The impact of EDGES 21-cm data on WIMP dark matter interactions

Yue-Lin Sming Tsai
(IOP, Academia Sinica)

In collaboration with
Kingman Cheung, Jui-Lin Kuo, Kin-Wang Ng
(arXiv:1803.09398, accepted by PLB)

Outline

① 21 cm physics and EDGES measurement.

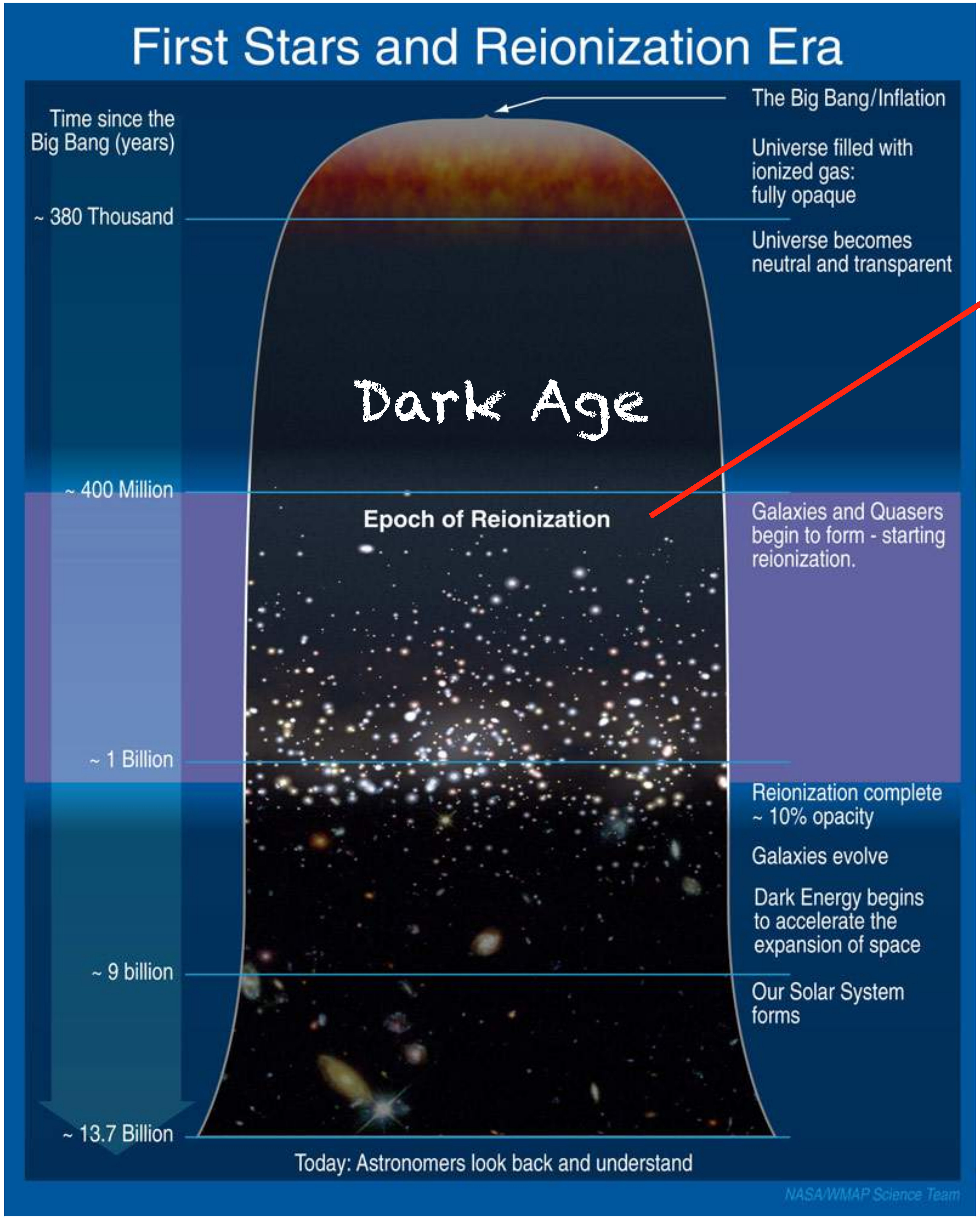
② Dark Matter status. (Why is 21 cm important to DM?)

③ Constraints on the DM annihilation.

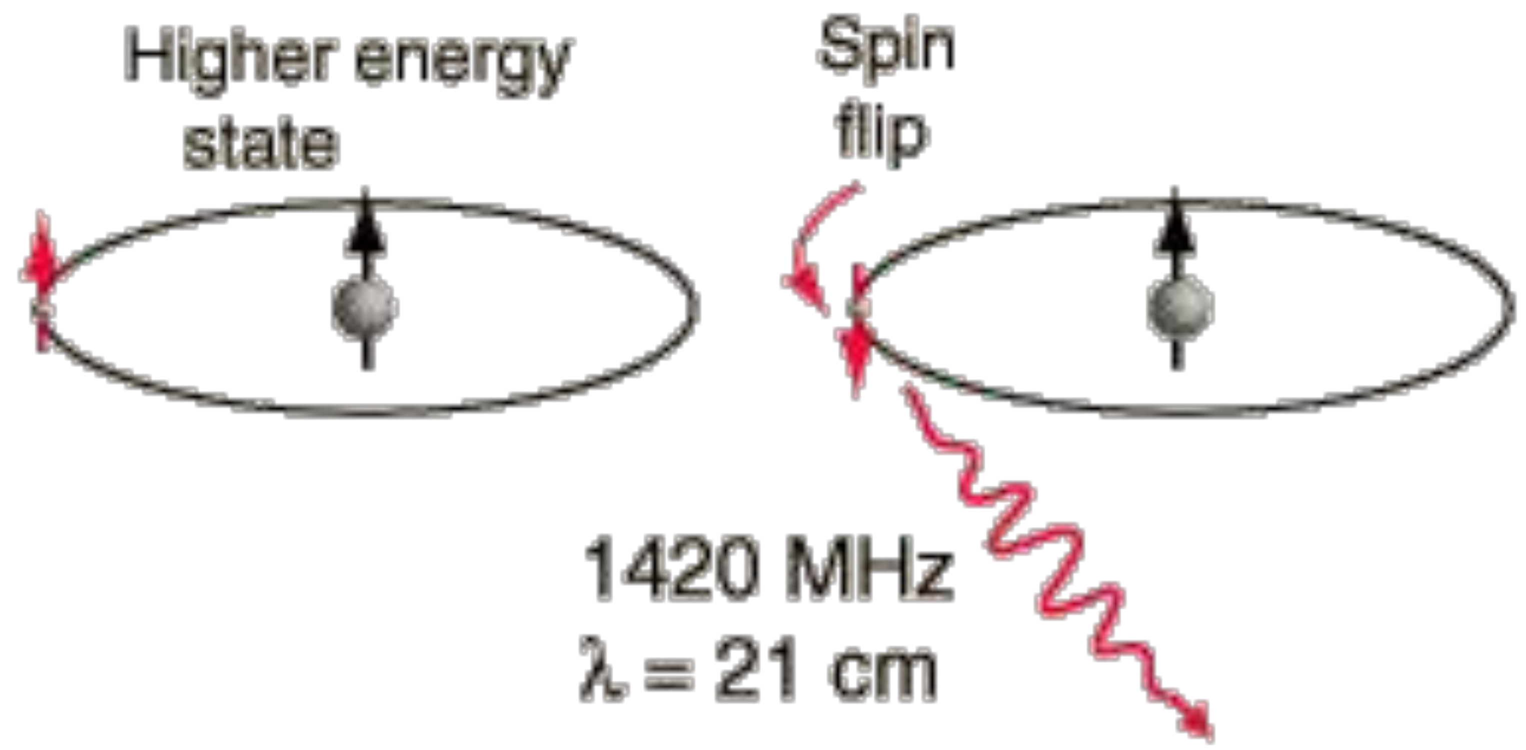
④ Summary and Conclusion.

21 cm physics
and
EDGES measurement.

What is 21 cm ???



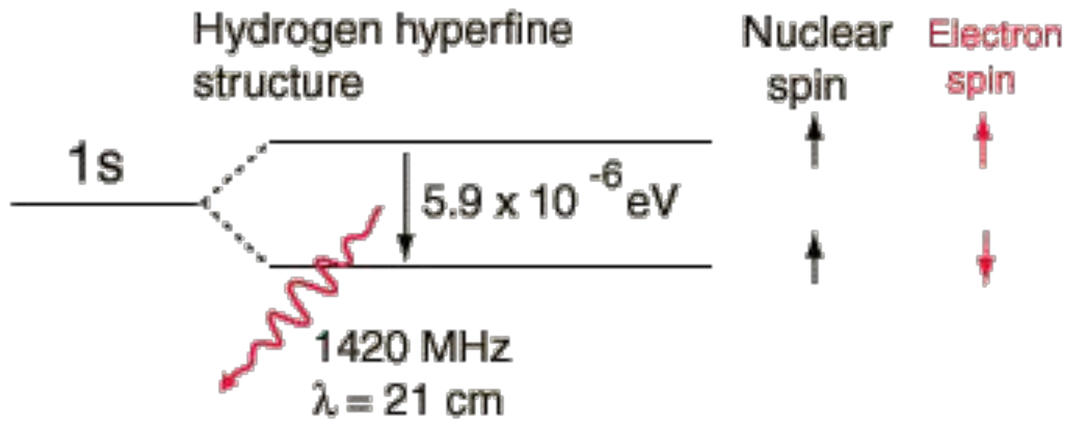
The 21-cm line in hydrogen is potentially a means of studying this period.



- The transition (up, down) "directly" to (up, up) is ALMOST forbidden, a mean lifetime of 3e7 yrs. (Good target!)
- Only objects form in the "dark ages" and emit a lots of Lyman-alpha photons absorbed and re-emitted by surrounding neutral hydrogen.
- Distribution of two different states are changed via Wouthuysen-Field effect.

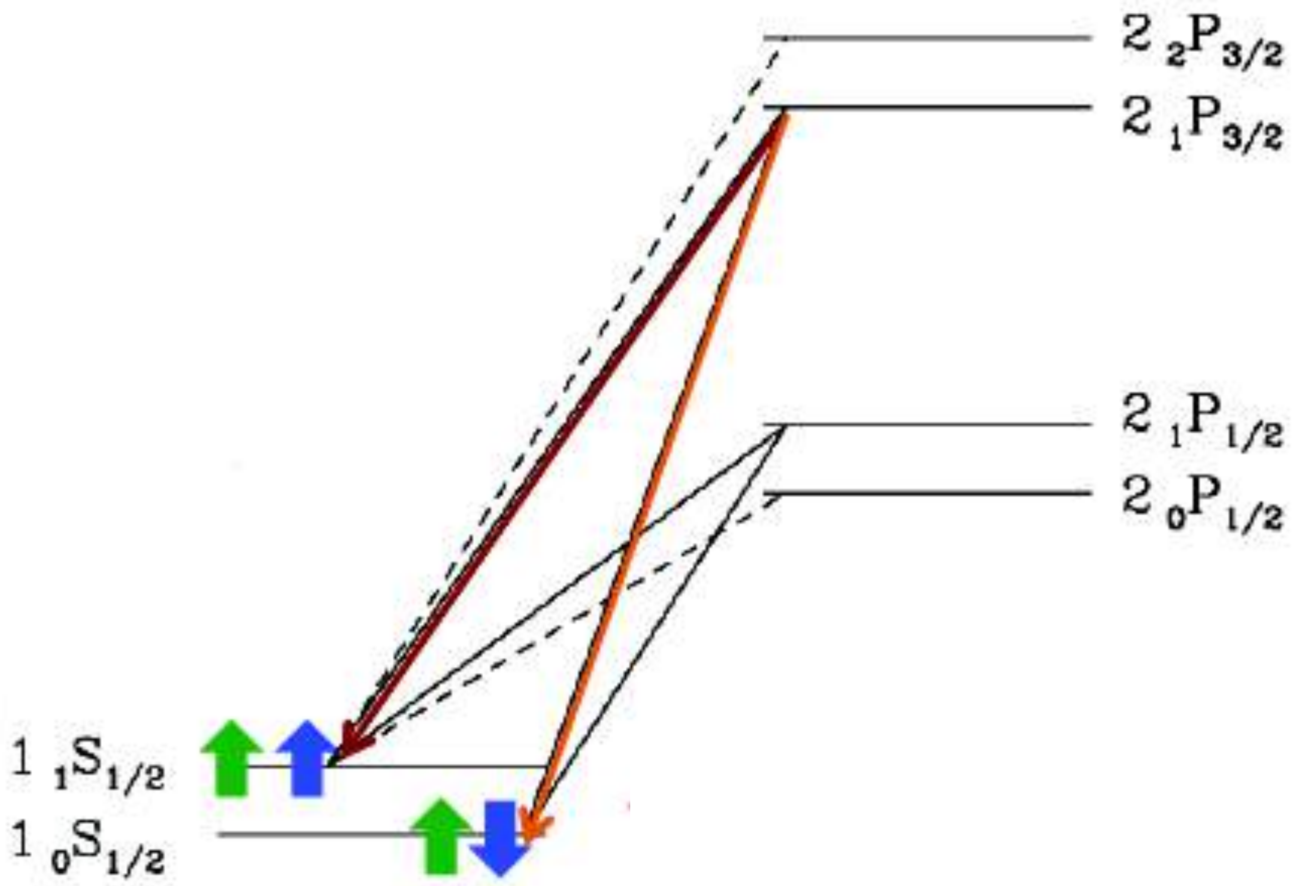
21 cm brightness temperature

and Spin temperature



@ 21 cm brightness temperature:

$$T_{21}(z) \simeq 23\text{mK}\left[1 - \frac{T_\gamma(z)}{T_s(z)}\right]\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{0.15}{\Omega_m h^2}\right)\sqrt{\frac{1+z}{10}}\,x_{HI}$$



Wouthuysen-Field effect

@ Spin temperature:

Color temperature of ambient Ly-α radiation

Gas temperature

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

Gas collision pumping efficiency

Ly-α pumping efficiency

Electron spin redistribution: $\frac{n_u}{n_l} = \frac{g_u}{g_l}\exp\left(-\frac{\Delta E_{\ 21\text{cm}}}{k_b T_s}\right)$

Experiment to Detect the Global Epoch of Reionization Signature (EDGES)

EDGES is to measure baryon gas temperature T_b with a single wide field-of-view well-calibrated antenna.

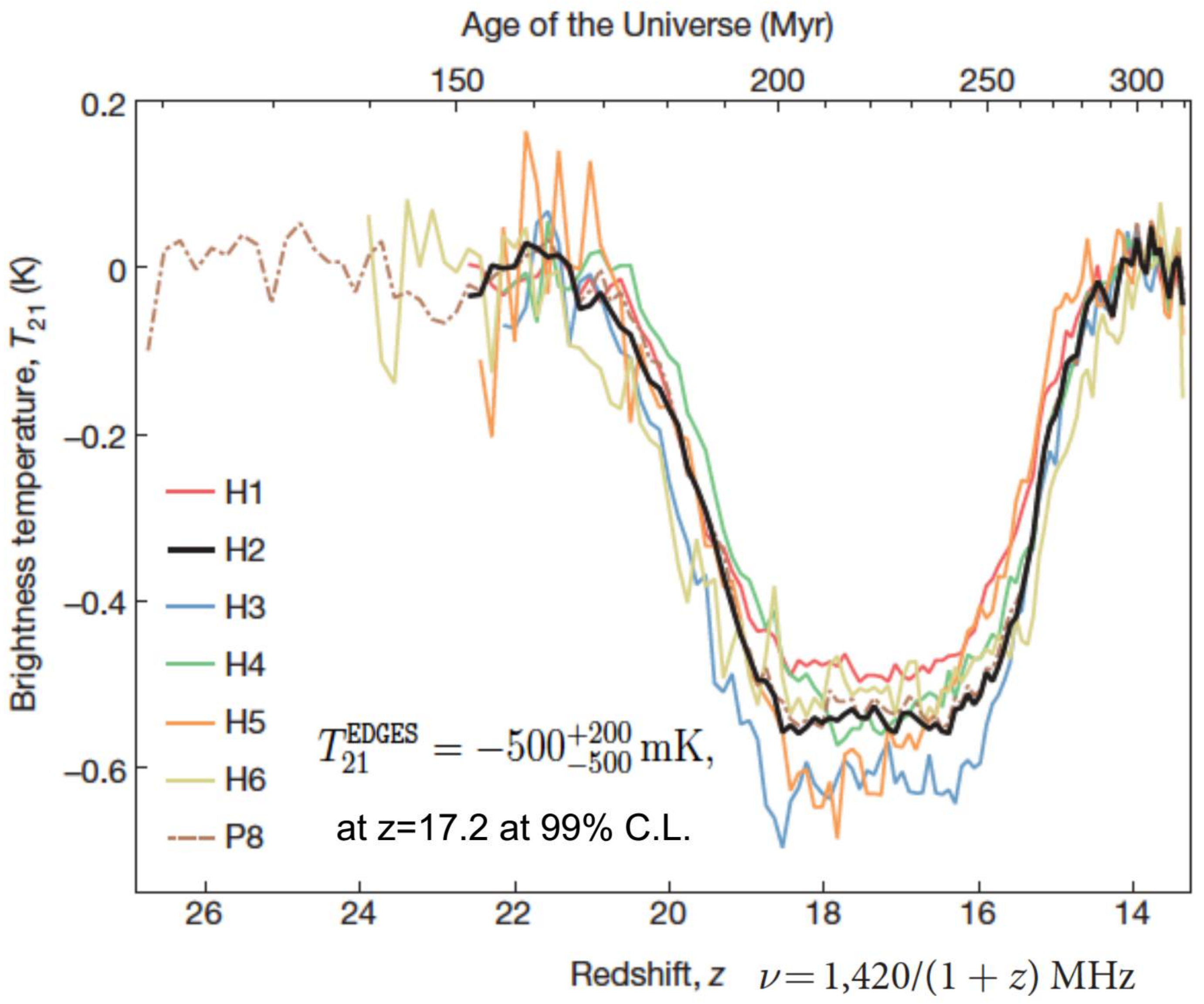
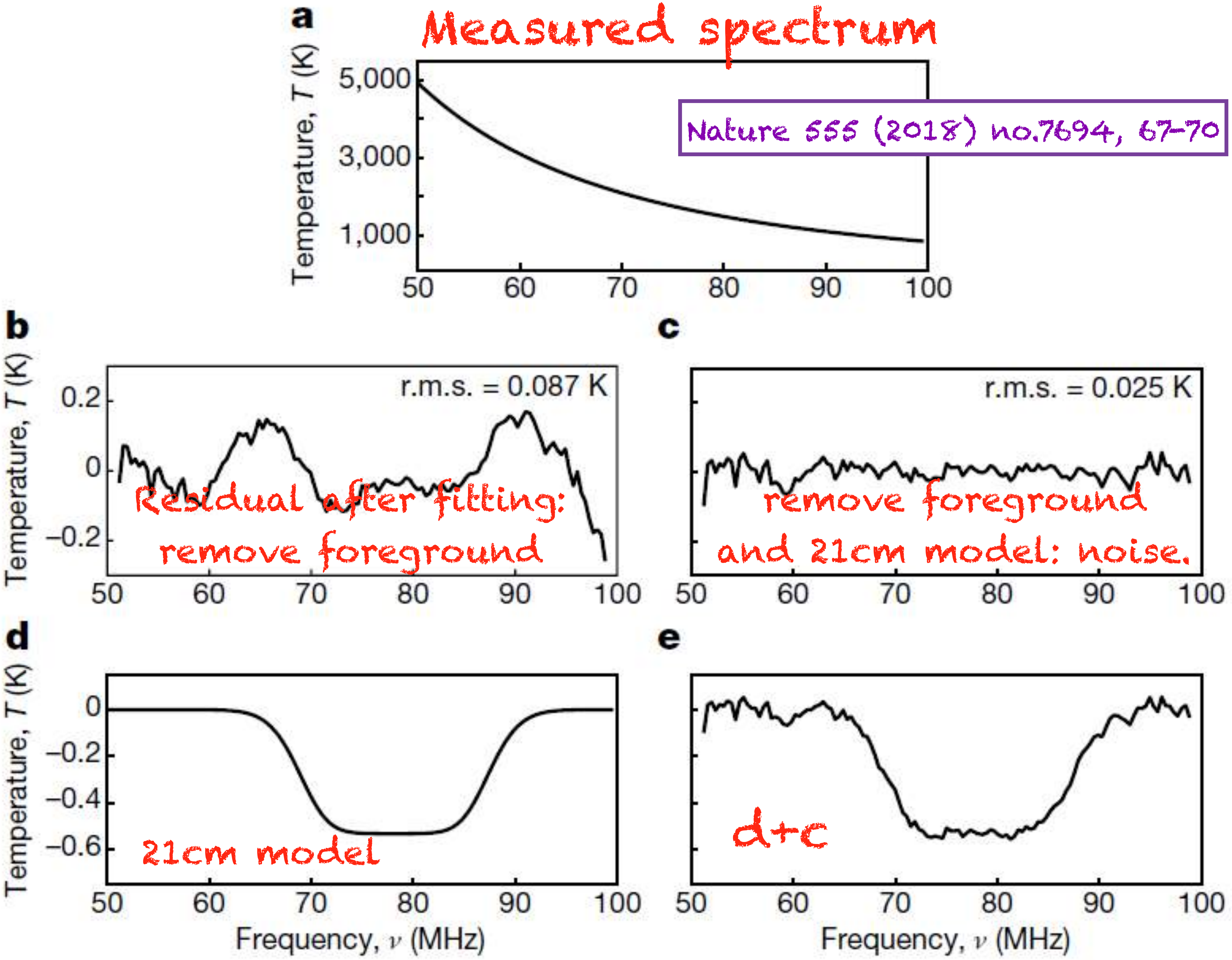


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

$$T_{21}^{\rm EDGES} = -500^{+200}_{-500}\,{\rm mK},$$

The "BF model" for T21 @z=17.2 and 99% CL.

-500+200-500 mK is 99% of "BF models".



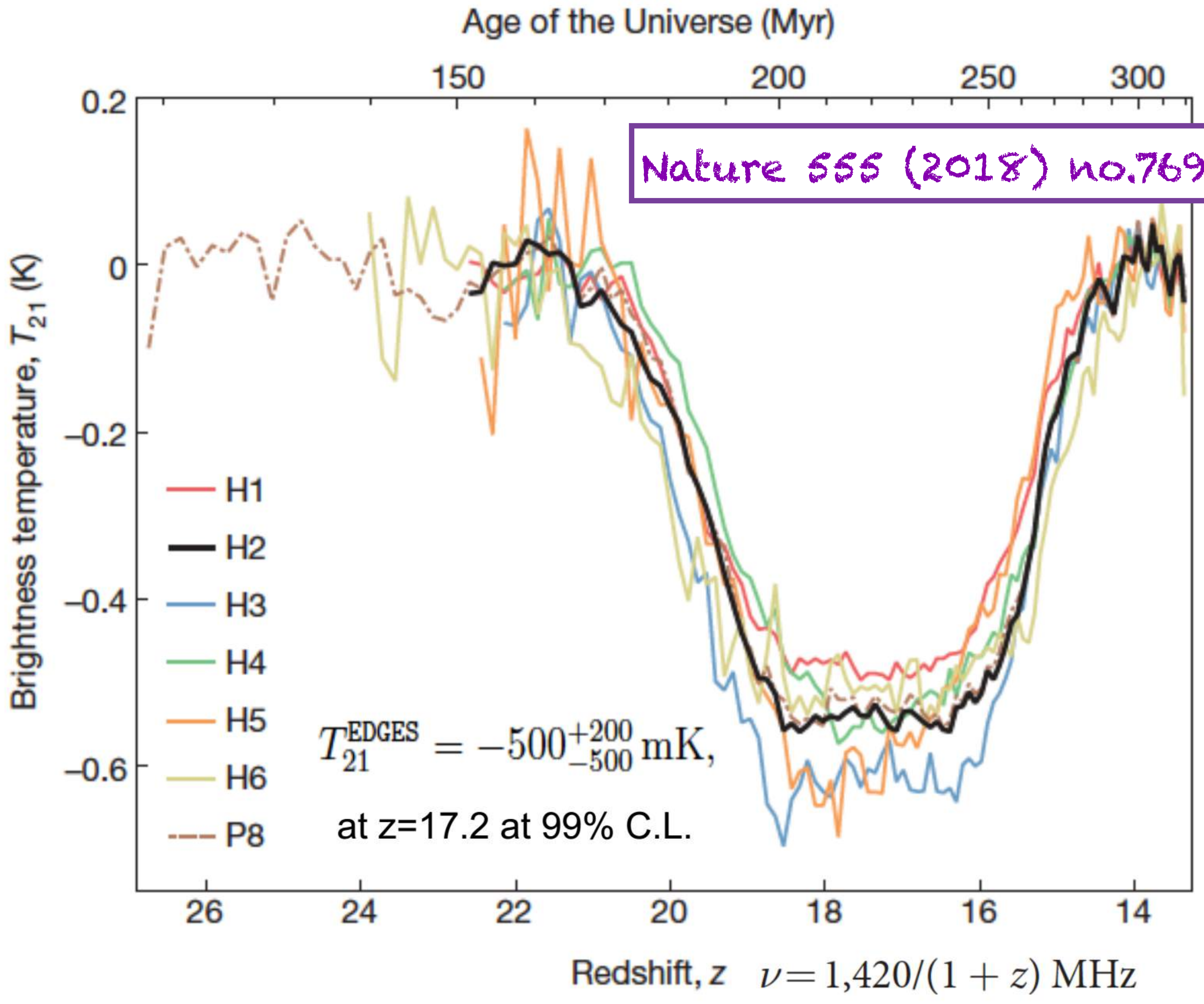


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

$$T_{21}^{\mathrm{EDGES}} = -500^{+200}_{-500}\,\mathrm{mK}$$ @ 99% CL

(The first-star model)
T21=-209 mK
is 3.8 sigma away

Rennan Barkana
Nature 555 (2018) no.7694, 71-74

$$\sigma_{\mathrm{EDGES}} = (500-209)/3.8\,\mathrm{mK}$$

For the EDGES best-fit model, the reported signal-to-noise ratio is 37 at frequency of 78.1 MHz with the amplitude of 0.53 K which is strong enough to treat its likelihood as Gaussian.

$$\mathcal{L} \propto \exp\left[-\frac{\chi^2}{2}\right], \quad \text{where} \quad \chi^2 = \frac{(T_{21}^{\mathrm{EDGES}} - T_{21}^{\mathrm{TH.}})^2}{\sigma_{\mathrm{EDGES}}^2}.$$

How to explain the EDGES measurement?

$$T_{21}(z) \simeq 23\text{mK}\left[1-\frac{T_\gamma(z)}{T_s(z)}\right]\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{0.15}{\Omega_m h^2}\right)\sqrt{\frac{1+z}{10}}x_{HI}$$

The first-star model
T21=-209 mK
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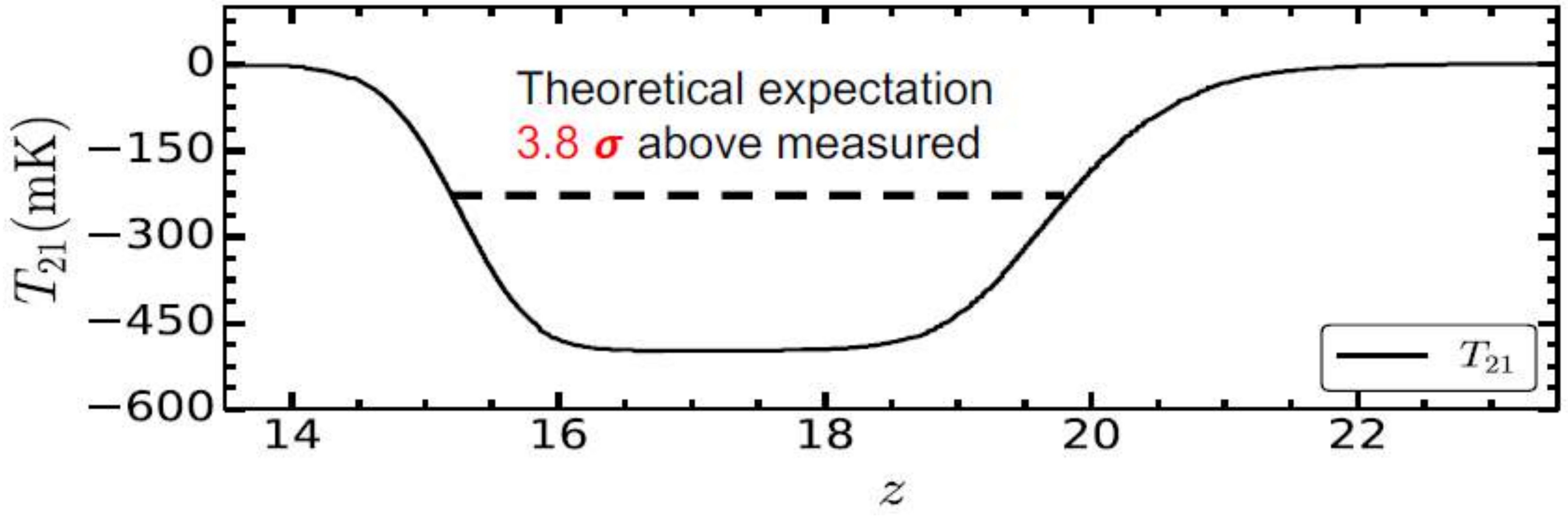
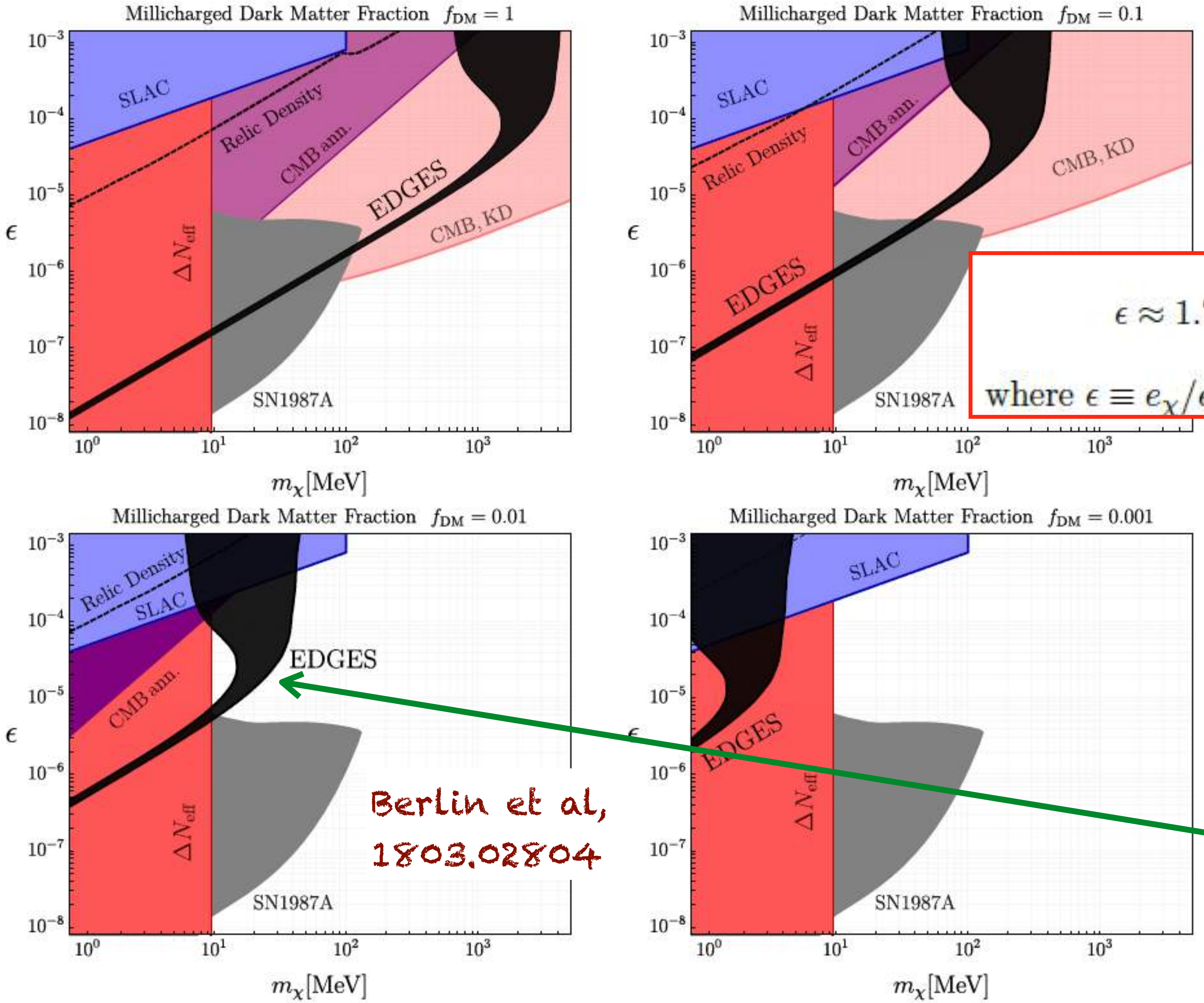
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$



180 m years

① Increase T_gamma:
Excess radiation at cosmic dawn.

② Decrease T_s:
Cold First star, DM cooling.



① Decrease T_s.

② Increase T_gamma.

$$\epsilon \approx 1.7 \times 10^{-4} \left(\frac{m_\chi}{300\,\mathrm{MeV}} \right) \left(\frac{10^{-2}}{f_{\mathrm{DM}}} \right)^{3/4}, \qquad (1)$$

where $\epsilon \equiv e_\chi / e$ is the electric charge of the dark matter.

@ Rutherford Cooling, Xsec ~ v^-4.

@ Too weak coupling to satisfy Relic density.

@ ONLY tiny fraction and small parameter space is ok.

① Decrease T_s.

② Increase T_gamma.

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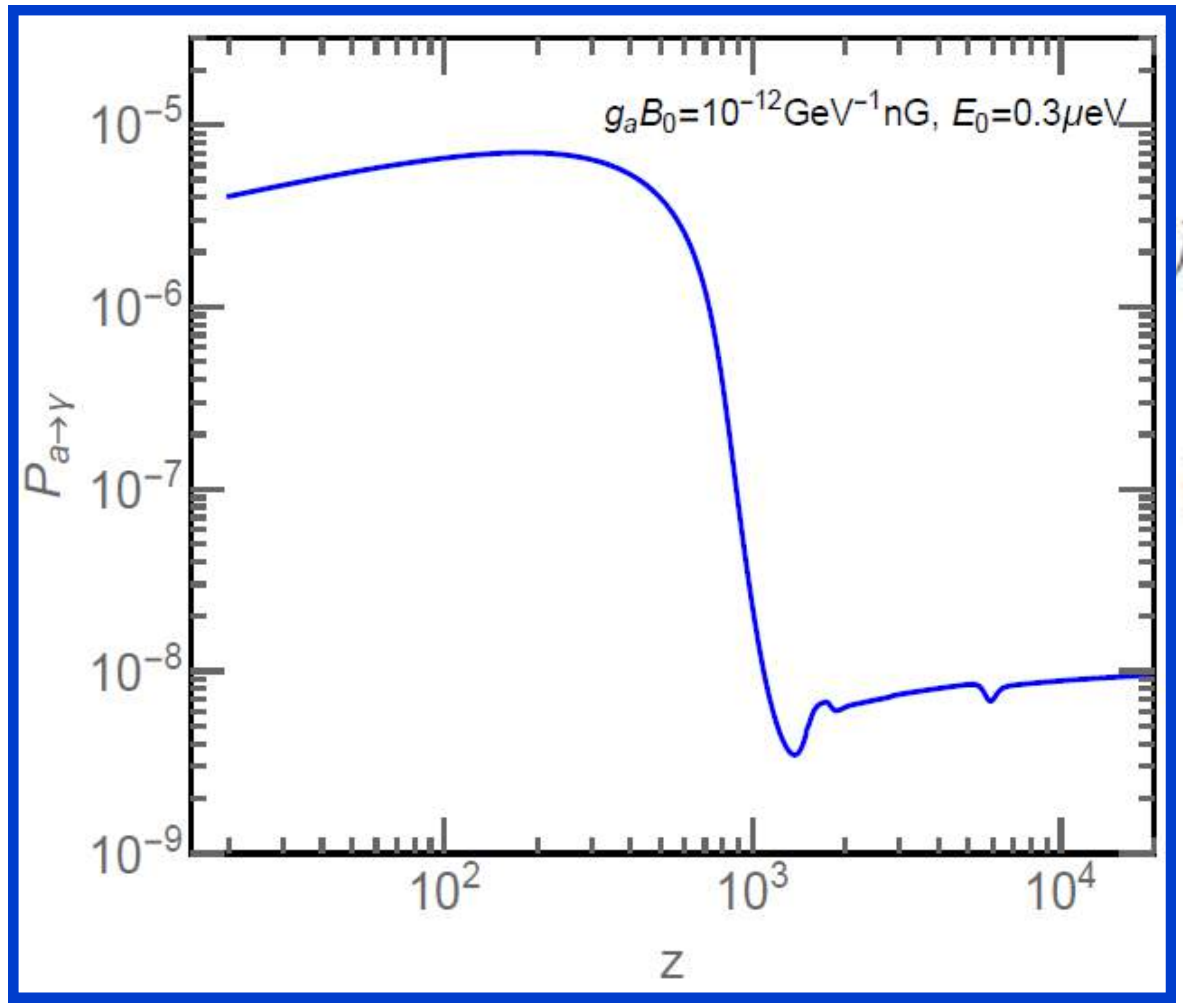


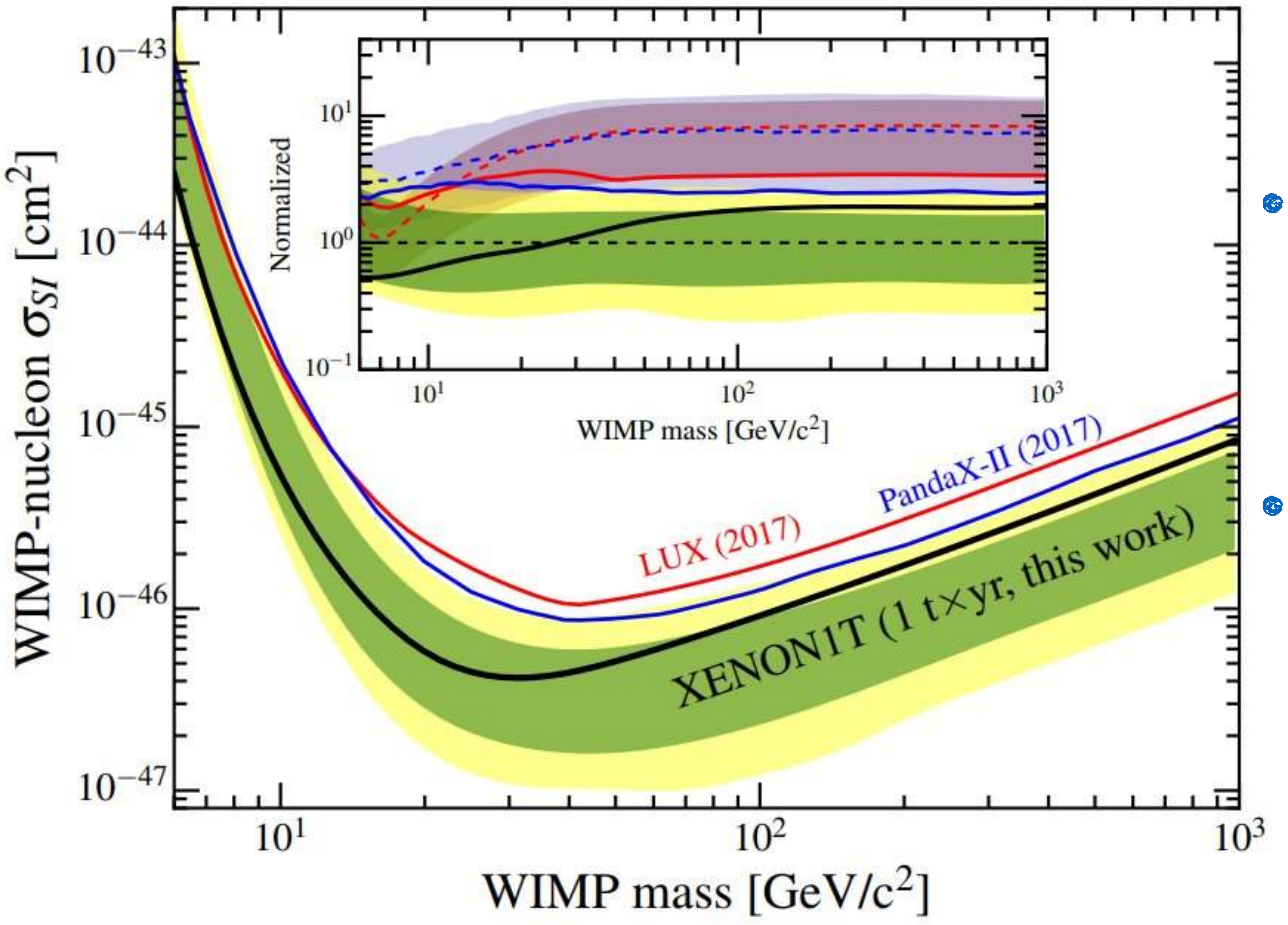
Moroi, Nakayama, and Tang
1804.10378

Abstract

Recently the EDGES experiment reported an enhanced 21cm absorption signal in the radio wave observation, which may be interpreted as either anomalous cooling of baryons or heating of cosmic microwave background photons. In this paper, we pursue the latter possibility. We point out that dark radiation consisting of axion-like particles can resonantly convert into photons under the intergalactic magnetic field, which can effectively heat up the radiation in the frequency range relevant for the EDGES experiment. This may explain the EDGES anomaly.

EDGES 21 cm constraints on the DM (WIMP) annihilation

WIMP-nucleon scattering



- The constraint from WIMP-nucleon scattering is very stringent.
- Based on such a small cross section, DM Cooling is too small.

Dark Matter modified gas temperature and the ionization fraction of hydrogen atom.

$$-\left[\frac{dx_e}{dz}\right]_{\mathrm{DM}} = \sum_{\mathrm{ch}} \int_z \frac{dz'}{H(z')(1+z')} \frac{n_\chi^2(z')}{2n_H(z')} \langle\sigma v\rangle \mathcal{B}(z')\mathrm{BR}_{\mathrm{ch}} \frac{m_\chi}{E_{\mathrm{Ry}}} \frac{d\chi_i(\mathrm{ch}, m_\chi, z', z)}{dz},$$

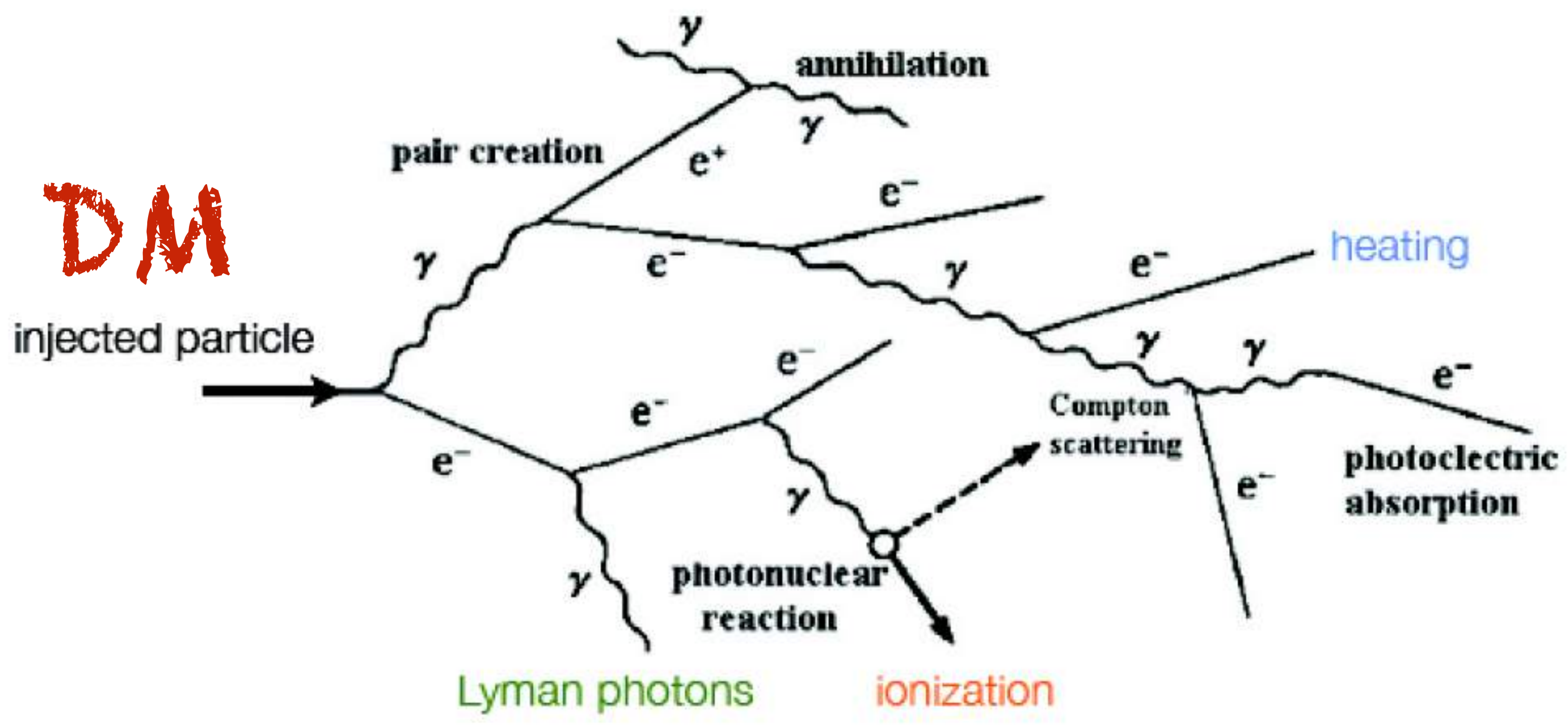
$$-\left[\frac{dT_g}{dz}\right]_{\mathrm{DM}} = \sum_{\mathrm{ch}} \int_z \frac{dz'}{H(z')(1+z')} \frac{n_\chi^2(z')}{3n_H(z')} \langle\sigma v\rangle \mathcal{B}(z')\mathrm{BR}_{\mathrm{ch}} m_\chi \frac{d\chi_h(\mathrm{ch}, m_\chi, z', z)}{dz}$$

dE/dV/dt

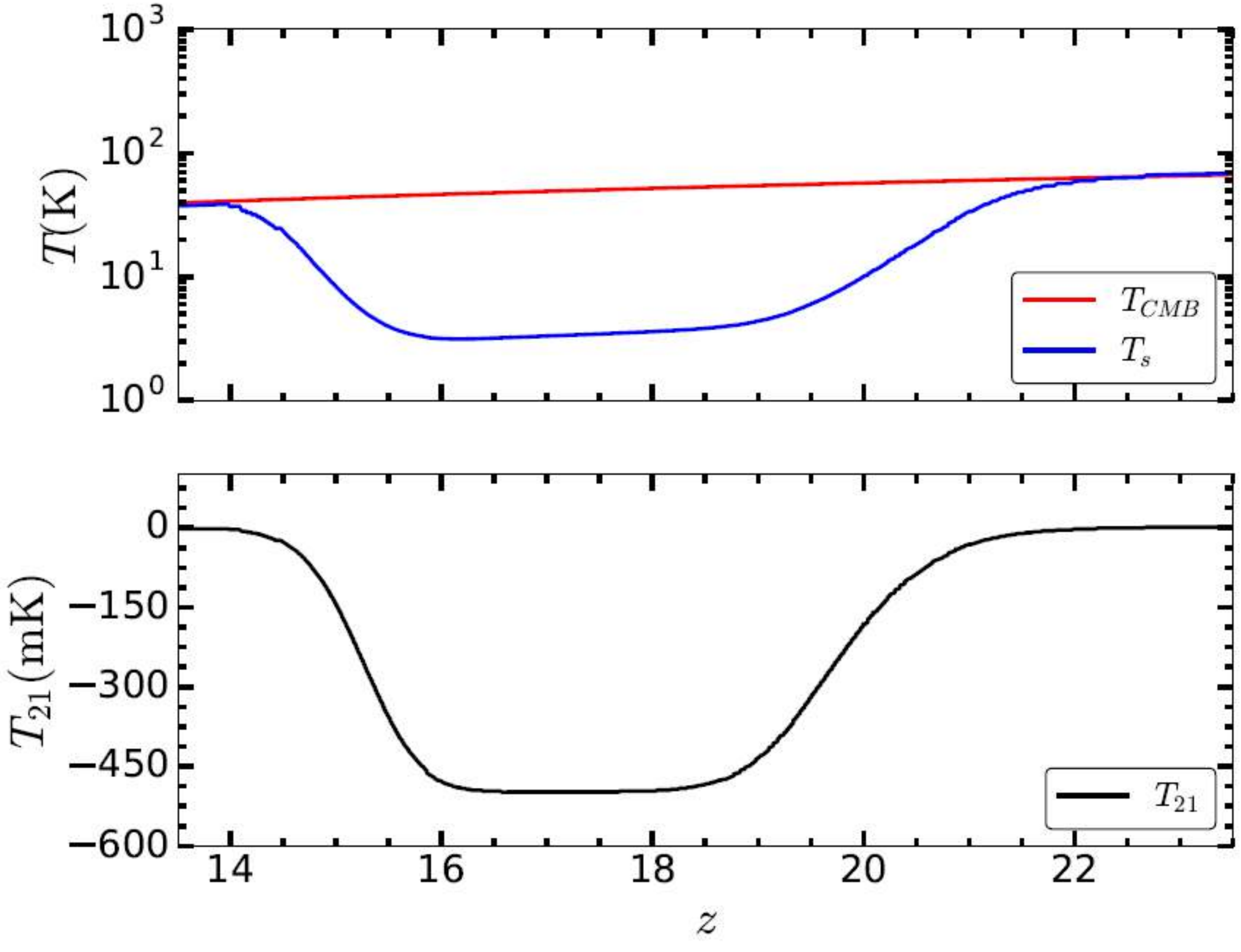
Masahiro Kawasaki, Kazunori Nakayama, Toyokazu Sekiguchi

$$\frac{d\chi_{i,h}(\mathrm{ch}, m_\chi, z', z)}{dz} = \int dE \frac{E}{m_\chi} \left[2\frac{dN_e(\mathrm{ch}, m_\chi)}{dE} \frac{d\chi_{i,h}^{(e)}(E, z', z)}{dz} + \frac{dN_\gamma(\mathrm{ch}, m_\chi)}{dE} \frac{d\chi_{i,h}^{(\gamma)}(E, z', z)}{dz} \right]$$

DM



Null DM signal search



$$T_{21}(z) \simeq 23\text{mK} \left[1 - \frac{T_\gamma(z)}{T_s(z)}\right] \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{0.15}{\Omega_m h^2}\right) \sqrt{\frac{1+z}{10}} x_{HI}$$

① The first-star profile is unsure.

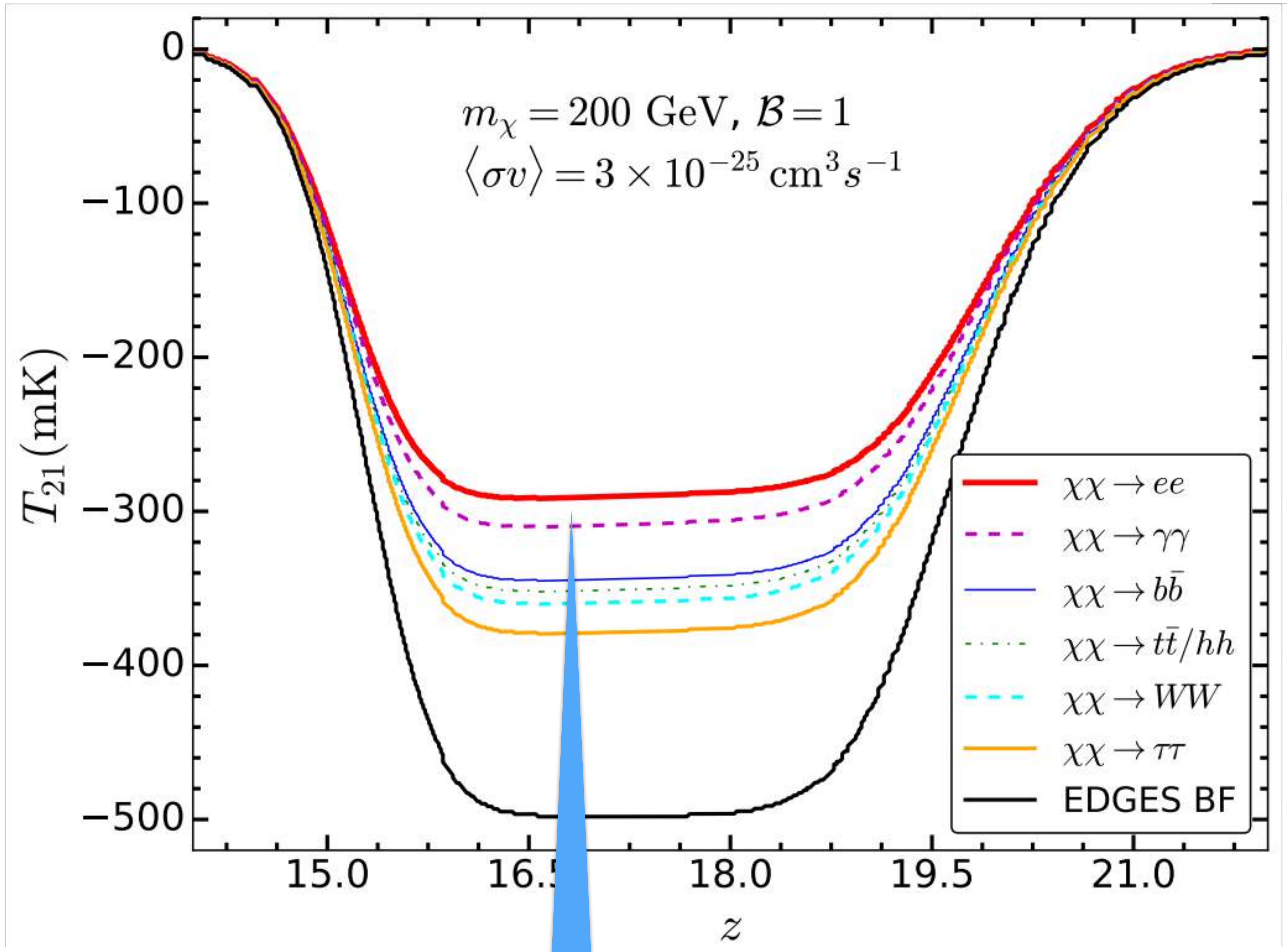
② Our new idea: DM annihilation is not dominant contribution. Hence, the inverted Ts can be presented as the most conservative estimation.

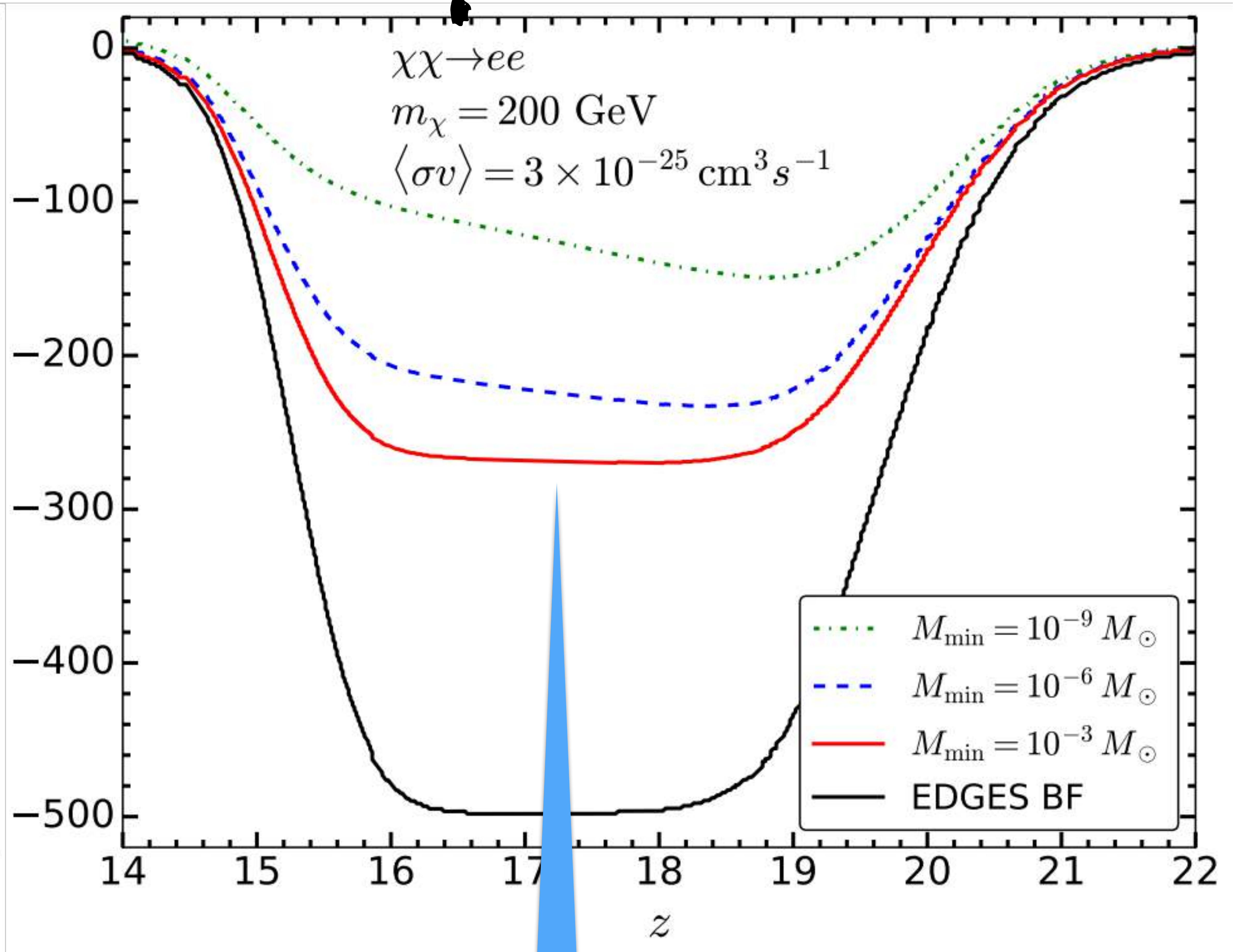
③ Based on such a Ts, one can get rid of the systematical uncertainties of the first star.

FIG. 1: The best-fit model for T_{21} (lower panel) given in the extended data in Fig. 8 of Ref. [6]. The upper panel presents the T_s which is converted from the best-fit model of T_{21} by assuming a null DM search.

Model setup

$$\mathcal{B}(z') = 1 + \frac{b_h \times \texttt{erfc}\left[(1+z')/(1+z_h)\right]}{(1+z')^{\delta}} \times 10^5.$$





The annihilation final state ee and bb are most representative channels.

We choose largest mass resolution.

T_gas=(Data - B + X - Ann);

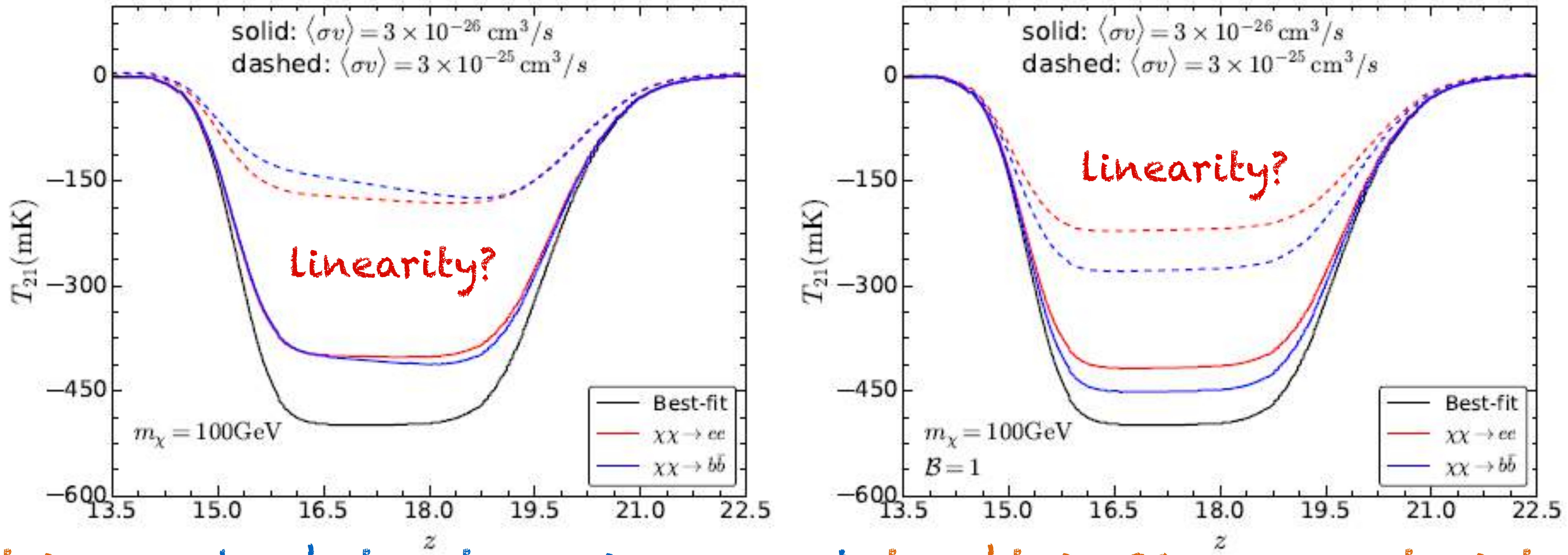
where

B: All non-DM annihilation sources

Ann: DM annihilation

X: Some additional DM introduced cooling, X~(1+eta)*Ann

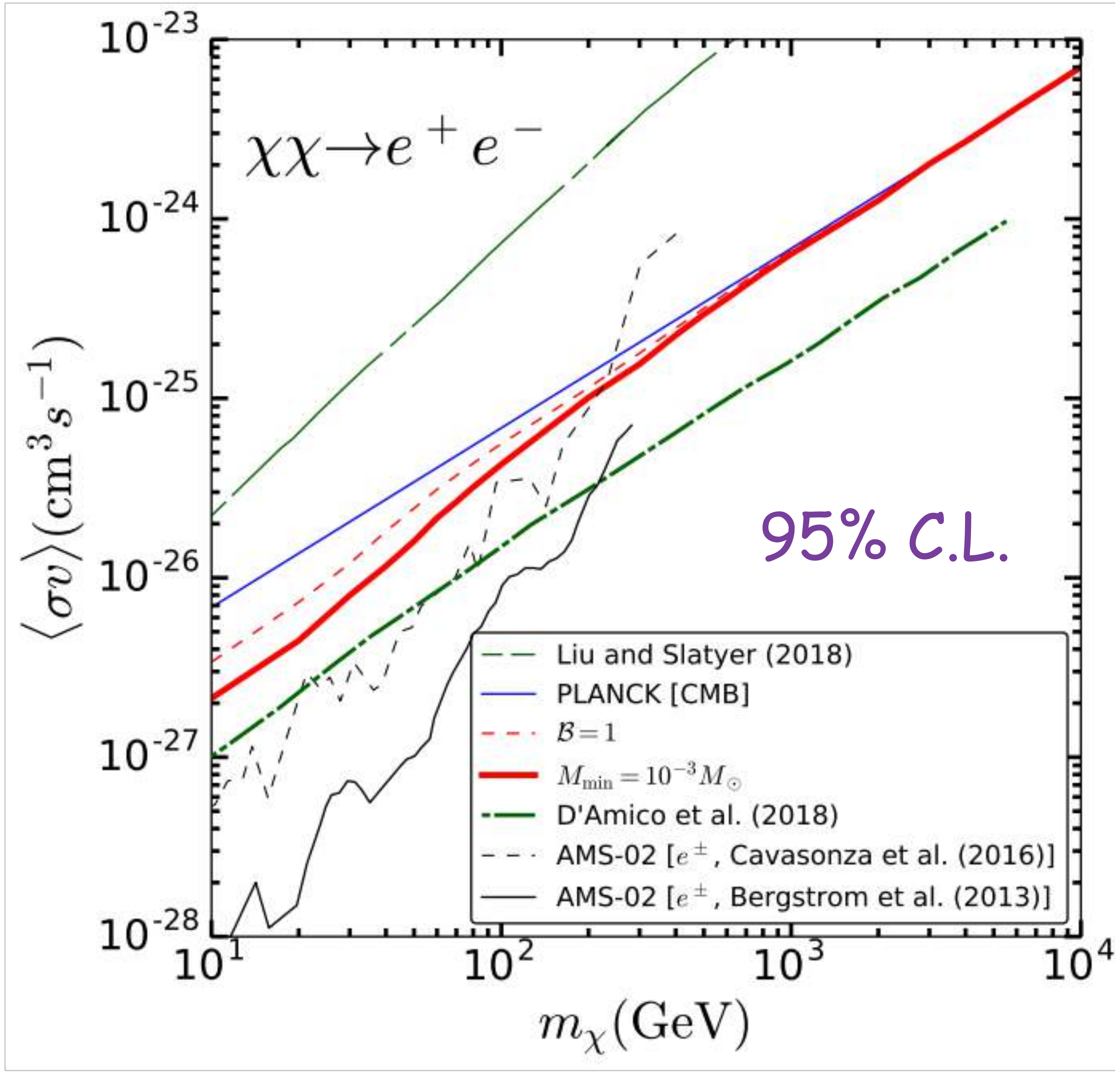
- For null-DM-signal search, Data-B=0.
- eta+1<0 shall be counted as B but our limit is more conservative.
- eta+1>0, some uncertainties are introduced but it is unrealistic for WIMP.
- If |X|~Ann (eta=0, subset of above), it will be not possible under WIMP scenario, because of DM Direct detection limit.
- Exception: X is new source and not DM. X-Ann~zero, very fine-tuned.



It is popular but not precise enough to obtain 21 cm constraints by using wrapped energy fraction (feff).

FIG. 2: The comparison of the effects from different DM annihilation channels and cross sections on the T_{21} signal, with the boost factor (left panel) and without the boost factor (right panel). The black solid line is the T_{21} signal from EDGES. The red lines represent the modified T_{21} temperatures with DM annihilation process $\chi\chi\to e^+e^-$ while the blue lines represent those with DM annihilation process $\chi\chi\to b\bar{b}$.

EDGES DM constraints



- EDGES limit is more stringent than Planck CMB limits.
- Below 100 GeV, EDGES limit is stronger than Fermi dSphs limit.
- AMS02 antiproton constraints is overall stronger, except 100 GeV window.
- With the boost factor: the ee channel is only slightly more stringent than bb channel.
- Without the boost factor: the ee channel is 2-3 times more stringent than bb channel.

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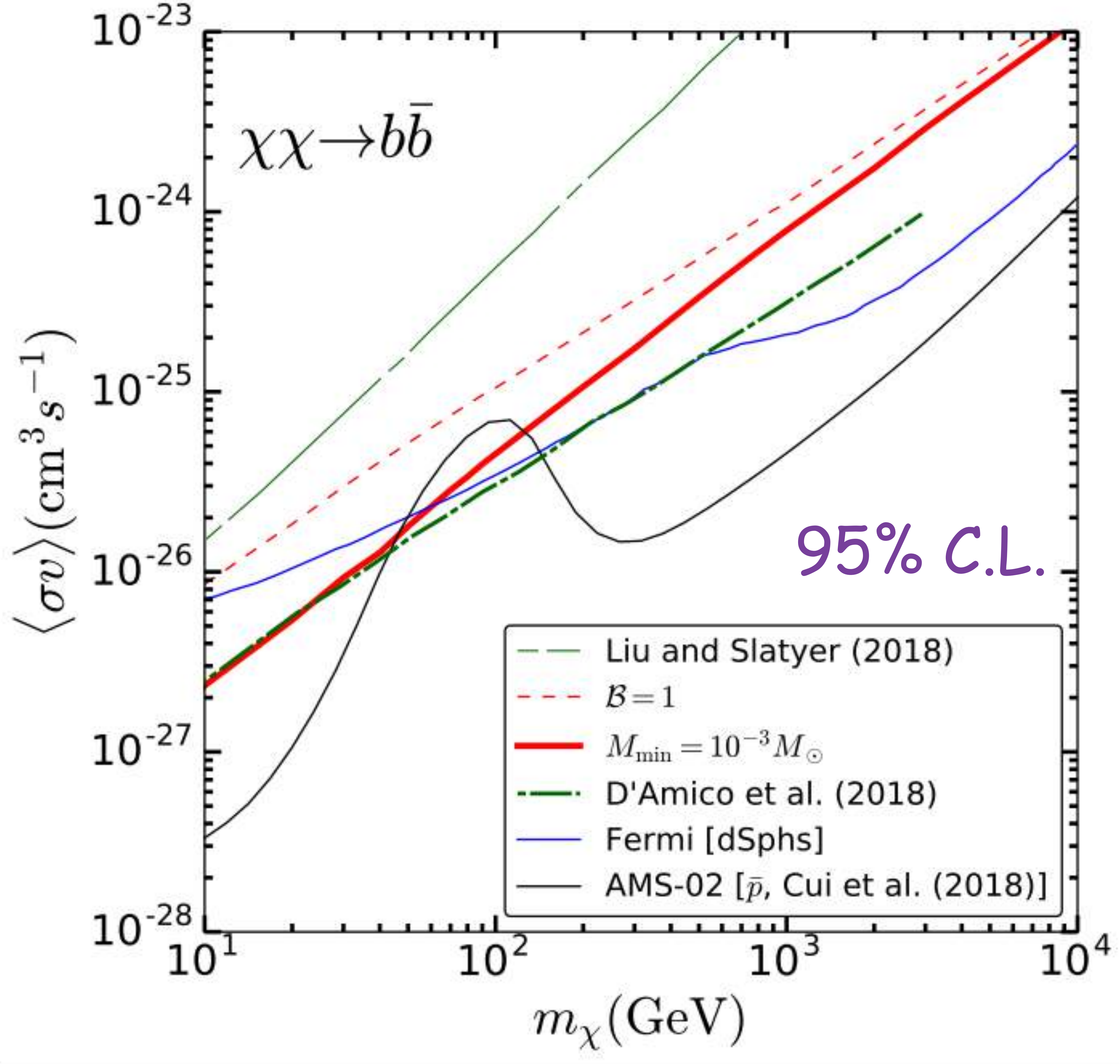
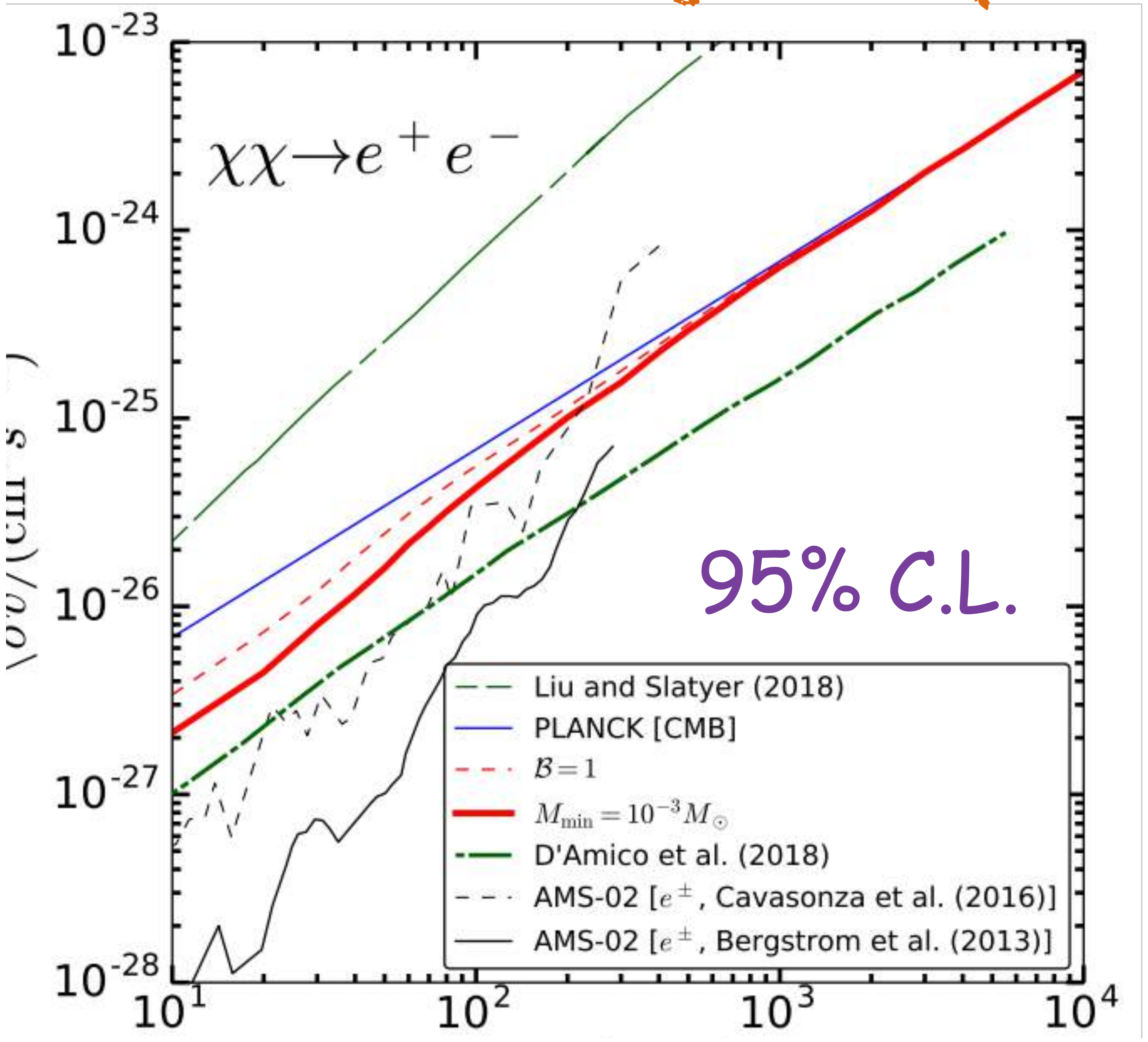
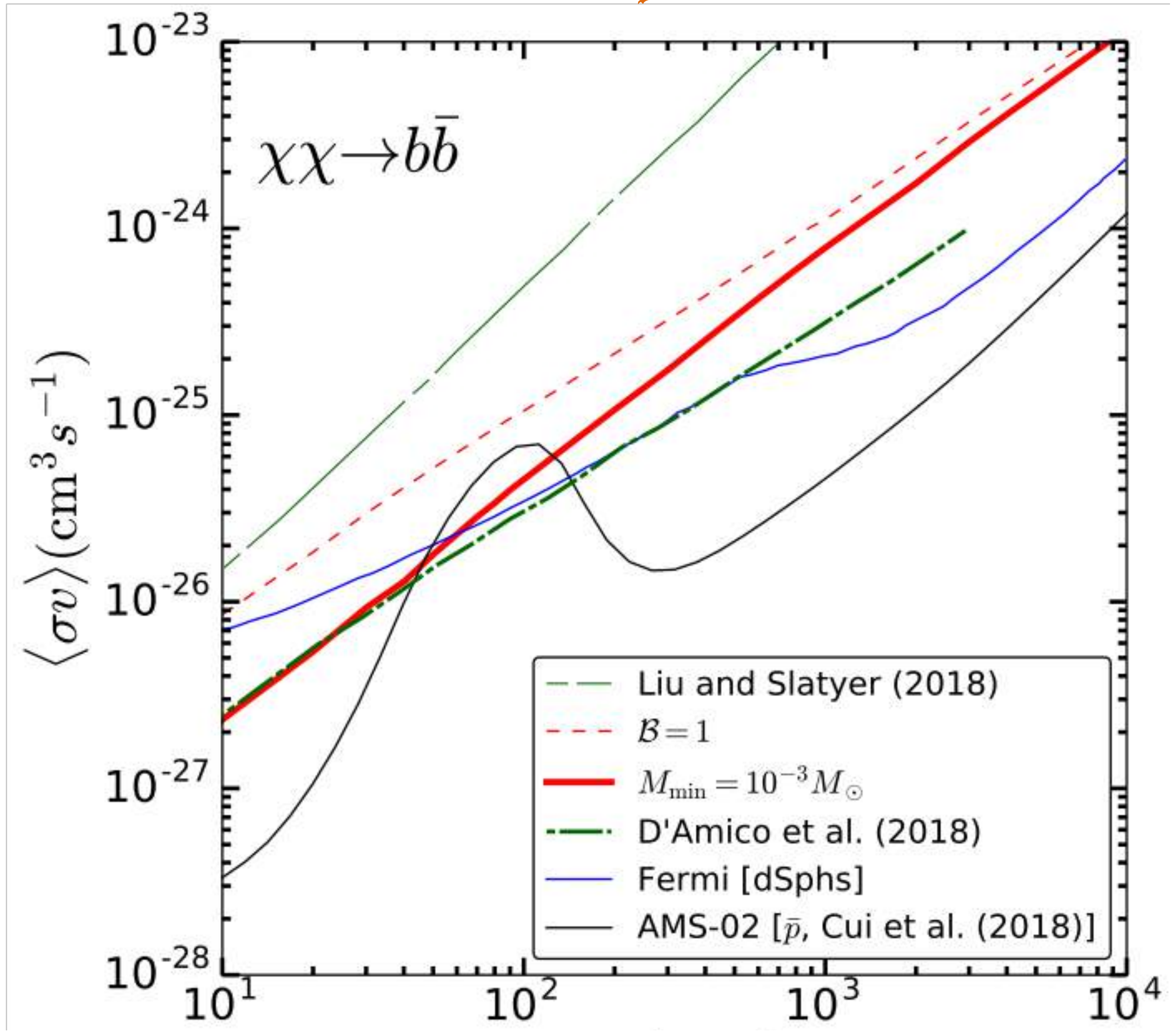


EDGES DM constraints





With the boost factor:

the ee channel is only slightly more stringent than bb channel.

Without the boost factor:

the ee channel is 2-3 times more stringent than bb channel.

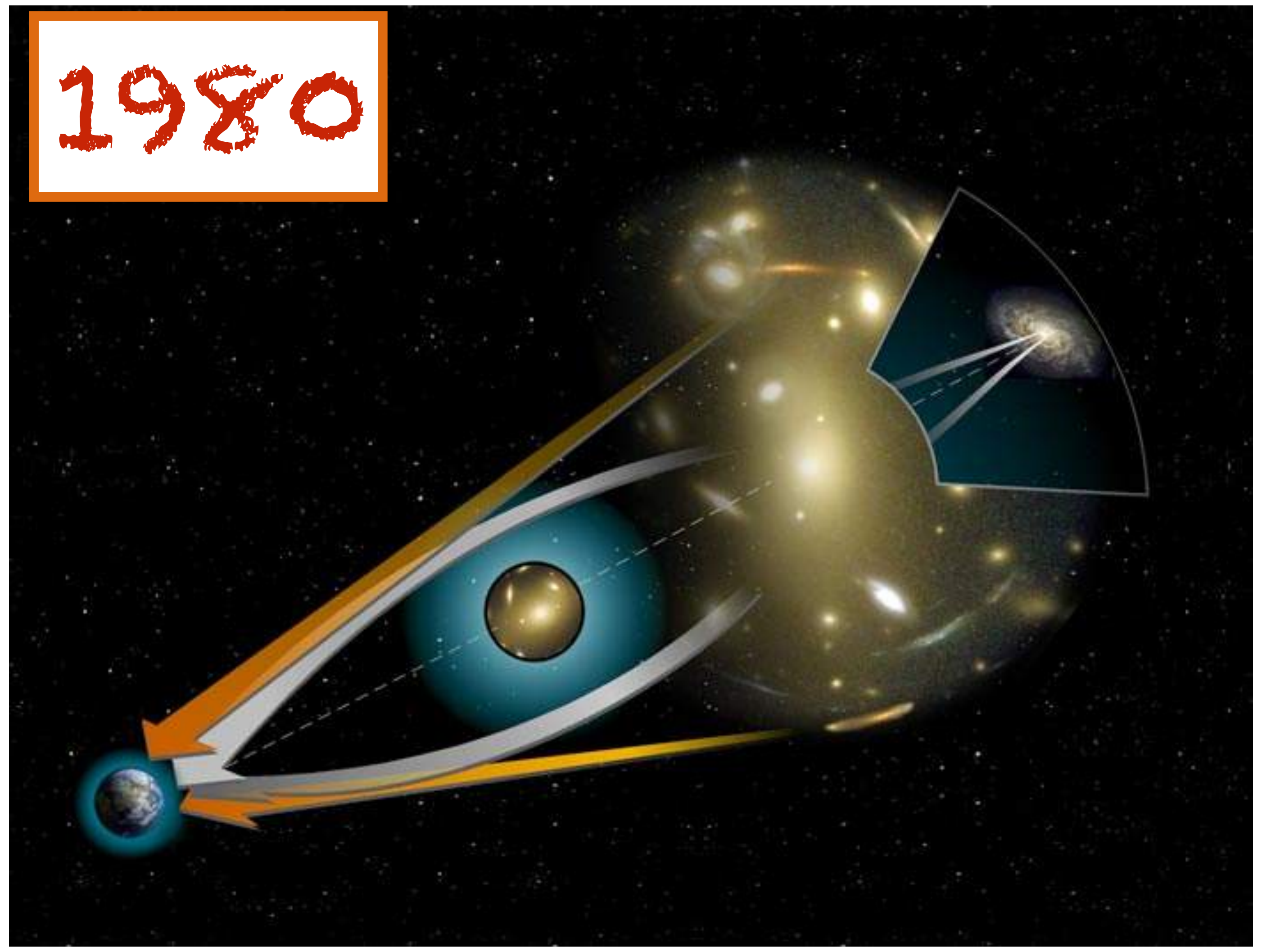
Summary and conclusion

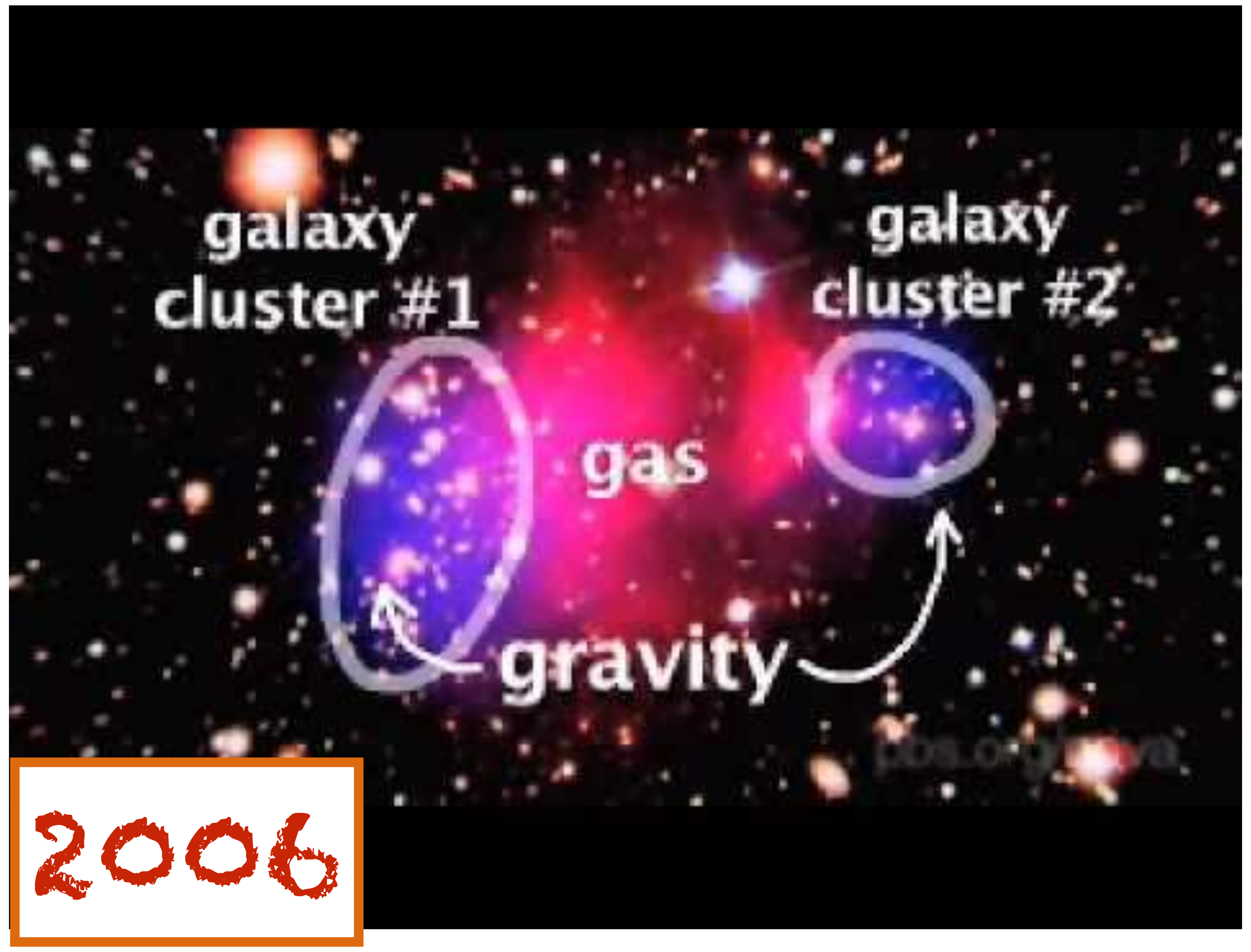
- In null DM-signal approach, one can simply bypass the unclear model uncertainties of the formation of first stars.
- We directly computes the propagation of the injected energy and does not assume any energy fraction (feff) in the calculation.
- With the modified 21 cm brightness temperature evolution, the new constraints on the ee and bb channels are given.
- EDGES limits are comparable to the constraints from the Fermi dSphs data and the AMS-02 antiproton data.
- EDGES limits are more stringent than Planck CMB limits.

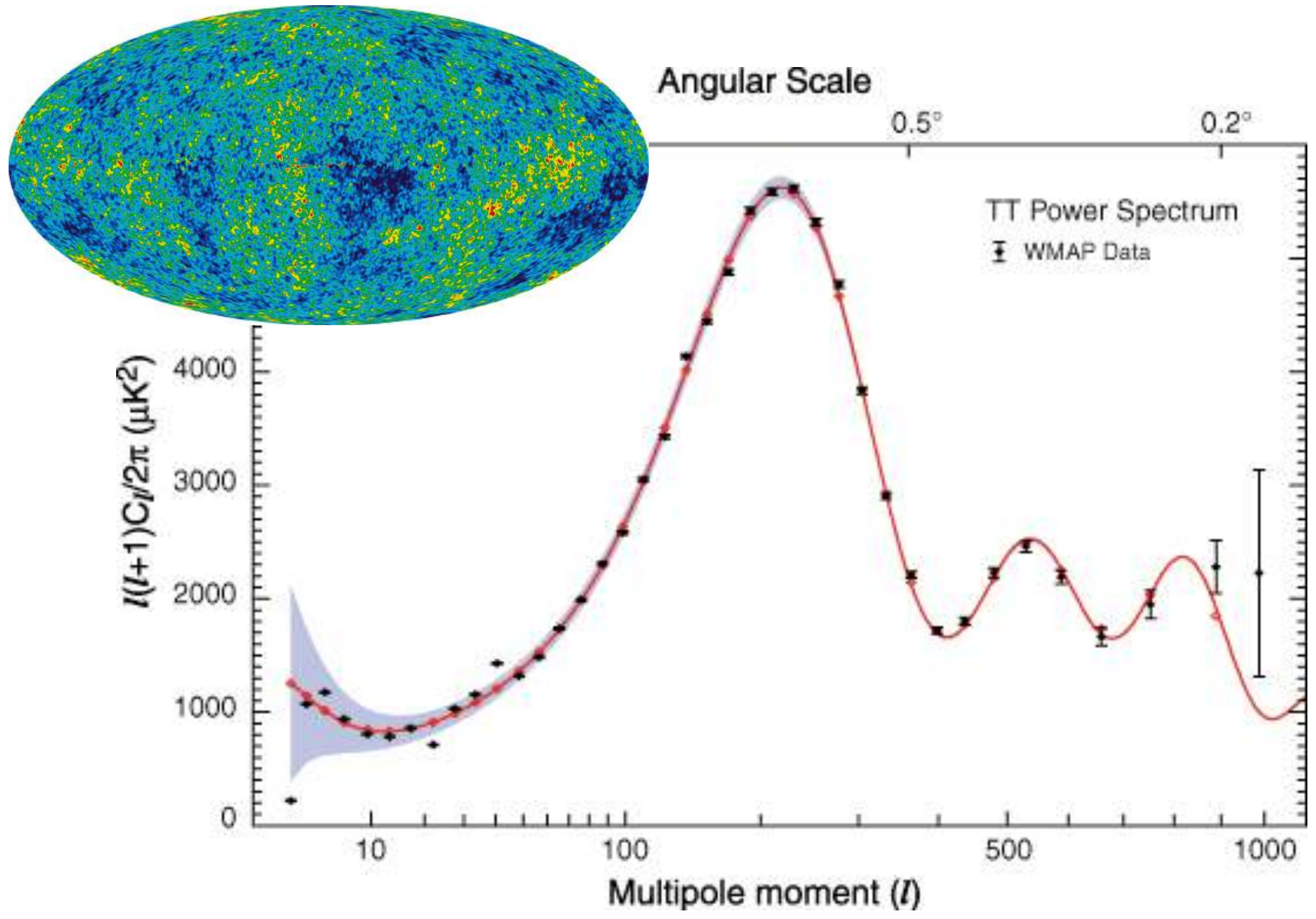
「Right now is an exciting time, because everybody is thinking about where we should go next with new frontiers opening up。」

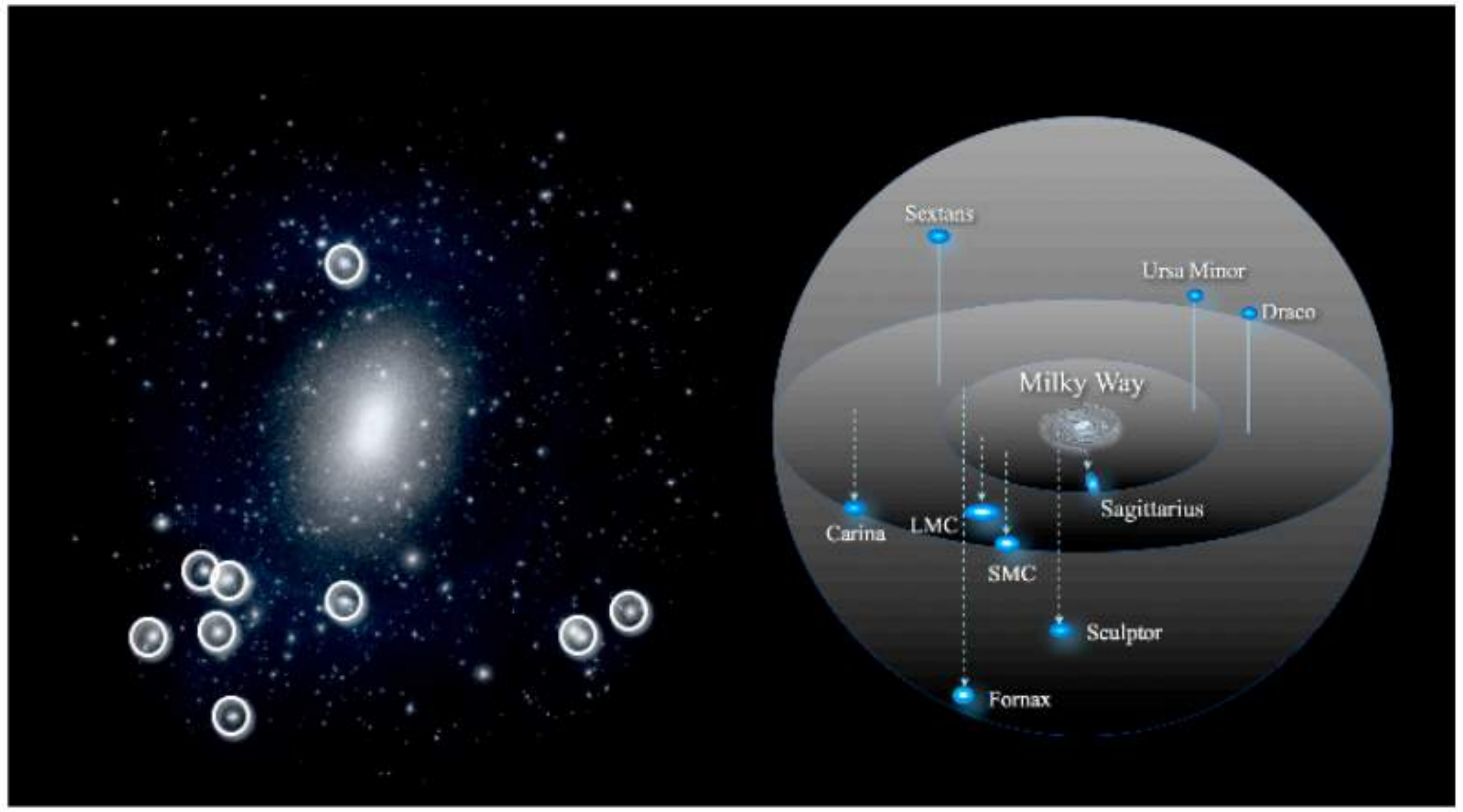
- Cooley, APS NEWS, July 2018 (Volume 27, Number 7)

Dark Matter

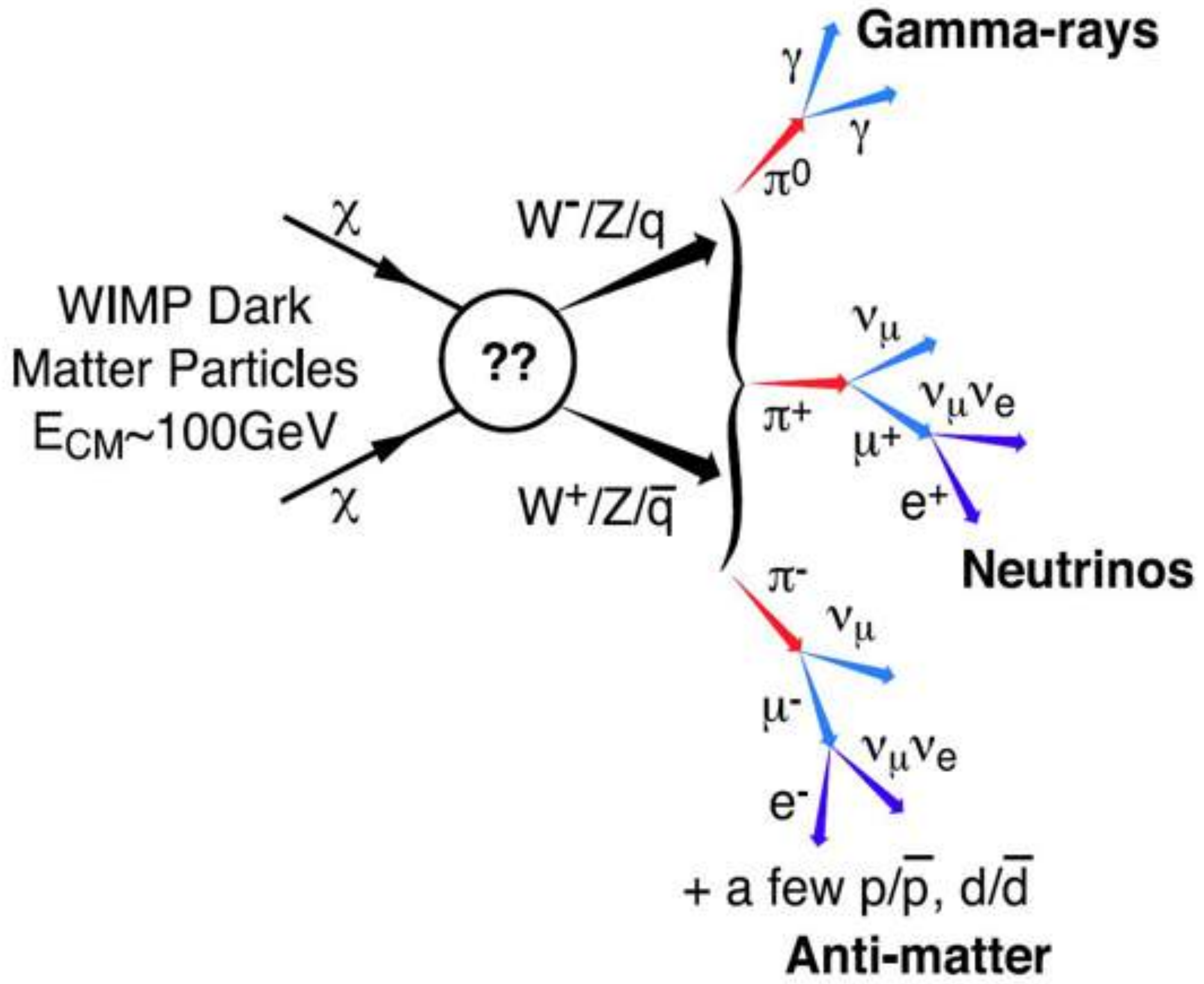








It will be difficult to explain the universe without DM assumption.



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The first-star model
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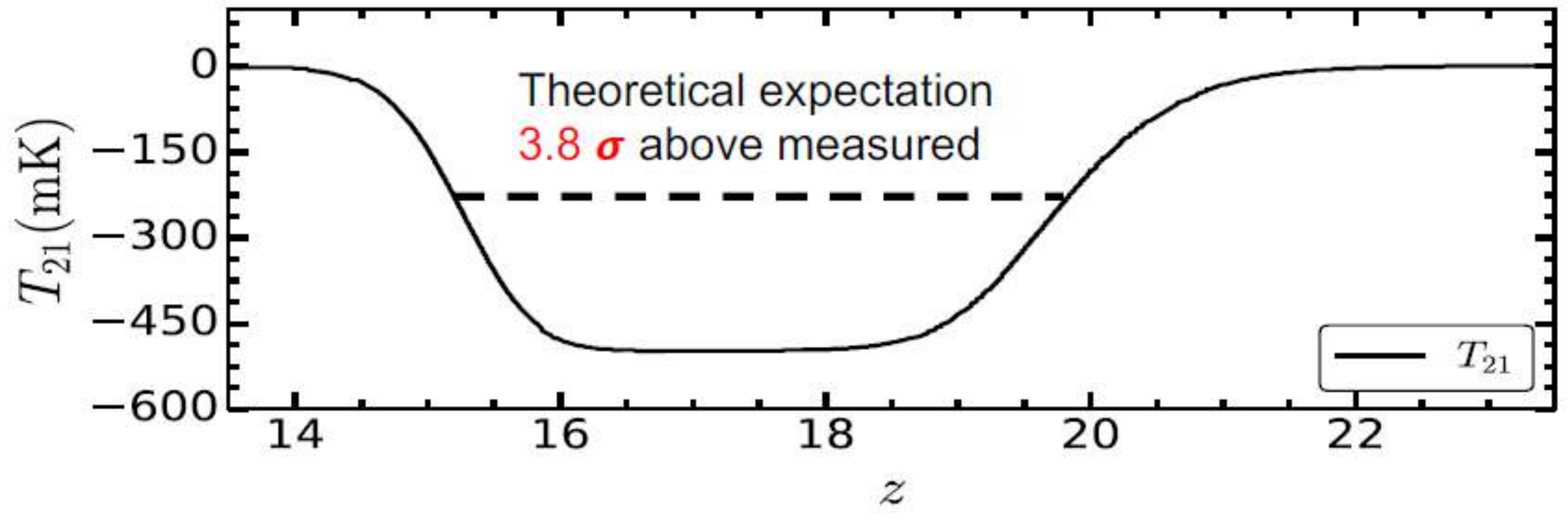
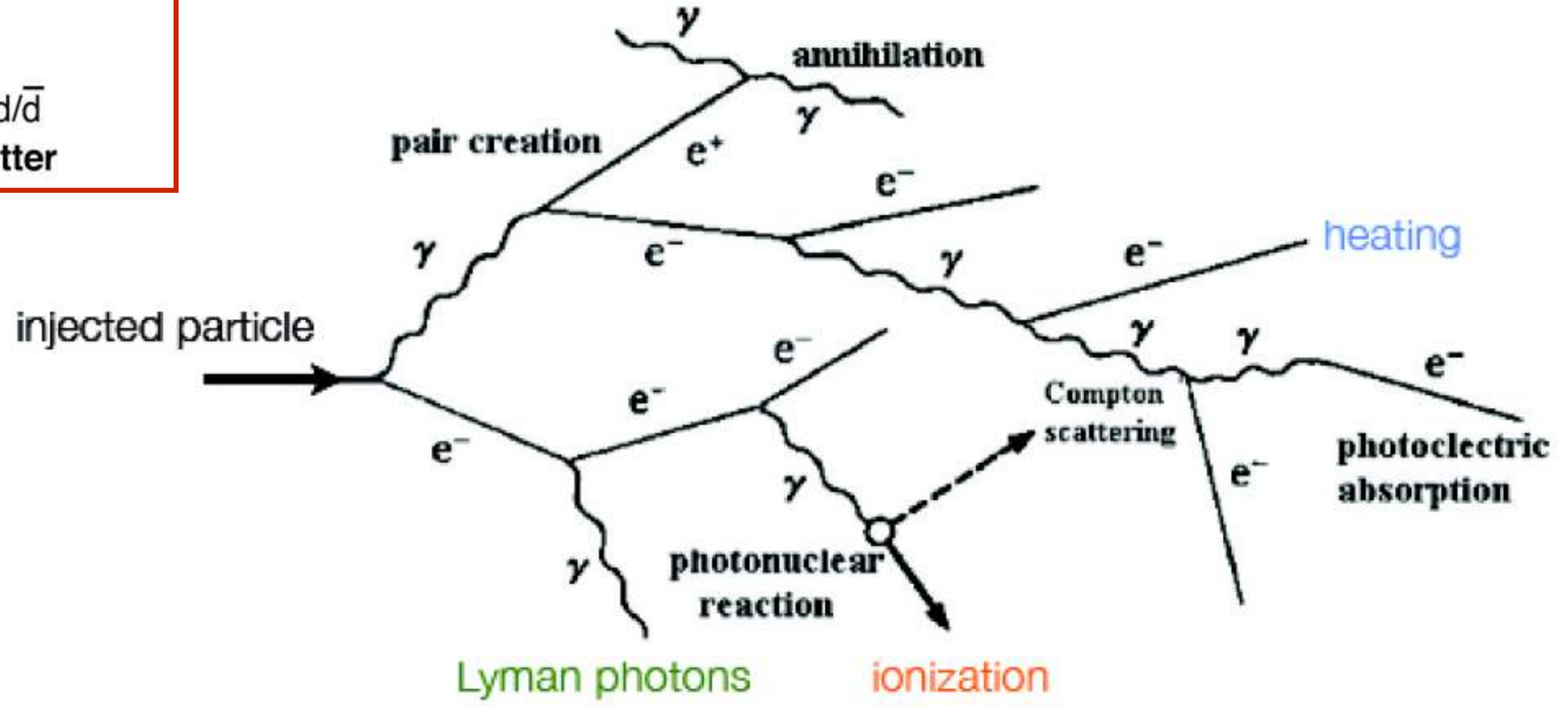
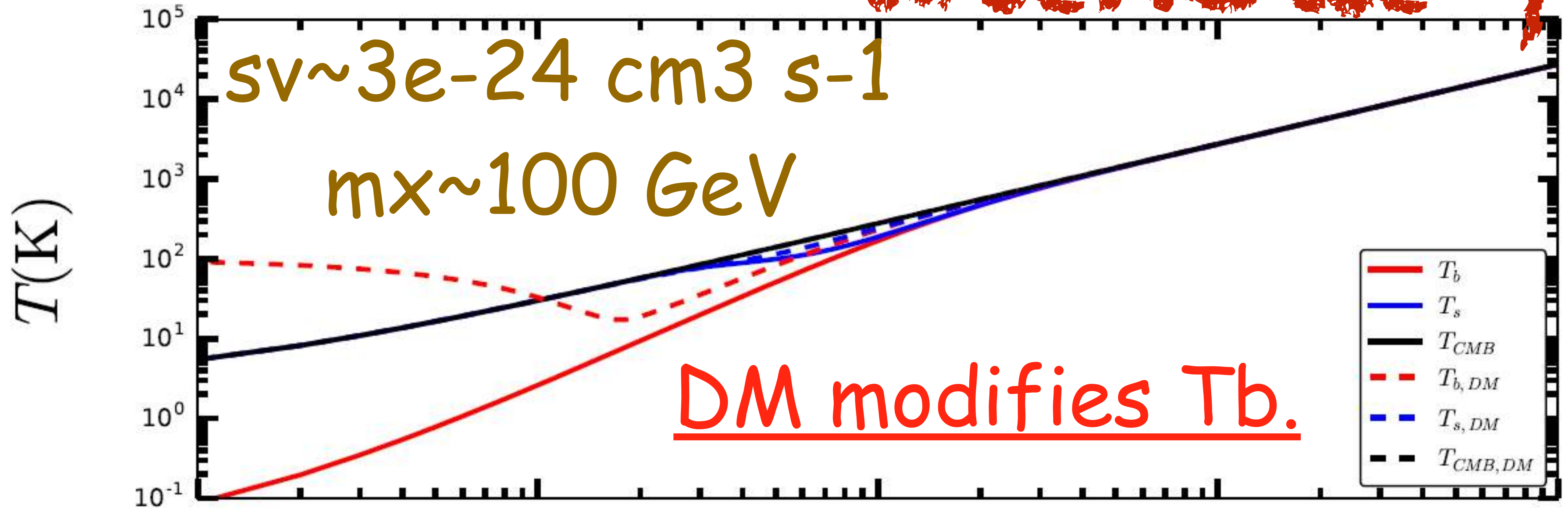
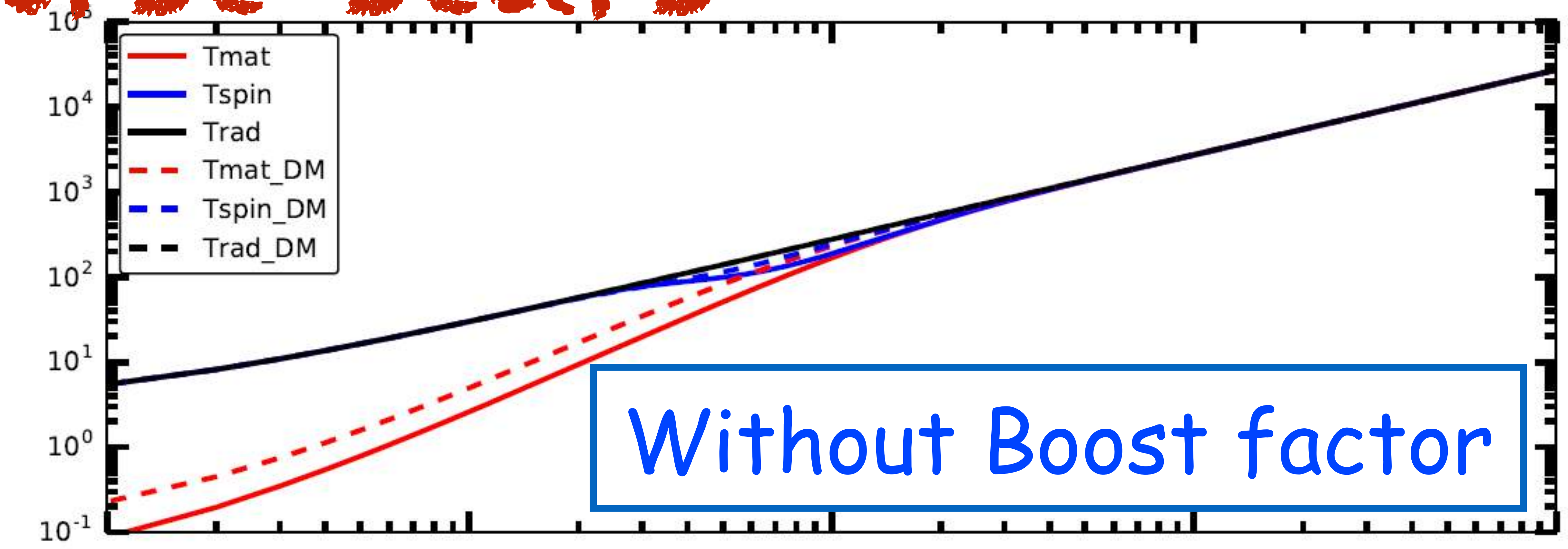


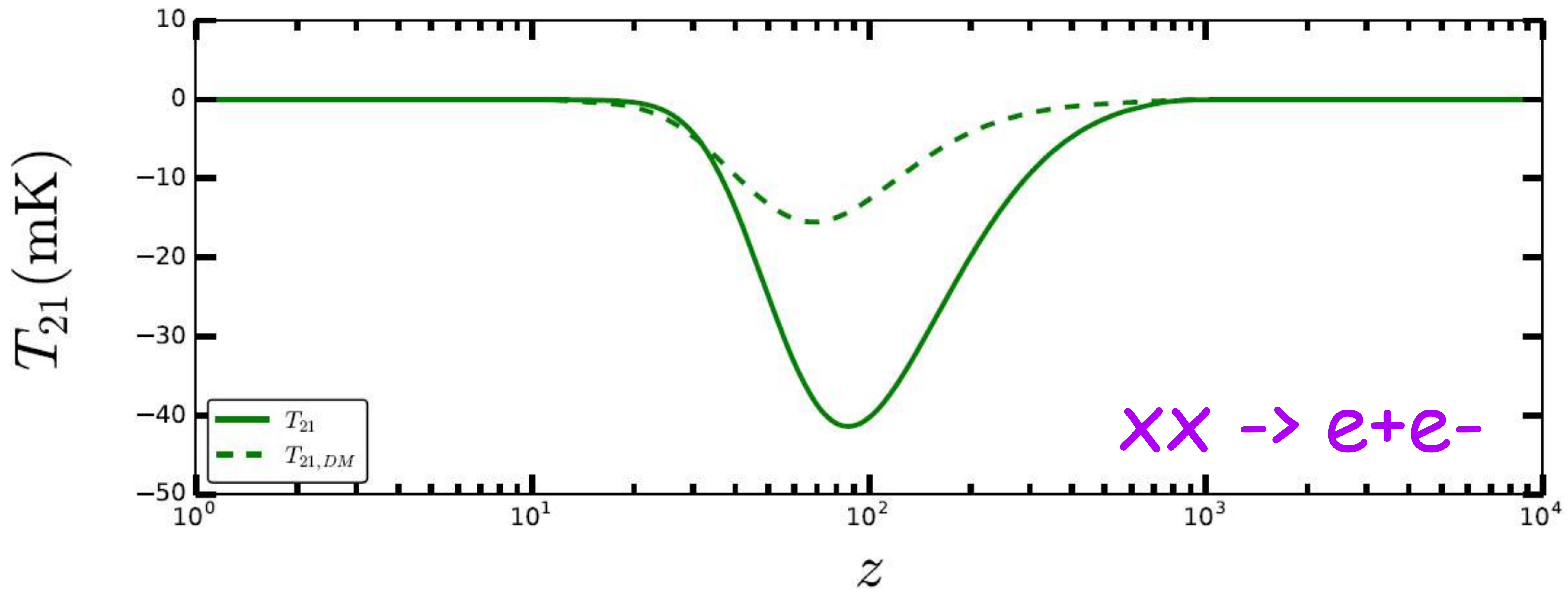


The DM annihilation can only HEAT the gas temperature. This means the power of constraint can be strong!

Temperatures versus redshift without first stars







With Boost factor

① Boost factor is larger at small redshift.

$$\mathcal{B}(z') = 1 + \frac{1.6 \times \mathrm{erfc}\left[(1+z')/20.5\right]}{(1+z')^{1.54}} \times 10^5.$$

② DM annihilation only enhance T21, so it is some tension with the EDGES data.

③ DM contribution is varied with redshift.

Foregrounds

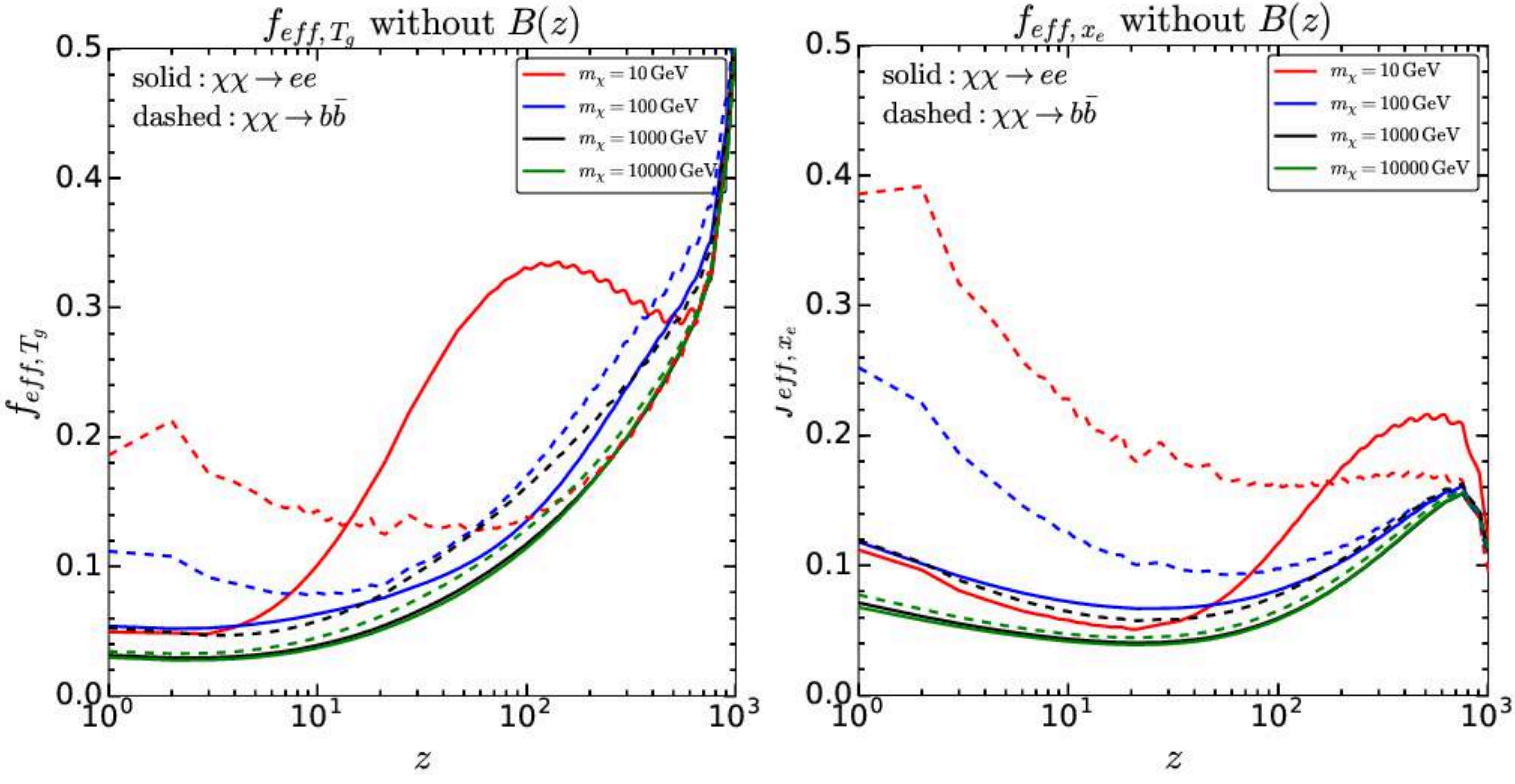
- Many foregrounds
  - Galactic synchrotron (especially polarized component)
  - Radio Frequency Interference (RFI)
    e.g. radio, cell phones, digital radio
  - Radio recombination lines
  - Radio point sources
- Foregrounds dwarf signal:
  foregrounds ~1000s K vs 10s mK signal
- Strong frequency dependence $T_{sky} \propto \nu^{-2.6}$
- Foreground removal exploits smoothness in frequency and spatial symmetries

Taken from J. Pritchard's Talk.

Why EDGES measurement is important to DM search?

Signals at	Experiments	DM Hints
Coillders (missing energy)	LHC, LEP, Tevatron, ...	~~760 GeV scalar~~
Direct detection (SM recoil energy)	XENON1T, LUX, PandaX...	DAMA, CoGeNT, CRESST at low DM mass region.
Cosmic rays 1. Positrons 2. antiprotons 3. neutrinos	1. PAMELA, Fermi-LAT, AMS02, DAMPE 2. PAMELA, AMS02 3. IceCube	1. High energy positron excess 2. 70 GeV excess 3. TeV-PeV neutrinos
Gamma rays	Fermi-LAT, HESS, ...	FERMI bubbles, GCE
X-ray	XMM-Newton	~~3.55 keV line(?)~~

Those signals are contradictory.
Sounds like WIMPs search is pessimistic.



f_{eff,T_g} without $B(z)$
solid : $\chi\chi \to ee$
dashed : $\chi\chi \to b\bar{b}$
$m_\chi = 10\,\mathrm{GeV}$
$m_\chi = 100\,\mathrm{GeV}$
$m_\chi = 1000\,\mathrm{GeV}$
$m_\chi = 10000\,\mathrm{GeV}$
f_{eff,T_g}
z
f_{eff,x_e} without $B(z)$
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$m_\chi = 10\,\mathrm{GeV}$
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z