Constraining TeV-scale dark matter with cosmic-ray antiprotons

[based on Cuoco, JH, Korsmeier, Krämer, 1711.05274, JCAP]

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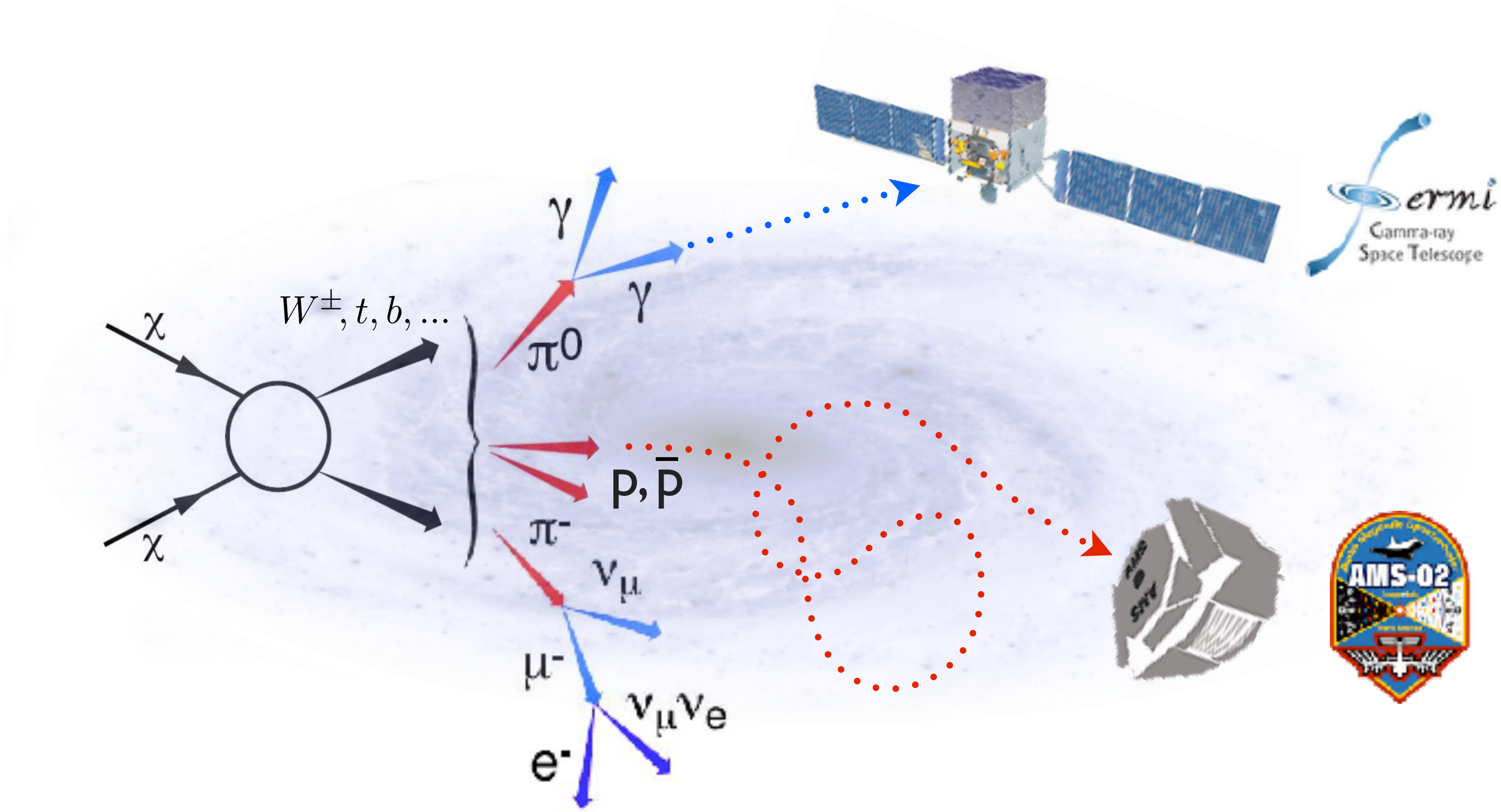
June 26, Annecy-le-Vieux, France

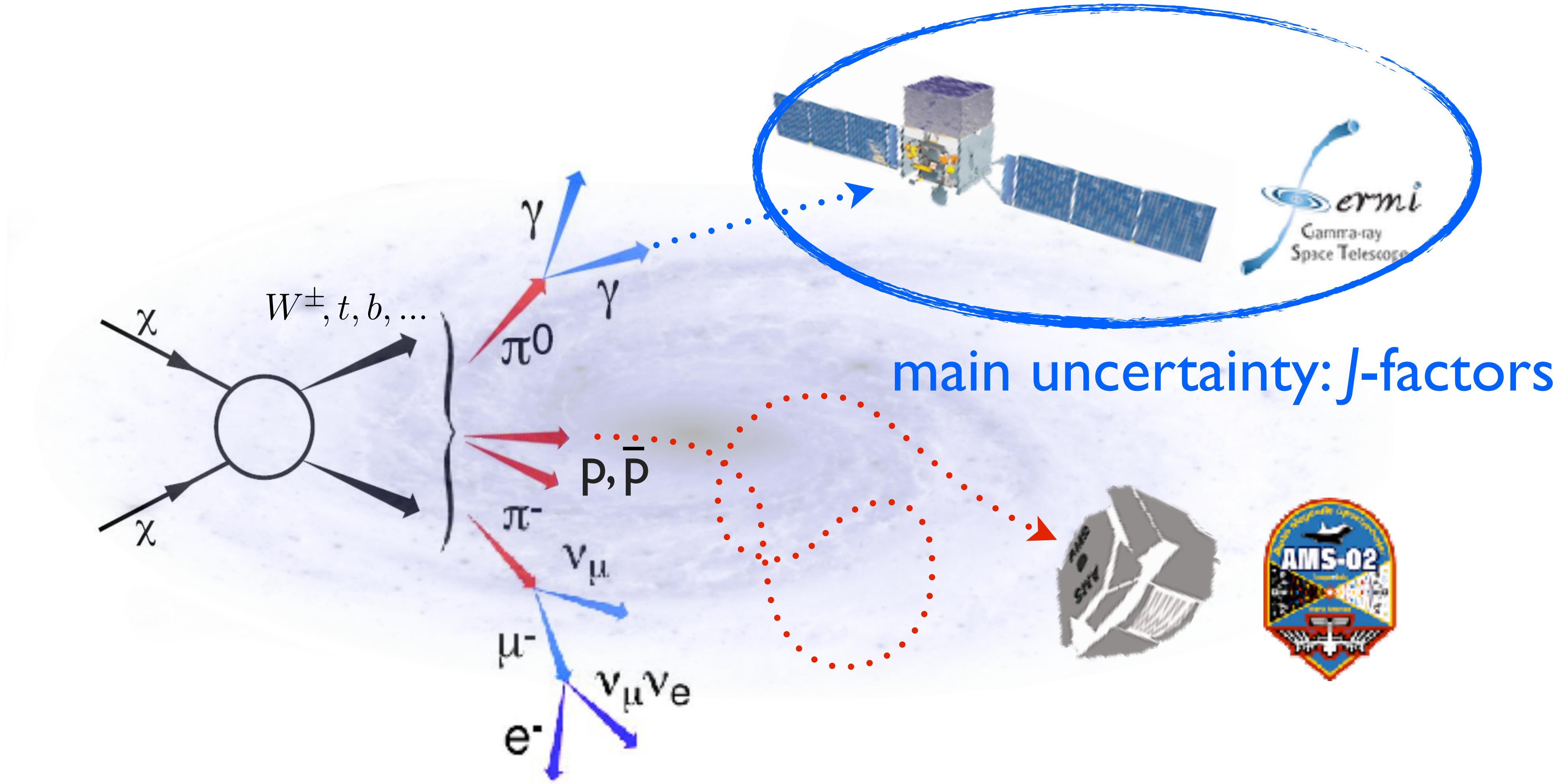
THE 14TH INTERNATIONAL WORKSHOP ON THE DARK SIDE OF THE UNIVERSE DSU 2018

Dark matter indirect detection:



- Dark matter searches joint effort
- Indirect detection probes annihilation
- AMS-02: cosmic-ray precision era

Dark matter indirect detection:



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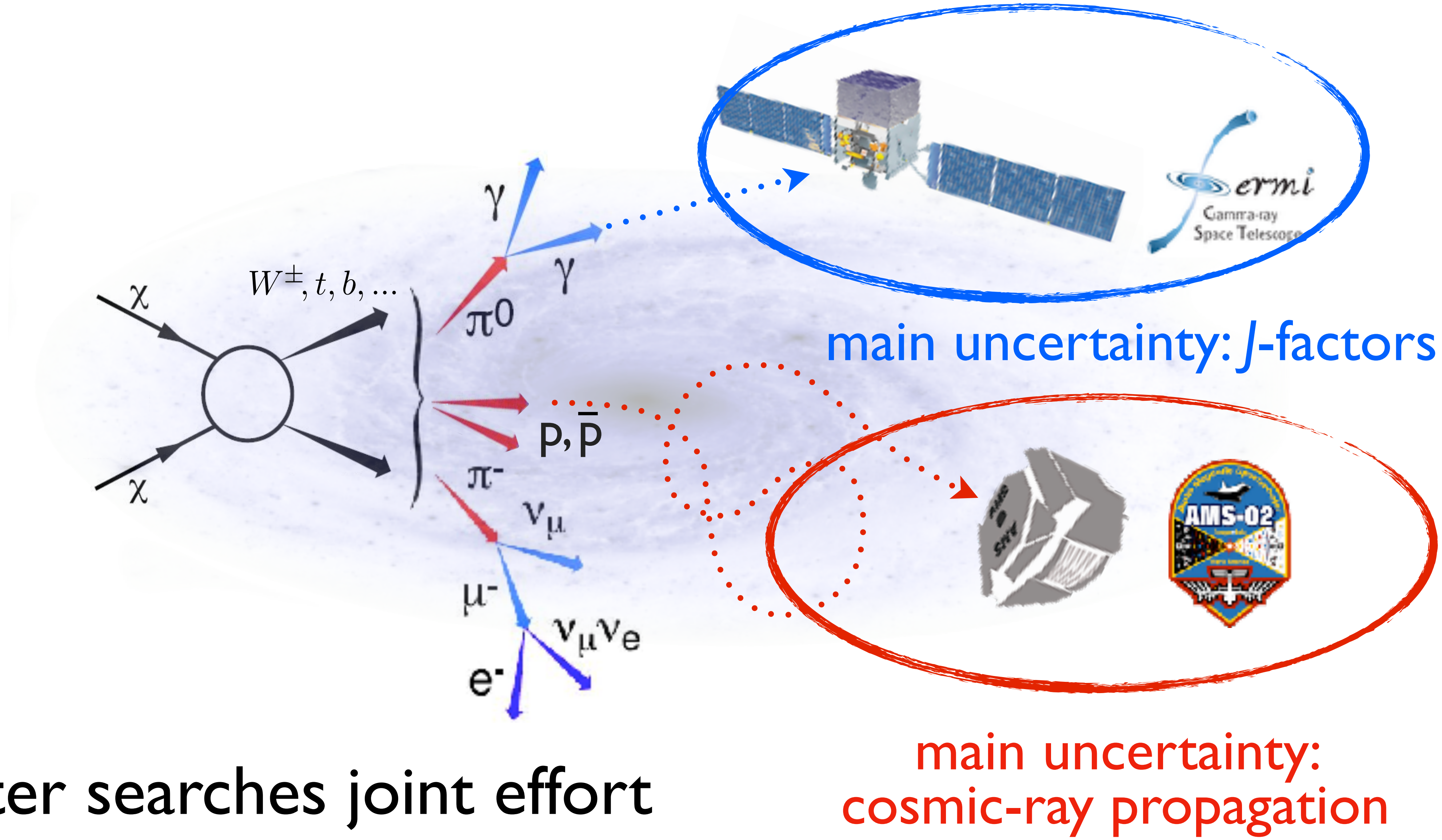
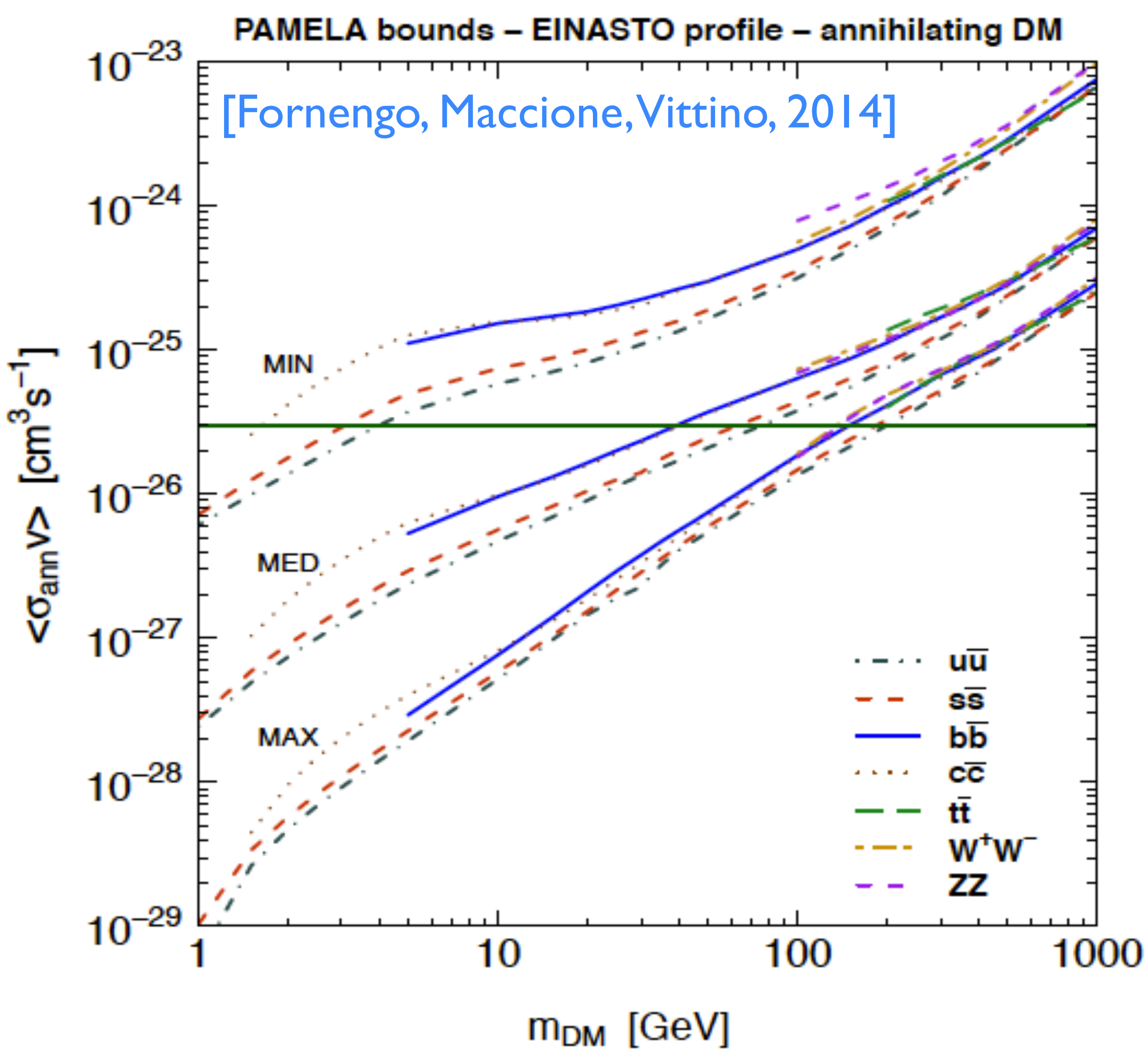


- Dark matter searches joint effort
- Indirect detection probes annihilation
- AMS-02: cosmic-ray precision era

Searches for dark matter in cosmic-rays



[see e.g. L. Bergstrom, J. Edsjo, and P. Ullio, ApJ,526,215 (1999); F. Donato, N. Fornengo, D. Maurin, and P. Salati, PRD69, 063501 (2004); T. Bringmann and P. Salati, PRD75, 083006 (2007); F. Donato, D. Maurin, P. Brun, T. Delahaye, and P. Salati, PRL. 102, 071301 (2009); N. Fornengo, L. Maccione, and A. Vittino, JCAP1404,003; D. Hooper, T. Linden, and P. Mertsch, JCAP 1503, 021; V. Pettorino, G. Busoni, A. De Simone, E. Morgante, A. Riotto, and W. Xue, JCAP 1410, 078 (2014); M. Boudaud, M. Cirelli, G. Giesen, and P. Salati, JCAP1505, 013 (2015); J. A. R. Cembranos, V. Gammaldi, and A. L. Maroto, JCAP 1503, 041 (2015); M. Cirelli, D. Gaggero, G. Giesen, M. Taoso, and A. Urbano, JCAP 1412, 045 (2014); T. Bringmann, M. Vollmann, and C. Weniger, Phys. Rev. D90, 123001 (2014); G. Giesen, M. Boudaud, Y. Genolini, V. Poulin, M. Cirelli, P. Salati, and P. D. Serpico, JCAP 1509, 023 (2015); C. Evoli, D. Gaggero, and D. Grasso, JCAP 1512, 039]

- MIN/MED/MAX scenario: Large uncertainties

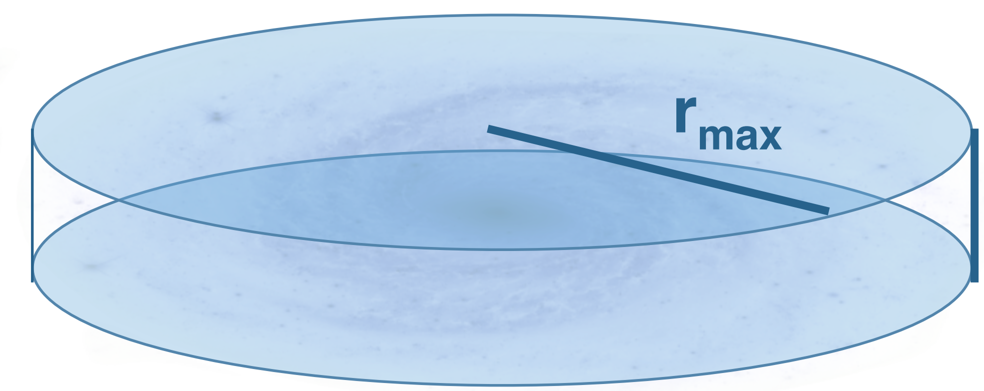
⇒ Joint fit of propagation parameters using precise AMS-02 data

Cosmic-ray propagation in the Galaxy

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

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

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



Figures: Credit to Michael Korsmeier

Fit parameters: z_h

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- Numerically solve diffusion equation:
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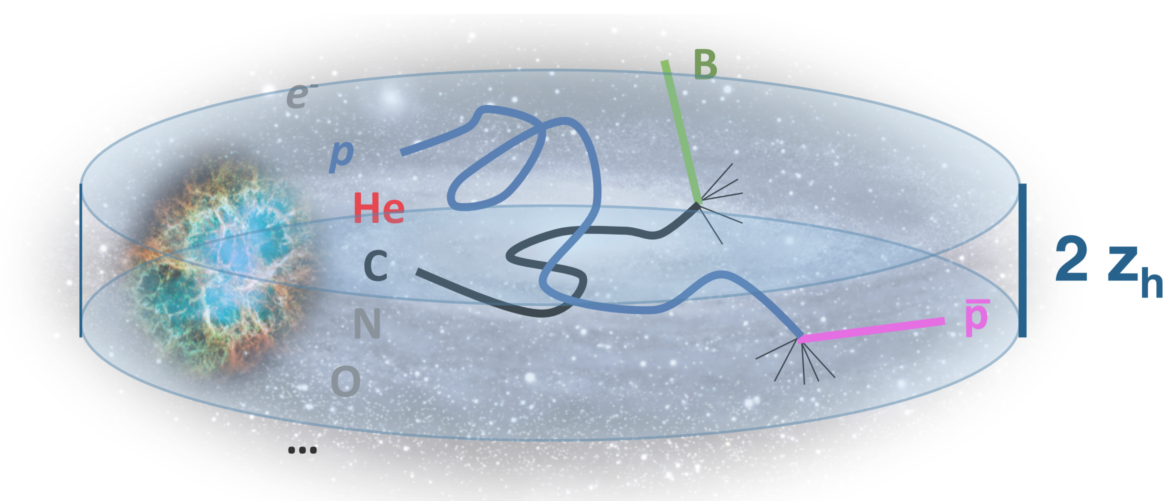
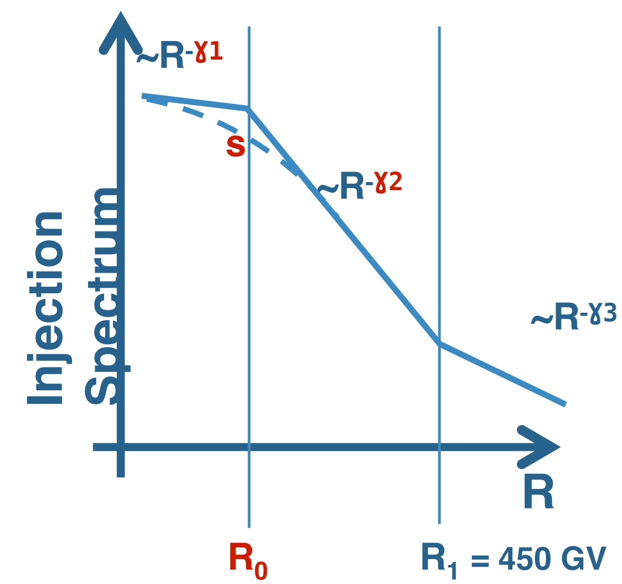
$$\frac{d\psi_i}{dt} = q_i(\boldsymbol{x},p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi_i - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi_i - \frac{\partial}{\partial p}\left(\frac{dp}{dt}\psi_i - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{V}\psi_i\right) - \frac{1}{\tau_f}\psi_i - \frac{1}{\tau_r}\psi_i$$



Source term - primaries:

- Astrophysical Sources:
  SNR or Pulsars
  ⇒ p, He, …

  Injection spectrum:



AMS-02 requires individual slopes for p, He!

Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\rm h}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s$

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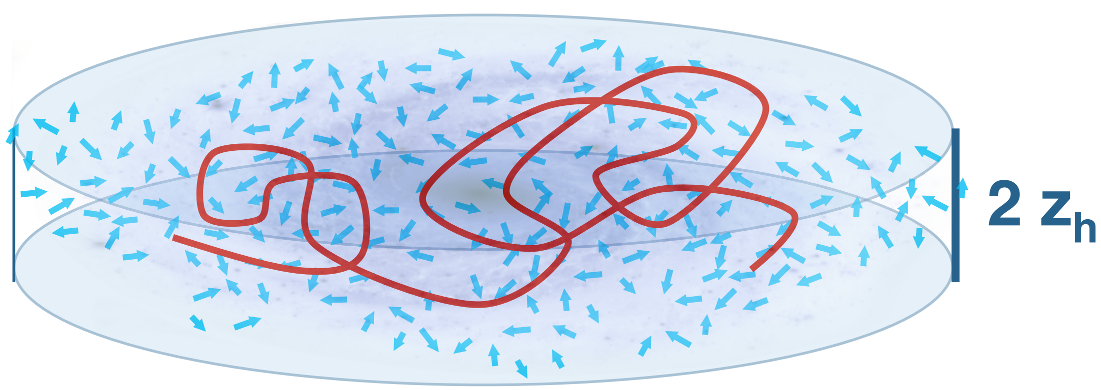
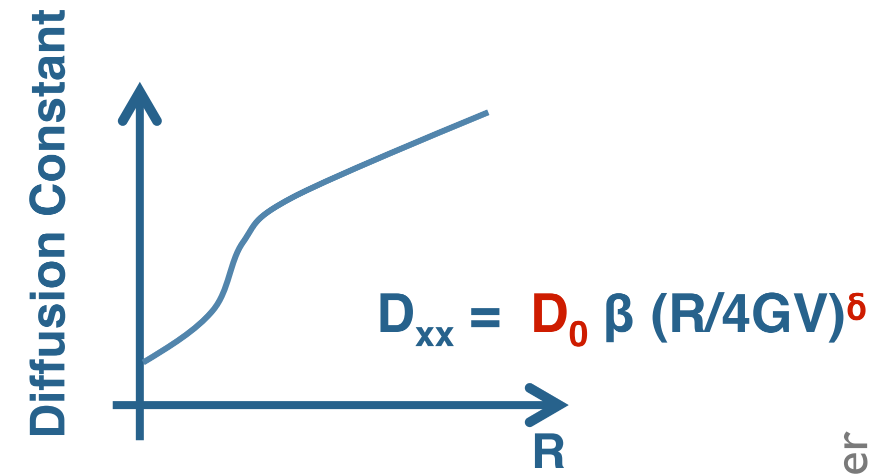


- Astrophysical Sources
- Diffusion



Figures: Credit to Michael Korsmeier

Fit parameters: $z_\mathrm{h}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta$

Cosmic-ray propagation in the Galaxy

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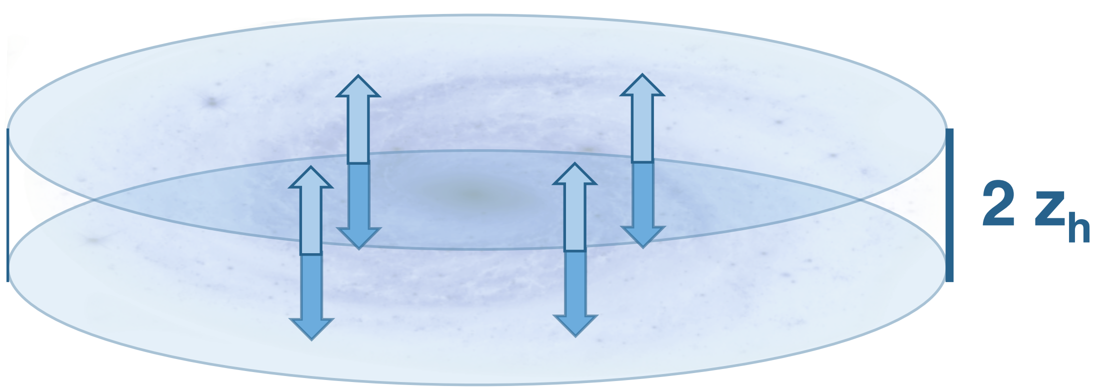
$$- \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi_i - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi_i \right) - \frac{1}{\tau_f} \psi_i - \frac{1}{\tau_r} \psi_i$$

- Astrophysical Sources
- Diffusion
- Convection

  Winds perpendicular to the galactic plane

  $\mathbf{V} = \mathbf{v_{0,c}}\, \mathrm{sign}(z)\, \mathbf{e_z}$



Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\mathrm{h}}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}$

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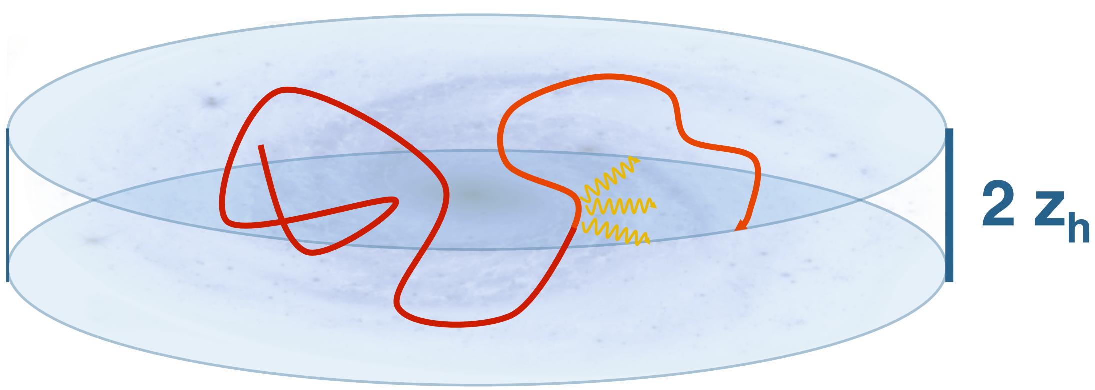
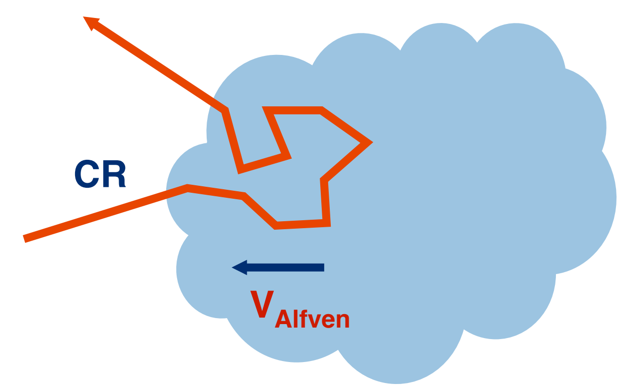


- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
  Scattering off magnetic clouds:



- Energy loss
  e.g. synchrotron radiation or ionization

Figures: Credit to Michael Korsmeier

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

Cosmic-ray propagation in the Galaxy

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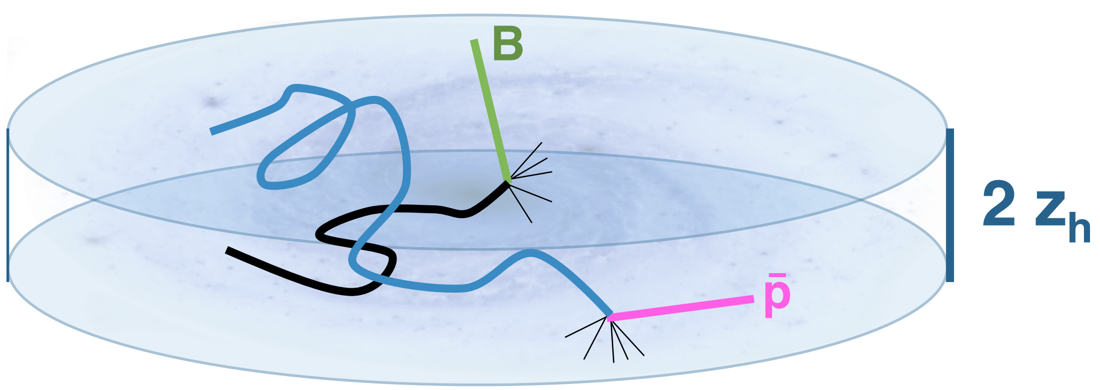

- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay

  Loss for one species is gain for the other

  Secondaries:
  $\bar{p}$, (Li, B, …)

Figures: Credit to Michael Korsmeier

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

Cosmic-ray propagation in the Galaxy

- Numerically solve diffusion equation:
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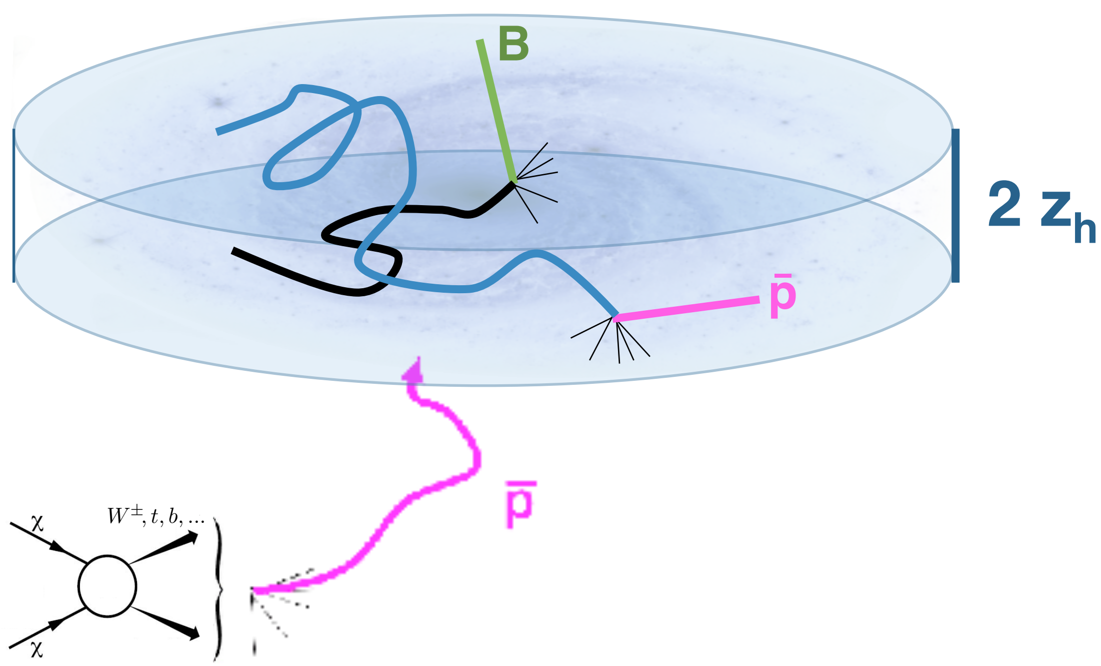
- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay
- Additional primary source for $\bar{p}$: Dark Matter!



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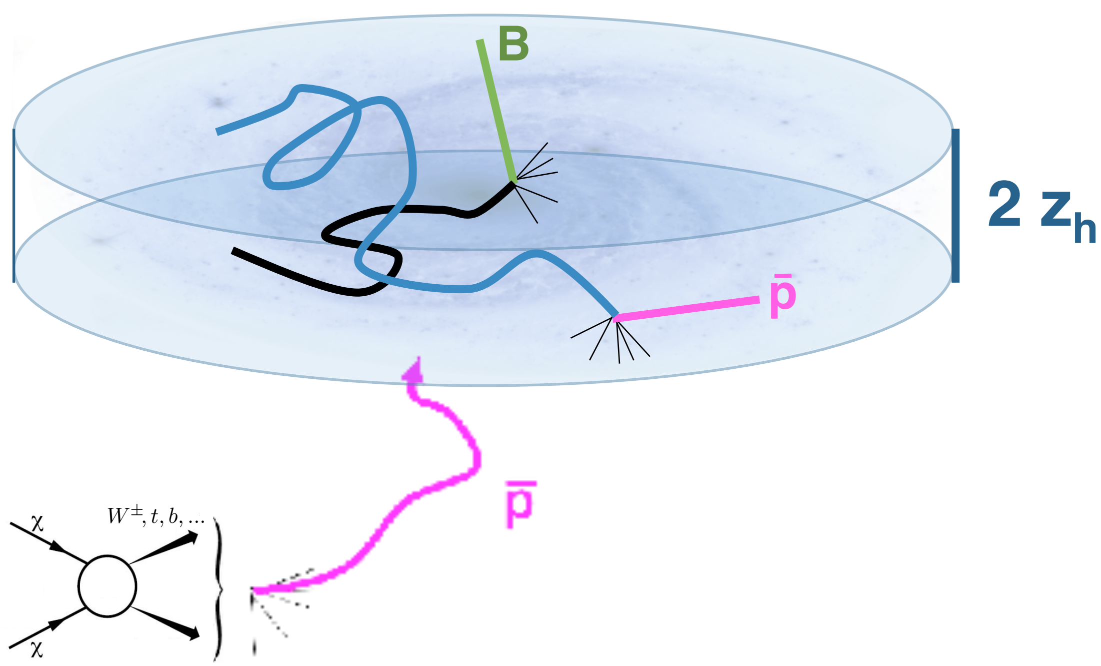


- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay
- Dark Matter
- Data:
  - AMS-02: *p*, He, $\bar{p}$
    [AMS 2015, 2016]
  - CREAM: *p*, He
    [Yoon *et al.* 2011]
  - VOYAGER: *p*, He
    [Stone *et al.* 2013]

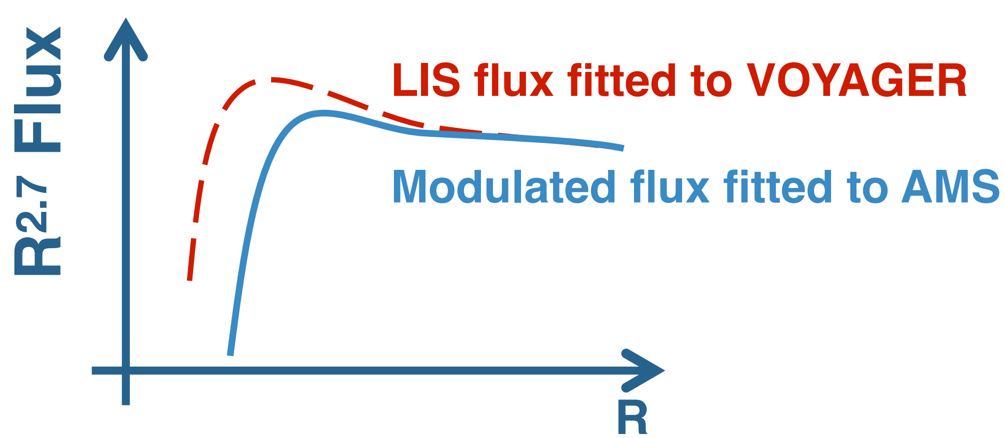
Figures: Credit to Michael Korsmeier

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

Cosmic-ray propagation in the Galaxy

Solar modulation:

- Phenomenological description: force-field approximation with ϕ_{AMS}
- Our approach:
  - Constrain local interstellar space (LIS) flux directly by VOYAGER data
  - Exclude data below 5 GV in the main fit
  - Marginalized over ϕ_{AMS} on-the-fly for each GALPROP evaluation



- Astrophysical Sources
- Diffusion
- Convection
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- Dark Matter
- Data:
  - AMS-02: p, He, $\bar{p}$ [AMS 2015, 2016]
  - CREAM: p, He [Yoon *et al.* 2011]
  - VOYAGER: p, He [Stone *et al.* 2013]

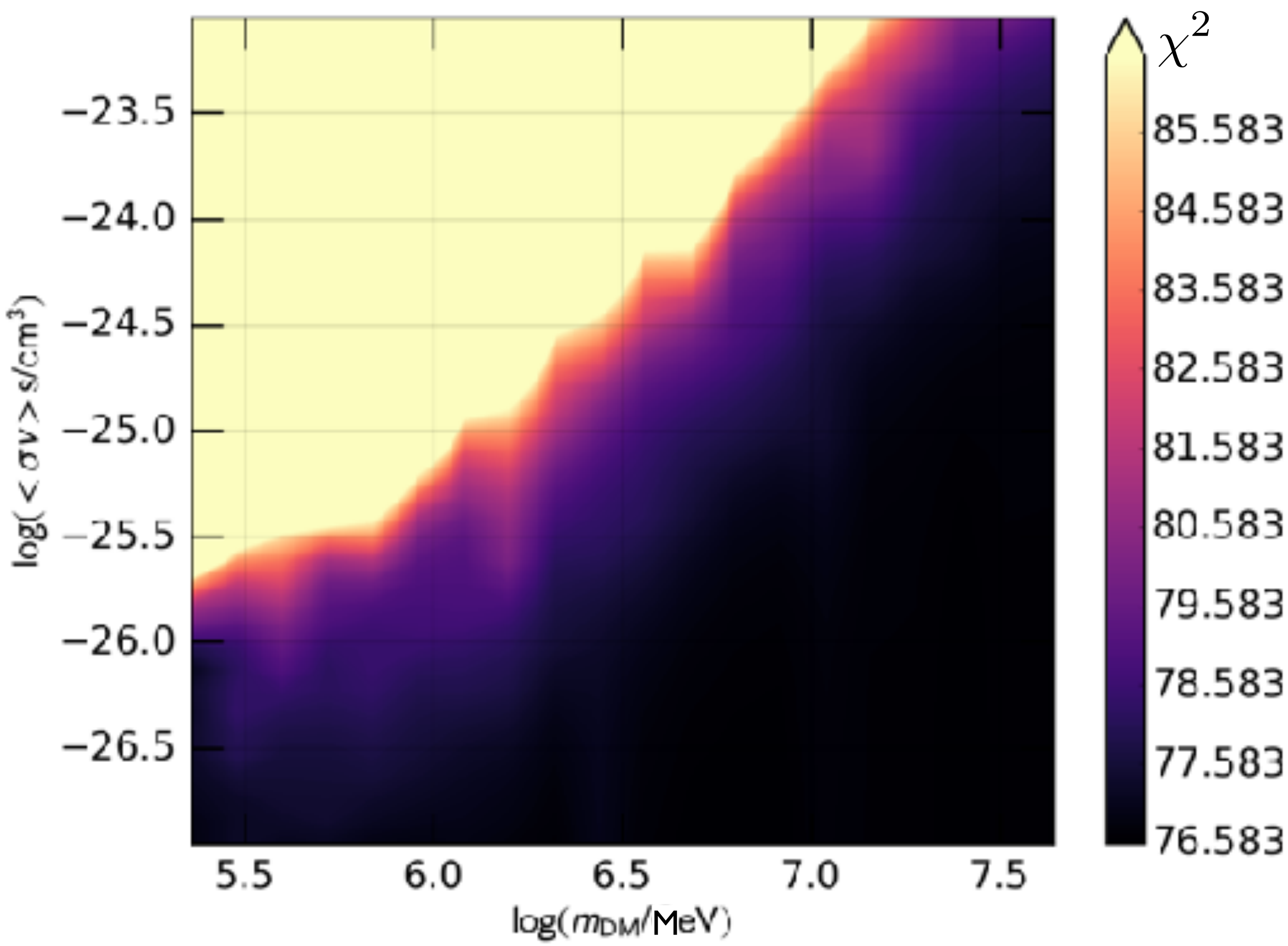
Figures: Credit to Michael Korsmeier

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

Limit setting

- Explore 13-dim. parameter space with MultiNest

Marginalized over all propagation (nuisance) parameters:



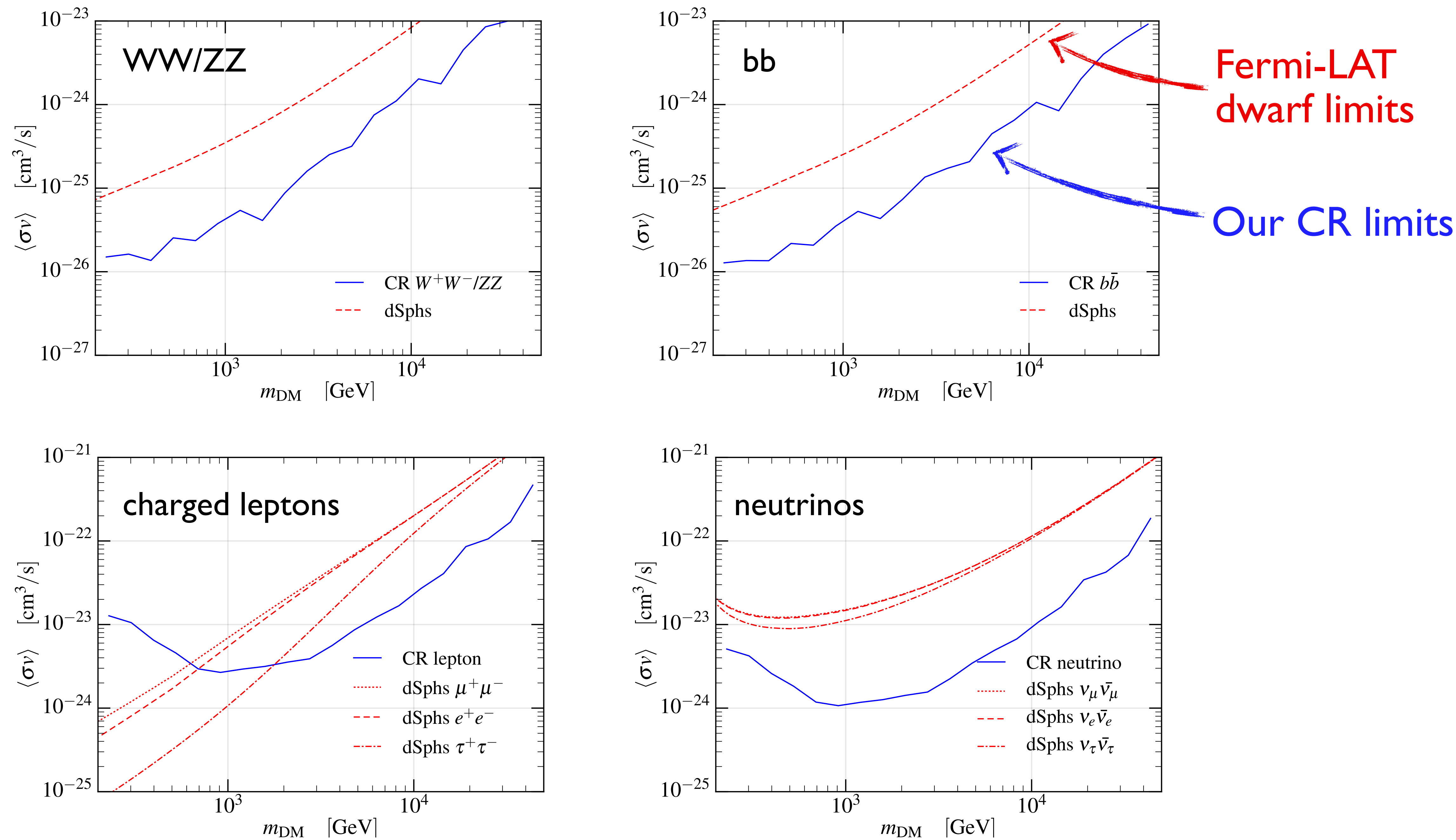
For a certain DM mass test-statistic:

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

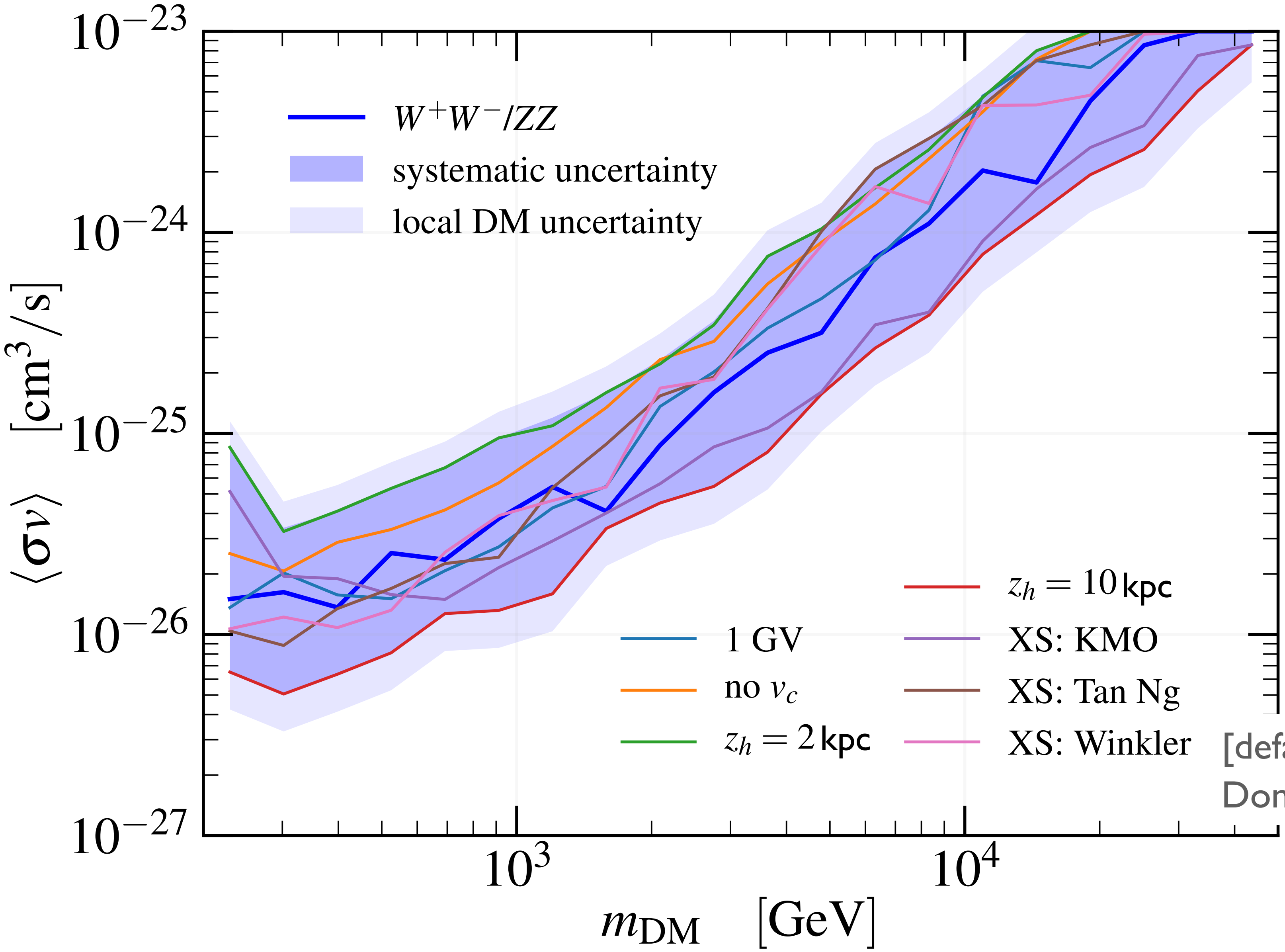
Best-fit value for considered mass (usually σv ~ 0)

⇒ Propagation uncertainties taken into account

Results for dark matter limits

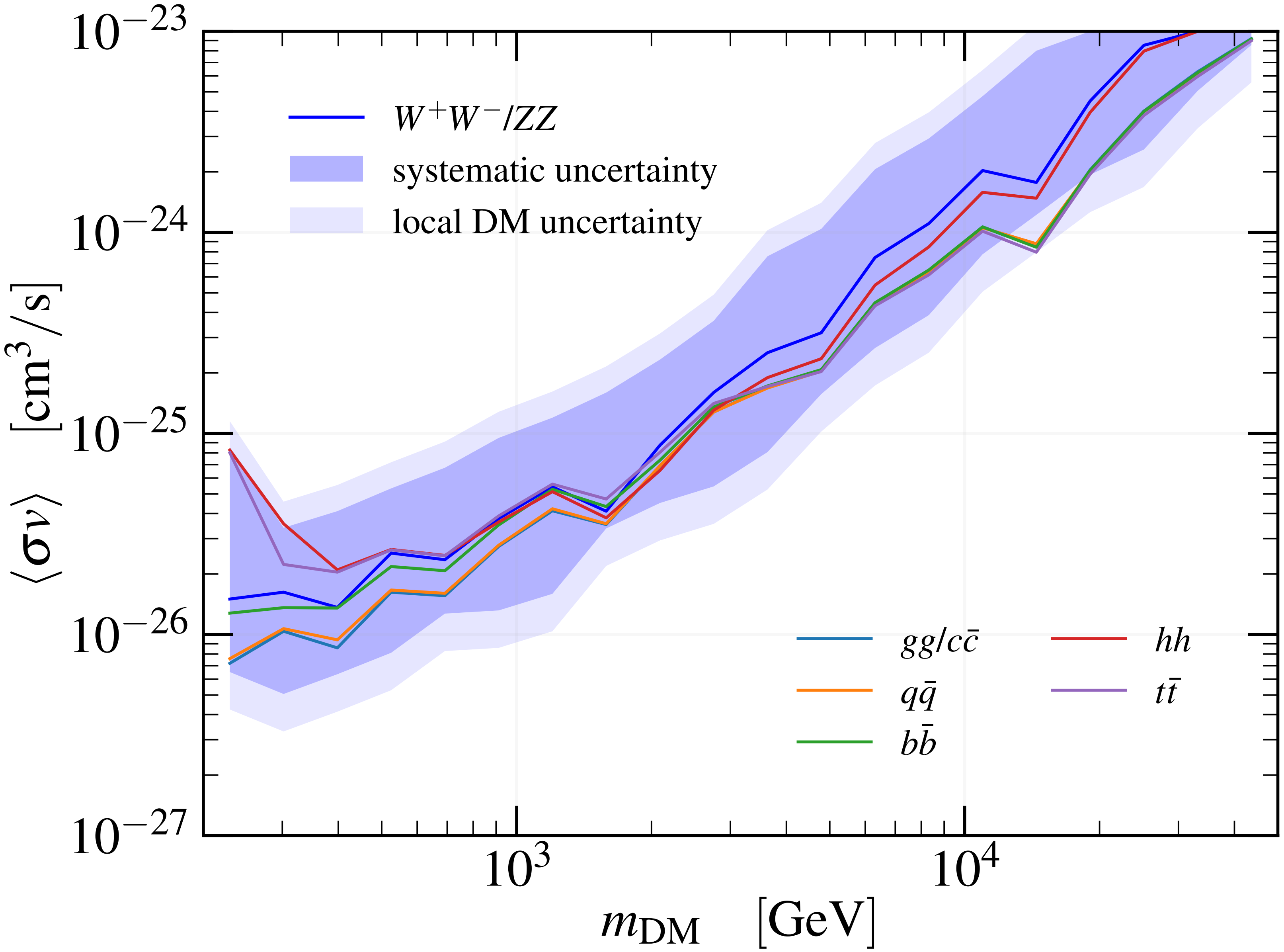


Systematic uncertainties



[default XS here: di Mauro, Donato, Goudelis, Serpico 2014]

Results for all non-leptonic SM channels



$\Rightarrow$ All non-leptonic channels very similar

Uncertainties from DM density profile

- Dark matter source term $\propto \rho^2$:

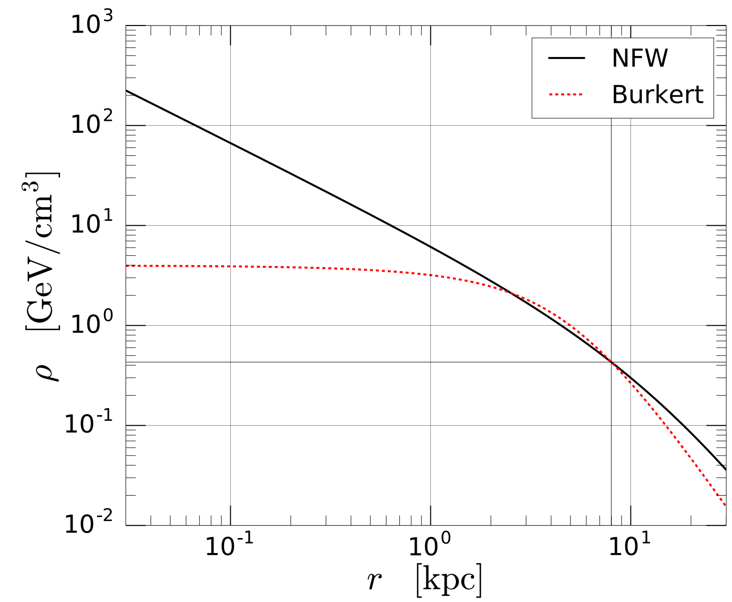
$$q_{\bar{p}}^{(\mathrm{DM})}(\boldsymbol{x}, E_{\mathrm{kin}}) = \frac{1}{2}\left(\frac{\rho(\boldsymbol{x})}{m_{\mathrm{DM}}}\right)^2 \sum_f \langle \sigma v \rangle_f \frac{\mathrm{d}N_{\bar{p}}^f}{\mathrm{d}E_{\mathrm{kin}}}$$

- Cuspy profile:

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_{\mathrm{h}}}{(r/r_{\mathrm{h}})(1+r/r_{\mathrm{h}})^2}$$

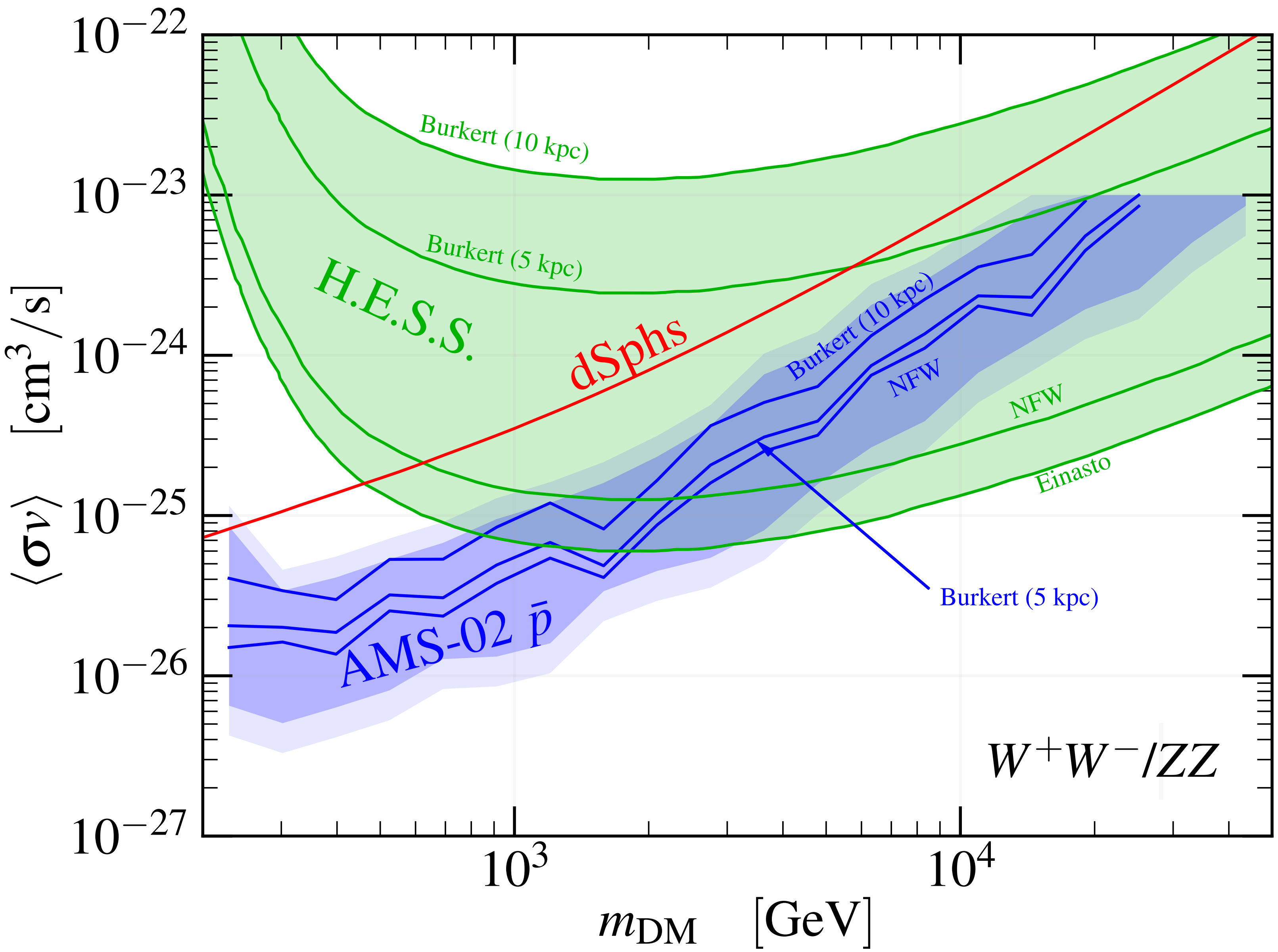
- Cored profile:

$$\rho_{\mathrm{Bur}}(r) = \frac{\rho_{\mathrm{c}}}{(1+r/r_{\mathrm{c}})(1+r^2/r_{\mathrm{c}}^2)}$$



[Korsmeier]

Uncertainties from DM density profile



Comparison:
HESS limits on *WW*
[HESS 1607.08142]

⇒ CRs observation much less sensitive to DM profile than GC gamma-rays

Interpretations within DM models

Interpretation within minimal dark matter

[Cirelli, Fornengo, Strumia hep-ph/0512090, see also 0706.4071, 1507.05519, ...]

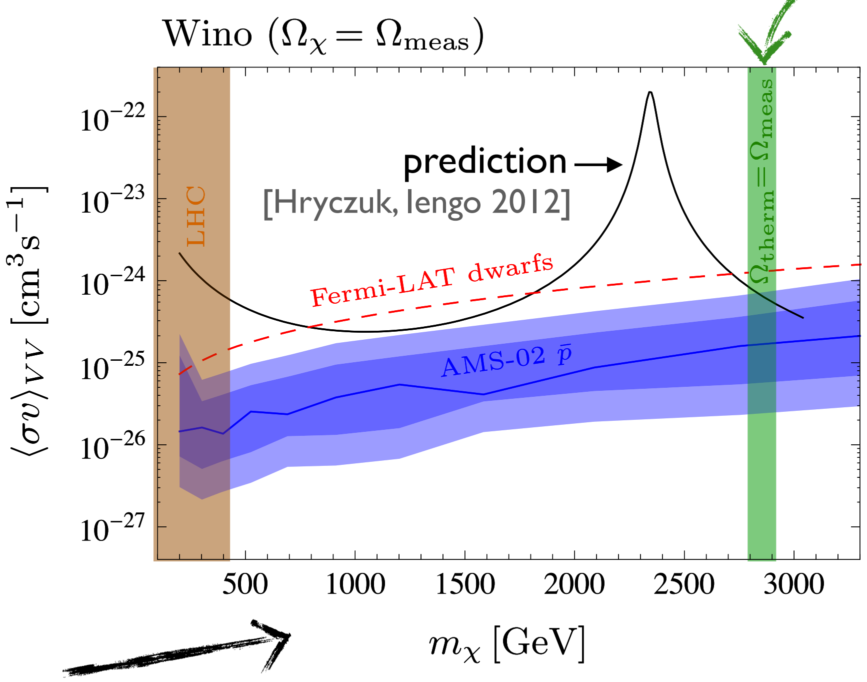
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}(i\not{D} + M)\chi$$

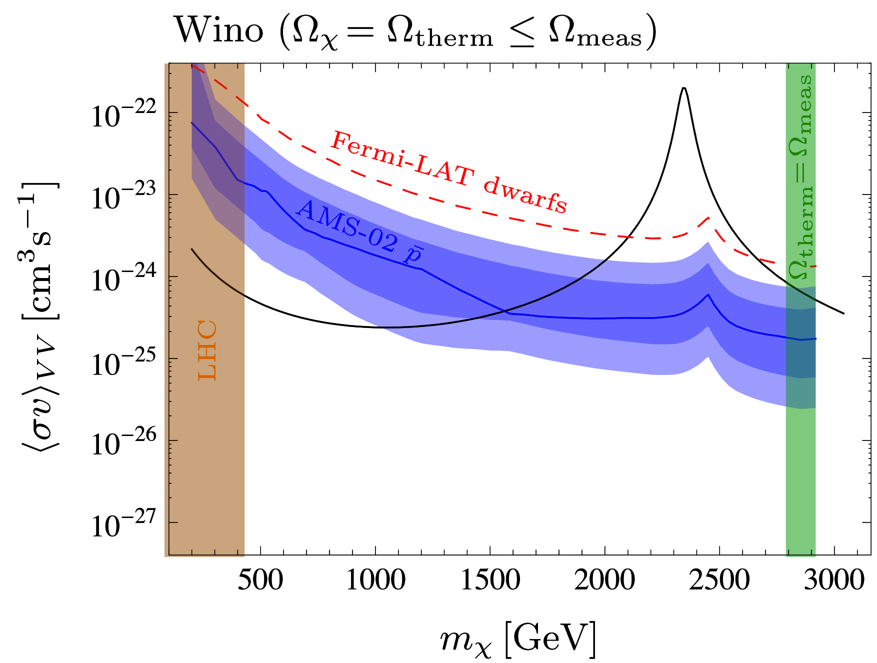
Quantum numbers $\mathrm{SU(2)_L}$	$\mathrm{U(1)}_Y$	Spin	DM can decay into	DM mass in TeV	$m_{\rm DM^\pm} - m_{\rm DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\mathrm{fb}$	$\sigma_{\rm SI}$ in $10^{-45}\,\mathrm{cm}^2$	
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2	
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2	Higgsino
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3	
3	0	1/2	LH	~ 2.8	166	$0.8 \div 4.0$	1.3	Wino
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7	
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7	
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6	
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6	
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5	
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5	
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12	
5	0	1/2	–	~ 9.4	166	$\ll 1$	12	Quintuplet
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46	

no Z_2 symmetry needed for stabilization!

Constraints on minimal dark matter: wino

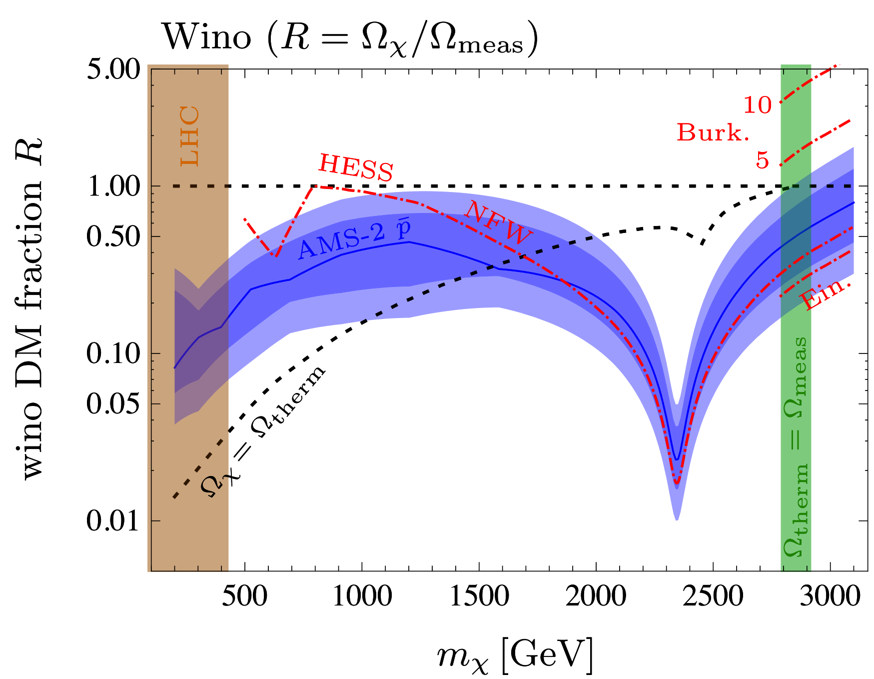
Thermal = all DM





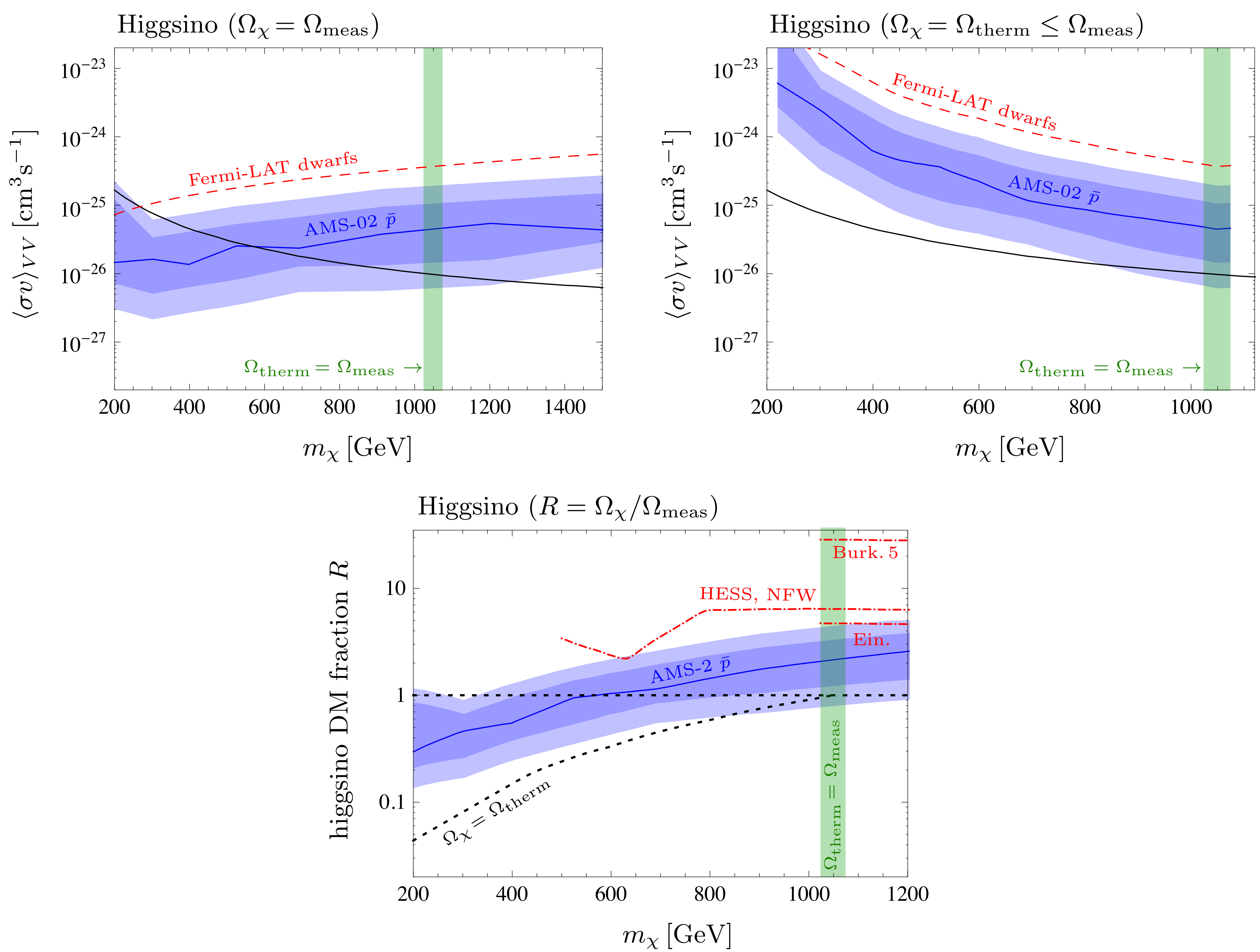
Upper cross section limits

Upper limits on wino DM fraction

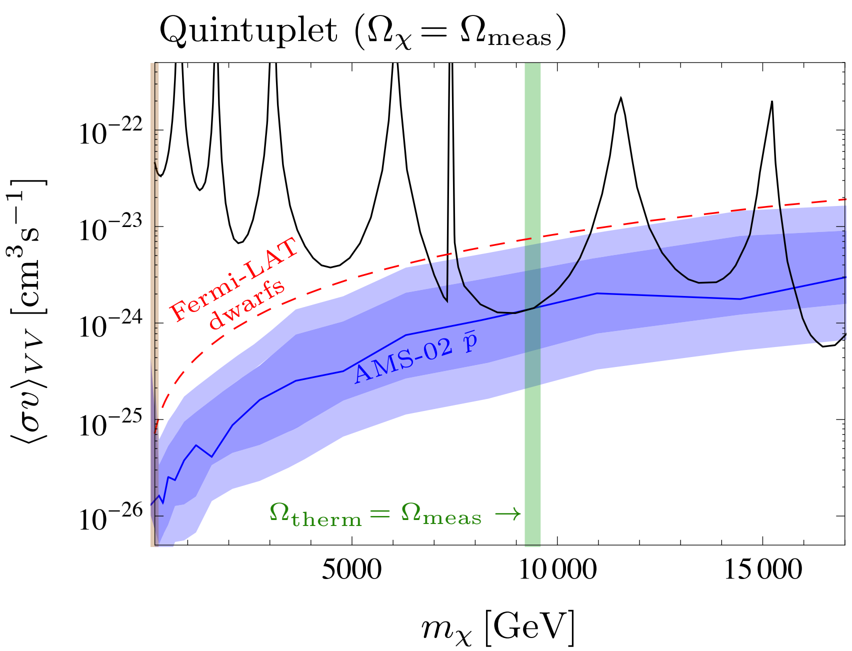


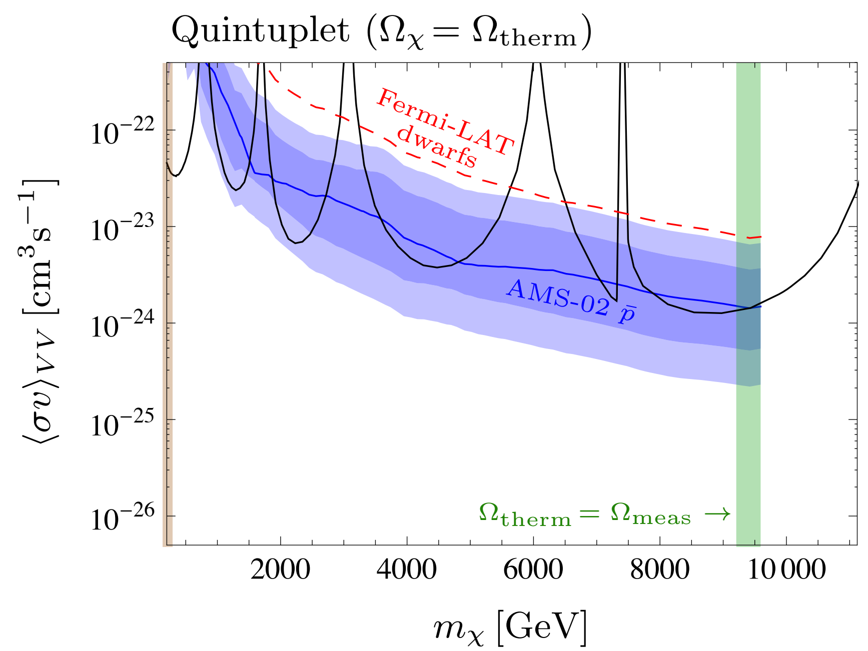
Searches for gamma-lines [HESS 1301.1173]

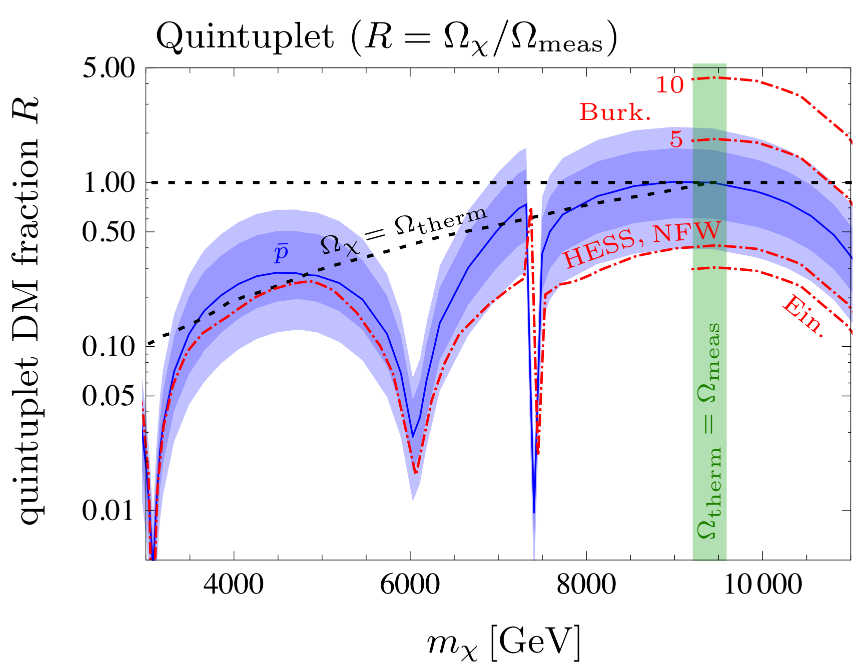
Constraints on minimal dark matter: higgsino



Constraints on minimal dark matter: quintuplet





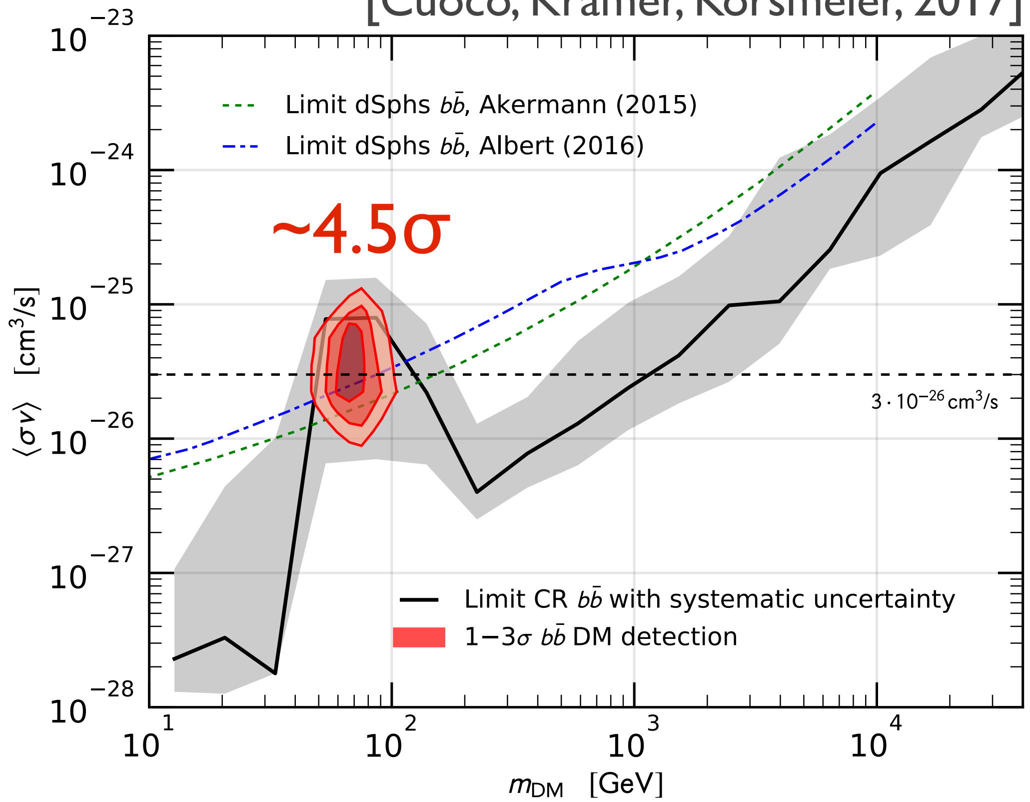


What about lighter dark matter?

- Constrain much weaker
- Possible signal around ~100GeV
- More difficult to establish DM signal than excluding DM

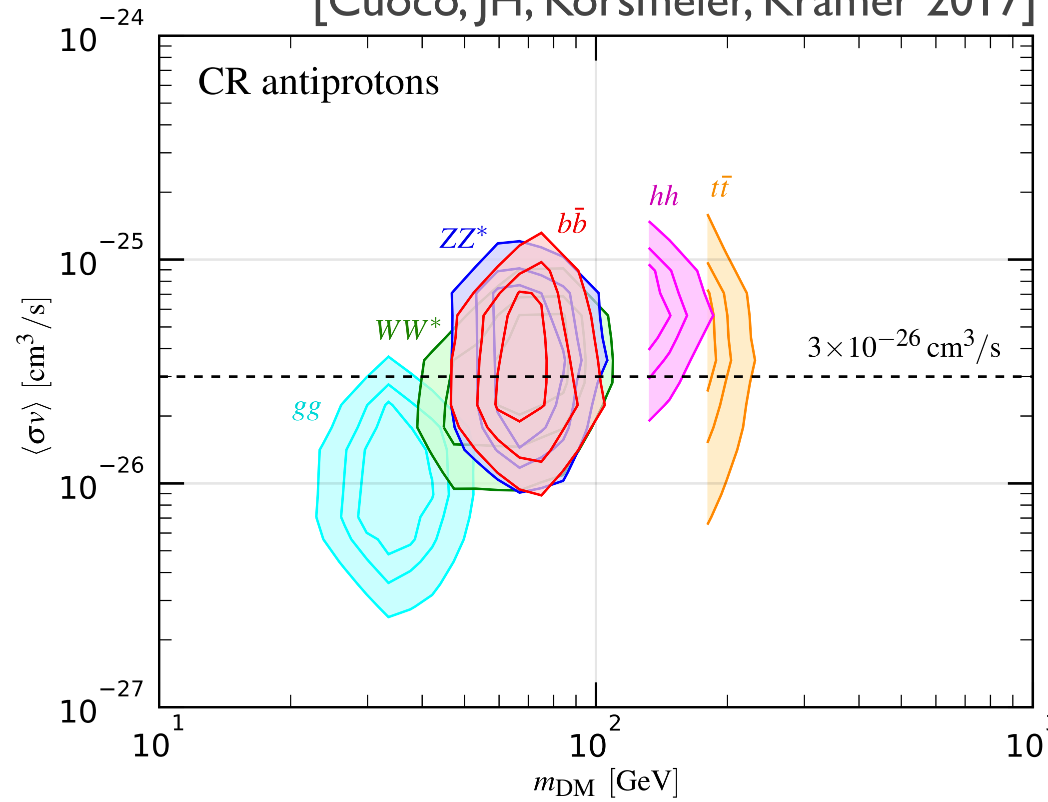
[Talk of Michael Korsmeier]

[Cuoco, Krämer, Korsmeier, 2017]



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

[Cuoco, JH, Korsmeier, Krämer 2017]



- Antiproton xs errors [see e.g. Winkler 2017; Korsmeier, Donato, Di Mauro 2018] [*cf.* Reinert, Winkler 2018]
- Solar modulation uncertainties
- Missing information on correlations in AMS-02 data

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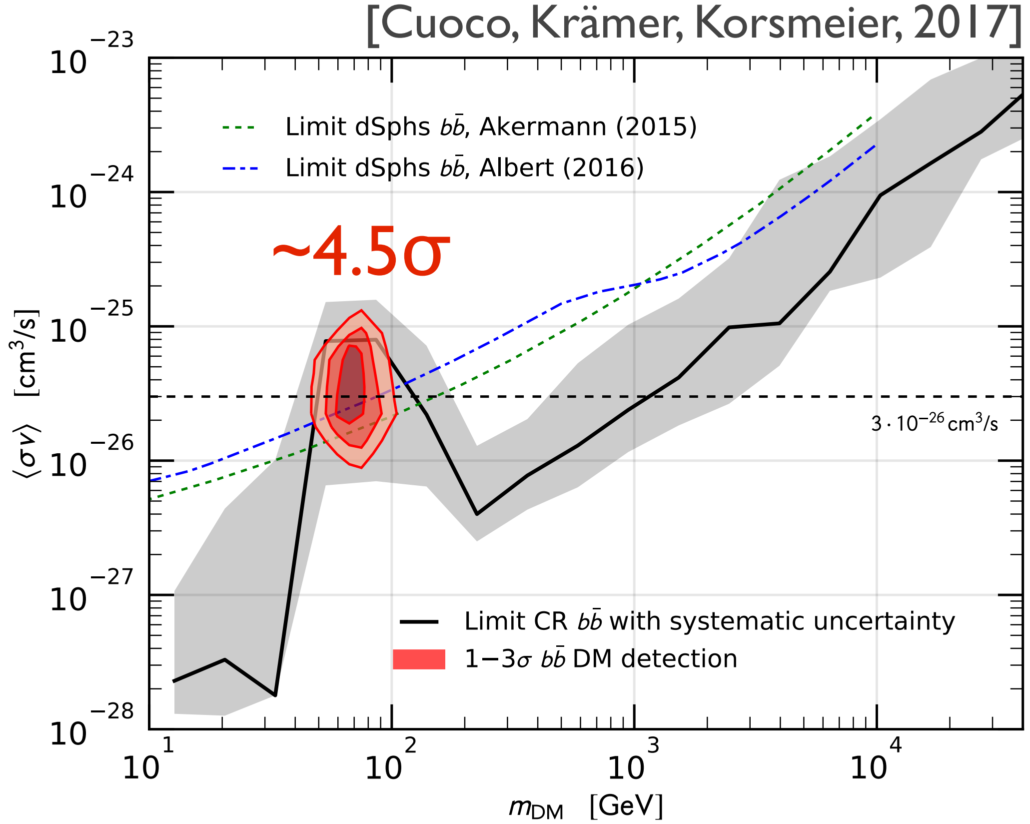
- Constrain much weaker
- Possible signal around ~100GeV
- More difficult to establish DM signal than excluding DM

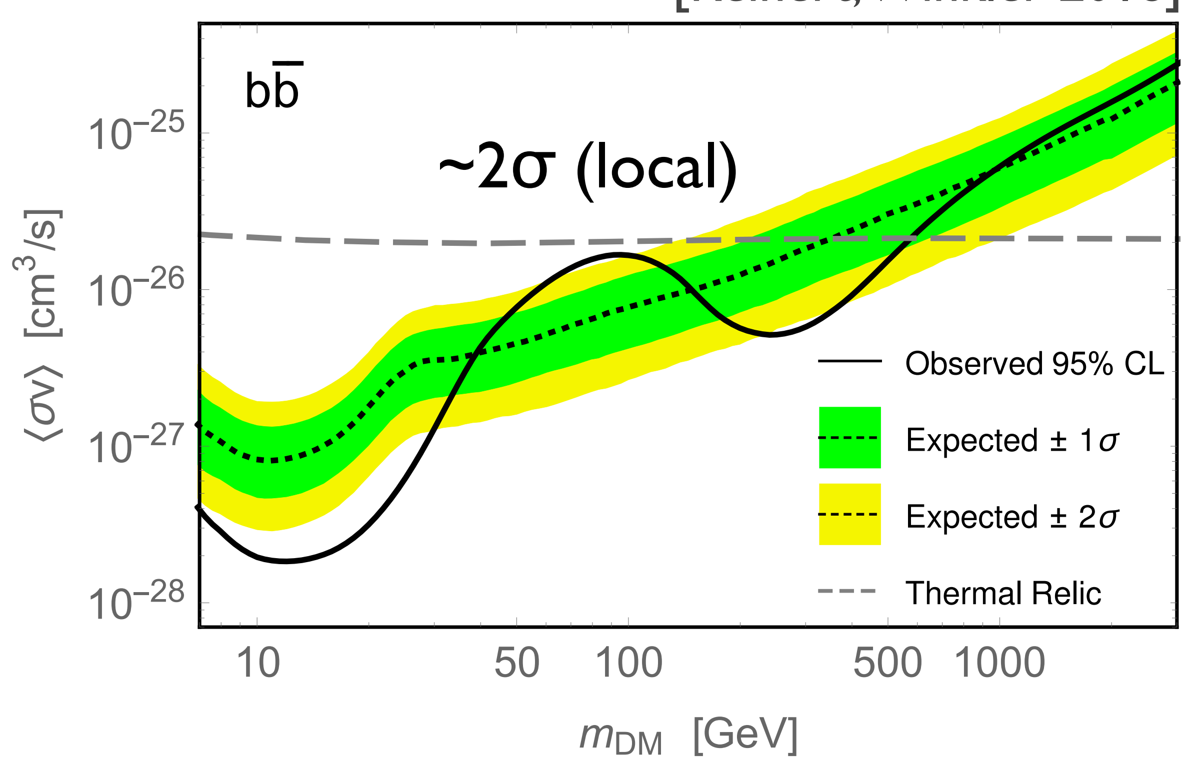
[Talk of Michael Korsmeier]

[Cuoco, Krämer, Korsmeier, 2017]



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

[Reinert, Winkler 2018]

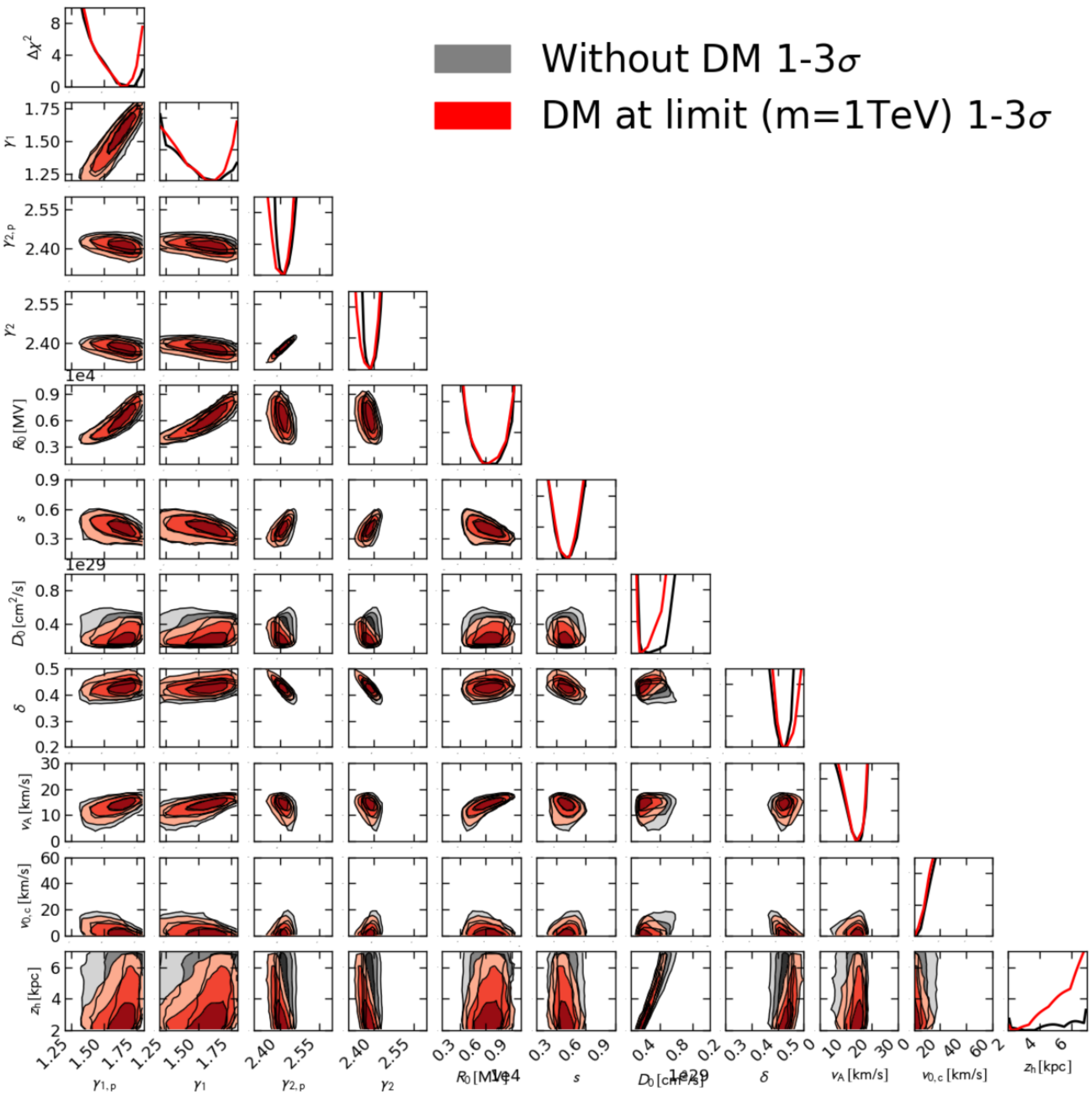


- Antiproton xs errors [see e.g. Winkler 2017; Korsmeier, Donato, Di Mauro 2018]
- Solar modulation uncertainties
- Missing information on correlations in AMS-02 data

Conclusions

- With AMS-02 cosmic-ray precision era started
- Reduce uncertainties w.r.t. MIN/MED/MAX scenario:
  $\Rightarrow$ Joint fit of propagation parameters and dark matter
- Strong limits on heavy dark matter
- Robust w.r.t. choice of DM profile
- Minimal DM: wino scenario strongly disfavored
- Possible hint for dark matter, future investigations:
  - Antiproton cross sections
  - Solar modulation
  - Correlations in AMS data

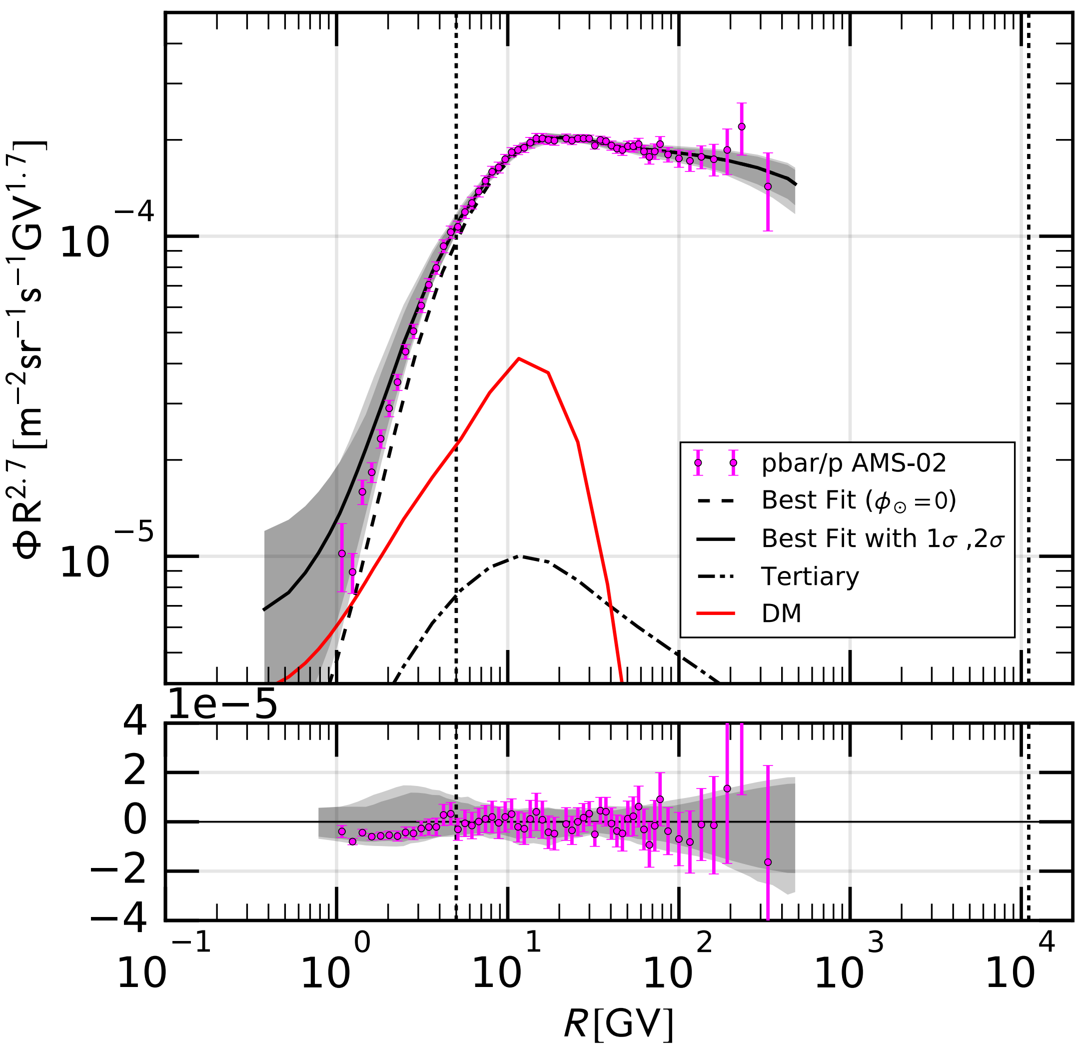
Backup



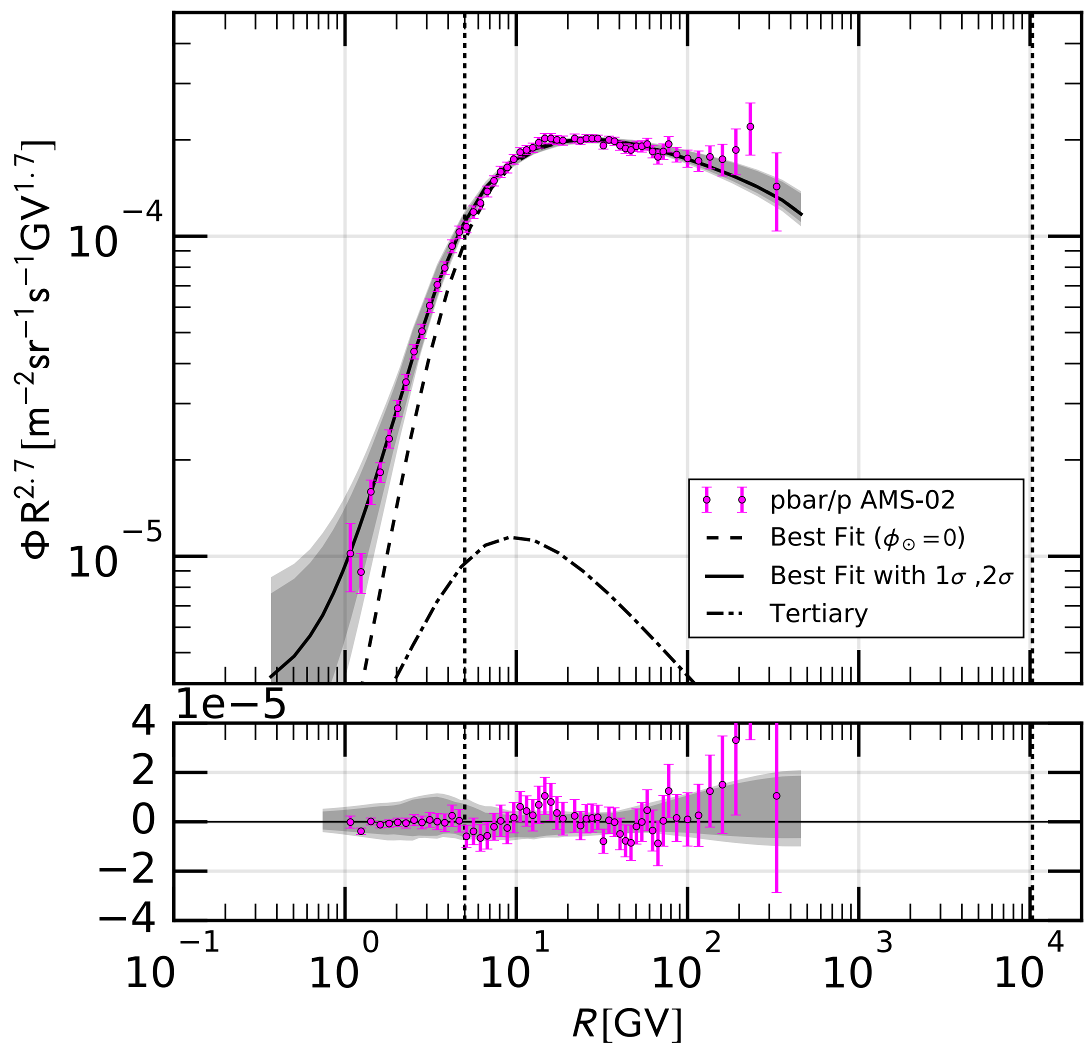
[Cuoco, JH, Klamt, Korsmeier, Krämer]

Cosmic-ray fit results

With dark matter (*bb*):



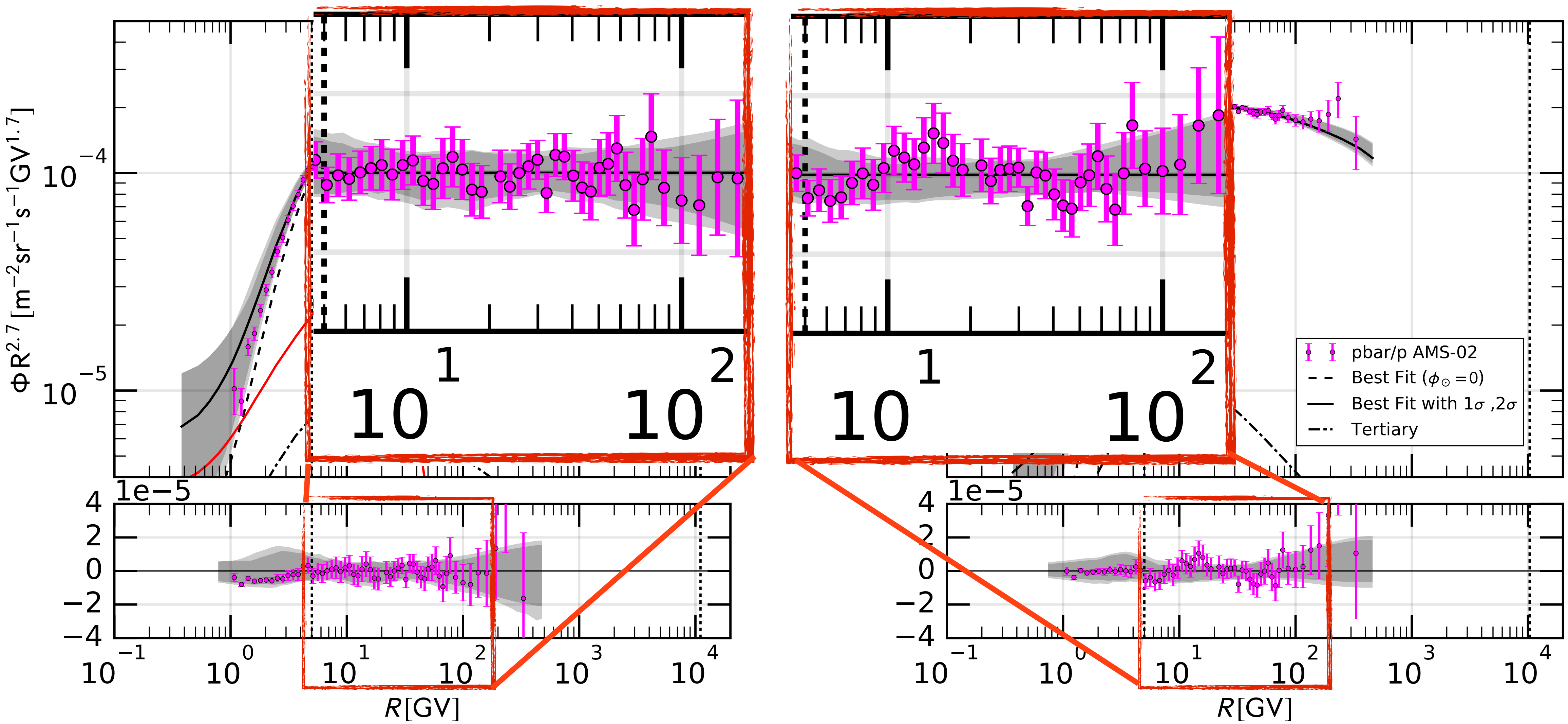
Without dark matter:



[Cuoco, Krämer, Korsmeier, 2017]

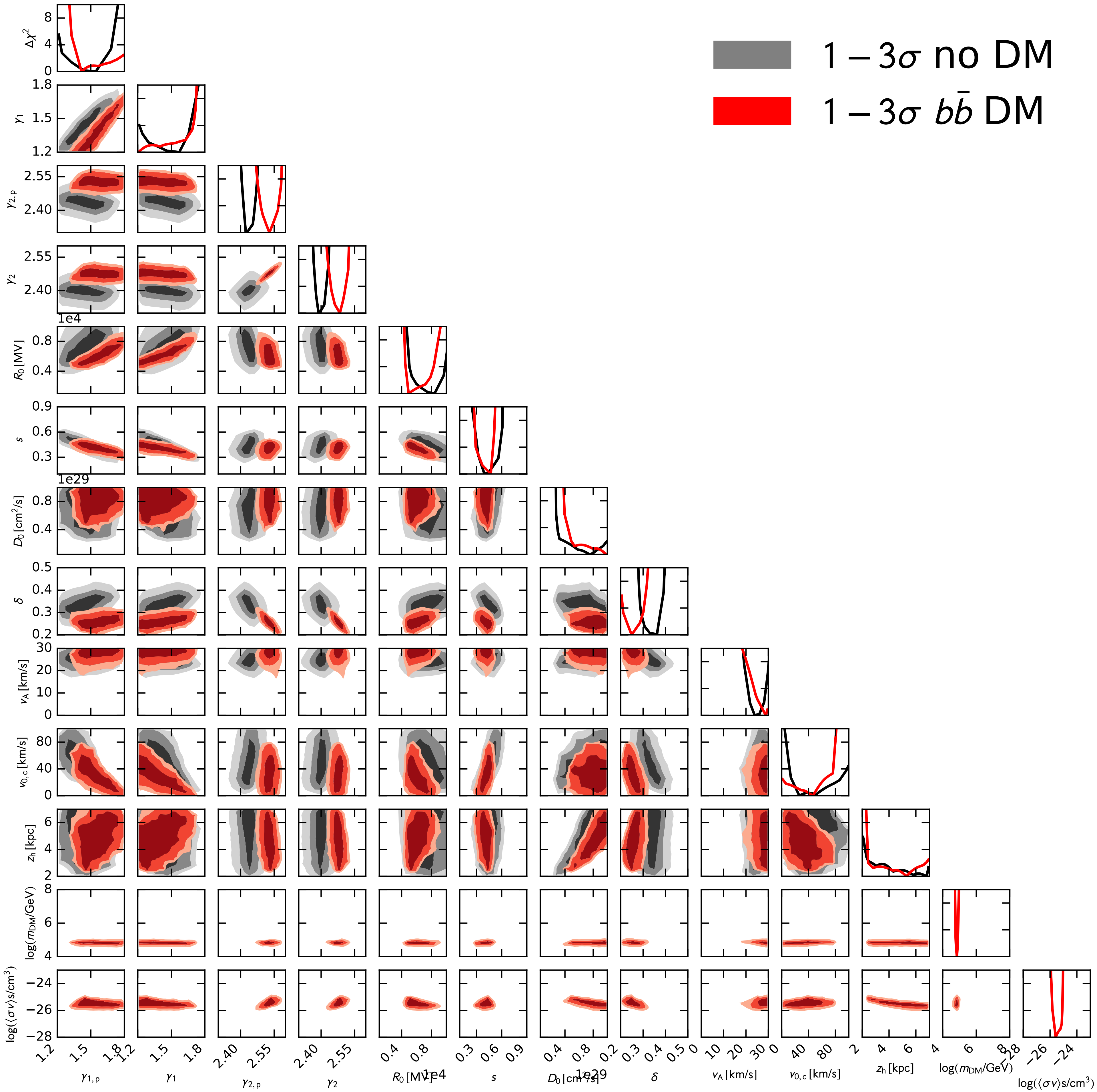
Cosmic-ray fit results

With dark matter (*bb*): Without dark matter:



[Cuoco, Krämer, Korsmeier, 2017]

Diffusion slope: $\delta \approx 0.25$ $\delta \approx 0.36$



[Cuoco, Krämer, Korsmeier, 2017]