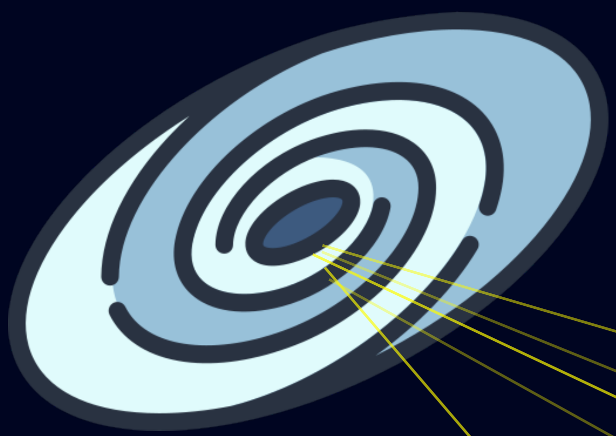
NOW 2022
Neutrino Oscillation Workshop
4–11 Sep 2022



Dark Matter Signatures from PBH evaporation

Ninetta Saviano

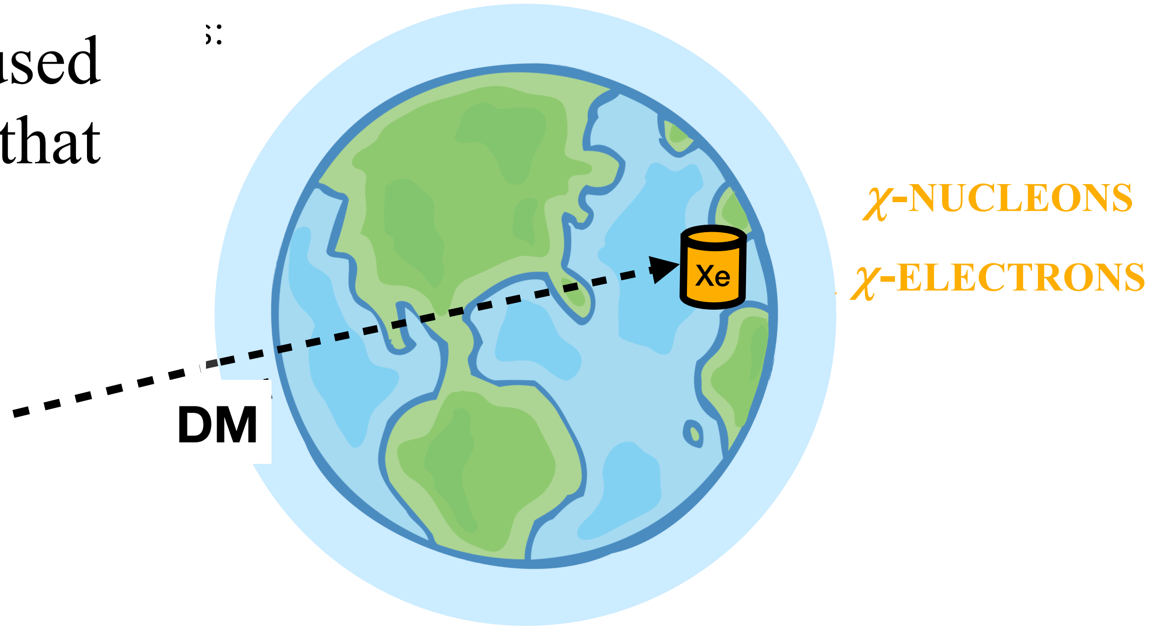
SSM and INFN Naples

Based on PRD 105 (2022) 2 [2107.13001] and 105 (2022) 10 [2203.17093]
With R. Calabrese, M. Chianese and D. Fiorillo

Dark matter direct-detection

Search for the nuclear and electron recoil energy caused by the possible scatterings with DM particles that surround us.

$$E_{rec} = \frac{2m_\chi^2 v^2}{m_T}$$



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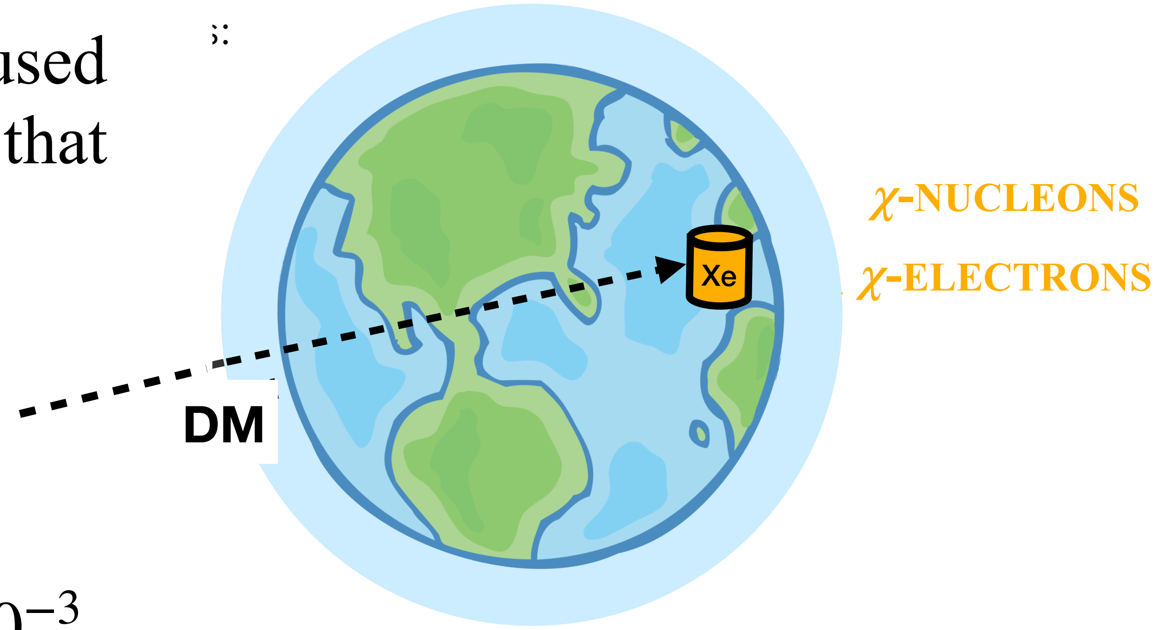

$$E_{rec}^{max} = \frac{2m_\chi^2 v_{esc}^2}{m_T};$$

Milky Way escape velocity: $v_{esc} \sim 10^{-3}$

$m_\chi(MeV)$	$E_T^{max}(keV)$
1.5	0.009
15	0.9
150	90
1500	9000

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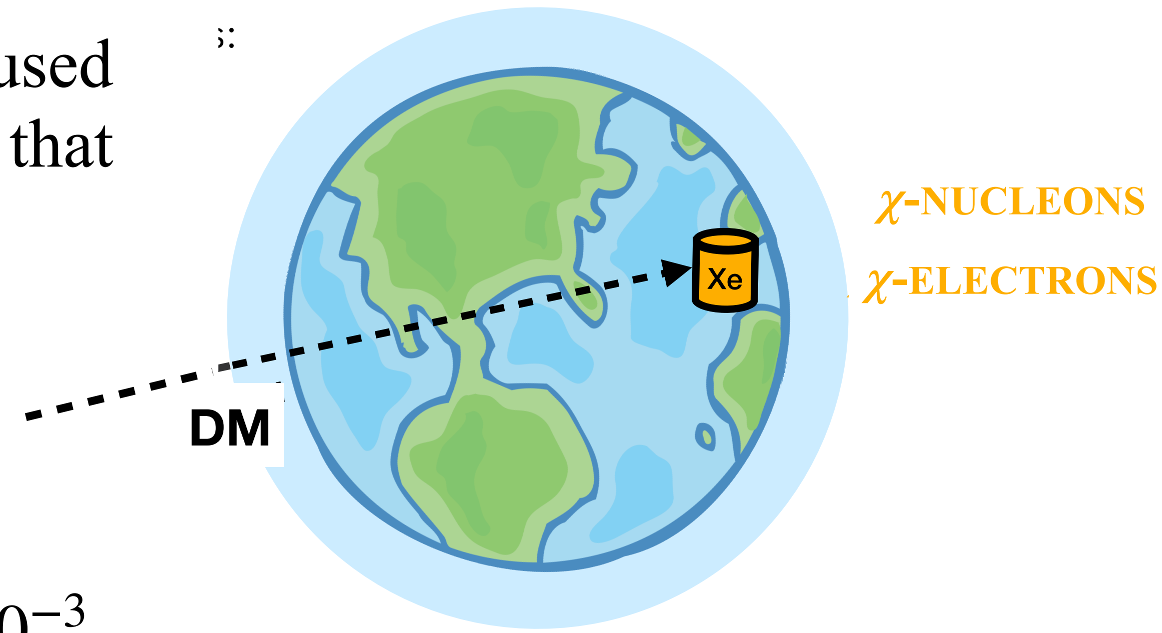

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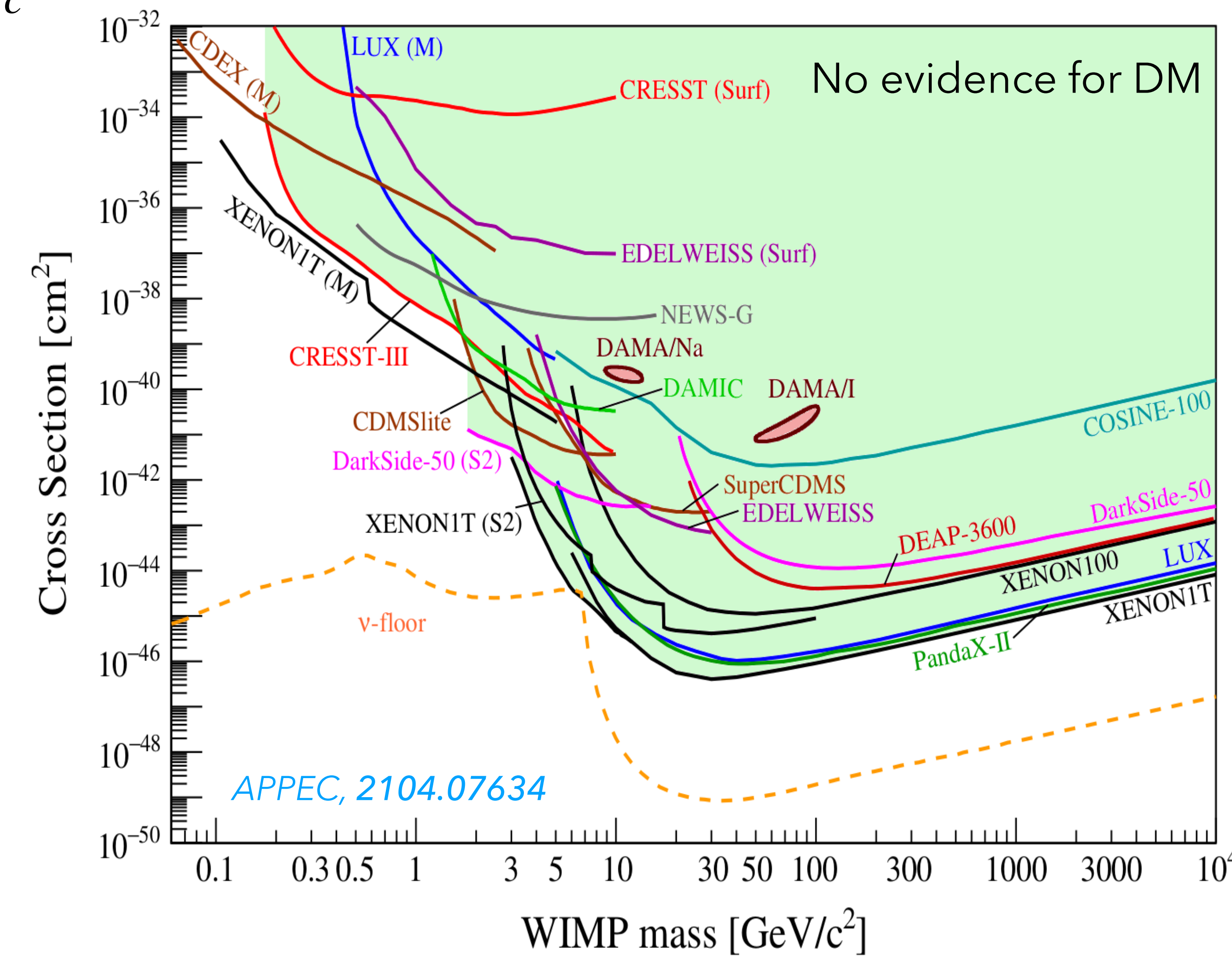


Mass lower limit for noble liquid technologies:

- ~ GeV for χ-nucleon scattering
- ~ 10 MeV for χ-electron scattering

How to probe sub-GeV DM?

Possibile way out: Boosted DM

New ideas are needed for model independent probes of sub-GeV Dark Matter

- **Boosted DM: Light dark matter with velocities higher than v_{esc}**

Several mechanisms have been proposed in the recent years:

In the recent years:

- Small population of DM, produced non thermally by late time processes, results to be relativistic

  K. Agashe et al, (2014), G. F. Giudice et al,(2018), B. Farnal et al, 161804 (2020)….

- Light DM particles can be up scattered to semi-relativist velocities through collision with CR.

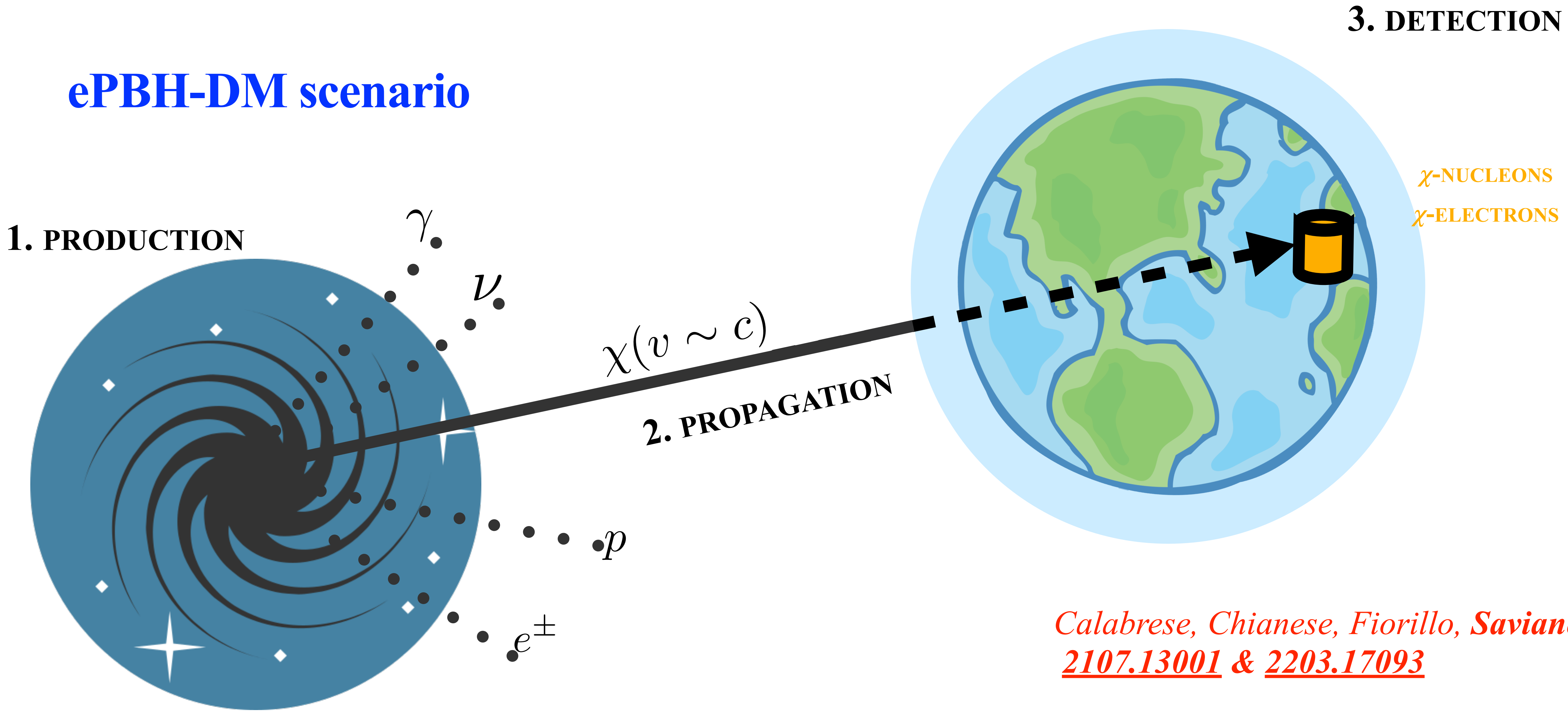
  C. V. Cappiello et al, (2019); T. Bringmann and M. Pospelov, (2019);Y. Ema et al,(2019)
  C. Cappiello and J. F. Beacom, (2019)

Our idea: PBHs enter this game as possibile source of boosted DM

Boosted DM from ePBH

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

ePBH-DM scenario

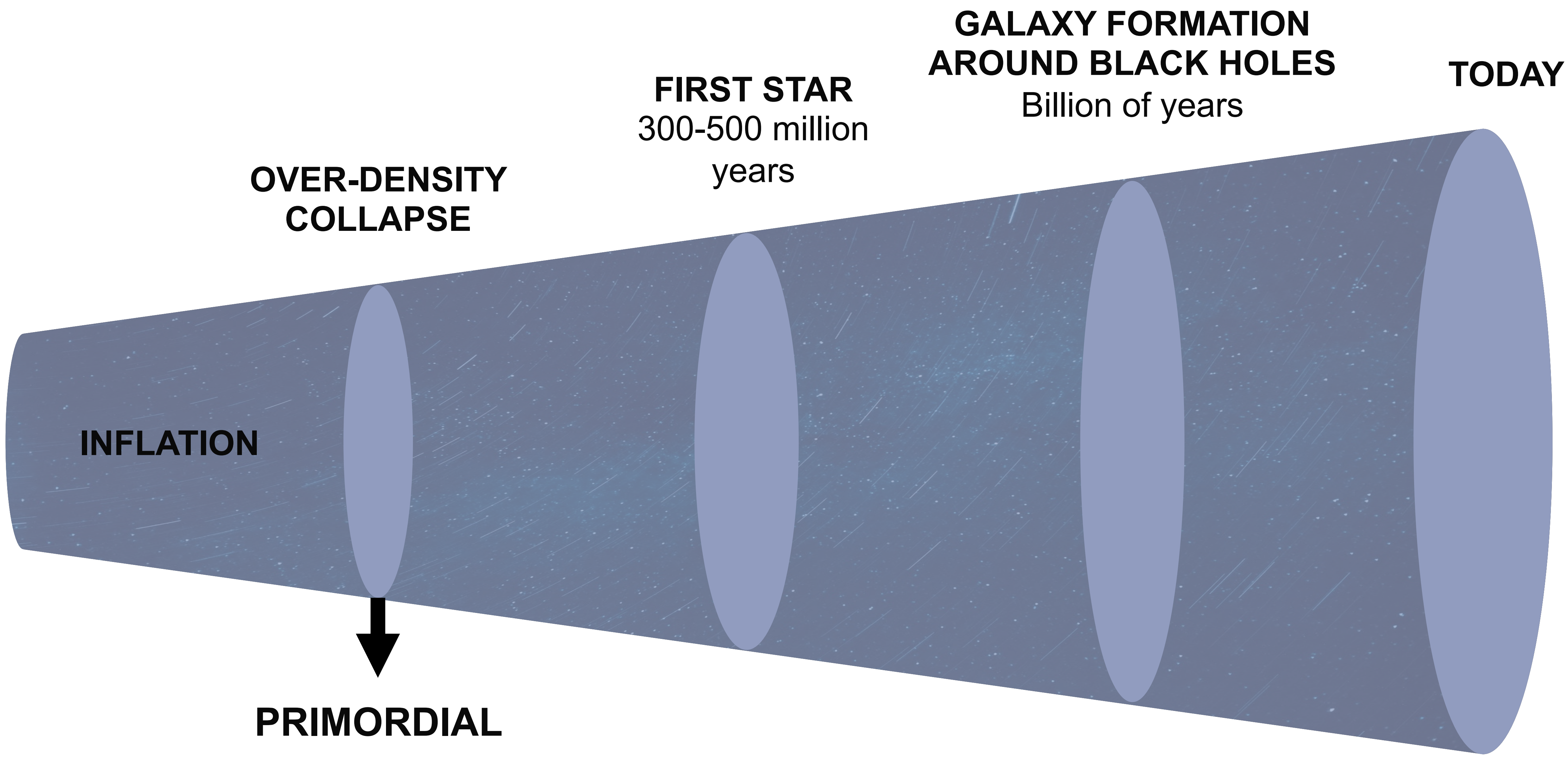


*Calabrese, Chianese, Fiorillo, **Saviano**, **2107.13001** & **2203.17093***

For DM production previously studied in the Early Universe, see:

*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***

Primordial Black Holes



PRIMORDIAL

BLACK HOLES

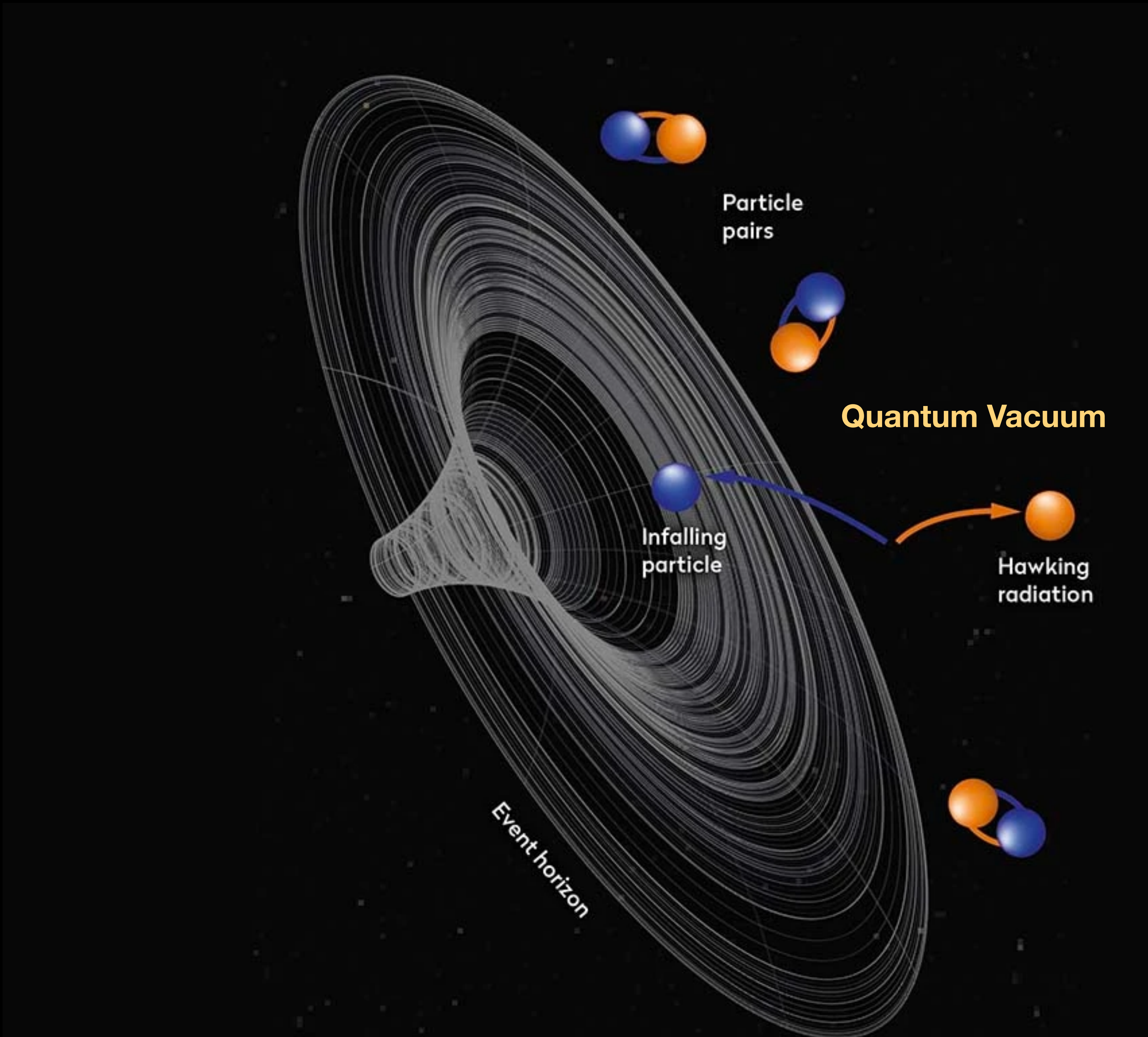
MASS $[0.1 - 10^{50}]\mathrm{g}$

CHARGE

SPIN

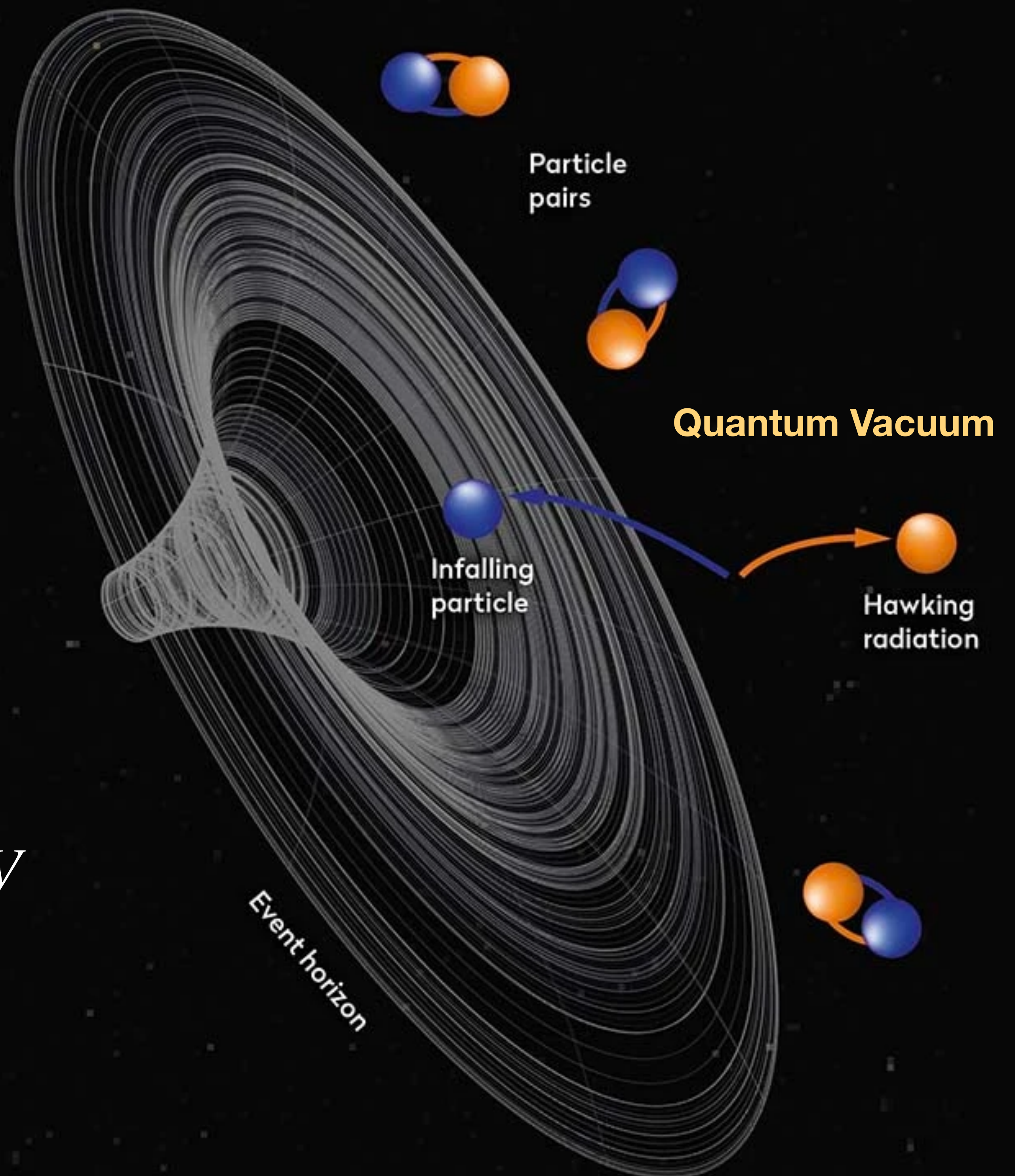
S. W. Hawking, Commun.Math.Phys. 43 (1975) 199-220 B. J. Carr, Astrophys.J. 201 (1975) 1-19 J. Auffinger, arXiv: 2206.02672

Hawking Evaporation



Hawking Evaporation

Due to a mixture of quantum and general relativity effects, the PBH can emit particles in a “black body” like (**grey-body**) with a temperature T_{PBH}



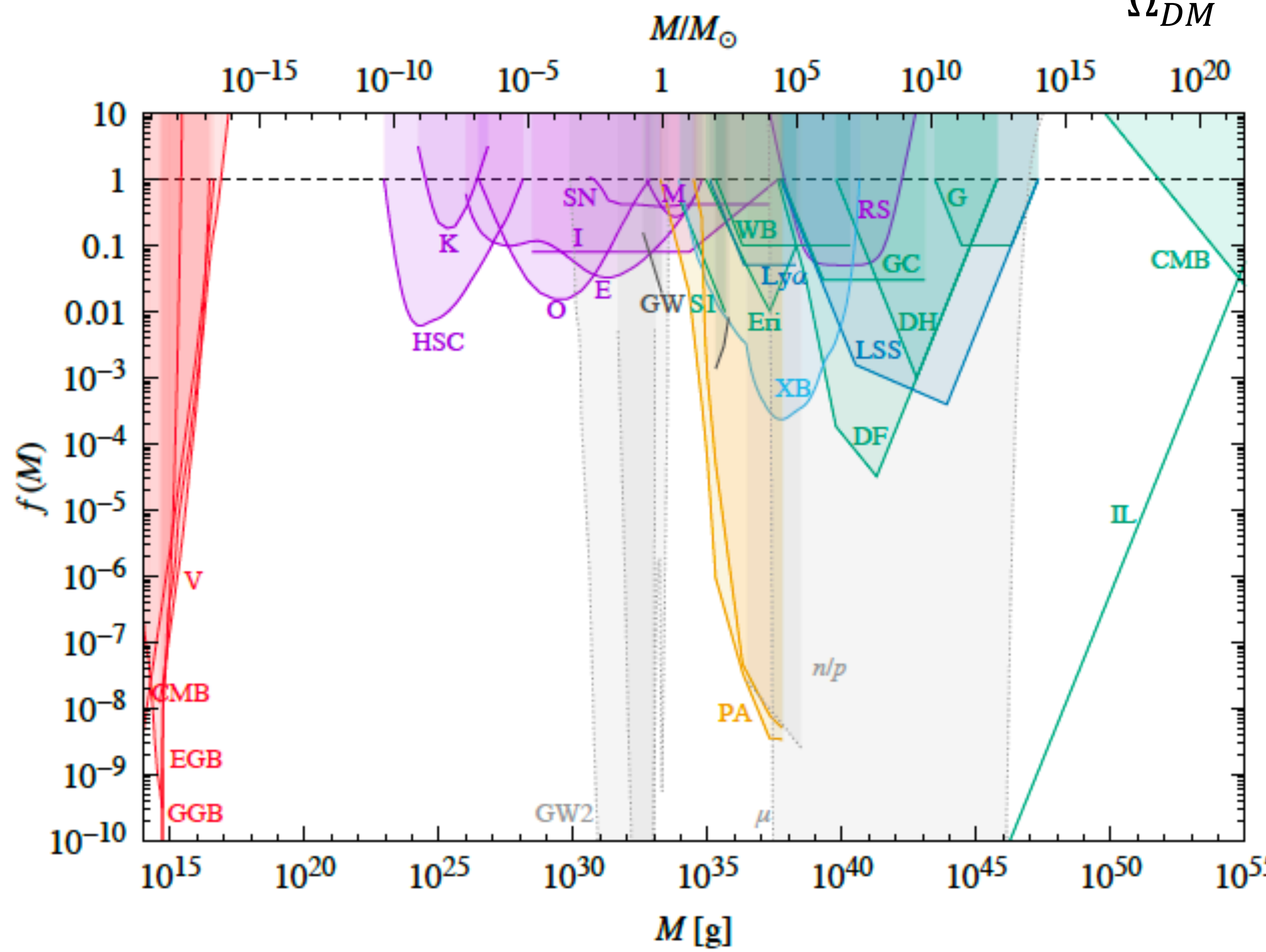
Hawking radiation: emission of all elementary particles with mass < T_H

For non-rotating and neutral PBH:

$$T_{PBH} = \frac{\hbar c^3}{8\pi G k_B M_{pl}} \simeq 10.6 \left[\frac{10^{15} g}{M_{pl}}\right] MeV$$

Constraints on PBH abundance

Several observations strongly constrain the PBH abundance: $f(M) = \dfrac{\Omega_{PBH}}{\Omega_{DM}}$



- Lensing
- Evaporation
- CMB distortions
- Dynamical effects
- Accretion
- Large Scale Structure (LSS)
- Gravitational Waves (GWs)

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

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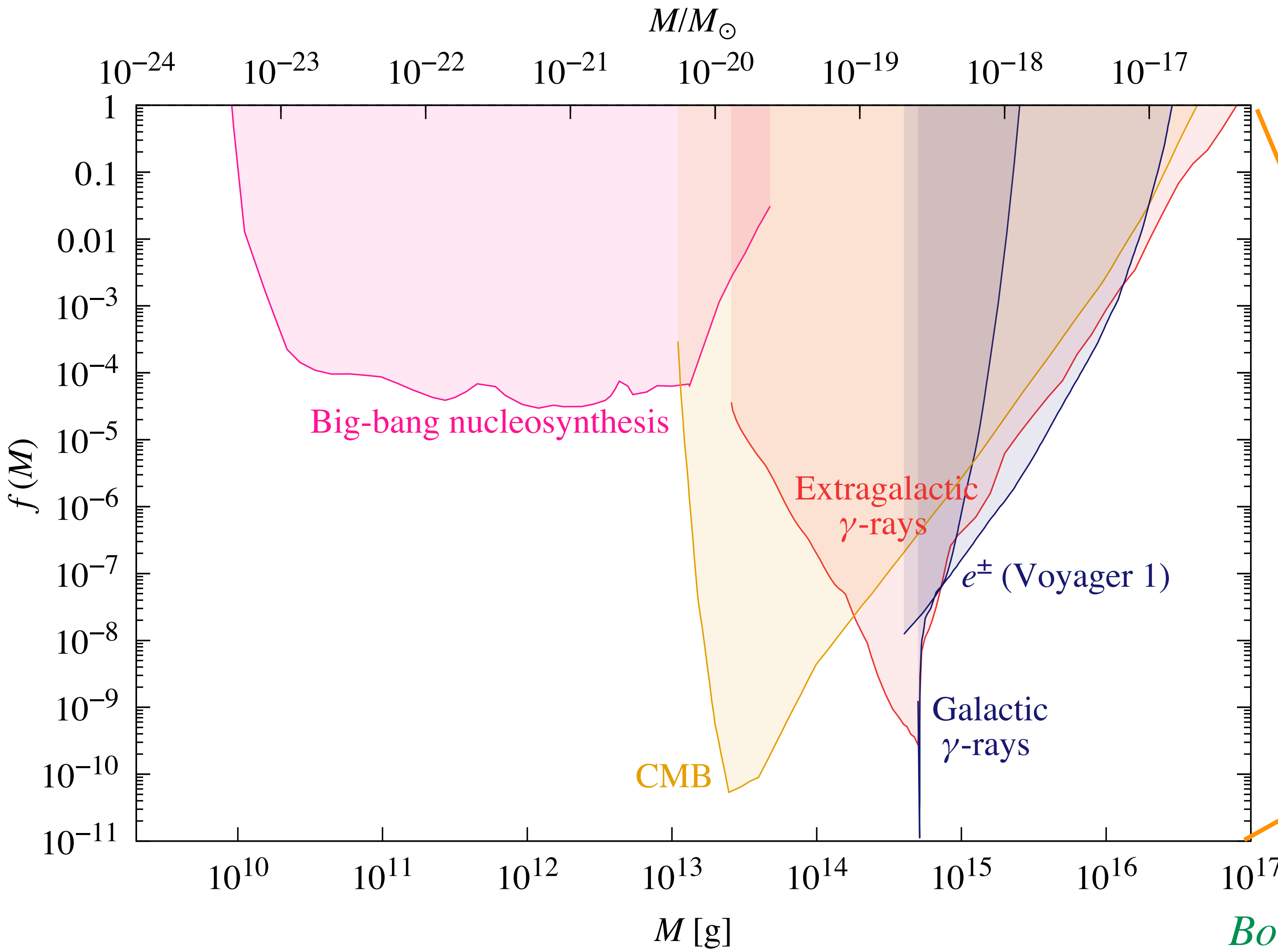

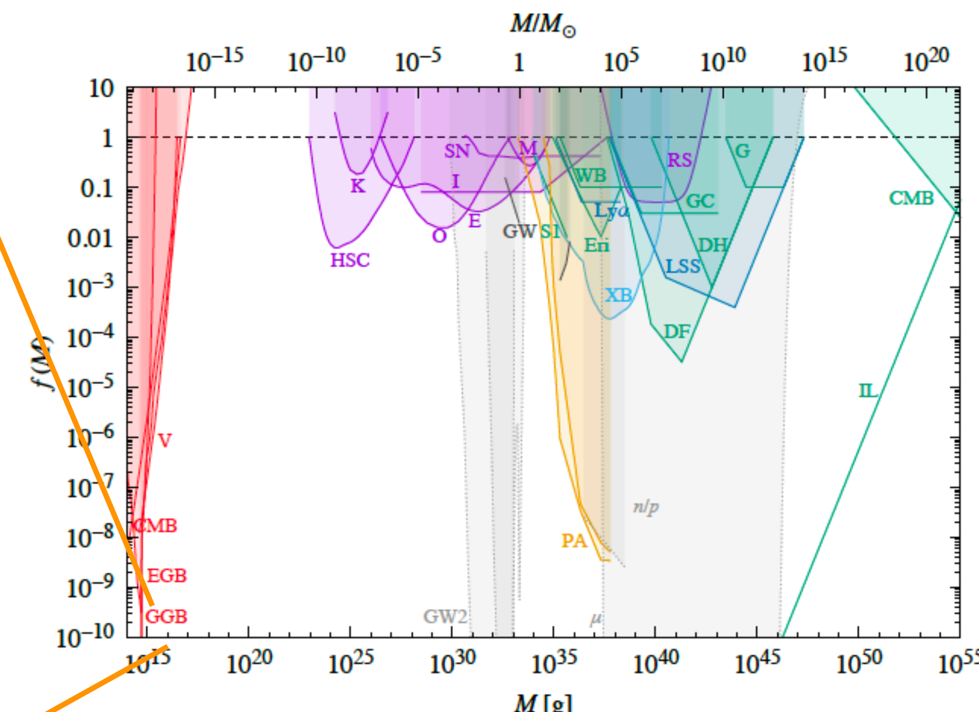

Boudaud and Cirelli 2019;
Ballesteros, Coronado-Blazquez, and Gaggero 2020;
Dasgupta, Laha, and Ray 2020;
Coogan, Morrison, and Profumo, 2021;
Calabrese et al 2021;
De Romeri, Martınez-Mirave, and Tortola 2021

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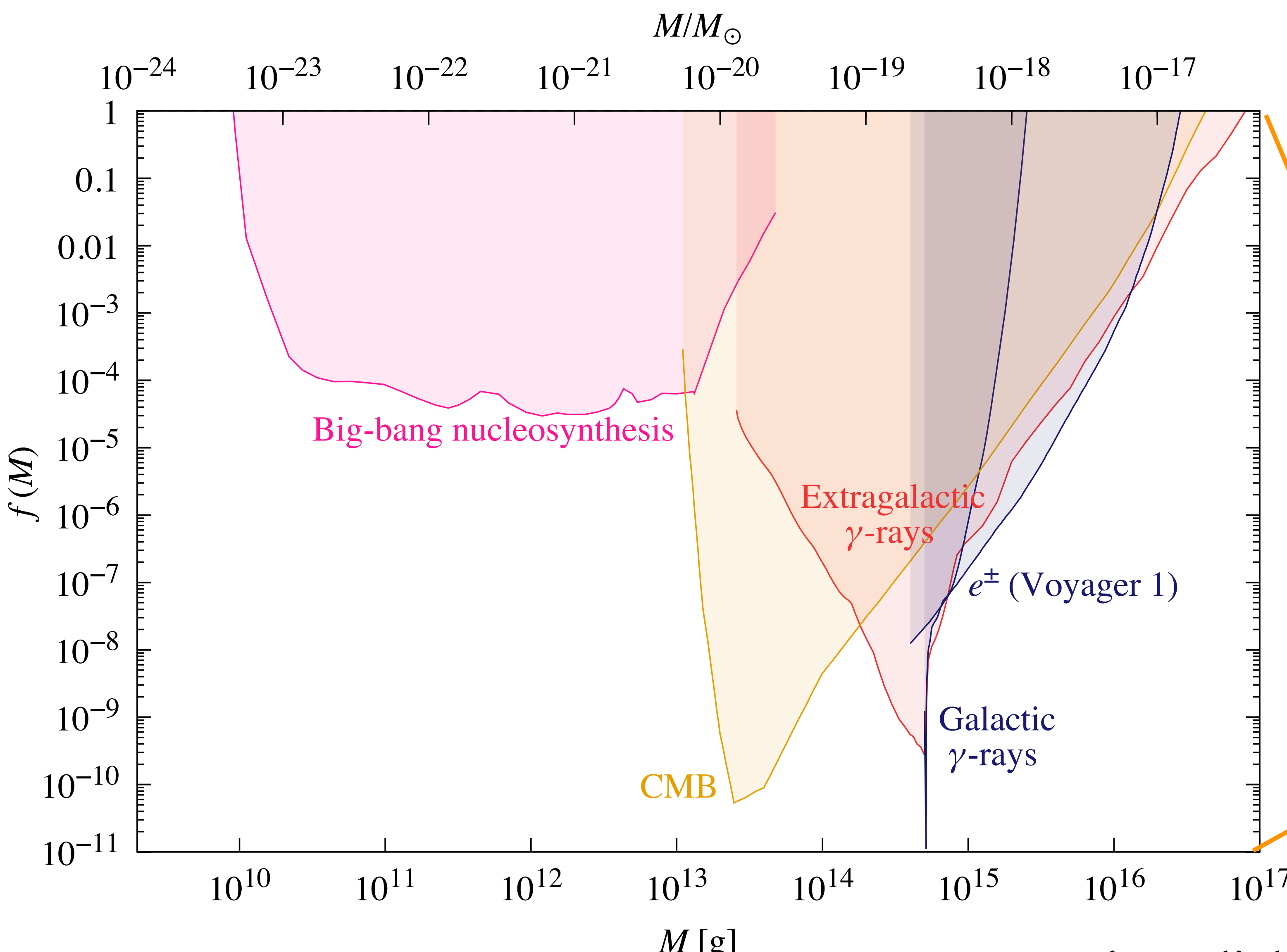

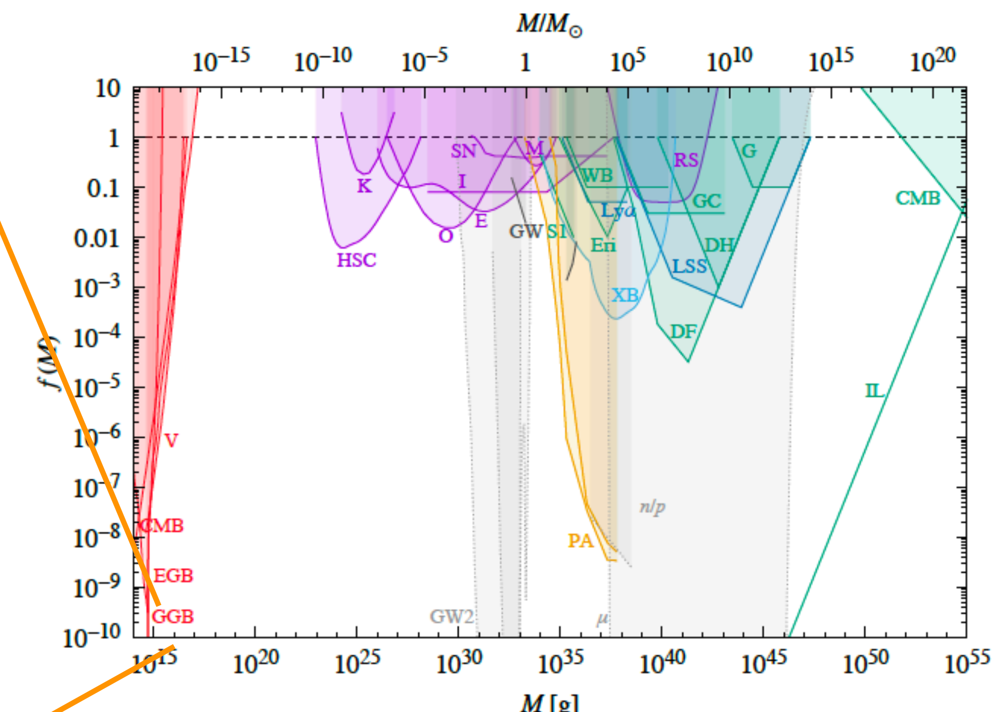

Primordial Black Holes with $M_{\rm PBH} < 5\ 10^{14}$ g are completely evaporated today

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

$$f(M) = 3.81 \times 10^{8}\, \beta'(M) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

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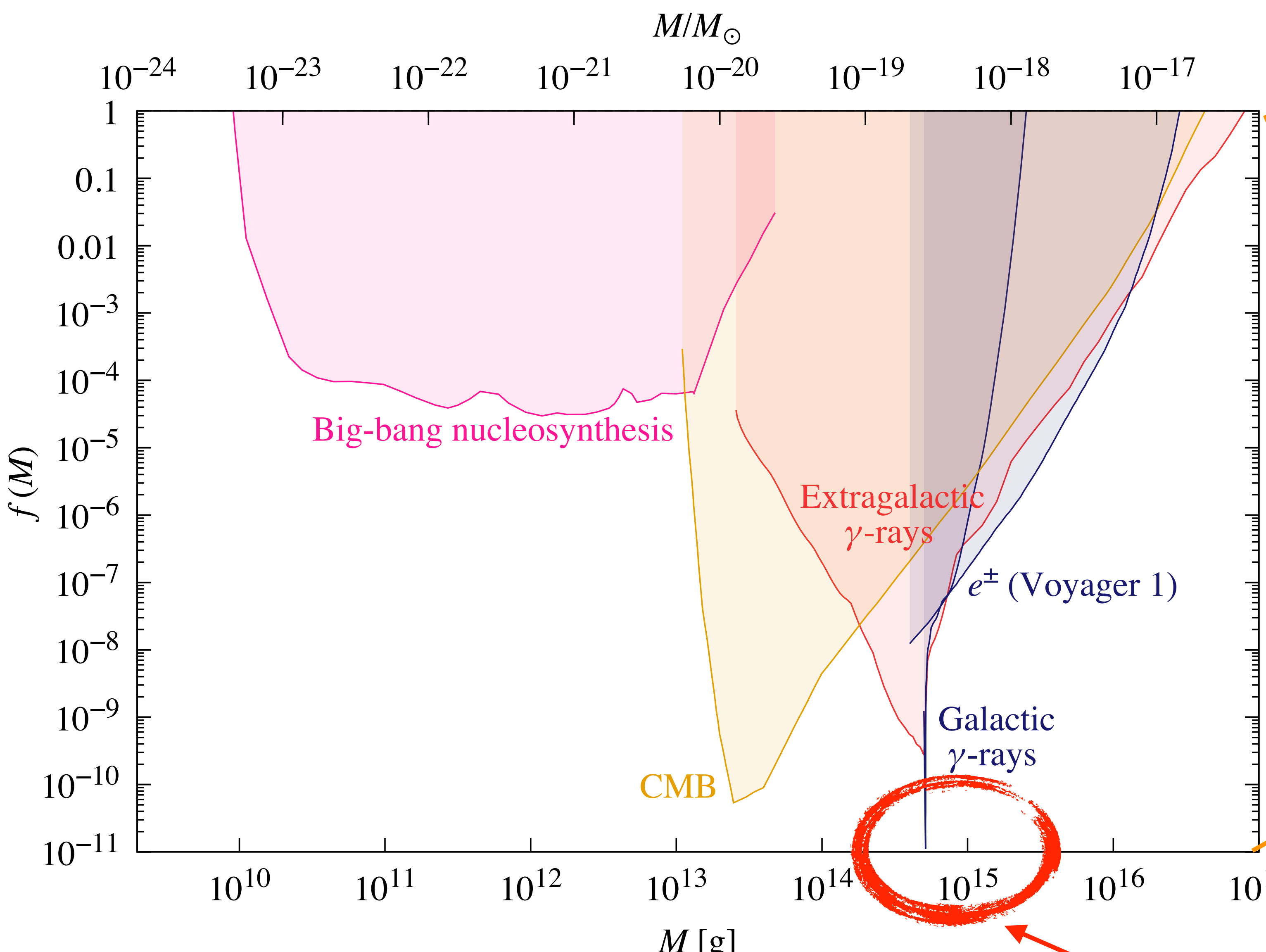
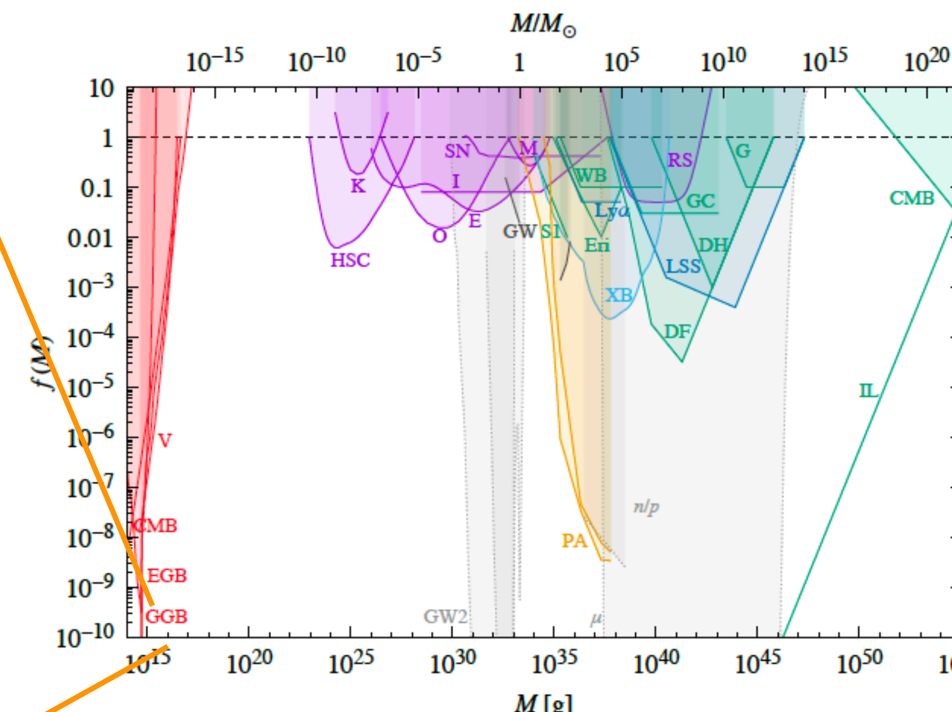




Evaporating now

⇩

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

Emission of DM particles with ultra-relativistic velocities.

Diffuse DM flux from ePBHs

PBHs emit thermal Hawking radiation at a temperature:

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

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

$$\frac{d\phi_\chi}{dT d\Omega} = \frac{d\phi_\chi^{\rm gal.}}{dT d\Omega} + \frac{d\phi_\chi^{\rm egal.}}{dT d\Omega}$$

dependent on

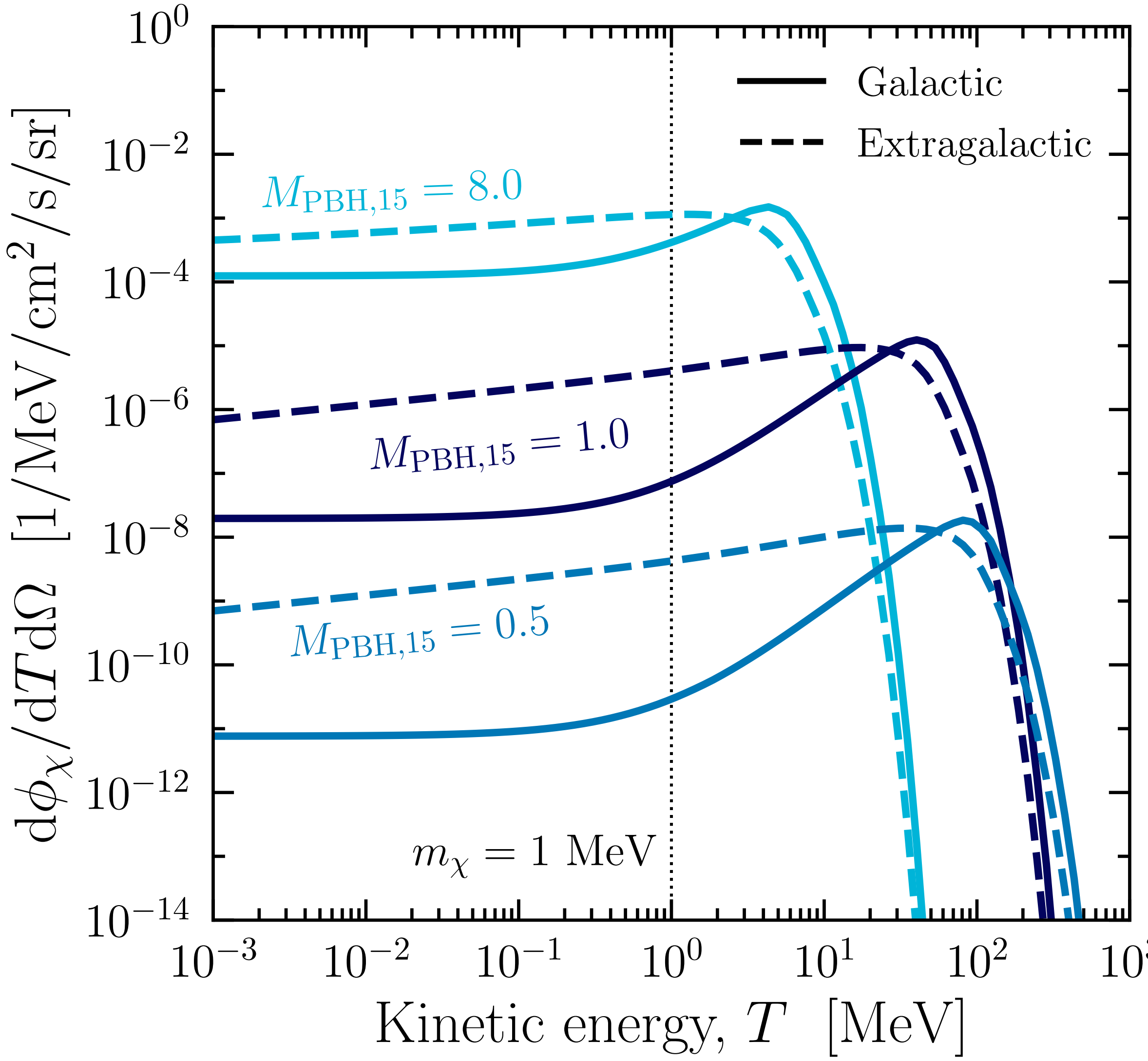
- $f_{\rm PBH}$
- $\frac{dN_\chi}{dT dt}$ = differential spectrum per unit time

Gray-body factor computed with **BlackHawk** code

A. Arbey and J. Auffinger, (2019), (2022)

- Spinless and chargeless PBHs (*conservative scenario*)

*Calabrese, Chianese, Fiorillo, **Saviano**, 2107.13001*



$f_{\rm PBH} = 3.9 \times 10^{-7}$ Maximum value allowed by the present constrains

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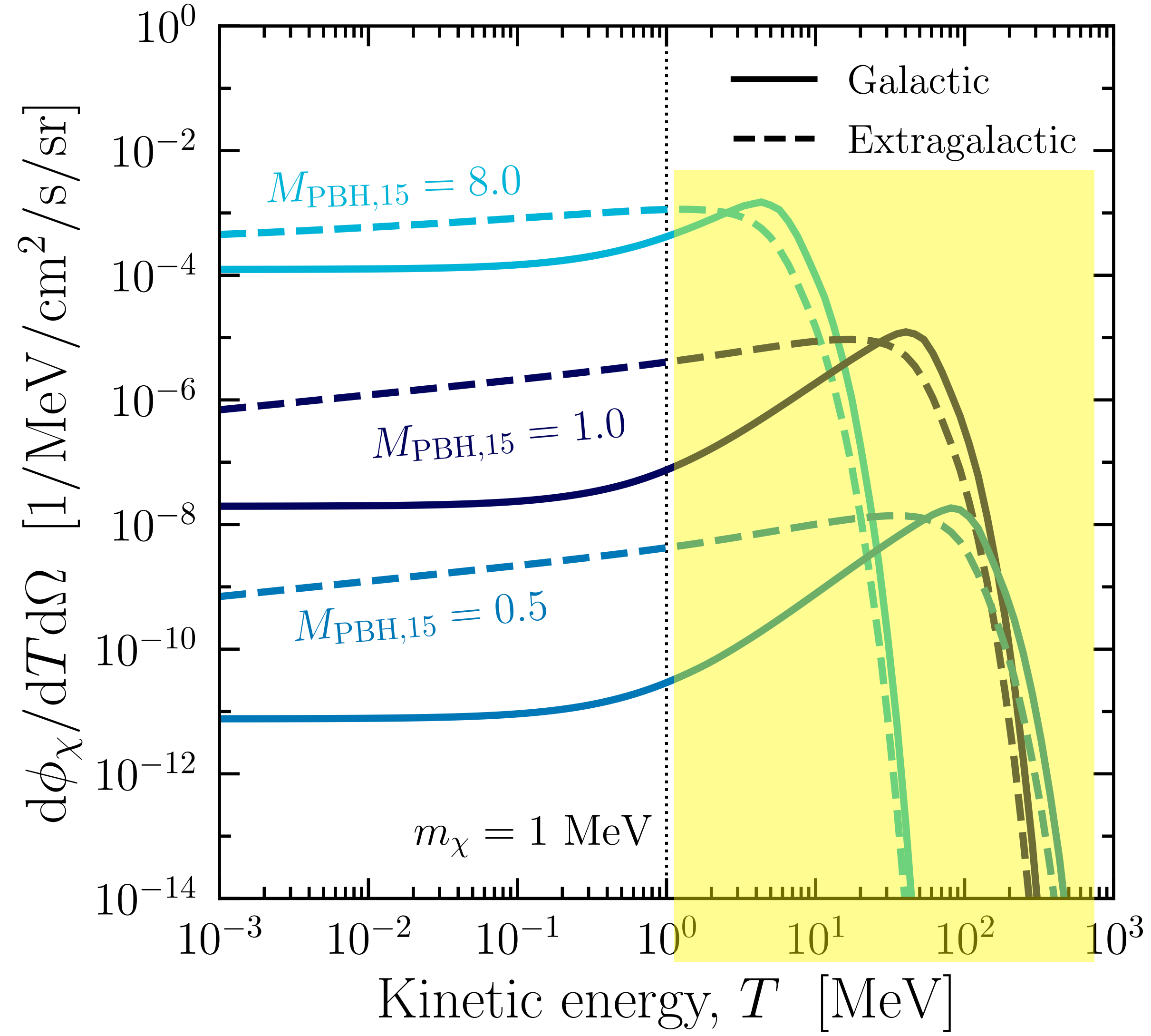


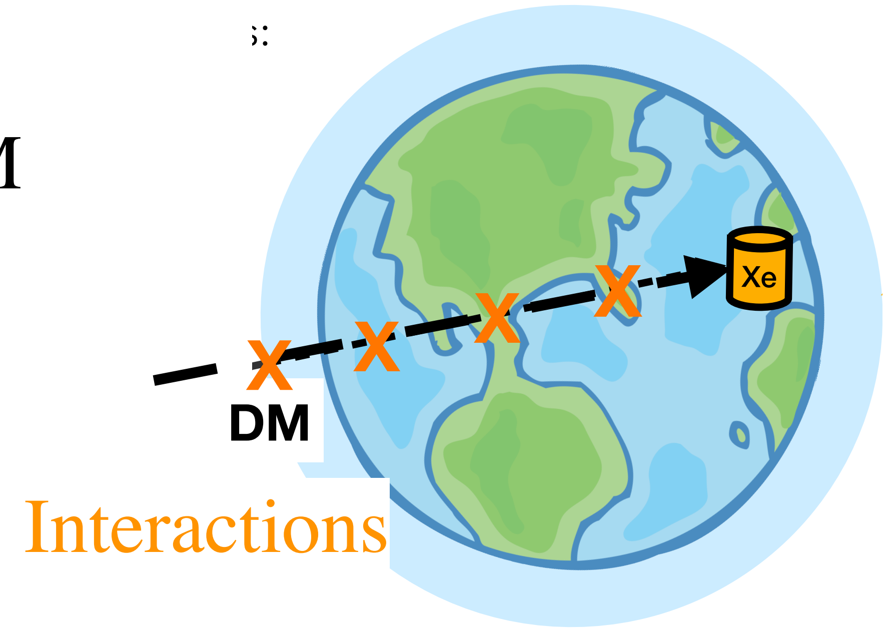
$$10^{14} \lesssim M_{\rm PBH}/{\rm g} \lesssim 10^{16}$$ →

→ **DM particles lighter than about 1 MeV emitted with ultra-relativistic velocities**

BOOSTED DM

Propagation through Earth and atmosphere

We analytically account for the energy loss of DM particles in the ballistic-trajectory approximation
(based on the collinear propagation in matter)



The interactions with nucleons might also cause an attenuation of the DM flux at the detector position due to the propagation in the Earth and in the atmosphere

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

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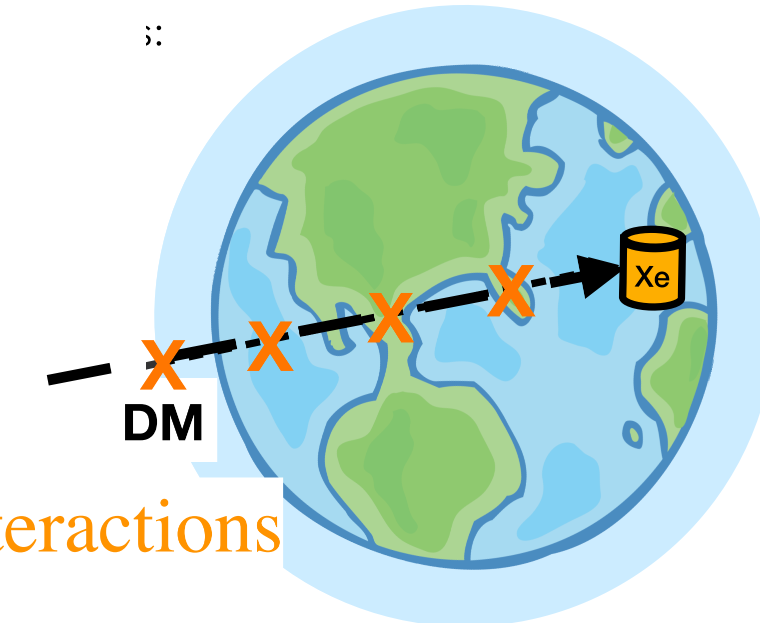

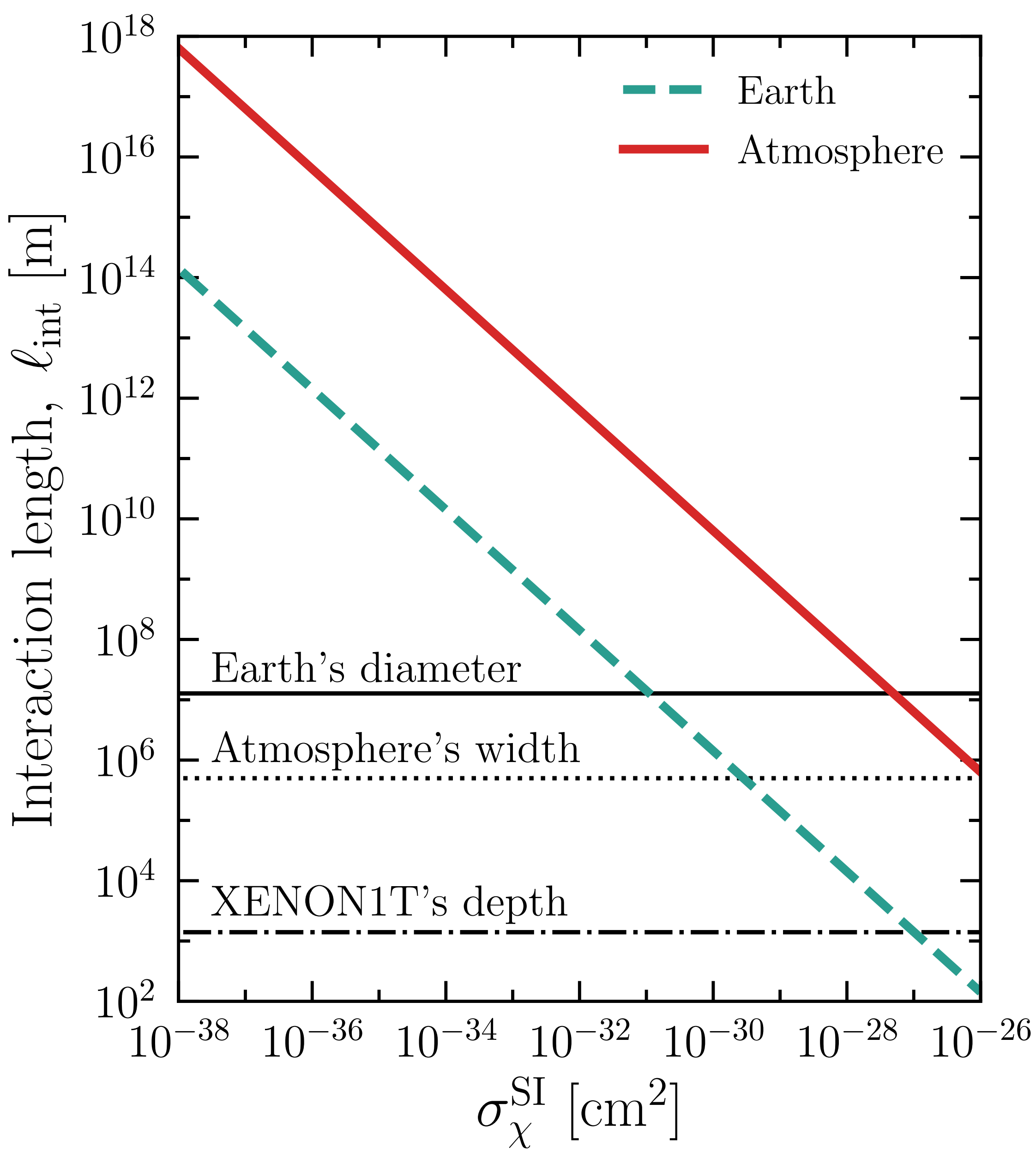

The interactions with nucleons might also cause an attenuation of the DM flux at the detector position due to the propagation in the Earth and in the atmosphere

DM particles with an initial kinetic energy T_0 reach the detector with a smaller kinetic energy T_d after traveling a total geometrical distance $d = d_{atm} + d_\oplus$.

Propagation effects are important for

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

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

χ -nucleons interaction: event rate

EVENT RATE: key quantity to characterize the detection of a signal, namely n[0] of events per ton year

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

Recoil Energy

total number of targets

Attenuated Dark Matter flux

Flat distribution for the maximum allowed E_r

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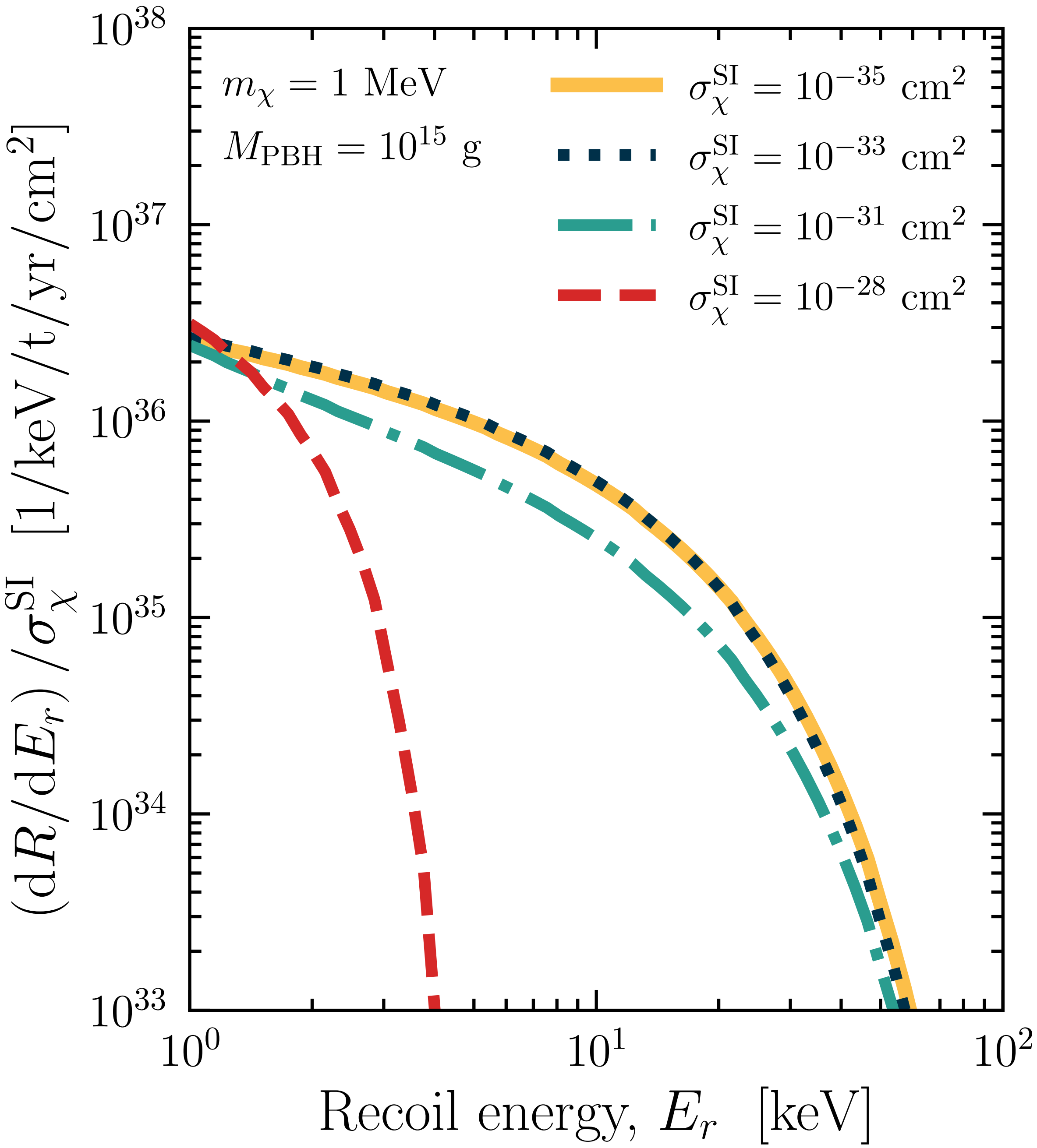

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For low DM-nucleon cross-section, the event rate scale as:

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

For $\sigma_\chi^{\mathrm{SI}} \gtrsim 10^{-31}$ cm^2 the propagation pushes the events to lower recoil energies and weakening the sensitivity to the ePBH-DM signal.

Results: DM-nucleon cross-section limits

Comparison with the expected event rate with the current data from XENON1T

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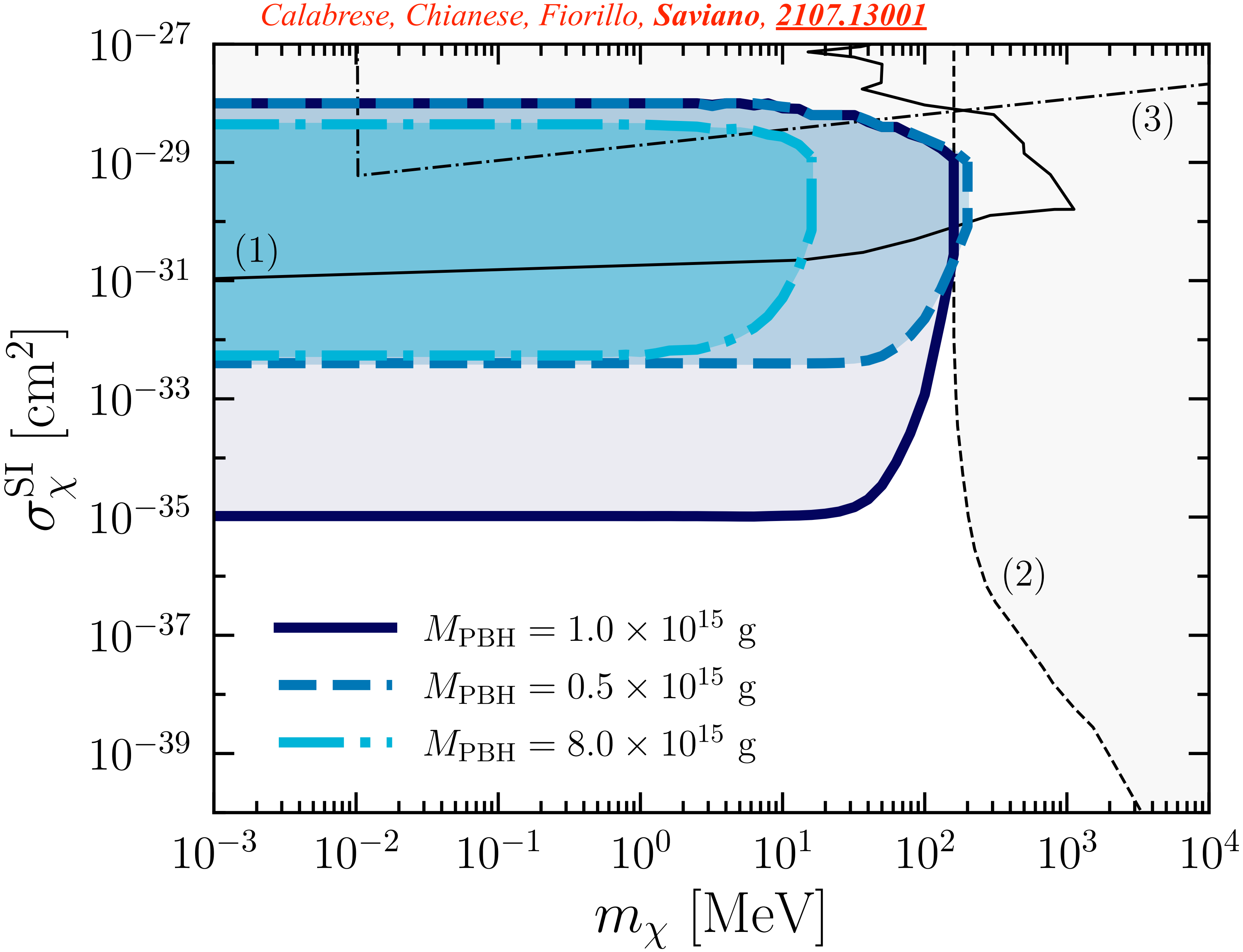

No excess of events in **XENON1T** from 4.9 to 40.9 keV.

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

f_{PBH} maximum allowed by existing constraints

DM-nucleon cross-section are improved up to four orders of magnitude

Previous constraints: 1) CRs up-scatterings *Bringmann & Pospelov, 2019; Cappiello & Beacom, 2019*

2) CRESST experiment *Angloher et al, 2017; Abdelhameed et al, 2019*

3) Cosmology *Gluscevic & Boddy, 2018; W. L. Xu et al, 2018; Slatyer and C. L. Wu, 2018; Nadler et al, 2019*

Results: PBH abundance

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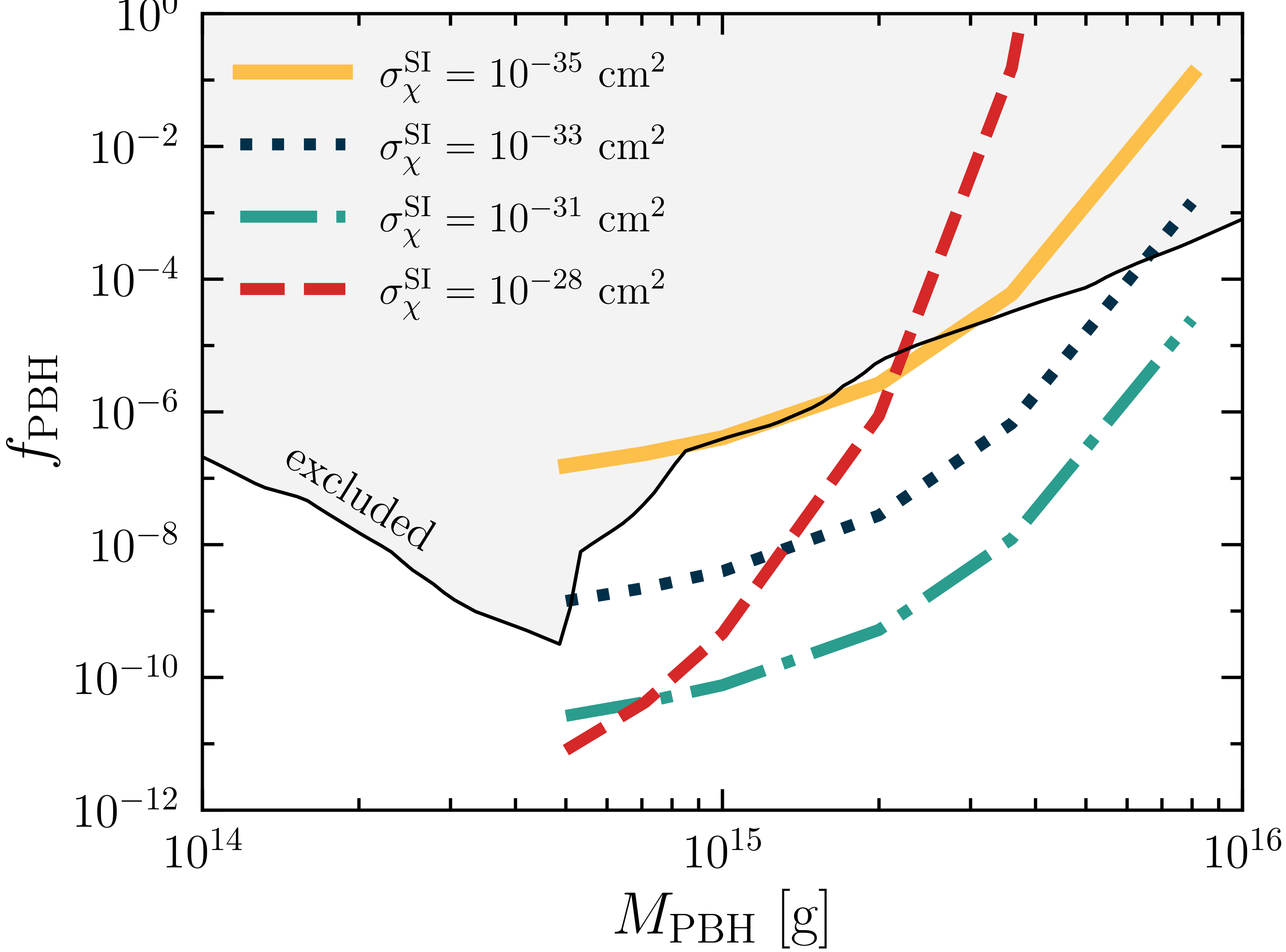

Valid for any model of light dark particle

Dependence on the strength of DM-nucleon interactions.

Almost independent from DM mass

For large cross-section, propagation effects are important (red dashed line)

Grey region: B. Carr et al, Rept.Prog.Phys. 84 21) 11, 116902

Conclusions

DM-nucleon

- We explore for the first time the **phenomenological implications of the ePBH-DM** scenario in direct detection experiments.
- Even a tiny fraction of evaporating PBHs is enough to give rise to a **sizeable flux of boosted light DM particles**, translating into a detectable event rate in XENON1T
- Assuming PBHs abundances compatible with current bounds, the **limits on the spin independent (SI) DM-nucleon cross-section are improved up to 4 orders of magnitude**
- Form the non-observation of the ePBH-DM signal, we derive **upper bound on the PBHs abundance a few orders of magnitude stronger than current constraints**, depending on the strength of DM-nucleon interactions.

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DM-electron

- We extended our studi to the case of **DM interactions with electrons.**
- The simultaneous presence of PBH and species lighter than about 100 MeV can be constrained by the **measurements of direct detection experiments**, such as **XENON1T**, and water Cherenkov neutrino detectors, such as **Super-Kamiokande**.
- Our results provide a complementary and alternative way of investigation with respect to cosmological and collider searches.


NEHOP: New Horizon in
Primordial Black Holes Physics
Napoli, Italy, 19 - 21 June 2023
[check on INSPIRE]
ORGANIZERS
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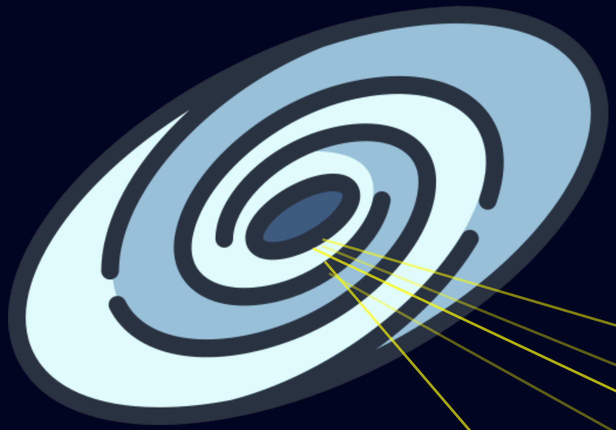
Ninetta Saviano (SSM, IT)
Jessica Turner (Durham Univ., UK)



Thank you

Scatterings with Xe's electrons

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

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

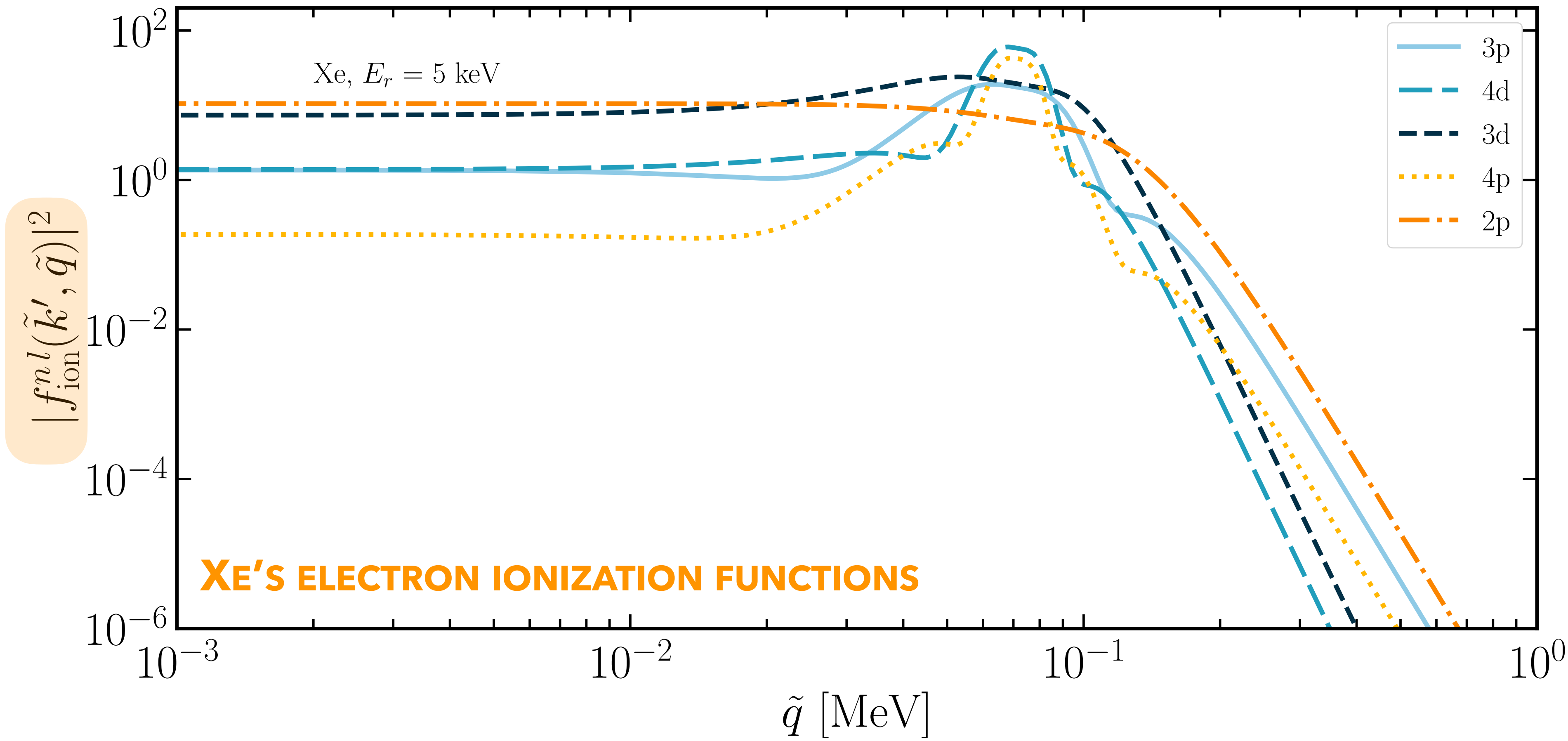
EVENT RATE

Fermi factor

Detector's efficiency

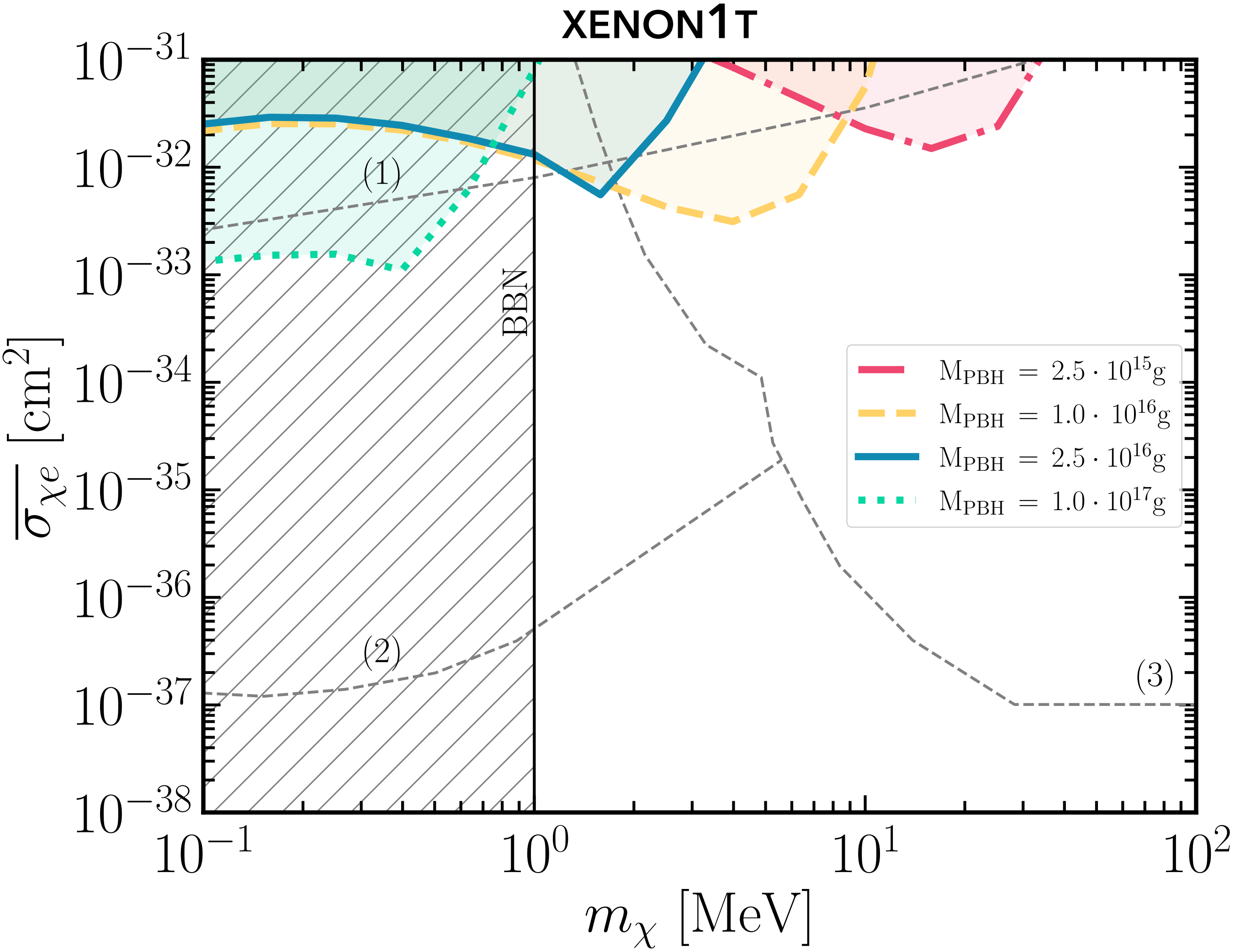
Differential cross-section for all orbitals

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

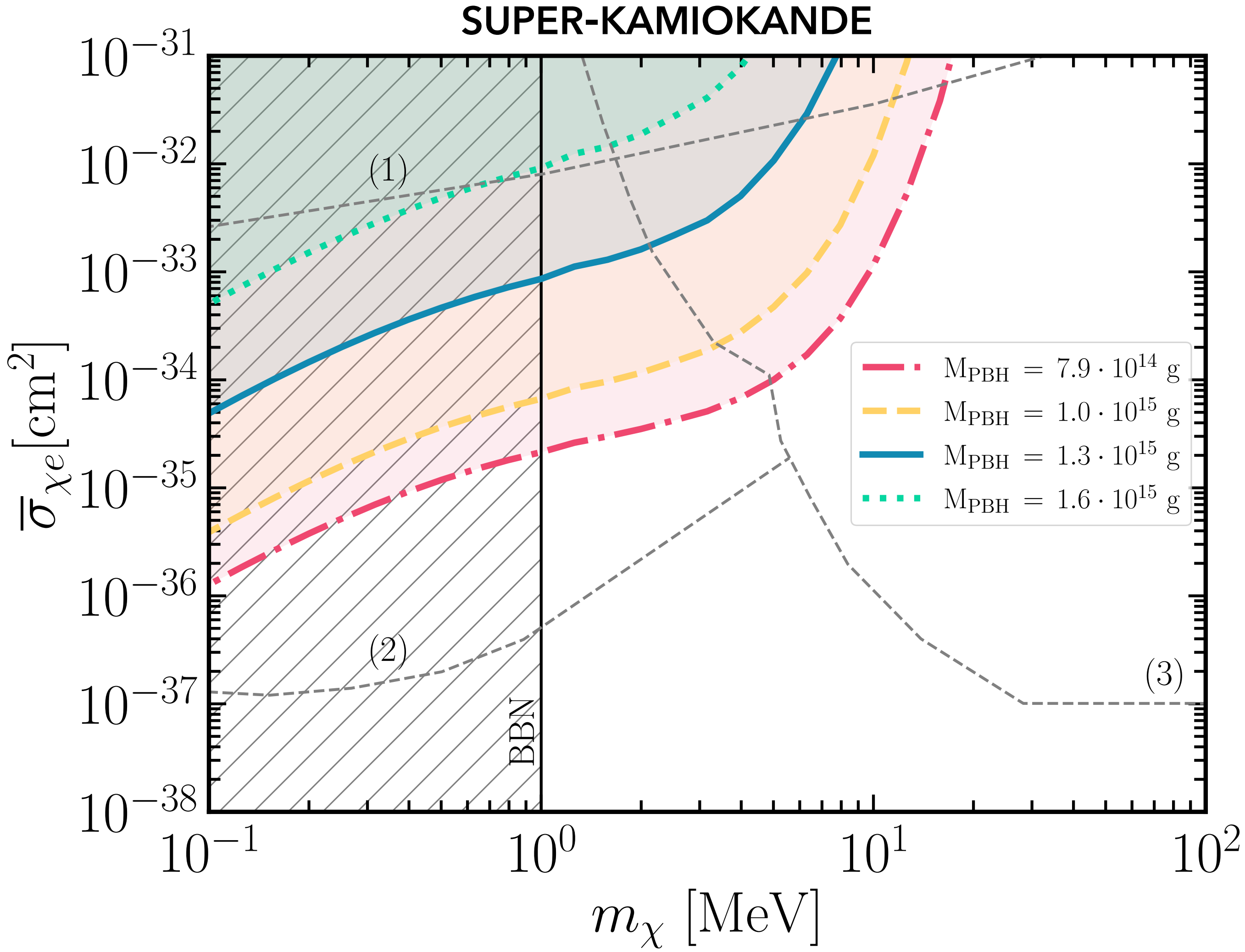


See also: Kopp+ **PRD 80 (2009)**; Lee+ **PRD 92 (2015)**; Catena+ **PRR 2 (2020)**

DM-electron cross-section limits

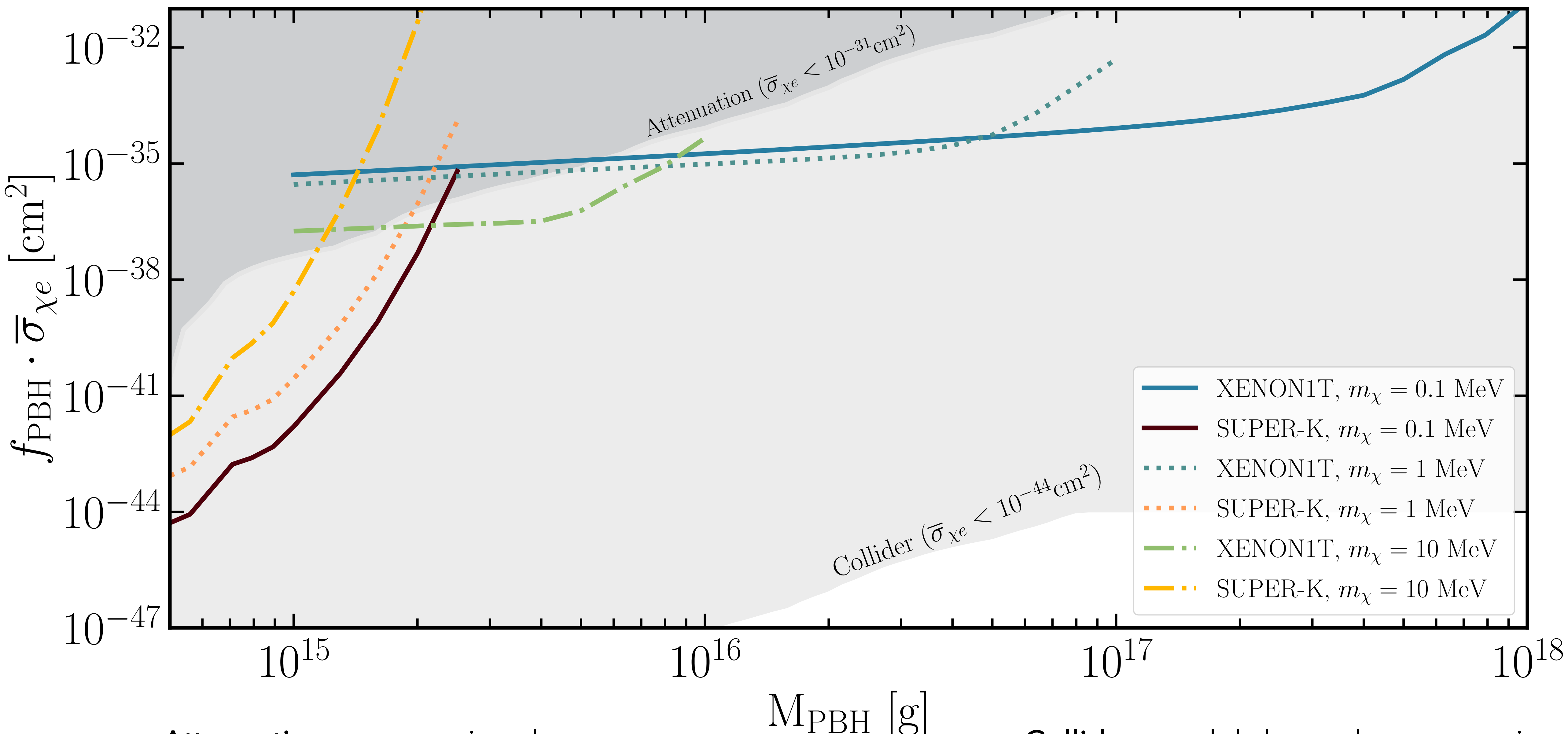


- Binned analysis
- Data taken from Aprile+ PRD 2020
- Bound electrons



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

Constraints on PBH-DM space



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