

Primordial Black Holes and Ultra High-Energy Cosmic Rays

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What is a PBH?

◆ Black hole formed by gravitational collapse of primordial overdensities (See e.g. [arXiv:2002.12778v2](#))

(Potentially) Formed before any primordial stars

(Potentially) connected with the baryonic asymmetry

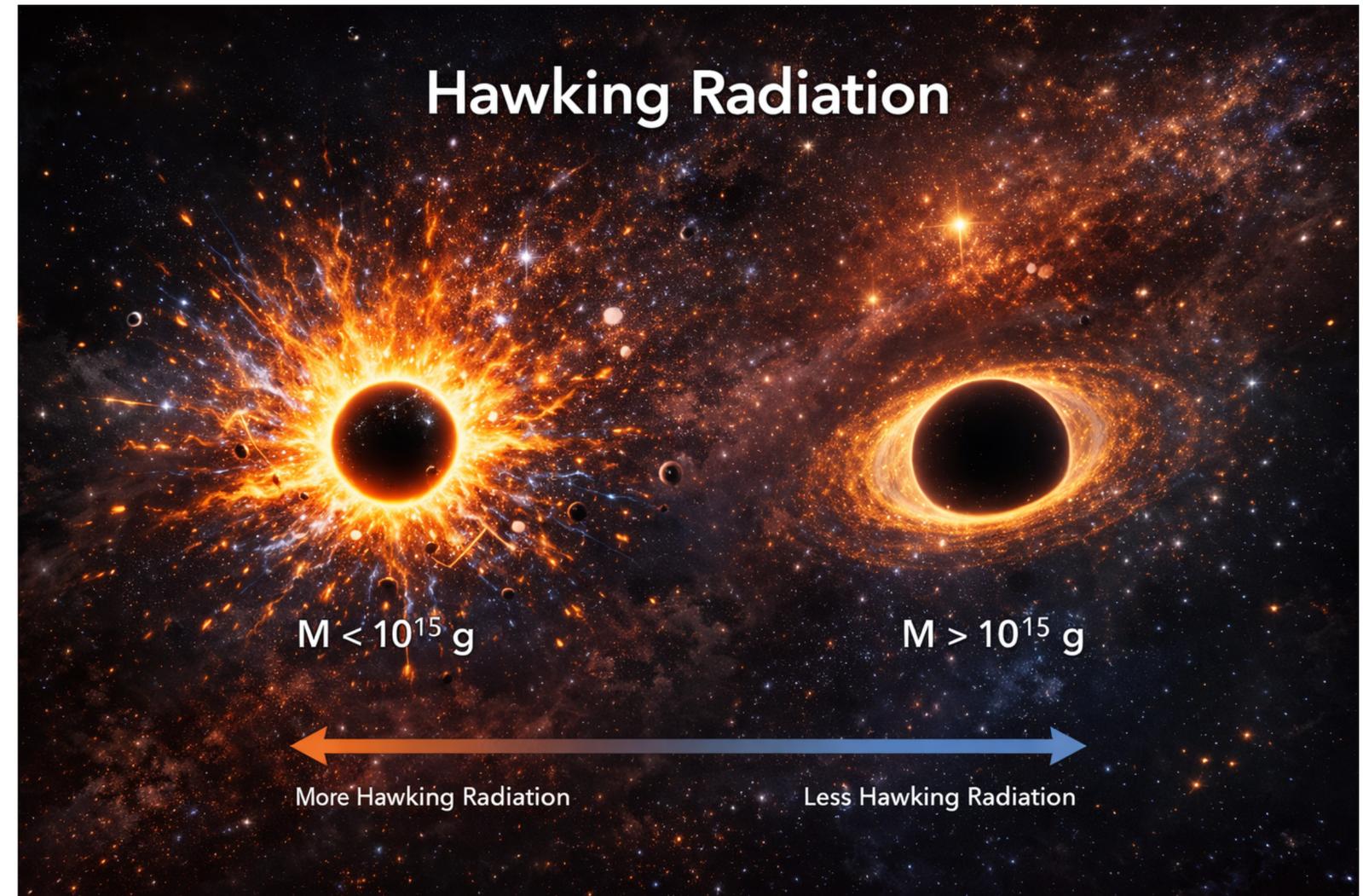
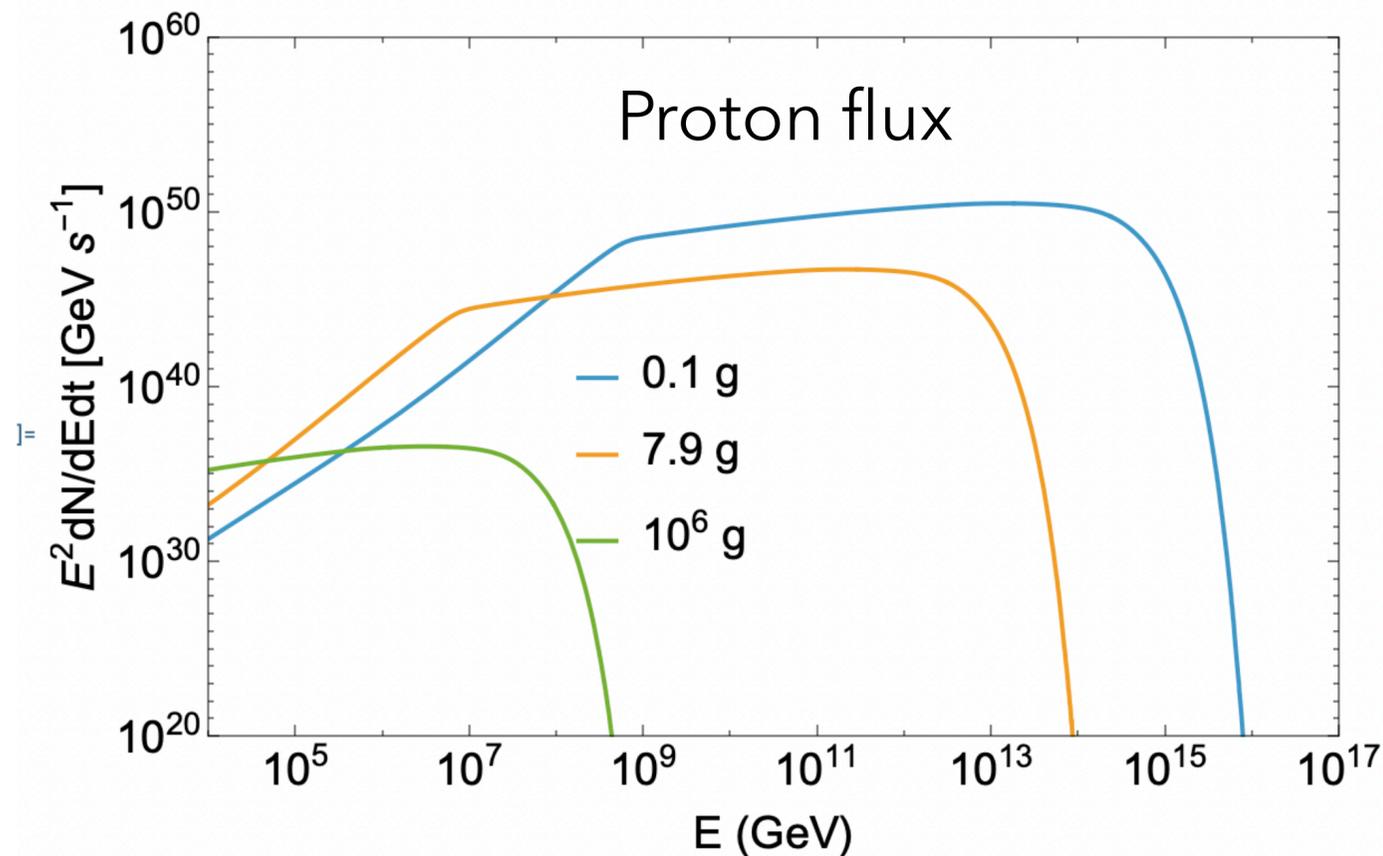
(Potentially) compose some of the dark matter found today



Is there any PBH phenomenology?

- ◆ Hawking demonstrated that black holes behave as thermal emitters of particles.
(Semi-classical approximation, neglecting the black hole's quantum state.)

$$\frac{d^2 N_q}{dE dt}(E, M_{\text{PBH}}) = \frac{g_q}{2\pi} \frac{\mathcal{F}(E, M_{\text{PBH}})}{e^{\frac{E}{k_b \cdot T_H}} - 1}$$



$$T_H = \frac{1}{8\pi G M_{\text{PBH}}} \simeq 10^4 \left(\frac{10^9 \text{ g}}{M_{\text{PBH}}} \right) \text{ GeV}$$

Is there any PBH phenomenology?

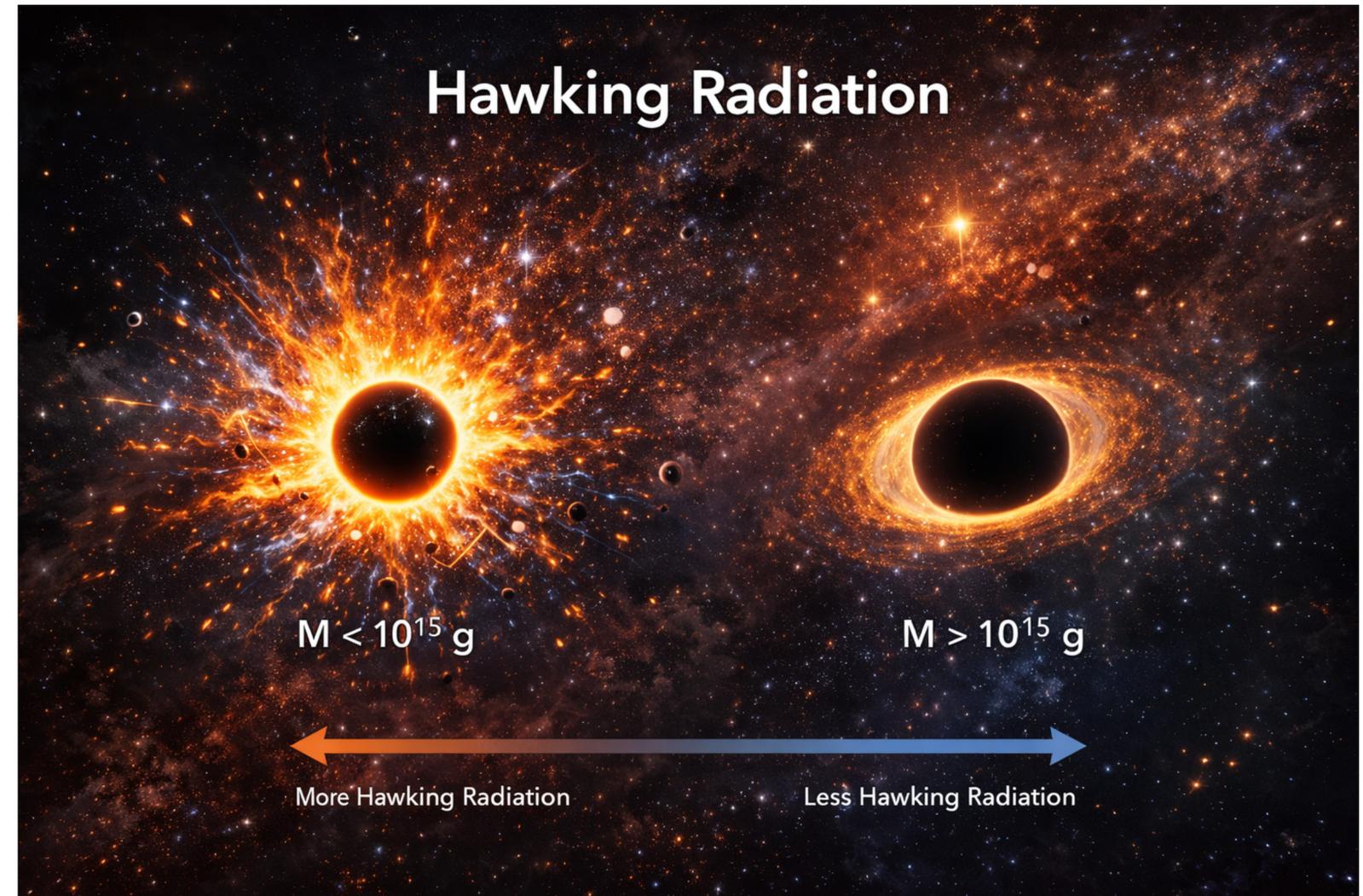
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$$\tau(M) \sim 10^{-36} \left(\frac{M}{1 \text{ g}} \right)^3 \text{ yr}$$



$M \lesssim 10^{15} \text{ g}$ emits more particles but evaporated by now... cosmological interesting (BBN, baryonic asymmetry...)

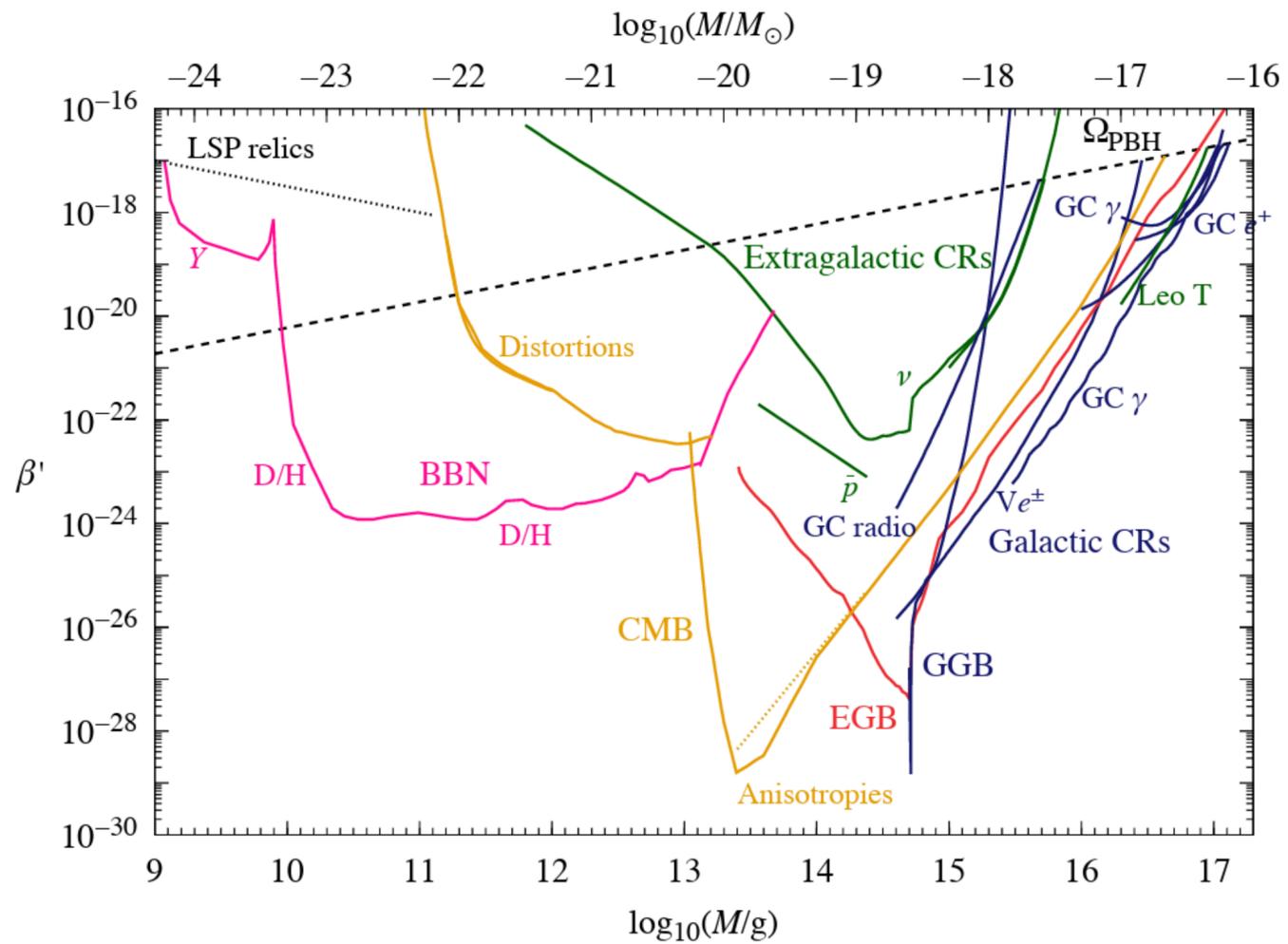
$M \gtrsim 10^{15} \text{ g}$ emits less particles but are still alive now!... potentially constituting Dark Matter



Status of the Constraints

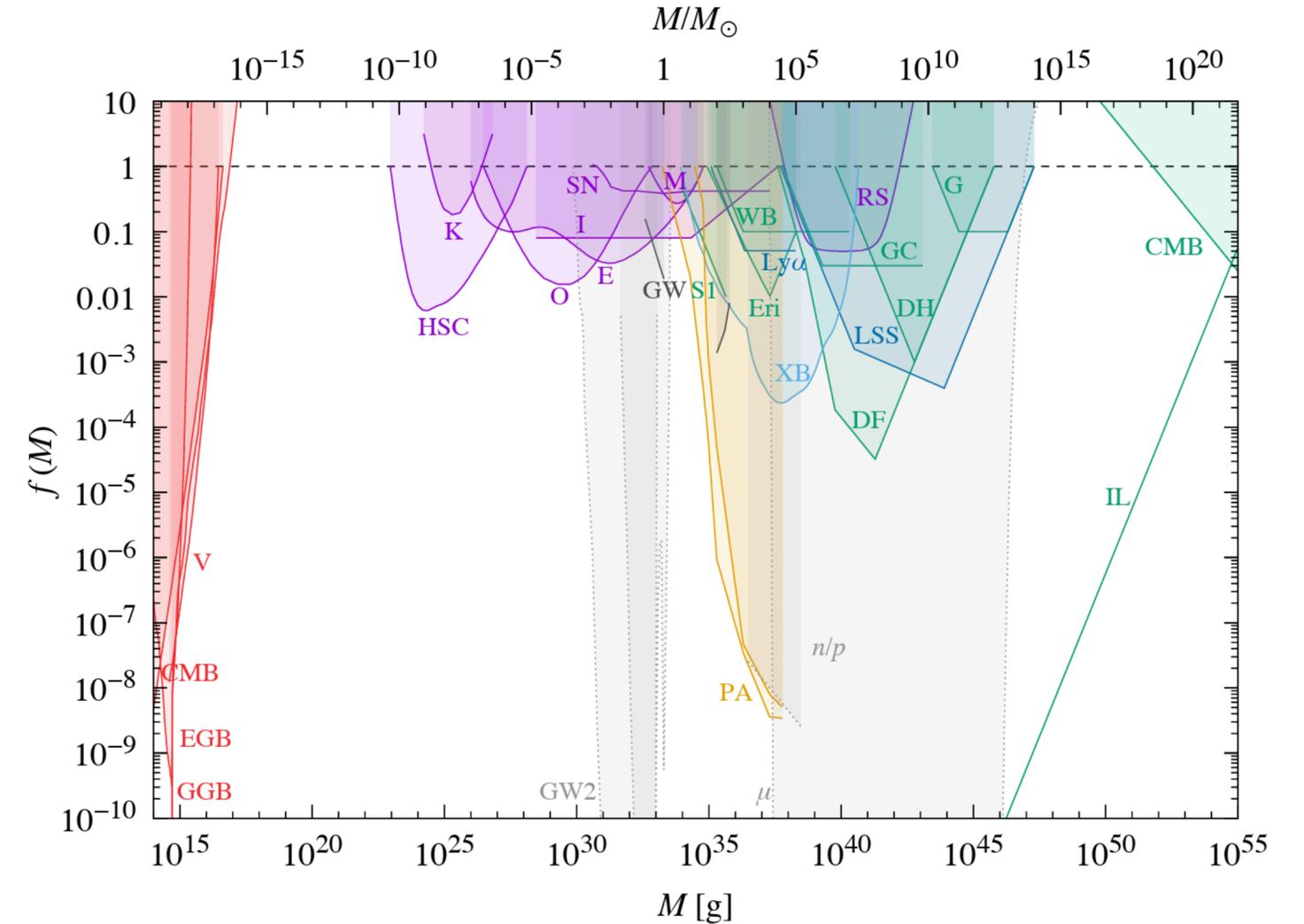
◆ PBHs are yet to be discovered... observables can be used to constrain their parameter space

arXiv:2002.12778v2



$$\beta = \frac{\rho_{\text{PBH}}}{\rho_{\gamma}} \Big|_{t=t_{\text{formation}}}$$

arXiv:2002.12778v2



$$f = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}}$$

And Yet ...

Memory Burden

arXiv:2405.13117v1

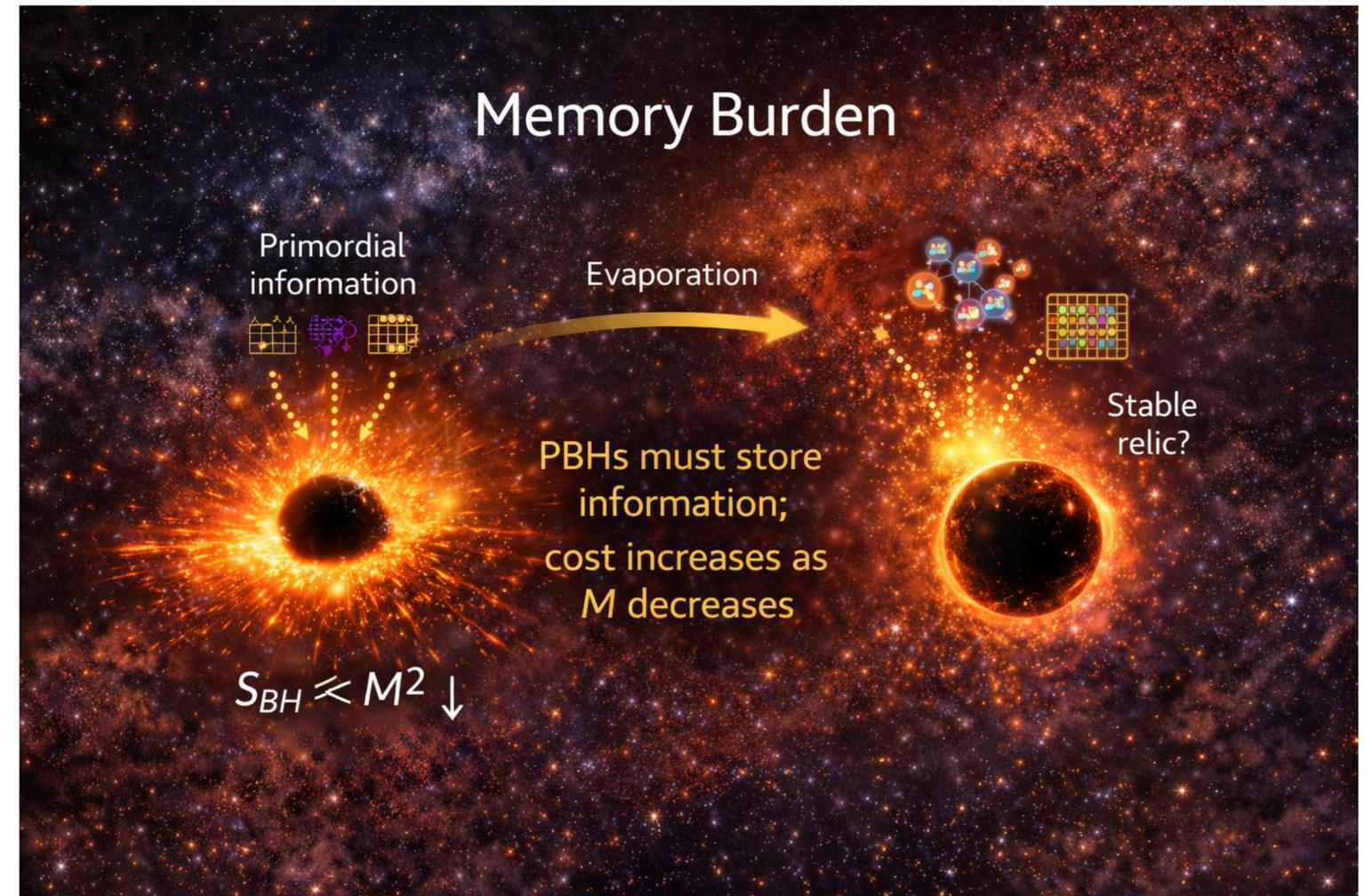
Information loaded in a system resists its decay



When $M_{\text{evaporated}} \simeq \frac{1}{2} M_{\text{BH}}$, the back-reaction of particles on BHs strongly suppresses evaporation



Light PBHs could still be evaporating by now... strong phenomenology connected



Memory Burden

◆ Instantaneous switch between the Semi-Classical and memory-burdened phase at

$$M^{\text{mb}} = q \cdot M_{\text{BH}} \simeq \frac{1}{2} M_{\text{BH}}$$

$$\frac{d^2 N^M}{dE dt}(E, M_{\text{PBH}}, k) = \boxed{\frac{1}{S(q \cdot M_{\text{PBH}})^k}} \frac{d^2 N}{dE dt}(E, q \cdot M_{\text{PBH}})$$

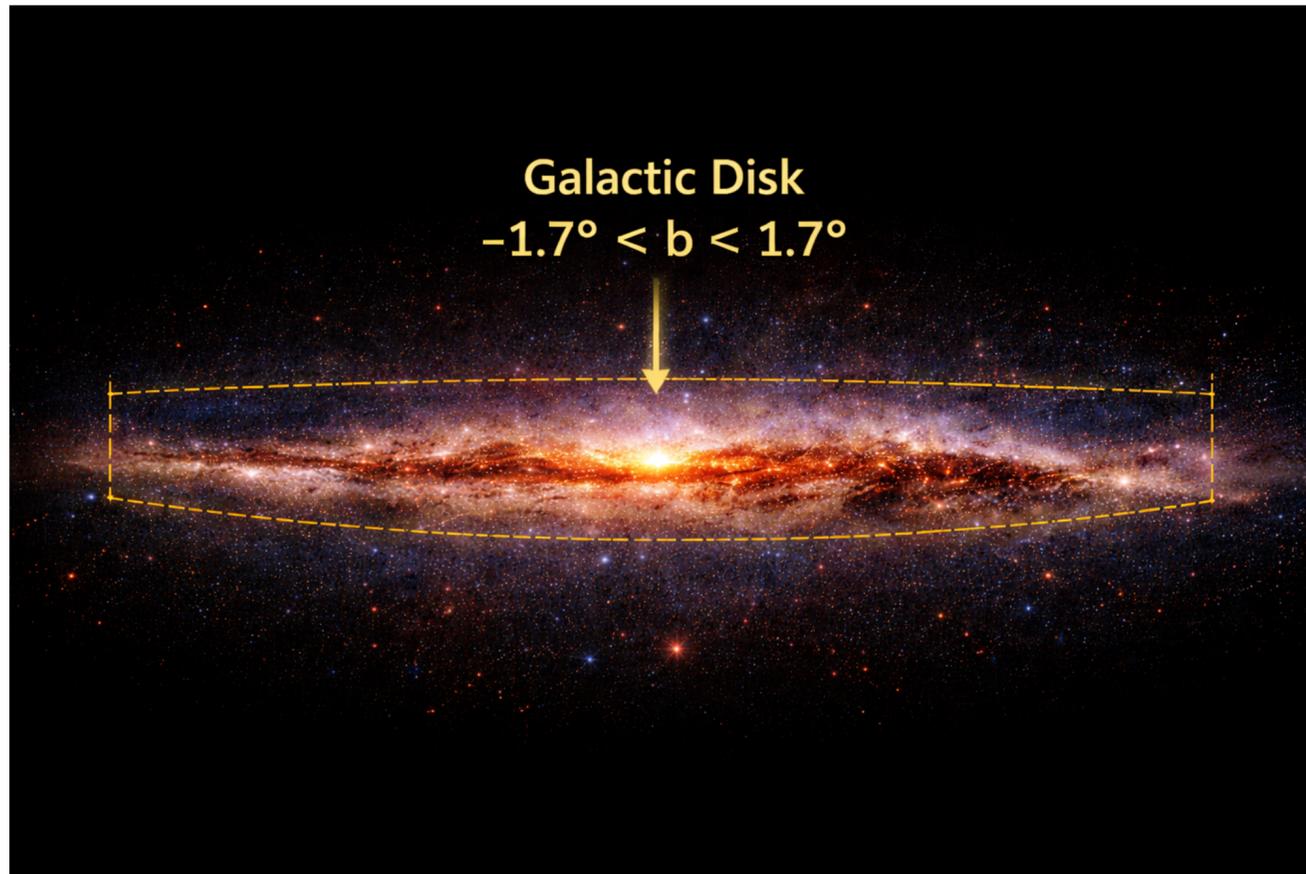


Strong suppression factor given the suppression of the mass ejected ($S = 4\pi GM^2$)

Probing PBHs With UHECRs

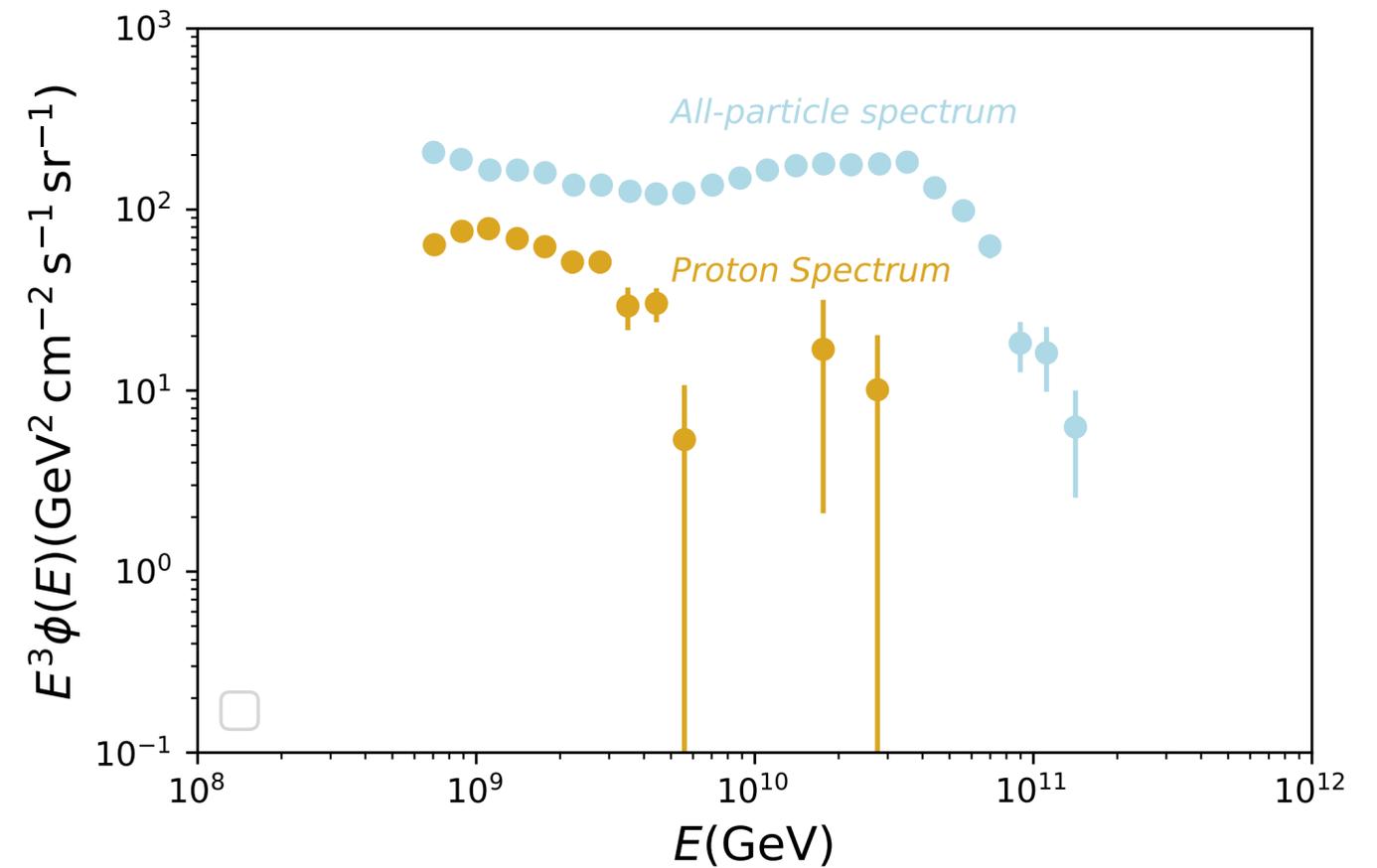
Neutrons

Auger's upper limit: arXiv:1406.4038



$$\phi_{\text{PBH}}^n \lesssim \text{upper limit}$$

Protons



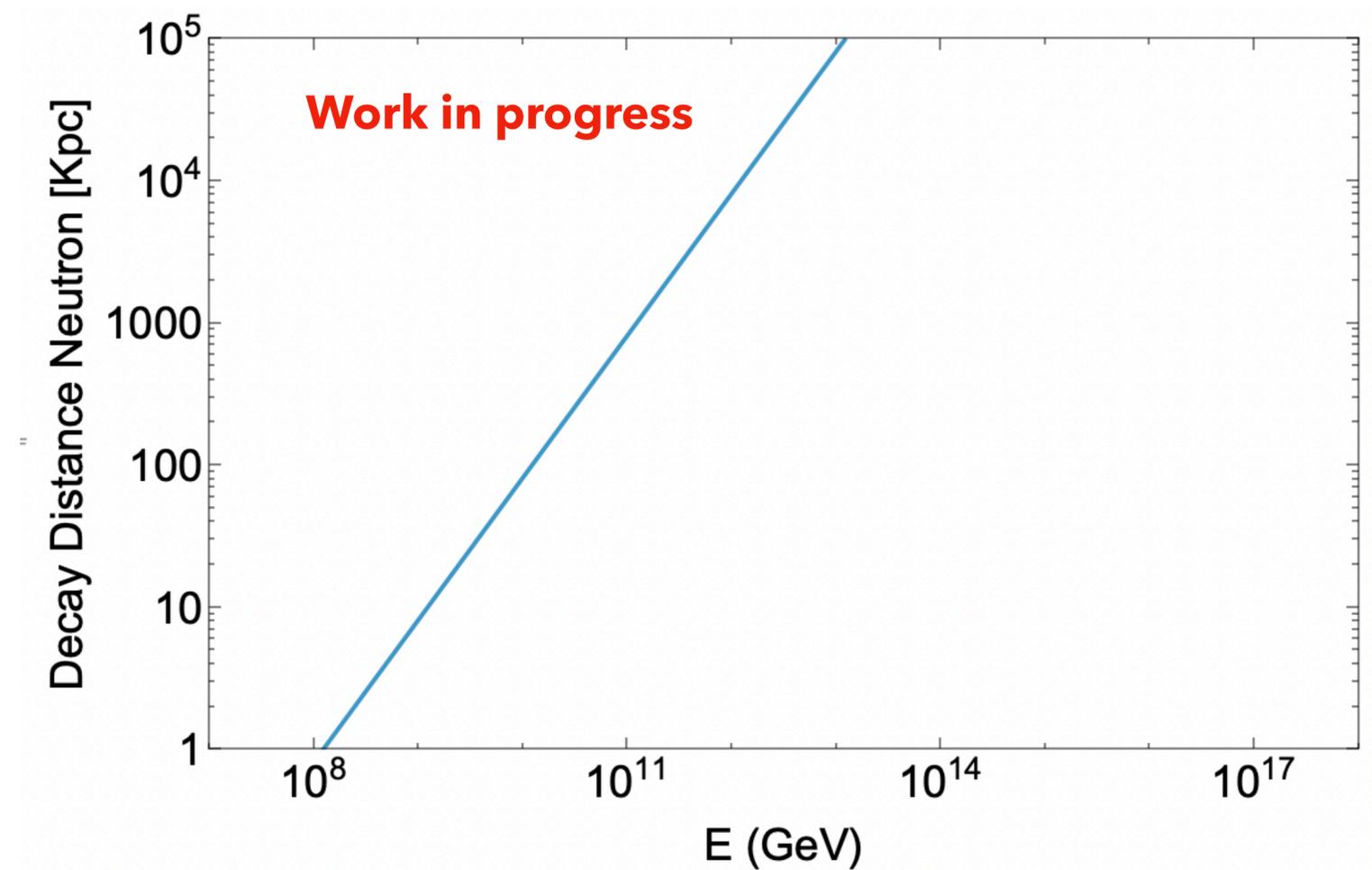
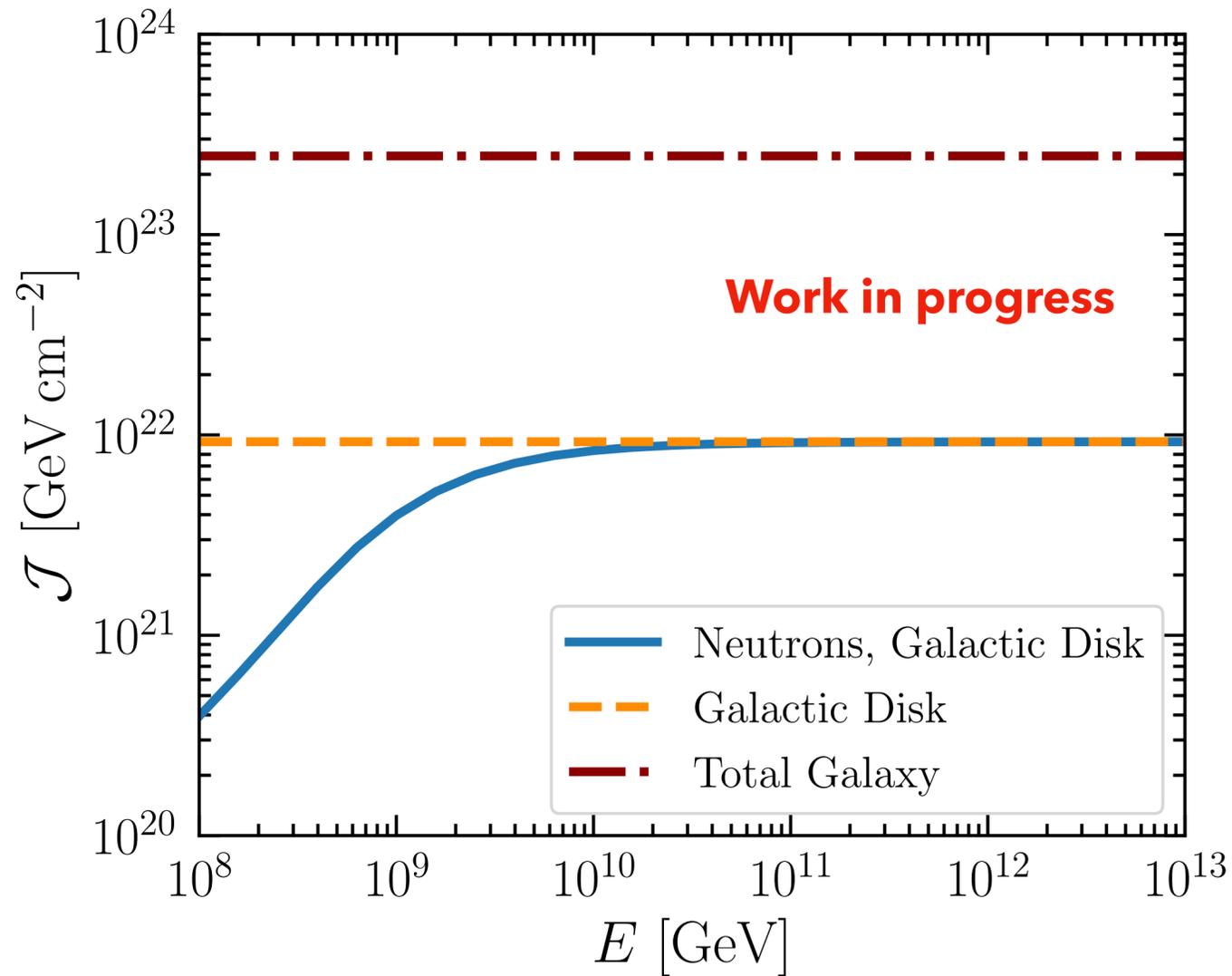
$$\phi_{\text{PBH}}^p \lesssim \phi_p^{\text{AUGER}}$$

Let's Look at the Neutrons

$$\frac{d\phi_{\text{CR}}^G}{dEd\Omega}(E, M_{\text{PBH}}, k) = \frac{1}{4\pi q \cdot M_{\text{PBH}}} \frac{d^2 N_{\text{CR}}^M}{dEdt}(E, M_{\text{PBH}}, k) \mathcal{J}(E, \Omega)$$

$$\mathcal{J}(E, \Omega) = \int_0^{+\infty} ds \rho_{\text{PBH}}(s, \Omega) e^{-s/L_{\text{CR}}(E)}$$

◆ Just galactic because of their decay

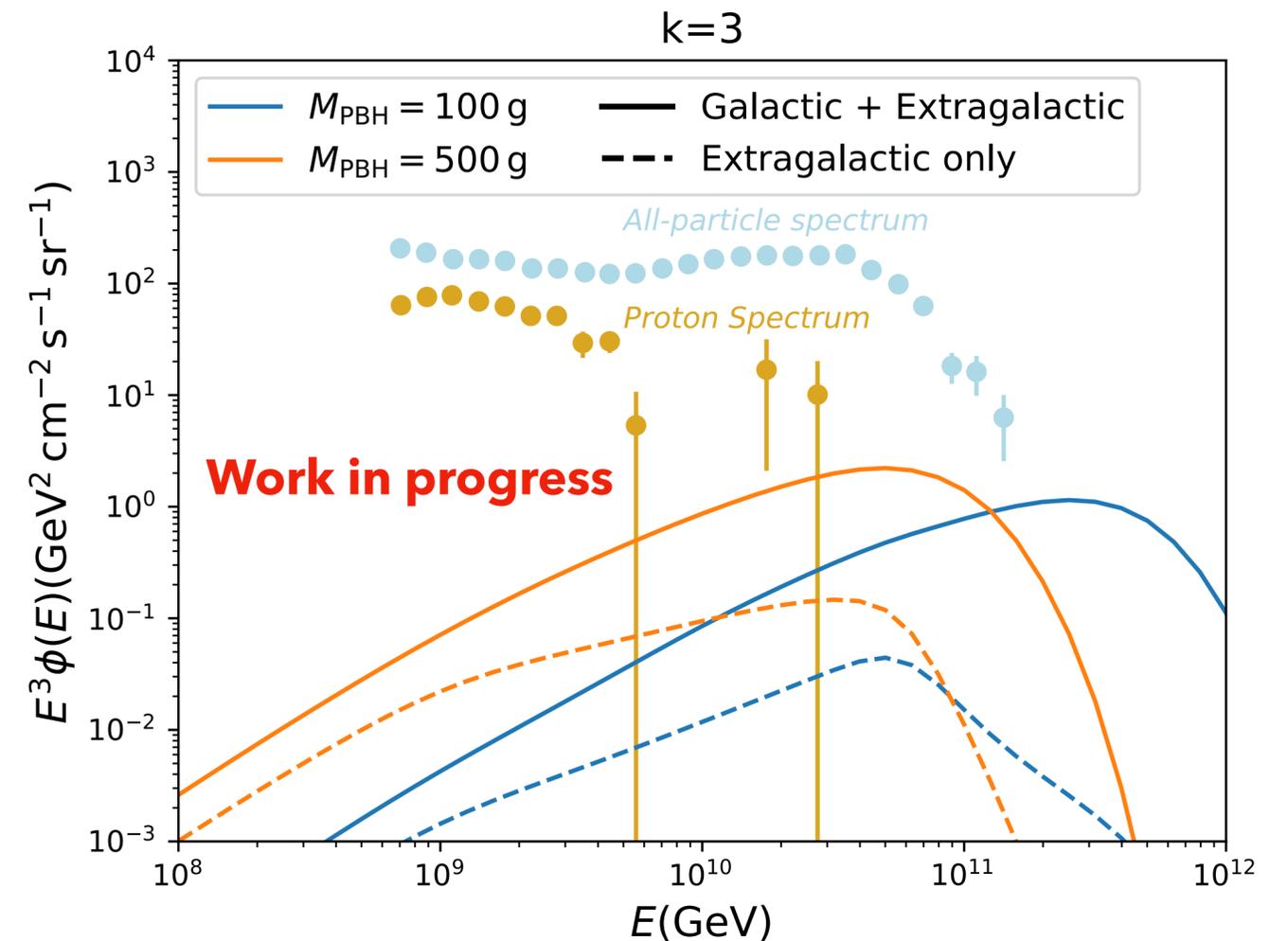
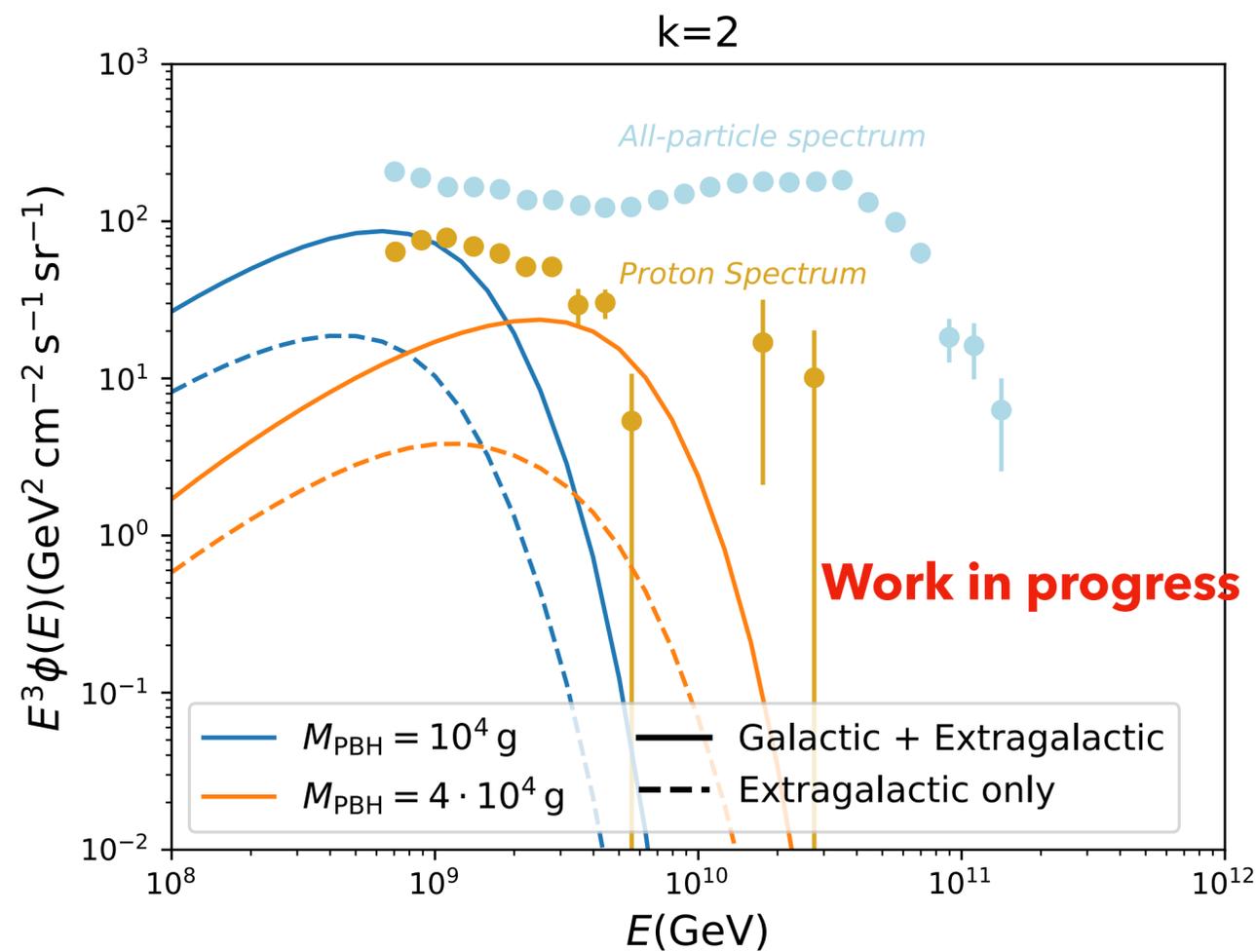


Let's Look at the Protons

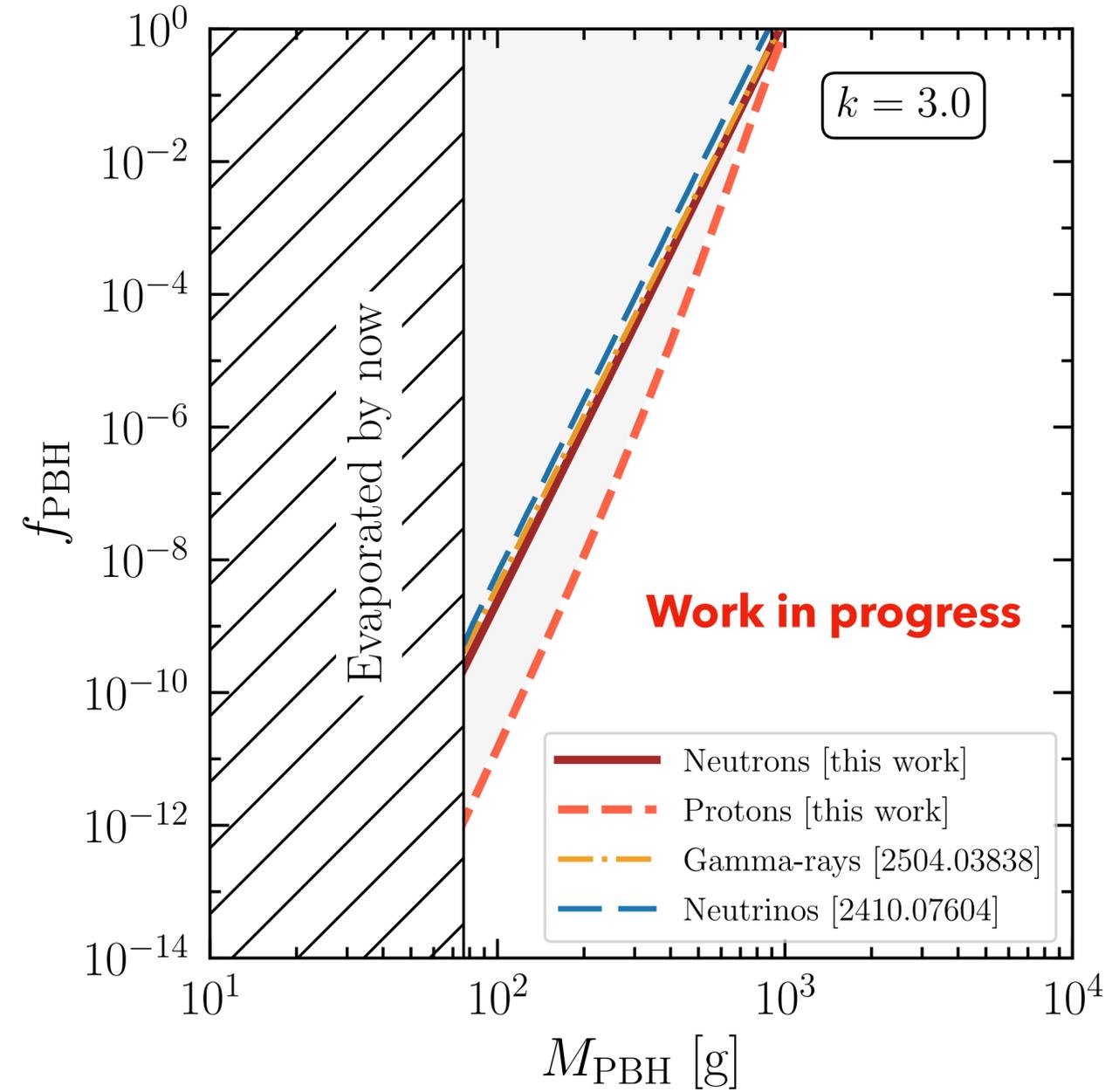
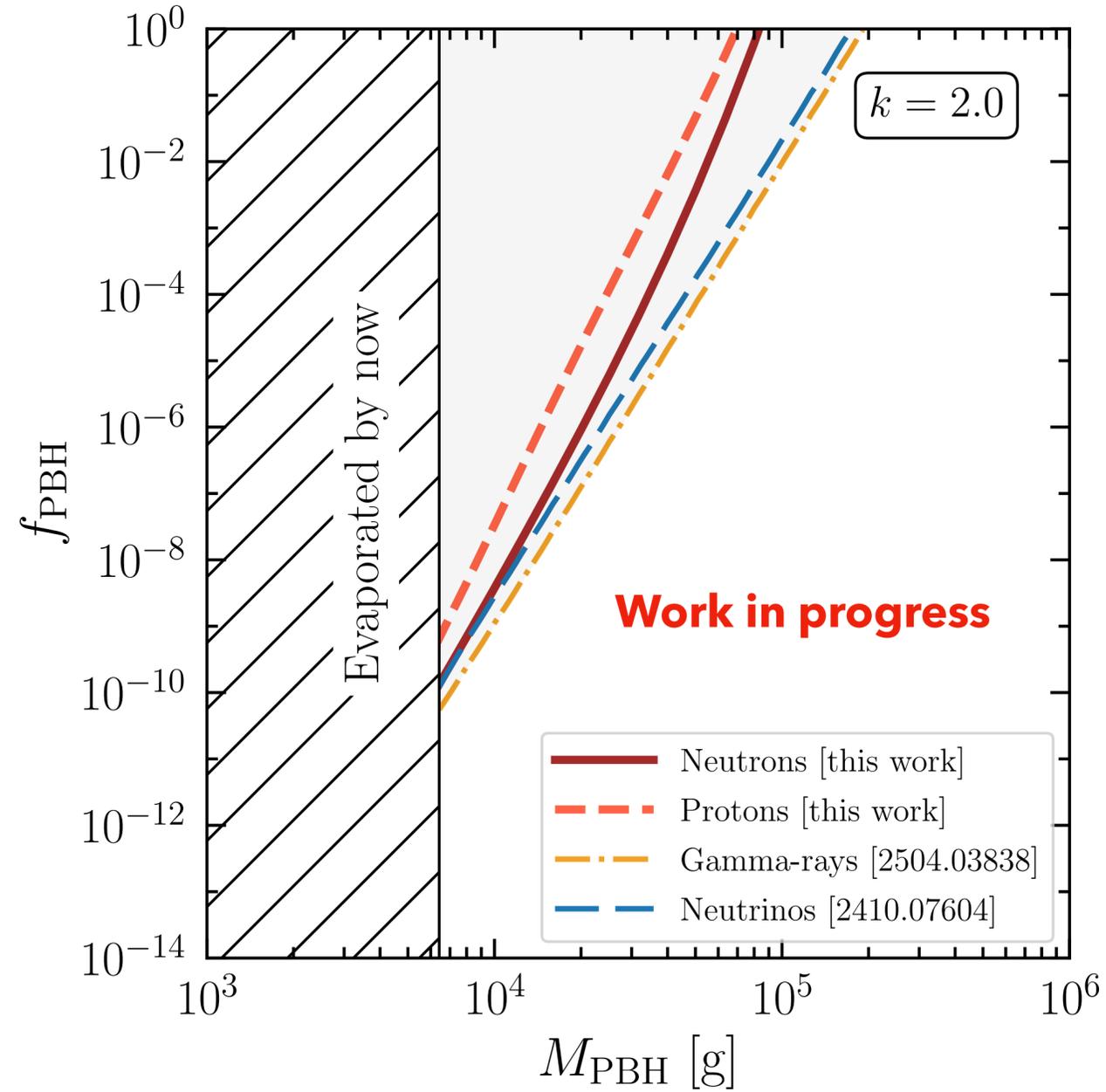
◆ Protons do not decay so Extra-Galactic contribution must be taken into account

$$\frac{d\phi_{\text{CR}}^G}{dEd\Omega}(E, M_{\text{PBH}}, k) = \frac{1}{4\pi q \cdot M_{\text{PBH}}} \frac{d^2 N_{\text{CR}}^M}{dEdt}(E, M_{\text{PBH}}, k) \mathcal{F}(E, \Omega)$$

$$\frac{\phi_p^{\text{EG}}}{dEd\Omega}(E, M_{\text{PBH}}, k) = \frac{\Omega_{\text{DM}} \rho_{\text{cr}} \cdot c f_{\text{PBH}}}{4\pi q \cdot M_{\text{PBH}} H_0} \int_0^{z_{\text{max}}} \frac{dz}{E(z)(1+z)} \frac{dN_p^M}{dEd\Omega}(E_g(E, z), M_{\text{PBH}}, k) \frac{dE_g}{dE}(E, z)$$



Let's Look at the Constraints



Let's Look at the Constraints

