Is the EDGES result compatible with the WIMP paradigm?

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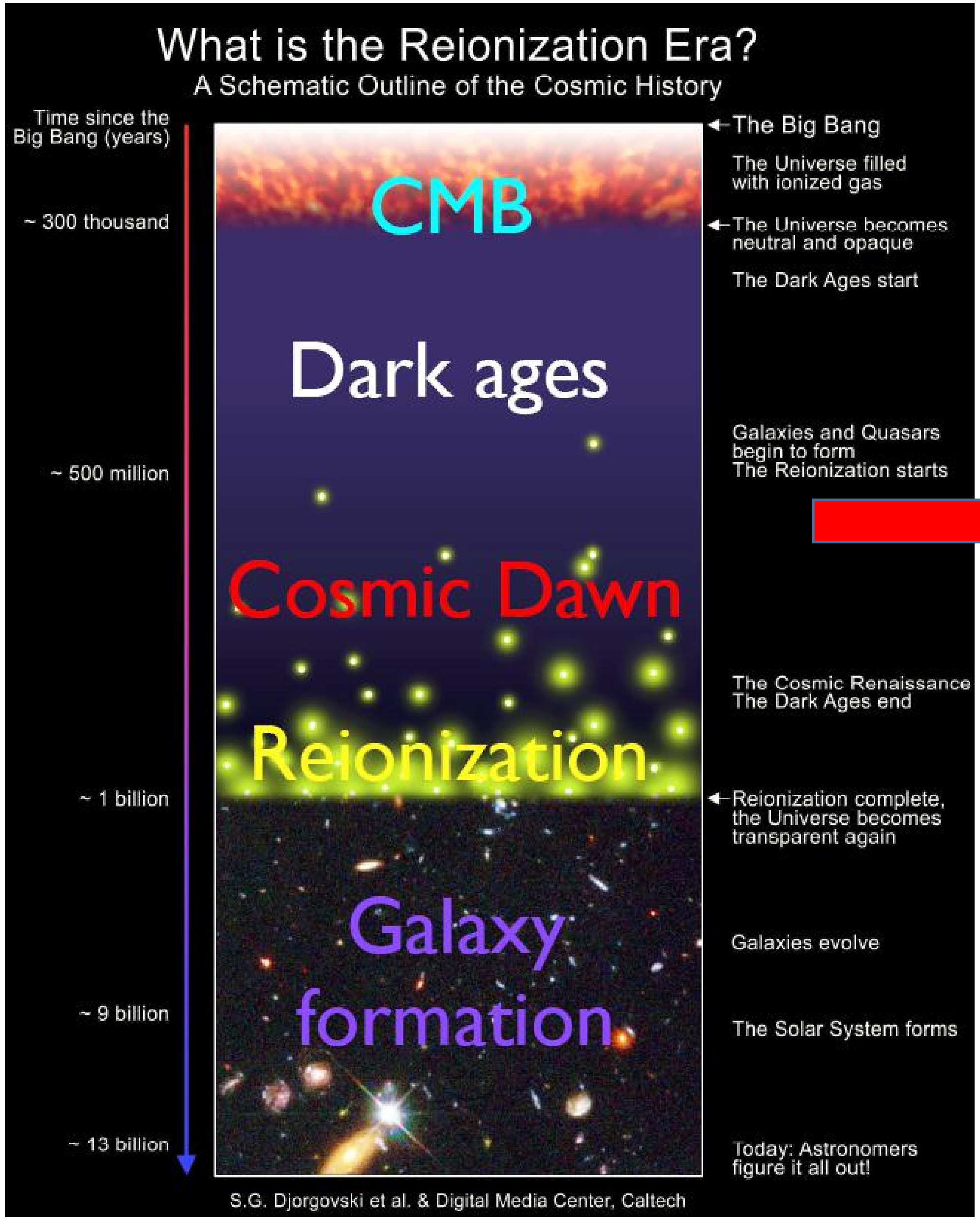
Outline

- Introduction
- Calculation of Global 21 cm Signal with Dark Matter Annihilation and Synchrotron Radiation

The first billion years

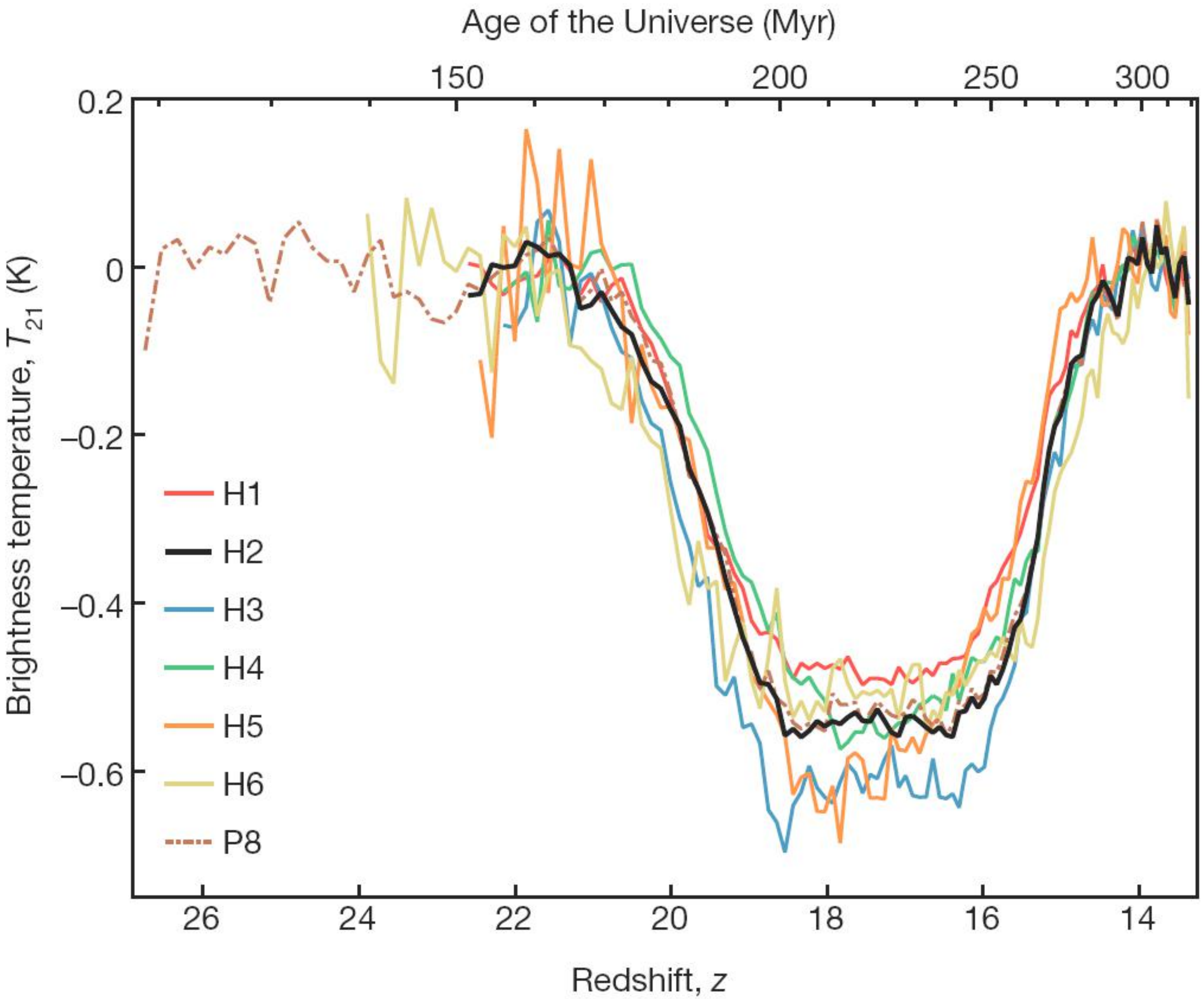


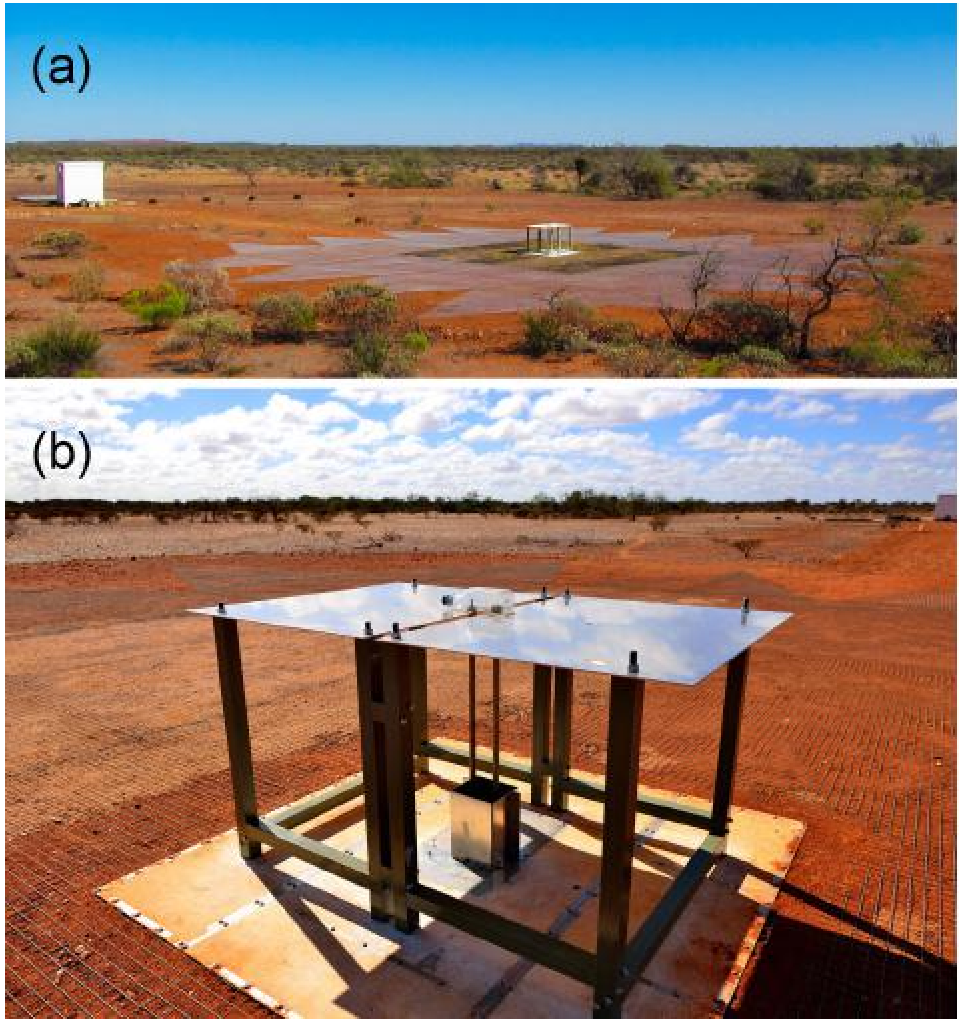
- ◆ When did the first galaxies from?
- ◆ When did the first black hole from?
- ◆ When did reionization happen ?
- ◆ Were there exotic sources of cooling or heating?

The first result from the dark age !

J. Bowman, A. Rogers, R. Monsalve, T. Mozdzen and N. Mahesh, Nature 555, 67 (2018)

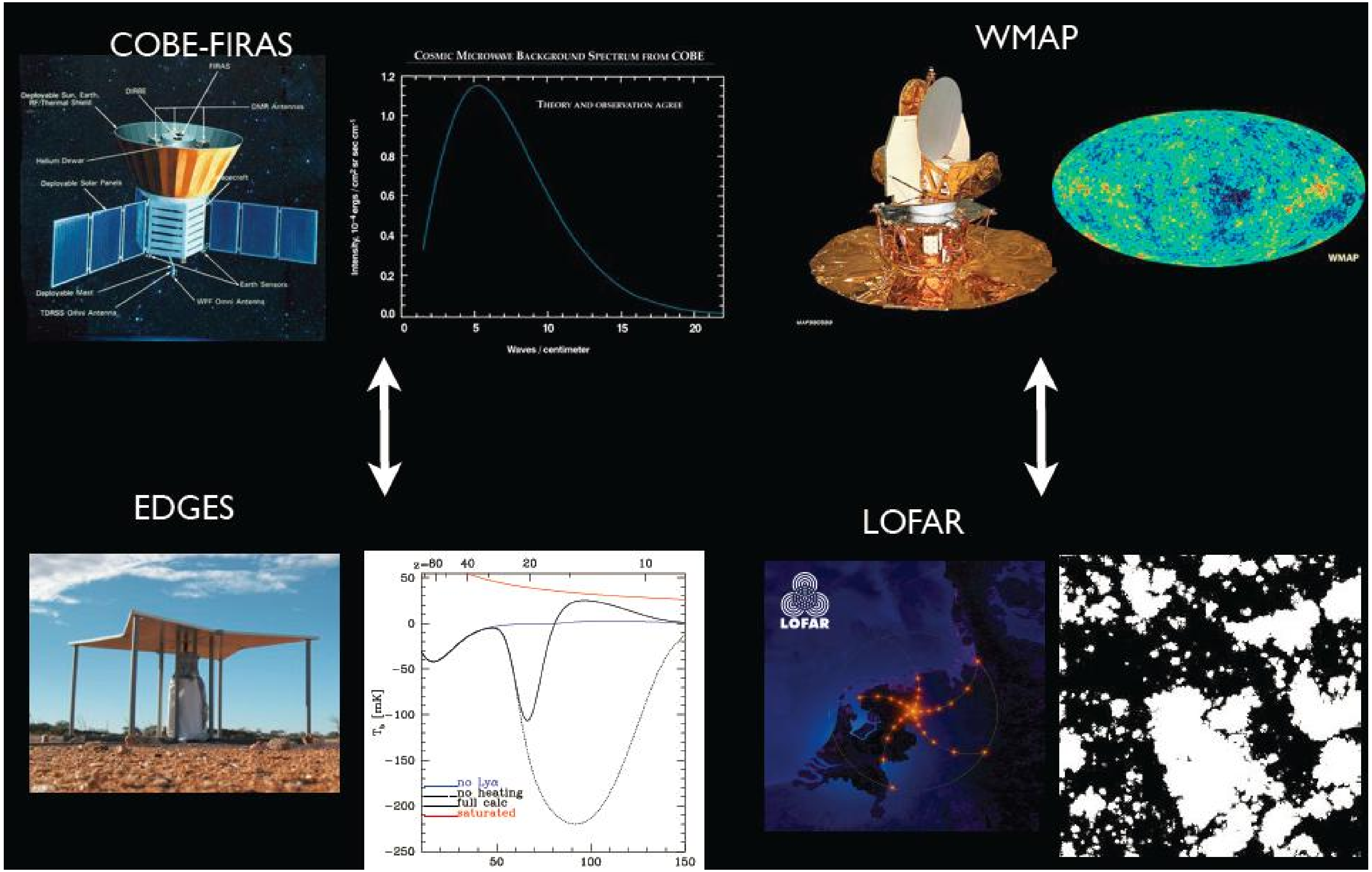
- The global 21 cm signal





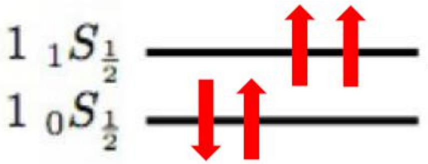
What is EDGES experiment measuring ?

- Global vs fluctuations



Basic picture of global 21 cm signal evolution

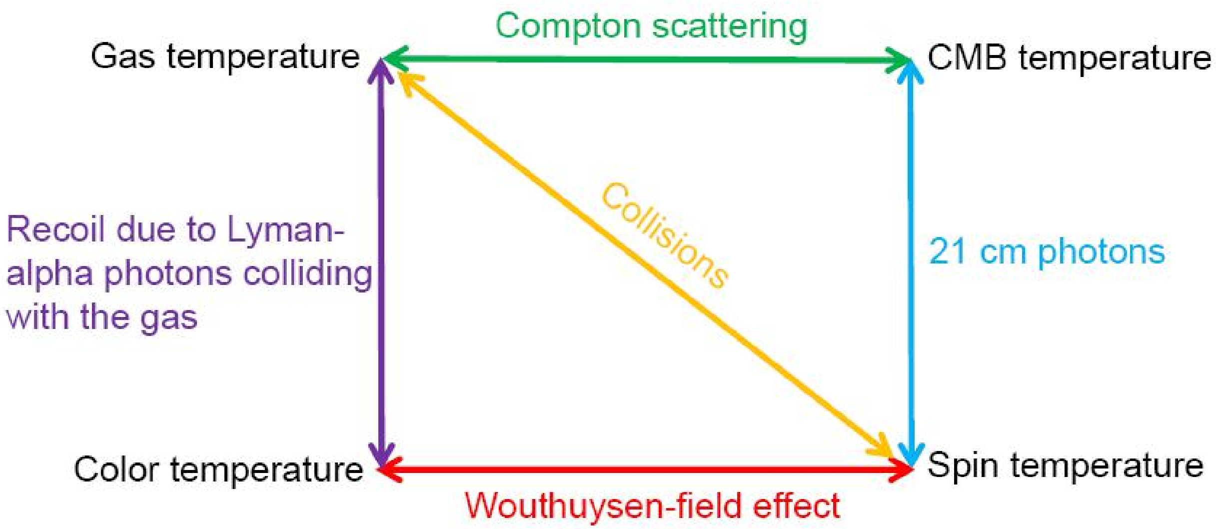
- Spin-flip transition of neutral hydrogen can be used to probe temperature and distribution of the neutral gas in the early universe prior to reionization (z > 6).



Aligend porton and electron

Anti-aligend porton and electron

- 21cm absorption/emission signal strength depends on “spin temperature” T_S, measure # of H in ground vs excited state - expected to lie between gas temperature T_{gas} and CMB temperature T_{CMB}.



- Spin temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\Delta E_{21}/k_B T_s} = \frac{g_1}{g_0} e^{-h\nu_{21}/k_B T_s} = 3e^{-T_*/T_s} \approx 3\left(1 - \frac{T_*}{T_s}\right)$$

- CMB temperature

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_B T_{\rm CMB}} - 1}$$

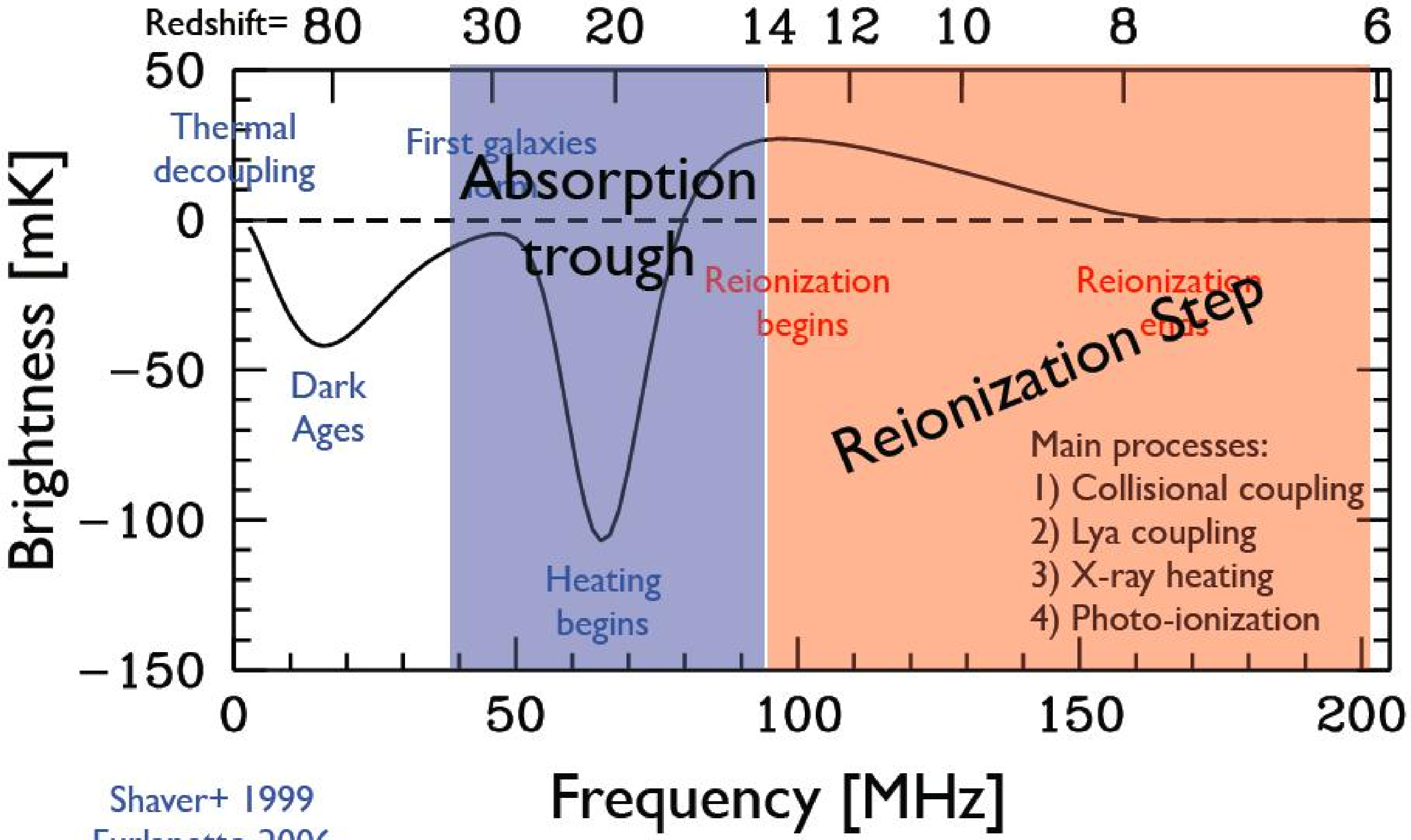
- Gas temperature

$$\frac{C_{01}}{C_{10}} = \frac{n_1}{n_0} = \frac{g_1}{g_0}e^{-T_*/T_K} \approx 3\left(1-\frac{T_*}{T_K}\right)$$

- Color temperature

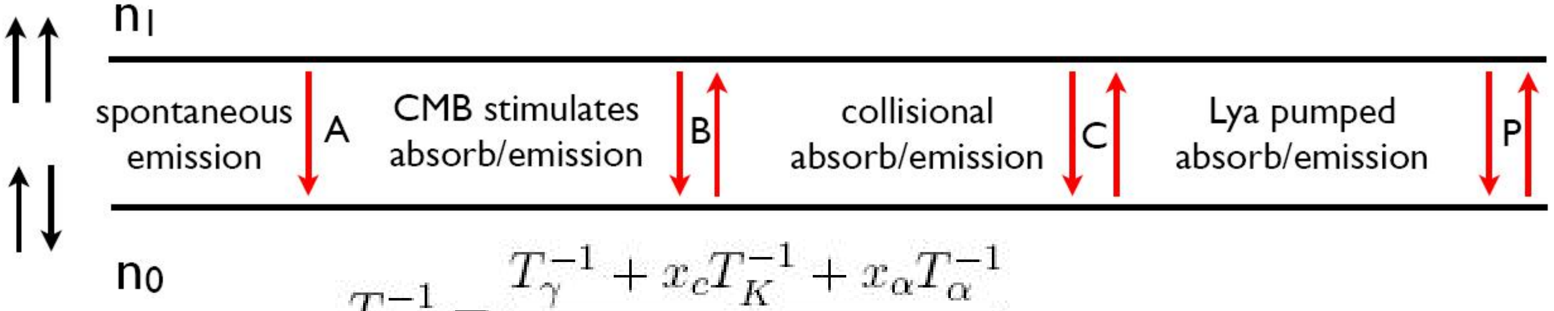
$$\frac{P_{01}}{P_{10}} = \frac{g_1}{g_0}e^{-T_*/T_\alpha} \approx 3\left(1-\frac{T_*}{T_\alpha}\right)$$

- Absorption signal when $T_S < T_R$ (radiation temperature), emission signal if $T_S > T_R$. T_R here describes # photons at 21cm wavelength - not necessarily thermally distributed.
- Expected behavior: Tgas decouples from T_{CMB} around redshift z~150, subsequently satisfies $T_{gas} \sim T_{CMB} (1+z)/(1+z)_{dec}$. Gas is later heated by the stars, and eventually T_{gas} increases above T_{CMB}. Thus expect early absorption, later emission.



Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

- Detailed balance implies



n₁

spontaneous emission A

CMB stimulates absorb/emission B

collisional absorb/emission C

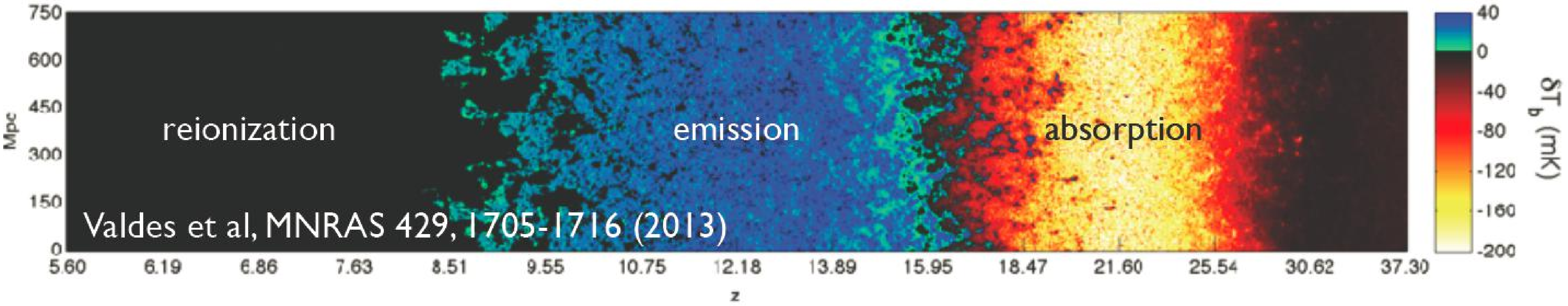
Lya pumped absorb/emission P

n₀

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha}$$

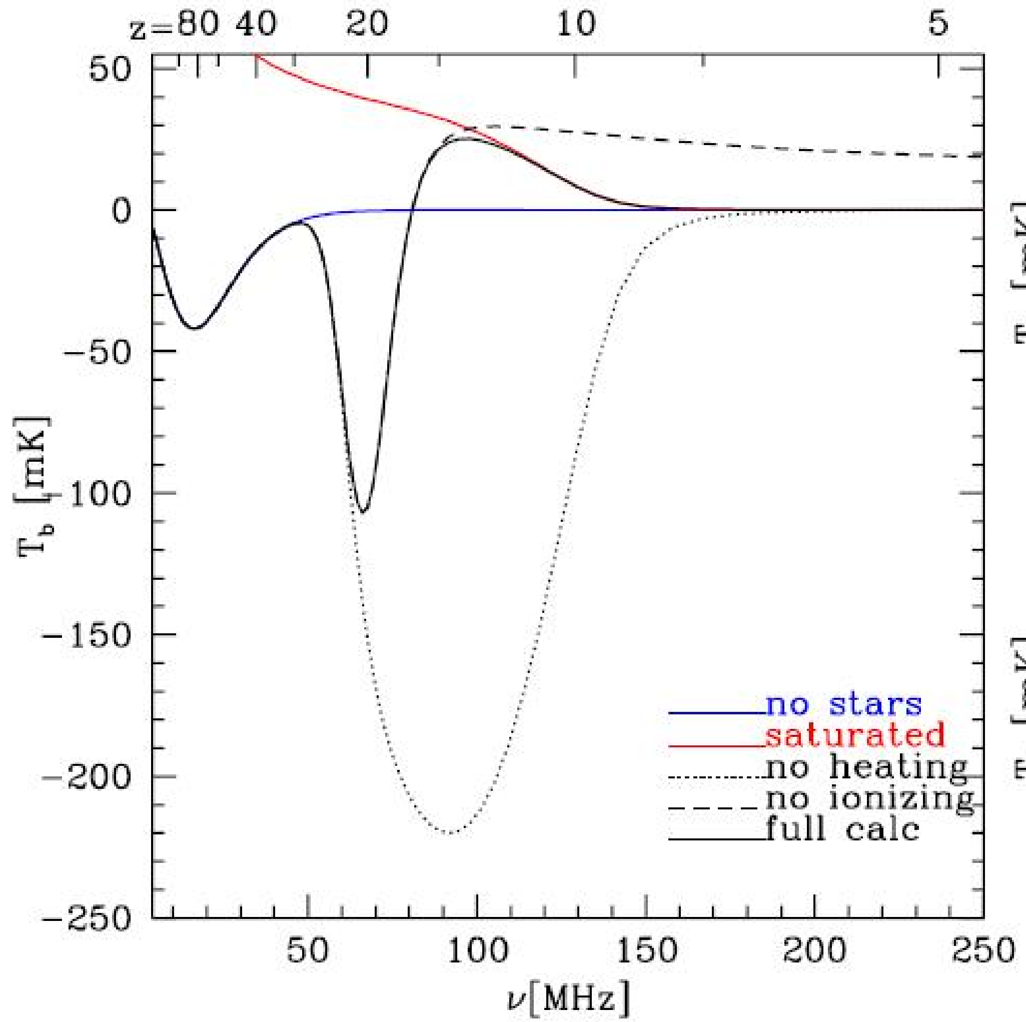
- Observable signal : brightness temperature

$$\delta T_b(z) \approx 27 x_{\rm HI}(z)(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2}\left(1 - \frac{T_R(z)}{T_s(z)}\right)\ \mathrm{mK}$$

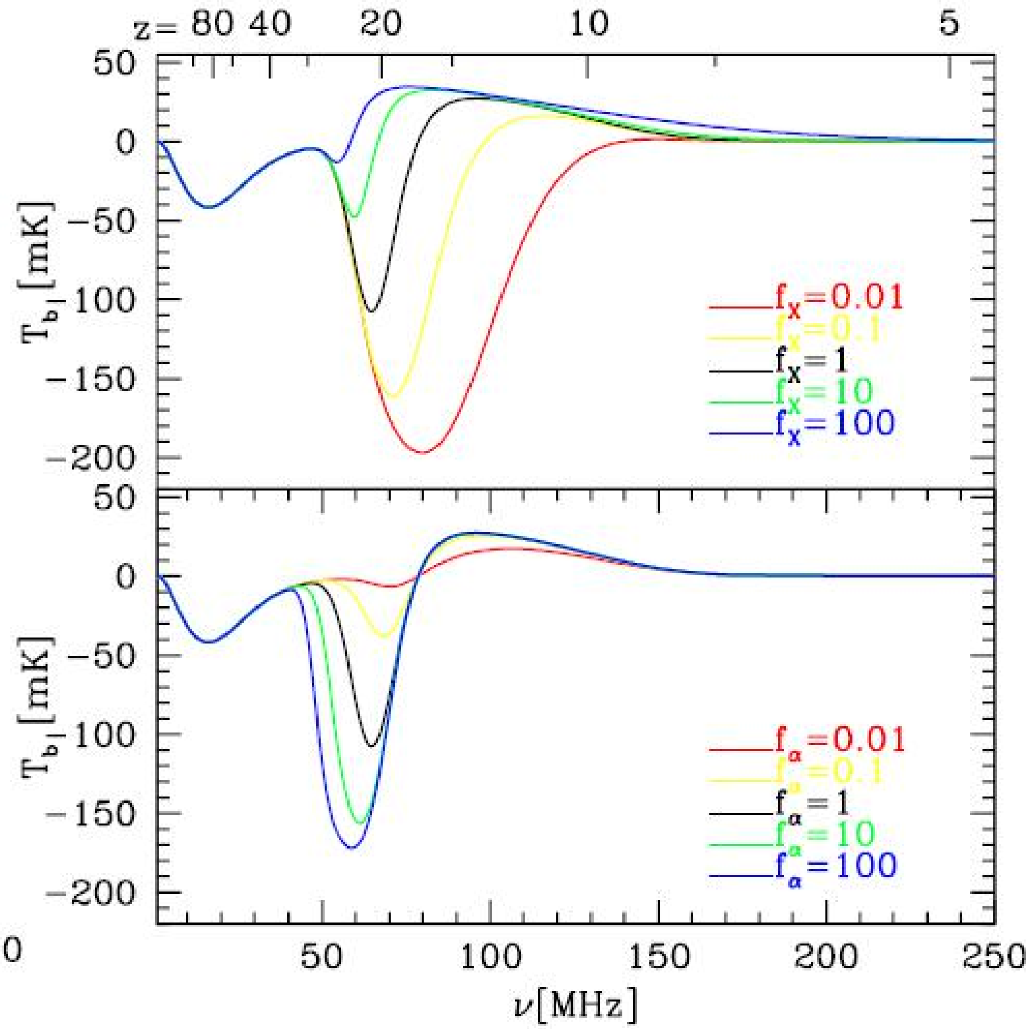


Valdes et al, MNRAS 429, 1705-1716 (2013)

Do we have all the physics?



What do first galaxies look like?

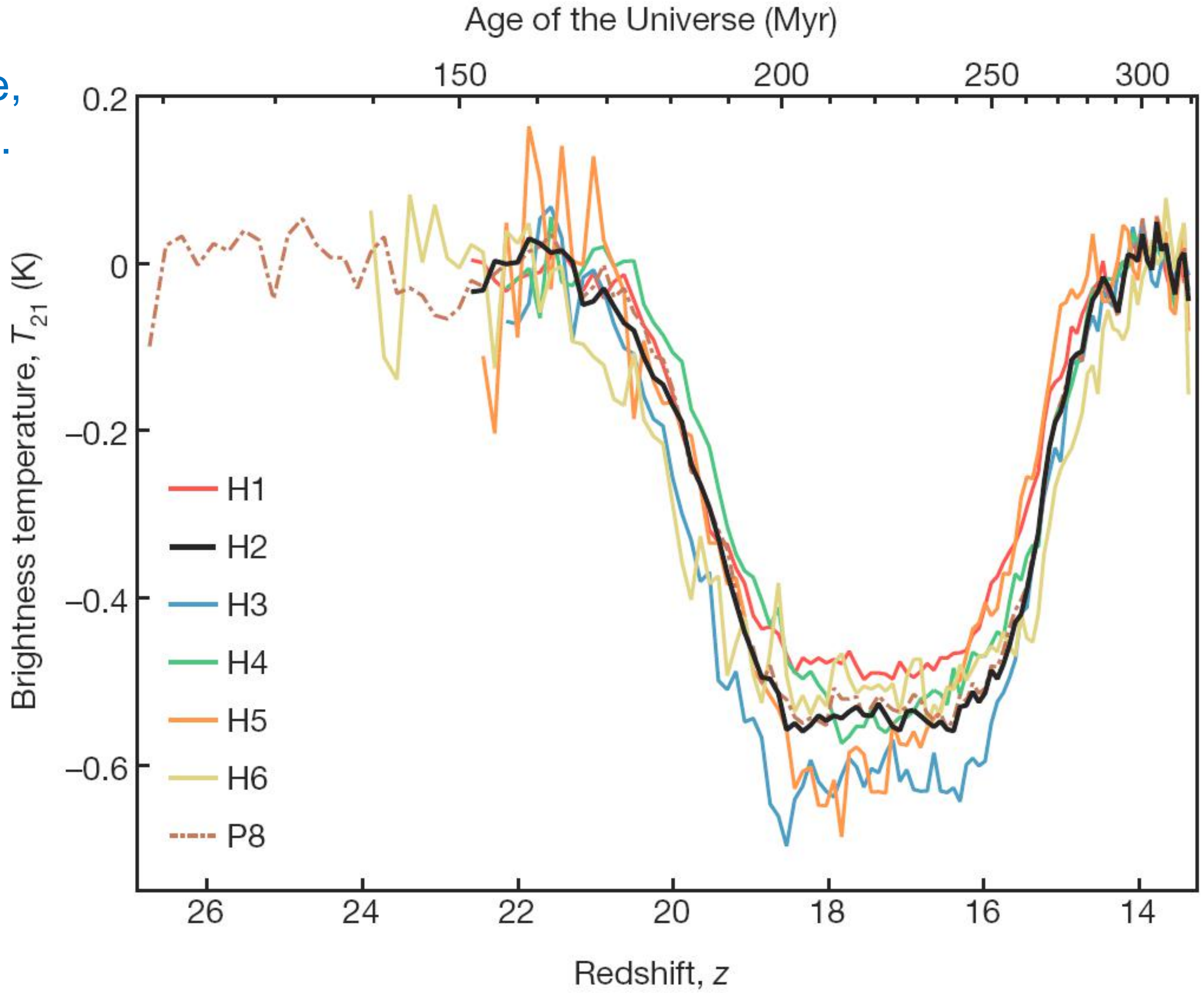


Pritchard & Loeb 2010

- Claim is a deep absorption trough corresponding to z~15-20 - implies Ts < TCMB
- Measurement of T_{gas}/T_R (z=17) < T_S/T_R < 0.105 (99% confidence).

J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen and N. Mahesh, Nature 555, no. 7694, 67 (2018).

$$T_{21}^{EDGES}(z \simeq 17) = -500^{+200}_{-500} \text{ mK}$$



The discrepancy between data and fiducial model prediction

- If T_R is taken to be the CMB temperature, this gives $T_{gas} < 5.2$ K
- But assuming standard decoupling and no stellar heating, one gets $T_{gas} \sim 7$ K
- Of course, It is possible due to instrumental effects and/or unappropriate recast of foregrounds.

How to solve this puzzle ? —— Exotic result requires exotic model !

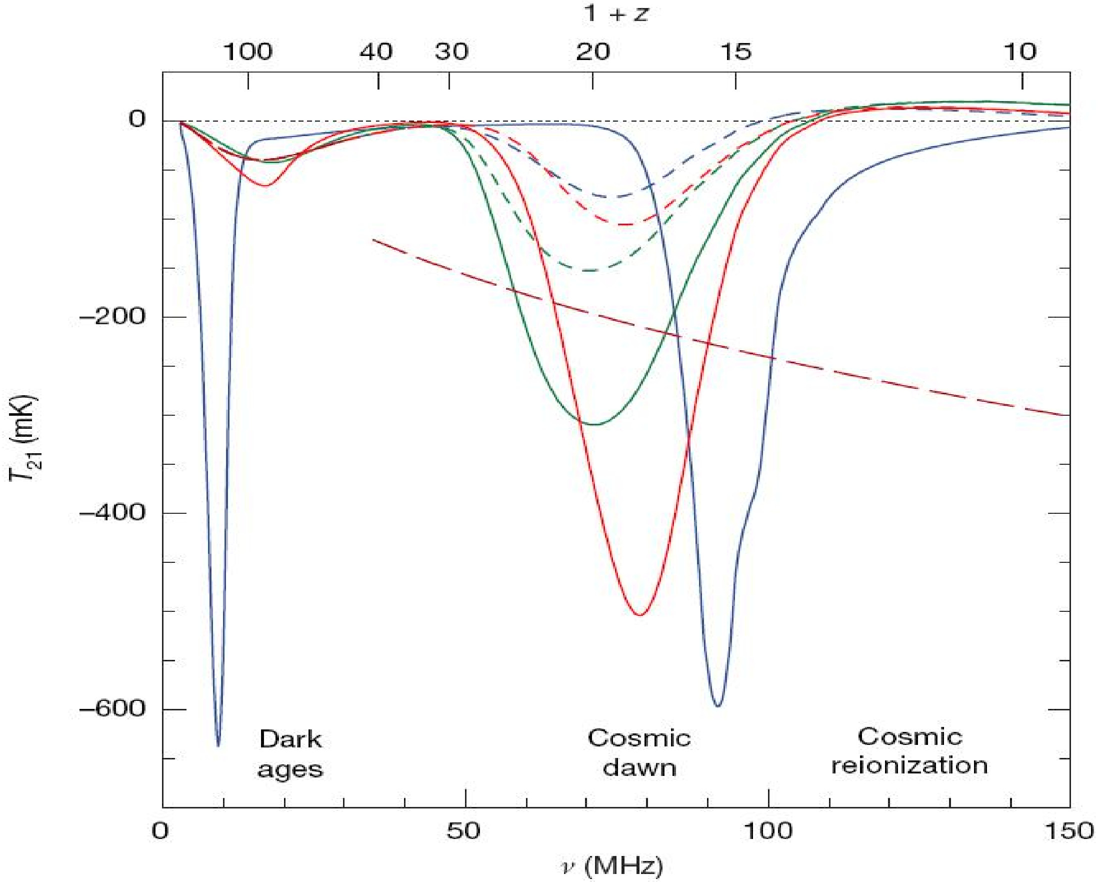
- "Heating the CMB":introducing new radiation backgrounds [Feng and Holder 1802.07432], which could arise from either novel astrophysics, i.e. radio emission from early black holes [Ewall-Wice et al 1803.01815] or from more exotic sources [Fraser et al 1803.03245, Pospelov et al 1803.07048].
- "Cooling the gas": introducing additional cooling sources of the gas, which could be due to modified recombination history (earlier decoupling from CMB), or scattering of the gas on a colder (some fraction of) DM [Barkana, Nature 555, no. 7694, 71 (2018) ; Munoz & Loeb 1802.10094; Berlin et al 1803.02804; Barkana et al 1803.03091]

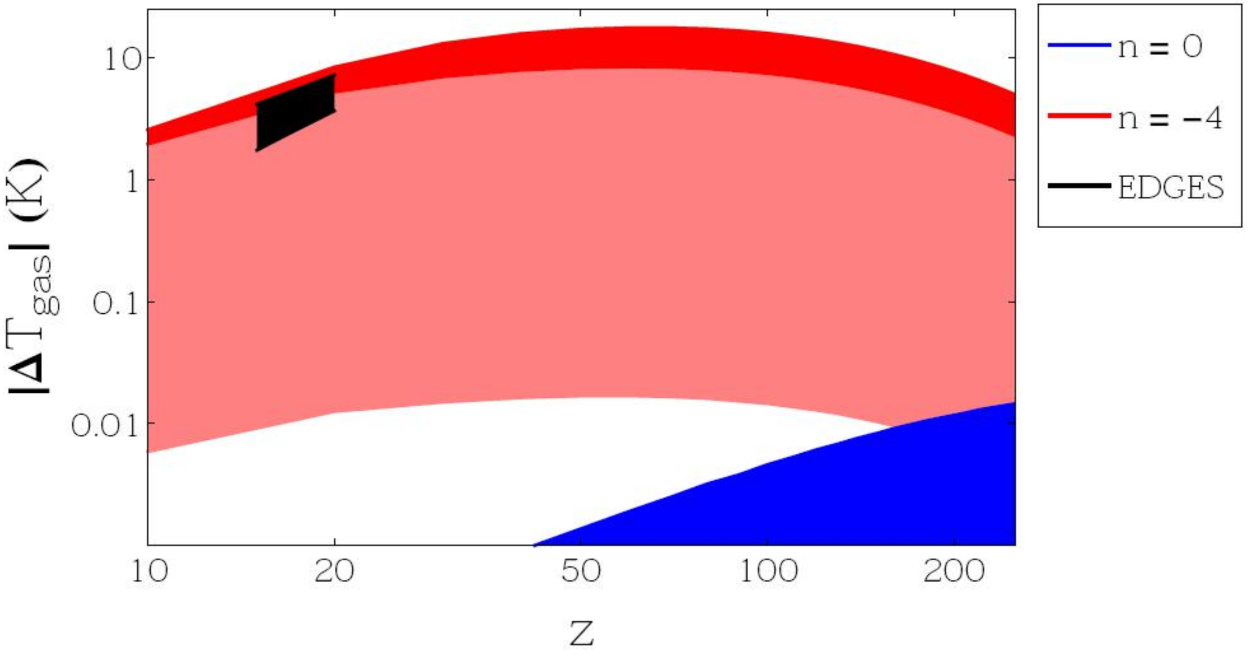
Concrete examples

- Requiring σ~v^{-4} scattering between sub-GeV DM and baryons in order to cool the gas enough,without violating CMB bounds.

R. Barkana, Nature 555, no. 7694, 71 (2018) [arXiv:1803.06698 [astro-ph.CO]].

T. R. Slatyer and C. L. Wu, Phys.Rev. D98 (2018) no.2, 023013

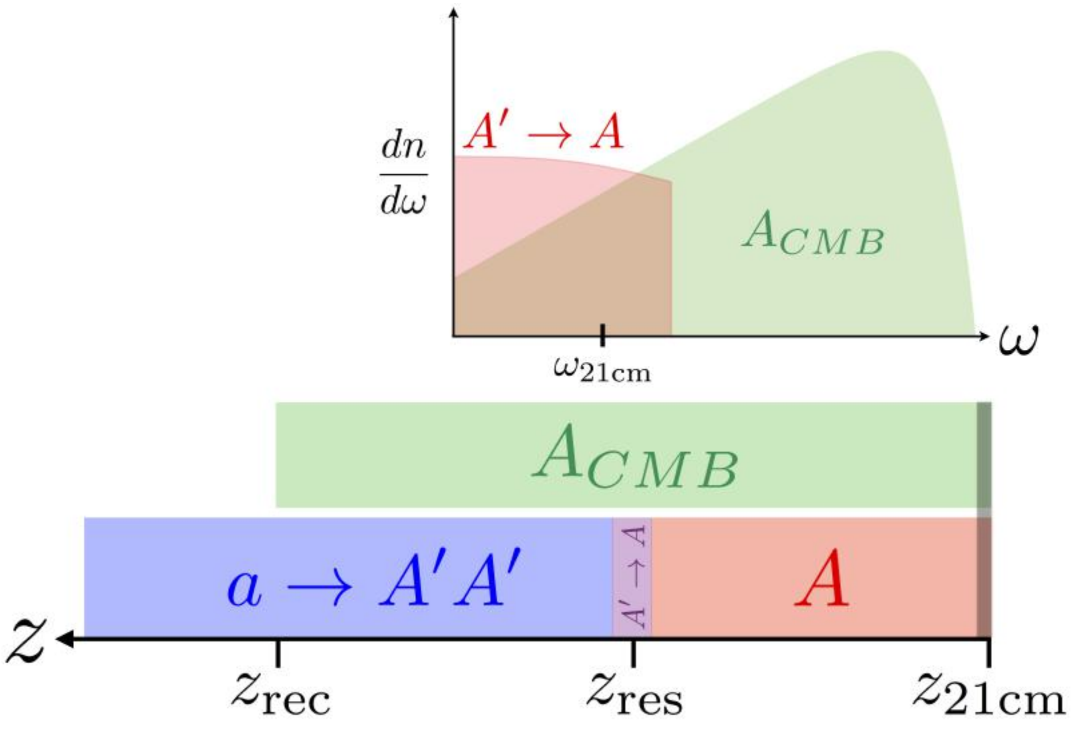


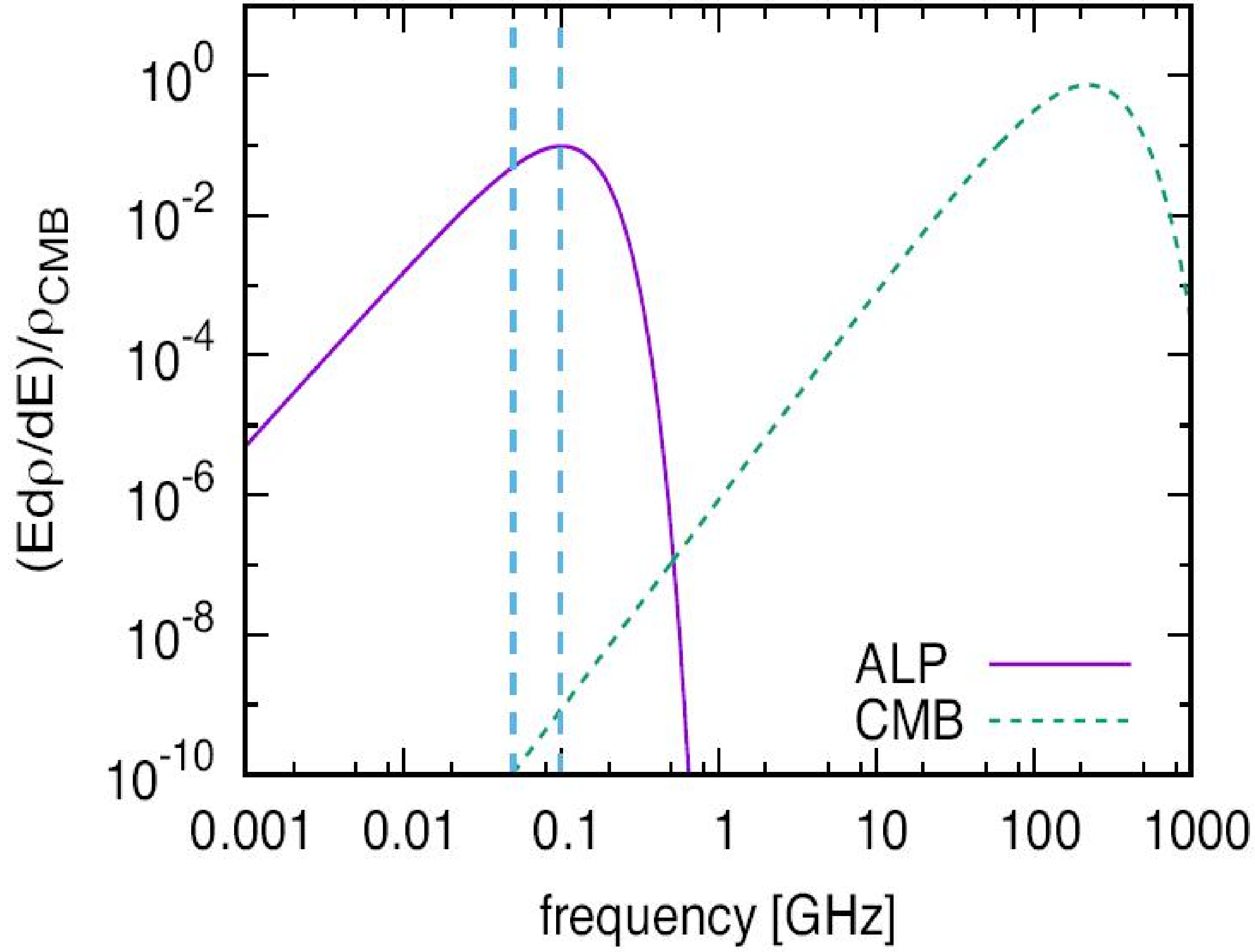


- Requiring ultra-light axion-like particle/dark photon with tiny mixing with photon in order to create sufficient new radiation backgrounds.

M. Pospelov, J. Pradler, J. T. Ruderman and A. Urbano, Phys.Rev.Lett. 121 (2018) no.3, 031103

T. Moroi, K. Nakayama and Y. Tang, Phys.Lett.B 783, 301 (2018)

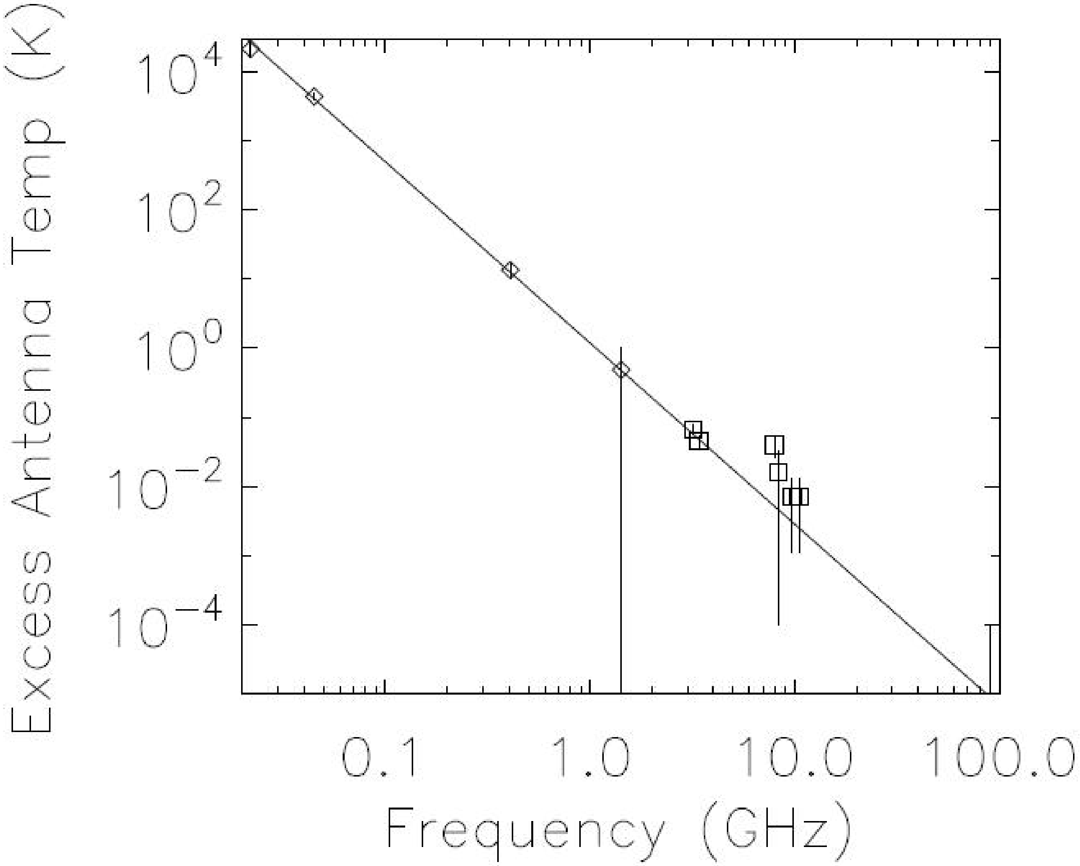


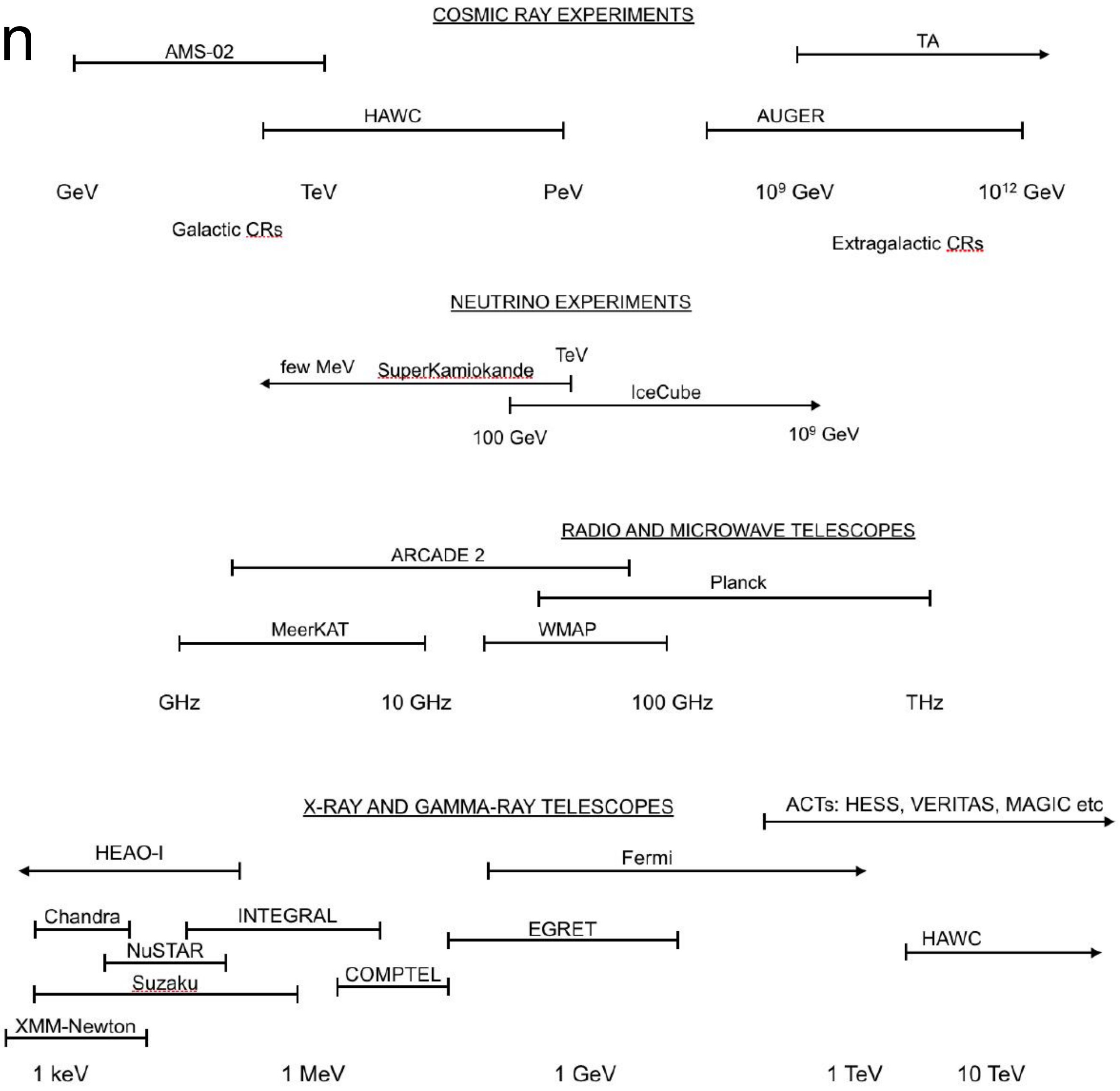


- Both above recipes potentially conflict with the WIMP scenario.
- Can we interpret EDGES result within conventional WIMP framework?
  ——Not very natural, but possible!
- The DM annihilation can produce secondary particles that can heat the gas (also produce extra ionization, extra photons, etc). At the same time, the electron-positron final states also produce synchrontron radiation in the intergalactic magnetic field, e.g., DM annihilation can heat gas and radiation background (CMB) simultaneously.
- If two “heating effects” can reach a certain balance, the EDGES anomaly can be explained by only using DM annihilation effect.

Hint from ARCADE-2 observation

D.J. Fixsen et al., Astrophys.J. 734 (2011) 5





COSMIC RAY EXPERIMENTS

AMS-02

TA

HAWC

AUGER

GeV

TeV

PeV

10^9 GeV

10^{12} GeV

Galactic CRs

Extragalactic CRs

NEUTRINO EXPERIMENTS

few MeV

SuperKamiokande

TeV

IceCube

100 GeV

10^9 GeV

RADIO AND MICROWAVE TELESCOPES

ARCADE 2

Planck

MeerKAT

WMAP

GHz

10 GHz

100 GHz

THz

X-RAY AND GAMMA-RAY TELESCOPES

ACTs: HESS, VERITAS, MAGIC etc

HEAO-I

Fermi

Chandra

INTEGRAL

NuSTAR

EGRET

HAWC

Suzaku

COMPTEL

XMM-Newton

1 keV

1 MeV

1 GeV

1 TeV

10 TeV

Fiducial model

- Compton scattering initially dominates heating/cooling post-recombination. Thermal decoupling when scattering CMB photons can no longer heat gas at z_{dec}~150, thereafter gas cools adiabatically as non-relativistic particles $T_{gas} \sim (1 + z)^2$.
- After first galaxies form, gas is reheated by X-ray and Ly-alpha photons. X-ray heating can be efficient, while Ly-alpha heating less efficient, unless gas very cold.
- The evolution of Tgas can be described by standard evolution equations

$$\frac{dT_{\rm gas}}{dt} = -2H(z)T_{\rm gas} + \frac{8\sigma_T a_R T_\gamma^4 x_e (T_\gamma - T_{\rm gas})}{3(1+f_{\rm He}+x_e)m_e c},$$

$$\frac{dx_e}{dt} = -C\left[n_H \alpha_B(T_{\rm gas})x_e^2 - (1-x_e)\beta_B(T_\gamma)e^{-E_{12}/T_\gamma}\right]$$

- Taking into account X-ray heating, introducing additional terms in evolution equations

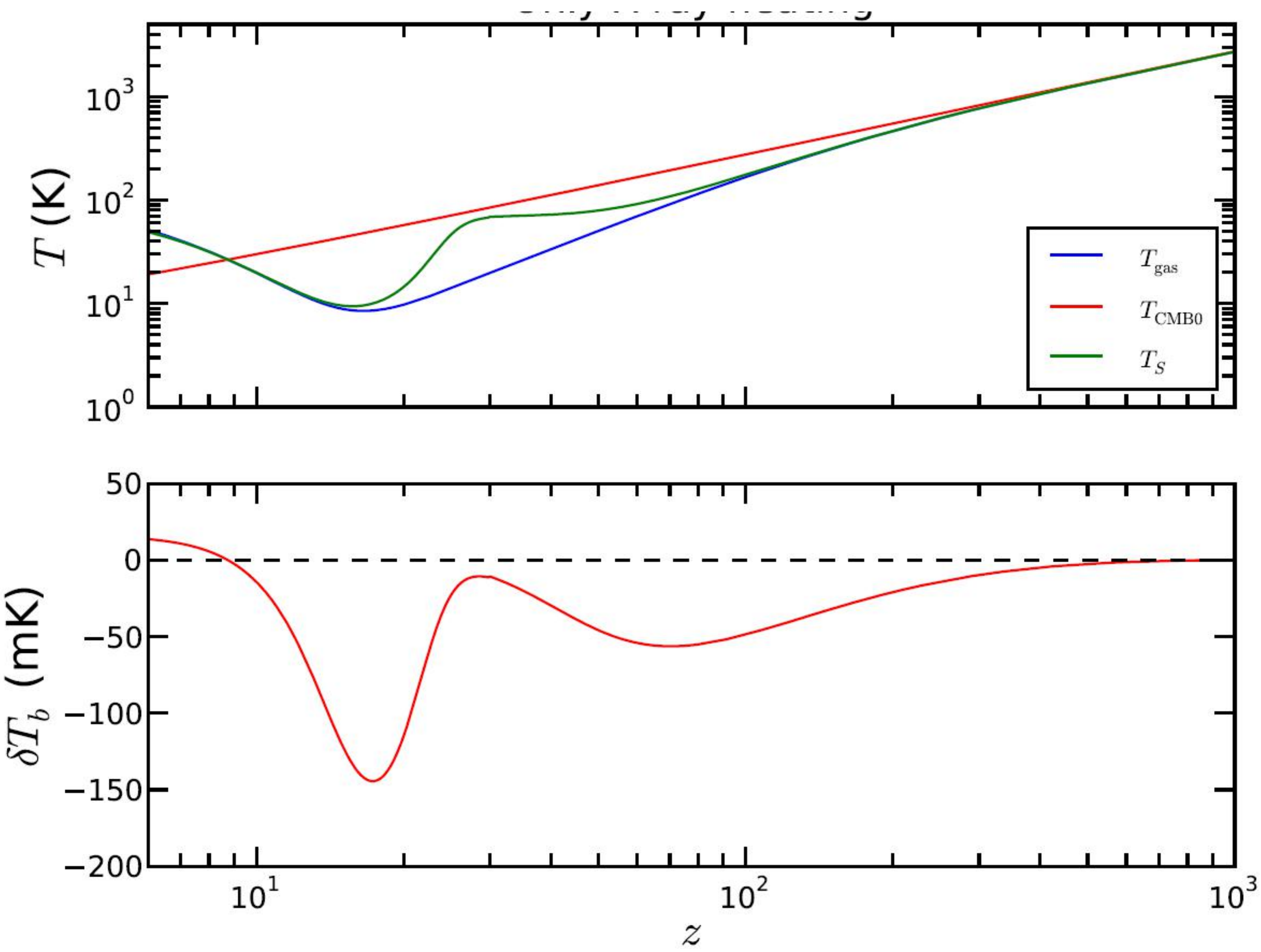
$$\delta\left(\frac{dT_{\rm gas}}{dt}\right) = \frac{2\epsilon_X(z)}{3k_B}\frac{1+2x_H+f_{\rm He}(1+2x_{\rm He})}{3(1+f_{\rm He})}$$

$$\delta\left(\frac{dx_H}{dt}\right) = \frac{\epsilon_X(z)}{13.6{\rm eV}}\frac{1-x_H}{3(1+f_{\rm He})},$$

$$\delta\left(\frac{dx_{\rm He}}{dt}\right) = \frac{\epsilon_X(z)}{24.6{\rm eV}}\frac{1-x_{\rm He}}{3(1+f_{\rm He})},$$

$$x_e = x_H + f_{\rm He}x_{\rm He}$$

Fiducial model



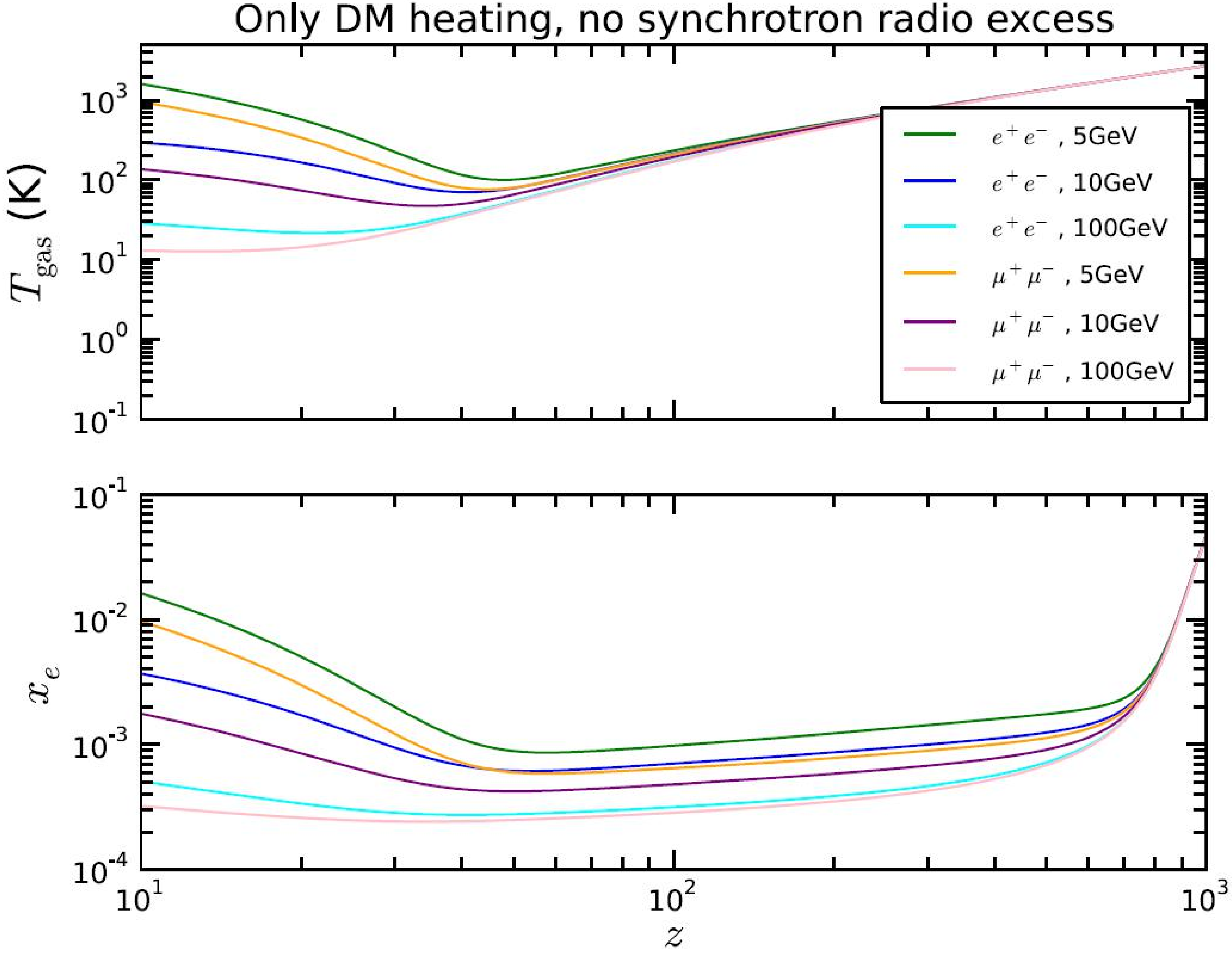
Effect of DM annihilation

$$\frac{dT_{\rm gas}}{dz} = -\sum_i \int \frac{dz'}{H(z')(1+z')} \frac{n_{\rm DM}^2}{3n_H(z')} \langle \sigma v \rangle B(z', M_{\rm min}) {\rm Br}_i m_{\rm DM} f_{\rm eff}(m_{\rm DM}, i, z', z)\,,$$

$$\frac{dx_{\rm e}}{dz} = -\sum_i \int \frac{dz'}{H(z')(1+z')} \frac{n_{\rm DM}^2}{2n_H(z')} \langle \sigma v \rangle B(z', M_{\rm min}) {\rm Br}_i \frac{m_{\rm DM}}{13.6{\rm eV}} f_{\rm eff}(m_{\rm DM}, i, z', z)$$

$$f_{\rm eff}(m_{\rm DM}, i, z', z) = \int dE \frac{E}{m_{\rm DM}} \left[2 \frac{dN_{e^+e^-}(i, m_{\rm DM})}{dE} f_{\rm eff}^{e^+e^-}(E, z', z) + \frac{dN_\gamma(i, m_{\rm DM})}{dE} f_{\rm eff}^{\gamma}(E, z', z) \right]$$

Effect of DM annihilation



Extragalactic synchrotron emission due to DM annihilation

- Isotropic spectrum of synchrotron emission

halo mass function

$$1+\frac{\Delta_c}{3\bar{\rho}_{m,0}}\int_{M_{\rm min}}^{\infty} dM\, M\,\frac{dn}{dM}(M,z)\,f[c(M,z)]$$

function of concentration parameter

cosmological boost factor

$$\phi_{\nu}^{\rm syn}(E_{\rm syn},z)=\frac{c(1+z)^2}{4\pi}\frac{\langle\sigma v\rangle\bar{\rho}^2_{\rm DM,0}}{2m^2_{\rm DM}}\int_z^{\infty}dz'\frac{(1+z')^3}{H(z')}\left[B(z',M_{\rm min})-1\right]\frac{dN_{\rm syn}}{dE'_{\rm syn}}(E'_{\rm syn})$$

Hubble function

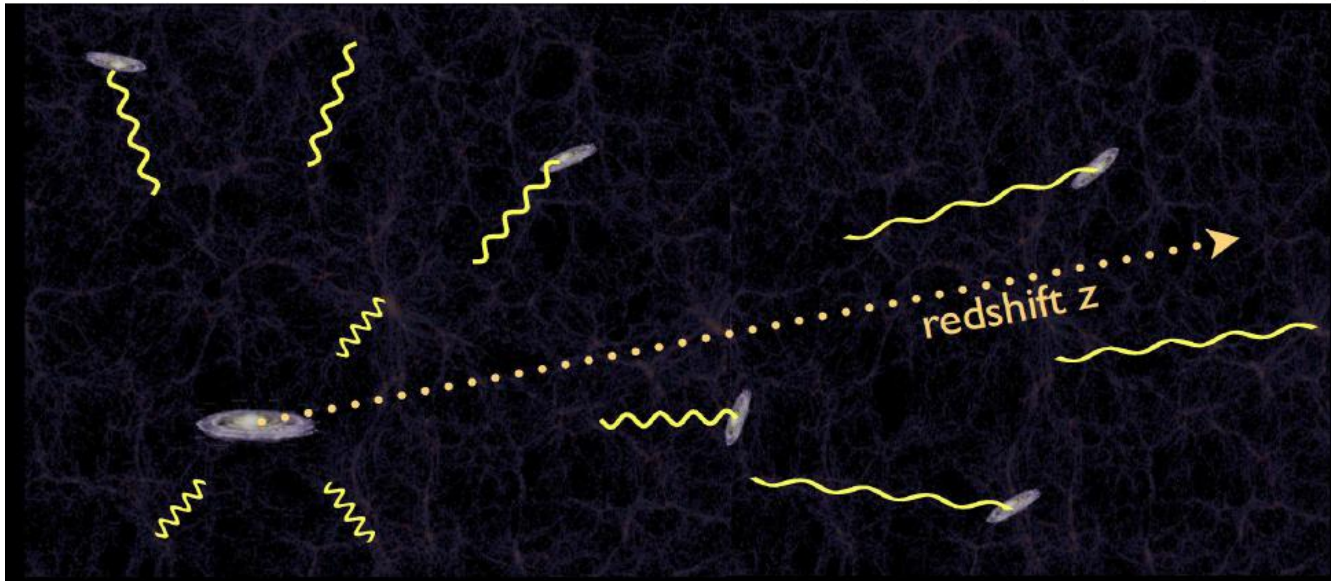
$$H_0\sqrt{\Omega_m(1+z)^3+(1-\Omega_m)}$$

synchrotron radiation spectrum

$$\frac{4\sqrt{3}e^3Bm^2_{\rm DM}}{m_ec^2\langle\sigma v\rangle\rho^2_{\rm DM}}\int_{m_e}^{m_{\rm DM}}dE'\,F(E/E_c)\frac{dN_{e^{\pm}}}{dE}(E')$$

DM injection spectrum

$$\frac{\langle\sigma v\rangle\rho^2_{\rm DM}}{2m^2_{\rm DM}b(\vec{x},E)}\int_E^{m_{\rm DM}}dE'\frac{dN^{\rm inj}_{e^{\pm}}}{dE}(E')$$



- B(z) quickly drop-off at high redshift for massive halo, implies smaller M_{min} is favored.

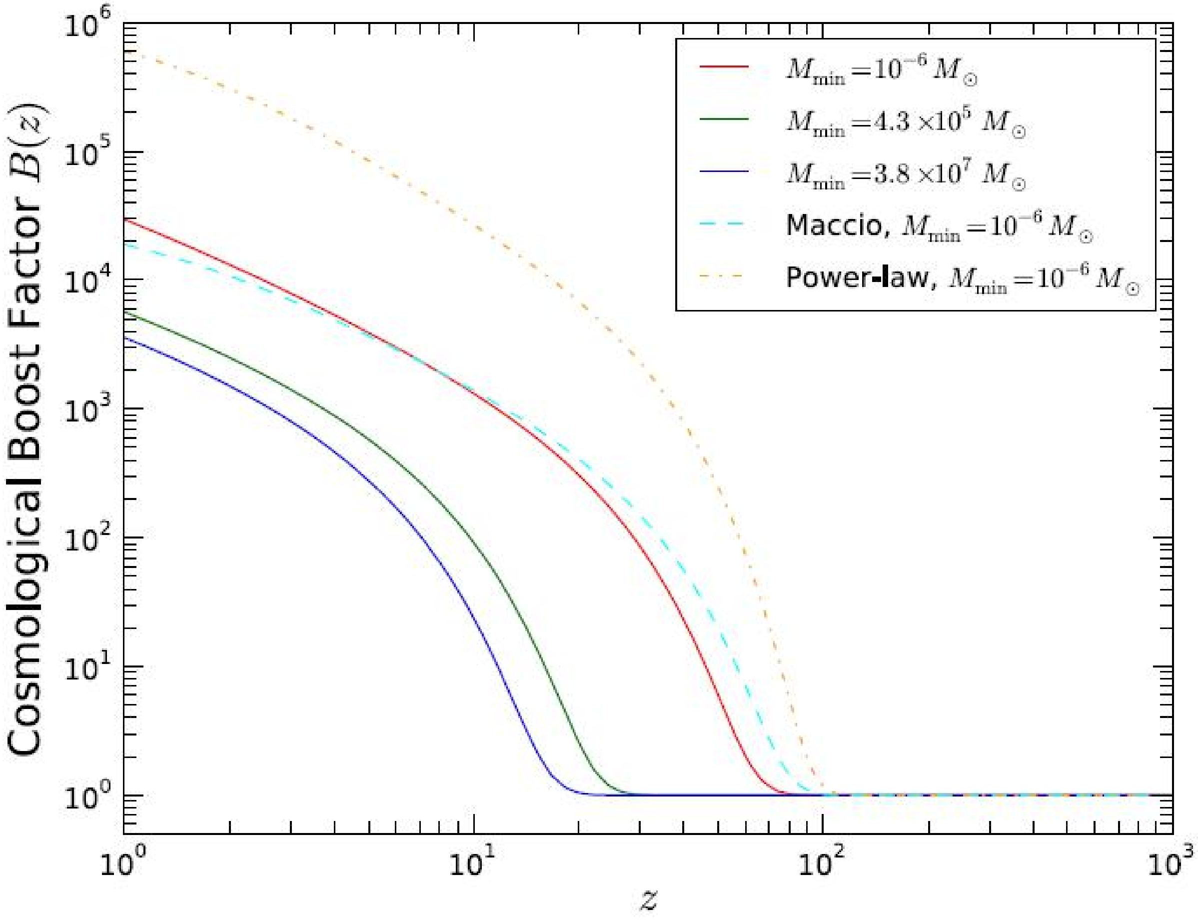
- On the other hand, large B(z) also contributes to DM annihilation.

- Isotropic intensity of radiation background

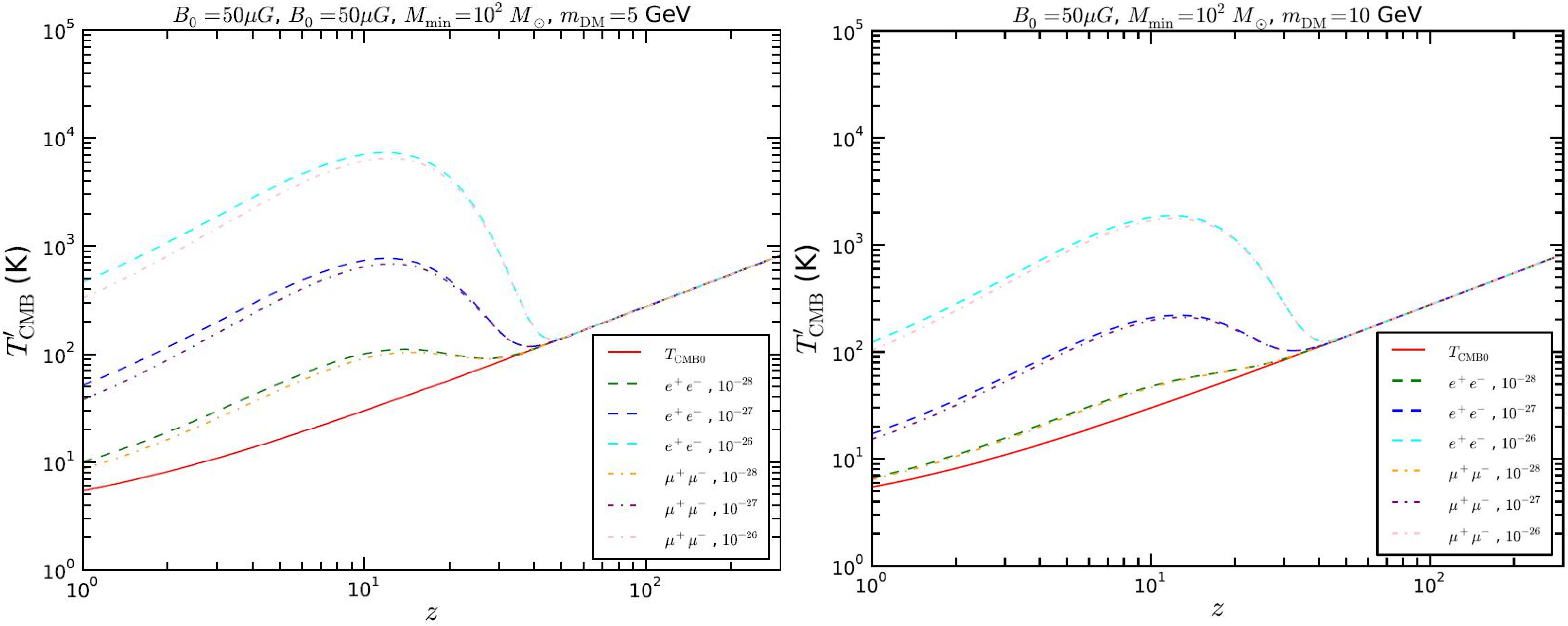
$$I'(\nu, z) \simeq \frac{2\nu^2 k_B}{c^2}[T_{\rm CMB} + T_{\rm syn}(\nu, z)]$$

$$T_{\rm syn}(\nu, z) \equiv \frac{c^2 \phi_\nu^{\rm syn}(\nu,z)}{2\nu k_B}$$

- ARCADE-2 result corresponding to $T_{\rm syn}(\nu, z=0)$



Preliminary results



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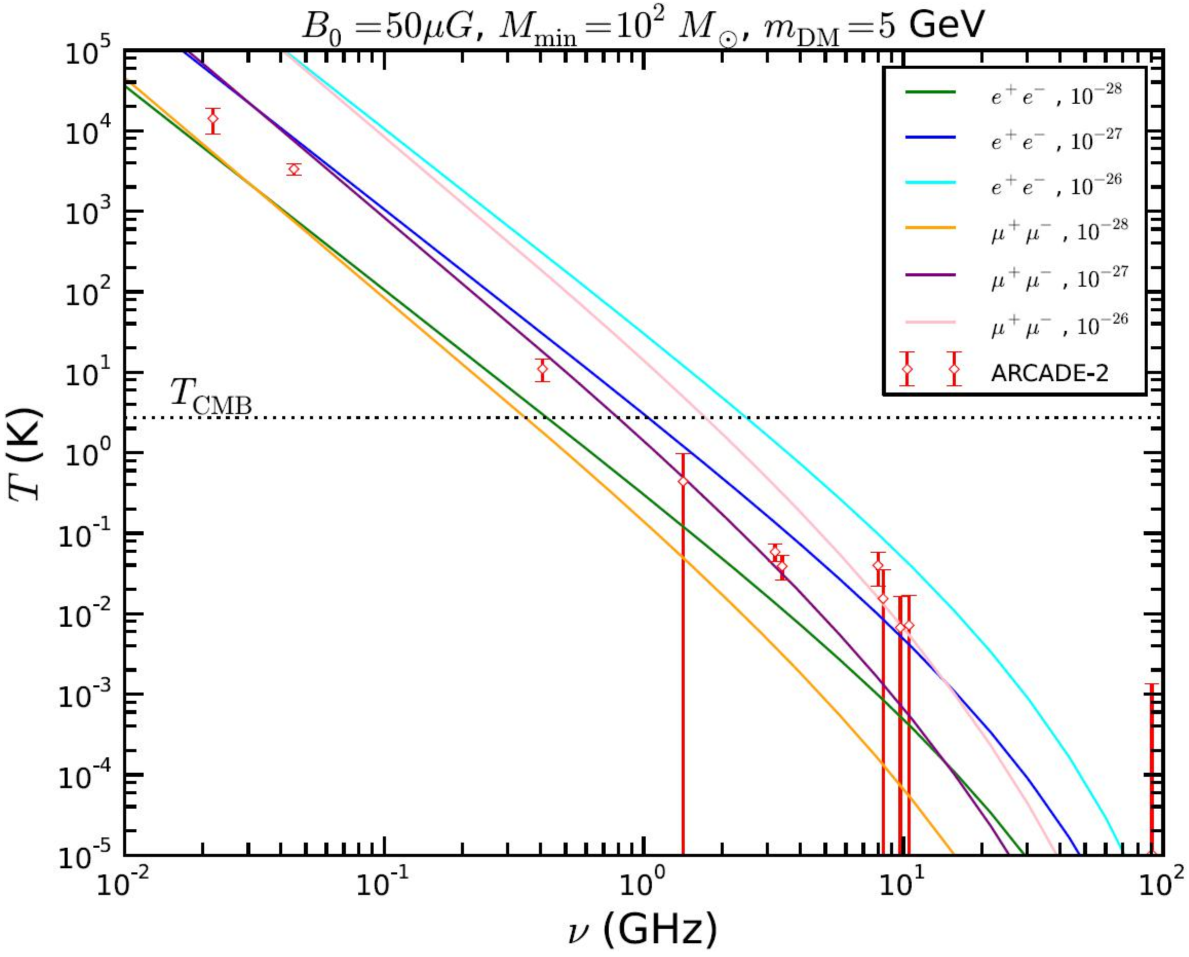

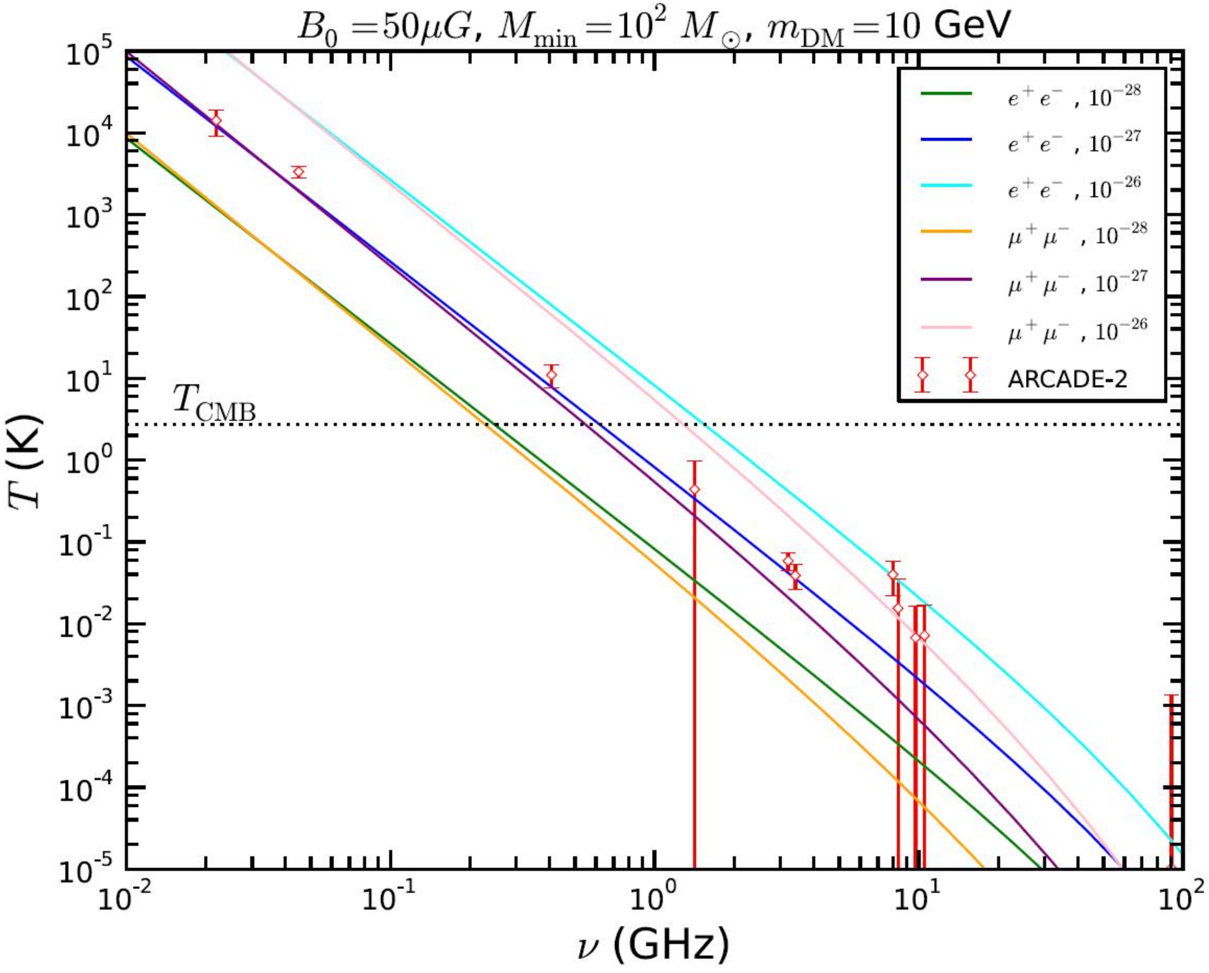

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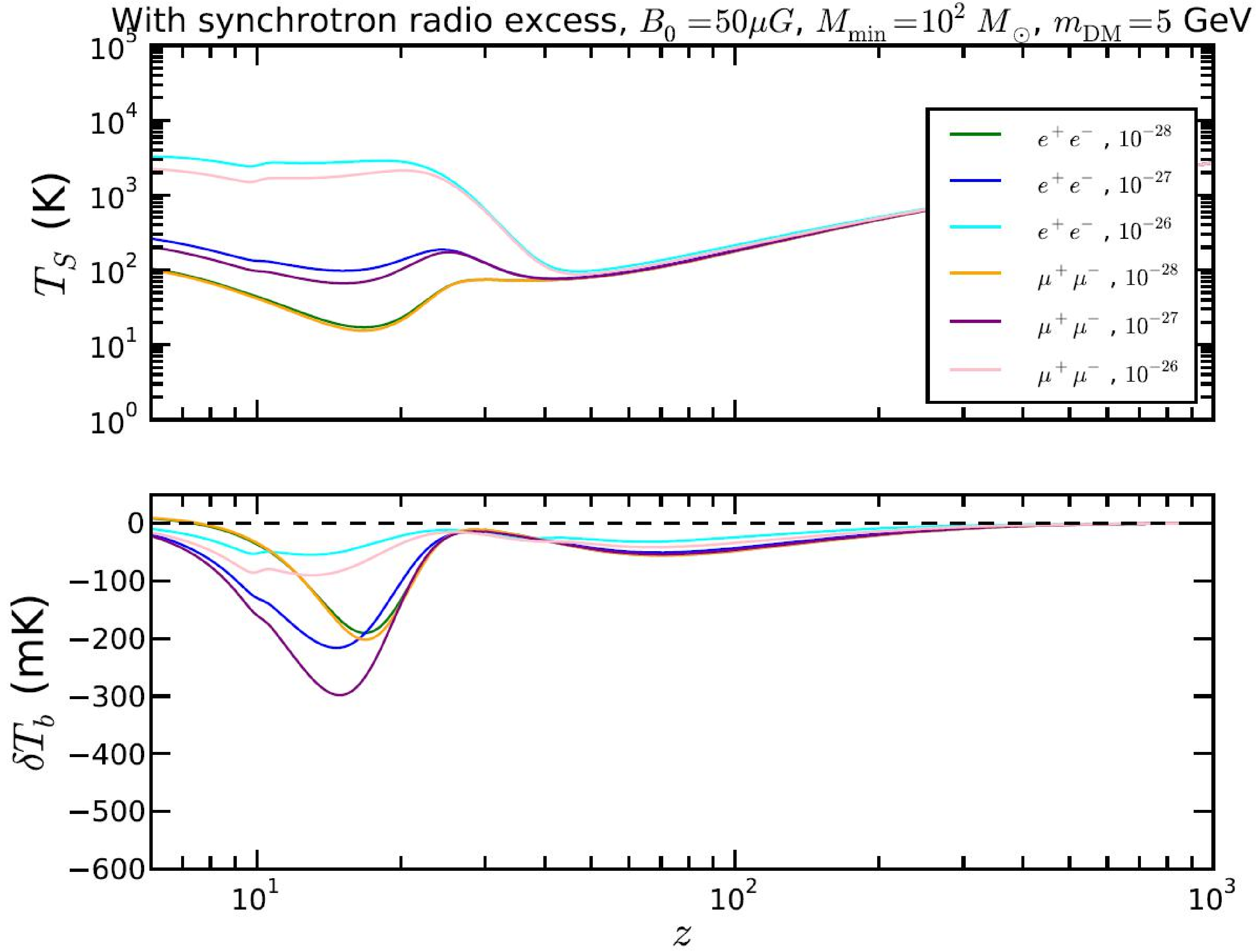
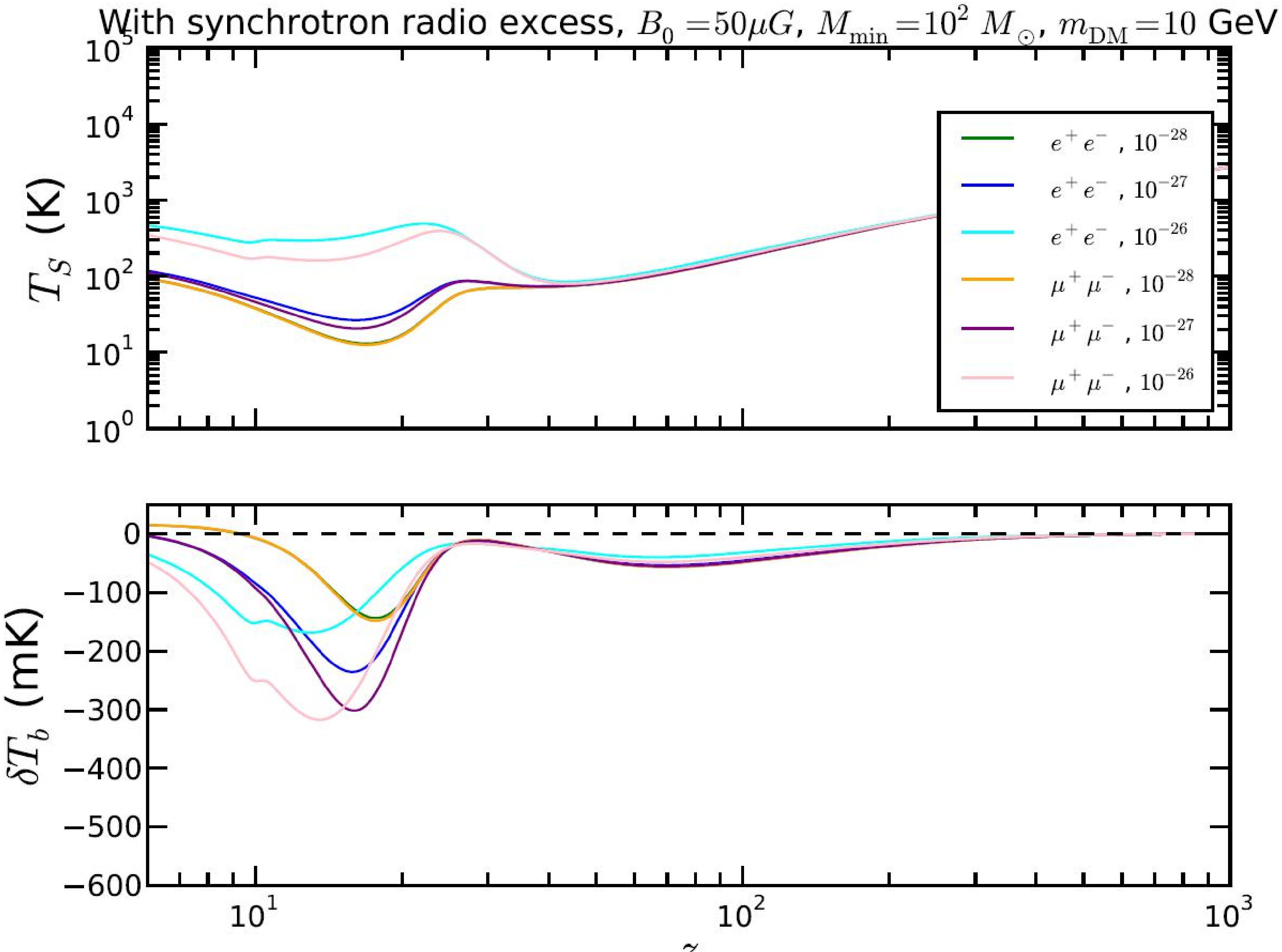
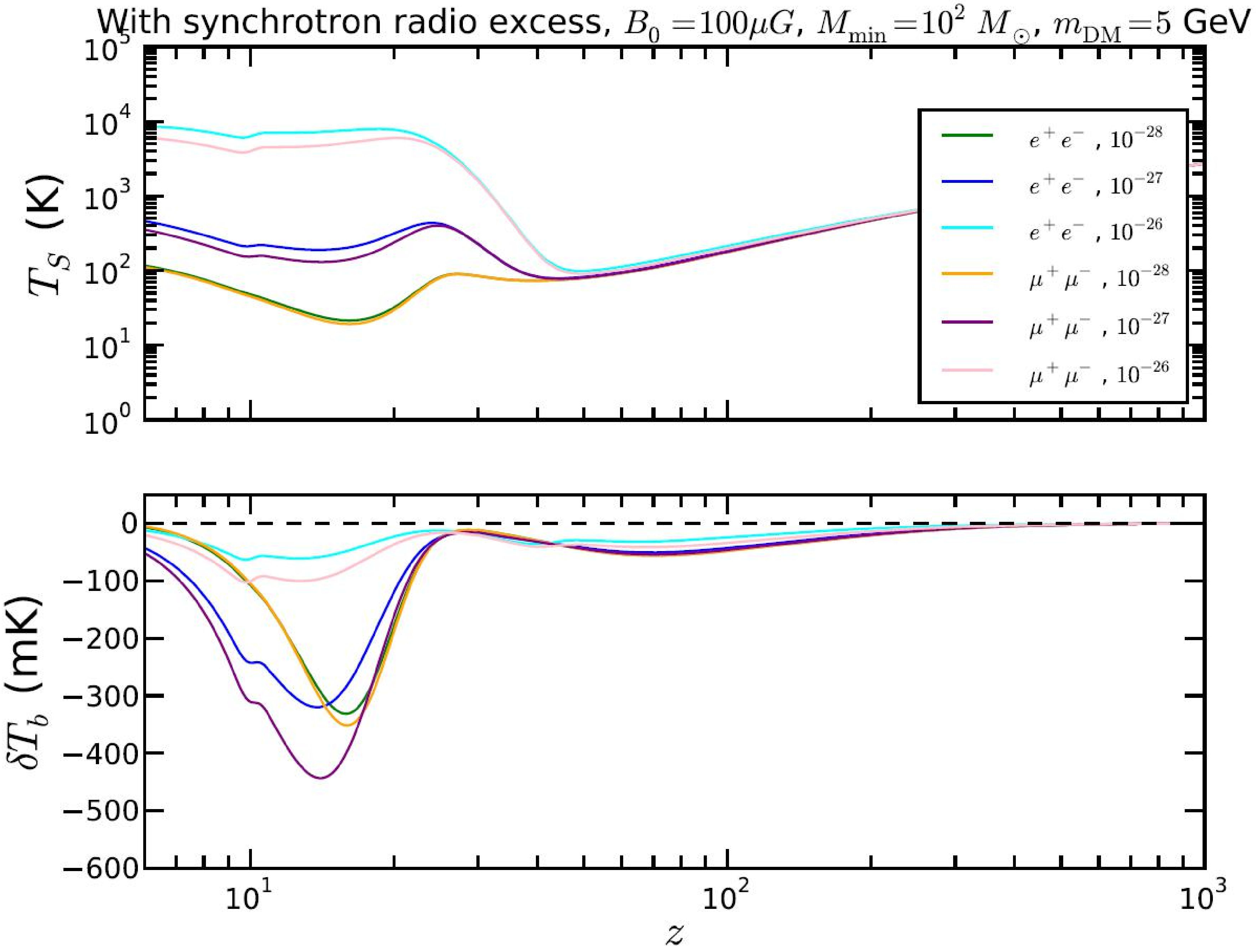
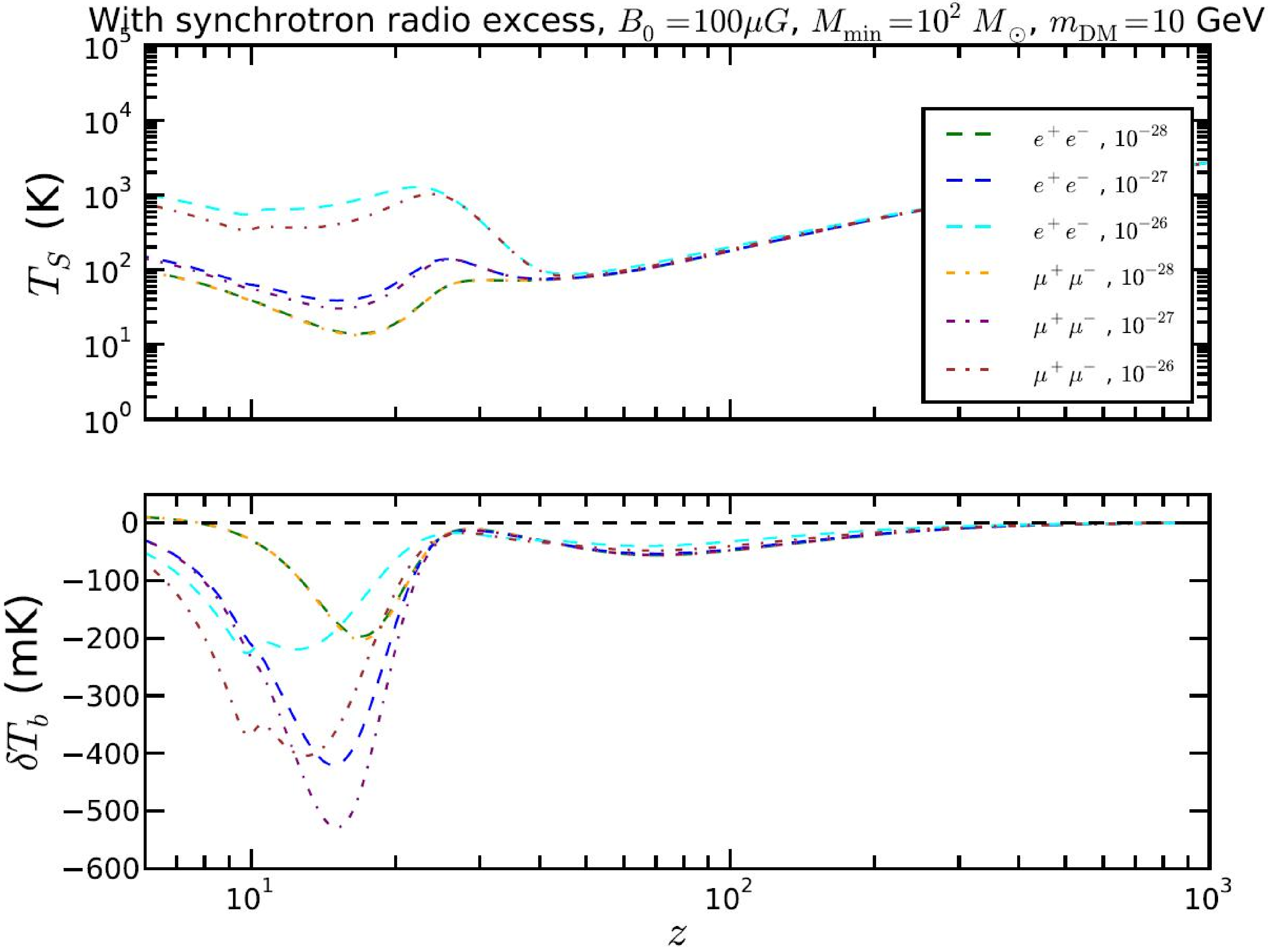



With synchrotron radio excess, $B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 10$ GeV
T_S (K)
10^0
10^1
10^2
10^3
10^4
10^5
e^+e^- , 10^{-28}
e^+e^- , 10^{-27}
e^+e^- , 10^{-26}
$\mu^+\mu^-$, 10^{-28}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
δT_b (mK)
0
−100
−200
−300
−400
−500
−600
10^1
10^2
10^3
z


With synchrotron radio excess, $B_0 = 100\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 5$ GeV
T_S (K)
10^0
10^1
10^2
10^3
10^4
10^5
e^+e^- , 10^{-28}
e^+e^- , 10^{-27}
e^+e^- , 10^{-26}
$\mu^+\mu^-$, 10^{-28}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
δT_b (mK)
0
−100
−200
−300
−400
−500
−600
10^1
10^2
10^3
z

Preliminary results



谢谢大家