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

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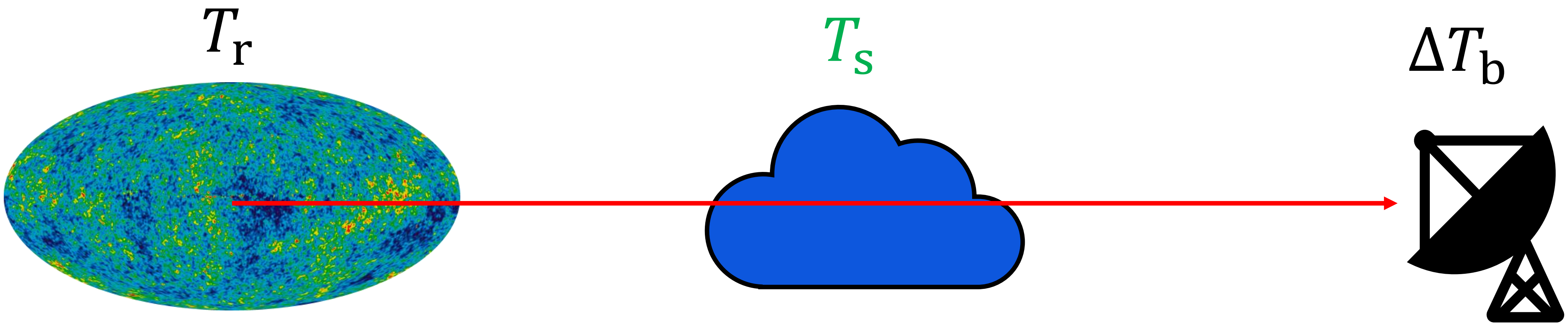
The Global 21-cm Signal



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

$$\Delta T_\mathrm{b} = 27 x_\mathrm{HI} \left(\frac{1 - Y_\mathrm{P}}{0.76}\right) \left(\frac{\Omega_\mathrm{B} h^2}{0.023}\right) \sqrt{\frac{0.15}{\Omega_\mathrm{m} h^2} \frac{1+z}{10}} \left(1 - \frac{T_\mathrm{r}}{T_\mathrm{s}}\right) \mathrm{mK}$$

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

T_s is determined by 2 processes at cosmic dawn

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

- Stimulated, spontaneous emission and stimulated absorption
- 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

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

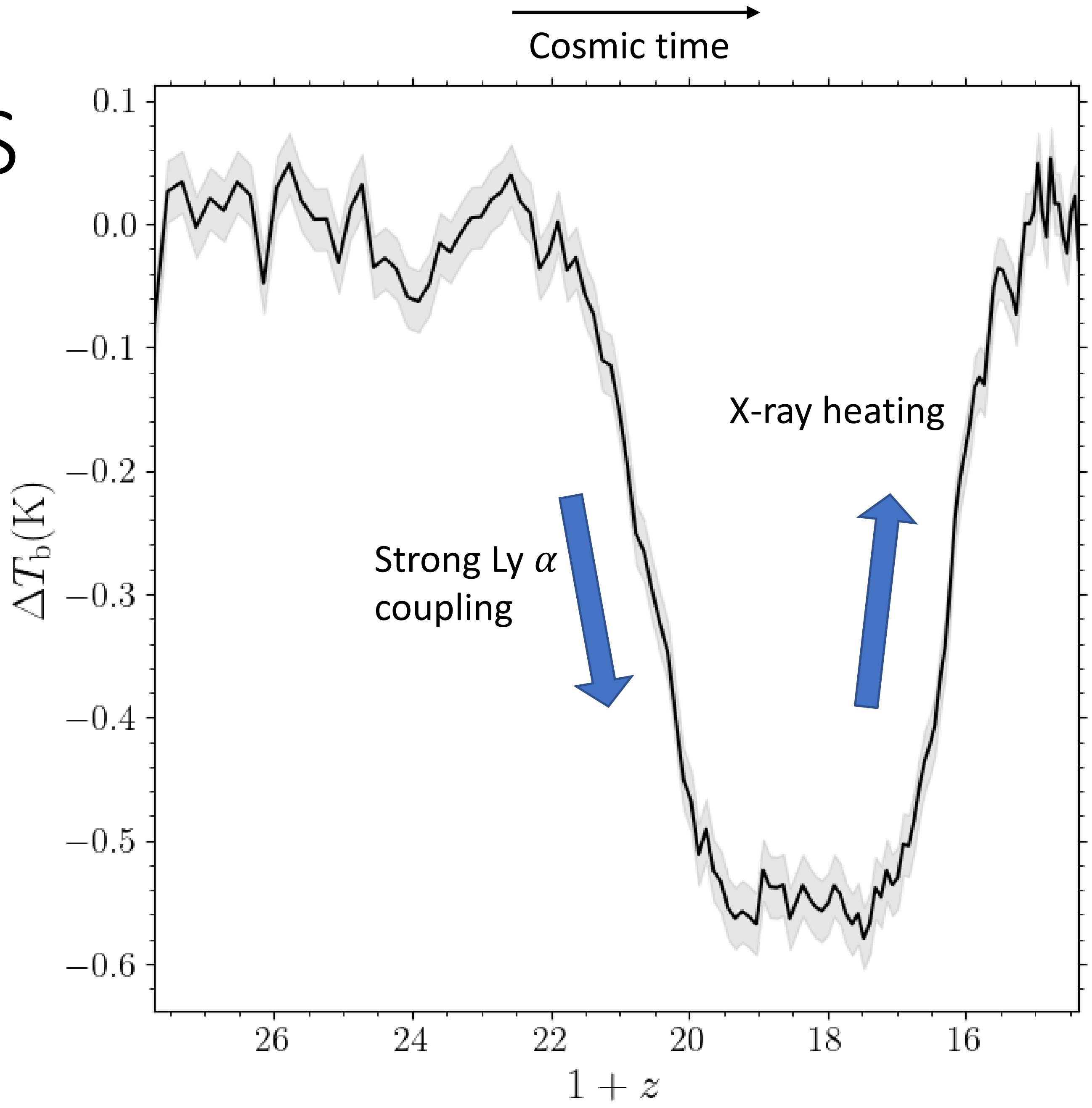
Adiabatic
cooling

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



Bowman et al. (2018)

Summary of parameters affecting 21-cm signal

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

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)

1. Changing the strength of Ly α Coupling

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

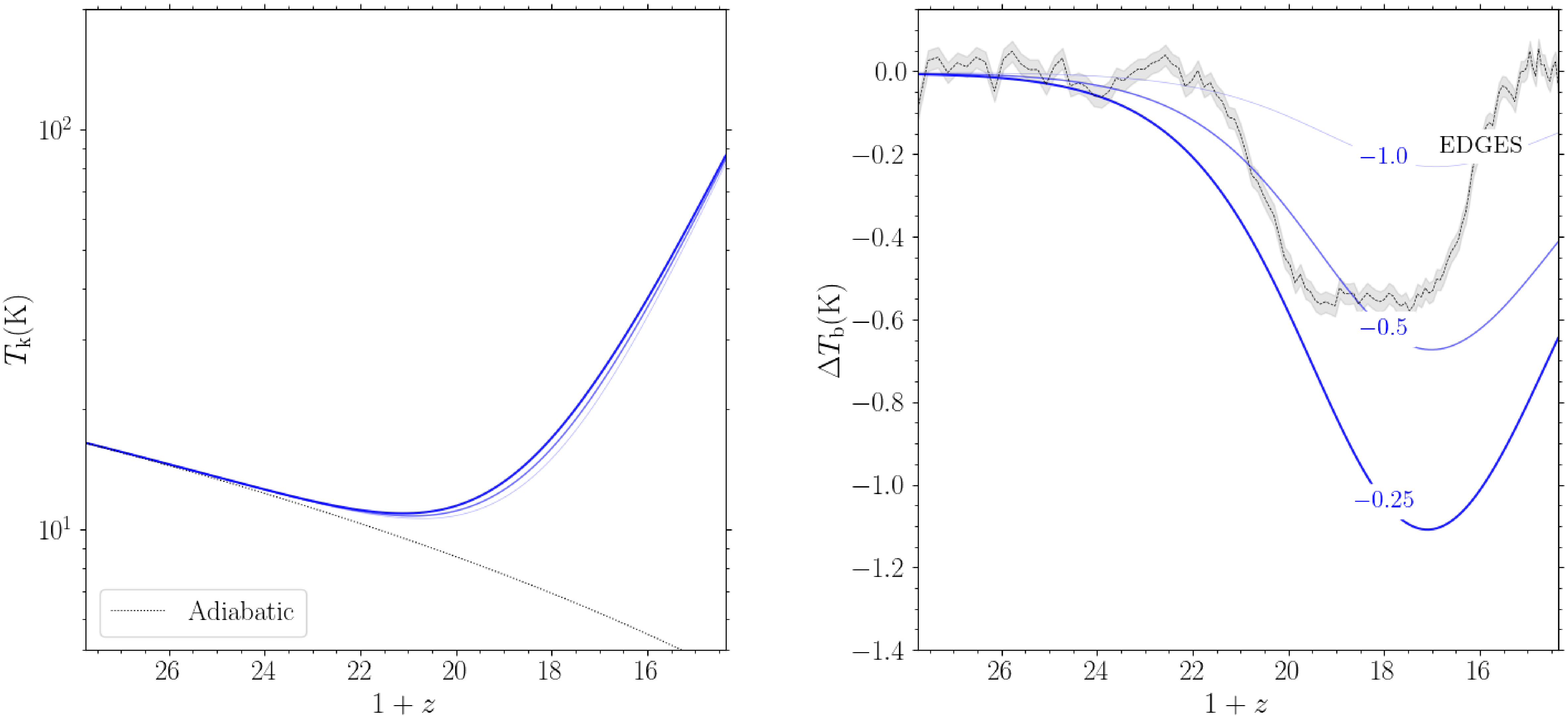
J_α = Background of Ly α photons

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}

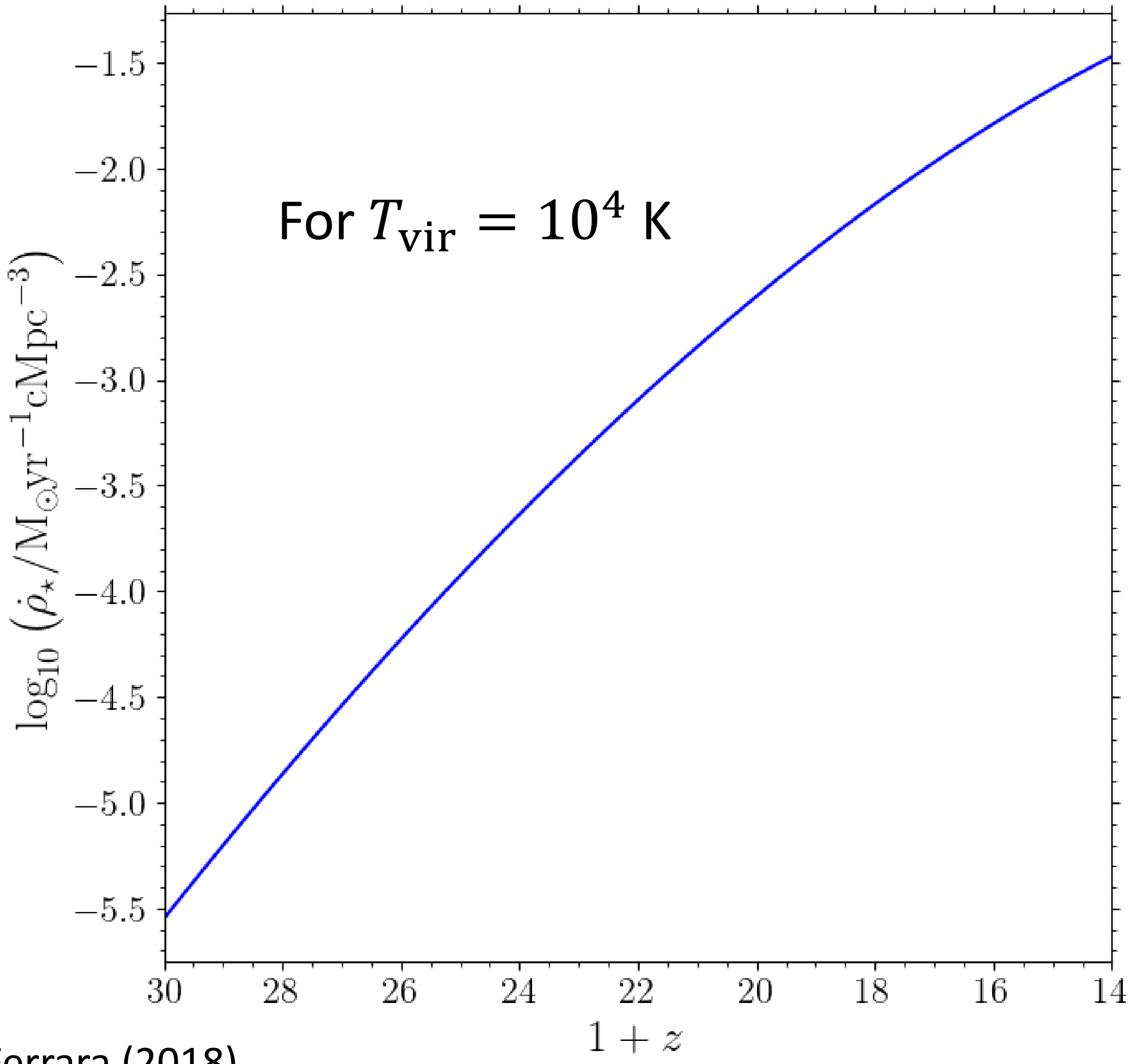


2. Changing the star formation rate density

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

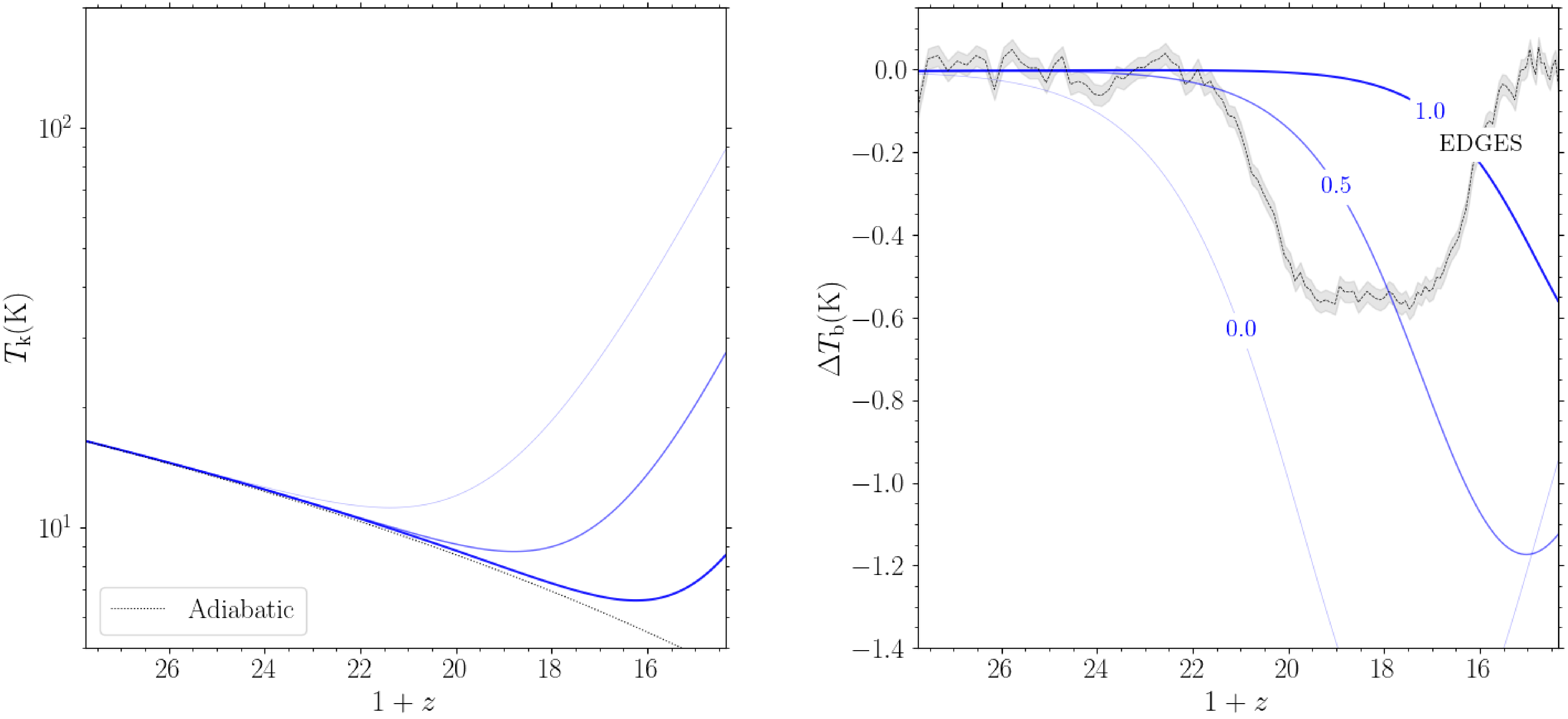
$$F_{\mathrm{coll}} = \mathrm{erfc}\left[\frac{\delta_\mathrm{c}}{\sqrt{2}\sigma(m_{\mathrm{min}})}\right]$$

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



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

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



3. Changing the strength of X-ray background

$$q_{\mathrm{X}} \propto J_{\mathrm{X}} \propto f_{\mathrm{X}} \phi_{\mathrm{X}} \dot{\rho}_{\star}$$

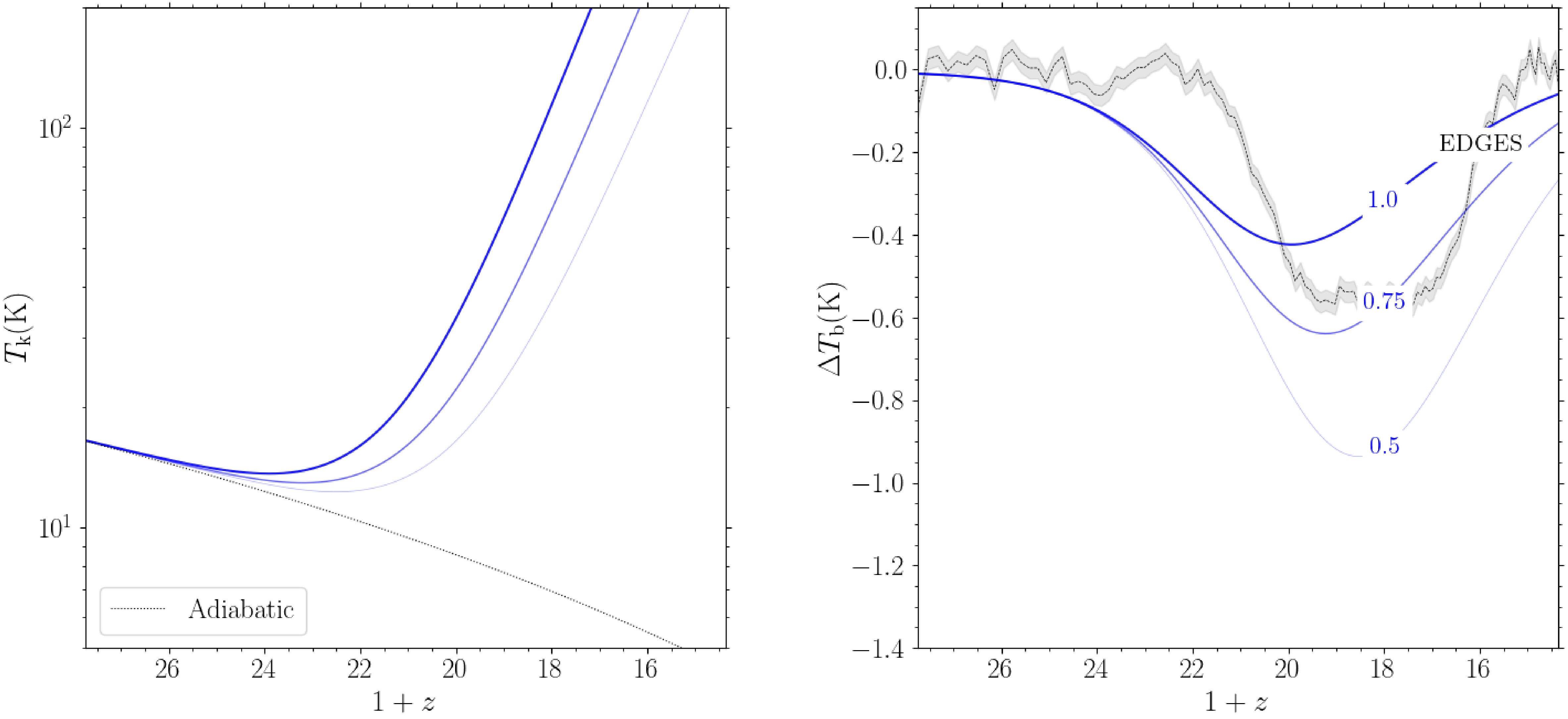
J_{X} = Background of X-ray photons

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), Mirocha & Furlanetto (2019)

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



4. Changing the strength of excess radio background

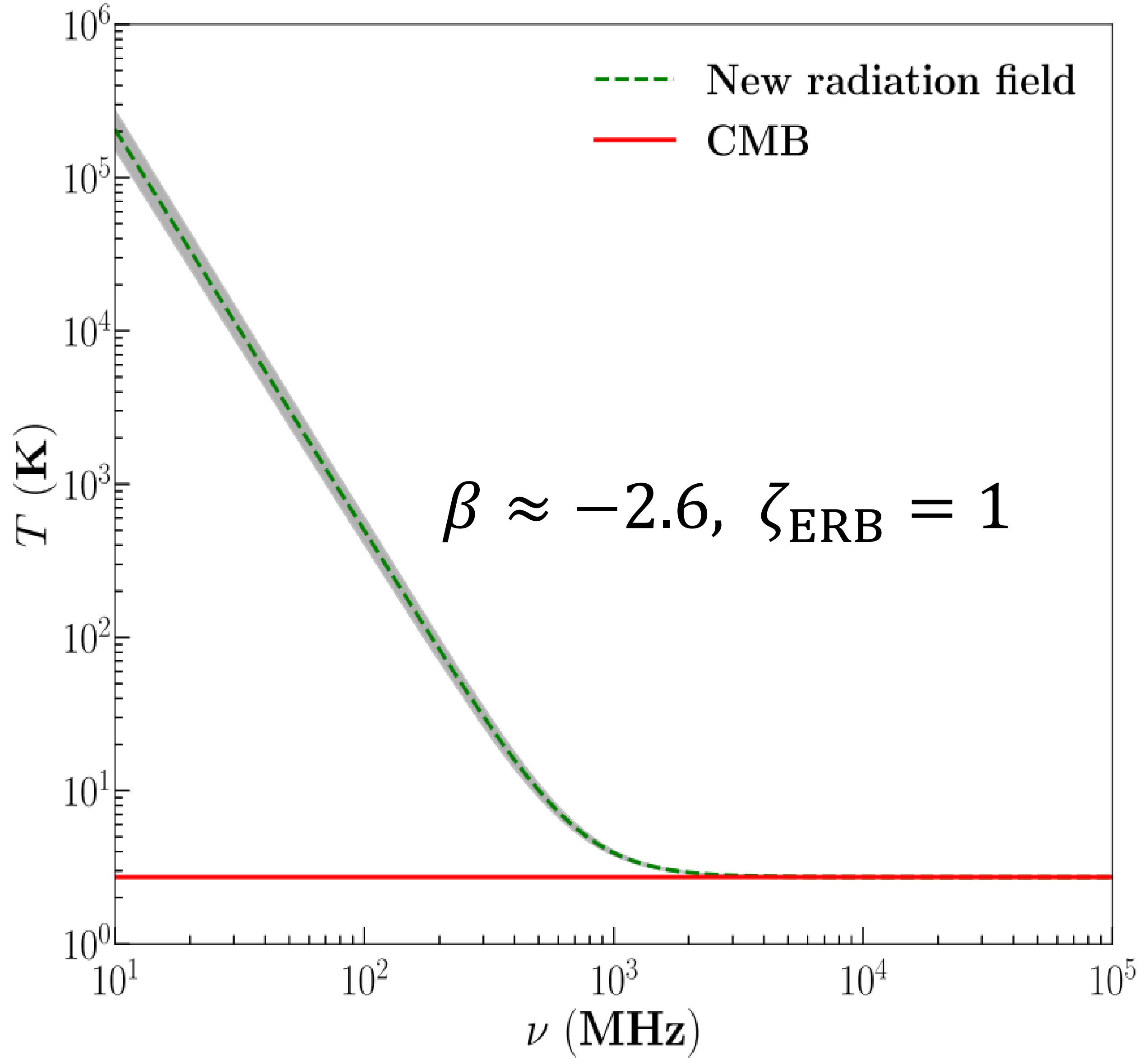
Net background = CMB + ERB

ARCADE 2

LWA 1

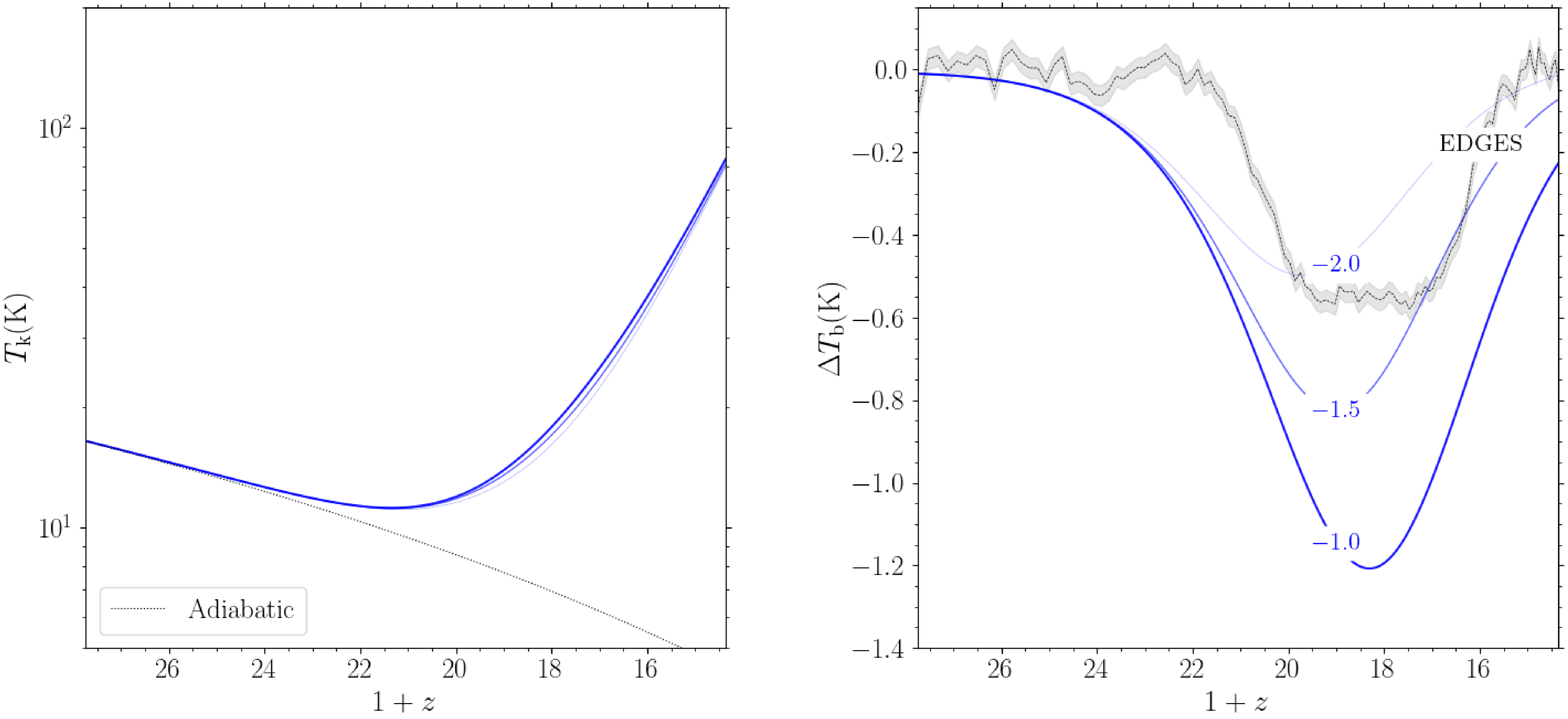
$$T_{\mathrm{r}} = T_{\gamma} + \zeta_{\mathrm{ERB}} T_0 \left(\frac{\nu}{\nu_0}\right)^{\beta},$$

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

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

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

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

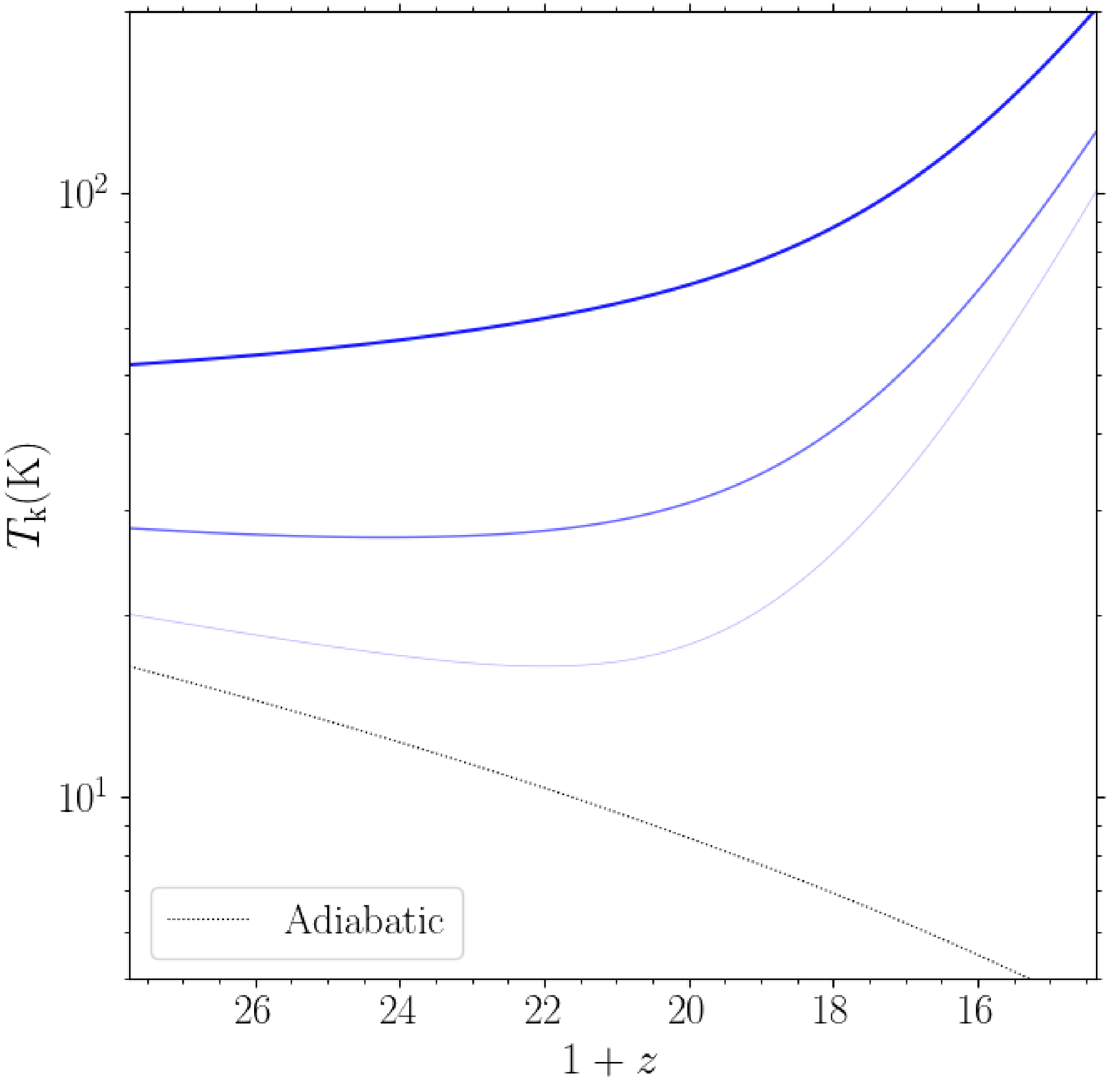
Hawking emission is relevant for $10^{15} - 10^{17}$g BHs

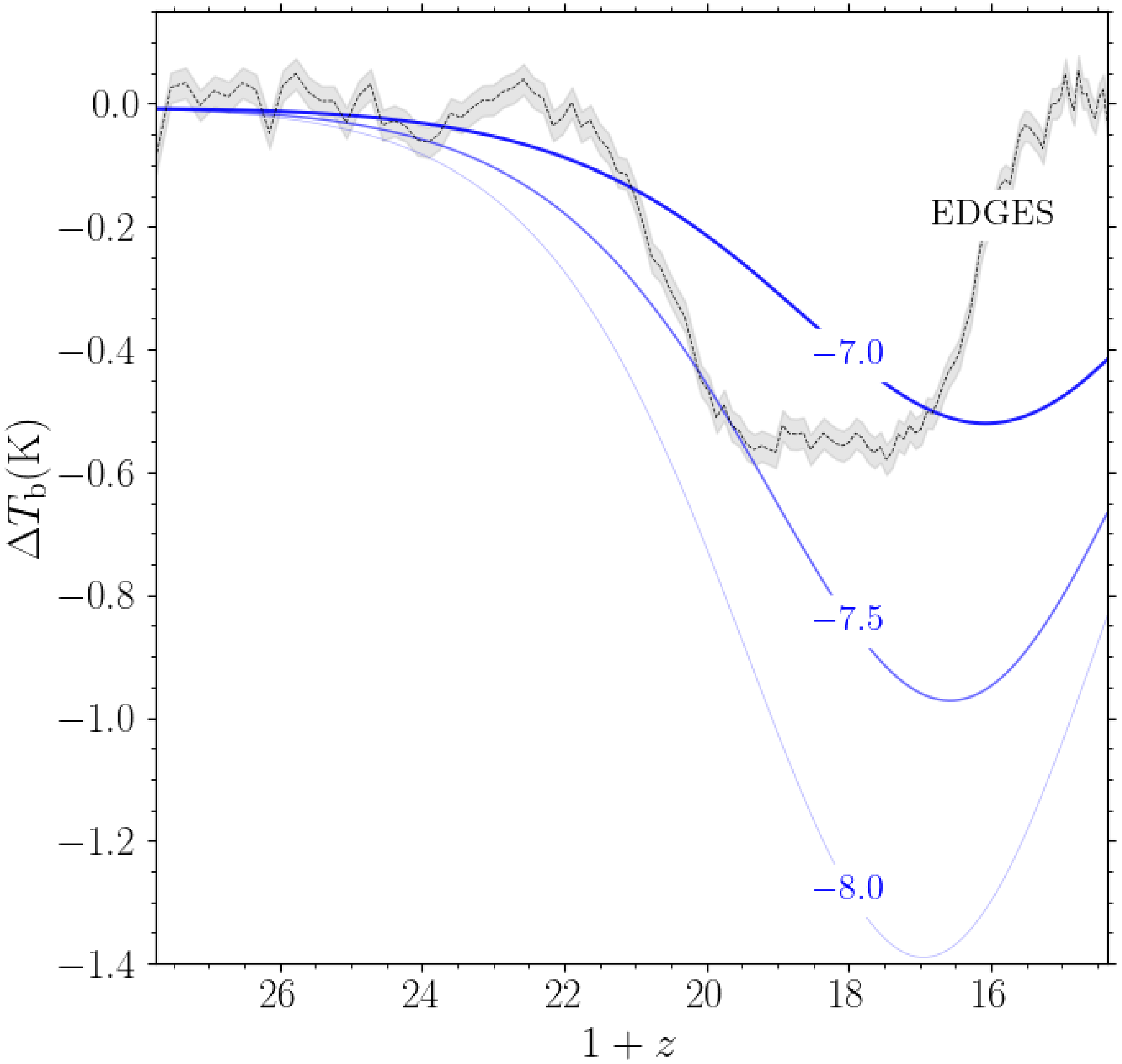
Emission peaks around 10 MeV to 100 keV

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}





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

Case I: No X-ray heating

For 10^{15}g PBH

Best-fitting values:

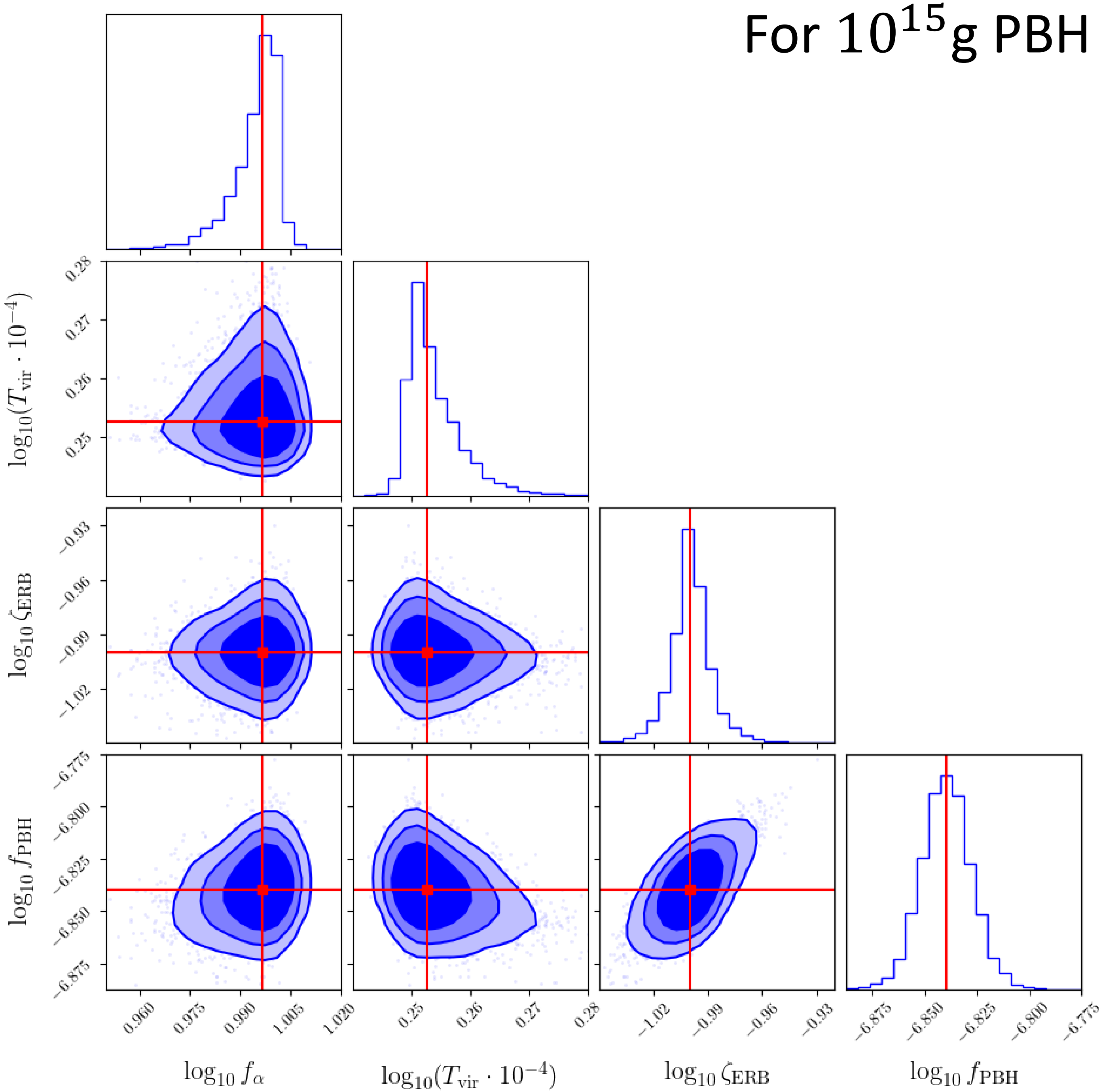
$$\log f_\alpha = 1.0^{+0.01}_{-0.02}$$

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

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

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

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



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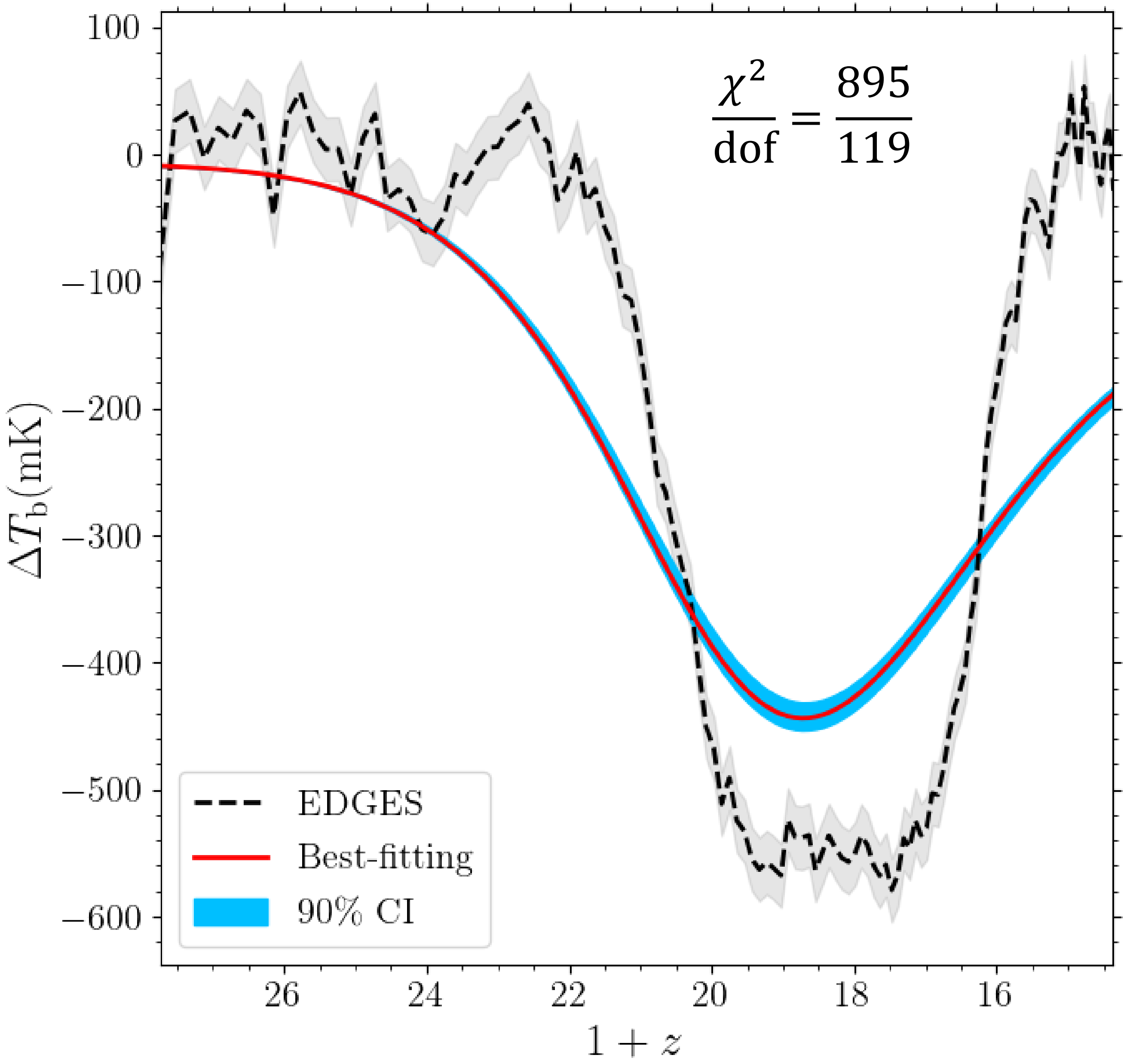


Case II: X-ray heating present

For 10^{15}g PBH

Best-fitting values:

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

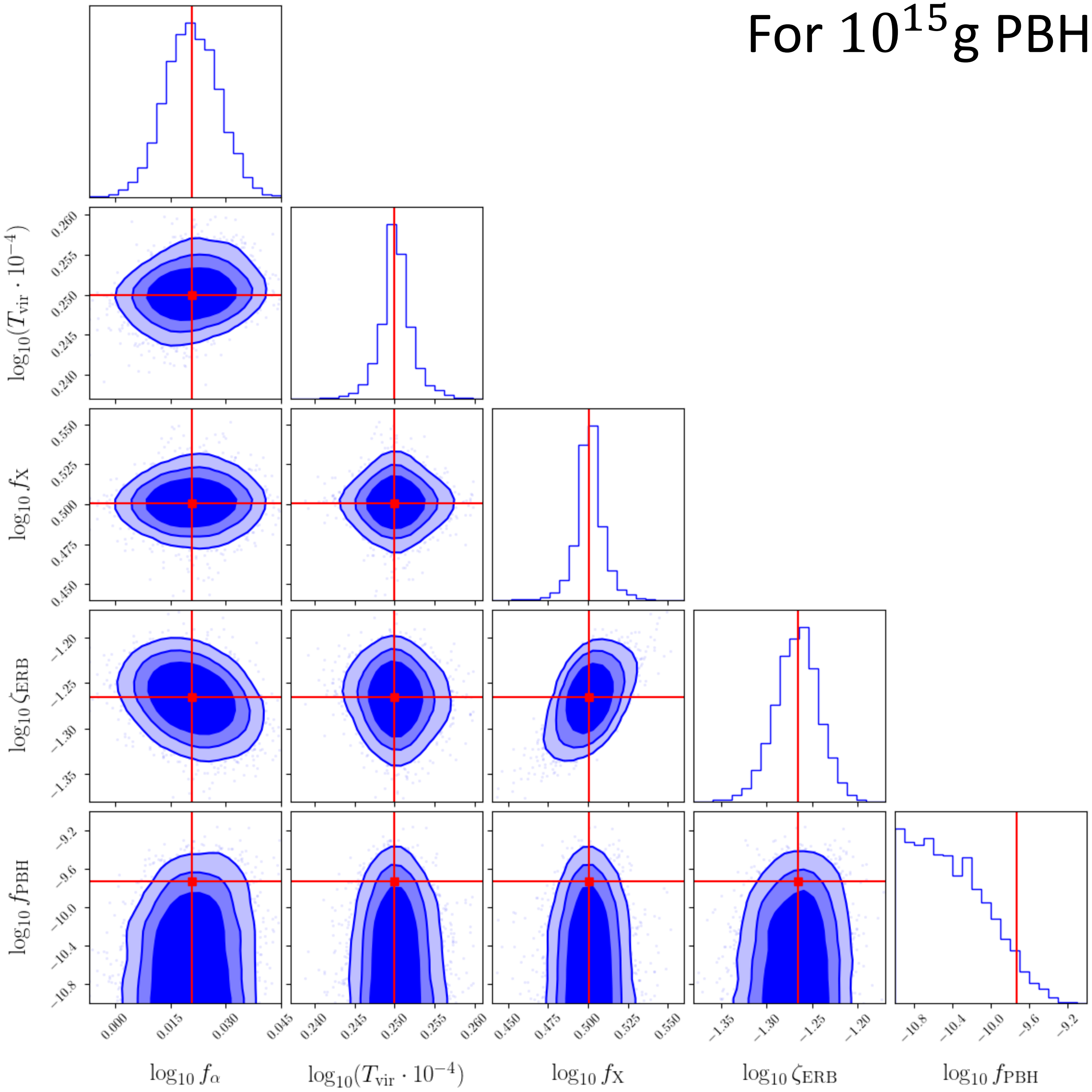
$$\log\left(T_{\rm vir}\cdot 10^{-4}\right) = 0.25^{+0.001}_{-0.001}$$

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

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

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

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



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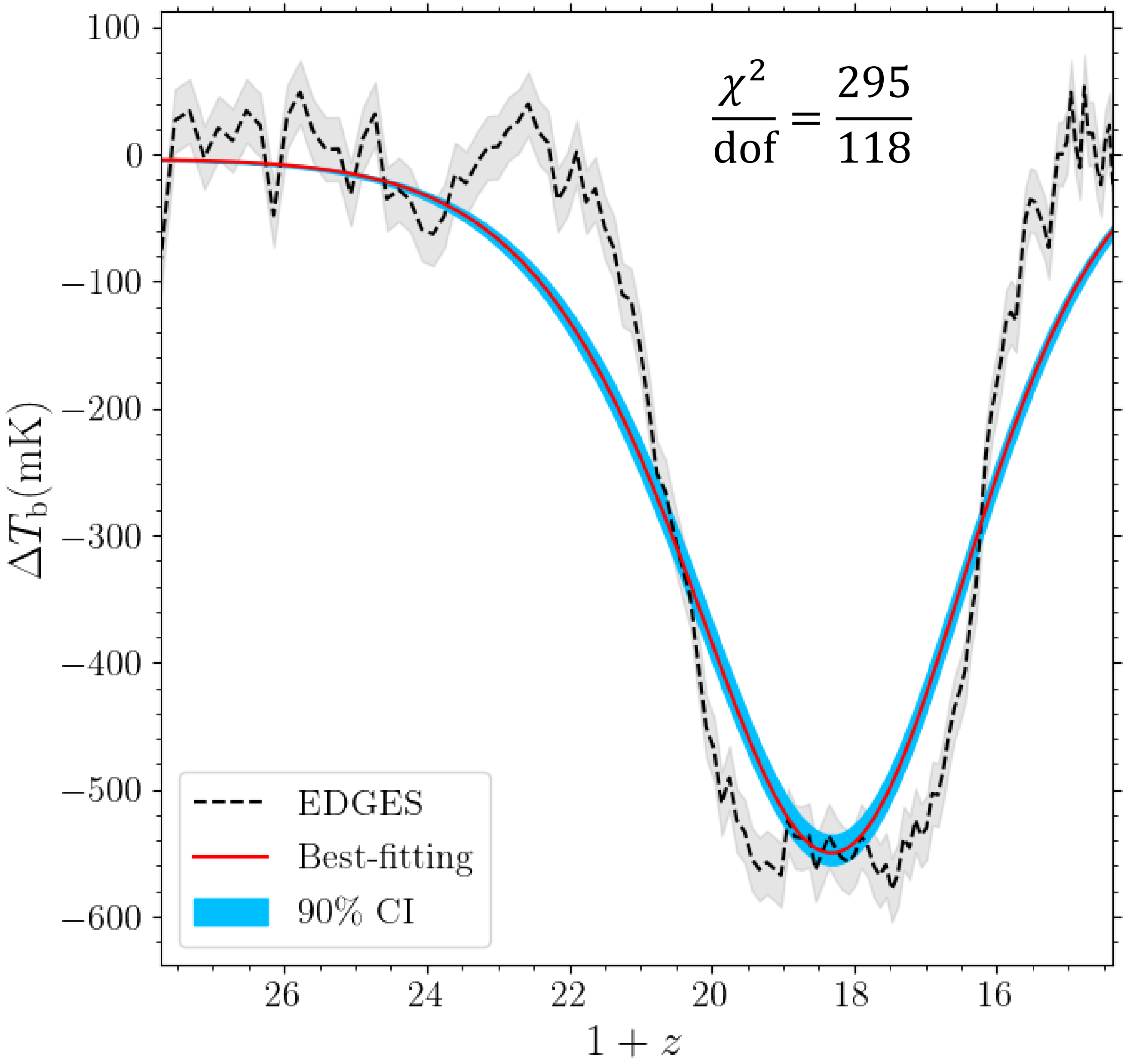
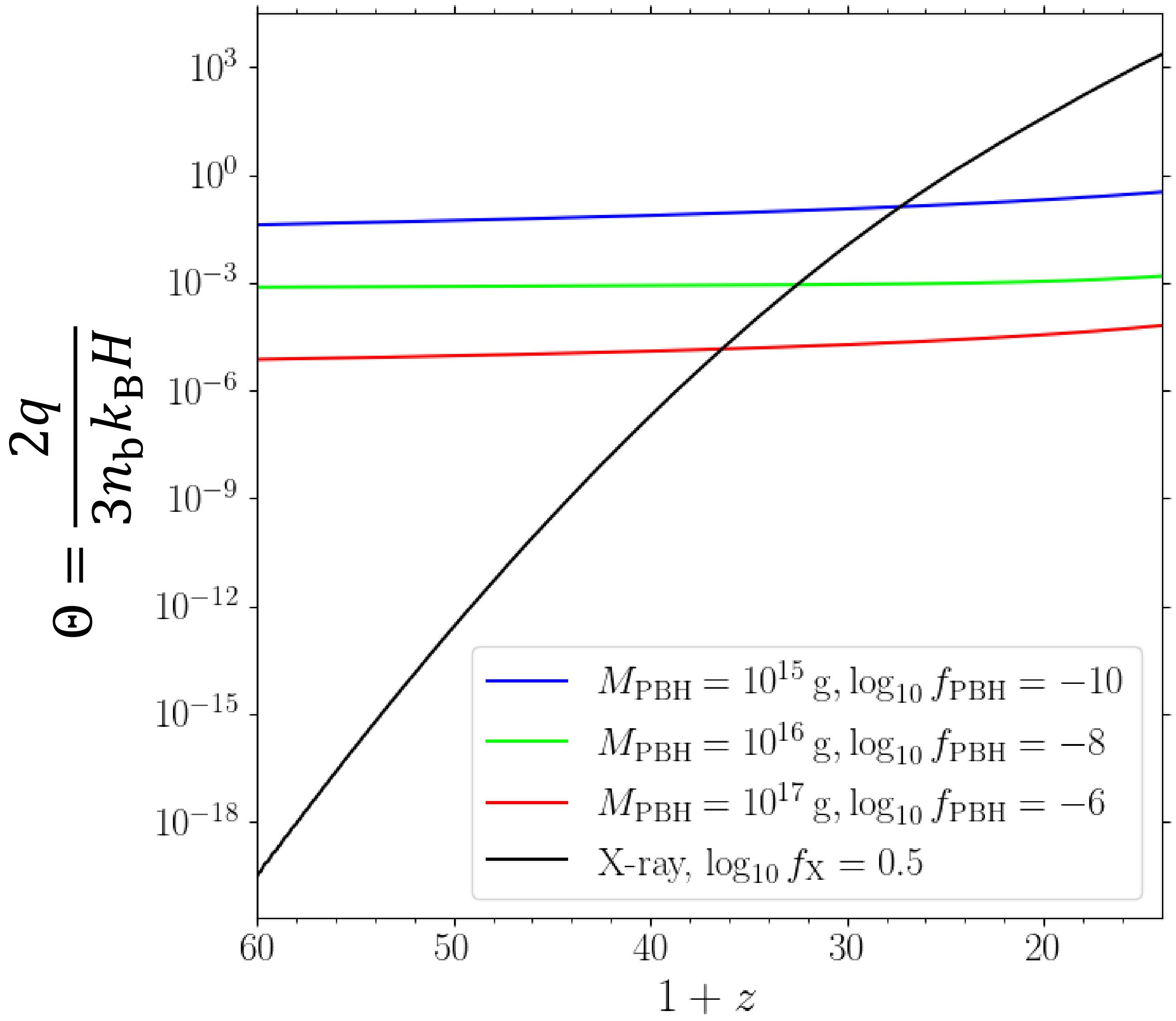
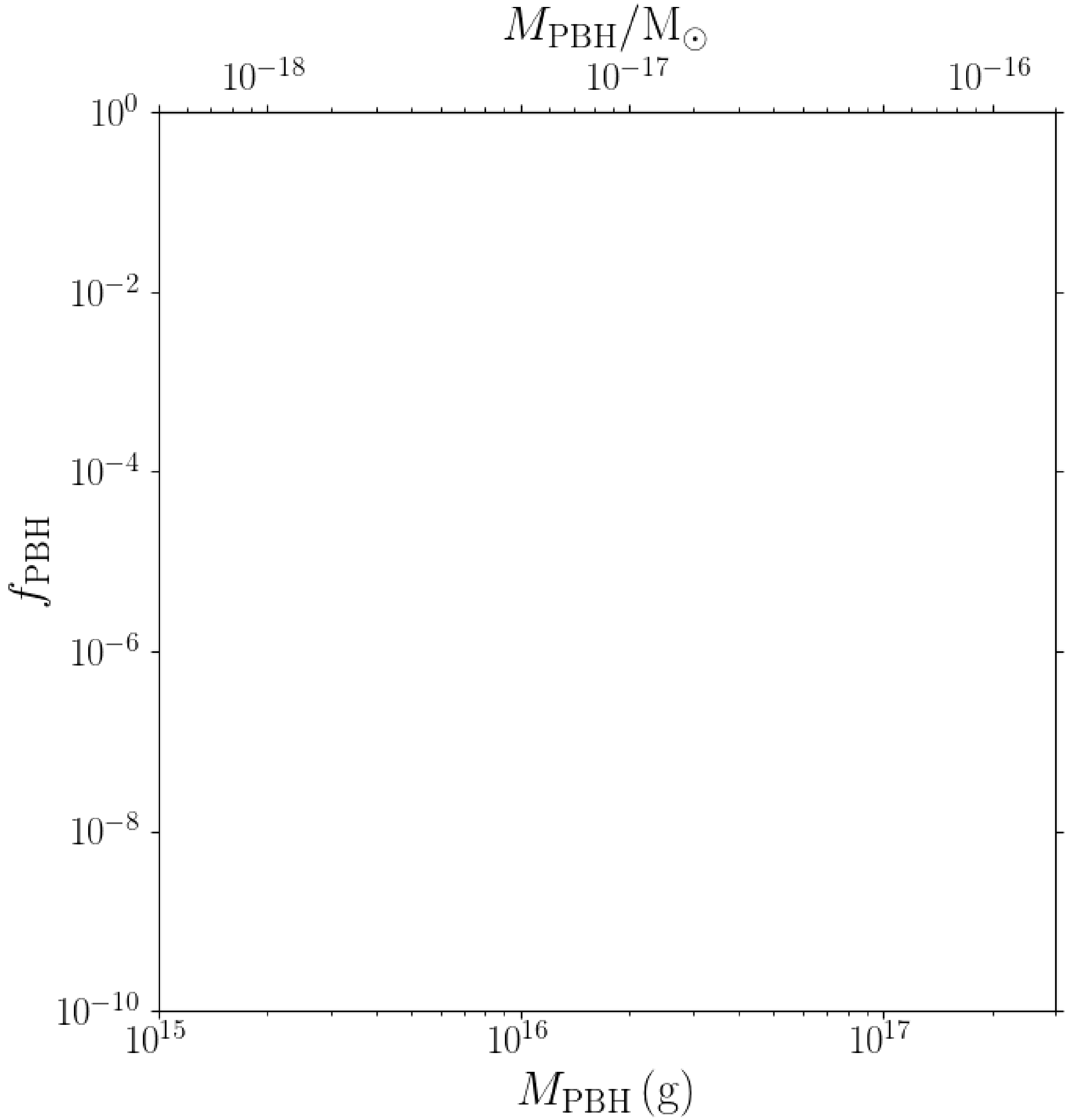
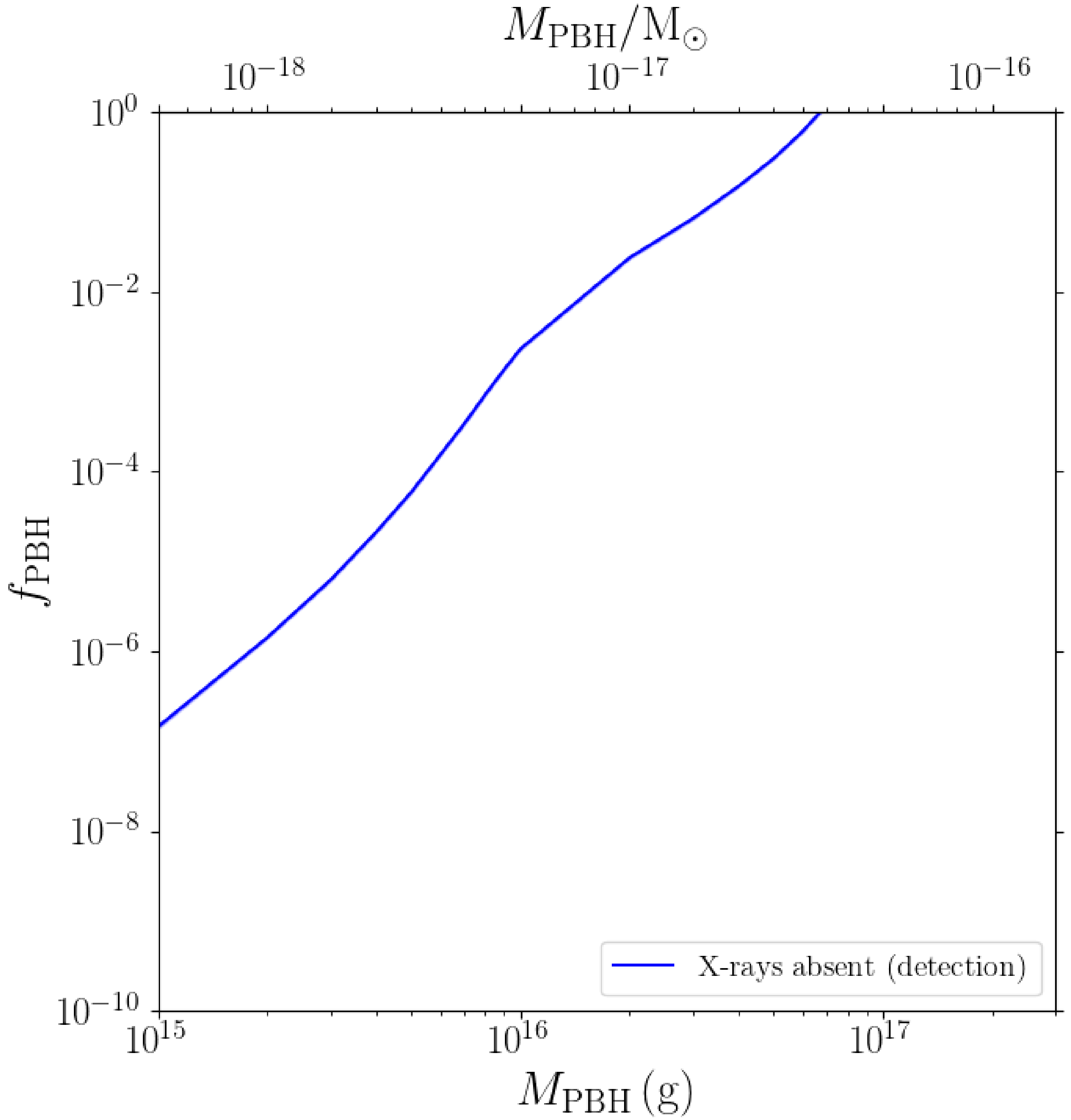


Comparing the heating rate by PBHs and X-rays




$M_{\rm PBH}/{\rm M}_\odot$
10^{-18}
10^{-17}
10^{-16}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$f_{\rm PBH}$
10^{15}
10^{16}
10^{17}
$M_{\rm PBH}\,({\rm g})$



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10^{-18}
10^{-17}
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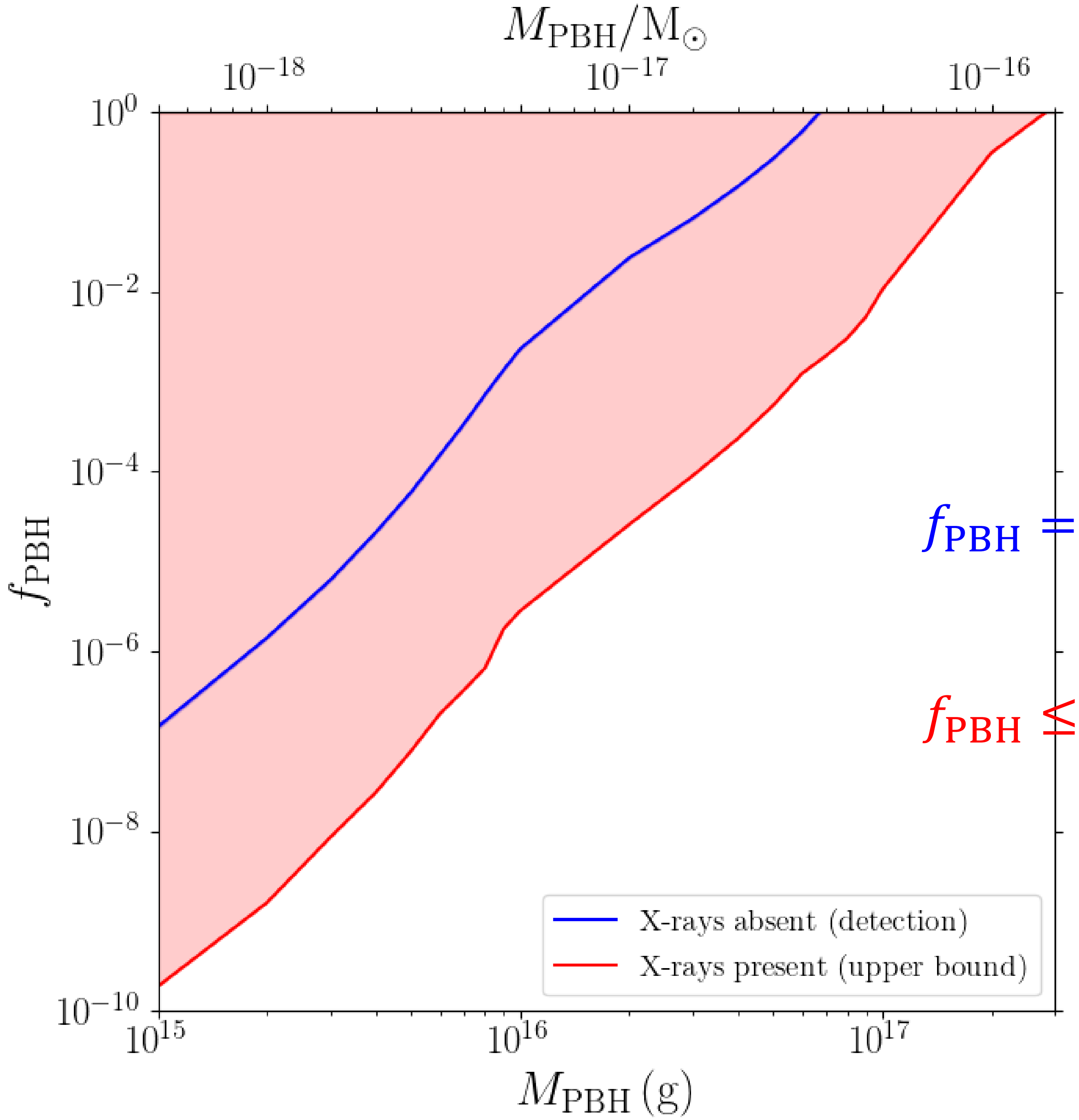
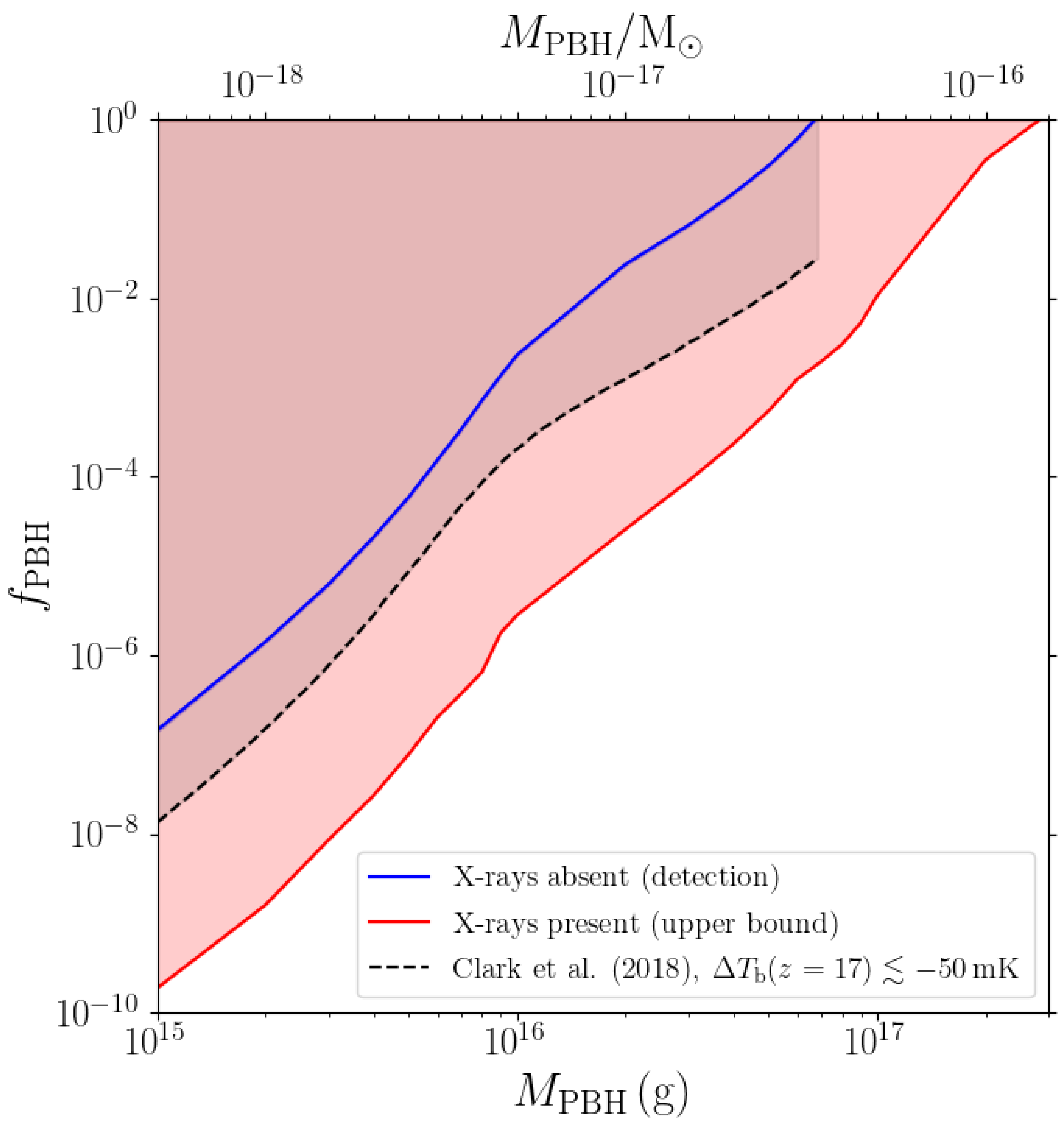
$f_{\rm PBH}$
X-rays absent (detection)
10^{15}
10^{16}
10^{17}
$M_{\rm PBH}\,({\rm g})$



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

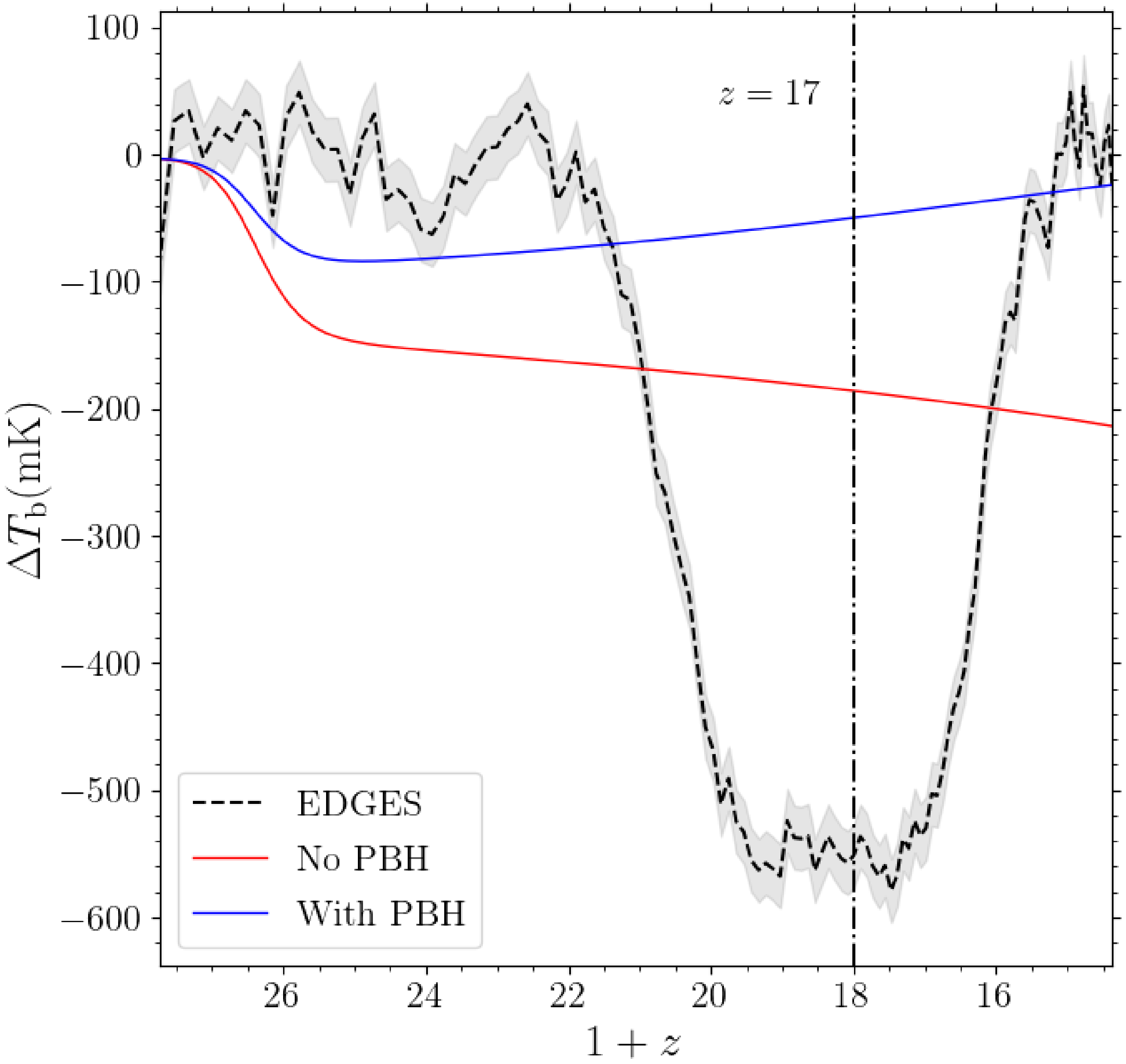
$$f_{\rm PBH} \leq 10^{-9.73}\left(\frac{M_{\rm PBH}}{10^{15}{\rm g}}\right)^{3.96}$$



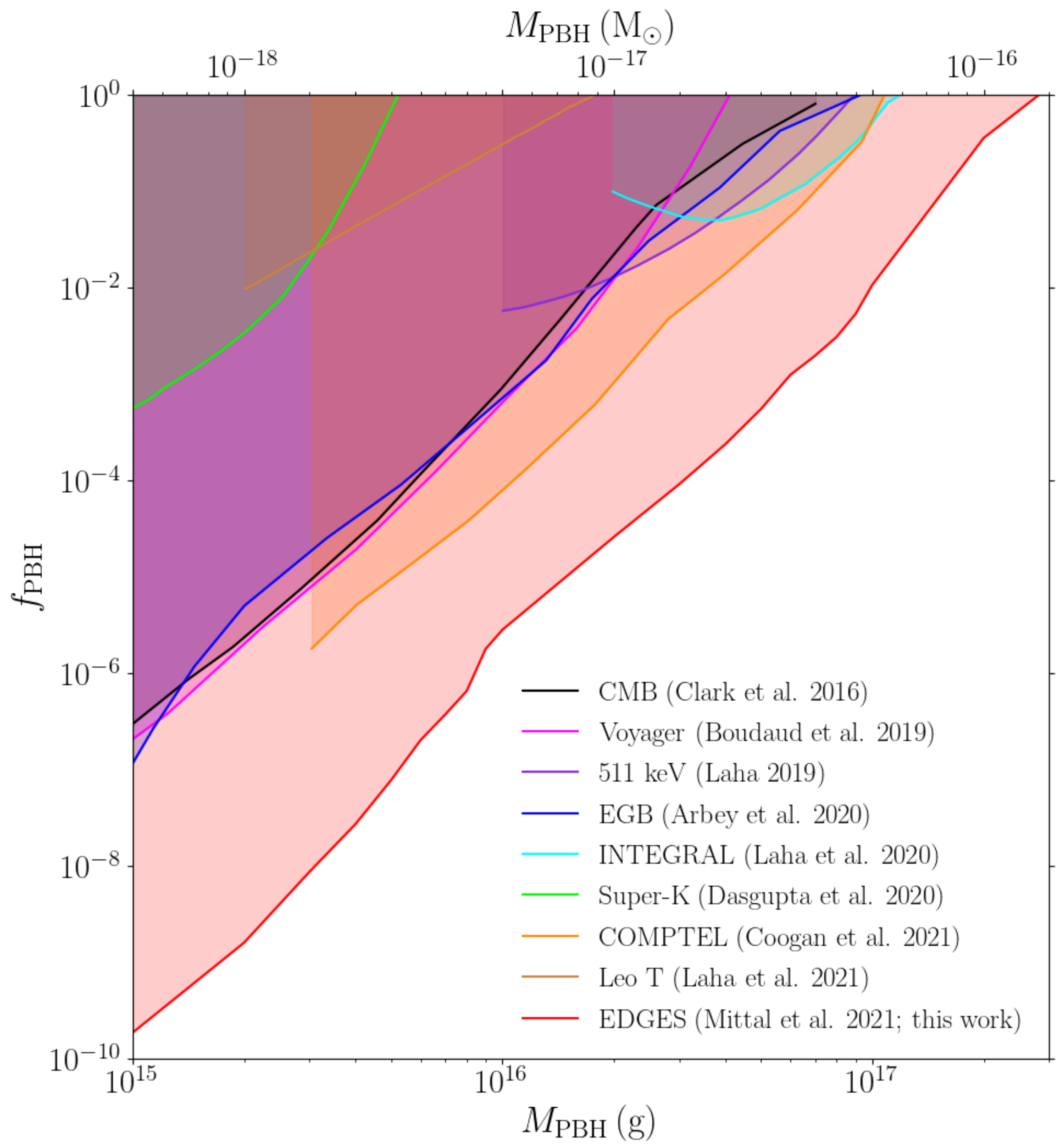
$M_{\rm PBH}/{\rm M}_\odot$
10^{-18}
10^{-17}
10^{-16}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$f_{\rm PBH}$
X-rays absent (detection)
X-rays present (upper bound)
Clark et al. (2018), $\Delta T_{\rm b}(z = 17) \lesssim -50\,{\rm mK}$
10^{15}
10^{16}
10^{17}
$M_{\rm PBH}\,({\rm g})$

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



Constrain curvature power spectrum at small scales

Initial mass fraction
(All PBHs formed the
radiation dominated era)

$$\beta \equiv \frac{\rho^{\mathrm{i}}_{\mathrm{PBH}}}{\rho^{\mathrm{i}}_{\mathrm{r}}} \propto f_{\mathrm{PBH}}\sqrt{M_{\mathrm{PBH}}}$$

By Press-Schechter formalism

$$\beta = 2\int_{\delta_{\mathrm{c}}}^{1} P(\delta)\mathrm{d}\delta \approx \mathrm{erfc}\left(\frac{\delta_{\mathrm{c}}}{\sqrt{2}\sigma}\right)$$

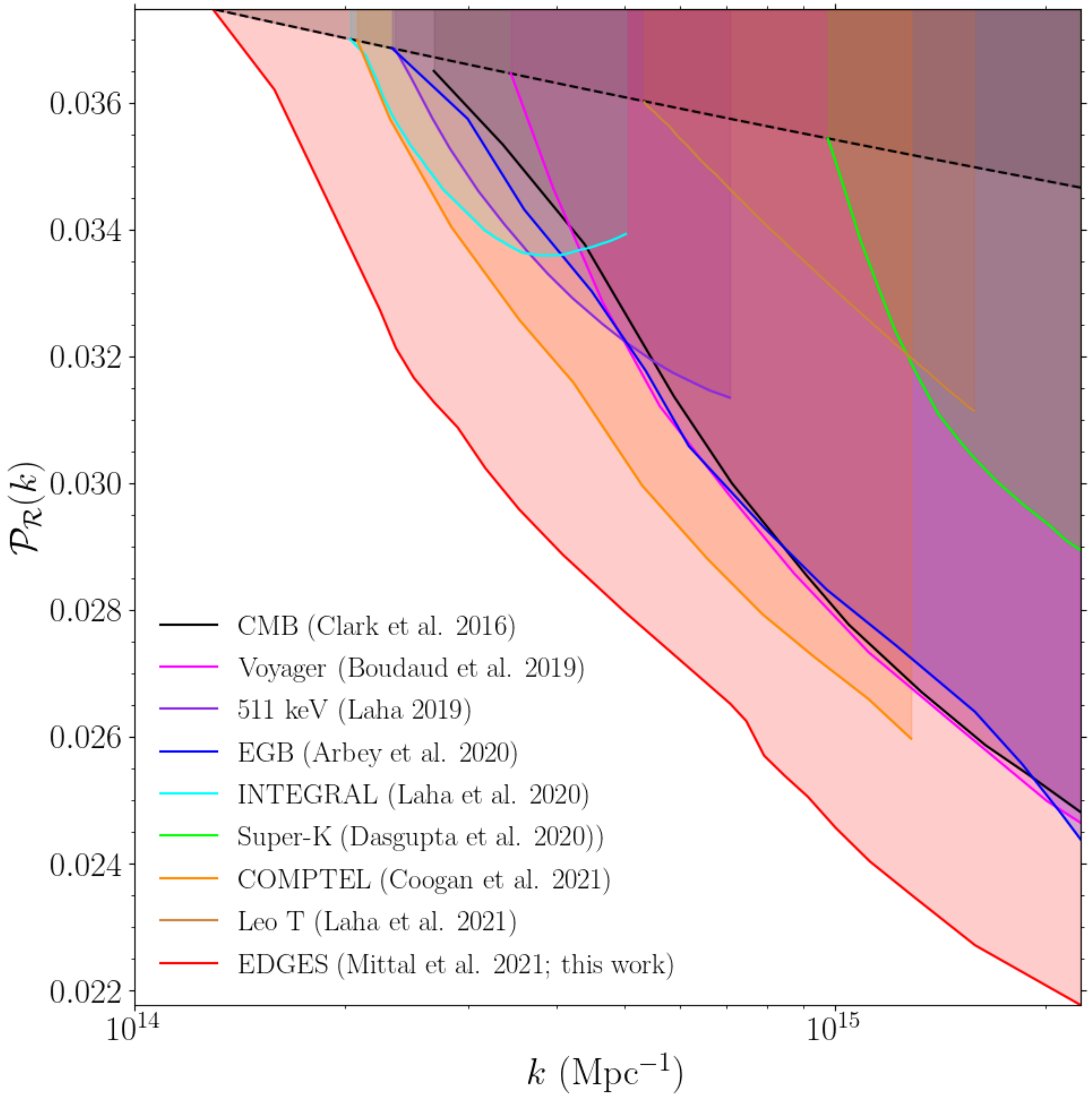
Connecting variance to CPS

$$\sigma^2 \propto \mathcal{P}_{\mathcal{R}}(k)$$

$$(f_{\mathrm{PBH}}, M_{\mathrm{PBH}}) \to (k, \mathcal{P}_{\mathcal{R}}(k))$$

e.g. Bugaev and Klimai (2009), Josan et al. (2009), Sato-Polito et al. (2019)

Constrain curvature power spectrum at small scales



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, $f_{\mathrm{PBH}} \sim 10^{-7}$ and increases with mass
- In the presence of X-ray heating, there is an upper bound on PBHs. For 10^{15}g PBH, $f_{\mathrm{PBH}} < 10^{-10}$ and increases as $\sim M^4$
- Non-PBH astrophysical parameters prefer reasonable values in agreement with literature