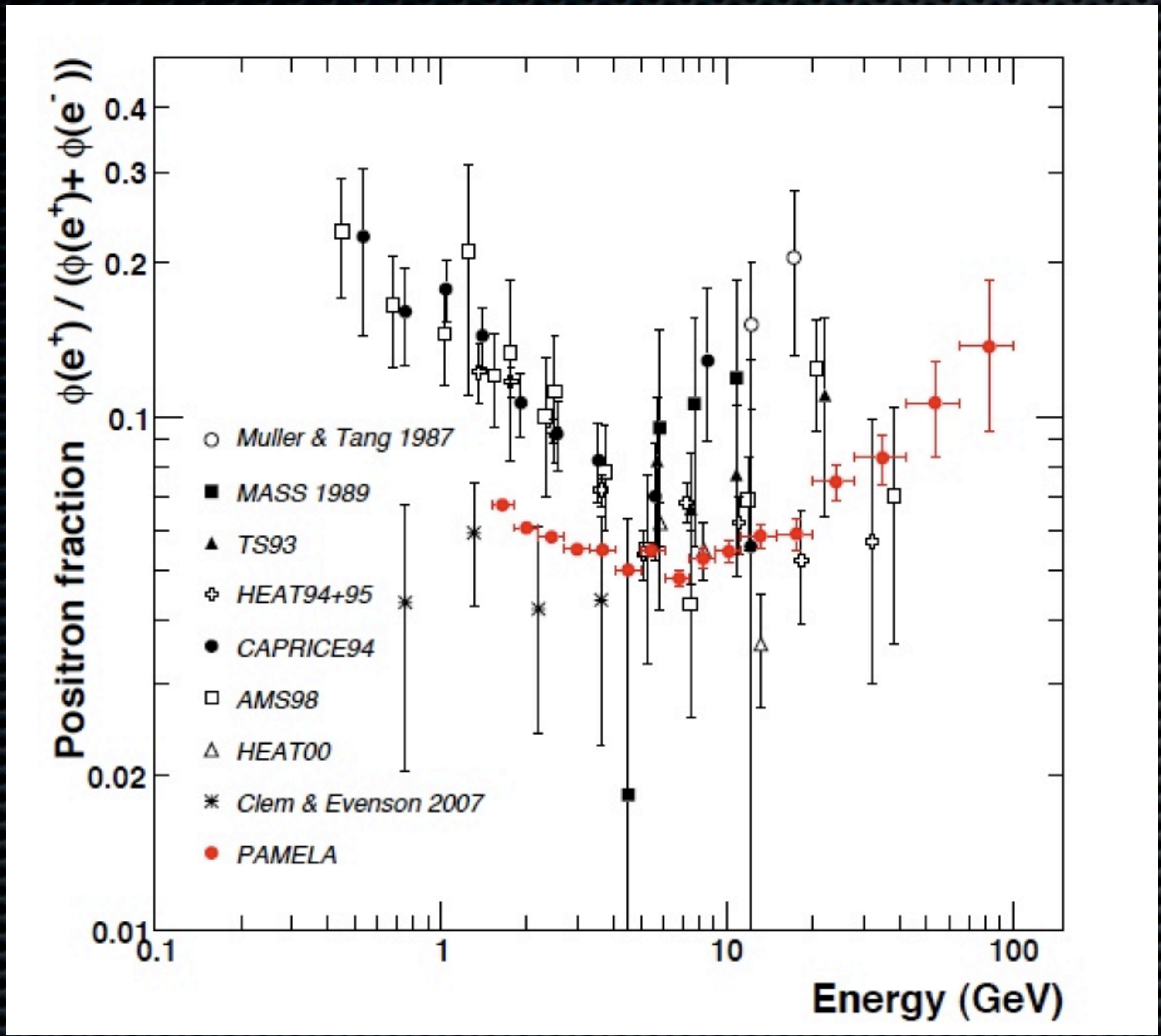
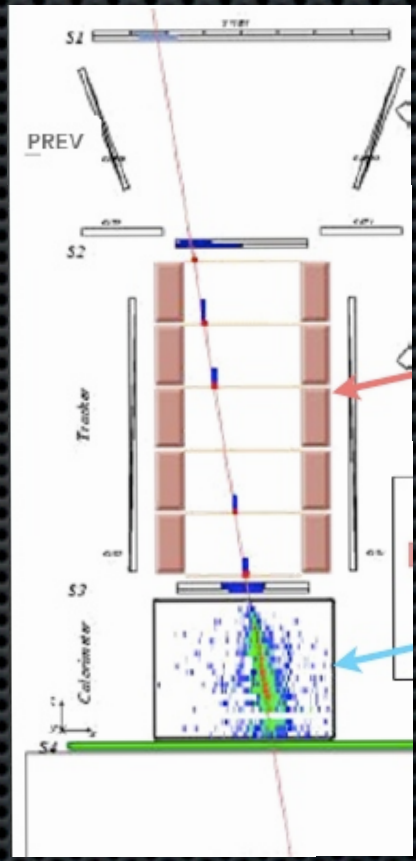
The cosmic positron excess and its possible interpretations

Dario Grasso (INFN)

The recent beginning of this story

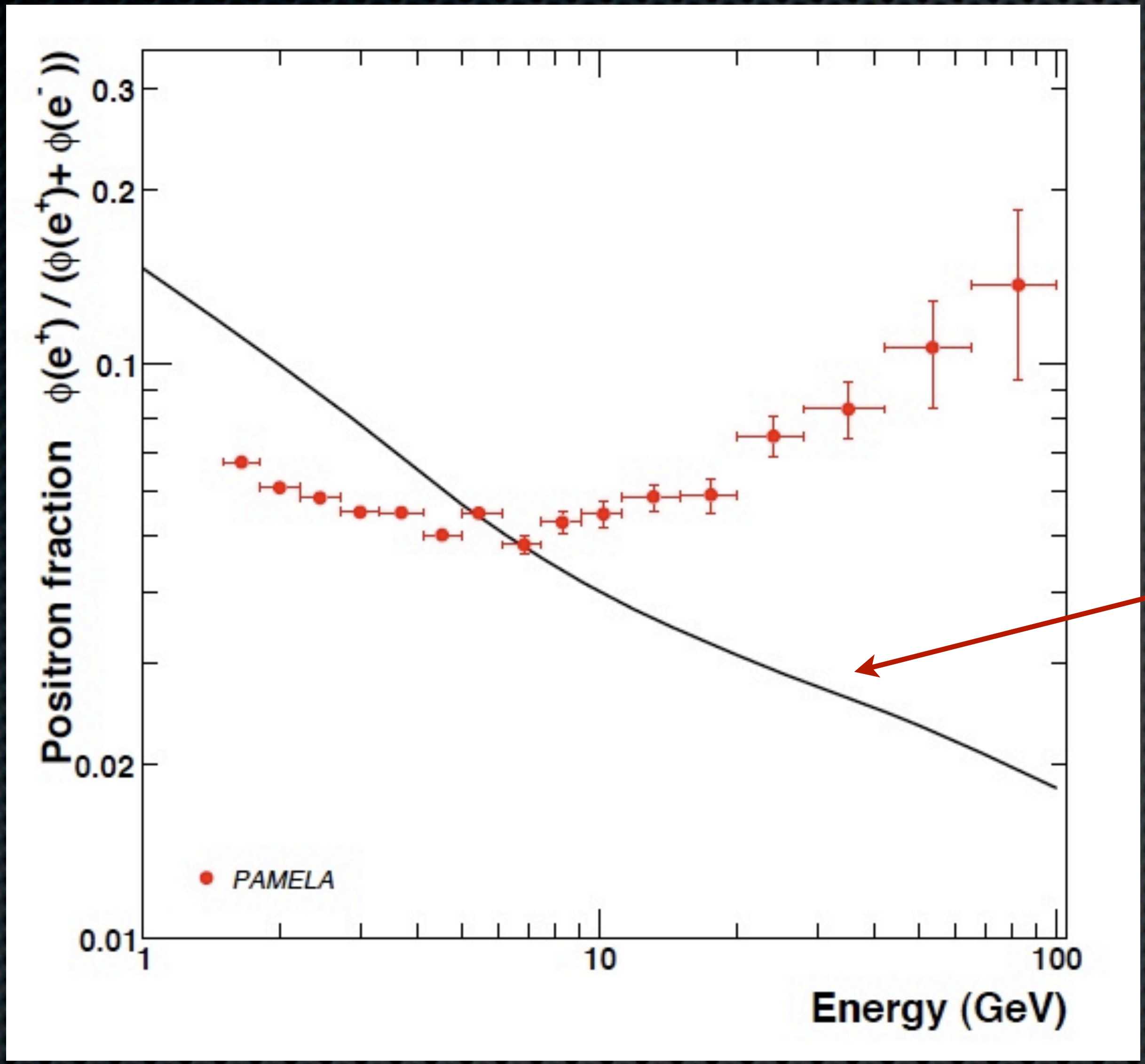


PaMeLa



Adriani et al.[PAMELA coll.], Nature 2008

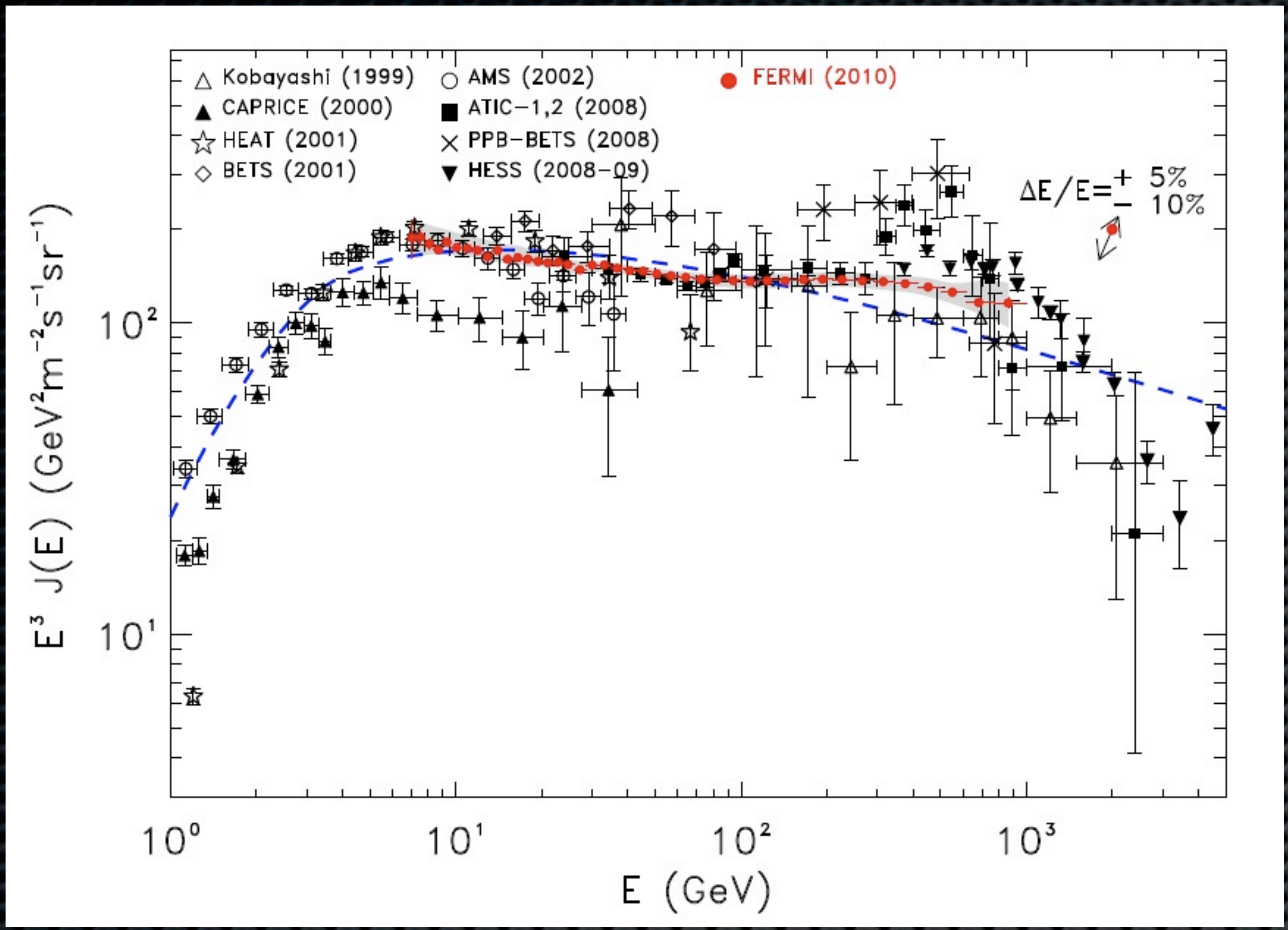
Excess respect to what ?



under the "standard" assumption that e^+ are produced only by CR nuclei scattering in the interstellar medium
and using pre-Fermi $e^- + e^+$ data

Adriani et al., Nature 2008

The electron + positron spectrum

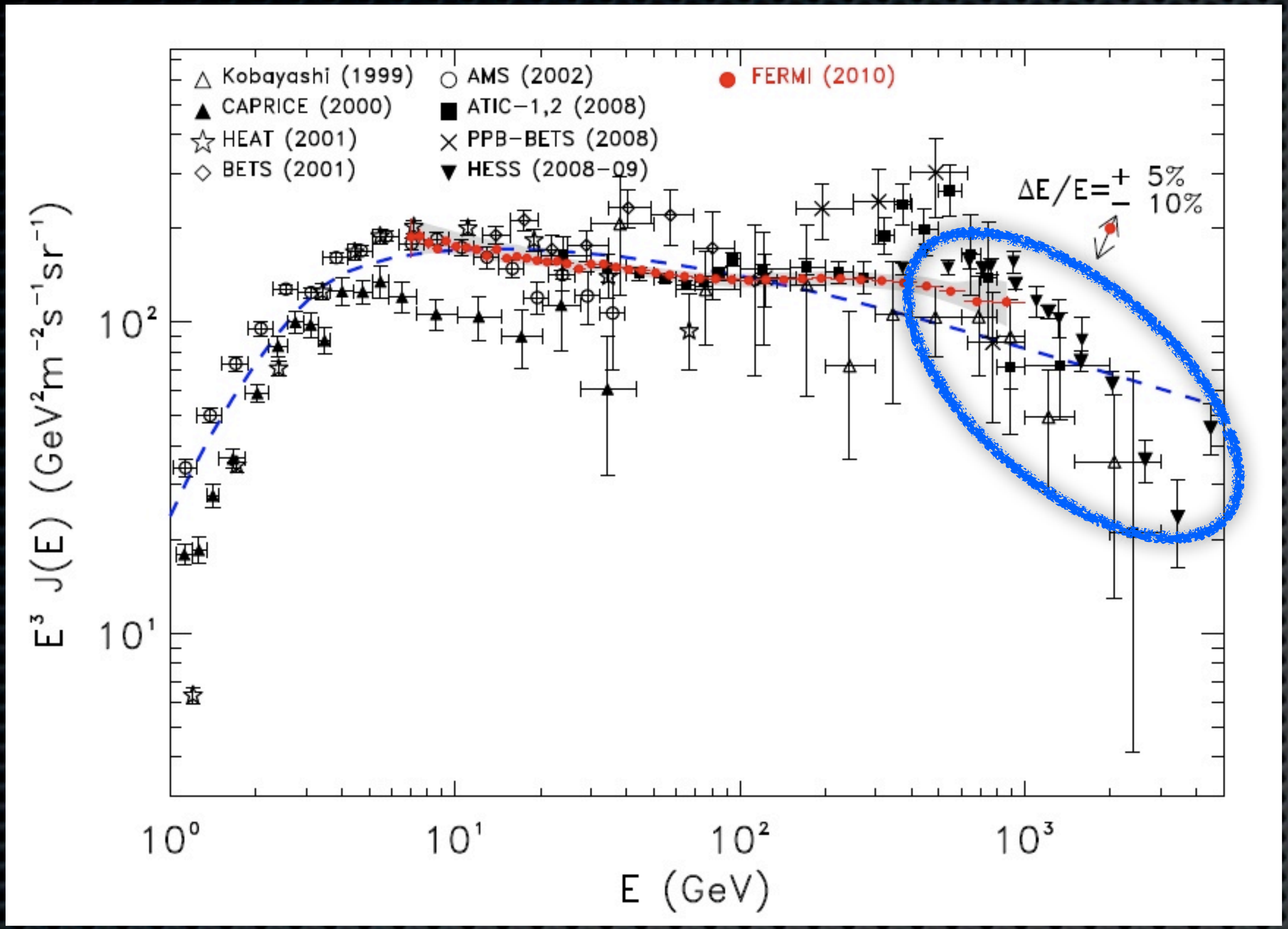


Fermi-LAT coll. PRL 2009; PRD 2010

Compatible with a Power-law with $\gamma(e^{\pm}) = 3.045 \pm 0.008$

anisotropy stringent limits (see below)

The electron + positron spectrum

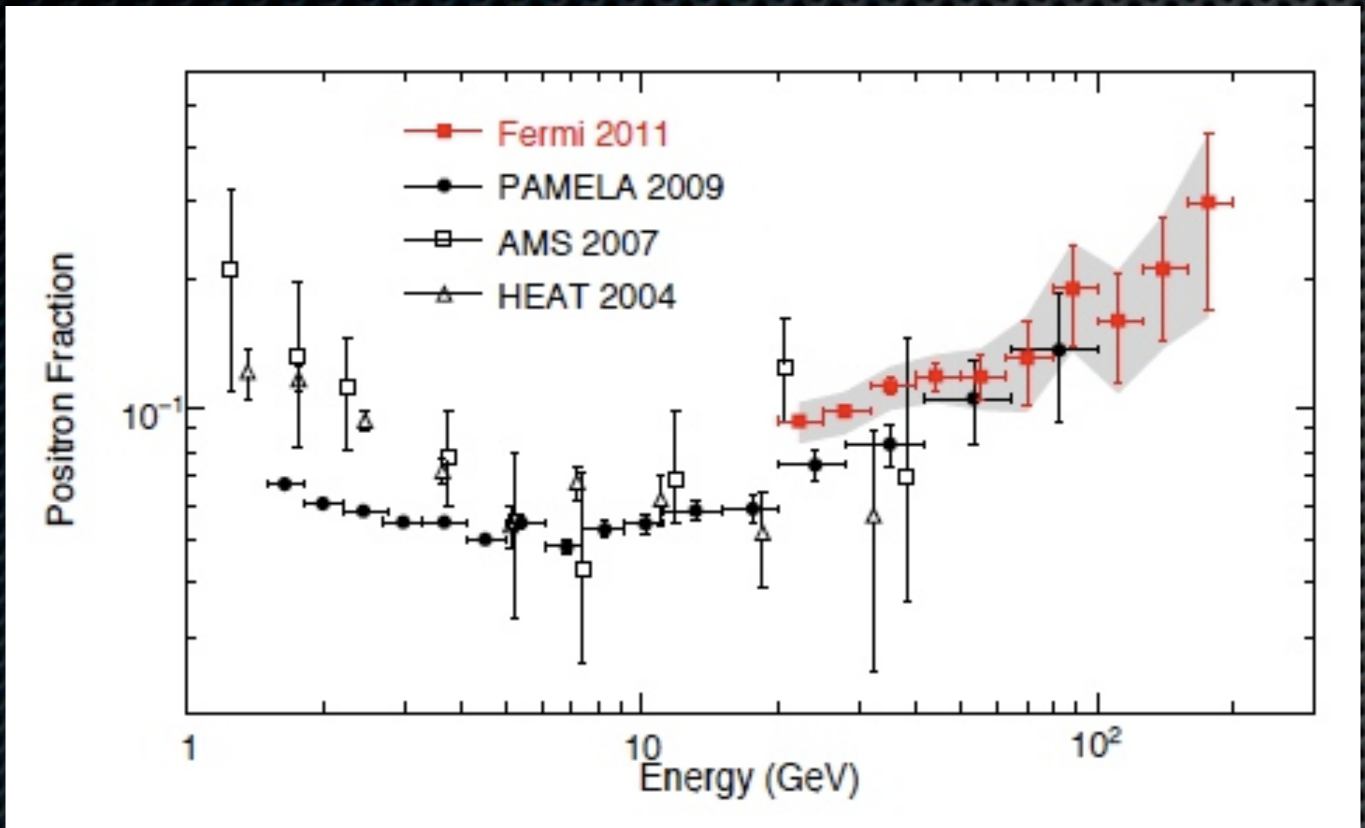


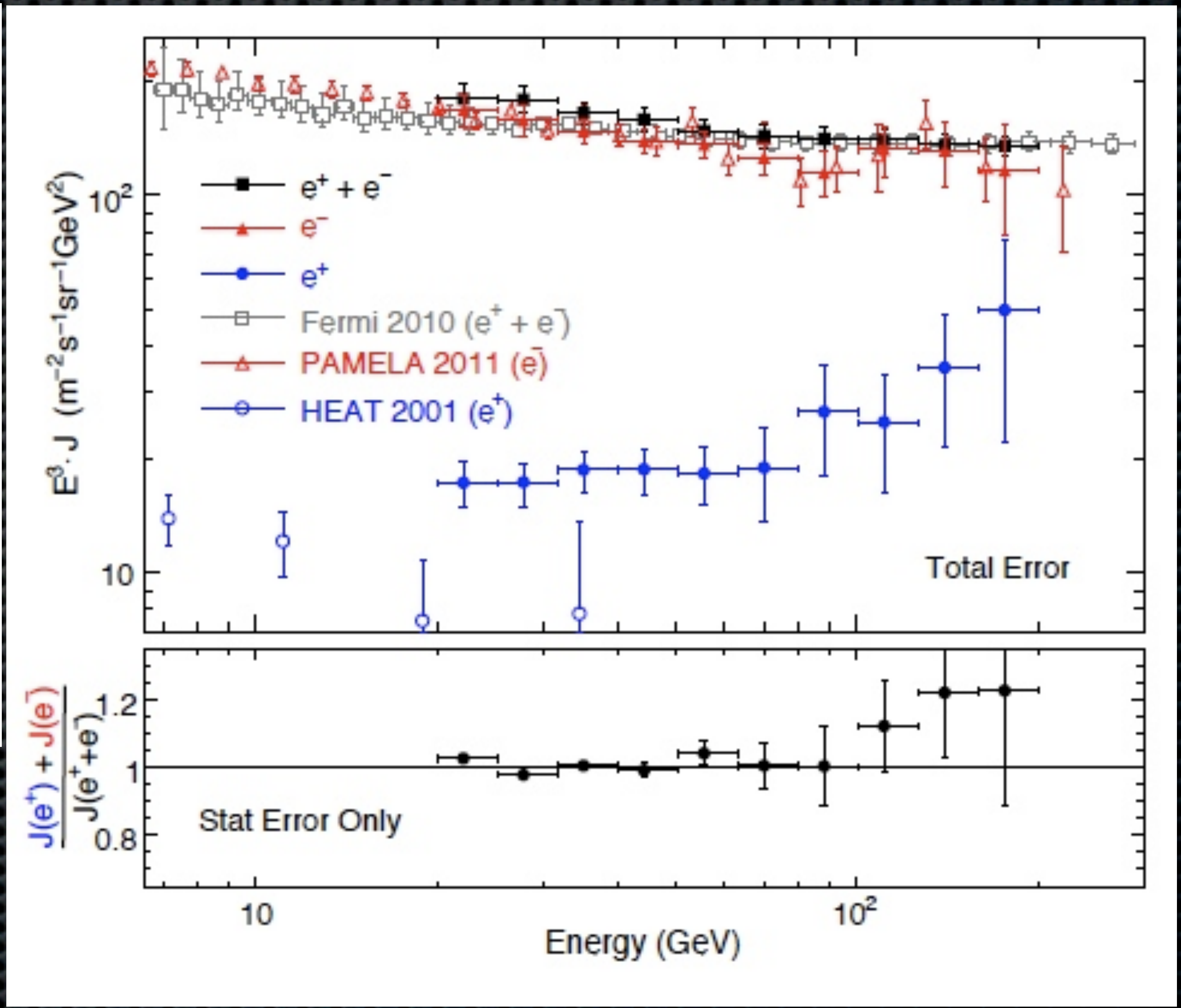
H.E.S.S. coll. Astron. & Astroph. 2009

spectral steepening above ~ 1 TeV

Fermi-LAT: first indipendent confirmation and positron measurement above 10 GeV

Fermi-LAT - PRL 2012



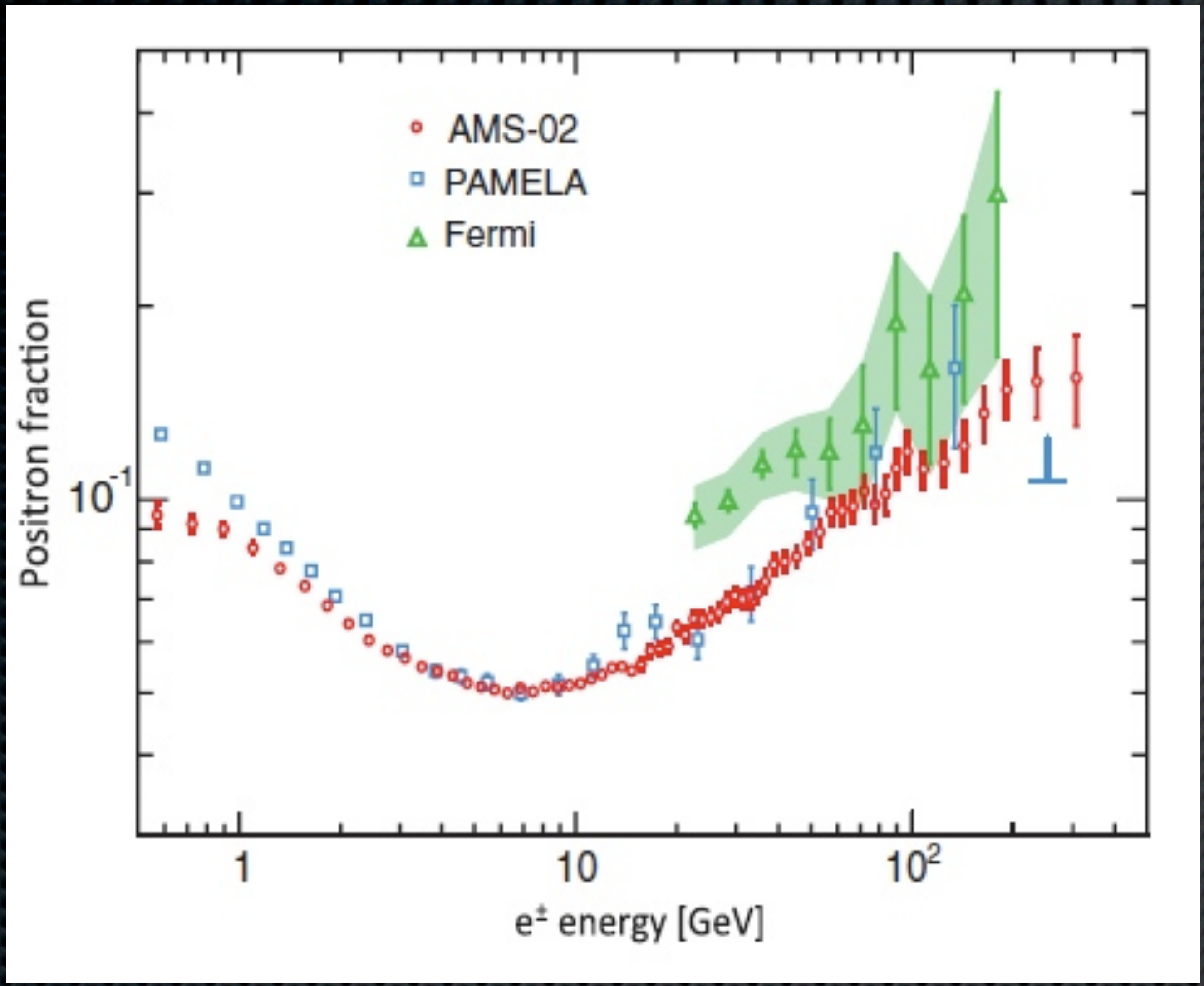


$\gamma(e^+) \simeq 2.77 \pm 0.14 \simeq \gamma(p)$

→ e^+ cannot be CR secondaries !!

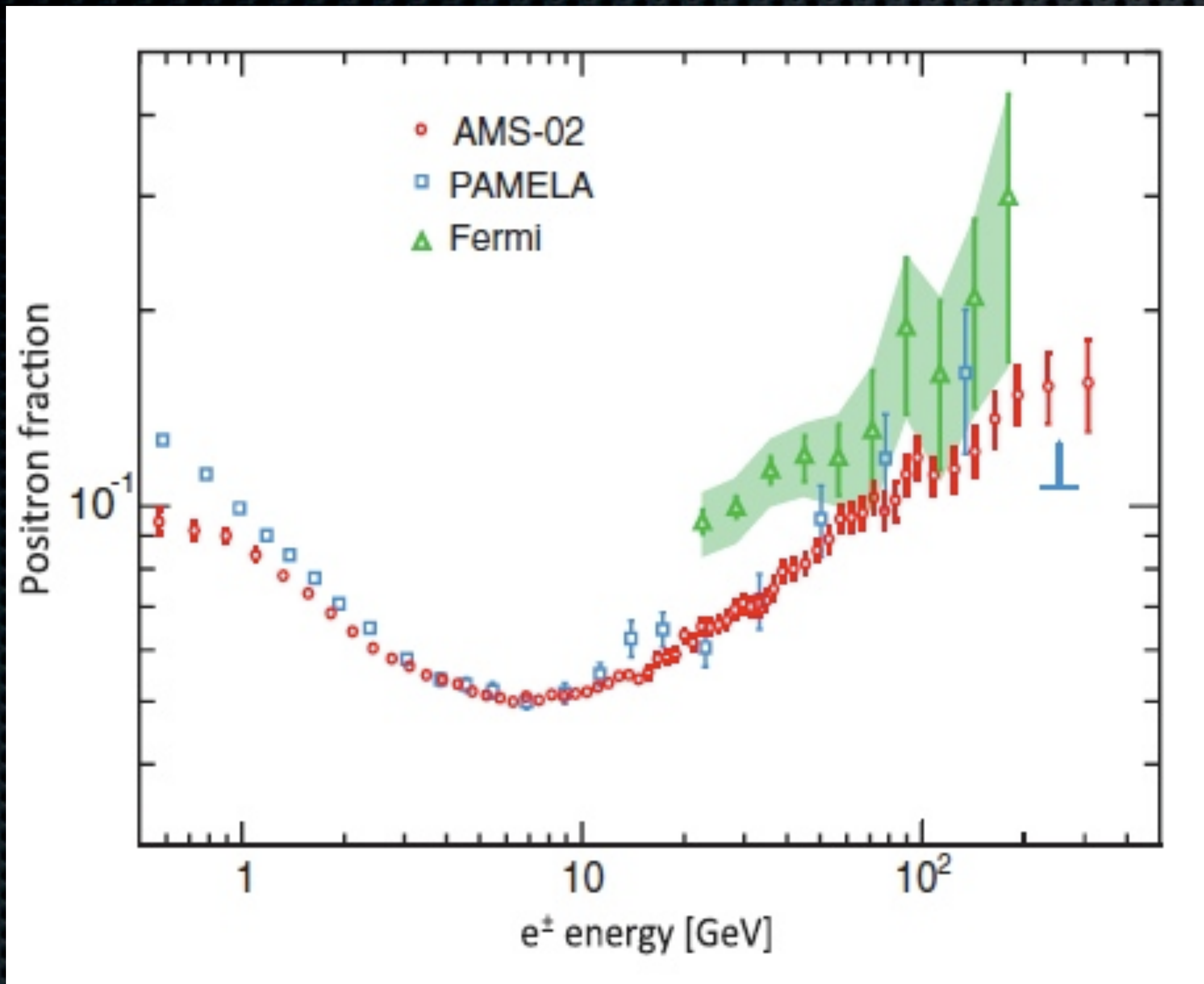
see below

AMS-02 first result: positron fraction up to 350 GeV



AMS-02 coll. - PRL April 2013

AMS-02 first result: positron fraction up to 350 GeV



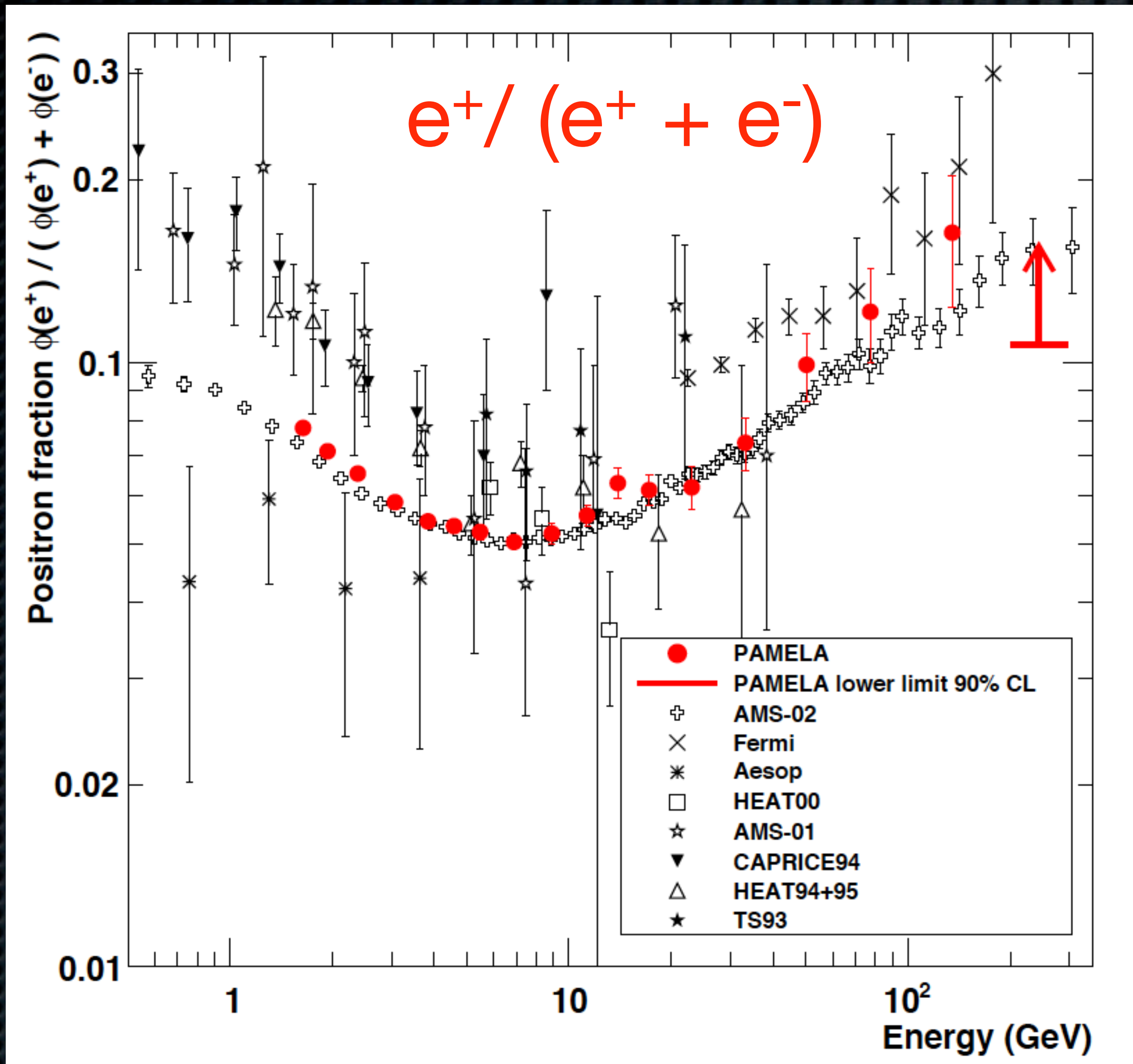
$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

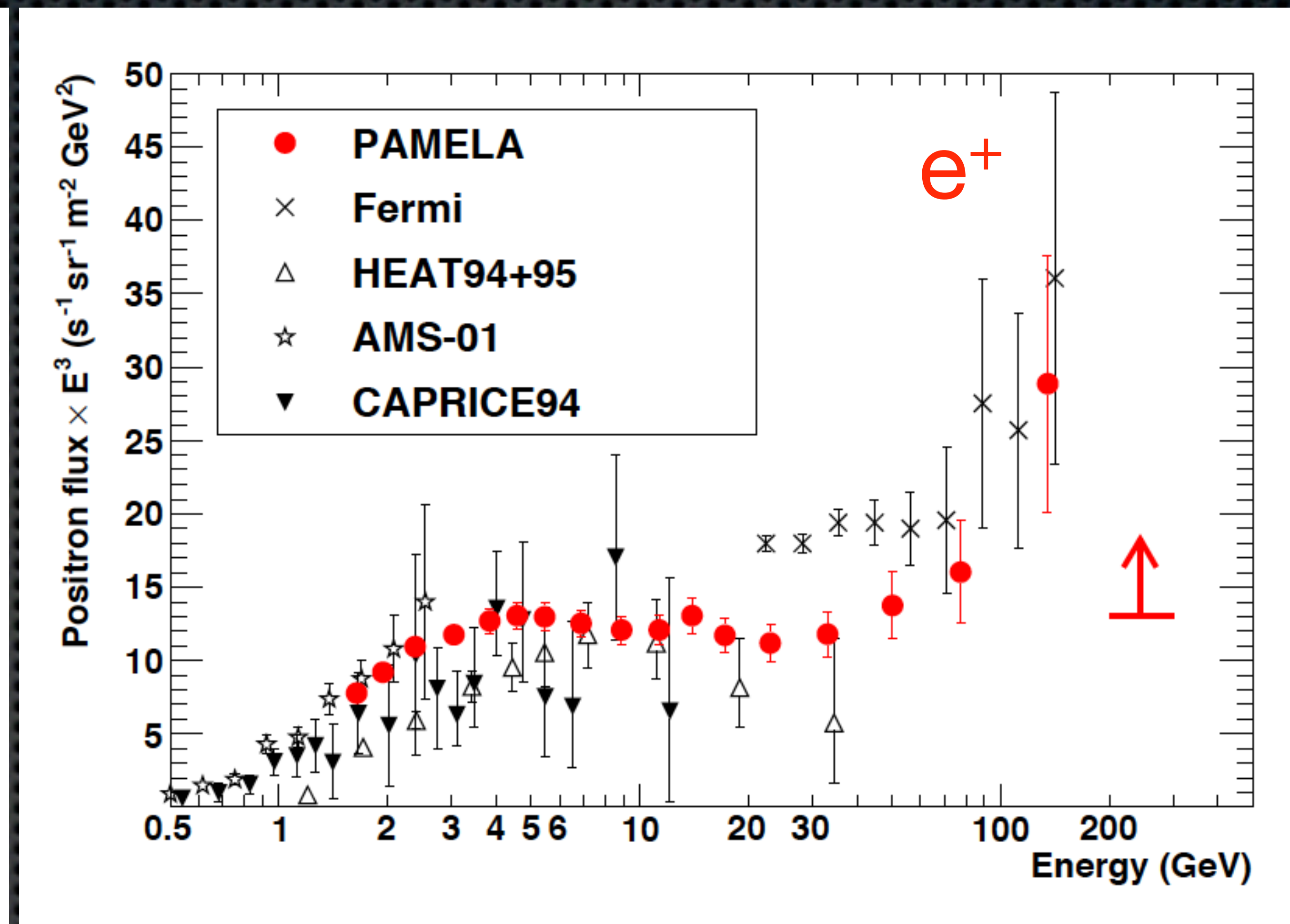
$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

AMS-02 coll. - PRL 2013

- softer than PAMELA between 20 - 250 GeV
- hints of a flattening above 250 GeV
- no anisotropy

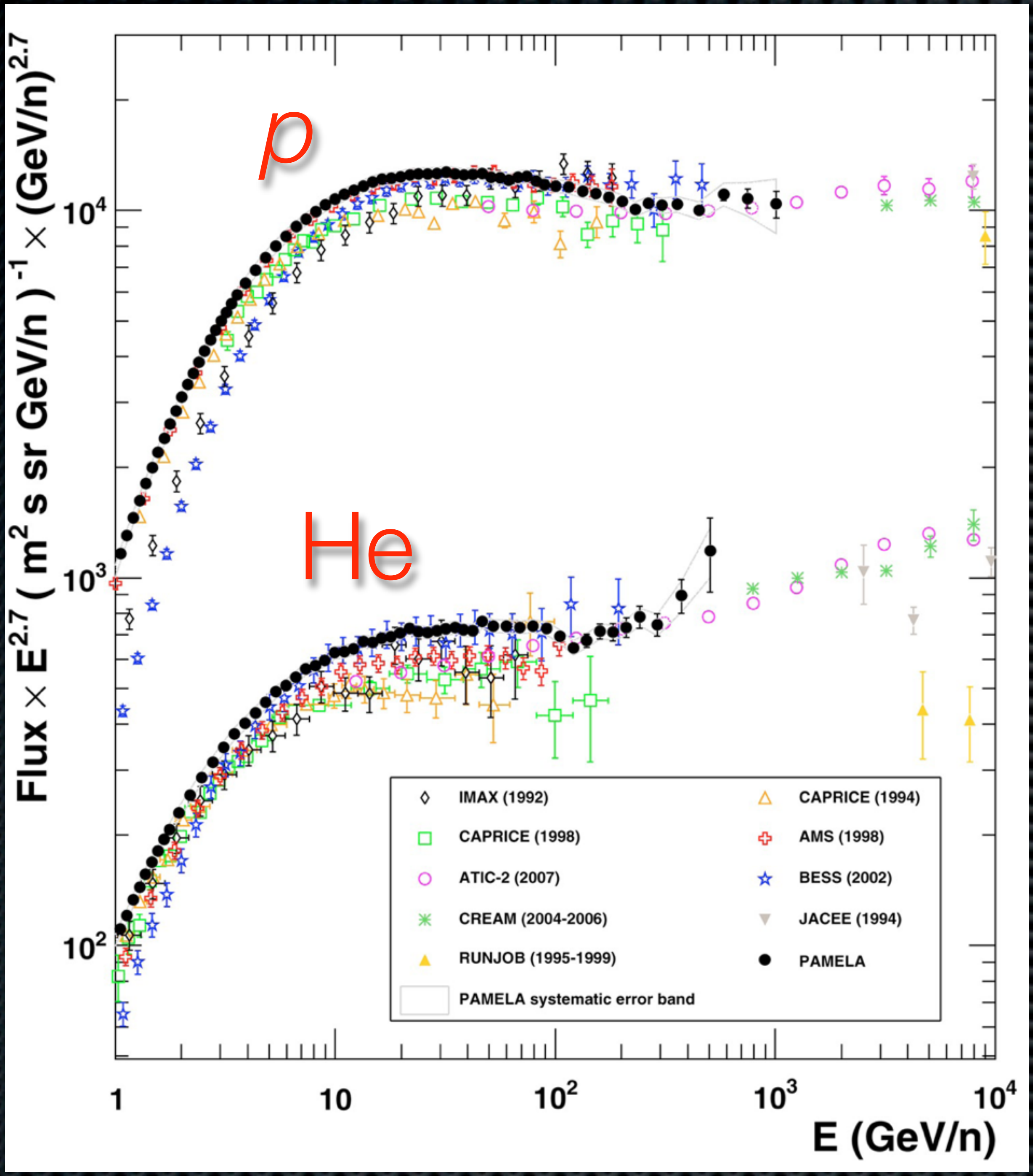
PAMELA: improved PF and absolute e+



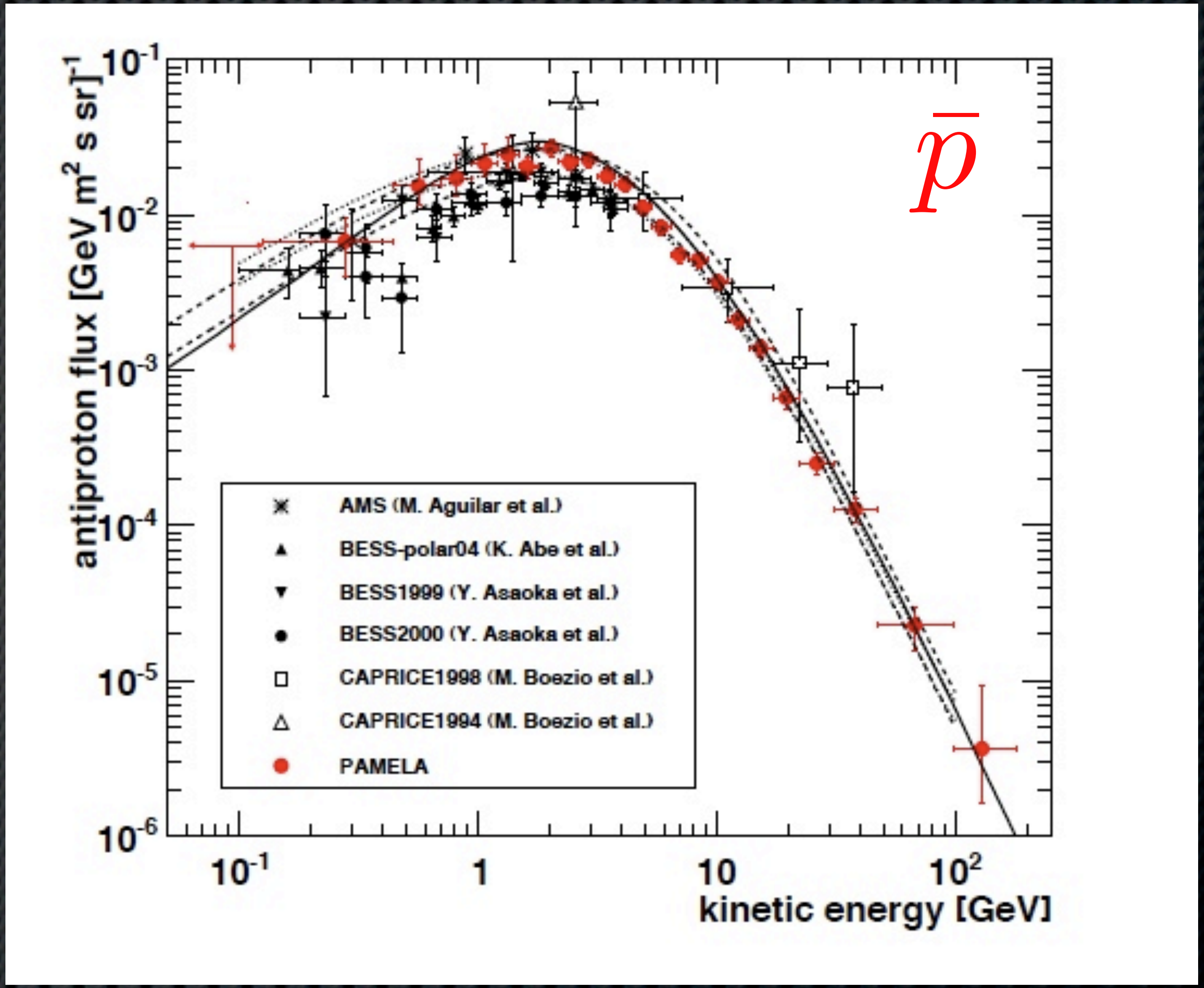


PAMELA coll. - PRL 2013

PAMELA other important results

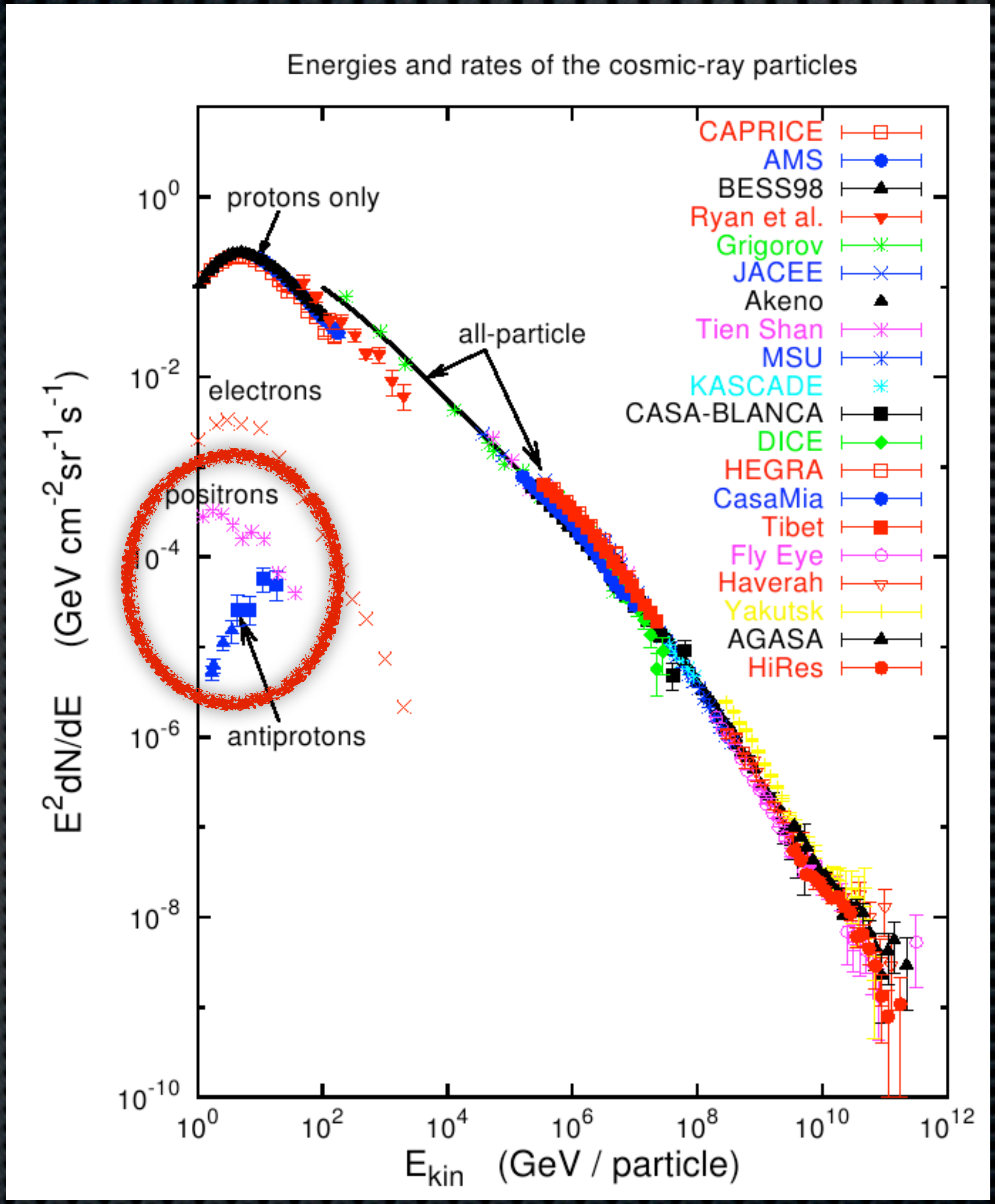


PAMELA coll. - 2011

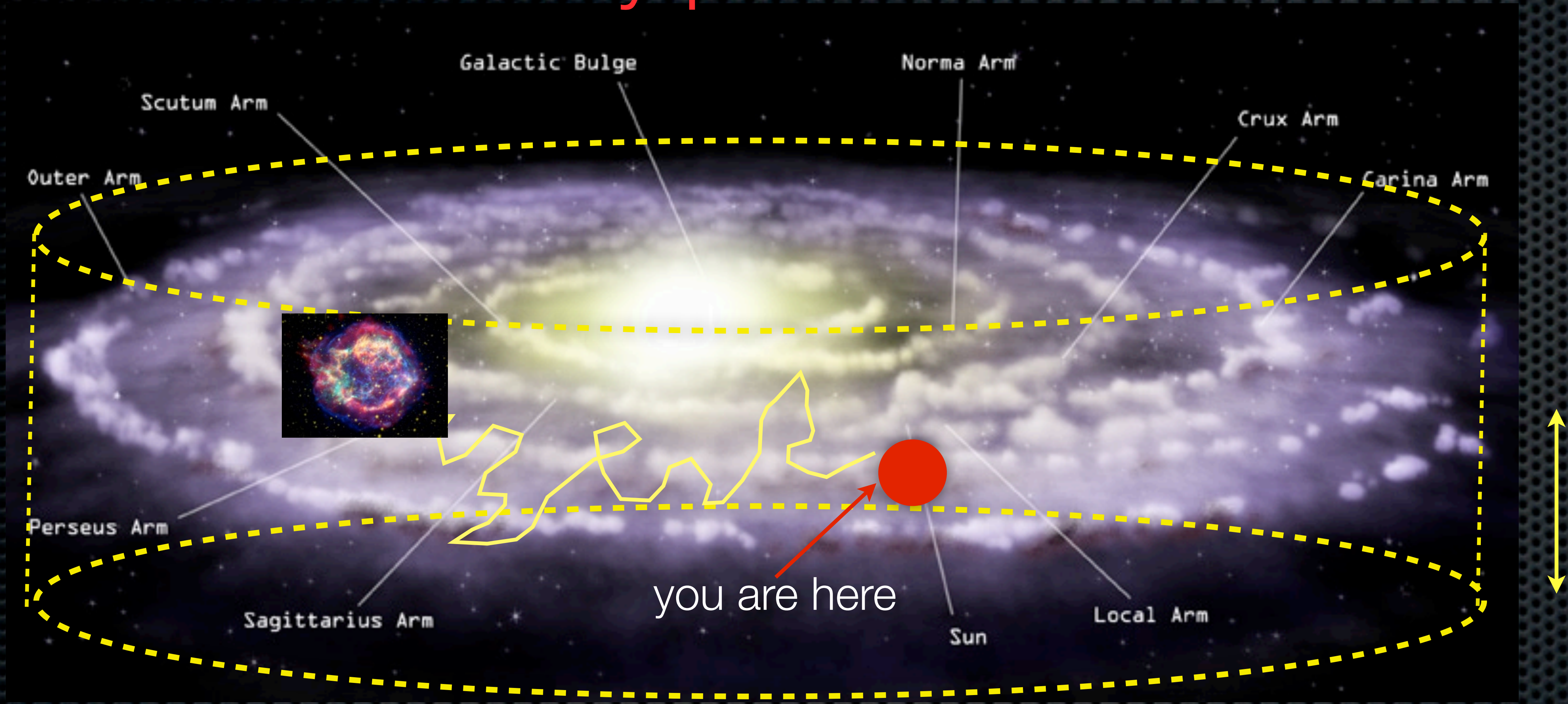


PAMELA coll. - 2009-2010

The cosmic ray spectrum



CR secondary production in the Galaxy



CR (p and He mainly) spallation onto the ISM gas produce secondaries

$p + p_{ISM} \rightarrow \ldots + \pi^{\pm} \rightarrow \ldots + e^{\pm}$

$p + p_{ISM} \rightarrow p + p + p + \bar{p}$

C,N,O → B, Be, Li

secondary nuclei: our reference

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

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

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

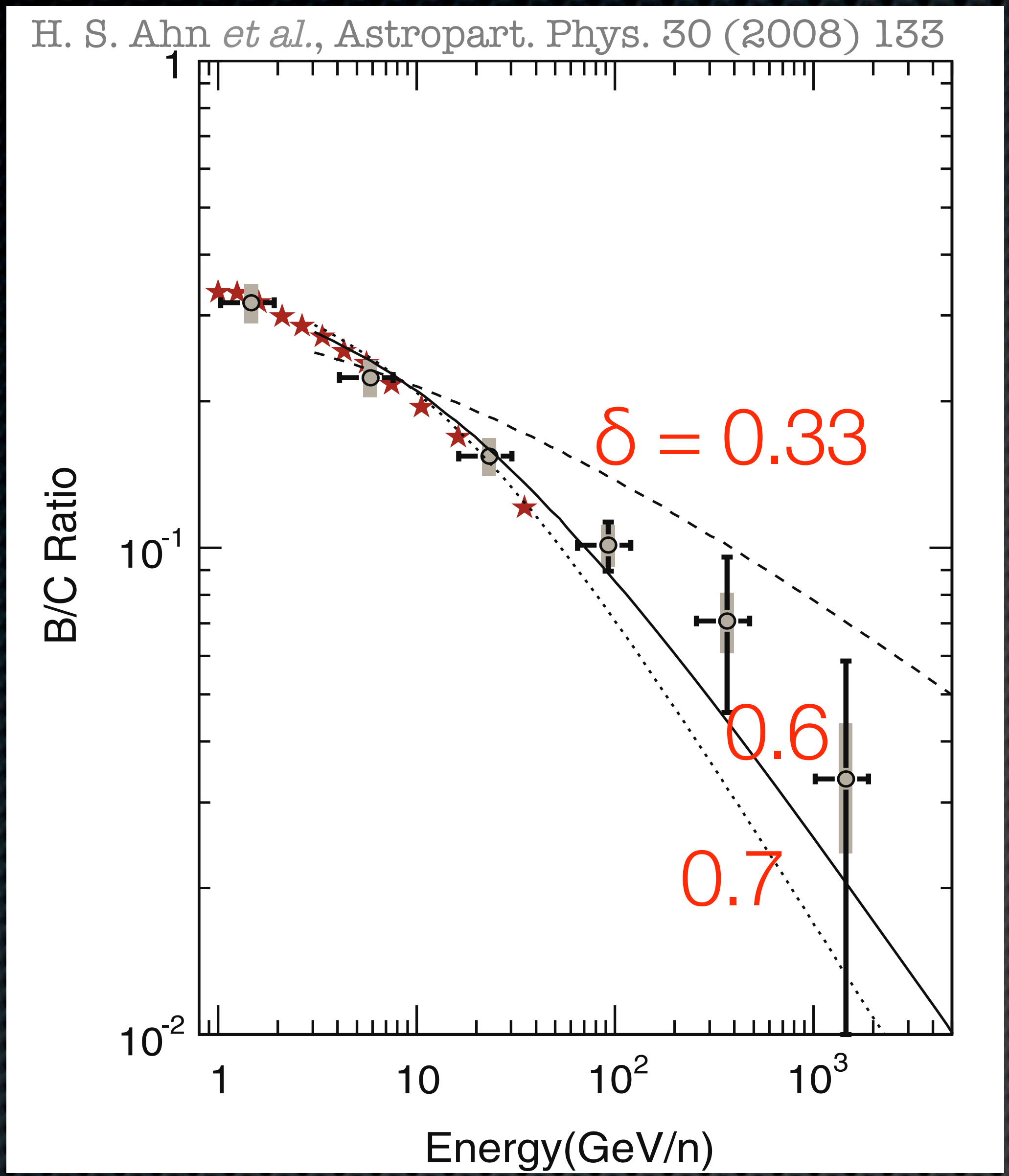
SN source term.
We assume everywhere
a power law energy spectrum

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 multichannel CR data !

Secondary / Primary nuclei



- Primary propagated spectra depend on diff. + source: if $D \propto E^{\delta}$ $Q \propto E^{-\gamma}$

  $N_p \sim E^{-\gamma-\delta}$

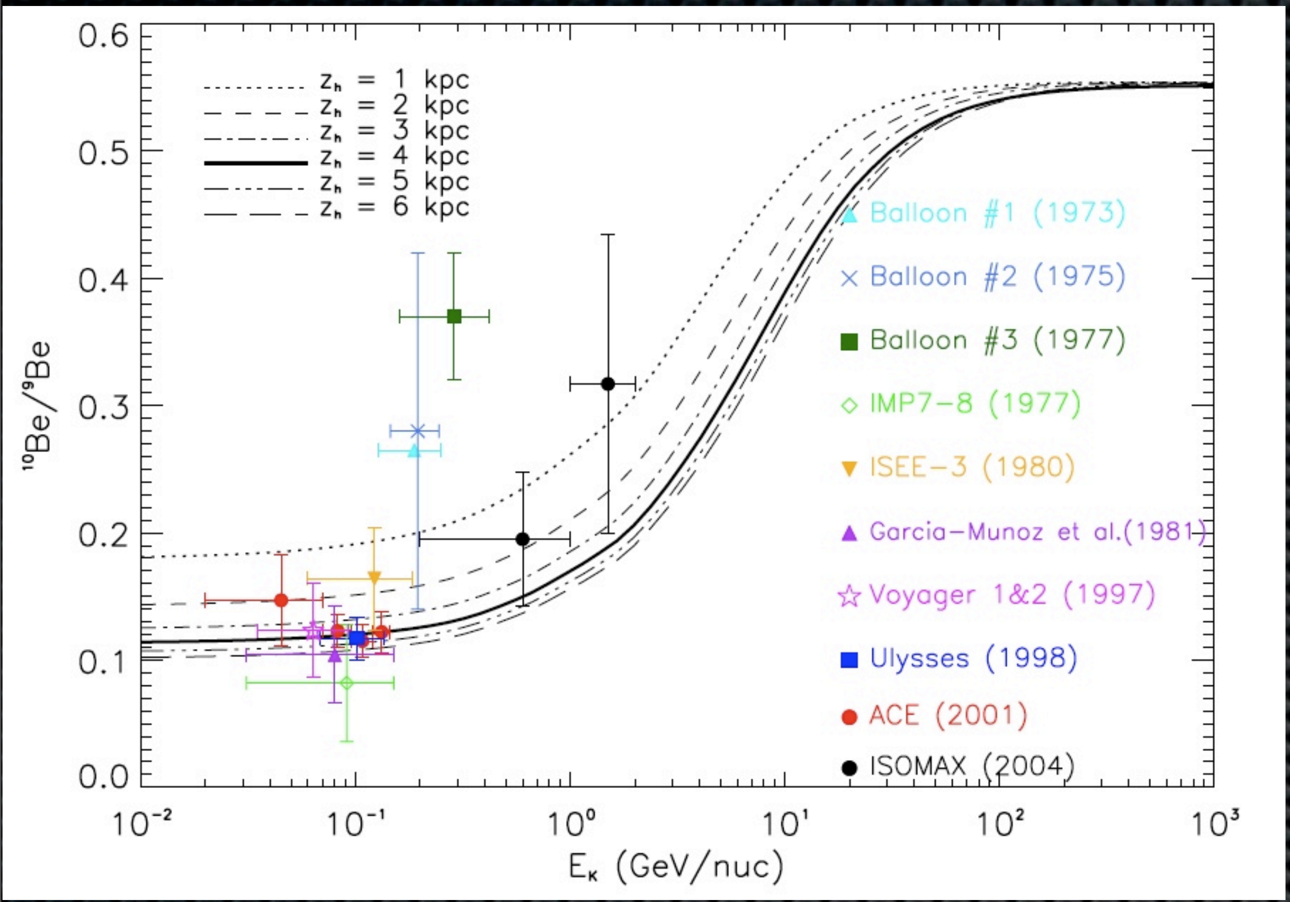
- S/P ratios depend on diffusion only:

  $N_s/N_p \sim E^{-\delta}$

  degeneration D_0 - L

Below ~ 100 GeV several other effects are relevant

Secondary / Primary unstable nuclei



- Primary propagated spectra depend on

diff. + source: if $D \propto E^{\delta}$ $Q \propto E^{-\gamma}$

$N_p \sim E^{-\gamma-\delta}$

S/P ratios depend on diffusion only:

$N_S/N_p \sim E^{-\delta}$

degeneration D_0 - L

Below ~ 100 GeV several other effects are relevant

Data are not enough !
We need theory and **equation solvers**

Several ways of solving the transport equation:

- semi-analytic models: assume simplified distributions for sources and gas, and try to solve the diffusion equation analytically
  USINE Maurin et al.
  Pro: fast, sometimes easy interpretation
  Con: can hardly model $e^{\pm}$ at high E hence synchrotron and diffuse γ-rays;

- numerical models are required to deal with more realistic physical conditions
  GALPROP most commonly used package   Strong, Moskalenko et al.
  DRAGON recently developed (faster, new features) Maccione, Evoli, Gaggero, D.G.
  Pro: comprehensive. They allow multi-channel analysis
  Con: slower (is compensated by faster parallel computation)

DRAGON

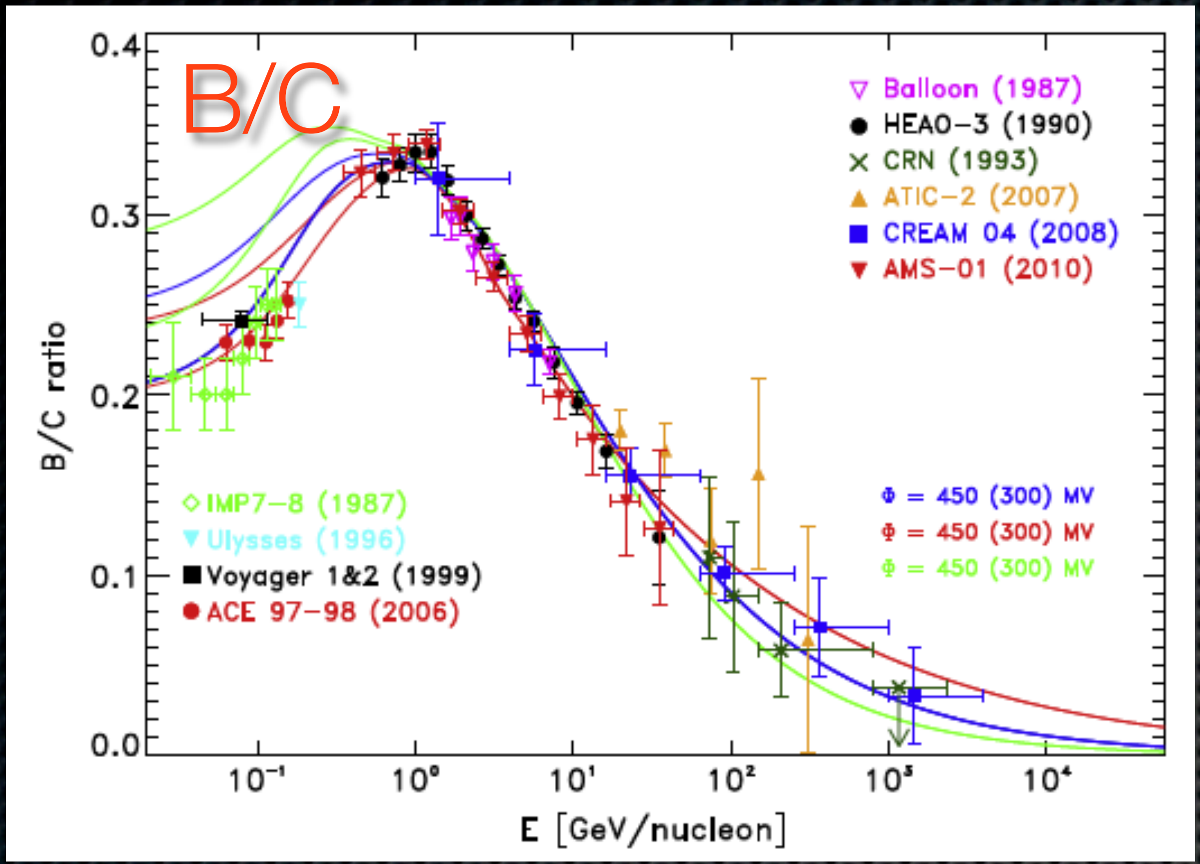
L. Maccione, C. Evoli, D. Gaggero, D.G.

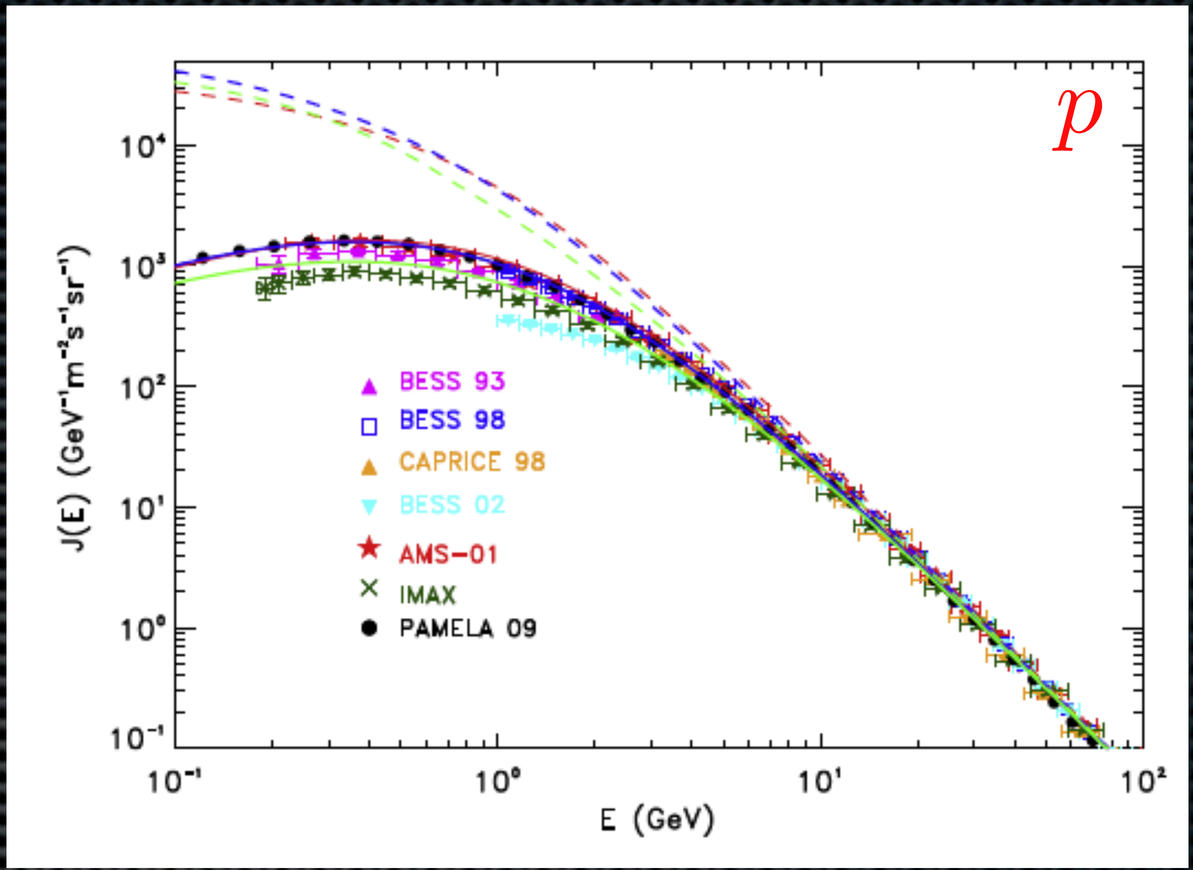
several inputs from I. Gebauer and coll. (KIT)

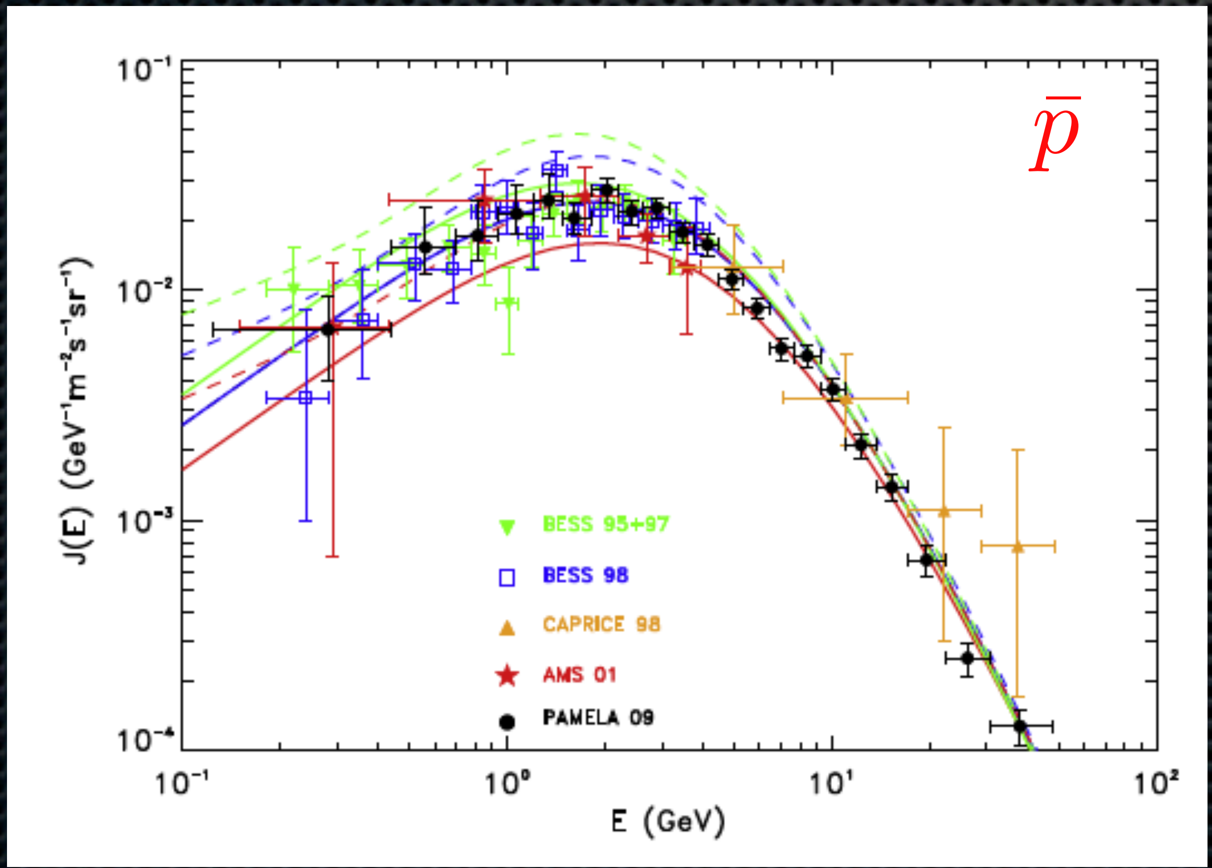
- solve the diffusion equation on a 2D+1 (r,z,E) and 3D+1 (new !) (x,y,z,E) grid . In 2D reproduces GALPROP under same conditions
- realistic distribution for sources and ISM
- position dependent, anisotropic diffusion (new !)
- can model diffuse γ-rays, synchrotron, neutrinos (new !) emissions.
- faster (better memory allocation, linkable library)
- interfaced to DARKSUSY to treat DM product propagation consistently with ordinary CR
- public: http://dragon.hepforge.org/

The machine works well !

Di Bernardo et al. Astropart. Phys. 2010, 2011







$\delta \cong$ 0.33 0.5 0.6

$\gamma =$ 1.6/2.4 2.25 2.15 source index

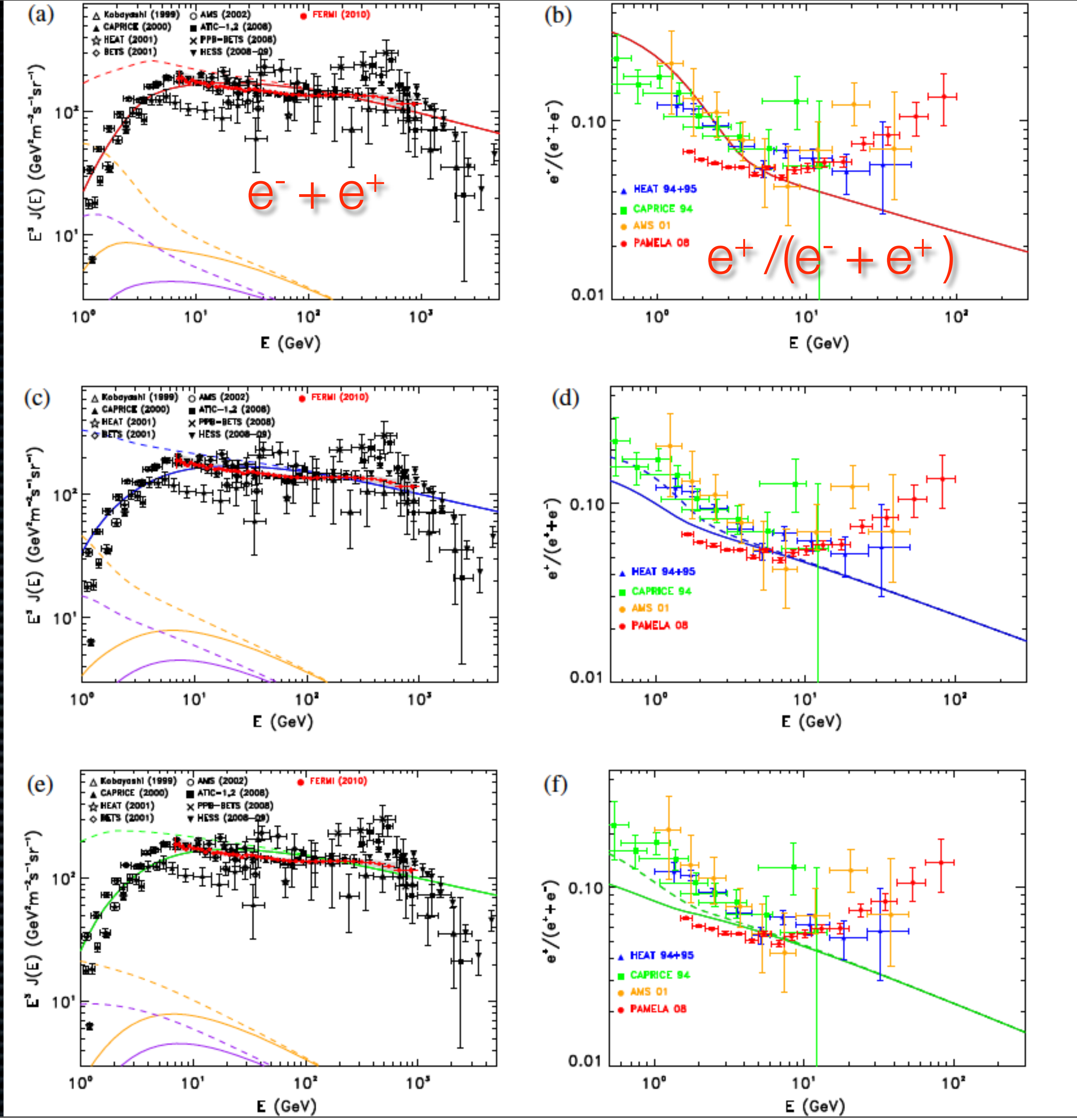
$v_A \cong$ 30 15 0 km/s Alfven velocity

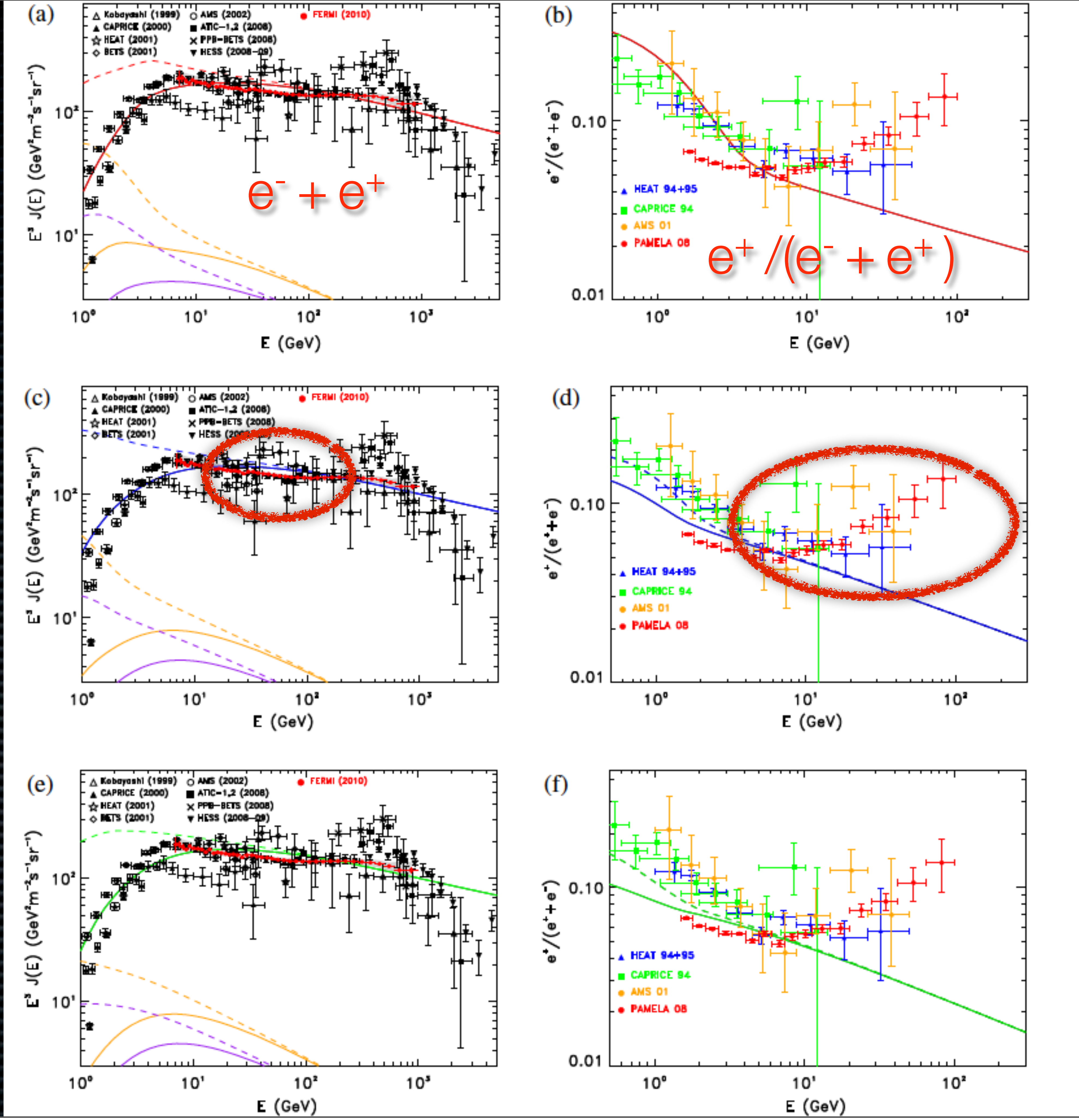
2D models - uniform diffusion

Cosmic ray positrons and electrons

Standard approach:

- the propagation parameters are tuned to reproduce secondary/primary nuclear ratios
- p, He and primary *e*$^-$ source spectrum are tuned to reproduce CR data (a power-law is adopted as follows from Fermi acceleration theory)
- The secondary e^+ propagated spectrum is computed


(a)
Kobayashi (1999)
CAPRICE (2000)
HEAT (2001)
BETS (2001)
AMS (2002)
ATIC-1,2 (2008)
PPB-BETS (2008)
HESS (2008-09)
FERMI (2010)
E^3 J(E) (GeV^{2}m^{-2}s^{-1}sr^{-1})
E (GeV)
$e^- + e^+$
(b)
$e^+/(e^++e^-)$
HEAT 94+95
CAPRICE 94
AMS 01
PAMELA 08
E (GeV)
$e^+/(e^- + e^+)$
(c)
(d)
(e)
(f)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E^3 J(E) ($GeV^2m^{-2}s^{-1}sr^{-1}$)
E (GeV)
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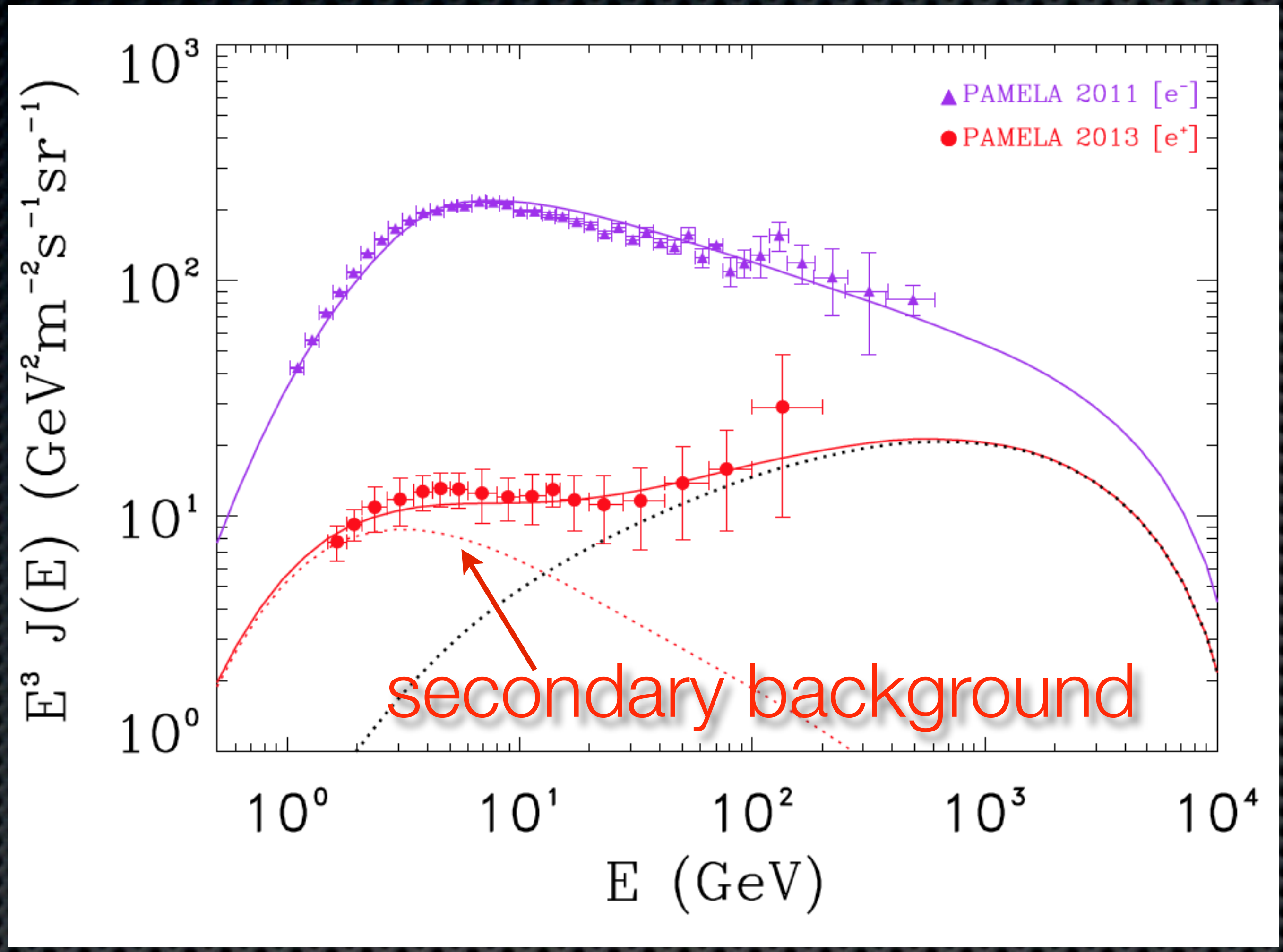
(b)
HEAT 94+95
CAPRICE 94
AMS 01
PAMELA 08
$e^+/(e^++e^-)$
E (GeV)
$e^+/(e^- + e^+)$
(c)
(d)
(e)
(f)

Anomaly in the e^+ channel



data $\gamma(e^+) \sim 2.8$ above 20 GeV

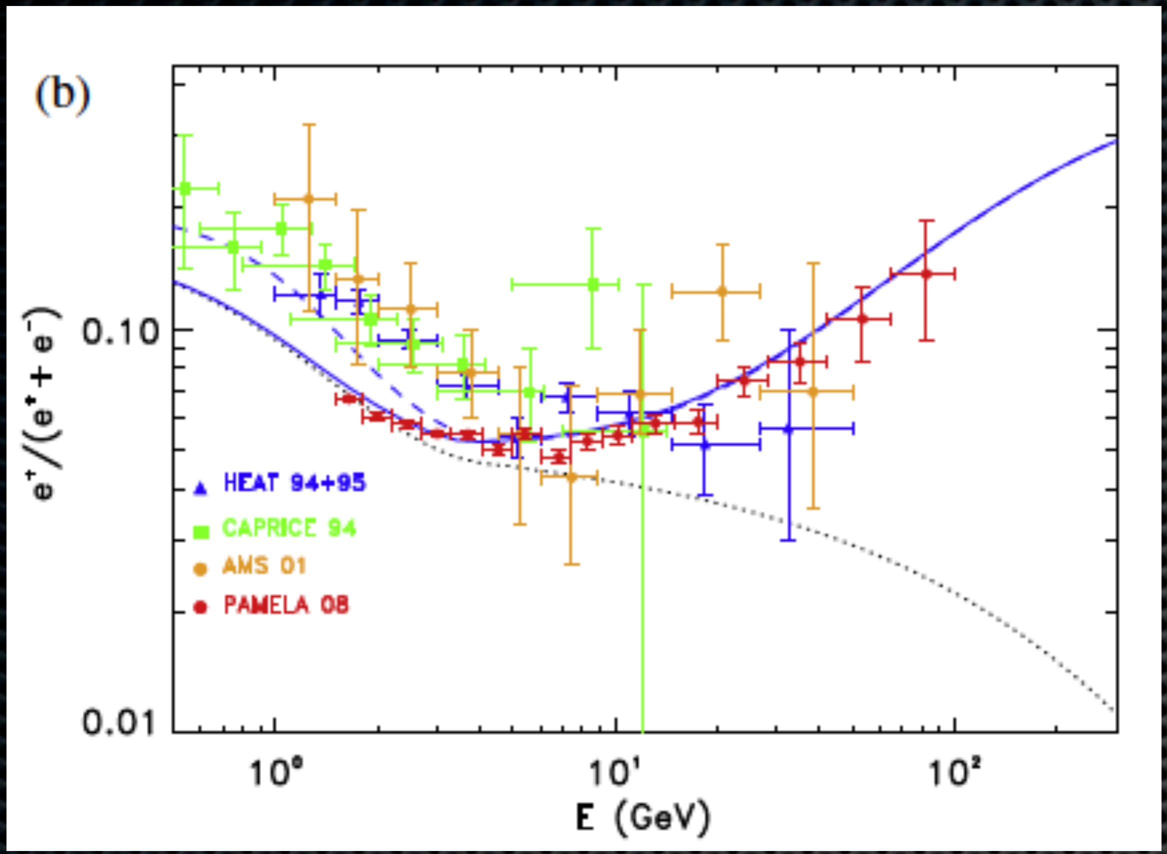
simple propagation theory (see e.g. Bulanov & Dogel)

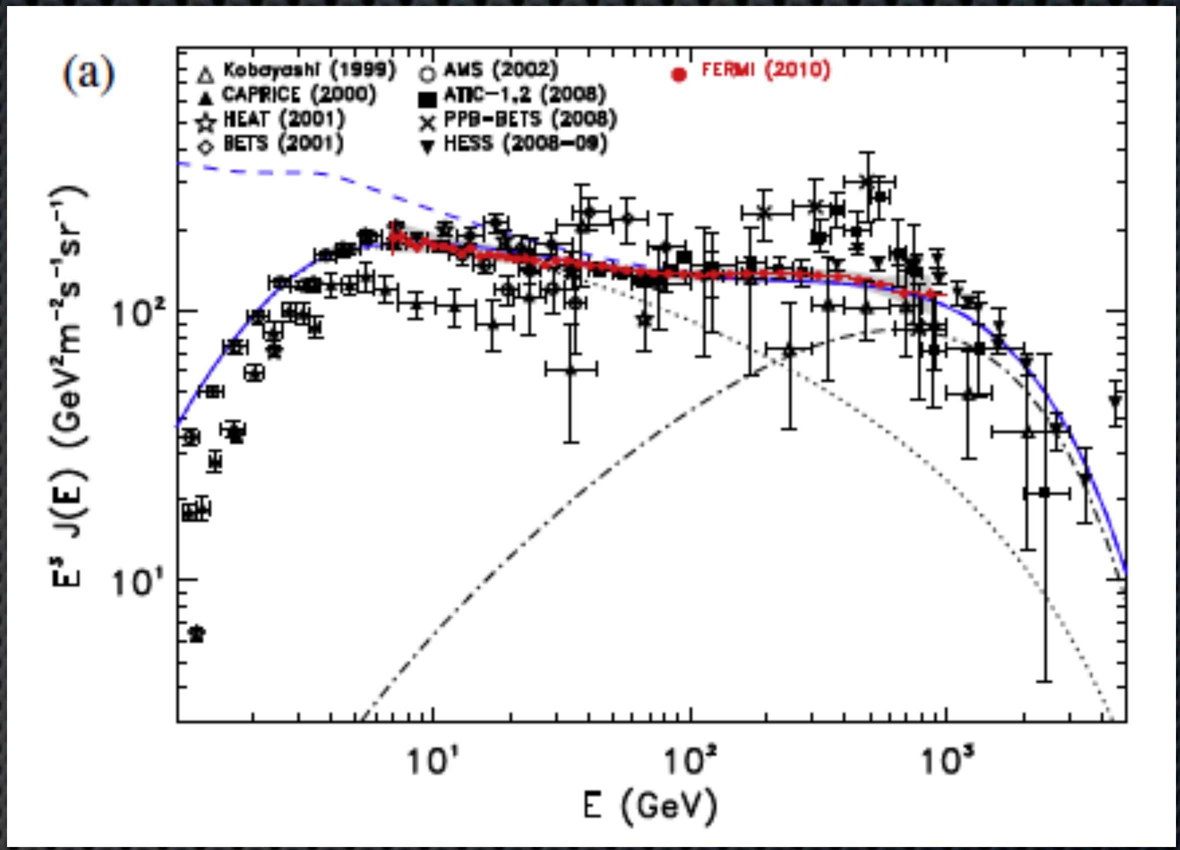
$$\gamma(e^+) \simeq \gamma(p) + \delta/2 + 0.5$$

primary diffusion energy losses

since $Y(p) \simeq 2.7\text{-}2.8$ positrons cannot be only secondaries !

The extra-component scenario





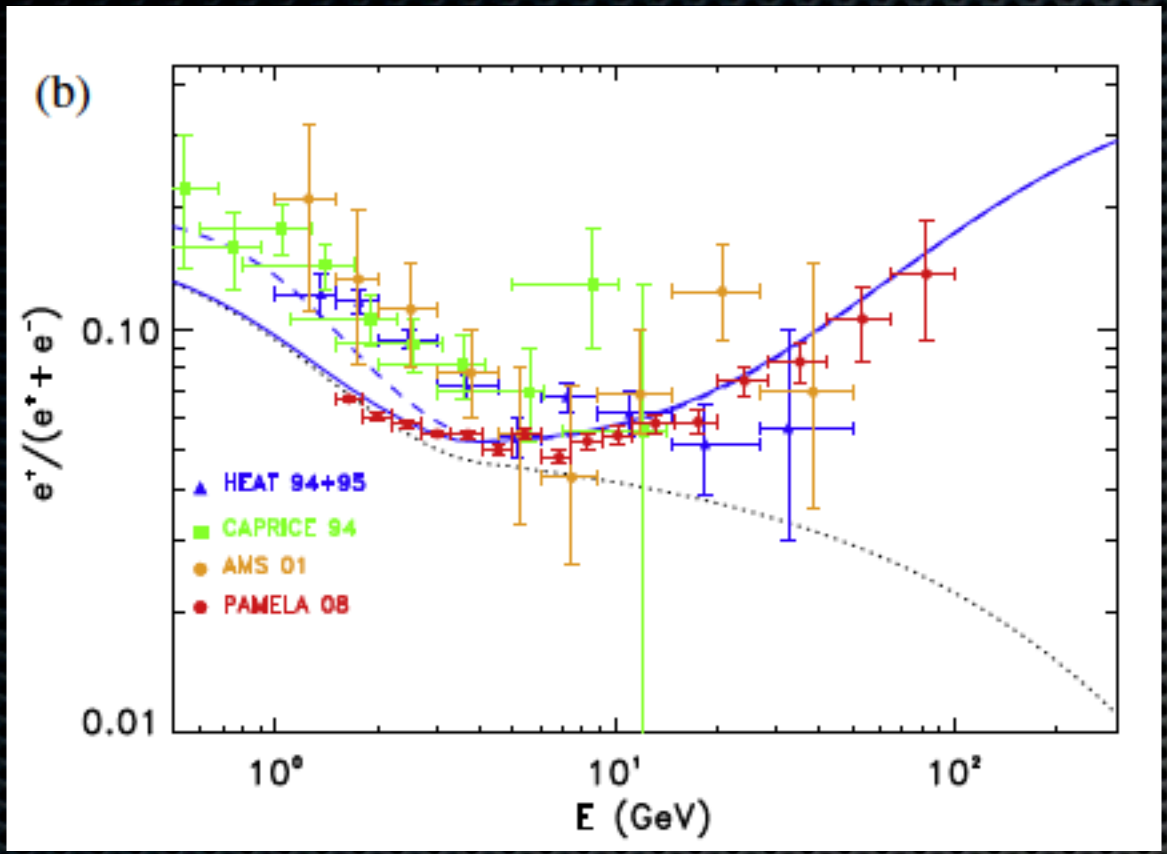
An electron + positron charges symmetric component with source spectrum

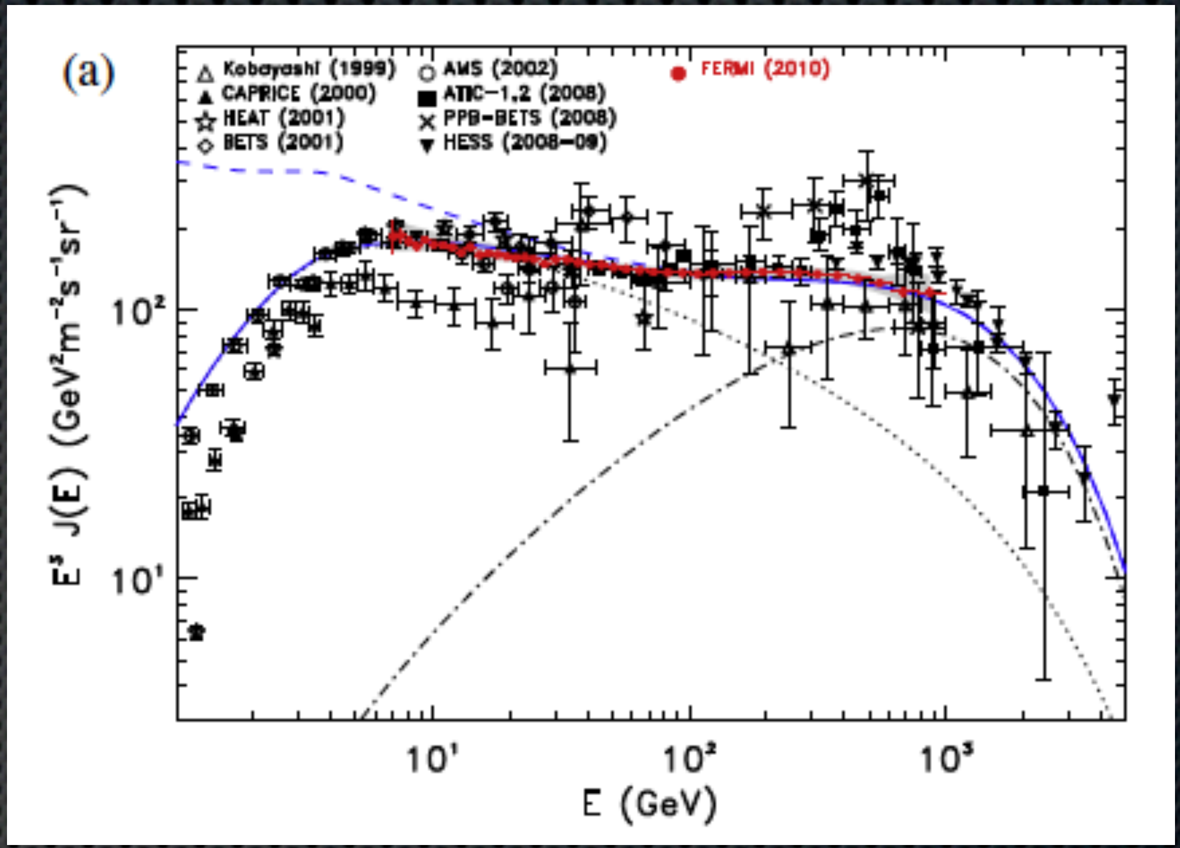
$$N(e^{\pm}) \propto E^{-1.5} \exp\left(-E/1\ \mathrm{TeV}\right)$$

is added to the standard background

Ackermann et al. [Fermi-LAT coll.] , PRD 2010

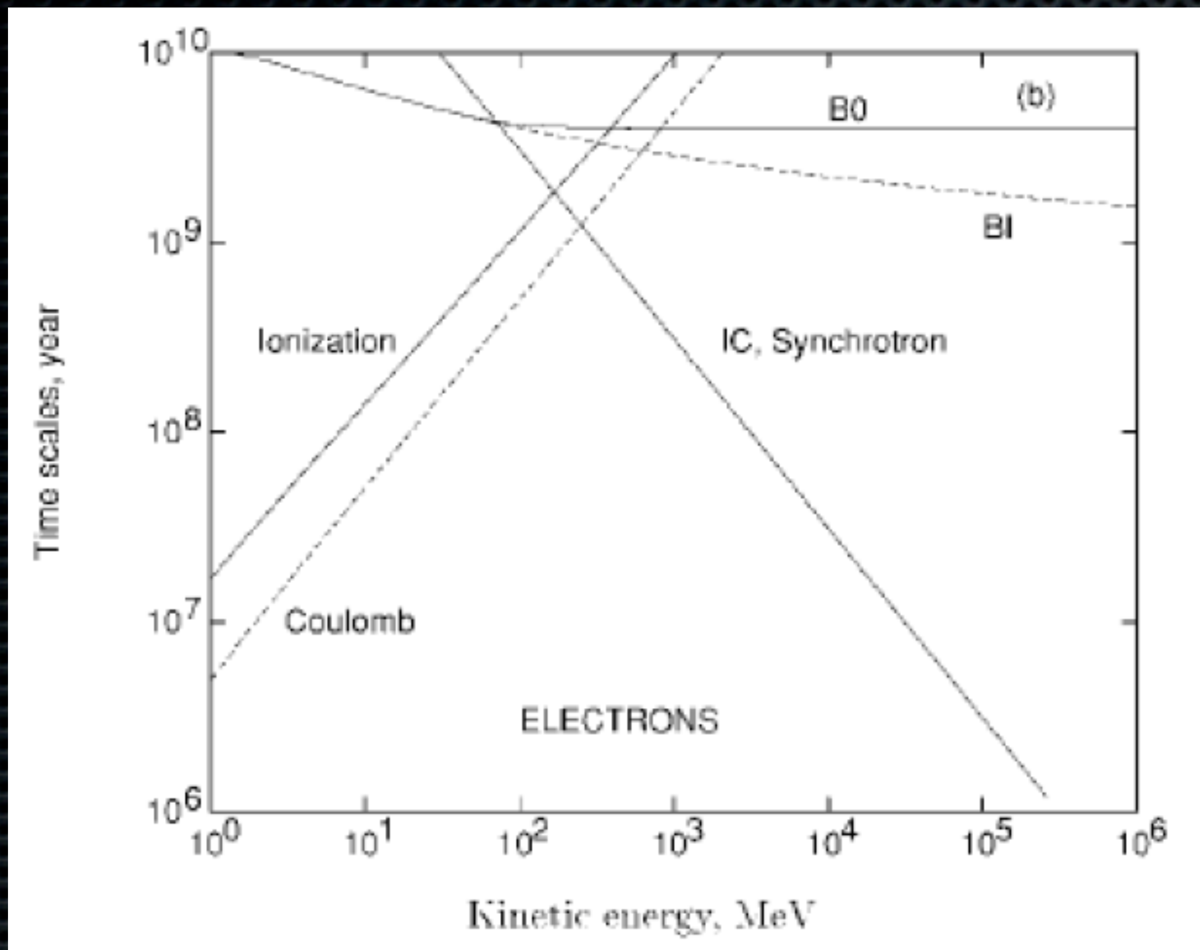
The extra-component scenario





This is a “toy-model” where electron and positrons sources are treated as a continuos azimuthally symmetric 2D (r,z) distribution similarly to what done for CR nuclei

Galactic propagation of $e^{\pm}$



$$\lambda(E, E_0) = \sqrt{\int_{E_0}^{E} \frac{D(E')\mathrm{d}E'}{b(E')}}$$

$b(E) = b_0 E^2$

$b_0 = 1.4 \ 10^{-16}$ GeV^{-1} s^{-1}

Average loss length due to synchrotron and IC

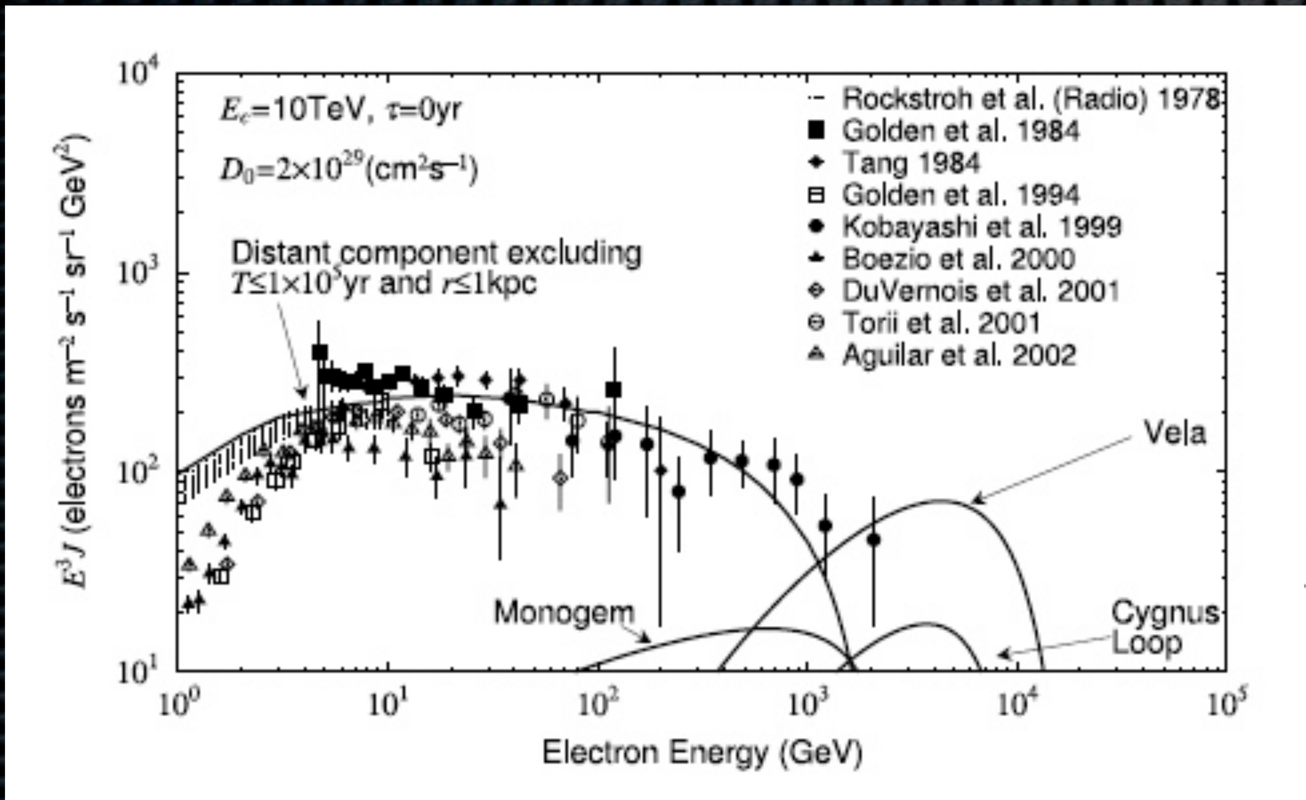
$e^{\pm}$ λ(100 GeV) ≃ 1 kpc

λ(1 TeV) ≃ 500 pc

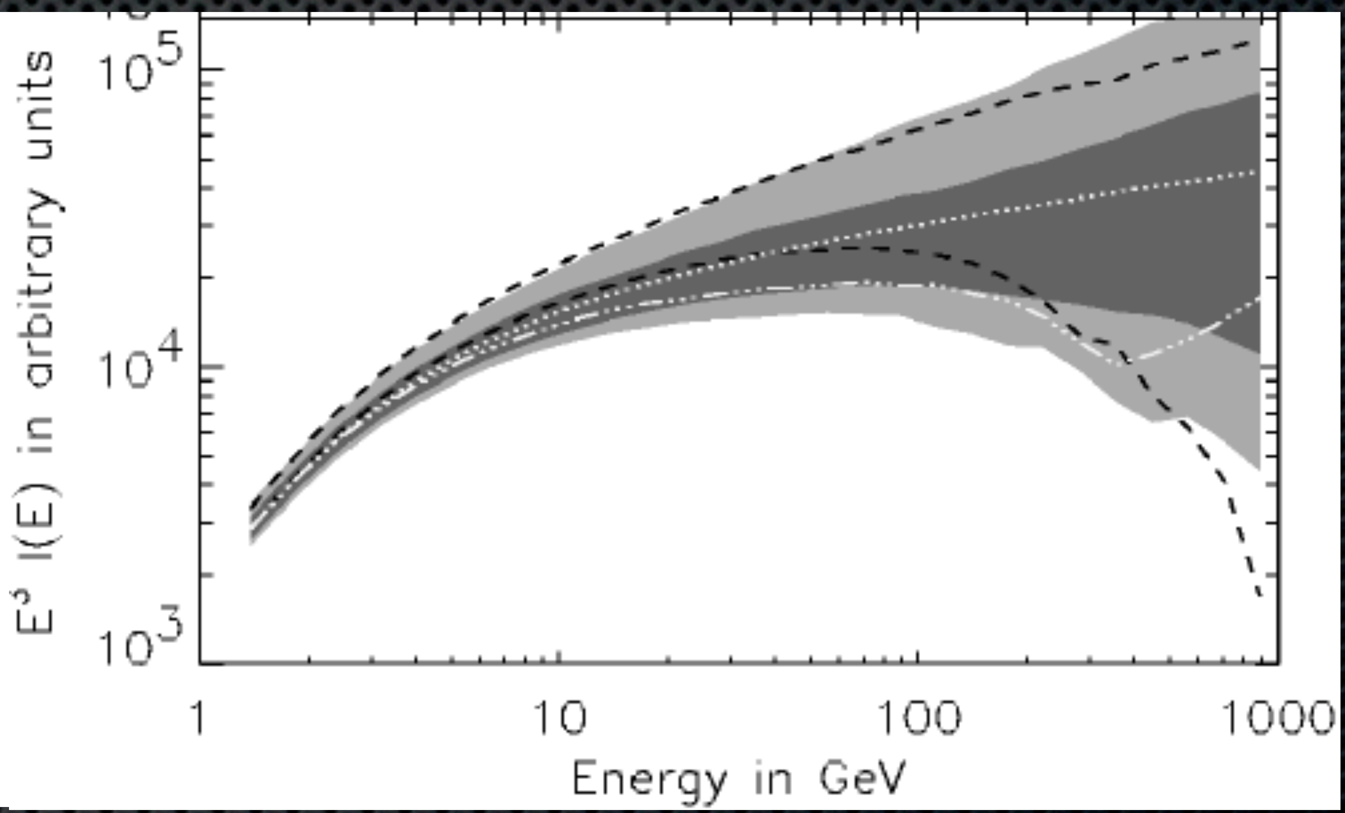
p $\lambda = (n_{gas}\, \sigma_{pp})^{-1} \gg 1$ kpc

for E ≳ 100 GeV electron loss length is comparable to astrophysical SNR mutual distances ! A smooth source approximation is often inappropriate

The effect of source discreteness/ stochasticity

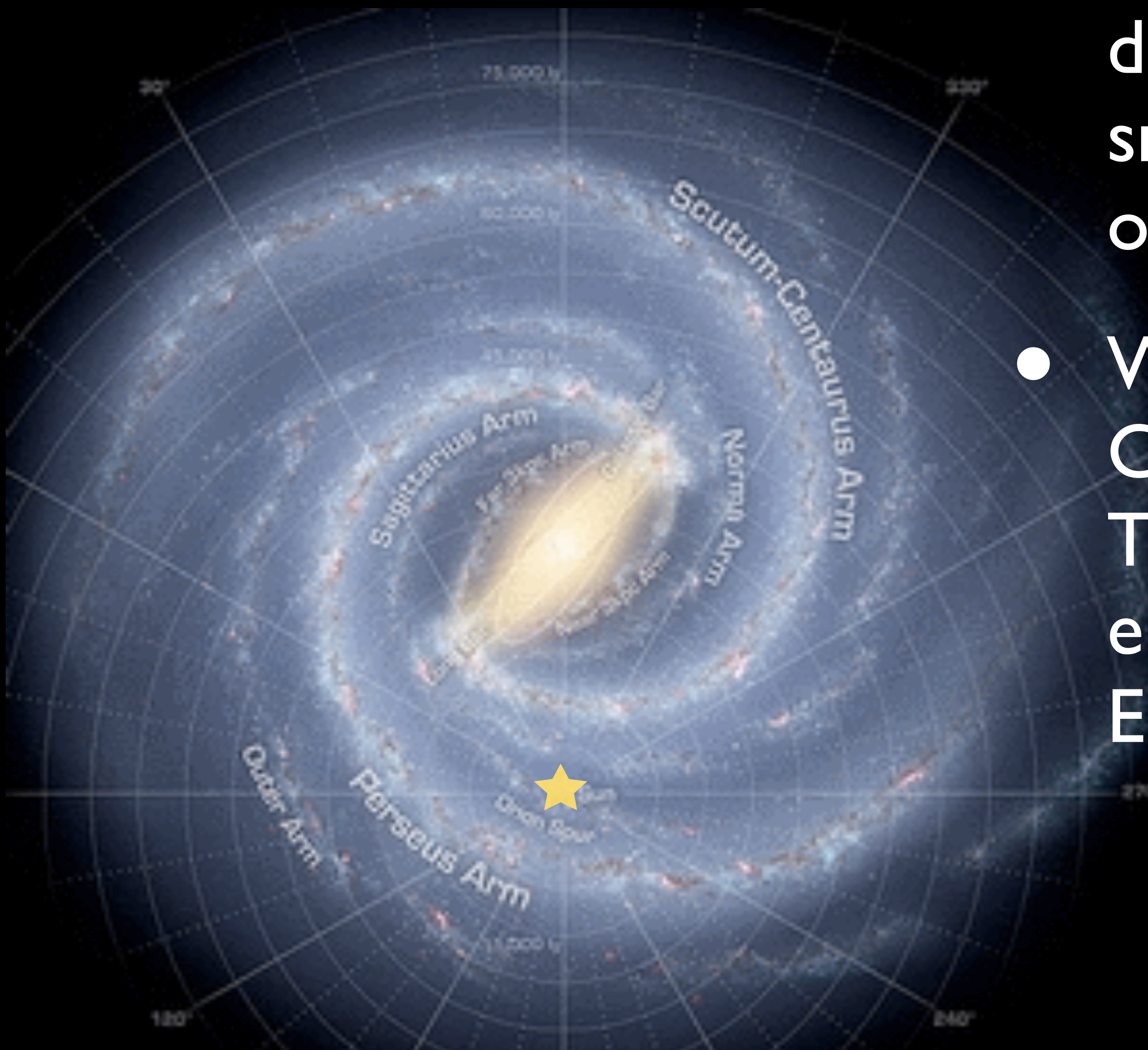


Kobayashi et al. 2004



Pohl & Esposito 1998

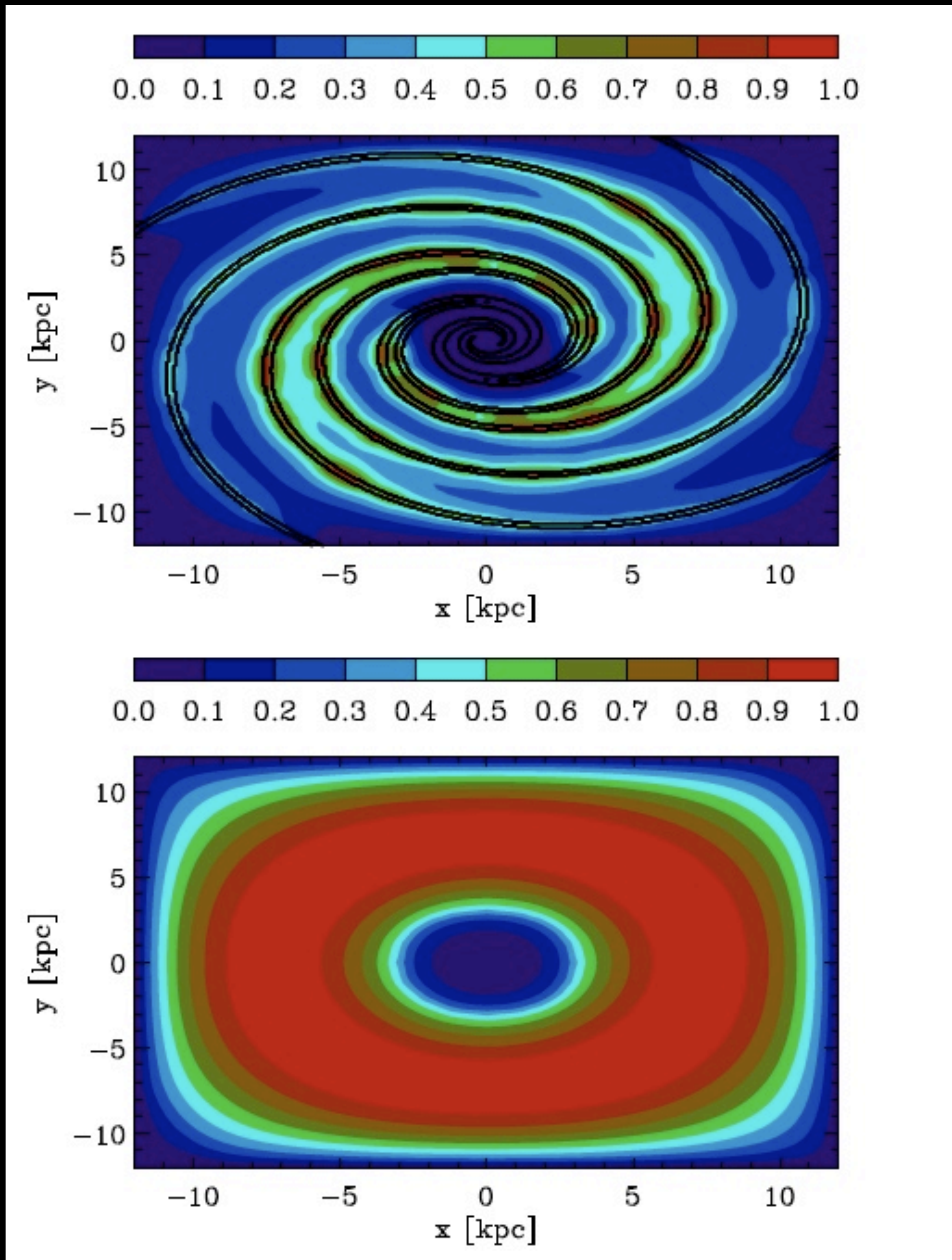
Why to consider a 3D model of CR propagation ?



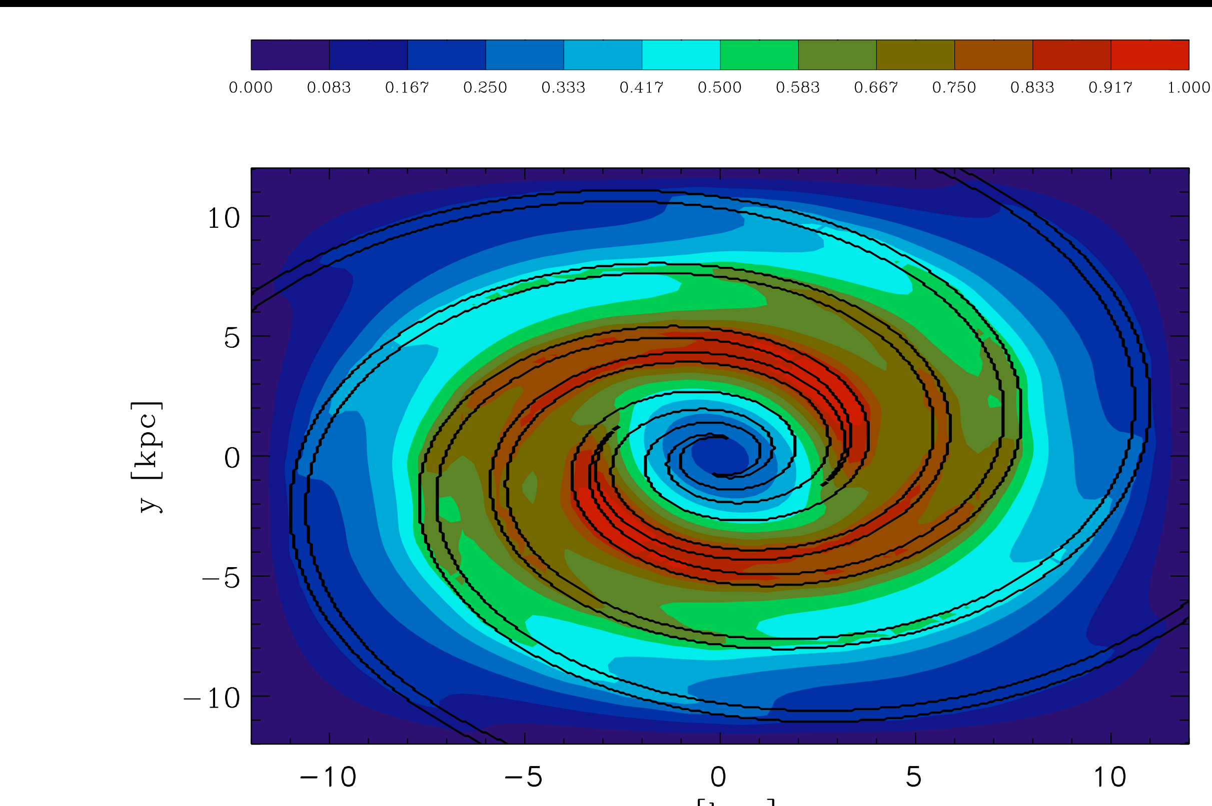
- The Galaxy star (SNR) distribution is far from being smooth due to the presence of Galactic arms
- We sit between two arms. Closest arm is ~ 500 pc away This is comparable with the electron loss lenght for E≳100 GeV

CRE distribution - 3D vs 2D

100 GeV



1 GeV



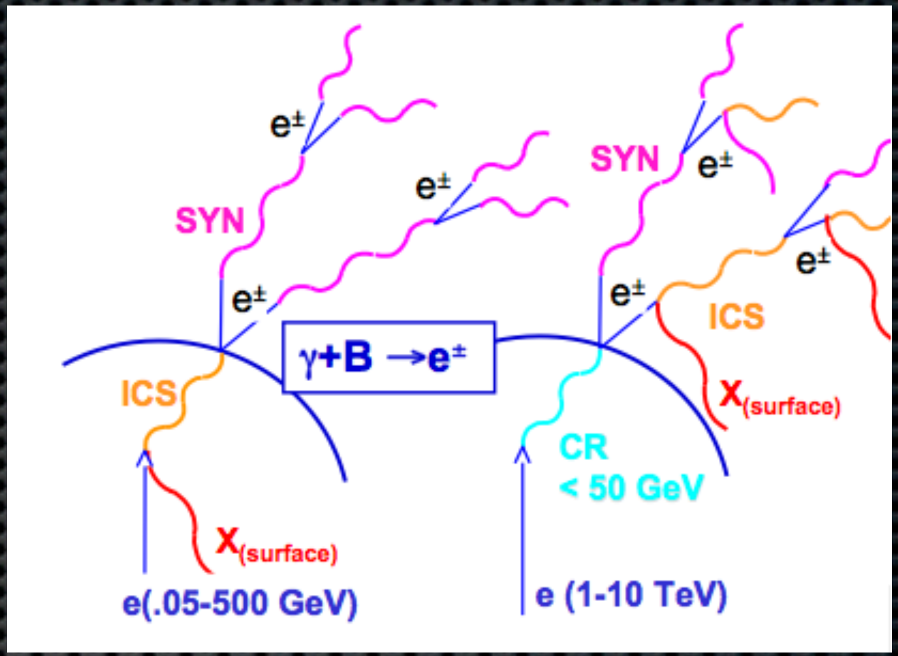
Gaggero, Maccione, Evoli, Di Bernardo, DG, PRL 2013

➡ 2D
clearly unrealistic !!

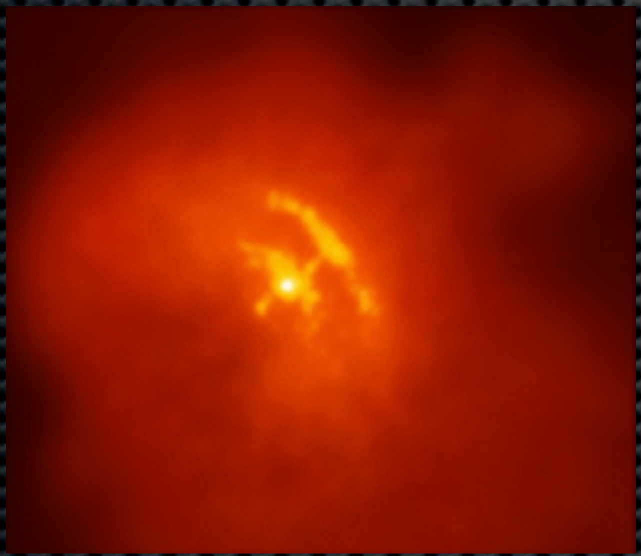
The extra-component puzzle
main hypothesis

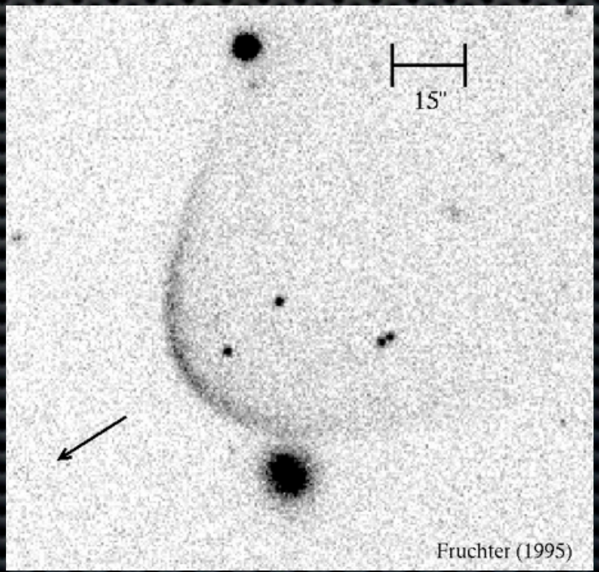
- Pulsars
- Secondary production in Supernova Remnants (SNRs)
- Dark Matter

$e^{\pm}$ from Pulsar Wind Nebulae



Rotational energy + strong magnetic field → Induced electric field electron extraction → electron-positron pairs





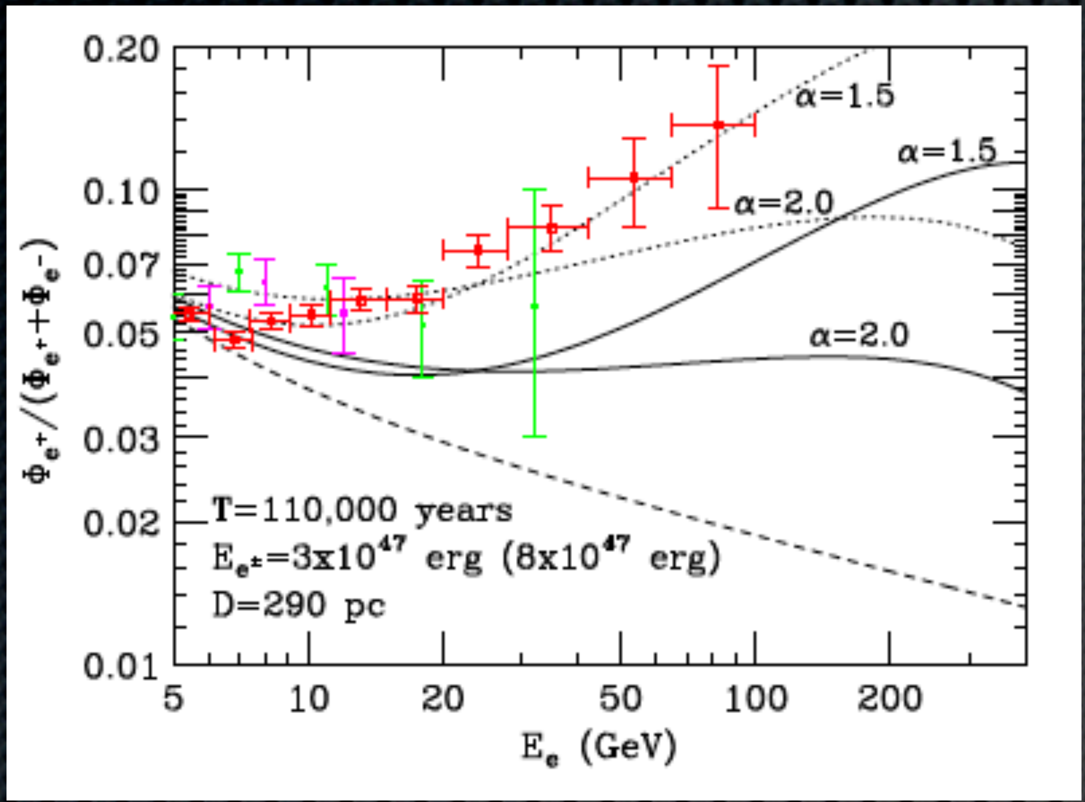
$e^{\pm}$ should be trapped until the SNR is dissipated or the pulsar get out due to its proper motion

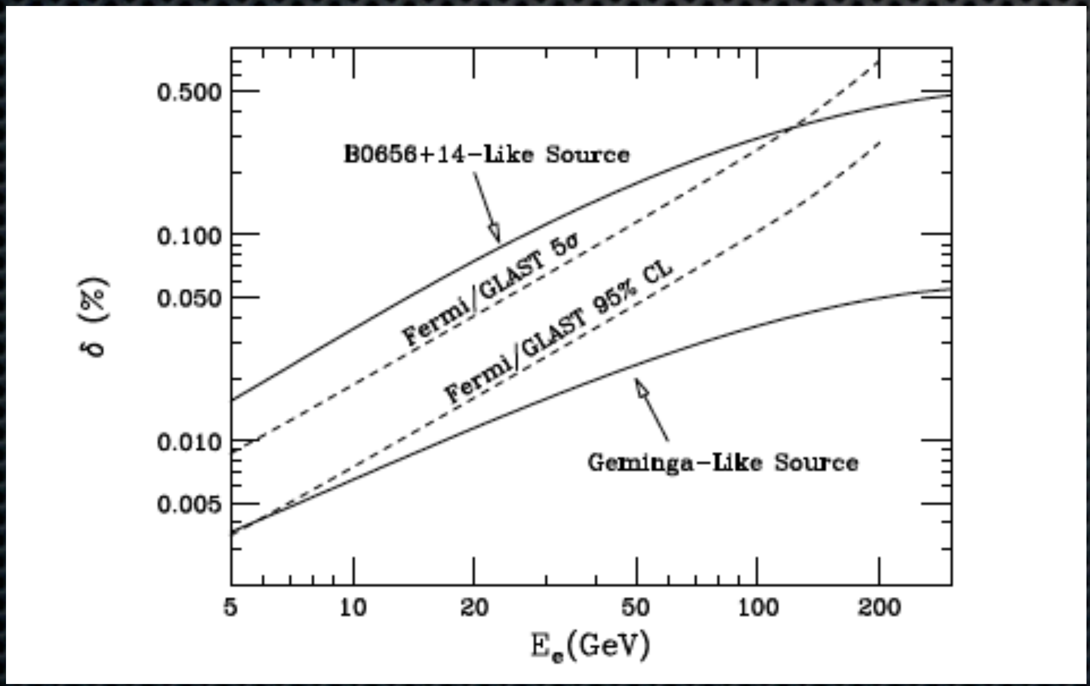
it takes ~ 10^4 - 10^5 years

→ shock wave formation → Fermi acceleration of the $e^{\pm}$

The pulsar interpretation

Blasi & Serpico 2008; Blasi & Amato 2010

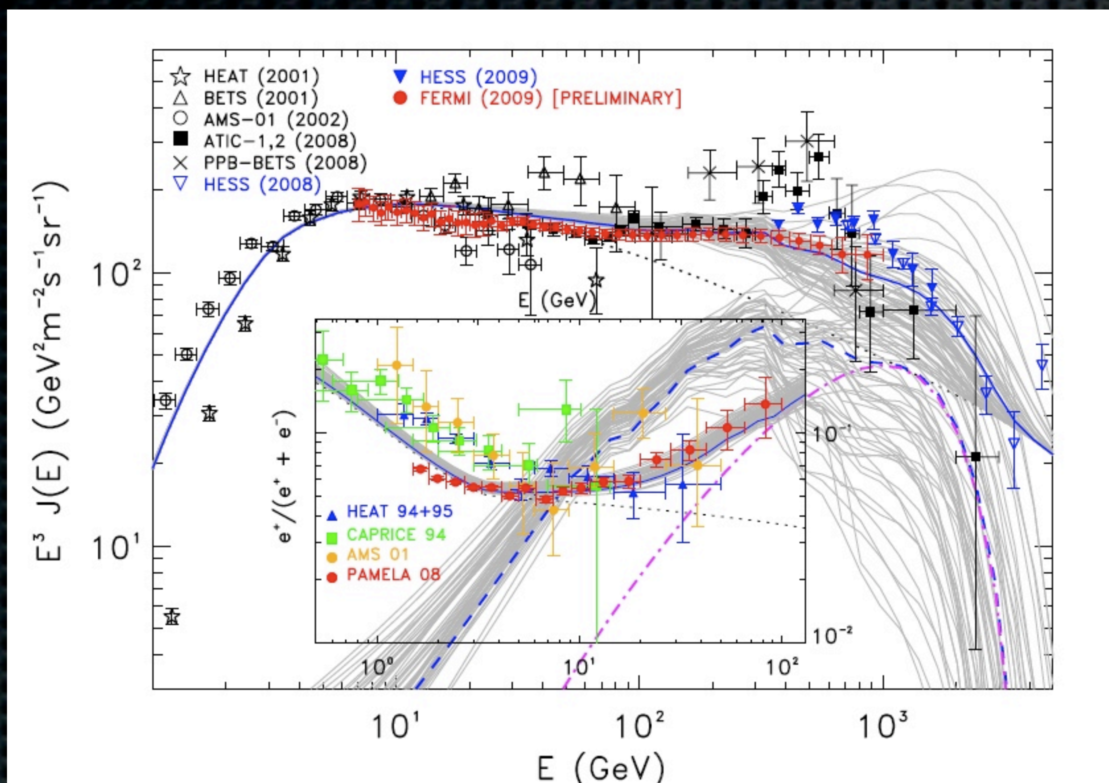




- A nearby middle-age pulsar may explain PAMELA (high efficiency is required)
- the required hard spectral slope is found also in γ-ray data (though at lower energies)
- a large anisotropy in the e^- + e^+ flux is expected at a level detectable by Fermi-LAT

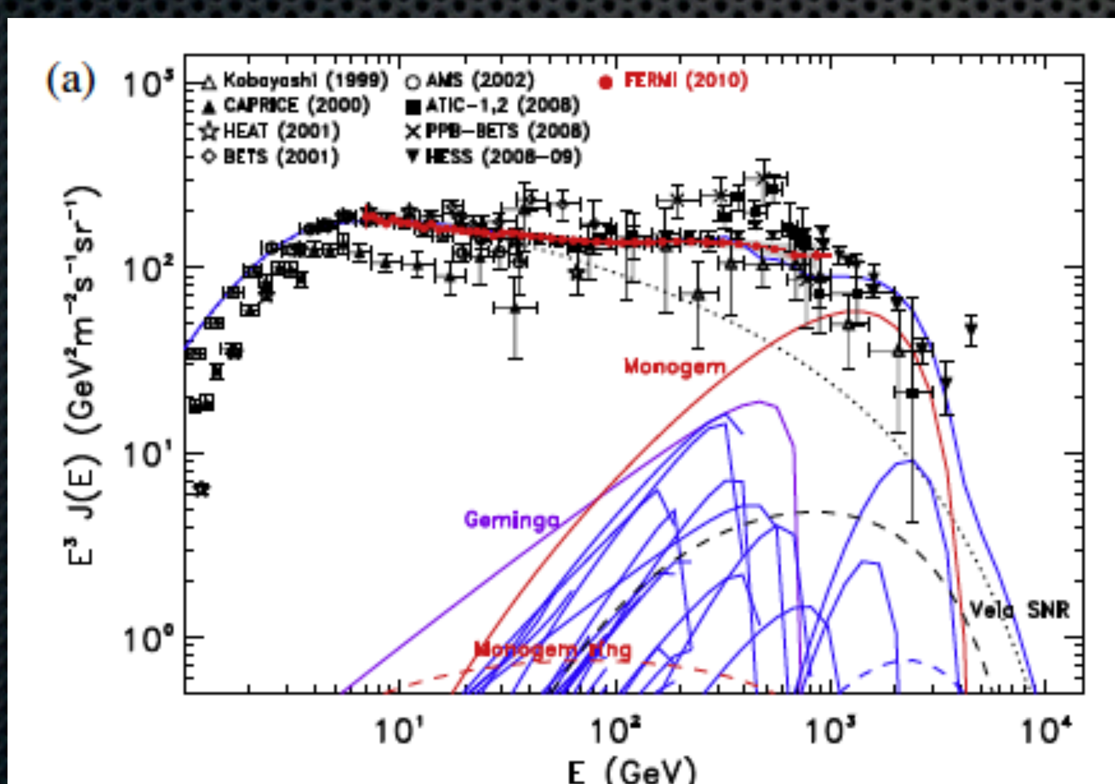
Problems with the pulsar interpretation (?)

Bumpiness problem in the $e^- + e^+$ spectrum (source stochasticity)



D.G. et al. Fermi-LAT. coll. 2009

The flux from all observed pulsars with **all observed pulsars with d < 2 kpc** is computed analitically and consistently added to the background computed with GALPROP/DRAGON (2D)



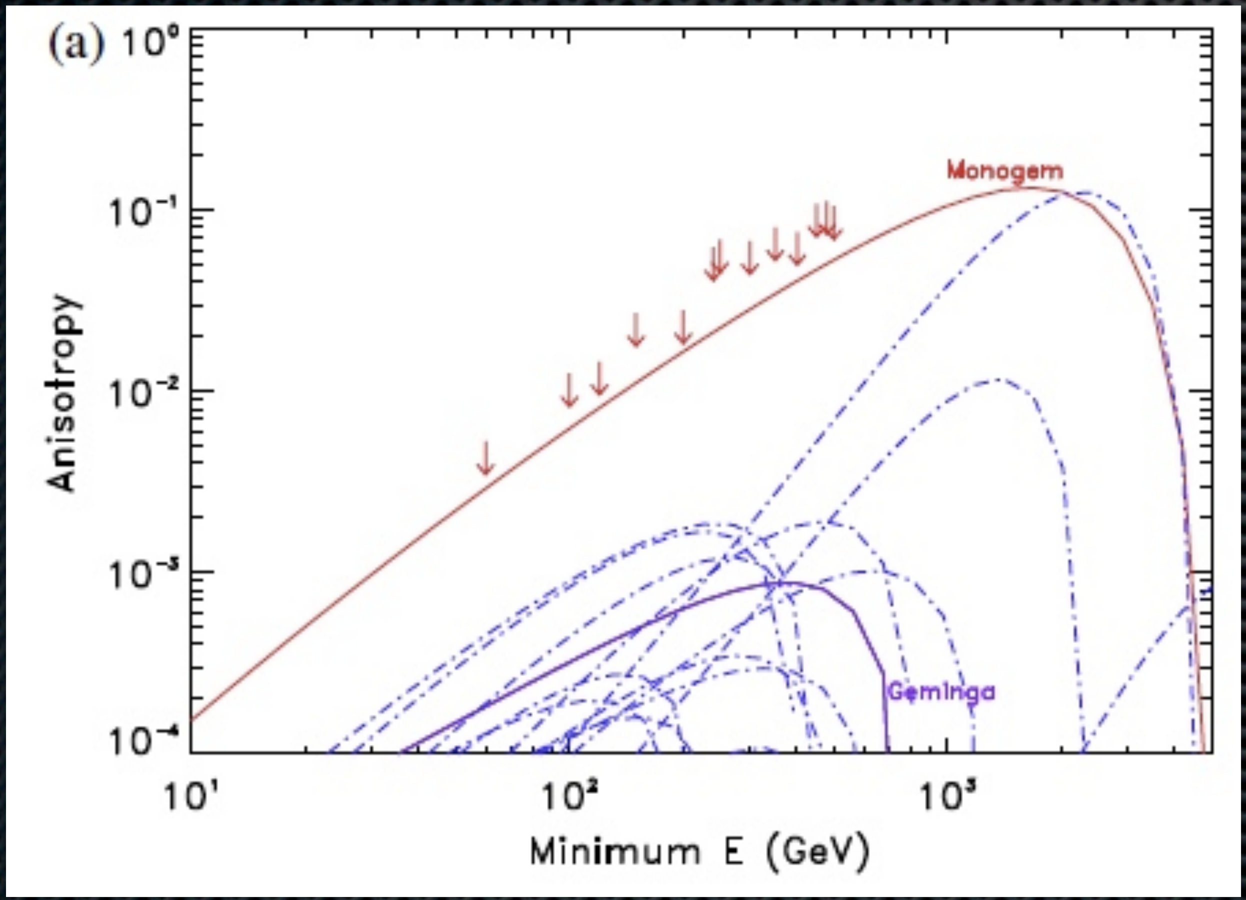
Also the background should be subject to source (SNR) stochasticity

Di Bernardo, Evoli, Gaggero, DG, Maccione 2011

Problems with the pulsar interpretation (?)

Anisotropy problem in the $e^- + e^+$ flux

$$\text{Anisotropy} = \frac{3D}{c}\frac{\Delta N_e}{N_e} = \frac{3}{2c}\frac{r}{t-t_0}\left(\frac{1-(1-E/E_{max}(t))^{1-\delta}}{(1-\delta)E/E_{max}(t)}\right)^{-1}\frac{N_e^{\rm PSR}(E)}{N_e^{\rm tot}(E)}$$



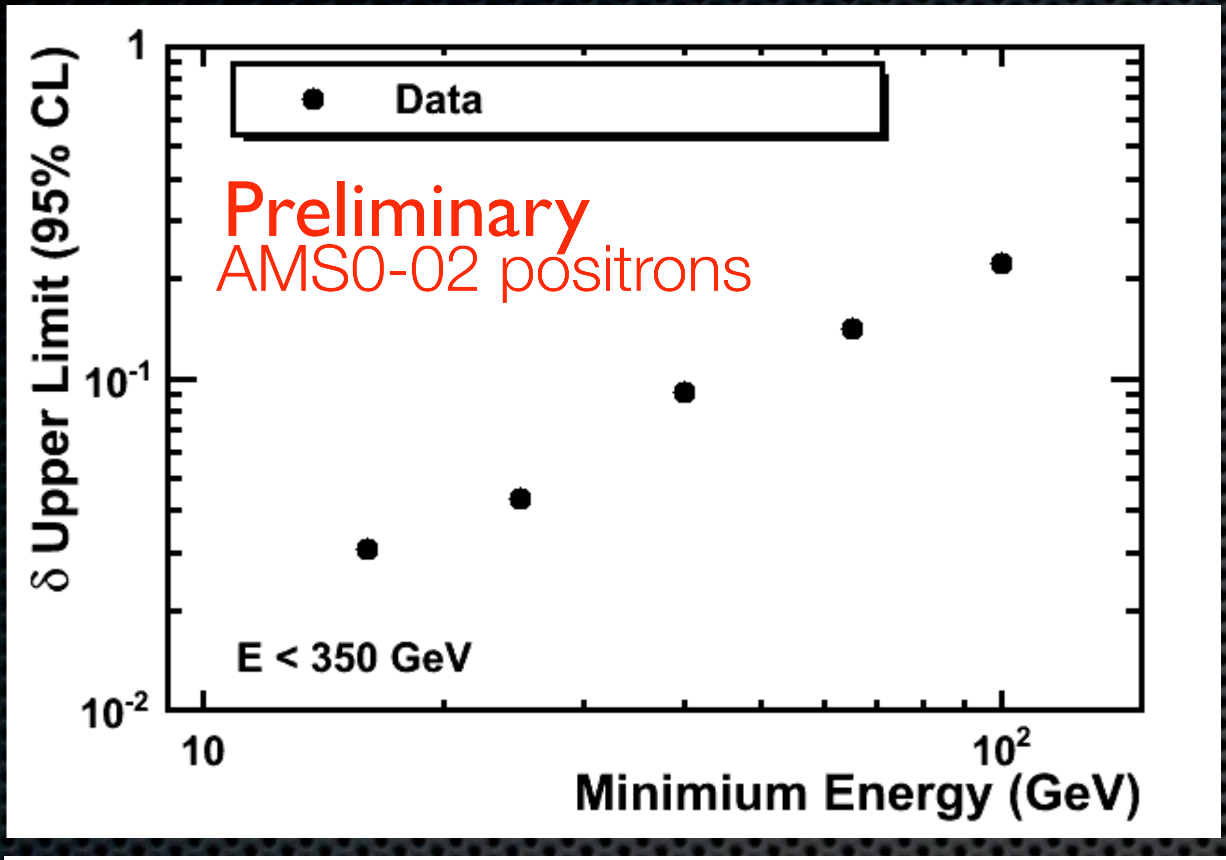
No anisotropy observed by Fermi-LAT yet !

Ackermann et al. [Fermi-LAT coll.] , PRD 2010

Di Bernardo, Evoli, Gaggero, DG, Maccione 2011

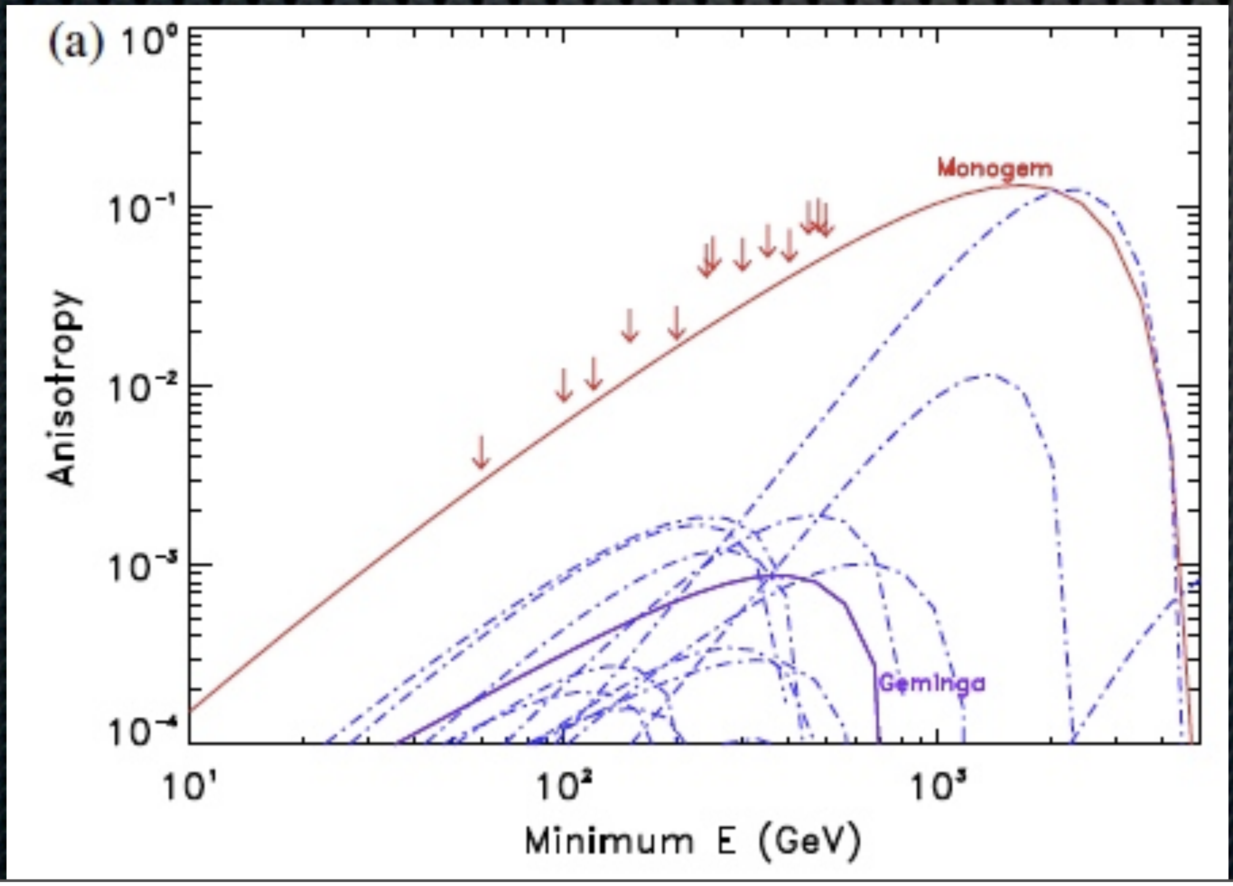
Which news from AMS-02 ?

No anisotropy (limits however are less stringent than Fermi-LAT)



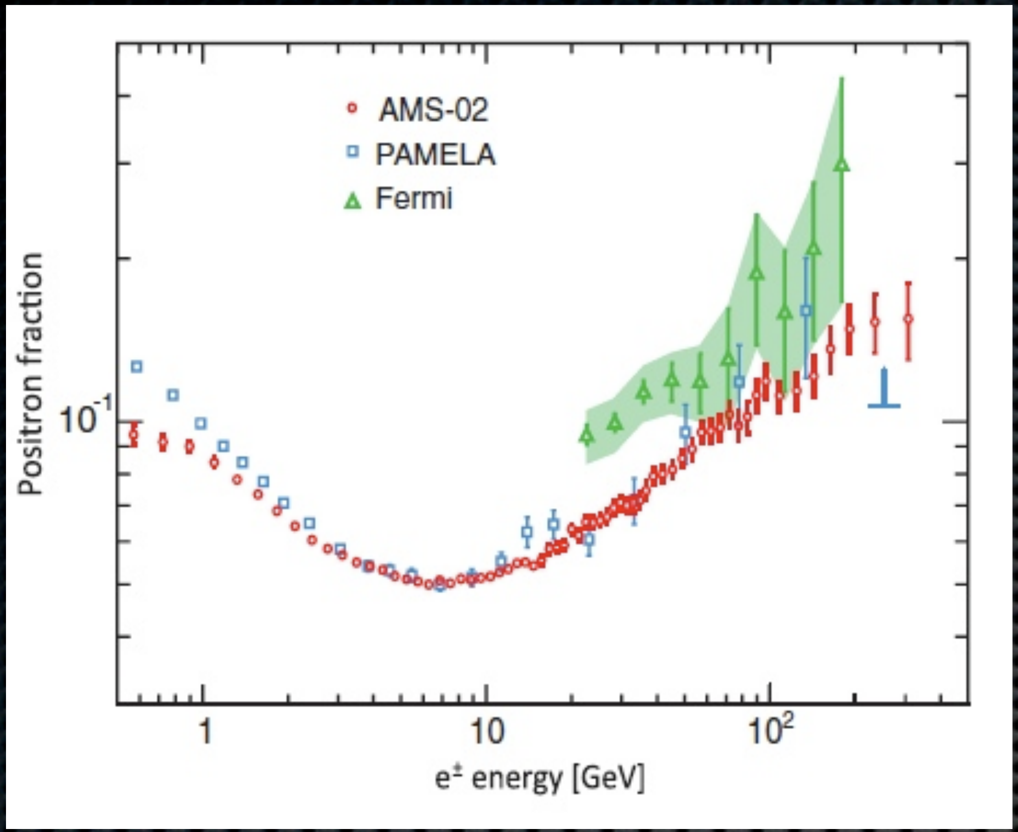
$\delta<0.030$ **for** $16<E<350$**GeV**

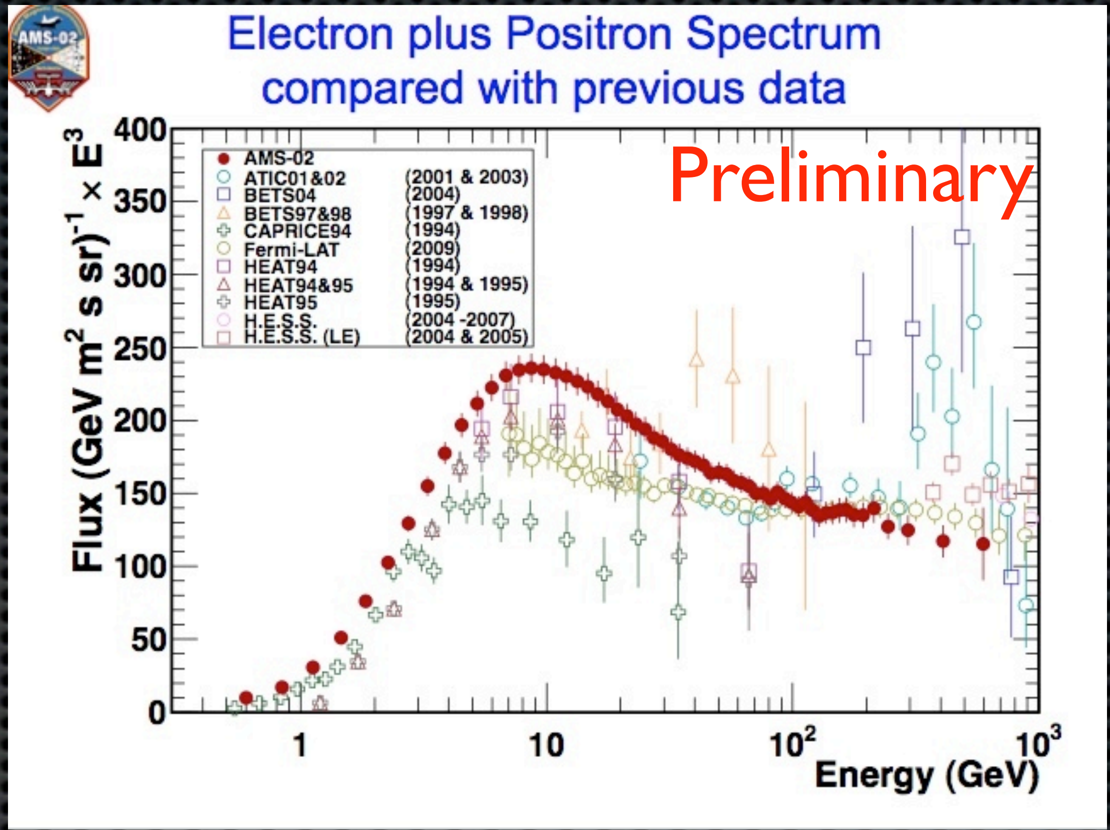
Casaus [AMS-02 coll.] ICRC 2013

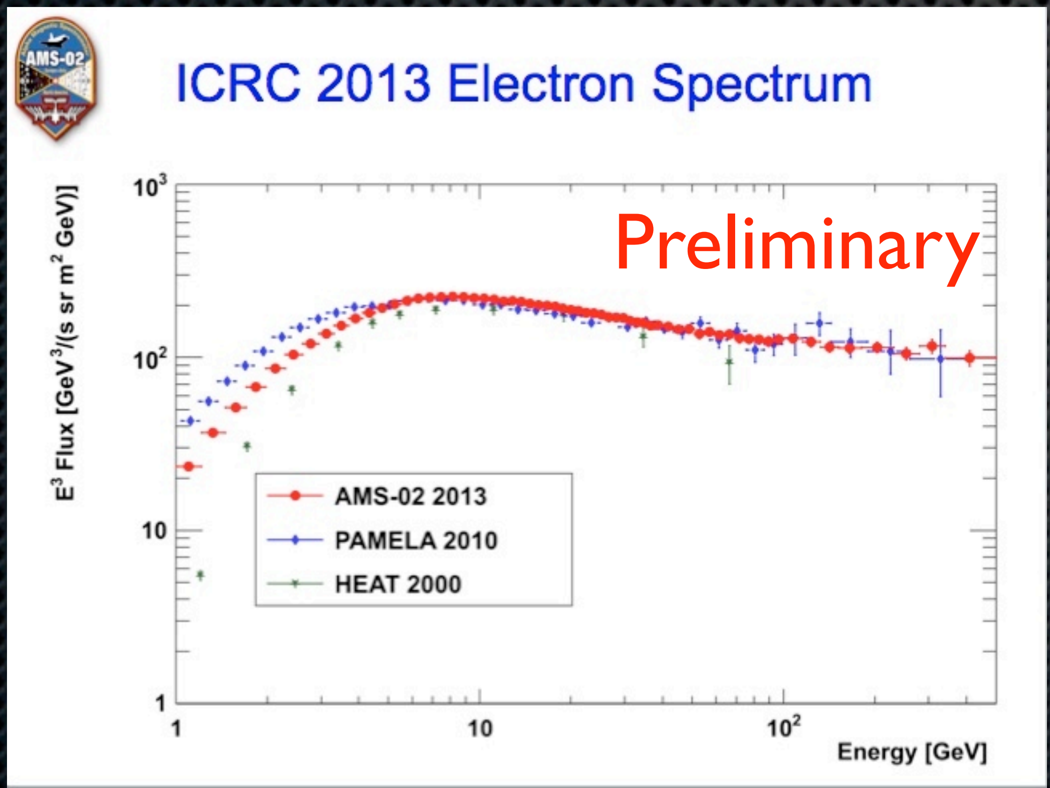


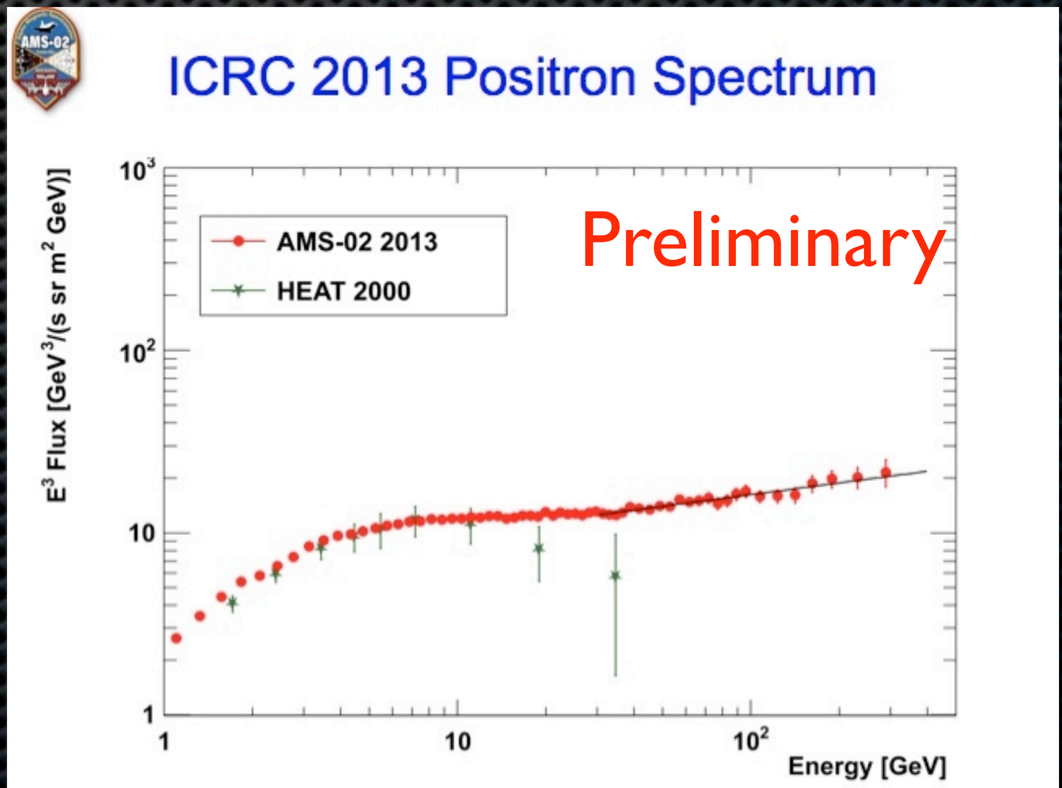
Which news from AMS-02 ?

No sign of bumpiness and <u>softer spectra</u>





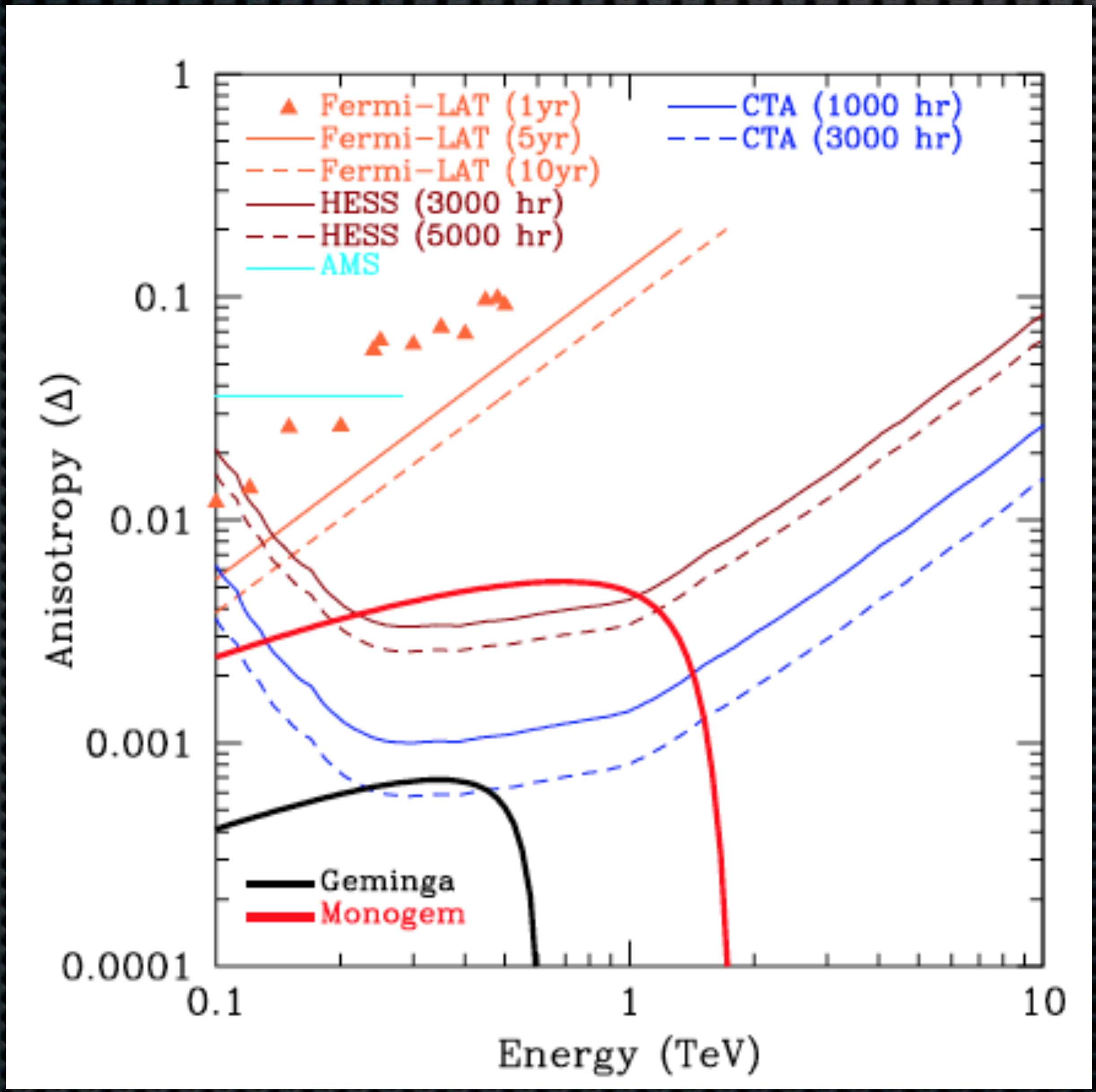




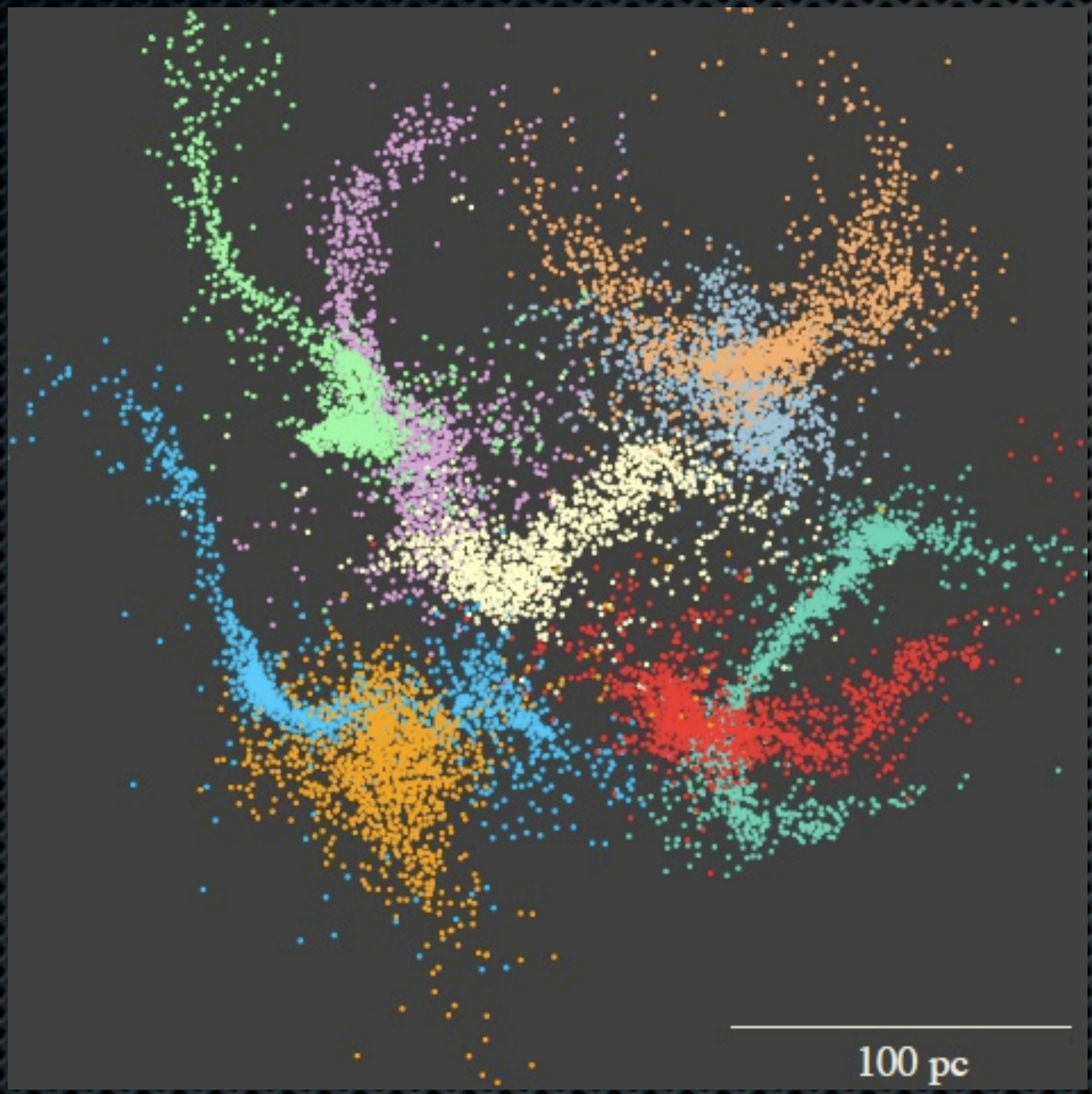
Anisotropy in future

CTA may put strong constraints

Linden & Profumo 2013



Is the absence of bumpiness and anisotropy a good criterion to exclude this interpretation ?



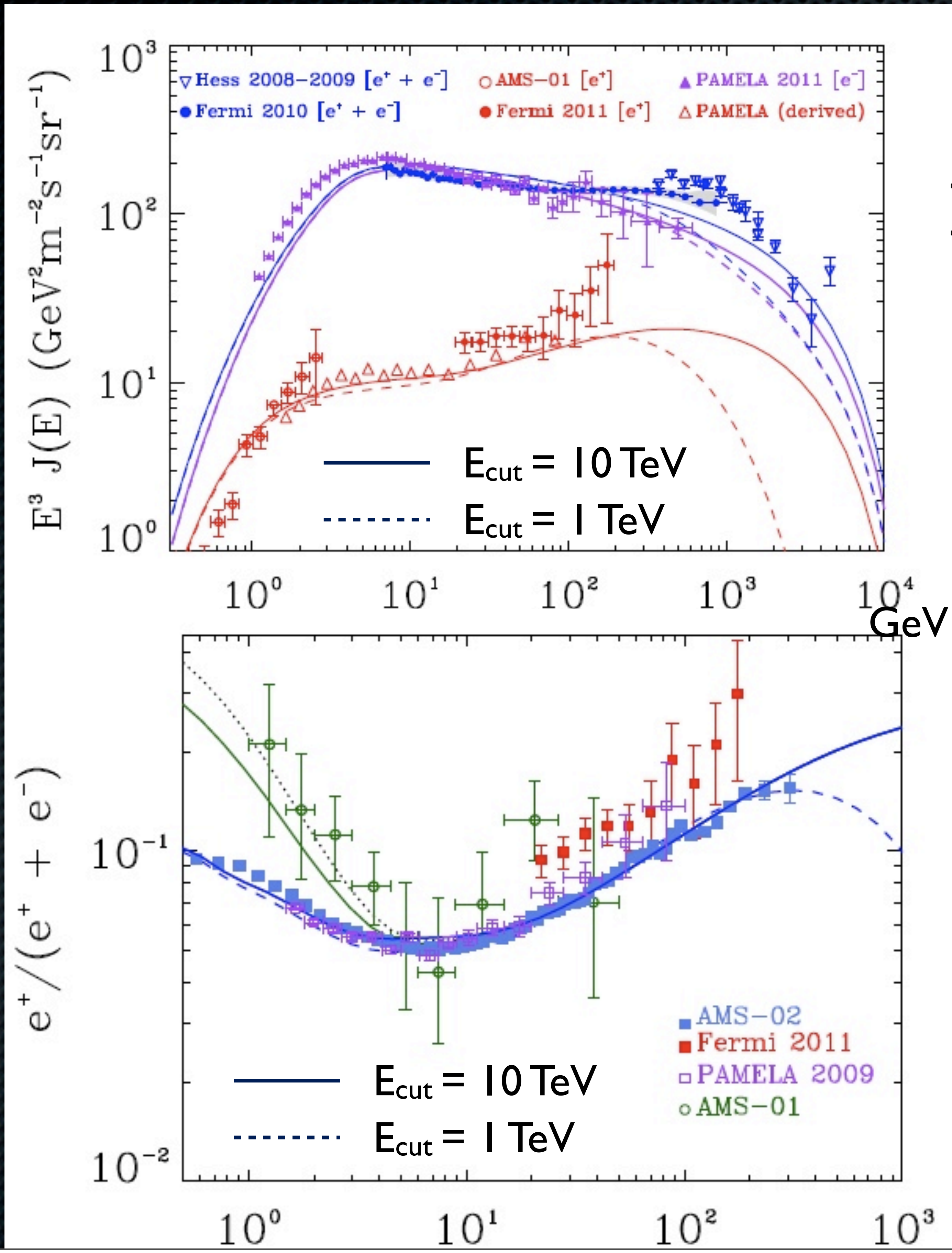
Kistler, Yuksel & Friedland 2012
Giacinti & Sigl PRL 2012

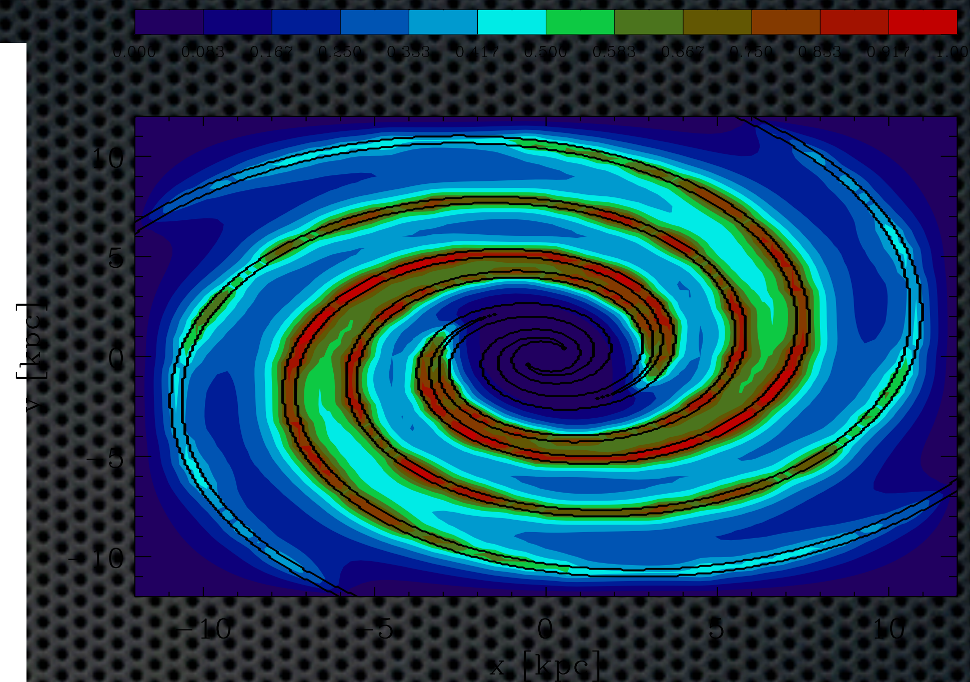
On small scales propagation in turbulent magnetic field is not spherically symmetric (as generally adopted)

rather it takes place along streams

the observer may not be reached by a significant flux even in the presence of several nearby sources

We may not need nearby sources





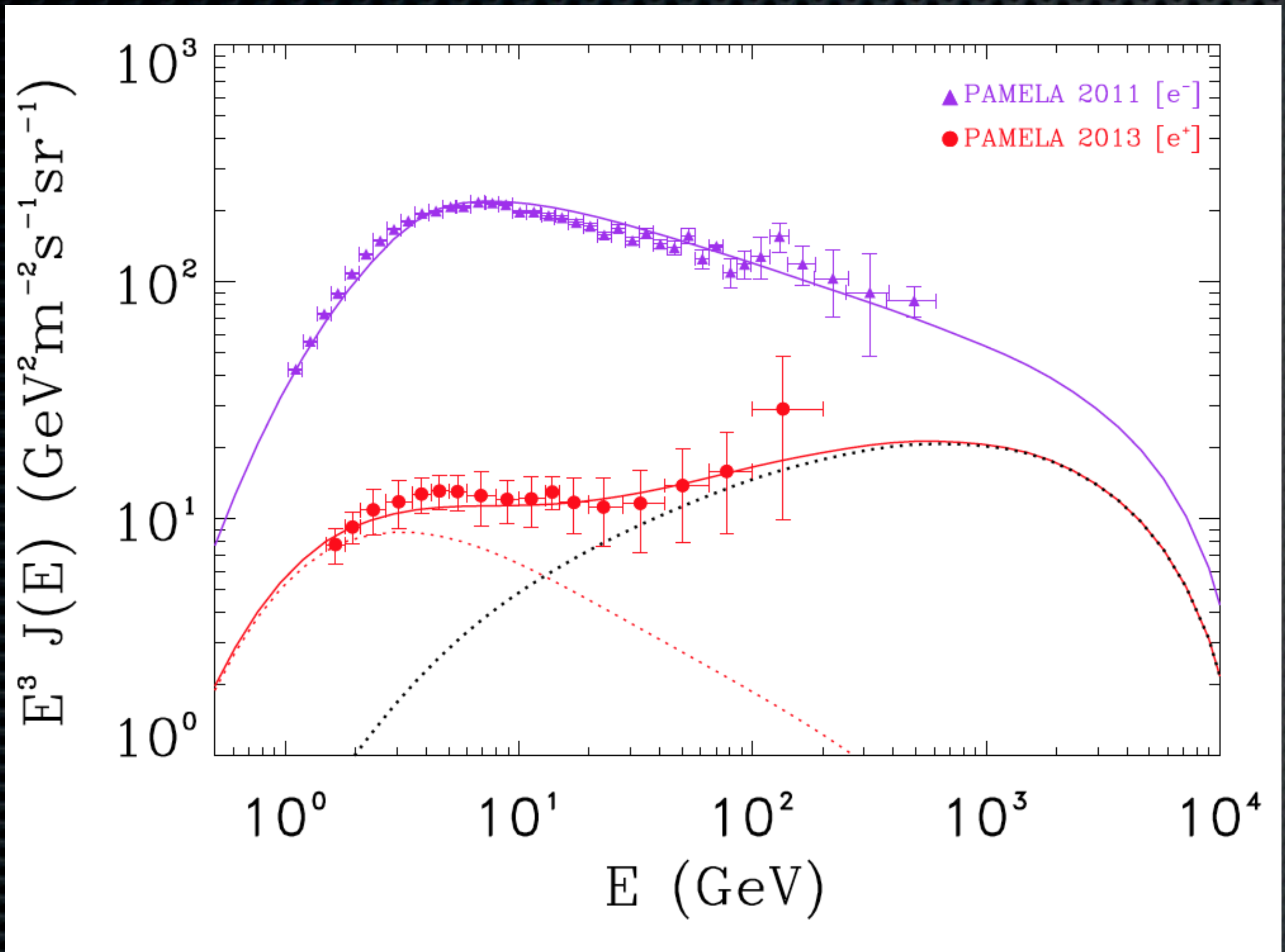
obtained under the hypothesis that the extra-component sources are distributed along the Galactic arms !

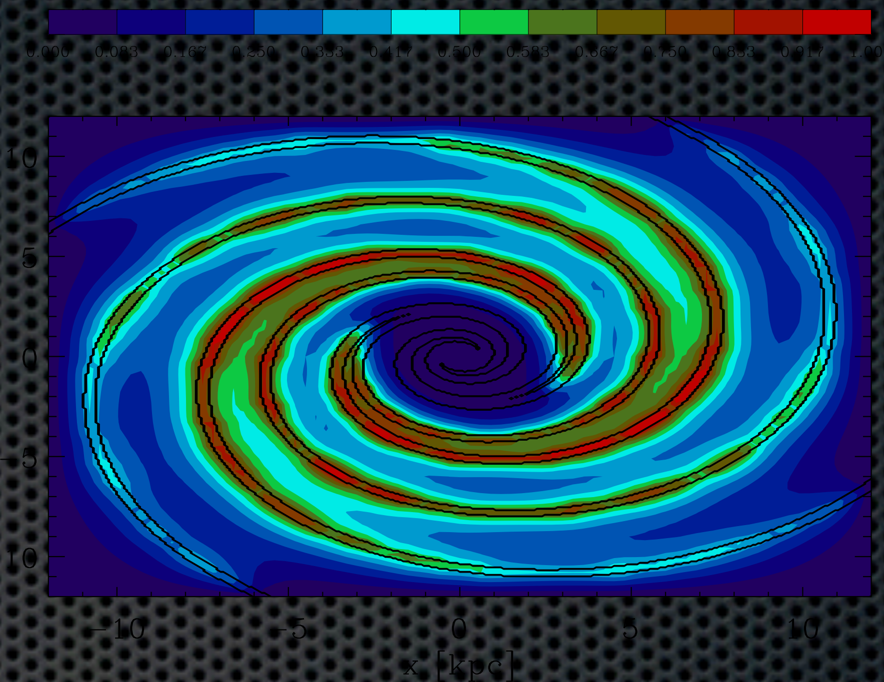
Undetectable anisotropy is expected in this case

Gaggero, Maccione, Evoli, Di Bernardo, DG, PRL 2013

We may not need nearby sources

comparison with PAMELA





obtained under the hypothesis that the extra-component sources are distributed along the Galactic arms !

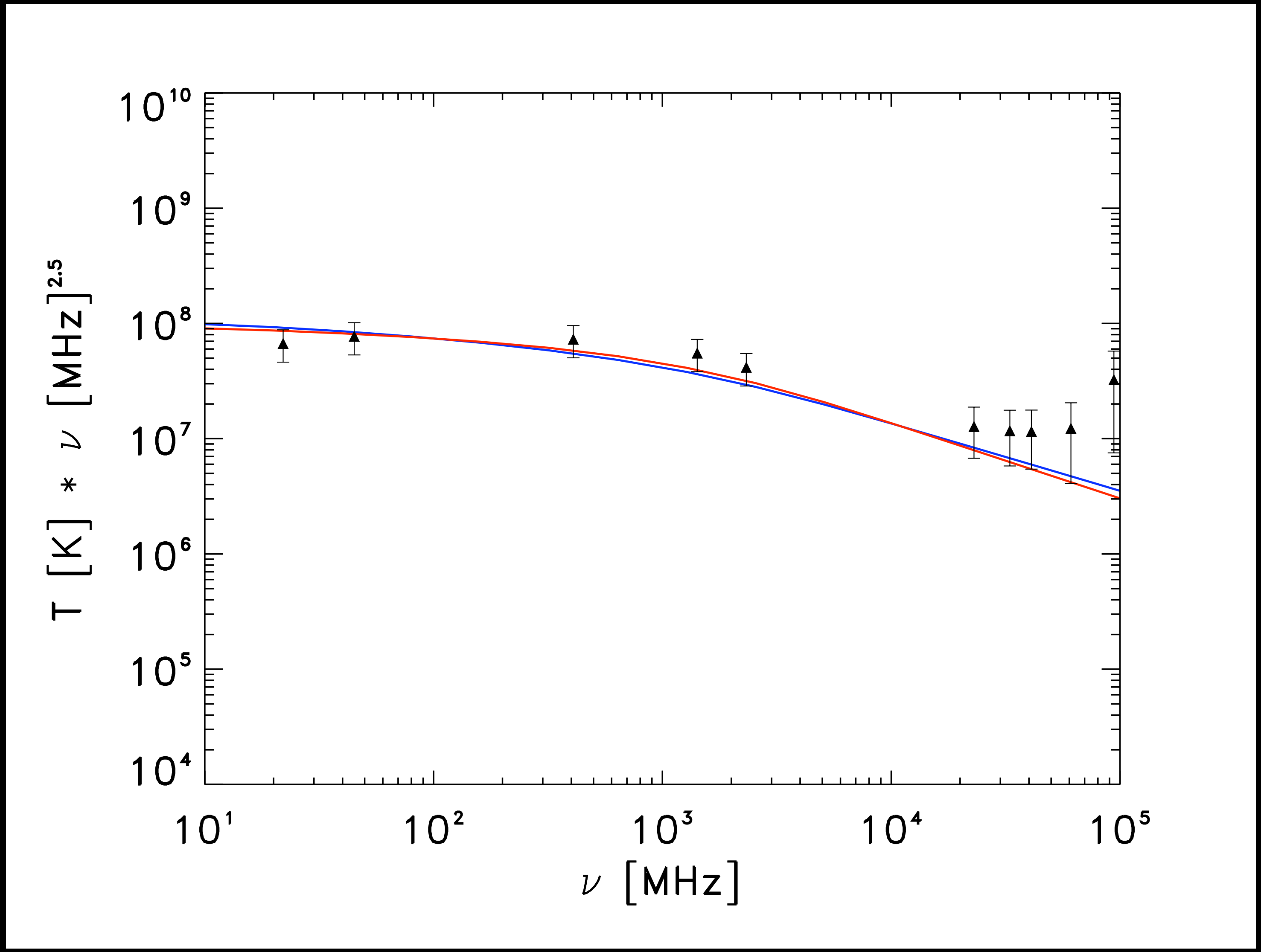
Undetectable anisotropy is expected in this case

DRAGON team, in progress

e+ and e- can be consistently be reproduce using a realistic charge dependent solar modulation model

see Maccione PRL 2013

The synchrotron spectrum



the radio spectrum, the time dependent PF and e^{+} spectrum are consistently reproduced for the first time.

see Di Bernardo et al. JCAP 2013

This also ameliorate the steepness problem

- Fermi acceleration generally predicts
  $\Upsilon_{source}(e^-) \simeq \Upsilon_{source}(p) \lesssim 2.3$

- Radio observations (synchrotron) of SNRs implies

  $<\Upsilon_{source}(e)> = 2<\Upsilon_{radio}> + 1 = 2.0 \pm 0.3$

- The presence of the extra-component implies a steeper background

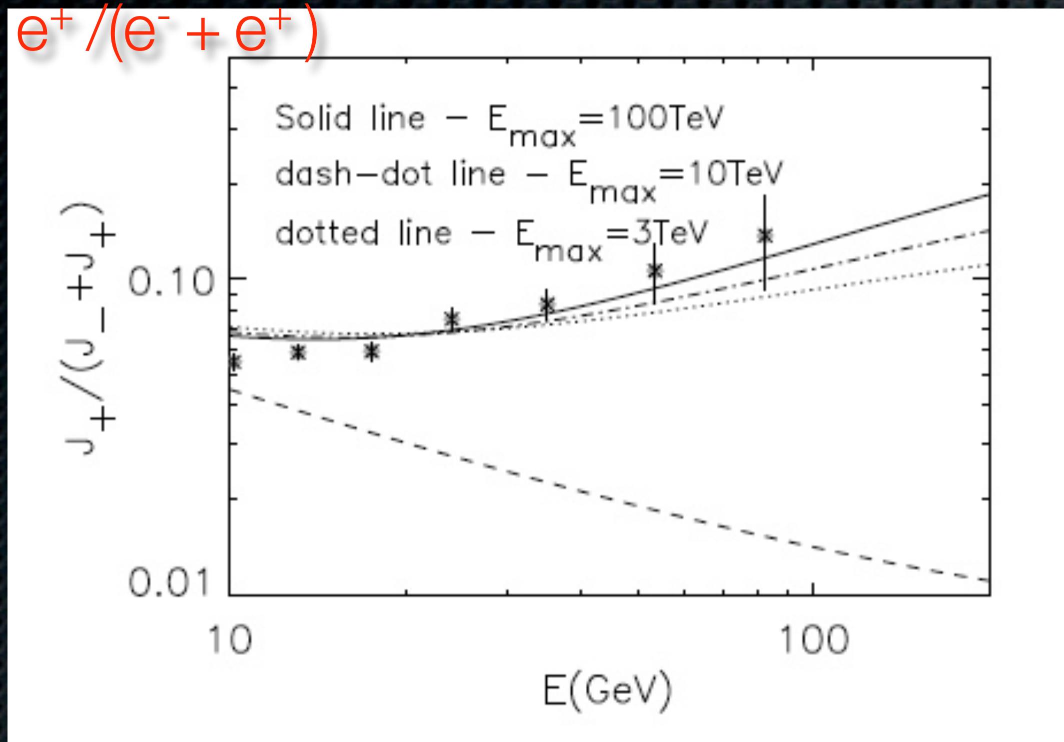
  $\Upsilon_{source}(e^-) \simeq 2.6 - 2.7$!!

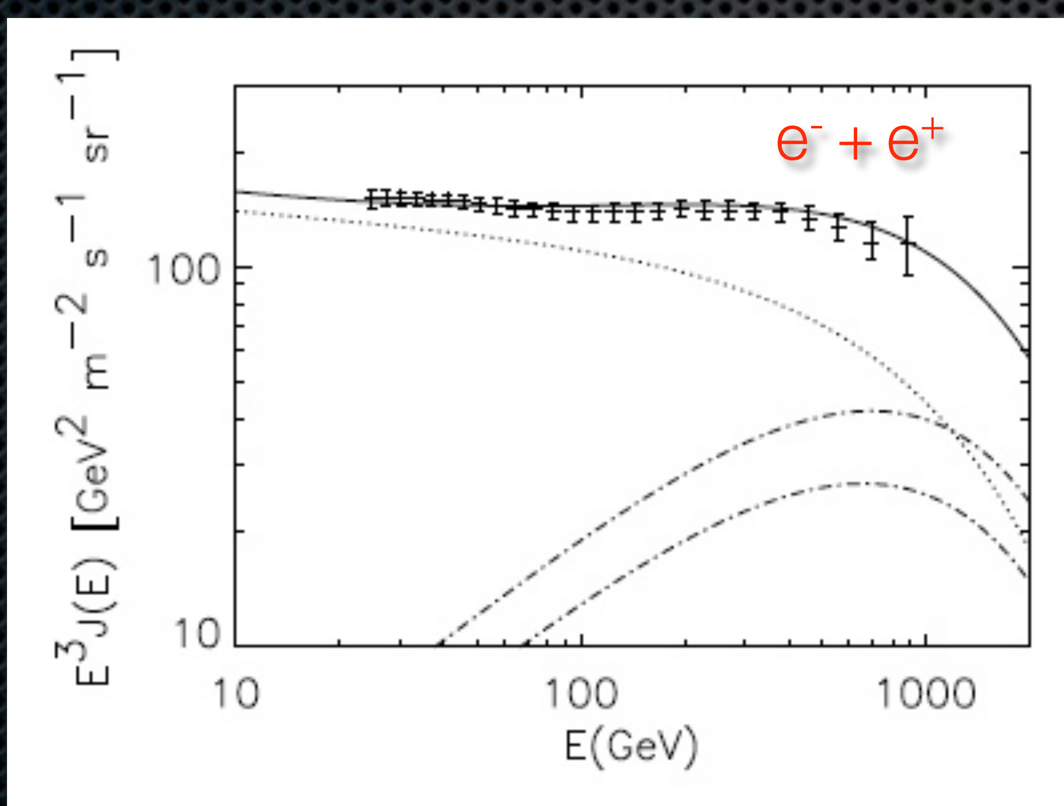
- Accounting for energy losses between galactic arms we find

  $\Upsilon_{source}(e^-) \simeq 2.38$

Secondary positron production in SNRs

Blasi, PRL 2009, Blasi & Serpico 2009





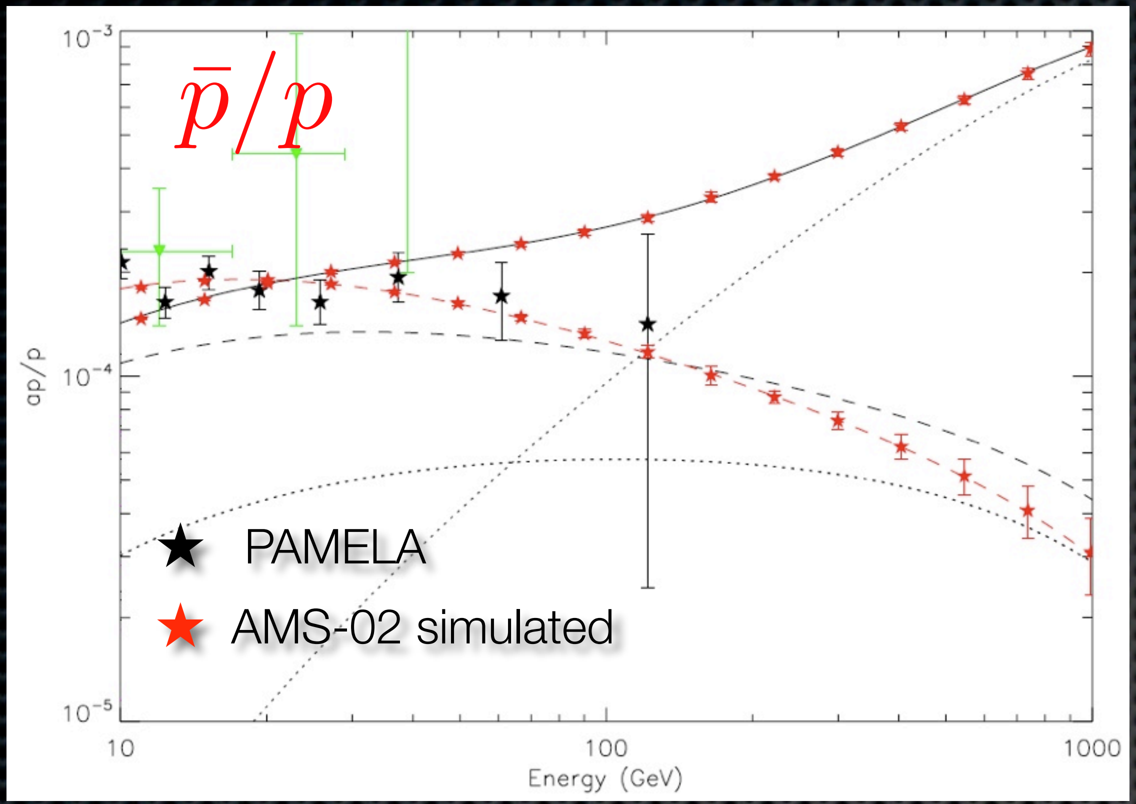
Middle age SNR are expected to contribute most

Most SNR are in the Galactic arms ⇒ our previous results naturally apply to this scenario

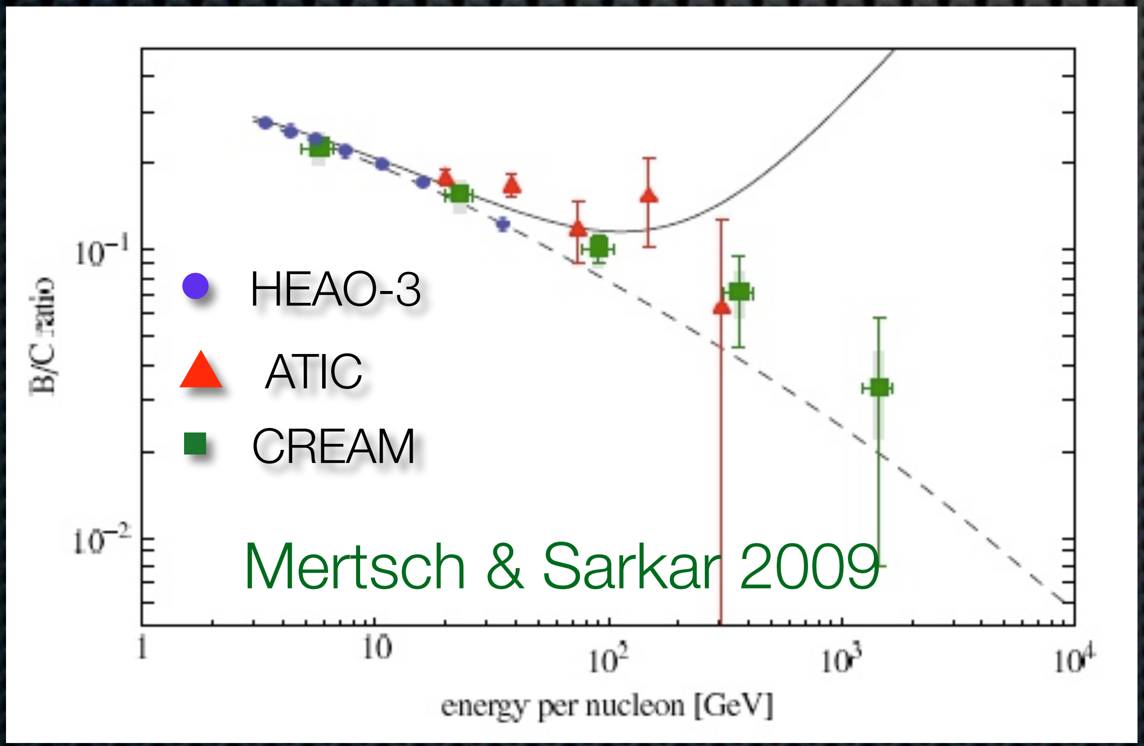
no detectable bumpiness and anisotropy is expected

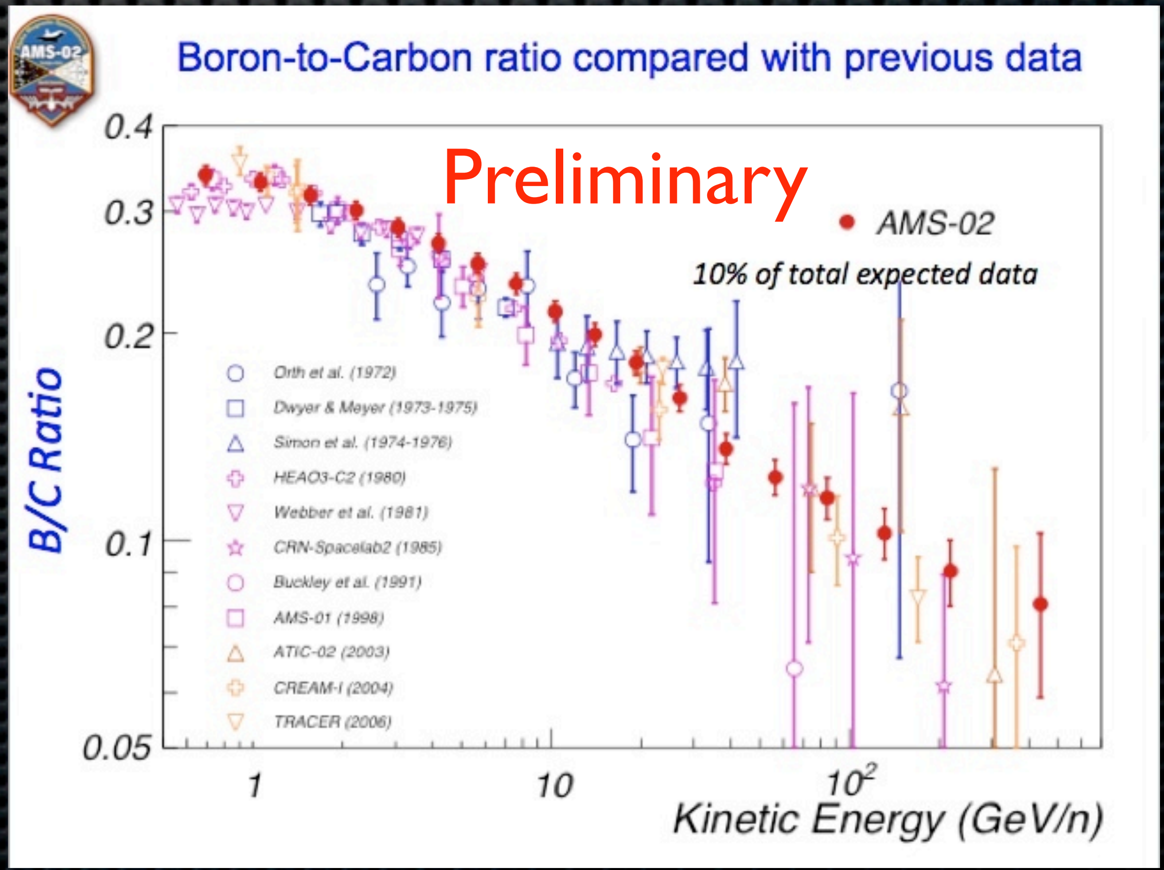
Secondary nuclei and antiproton production in SNRs

Blasi, PRL 2009, Blasi & Serpico 2009

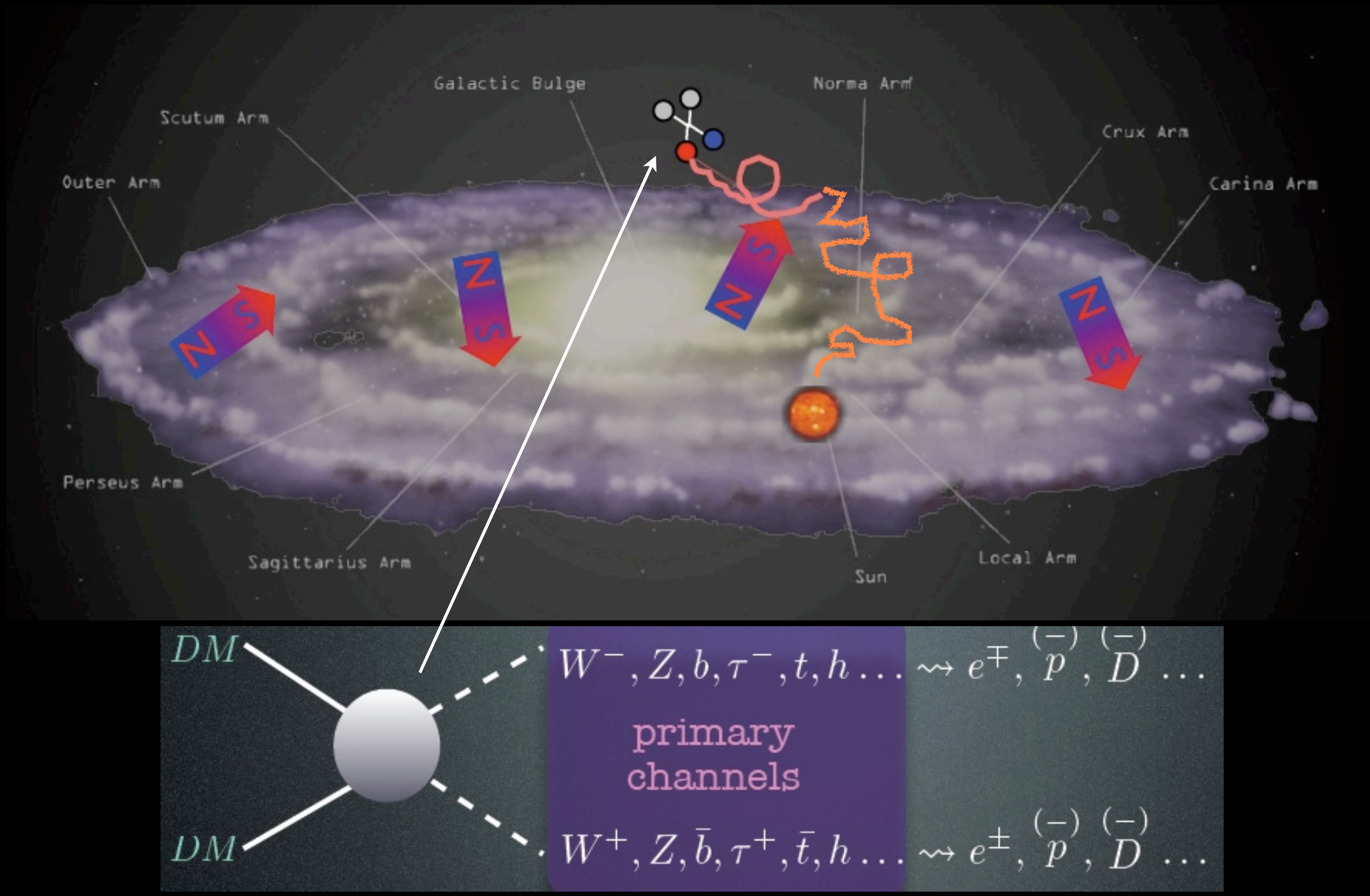


already in tension with data !





Dark Matter Annihilation Interpretation



Dark Matter Annihilation Interpretation

Main (harsh) demands:

- very large cross section/boost factor
($<\sigma v> \sim 10^{-23}$ cm^3/s rather than $<\sigma v> \sim 3\ 10^{-26}$ cm^3/s as expected from standard cosmology). Rather difficult to get.

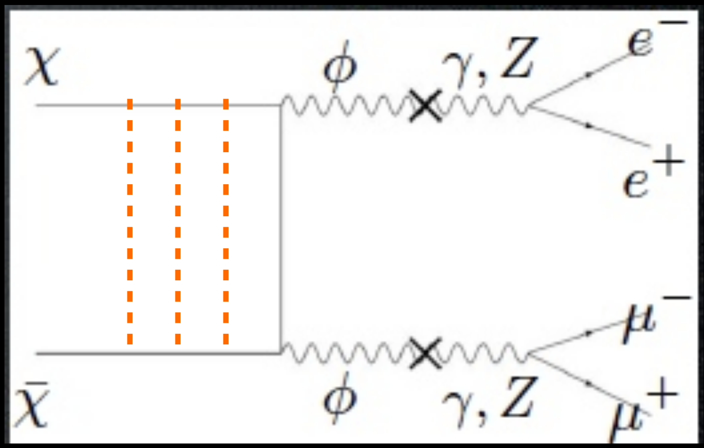
- $m_\chi \sim 1$ TeV (smaller would be in contrast with Fermi; larger would be in contrast with HESS). SUSY model tipically predict smaller masses

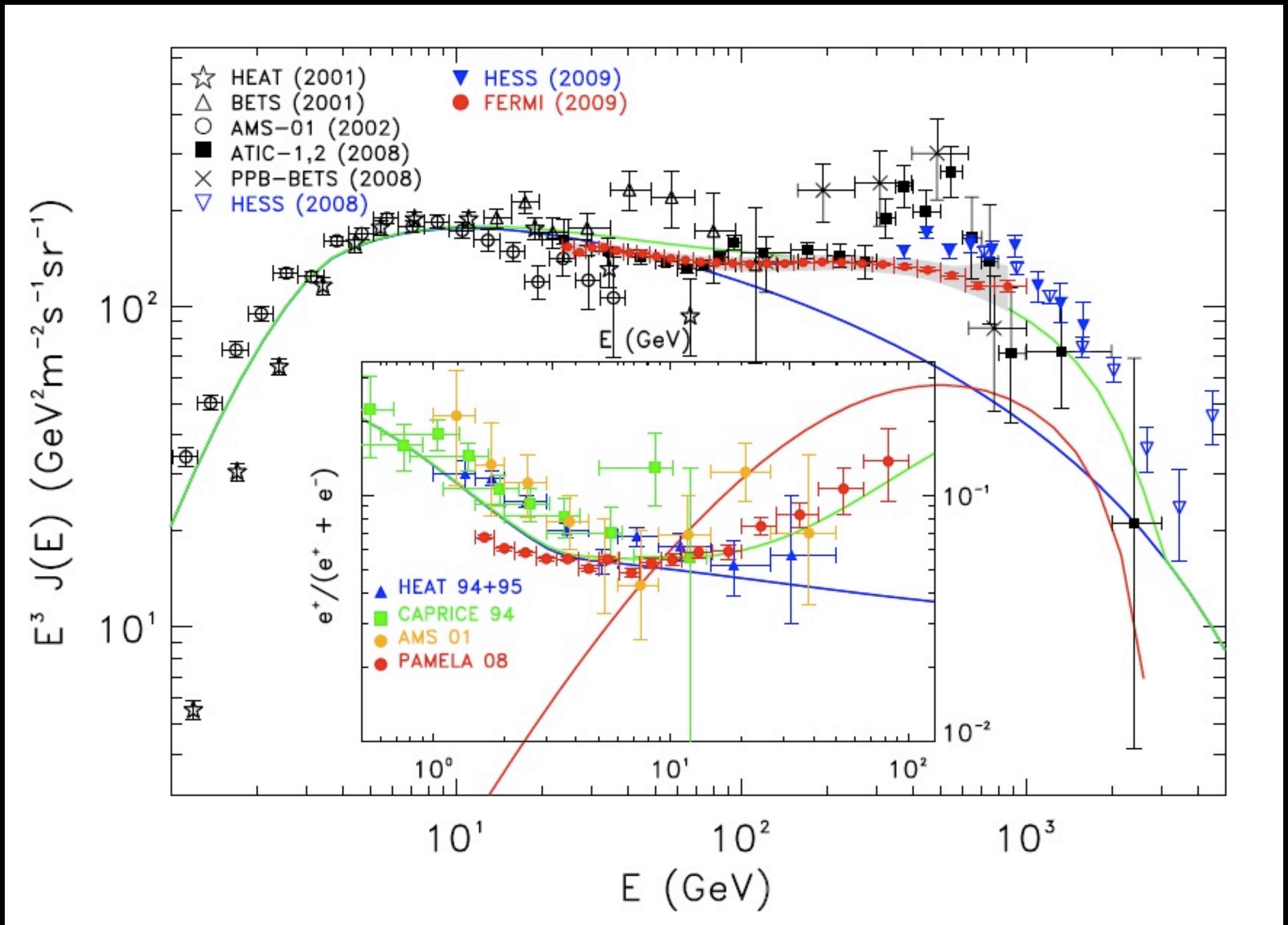
- do not overproduce antiprotons (only leptophilic models)

- do not overproduce γ-rays from the Galactic center, dwarf galaxies ..

Dark matter annihilation interpretation

Viable models invoke (pseudo)scalar particle(s) which may decay mainly into leptons (such to avoid PAMELA antiproton constraints) and boost the annihilation cross above the value expected from standard cosmology due to the Born-Sommerfeld effect



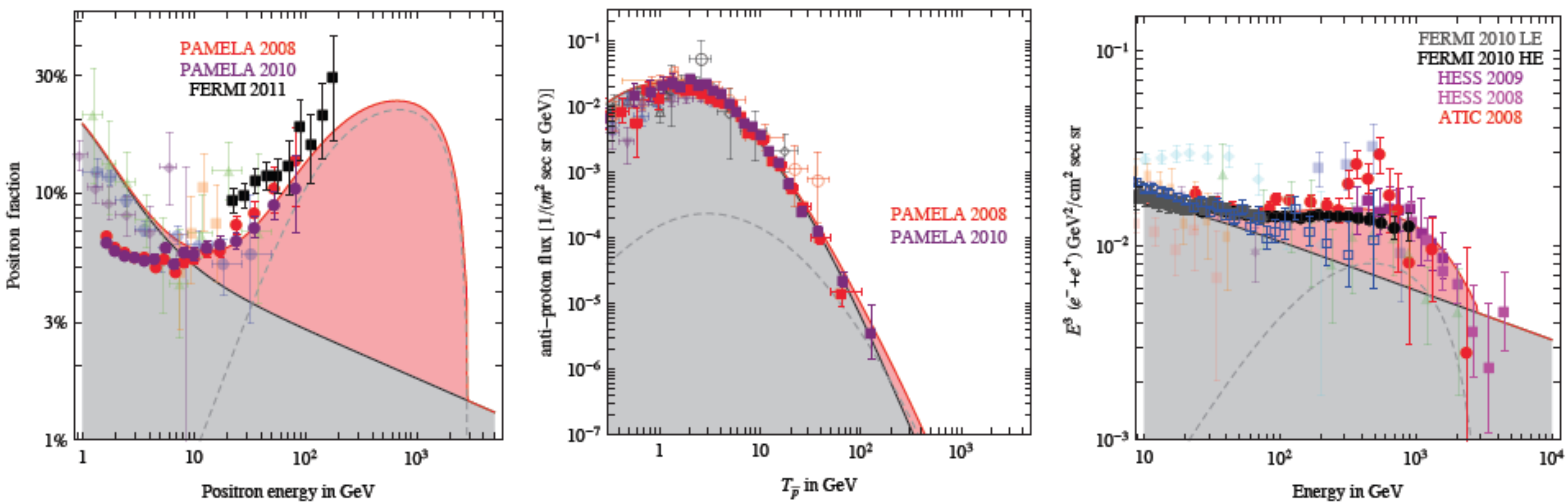


In the figure:
$m_\chi = 3$ TeV $<\sigma v> = 1.2 \times 10^{-22}$ cm^3 s
annihilating mainly in $\tau^\pm$
see e.g. *Bergstrom et al. 2009*

Computed with DRAGON + DARKSUSY
this allows a consistent treatment of DM products and CR background propagation

Dark matter annihilation interpretation

Cirelli 2013

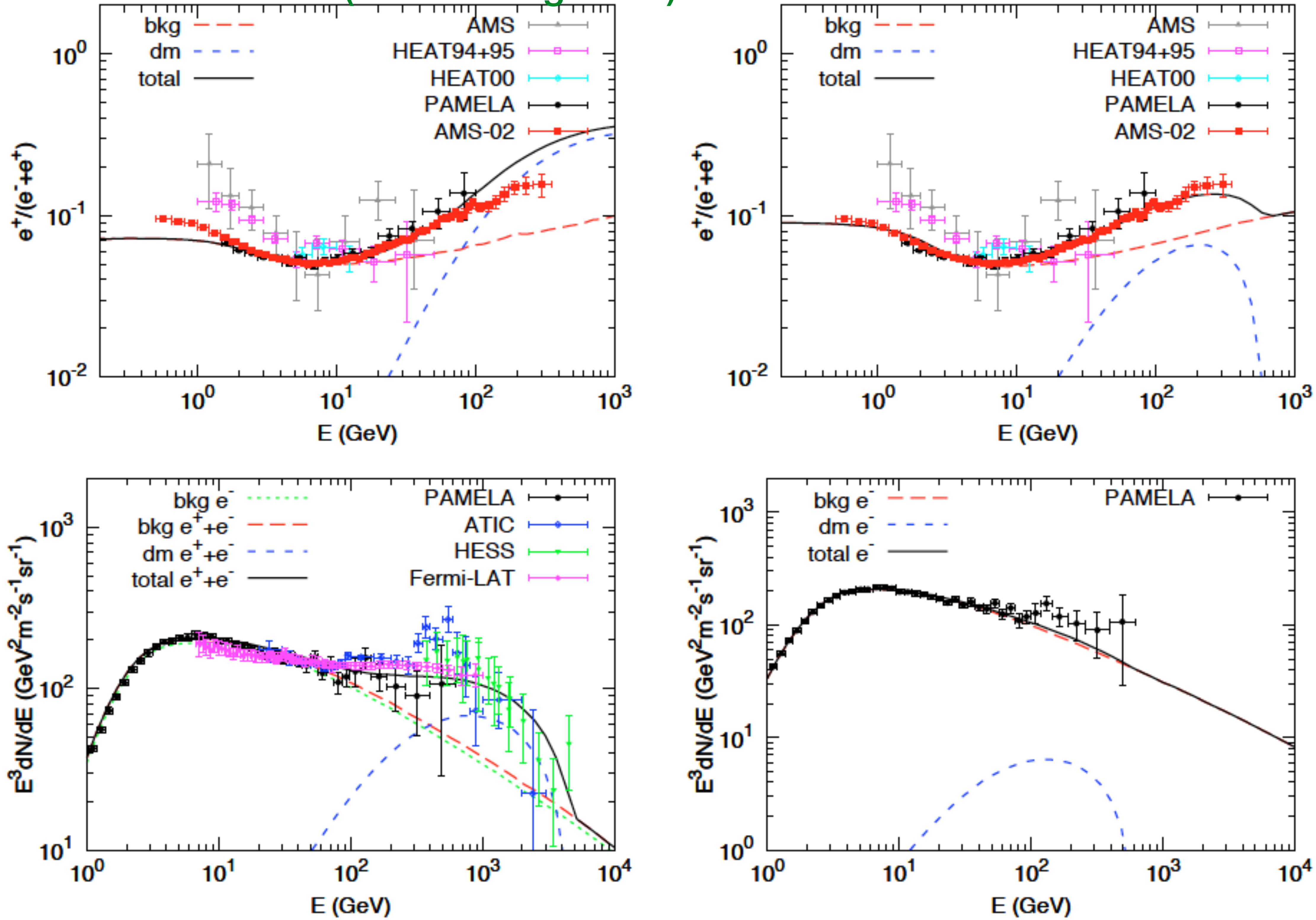


m_X = 3 TeV $<\sigma v>$ = 1.2 x 10^{-22} cm^3 s annihilating mainly in $\tau^{\pm}$

Dark matter annihilation interpretation

Use Fermi $e^+ + e^-$ Use PAMELA e^-

Yan et al. 1304.1408 (naive background)

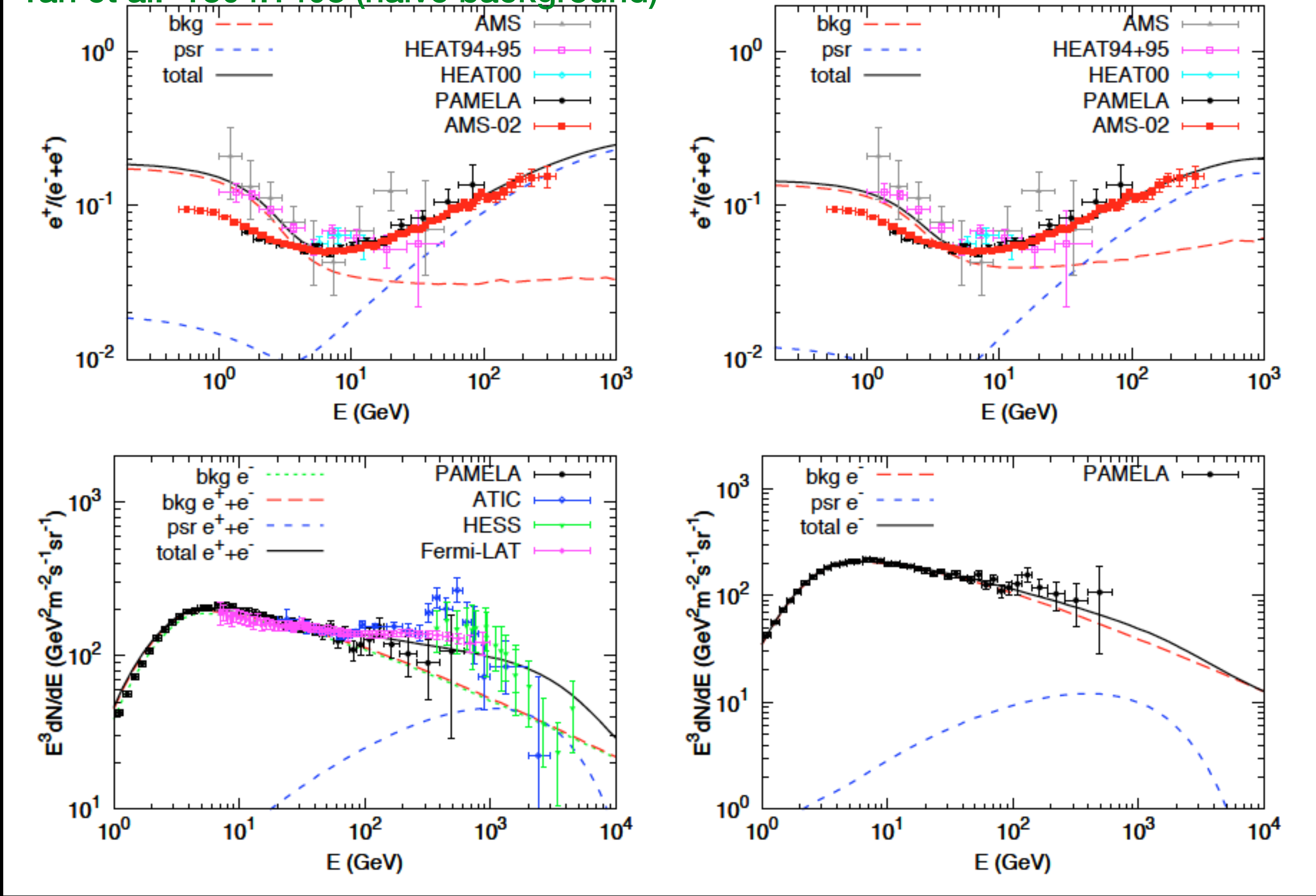


see also Cholis & Hooper 2013

"Pulsar" interpretation

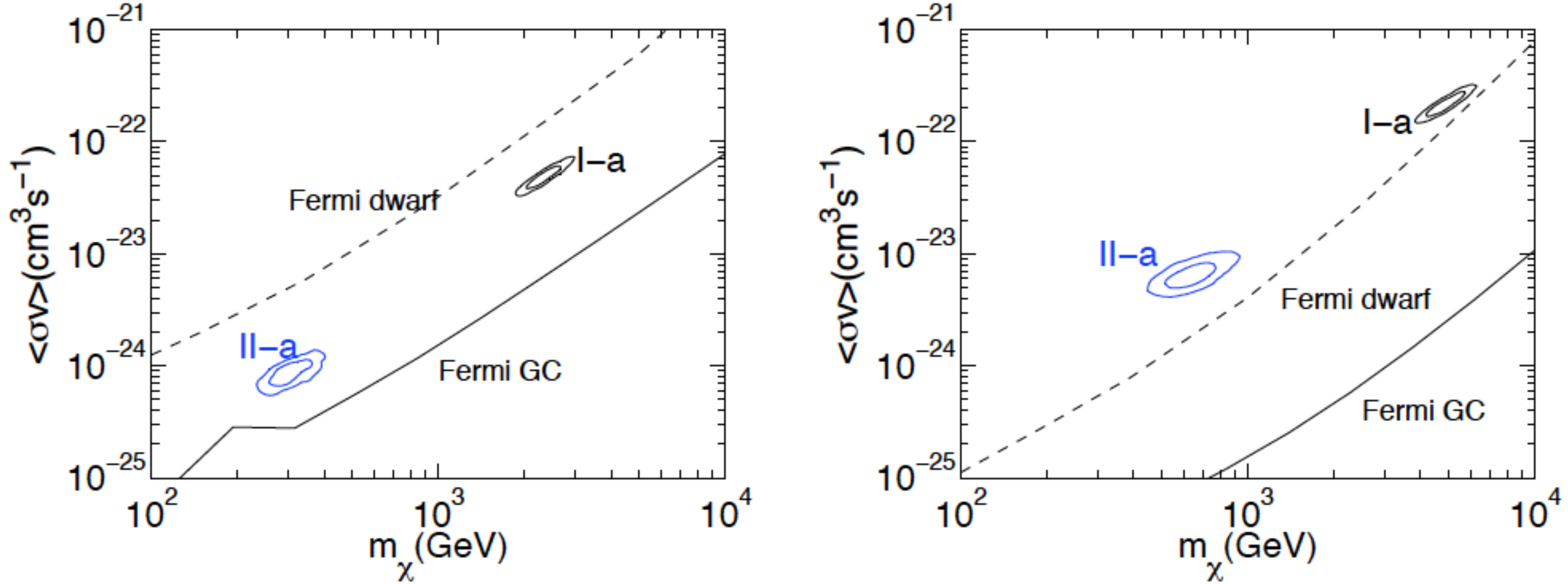
Use Fermi $e^+ + e^-$ | Use PAMELA e^-

Yan et al. 1304.1408 (naive background)



Problems with γ-rays ?

Yan et al. 1304.1408



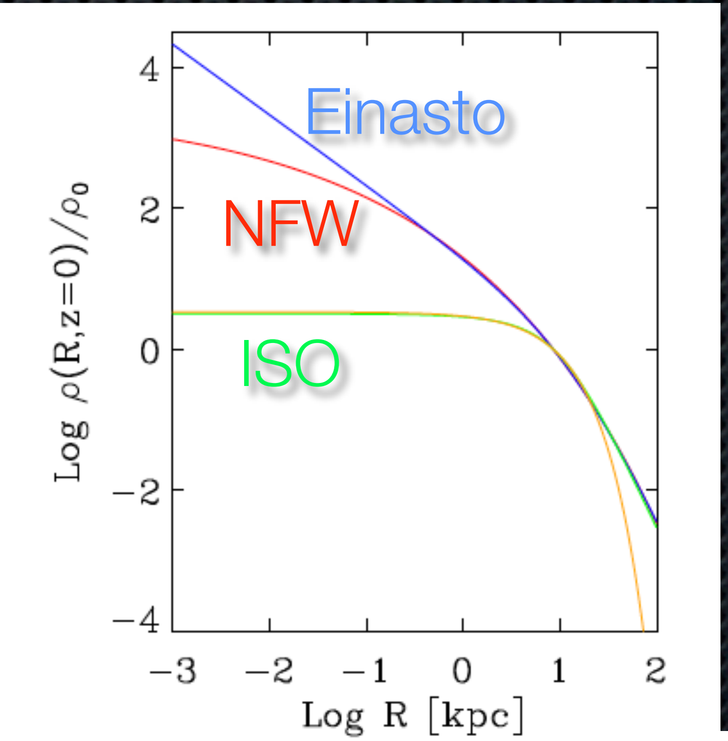
I-a Use Fermi $e^+ + e^-$ II-a Use PAMELA e^-

This should be taken with caution since data sets may not be compatible and the background was not computed in the proper way !

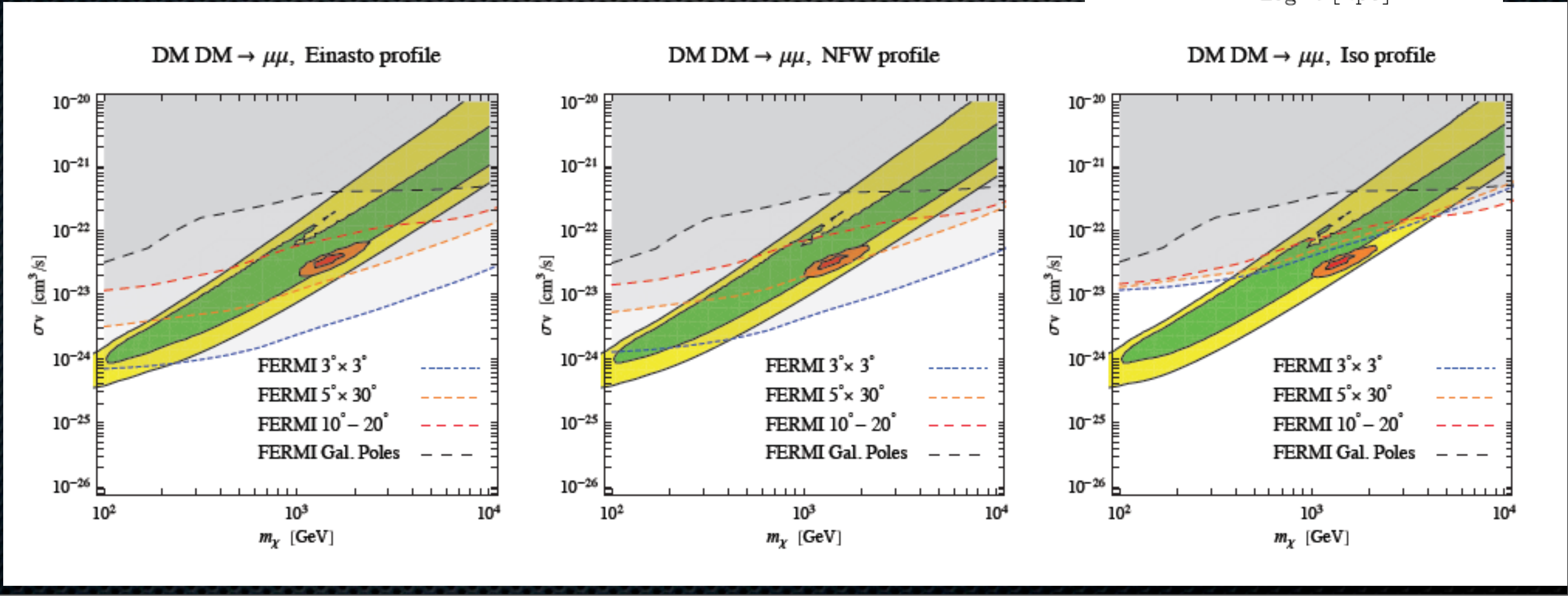
Gamma-ray constraints

produced by decay/brem. of hadronization products + internal brem.

the flux strongly depends on the DM profile

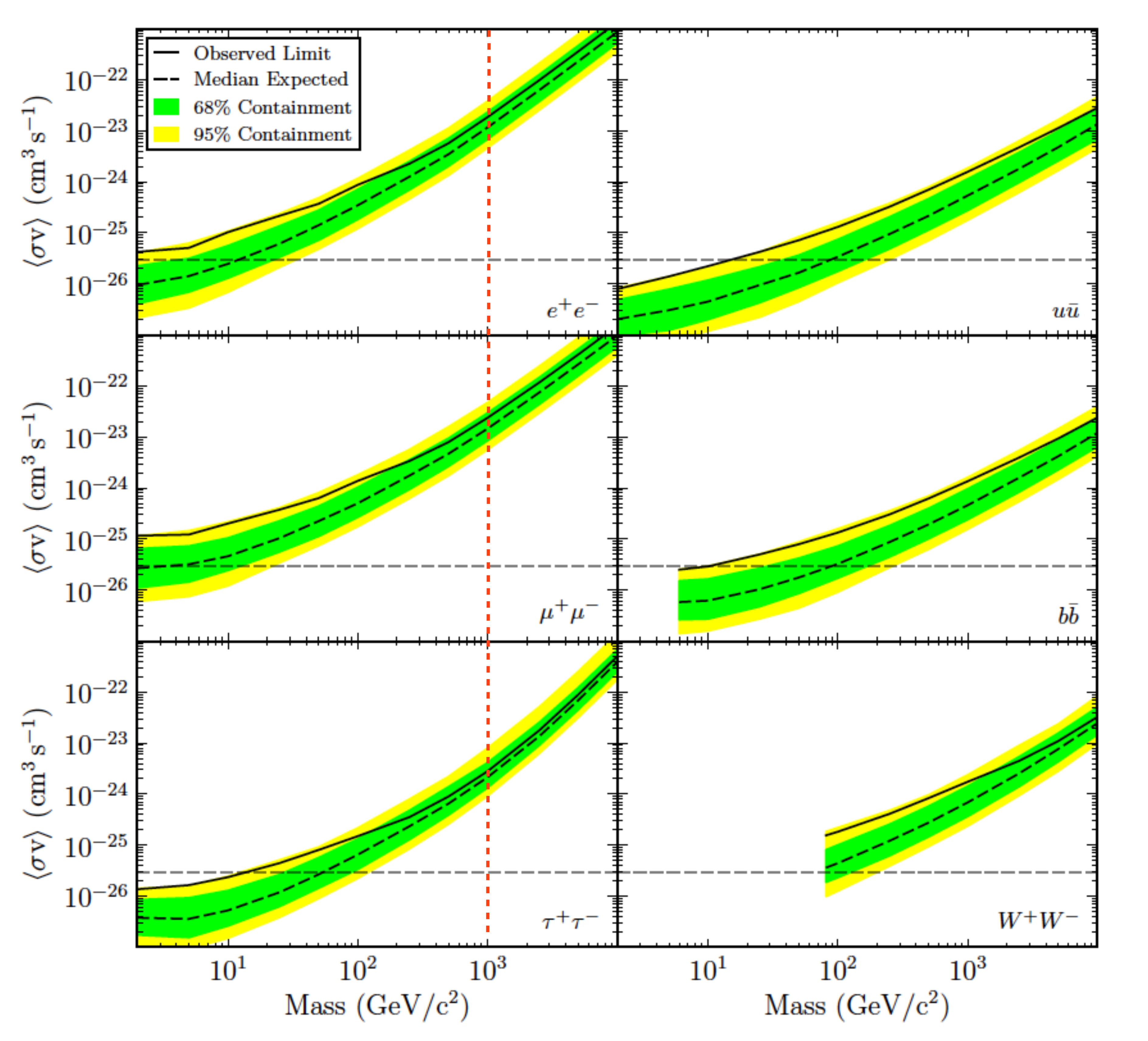


Fermi-LAT constr. from Gal. Center data
Cirelli, Panci, Serpico 09, Cirelli 2013
(background not subtracted)



Gamma-ray constraints

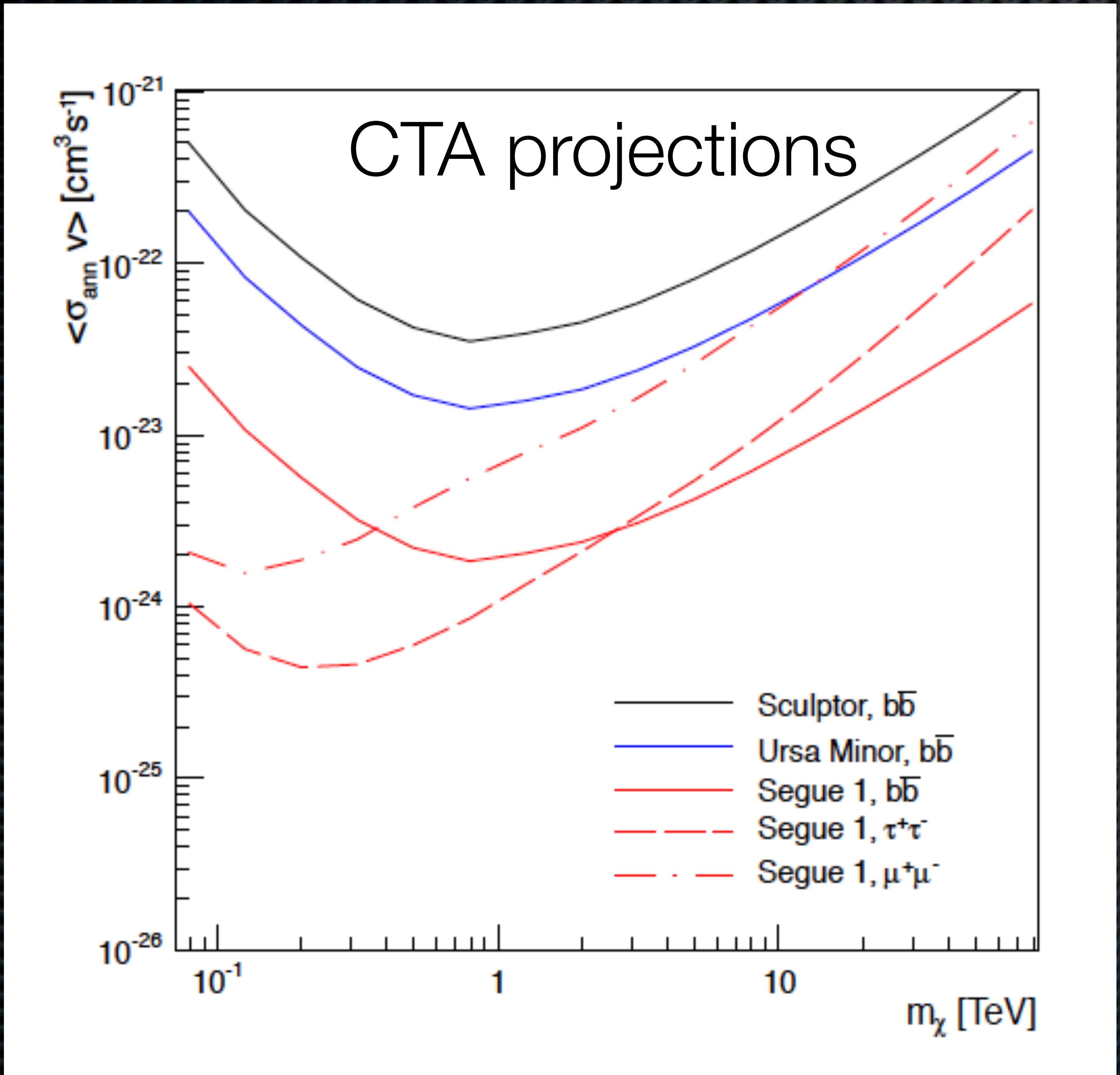
Fermi-LAT coll. arXiv:1310.0828



15 dwarf galaxies assuming NFW DM profile

Gamma-ray constraints (the future)

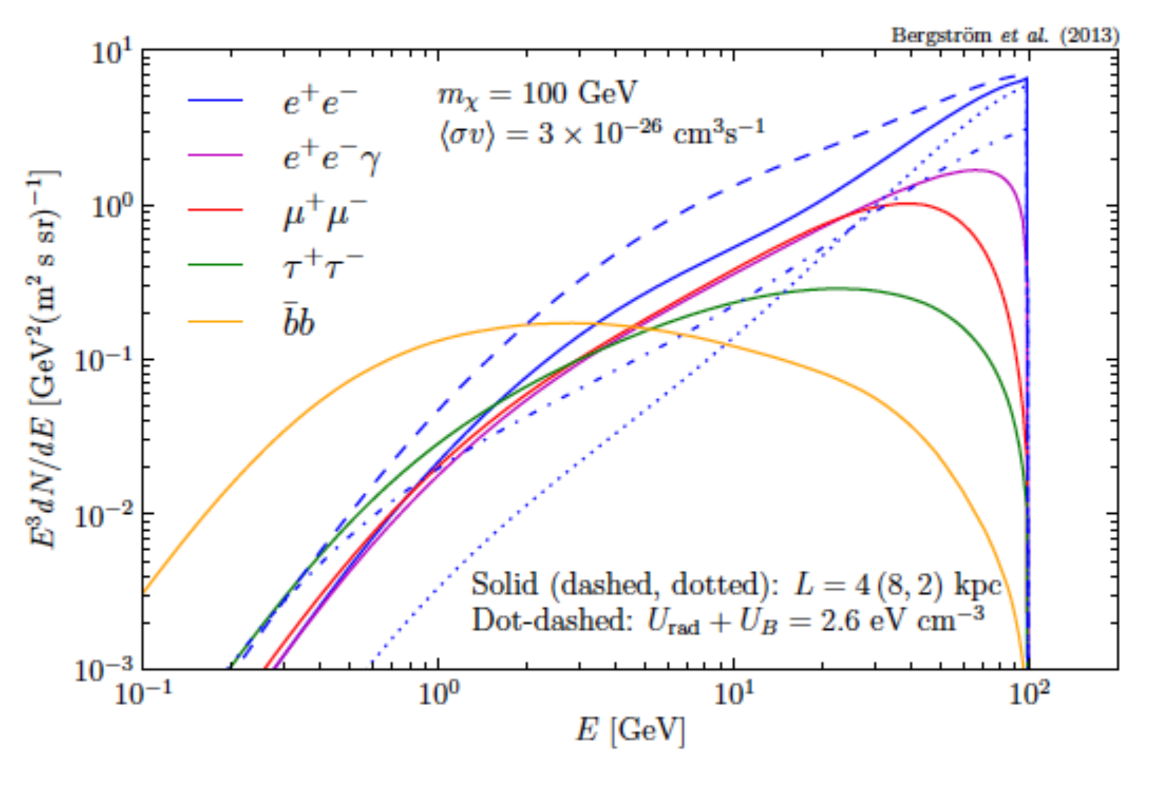
Doro et al. arXiv:1208.5356

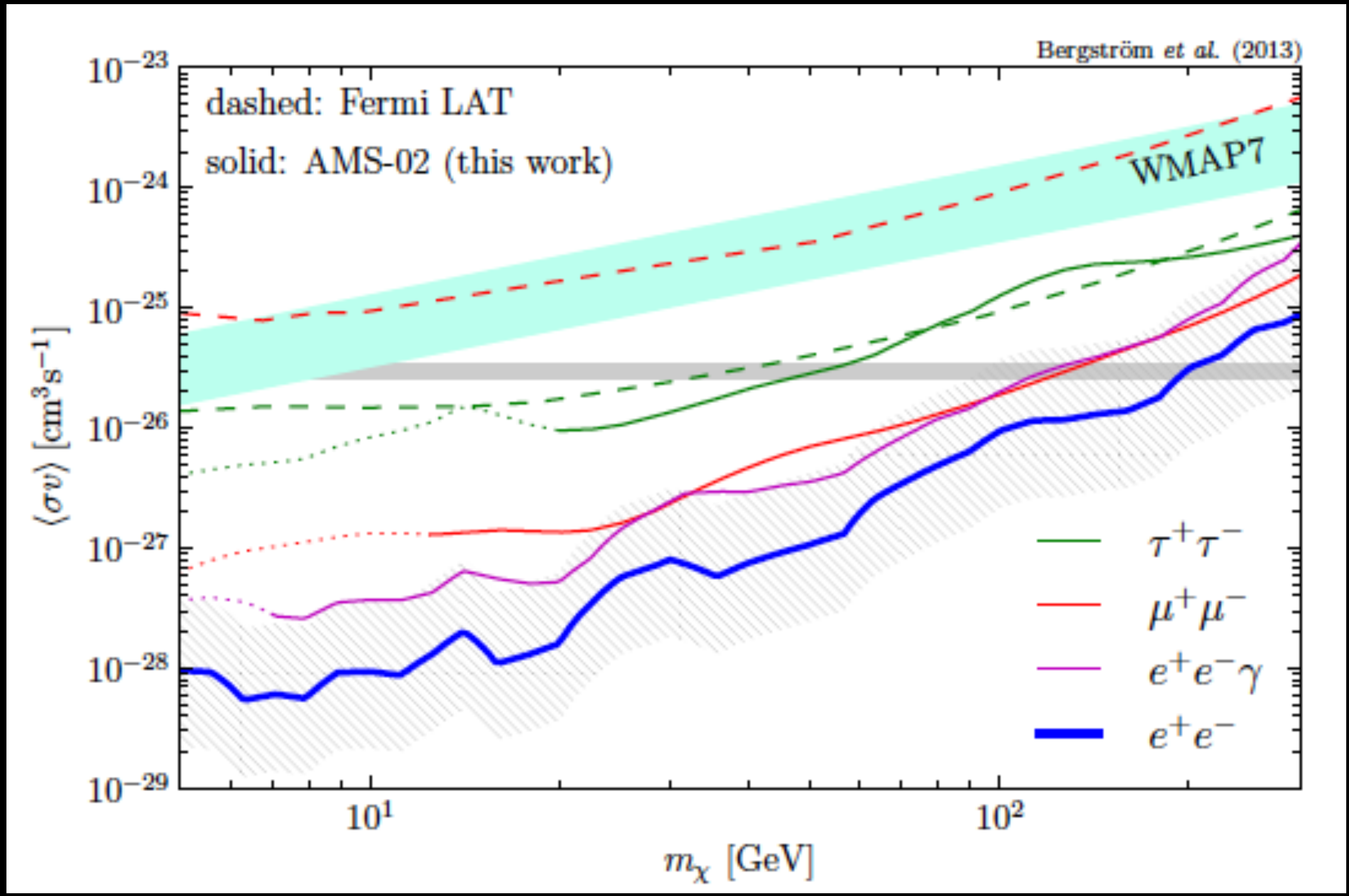


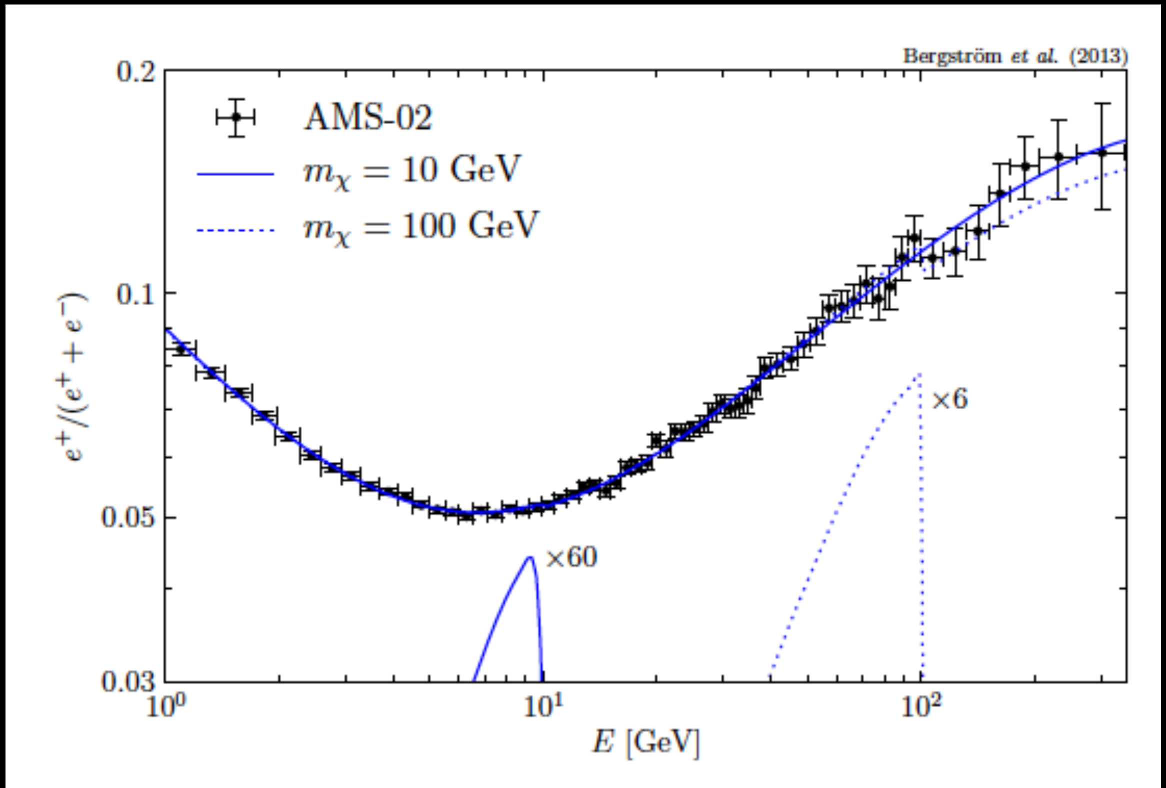
100 hr observations
of several dwarf galaxies

Dark matter constraints

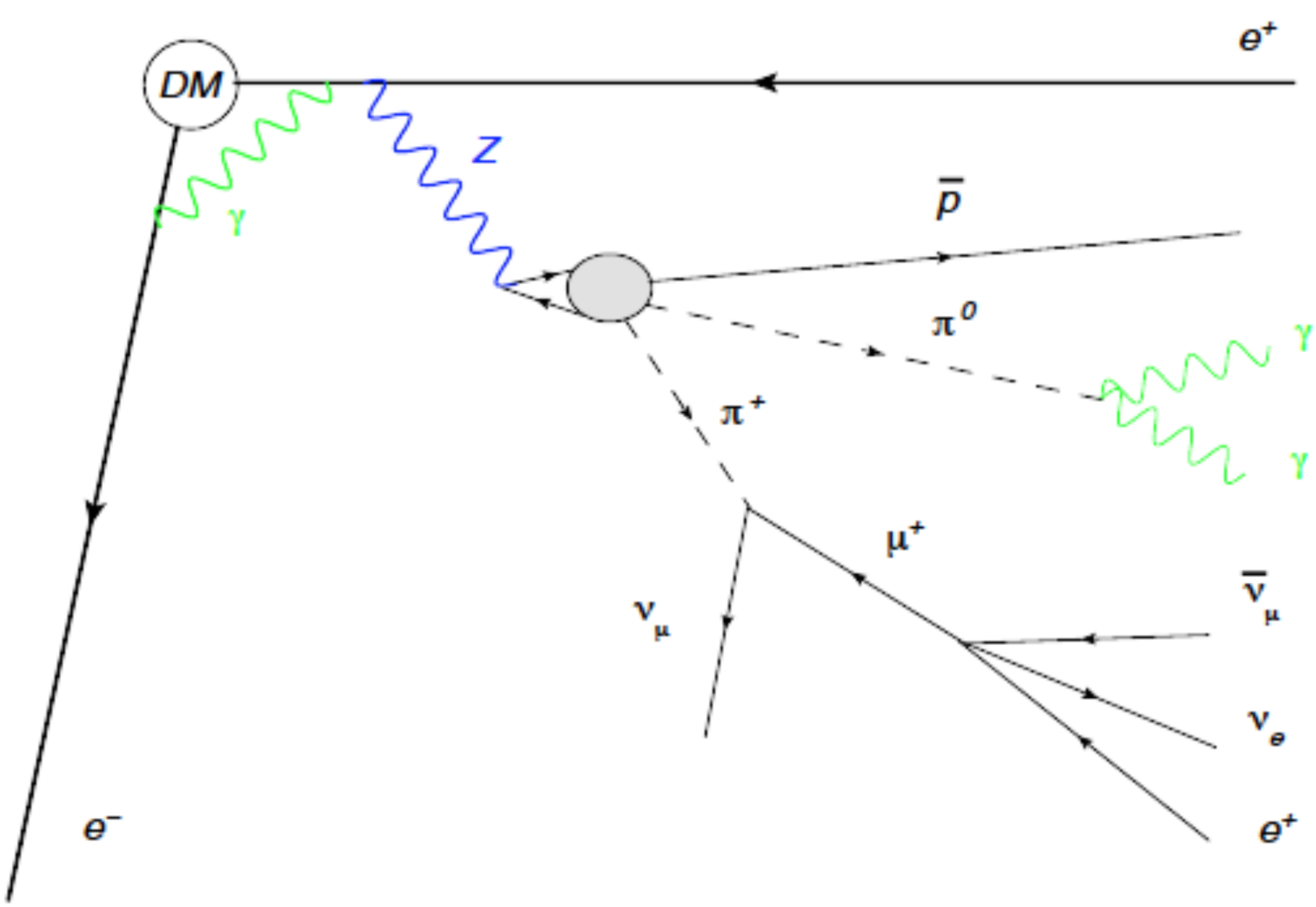
Bergstrom et al. 1306.3983







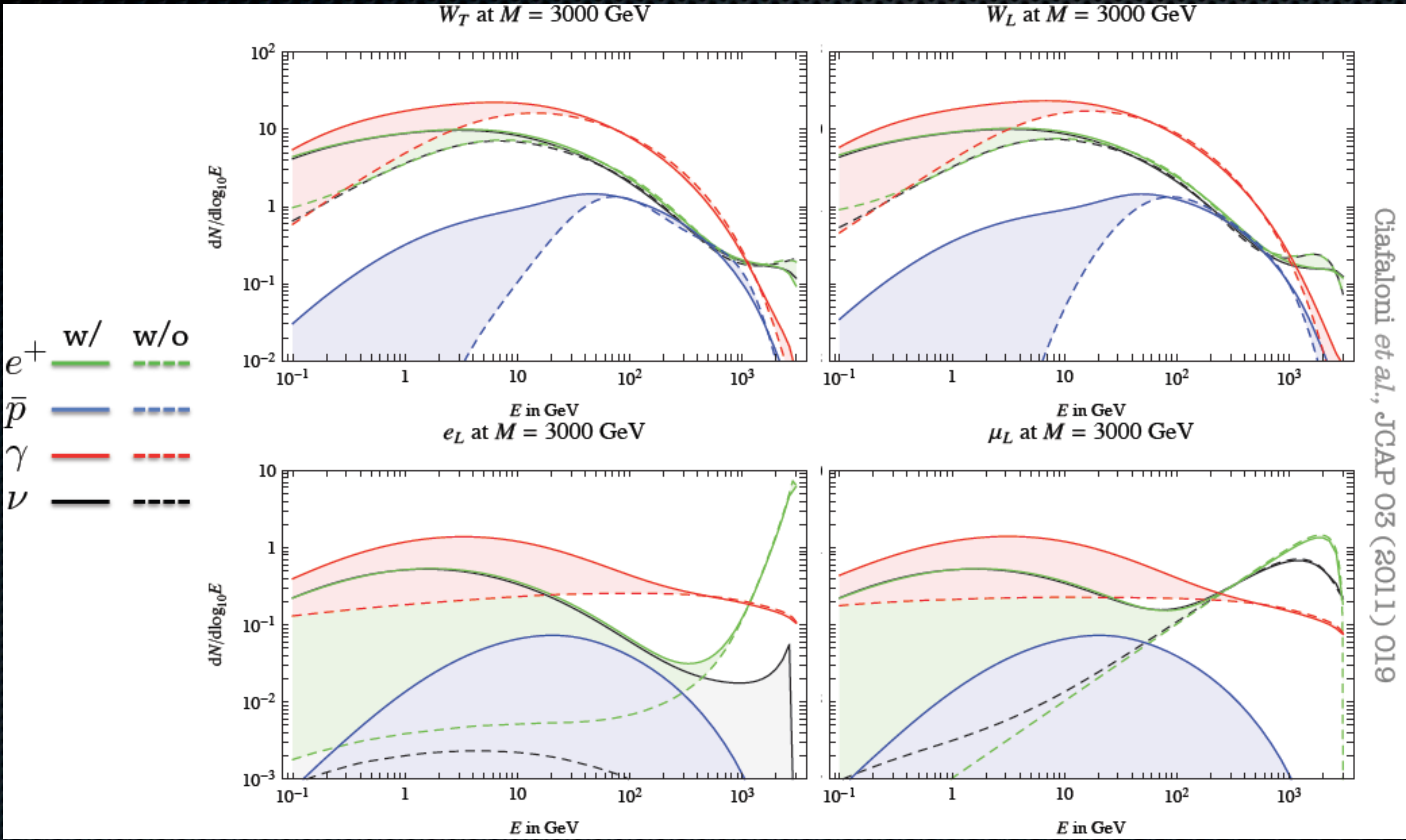
Electroweak corrections
leptophilic models are not hadron free



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

Electroweak corrections

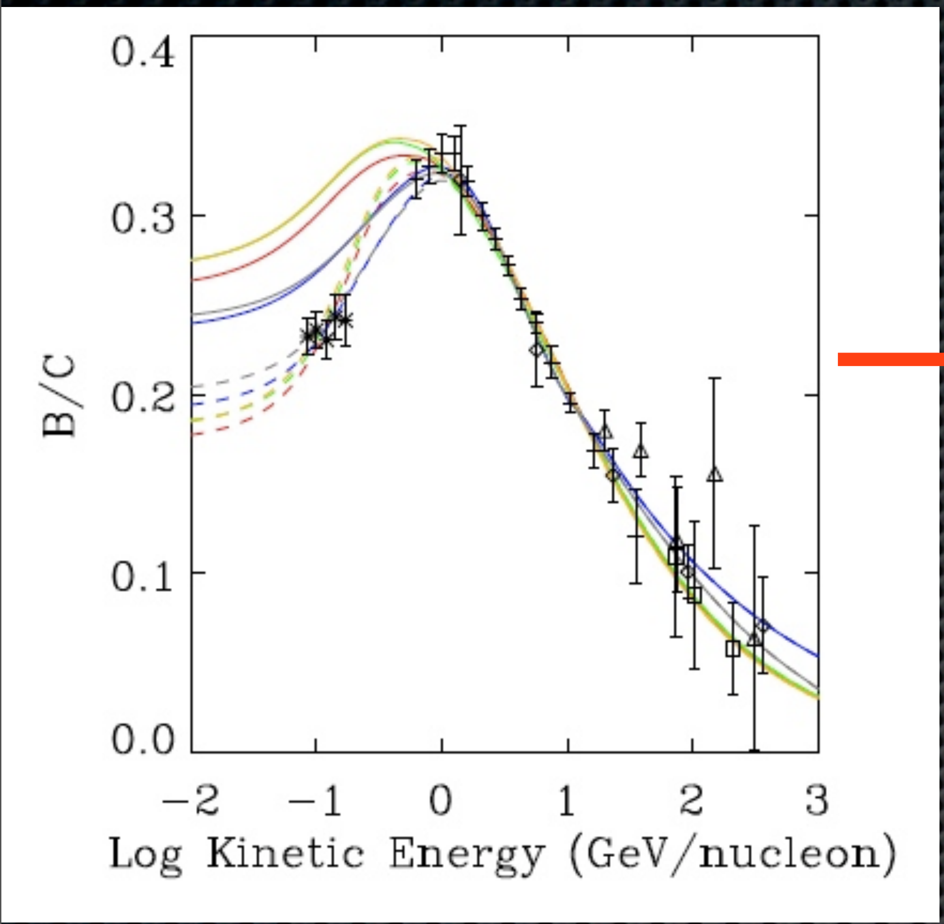


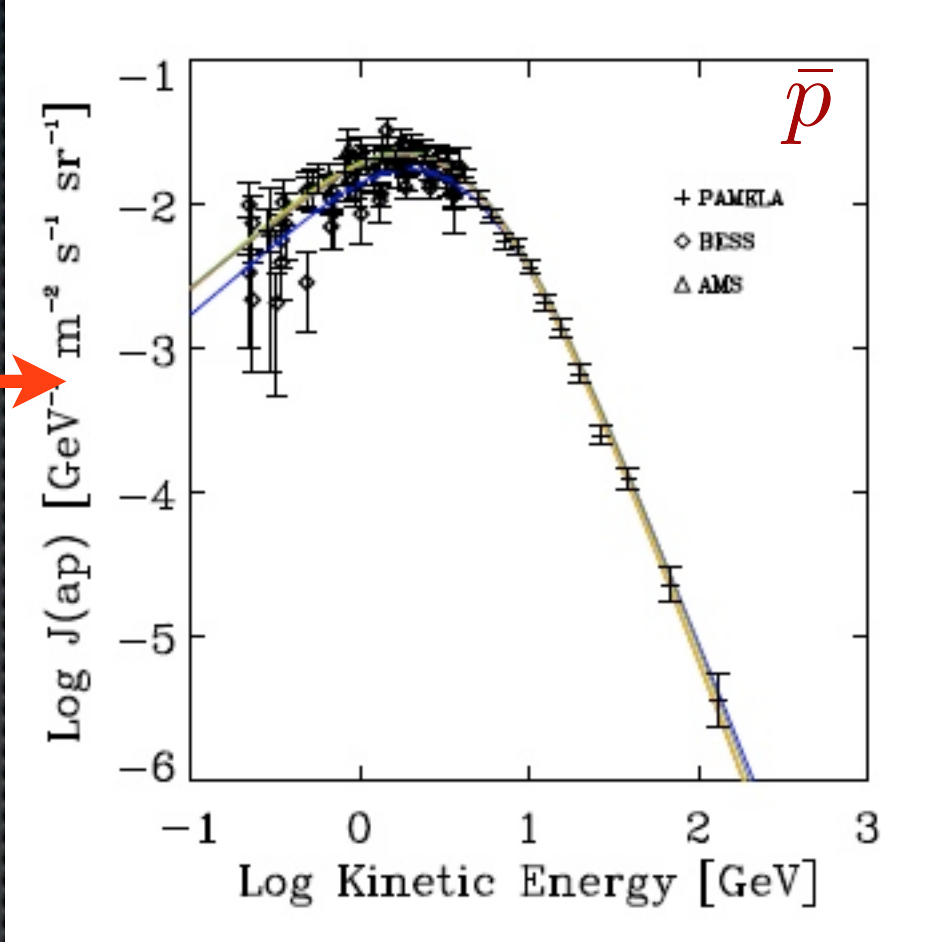
antiprotons can be used to constrain “leptophilic” models

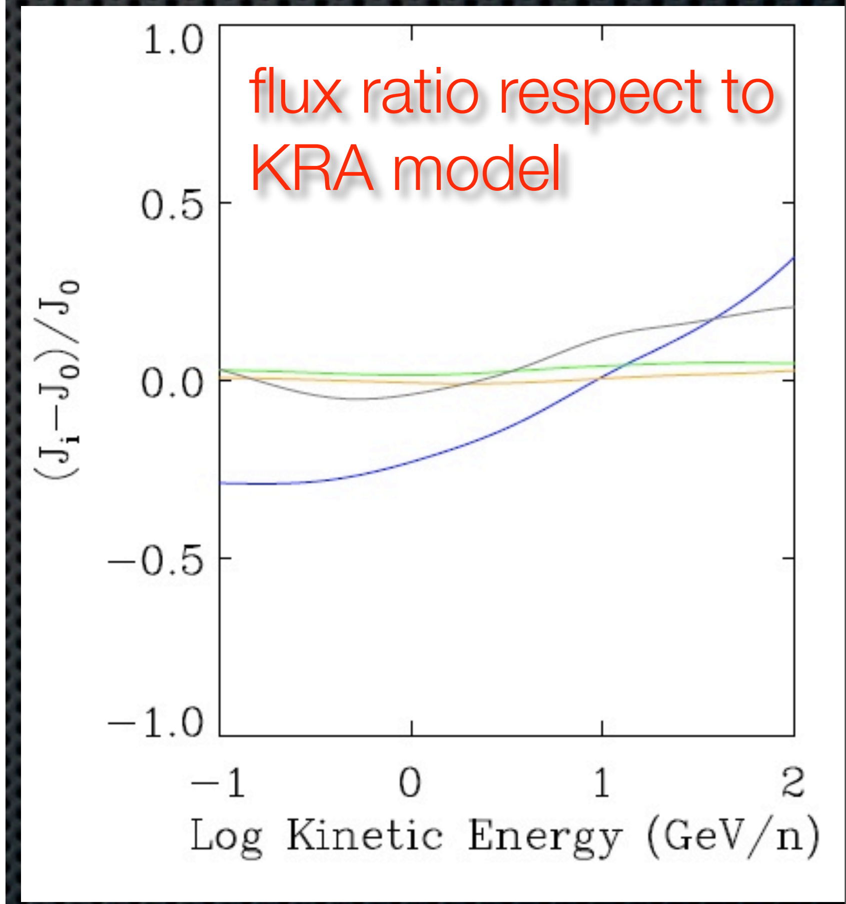
The $\bar{p}$ background and its uncertainty

This is mainly due to the uncertainty on the CR propagation parameters

Evoli, Cholis, DG, Maccione, Ullio 2011







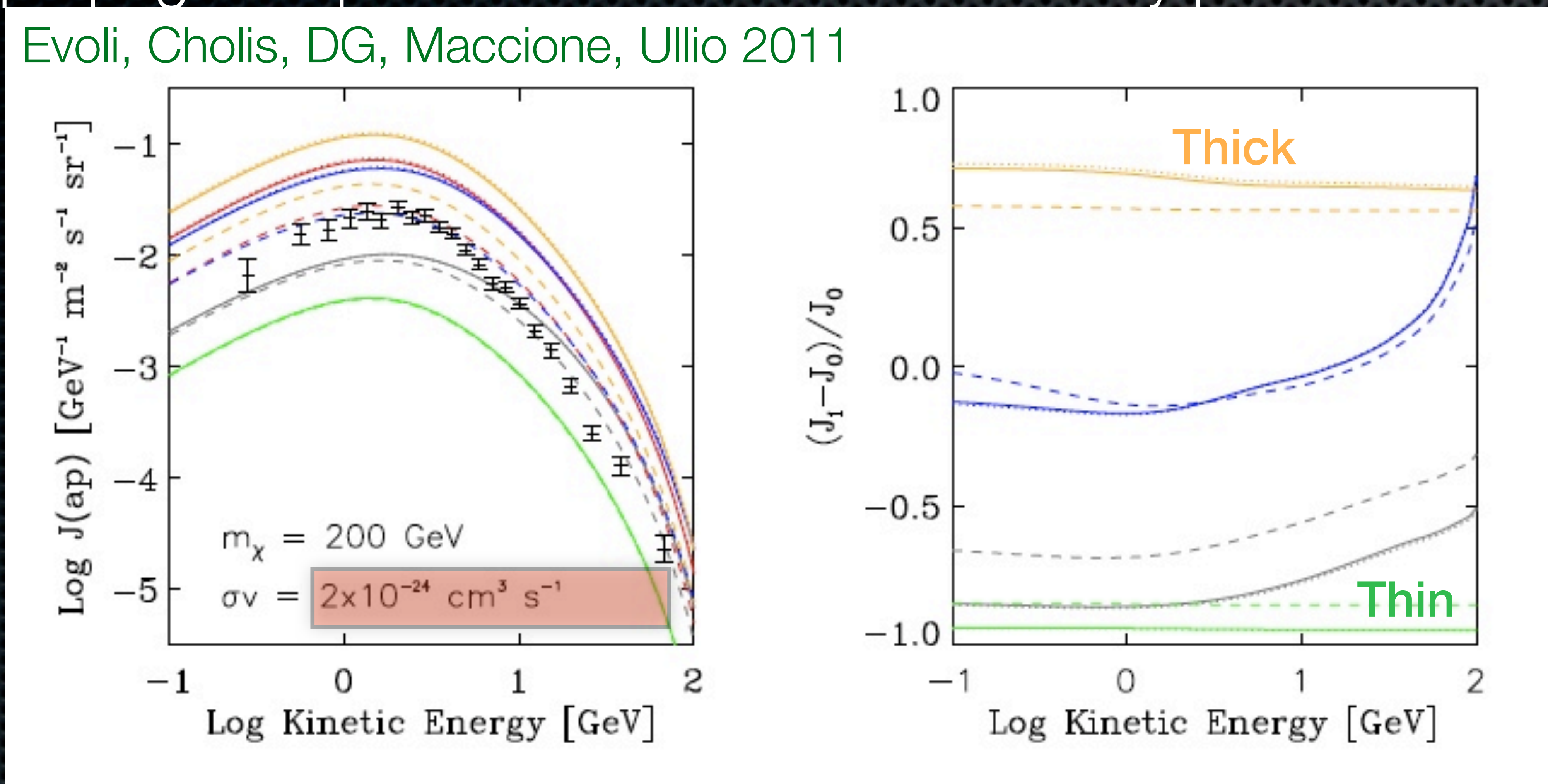
Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_c/dz(km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Fig.s
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	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 max uncertainty is ~ 30%

This can be considerably reduced by AMS-02 (see below)

Uncertainties on the $\bar{p}$ flux from DM

For a given DM model, the main uncertainties are those on the propagation parameters and the DM density profile



Einasto DM profile

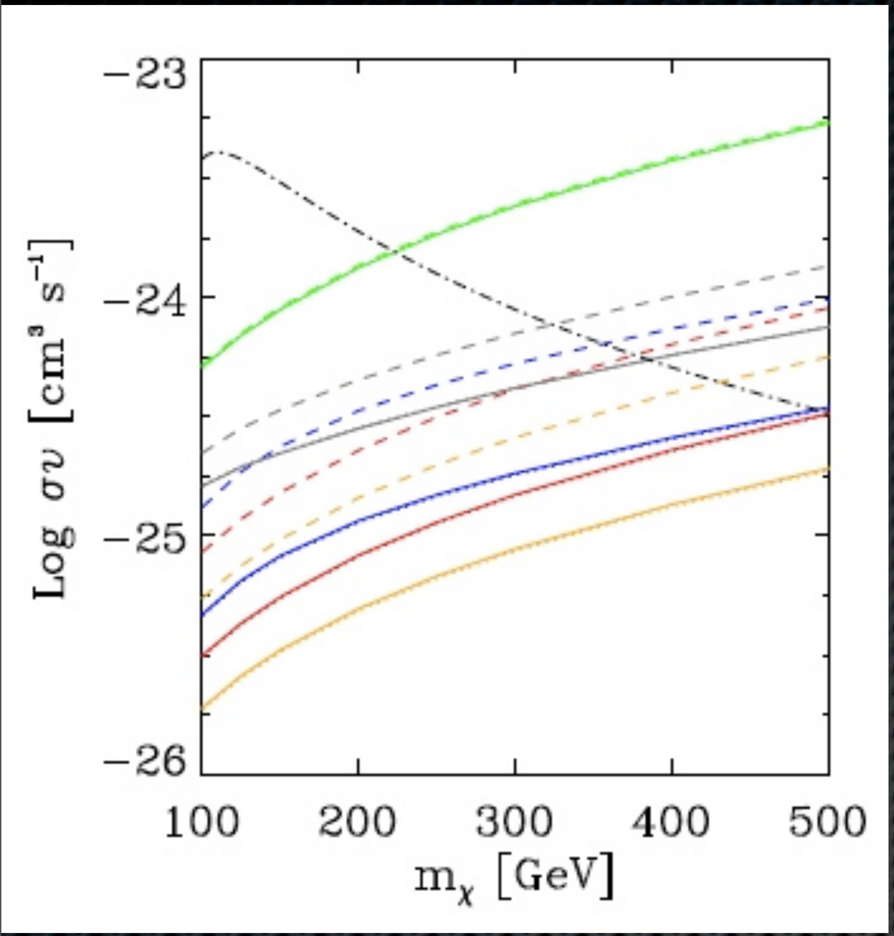
NFW or Burkert

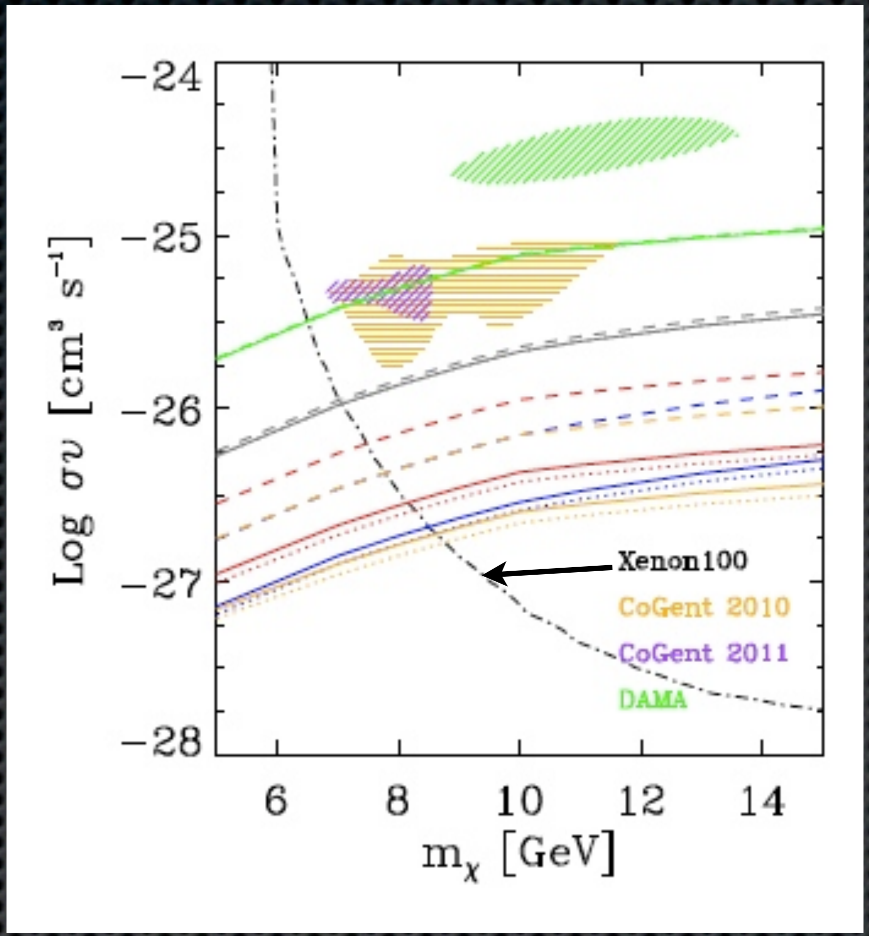
Very large scatter mainly due to the uncertainty on the propagation setup !

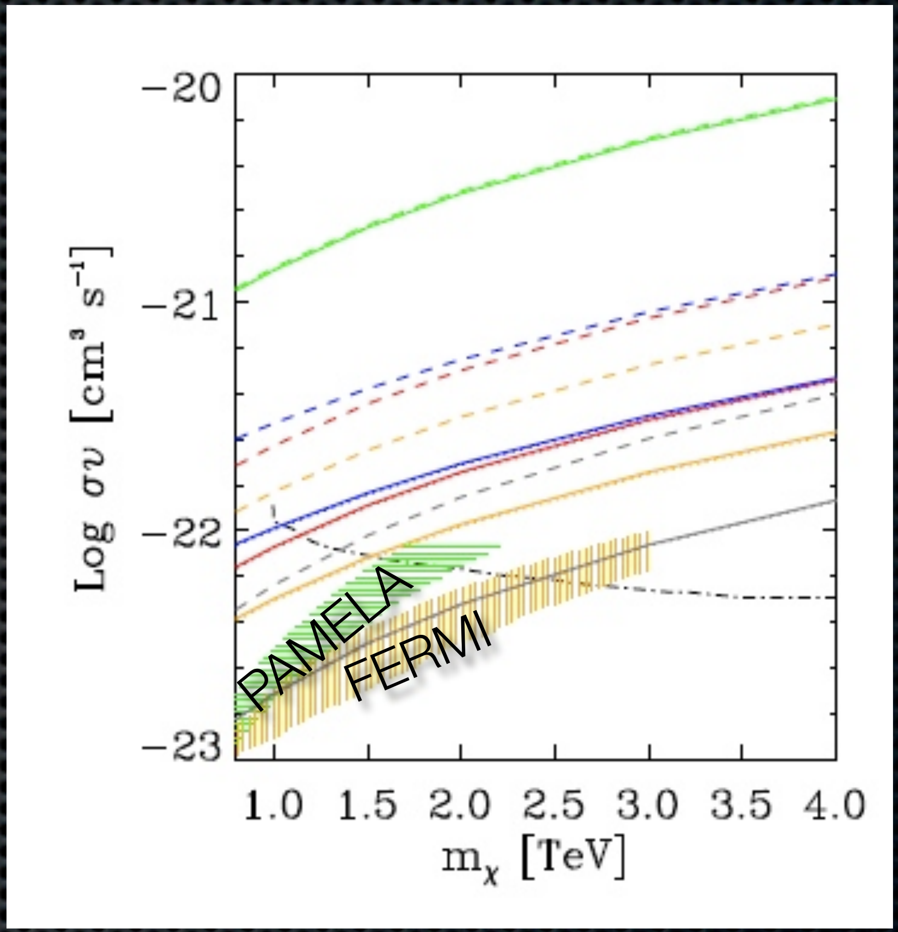
<u>The dominant uncertainty source is that on the diffusive halo height</u>

Constraints on DM models

Evoli, Cholis, DG, Maccione, Ullio 2011







W-ino model

(motivated by SUSY and PAMELA e^+ anomaly)

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

Models with $M_\chi < 500$ GeV are excluded for the most favored setups

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

$$\chi\chi \rightarrow \bar{b}b$$

DAMA and CoGent preferred regions are disfavored for most setups

Heavy "leptophilic" WIMPs

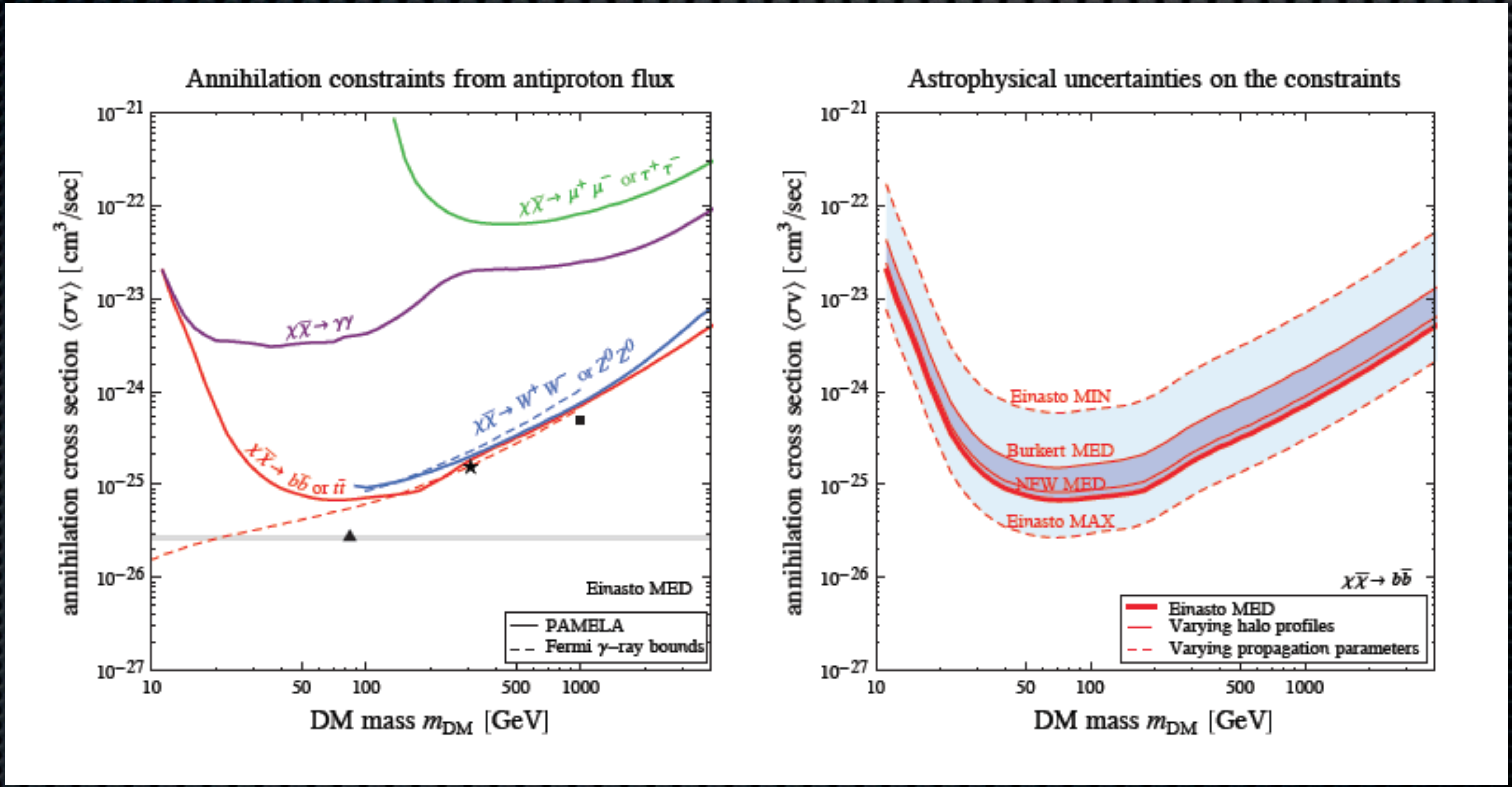
(motivated by PAMELA, Fermi, HESS)

$$\chi\chi \rightarrow \mu^+\mu^-$$

A consistent interpretation of PAMELA and Fermi is still allowed

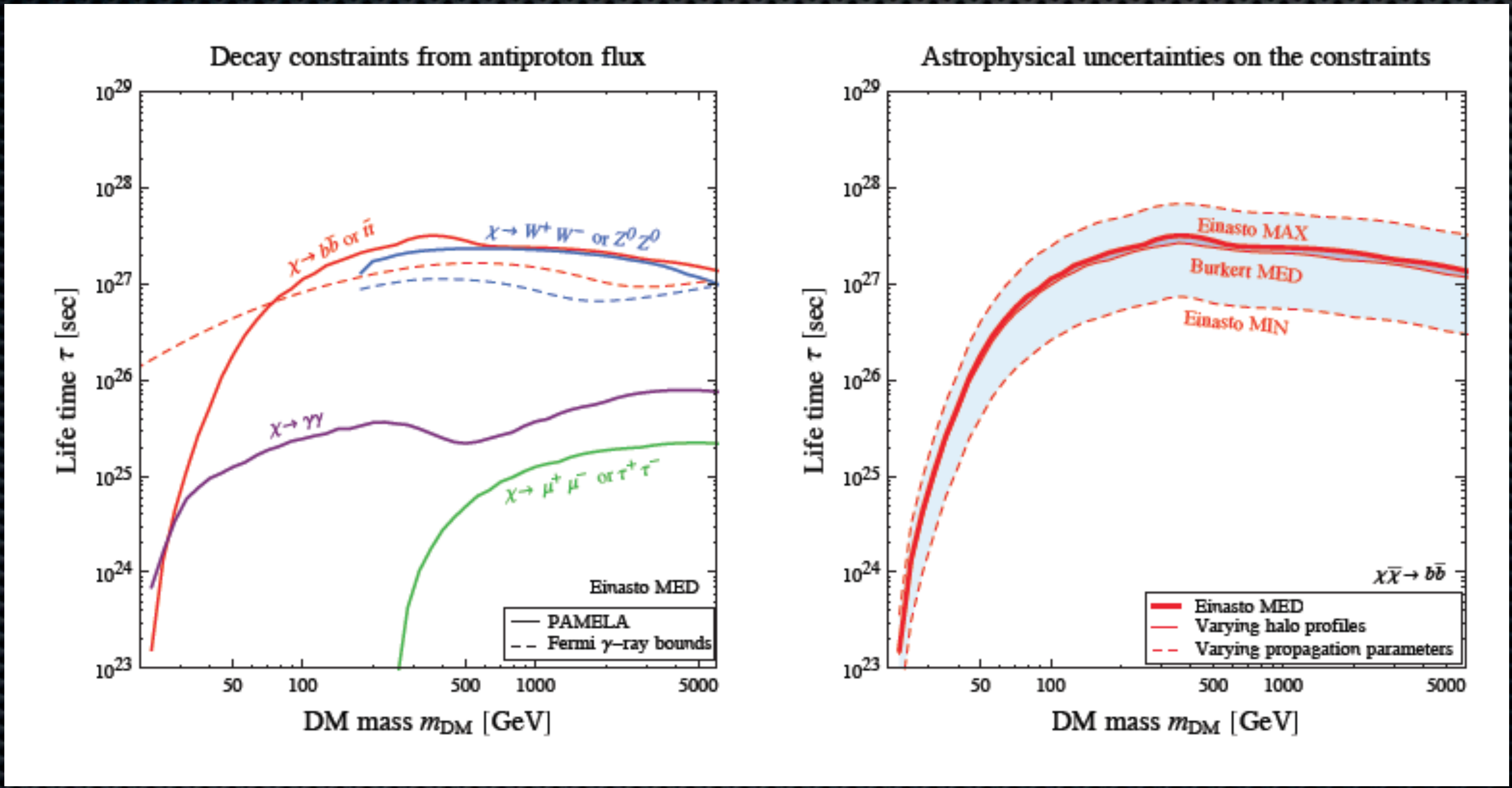
Annihilating DM current constraints from $\bar{p}$

Cirelli & Giesen 2013

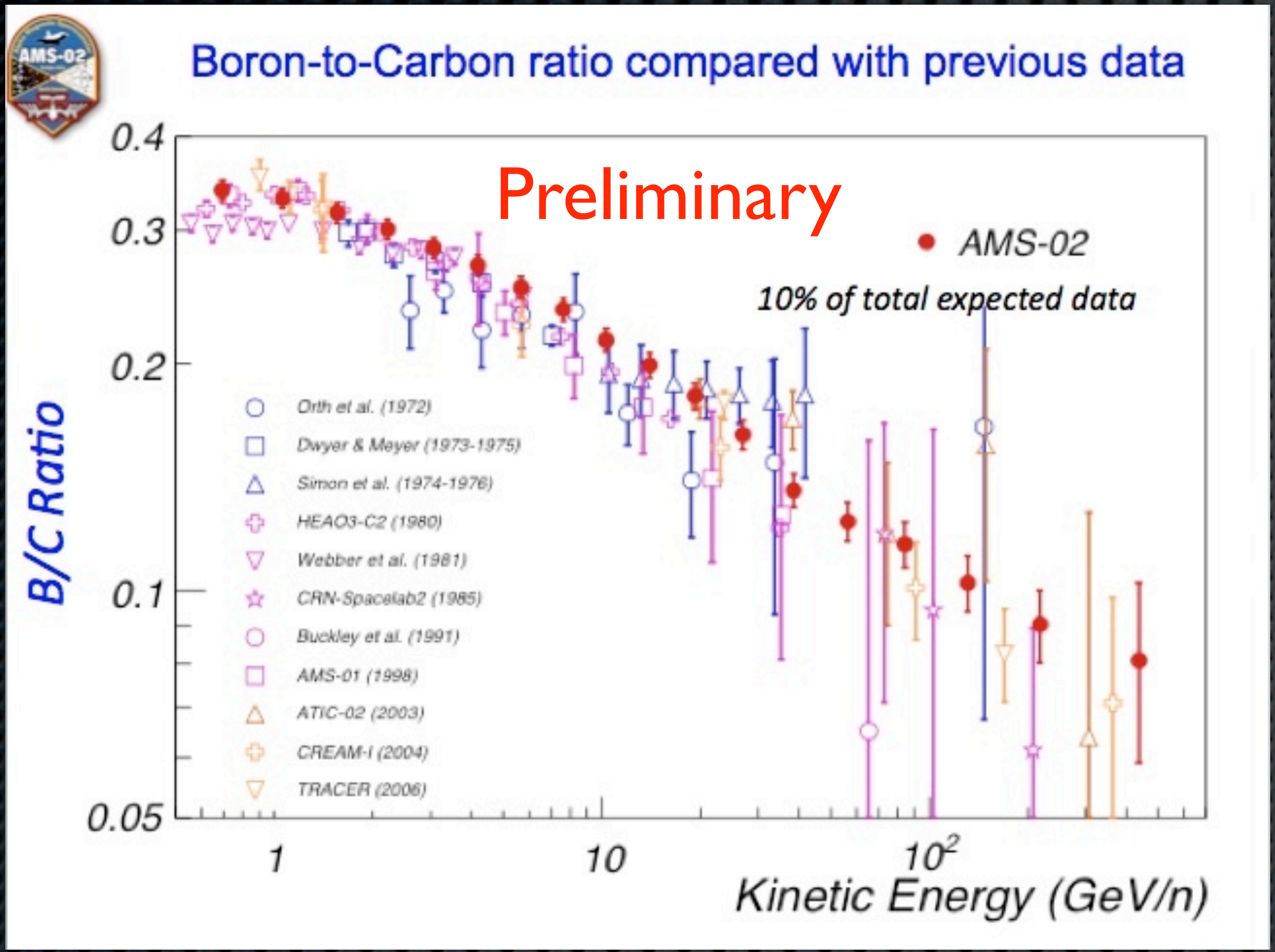


Decaying DM current constraints from $\bar{p}$

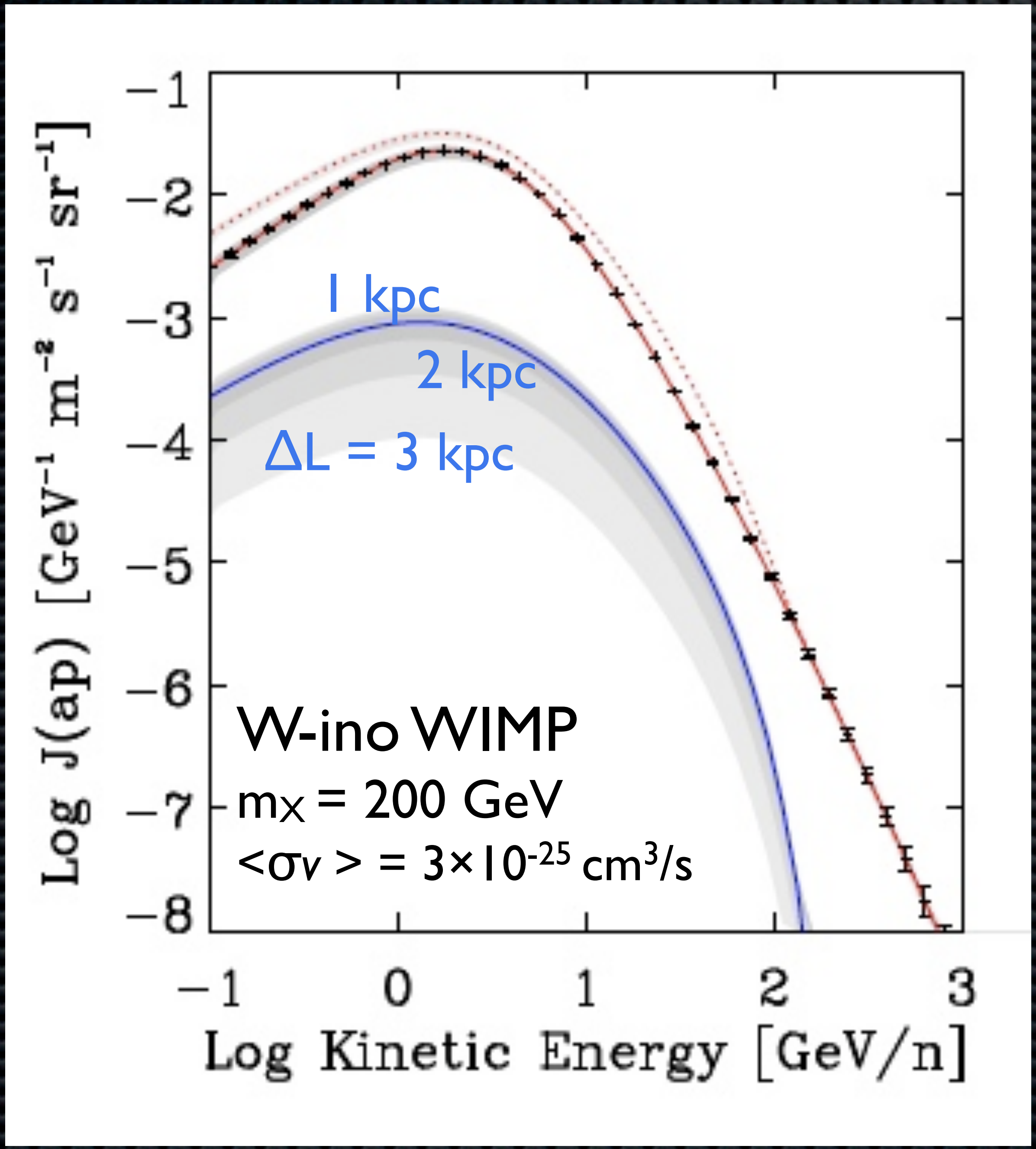
Cirelli & Giesen 2013



The role of AMS-02
reducing the uncertainty on the background

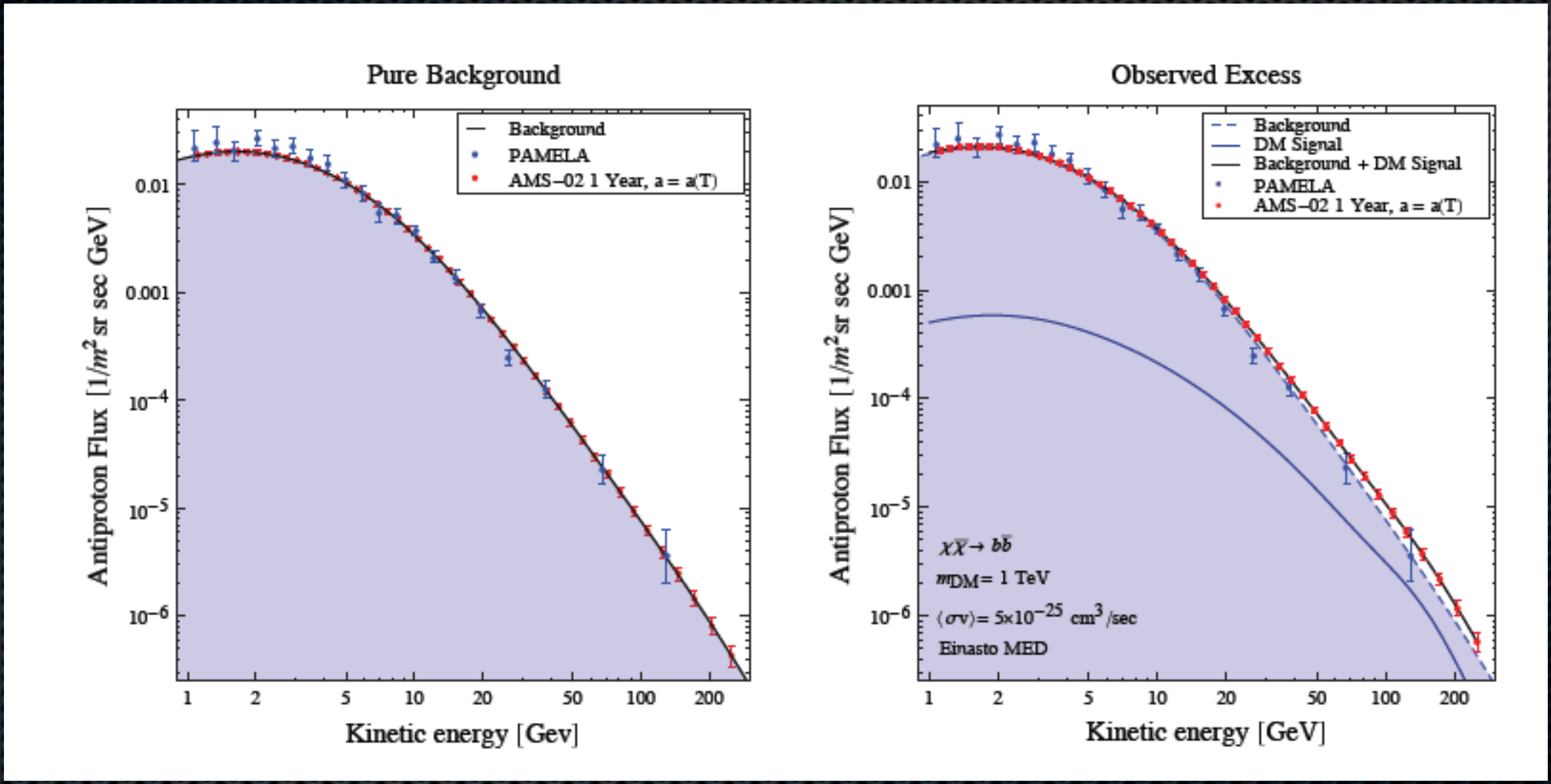


The role of AMS-02
reducing the uncertainty on the background and improving the sensitivity on the $\bar{p}$ flux



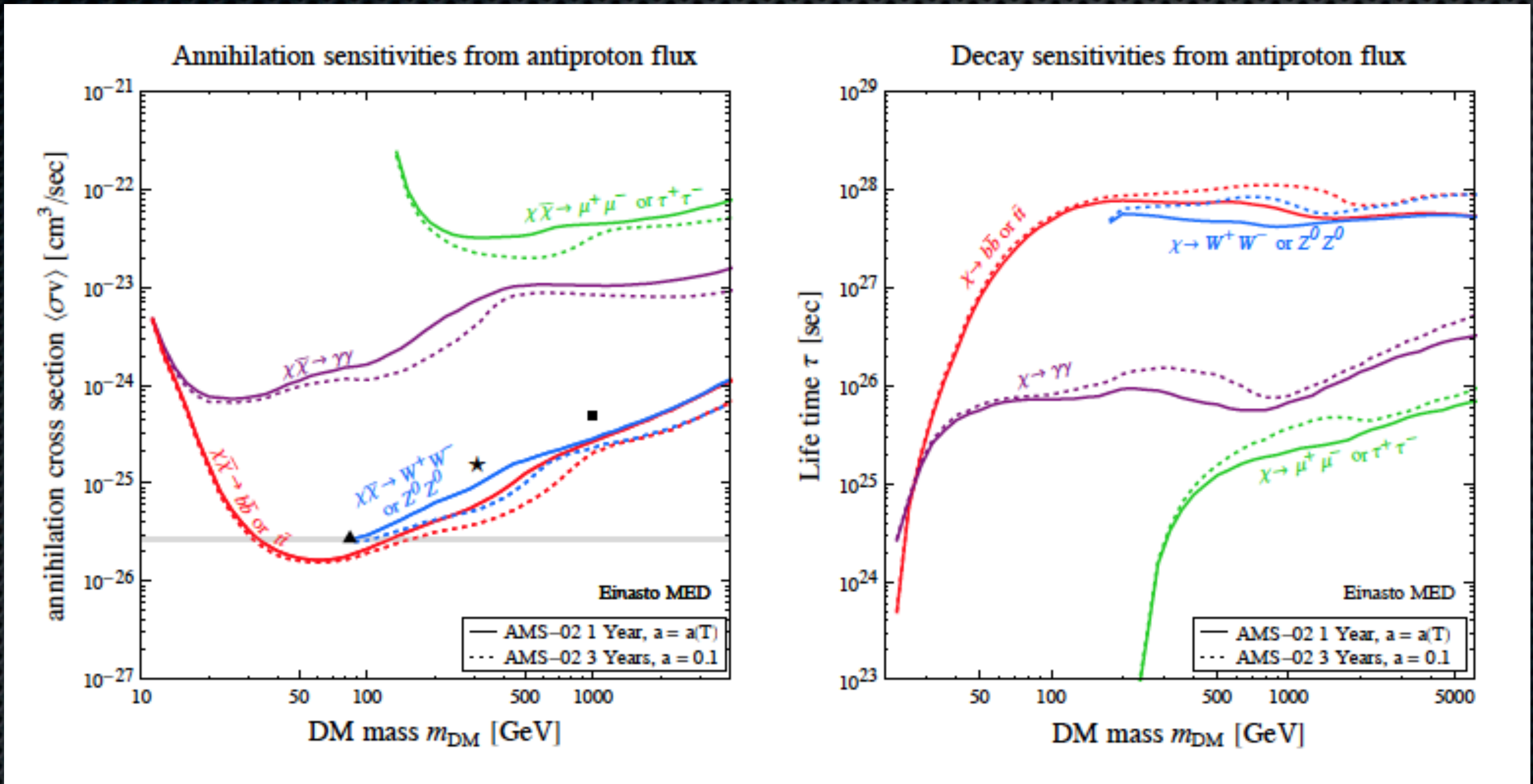
How DM annihilation may look like in AMS-02 in the $\bar{p}$ channel

Cirelli & Giesen 2013



AMS-02 expected sensitivities

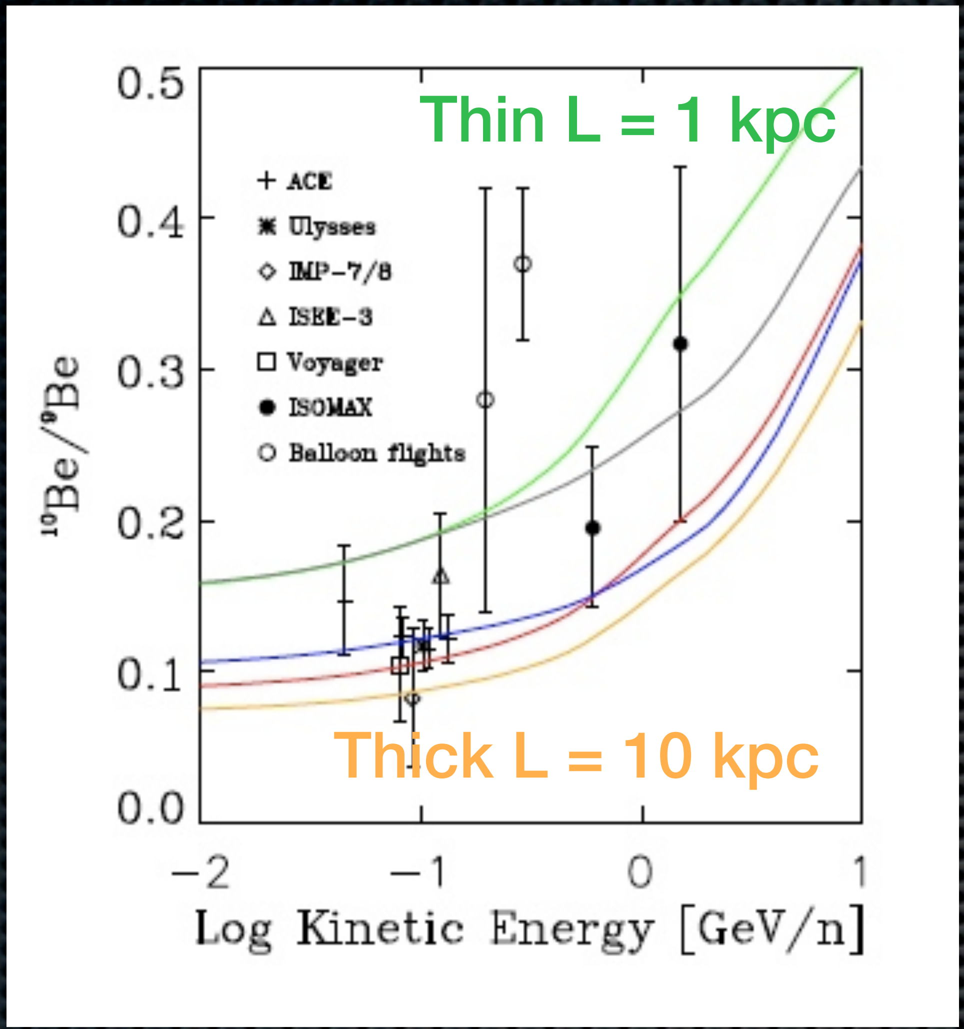
according to Cirelli & Giesen 2013

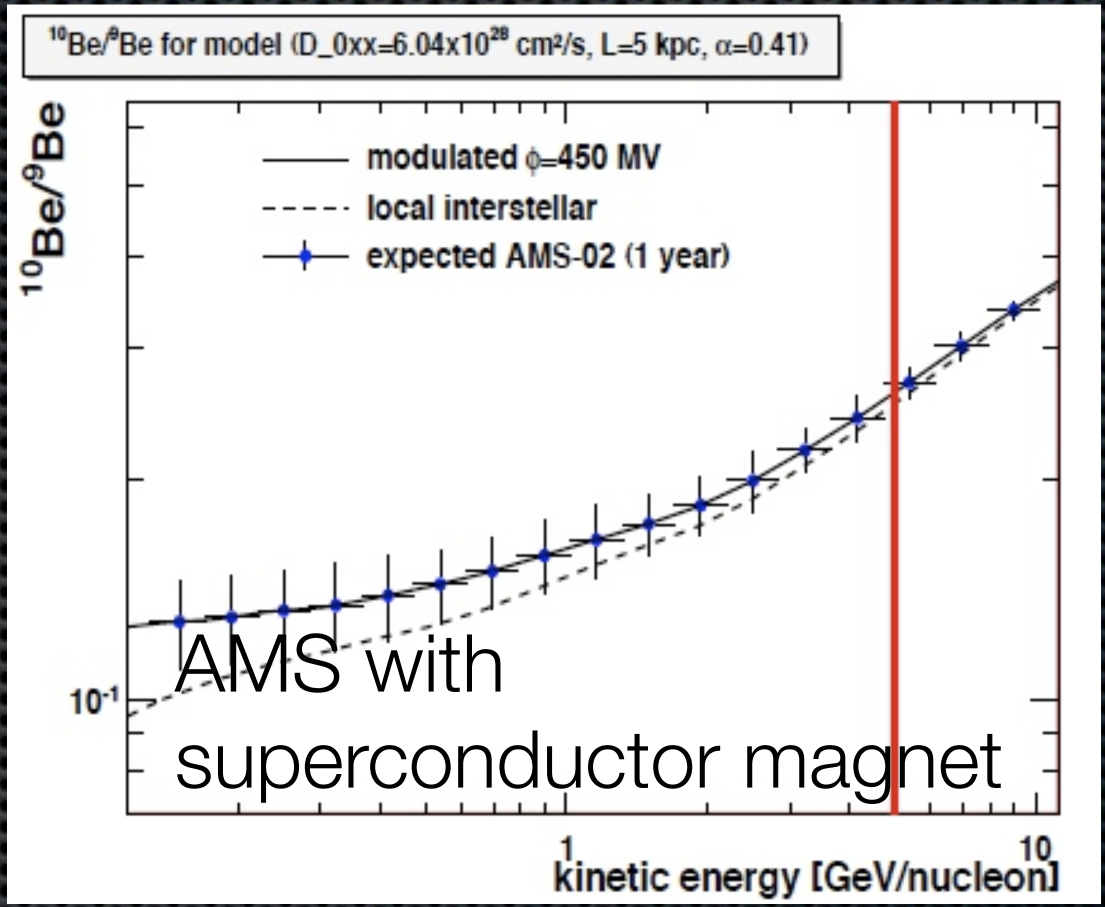


this is assuming a given propagation model and <u>halo profile</u>

<u>This is a promising approach if the uncertainty on this quantity can be reduced</u>

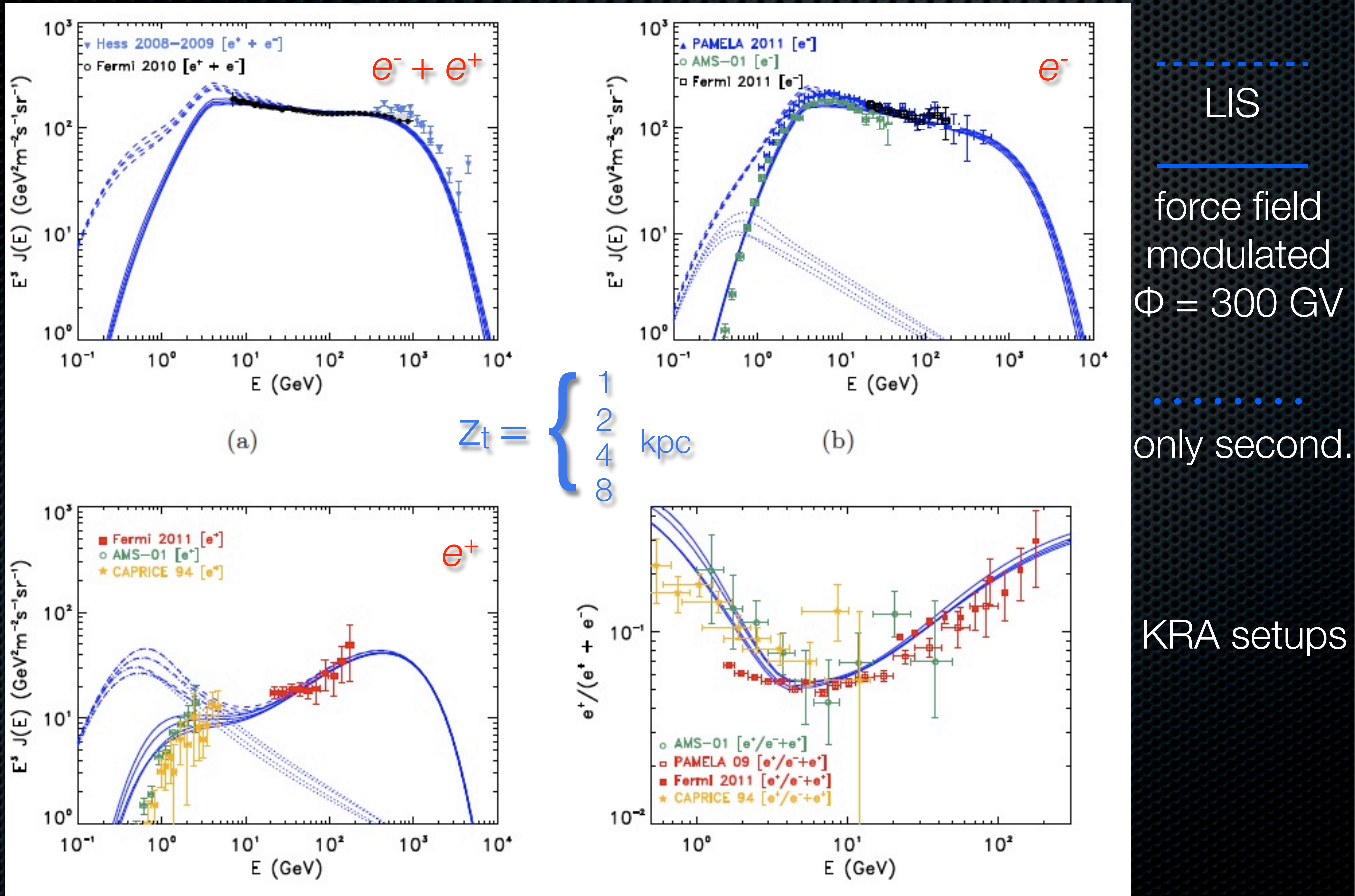
The halo height from unstable nuclei ?





It is still unknown (to me) the current AMS-02 sensitivity to this quantity

The halo height from the e⁺ spectrum ?

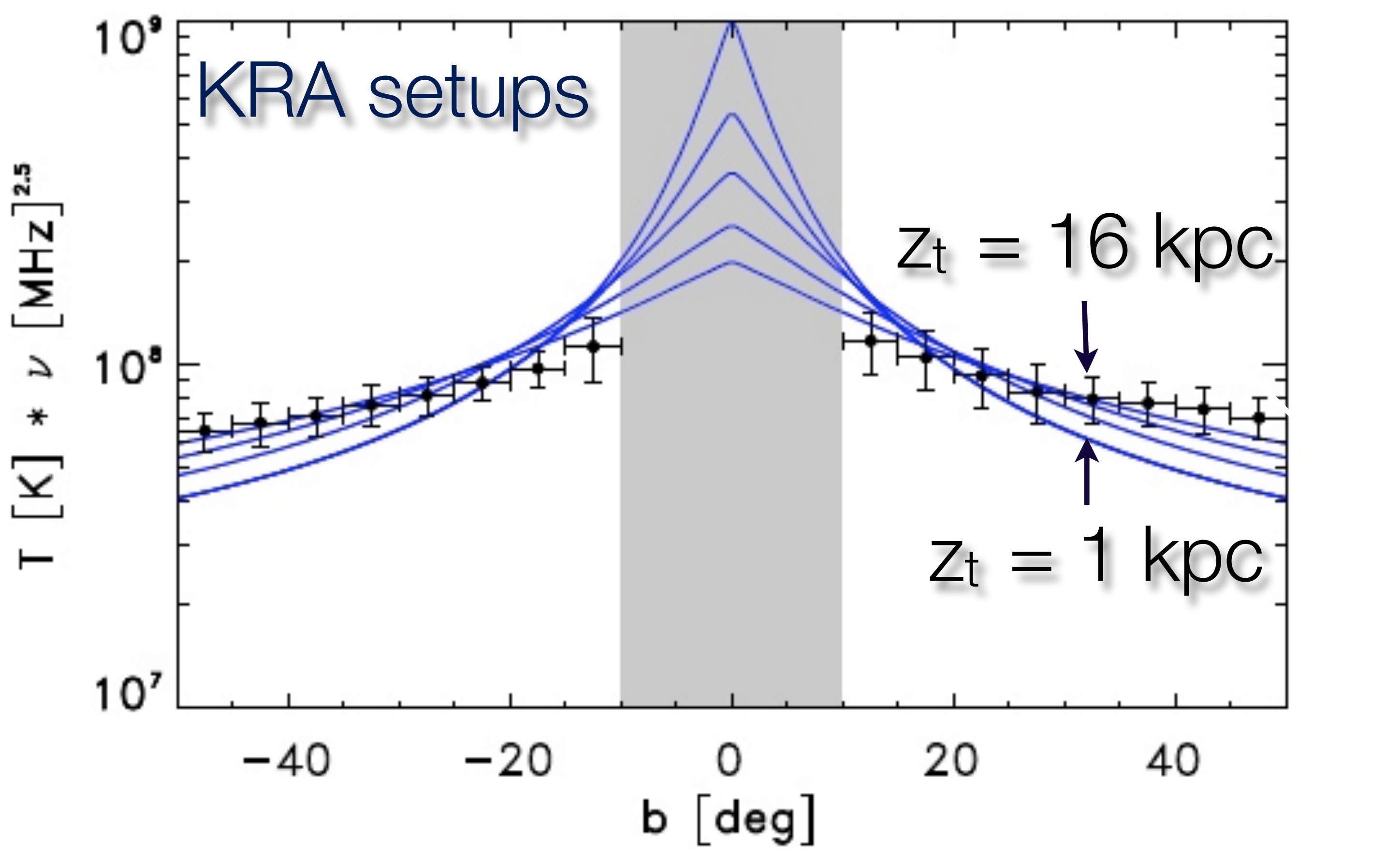


Di Bernardo, Evoli, Gaggero, DG, Maccione, 2012

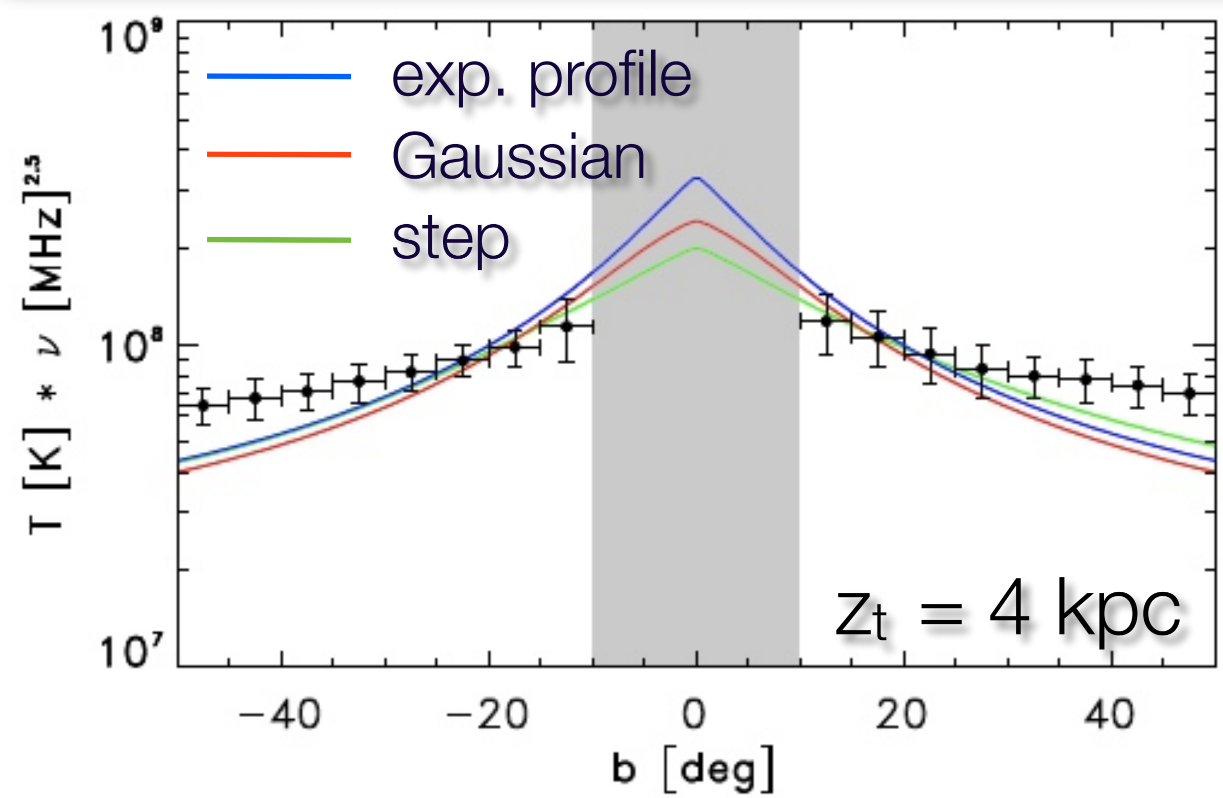
The halo height from the synchrotron latitude profile

Bringmann & Donato 2011

Di Bernardo, Evoli, Gaggero, DG, Maccione, 2012



$40^o < l < 100^o$



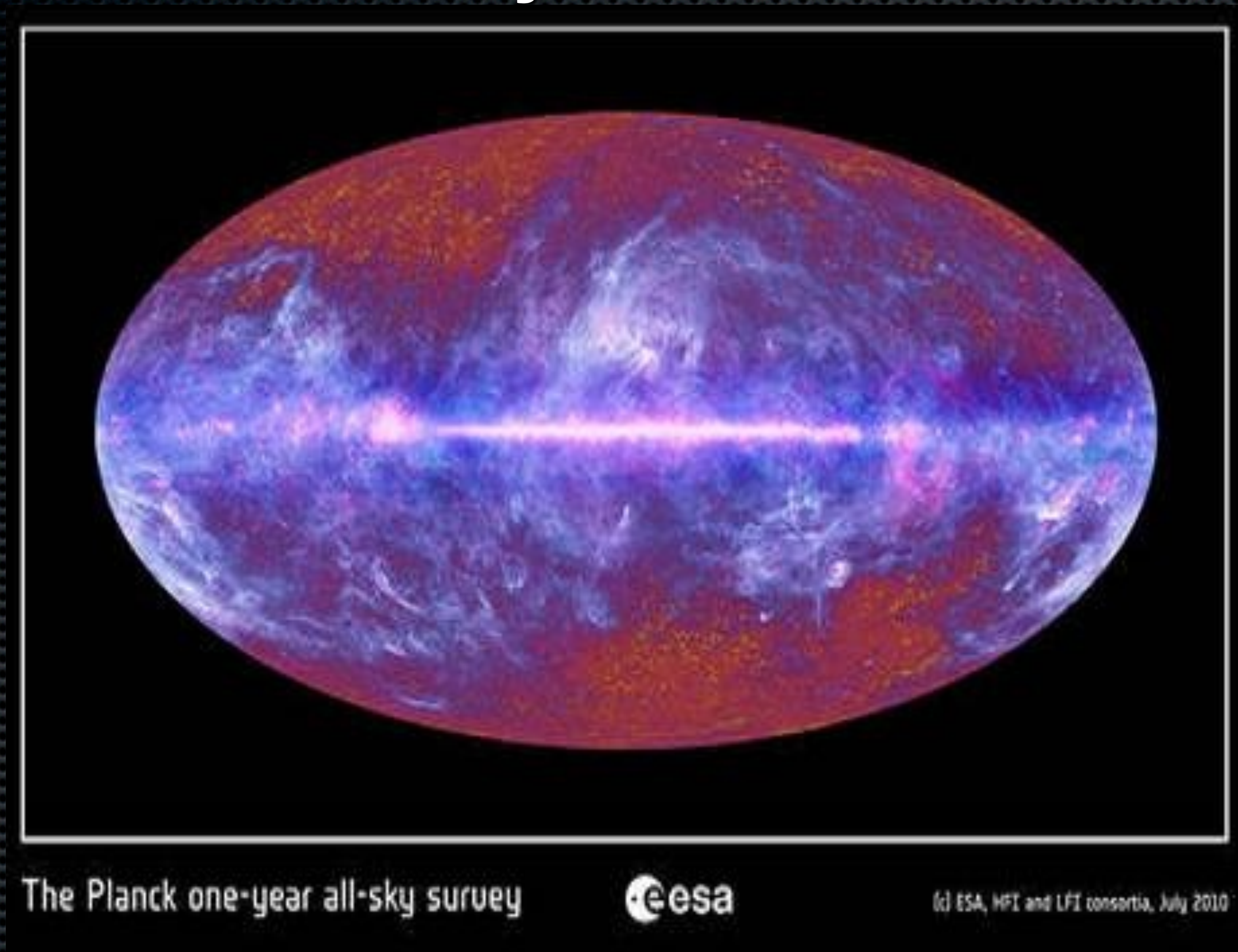
z_t (kpc)	χ^2
1	2.7
2	2.5
4	1.6
8	0.9
16	0.4

point and local radio sources are masked out

z_t < 2 kpc excluded at 3 σ

a thick halo is favoured

The Planck sky



A full Montecarlo analysis using

- DRAGON (or a similar 3D code)
- multichanell AMS-02 (and in future CALET) nuclear and lepton data
- recent improvements in solar modulation modeling
- constraints from synchrotron and diffuse gamma-ray data

should allow to sensibly reduce the astrophysical uncertainties making antiproton a valuable DM indirect search channel complementary to gamma-ray observations.

Conclusions

- The CR positron anomaly is confirmed and it needs a primary (almost symmetric) e^+ and e^- primary component with a hard spectrum
- Electron propagation has be treated taking into account the spatial distribution of sources. This requires 3D propagation codes
- The absence of bumpiness and anisotropy are not compelling evidences to exclude the astrophysical solutions
- Extra-component sources located in the Galactic arms can very well describe the available data. Pulsars are still the most natural candidates (but the details of the acceleration mechanism have to be understood).
- SNR secondary acceleration is disfavored by antiproton and nuclear data. This should be further constrained (or confirmed) by AMS-02

Conclusions

- Lepton data alone may hardly allow to decide between the astrophysical and dark matter interpretations
- Dark matter is still a viable interpretation which may be tested using gamma-ray (especially from dwarf galaxies) and antiprotons
- The latter channel requires a multichannel analysis and dedicated numerical tools

Galper et al. 2012

	Space-based experiments			Ground-based experiments		
	Fermi	**AMS-2**	**GAMMA-400**	**H.E.S.S.-II**	**MAGIC**	**CTA**
Energy range, GeV	0.02-300	10-1000	**0.1-3000**	> 30	> 50	> 20
Field-of-view, sr	2.4	0.4	**~1.2**	0.01	0.01	0.1
Effective area, m^2	0.8	0.2	**~0.4**	10^5	10^5	10^6
Angular resolution (E_γ > 100 GeV)	0.2º	1.0º	**~0.01º**	0.07º	0.05º	0.06º
Energy resolution (E_γ > 100 GeV)	10%	2%	**~1%**	15%	15%	10%