Lyman-α Constraints on Primordial Black Hole Dark Matter

Priyank Parashari
Centre for High Energy Physics
IISc, Bangalore

Based on an ongoing work
In collaboration with Akash Kumar Saha and Ranjan Laha

Primordial Black Holes (PBHs)

What are PBHs and why are PBHs interesting?

- PBHs are black holes formed in the early Universe from the gravitational collapse of large density perturbations.

Zel'dovich and Novikov Astron. Zhu, 1966, Hawking MNRAS 1971, Carr and Hawking MNRAS 1974.

Some review articles: Green et al. 2020, Carr et al. 2020 & Escrivà et at. 2022

- PBHs can have a wide mass range:

Time of PBH formation

$$M_{\mathrm{PBH}} \approx 10^{15} \left(\frac{t}{10^{-23}\, s} \right) g$$

- Can have zero and non-zero spin.
- A candidate for Dark matter.
- Can probe the very early Universe.

Minimum Mass for the PBH Dark Matter

$$M_{\mathrm{PBH}} \approx 5 \times 10^{14} g$$

(For nonspinning BHs)

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How to detect PBHs? Various search strategies have been explored to find or constrain the PBHs, e.g., Evaporating PBHs

Evaporating PBHs

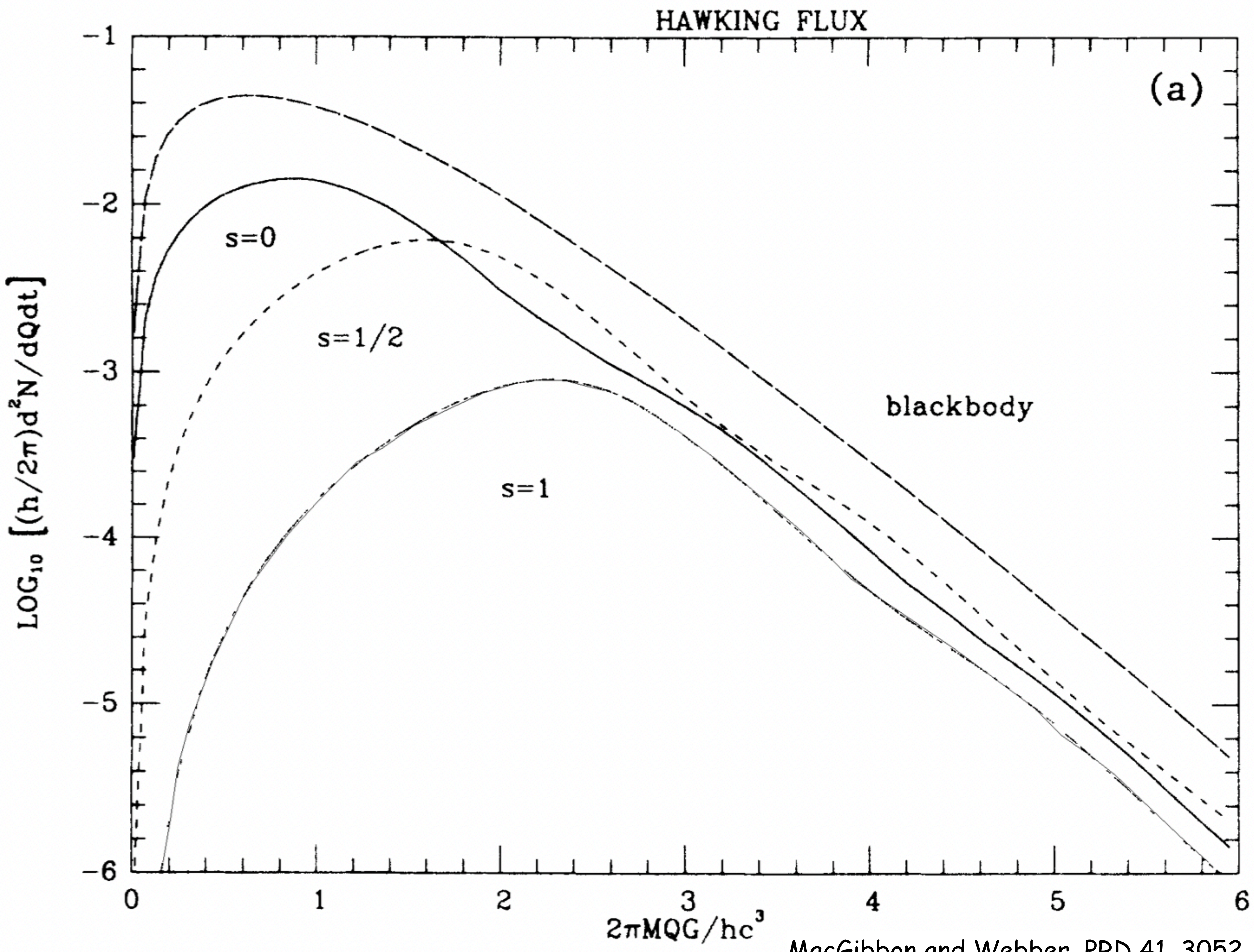
Black Holes evaporate and emit thermal Hawking radiation at a temperature.

$$T_{\rm PBH} = 1.06 \left(\frac{10^{13}\, g}{M_{\rm PBH}} \right) GeV$$

For non-rotating black holes

Mass of PBH

The spectrum closely resembles a black-body radiation



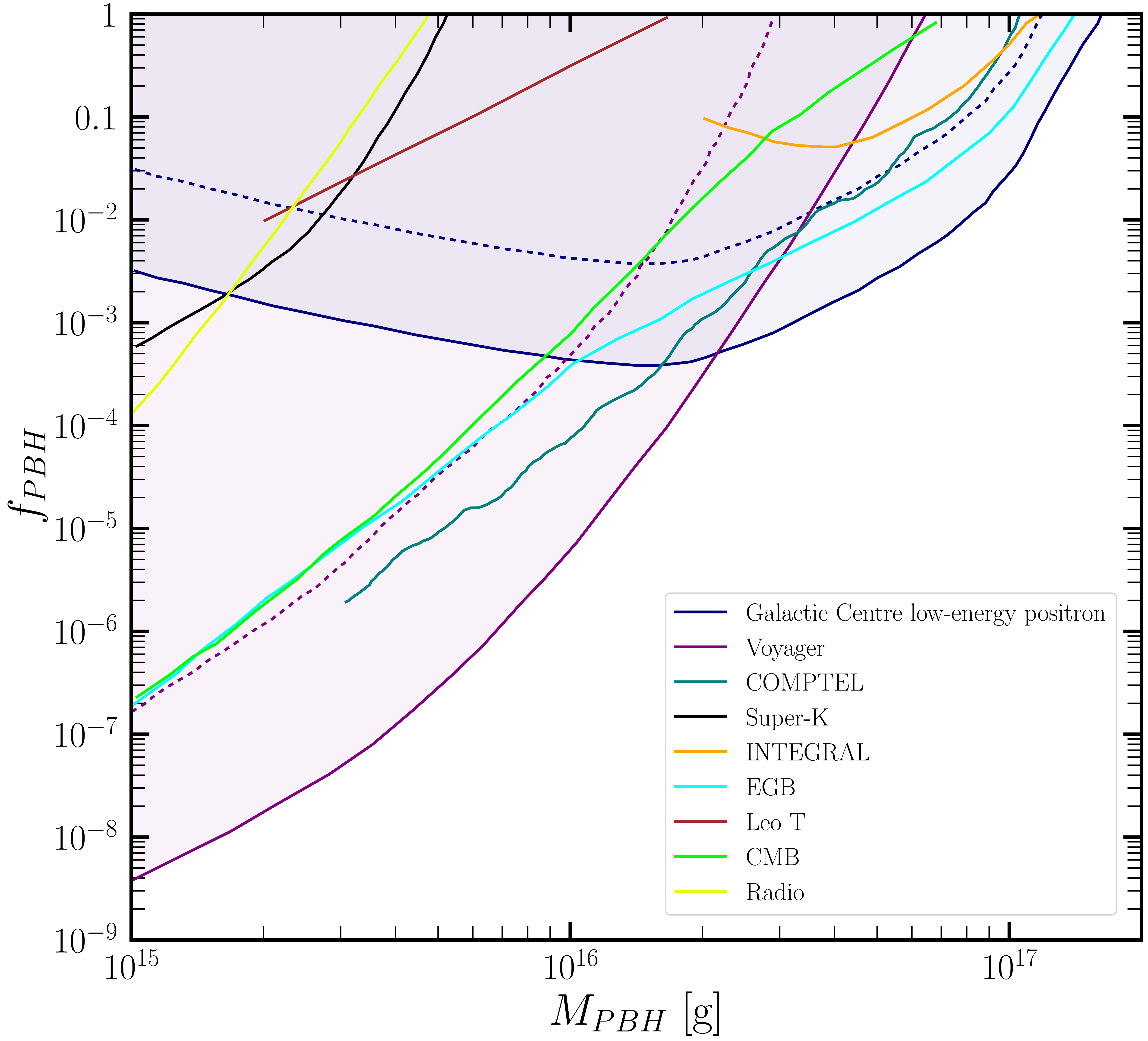
MacGibbon and Webber, PRD 41, 3052, 1990

Energy spectrum of emitted particles

$$\frac{d^2 N_s}{dEdt} = \frac{\Gamma_s}{2\pi} \frac{1}{e^{E/T_{\rm PBH}} - (-1)^s}$$

Evaporating PBHs can have observable consequences, which can be used to detect the signal of low mass PBHs ($10^{15} - 10^{18}$ g)

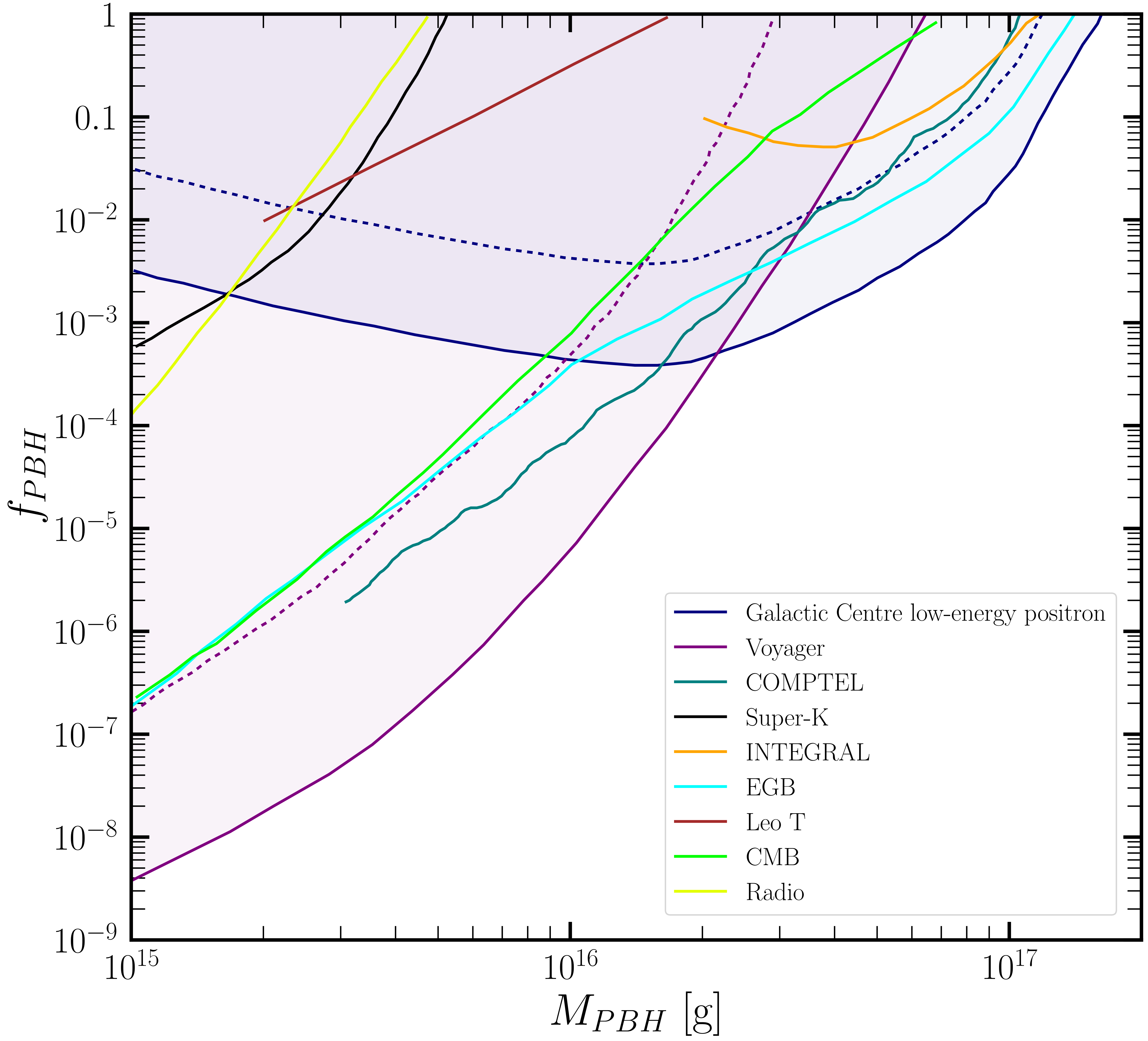
PBH as Dark Matter



Existing constraints for low mass evaporating PBHs obtained using various measurements

$$f_{\mathrm{PBH}} = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{DM}}}$$

PBH as Dark Matter



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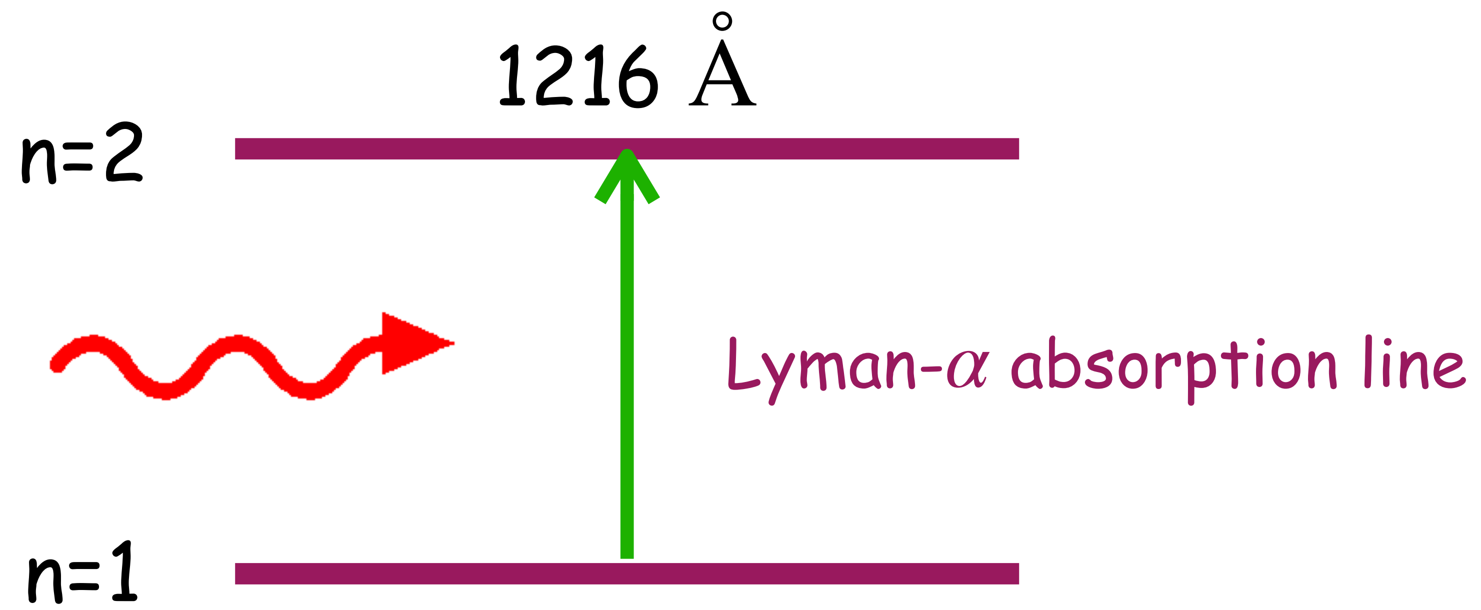
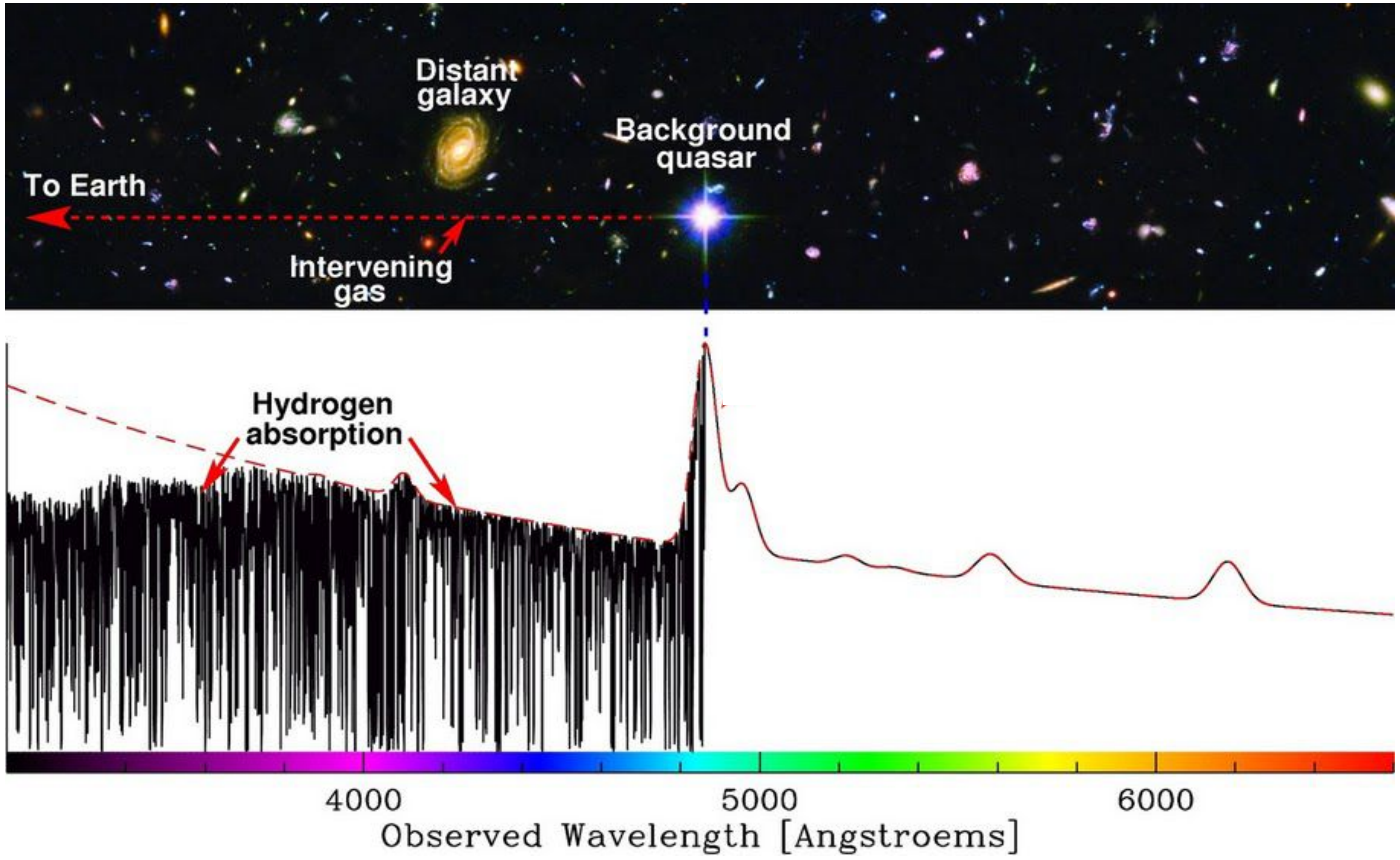
$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}$$

Any other observable?

Lyman-α Forest measurements

Lyman-α Forest Measurement



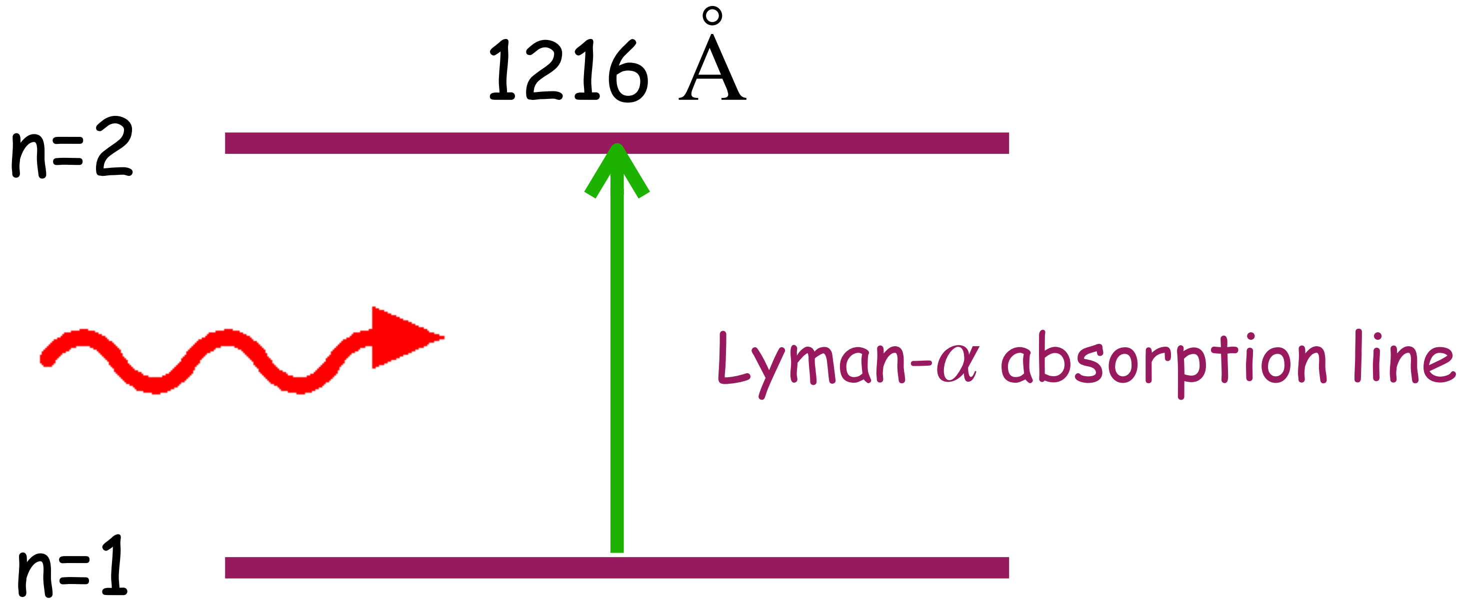


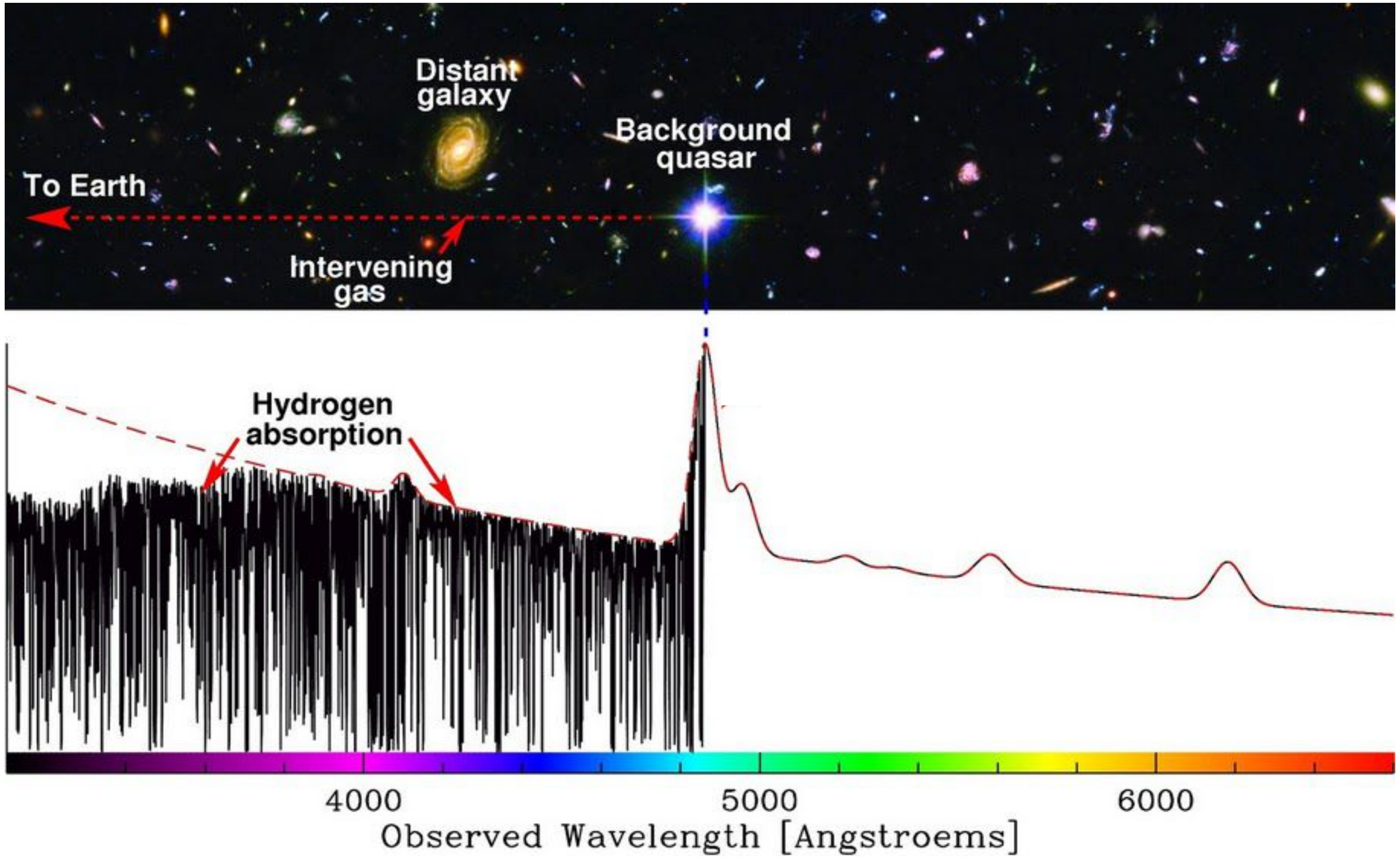
What is Lyman-α forest?

Series of absorption lines in the distant galaxies or quasars spectra due to Lyman-α transition of neutral Hydrogen

Picture credit: Futura Sciences Webpage

Lyman-α Forest Measurement





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Series of absorption lines in the distant galaxies or quasars spectra due to Lyman-α transition of neutral Hydrogen

Lyman-α forest observations can be used to infer IGM temperatures.

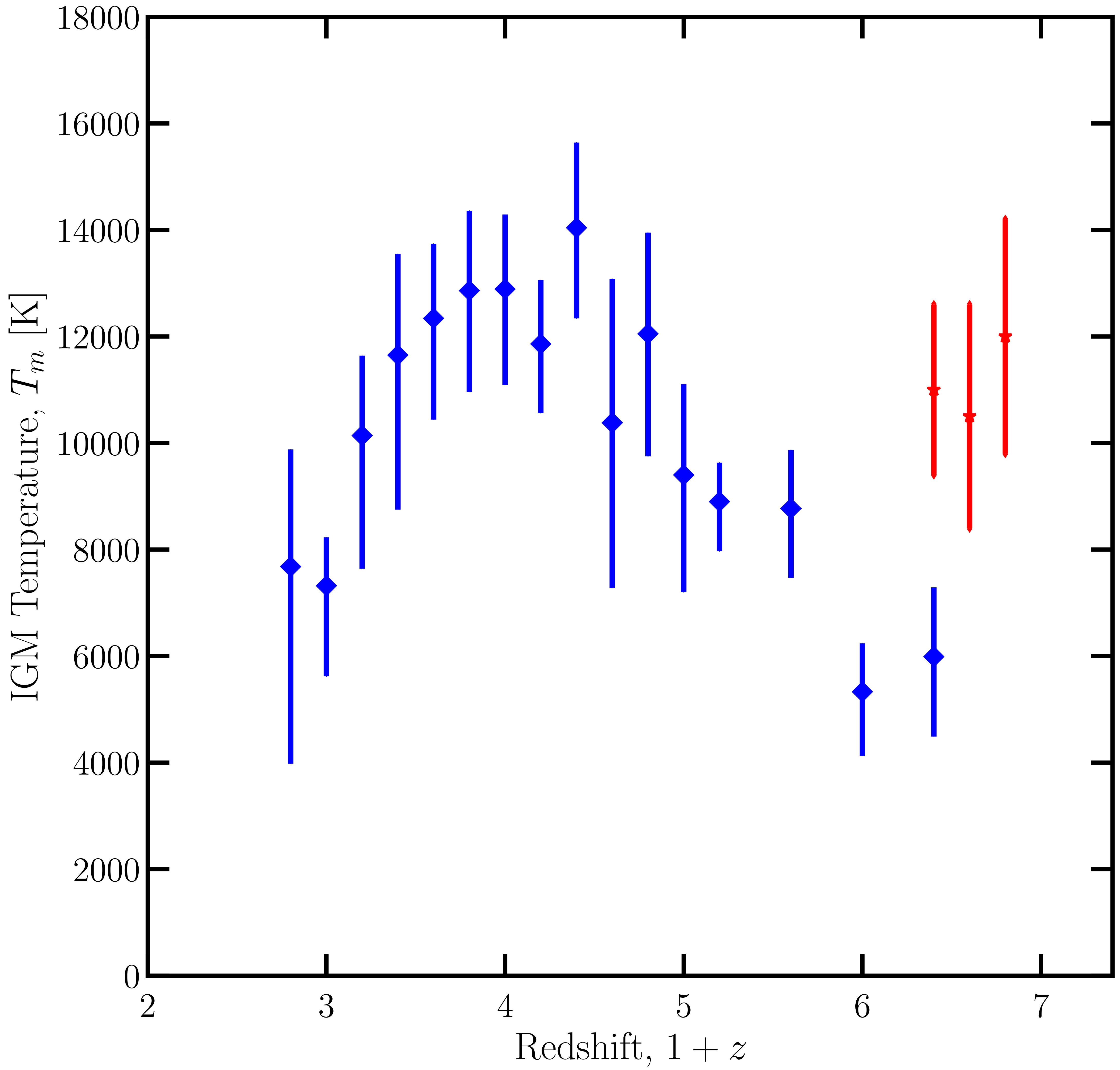
Picture credit: Futura Sciences Webpage

IGM Temperature Measurements

Infer thermal evolution of IGM by comparing the measured Lyman-α forest power spectra to the hydrodynamical simulations.

Walther et al. (2019) & Gaikwad et al. (2020) determined the IGM temperature in the redshift range 1.8 < z < 5.8

Measurements: BOSS, HIRAS, MIKE, etc.



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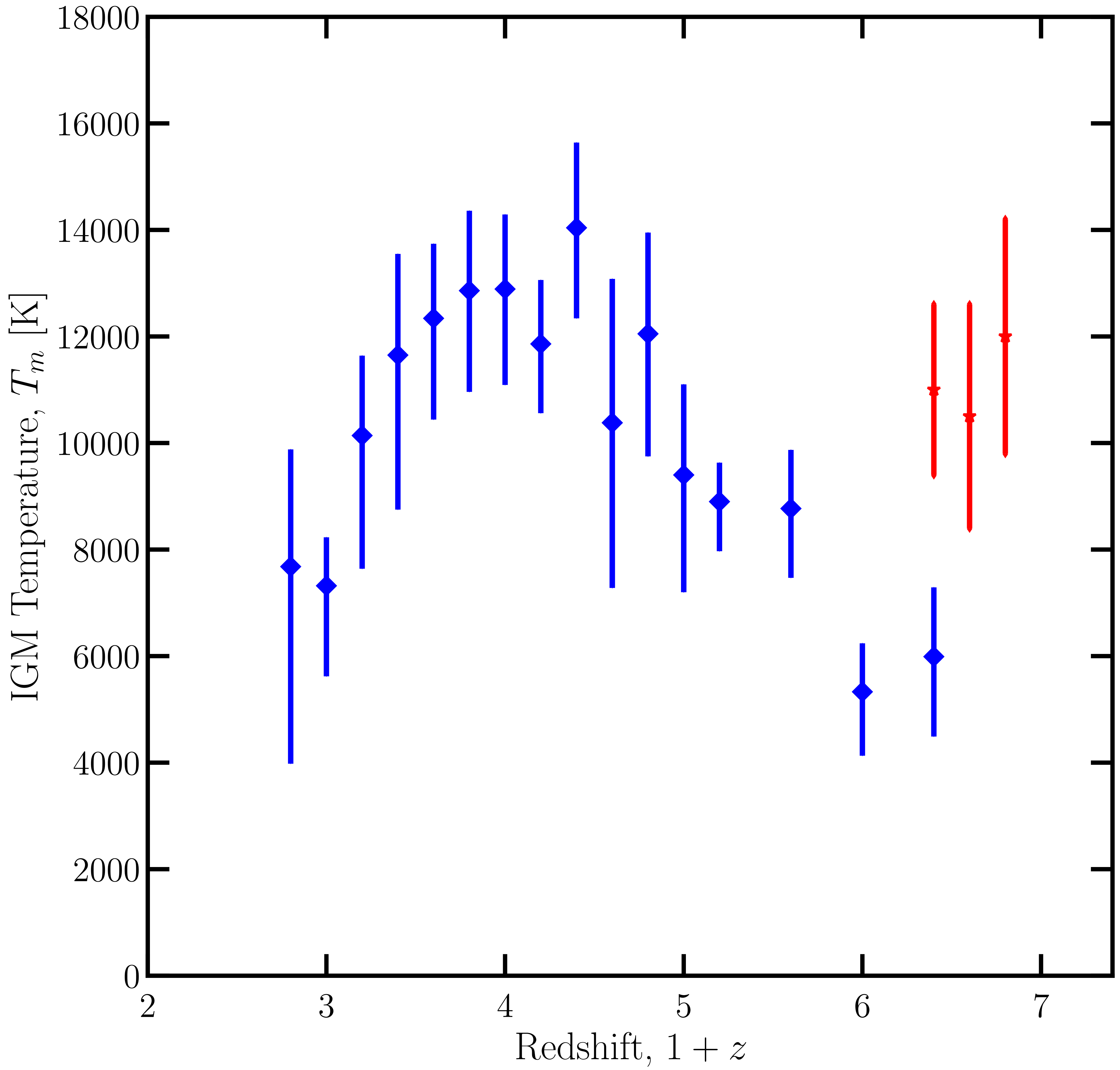
Can we use these IGM temperature measurements to probe PBHs?



Ionization & IGM Temperature Evolution

Evaporating PBHs will inject energetic particles into the intergalactic medium and therefore, can affect the reionization and IGM temperature.

HI: Neutral Hydrogen
HII: Ionized Hydrogen

x_{HII} = ratio of number density of free protons to the total number density of hydrogen

$$\dot{x}_{\mathrm{HII}} = \dot{x}^{(0)}_{\mathrm{HII}} + \dot{x}^{\mathrm{PBH}}_{\mathrm{HII}} + \dot{x}^{\star}_{\mathrm{HII}}$$

- $\dot{x}^{(0)}_{\mathrm{HII}}$: Base Term: Recombination
- $\dot{x}^{\mathrm{PBH}}_{\mathrm{HII}}$: Energy injection due to PBH evaporation
- $\dot{x}^{\star}_{\mathrm{HII}}$: Reionization due to astrophysical sources; Use Planck results

T_{m} = Intergalactic medium temperature

$$\dot{T}_{\mathrm{m}} = \dot{T}_{(0)} + \dot{T}_{\mathrm{PBH}} + \dot{T}^{\star}$$

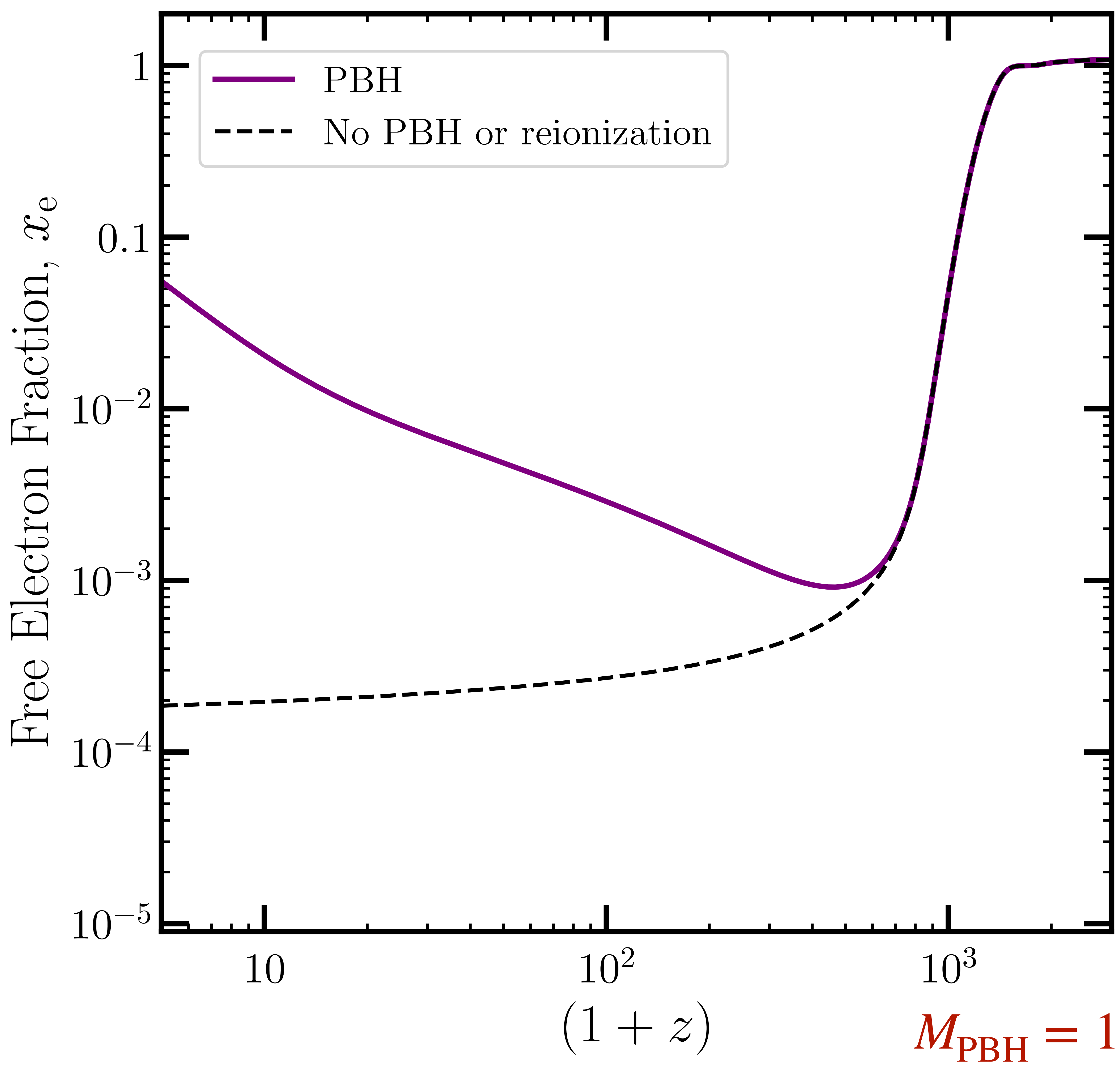
- $\dot{T}_{(0)}$: Base term: Hubble expansion, Recombination, Compton scattering
- $\dot{T}_{\mathrm{PBH}}$: Energy injection due to PBH evaporation
- $\dot{T}^{\star}$: Photoheating due to astrophysical reionization

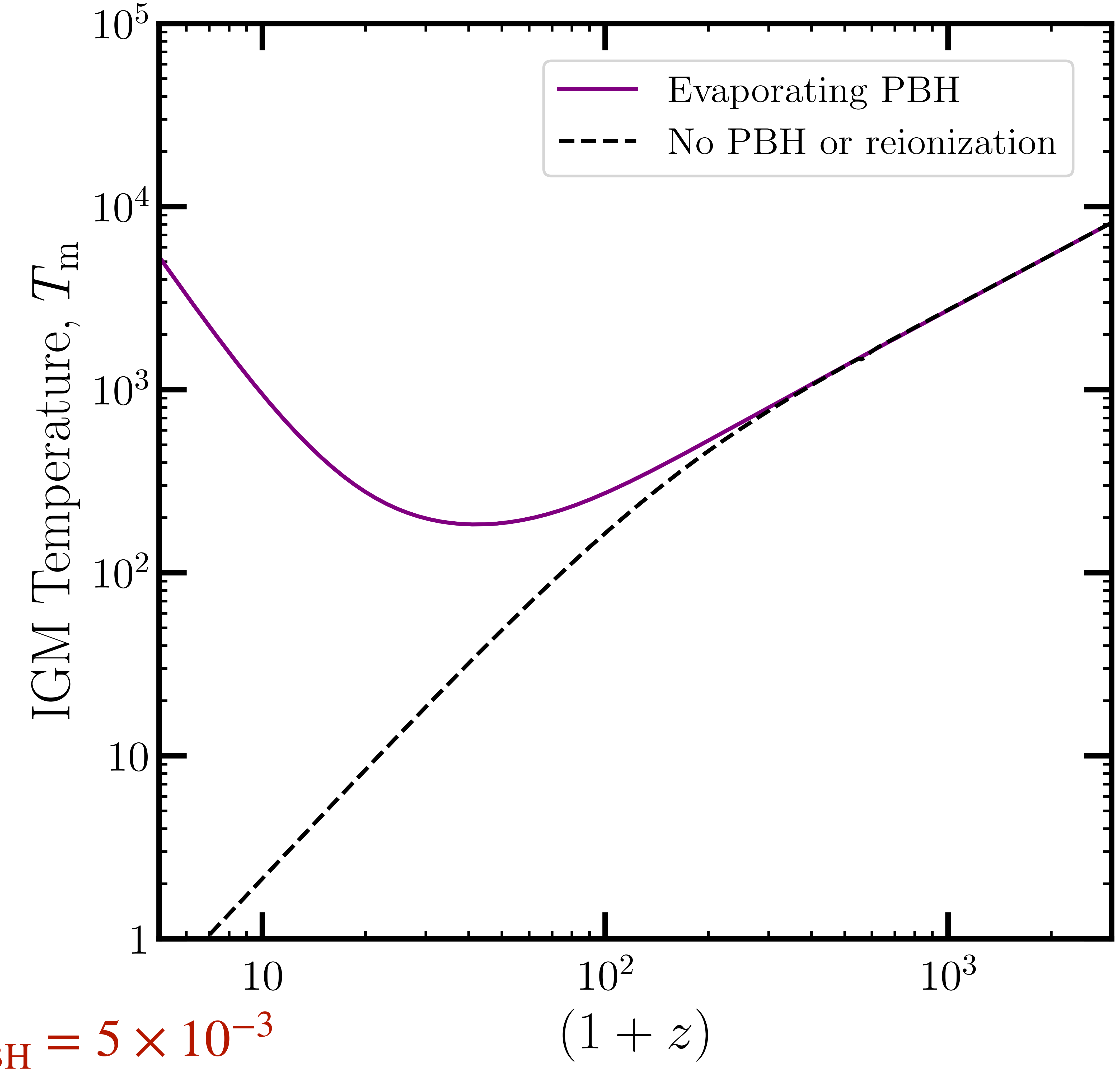
Ionization and IGM Temperature

Obtained by modifying the DarkHistory Code by Liu et al. arXiv:1904.09296

$$\dot{x}_{HII} = \dot{x}_{HII}^{(0)} + \dot{x}_{HII}^{PBH}$$

$$\dot{T}_m = \dot{T}_{(0)} + \dot{T}_{PBH}$$



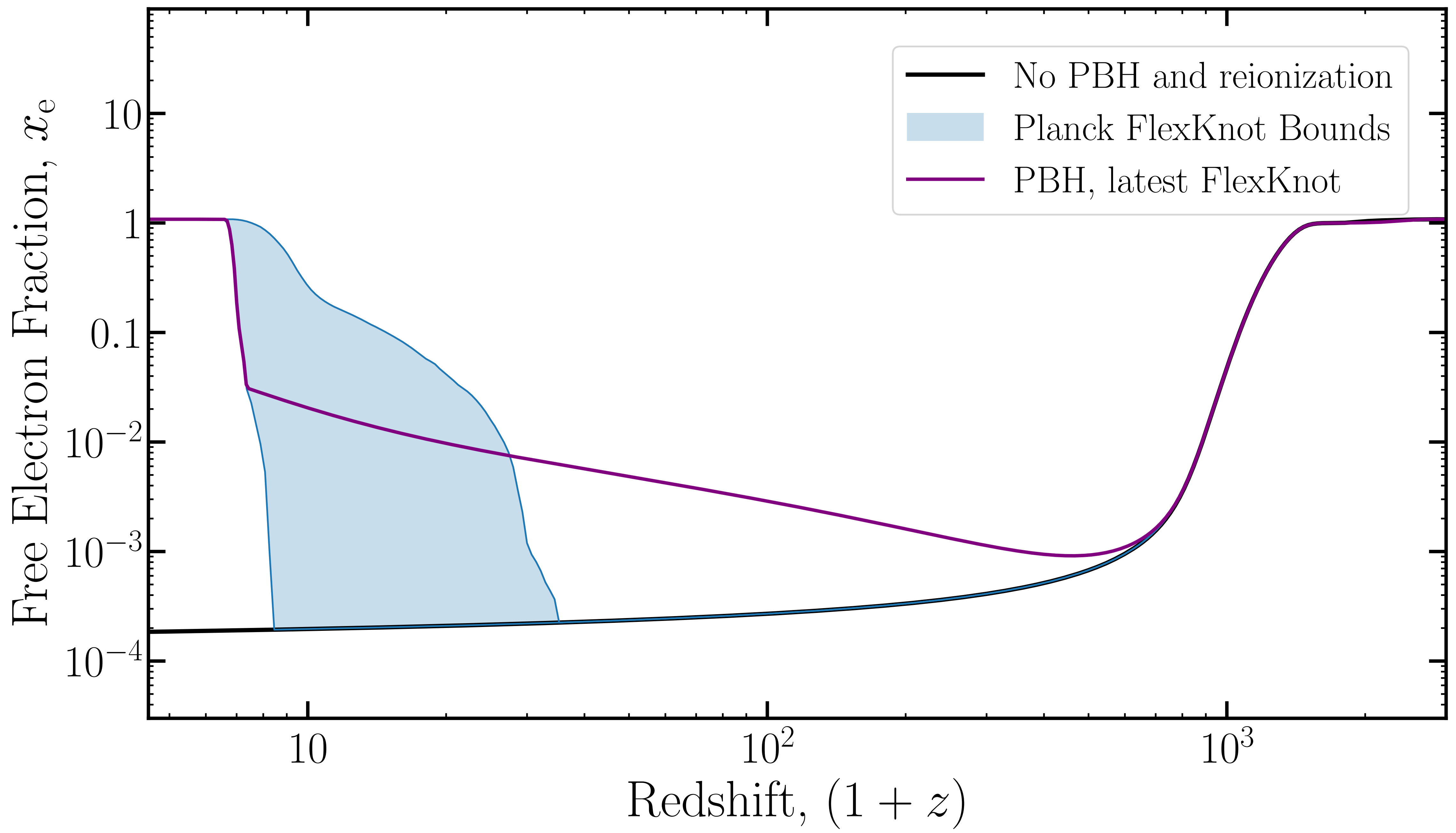


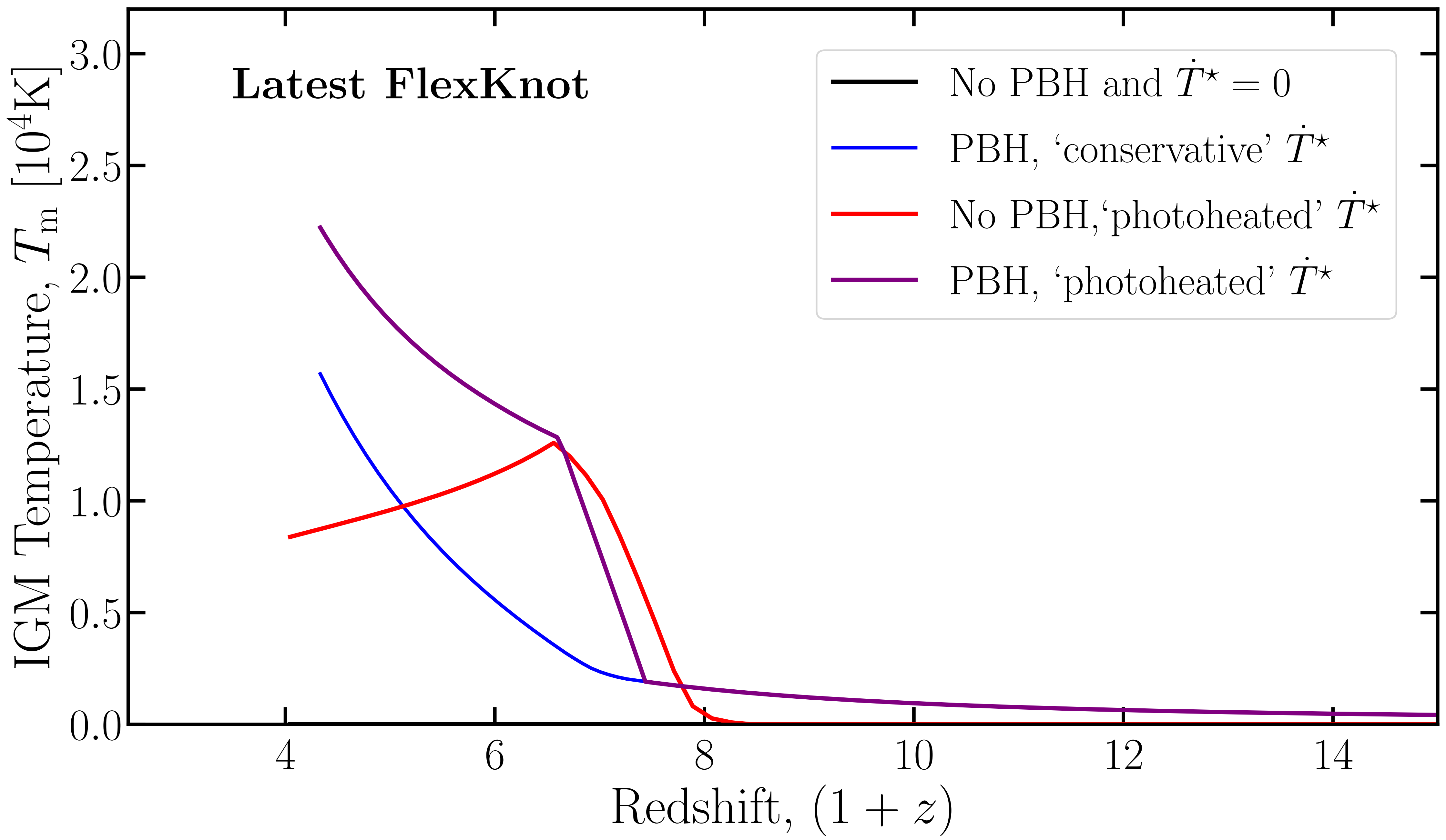
$M_{PBH} = 10^{16}g$ $f_{PBH} = 5 \times 10^{-3}$

Ionization and IGM Temperature

$$\dot{x}_{\rm HII} = \dot{x}^{(0)}_{\rm HII} + \dot{x}^{\rm PBH}_{\rm HII} + \dot{x}^{\star}_{\rm HII}$$

$$\dot{T}_{\rm m} = \dot{T}_{(0)} + \dot{T}_{\rm PBH} + \dot{T}^{\star}$$





$M_{\rm PBH} = 10^{16} g \quad f_{\rm PBH} = 5 \times 10^{-3}$

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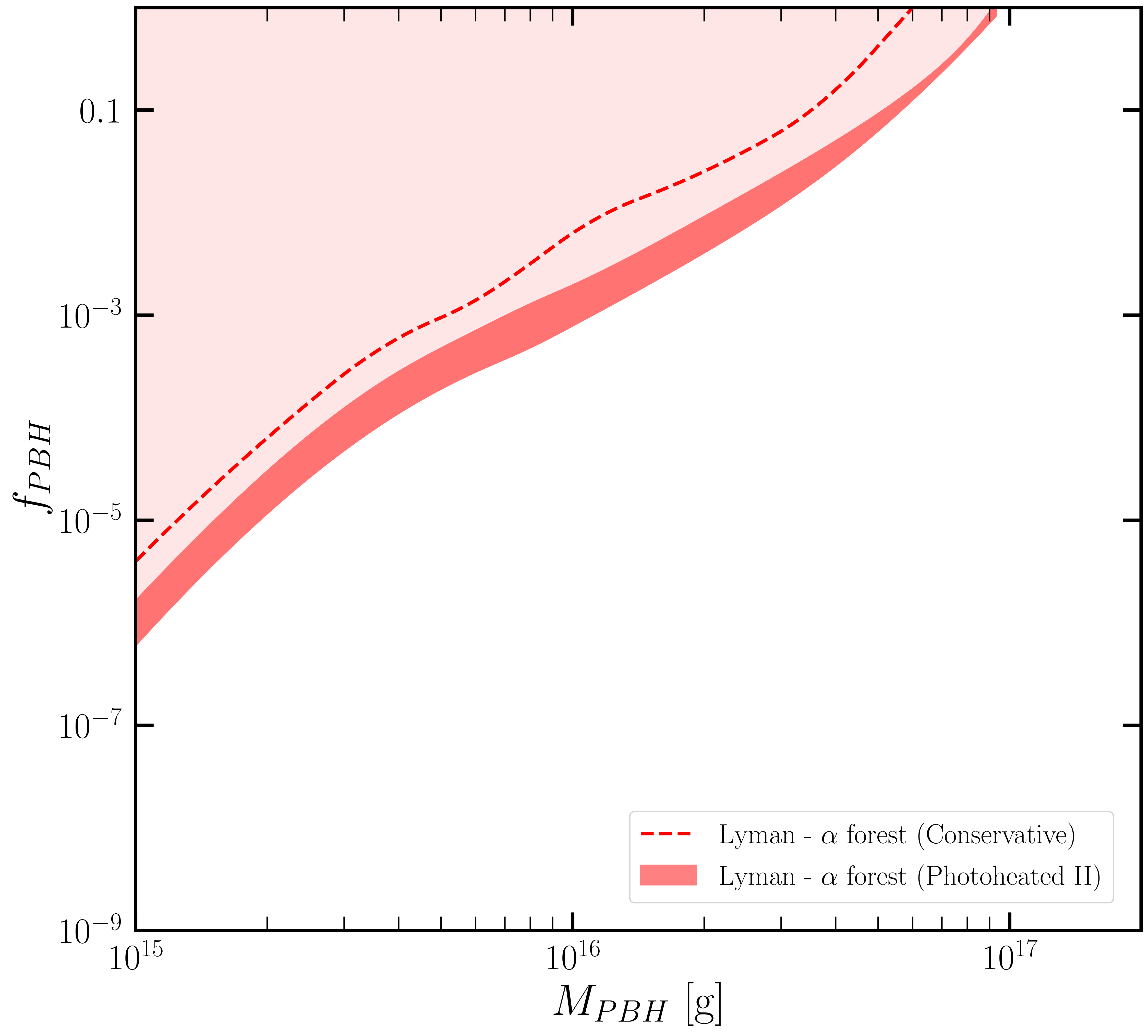
Constraints on PBH Abundance



The IGM temperature does not exceed with the IGM temperature obtained by Walther et al. (2019) & Gaikwad et al. (2020) from Lyman-α forest measurement.

Parashari et al. (in preparation)

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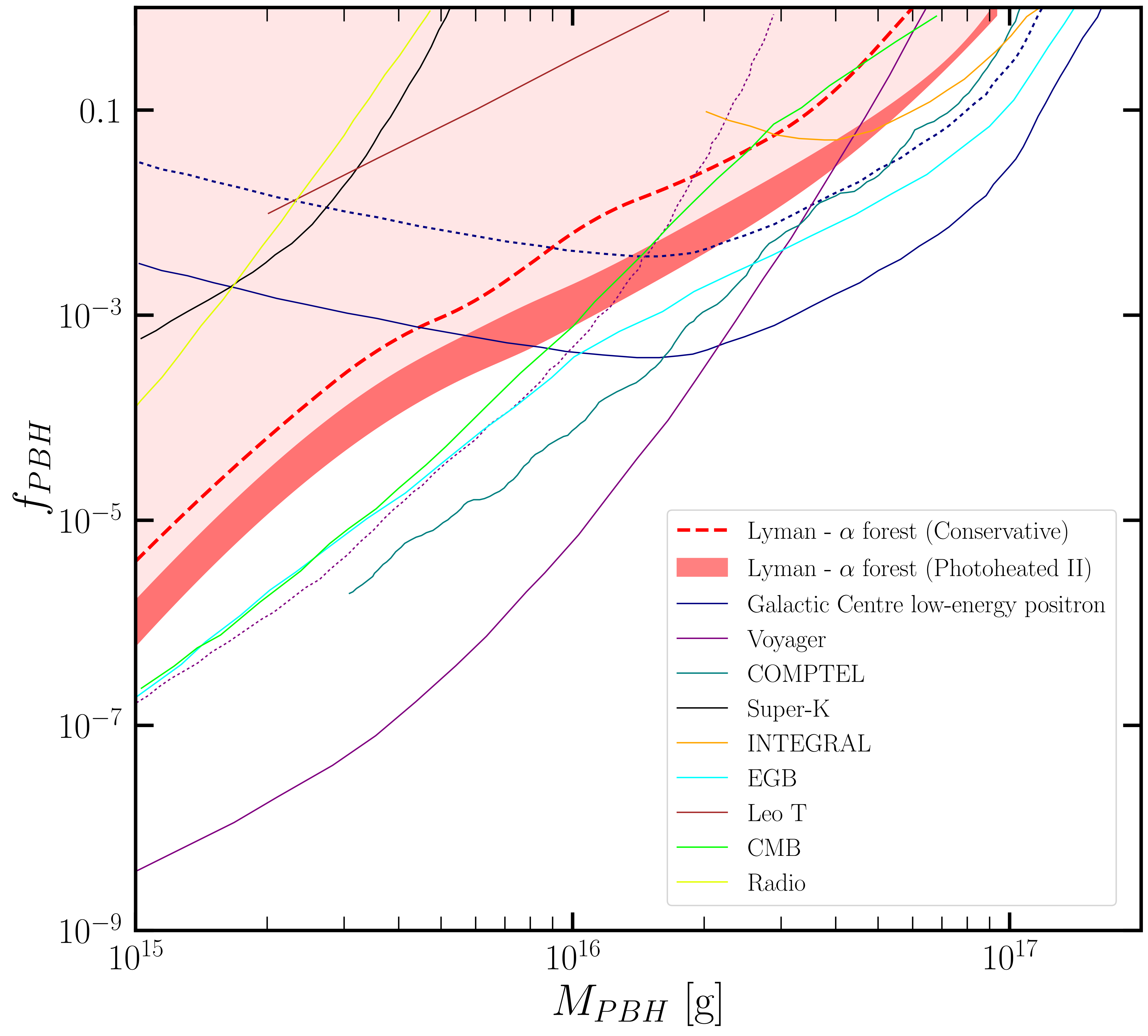

The IGM temperature does not exceed with the IGM temperature obtained by Walther et al. (2019) & Gaikwad et al. (2020) from Lyman-α forest measurement.

These constraints are complementary to the already existing constraints in this mass range.

Parashari et al. (in preparation)

Summary

- Evaporating PBHs can inject energetic particles into the intergalactic medium and therefore, can affect the reionization and IGM temperature.
- We compute the reionization and thermal IGM histories in the presence of PBH energy injection and astrophysical reionization (Planck results).
- Lyman-α forest measurements of IGM temperature can constrain the evaporating PBHs.

Summary

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- We compute the reionization and thermal IGM histories in the presence of PBH energy injection and astrophysical reionization (Planck results).
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Thank you!

Email: ppriyank@iisc.ac.in

Spinning PBHs

- Similar analysis can be done for the spinning PBHs.

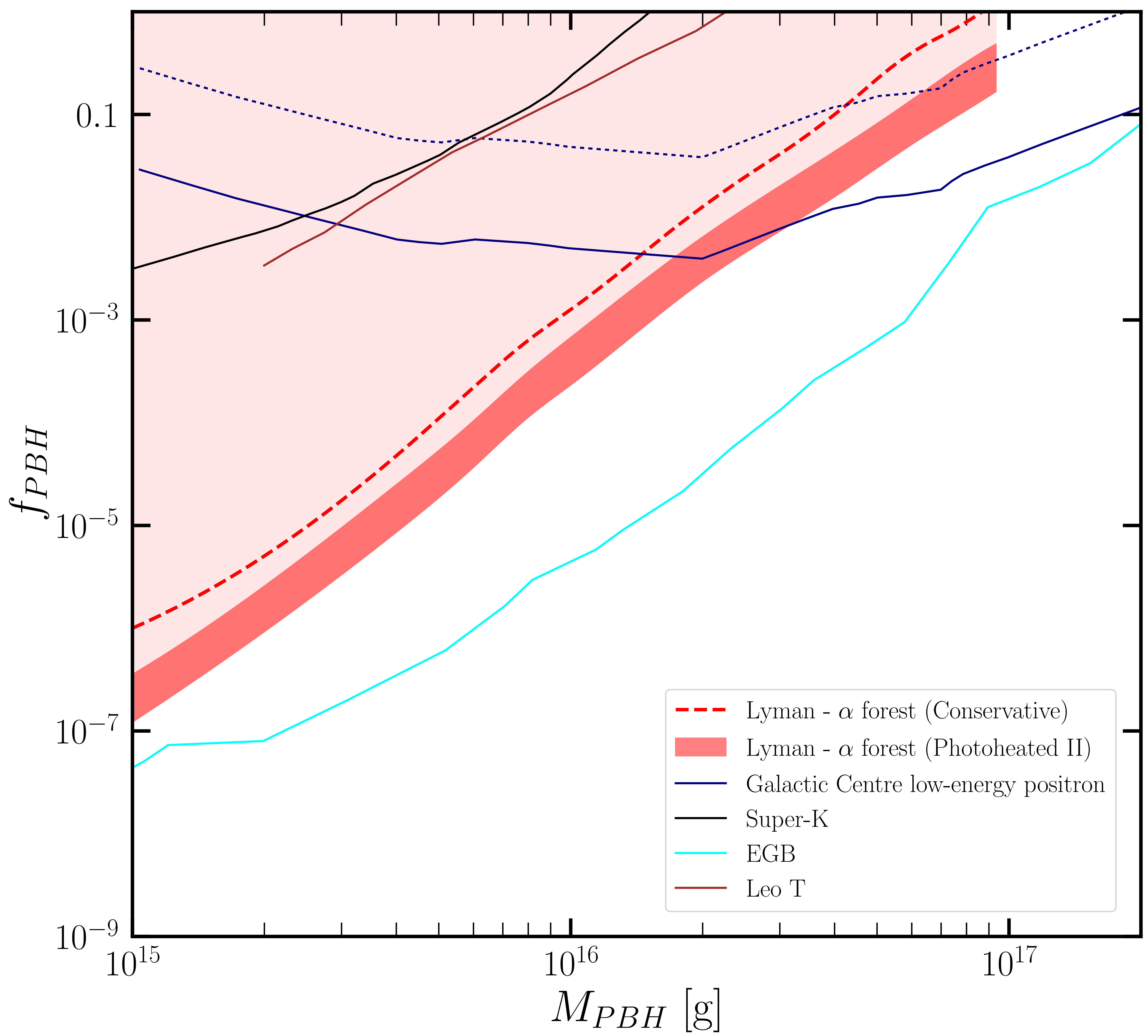
$$T_{\rm PBH} = 1.06 \left(\frac{10^{13}\,\text{g}}{M_{\rm PBH}}\right)\left(\frac{\sqrt{1-a_*^2}}{1+\sqrt{1-a_*^2}}\right) \text{GeV}$$

Dimensionless spin Parameter

$$a_* = \frac{J}{GM_{\rm PBH}^2}$$

Constraints on PBH abundance using Lyman-α measurements

$a_* = 0.9999$



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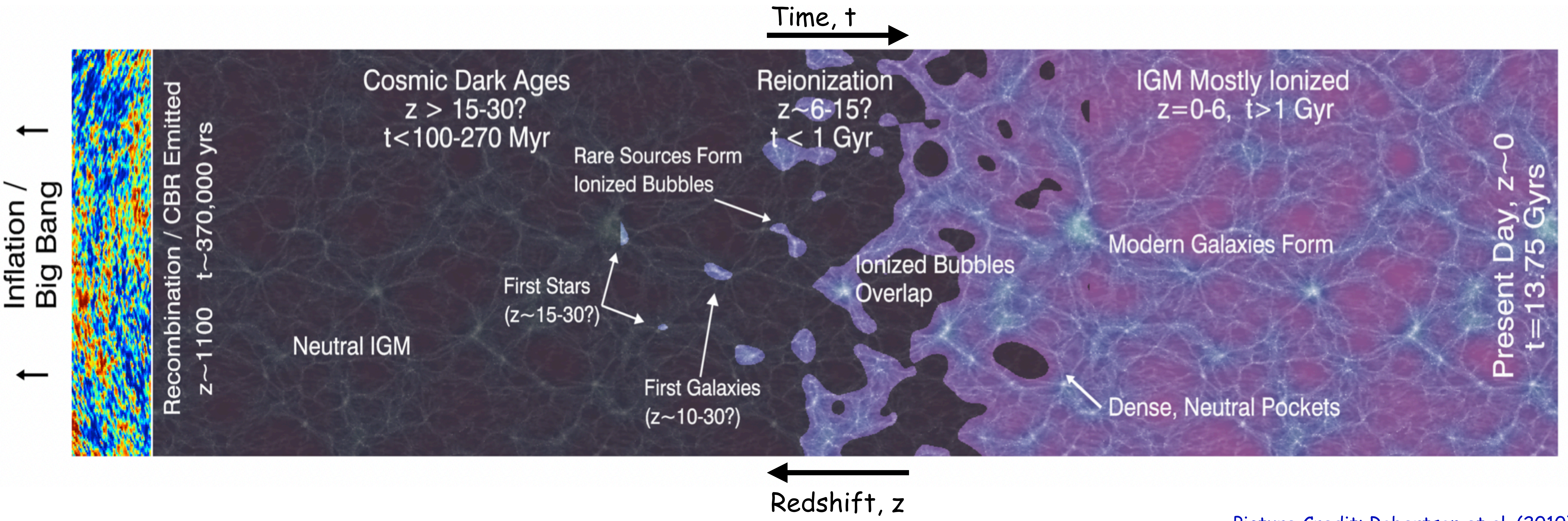
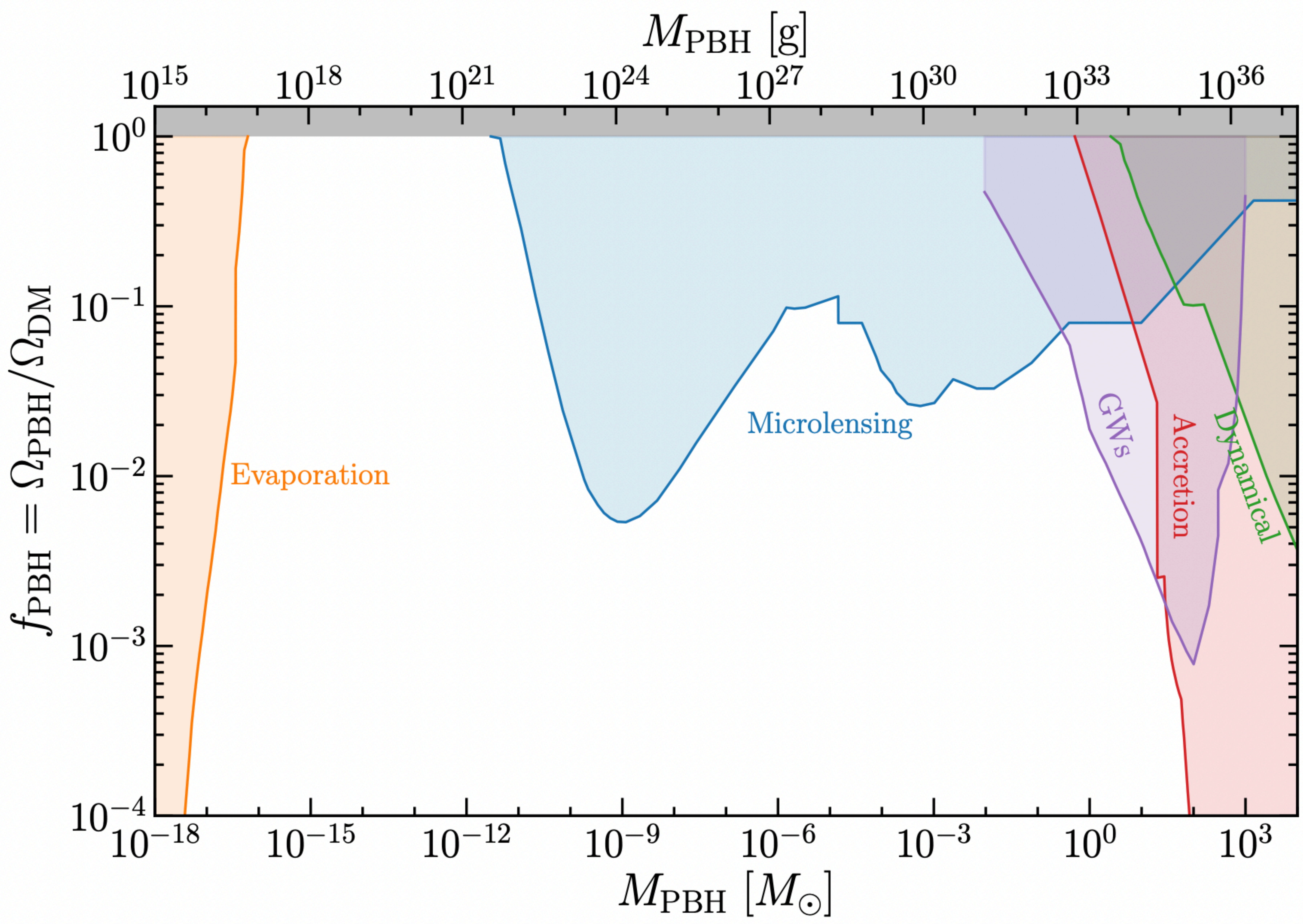
Universe Timeline



Picture Credit: Robertson et al. (2010)



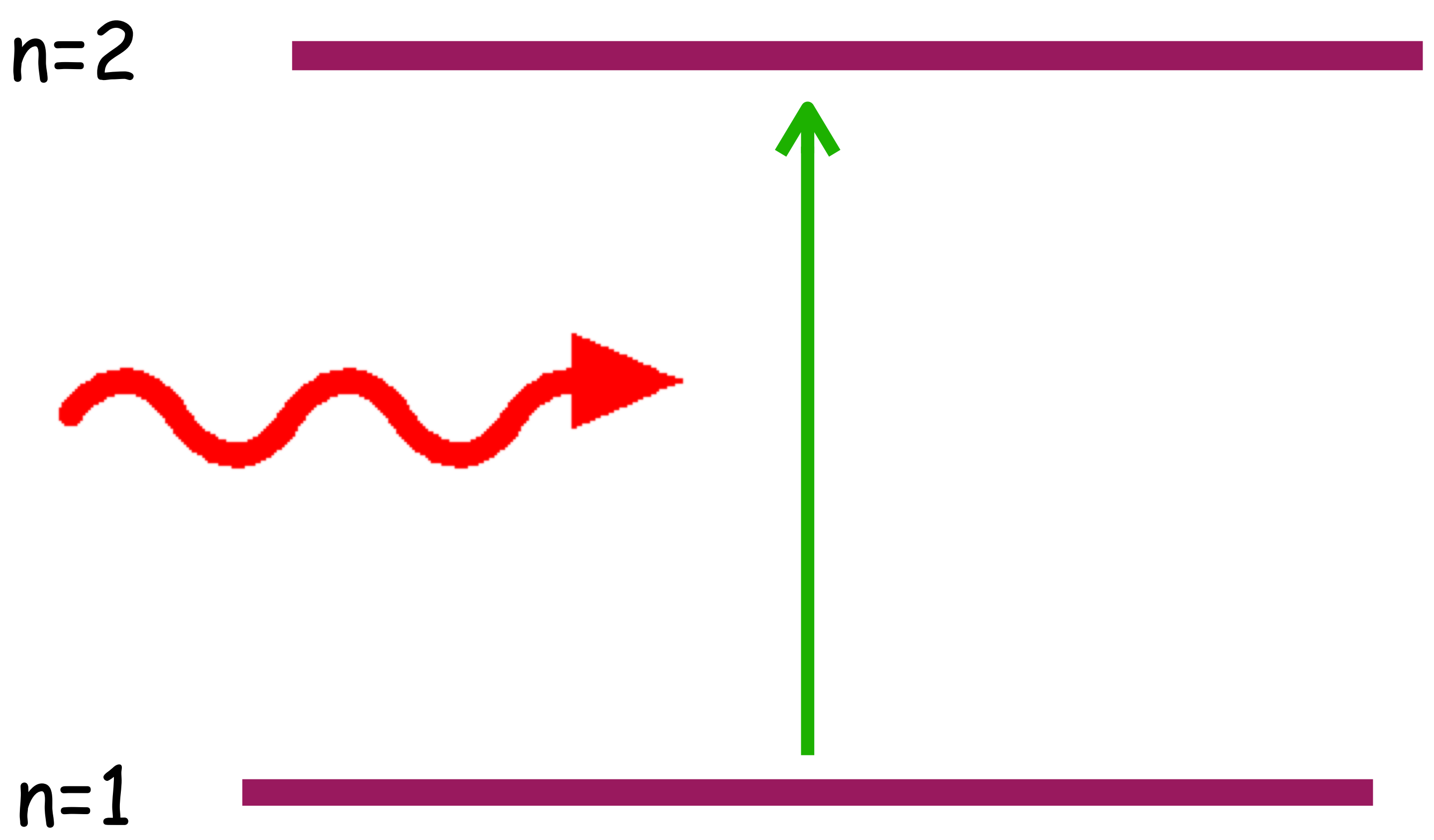
$M_{\rm PBH}$ [g]
10^{15}
10^{18}
10^{21}
10^{24}
10^{27}
10^{30}
10^{33}
10^{36}
$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Evaporation
Microlensing
GWs
Accretion
Dynamical
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
$M_{\rm PBH}$ [$M_\odot$]

What is Lyman-α Line?

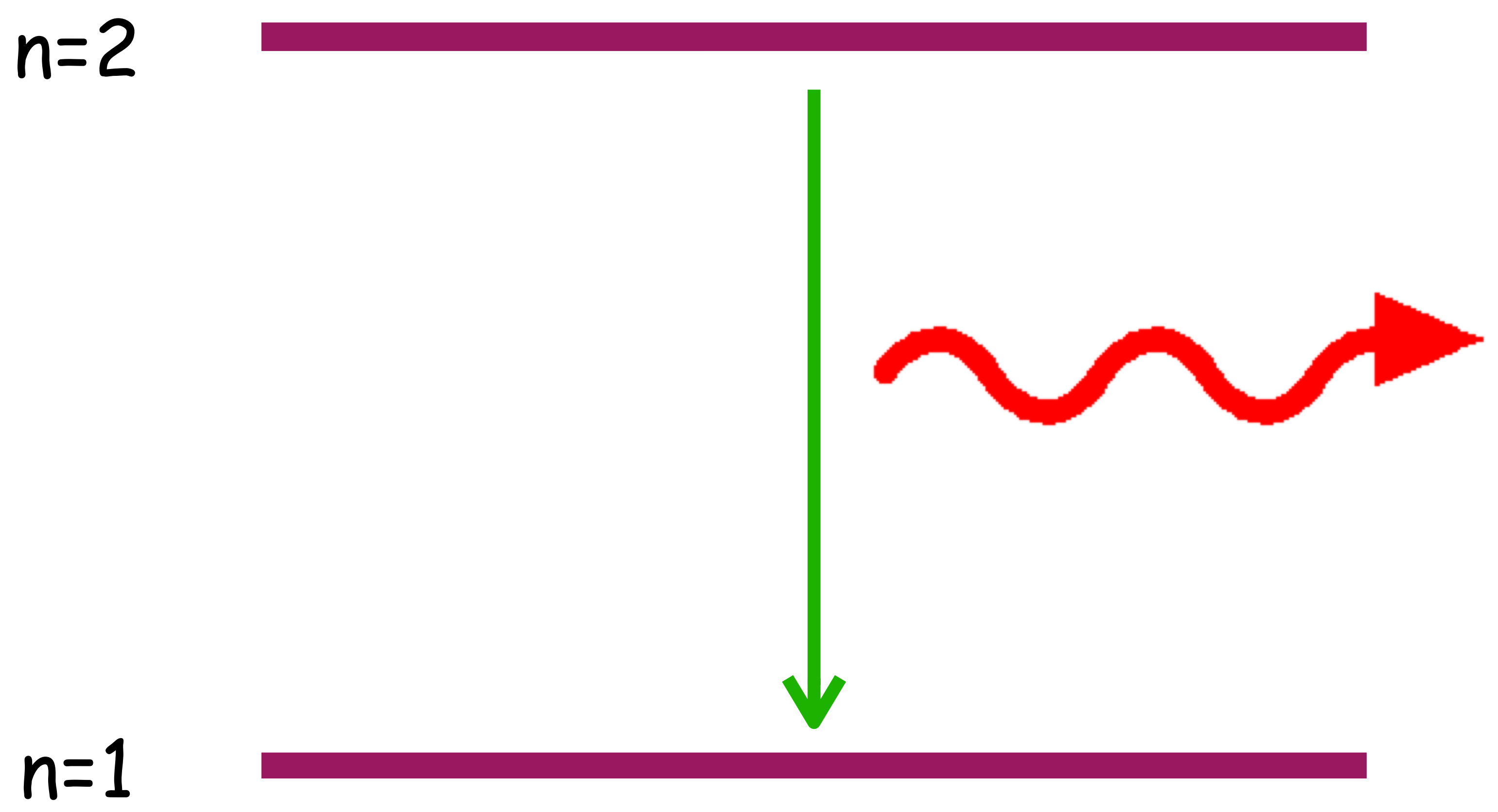
Spectral Line of Hydrogen atom in the Lyman Series.

Lyman-α : Electron transition between n=1 and n=2

n = Principle quantum number

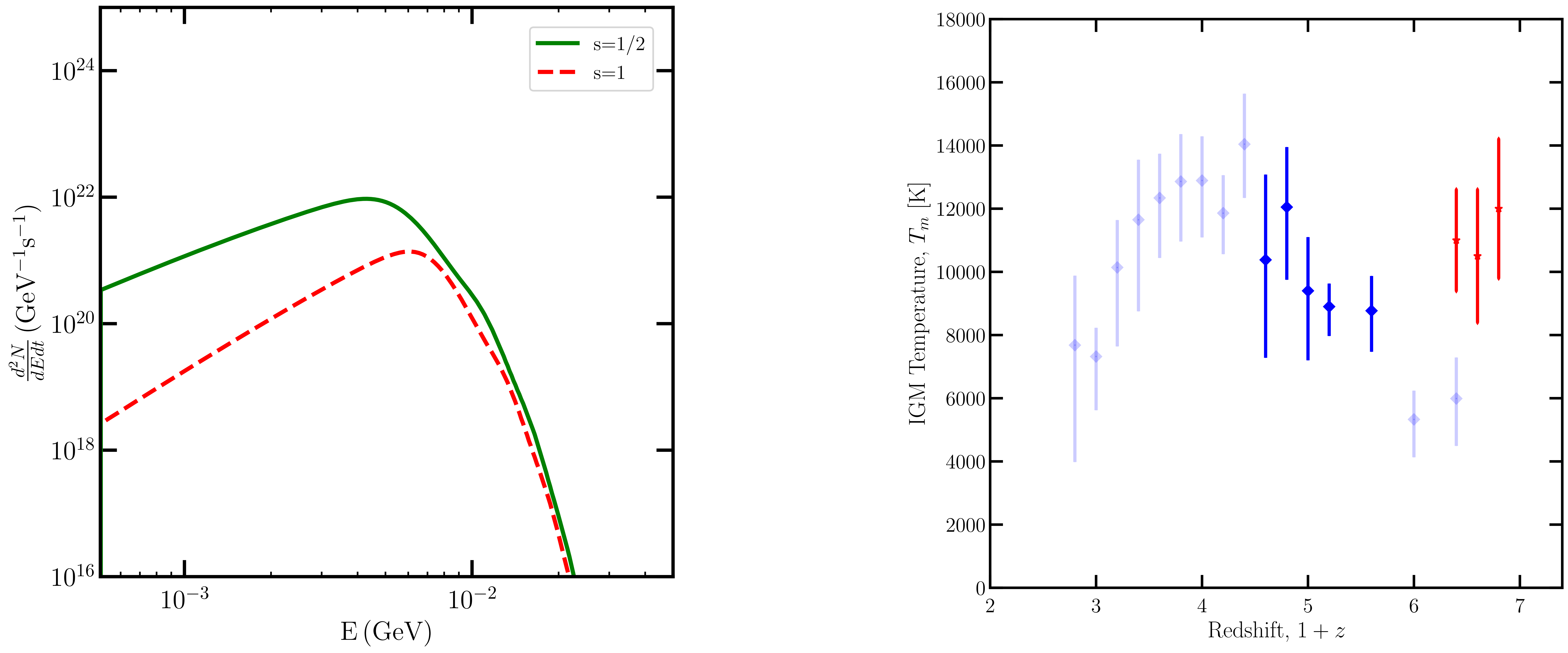


Lyman-α absorption line



Lyman-α emission line

λ = 1216 Å



s=1/2
s=1
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
$\frac{d^2N}{dEdt}\,(\mathrm{GeV}^{-1}\mathrm{s}^{-1})$
10^{-3}
10^{-2}
E (GeV)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
IGM Temperature, T_m [K]
2
3
4
5
6
7
Redshift, $1+z$

$$\dot{T}_{\mathrm{m}} = \dot{T}_{\mathrm{adia}} + \dot{T}_{C} + \dot{T}_{\mathrm{PBH}} + \dot{T}_{\mathrm{atom}} + \dot{T}^{\star}$$

- $\dot{T}_{\mathrm{adia}} = -2HT_{\mathrm{m}}$ $\quad \dot{T}_{C} = -\Gamma_C(T_{\mathrm{CMB}} - T_{\mathrm{m}})$ $\quad \dot{T}_{\mathrm{PBH}} = \frac{2f_{heat}(z)}{3(1+f_{He}+x_e)n_H}\left(\frac{dE}{dVdt}\right)_{\mathrm{inj}}$
- $$\dot{T}^{\star} = \begin{cases} \dot{x}^{\star}_{\mathrm{HII}}(1+\chi)\Delta T, & x_{\mathrm{HII}} < 0.99, \\ \sum_{i\in\{\mathrm{H,He}\}} \frac{E_{i\mathrm{I}} x_i}{3(\gamma_{i\mathrm{I}} - 1 + \alpha_{\mathrm{bk}})} \alpha_{\mathrm{A},i\mathrm{I}} n_{\mathrm{H}}, & x_{\mathrm{HII}} \geq 0.99, \end{cases}$$
- $$\Gamma_C = \frac{x_{\mathrm{e}}}{1+\chi+x_{\mathrm{e}}} \frac{8\sigma_T a_r T^4_{\mathrm{CMB}}}{3m_{\mathrm{e}}}$$

- $$\dot{x}^{\star}_{\mathrm{HII}} = \left(\frac{\dot{x}^{\mathrm{PI}}_{\mathrm{e}}}{1+\chi} - \dot{x}^{\mathrm{atom}}_{\mathrm{HII}} - \dot{x}^{\mathrm{DM}}_{\mathrm{HII}} \right) \theta(z^{\star} - z)\,,$$
- $$\dot{x}^{\mathrm{PBH}}_{HI} = \left[\frac{f_{ion}(z)}{\mathcal{R} n_H} + \frac{(1-\mathcal{C}) f_{exc}(z)}{0.75 \mathcal{R} n_H} \right] \left(\frac{dE}{dVdt} \right)_{\mathrm{inj}}$$

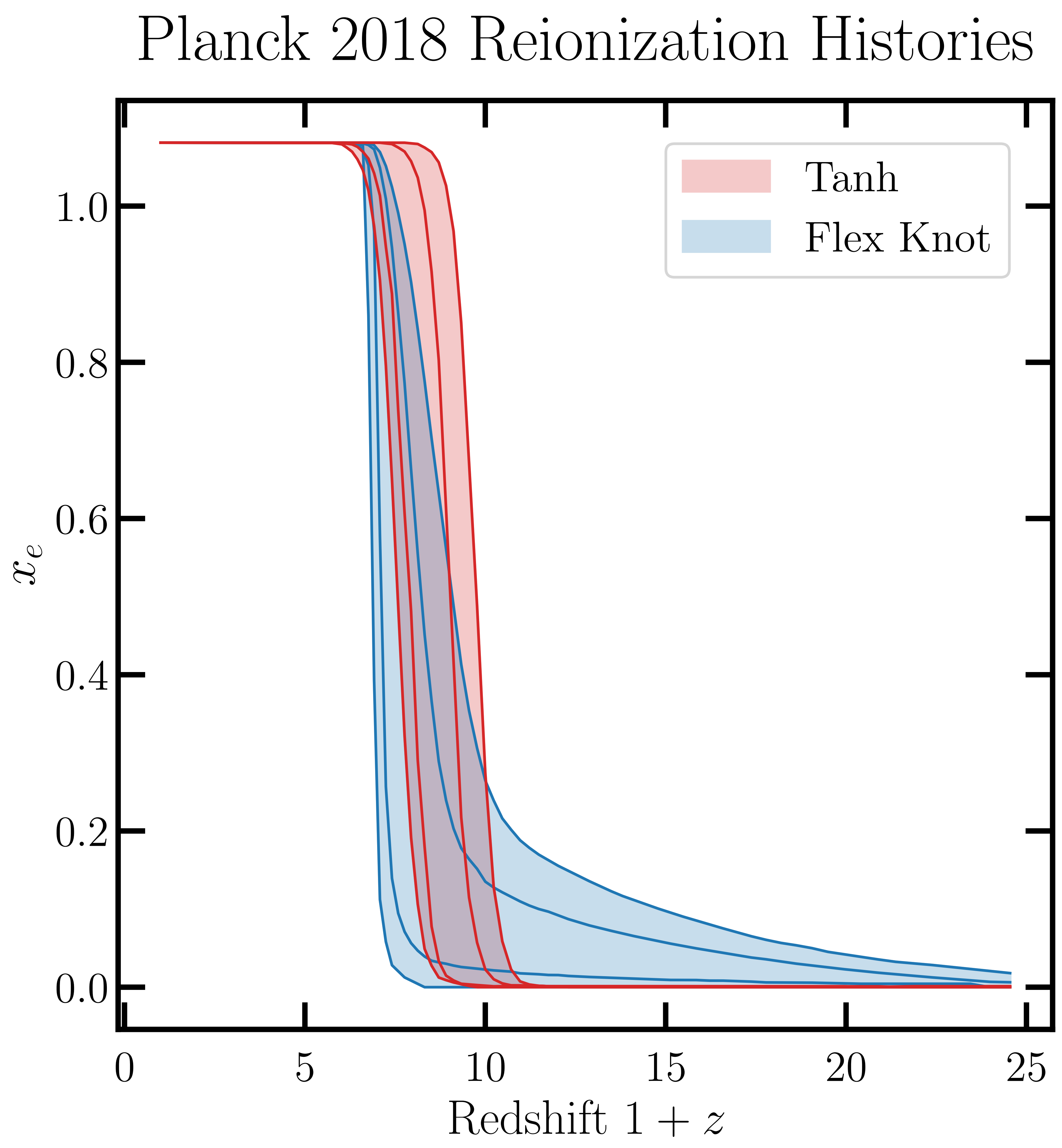
$$\dot{x}_{\mathrm{HeII}} = \dot{x}^{0}_{\mathrm{HeII}} + \dot{x}^{\mathrm{PBH}}_{\mathrm{HeII}} + \dot{x}^{\star}_{\mathrm{HeII}}$$

$$x_{\mathrm{HeIII}} = 0$$

Astrophysical Reionization and Photoheating

For astrophysical reionization, we use the results given by Planck 2018 for two different models. $\dot{x}^{\star}$ term

Planck collaboration 2018 arXiv:1807.06209



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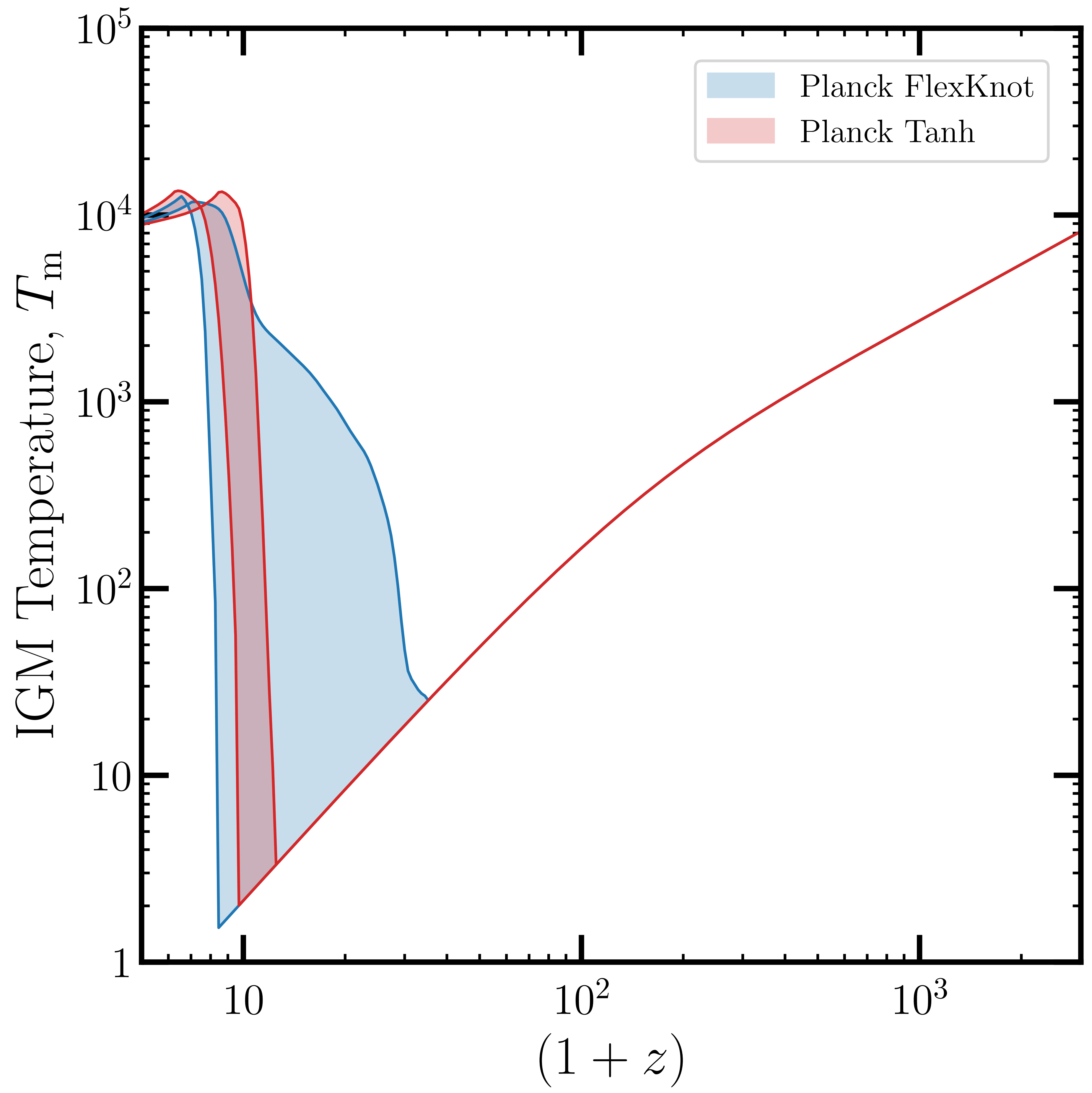

No heating due to PBH evaporation

How to treat Photoheating ($\dot{T}^\star$) from reionization?

Two scenarios:

1. **Conservative** - No photoheating, i.e., $\dot{T}^\star = 0$
2. **Photoheated** - Assume photoheating rate is proportional to the reionization rate $\dot{x}^\star$

Miralda-Escudé et al. (1994), McQuinn (2012)

McQuinn et al. (2016)

- $$\mathrm{TS}_i = \begin{cases} 0, & T_{i,\mathrm{pred}} < T_{i,\mathrm{data}}, \\ \left(\dfrac{T_{i,\mathrm{pred}} - T_{i,\mathrm{data}}}{\sigma_{i,\mathrm{data}}} \right)^2, & T_{i,\mathrm{pred}} \geq T_{i,\mathrm{data}}, \end{cases}$$
- $$f(\mathrm{TS} \mid \{T_{i,\mathrm{pred}}\}) = \frac{1}{2^N} \sum_{n=0}^{N} \frac{N!}{n!(N-n)!} f_{\chi^2}(\mathrm{TS}; n) .$$

A. $\Delta T > 0$; Photoheated I

B. $\Delta T > 2 \times 10^4$ K; Photoheated II