ANTINUCLEI FROM PBHS

Based on **Phys.Rev.D 112 (2025) 2, 2**

in collaboration with V. De Romeri, F. Donato, D. Maurin & L. Stefanuto

Agnese Tolino

IFIC (CSIC-UV)

XVII CPAN DAYS

November 20th, 2025

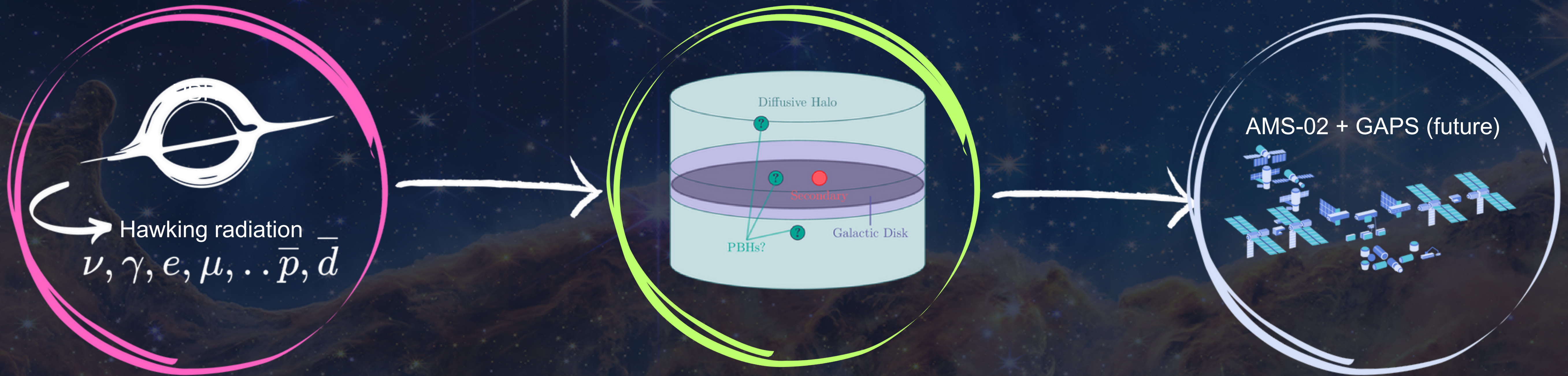
Valencia

More details here!

arXiV:2505.04692

See also: J. Herms et al., JCAP 02 (2017)
A. Barrau et al., Astron. Astrophys. 388 (2002) 676
A. Barrau et al. Astron. Astrophys. 398 (2003) 403

OUR WORK IN A NUTSHELL



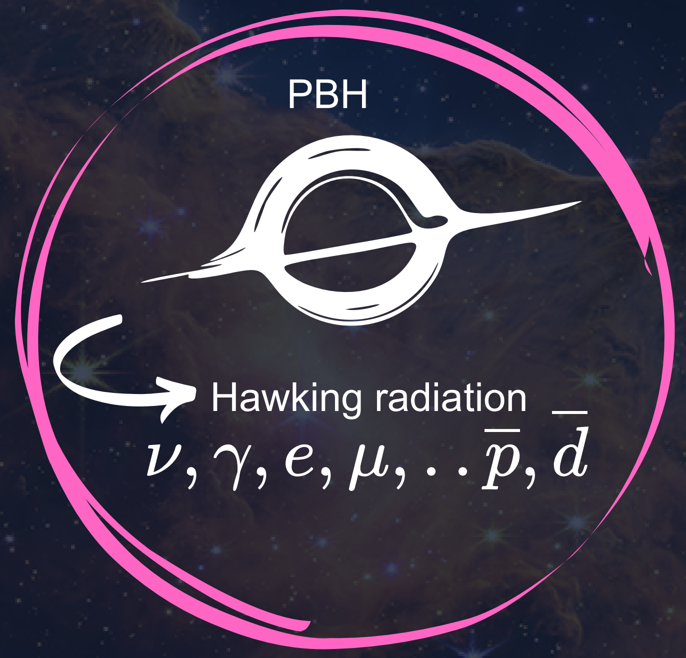
Source

Propagation

Detection

In Phys.Rev.D 112 (2025) 2, 2,
we estimated the **antiproton** and **antideuteron signals** from a population of **primordial black holes** (PBHs) following a **lognormal** mass distribution. By comparing with AMS-02 data, we derived competitive **constraints** on the fraction of dark matter that such PBHs could represent and discussed **perspectives** for antideuteron measurements with **AMS-02** and **GAPS**

IDENTIKIT OF PBHS



Source

- Might have formed in the Early Universe by the collapse of **overdensities**

Hawking, Nature 248 (1974) 30-31
Carr et al., Ann. Rev. Nucl. Part. Sci. 70 (2020)
Carr et al., Rept. Prog. Phys. 84 (2021) 11, 116902

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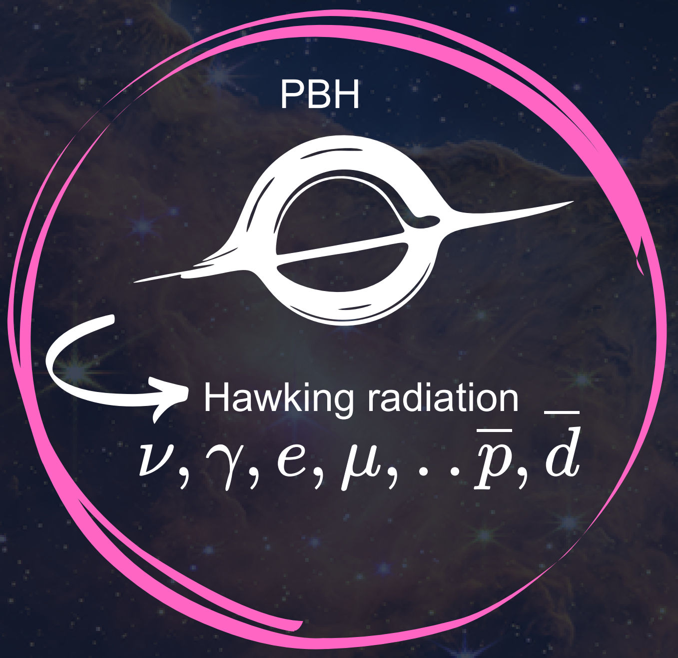

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- **Schwarzschild** (i.e. non-rotating & uncharged) PBHs are uniquely described by their **mass**

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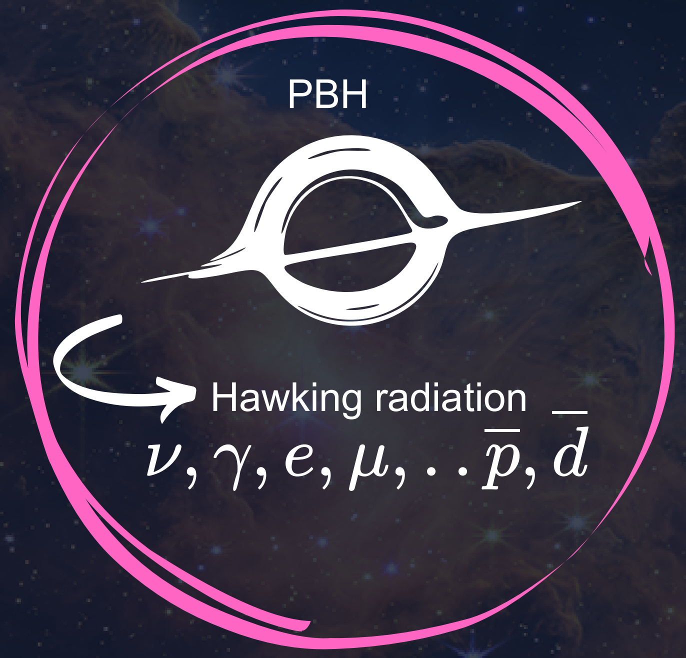

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- Masses span from 10^{-5} g to $10^5 M_\odot$

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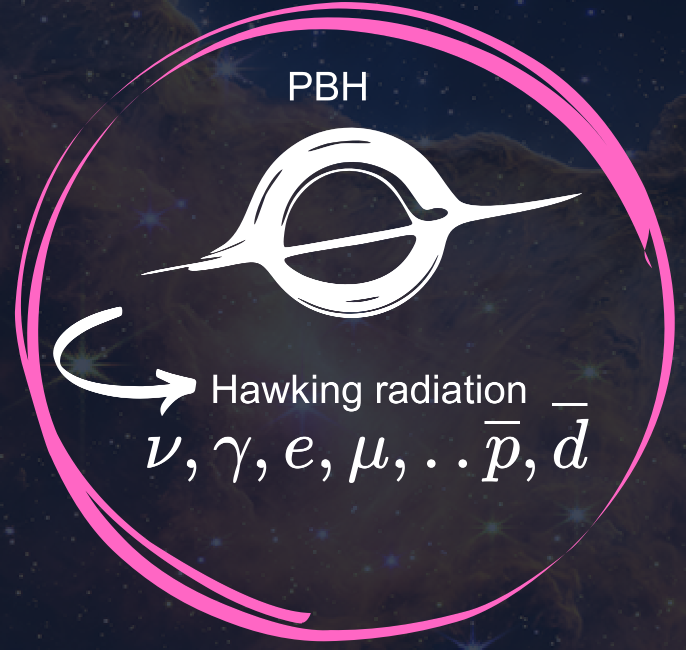

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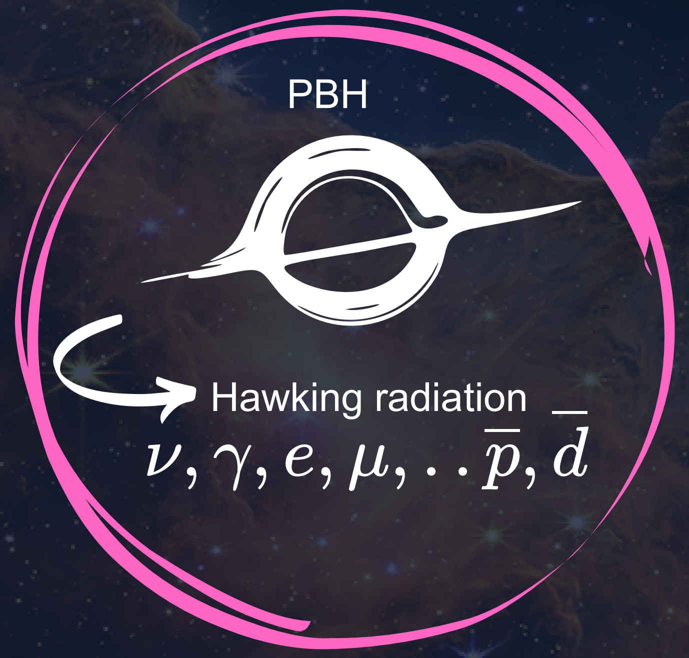
- **Schwarzschild** (i.e. non-rotating & uncharged) PBHs are uniquely described by their **mass**
- Masses span from 10^{-5} g to $10^{5} M_{\odot}$
- PBHs above 5×10^{14} g could be viable DM candidates, as they would have not completely evaporated yet

Hawking, Nature 248 (1974) 30-31
Carr et al., Ann. Rev. Nucl. Part. Sci. 70 (2020)
Carr et al., Rept. Prog. Phys. 84 (2021) 11, 116902

HAWKING RADIATION



Source

- Hawking predicted that PBHs **evaporate** with a temperature

$$T = \frac{1}{8\pi G M_{\text{PBH}}}$$

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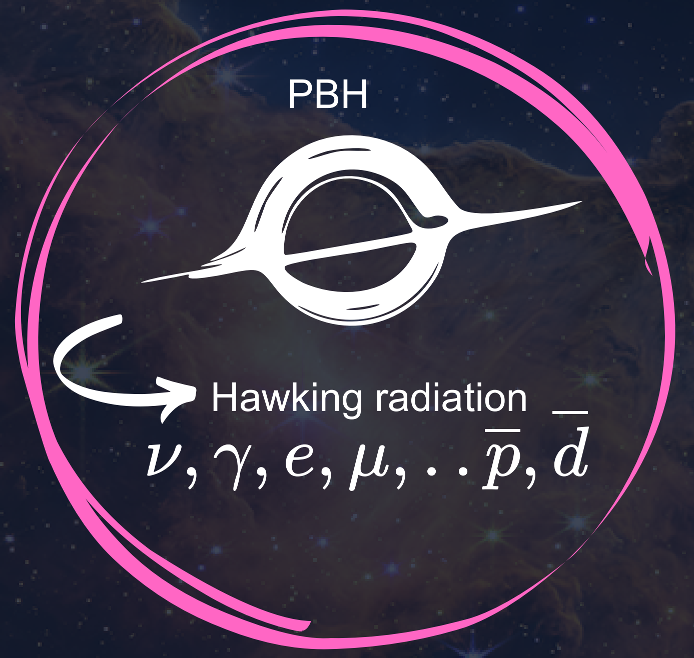

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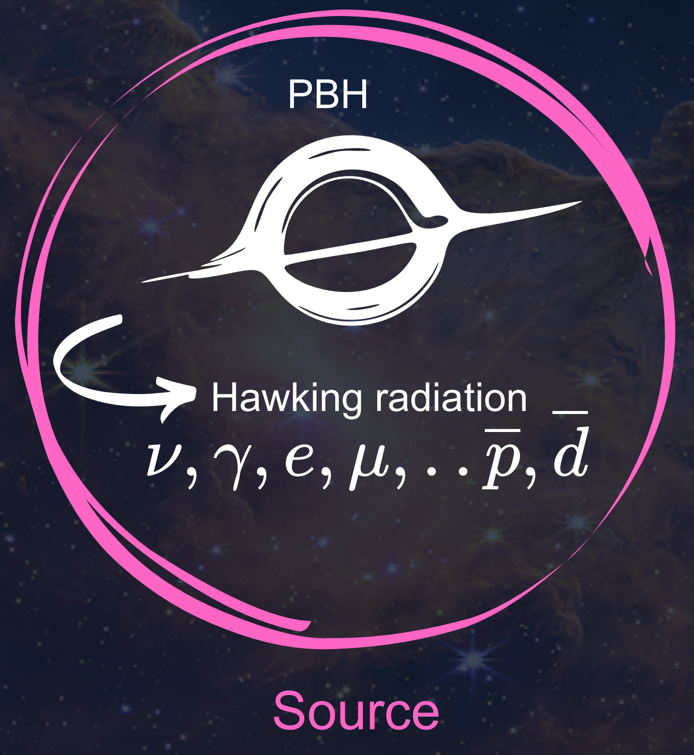

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$$T = \frac{1}{8\pi G M_{\mathrm{PBH}}}$$

- Mass loss goes as $\frac{dM}{dt} \sim M_{\mathrm{PBH}}^{-2}$

- The evaporation corresponds to the emission of particles with a semi-thermal spectrum

$$\left.\frac{dN^i}{dEdt}\right|_{\mathrm{prim}} = \frac{g_i \Gamma\left(M_{\mathrm{PBH}}, E_i\right)}{2\pi\left(\exp\left\{\frac{E_i}{T_{\mathrm{PBH}}}\right\} - (-1)^{2s_i}\right)}$$

Hawking, Nature 248 (1974) 30-31
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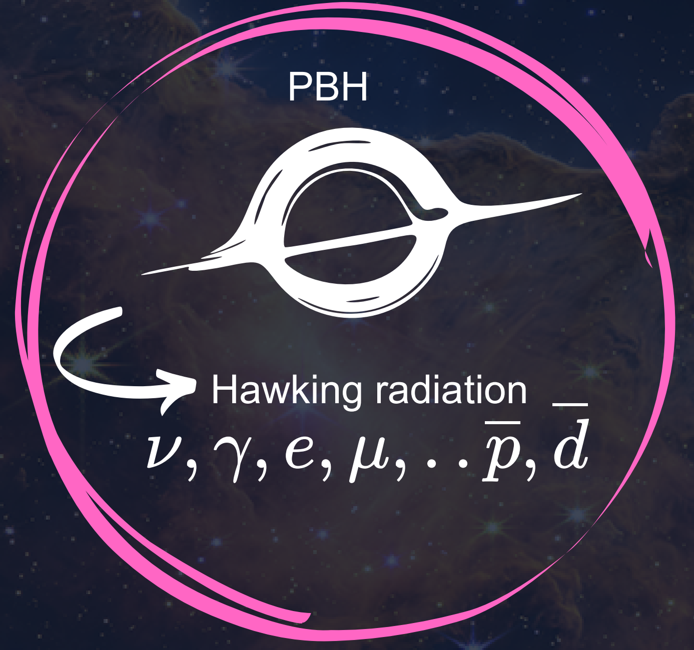
ANTIPARTICLES FROM PBHs



Source

- **Antiprotons** and **antineutrons** result from the **hadronization** of **quarks** and **bosons** directly emitted throughout the evaporation

A. Barrau et al., A&A 388, 676-687 (2002)
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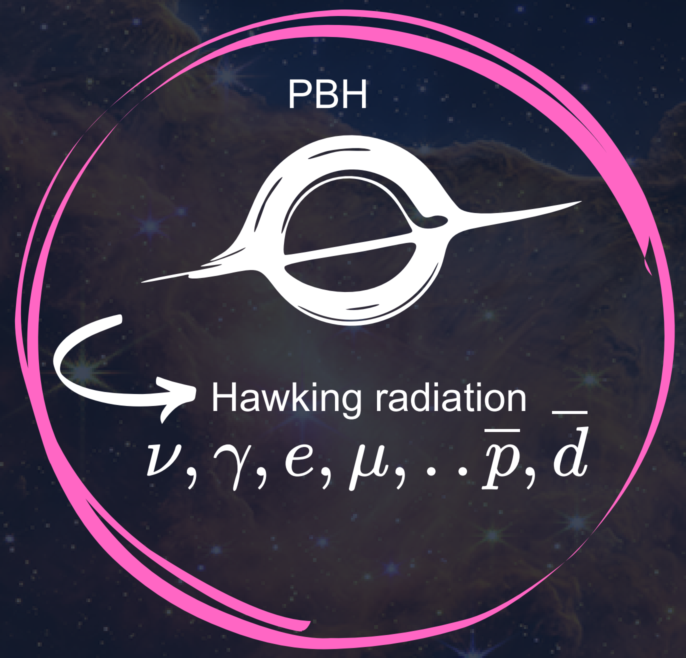
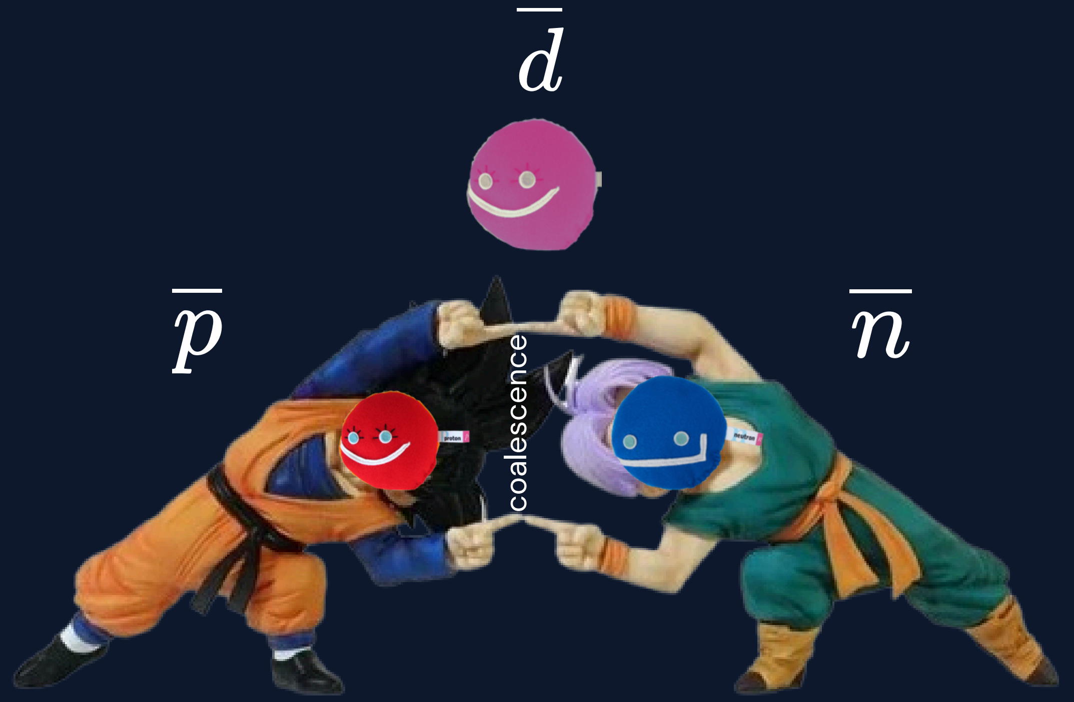


Source

- **Antiprotons** and **antineutrons** result from the **hadronization** of **quarks** and **bosons** directly emitted throughout the evaporation
- **Antideuterons** result from the coalescence of an antineutron and antiproton (Argonne-Wigner coalescence)



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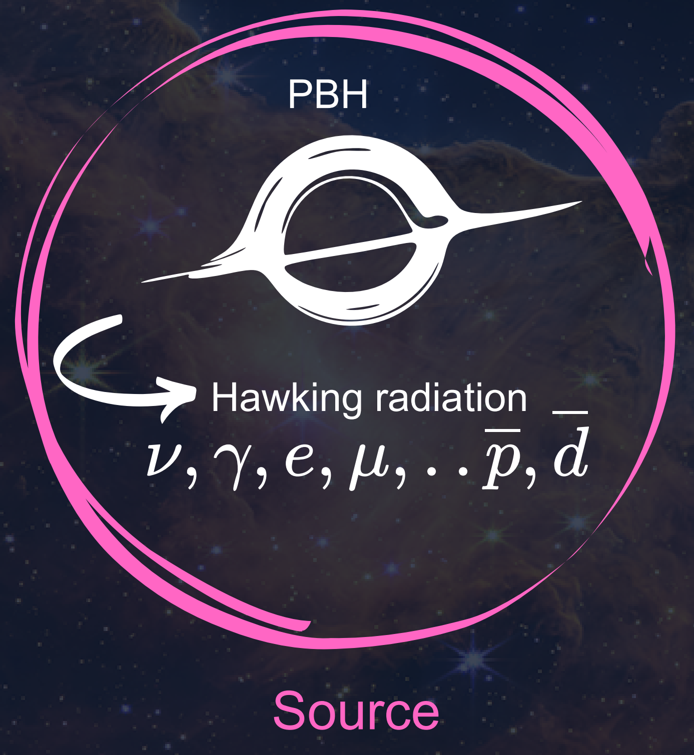
EXTENDED MASS DISTRIBUTIONS



- PBHs can follow **extended mass distributions (EMD)**

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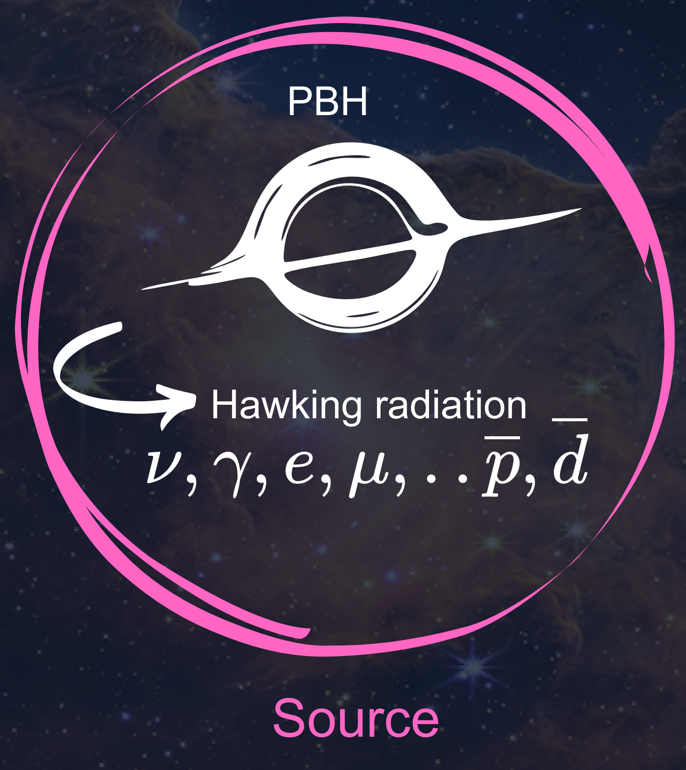

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- In our work, we considered a lognormal EMD at the formation time with critical mass μ_c and standard deviation σ

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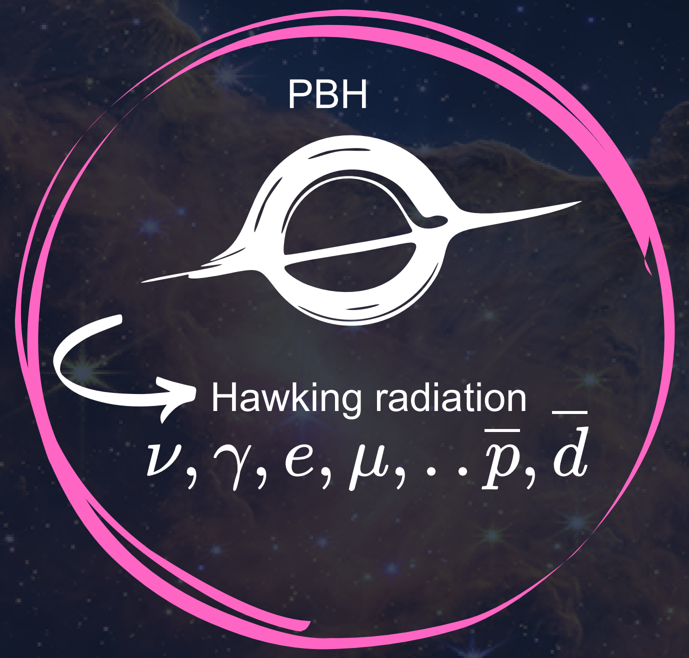
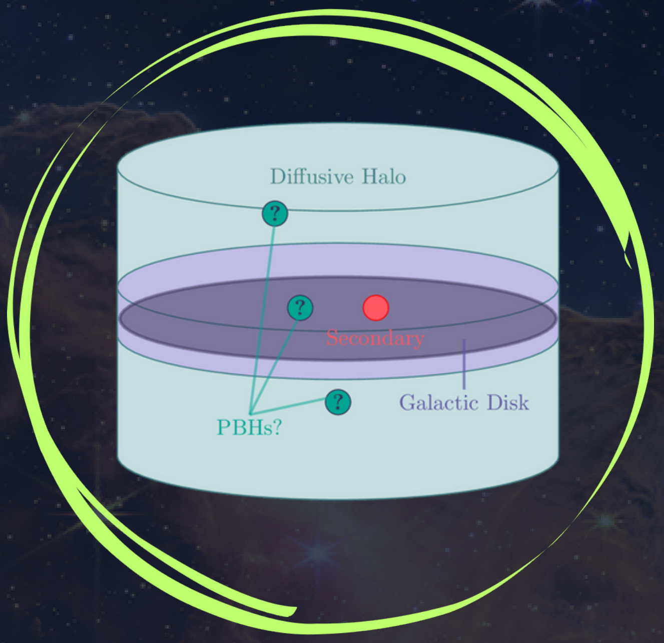


Source

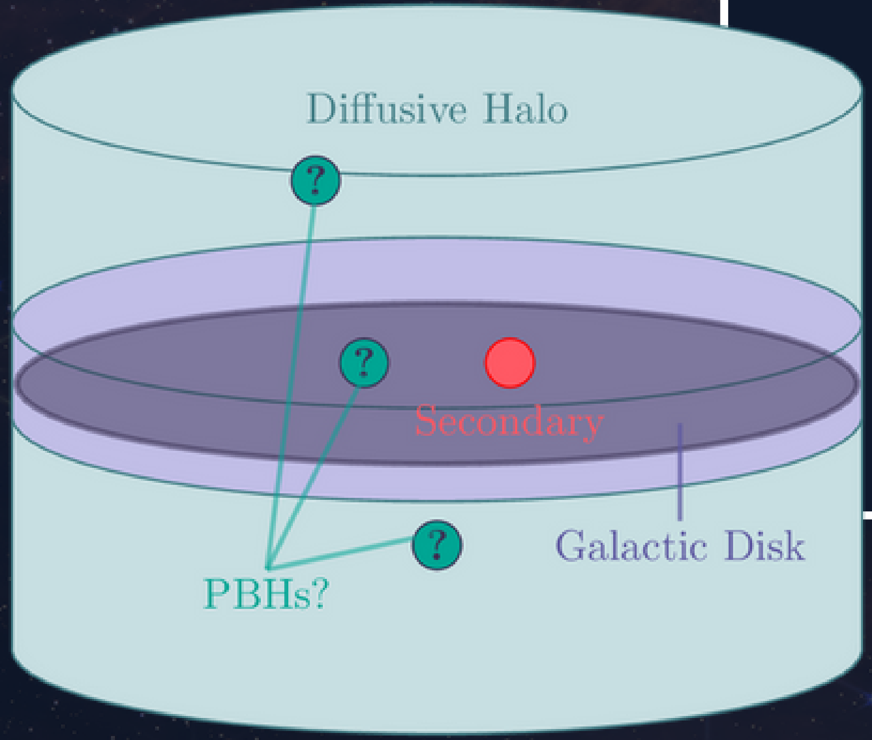
- PBHs can follow **extended mass distributions (EMD)**
- In our work, we considered a lognormal EMD at the formation time with critical mass μ_c and standard deviation σ
- EMDs evolve over time due to evaporation, but during the typical antinuclei propagation period, they stay nearly constant:
  → **static cosmic-ray sources**

COSMIC RAYS PROPAGATION



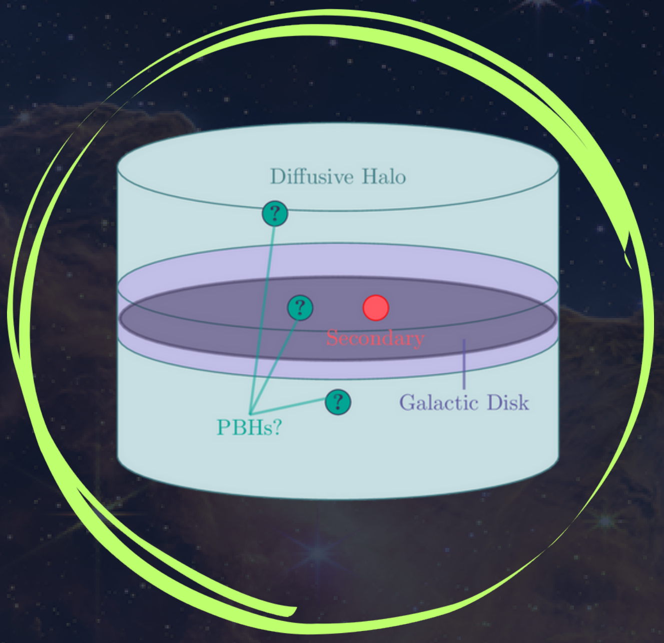
Propagation

- The Galaxy is a thin disk surrounded by inhomogeneous magnetic fields, that cause **cosmic rays (CRs)** to diffuse in the so called **diffusive halo**



V.S. Berezinskii, et al., *Astrophysics of cosmic rays,* Elsevier Science and Technology (1990)
Y. Genolini et al., Phys. Rev. D 99 (2019) 123028,

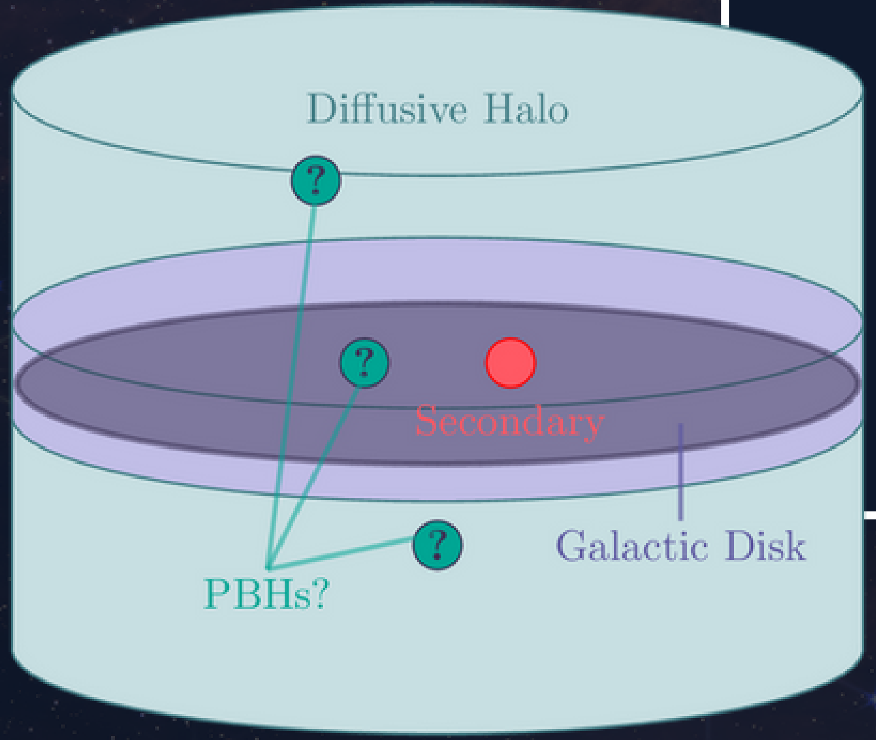
COSMIC RAYS PROPAGATION



Propagation

- The Galaxy is a thin disk surrounded by inhomogeneous magnetic fields, that cause **cosmic rays (CRs)** to diffuse in the so called diffusive halo

- **PBHs** could be located anywhere in the diffusive halo



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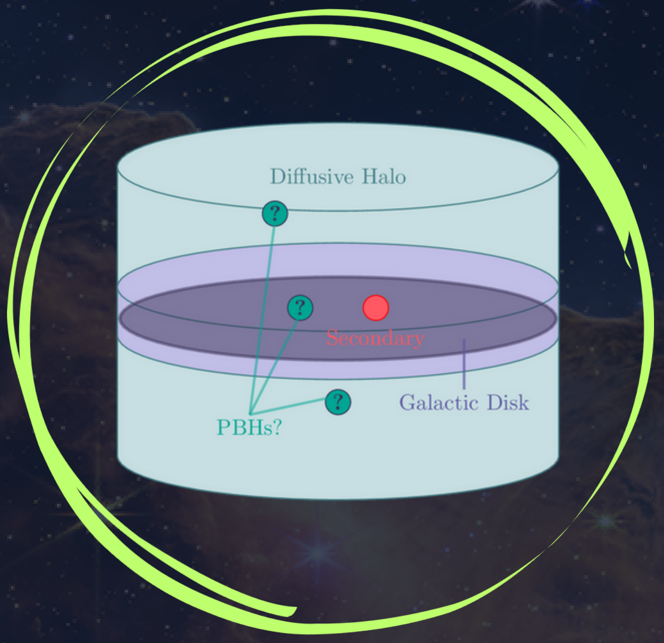

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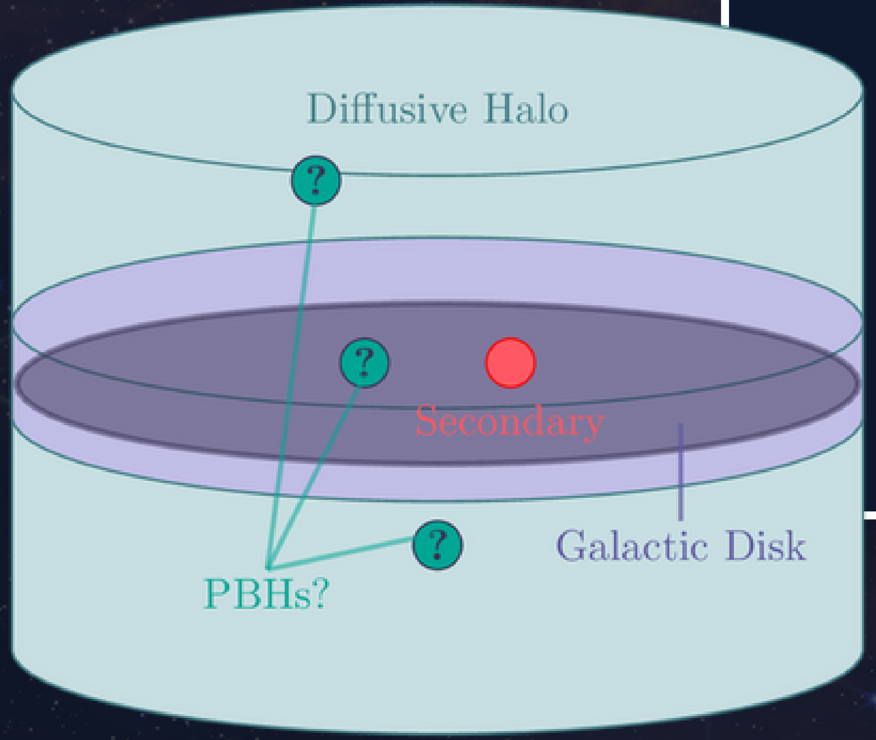

- The Galaxy is a thin disk surrounded by inhomogeneous magnetic fields, that cause **cosmic rays (CRs)** to diffuse in the so called diffusive halo

- PBHs could be located anywhere in the diffusive halo

- Once produced by PBHs, the antinuclei propagate and arrive to the **Earth**

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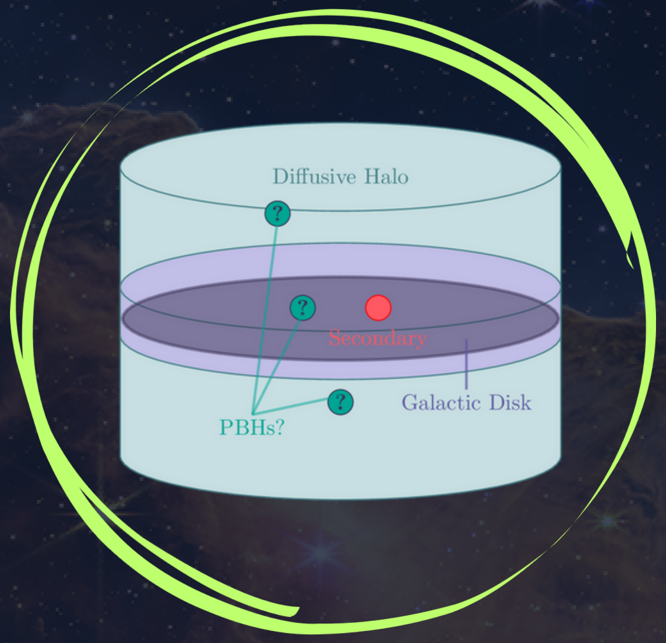
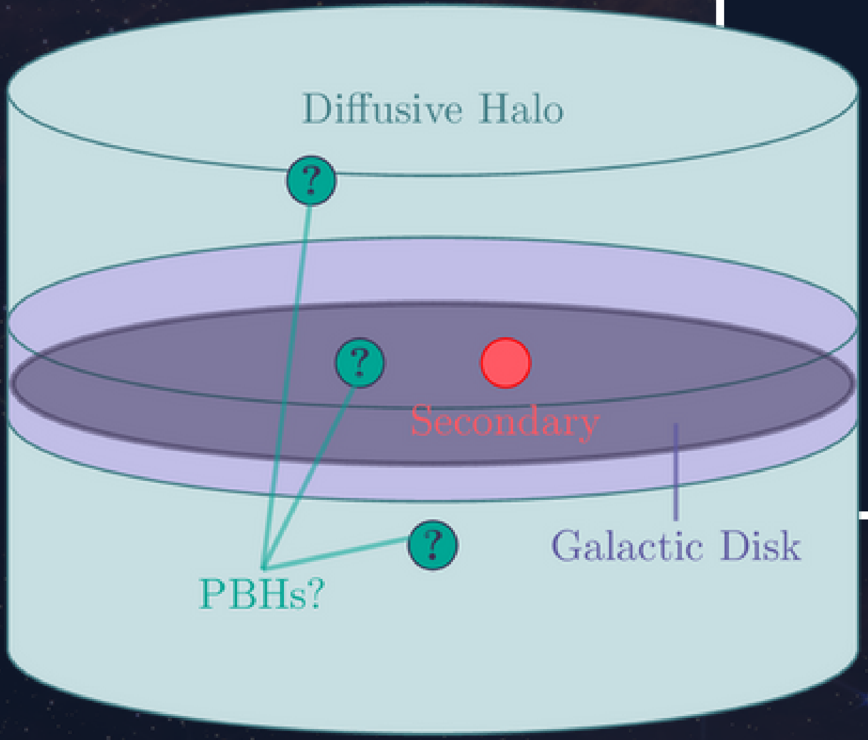


Propagation

- The Galaxy is a thin disk surrounded by inhomogeneous magnetic fields, that cause **cosmic rays (CRs)** to diffuse in the so called diffusive halo
- PBHs could be located anywhere in the diffusive halo
- Once produced by PBHs, the antinuclei propagate and arrive to the Earth
- In addition to this, secondary antinuclei are produced by the **spallation** of primary (mainly from supernovae shock waves) CRs over the H and He in the Galactic disk



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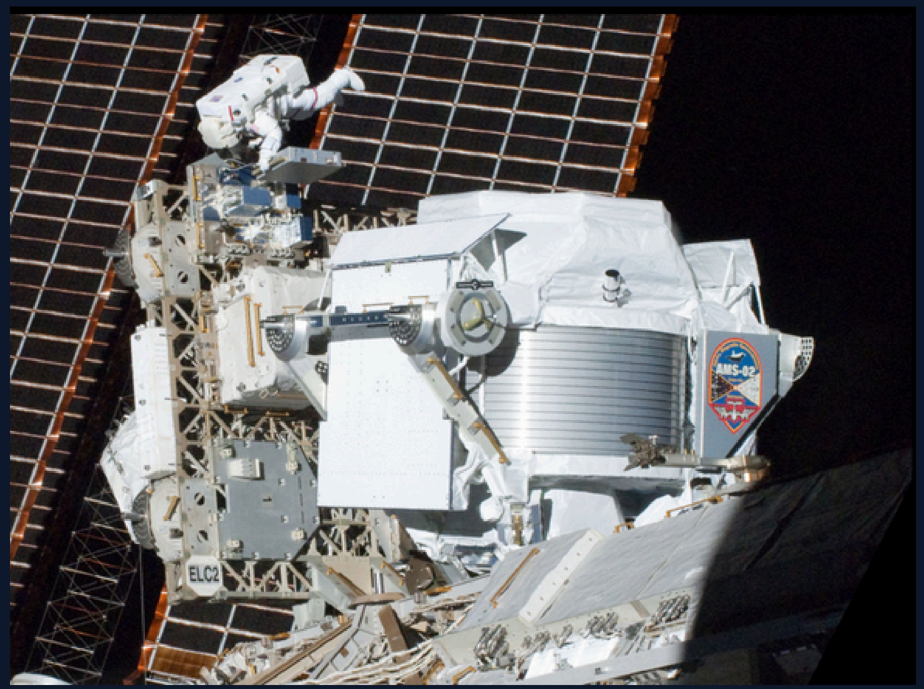
DETECTION OF ANTINUCLEI: AMS-02 & GAPS

Detection

The **Alpha Magnetic Spectrometer (AMS-02)** on the International Space Station has **measured cosmic-ray antiprotons** (latest data: 2021), which are still **well fitted by secondary production** models



AMS collaboration, Phys. Rev. Lett. 117 (2016) 091103
AMS collaboration, Phys. Rept. 894 (2021)
T. Aramaki et al., GAPS, Appl. Phys. 74 (2016) 6
GAPS collaboration, Astropart. Phys. 145 (2023) 102791

DETECTION OF ANTINUCLEI: AMS-02 & GAPS

AMS-02 + GAPS (future)

Detection

The **General AntiParticle Spectrometer (GAPS)** is a balloon-borne future experiment in Antarctica that will search for **low-energy cosmic antinuclei** (< 0.25 GeV/n), where PBH signals could be most **visible**

AMS collaboration, Phys. Rev. Lett. 117 (2016) 091103
AMS collaboration, Phys. Rept. 894 (2021)
T. Aramaki et al., GAPS, Appl. Phys. 74 (2016) 6
GAPS collaboration, Astropart. Phys. 145 (2023) 102791

COMPUTATIONAL ASPECTS AND STATISTICAL ANALYSIS

1

Through **BlackHawk**, we compute the Hawking radiation from a population of **PBHs** with a **lognormal mass distribution**,
for different μ_c and σ

2

We derive the antiproton emission with **CosmiXs** from quarks and bosons

3

We propagate the $\bar{p}$ flux with **USINE** in the **BIG** configuration

4

By comparing with AMS-02 2021 data, we derived **UL PBH densities** at 95% CL

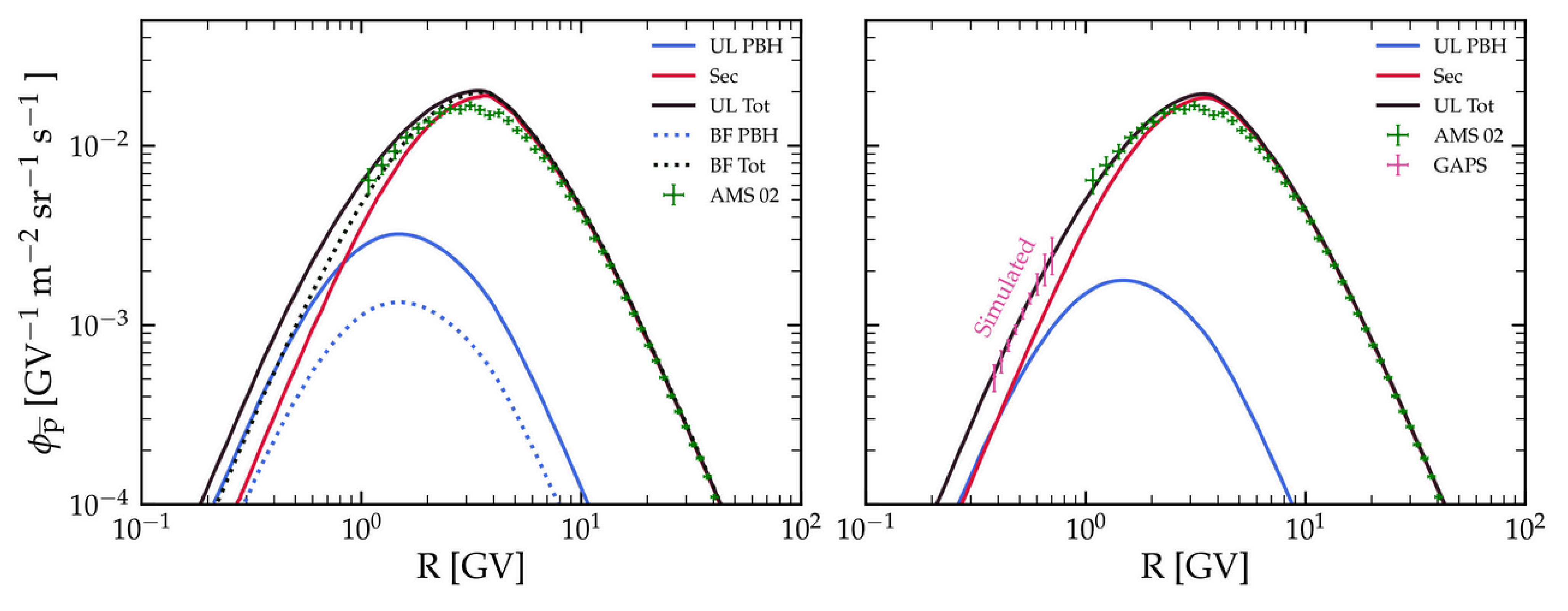
5

We evaluate the antideuteron primary fluxes using the **Argon-Wigner coalescence of CosmiXs**, and applying the **antiproton density bounds**.

Y. Genolini et al., PRD 99 (2019) 123028
M. Boudaud et al., Phys. Rev. Res. 2 (2020) 02302
F. Calore et al., SciPost Phys. 12 (2022) 16
A. Arbey et al., Eur. Phys. J. C 79 (2019) 693 C.
Arina et al., JCAP 03 (2024) 035
M. Di Mauro et al., 2411.04815
D. Maurin, Communications 247 (2020) 106942

RESULTS

ANTIPROTON FLUXES



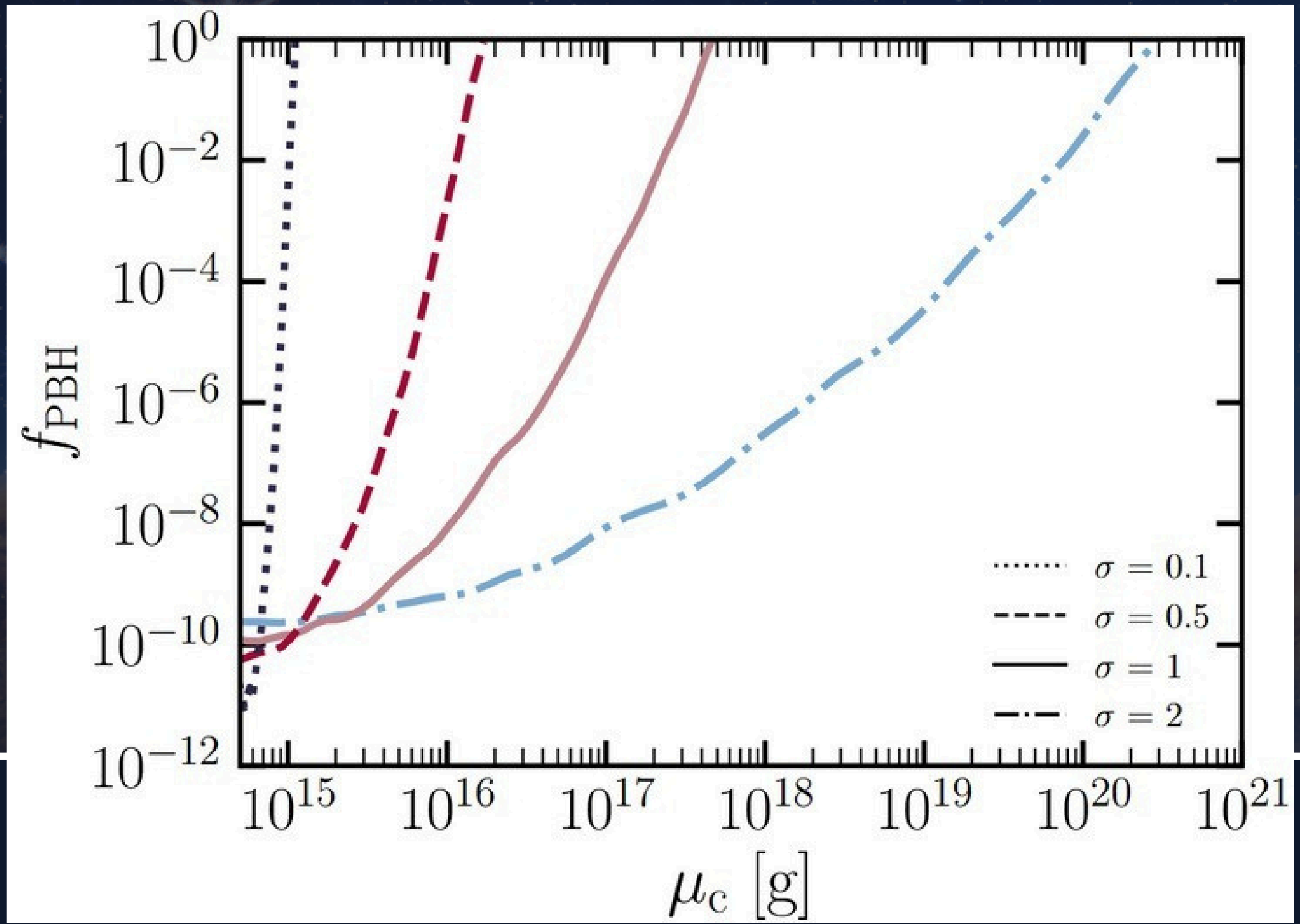
- The **Upper Limit (UL)** is evaluated at 95% C.L. with **AMS-02 2021 data only** (left) and adding **GAPS simulated** data (right) - Best Fit (BL) only illustrative
- AMS-02 2021 data are well fitted by the secondary contribution → **suppressed PBH contribution**
- GAPS data would help to investigate the **low energy tail** where the PBH contribution is significant

AMS collaboration, Phys. Rept. 894 (2021)
GAPS collaboration, Astropart. Phys. 145 (2023) 102791
F. Calore et al., SciPost Phys. 12 (2022) 163

P. De la Torre Luque et al. PRD 110 (2024) 123022
M. Boudaud et al., PRL 122 (2019) 041104
A. Arbey et al., PRD 101 (2020) 023010

BOUNDS ON PBHs AS DM

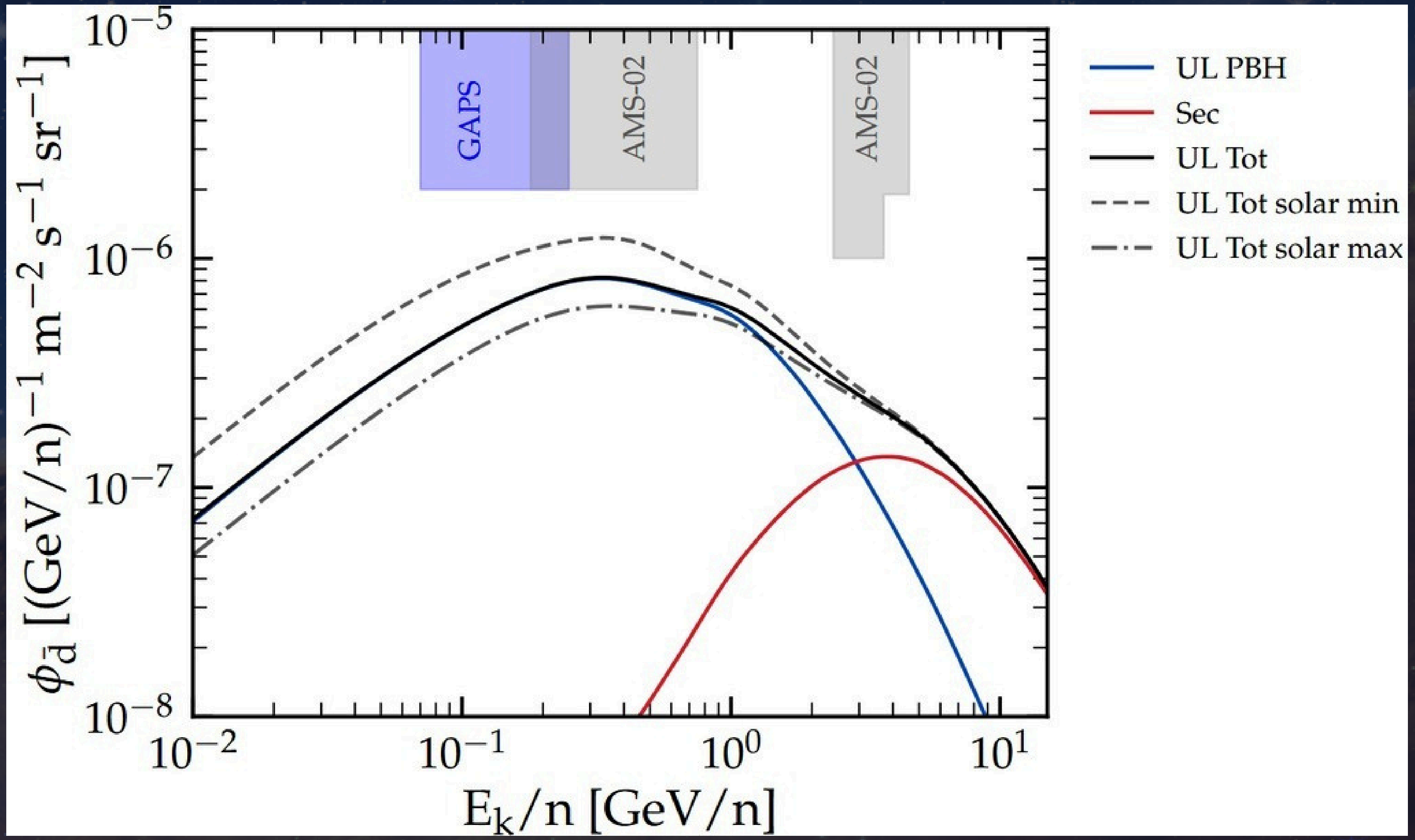
$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{DM}}$$



- 95% CL UL on $\rho_{\rm PBH}$ and $f_{\rm PBH}$ with **AMS-02 2021** data
- Higher widths imply that a bigger portion of the asteroid mass range is constrained, although the **constraining power gets reduced** with increasing mass

ESTIMATED ANTIDEUTERON FLUX

- We applied the **UL densities from antiprotons**
- The PBH contribution is more relevant than the secondary one below 3 GeV/n, but it is **far from GAPS** and **AMS-02** sensitivities, even accounting for solar modulation effects
- If antideuterons were to be detected, they **could not be explainable by PBHs only** as BSM physics



$$\mu_c = 10^{15} g$$
$$\sigma = 1$$
$$\rho_{PBH} = 5.2 \times 10^{-11}\ \mathrm{GeV\ cm^{-3}}$$

M. Di Mauro, et al., 2411.04815
T. Aramaki et al., Appl. Phys. 74 (2016) 6
T. Aramaki, et al., Physics Reports 618 (2016) 1

arXiV:2505.04692

CONCLUSIONS

1

We **revisited** the **CR antiproton and antideuterons signatures from PBH** evaporation in the Galaxy

2

We **improved previous calculations** w/ lognormal PBH mass distribution, updated Galactic propagation parameters, the most recent AMS-02 $\bar{p}$ data & a sophisticated statistical analysis

3

We cast **competitive bounds** with antiprotons on $f_{\rm PBH}$ in the asteroid mass range

4

We estimated that if one or more **antideuterons** were to be measured by AMS-02 or by GAPS, they would clearly be a signal of new physics, but **not completely expainable with PBH emission** arXiV:2505.04692

CONCLUSIONS

THANKS FOR YOUR ATTENTION! QUESTIONS?

1. We **revisited** the **CR antiproton and antideuterons signatures from PBH** evaporation in the Galaxy

2. We **improved previous calculations** w/ lognormal PBH mass distribution, updated Galactic propagation parameters, the most recent AMS-02 $\bar{p}$ data & a sophisticated statistical analysis

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BACKUP

EXTENDED MASS DISTRIBUTIONS

See M.R. Mosbech et al., SciPost Phys. 13 (2022) 100 for a more in-depth discussion.

We define

$$g(r, z, M_{\rm in}) \equiv M_{\rm in} \frac{\mathrm{d}n_{\rm PBH}}{\mathrm{d}M_{\rm in}} = M_{\rm in} \frac{\mathrm{d}^2 N_{\rm PBH}}{\mathrm{d}M_{\rm in}\mathrm{d}V}, \tag{1}$$

A lognormal mass distribution (at the time of the PBHs formation) follows

$$g(r,z,M_{\rm in})|_{\rm ln} = \rho_{\rm PBH}(r,z) \frac{\mathcal{A}}{\sqrt{2\pi}\sigma M_{\rm in}} \exp\left[-\frac{\log^2(M_{\rm in}/\mu_c)}{2\sigma^2}\right], \tag{2}$$

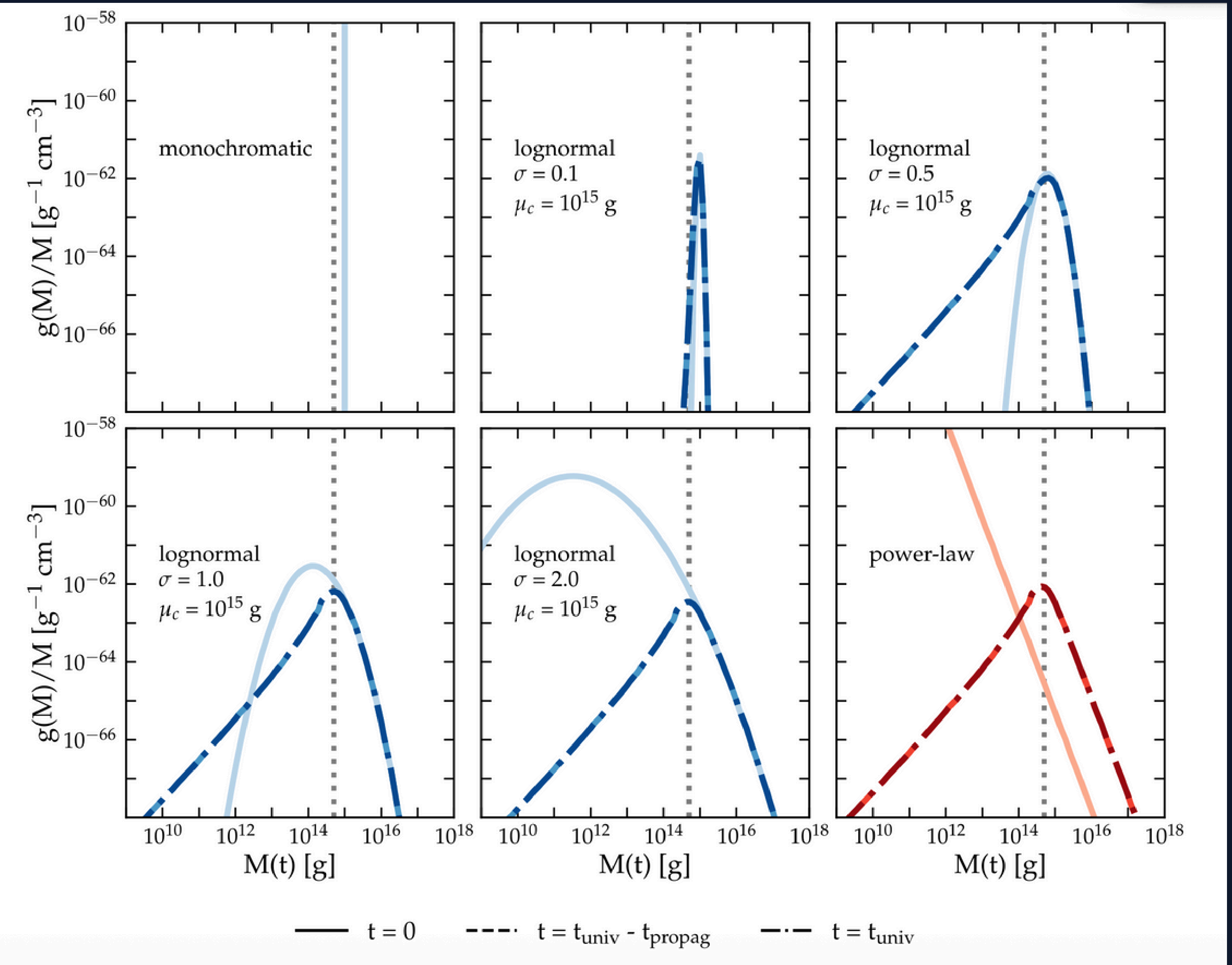
Another example is the power-law:

$$g(r, z, M_{\rm in})|_{\rm pow} = \rho_{\rm PBH}(r, z) \mathcal{A} M_{\rm in}^{-3/2}. \tag{3}$$

A monochromatic (i.e. non-extended) distribution can be represented as a Dirac delta around a specific mass value.

EVOLUTION OF THE MASS DISTRIBUTION

The mass distribution will evolve through time due to the evaporation



$$\frac{dn_{PBH}}{dM} = \frac{dn_{PBH}}{dM_{in}} \frac{dM_{in}}{dM} = \frac{dn_{PBH}}{dM_{in}} \frac{M^2 \alpha(M_{in})}{M_{in}^2 \alpha(M)}, \quad (9)$$

$$\frac{dM}{dt} = -\frac{\alpha(M)}{M^2},$$

SOURCE TERM OF ANTINUCLEI

$$\mathcal{Q}_{\bar{p}(\bar{d})}(r,z,E) = \int_{M_{\min}}^{M_{\max}} \mathrm{d}M \, \frac{g(r,z,M)}{M} \times \sum_{i=g,q,W,Z,h} \int_{m_i}^{\infty} \mathrm{d}E_i \frac{\mathrm{d}^2 N_i(E_i,M)}{\mathrm{d}E_i \mathrm{d}t}\bigg|_{\mathrm{HR}} \times \frac{\mathrm{d}N_{i\to\bar{p}(\bar{d})}}{\mathrm{d}E}(E,E_i), \quad (10)$$

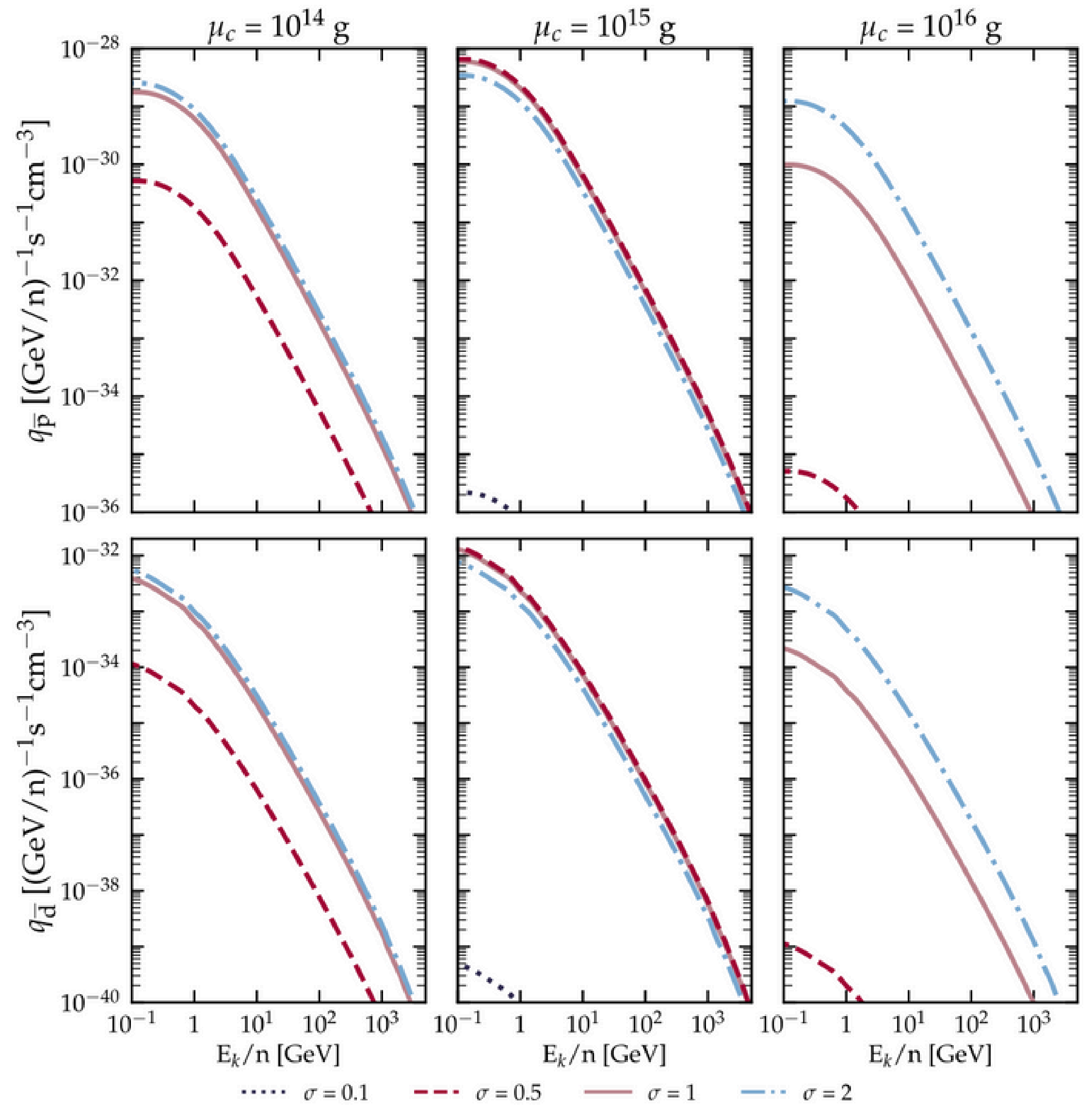


FIG. 2. The antiproton (top panels) and antideuteron (bottom panels) source spectra from PBH evaporation, as a function of the kinetic energy E_k per nucleon. The spectra have been evaluated for PBHs with a lognormal mass distribution and assuming $\rho_{\mathrm{PBH}} = 10^{-32}\ \mathrm{g\,cm^{-3}} = 5.6 \times 10^{-9}\ \mathrm{GeV\,cm^{-3}}$, for different values of the critical masses μ_c and standard deviation σ; see the legend.

THE TRANSPORT EQUATION

$$
-\left[K\left(\frac{\partial^2}{\partial z^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)\right)-V_c\frac{\partial}{\partial z}\right]n+2h\delta(z)\frac{\partial}{\partial E}\left[b(E)n-c(E)\frac{\partial n}{\partial E}\right]
= q^{\mathrm{prim}}(E)+2h\delta(z)[q^{\mathrm{sec}}(E)+q^{\mathrm{ter}}(E)]-2h\delta(z)\sum_{t\in\mathrm{ISM}}n_t v\sigma_{\mathrm{inel}}n.
$$

Transport parameters

$$
K(R)=\beta^{\eta}K_0\left\{1+\left(\frac{R}{R_{\mathrm{l}}}\right)^{\frac{\delta_{\mathrm{l}}-\delta}{s_{\mathrm{l}}}}\right\}^{s_{\mathrm{l}}}\left\{\frac{R}{R_0=1\ \mathrm{GV}}\right\}^{\delta}\left\{1+\left(\frac{R}{R_{\mathrm{h}}}\right)^{\frac{\delta-\delta_{\mathrm{h}}}{s_{\mathrm{h}}}}\right\}^{-s_{\mathrm{h}}},
$$

$$
K_{pp}=\frac{4}{3}V_a^2\beta^2E^2\frac{1}{\delta(4-\delta^2)(4-\delta)K(R)}. \qquad (15)
$$

+ the convective wind velocity

Source and sink terms

$$
q^{\mathrm{sec}}(E)=\int_{E'_{\mathrm{th}}}^{\infty}\mathrm{d}E'\sum_{c\in\mathrm{CRs}}\left[\sum_{t\in\mathrm{ISM}}\left(n_t v'\frac{\mathrm{d}\sigma_{\mathrm{prod}}}{\mathrm{d}E}(E',E)\right)n^c(E')\right],
$$

$$
q^{\mathrm{ter}}(E)=\int_{E}^{\infty}\mathrm{d}E'\left[\sum_{t\in\mathrm{ISM}}\left(n_t v'\frac{\mathrm{d}\sigma_{\mathrm{nar}}(E',E)}{\mathrm{d}E}\right)n(E')\right]-\sum_{t\in\mathrm{ISM}}(n_t v\sigma_{\mathrm{ina}}(E))n(E),
$$

+ first and second order energy redistribution terms (ionization & Coulomb losses)

STATISTICAL ANALYSIS

See F. Calore et al., SciPost Phys. 12 (2022) 16 and M. Boudaud et al., Phys. Rev. Res. 2, 023022 (2020) for a more in-depth discussion.

$$-2\ln\mathcal{L}(L,\mu) = \sum_{i,j} x_i (C^{-1})_{ij} x_j + \left\{ \frac{\log L - \log \hat{L}}{\sigma_{\log L}} \right\}^2, \quad (18)$$

$$\mathrm{LR}(\rho_{\mathrm{PBH}}) = -2\ln\mathcal{L}(L_{\min},\rho_{\mathrm{PBH}}) + 2\ln\mathcal{L}(L',\rho'_{\mathrm{PBH}}), \quad (19)$$

PBH DENSITY U.L. AT 95% C.L.

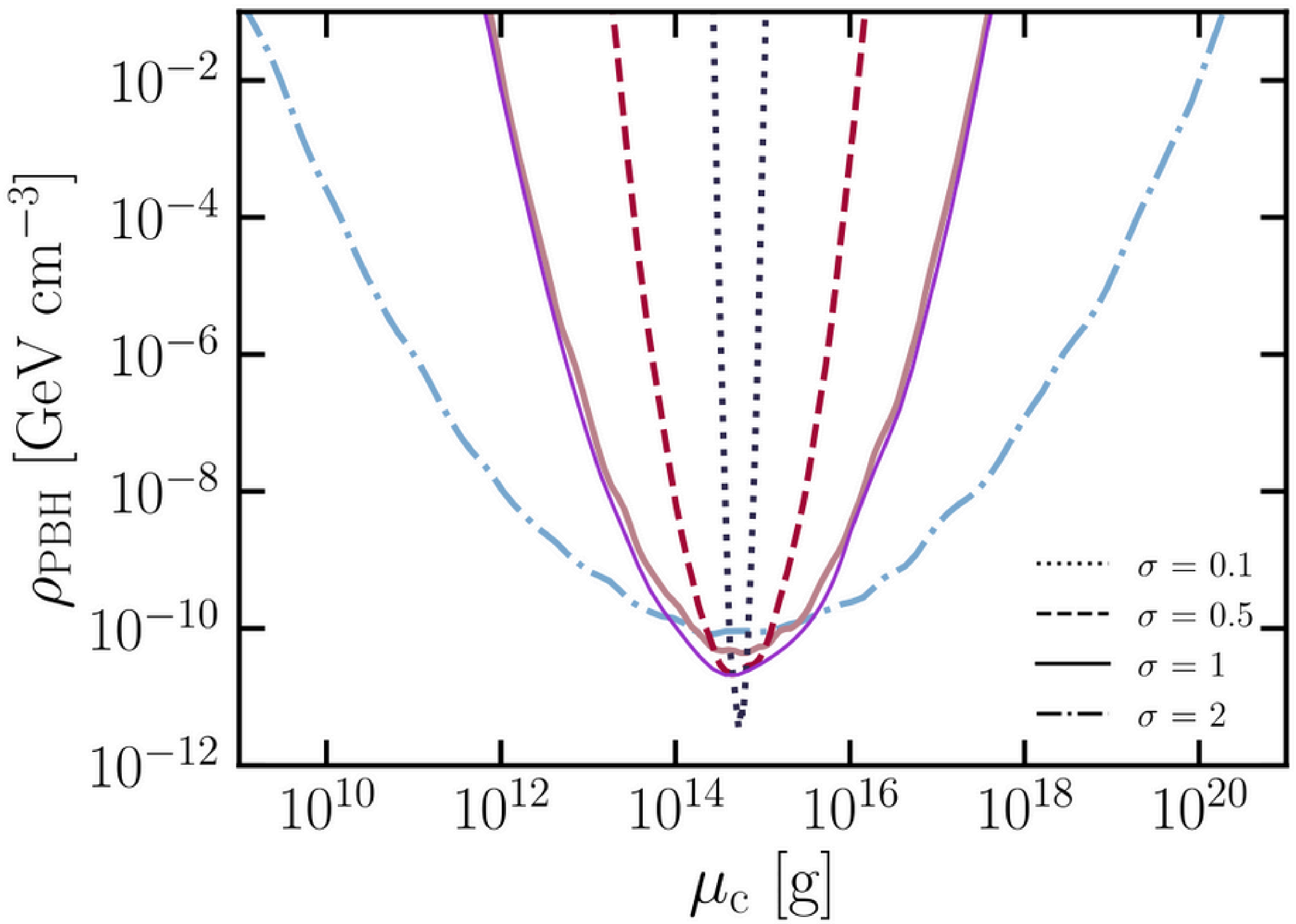


FIG. 4. Upper bounds for ρ_{PBH} as a function of μ_c, for $\sigma = 0.1$ (dotted), 0.5 (dashed), 1 (solid), and 2 (dot-dashed), after a fit on AMS-02 data [49]. The thin solid purple line denotes the future sensitivity obtained from a combined fit of AMS-02 and the simulated GAPS data [53], for $\sigma = 1$.

U.L. AT 95% ON f_{PBH}

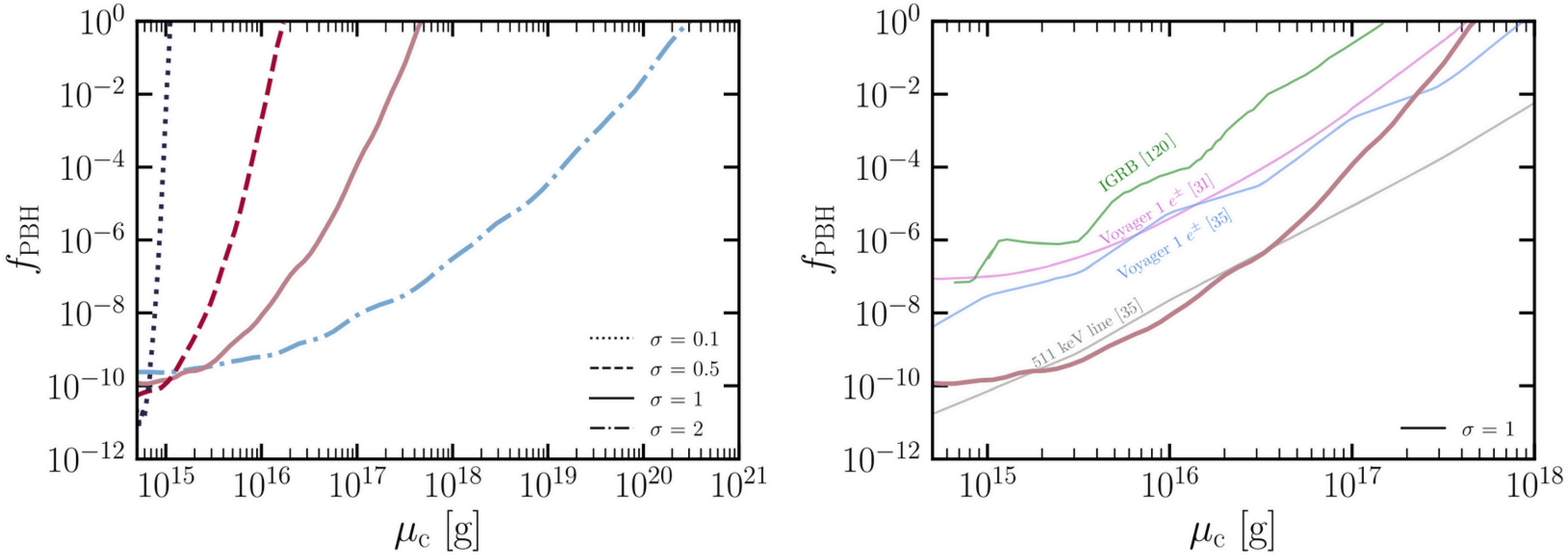


FIG. 5. Antiproton bounds on the fraction f_{PBH} of the PBH to the local DM density, $\rho_{\mathrm{PBH}}/\rho_{\odot}$, as a function of μ_c. Left panel: 95% CL exclusion limits based on AMS-02 data [49] for a lognormal PBH mass distribution with width $\sigma = 0.1$ (dotted), 0.5 (dashed), 1 (solid), and 2 (dot dashed). Right panel: our result (red thick line) for $\sigma = 1$, compared with other bounds from different messengers, Voyager-1 $e^{\pm}$ from Refs. [31,35], γ rays in the IGRB [119], and the 511 keV line [35].