Cosmic antiparticles
Is there room for dark matter?

Yoann Génolini

IRN Terascale – April 2023

Collaborators :

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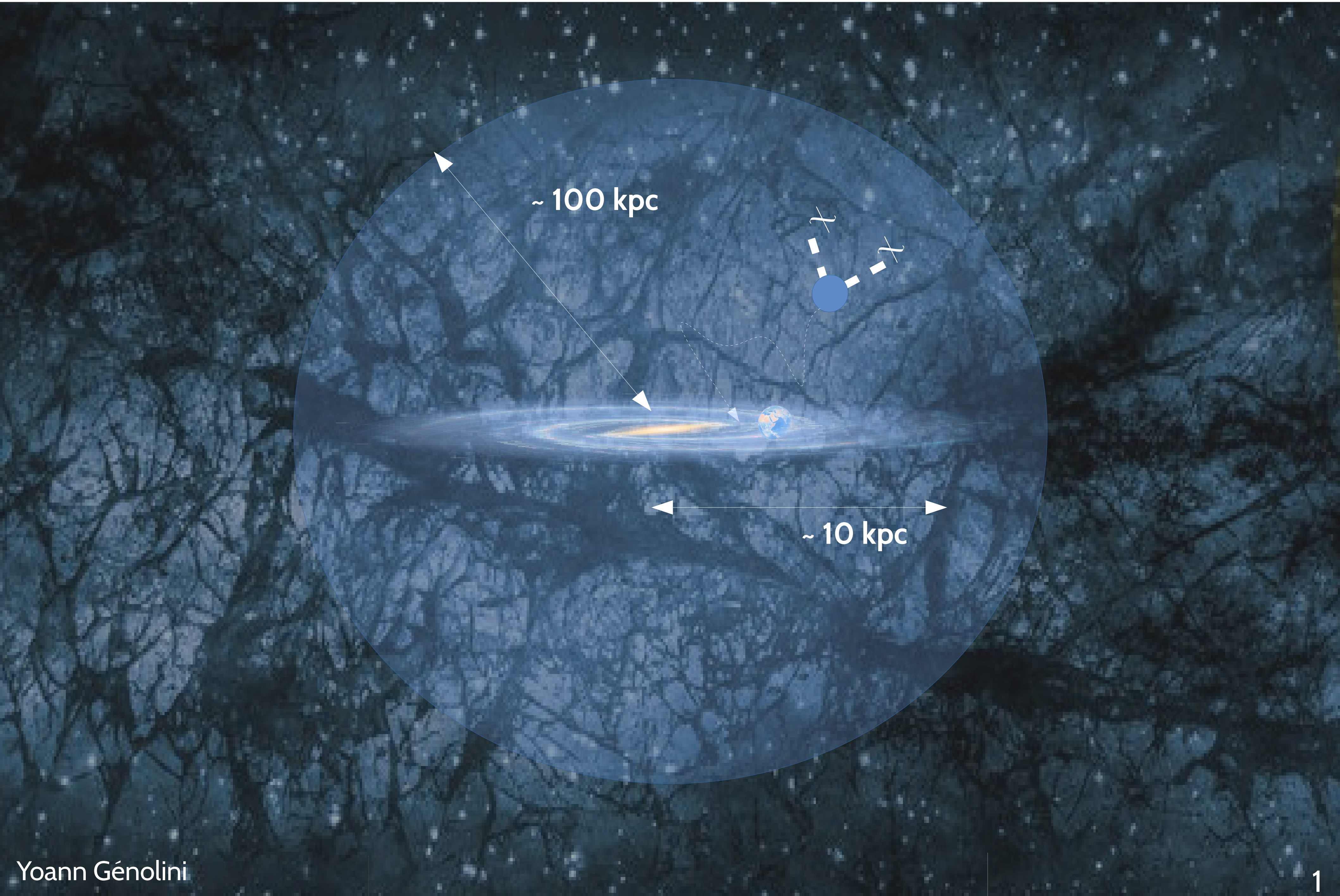
V.Poireau, V. Poulin, S. Rosier, P. Salati,
P. D. Serpico , M. Vecchi and N. Weinrich

Introduction



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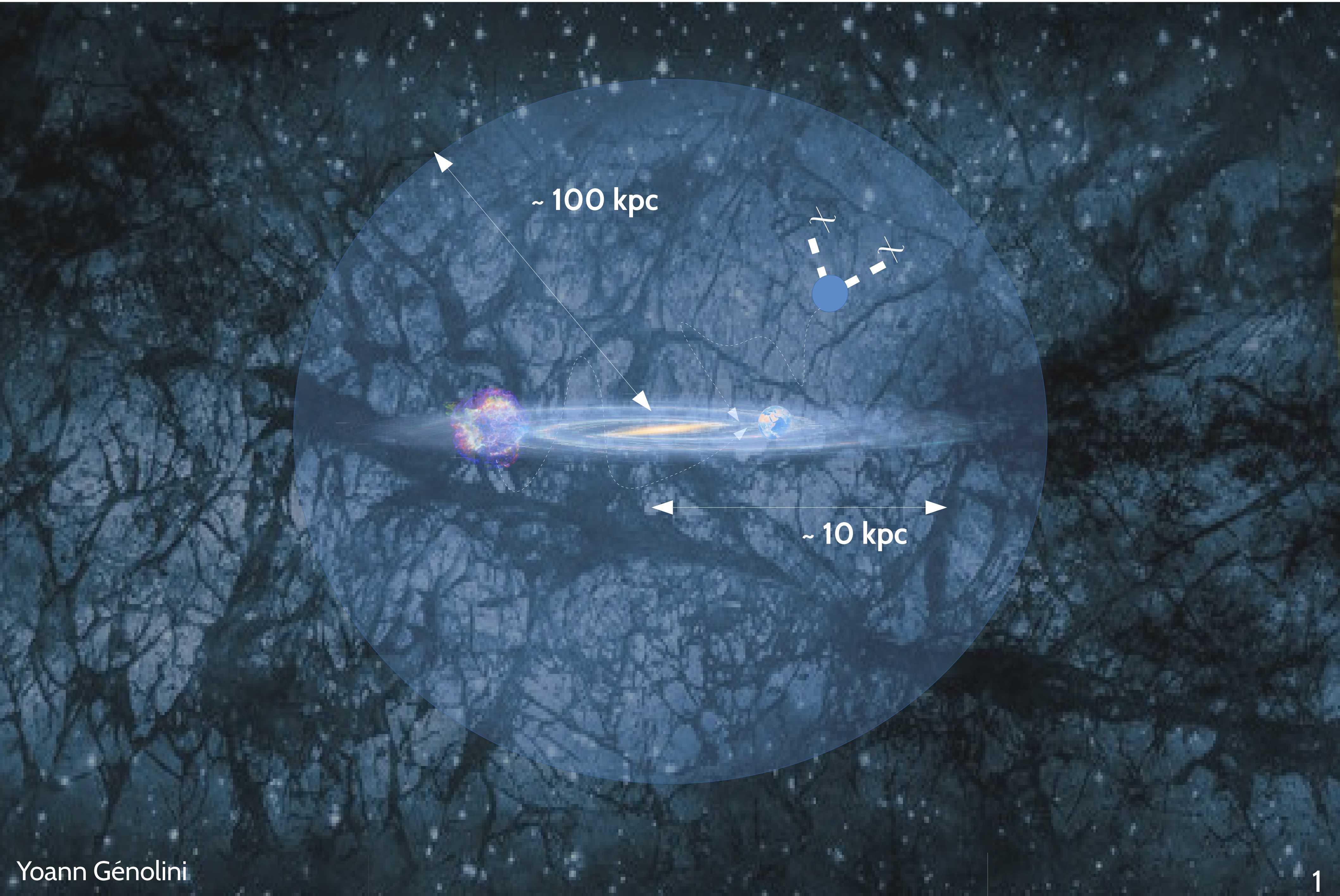
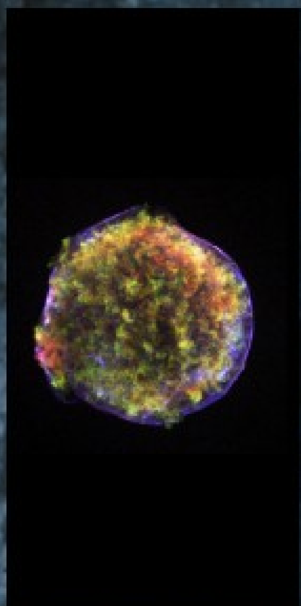


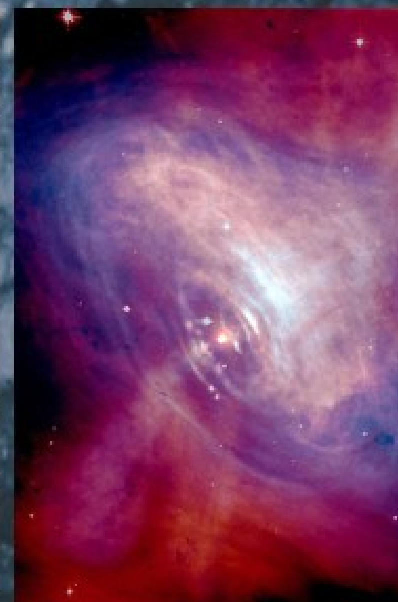
Introduction

Galactic cosmic-ray sources



SNRs

Star clusters



Pulsar Wind Nebulae

Colliding wind binaries

Protostellar jets microquasars

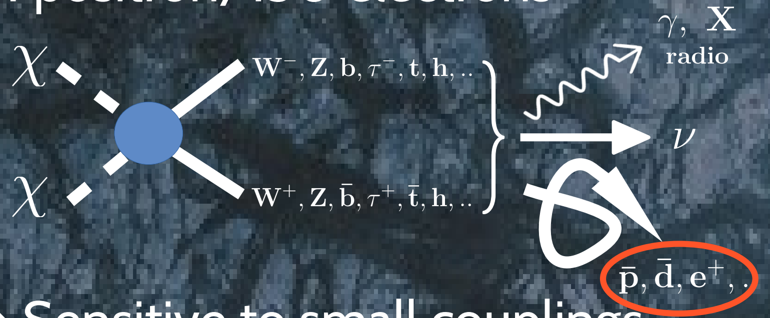
... and others !

Two reasons to focus on cosmic-ray antiparticles:

1 - Very low fluxes:

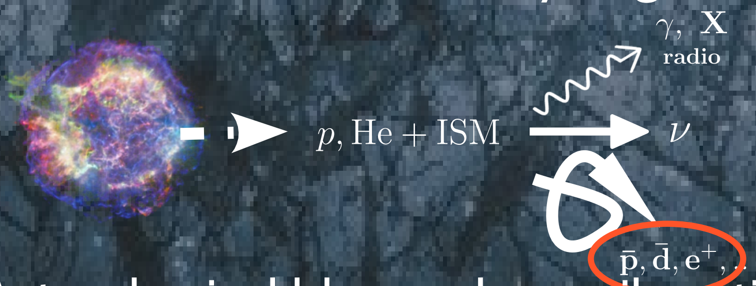
~ 1 antiproton/10^4 protons

~ 1 positron/150 electrons

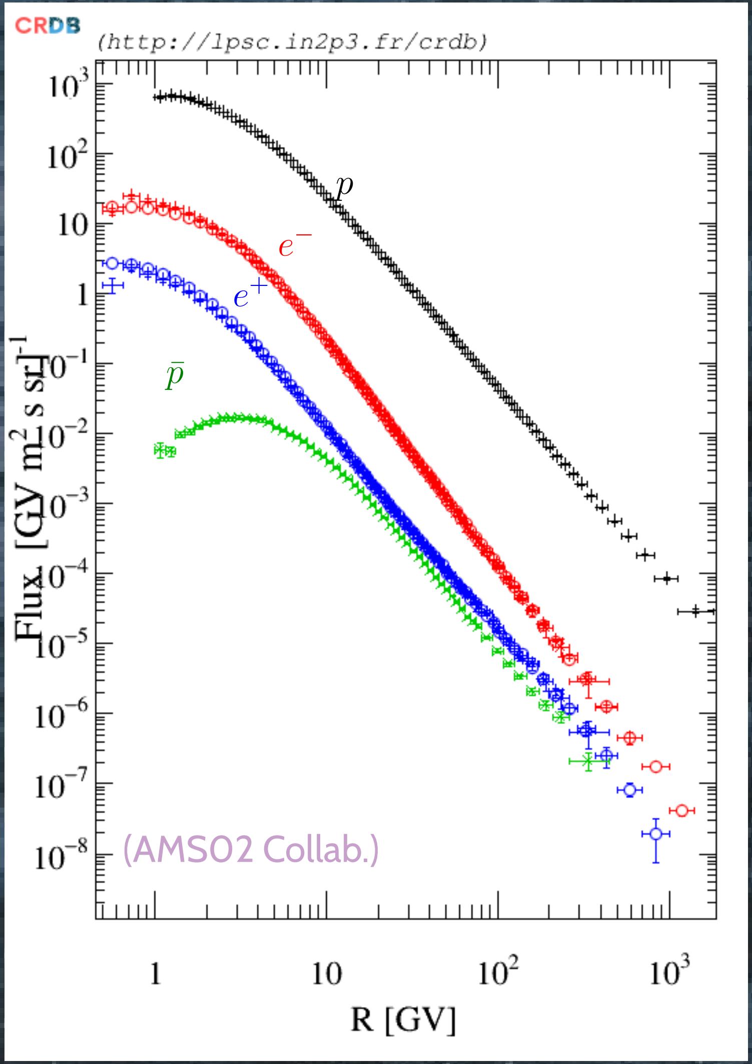


→ Sensitive to small couplings

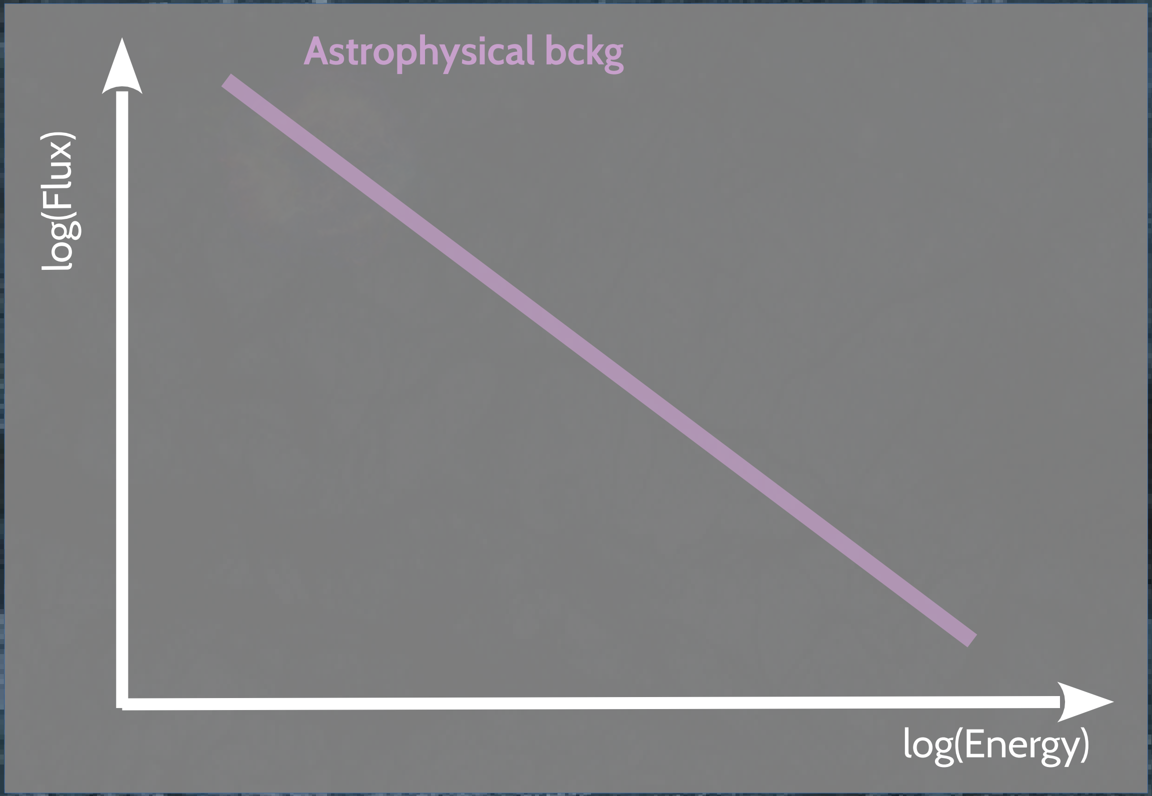
2 - Believed to be of secondary origin:



→ Astrophysical bkg can be easily estimated



Dark matter indirect search



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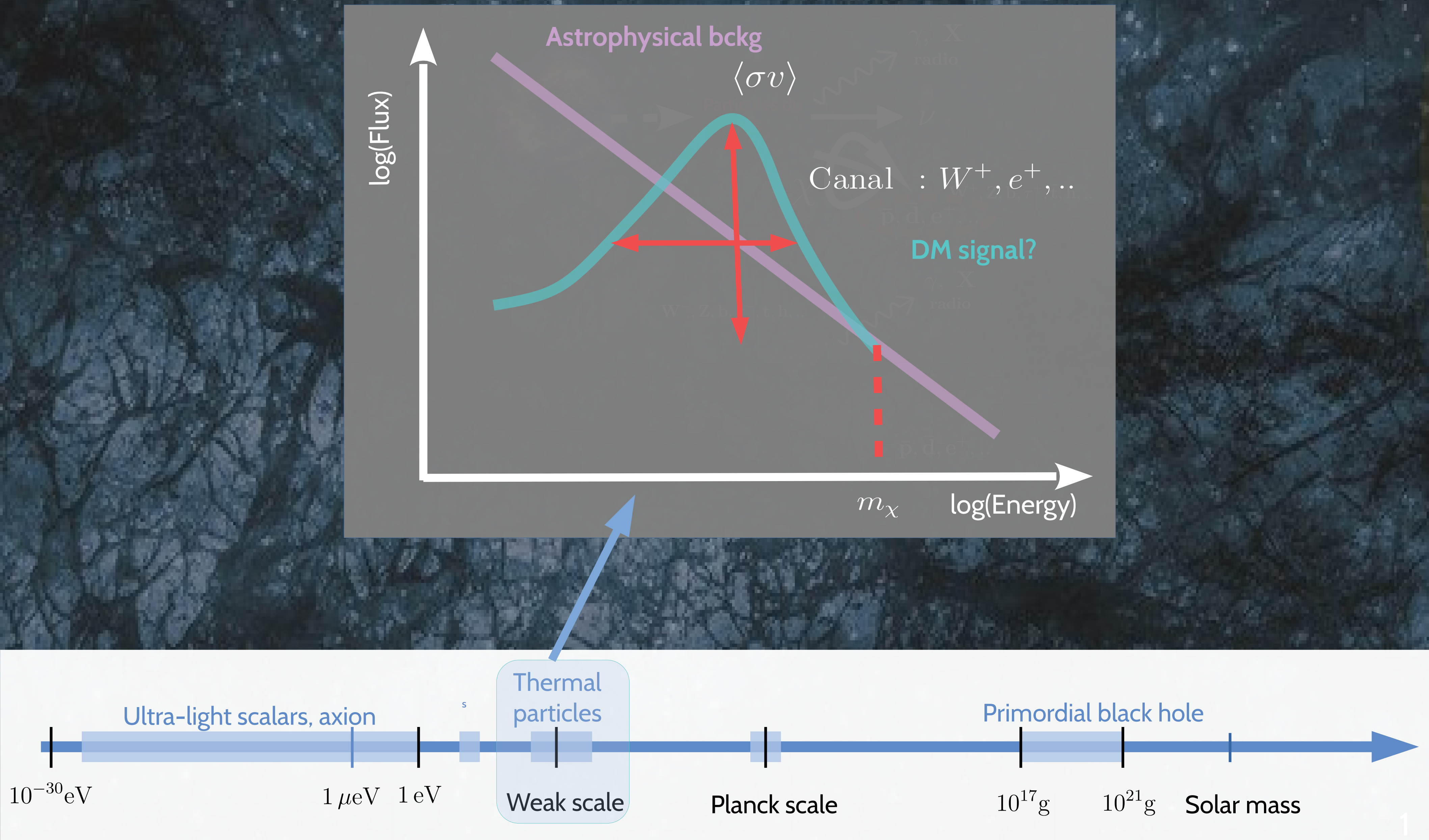


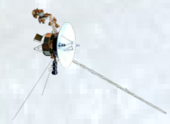
Game changer: high-quality data!

Numerous precison experiments in a large energy range

Precision level % from GeV to TeV

VOYAGER (1977)

5 – 500 MeV



PAMELA (2006)

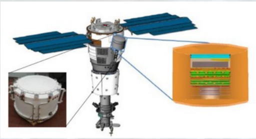
1 GeV – 1.2 TeV

AMS-02 (2011)

1 GeV – 1.9 TeV

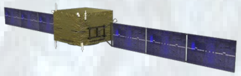
NUCLEON (2014)

100 GeV – 1 PeV



DAMPE (2015)

50 GeV – 500 TeV



CALET (2015)

10 GeV – 1 PeV

LHAASO (202X)

10TeV-100 PeV

Observatoire Pierre AUGER (1999)

0.3-100 EeV

Outline

1 – Few words on positrons

2 – More words on antiprotons

3 – Conclusion and prospects

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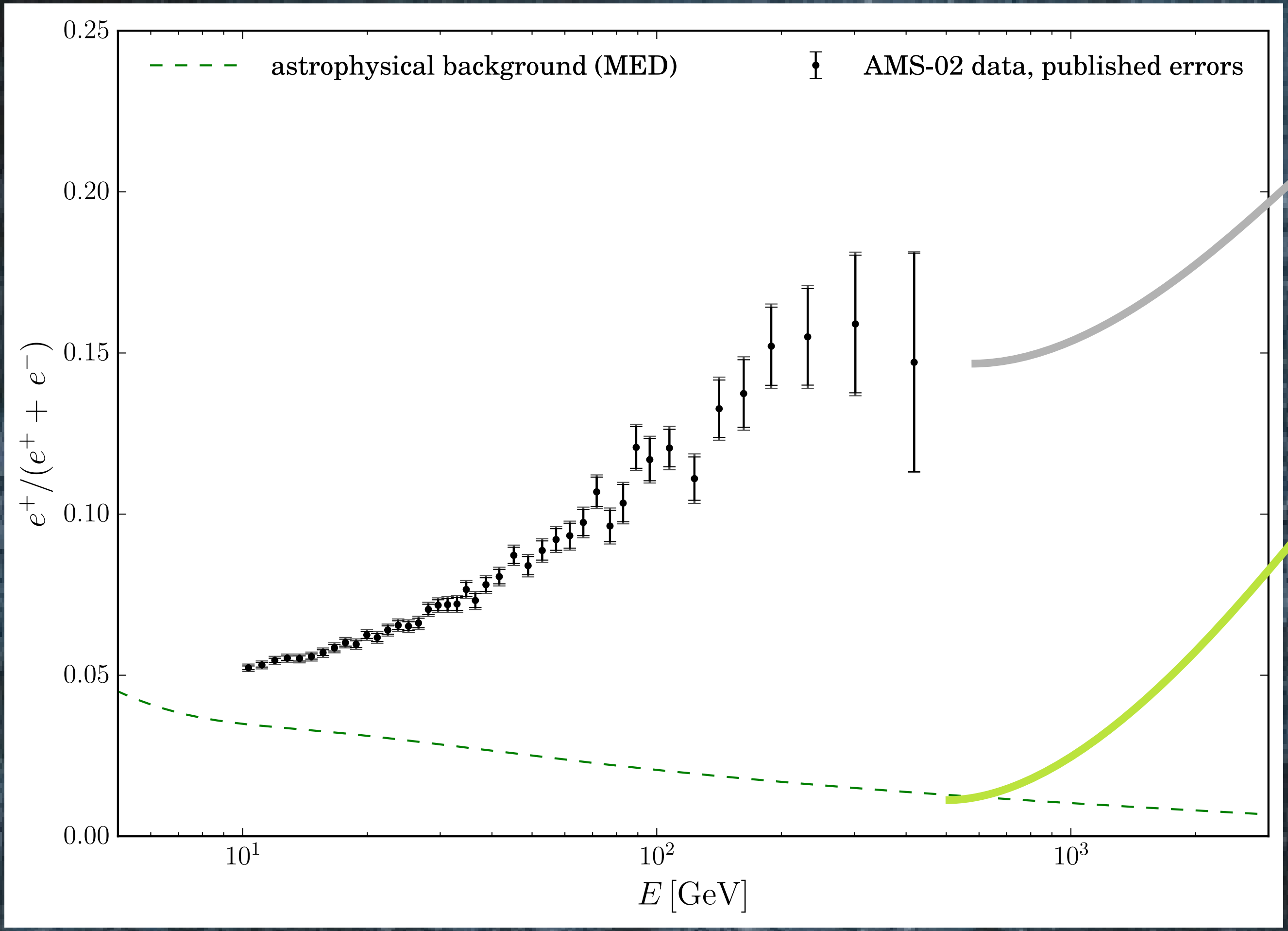
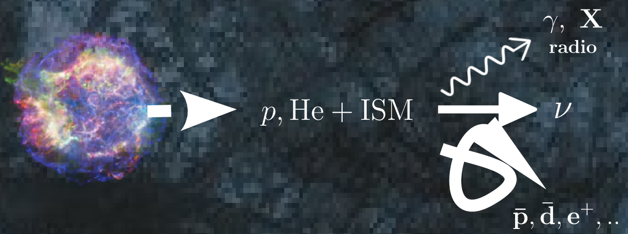
Few words on positrons



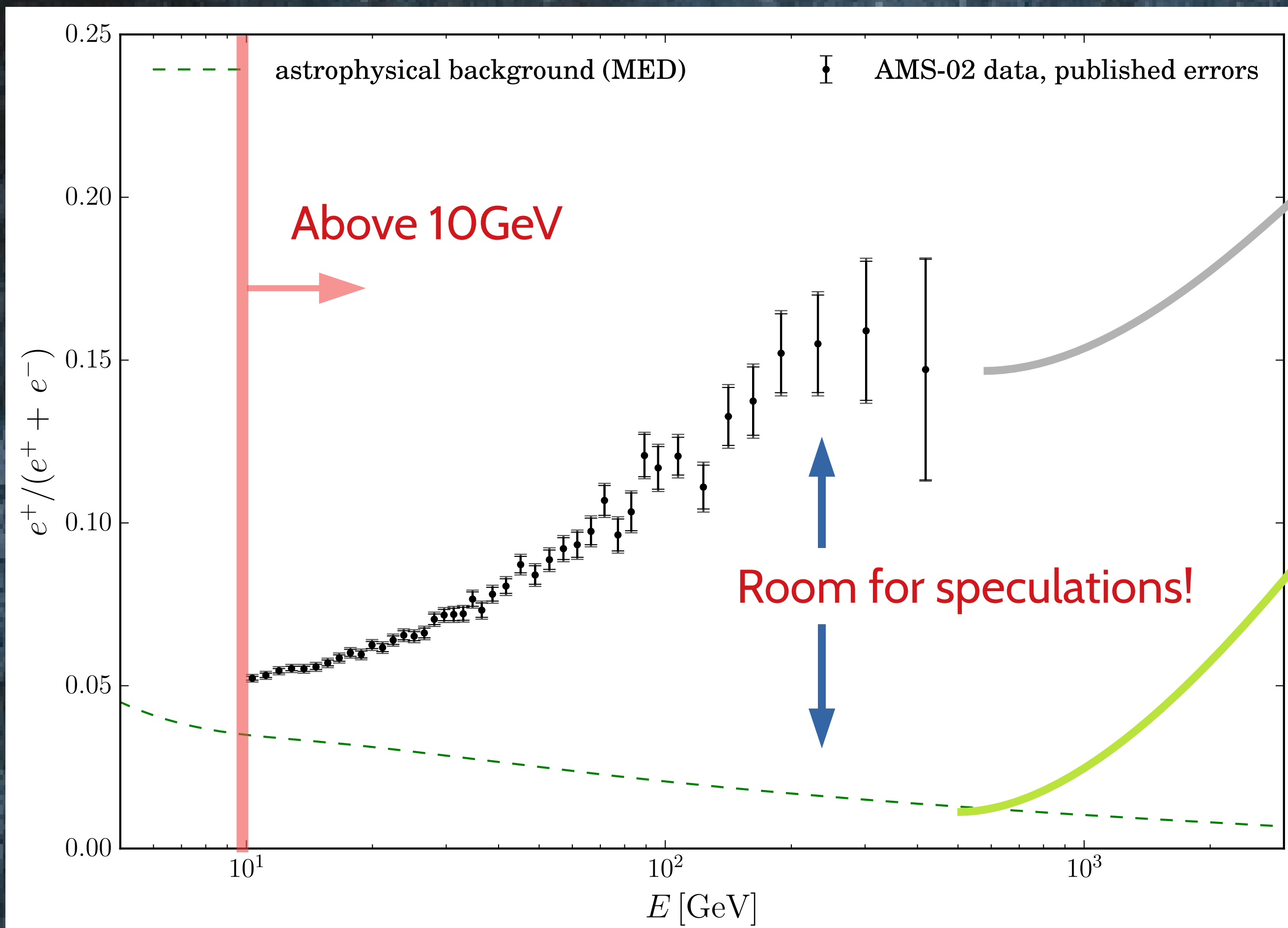
Also measured by:
-HEAT (1997)
-PAMELA (2009)
-FERMI (2010)

Astrophysical bckg from secondary production:



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

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



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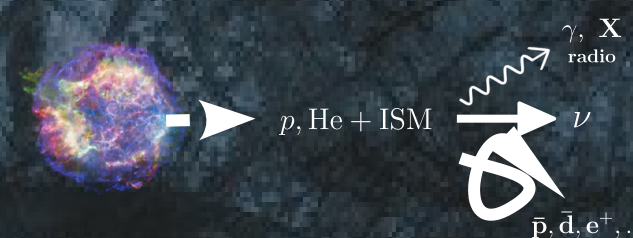
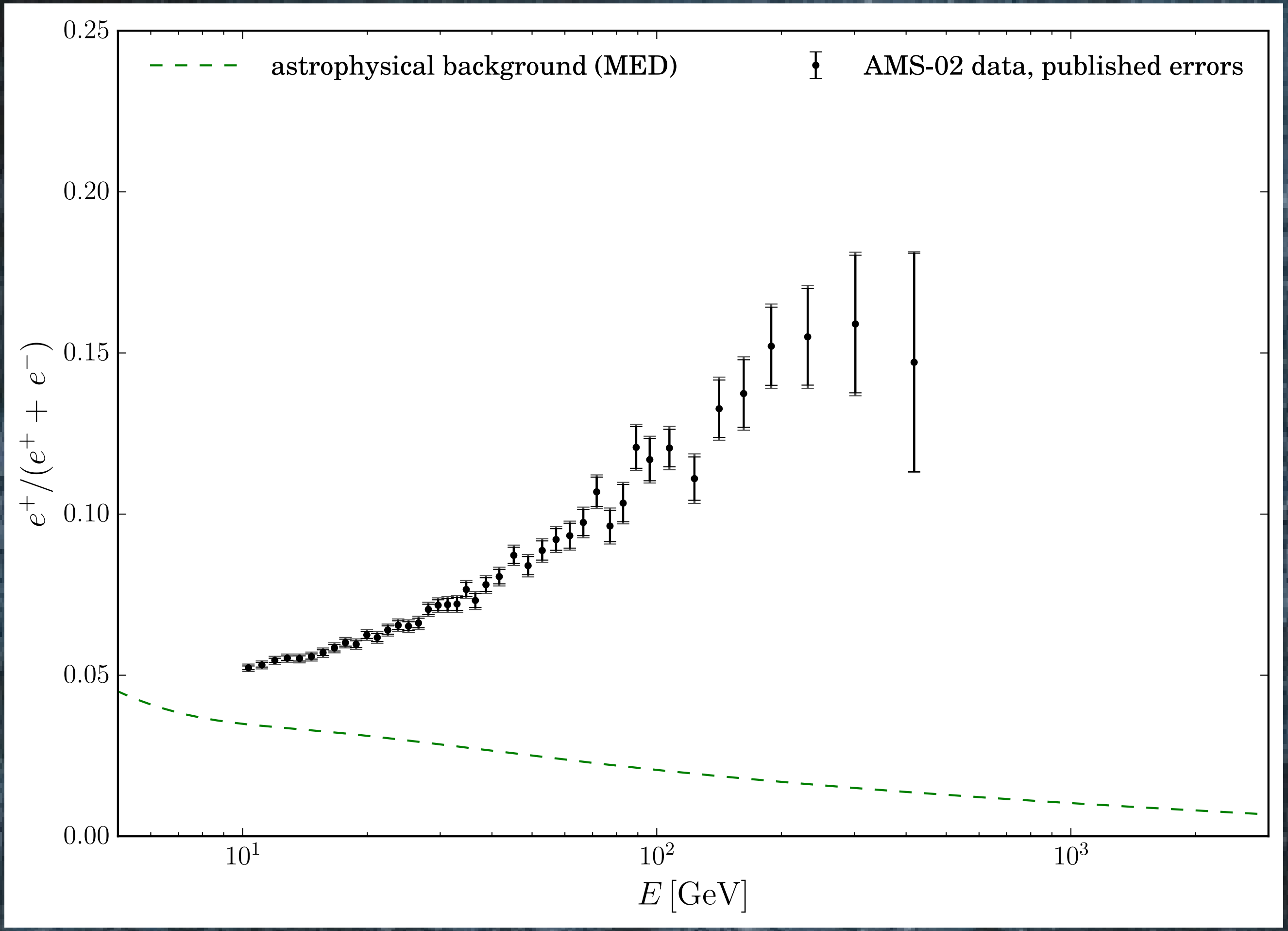


(Boudaud, ..., Y.G.+ 2015)

Few words on positrons

The WIMP explanation of the positron excess



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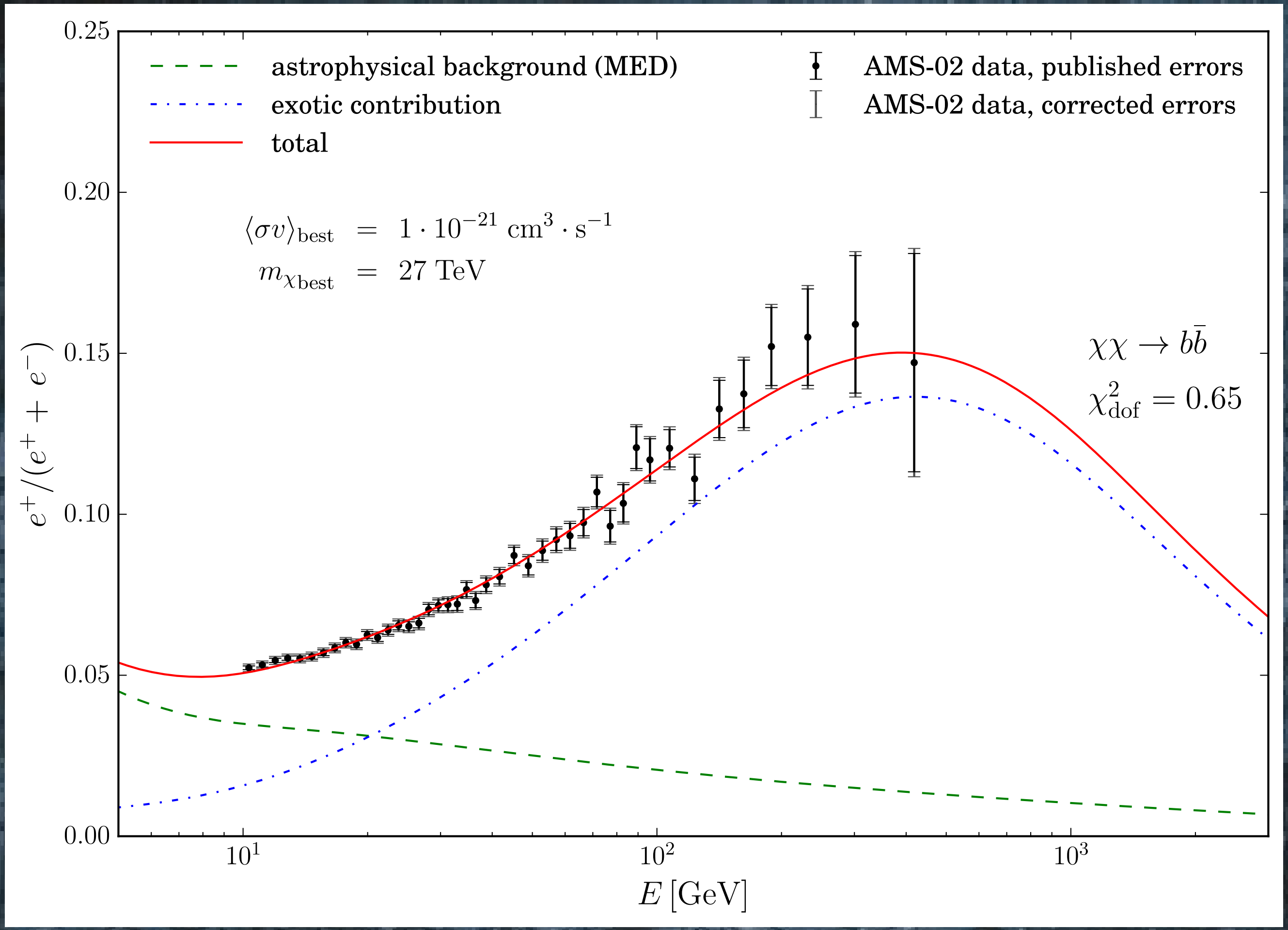

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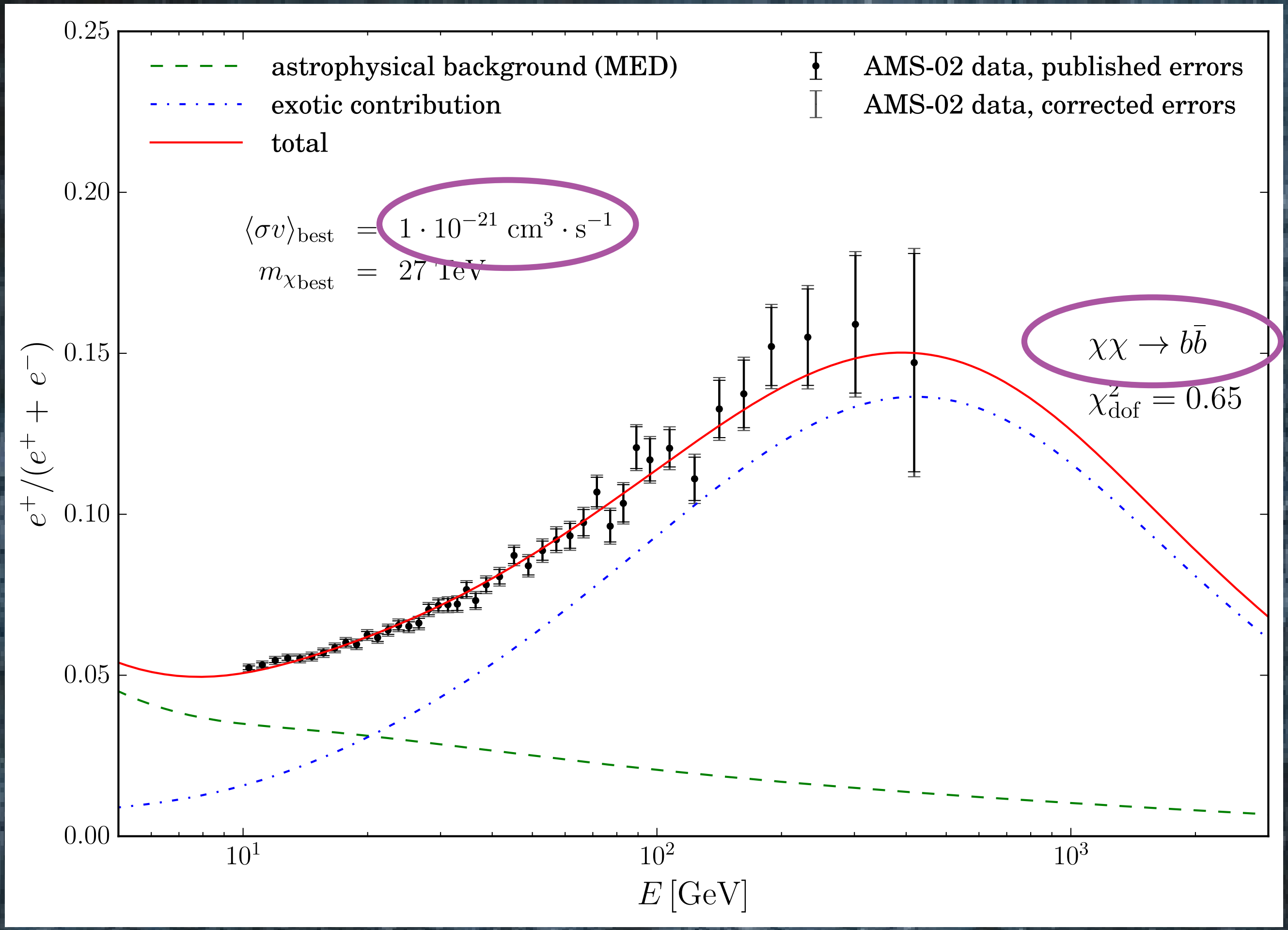


(Boudaud, ..., Y.G.+ 2015)

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)

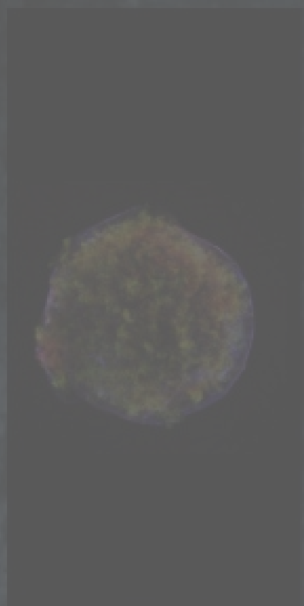
Leptonic channel
Tensions with CMB+DS constraints
(Lopez, A.+ 2015, Planck Col.XIII+2015)

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

→ Analysis extended to low-E
No good fit found
(Boudaud, ..., Y.G.+ 2016)

Origin of this excess?

Galactic cosmic-ray sources



SNRs

Star clusters

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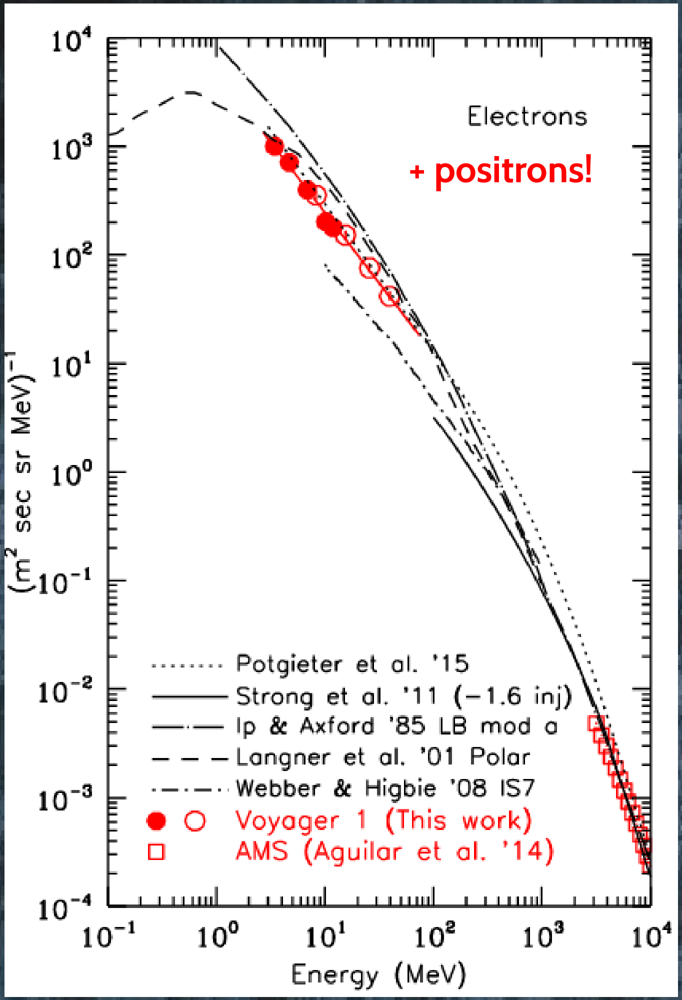
... and others !

→ 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)

Dark matter constraints with low-energy positrons



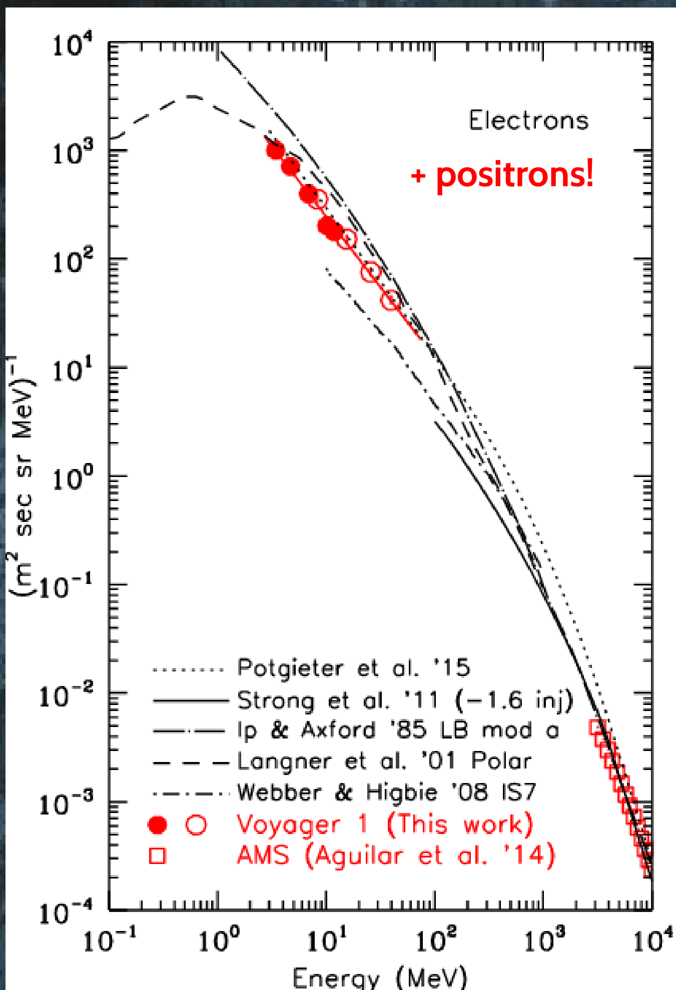
(Cummings, A .+ 2016)

→ 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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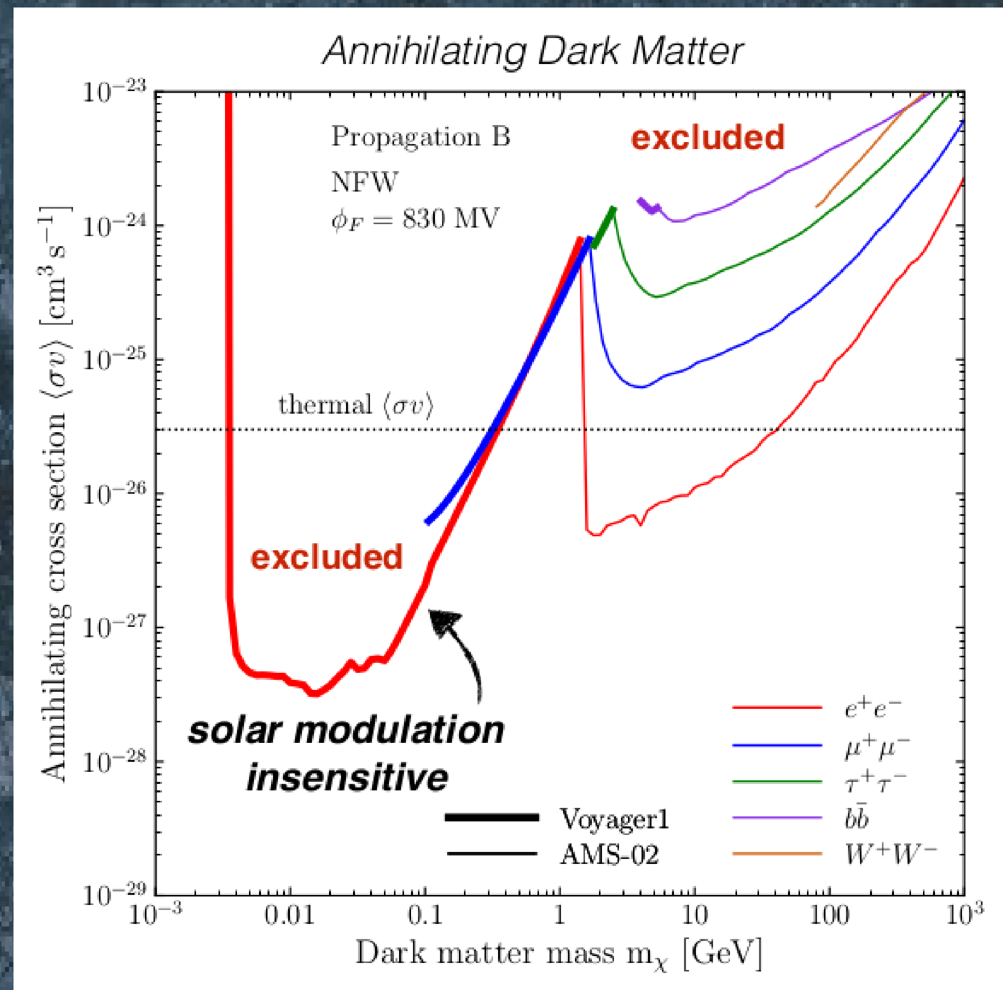

(Boudaud, M.+ 2016, 2018)

→ Stringent constraints on S and P wave annihilition

Outline

1 – Few words on positrons

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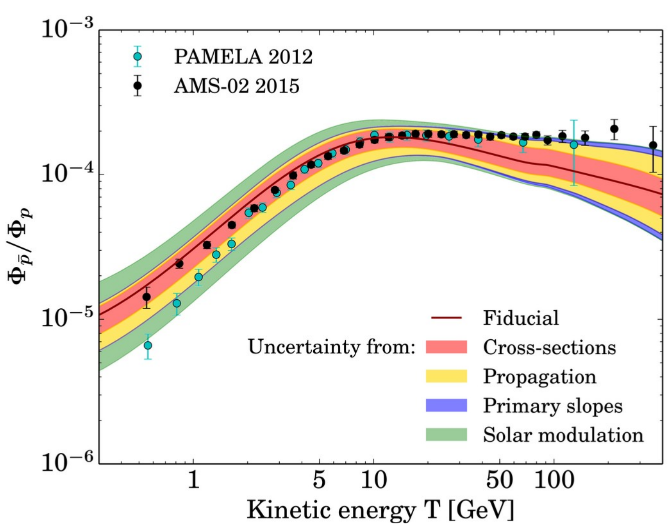
3 – Conclusion and prospects

More words on antiprotons

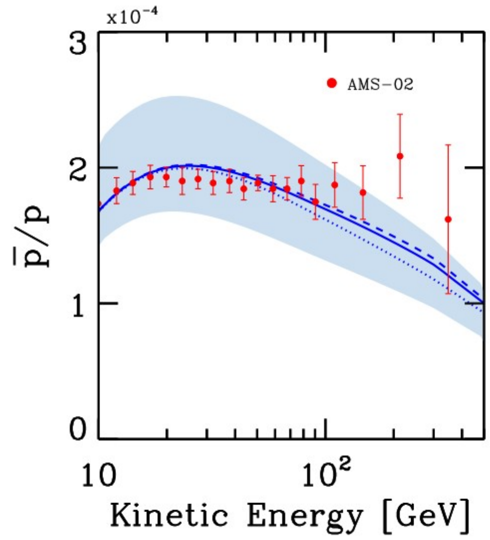
Secondary

Is the case of antiprotons more exciting?

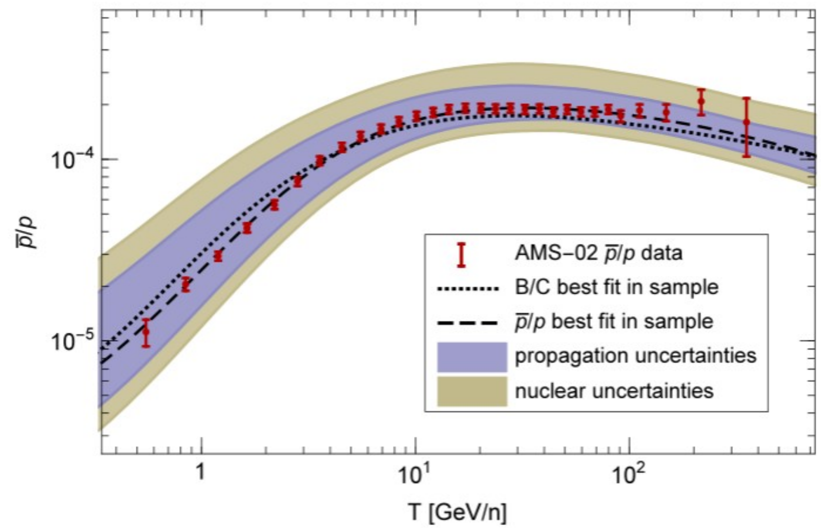
→ Preliminary AMS02 antiproton data from 2015



(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!

More words on antiprotons

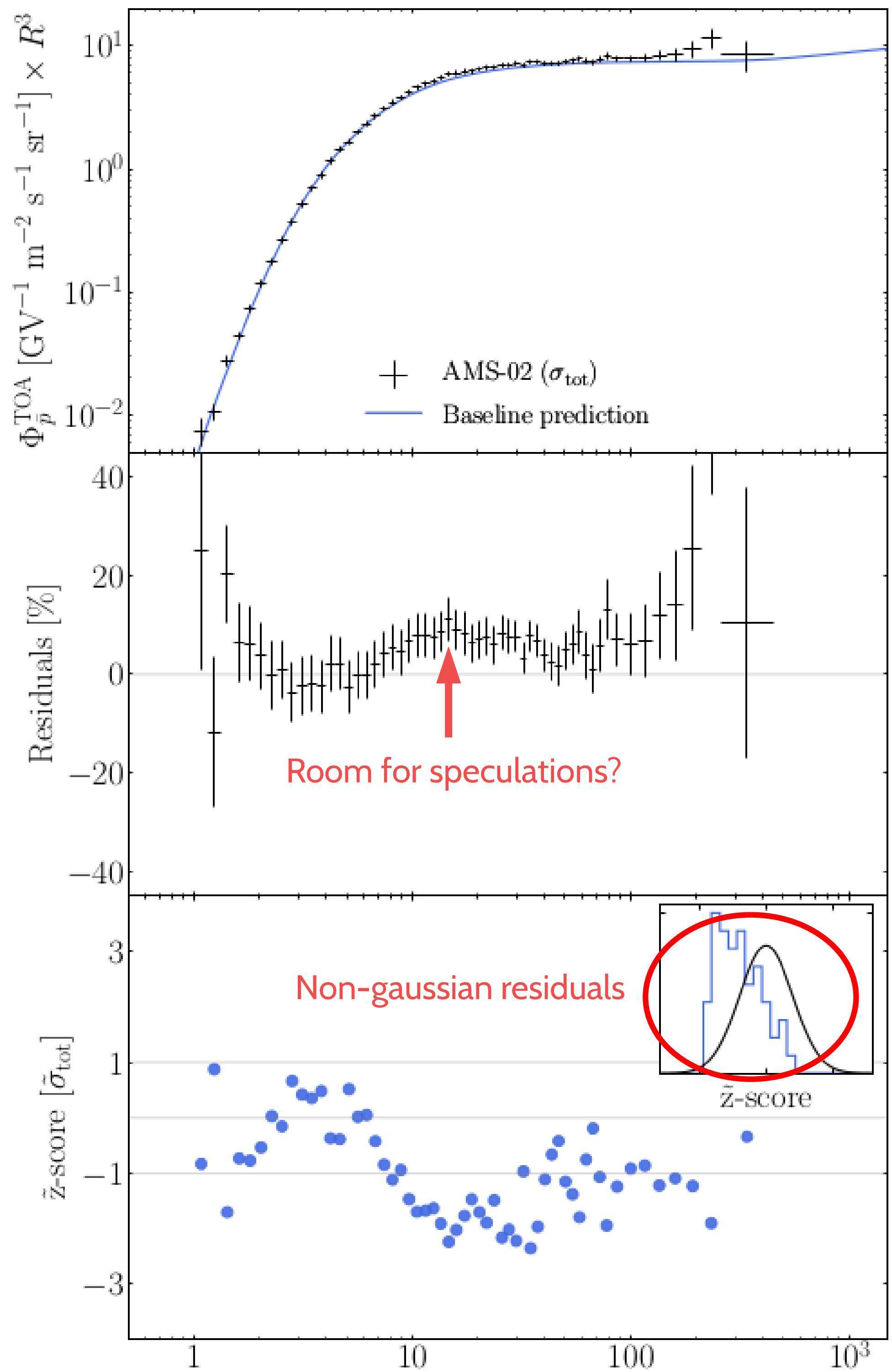
Secondary

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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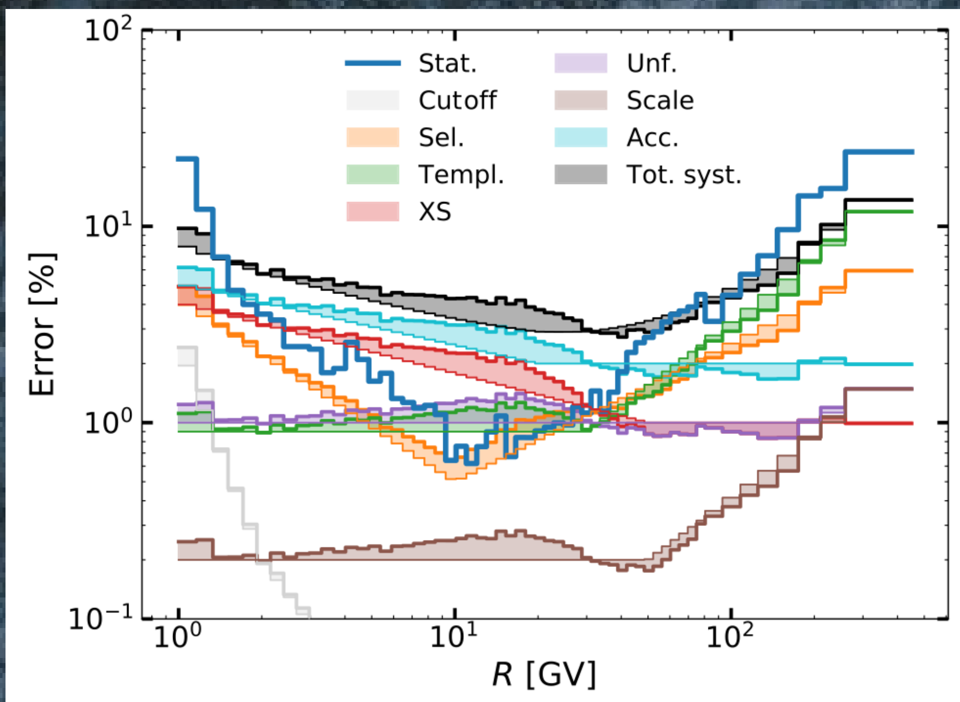
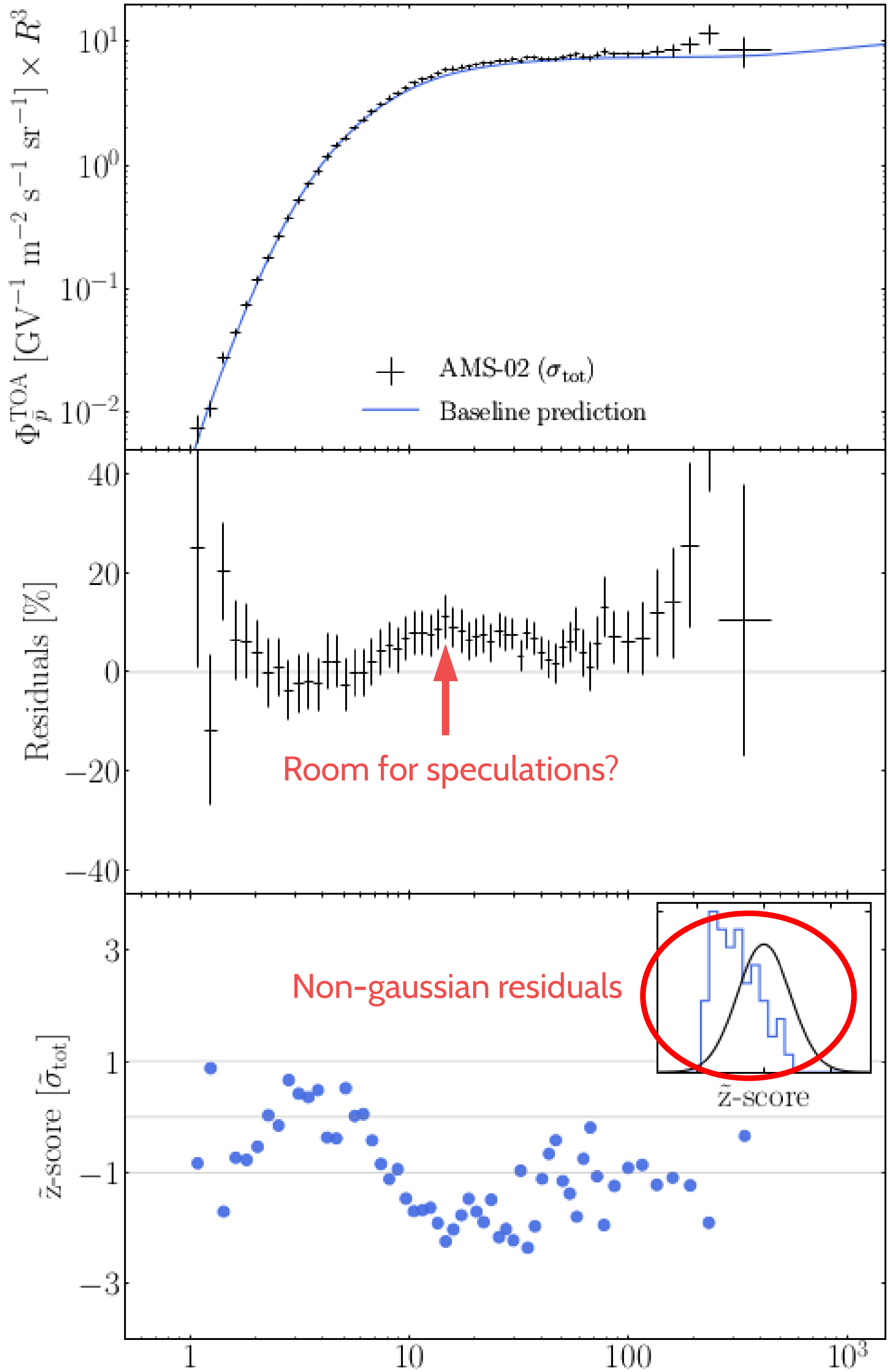


Small total error / Different correlation lengths
Dominated by acceptance around the excess

→ Covariance matrix estimated from detector info.



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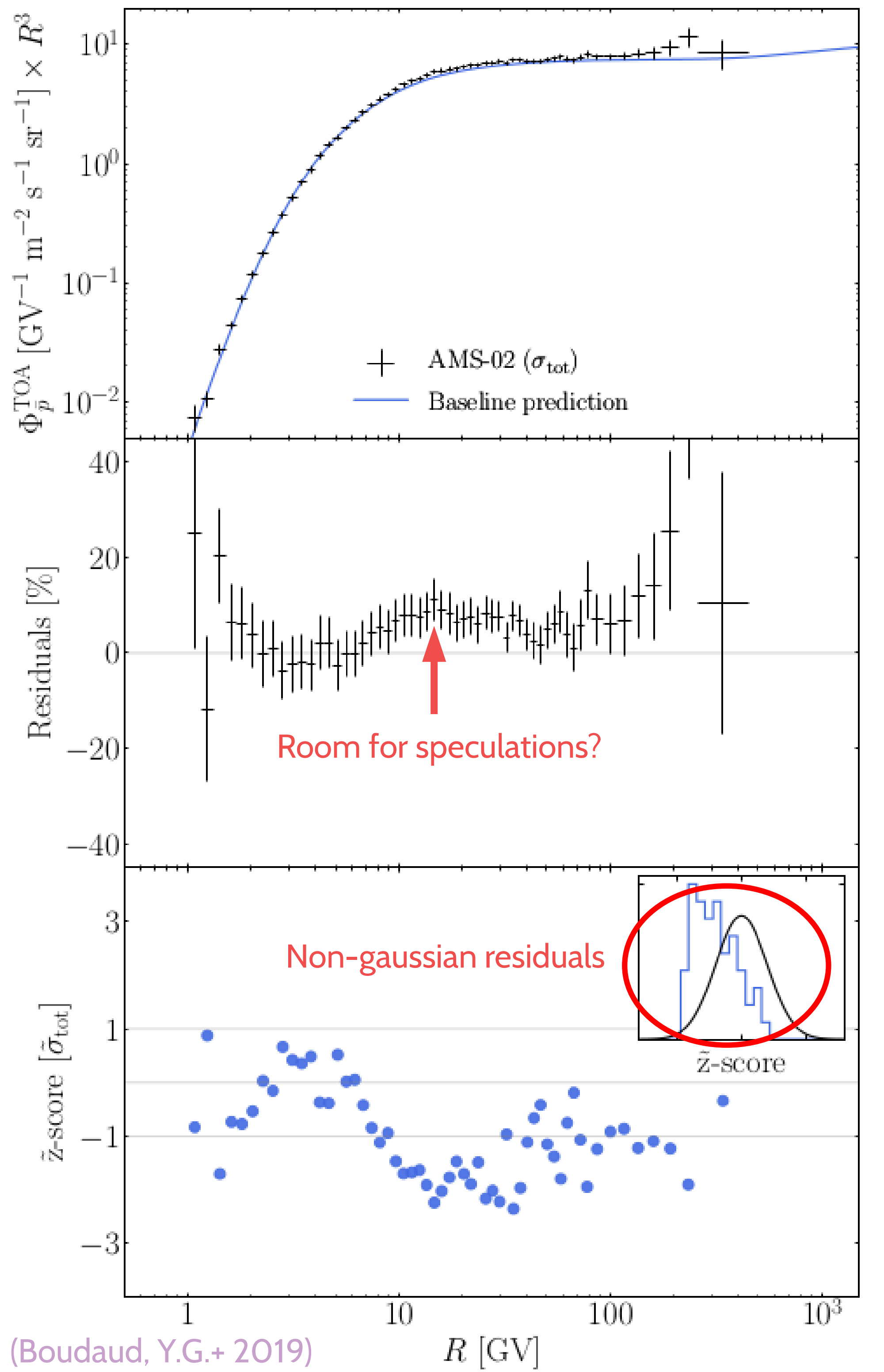
- Pbar production cross-sections



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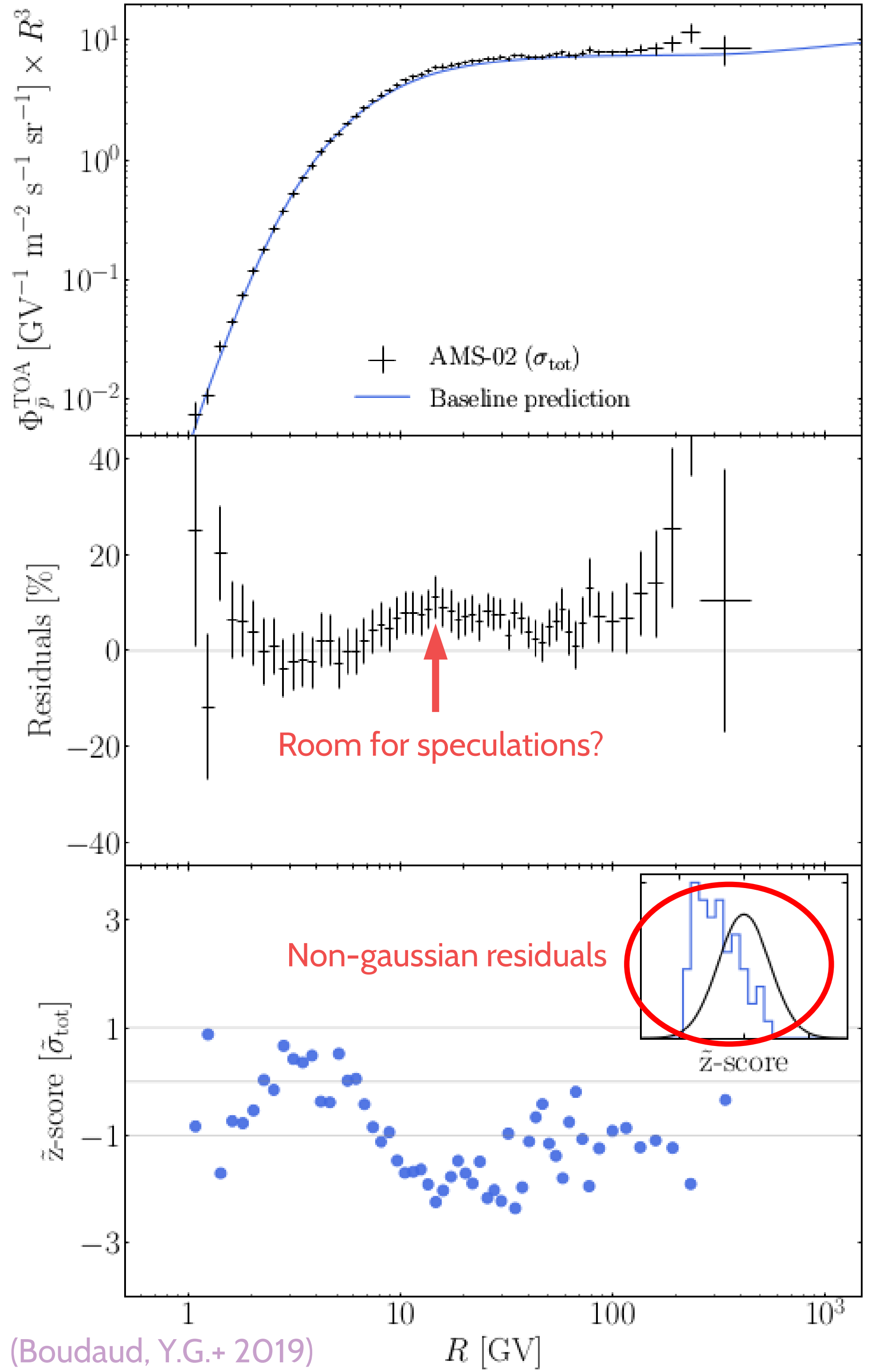
New data from NA61/SHINE (p+p)
NA49: (p+C) & LHCb: (p+He)
(Aduszkiewicz+2017,*Anticic+ 2010, Aaij+2018)*

→ Updated parameterisation and uncertainties
(Winkler, M. 2016, Korsmeier+ 2018)



(Boudaud, Y.G.+ 2019)

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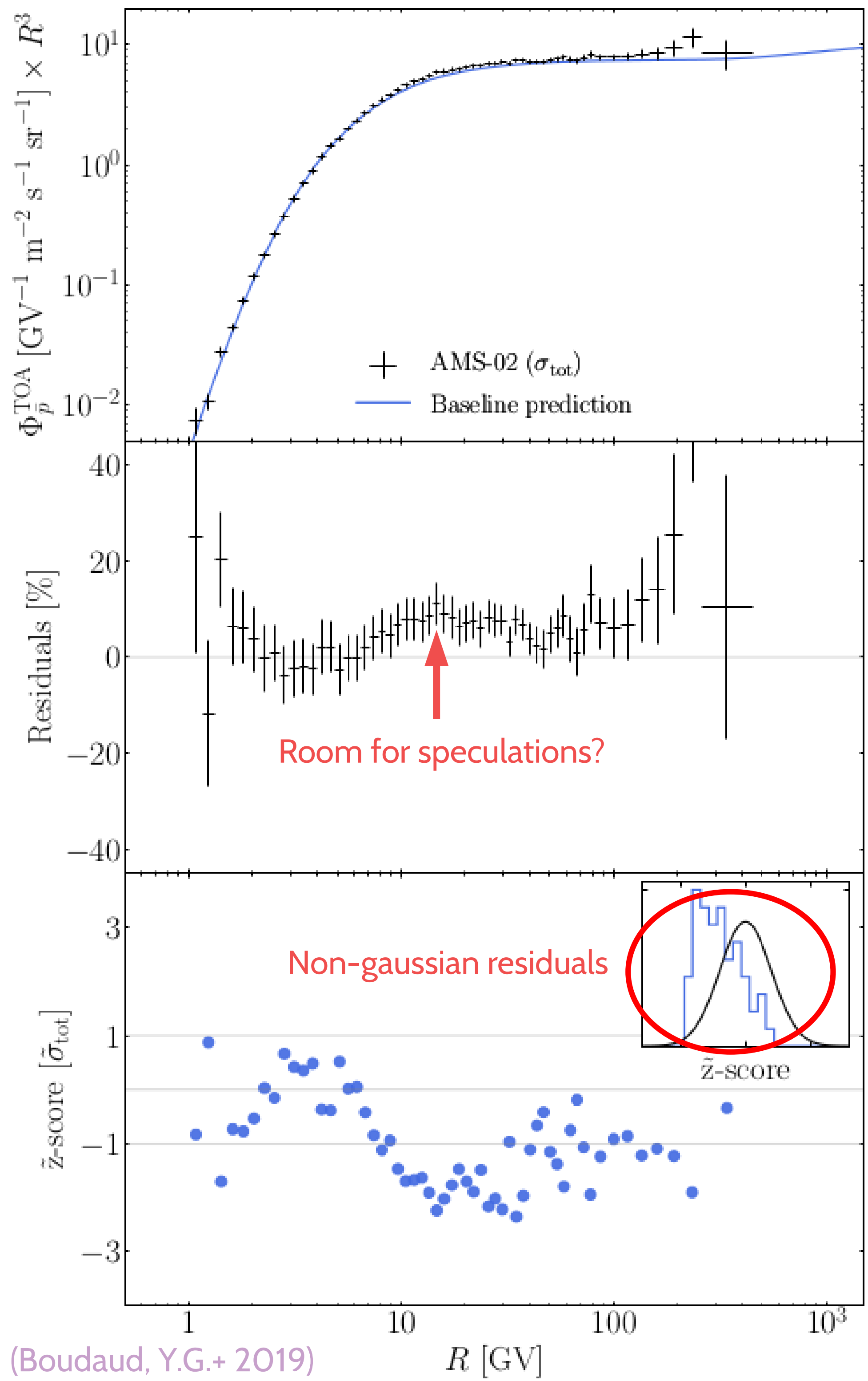
- Transport



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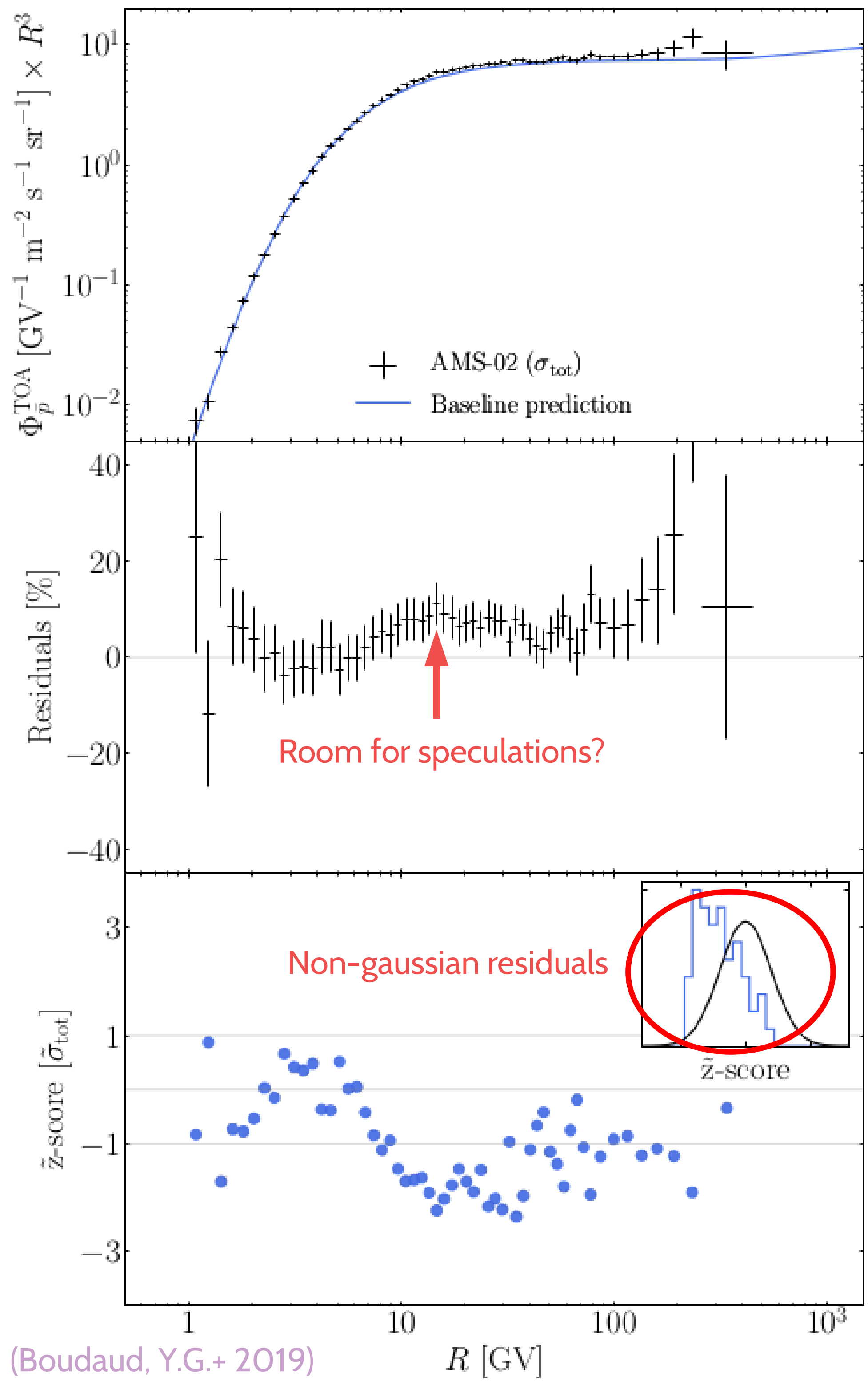
New Li, Be, B/C data from AMS02

→ Updated transport models and uncertainties

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



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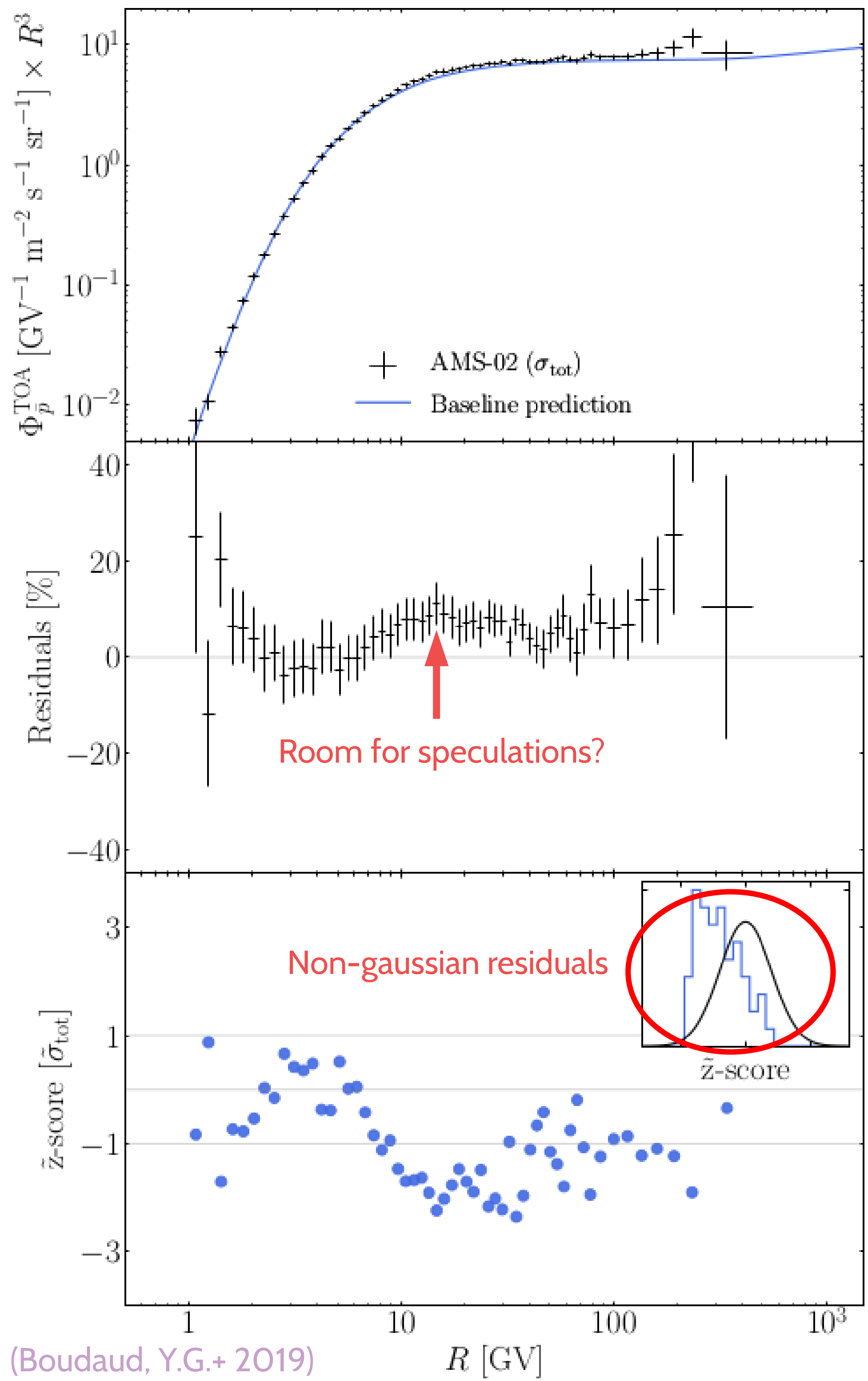
→ Updated transport models and uncertainties
- Parents



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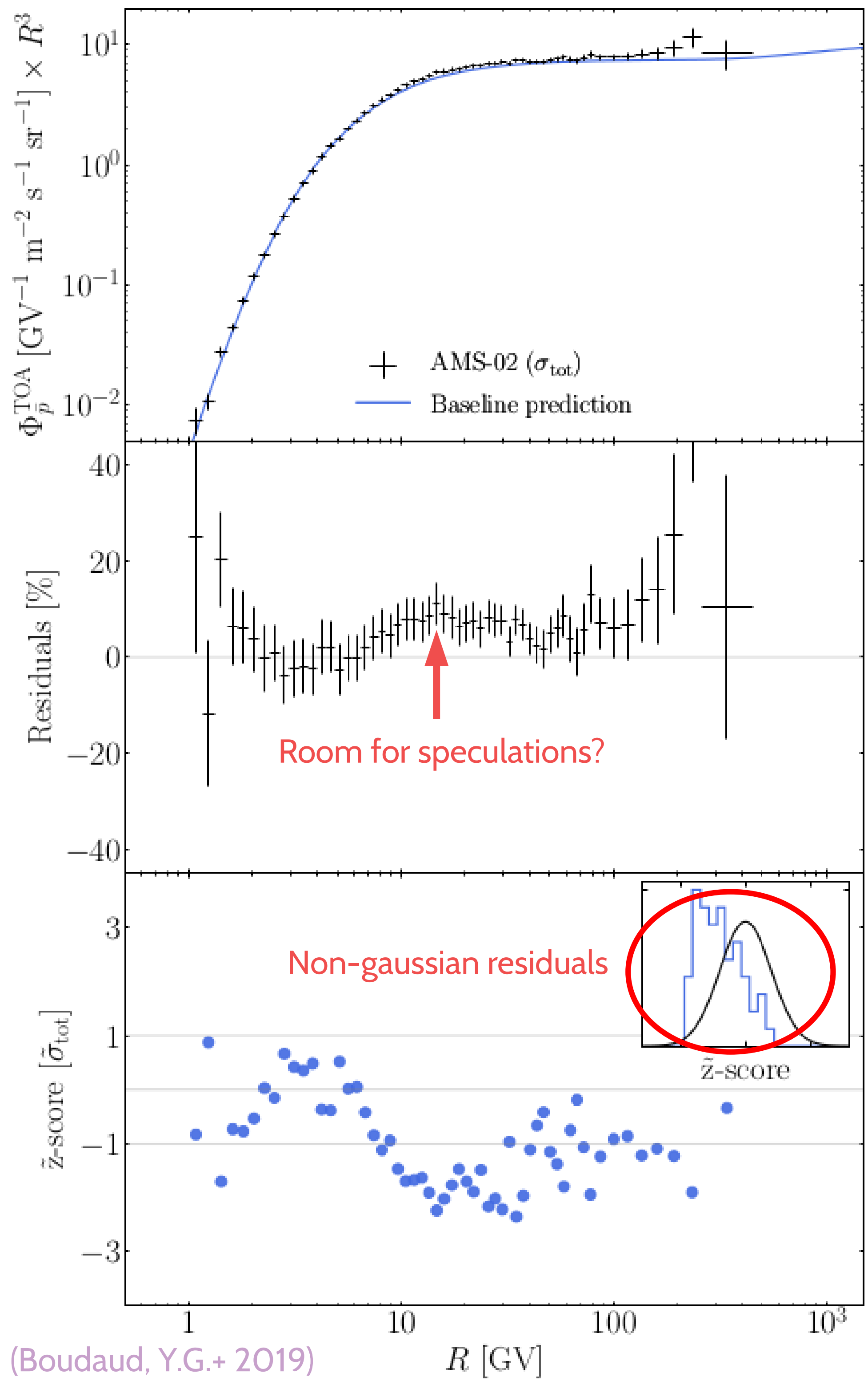
- Parents

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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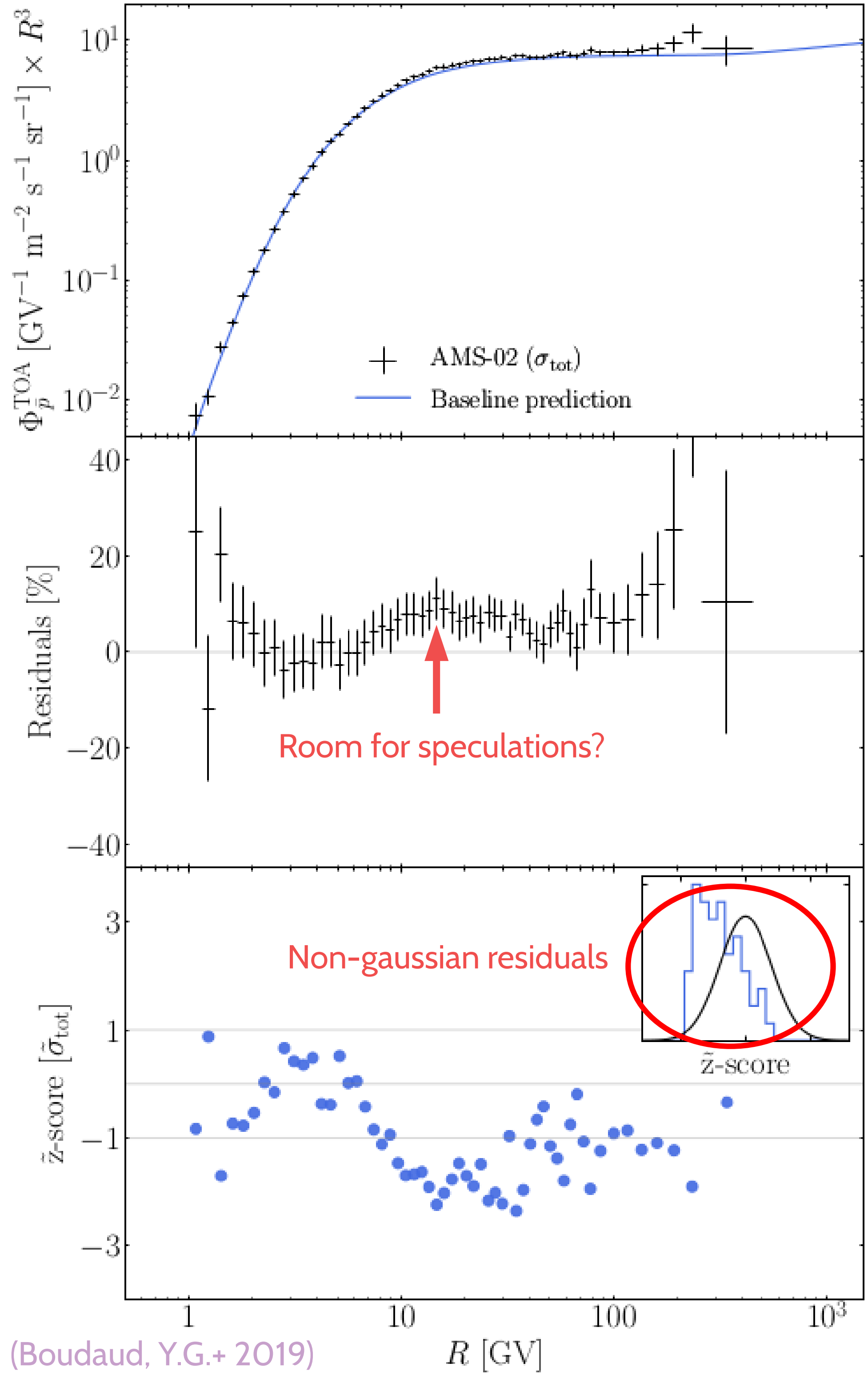

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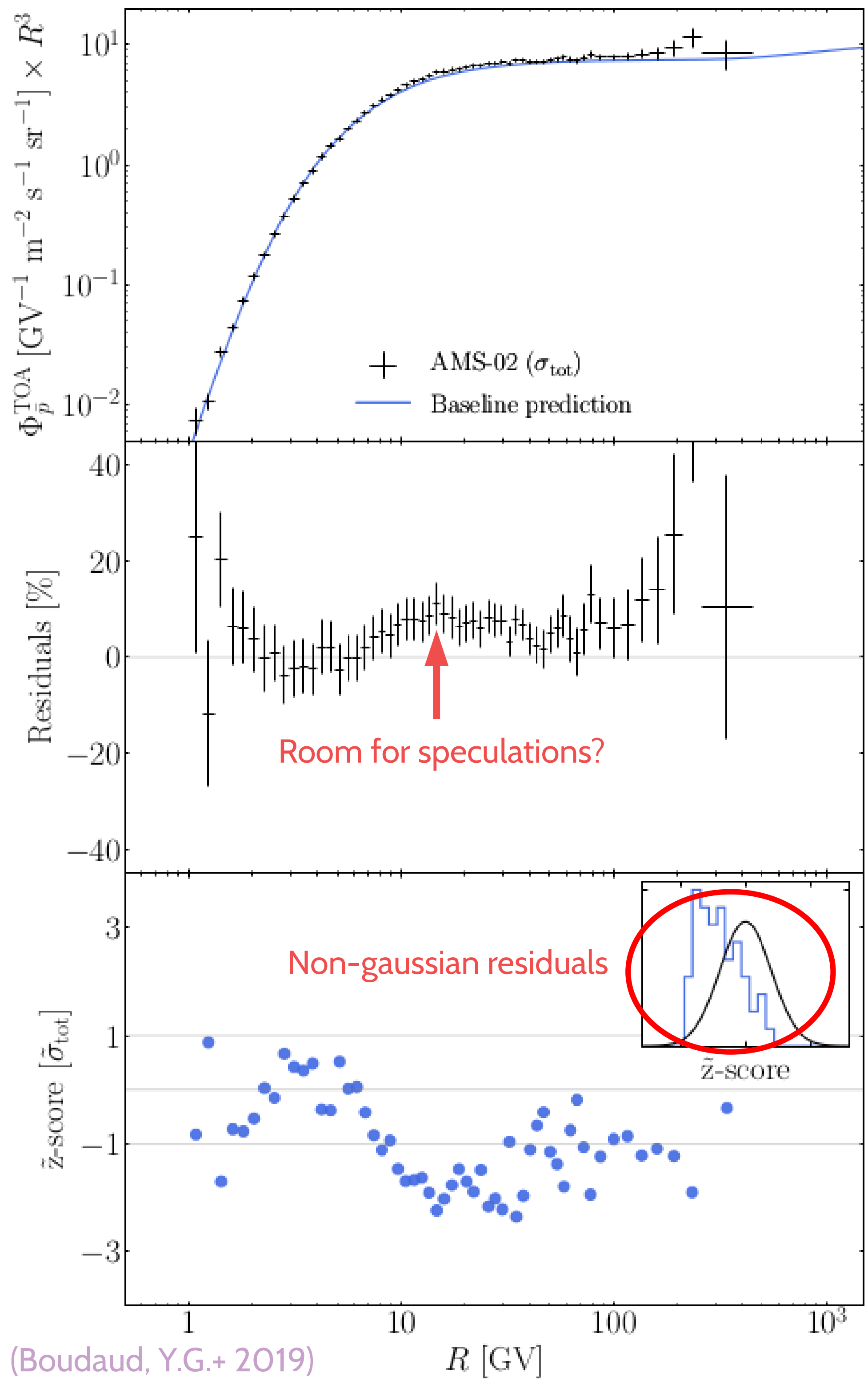

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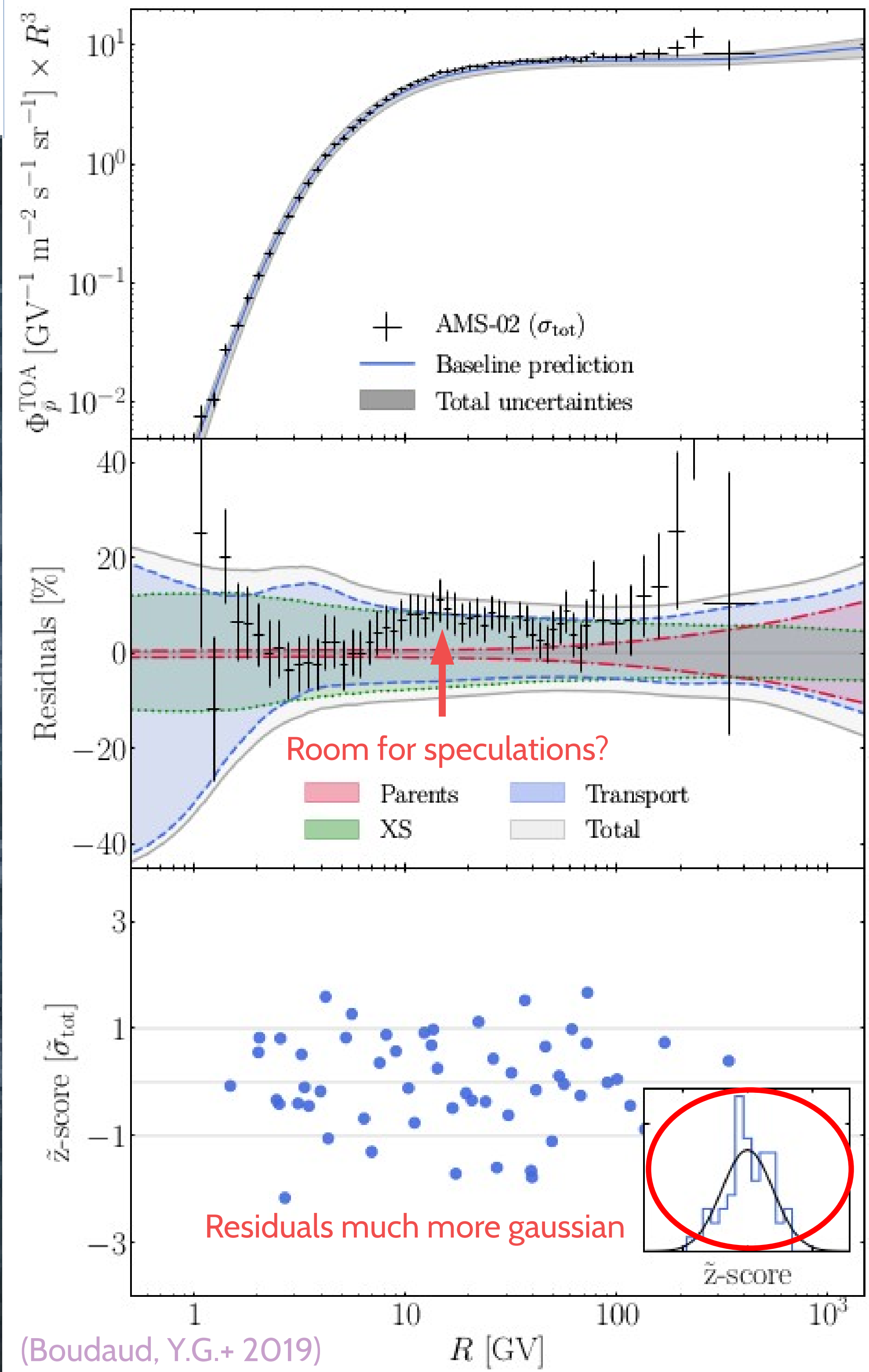
→ Chi2 test with:

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



(Boudaud, Y.G.+ 2019)

More words on 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:

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

$$p_{value} = 0.90$$

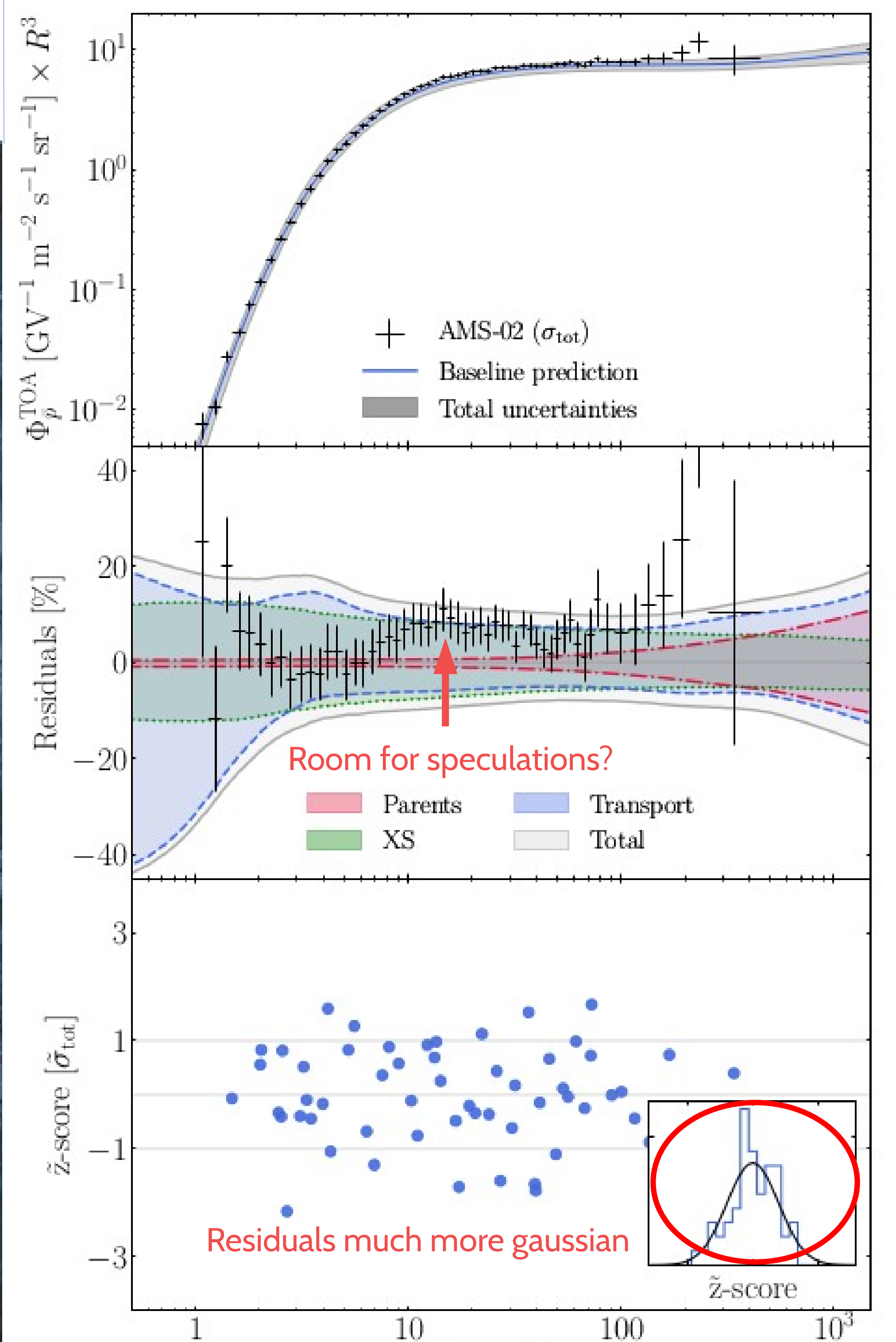
→ KS-test:

$$p_{value} = 0.27$$

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

Other studies confirmed (Heisig+ 2020)

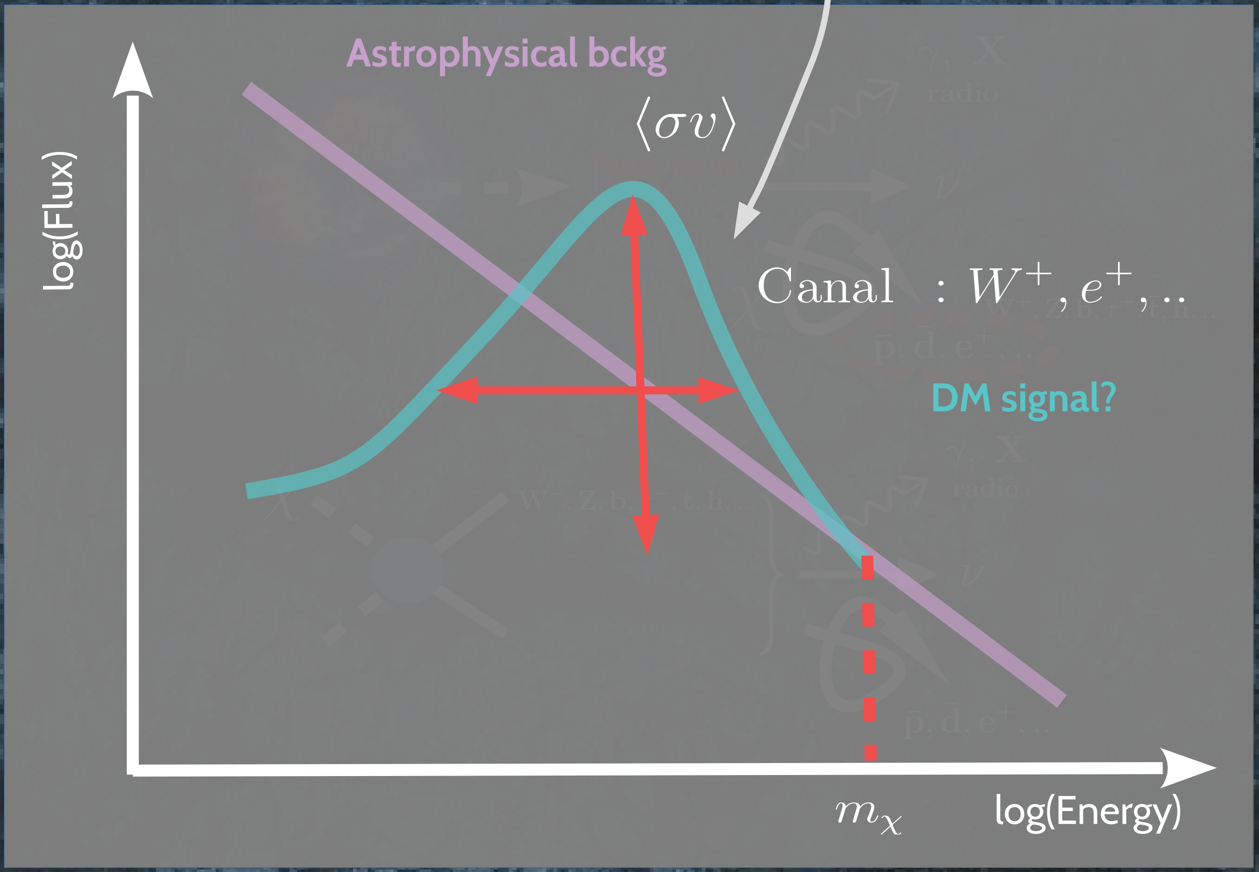
Does that mean there cannot be statistical evidence for DM?



(Boudaud, Y.G.+ 2019)

Secondary
+Dark Matter

Dark Matter antiproton component



Secondary +Dark Matter

Calore, Cirelli, Derome, Genolini, Maurin, Salati, Serpico
SciPost Phys. 12, 163 (2022)

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)

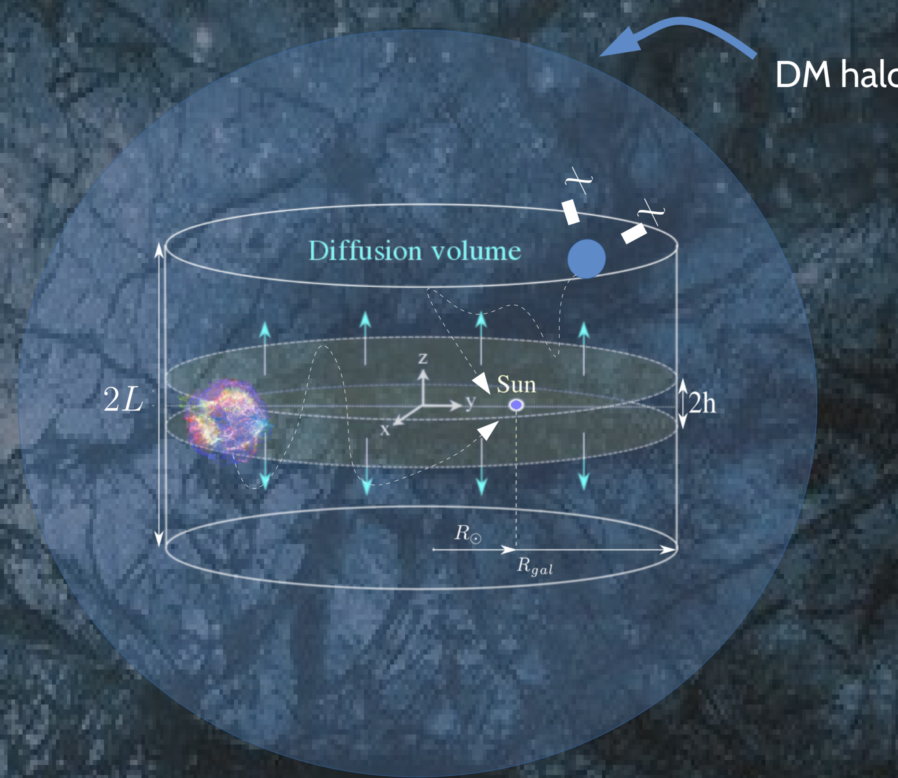
$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^\gamma\ (1+r/r_s)^{3-\gamma}}$$

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)

More words on antiprotons

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Exploring the nul hypothesis

→ No significant excess found

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

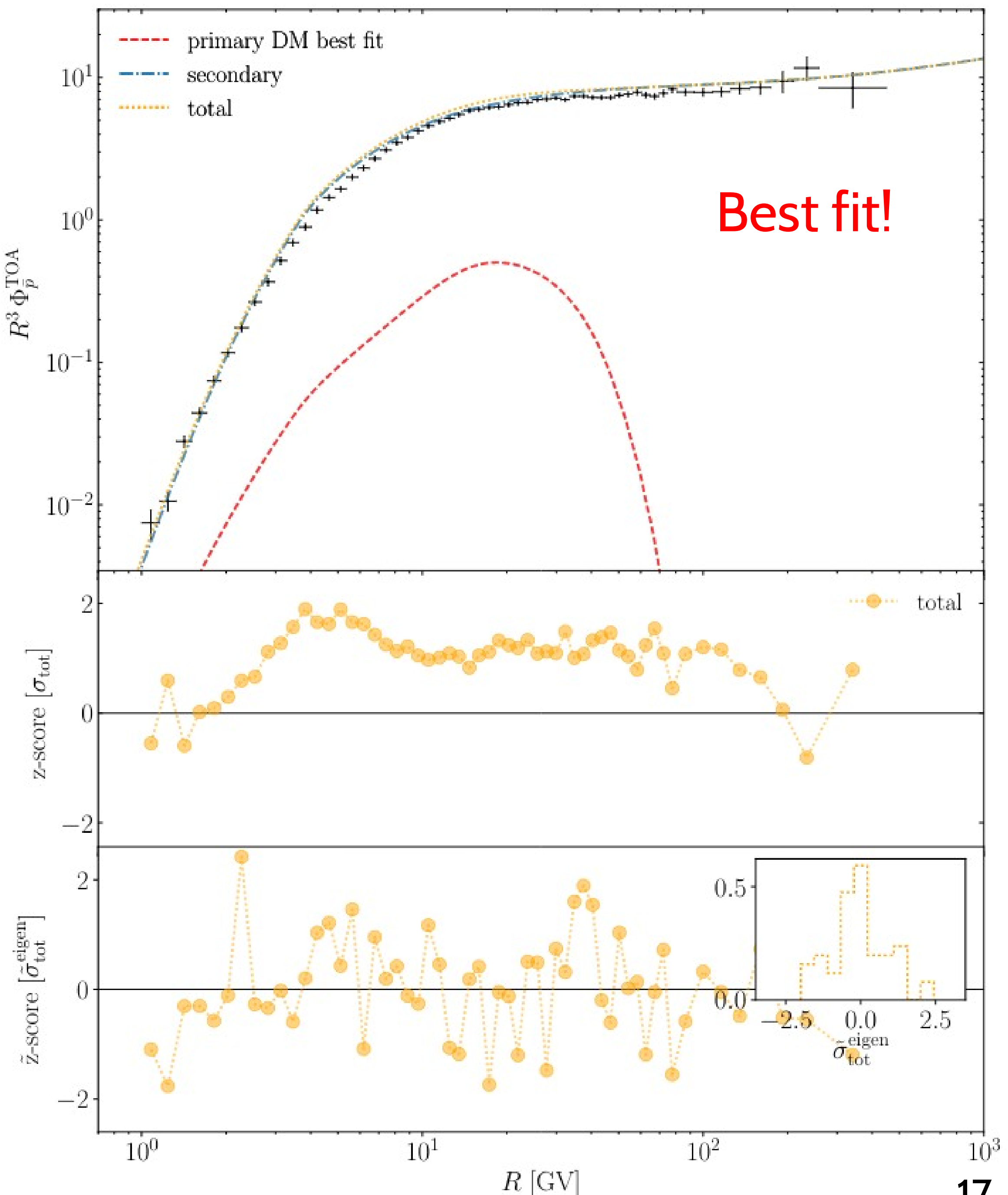
Chernoff's theorem used, $\langle\sigma v\rangle = 0$
= pure secondary antiprotons

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

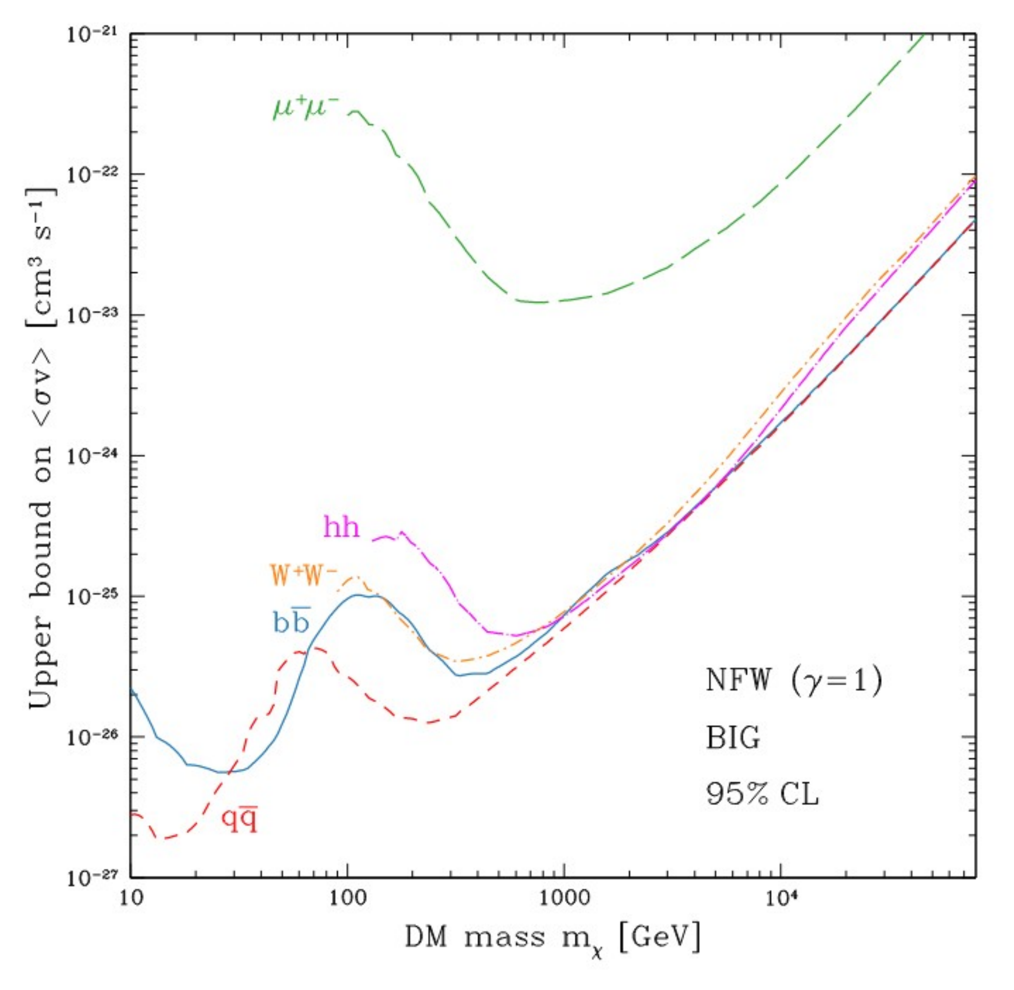
Err. data / model	local signif. [σ]	m^* [GeV]	$\langle\sigma v\rangle^*$ [cm^3/s]
cov/cov	1.81	109.3	1.71e-26
cov/none	2.39	10.5	5.07e-26
diag/cov	3.33	98.8	2.14e-26
diag/none	2.75	8.5	1.70e-25
stat/cov	5.19	89.7	1.48e-26
stat/none	4.49	8.0	2.98e-25

Some studies confirmed (Heisig+ 2020)
Some less cautious studies find excesses (Cholis+ 2019, Cuoco+ 2017, Cui+2017)



Calore, Cirelli, Derome, Genolini, Maurin, Salati, Serpico
SciPost Phys. 12, 163 (2022)

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

Secondary +Dark Matter

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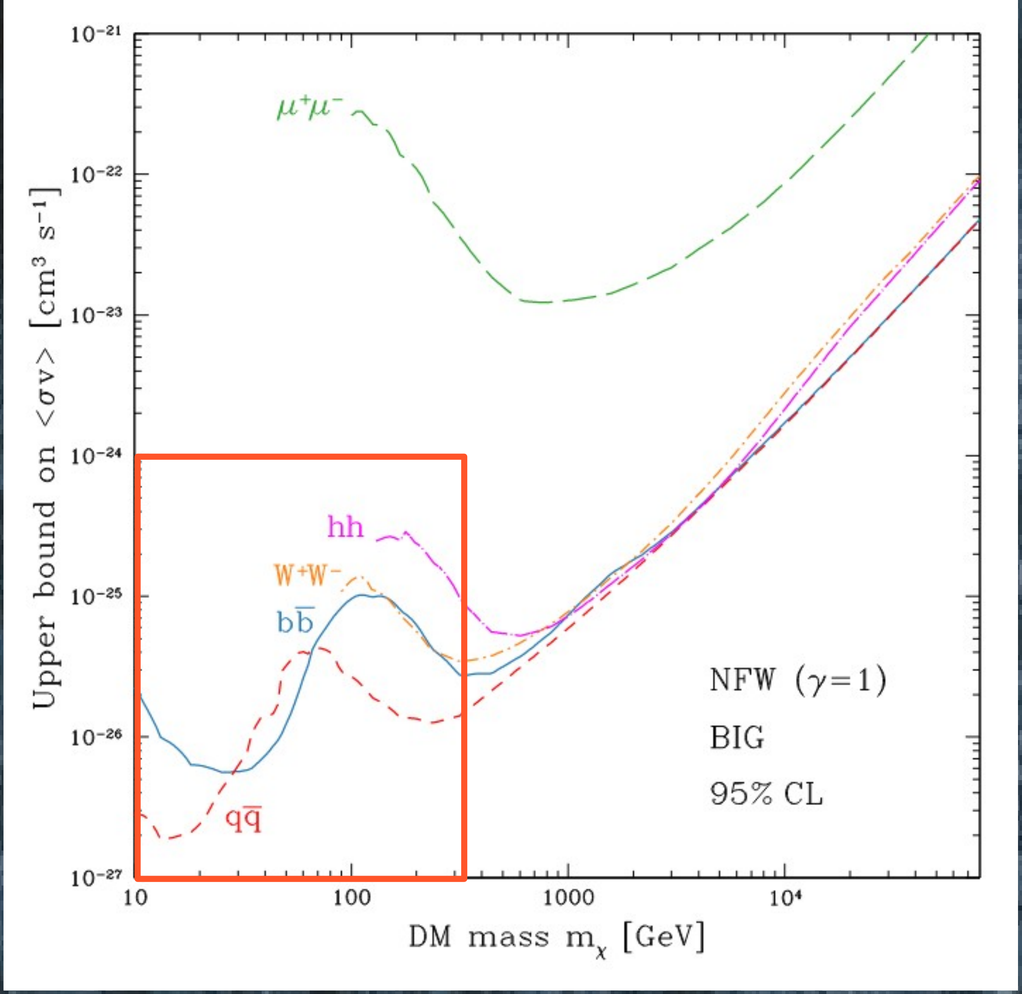

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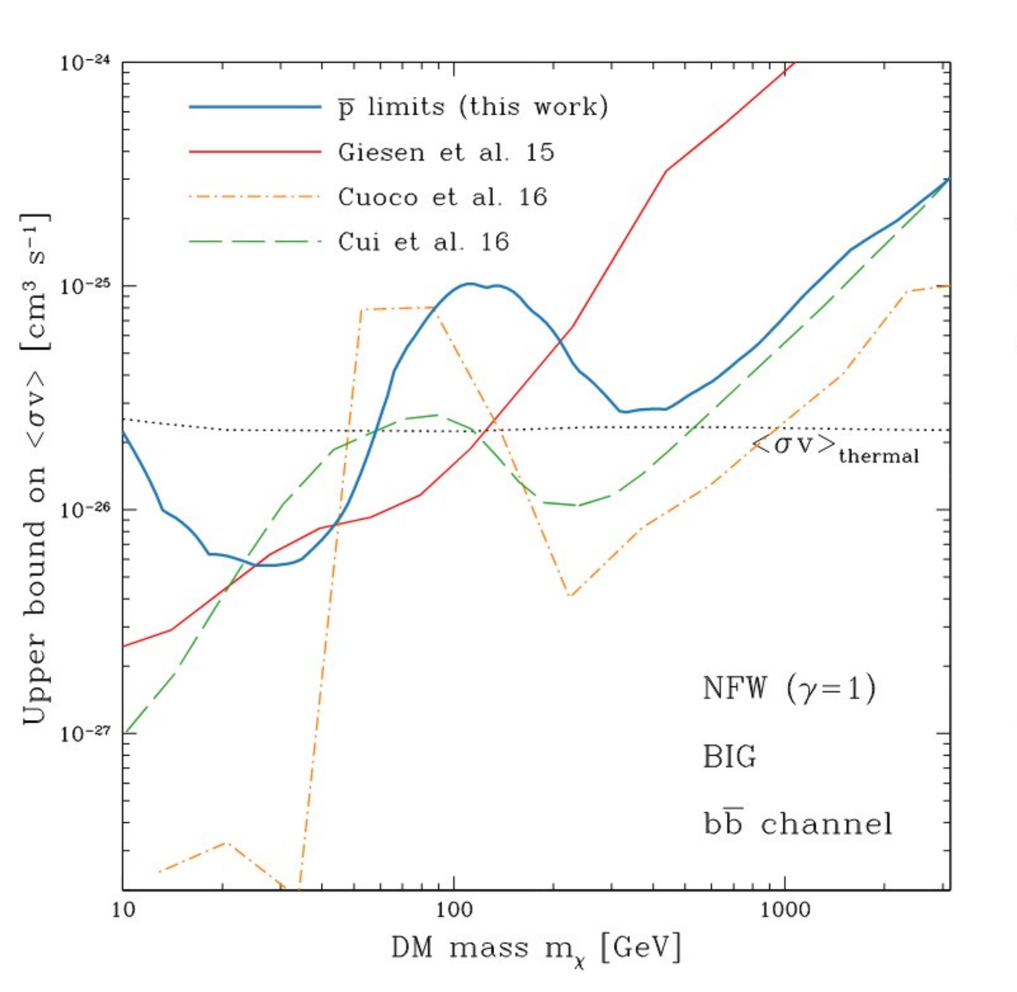
Upper limits on the DM annihilation xs: comparison with other works



→ 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

Secondary +Dark Matter

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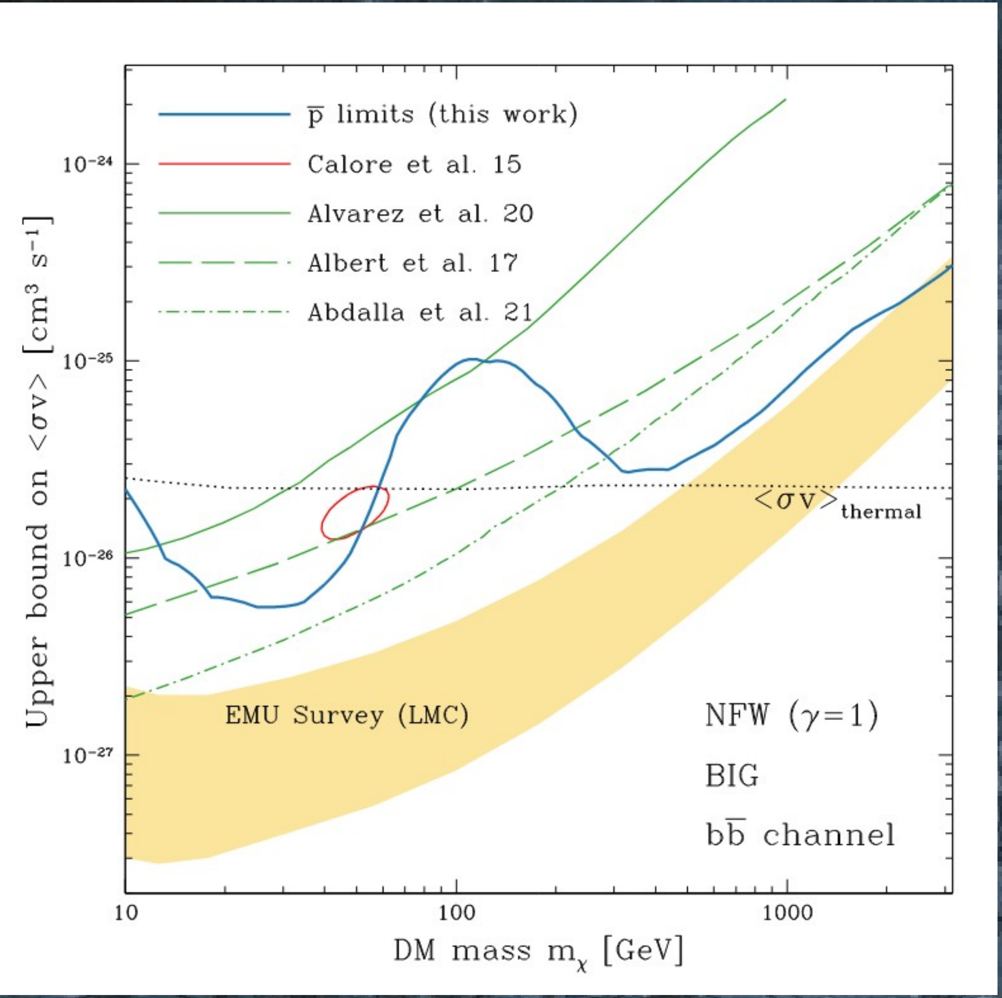
SciPost Phys. 12, 163 (2022)

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

Outline

Conclusion and prospects

Cosmic antiparticles: Is there room for dark matter?

→ 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

Backup slides

More words on antiprotons

Secondary +Dark Matter

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

→ Likelihood ratio definition

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

$(L, K, \delta, V_a, V_C, \sigma_{CR}, ...)$ 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

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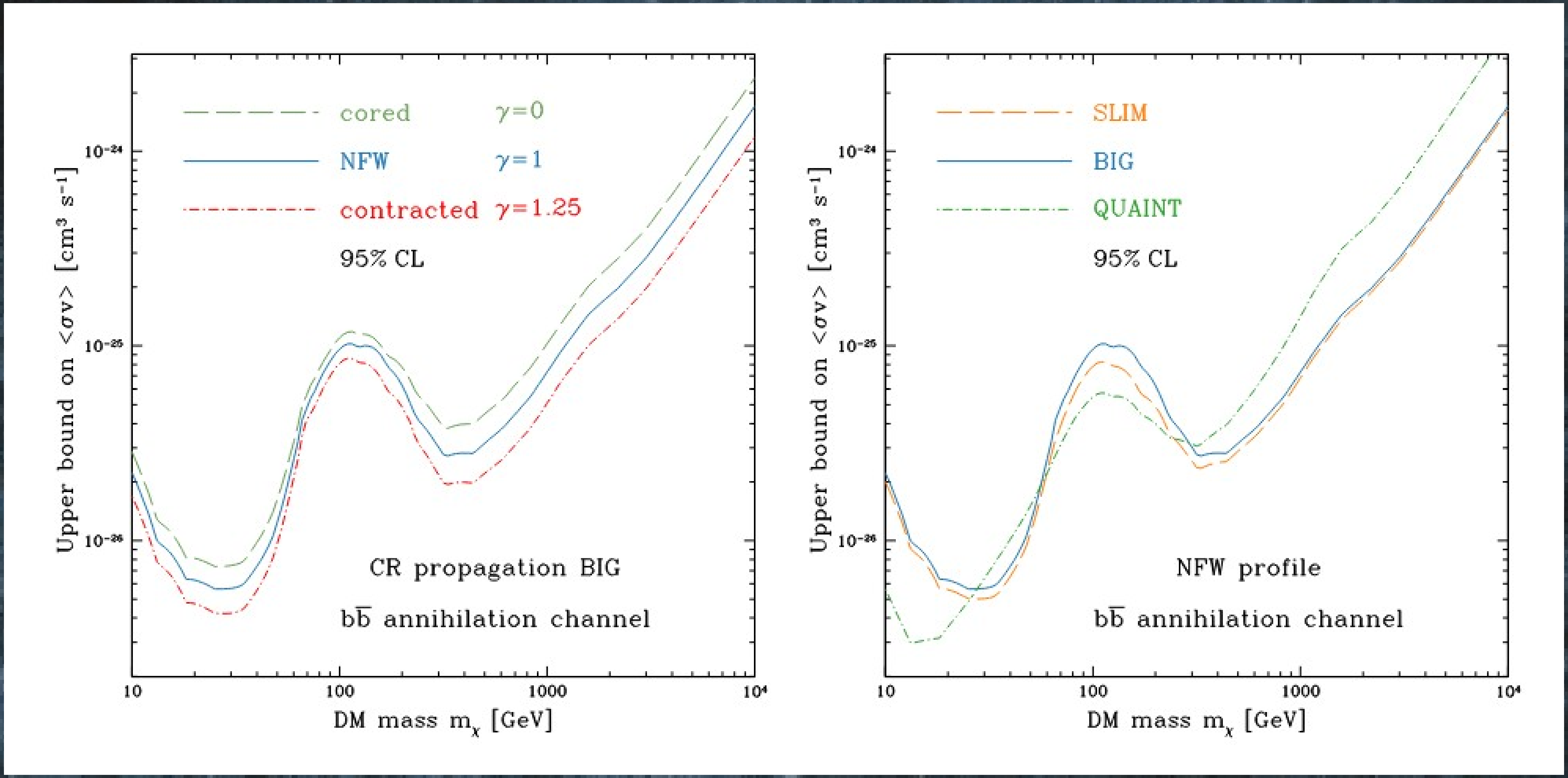
Upper limits on the DM annihilation cross section



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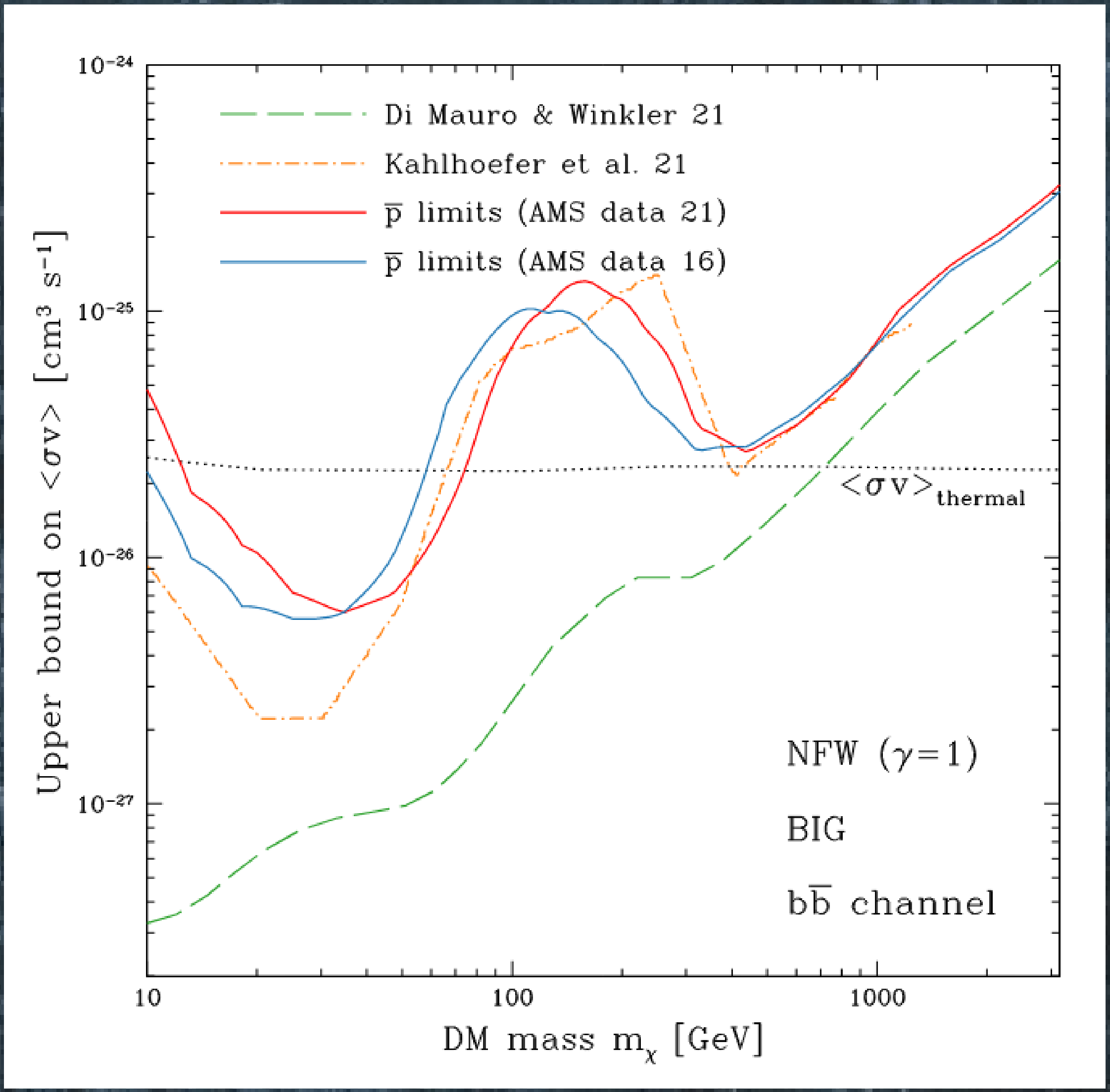
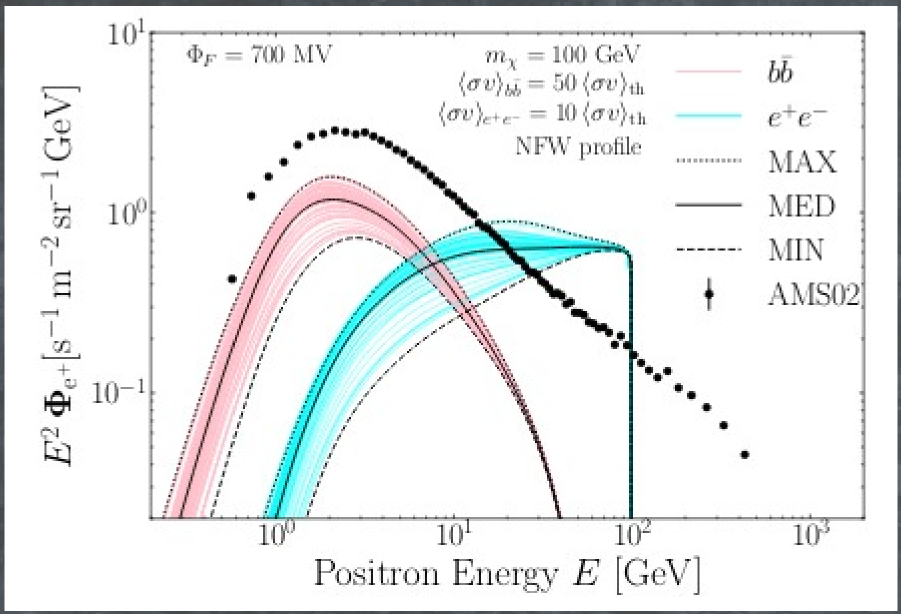
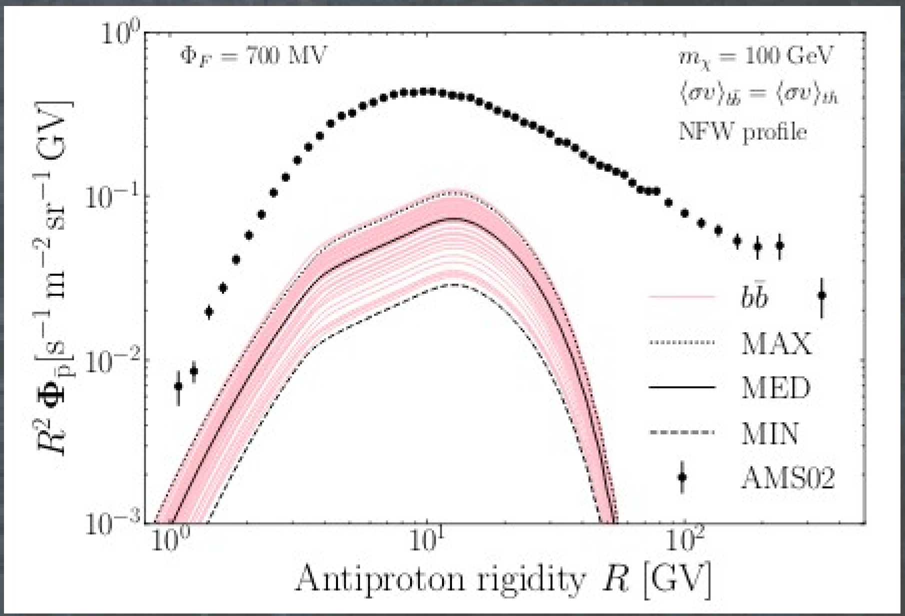


→ New data from 2021

New definition of MIN/MED/MAX → generalisation to positrons

Y.G. et al., arxiv 2103,04108





Benchmark models for indirect DM search

SLIM	L [kpc]	δ	$\log_{10} K_0$ [kpc^2 Myr^{-1}]	R_l [GV]	δ_l
MAX	8.40	0.490	-1.18	4.74	-0.776
MED	4.67	0.499	-1.44	4.48	-1.11
MIN	2.56	0.509	-1.71	4.21	-1.45

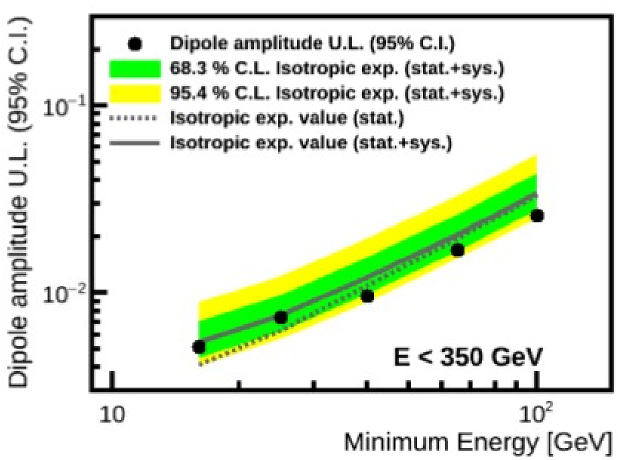
Prospects for Dark-Matter exploration with Cosmic-rays

UPPER LIMITS ON DIPOLE AMPLITUDE:
ELECTRONS AND POSITRONS

Karlsruhe Institute of Technology

Electrons

1.3 x 10^6 events, 16 GeV<E<350 GeV



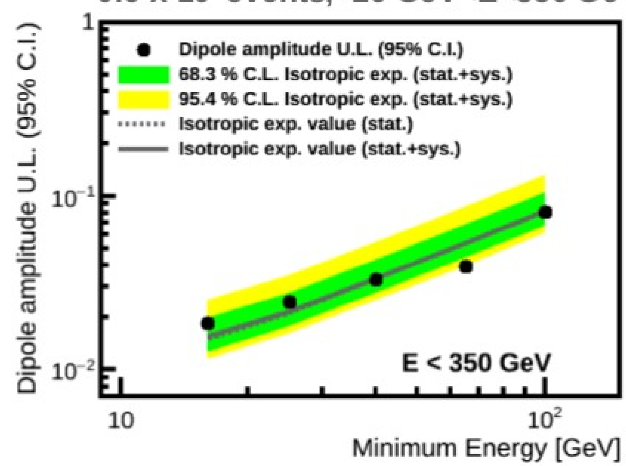
Upper limit on dipole amplitude:

δ_{e-}(>16 GeV) < 0.5% at 95% C.I.

[Phys. Rev. Lett. 122, 101101]

Positrons

9.9 x 10^4 events, 16 GeV<E<350 GeV

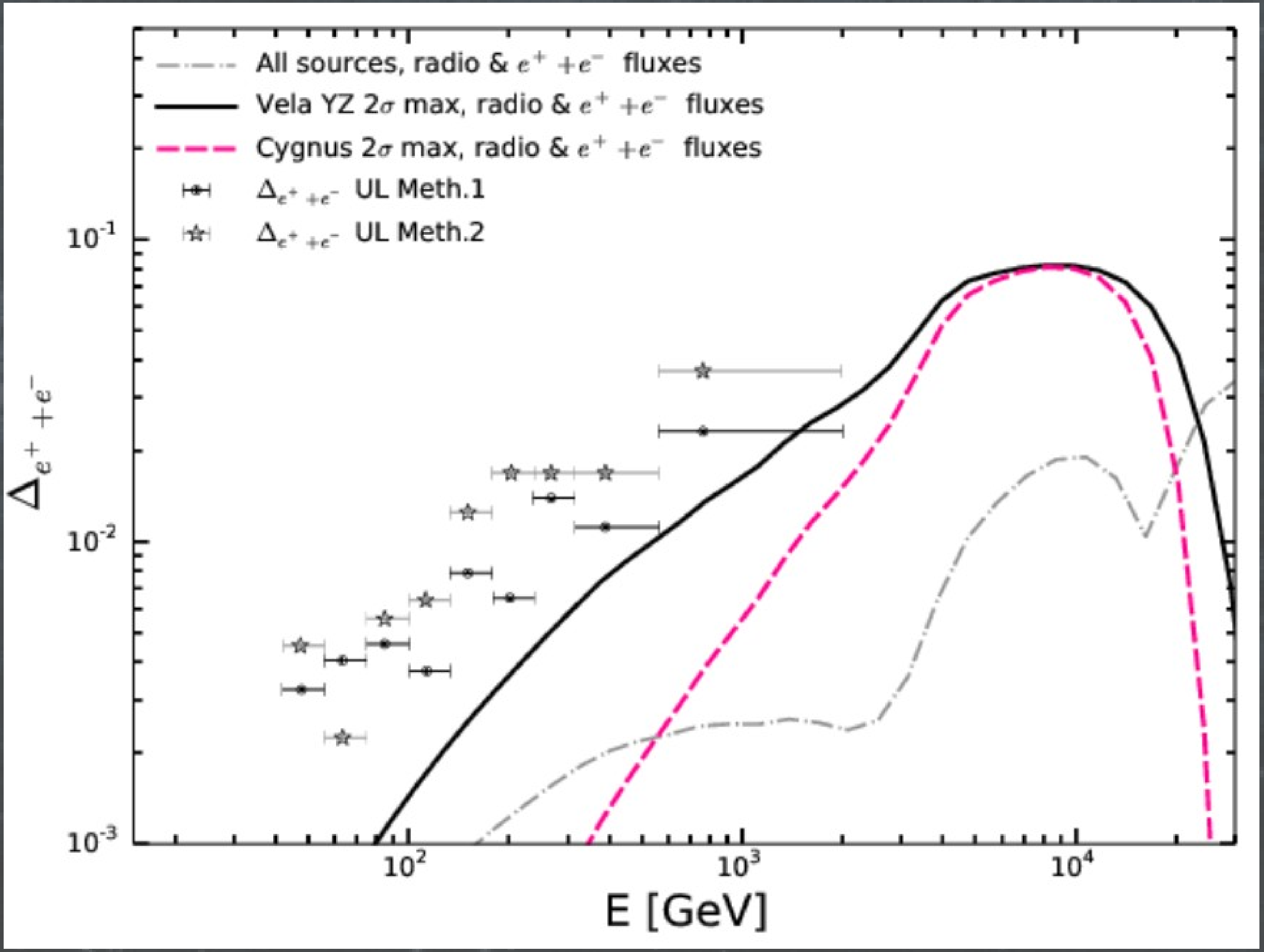


Upper limit on dipole amplitude:

δ_{e+}(>16 GeV) < 1.9% at 95% C.I.

[Phys. Rev. Lett. 122, 041102]

Prospects for Dark-Matter exploration with Cosmic-rays



(Manconi, S.+ 2019)

Prospects for Dark-Matter exploration with Cosmic-rays

TABLE I. Respective p-values for different sources of errors. We take dof$=57$, i.e. the number of $\bar{p}$ data. Total errors on data are defined to be $\sigma_{\rm tot} = \sqrt{\sigma^2_{\rm stat} + \sigma^2_{\rm syst}}$.

Error considered	χ^2/dof	p-value (χ^2)	p-value (KS)
$\sigma_{\rm stat}$	23	0	0
$\sigma_{\rm tot}$	1.69	8.3×10^{-4}	0
$\mathcal{C}^{\rm data}$	0.84	0.79	0.98
$\sigma_{\rm stat}$ and $\mathcal{C}^{\rm model}$	1.32	0.05	0.99
$\sigma_{\rm tot}$ and $\mathcal{C}^{\rm model}$	0.37	1.0	0.04
$\mathcal{C}^{\rm data}$ and $\mathcal{C}^{\rm model}$	0.77	0.90	0.27

(Boudaud, M.+ 2019)