Indirect Dark Matter Detection

Martin W. Winkler

DMI 2019

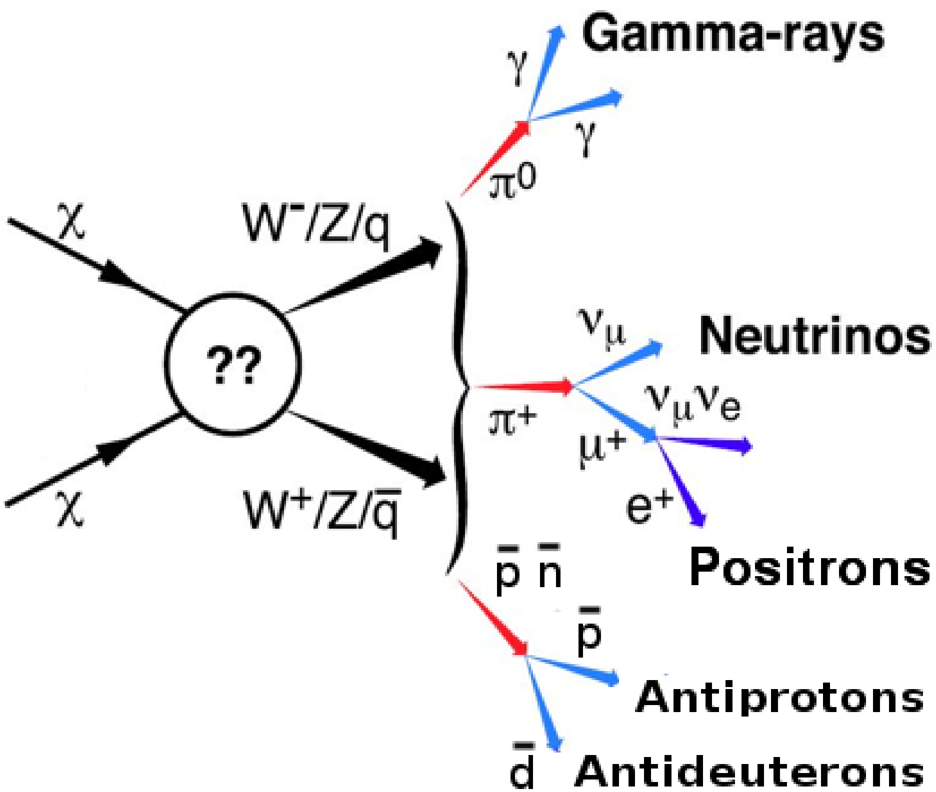
Mainz,

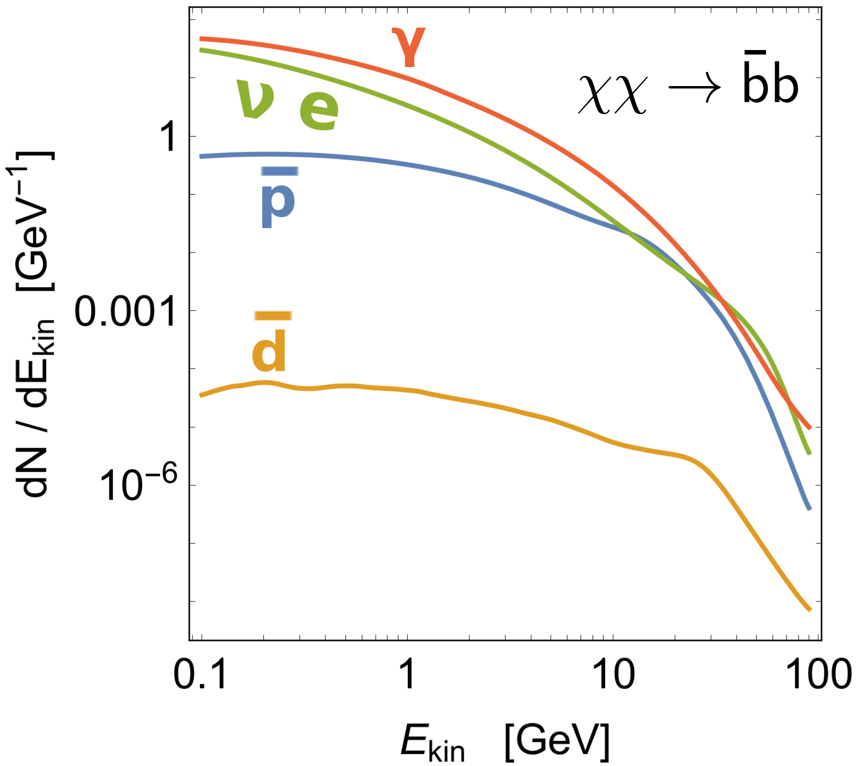
April 8, 2019

Outline

- WIMPs and beyond
- Gamma Rays
- (Neutrinos)
- Positrons
- Antiprotons

Indirect Dark Matter Detection





Emissivity $$\frac{d^3N_X}{dV\,dt\,dE} = \frac{\langle\sigma v\rangle \rho_{DM}{}^2}{2m_{DM}^2}\frac{dN}{dE}$$

annihilation cross section

dark matter density

particle spectrum

WIMPs

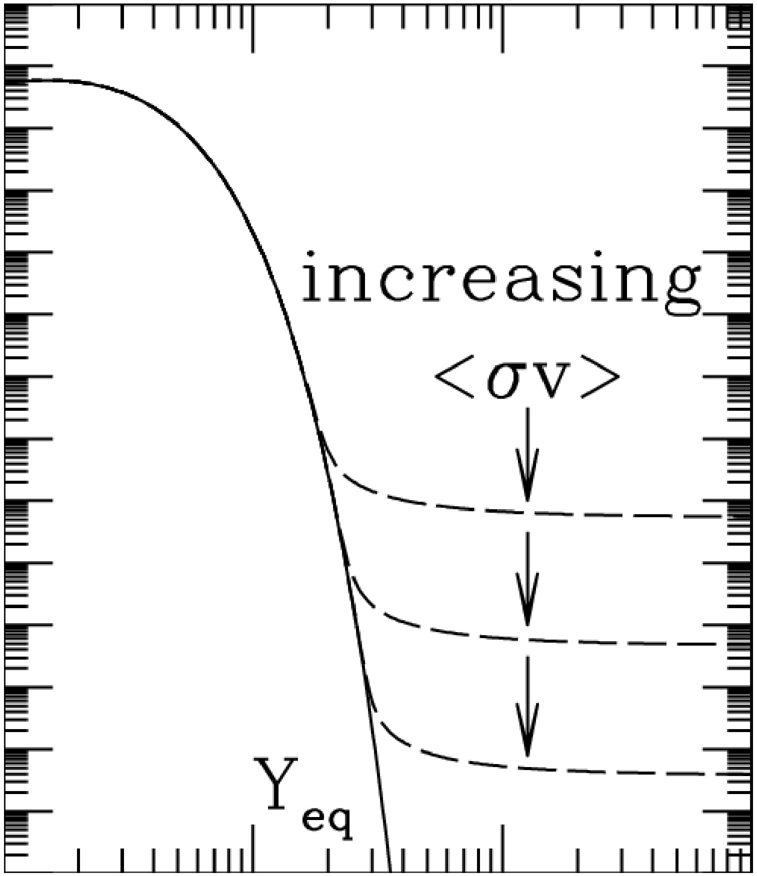
- in the early universe dark matter particles are in thermal equilibrium with the radiation bath

annihilation rate

$$n_\chi \langle \sigma v \rangle \propto \exp\left[-\frac{m_\chi}{T}\right]$$

expansion rate

$$H \propto T^2/M_P$$



- freeze-out for $n_\chi \langle \sigma v \rangle \simeq H$

$$\Omega_\chi \simeq \Omega_{DM} \frac{1\,\text{pb}}{\langle \sigma v \rangle}$$

Dicus et al., PRL 39 (1977), Lee, Weinberg, ibid., Hut, Phys.Lett. B69 (1977)

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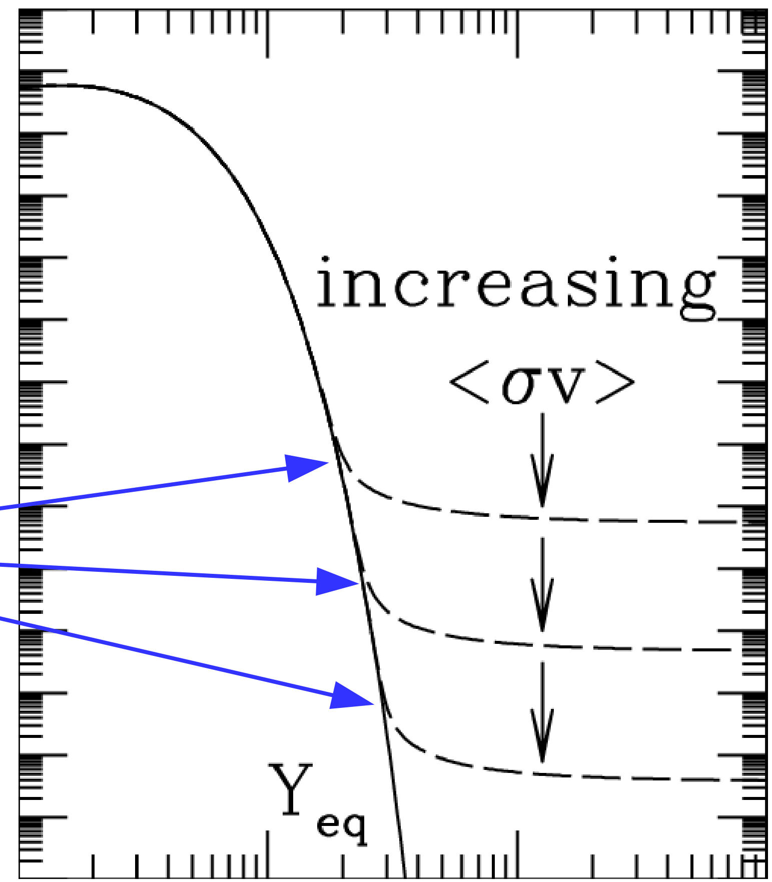

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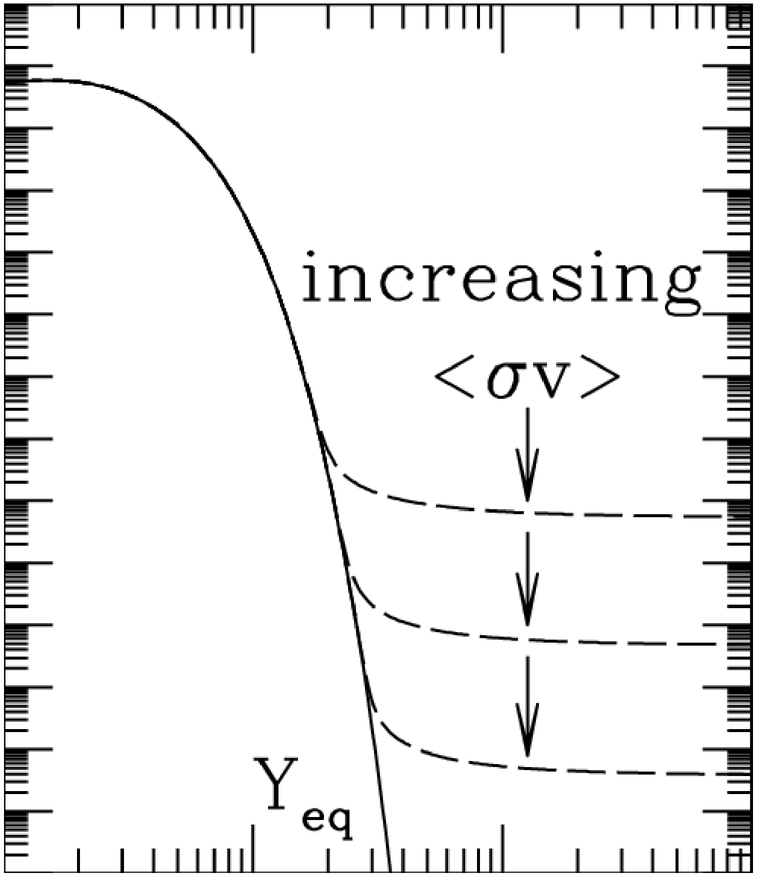
"WIMP miracle"

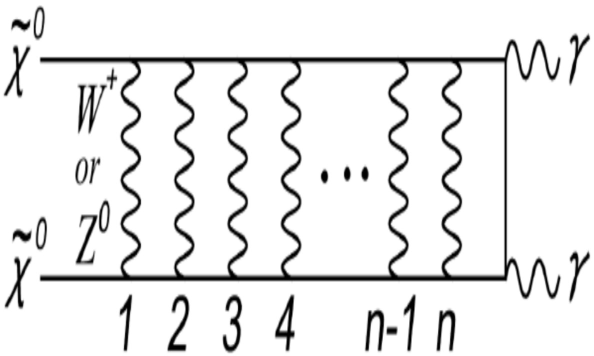


Dicus et al., PRL 39 (1977), Lee, Weinberg, ibid., Hut, Phys.Lett. B69 (1977)

Beyond Canonical WIMPs

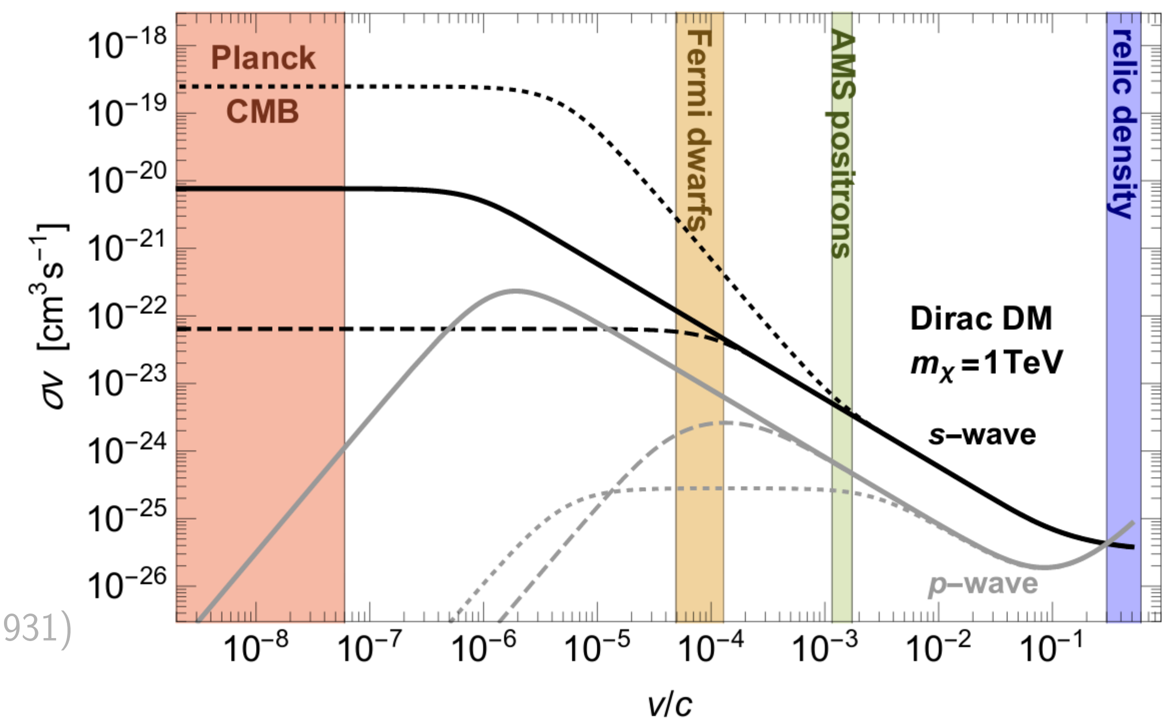
- p-wave annihilation $\sigma \text{v} = \cancel{\sigma_\text{s}} + \sigma_\text{p} \text{v}^2$ (CP)

- Sommerfeld enhancement



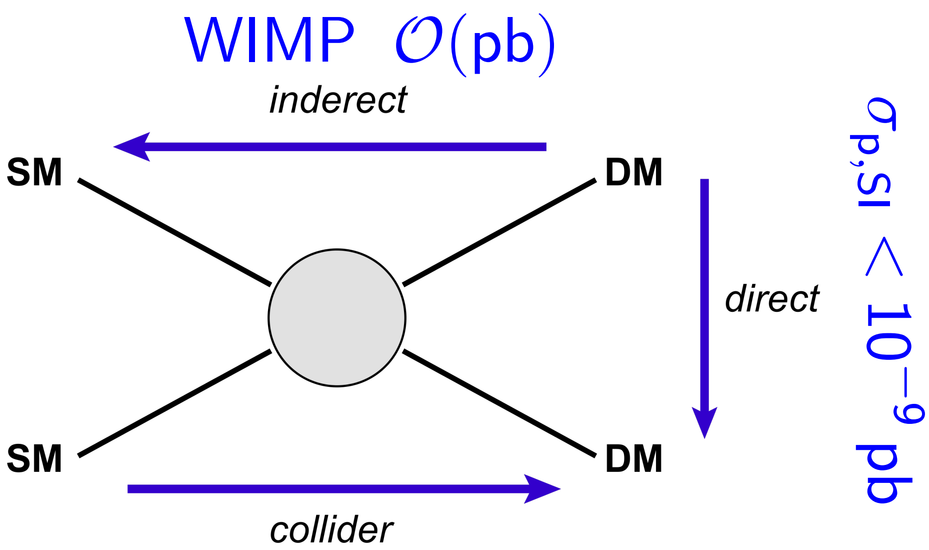
$$\sigma \text{v} \sim (\sigma \text{v})_0 \frac{\alpha \pi}{\text{v}}$$

Sommerfeld, Annalen der Physik 403 (1931)



from Bringmann et al., Phys. Rev. Lett. 118 (2017)

- resonance, non-thermal, asymmetric DM, freeze-in, decaying DM...

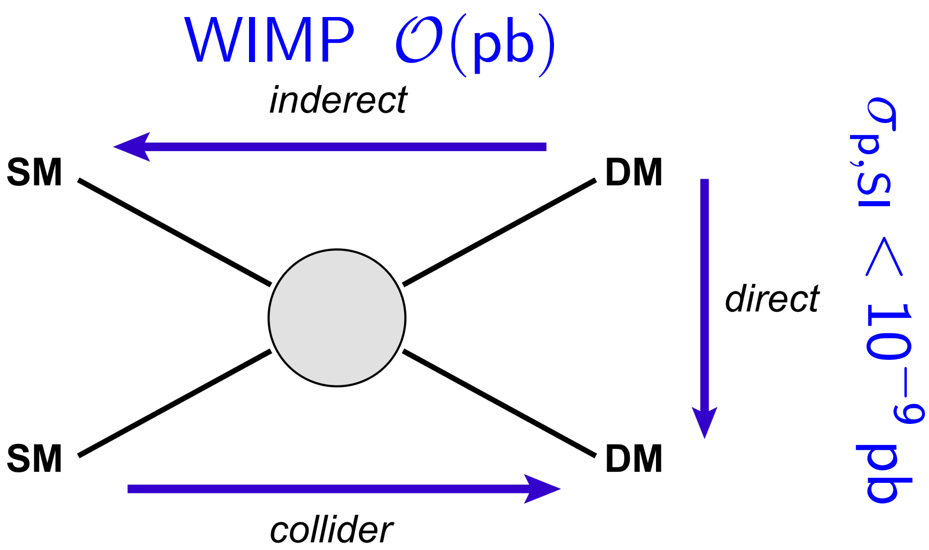


?

Name	Interaction Structure	σ_{SI} suppression	σ_{SD} suppression	s-wave?
F1	$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	q^2 (SM); q^2 (DM)	Yes
F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
F9	$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	1	Yes
F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes

Kumar, Marfatia, Phys. Rev. D88 (2013)

Direct vs. Indirect Detection



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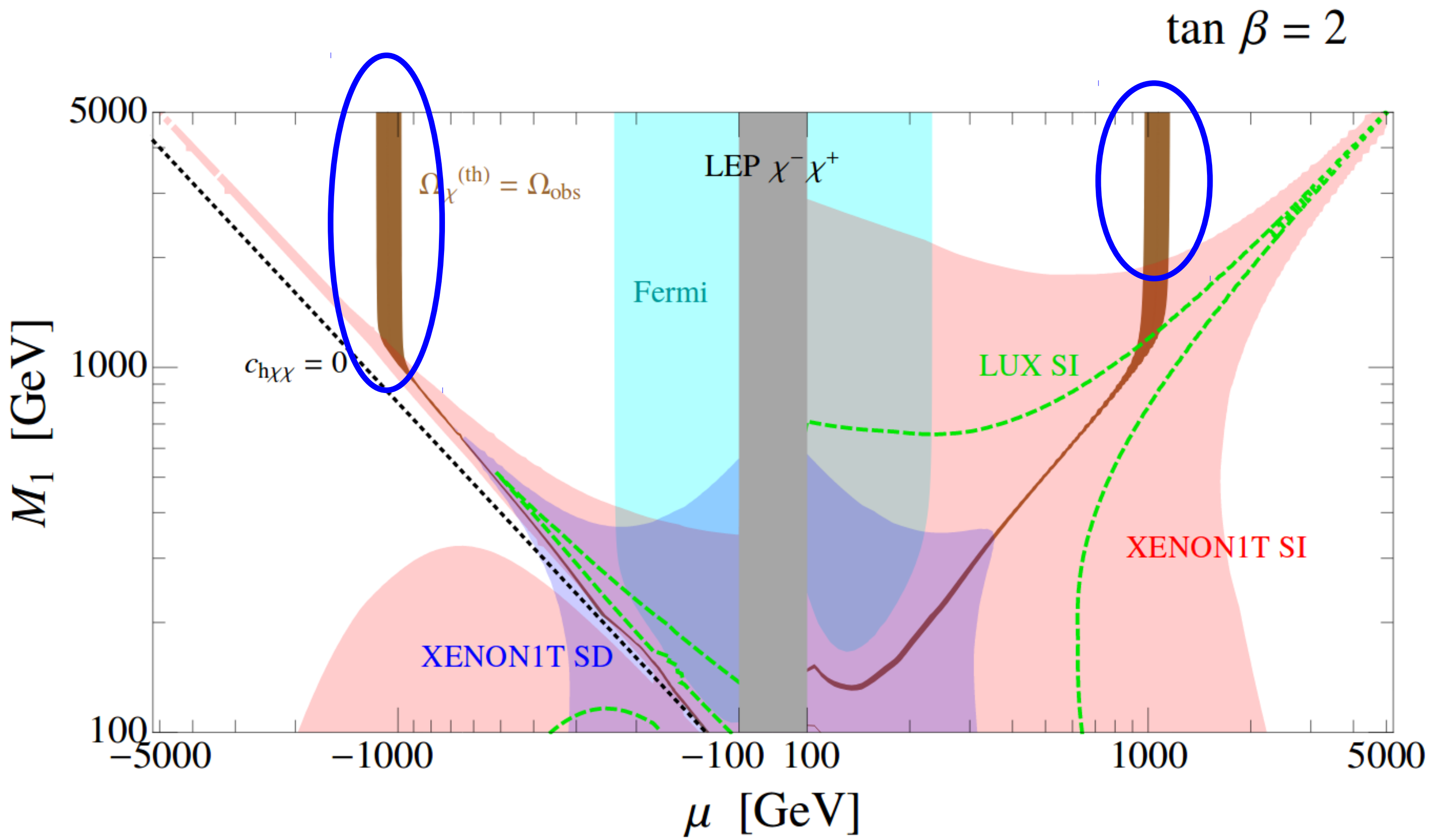
$\sigma_p \sim 0$

Kumar, Marfatia, Phys. Rev. D88 (2013)

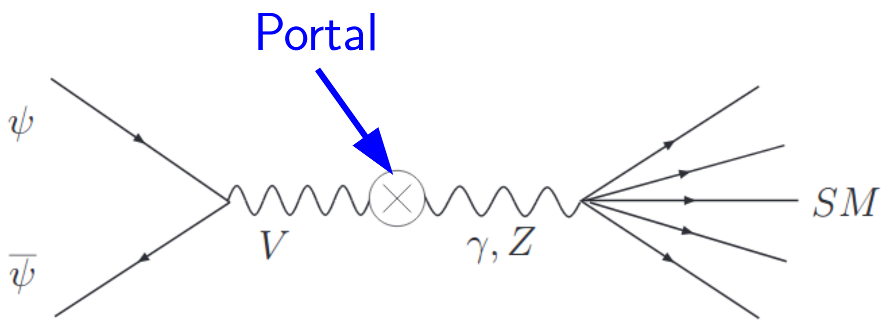
"pure" higgsino perfectly viable dark matter candidate



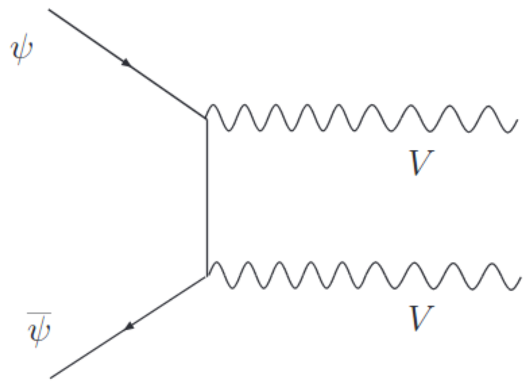
Cheung, Hall, Pinner, Ruderman, JHEP 1305 (2013)

"Secluded" WIMPs

Pospelov, Ritz, Voloshin, Phys .Lett. B662 (2008)



suppressed direct detection



unsuppressed indirect detection

$H^\dagger H\, \phi^\dagger \phi$	Higgs Portal
$F^{\mu\nu} F'_{\mu\nu}$	Vector Portal
HLN_R	Neutrino Portal

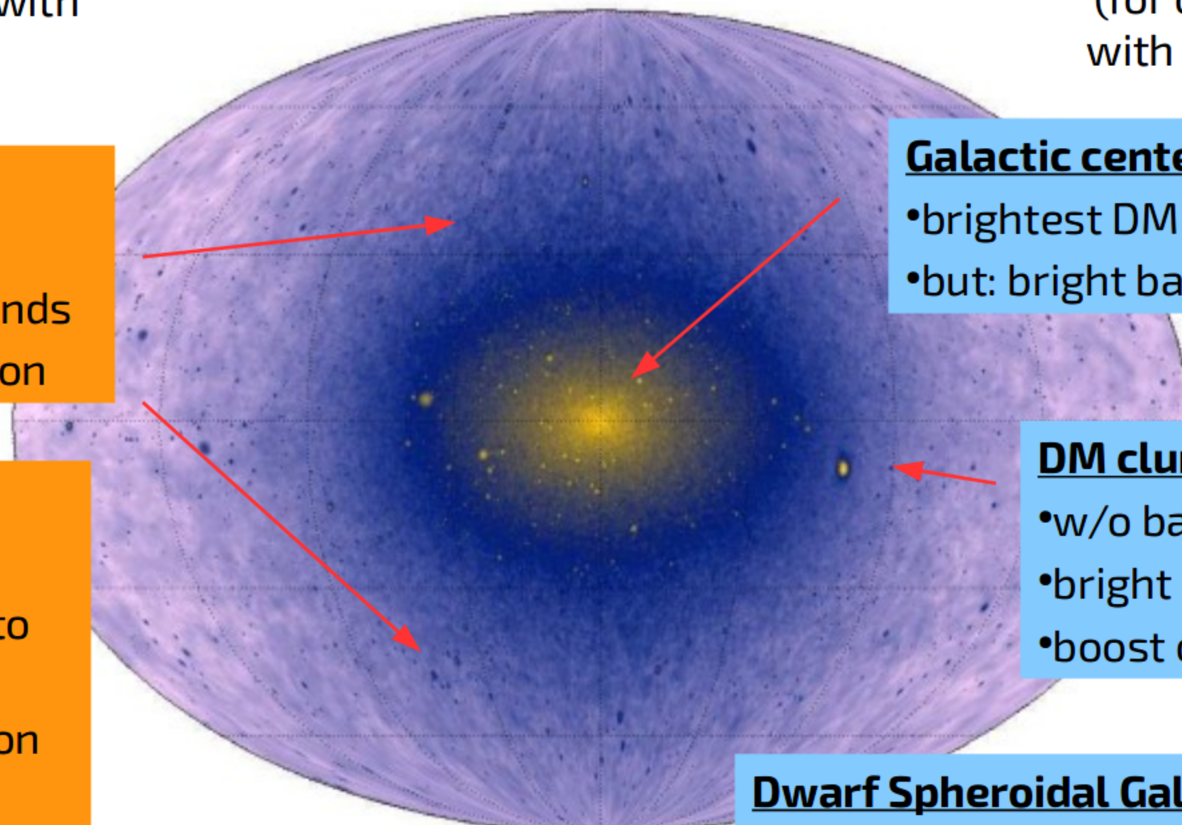
Gamma Ray Searches

Signal is approx. proportional to column square density of DM:

$$\propto \int_{\mathrm{l.o.s.}} ds\, \rho_{\mathrm{DM}}^2$$

Extended or diffuse:
(for observations with gamma rays)

Point-like:
(for observations with gamma rays)



Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: bright backgrounds

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

Dwarf Spheroidal Galaxies
- harbor small number of stars
- otherwise dark (no gamma-ray emission)

review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)

from C. Weniger

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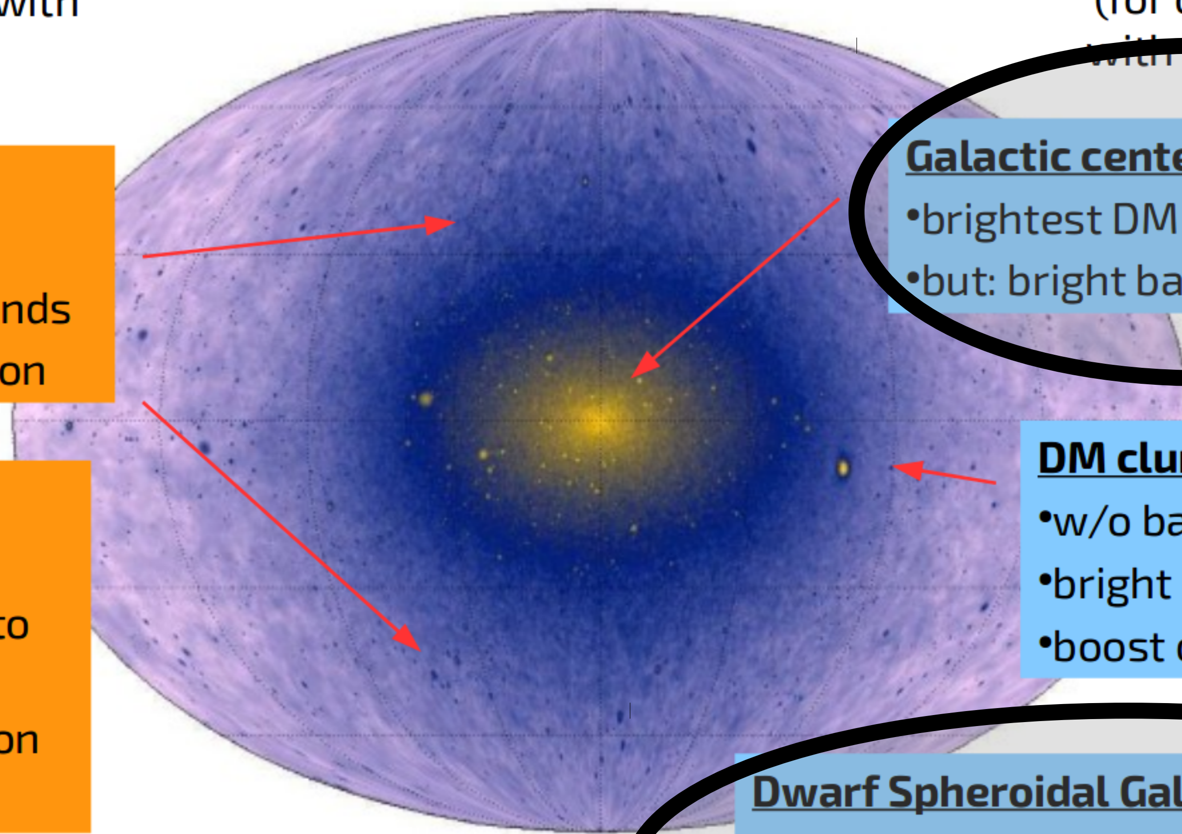

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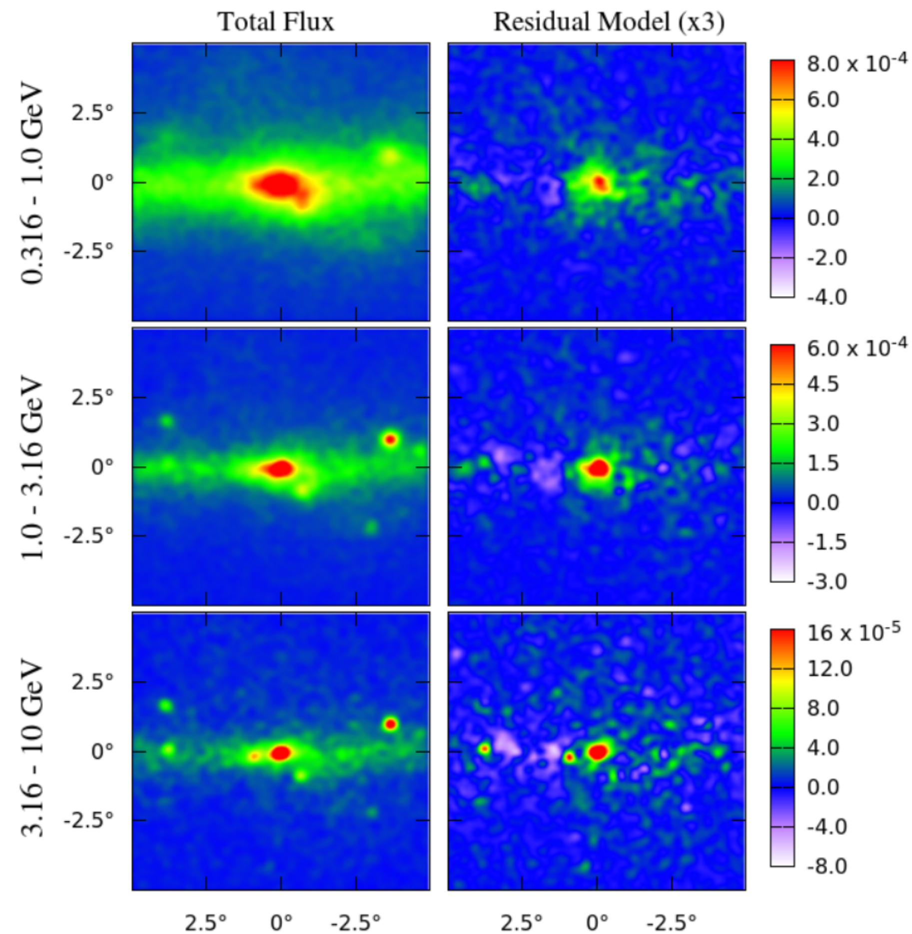
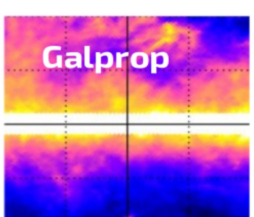
Galactic Center Gamma Ray Excess

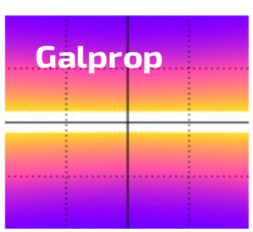
- GeV excess in the Fermi galactic center emission
  Goodenough, Hooper, arXiv:0910.2998 (2009)
- confirmed by Fermi collaboration in 2015
  Fermi-Lat, Astrophys.J. 819 (2016)
- also found in Andromeda
  Fermi-LATAstrophys.J. 836 (2017)

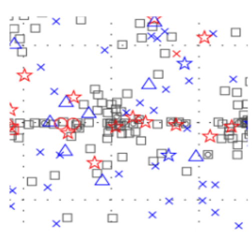


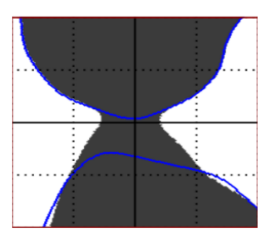
Daylan et al., Phys. Dark. Univ. 12 (2016)

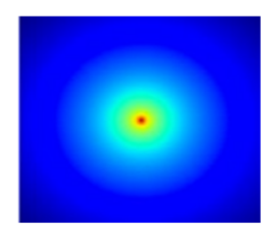
π^0+Bremss | ICS | 2FGL | Bubbles | Isotropic | Excess template





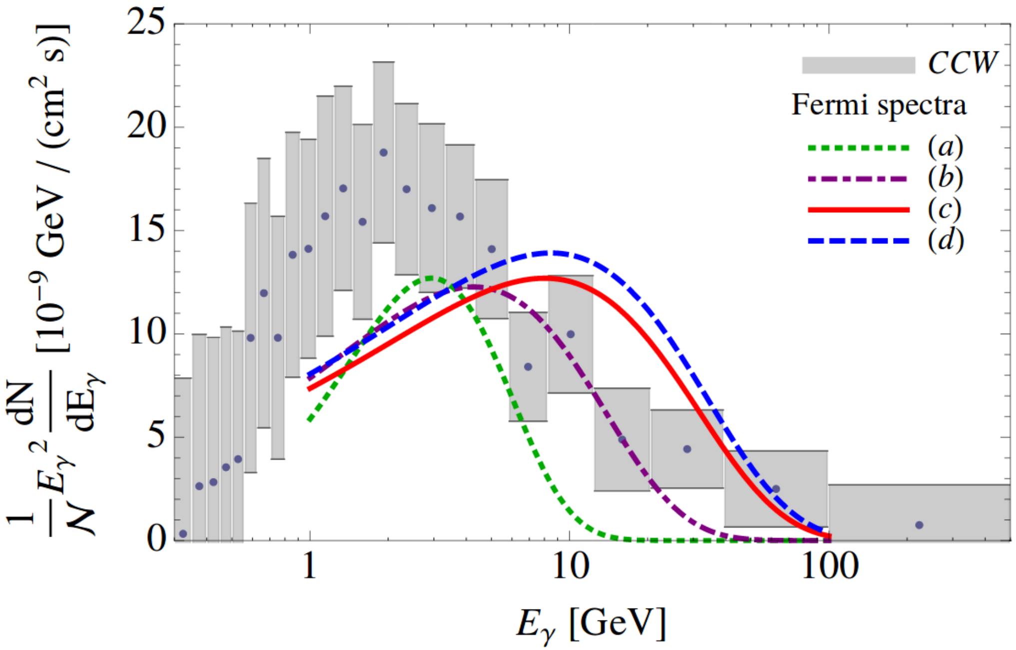


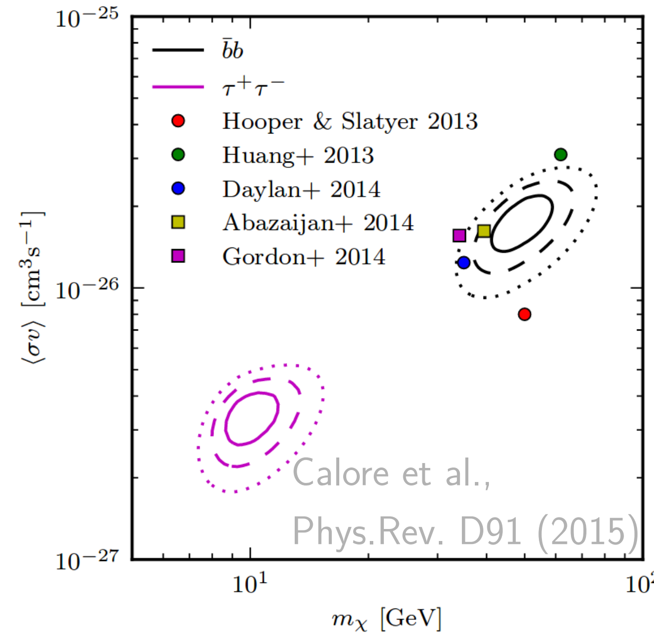




from C. Weniger

Spectrum



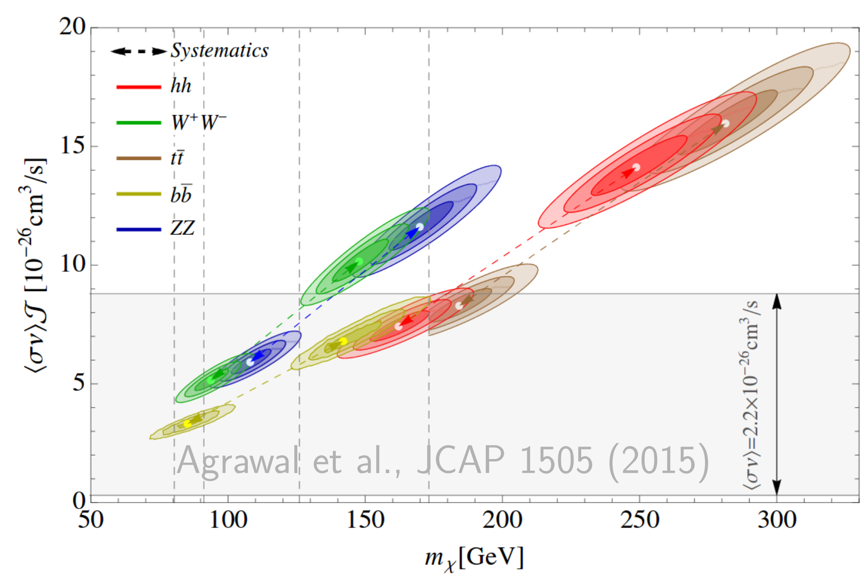


- spectrum roughly consistent with thermal WIMP, but background poorly modeled

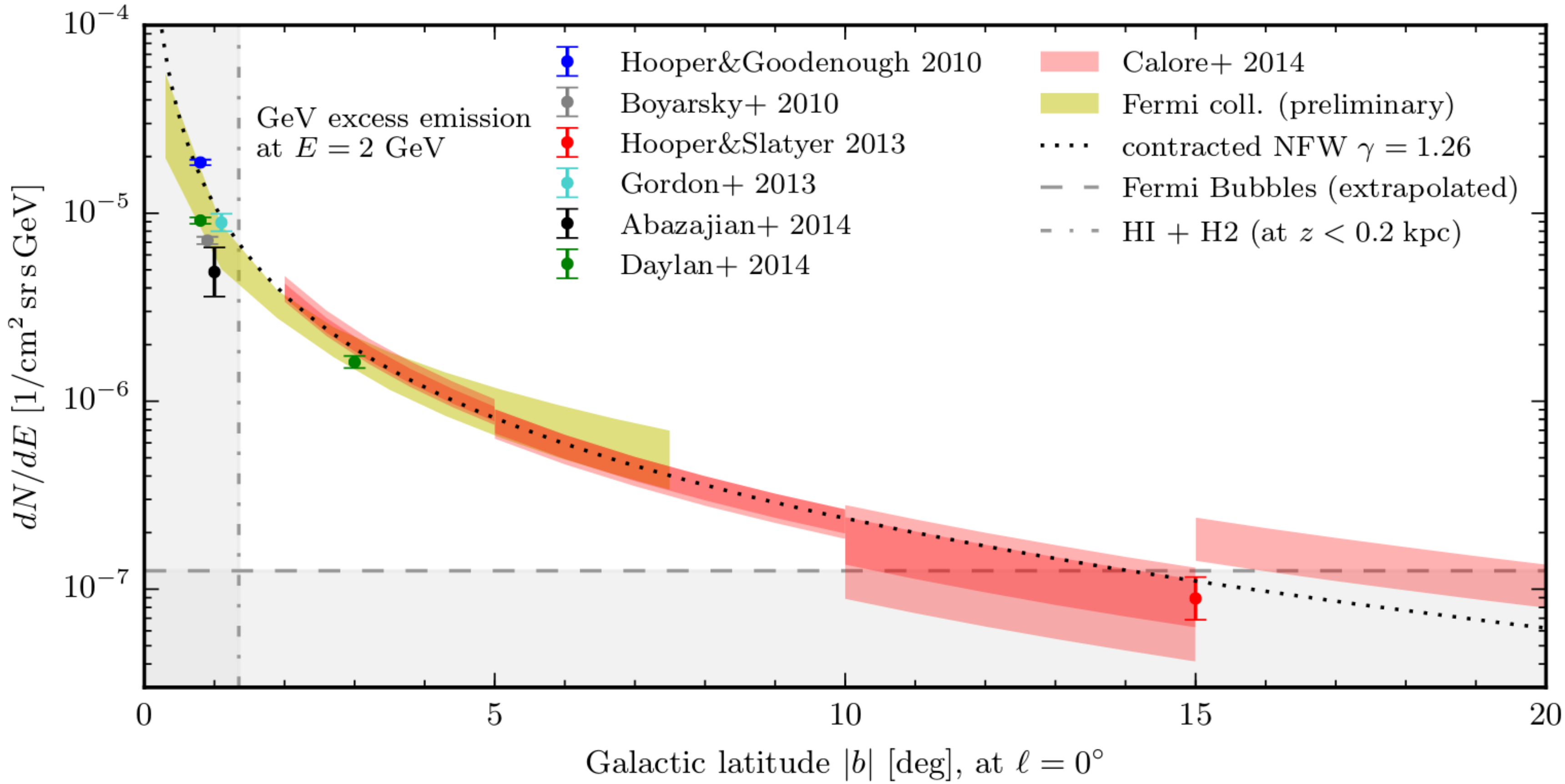
$$m_{DM} \sim 70\ \text{GeV} \quad \langle\sigma v\rangle_{\bar{b}b} \sim 2 \times 10^{-26}\text{cm}^3\text{s}^{-1}$$

(larger for long decay chains)

Krauss et al., Phys.Dark Univ. 14 (2016)



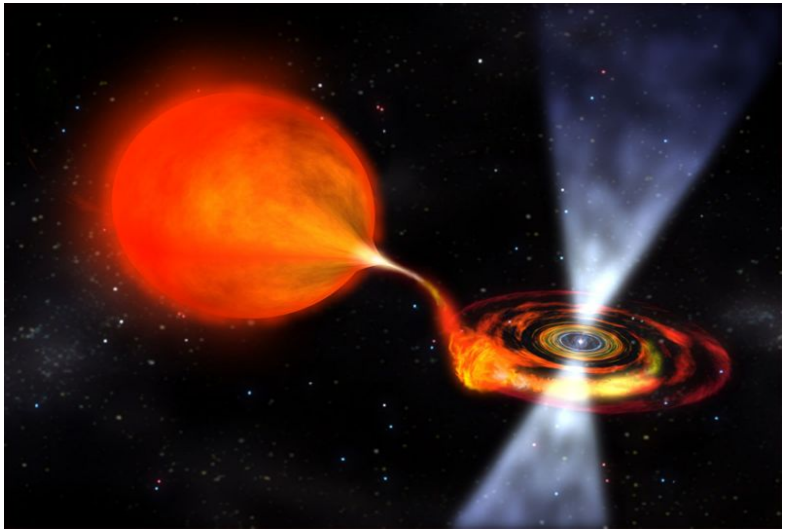
Morphology



Calore et al., Phys.Rev. D91 (2015)

- follows contracted NFW profile

Millisecond Pulsars

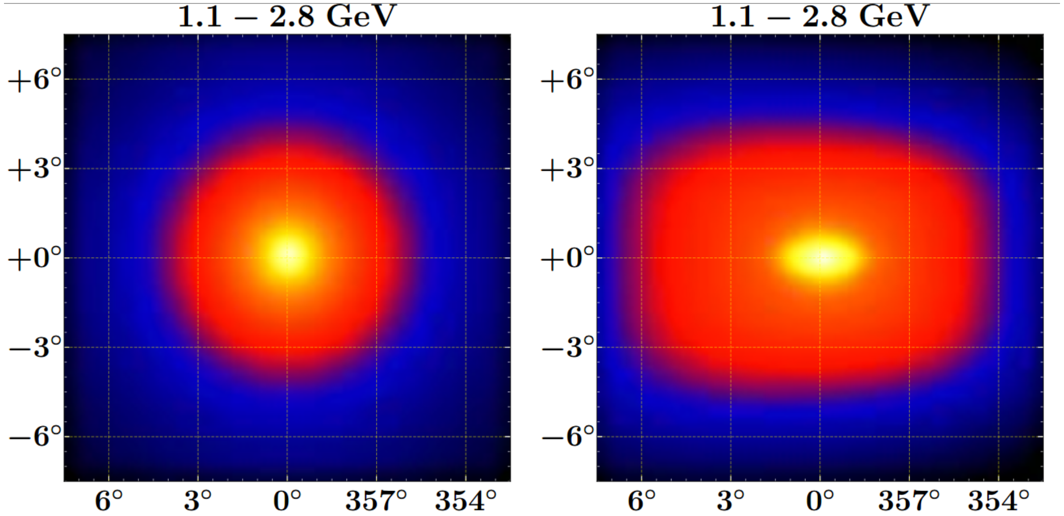


- neutron stars spun-up by accretion of matter from star companion
- unresolved population can fit excess spectrum

Abazajian, JCAP 1103 (2011)

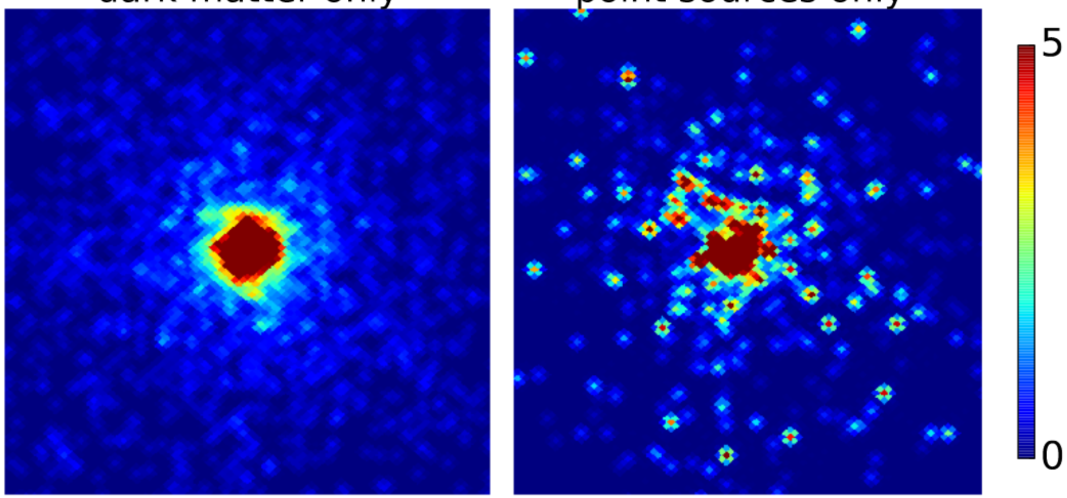
- excess might be correlated with bulge (rather than NFW)

Macias et al., Nature Astronomy (2018)



cNFW Bulge

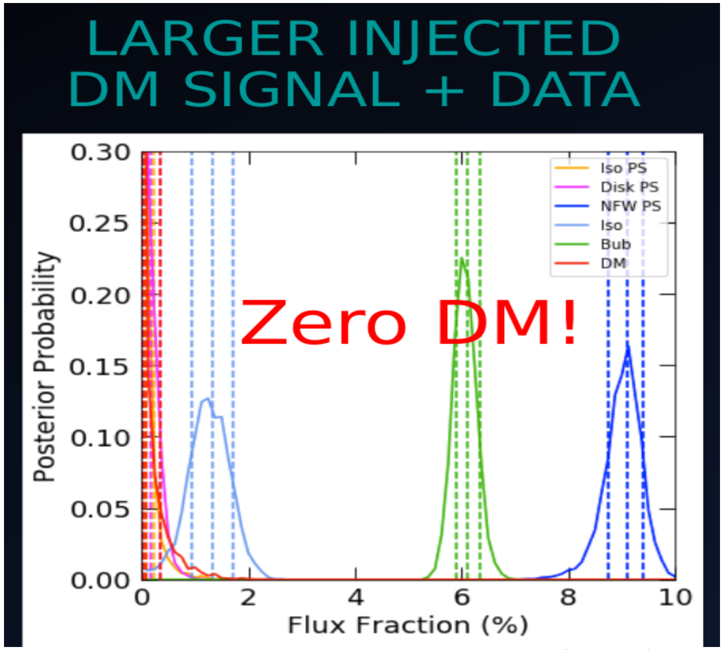
Millisecond Pulsars vs. Dark Matter



- excess appears more clumpy than from smooth DM distribution → dim point sources

Bartels, Krishnamurthy, Weniger, PRL 116 (2016), Lee, Lisanti, Safdi, Slatyer, Xue, ibid

"Dark Matter Strikes Back at the Galactic Center"

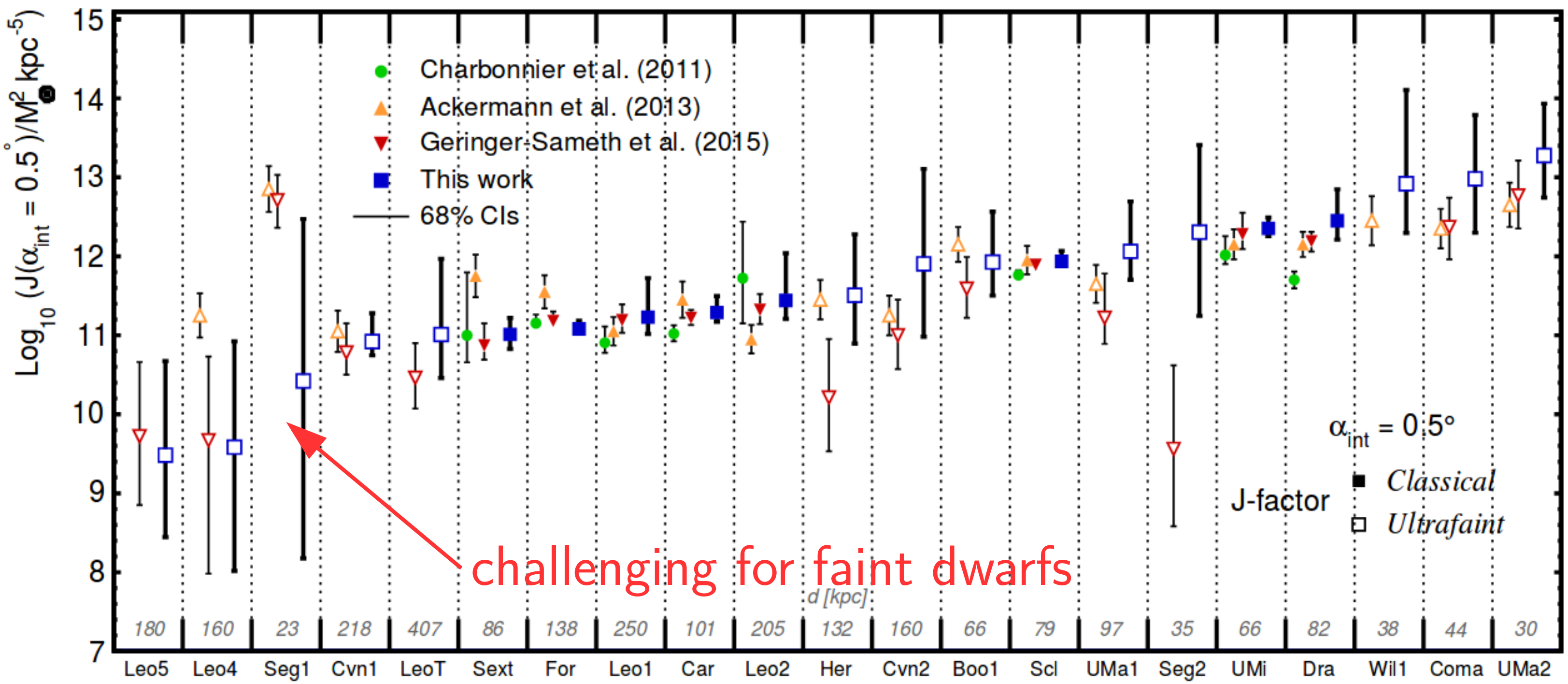


R. Leane, TRIUMF Workshop (2019)

- caveat?
  unmodeled clumpy sources (in the Fermi Bubbles)
- radio searches for millisecond pulsars (e.g. MeerKAT)

Calore et al., Astrophys.J. 827 (2016)

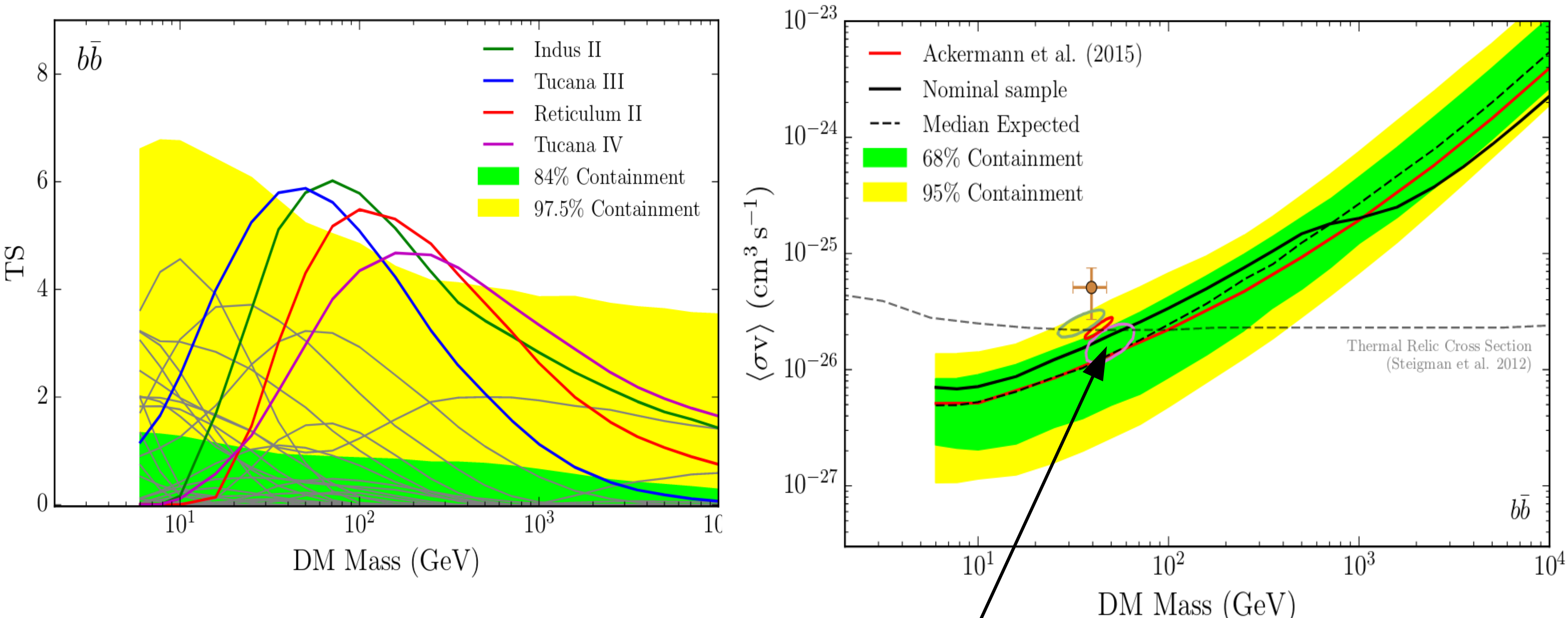
Fermi Dwarf Galaxies



Bonnivard et al., Mon. Not. Roy. Astron. Soc.453, 849 (2015)

- measure line-of-sight velocity of brightest stars
- dark matter density ($\rightarrow$ J-factor) inferred assuming steady state, spherical symmetry, no rotation

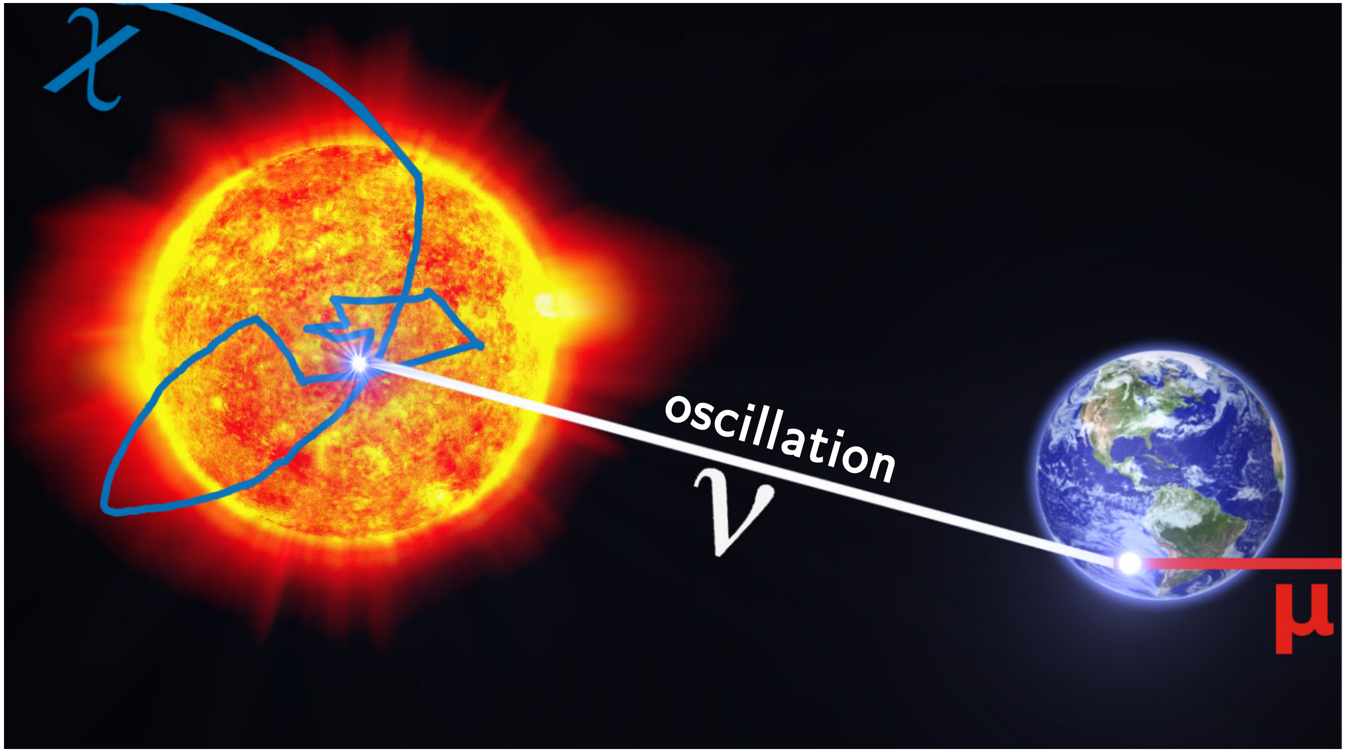
Fermi Dwarf Galaxies



Fermi-LAT, Astrophys.J. 834 (2017)

inconclusive for galactic center excess

Dark Matter Capture

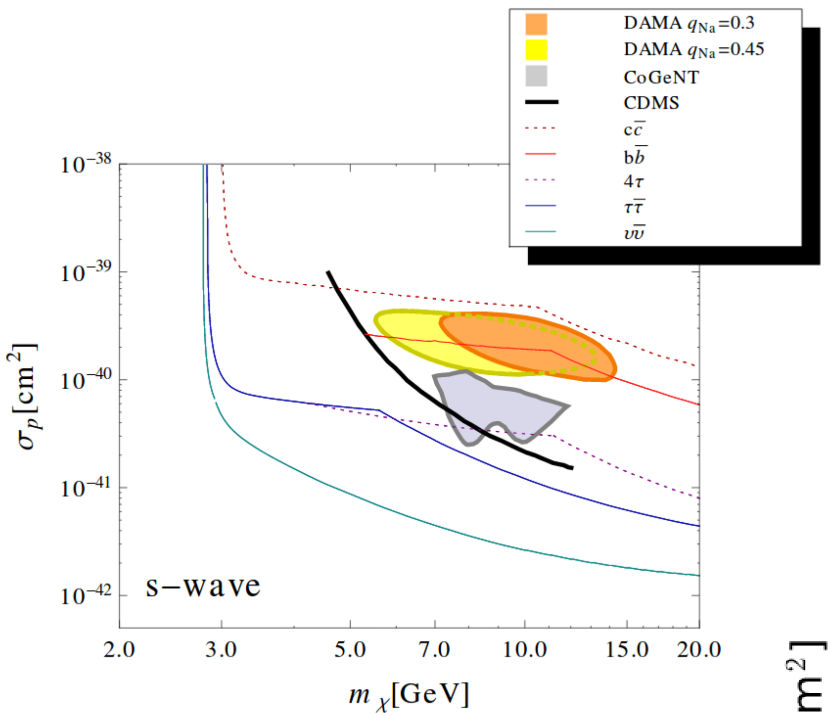


- dark matter gets trapped in the sun and annihilates, neutrinos escape

$$C \sim \text{Flux} \cdot \text{Kinematics} \cdot \rho_i \cdot \sigma_i \qquad (i = H, He, \dots)$$

$$\Gamma = C/2 \quad (\text{in equilibrium})$$

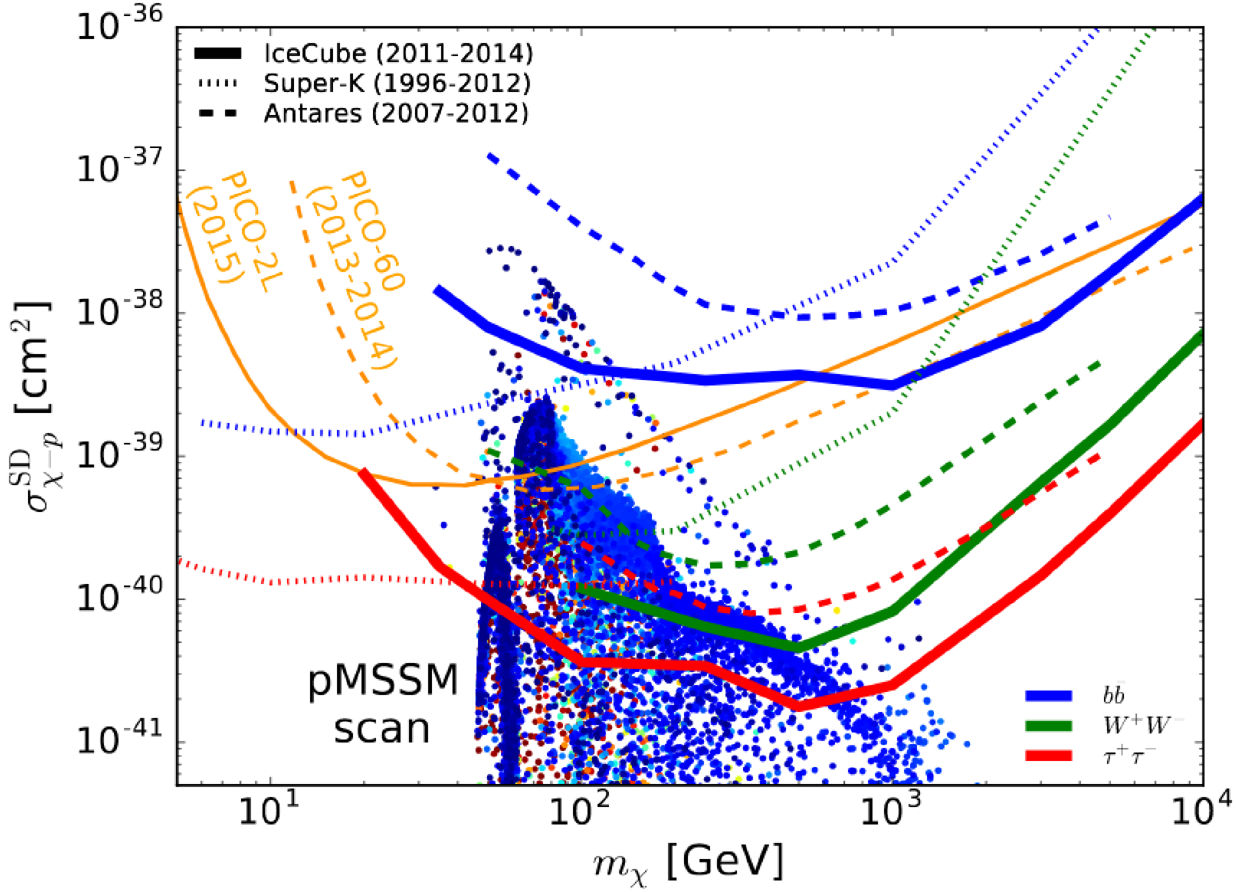
Neutrino Constraints



- strong constraints on spin-dependent DM-proton coupling

- back in 2011: excluding common explanation to GCE + DAMA

Rolf Kappl, M.W., Nucl.Phys. B850 (2011)



IceCube, Eur. Phys. J. C77 (2017)

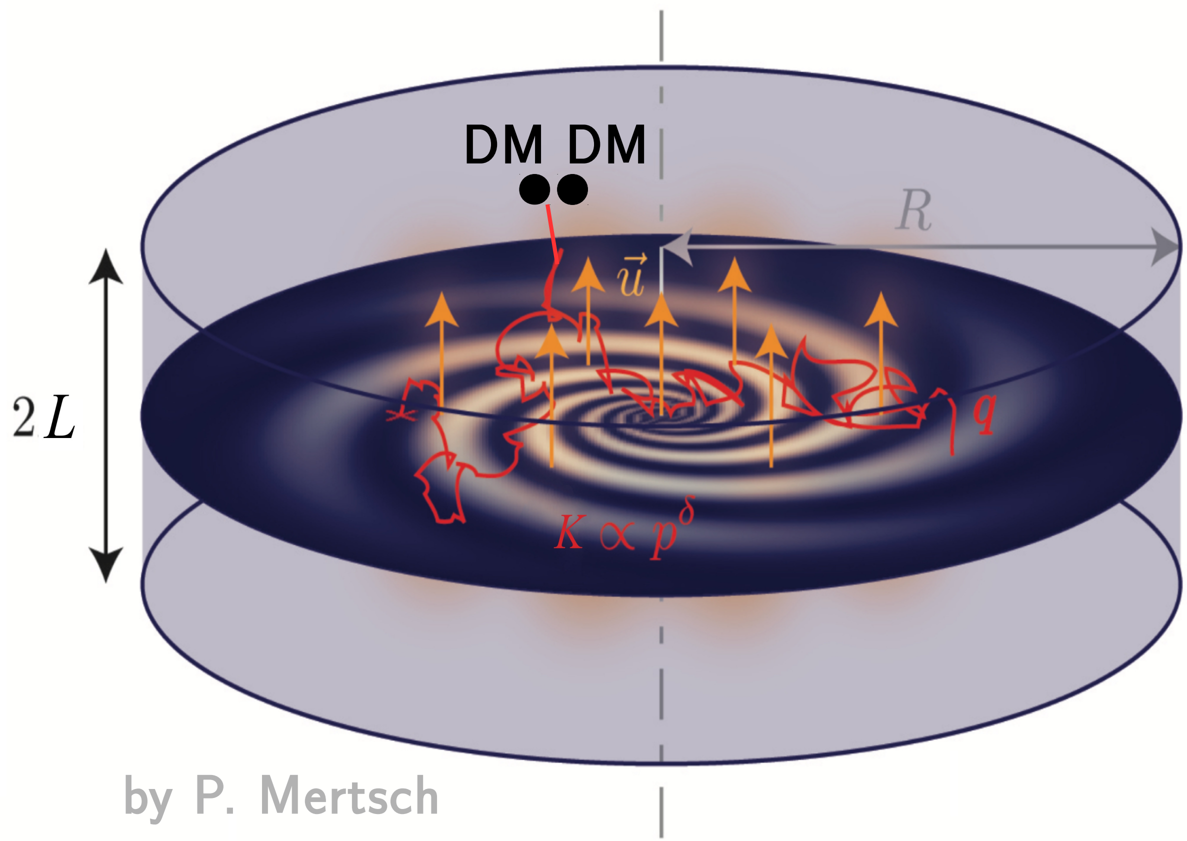
Charged Cosmic Rays

- propagation described by diffusion equation

Ginzburg & Syrovatzkii (1964)

$$\nabla(-K\,\nabla N_{\bar{p}} + \mathbf{V}_c\,N_{\bar{p}}) + \partial_E((b_{disc} + b_{halo})\,N_{\bar{p}} - K_{EE}\,\partial_E N_{\bar{p}}) + \Gamma_{ann}\,N_{\bar{p}} = q_{\bar{p}}$$

only for $e^{\pm}$



- two-zone diffusion model

$K_0,\ \delta,\ L,\ V_c,\ V_a$

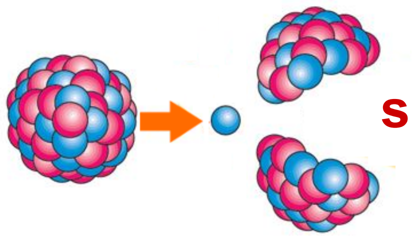
Maurin et al., Astrophys. J. 555 (2001), Donato et al., Astrophys. J. 563 (2001)

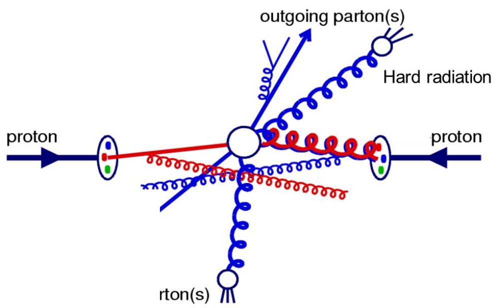
- GALPROP, DRAGON

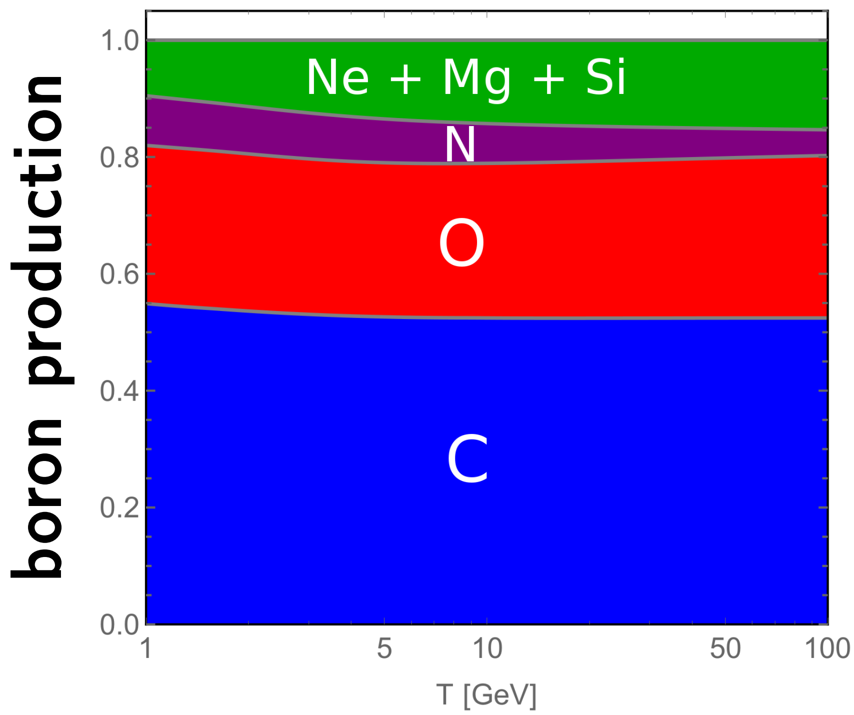
Strong, Moskalenko, Astrophys. J. 509 (1998), Evoli et al., JCAP 0810 (2008)

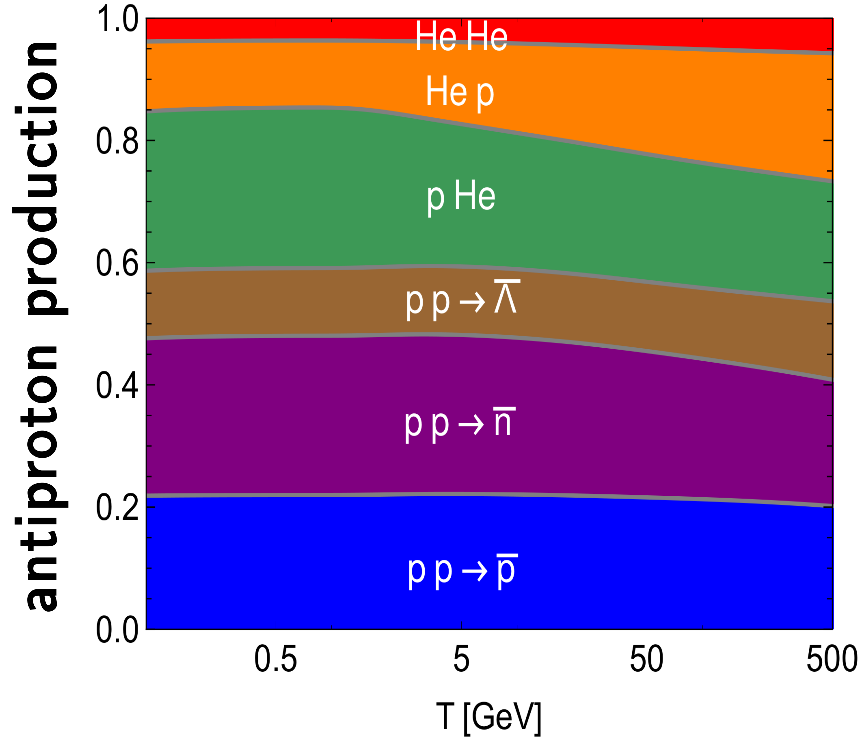
Secondary Cosmic Rays

- primary cosmic rays scatter on interstellar matter and produce secondaries: some nuclei (Li, Be, B), antimatter ← background for DM search





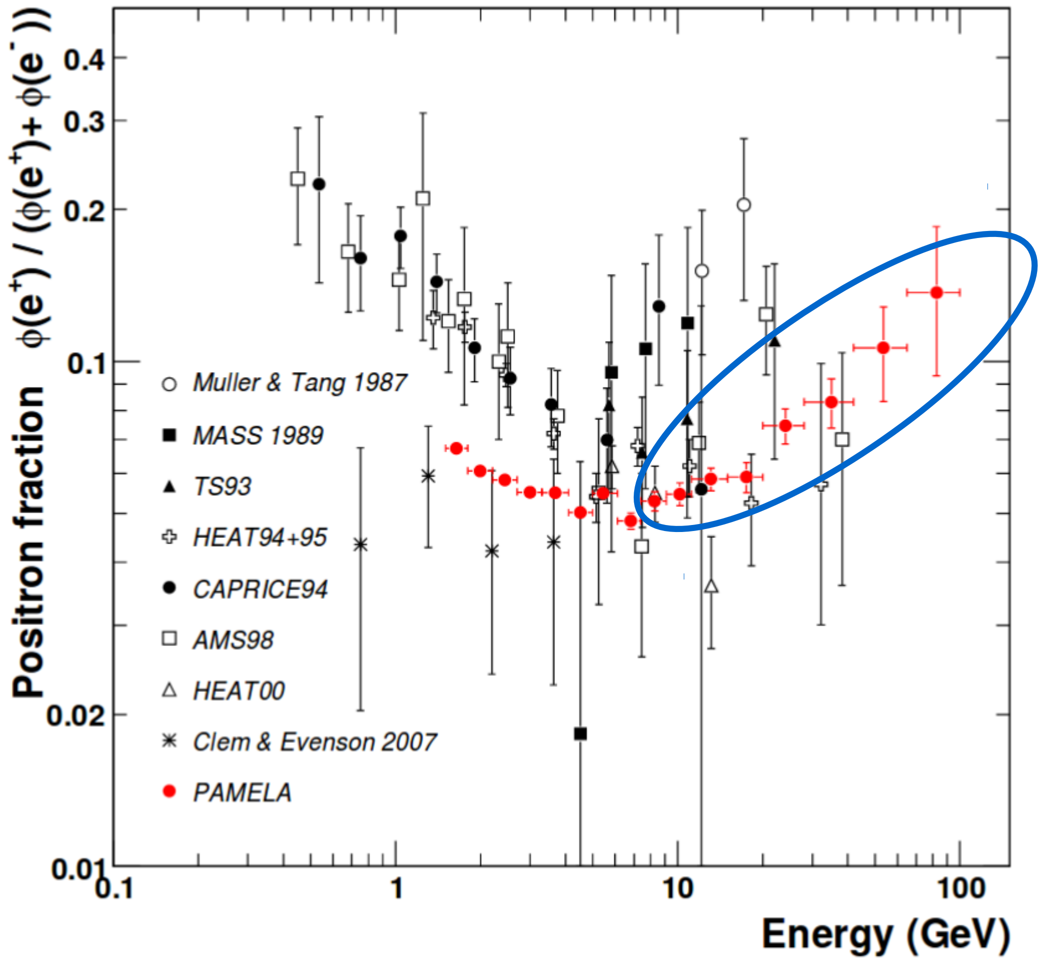




Positron Excess

- 2008: PAMELA observes rise of the positron fraction

PAMELA, Nature 458 (2009)

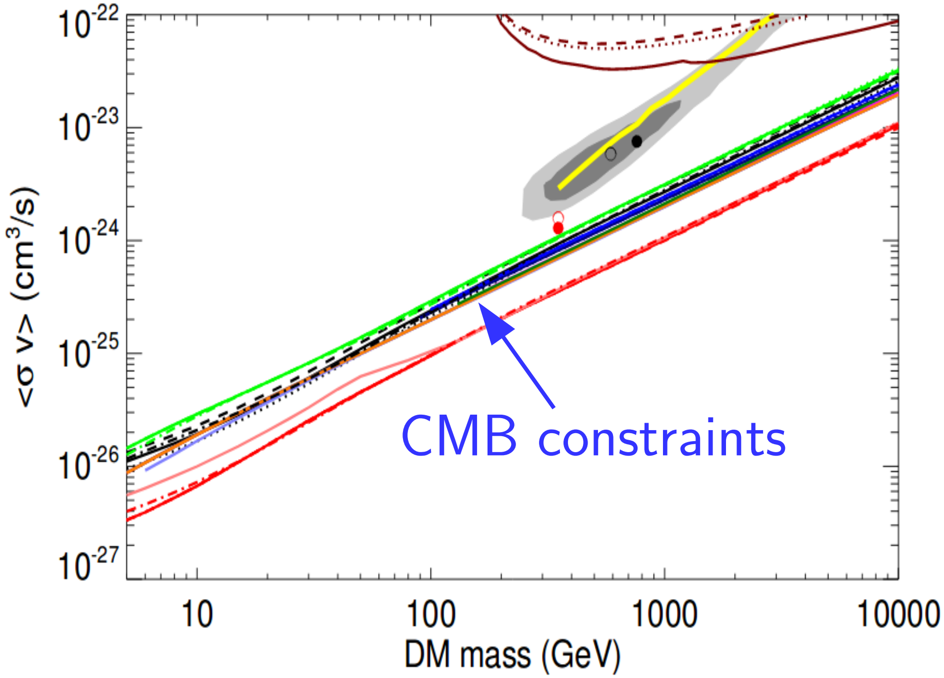


unexpected from secondary production

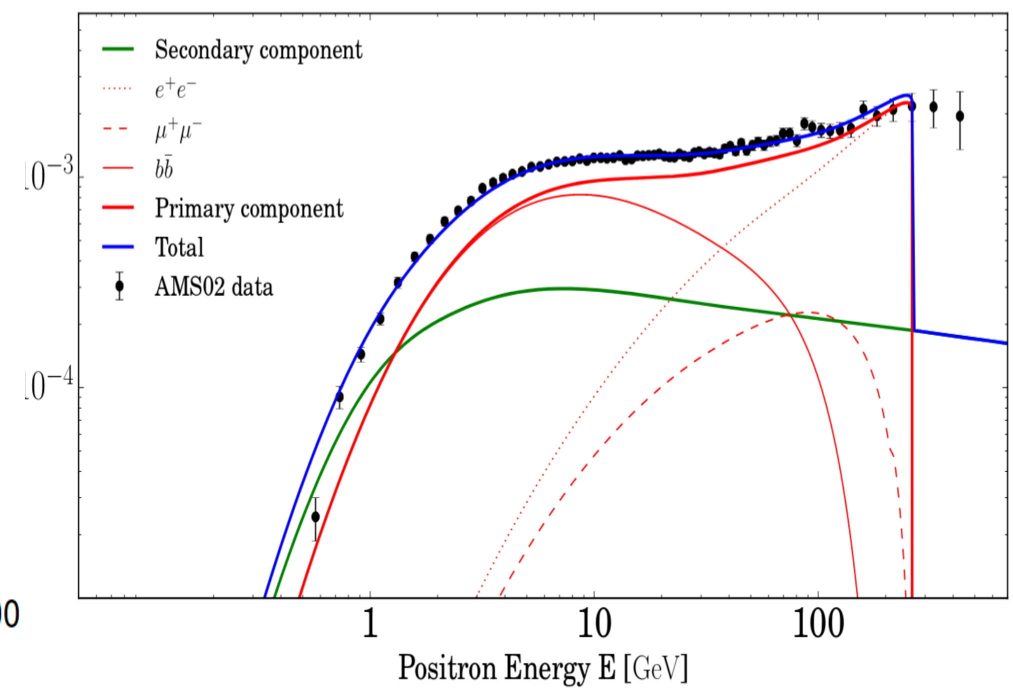
Dark Matter Explanation

- dark matter interpretation requires large boost (Sommerfeld?), challenged by complementary searches (γ, $\bar{p}$, CMB)
- spectrum not well fit by DM at the precision level (AMS-02)

Cirelli et al., arXiv:0809.2409, updated appendix, AMS positrons spectrum in Phys. Rev. Lett. 122 (2019)

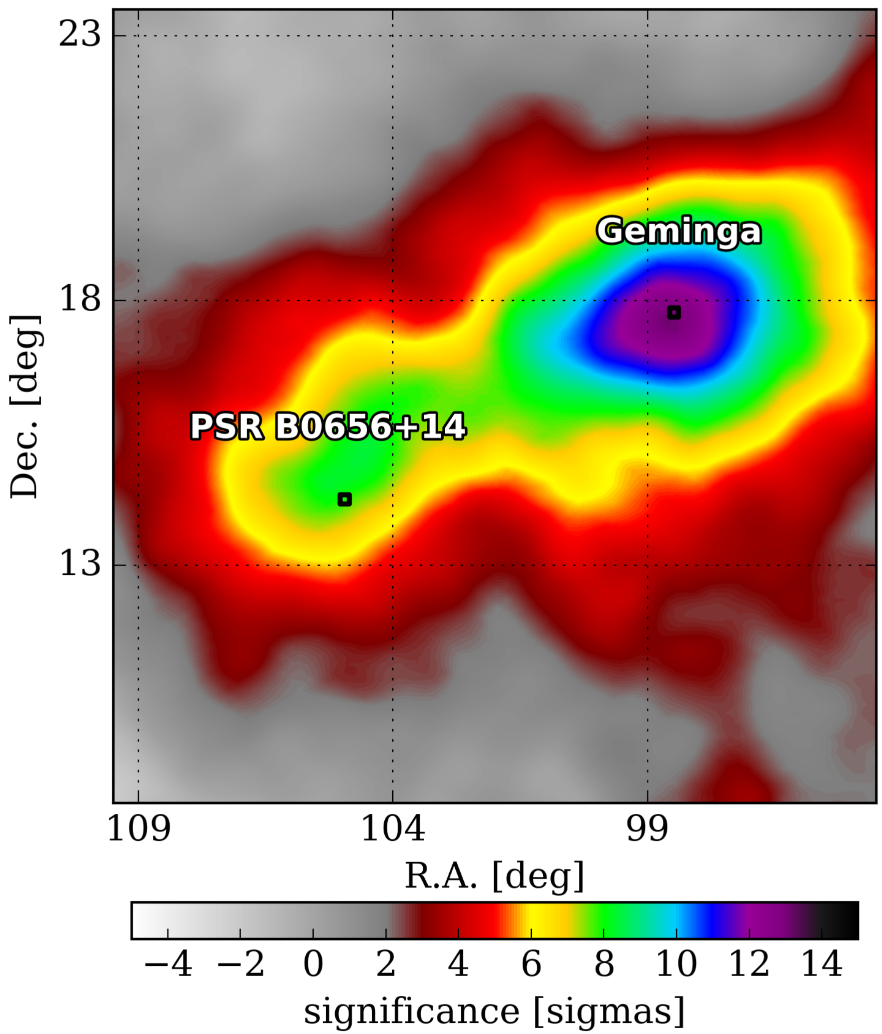


Slatyer, Phys.Rev. D93 (2016)



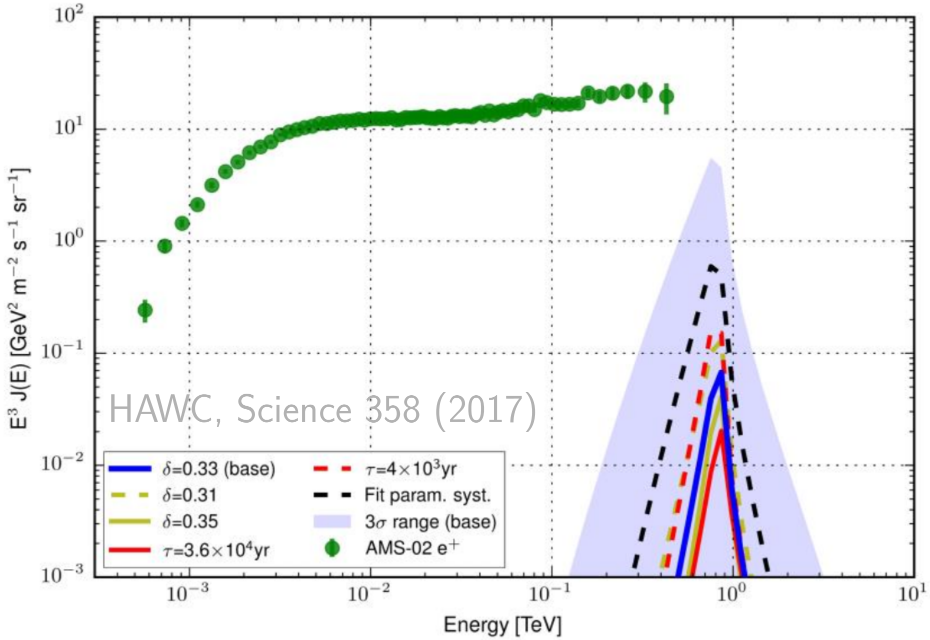
Boudaud et al., A.A. 605 (2017)

Pulsar Explanation



- pulsars might significantly contribute to $e^{\pm}$ flux
  Harding, Ramaty, ICRC (1987), Aharonian, Atoyan, Voelk, A.A. 294 (1995)
- e^{-} extracted from surface by strong electric fields create electromagnetic cascades
- extended γ-ray emission indicates that energetic $e^{\pm}$ are emitted from pulsar
  Milagro, Astrophys.J. 700 (2009), HAWC, Astrophys. J. 843 (2017)

Pulsars and HAWC



- HAWC claims pulsars do not contribute to positron excess
- based on assumption that diffusion around pulsar and in ISM are identical

<u>problems:</u>

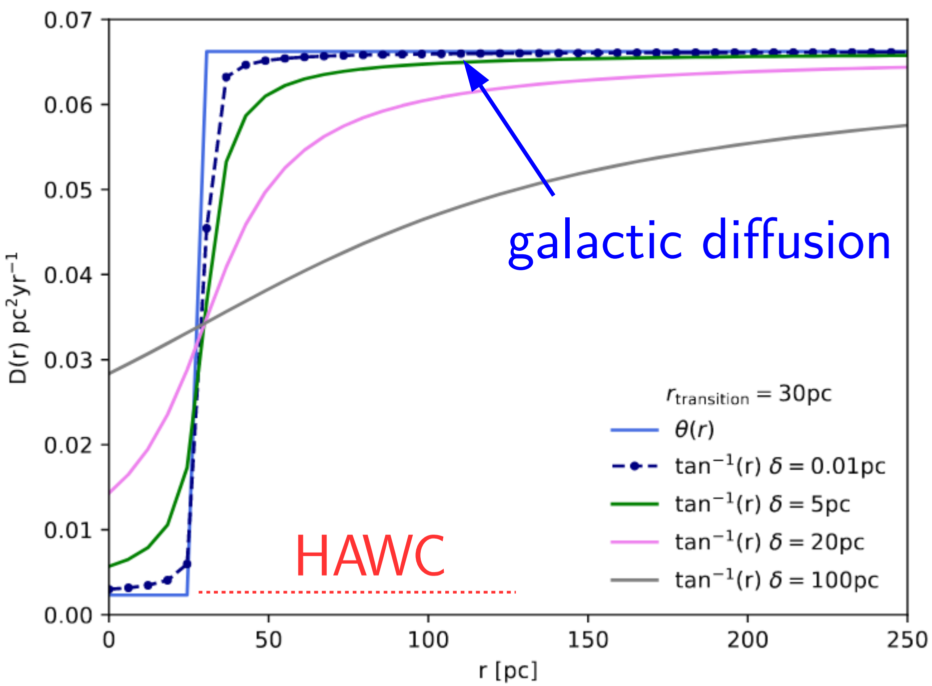
- leptons and hadrons would diffuse differently $K_{\text{lepton}} \sim \dfrac{K_{\text{hadron}}}{100}$
- leptonic diffusion so inefficient that multi-TeV electrons would have to come from within $\sim$30 pc, but no sources!

Hooper, Linden, Phys. Rev. D 98 (2018)

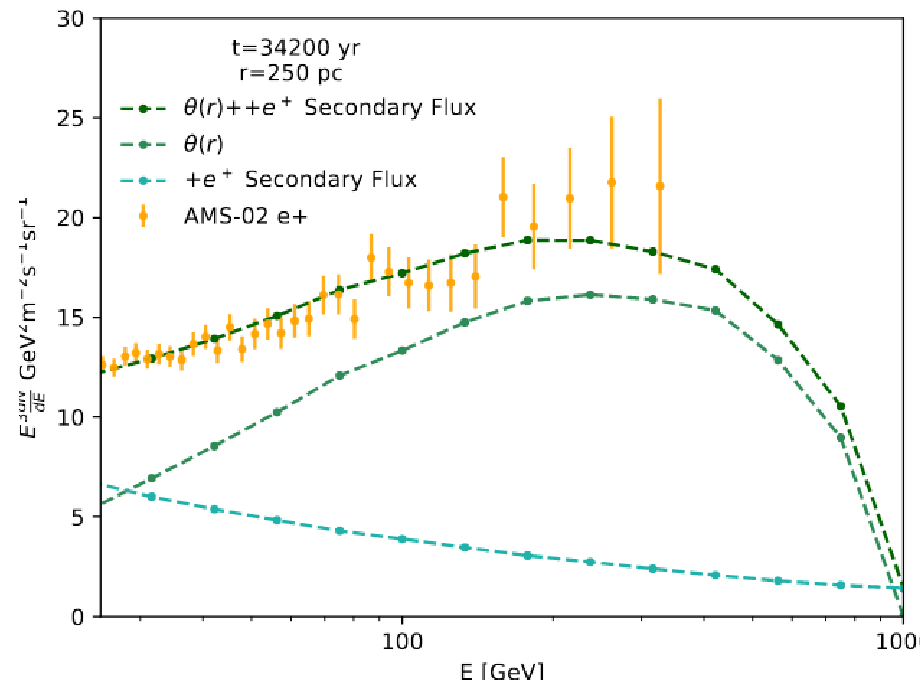
Pulsars and HAWC

- escaping CRs generate Alphen waves → diffusion locally affected

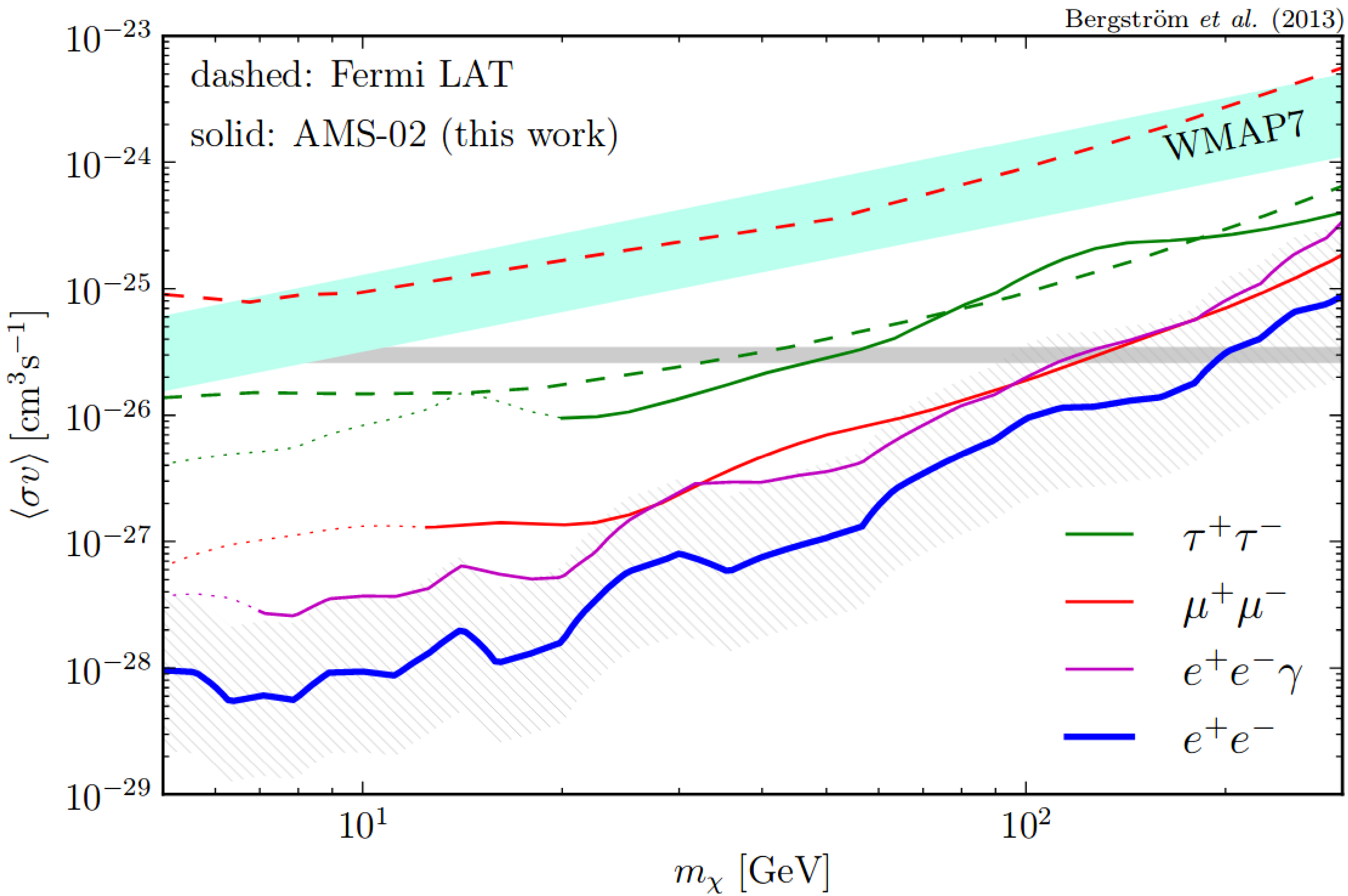
  Ptuskin et al., Adv.Space Res. 42 (2008), Malkov et al. Astrophys.J. 768 (2013), Evoli, Linden, Morlino, Phys. Rev. D98 (2018), Johannesson, Porter, Moskalenko, arXiv:1903.05509 (2019)



Profumo et al, Phys.Rev. D97 (2018)



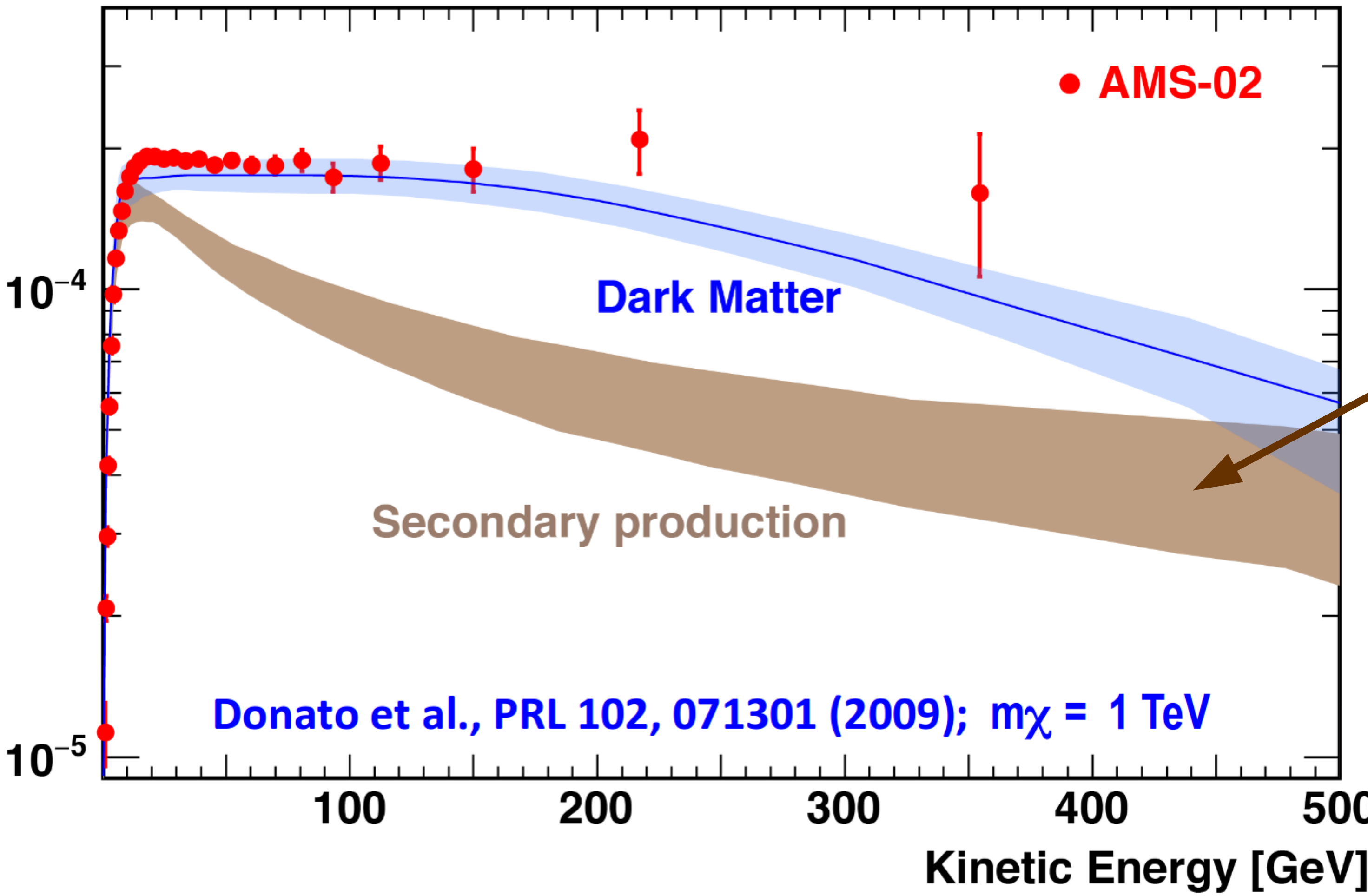
Constraints from Positrons



AMS-02 Antiprotons

- 2015: surprisingly hard $\bar{p}$ spectrum observed by AMS-02

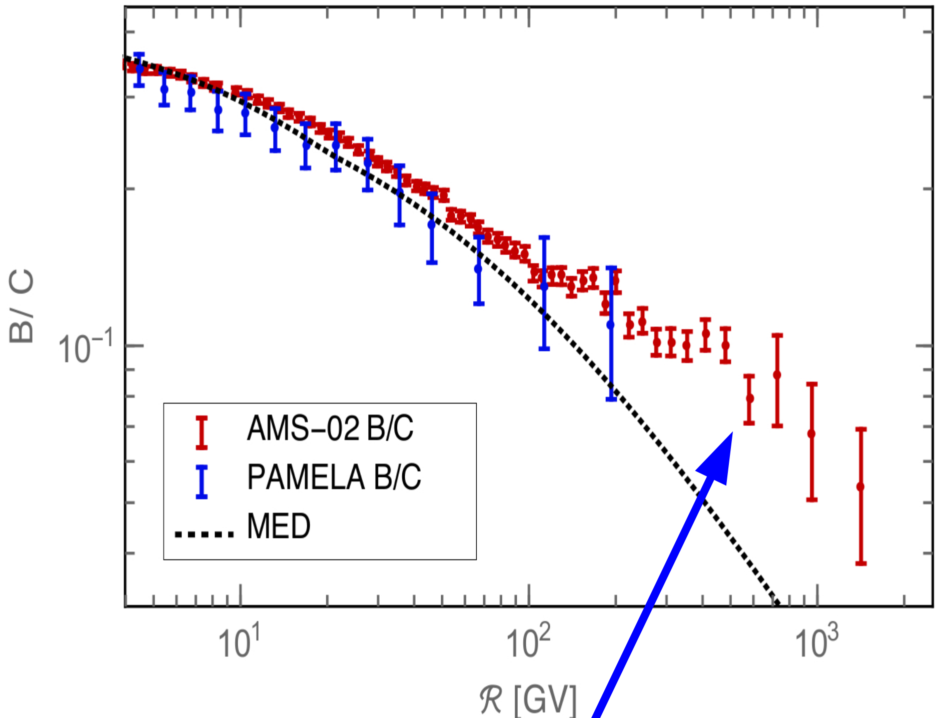
S.Ting, A. Kounine, AMS Days at CERN (2015)

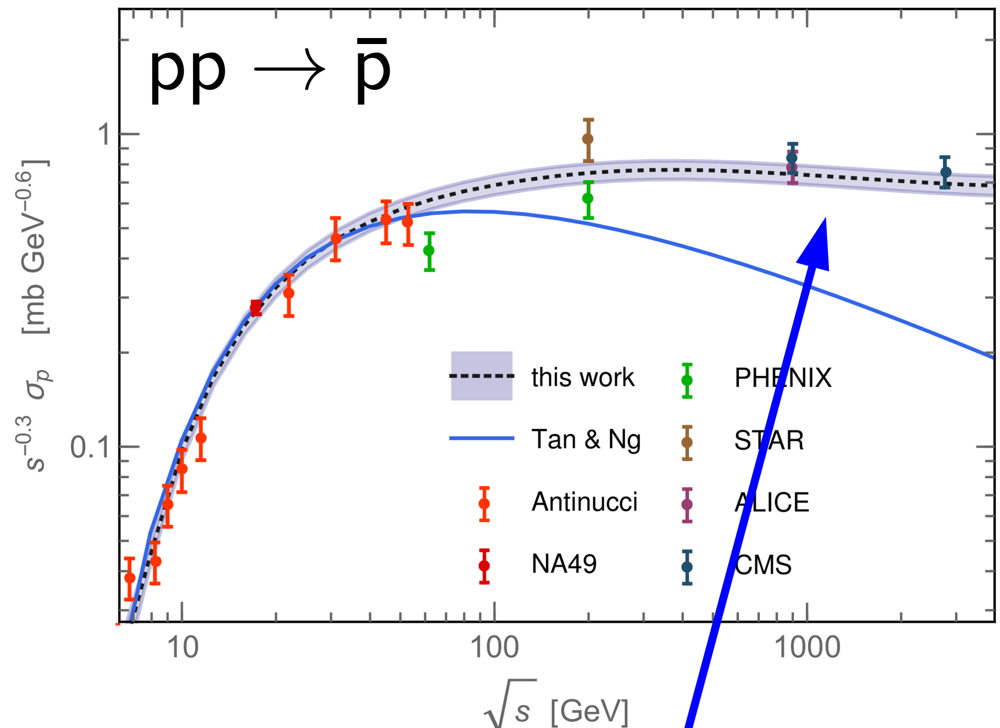


Uncertainties:
cross section,
propagation

What was missed

- background improvements





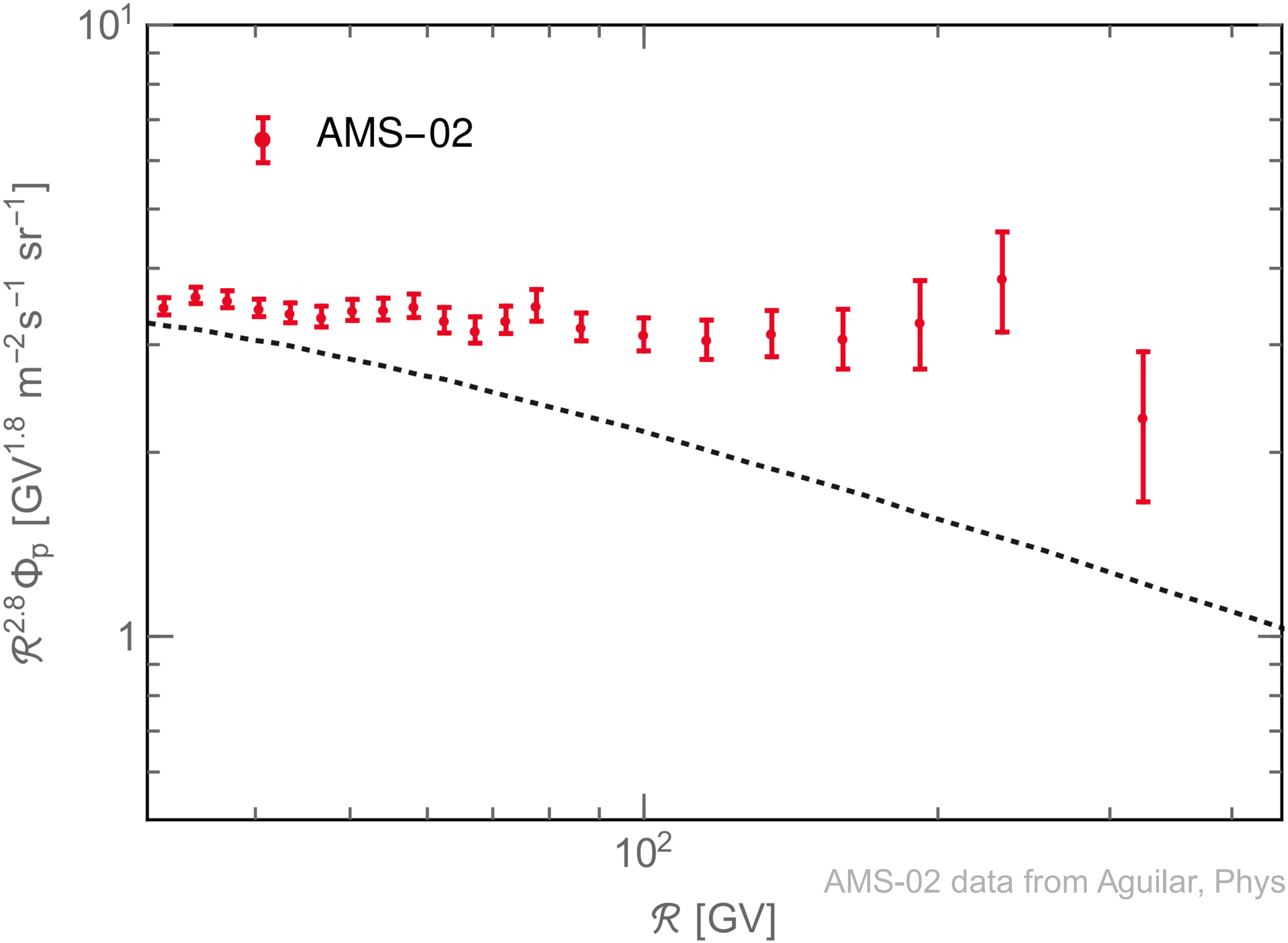
propagation update to fit B/C

Giesen et al., Evoli et al.,
Kappl, Reinert, M.W., JCAP (2015)

cross section increase

M.W., JCAP 02 (2017)

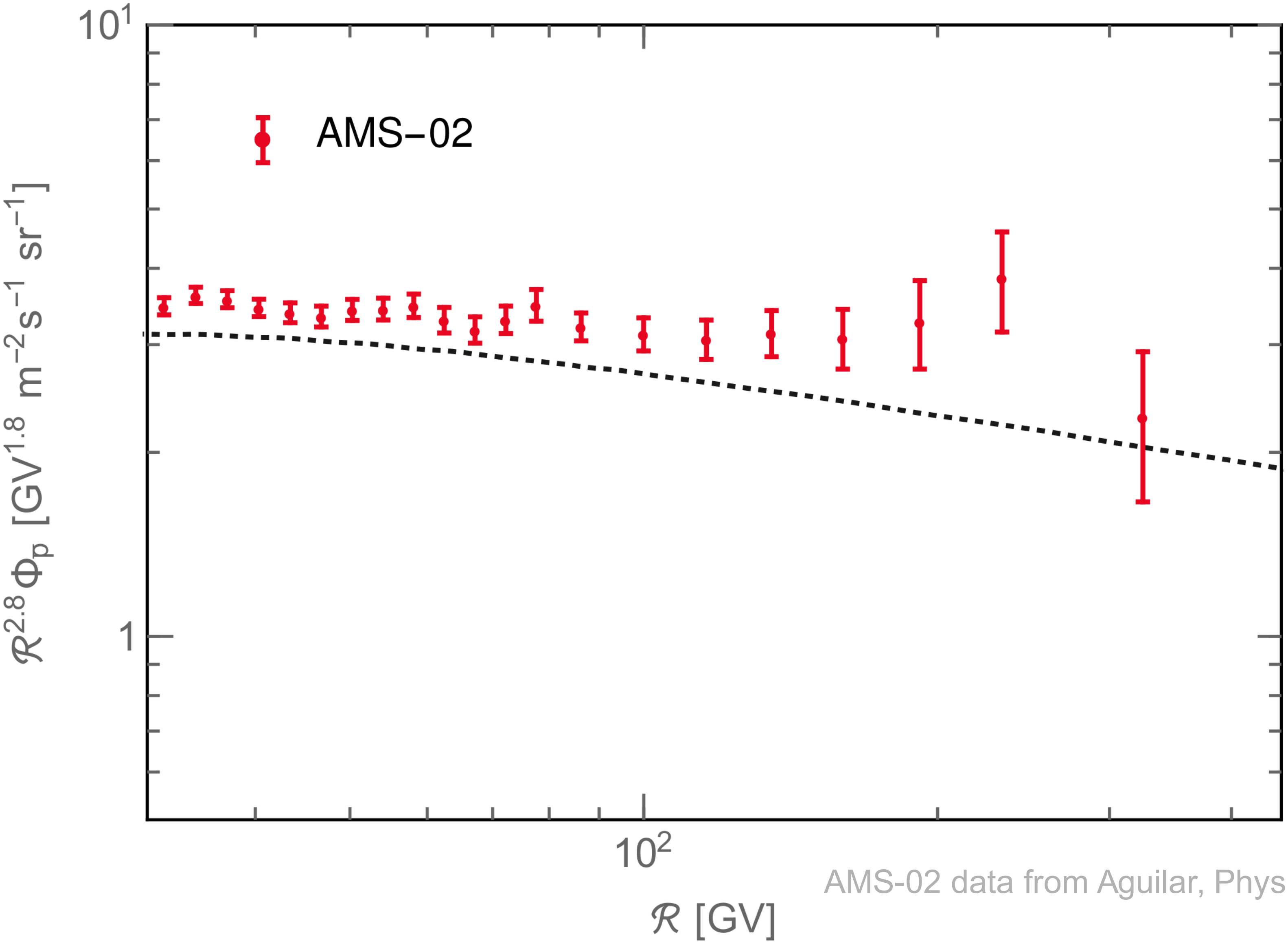
High Energy Antiproton Flux



background 2015

AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

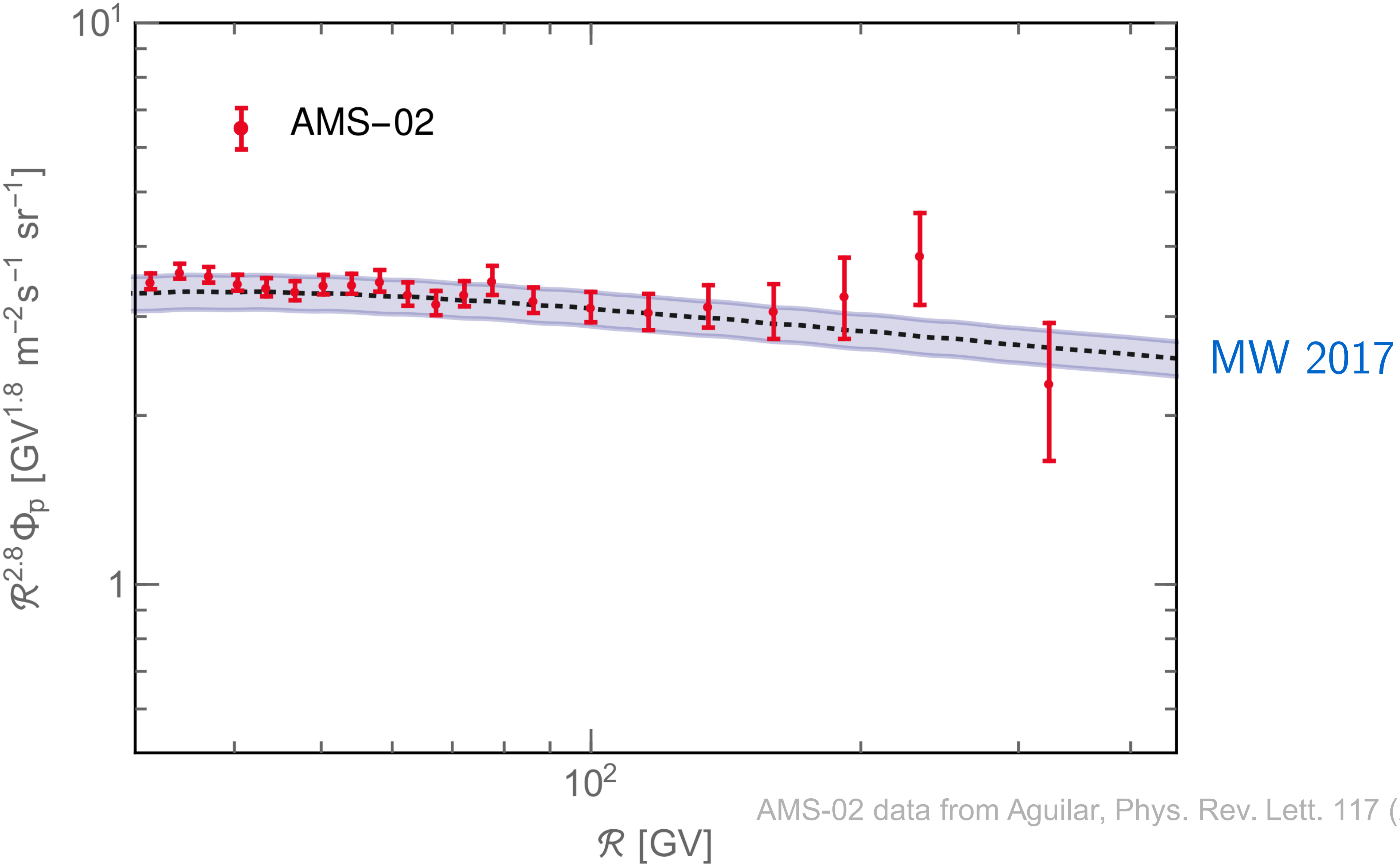
High Energy Antiproton Flux



updated propagation

AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

High Energy Antiproton Flux

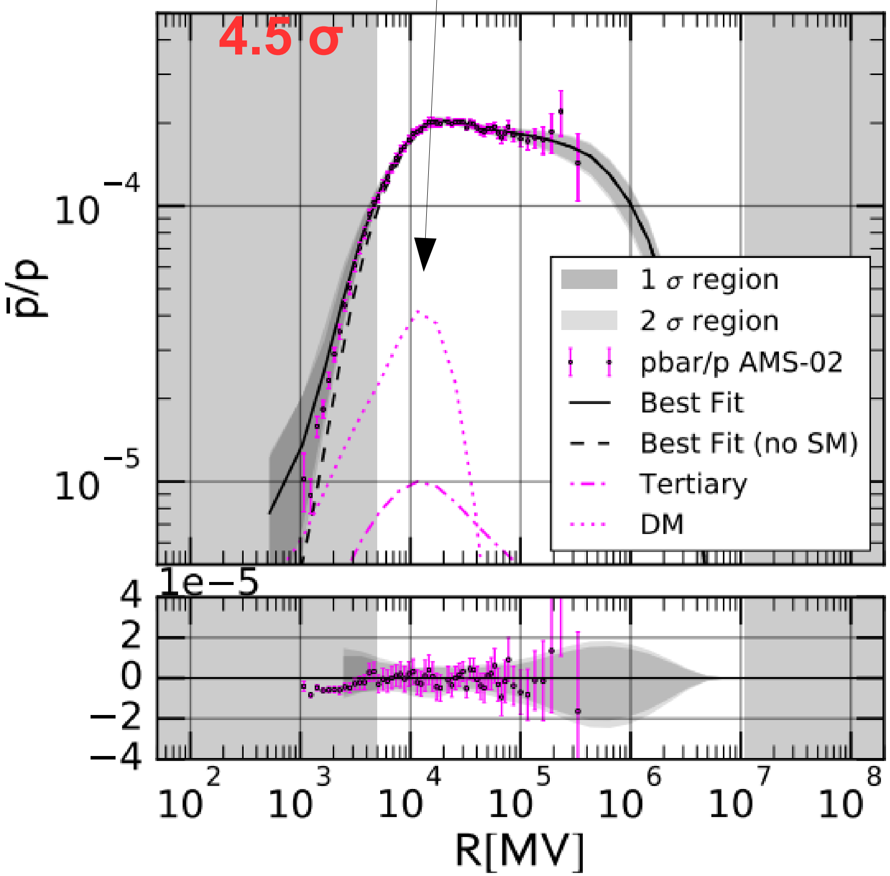


AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

A new Antiproton Excess

$m_{DM} \sim 70$ GeV

$\langle \sigma v \rangle_{\bar{b}b} \sim 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$



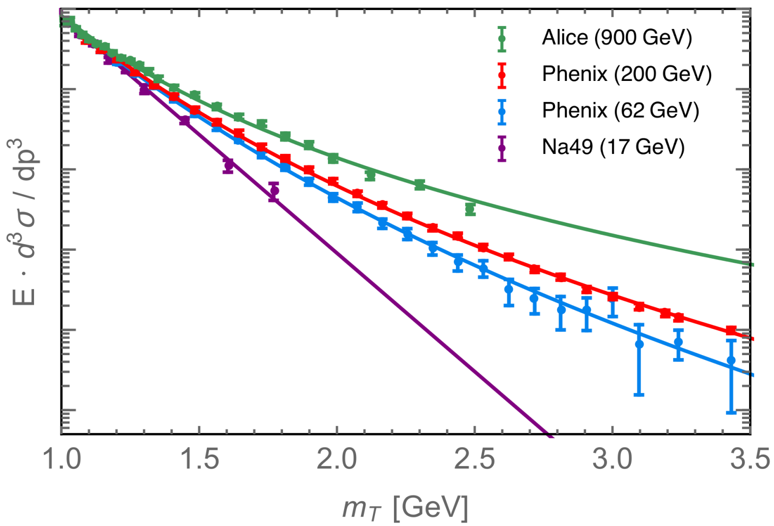
Cuoco, Krämer, Korsmeier, PRL 118 (2017),
Cui et al., PRL 118 (2017)

<u>how robust</u> ?

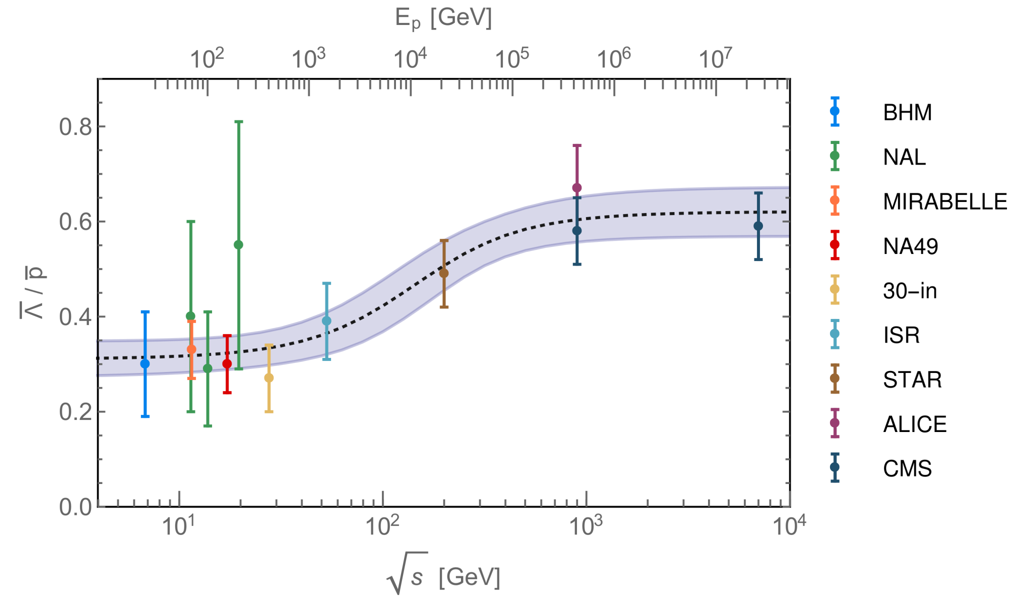
- include cross section uncertainties
- include B/C
- include low energy $\bar{p}$

Antiproton Cross Section for Astro Background

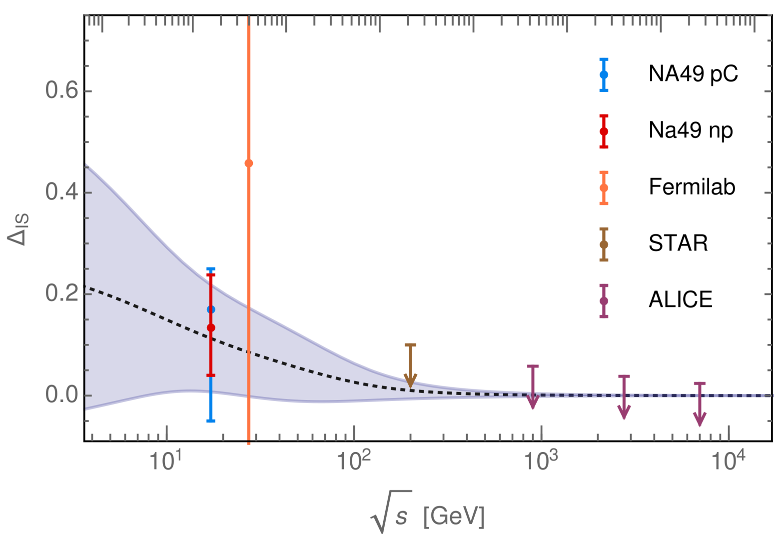
scaling violation



hyperons



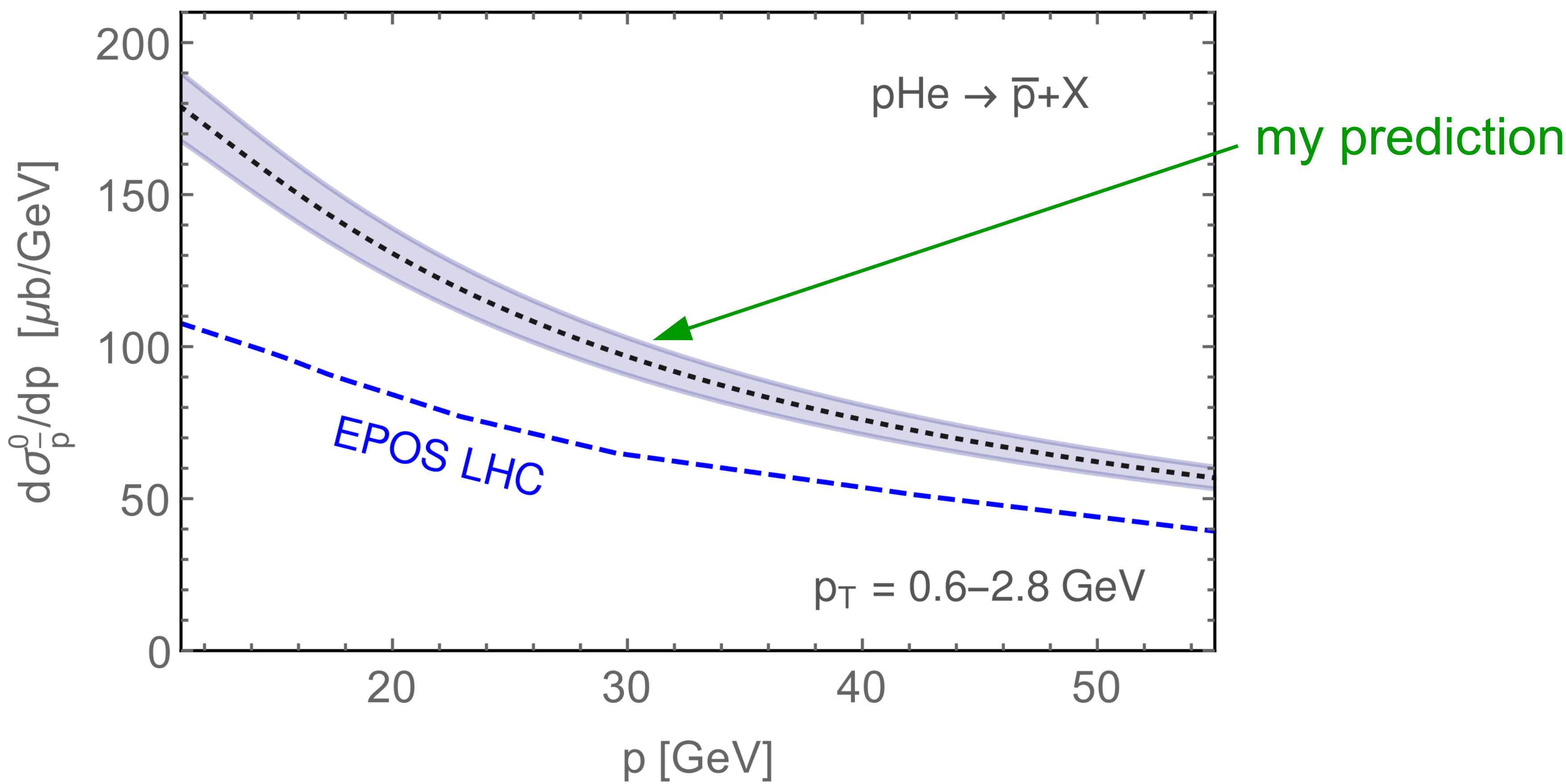
antineutrons



Data: PHENIX, Phys. Rev. C83 (2011), ALICE, Eur. Phys. J. C71 (2011), CMS, Eur. Phys. J. C72 (2012), Blobel, Nucl. Phys. B69 (1974), Amaldi, Nucl. Phys. B86 (1975), Whitmore, Phys. Rept. 10 (1974), Kichimi, Phys. Rev. D20 (1979), Ammosov, Nucl. Phys. B115 (1976), Abelev, Phys. Rev. C75 (2007), Aamodt, Eur. Phys. J. C71 (2011), Khachatryan, JHEP 05 (2011), Antreasyan, Phys. Rev. D19 (1979), Fischer, Heavy Ion Phys. 17 (2003), Baatar, Eur. Phys. J. C73 (2013), Aamodt et al., Phys. Rev. Lett. 105 (2010), Abbas et al., Eur. Phys. J. C73 (2013)

Proton Helium Scattering

- p-He scattering predicted from pp and p-C data
- confirmed by first LHCB measurement
  LHCb-CONF-2017-002



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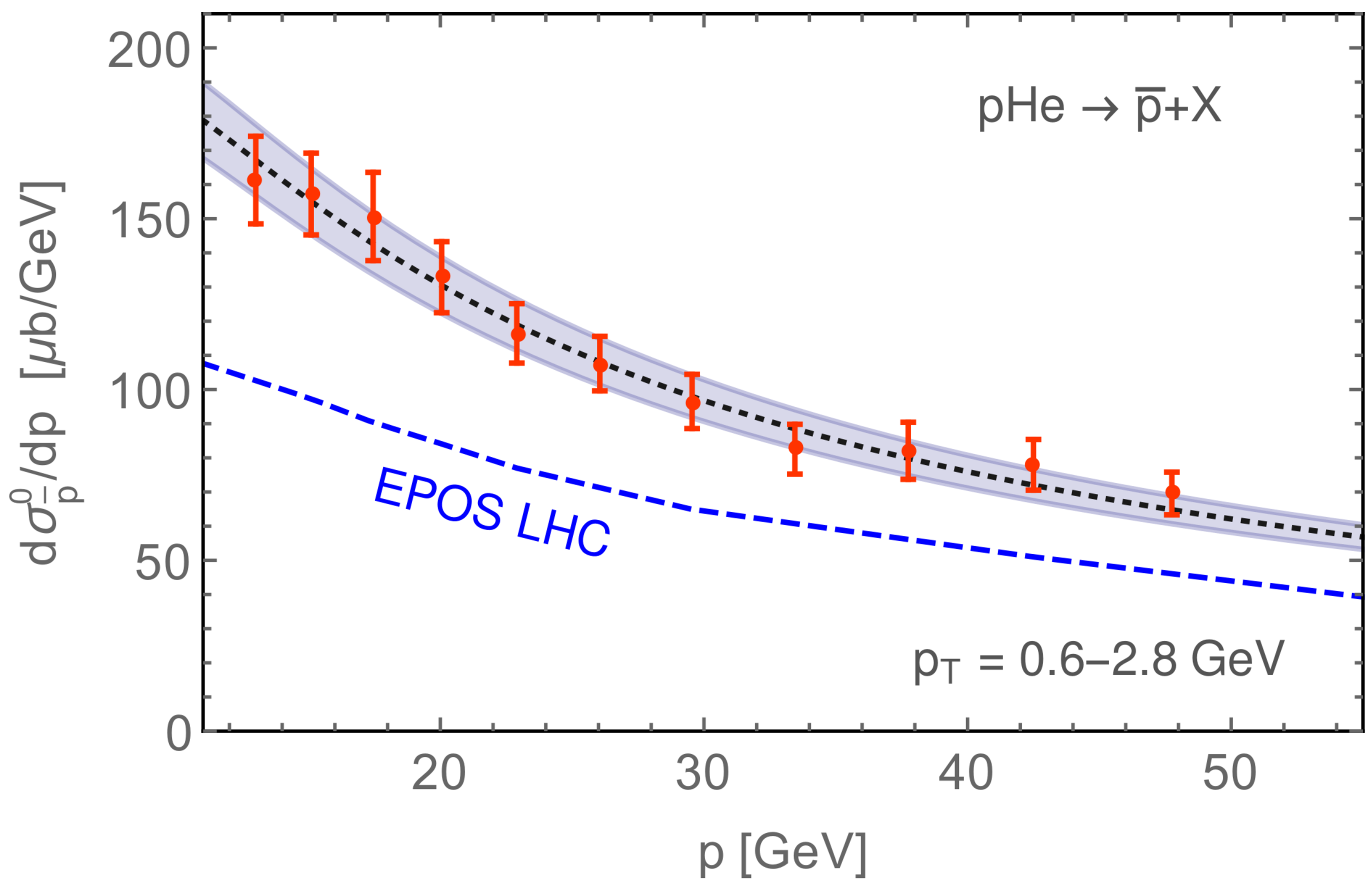
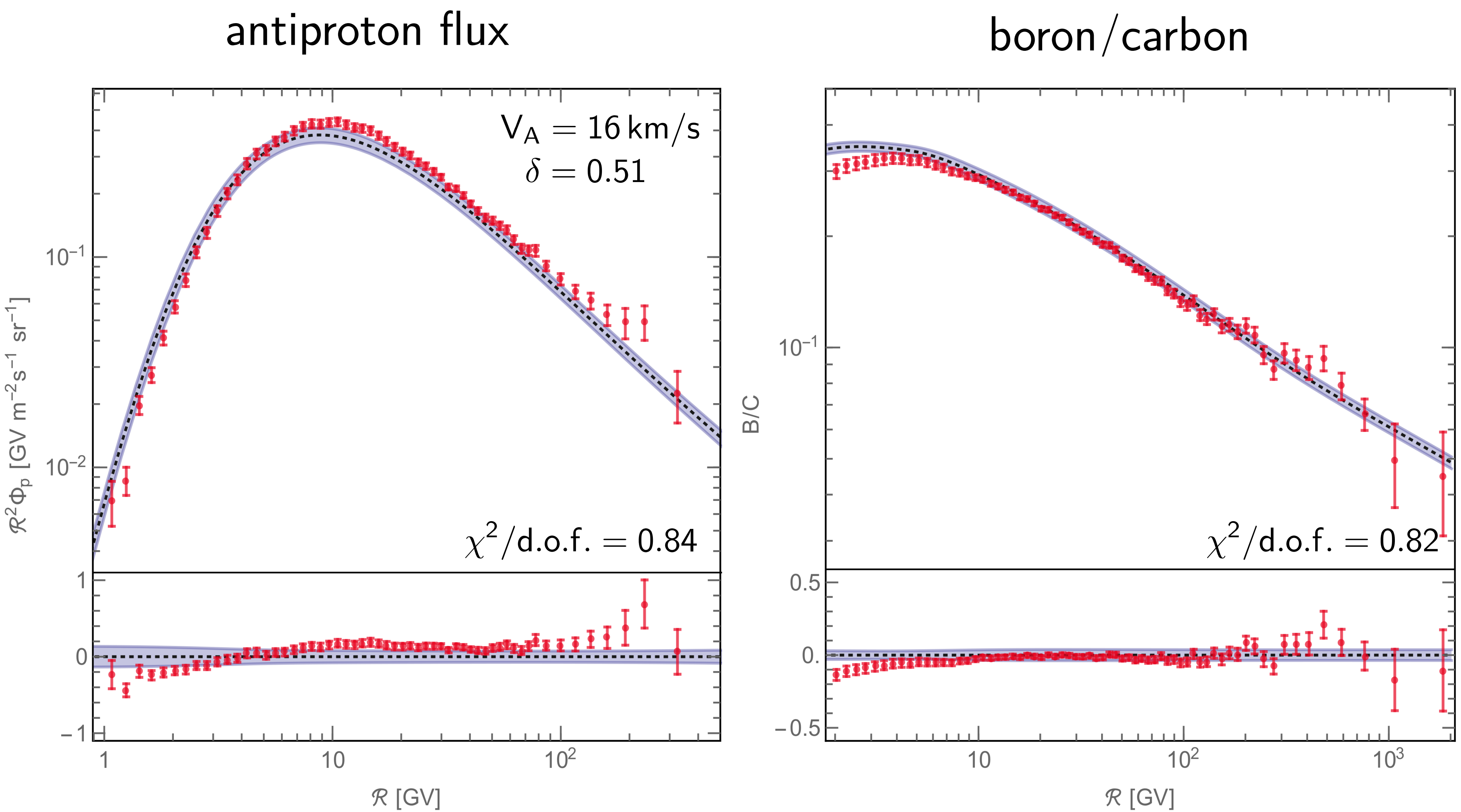


Antiproton + B/C Fit

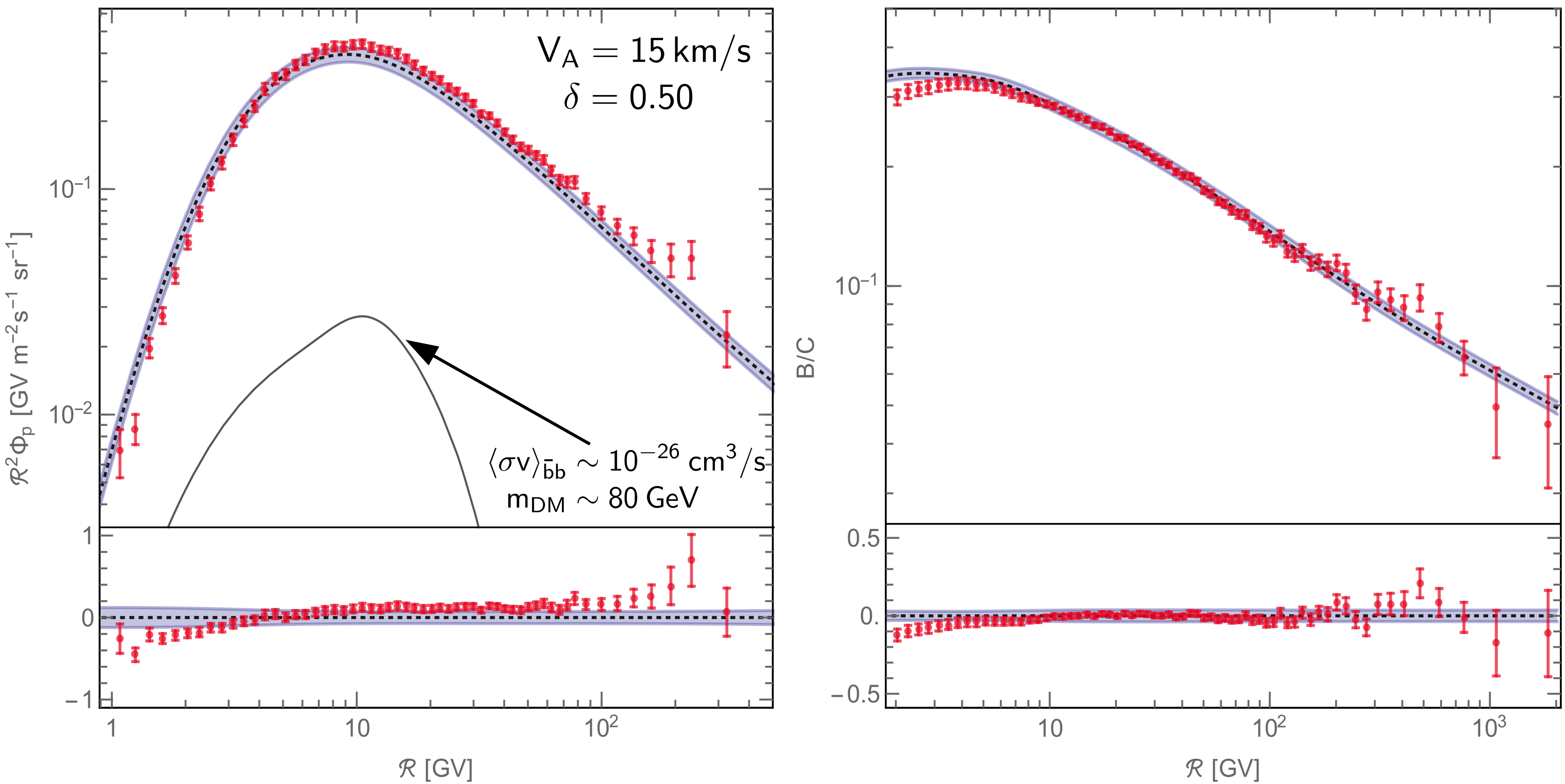


AMS-02 data: Aguilar et al., Phys. Rev. Lett. 117 (2016)

Fit with Dark Matter

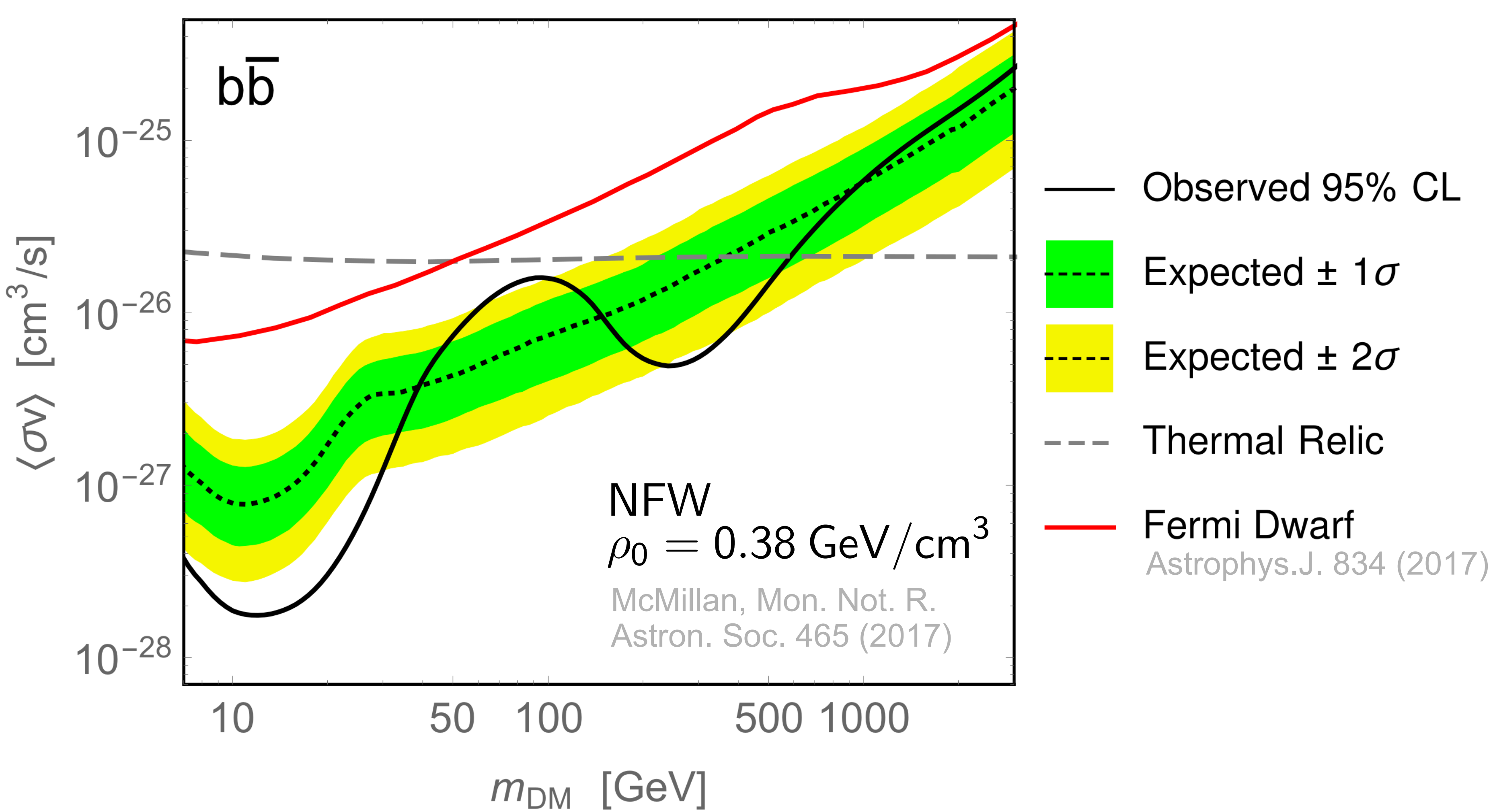
antiproton flux

boron/carbon



local significance 2.2σ (look-elsewhere ▶ 1.1σ)

Constraints on Dark Matter



Update by Cuoco et al.

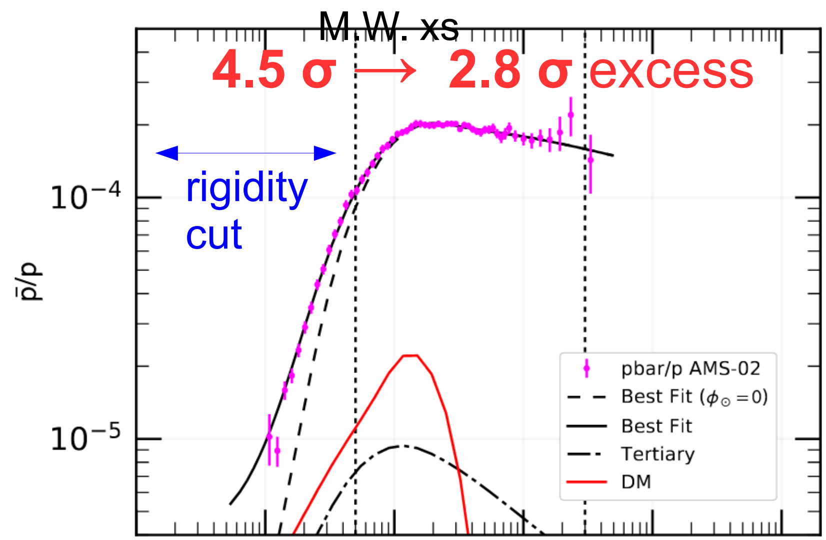
	χ^2		$\Delta\chi^2$
	no DM	**with DM**	
[Cuoco, Krämer, **MK;** 2017]	71.0	45.6	25.4
Restrict data to R < 300 GV	43.6	23.0	20.6
Change cross section to Winkler	**35.6**	**22.9**	**12.7**
Include data R > 300 GV (include CREAM) + fit of the break in diffusion	50.7	35.6	15.1

← New default setup in Ref. [Cuoco, **MK**, + ; 2019]

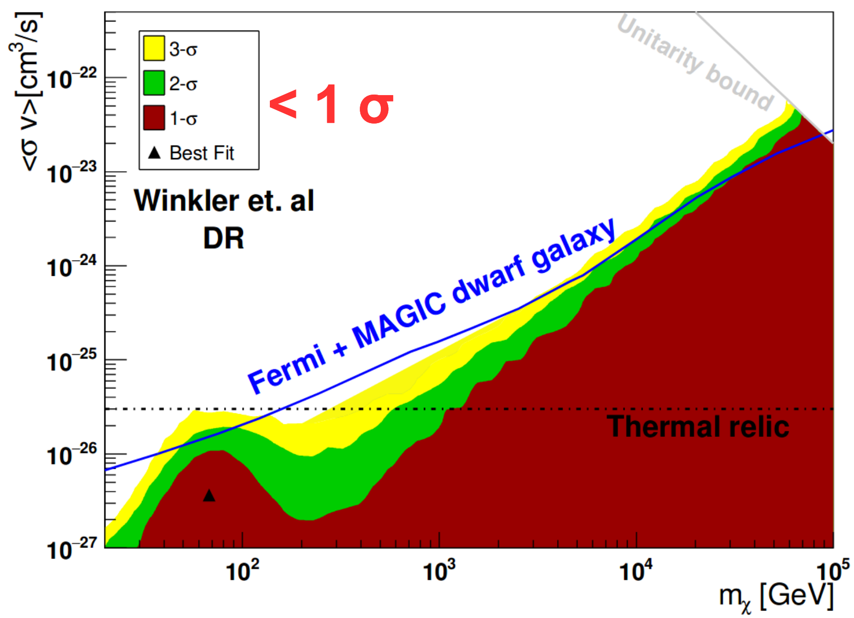
$$\Delta\chi^2 = 10.7 \quad \text{(with xs uncertainties)}$$

from M. Korsmeier (2019)

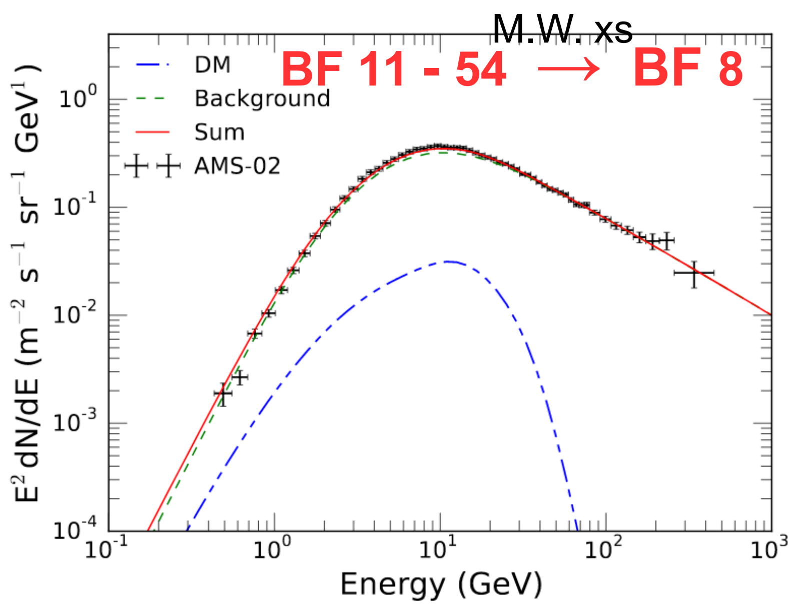
Comparison



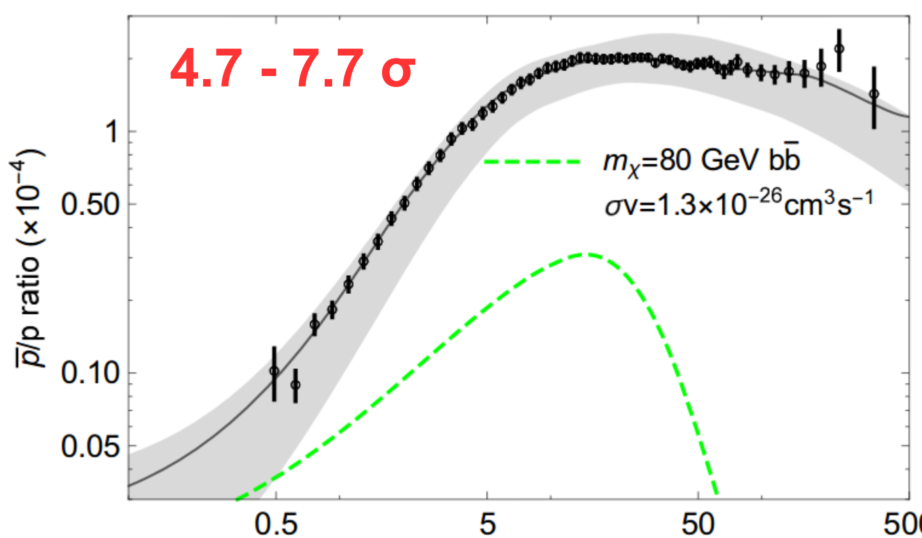
Cuoco et al., arXiv:1903.01472 (2019)



Lin et al., arXiv:1903.09545 (2019)

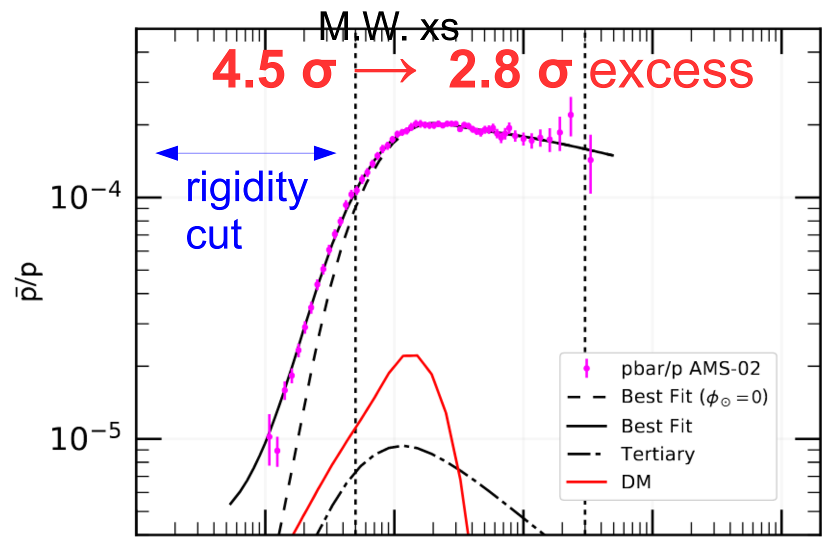


Cui et al., JCAP 1806 (2018)

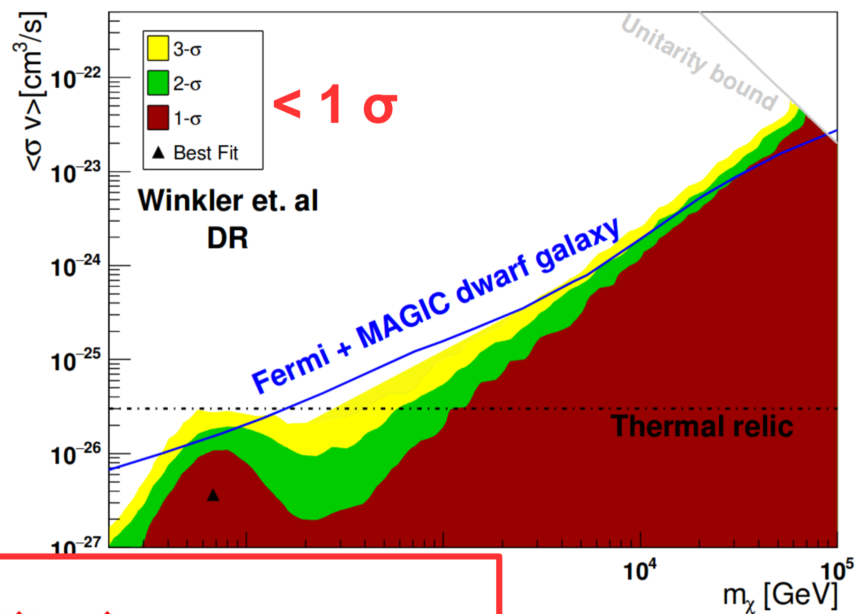


Cholis, Hooper, Linden, 1903.02549 (2019)

Comparison

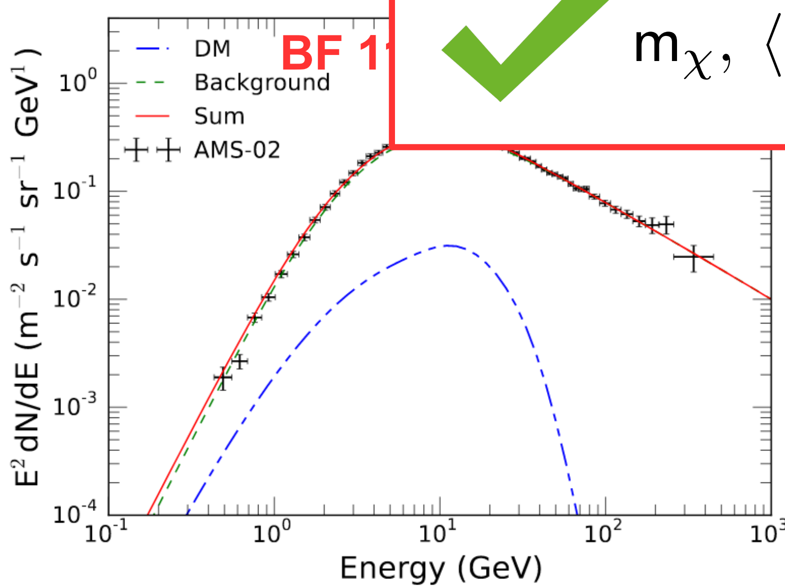


Cuoco et al., arX

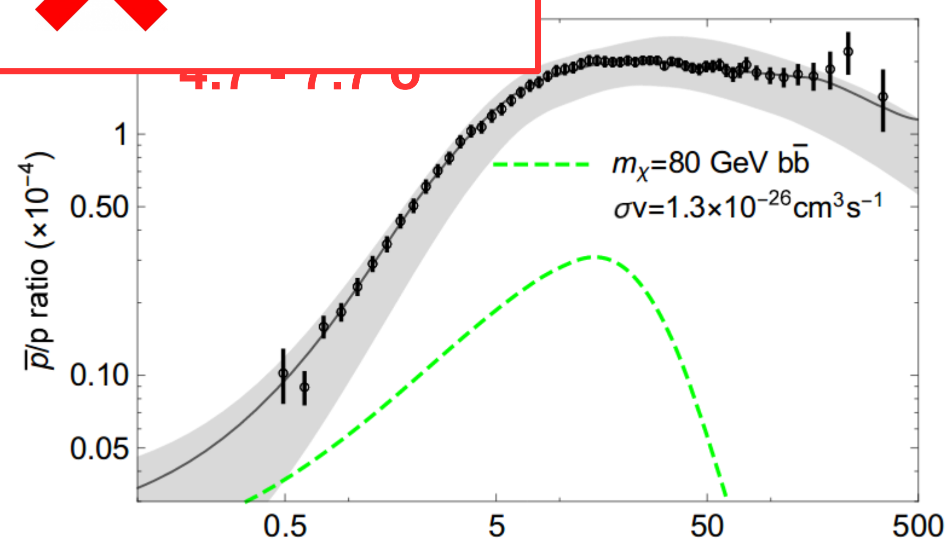


9545 (2019)

✔ $m_\chi,\ \langle\sigma v\rangle$ ✘ significance



Cui et al., JCAP 1806 (2018)



Cholis, Hooper, Linden, 1903.02549 (2019)

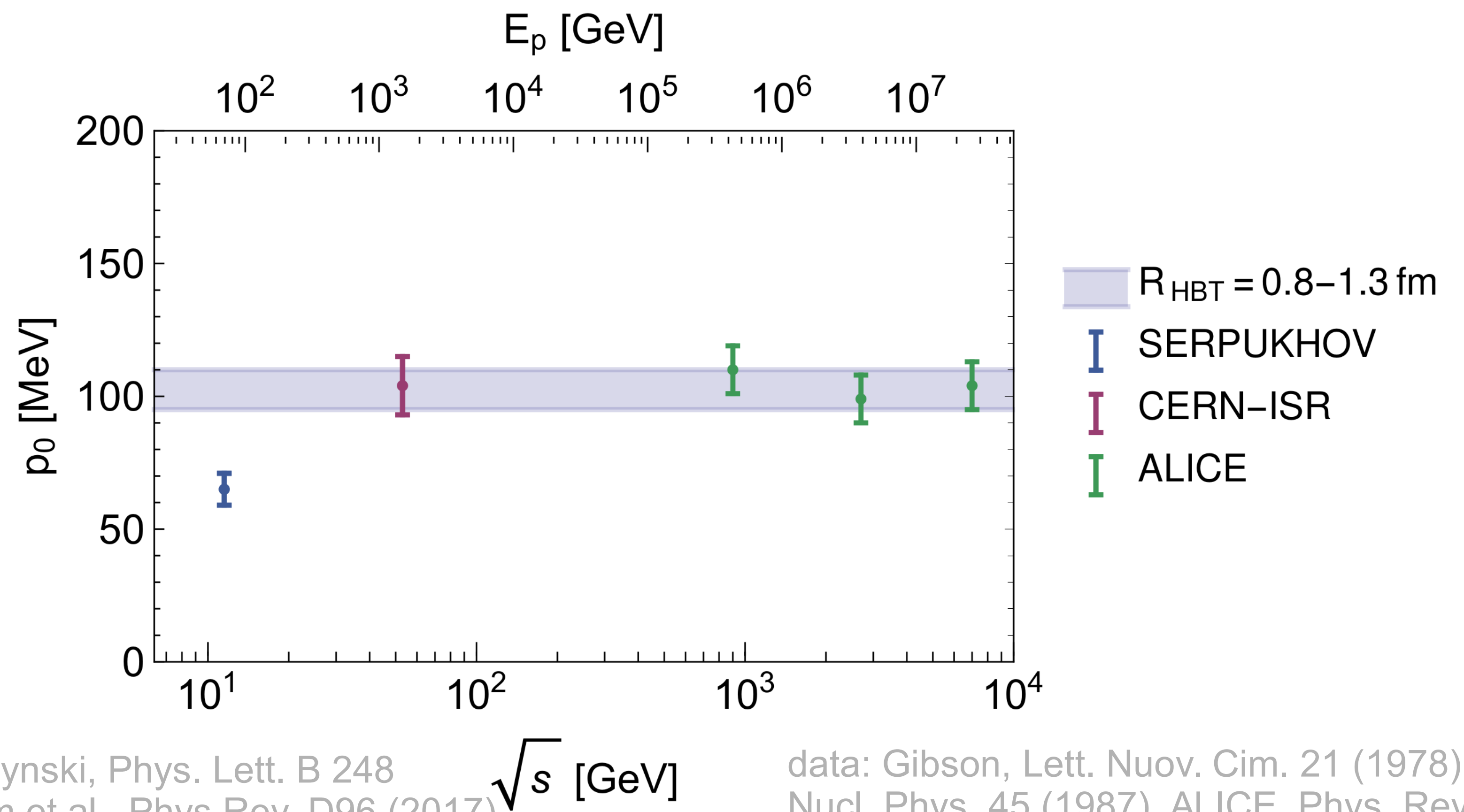
Antideuteron Coalescence

- coalescence model

Schwarzschild, Zupancic, Phys. Rev. 129 (1963)

$$\frac{d^3 n_d}{dp_d^3} = \frac{1}{8}\int d^3q \quad \frac{d^6 n_{pn}}{dp_p^3\, dp_n^3}\bigg|_{\mathbf{p}_{p,n}=\frac{\mathbf{p}_d \pm \mathbf{q}}{2}} \Theta\left(p_0 - q\right)$$

p_0: coalescence momentum

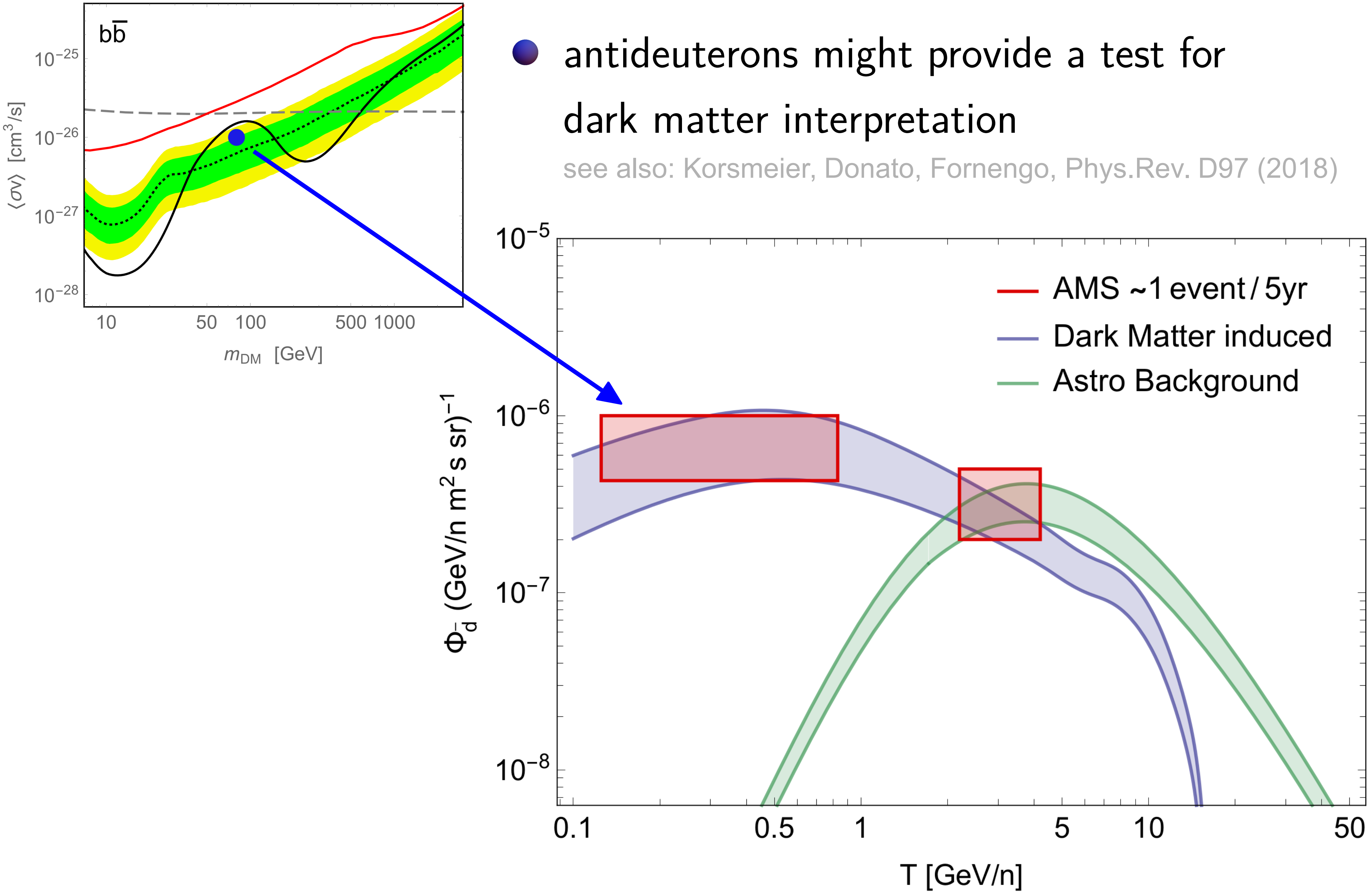


see Mrowczynski, Phys. Lett. B 248 (1990), Blum et al., Phys.Rev. D96 (2017)

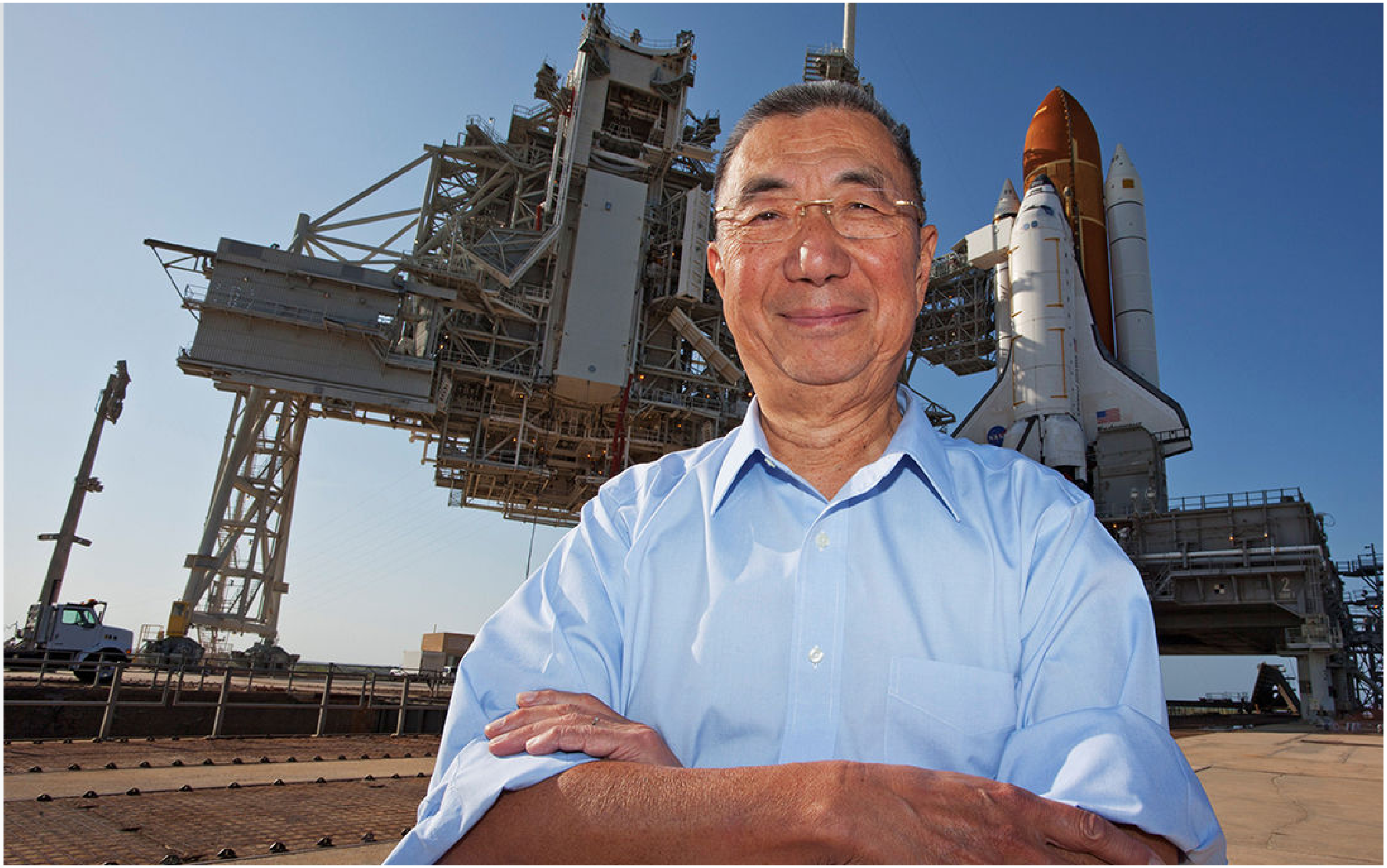
data: Gibson, Lett. Nuov. Cim. 21 (1978), Abramov, Sov. J. Nucl. Phys. 45 (1987), ALICE, Phys. Rev. C 97 (2018)

- antideuterons might provide a test for dark matter interpretation

see also: Korsmeier, Donato, Fornengo, Phys.Rev. D97 (2018)



Antihelium



Sam Ting's Alpha Magnetic Spectrometer was delivered to space in 2011 on the next-to-last space shuttle flight. RGB VENTURES/SUPERSTOCK/ALAMY STOCK PHOTO

Science Magazine 2017

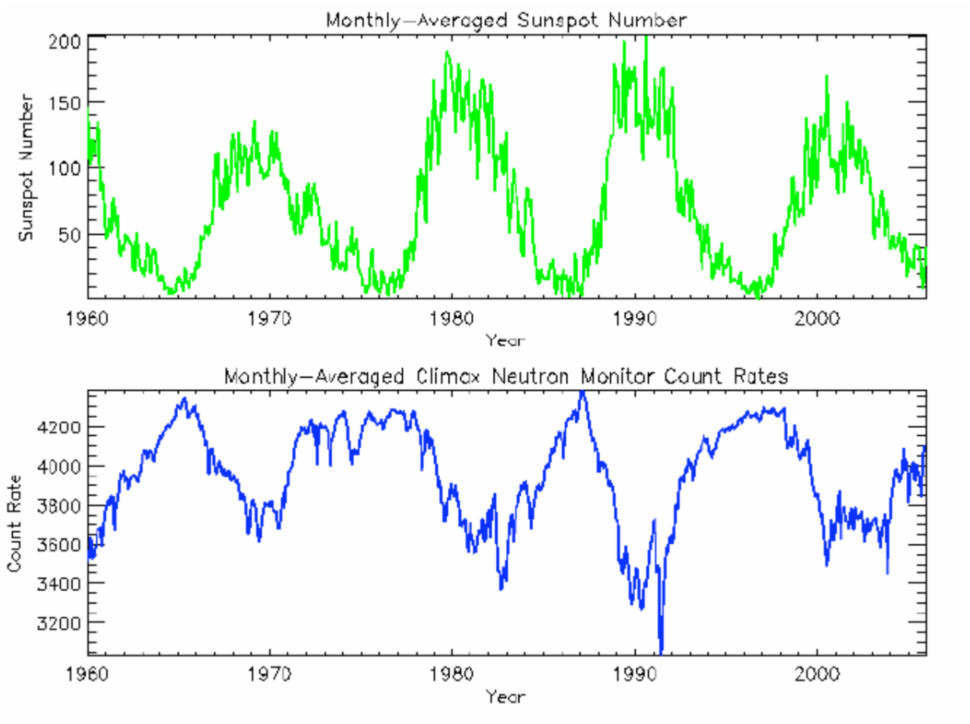
SHARE

Giant space magnet may have trapped antihelium, raising idea of lingering pools of antimatter in the cosmos

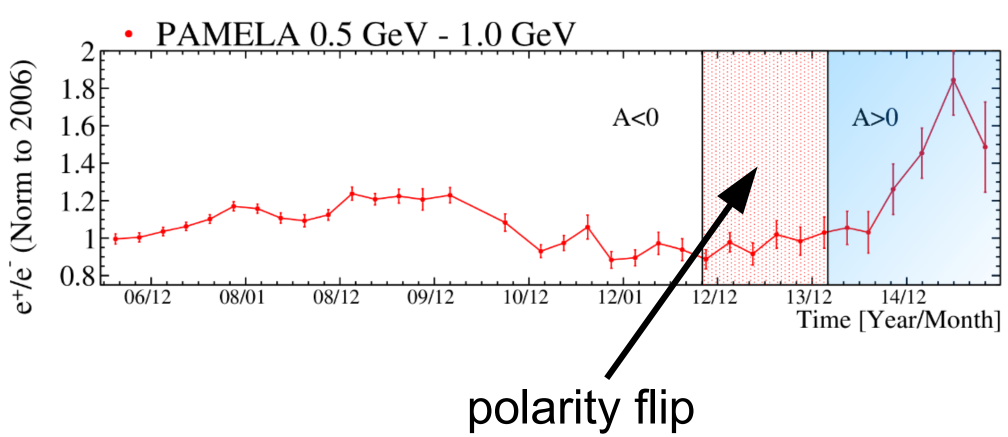
Conclusion

- indirect dark matter searches have reached the sensitivity to probe canonical thermal WIMPs
- astrophysical backgrounds (pulsars, secondary cosmic rays, ...) pose severe challenge, but understanding is improving
- no conclusive evidence for dark matter yet, but excesses (galactic center, antiproton) define interesting target for future searches

Solar Modulation

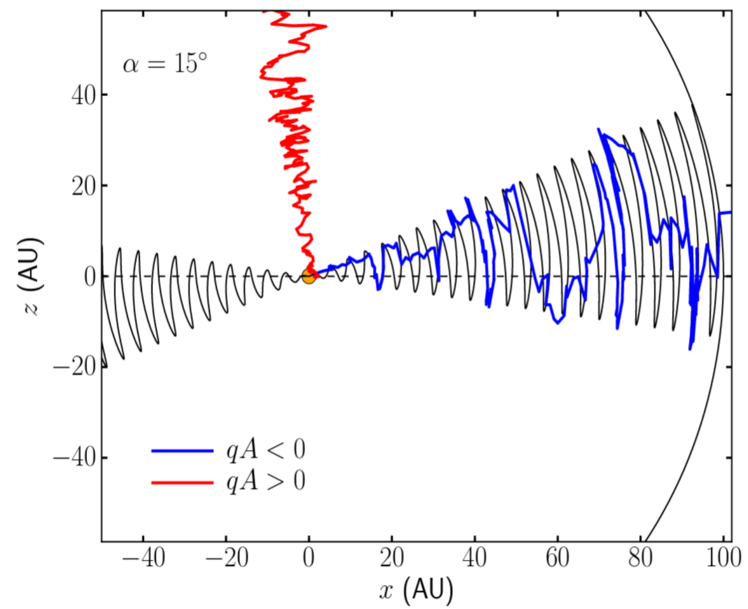


Mertens et al., AIAA Meeting (2008)



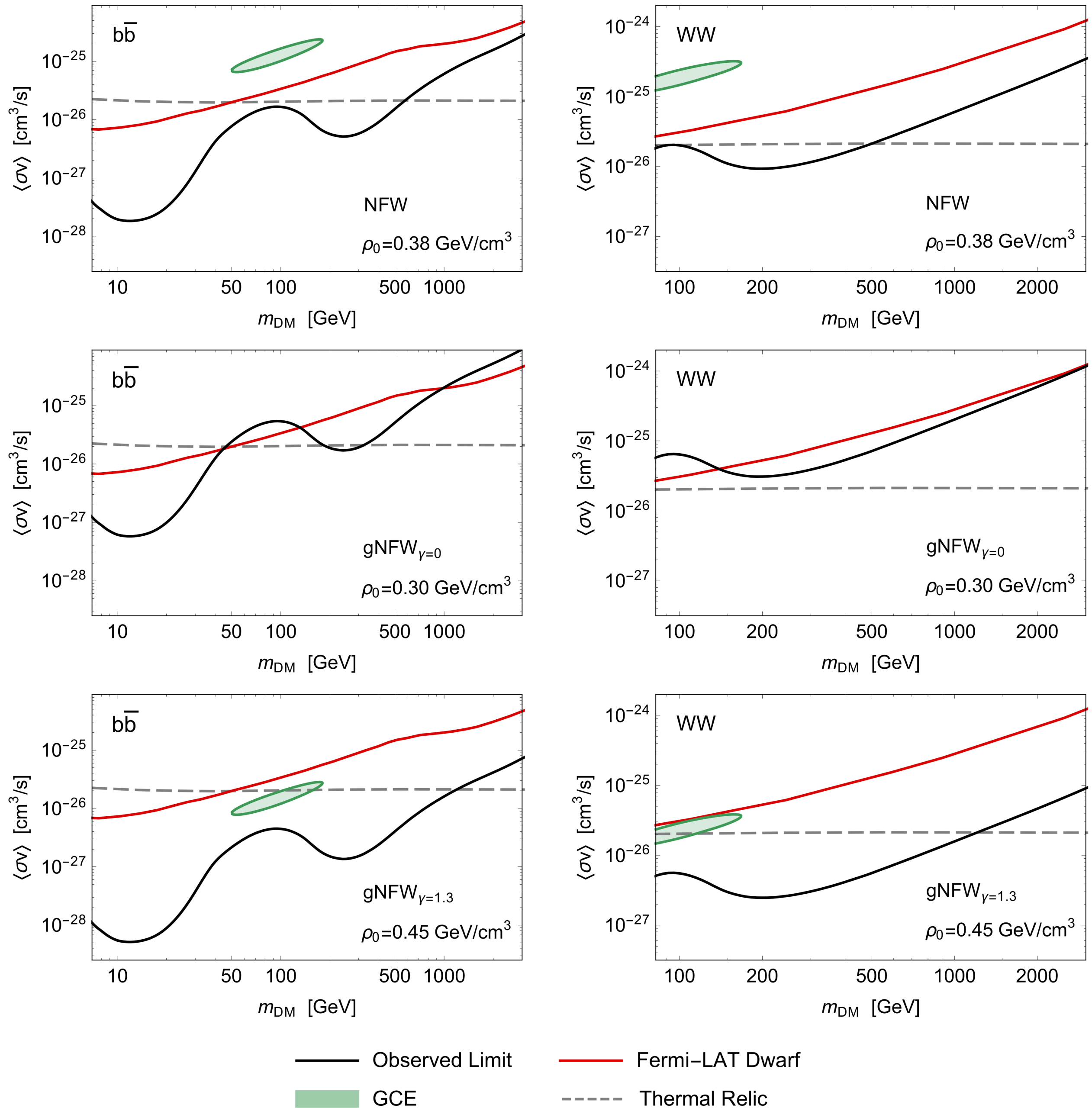
- low-energy (E<10 GeV) cosmic rays are significantly affected solar magnetic fields
- charge-sign dependent

Jokipii, Thomas, Astrophys. J. 243 (1981)

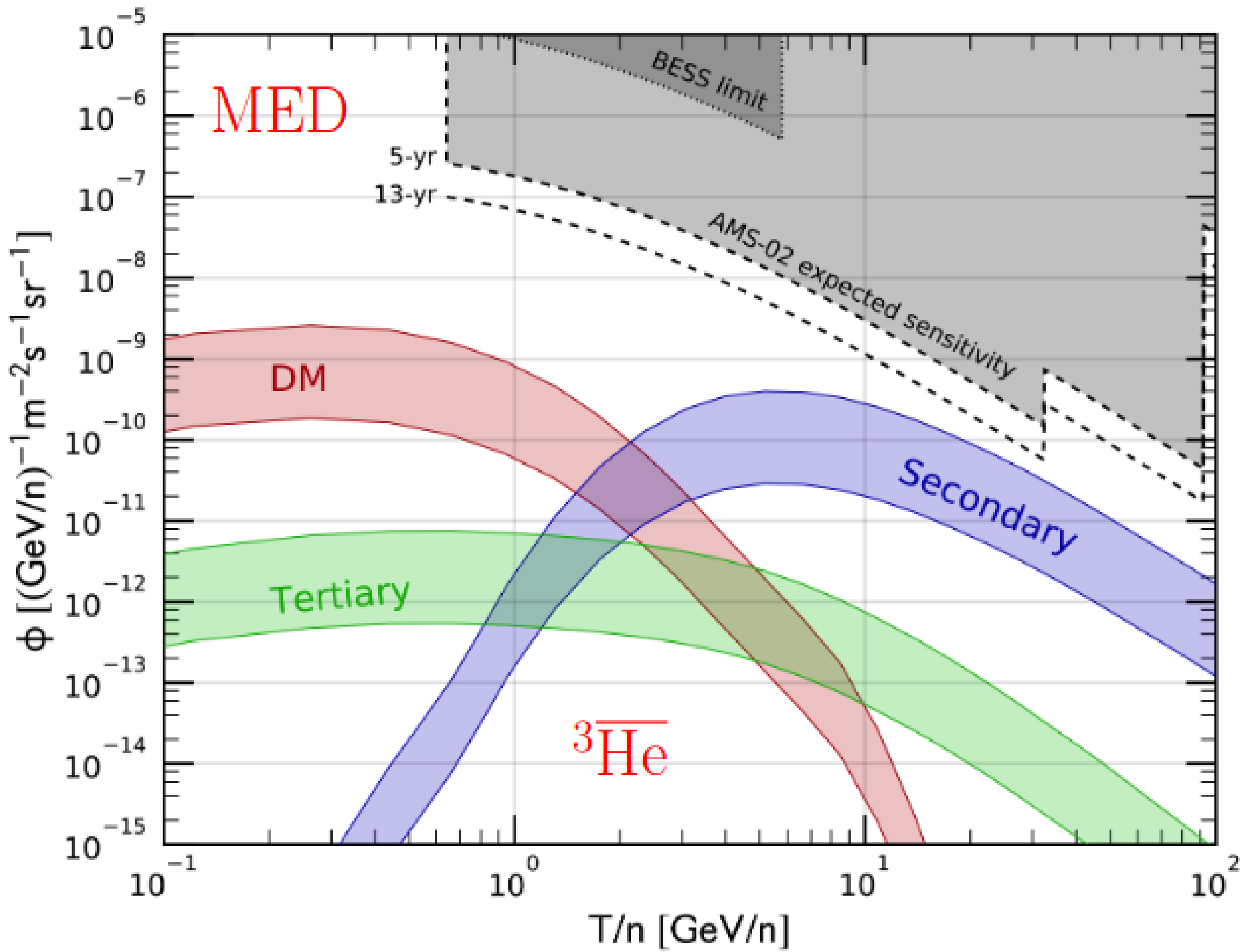


Cholis, Hooper, Linden, Phys. Rev. D 93 (2016)

Antiproton vs.Gamma Ray Excess



Antihelium



Korsmeier et al., Phys. Rev. D97 (2018)