Journal Club: Constraints on PBHs from BBN revisited

Based on 2006.03608 by C. Keith, D. Hooper, N. Blinov, and S. D. McDermott

Paul Frederik Depta
22 October 2020
DESY Journal Club

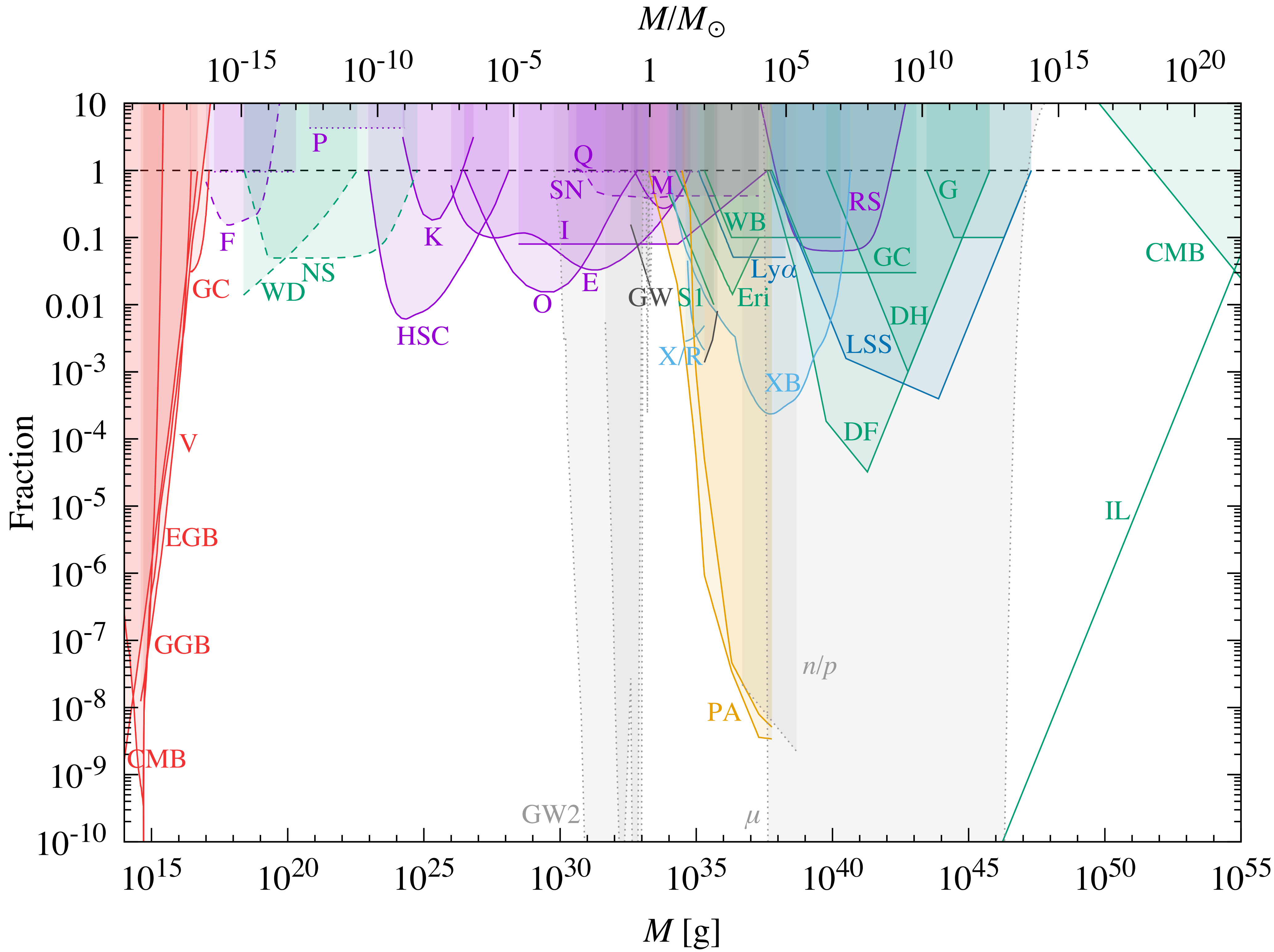
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
erc European Research Council Established by the European Commission
DESY.

Outline

- How does BBN constrain PBHs?
- Recasting BBN constraints on long-lived particles for PBHs
- Going beyond the SM

How does BBN constrain PBHs?

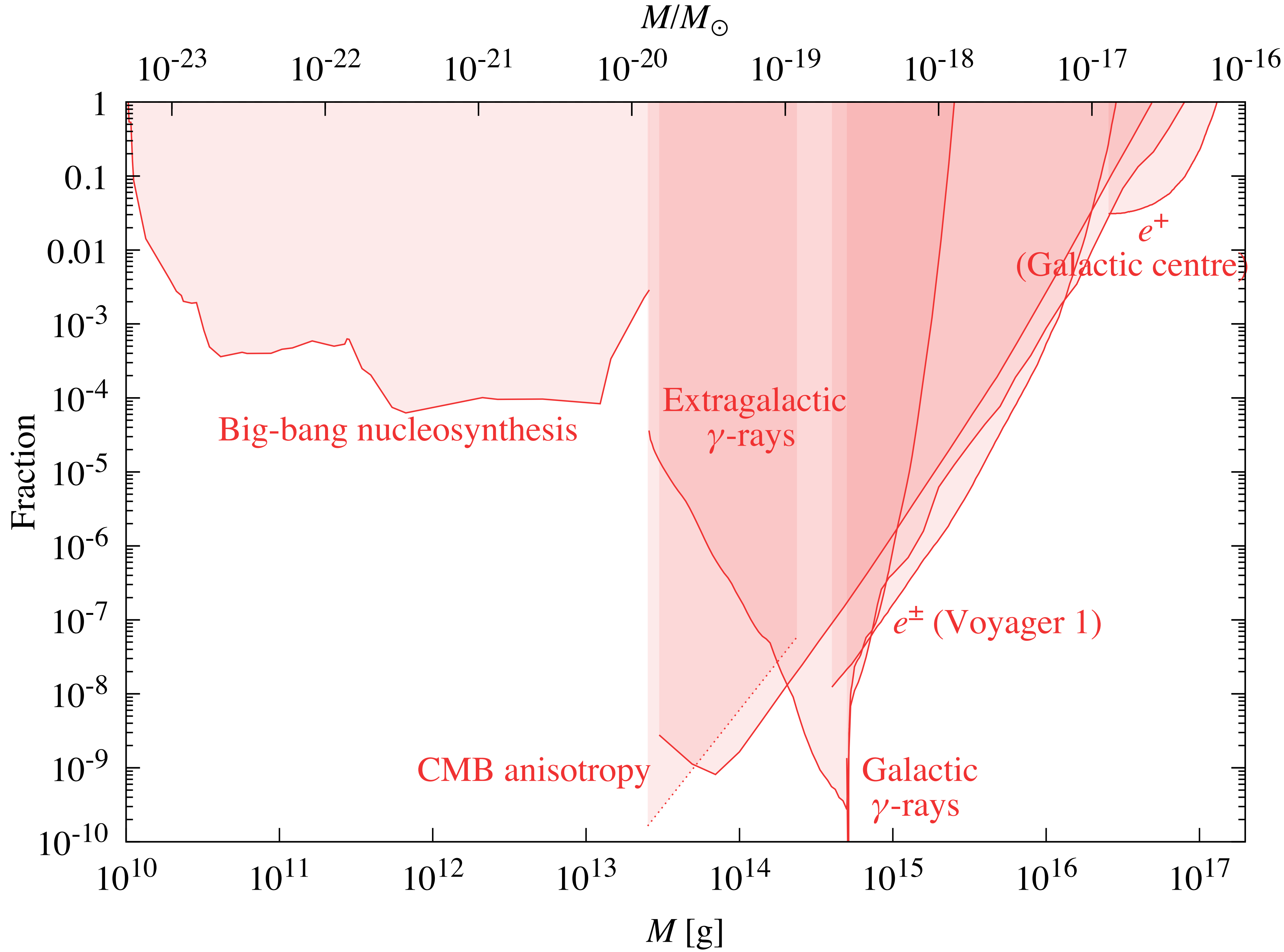
PBH DM constraints



[arXiv: 2002.12778]

How does BBN constrain PBHs?

PBH evaporation constraints



[arXiv: 2002.12778]

How does BBN constrain PBHs?

- PBHs produced via collapse of large density fluctuations, mass roughly comparable to energy enclosed within Hubble horizon at formation

$$M_{\rm hor} = M_{\rm Pl}^2/(2H) \simeq 10^{10}\,{\rm g} \times (10^{11}\,{\rm GeV}/T)^2\,(106.75/g_\star(T))^{1/2}$$

- Hawking radiation leads to mass loss

$$\frac{dM}{dt} = -\frac{\mathcal{G}\, g_{\star,H}(T_{\rm BH}) M_{\rm Pl}^4}{30720\pi M^2} \simeq -8.2\times 10^6\,{\rm g/s} \times (g_{\star,H}(T_{\rm BH})/108)\,(10^{10}\,{\rm g}/M)^2$$

- $\mathcal{G} \approx 3.8$
- $T_{\rm BH} = M_{\rm Pl}^2/(8\pi M) \simeq 1.05\,{\rm TeV} \times (10^{10}\,{\rm g}/M)$
- $g_{\star,H}$ counts d.o.f.s below $\sim T_{\rm BH}$ weighted by 1.82, 1.0, 0.41, or 0.05 for spin 0, 1/2, 1, or 2 (Schwarzschild BH)
  - In principle includes all particle species, depending only on mass and spin
  - SM at $T_{\rm BH} \gg 100\,{\rm GeV}$ ($M \ll 10^{11}$ g): $g_{\star,H} = 108$

How does BBN constrain PBHs?

- Evaporation time

$$t_{\rm evap} = \frac{30720\pi}{\mathcal{G} M_{\rm Pl}^4} \int_0^{M_i} \frac{dM M^2}{g_{\star,H}(T_{\rm BH})} \approx 4.0 \times 10^{12}\,{\rm s} \times (M_i/10^{10}\,{\rm g})^3\,(108/\langle g_{\star,H}\rangle)$$

- Hawking radiation leads to production of SM particles
- If this production happens during BBN this can influence the primordial light element abundances
- BBN gives most stringent constraints for $t_{\rm evap} \sim (10^{-1} - 10^{13})\,{\rm s}$ corresponding to $M \sim (6 \times 10^8 - 2 \times 10^{13})\,{\rm g}$ assuming only SM particle content
- Focus on deuterium and helium-4 abundances

How does BBN constrain PBHs?

- Consider impact of PBH evaporation on BBN in four different ways:
  - Presence of PBHs at neutron-proton conversion freeze-out ($T \sim 1\,\mathrm{MeV}$) leads to earlier freeze-out (Hubble rate larger), more neutrons and thus more helium
  - Hadrons and mesons radiated from PBHs can alter neutron-proton ratio after conversion freeze-out via e.g. $n + \pi^+ \leftrightarrow p + \pi^0$, enhances ratio and helium abundance
  - Photodisintegration of helium via high energetic photons (decreases helium and increases deuterium abundance), only possible if background temperature is too low to absorb disintegrating photon via e^+e^- pair production, $T \lesssim 0.4\,\mathrm{keV}$
  - For $T \gtrsim 0.4\,\mathrm{keV}$ disintegration of helium via hadrodisintegration

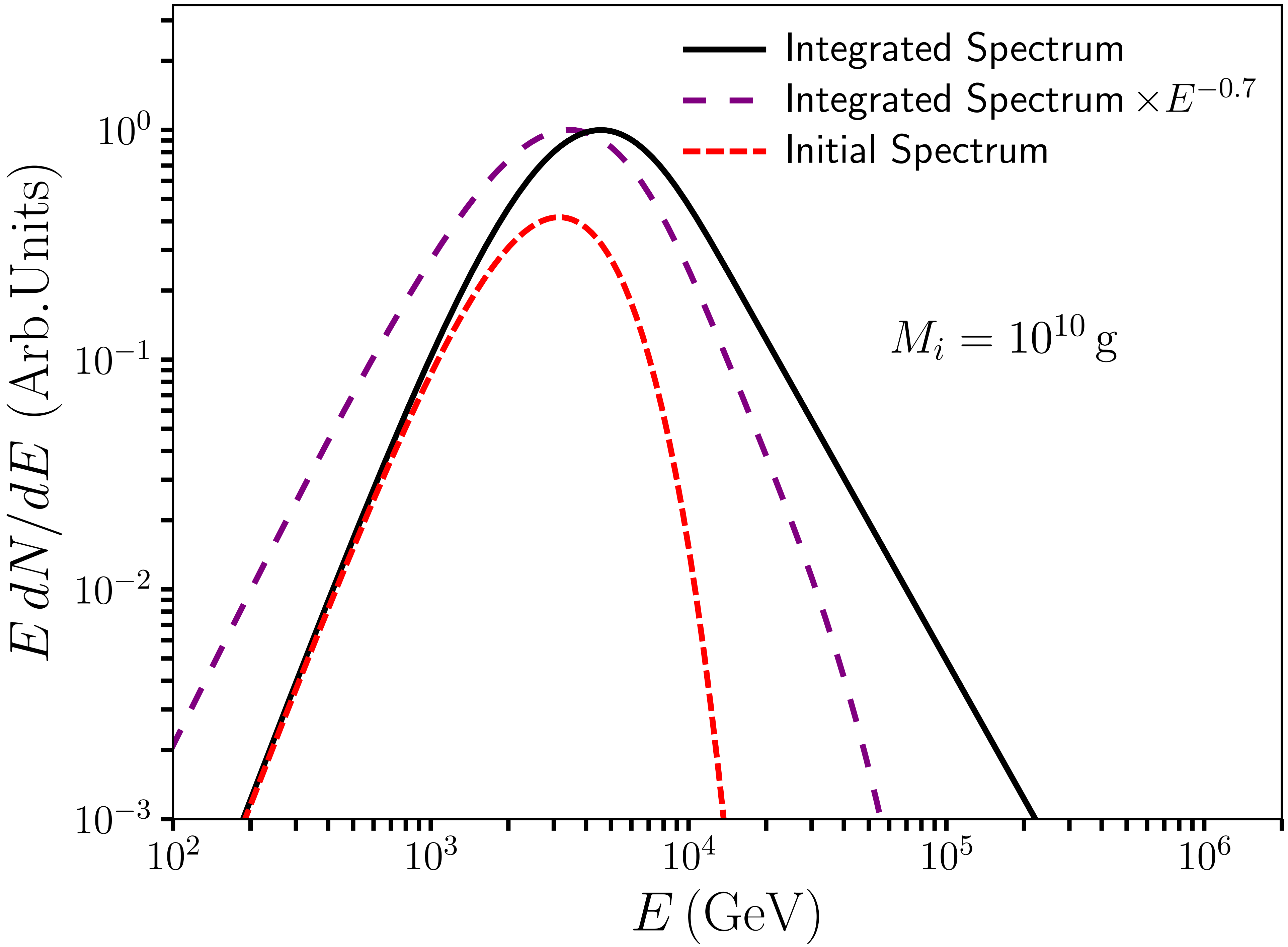
Recasting BBN constraints on LLPs for PBHs

- Assume only SM + PBHs
- Recast limits on long-lived particle decays from Kawasaki et al. [arXiv:1709.01211]
  - Constraints in terms of decaying particle mass times number of particles per unit entropy MY
  - Related to ratio of PBH energy density and SM density via $\beta = \rho_{\rm BH}/\rho = 4MY/(3T_{\rm form})$
- Idea: relate spectra of decay products from PBH evaporation to that of LLP decays

Recasting BBN constraints on LLPs for PBHs

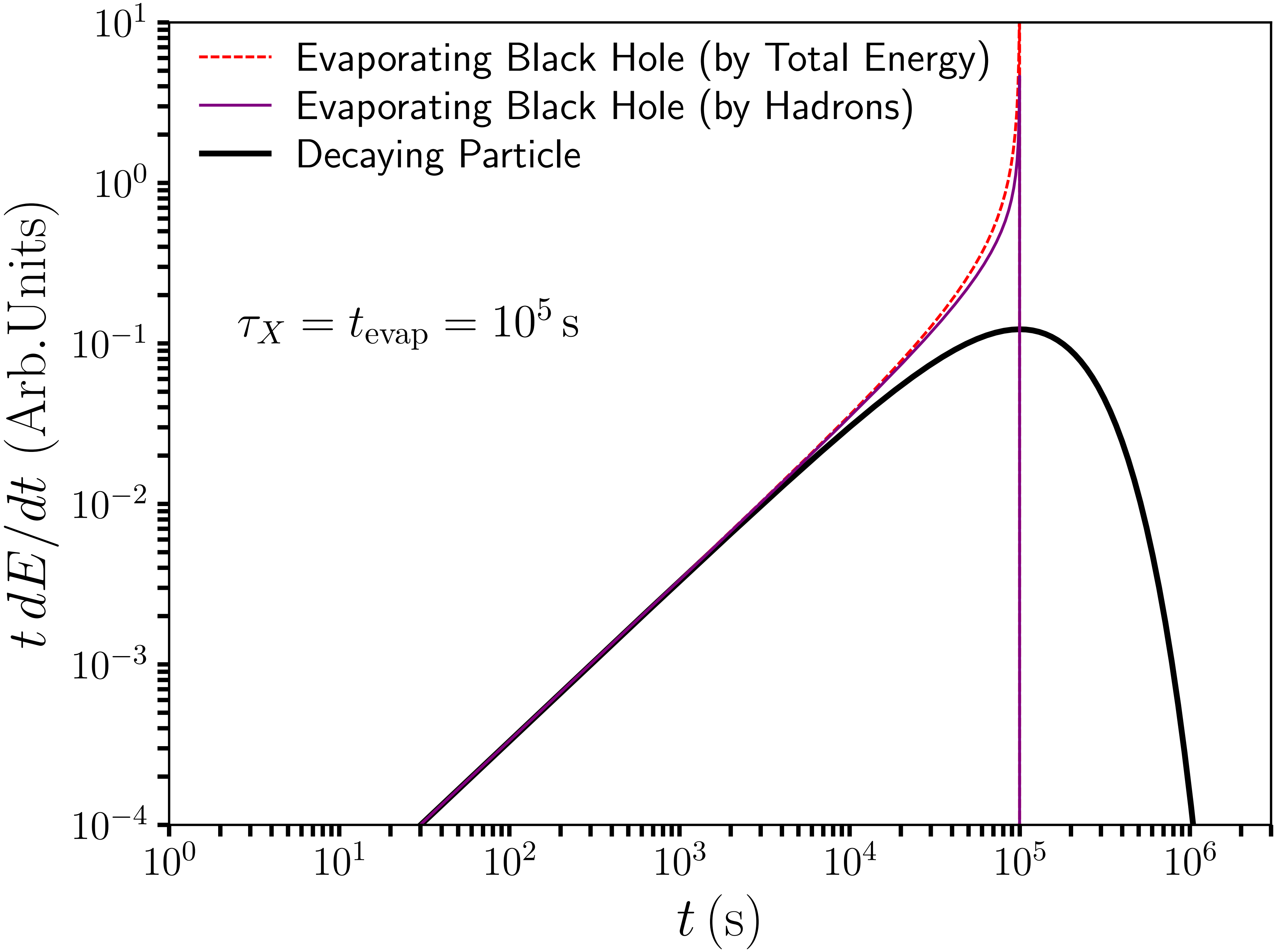
- 73% of total energy goes into quarks and gluons, 94.5% in particles other than neutrinos $\Rightarrow$ reduce decay rate by corresponding factor (hadro- or photodisintegration)
- Injected energy sets constraint from photodisintegration:
  - Over course of evaportation mean energy of radiated fermion $\langle E_q \rangle \simeq 6.3 T_{\mathrm{BH},i}$ ($m_X/2$ for LLP decay) as Hawking radiation produces approximately thermal spectrum of particles $\Rightarrow$ Approximate spectrum with the one from LLP with $m_X = 12.6 T_{\mathrm{BH},i}$
  - Shift LPP lifetime by factor of 0.79 to match time of mean unit of energy release
- Number of injected energetic hadrons sets constraint from hadrodisintegration:
  - Average hadron is produced by quark with energy $\langle E_q \rangle \simeq 3.7 T_{\mathrm{BH},i} \Rightarrow$ Approximate spectrum with the one from LLP with $m_X = 7.4 T_{\mathrm{BH},i}$
  - Shift LLP lifetime by 1.03 to match median hadron injection

Recasting BBN constraints on LLPs for PBHs



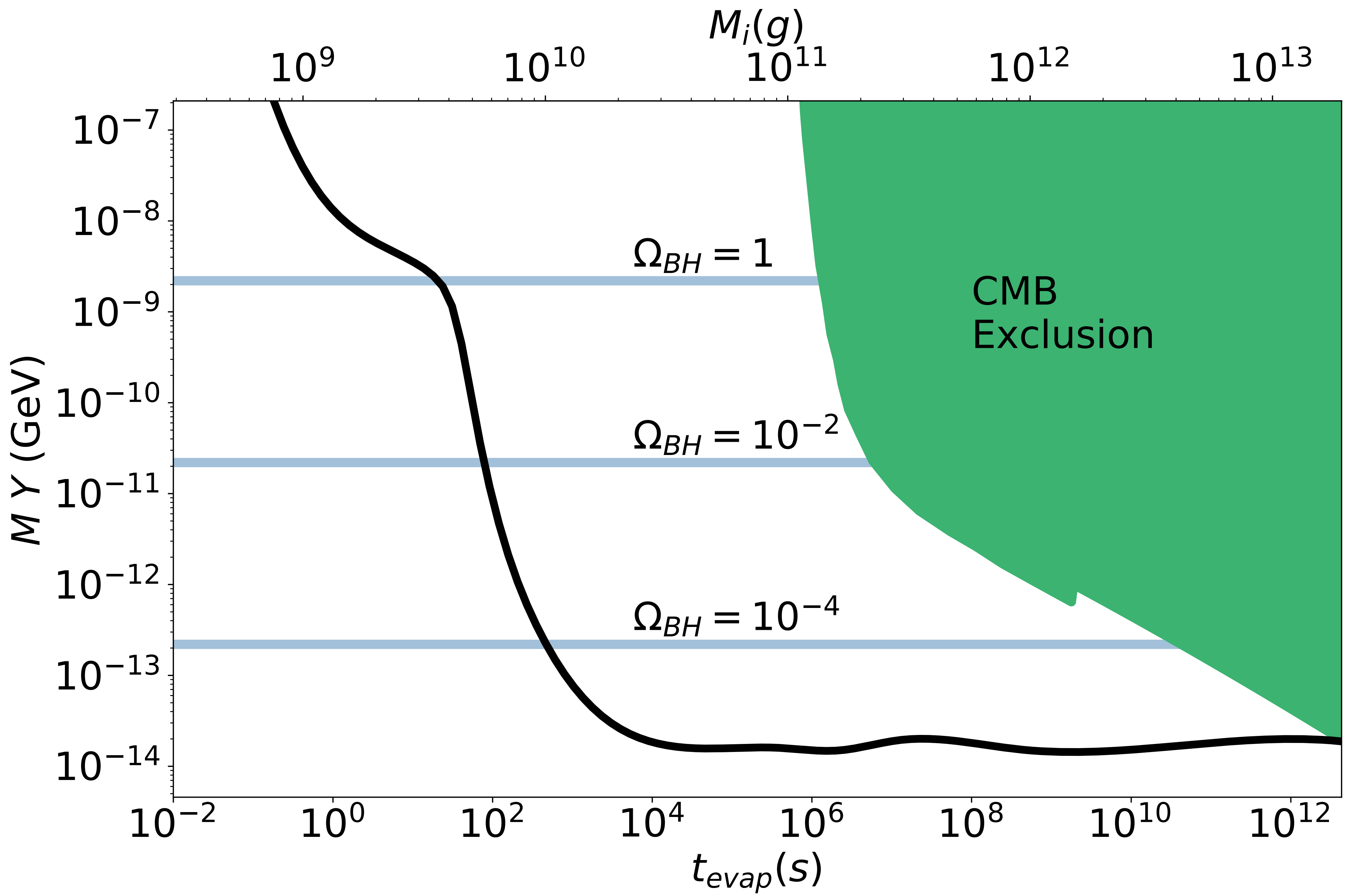
[arXiv: 2006.03608]

Recasting BBN constraints on LLPs for PBHs



[arXiv: 2006.03608]

Recasting BBN constraints on LLPs for PBHs



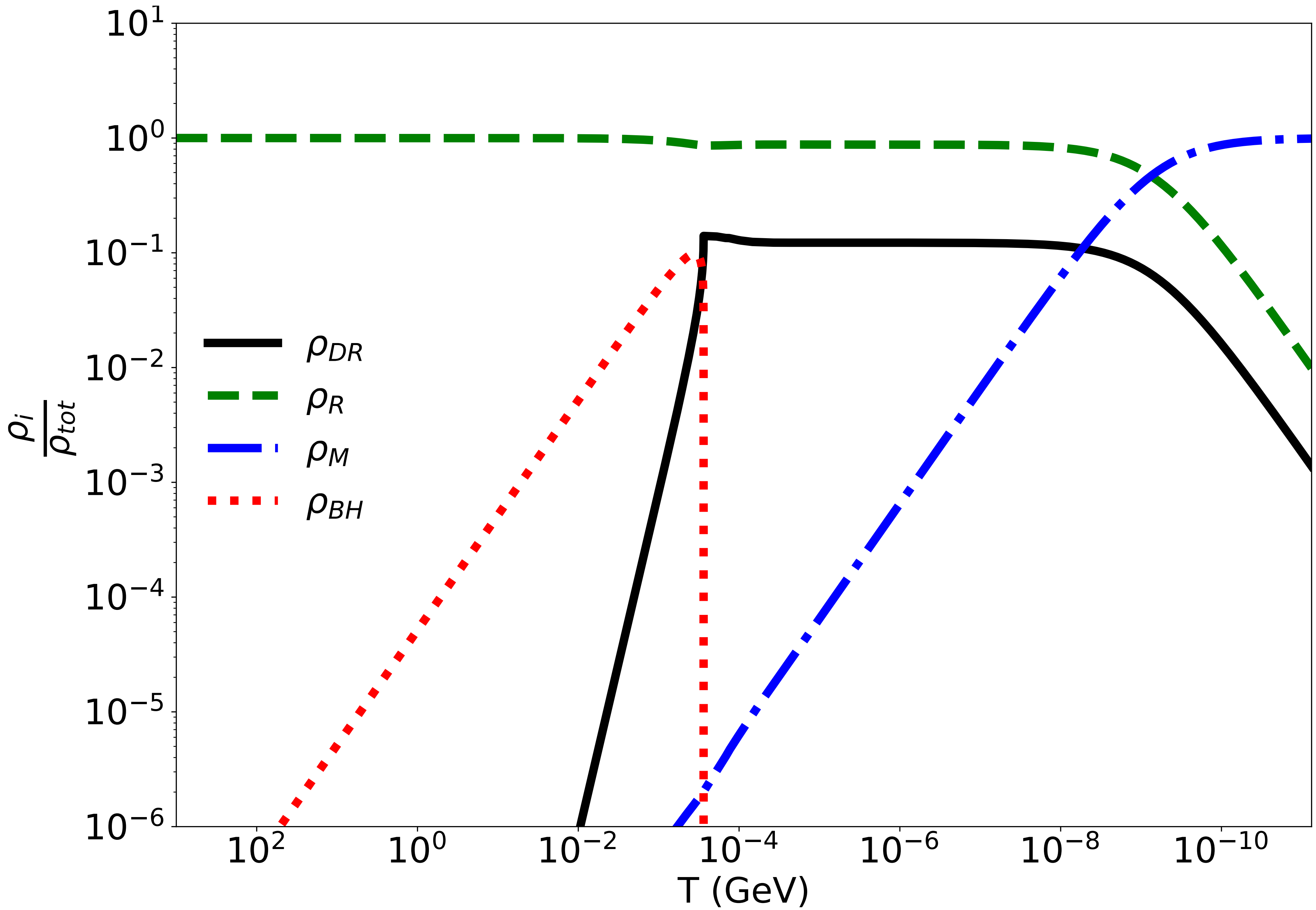
[arXiv: 2006.03608]

Going beyond the SM

- Why?
- Mass loss due to Hawking radiation depends on (effective number of relativistic) d.o.f.s including entire particle spectrum $dM/dt = -\mathcal{G} g_{\star,H}(T_{\rm BH}) M_{\rm Pl}^4/(30720\pi M^2)$
- Solve system of differential equations
- $$\frac{d\rho_{\rm BH}}{dt} = -3H\rho_{\rm BH} + \frac{\rho_{\rm BH}}{M}\frac{dM}{dt}$$
- $$\frac{d\rho_{\rm SM}}{dt} = -3(w_{\rm SM}+1)H\rho_{\rm SM} - (1-f_d)\frac{\rho_{\rm BH}}{M}\frac{dM}{dt}$$
- $$\frac{d\rho_d}{dt} = -3(w_d+1)H\rho_d - f_d\frac{\rho_{\rm BH}}{M}\frac{dM}{dt}$$
- BBN calculation with AlterBBN (no photo- or hadrodisintegration since evaporation mostly in hidden sector, $f_d \approx 1$)

Going beyond the SM

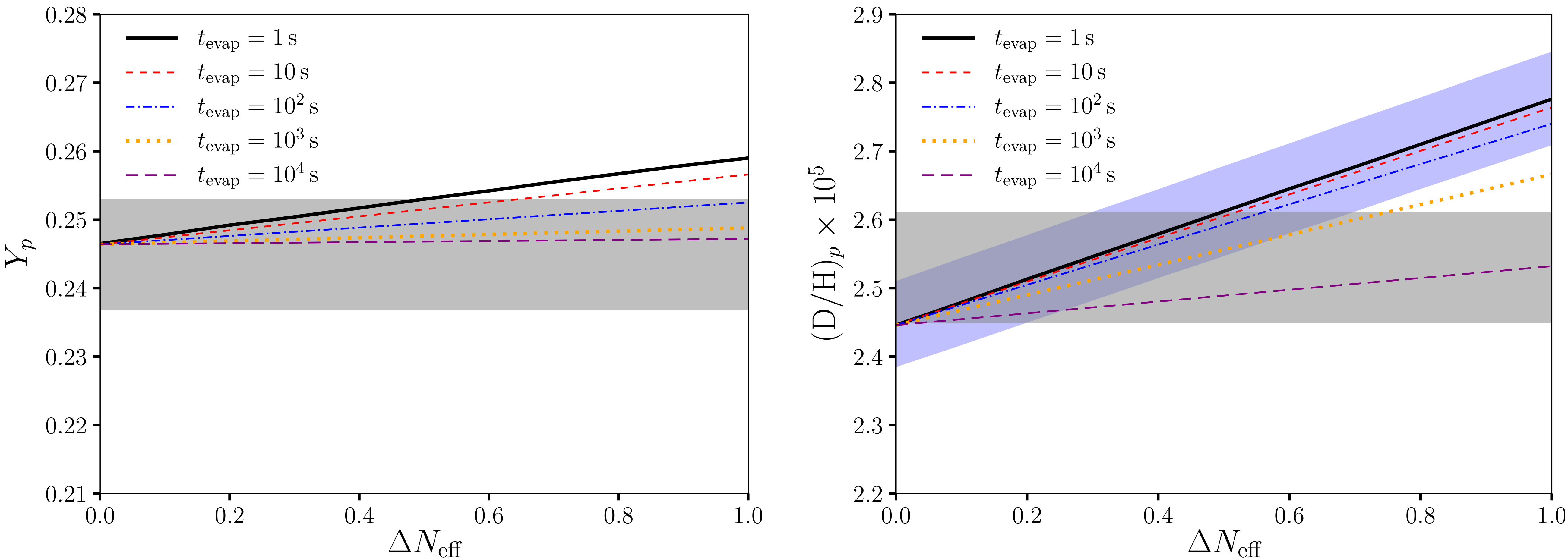
Light hidden sectors, $w_d = 1/3, f_d \approx 1, t_{\rm evap} = 10\,{\rm s}, \Omega_{\rm BH} = 2.6 \times 10^4$



[arXiv: 2006.03608]

Going beyond the SM

Light hidden sectors, $w_d = 1/3$, $f_d \approx 1$

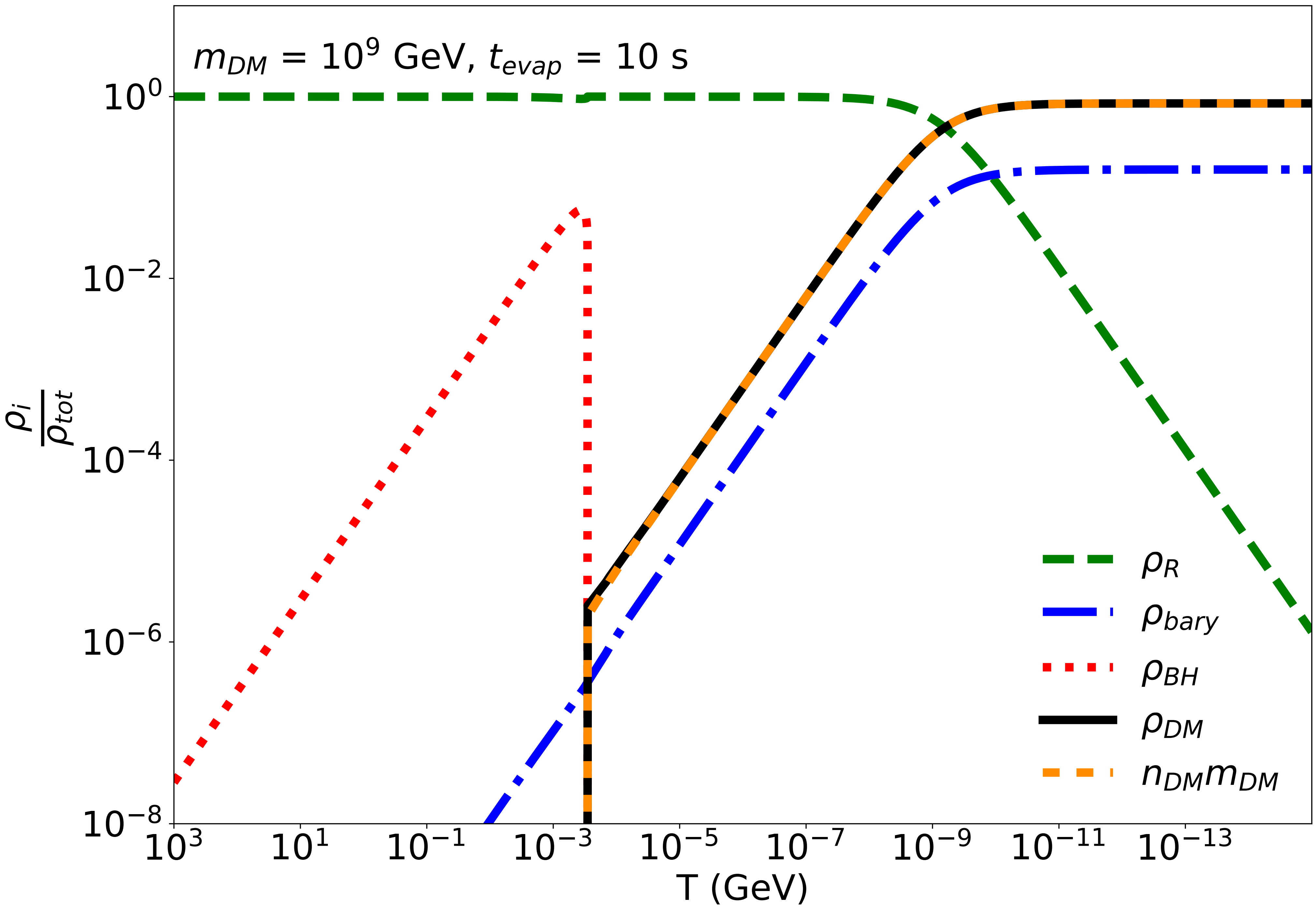


[arXiv: 2006.03608]

$$\Delta N_{\rm eff} \approx 1.0 \times \left(\frac{\Omega_{\rm BH}}{2.6\times 10^4}\right)\left(\frac{t_{\rm evap}}{10\,{\rm s}}\right)^{1/2}\left(\frac{10}{g_\star(T_{\rm evap})}\right)\left(\frac{g_{\star,S}(T_{\rm evap})}{10}\right)^{4/3}$$

Going beyond the SM

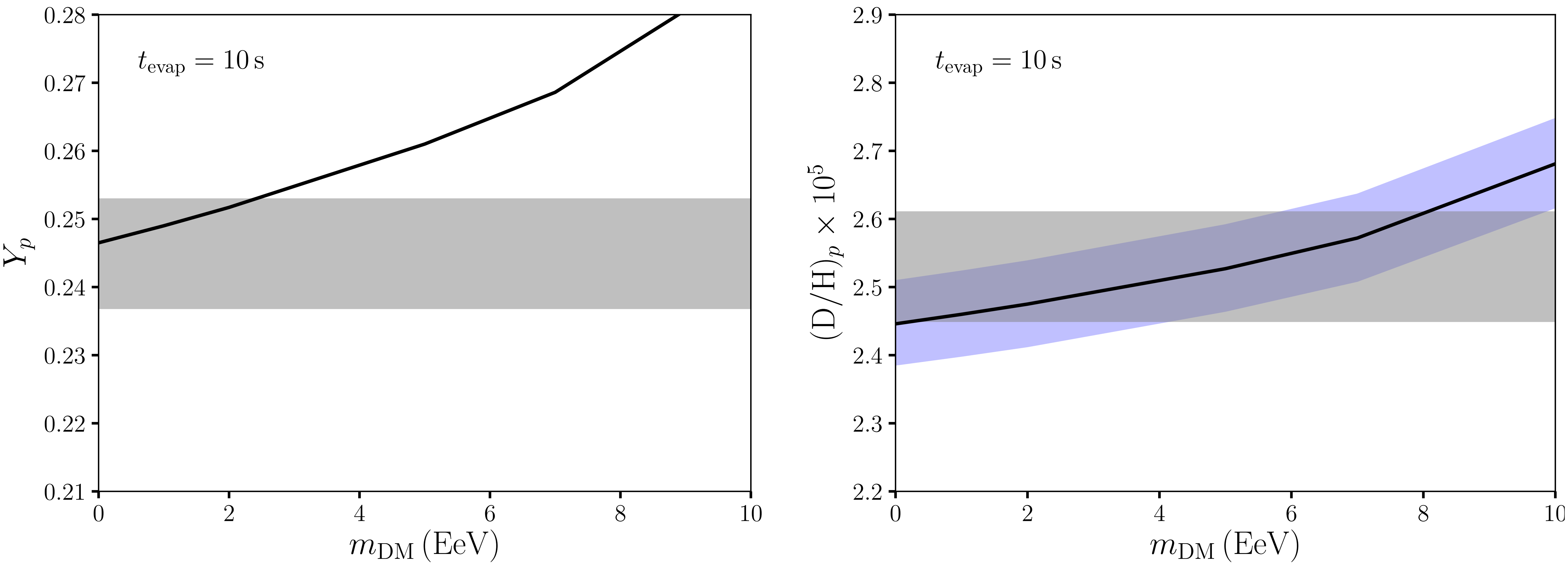
Heavy hidden sectors as DM, $g_{\star,H} = 10^6$ for $T_{\rm BH} \gg m_{\rm DM}$



[arXiv: 2006.03608]

Going beyond the SM

Heavy hidden sectors as DM, $g_{\star,H} = 10^6$ for $T_{\mathrm{BH}} \gg m_{\mathrm{DM}}$



[arXiv: 2006.03608]

Going beyond the SM

TeV-scale SUSY

- MSSM: $g_{\star,H} = 316$ for $T_{\mathrm{BH}} \gg m_{\mathrm{SUSY}}$
- Consider $m_{\mathrm{SUSY}} \sim 2\,\mathrm{TeV}$
- Can lower evaporation time, e.g. for $M \sim 5 \times 10^9\,\mathrm{g}$ from 50 s to 17 s, relaxes constraints for masses similar and lower by a factor $\sim 2-3$
- R-parity conserved ⇒ produced SUSY particles decay to lightest SUSY particle (LSP)
- This can produce observed DM abundance e.g. if $m_{\mathrm{SUSY}} = 2\,\mathrm{TeV}$, $m_{\mathrm{LSP}} = 1\,\mathrm{TeV}$, $M = 5 \times 10^9\,\mathrm{g}$, and $\beta' \simeq 10^{-20}$

Summary

- BBN can constrain PBHs evaporating via Hawking radiation
- Constraints in principle depend on complete particle spectrum, also BSM
- Opens up additional phenomenological opportunities, see also e.g. [arXiv:1905.01301, 2004.14773, 2010.01134]

Thank you