Cosmic ray antiprotons as a dark matter probe

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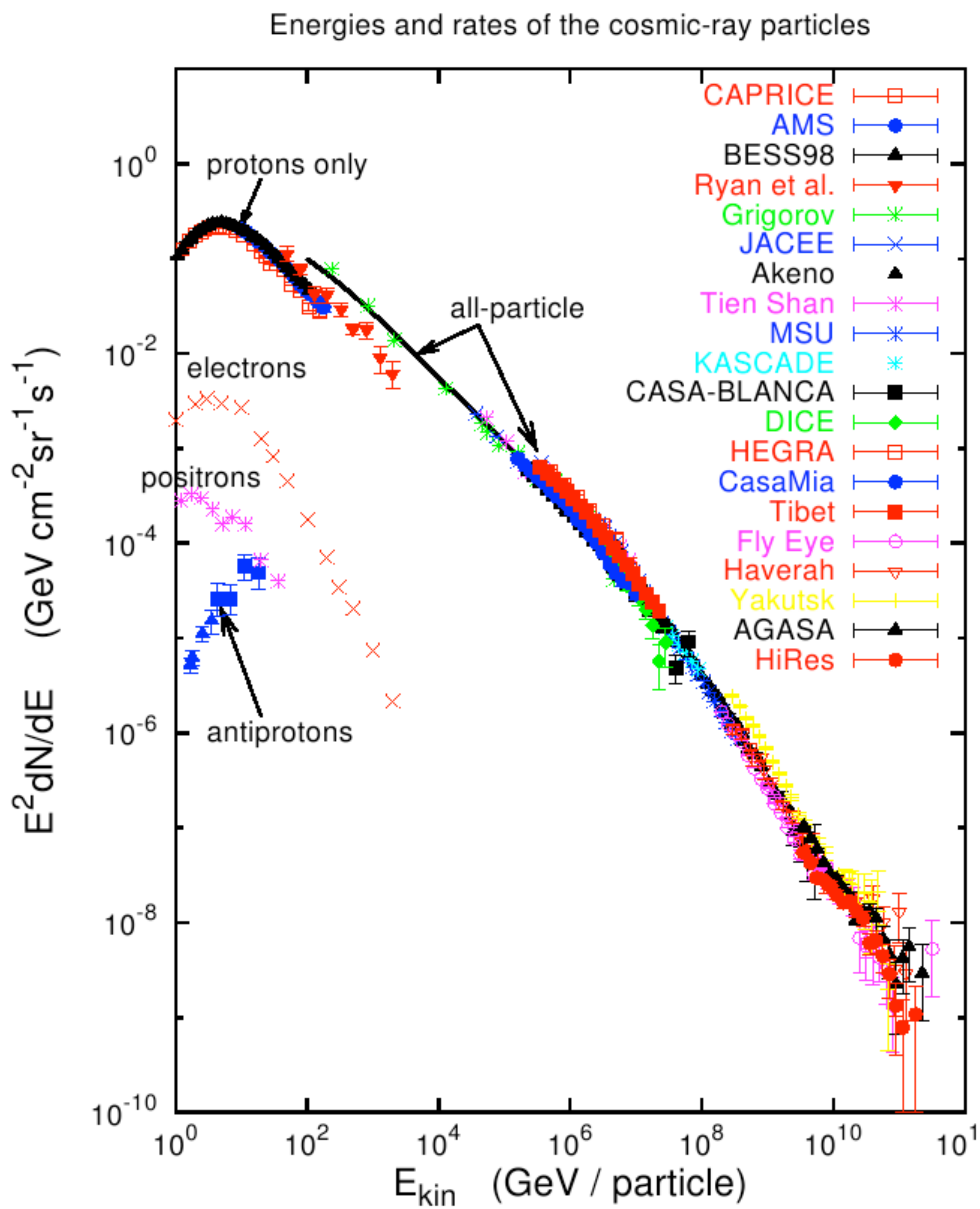
LFC15, ECT* Trento

Outline

- Basic facts about Galactic cosmic rays and their propagation
- Secondary antiprotons: main uncertainties
- Is there a AMS-02 antiproton excess ?
- Antiprotons from dark matter annihilation: astrophysical uncertainties
- Antiproton constraints on the Galactic center GeV excess
- Conclusions and few personal considerations

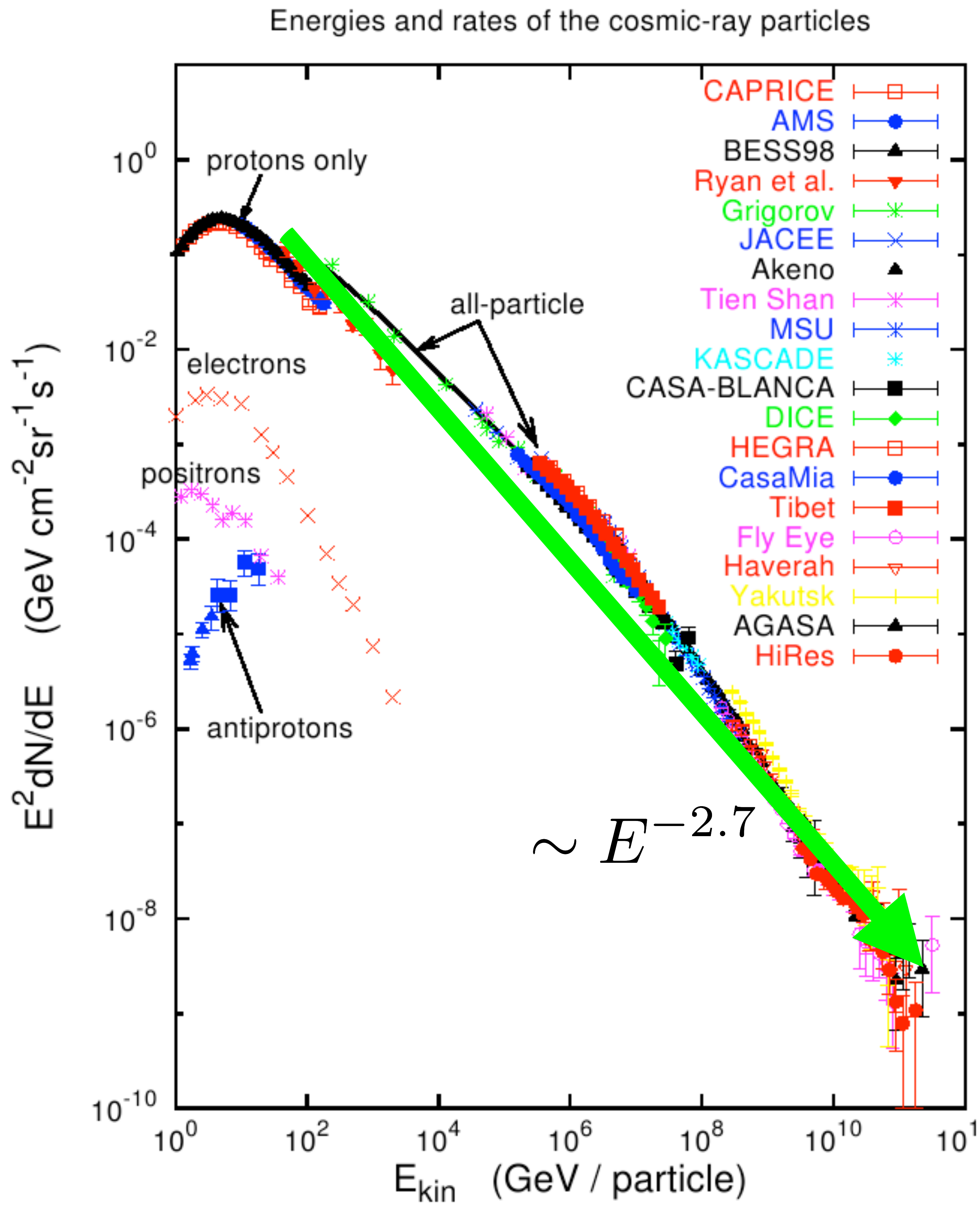
Few basic facts about cosmic rays

Cosmic-ray flux



Cosmic-ray flux

- Almost a perfect power-law over 12 energy decades.



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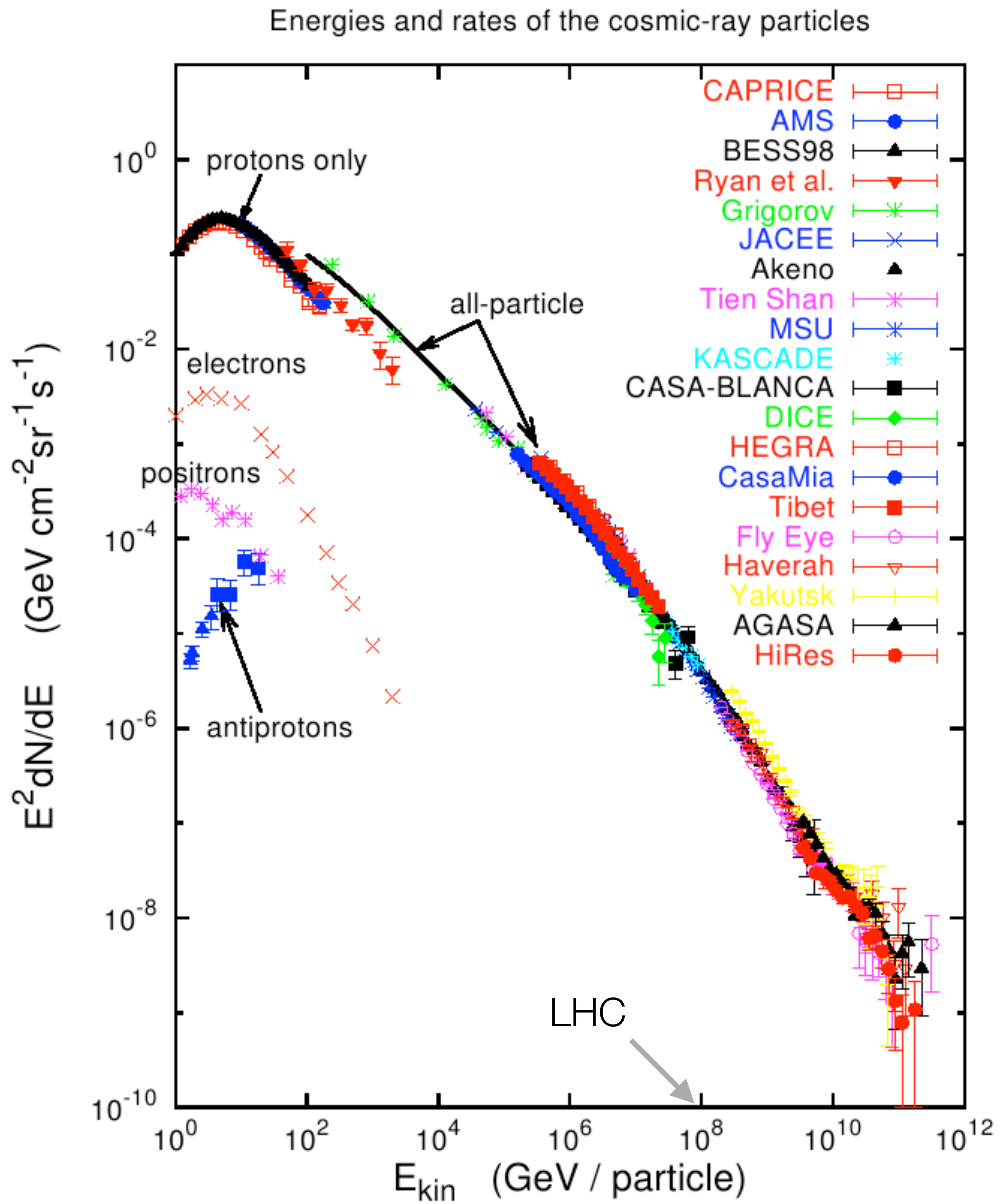

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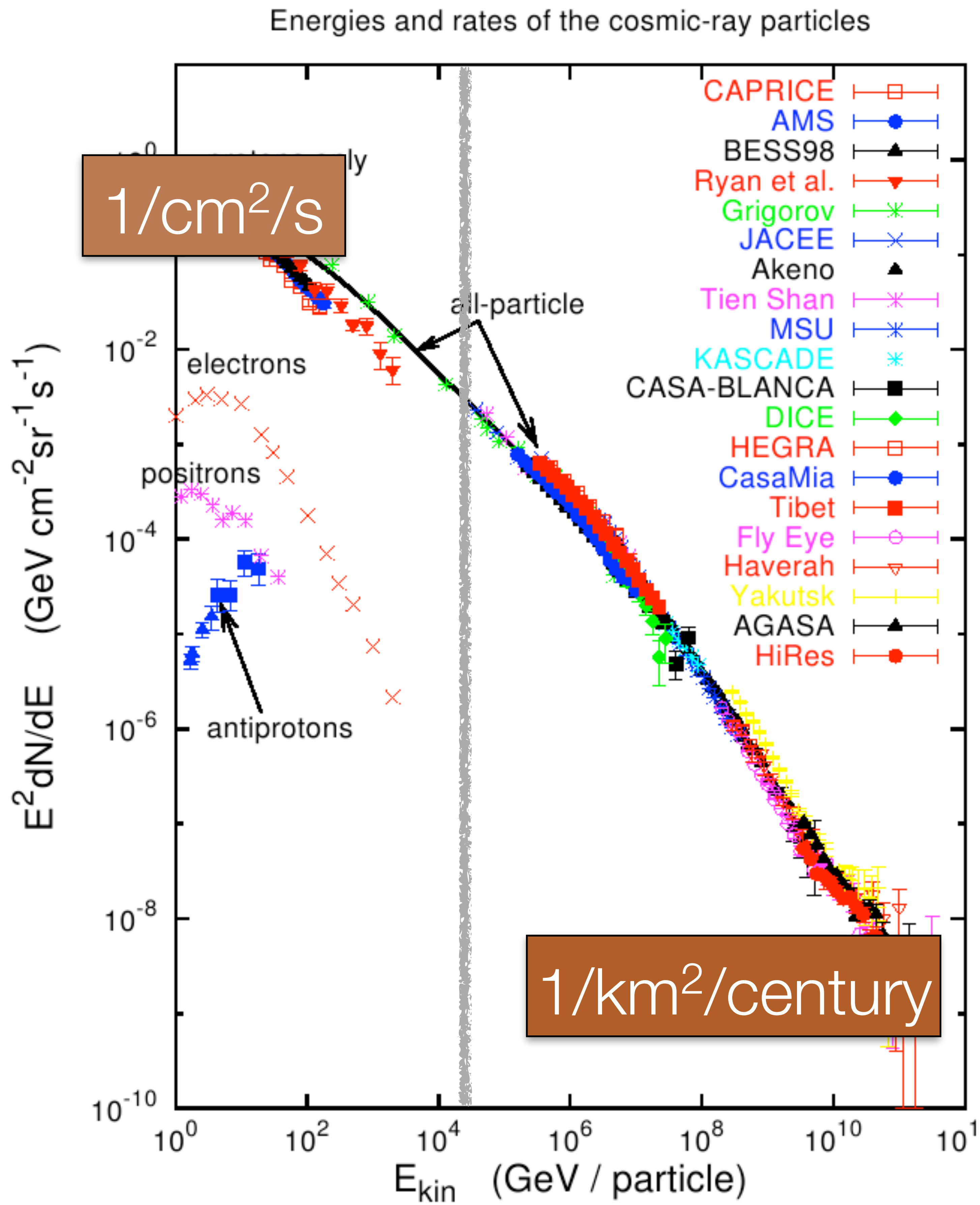

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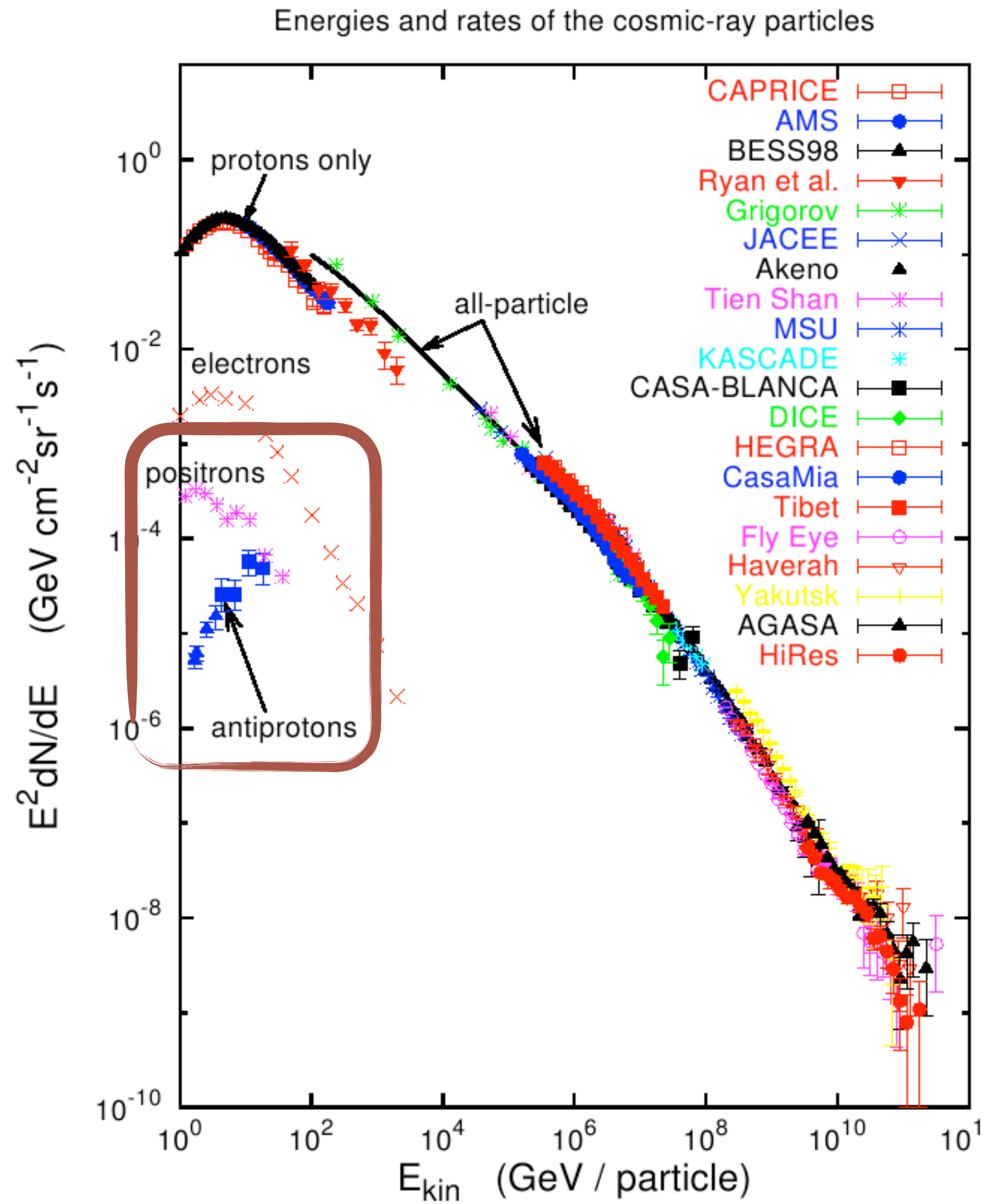

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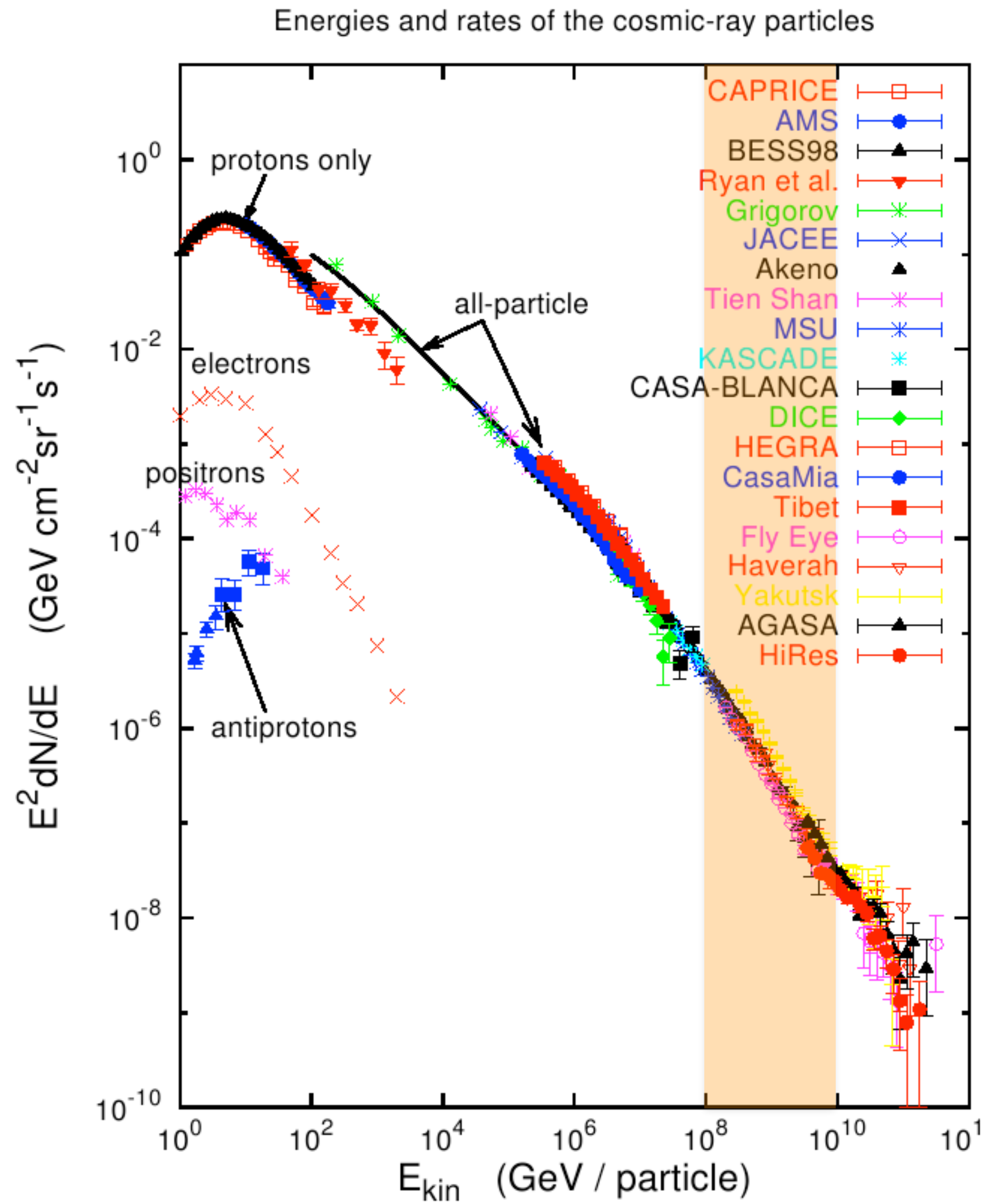

Cosmic-ray flux

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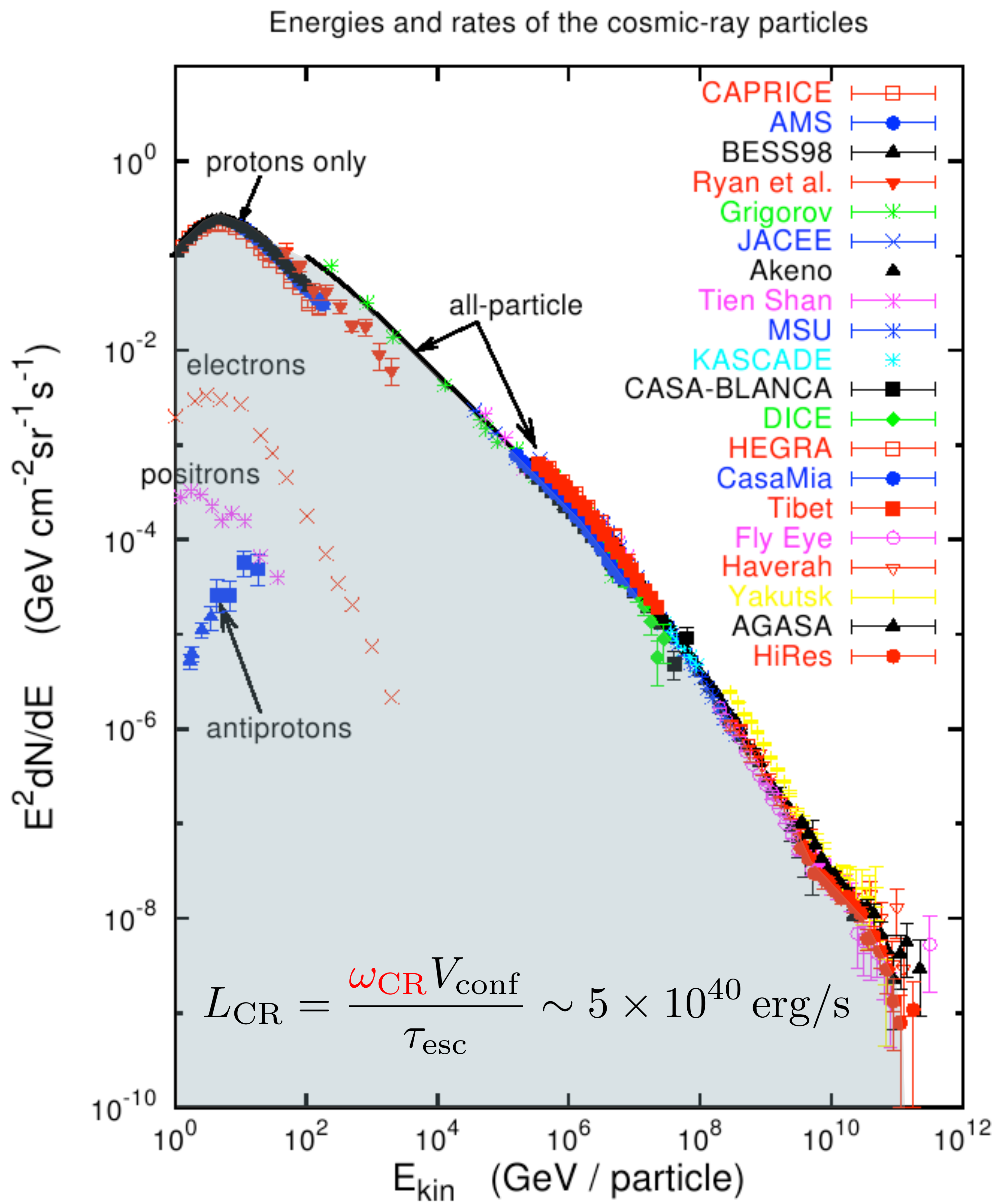
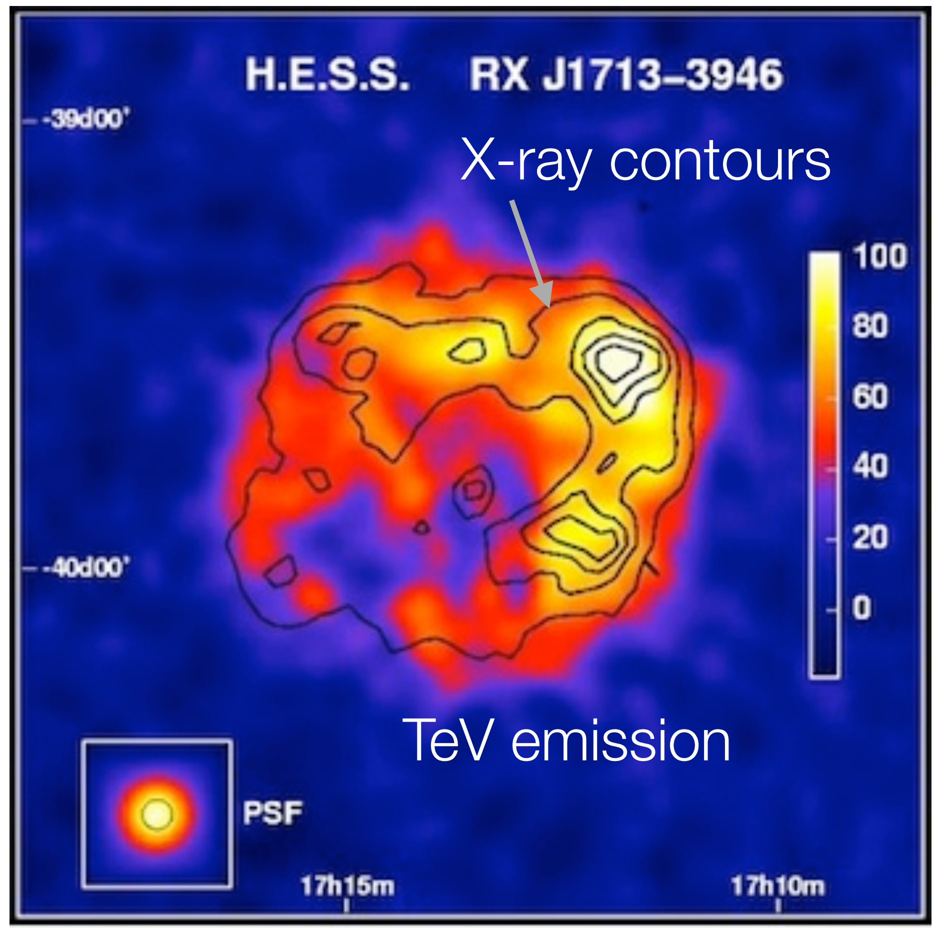
- Observed at energies higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.
- Anti-matter component.
- Transition from galactic to extra-galactic?
- Energy density in equipartition with starlight, turbulent gas motions and magnetic fields.



The SN paradigm



Aharonian et al., Nature, 2007

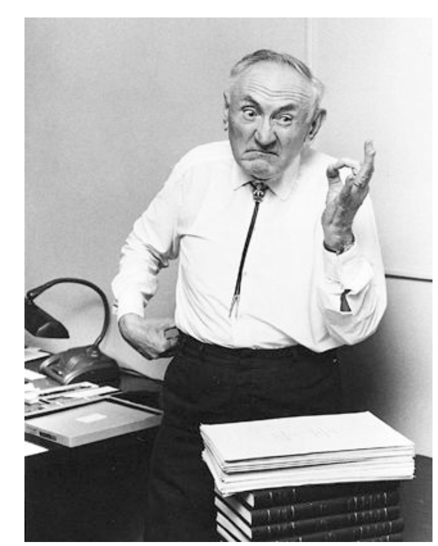
hadronic:

$$p\, p_{\rm ISM} \to \pi^0 \to \gamma\gamma$$

or leptonic:

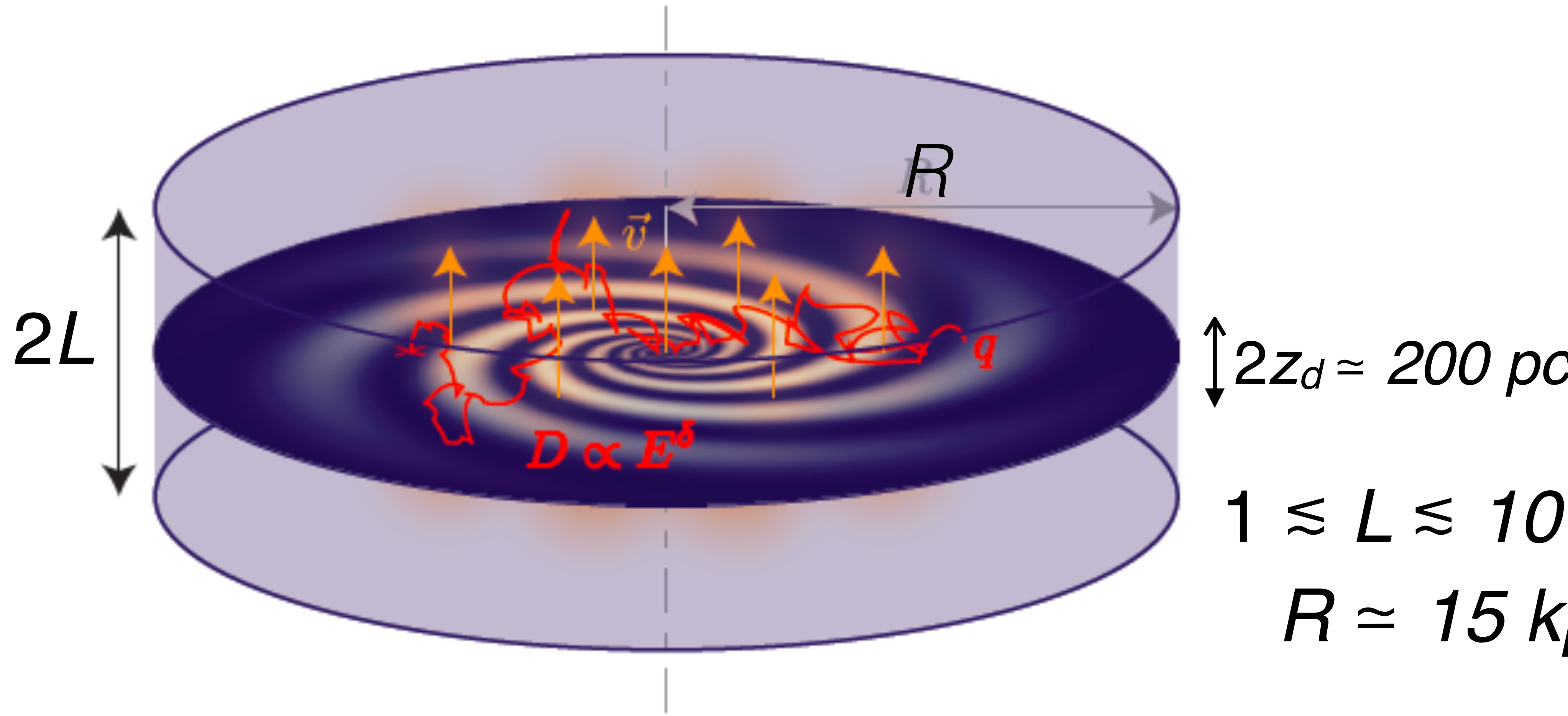
$$e^-\, \gamma_{\rm ISRF} \to e^-\, \gamma$$

$$L_{\rm SN} \sim R_{\rm SN} E_{\rm kin} \sim 3 \times 10^{41}\, {\rm erg/s}$$



Fritz Zwicky

The Galactic CR pool



$1 \lesssim L \lesssim 10$ kpc

$R \simeq 15$ kpc

Our position: $R \simeq 8.3$ kpc $\quad z \simeq 0$

The CR transport equation

CRs obey essentially a diffusion equation (**Ginzburg & Syrovatsky, 1964**)

Diffusion tensor
$D(E) = D_0\,(\rho/\rho_0)^\delta$
$\rho = \text{rigidity} \sim p/Z$

Convection term

Energy loss

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

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\,\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$
$$= Q^i(p,r,z) + \sum_{j>i} c\beta n_{\rm gas}(r,z)\sigma_{ji}N^j - c\beta n_{\rm gas}\sigma_{\rm in}(E_k)N^i$$

SN source term.
We assume everywhere
a power law energy spectrum

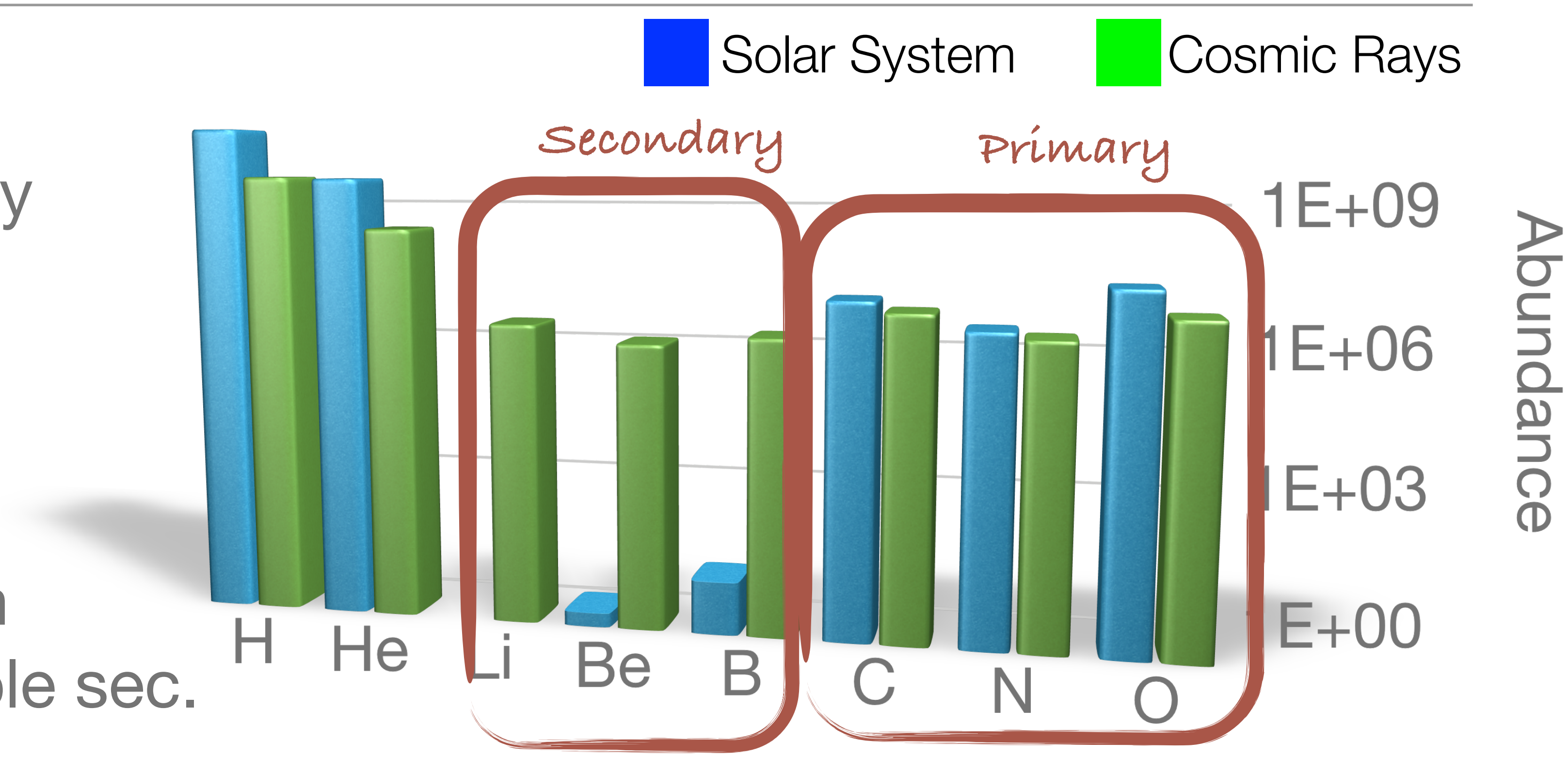
Spallation cross section. Appearance of nucleus i due to spallation of nucleus j

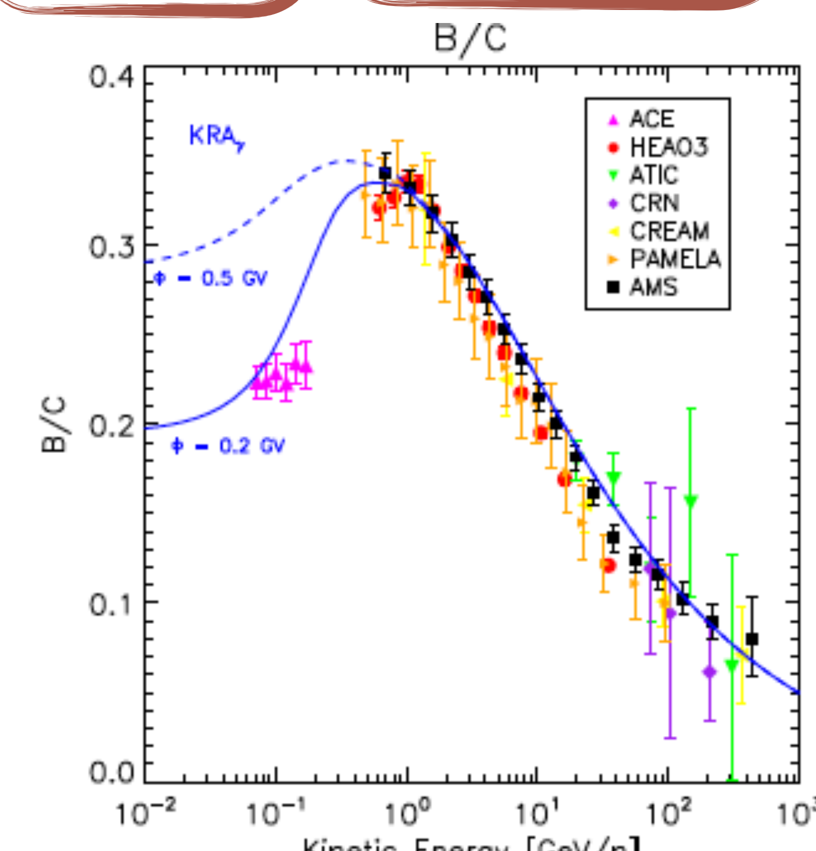
Total inelastic cross section.
Disappearance of nucleus i

A large number of parameters to be fixed against data !

Cosmic-ray primary and secondary components

- Li, Be and B as well sub Fe elements must be produced by spallation of heavier primaries
- Secondary/primary (B/C most importantly) provide valuable information about propagation (barring degeneracies, possible sec. production in the acceleration sites, ..)
- Once constrained in that way the same parameters can be used to compute other secondaries (e^+,$\bar{p}$) or to model Dark Matter products propagation





Solar modulation

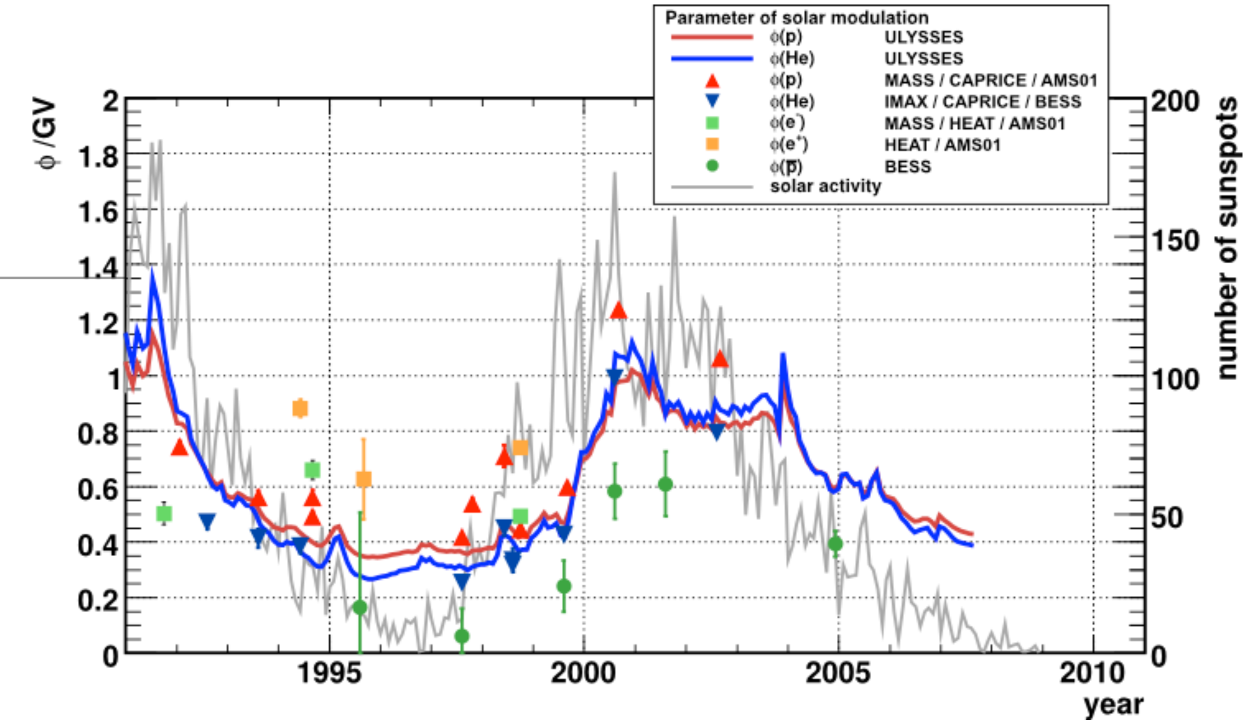
- The magnetized solar wind advects CRs reducing their energy

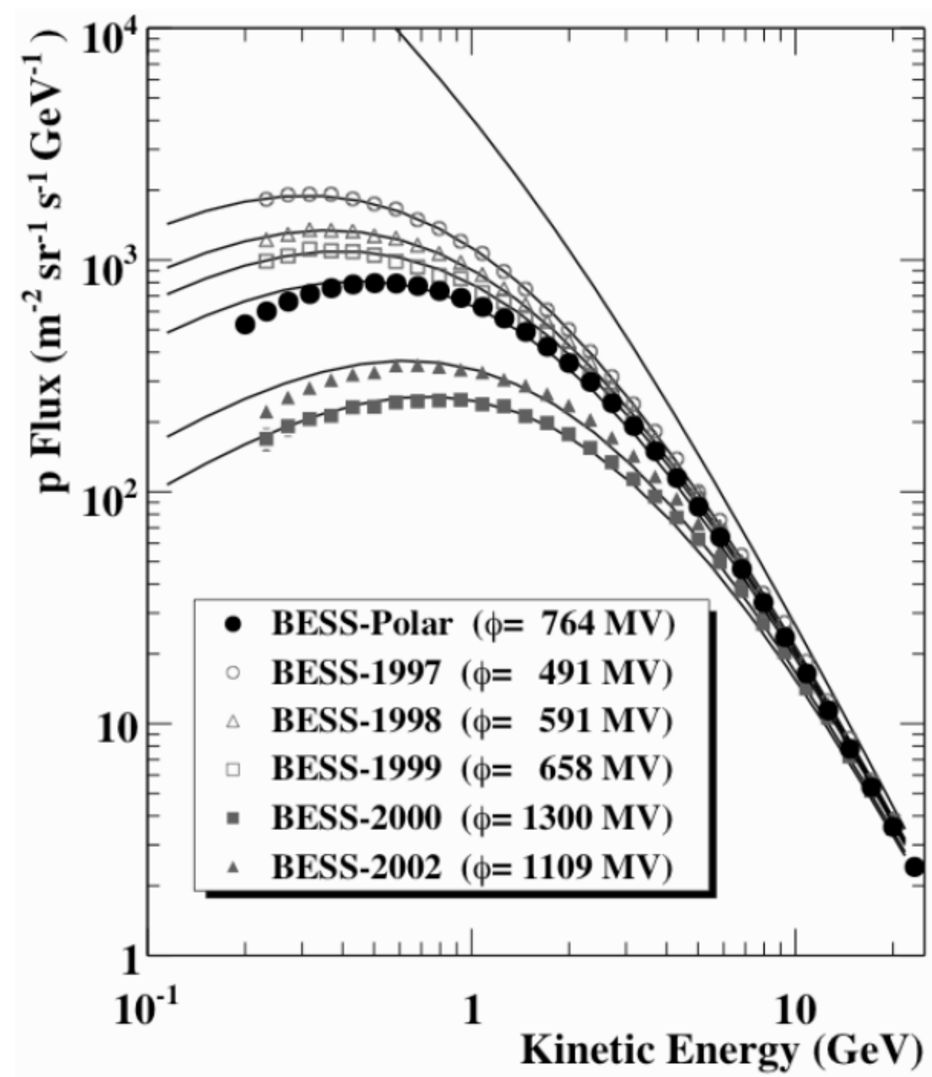
- The effect is relevant below 10 GV and it temporally anti-correlated with solar activity

- Neglecting charge-dependent drifts (see below) in the heliosphere (pure adiabatic cooling) the effect can be treated in terms of a single time dependent parameter Φ: **force field approximation**

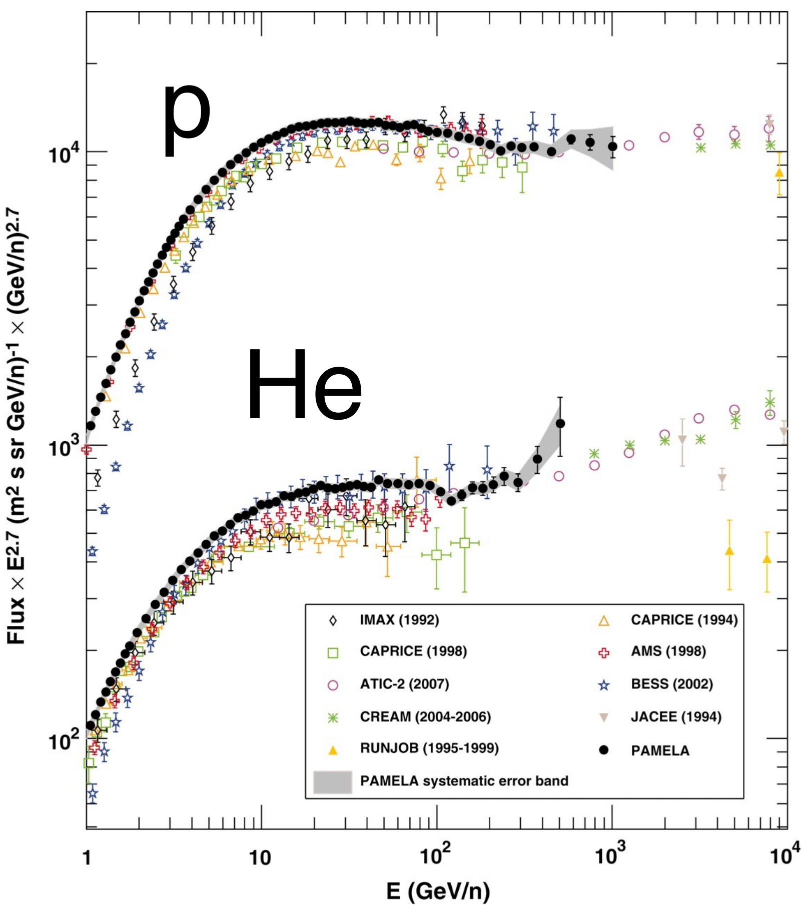
$$J(E_k, Z, A) = \frac{(E_k + m)^2 - m^2}{\left(E_k + m + \frac{Z|e|}{A}\Phi\right)^2 - m^2} \; J_{\rm LIS}(E_k + \frac{Z|e|}{A}\Phi, Z, A)$$

Gleeson & Axforfd 1968



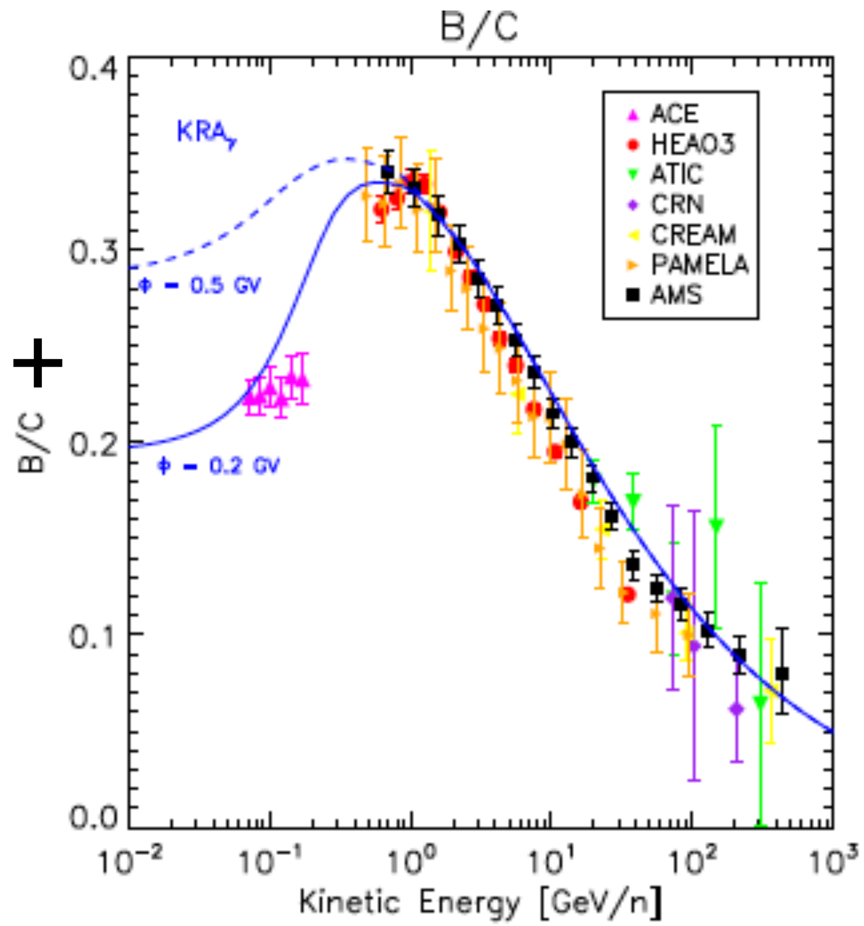


Secondary Antiprotons

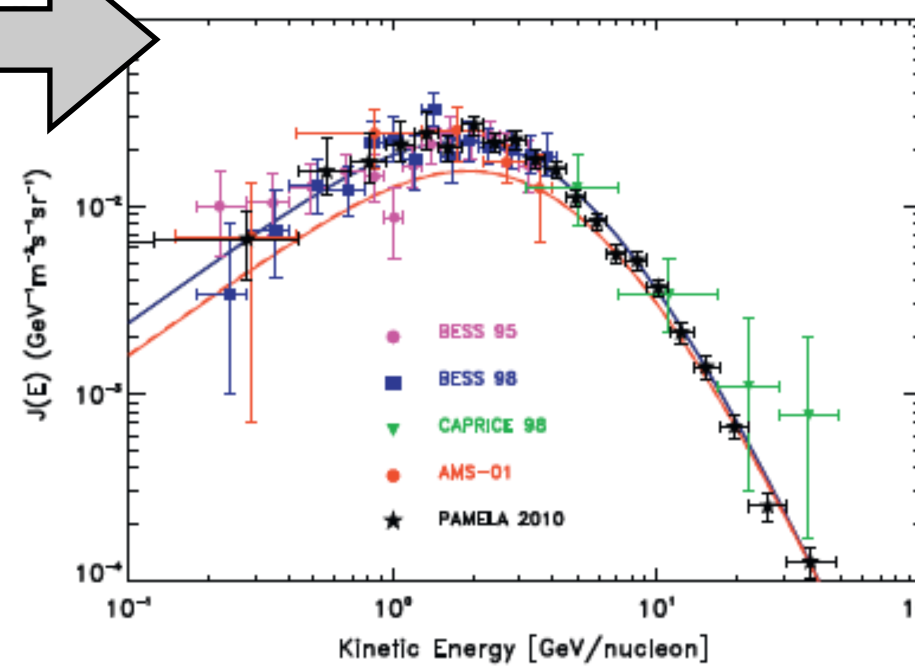


fix primaries

+



fix propagation



get secondaries $\bar{p}$

Main processes: $\mathrm{p} + \mathrm{p}_{gas} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{p} + \bar{p}$

$^4He + p_{gas}$; $p + {}^4He_{gas}$; $^4He + {}^4He_{gas}$

tertiary $\bar{p}$ (produced by scattering of secondaries onto the ISM), as well as inelastic scattering and annihilation are accounted

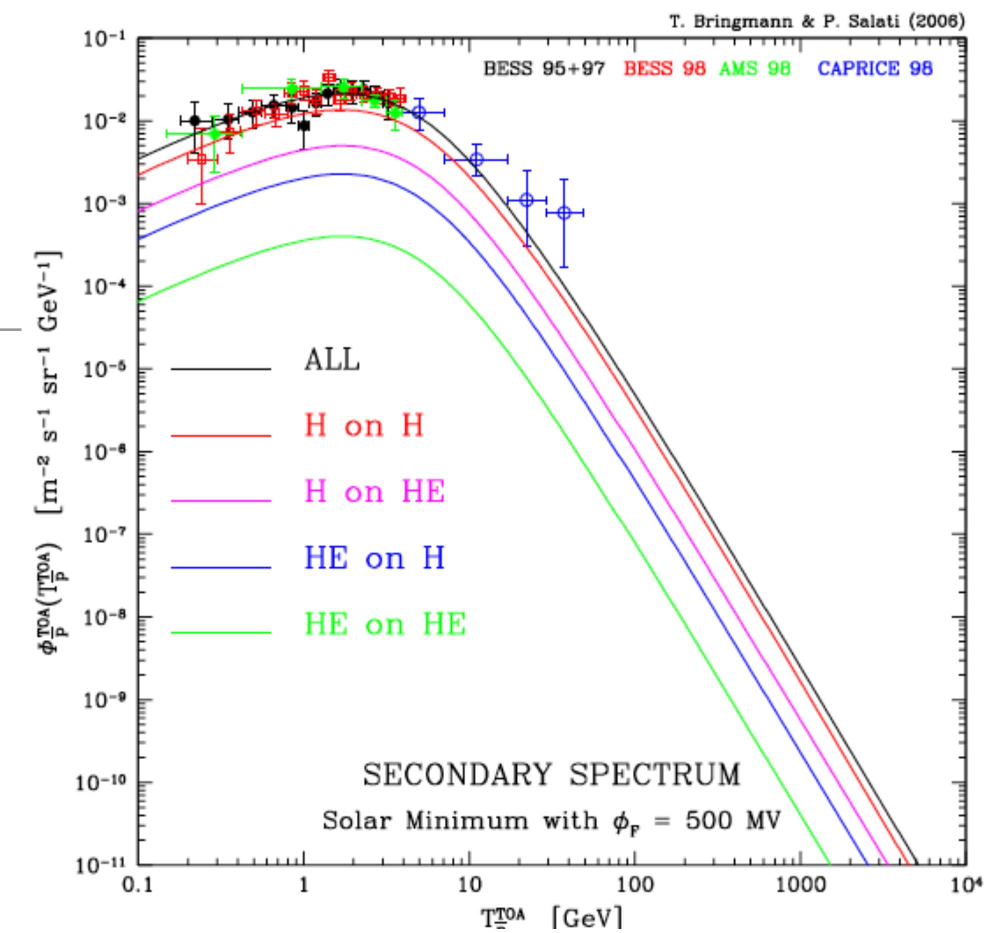
Secondary Antiprotons

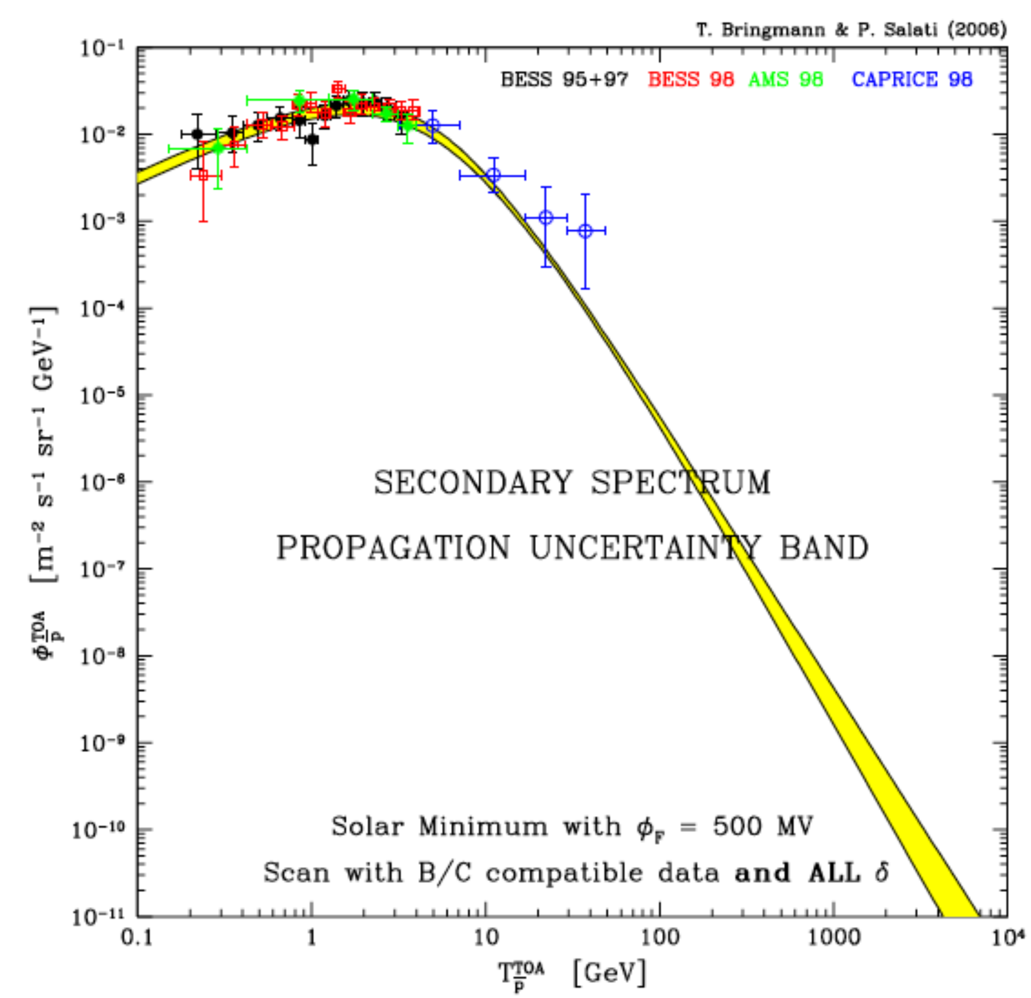
Main approaches

Analytical (solve transport eq. under simplified conditions). Less realistic but faster it allows to perform statistical analysis . See e.g.
Donato et al. astro-ph/0103150
Bringmann & Salati astro-ph/0612514 ➡
Donato et al. astro-ph/0810.5292

Numerical (solve transport equation numerically with codes like GALPROP or DRAGON)
More realistic physical conditions but slower
(not a serious problem anymore !)

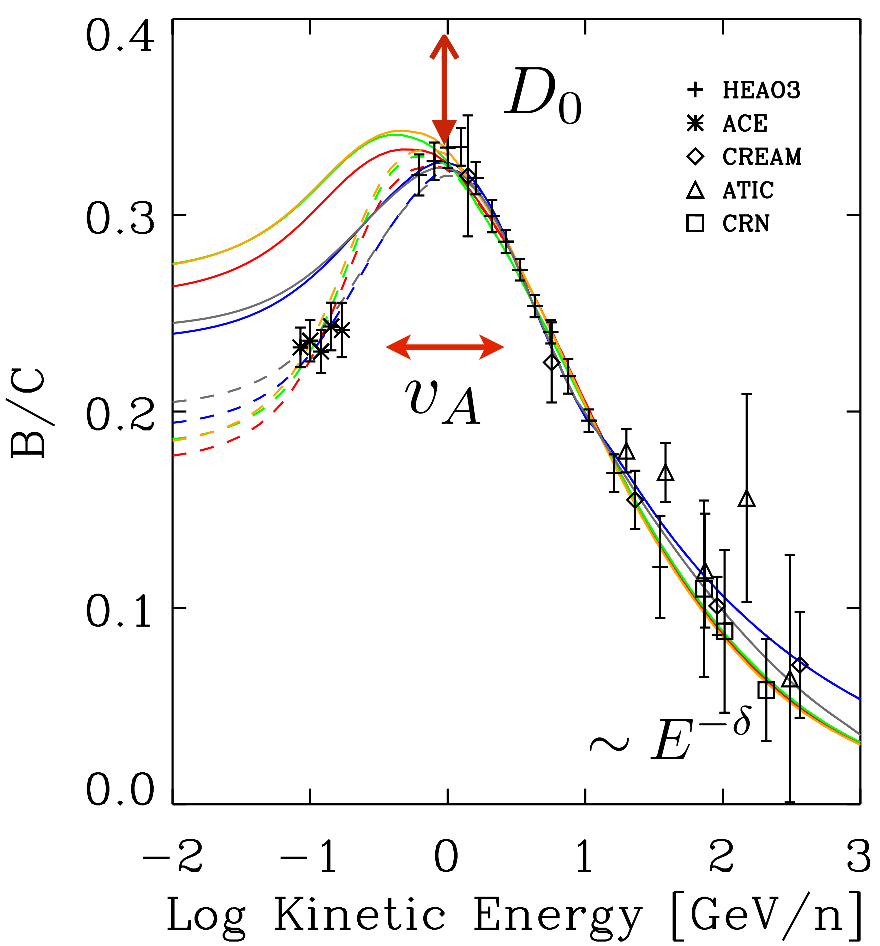
Moskalenko, Strong, Ormes & Portgetier astro-ph/0106567
Di Bernardo, Evoli, Gaggero, D.G. & Maccione   0909.4548

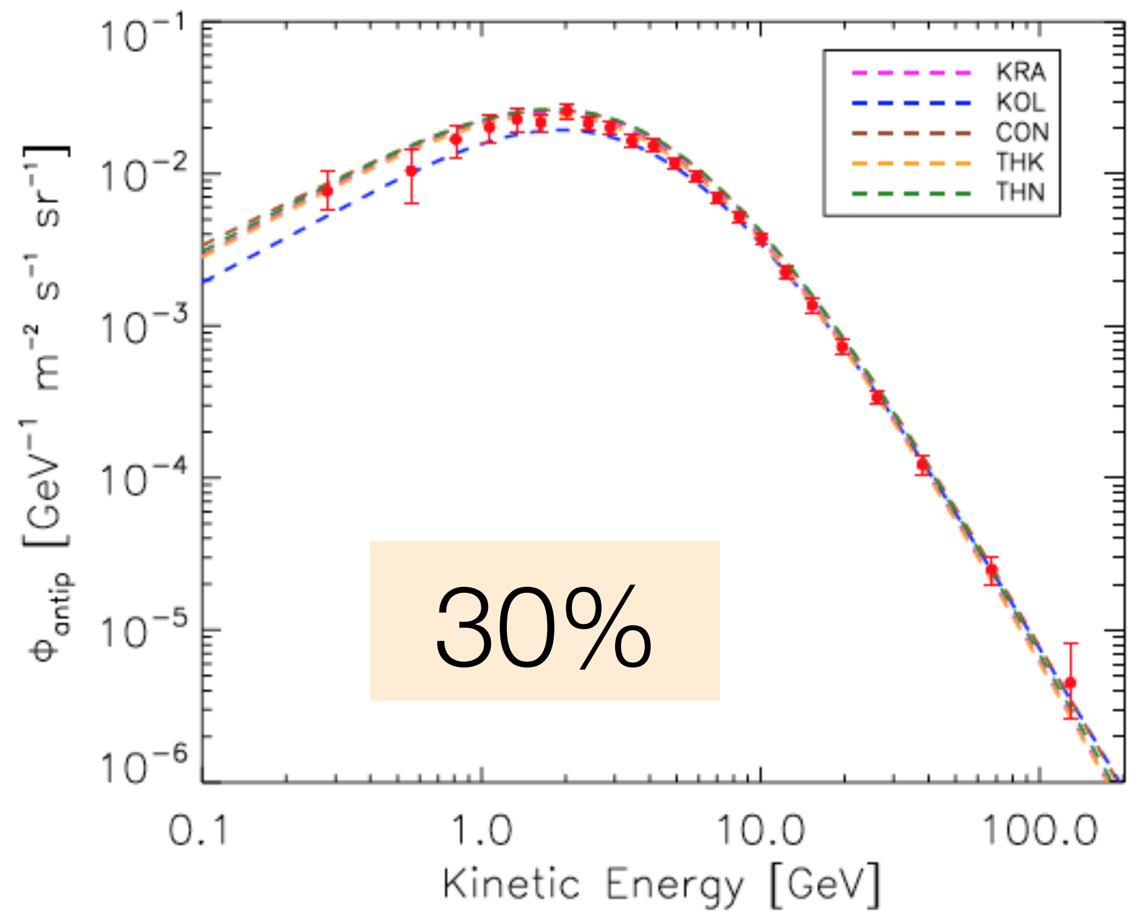




A very stable prediction !

C. Evoli, I.Cholis, D.G., L.Maccione & P.Ullio, PRD, 2012, 1108.0664

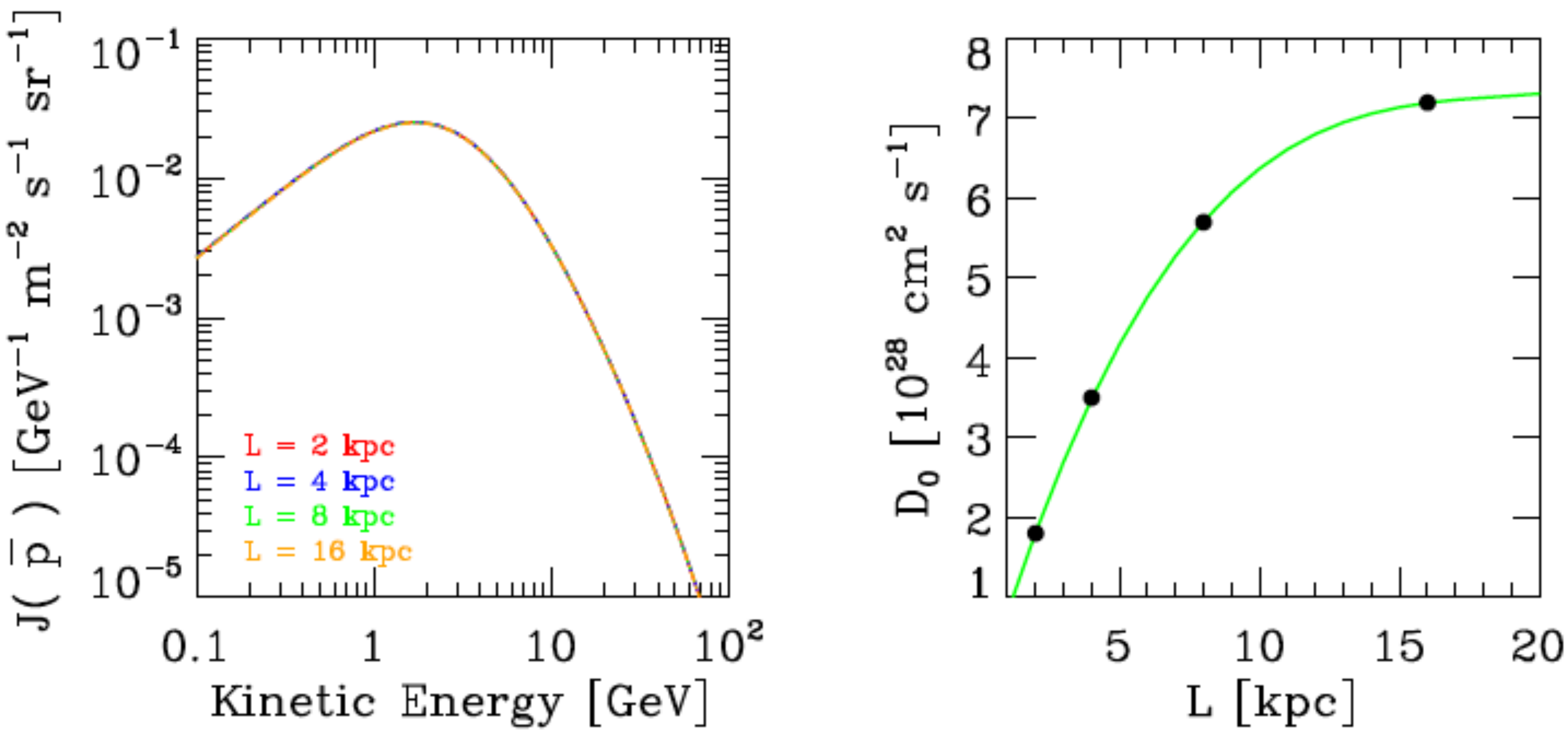




$$D(E) = D_0 (E/E_0)^{\delta} \exp(z/z_t)$$

Model	z_t (kpc)	δ	$D_0(10^{28}$ cm^2/s)	η	v_A (km/s)	γ	dv_c/dz (km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Figs.
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70	0.73	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69	0.62	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21	1.32	Gray

The problem of degeneracies



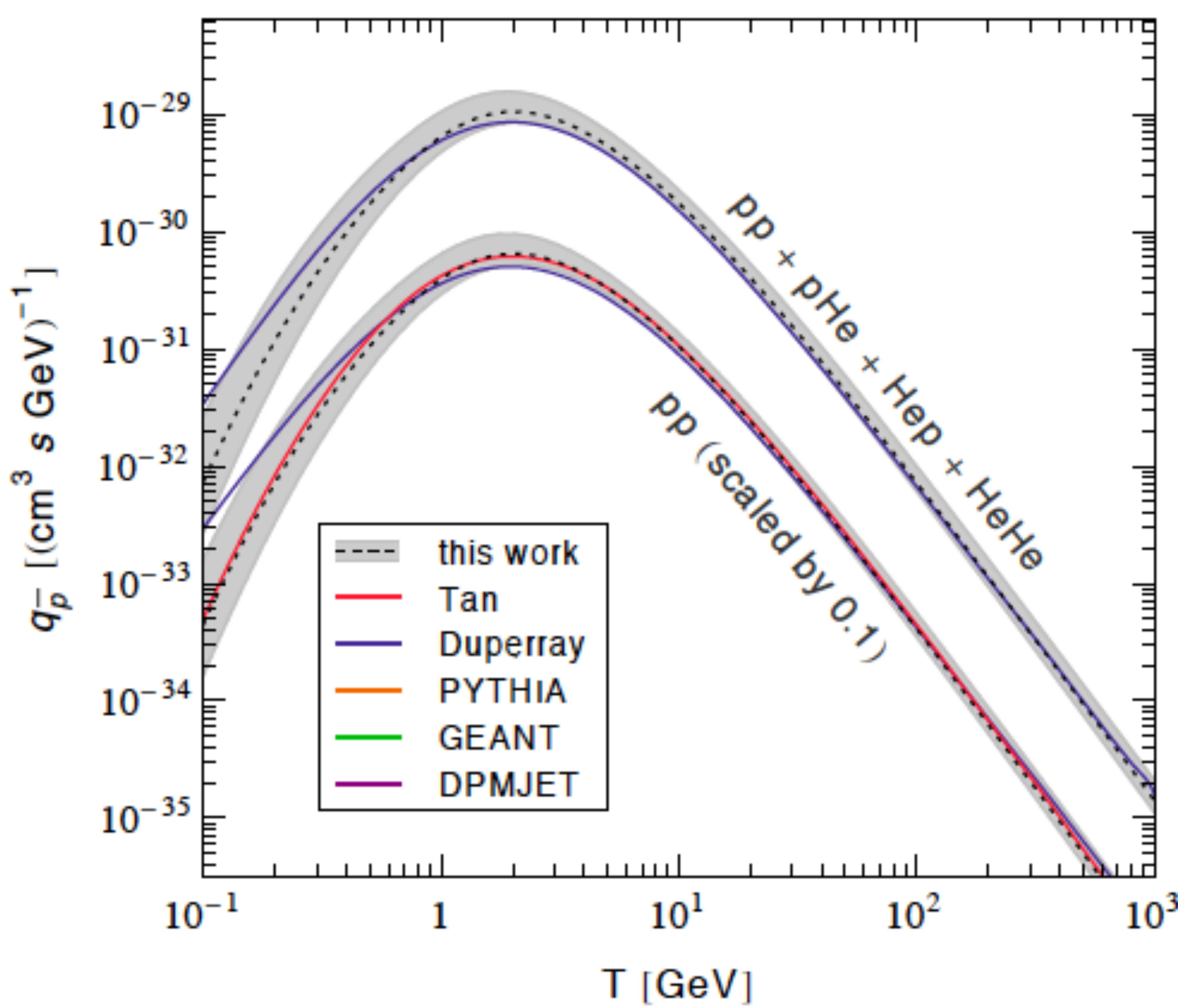
Particle physics uncertainties

R. Kappl & M.W. Winkler, 1408.0299

Data driven (NA49) approach using established scaling relation. With respect to previous work they

- account for hyperon (Λ and Σ) decay
- account for isospin asymmetry (more $\bar{n}$ than $\bar{p}$ produced by pp scattering)
- use improved model for p-He and He-He scattering based on p-C NA49 data

Dominant uncertainties for the $\bar{p}$ source terms:
~ 20% due to isospin factor for T ~ 10 GeV
up to 50 % at lower T due to breaking of scaling at low energy



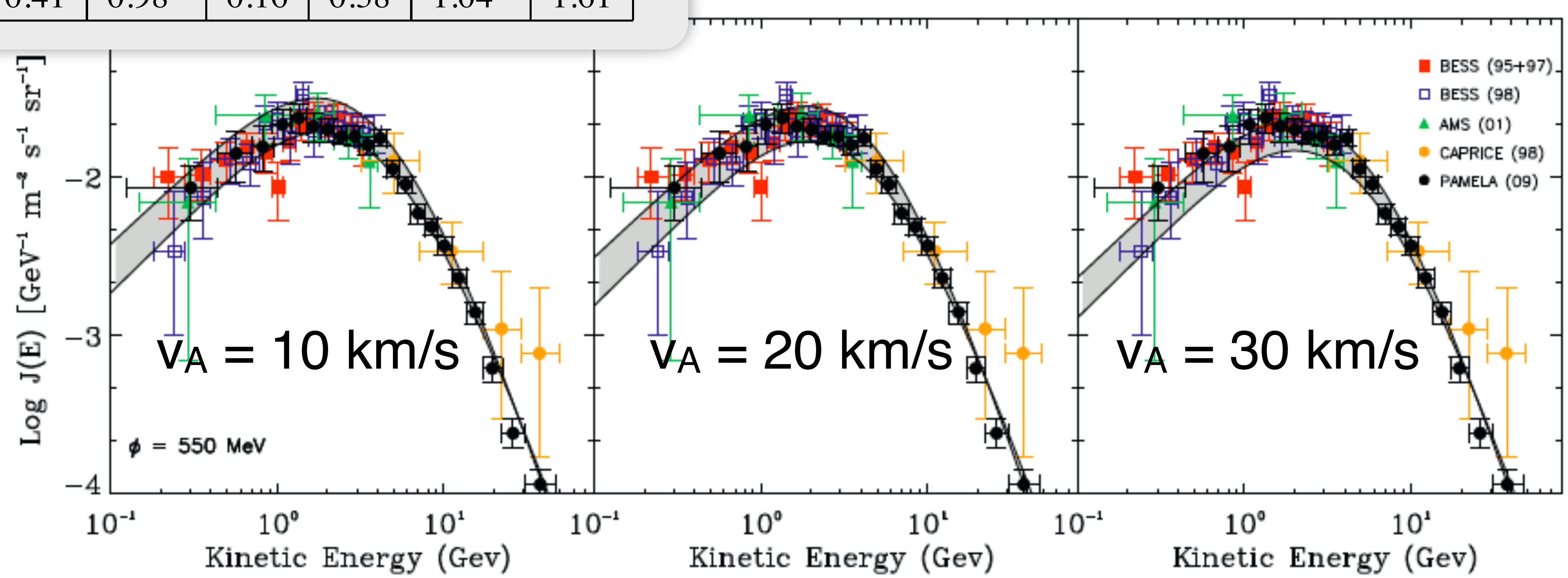
How to bracket propagation uncertainties?

Di Bernardo, Evoli, Gaggero, D.G, & Maccione JCAP 2010

		B/C analysis			joint analysis		
v_A [km/s]	E_{min} [GeV/n]	δ	D_0/z_t	χ^2	δ	D_0/z_t	χ^2
0	1	0.57	0.60	0.38	0.47	0.74	3.25
	5	0.52	0.65	0.33	**0.41**	**0.85**	**2.04**
	10	0.46	0.76	0.19	0.44	0.82	1.57
10	1	0.52	0.68	0.32	0.49	0.71	1.47
	5	0.49	0.71	0.28	**0.41**	**0.85**	**1.69**
	10	0.44	0.82	0.20	0.44	0.82	0.12
15	1	0.46	0.76	0.33	0.47	0.76	0.94
	5	0.49	0.73	0.26	**0.44**	**0.82**	**0.12**
	10	0.44	0.84	0.18	0.41	0.98	0.16
20	1	0.41	0.90	0.47	0.47	0.79	2.28
	5	0.44	0.84	0.22	**0.44**	**0.84**	**0.85**
	10	0.44	0.87	0.20	0.44	0.85	0.98
30	1	0.33	1.20	0.40	0.33	1.20	5.84
	5	0.38	1.06	0.20	**0.36**	**1.09**	**2.47**
	10	0.41	0.98	0.16	0.38	1.04	1.61

@95% C.L.
$0.2 < \delta < 0.7$
$v_A < 30$ km/s

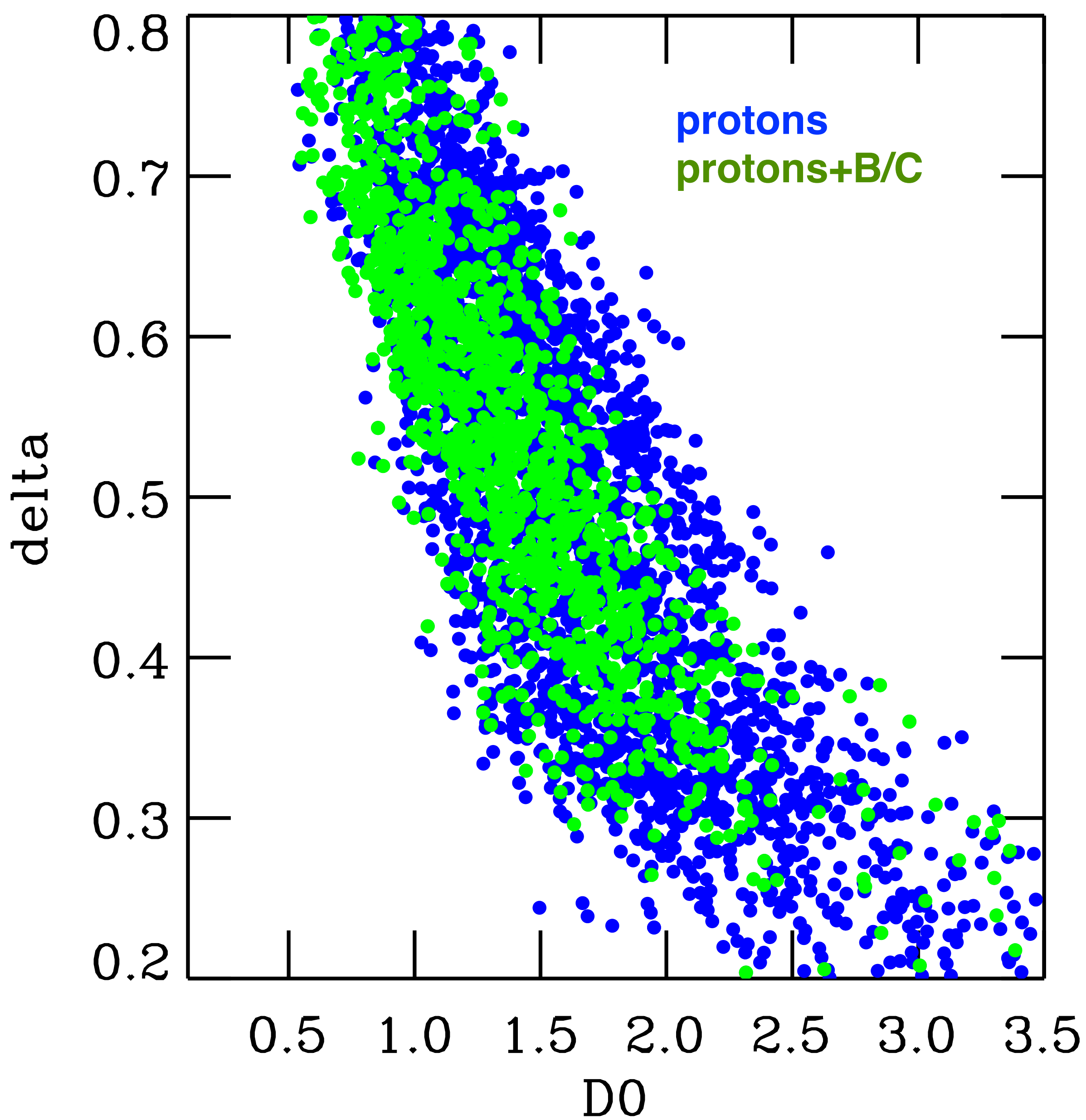
@best-fit:
$\delta = 0.45$
$v_A = 15$ km/s



How to bracket propagation uncertainties?

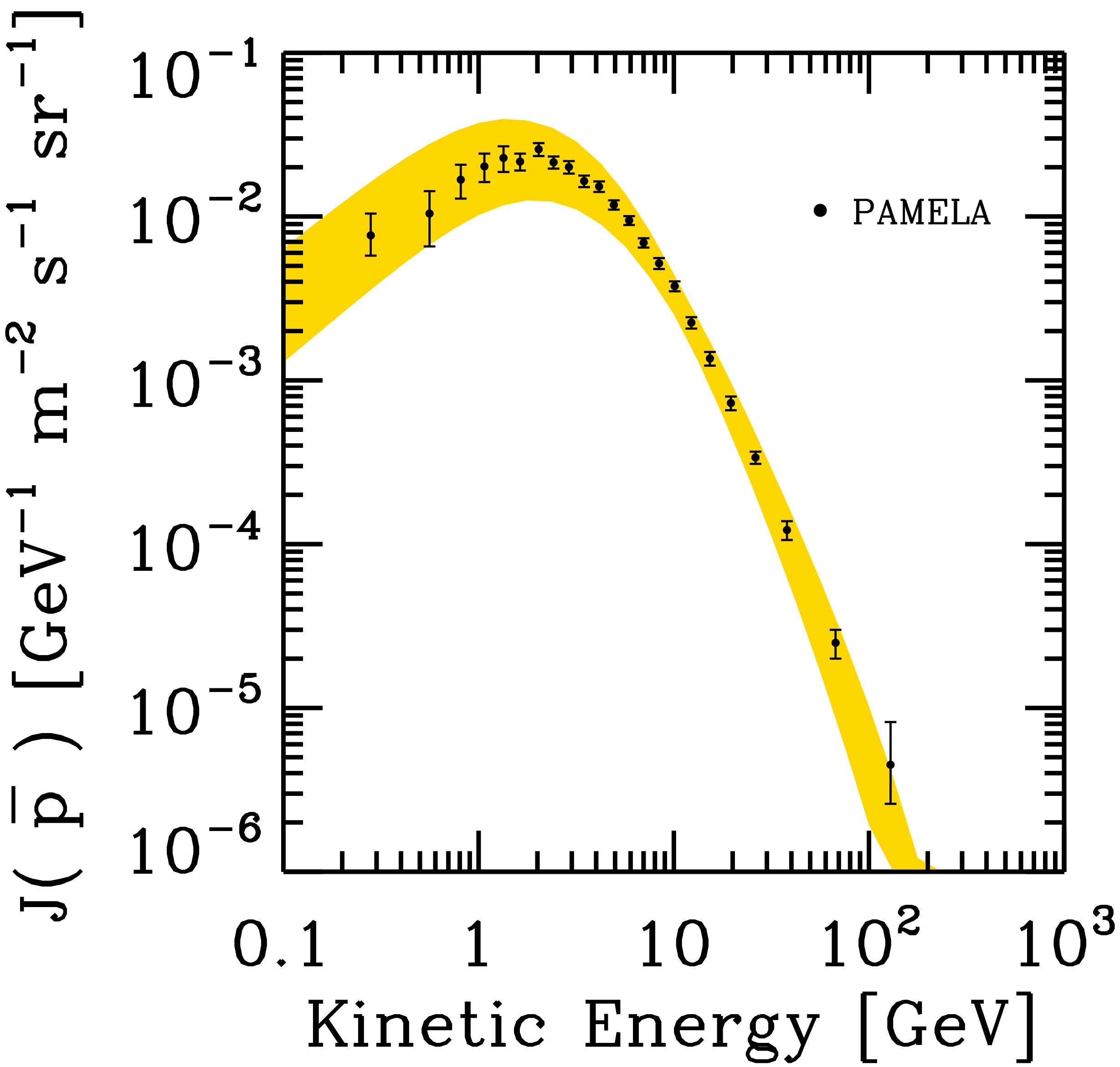
C. Evoli, E, D.Gaggero & D.G, 1504.05175

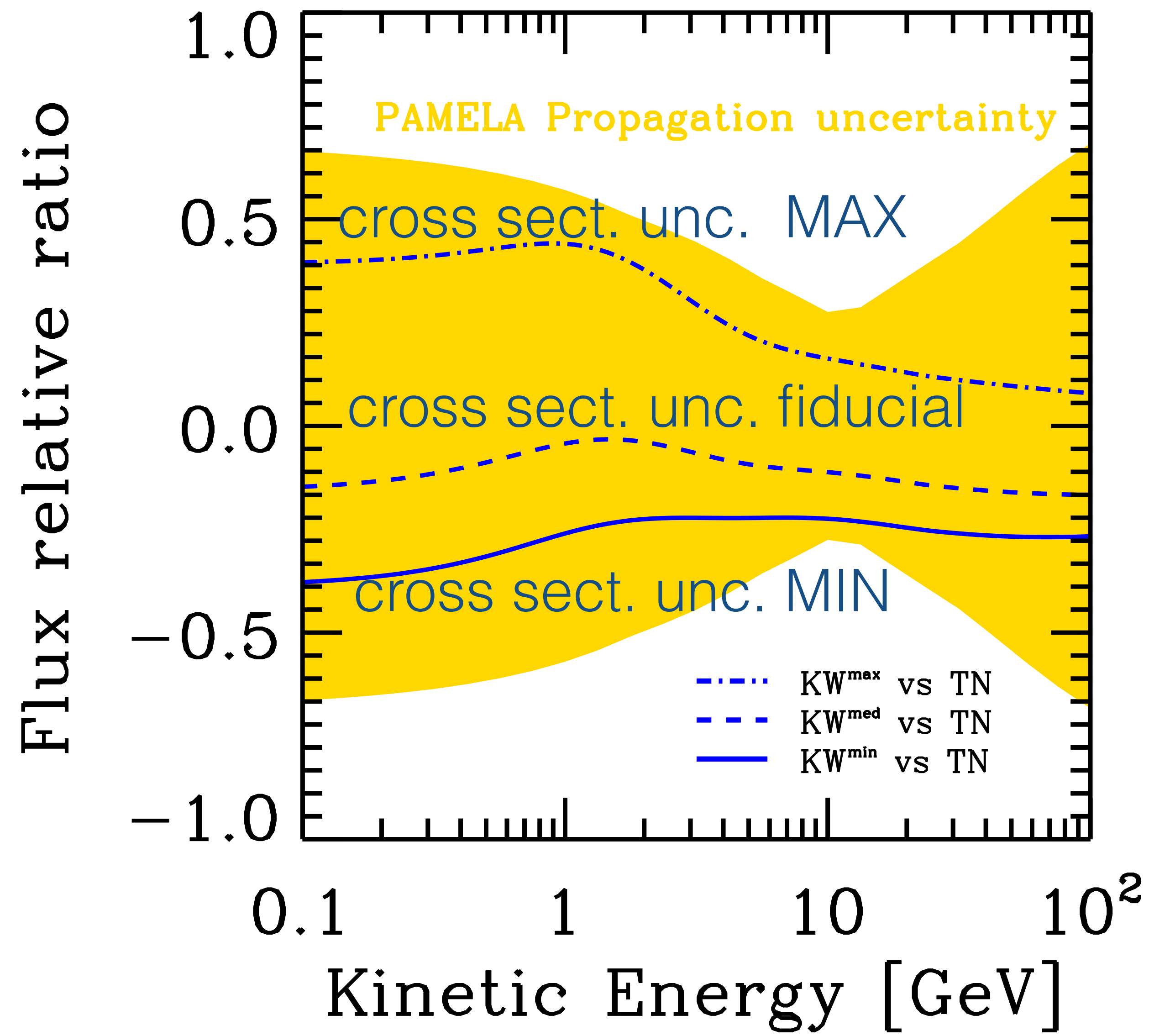
- We use CR data from the same experiment (PAMELA) to reduce systematics and uncertainties due to solar modulation
- We vary all relevant, propagation and modulation parameters (10^4 DRAGON runs)
- We require that primary spectra (protons and Heliums) and B/C are reproduced



Propagation vs nuclear uncertainties

C. Evoli, E, D.Gaggero & D.G, 1504.05175

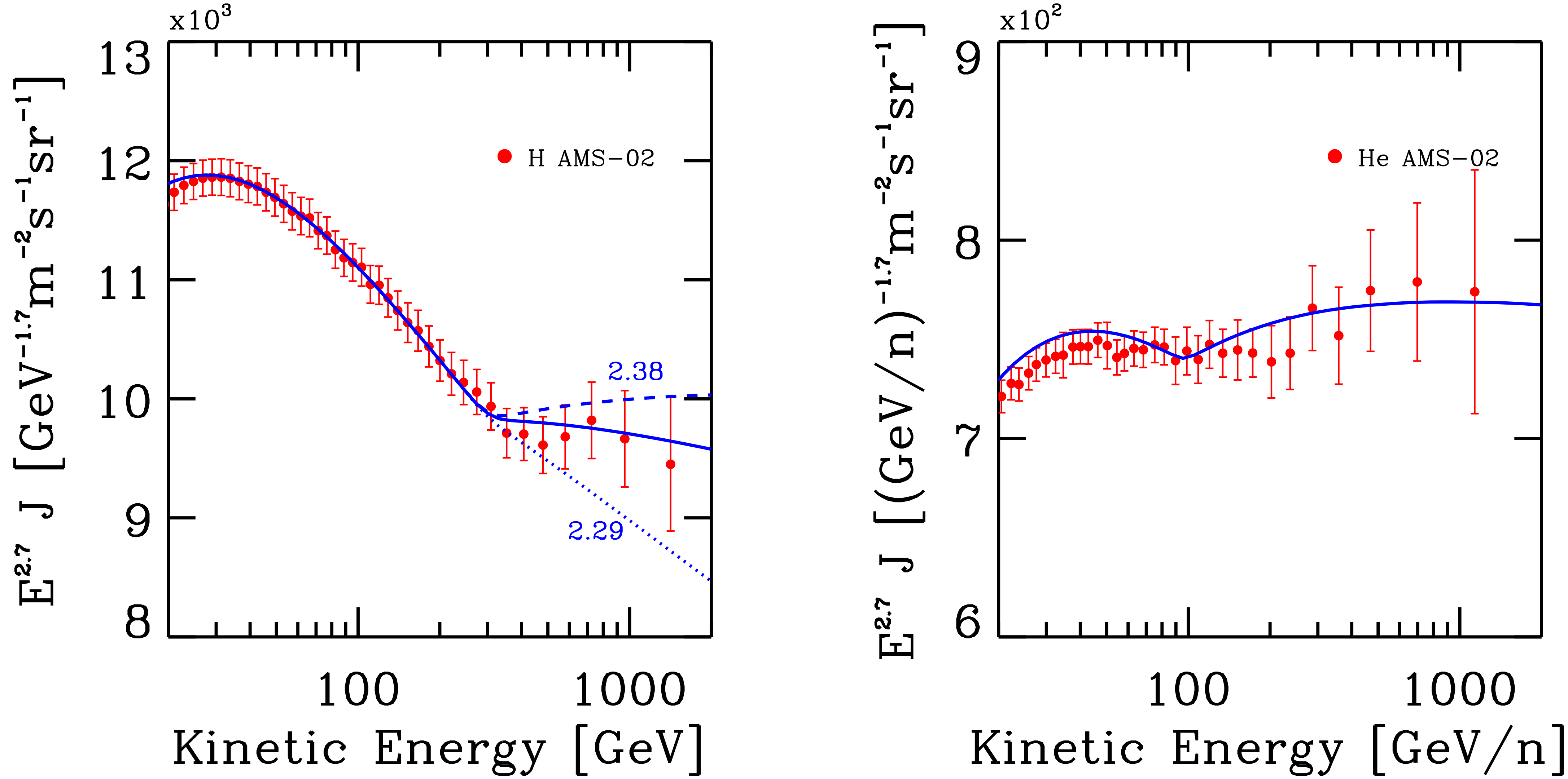




No evidence of an excess !

AMS-02 anomaly ?

C. Evoli, E, D.Gaggero & D.G, 1504.05175



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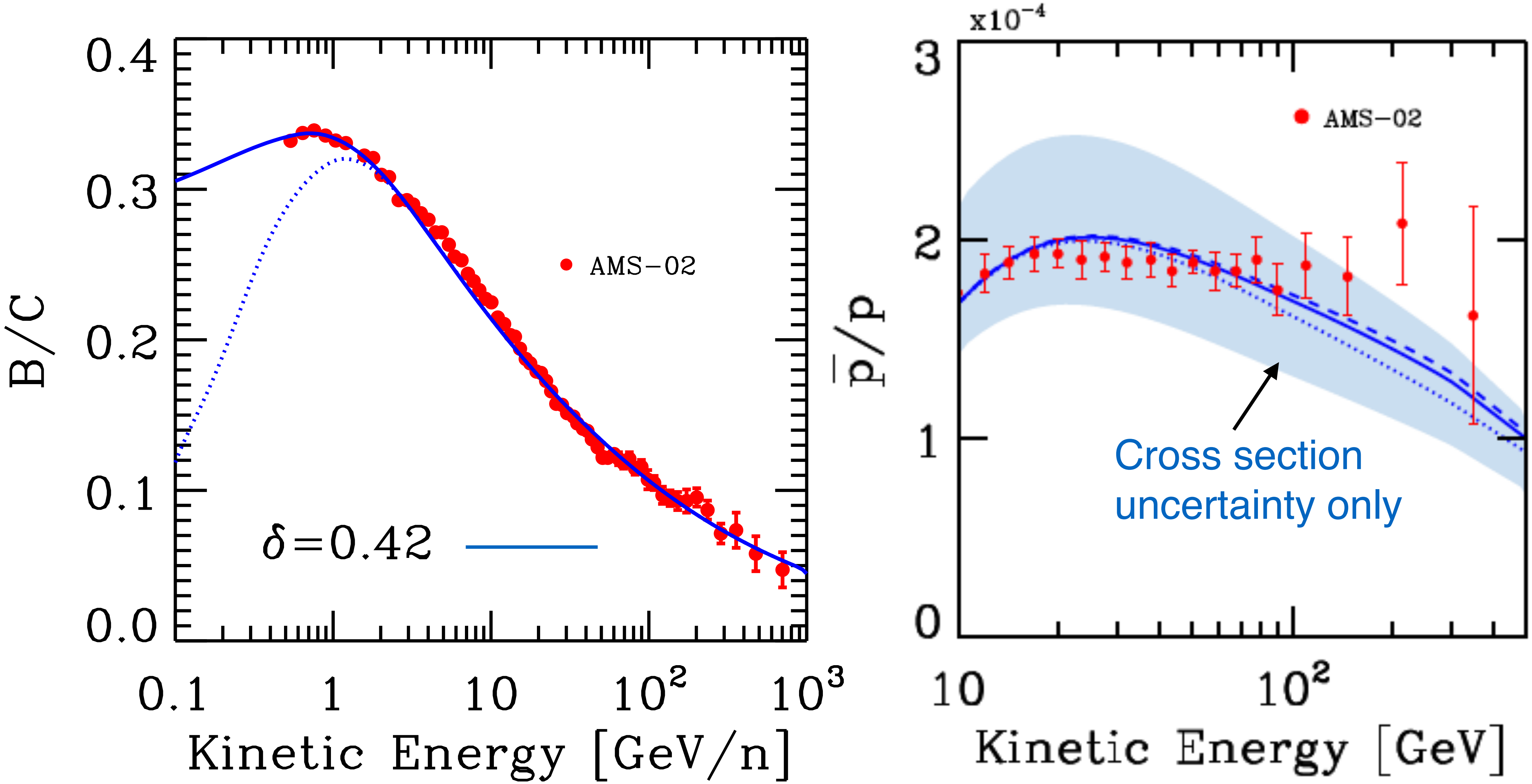
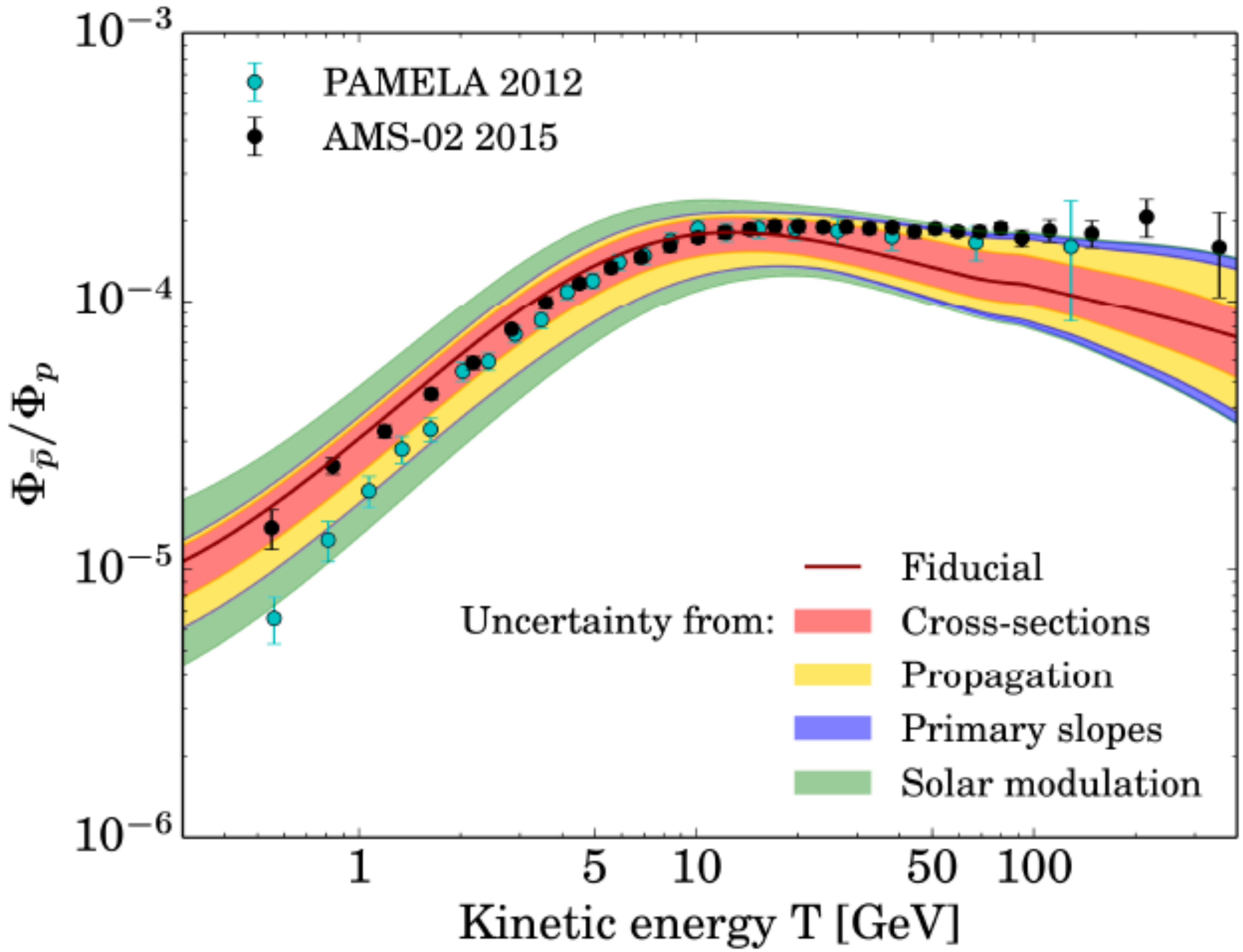
C. Evoli, E, D.Gaggero & D.G, 1504.05175



AMS-02 anomaly ?

Gisen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276



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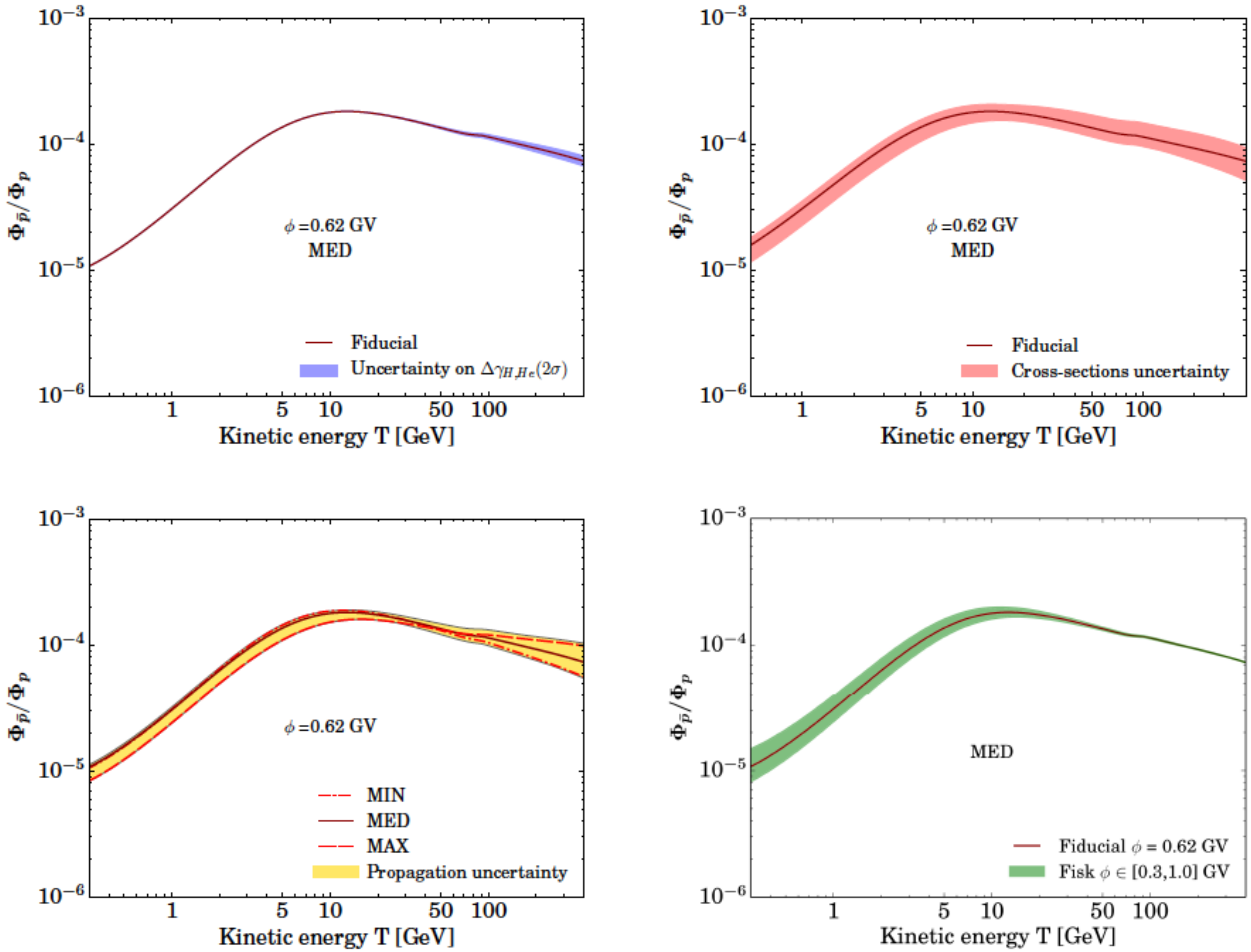

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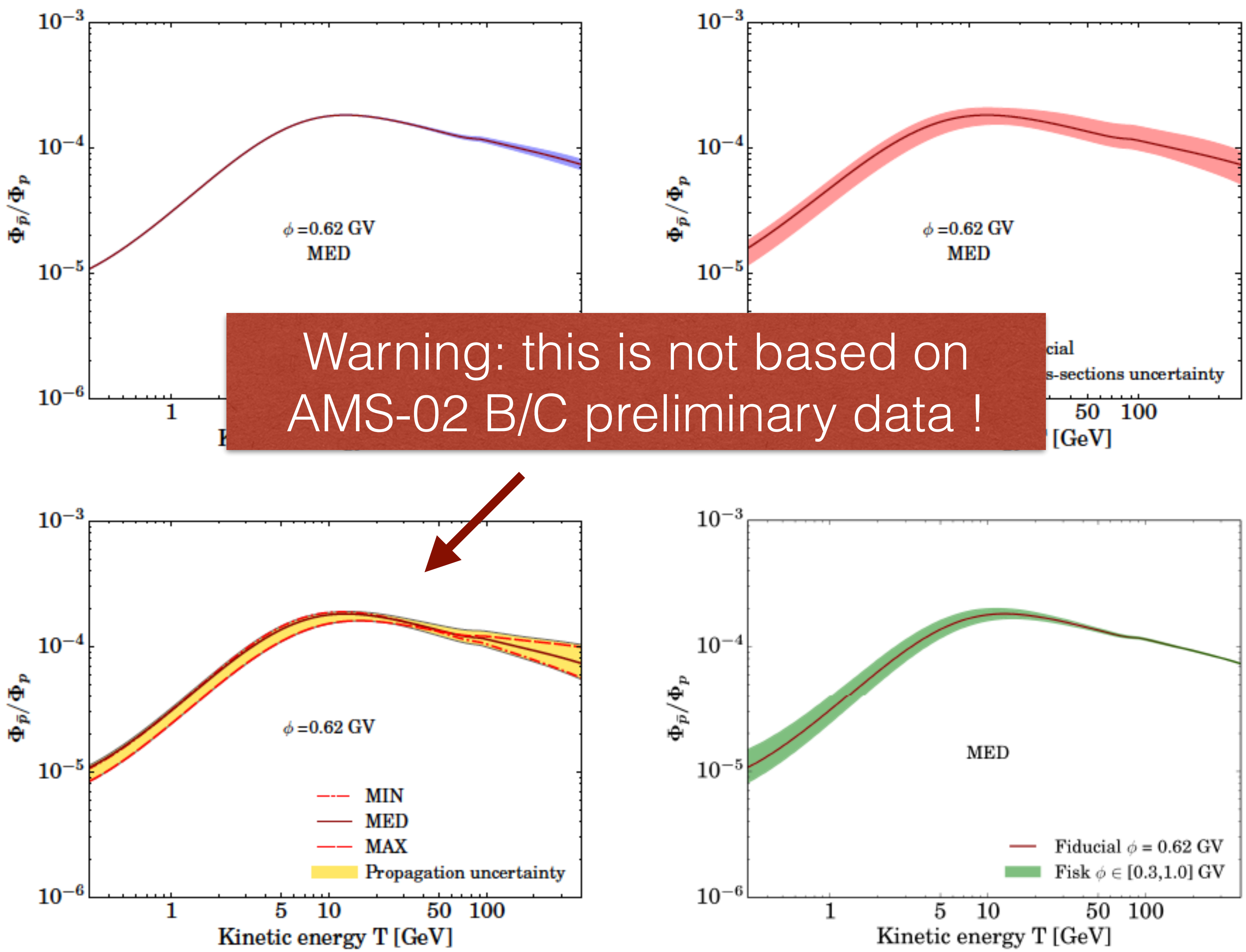
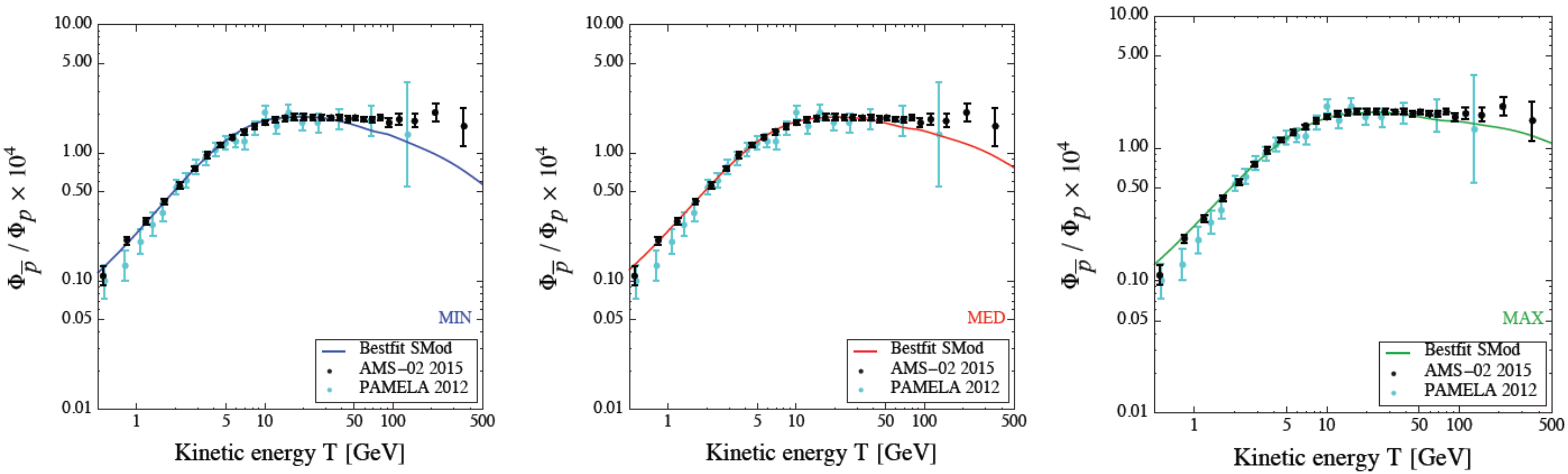


Warning: this is not based on AMS-02 B/C preliminary data !

AMS-02 anomaly ?

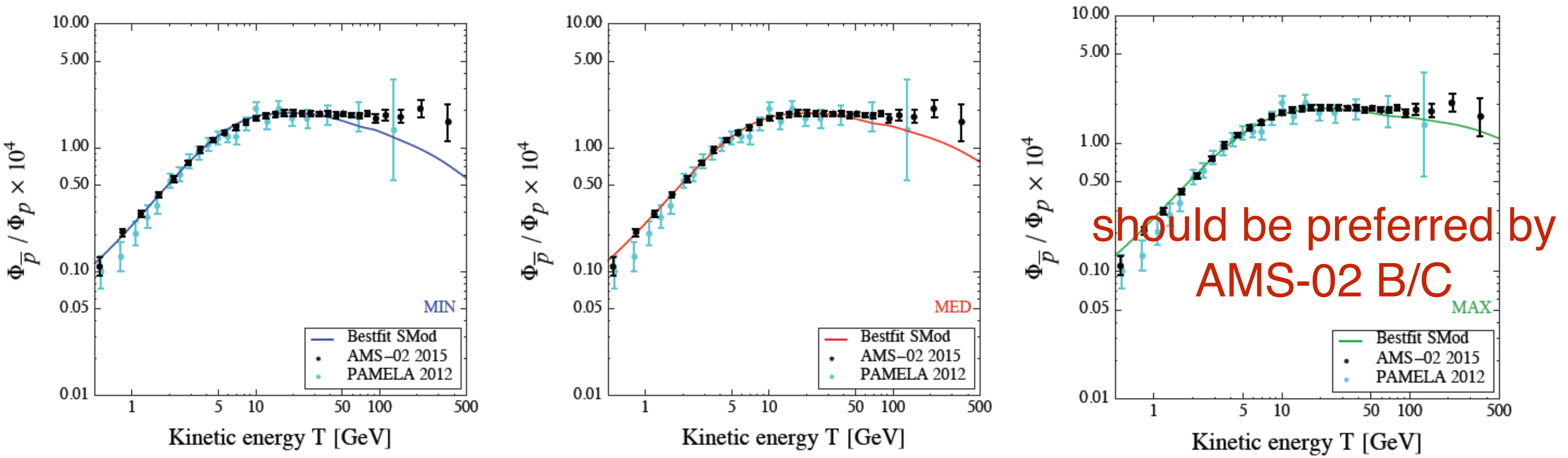
Gisen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276



Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
max	0.46	0.0765	15	5	117.6
med	0.70	0.0112	4	12	52.9
min	0.85	0.0016	1	13.5	22.4

AMS-02 anomaly ?

Gisen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276



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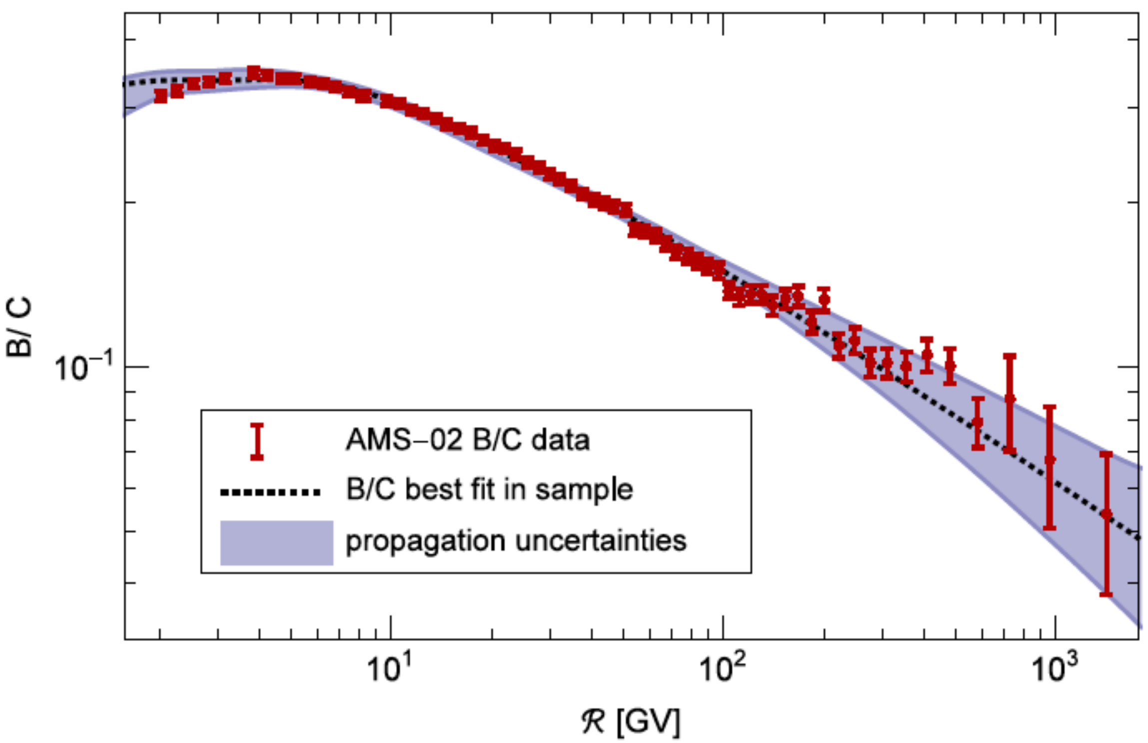
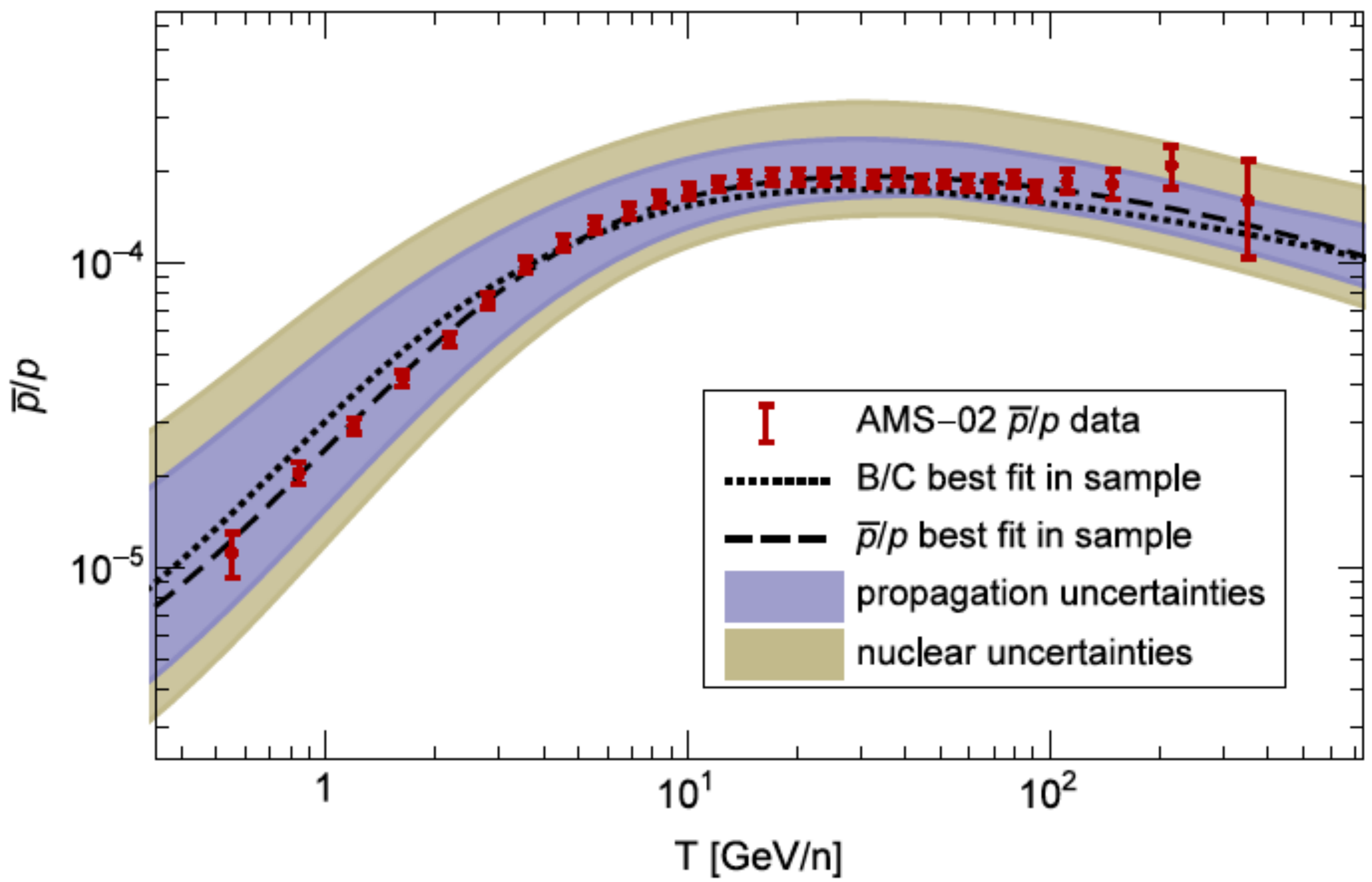
AMS-02 anomaly ?

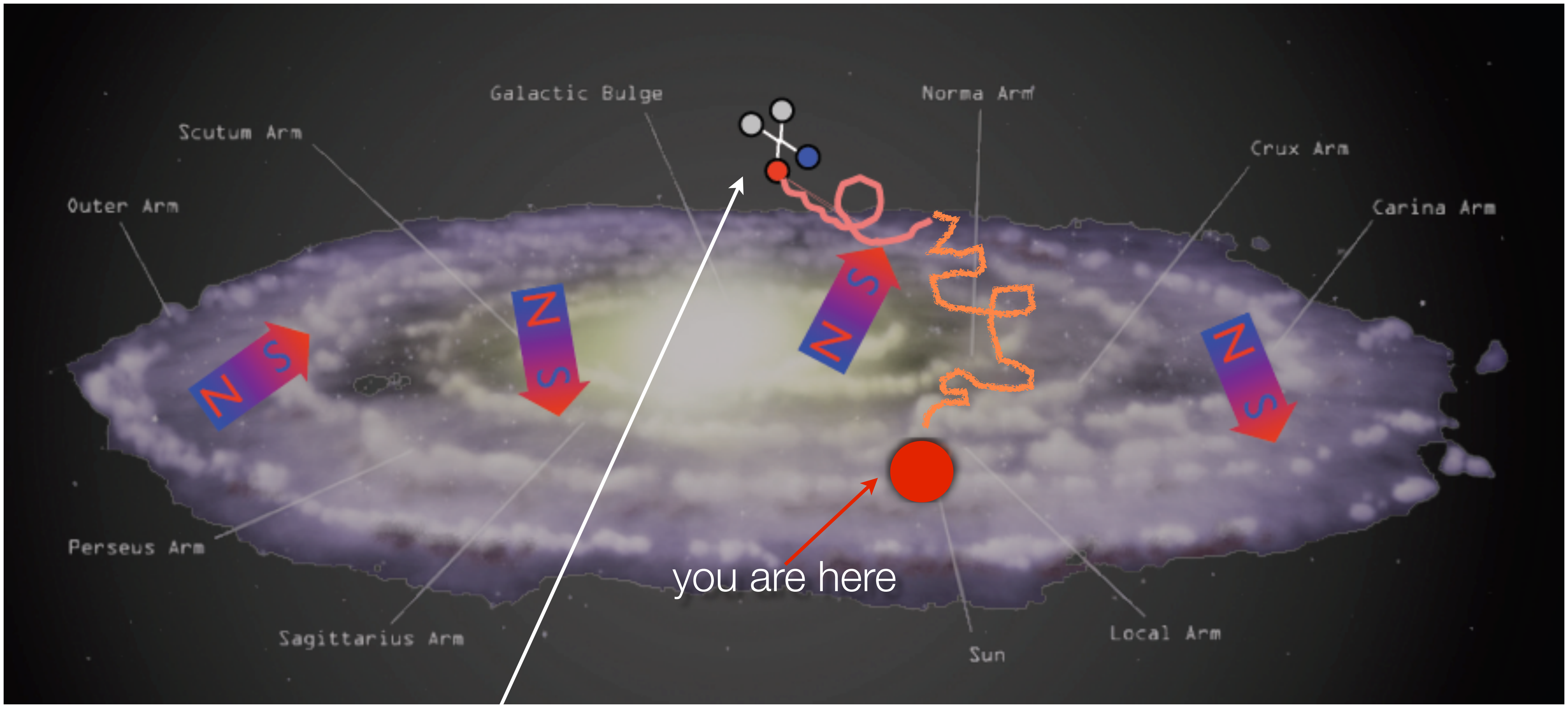
R. Kappl & M.W. Winkler, 1506.04145

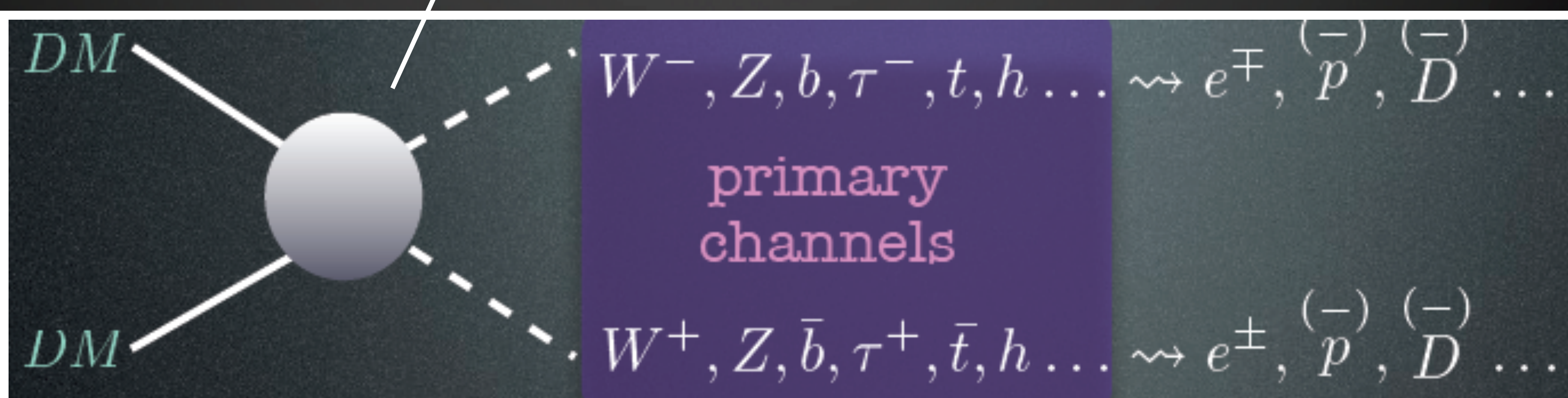




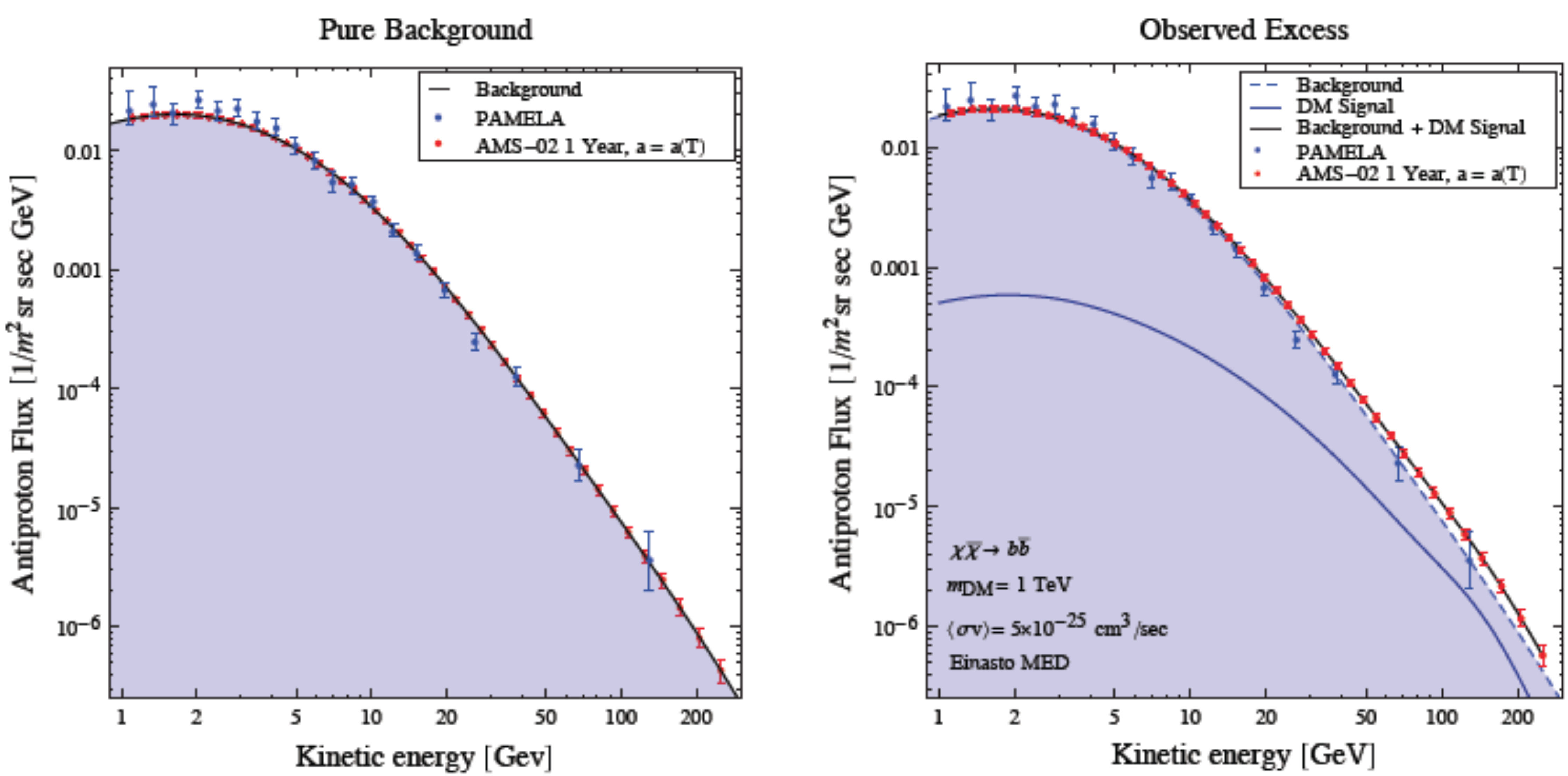
Antiproton from DM

M. Cirelli courtesy





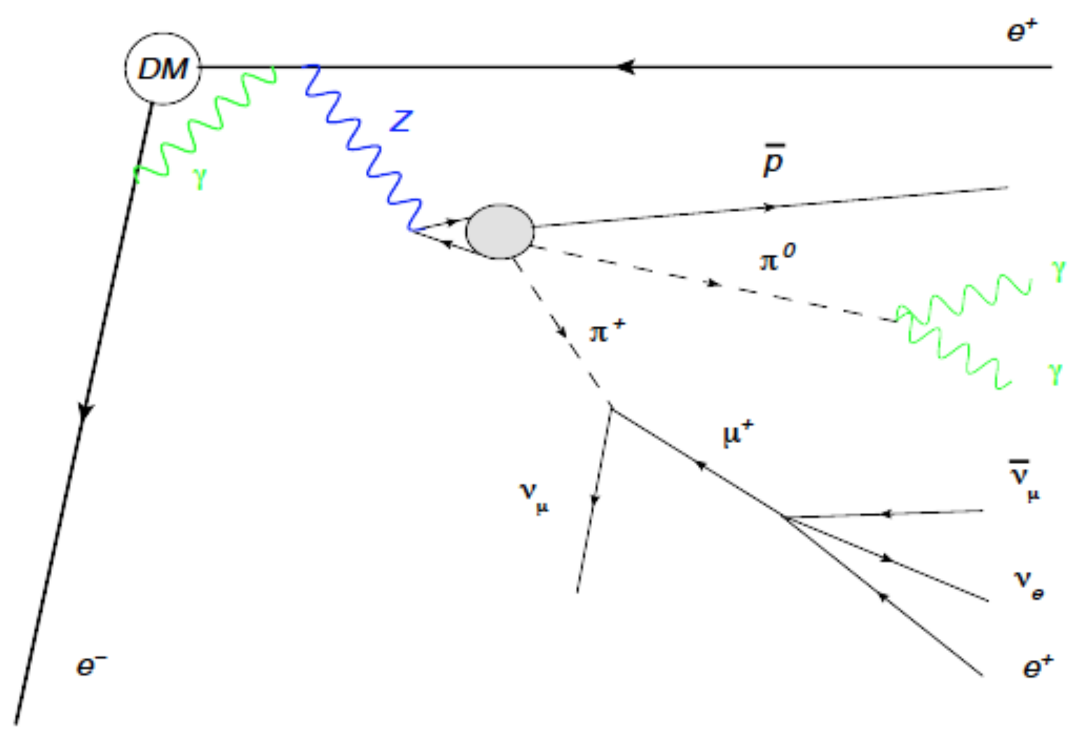
Antiproton from DM: how it may look like



Antiproton from DM

Ciafaloni,Cirelli,Comelli,De Simone,Sala, Strumia, Riotto,Urbano, 1009.0224, 1104.2996

Electroweak corrections have to be taken in account for large WIMP masses



Ciafaloni *et al.*, JCAP 03 (2011) 019

- naively might expect electroweak corrections to be negligible: $\alpha_2 \ln M^2/M_W^2$ or $\alpha_2 \ln^2 M^2/M_W^2$
- for 100 GeV typically of $\mathcal{O}(0.1)$ % even at a few TeV only $\mathcal{O}(30)$ %
- but:
  - evade helicity suppression
    see e.g. Bell, Dent, Jacques, Weiler
  - prevents leptophilic or hadrophobic models
  - changes spectral shape

In the following we use the PPPC4DMID
Cirelli et al. 2011 and upgrades

DarkSUSY can also be used and interfaced with CR codes , Ullio et al

Antiproton from DM

Ciafaloni,Cirelli,Comelli,De Simone,Sala, Strumia, Riotto,Urbano,
1009.0224, 1104.2996

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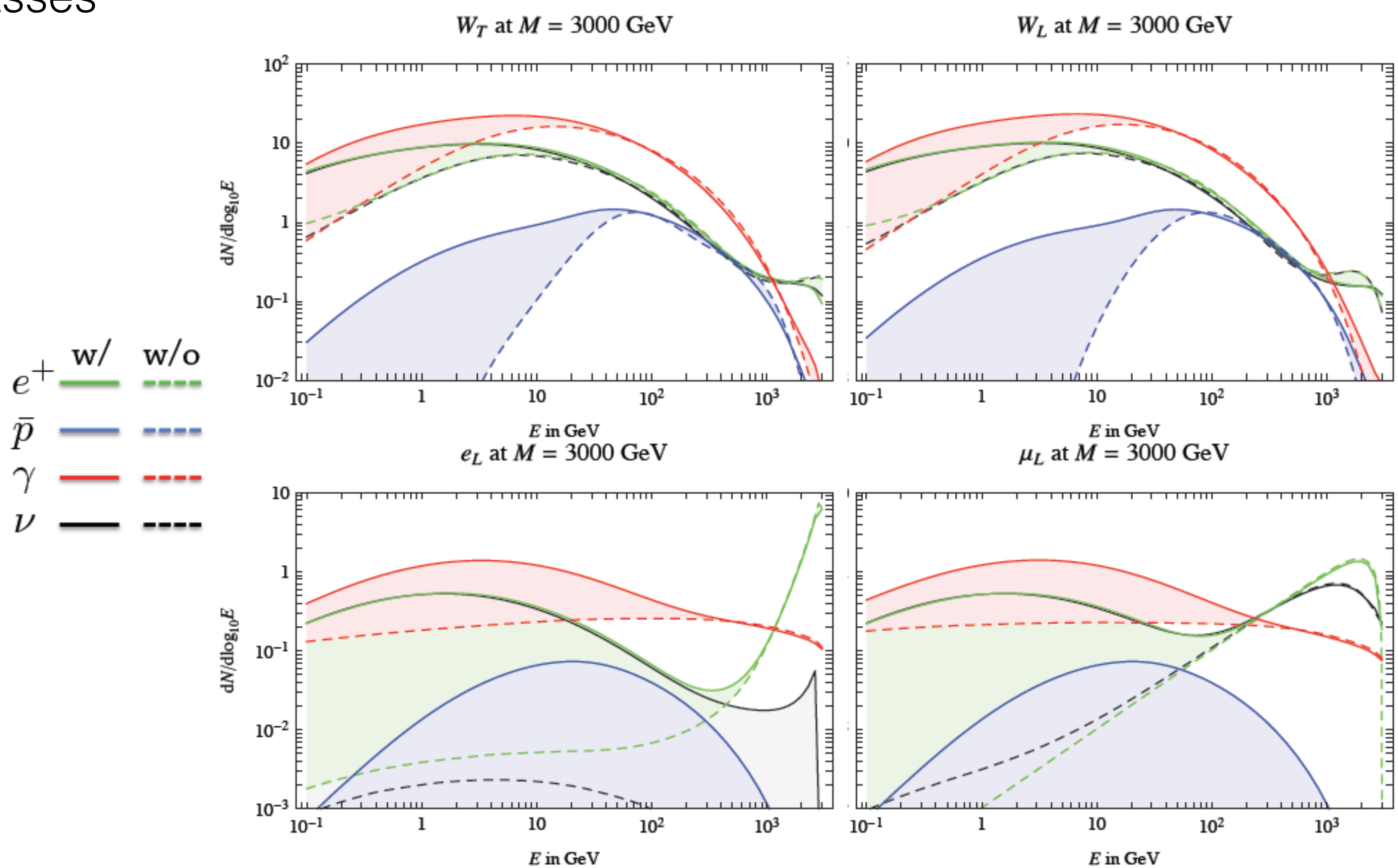
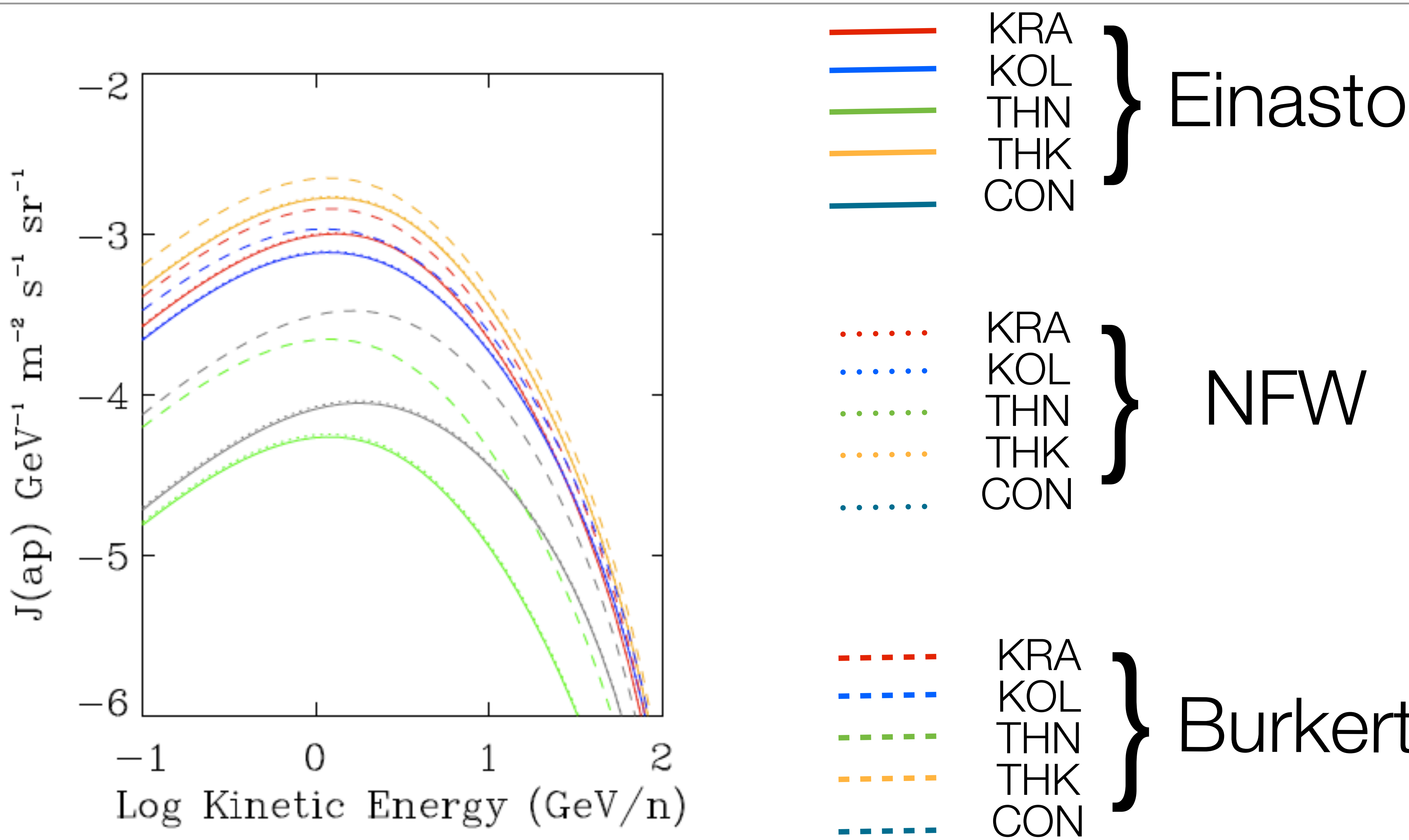


Ciafaloni *et al.*, JCAP 03 (2011) 019

Antiproton from DM: astrophysical uncertainties

C. Evoli, I.Cholis, D.G., L.Maccione & P.Ullio, PRD, 2012, 1108.0664

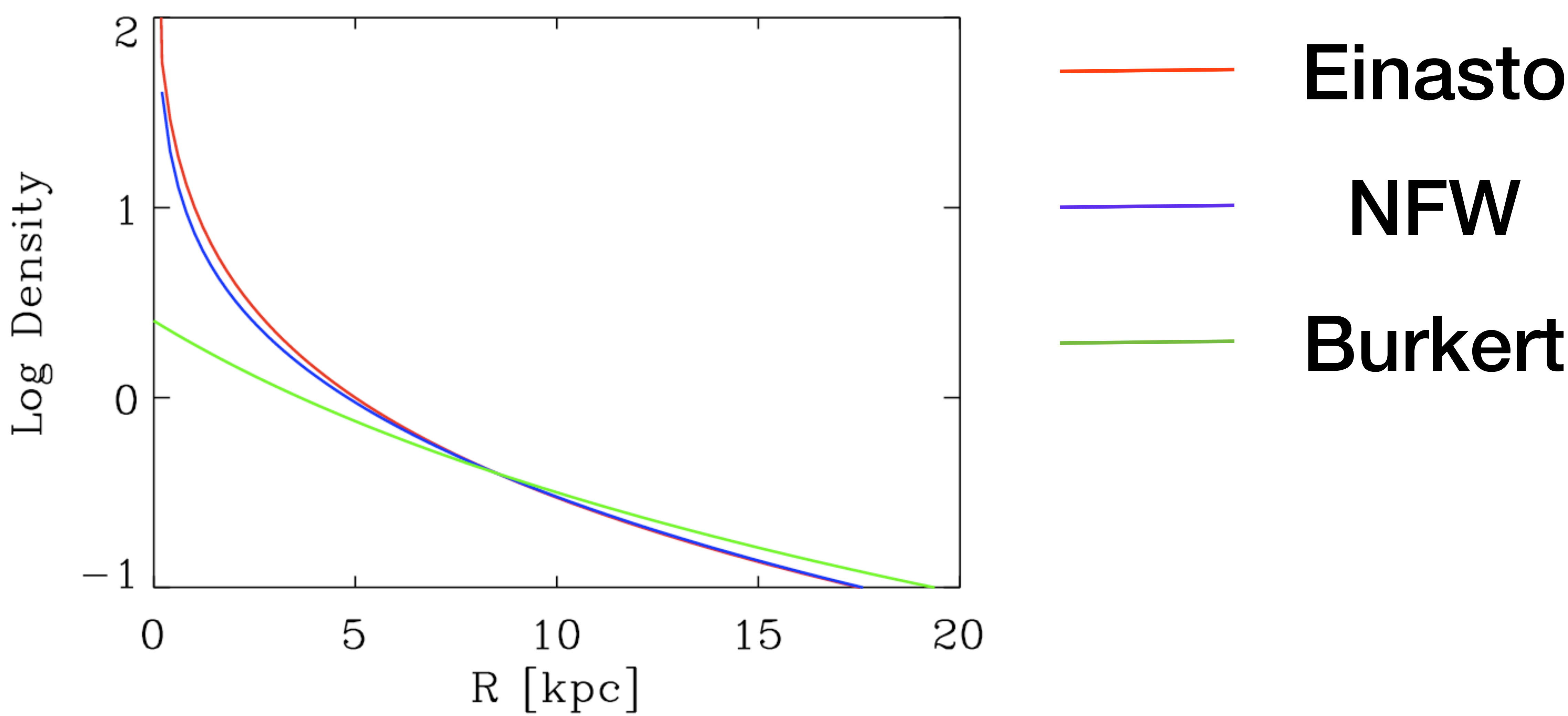


Uncertainty due to the DM profile >> Propagation uncertainty

Antiproton from DM: astrophysical uncertainties

C. Evoli, I.Cholis, D.G., L.Maccione & P.Ullio, PRD, 2012, 1108.0664

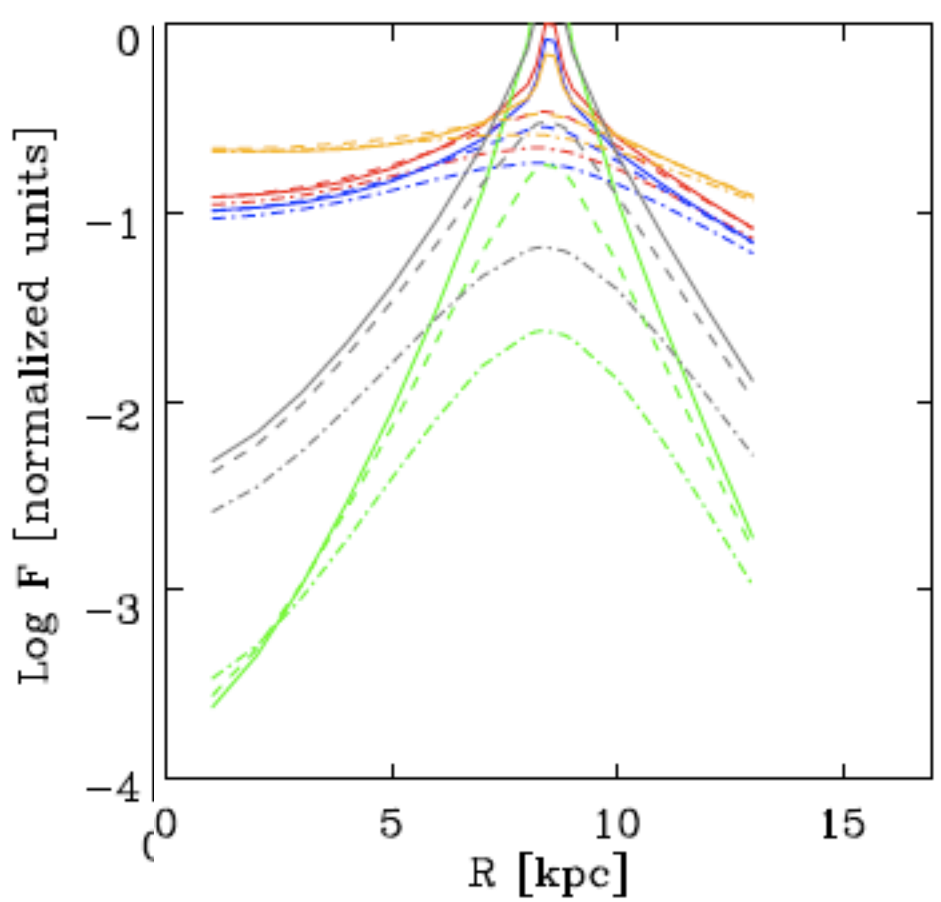
The DM density profile (estimated on N-body simulations) strongly affects the annihilation rate (J fact.)



Antiproton from DM: astrophysical uncertainties

C. Evoli, E, D.Gaggero & D.G, 1504.05175

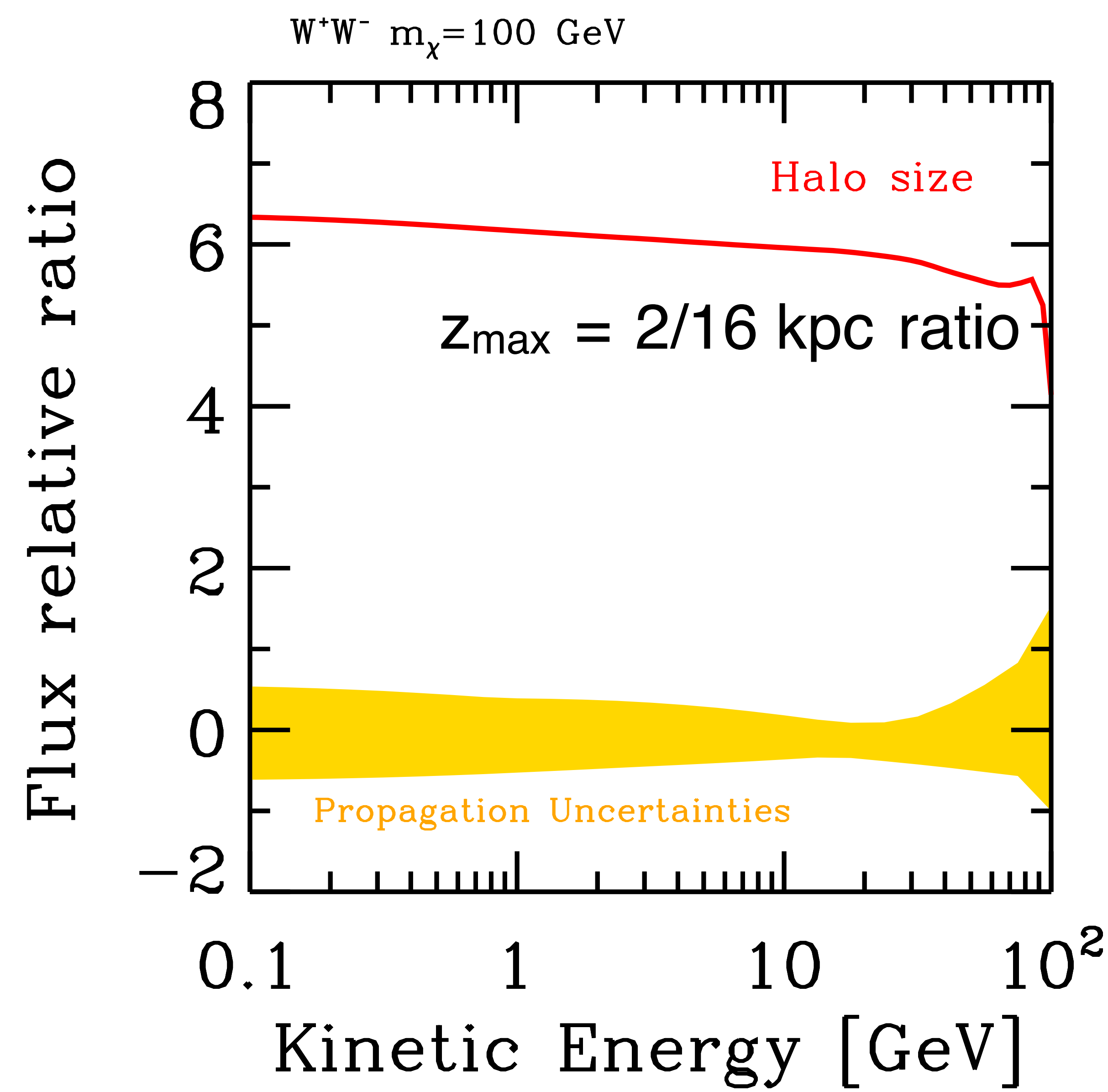
Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_C/dz(km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21



Relative $\bar{p}$ flux from a source at R

Antiproton from DM: astrophysical uncertainties

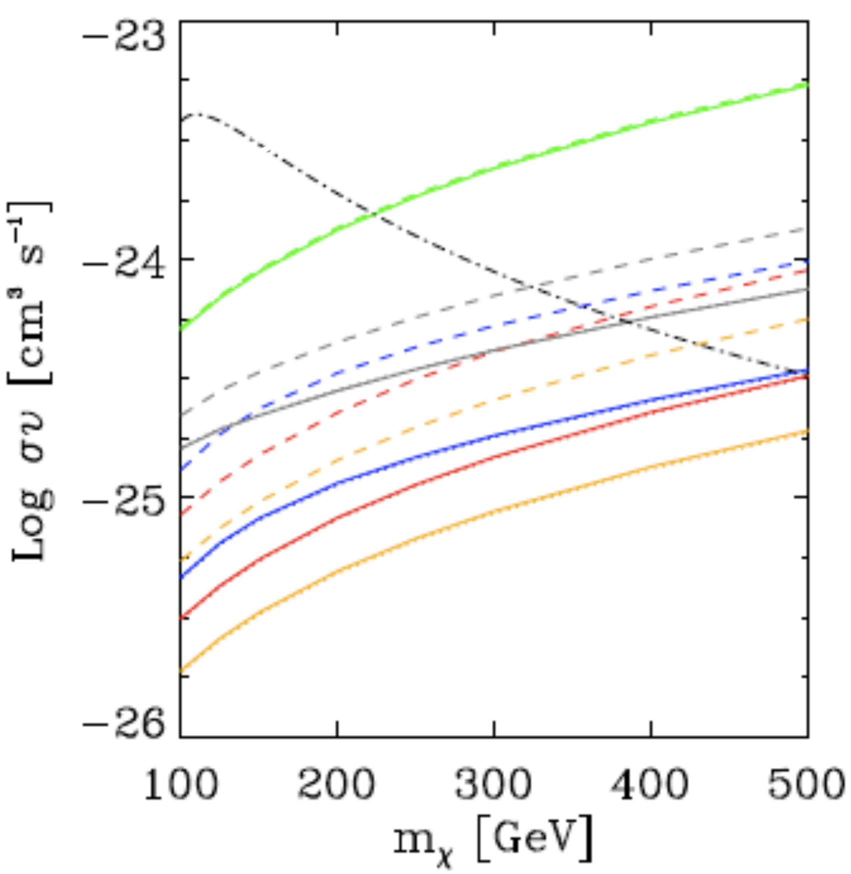
C. Evoli, E, D.Gaggero & D.G, 1504.05175



Uncertainty due to the DM profile >> Propagation uncertainty

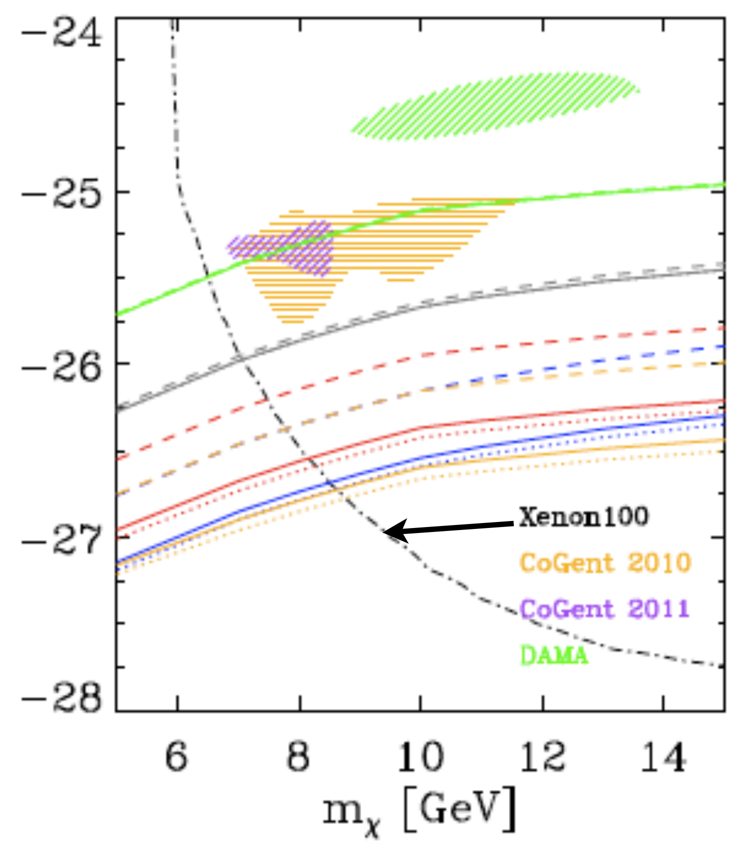
Antiproton constraints on DM

C. Evoli, I.Cholis, D.G., L.Maccione & P.Ullio, PRD, 2012, 1108.0664



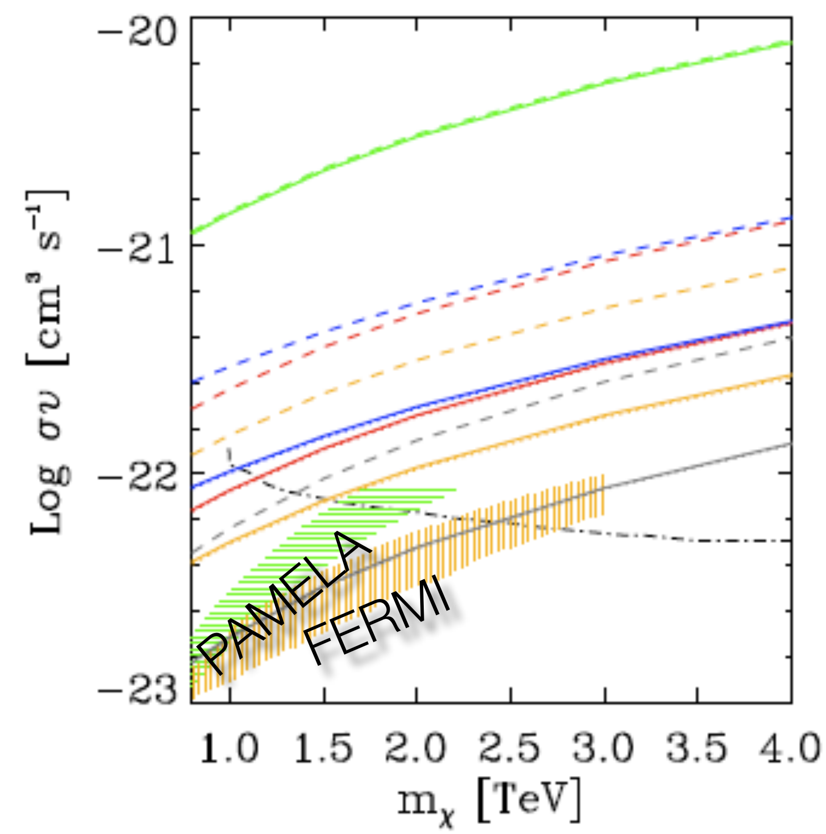
W-ino model

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



Light WIMPs

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

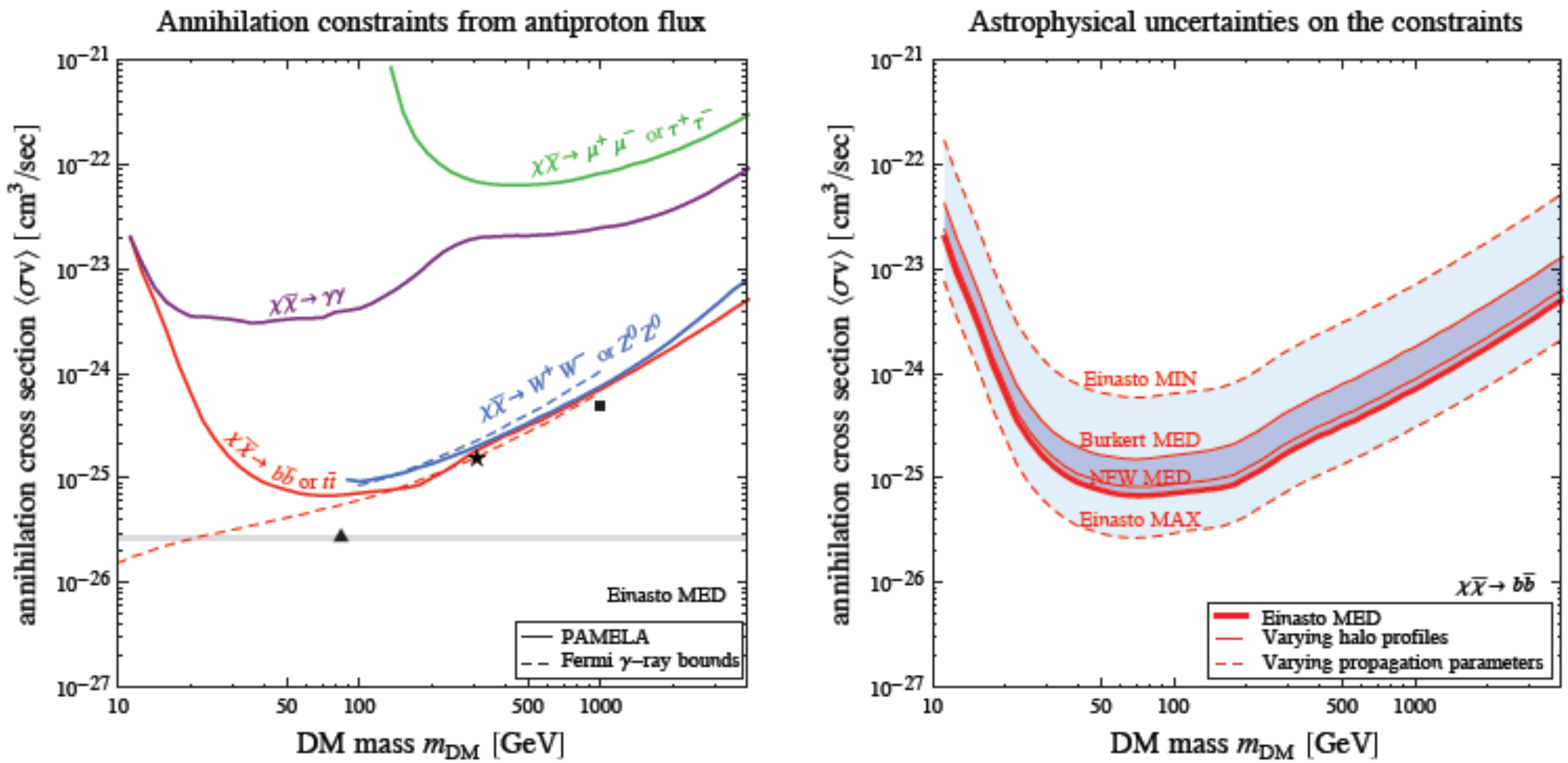


Heavy WIMPs

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

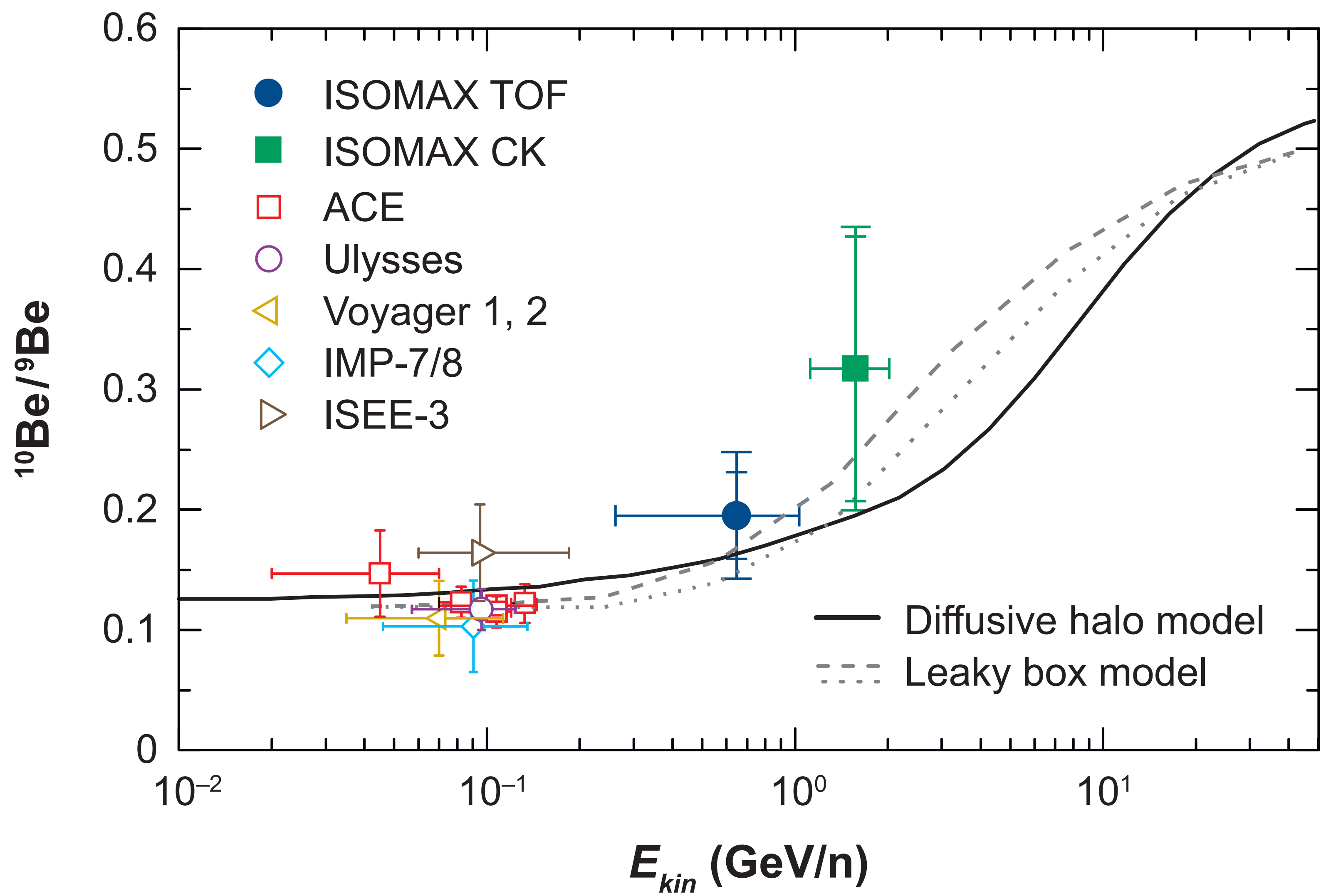
Antiproton constraints on DM

G. Giesen & M.Cirelli, 1301.7079



Cosmic-ray clocks

In principle remove the degeneracy between the diffusion coefficient and halo height determined from the B/C
in practice provide only a very weak constraint on z_t

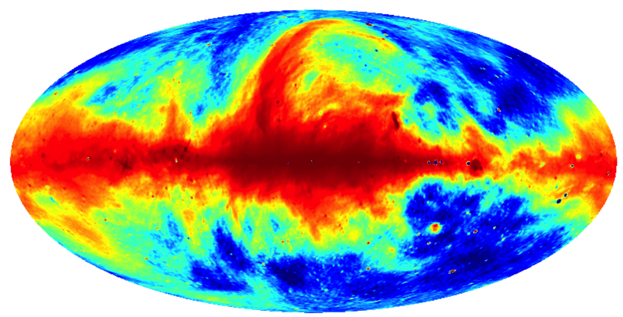


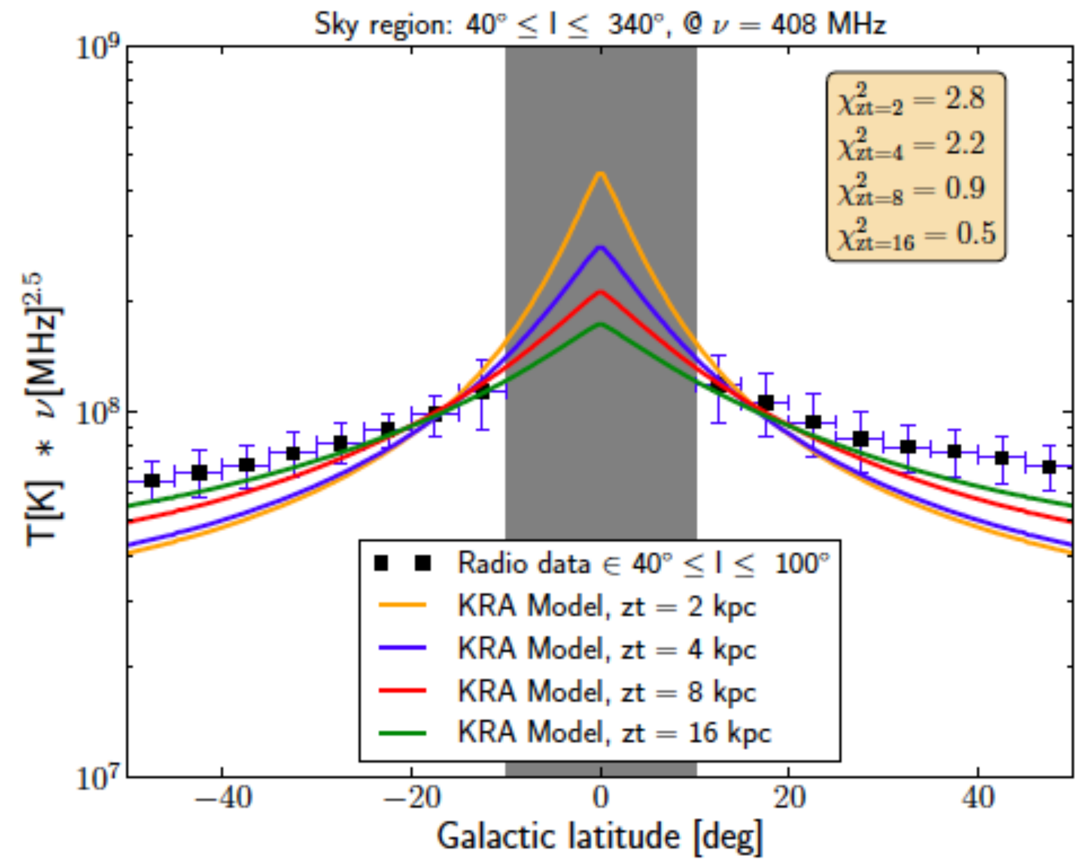
How to constrain the diffusive halo thickness ?

Bringmann & Donato 2011

Di Bernardo, Evoli, Gaggero, D.G, & Maccione JCAP 2012

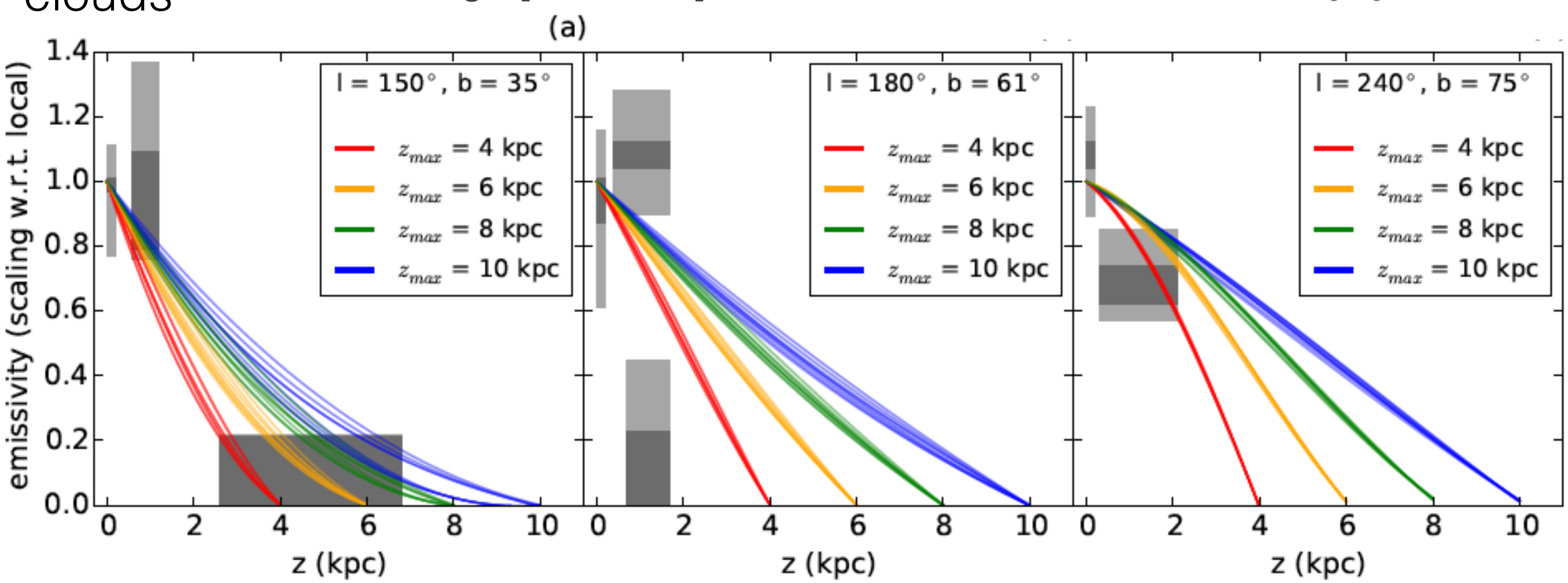
synchrotron emission
of the Galaxy





γ-ray from high latitude
molecular clouds

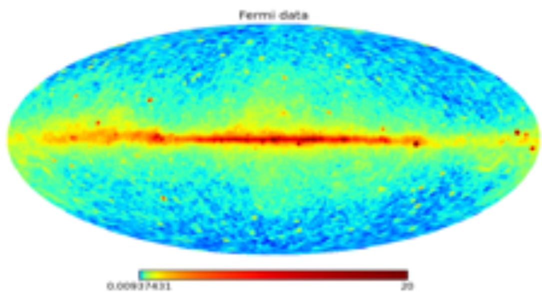
Tibaldo & Digel [Fermi coll.] 2015

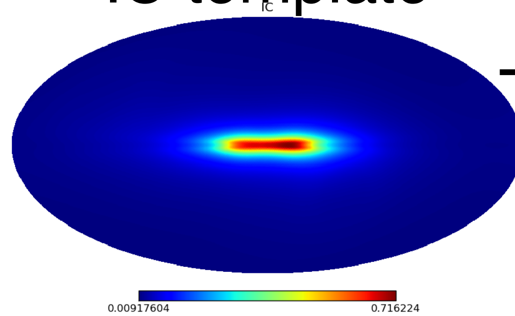


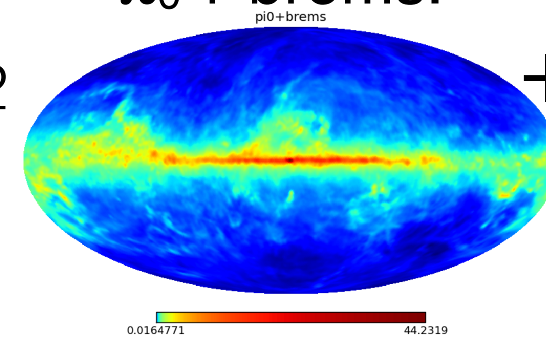
The Galactic Center (GC) GeV excess

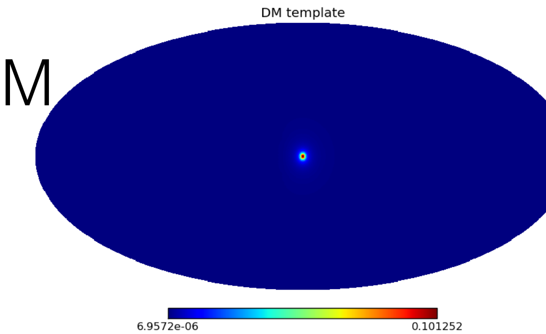
Template fitting analysis of Fermi-LAT favor the presence of a DM comp.

Fermi data = C_1 IC template $+ C_2$ π_0 + brems. $+ C_{DM}$ DM template

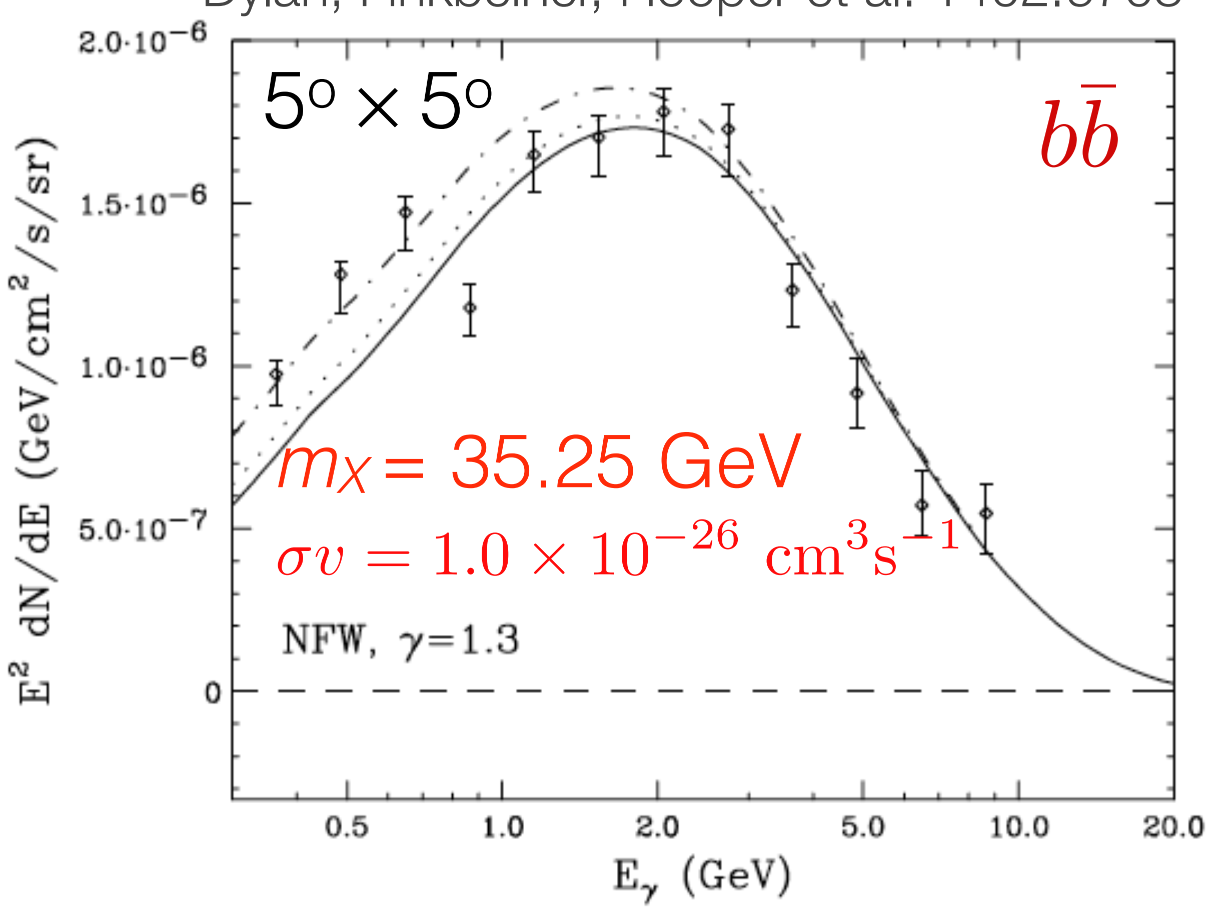








Dylan, Finkbeiner, Hooper et al. 1402.6703



D. Dixon et al. 1998 [arXiv:9803237]
V. Vitale et al. 2009 [arXiv:0912.3828]
L Goodenough and D. Hooper, 2009
D. Hooper and L. Goodenough, 2010
D. Hooper and T. Linden, 2011
K. N. Abazajian and M. Kaplinghat, 2012
D. Hooper and T. R. Slatyer, 2013
C. Gordon and O. Macias, 2013
T. Daylan, et al. [arXiv:1402.6703]
F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]
F. Calore et al. 2015 [arXiv;1411.4647]

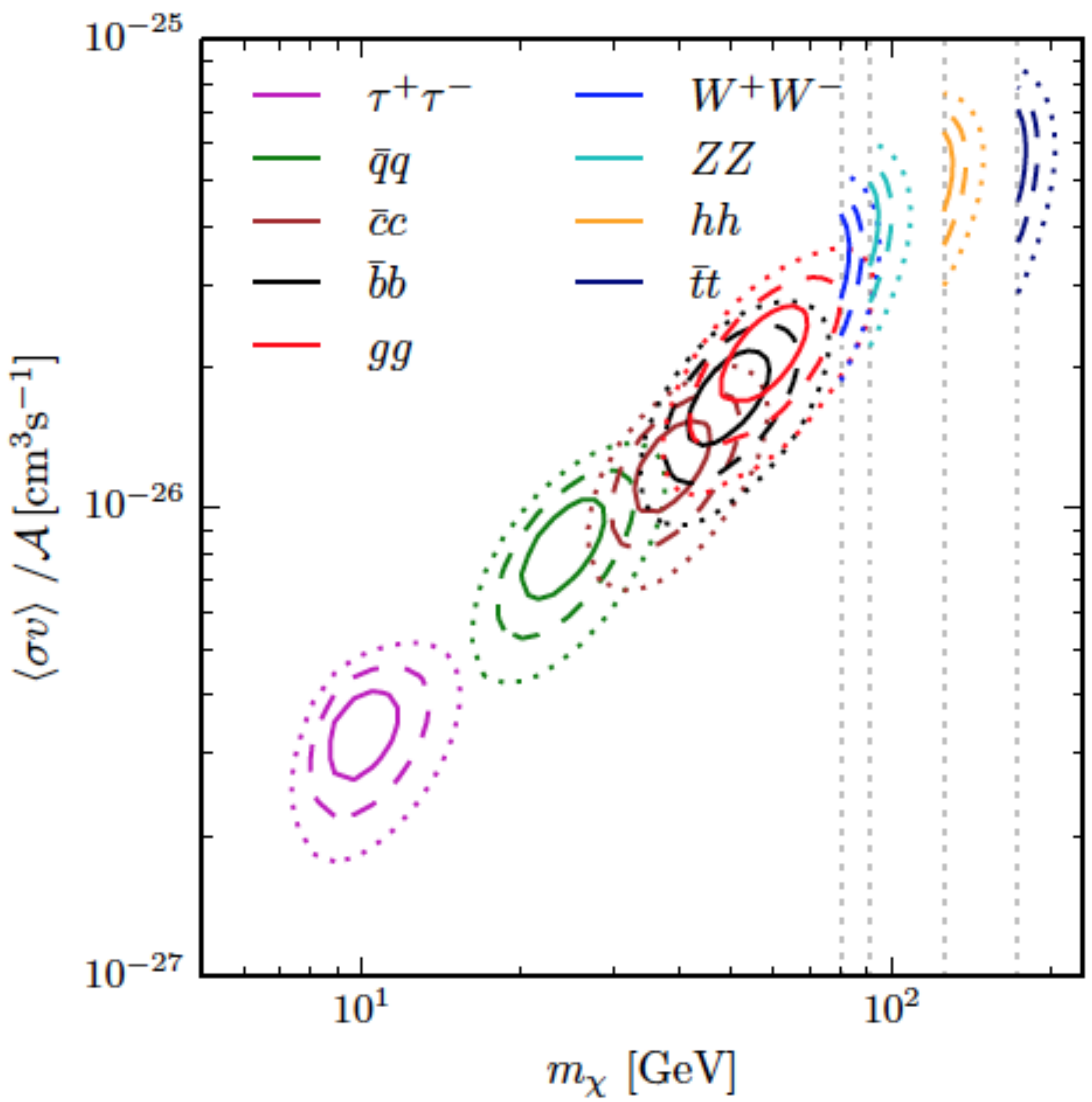
DM interpretation of the GC GeV excess

Calore, Cholis, McCabe, Weniger 1411.4647

A detailed study of the uncertainties of Galactic diffuse background is performed.

A larger set of DM annihilation channels is allowed

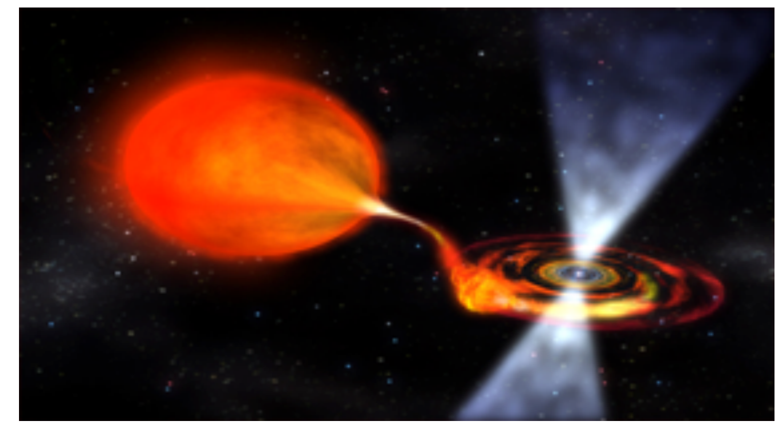
It was checked that constraints from Dwarf Spheroidal galaxy emissions are not violated



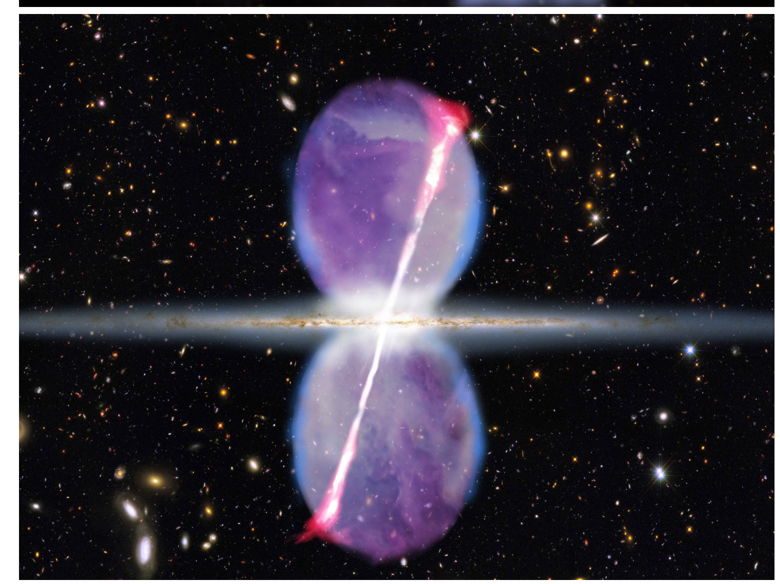
Astrophysical interpretations of the GC GeV excess

Main interpretations:

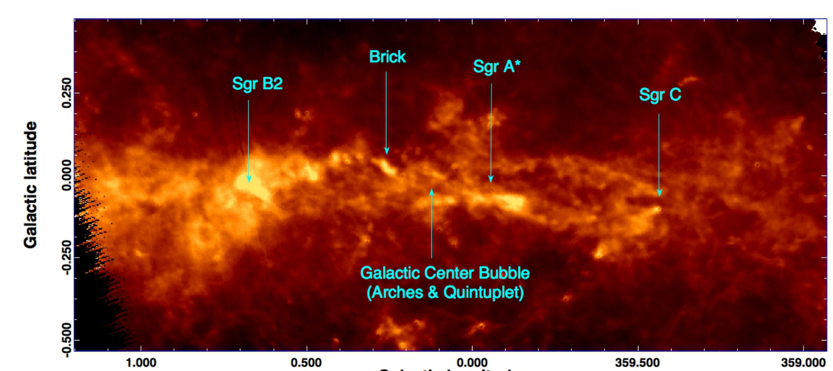
a population of milli-second pulsars
Wang et al. 2015; Gordon & Macias 2013; Lee et al. 2015; Bartels et al 2015



transient phenomena (SMBH outburst)
Carlson et al. 2014; Petrovic et al. 2015
Cholis et al. 1506.05119

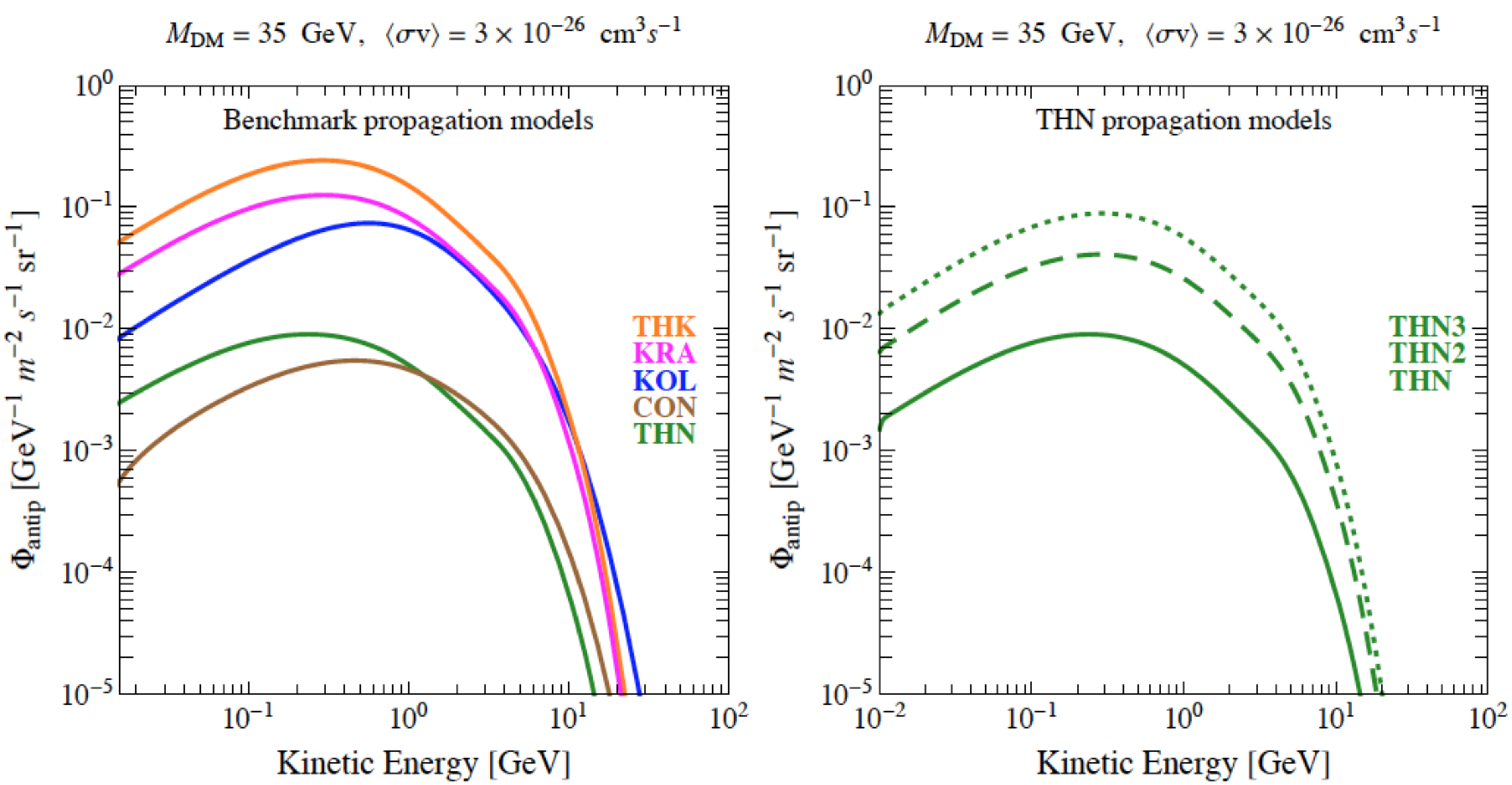


a peaked SNR density in the GC
Gaggero et al. 1507.06129



Antiproton constraints on the DM interpretation of the GC GeV excess - propagation uncertainties

Cirelli, Gaggero, Giesen, Taoso, Urbano, 1407.2173



	KRA	KOL	CON	THK	THN	THN2	THN3
z_t [kpc]	4	4	4	10	0.5	2	3
D_0 [10^{28} cm^2 s^{-1}]	2.64	4.46	0.97	4.75	0.31	1.35	1.98
δ	0.50	0.33	0.6	0.50	0.50	0.50	0.50
η	-0.39	1	1	-0.15	-0.27	-0.27	-0.27
v_A [km s^{-1}]	14.2	36	38.1	14.1	11.6	11.6	11.6
γ	2.35	1.78/2.45	1.62/2.35	2.35	2.35	2.35	2.35
dv_c/dz [km s^{-1} kpc^{-1}]	0	0	50	0	0	0	0
ϕ_F^p [GV]	0.650	0.335	0.282	0.687	0.704	0.626	0.623
χ^2_{min}/dof (p in [25])	0.462	0.761	1.602	0.516	0.639	0.343	0.339

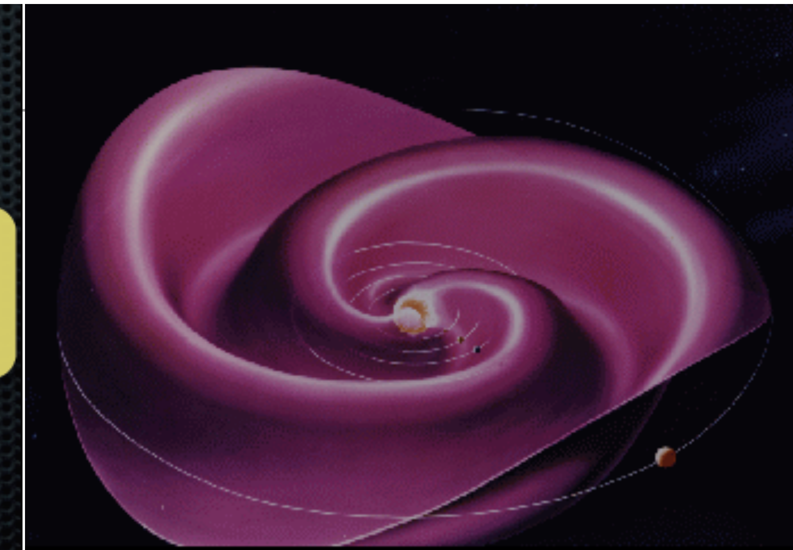
Charge dependent solar modulation

Propagation equation

(notation from Strauss et al, 2012, eqn. dating back to Parker, Burger, Jokipii et al., 60/70's)

$$\frac{\partial f}{\partial t} = -(\vec{V}_{\rm sw} + \vec{v}_d) \cdot \nabla f + \nabla \cdot (\boldsymbol{K} \cdot \nabla f) + \frac{P}{3}(\nabla \cdot \vec{V}_{\rm sw}) \frac{\partial f}{\partial P}$$

$$\vec{v}_d = \frac{qv}{3} \nabla \times r_L \frac{\vec{B}}{B}$$

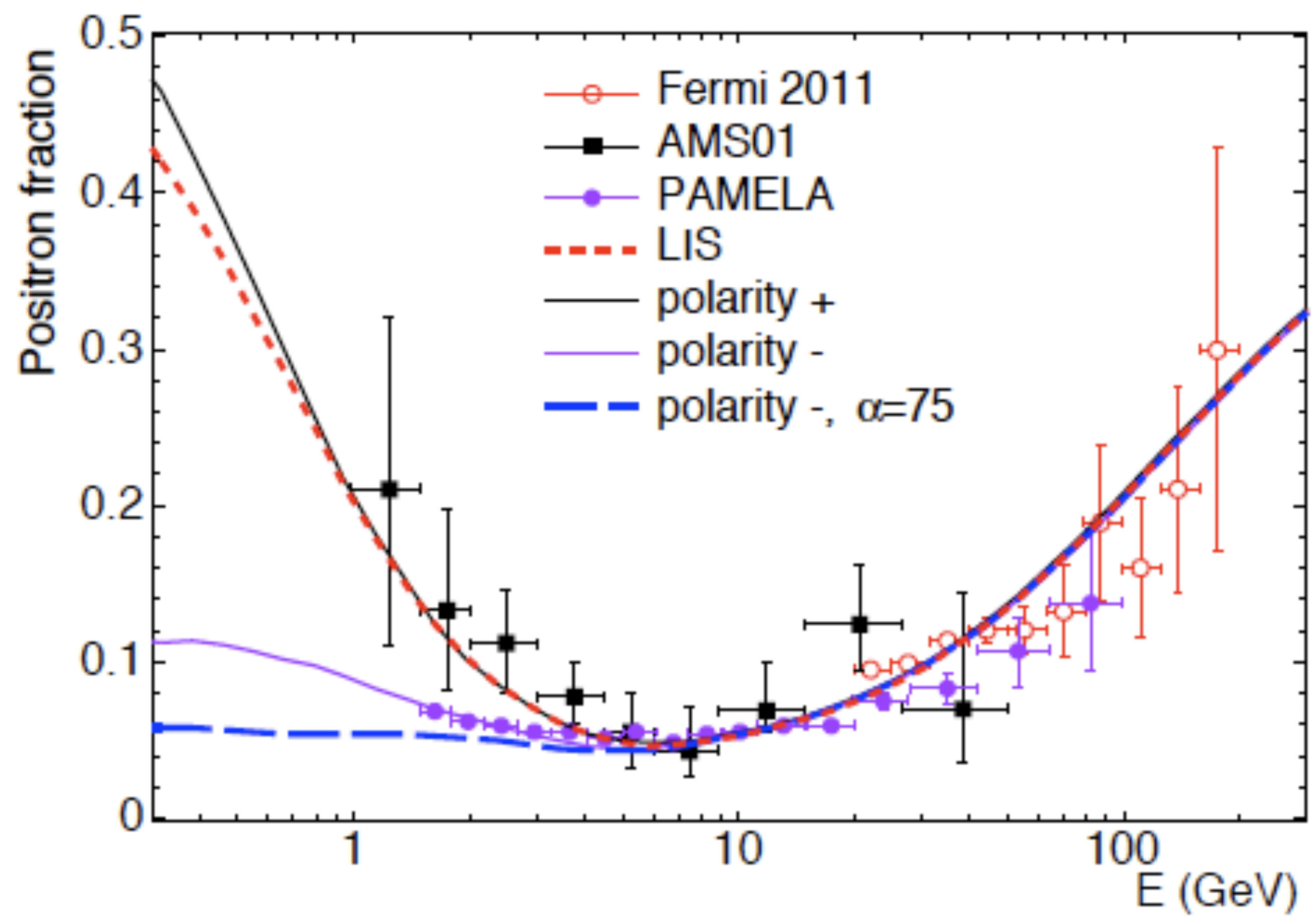


Dedicated codes treating propagation in the heliosphere by means of stochastic differential equations have been developed

L. Maccione PRL (HelioProp code)

This was shown to work for the positron fraction

We used HelioProp to modulate antiprotons as well.

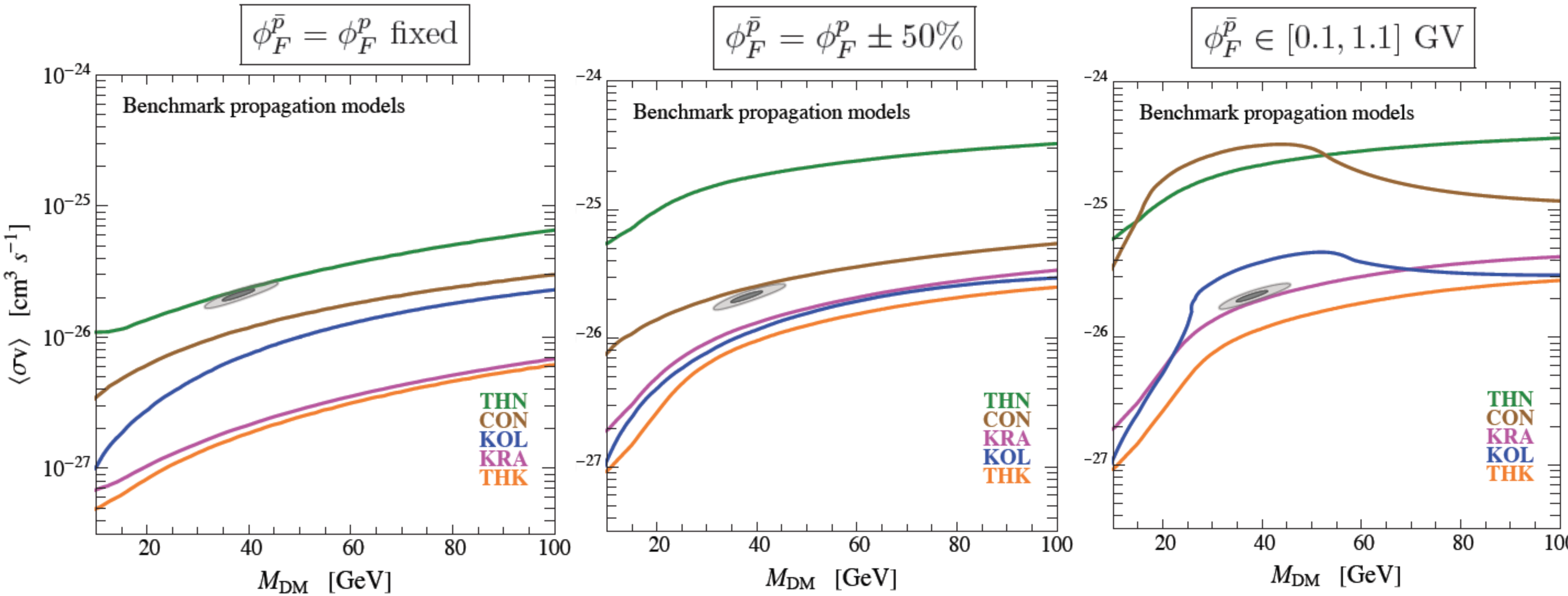


Antiproton constraints of the DM interpretation of the GC GeV excess

Cirelli, Gaggero, Giesen, Taoso, Urbano, 1407.2173

The role of solar modulation

$b\bar{b}$ channel



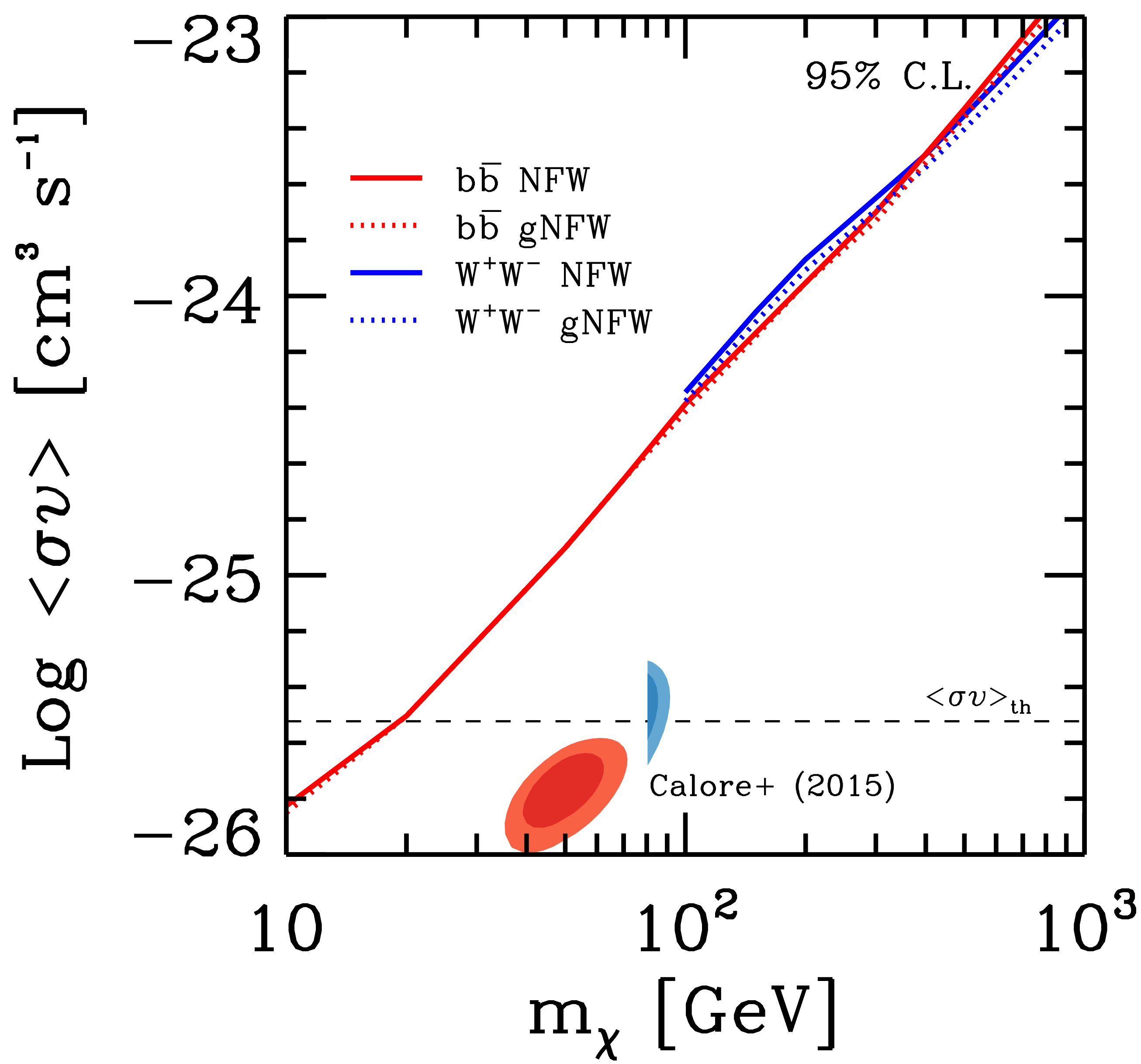
Warning: the background is kept fixed here !

DM bounds after PAMELA data

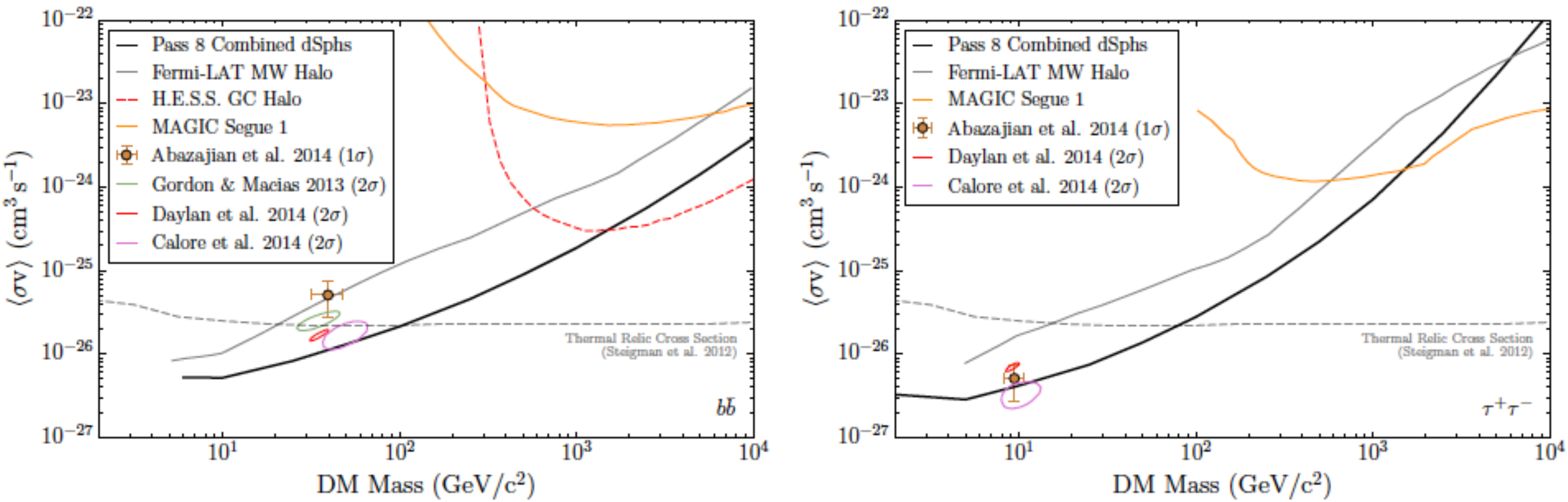
C. Evoli, E, D.Gaggero & D.G, 1504.05175

Upper limits obtained taking

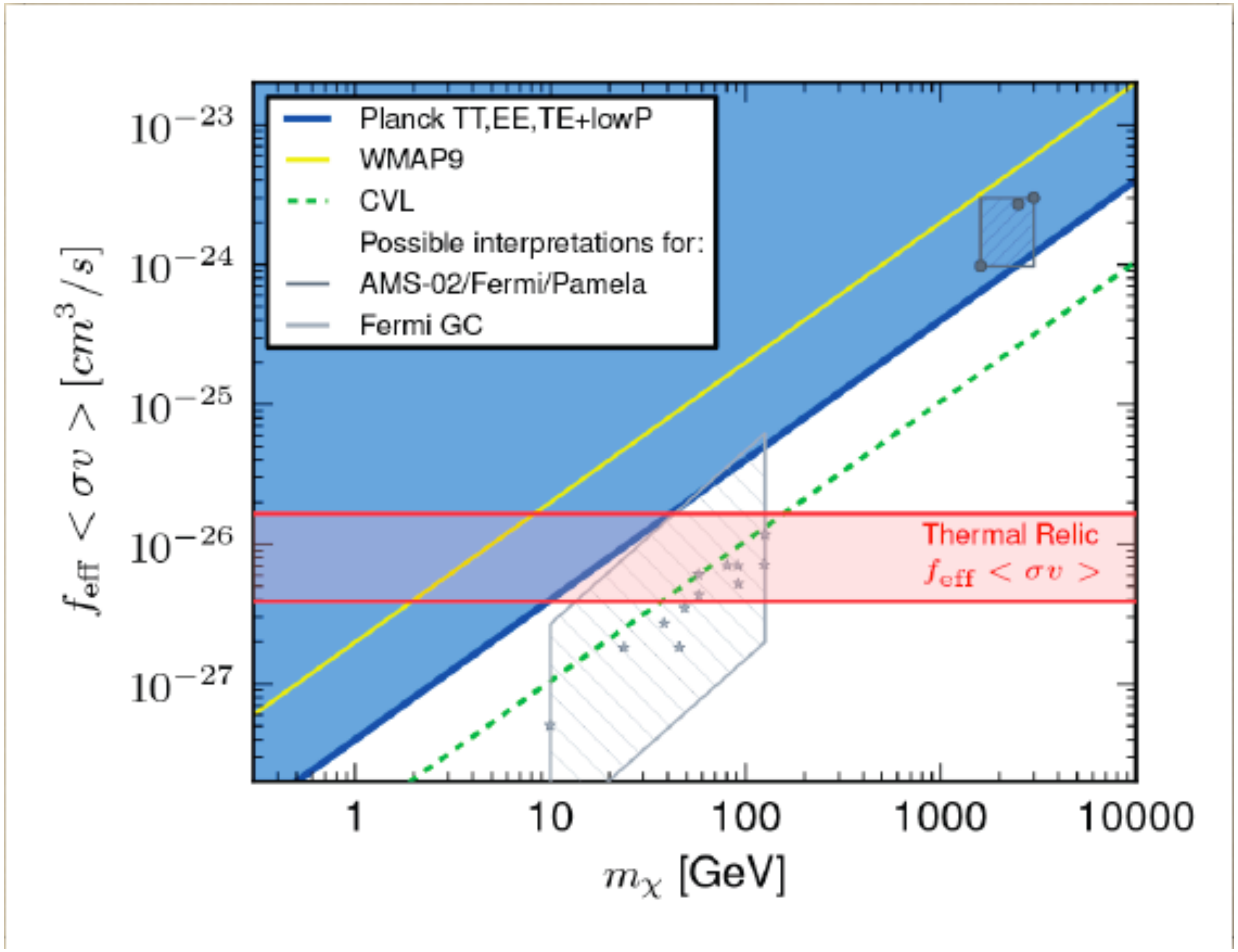
- z_t = 2 kpc (minimal CR halo height compatible with radio obs. ⇒ max $\bar{p}$ flux from DM annihilation)
- minimal secondary antiproton spectrum at E ~ m_χ compatible with PAMELA B/C data
- minimal $\bar{p}$ production cross-section compatible with NA49 data
  Kappl & Winkler 1408.0299



Constraints from γ-rays



Constraints from the CMB



Conclusions

- The secondary antiproton spectrum can be computed with good accuracy (30 % unc. at most) on the basis of CR nuclear data

- Present data (including preliminary AMS   data) do not show any presence of an excess respect to that background

- Antiprotons from dark matter annihilation are subject to much larger uncertainties mainly due to the poorly known diffusive halo height. Gamma ray and radio/microwave observation may help to reduce this uncertainty.

- The DM interpretation of the GC GeV excess is still compatible with antiproton (as well as gamma and CMB) constraints