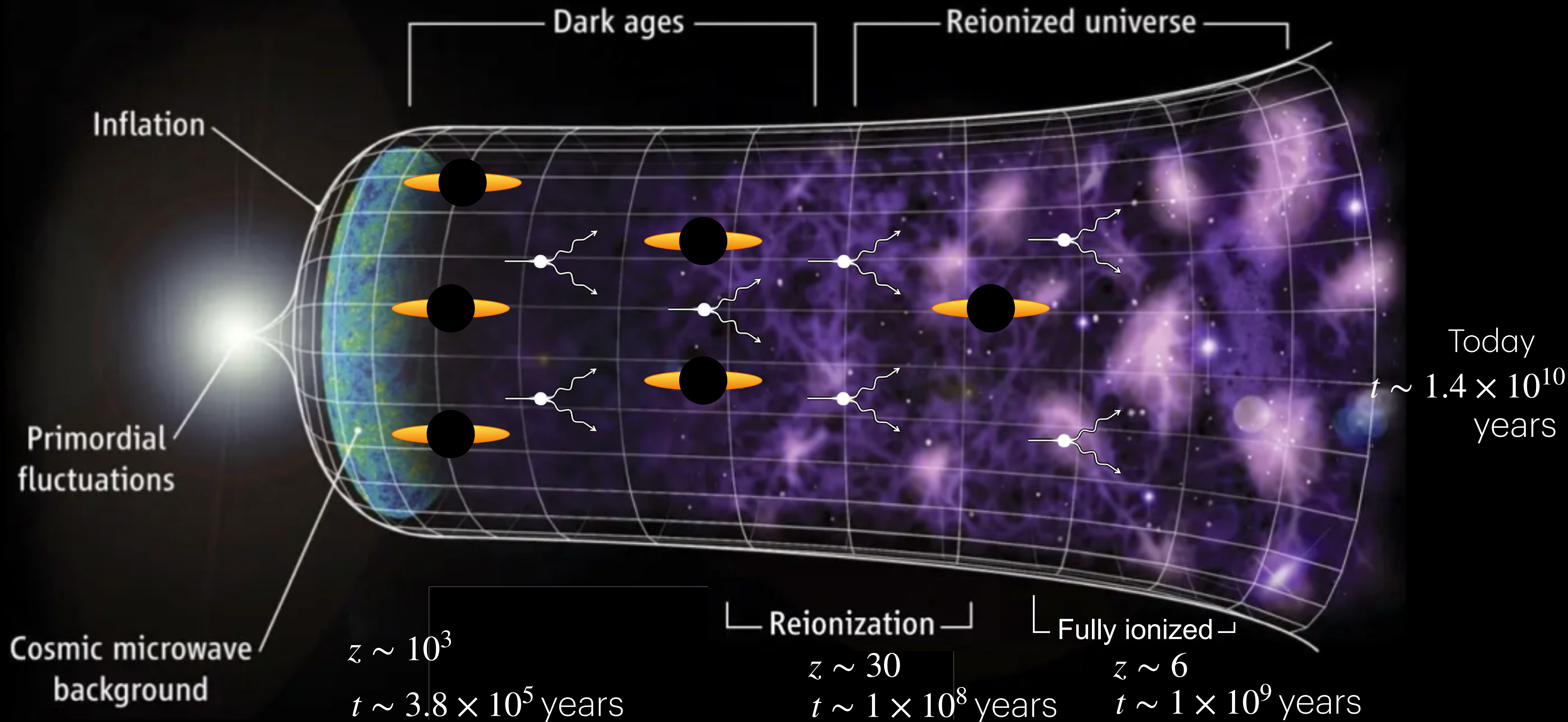
Radiative coupling most efficient (too low densities for collisions) and $T_S \simeq T_\gamma$

Lyman-alpha photons from first sources **dark matter** couples $T_S \rightarrow T_K$, through the WF effect

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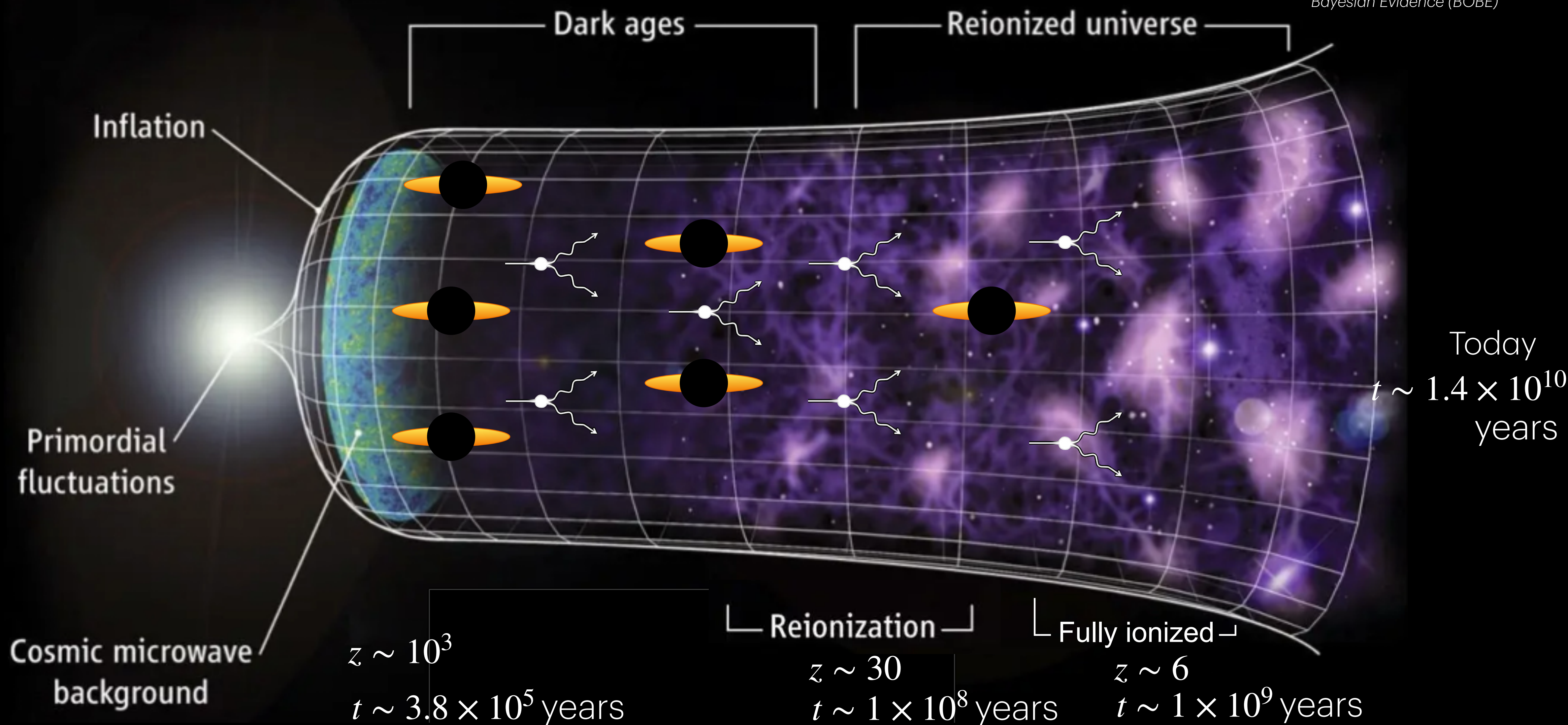
The broad picture



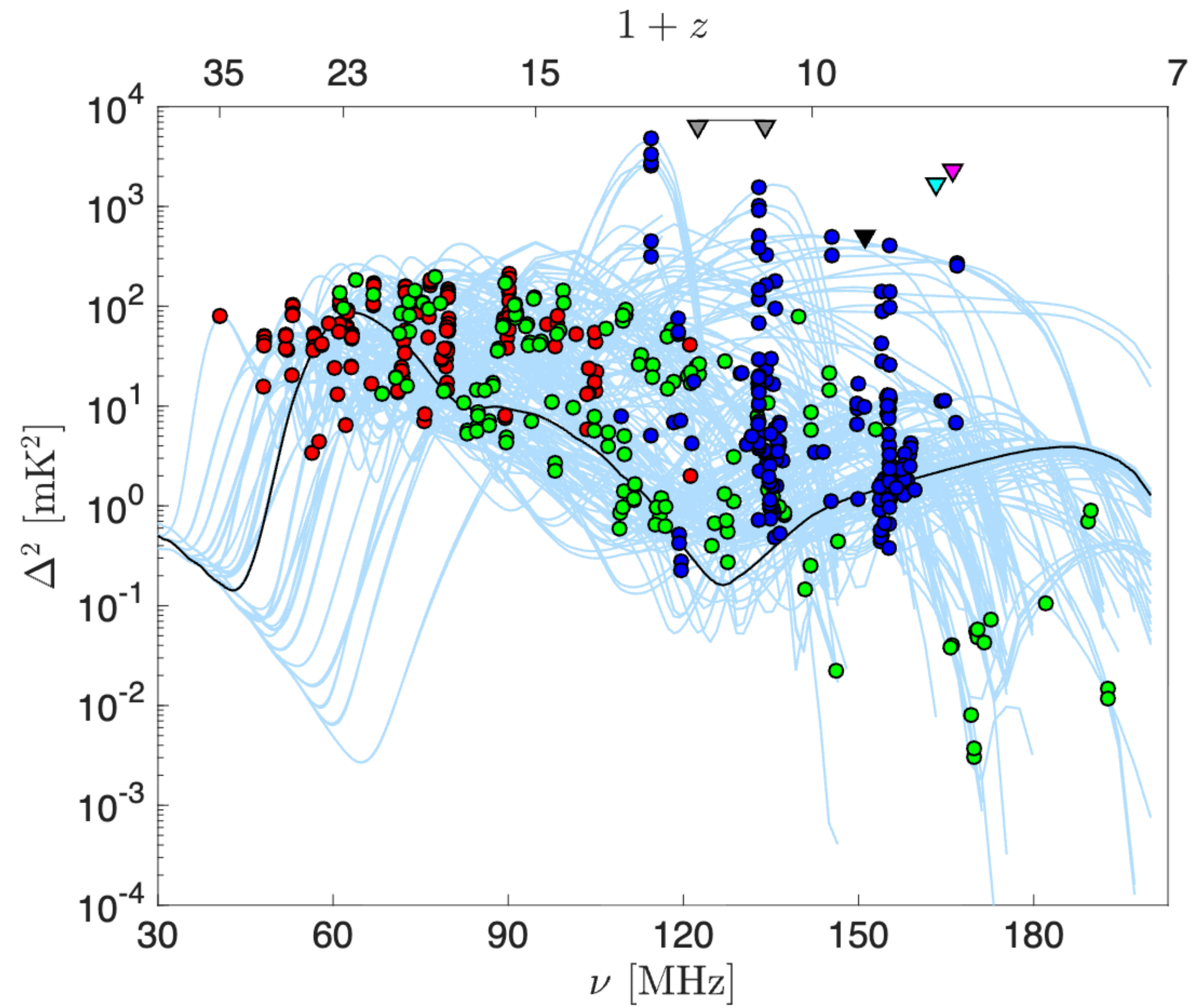
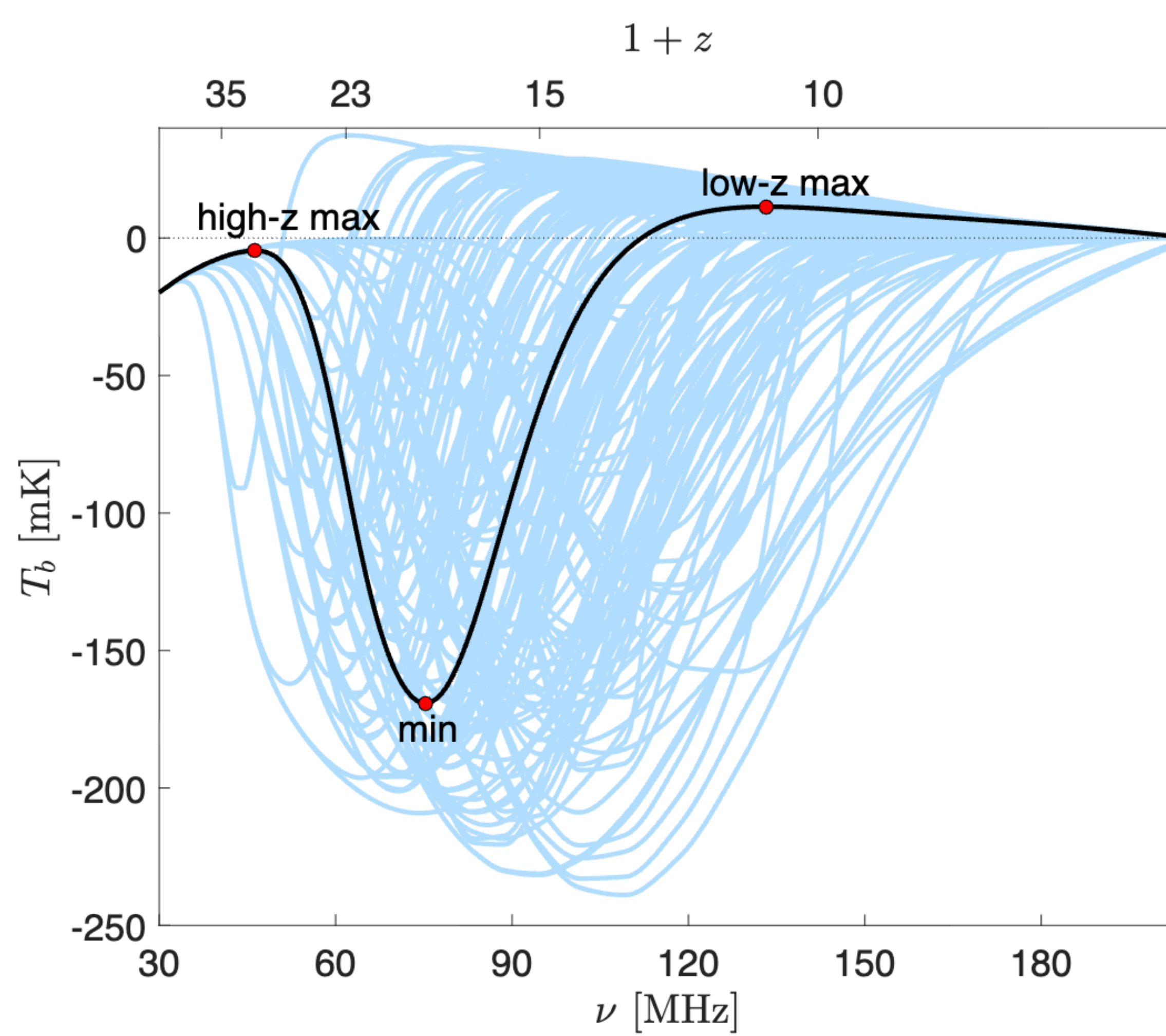
The broad picture — Expensive Simulations

See Nathan Cohen's
talk tomorrow
afternoon

"Bayesian Optimisation for
Bayesian Evidence (BOBE)"



The signal space from “standard” astrophysics is wide

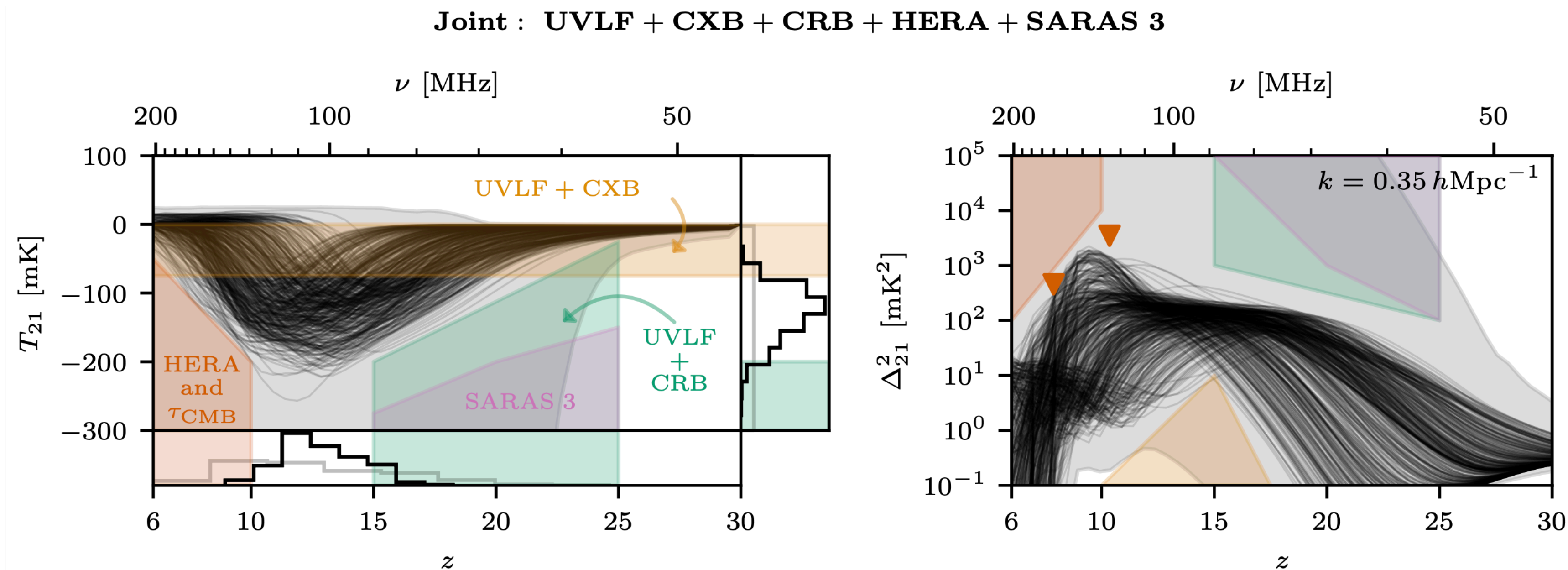


1709.02122

- redshift of the Ly α coupling
- moment of the heating transition
- midpoint of reionization

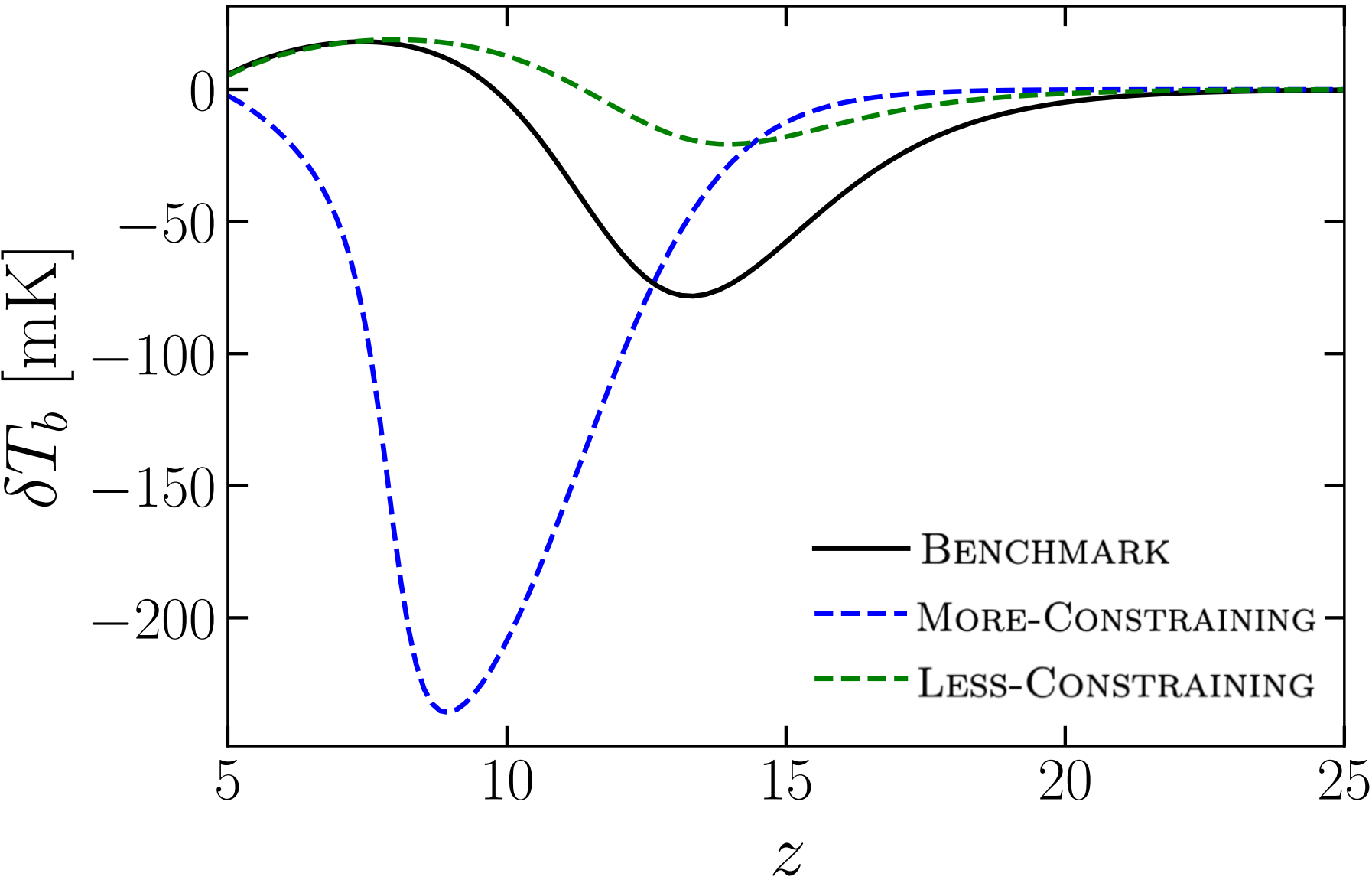
Independent constraints on astrophysics

- UVLFs [1809.08995, 2003.04442, 2110.13919, etc.]
- CMB optical depth [1809.08995, 2502.03525, etc.]
- Chandra X-ray and HERA additional heating [2502.03525, 2108.07282, etc.]
- Starburst99 Synthesis models (+ more recent)

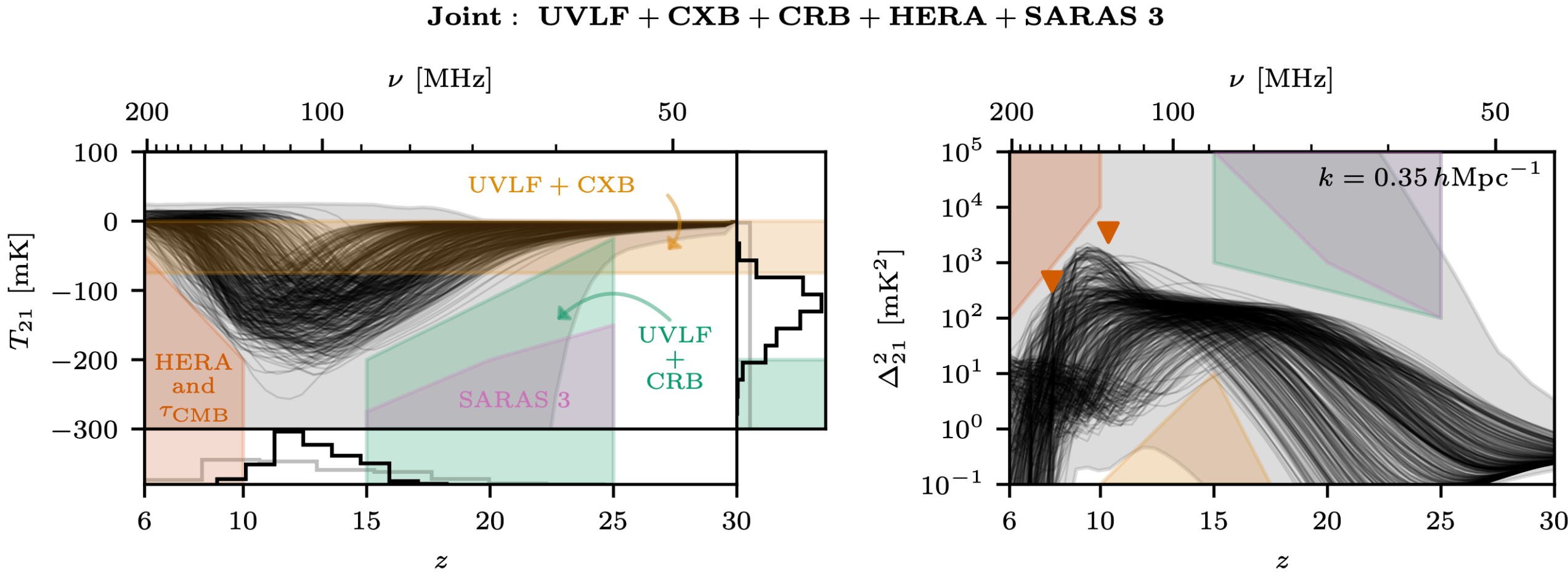


Dhanda+2508.13761

We choose scenarios consistent with observations:

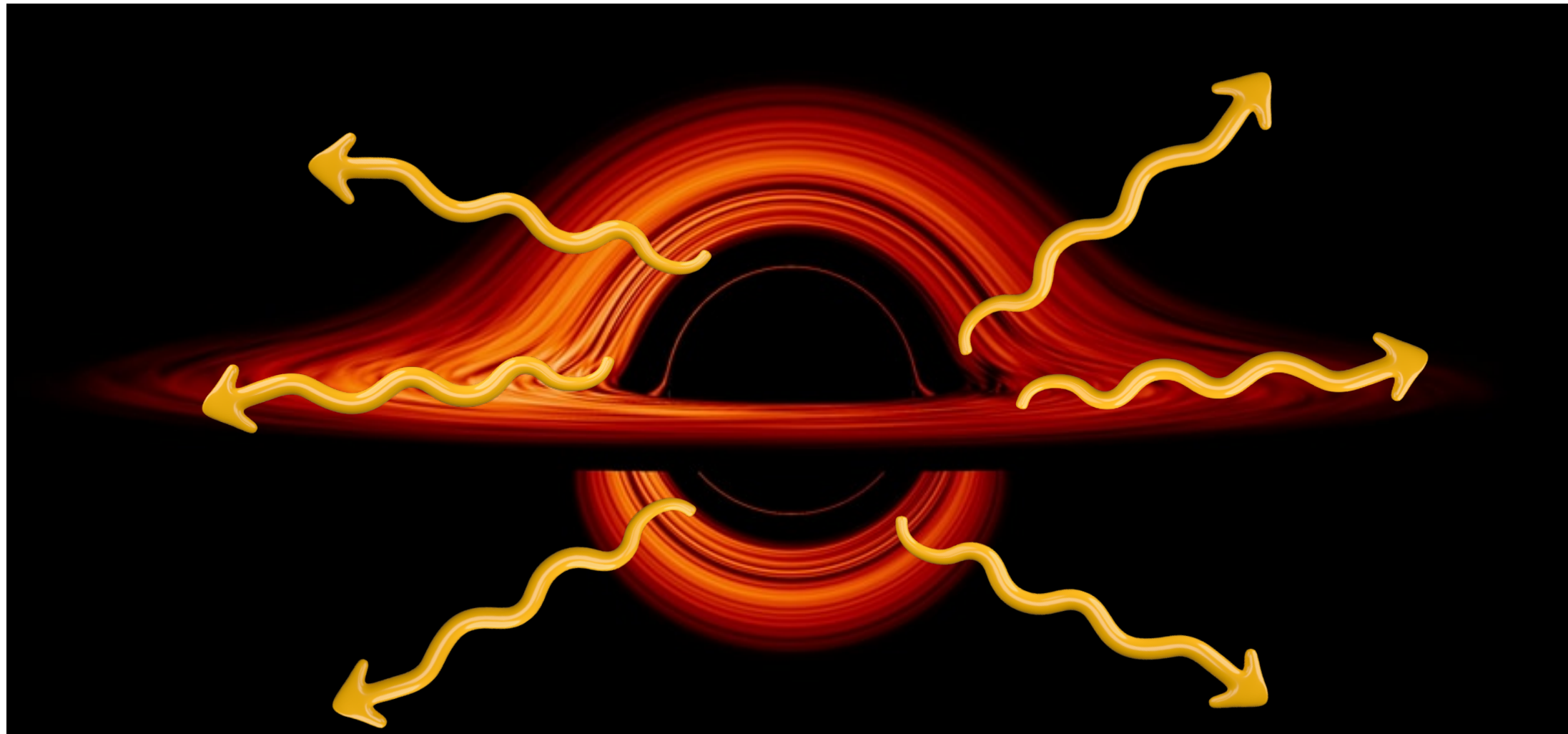


Astrophysical parameter	BENCHMARK	LESS-CONSTRAINING	MORE-CONSTRAINING
N_α	9690	3×10^3	4×10^4
$\log_{10} L_X / \dot{M}_* \left[\frac{\text{erg}}{\text{s}} \frac{\text{yr}}{M_\odot} \right]$	40.5	41	39.5
$T_{\text{vir}} [K]$	10^4	10^4	10^5



Dhanda+2508.13761

Accreting PBHs: A typical heating signal



[Image from Jeremy Schnittman - NASA]

$$L = \epsilon (\dot{M}) \dot{M} c^2$$

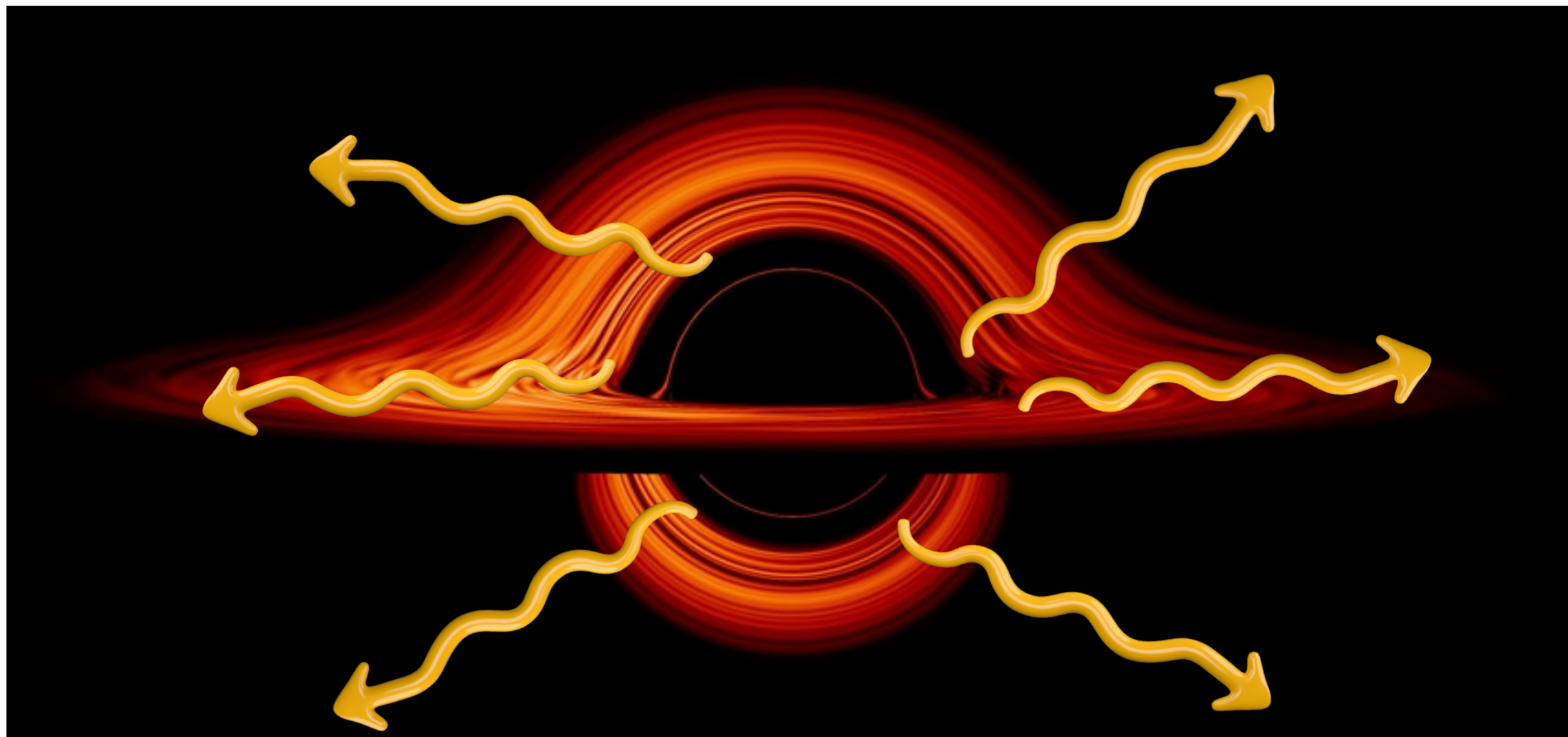
$$\left. \frac{d^2 E}{dV dt} \right|_{\text{inj}} = L f_{\text{PBH}} \frac{\rho_{\text{DM}}}{M}$$

Details in [2403.18895, 2510.14877]

Accreting PBHs: A typical heating signal

**For other heating signals
see Daniela Montes Doria's
talk on Thursday**

**"Exotic energy injection in
the 21-cm power spectrum"**



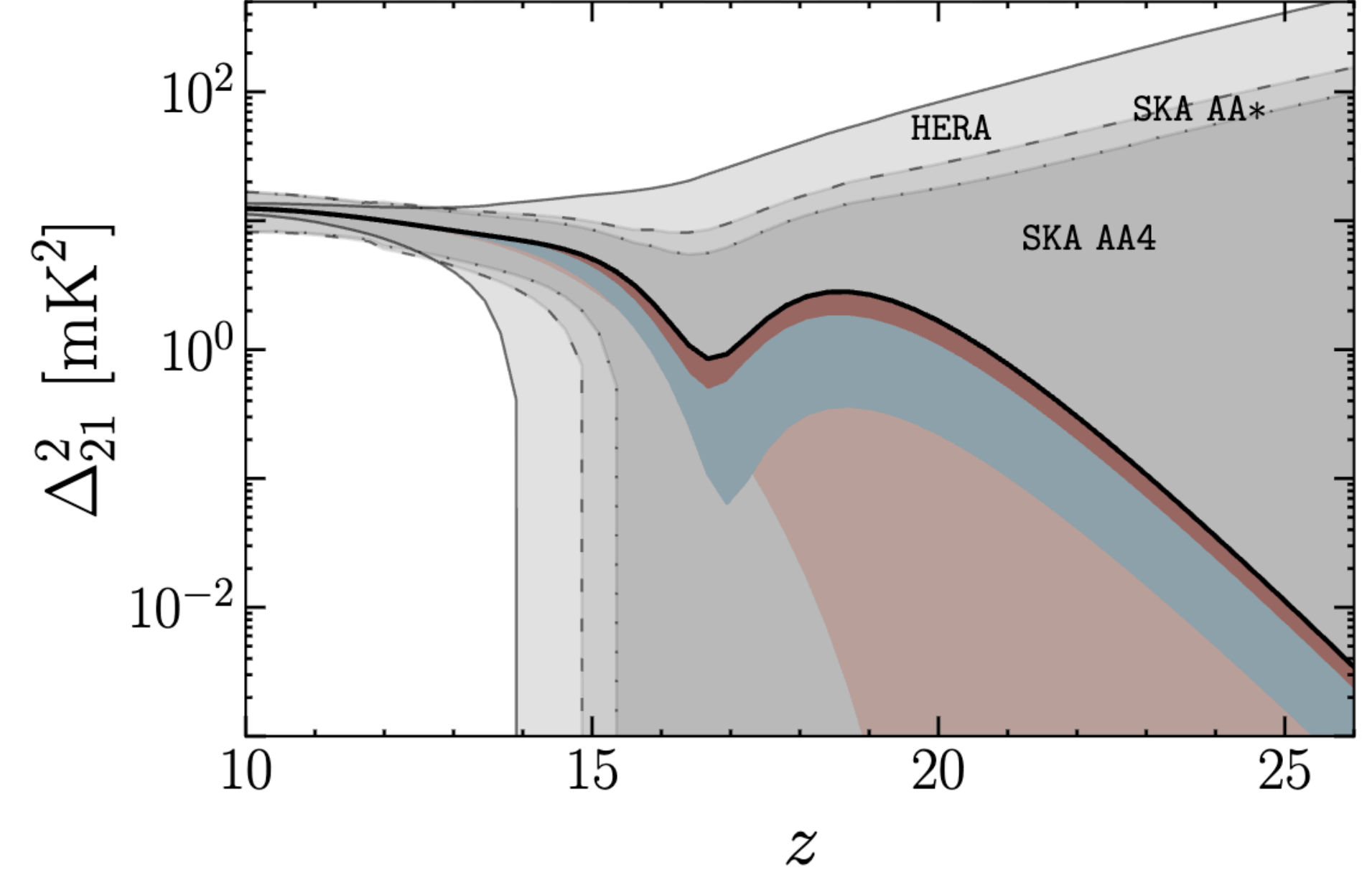
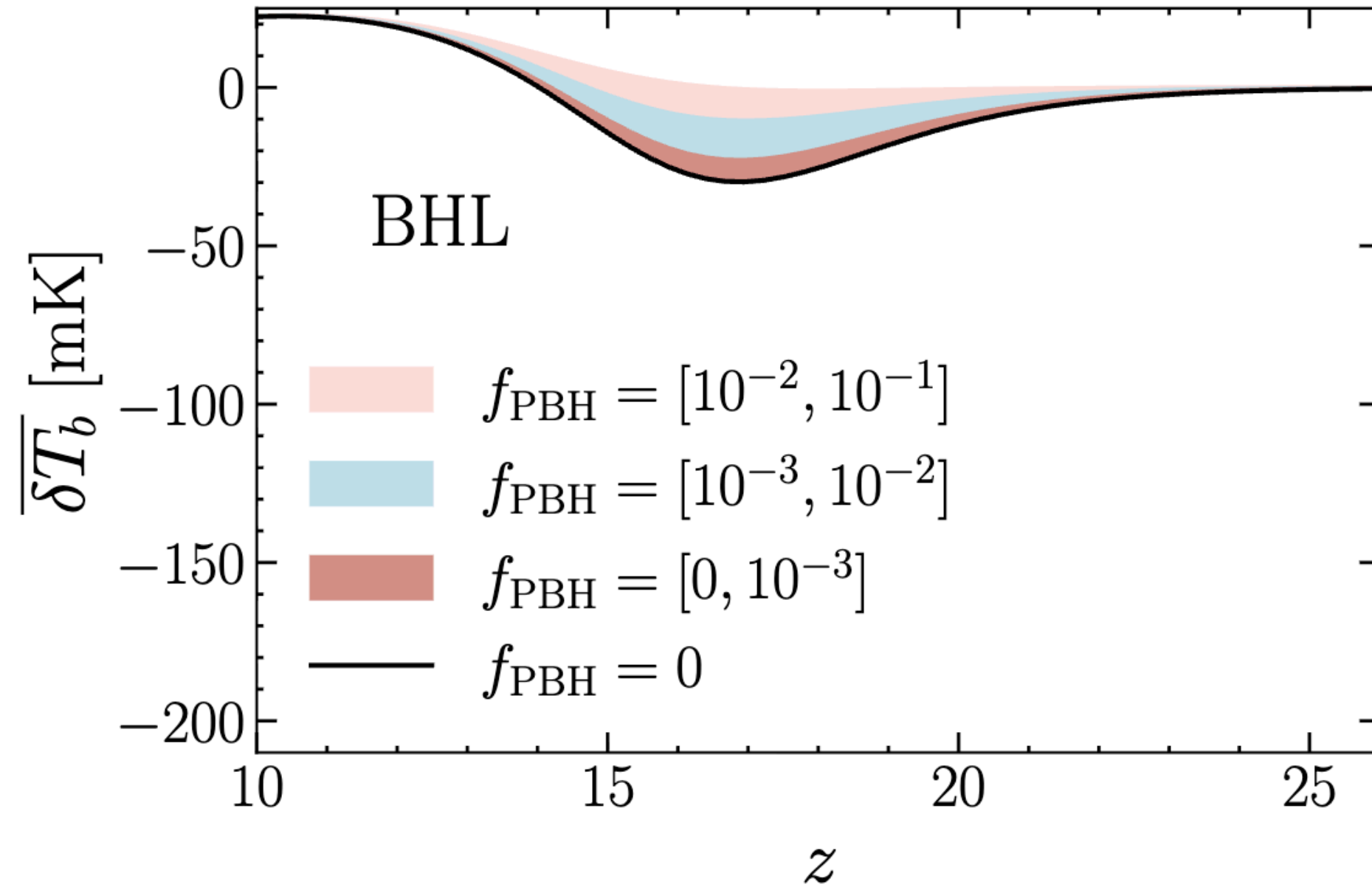
[Image from Jeremy Schnittman - NASA]

$$L = \epsilon (\dot{M}) \dot{M} c^2$$

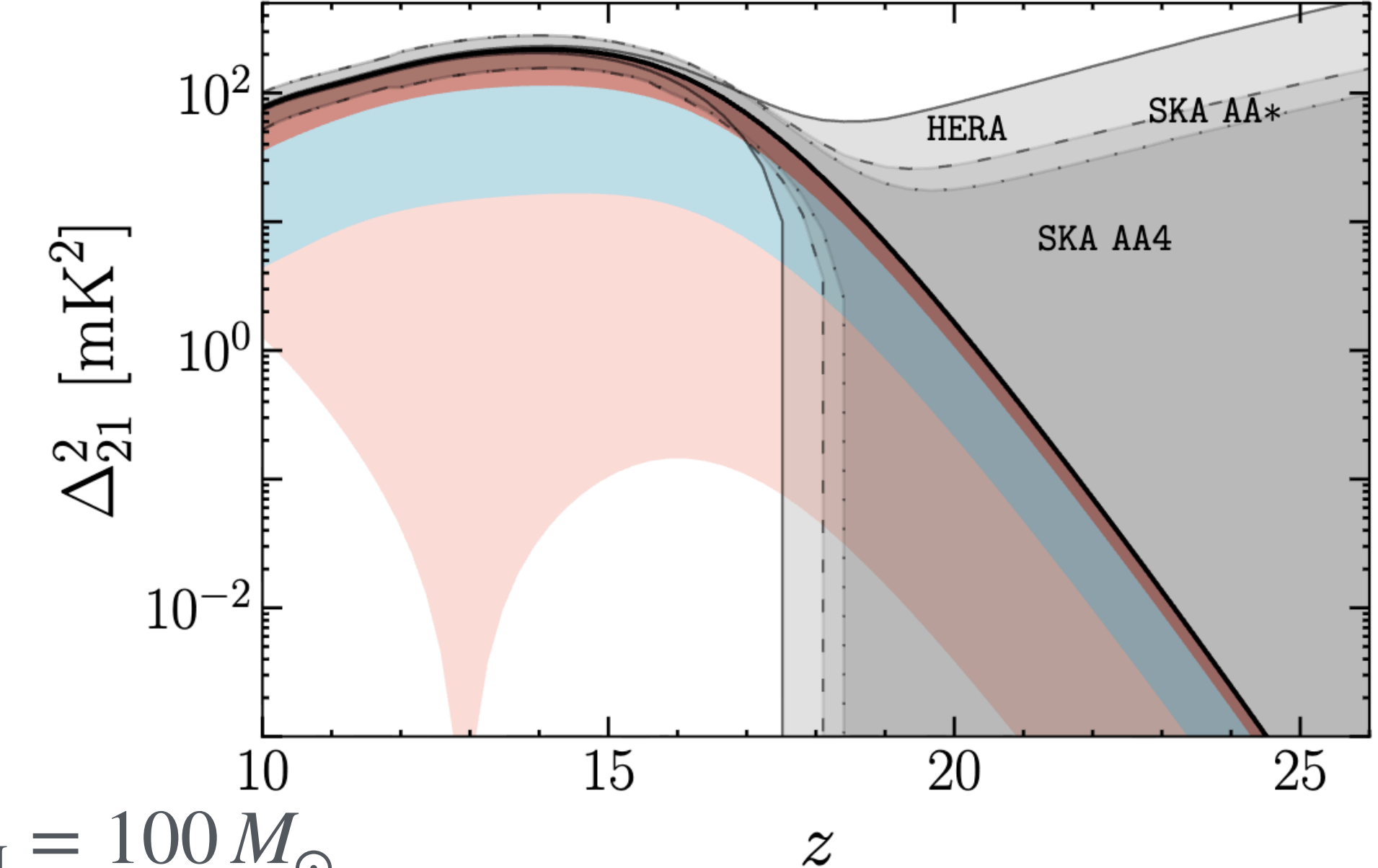
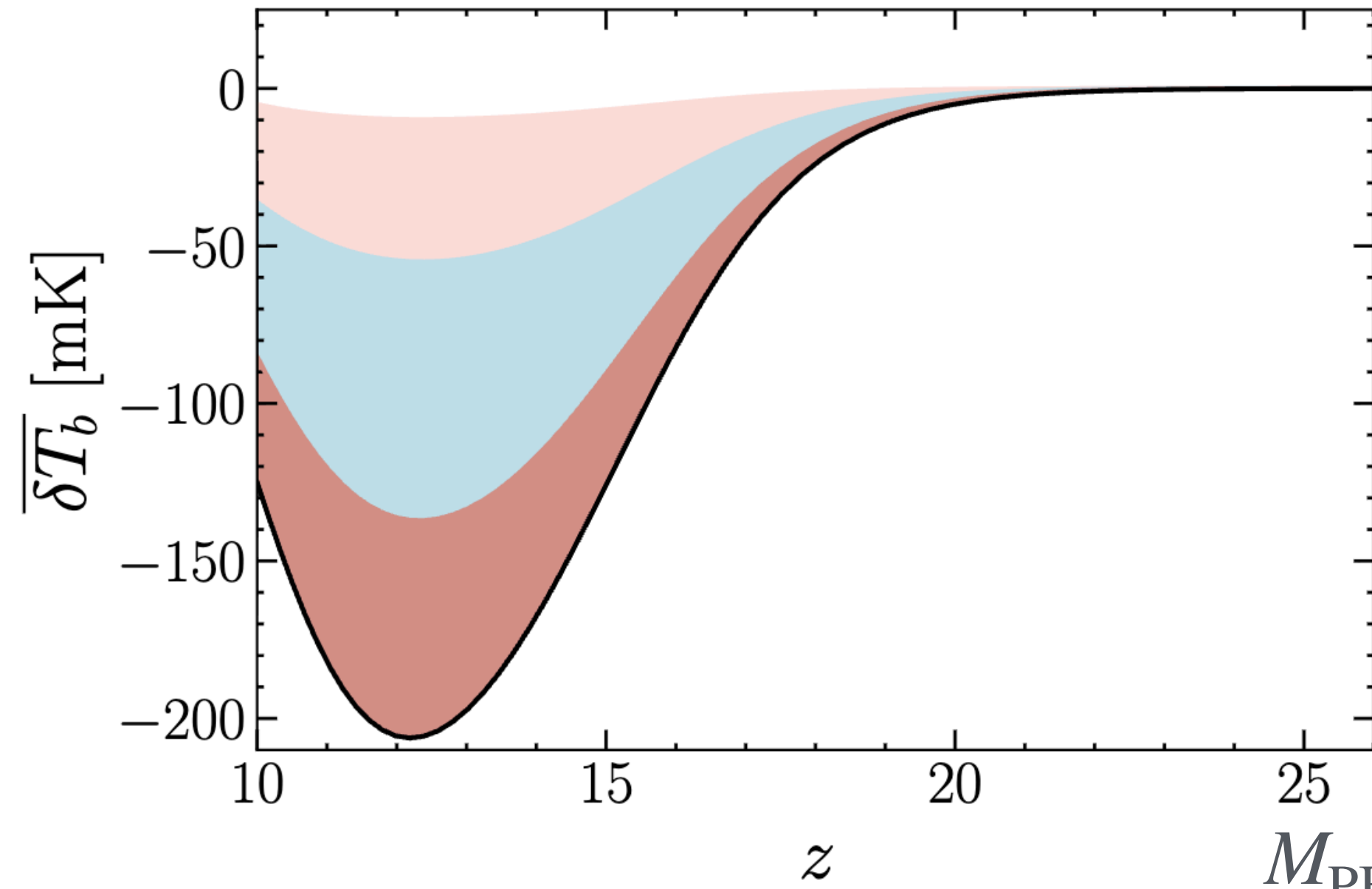
$$\left. \frac{d^2 E}{dV dt} \right|_{\text{inj}} = L f_{\text{PBH}} \frac{\rho_{\text{DM}}}{M}$$

Details in [2403.18895, 2510.14877]

LESS-CONSTRAINING SCENARIO: $N_\alpha = 3 \times 10^3$, $L_X = 10^{41} \text{ erg s}^{-1} M_\odot^{-1} \text{ yr}$, $T_{\text{vir}} = 10^4 \text{ K}$.

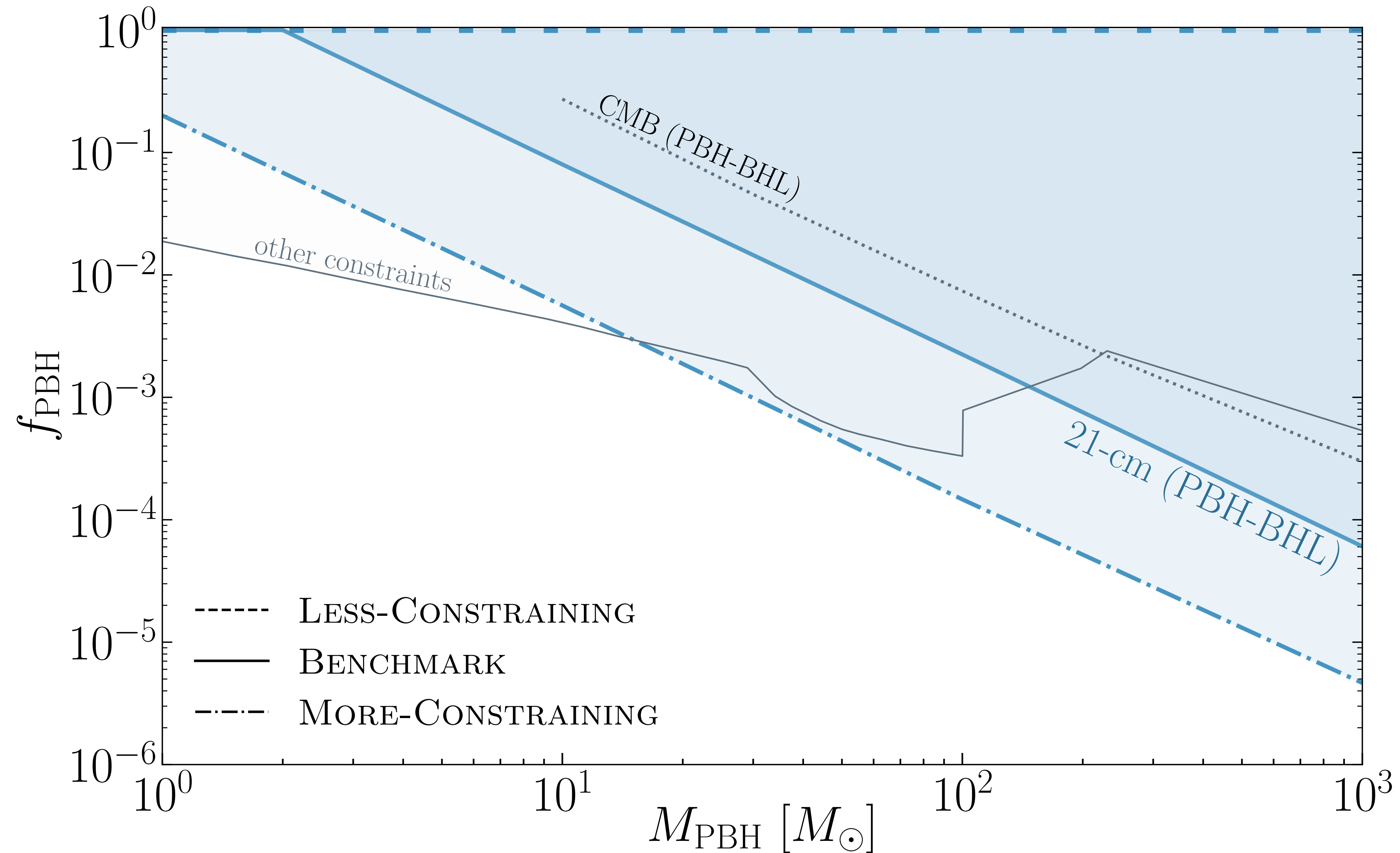


MORE-CONSTRAINING SCENARIO: $N_\alpha = 4 \times 10^4$, $L_X = 10^{39.5} \text{ erg s}^{-1} M_\odot^{-1} \text{ yr}$, $T_{\text{vir}} = 10^5 \text{ K}$.



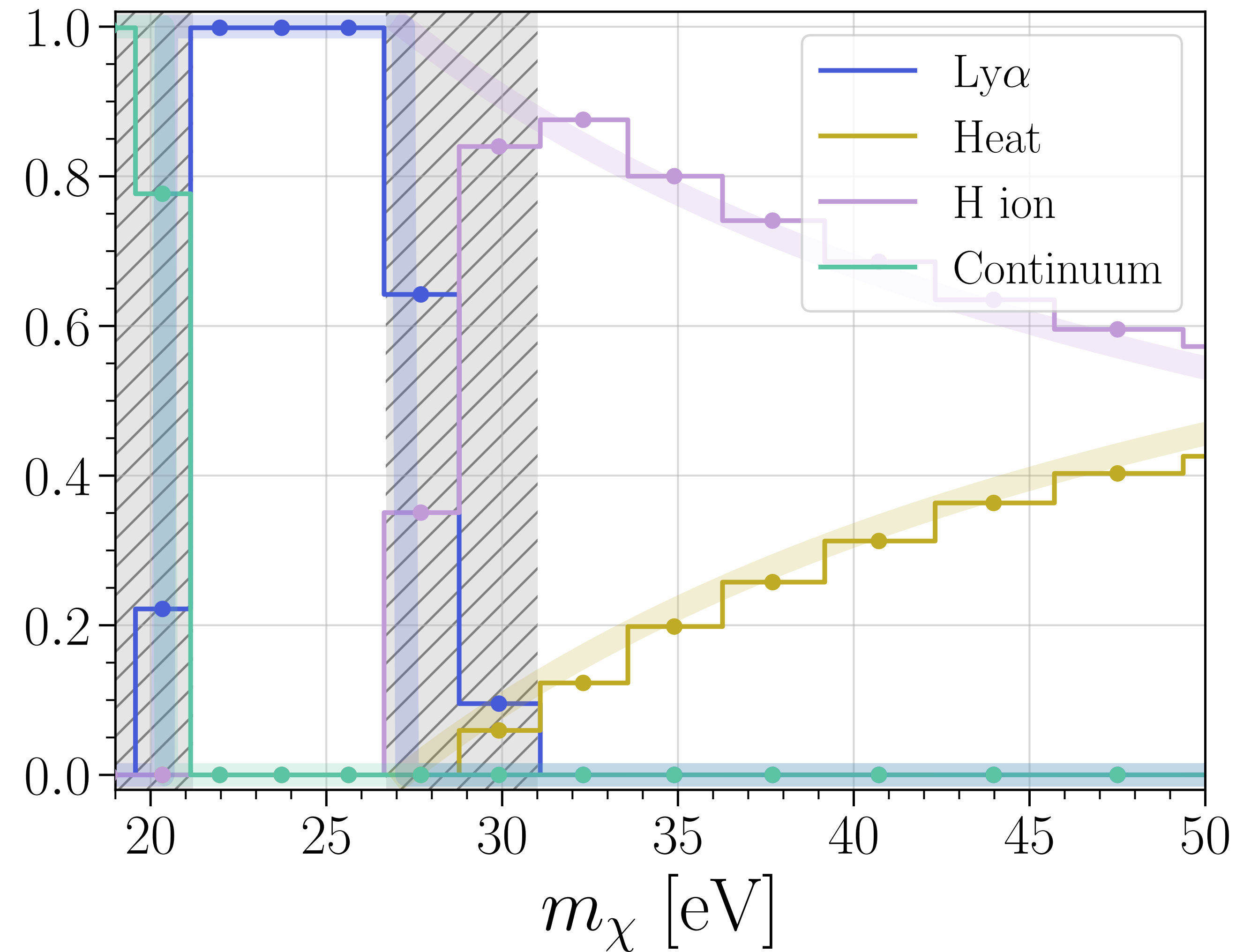
$M_{\text{PBH}} = 100 M_\odot$

The astrophysical scenario matters!



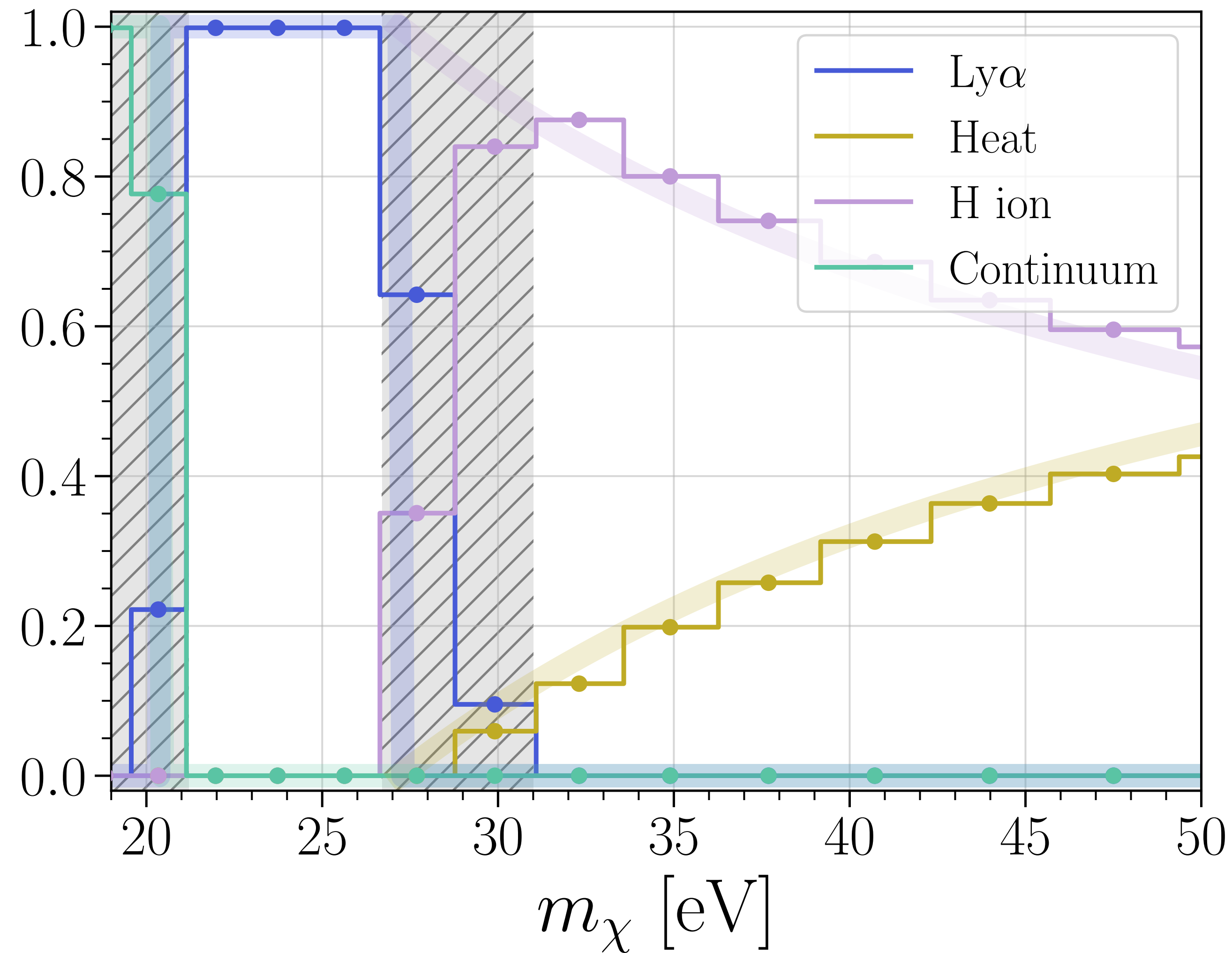
Consider Lyman- *α* instead of
heating

Lyman-alpha from particle (e.g. axion) decay



$$\chi \rightarrow \gamma\gamma$$

Lyman-alpha from particle (e.g. axion) decay



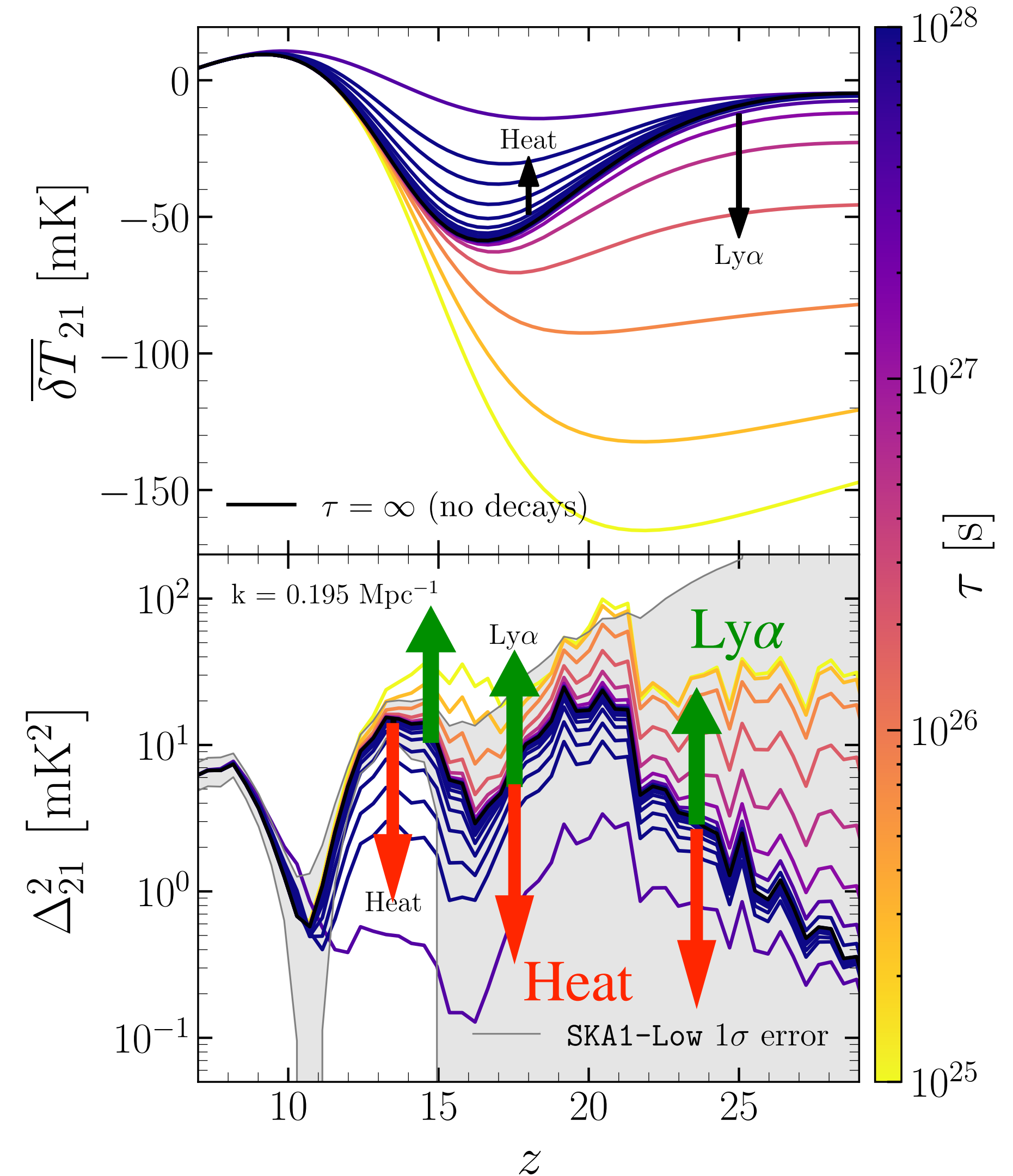
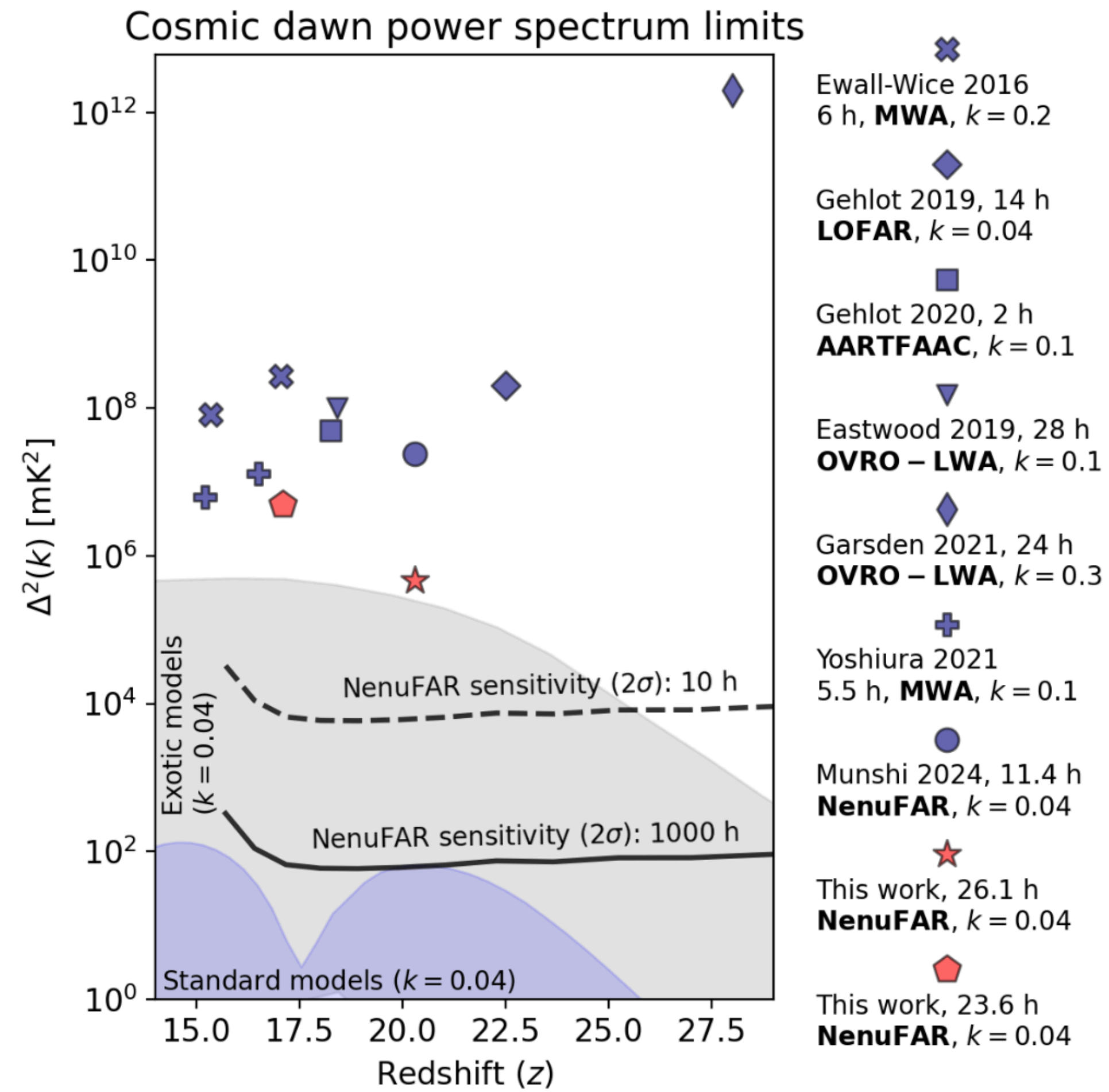
$$\chi \rightarrow \gamma\gamma$$

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

extra Lyman- α (new)

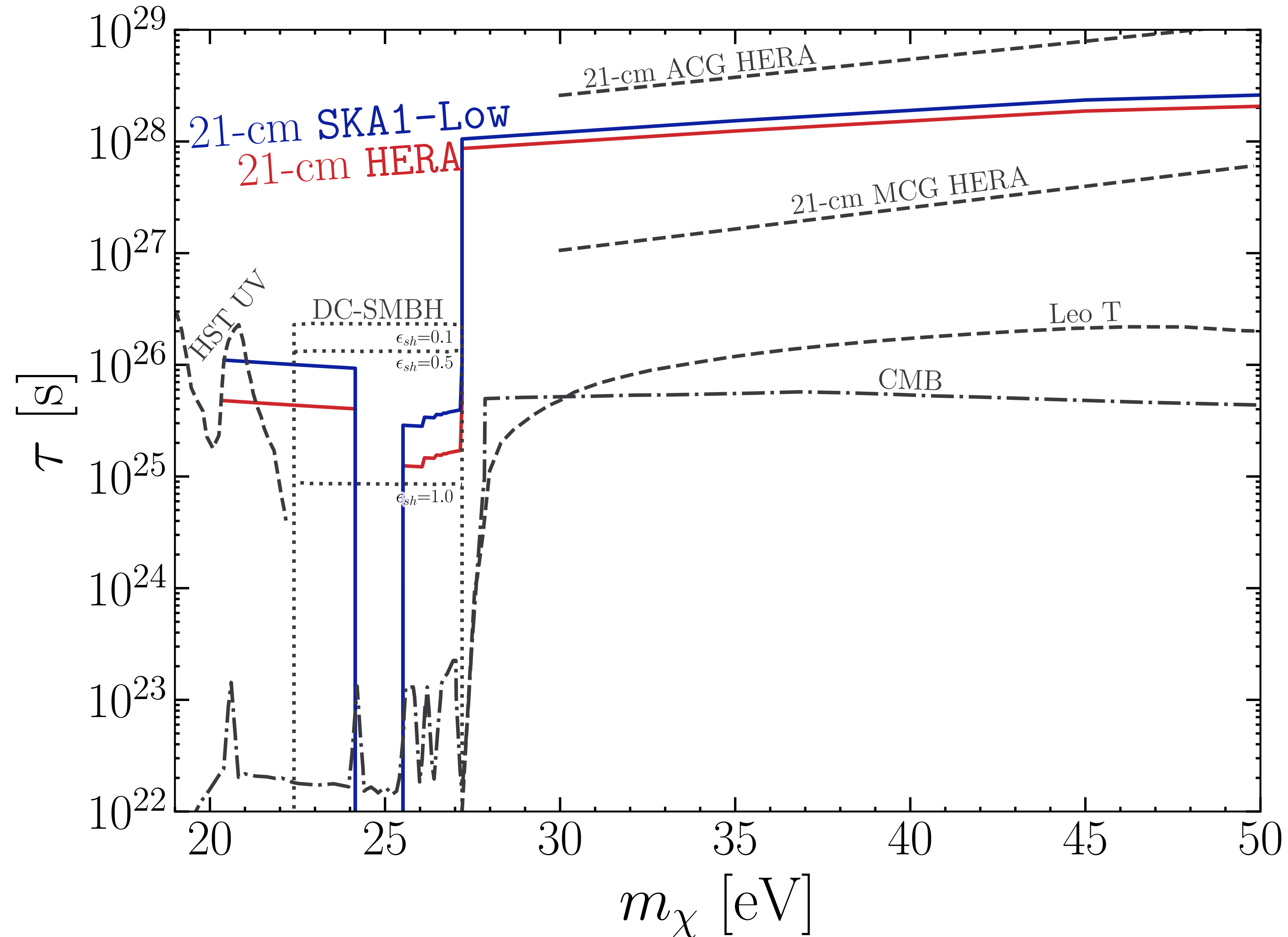
extra heating (old)

Back to the 21-cm signal



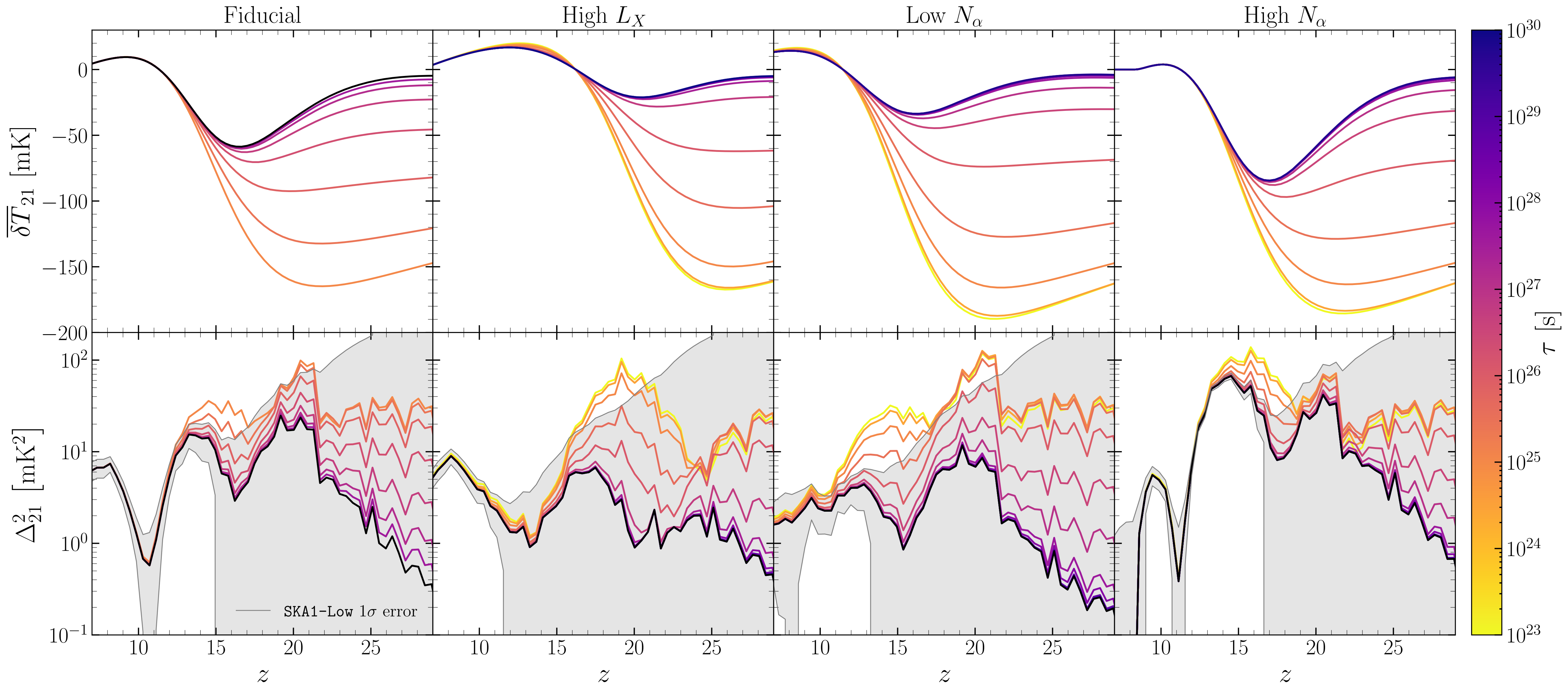
2507.10533

Fiducial scenario bound

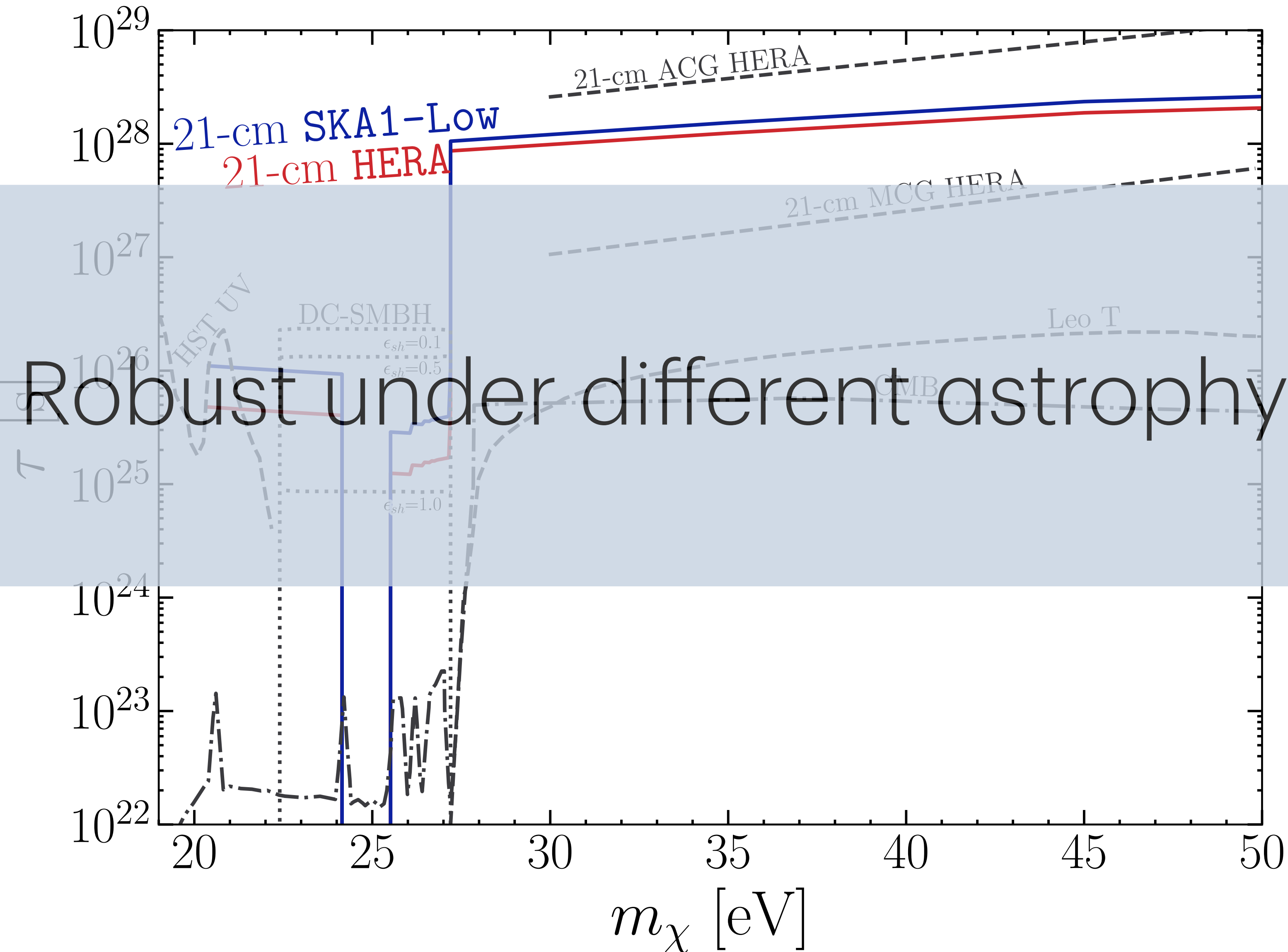


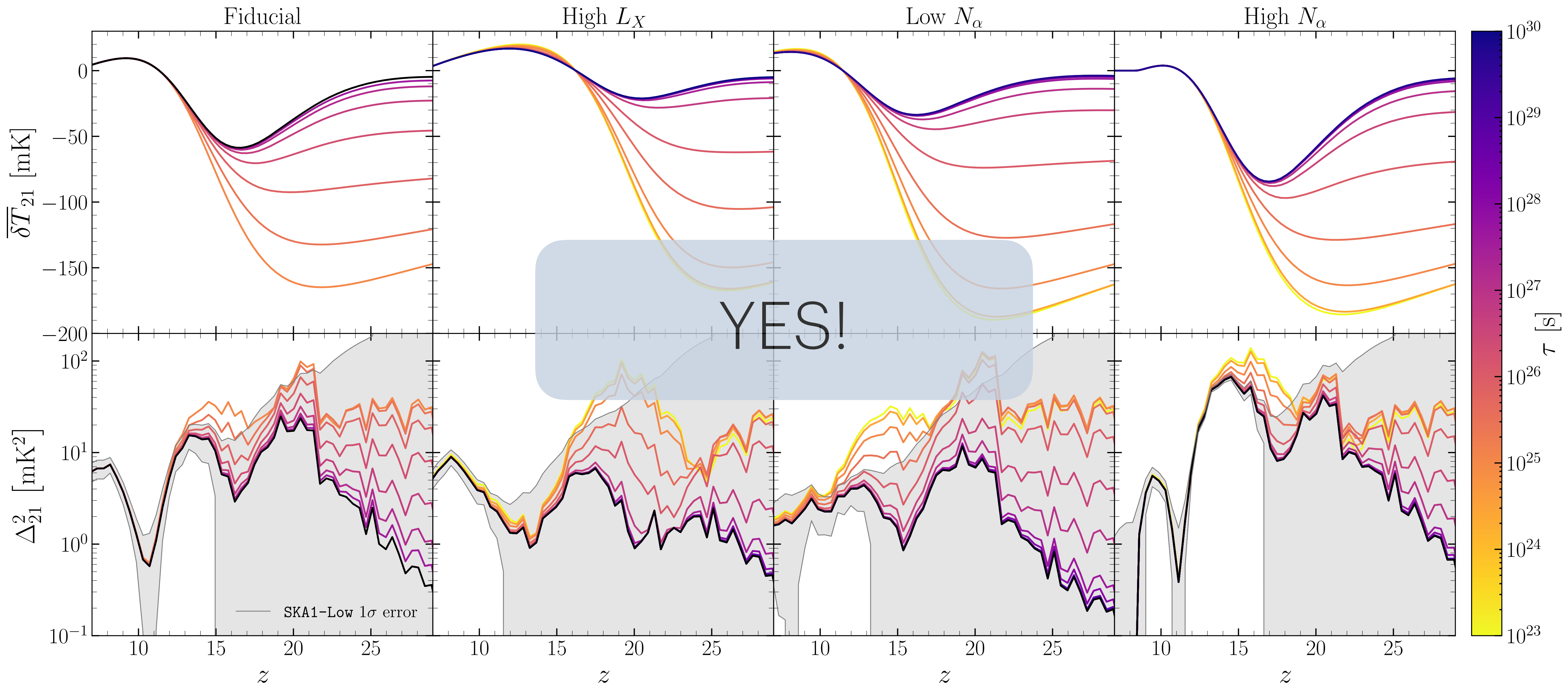
What if astrophysics is “unfavourable”

Scenario	$L_X/\dot{M}_*$	$N_{\text{ion}}^{\text{ACG}}$	$N_{\text{Ly}\alpha}^{\text{ACG}}$	$N_{\text{ion}}^{\text{MCG}}$	$N_{\text{Ly}\alpha}^{\text{MCG}}$
Fiducial	$10^{40.5}$	5×10^3	1.1×10^4	4.4×10^4	4.8×10^3
High L_X	$10^{41.5}$	5×10^3	1.1×10^4	4.4×10^4	4.8×10^3
Low N_α	$10^{40.5}$	1×10^3	2.2×10^3	2×10^4	2.1×10^3
High N_α	$10^{40.5}$	2×10^4	4.4×10^4	8×10^4	8.7×10^3



Fiducial scenario bound



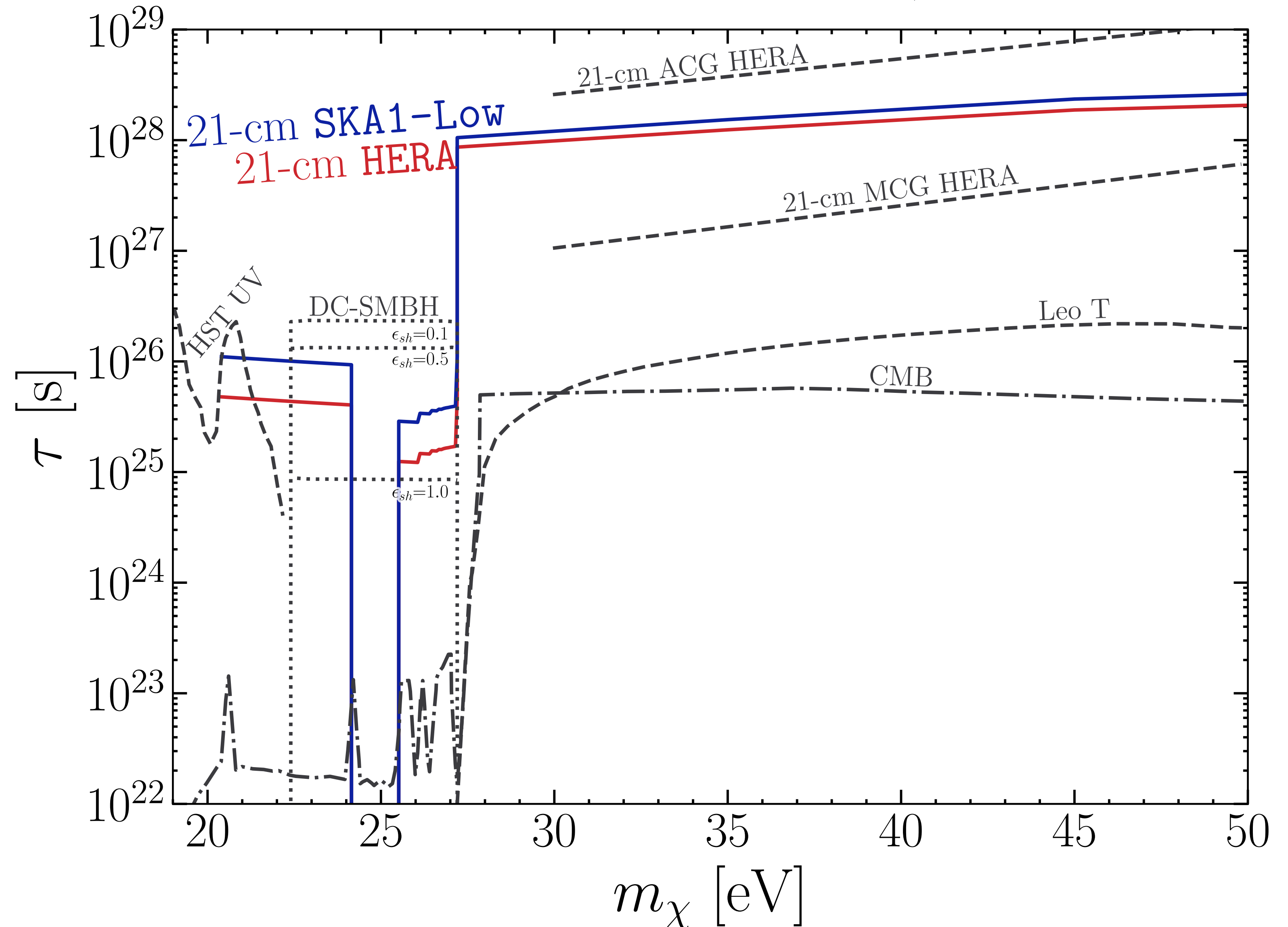


$$m_\chi = 20.4 \text{ eV}$$

	Fiducial	High L_X	High N_α	Low N_α
τ_{95} [s]	1.1×10^{26}	5.2×10^{25}	2.2×10^{26}	1.1×10^{26}

What else can we learn from this?

- Other DM candidates at different scales may emit efficiently in to Lyman-band
- Astrophysics robust probes?
- Dark Ages signal even more robust to these signatures (future lunar detectors)



Summary

- Narrowing down on the **uncertainties on the astrophysics**, entering in the null hypothesis, is very important for 21-cm forecasts on dark matter heating
- Exploring **synergies between independent observables** is a good path forward
- **Lyman-alpha from dark matter could help**
- **Speeding up inference pipelines is super useful** (see Nathan Cohen's talk!)

