Cosmic-ray antinuclei in dark matter searches: Insights from collider data

Based on:
Di Mauro, Jueid, **JK**, Ruiz de Austri, *Phys.Rev.D* 112 (2025) 083017
Di Mauro, **JK**, Stefanuto, Bellini, Donato, Fornengo, arXiv:2603.19352, accepted in *Phys.Rev.D*
Stefanuto, Di Mauro, Donato, Fornengo, **JK**, Maurin, arXiv:2605.08338, submitted to *Phys.Rev.D*

Jordan Koechler
INFN Turin

IDM 2026
June 2nd, 2026

Jiuguang Wang
Basilica of Our Lady of the Pillar and the Ebro River, Zaragoza
2012

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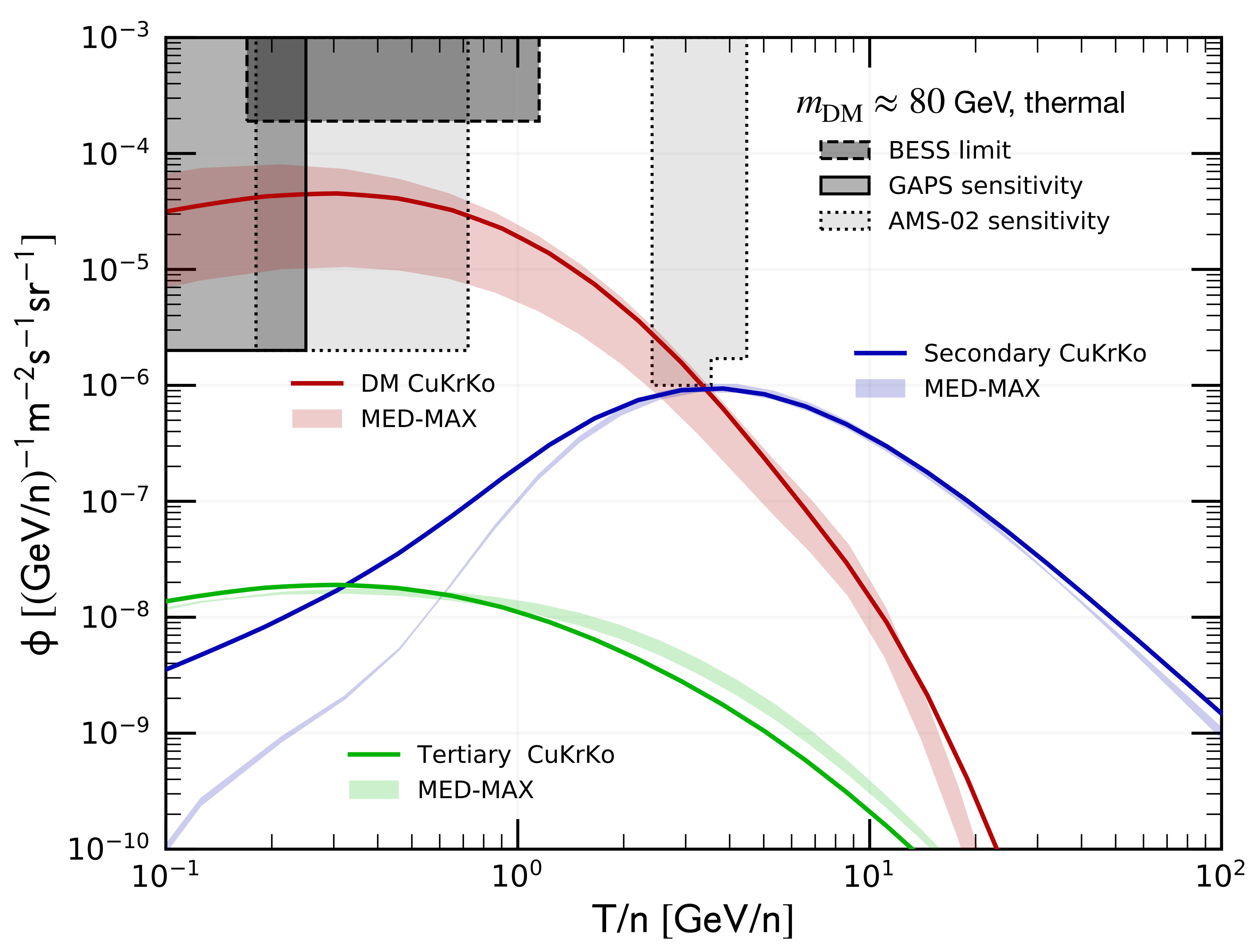
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN TORINO

Why antinuclei?

Antinuclei can provide a background free signal for DM below 1 GeV/n



Korsmeier, Donato, Fornengo, *Phys.Rev.D* 97 (2018) 10, 103011

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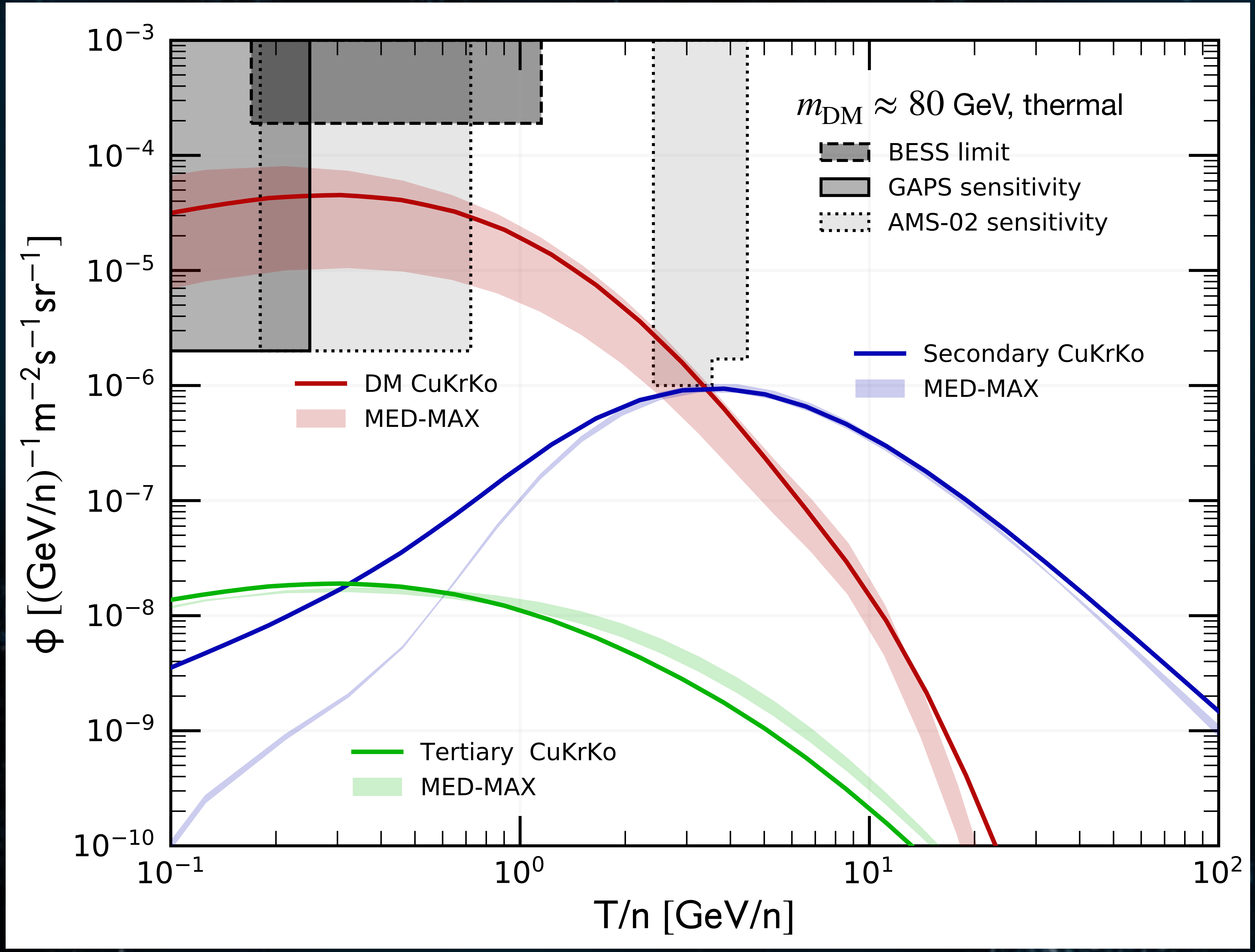
AMS-02 sensitivity to $\overline{\mathrm{D}}$ will be improved by 2030
GAPS made its first flight!



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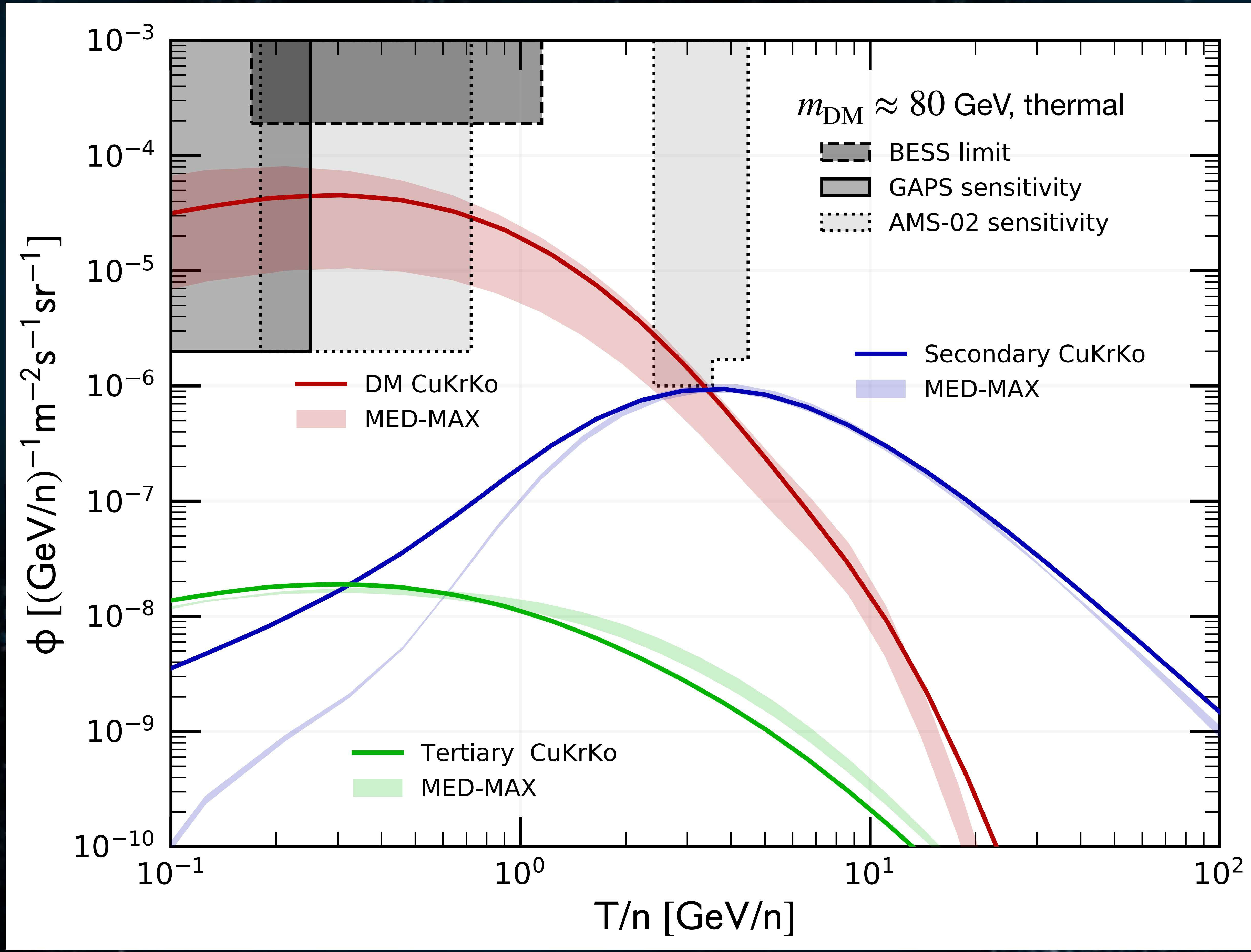
Everything calls for an improvement of the theoretical uncertainties in antinuclei predictions (both DM and secondary)



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How are antinuclei formed?

Secondary production

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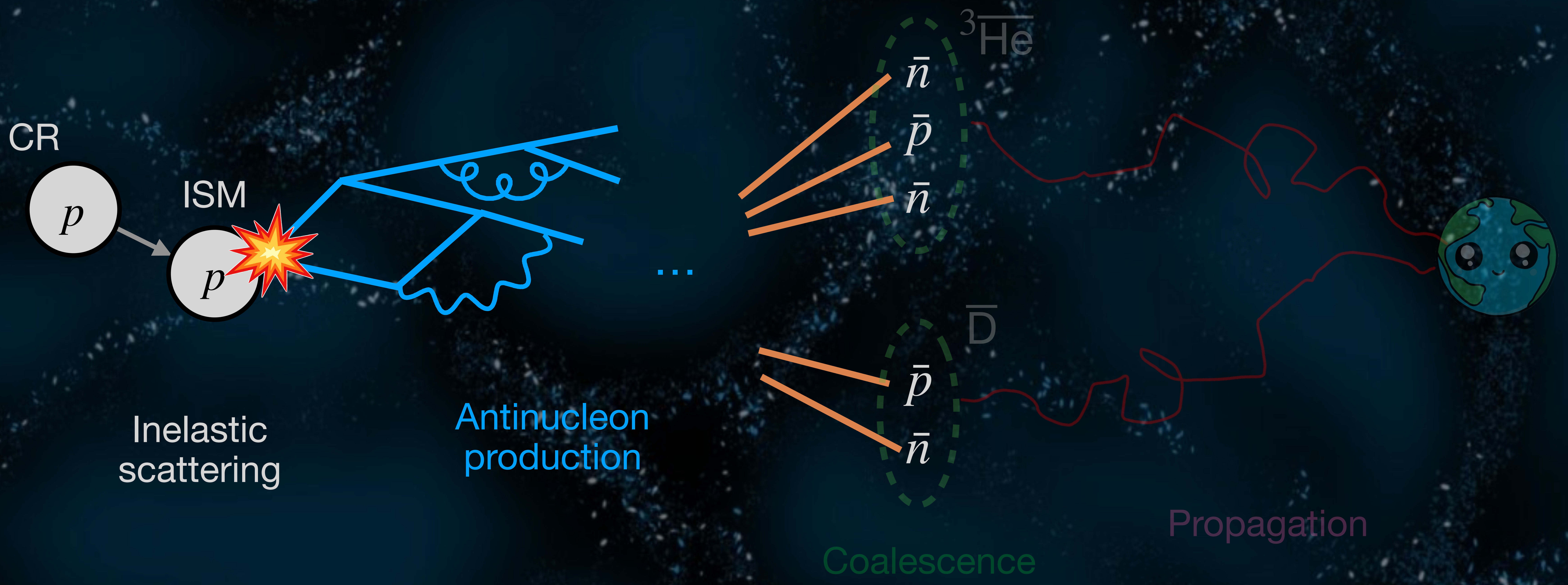

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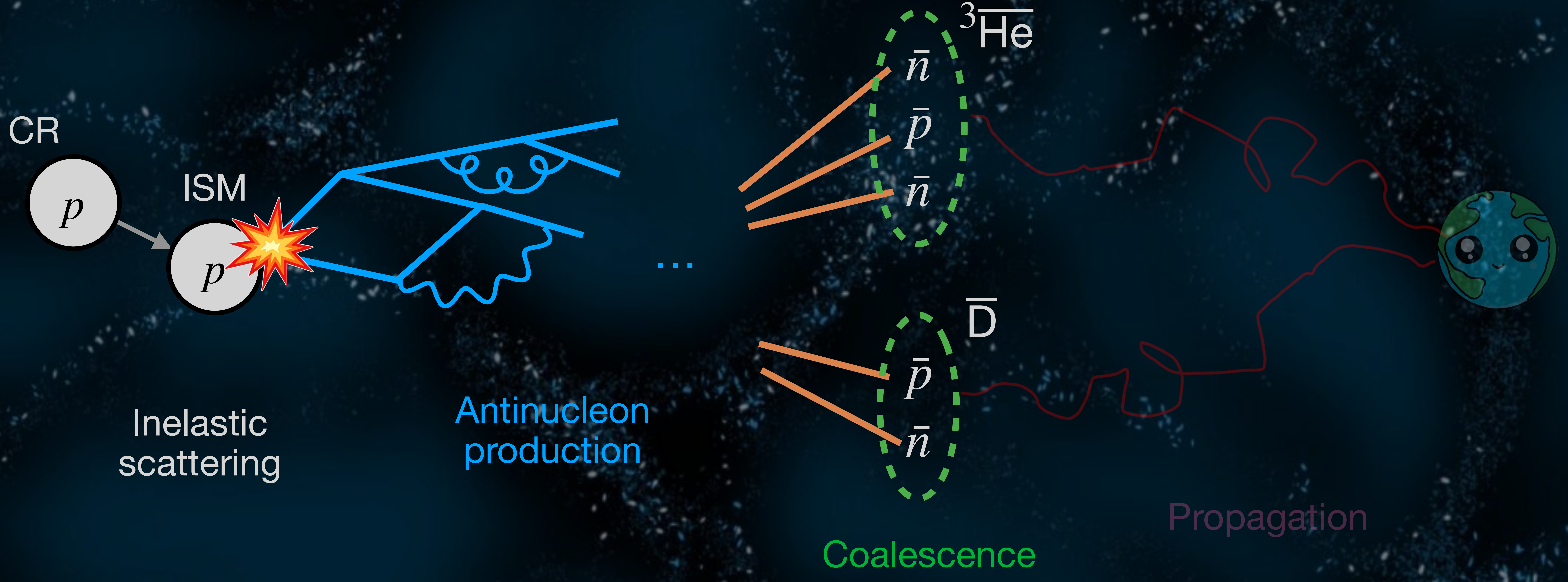

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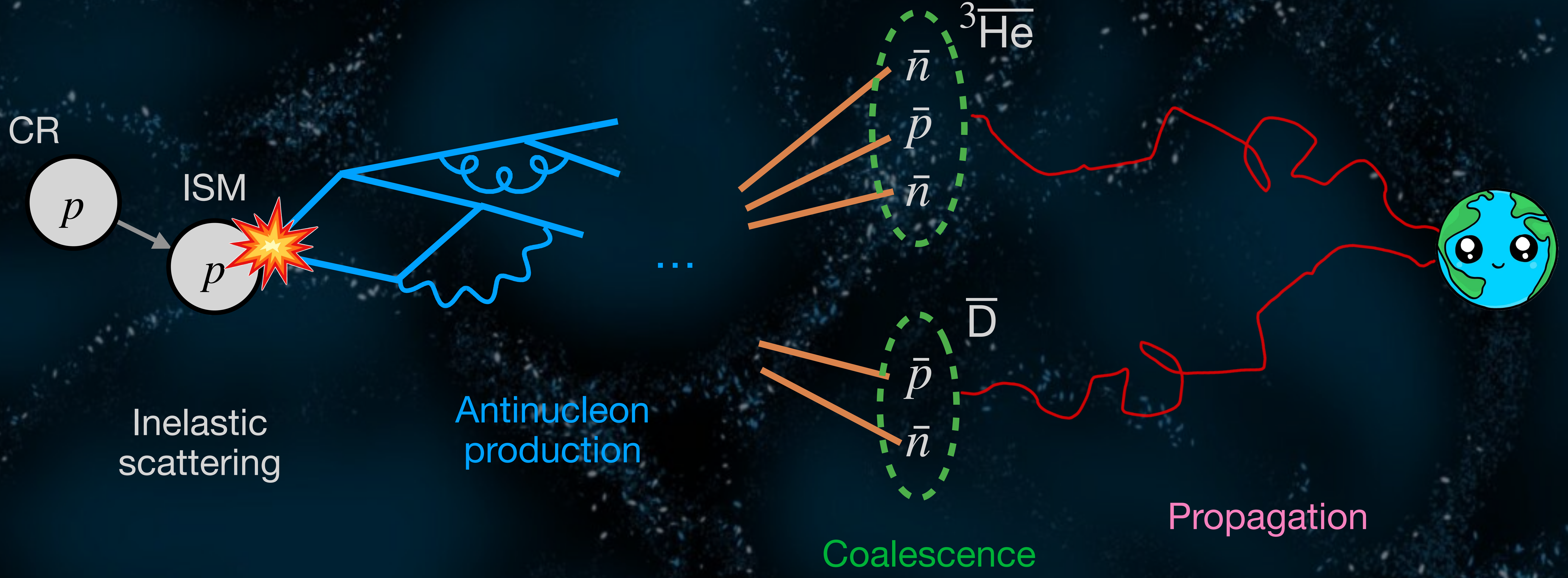
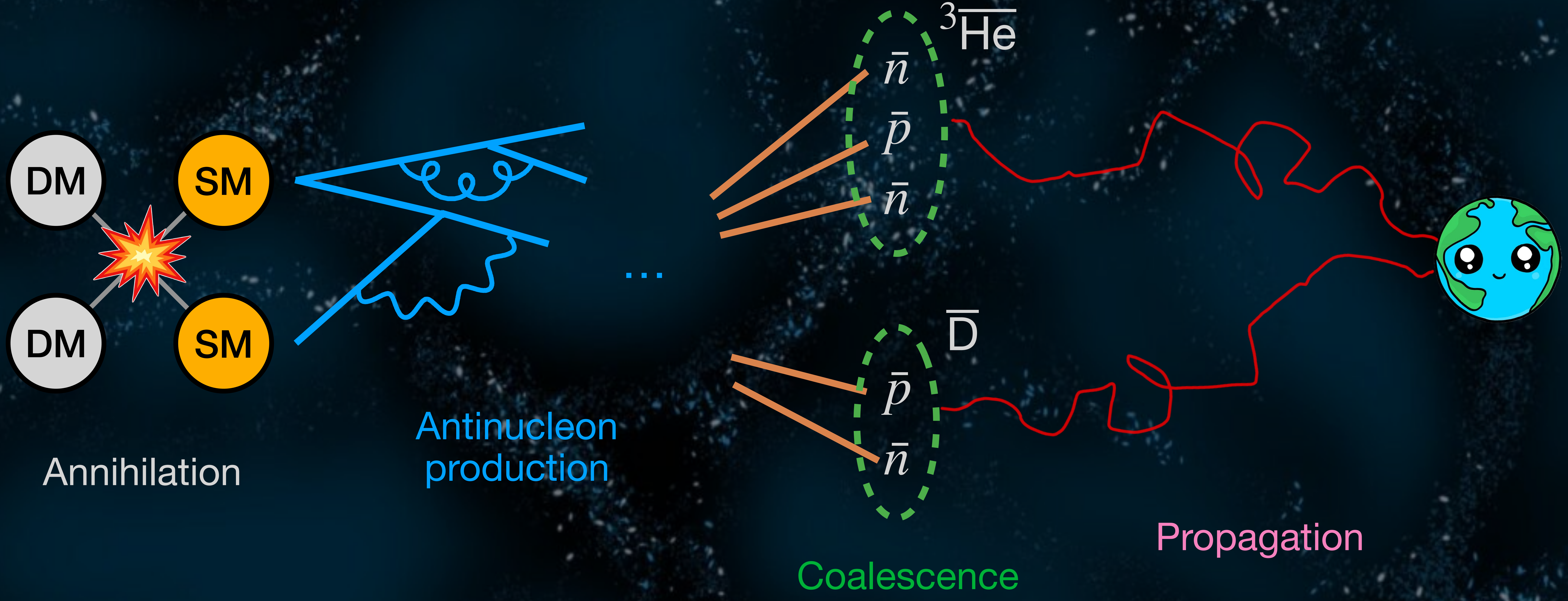


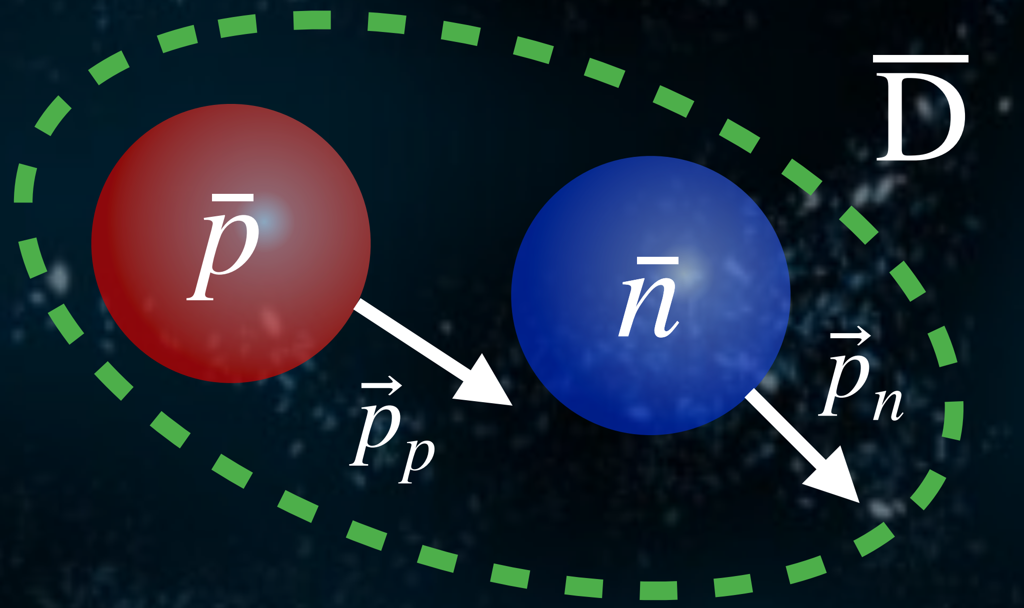
How are antinuclei formed?

DM annihilation



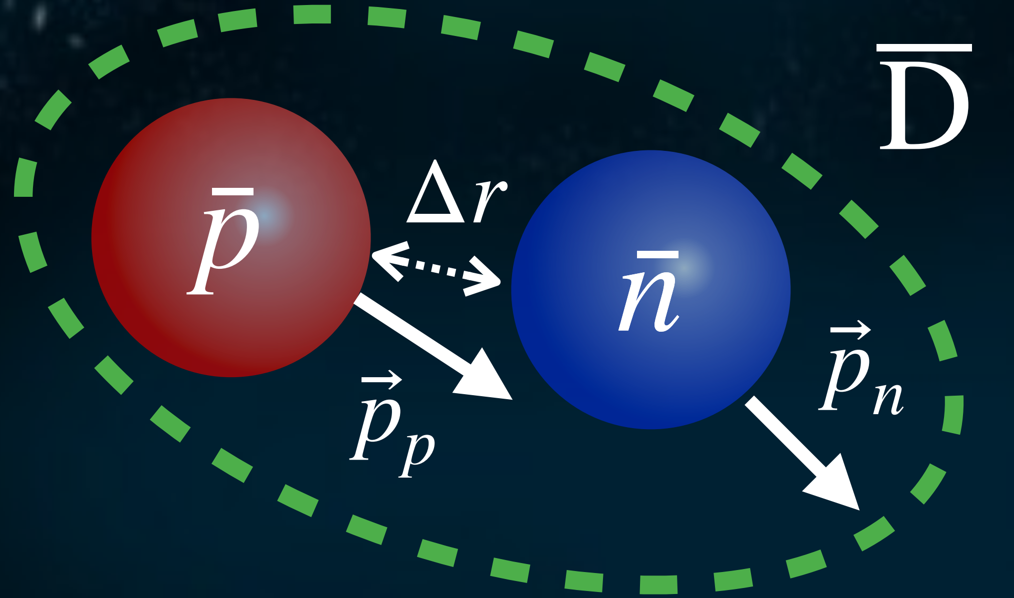
Coalescence models

Δp model



$\Delta p = |\vec{p}_p - \vec{p}_n| < p_{\mathrm{coal}}$

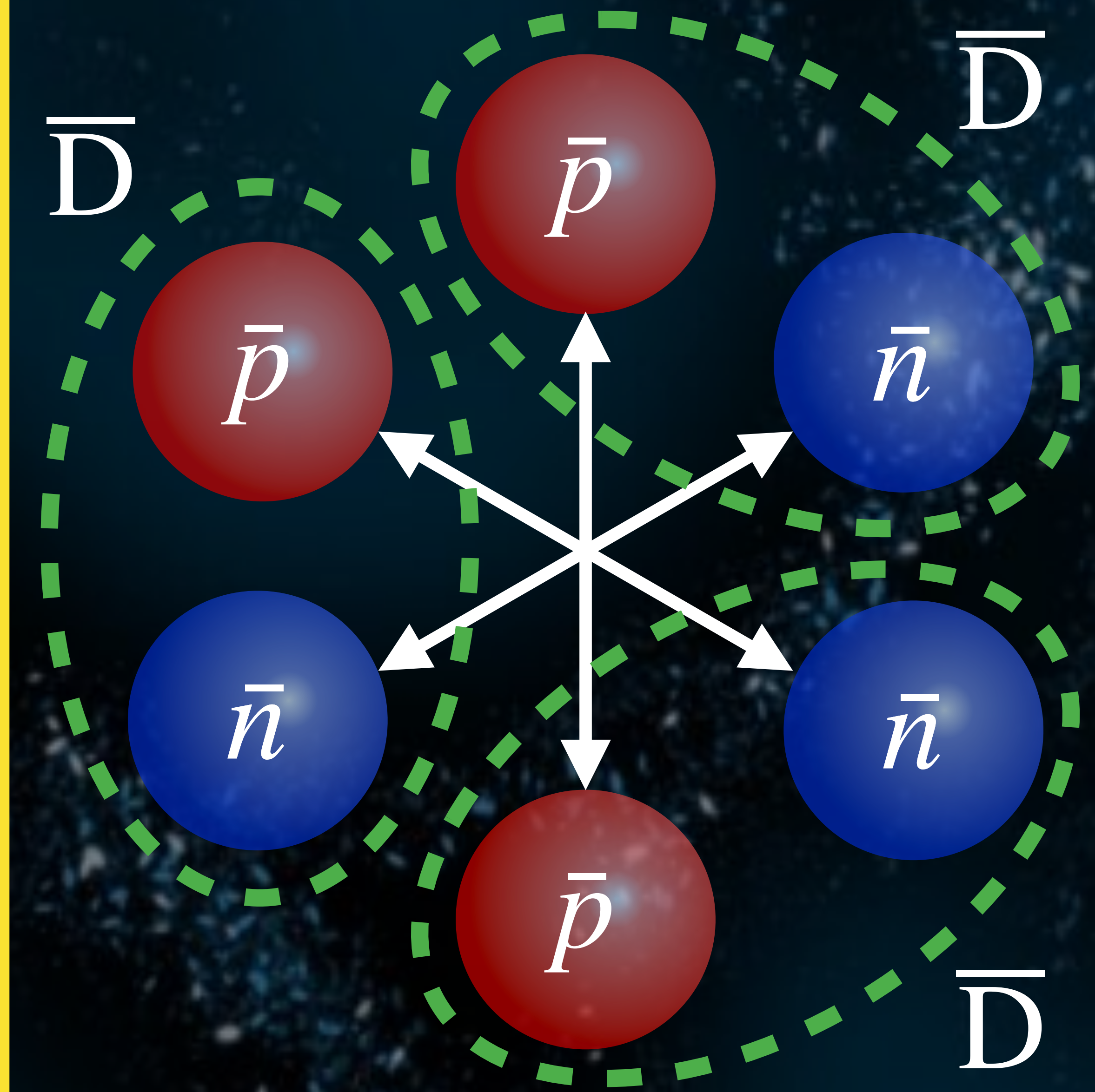
$\Delta p + \Delta r$ model



$\Delta p = |\vec{p}_p - \vec{p}_n| < p_{\mathrm{coal}}$

$\Delta r = |\vec{r}_p - \vec{r}_n| < r_{\mathrm{coal}} = 3$ fm

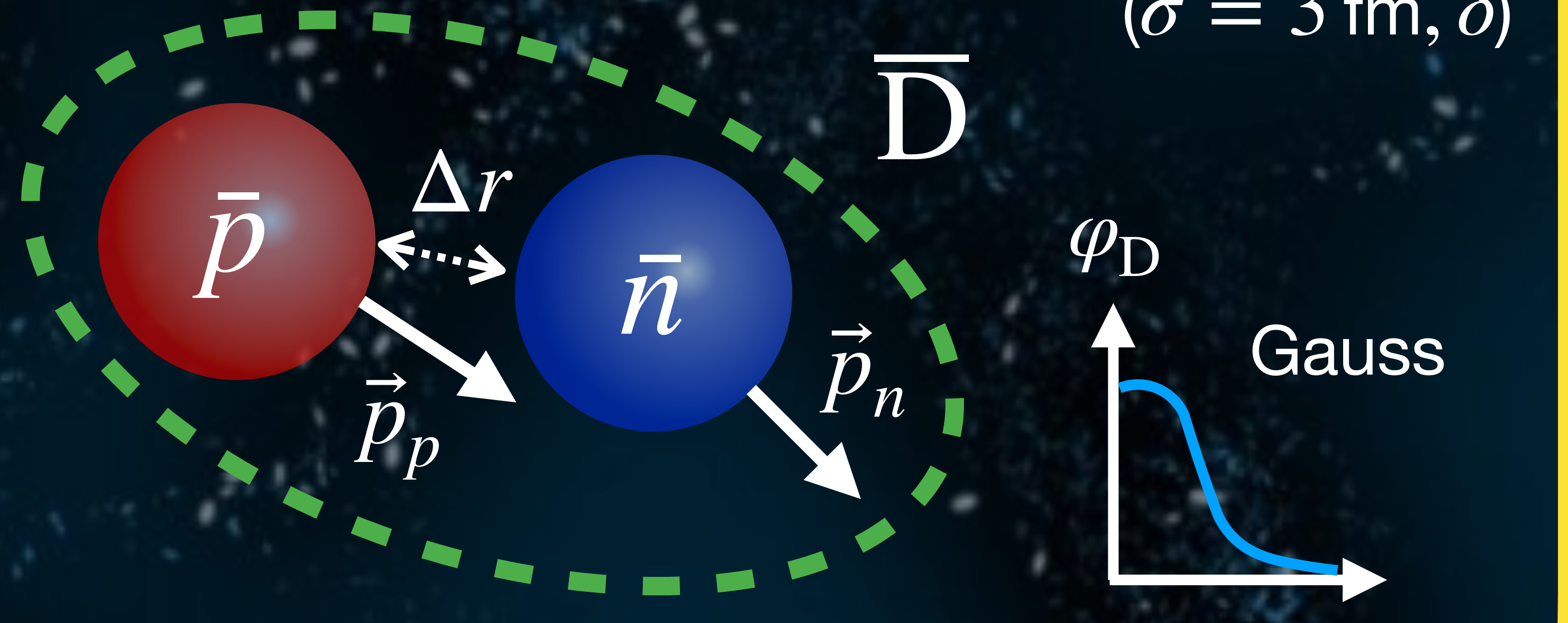
Spherical Model



$\Delta p = |\vec{p}_p - \vec{p}_n| < p_{\mathrm{coal}}$

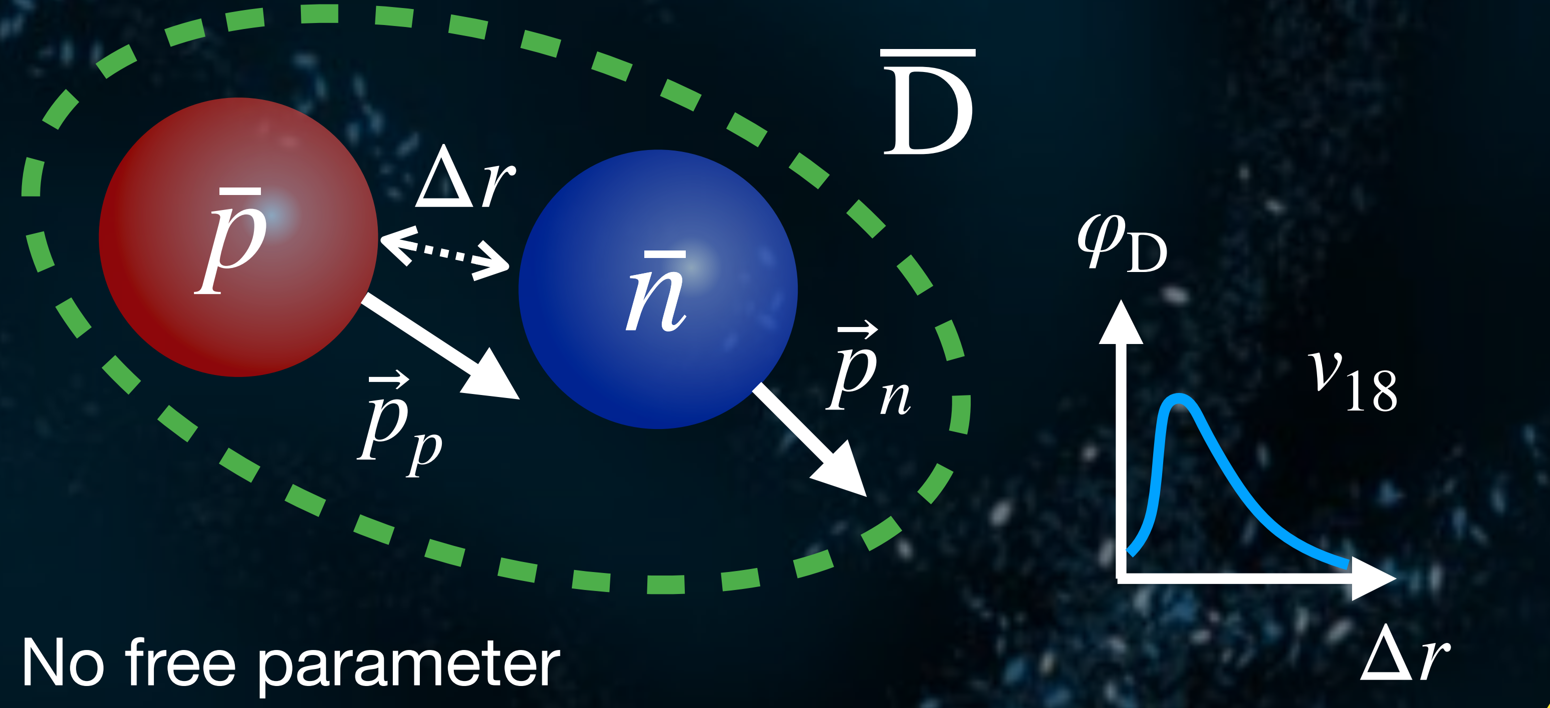
Wigner + Gaussian WF

($\sigma = 3$ fm, δ)



$\mathscr{P}(\Delta p, \Delta r) \propto e^{-\Delta r^2/(2\sigma^2)} e^{-\Delta p^2 \delta^2/2}$

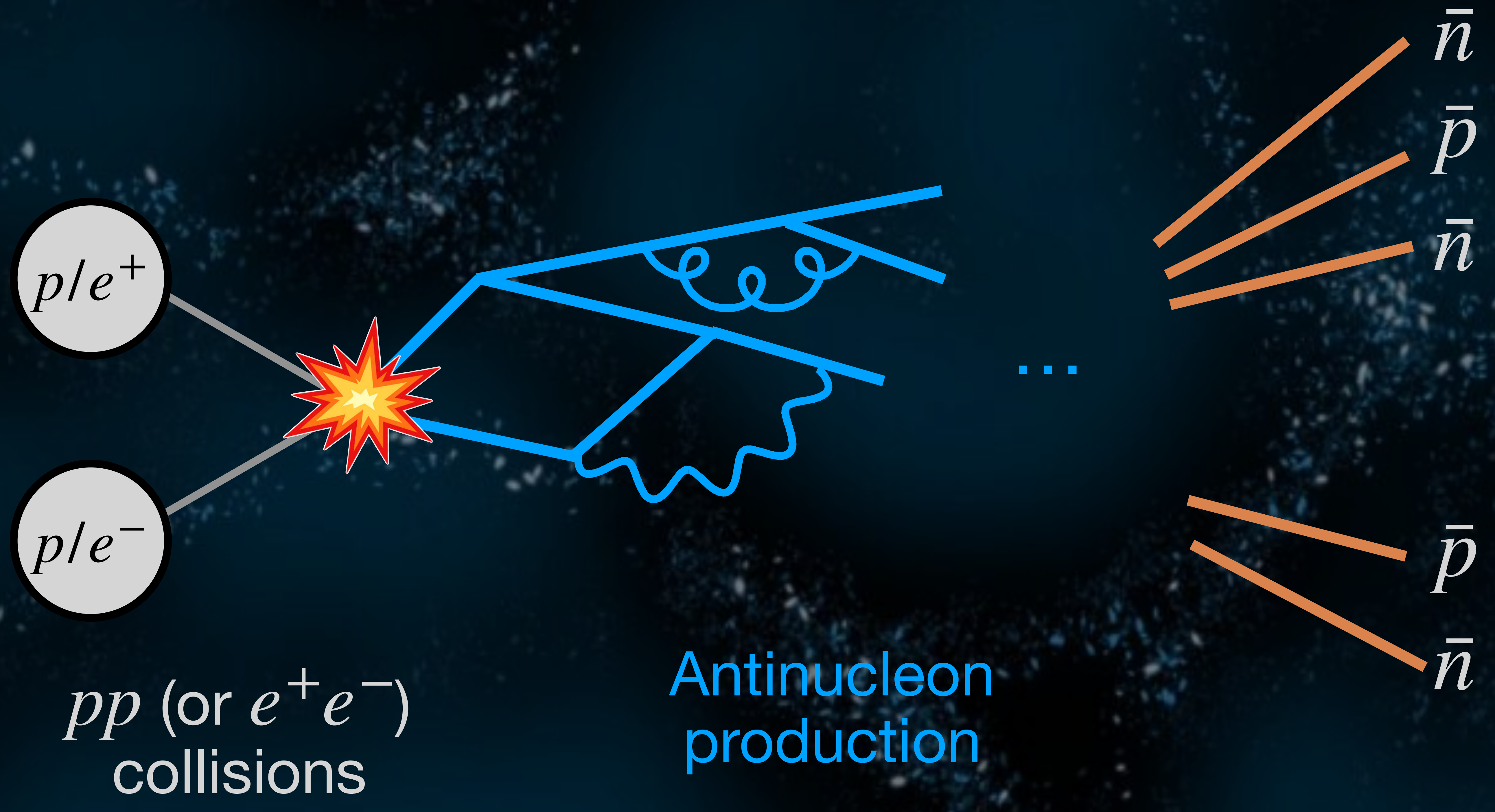
Wigner + Argonne WF



No free parameter

Antinucleon production

How to predict?



e^+e^- collisions at the $Z-$pole

Ideal for DM annihilation

pp collisions

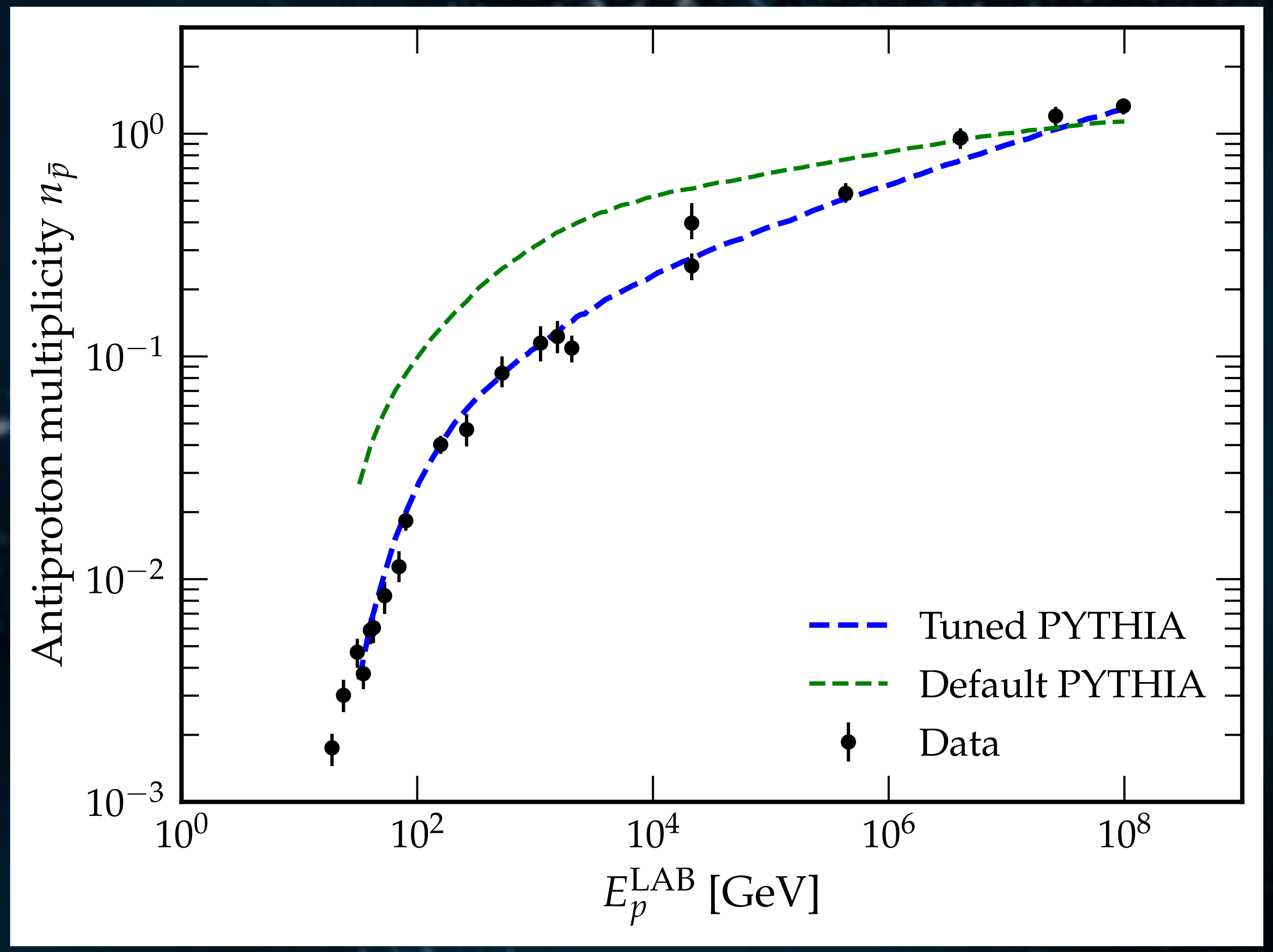
Ideal for secondaries

Allow to compute XS

Goal: Appropriately tune a Monte Carlo collision generator (e.g., PYTHIA)

Antinucleon production

Secondary production



$$\texttt{StringPT:sigma} = \begin{cases} 0.40, & E_p^{\rm LAB} \le 1~\text{TeV}, \\ 0.40 + 0.035\,\log_{10}\left(\frac{E_p^{\rm LAB}}{1~\text{TeV}}\right), & E_p^{\rm LAB} > 1~\text{TeV}. \end{cases} \quad (23)$$

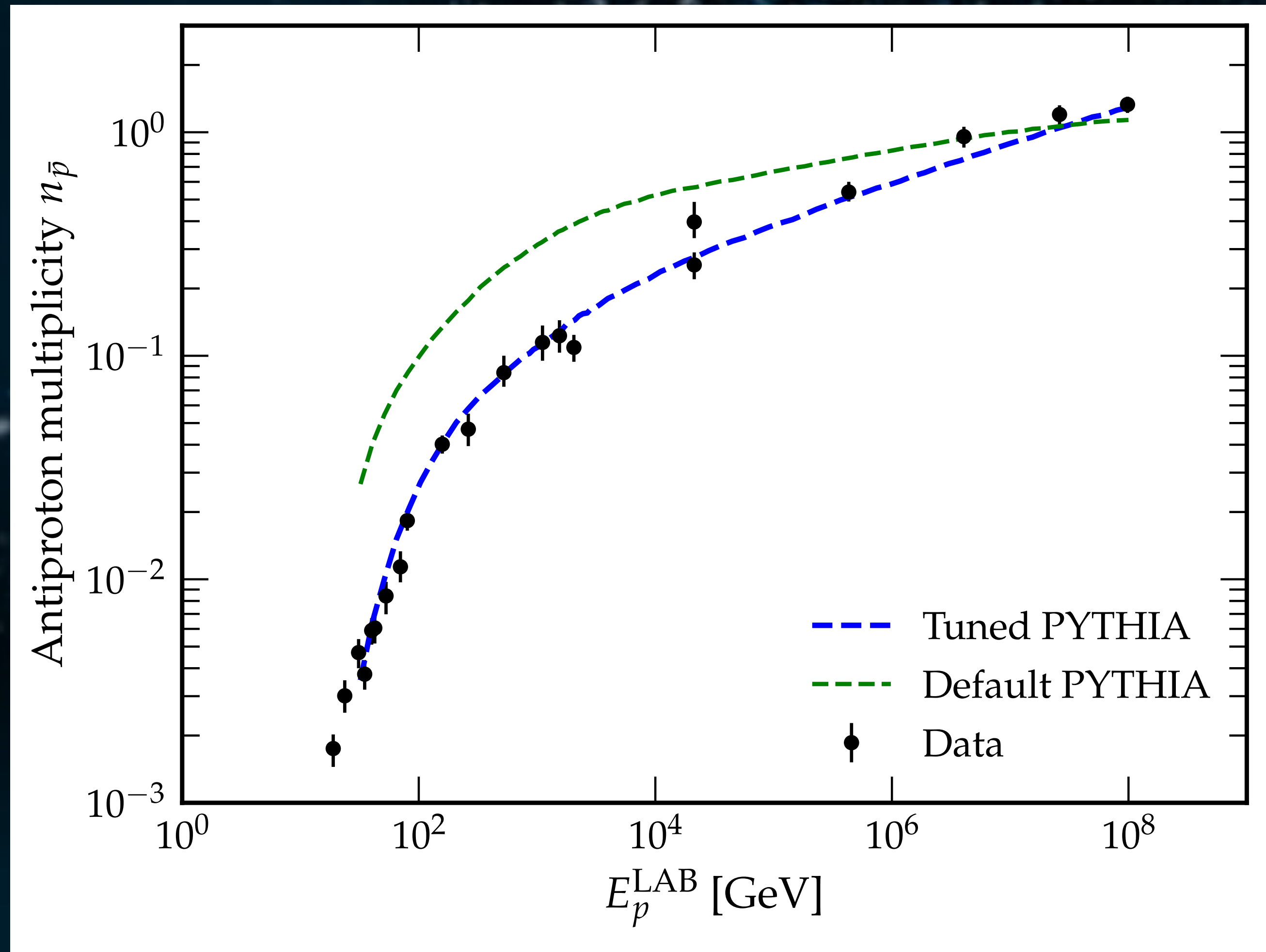
$$\texttt{StringFlav:probQQtoQ} = \begin{cases} 0.055 - 0.017\,\log_{10}^2\left(\frac{E_p^{\rm LAB}}{1~\text{TeV}}\right), & E_p^{\rm LAB} \le 1~\text{TeV}, \\ 0.030 + 0.002\,\log_{10}\left(\frac{E_p^{\rm LAB}}{1~\text{TeV}}\right), & E_p^{\rm LAB} > 1~\text{TeV}. \end{cases} \quad (24)$$

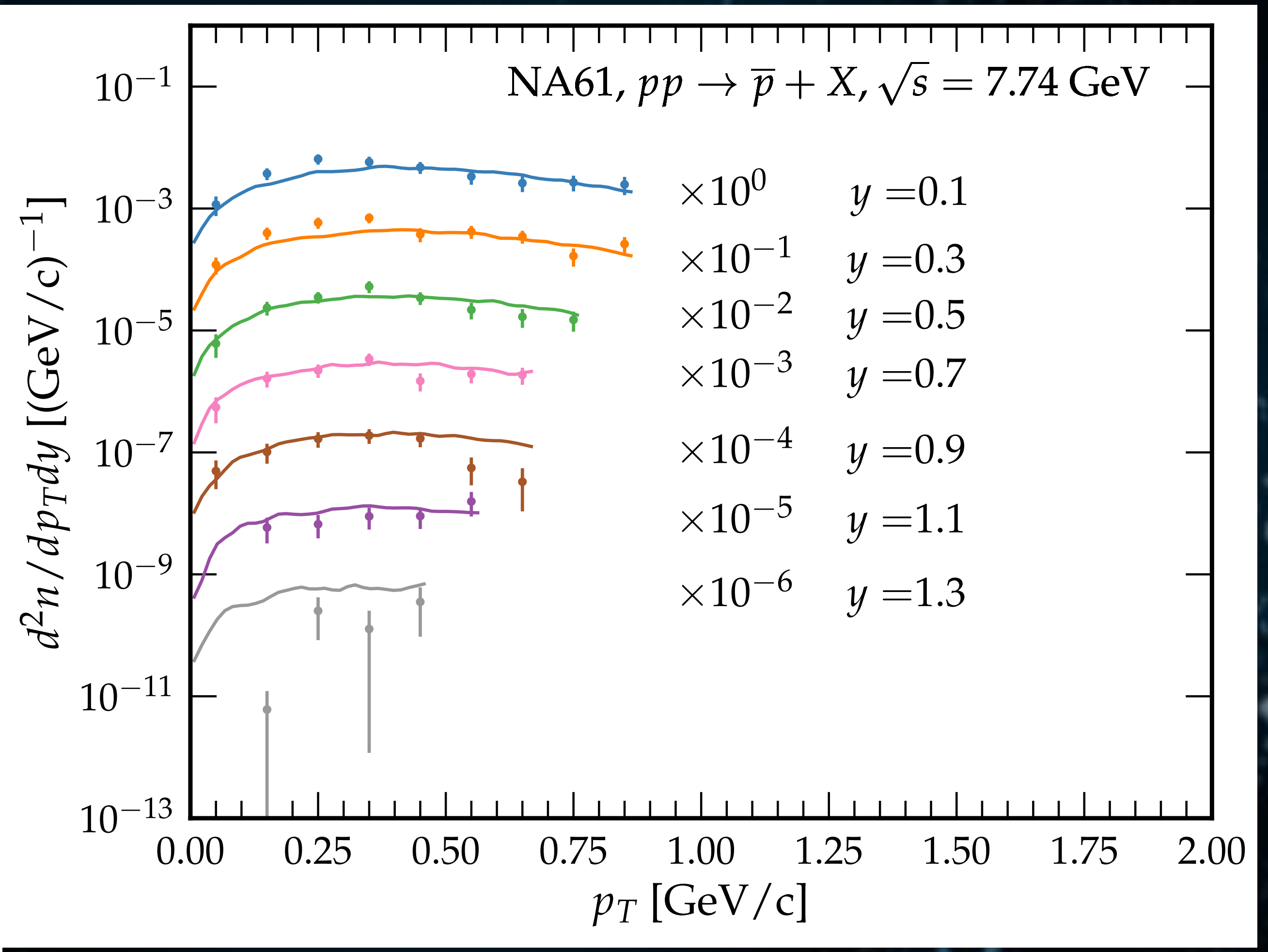
Tuning to pp collider data

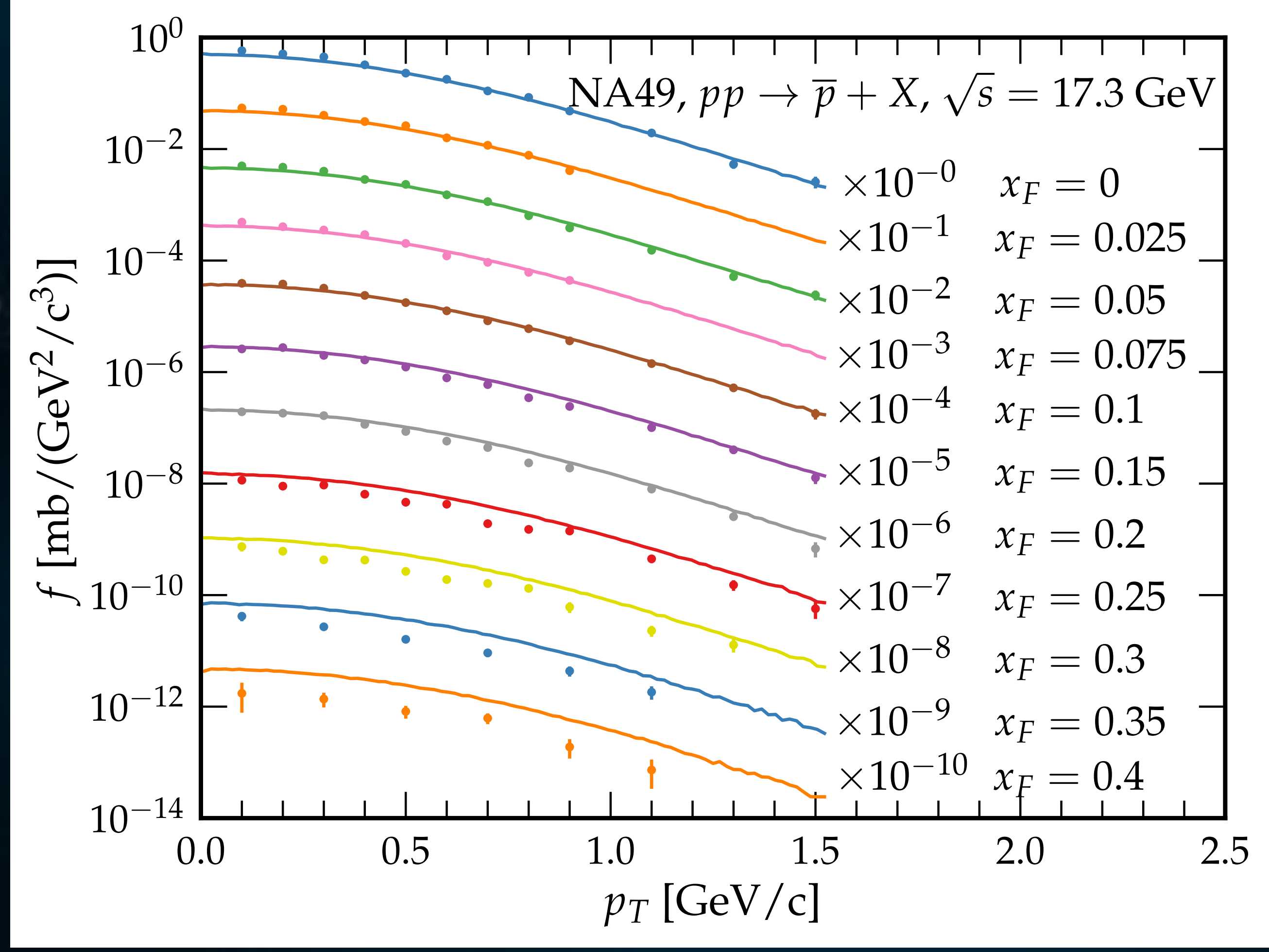
Di Mauro, **JK**, Stefanuto, Bellini, Donato, Fornengo, arXiv:2603.19352, submitted to *Phys.Rev.D*

Antinucleon production

Secondary production







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NA49/NA61: SPS fixed-target exp.
$\sqrt{s} = 7$ to 17 GeV

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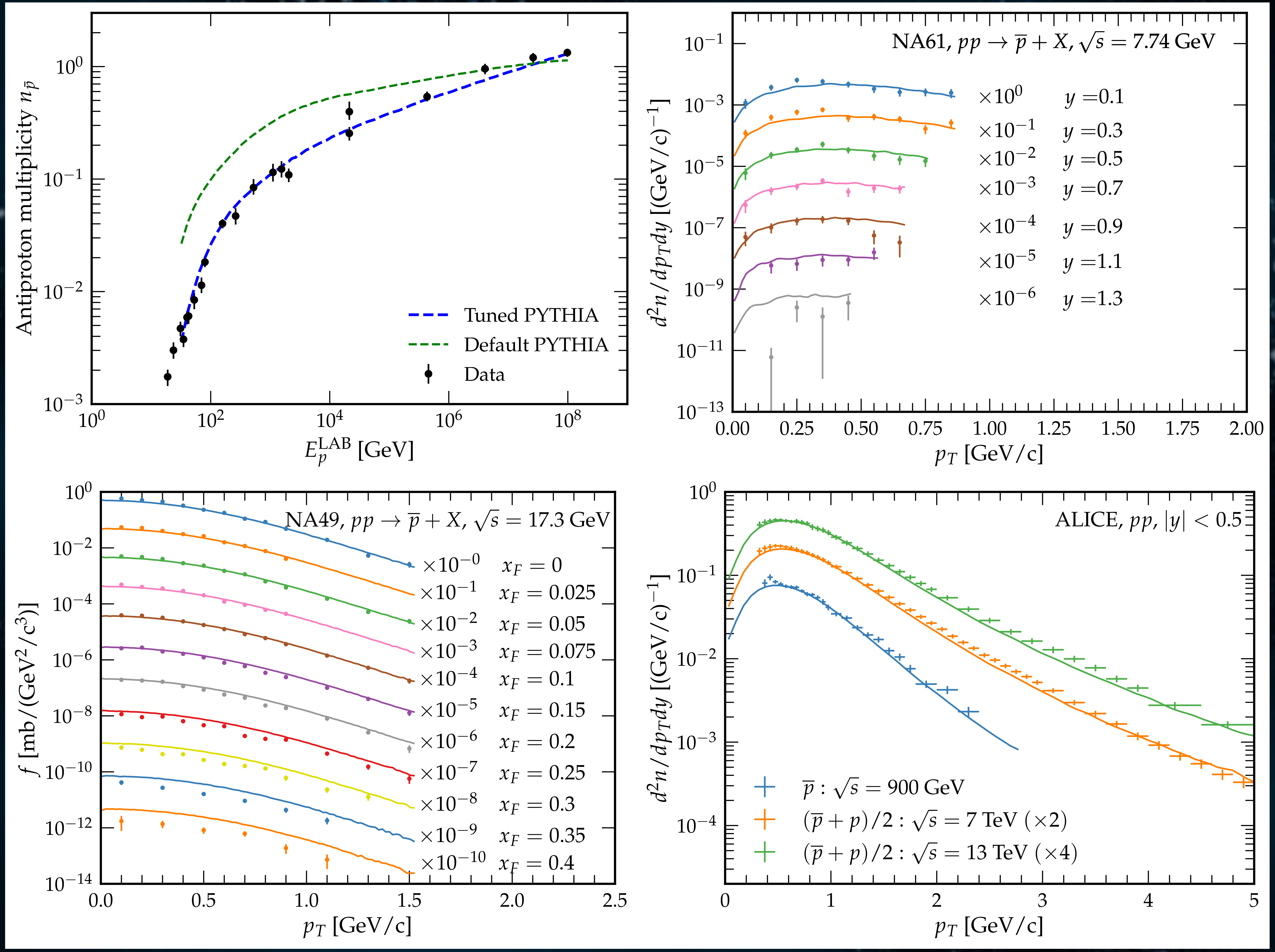

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Tuning to pp collider data

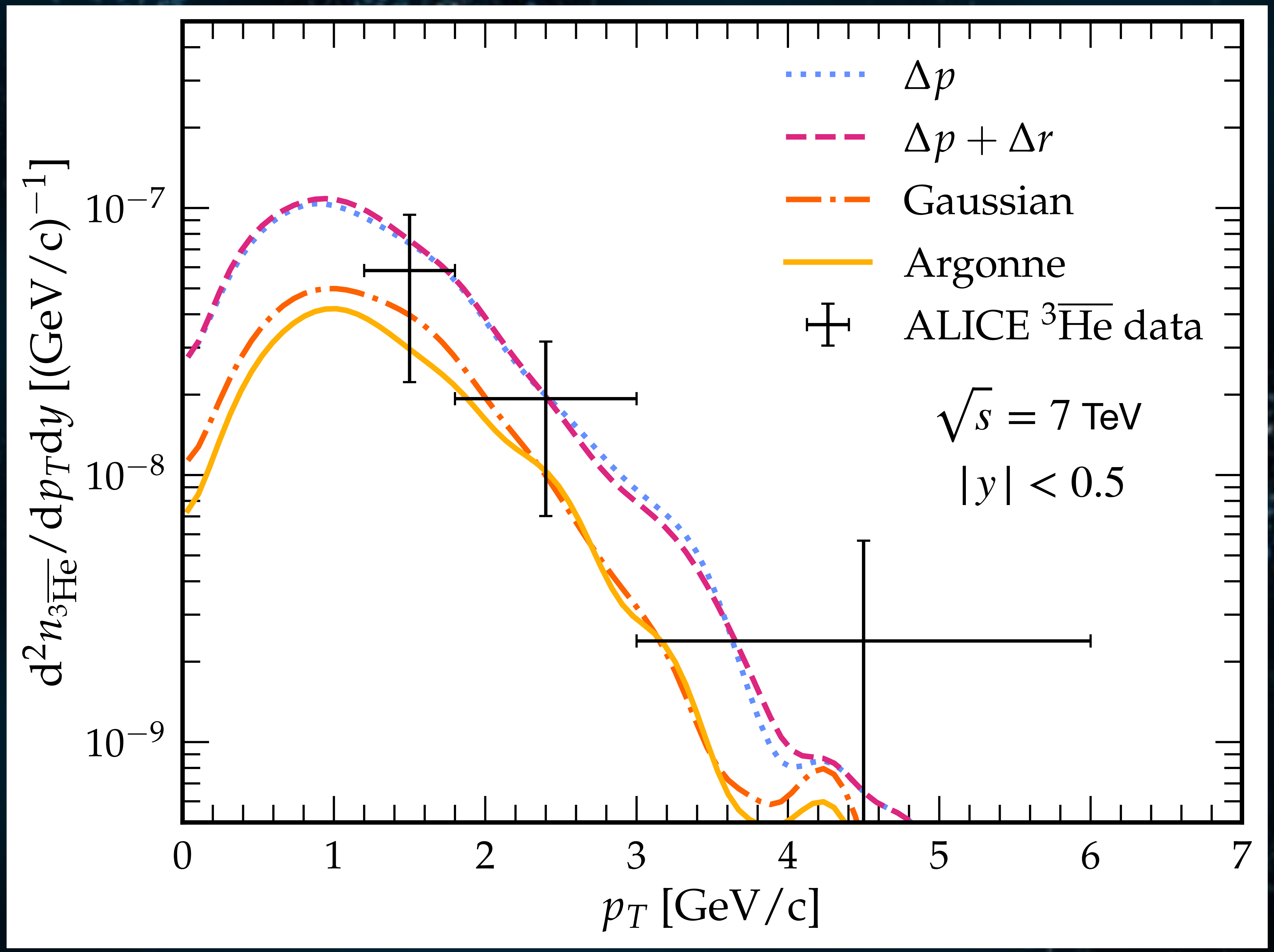
NA49/NA61: SPS fixed-target exp.
$\sqrt{s}$ = 7 to 17 GeV

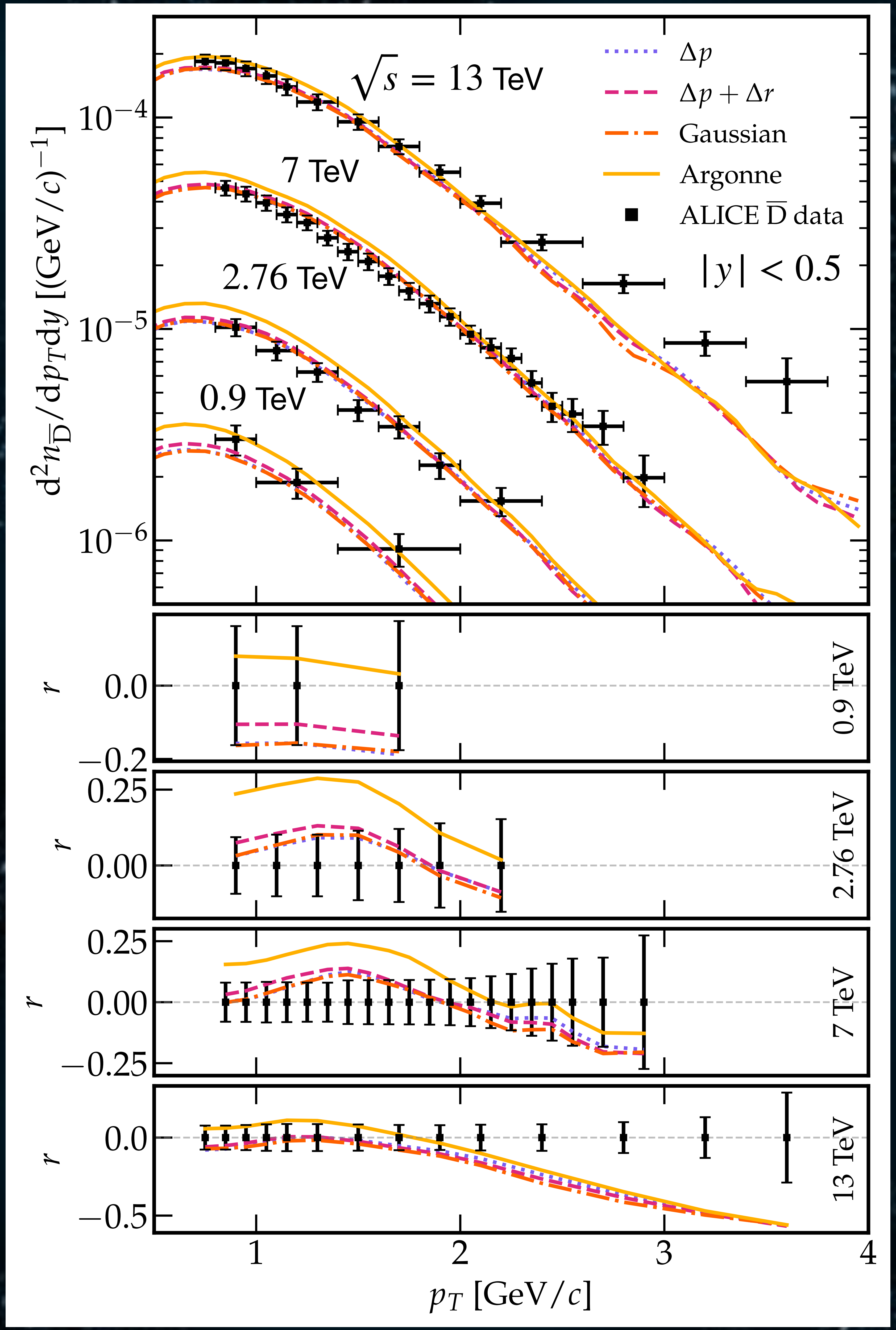
ALICE: LHC collider exp.
$\sqrt{s}$ = 900 GeV to 13 TeV

Antinuclei production

Secondary production

$^{3}\overline{\mathrm{He}}$ p_T-spectrum in pp collisions @ ALICE





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Antinucleon production

DM annihilation

47 measurements containing 856 bins

Measurement	Experiment	$\chi^2/N_{\rm bins}$	Measurement	Experiment	$\chi^2/N_{\rm bins}$
$1-T$	ALEPH [54]	0.13	C–parameter	ALEPH [54]	0.39
$\log(1/x_p)$	ALEPH [54]	0.19	$\langle N_{\rm ch}\rangle$	ALEPH [54]	0.028
$\langle N_{\rm ch}\rangle$ ($\lvert Y\rvert < 0.5$)	ALEPH [54]	0.012	$\langle N_{\rm ch}\rangle$ ($\lvert Y\rvert < 1.0$)	ALEPH [54]	0.028
$\langle N_{\rm ch}\rangle$ ($\lvert Y\rvert < 1.5$)	ALEPH [54]	0.030	$\langle N_{\rm ch}\rangle$ ($\lvert Y\rvert < 2.0$)	ALEPH [54]	0.040
$\pi^{\pm}$ spectrum	ALEPH [54]	0.67	π^0 spectrum	ALEPH [54]	0.24
Λ^0 spectrum	ALEPH [55]	1.24	Λ^0 spectrum (2–jet events)	ALEPH [55]	1.31
Thrust	ALEPH [56]	0.097	C–parameter	ALEPH [56]	0.35
$N_{\rm ch}$ ($y_{\rm cut} = 0.01$)	DELPHI [57]	5.99	$N_{\rm ch}$ ($y_{\rm cut} = 0.02$)	DELPHI [57]	4.88
Λ^0 spectrum	DELPHI [58]	1.34	$\langle N_{\Lambda^0}\rangle$	DELPHI [58]	0.53
π^0 momentum	DELPHI [59]	0.41	$\log(1/x_p)$	DELPHI [59]	0.33
$1-T$	DELPHI [59]	0.18	C–parameter	DELPHI [59]	0.34
$\langle N_{\rm ch}\rangle$	DELPHI [59]	0.031	$\langle N_{\pi^{\pm}}\rangle$	DELPHI [59]	0.063
$\langle N_{\pi^0}\rangle$	DELPHI [59]	0.39	$\langle N_{\rho}\rangle$	DELPHI [59]	3.40
$\langle N_p\rangle$	DELPHI [59]	2.30	$\langle N_{\Lambda^0}\rangle$	DELPHI [59]	1.54
$\langle N_{\rm ch}\rangle$	DELPHI [60]	0.005	$\langle N_{\pi^{\pm}}\rangle$	DELPHI [60]	0.10
$\langle N_p\rangle$	DELPHI [60]	0.05	$N_{p/\bar{p}}/N_{\rm ch}$	DELPHI [60]	0.27
$\pi^{\pm}$ momentum	DELPHI [60]	0.46	$p/\bar{p}$ momentum	DELPHI [60]	0.43
Thrust (udsc events)	L3 [61]	0.34	C–parameter (udsc events)	L3 [61]	0.22
Charged multiplicity	L3 [61]	3.39	$\log(1/x_p)$	L3 [61]	0.96
x_p (udsc events)	L3 [61]	0.78			
$\langle N_{\rm ch}\rangle$	OPAL [62]	0.37	$\pi^{\pm}$ spectrum	OPAL [63]	0.25
Λ^0 scaled energy	OPAL [64]	1.49	π^0 scaled momentum	OPAL [65]	0.12
All events $\log(1/x_p)$	OPAL [66]	0.38	$\langle N_{\rm ch}\rangle$	OPAL [66]	0.16
$1-T$	OPAL [67]	0.10	C–parameter	OPAL [67]	0.35

Table 3. Contributions to the $\chi^2/N_{\rm df}$ per each measurement that was included in the tuning.

CosmiXs: Arina, Di Mauro, Fornengo, Heisig, Jueid, Ruiz de Austri, *JCAP* 03 (2024) 035

Parameter	MONASH	VINCIA (default)	PYTHIA [17, 18]	This work
a_L	0.68	0.45	0.601	0.337 ± 0.015
b_L	0.98	0.80	0.897	0.784 ± 0.020
$\sigma_{\perp}$ (GeV)	0.335	0.305	0.307	0.296 ± 0.003
a_{QQ}	0.97	0.90	1.671	1.246 ± 0.082
$\chi^2/N_{\rm df}$	1034.52/852	786.11/852	676.69/852	660.21/852

Table 2. Tuning results of the parameters of the hadronization model in PYTHIA 8 using the VINCIA shower plugin. For comparison, we show the results in the baseline MONASH tuning in both PYTHIA and VINCIA as well as the results of Refs. [17, 18].

Tuning to e^+e^- collider data @ Z-pole

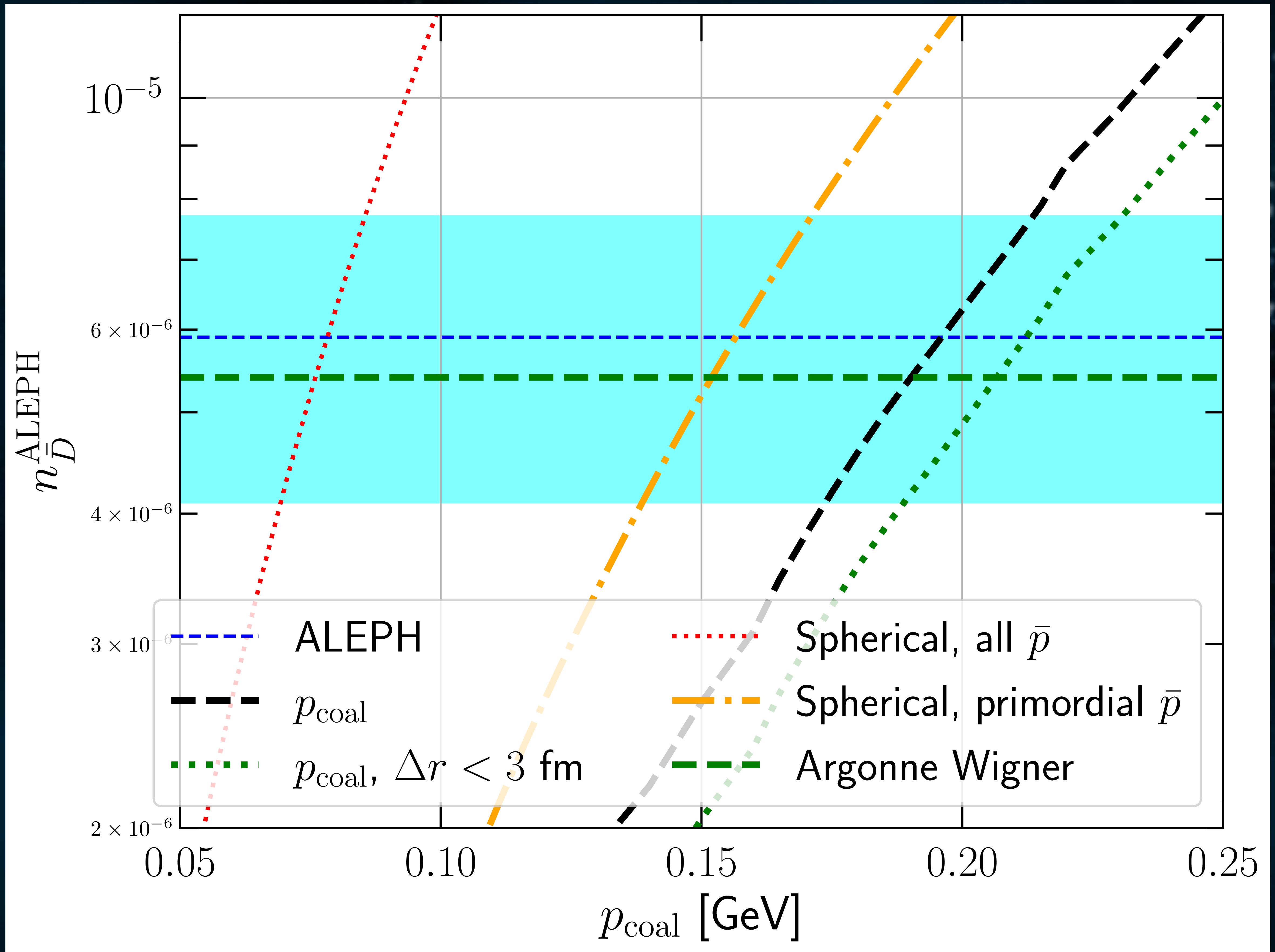
ALEPH, DELPHI, L3, OPAL:
LEP collider exp

$$\sqrt{s} = m_Z \sim 91 \text{ GeV}$$

Antinuclei production

DM annihilation

$\overline{\mathrm{D}}$ multiplicity in e^+e^- collisions @ Z-pole



Only ALEPH at LEP measured the $\overline{\mathrm{D}}$ multiplicity

(with a ~30% uncertainty!)

CosmiXs $\overline{\mathrm{D}}$: Di Mauro, Fornengo, Jueid, Ruiz de Austri, Bellini, *Phys.Rev.Lett* 135 (2025) 131002

Towards coalescence universality?

TABLE III. Comparison of coalescence parameters extracted from pp and e^+e^- collisions. The ALICE results correspond to a simultaneous global fit of deuteron and antideuteron spectra across four center-of-mass energies ($\sqrt{s} = 0.9, 2.76, 7, 13$ TeV). The ALEPH results refer to antideuteron production in e^+e^- collisions at the Z resonance ($\sqrt{s} = 91$ GeV) and are taken from Ref. [35].

Model	ALICE (Global fit) pp @ 0.9–13 TeV	χ^2/N_{dof} (ALICE)	ALEPH (Reference) e^+e^- @ 91 GeV
Δp	$p_{\mathrm{coal}} = 0.201 \pm 0.001$ GeV	1.75	$p_{\mathrm{coal}} = 0.196^{+0.018}_{-0.023}$ GeV
$\Delta p + \Delta r$	$p_{\mathrm{coal}} = 0.214 \pm 0.001$ GeV	2.19	$p_{\mathrm{coal}} = 0.212^{+0.019}_{-0.024}$ GeV
`Gaussian`	$\delta = 1.69 \pm 0.01$ fm	2.05	$\delta = 1.80^{+0.2}_{-0.3}$ fm

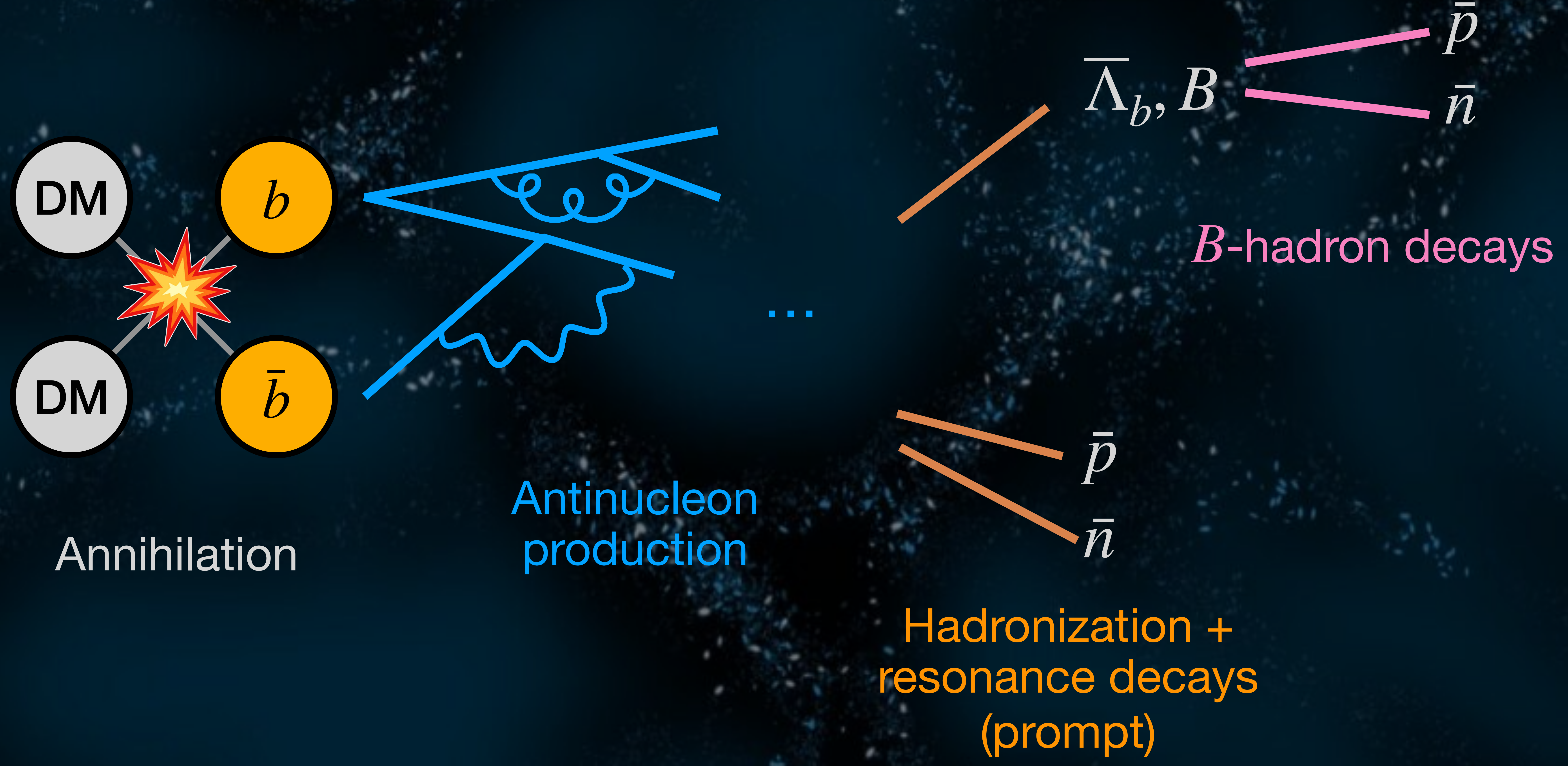
TABLE IV. Fit quality excluding the highest-energy dataset. Same comparison as in Table III, but performing the ALICE global fit only for $\sqrt{s} = 0.9, 2.76$, and 7 TeV (thus excluding 13 TeV).

Model	ALICE (Lower $\sqrt{s}$ only) pp @ 0.9–7 TeV	χ^2/N_{dof} (ALICE)	ALEPH (Reference) e^+e^- @ 91 GeV
Δp	$p_{\mathrm{coal}} = 0.198 \pm 0.001$ GeV	0.73	$p_{\mathrm{coal}} = 0.196^{+0.018}_{-0.023}$ GeV
$\Delta p + \Delta r$	$p_{\mathrm{coal}} = 0.211 \pm 0.001$ GeV	0.91	$p_{\mathrm{coal}} = 0.212^{+0.019}_{-0.024}$ GeV
`Gaussian`	$\delta = 1.72 \pm 0.01$ fm	0.75	$\delta = 1.80^{+0.2}_{-0.3}$ fm

Di Mauro, **JK**, Stefanuto, Bellini, Donato, Fornengo, arXiv:2603.19352, accepted in *Phys.Rev.D*

Antinucleon production

DM annihilation ($b\bar{b}$ channel)



Antinucleon production

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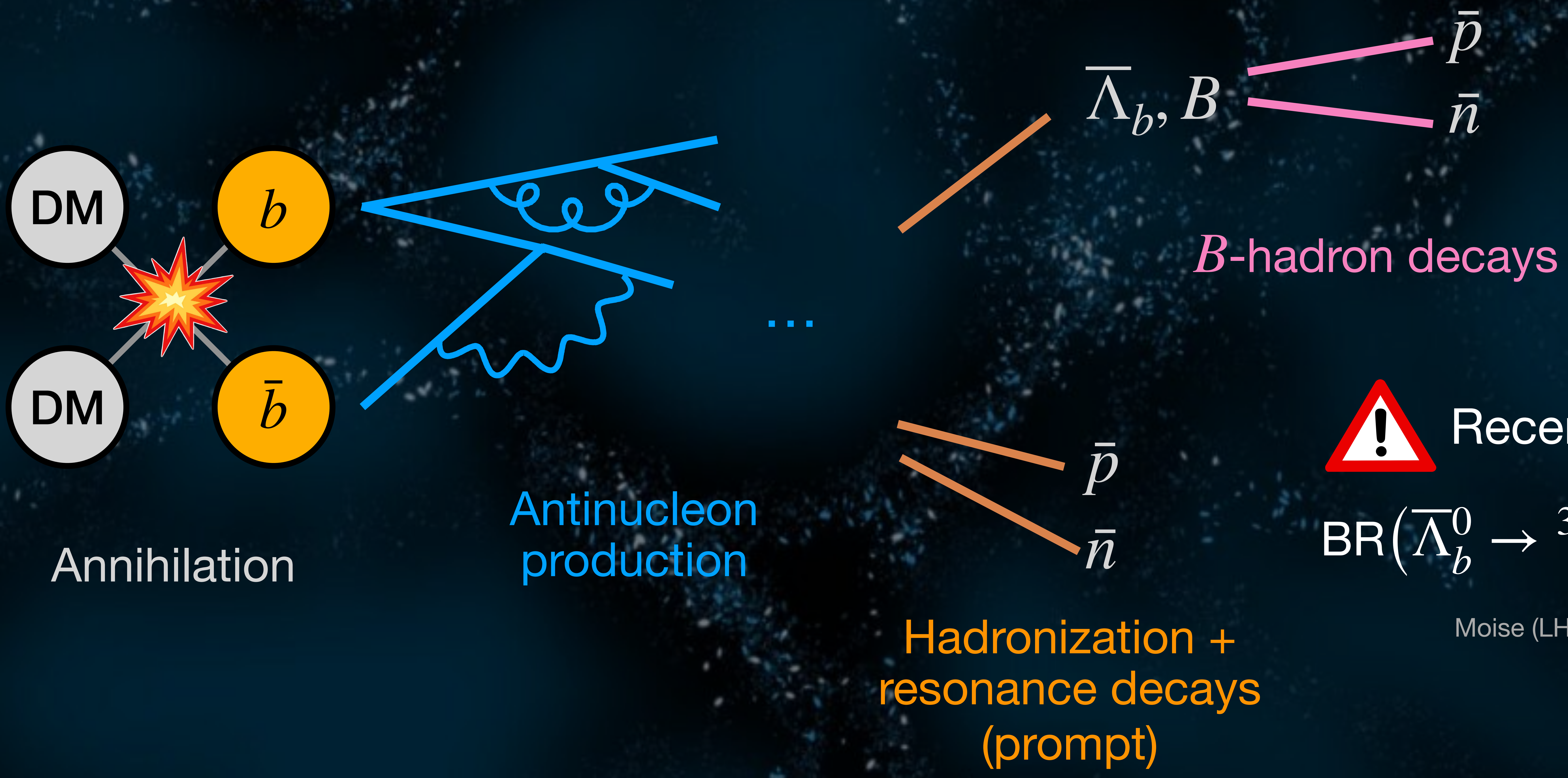


Recent (2024) LHCb limit

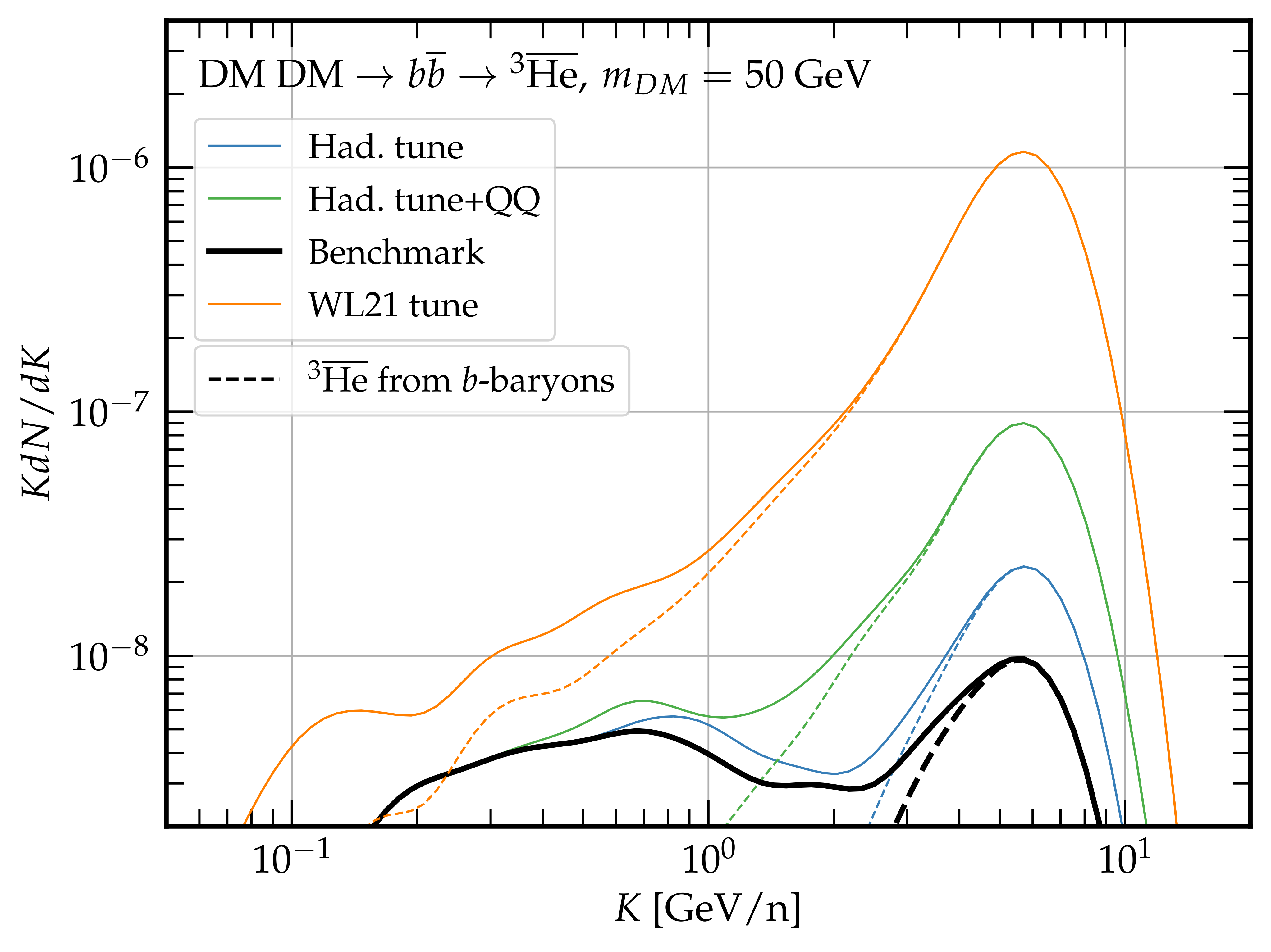
$$\mathrm{BR}\left(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X\right) < 6.3 \times 10^{-8}$$

Moise (LHCb coll.), *PoS* ICHEP2024 (2025) 676

Antinuclei production

DM annihilation ($b\bar{b}$ channel)

$^3\overline{\text{He}}$ spectrum from DM annihilation



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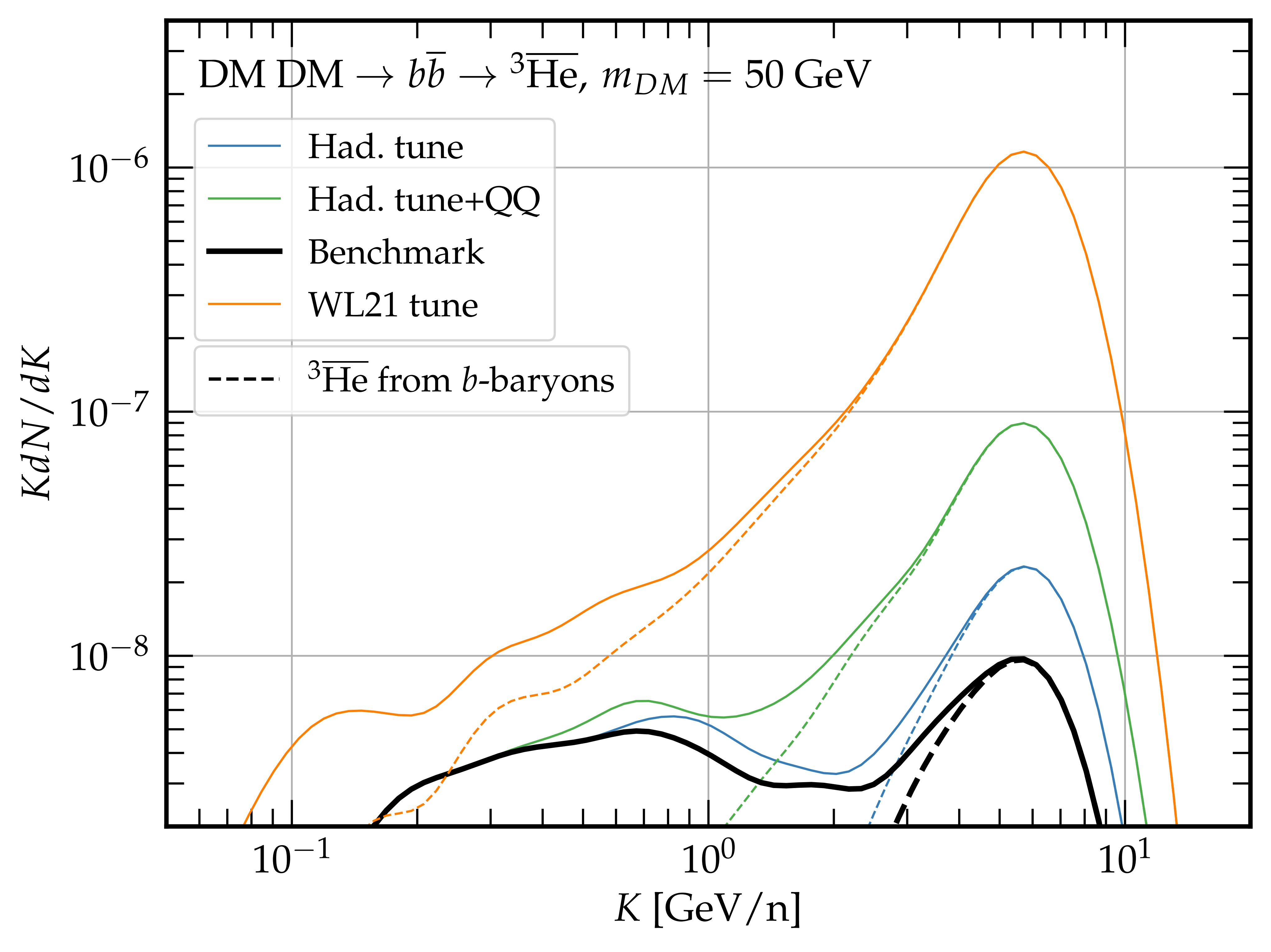
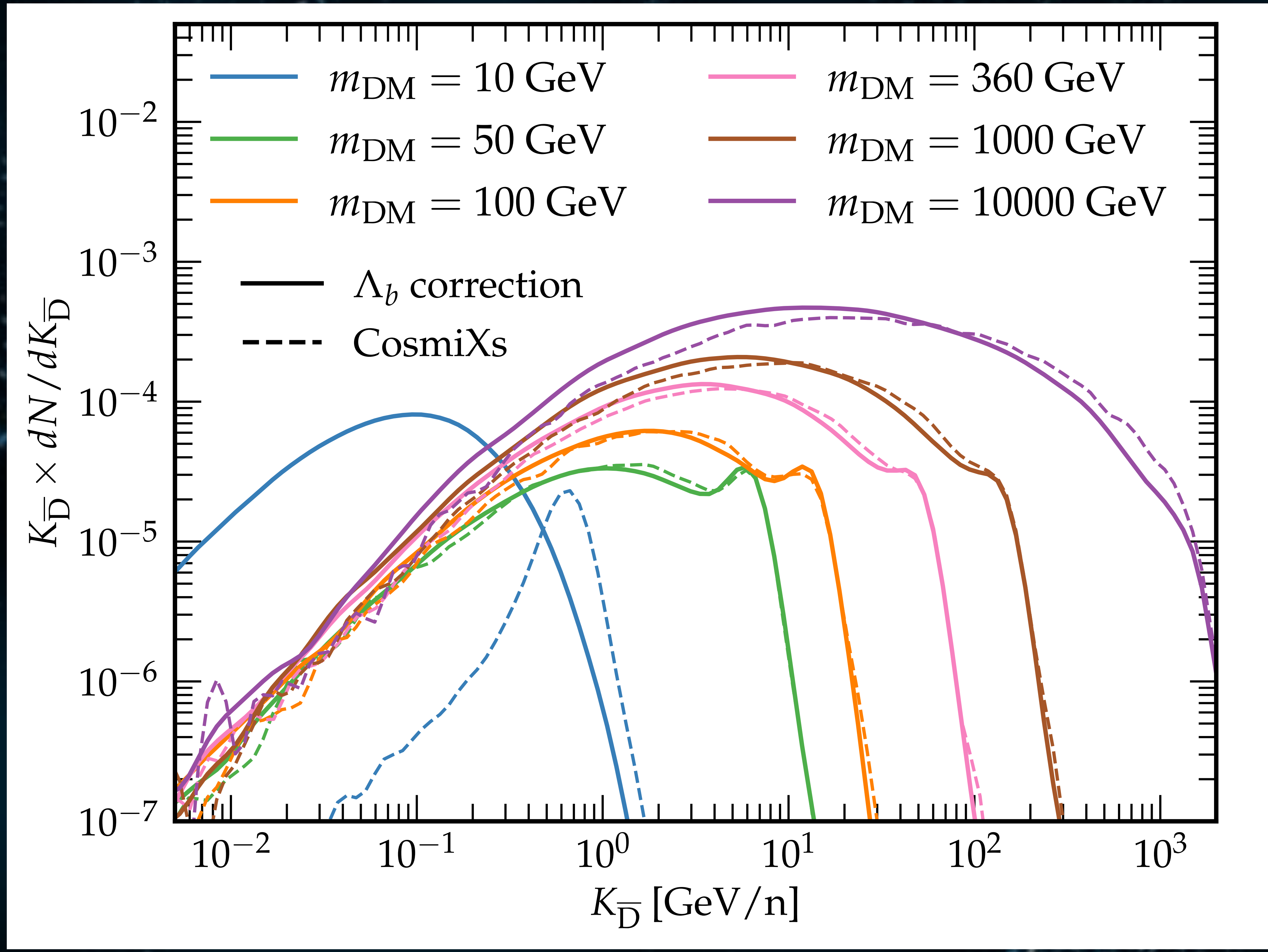


$\overline{\mathrm{D}}$ spectrum (Λ_b tuning vs CosmiXs)



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AMS-02 antiproton upper limits

CR propagation w/ USINE, using BIG/QUAINT models

Maurin, *Comput.Phys.Commun.* 247 (2020) 106942 Génolini et al., *Phys.Rev.D* 99 (2019) 12, 123028

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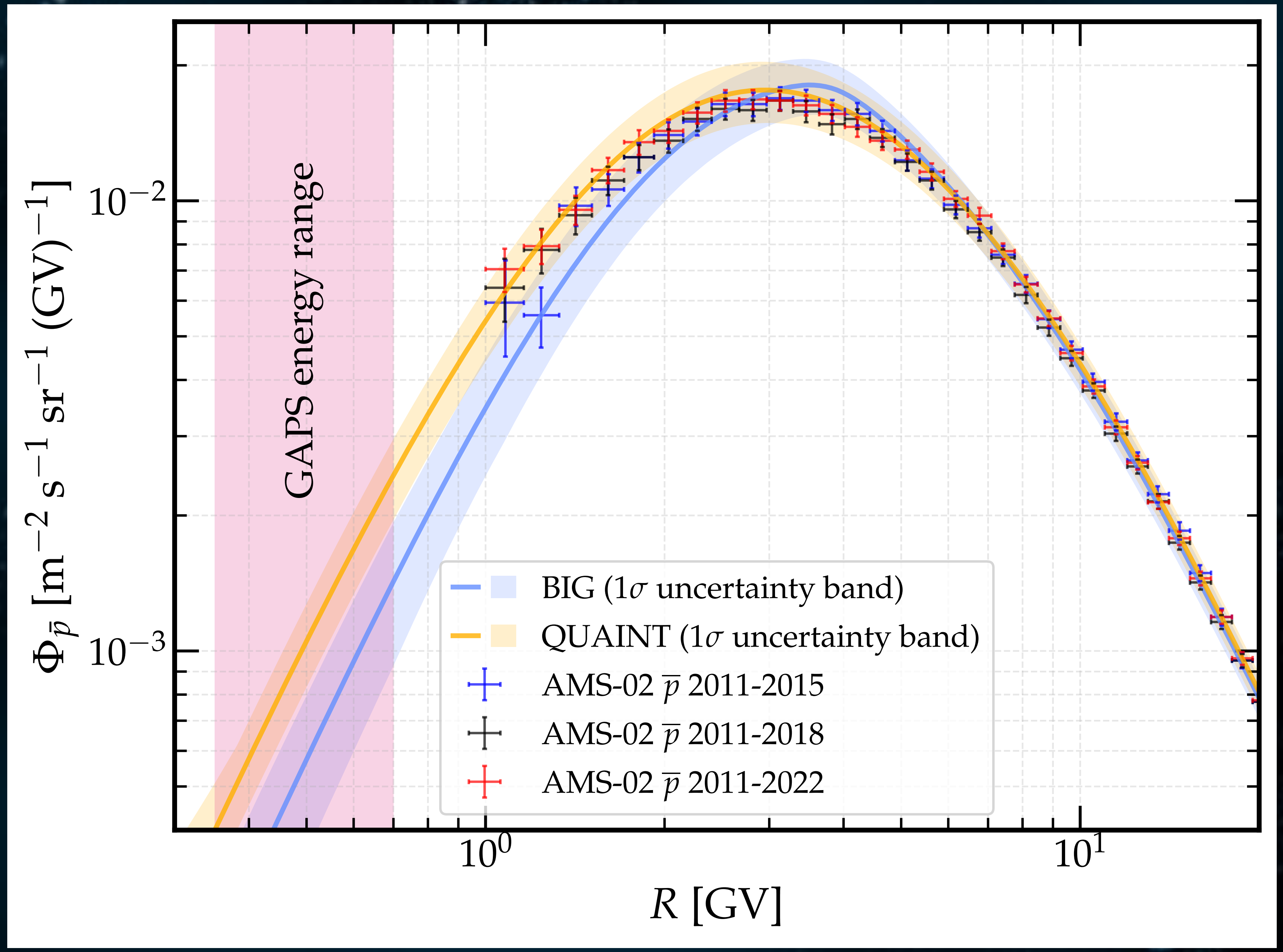

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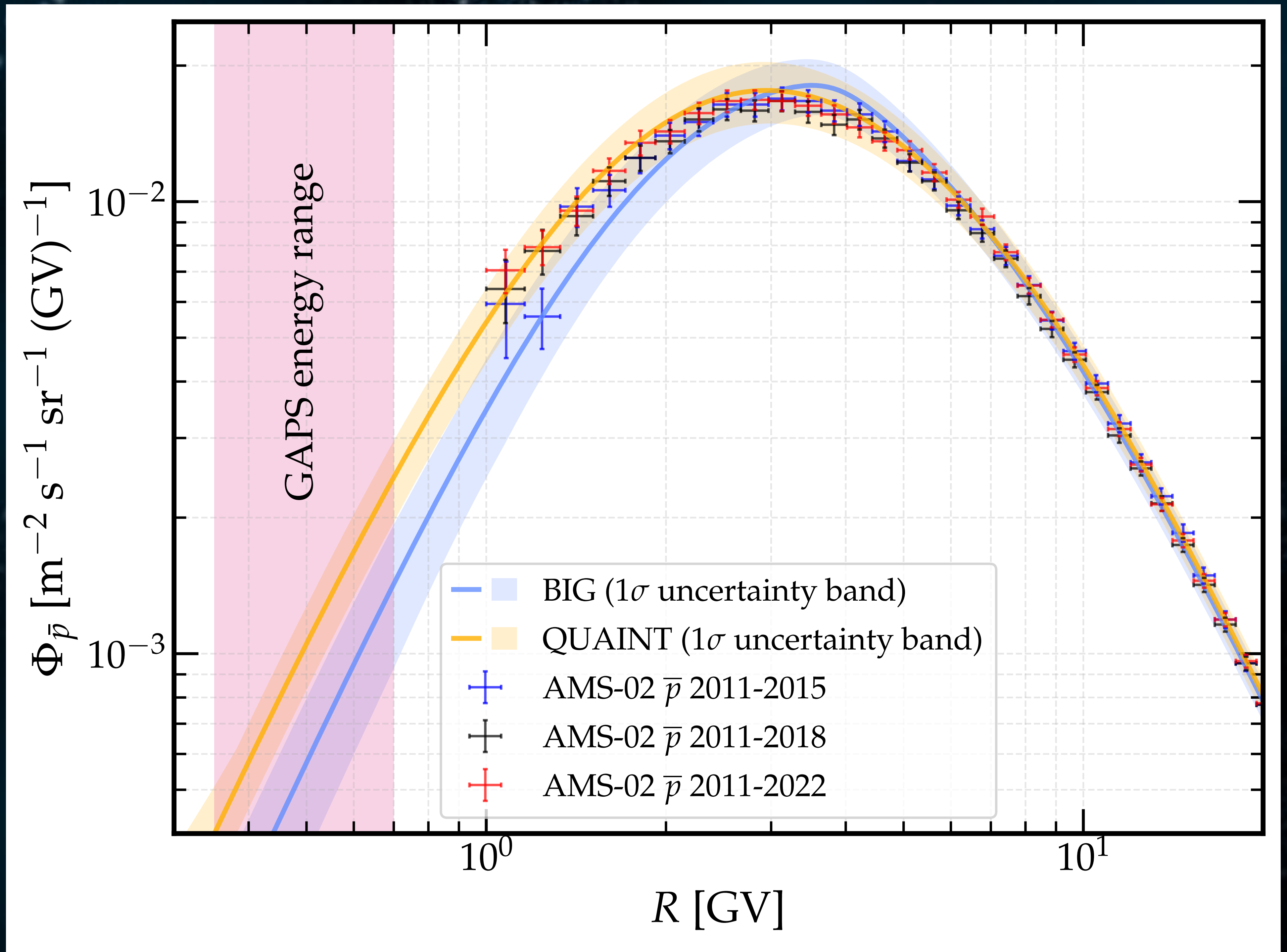

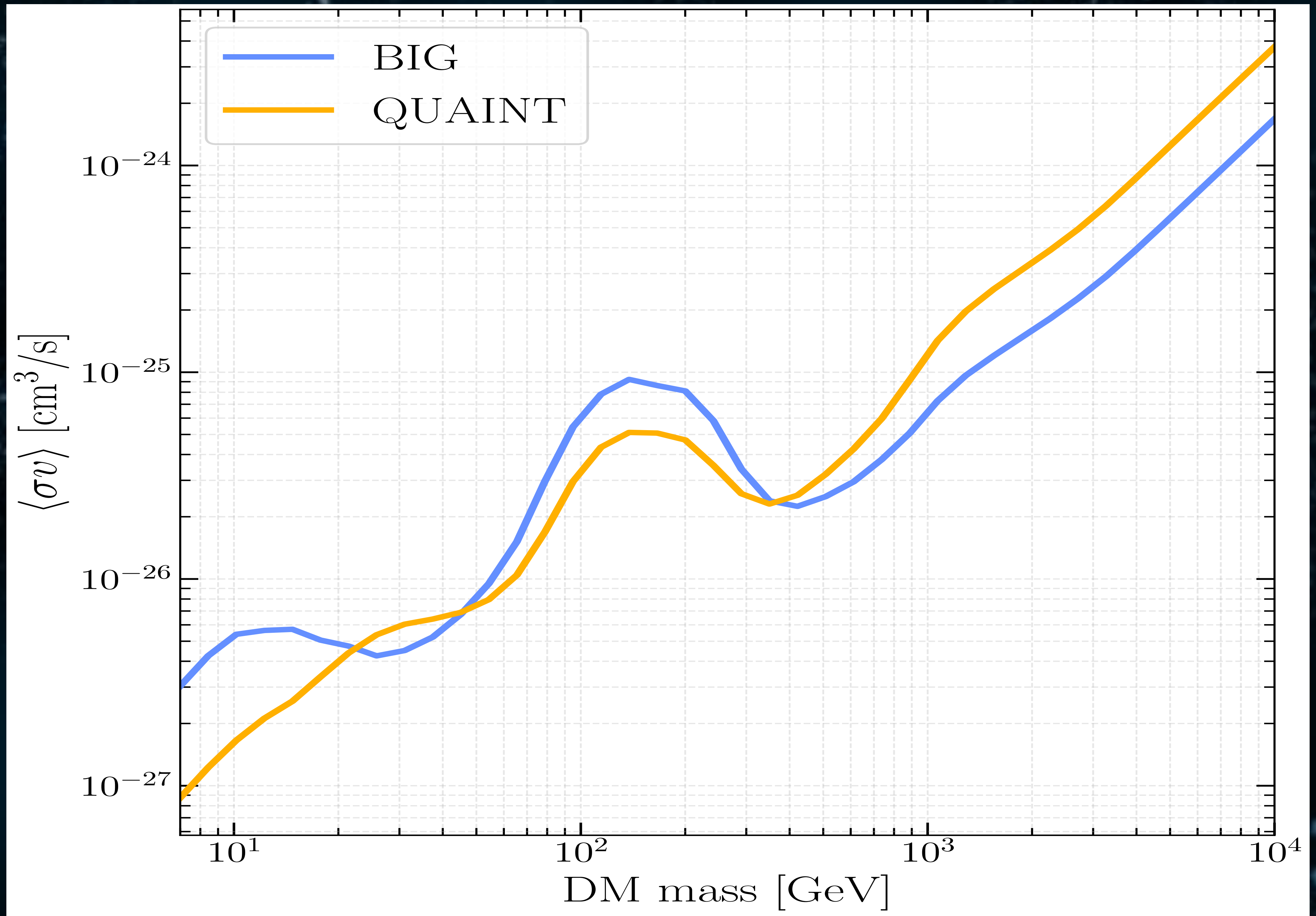

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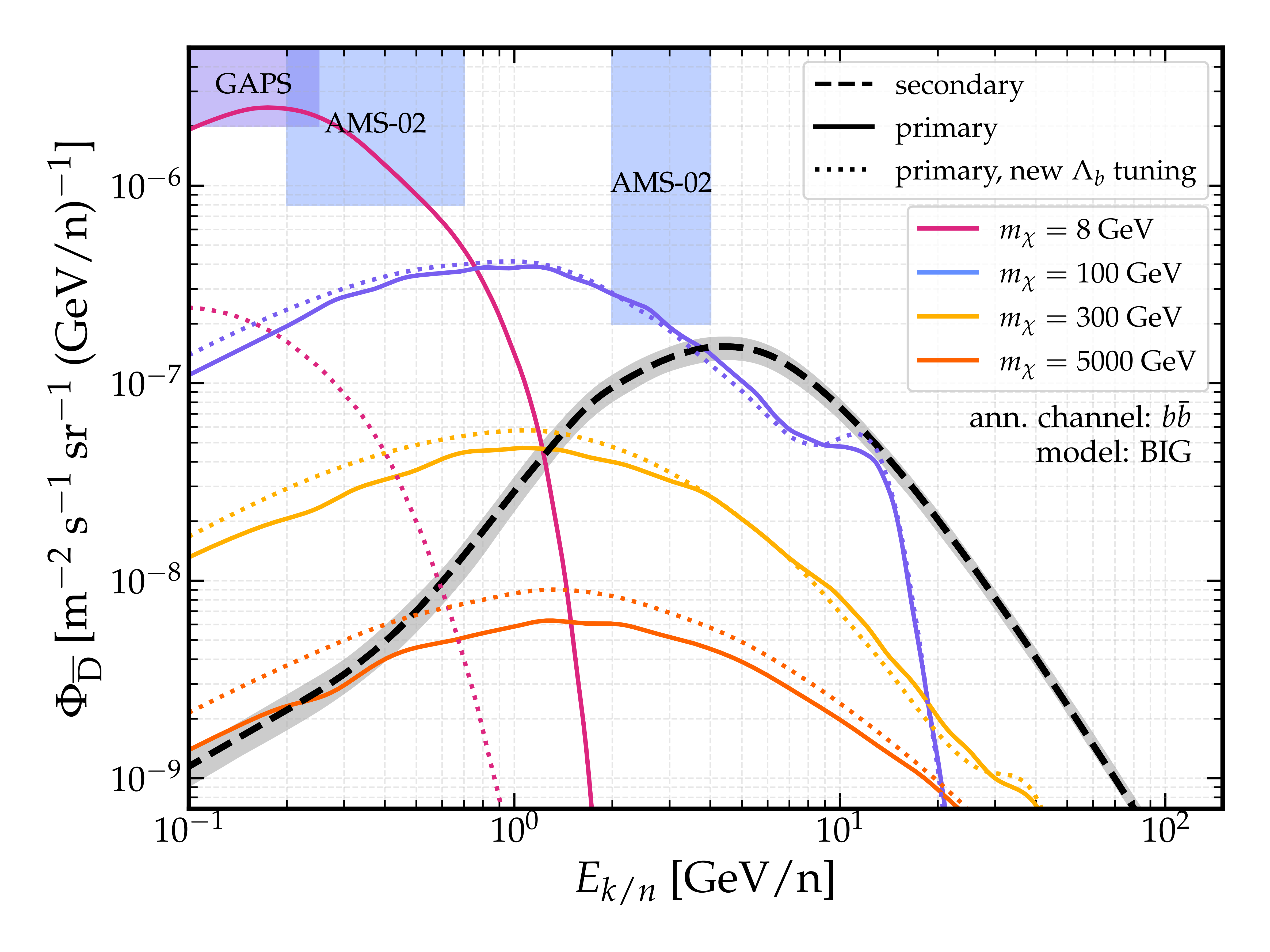
Antideuteron flux at Earth



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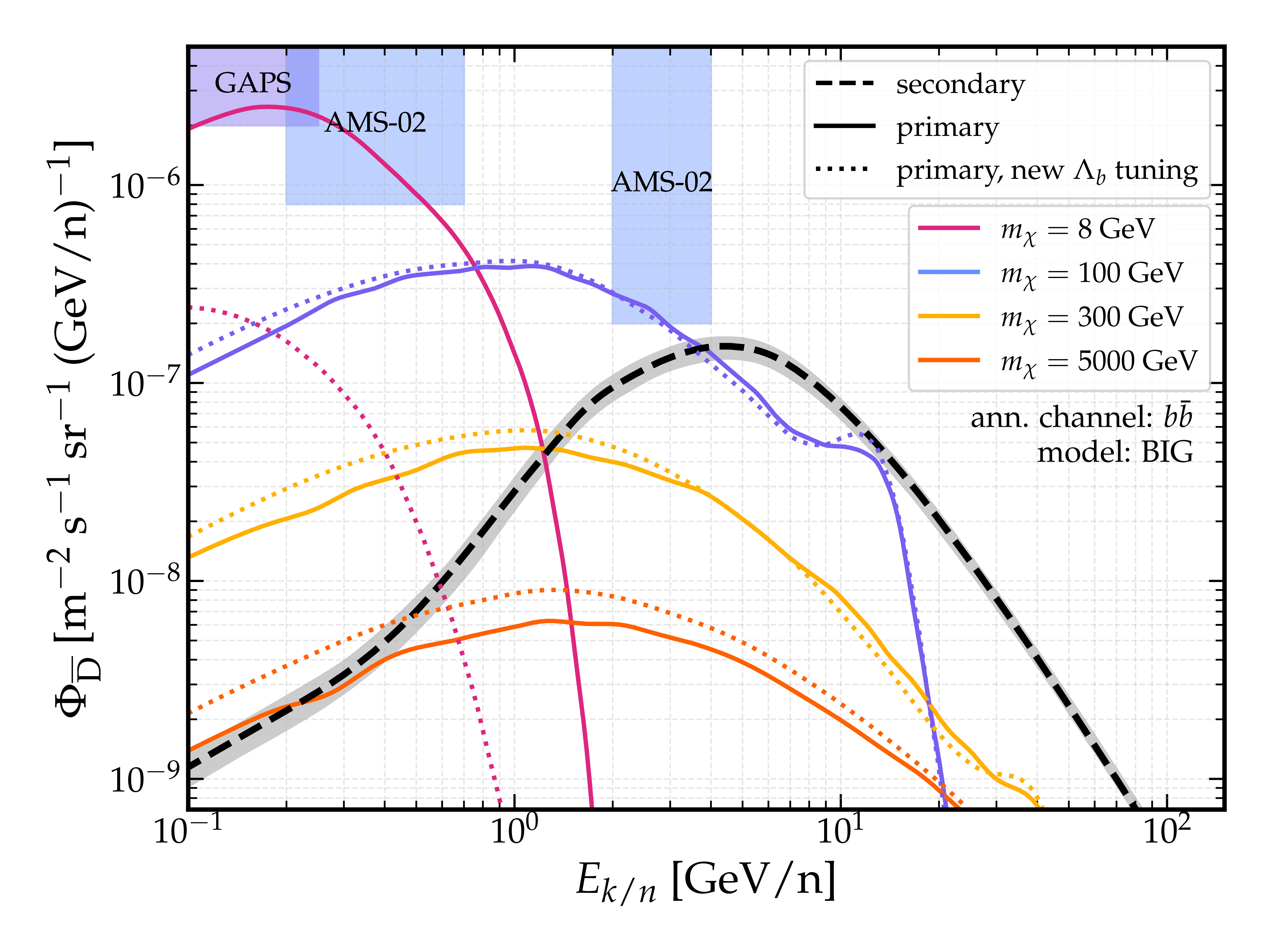

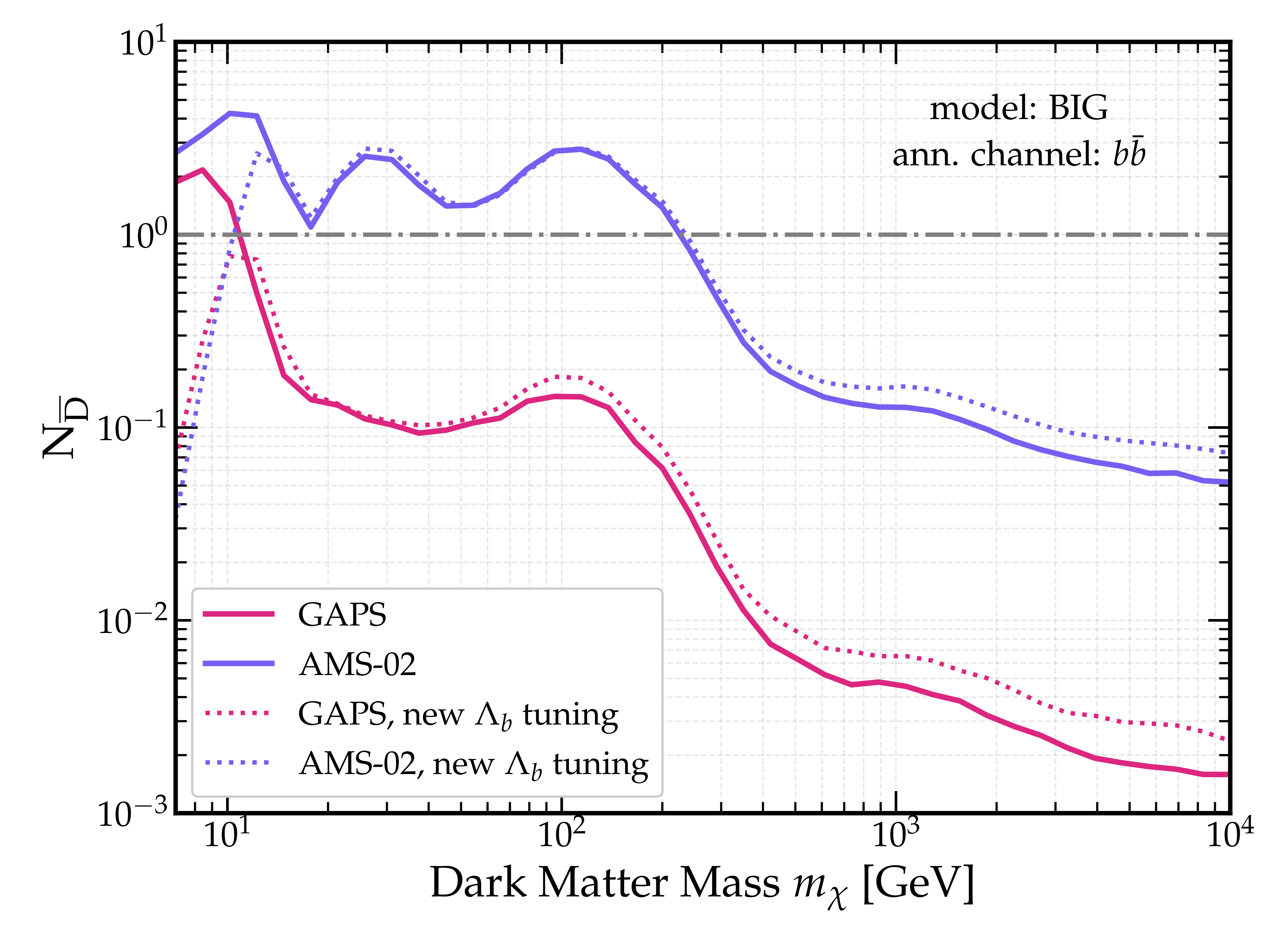

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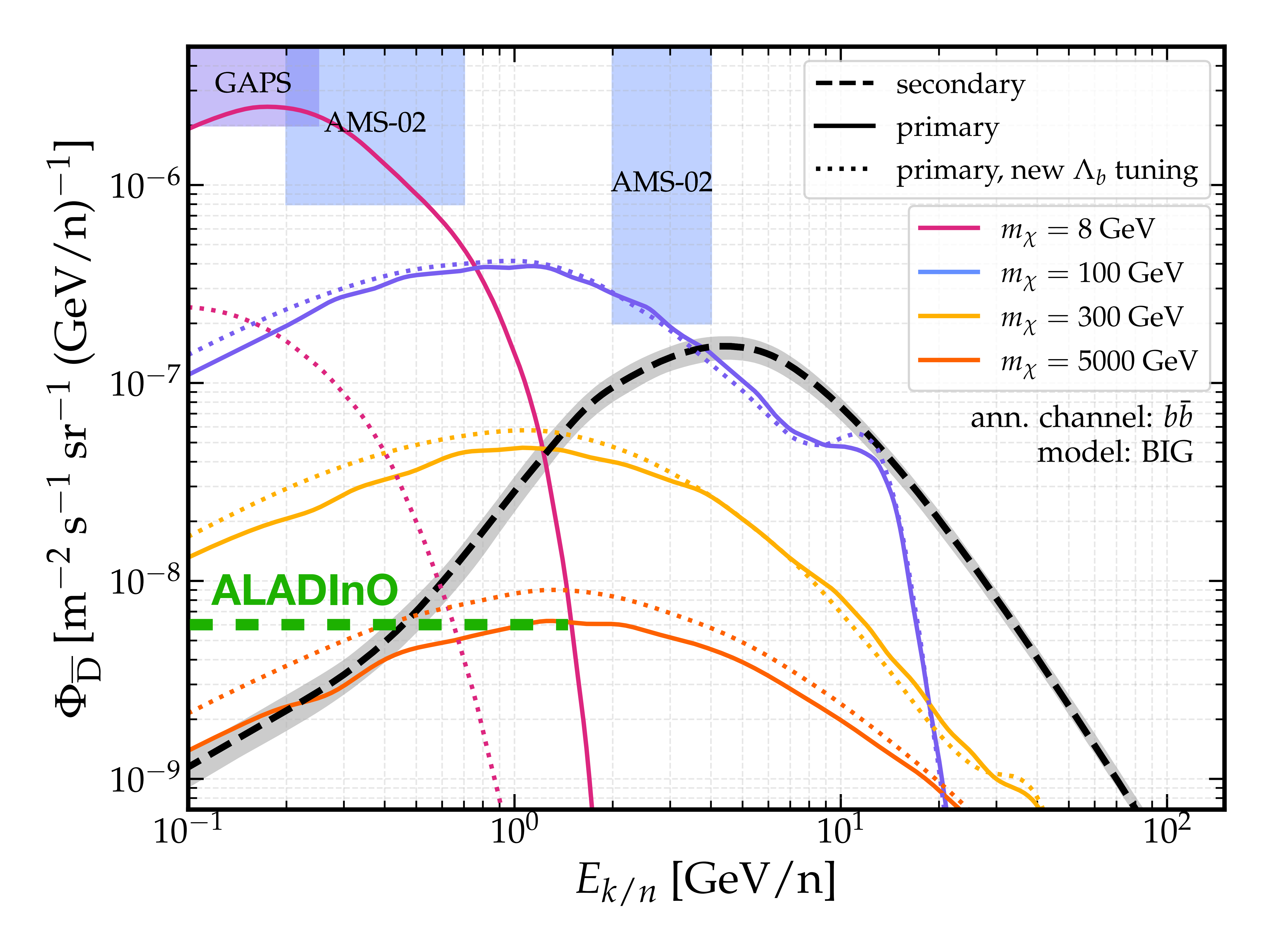
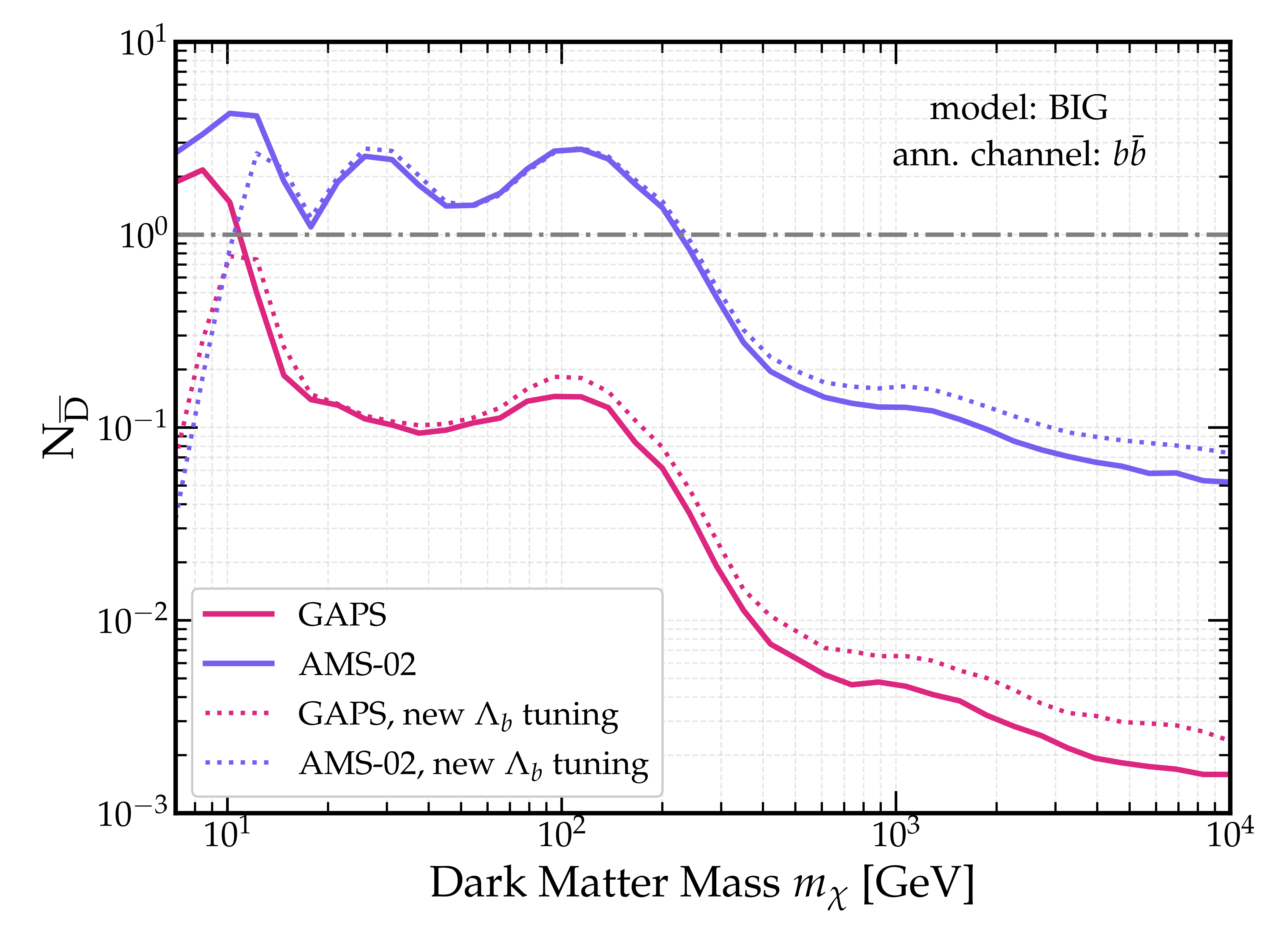
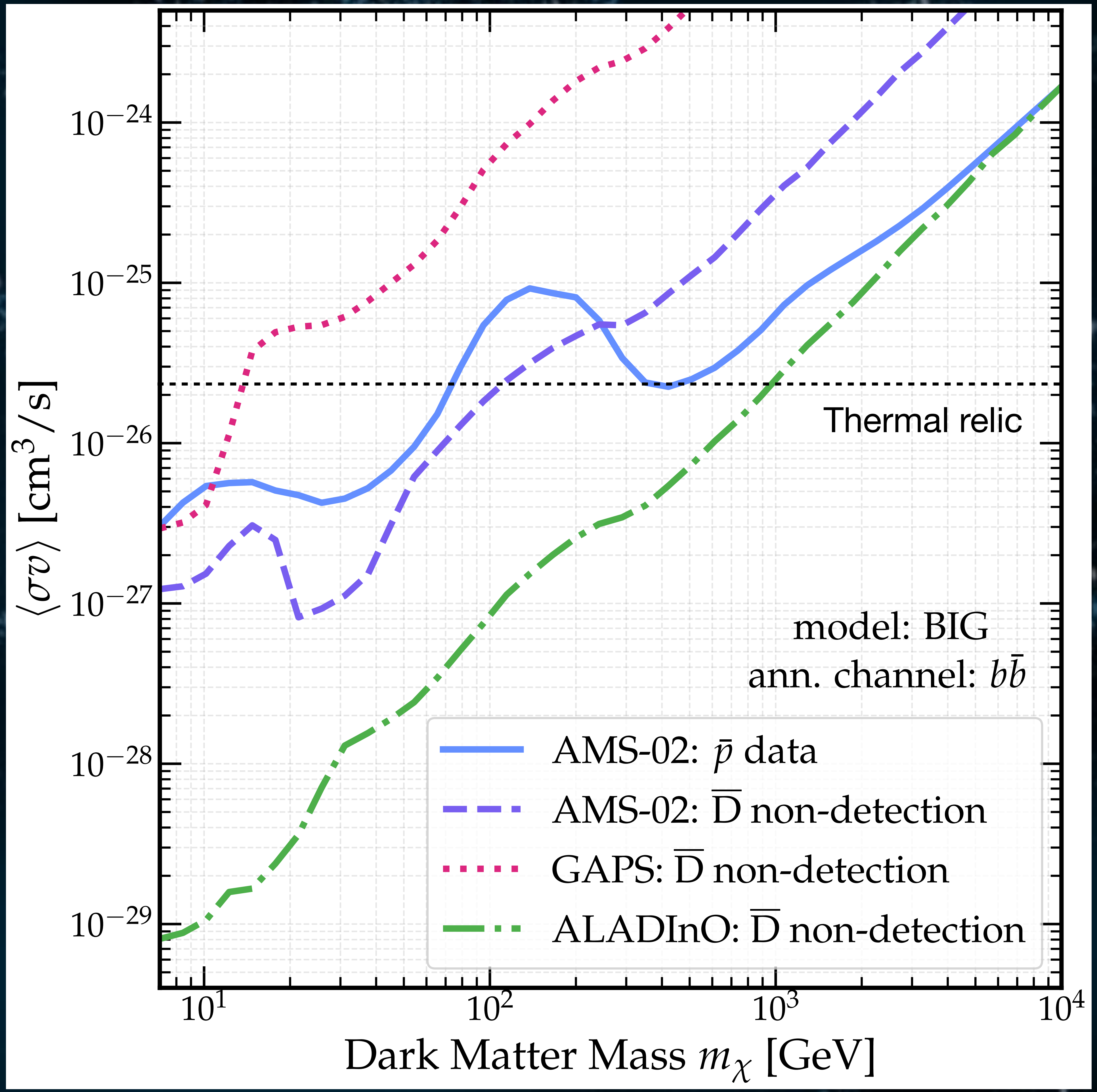
Antideuteron flux at Earth





Stefanuto, Di Mauro, Donato, Fornengo, **JK**, Maurin, arXiv:2605.08338, submitted to *Phys.Rev.D*

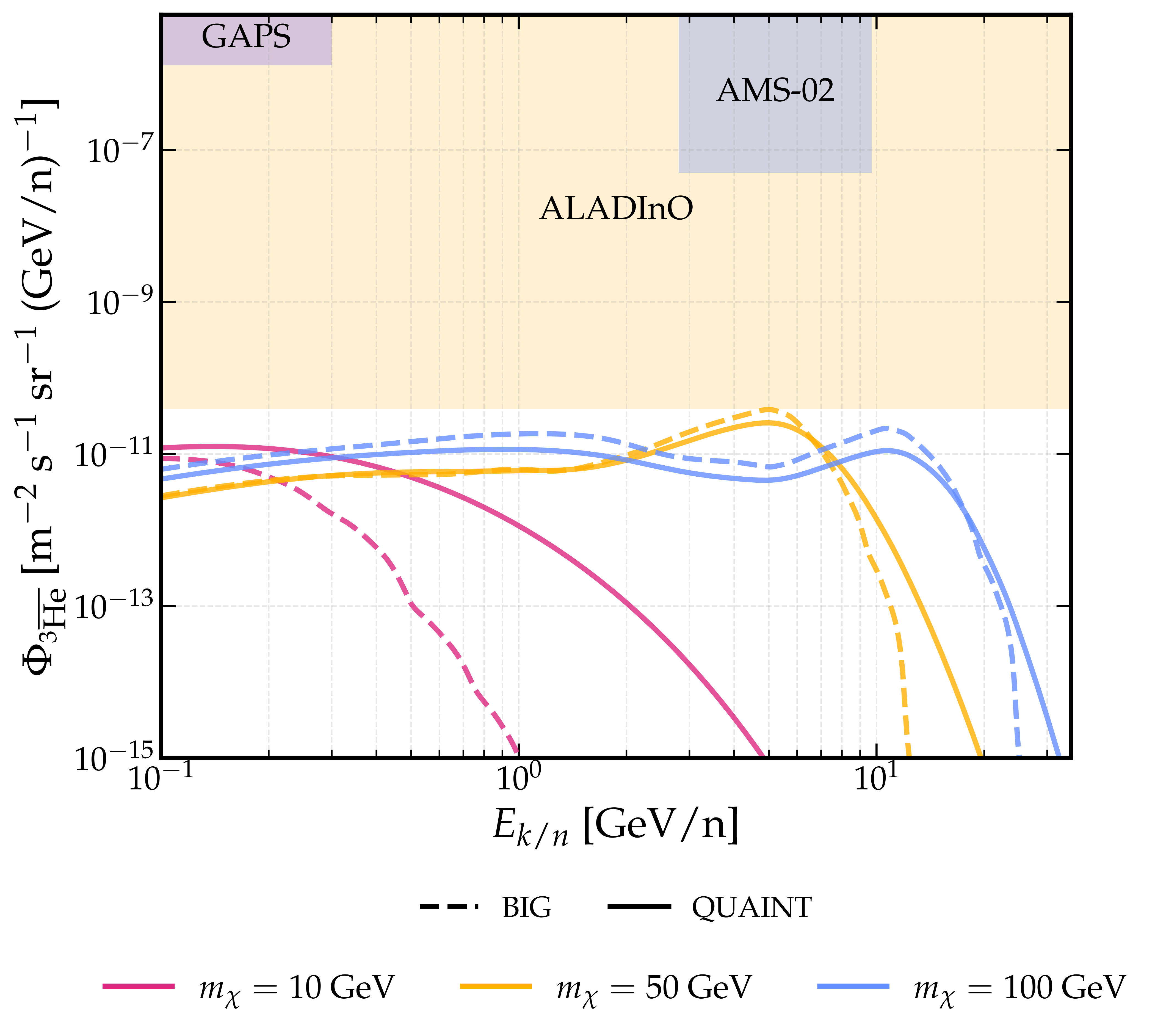
Antideuteron upper limits on DM



An ALADInO-like exp. could help us probe the remaining open window for WIMPs…

Stefanuto, Di Mauro, Donato, Fornengo, **JK**, Maurin, arXiv:2605.08338, submitted to *Phys.Rev.D*

Antihelion-3 flux at Earth



This excludes also the DM interpretation of the '$\overline{He}$ excess' reported in a few talks by AMS…

S. Ting, CERN (2016)
P. Zuccon, MIAPP (2022)

Stefanuto, Di Mauro, Donato, Fornengo, **JK**, Maurin, arXiv:2605.08338, submitted to *Phys.Rev.D*

Summary

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Summary

- Cosmic-ray antinuclei detection are among the most promising avenues to probe dark matter particles
- The astrophysical background for $\overline{\mathrm{D}}$ is well predicted, and orders of magnitude below a potential signal from DM annihilation
- The theoretical uncertainties coming from the choice of the coalescence model are negligible compared to the ones related to the DM density distribution and propagation models
- AMS-02 and GAPS could in principle detect a couple of $\overline{\mathrm{D}}$ from DM. But a new detector like ALADInO could probe the remaining open window for WIMPs

Backup

Antinucleon production

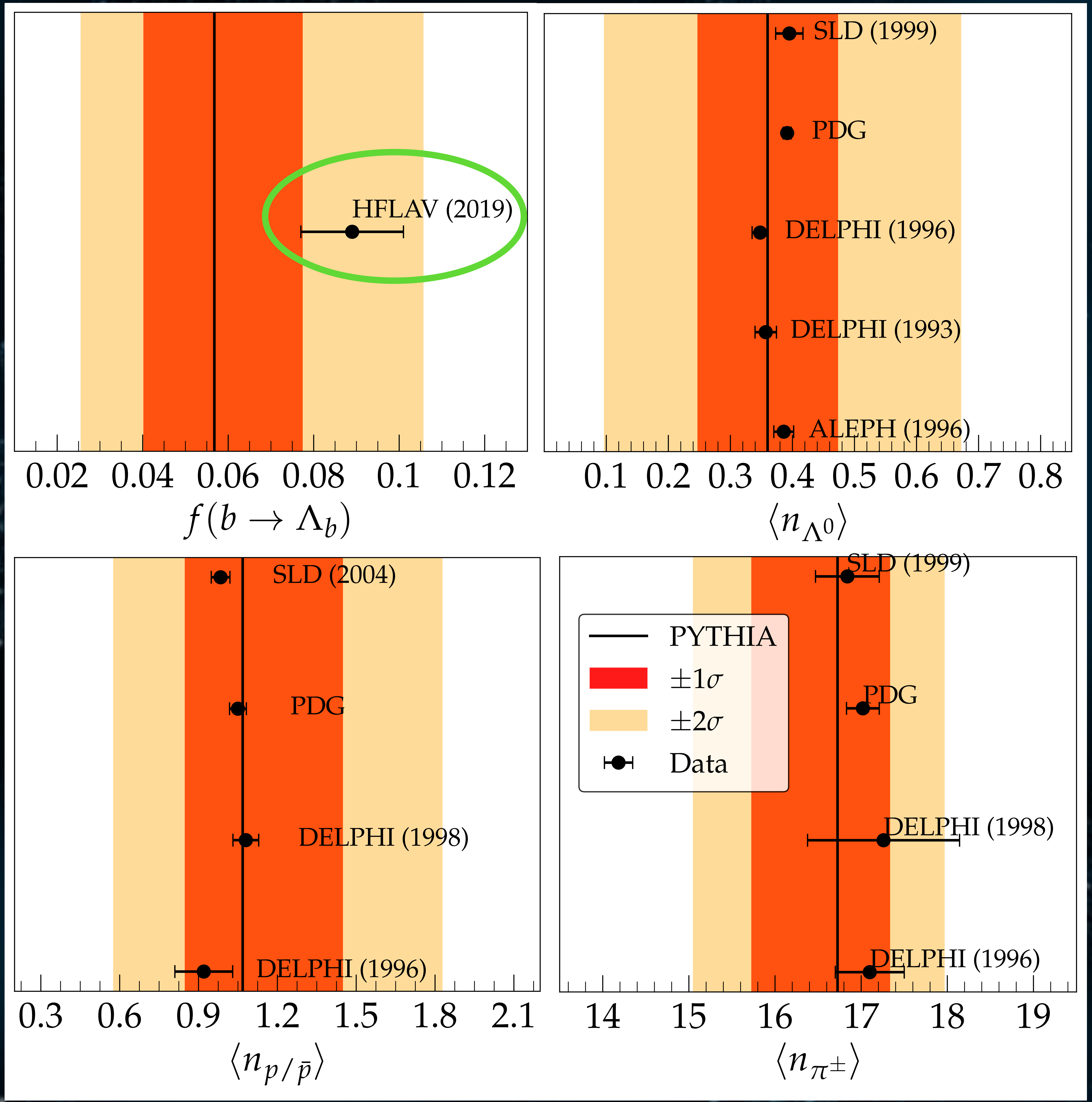
DM annihilation ($b\bar{b}$ channel)

Good enough for prompt antinucleons
Refinement needed for B-hadron production

Parameter	Range	Monash	Had. tune
StringZ:aLund	0.0 – 2.0	0.68	0.7832 ± 0.0123
StringZ:bLund	0.2 – 2.0	0.98	1.1729 ± 0.0100
StringZ:aExtraDiquark	0.0 – 2.0	0.97	0.9251 ± 0.0175
StringFlav:ProbStoUD	0.0 – 1.0	0.217	0.2265 ± 0.0016
StringFlav:mesonUDvector	0.0 – 3.0	0.50	0.6655 ± 0.0152
StringFlav:mesonSvector	0.0 – 3.0	0.55	0.5842 ± 0.0177
StringFlav:etaSup	0.0 – 1.0	0.60	0.6499 ± 0.0005
StringFlav:etaPrimeSup	0.0 – 1.0	0.12	0.1778 ± 0.0037
StringFlav:probQQtoQ	0.0 – 1.0	0.081	0.1112 ± 0.0008
StringFlav:probSQtoQQ	0.0 – 1.0	0.915	0.9791 ± 0.0061
StringFlav:probQQ1toQQ0	0.0 – 1.0	0.0275	0.8761 ± 0.0171
StringFlav:popcornSpair	0.0 – 1.0	0.50	0.6108 ± 0.0241
StringFlav:popcornSmeson	0.0 – 1.0	0.90	0.8306 ± 0.0231
StringFlav:popcornRate	0.0 – 1.0	0.50	0.4117 ± 0.0055

Di Mauro, Jueid, **JK**, Ruiz de Austri, *Phys.Rev.D* 112 (2025) 083017

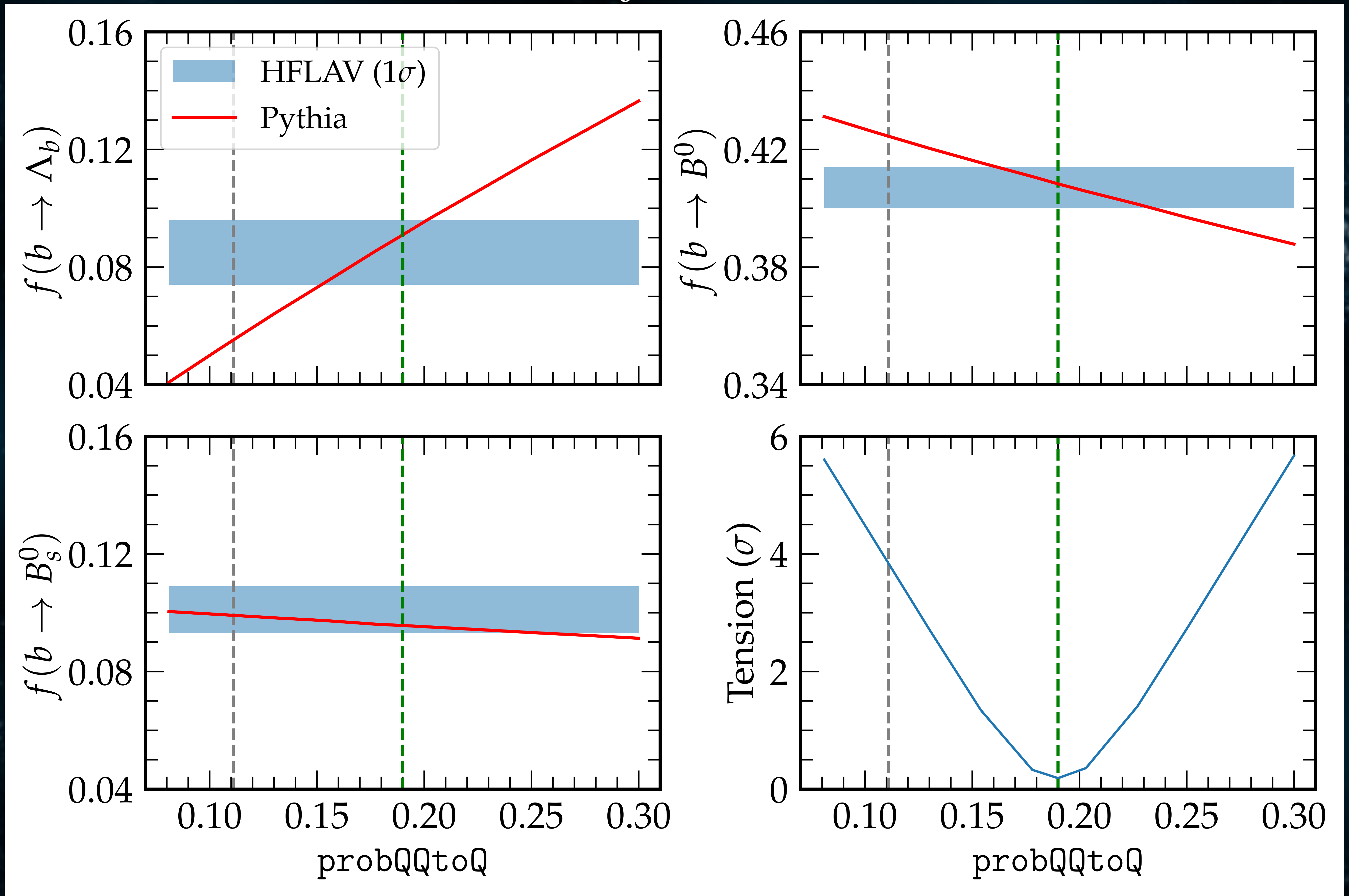
Fit over 4185 bins! $(\chi^2/N_{\rm dof} \approx 1.18)$



Antinucleon production

DM annihilation ($b\bar{b}$ channel)

Refinement of $f(b \to B\text{-hadrons})$



Di Mauro, Jueid, **JK**, Ruiz de Austri, *Phys.Rev.D* 112 (2025) 083017

Refinement of $\text{BR}(\overline{\Lambda}_b^0 \to {}^3\overline{\text{He}}X)$

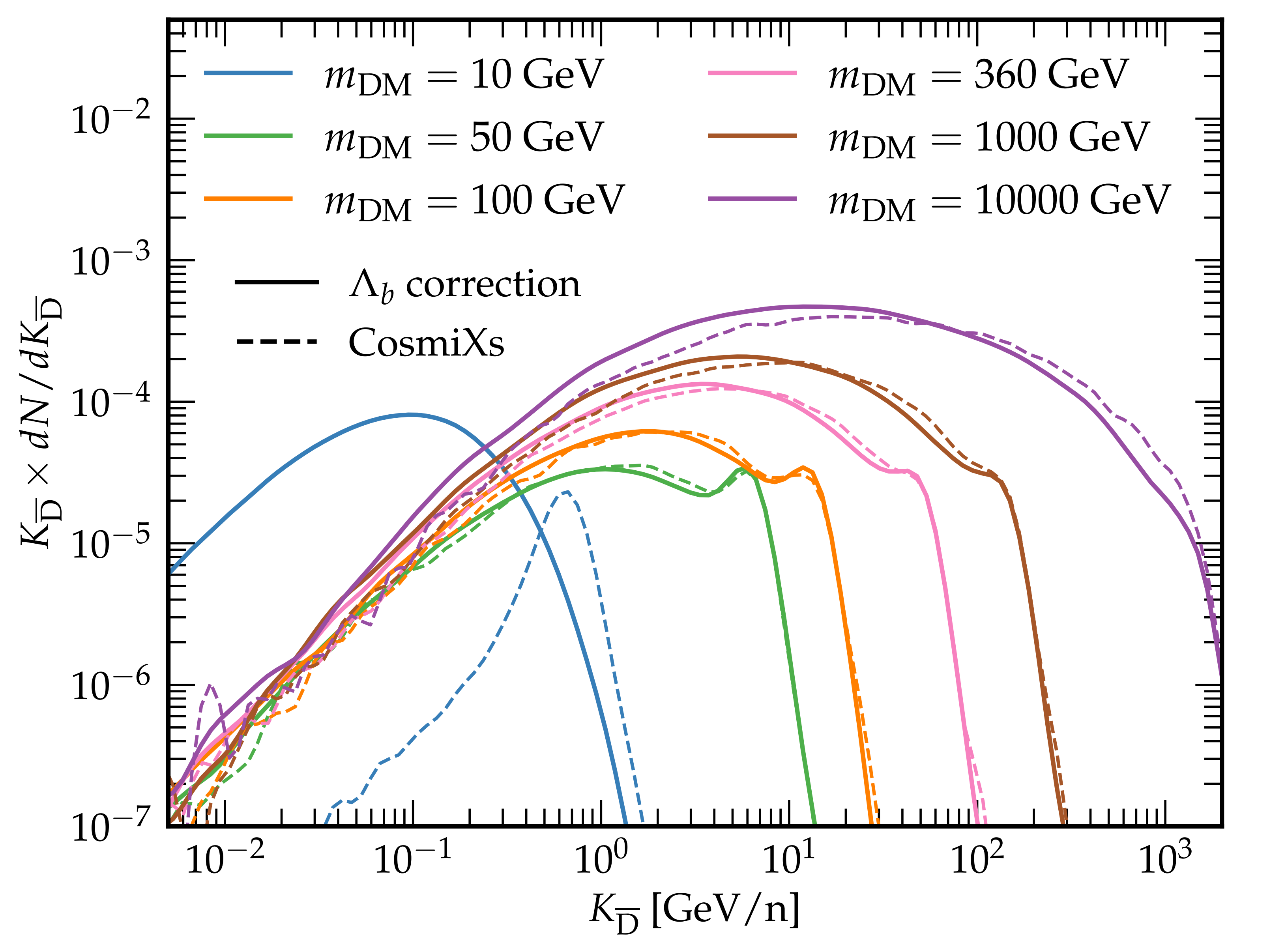
Λ_b^0 decay mode	Default Pythia	Tuned Pythia
$\overline{u}du(ud)_0$	0.012	0.001
$\overline{u}dc(ud)_0$	0.5321147	0.5321147
$\overline{c}su(ud)_0$	0.012	0
$\overline{c}sc(ud)_0$	0.08	0.103

$\bar{\Lambda}_b^0$ decay mode	Measured BR	Benchmark
$\Lambda_c^- \ell^+ \nu_\ell$	$(6.2^{+1.4}_{-1.3})\%$	$(5.957 \pm 0.001)\%$
$\bar{p}\overline{D}^0\pi^+$	$(6.2 \pm 0.6) \times 10^{-4}$	$(6.64 \pm 0.01) \times 10^{-4}$
$\bar{p}D^-\pi^-\pi^+$	$(2.7 \pm 0.4) \times 10^{-4}$	$(2.215 \pm 0.006) \times 10^{-4}$
$\bar{p}\pi^+$	$(4.6 \pm 0.8) \times 10^{-6}$	$(1.41 \pm 0.02) \times 10^{-5}$
$\Lambda_c^- K^+ K^- \pi^+$	$(1.02 \pm 0.11) \times 10^{-3}$	$(1.354 \pm 0.002) \times 10^{-3}$
$\Lambda_c^- p\bar{p}\pi^+$	$(2.63 \pm 0.23) \times 10^{-4}$	$(4.615 \pm 0.009) \times 10^{-4}$
$\bar{p}\bar{n}X$	–	$(6.56 \pm 0.01) \times 10^{-4}$
$\bar{p}\bar{p}\bar{n}X$	–	$(2.4 \pm 0.3) \times 10^{-7}$
${}^3\overline{\text{He}}X$	$< 6.8 \times 10^{-8}$	$(7 \pm 1) \times 10^{-8}$

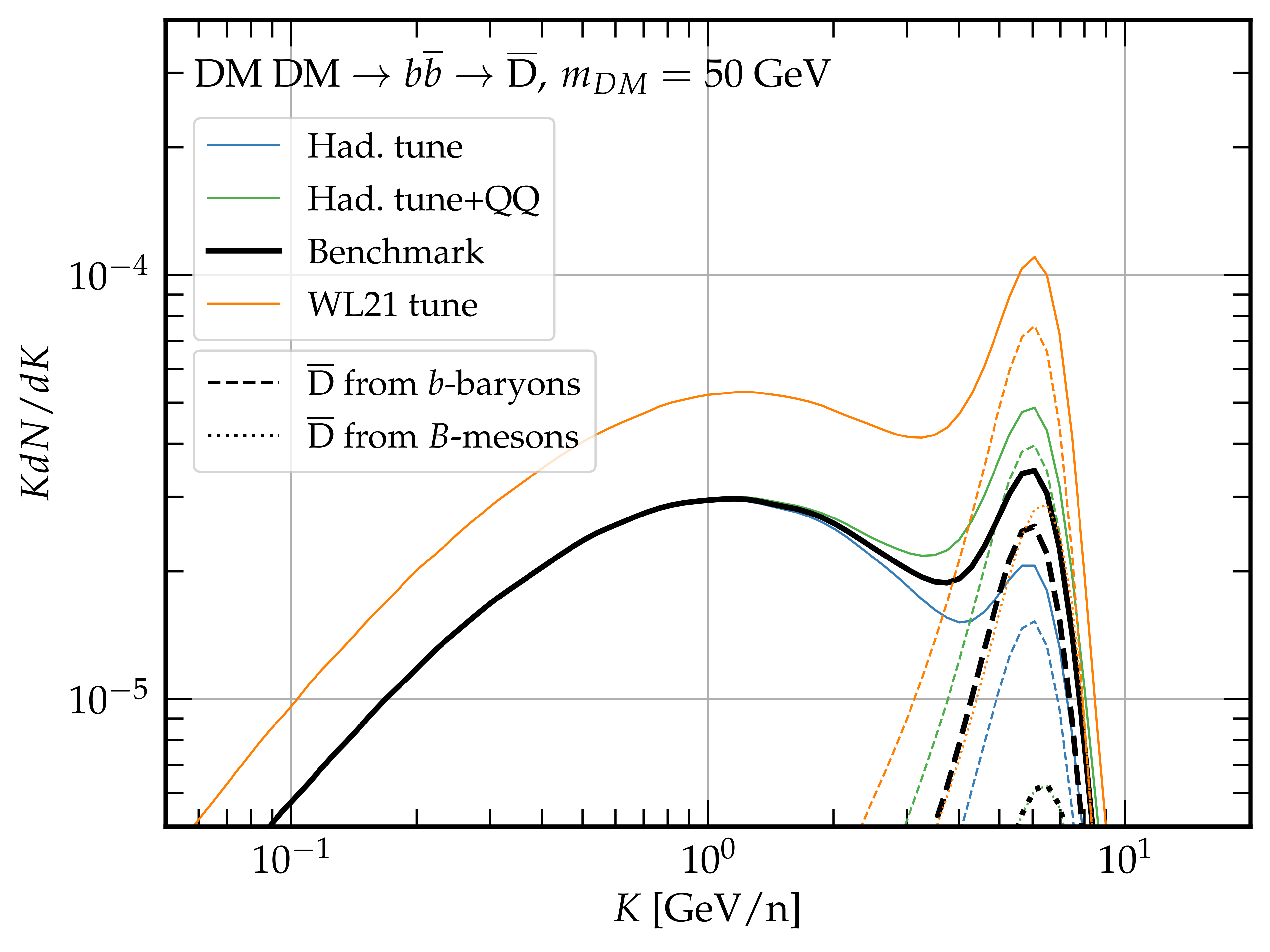
Antinuclei production

DM annihilation ($b\bar{b}$ channel)

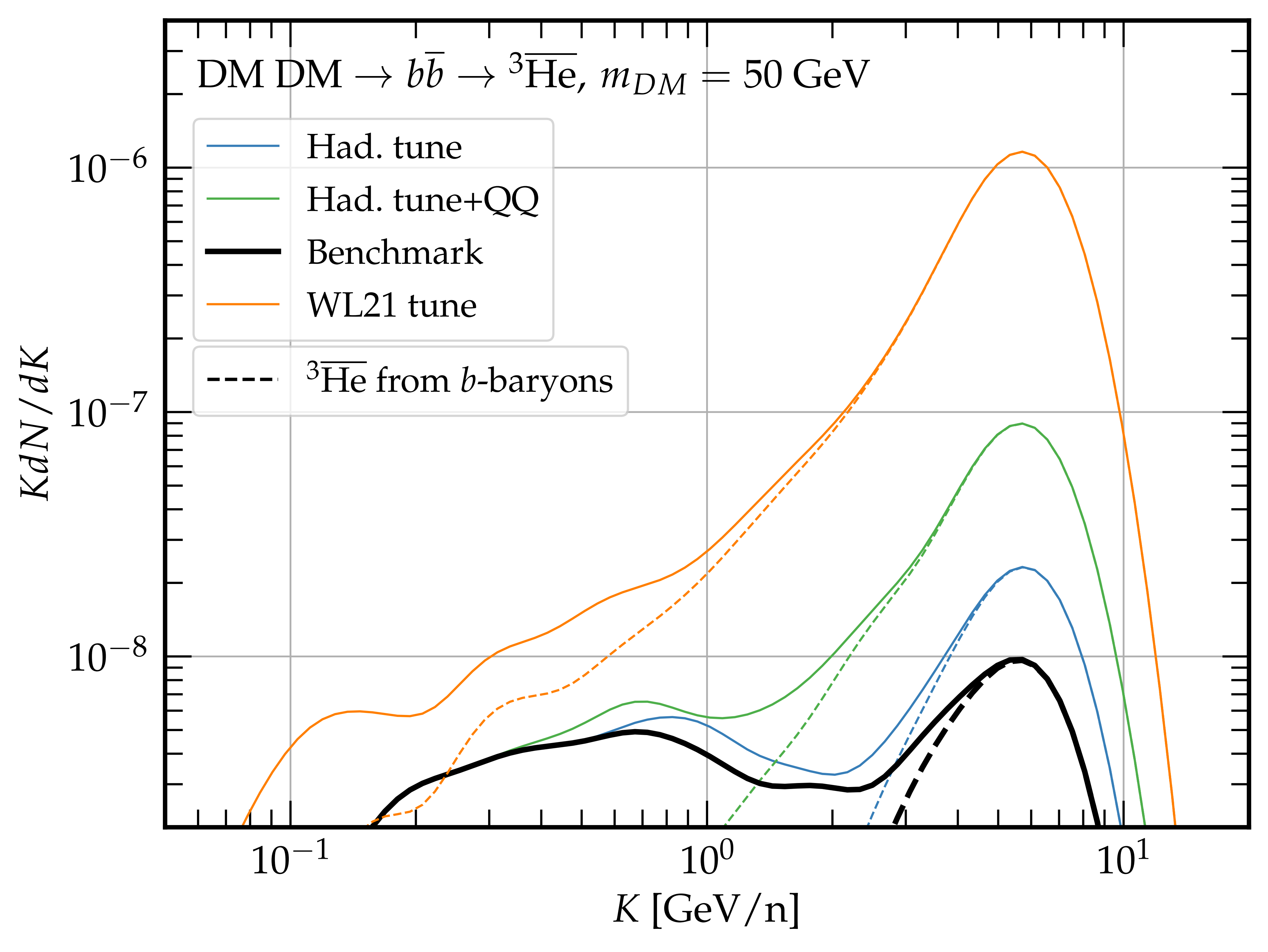
$\overline{\mathrm{D}}$ spectrum vs CosmiXs



DM annihilation $\overline{\mathrm{D}}$ spectrum



$^3\overline{\mathrm{He}}$ spectrum



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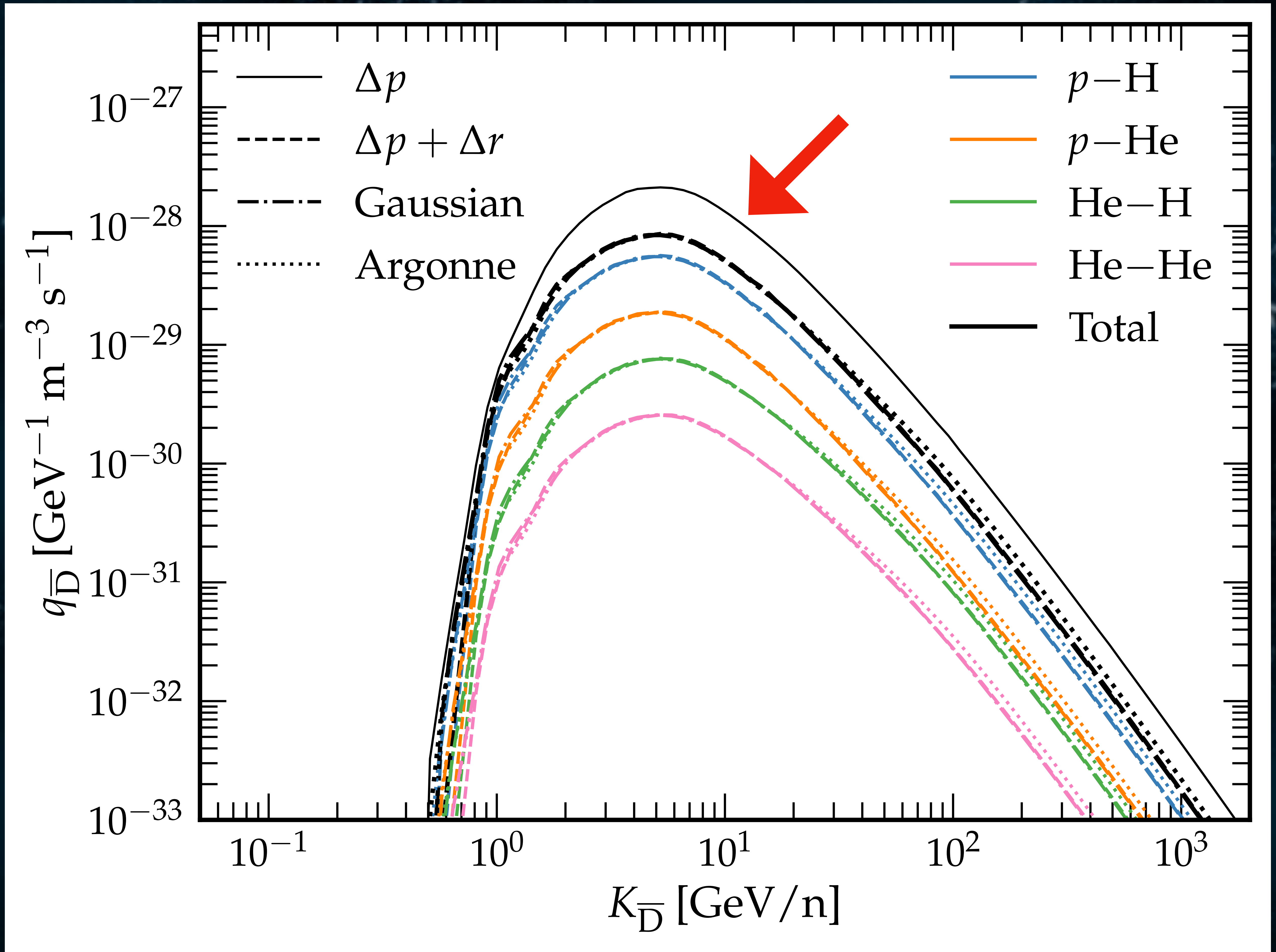
Careful when using the Δp model…

Source term for secondary $\overline{\mathrm{D}}$



Di Mauro, **JK**, Stefanuto, Bellini, Donato, Fornengo, arXiv:2603.19352, accepted in *Phys.Rev.D*

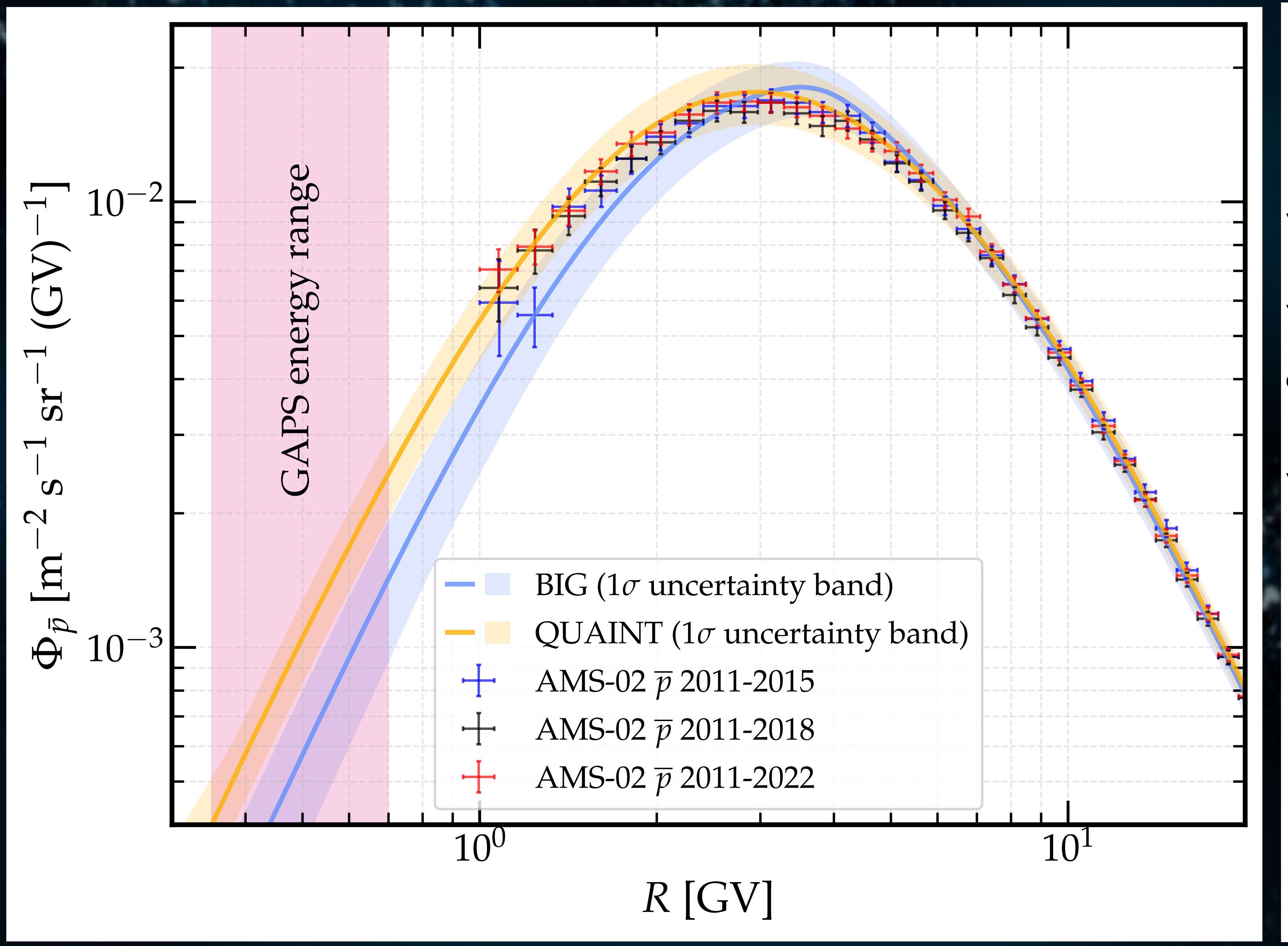
$$\sigma^{\mathrm{inel}}_{\mathrm{proj,targ}} \sim \sigma^{\mathrm{inel}}_{pp} \left(A_{\mathrm{proj}} A_{\mathrm{targ}} \right)^{0.8}$$

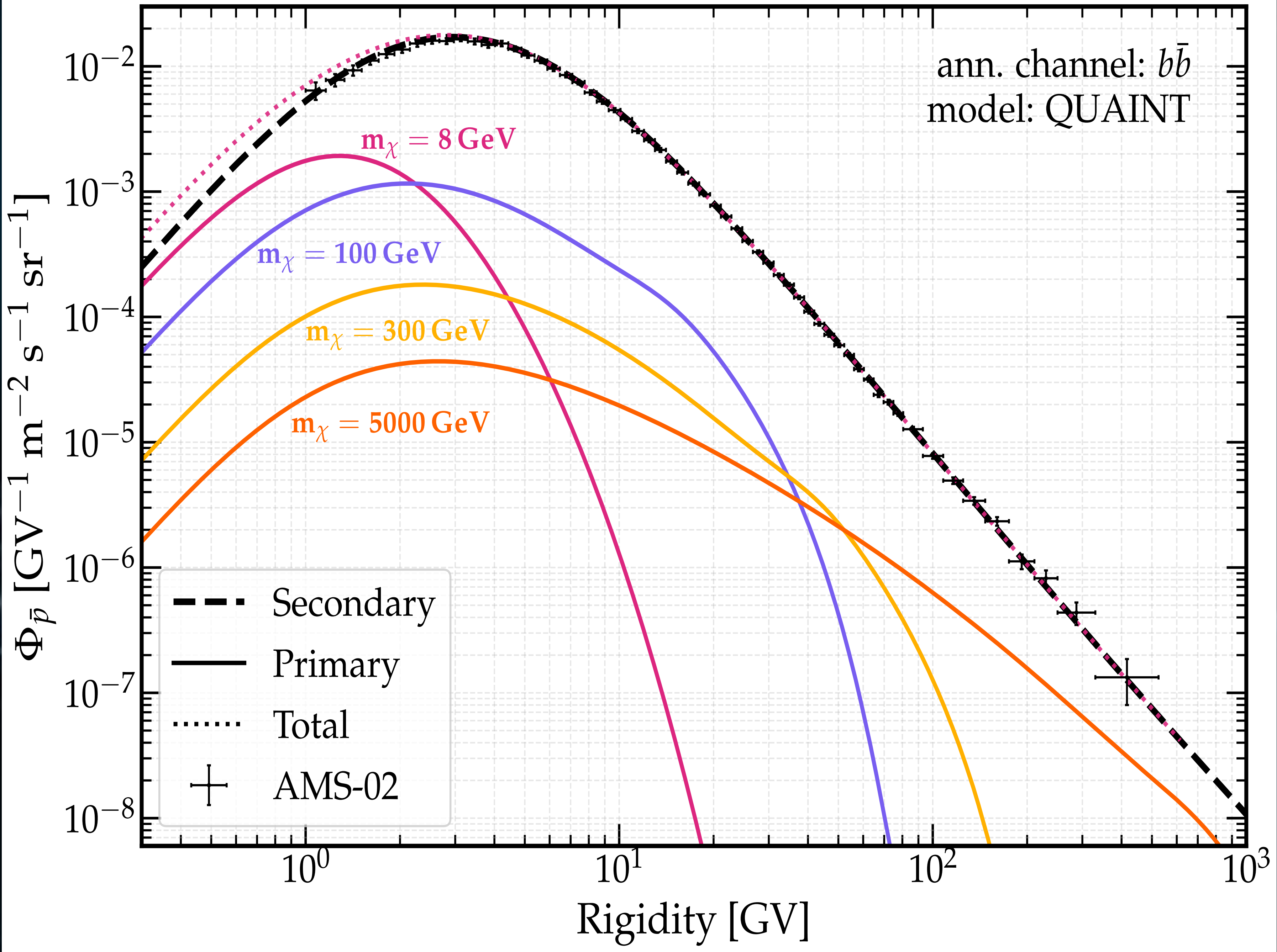
In astrophysical contexts, the Δp model can yield unphysical $\overline{\mathrm{D}}$

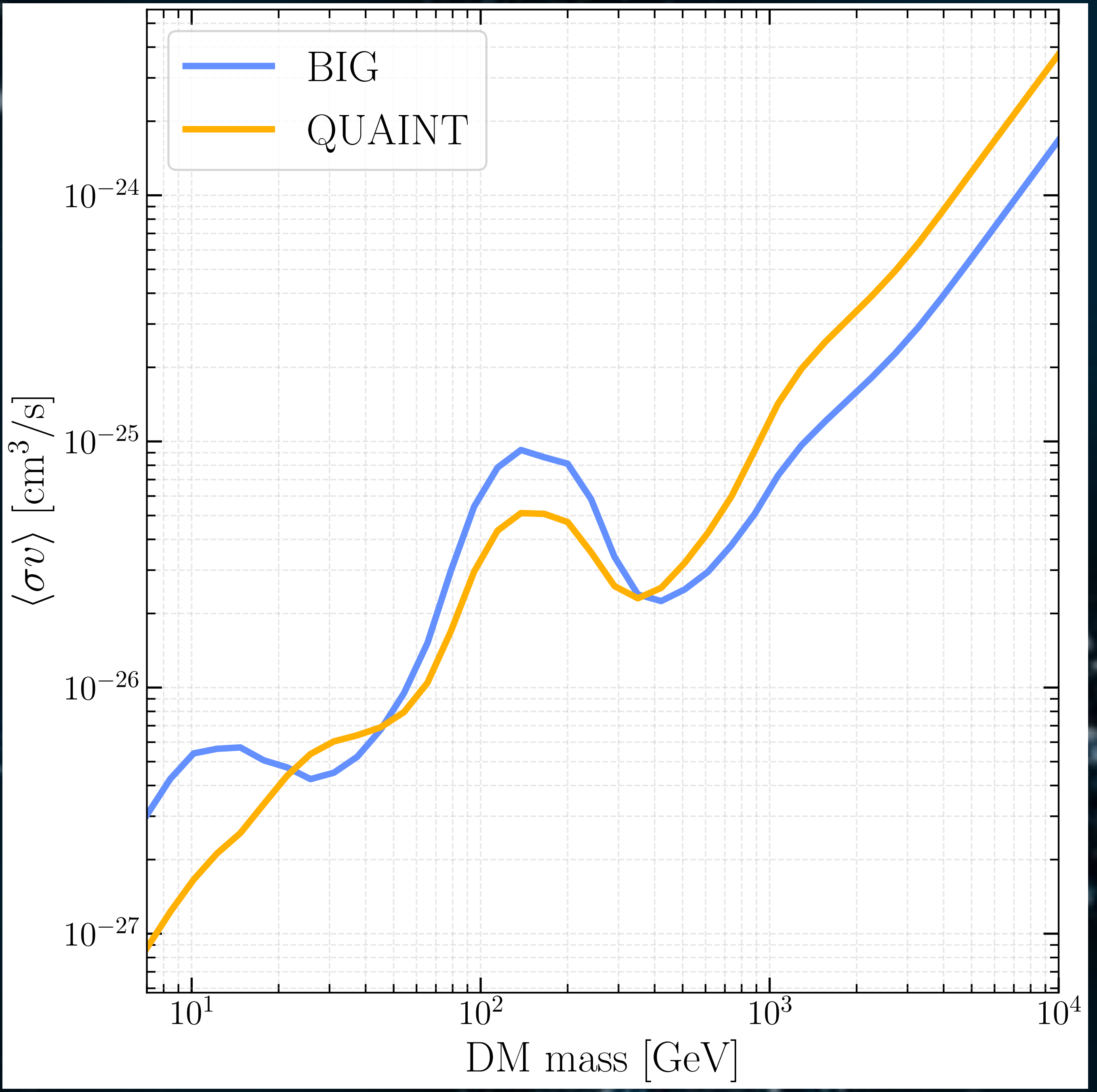
AMS-02 antiproton upper limits

CR propagation w/ USINE, using BIG/QUAINT models

Maurin, *Comput.Phys.Commun.* 247 (2020) 106942 Génolini et al., *Phys.Rev.D* 99 (2019) 12, 123028







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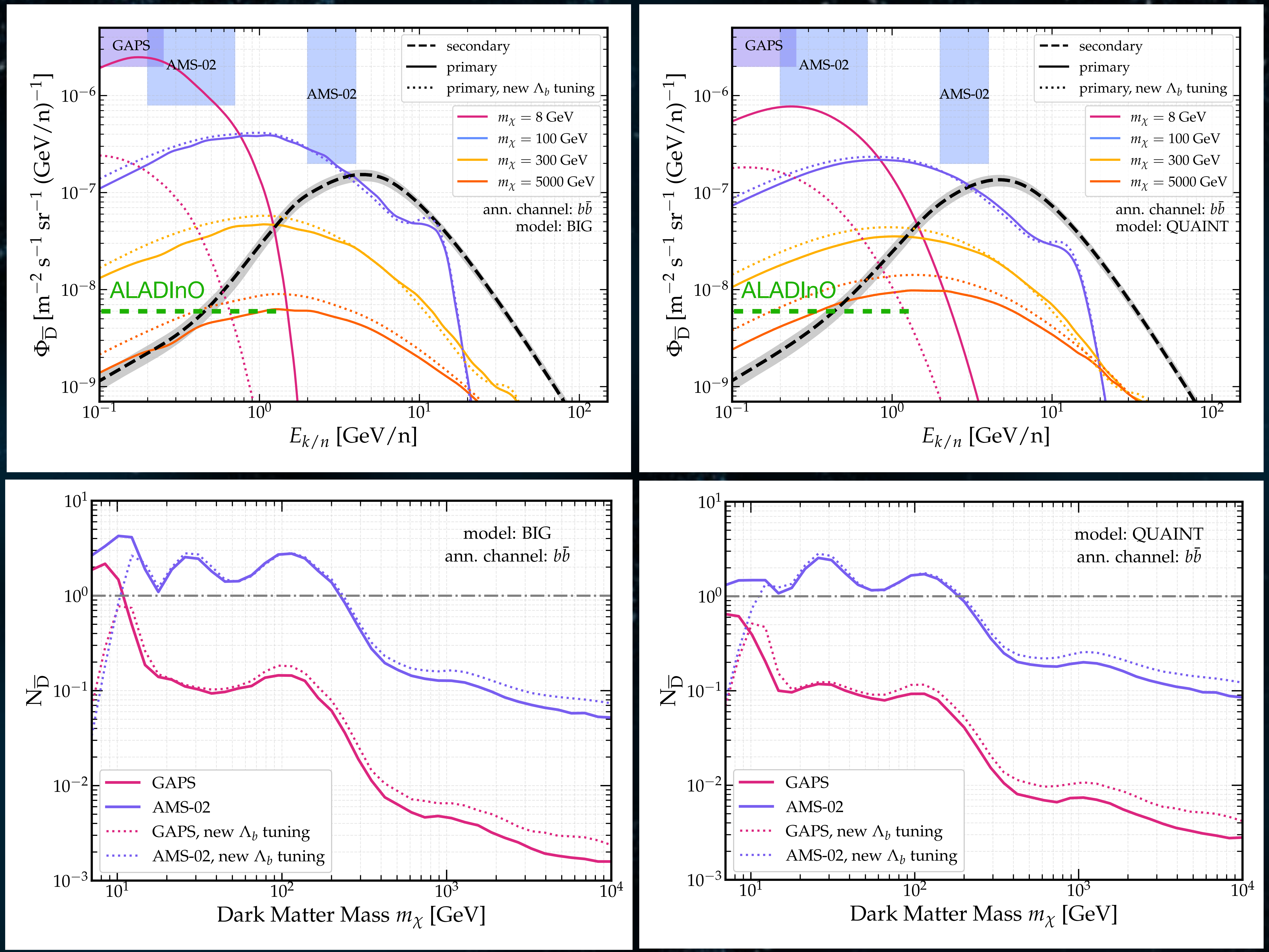

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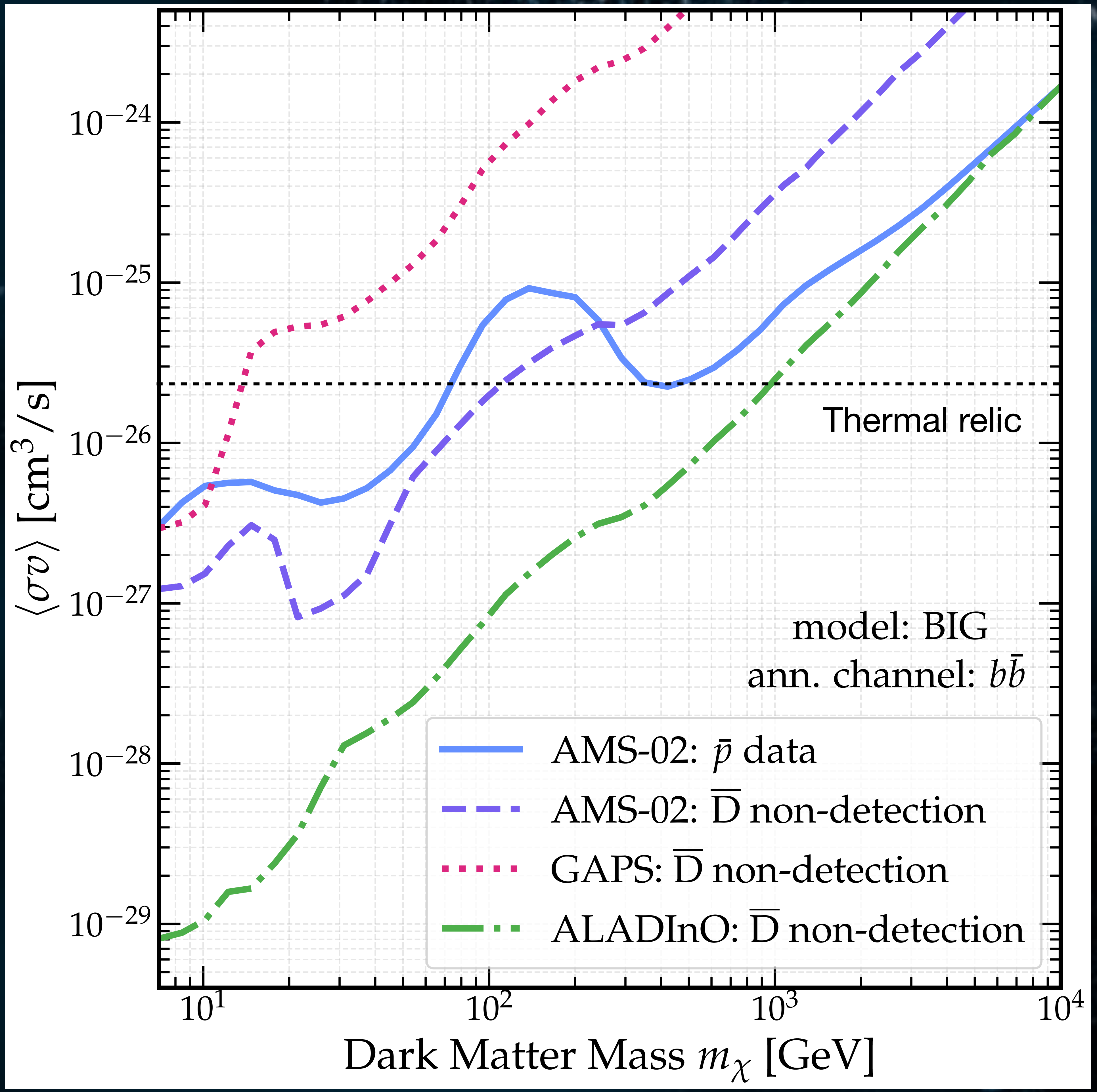

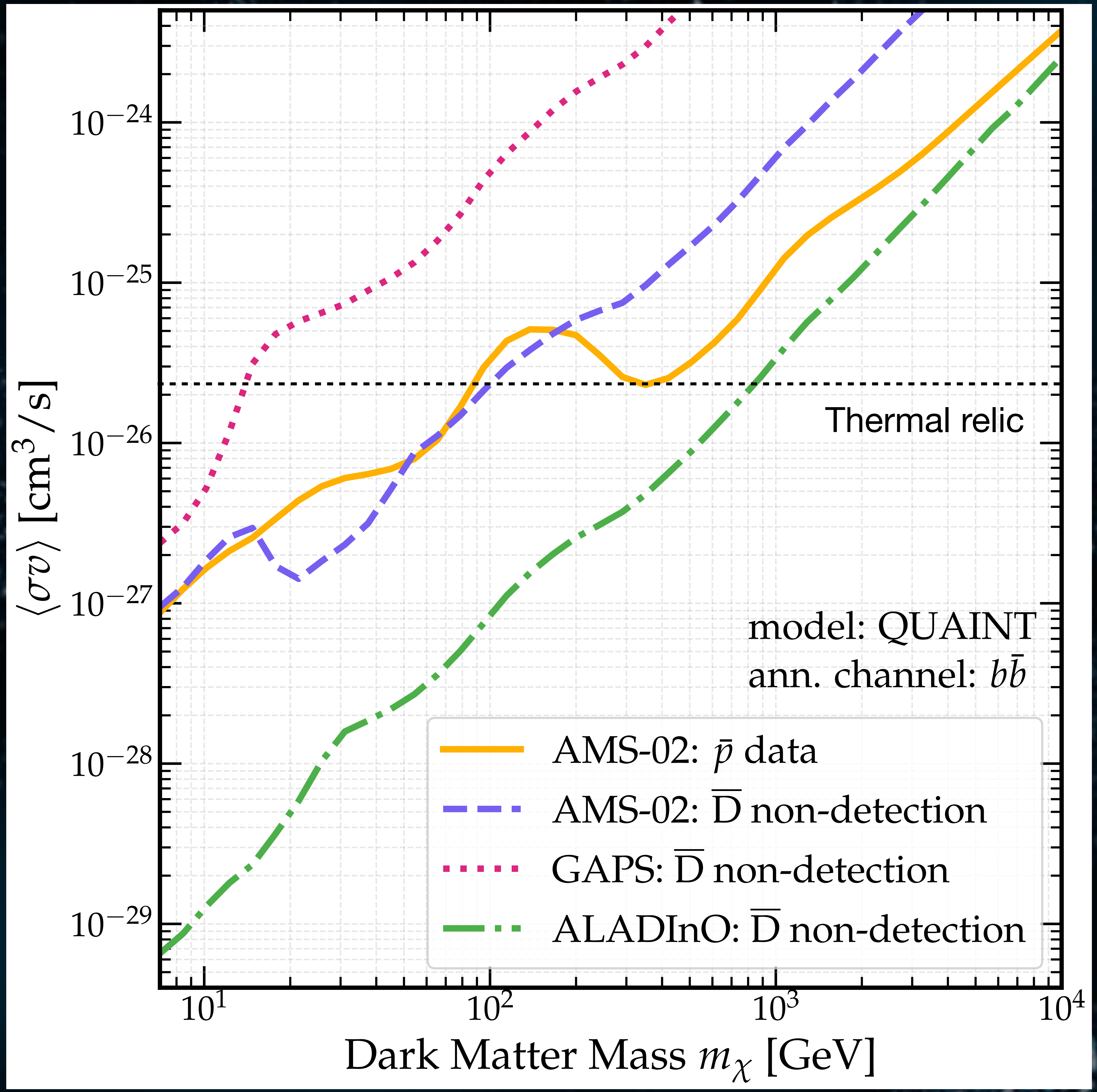

Stefanuto, Di Mauro, Donato, Fornengo, **JK**, Maurin, arXiv:2605.08338, submitted to *Phys.Rev.D*