Lyman-α Constraints on Primordial Black Hole Dark Matter

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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

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

- 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

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

(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 Hawking radiation at a temperature

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

Mass of PBH

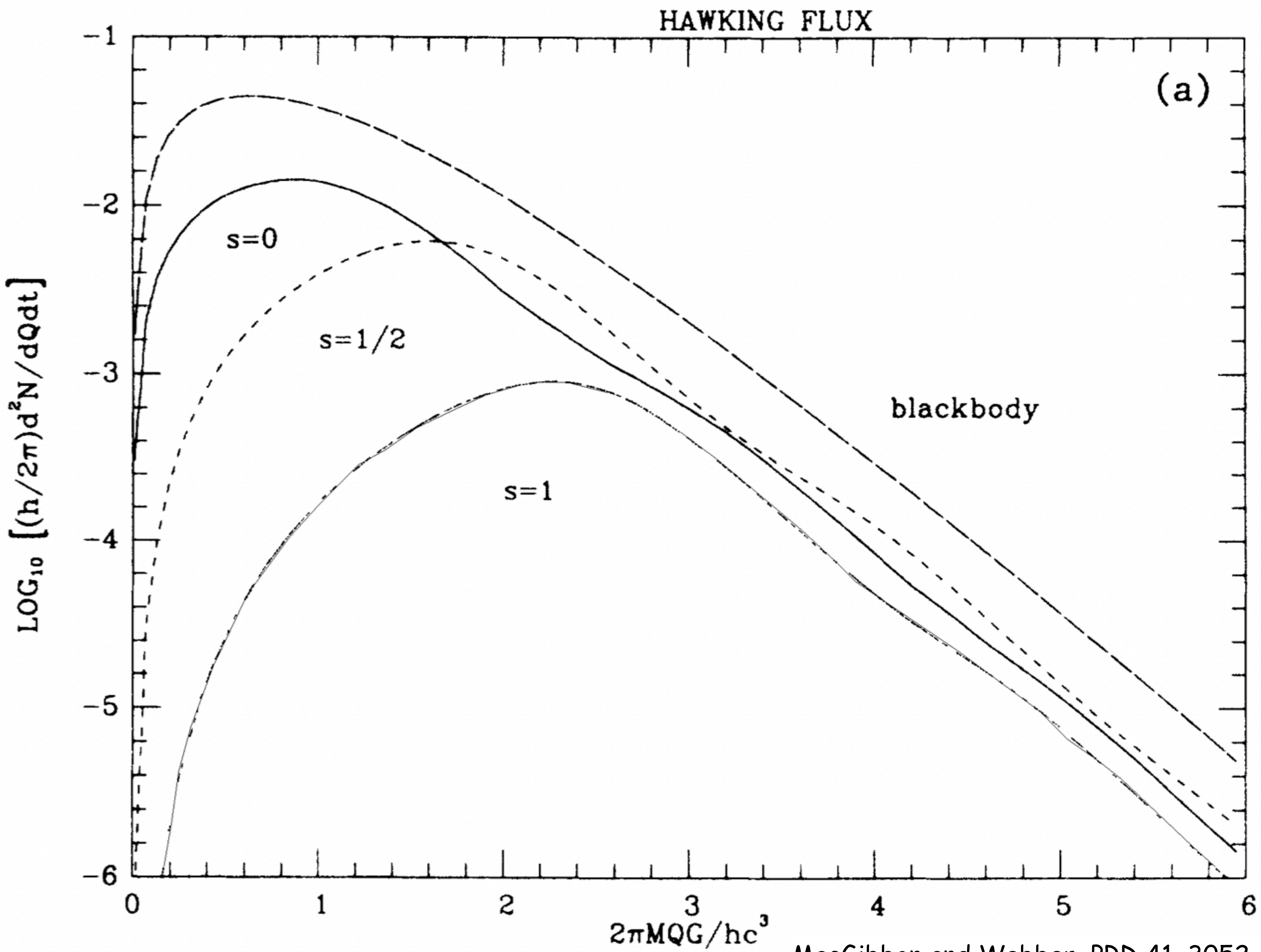
For non-rotating black holes

Energy spectrum of emitted particles

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

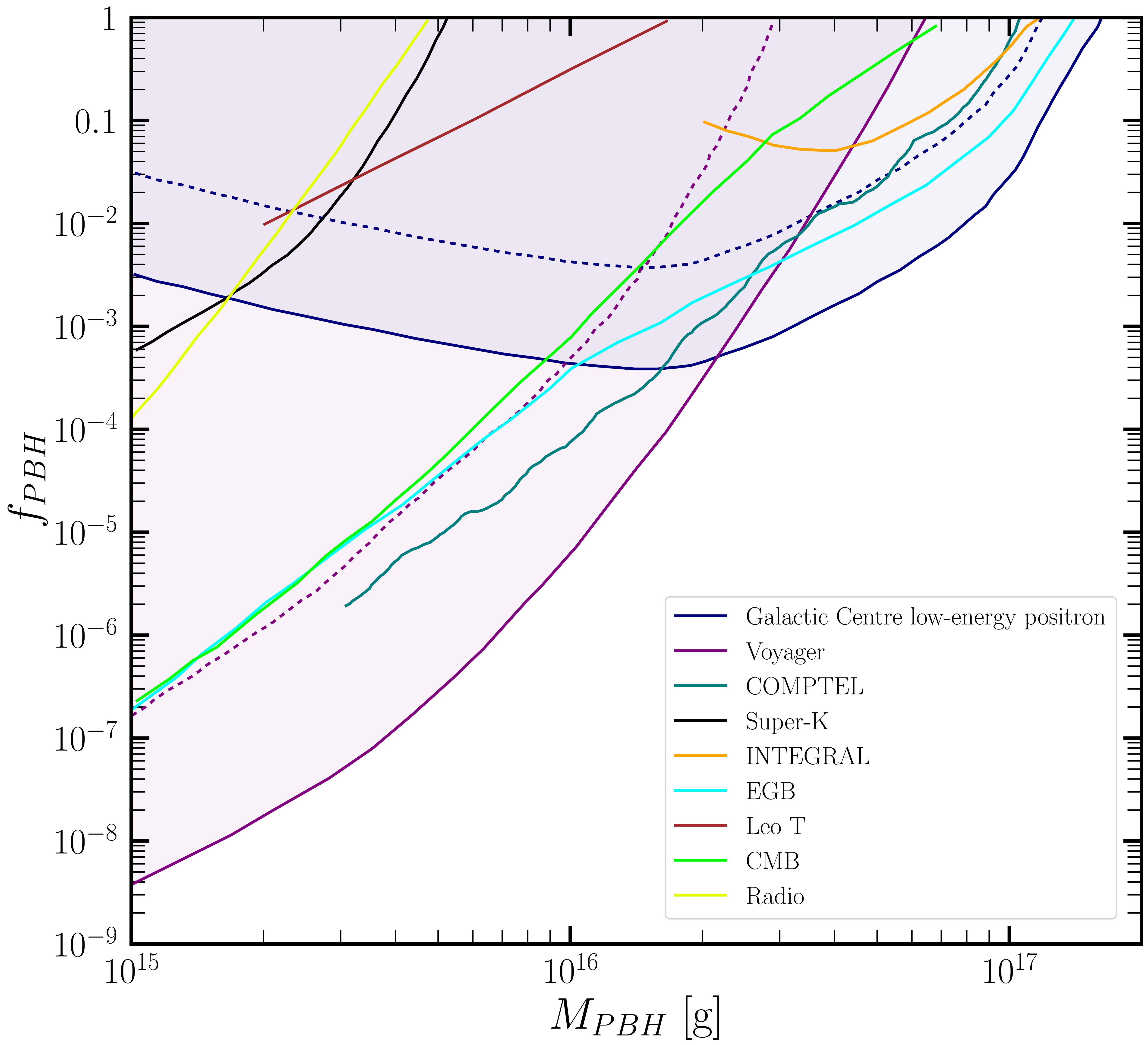
Evaporating PBHs can have observable consequences, which can be used to detect the signal of low mass PBHs ($10^{15} - 10^{18}$ g)

The spectrum closely resembles a black-body radiation



MacGibbon and Webber, PRD 41, 3052, 1990

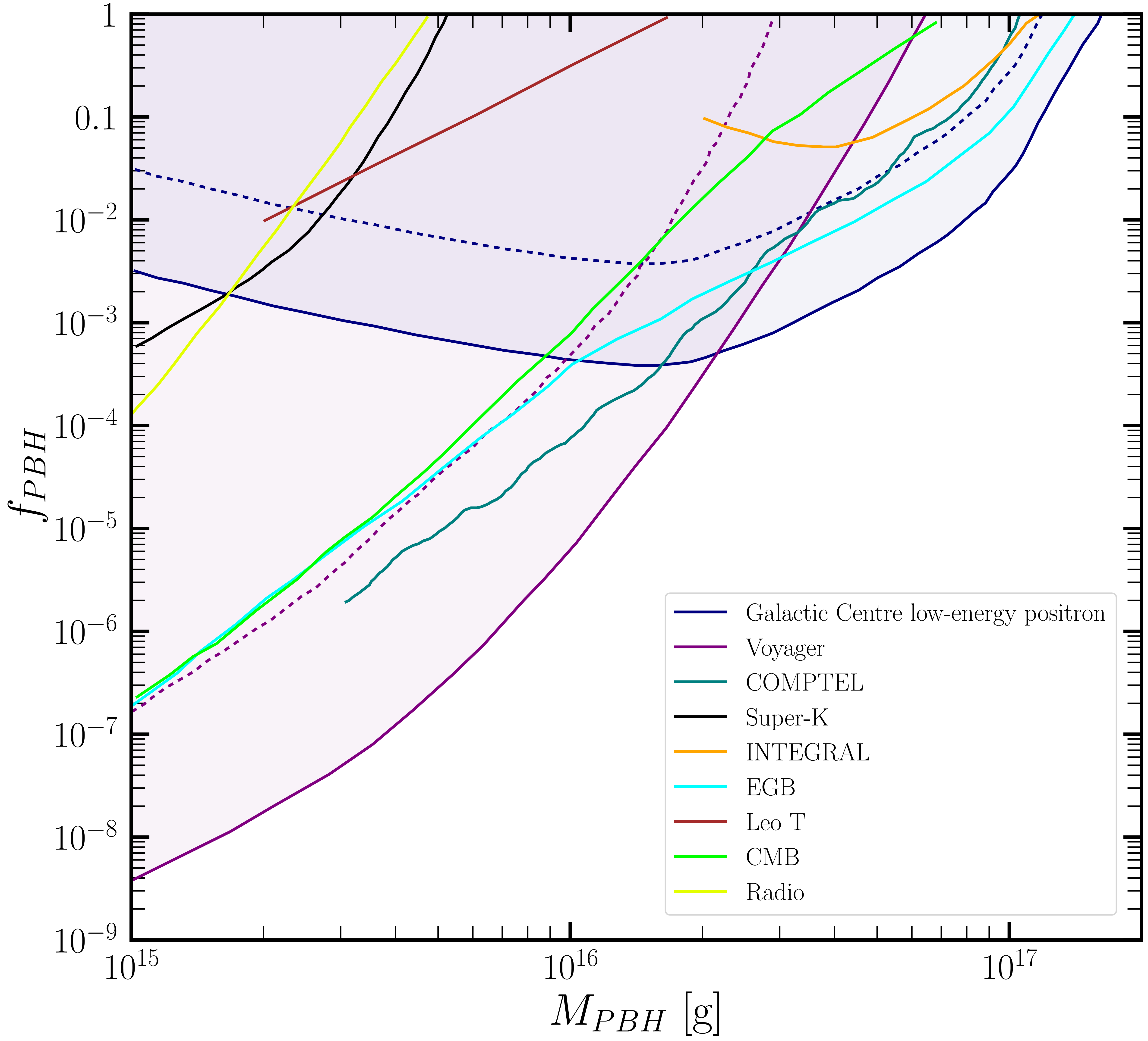
PBH as Dark Matter



Existing constraints for low mass evaporating PBHs obtained using various measurements

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

PBH as Dark Matter



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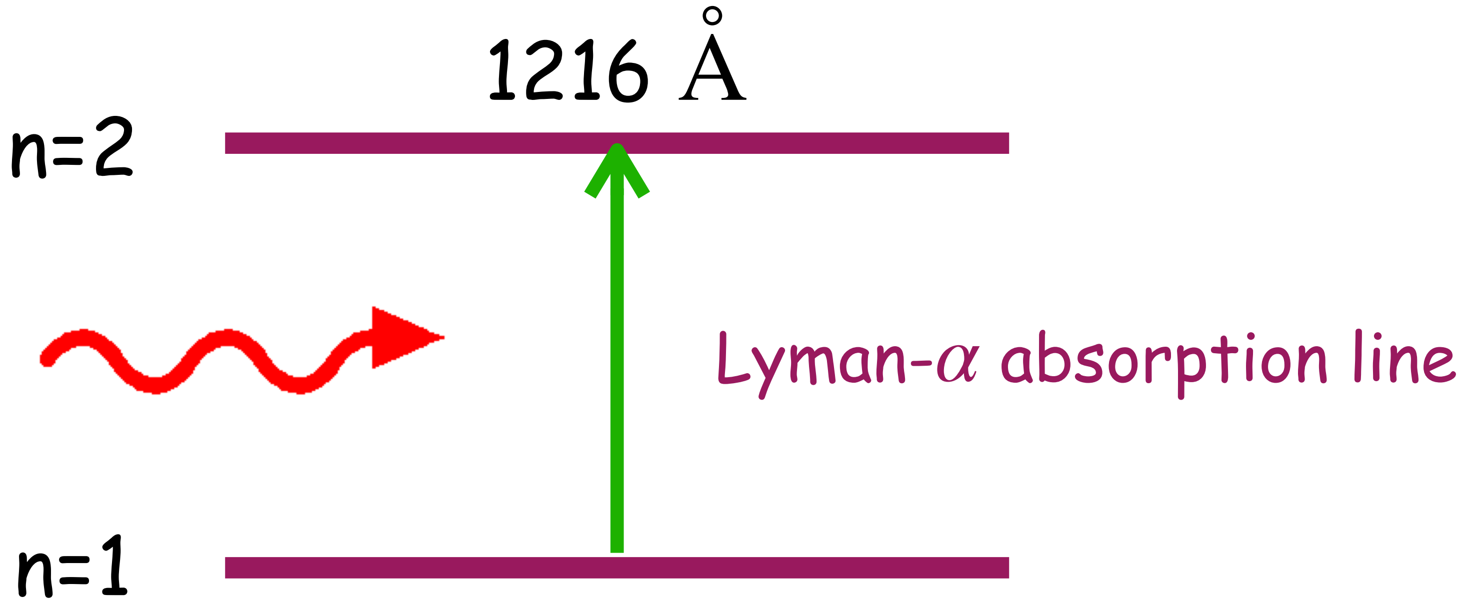
$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}$$

Any other observable?

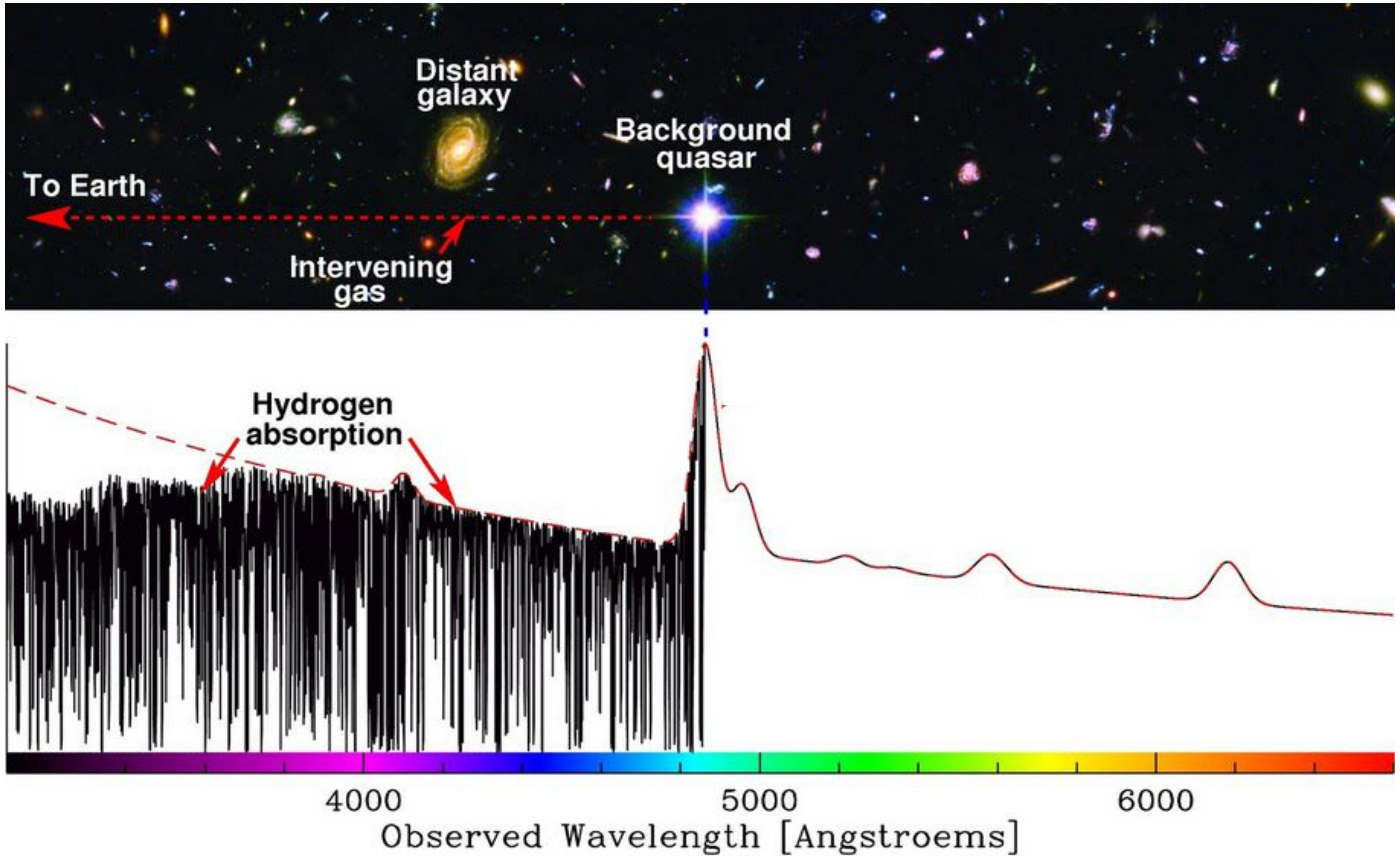
Lyman-α Forest measurements

Lyman-α Forest Measurement



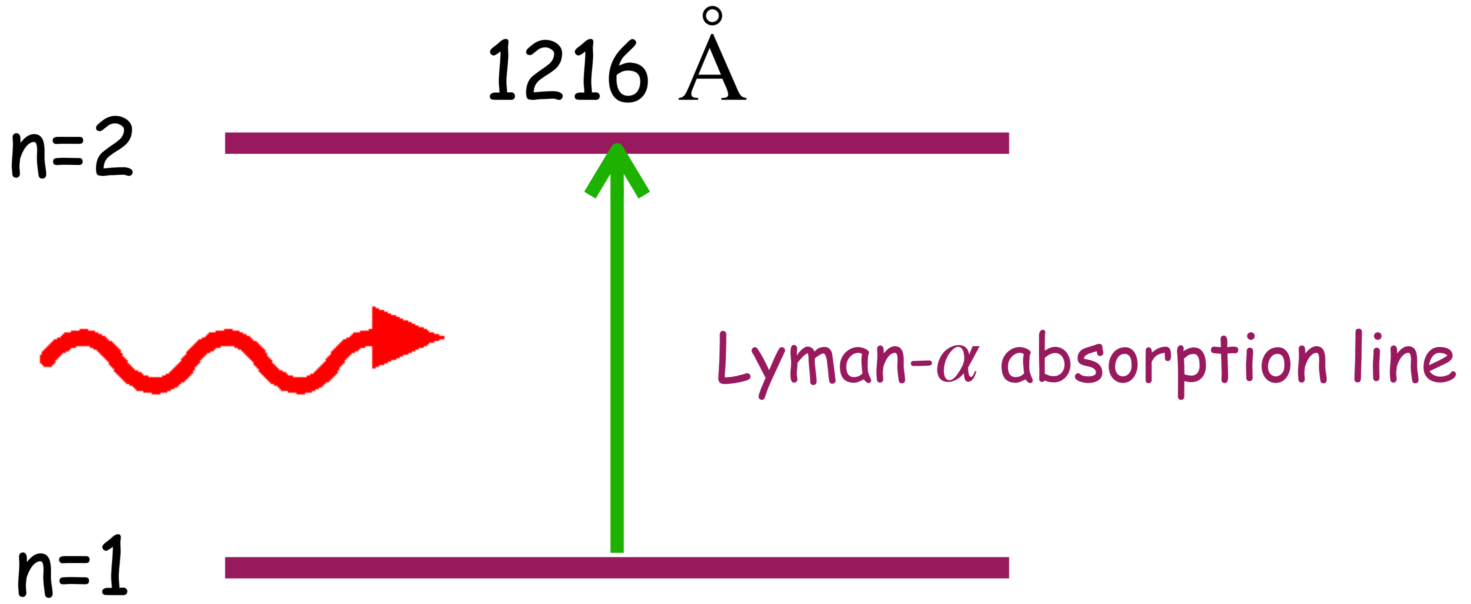
What is Lyman-α forest?

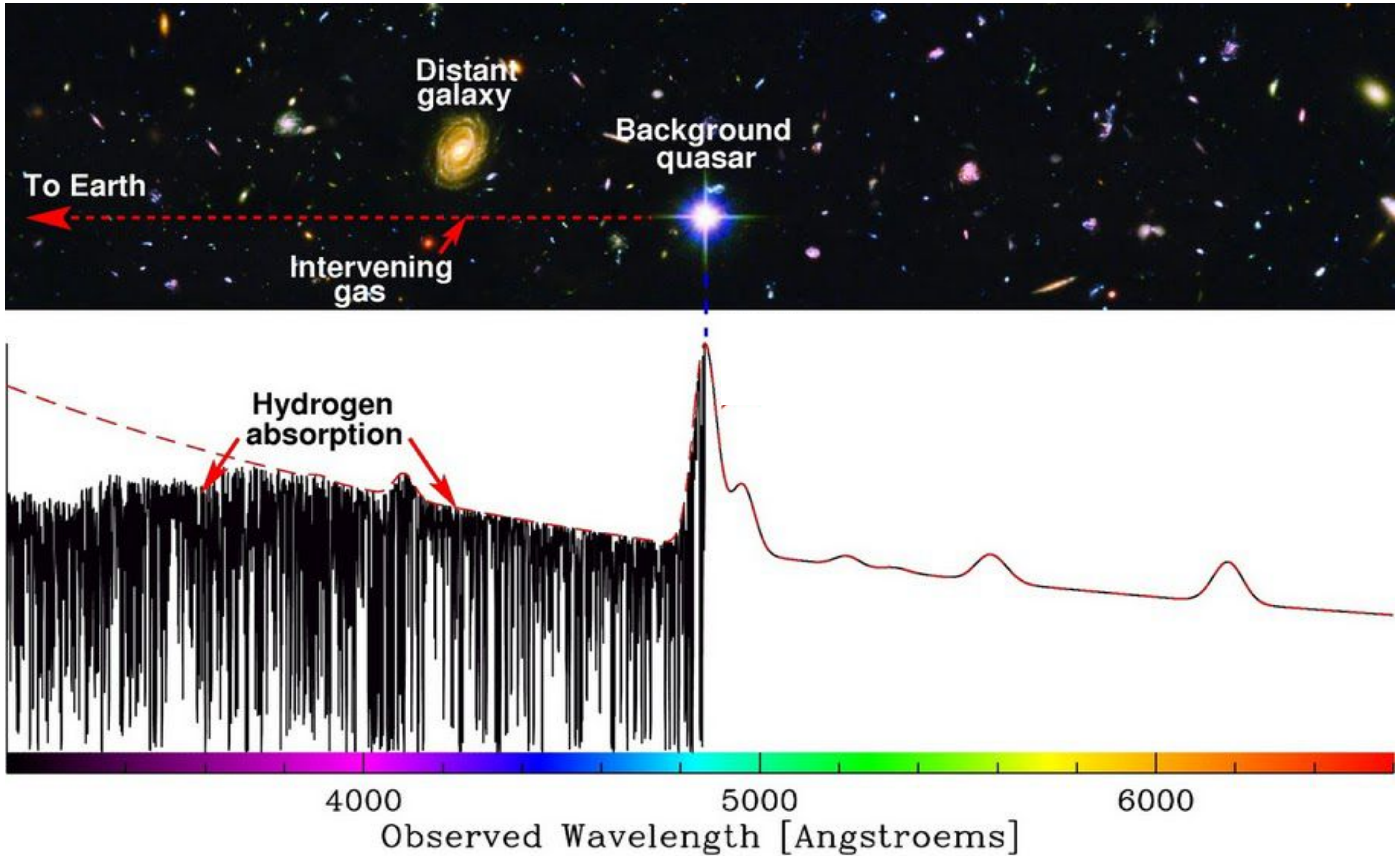
Series of absorption lines in the distant galaxies or quasars spectra due to Lyman-α transition of neutral Hydrogen



Picture credit: Futura Sciences Webpage

Lyman-α Forest Measurement





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Lyman-α forest observations can be used to infer intergalactic medium (IGM) temperatures

Picture credit: Futura Sciences Webpage

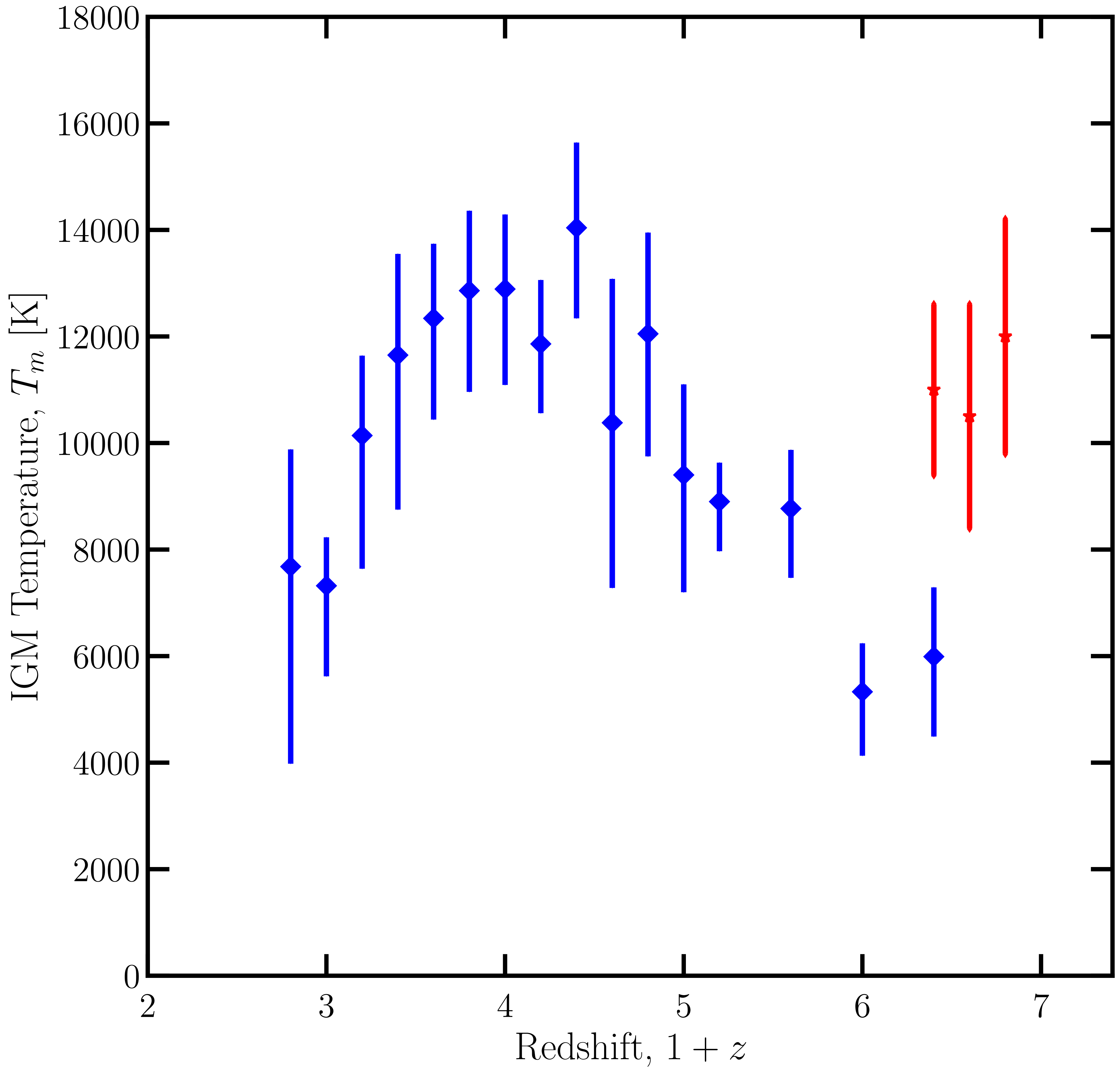
IGM Temperature Measurements

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

By comparing the measured Lyman-α forest power spectra to the hydrodynamical simulations. Walther et al. (2019)

Measurements: BOSS, HIRAS, MIKE, etc.

By fitting the observed width distribution of the Lya transmission spikes to simulation results. Gaikwad et al. (2020)



Can we use these IGM temperature measurements to probe PBHs?

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

Ionization & IGM Temperature Evolution

HI: Neutral Hydrogen
HII: Ionized Hydrogen

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

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

Base Term: Recombination

Energy injection due to PBH evaporation

Reionization due to astrophysical sources; Use Planck results

T_{m} = Intergalactic medium temperature

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

Base term: Hubble expansion, Recombination, Compton scattering

Energy injection due to PBH evaporation

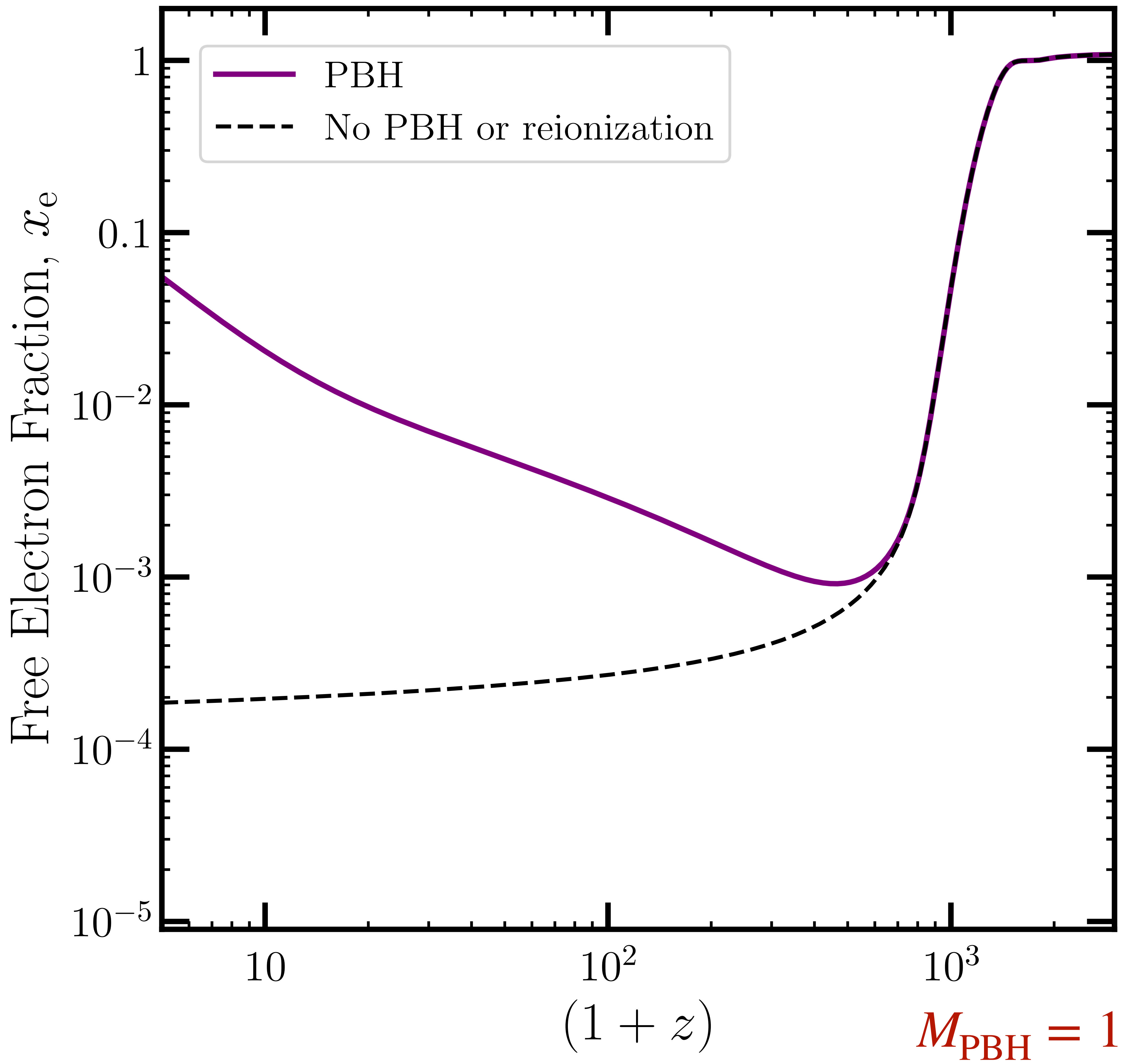
Photoheating due to astrophysical reionization

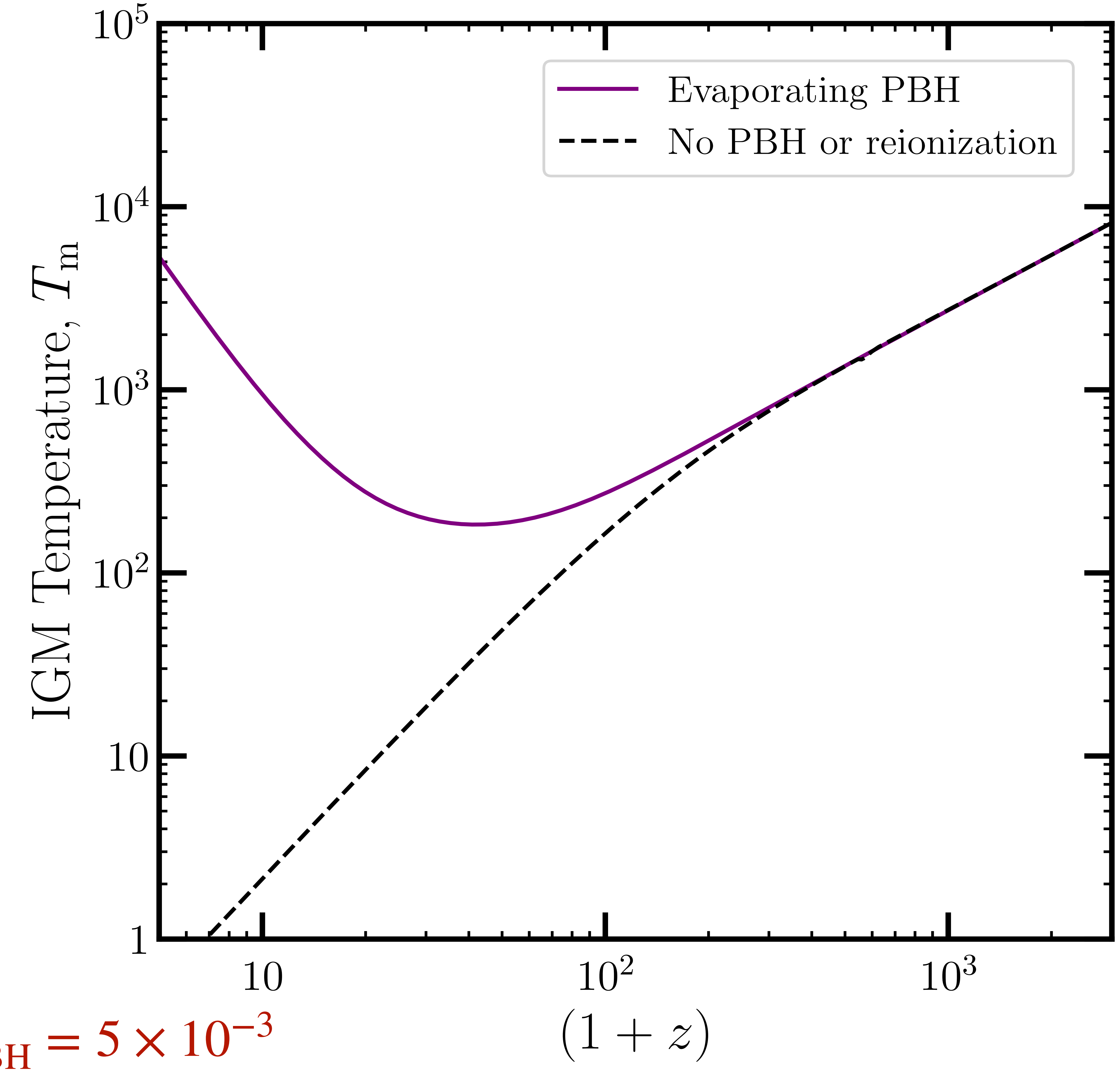
Ionization and IGM Temperature

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

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

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



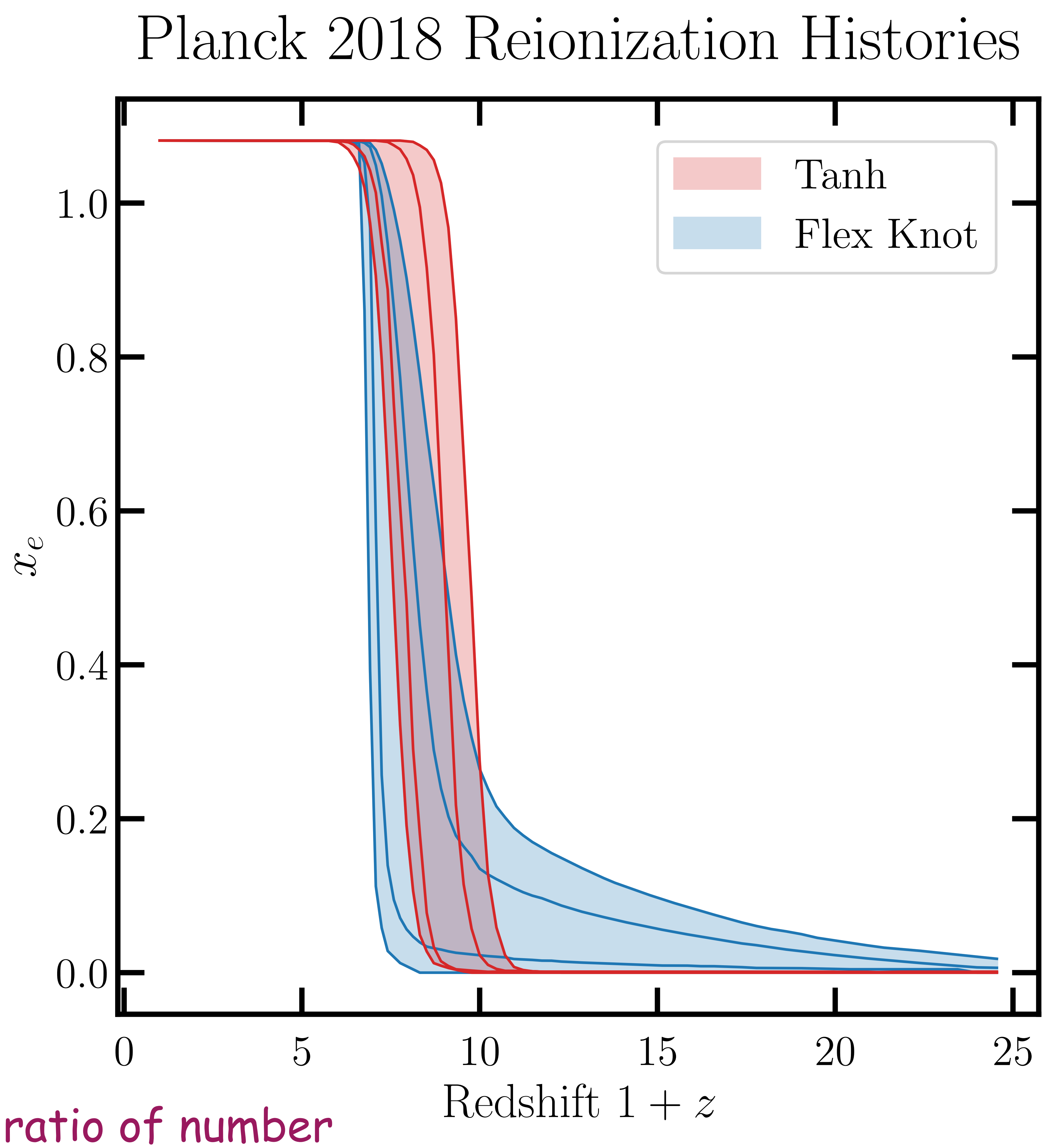


$M_{\rm PBH} = 10^{16}g$ $f_{\rm PBH} = 5 \times 10^{-3}$

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



x_e = ratio of number density of free electrons to the total number density of hydrogen

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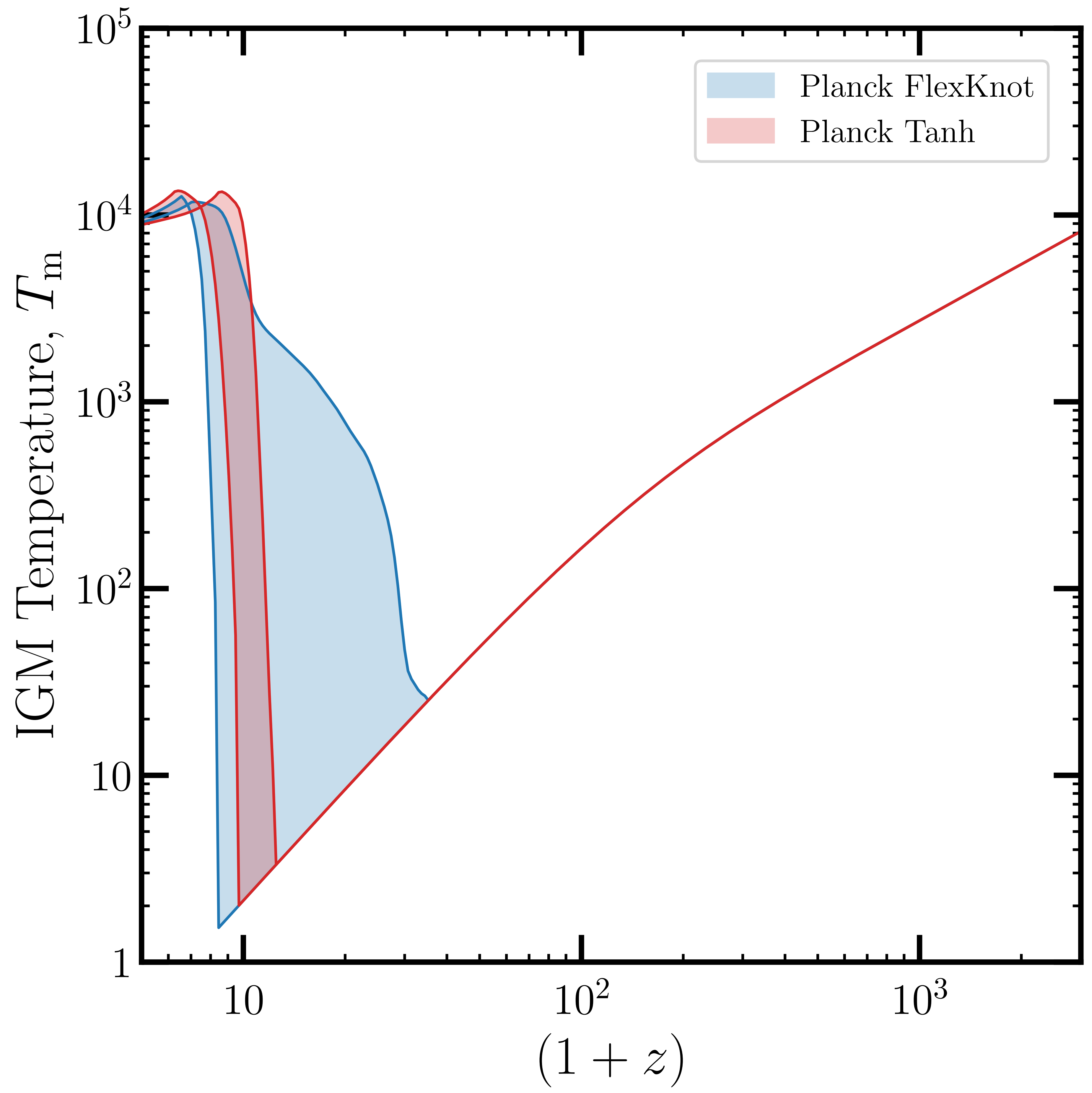
How to treat Photoheating ($\dot{T}^{\star}$) from reionization?

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)

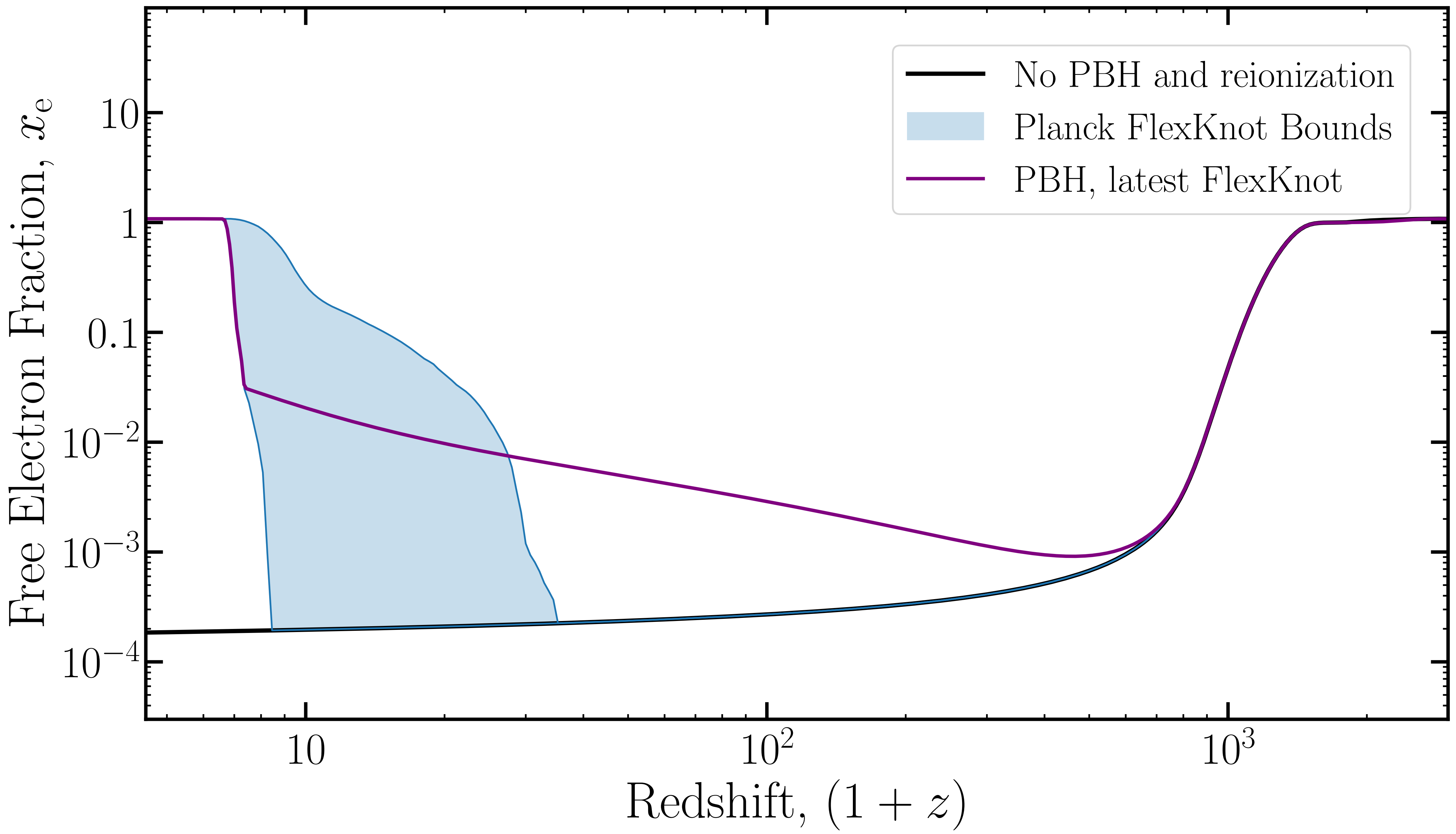


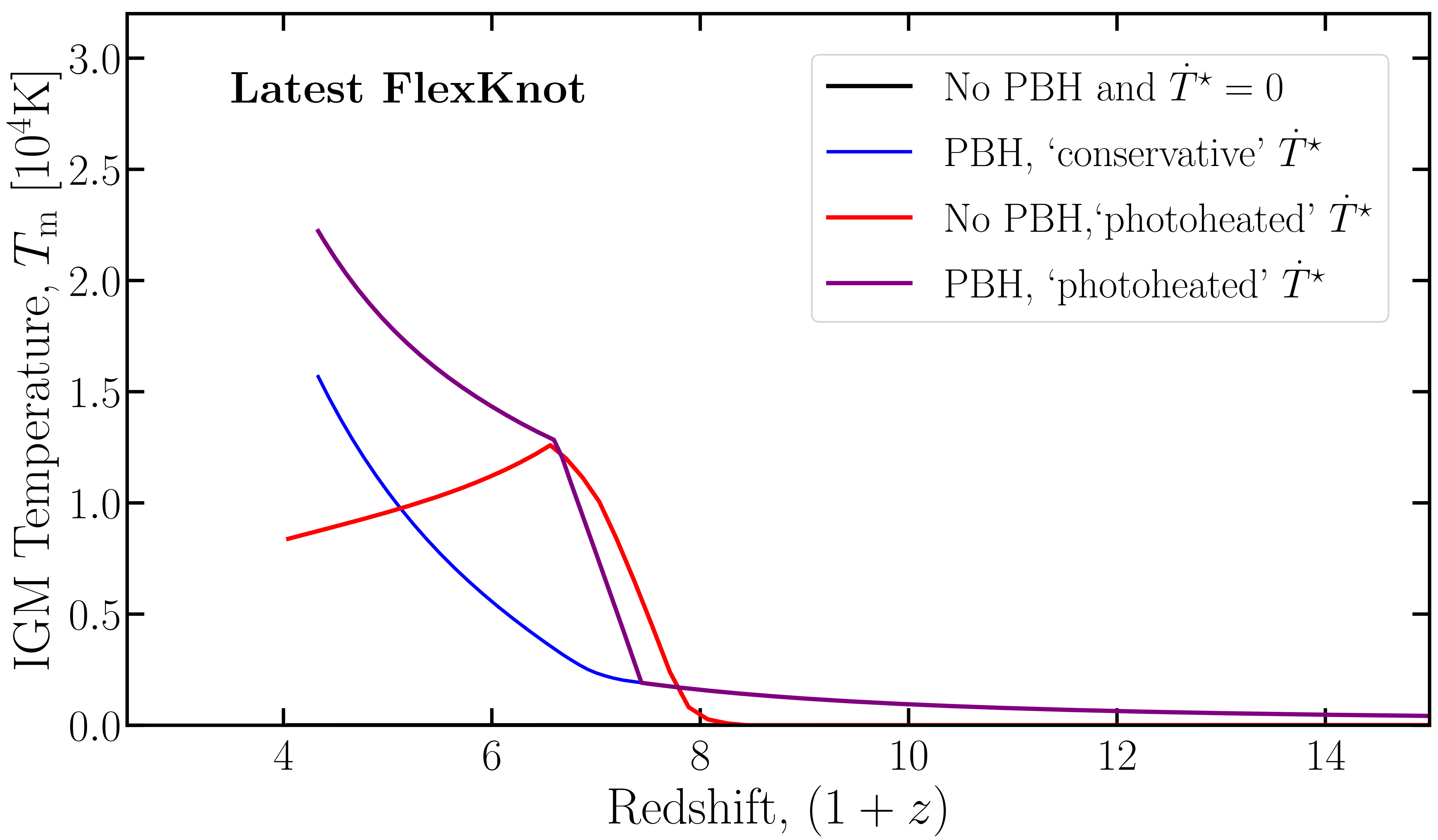
No heating due to PBH evaporation

Ionization and IGM Temperature

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

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





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

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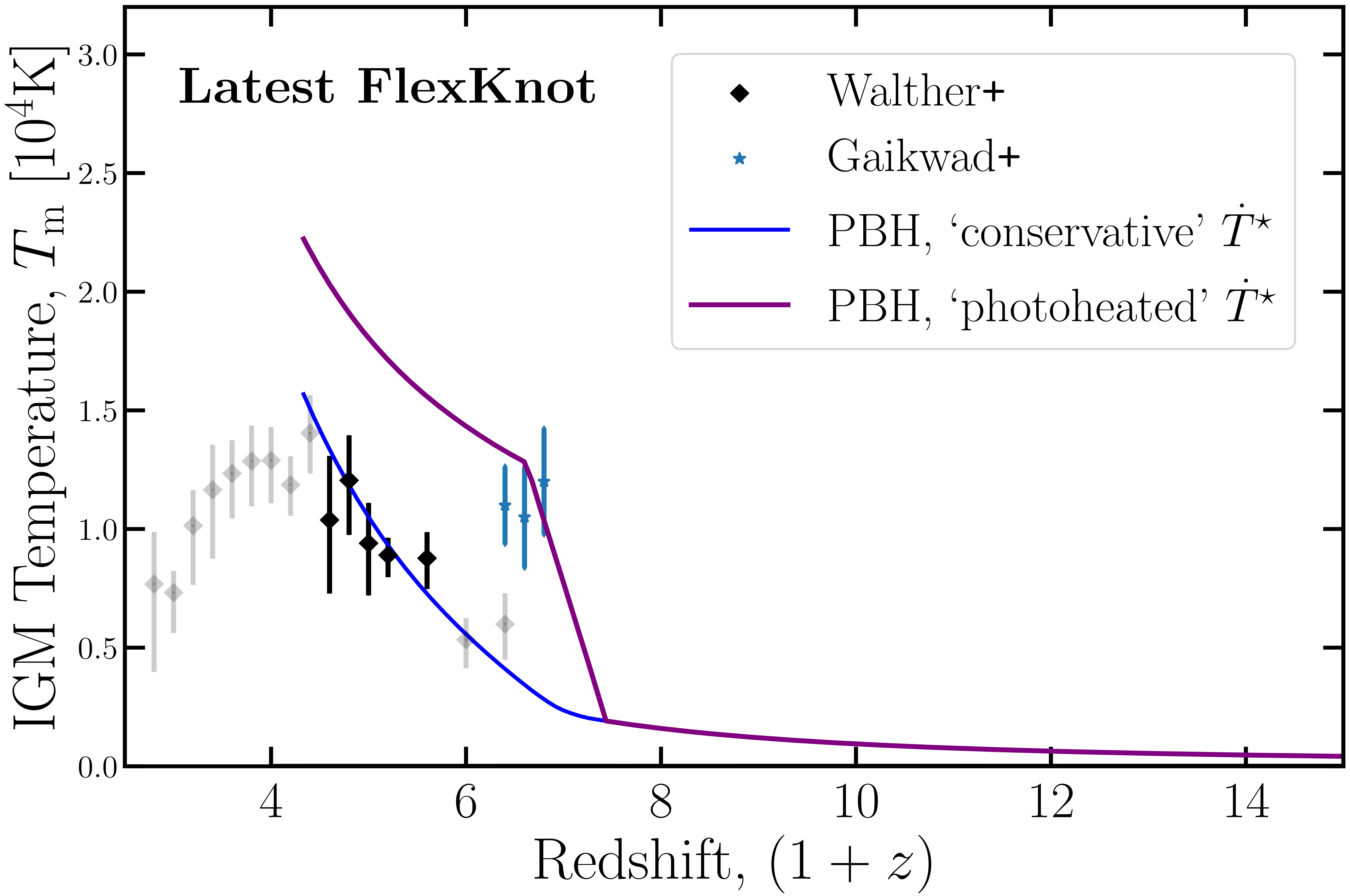
Comparison with IGM Temperature Data



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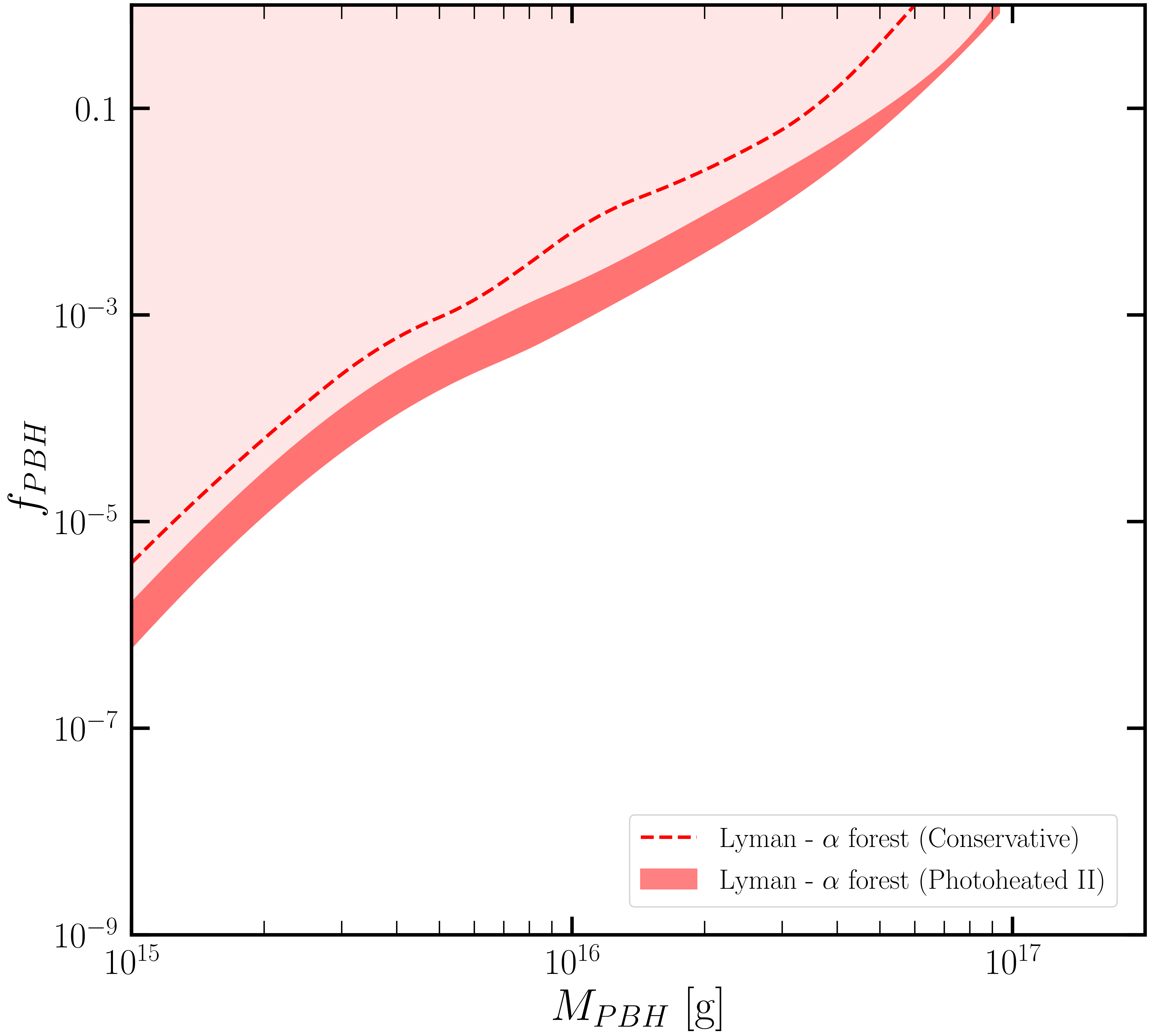
Constraints on PBH Abundance



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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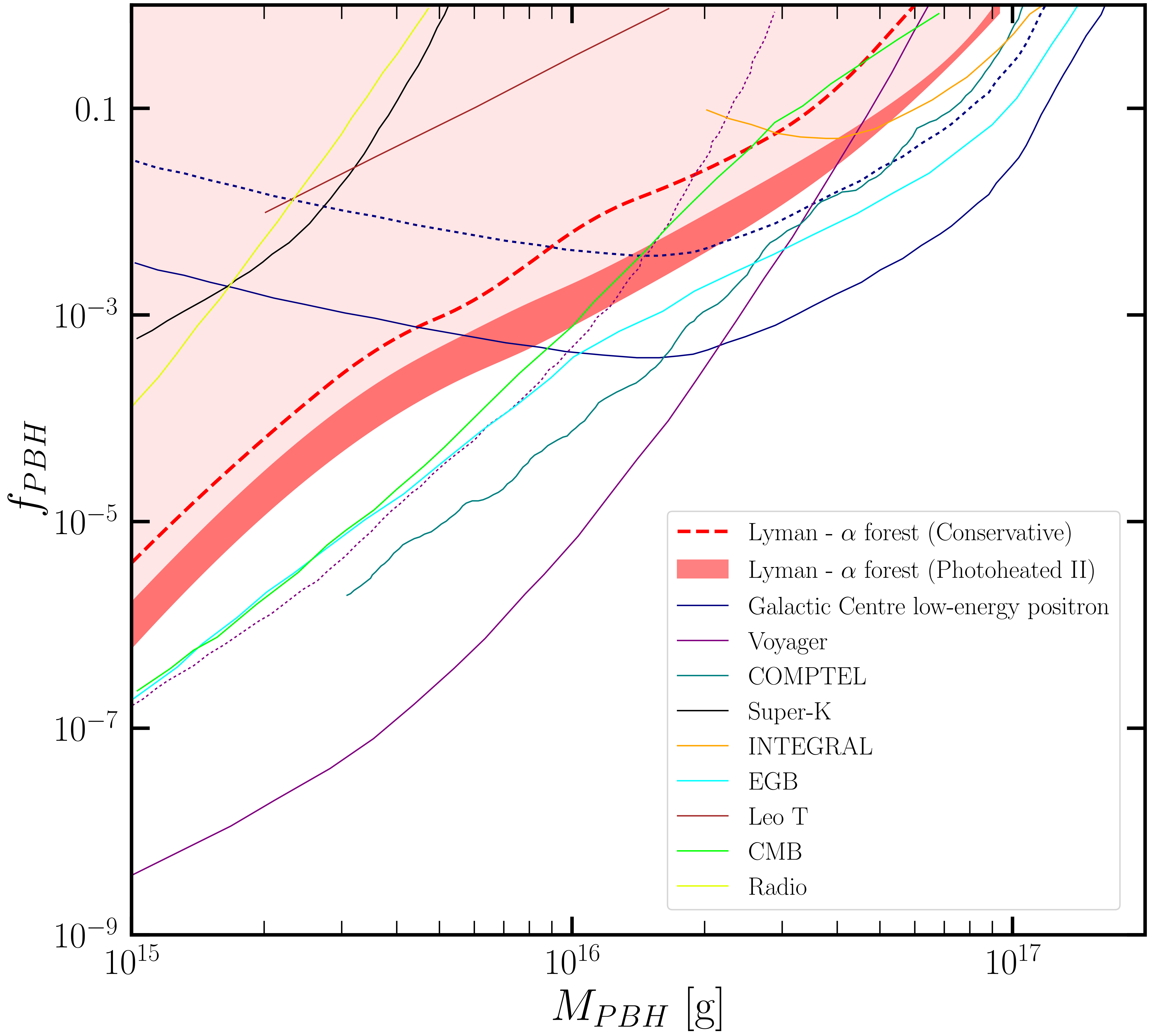

The IGM temperature does not exceed with the IGM temperature obtained by Walther et al. (2019) & Gaikwad et al. (2020) from Lyman-α forest measurement.

These constraints are complementary and comparable
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 low mass PBHs.

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 low mass PBHs.

Thank you!

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Spinning PBHs

- Similar analysis can be done for the spinning PBHs.

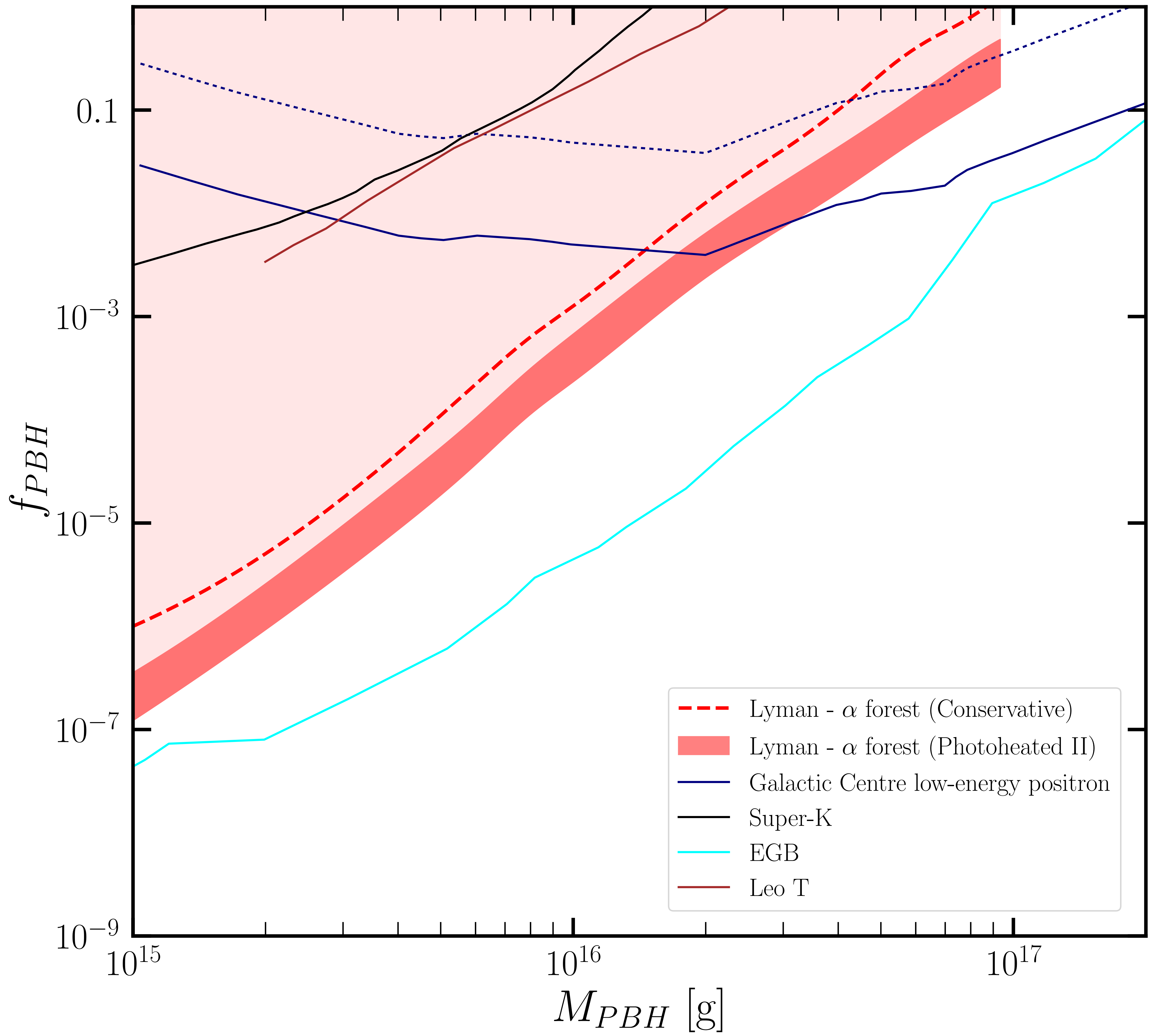
$$T_{\rm PBH} = 1.06 \left(\frac{10^{13}\,\text{g}}{M_{\rm PBH}}\right)\left(\frac{\sqrt{1-a_*^2}}{1+\sqrt{1-a_*^2}}\right)\text{GeV}$$

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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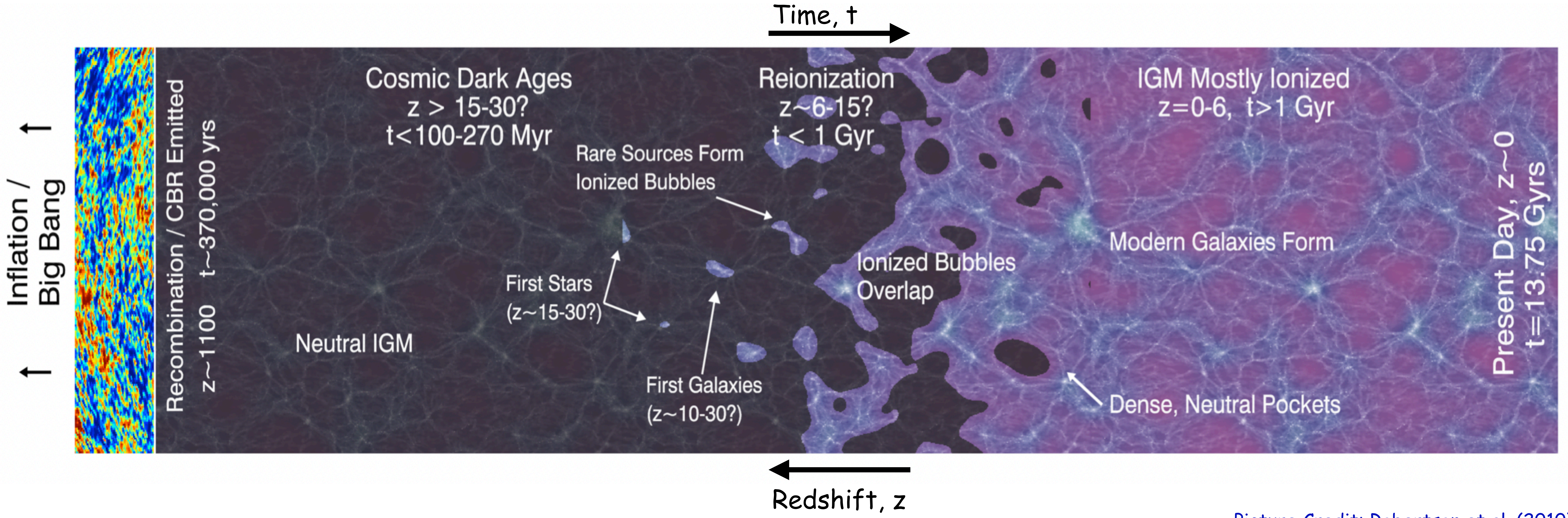
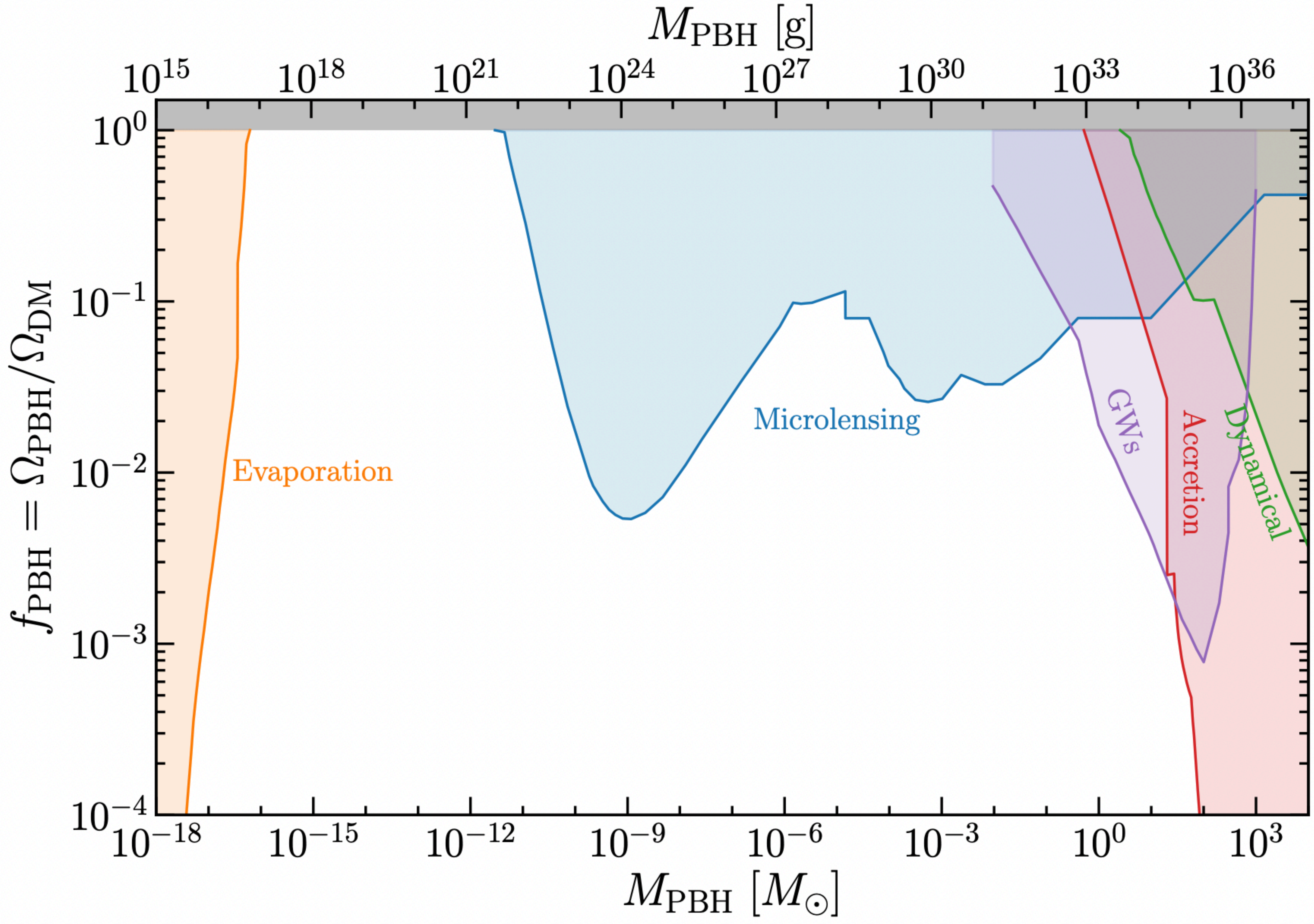
Universe Timeline



Picture Credit: Robertson et al. (2010)



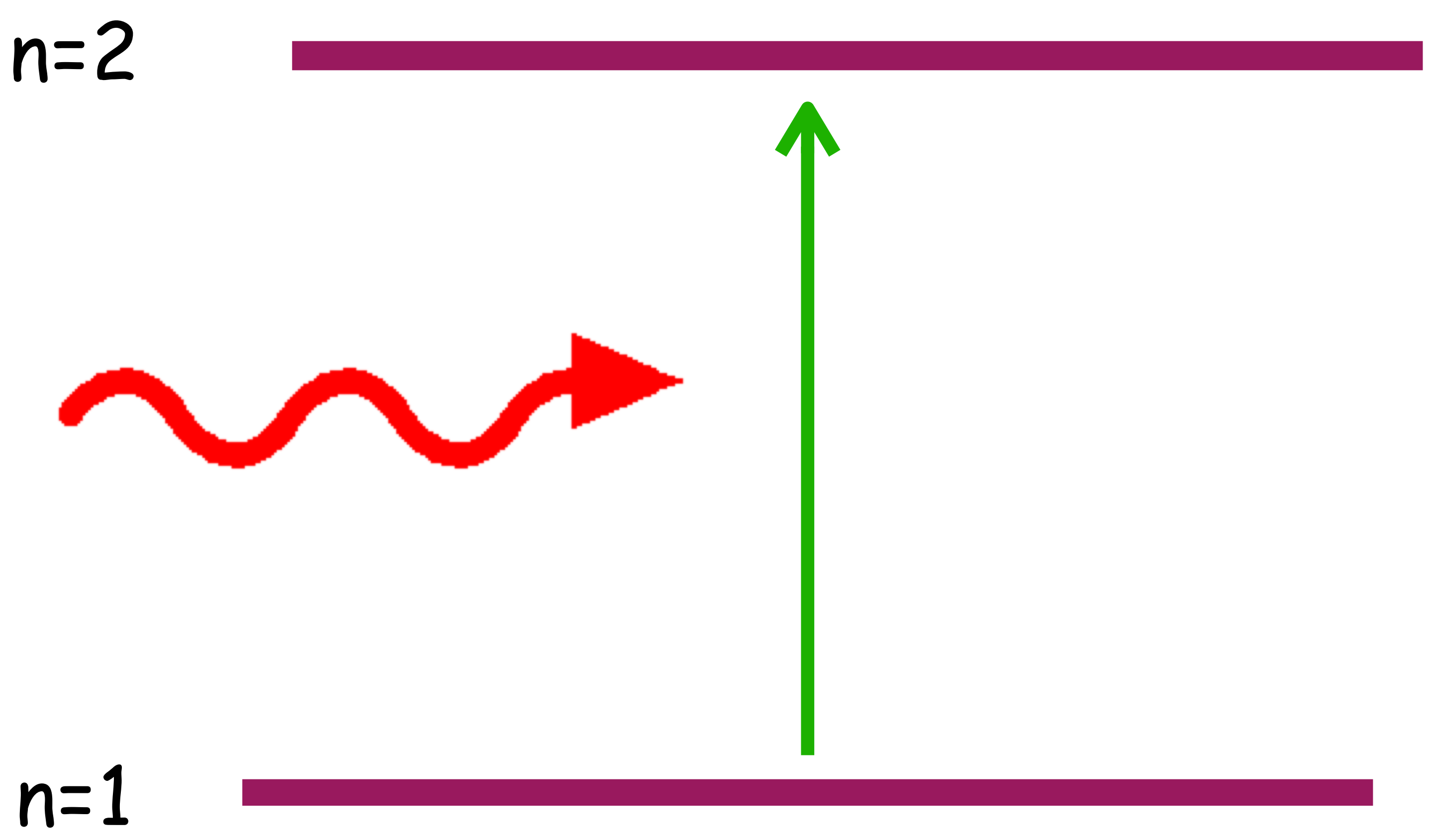
$M_{\rm PBH}$ [g]
10^{15}
10^{18}
10^{21}
10^{24}
10^{27}
10^{30}
10^{33}
10^{36}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$
Evaporation
Microlensing
GWs
Accretion
Dynamical
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
$M_{\rm PBH}$ $[M_\odot]$

What is Lyman-α Line?

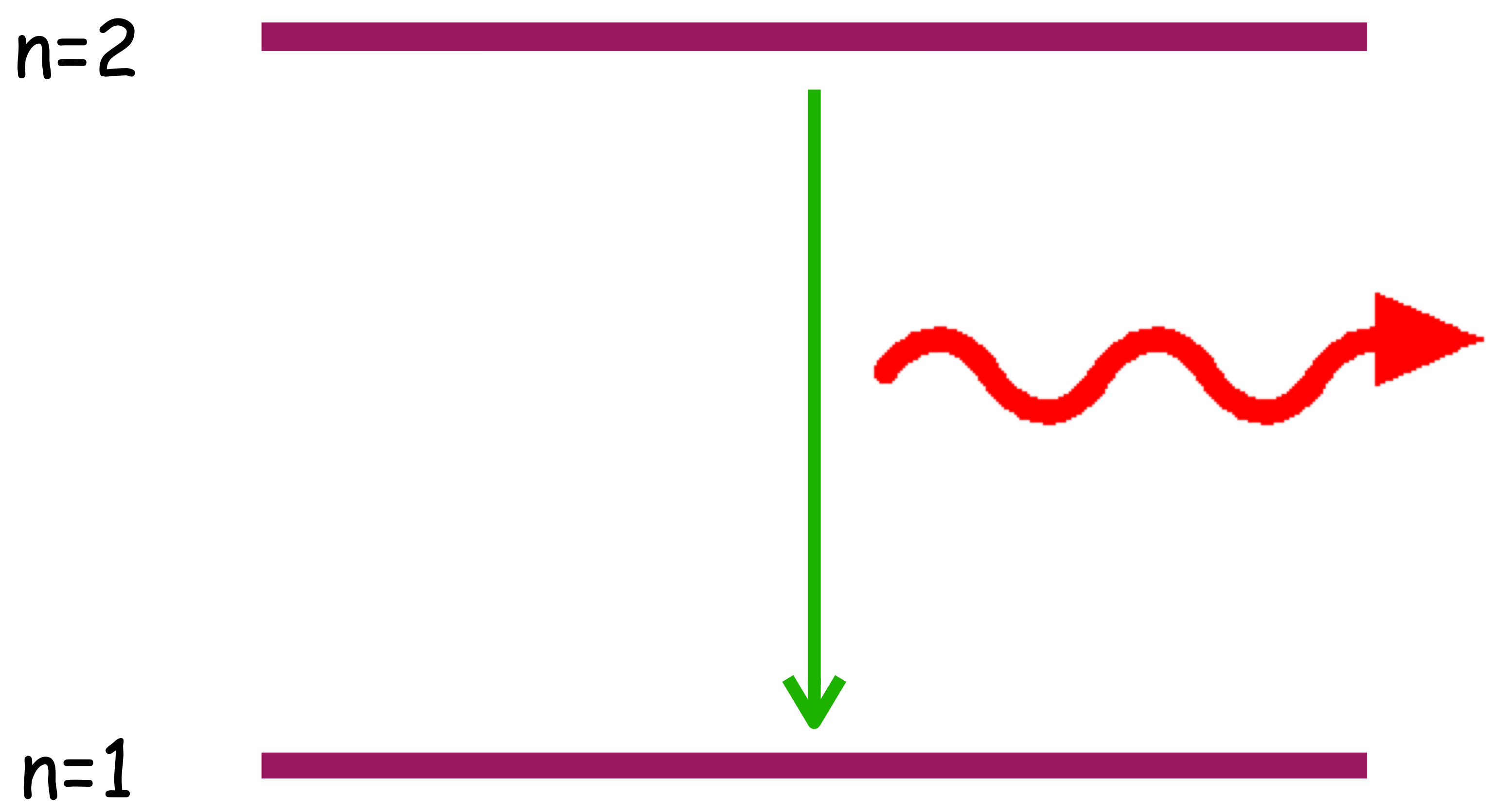
Spectral Line of Hydrogen atom in the Lyman Series.

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

n = Principle quantum number

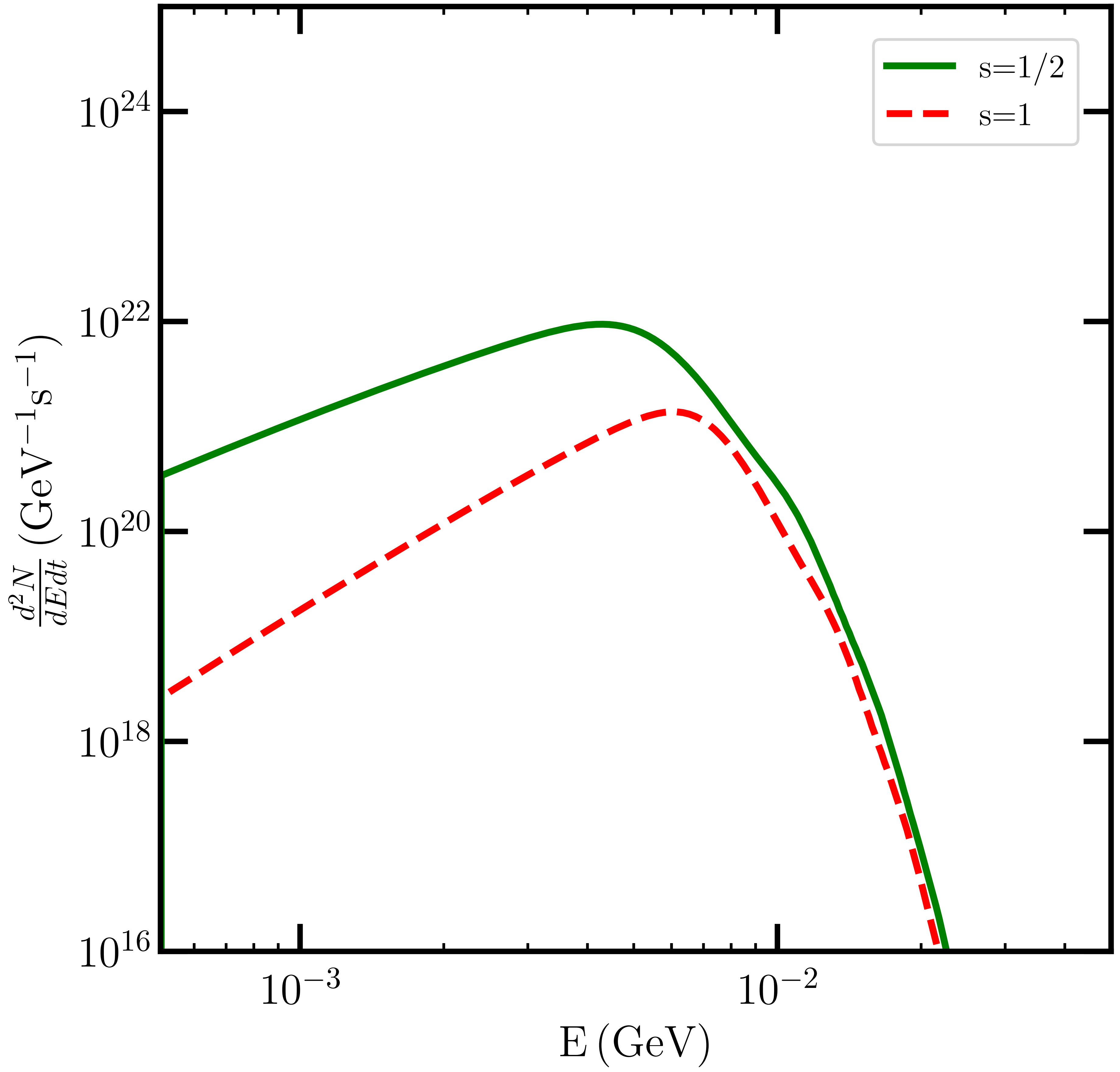


Lyman-α absorption line



Lyman-α emission line

λ = 1216 Å


s=1/2
s=1
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{-3}
10^{-2}
E (GeV)
$\frac{d^2N}{dEdt}\,(\mathrm{GeV}^{-1}\mathrm{s}^{-1})$

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

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

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

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

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

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

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