Cosmic antinuclei from primordial black holes

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PRD112(2025)023003 ; ArXiv: **2505.04692**

05/11/2025

Primordial Black Holes (PBHs)

- PBHs are **hypothetical** black holes formed in the **Early Universe**
- **Many production mechanisms** have been proposed
- **Initial masses** can span an **extremely wide range** → from sub-g scales to $10^5\, M_\odot$
- Thanks to **Hawking Radiation (HR)**, light PBHs could produce **antinuclei**
- PBHs are studied as **dark matter candidates** and as possible **sources of exotic CR signatures**

$$\left.\frac{\mathrm{d}^2 N}{\mathrm{d}E\mathrm{d}t}\right|_{\mathrm{HR}}(E, M) = \frac{g}{2\pi}\frac{\Gamma_s(E)}{\exp(E/T) - (-1)^{2s}} \qquad T = \frac{1}{8\pi G_N M}$$

Hawking 1971 MNRAS152 (1971)75; MacGibbon 1990 *PRD41(1990)3052;* Carr et al. 2020 *RPP84(2021)*116902

Galactic antiprotons ($\overline{p}$) and antideuterons ($\overline{D}$)

We will focus on the energy range **10^{-1} - 10^{2} GeV**

Antinuclei	Production mechanism	Expected by standard astrophysics?
Primary	Produced **directly at CR sources**	**NO**: exotic sources invoked → **WIMP**, **PBH**
Secondary	**CR spallation** on the interstellar medium	YES

Why galactic antinuclei

Relatively small background expected, especially at **energies $\lesssim$ GeV**
Donato et al. 2000 PRD62(2000)043003; *Barrau et al. 2002* *AA388(2002)676*

↓

Galactic $\overline{D}$ → one of the **cleanest channels** for **indirect DM detection**

Very precise $\overline{p}$ data
AMS collaboration 2021 PR894(2021)1

No confirmed $\overline{D}$ detections

Design to detect **sub-Gev $\overline{D}$**
Aramaki et al. 2015 AP74(2016)6

Launching next year

Goals of our paper - PRD112(2025)023003 ArXiv: 2505.04692

- Compute the top of the atmosphere **(TOA) fluxes** of $\bar{p}$ and $\bar{D}$ from **galactic PBH evaporation**

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- Compare the $\bar{p}$ flux with **AMS-02 data** to **constrain the local PBH density**

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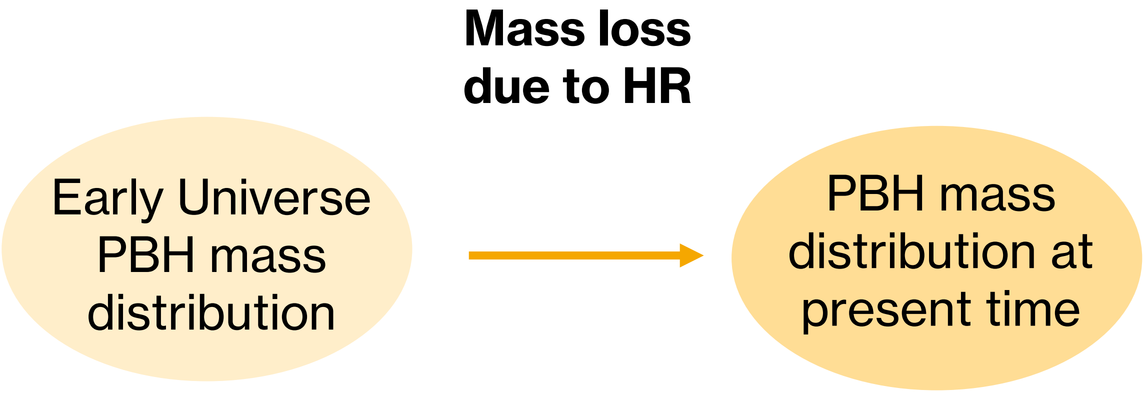
- Compute the top of the atmosphere **(TOA) fluxes** of $\bar{p}$ and $\bar{D}$ from **galactic PBH evaporation**
- Compare the $\bar{p}$ flux with **AMS-02 data** to **constrain the local PBH density**
- Compare the $\bar{D}$ flux with **GAPS sensitivity** to **evaluate detection perspectives**

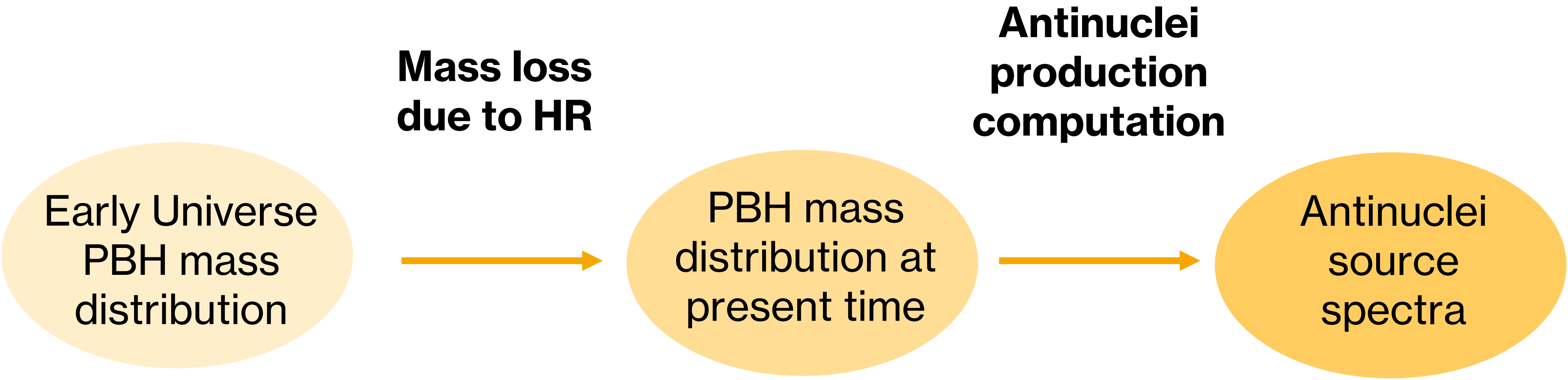
Flux computation pipeline

Early Universe
PBH mass
distribution

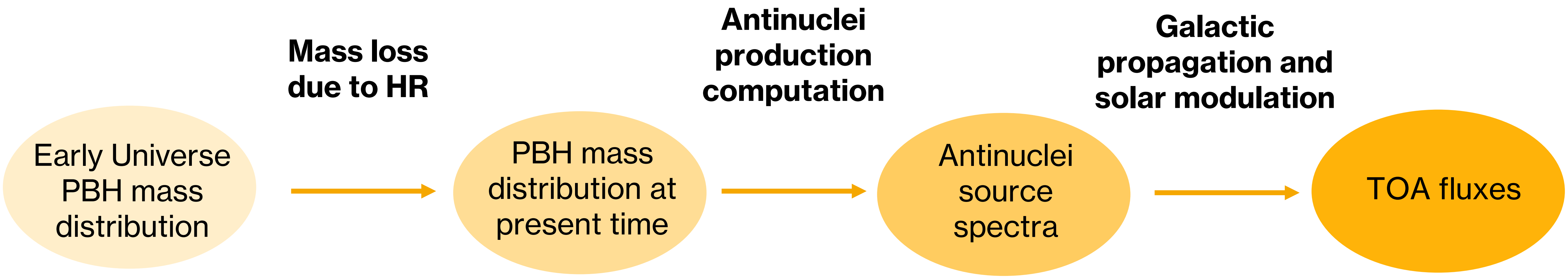
Flux computation pipeline



Flux computation pipeline



Flux computation pipeline



PBH initial mass distribution

Lognormal distribution

Dolgov et al. 1993 PRD47(1993)4244

Mean value = critical mass [g]

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

PBH mass at t=0

PBH density [GeV/cm³]

Standard deviation

Hawking radiation mass loss rate

Hawking 1975

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\alpha\,(M)}{M^2}$$

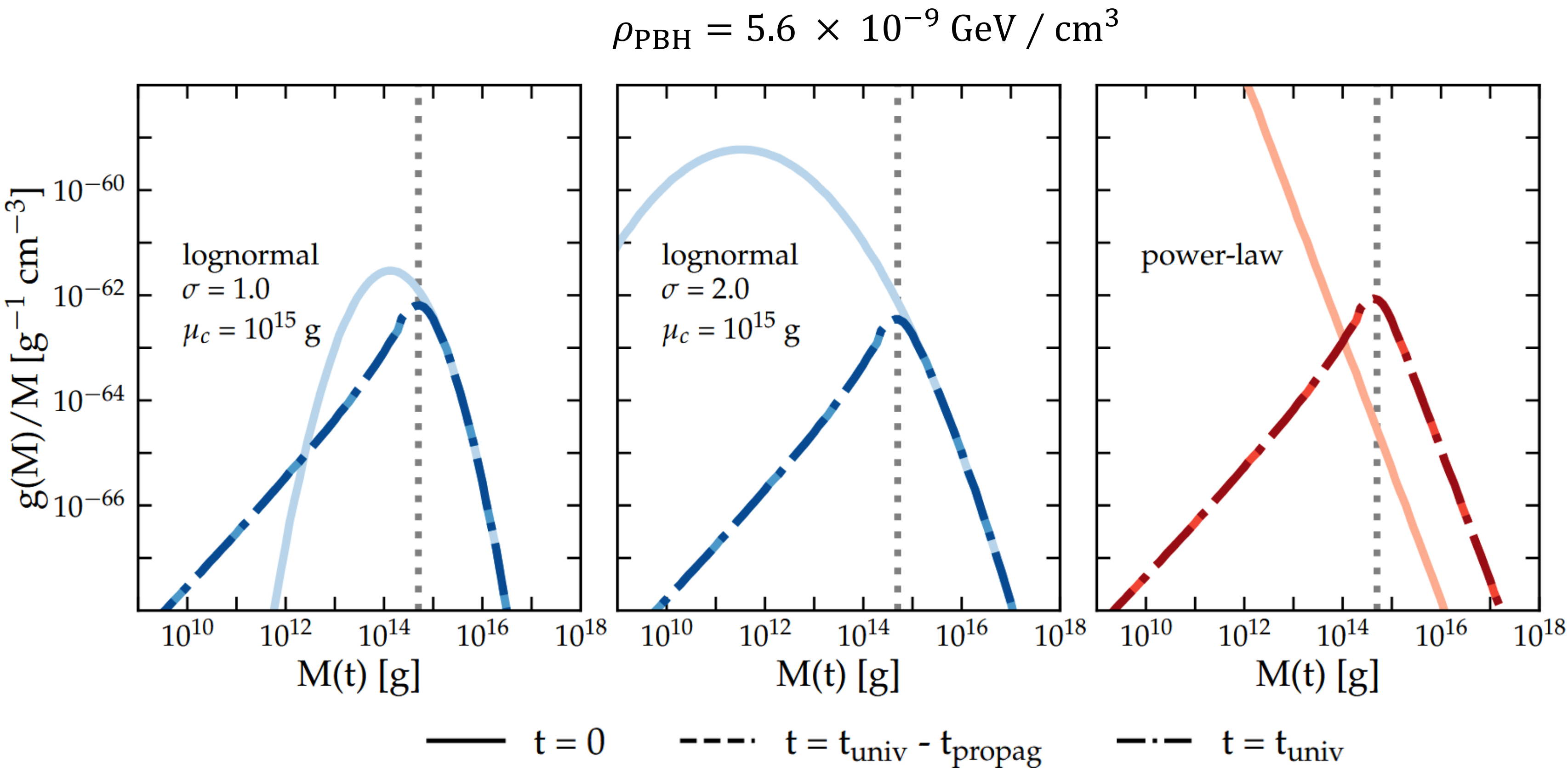
Evaporation coefficient

Evolution of mass distributions

The evolved distributions share the **same spectral shape for $M \lesssim 10^{14}$ g**

Due to Boltzmann suppression, $\bar{p}$ can only be **efficiently produced for $M \lesssim 10^{14}$ g**

The distribution are proportional to the **local PBH density** $\rho_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}(R_{\odot}, 0)$



Antinuclei production

MacGibbon 1990 PRD41(1990)3052

- Antinuclei are **not directly** produced by PBHs
- PBHs emit fundamental particles which can **hadronize** into antinuclei

Evolved mass distribution

HR spectra from **BlackHawk code**
Arbey et al. 2020 EJC79(2019)693

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

Antinuclei source spectrum

Summation over all
the emitted particles

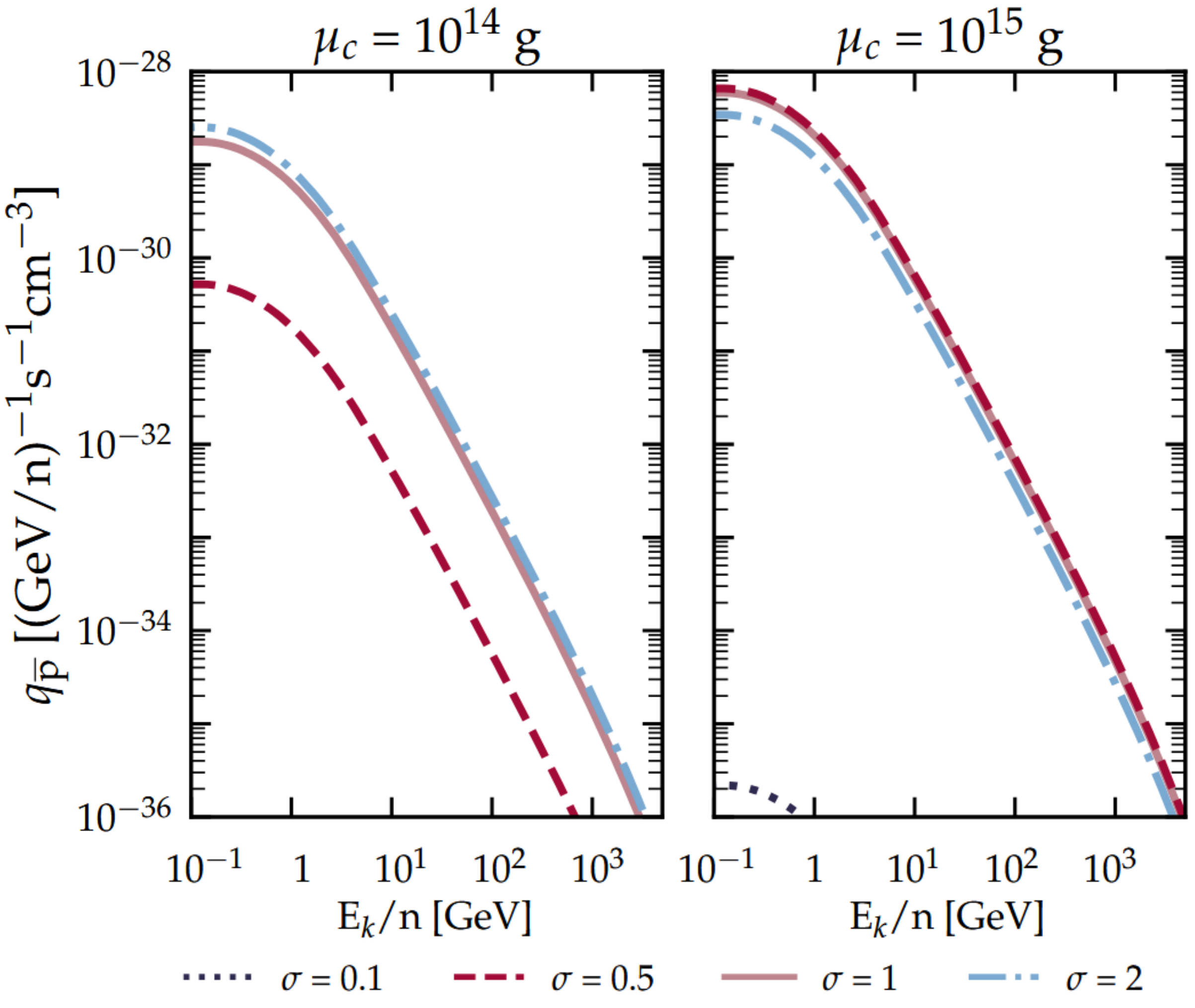
Fragmentation functions from **CosmiXs**
Arina et al. 2024 JCAP03(2024)035
Di Mauro et al. 2024 2411.04815

$\bar{p}$ source spectra

The source spectra share the **same spectral shape for all values of μ_c and σ**

↓

Due to similar evolved mass distributions



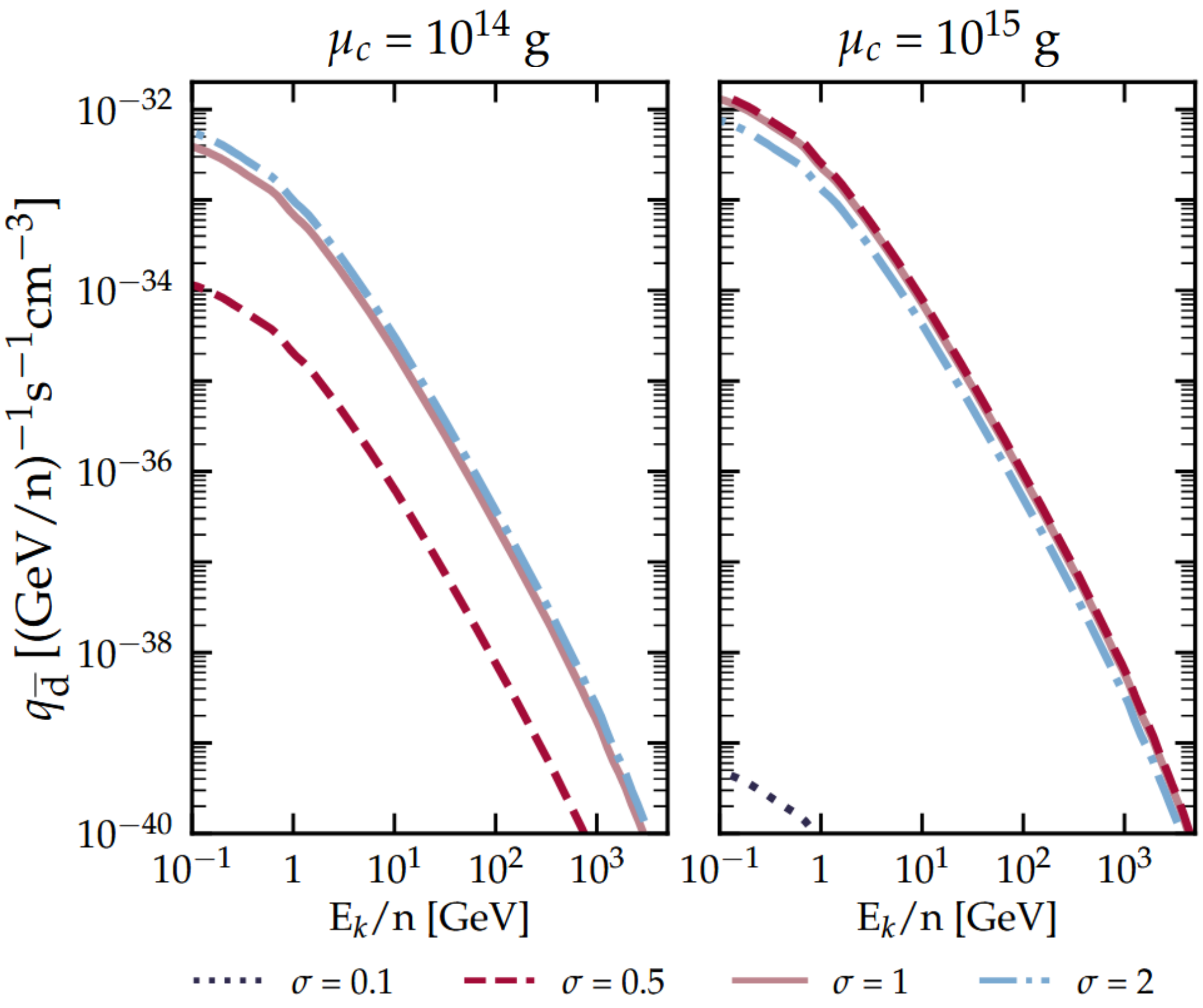
$\rho_{\rm PBH} = 5.6 \times 10^{-9}$ GeV / cm^3

$\bar{D}$ source spectra

Same spectral shape for all values of μ_c and σ

Coalescence modeled using the **Argonne–Wigner formalism**
Di Mauro et al. 2024 2411.04815

$\bar{D}$ source spectra are **10^4 times lower** than $\bar{p}$ spectra



$\rho_{\rm PBH} = 5.6 \times 10^{-9}$ GeV / cm^3

Charged galactic CR transport equation

Berezinskii et al. 1990

Source spectra are **propagated in the galaxy** using the **galactic CR transport equation**

Space diffusion coefficient

Convection

Number density energy spectrum

Energy losses and reacceleration

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

Primary source spectra

Secondary contibution

Destruction by scattering on ISM

Galaxy and propagation models

CRs propagate in a **cylindrical diffusion volume**:

$\boldsymbol{L}$ **~ 1 - 10 kpc**, $2h$ = 200 pc, R = 20 kpc

Weinrich et al. 2020 AA639(2020)A74

PBHs follow the CDM radial distribution → **NFW profile**

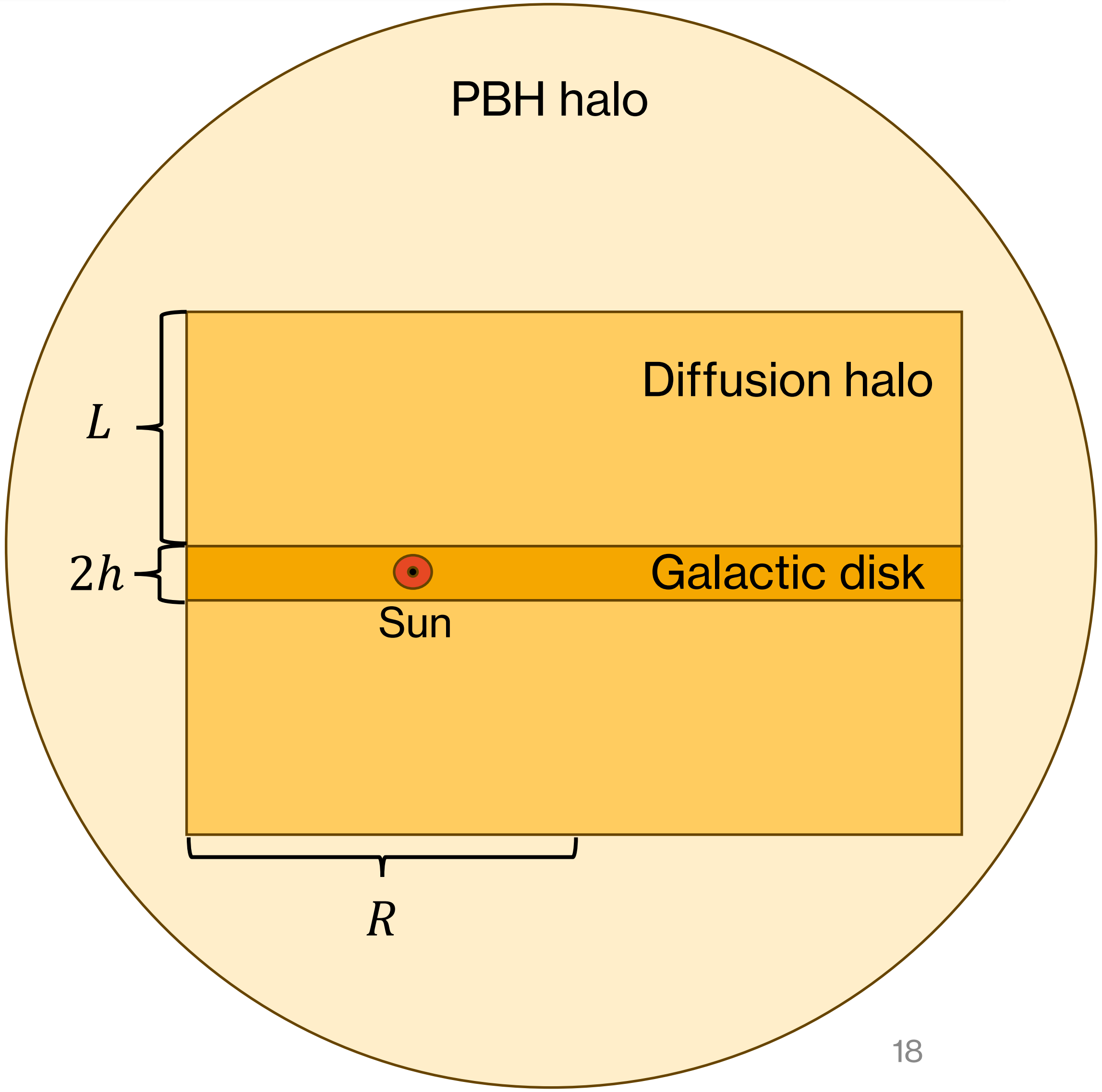
Navarro et al. 1996 AJ462(1996)563

We use the transport parameters of the benchmark **configuration BIG**

Calore et al. 2022 SPP12(2022)163

We solve semi-analytically the transport equation with the **USINE code** to **obtain the antinuclei TOA fluxes**

Maurin 2020 CPC247(2020)106942



Statistical analysis with AMS-02 $\overline{p}$ data

- We aim to derive **upper limits (UL) on the local PBH density ρ_{PBH}**, for fixed μ_c and σ
- $\bar{p}$ fluxes are **proportional to ρ_{PBH}**
- We follow the **$\overline{p}$ analysis of *Calore et al. 2022***, using the **most recent AMS-02 data**
  Calore et al. 2022 SPP12(2022)163; AMS collaboration 2021 PR894(2021)1

Covariance matrix,
for data and transport uncertainties
Boudaud et al. 2020 PRR2(2020)023022

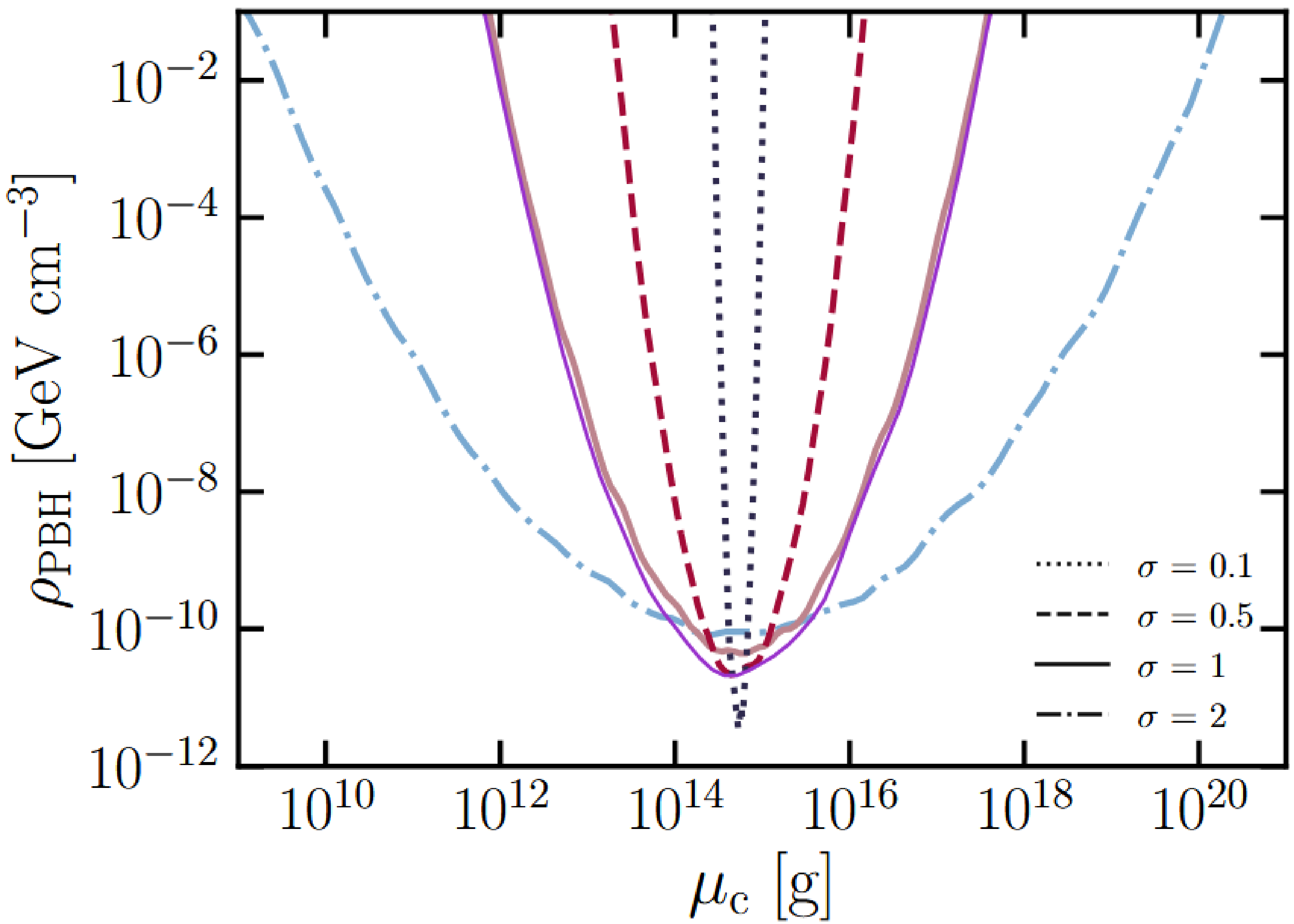
Nuisance parameter,
for halo size uncertainties
Weinrich et al. 2020 AA639(2020)A74

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

PBH parameters
$(\mu_c, \sigma, \rho_{\mathrm{PBH}})$

$$x_i \equiv \psi_i^{\mathrm{exp}} - \psi_i^{\mathrm{th}}(L,\mu)$$

95% confidence level UL on ρ_{PBH}



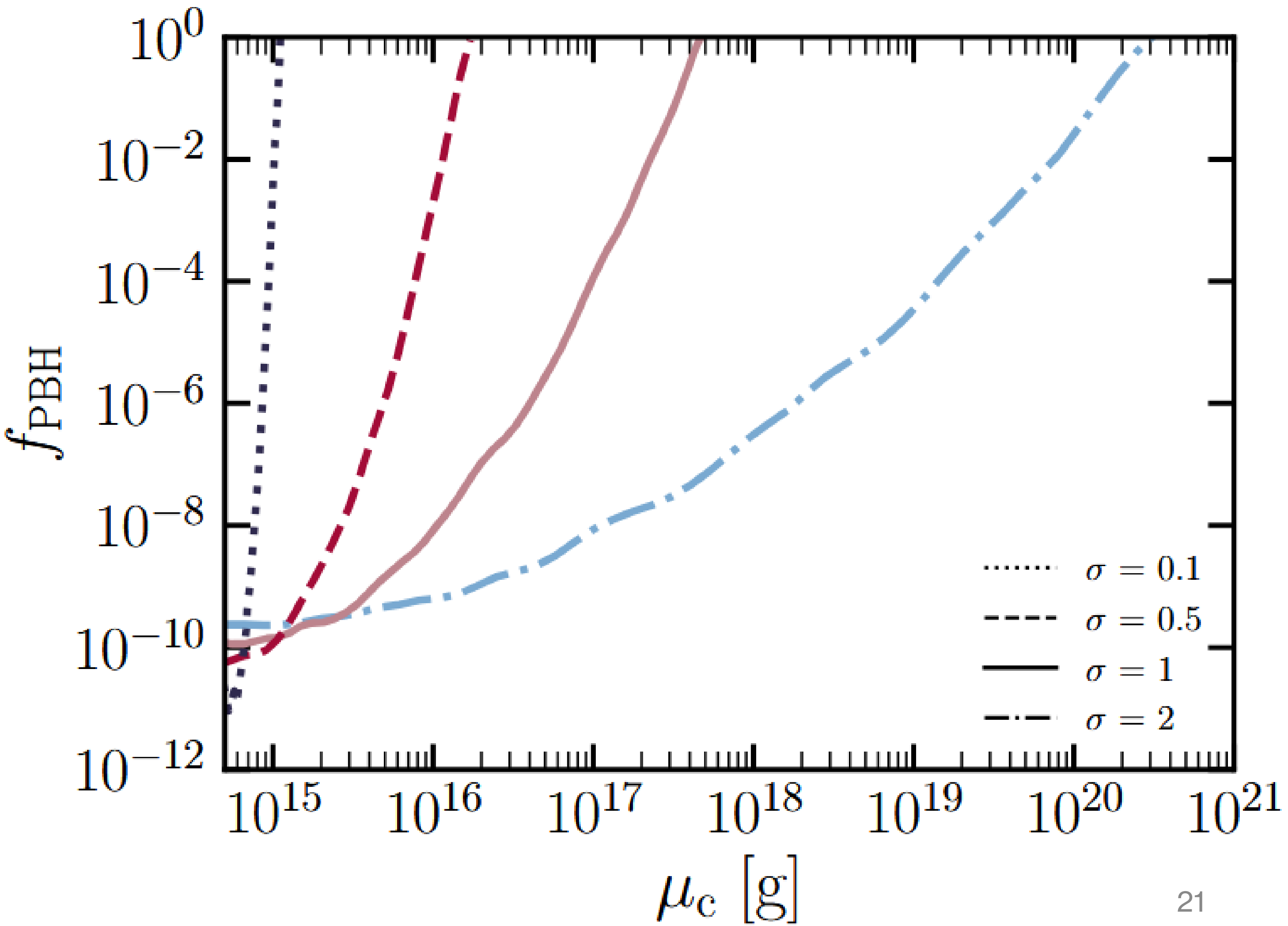
95% CL upper bounds on f_{PBH}

$$f_{\mathrm{PBH}} = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{CDM},\odot}} = \frac{\rho_{\mathrm{PBH}}}{0.385\ \mathrm{GeV/cm^3}}$$

Very strong constraints at

μ_c~ **5 · 10¹⁴ g**

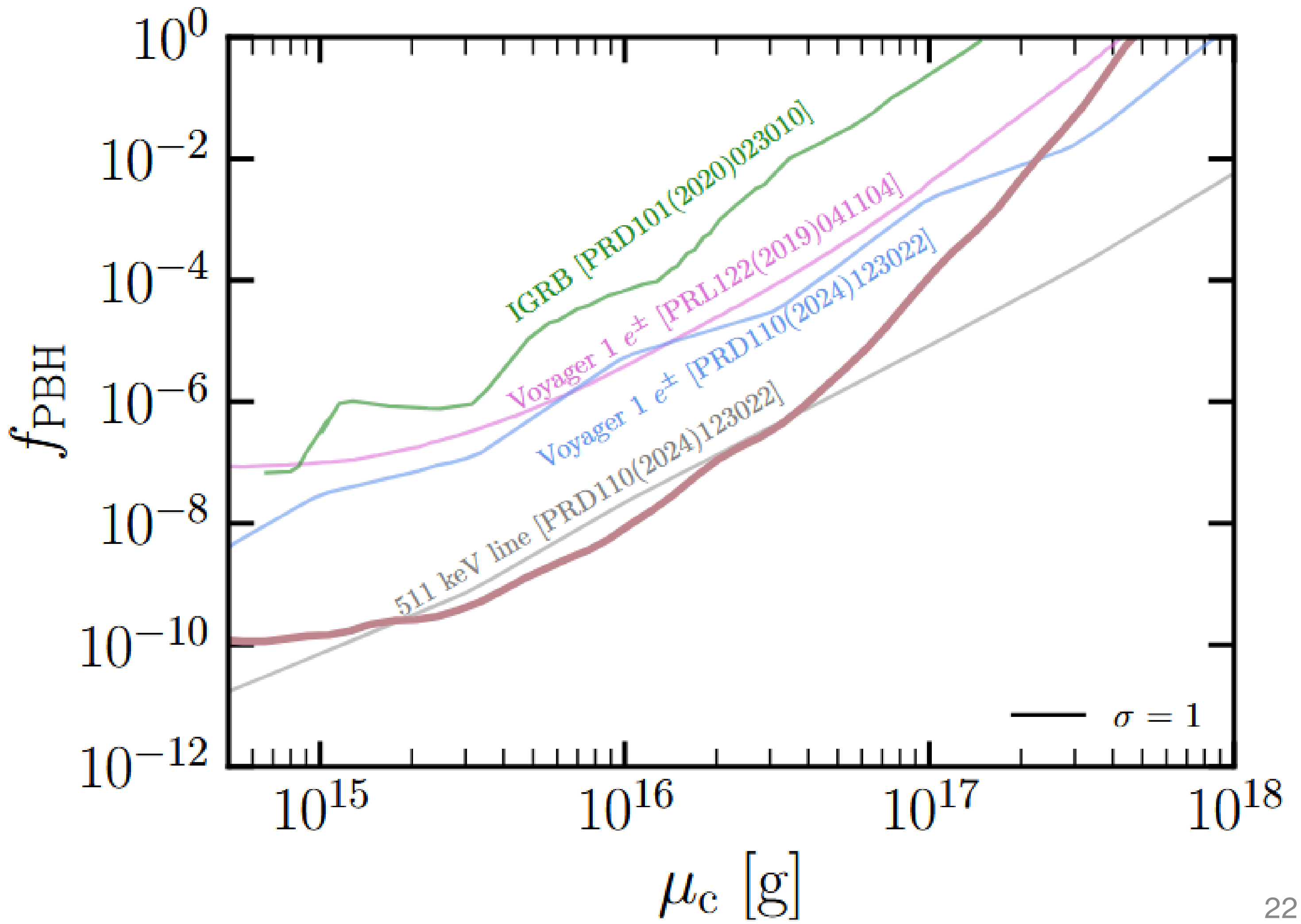
Constraints weaken for larger μ_c, with a **strong dependence on σ**



Comparison with bounds in literature

Different models, methods and assumptions are considered

Our $\overline{p}$ analysis provides very competitive constraints



$\bar{p}$ flux upper limit

Flux **computed using $\rho_{\mathrm{PBH}}^{\mathrm{UL}}$**, for fixed μ_c and σ

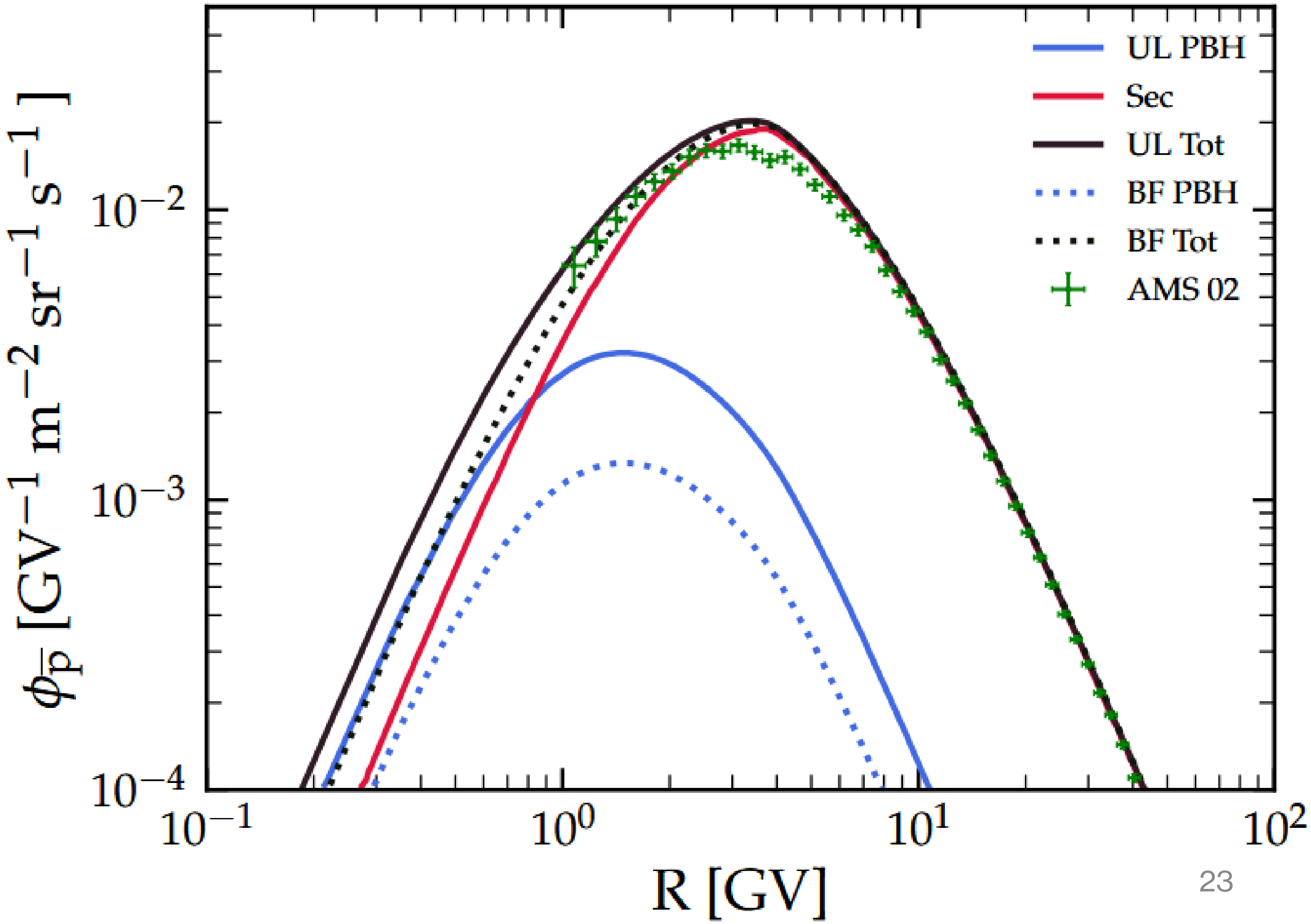
Primary flux peaks at **1-2 GV**

Secondary flux (computed in *Calore et al. 2022*) provides a **strong constraining power**

The flux spectral shape **does not depend** on μ_c and σ

The flux UL remains **the same for all values of μ_c and σ**

$\mu_c = 10^{14}$g   σ = 1 $\rho_{\mathrm{PBH}}^{\mathrm{UL}} = 1.9 \times 10^{-10}$ GeV / cm^3



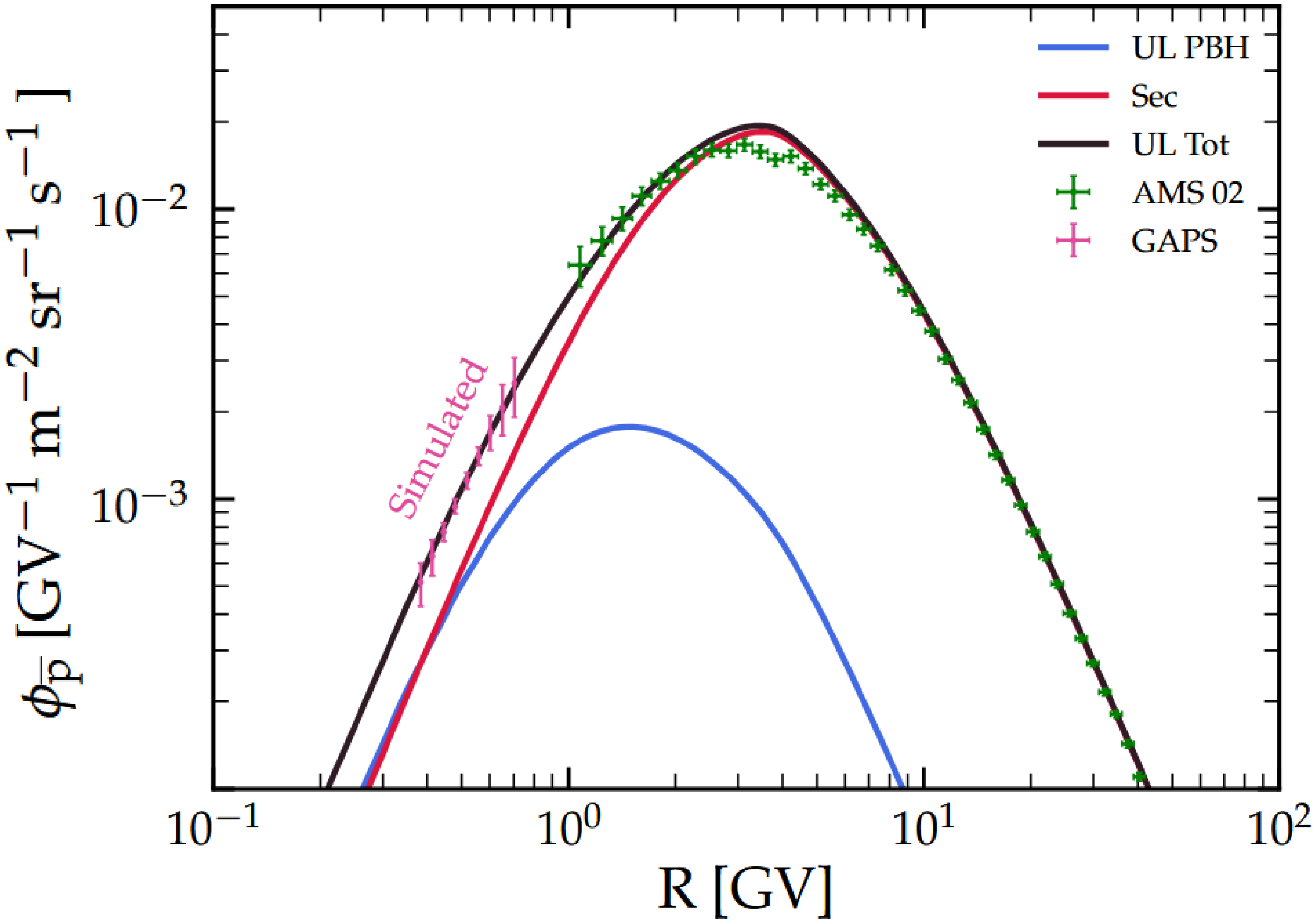
$\bar{p}$ flux and GAPS simulated data

We consider a set of **simulated data from GAPS** at lower energies

Rogers et al. 2023 *AP145(2023)102791*

GAPS could improve the constraints on ρ_{PBH} **by a factor ~ 2**

$\mu_c = 10^{14}\text{g} \quad \sigma = 1$



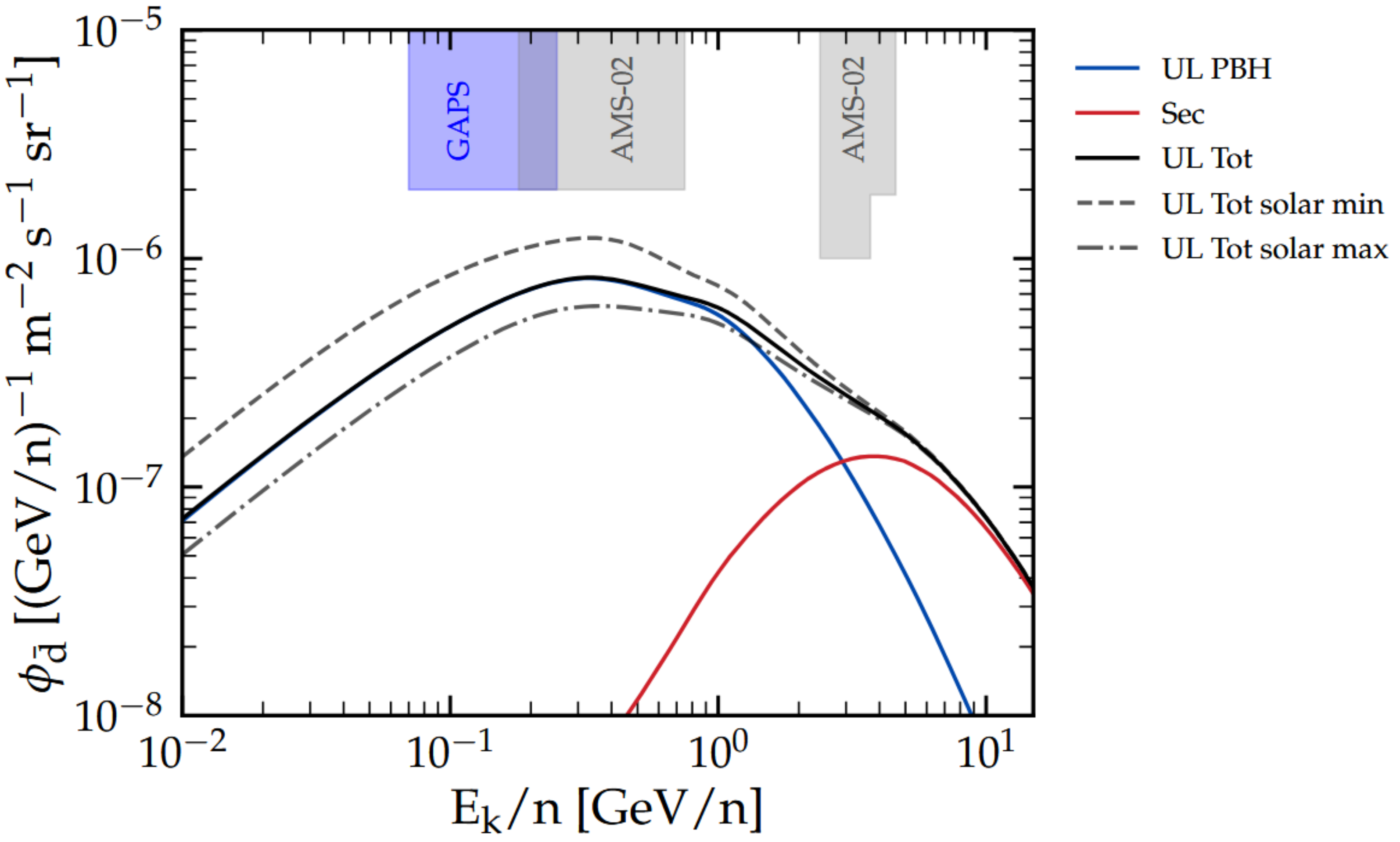
$\bar{D}$ flux upper limit

Flux computed **using $\rho_{\mathrm{PBH}}^{\mathrm{UL}}$ from the $\bar{p}$ analysis,** for fixed μ_c and σ

The flux UL remains **the same for all values of μ_c and σ**

Primary contribution is **dominant at sub-GeV energies**

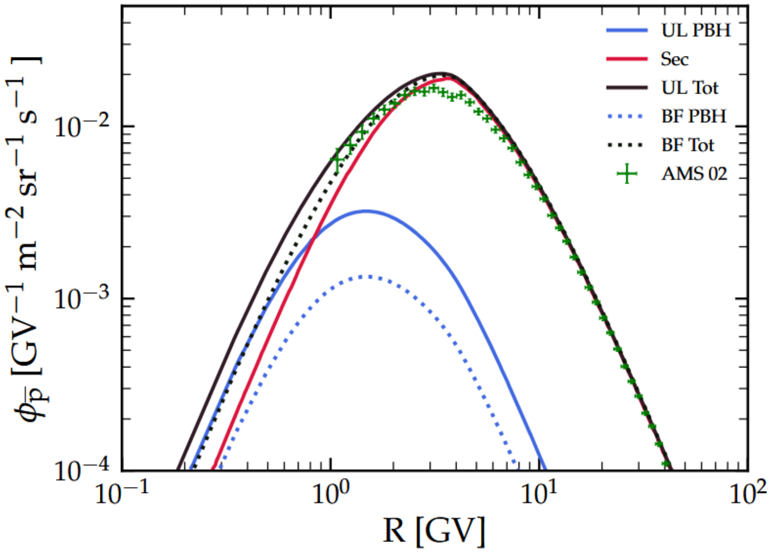
$\bar{\mathrm{D}}$ flux UL does not reach experiment sensitivities



Conclusions

- We computed $\overline{p}$ **and** $\overline{D}$ **fluxes from PBHs**, using state-of-the-art CR propagation models

- The resulting fluxes exhibit **universal spectral shapes**, independent of the PBH initial mass distribution



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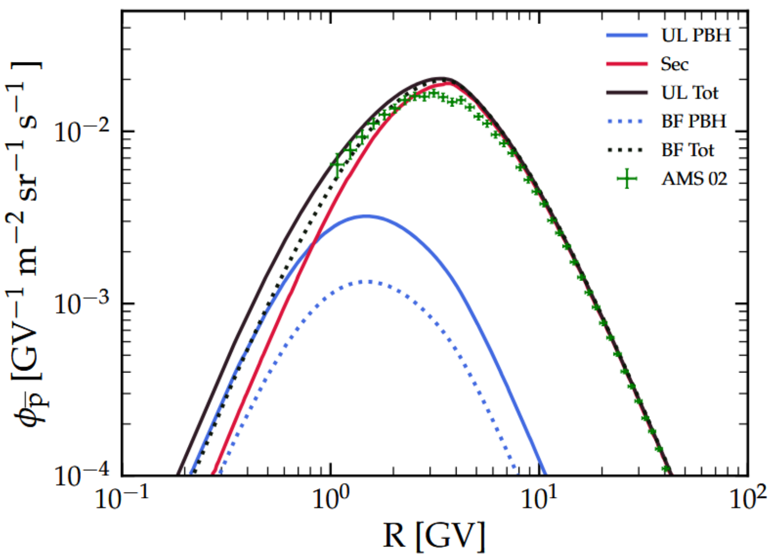
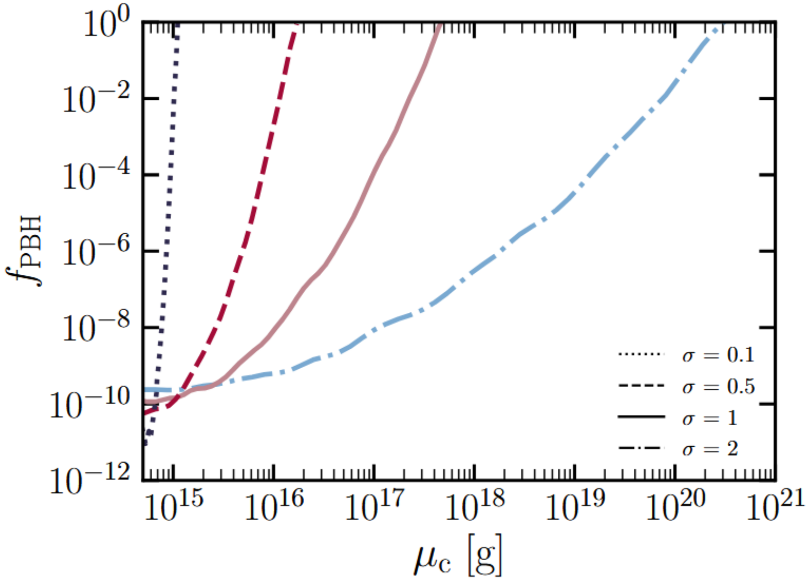
- **AMS-02** $\overline{p}$ **data provide strong constraining power**: we derived **very competitive upper limits on** f_{PBH}, sensitive to the choice of the PBH initial mass distribution





Conclusions

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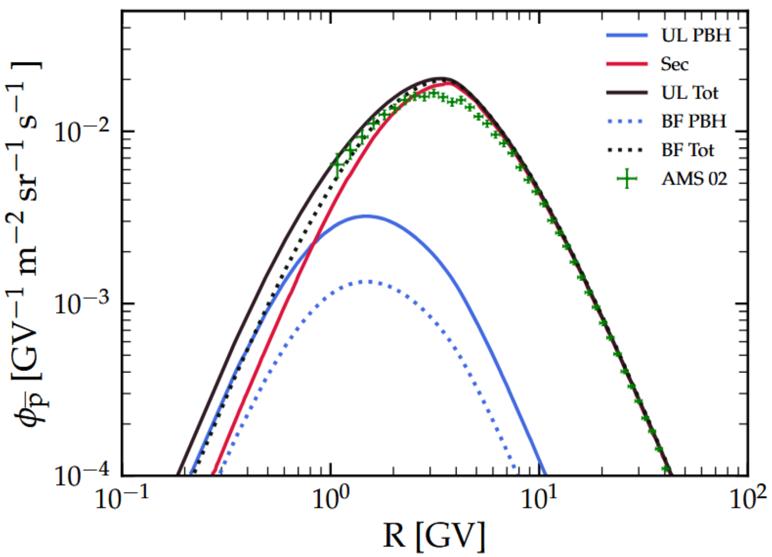
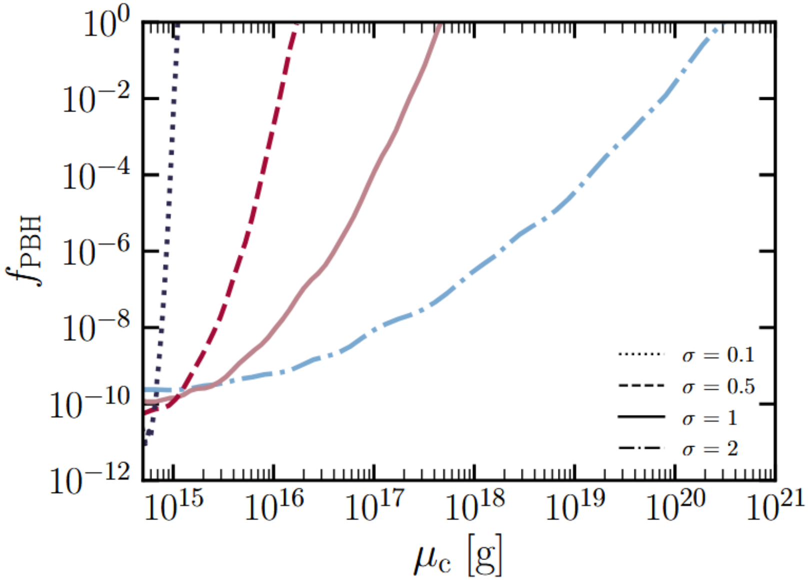
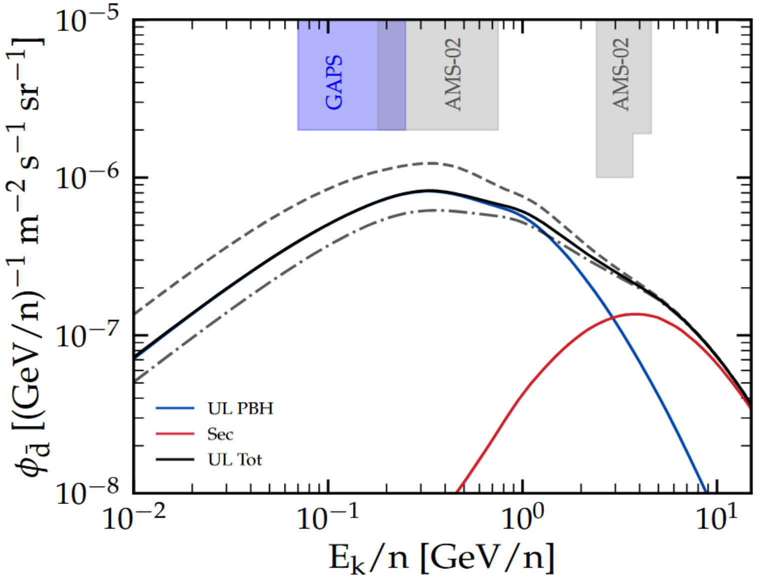
- The resulting fluxes exhibit **universal spectral shapes**, independent of the PBH initial mass distribution

- **AMS-02** $\overline{p}$ **data provide strong constraining power**: we derived **very competitive upper limits on** f_{PBH}, sensitive to the choice of the PBH initial mass distribution

- At sub-GeV energies, **PBH-induced** $\overline{D}$ **fluxes could dominate** over astrophysical backgrounds
- **Due to** $\overline{p}$ **constraints**, any future detection of $\overline{D}$ could be, at most, **only partially attributed to PBHs**







Thanks for your attention

Backup

PBH initial mass distributions

Galactic coordinates

PBH mass at t=0

Number density spectrum at t=0 [g^{-1} cm^{-3}]

$$g(r, z, M_{\rm in}) \equiv M_{\rm in} \frac{{\rm d}n_{\rm PBH}}{{\rm d}M_{\rm in}}$$

Lognormal distribution

Dolgov et al. 1993, PRD47(1993)4244

Mean value = critical mass [g]

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

PBH density [GeV/cm^3]

Standard deviation

Hawking radiation (HR) and PBH mass evolution

Hawking 1975, CMP46(1976)206

$$\left.\frac{\mathrm{d}^2 N}{\mathrm{d}E\mathrm{d}t}\right|_{\mathrm{HR}}(E, M) = \frac{g}{2\pi}\frac{\Gamma_s(E)}{\exp(E/T) - (-1)^{2s}} \qquad T = \frac{1}{8\pi G_N M}$$

Mass evolution in time due to HR

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\alpha(M)}{M^2}$$

Evaporation coefficient

Number density spectrum today

$$\frac{\mathrm{d}n_{\mathrm{PBH}}}{\mathrm{d}M} = \frac{\mathrm{d}n_{\mathrm{PBH}}}{\mathrm{d}M_{\mathrm{in}}}\frac{\mathrm{d}M_{\mathrm{in}}}{\mathrm{d}M} = \frac{\mathrm{d}n_{\mathrm{PBH}}}{\mathrm{d}M_{\mathrm{in}}}\frac{M^2\alpha(M_{\mathrm{in}})}{M_{\mathrm{in}}^2\alpha(M)}$$

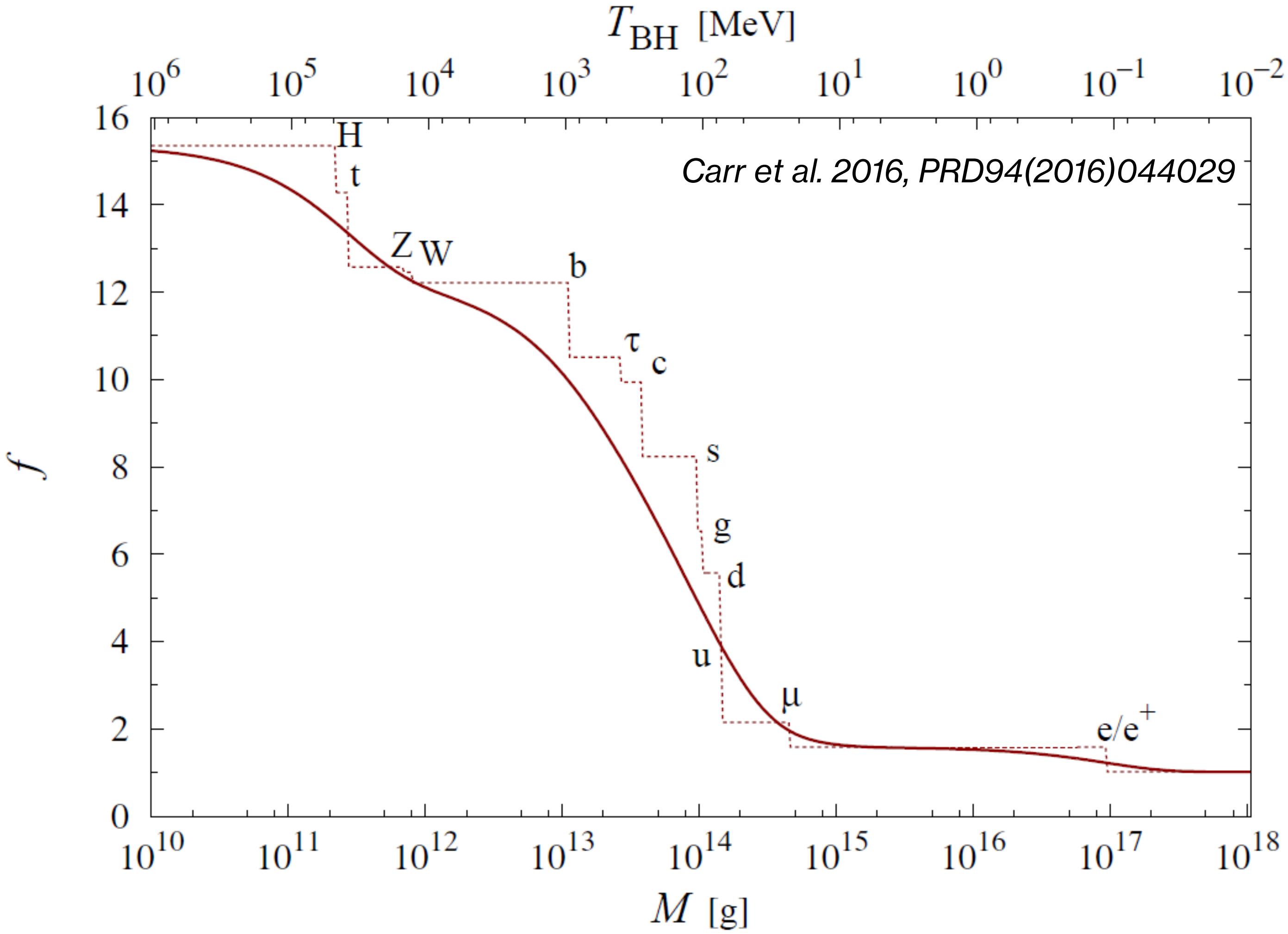
Alfa/evaporation parameter

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\alpha\left(M\right)}{M^2}$$

$$\alpha\left(M\right) = M^2 \sum_i \int_0^\infty \frac{\mathrm{d}^2 N_i}{\mathrm{d}E\mathrm{d}t} E\mathrm{d}E$$

f is proportional to α

Carr et al. 2016, PRD94(2016)044029



Propagation model

Genolini et al. 2019, PRD99 (2019)123028

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

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

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

Statistical analysis with AMS-02 $\bar{p}$ data

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- $\bar{p}$ fluxes are **proportional to ρ_{PBH}**
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  Calore et al. 2022 SPP12(2022)163; AMS collaboration 2021 PR894(2021)1

Log-likelihood function

Covariance matrix,
for propagation uncertainties
Boudaud et al. 2020 PRR2(2020)023022

Nuisance parameter,
for diffusion-halo uncertainties
Weinrich et al. 2020 AA639(2020)A74

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

PBH parameters
$(\mu_c, \sigma, \rho_{\mathrm{PBH}})$

$$x_i \equiv \psi_i^{\exp} - \psi_i^{\mathrm{th}}(L,\mu)$$

Upper limits (UL) on ρ_{PBH}

$\bar{p}$ fluxes are proportional to the **local PBH density ρ_{PBH}**

For fixed μ_c and σ, we rely on this **likelihood ratio (LR)**:

given

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

free

Assuming Wilks' theorem, the LR is distributed as χ^2 with 1 d.o.f. (ρ_{PBH})

The **95% confidence level UL** is obtained **finding the ρ_{PBH} which increases the LR by 3.84**

Calore et al. 2022, SPP12(2022)163