Indirect detection of dark matter with cosmic rays

Is there (still) anything exciting?

Yoann Génolini

Dark Tools – June 2025

Collaborators :

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V.Poireau, V. Poulin, S. Rosier, P. Salati,
P. D. Serpico , M. Vecchi and N. Weinrich

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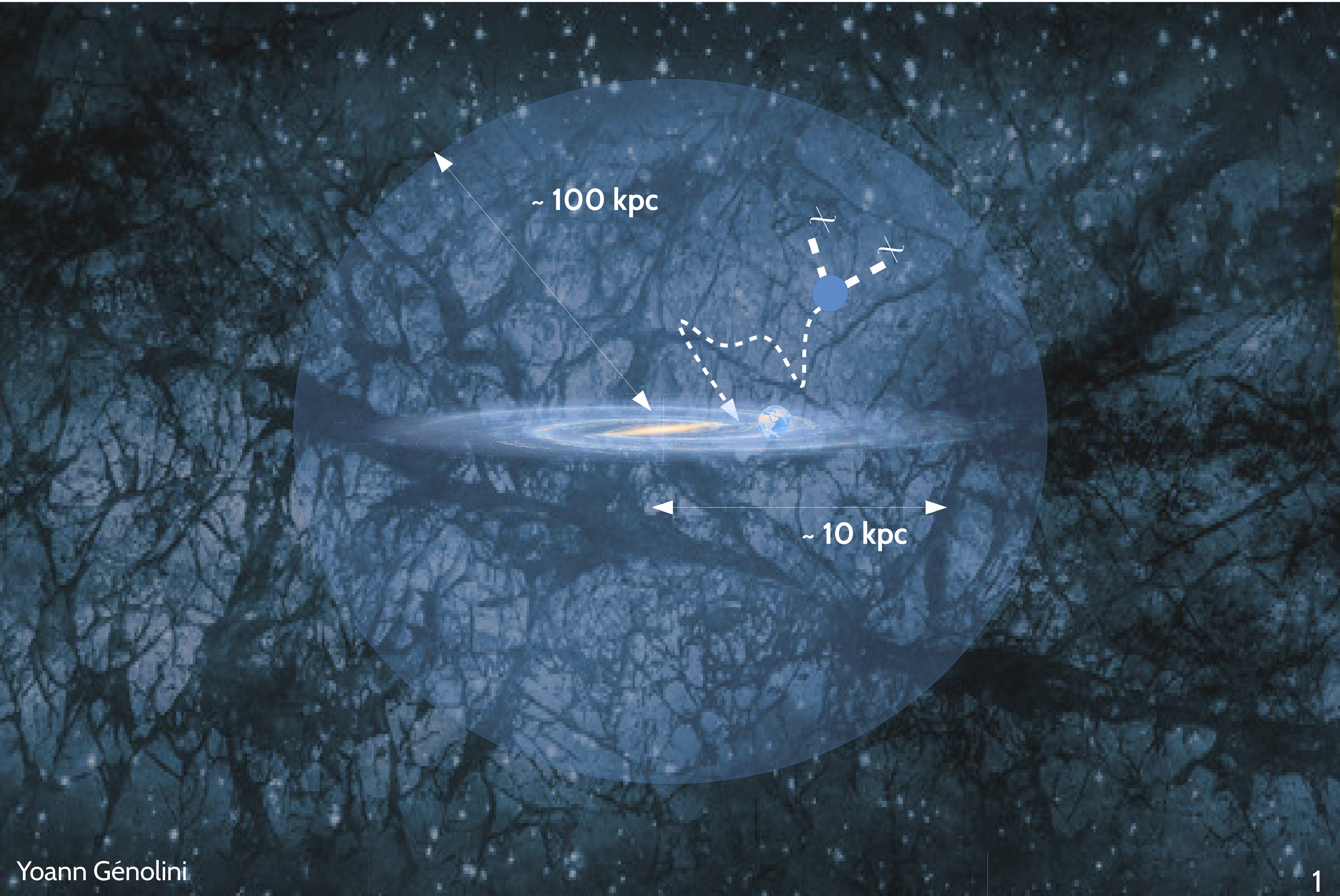
CNRS

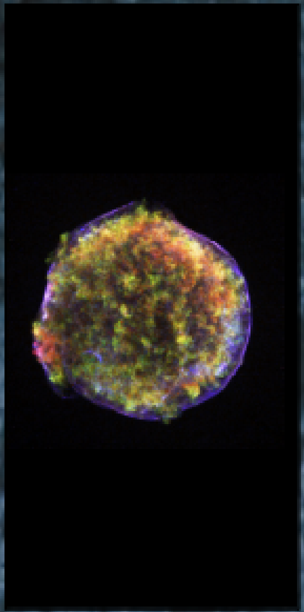
LAPTh

Introduction

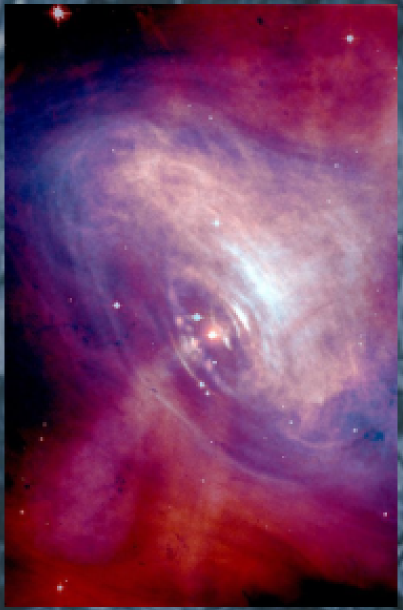


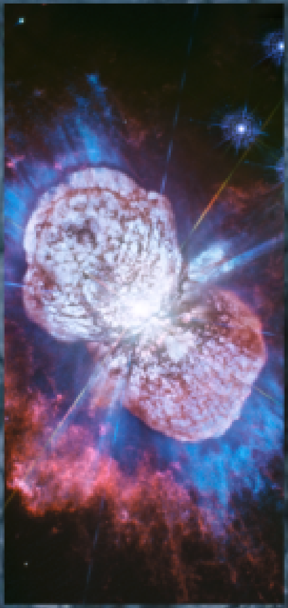
Introduction

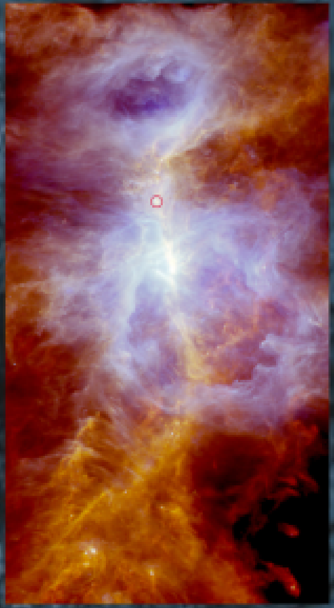
Galactic cosmic-ray sources


SNRs


Star clusters

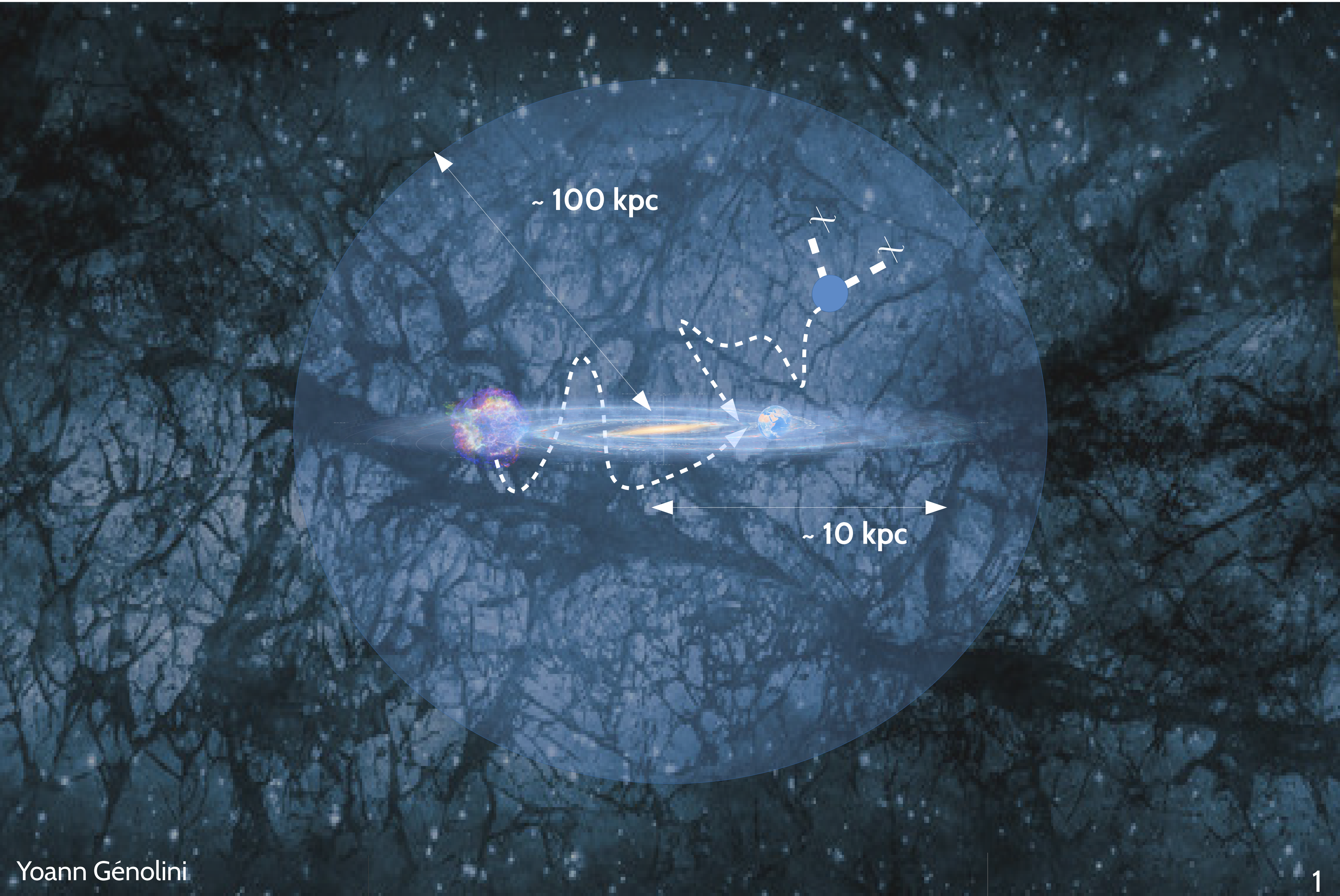

Pulsar Wind Nebulae


Colliding wind binaries


Protostellar jets microquasars

... and others !

Introduction

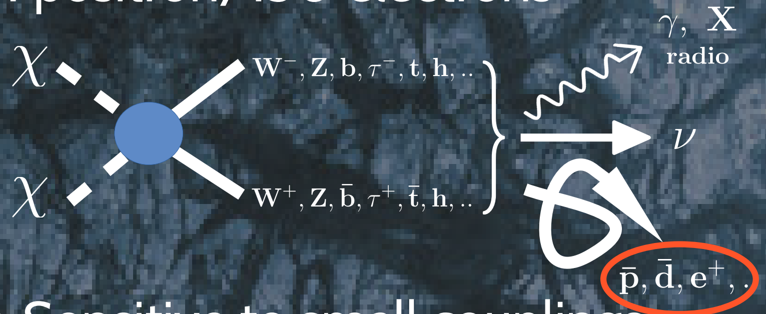


Two reasons to focus on cosmic-ray antiparticles:

1 - Very low fluxes:

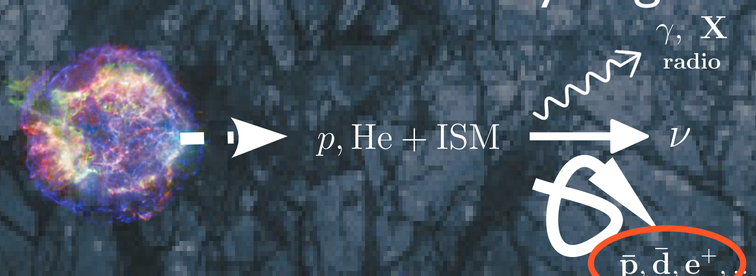
~ 1 antiproton/10^4 protons

~ 1 positron/150 electrons



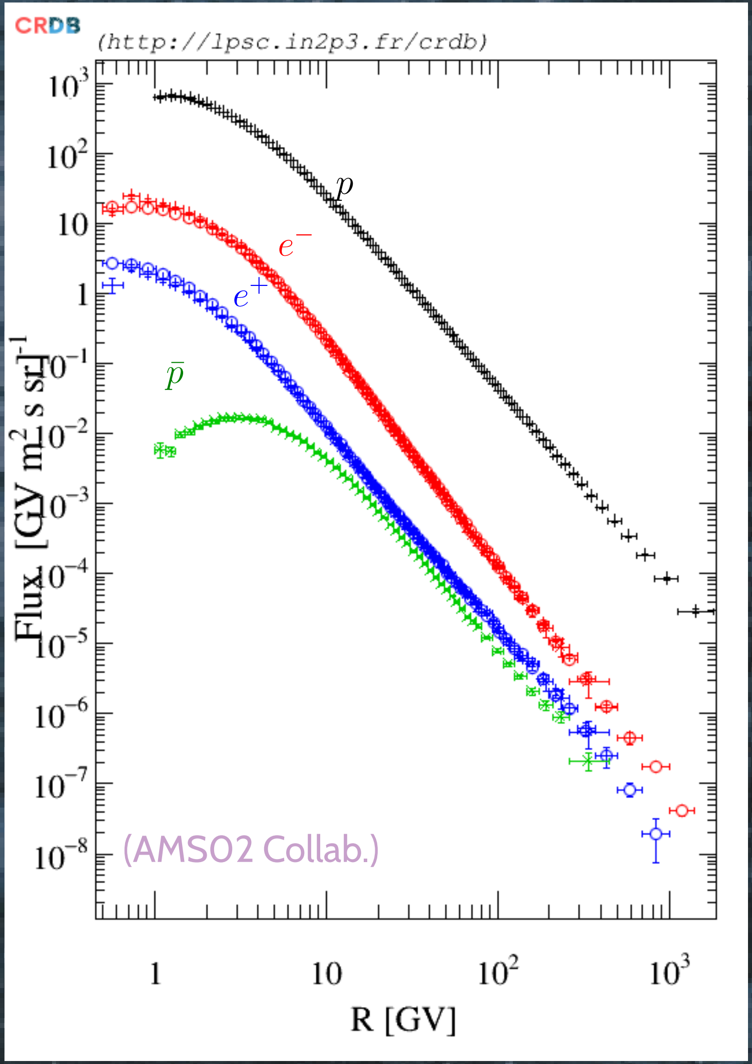
→ Sensitive to small couplings

2 - Believed to be of secondary origin:

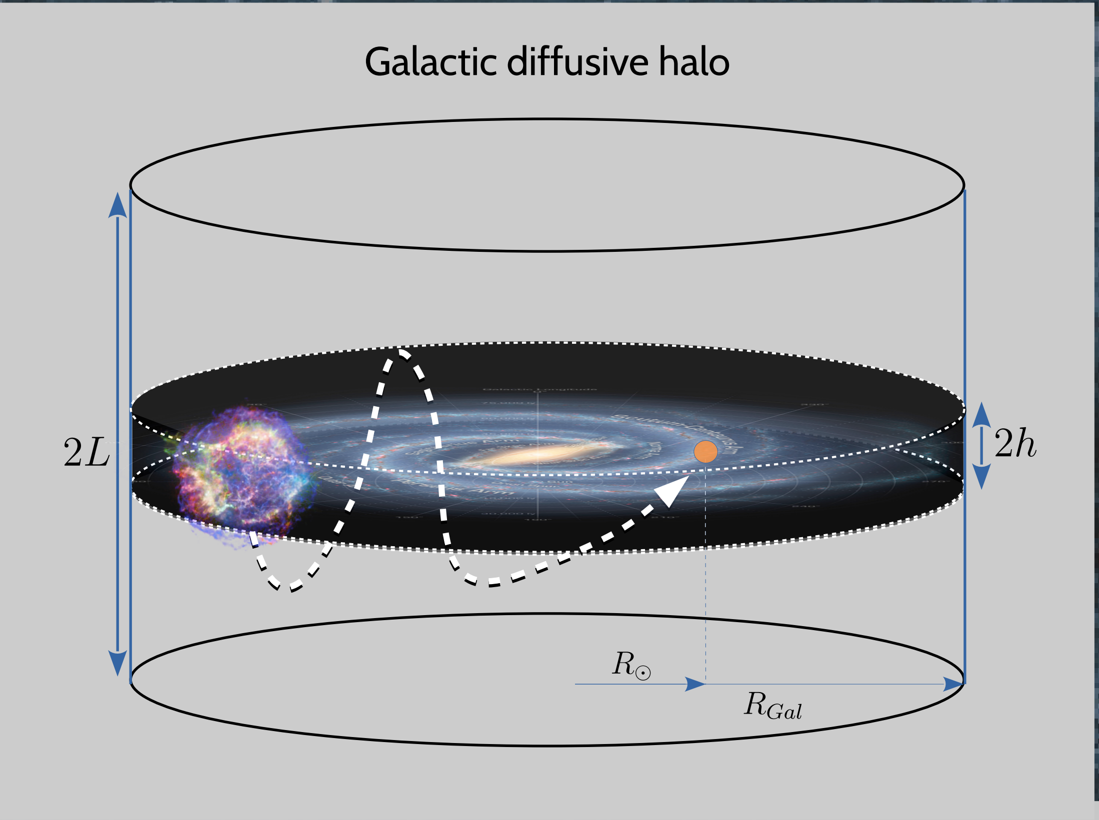


→ Astrophysical bkg can be easily estimated

Up to a good production XS knowledge..



Indirect dark matter search



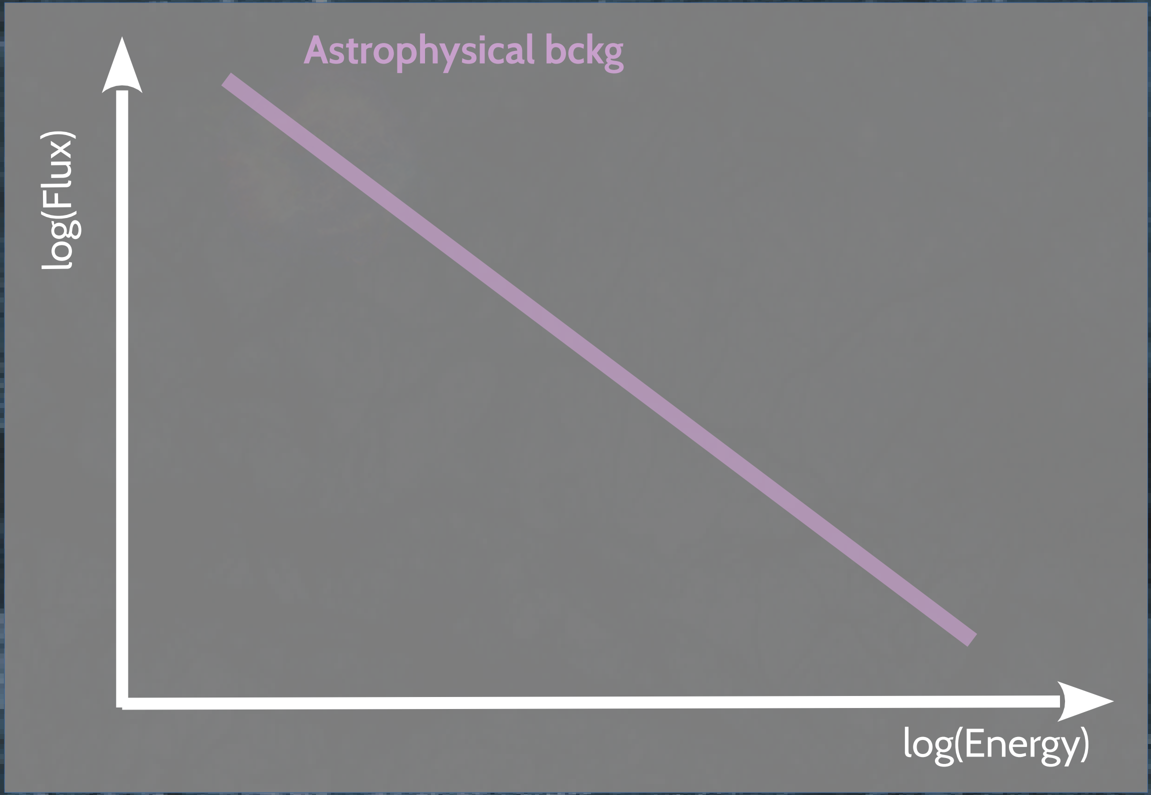
Resolution of **CR transport equation** in steady state:

$$\frac{\partial \psi_\alpha}{\partial t} - \vec{\nabla}_{\mathbf{x}} \left\{ K(E)\, \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \vec{V}_c \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ b_{\rm tot}(E)\, \psi_\alpha - \beta^2 K_{pp} \frac{\partial \psi_\alpha}{\partial E} \right\}$$

$$+ \sigma_\alpha\, v_\alpha\, n_{\rm ism}\, \psi_\alpha + \Gamma_\alpha\, \psi_\alpha = q_\alpha + \sum_\beta \left\{ \sigma_{\beta\to\alpha} v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha} \right\} \psi_\beta \, .$$

Ginzburg&Syrovatskii (1964)

Indirect dark matter search



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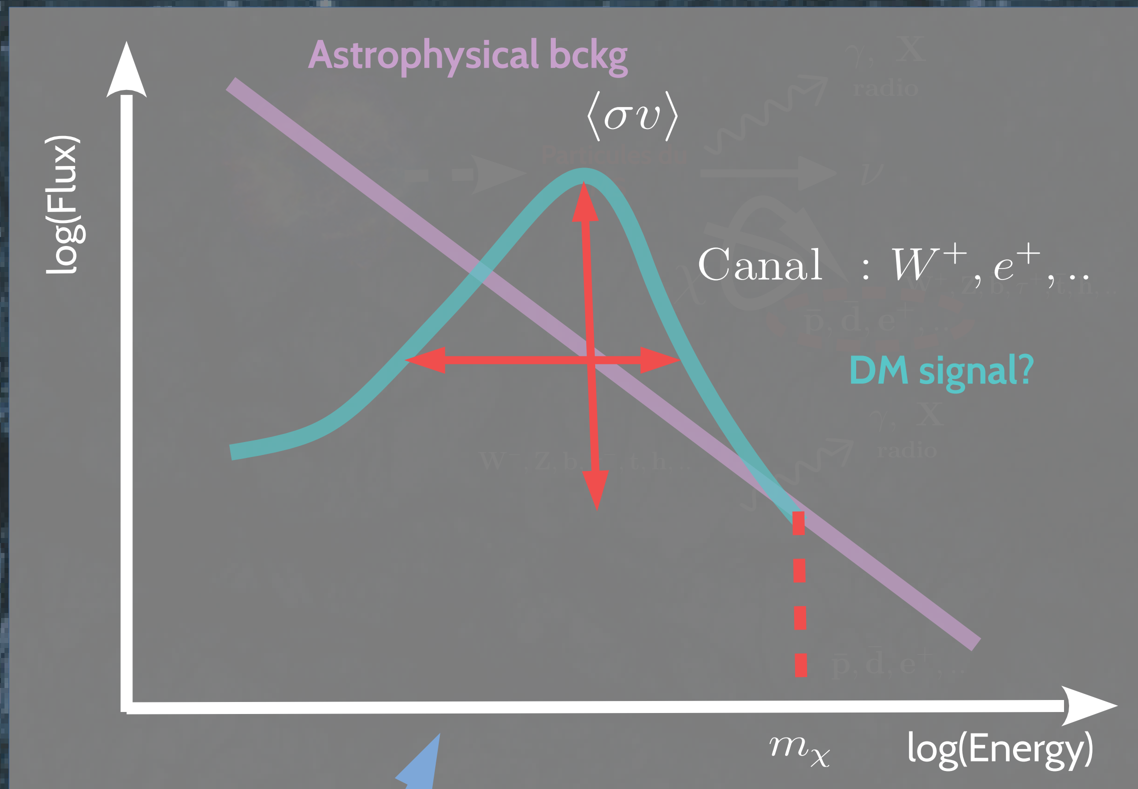
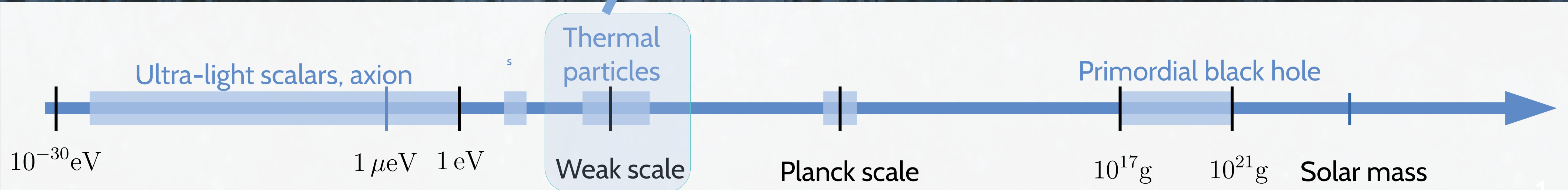


$$\dot{q}^{\rm prim}(\vec{r}, E) \;=\; \rho^2_{\rm DM}(\vec{r}) \times \frac{\langle \sigma v \rangle}{2\xi m_\chi^2} \times \sum_f B_f \frac{dn^{\chi\chi\to f\to\bar{p}}}{dE}(E)$$



Introduction

Game changer: high-quality data!

Numerous precison experiments in a large energy range

Precision level % from GeV to TeV

Sensitive to particles & antiparticles independently

VOYAGER (1977)

5 – 500 MeV

PAMELA (2006)

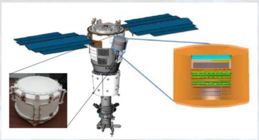
1 GeV – 1.2 TeV

AMS-02 (2011)

1 GeV – 1.9 TeV

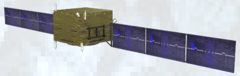
NUCLEON (2014)

100 GeV – 1 PeV



DAMPE (2015)

50 GeV – 500 TeV

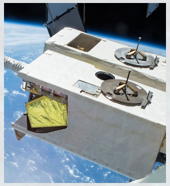


CALET (2015)

10 GeV – 1 PeV

ISS-CREAM (2017)

1TeV-500 TeV



GAPS (2025)

0.07-0.25 GeV

Outline

1 – A few words about positrons

2 – An excess in CR antiprotons?

3 – The antinuclei frontier

4 – Conclusion and prospects

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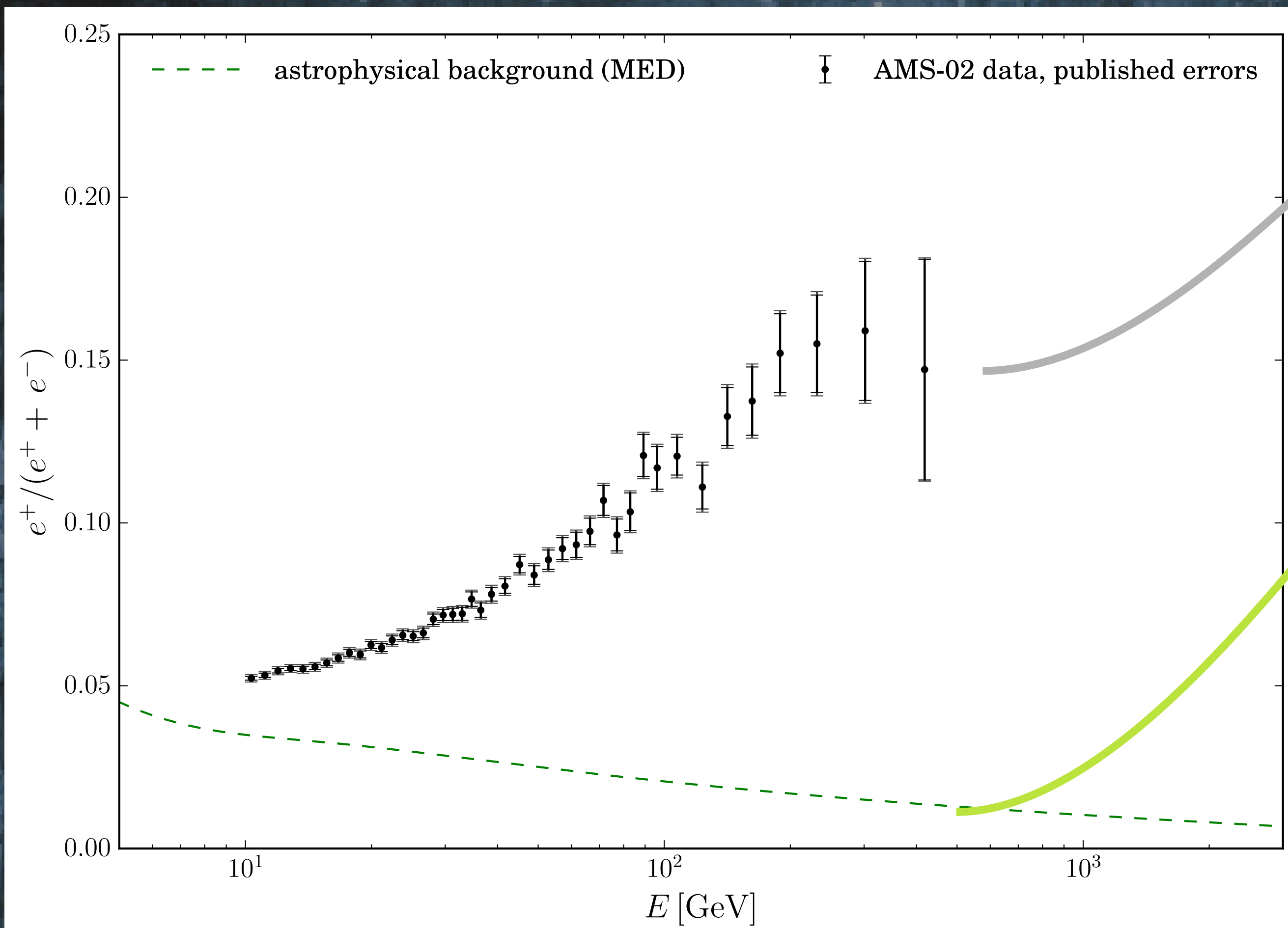
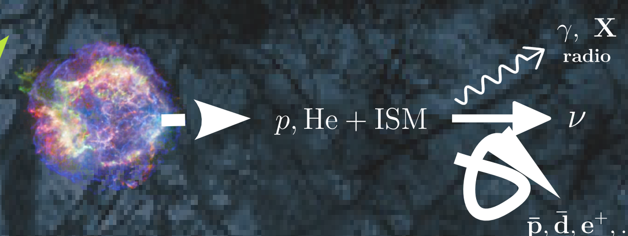
A few words about positrons



(Boudaud, ..., Y.G.+ 2015)

Also measured by:
-HEAT (1997)
-PAMELA (2009)
-FERMI (2010)

Astrophysical bckg from secondary production:



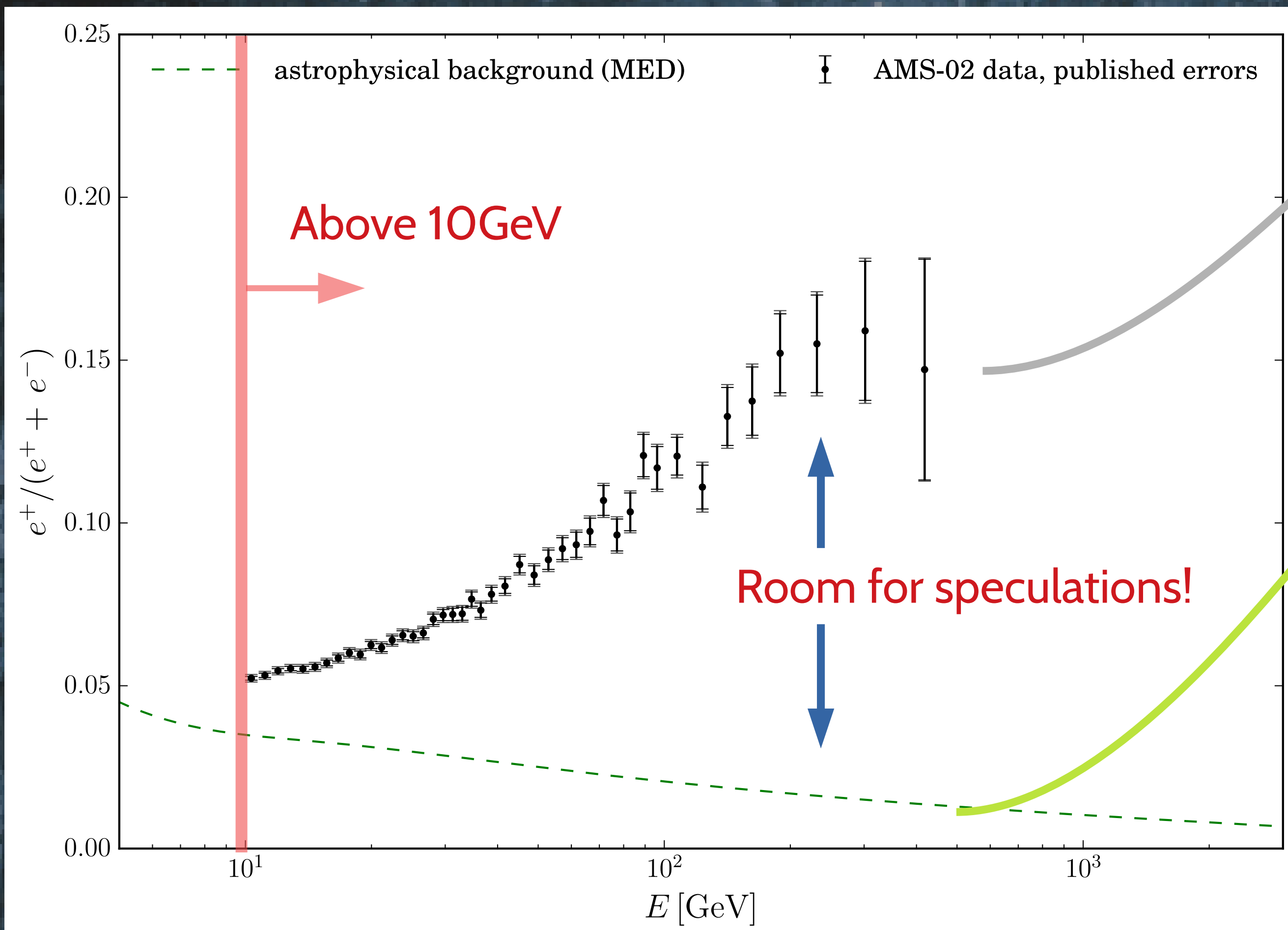
- Recently reevaluated with updated XS
(NA49 - NA61/SHINE – ALICE- CMS)

(Orusa + 2022 & Di Mauro + 2023)

→ 5-7 % uncertainty

A few words about positrons

High-energy cosmic positrons: the need for a primary source



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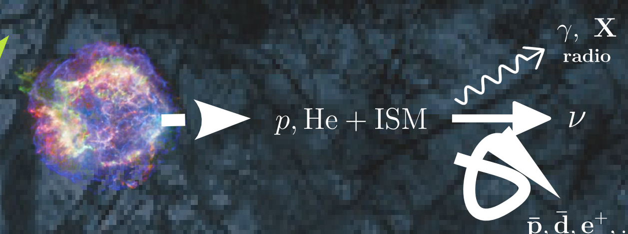

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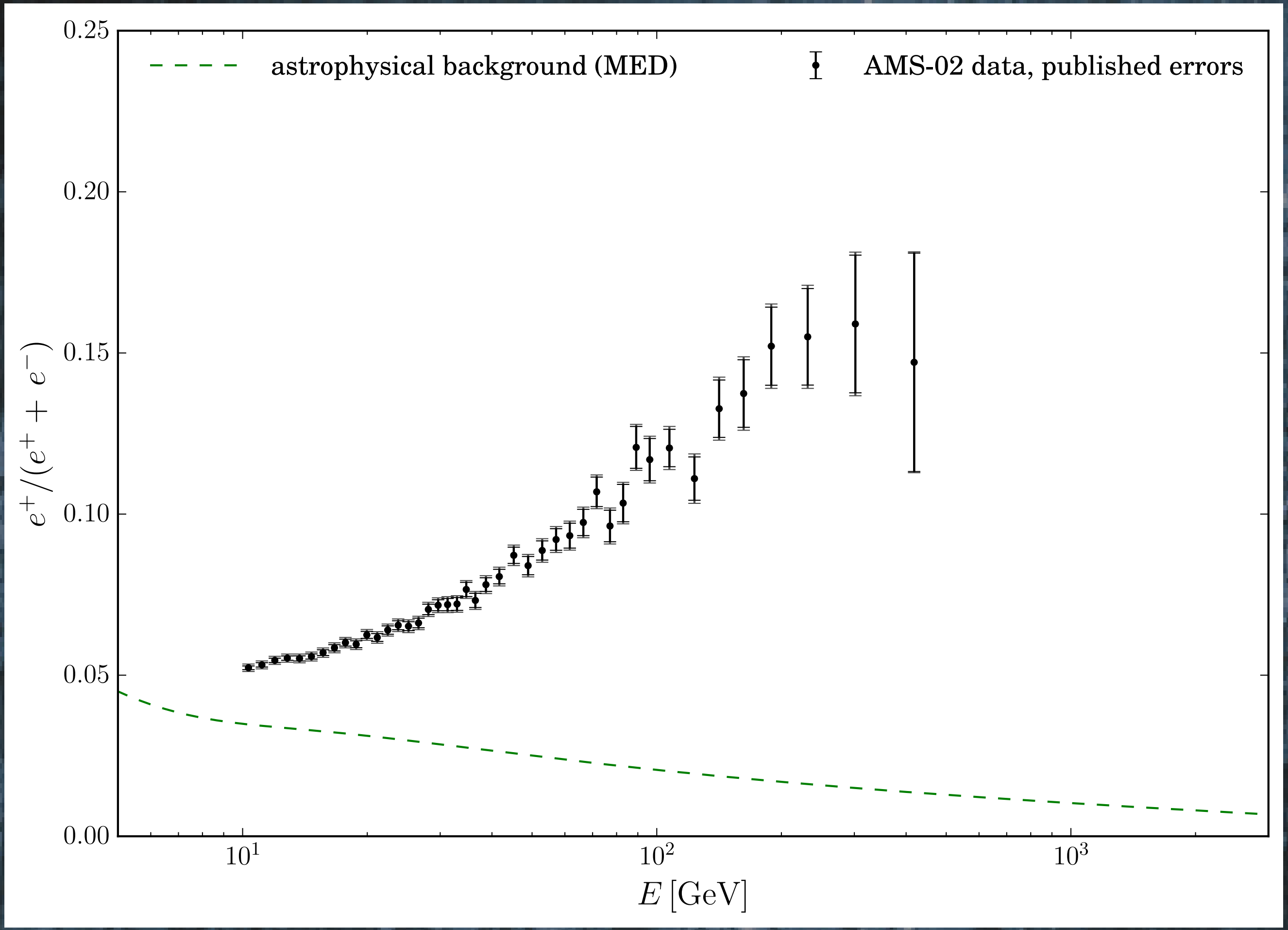
The WIMP explanation of the positron excess



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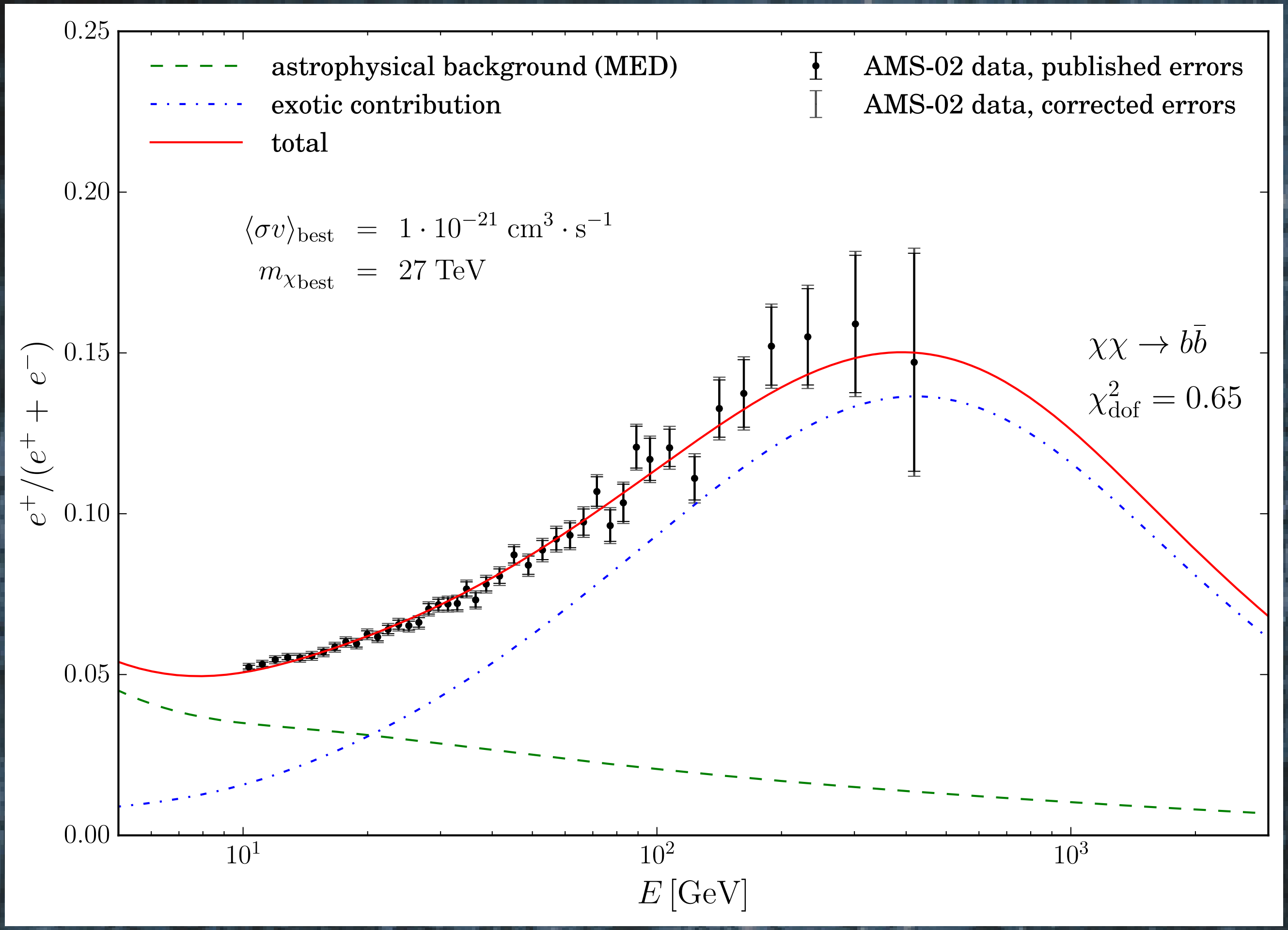

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A few words about positrons

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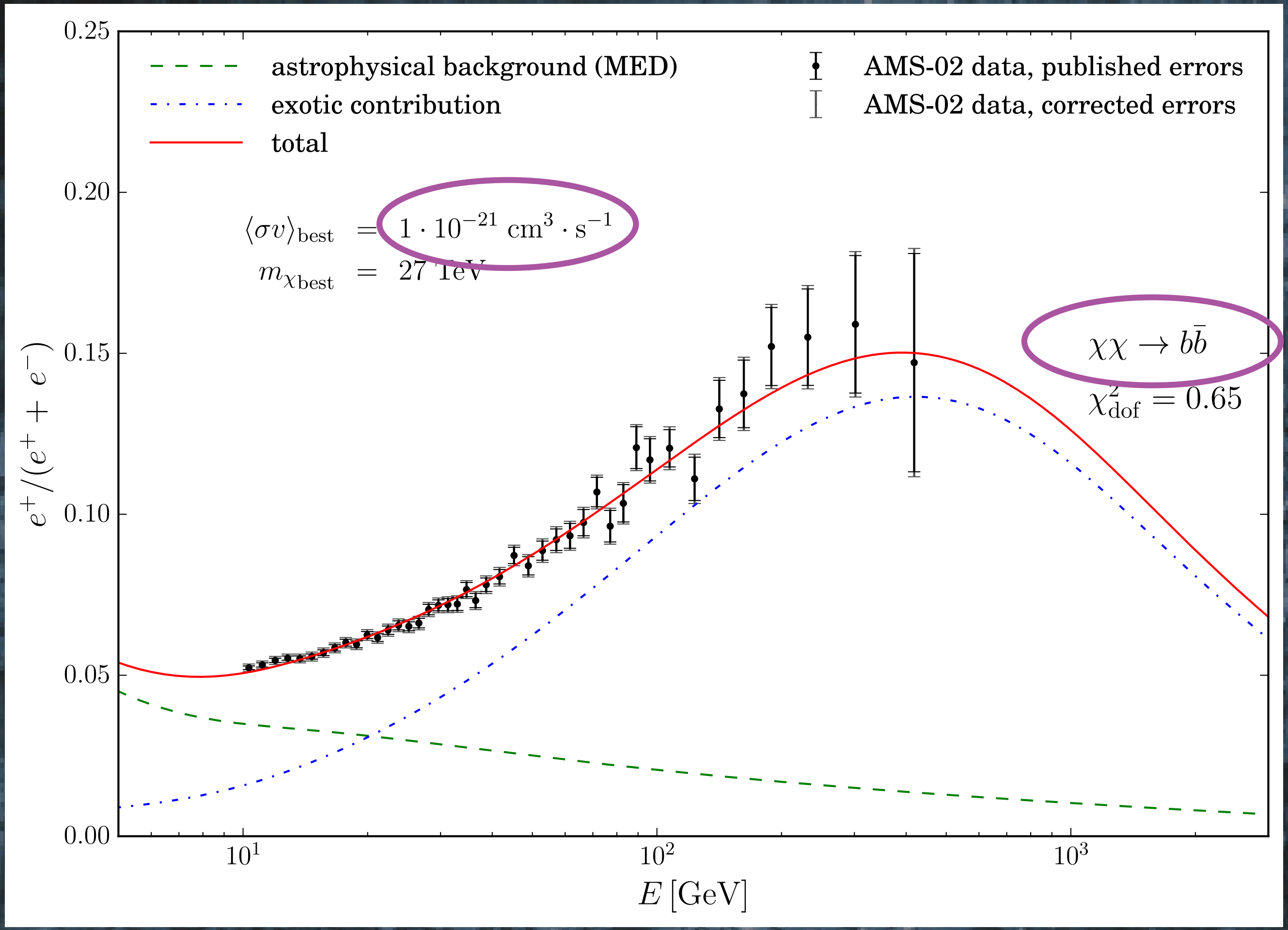


(Boudaud, ..., Y.G.+ 2015)

One DM candidate

→ Very few channels giving a good fit

→ Huge boost factors 10^3-10^5

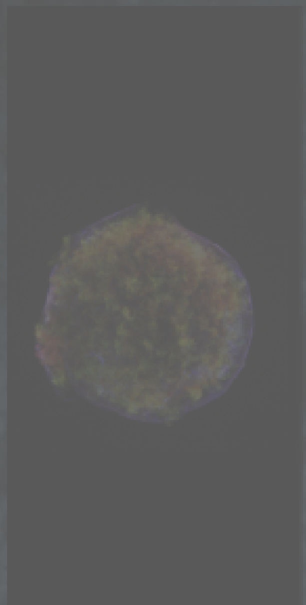
Hadronic channel
Ruled out by pbars constraints
(See second part)

Leptonic channel
Tensions with CMB+DS constraints
(Lopez, A.+ 2015, Planck Col.XIII+2015)

Cannot come from DM clumpiness
(Lavalle, J.+ 2006, Brun, P.+ 2009)

→ Analysis extended to low-E
No good fit found
(Boudaud, ..., Y.G.+ 2016)
(Di Mauro&Winkler 2021)
Origin of this excess?

Galactic cosmic-ray sources



SNRs

Star clusters

Pulsar Wind Nebulae

Colliding wind binaries

Protostellar jets microquasars

... and others !

→ Could also be SNRs (see e.g. Mertsch, P.+ 2020)

A natural astrophysical candidate

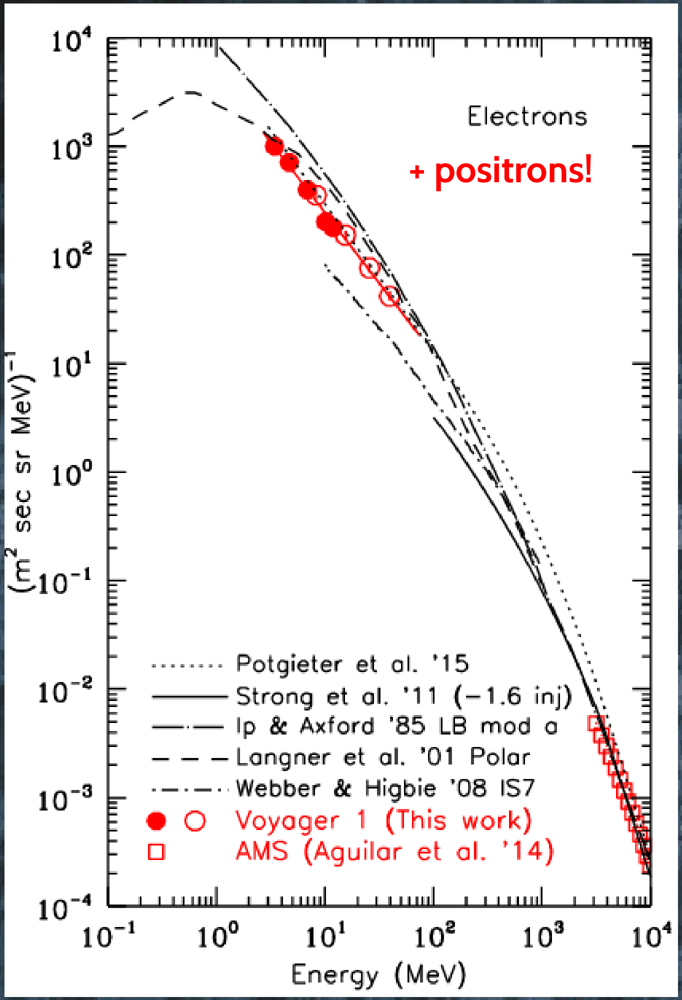
→ Currently investigated with multimessenger studies:

γ-ray/radio signal and e^+ anisotropies

(see e.g. Manconi, S.+ 2019, Orusa, L. + 2025)

A few words about positrons

Dark matter constraints with positrons



(Cummings, A .+ 2016)

@ High-energy

→ Not that competitive (see e.g. Di Mauro&Winkler 2021)

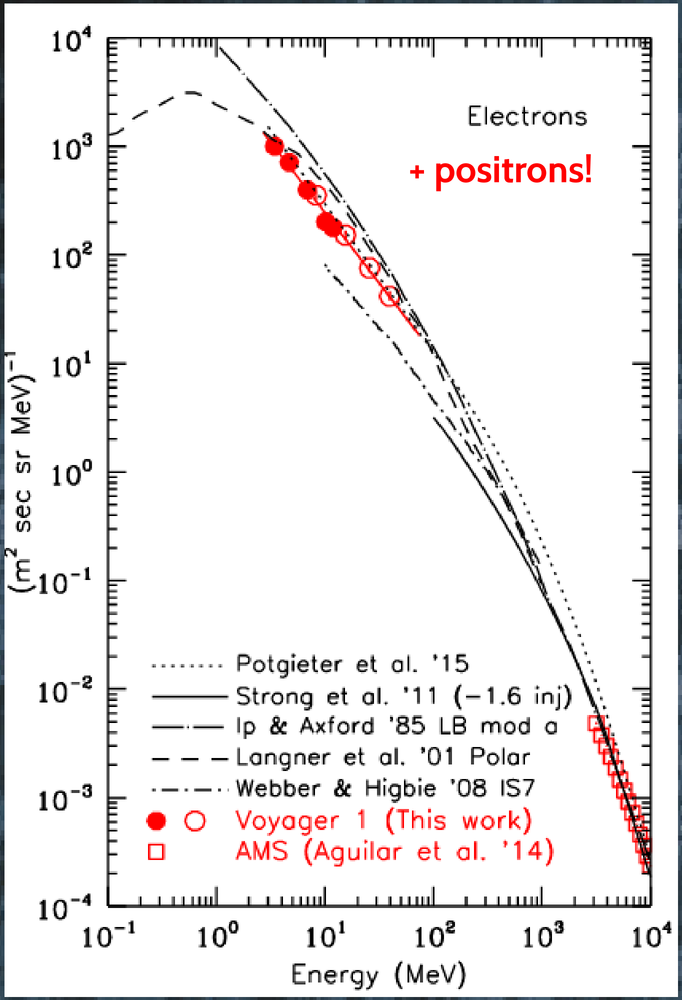
@ Low-energy

→ Voyager-1 crossed the heliopause in 2012

→ Direct measurement of the IS $e^+ + e^-$ flux

→ Low-energy cosmic positrons provide a stringent constraint on leptophilique DM models

Dark matter constraints with low-energy positrons



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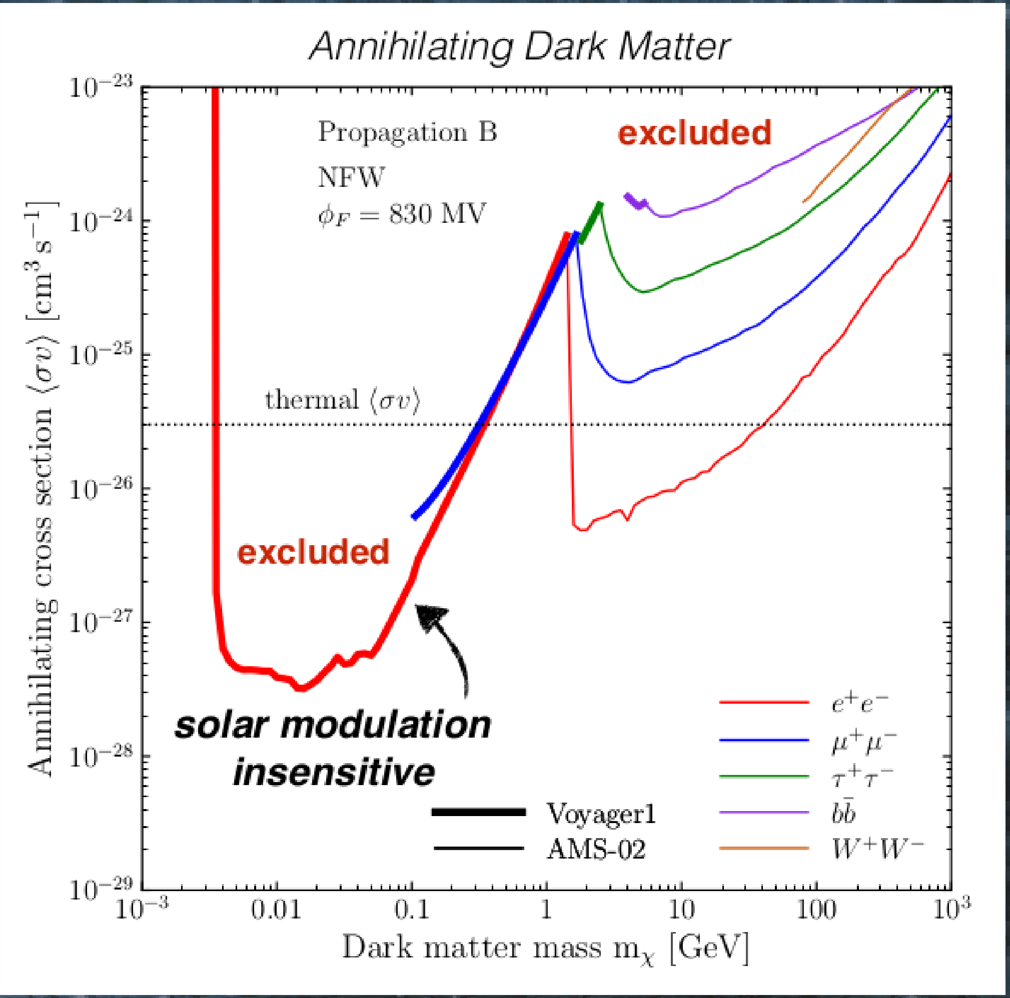


(Boudaud, M.+ 2016, 2018)

→ Stringent constraints on S and P wave annihilition

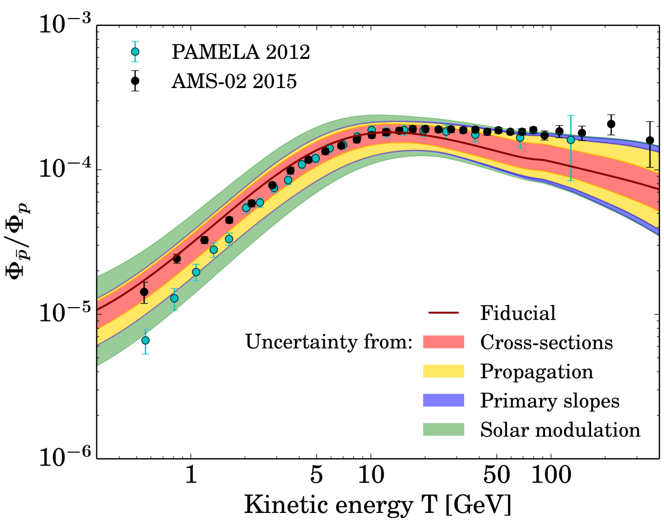
Outline

An excess in CR antiprotons?

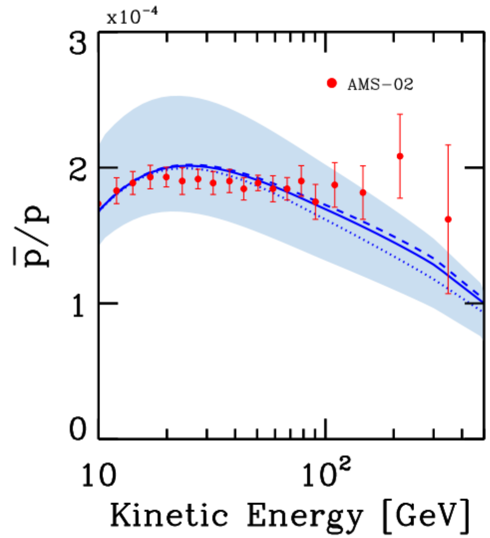
Secondary

Is the case of antiprotons more exciting?

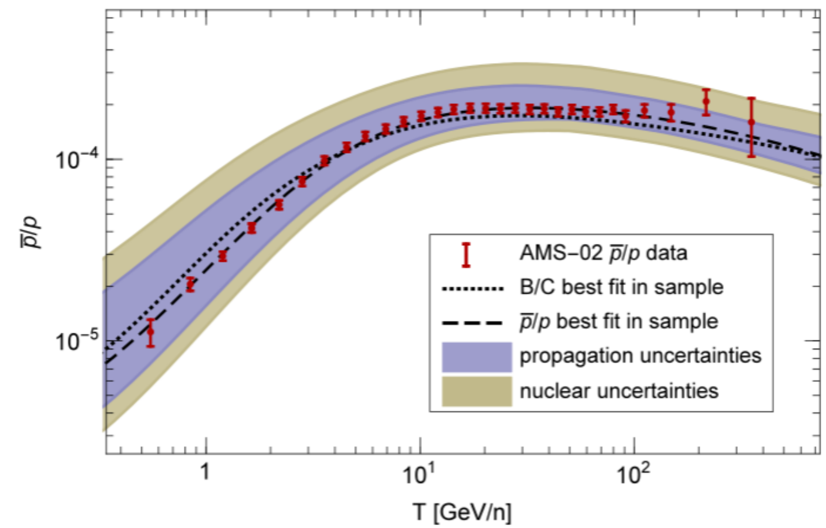
→ Preliminary AMS02 antiproton data from 2015



(Giesen,..., Y.G.+ 2015)



(Evoli, C.+ 2015)



(Kappl, R.+ 2015)

→ Secondary predictions very close to the data

→ Small deviations may indicate typical WIMP DM

→ Some claimed excesses

(Cui, M-Y.,+2017, Cuoco, A.+2017, Cholis, I.+2017)

Uncertainties data + prediction from different origins...

... A refined treatment of uncertainties is needed!

An excess in CR antiprotons?

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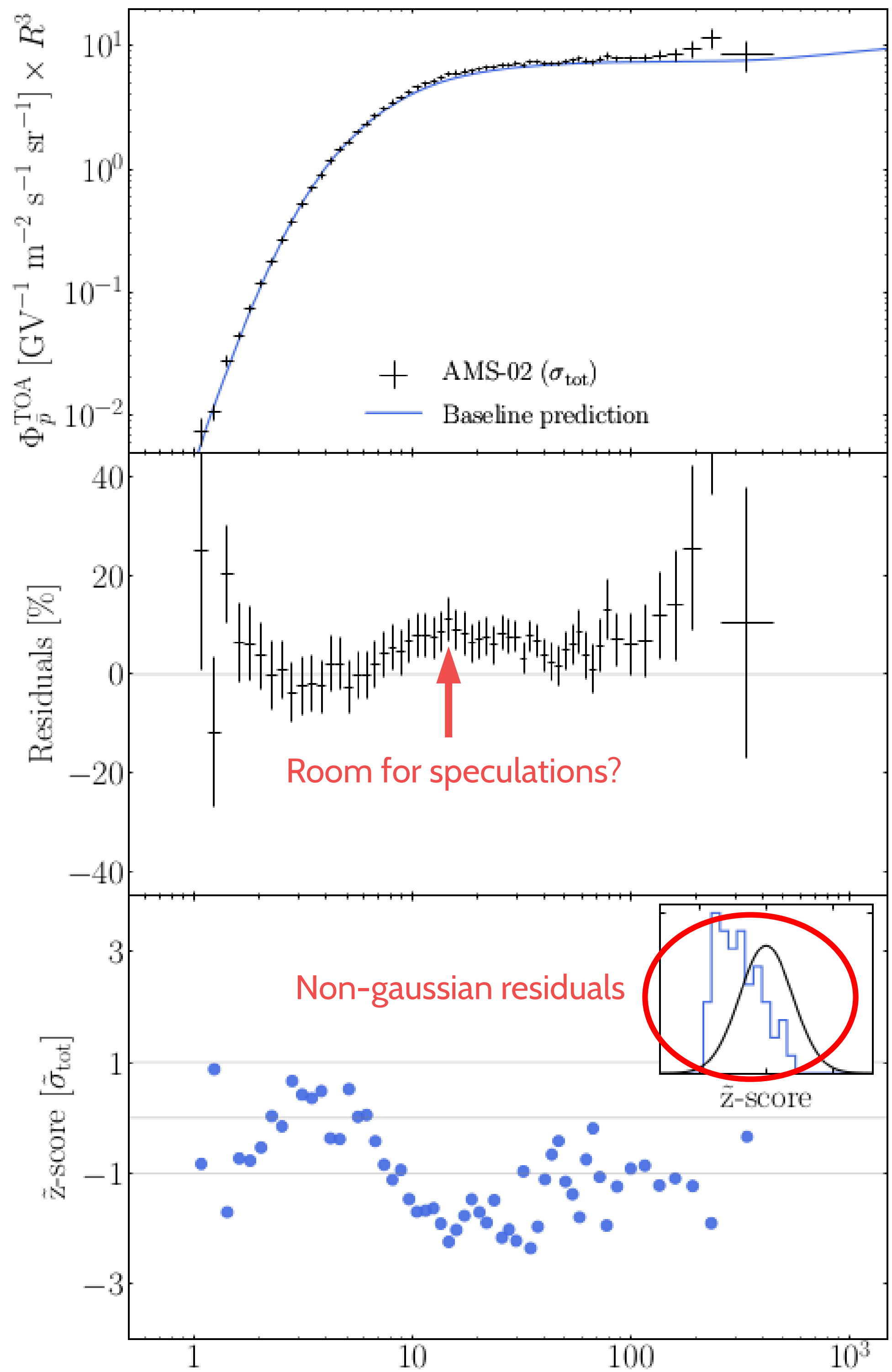
A refined treatment of uncertainties

→ Data: AMS02 antiproton from 2016

→ Model: semi-analytical (USINE) (Maurin 2020)

Comparison with data = discrepancy ~ few 10GV



(Boudaud, Y.G.+ 2019)

Courtesy M. Boudaud

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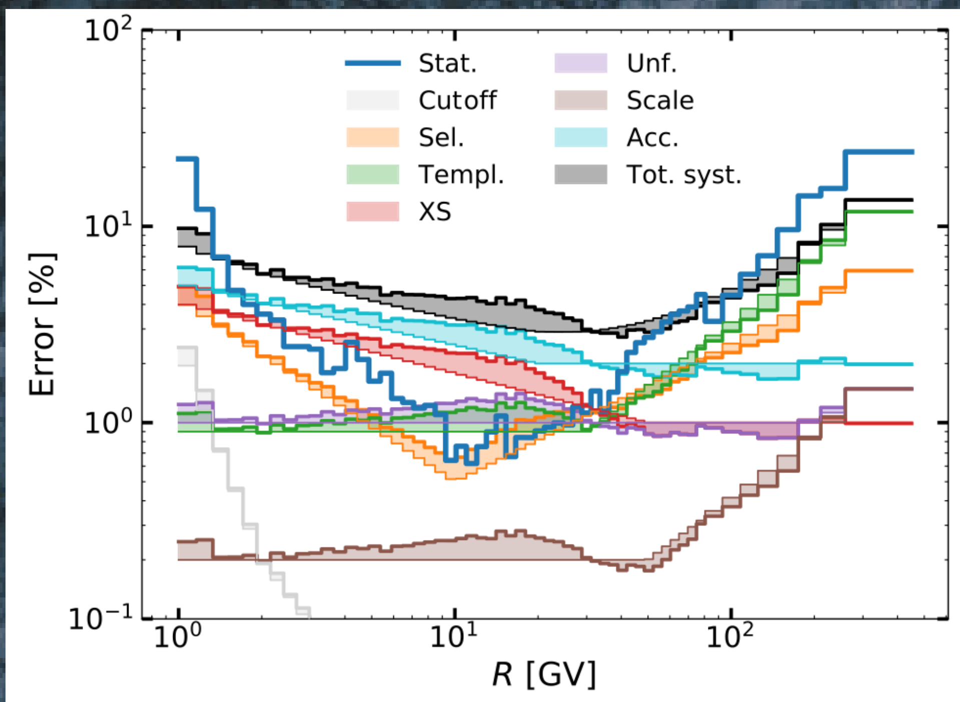
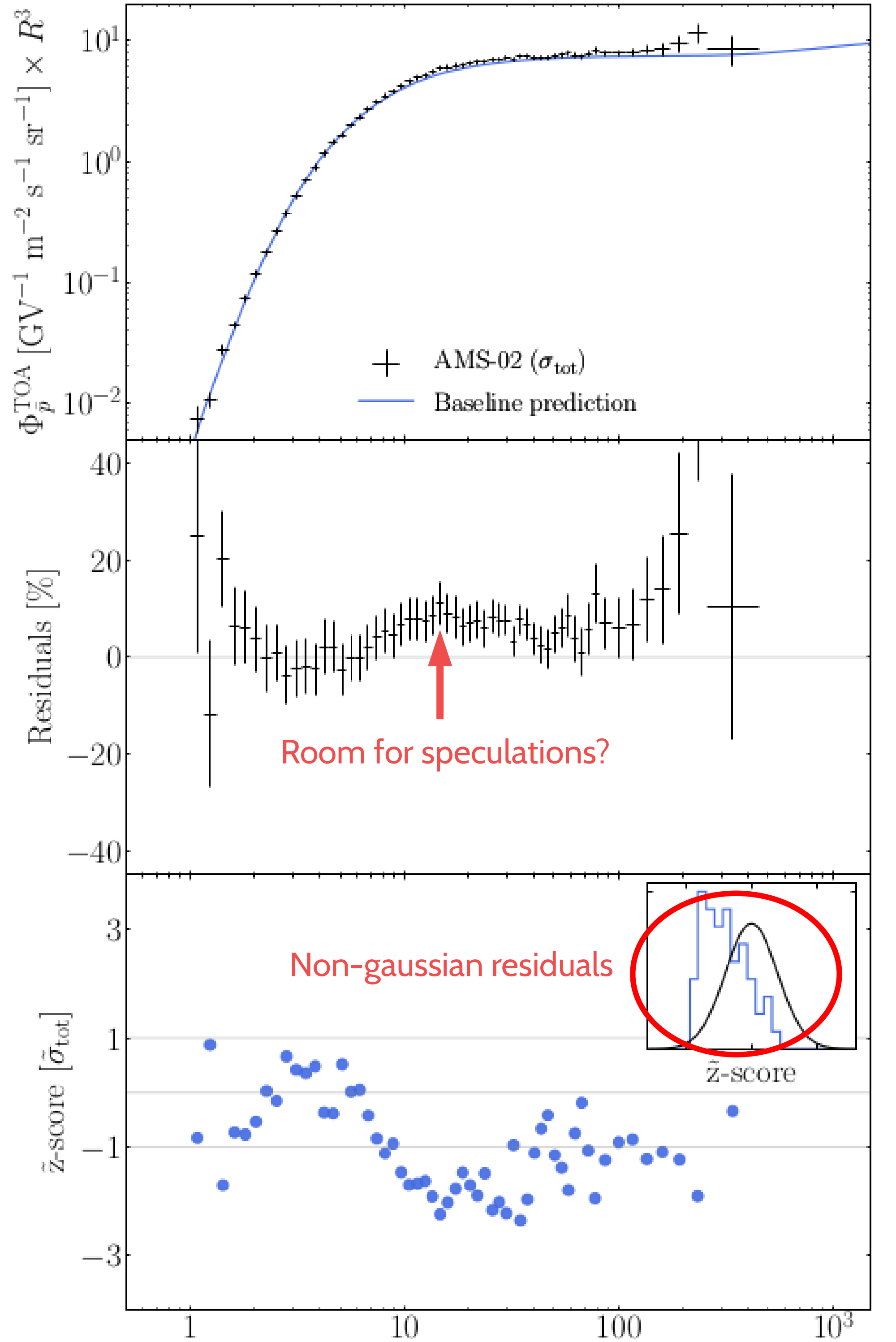


Small total error / Different correlation lengths
Dominated by acceptance around the excess

→ Covariance matrix estimated from detector info.



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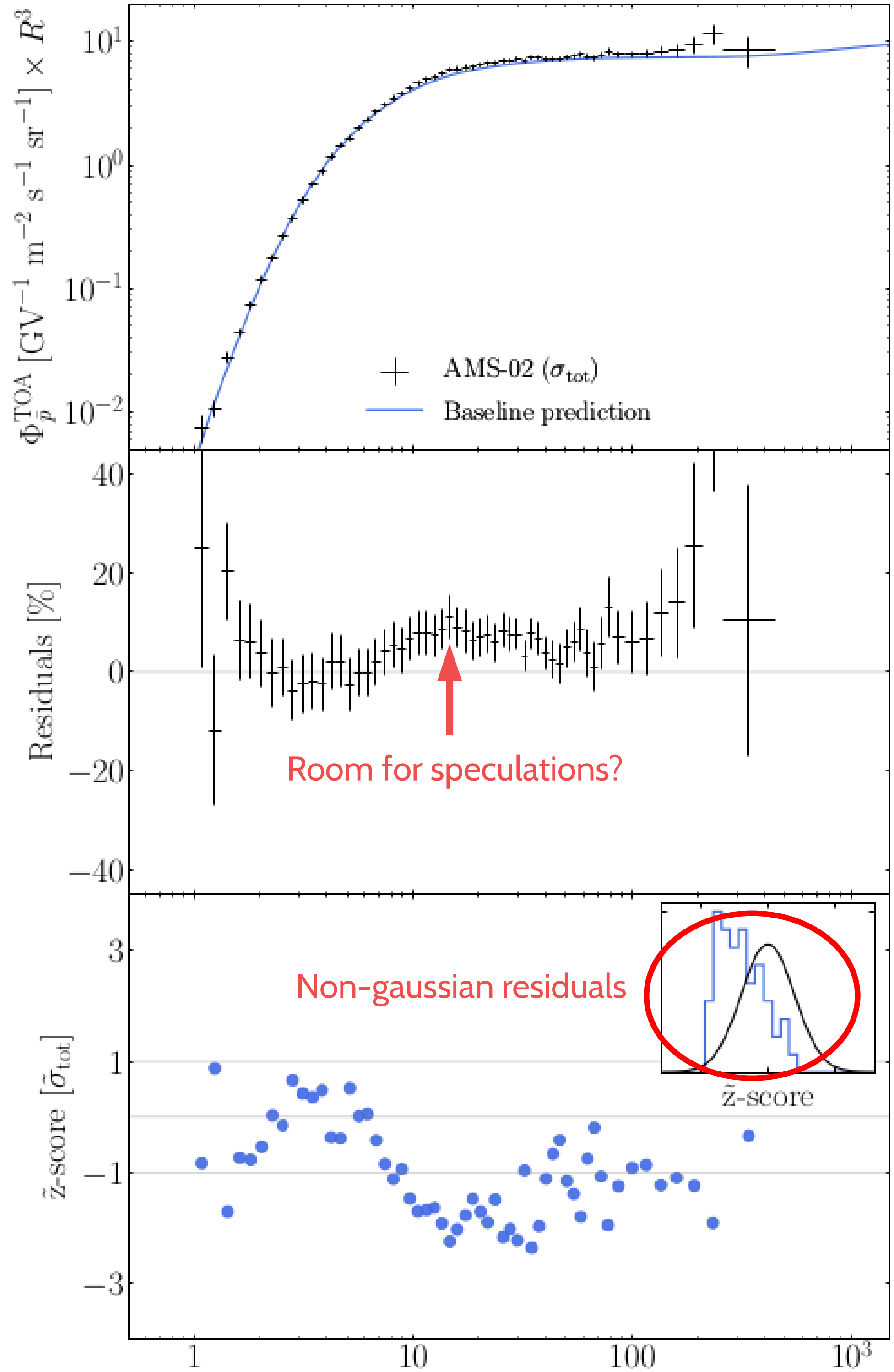

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New data from NA61/SHINE (p+p)

NA49: (p+C) & LHCb: (p+He)

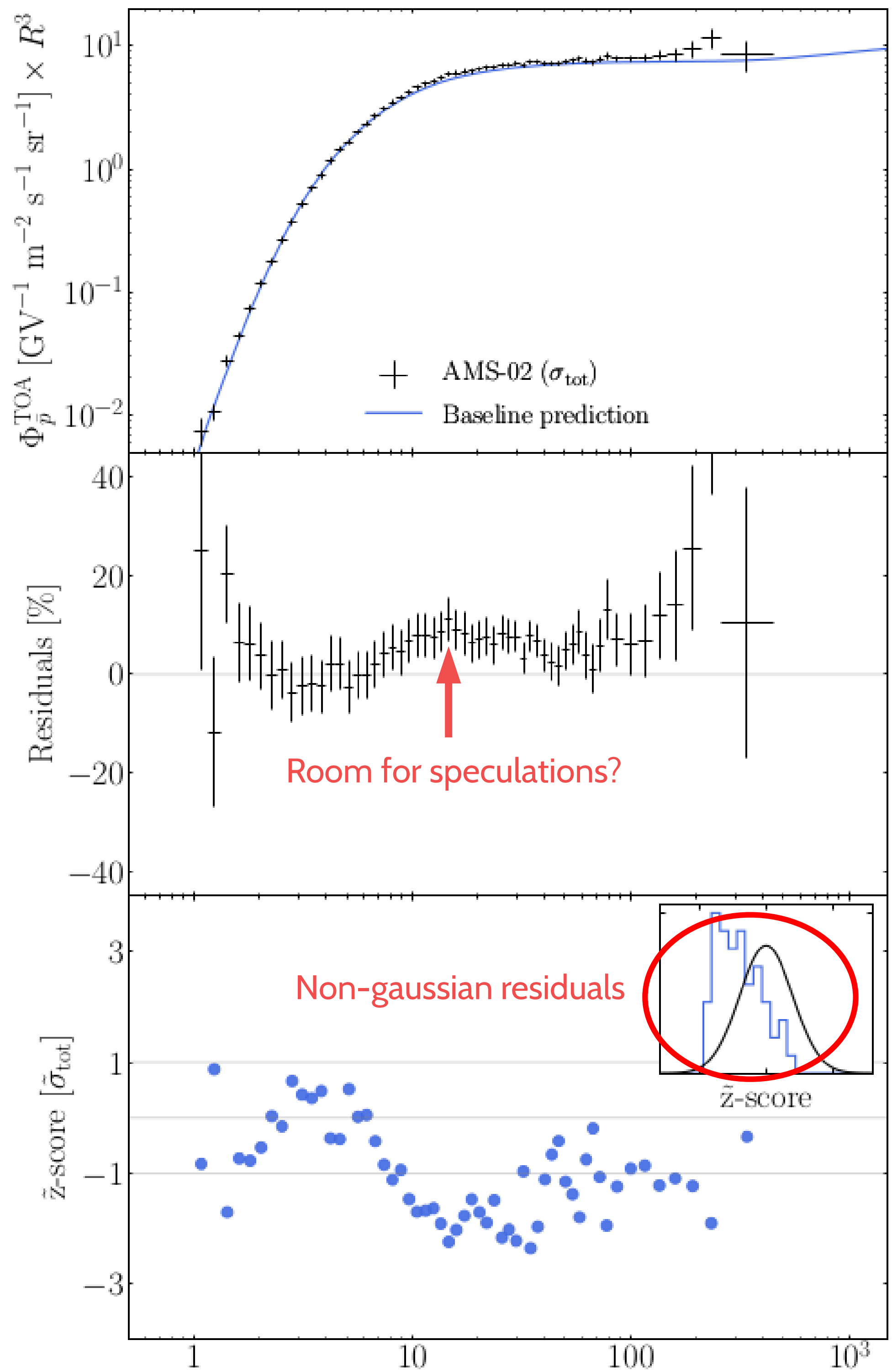
(Aduszkiewicz+2017,*Anticic+ 2010, Aaij+2018)*

→ Updated parameterisation and uncertainties

(Winkler, M. 2016, Korsmeier, M. + 2018)

→ Isospin asymetry taken into account

(H.Fischer for NA49 Collab. 2003)



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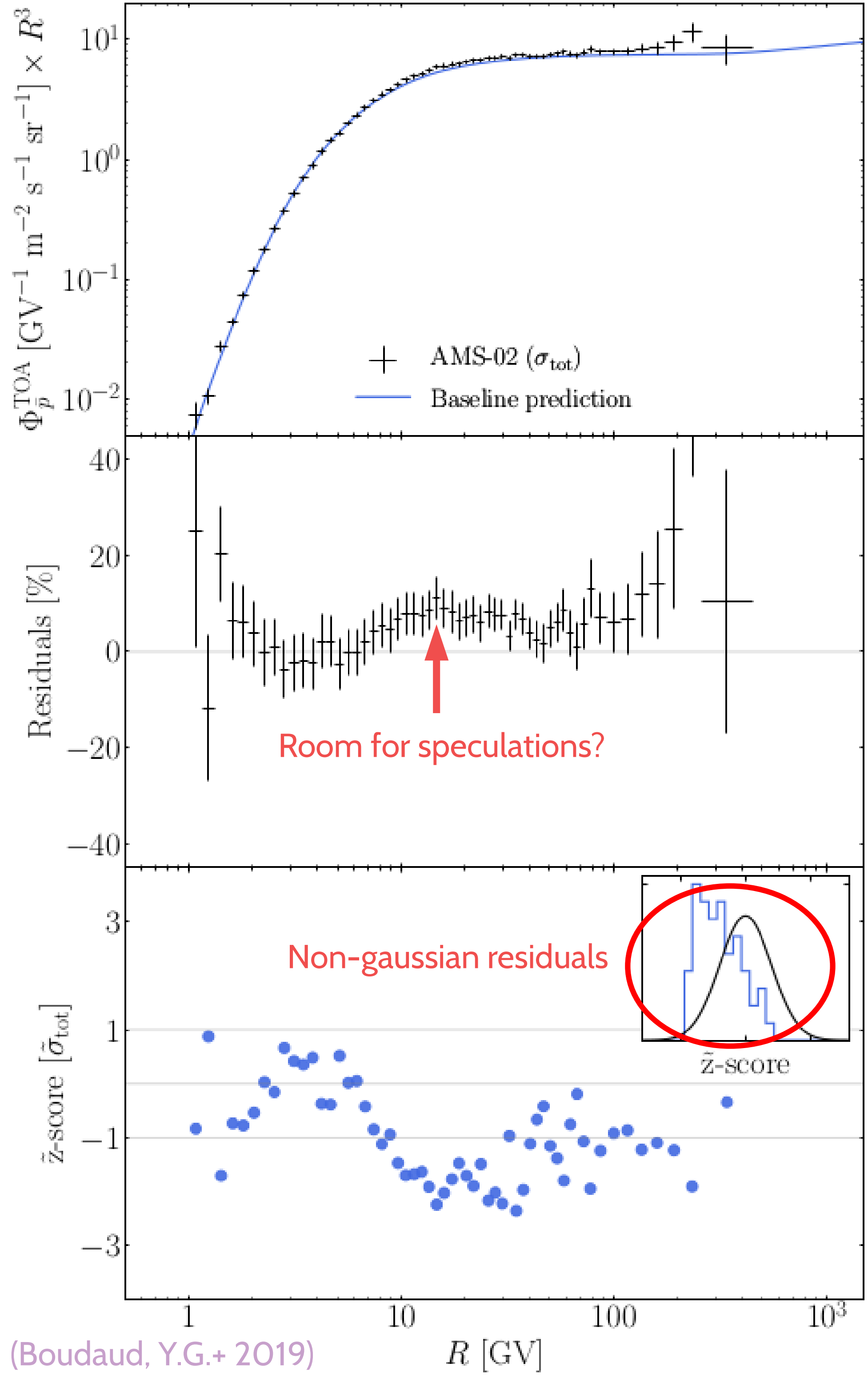

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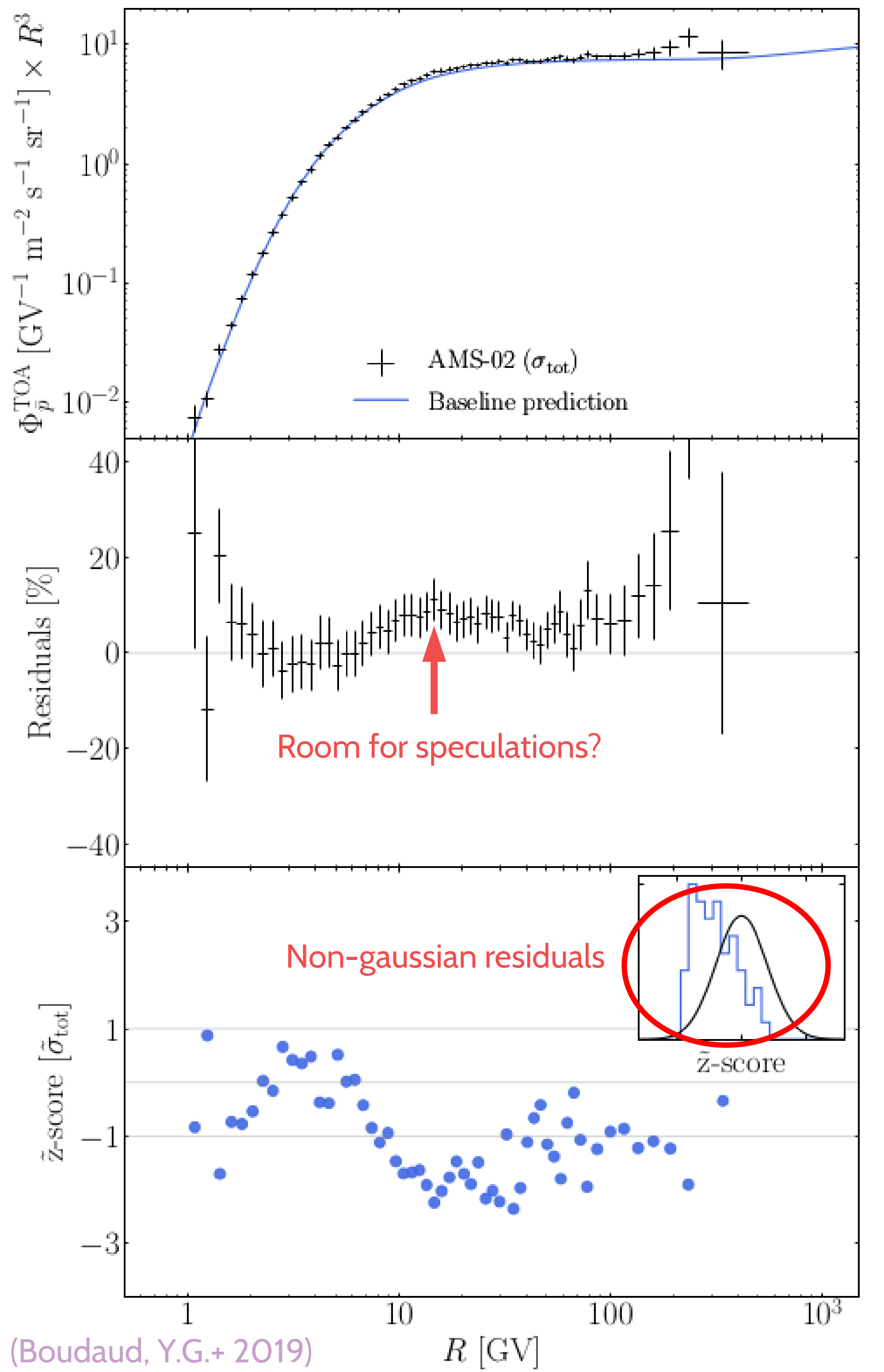
New Li, Be, B/C data from AMS02

→ Updated transport models and uncertainties

(Y.G.+ 2017, 2019, 2021 Derome+ 2019, Weinrich, Y.G.+ 2020)



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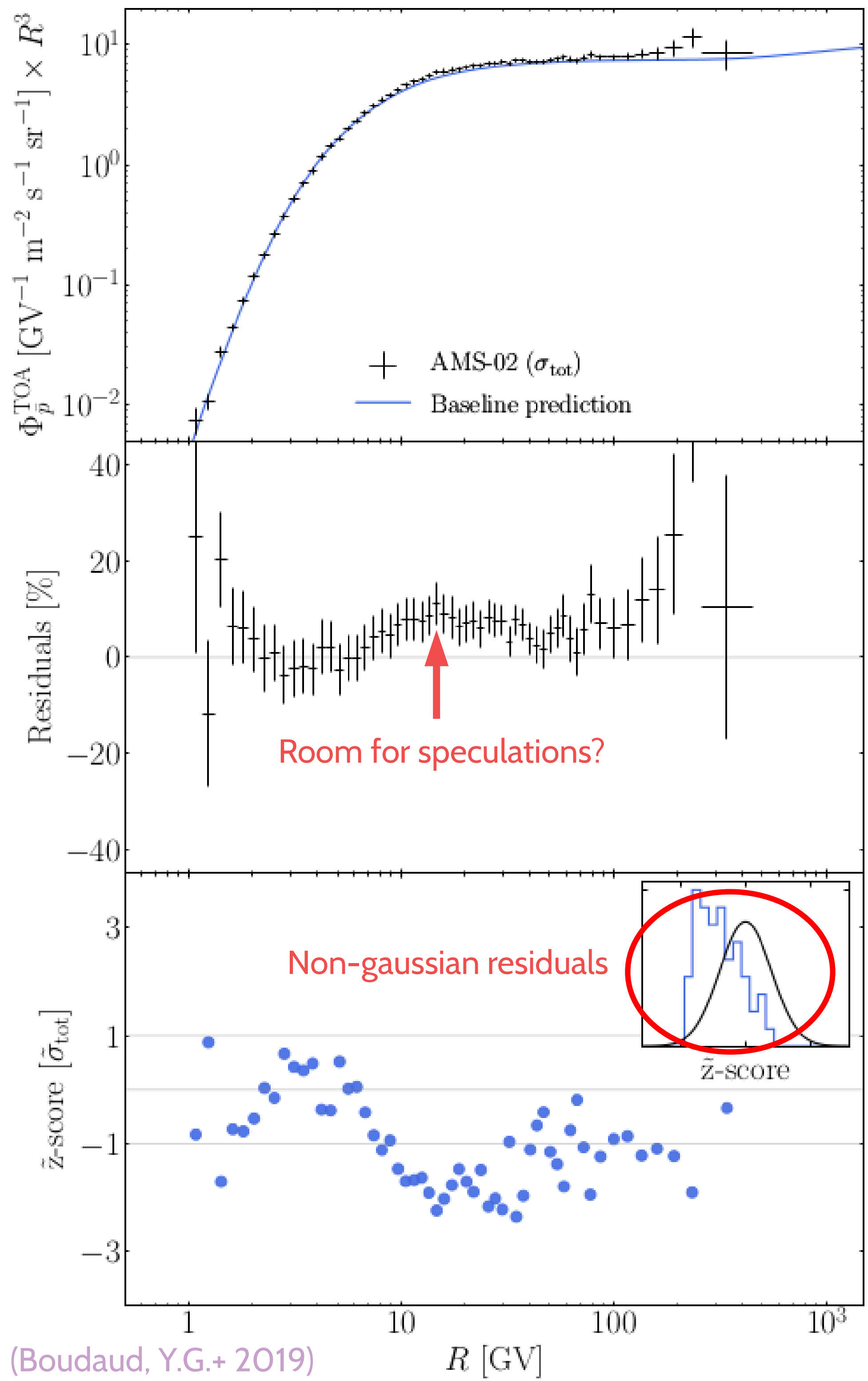

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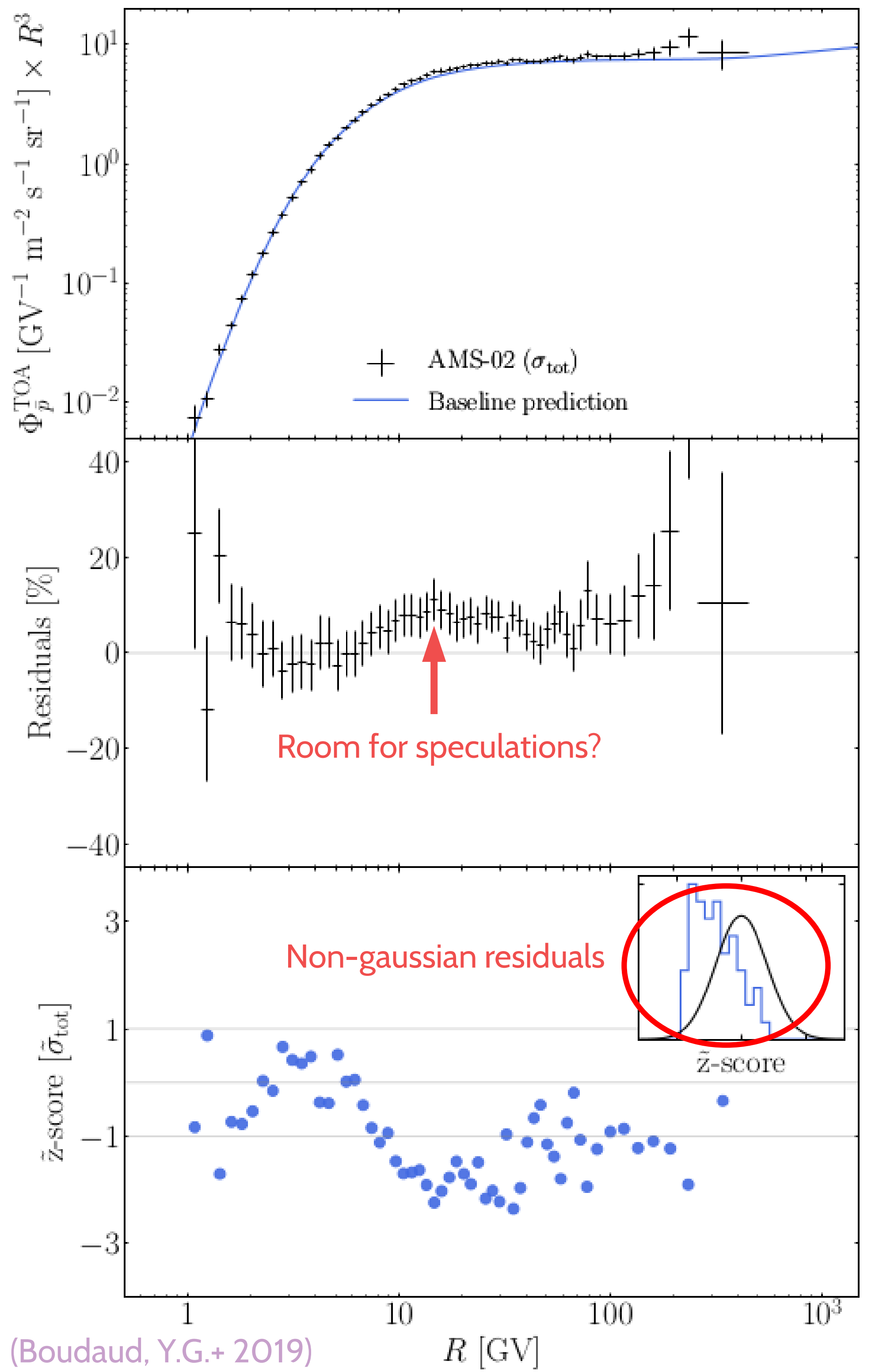
New H, He, C,N,O... data from AMS02
(AMS02 Collab. 2017, 2019)

→ Updated fit and contribution of high-Z elements



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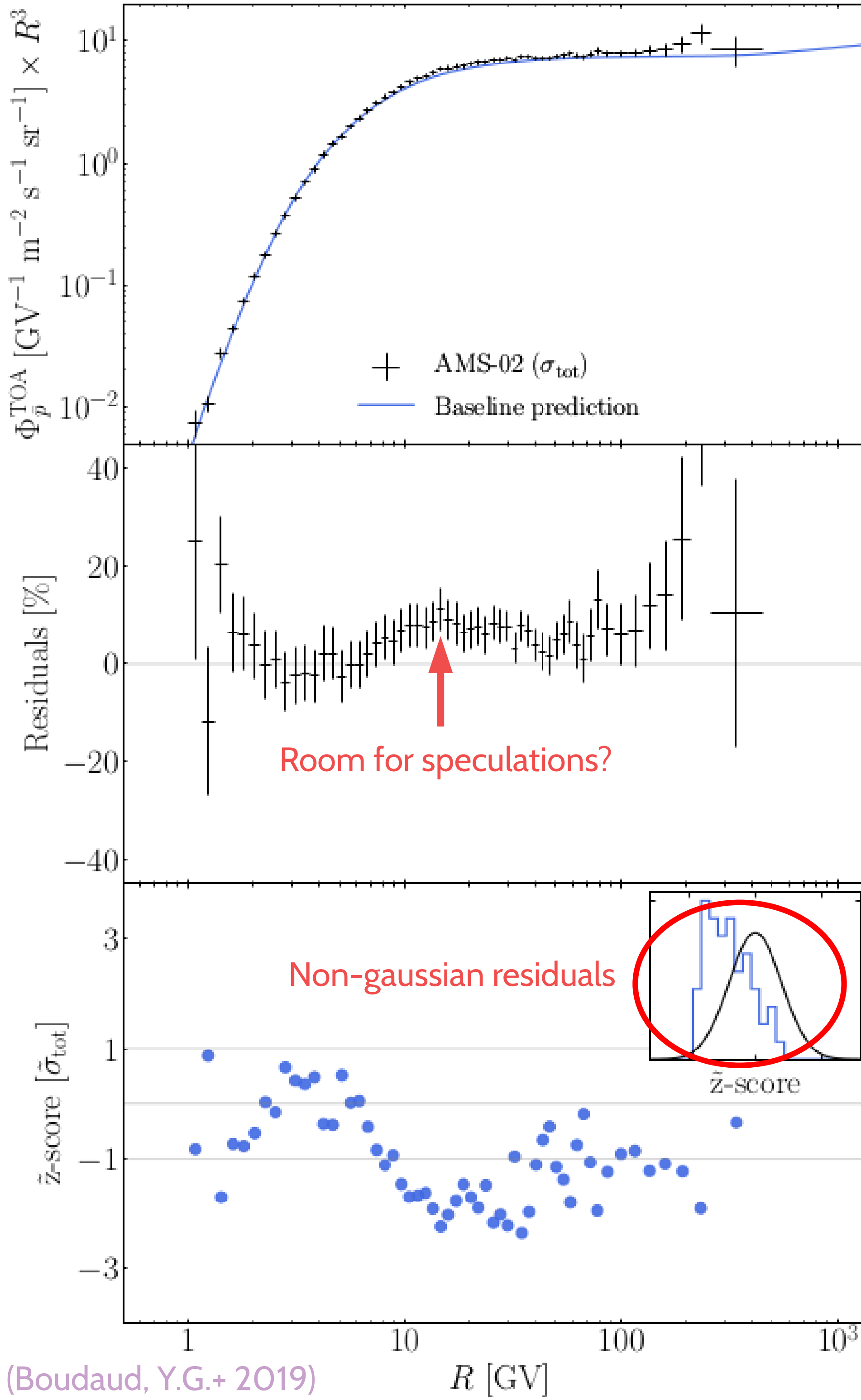

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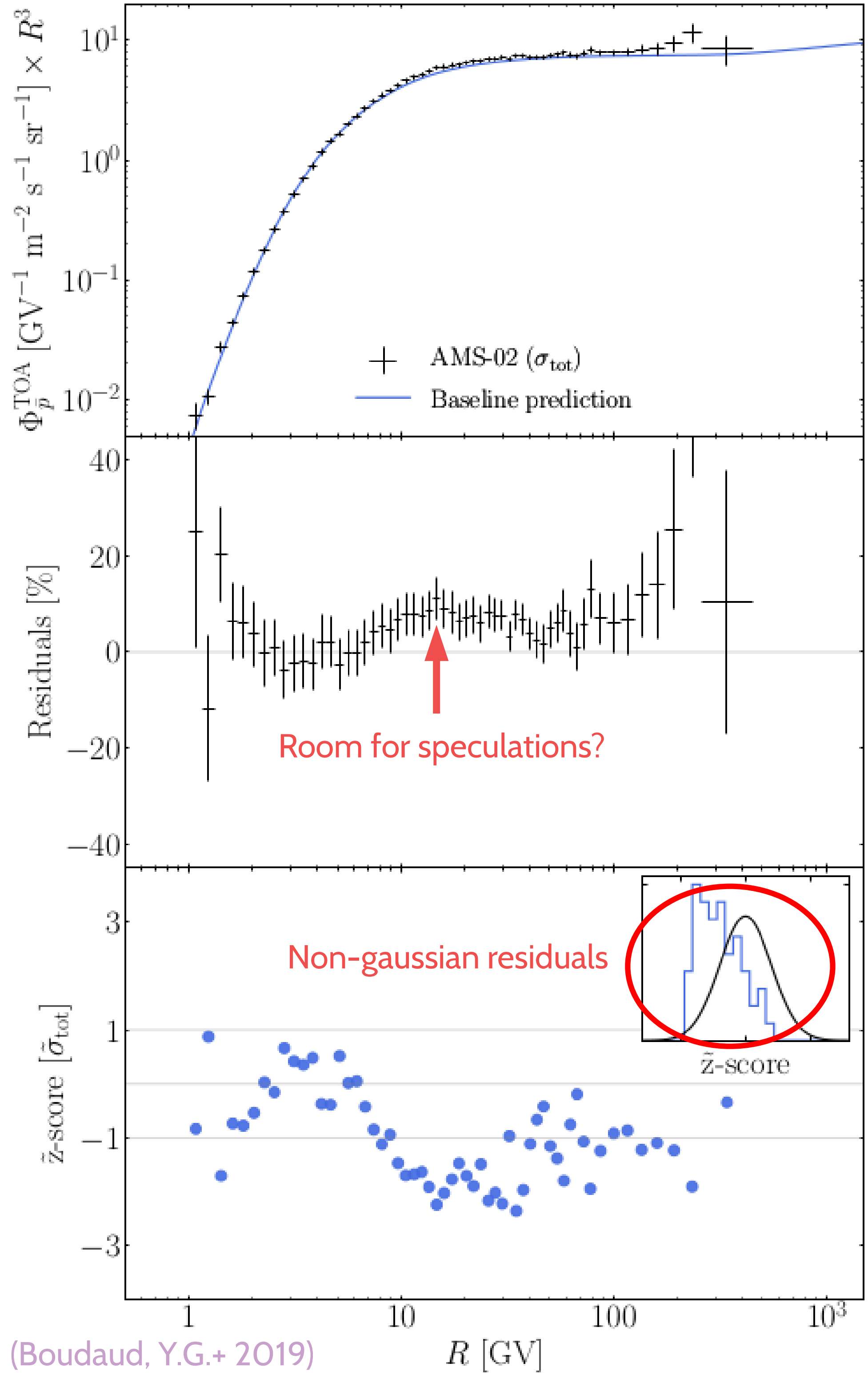

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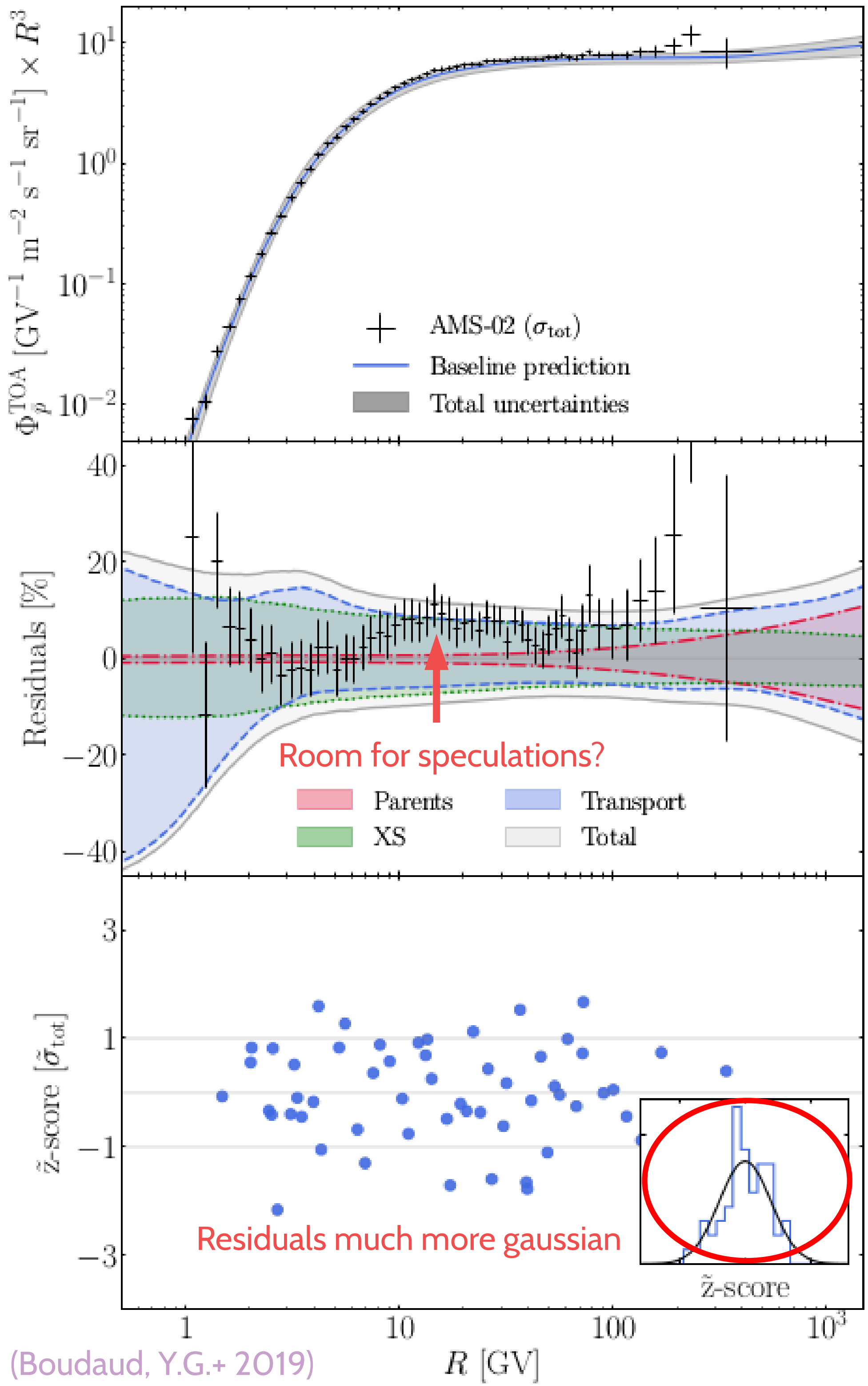
→ Chi2 test with:

$$\chi^2=(\text{data}-\text{model})^T(\mathcal{C}^{\text{model}}+\mathcal{C}^{\text{data}})^{-1}(\text{data}-\text{model})$$



(Boudaud, Y.G.+ 2019)

An excess in CR antiprotons?

Secondary

Statistical tests (Boudaud, Y.G.+ 2019)

→ Chi2 definition:

$$\chi^2 = (\text{data}-\text{model})^T (\mathcal{C}^{\text{model}} + \mathcal{C}^{\text{data}})^{-1} (\text{data}-\text{model})$$

→ Chi2-test:

$$\chi^2/dof = 0.77$$

$$p_{value} = 0.90$$

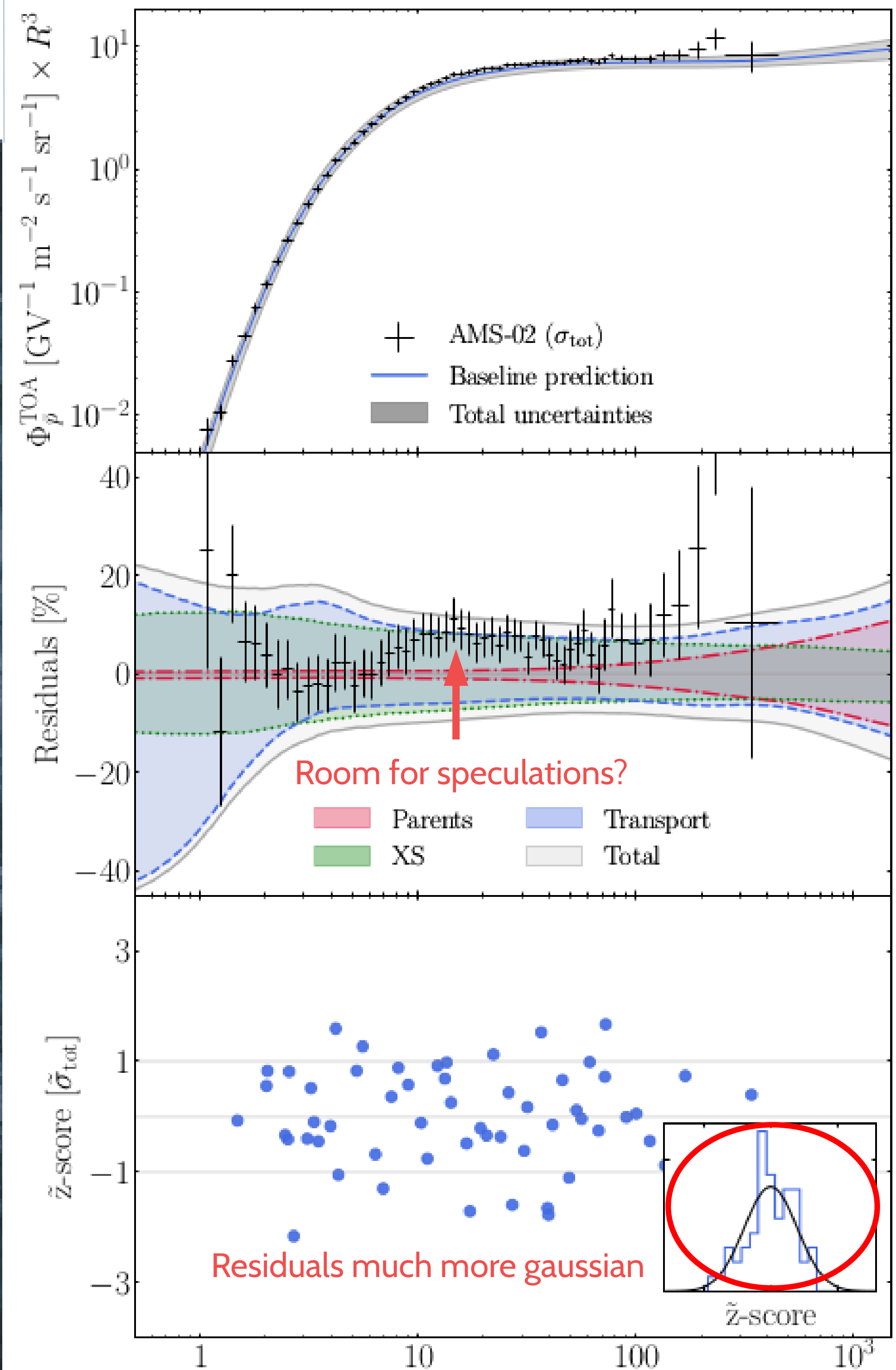
→ KS-test:

$$p_{value} = 0.27$$

→ AMS-02 antiprotons are consistent with a secondary astrophysical origin

Other studies confirmed (Heisig+ 2020)

Does that mean there cannot be statistical evidence for DM?

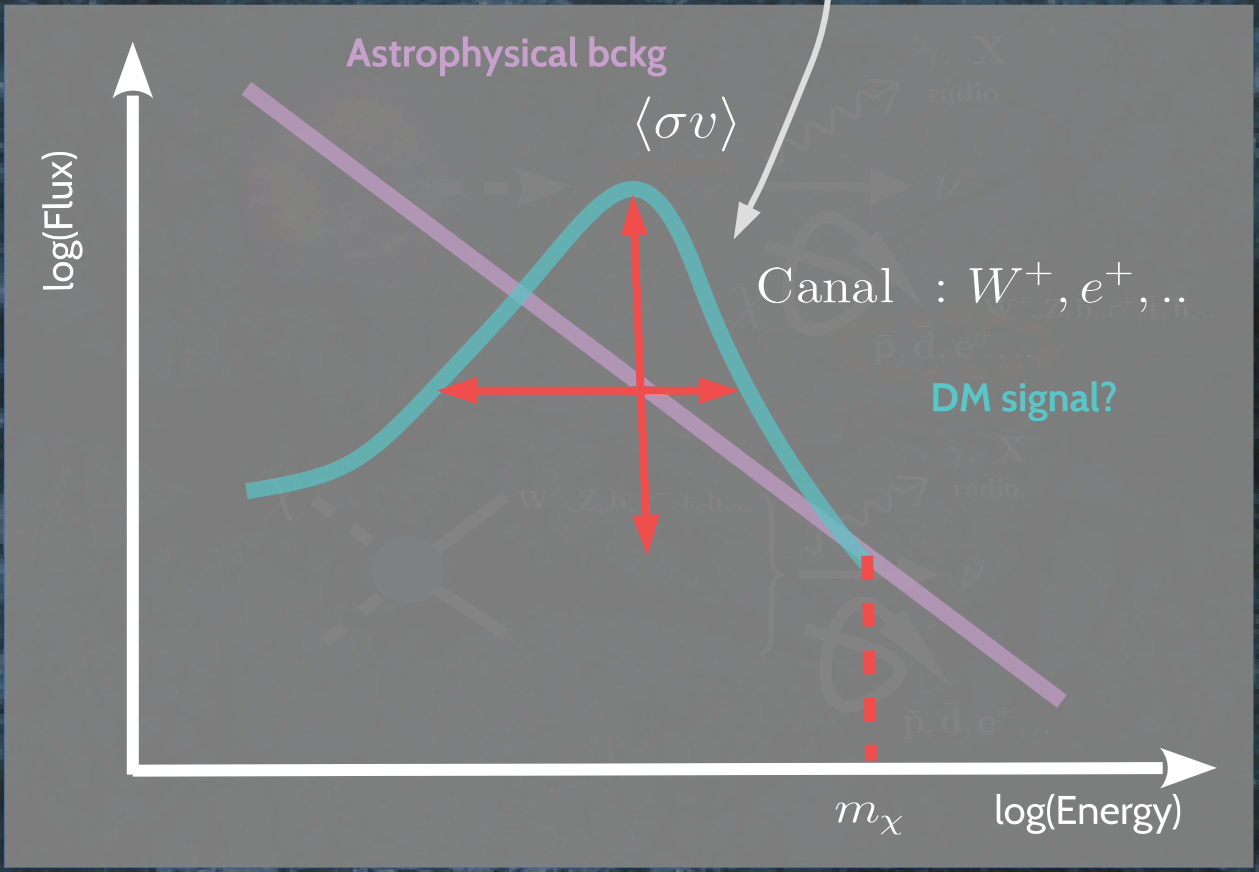


(Boudaud, Y.G.+ 2019)

An excess in CR antiprotons?

Secondary +Dark Matter

Dark Matter antiproton component



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Dark Matter antiproton component

→ Typical DM annihilation channels

$$b\bar{b},\ W^+W^-,\ \mu^+\mu^-,\ q\bar{q},\ hh$$

→ Inputs spectra from PPPC4MID

(Cirelli+ 202X)

→ DM profile considered

Generalized NFW profile (Navarro+ 1996)

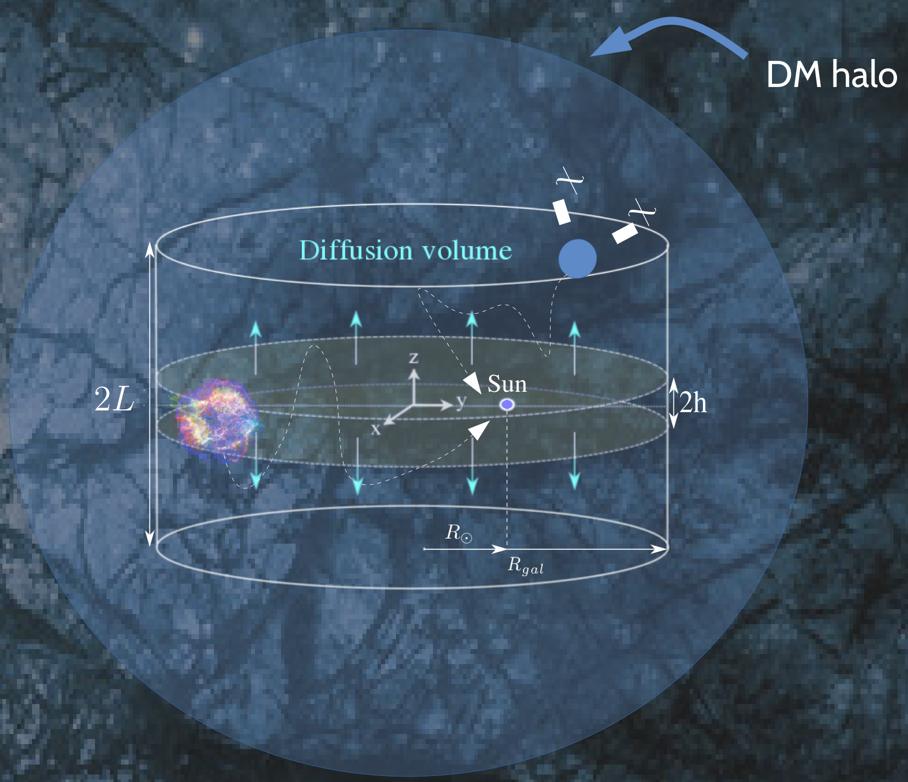
$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^\gamma\ (1+r/r_s)^{3-\gamma}}$$

Profile	γ	r_s [kpc]	ρ_s [$M_\odot$/pc^3]
benchmark NFW	1.0	19.6	0.00854
cored	0.0	7.7	0.08931
contracted NFW	1.25	27.2	0.00361

(McMillan+ 2016 → but renormalized)

→ We use NFW as benchmark

→ Depends on the magnetic halo size H



Above GeV, at first order $\phi_{\bar{p}}^{DM} \propto L$

New AMS02 data on Be/B + e⁺ sensitive to L

→ Reevalutation of the halo size $L \approx 5 \pm 2$ kpc

(Weinrich,..., Y.G. + 2020)

An excess in CR antiprotons?

Secondary + Dark Matter

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Exploring the nul hypothesis

→ No significant excess found

$$LR = -2\ln \frac{\sup_{\lambda\in\Lambda}\mathcal{L}(\lambda)}{\sup_{\{\lambda,\mu\}\in\Lambda\cup M}\mathcal{L}(\lambda,\mu)}$$

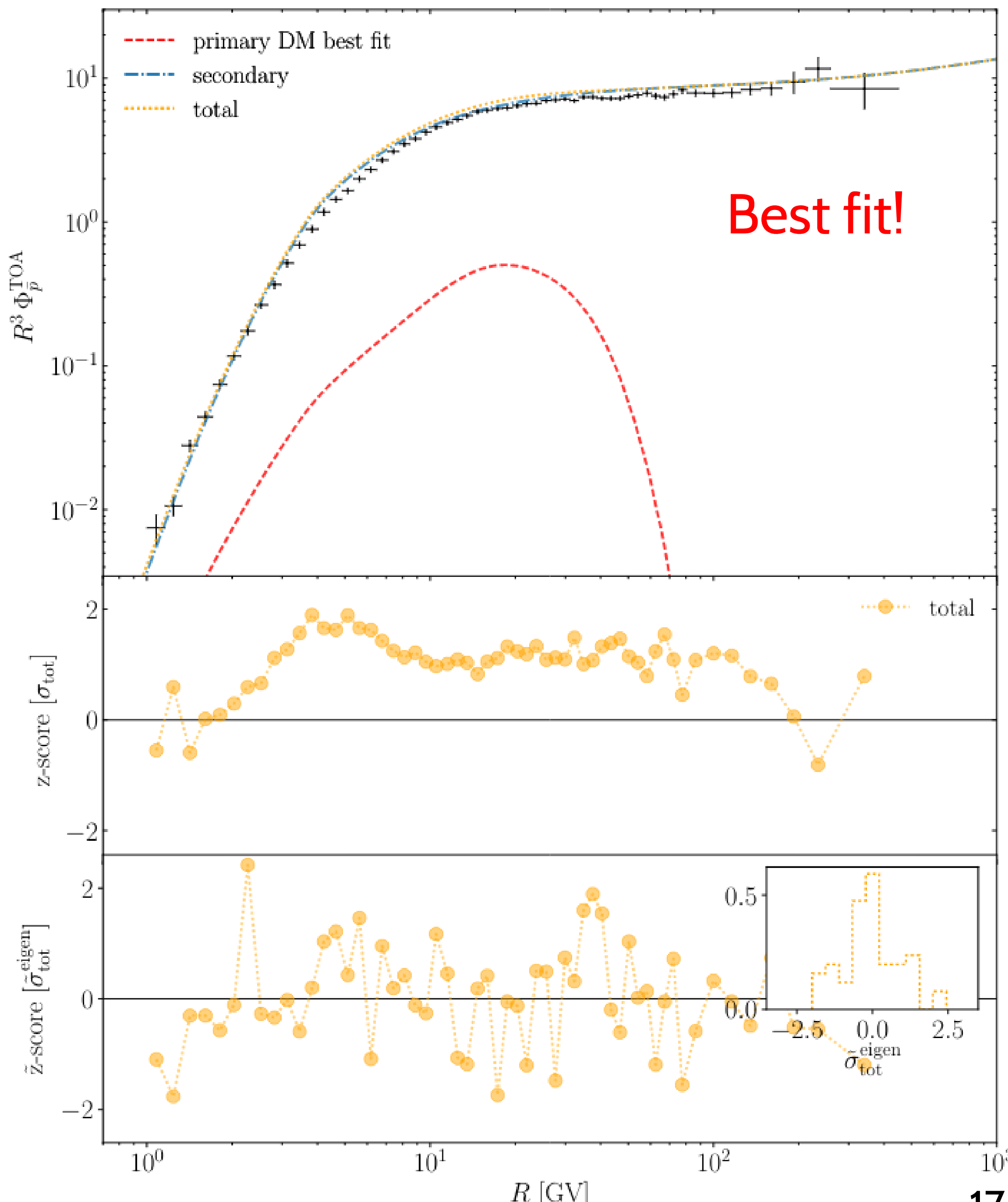
Chernoff's theorem used, $\langle\sigma v\rangle = 0$
= pure secondary antiprotons

Final state	Model	m^* [GeV]	$\langle\sigma v\rangle^*$ [cm^3/s]	LR (denom)	LR (num)	LR	local signif. [σ]
$b\bar{b}$	BIG	109.3	1.71e-26	48.37	51.65	3.28	1.8
$b\bar{b}$	SLIM	109.1	1.48e-26	48.77	51.70	2.93	1.7
$b\bar{b}$	QUAINT	106.7	4.28e-27	45.32	45.53	0.22	0.5
$q\bar{q}$	BIG	88.5	4.41e-27	50.31	51.65	1.35	1.2
$\mu^+\mu^-$	BIG	155.7	2.65e-23	49.76	51.65	1.90	1.4
W^+W^-	BIG	106.8	2.20e-26	49.24	51.65	2.41	1.6
hh	BIG	166.7	3.62e-26	49.28	51.65	2.38	1.5

→ Major impact of uncertainty choice

Err. data / model	local signif. [σ]	m^* [GeV]	$\langle\sigma v\rangle^*$ [cm^3/s]
cov/cov	1.81	109.3	1.71e-26
cov/none	2.39	10.5	5.07e-26
diag/cov	3.33	98.8	2.14e-26
diag/none	2.75	8.5	1.70e-25
stat/cov	5.19	89.7	1.48e-26
stat/none	4.49	8.0	2.98e-25

Some studies confirmed (Heisig+ 2020)
Some less cautious studies find excesses



An excess in CR antiprotons?

Secondary +Dark Matter

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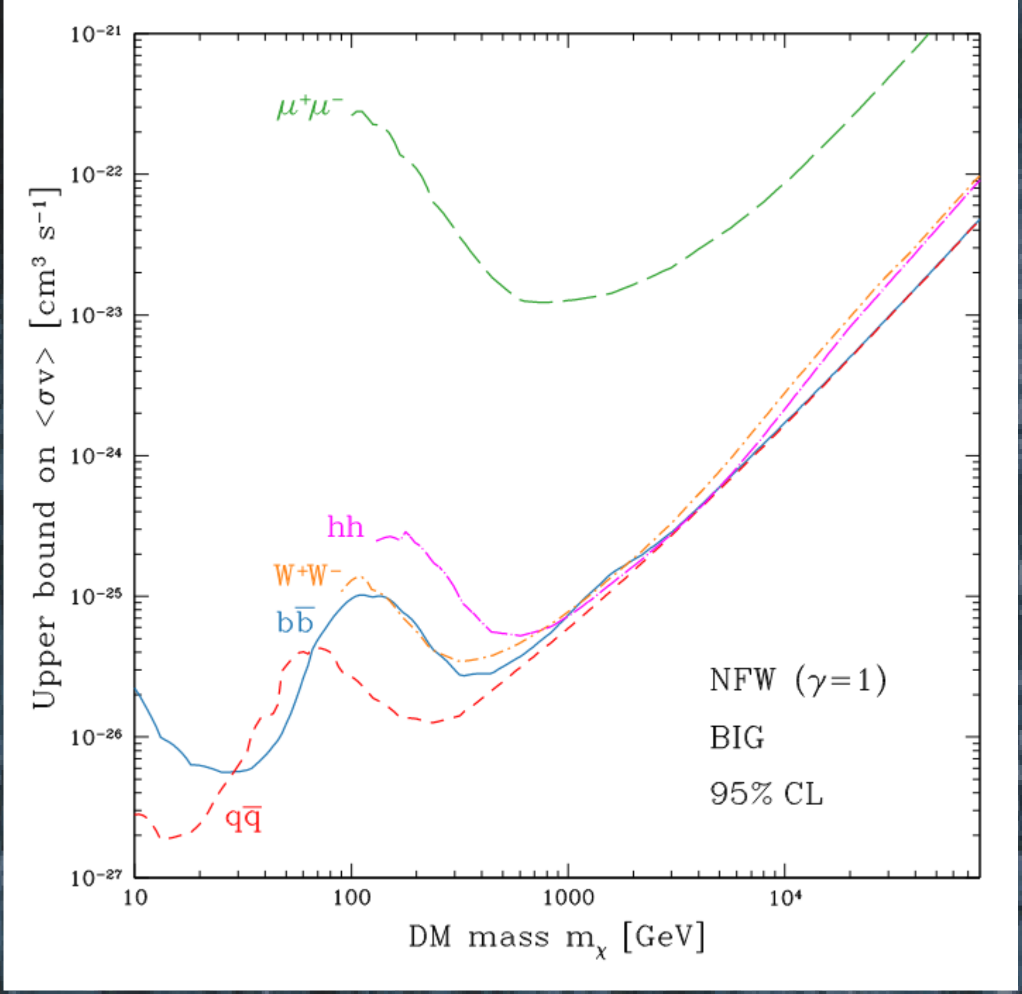
Upper limits on the DM annihilation xs: our results



→ Bounds for 5 representative annihilation channels

→ NFW DM profile / BIG propagation model

→ Weakening of the bound = *slight excess*

→ mu⁺ mu⁻ bound not competitive

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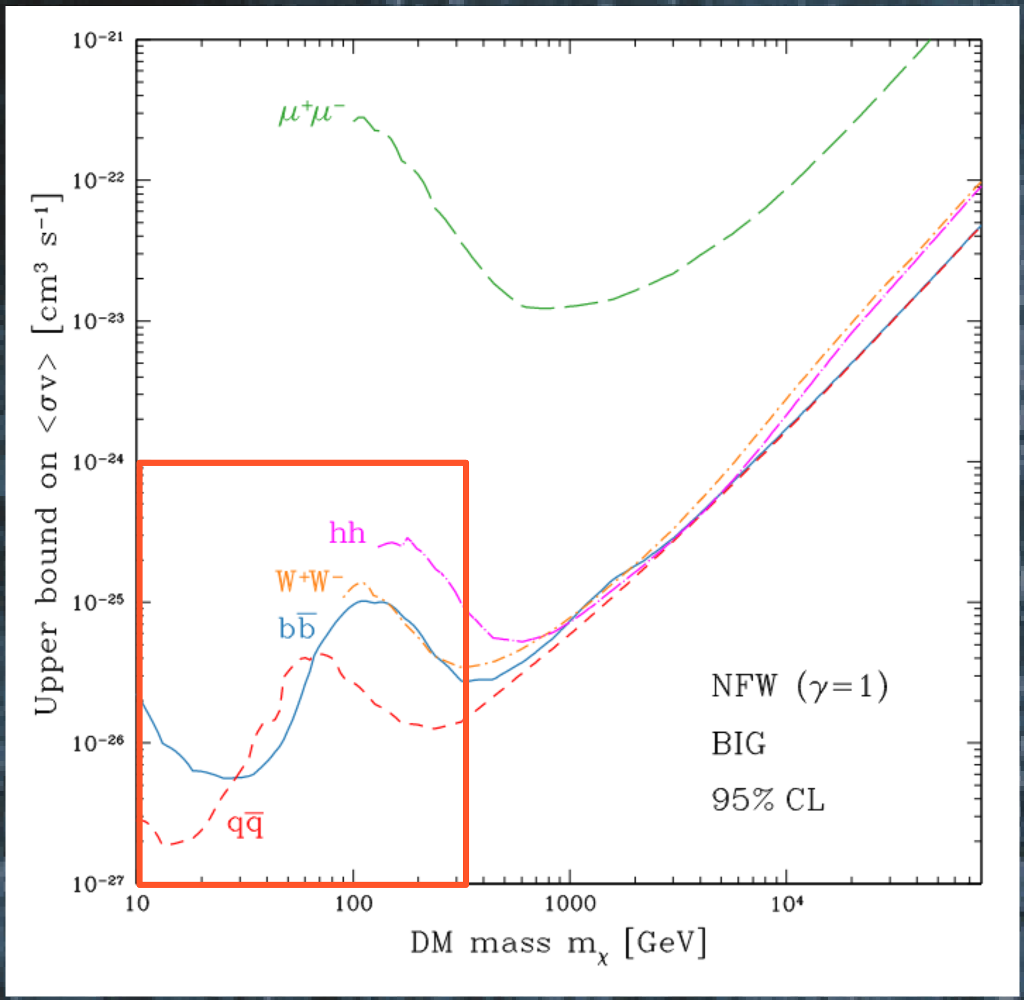
Upper limits on the DM annihilation xs: our results



→ Bounds for 5 representative annihilation channels

→ NFW DM profile / BIG propagation model

→ Weakening of the bound = *slight excess*

→ mu^+ mu^- bound not competitive

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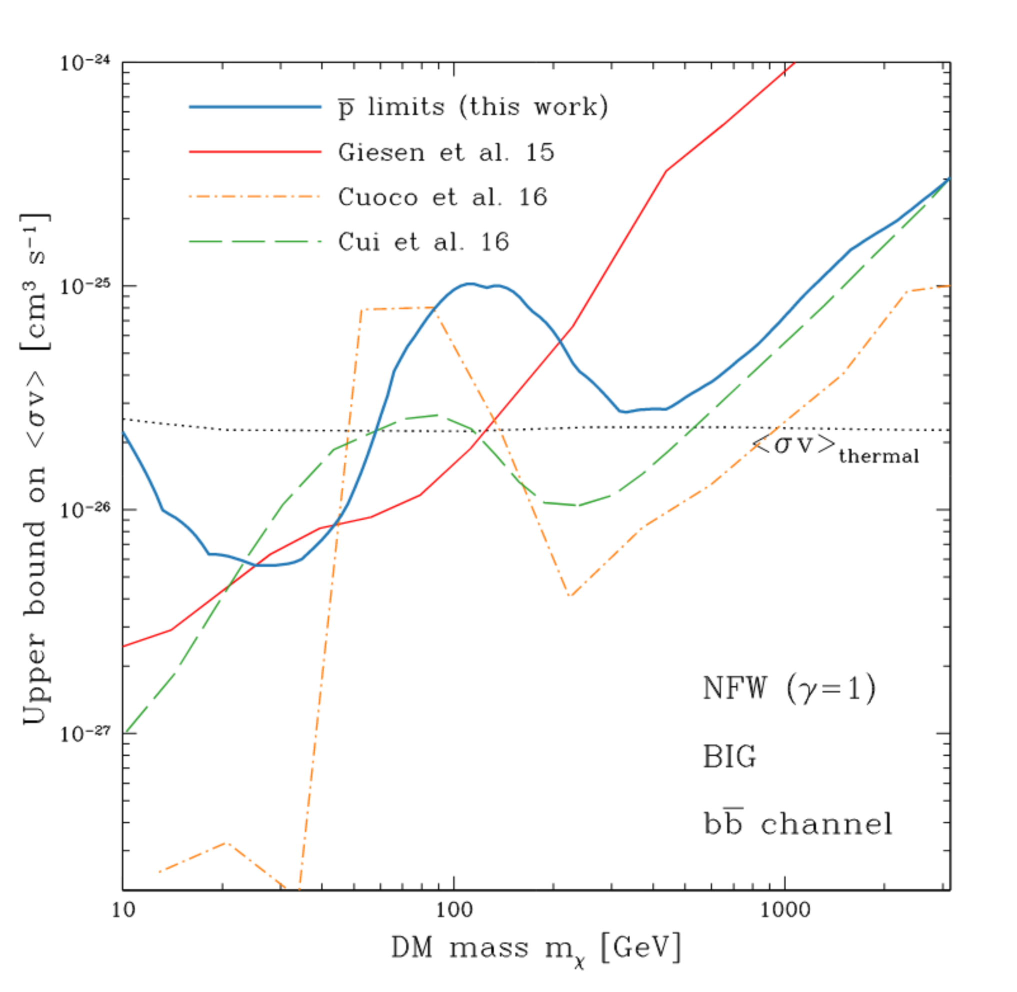
Upper limits on the DM annihilation xs: comparison with other works



→ New propagation models, callibrated on AMS02, fit better HE pbars

→ Cui et al. 16: agree with high masses, at low masses difference in propagation model + significance of the excess

→ Cuoco et al. 16: same qualitative differences

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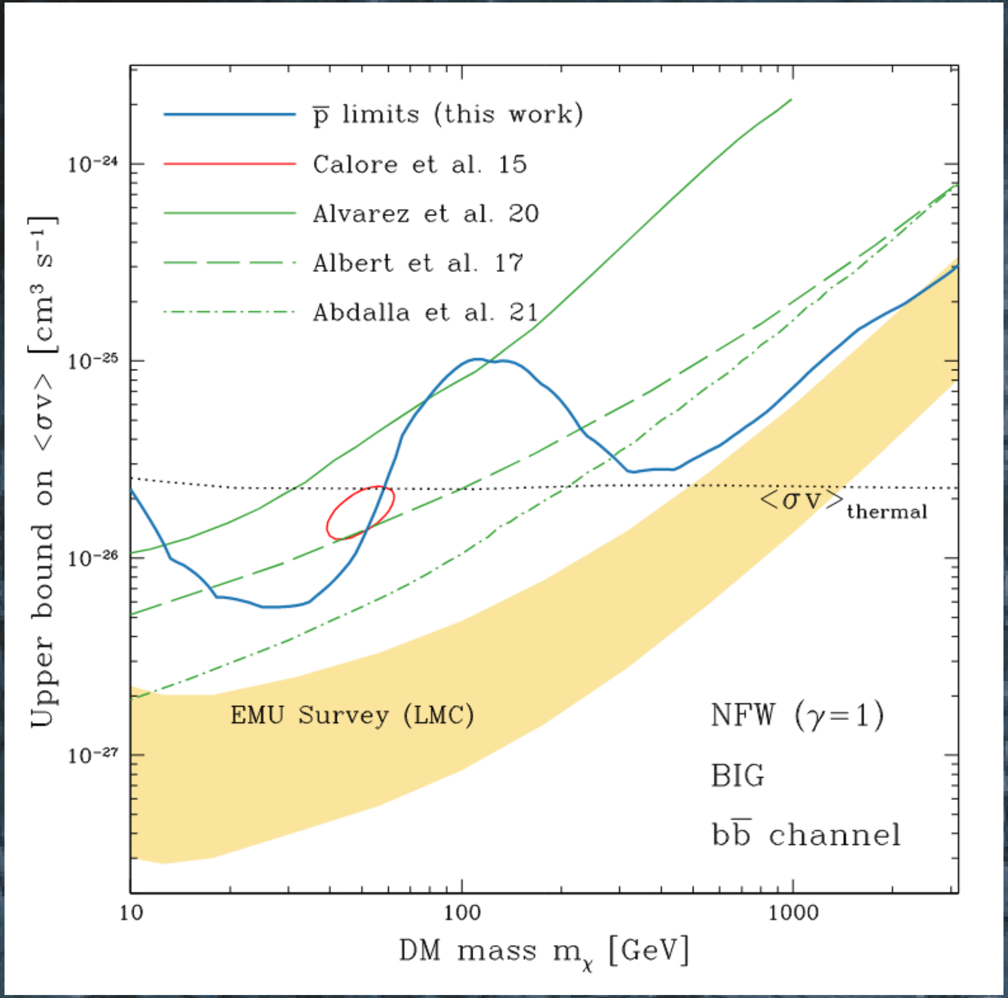
Upper limits on the DM annihilation xs: comparison with photon constraints



→ Three different dSph gamma ray constraints:
- conservative → aggresive

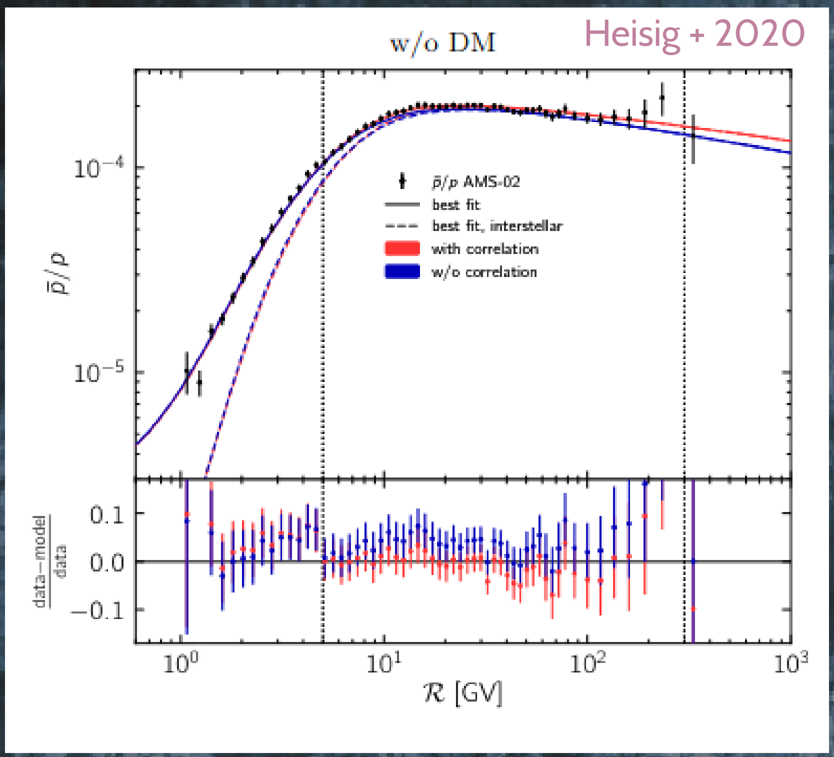
→ Large Magellanic Cloud (LMC):
- no excess in synchrotron radiation from $e^+ e^-$
- band = uncertainties in B field and DM profile

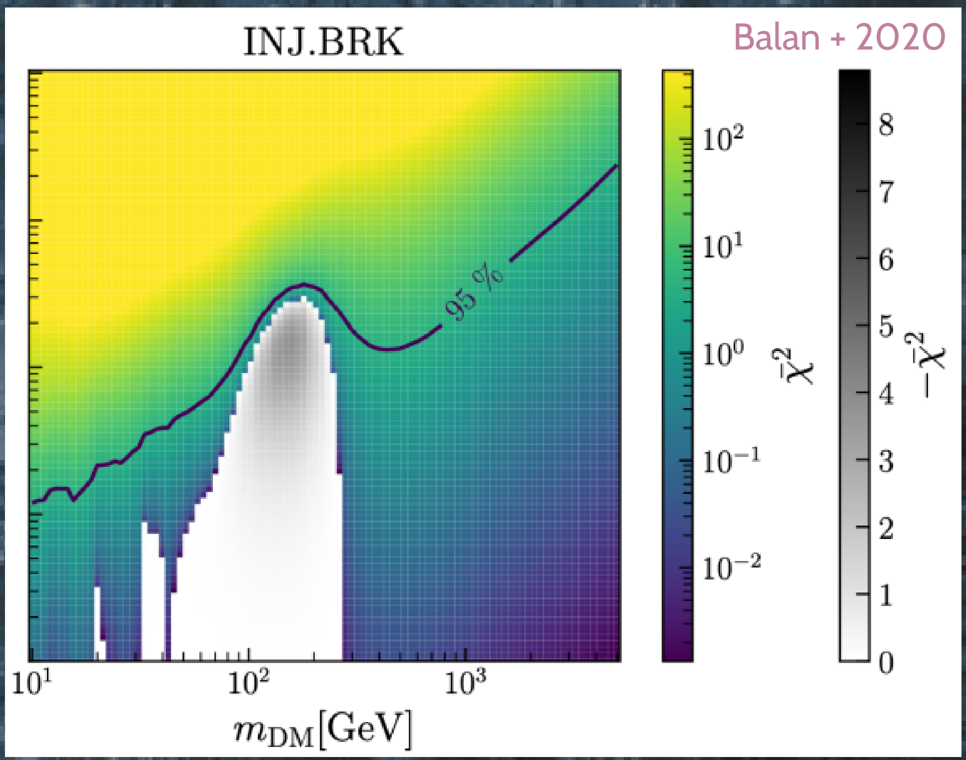
→ Complementarity of the pbar bound

→ We plan to implement this constraint in micrOmega

An excess in CR antiprotons?

Works from other groups





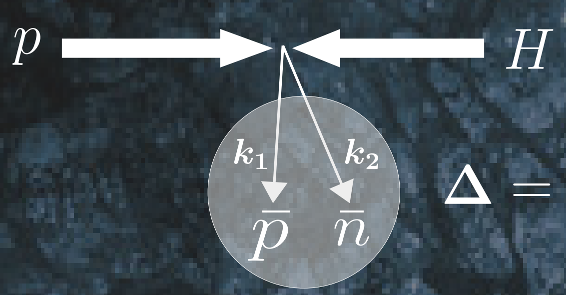
→ Similar statistical analysis using covariance matrix for systematic errors
→ Excess insignificant

→ DarkRayNet new public tool developped
→ Predict secondary and primary with NN
→ Make the comparison with DM models more versatile

Outline

Antideterons in CR

(recent review : P. Von Doetinchem +2020)



$$\Delta = k_1 - k_2$$

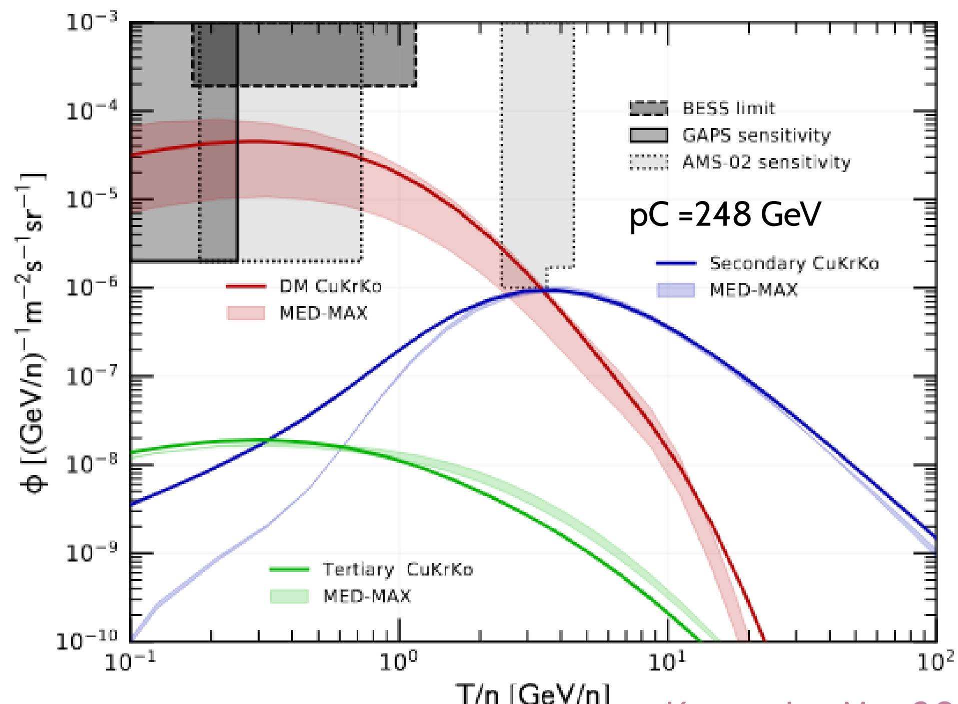
Production rules for antinuclei:
→ fusion of antinucleons occurs when

$$||\Delta|| < p_C$$

→ formation around the thershold energy of antinucleons form spallation reactions

→ spread at low energy from solar modulation

→ DM annihilation ~at rest produces low-energy antideterons



Korsmeier, M. + 2018

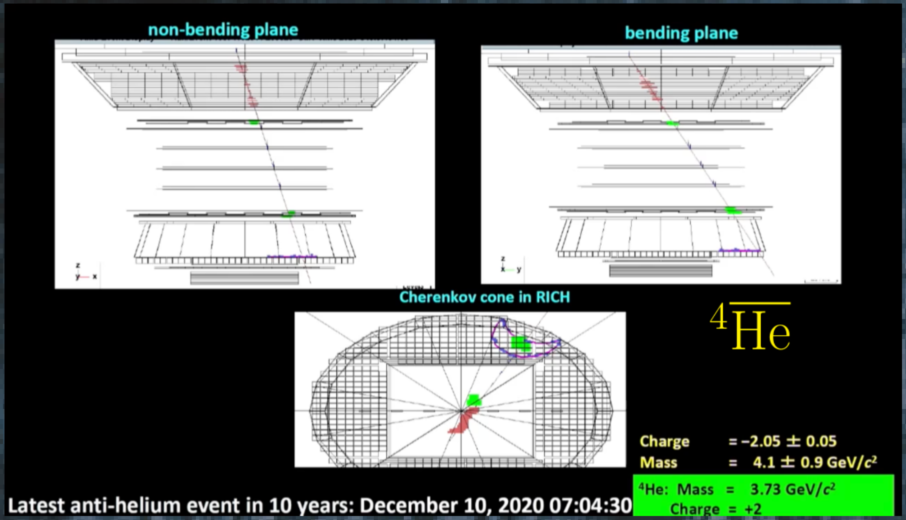
→ Update of the coalescence factor from the ALICE experiment (Acharya, S. +2018)
→ Update of the expected secondary antideuterons flux (Korsmeier, M. + 2018, Poulin, V + 2019)

→ AMS02 and GAPS will give at least upper bounds

The antinuclei frontier

Anti-helium in CR

Anti-helium 4 detected in AMS02?

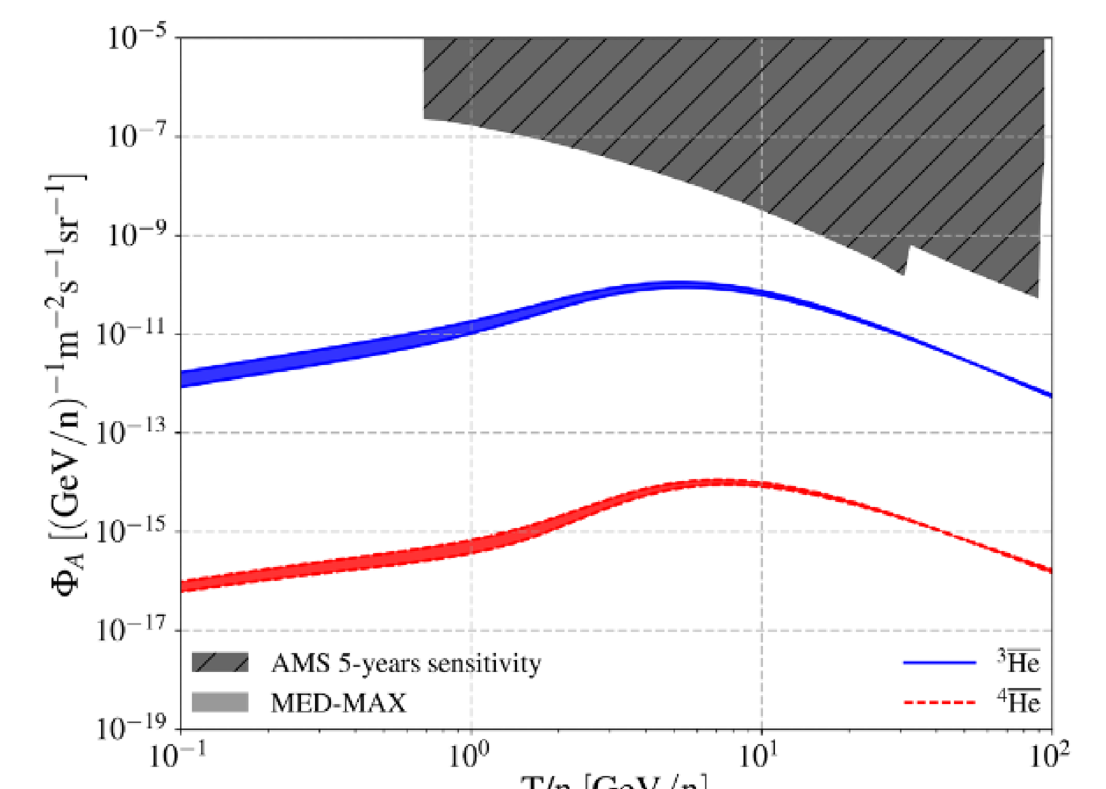


(V. Choutko, COSPAR conf. July 17th 2022)

→ Few events [0, 10] GeV with Z=-2
→ 6 anti-He 3 and 2 anti-He 4
→ Rate ~1 anti-He/ 100M He

→ Difficult to evaluate the significance
→ So far no anti-He bckgd event in simulations
→ Heavy MC simulation needed

→ Required further investigations (GAPS, etc)



Poulin, V + 2019

→ Update of the coalescence factor from the ALICE experiment (Acharya, S. +2018)
→ Update of the expected secondary antiHe flux (Korsmeier, M. + 2018, Poulin, V + 2019)
→ AMS02 antiHe = new exotic production needed
.. if true!

Conclusion and prospects

Indirect detection of dark matter with cosmic rays

→ e^+ Presistent excess in tension with present DM bounds
Better explained by local pulsars
→ HE γ-ray/radio signal and e^+ anisotropies data are coming
(HESS, LHAASO, CTA, Fermi, AMS100?...)

→ $\bar{p}$ No significant excess reported untill now
Refined treatment of errors is essential
→ Finer analysis needs: statistic does not help!
experimental data covariance matrix from AMS02 collab.
better pbar production xs (LHCb, AMBER, ..)
→ AMS02 2021 data bring new challenges: needs new CR models?
→ Meanwhile, constraints competitive with the best bound of the literature

→ $\bar{d}$ Measurements eagerly awaited from GAPS !
→ First flight at the end of this year?

→ *anti-He* Few events presumably detected by AMS02...
→ Let's wait a published version

Conclusion and prospects

D. Maurin et al. 2503.16173, submitted. To Physics Report

Precision cross-sections for advancing cosmic-ray physics and other applications: a comprehensive programme for the next decade

D. Maurin[a,*], L. Audouin[b], E. Berti[c], P. Coppin[d], M. Di Mauro[e], P. von Doetinchem[f], F. Donato[e,g,h], C. Evoli[i,j], Y. Génolini[k], P. Ghosh[l], I. Leya[m], M. J. Losekamm[n,o], S. Mariani[h], J. W. Norbury[p], L. Orusa[q,r], M. Paniccia[d], T. Poeschl[h], P. D. Serpico[k], A. Tykhonov[d], M. Unger[s], M. Vanstalle[t], M.-J. Zhao[u,v], D. Boncioli[w,j], M. Chiosso[e,g], D. Giordano[e], D. M. Gomez Coral[x], G. Graziani[c], C. Lucarelli[h], P. Maestro[y,z], M. Mahlein[n], L. Morejon[aa], J. Ocampo-Peleteiro[ab], A. Oliva[ab], T. Pierog[t], L. Šerkšnytė[h]

→ Collection of requests for XS measurements (sought energies & precision)
- Antinuclei production
- Fragmentation cross-sections

→ Main Facilities:
- At the SPS AMBER – NA61/SHINE
- At LHC: ALICE – LHCb
- And other Multi-GeV facilities for nuclear cross-sections

Tools

Codes:

→ Solving the advection/diffusion transport equation
Numerical solvers: GALPROP, DRAGON, PICARD
Semi-analytical solver: USINE

→ Setting constraints on DM annihilation into CRs
Channel by channel
From antiprotons : Calore+ (2022)
From leptons : - High masses Di Mauro&Winkler (2021)
- Small masses Boudaud+ (2016, 2018)

DM models with specific injection spectra (peculiar resonance, kinematics..)
MicrOmega : update to come!
DarkRayNet : Balan+ (2021)

Methodology points presented today:

→ Prediction VS Data : Chi2 test → Must include data+model uncertainties and their correlations
→ KS test : test the overfiting, probe the gaussianity of a distribution
→ Likelihood ratio : hypotheses testing / +Chernoff's theorem

Secondary +Dark Matter

Calore, Cirelli, Derome, Genolini, Maurin, Salati, Serpico
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Statistical analysis

→ Likelihood ratio definition

$$LR(\mu_0) = -2\ln \frac{\sup_{\lambda\in\Lambda} \mathcal{L}(\lambda,\mu_0)}{\sup_{\{\lambda,\mu\}\in\Lambda\cup M} \mathcal{L}(\lambda,\mu)}$$

$(L, K, \delta, V_a, V_C, \sigma_{CR}, \ldots)$ CR-space

$(\langle\sigma v\rangle, m_\chi, channel)$ DM-space

→ With the following factorisation

$$-2\ln\mathcal{L}(\lambda,\mu) \equiv \chi^2_{\rm LiBeB}(\lambda) + \chi^2_{\bar{p}}(\lambda,\mu)$$

Constraints on the CR space

Tightest constraints on the DM space

→ Simplification of the likelihood

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

More words on antiprotons

Secondary +Dark Matter

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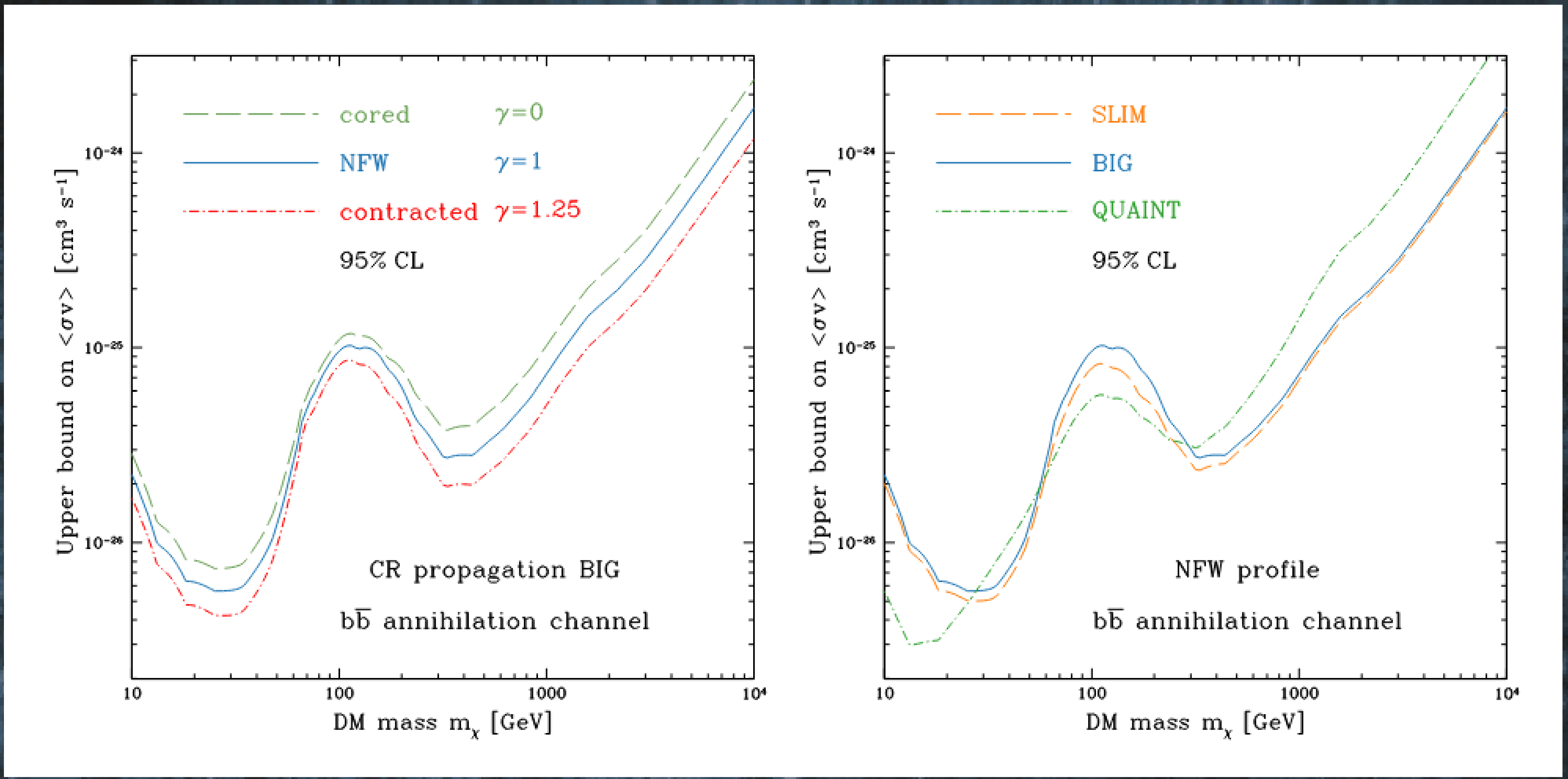
Upper limits on the DM annihilation cross section



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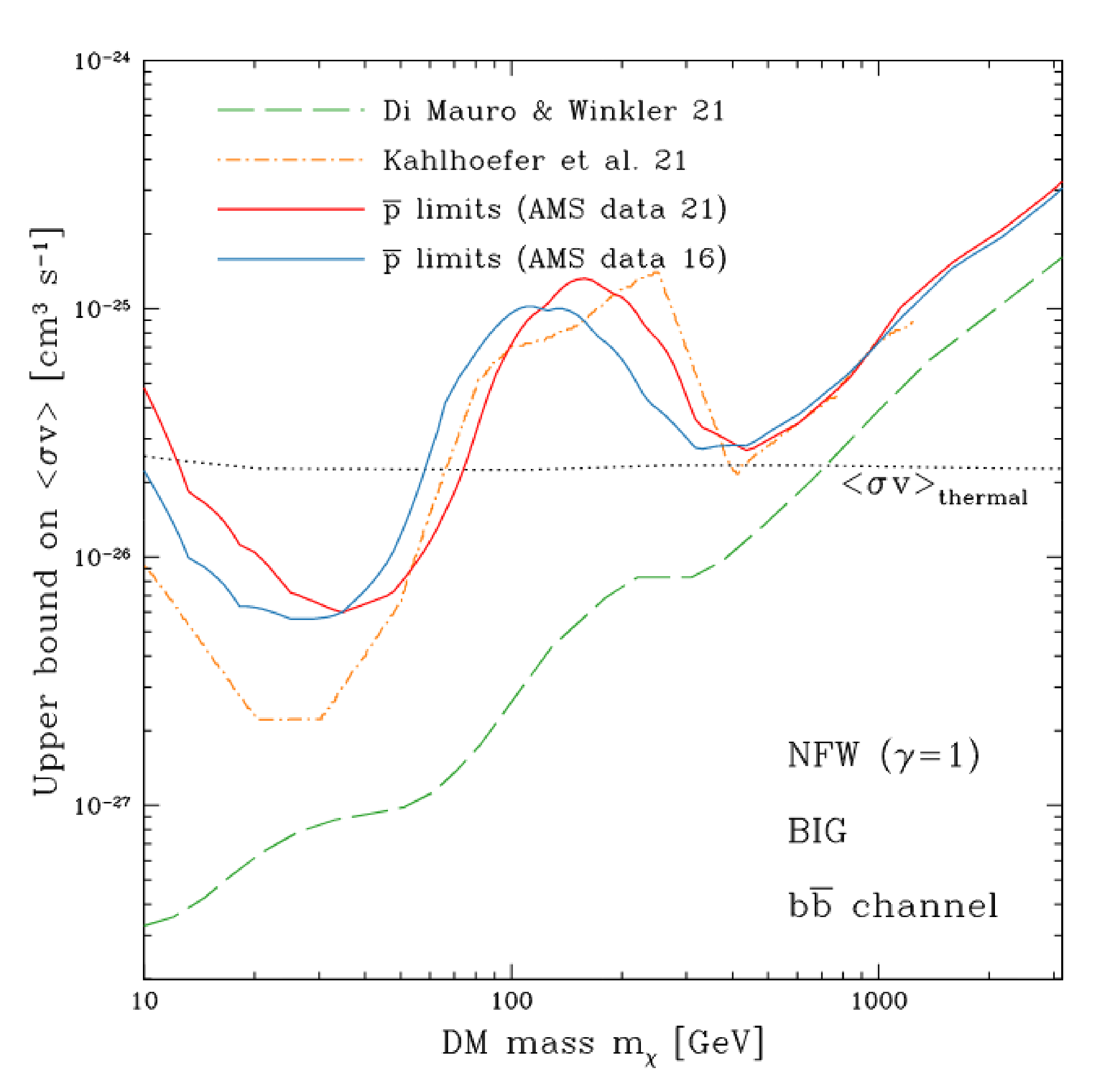

→ New data from 2021