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Constraining the abundance of primordial black holes using EDGES 21-cm signal

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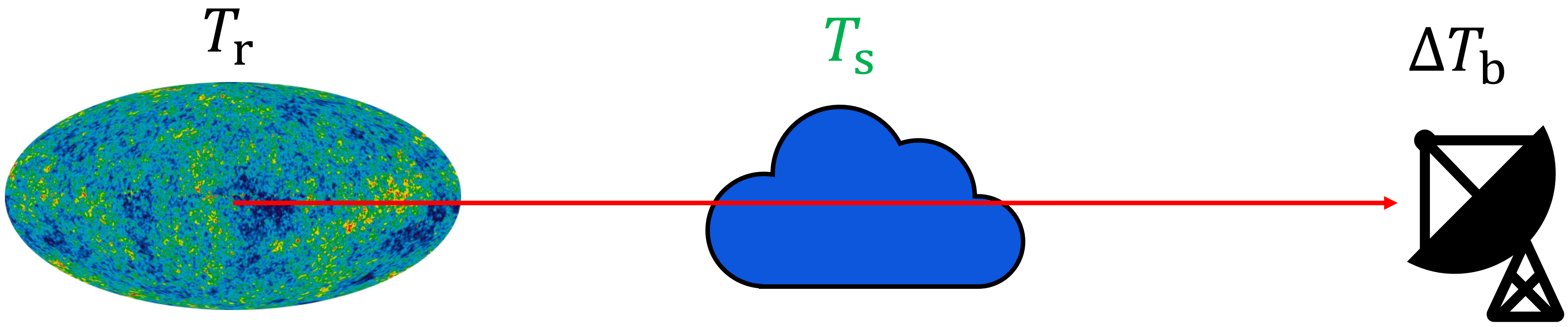
State of the Universe

The Global 21-cm Signal



Our observable is the 21-cm brightness temperature relative to the background (CMB) temperature:

$$\Delta T_b = 27 x_{HI} \left(\frac{1 - Y_P}{0.76}\right) \left(\frac{\Omega_B h^2}{0.023}\right) \sqrt{\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}} \left(1 - \frac{T_r}{T_s}\right) \text{ mK}$$

e.g., Madau et al. (1997), Furlanetto (2006)

T_s is determined by 2 processes at cosmic dawn

$$\frac{n_1}{n_0} \equiv 3\exp\left(-\frac{h\nu_{21\mathrm{cm}}}{k_\mathrm{B}T_\mathrm{s}}\right), \qquad \nu_{21\mathrm{cm}} = 1420\ \mathrm{MHz}$$

1. Stimulated, spontaneous emission and stimulated absorption
2. By the Lyman-α photons (through Wouthuysen-Field effect)

$$T_\mathrm{s}^{-1} \approx \frac{T_\mathrm{r}^{-1} + x_\alpha T_\mathrm{k}^{-1}}{1 + x_\alpha}$$

T_k = Gas temperature

x_α = Ly α coupling

Wouthuysen (1952); Field (1958); Madau et al. (1997)

Equation governing the evolution of T_k with z

$$(1+z)\frac{\mathrm{d}T_\mathrm{k}}{\mathrm{d}z} = 2T_\mathrm{k} - \sum \frac{2q}{3n_\mathrm{b}k_\mathrm{B}H(z)}$$

Adiabatic cooling

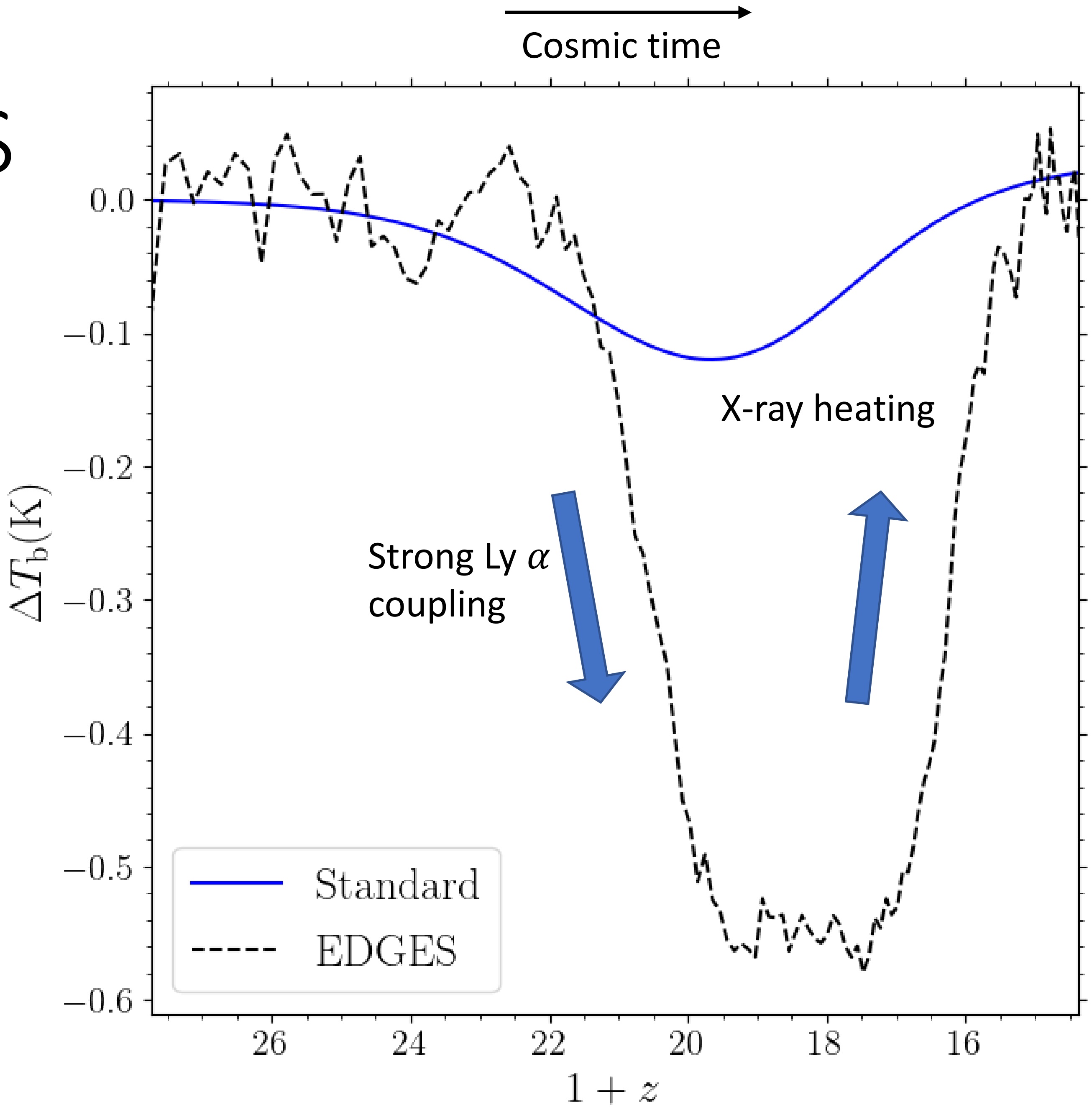
where q is the volumetric heating rate.

e.g. Mittal & Kulkarni (2020)

The 21-cm signal detected by the EDGES collaboration

EDGES: **E**xperiment to **D**etect the **G**lobal **E**poch of reionization **S**ignal

$$\Delta T_{\mathrm{b}} \propto \left(1 - \frac{T_{\mathrm{r}}\uparrow}{T_{\mathrm{s}}\downarrow}\right)$$



Bowman et al. (2018)

Summary of parameters affecting 21-cm signal

Parameter	Description
$\log f_\alpha$	Lyα background
$\log\left(\frac{T_{\rm vir}}{10^4}\right)$	Star formation rate
$\log f_{\rm X}$	X-ray background
$\log \zeta_{\rm ERB}$	Excess radio background
$\log f_{\rm PBH}$	Abundance of PBH

1. Changing the strength of Ly α Coupling

$$x_\alpha \propto J_\alpha \propto f_\alpha \phi_\alpha \dot{\rho}_\star$$

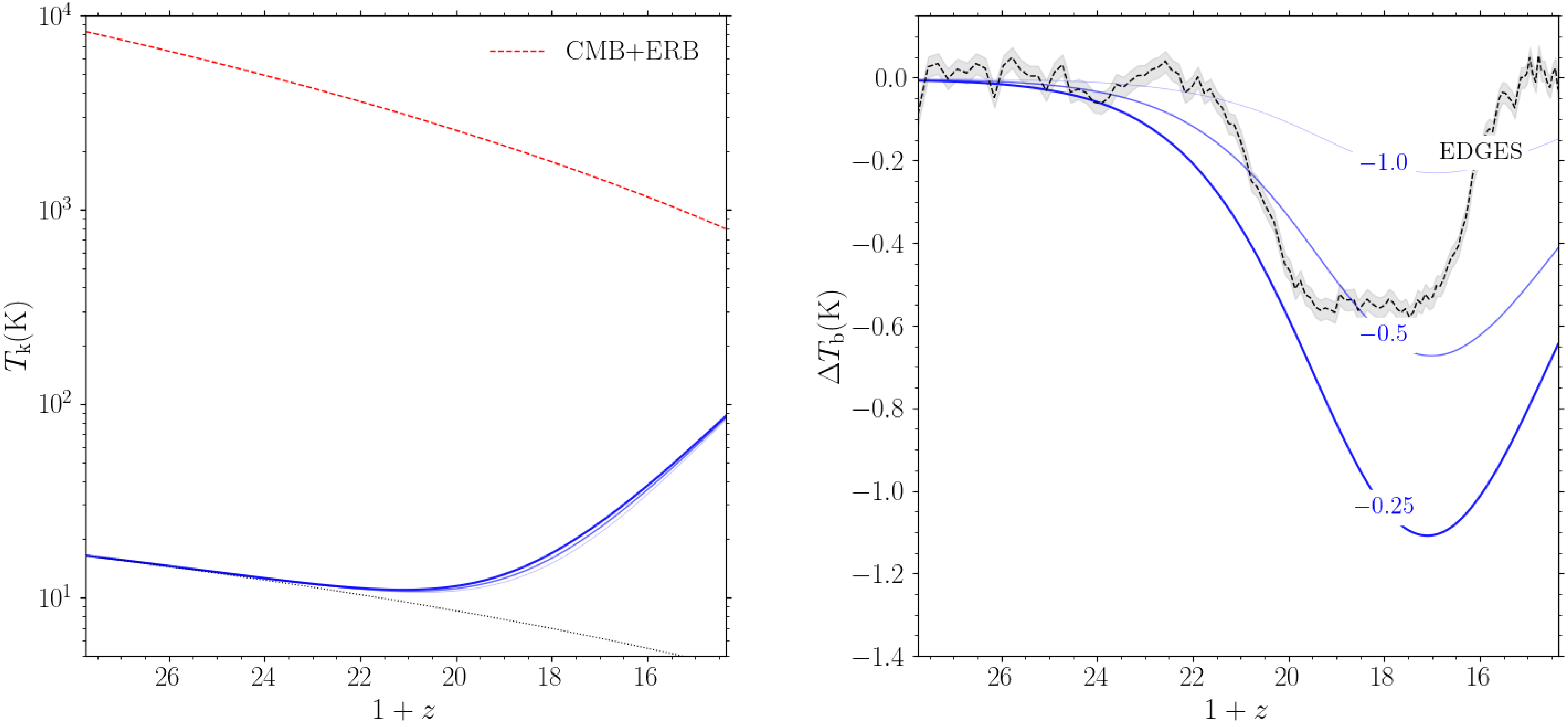
J_α = Background of Ly α photons

ϕ_α = Spectral energy distribution (Pop II)

$\dot{\rho}_\star$ = Star formation rate density

Barkana & Loeb (2005), Mittal & Kulkarni (2020)

Effect of varying $\log f_\alpha$ on T_k and ΔT_b

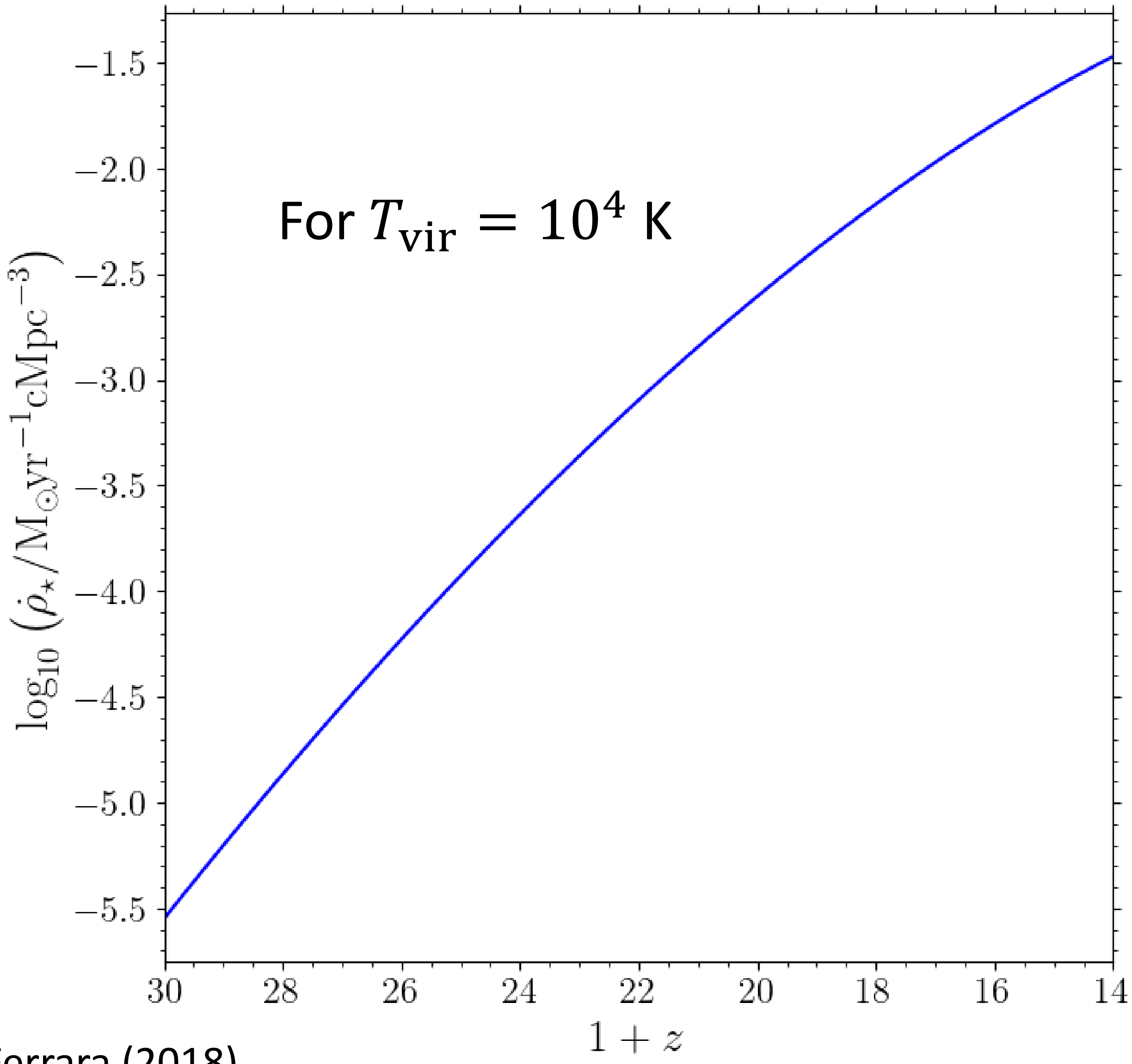


2. Changing the star formation rate density

$$\dot{\rho}_\star \propto \frac{\mathrm{d}F_{\mathrm{coll}}}{\mathrm{d}t}$$

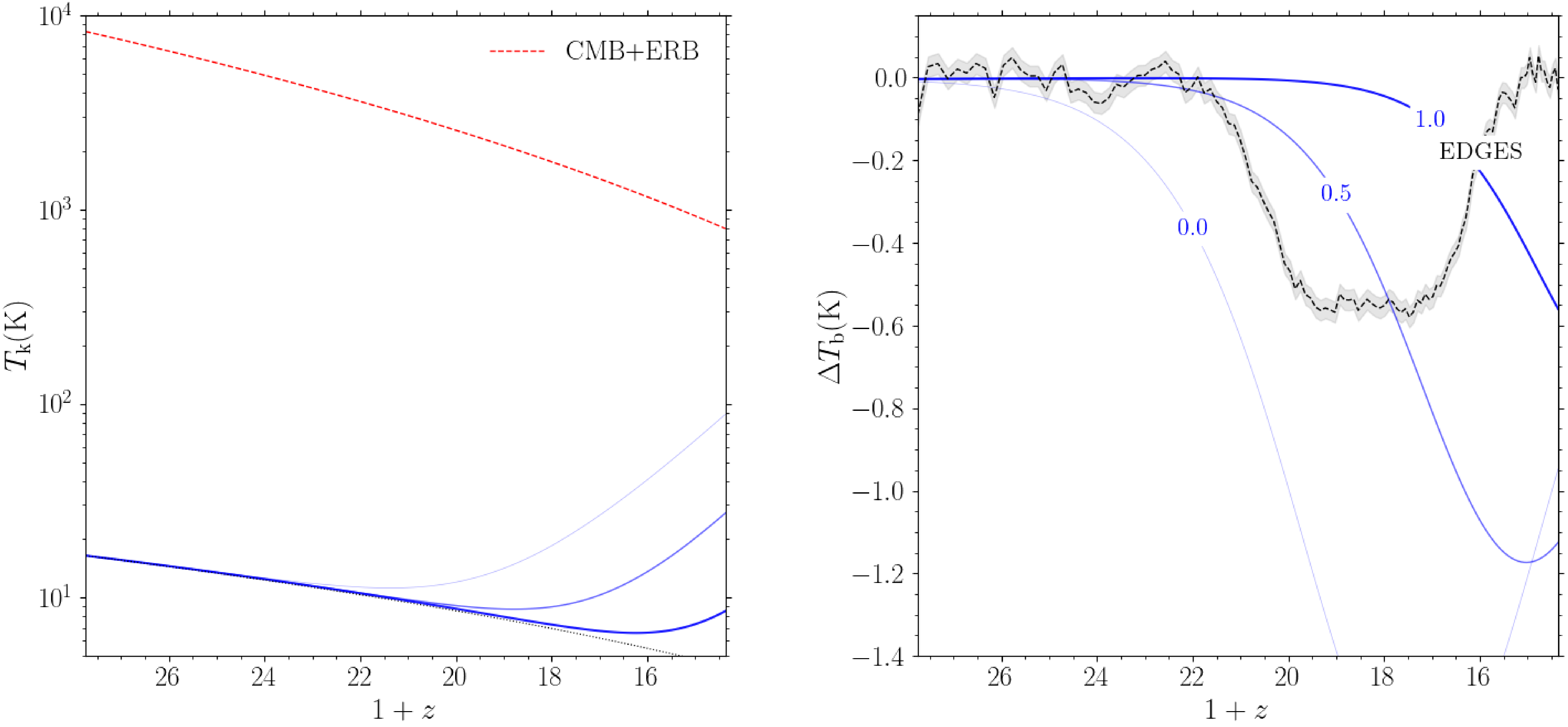
$$F_{\mathrm{coll}} = \mathrm{erfc}\left[\frac{\delta_{\mathrm{c}}}{\sqrt{2}\sigma(m_{\mathrm{min}})}\right]$$

$$m_{\mathrm{min}} \propto T_{\mathrm{vir}}^{3/2}$$



Press & Schechter (1974), Barkana & Loeb (2001), Dayal & Ferrara (2018)

Effect of varying $\log(T_{\mathrm{vir}} \cdot 10^{-4})$ on T_{k} and ΔT_{b}



3. Changing the strength of X-ray background

$$q_X \propto J_X \propto f_X \phi_X \dot{\rho}_\star$$

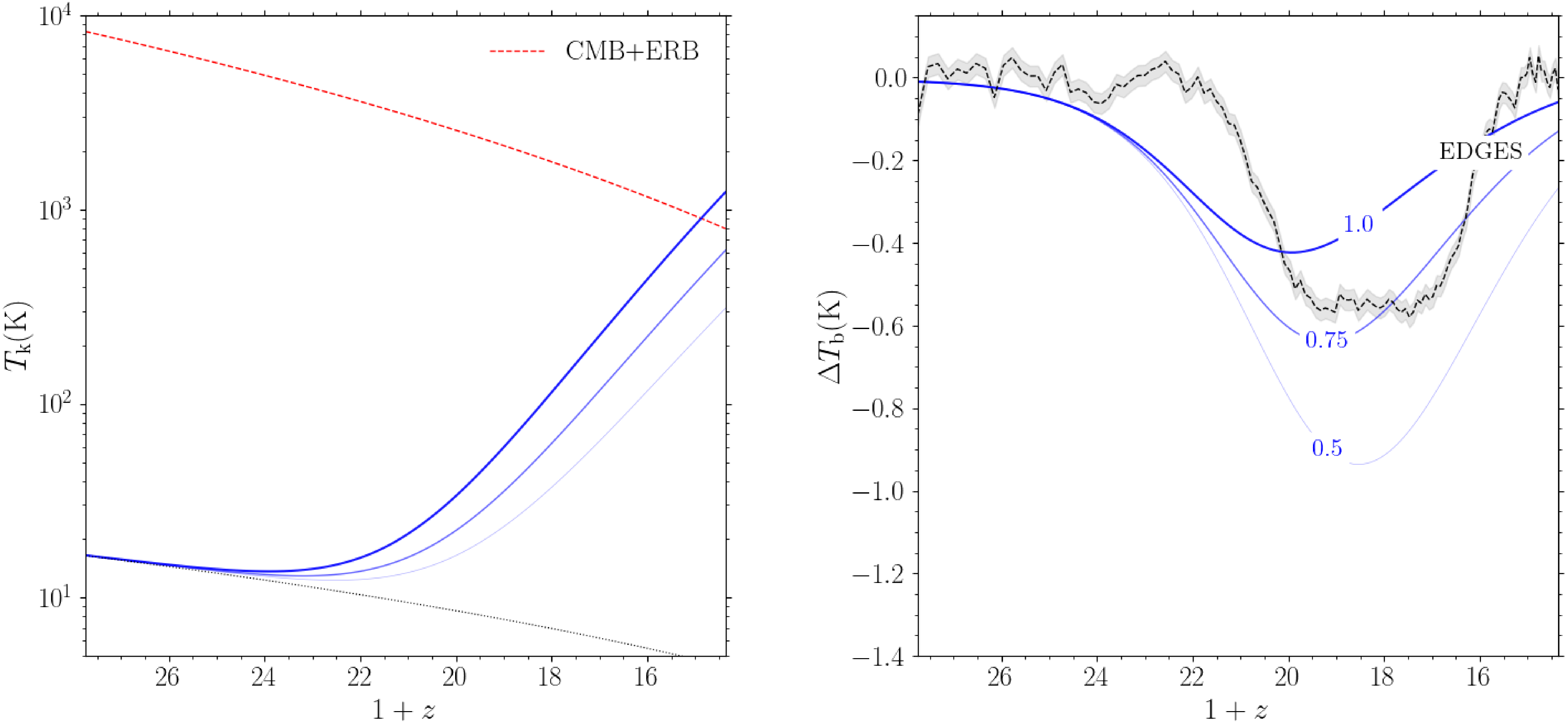
J_X = Background of X-ray photons

ϕ_X = Spectral energy distribution (0.2 – 30 keV and power law index 1.5)

$\dot{\rho}_\star$ = Star formation rate density

Grimm et al. (2003), Gilfanov et al. (2004), Mineo et al. (2012), Mesinger et al . (2013), Mirocha & Furlanetto (2019)

Changing the strength of X-ray background ($\log f_X$)



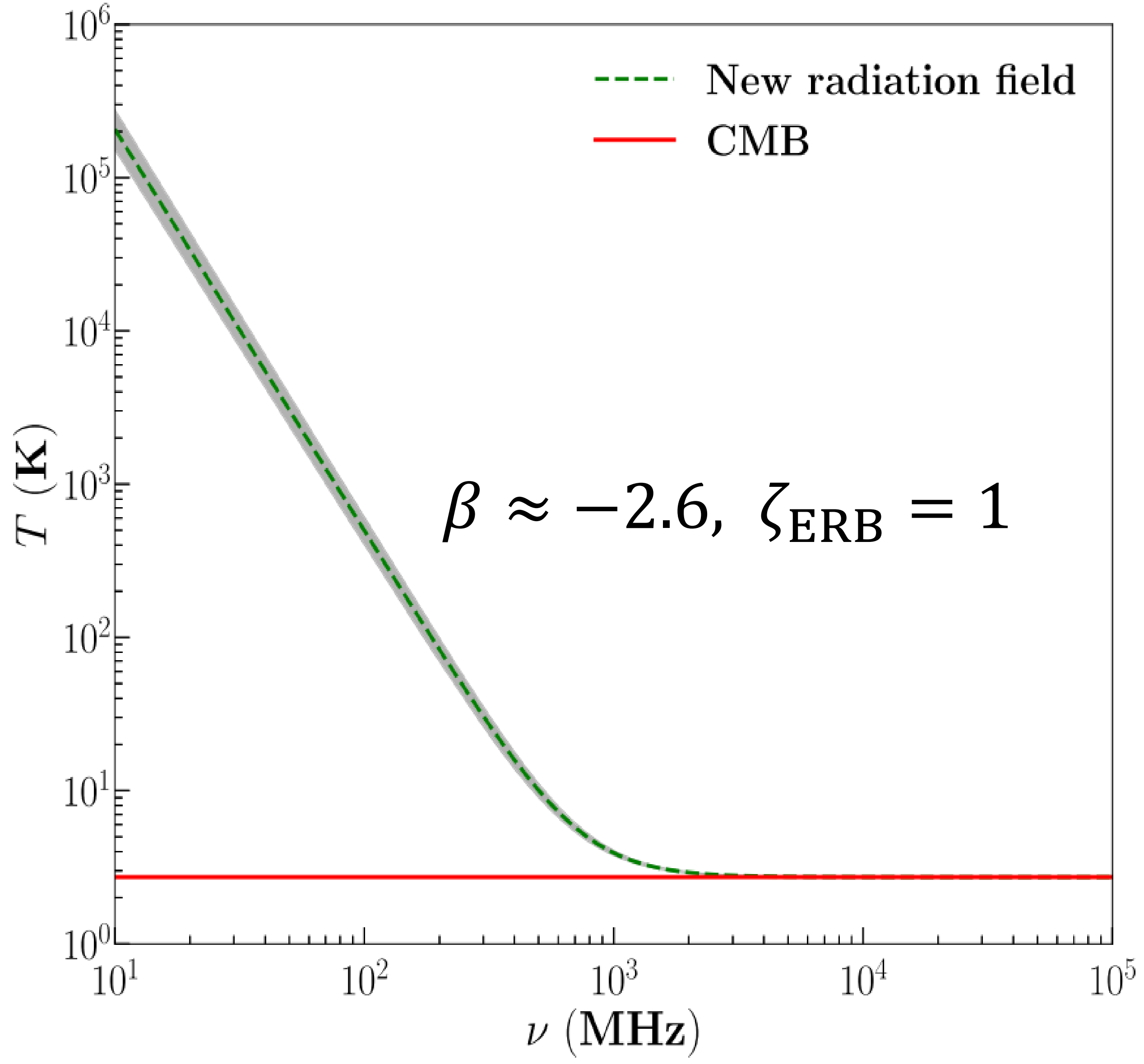
4. Changing the strength of excess radio background

Net background = CMB + ERB

ERB → ARCADE 2, LWA 1

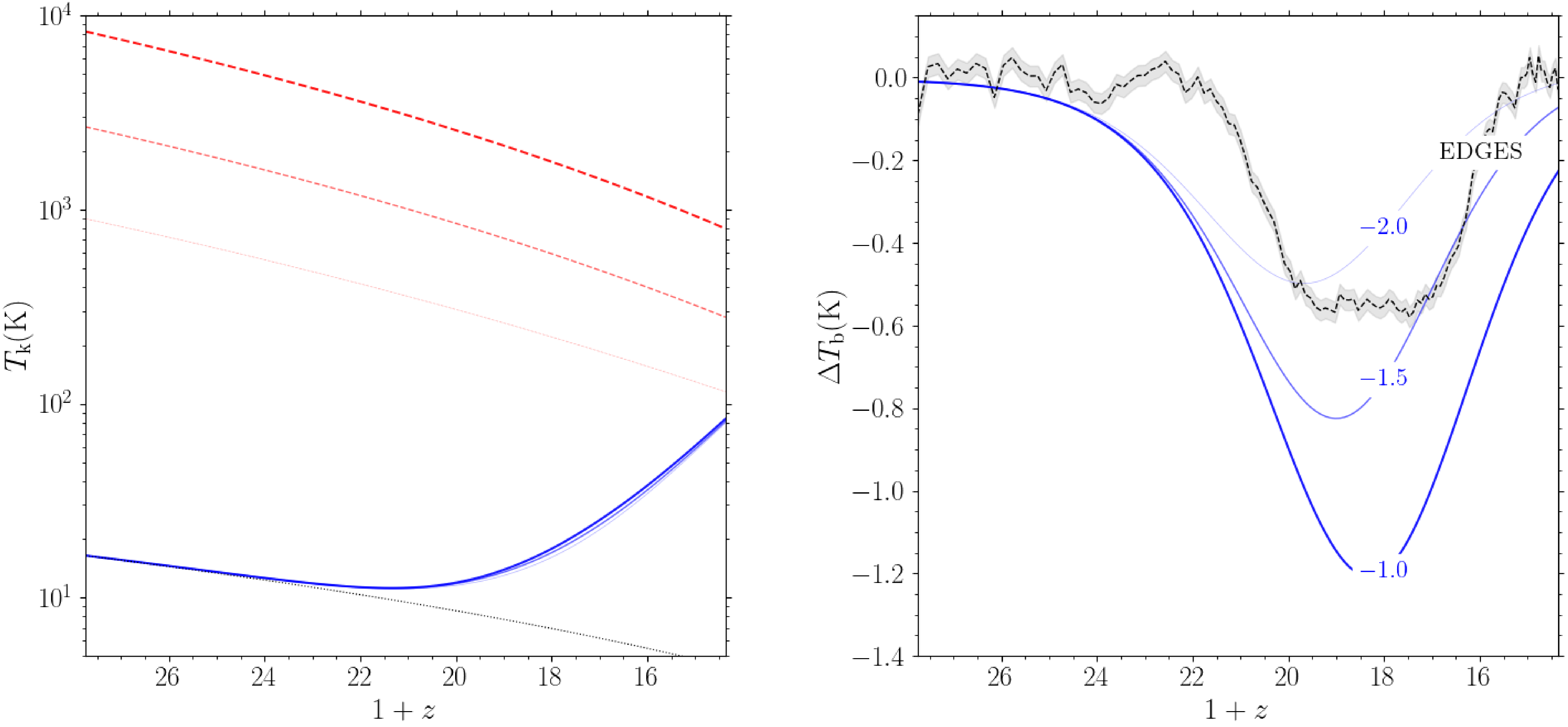
$$T_{\rm r} = T_{\gamma} + \zeta_{\rm ERB} T_0 \left(\frac{\nu}{\nu_0}\right)^{\beta},$$

T_{γ} → 2.73 K



Fixsen et al. (2011), Dowell & Taylor (2018), Feng & Holder (2018)

Effect of varying $\log \zeta_{\mathrm{ERB}}$ on T_{k} and ΔT_{b}



5. Abundance of primordial black holes

$$P = -n_{\mathrm{PBH}}\dot{M}c^2$$

$$n_{\mathrm{PBH}} = \frac{\Omega_{\mathrm{PBH}}\rho_{\mathrm{crit}}}{M} = f_{\mathrm{PBH}}\frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{crit}}}{M}$$

$$q_{\mathrm{PBH}} = f_{\mathrm{heat}}(E,z)P \propto \frac{f_{\mathrm{PBH}}}{M^3}$$

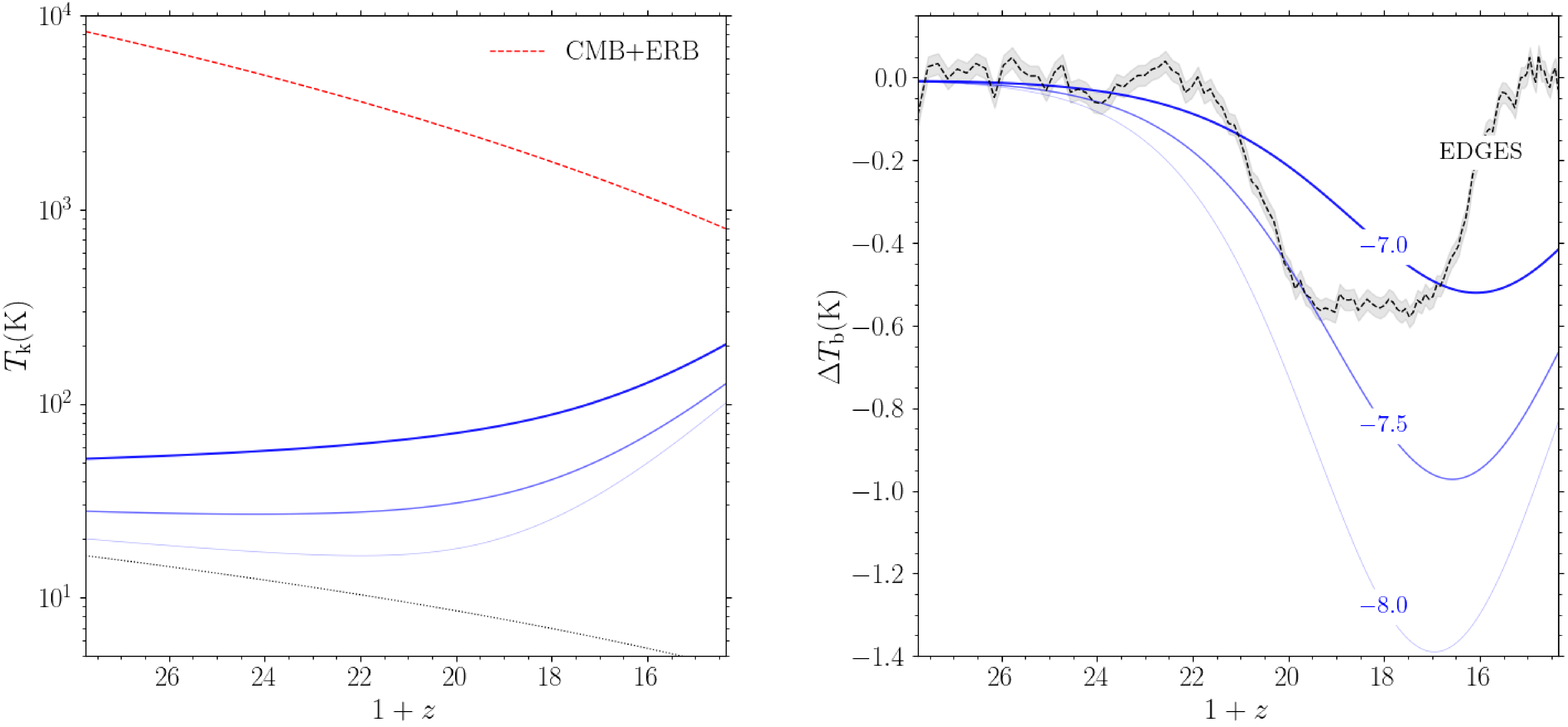
Hawking emission is relevant for $\sim 10^{15} - 10^{17}$g BHs

Emission peaks around 10 MeV to 100 keV

Assuming a monochromatic mass distribution

e.g. Hawking (1976), Clark et al. (2018)

Effect of varying $\log f_{\mathrm{PBH}}$ on T_{k} and ΔT_{b}



Inference procedure

- Gaussian Likelihood

$$\mathcal{L}(\mathrm{D}|\theta) = \prod_{i=1}^{123} \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left[-\frac{\left(\Delta T_{\mathrm{b}}^{\mathrm{EDGES}} - \Delta T_{\mathrm{b}}^{\mathrm{prid}}\right)^2}{2\sigma_i^2}\right], \qquad \sigma_i = 50\ \mathrm{mK}$$

- Uniform (uninformative) priors, $\mathcal{P}(\theta)$
- By Bayes' theorem, the posterior sampling is:

$$P(\theta|\mathrm{D}) \propto \mathcal{L}(\mathrm{D}|\theta)\mathcal{P}(\theta)$$

Mirocha et al. (2015); Hills et al. (2018)

Can EDGES 21-cm signal constrain the abundance of PBHs?

Case I: X-ray heating absent
Case II: X-ray heating present

Case I: No X-ray heating

For 10^{15}g PBH

Best-fitting values:

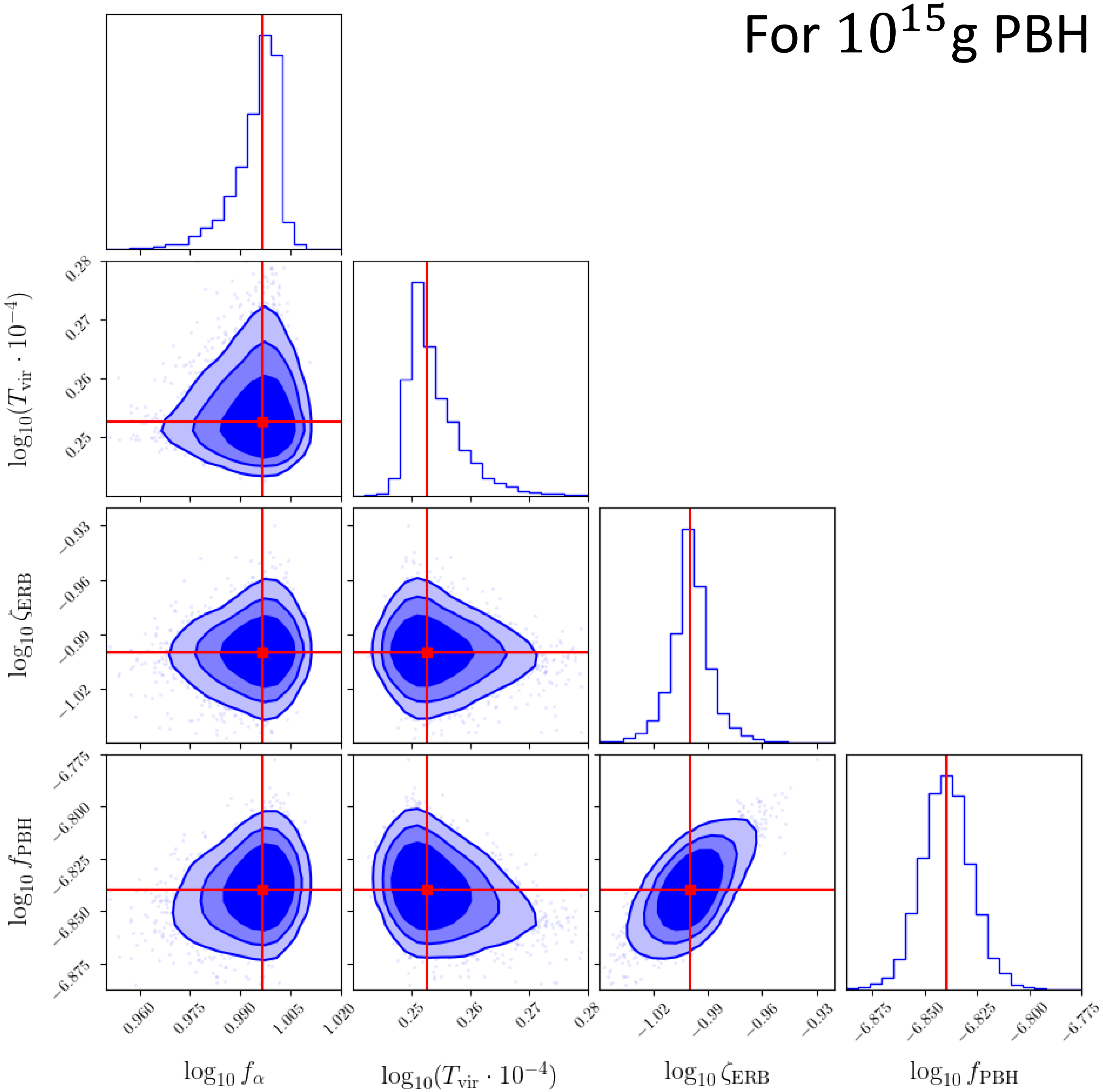
$$\log f_\alpha = 1.0^{+0.01}_{-0.02}$$

$$\log\left(T_{\rm vir}\cdot 10^{-4}\right) = 0.25^{+0.01}_{-0.01}$$

$$\log \zeta_{\rm ERB} = -1.0^{+0.03}_{-0.01}$$

$$\boxed{\log f_{\rm PBH} = -6.84^{+0.02}_{-0.02}}$$

Instead of a range, we have a definite value of $f_{\rm PBH}$



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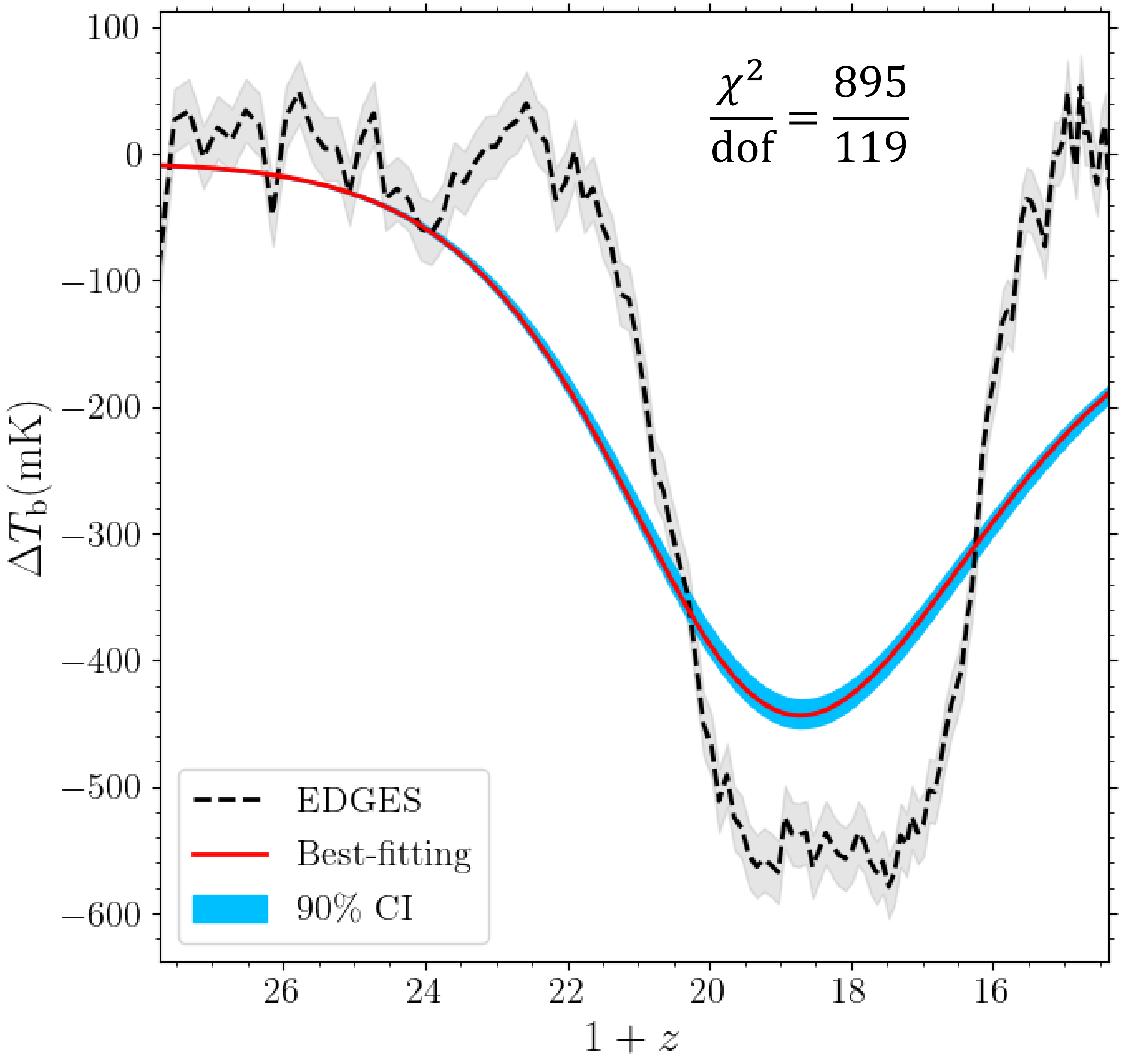


Case II: X-ray heating present

For 10^{15}g PBH

Best-fitting values:

$$\log f_\alpha = 0.02^{+0.007}_{-0.007}$$

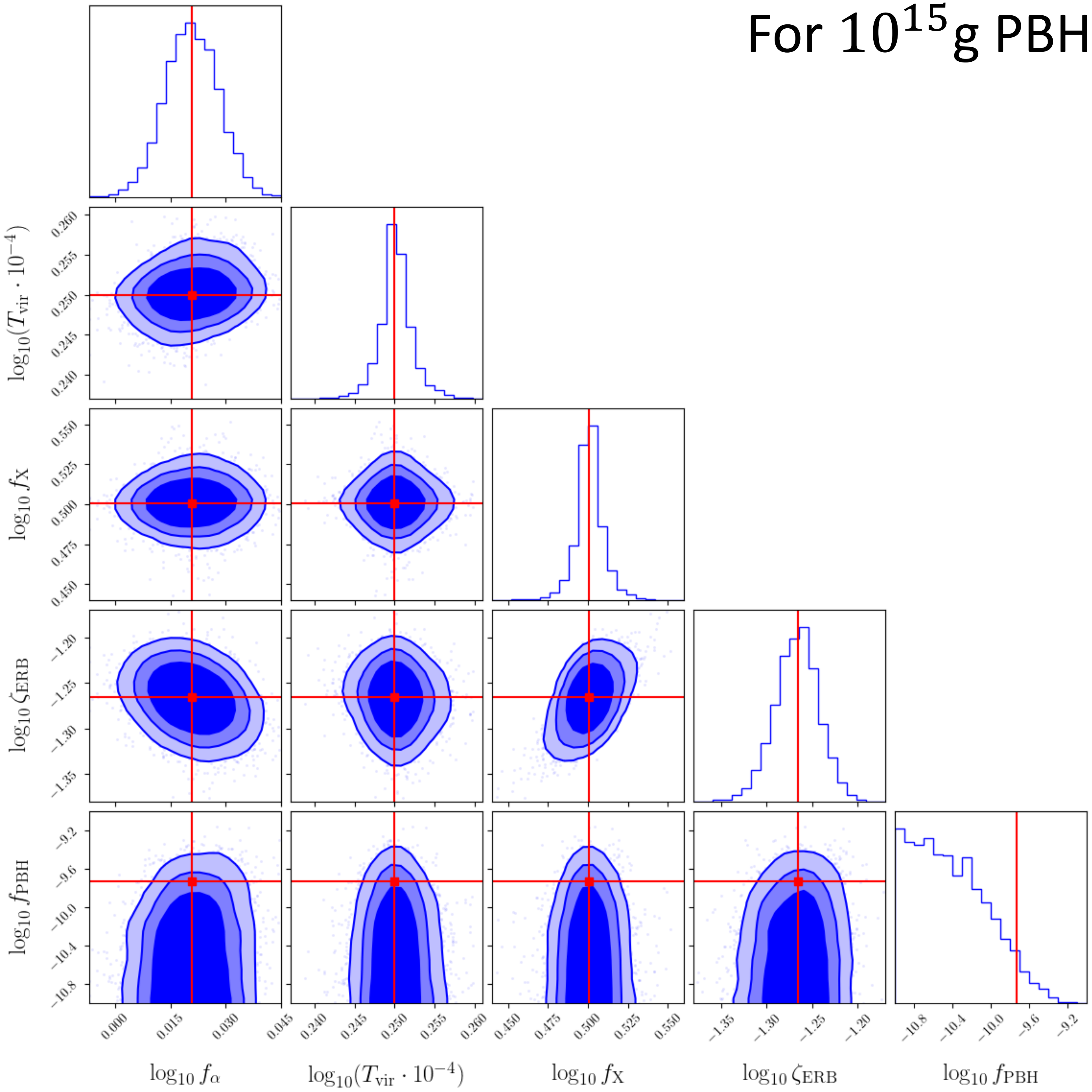
$$\log\left(T_{\mathrm{vir}} \cdot 10^{-4}\right) = 0.25^{+0.001}_{-0.001}$$

$$\log f_{\mathrm{X}} = 0.50^{+0.01}_{-0.01}$$

$$\log \zeta_{\mathrm{ERB}} = -1.27^{+0.02}_{-0.02}$$

$$\boxed{\log f_{\mathrm{PBH}} \leq -9.73}$$

There is an upper bound on f_{PBH}, but no lower bound.



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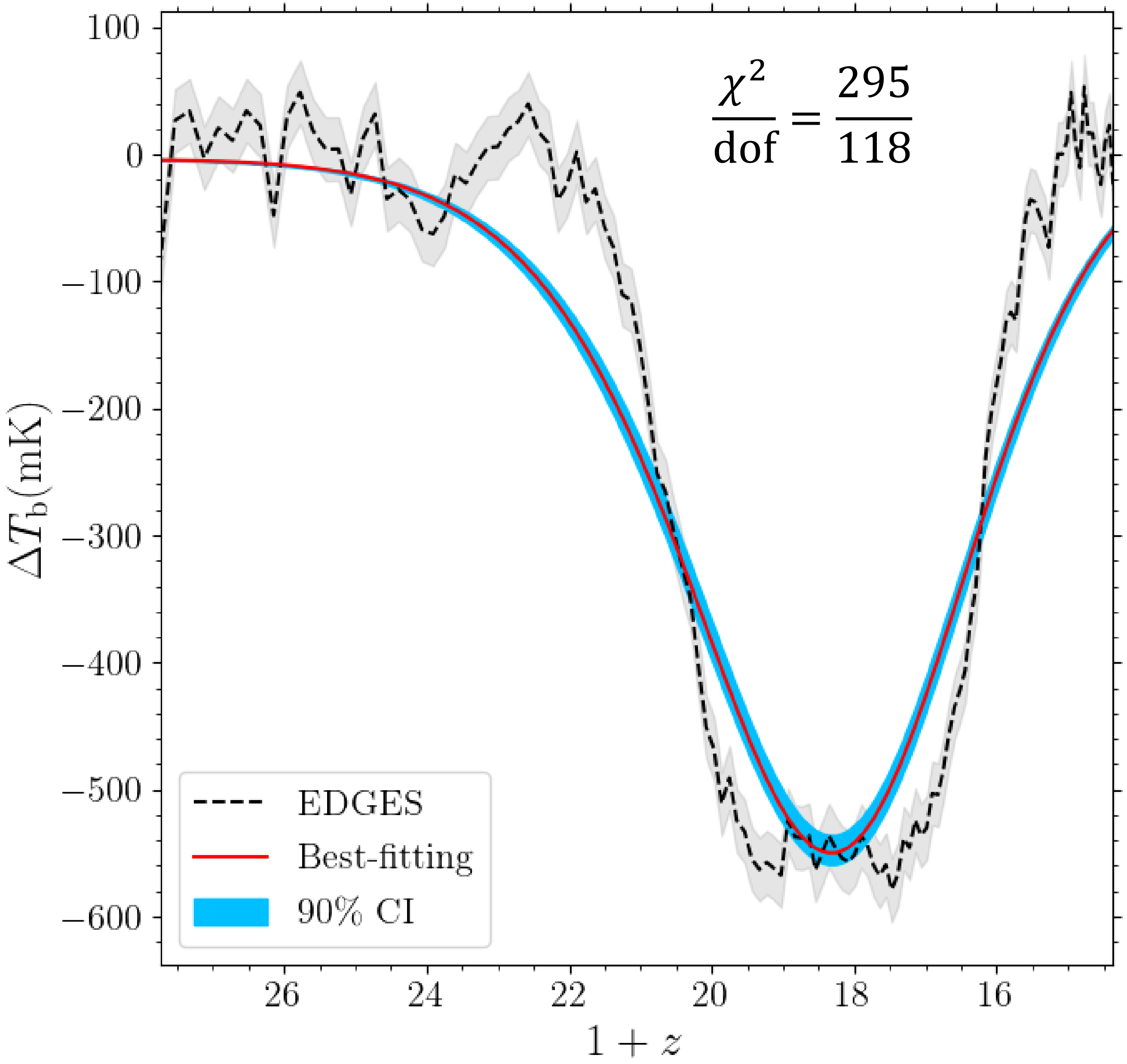
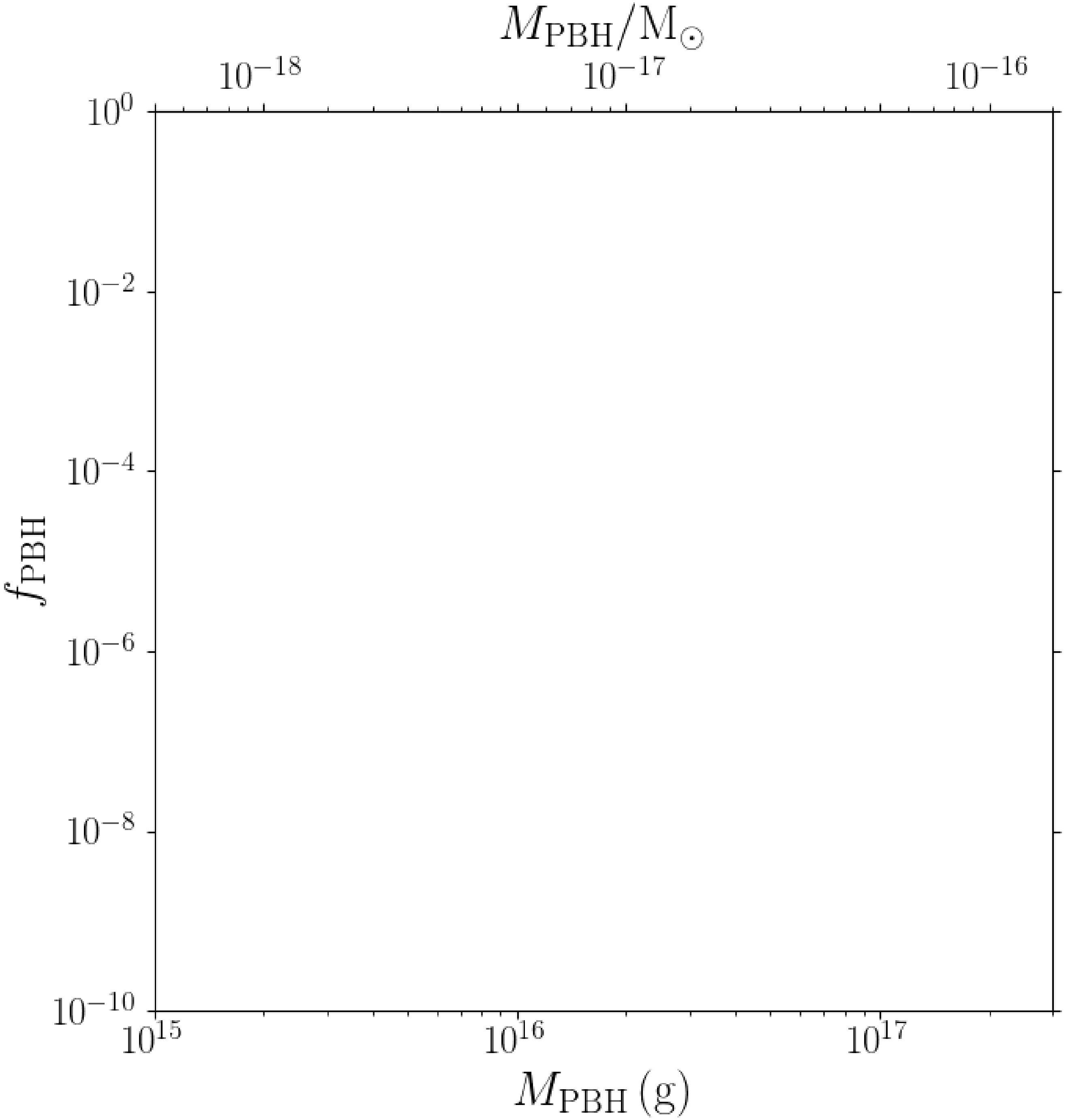
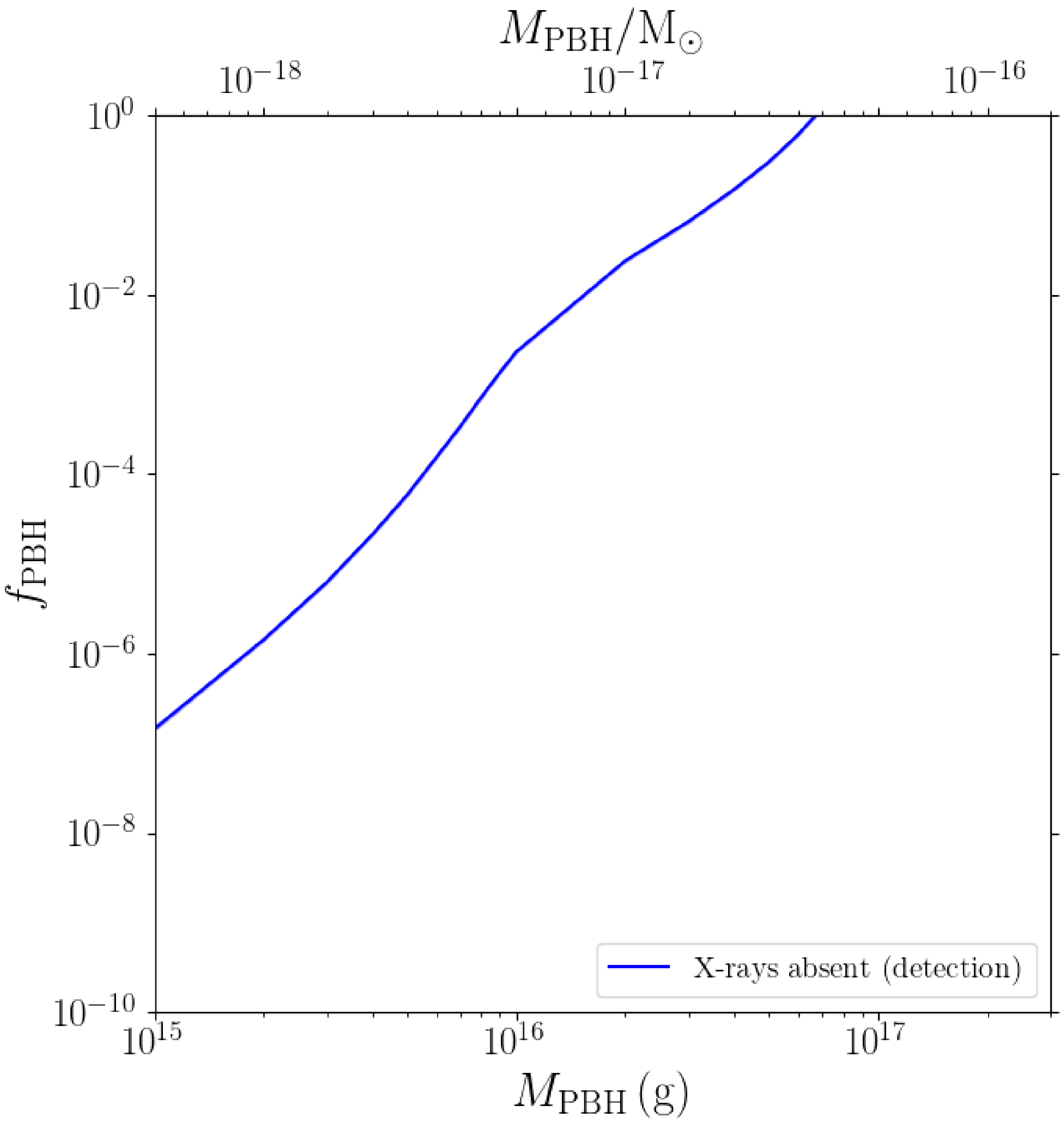


Repeating the analysis for higher mass PBHs



Repeating the analysis for higher mass PBHs

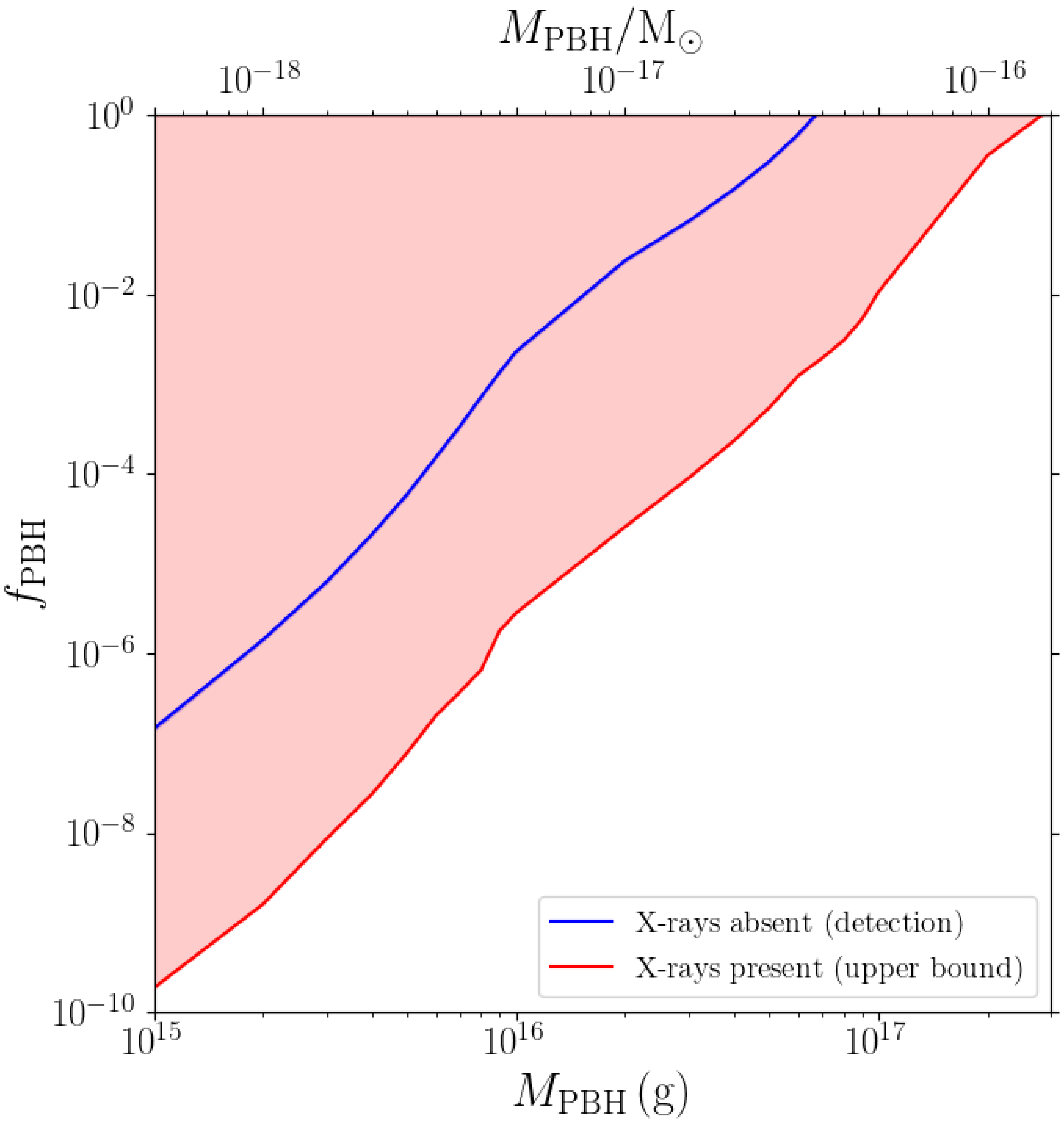
$$f_{\mathrm{PBH}} = 10^{-6.84}\left(\frac{M_{\mathrm{PBH}}}{10^{15}\mathrm{g}}\right)^{3.75}$$



Repeating the analysis for higher mass PBHs

$$f_{\mathrm{PBH}} = 10^{-6.84}\left(\frac{M_{\mathrm{PBH}}}{10^{15}\mathrm{g}}\right)^{3.75}$$

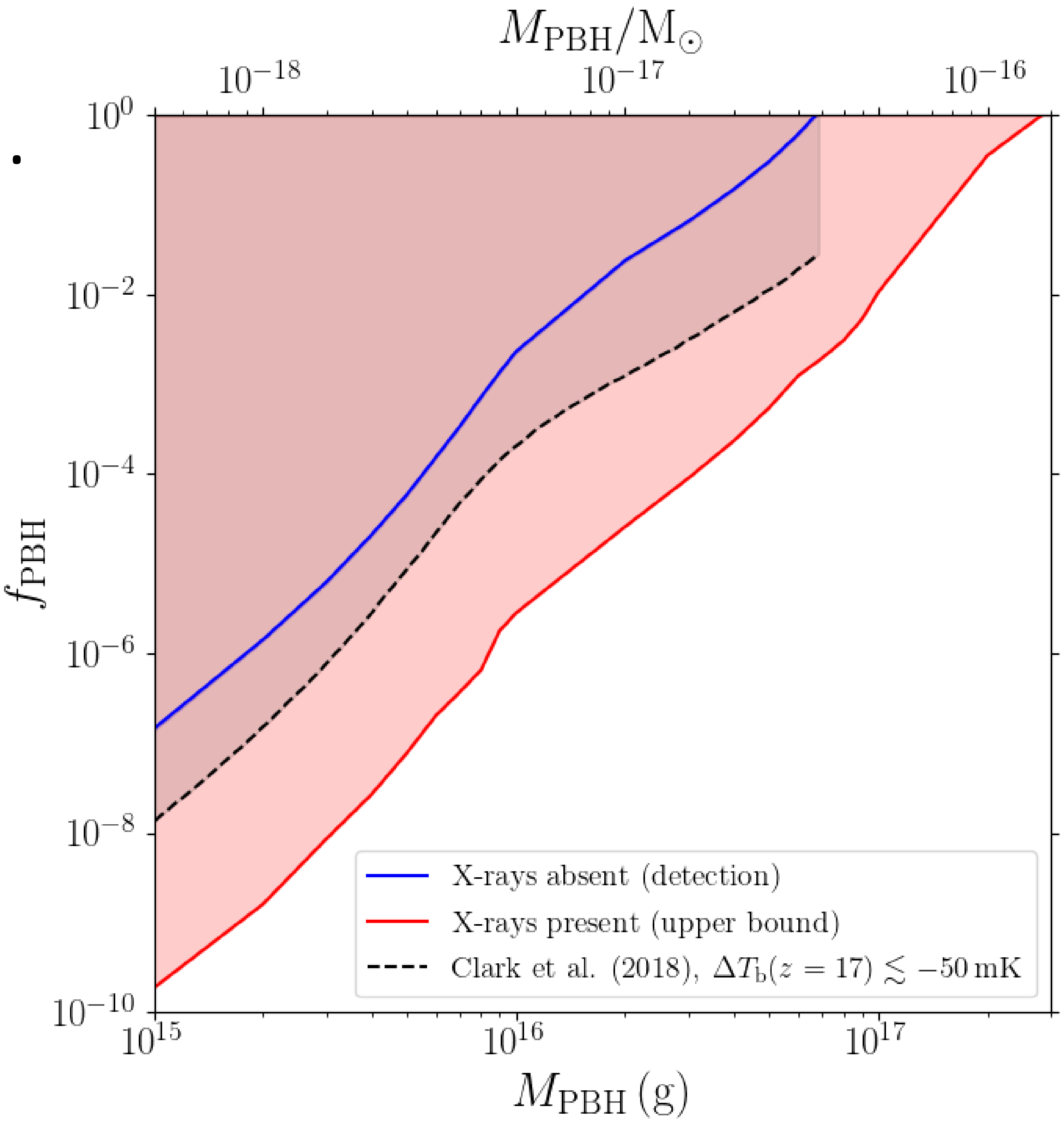
$$f_{\mathrm{PBH}} \leq 10^{-9.73}\left(\frac{M_{\mathrm{PBH}}}{10^{15}\mathrm{g}}\right)^{3.96}$$



Compare with the results from Clark et al. (2018)

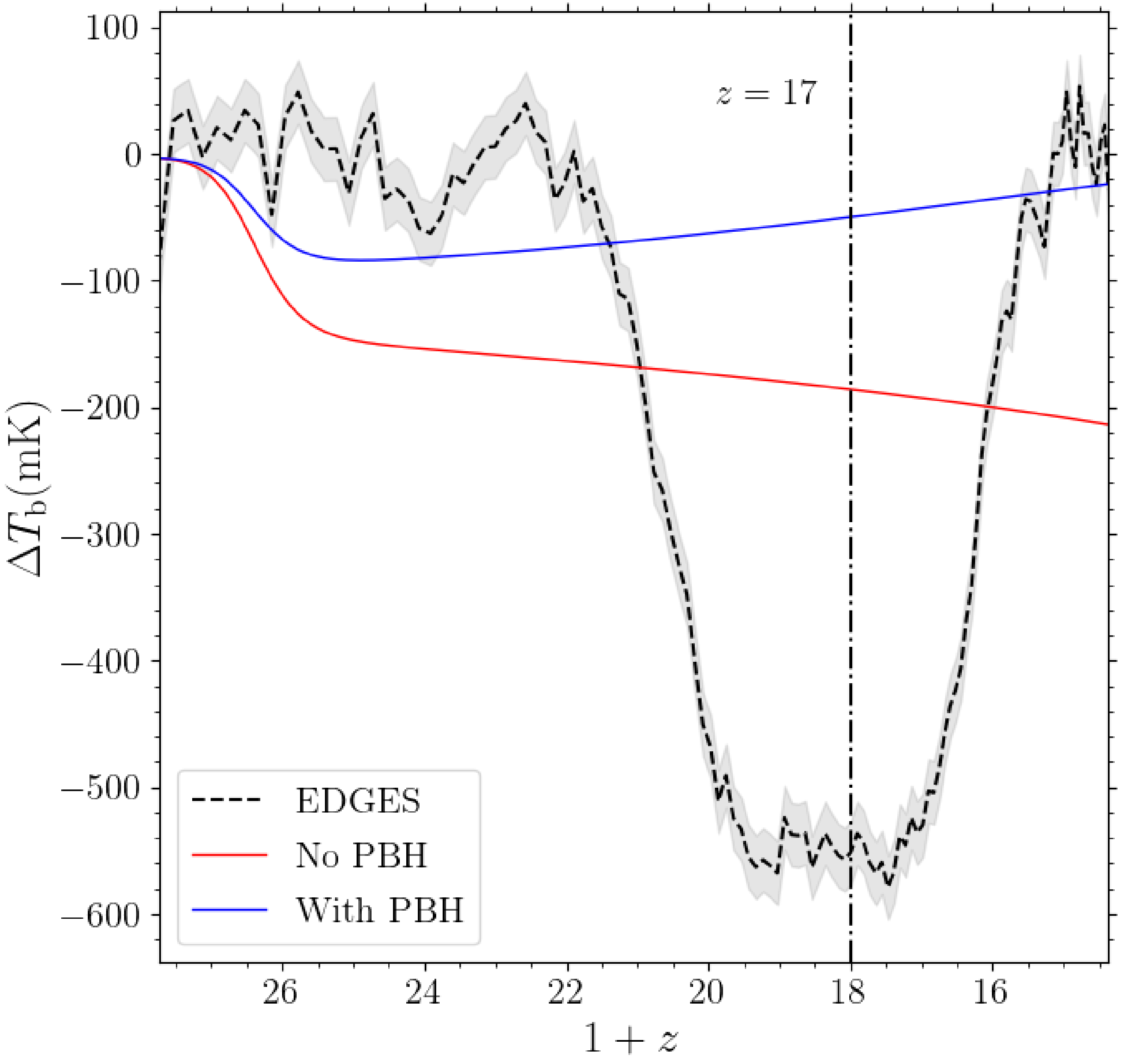
$$f_{\rm PBH} = 10^{-6.84}\left(\frac{M_{\rm PBH}}{10^{15}{\rm g}}\right)^{3.75}$$

$$f_{\rm PBH} \leq 10^{-9.73}\left(\frac{M_{\rm PBH}}{10^{15}{\rm g}}\right)^{3.96}$$

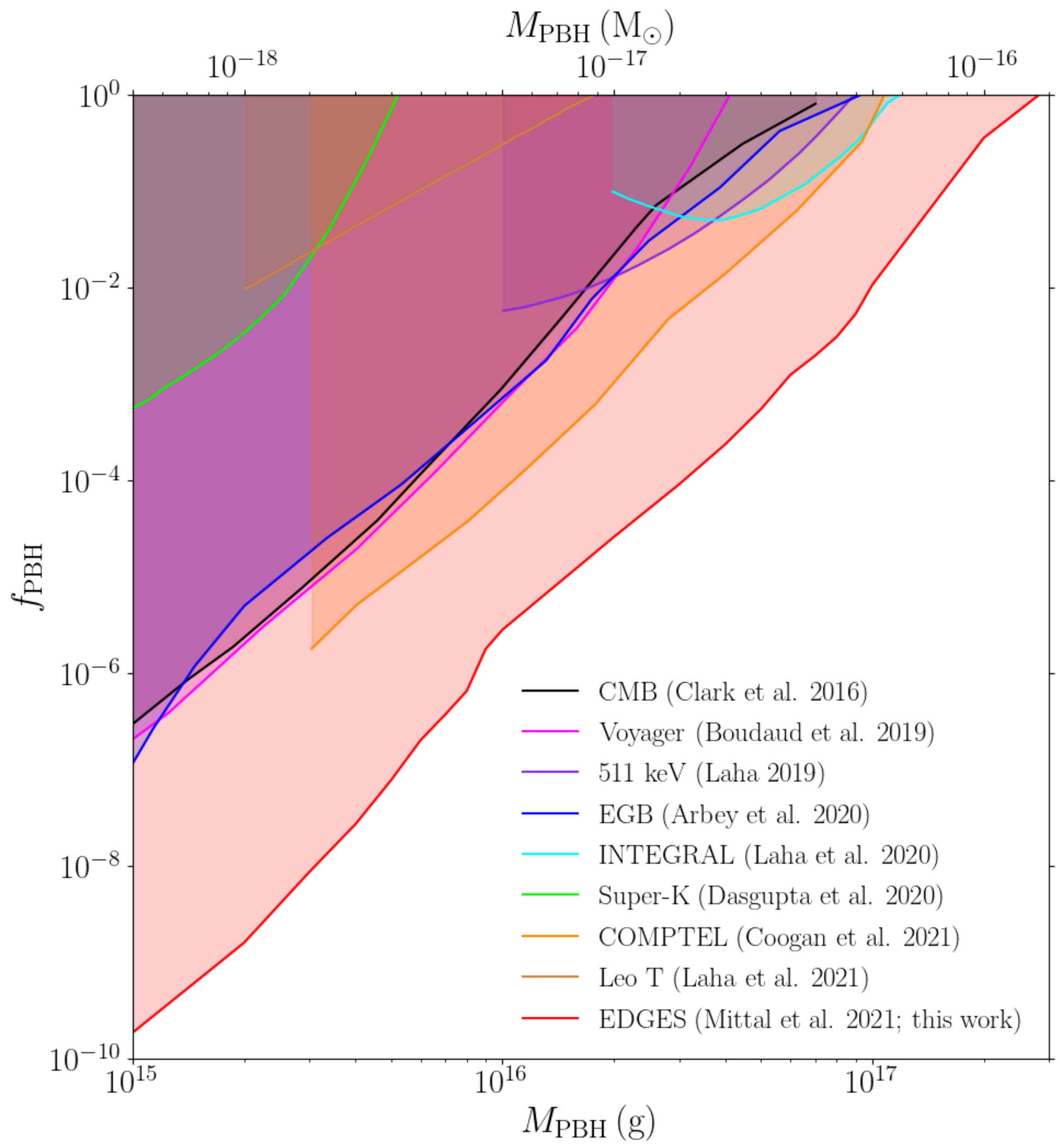


Analysing the strategy of Clark et al. (2018)

- In their ‘standard model’ (no involvement of PBHs), $\Delta T_{\mathrm{b}}(z = 17) = -200$ mK
- Upper bound by setting $\Delta T_{\mathrm{b}}(z = 17) < -50$ mK, when PBH heating is added



The EDGES 21-cm signal gives stronger constraints



Summary

- Global 21-cm signal can constrain PBH abundance in the range 10^{15}-10^{17}g
- We derived constraints using the full shape of EDGES absorption profile
- Data prefer models with X-ray heating
- In the absence of X-ray heating, we 'detect' PBHs. For 10^{15}g PBH, $f_{\rm PBH}{\sim}10^{-7}$ and increases with mass
- In the presence of X-ray heating, there is an upper bound on PBHs. For 10^{15}g PBH, $f_{\rm PBH} < 10^{-10}$ and increases as $\sim M^4$
- Non-PBH astrophysical parameters prefer reasonable values in agreement with literature

Comparing the heating rate by PBHs and X-rays