A unified interpretation for EDGES 21 cm signal and ARCADE-2 excess

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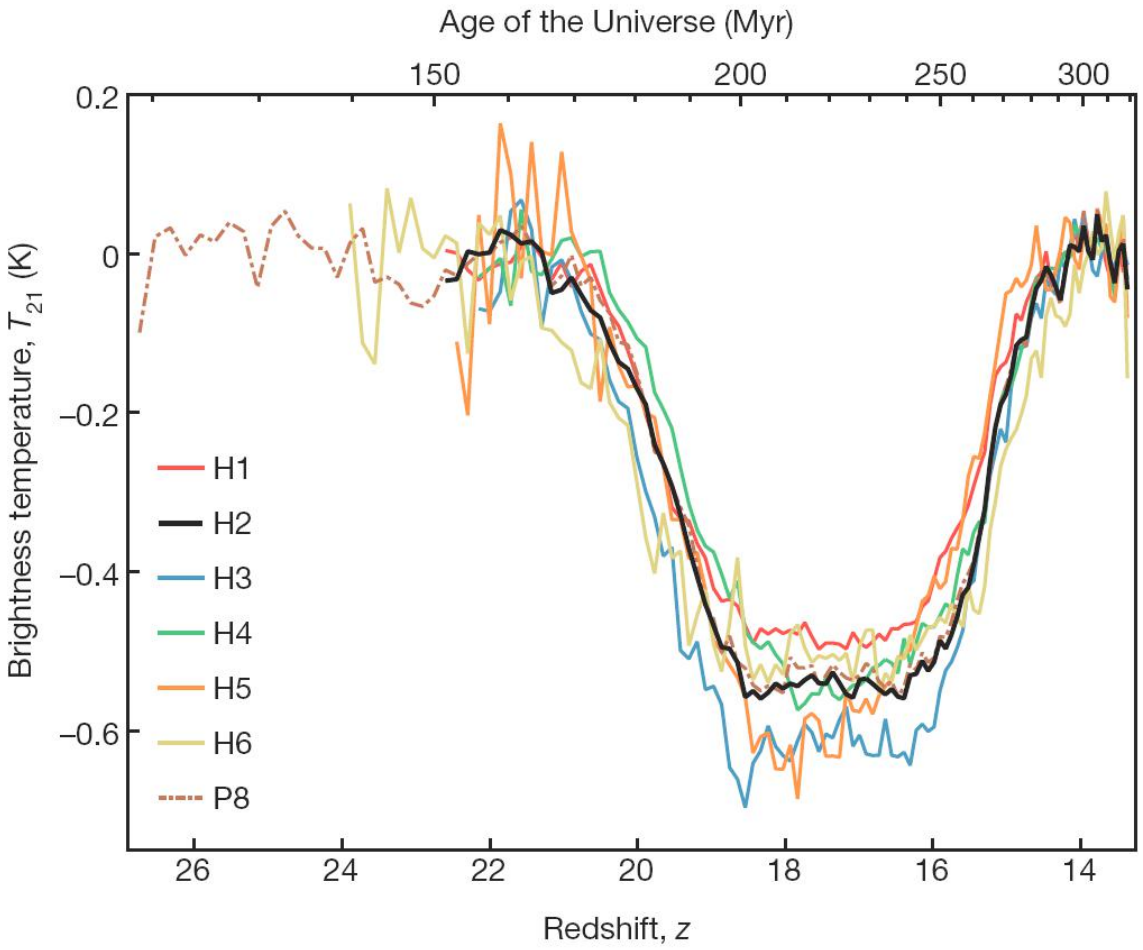
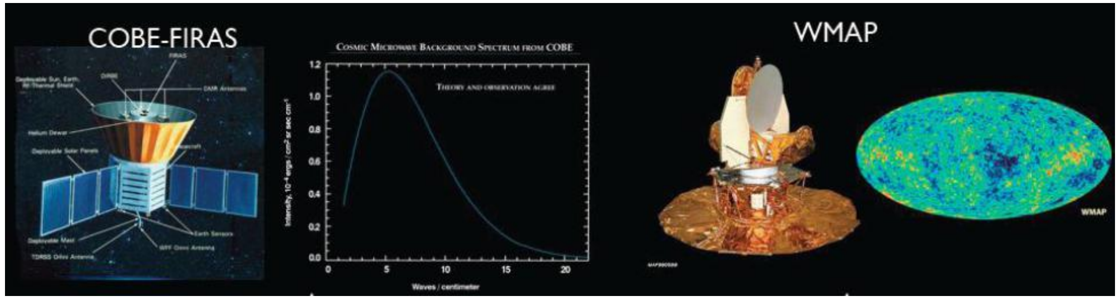
First claim of observation: The EDGES 21cm result

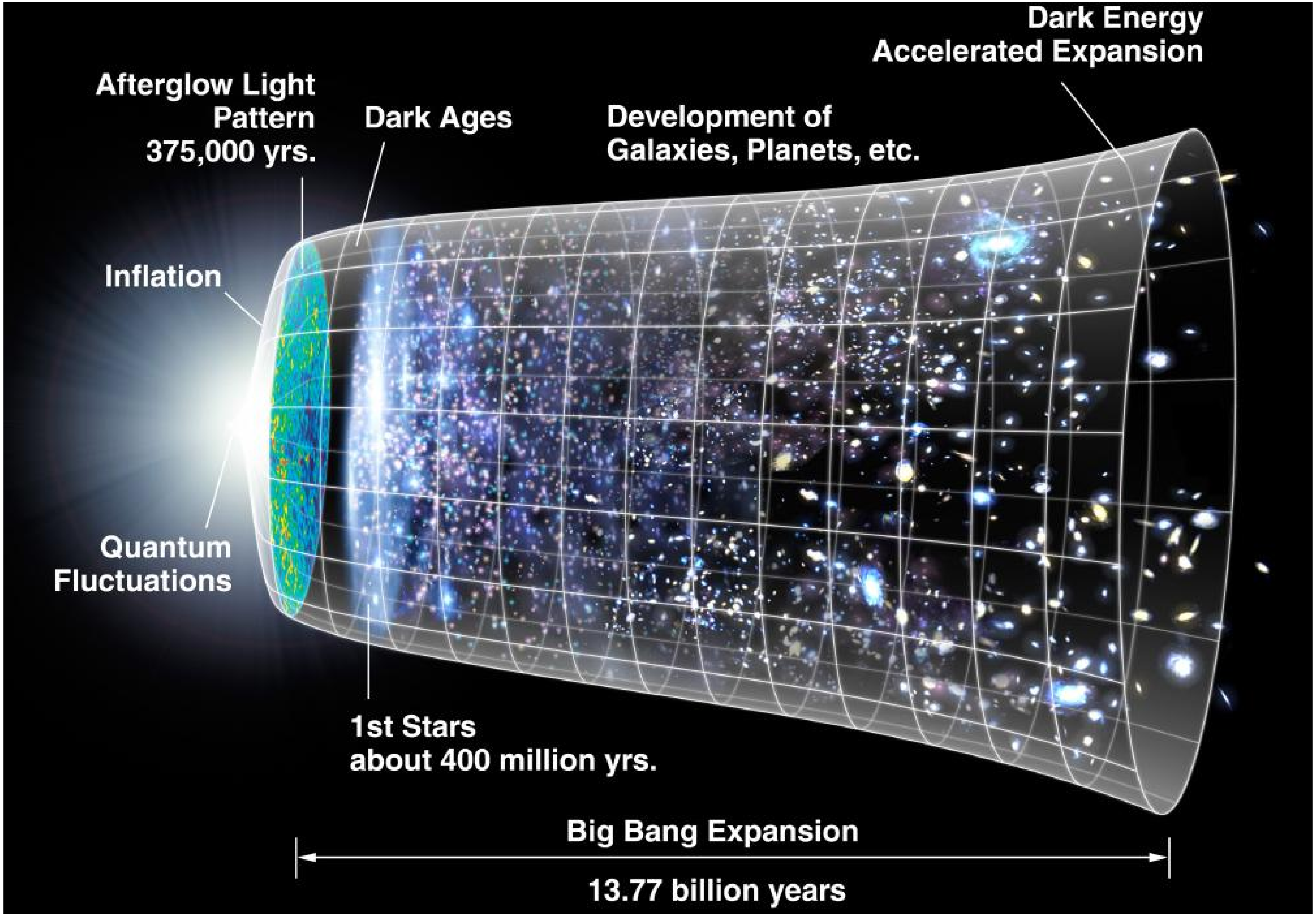
J. Bowman, A. Rogers, R. Monsalve, T. Mozdzen and N. Mahesh, Nature 555, 67 (2018)



- What is EDGES experiment measuring ?
- Global vs fluctuations



Chronology of the Universe



Why we care 21 cm signal

- Dark Ages
  - Period from recombination (~380,000 years) to first star formation (~4 million years) .
  - No light-producing structures such as stars and galaxies.
  - Only two sources of photons:
  - CMB photons (had redshifted out of visible light to infrared) ,
  - 21 cm photons from spin line of neutral hydrogen (microwave range of frequencies).
  - No visible light photons, the universe was truly dark.
  - It is crucial to probe structure formation in the Universe.

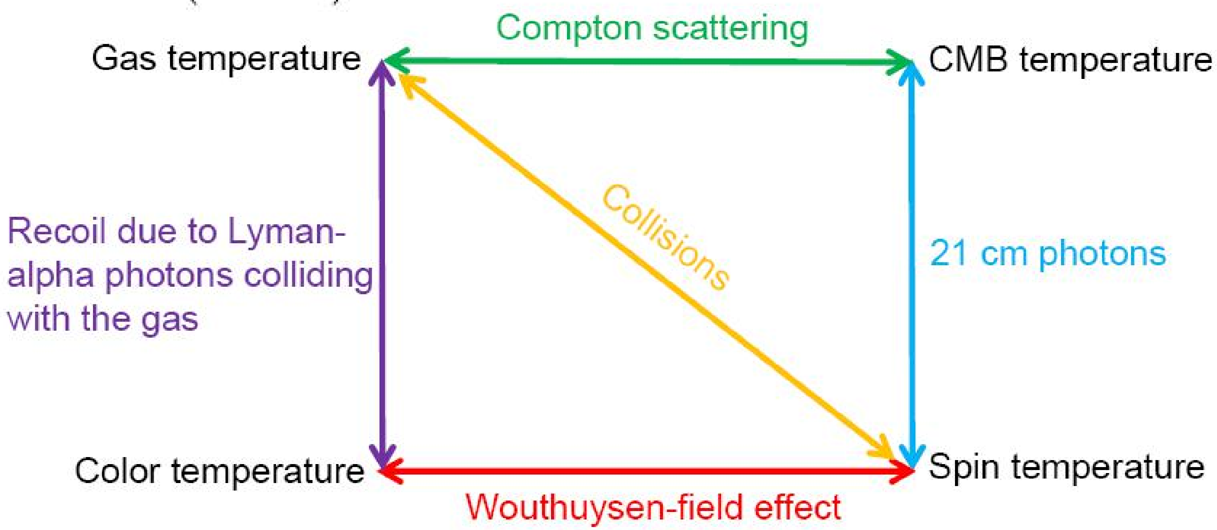
- Spin-flip transition of neutral hydrogen can be used to probe temperature and distribution of the neutral gas in the early universe prior to reionization (z > 6).

Basic picture of global 21 cm signal evolution

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

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

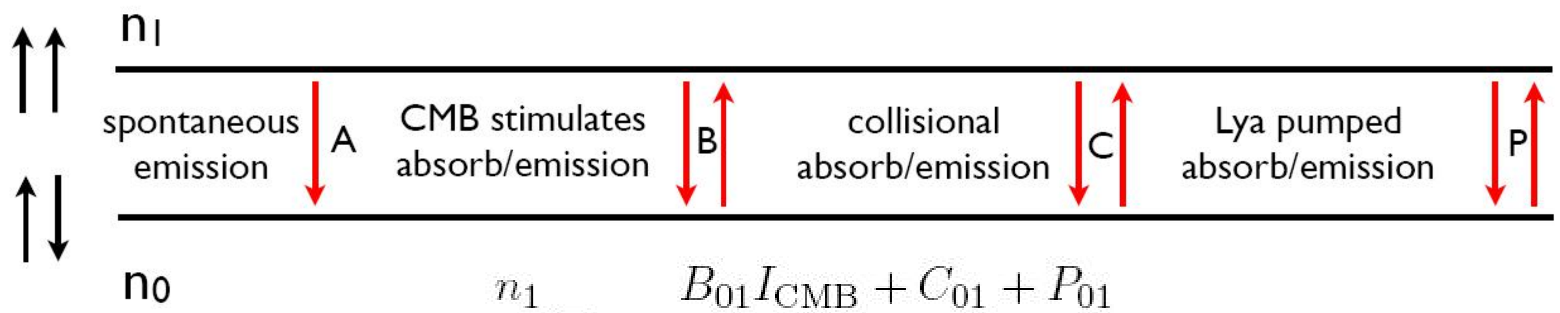
$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T_{\mathrm{CMB}}} - 1}$$



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

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

- Detailed balance implies



$$\frac{n_1}{n_0} = \frac{B_{01} I_{\rm CMB} + C_{01} + P_{01}}{A_{10} + B_{10} I_{\rm CMB} + C_{10} + P_{10}}$$

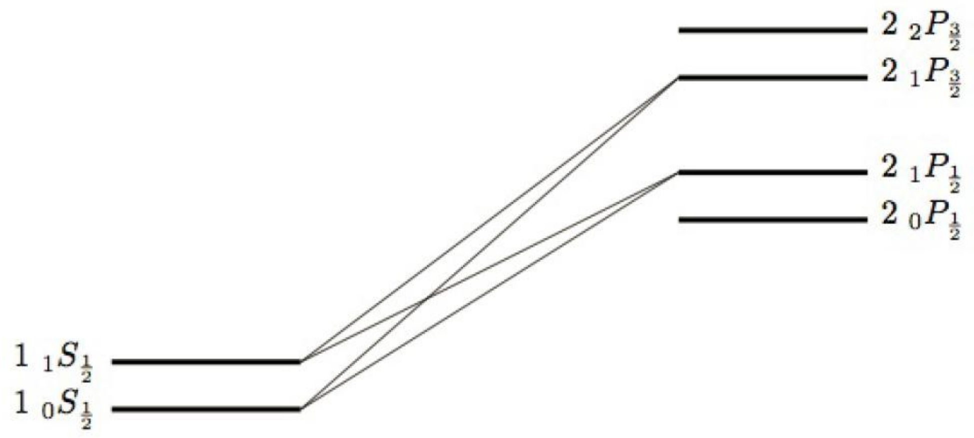
$$\Rightarrow 3\left(1 - \frac{T_*}{T_s}\right) = 3\frac{\frac{T_\gamma}{T_*} A_{10} + \left(1 - \frac{T_*}{T_{\rm gas}}\right) C_{10} + \left(1 - \frac{T_*}{T_\alpha}\right) P_{10}}{\left(1 + \frac{T_\gamma}{T_*}\right) A_{10} + C_{10} + P_{10}}$$

$$\Rightarrow T_s = \frac{T_\gamma + y_c T_{\rm gas} + y_\alpha T_\alpha}{1 + y_c + y_\alpha}.$$

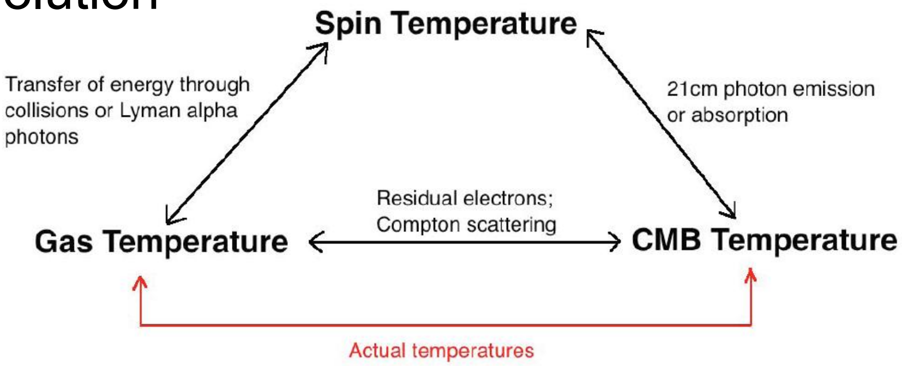
$$y_c = \frac{C_{10}}{A_{10}} \frac{T_*}{T_{\rm gas}}, \quad y_\alpha = \frac{P_{10}}{A_{10}} \frac{T_*}{T_\alpha} \qquad P_{10} \approx 1.3 \times 10^9 J_\alpha(\nu_\alpha, z)$$

- Wouthuysen-Field effect $\quad T_{\rm gas} \simeq T_\alpha, \quad y_\alpha \to y_{{\rm eff},\alpha}$

$$T_s = \frac{T_R(z) + (y_c + y_{{\rm eff},\alpha}) T_{\rm gas}}{1 + y_c + y_{{\rm eff},\alpha}}$$



Phases of the Global 21 cm Signal's Evolution



Phase I: Initially no signal

- Residual electrons drive $T_{gas} = T_{CMB}$ via Compton scattering until z~200,
- Collisions drive $T_{gas} = T_{spin}$,
- If the coupling is strong enough, $T_{spin} = T_{gas} = T_{CMB} \sim a^{-1}$, signal disappears.

Phase II: Absorption

- Collisions maintain T_{gas} and T_{spin} equilibrium,
- CMB has become too dilute to remain T_{gas} and T_{CMB} coupled the gas adiabatic expanded as $T_{gas} \sim a^{-2}$, while $T_{CMB} \sim a^{-1}$, so the gas is cooling faster than the CMB,
- Since collisions keep T_{gas} and T_{spin} coupled， $T_{spin} = T_{gas} \sim a^{-2}$, the gas is a net absorber of 21cm radiation.

Phase III: Back to nothing

- Gas becomes too dilute for collisions to keep T_{gas} and T_{spin} in equilibrium,
- Absorption and emission of 21 cm photons makes $T_{spin} = T_{CMB}$， no net absorption or emission.

Phase IV: First Stars and Galaxies Form

- First stars create Ly-photons which have the right energy to cause the hyperfine transition.This causes coupling between T_{gas} and T_{spin} via the Wouthuysen-Field effect.
- $T_{spin} = T_{gas} < T_{CMB}$,absorption.

Phase V: X-ray reheating

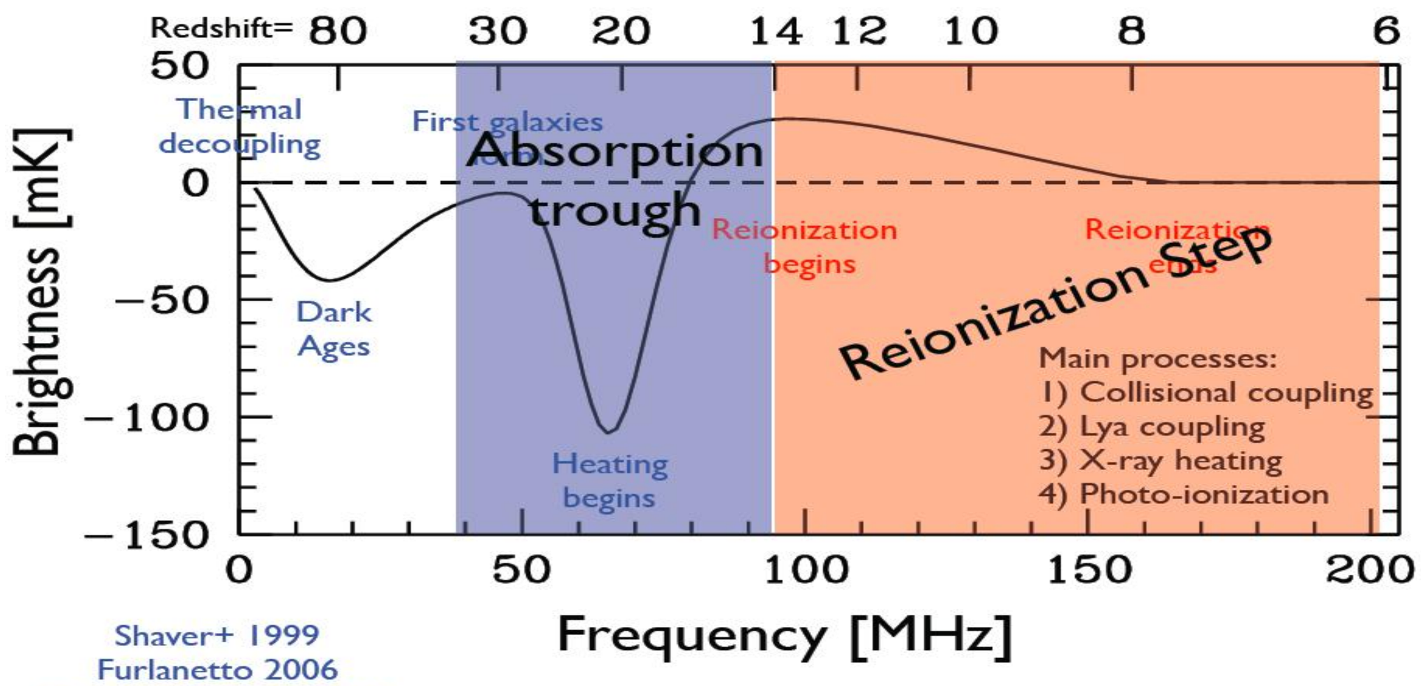
- X-rays from early stars heat the IGM, T_{gas} is still coupled to T_{spin} because of the Wouthuysen-Field effect.
- Electrons undergo all sorts of atomic transitions, $T_{spin} = T_{gas} > T_{CMB}$,emission.

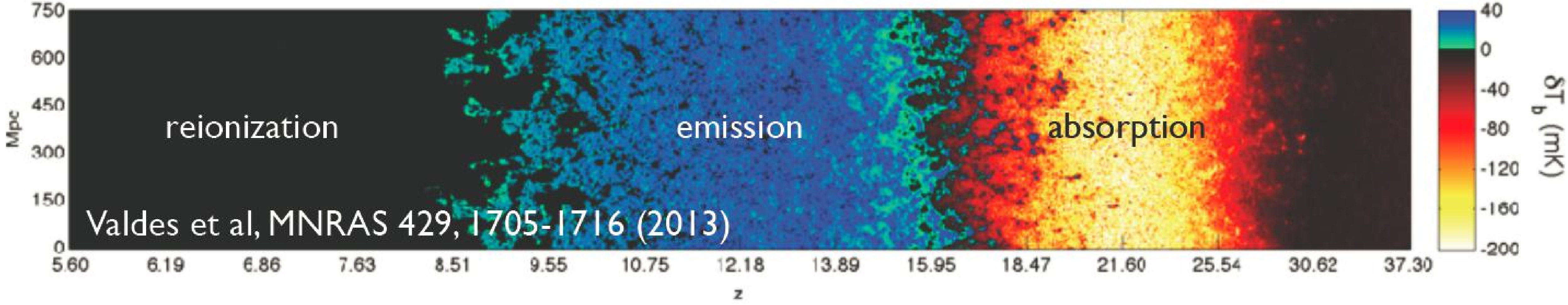
Phase VI: Reionization

- No more signal, since the the signal disappears when the neutral hydrogen disappears

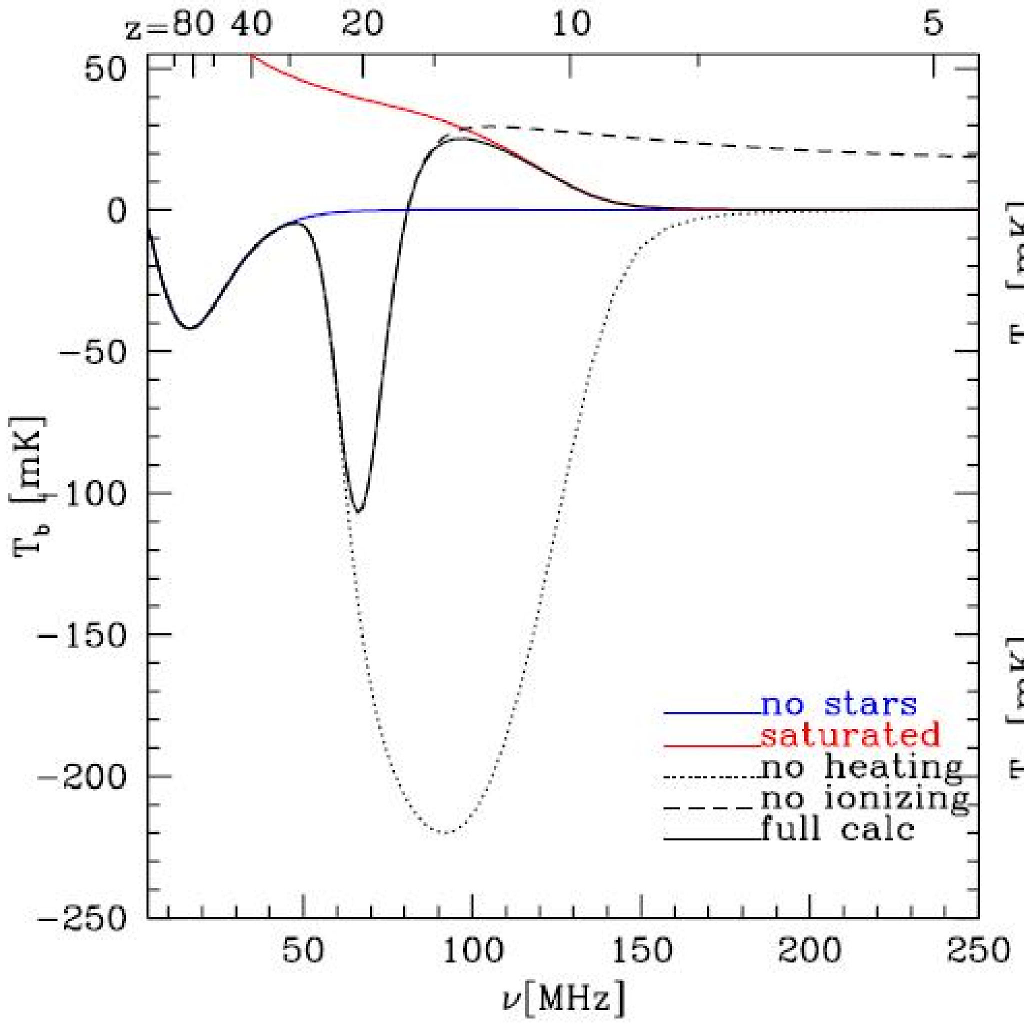
- Observable signal : brightness temperature

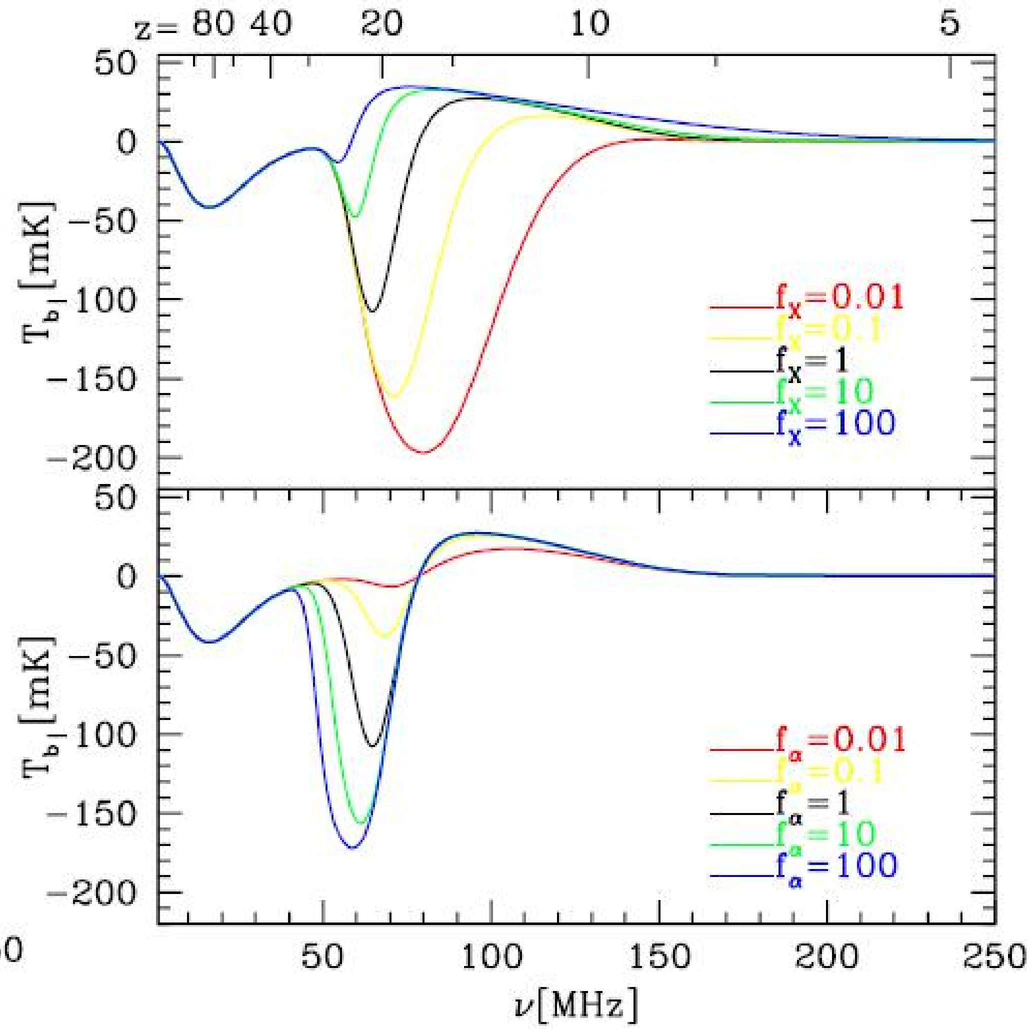
$$\delta T_b(z) \approx 27 x_{\rm HI}(z)(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_R(z)}{T_s(z)}\right)\ \mathrm{mK}$$





- Do we have all the physics?
- What do first galaxies look like?

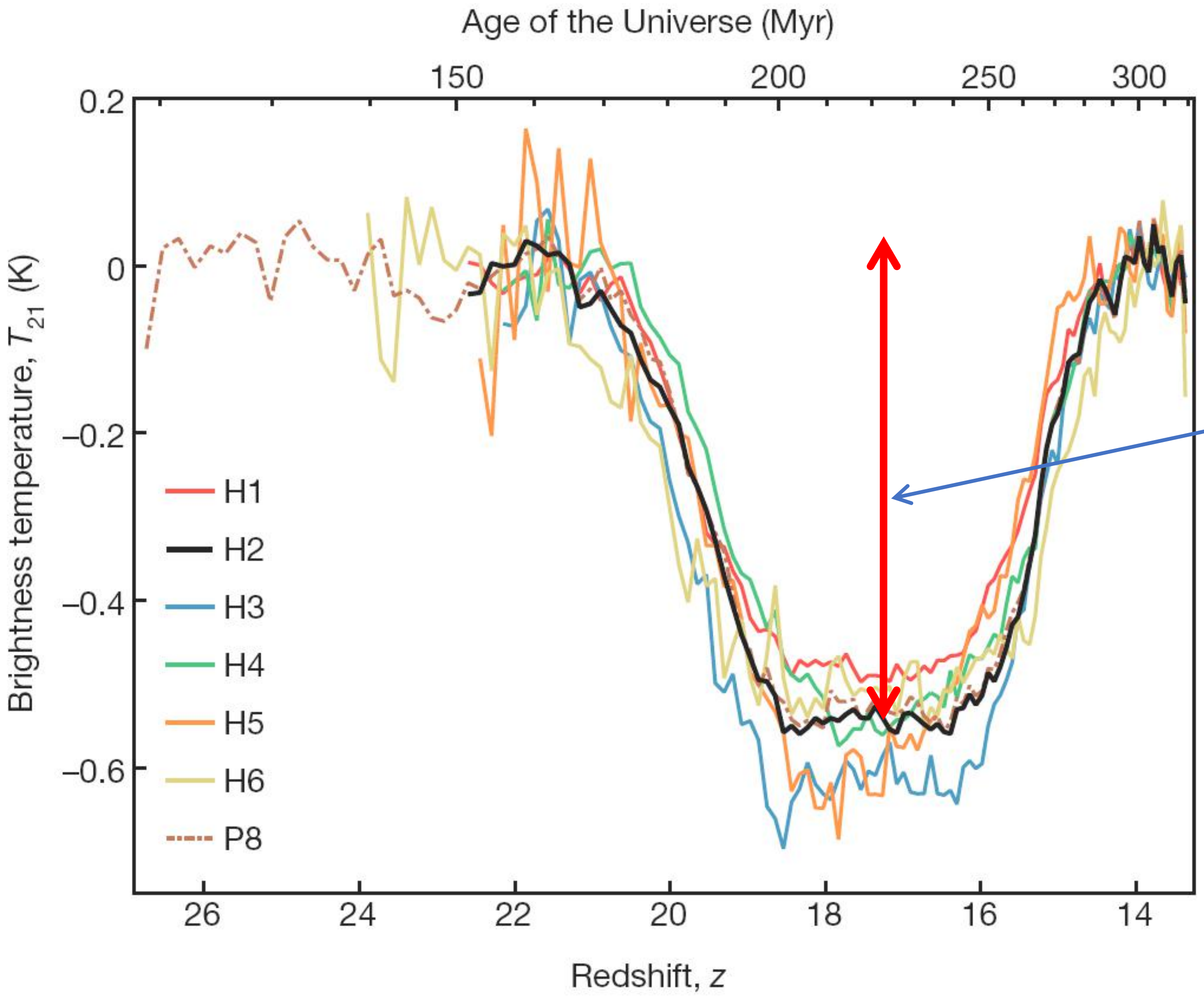




Pritchard & Loeb 2010

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

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



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

The discrepancy between data and fiducial prediction

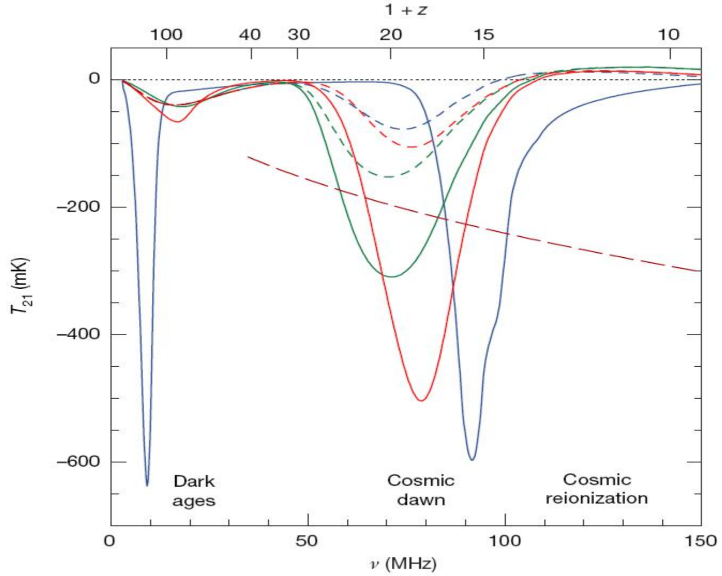
- If T_R is taken to be the CMB temperature, this gives $T_{gas} < 5.2$ K
- But assuming standard decoupling and no stellar heating, one gets T_{gas} ~7 K
- It is possible due to instrumental effects and/or unappropriate recast of foregrounds.

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

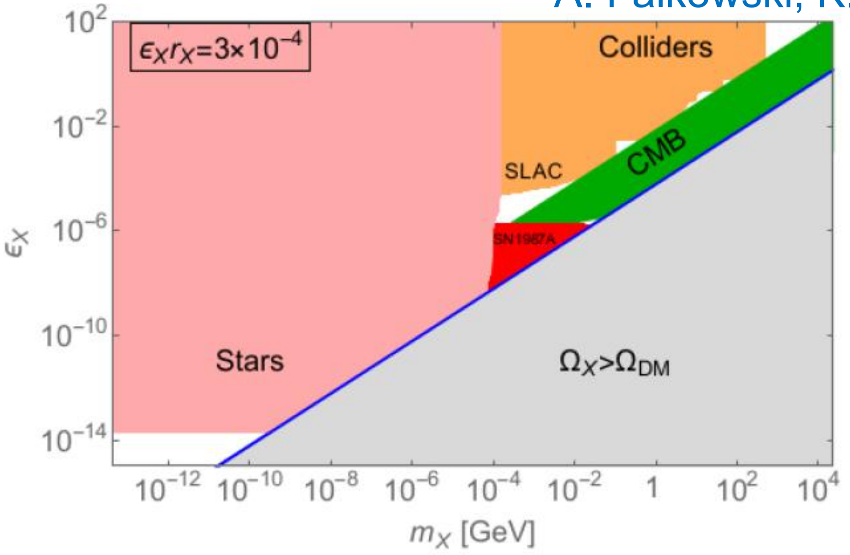
- Recipe I: “Heating the CMB”,introducing new radiation backgrounds [Feng and Holder 1802.07432], which could arise from either novel astrophysics, i.e. radio emission from early black holes [Ewall-Wice et al 1803.01815] or from more exotic sources [Fraser et al 1803.03245, Pospelov et al 1803.07048].
- Recipe II: “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]
- Recipe III: “Changing the cosmology ”,

Cooling the gas

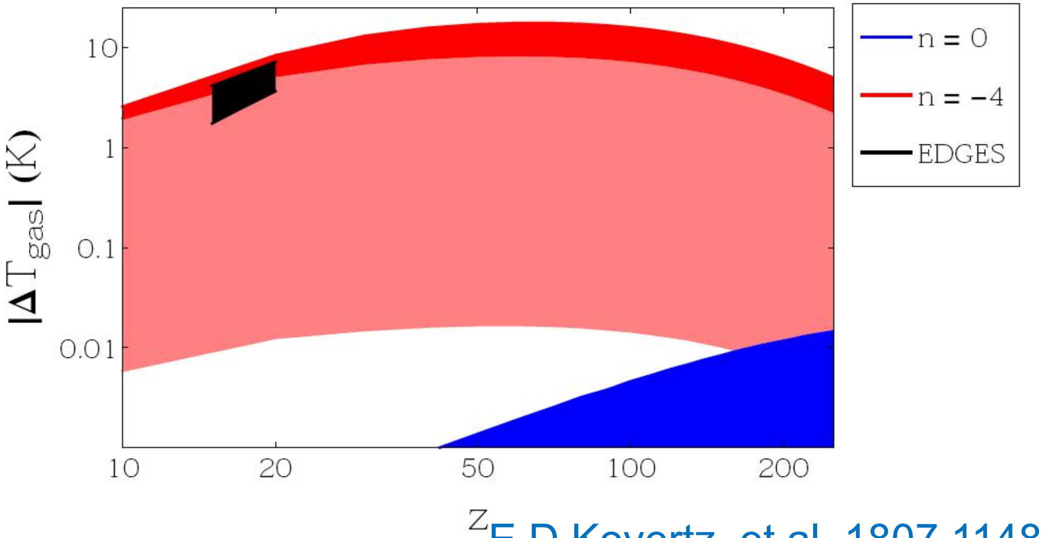
R. Barkana, Nature 555, no. 7694, 71 (2018) [arXiv:1803.06698 [astro-ph.CO]].



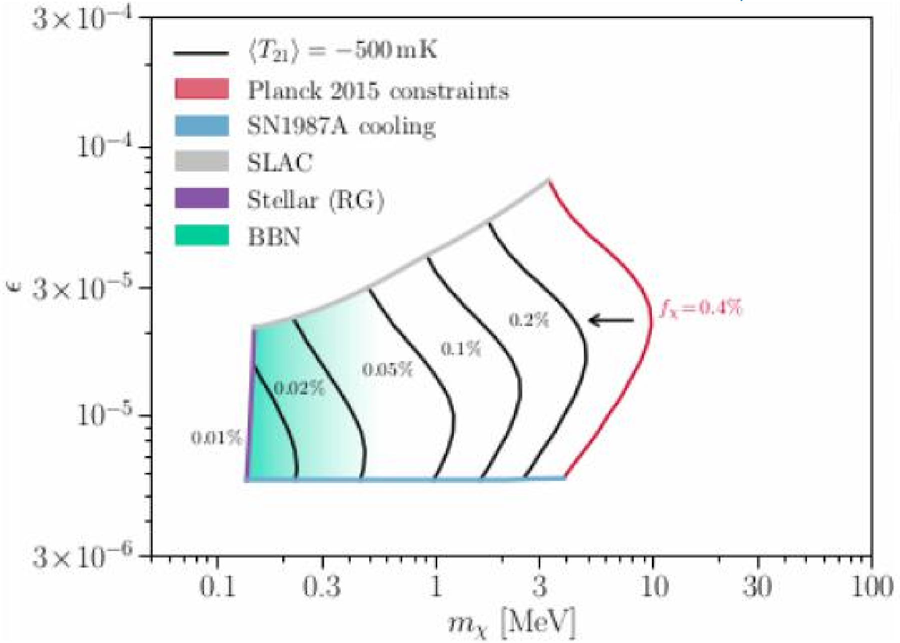
A. Falkowski, K. Petraki, 1803.10096



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

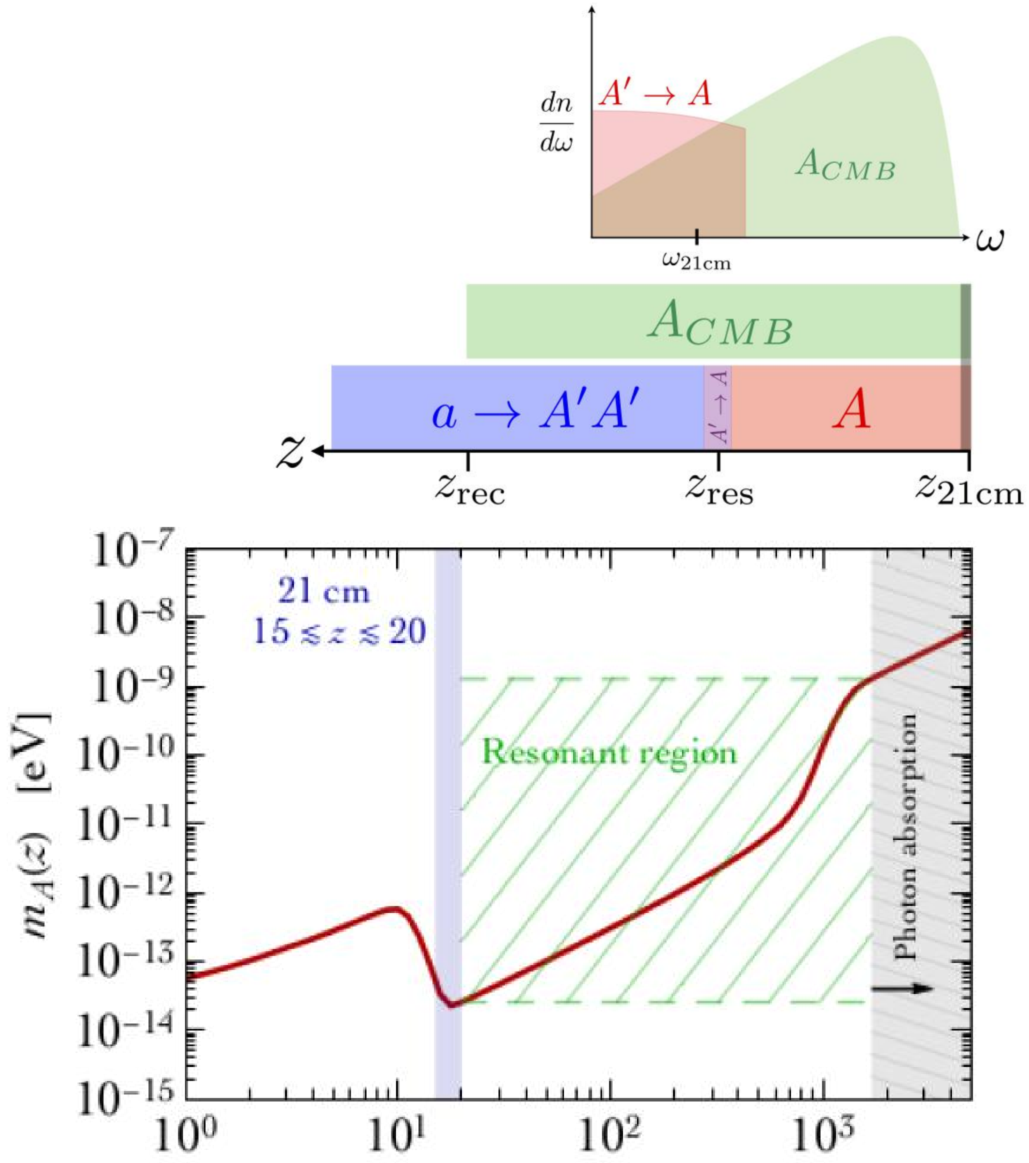


E.D.Kovertz, et.al. 1807.11482

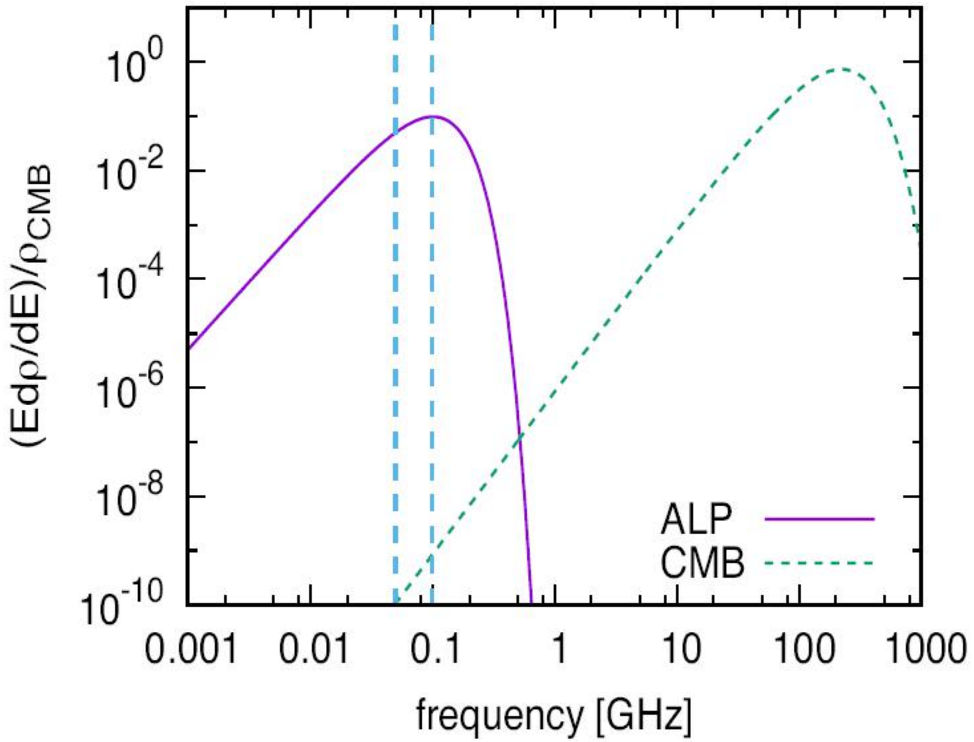


Heating the CMB

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



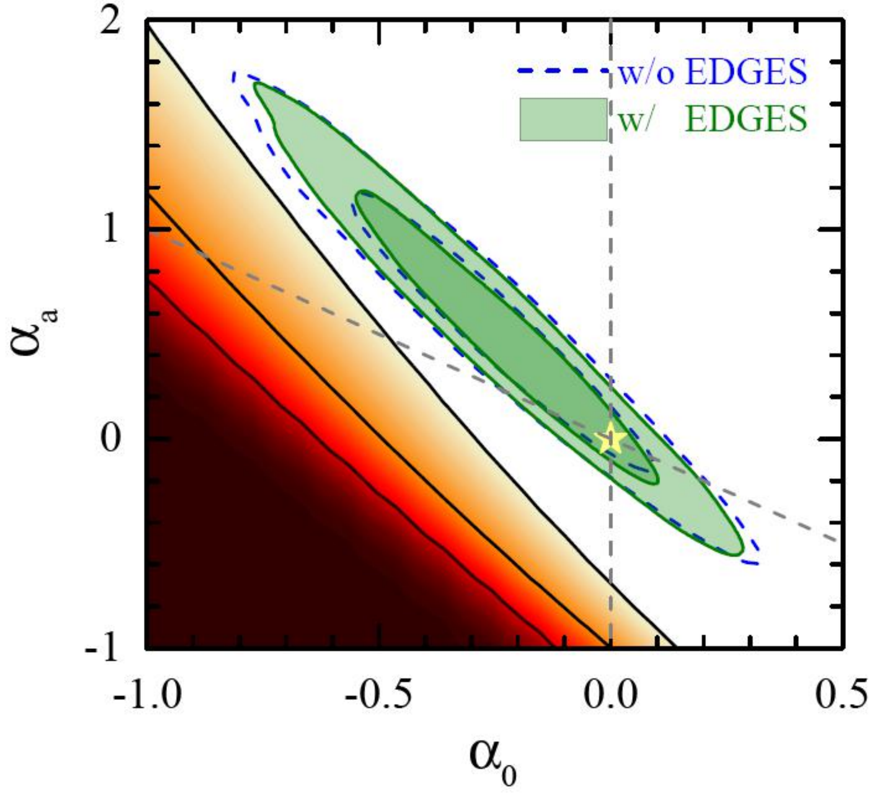
T. Moroi, K. Nakayama and Y. Tang, Phys.Lett.B 783, 301 (2018)



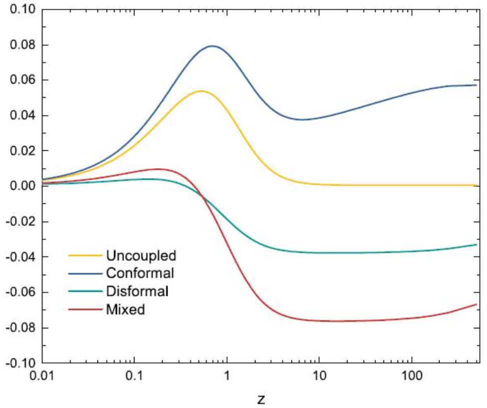
Changing the cosmology

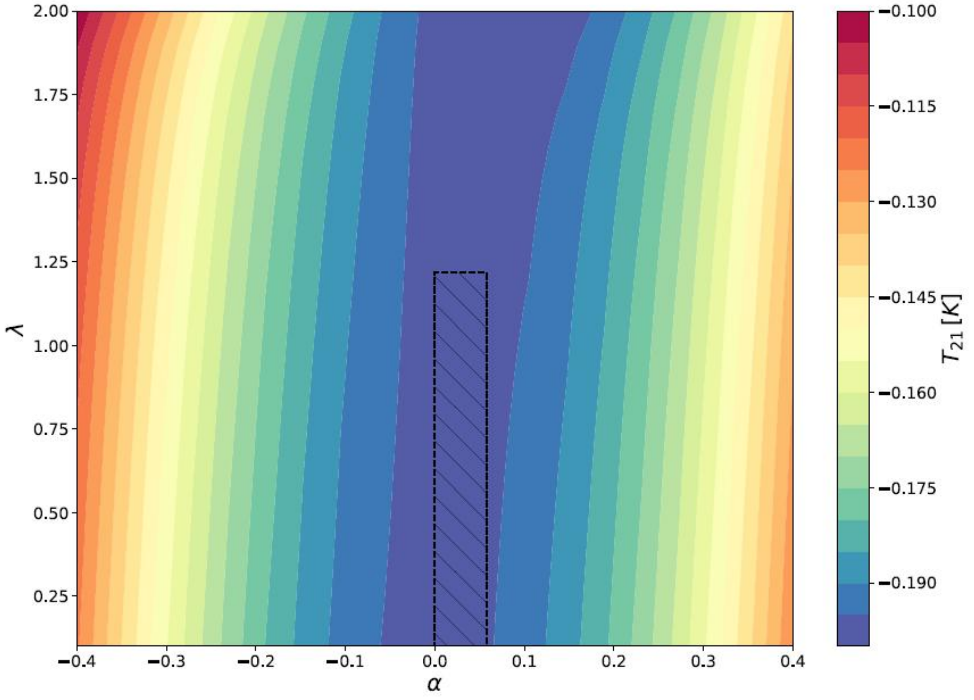
- Modified cosmology/Friedmann equation, thus for H(z)
- New interactions betwwen DE and DM (difficult to realize in particle physics)

Y.Wang G-B. Zhao, 1805.11210



L-F Xiao, R.An, L.Zhang , B.Yue, Y-D Xu B. Wang, 1807.05541



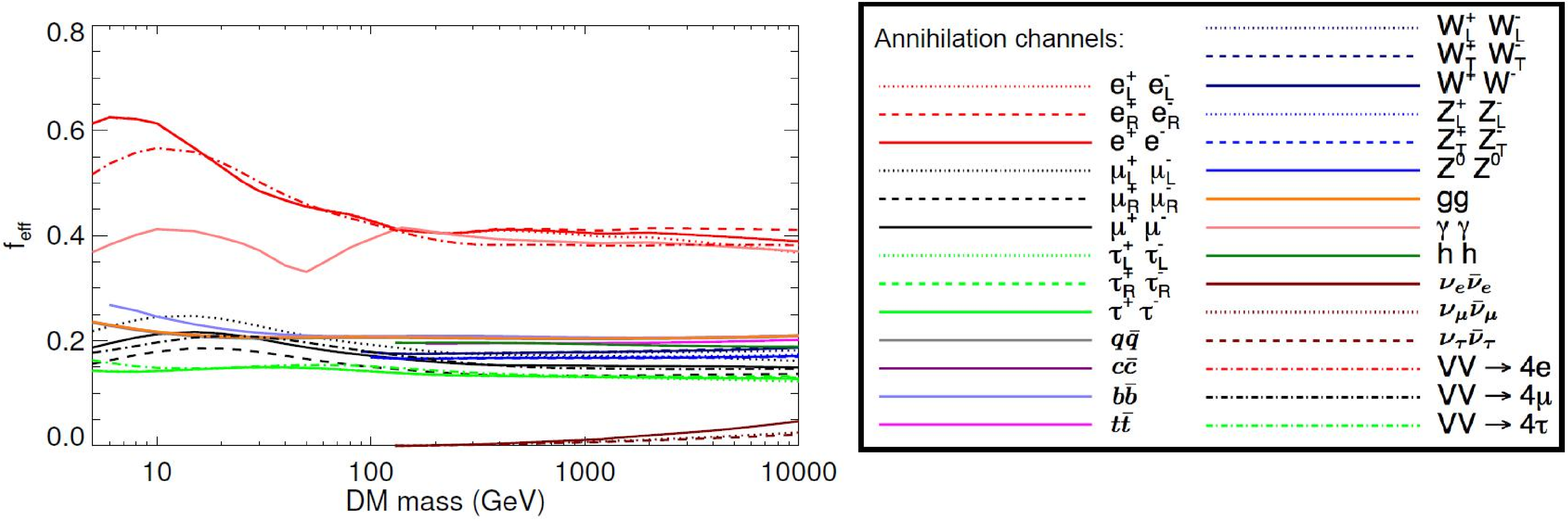


DM annihilation /decay

- Injection of energy into intergalactic gas suppress 21cm absorption signal.
- The observation of any 21cm absorption signal thus impose an upper limit on cross secton/lifetime.
- DM annihilation /decay during the cosmic dark ages cause additional ionization of the hydrogen gas.
- Resulting free electrons scatter the CMB photons and modify the measured anisotropies of the CMB.
- Three ingredients to calculate this effect:
  - The spectrum of stable electromagnetically interacting particles produced by DM annihilation /decay and their redshift dependence of the energy injection.
  - Calculating the cooling and energy losing of these electromagnetically interacting particles, the fraction of their energy converted into IGM and the duration of cooling process.
  - Calculating the modification of ionization history due to these extra ionizing energy, and their effects on the anisotropies of the CMB.

- Primarily depending on how much of the injected power deposits into electromagnetically interacting particles.
- Secondly depending on the spectrum of the injected electrons, positrons and photons.

T. R. Slatyer, [arXiv:1506.03811,1506.03812].



● The observation of 21cm signal as an upper limit

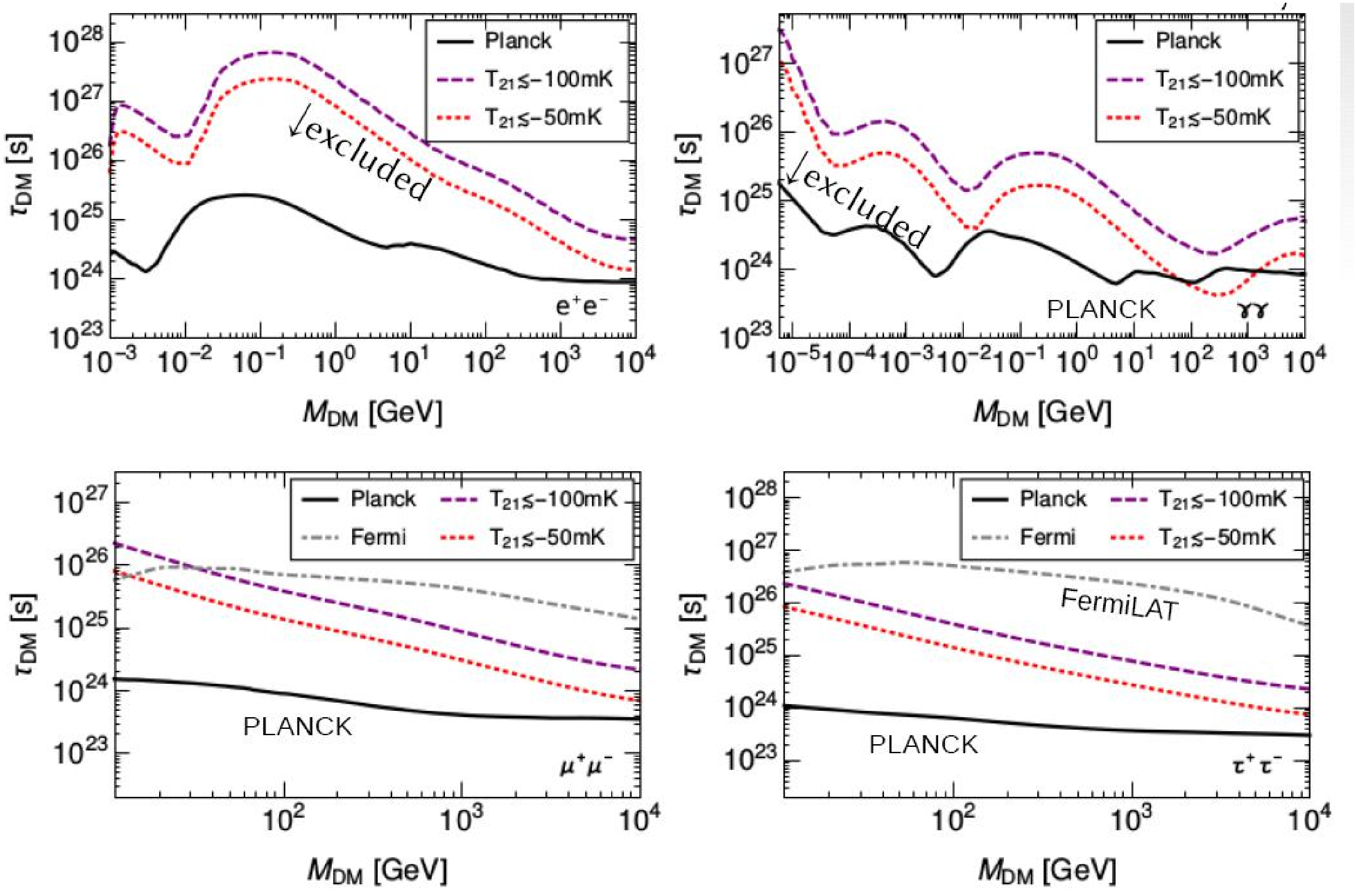
On DM annihilation: by requiring injection induced ΔT_{21} < +100 or +150 mK

G. D′ Amico, P. Panci, A. Strumia 1803.03629

K. Cheung J-L Kuo, K-W Ng Yue-Lin S. Tsai,arXiv:1803.09398

S.Clark, B.Dutta, Y.Gao, Y.-Z.Ma, L.E.Strigari, 1803.09390

H. Liu and T. R. Slatyer, arXiv:1803.09739



A unified interpretation for the EDGES anomaly and ARCADE-2 excess

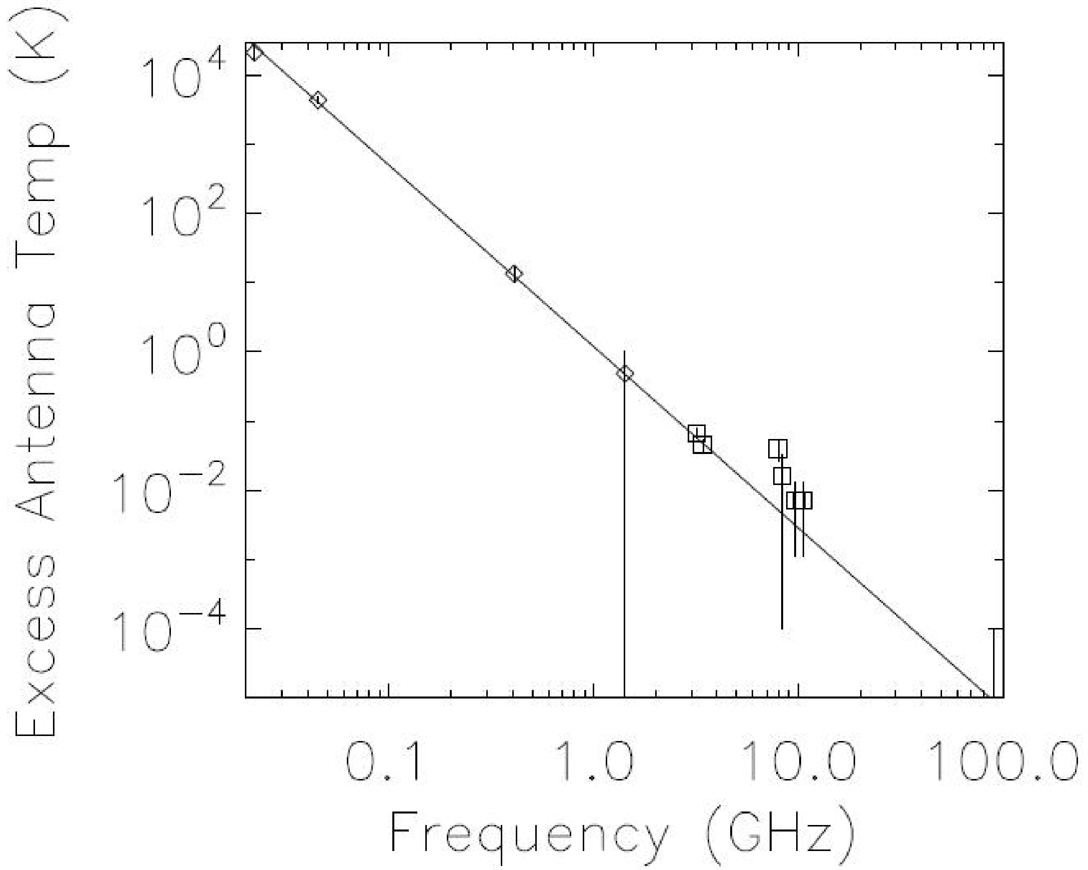
- Recipe I: requiring $\sigma \sim v^{-4}$ scattering between sub-GeV DM and baryons in order to cool the gas enough,without violating CMB bounds.
- Recipe II: requiring ultra-light axion-like particle/dark photon with tiny mixing with photon in order to create sufficient new radiation backgrounds.
- Both above recipes potentially conflict with the WIMP scenario.
- Can we interpret EDGES result within conventional WIMP framework?

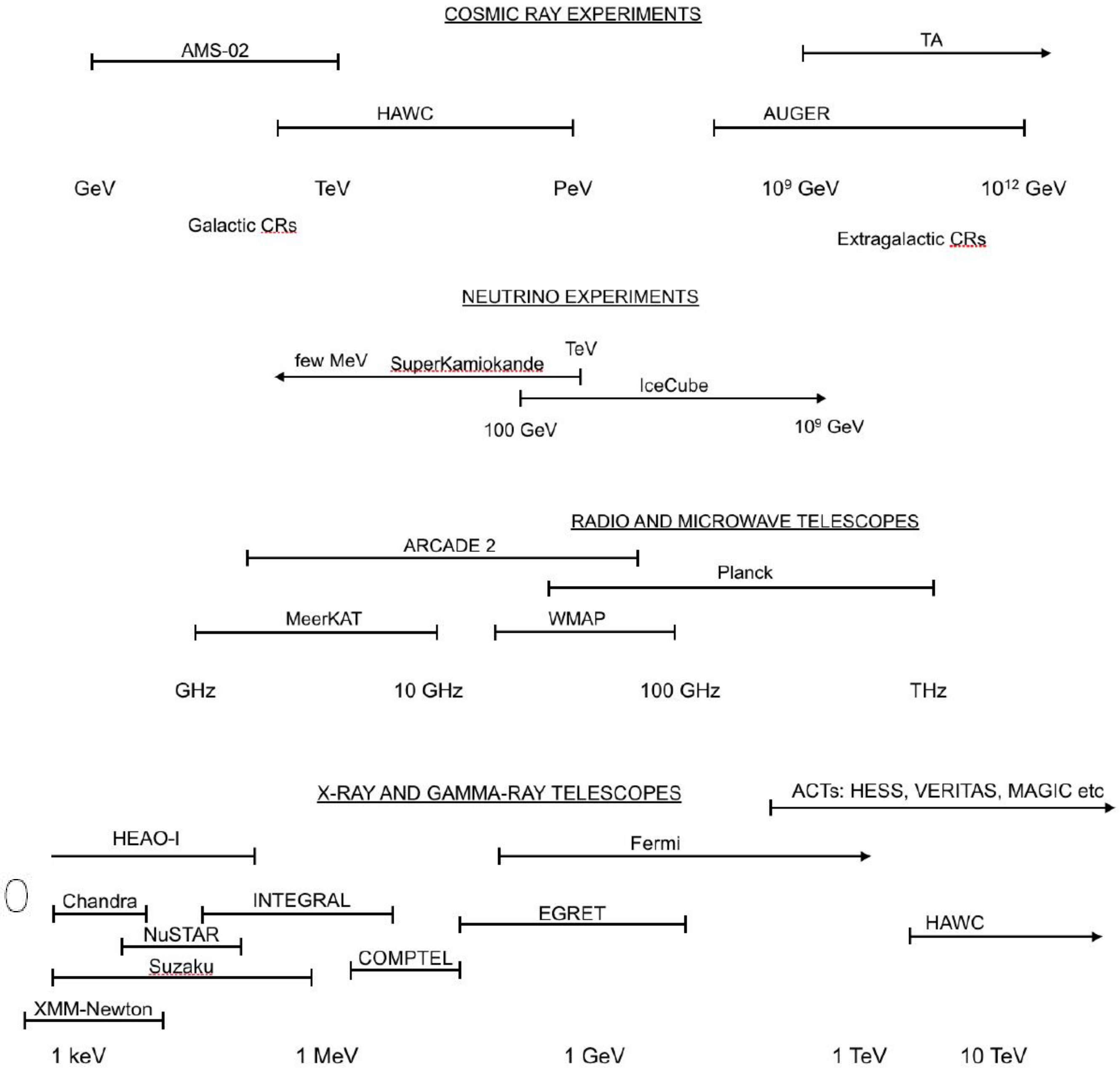
——Not perfect, but possible!

- 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.

A hint from ARCADE-2 observation

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





Fiducial calculation

- 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

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

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

Peebles C-factor $$C = \frac{1+K\Lambda_{2s\rightarrow 1s} n_H (1+x_e)}{1+K\Lambda_{2s\rightarrow 1s} n_H (1-x_e) + K\beta_B(T_\gamma) n_H (1-x_e)}$$

Fiducial calculation

- Taking into account X-ray and Lyman-alpha heating from first star formation, introducing additional terms in evolution equations

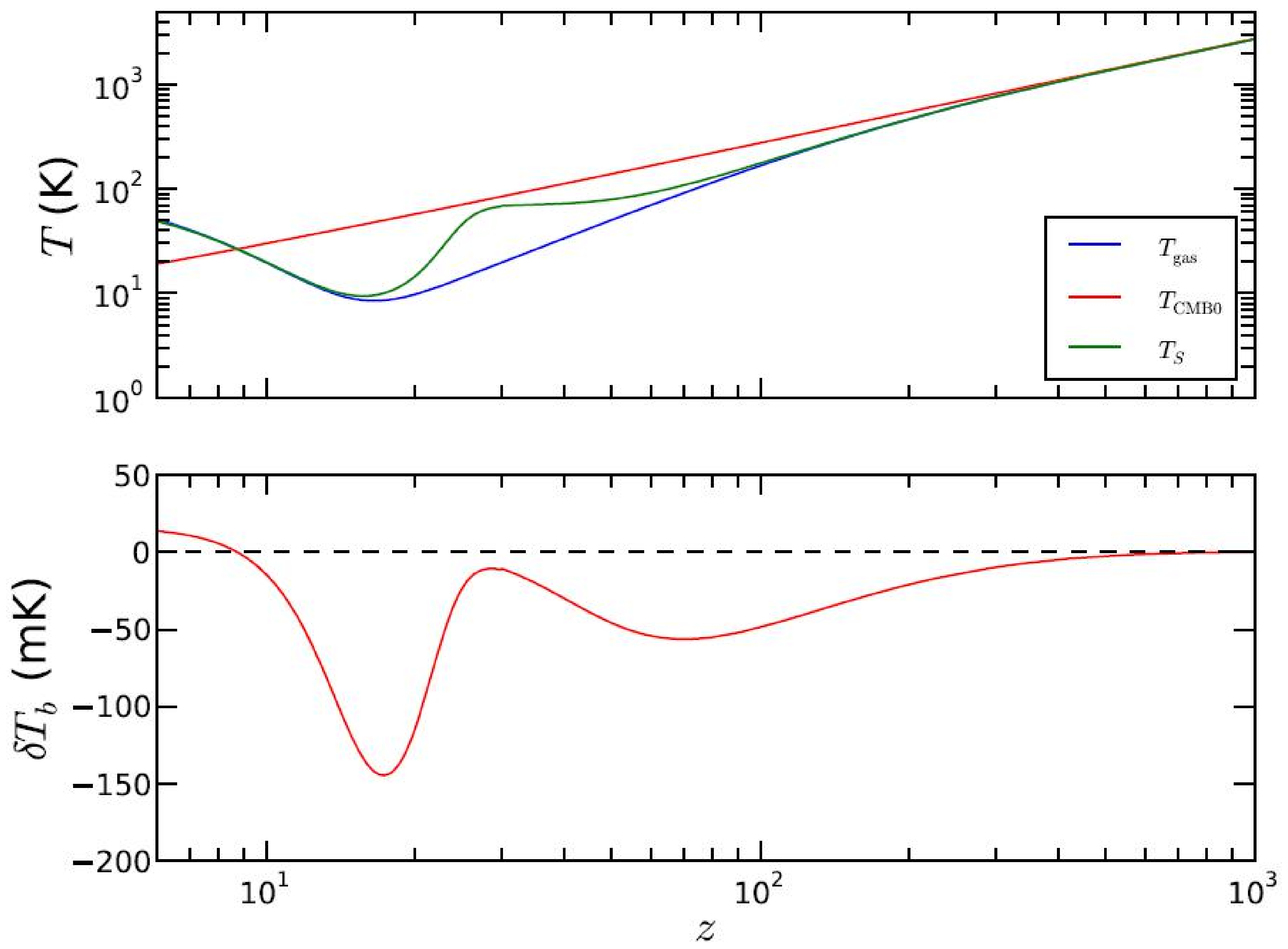
$$
\begin{aligned}
J_X(E,z) &= \frac{(1+z)^3}{4\pi}\int_z^\infty \epsilon_X(E',z')\frac{dr_p}{dz'}dz' \\
&= \frac{(1+z)^3}{4\pi}\int_z^\infty \epsilon_X(E',z')\frac{c}{(1+z')H(z')}dz'
\end{aligned}
$$

$$
\epsilon_X(E',z') = L_X(E')[\rho_{\rm III}^{\rm SFR}(z') + \rho_{\rm II}^{\rm SFR}(z')]
$$

$$
\begin{aligned}
J_\alpha(\nu_\alpha,z) &= \frac{(1+z)^3}{4\pi}\int_z^{z_{\rm max}} \epsilon_\alpha(\nu',z')\frac{dr_p}{dz'}dz' \\
&= \frac{(1+z)^3}{4\pi}\int_z^{z_{\rm max}} \epsilon_\alpha(\nu',z')\frac{c}{(1+z')H(z')}dz'
\end{aligned}
$$

$$
\begin{aligned}
\epsilon_\alpha(\nu',z') &= \epsilon_\alpha^{\rm III}(\nu',z') + \epsilon_\alpha^{\rm II}(\nu',z') \\
&= s_{\rm III}(\nu')\rho_{\rm III}^{\rm SFR}(z') + s_{\rm II}(\nu')\rho_{\rm II}^{\rm SFR}(z')
\end{aligned}
$$

Fiducial calculation



Effect of DM annihilation

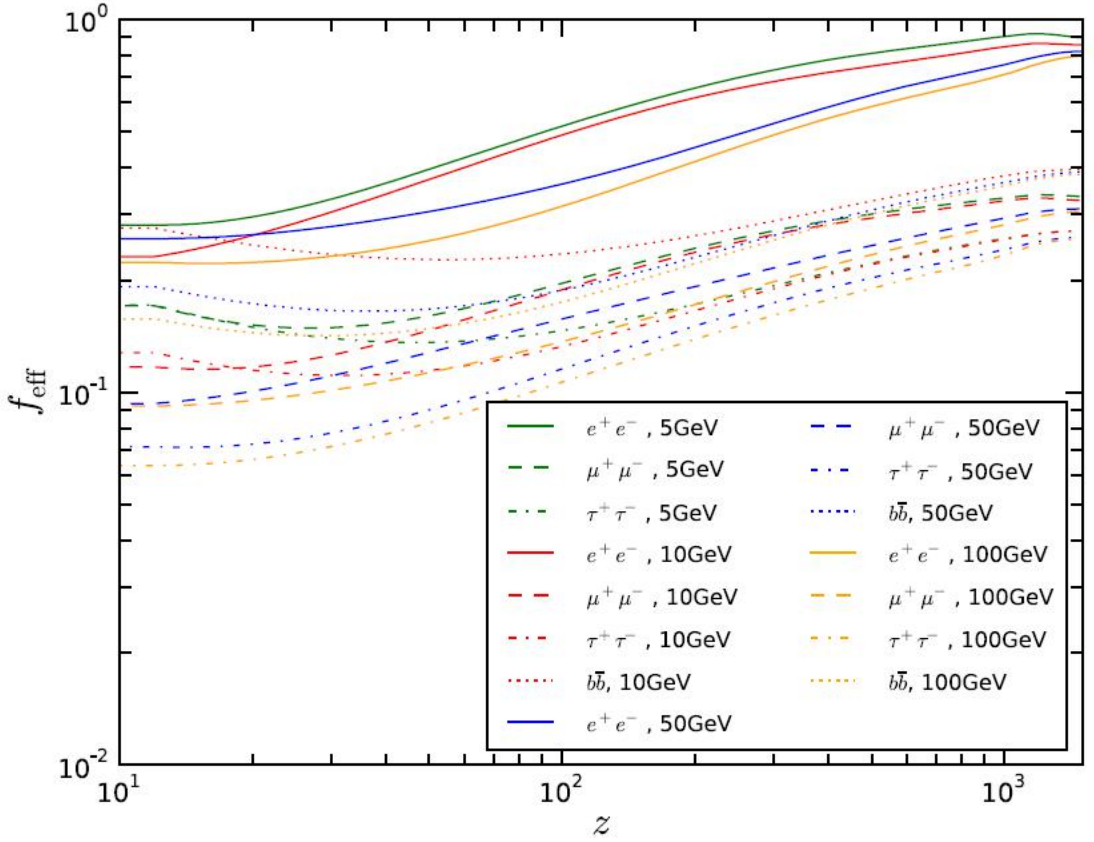
- Extra contributions from DM annihilation   T. Kanzaki, M. Kawasaki, K. Nakayama, arXiv:0907.3985

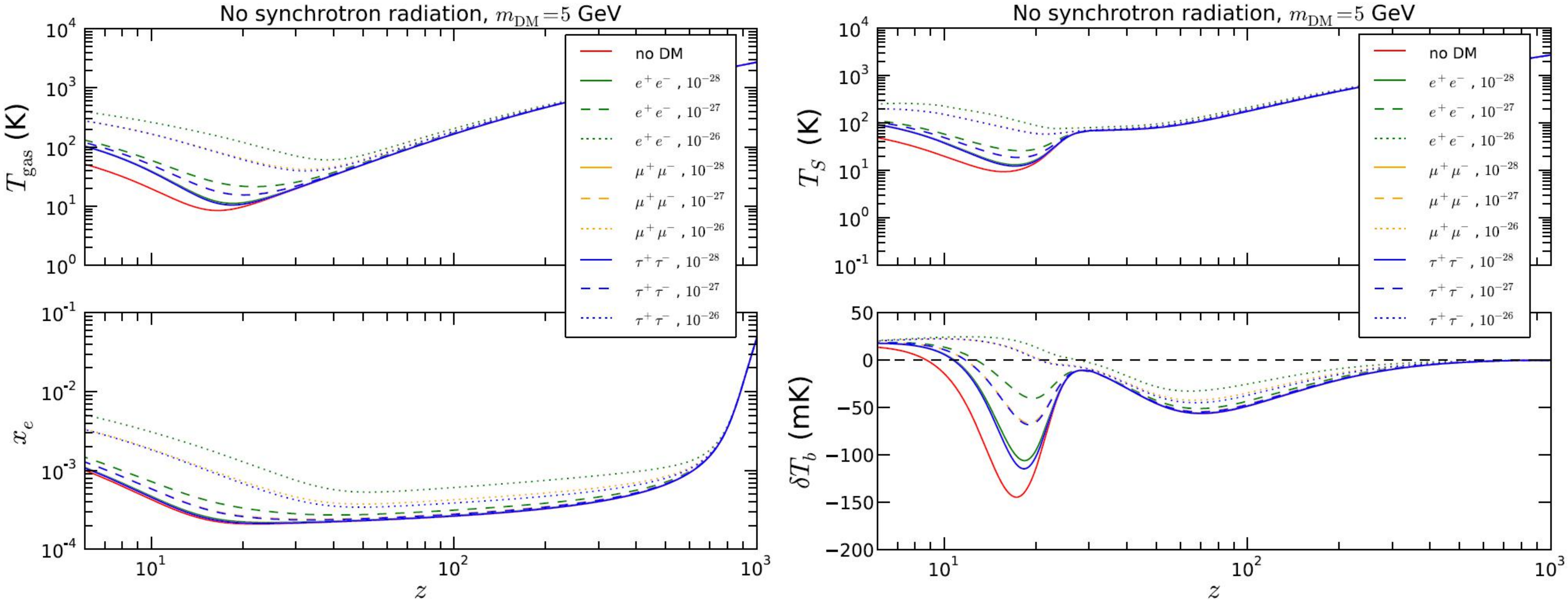
$$\frac{dx_e}{dz} = -\sum_i \int \frac{dz'}{H(z')(1+z')} \frac{n_{\rm DM}^2}{2n_H(z')} \langle\sigma v\rangle B(z', M_{\rm min}) {\rm Br}_i \frac{m_{\rm DM}}{13.6{\rm eV}} f_{\rm eff}(m_{\rm DM}, i, z', z)$$

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

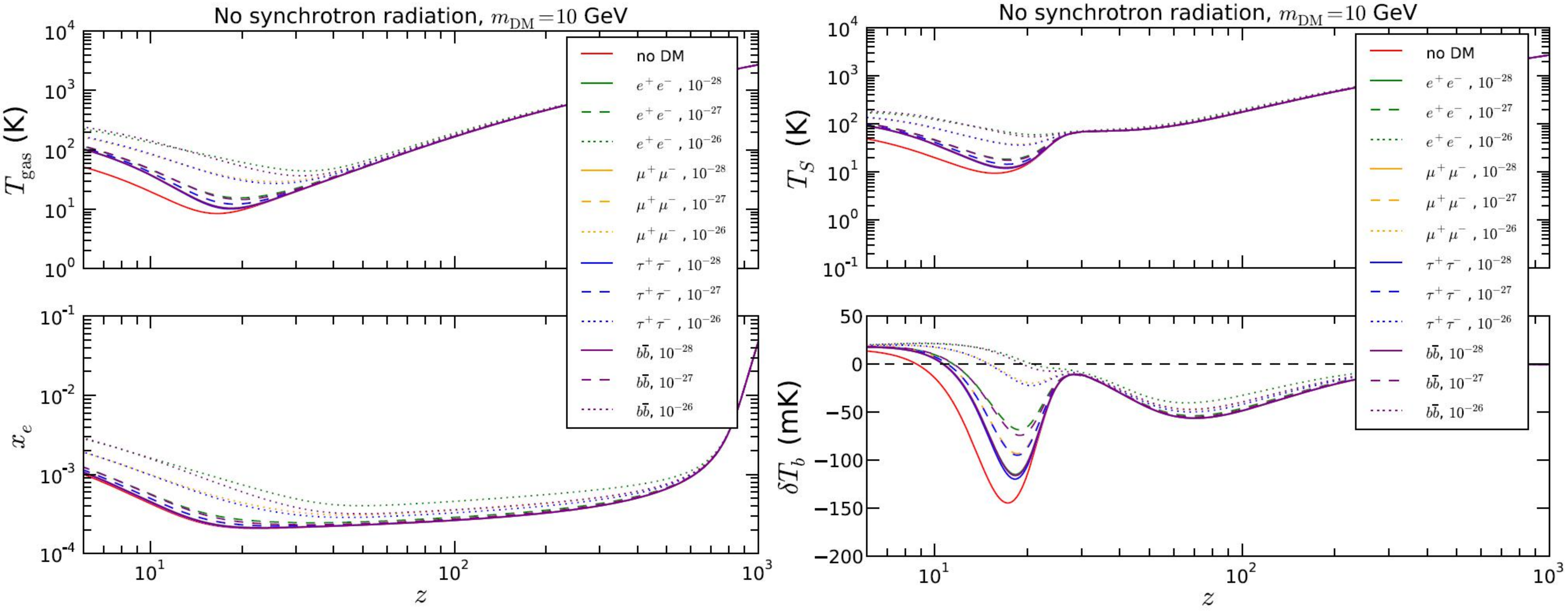
- The effective energy deposit rate (ionization, excitations, heating)

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

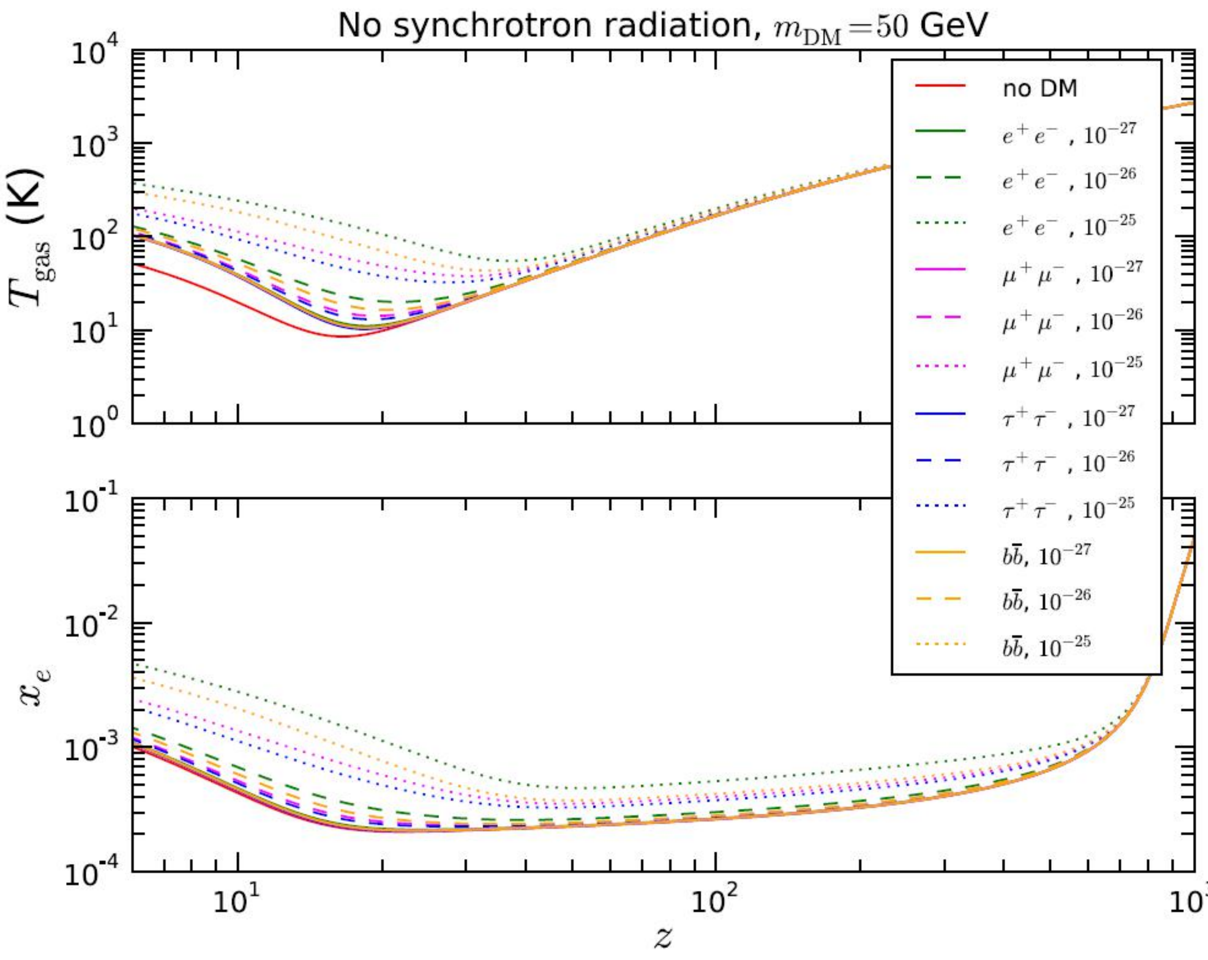


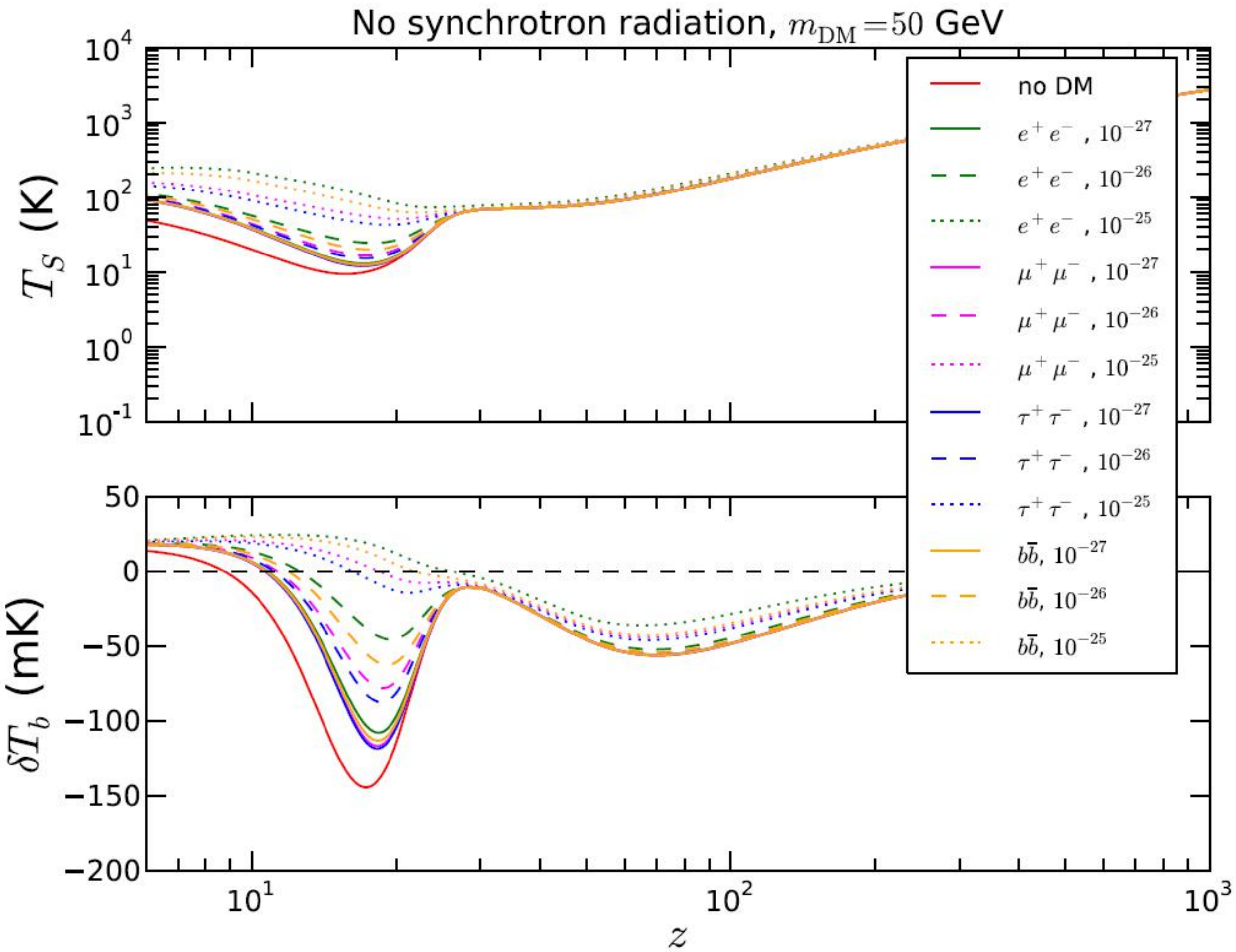


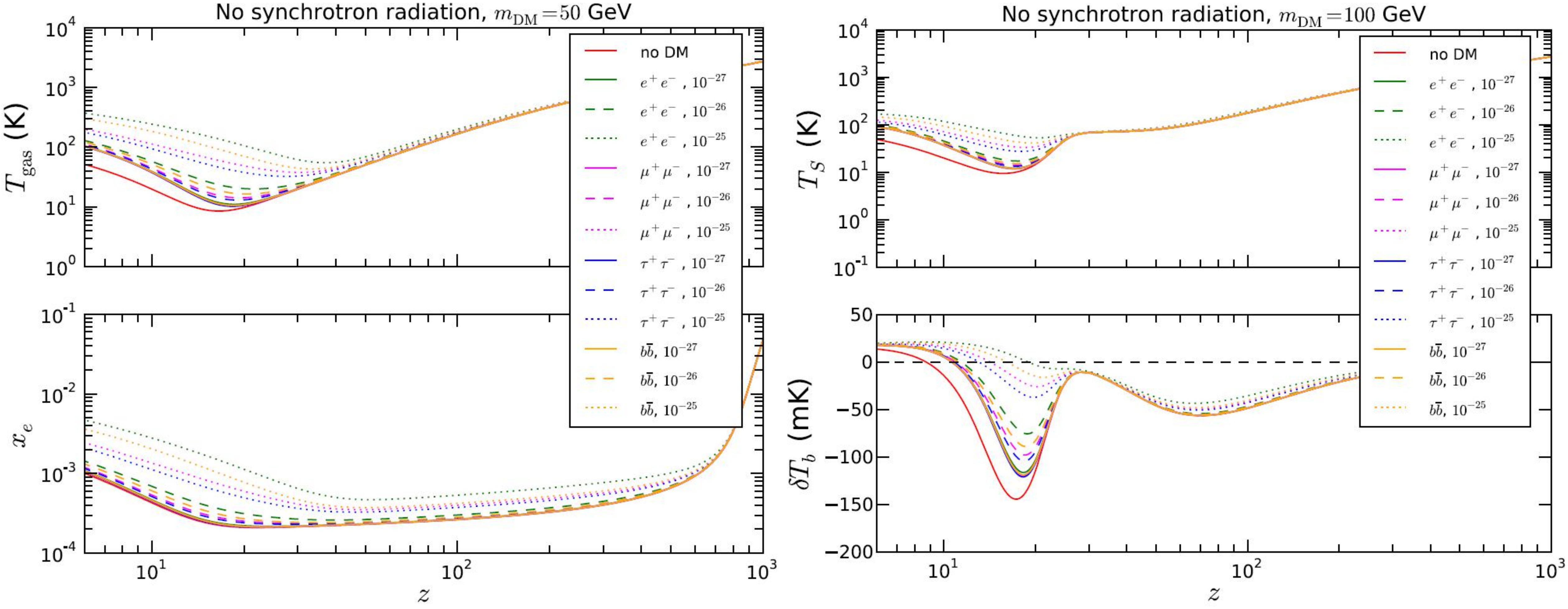
No synchrotron radiation, $m_{\rm DM}=5$ GeV
$T_{\rm gas}$ (K)
x_e
z
No synchrotron radiation, $m_{\rm DM}=5$ GeV
T_S (K)
δT_b (mK)
z
no DM
e^+e^-, 10^{-28}
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
$\mu^+\mu^-$, 10^{-28}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-28}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}



No synchrotron radiation, $m_{\rm DM}=10$ GeV
$T_{\rm gas}$ (K)
x_e
z
T_S (K)
δT_b (mK)
no DM
e^+e^-, 10^{-28}
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
$\mu^+\mu^-$, 10^{-28}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-28}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$b\bar{b}$, 10^{-28}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}


No synchrotron radiation, $m_{\rm DM} = 50$ GeV
$T_{\rm gas}$ (K)
x_e
z
no DM
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
e^+e^-, 10^{-25}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\mu^+\mu^-$, 10^{-25}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-25}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$b\bar{b}$, 10^{-25}


No synchrotron radiation, $m_{\rm DM} = 50$ GeV
T_S (K)
δT_b (mK)
z
no DM
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
e^+e^-, 10^{-25}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\mu^+\mu^-$, 10^{-25}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-25}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$b\bar{b}$, 10^{-25}



No synchrotron radiation, $m_{\rm DM}=50$ GeV
No synchrotron radiation, $m_{\rm DM}=100$ GeV
$T_{\rm gas}$ (K)
x_e
T_S (K)
δT_b (mK)
z
no DM
e^+e^- , 10^{-27}
e^+e^- , 10^{-26}
e^+e^- , 10^{-25}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\mu^+\mu^-$, 10^{-25}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-25}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$b\bar{b}$, 10^{-25}

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

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

Hubble function

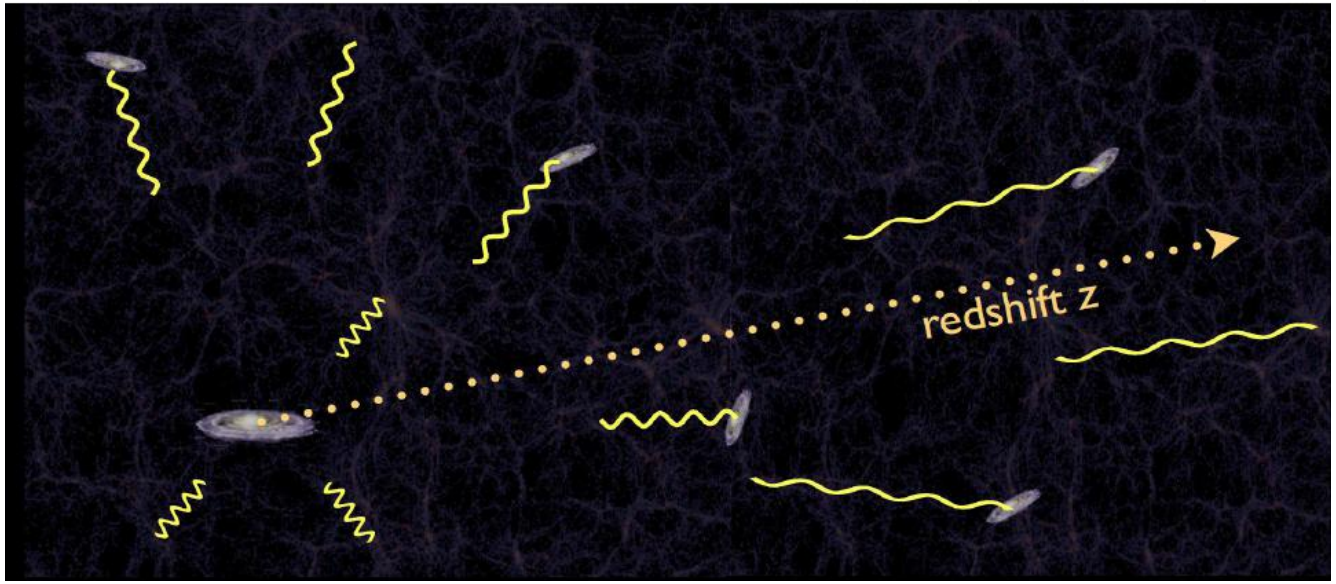
$$H_0\sqrt{\Omega_m(1+z)^3+(1-\Omega_m)}$$

synchrotron radiation spectrum

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

DM injection spectrum

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



- 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

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

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

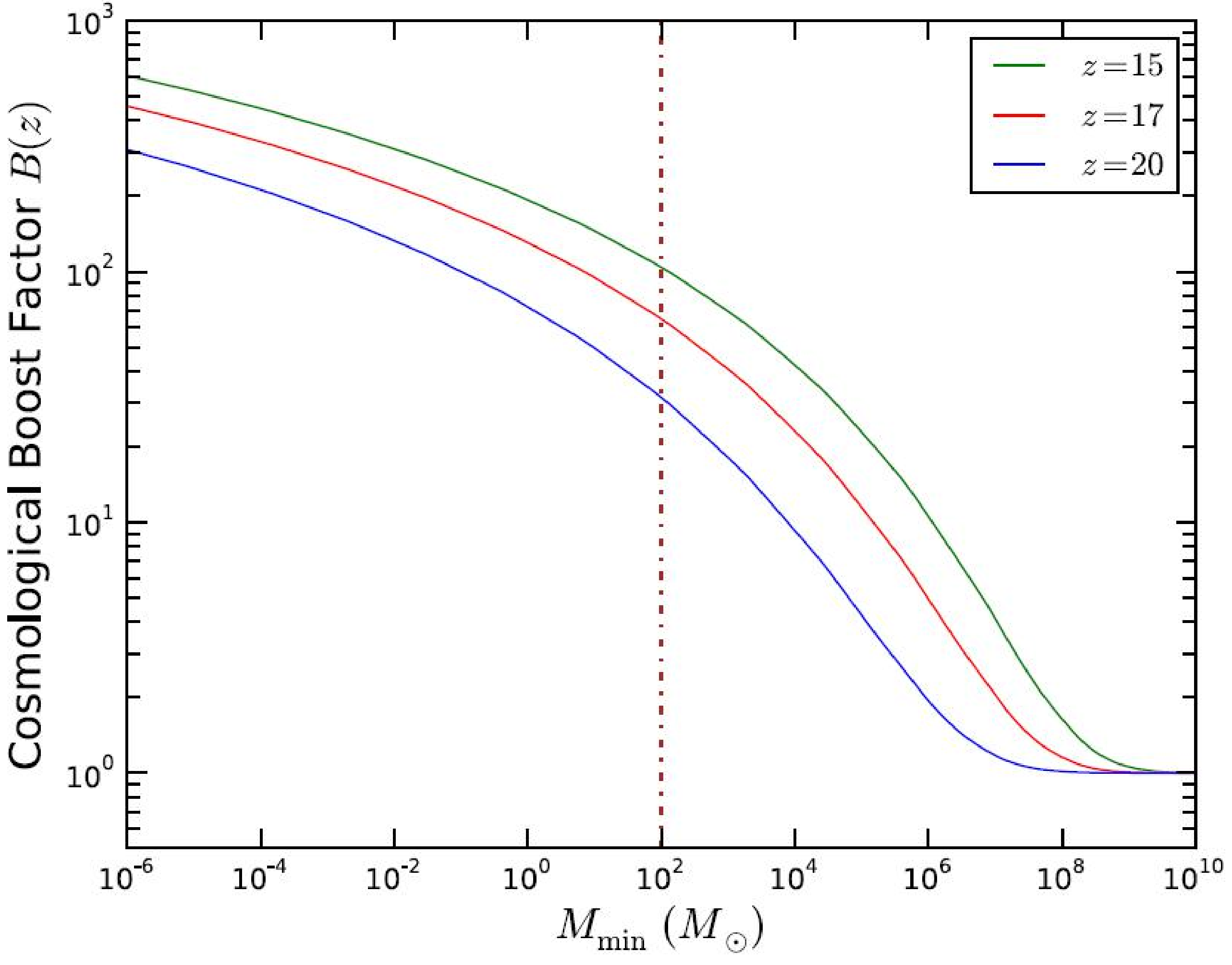
- ARCADE-2 excess corresponding to

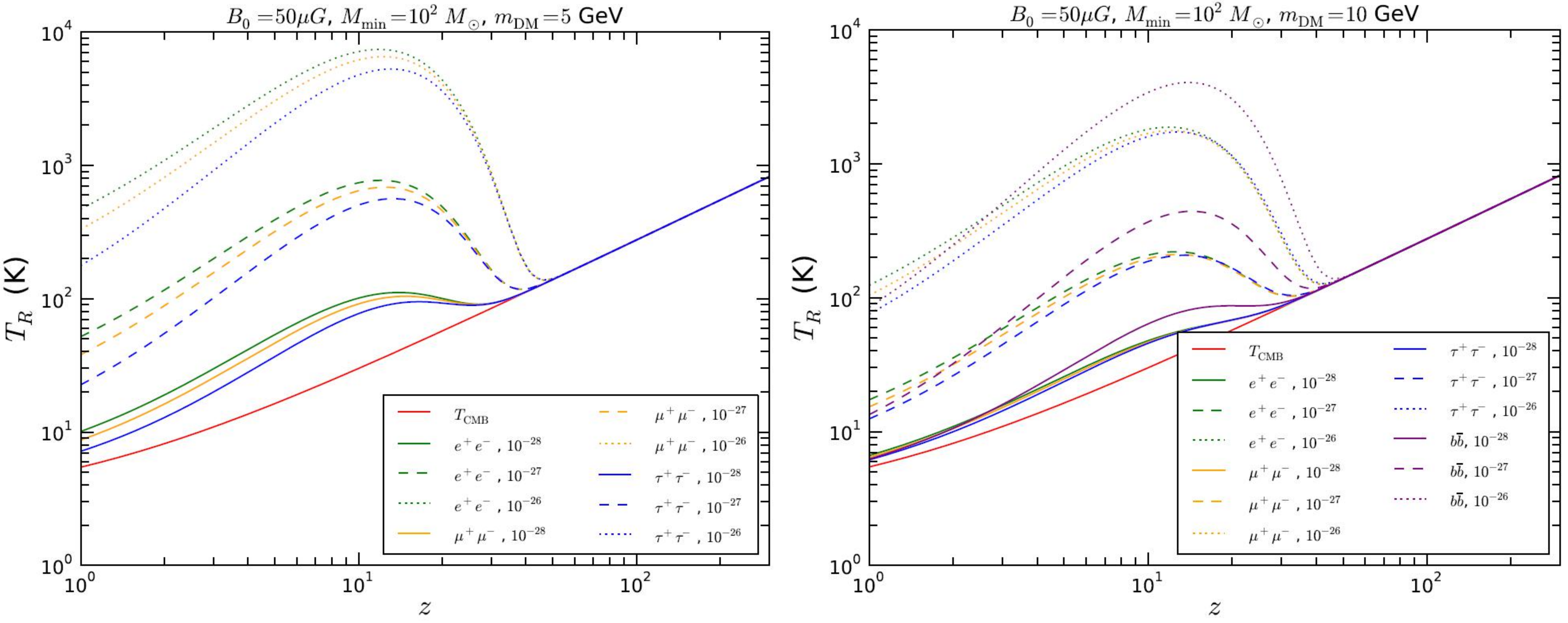
$$T_{\rm syn}(\nu, z = 0)$$

- spin-temperature with synchrotron emission

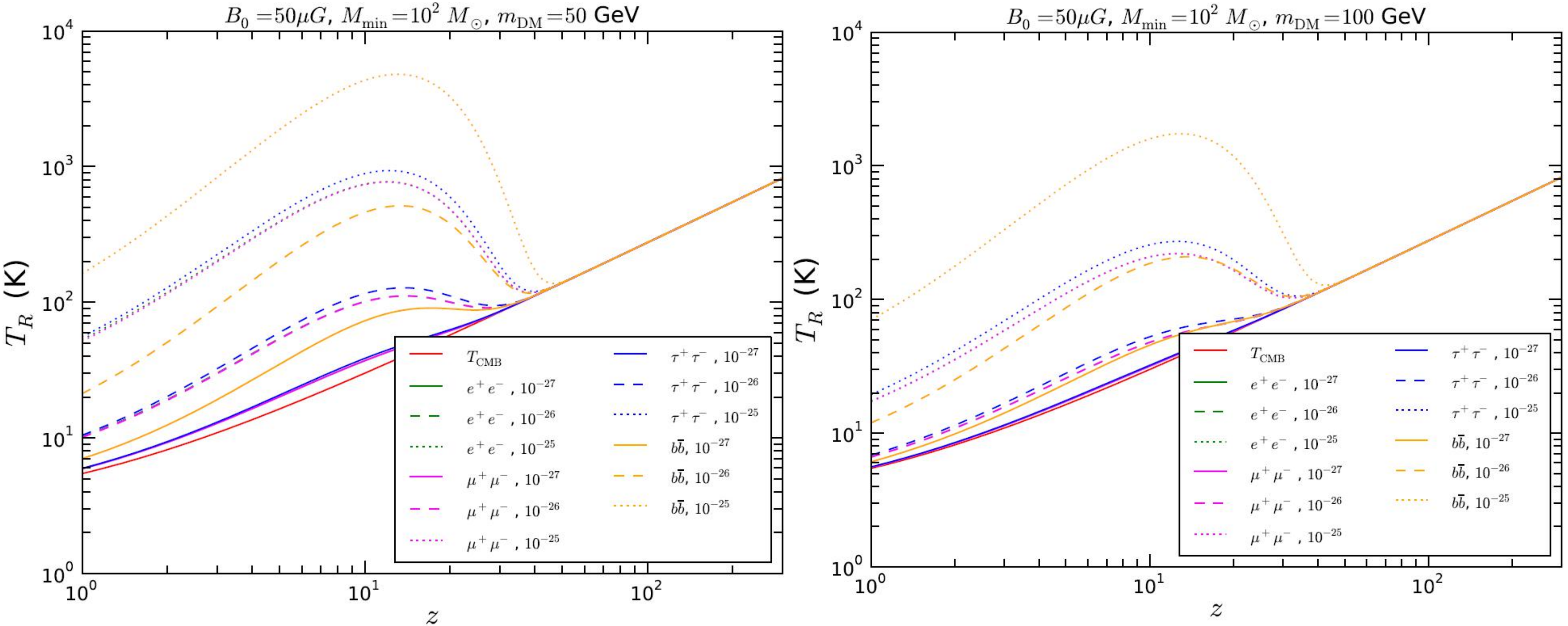
$$T_R(z) \equiv T_{\rm CMB} + T_{\rm syn}(\nu_{21}, z)$$

$$T_s = \frac{T_R(z) + (y_c + y_{{\rm eff},\alpha})T_{\rm gas}}{1 + y_c + y_{{\rm eff},\alpha}}$$



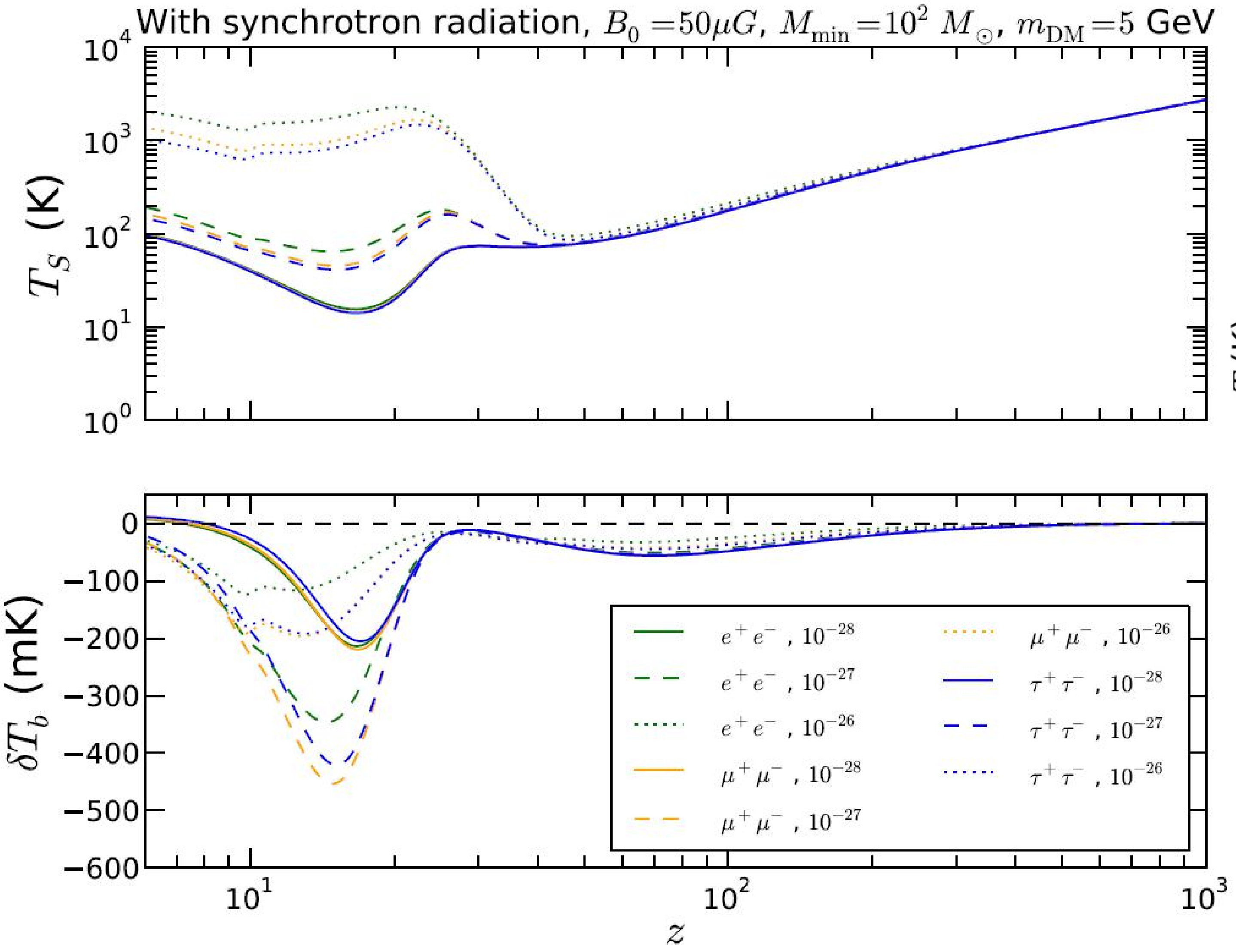


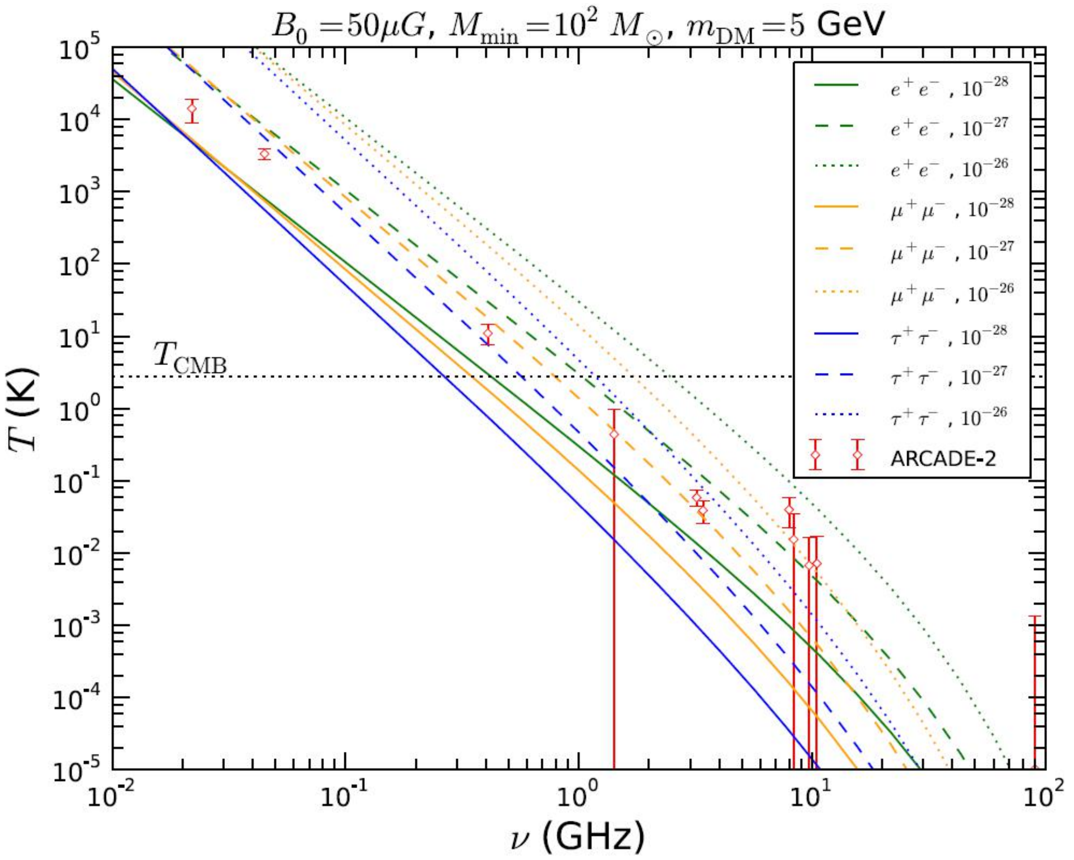
$B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 5$ GeV
$B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 10$ GeV
T_R (K)
z
$T_{\rm CMB}$
e^+e^-, 10^{-28}
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
$\mu^+\mu^-$, 10^{-28}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-28}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$b\bar{b}$, 10^{-28}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}

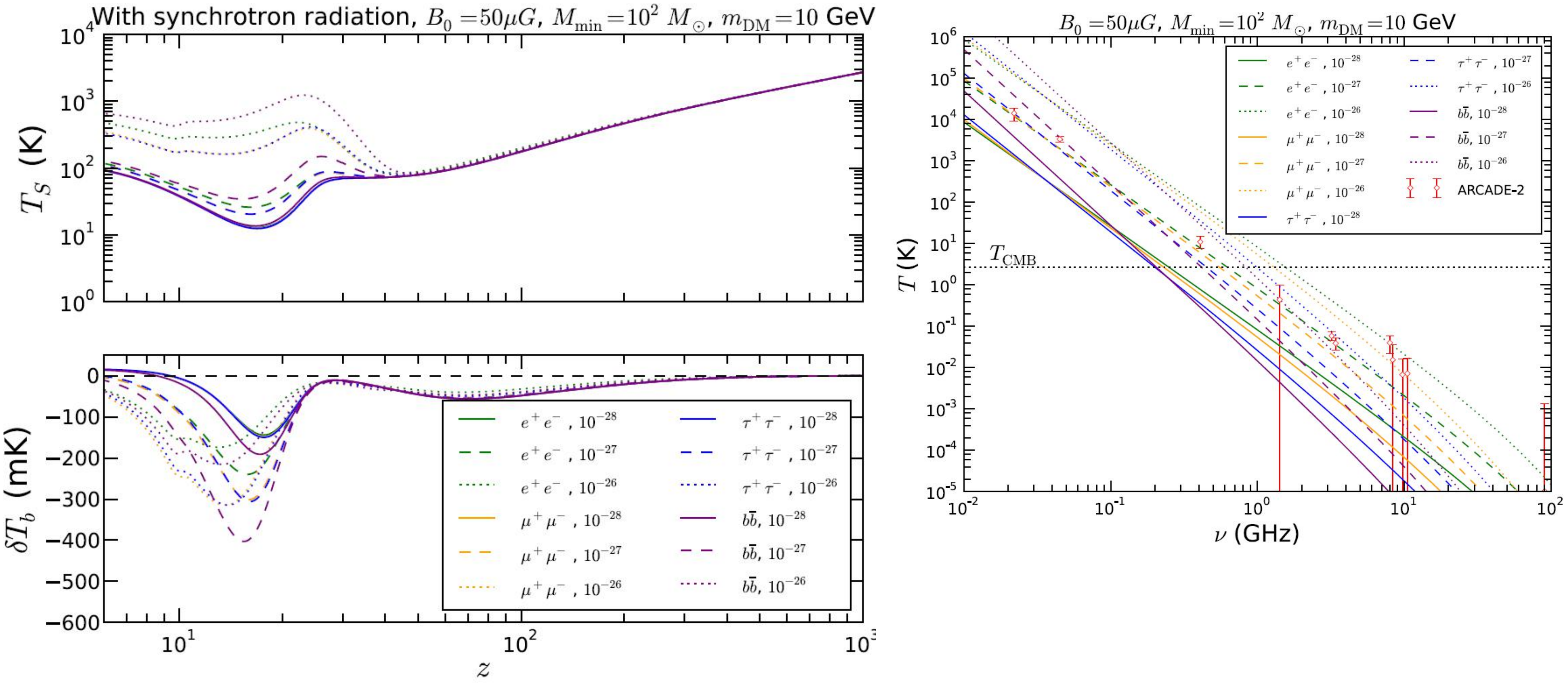


$B_0 = 50 \mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 50$ GeV
$B_0 = 50 \mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 100$ GeV
T_R (K)
z
$T_{\rm CMB}$
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
e^+e^-, 10^{-25}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\mu^+\mu^-$, 10^{-25}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-25}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$b\bar{b}$, 10^{-25}

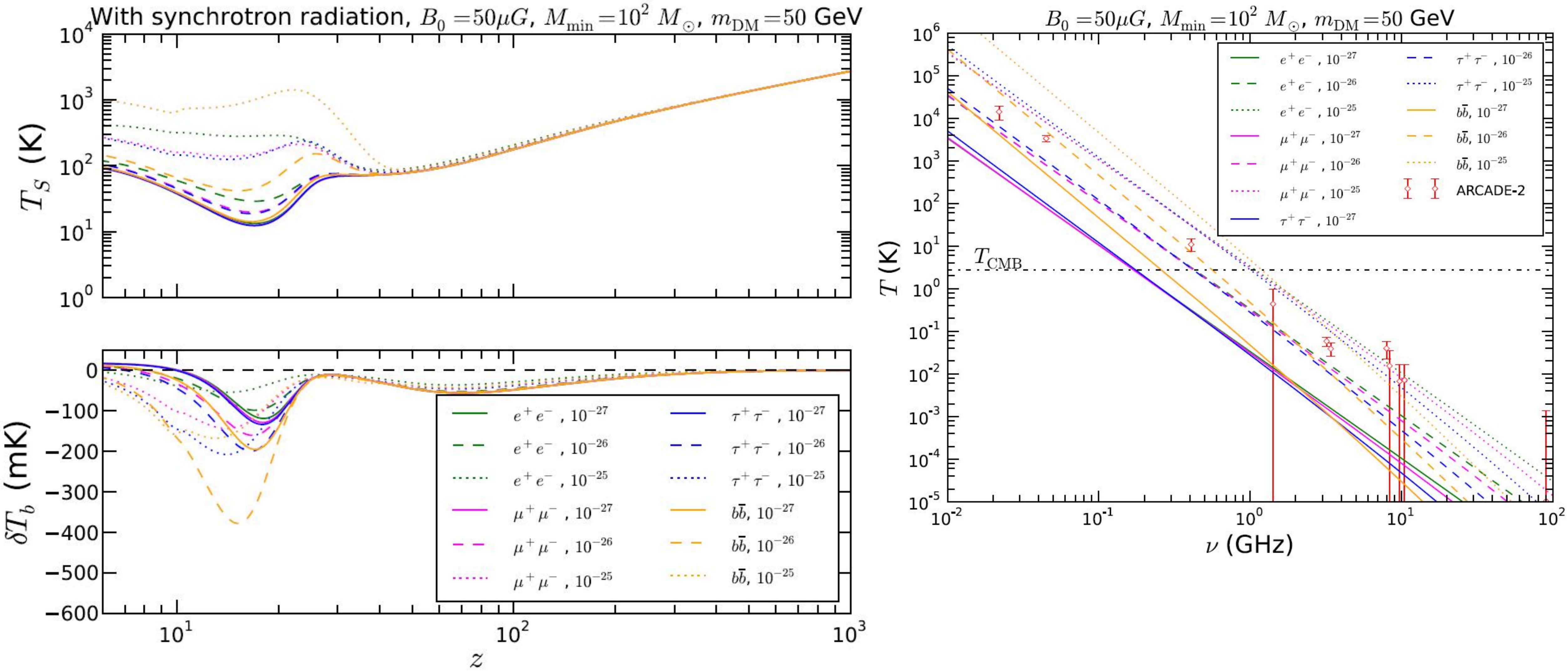
Preliminary results



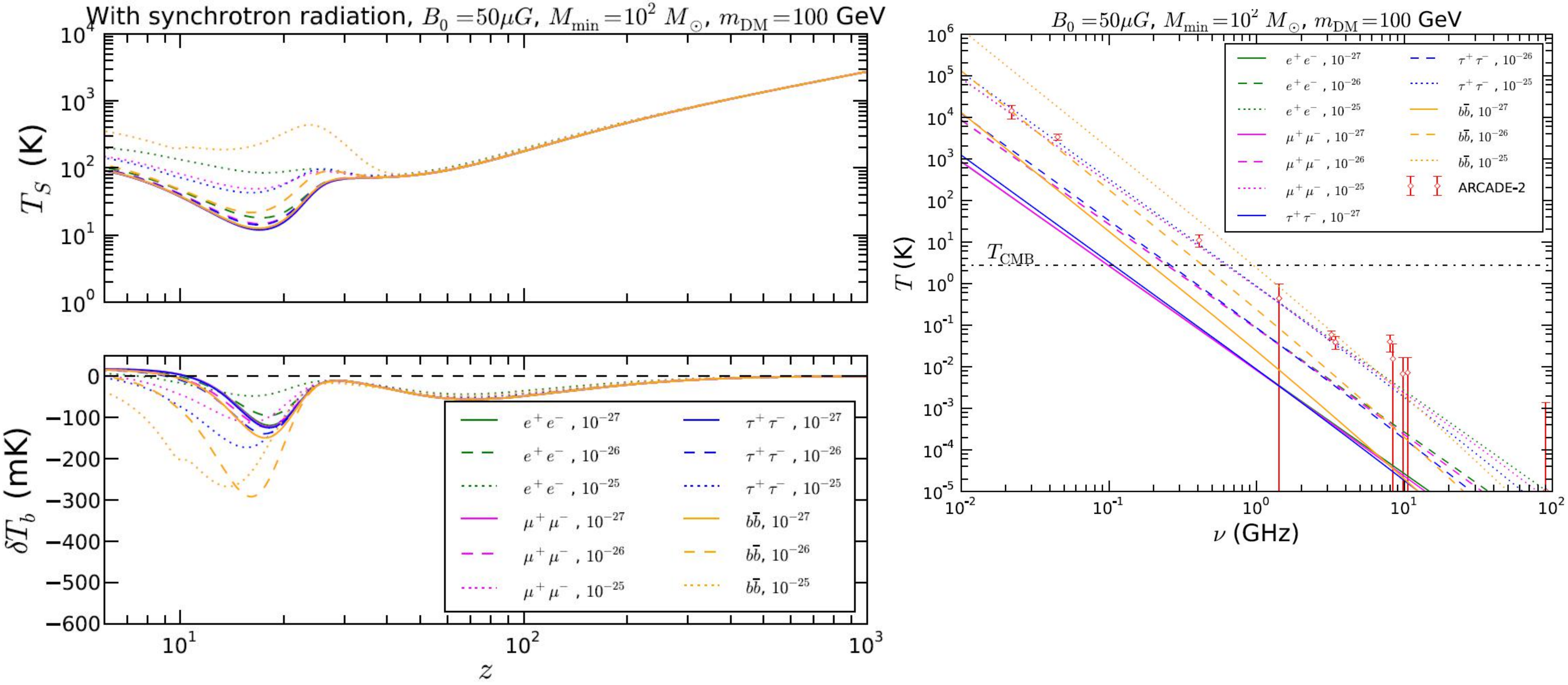




With synchrotron radiation, $B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 10$ GeV
T_S (K)
δT_b (mK)
z
e^+e^-, 10^{-28}
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
$\mu^+\mu^-$, 10^{-28}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-28}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$b\bar{b}$, 10^{-28}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 10$ GeV
T (K)
ν (GHz)
$T_{\rm CMB}$
ARCADE-2



With synchrotron radiation, $B_0 = 50\mu G$, $M_{\rm min} = 10^2\, M_\odot$, $m_{\rm DM} = 50$ GeV
T_S (K)
δT_b (mK)
z
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
e^+e^-, 10^{-25}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\mu^+\mu^-$, 10^{-25}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-25}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$b\bar{b}$, 10^{-25}
$B_0 = 50\mu G$, $M_{\rm min} = 10^2\, M_\odot$, $m_{\rm DM} = 50$ GeV
T (K)
ν (GHz)
$T_{\rm CMB}$
ARCADE-2



With synchrotron radiation, $B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 100$ GeV
T_S (K)
δT_b (mK)
z
e^+e^-, 10^{-27}
e^+e^-, 10^{-26}
e^+e^-, 10^{-25}
$\mu^+\mu^-$, 10^{-27}
$\mu^+\mu^-$, 10^{-26}
$\mu^+\mu^-$, 10^{-25}
$\tau^+\tau^-$, 10^{-27}
$\tau^+\tau^-$, 10^{-26}
$\tau^+\tau^-$, 10^{-25}
$b\bar{b}$, 10^{-27}
$b\bar{b}$, 10^{-26}
$b\bar{b}$, 10^{-25}
$B_0 = 50\mu G$, $M_{\rm min} = 10^2\ M_\odot$, $m_{\rm DM} = 100$ GeV
T (K)
$T_{\rm CMB}$
ARCADE-2
ν (GHz)

谢谢大家