# Scrutinizing the evidence for dark matter in cosmic-ray antiprotons

in collaboration with A. Cuoco, L. Klamt, M. Korsmeier, M. Krämer

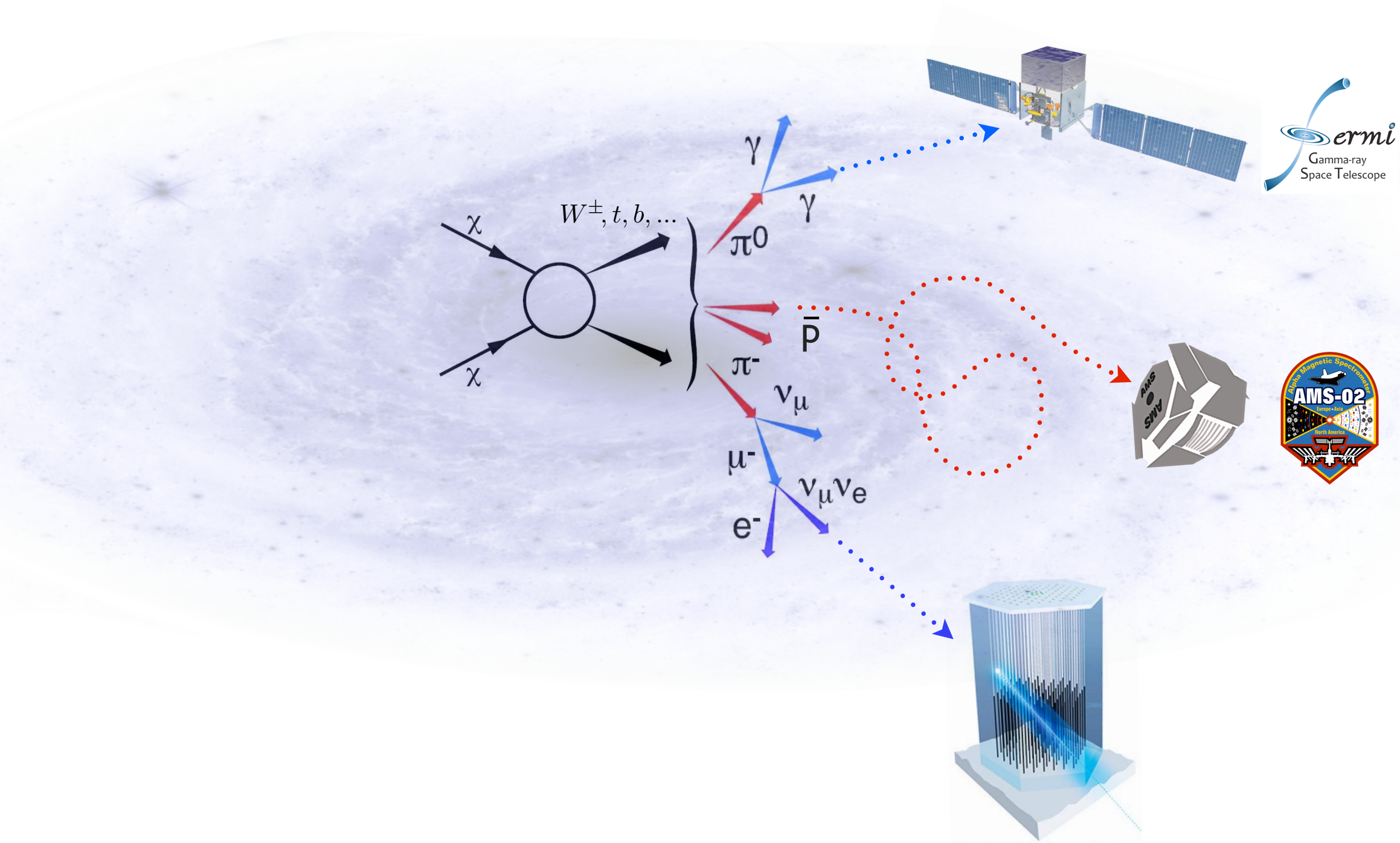

Jan Heisig

*Université catholique de Louvain*

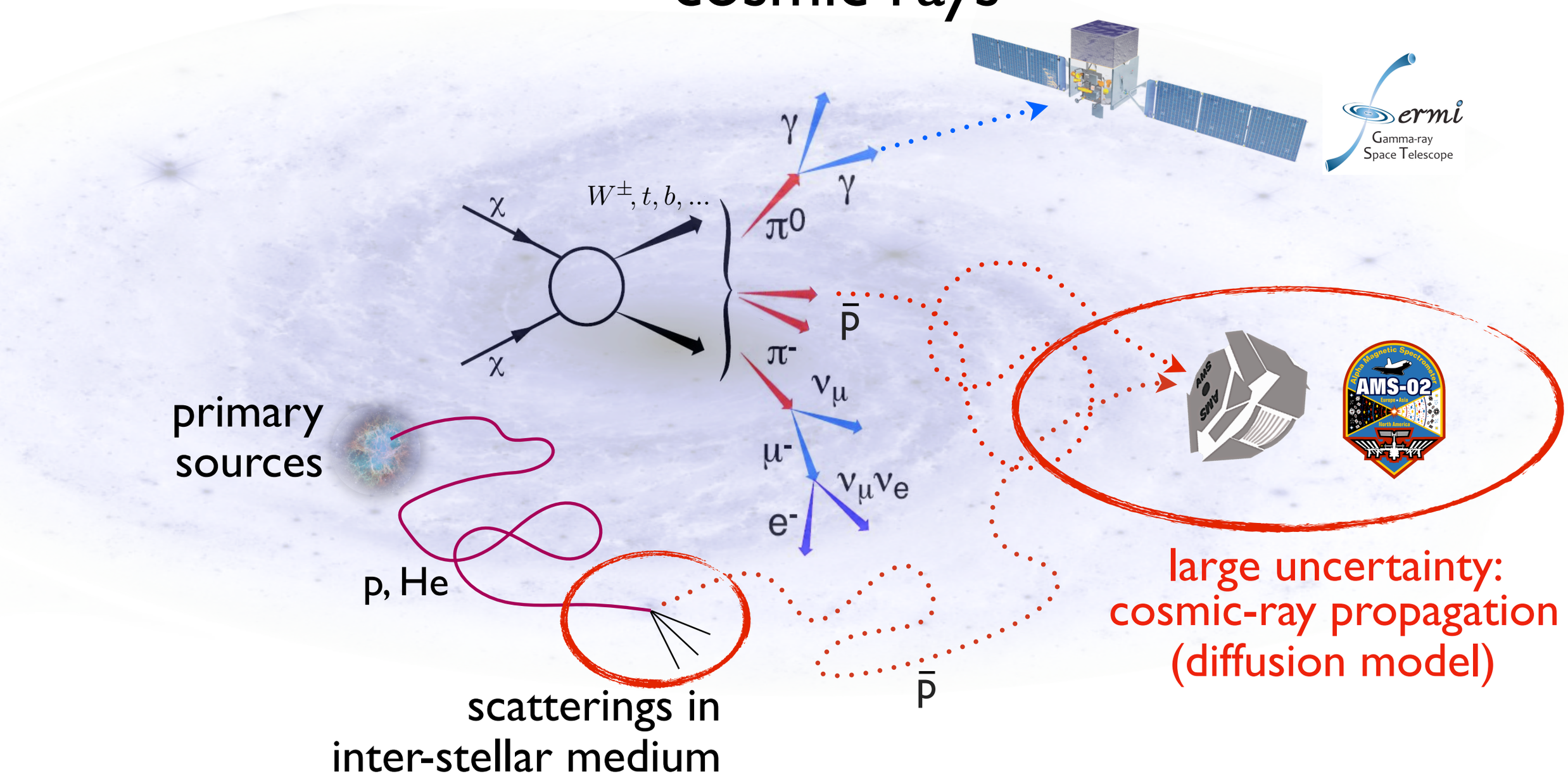
Chargé de recherches


*July 10-17, 2019*
*Ghent, Belgium*

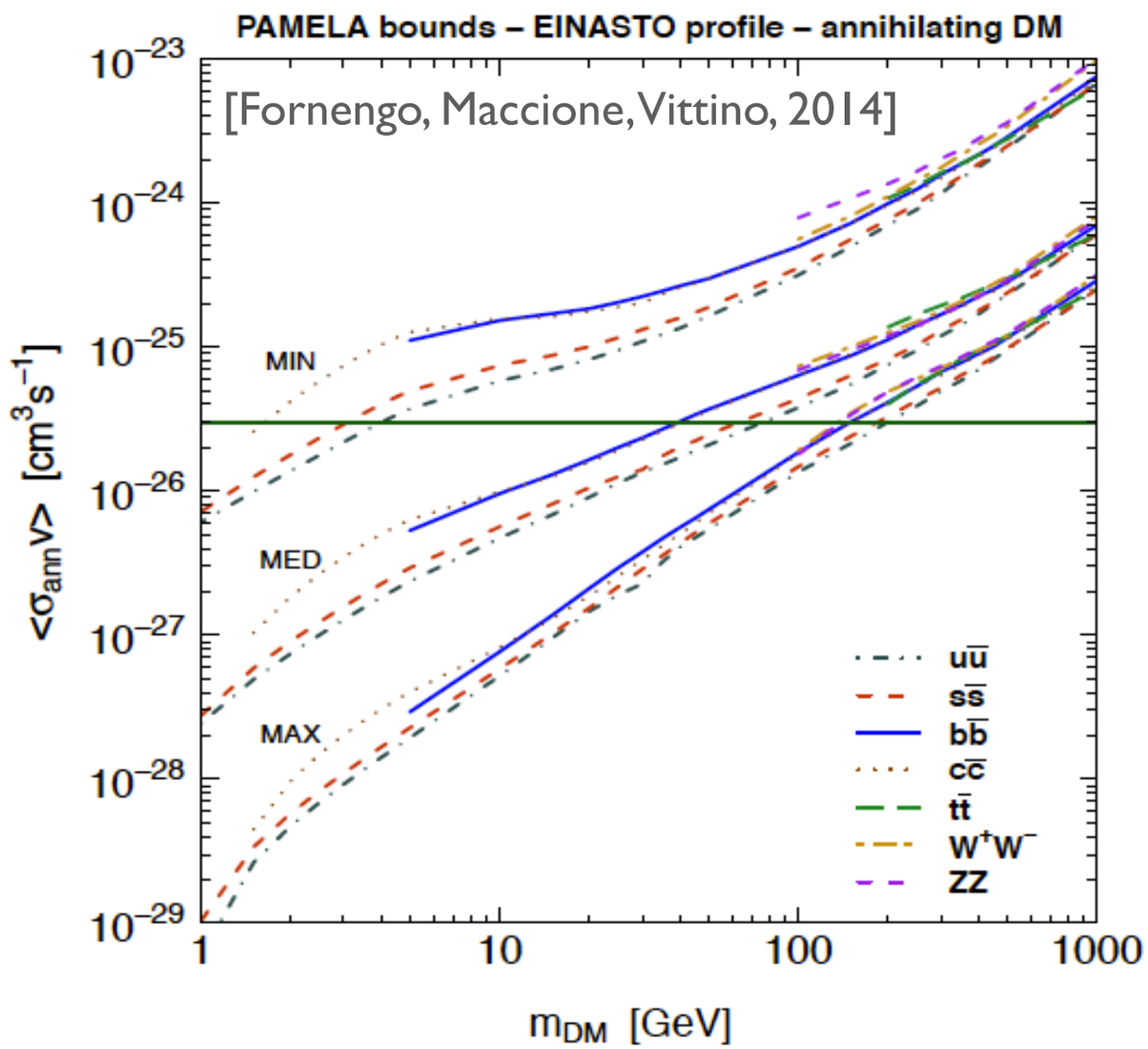
# Dark matter indirect detection searches:



# Dark matter indirect detection searches: cosmic rays



# Uncertainties in the PAMELA era



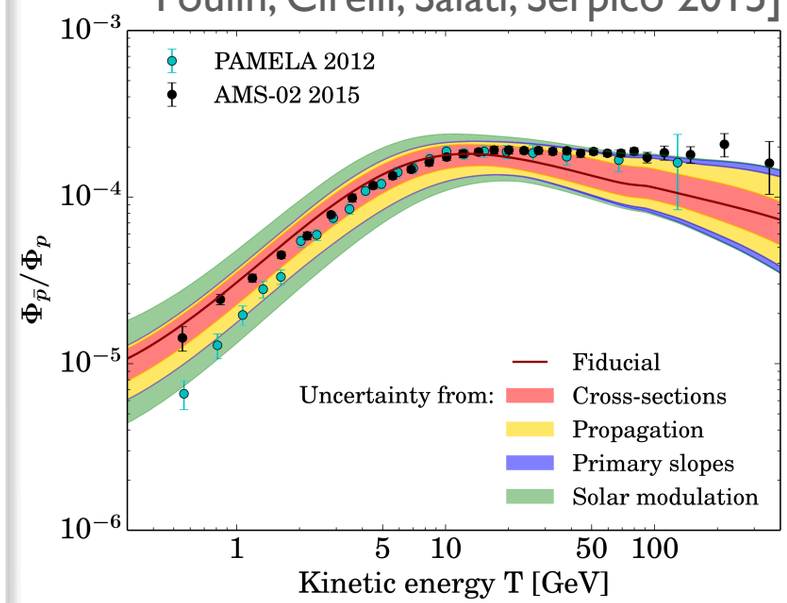

[see also e.g. L. Bergstrom, J. Edsjo, P. Ullio, ApJ,526,215 (1999); F. Donato, N. Fornengo, D. Maurin, P. Salati, PRD69, 063501 (2004); T. Bringmann, P. Salati, PRD75, 083006 (2007); F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, PRL. 102, 071301 (2009); D. Hooper, T. Linden, P. Mertsch, JCAP 1503, 021; V. Pettorino, G. Busoni, A. De Simone, E. Morgante, A. Riotto, W. Xue, JCAP 1410, 078 (2014); M. Boudaud, M. Cirelli, G. Giesen, P. Salati, JCAP1505, 013 (2015); J. A. R. Cembranos, V. Gammaldi, A. L. Maroto, JCAP 1503, 041 (2015); M. Cirelli, D. Gaggero, G. Giesen, M. Taoso, A. Urbano, JCAP 1412, 045 (2014); T. Bringmann, M. Vollmann, C. Weniger, Phys. Rev. D90, 123001 (2014)]

MIN/MED/MAX scenario: Large uncertainties in limits on dark matter annihilation cross section

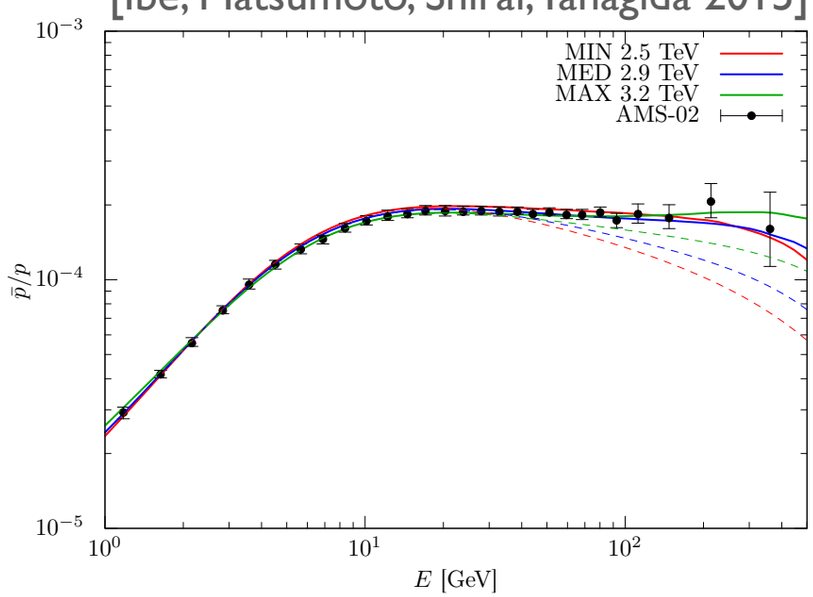
# Uncertainties in the AMS-02 era

- High precision data (down to few percent uncertainties)
- Sensitive probe of CR propagation
- Potential to detect a DM flux contribution as low as 10%

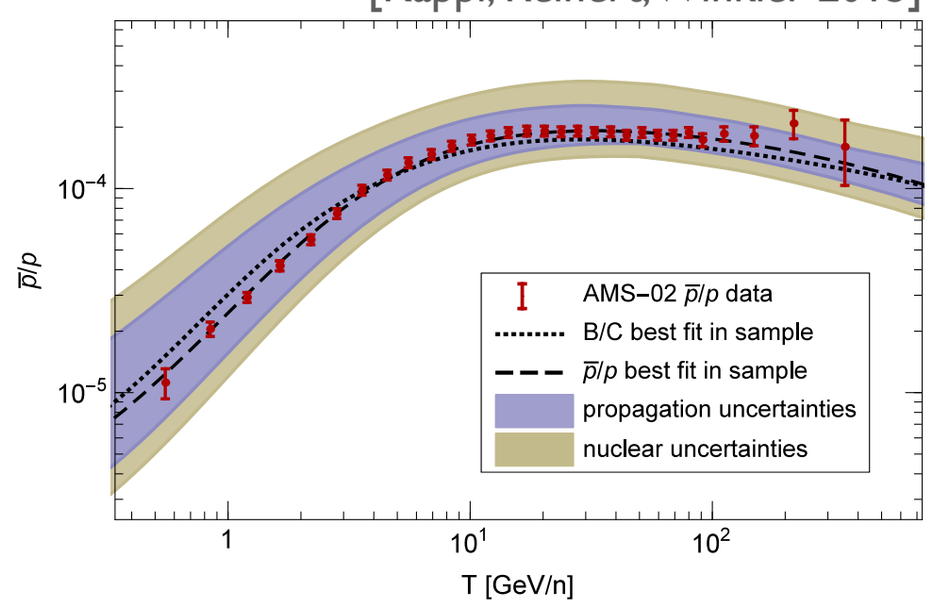
[Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 2015]




[Ibe, Matsumoto, Shirai, Yanagida 2015]



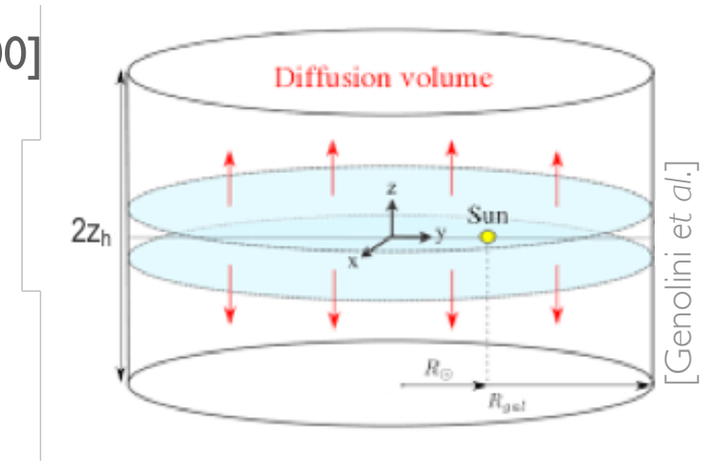

[Kappl, Reinert, Winkler 2015]



# Cosmic-ray propagation: Setup

- Propagation: Two-zone diffusion model with convection and reacceleration using Galprop [Strong, Moskalenko, Reimer 2000]

  Free parameters: $D_0,\ \delta,\ v_{0,\mathrm{c}},\ v_{\mathrm{Alven}},\ z_{\mathrm{h}}$



[Genolini *et al.*]

- Injection spectra: Smoothly broken power laws with separate spectral indices for p, He

  Free parameters: $\gamma_{1,p},\ \gamma_{2,p},\ \gamma_{1,\mathrm{He}},\ \gamma_{2,\mathrm{He}},\ R_0,\ s$

- Minimal consistent data set: Use AMS-02 data on He, p, $\bar{p}$/p (no B/C)
  Diffusion constrained by $\bar{p}$/p! [AMS 2015, 2016]

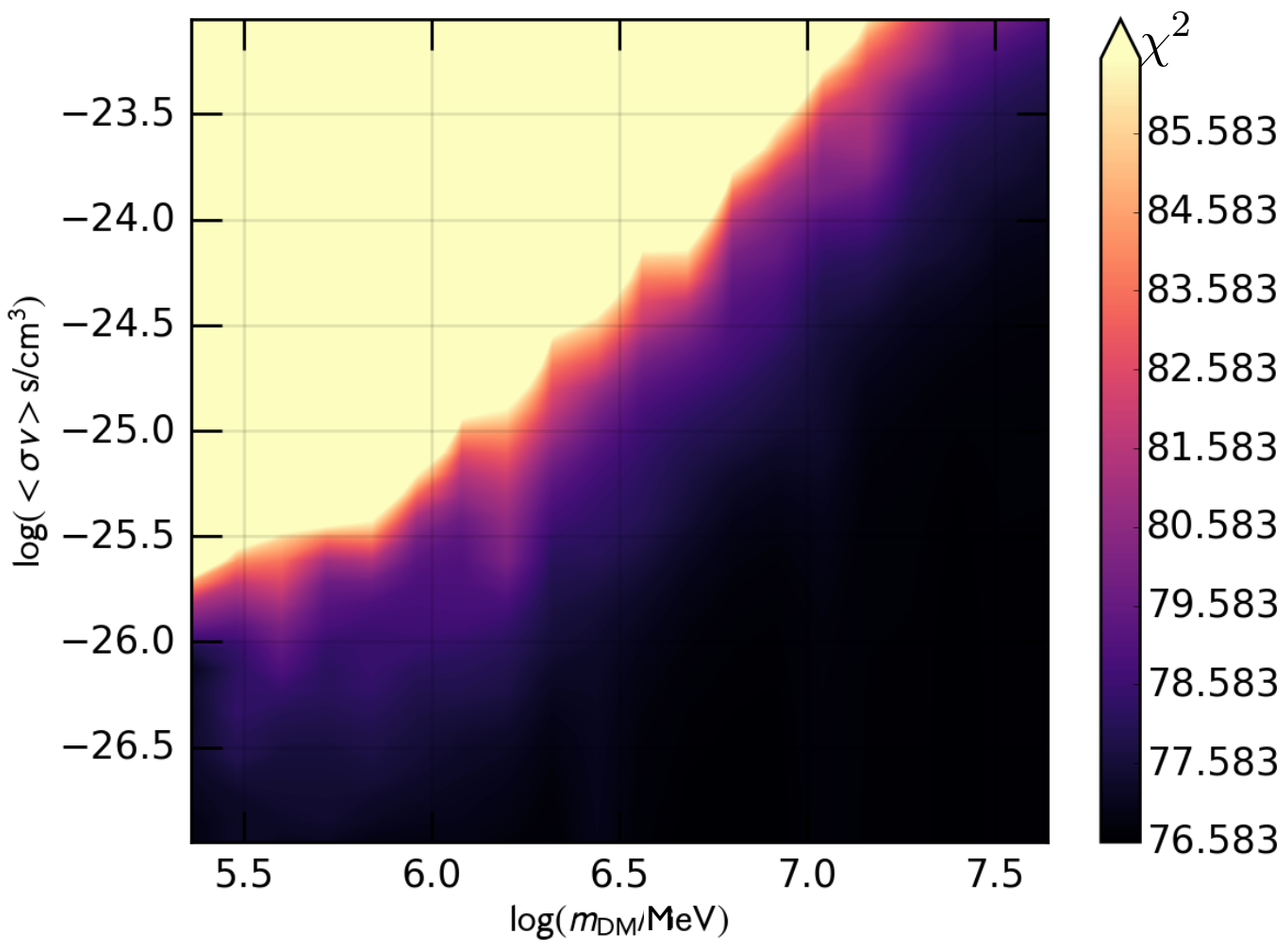
- p, He Voyager data to constrain Solar modulation (force-field appr.) [Stone *et al.* 2013]
  - Separat Fisk-potentials for $\bar{p}$ and p, He
  - Cut data below 5GV (deviations from force-field appr. seen)

- Perform joint fit of propagation parameters *and* dark matter parameters $\langle \sigma v \rangle,\ m_{\mathrm{DM}}$

# Limit setting

- Explore 13-dim. parameter space with MultiNest

Profile over all propagation (nuisance) parameters:




For a certain DM mass test-statistic:

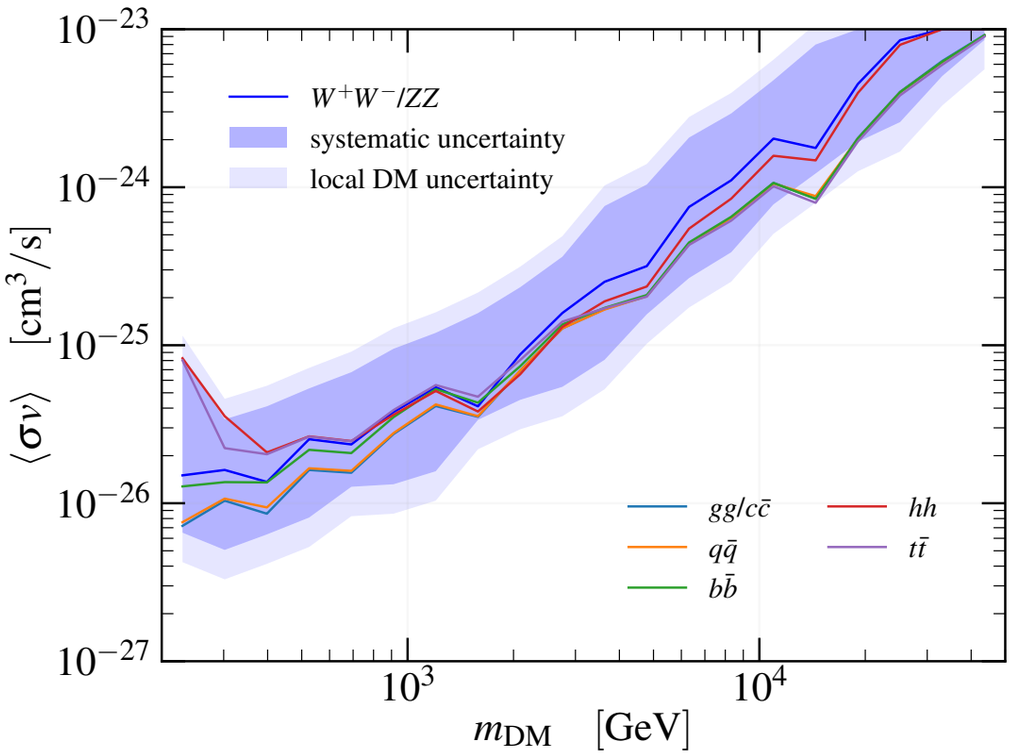
$$\Delta\chi^2 = -2\log\frac{\mathcal{L}(\widehat{\Theta}', \sigma v)}{\mathcal{L}(\widehat{\Theta}, \widehat{\sigma v})}$$

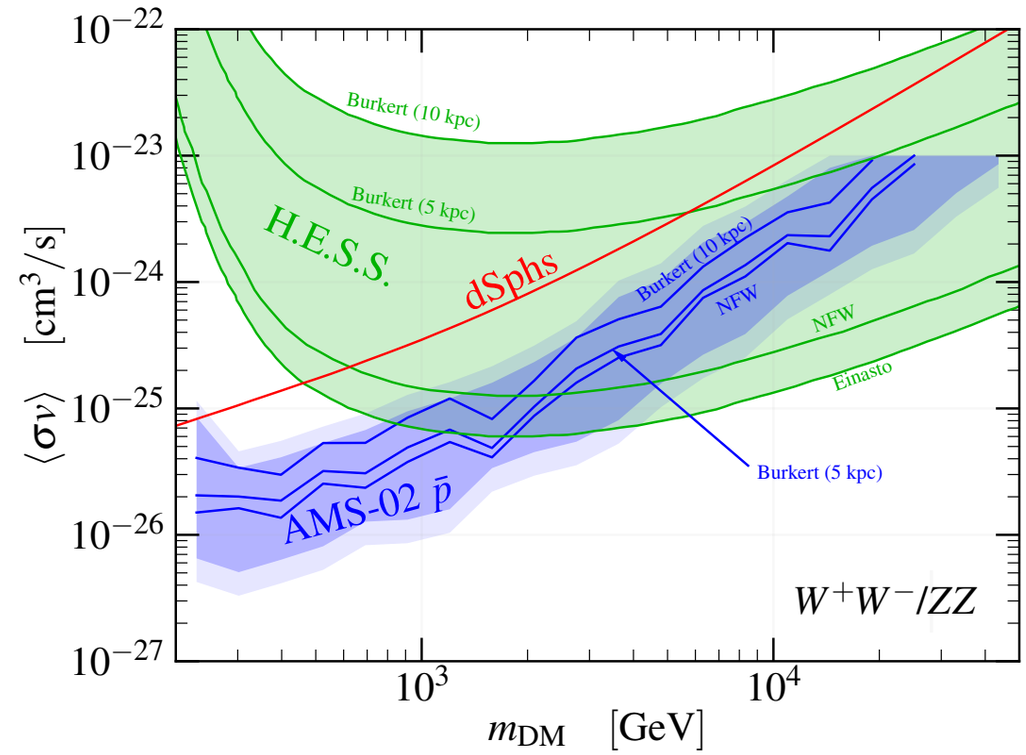
Best-fit value for considered mass (usually σv ~ 0)

⇒ Propagation uncertainties taken into account

# Constraints on heavy dark matter

[Cuoco, JH, Korsmeier, Krämer 2018]

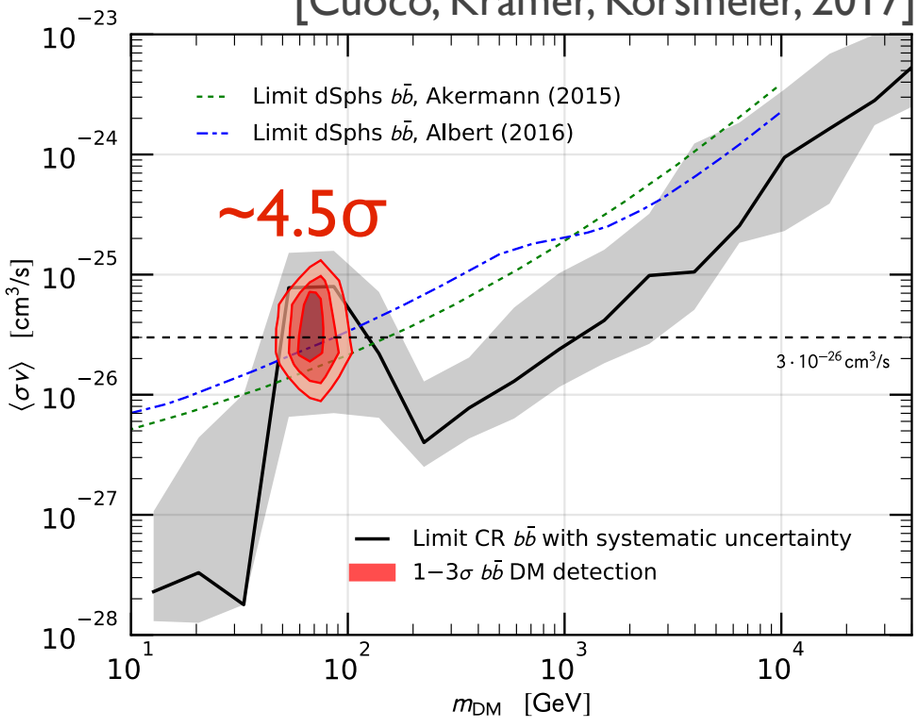


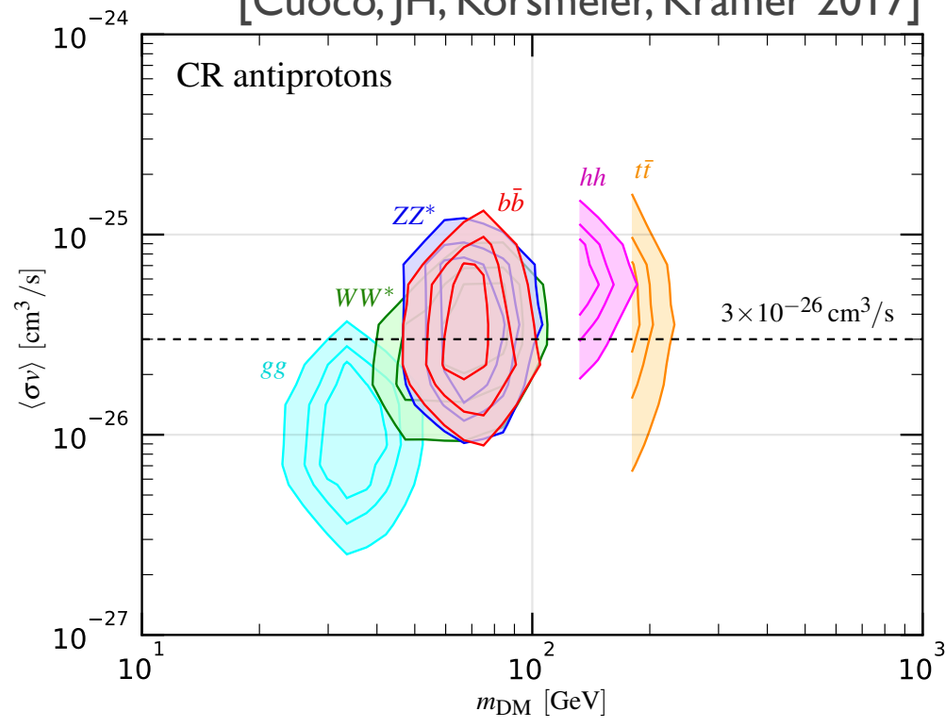

- Among strongest limits on DM annihilation for non-leptonic channels
- Robust against DM density profile

# Hint for 100 GeV-ish dark matter

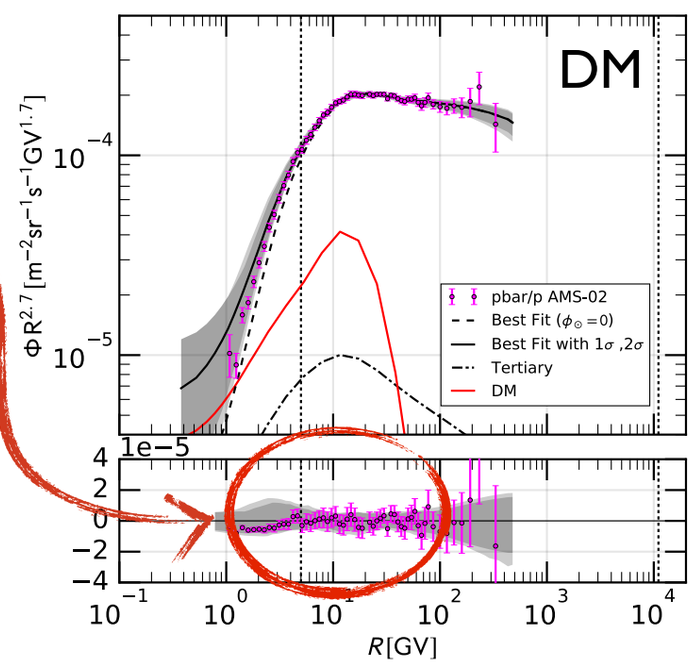
[Cuoco, Krämer, Korsmeier, 2017]

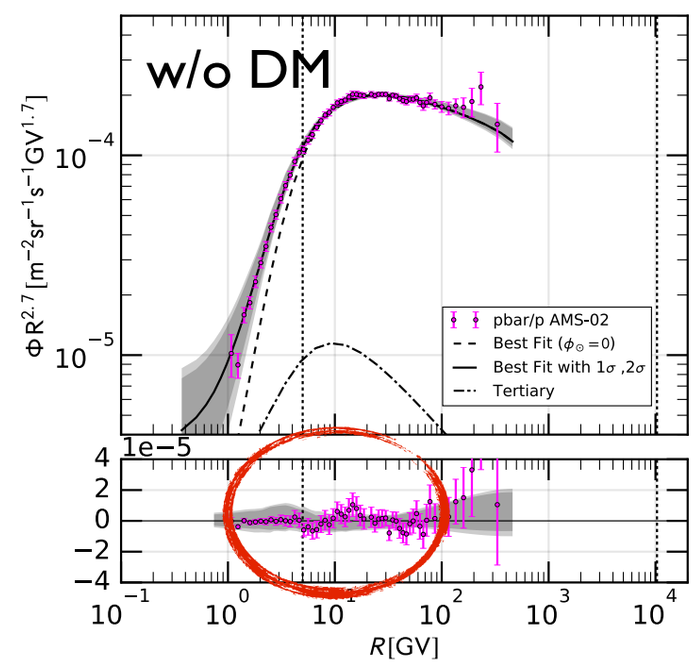



[Cuoco, JH, Korsmeier, Krämer 2017]




Feature around 10GV

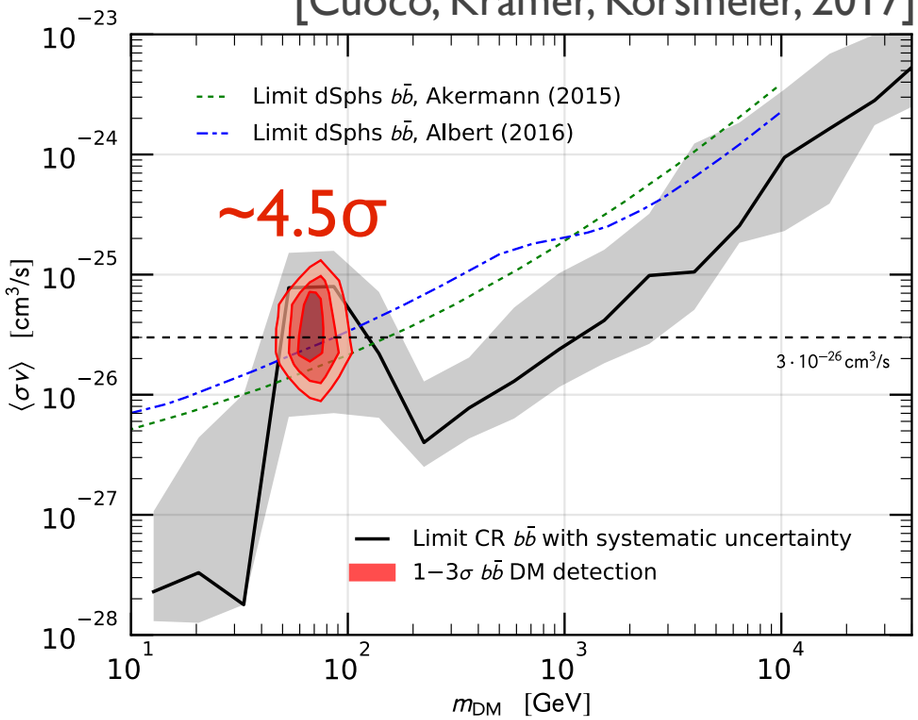


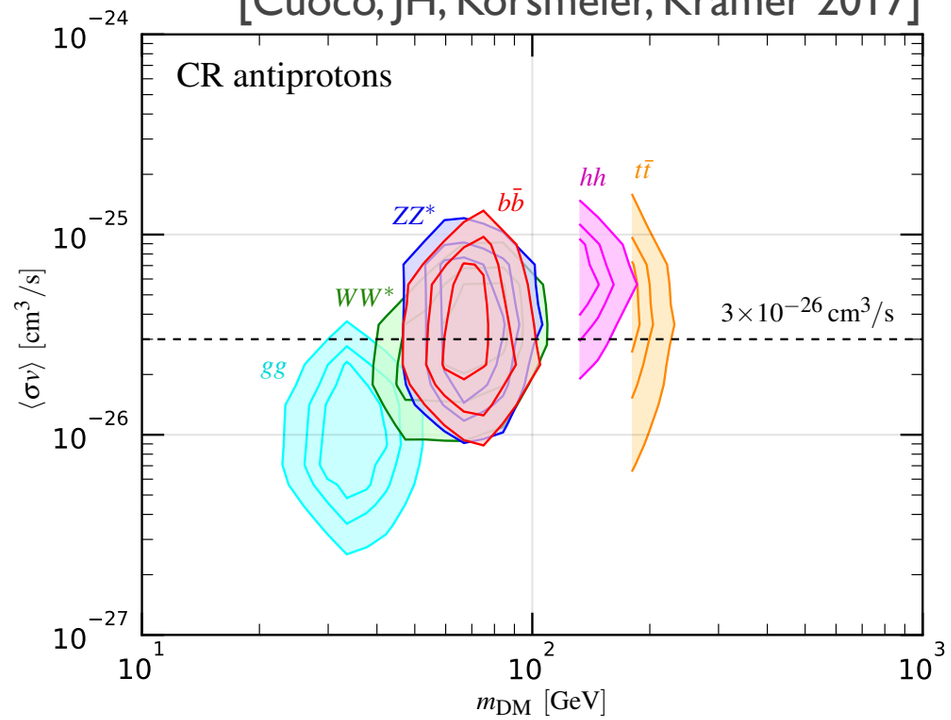

[see also Cui, Yuan, Tsai, Fan, 2017]

# Hint for 100 GeV-ish dark matter

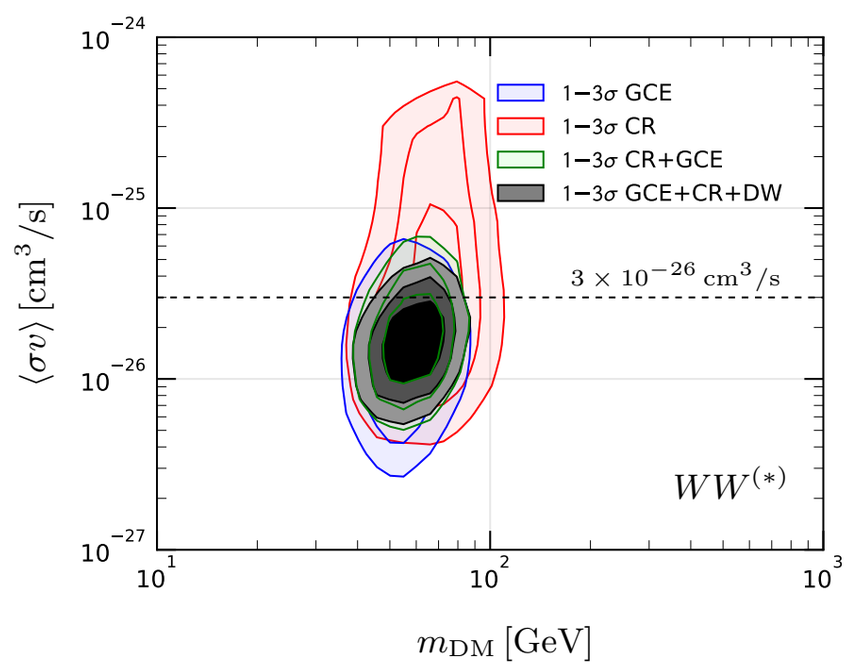
[Cuoco, Krämer, Korsmeier, 2017]




[Cuoco, JH, Korsmeier, Krämer 2017]

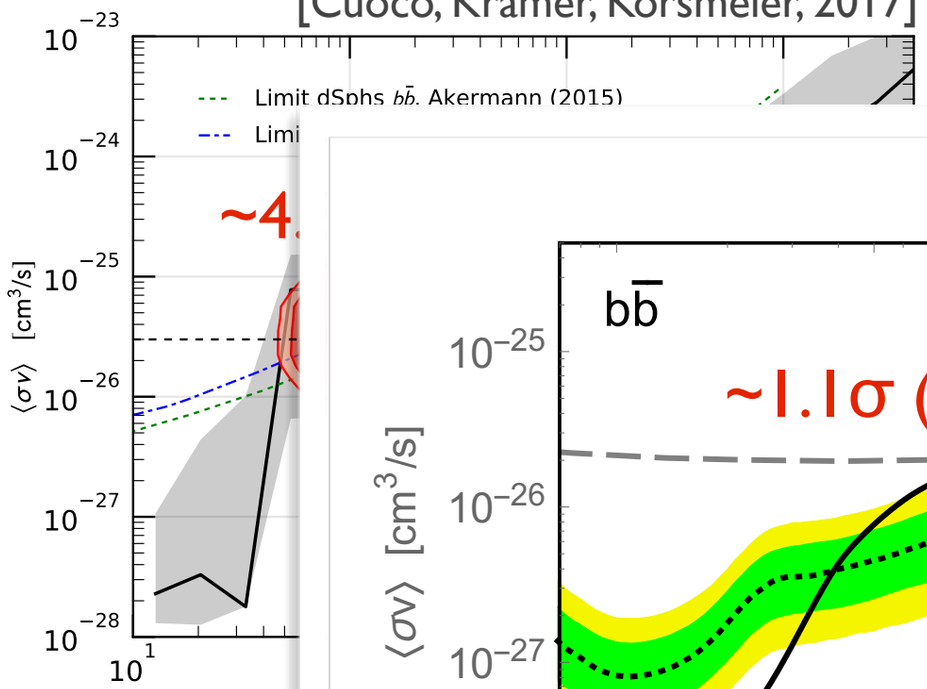



Compatible with Fermi-LAT gamma-ray Galactic center excess (GCE), dwarfs galaxies:
[Cuoco, JH, Korsmeier, Krämer 2017]



# Hint for 100 GeV-ish dark matter

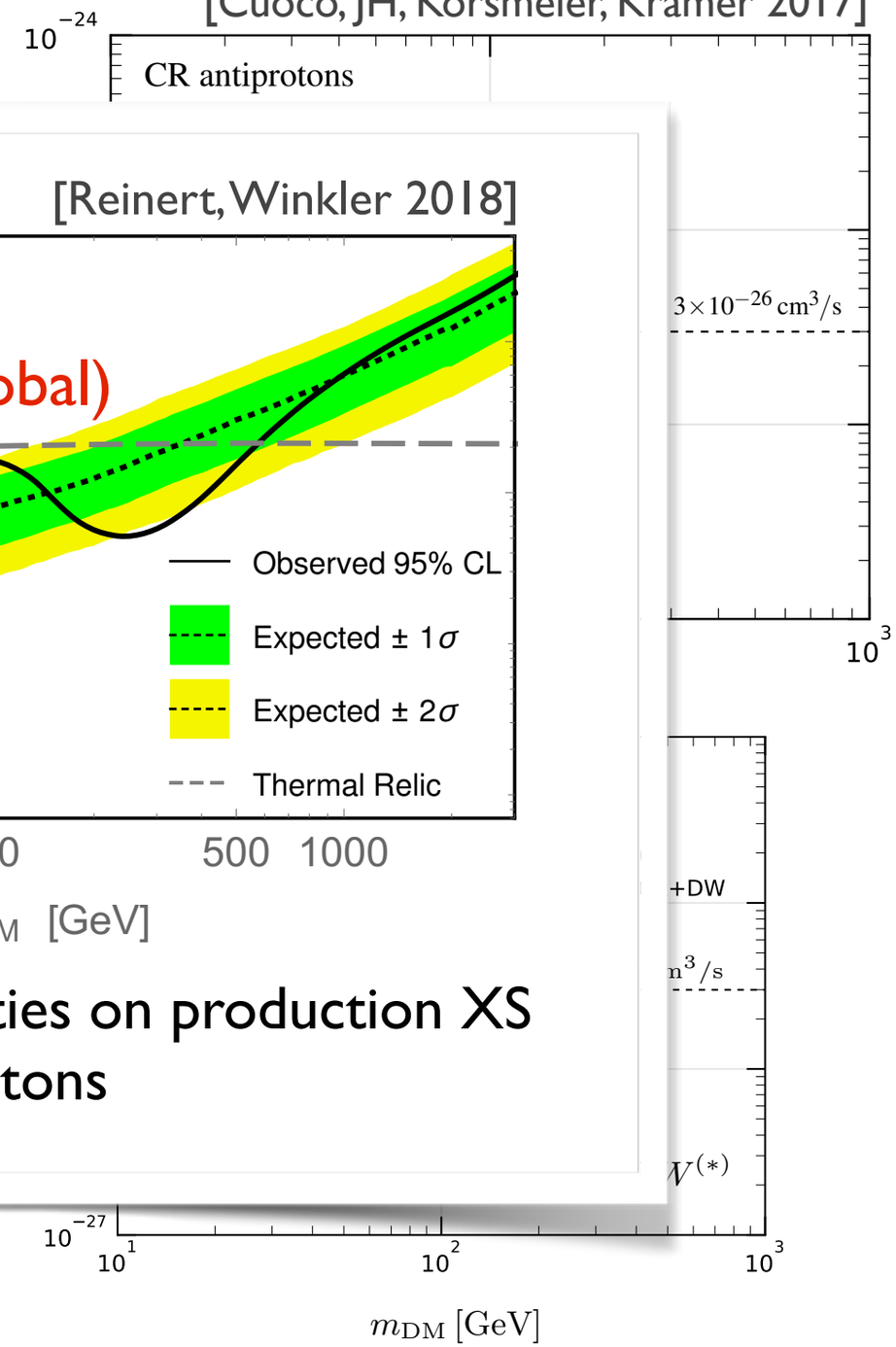
[Cuoco, Krämer, Korsmeier, 2017]



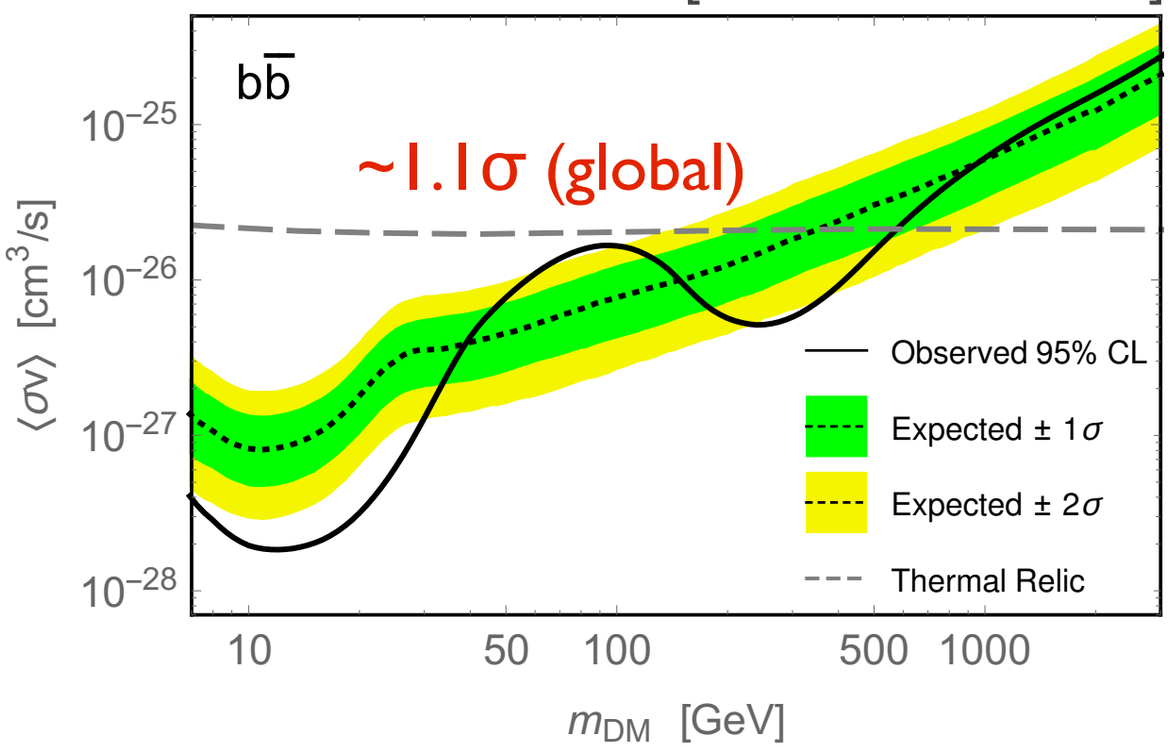

[see also C

Compa
gamma
excess
[Cuoco, JH

[Cuoco, JH, Korsmeier, Krämer 2017]




[Reinert, Winkler 2018]

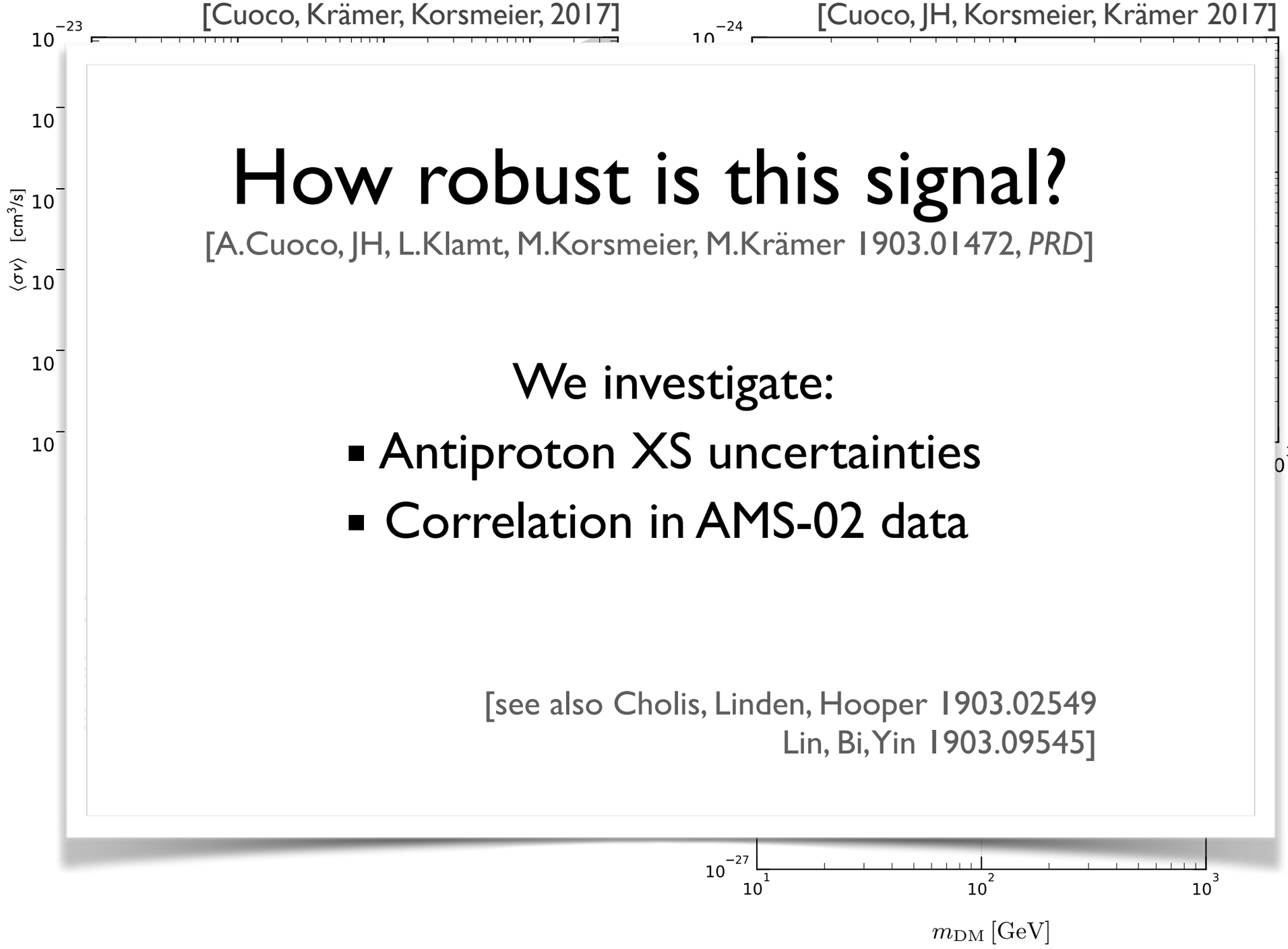



- Considers uncertainties on production XS of secondary antiprotons

# Hint for 100 GeV-ish dark matter

[Cuoco, Krämer, Korsmeier, 2017]

[Cuoco, JH, Korsmeier, Krämer 2017]




## How robust is this signal?

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 1903.01472, *PRD*]

We investigate:

- Antiproton XS uncertainties
- Correlation in AMS-02 data

[see also Cholis, Linden, Hooper 1903.02549
Lin, Bi, Yin 1903.09545]

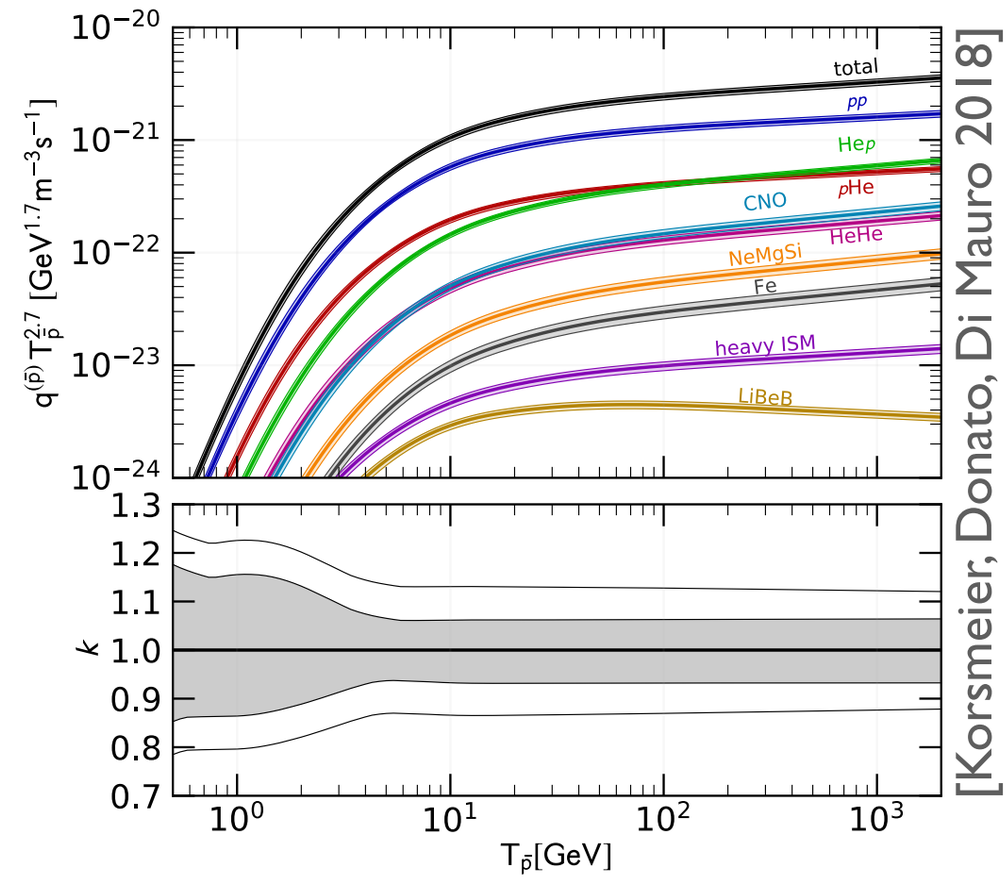
# Exploring cross-section uncertainties

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

- Source term for secondary antiprotons:

$$q_{ij}(T_{\bar{p}}) \propto \int_{T_{\min}}^{\infty} \mathrm{d}T_i \, \phi_i(T_i) \, \frac{\mathrm{d}\sigma_{ij}}{\mathrm{d}T_{\bar{p}}}(T_i, T_{\bar{p}})$$

- Sizeable uncertainties ~10-20% from $\bar{p}$ production XS
- Relevant given AMS-02 precision




[Korsmeier, Donato, Di Mauro 2018]

Use two XS parametrizations:

- Winkler *et al.* (MW) [Winkler 2017; Kappl, Winkler 2014] (default)
- Di Mauro *et al.* (MD) [diMauro, Donato, Goudelis, Serpico 2014]

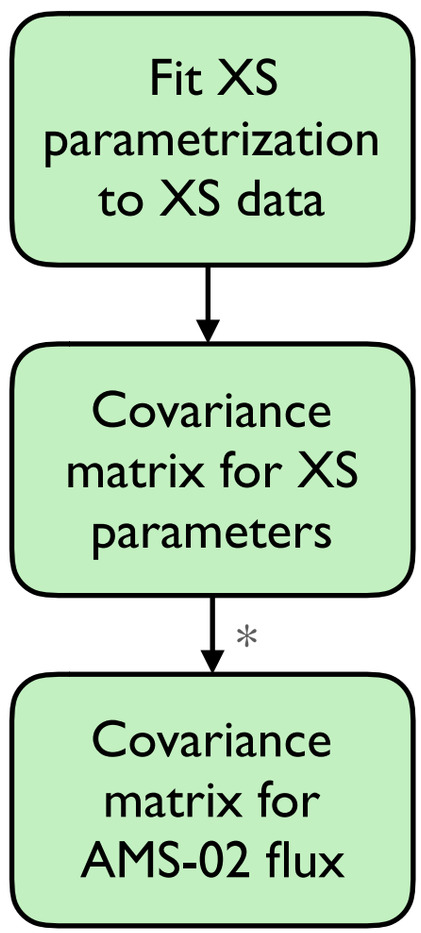
with updated parameters [Korsmeier, Donato, Di Mauro 2018] including recent data from NA61, LHCb

# Exploring cross-section uncertainties

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

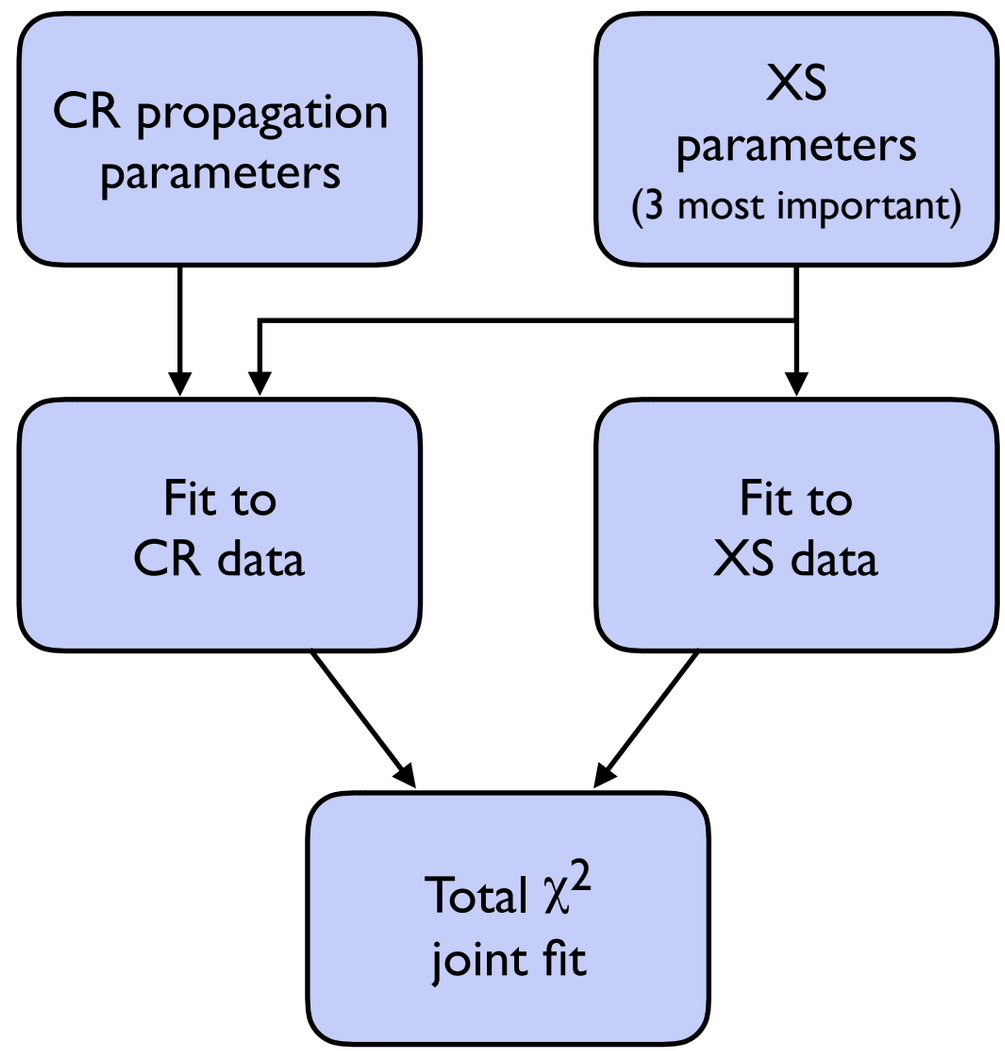
## Covariance matrix

[from Korsmeier, Donato, Di Mauro 2018]




[*approach already used in Reinert, Winkler 2018]

## Joint fit

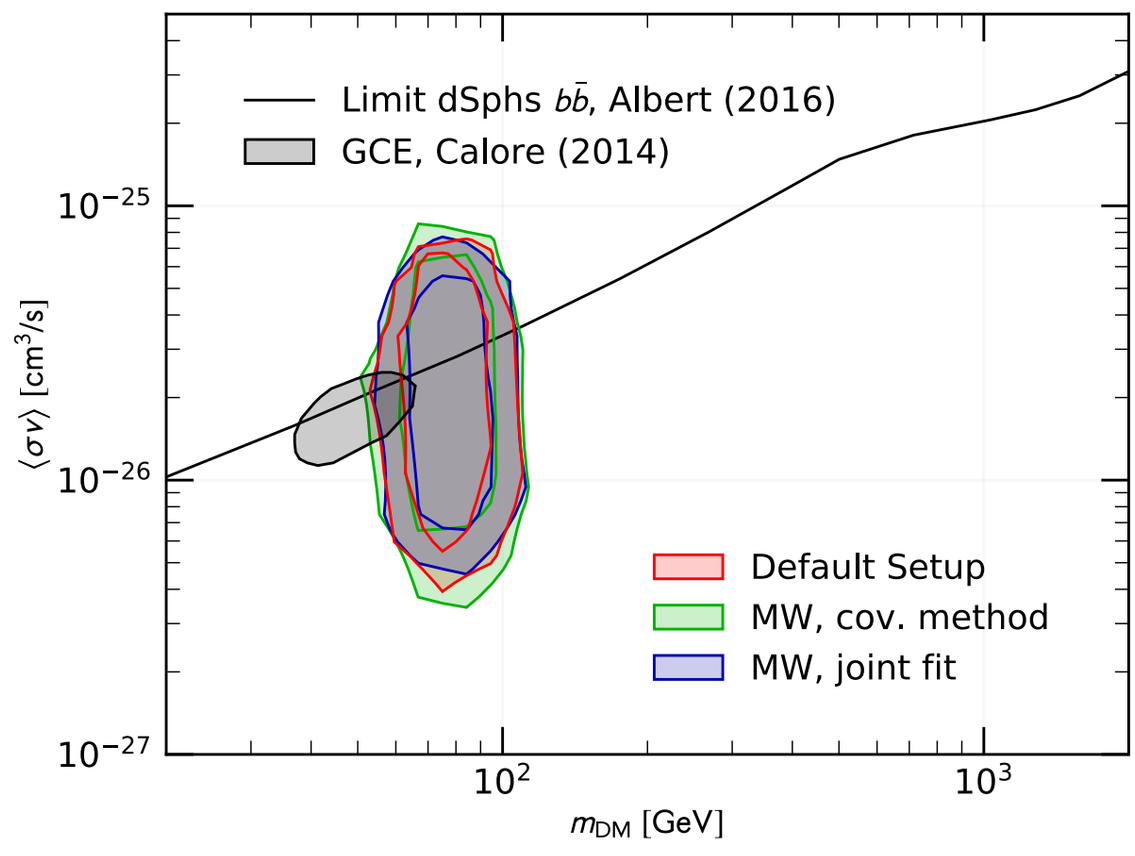


# Exploring cross-section uncertainties

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

- Significance around 3σ (4.5σ → ~3σ mainly due to Tan&Ng → updated MW/MD)
- No significant dependence on treatment of uncertainties
- No significant correlation between XS and CR uncertainties
  ⇒ cov-mat. method reliable

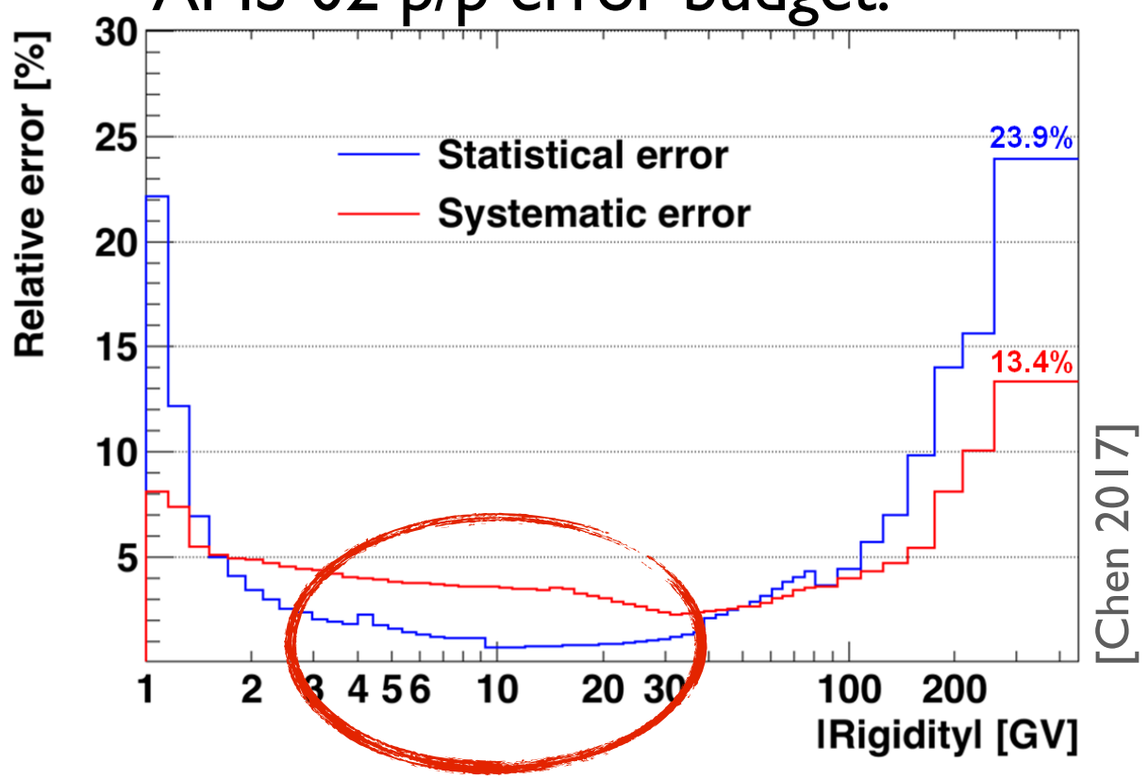
| | $\chi^2$ (DM) | $\chi^2$ (w/o DM) | $\Delta\chi^2$ | sign. |
|---|---|---|---|---|
| param. MW | 22.9 | 35.6 | 12.7 | $3.1\sigma$ |
| param. MD | 22.2 | 34.2 | 12.0 | $3.0\sigma$ |
| cov-mat. (MW) | 23.0 | 33.9 | 10.9 | $2.9\sigma$ |
| cov-mat. (MD) | 22.0 | 34.2 | 12.2 | $3.1\sigma$ |
| joint fit (MW) | 814.5 | 825.2 | 10.7 | $2.8\sigma$ |



# Correlations in AMS-02 uncertainties

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

AMS-02 $\bar{p}/p$ error budget:




[Chen 2017]

Systematic uncertainties contain:

- acceptance uncertainty
- trigger uncertainty
- rigidity scale uncertainty
- energy unfolding (migration)

- Systematic uncertainties dominate in relevant region: 5~25GV
- Rel. error around 4%
- No covariance provided by AMS-02, but correlations expected!
  ⇒ Errors overestimated

# Correlations in AMS-02 uncertainties

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

- So far: $\chi^2_{\rm CR} = \sum_{i,j} (\phi^{\rm ex} - \phi^{\rm th})_i \left(\mathcal{V}^{-1}\right)_{ij} (\phi^{\rm ex} - \phi^{\rm th})_j \,, \quad \overset{\text{uncorr}}{\mathcal{V}_{ij}} = \delta_{ij}\sigma_i^2$

- Now consider:

$$\mathcal{V} = \mathcal{V}_{\rm uncorr} + \mathcal{V}_{\rm short} + \mathcal{V}_{\rm long}$$

No correlation

Fully correlated

Finite correlation length $\ell_{\rm corr}$

Ansatz: $\mathcal{V}_{{\rm short},ij} = \exp\left(-\frac{|i-j|^\alpha}{\ell_{\rm corr}{}^\alpha}\right) f^2 \sigma_{{\rm sys},i}\sigma_{{\rm sys},j}$

Determine viable range for $f, \alpha$ from data,
choose maximal $f$ consistent at 90% CL.

# Correlations in AMS-02 uncertainties

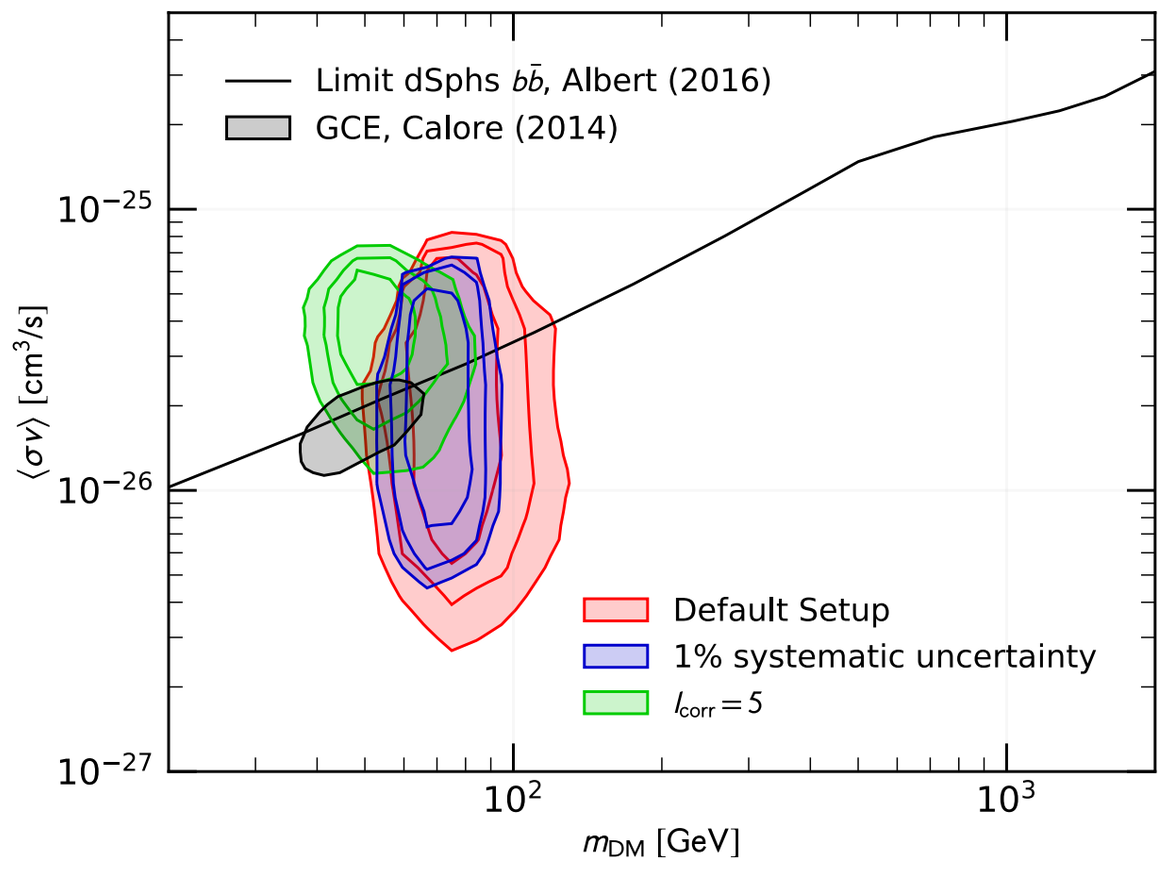
[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

Rest of systematics fully correlated

| | $\chi^2$ (DM) | $\chi^2$ (w/o DM) | $\Delta\chi^2$ | sign. |
|---|---|---|---|---|
| default | 35.6 | 22.9 | 12.7 | $3.1\sigma$ |
| 1% uncorr. | 47.4 | 77.4 | 30.0 | $5.1\sigma$ |
| $\ell_{\rm corr} = 0$ | 250.0 | 284.1 | 34.1 | $5.5\sigma$ |
| $\ell_{\rm corr} = 5$ | 232.6 | 250.2 | 17.6 | $3.8\sigma$ |
| $\ell_{\rm corr} = 10$ | 241.3 | 259.3 | 18.0 | $3.8\sigma$ |

- Significant effect on fits
- More realistic $\chi^2$ given dof~150
- More constraining, best-fit region shrinks!
- Higher DM significance!

Caution: Only 'true' covariance matrix from AMS-02 allows us to draw solid conclusions!



# Conclusions

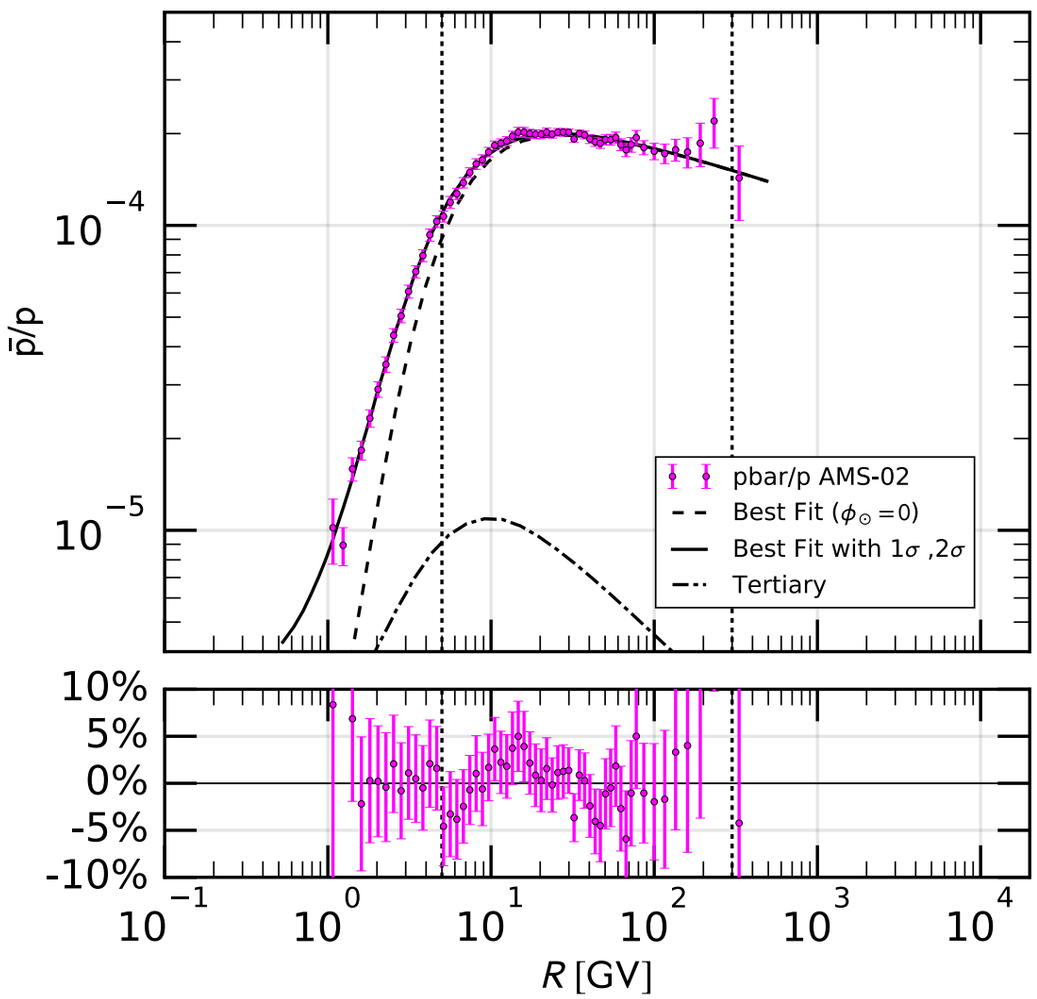
- With AMS-02 cosmic-ray precision era started
- Reduce uncertainties w.r.t. benchmark scenarios:
  ⇒ Joint fit of propagation parameters and dark matter
- Strong limits on heavy DM, hint for DM around 100GeV
  - Systematic uncertainties at few % level important
  - Antiproton cross-section uncertainties (cov-mat/joint fit):
    Signal persists at the ~3$\sigma$ level
  - Correlations in AMS-02 data:
    Potentially large effect, increases DM significance
  - Knowledge of correlations vital to fully exploit data

# Backup

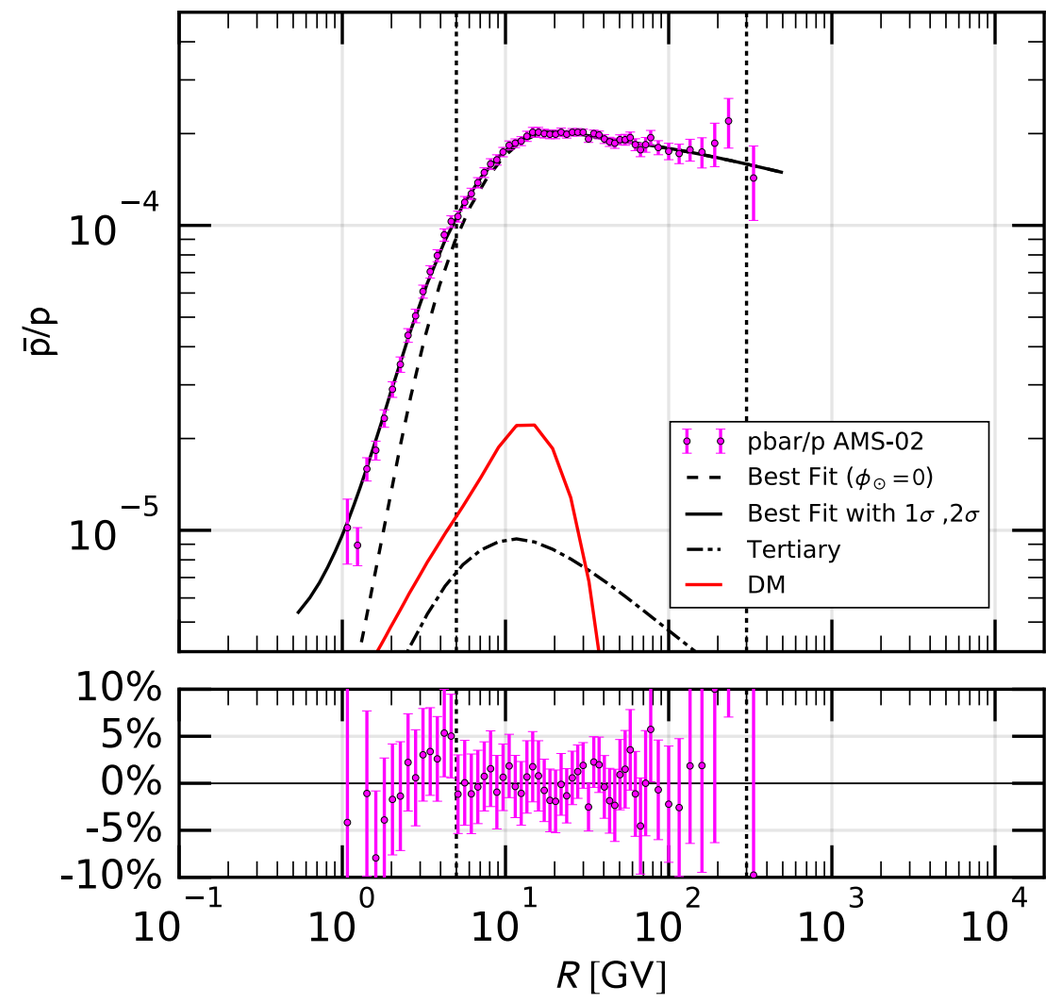
# Fits default setup

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

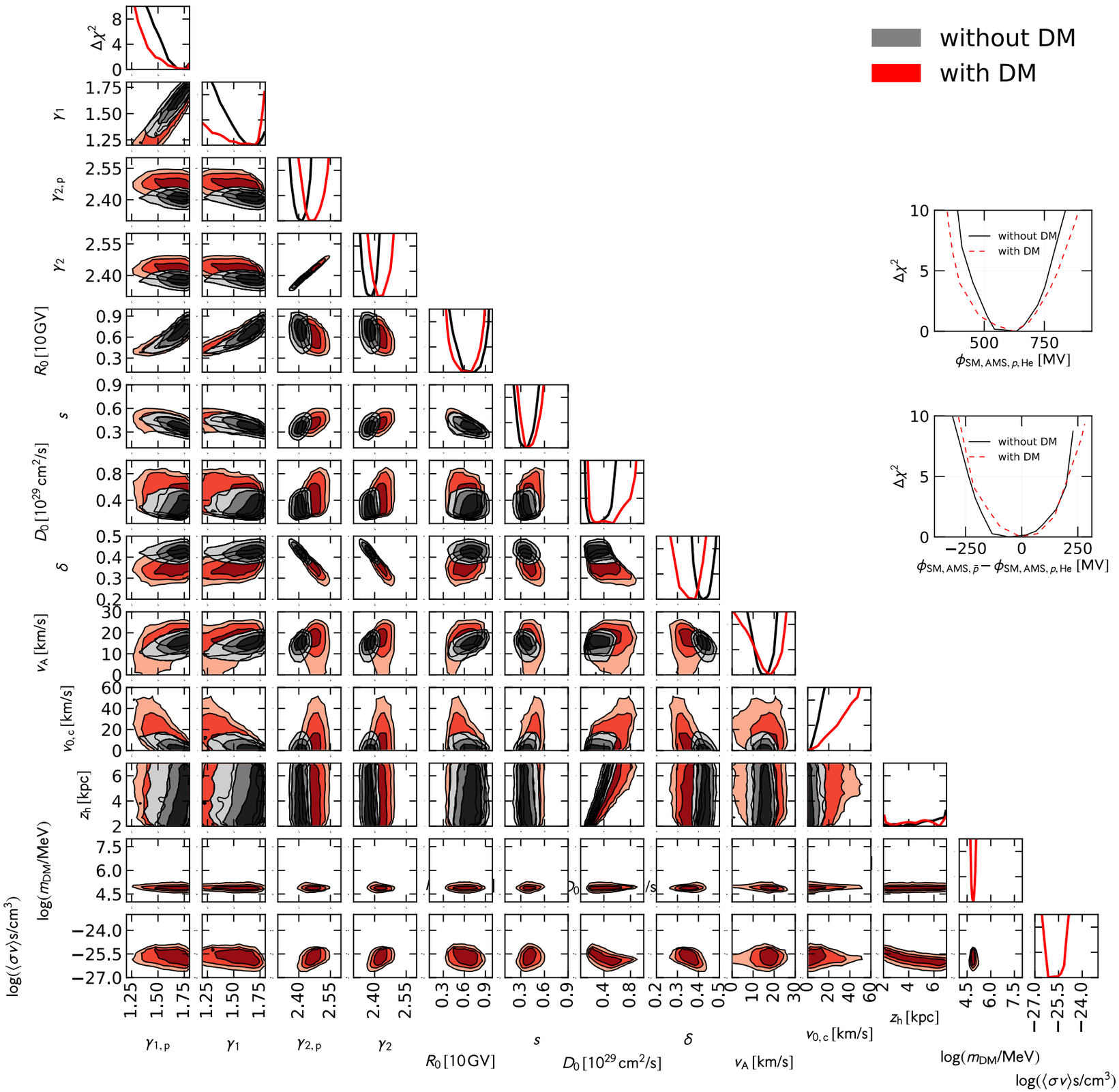
## Without dark matter:




## With dark matter (*bb*):

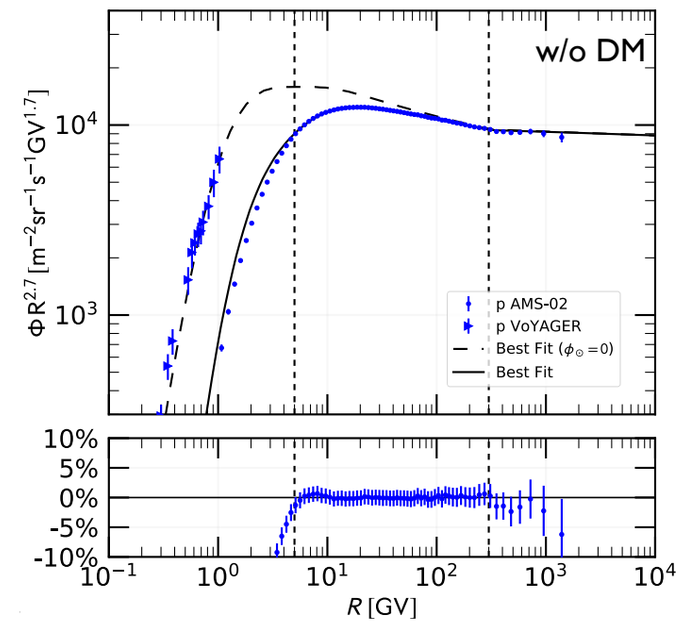


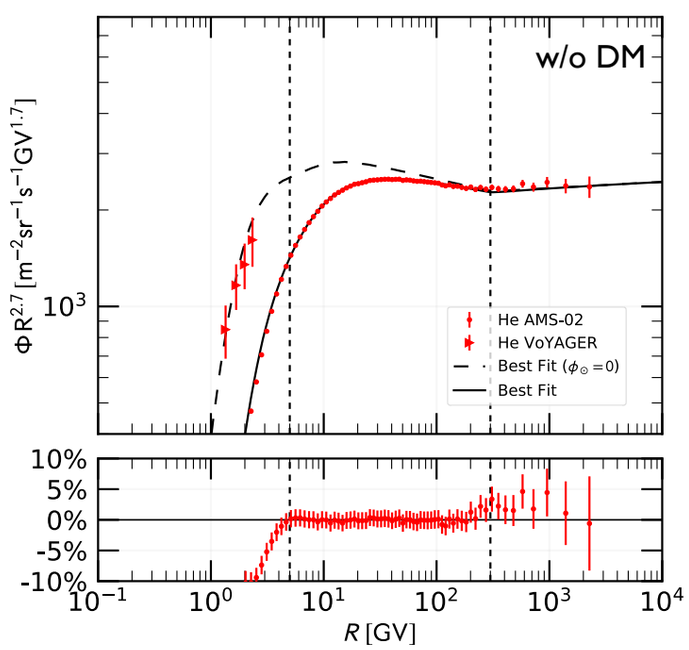
# Fits default setup









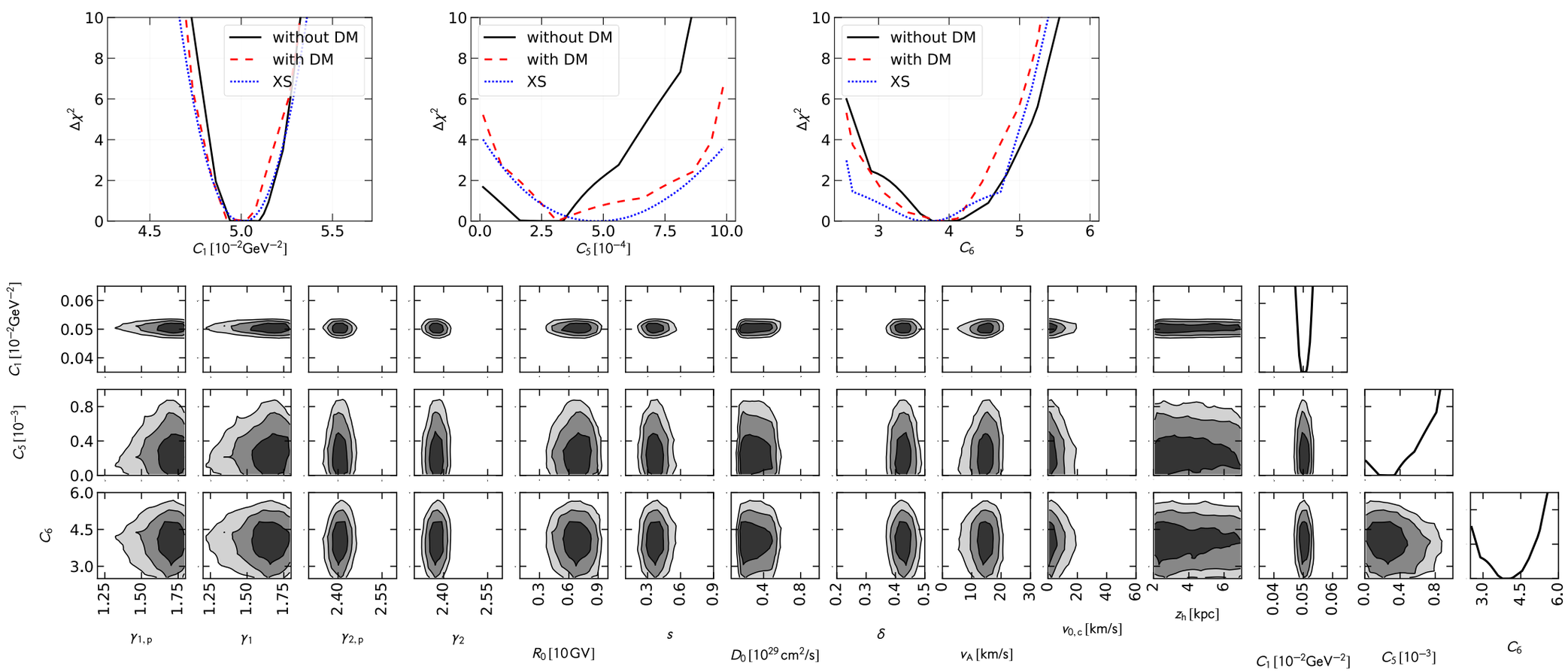

[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

# XS parametrization (MW)

$$E_{\bar{p}}\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\bar{p}}^3}(\sqrt{s}, x_\mathrm{R}, p_\mathrm{T}) = \sigma_\mathrm{in}\, R_\mathrm{XS}\, C_1 (1-x_\mathrm{R})^{C_2} \left[1 + \frac{X}{\mathrm{GeV}}(m_\mathrm{T} - m_p)\right]^{\frac{-1}{C_3 X}}$$

$$R_\mathrm{XS} = \begin{cases} \left[1 + C_5 \left(10 - \frac{\sqrt{s}}{\mathrm{GeV}}\right)^5\right] \cdot \exp\left[C_6 \left(10 - \frac{\sqrt{s}}{\mathrm{GeV}}\right)(x_\mathrm{R} - x_{R,\mathrm{min}})^2\right] & , \sqrt{s} \leq 10\,\mathrm{GeV} \\ 1 & , \text{ else} \end{cases}$$

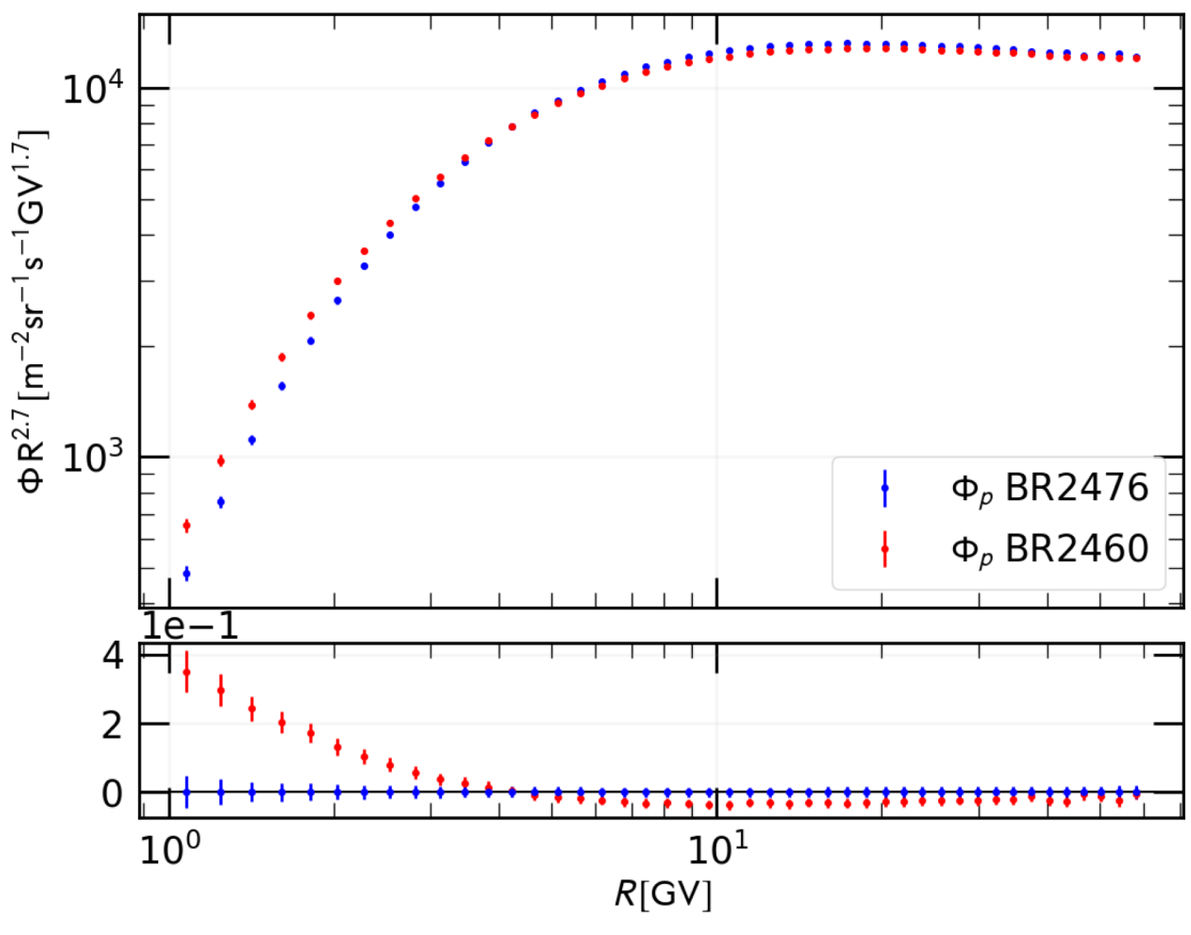
$$m_\mathrm{T} = \sqrt{p_\mathrm{T}^2 + m_p^2} \qquad X = C_4 \log^2\left(\frac{\sqrt{s}}{4m_p}\right).$$




[A.Cuoco, JH, L.Klamt, M.Korsmeier, M.Krämer 2019]

# Solar modulation

| rigidity cut [GV] | $\chi^2$/ndf excl. DM | incl. DM | $\Delta\chi^2$ | DM significance |
|---|---|---|---|---|
| 5 | $35.6/145 = 0.245$ | $22.9/143 = 0.160$ | 12.7 | $3.1\sigma$ |
| 3 | $52.7/160 = 0.329$ | $34.2/158 = 0.216$ | 18.5 | $3.9\sigma$ |
| 2 | $68.2/172 = 0.396$ | $57.1/170 = 0.336$ | 11.1 | $2.9\sigma$ |
| 1 | $105.4/182 = 0.579$ | $105.6/180 = 0.586$ | -0.2 | – |



# Joint fit with Fermi-LAT gamma-ray data

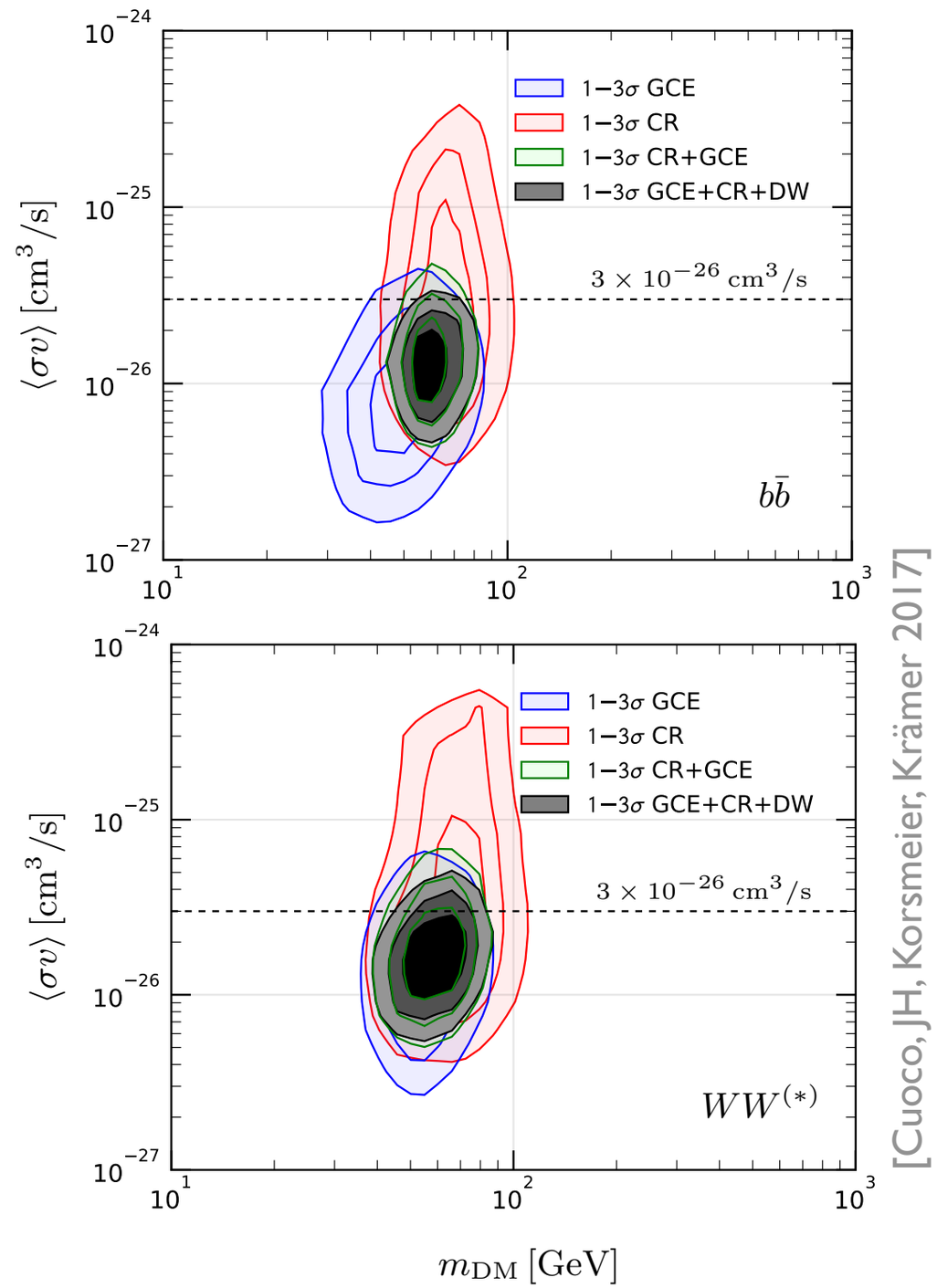
- Limits from dwarfs galaxies

  Used public likelihoods [Fermi-LAT 2017]

- Dark matter interpretation of Galactic center excess (GCE)

  - Used spectrum and covariance matrix from [Calore, Cholis, Weniger 2015]
  - *J*-factor from [Cuoco, Einteneuer, JH, Krämer, 2016] $\log(J/\mathrm{GeV}^2\mathrm{cm}^{-5}) = 53.54 \pm 0.43$
  - Local DM density [Salucci, Nesti, Gentile, Martins, 2010] $\rho_\odot = 0.43 \pm 0.15$

| | individual fits | | joint fit | |
|---|---|---|---|---|
| channel | $\chi^2_{\mathrm{CR}}$ | $\chi^2_{\mathrm{GCE}}$ | $\chi^2_{\mathrm{CR}}$ | $\chi^2_{\mathrm{GCE}}$ |
| $gg$ | 50.3 | 20.8 | 52.0 | 31.6 |
| $b\bar{b}$ | 45.8 | 21.2 | 47.9 | 23.5 |
| $WW^{(*)}$ | 50.4 | 25.6 | 54.6 | 25.6 |
| $ZZ^{(*)}$ | 45.6 | 25.0 | 45.8 | 25.9 |
| $hh$ | 47.6 | 25.8 | 48.4 | 25.8 |
| $t\bar{t}$ | 59.5 | 41.1 | 59.5 | 41.1 |



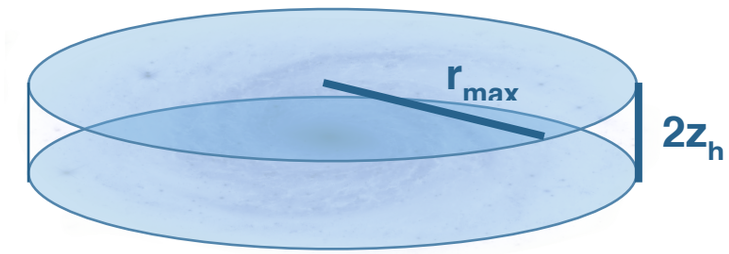

[Cuoco, JH, Korsmeier, Krämer 2017]

# Cosmic-ray propagation in the Galaxy

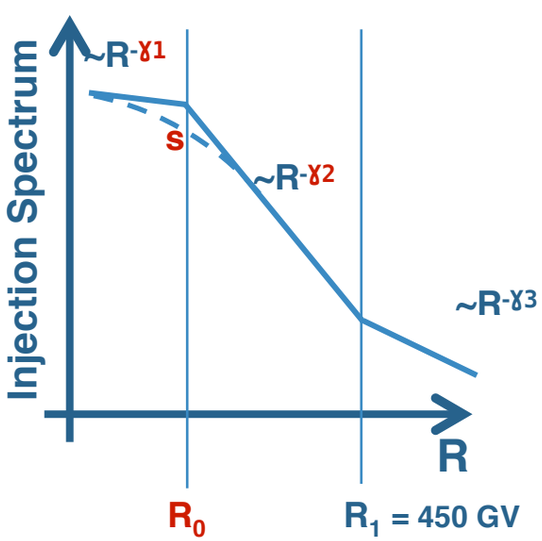
- Numerically solve diffusion equation:
  [using Galprop (or Dragon)]

$$\frac{\mathrm{d}\psi_i}{\mathrm{d}t} = q_i(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi_i - \boldsymbol{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i$$

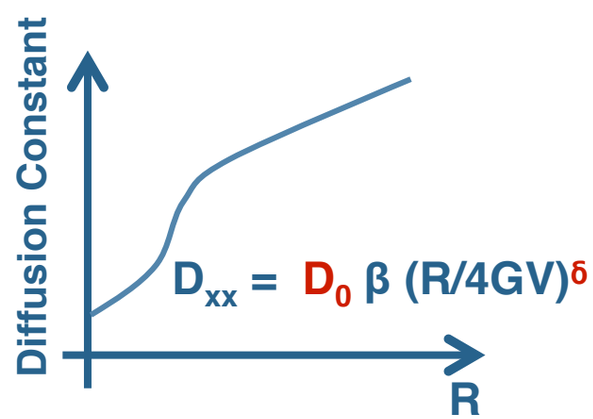
$$- \frac{\partial}{\partial p} \left( \frac{\mathrm{d}p}{\mathrm{d}t} \psi_i - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi_i \right) - \frac{1}{\tau_f} \psi_i - \frac{1}{\tau_r} \psi_i \qquad i = \mathrm{He}, p, \bar{p}$$




Injection spectra:



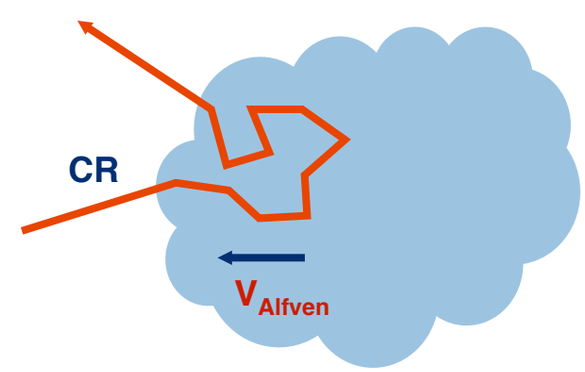

Diffusion:




Convection+Reaccelaration:

Winds perpendicular to the galactic plane

$\mathbf{V} = \mathbf{v}_{0,c}\ \mathrm{sign}(z)\ \mathbf{e}_z$




Fit parameters: $z_\mathrm{h}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}, v_\mathrm{Alfen}, \langle \sigma v \rangle_\mathrm{DM}, m_\mathrm{DM}$

Figures: Credit to Michael Korsmeier