# Direct detection of light dark matter from evaporating primordial black holes


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Based on PRD 105 (2022) 2 [2107.13001] and PRD 105 (2022) 10 [2203.17093]



with Roberta Calabrese, Damiano F.G. Fiorillo, and Ninetta Saviano

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# Dark matter direct-detection experiments

They search for the nuclear recoil energy $E_r$ caused by the possible scatterings with DM particles.

**Very low sensitivity to light DM**

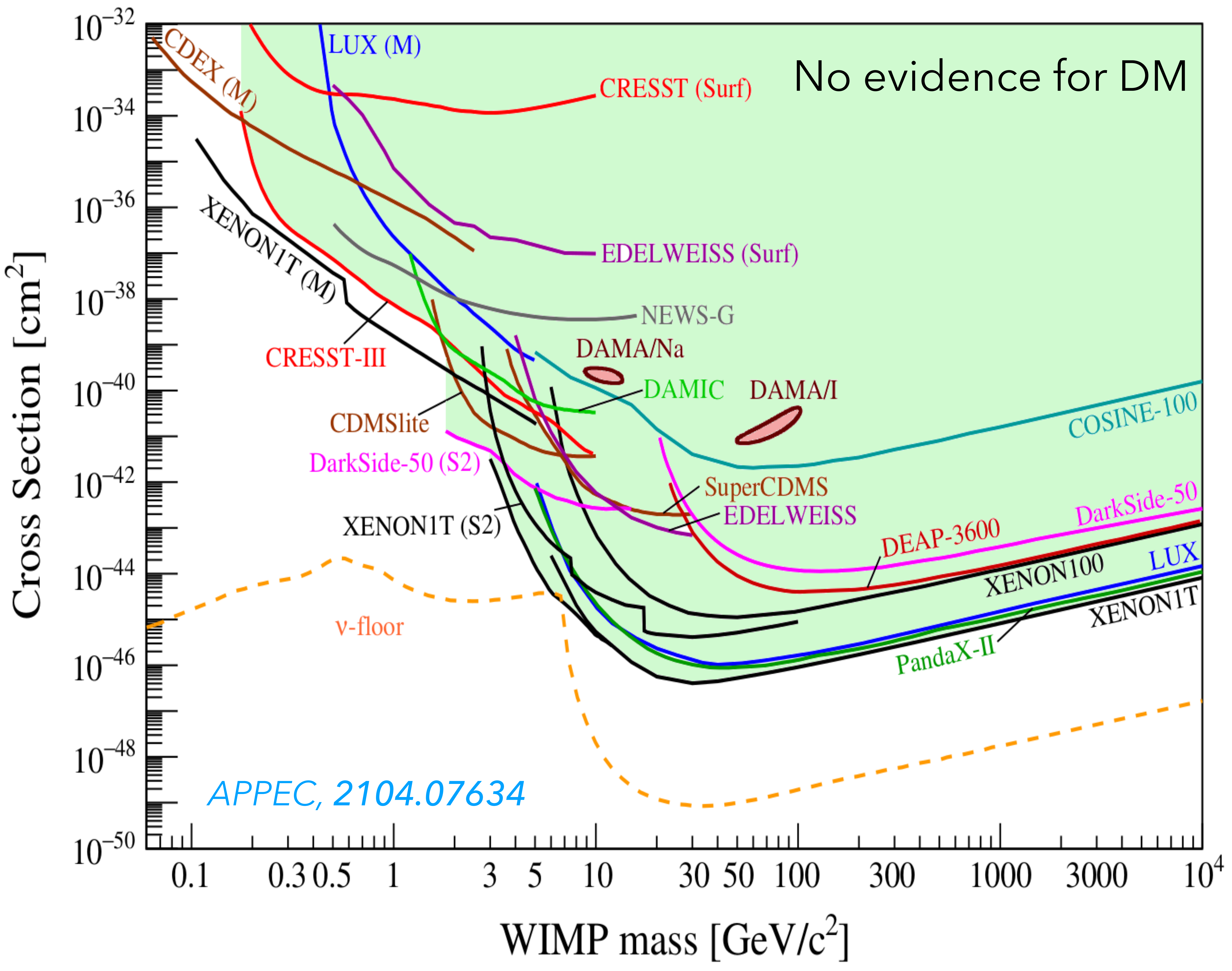
$$\frac{E_r}{50\ \mathrm{keV}} \simeq \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2 \left(\frac{v}{10^{-3}c}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_N}\right)$$

Undetectable energies for $m_\chi \leq 1$ GeV

**Possibile ways out**

- Lighter nuclei (e.g. Argon instead of Xenon)
- Migdal effect
- **Boosted dark matter $v \sim c$**

*Agashe+, **JCAP 1410**; Giudice+, **PLB 780 (2018)**; Fornal+, **PRL 125 (2020)**; Kannike+, **PRD 102 (2020)**; Cappiello+, **PRD 99 (2019)**; Bringmann+, **PRL 122 (2019)**; Ema+, **PRL 122 (2019)**; Cappiello+, **PRD 100 (2019)**; Ema+, **SciPost Phys. 10 (2021)***



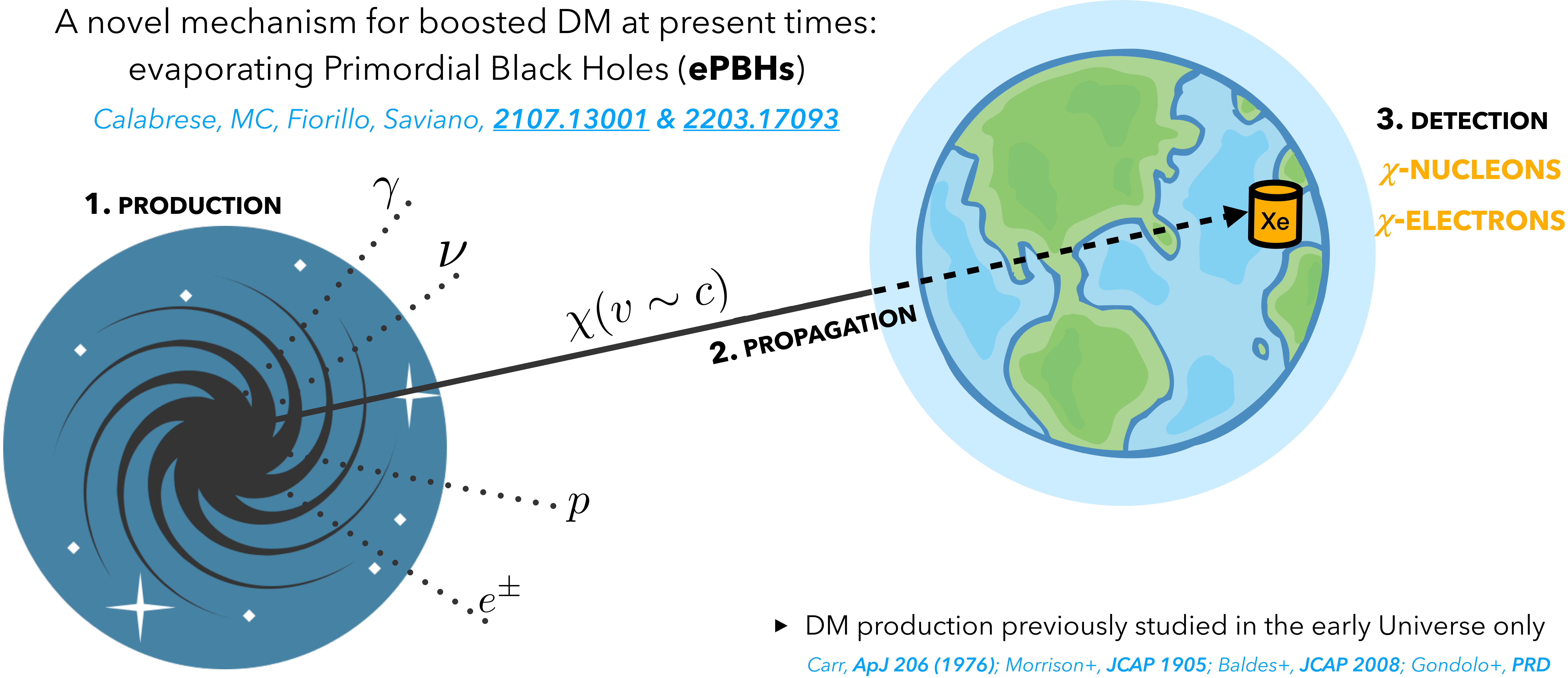



*[see also Mohlabeng's talk]*

# The ePBH-DM scenario

A novel mechanism for boosted DM at present times:
evaporating Primordial Black Holes (**ePBHs**)

*Calabrese, MC, Fiorillo, Saviano,* ***2107.13001*** ***&*** ***2203.17093***

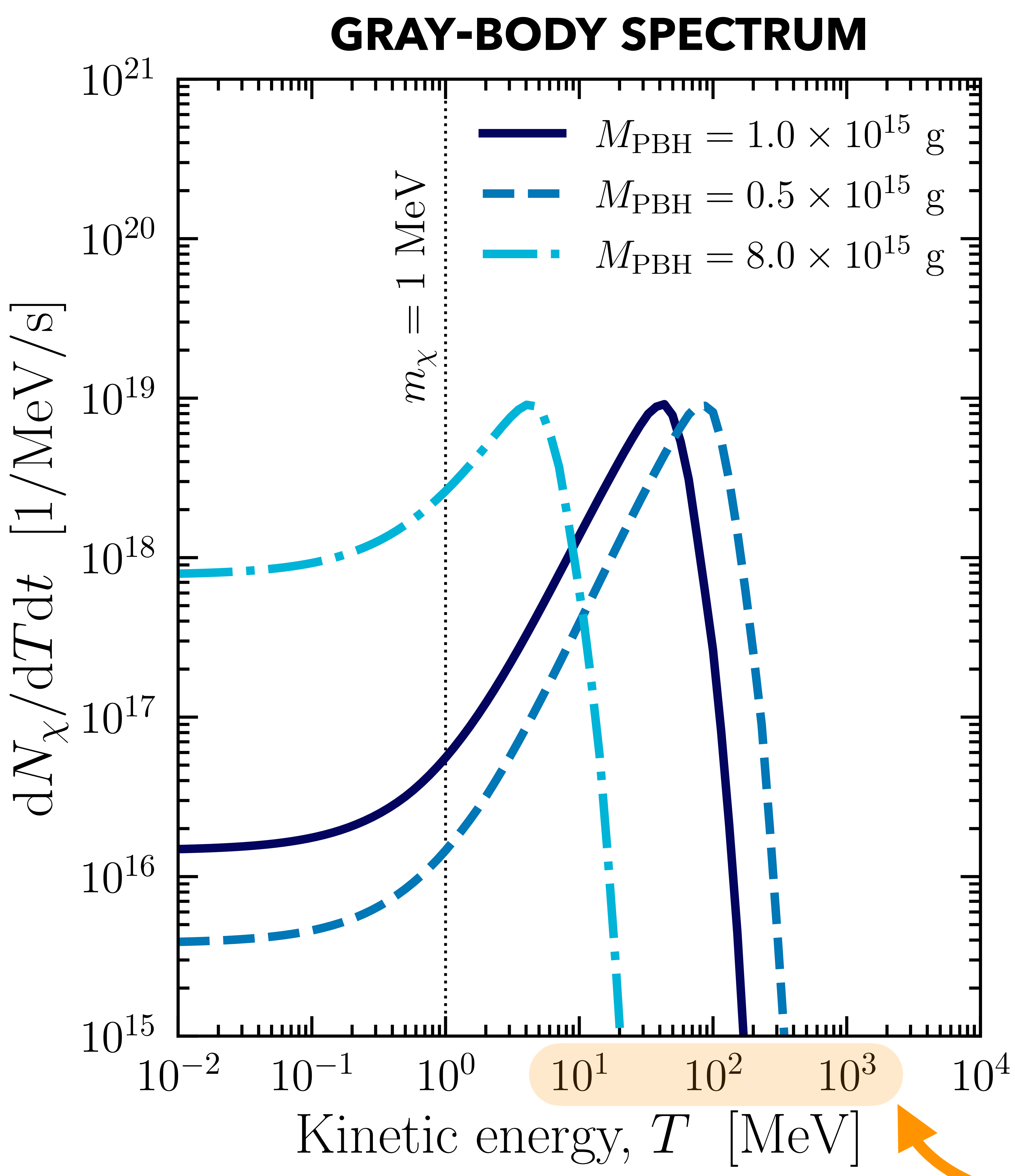



*PBHs possibly exist in our Galaxy and in the whole Universe*

- DM production previously studied in the early Universe only

*Carr,* ***ApJ 206 (1976)****; Morrison+,* ***JCAP 1905****; Baldes+,* ***JCAP 2008****; Gondolo+,* ***PRD 102 (2020)****; Bernal+,* ***JCAP 2103*** *&* ***PLB 815 (2021)****; Auffinger+,* ***EPJP 136 (2021)****; Masina,* ***arXiv:2103.13825****; Cheek+,* ***arXiv:2107.00013*** *&* ***arXiv:2107.00016***

# Evaporating Primordial Black Holes




- PBHs emit thermal Hawking radiation at a temperature:

$$T_{\rm PBH} = 10.6 \left( \frac{10^{15}\ {\rm g}}{M_{\rm PBH}} \right) \ {\rm MeV}$$

*Hawking*, ***Comm. Math. Phys. 43 (1976)***; *Page*, ***PRD 13 (1976)***

- DM particles are efficiently produced if $m_\chi \leq T_{\rm PBH}$

**Calculation details**

- Gray-body factor computed with **BlackHawk** code — *Arbey, Auffinger,* ***EPJC 79 (2019)***
- Spinless and chargeless PBHs (*conservative scenario*)
- Fermionic Dirac dark particles (4 degrees of freedom)

**Relativistic DM particles**

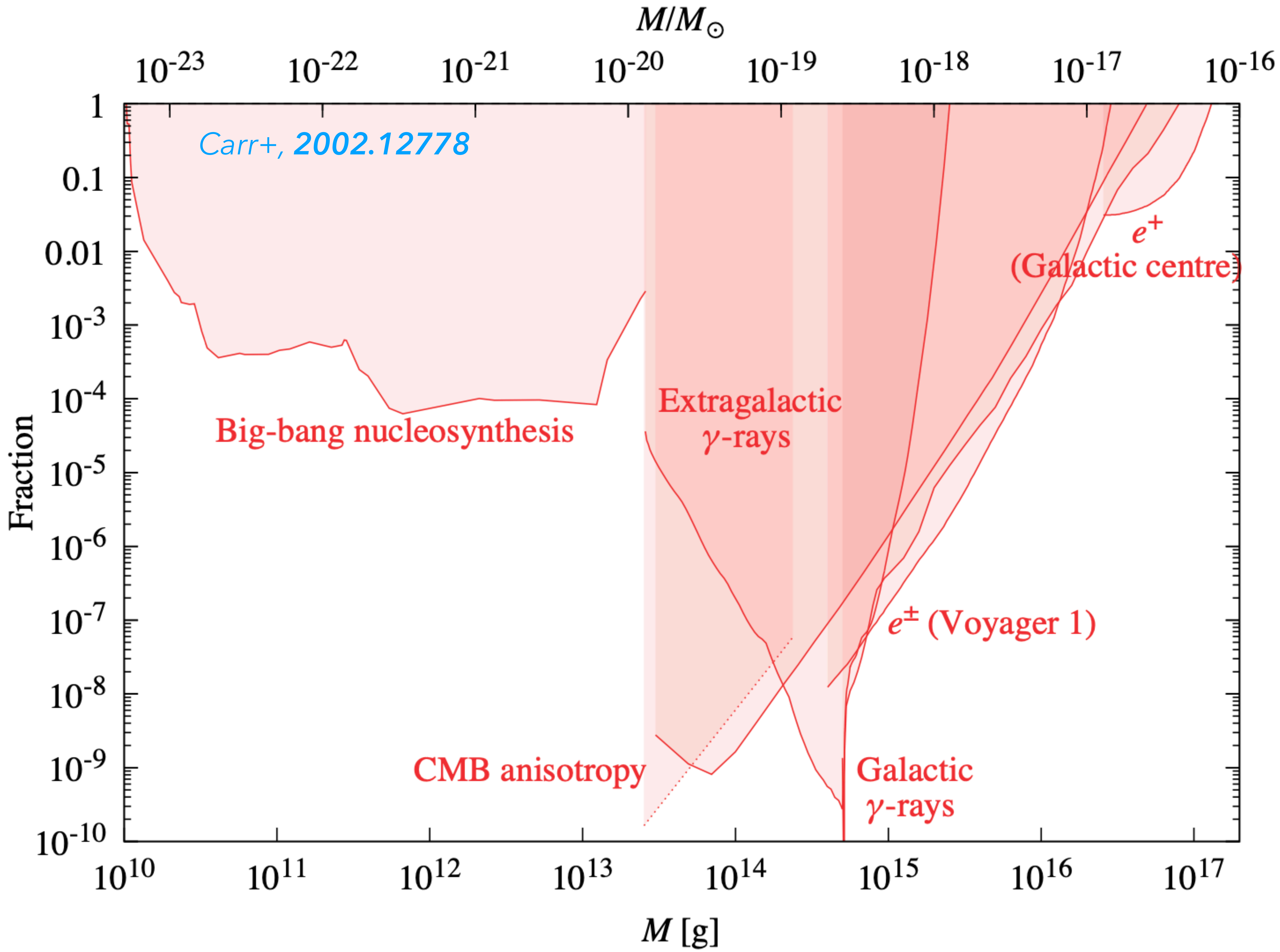
# Constraints on PBH abundance

- Several observations strongly constrain the PBH abundance:

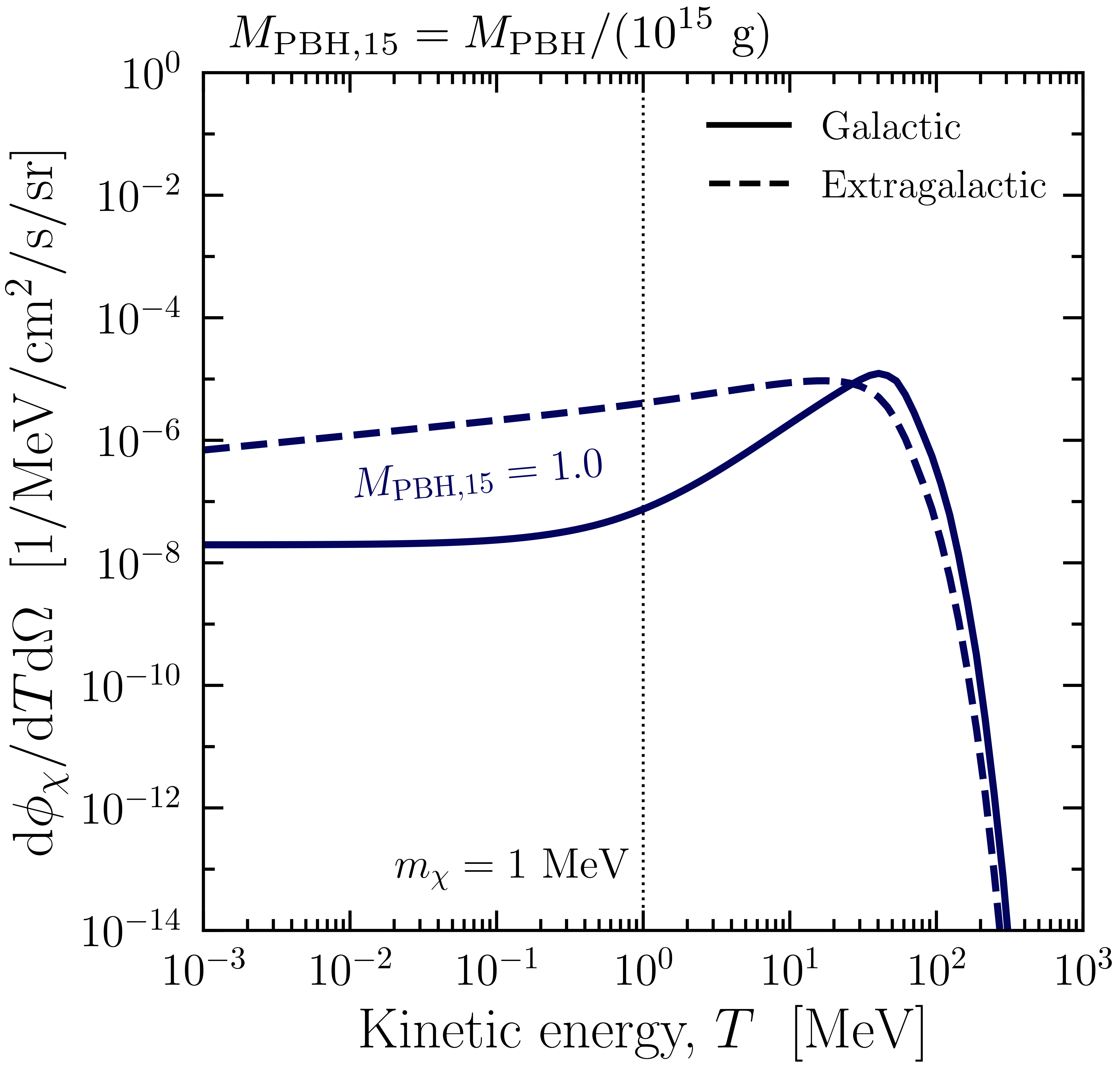
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \ll 1$$

- Active searches for neutrino and gamma-ray bursts from ePBHs!

VERITAS, **J. Phys. Conf. Ser. 375 (2012)**; H.E.S.S., **ICRC (2013)**; HAWC, **Astropart. Phys. 64 (2015)**; VERITAS, **PoS ICRC2017 691 (2018)**; Fermi-LAT, **ApJ 857 (2018)**; HAWC, **JCAP 2004**; IceCube, **PoS ICRC2019 863 (2021)**; SWGO, **2103.16895**



# Diffuse DM flux from ePBHs




## Galactic component

- Navarro-Frenk-White distribution
- Dependent on galactic coordinates

## Extragalactic component

- Cosmological DM distribution with redshift
- Independent from galactic coordinates (isotropic)

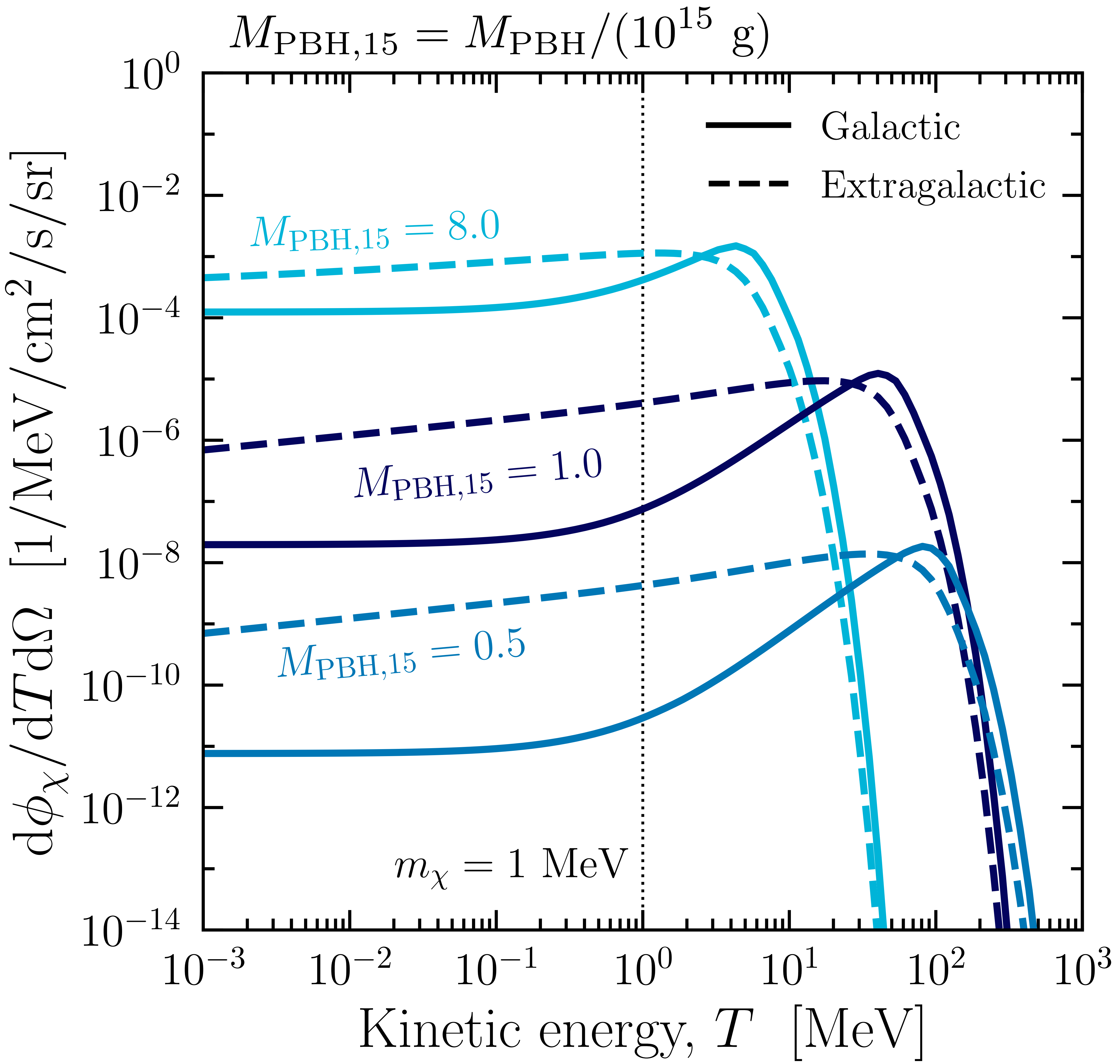
*DM density*

$$\frac{\mathrm{d}\phi_\chi}{\mathrm{d}T\mathrm{d}\Omega} \propto f_{\rm PBH} \cdot \rho_\chi$$

*Maximum allowed value*

*e.g. in this case* $f_{\rm PBH} = 3.9 \times 10^{-7}$

# Diffuse DM flux from ePBHs




## Larger PBH mass

- Smaller Hawking temperature, thus lower energies ⬇
- Slower evaporation rate ⬇
- Weaker constraints on $f_{\rm PBH}$ ⬆

## Smaller PBH mass

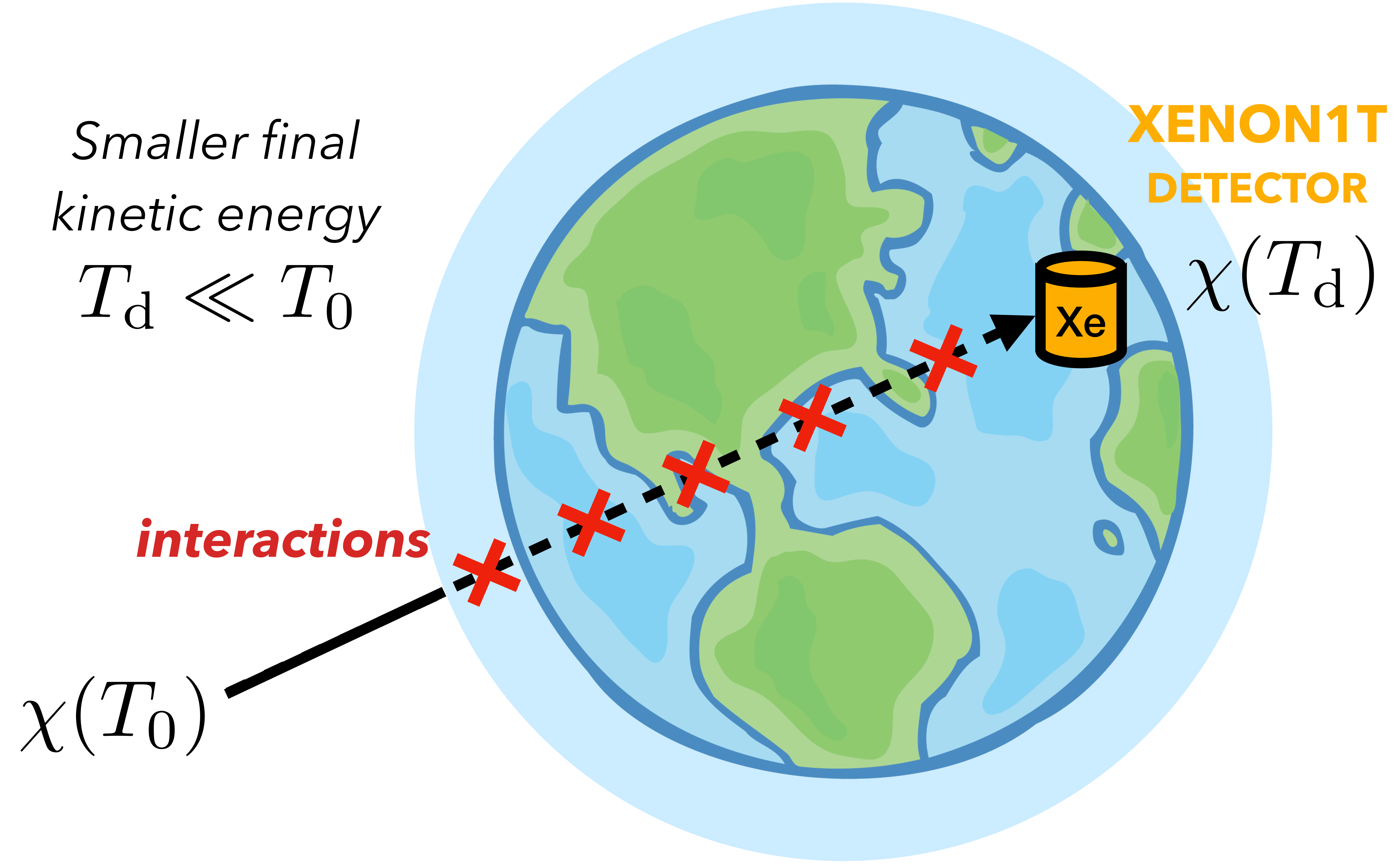
- Larger Hawking temperature, thus higher energies ⬆
- Faster evaporation rate ⬆
- Stronger constraints on $f_{\rm PBH}$ ⬇

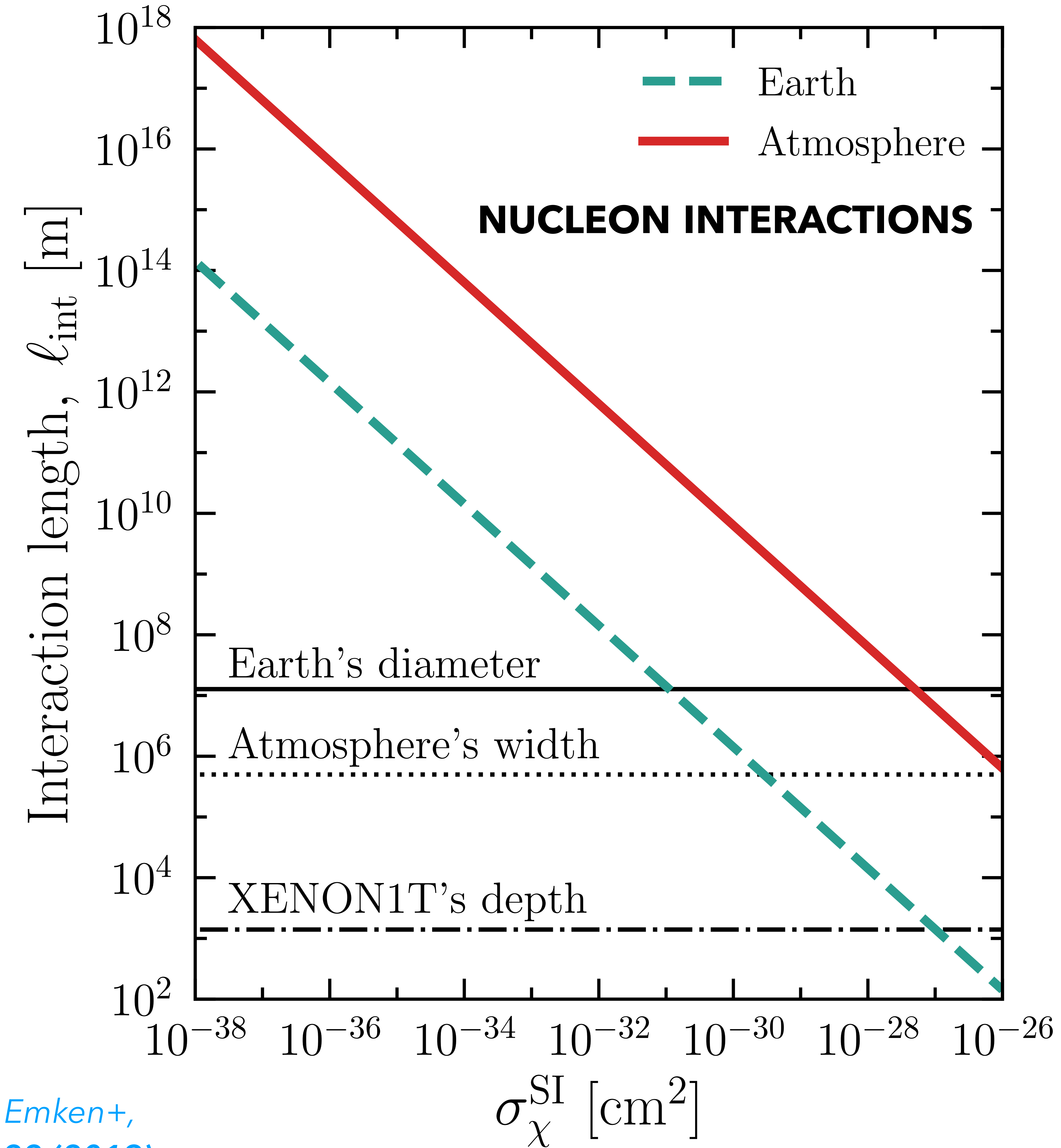
**PBH mass window**

$$10^{14} \lesssim M_{\rm PBH}/{\rm g} \lesssim 10^{18}$$

# Propagation through Earth and atmosphere

We analytically account for the **energy loss** of DM particles in the ballistic-trajectory approximation.



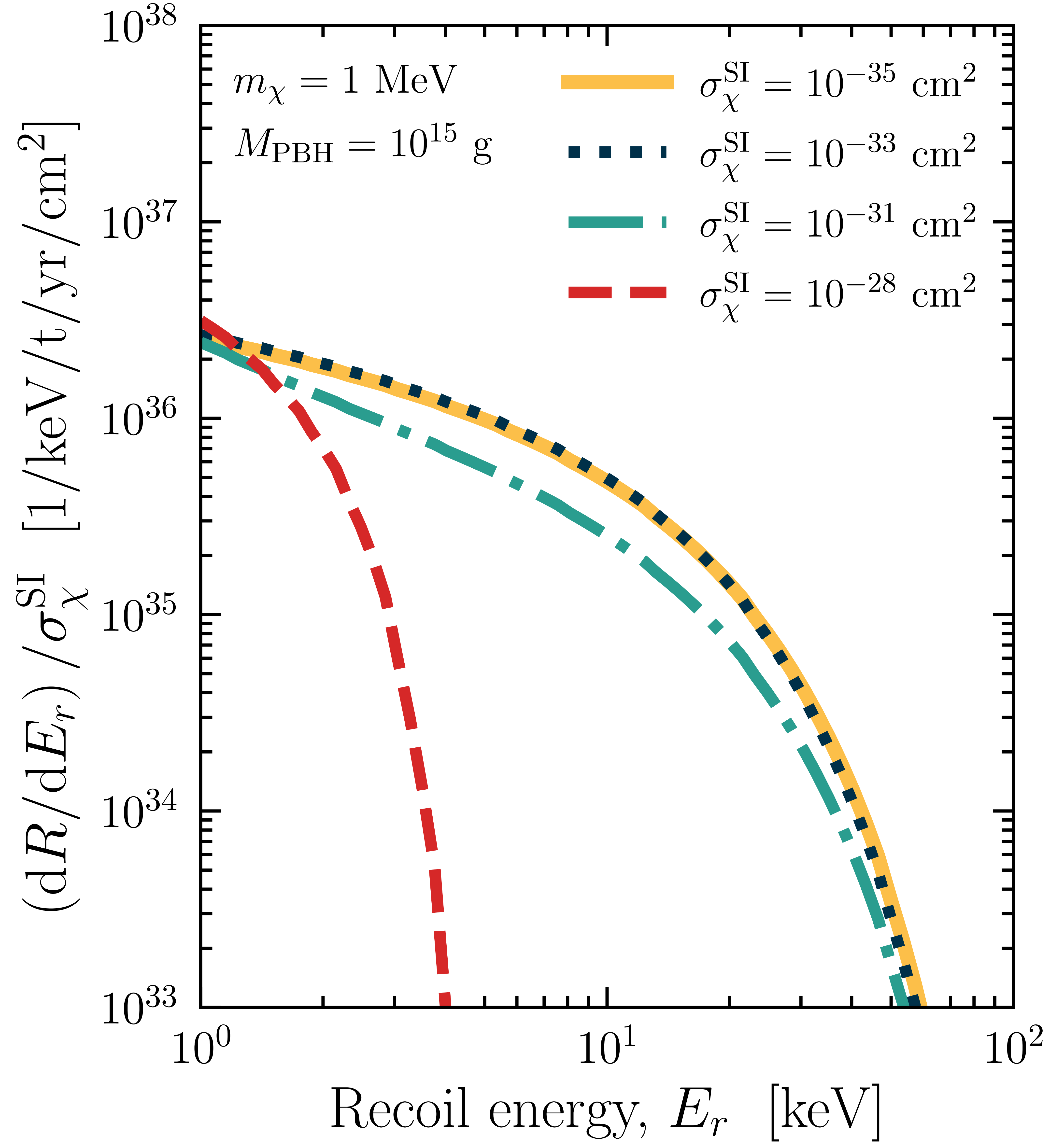

**Propagation effects are important for**

$$\sigma_\chi^{SI} \gtrsim 10^{-31}\ \mathrm{cm}^2$$

*See also: Kavanagh+, **JCAP 1701**; Emken+, **PRD 97 (2018)**; Bringmann+, **PRL 122 (2019)***

# Scatterings with Xe's nucleons

Calabrese, MC, Fiorillo, Saviano, [2107.13001]




$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \sigma_{\chi \mathrm{Xe}} \mathcal{N}_{\mathrm{Xe}} \int \mathrm{d}T_d \mathrm{d}\Omega \, \frac{\mathrm{d}\phi_\chi^d}{\mathrm{d}T_d \mathrm{d}\Omega} \, \frac{\Theta(E_r^{\max} - E_r)}{E_r^{\max}}$$

*Total number of Xenon nuclei (exposure of one ton year)*

*Flat distribution for the maximum allowed recoil energy*

- For small DM-nucleon cross-section, the event rate scale as

$$\frac{\mathrm{d}R}{\mathrm{d}E_r} \propto f_{\mathrm{PBH}} \cdot \sigma_\chi^{\mathrm{SI}}$$

*Strong degeneracy!*

- For $\sigma_\chi^{\rm SI} \gtrsim 10^{-31}$ cm$^2$, the propagation pushes the events to lower recoil energies (see red dashed line).

# DM-nucleon cross-section limits

Calabrese, MC, Fiorillo, Saviano, **2107.13001**

- No excess of events in **XENON1T** from 4.9 to 40.9 keV.

  *Aprile+ (XENON),* ***PRL 121 (2018)***

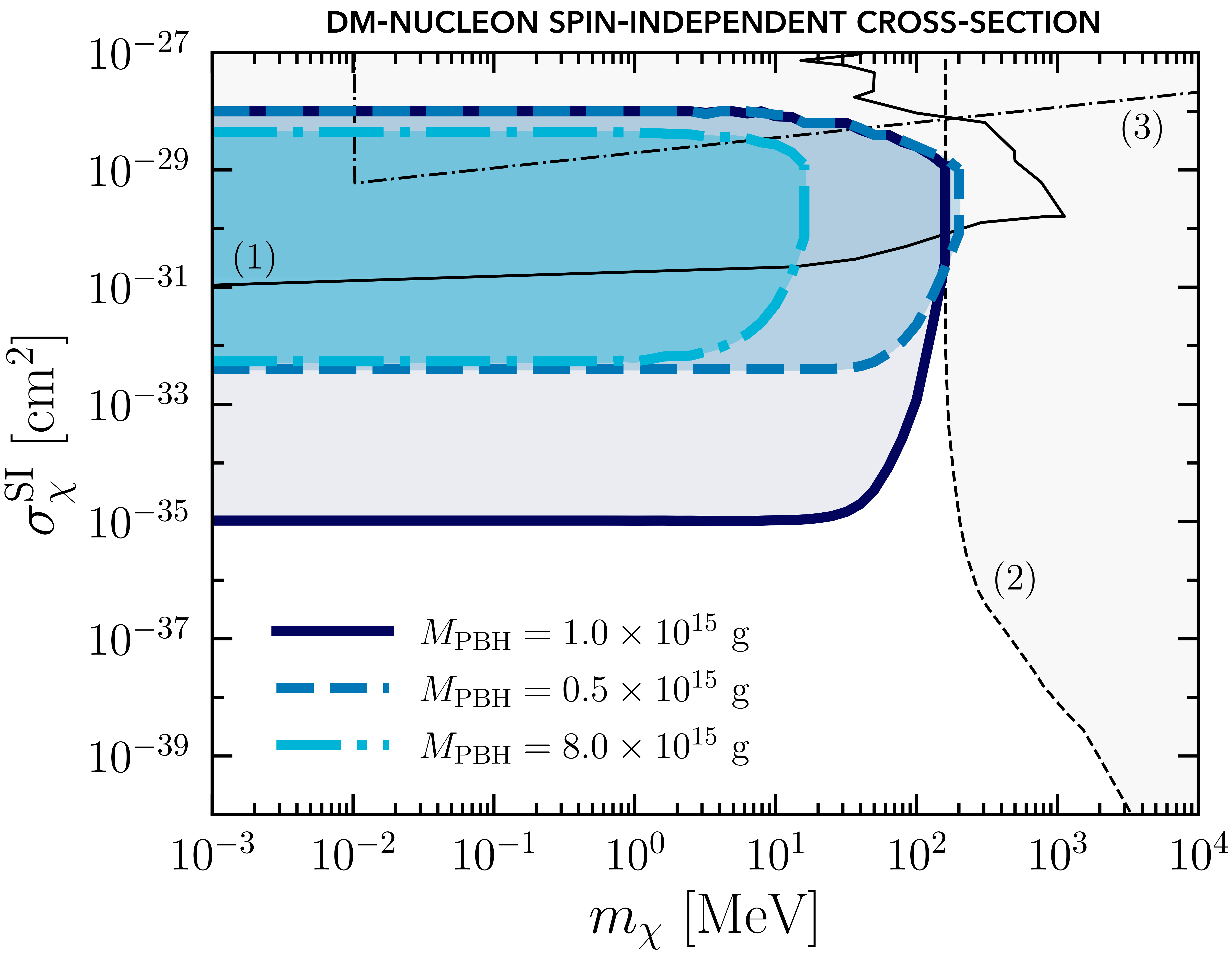
- **Significant improvement with respect to previous constraints:**

(1) CRs up-scatterings

(2) CRESST experiment

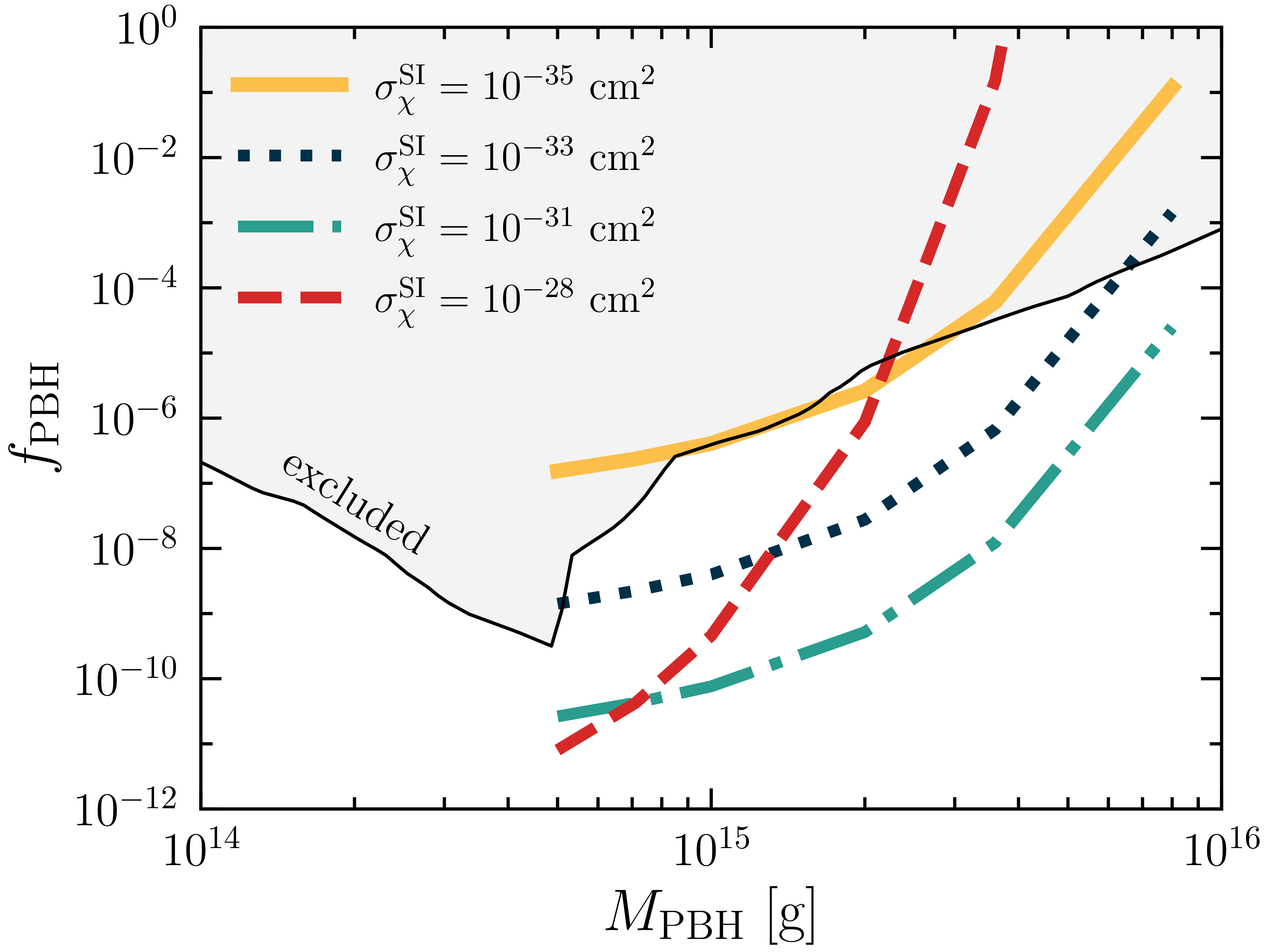
(3) Cosmology

- Our limits extend to lower DM masses though $m_\chi < 1$ keV highly disfavored.



# PBH abudance

*Calabrese, MC, Fiorillo, Saviano, [2107.13001]*




- **Valid in any model of light dark particles.**
- Dependence on the strength of DM-nucleon interactions.
- Almost independent from DM mass.
- For large cross-section, propagation effects are important (see red dashed line).

# Scatterings with Xe's electrons

Calabrese, MC, Fiorillo, Saviano, **2203.17093**

We consider an effective interaction (heavy) mediator and the ionization of bound electrons.

$$\frac{\mathrm{d}R_\chi}{\mathrm{d}E_r} = n_t\,\eta(E_r)\,F(E_r)\int \mathrm{d}T\,\frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T}\sum_{n,\,l}\frac{\mathrm{d}\sigma^{n,\,l}}{\mathrm{d}E_r}(E_r, m_\chi, T)$$

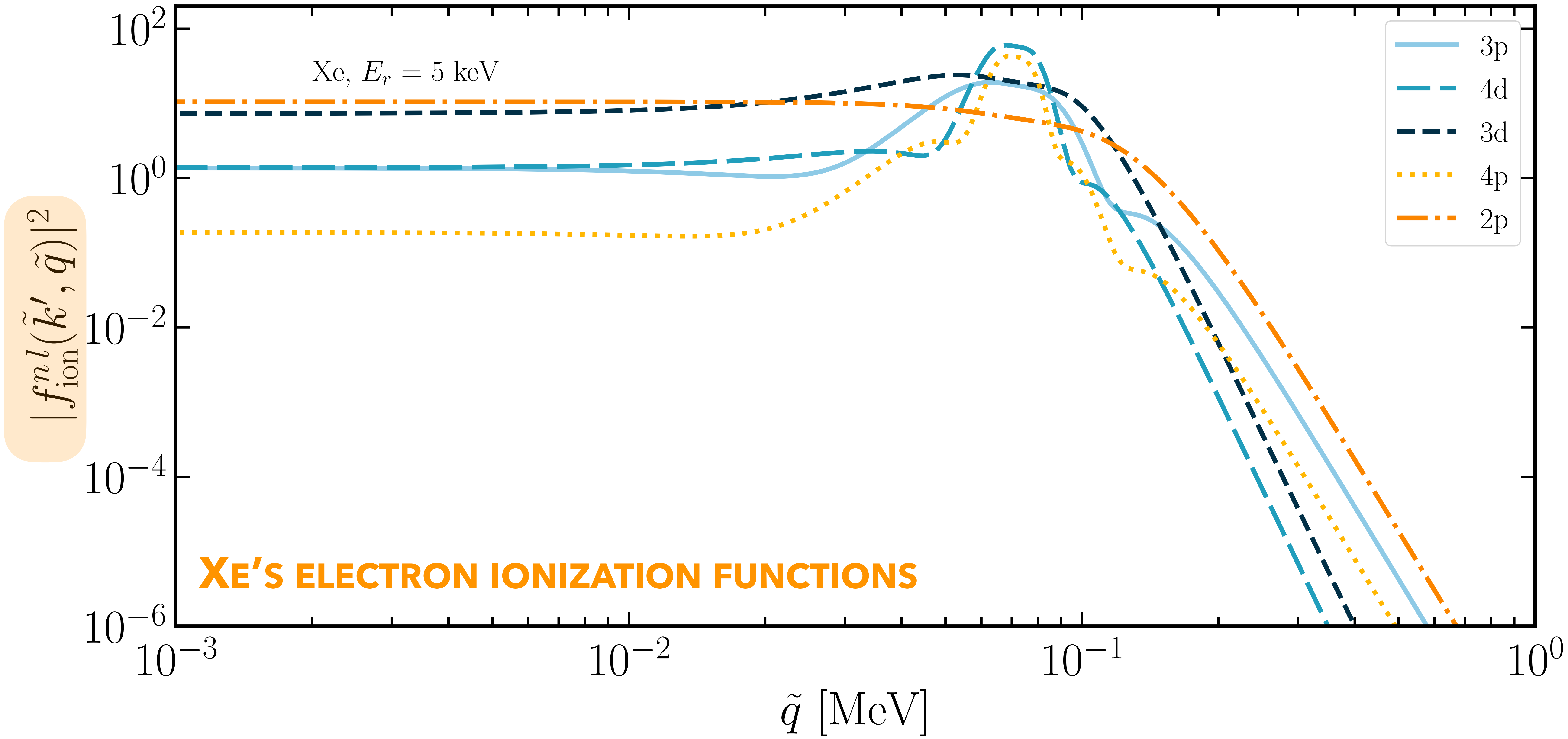
**EVENT RATE**

*Detector's efficiency*

*Fermi factor*

*Differential cross-section for all orbitals*

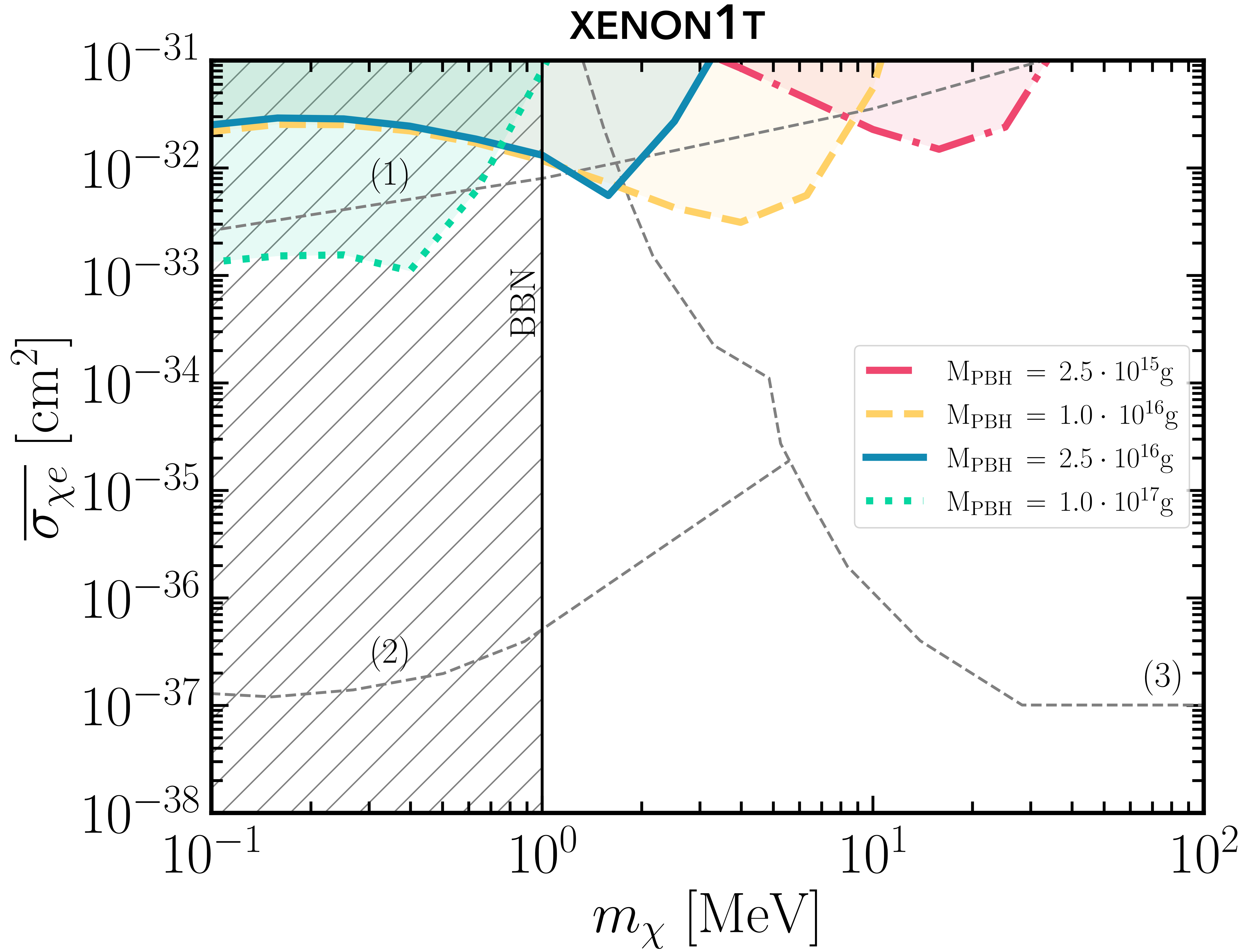
$$\frac{\mathrm{d}\sigma^{n,\,l}}{\mathrm{d}E_r} \propto \int \mathrm{d}\tilde{q}\,\left|f_{\mathrm{ion}}^{n,\,l}(\tilde{k}',\tilde{q})\right|^2 \ldots$$

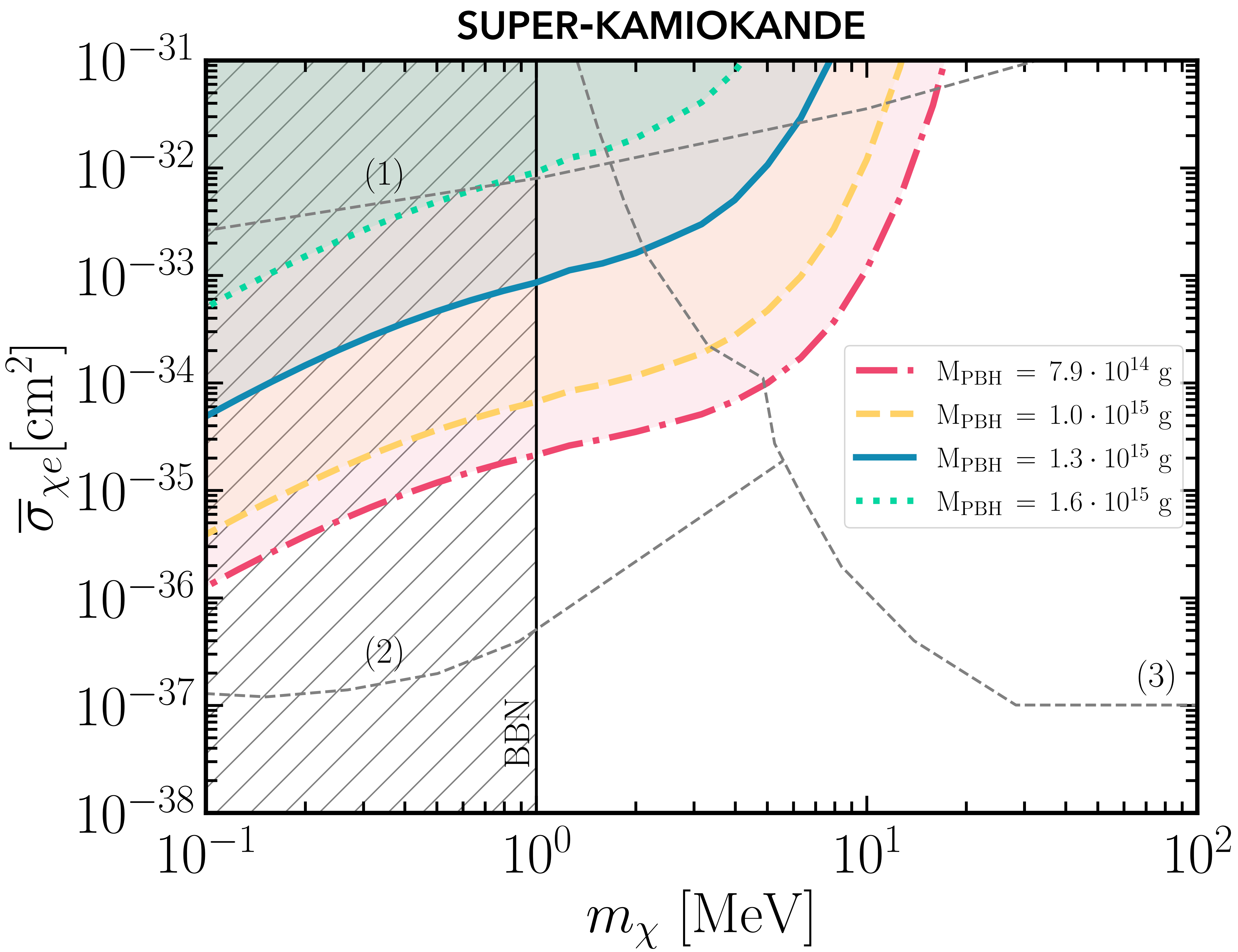



*See also: Kopp+* ***PRD 80 (2009)****; Lee+* ***PRD 92 (2015)****; Catena+* ***PRR 2 (2020)***

# DM-electron cross-section limits

*Calabrese, MC, Fiorillo, Saviano, __2203.17093__*



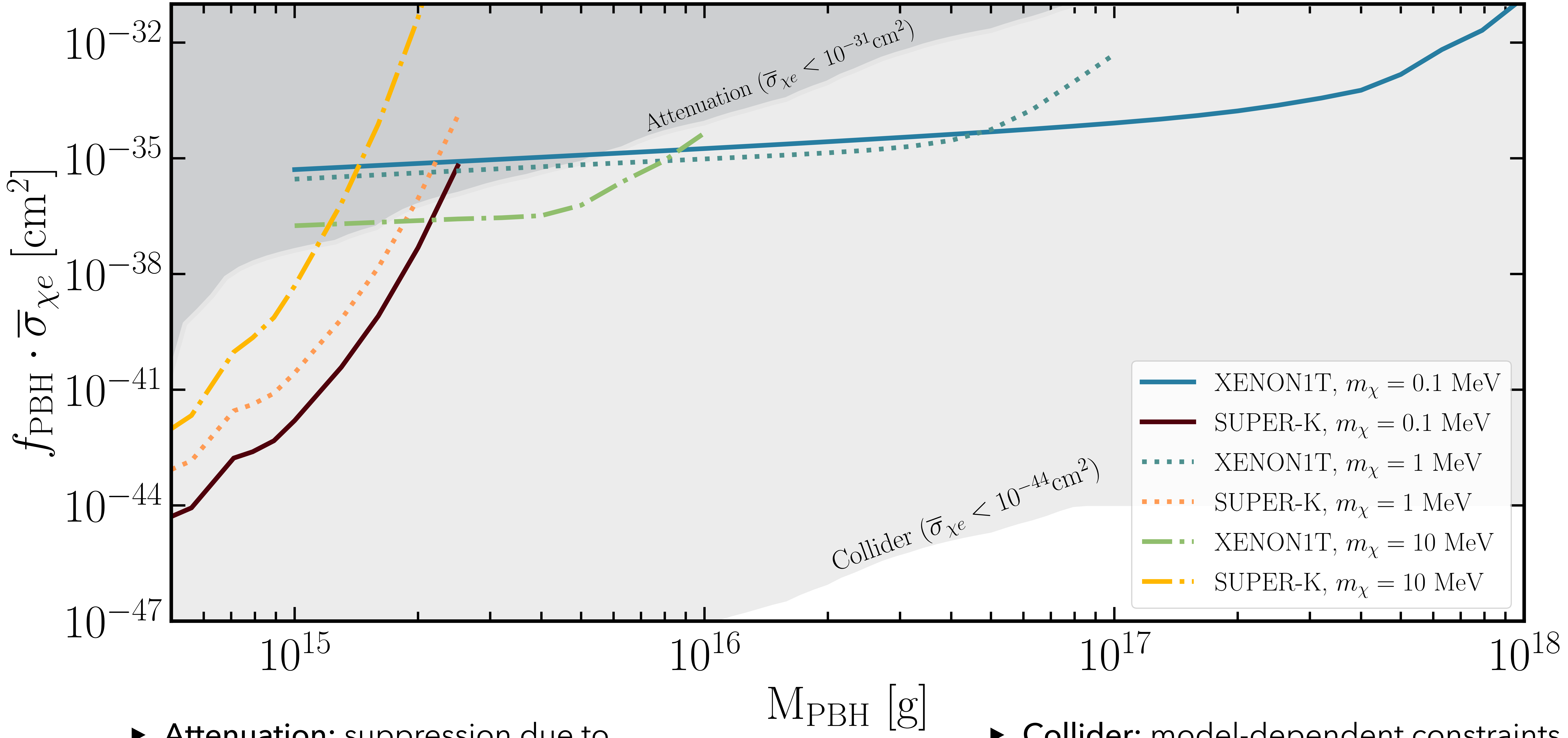




- Binned analysis
- Data taken from Aprile+ PRD 2020
- Bound electrons

- Same analysis as Ema+ PRL 2019
- Data taken from Kachulis+ PRL 2018
- Free electrons

# Constraints on PBH-DM space

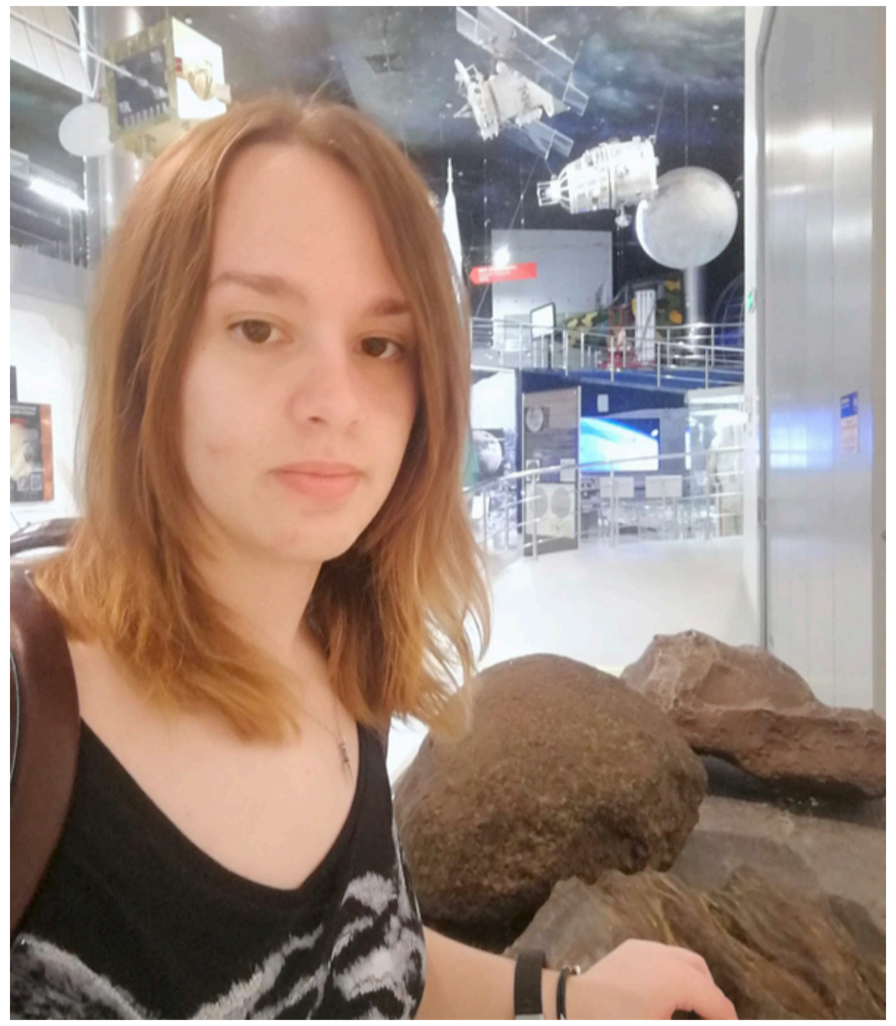
Calabrese, MC, Fiorillo, Saviano, **2203.17093**




- **Attenuation:** suppression due to propagation in Earth and atmosphere
- **Collider:** model-dependent constraints from Belle II [Liang+, JHEP 05 (2022)]

# Conclusions

- **ePBH-DM scenario**: evaporating Primordial Black Holes with a mass from $10^{14}$ to $10^{18}$ g are efficient sources of boosted light dark particles in the present Universe!
- Signatures in direct detection experiments (e.g. XENON1T and Super-Kamiokande) due to DM-nucleon and DM-electrons scatterings.
- Strong constraints on the combined parameter space of DM and PBHs.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# NEHOP: New Horizon in Primordial Black Holes Physics

## Napoli, Italy, 19 - 21 June 2023

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