CR antiproton constraints on WIMPs in our Galaxy

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The challenge!

Andromeda : a MW-like galaxy

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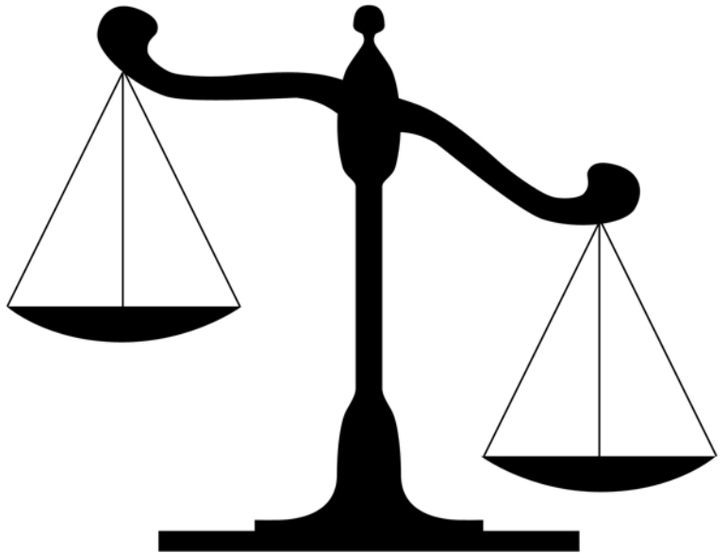

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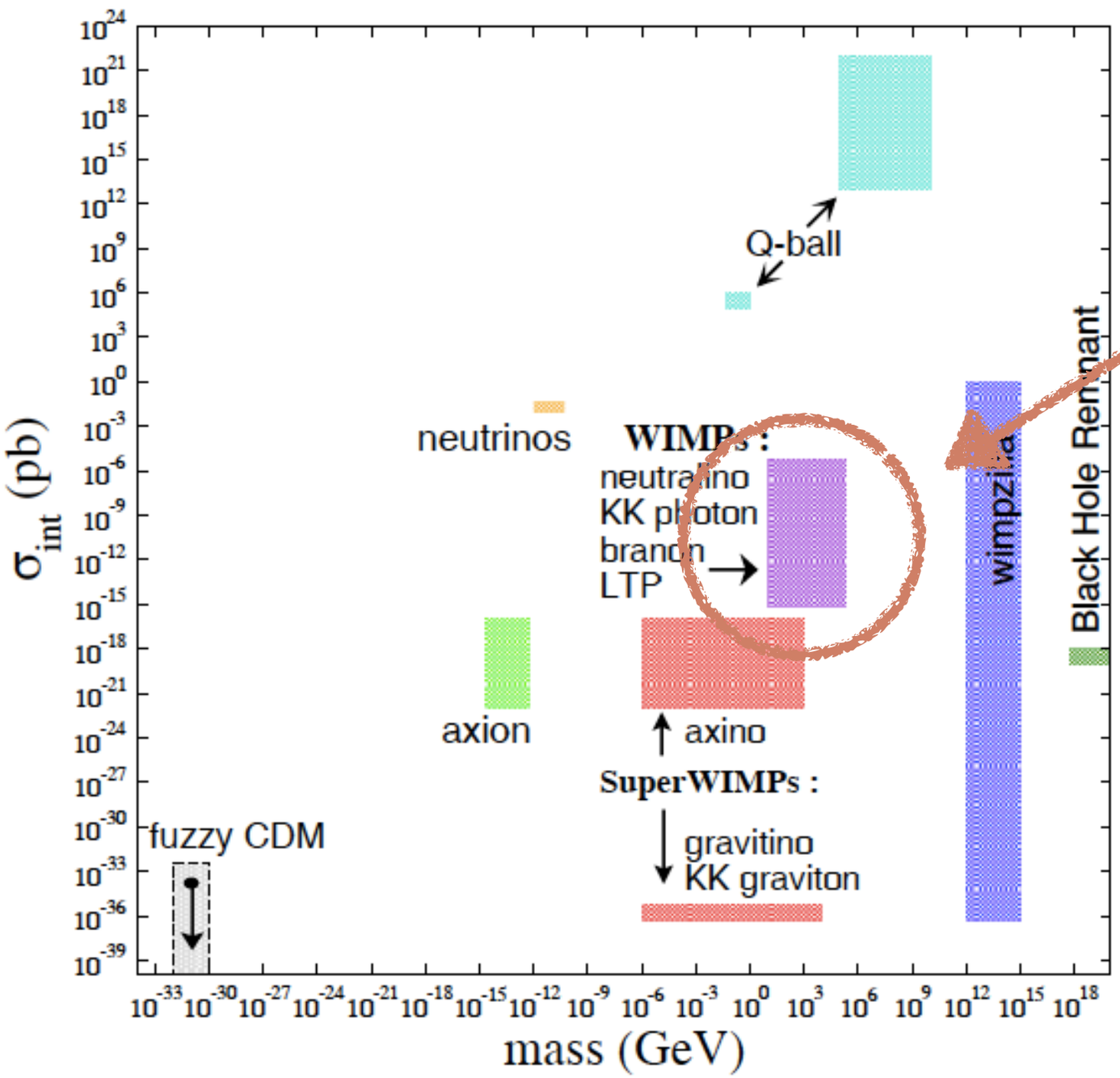
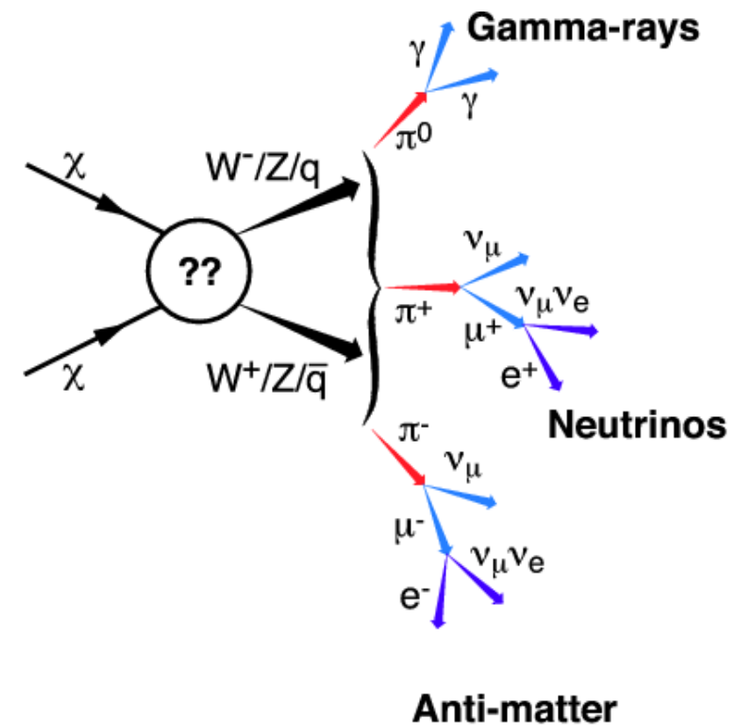
The importance of being WIMP





$$\epsilon_\chi \sim \frac{\rho_\chi^2}{m_\chi}\langle\sigma v\rangle \sim 5\times10^{-29}\,\mathrm{GeV\,cm^{-3}\,s^{-1}}$$

$$\epsilon_{\rm CR} \sim E^2\phi_{\rm CR}\,n_{\rm ISM}\,\sigma_{pp} \sim 5\times10^{-25}\,\mathrm{GeV\,cm^{-3}\,s^{-1}}$$

problem!

astrophysical emissivity is much larger than Dark one

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Source term:

- assumed to trace the SNR in the Galaxy
- assumed the same power-law everywhere

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j
- total inelastic cross-section: disappearance of nucleus i

Ginzburg & Syrovatsky, 1964

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Diffusion tensor:

- $D(E) = D_0(\rho/\rho_0)^{\delta}\exp(z/z_t)$

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Energy losses:

- ionization, Coulomb, synchrotron
- adiabatic convection

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Reacceleration:

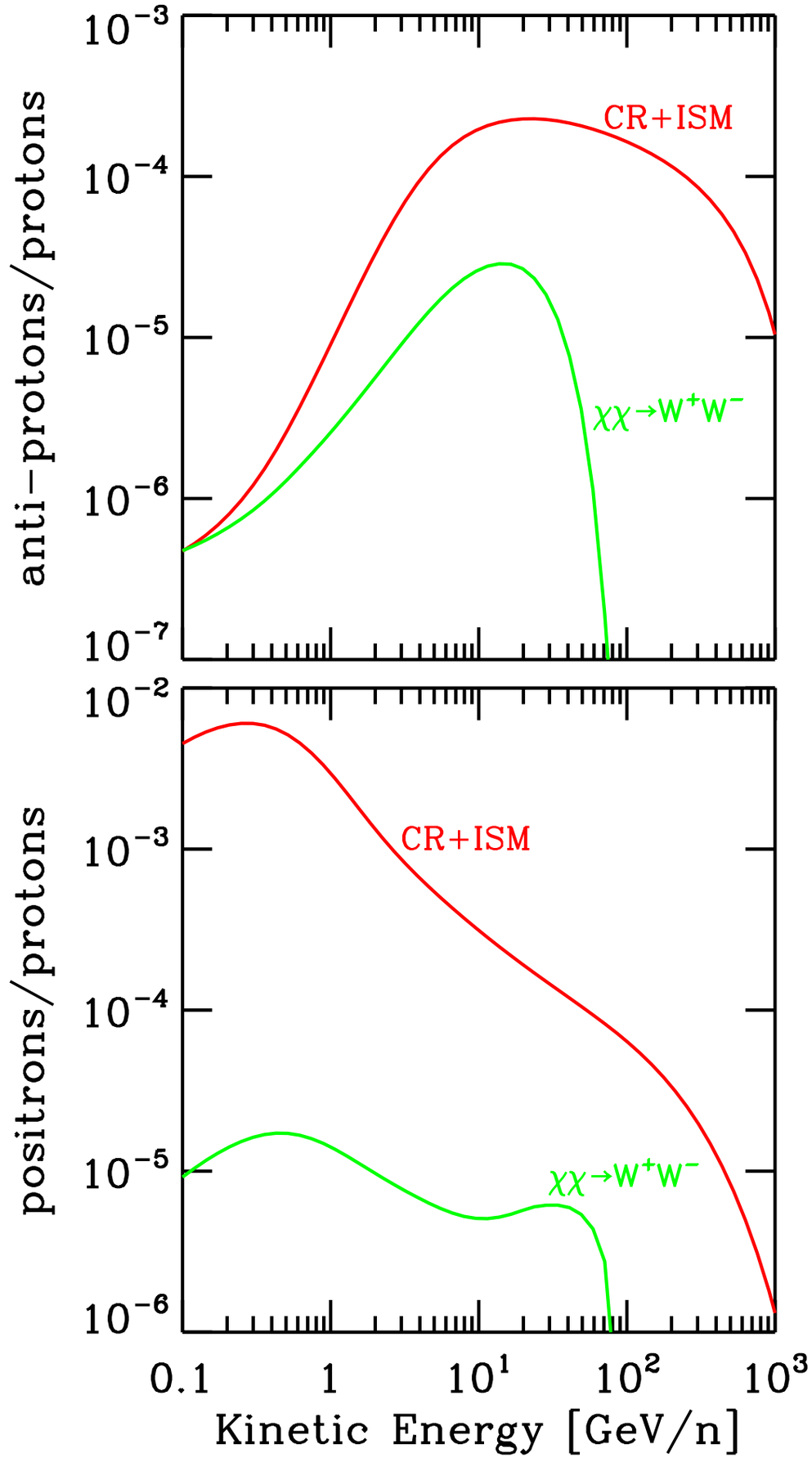
- $D_{pp} \propto \frac{p^2 v_A^2}{D}$

Ginzburg & Syrovatsky, 1964

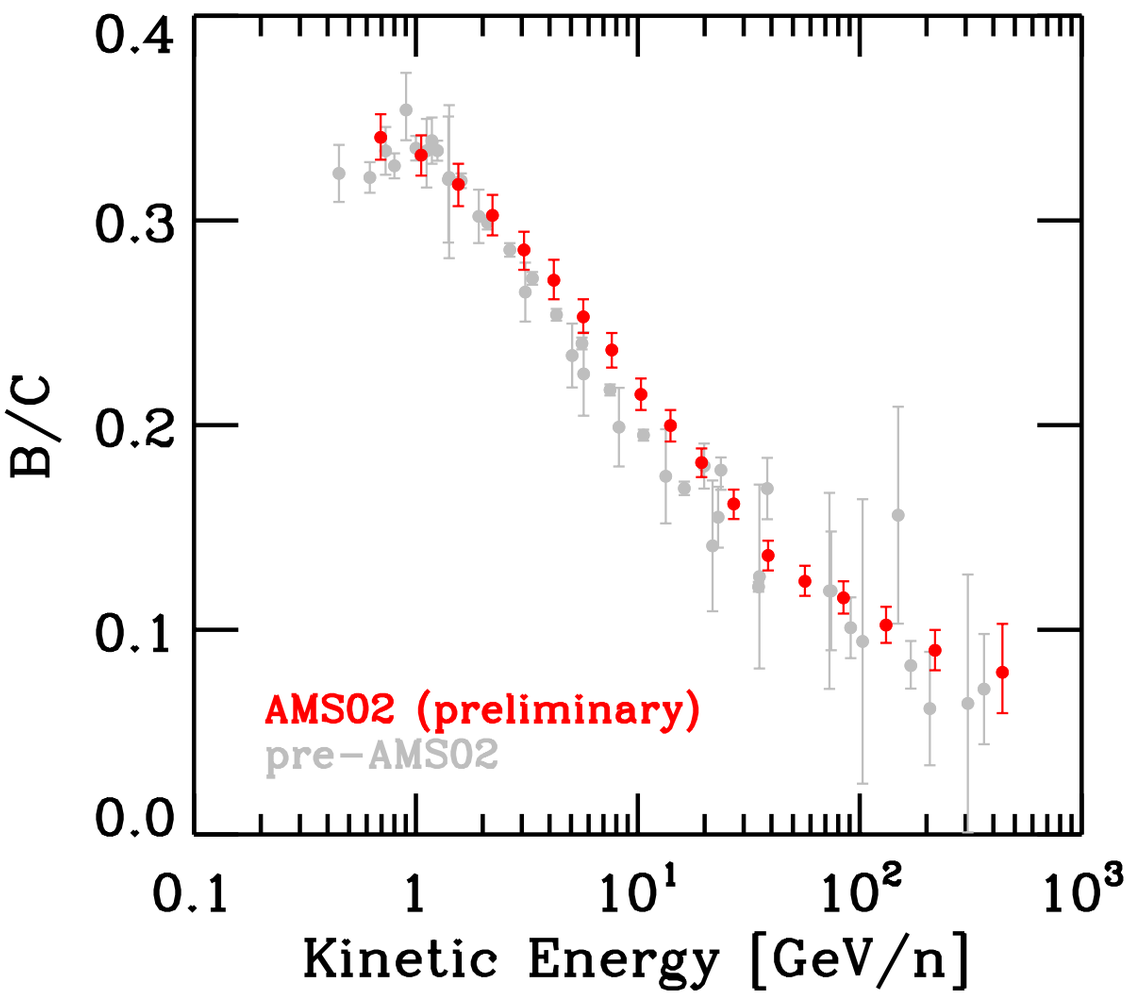
Why antiprotons?

- we know the **background** with good accuracy

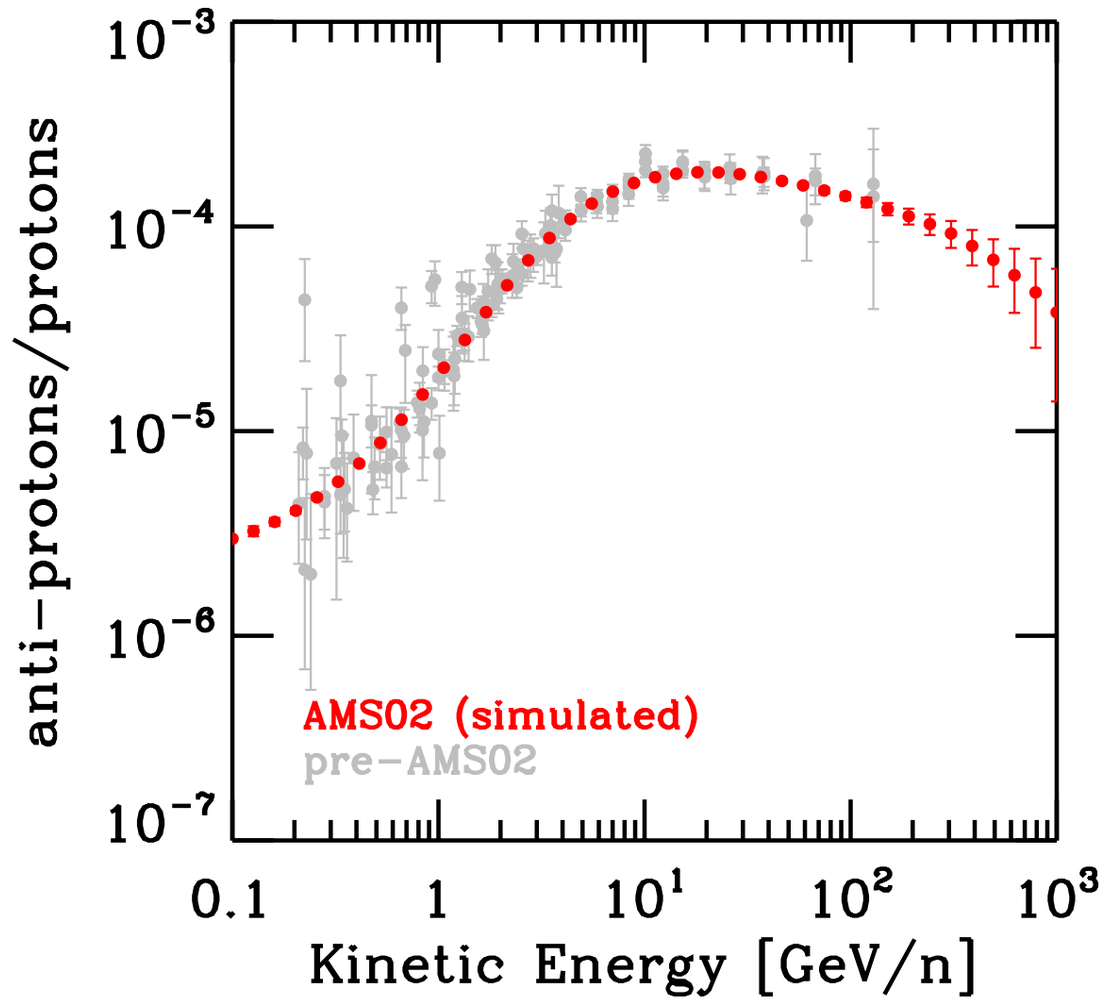
- in a **democratic** WIMP model the ratio between DM signal and background from standard astrophysical sources is usually much larger in the **antiproton** channel with respect to all other indirect detection methods.



Waiting for AMS-02



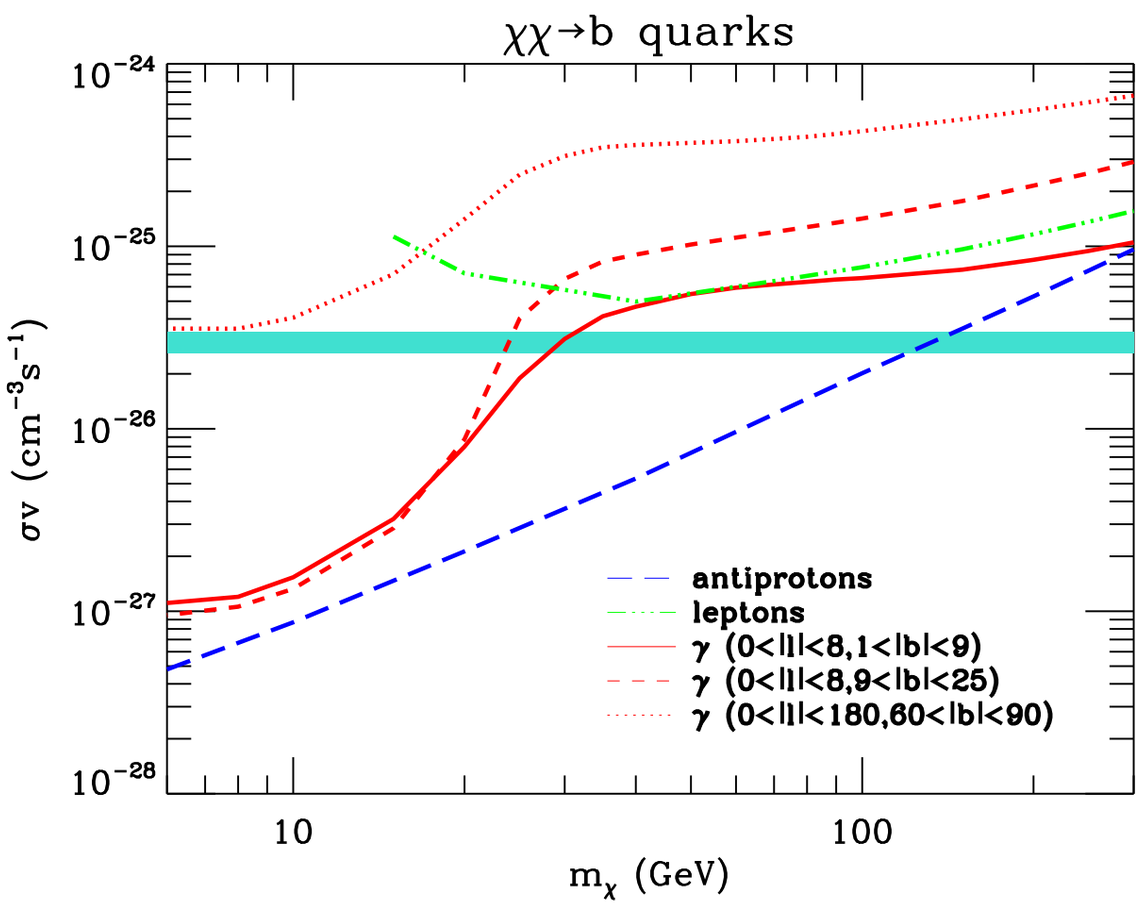
With secondary/primary ratios we calibrate our propagation models.

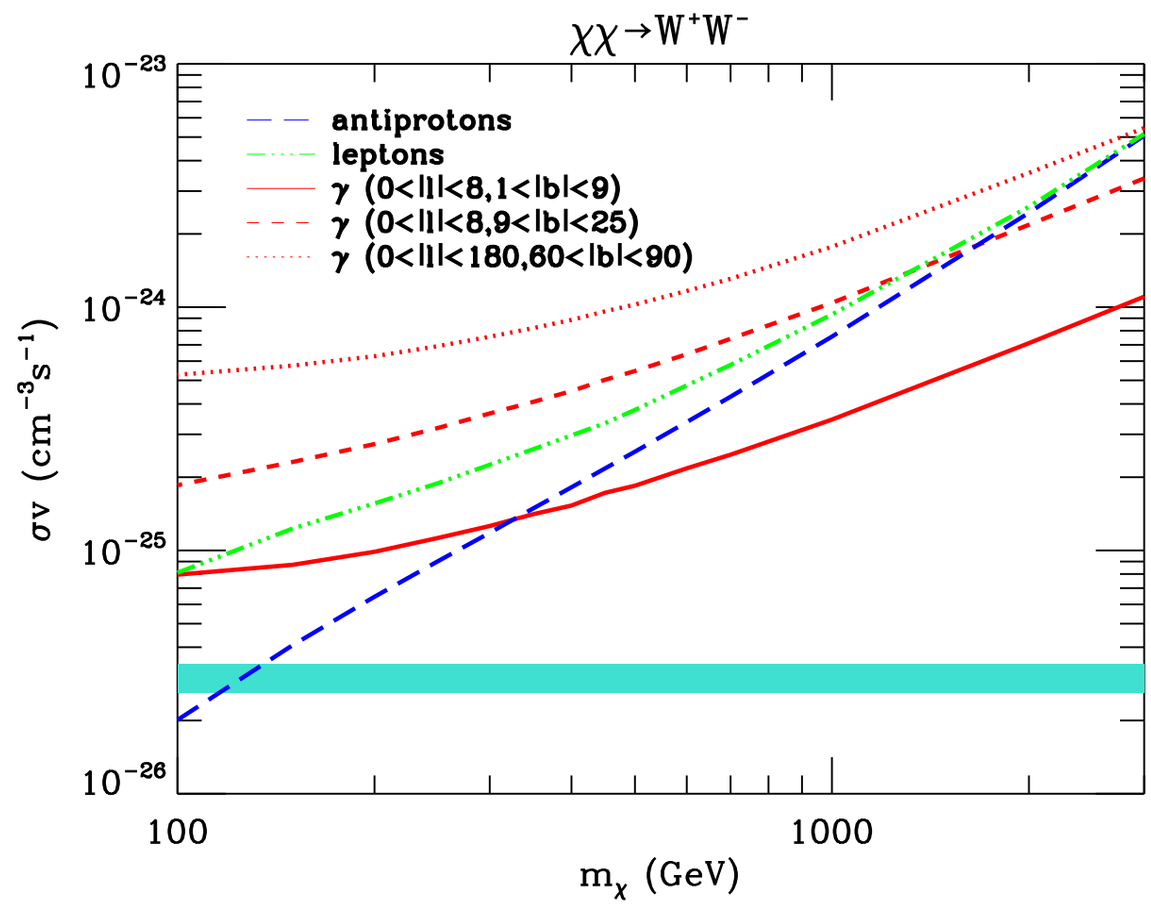


Having a prediction for the anti-matter fluxes from astrophysical sources, we can finally use data to hint/constraint an extra-component!

It's a worth-playing game!

M. Tavakoli, I. Cholis, CE & P.Ullio, JCAP, 2014, 1308.4135





It's a worth-playing game **today**!

T. Bringmann, M. Vollmann & C. Weniger, 1406.6027

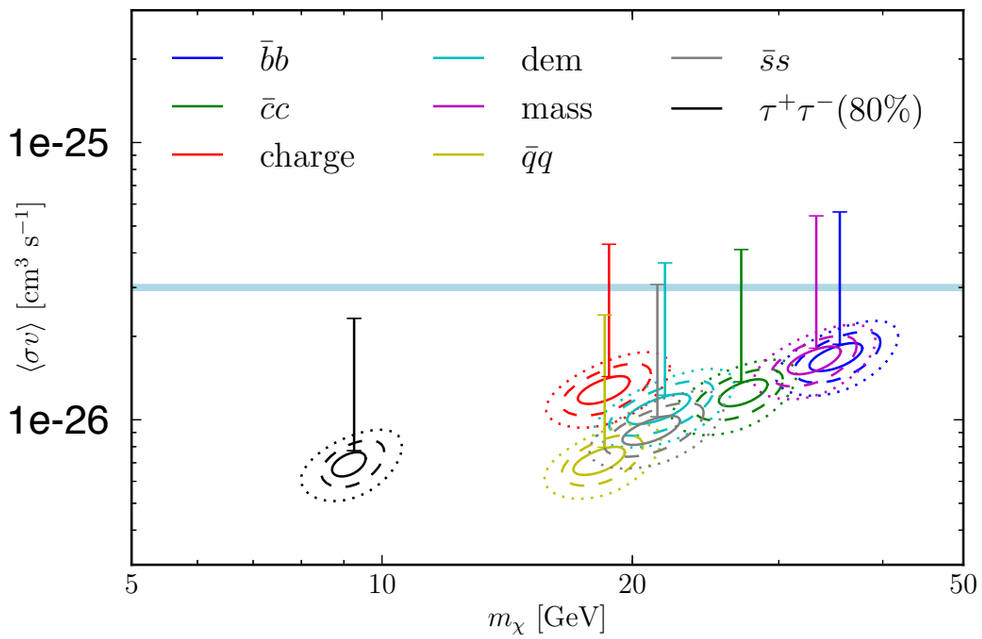


FIG. 2. The *ellipses* show the preferred values of the DM annihilation cross-sections and mass from the inner Galaxy analysis of Ref. [21], where we include the uncertainties coming from the DM profile slope in quadrature ($\Gamma = 1.26 \pm 0.05$ at 3σ); see also Tab. I. The *error-bars* indicate the annihilation cross-section preferred for the values $\Gamma = 1.04$–1.24, as found from the GC analysis in Ref. [21].

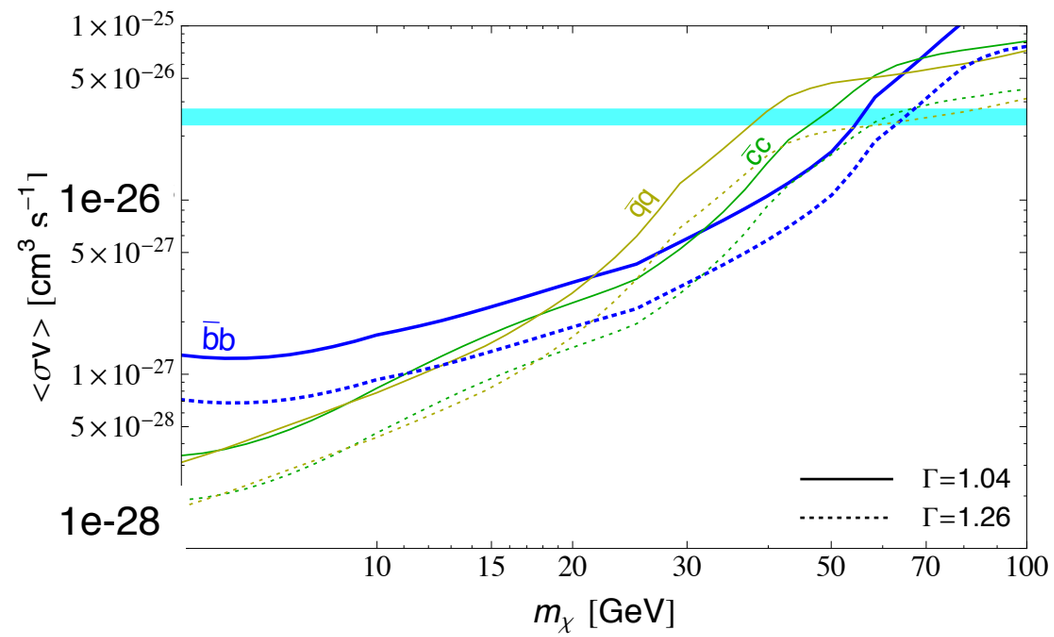
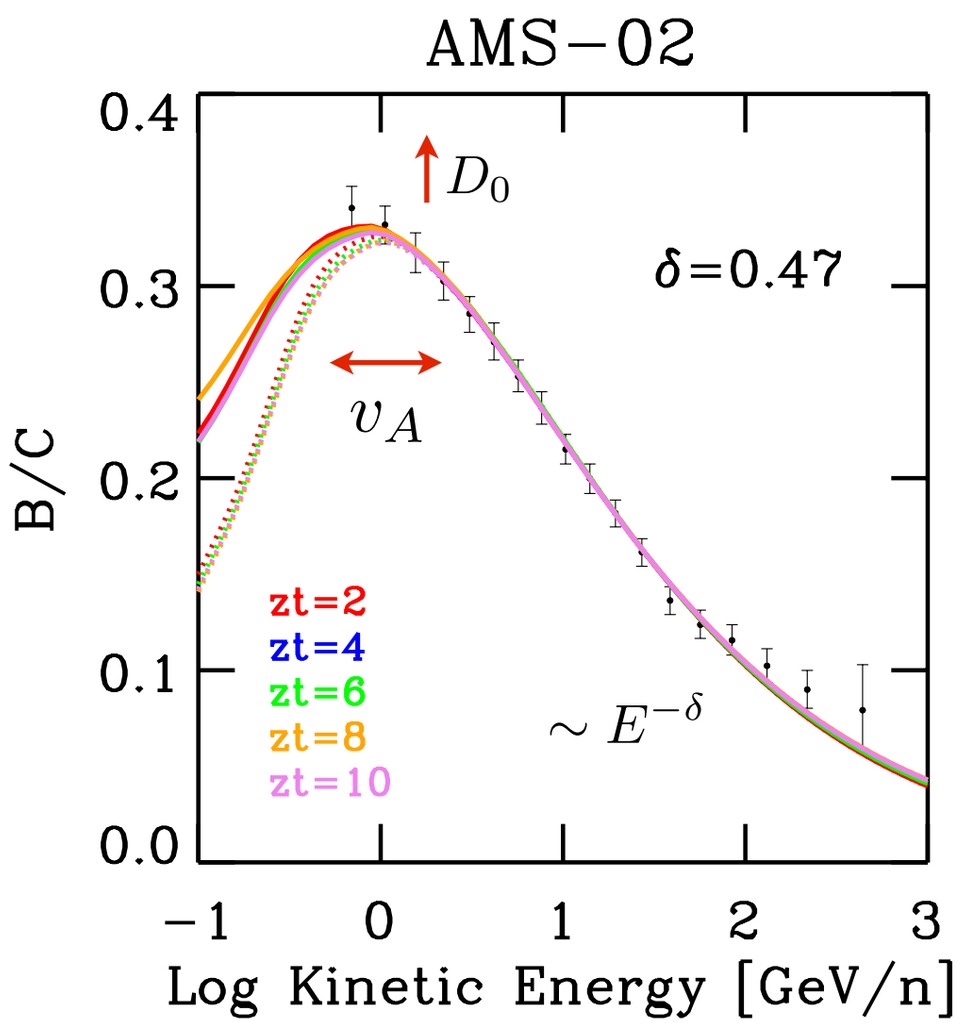
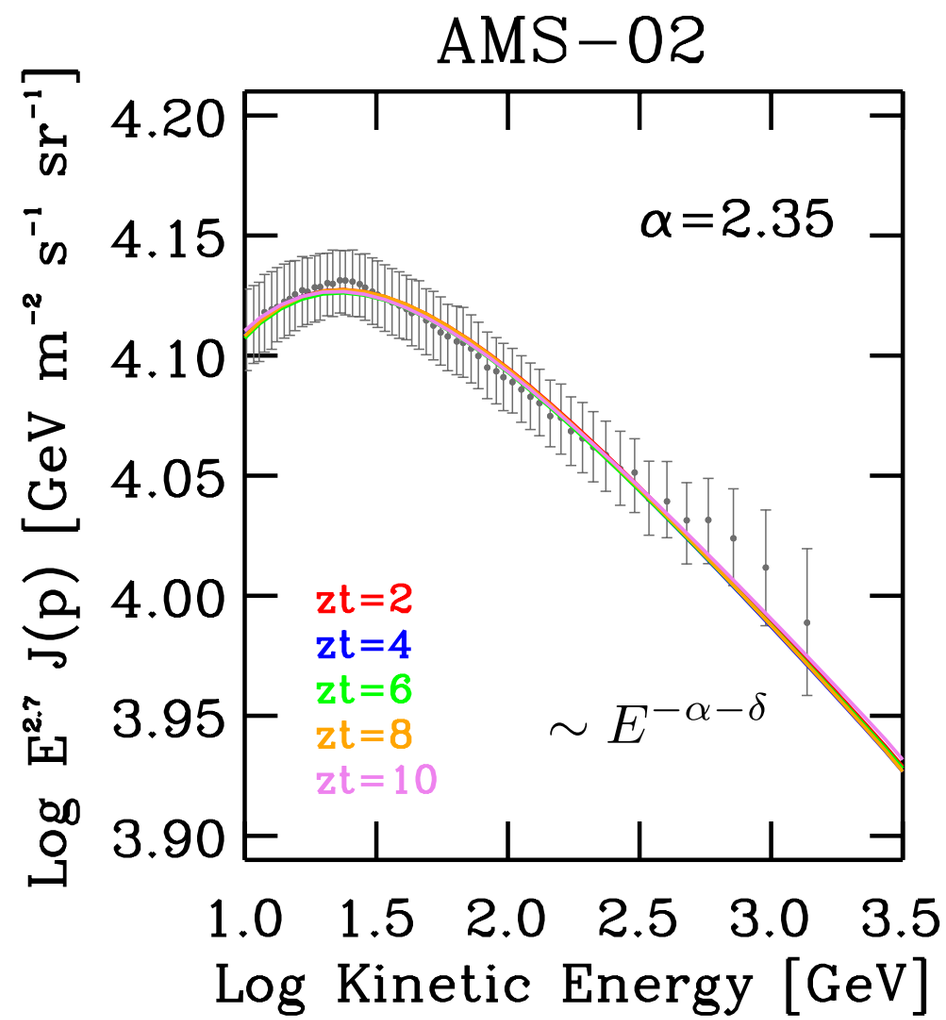


FIG. 4. Limits on the annihilation rate of DM into quark final states from our analysis of the PAMELA antiproton data. Solid lines refer to the generalized NFW profile of Eq. (2) with $\Gamma = 1.04$ and are essentially indistinguishable from the standard NFW ($\Gamma = 1$) case; dotted lines show the case for $\Gamma = 1.26$.

Let’s give a look to all known unknowns!

Varying the halo size in the range 2 - 10 kpc



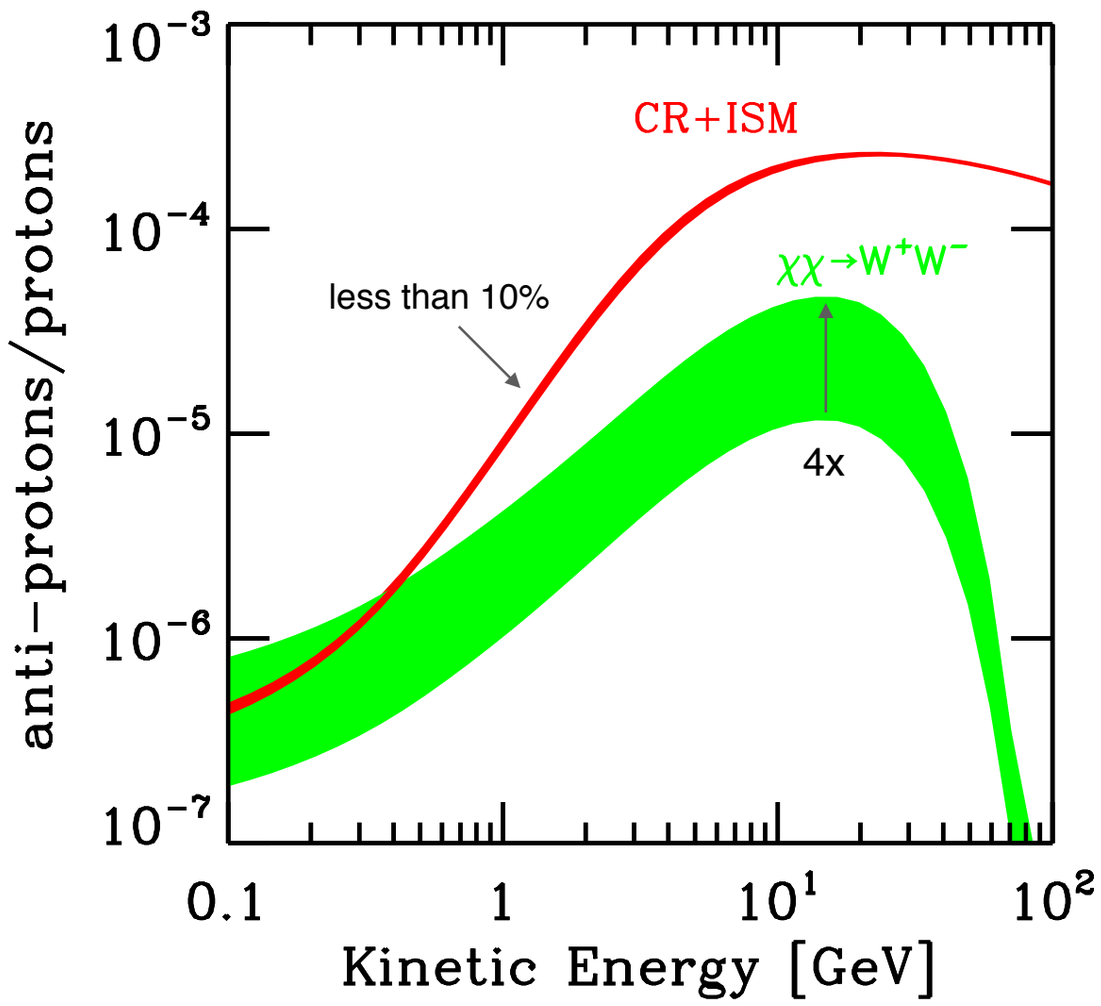


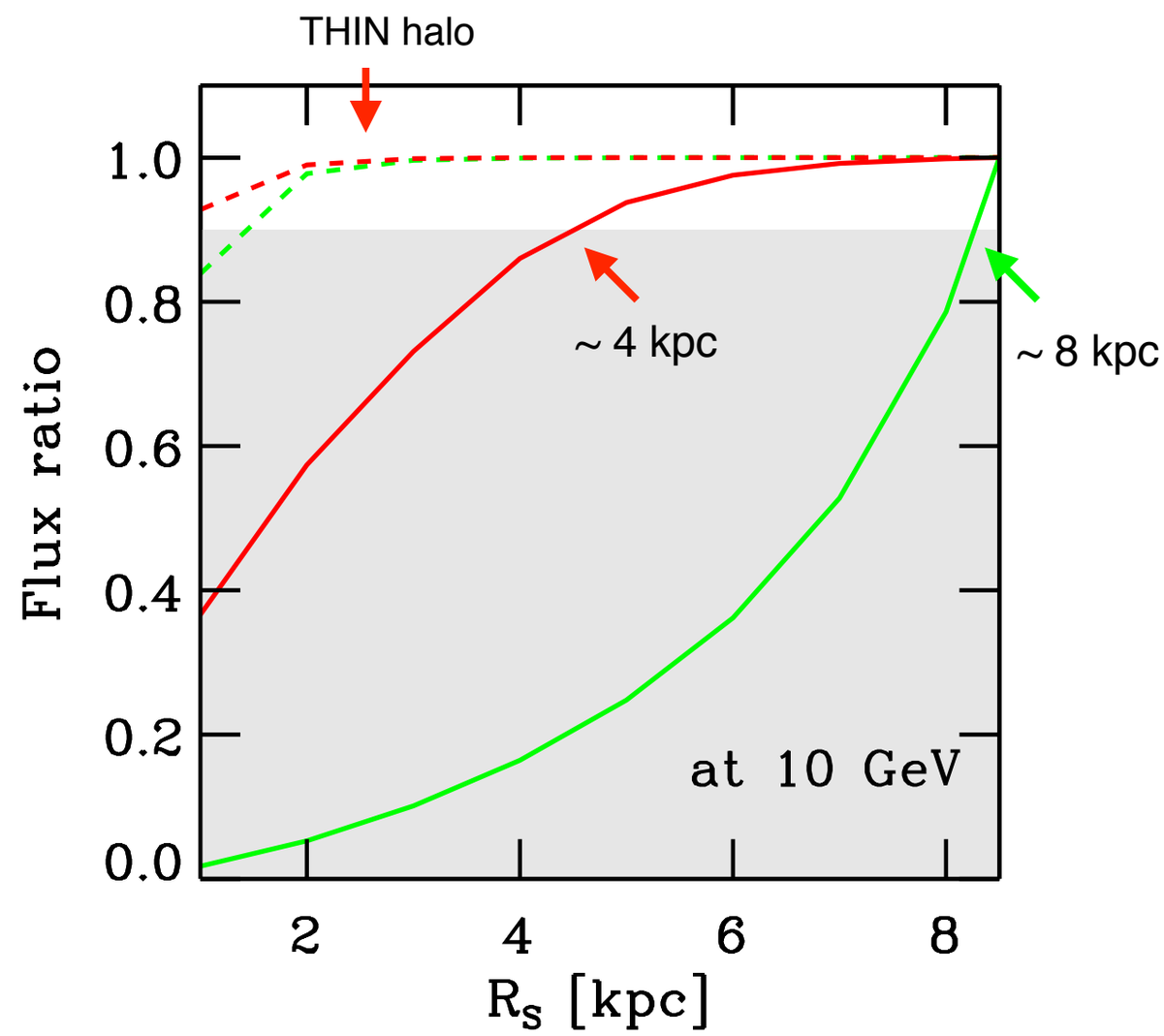
$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

The best constraints on the halo scale height (L > 2 kpc) are obtained from the galactic diffuse synchrotron emission (G.Di Bernardo, CE, D.Gaggero, D.Grasso and L.Maccione, JCAP, 2013)

Varying the halo size in the range 2 - 10 kpc

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664



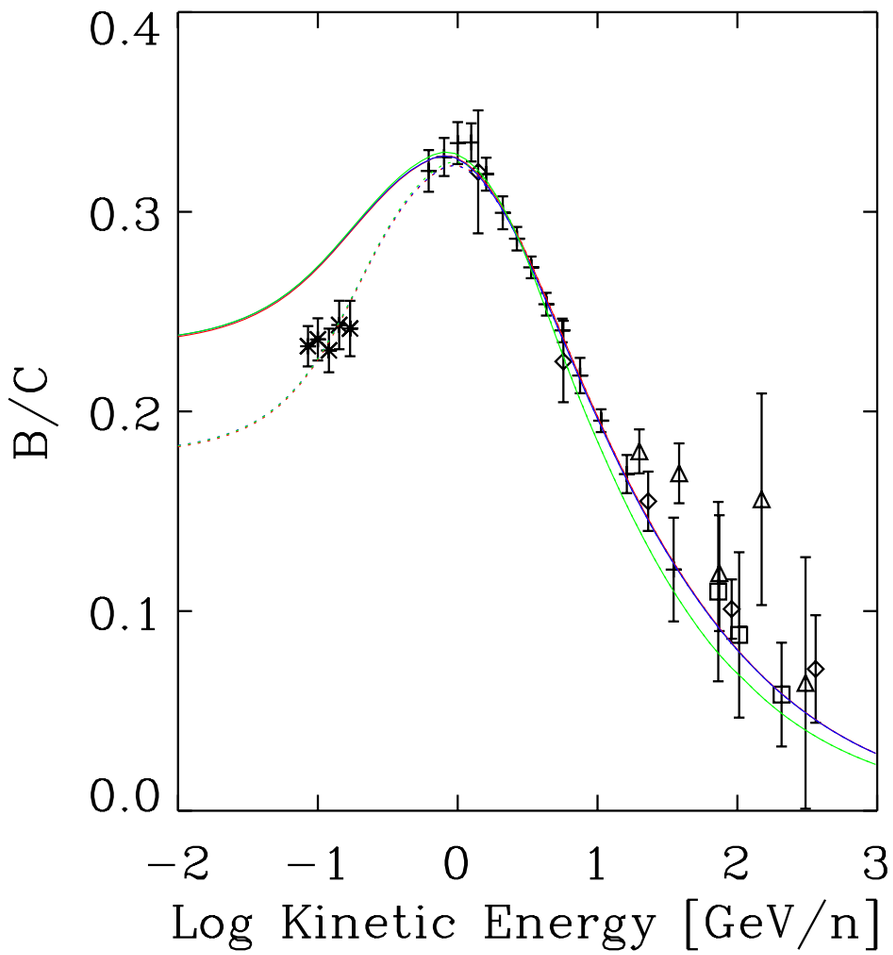


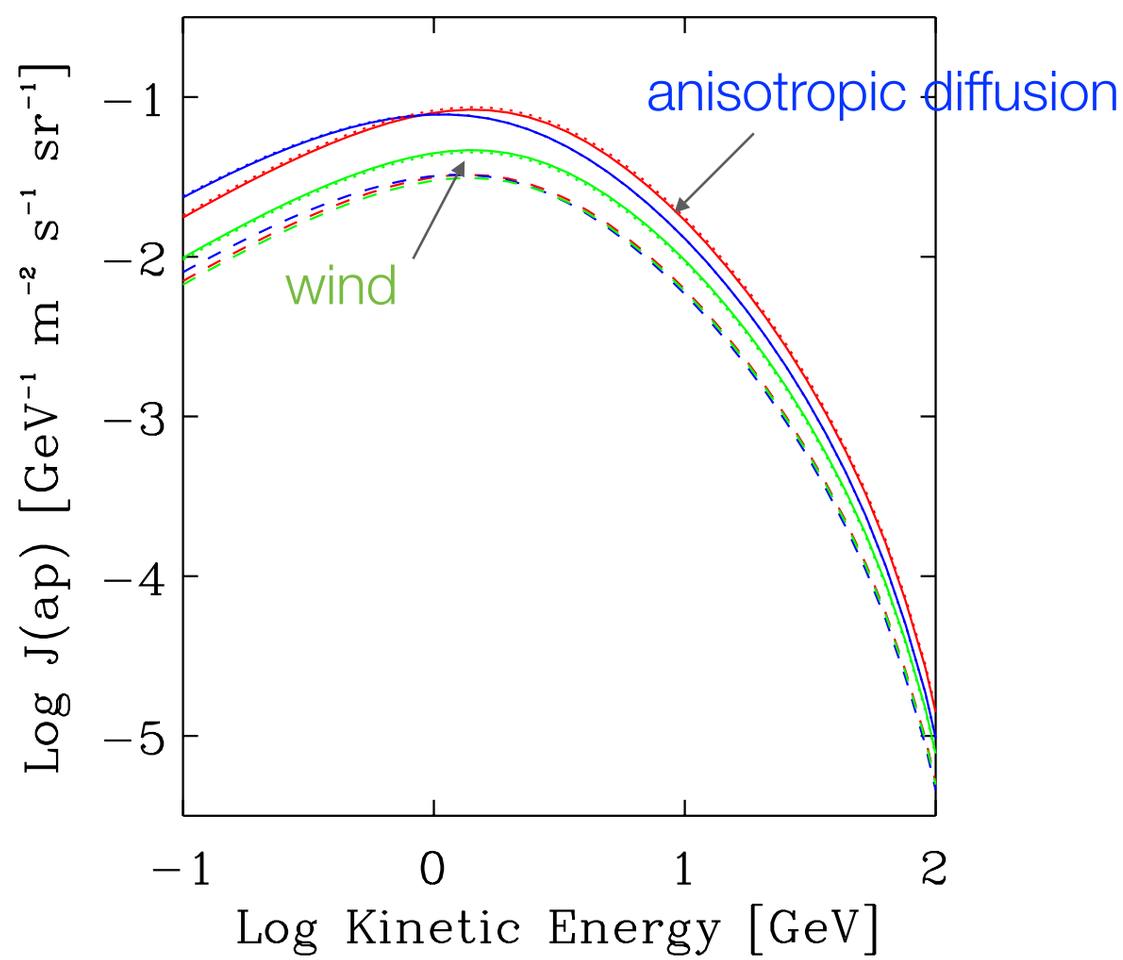
Much larger uncertainty in the DM fluxes!

The ratio of the local flux obtained considering sources with distance smaller than R_S to that obtained with $R_S = \infty$
(see also R. Taillet & D. Maurin, A&A, 2003)

Unavoidable uncertainties?

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664



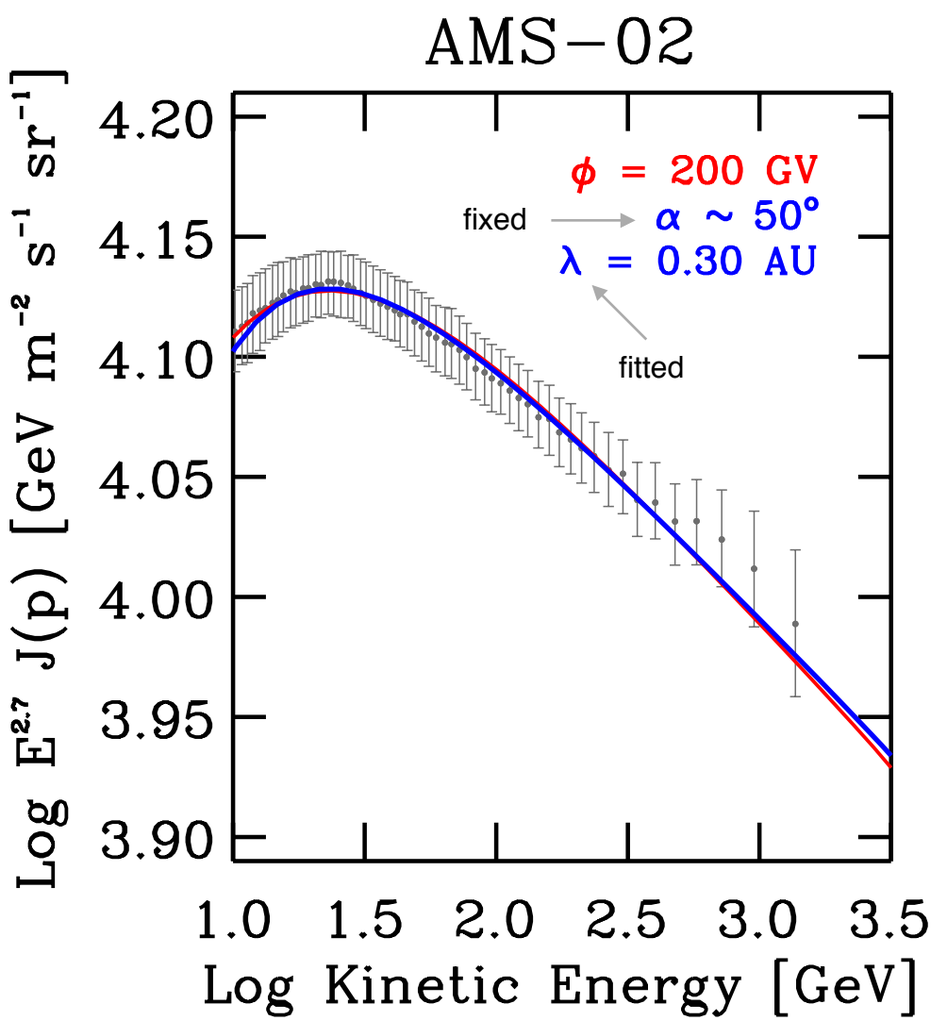


Changing diffusion conditions in the inner Galaxy gives significant effect on the DM contribution without affecting the local observables

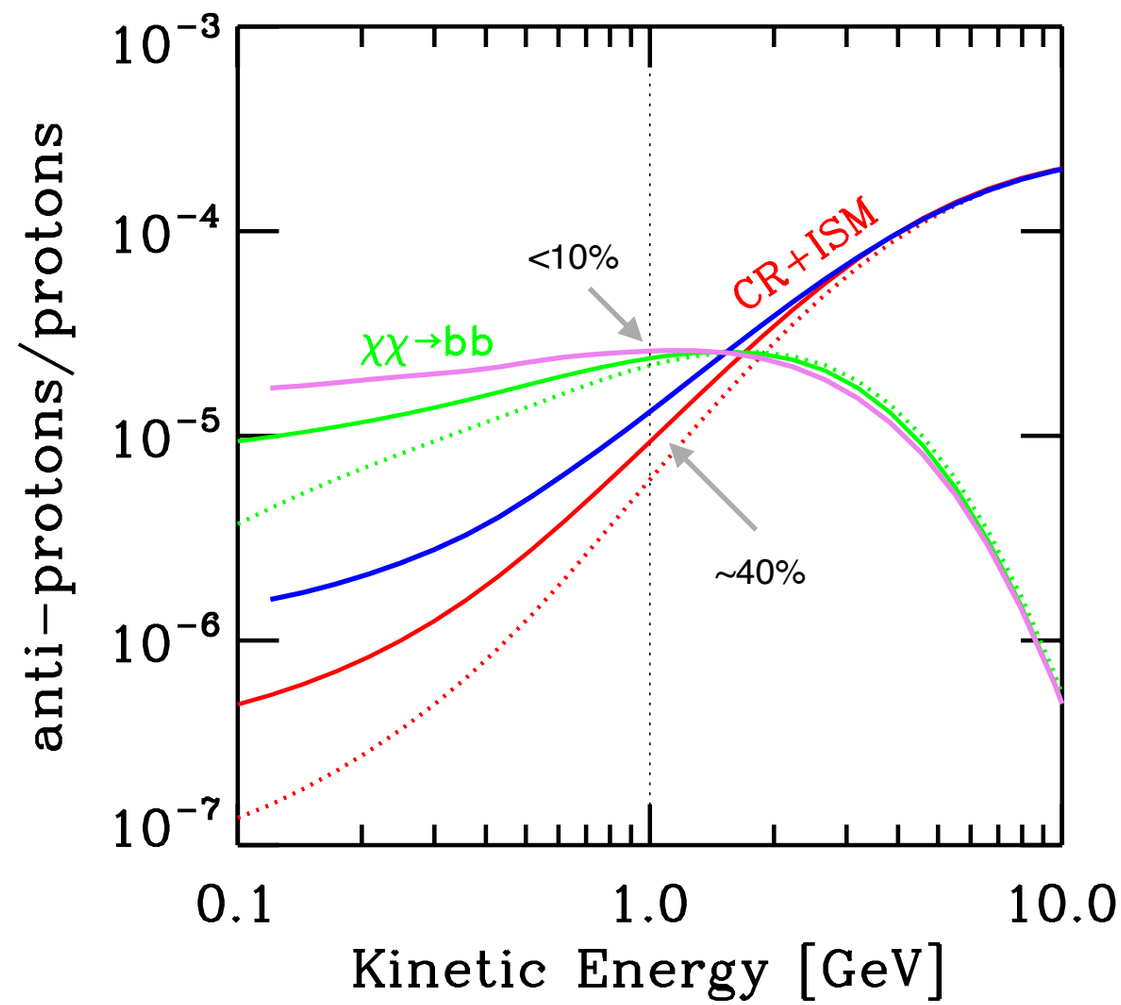
Only a comprehensive study including local and non-local observables may succeed in reducing safely the propagation uncertainties.

Solar wind is in negative polarity

CE, G. Di Bernardo, D.Gaggero & D.Grasso, *in preparation*



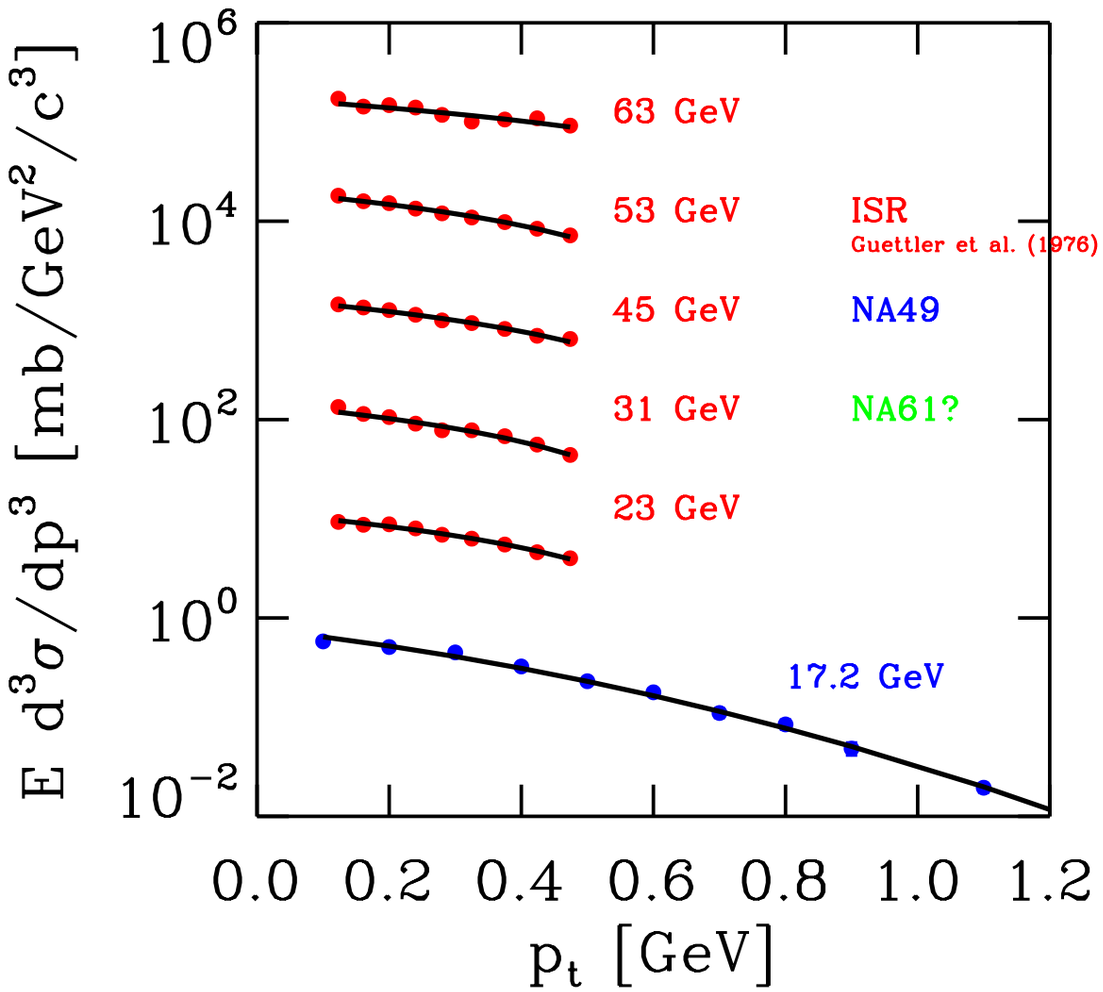
Protons and anti-protons propagate differently in the heliosphere (L. Maccione, PRL, 2013)

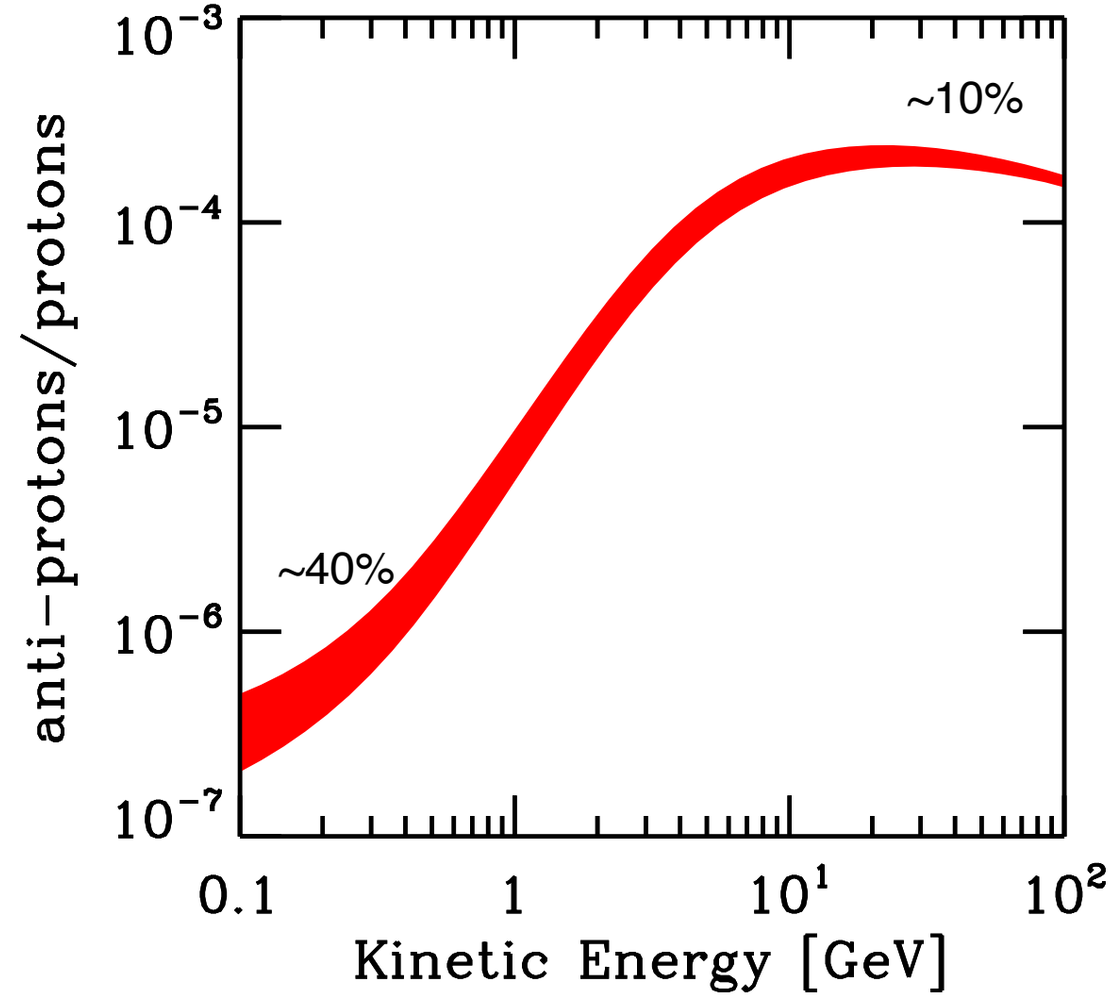


Charge dependent solar modulation can be relevant for low-mass WIMP candidates.

Production in low-energy *pp* collisions

CE, G. Di Bernardo, D.Gaggero & D.Grasso, *in preparation*





Fitted by a 7-parameter function proposed by
R. P. Duperray et al., Physical Review D 68 (2003)

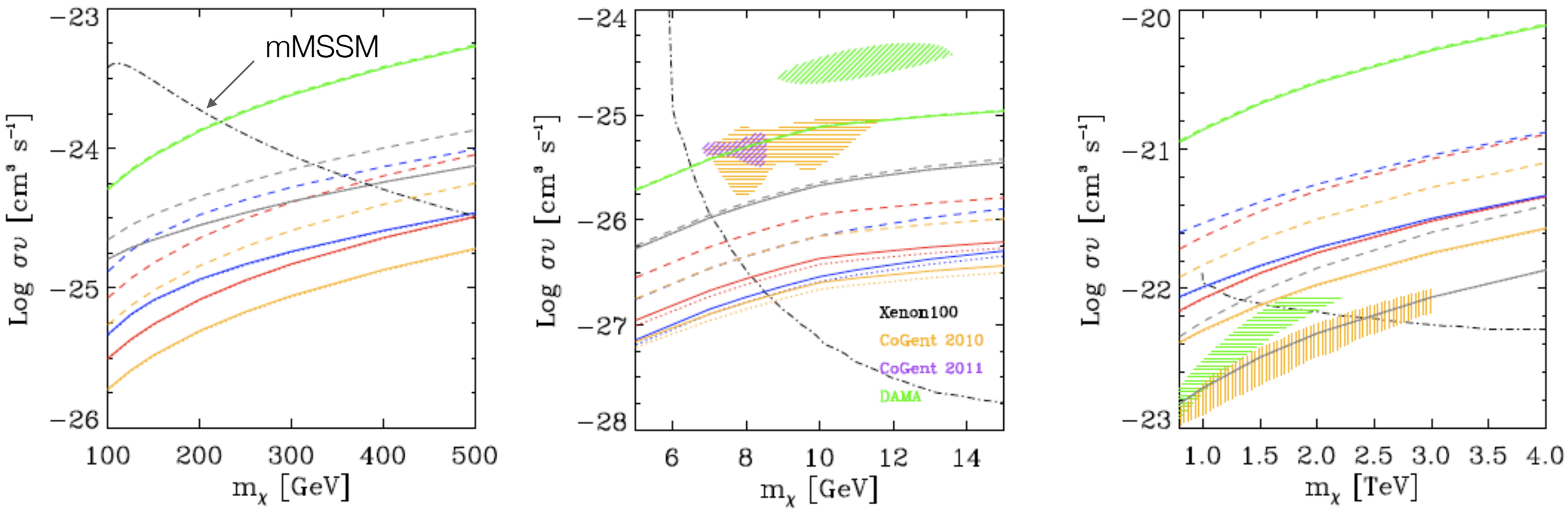
(see also Kachelrieß & Ostapchenko, PRD 86, 2012)

$$E\frac{d^3\sigma}{dp^3} = \sigma_{in}(1-x_R)^{D_1}e^{-D_2 x_R}$$

$$\times[D_3(\sqrt{s})^{D_4}e^{-D_5 p_\perp} + D_6 e^{-D_7 p_\perp^2}]$$

Constraints after PAMELA data

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664



$$\tilde{W}^0\tilde{W}^0 \to W^+W^-$$

Wino model
(motivated by SUSY and PAMELA e^+ anomaly)

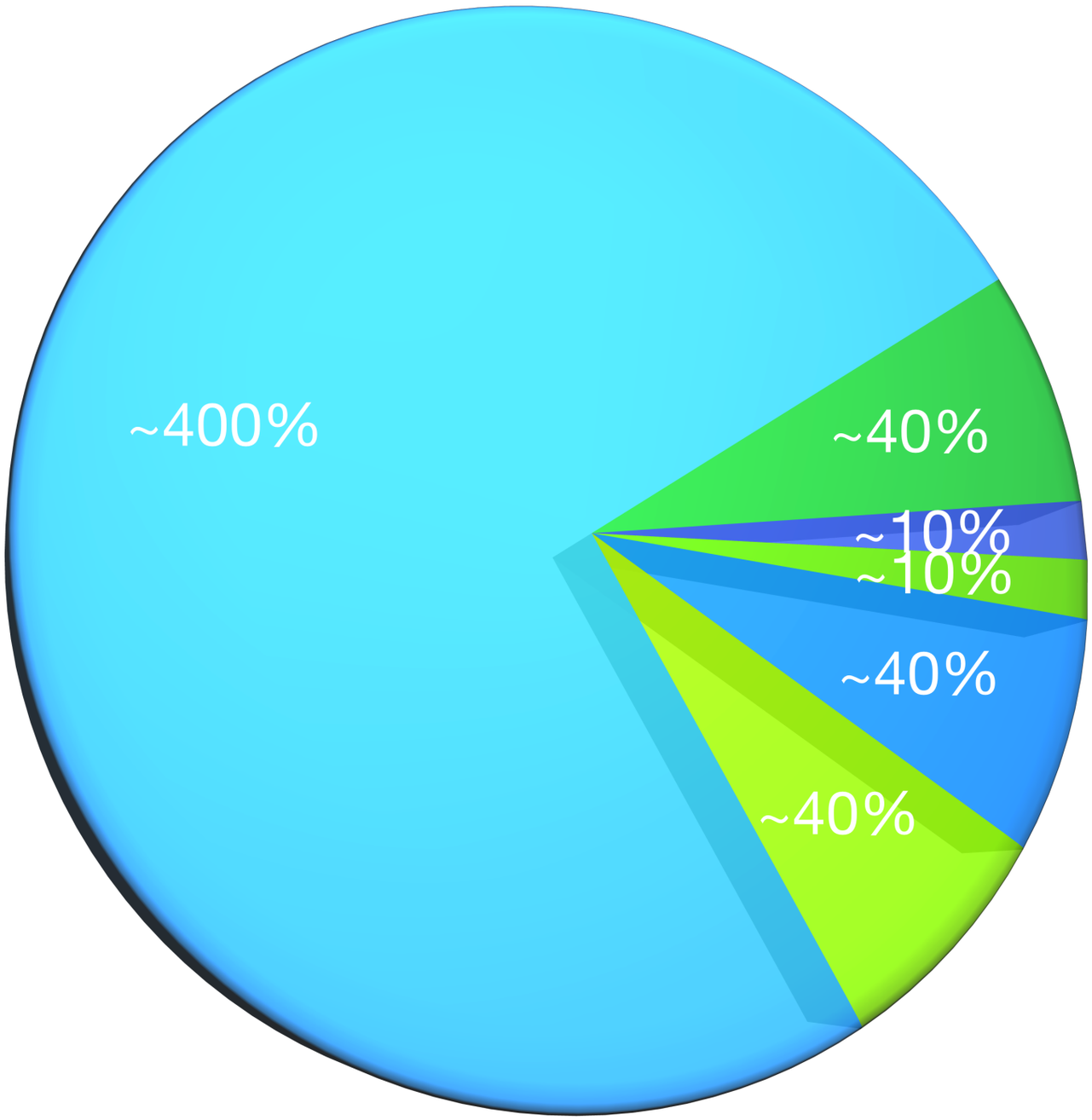
$$\chi\chi \to \bar{b}b$$

Light WIMPs
with sizable quark coupling
(motivated by direct detection results)

$$\chi\chi \to \mu^+\mu^-$$

Heavy "leptophilic" WIMPs
(motivated by PAMELA, Fermi, HESS)
+ radiative corrections

Take home message!



Modeling “signal”:
halo size ~ 400%
solar modulation ~ 10%
not-locality ~ 40%

Modeling background:
halo size ~ 10%
solar modulation ~ 40%
cross-sections ~ 40%