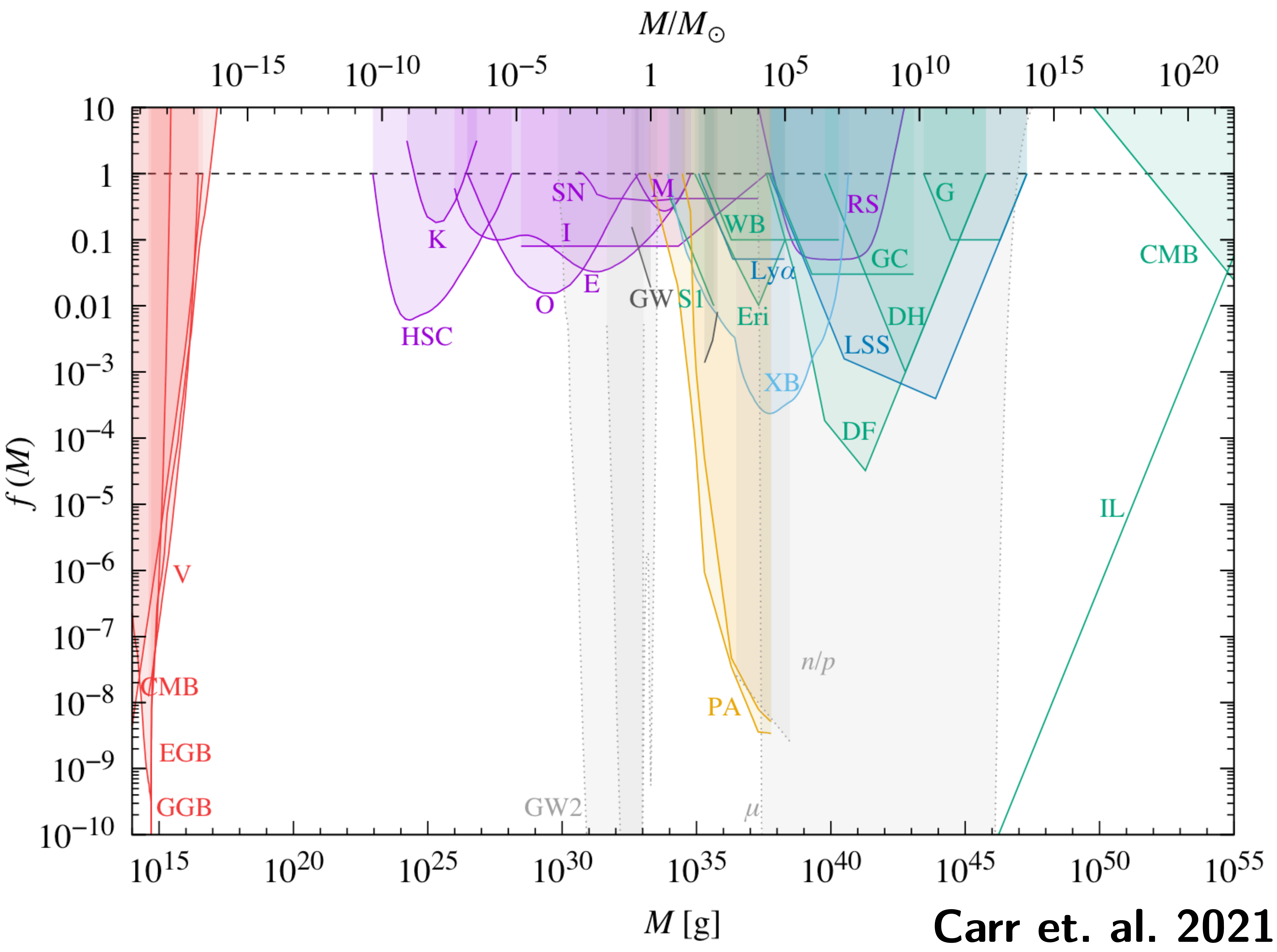
New Mass Window for light Primordial Black Holes as a Dark Matter candidate

Valentin Thoss, Andreas Burkert, Kazunori Kohri

arXiv:2402.17823

NEHOP 24, Edinburgh, 06/2024

Constraints on the dark matter fraction of PBH



Carr et. al. 2021

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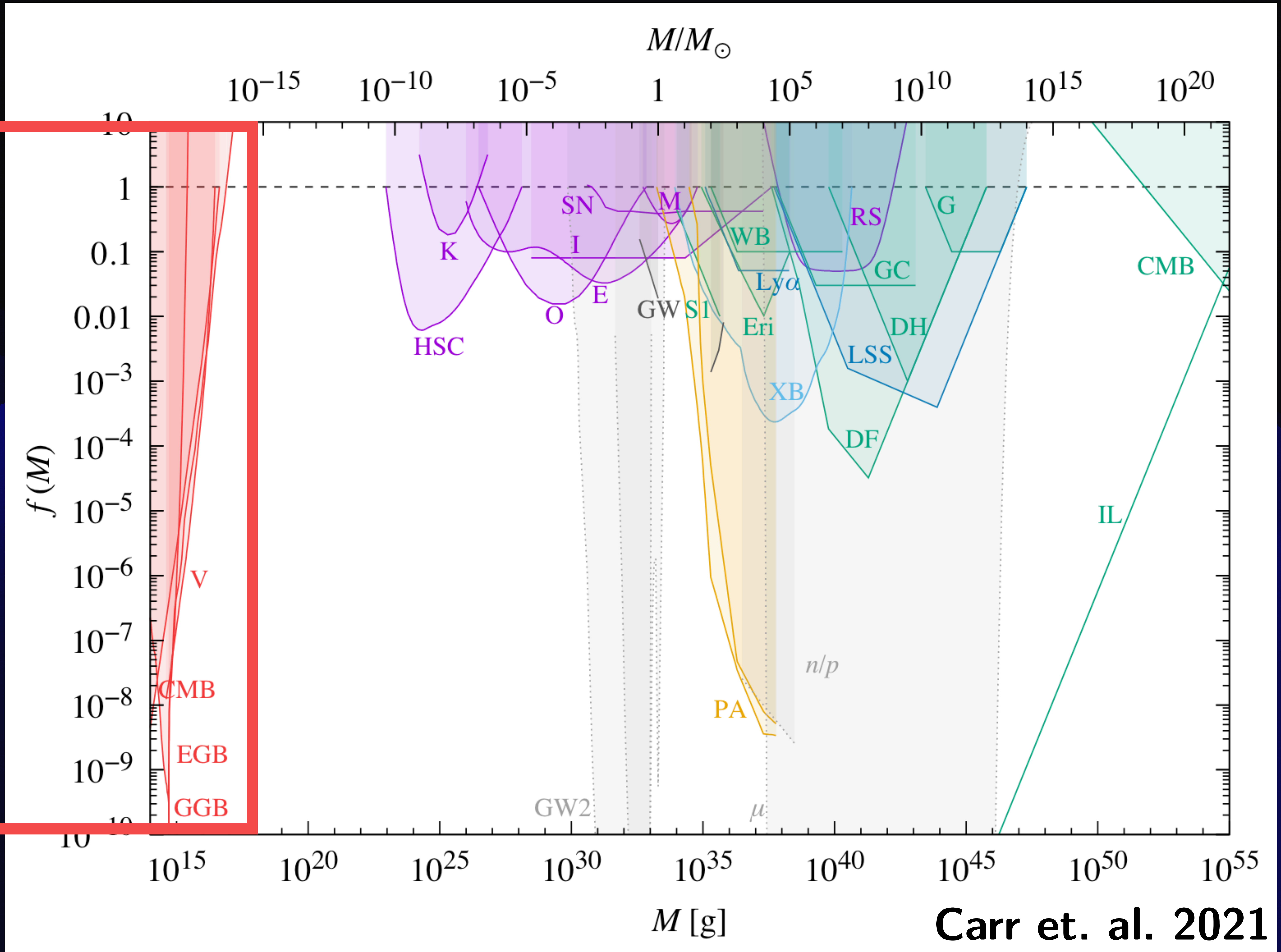
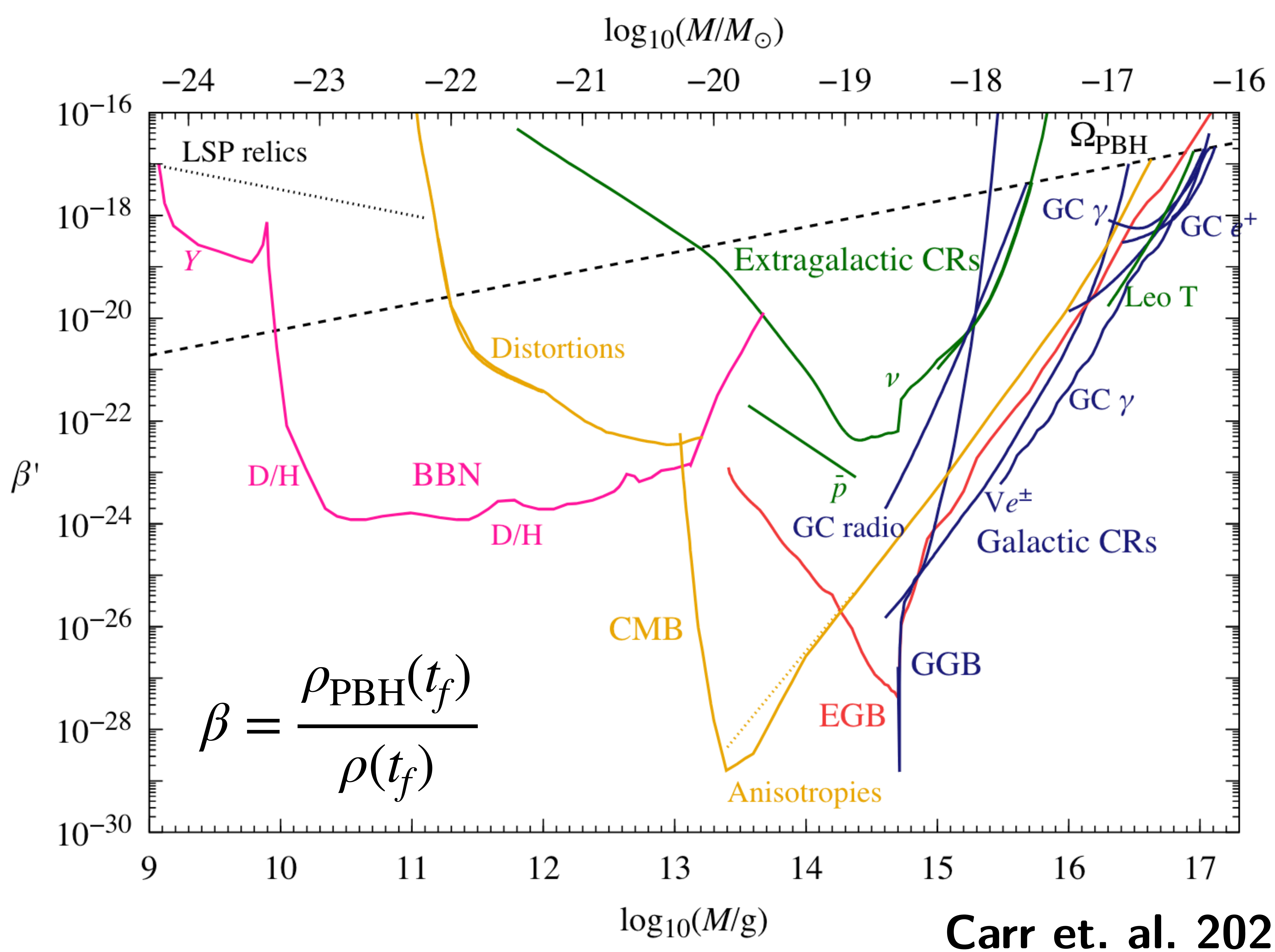
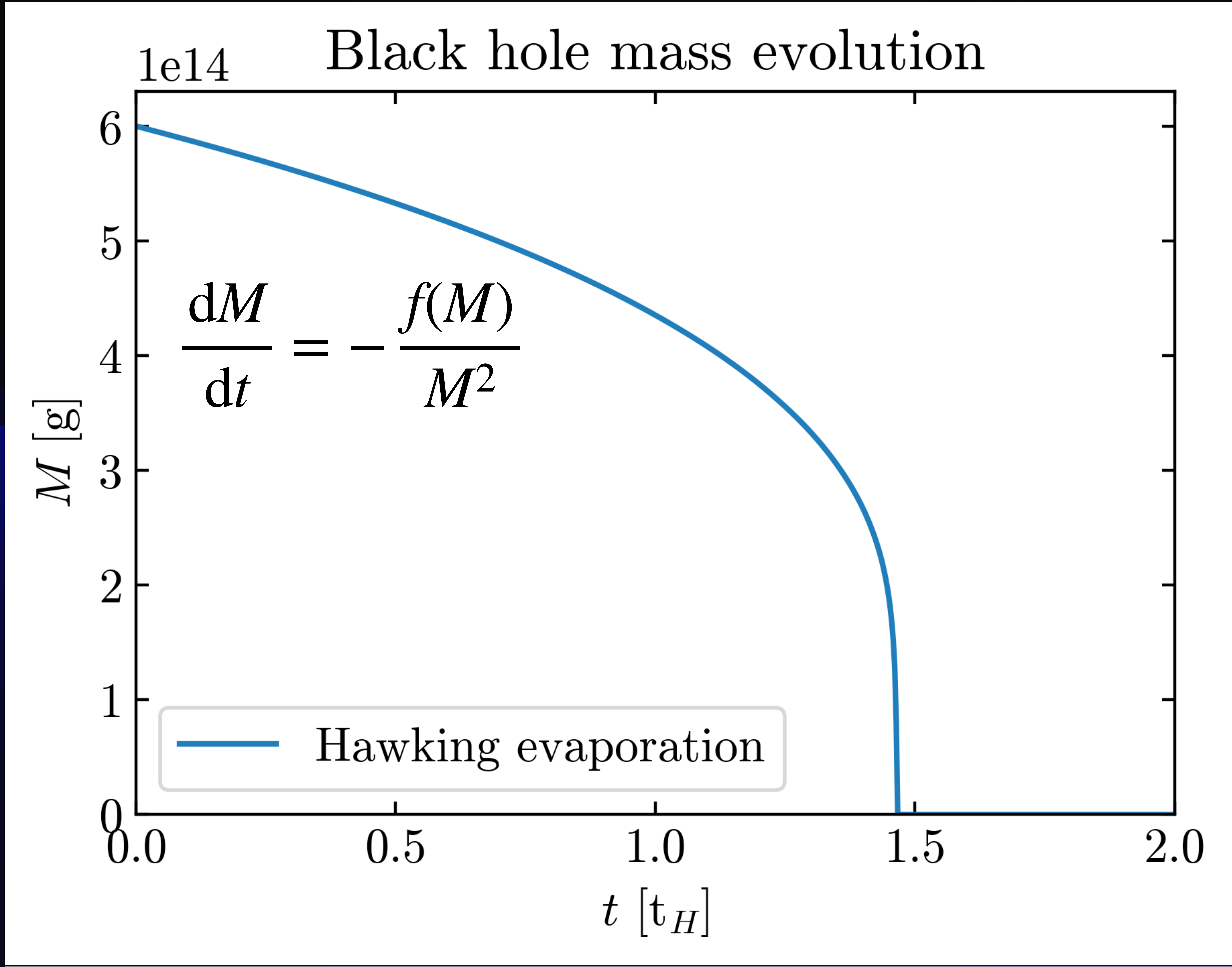


Carr et. al. 2021

Constraints on evaporated PBH



Carr et. al. 2021


Black hole mass evolution
1e14
6
5
4
3
2
1
0
0.0
0.5
1.0
1.5
2.0
M [g]
t [t_H]
$\frac{dM}{dt} = -\frac{f(M)}{M^2}$
Hawking evaporation

Black Hole Metamorphosis and Stabilization by Memory Burden

Gia Dvali,[1,2,*] Lukas Eisemann,[1,2,†] Marco Michel,[1,2,‡] and Sebastian Zell[3,1,2,§]

[1] *Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstraße 37, 80333 München, Germany*
[2] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*
[3] *Institute of Physics, Laboratory for Particle Physics and Cosmology, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

(Dated: July 18, 2022)

Systems of enhanced memory capacity are subjected to a universal effect of *memory burden*, which suppresses their decay. In this paper, we study a prototype model to show that memory burden can be overcome by rewriting stored quantum information from one set of degrees of freedom to another one. However, due to a suppressed rate of rewriting, the evolution becomes extremely slow compared to the initial stage. Applied to black holes, this predicts a metamorphosis, including a drastic deviation from Hawking evaporation, at the latest after losing half of the mass. This raises a tantalizing question about the fate of a black hole. As two likely options, it can either become extremely long lived or decay via a new classical instability into gravitational lumps. The first option would open up a new window for small primordial black holes as viable dark matter candidates.

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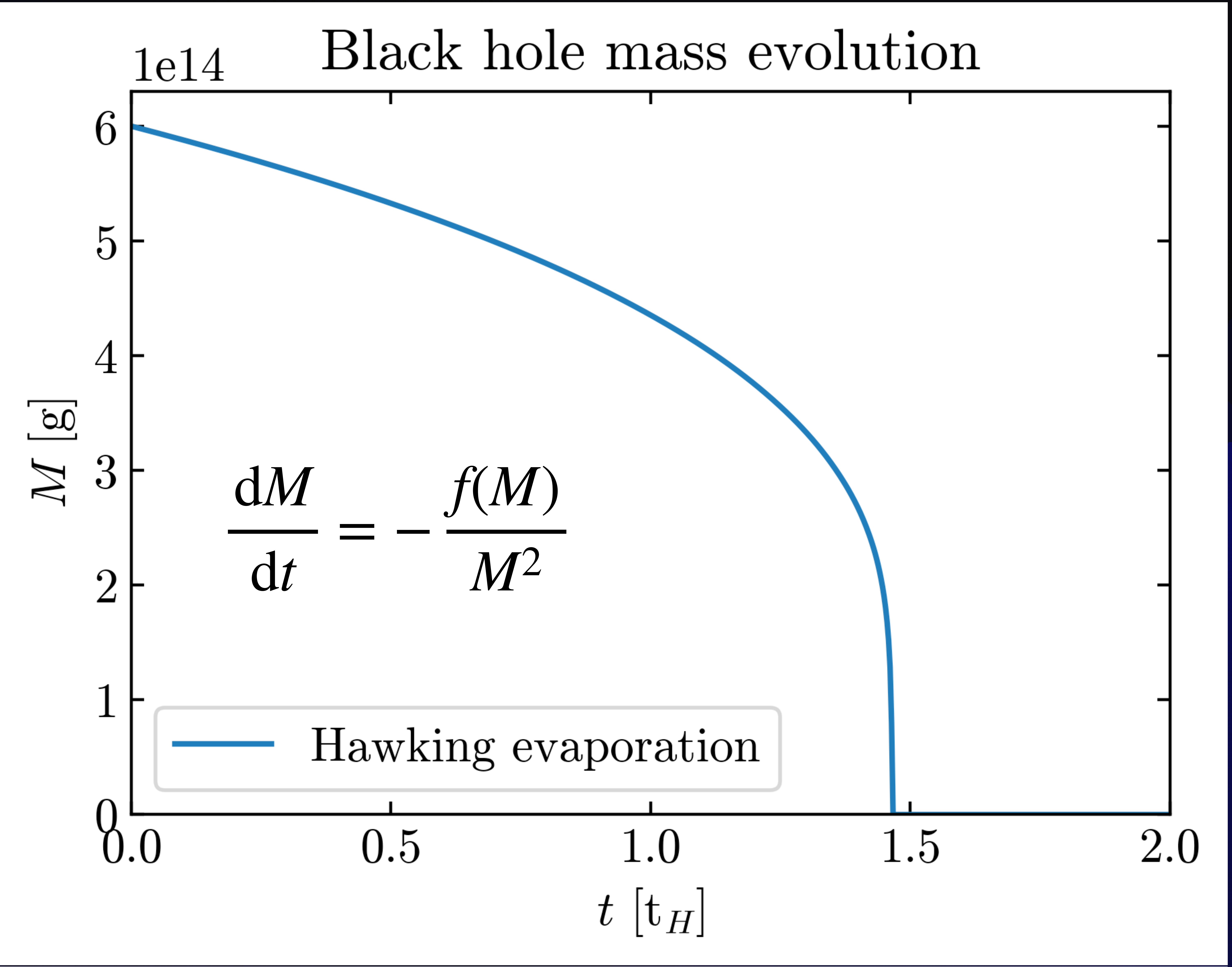
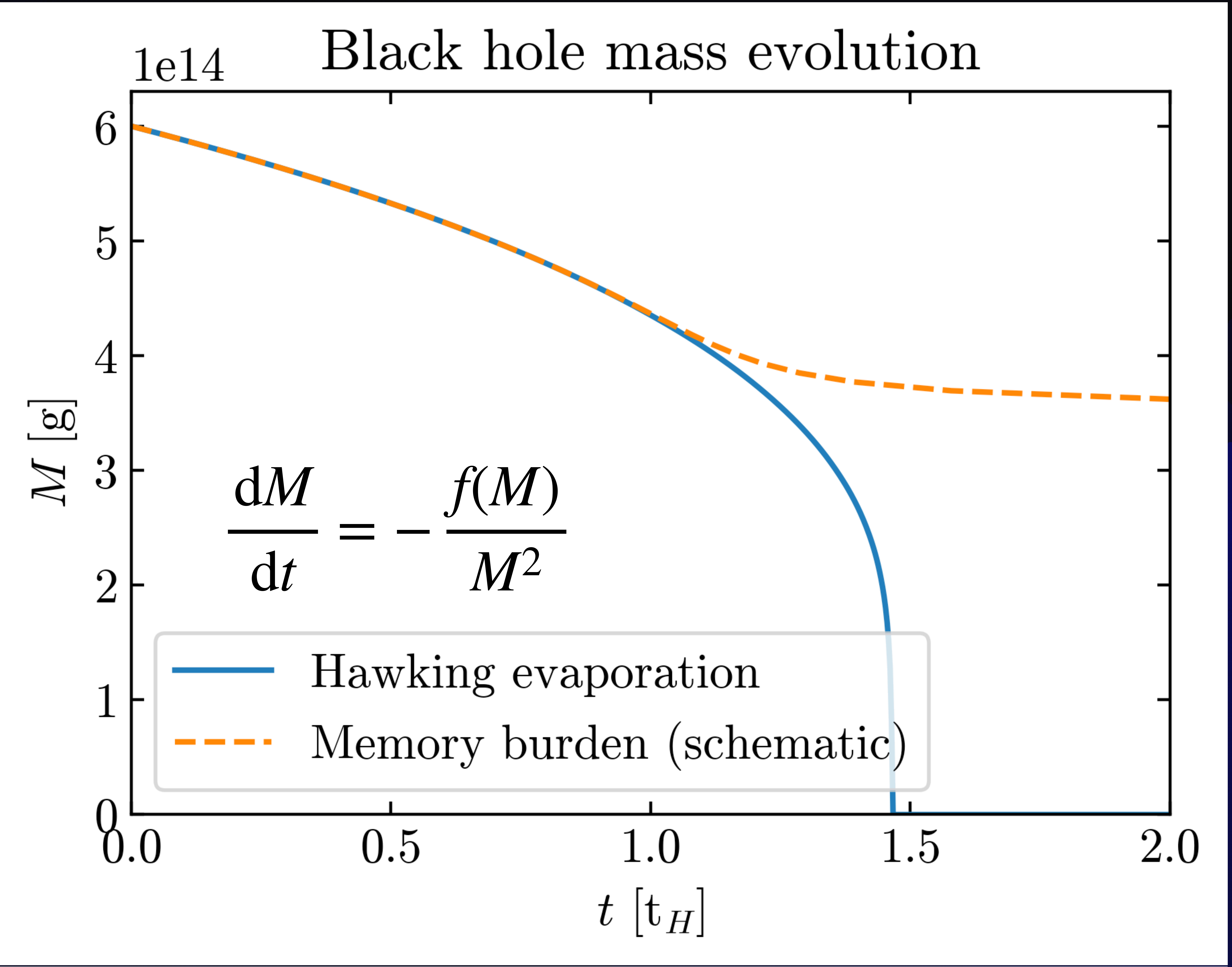


Memory burden:

- Quantum backreaction of the Hawking radiation on the BH
- Large information capacity stabilises black hole
- Effect sets in at latest when the black hole loses half of its initial mass
- Decay no longer self-similar



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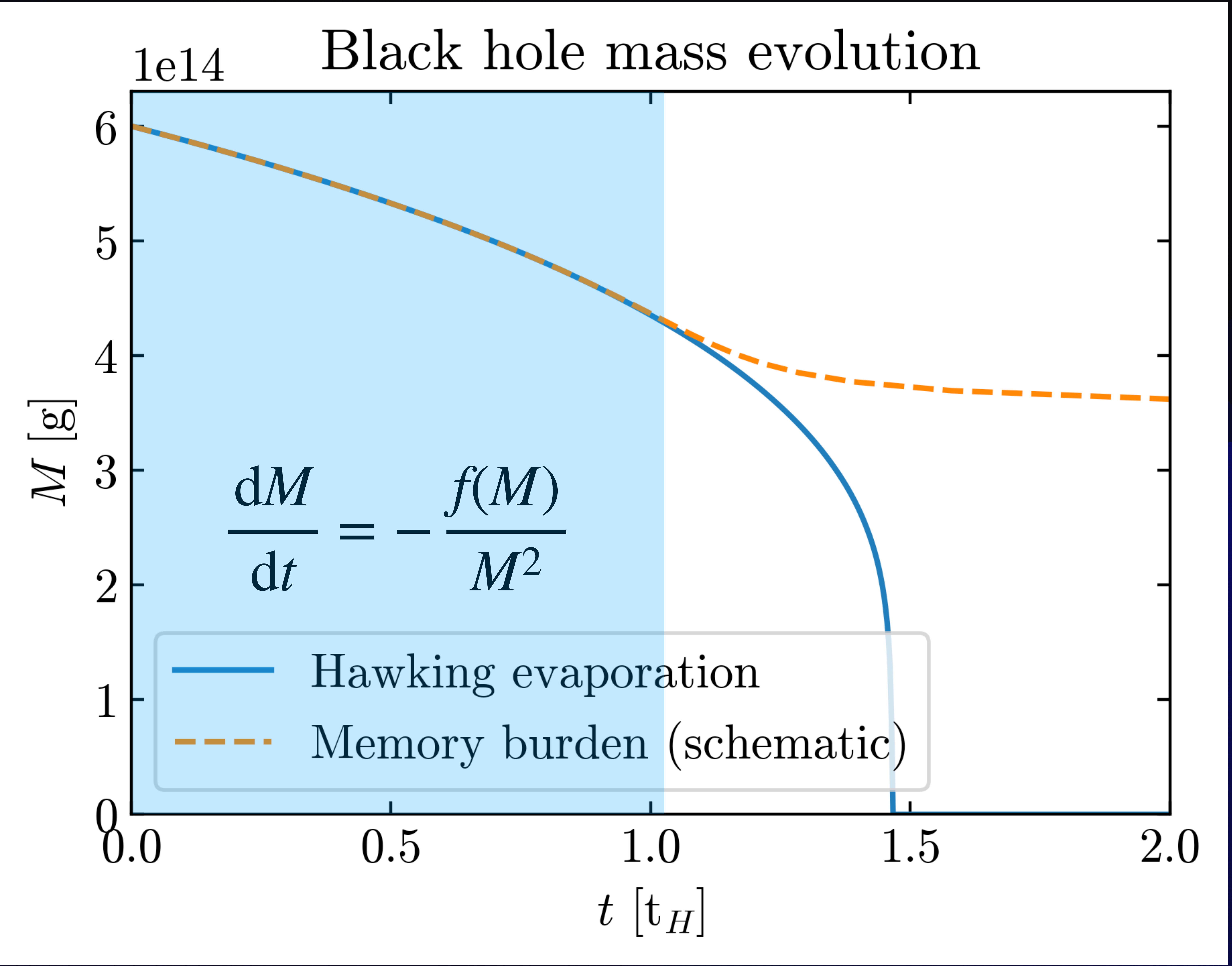

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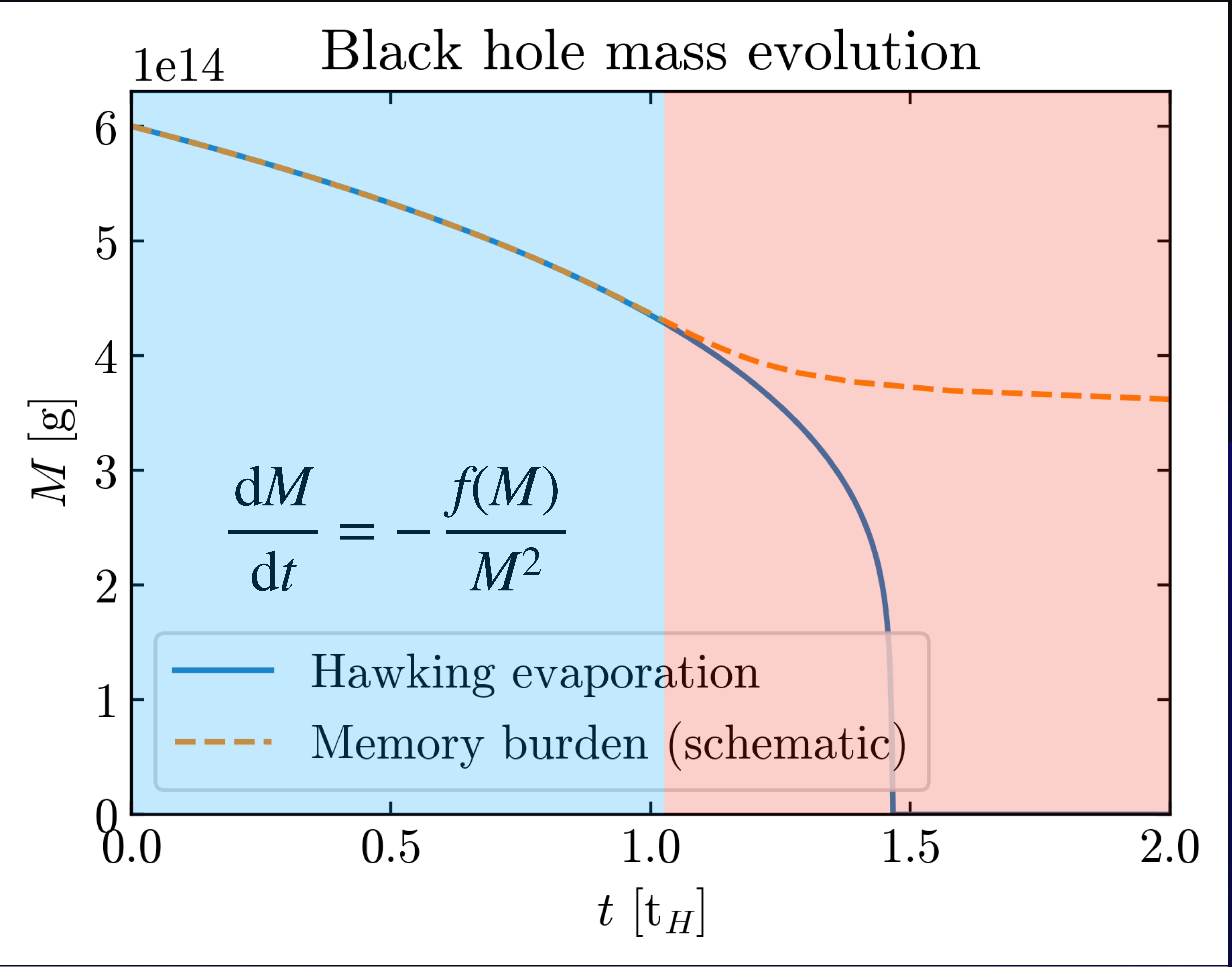

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	Coffee		
15:00	*National Galleries of Scotland*		14:40 - 15:10
	Characterising spacetime during cosmological collapse	*Robyn Munoz*	
	National Galleries of Scotland		15:10 - 15:30
	Consequence of vorticity in merging black hole prototype	*Michael Zantedeschi*	
	National Galleries of Scotland		15:30 - 15:50
	Scalar-Induced Gravitational Waves and its impact in understanding cosmology	*Ms Anjali Abirami Kugarajh*	
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Evaporation model

Evaporation model

Semiclassical :
(for $M > qM_0$)

$$\left.\frac{\mathrm{d}^2N}{\mathrm{d}E\mathrm{d}t}\right|_{\mathrm{SC}} = \frac{g}{2\pi\hbar}\frac{\Gamma(E,s,T)}{e^{E/k_BT}-(-1)^s}$$

$$k_BT = \frac{\hbar c^3}{8\pi GM}$$

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Memory burden : (for $M \leq qM_0$)

$$\left.\frac{\mathrm{d}^2N}{\mathrm{d}E\mathrm{d}t}\right|_{\mathrm{MB}} = \frac{1}{S_0^k}\left.\frac{\mathrm{d}^2N}{\mathrm{d}E\mathrm{d}t}\right|_{\mathrm{SC},M=qM_0} \qquad S_0 = \frac{4\pi(qM_0)^2G}{\hbar c}$$

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Entropy is huge : $S = 10^{10}\left(\frac{M}{1g}\right)^2$ Three parameters : f_{PBH}, M_0, and k

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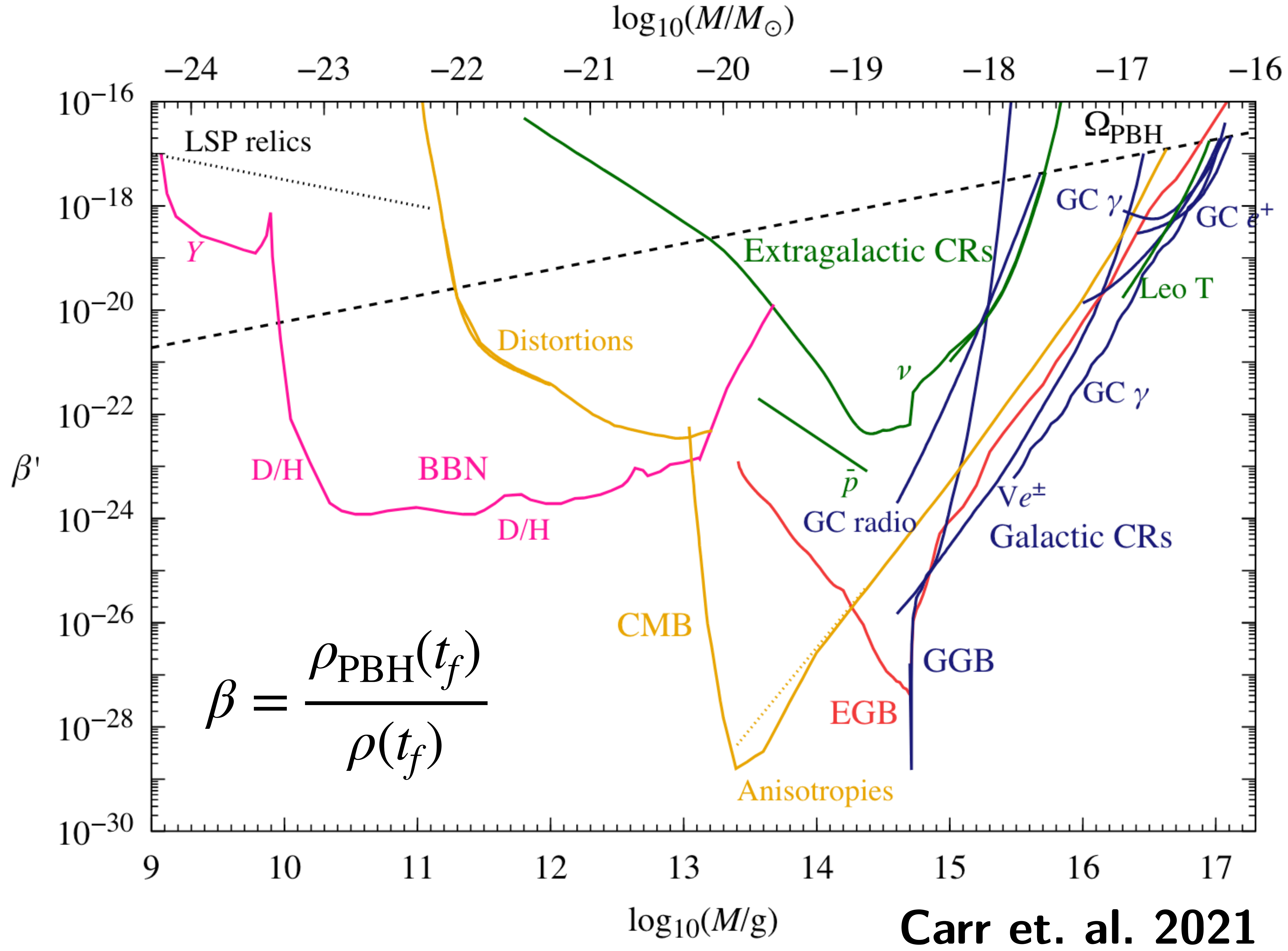
Constraints on evaporated PBH



$$\beta = \frac{\rho_{PBH}(t_f)}{\rho(t_f)}$$

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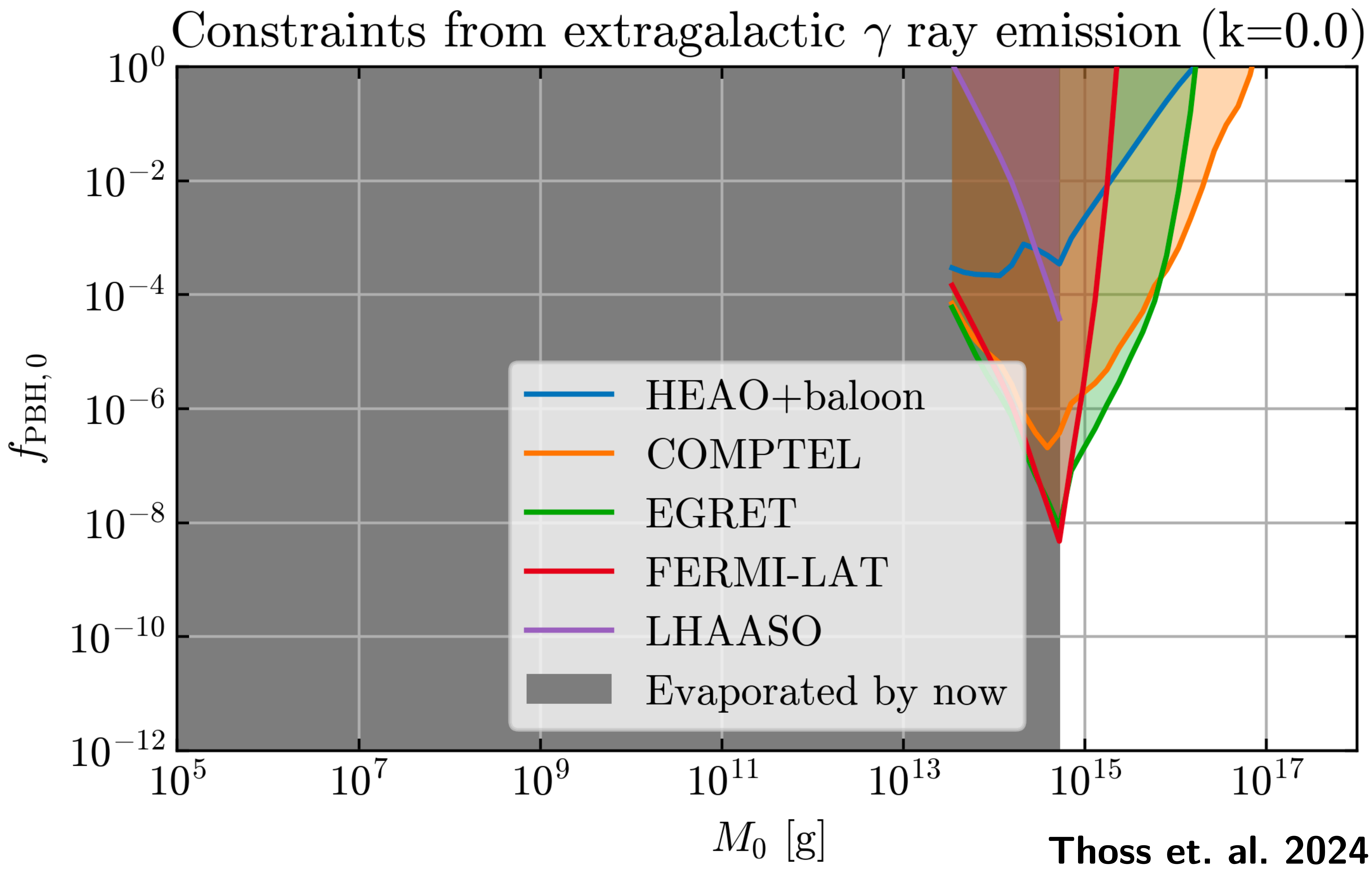

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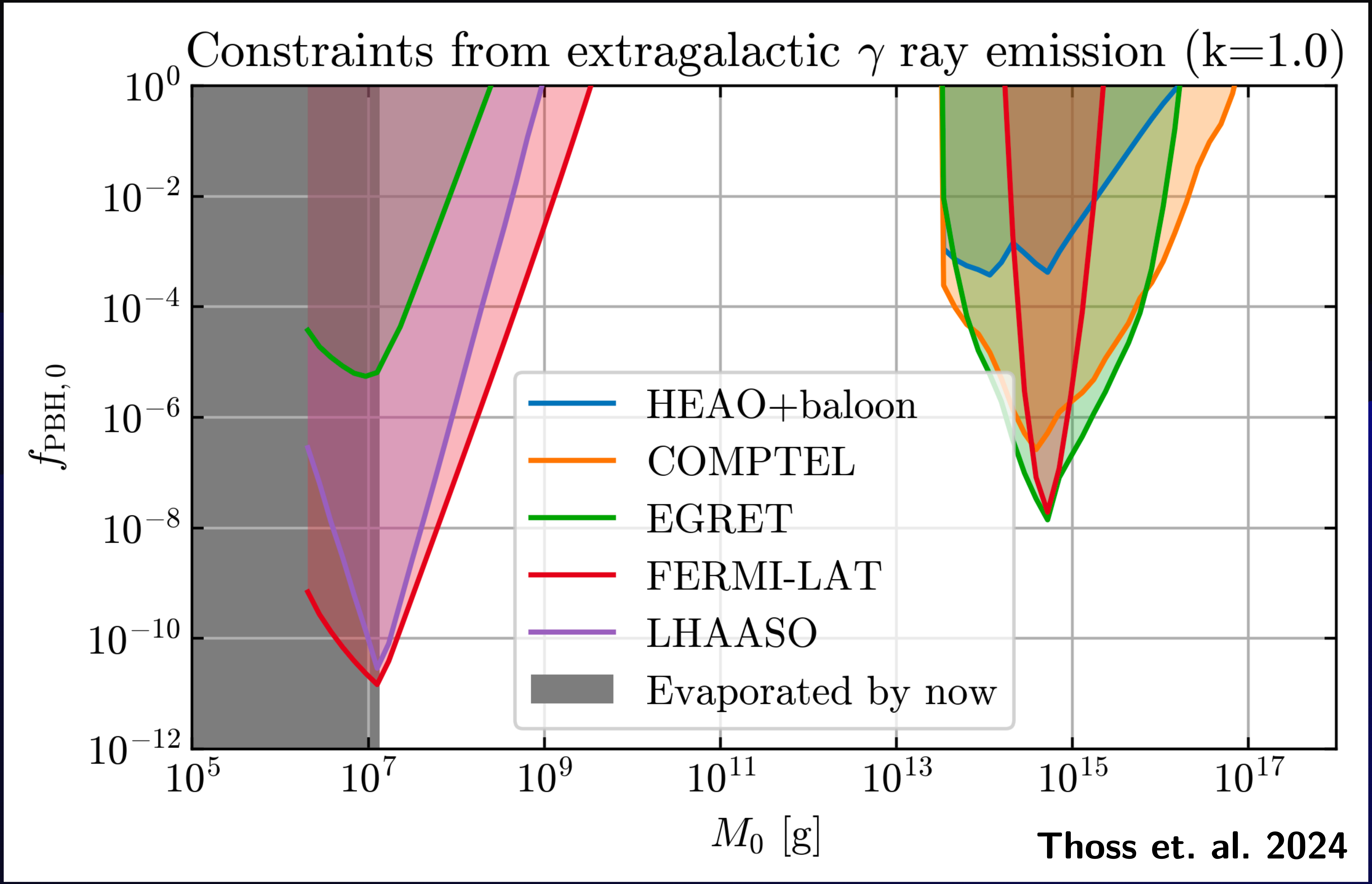

Constraints from extragalactic γ ray emission (k=1.0)
$f_{\mathrm{PBH},0}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^5
10^7
10^9
10^{11}
10^{13}
10^{15}
10^{17}
M_0 [g]
HEAO+baloon
COMPTEL
EGRET
FERMI-LAT
LHAASO
Evaporated by now
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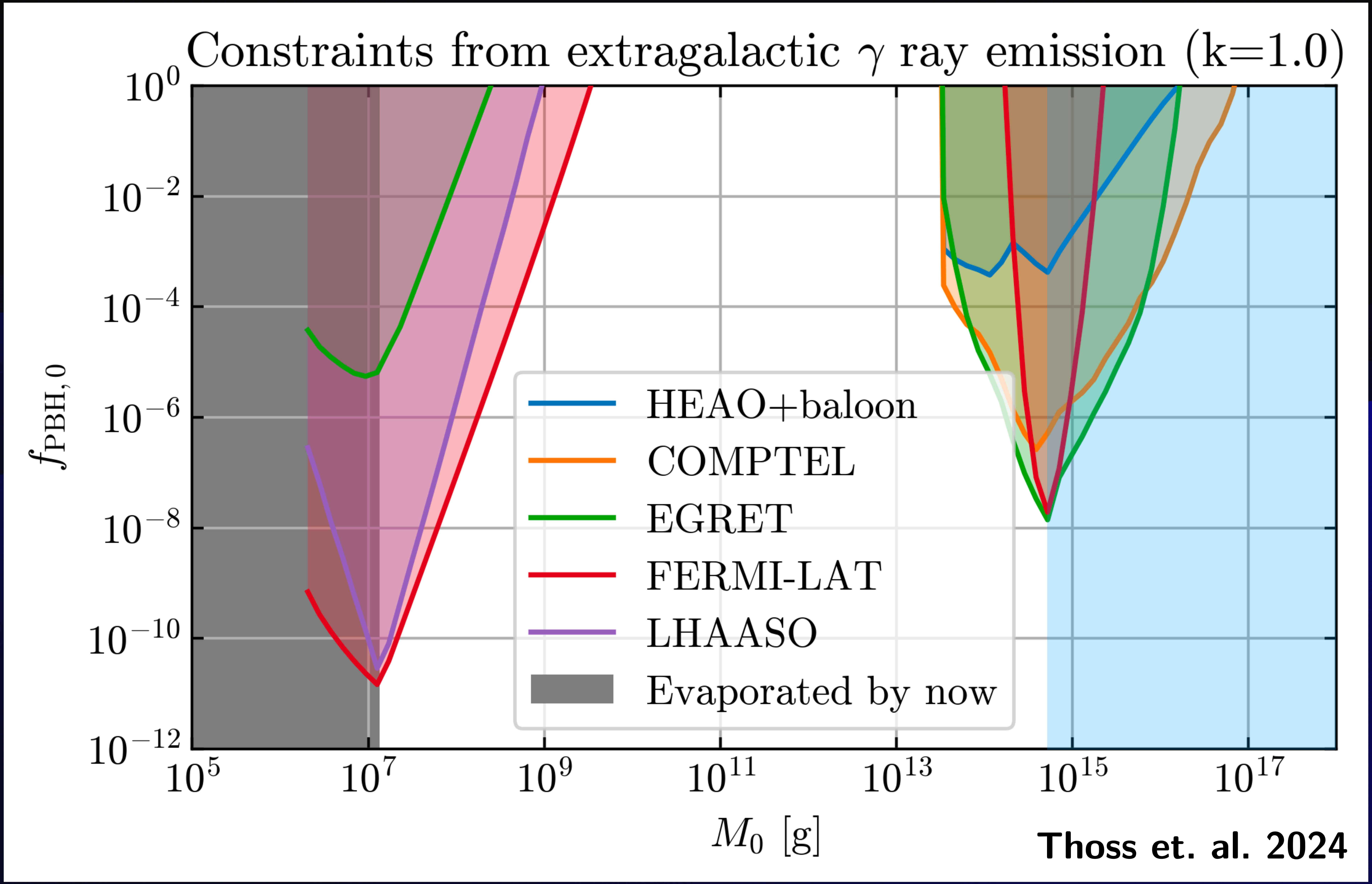
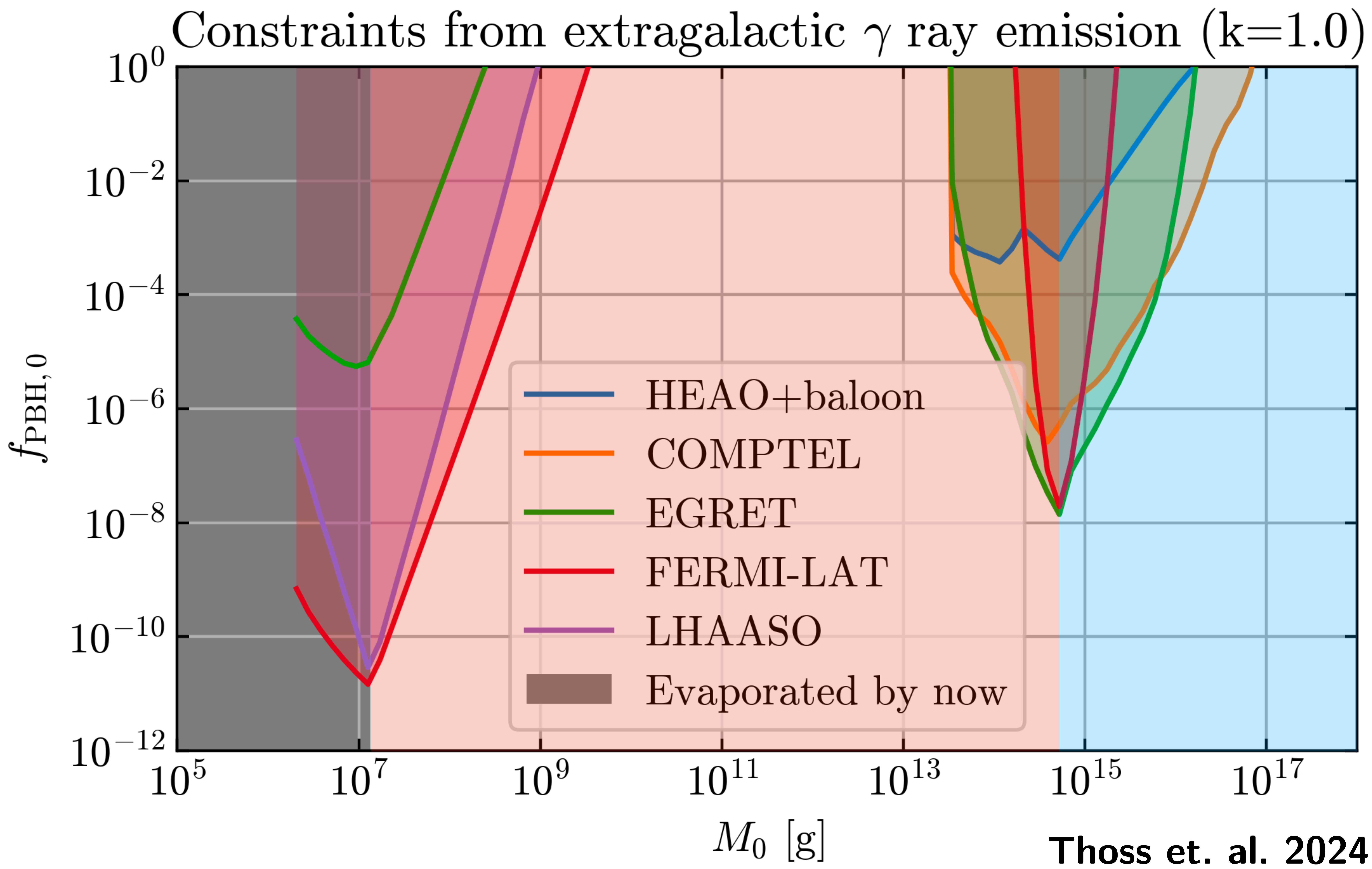

Constraints from extragalactic γ ray emission (k=1.0)
$f_{PBH,0}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^5
10^7
10^9
10^{11}
10^{13}
10^{15}
10^{17}
M_0 [g]
HEAO+baloon
COMPTEL
EGRET
FERMI-LAT
LHAASO
Evaporated by now
Thoss et. al. 2024



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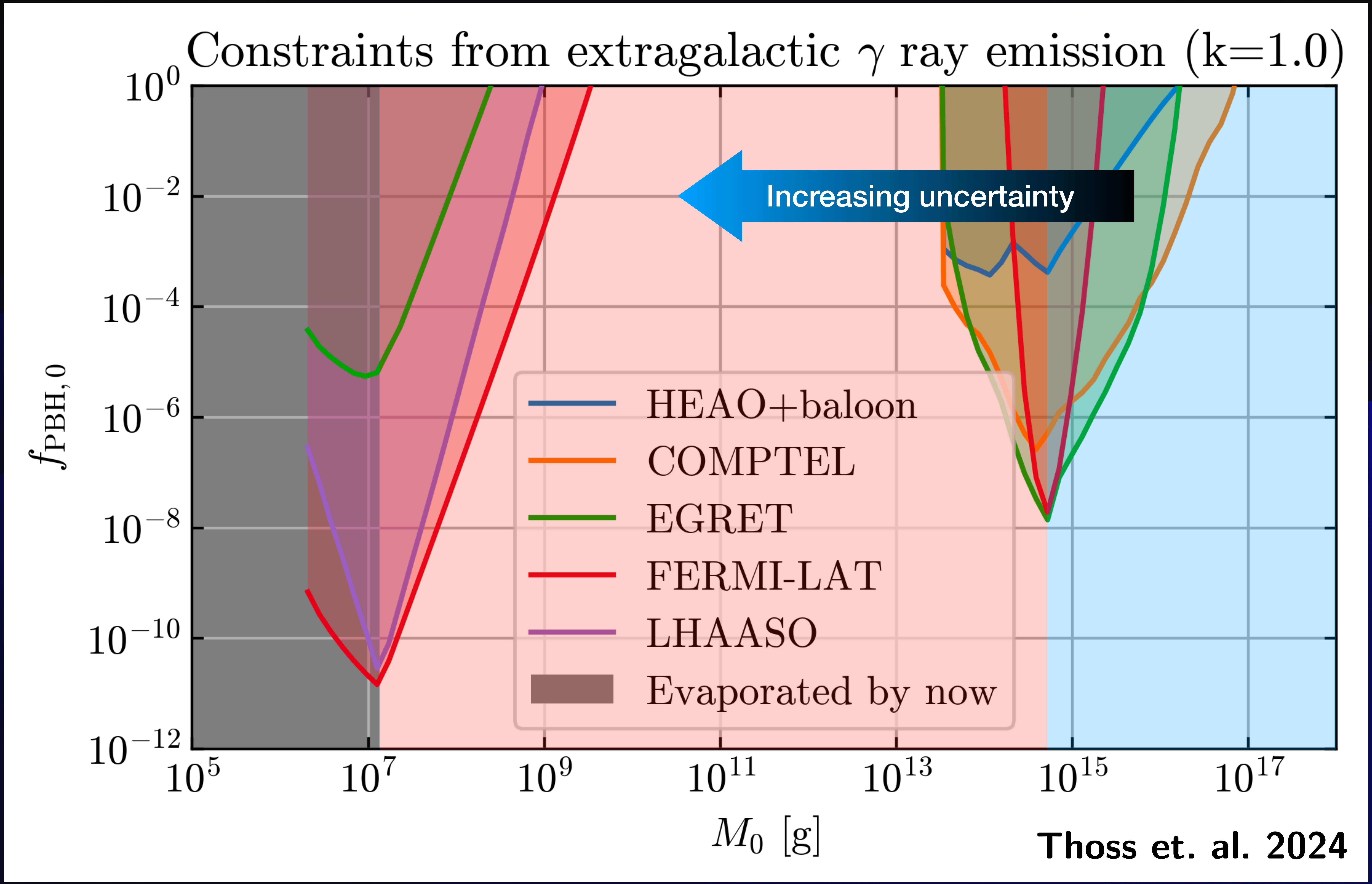
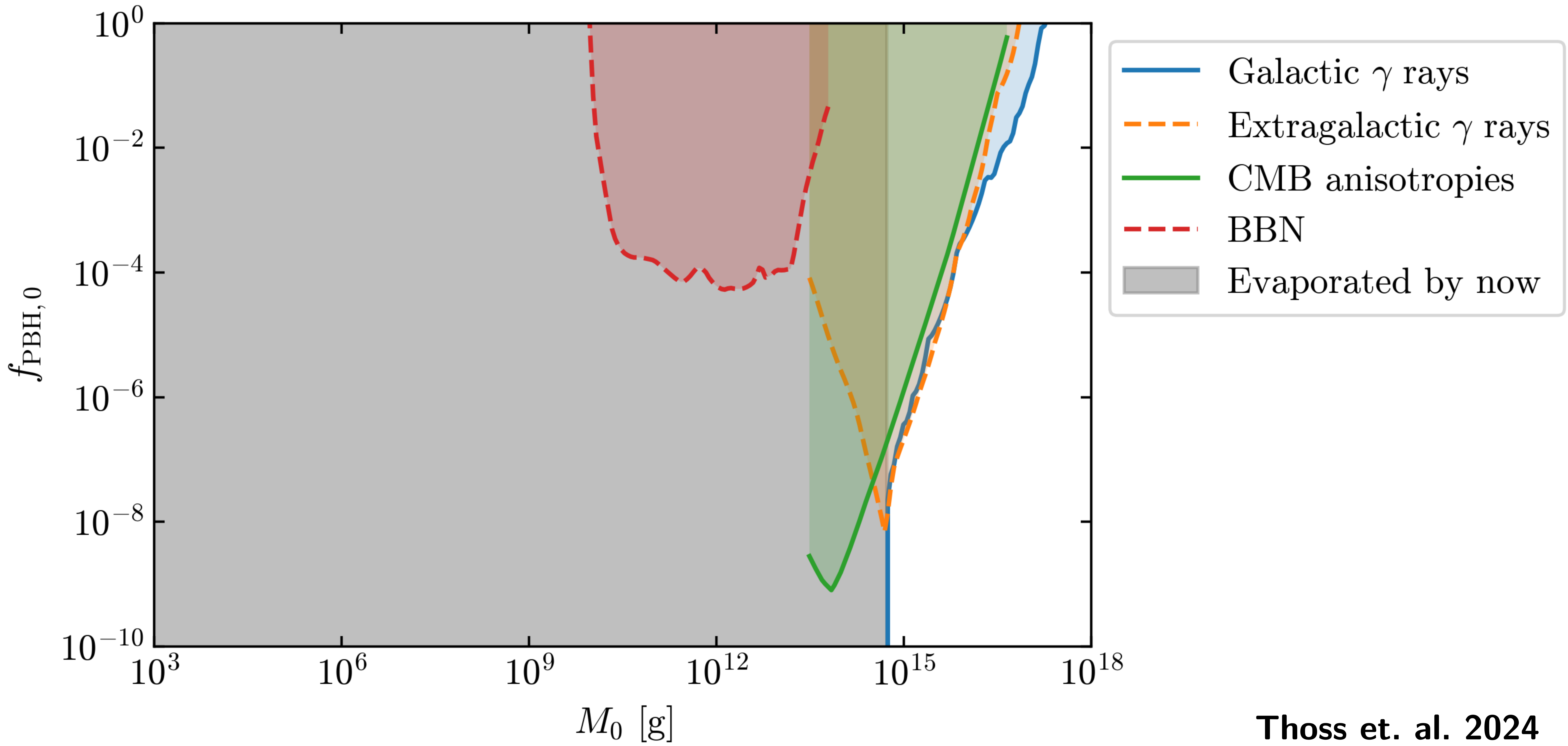
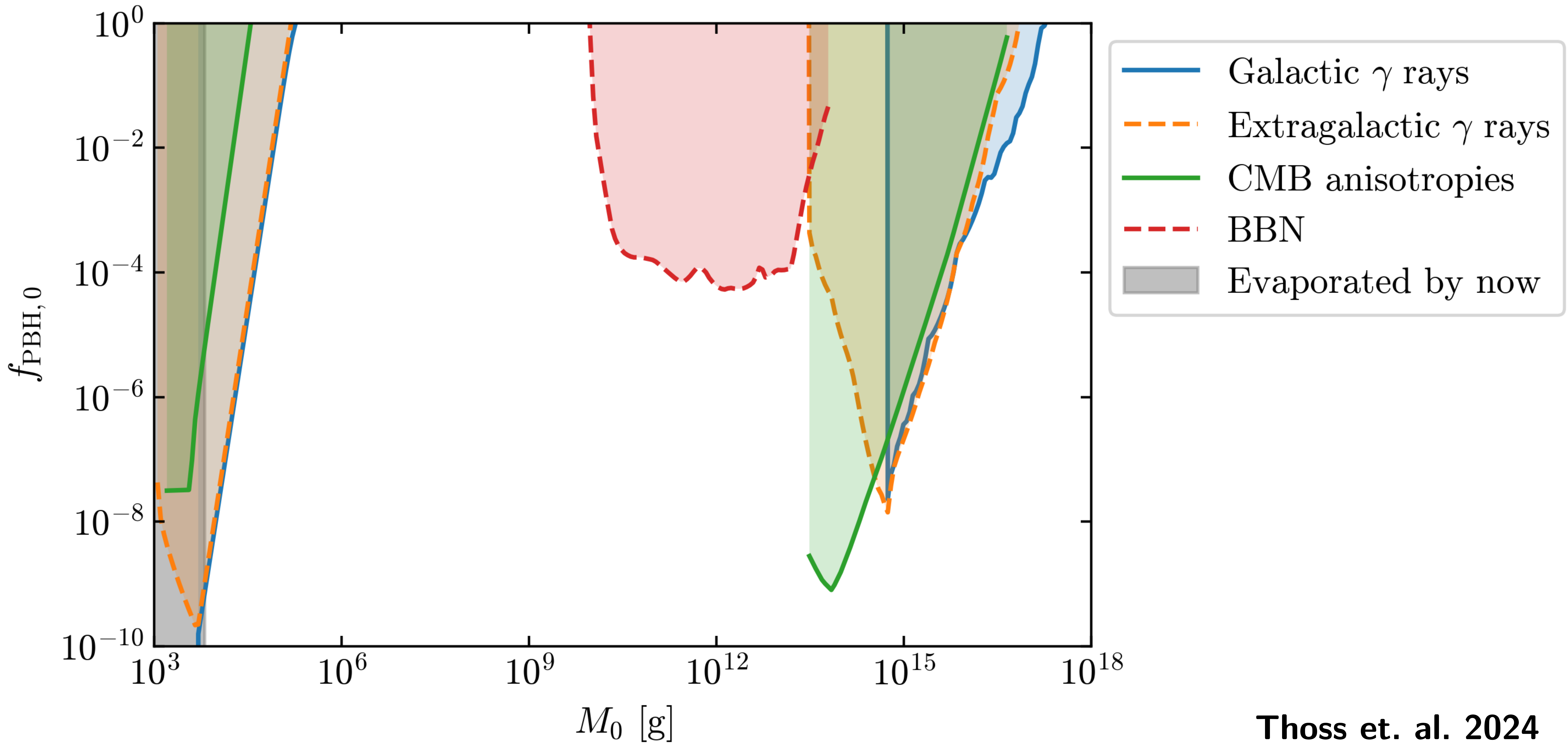

Constraints from extragalactic γ ray emission (k=1.0)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$f_{\mathrm{PBH},0}$
10^{5}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
M_0 [g]
Increasing uncertainty
HEAO+baloon
COMPTEL
EGRET
FERMI-LAT
LHAASO
Evaporated by now
Thoss et. al. 2024



Thoss et. al. 2024



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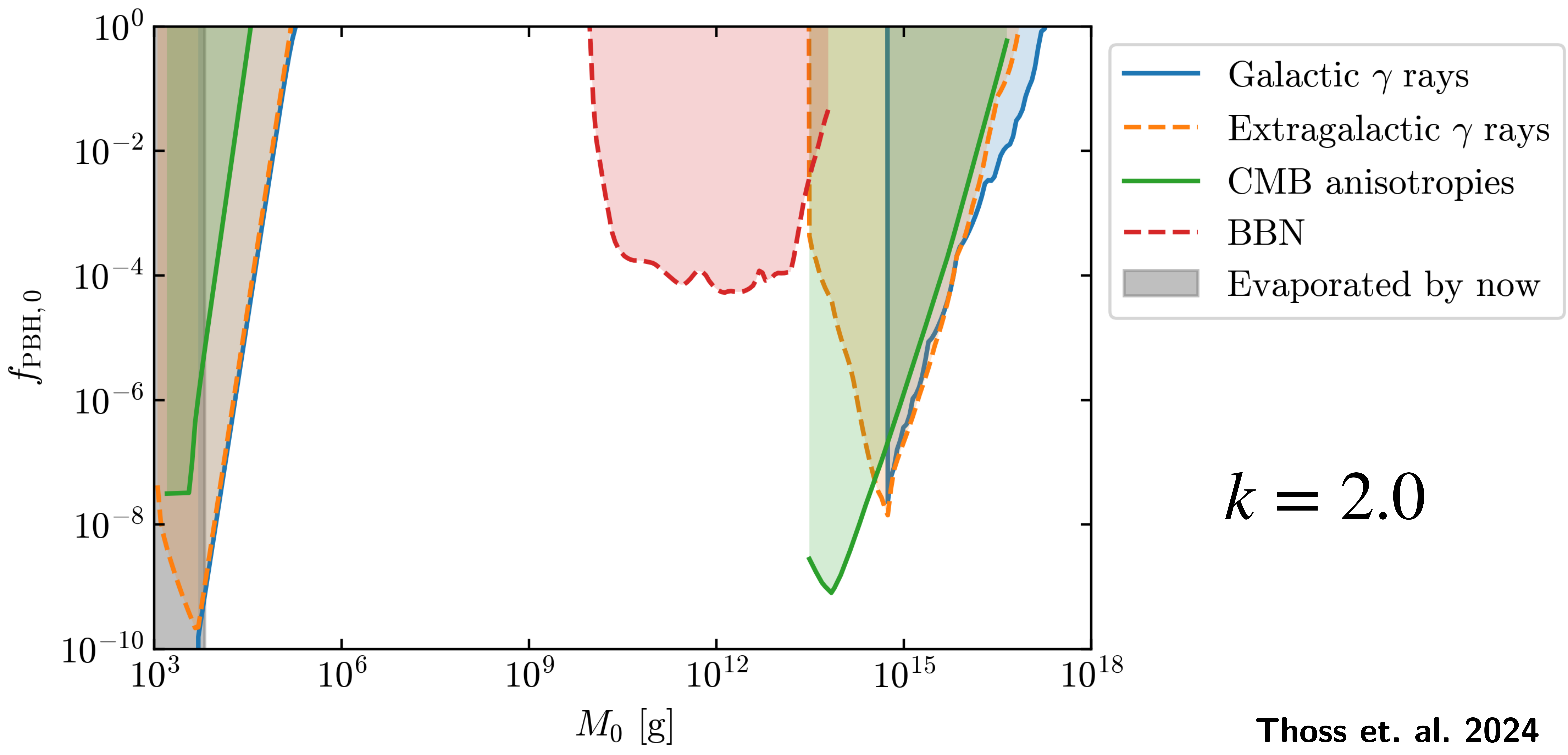

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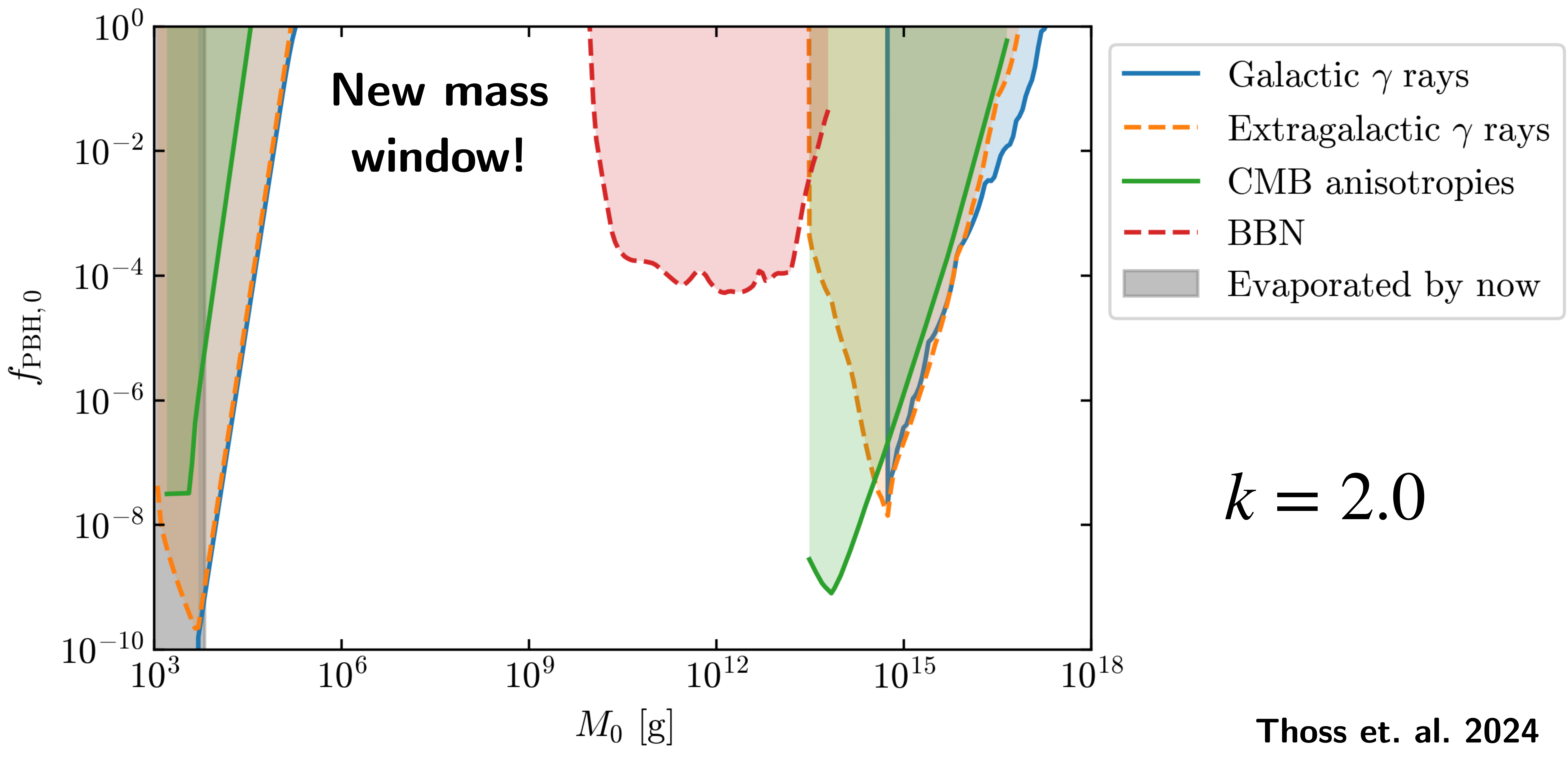

$k = 2.0$

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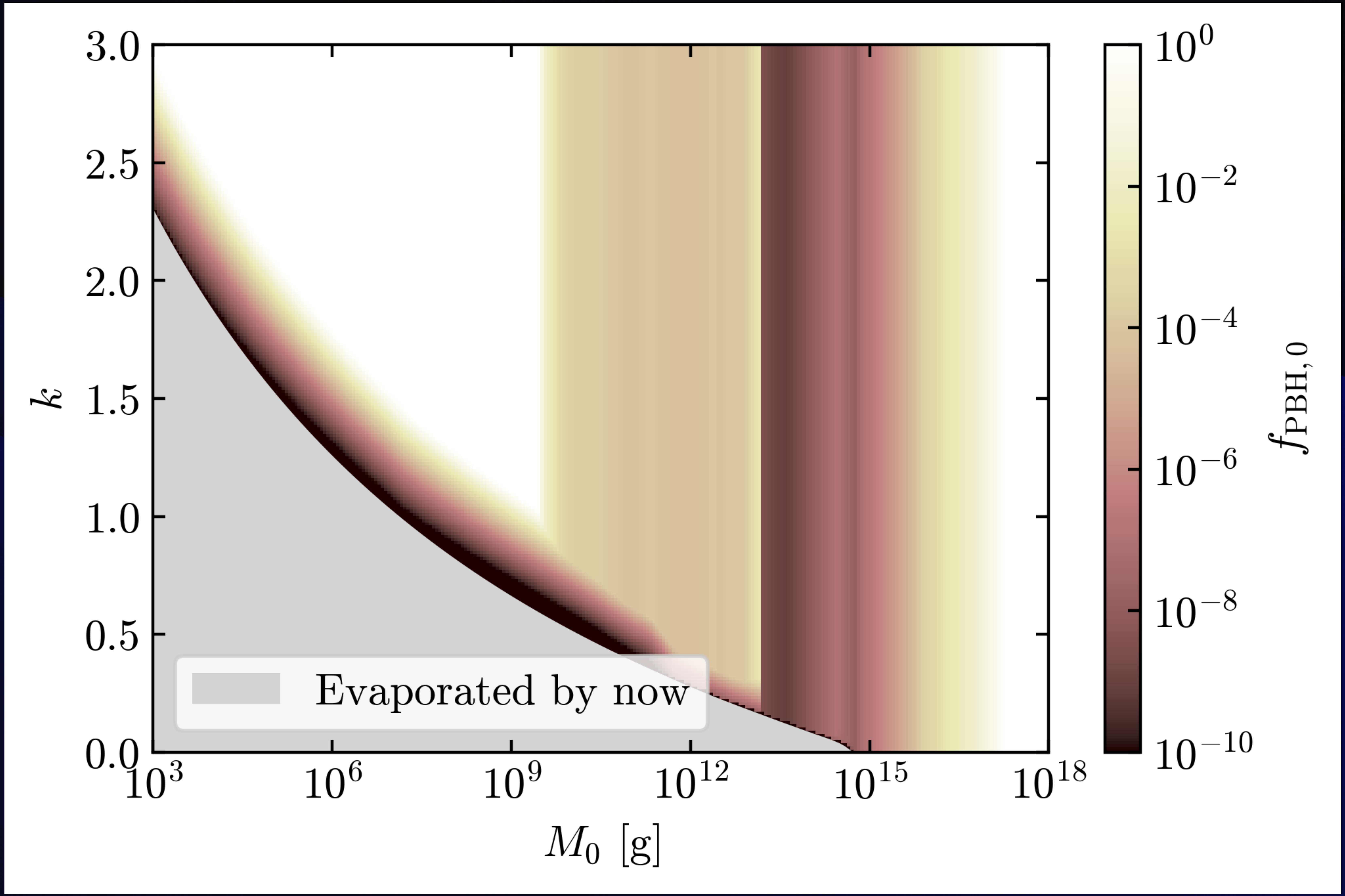
Full map of constraints



- Galactic γ ray
- Extragalactic γ ray
- CMB anisotropies
- BBN

Summary

arXiv:2402.17823

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- The „memory burden" can open open up a new window of light PBH ($M_0 < 10^{10}$ g) as dark matter candidates if $k \geq 1.0$.

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- The lower bound of this mass window depends on the strength of the memory burden

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- Only rough guide since we do not understand the full evaporation process beyond half-decay

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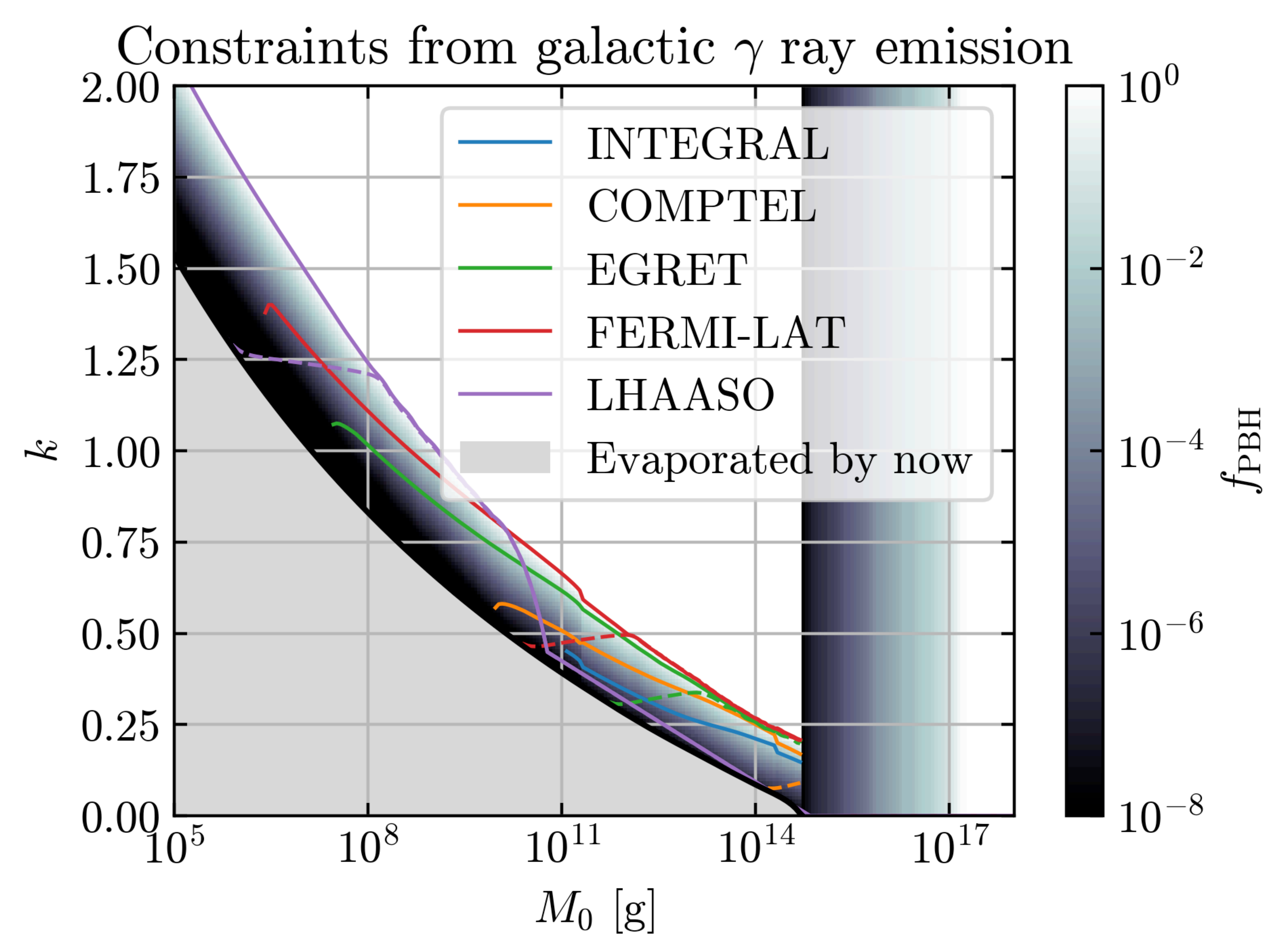
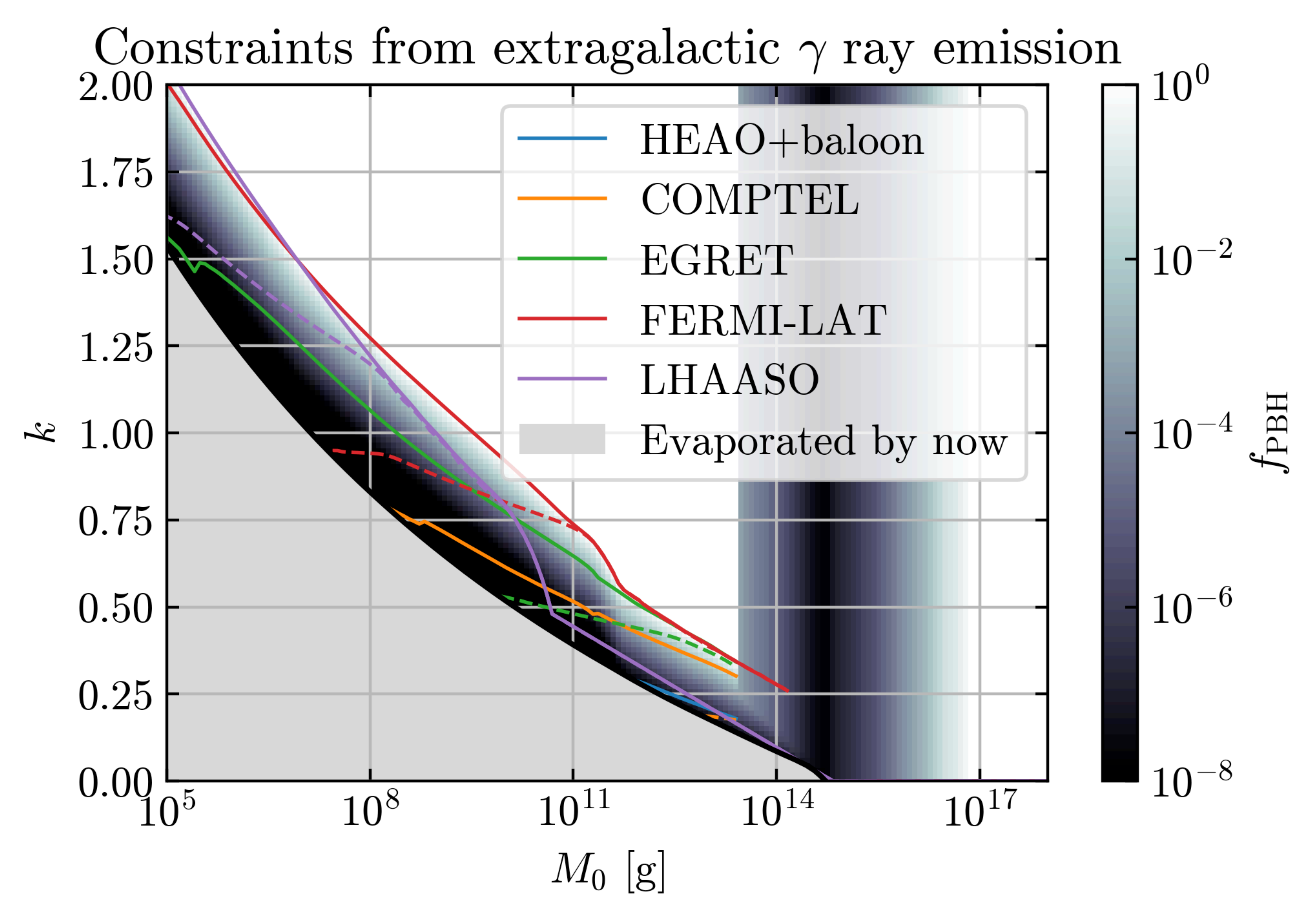


Constraints from galactic γ ray emission
INTEGRAL
COMPTEL
EGRET
FERMI-LAT
LHAASO
Evaporated by now
k
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^5
10^8
10^11
10^14
10^17
M_0 [g]
10^0
10^-2
10^-4
10^-6
10^-8
f_PBH

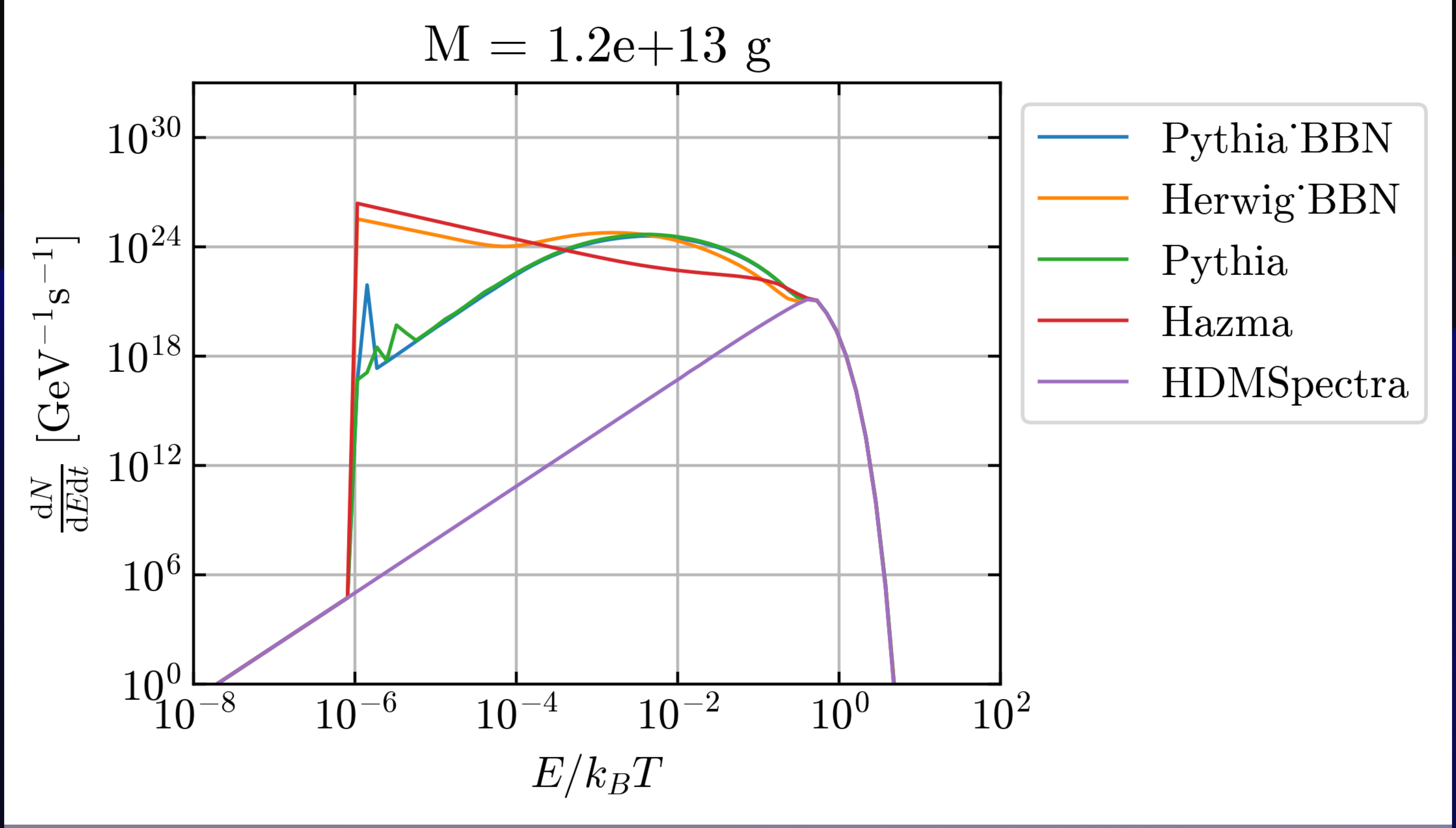


Constraints from extragalactic γ ray emission
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
k
10^5
10^8
10^{11}
10^{14}
10^{17}
M_0 [g]
HEAO+baloon
COMPTEL
EGRET
FERMI-LAT
LHAASO
Evaporated by now
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$f_{\rm PBH}$

Secondary emission

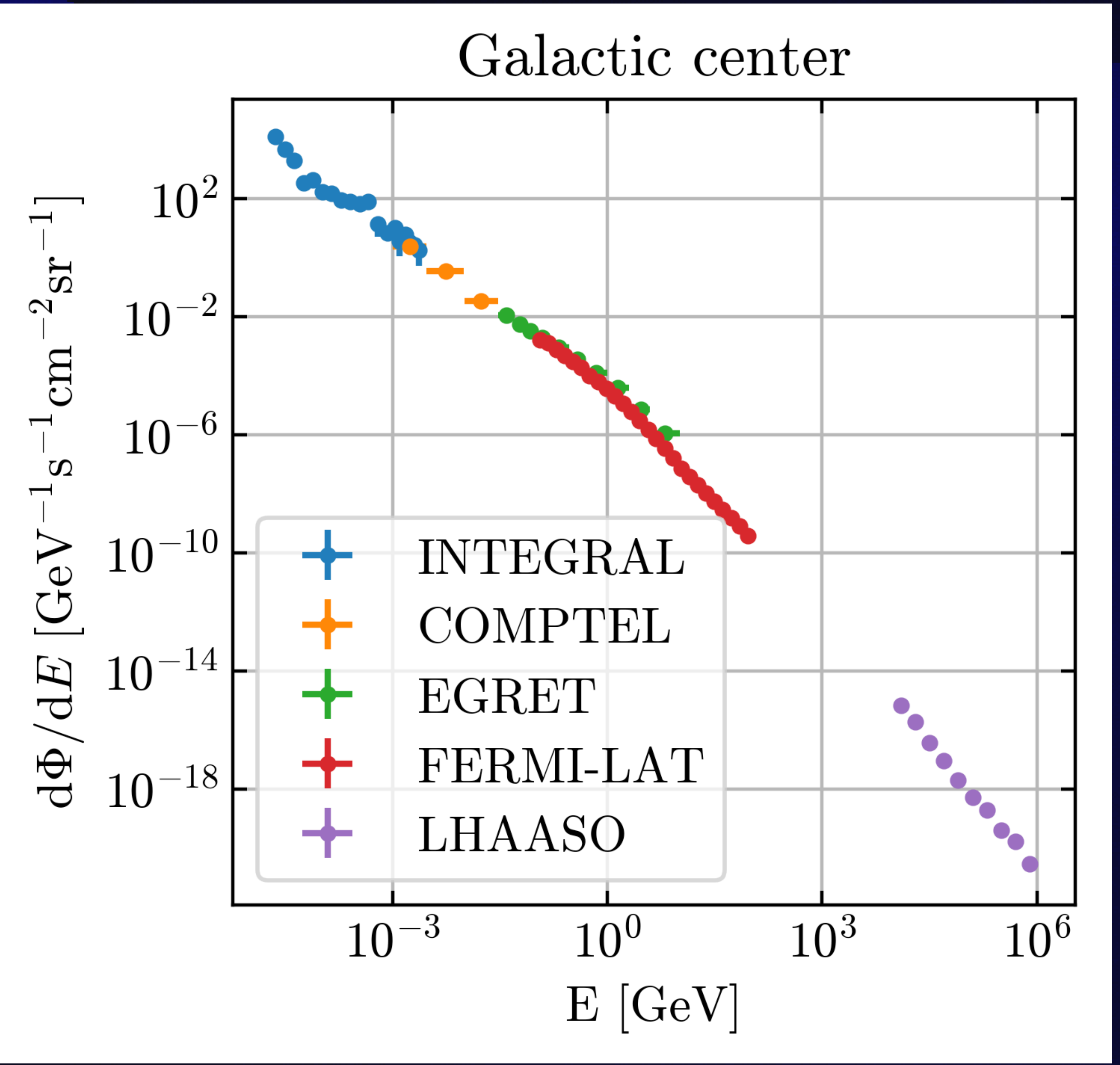
- Flux of particle of type i $$\frac{\mathrm{d}^2 N_i}{\mathrm{d}E\mathrm{d}t} = \int \mathrm{d}E' \, \mathrm{Br}_{j\to i}(E,E') \frac{\mathrm{d}^2 N_j}{\mathrm{d}E'\mathrm{d}t}$$
- Branching ratios can be obtained from PYTHIA, Herwig, Hazma (within the code BlackHawk) and HDMSpectra
- Huge differences between hadronization schemes, mainly due to focus on different energy ranges
- We choose Hazma for $k_B T < 0.1$ GeV, Herwig for $0.1\,\text{GeV} < k_B T < 100\,\text{GeV}$ and HDMSpectra for $k_B T > 100$ GeV
- For $E/k_B T < 10^{-6}$ we use the primary emission only

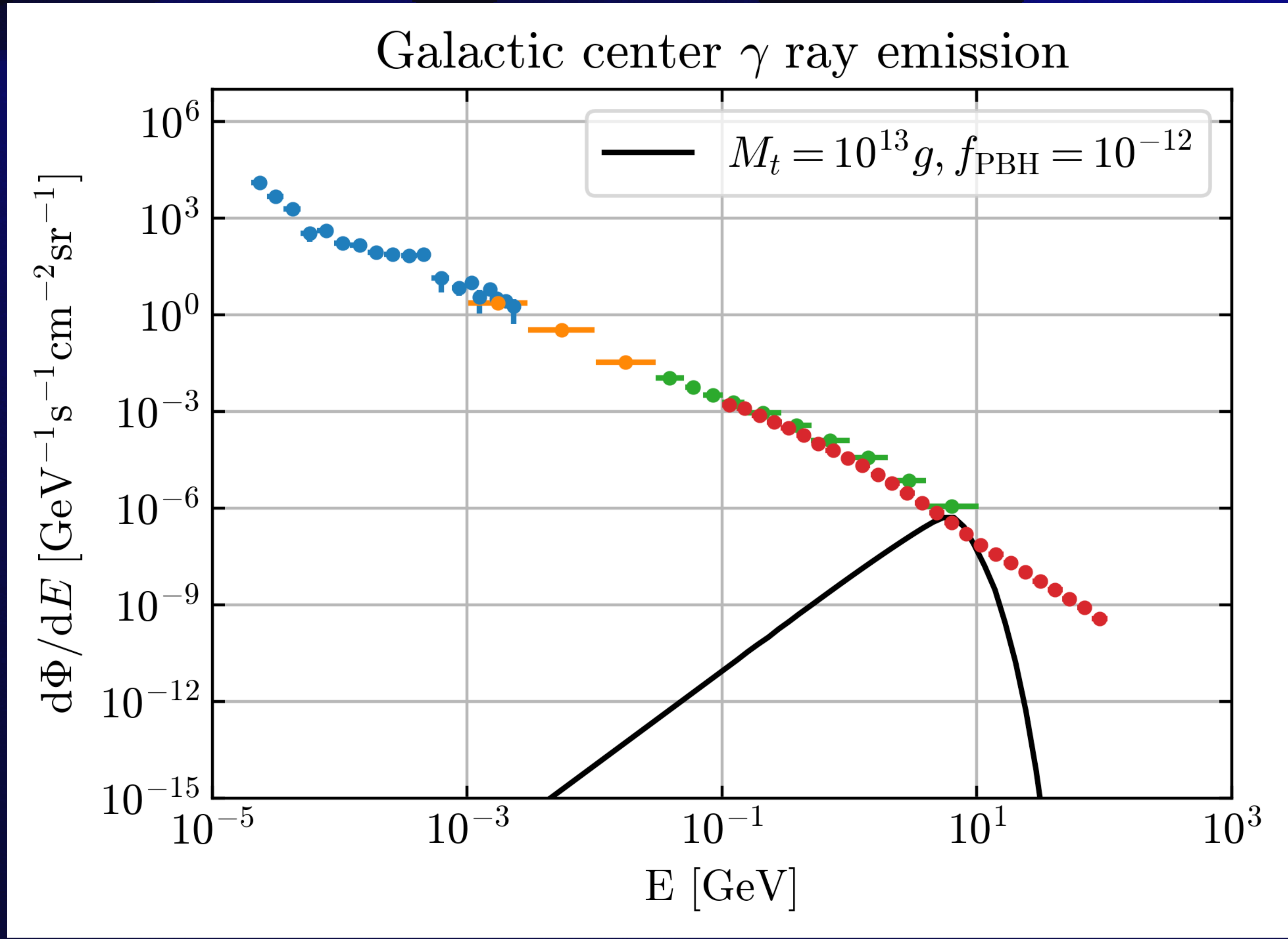
Secondary emission



Galactic γ ray emission

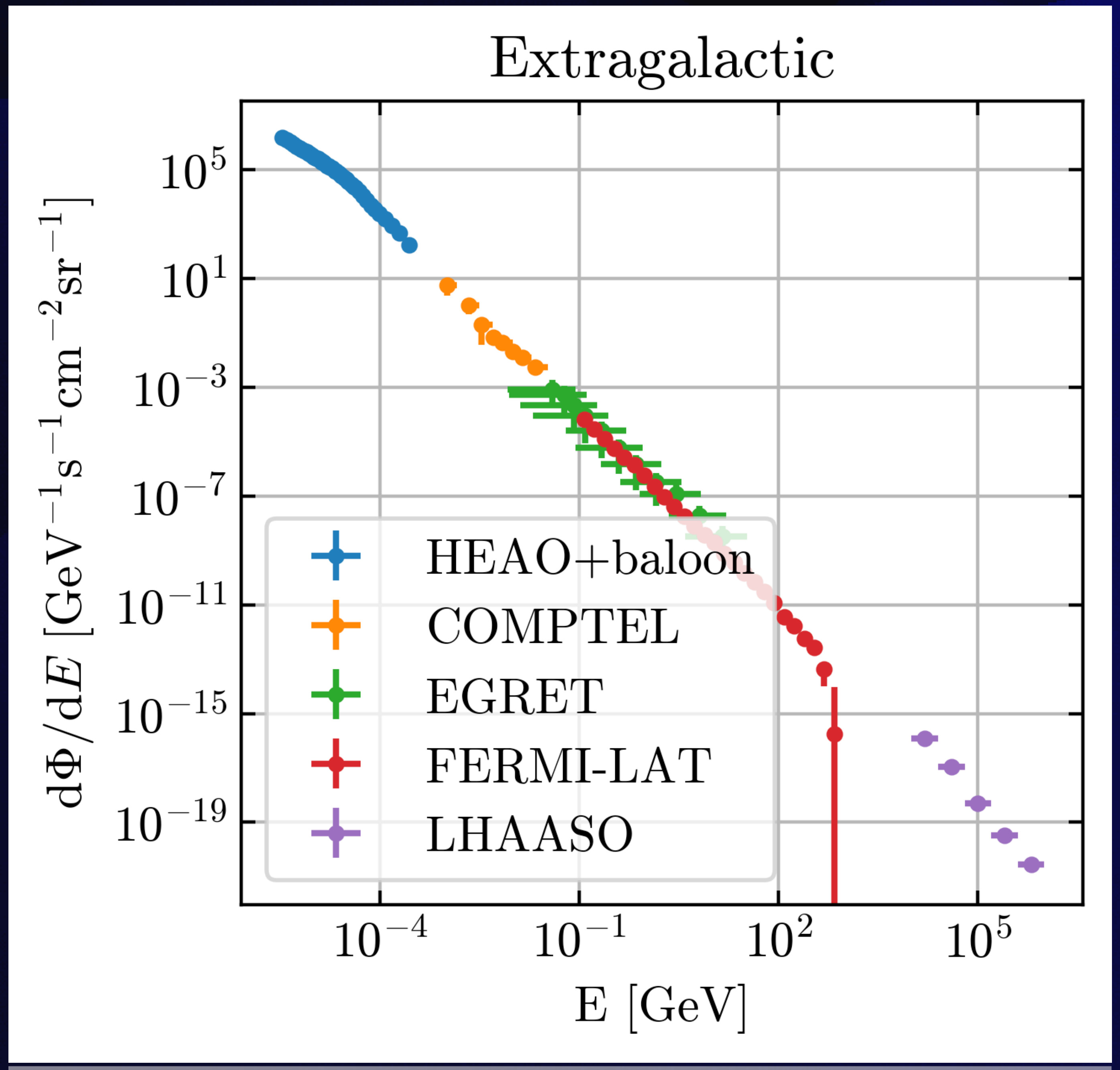
- Flux is given by $$\Phi_{\rm PBH} = \frac{f_{\rm PBH}}{4\pi M_t \Delta\Omega}\frac{{\rm d}^2 N_\gamma}{{\rm d}E{\rm d}t}\int_{\Delta\Omega}{\rm d}\Omega\int {\rm d}r\rho_{\rm DM}(R(r,l,b))$$
- Using observational data from INTEGRAL, COMPTEL, EGRET, Fermi-LAT and LHAASO

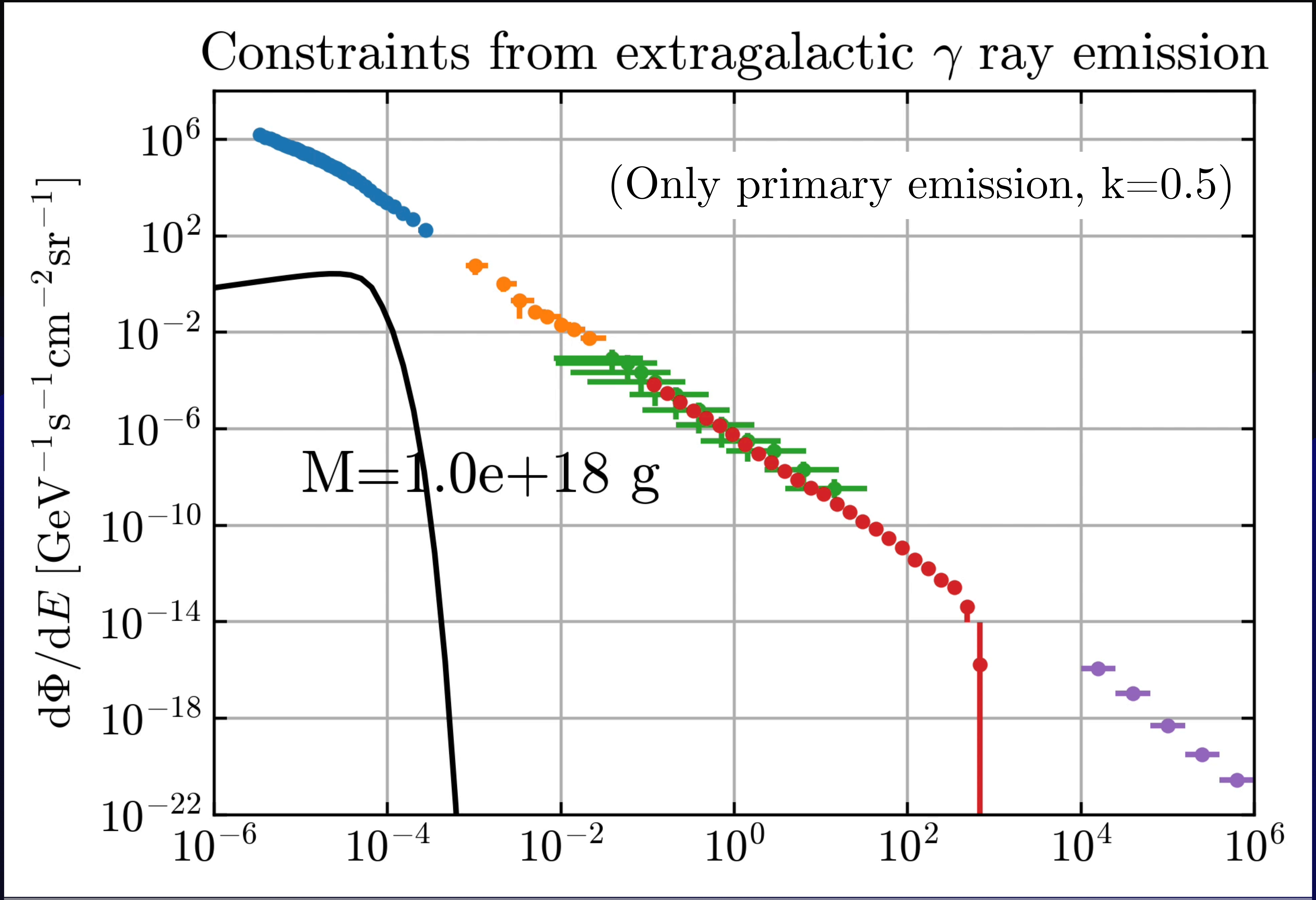




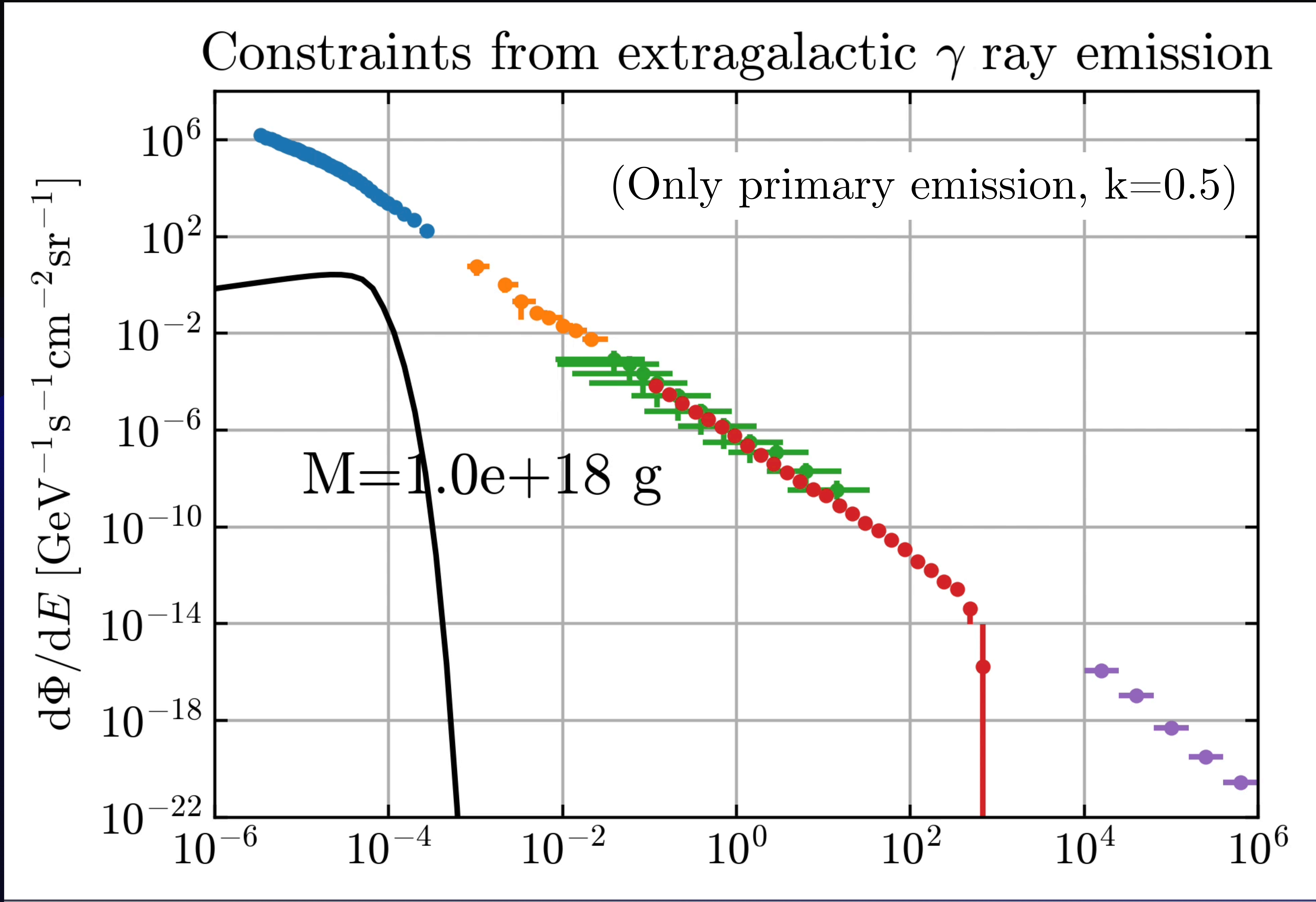
Extragalactic γ ray emission

- Flux is given by $$\Phi_{\rm PBH} = \frac{cn_t}{4\pi}\int_0^{z_{\rm rec}} \mathrm{d}z\,(1+z)\frac{\mathrm{d}^2N_\gamma}{\mathrm{d}E\mathrm{d}t}\Big(E(1+z), M(z(t))\Big)$$
- Using observational data from HEAO, COMPTEL, EGRET, Fermi-LAT and LHAASO





Constraints from extragalactic γ ray emission
(Only primary emission, k=0.5)
M=1.0e+18 g
$d\Phi/dE$ [$GeV^{-1}s^{-1}cm^{-2}sr^{-1}$]
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}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M=1.0e+18 g
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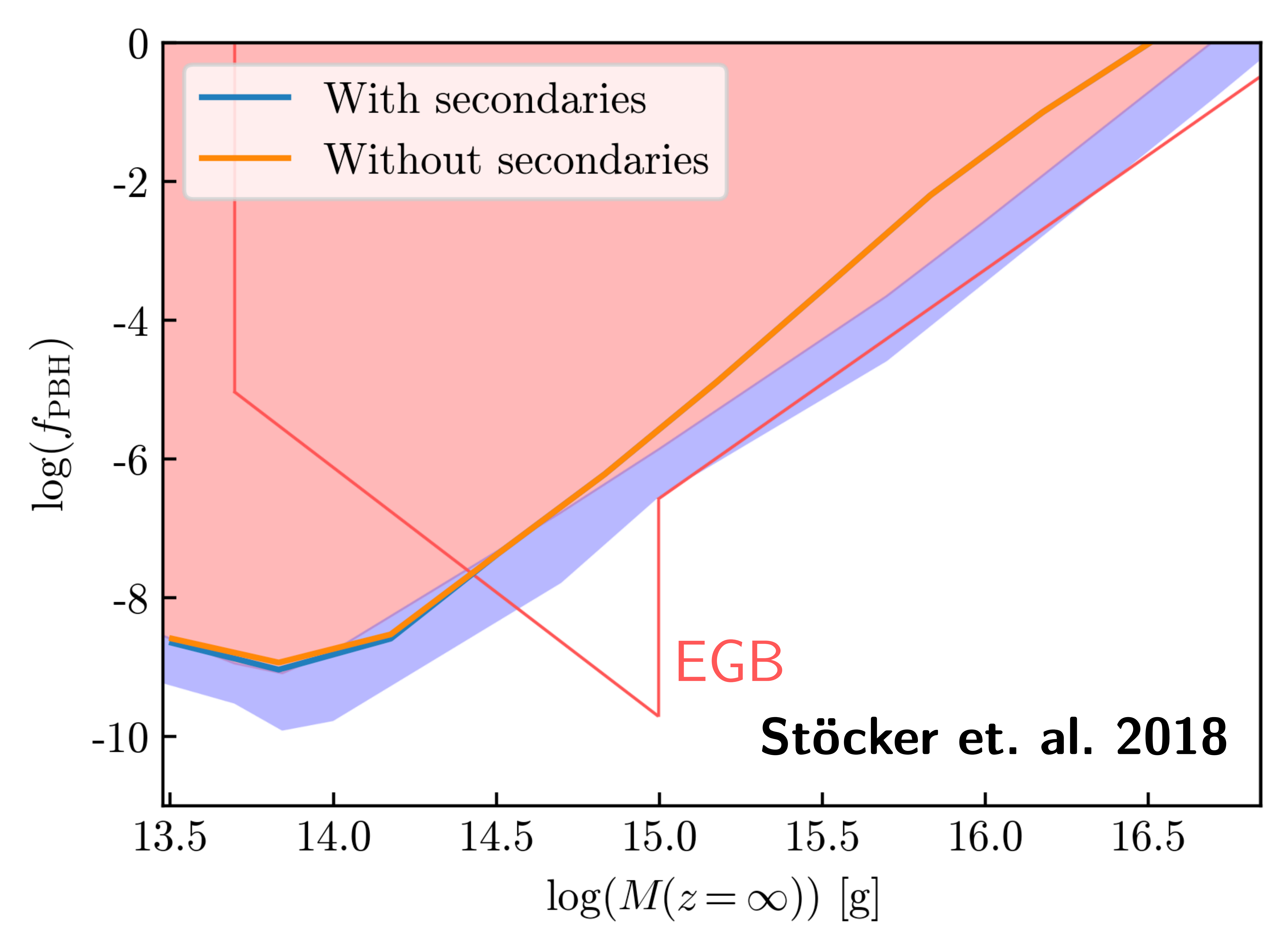
10^{6}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

CMB anisotropies

- Energy deposition after recombination will change the ionization fraction in the „Dark Ages“
- Small scale anisotropies (CMB angular power spectrum) will be damped through rescattering of the photons
- Existing code EXOCLASS to model effect of PBH evaporation on the CMB anisotropies

$$\left.\frac{\mathrm{d}^2E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{dep},\alpha}(z) = h_\alpha(z)\left.\frac{\mathrm{d}^2E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{inj}}(z) = \frac{h_\alpha(z) f_{\mathrm{PBH},0}\rho_{\mathrm{DM,t}}(1+z)^3\dot{M}}{M_0}$$

- Modification of the code to include the memory burden effect
  - Issue 1: Transfer functions do not extend to the energy range of light PBH. For k>0.5 one needs to rely on extrapolation.
  - Issue 2: No secondary emission implemented (yet)
  - Alternative: Rough estimation by rescaling $\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}$

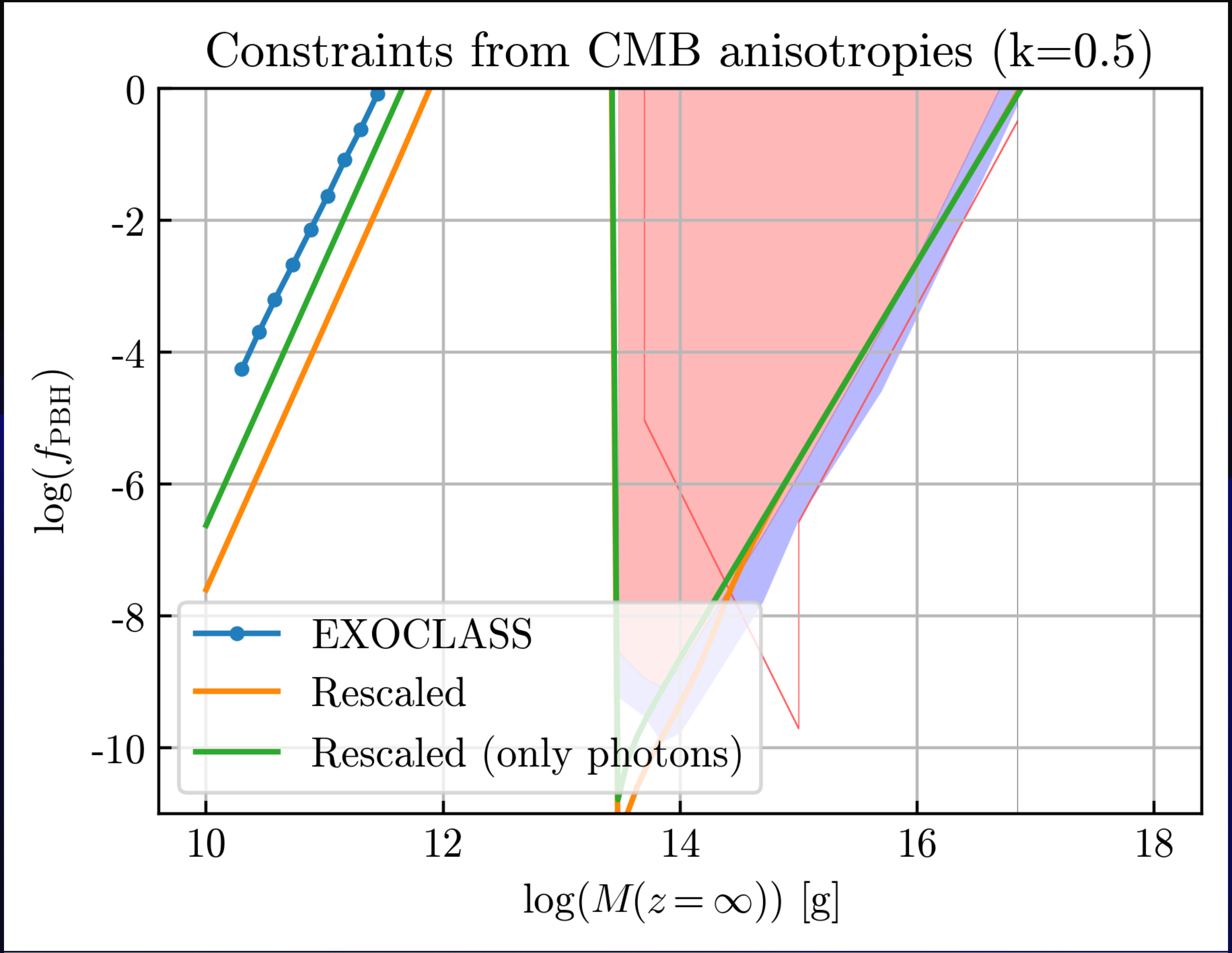


One more caveat:

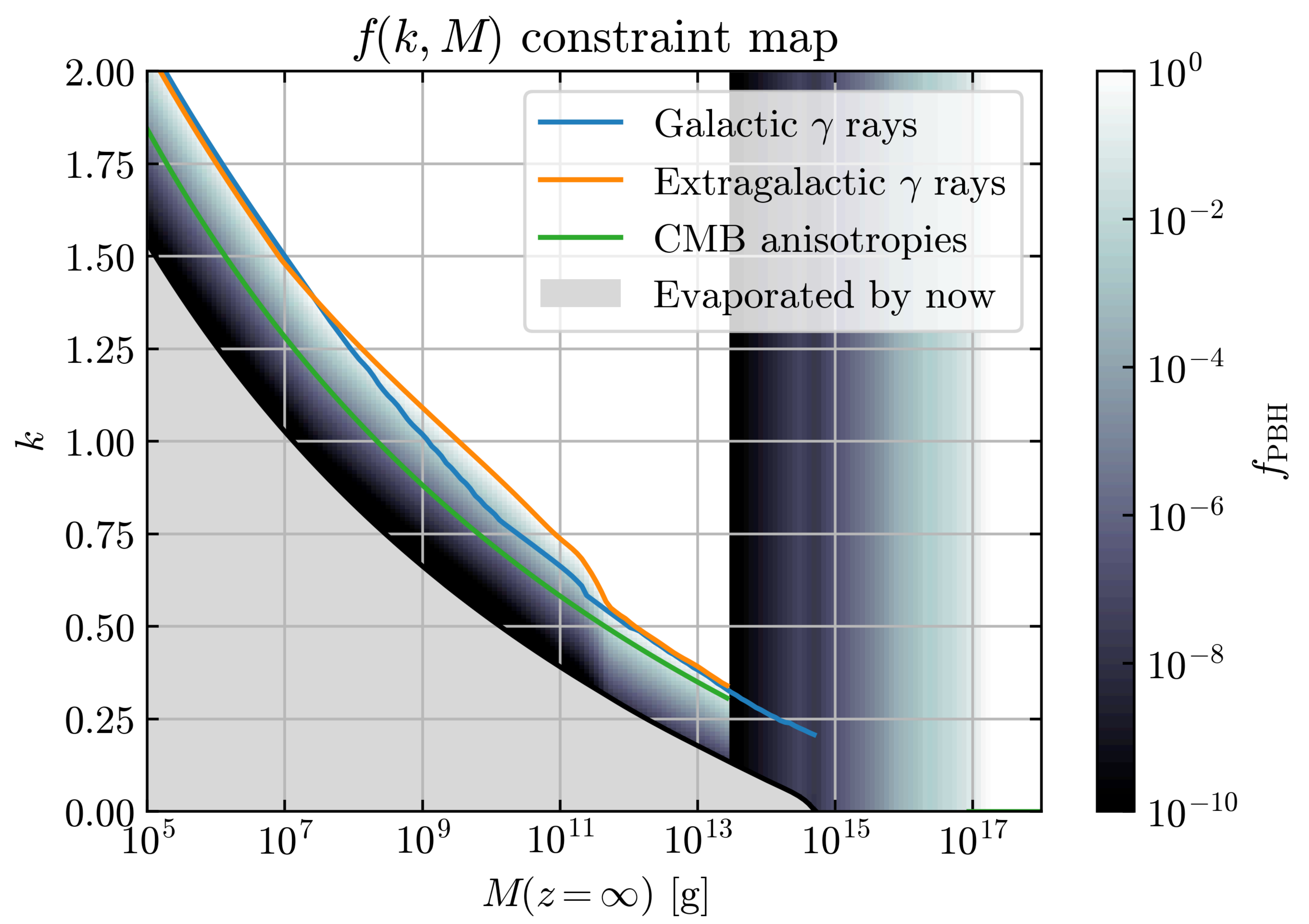
For full (correct) treatment one needs to sample all cosmological parameters e.g. with Montepython

For simplicity (yet) we only set f_{PBH} by requiring $\chi^2_{\rm red} < 1.5$ as an approximation

This produces too mild constraints for $f \sim 1$



Constraints from CMB anisotropies (k=0.5)
0
-2
-4
-6
-8
-10
$\log(f_{\mathrm{PBH}})$
10
12
14
16
18
$\log(M(z=\infty))$ [g]
EXOCLASS
Rescaled
Rescaled (only photons)



$f(k, M)$ constraint map
Galactic γ rays
Extragalactic γ rays
CMB anisotropies
Evaporated by now
k
$M(z=\infty)$ [g]
f_{PBH}
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^5 10^7 10^9 10^{11} 10^{13} 10^{15} 10^{17}
10^0 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10}