Dark matter searches in the antiproton and positron cosmic-ray spectra

- Intro on motivations and basic principles (to put everybody on the same page)
- The power and recent challenge of using leptonic data and positrons in particular
- The pbar channel: Precise secondary predictions from propagation benchmarks & bounds

Apologies for a far from exhaustive review of the literature, just hand-picked some recent papers (mostly ≥ 2019, last NftD…)

*Work within **C**osmic **R**ay **A**lpine **C**ollaboration & co., see D. Maurin's talk for list of people*

Pasquale Dario Serpico (Annecy, France)
News from the Dark, Annecy, France 22/11/2021

Why searching for DM in cosmic rays?

Rather ***expected*** within the ***WIMP class*** of DM particles
a single stable massive particle in chemical equilibrium with SM via EW-strength binary interactions in early universe down to T<<m

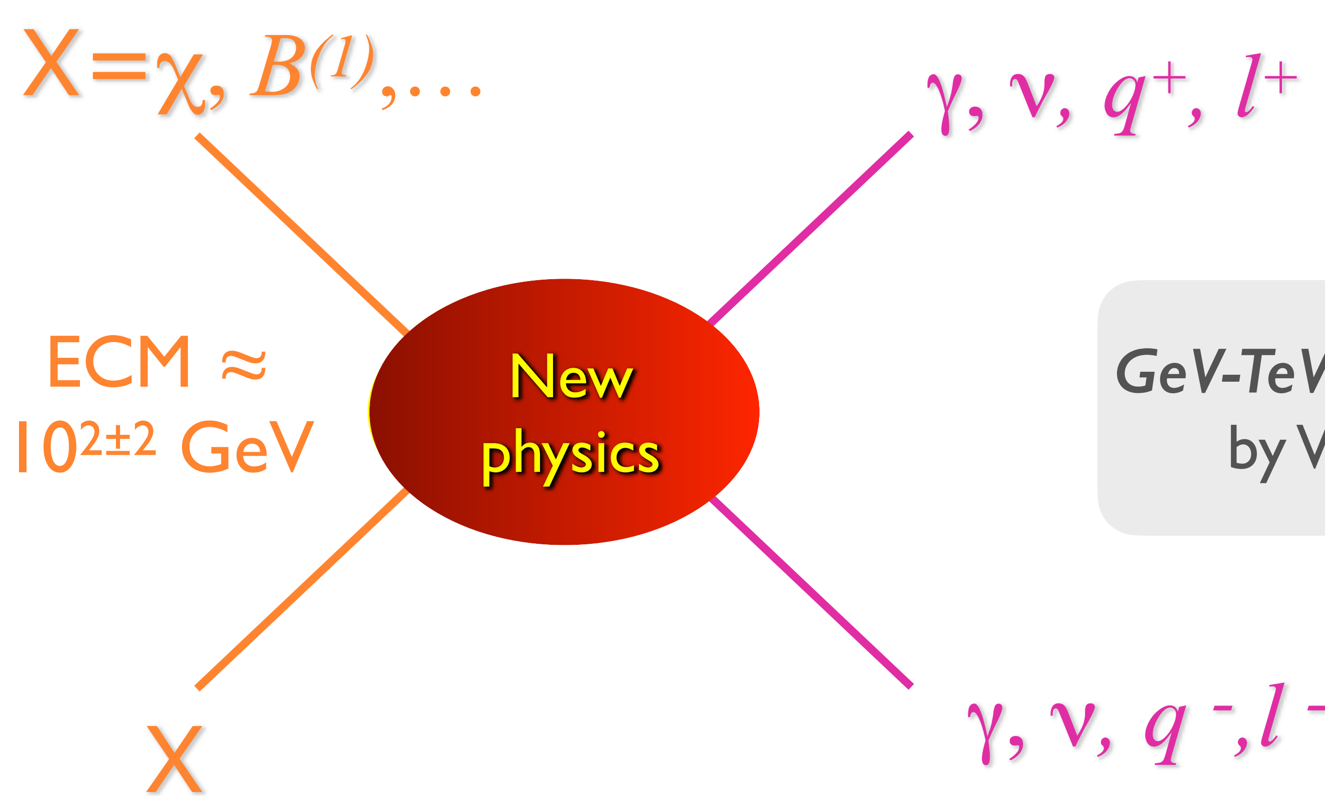
Textbook calculation yields the current average cosmological energy density

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle\sigma v\rangle}$$

Observationally inferred $\Omega_{DM}h^2$~0.1recovered for EW scale masses & couplings (aka ***WIMP miracle***)!

$$\langle\sigma v\rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb}\left(\frac{200\,\mathrm{GeV}}{m}\right)^2$$

Binary annihilations (relevant in overdense regions) to convert some DM into typically relativistic SM particles



GeV-TeV scale singled-out by WIMP miracle

Which particles?

All stable, kinematically accessible SM final states:
protons, nuclei, electrons, γ, ν (and their antiparticles)

γ, ν

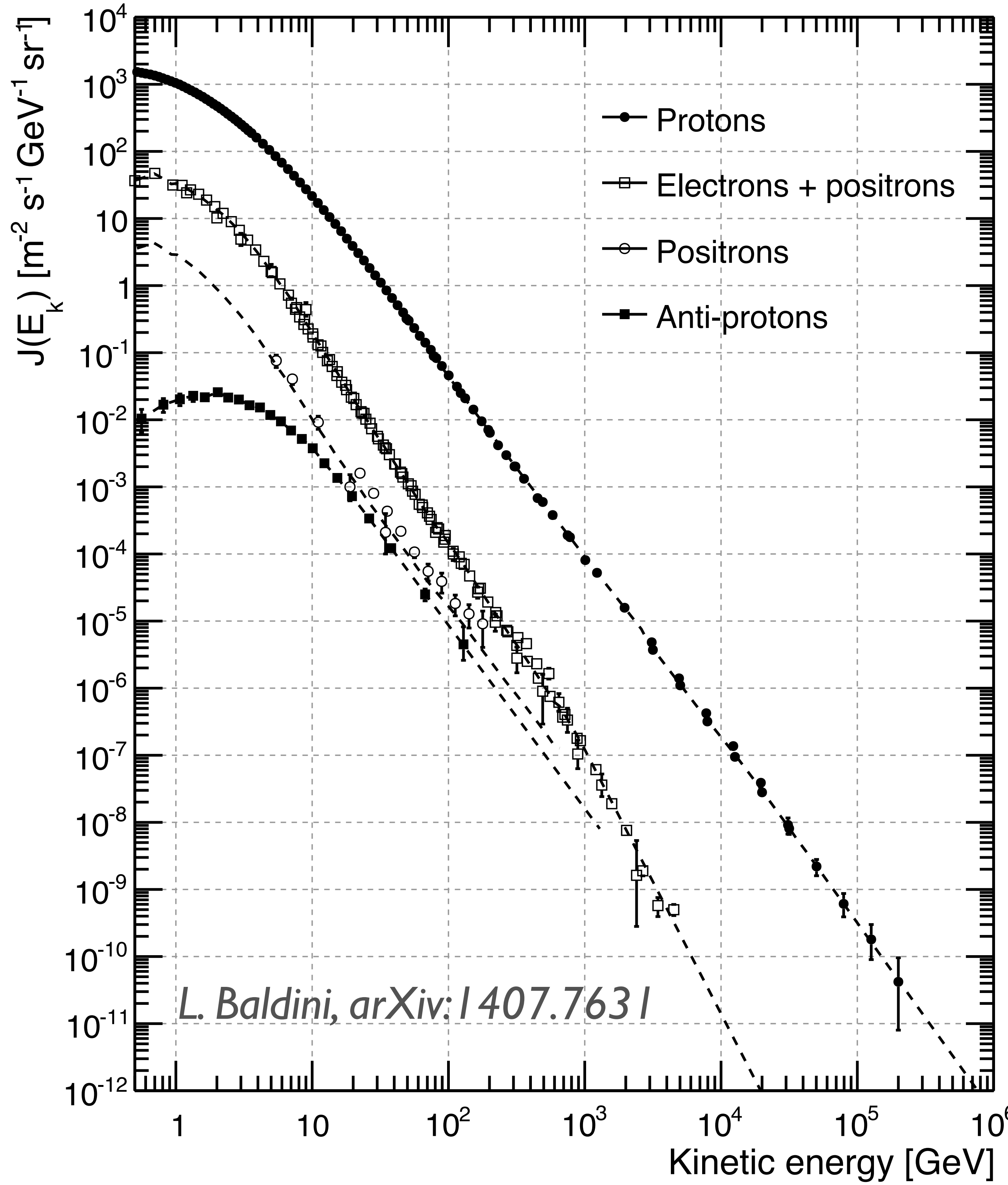
✓ propagate in straight lines, from production to observable fluxes via line-of-sight integration

✗ "Easily" produced in astrophysical processes; hard to detect

protons, nuclei, electrons

✓ CRs dominated by matter (as opposed to antimatter), 'obvious' background suppression strategy

✗ do not propagate in straight lines, sizeable energy-changing processes… harder to compute, both signal and background.



Computing fluxes at the Earth

Compare predicted and observed flux, to find indications of DM or constraints

Key hypothesis

Factorized problem (differences in time and spatial scales):
Sources ⊗ Propagation ⊗ Solar System effects *(solar modulation)*

While for neutral particles, even ignoring astro sources, one can still get conservative bounds, ***for charged particles no bound exists without propagation assumptions***

How to compute the flux at the Earth? Sources

Particle model fixes x-sec, spectrum, mass, self-conjugated nature or not…

$$Q_{\rm DM}(E,\mathbf{x}) = \frac{\langle \sigma v\rangle \rho^2(\mathbf{x})}{8\pi m_X^2}\frac{dN}{dE}$$

Add a model for **astro** sources (different spectra!)

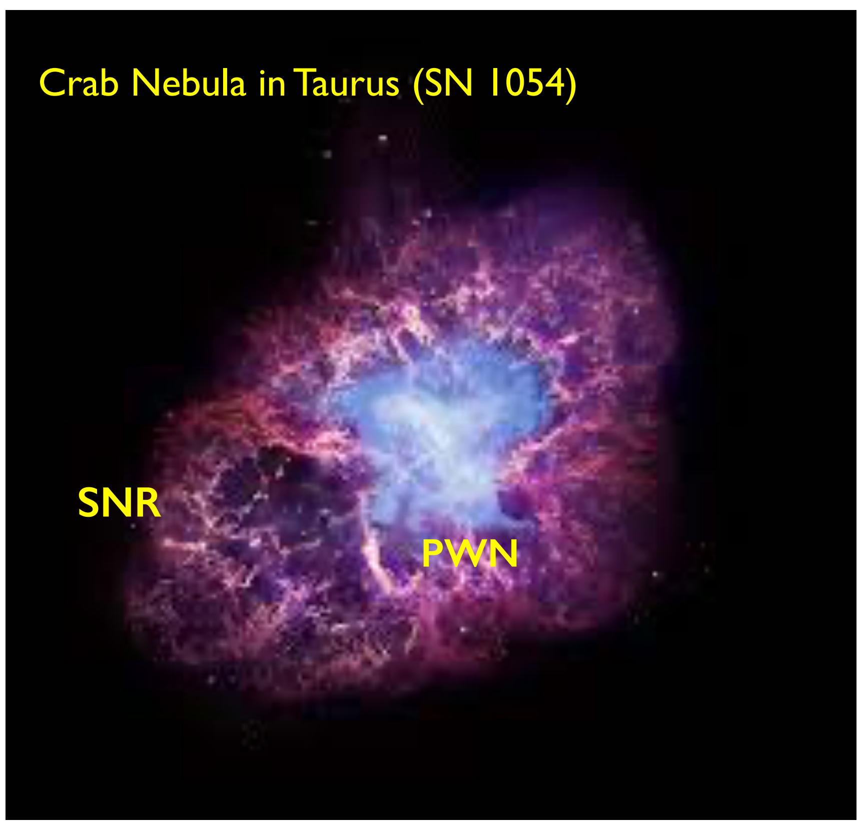
$$Q_{\rm tot}(E,\mathbf{x}) = Q_{\rm astro}(E,\mathbf{x}) + Q_{\rm DM}(E,\mathbf{x})$$

Density of DM

Resort to simulations with free parameters fitted to astro data

Can conservatively ignore substructure, or use models

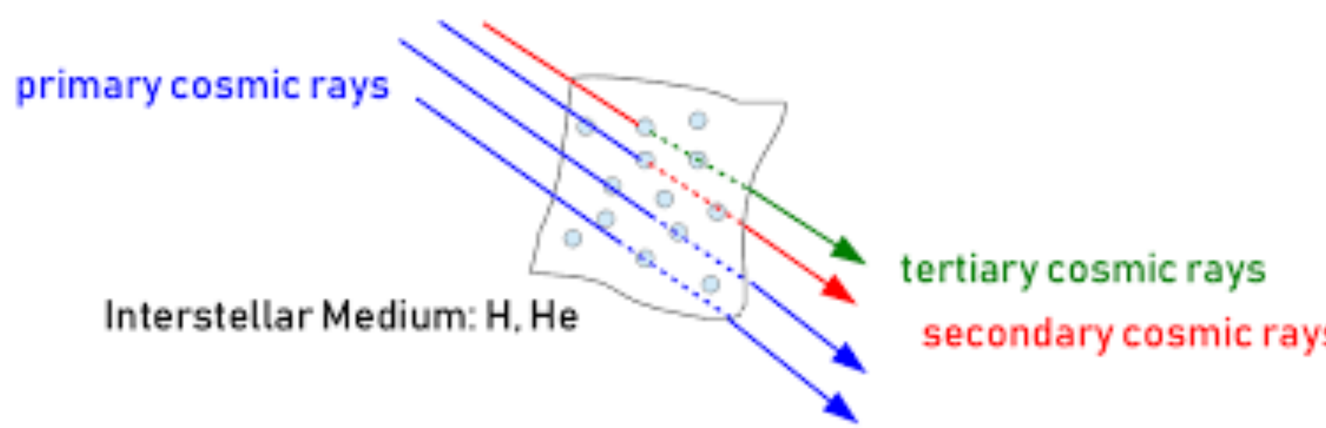
Primary sources *acceleration at SNRs, Pulsar wind nebulae…*



+ some hypotheses (e.g. often continuum injection limit in time and space…)

Secondary sources

Byproducts of collisions in the ISM



How well do we know the sources?

The 'positron rise' era (2008-2013)

Paradigm until ~13 years ago:

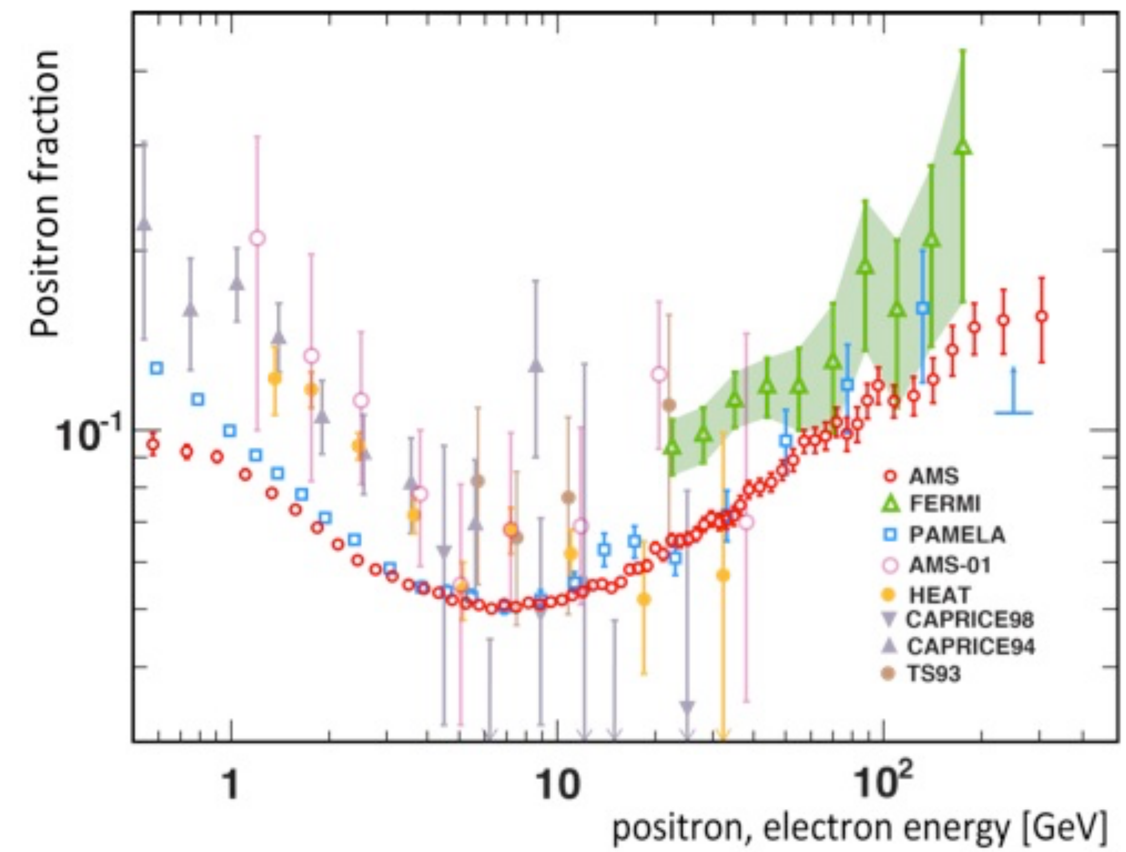
e$^-$: mostly primaries, matching p spectra (at injection in SNRs) but for a normalisation

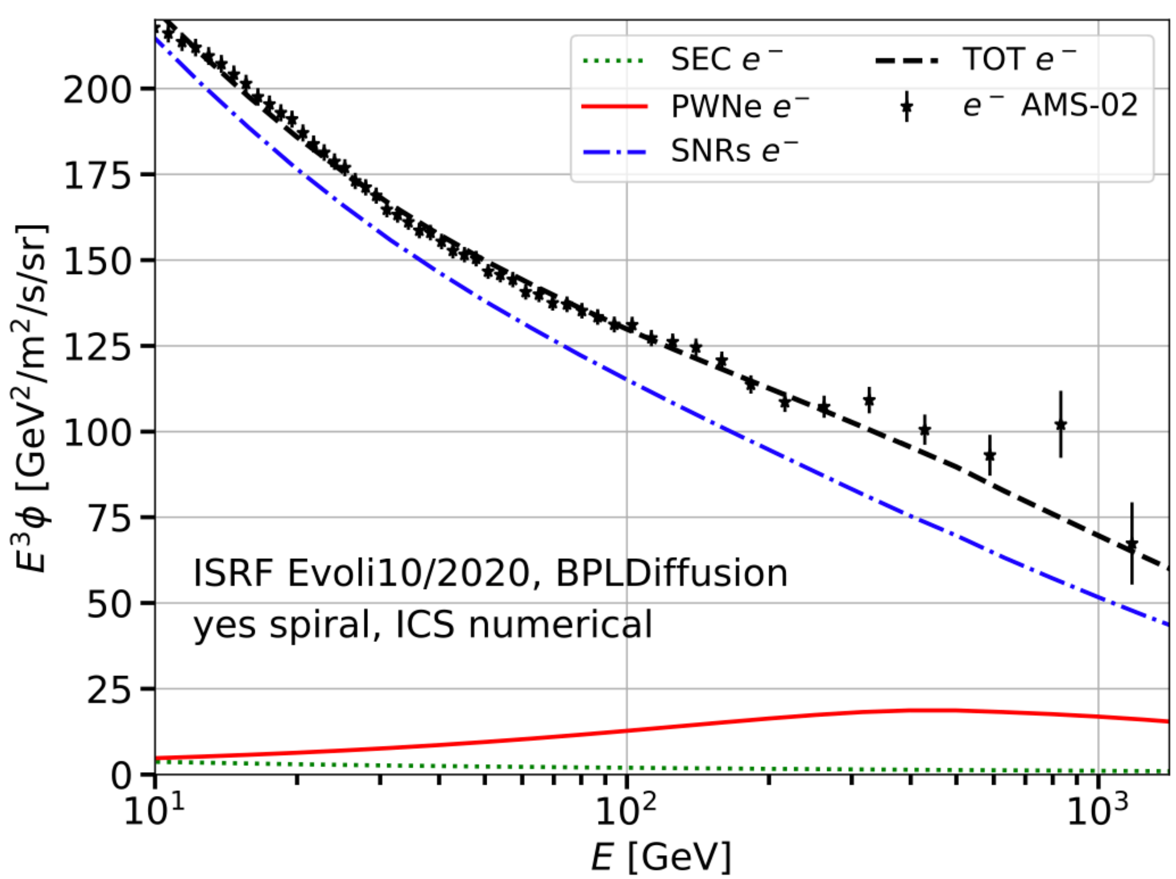
e$^+$: secondaries dominated by pion production e.g. via p_{CR}+ H_{ISM} → π +X

Over past decade, role of additional ***primary*** source(s) @ E> 10 GeV became clear

No single 'standard model', rather consistent with expectation from SNRs+PWN, but degeneracies in the source and propagation

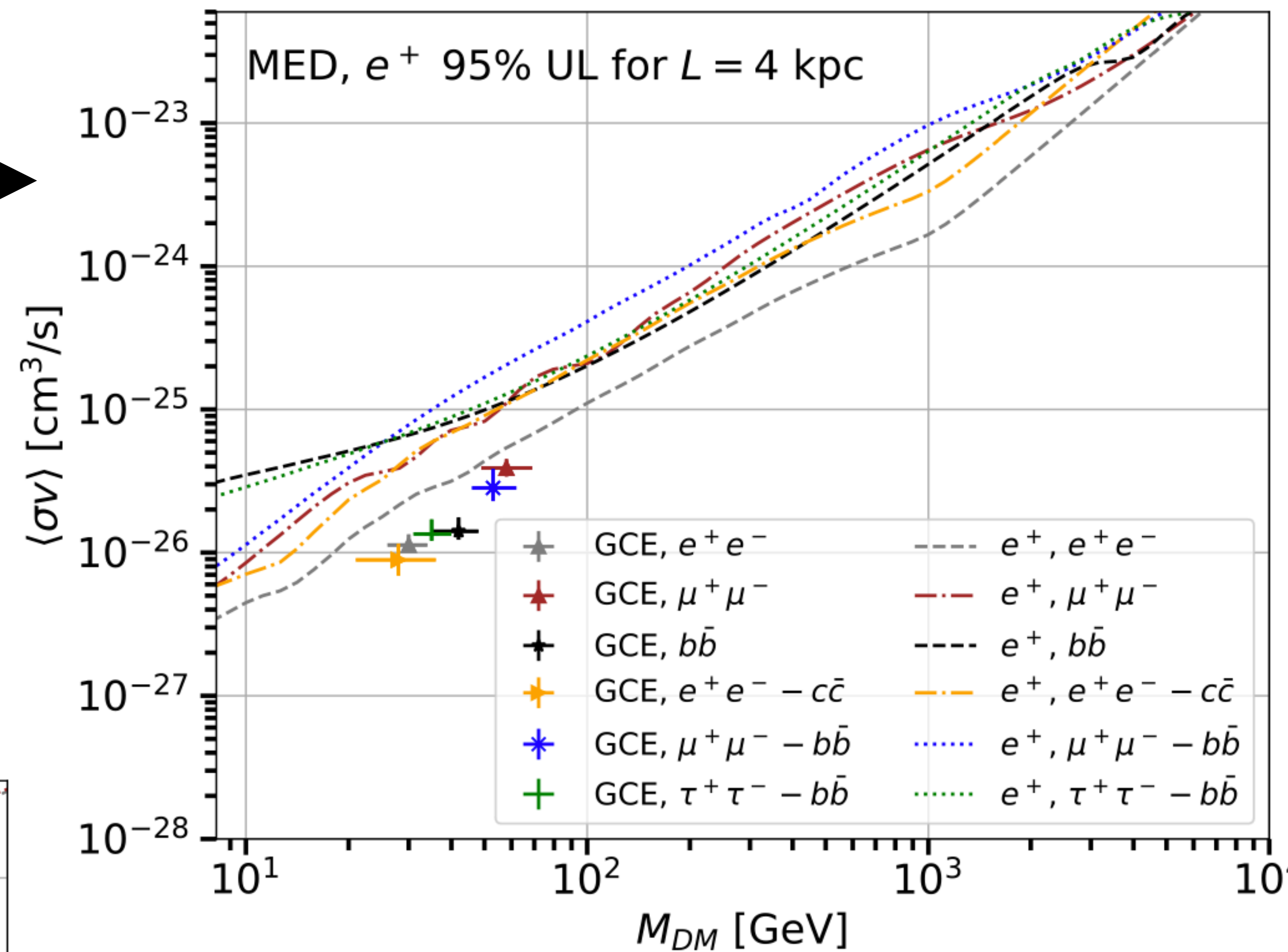
M. Di Mauro, F. Donato, S. Manconi, "Novel interpretation of the latest AMS-02 cosmic-ray electron spectrum," [arXiv:2010.13825]



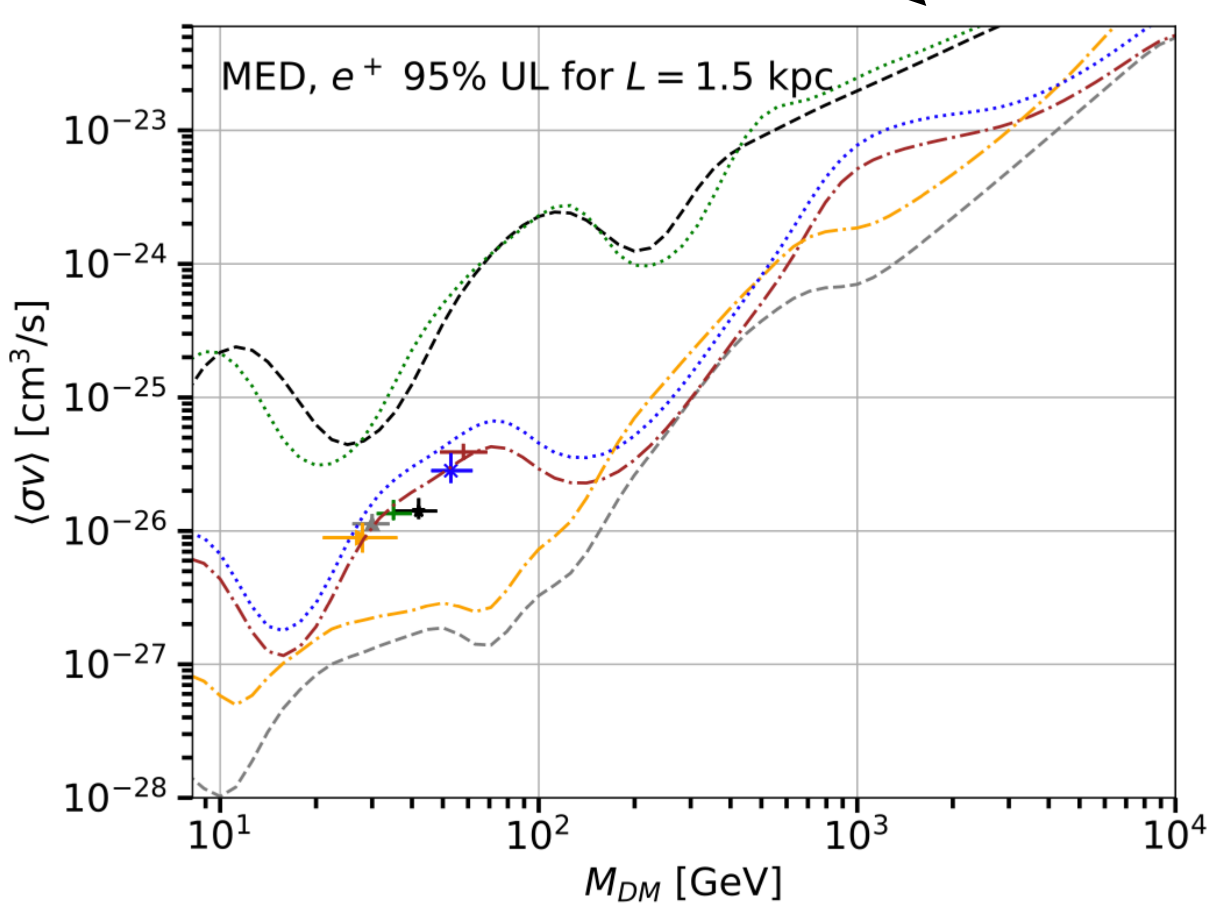


Can still set bounds from e⁺

e.g. conservatively accounting only for secondary e+ →



sensitive to prop. parameters (notably halo thickness *L*)
Assuming a "PWN-like" fit and different halo-size:



M. Di Mauro & M.W. Winkler, "Multimessenger constraints on the DM interpretation of the Fermi-LAT GC excess," Phys. Rev. D 103, 123005 (2021)[arXiv:2101.11027]

The situation is more under control for pbars, but need to tackle issue of propagation parameters (D. Maurin's talk)

Prediction of the antiproton flux (not a fit!)

M. Boudaud et al. Phys. Rev. Research 2, 023022 (2020) [1906.07119]

How often do you see that in astrophysics?

Monte Carlo simulations to determine the errors (and correlations!) due to

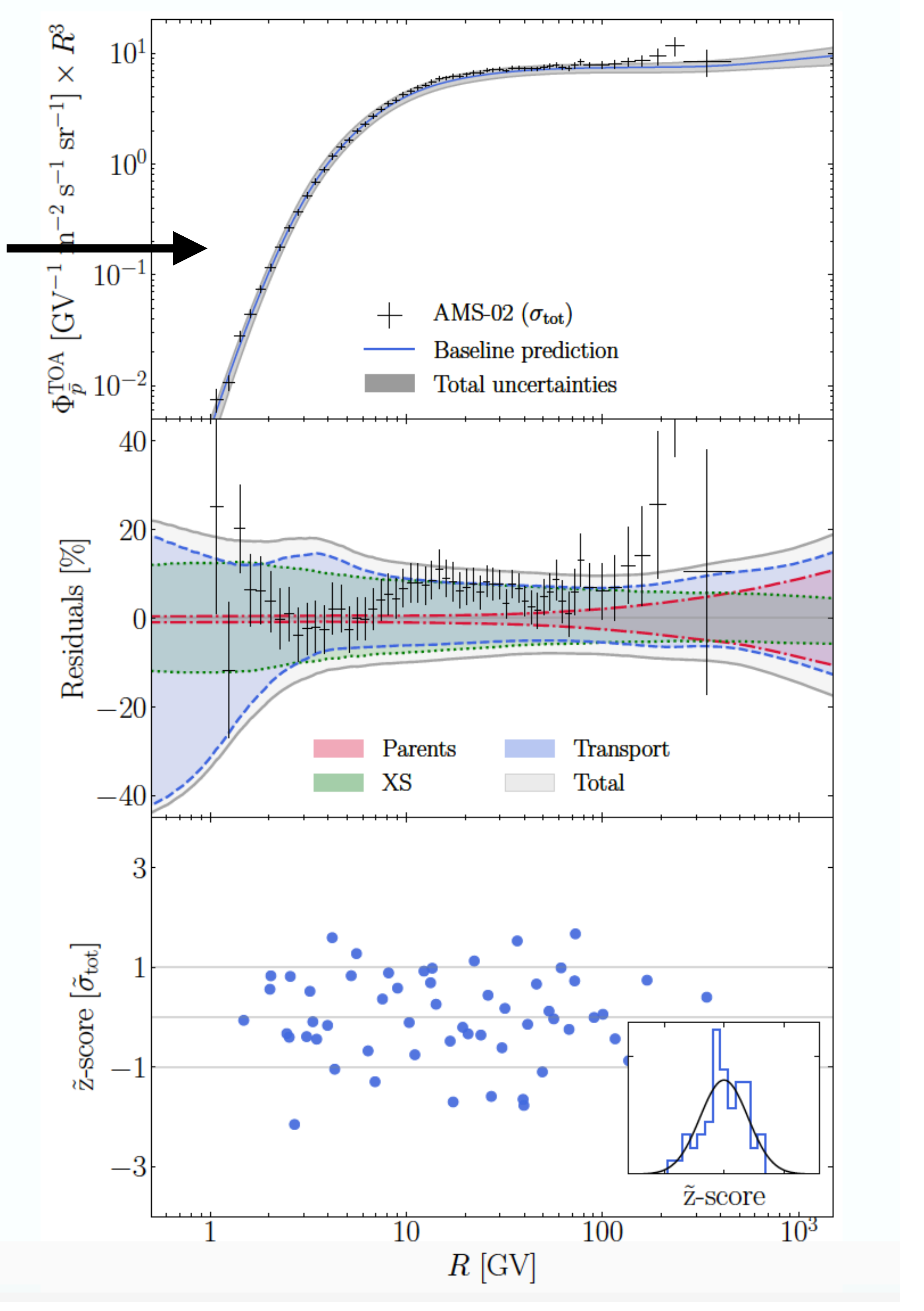
- Production XS (fits to collider data)
- Transport (fit B/C)
- Parent CR fluxes

accounting for production from heavy nuclei, 'non-prompt' production (essentially anti-hyperons), isospin violation effect & uncertainties…

Residuals which actually matter

"rotated" z-score $\tilde{z}_i = \tilde{x}_i / \tilde{\sigma}_i$

in terms of "decorrelated" dof's



AMS-02 pbar data consistent with secondary origin!

Probing DM with antiprotons

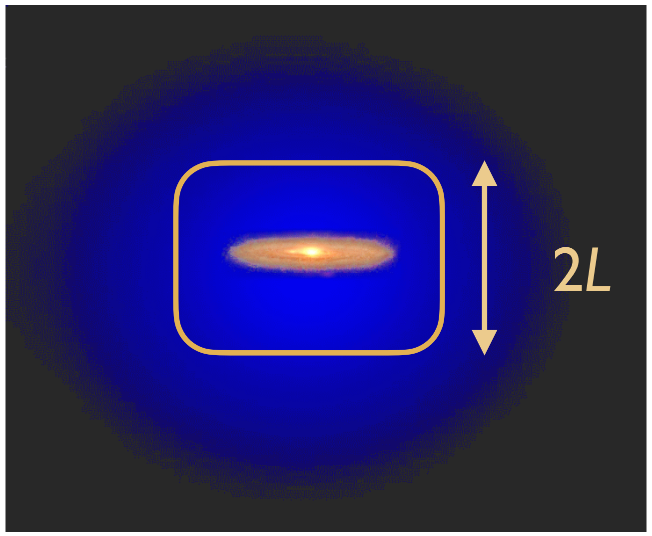
For a recent mini-review:

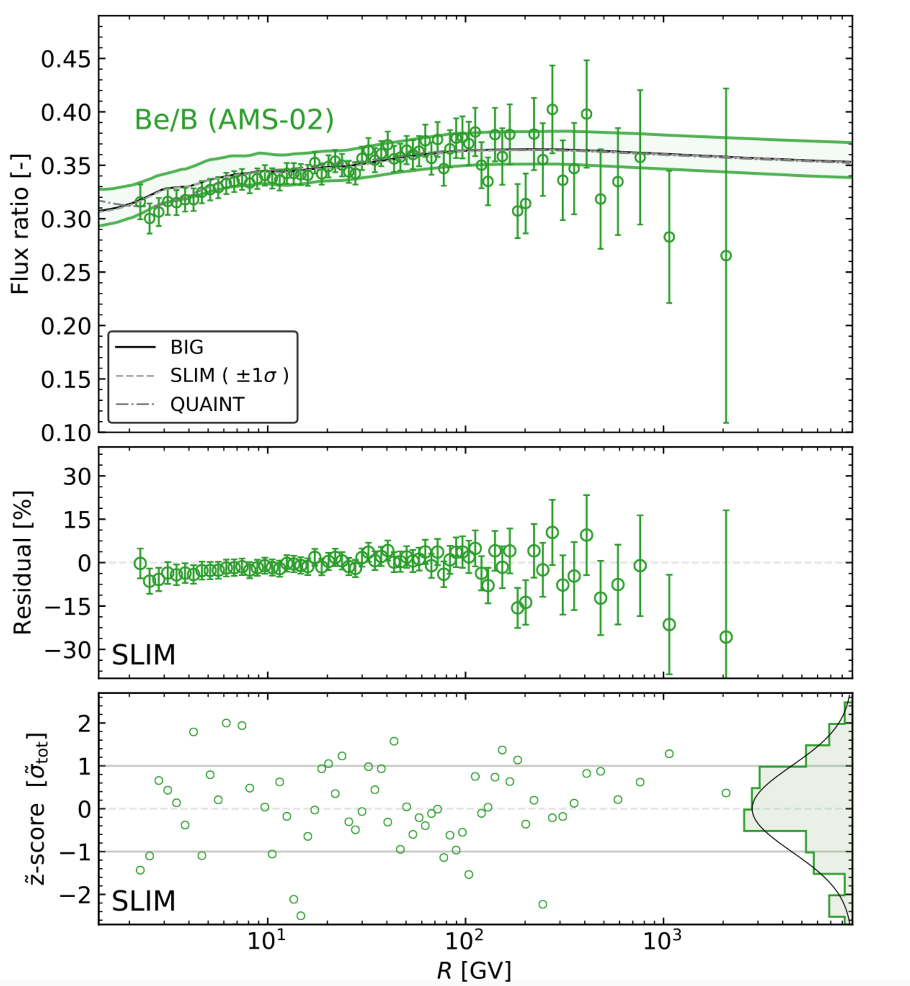
J. Heisig, "Cosmic-ray antiprotons in the AMS-02 era: A sensitive probe of dark matter,"
Mod. Phys. Lett. A 36 (2021) no.05, 2130003 [arXiv:2012.03956]

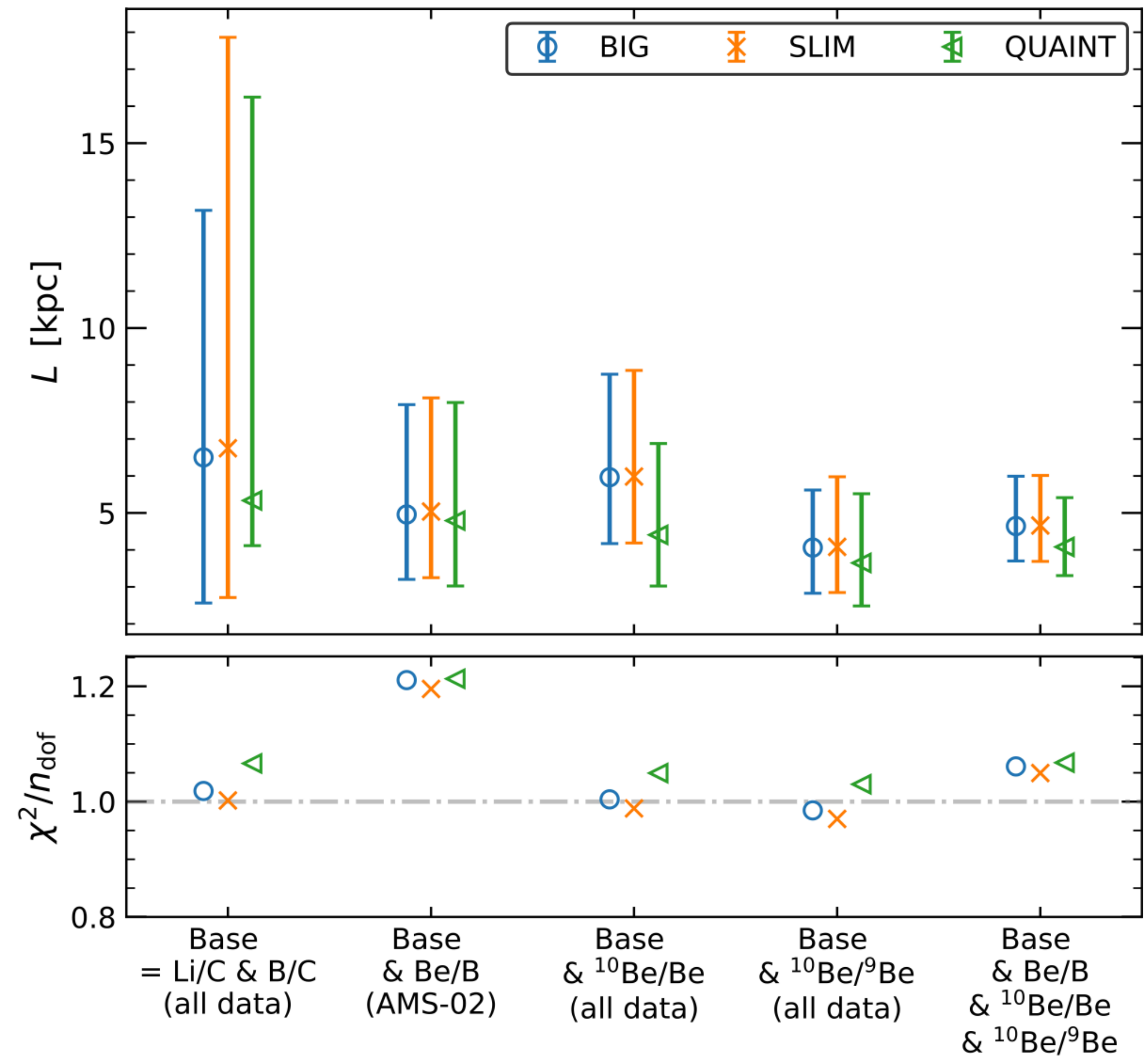
Preliminary: Global secondary analysis & constraints on halo thickness *L*

For ***stable*** secondaries, large degeneracy K/L,

For DM: large *L*, large signal!







Overall consistency with B/C

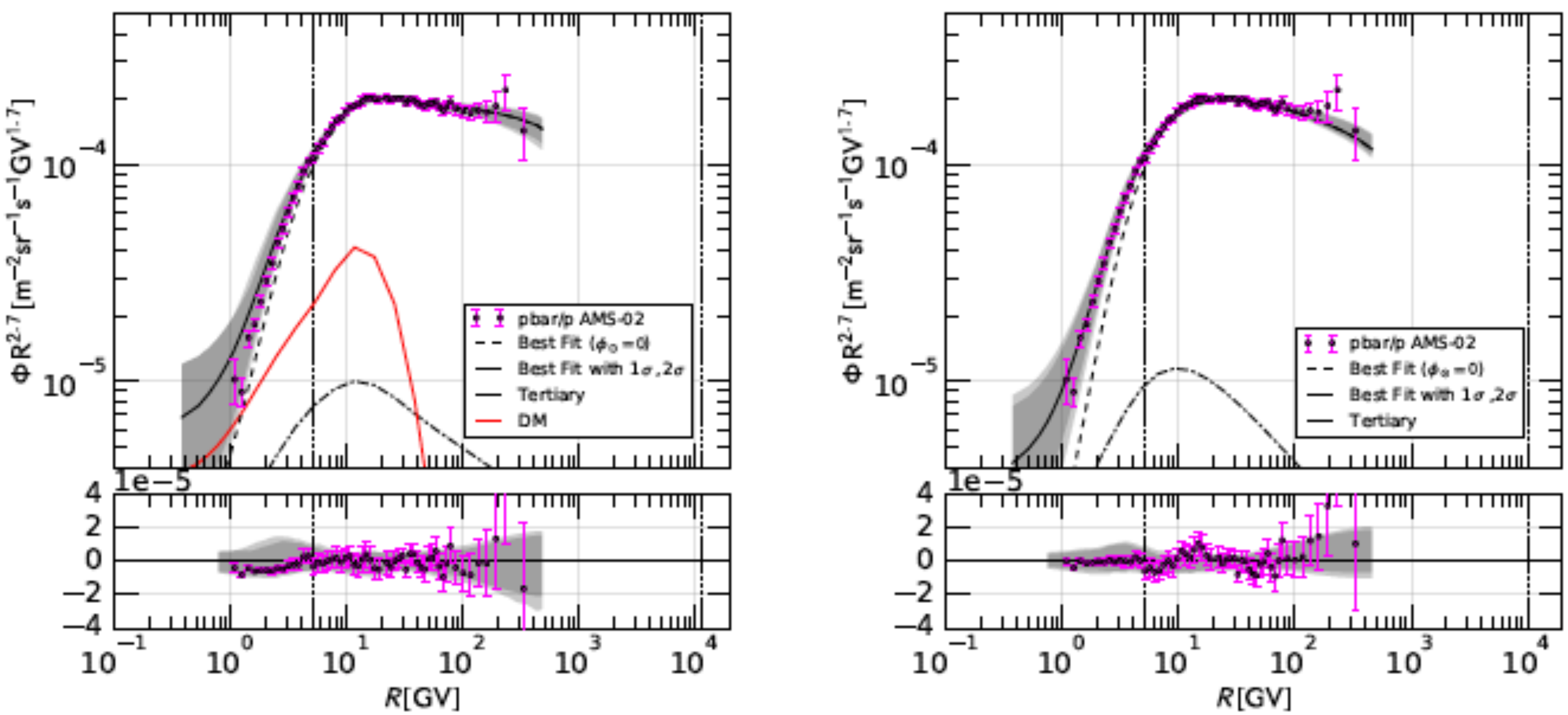
+ tightening of the constraints

N.Weinrich et al. A&A A74 (2020) [arXiv:2004.00441]

A DM signal hidden in the data?

A.Cuoco, M. Krämer, M. Korsmeier, "Novel dark matter constraints from antiprotons in the light of AMS-02," Phys. Rev. Letters 118, 191102 (2017) [1610.03071]

"DM favored at around 4.5 sigmas"



See also
M.Y. Cui, Q.Yuan, Y. L. S.Tsai and Y. Z. Fan, "A possible dark matter annihilation signal in the AMS-02 antiproton data," Phys. Rev. Letters 118, 191101 (2017) [1610.03840]

…much smaller effect (~2.2 sigma local, 1.1 sigma global) found in *A. Reinert and M.W.Winkler, "A Precision Search for WIMPs with Charged Cosmic Rays," JCAP 1801, 055 (2018) [1712.00002]*

2019: sequel(s)

A.Cuoco, J. Heisig, L. Klamt, M. Korsmeier, M. Krämer, "Scrutinizing the evidence for dark matter in cosmic ray antiprotons," 1903.01472

Confirmed excess, but at 3 sigma level (number of technical improvements and checks)

I. Cholis, T. Linden, D. Hooper, "A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter" 1903.02549

Hint claimed at the 4.7 sigma level

S. J. Lin, X.J. Bi, Y. P. F. Yin, "Investigating the dark matter signal in the cosmic ray antiproton flux with the machine learning method" 1903.09545

From very significant to below 1 sigma, depending on model for cross sections and treatment of solar modulation.

To cut a long story short, important element recently added changed the terms of the game!

The importance of correlated errors…

GALPROP propagation à la Cuoco et al. 1903.01472

	w/o corr.	with corr.
$\chi^2_{\bar{p}/p}$ (42 bins)	11.4 (16.2)	45.6 (46.4)
χ^2_p (50 bins)	1.8 (3.2)	104.5 (104.9)
χ^2_{He} (50 bins)	4.8 (4.5)	78.4 (77.6)
$\chi^2_{p,\mathrm{Voy}}$ (9 bins)	1.8 (1.7)	2.9 (4.3)
$\chi^2_{\mathrm{He,Voy}}$ (5 bins)	0.3 (1.0)	1.8 (2.0)
χ^2_{tot}	20.3 (27.2)	233.1 (236.3)
No. of fit param.	16(18)	16(18)
m_{DM} [GeV]	76	66
$\langle\sigma v\rangle$ [10^{-26} cm^3/s]	0.91	0.74
$\Delta\chi^2_{\mathrm{tot}}$	6.9	3.2
local sig.	2.6 σ	1.8 σ
global sig.	1.8 σ	0.5 σ

J. Heisig, M. Korsmeier and M.W.Winkler, "DM or correlated errors: Systematics of the AMS-02 antiproton excess," Phys. Rev. Res. 2 (2020) 043017[arXiv:2005.04237]

Final state	Model	m^* [GeV]	$\langle\sigma v\rangle^*$ [cm^3/s]	LR	$p-$value local	signif. local [σ]
$b\bar{b}$	BIG	103.4	1.76e-26	3.71	0.054	1.9
$b\bar{b}$	SLIM	102.9	1.61e-26	3.37	0.066	1.8
$b\bar{b}$	QUAINT	96.2	6.52e-27	0.45	0.501	0.7
W^+W^-	BIG	102.3	2.33e-26	3.01	0.083	1.7

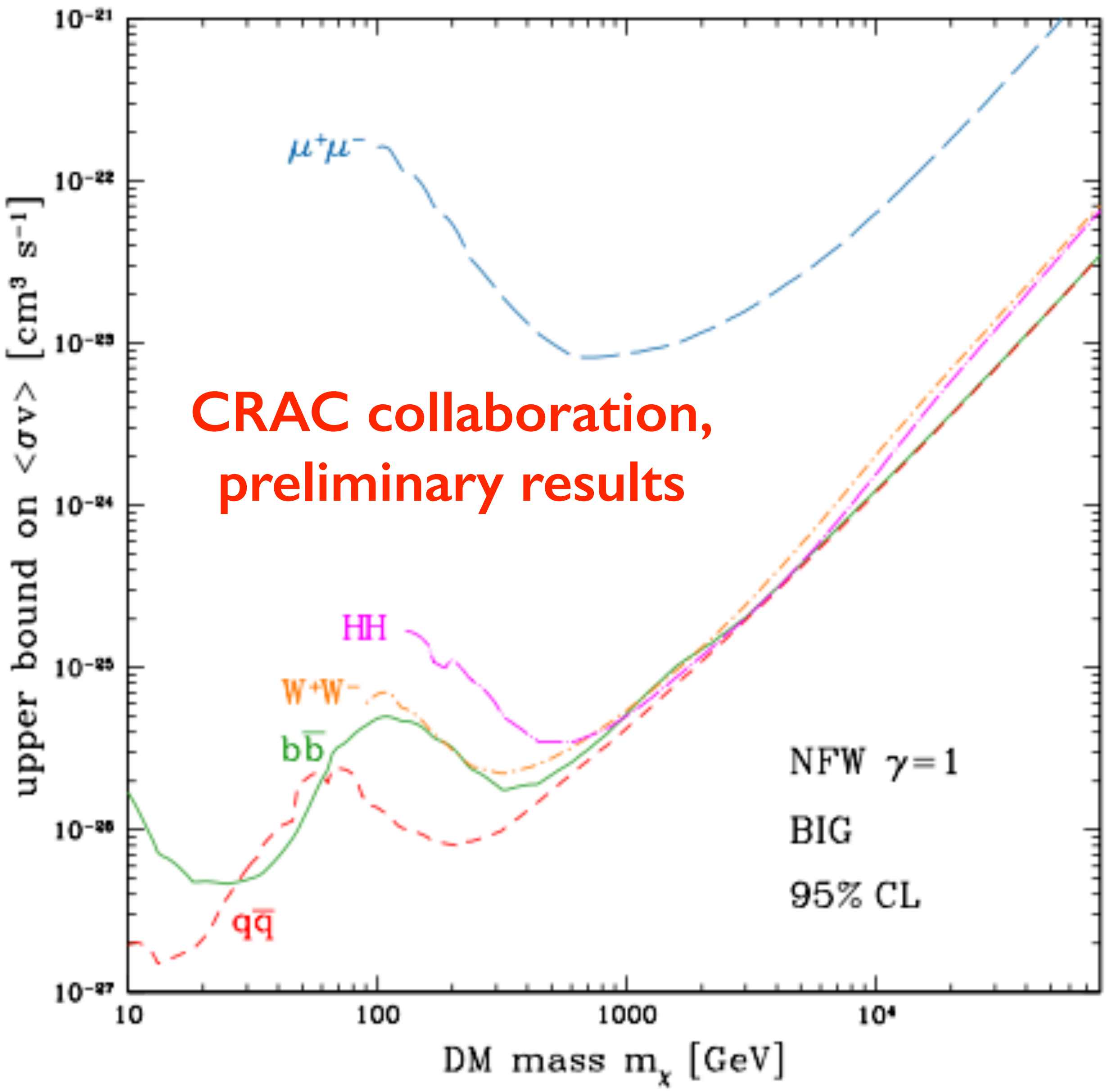
CRAC collaboration, preliminary results

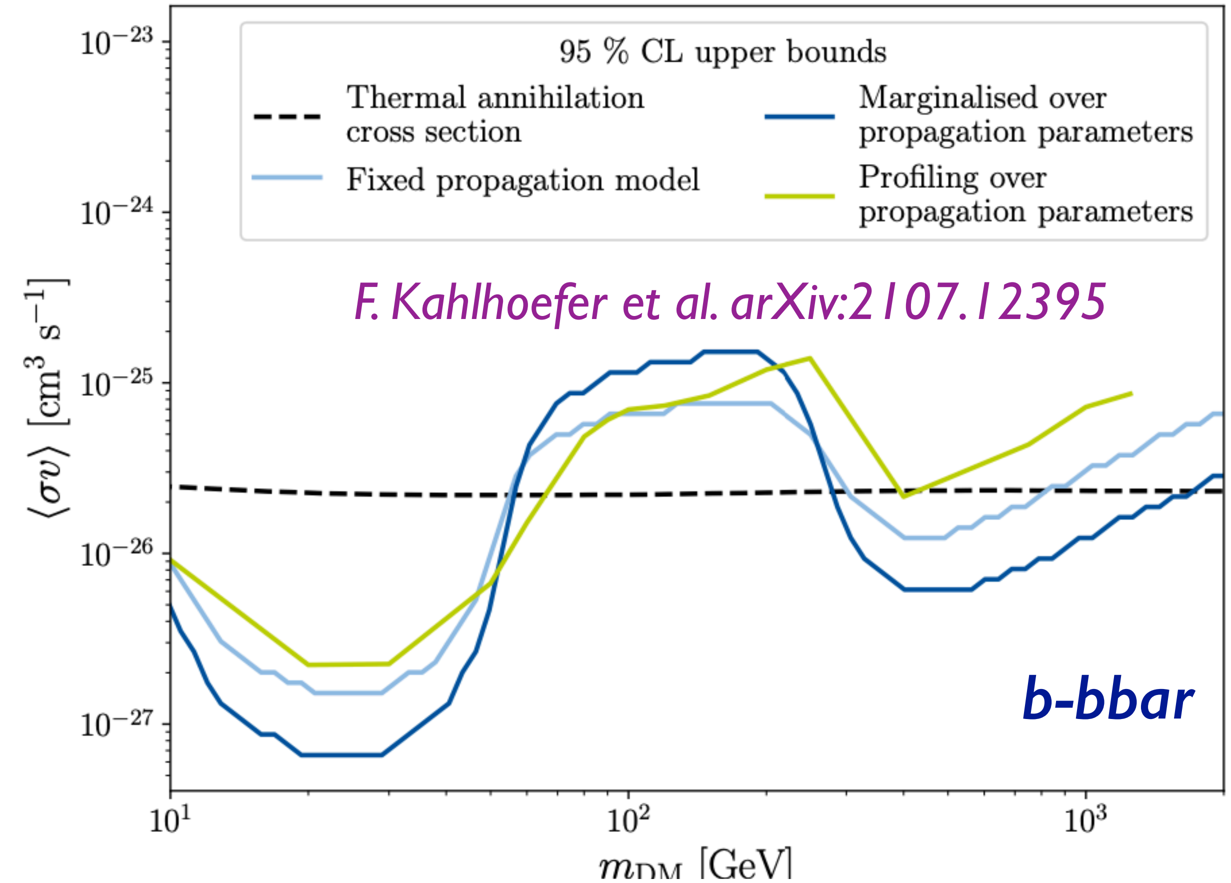
local signif. [σ]	Err. data / model
1.9	tot/tot
0.35	tot/none
5.5	stat/tot
3.3	tot_diag/tot
3.9	tot_diag/none

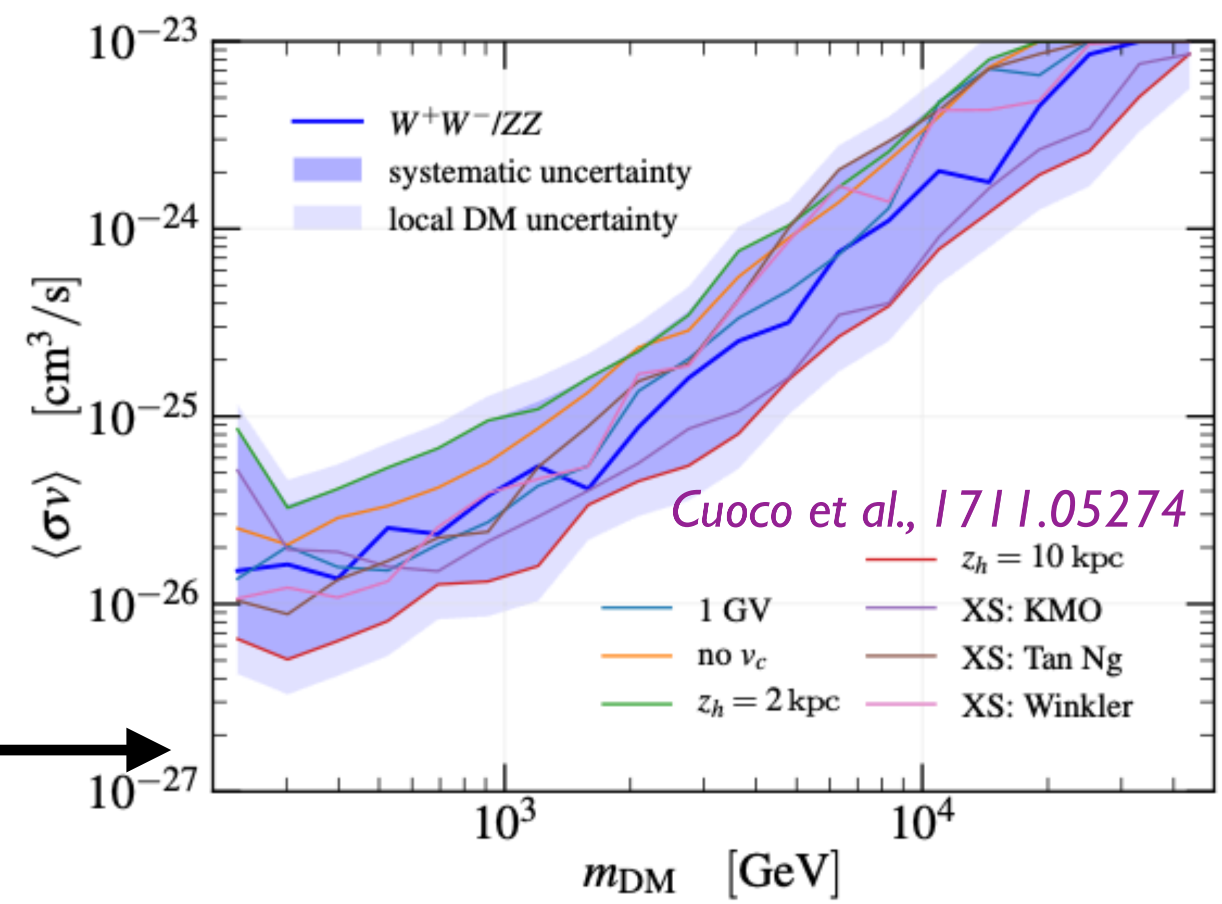
The way you treat the errors change the significance!

The excess is statistically irrelevant (at least, within the space of acceptable models)

DM bounds

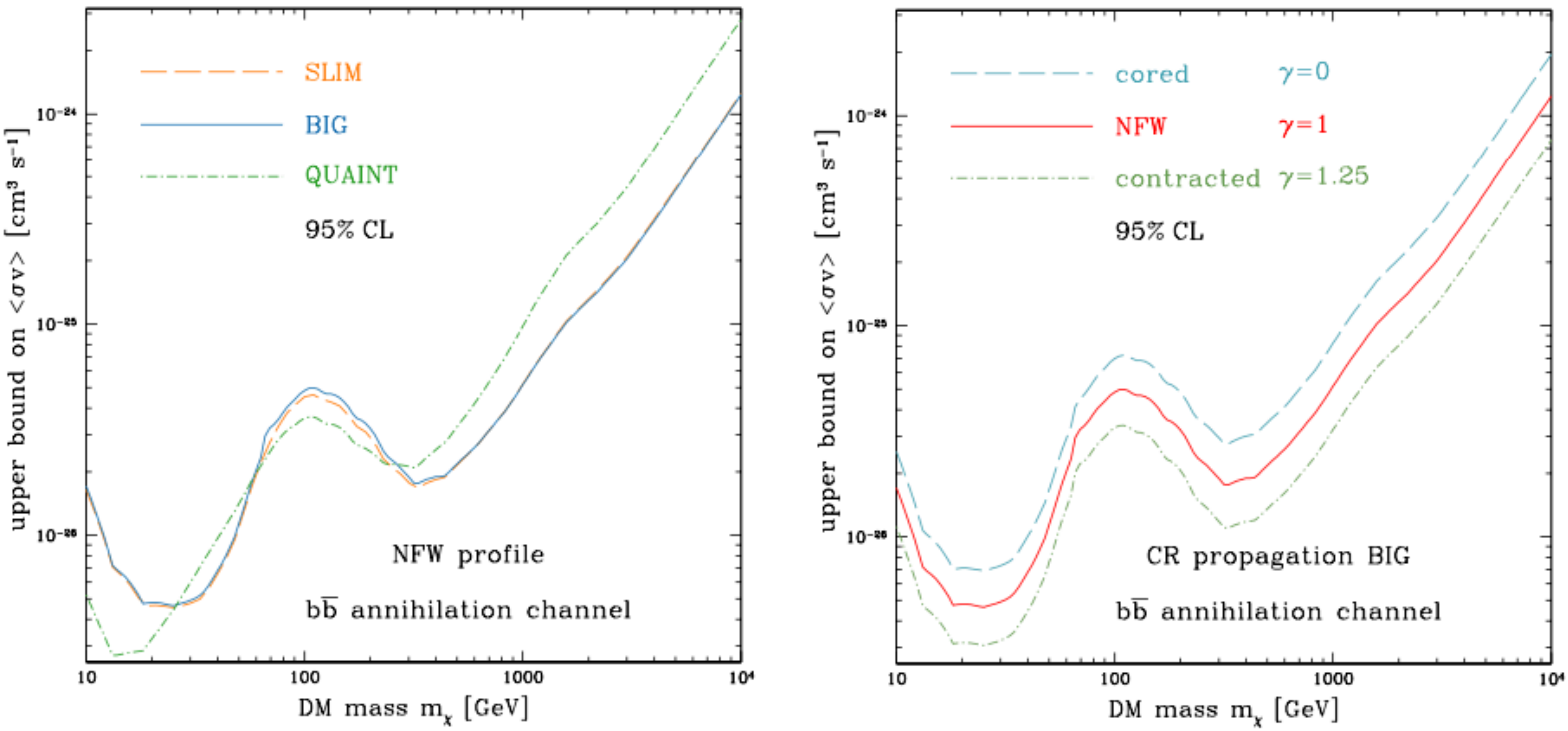






Close to the green curve/upper envelope, not surprising since we are profiling over L-uncertainty

Dependence on halo & propagation model



CRAC collaboration, preliminary results

Despite some (~factor 2) model sensitivity, remain among the strongest constraints to WIMPs

Summary

The current CR precision era offers us sharp tools for DM searches

However, "Great responsibility inseparably follows from great power"

Une grande responsabilité est la suite inséparable d'un grand pouvoir

*French Revolution Parliamentary Archives,
Tome 64 : Du 2 au 16 mai1793, Séance du mardi 7 mai 1793, page 287*

with great power comes great responsibility

Amazing Fantasy #15 (1962)

- e^+ hold great potential, but improvements limited by 'statistical' understanding of the primary astro sources, now almost universally considered necessary to explain the data
- pbar are very sensitive probes, secondaries seem to fully account for observations; require careful 'propagation calibration' and account of errors for reliable conclusions!
- In particular, the bump-like excess attributable to DM is statistically insignificant when accounting for correlated errors.