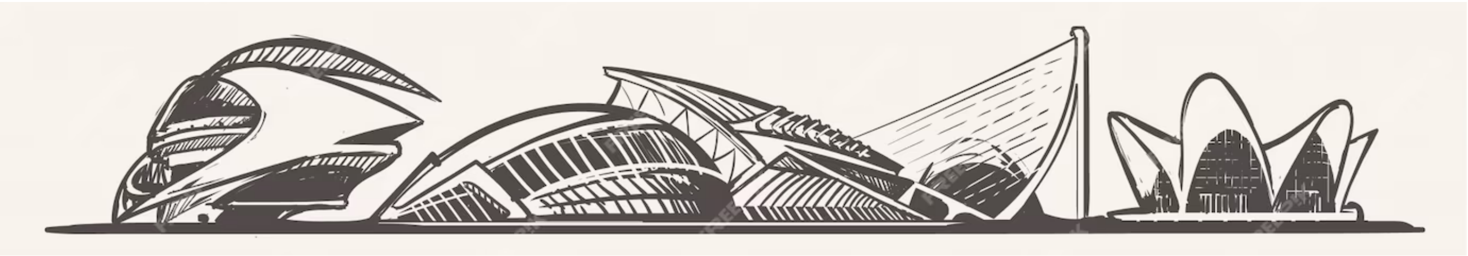
# Towards realistic bounds on PBHs from the CMB

*Feedback in the dark: a critical examination of CMB bounds on primordial black holes [2403.18895]*

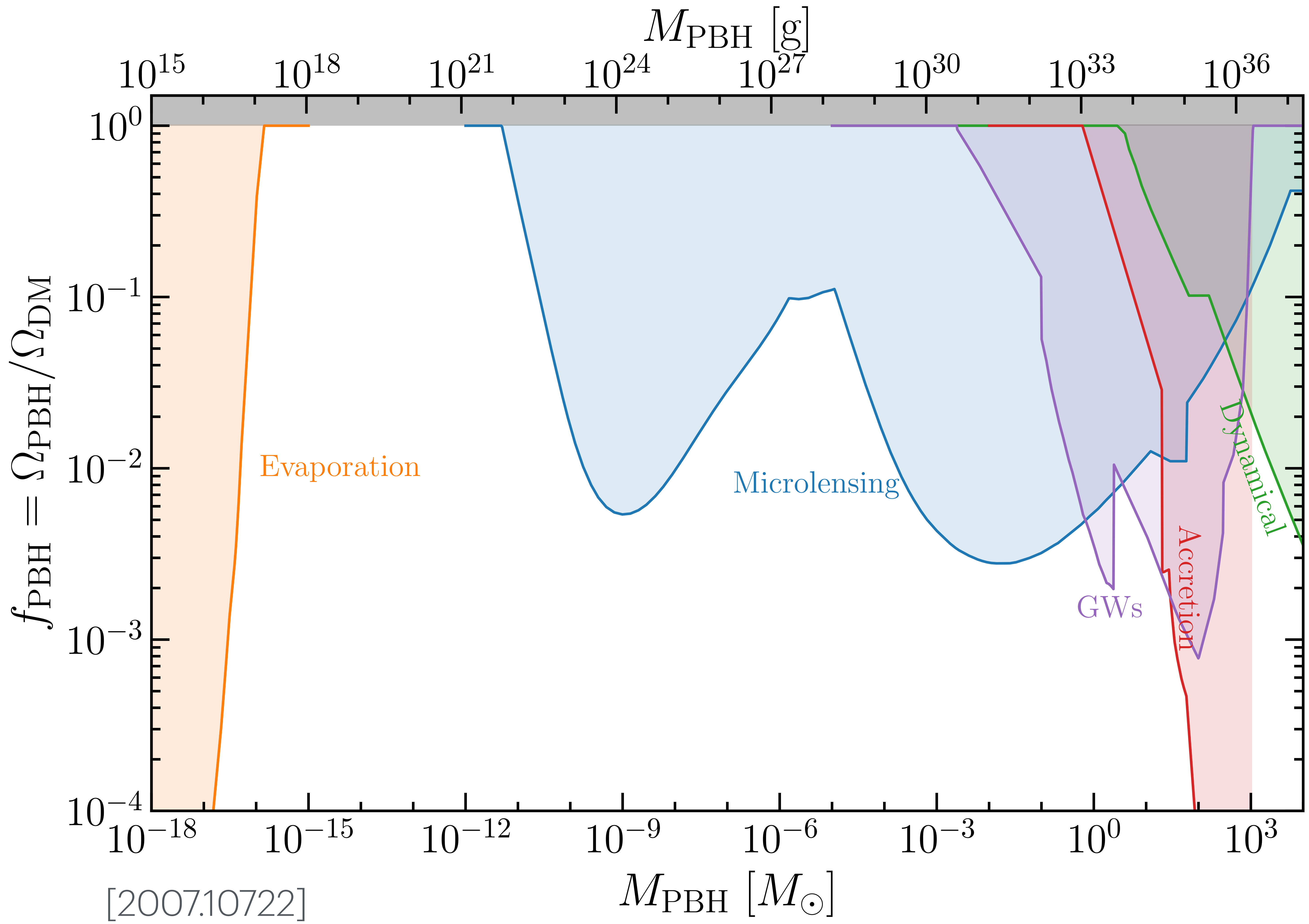
*In collaboration with Rouven Essig (YITP), Daniele Gaggero (INFN Pisa), Francesca Scarcella (U. Montpellier), Gregory Suczewski (YITP / Stony Brook U.), Mauro Valli (INFN Rome)*



Dominic Agius

NEHOP '24

# Existing bounds



[2007.10722]

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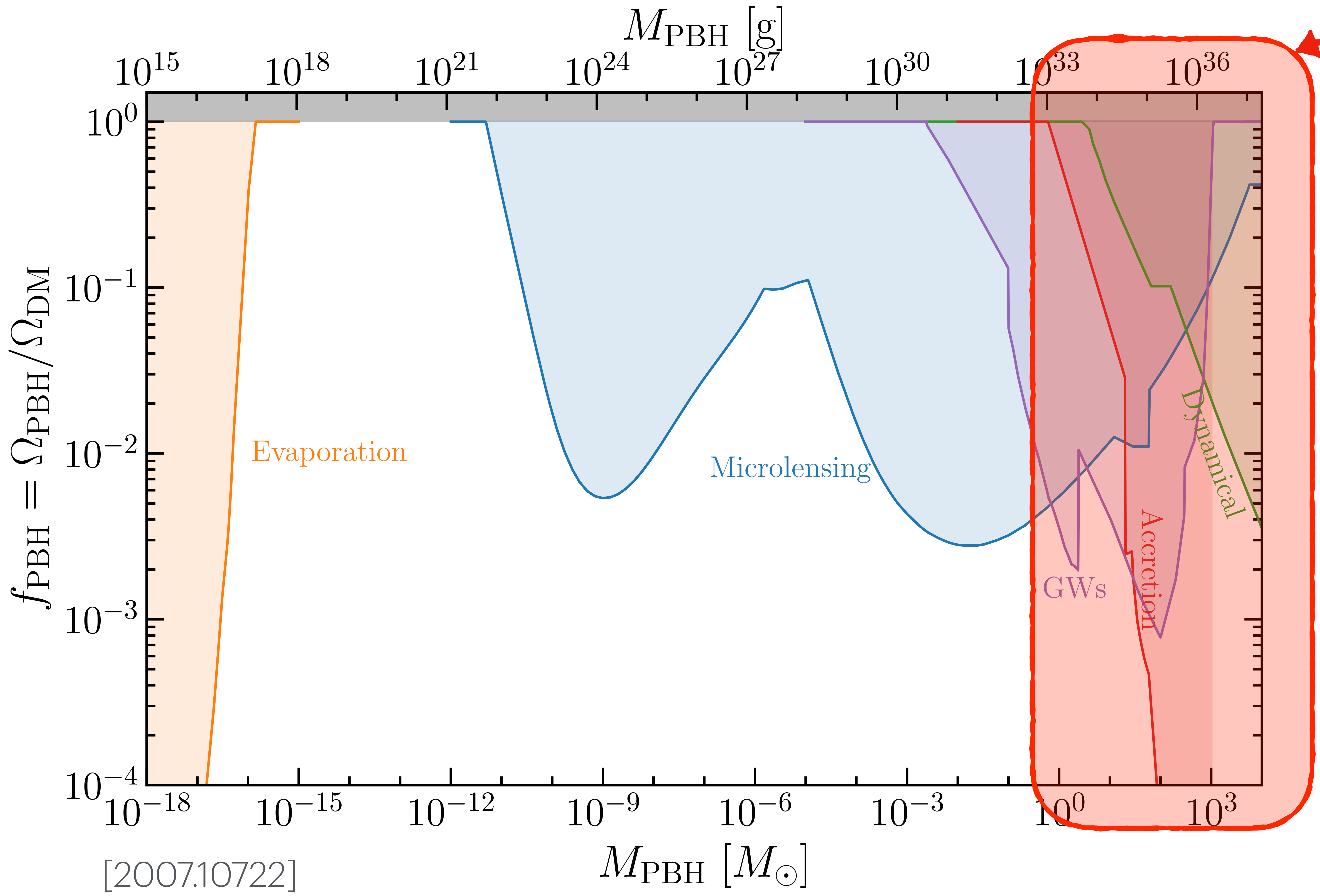


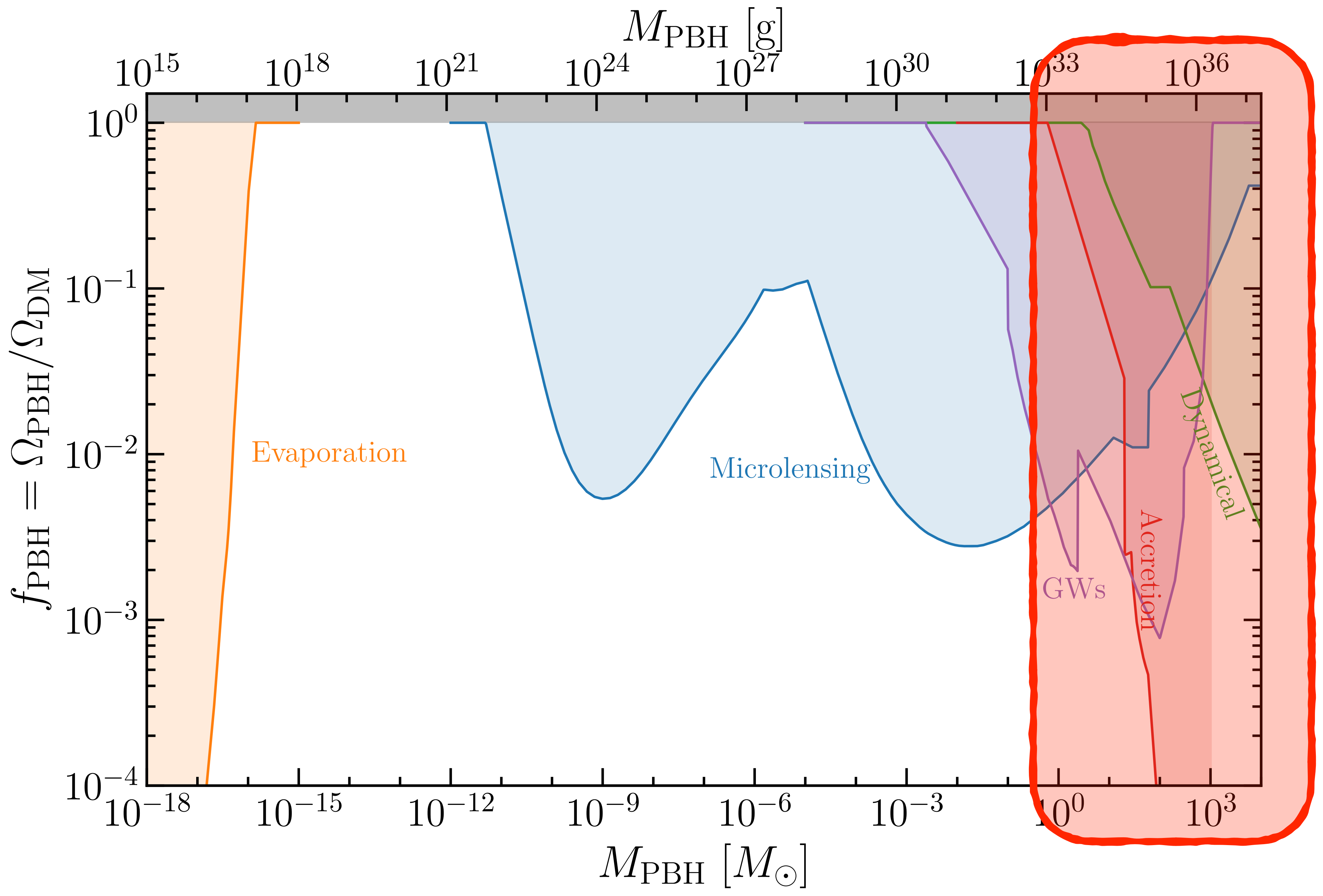
[2007.10722]

Region of interest

# Why care about subdominant populations?

- SMBH seed problem [2305.15458]
- LIGO/Virgo/KAGRA black hole mergers [e.g. 2009.01190]
- And more…

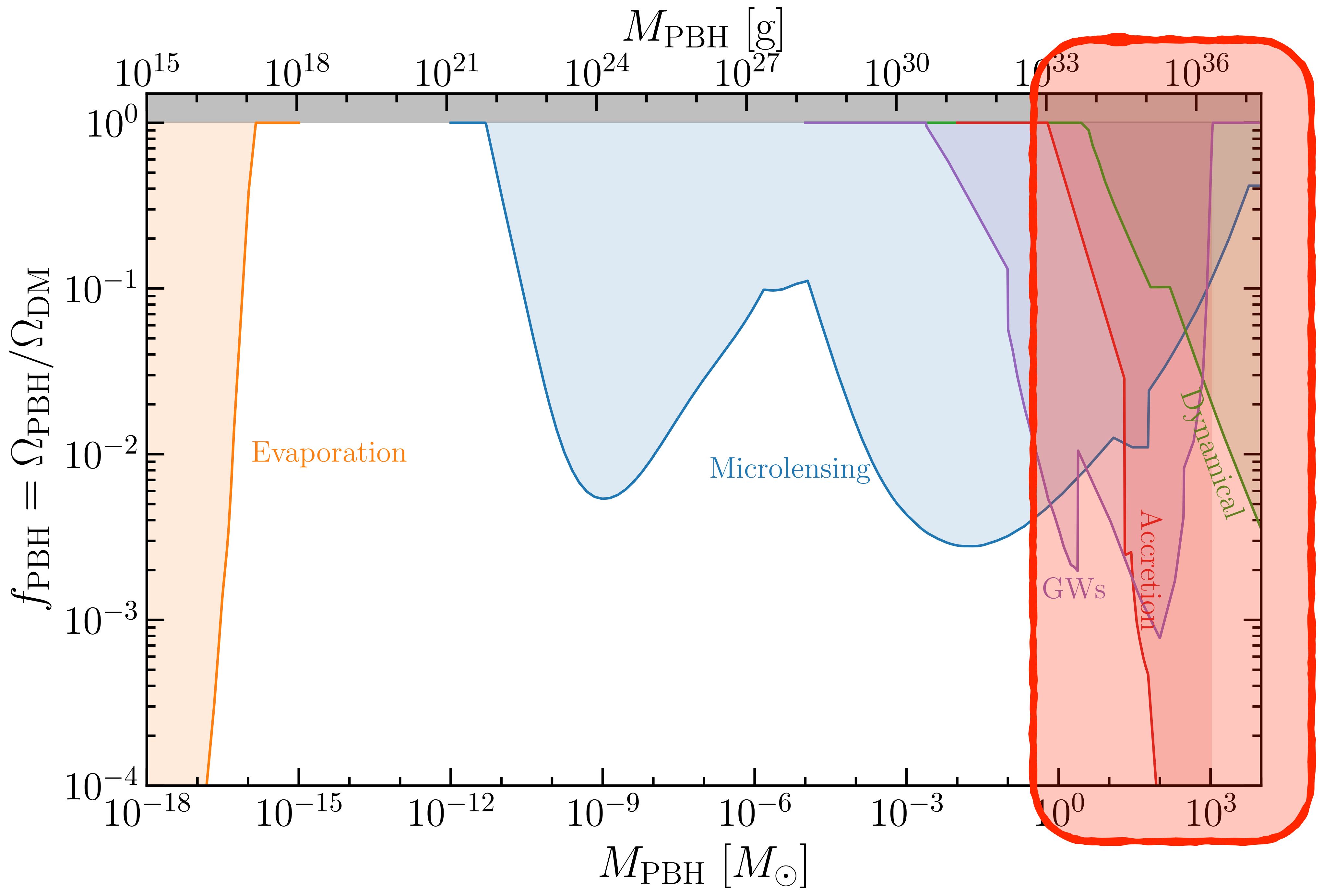
# Existing bounds



95% Confidence Exclusion Bounds

**ASSUMING SOMETHING!**

# Existing bounds



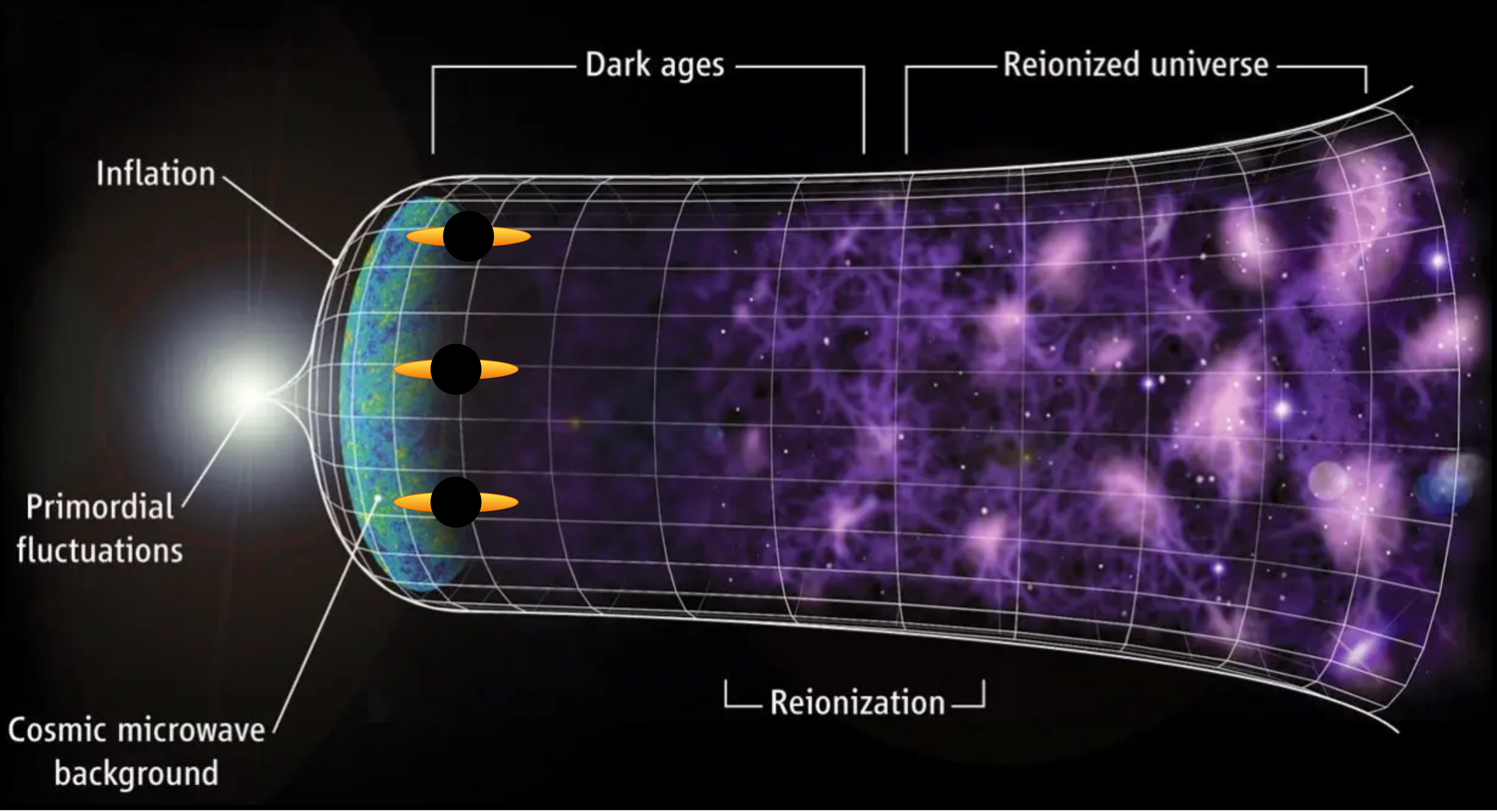
95% Confidence Exclusion Bounds

**ASSUMING SOMETHING!**

- Carr (1981)
- Ricotti, Ostriker, Mack (2008)
- Ali-Haïmoud, Kamionkowski (2017)
- Poulin, Serpico, Calore, Clesse, and Kohri (2017)
- Serpico, Poulin, Inman, Kohri (2020)
- Piga et. al. (2022)
- Facchinetti, Lucca, Clesse (2022)

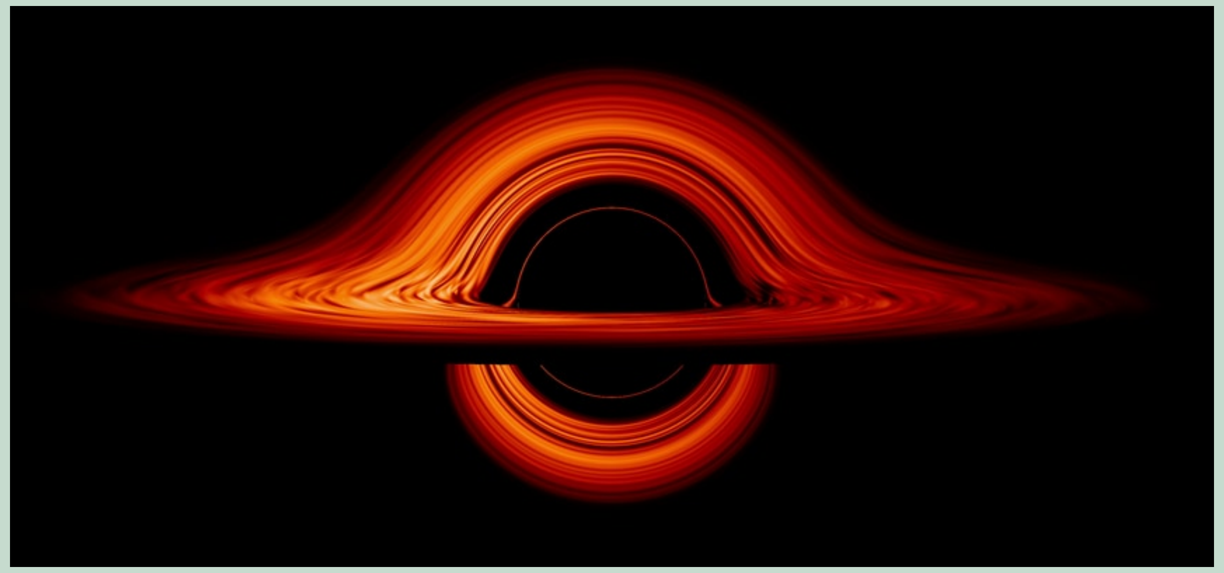
+ many others

# The physics of the CMB bound



# The physics of the CMB bound - systematics

**Accretion Rate**

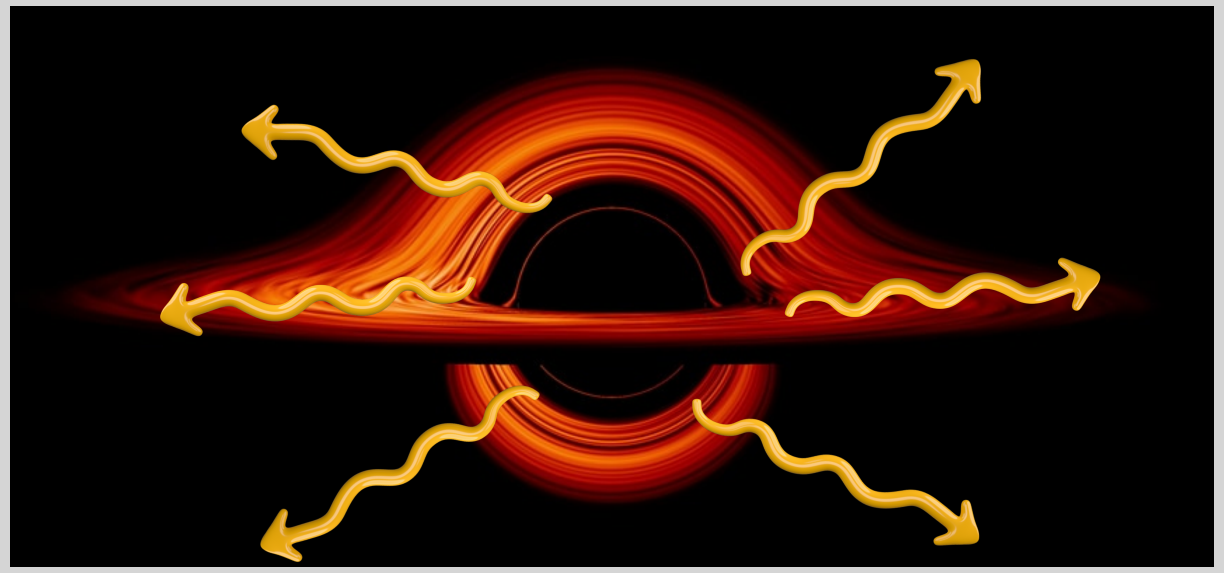


[Image from Jeremy Schnittman - NASA]

$$\dot{M} = \frac{dM}{dt}$$

- Accretion modelling

**Luminosity + Energy Injection**



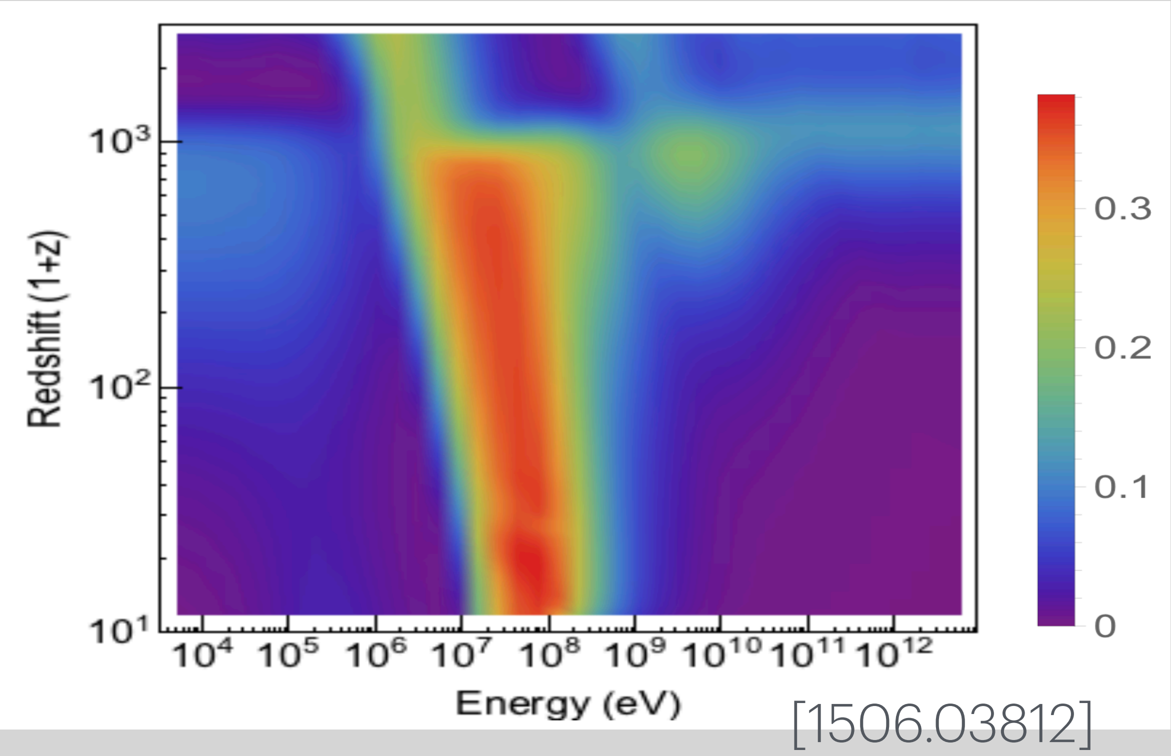
$$L = \epsilon\left(\dot{M}\right)\dot{M}c^2$$

$$\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\,\mathrm{d}t}\right|_{\mathrm{inj}} = Lf_{\mathrm{PBH}}\frac{\rho_{\mathrm{DM}}}{M}$$

- Geometry (spherical or disk)
- Type of disk

ADAF disk [1207.3113]

**Energy Deposition**



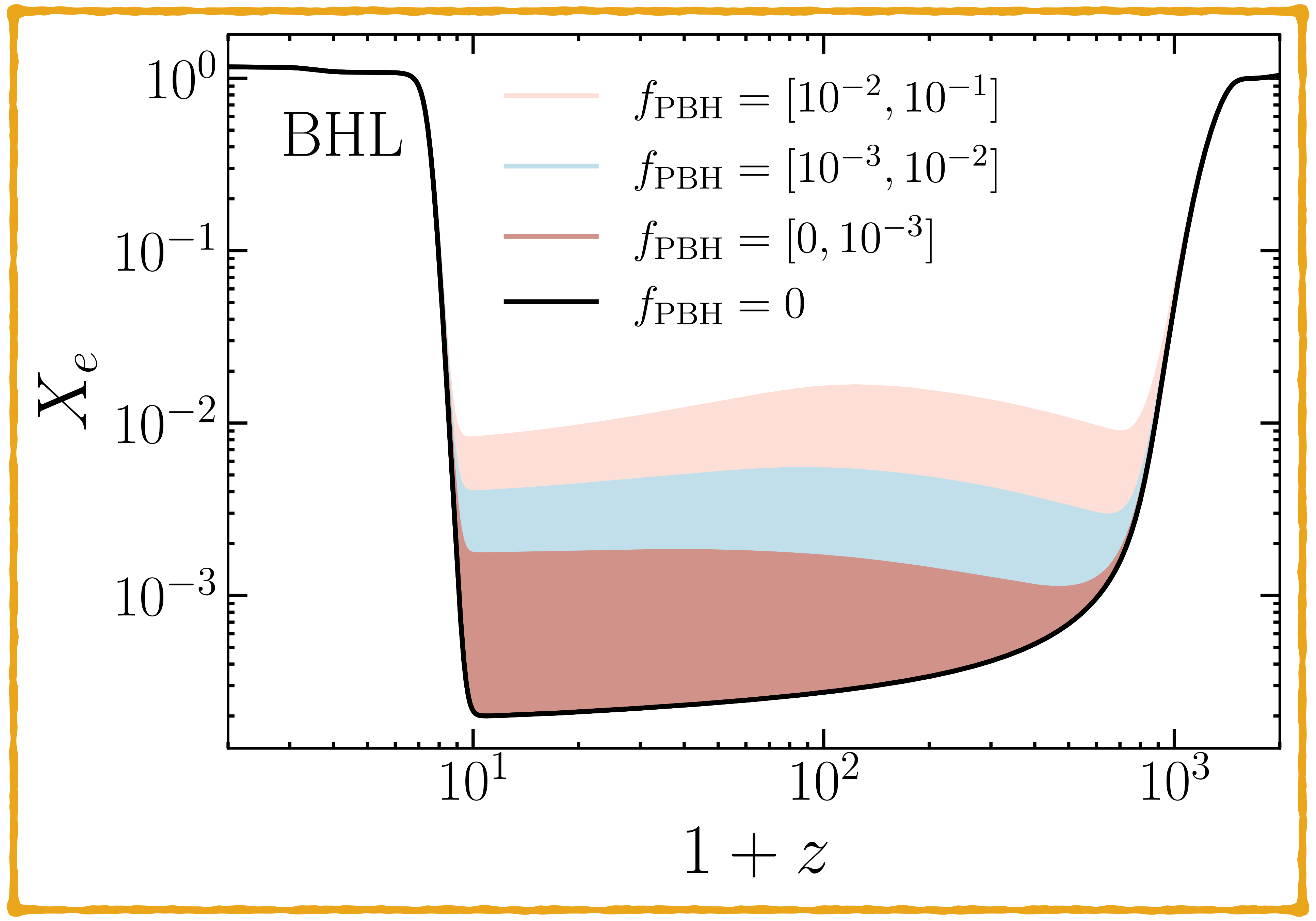
[1506.03812]

$$\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\,\mathrm{d}t}\right|_{\mathrm{dep},c} = f_c\left(z, x_e\right)\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\,\mathrm{d}t}\right|_{\mathrm{inj}}$$

- Energy deposition treatment

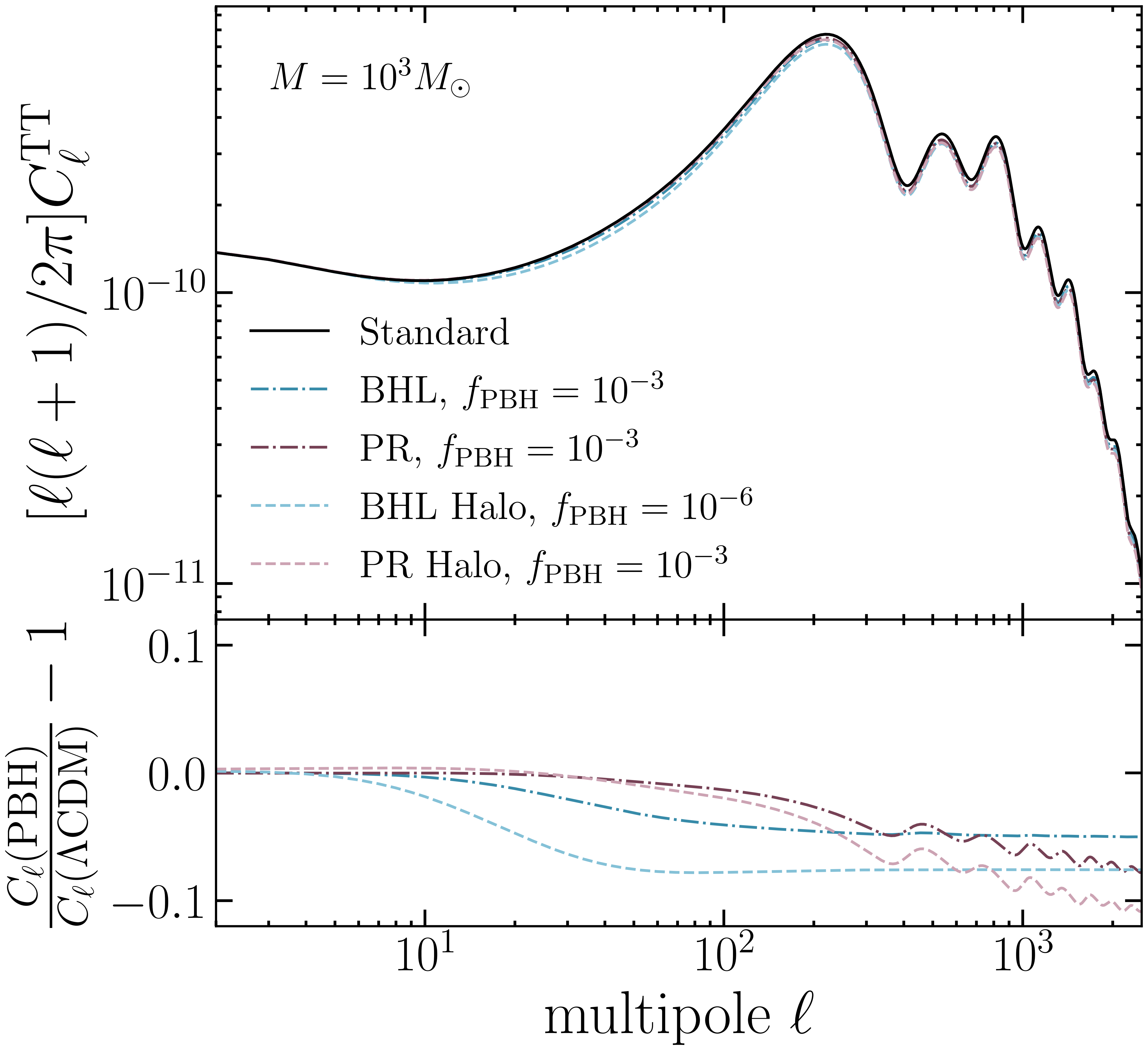
Slatyer's transfer functions [1211.0283]

# The physics of the CMB bound



+

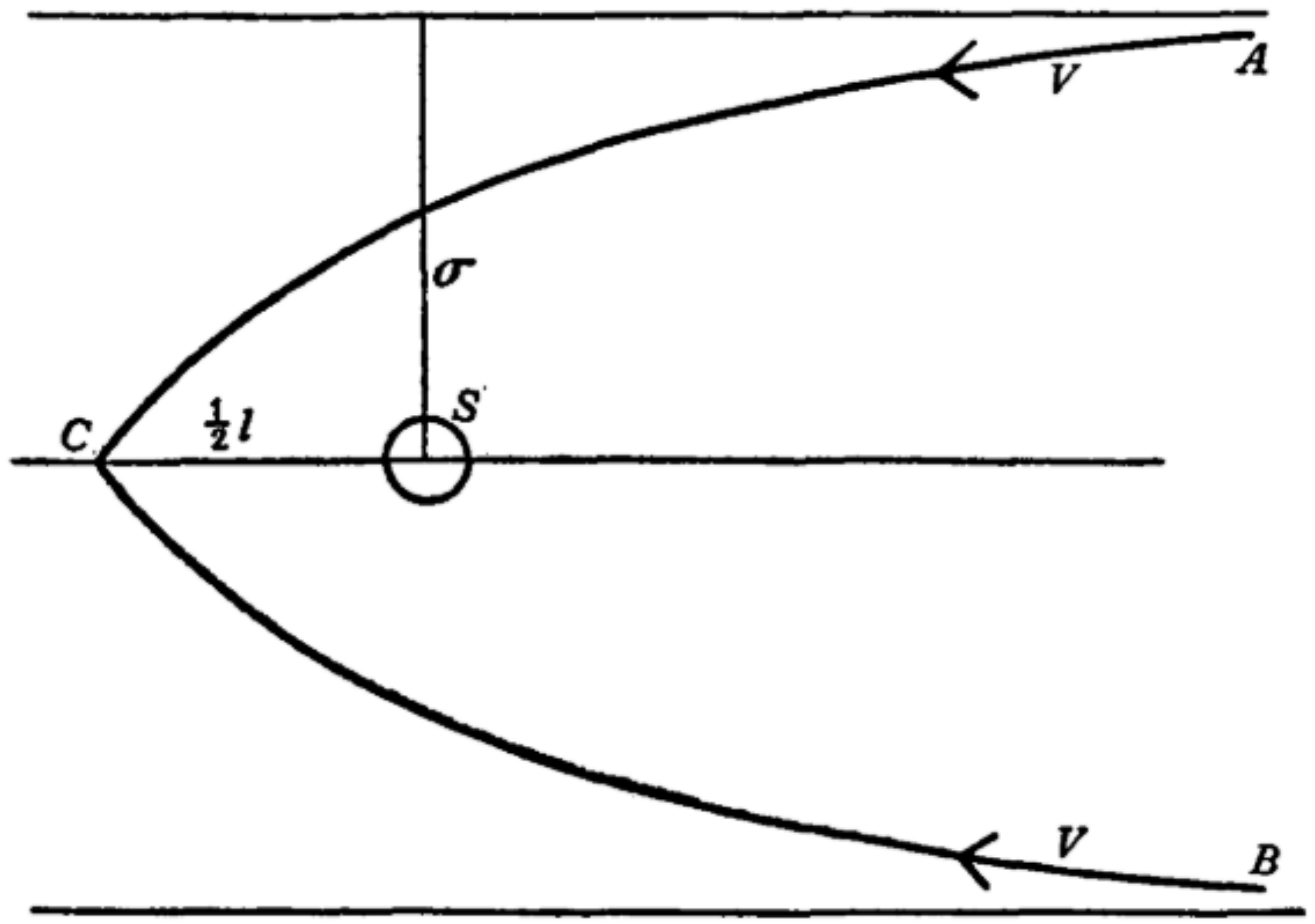
Temperature of IGM



[1801.01871]

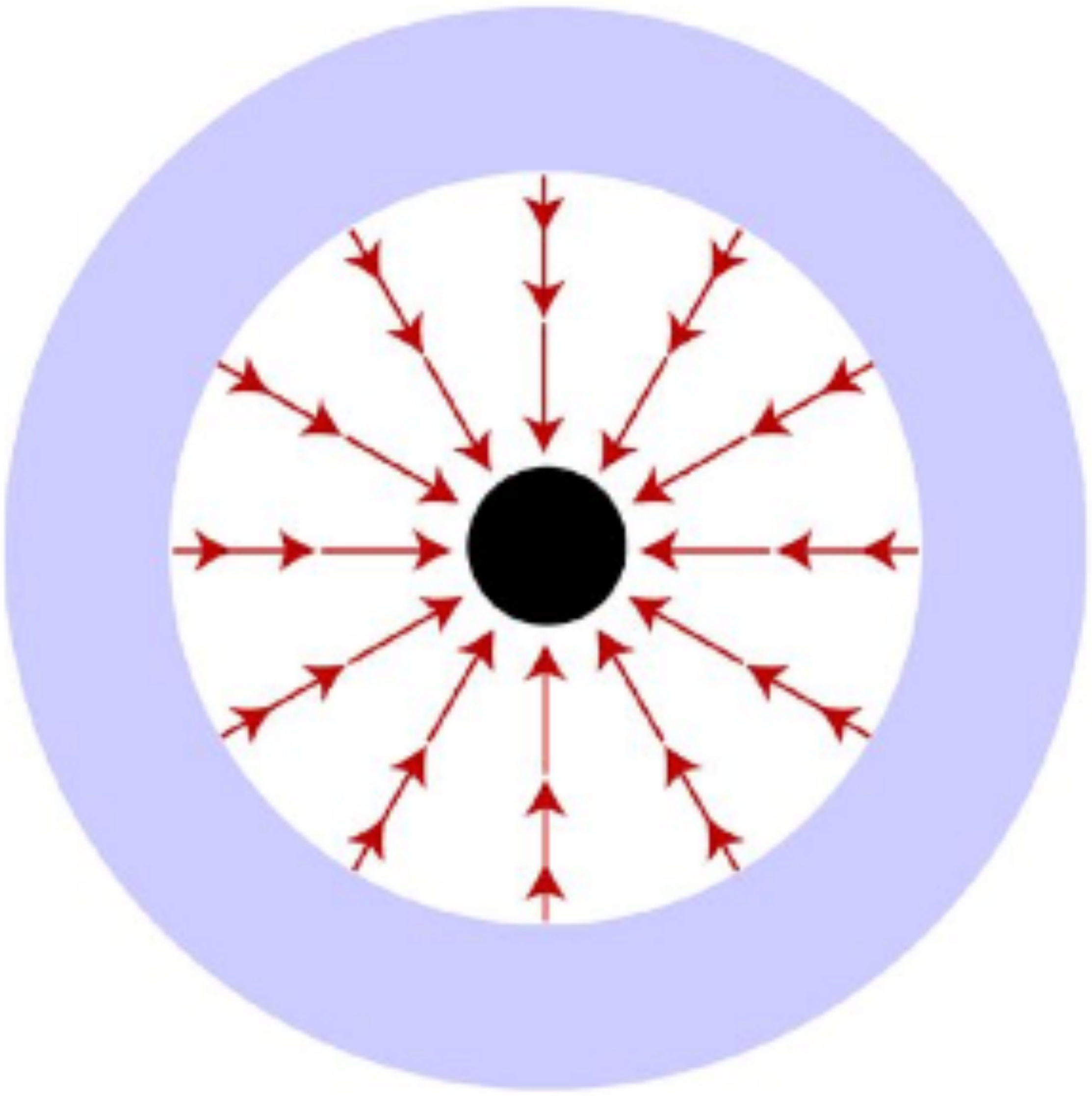
# Accretion physics - BHL

Hoyle, F., & Lyttleton, R. A. (1939)



Ballistic limit

H. Bondi (1952)



Steady state spherical

$$\dot{M}_{\rm BHL} = 4\pi\lambda \frac{(GM_{\rm PBH})^2 \rho_{\rm b}}{\left(v_{\rm BH}^2 + c_{\rm s}^2\right)^3}$$

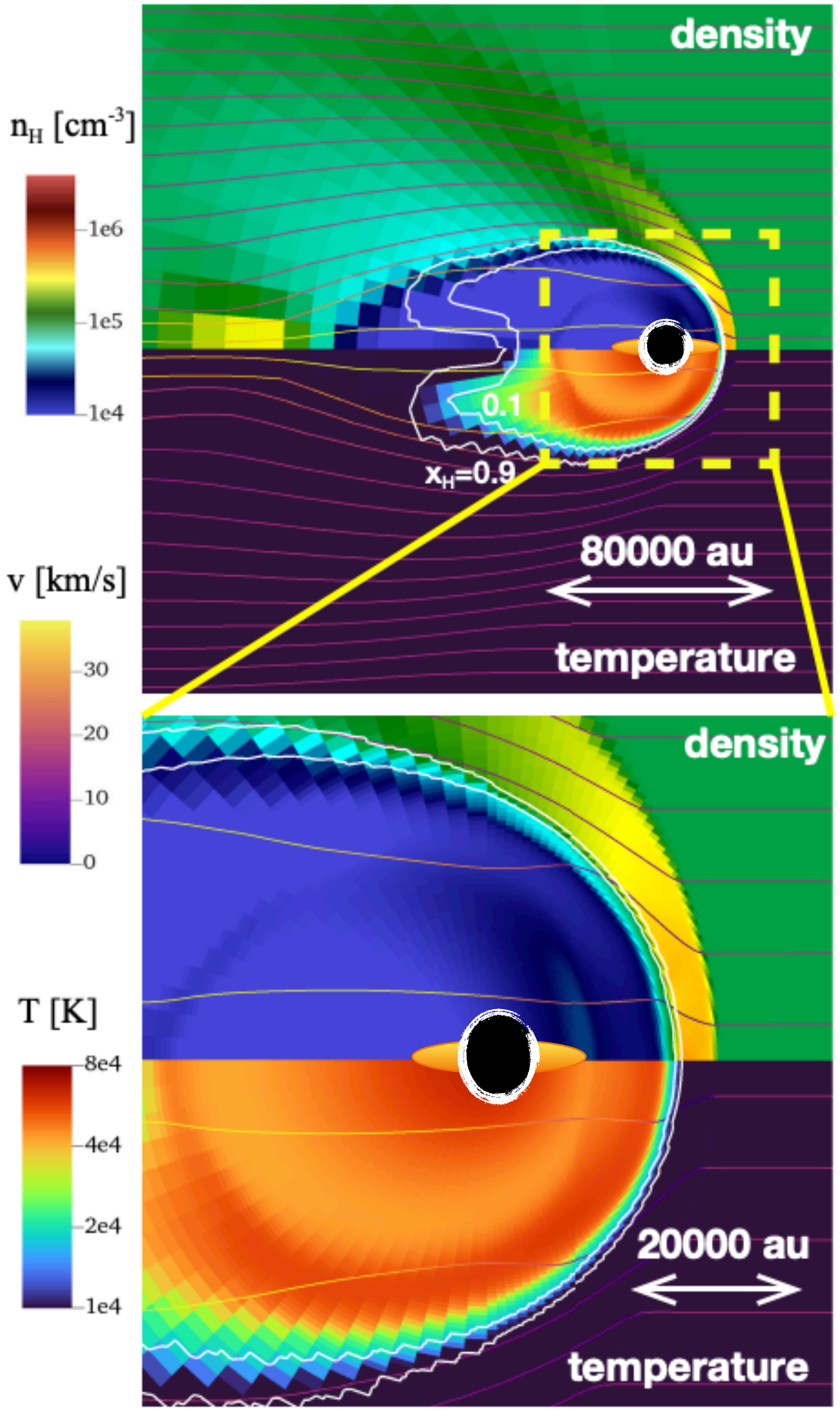
$\lambda \sim 10^{-2}$ tuned to observations

- Missing isolated neutron stars [0305421]
- X-Ray surveys of local BHs [1301.1341]
- SMBH, AGNs [1307.5845, 10.1086/429267]

*"It seems likely that it represents the order of magnitude of the accretion rate" - Bondi 1952*

# Accretion physics - PR

[2003.05625]



- Park and Ricotti 2013: numerical simulations + semi-analytic formula including radiative feedback.

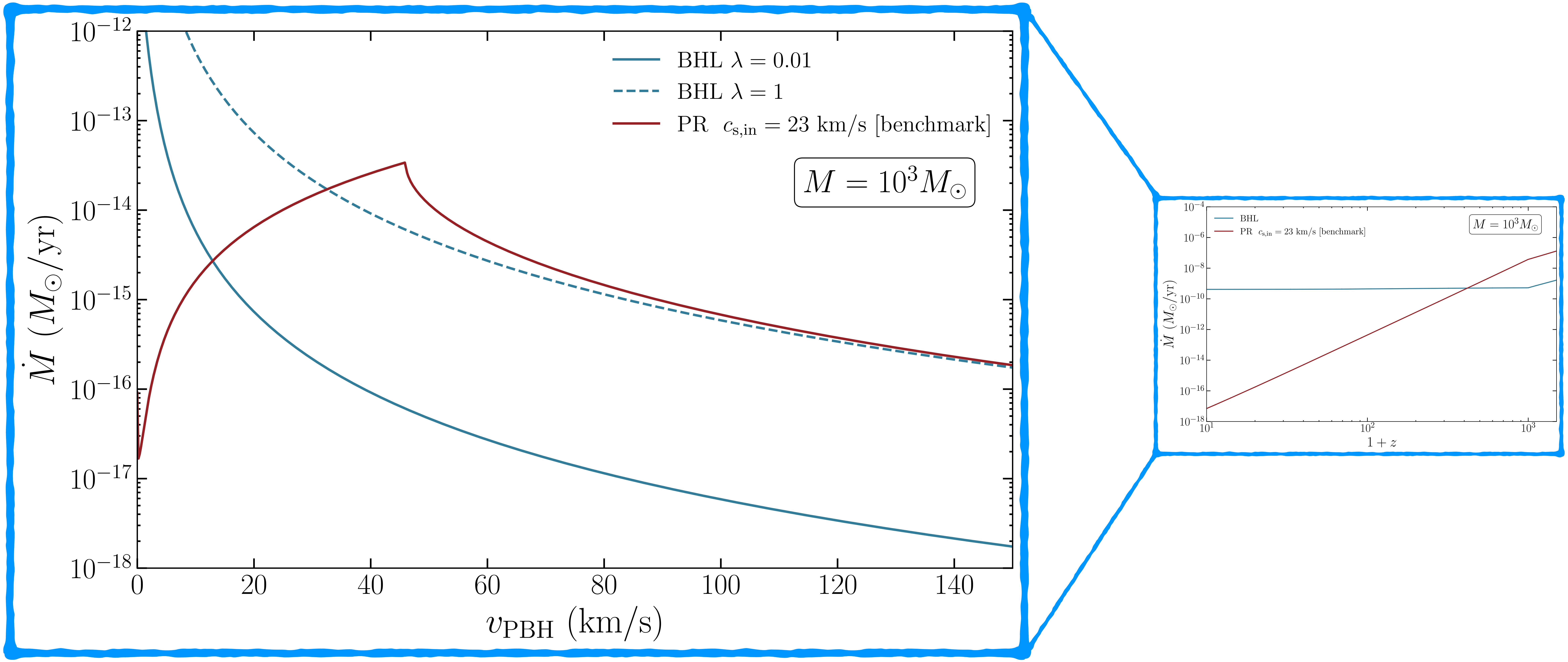
$$\dot{M}_{\rm PR} = 4\pi\rho_{\rm in}\frac{(GM_{\rm PBH})^2}{({v_{\rm in}}^2 + {c_{\rm s,in}}^2)^{3/2}}$$

Fixed by Euler's equations at the ionisation front

Free parameter parametrising temperature in the ionised region

- Can be considered like a Bondi problem inside an ionised region, regulated by feedback

# Accretion physics - PR



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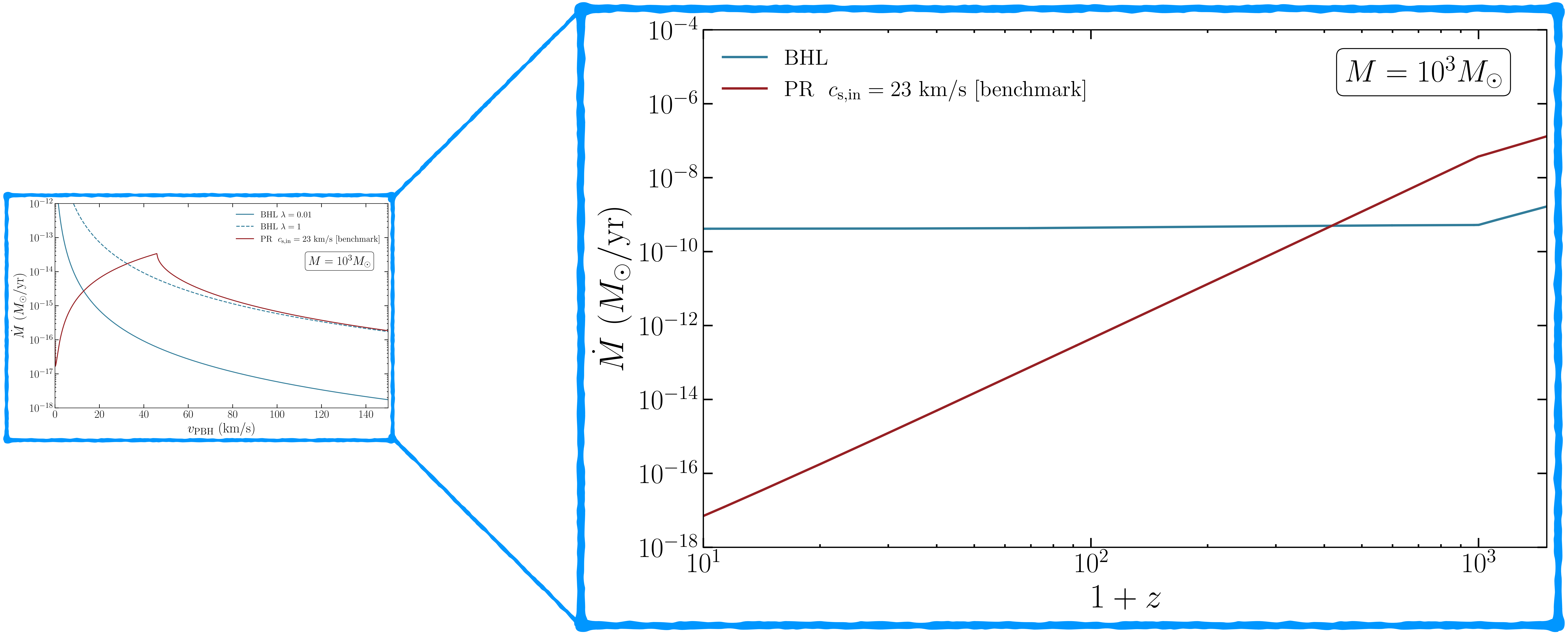
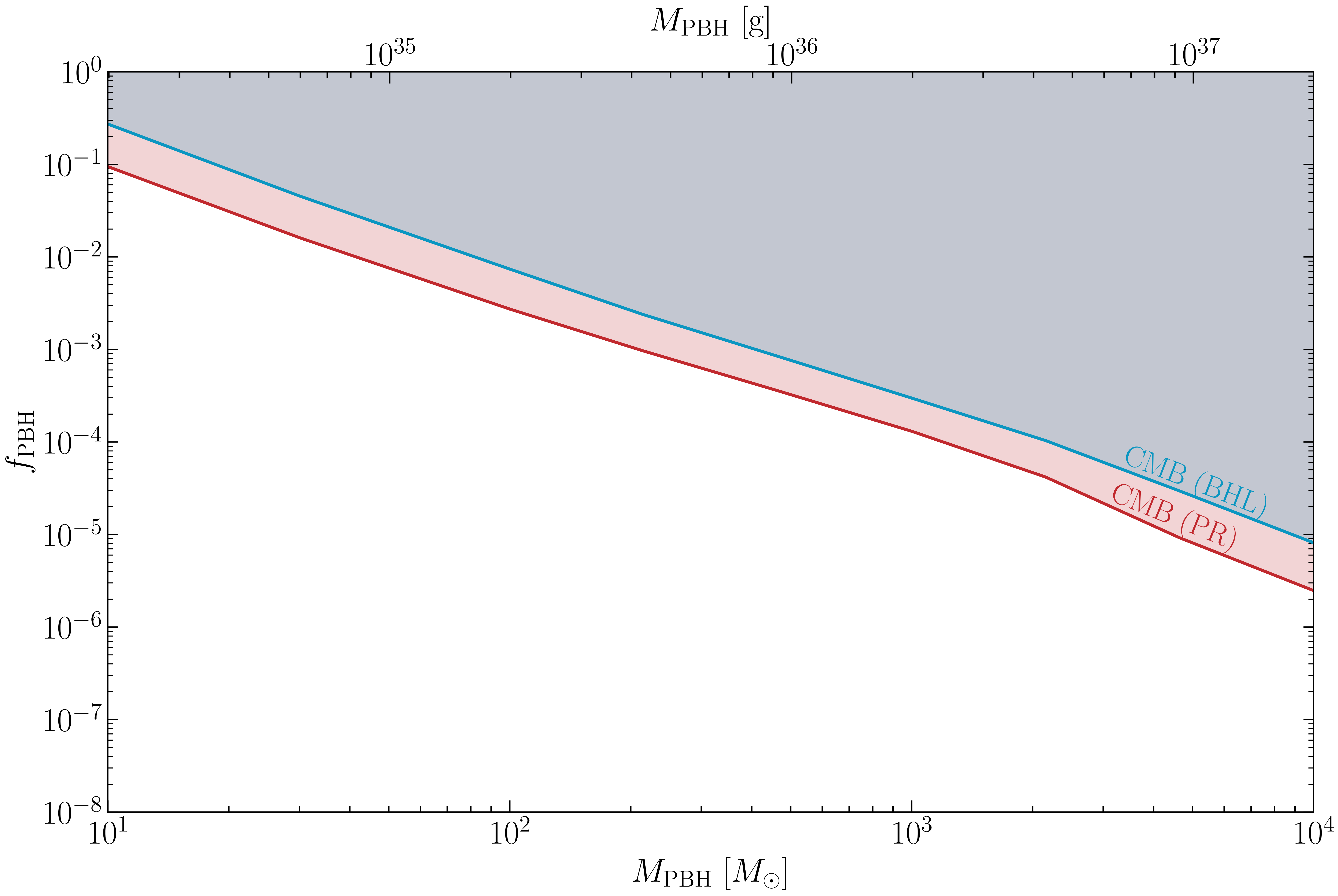


# BHL vs. PR



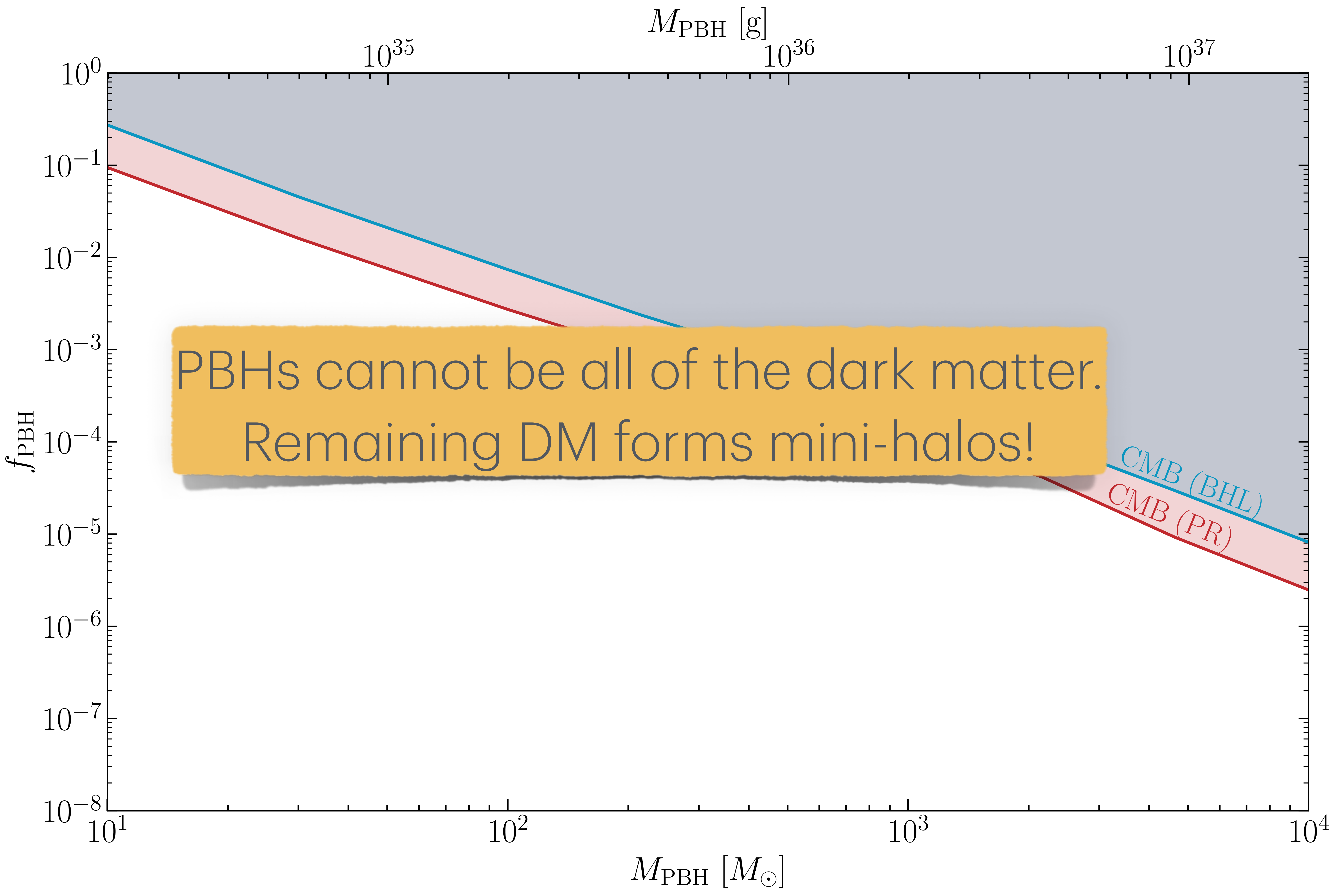
Cobaya + CLASS

[1104.2933, 2005.05290]

Planck2018 TTTEEE + lensing
Latest SPT + ACT
BAO consensus

[1807.06209, 2212.05642,2304.05203, 2007.08991, ...]

# BHL vs. PR



PBHs cannot be all of the dark matter.
Remaining DM forms mini-halos!

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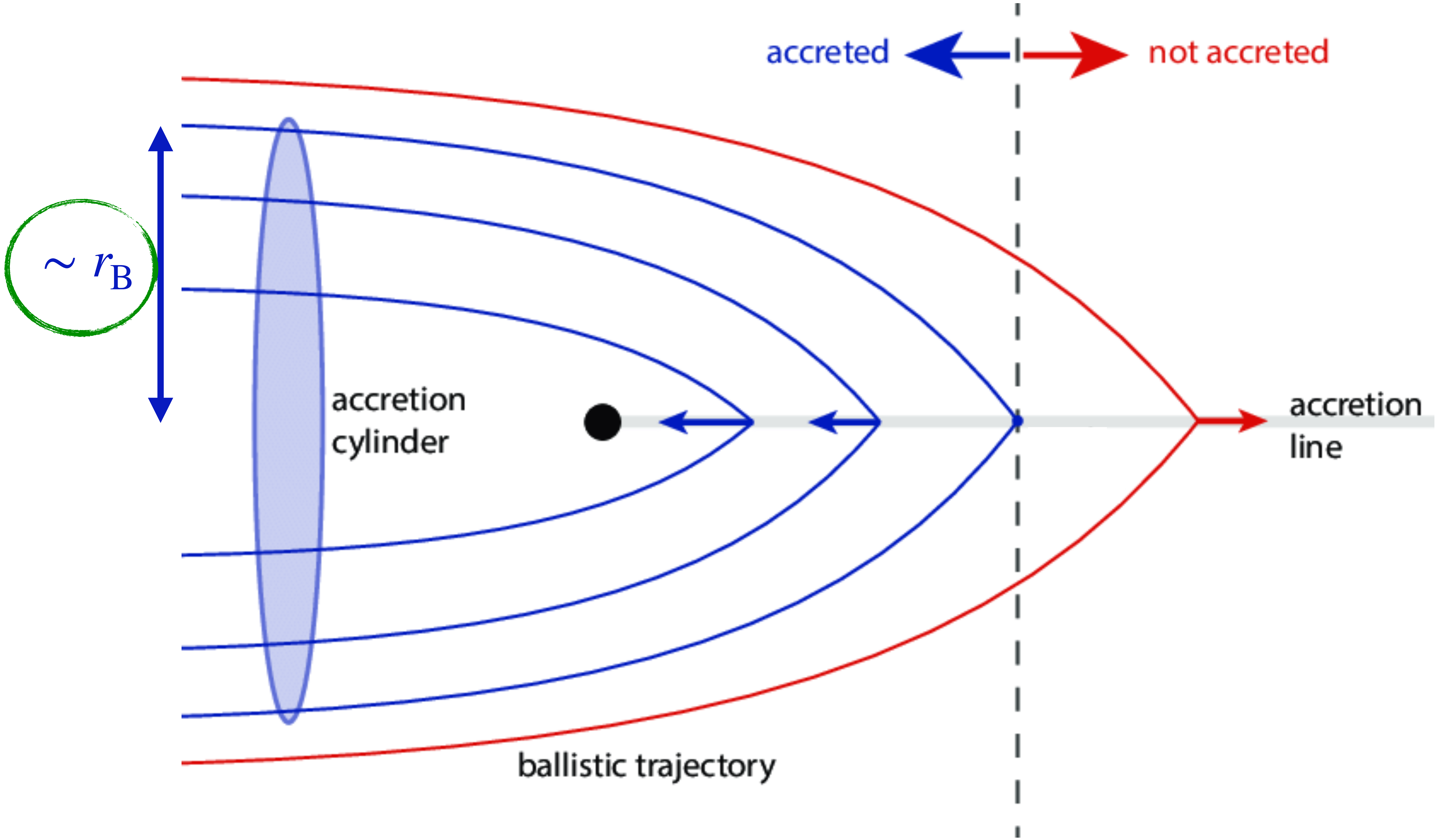
# Bondi radius



# Dark matter mini-halos

- PR model can be understood as a Bondi problem within the ionised region

$$\dot{M} = 4\pi\lambda\rho v_{\text{eff}}(r_{\text{B}}^{\text{eff}})^2$$

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- Same for BHL and PR
- Depends on halo profile and growth of halo

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Bondi radius grows for BHL
Remains almost constant for PR

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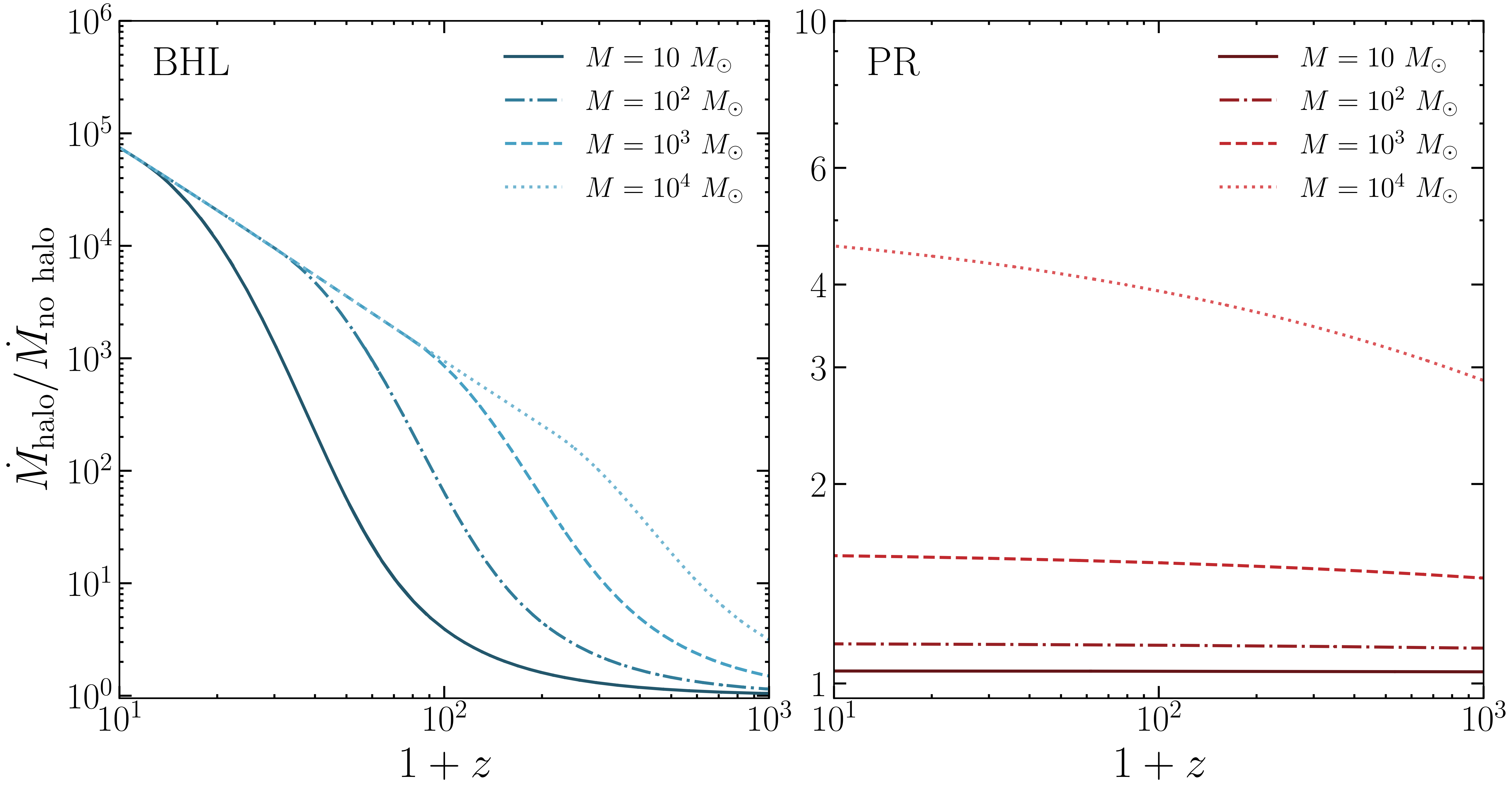
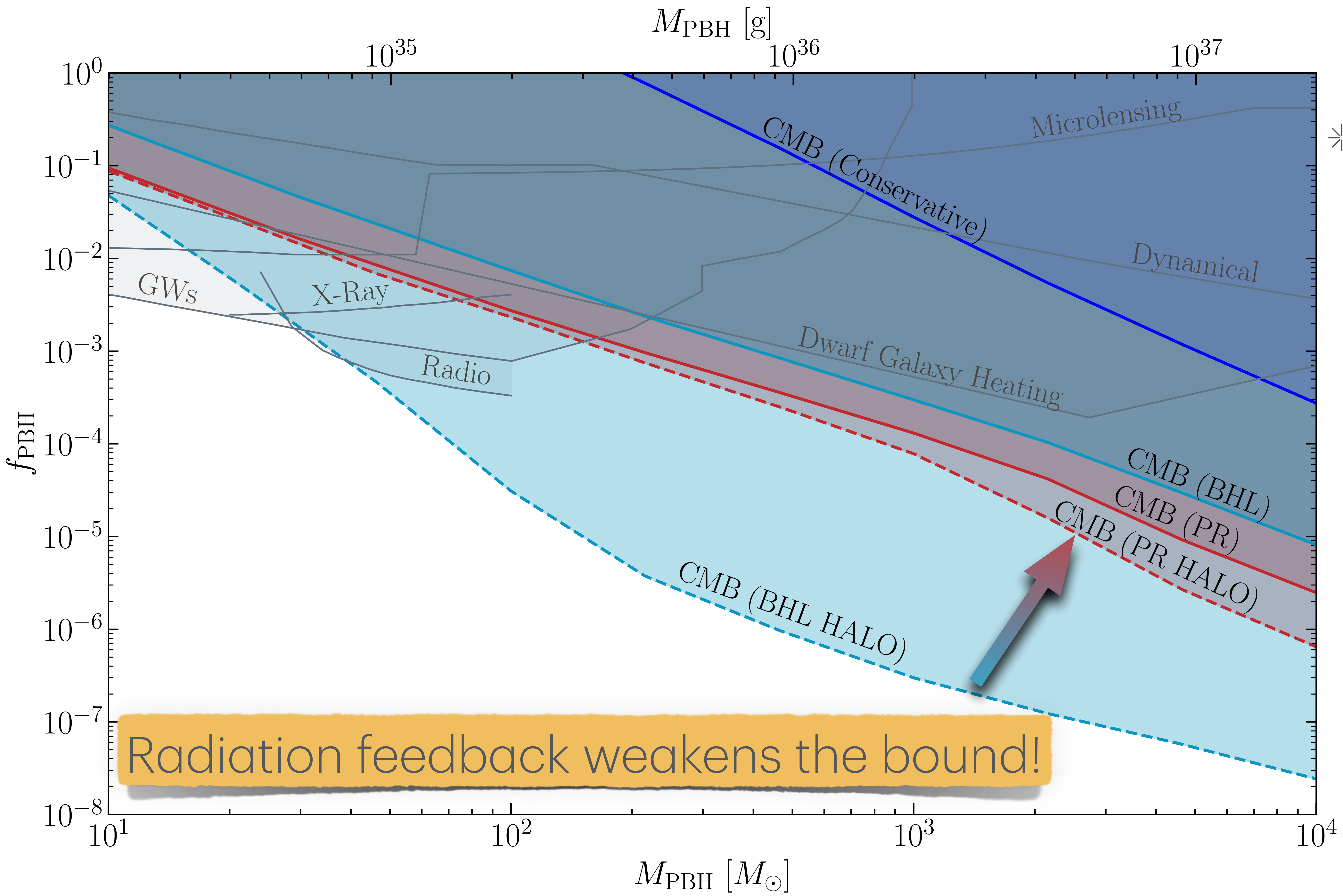


Accretion rate grows for BHL
Remains almost constant for PR

# The final bound



Radiation feedback weakens the bound!

Cobaya + CLASS

[1104.2933, 2005.05290]

Planck2018 TTTEEE + lensing
Latest SPT + ACT
BAO consensus

[1807.06209, 2212.05642,2304.05203, 2007.08991, ...]

# Summary

- Modelling radiation feedback weakens the bound including mini-halos

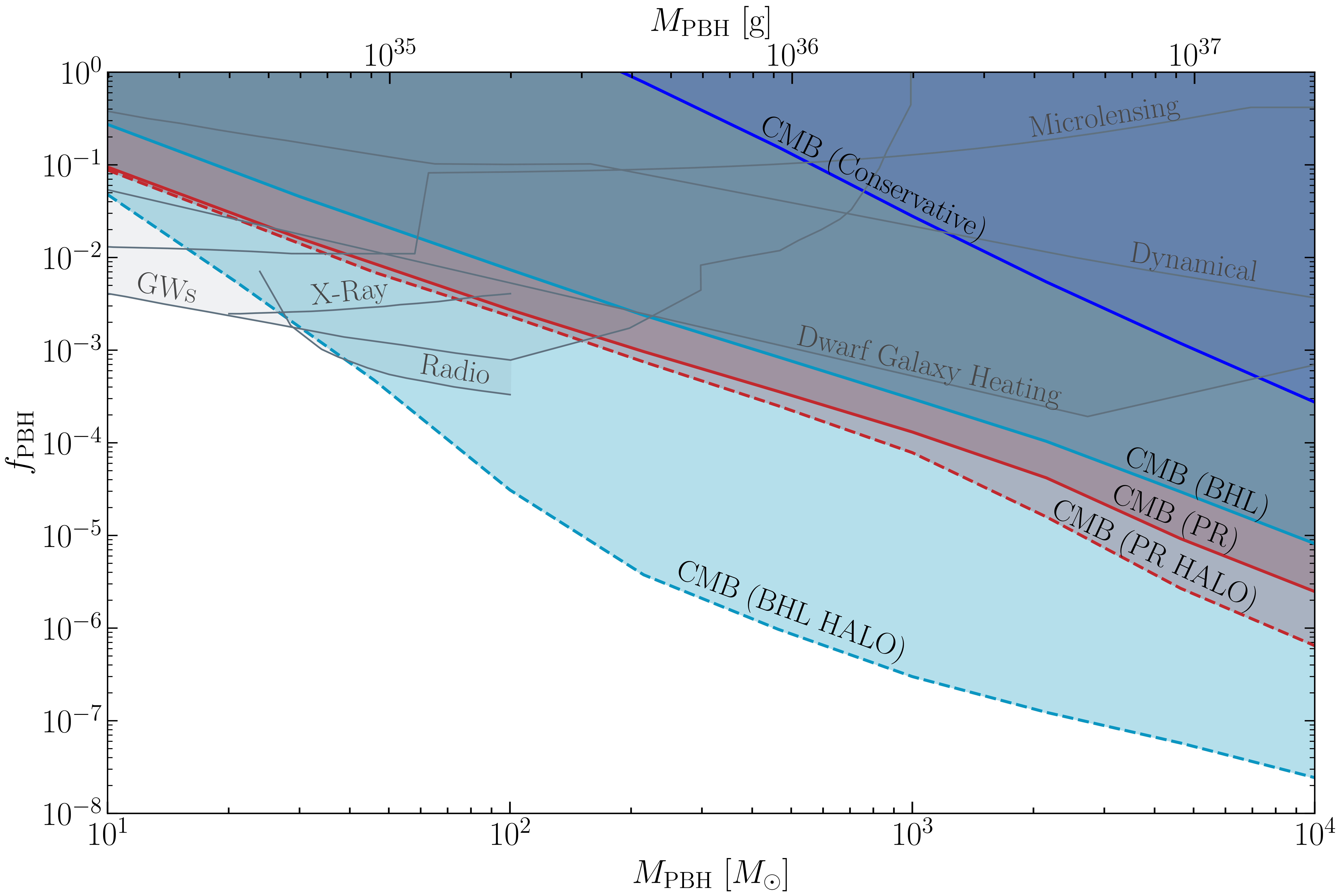
- CMB bound is still the most stringent in this mass range

- There is still a lot of work to do in understanding the theoretical uncertainties of this problem

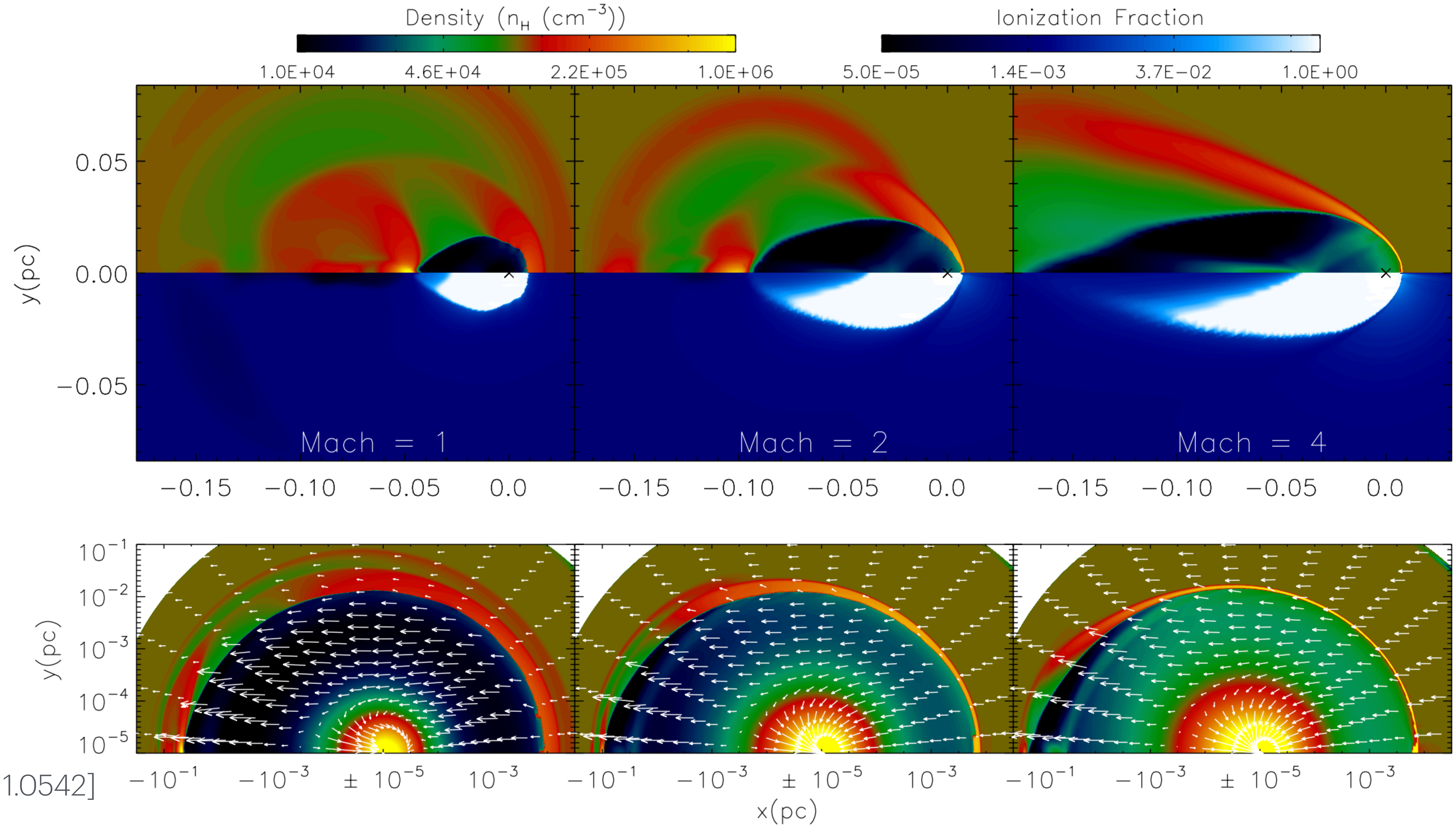
What's next?

- Dedicated hydrodynamical simulations of PR model in cosmology

- Study other systematics



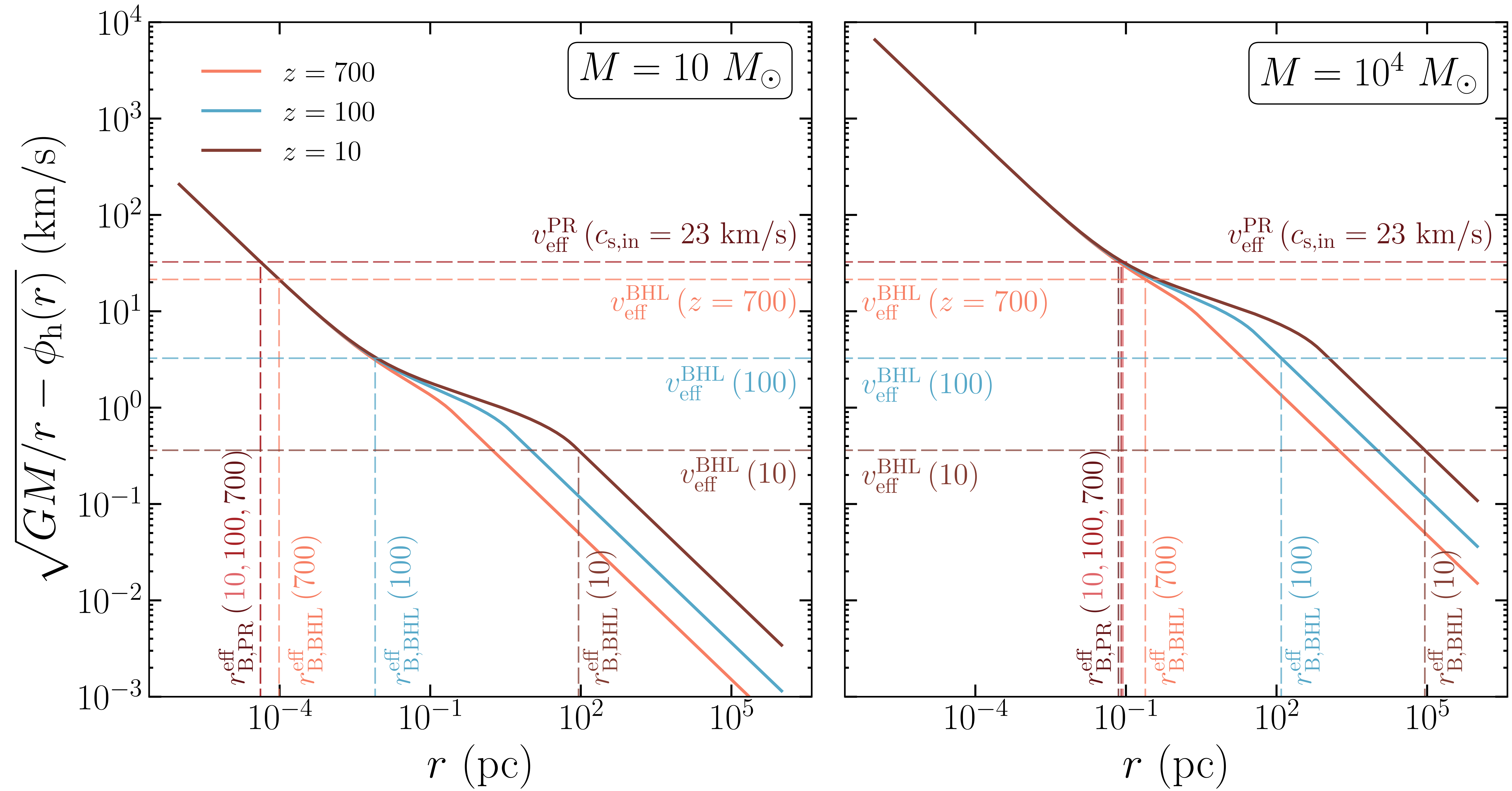
# A1: Park-Ricotti accretion modelling



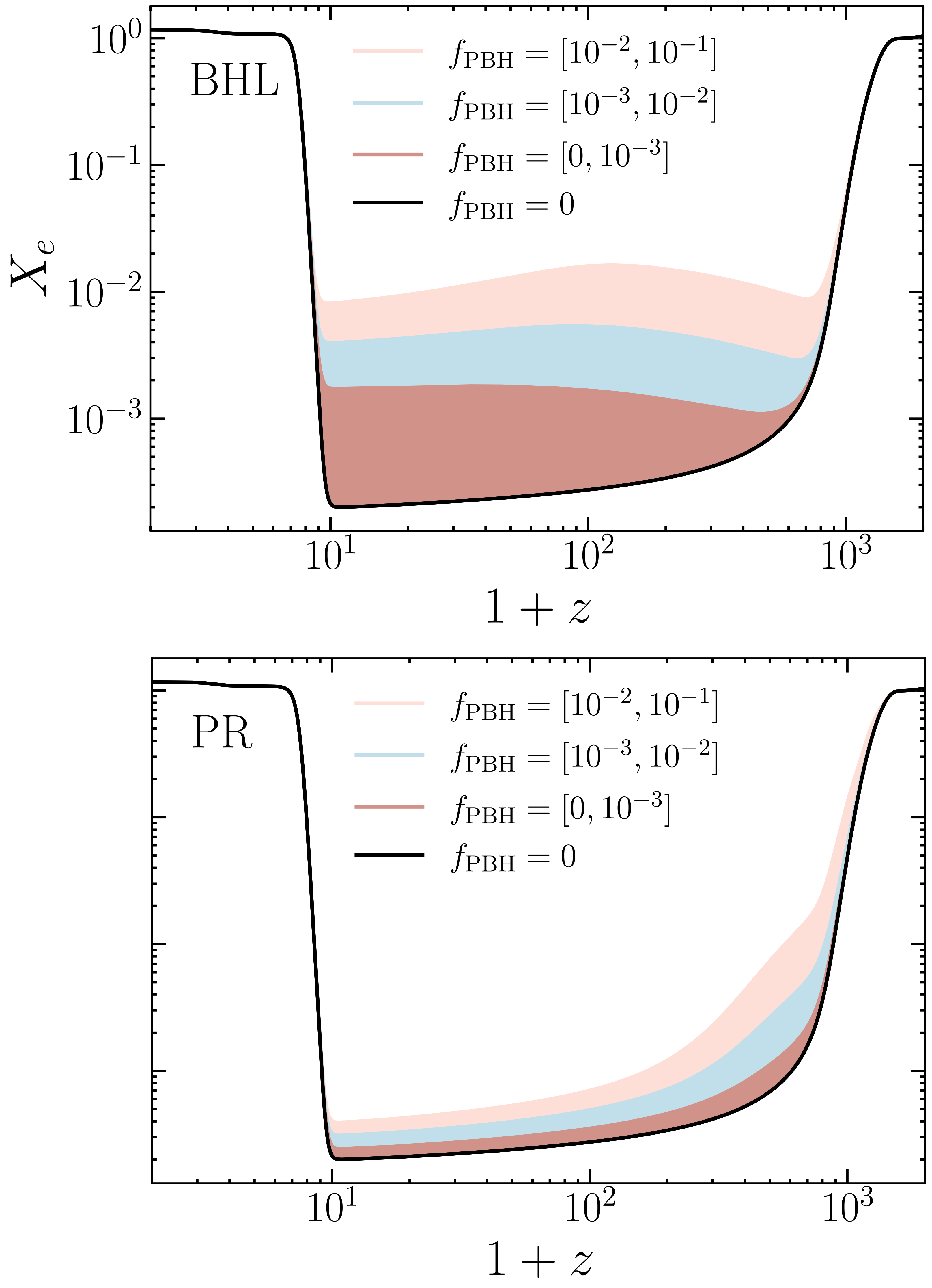
[1211.0542]

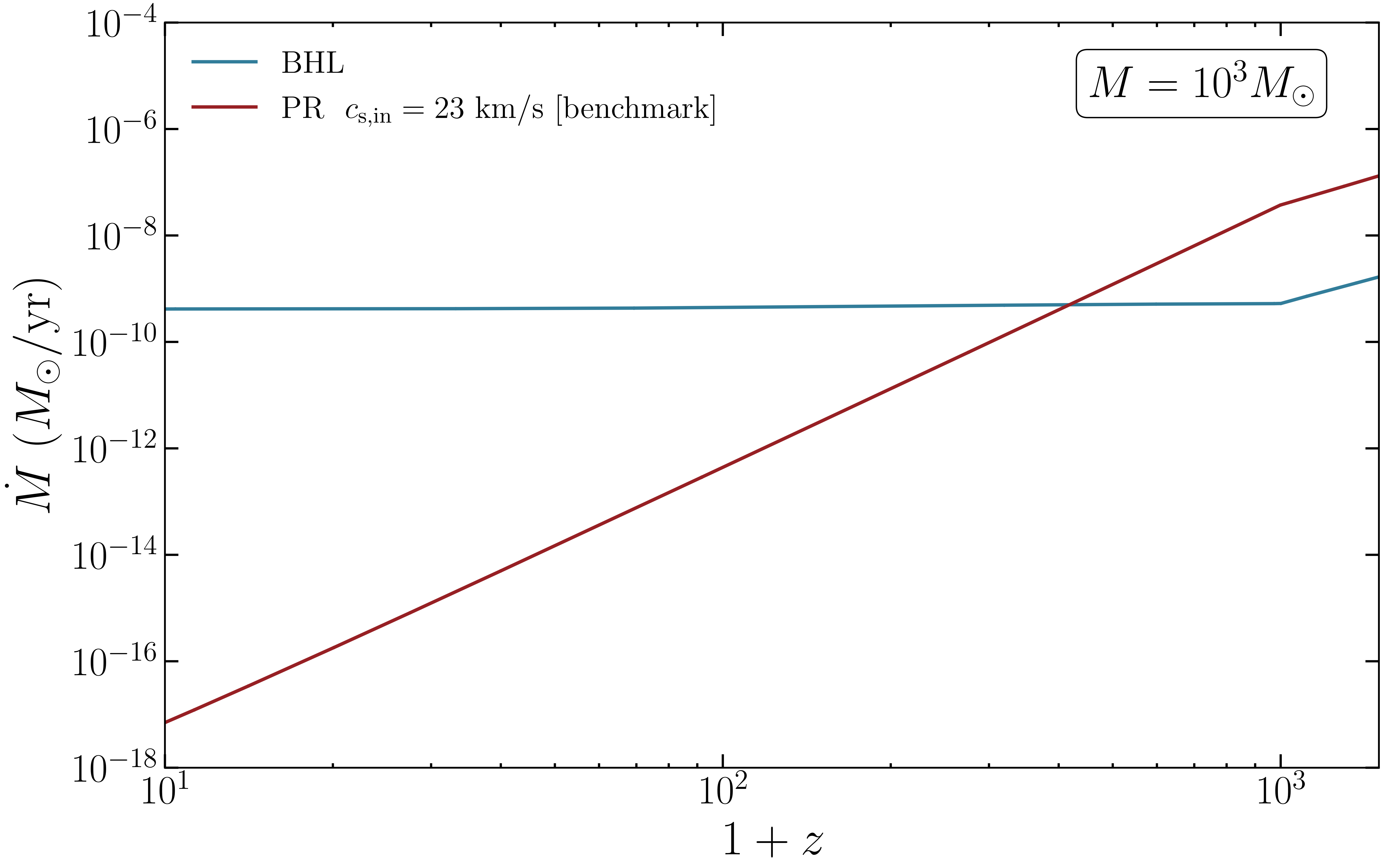
# A2: mini-halos

$$v_{\rm eff}^2 = \frac{GM}{r_{\rm B}^{\rm eff}} - \phi_{\rm h}(r_{\rm B}^{\rm eff})$$



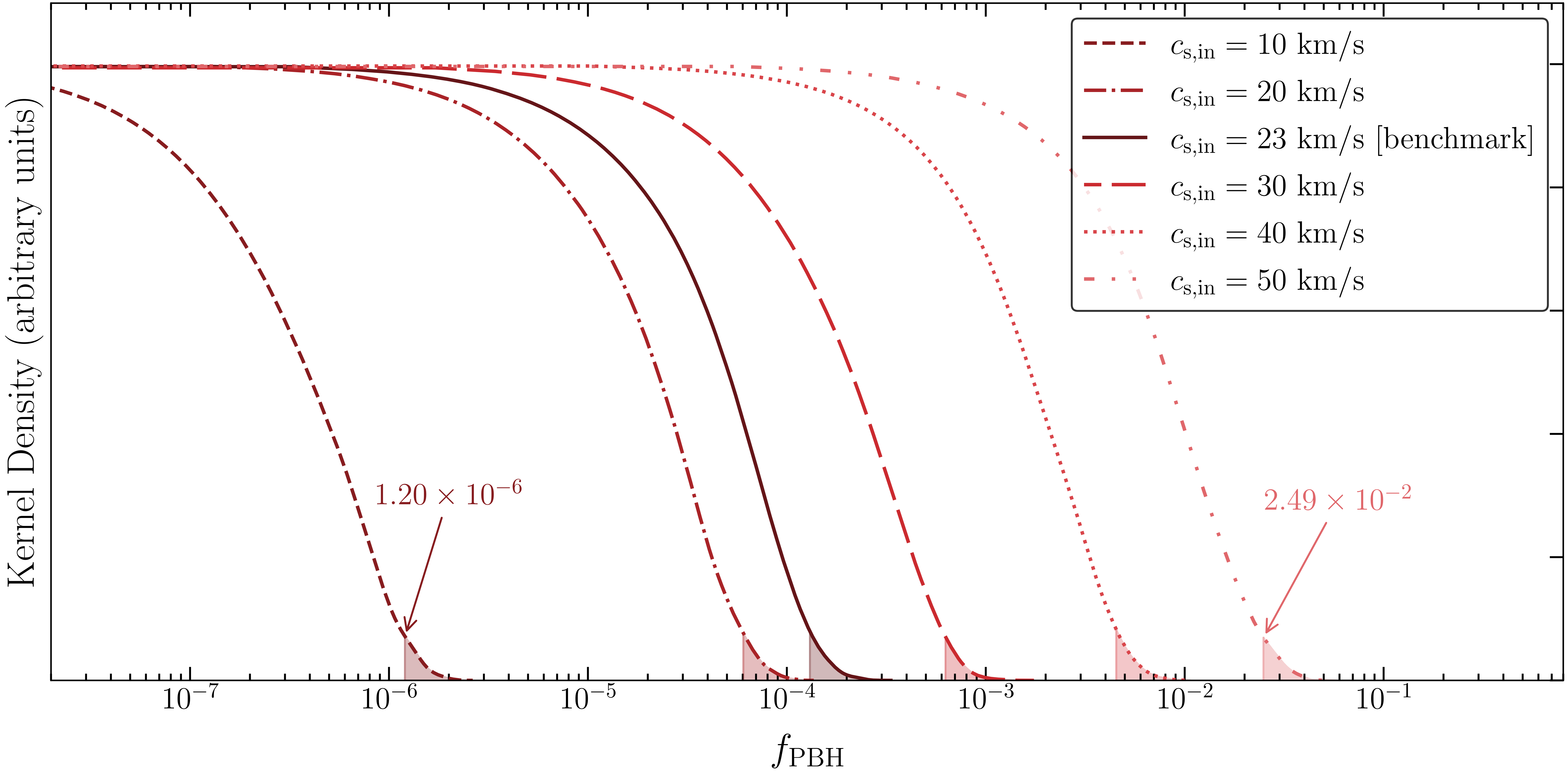
# A3: Why is the bound without halos robust?





# A4: Effect of sound speed $c_{s,in}$

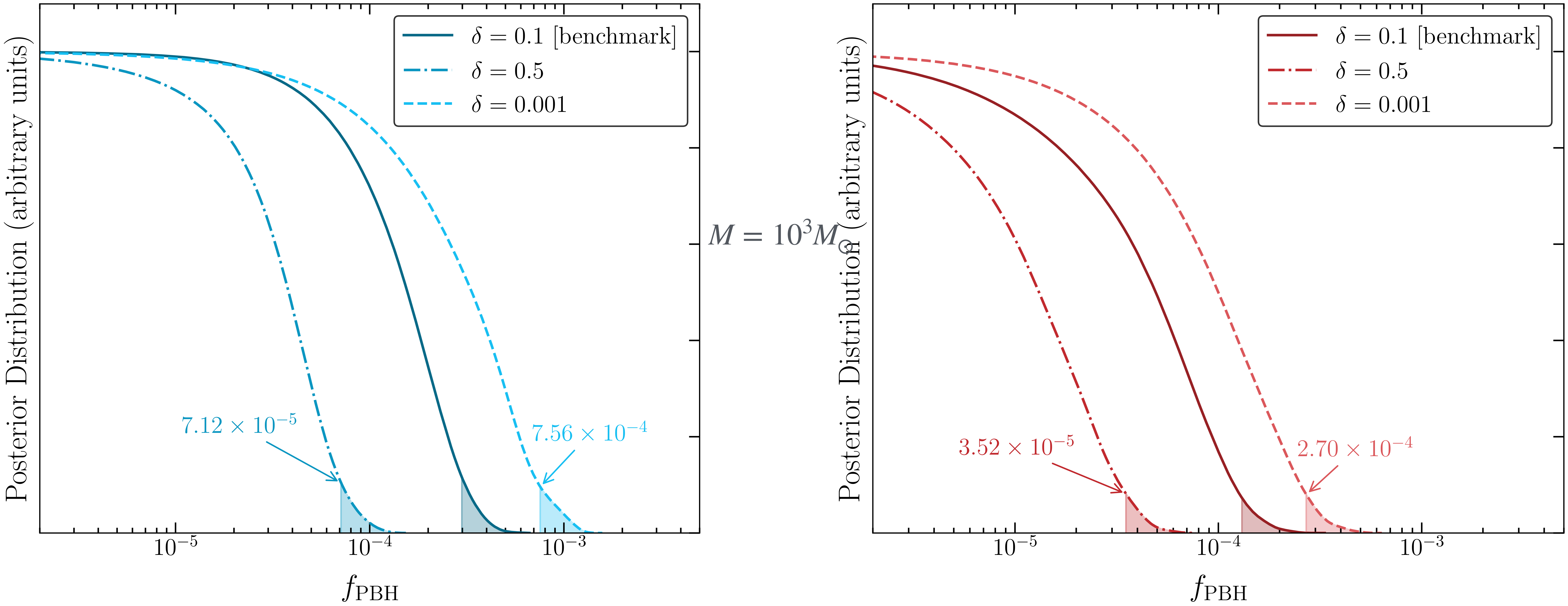
$M = 10^3 M_\odot$



# A5: Effect of delta (efficiency of ADAF disk)

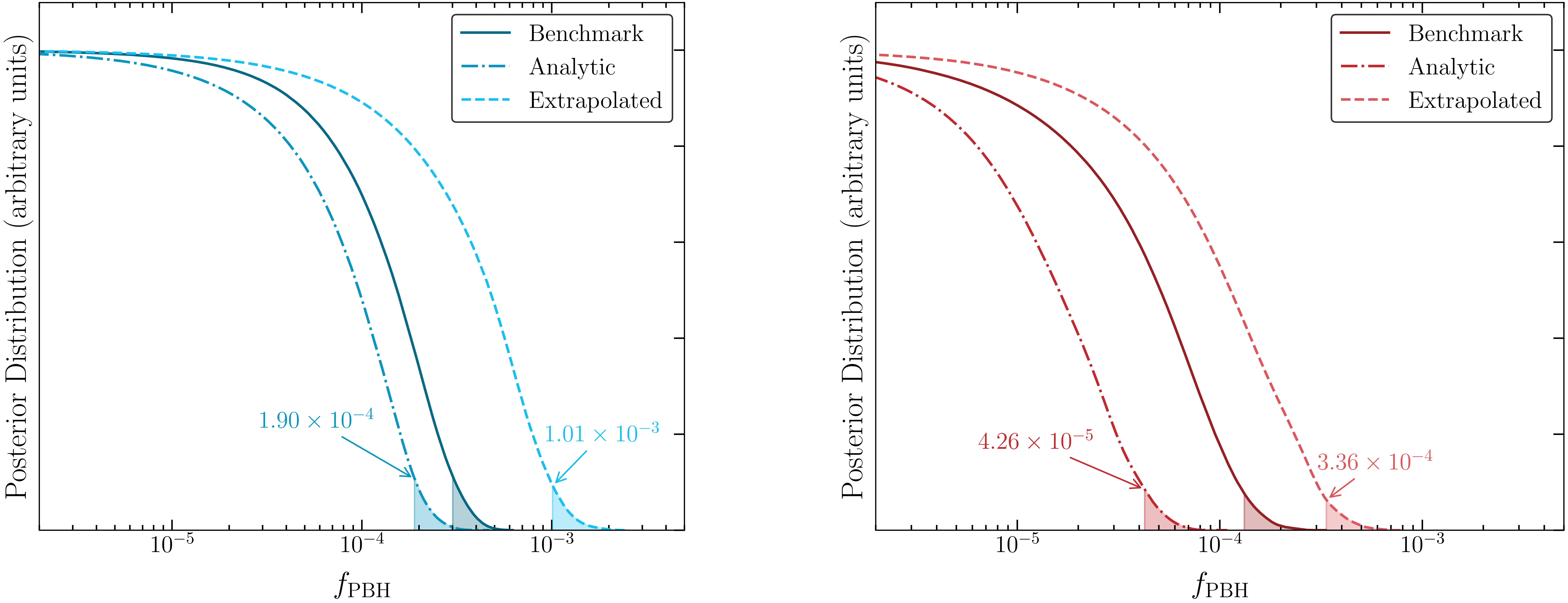
δ ~ % of ions interacting with leptons

$M = 10^3 M_\odot$



# A6: Energy deposition treatment

$M = 10^3 M_\odot$



# DM Halos

- PR model can be understood as a Bondi problem within the ionised region

$$M_{\mathrm{h}} \simeq \frac{3000}{1+z} M$$

$$\rho(r) = \rho_0 \left(\frac{r}{r_{\mathrm{h}}}\right)^{-9/4}$$

$$r_{\mathrm{h}} \simeq 58\,\mathrm{pc}\,(1+z)^{-1}\left(\frac{M_{\mathrm{h}}}{M_\odot}\right)^{1/3}$$

$$\dot{M} = 4\pi\lambda\rho v_{\mathrm{eff}}(r_{\mathrm{B}}^{\mathrm{eff}})^2$$

$$v_{\mathrm{eff}}^{\mathrm{BHL}} = \left(c_{\mathrm{s}}^2 + v_{\mathrm{PBH}}^2\right)^{1/2}$$

$$v_{\mathrm{eff}}^{\mathrm{PR}} = \left(c_{\mathrm{s,in}}^2 + v_{\mathrm{in}}^2\right)^{1/2}$$

$$\boxed{v_{\mathrm{eff}}^2} = \frac{GM}{r_{\mathrm{B}}^{\mathrm{eff}}} - \boxed{\phi_{\mathrm{h}}(r_{\mathrm{B}}^{\mathrm{eff}})}$$

$$v_{\mathrm{eff}}^2 = \begin{cases} \dfrac{GM}{r_{\mathrm{B}}^{\mathrm{eff}}} + \dfrac{GM_{\mathrm{h}}}{(\alpha-2)} \dfrac{1}{r_{\mathrm{B}}^{\mathrm{eff}}} \left[\left(\dfrac{r_{\mathrm{B}}^{\mathrm{eff}}}{r_{\mathrm{h}}}\right)^{3-\alpha} - (3-\alpha)\dfrac{r_{\mathrm{B}}^{\mathrm{eff}}}{r_{\mathrm{h}}}\right], & r_{\mathrm{B}}^{\mathrm{eff}} < r_{\mathrm{h}} \\ \dfrac{GM}{r_{\mathrm{B}}^{\mathrm{eff}}} + \dfrac{GM_{\mathrm{h}}}{r_{\mathrm{B}}^{\mathrm{eff}}}, & r_{\mathrm{B}}^{\mathrm{eff}} \geq r_{\mathrm{h}} \end{cases}$$

# The velocity regimes

- high-velocity regime: $v_{\rm rel} \geq v_{\rm R} \approx 2c_{\rm s,in}$

$$\begin{cases} \rho_{\rm in} = \rho \dfrac{v_{\rm rel}^2 + c_{\rm s}^2 - \sqrt{\Delta}}{2\, c_{\rm s,in}^2}, \\ v_{\rm in} = \dfrac{\rho}{\rho_{\rm in}} v_{\rm rel} \end{cases}$$

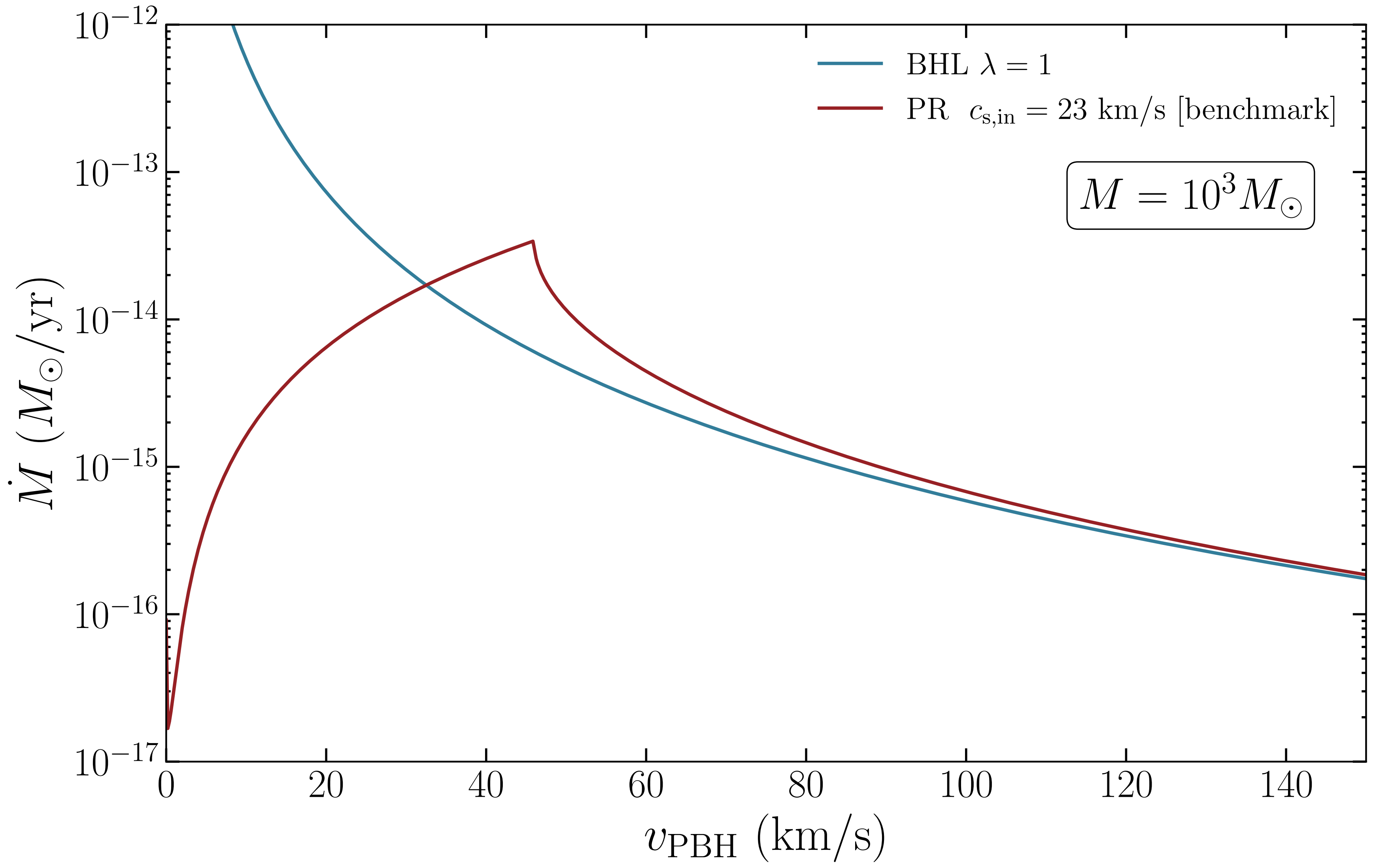
- low-velocity regime: $v_{\rm rel} \leq v_{\rm D} \approx c_{\rm s}^2/(2c_{\rm s,in})$

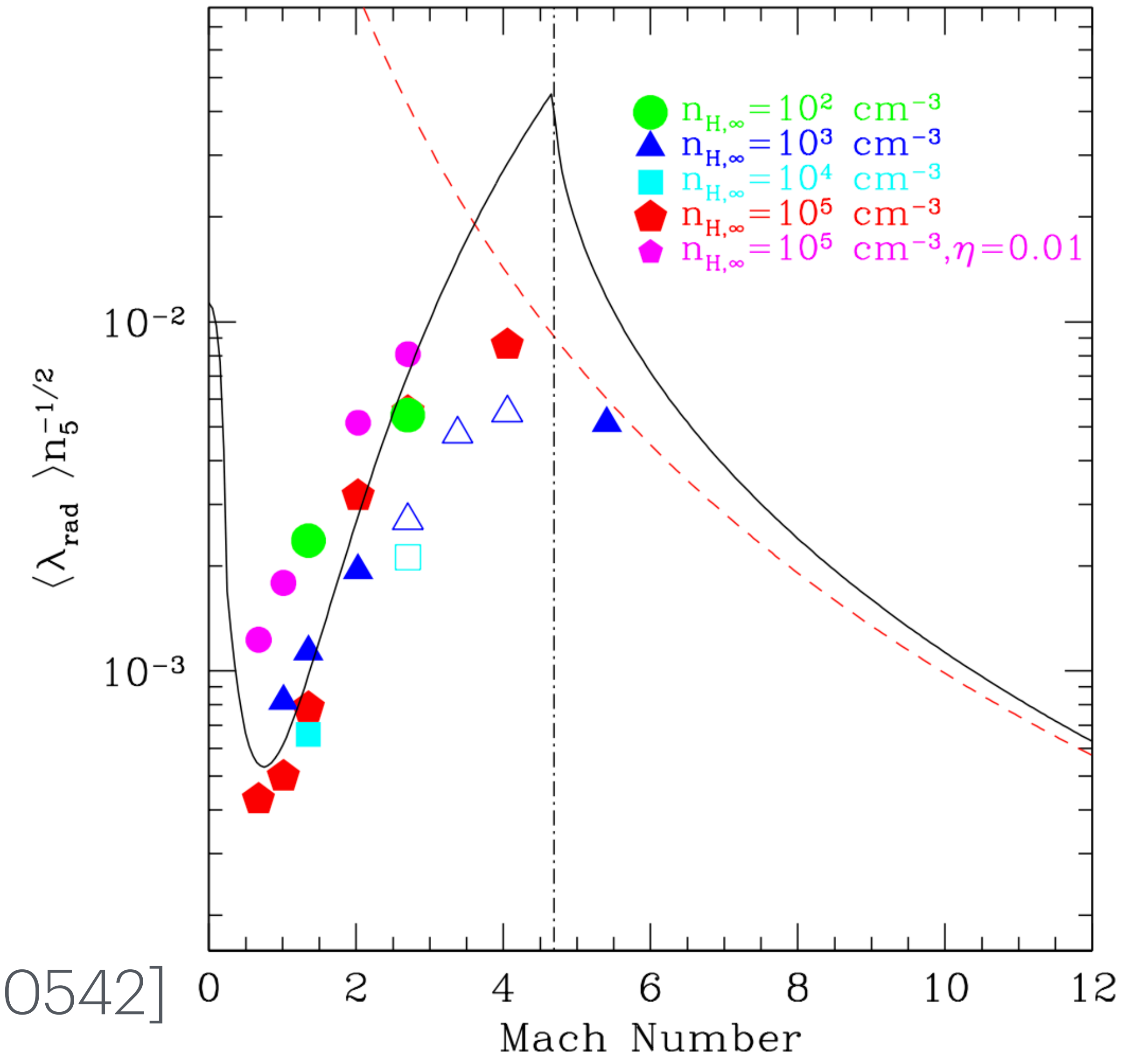
$$\begin{cases} \rho_{\rm in} = \rho \dfrac{v_{\rm rel}^2 + c_{\rm s}^2 + \sqrt{\Delta}}{2\, c_{\rm s,in}^2}, \\ v_{\rm in} = \dfrac{\rho}{\rho_{\rm in}} v_{\rm rel} \end{cases}$$

- intermediate velocity regime (a shock front is formed): $v_{\rm D} < v_{\rm rel} < v_{\rm R}$

$$\begin{cases} \rho_{\rm in} = \rho \dfrac{v_{\rm rel}^2 + c_{\rm s}^2}{2\, c_{\rm s,in}^2}, \\ v_{\rm in} = c_{\rm s,in} \end{cases}$$

$$\Delta = \sqrt{(v_{\rm rel}^2 + c_{\rm s}^2)^2 - 4 v_{\rm rel}^2 c_{\rm s,in}^2}$$





[1211.0542]