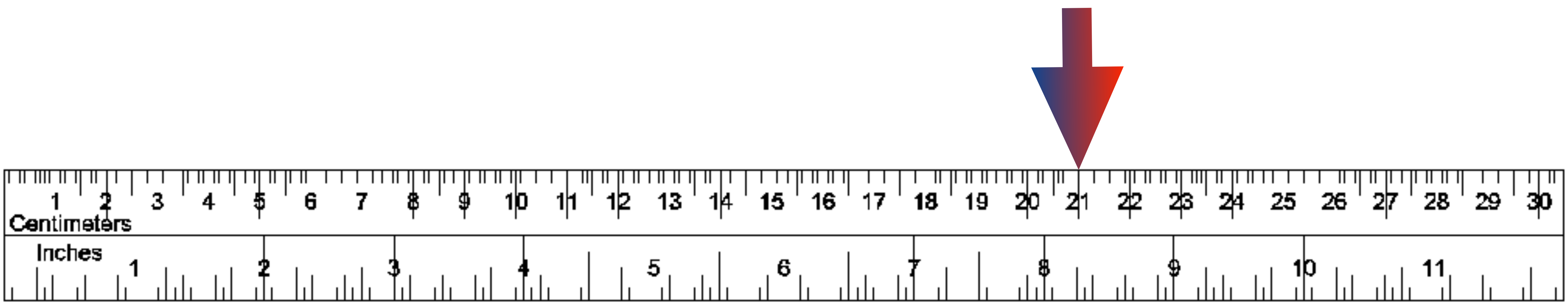
Adam Falkowski

Stronger 21cm absorption from charge sequestration

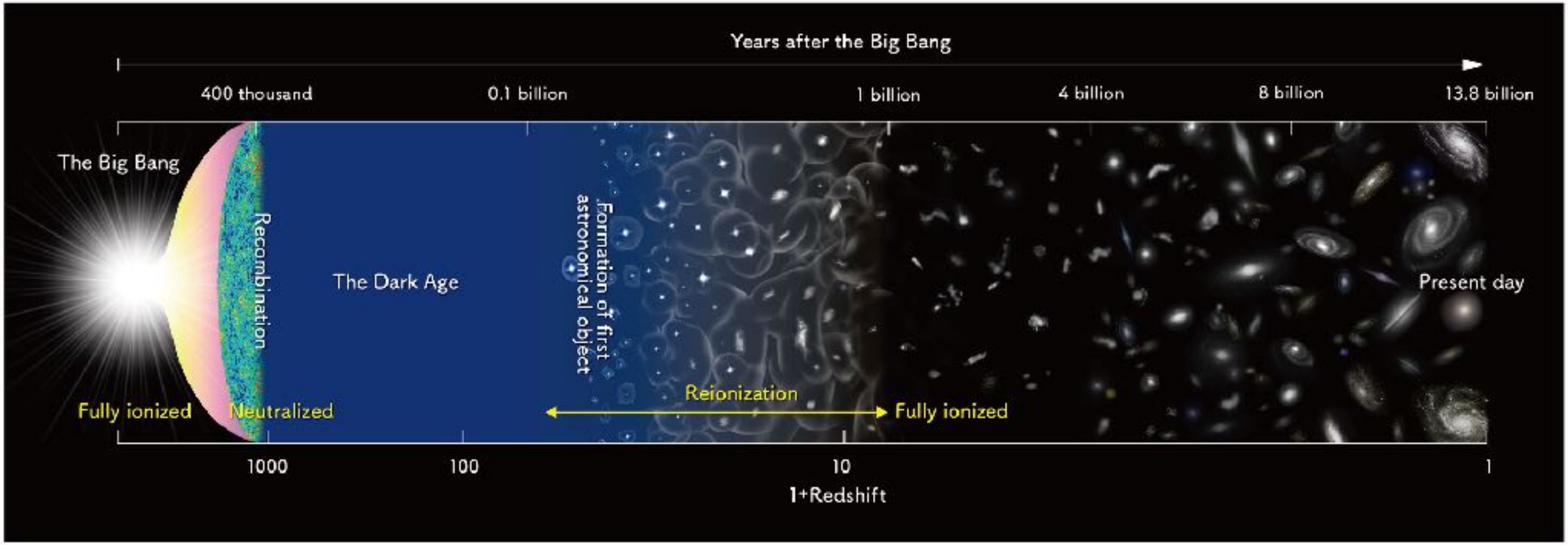


Actual Size!

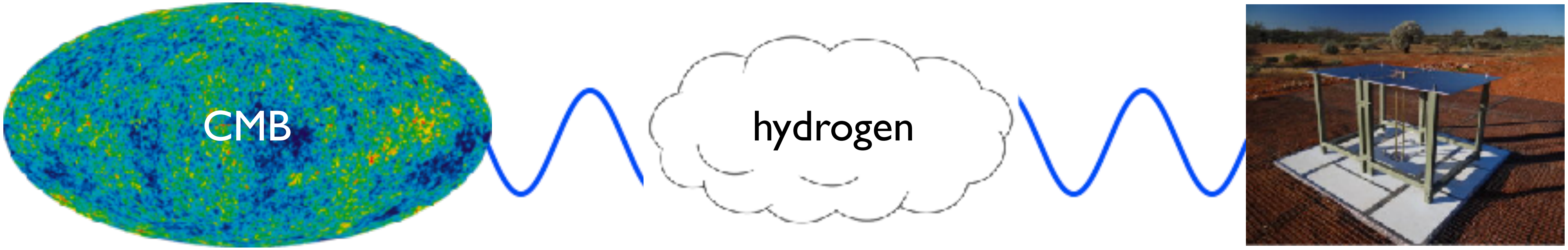
CERN, 27 June 2018

based on 1803.10096
with Kallia Petraki

Timeline



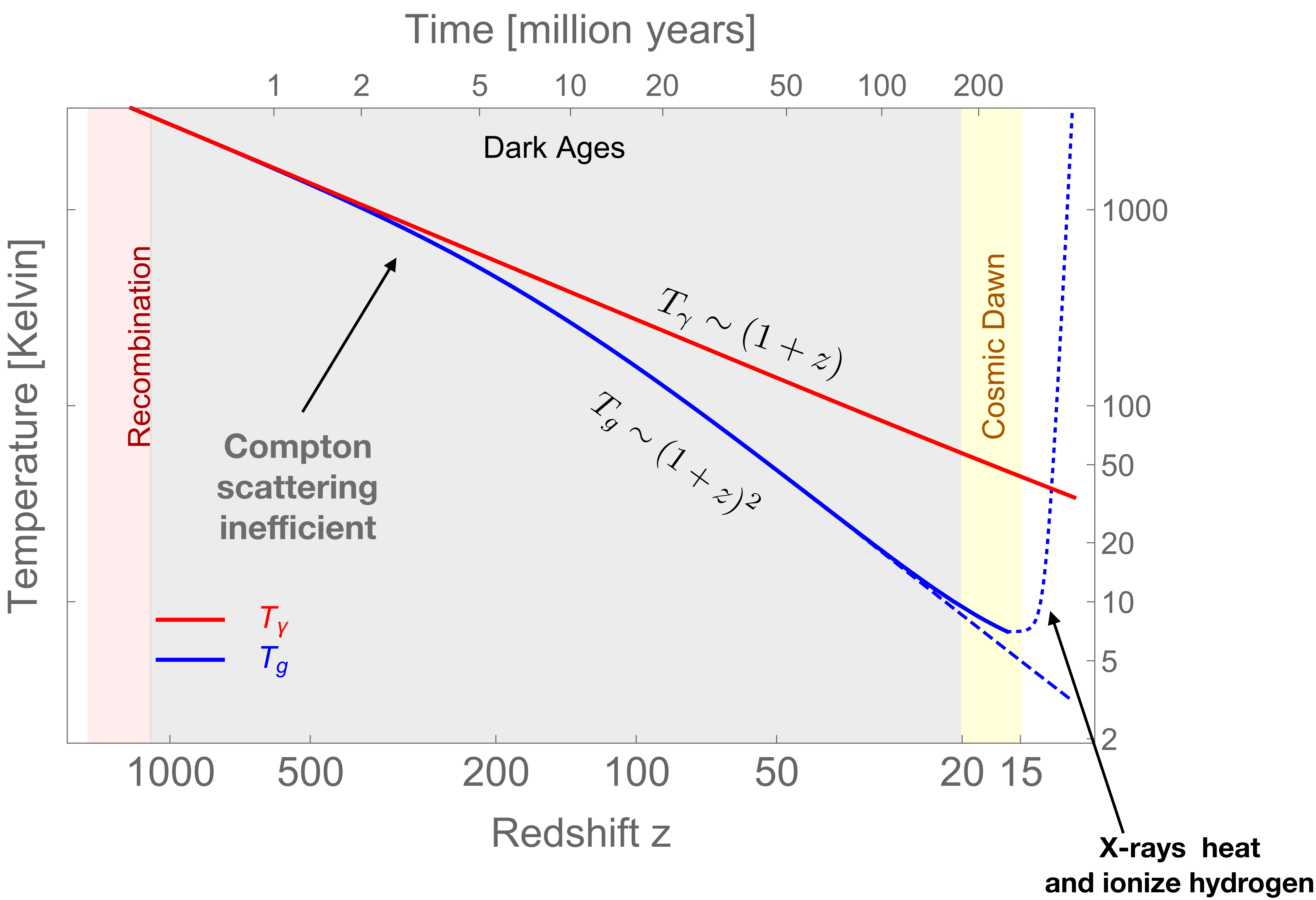
T_γ T_S δT_b



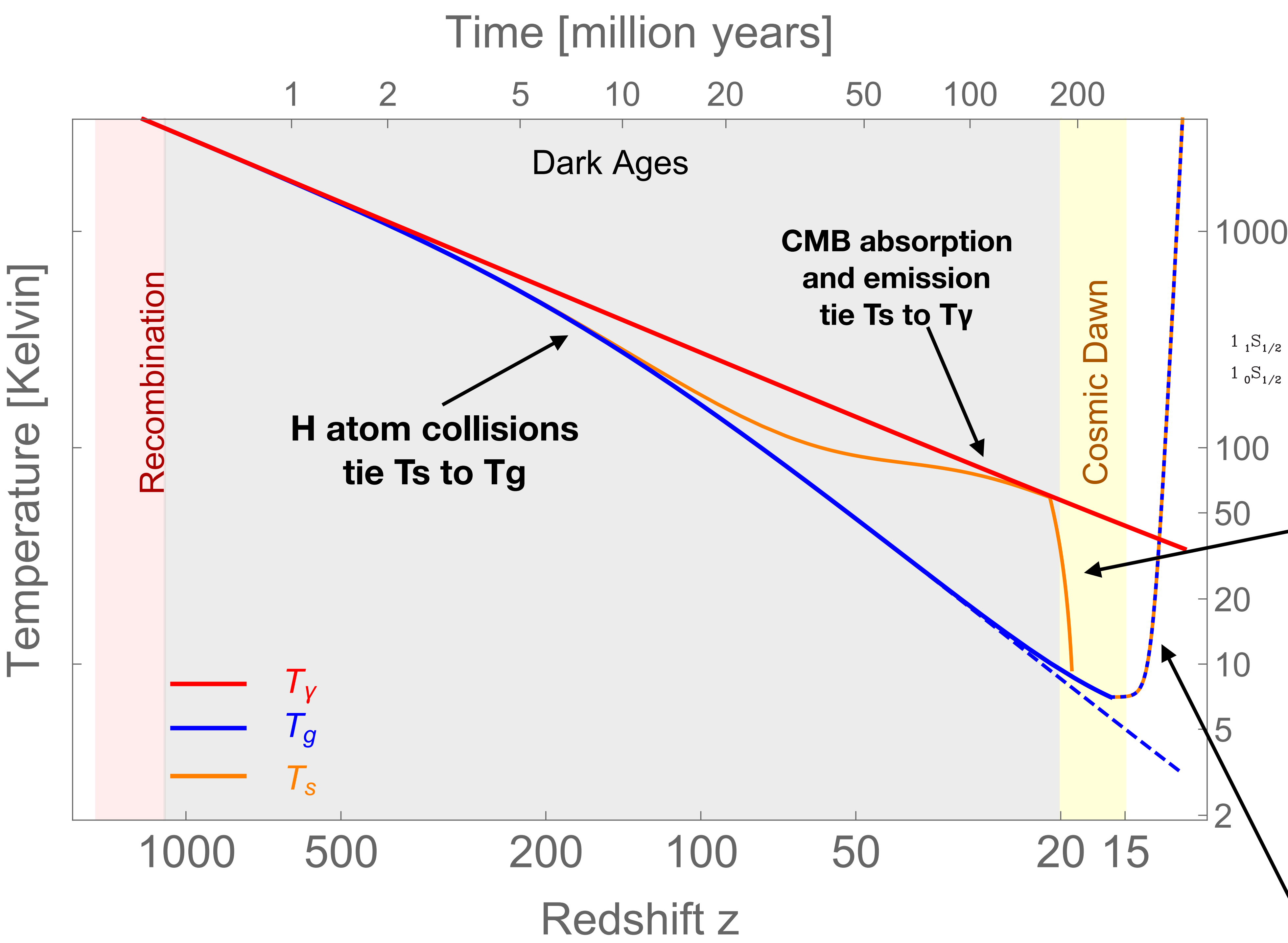
Adapted from J. Pritchard

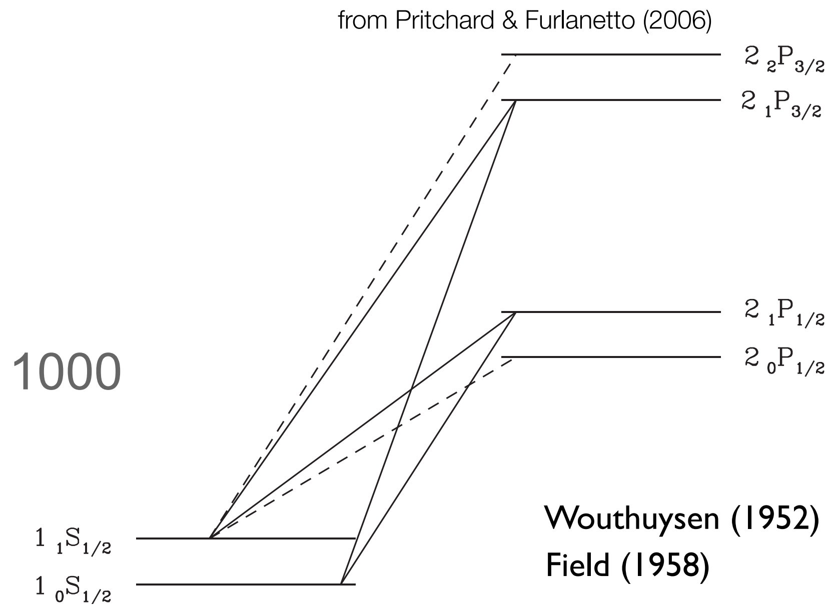
e.g., EDGES

Brief history of dark ages



Physics of 21 cm absorption





Lyman-α transitions mix hyper-fine levels and again tie Ts to Tg!

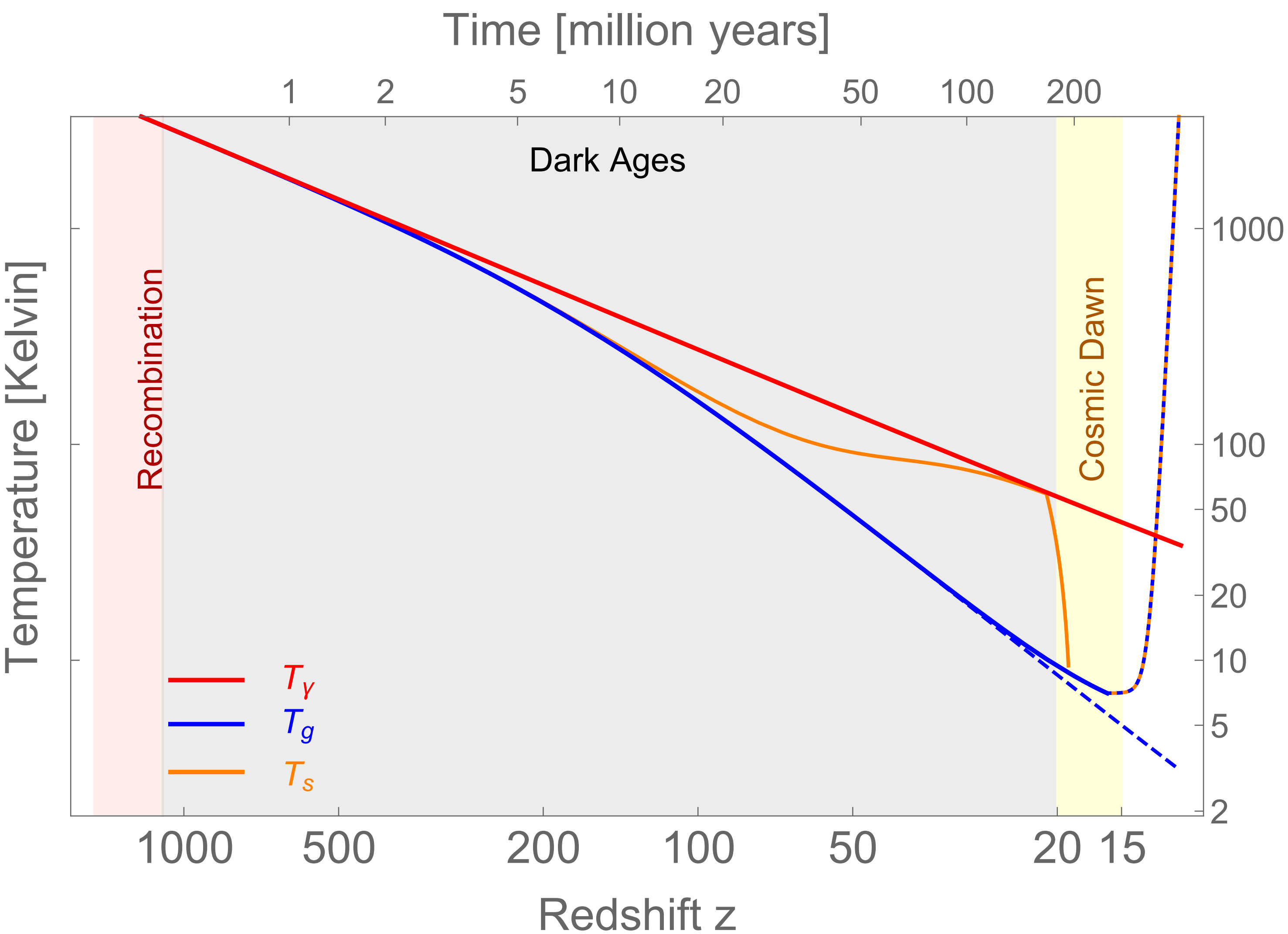
X-rays heat and ionize hydrogen

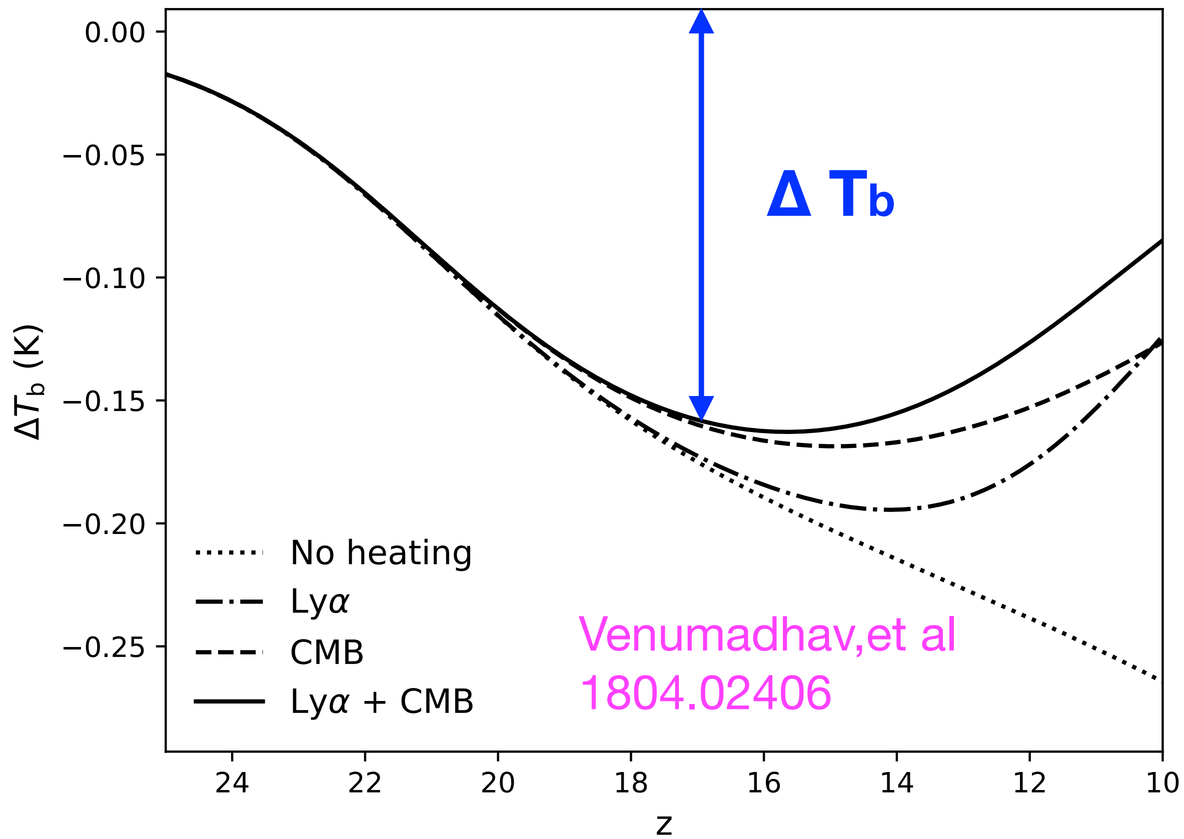
Spin temperature Ts defined by relative occupation number of singlet and triplet states

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{E_{10}}{T_s}\right)$$

$$E_{10} \approx 6\times 10^{-6}\ \text{eV}$$

Dark explanations





$$\Delta T_b \approx 0.04 \text{ K} \times \left(1 - \frac{T_\gamma(z)}{T_s(z)}\right) \sqrt{\frac{1+z}{18}}$$

Since Tg≤Ts≤Tγ, 2 ways to enhance absorption signal:

Predicted by SM: $\Delta T_{b,\mathrm{SM}} \gtrsim -0.2 \text{ K}$

Observed by EDGES:

$$\Delta T_b = -0.5^{-0.5}_{+0.2} \text{ K} \quad @99\% \text{ CL}$$

1. Increase Tγ(17)
2. Decrease Tg(17)

BSM explanations of strong absorption

- One option is to inject more photons corresponding to 21cm wavelength around cosmic dawn, e.g from new particle decay or from dark photon oscillations

see e.g
Pospelov et al
1803.07048

Fraser et al
1803.03245

- Another option for enhancing the 21cm absorption signal is to decrease temperature of the hydrogen gas at the cosmic dawn with respect to the standard scenario

- I know of two ways of achieving the latter

- One is through interactions between hydrogen and another colder fluid, which could be part or all of dark matter

see e.g
Barkana,
Nature 555

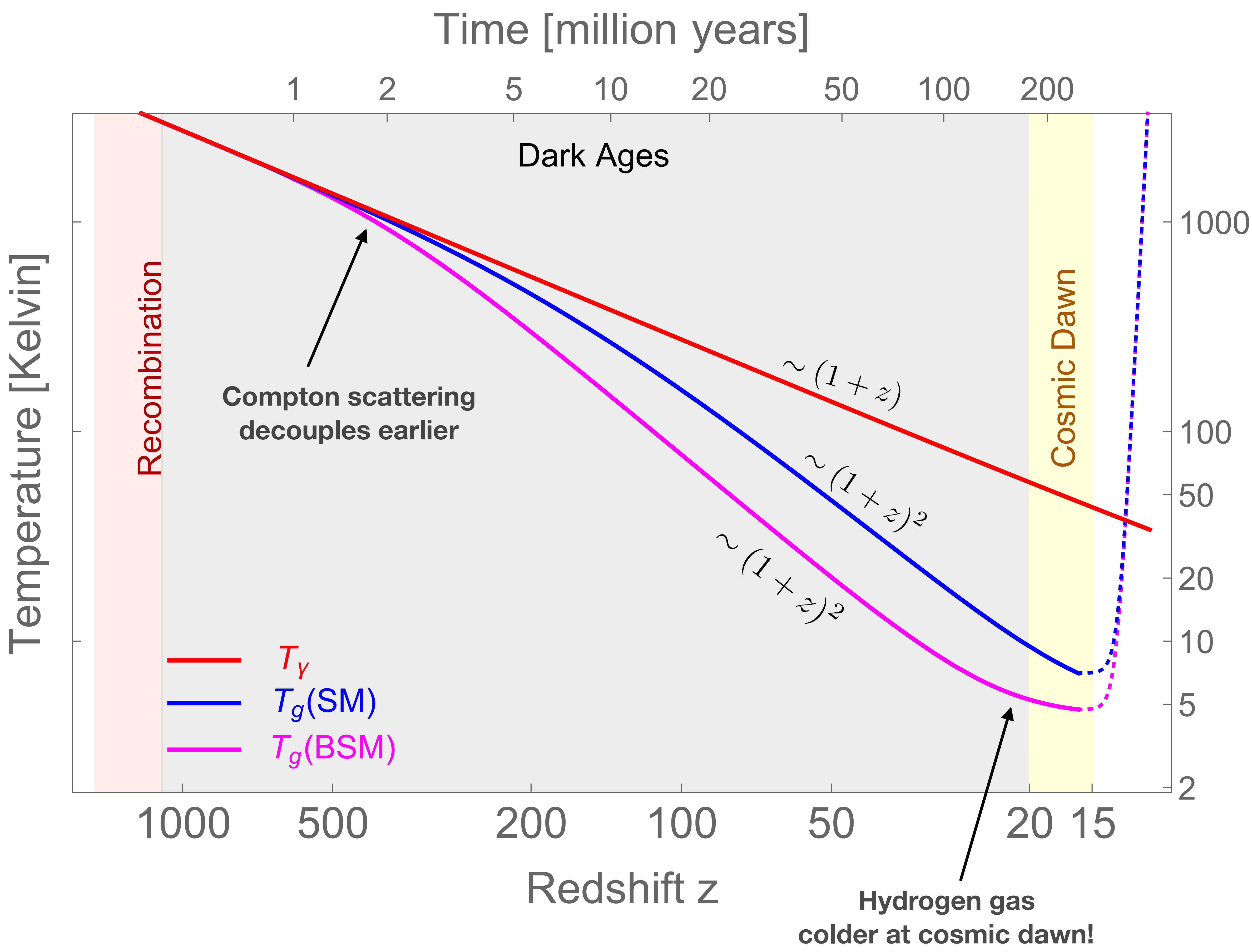
Berlin et al
1803.02804

Barkana et al
1803.03091

- The other is by arranging for an earlier decoupling of gas from the CMB

ⒶⒶ, Petraki
1803.10096

Colder gas from earlier Compton decoupling



Colder gas from earlier Compton decoupling

- Hydrogen gas decouples from the CMB at around z~150, after which its temperature decreases adiabatically as (1+z)^2, as opposed to the (1+z) evolution of the CMB temperature
- In the standard scenario, T_g is already 7 times smaller than T_γ around the cosmic dawn
- If the decoupling occurs earlier, the gas will be correspondingly colder at the cosmic dawn
- What keeps equilibrium for z⩾150 is Compton scattering on the free electron fraction

$$(1+z)\,\frac{\partial T_g}{\partial z} = 2T_g - \gamma_C (T_\gamma - T_g)$$

$$\gamma_C \equiv \frac{8\pi^2 \sigma_T T_\gamma^4}{45 H m_e} \, \frac{x_e}{1 + f_{\mathrm{He}} + x_e} \qquad x_e \equiv \frac{n_e}{n_H + n_p}$$

free electron fraction

Thomson cross section

helium fraction

Colder gas from earlier Compton decoupling

- Clearly, gas-CMB coupling through Compton scattering would be weaker if free electron fraction was suppressed

- In standard scenario, x_e is fully fixed by complex but perfectly understood physics of hydrogen recombination

- It's easy for new physics to *increase* x_e, e.g. via dark matter annihilation. However, *decreasing* is more tricky

- However, if there is a mismatch between proton and electron, numbers in the universe, such that $n_e < n_p$, then during dark ages x_e can be *reduced*

$$(1+z)\,\frac{\partial T_g}{\partial z} = 2T_g - \gamma_C (T_\gamma - T_g)$$

$$\gamma_C \equiv \frac{8\pi^2 \sigma_T T_\gamma^4}{45 H m_e}\,\frac{x_e}{1+f_{\rm He}+x_e}$$

$$\frac{\partial x_e}{\partial z} = \frac{\alpha_B(T_g)\frac{n_B}{1+f_{\rm He}} x_e x_p - \beta_B(T_\gamma) e^{-E_{12}/T_\gamma}(1-x_p)}{H(z)(1+z)} \times \frac{1+(1-x_p)\,\Lambda_{2S\to 1S}\,\frac{\pi^2 n_B}{H(z)E_{12}^3(1+f_{\rm He})}}{+(1-x_p)\left(\Lambda_{2S\to 1S}+\beta_B(T_\gamma)\right)\frac{\pi^2 n_B}{H(z)E_{12}^3(1+f_{\rm He})}}$$

Charge sequestration

- We postulate that there is a mismatch between proton and electron numbers in the universe, such that $n_e < n_p$

- If that was the whole story, the universe overall would not be charge neutral, which would be a disaster

- Thus we need to introduce another stable particle with negative charge, and non-zero abundance in the universe, such that on the whole the universe is charge neutral

$$Q_X = -\epsilon_X$$

- For this talk I will not discuss the identity of the particle X, but just parameterize the relevant phenomenology by its mass m_x, charge ε_x, and relative abundance r_x with respect to baryon. A priori, X can be all of dark matter or small fraction thereof

$$r_X \equiv \frac{n_X}{n_H + n_p} = \frac{n_X}{n_B}(1 + f_{\mathrm{He}})$$

- Charge neutrality of the universe imposes the relation

$$x_p = x_e + \epsilon_X r_X$$

$$x_i \equiv \frac{n_i}{n_H + n_p}$$

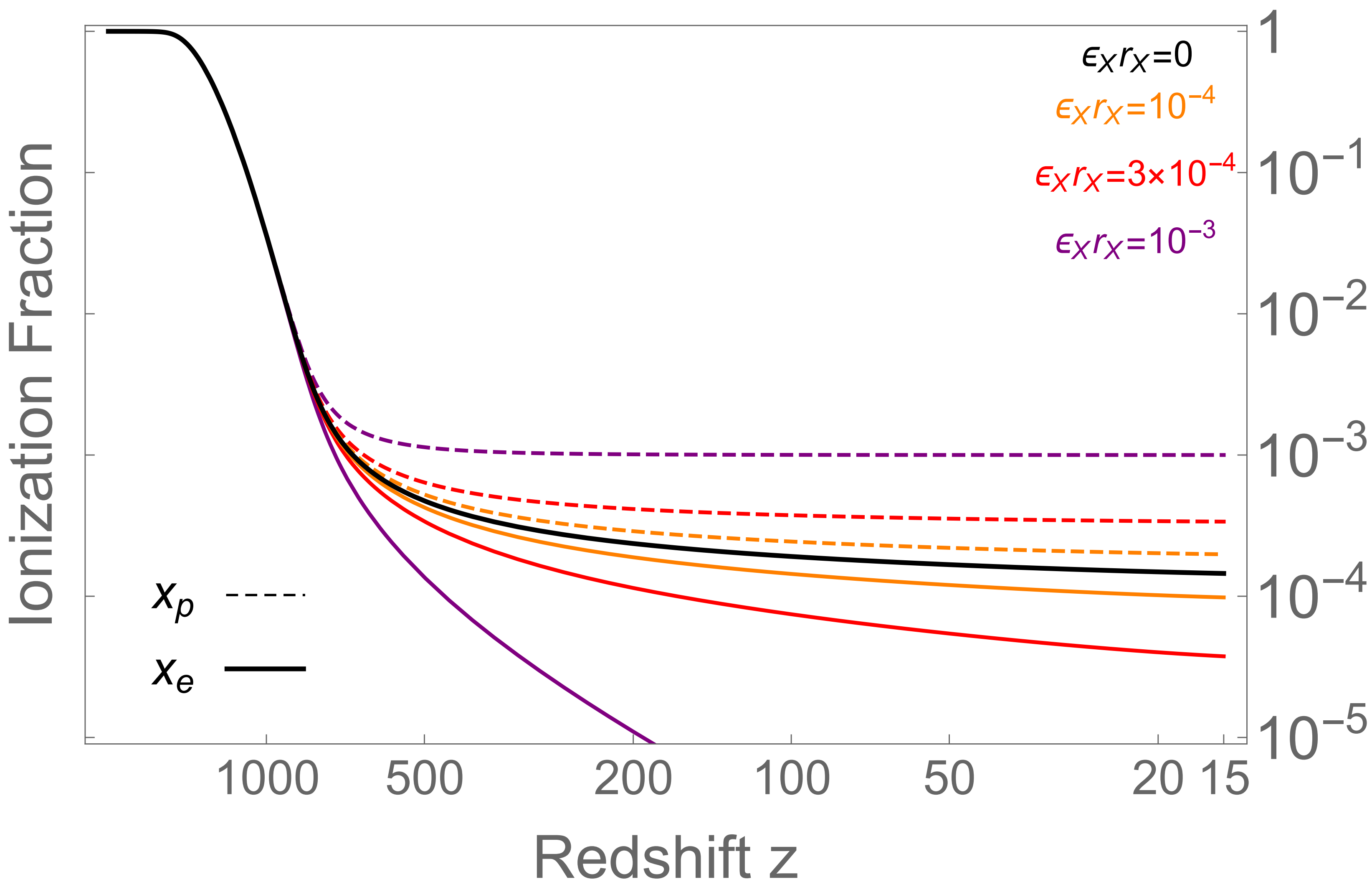
Decreasing Tg by sequestration

ⒶⒶ, Petraki
1803.10096

- Our scenario predicts smaller electron fraction and larger proton fraction during the dark ages

$$x_p = x_e + \epsilon_X r_X$$

- For $\epsilon_X r_X << 1$, recombination history is pretty standard at redshifts z ~ 1000



- But for z<<1000 universe starts running out of electrons

- For $\epsilon_X r_X \geqslant 10^{-4}$, standard ionization history significantly deviates from the standard scenario

Decreasing Tg by sequestration

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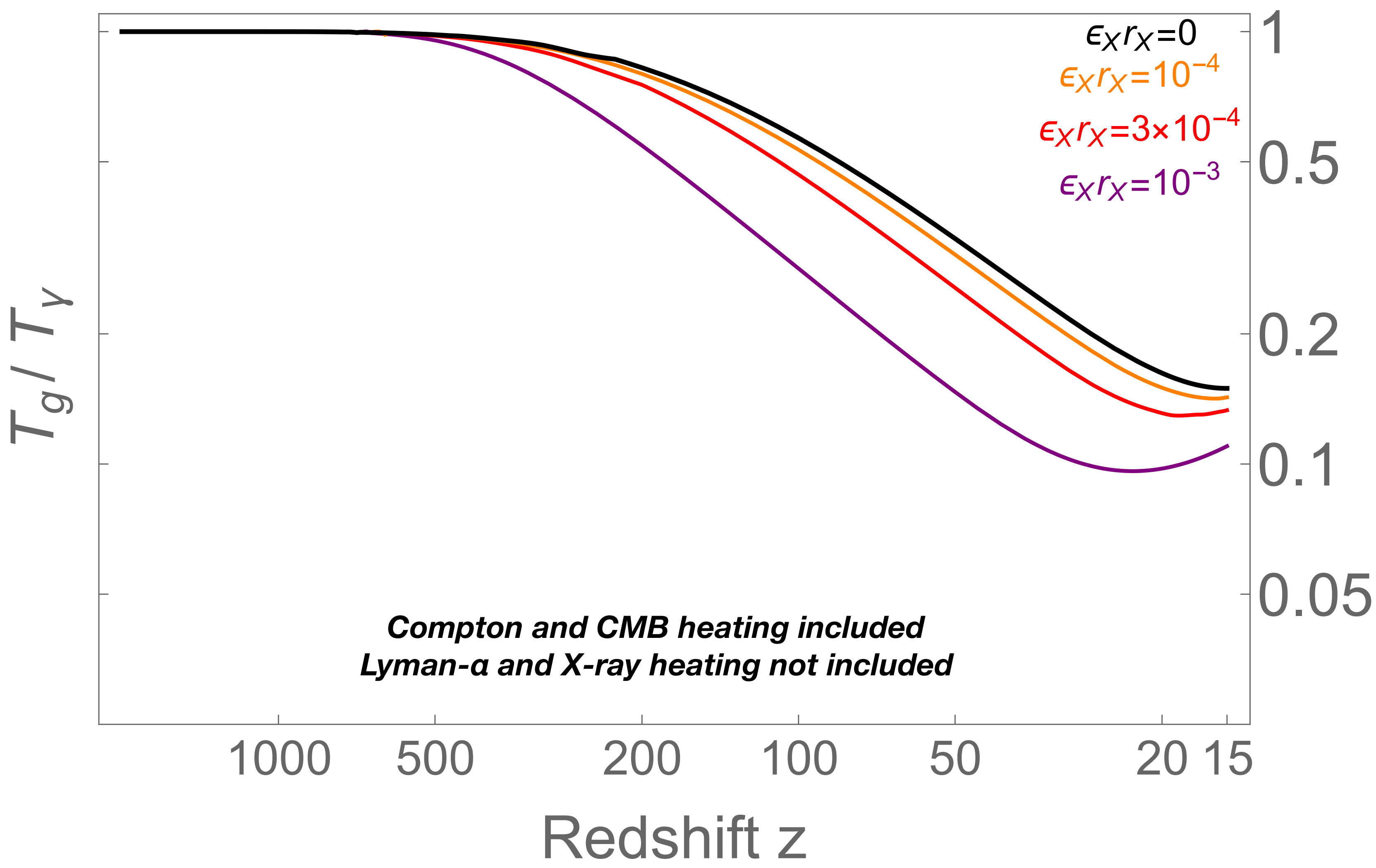


$\epsilon_X r_X$	$x_e(17)$	$x_p(17)$	$T_g(17)$ [K]	$T_\gamma(17)/T_g(17)$
0	1.5×10^{-4}	1.5×10^{-4}	7.5	6.6
10^{-5}	1.4×10^{-4}	1.5×10^{-4}	7.5	6.6
10^{-4}	1.0×10^{-4}	2.0×10^{-4}	7.0	7.0
3×10^{-4}	3.9×10^{-5}	3.4×10^{-4}	6.4	7.7
5×10^{-4}	1.1×10^{-5}	5.1×10^{-4}	5.8	8.5
10^{-3}	2.1×10^{-7}	1.0×10^{-3}	5.1	9.7

More charge asymmetry

↓

Smaller electron fraction

↓

Earlier gas-CMB decoupling

↓

Colder gas at cosmic dawn

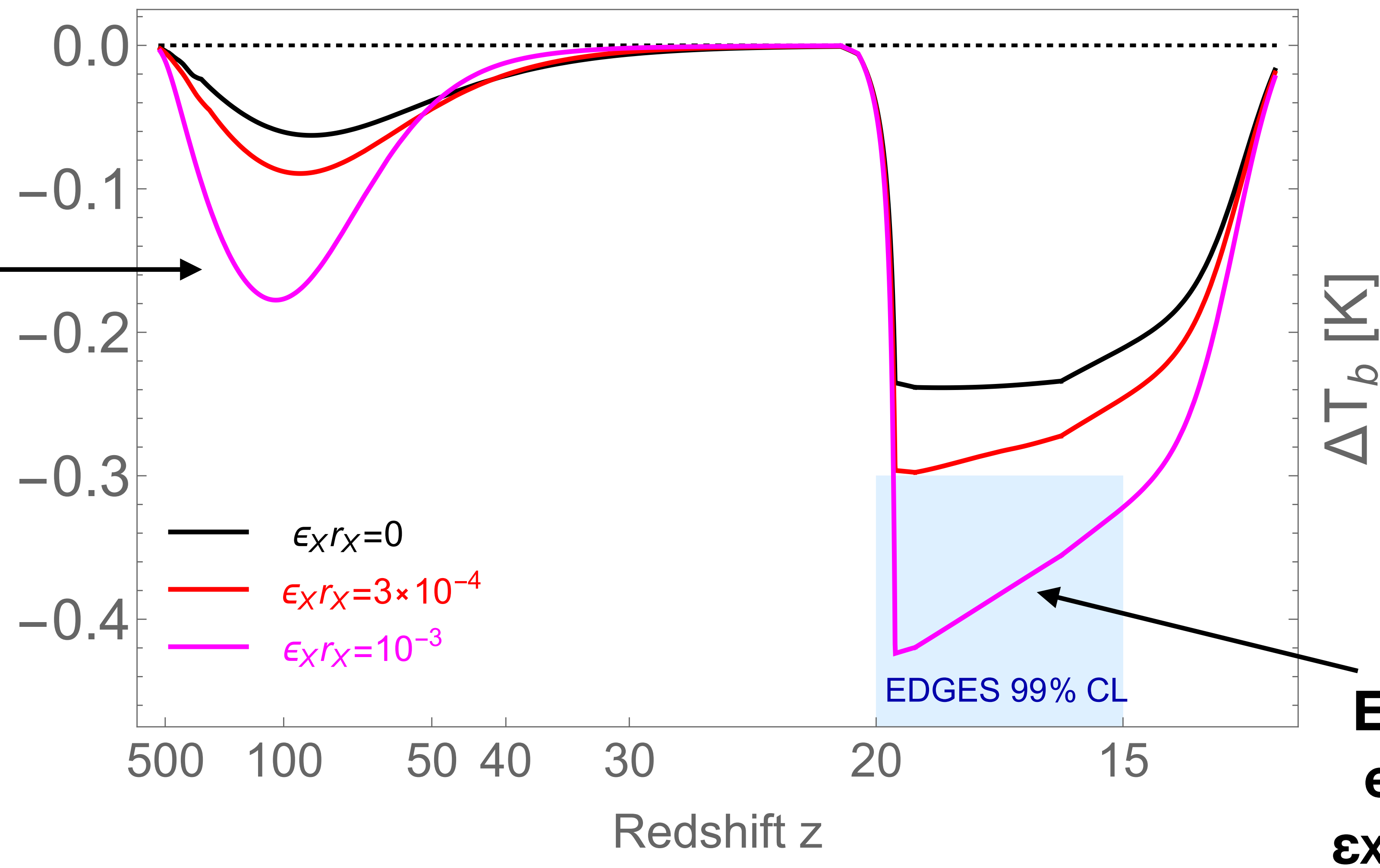
↓

Stronger 21cm absorption

Decreasing Tg by sequestration

$$\Delta T_b \approx 0.04\ \mathrm{K} \times \left(1 - \frac{T_\gamma(z)}{T_s(z)}\right)\sqrt{\frac{1+z}{18}}$$

Early 21cm absorption dip also enhanced



EDGES signal explained for εx rx ⩾ 3×10^-4

Ts evolution takes into account collisional and radiative transitions
Fields-Wouthuysen effect crudely modeled as sudden drop of Ts from Tγ to Tg at z=20

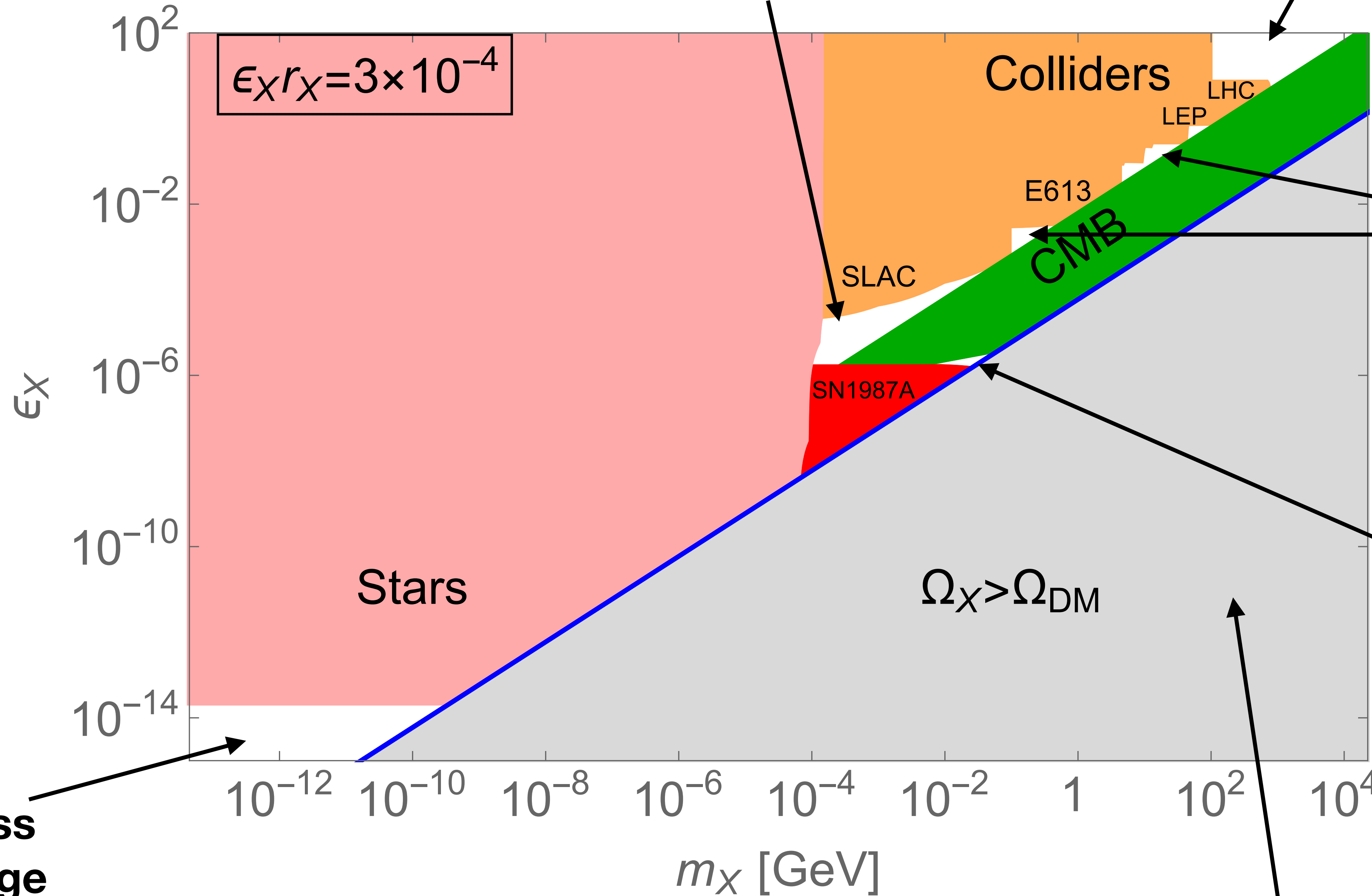
ⒶⒶ, Petraki
1803.10096

Parameter space for X

Very constrained parameter space
in a rather model independent way

MeV window similar to models with baryon-DM scattering

Large mass and charge window (but X cannot be around during nucleosynthesis)



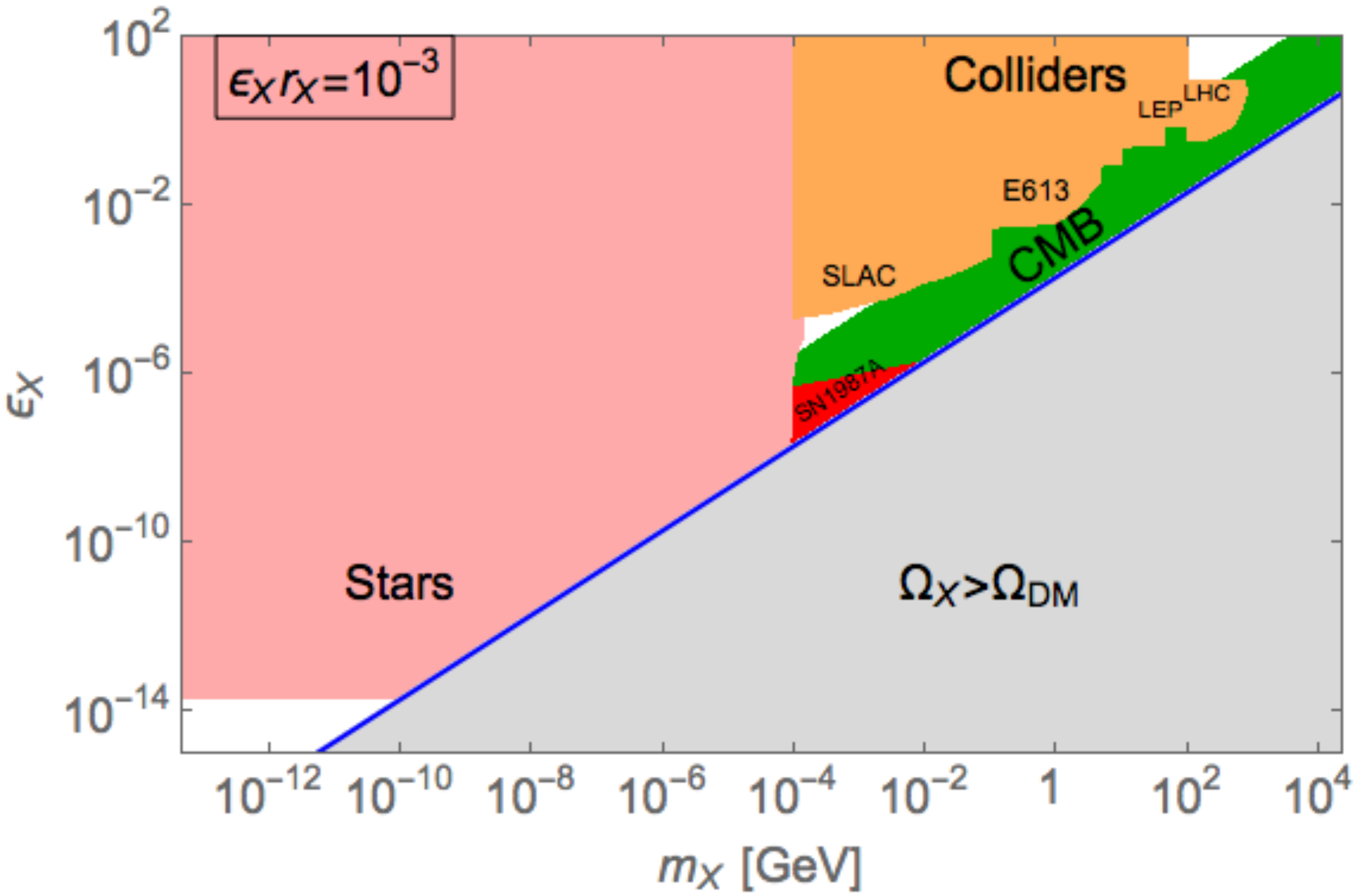
Flying under radar

O(10) MeV milli-charge particle as all of DM

Tiny mass and charge window (can by all of fuzzy-like DM)

$$\Omega_X = (\epsilon_X r_X)\frac{m_X}{\epsilon_X}\frac{\Omega_b}{m_p(1+f_{\rm He})}$$

Parameter space for X

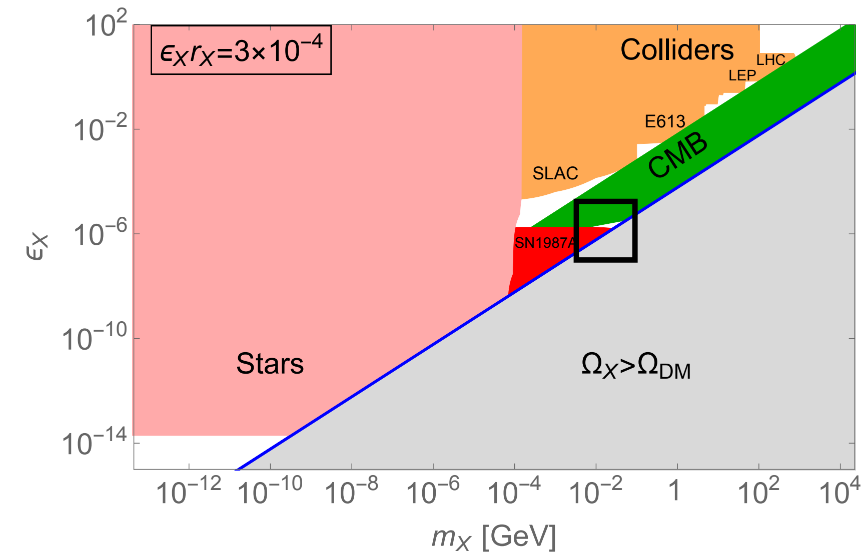


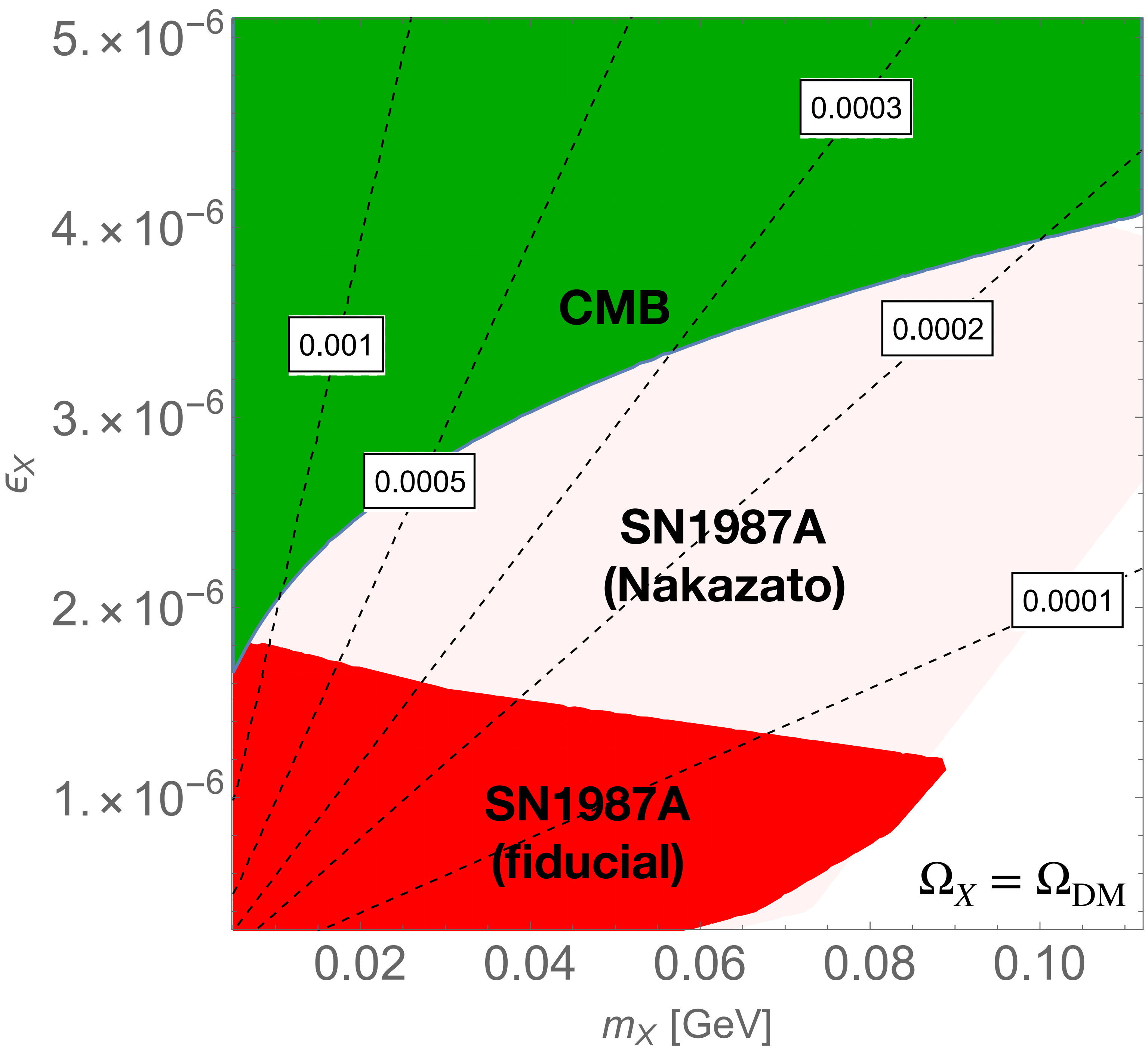
Even more constrained parameter space if one insists to reproduce the central value of EDGES measurement

Parameter space for X

Supernova bounds shown for two different sets of assumptions about density and temperature profiles

Chang et al
1803.00993





CMB bounds: Dolgov et al 1310.2376

If X tightly coupled to plasma

$$\epsilon_X^2 \frac{\mu_{X,p}^{1/2} + \mu_{X,e}^{1/2}}{m_X} \geq 5 \times 10^{-11}\ \mathrm{GeV}^{-1/2}$$

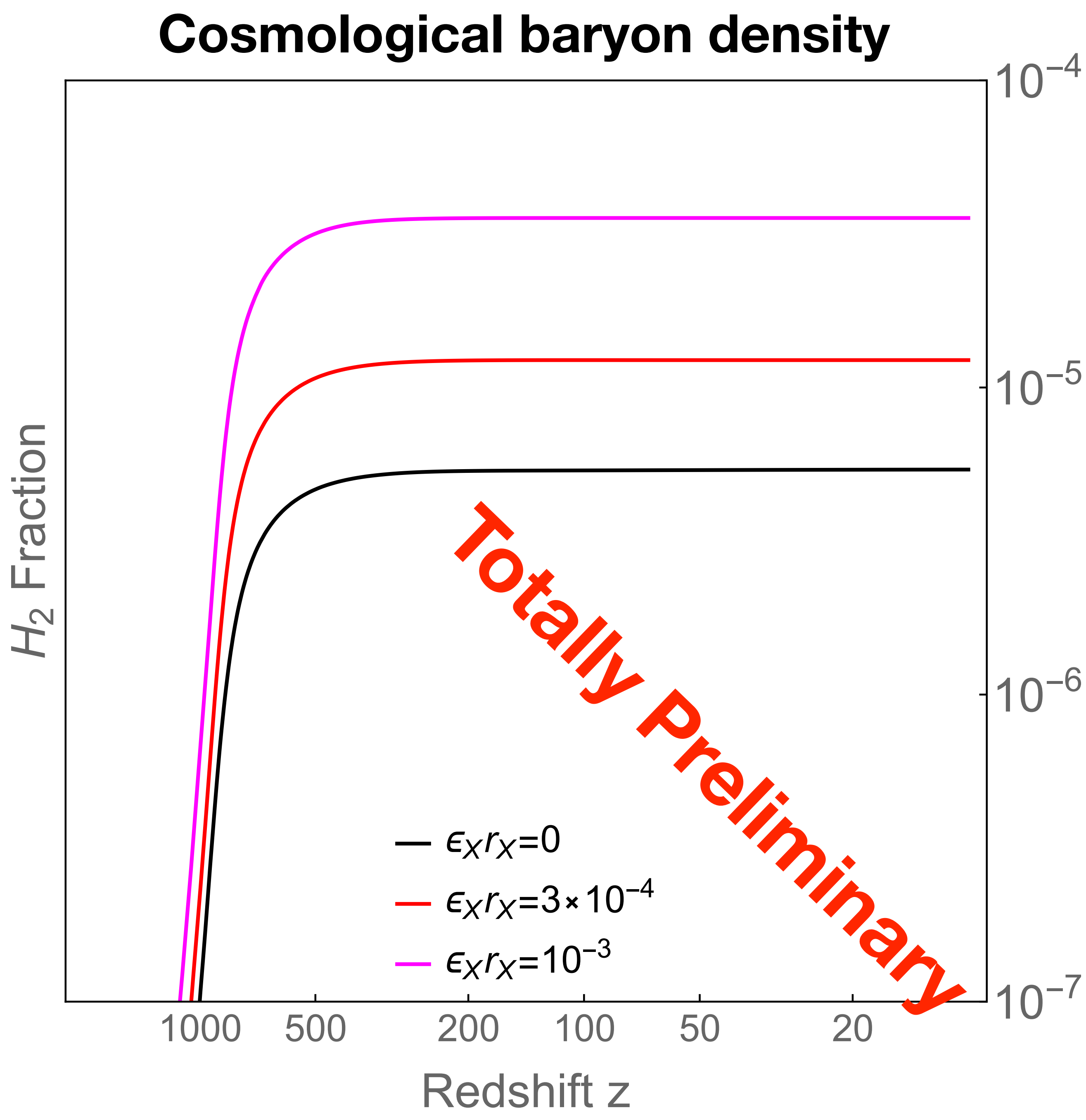
then X cannot be significant DM component

$$\Omega_X \lesssim 0.002$$

Smoking gun?

- Global absorption signal, also the early one, similar to cooling-by-DM scenario (what about anisotropies?)
- Distortion of CMB? But effects due to suppressed electron fraction estimated to be unobservable
- Plasma screening effects on photon propagation in the galaxy? But plasma frequency below 1Hz and small optical depth if X is subleading
- Modified chemical history of the universe?

Molecular hydrogen



Effect of charge sequestration on production of molecular hydrogen

$$H + p \to H_2^+ + \gamma$$

$$H + H_2^+ \to H_2 + p$$

$$H + e \to H_2^- + \gamma$$

$$H + H^- \to H_2 + e$$

H2 production via proton-initiated reaction chain (more relevant at cosmological density) may be enhanced by order of magnitude

H2 production via electron-initiated reaction chain (more relevant in high density clouds) may be suppressed by orders of magnitude

Take-away

- New window on the early Universe has just opened

- If the EDGES observation of the unexpectedly strong 21cm absorption is confirmed, we will have a strong hint of departure from the standard cosmological model

- Several (but not too many) models already constructed to explain the EDGES signal strength. Charge sequestration is one open possibility.