Antinuclei from Primordial Black Holes

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Galactic Cosmic Rays (CR)

Maurin et al. 2001, AJ 555(2001)585-596

Nuclei, **antinuclei**, leptons

Energies of ~ $10^{-1} – 10^{6}$ GeV

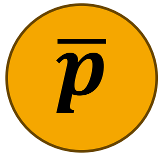
Primary CR

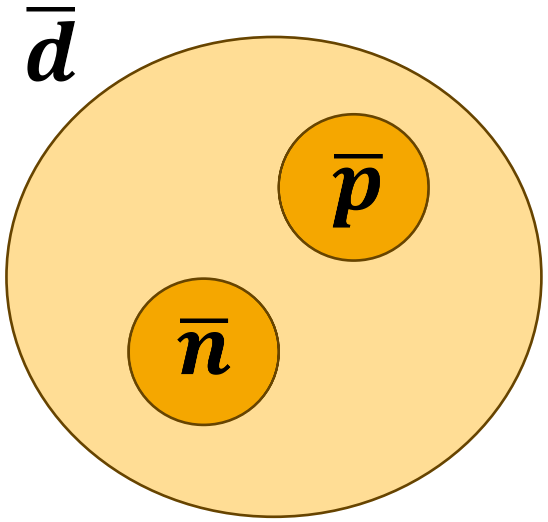
- Standard astrophysical sources → Supernova remnants, Pulsars
- Exotic source candidates → **Primordial Black Holes (PBH)**, Dark Matter particles

Secondary CR → **Produced by spallation** on the interstellar medium (ISM)

Antinuclei

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



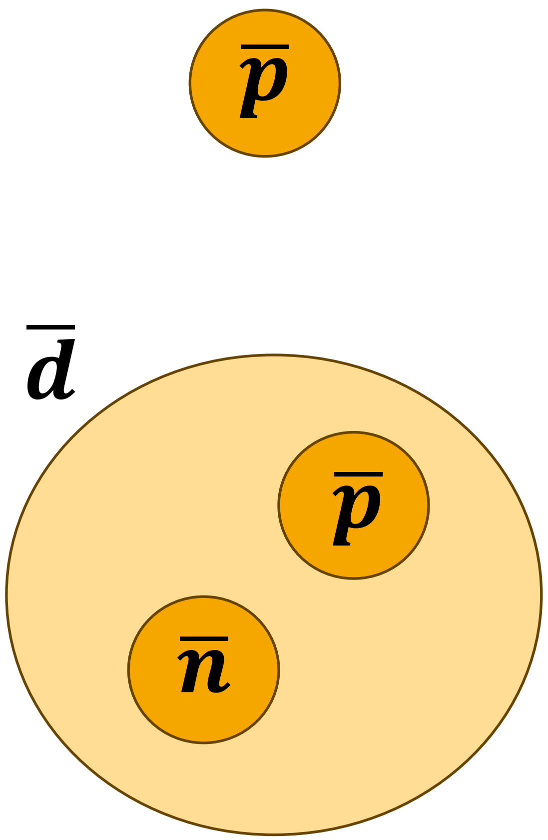


Antinuclei

Galactic **antiprotons** ($\bar{p}$) and **antideuterons** ($\bar{d}$)

No known primary sources of antinuclei
Only secondary production expected from standard astrophysics

Small background, especially for $\bar{d}$ at energies $\lesssim$ GeV
Donato et al. 2000, PRD62(2000)043003



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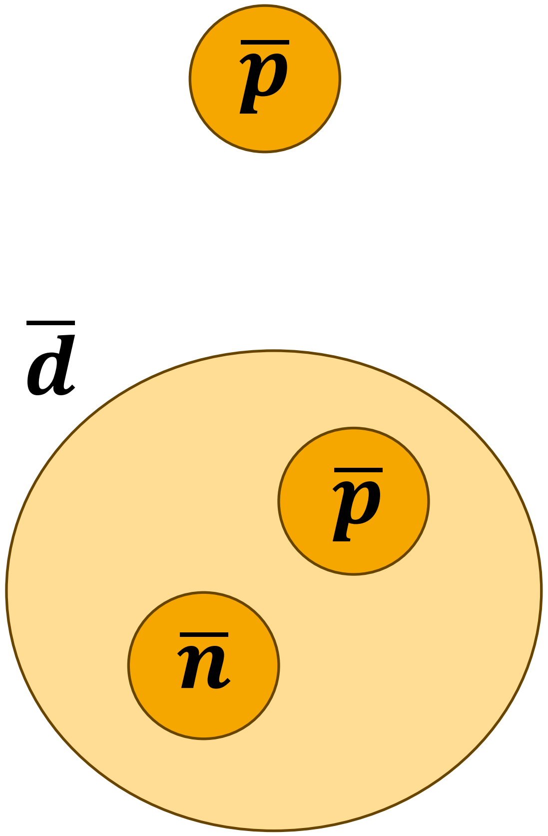
Experiments:

AMS-02 → on the International Space Station
AMS collaboration 2021, PR894(2021)1

GAPS → balloon-borne experiment, to be launched
Aramaki et al. 2016, AP74(2016)6



Goals of our paper - 2505.04692

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

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Compare the predicted $\bar{p}$ flux with **AMS-02 data**

Obtain **constraints on the local density** of PBHs

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

Compare the predicted $\bar{p}$ flux with **AMS-02 data**

Obtain **constraints on the local density** of PBHs

Compare the predicted $\bar{d}$ flux with **GAPS expected sensitivity**

Obtain **perspectives on $\bar{\mathrm{d}}$ detection**

PBH initial mass distribution

Mean value = critical mass [g]

Lognormal distribution
Dolgov et al. 1993, PRD47(1993)4244

Galactic coordinates

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

PBH mass at t=0

PBH density [GeV/cm^3]

Standard deviation

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PBH density [GeV/cm^3]

Standard deviation

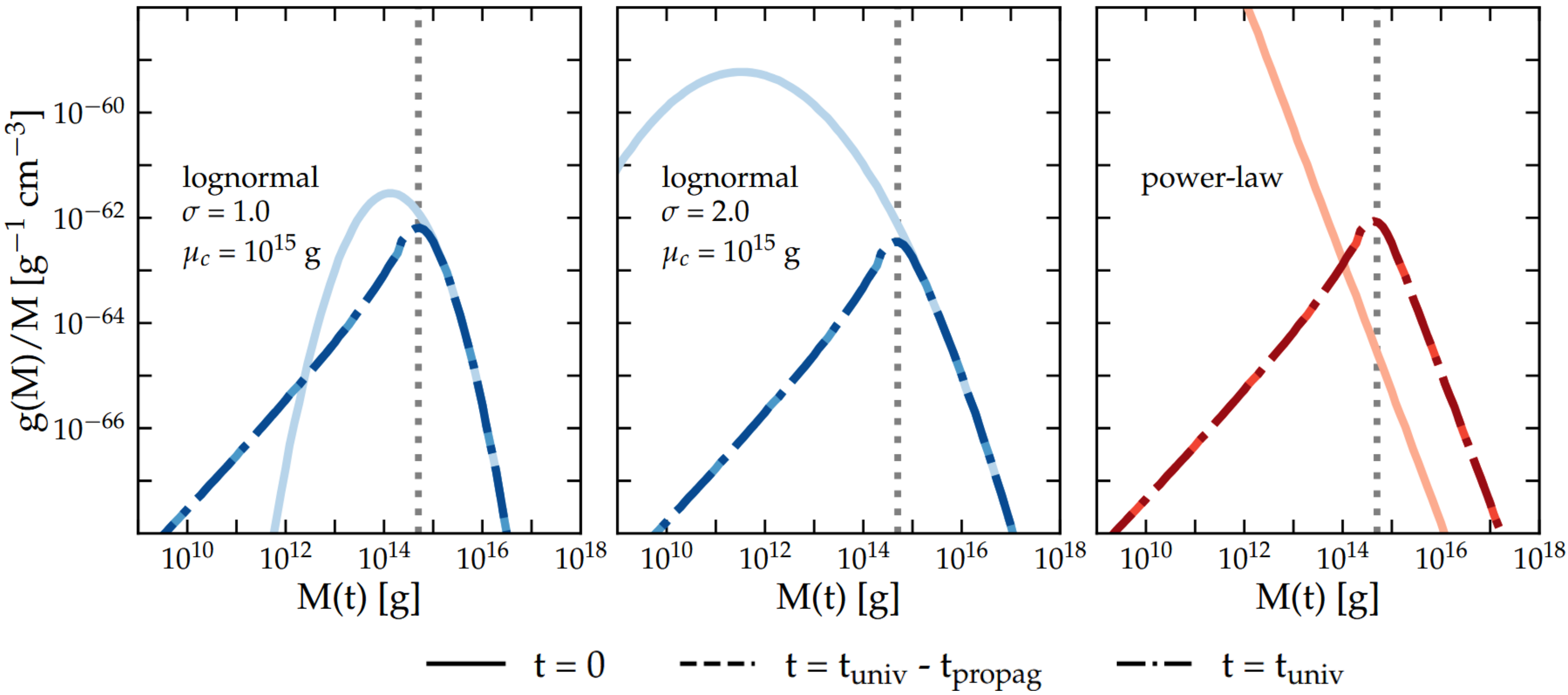
Hawking radiation mass loss rate

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

Evaporation coefficient

Evolution of mass distributions

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



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

$\bar{p}$ *can be produced for* **$M \lesssim 10^{13}$ g**

The distribution normalizations depend on the **local PBH density**
$\rho_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}(R_\odot, 0)$

Antinuclei source spectrum

MacGibbon et al. 1990, PRD41(1990)3052

Antinuclei are **not directly** produced by PBHs

PBHs emit fundamental particles which can **hadronize** into antinuclei

Mass distribution

HR spectra from **BlackHawk code**
Arbey et al. 2019, EPJC81(2021)910

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

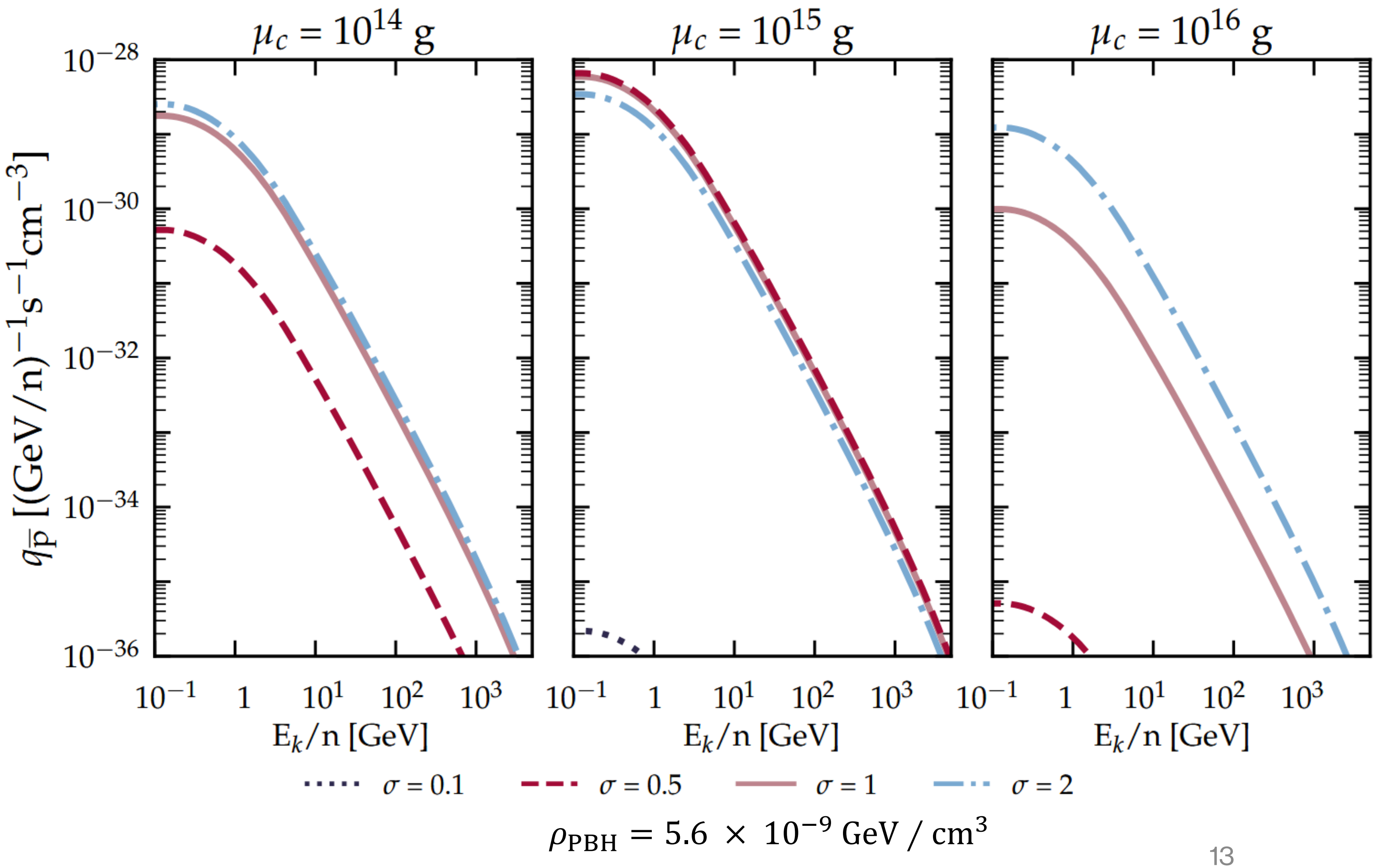
Antinuclei source spectrum

Summation over all
the emitted particles

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

$\overline{p}$ source spectra

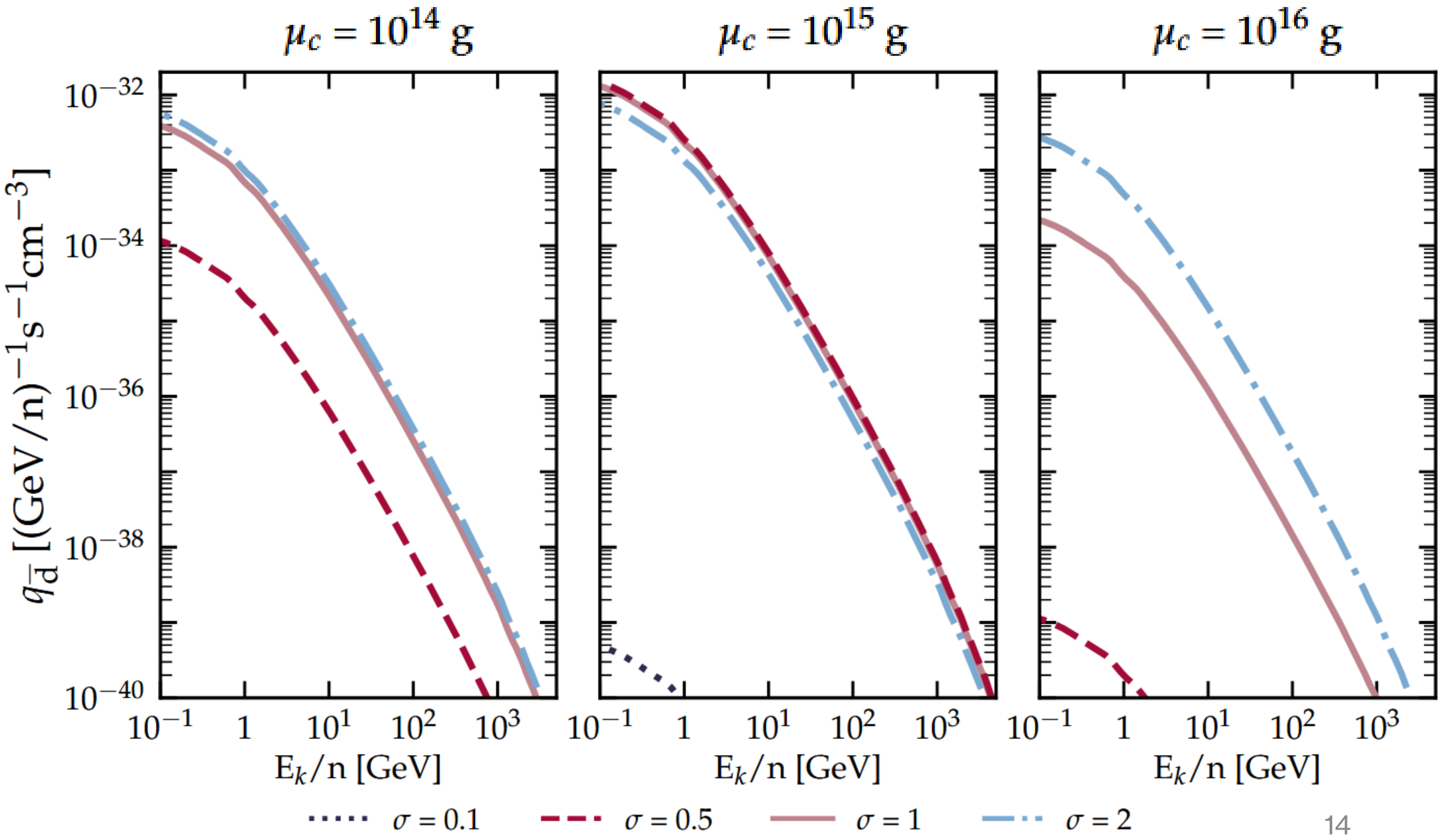
Due to similar evolved mass distributions, the source spectra share the **same spectral shape for all values of μ_c and σ**



$\overline{d}$ source spectra

Same spectral shape for all values of μ_c and σ

$\overline{d}$ source spectra are 10^4 times smaller than $\overline{p}$ spectra



Charged galactic CR transport equation

Berezinskii et al. 1990, Astrophysics of cosmic rays

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 model

CRs propagate in a **2-zone cylindrical diffusion volume,** composed by the Galactic disk and the Diffusion halo:

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**

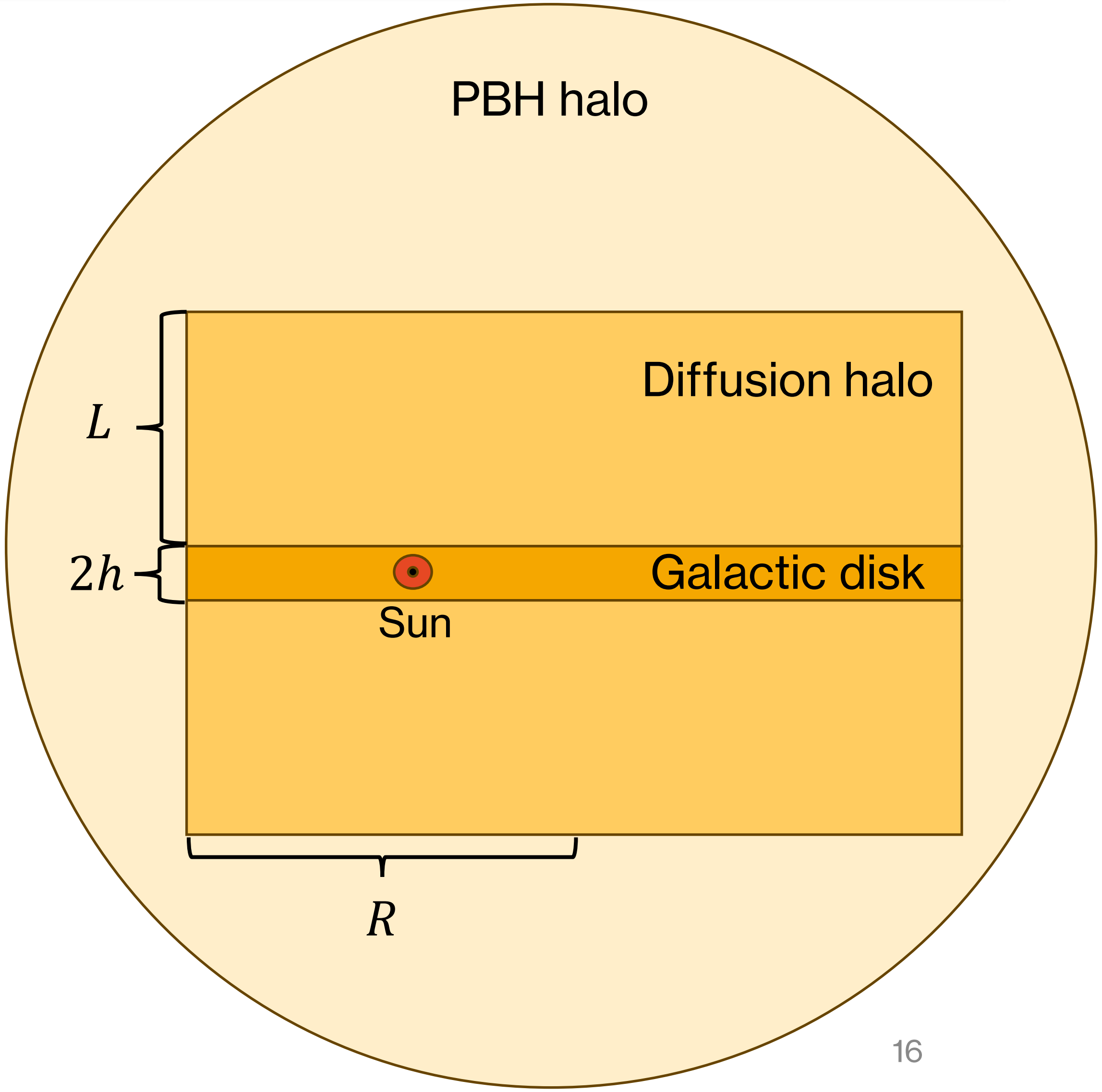
Navarro et al. 1996, AJ462(1996)563

This simplified geometry allows us to solve semi-analytically the transport equation with the **USINE code** and **obtain the antinuclei TOA fluxes**

Maurin 2020, CPC247(2020)106942

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

Calore et al. 2022, SPP12(2022)163



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

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

Nuisance parameter,
for halo-size uncertainties

Log-likelihood function

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

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

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

Upper limits (UL) on ρ_{PBH}

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

To obtain upper limits on ρ_{PBH}, **for fixed μ_c and σ**, we rely on the likelihood ratio (LR):

fixed

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

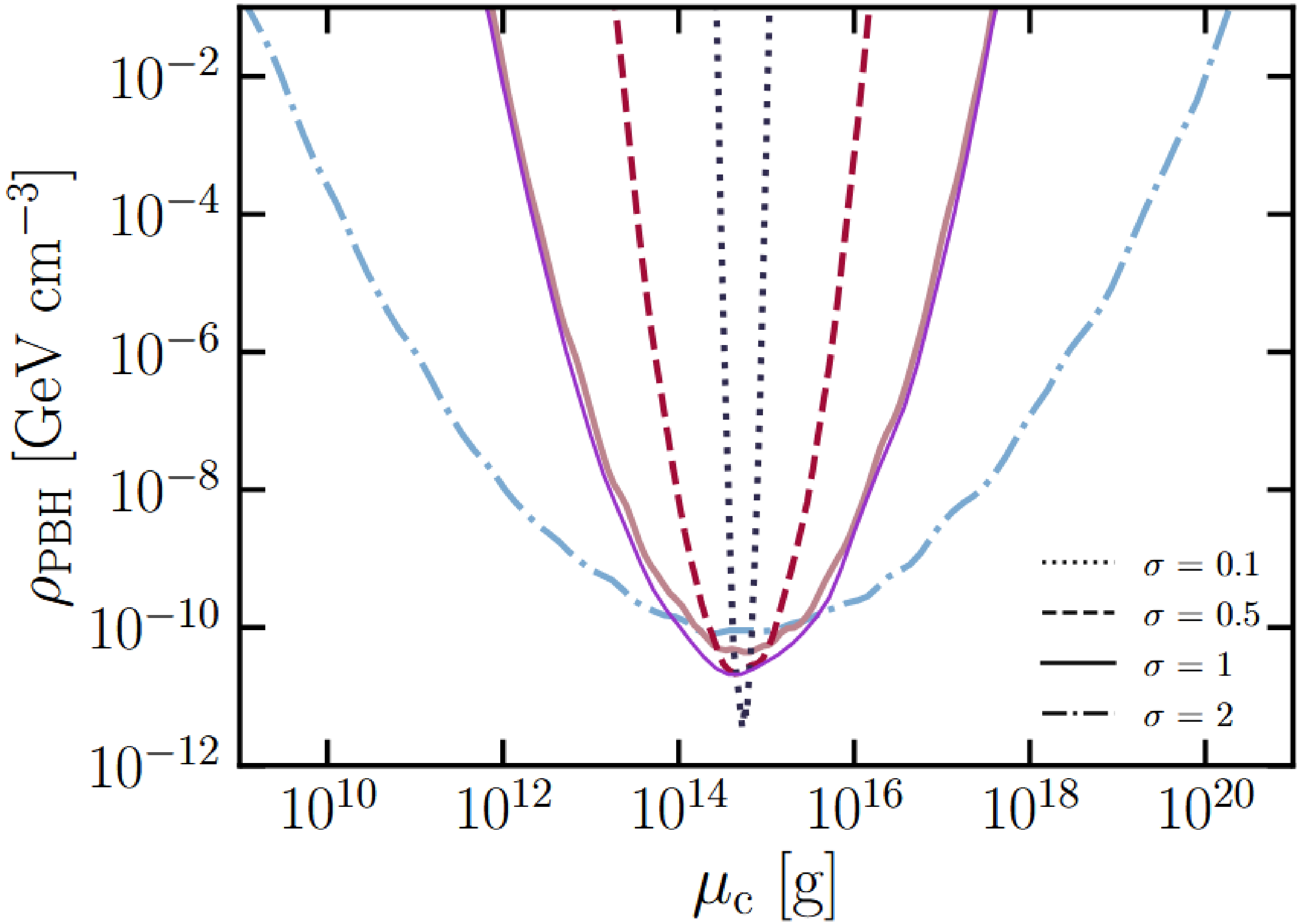
free

According to Wilk's 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

95% CL upper bounds on ρ_{PBH}



$\bar{p}$ upper limit flux

For fixed μ_c and σ, the UL flux is **normalized by the value of $\rho_{\mathrm{PBH}}^{\mathrm{UL}}$**

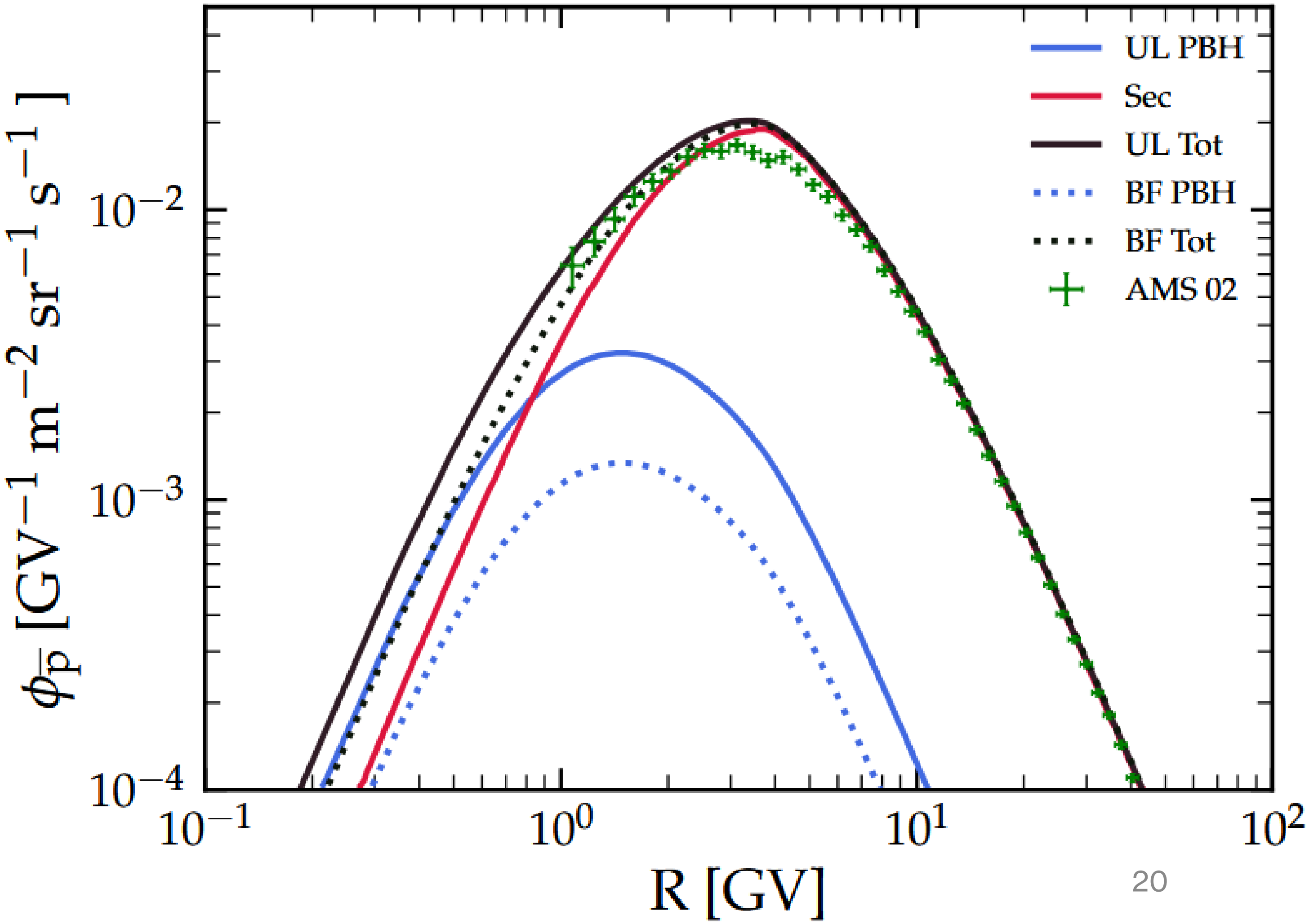
Primary flux spectral shape **does not depend** on μ_c and σ

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

Secondary flux (predicted in *Boudaud et al. 2020)* provides a **great constraining power**

Boudaud et al. 2020, PRR2(2020)023022

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



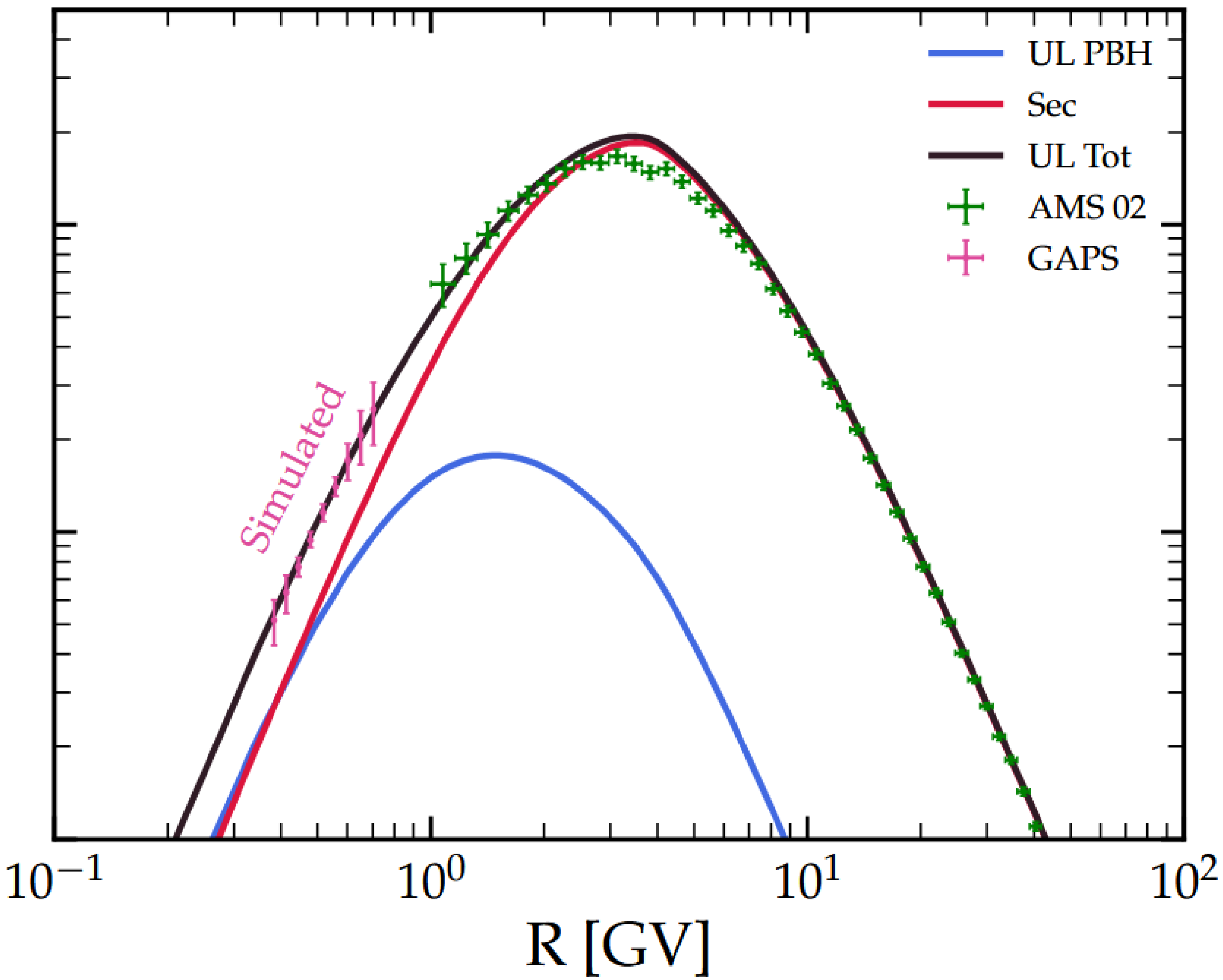
$\overline{p}$ flux and GAPS simulated data

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

GAPS collaboration 2023, AP145(2023)102791

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

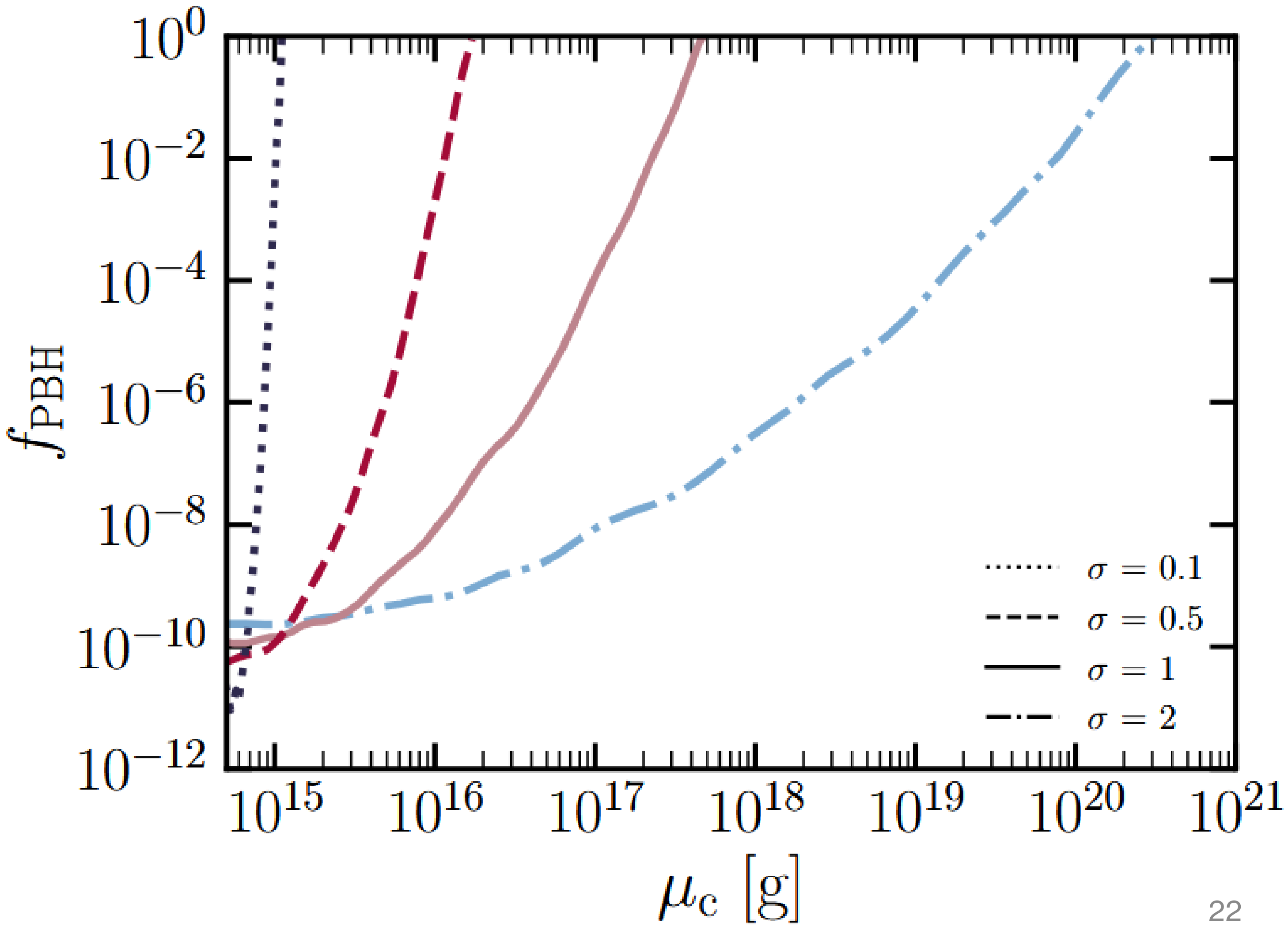
$\mu_c = 10^{14}$g σ = 1



95% CL upper bounds on f

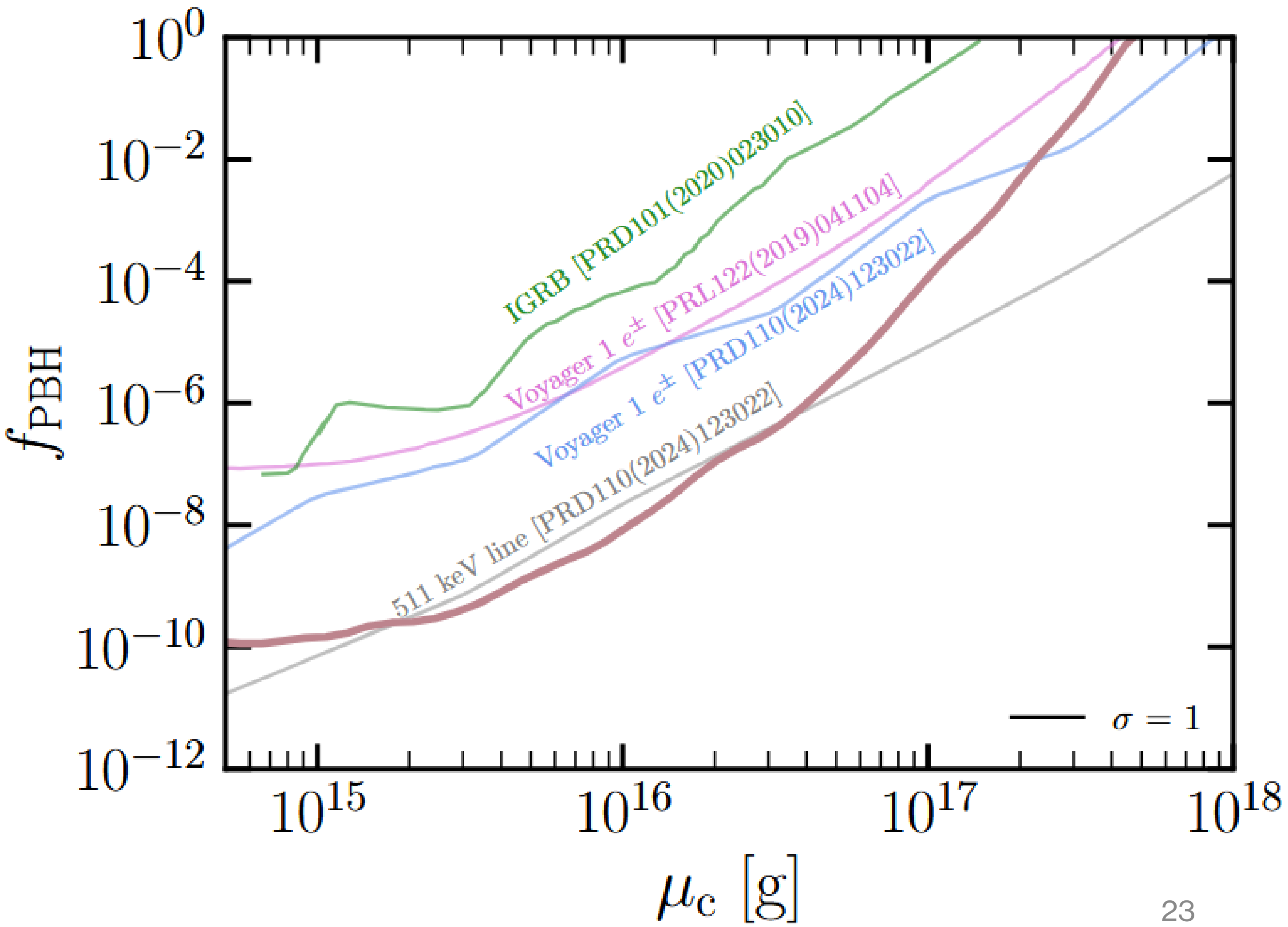
$$f = \frac{\rho_{PBH}}{\rho_{\mathrm{CDM},\odot}} = \frac{\rho_{PBH}}{0.385\ \mathrm{GeV/cm^3}}$$

deSalas et al. 2021, RPP84(2021)104901



Comparison with bounds in literature

Comparison not really feasible, since **very different methods and assumptions** are considered



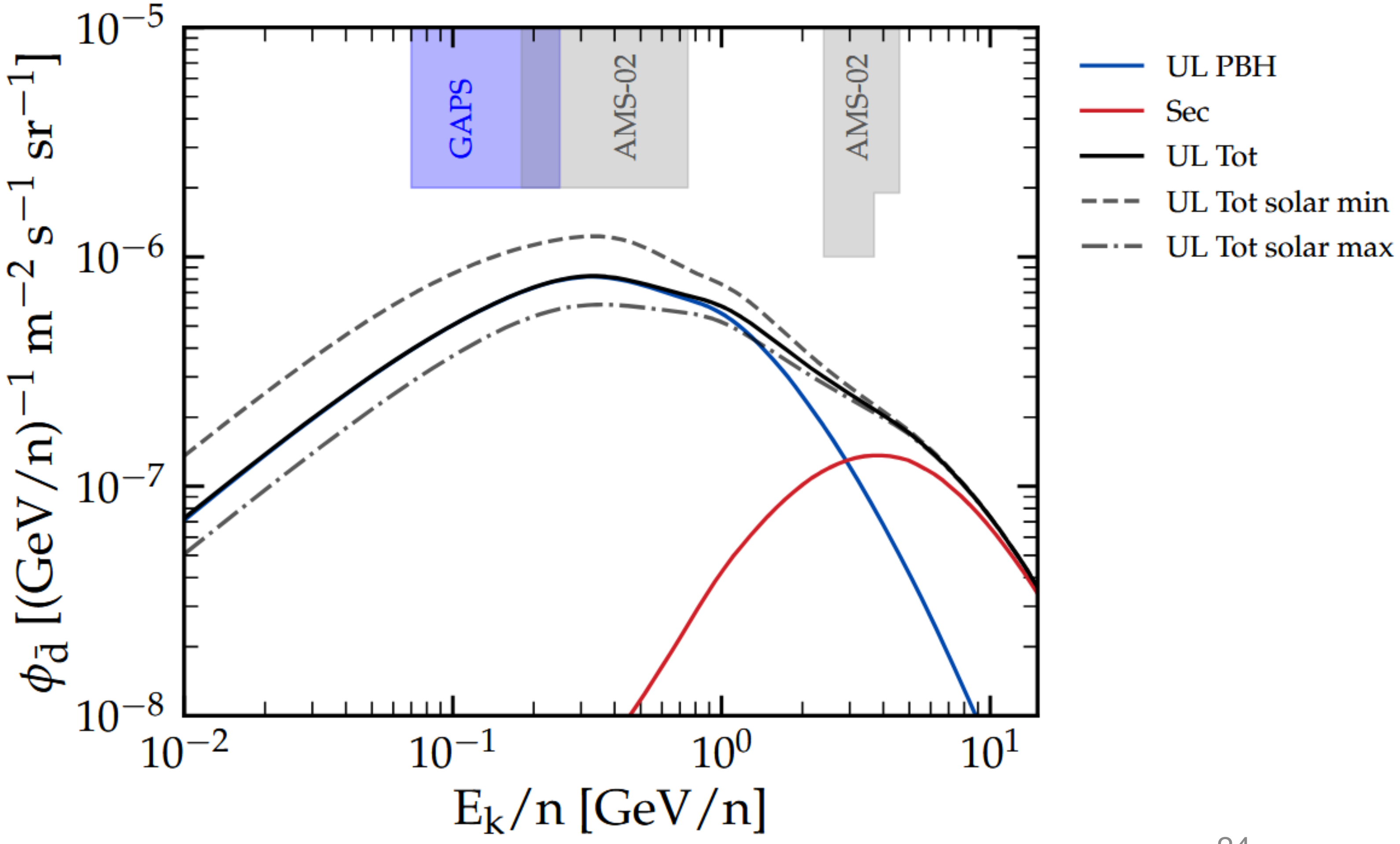
Antideuteron fluxes

For fixed μ_c and σ, the fluxes are obtained **considering the $\rho^{\mathrm{UL}}_{\mathrm{PBH}}$ value of $\overline{p}$ analysis**

Since fluxes have the same spectral shape, this plot remains unchanged for all values of μ_c and σ

Primary contribution is dominant at energies lower than few GeV

$\overline{d}$* UL fluxes *do not reach experiment sensitivities



Conclusions

We have calculated $\bar{p}$ **and** $\bar{d}$ **fluxes from PBHs**, for the first time considering lognormal distributions and using state-of-the-art CR propagation models

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We have calculated $\bar{p}$ **and** $\bar{d}$ **fluxes from PBHs**, for the first time considering lognormal distributions and using state-of-the-art CR propagation models

AMS-02 $\bar{p}$ **data provide a great constraining power**: we derived **very competitive constraints on** ρ_{PBH}, dependent on the choice of the initial mass distribution

$\bar{d}$ from PBHs could provide the **dominant flux contribution at energies** $\lesssim$ **GeV**, **Due to** $\bar{p}$ **constraints**, if experiments were to detect a $\bar{d}$, this would be **hardly or only partially explainable with 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}]

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

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 →

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

Galaxy model

CRs propagate in a **2-zone cylindrical diffusion volume,** composed by the Galactic disk and the Diffusion halo:

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

ref

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

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Solar modulation effects are modeled using the **force-field approximation**

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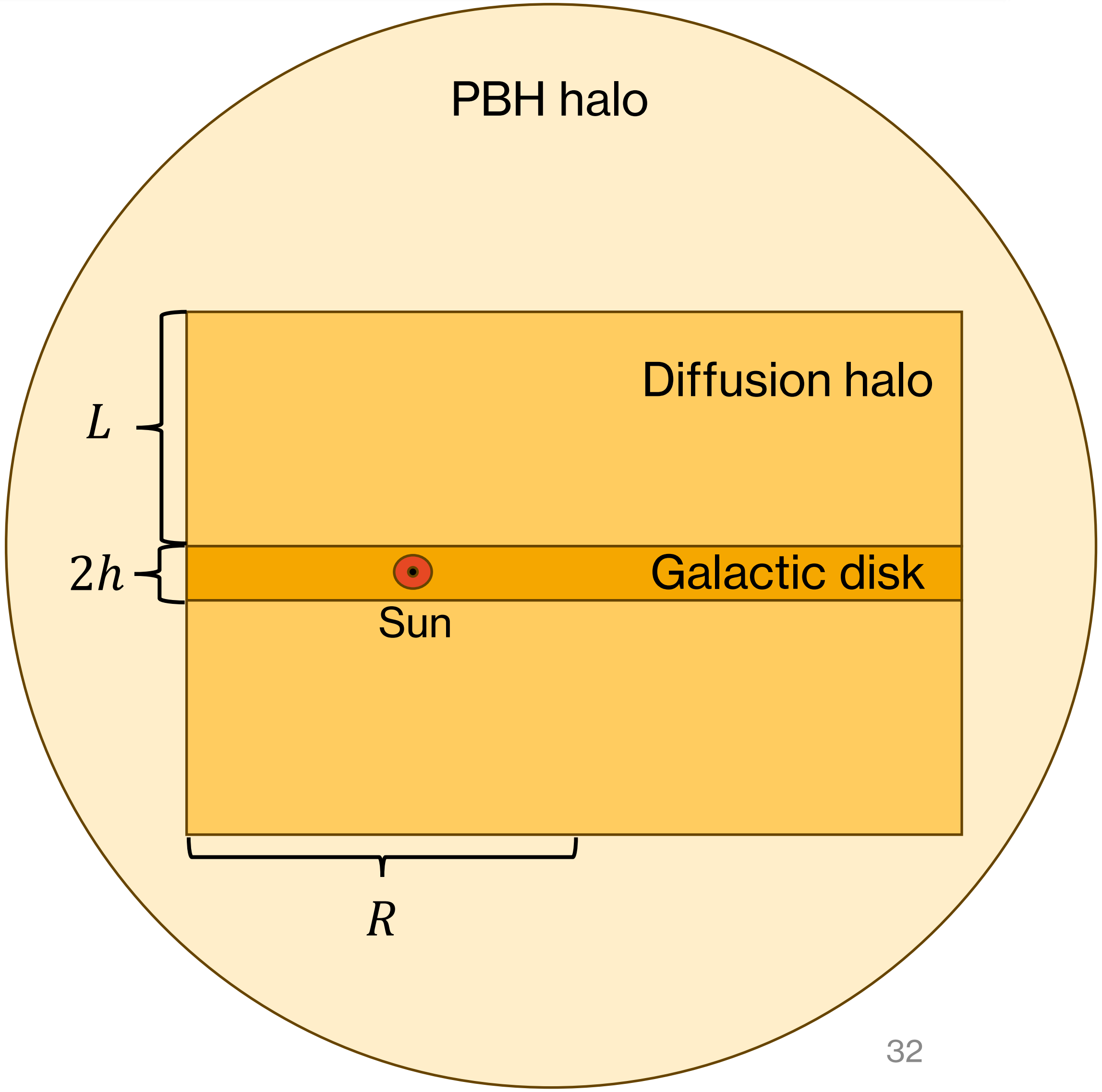


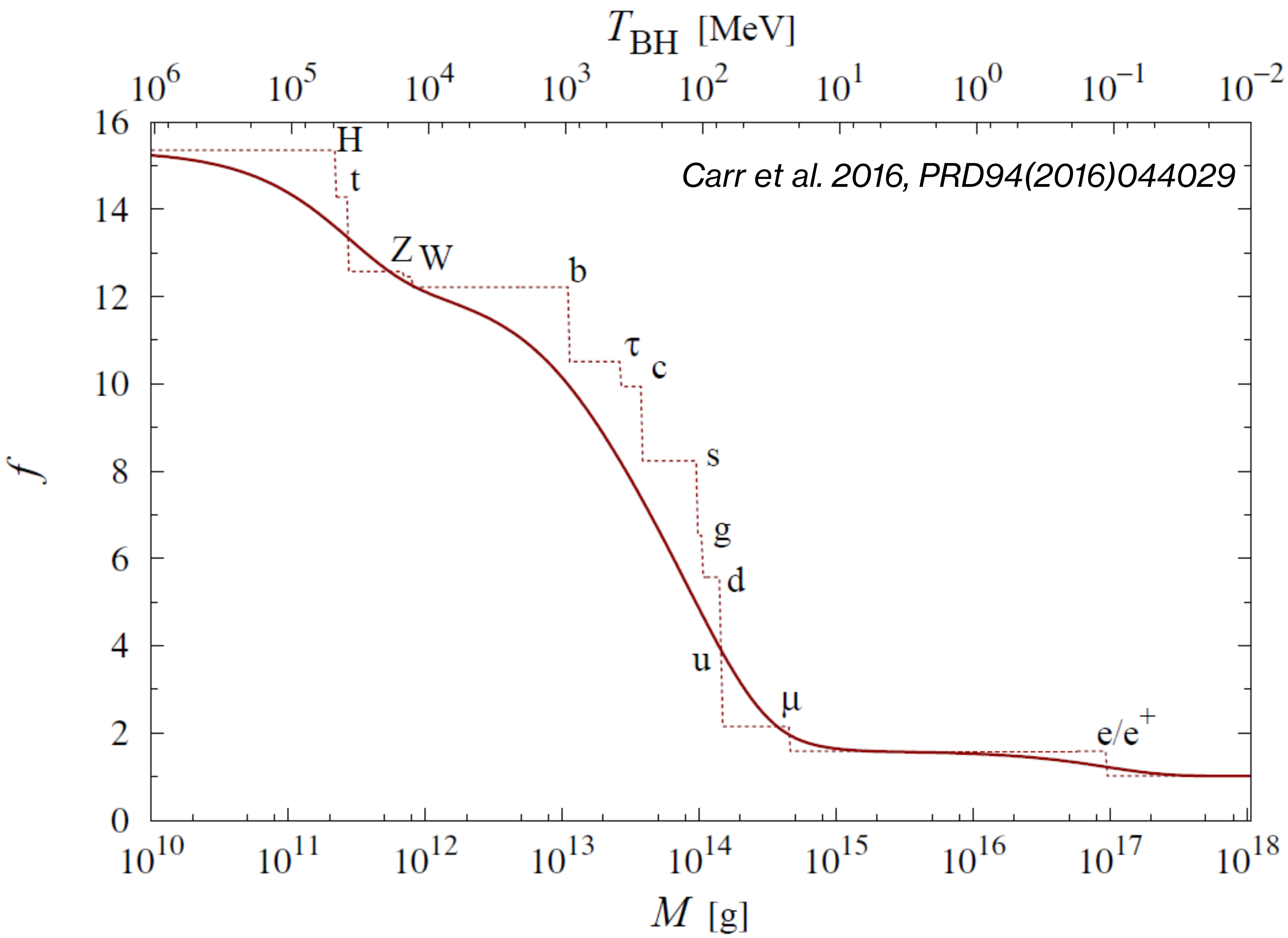
Alfa/evaporation parameter

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

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

f is proportional to *α*

Carr et al. 2016, PRD94(2016)044029



Propagation model

Genolini et al. 2019, PRD99 (2019)123028

$$- \left[K \left(\frac{\partial^2}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial}{\partial r} \right) \right) - V_c \frac{\partial}{\partial z} \right] n + 2h\,\delta(z) \frac{\partial}{\partial E}\left[b(E)\, n - c(E)\, \frac{\partial n}{\partial E} \right]$$

$$= q^{\rm prim}(E) + 2h\delta(z)\left[q^{\rm sec}(E) + q^{\rm ter}(E) \right] - 2h\,\delta(z) \sum_{t \in {\rm ISM}} n_t v\, \sigma_{\rm inel}\, n$$

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

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