Antimatter in the Universe

and the PAMELA/FERMI/AMS… anomaly

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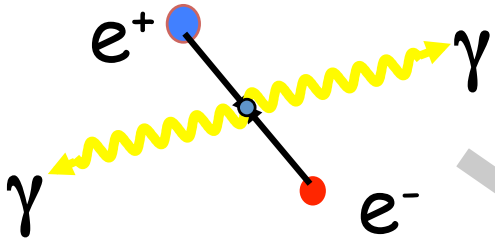
There is direct evidence for

1) Anti-protons and positrons ~0.1-100 GeV in Cosmic Rays

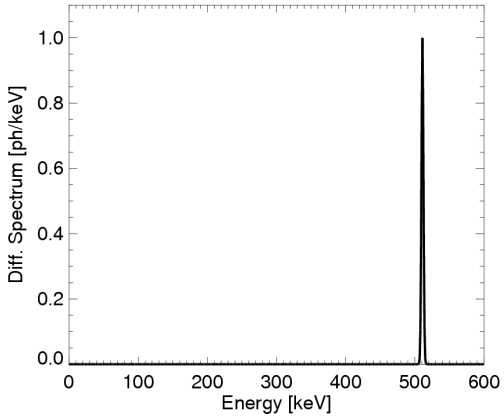
2) The annihilation of 10^{43} low energy (<~ keV) positrons per second in the Inter-Stellar Medium

Electron Positron Annihilation

- **Direct annihilation**



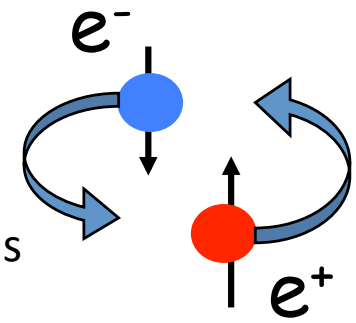
Annihilation line
E = 511 keV

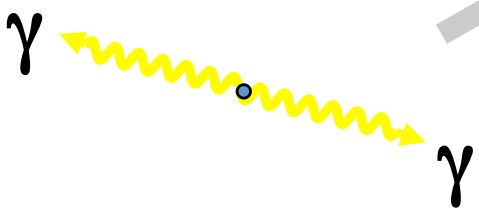


- **Annihilation via positronium (Ps) formation**

para-positronium
1/4

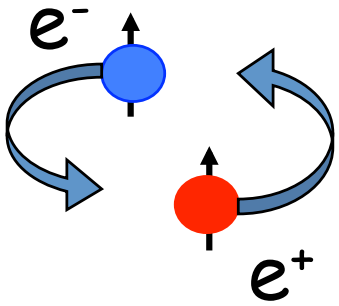
$\tau = 1.2\times10^{-10}$ s

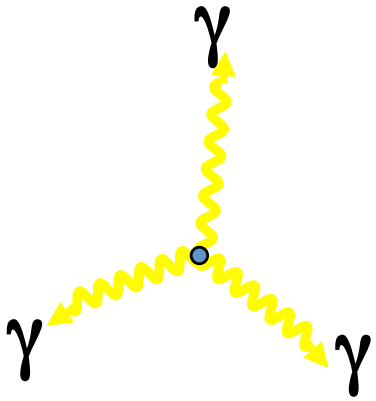




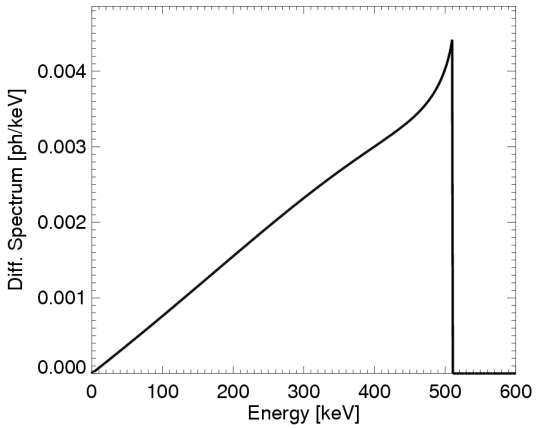
ortho-positronium
3/4

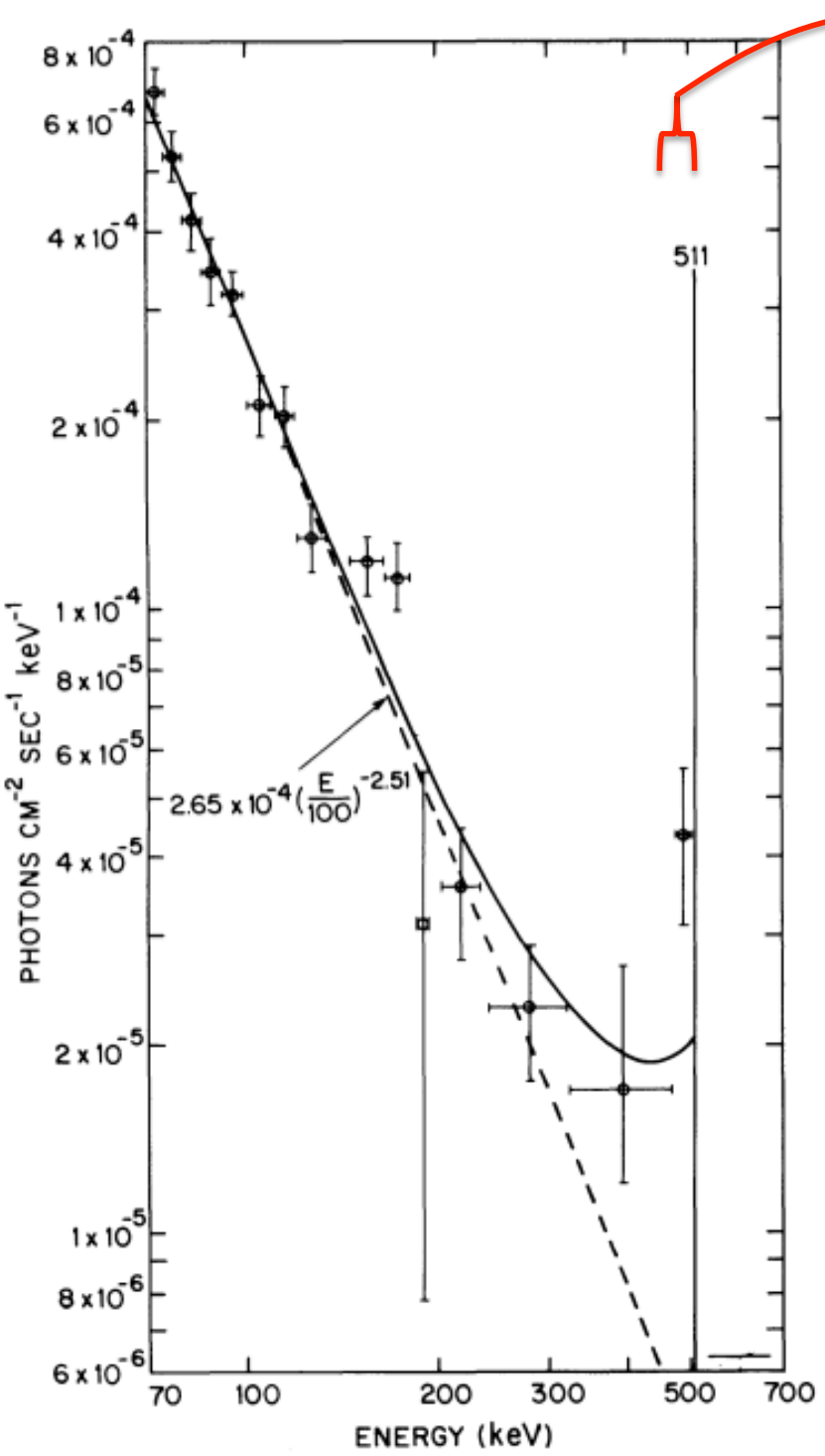
$\tau = 1.4\times10^{-7}$ s

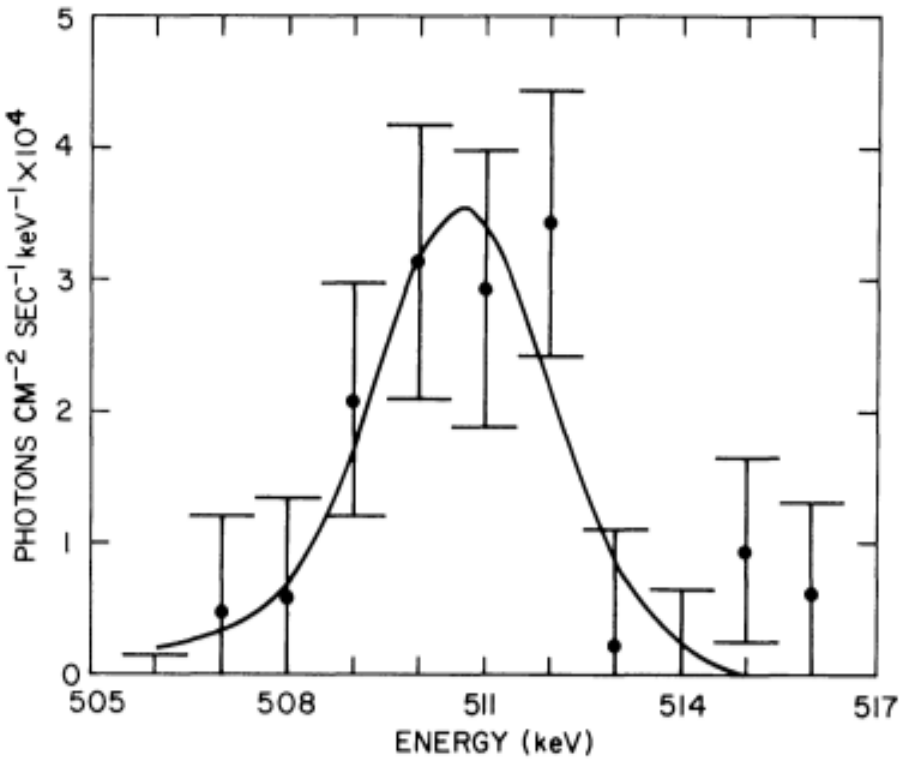




Positronium continuum
E < 511 keV







Line flux $(12.2 \pm 2.2) \times 10^{-4}$ cm^{-2} s^{-1}
in 15° FWHM field of view
Centroid (510.7 ± 0.5) keV

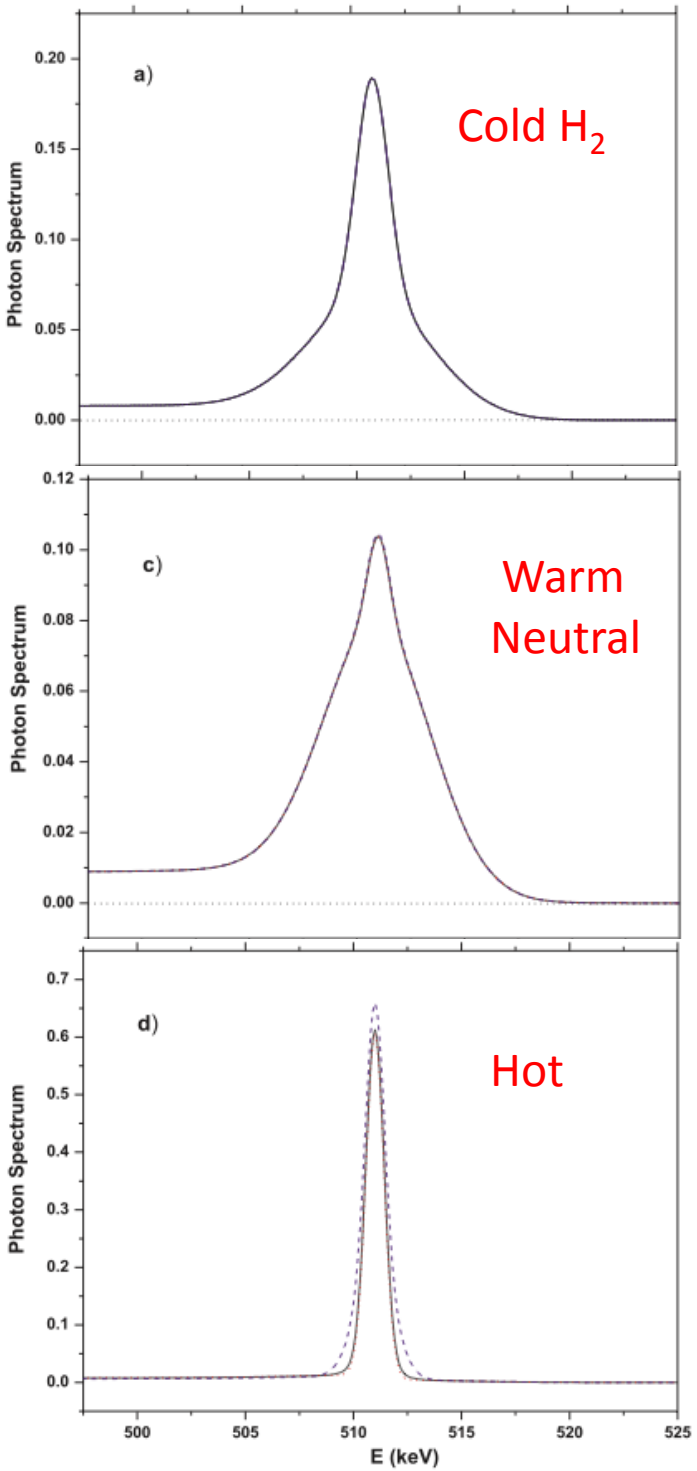
Leventhal, MacCallum & Stang
Ap J 225 L11 (1978)

Integral has confirmed earlier conclusions that the positronium fraction is close to unity.

$f_p = 94 \pm 6\%$ *(Sazonov et al, 2005)*

$f_p = 97 \pm 2\%$ *(Jean et al., 2006)*

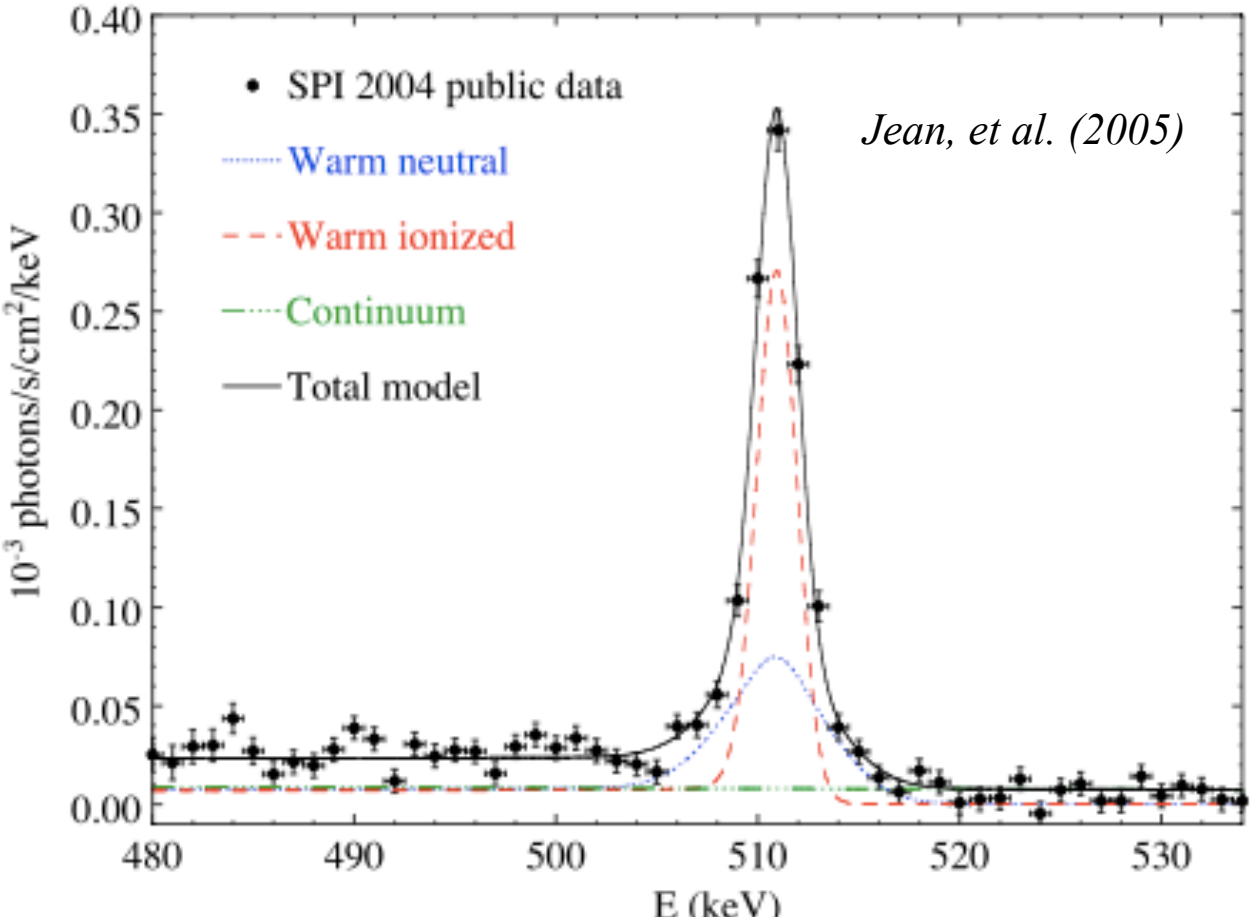
$f_p = 100 \pm 2\%$ *(Churazov et al., 2011)*



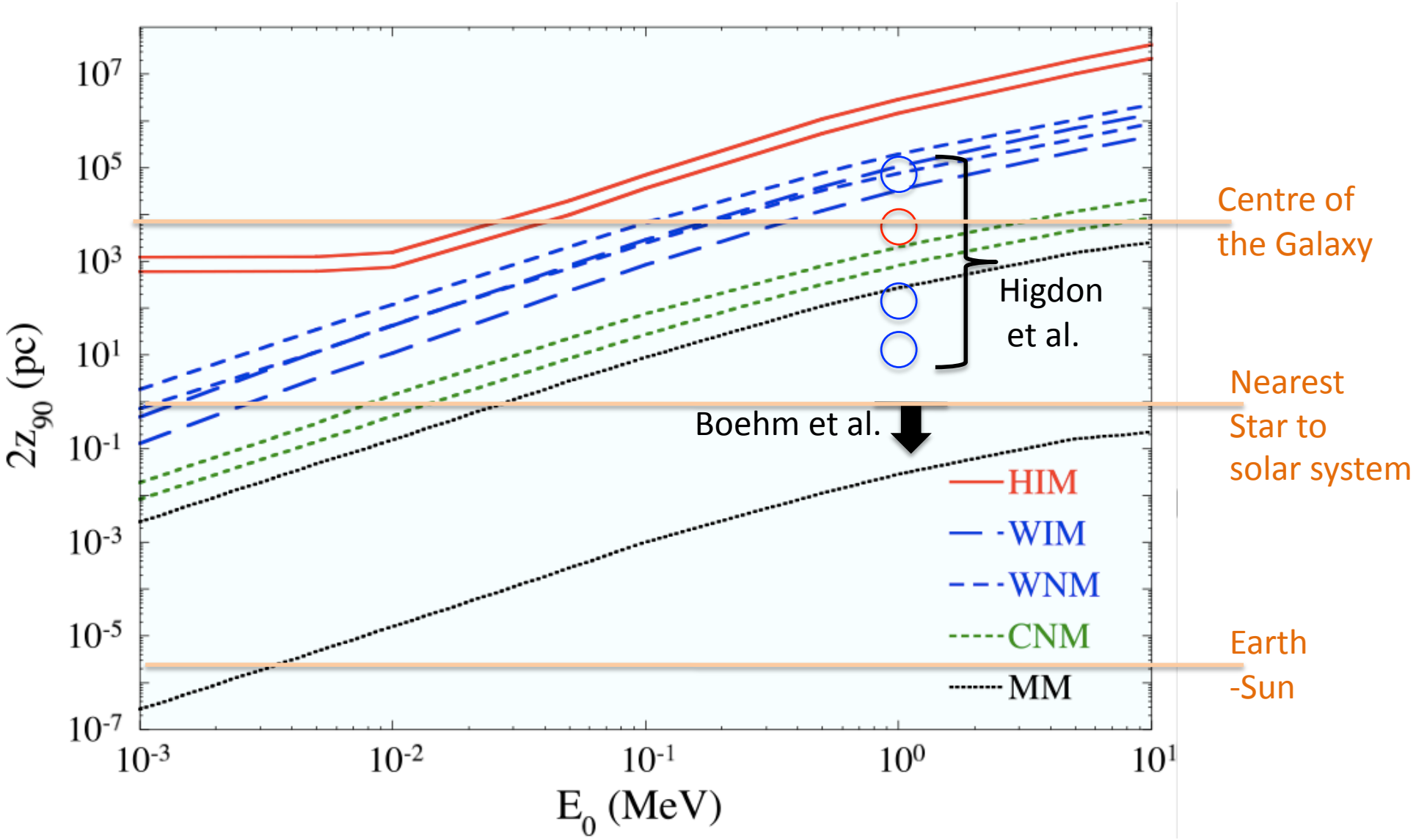
Line shapes expected for annihilation in different media

Gessoum, Jean, Gillard (2005)

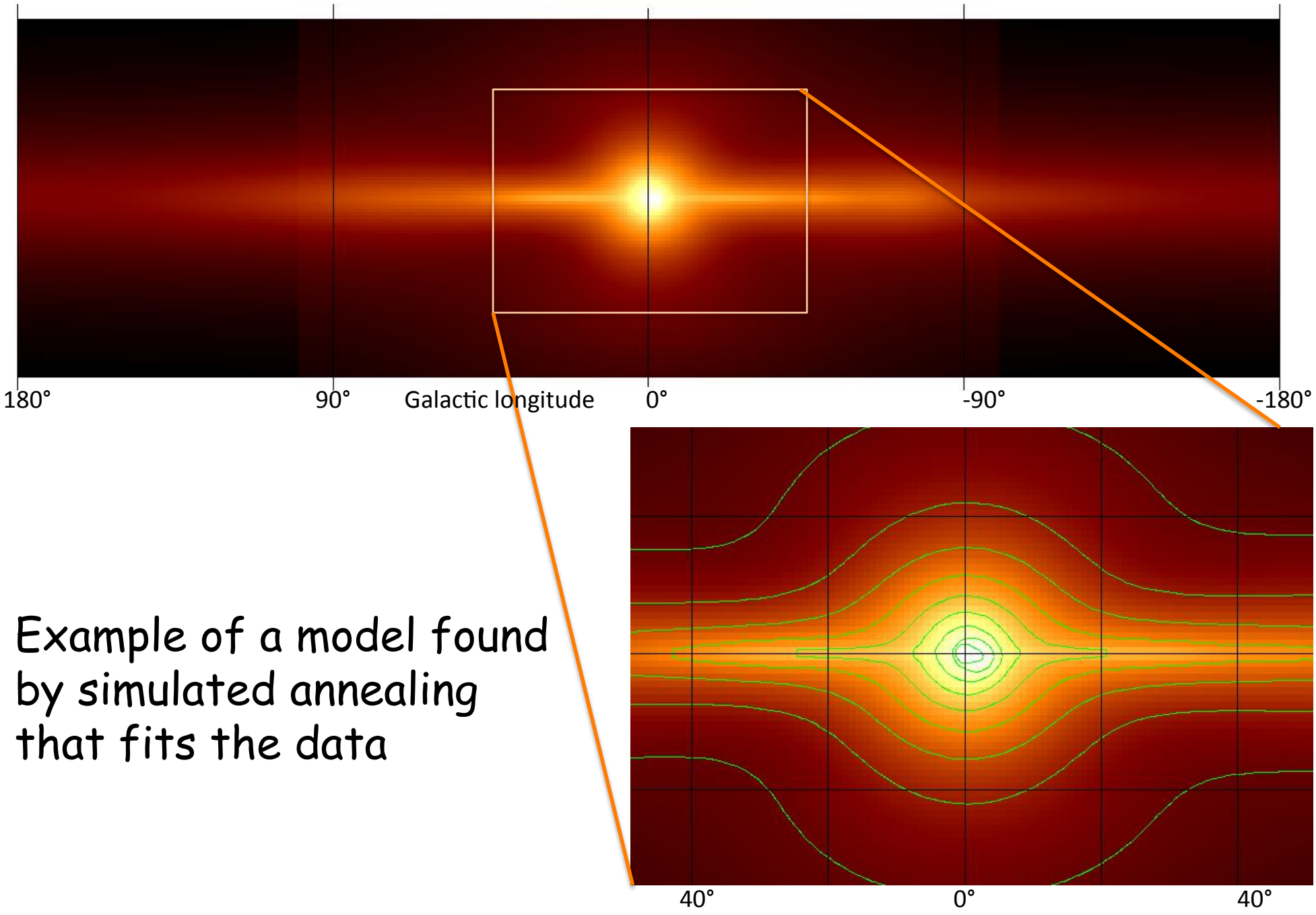
The detailed 511 keV line shape observed by INTEGRAL-SPI implies annihilation is in a mixture of warm neutral and warm ionized environments



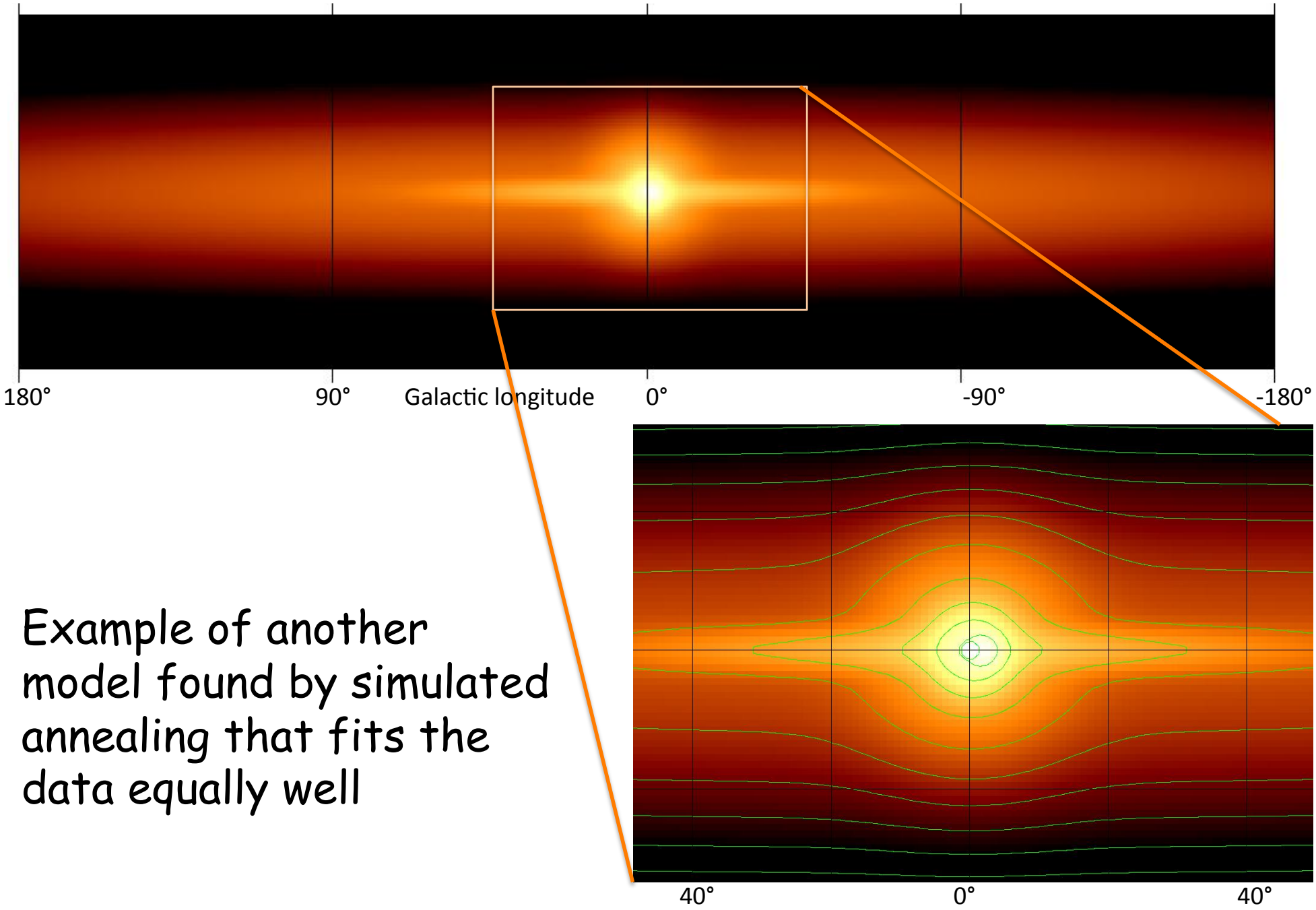
Phase	T (K)	$n_{\rm H}$ (cm^{-3})	$x_{\rm ion}$
Molecular (MM)	10–20	10^2–10^6	$\lesssim 10^{-4}$
Cold neutral (CNM)	20–100	20–100	4×10^{-4}–10^{-3}
Warm neutral (WNM)	10^3–10^4	0.2–2	0.007–0.05
Warm ionized (WIM)	~8000	0.1–0.3	0.6–0.9
Hot ionized (HIM)	~10^6	0.003–0.01	1



Distance traveled before annihilation as a function of initial positron energy according to the analysis of *Jean et al (2009)* . Upper and lower extents of a band are shown for each medium. Data are for travel along field lines. The corresponding plot for transverse motion is similar with somewhat lower values.



Example of a model found by simulated annealing that fits the data



Example of another model found by simulated annealing that fits the data equally well

The problem is not that we don't know how the positrons **could be** produced …

… it is that there are too many possible explanations !

Hypernovae/GRB explosions in the galaxy *(Lingenfelter &Heuter, 1984; Bertone et al., 2006)*

Galactic Supernovae *(Ramaty & Lingenfelter, 1979)*

Galactic Supernovae + escape from the disk *(Higden et al., 2007)*

Novae *(Clayton & Hoyle, 1974; Jose, Coc & Hernanz, 2003)*

LMXBs *(Prantzos, 2004)*

HMXBs / Micro-Quasars *(Guessoum et al, 2006)*

Wolf-Rayet stars *(Dearbourne & Blake, 1985)*

Red Giants *(Norgaard, 1980)*

Pulsars *(Sturrock, 1971)*

Millisecond pulsars *(Wang, 2005; 2006)*

Cosmic Ray interactions with matter *(Ramaty, 1970)*

Light (MeV) dark matter *(Boehm et al., 2004)*

'Heavy' 500 GeV dark matter + de-excitation from an excited state *(Finkbeiner & Weiner, 2007).*

Sgr A* *(Titarchuk & Chardonnet, 2006; Totani, 2007; Alexis et al, 2013)*

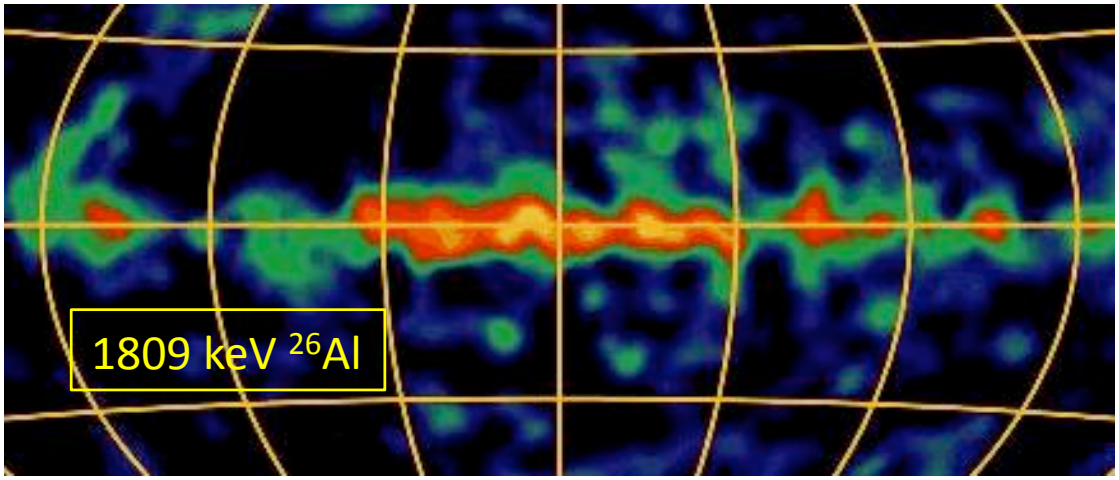
Color superconducting dark matter droplets (strangelets) *(Oaknin & Zhitnitsky, 2005)*

Intergalactic space *(Vecchio et al., 2013)*

Small H atoms *(Va'vra, 2013)*

Dichromic dark matter *(Bai et al., 2013)*

	Rate century^{-1}	Production $M_\odot$ per event	Escape probability	Positrons × 10^{43} s^{-1}
^{44}Ti	0.4/2.1 SNIa/SNII	2×10^{-5} /2×10^{-4}	100%	0.17-0.51
^{56}Co	0.4/2.1 SNIa/SNII	0.6/0.1	1.5-15%	0.31-3.1
^{26}Al	Rate from 1809 keV line		non issue	0.20-0.33
^{22}Na	~1000 [ONe novae)	2×10^{-8}	100%	0.01
Total				0.69-3.95
To explain				2.6-3.4



Positrons from radioactive decay

Data from :
Martin et al. (2012)
Higdon et al. (2009)
Hernanz (2005)
Prantzos (2011)

Another processes that certainly produces positrons:

Cosmic Ray interactions with the ISM

$$pp \rightarrow \pi + X$$

$$pp \rightarrow K + X$$

X = other products (includes anti-protons)

$$K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$$

$$K^{\pm} \rightarrow \pi^{0} \pi^{\pm}$$

$$\pi^{0} \rightarrow \gamma\,\gamma \quad (99\%)$$

$$\pi^{0} \rightarrow \gamma\, e^{-} e^{+} \quad (1\%)$$

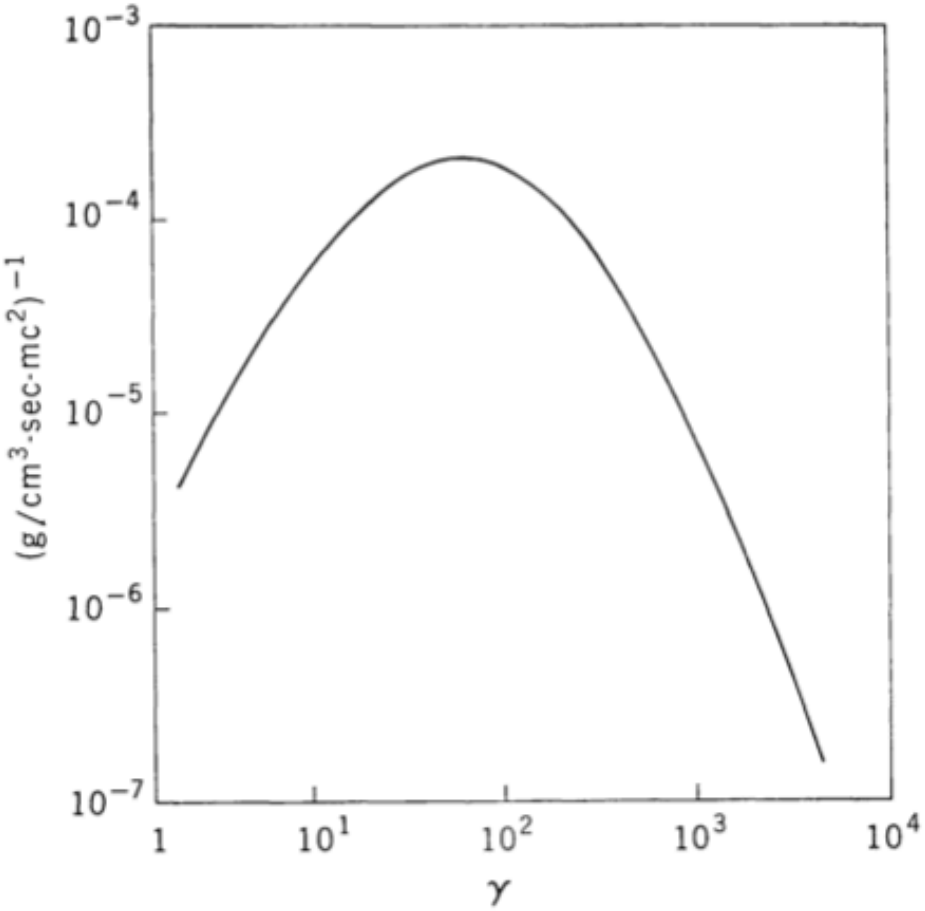
$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \quad (99.99\%)$$

$$\mu^{+} \rightarrow \bar{\nu}_{\mu} \nu_{e} e^{+} \quad (100\%)$$

Masses

$K^{\pm}$	493.7	MeV/c^2
K^0	497.6	
$\pi^{\pm}$	139.6	
π^0	135.0	
μ	105.7	

Positrons produced have energies
10 MeV → GeV



Energy distribution of positrons from π^+/μ^+ decay
(Stecker, 1969)

Gamma-ray excess due to annihilation in flight of high energy positrons

The curious fact :

- there isn't any excess

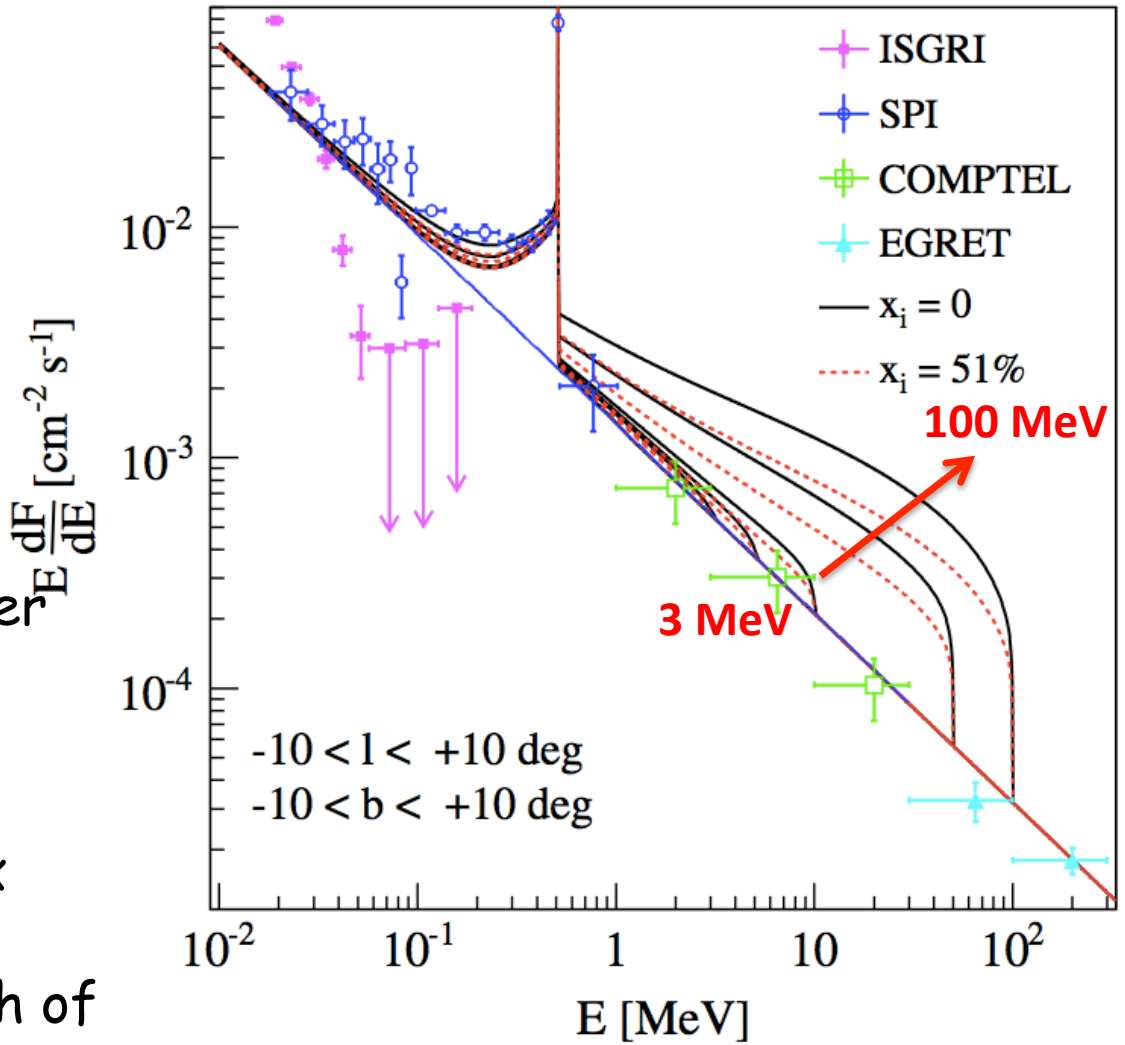
Conclusion :

The positrons cannot have originated at energies greater than a few MeV

Cosmic ray positrons cannot explain the observed 511 flux

(anyway, there are not enough of them and they are produced mainly in the disk)

MeV excess from annihilation in flight

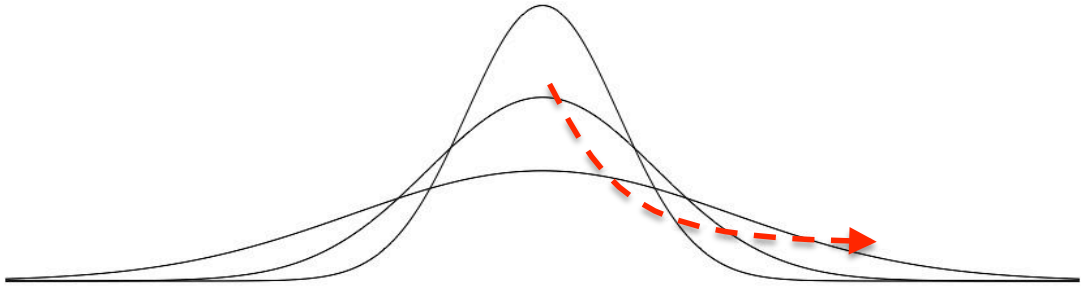


Sizun et al., (2006)

Need a separate component to explain the 'bulge' emission which is more concentrated than almost all of the proposed positron sources.

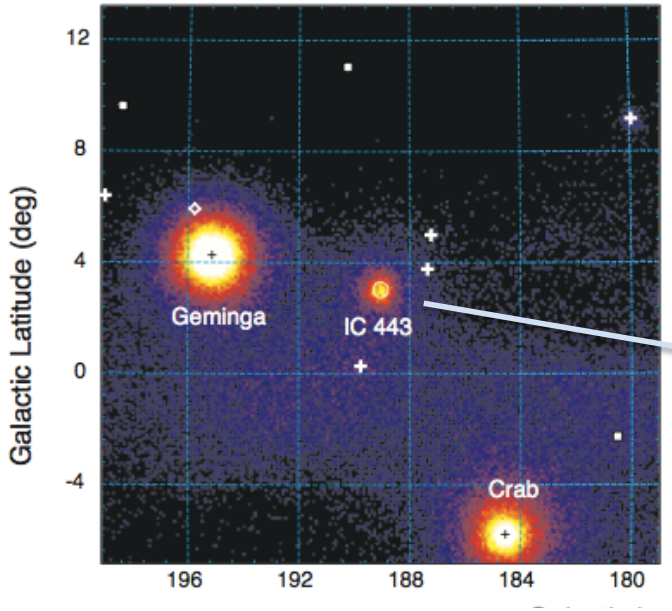
Transport should only allow the positrons to diffuse away from their origin, and so make the emission more diffuse, so must be very compact.

Some possibilities :-



- Mini-Quasar-like outburst from the GC black hole 10^5-10^6 years ago
- Burst of star formation ditto
- Dark matter annihilation – arguably must be low mass (~MeV)
- Decay of excited dark matter – must be a 2-body (ρ^2) process

Gamma-rays from π^0 decay

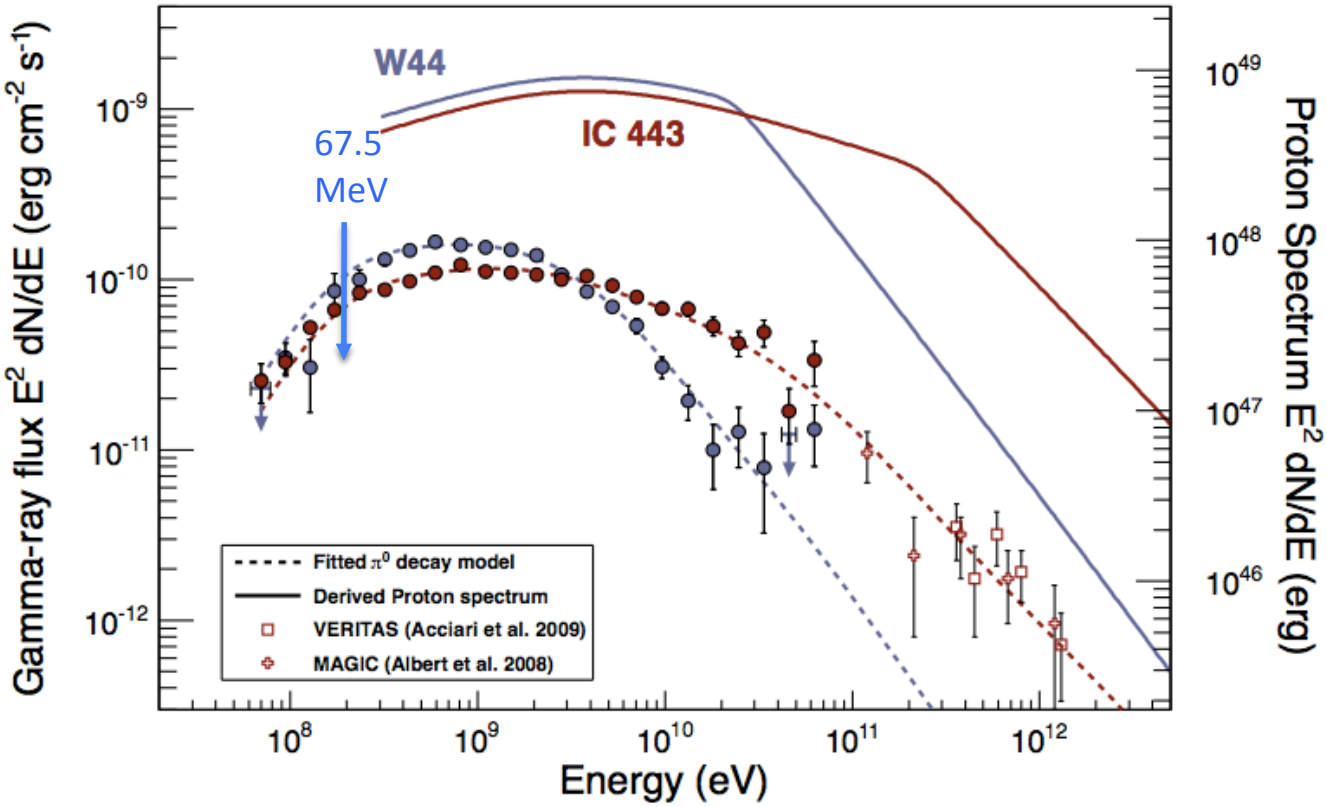


IC 443 Supernova remnant

Age ~ 10, 000 years

Distance 1.5 kpc

Ackermann et al., (2013)



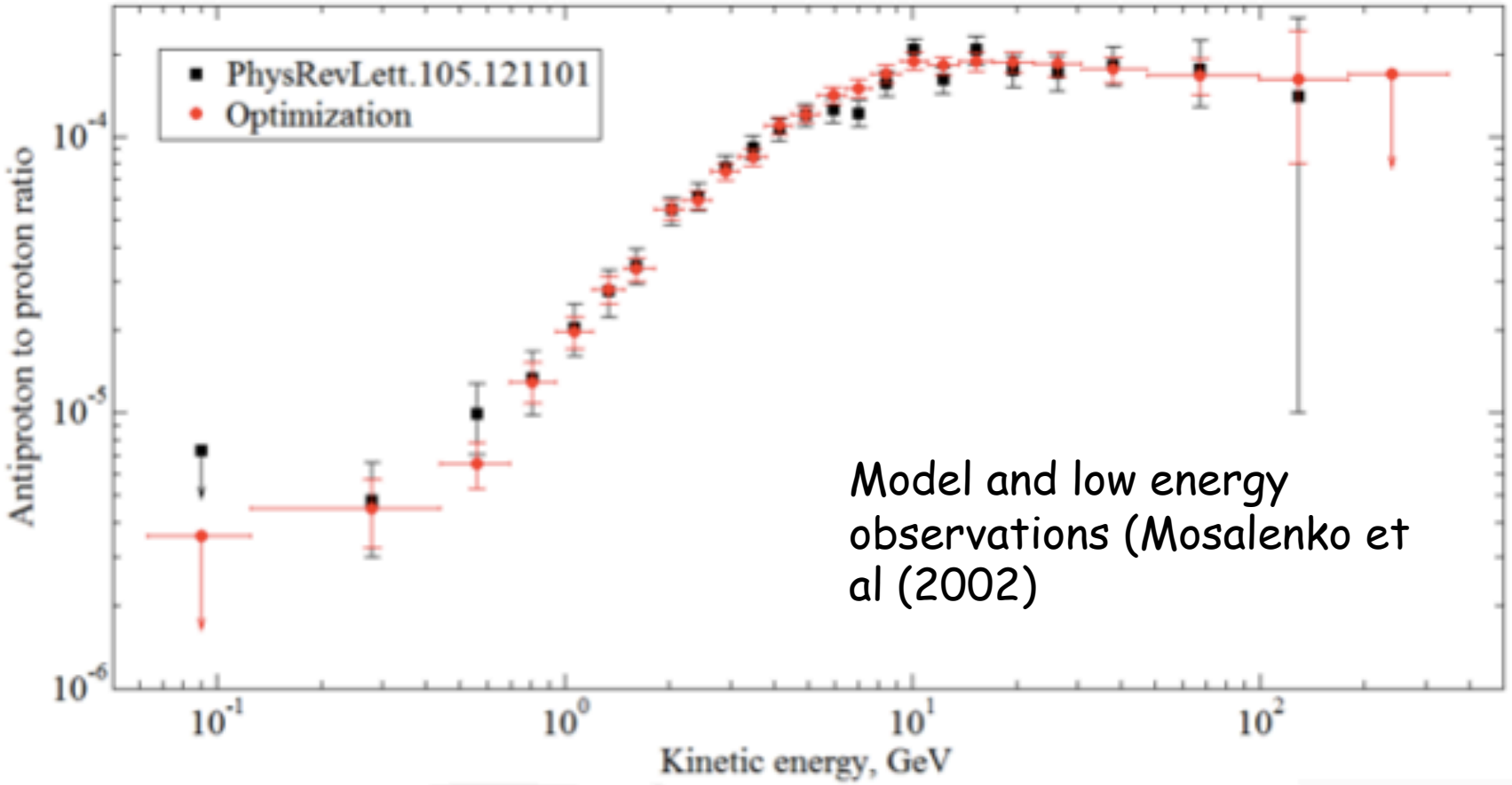
Also

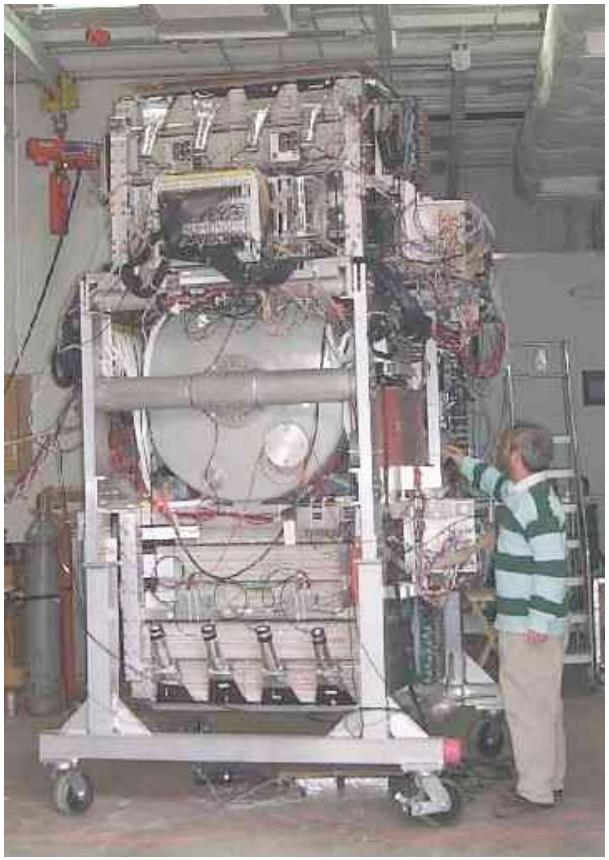
W44 Supernova remnant

Age ~ 10, 000 years

Distance 2.9 kpc

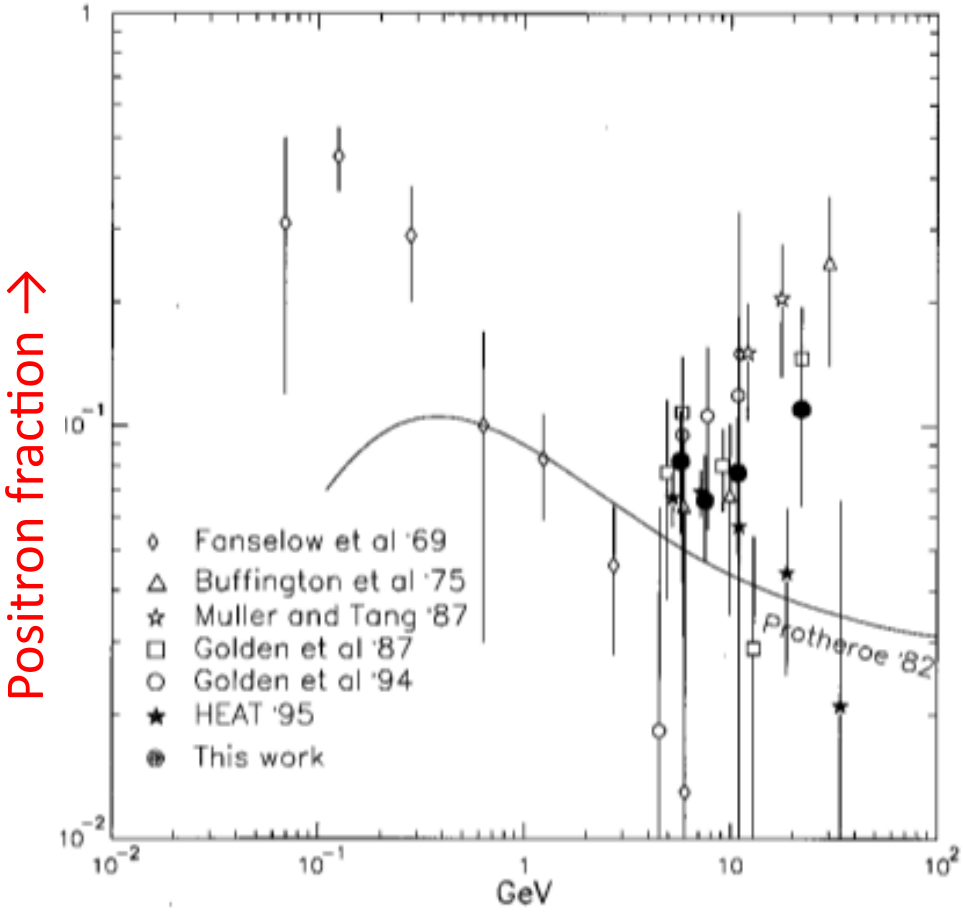
- More direct evidence – Cosmic Rays measured inside the Solar System



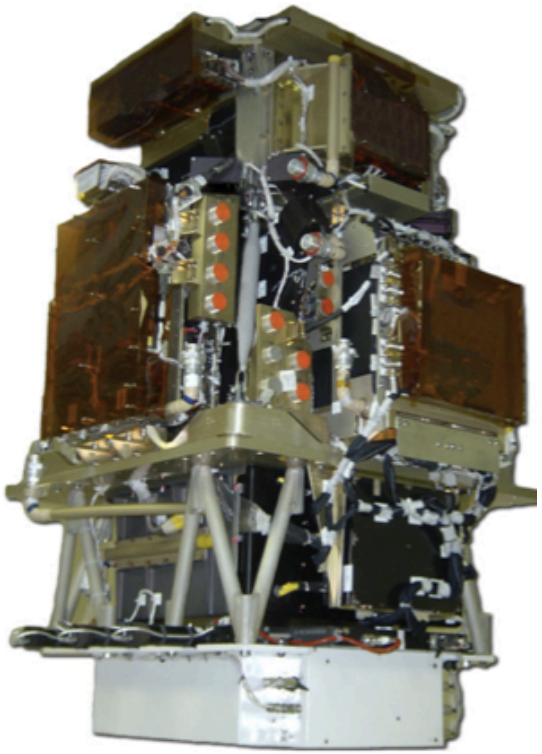


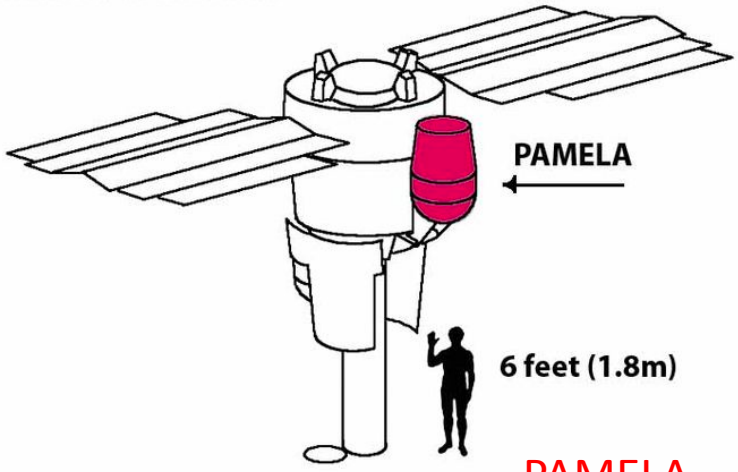
Anti-protons and positrons are seen in Cosmic Rays

Early balloon measurements of positron fraction hinted at an unexpected excess at high energies



Golden et al (1996)



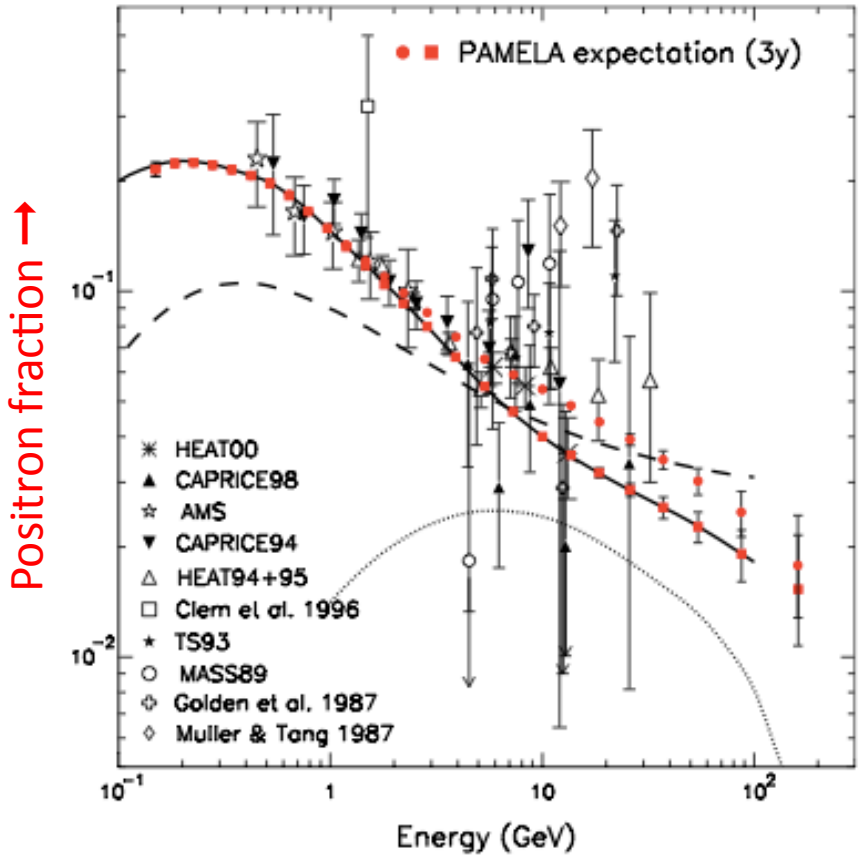


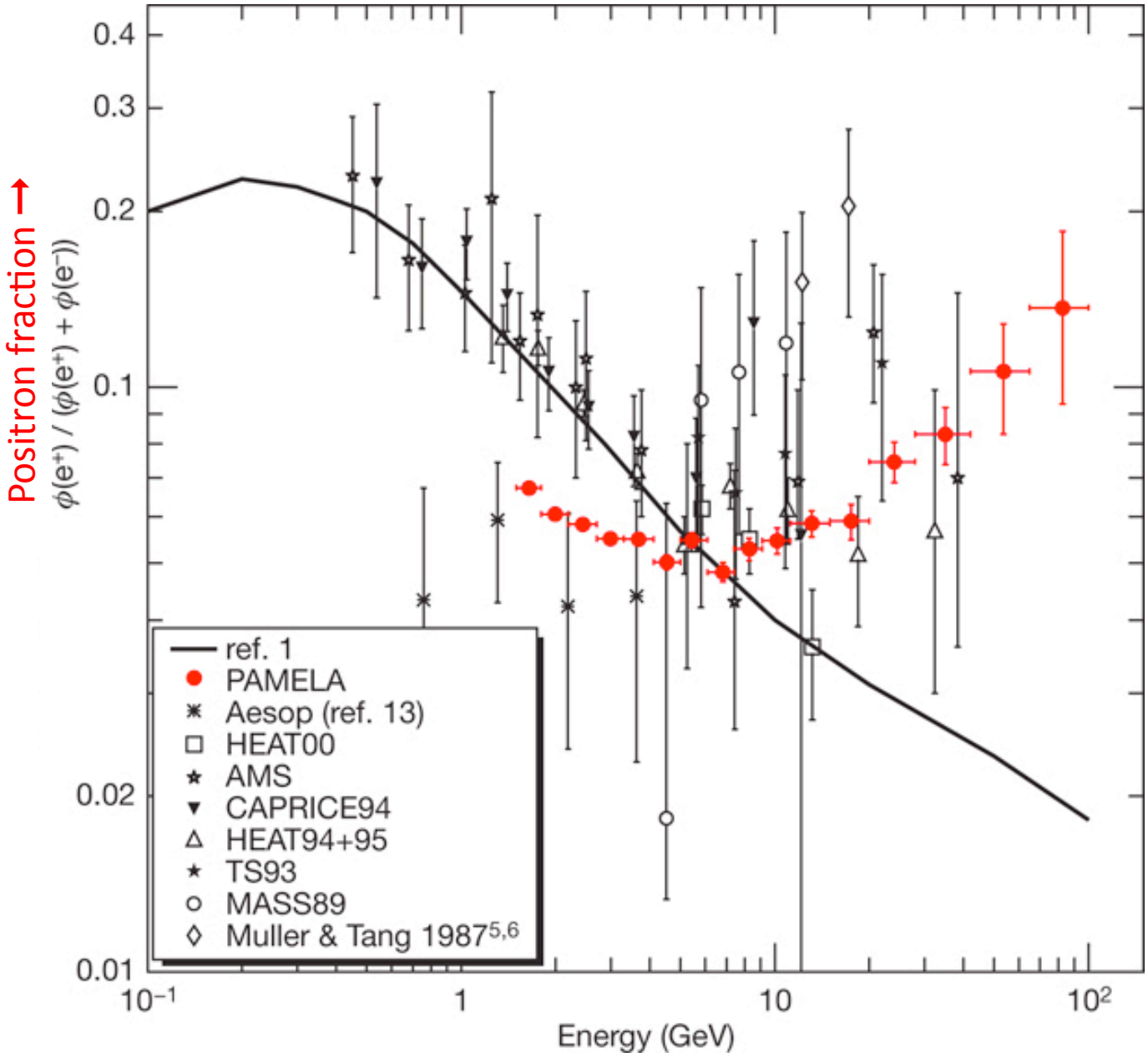
PAMELA

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

Launched June 2006

PAMELA – pre-launch prediction

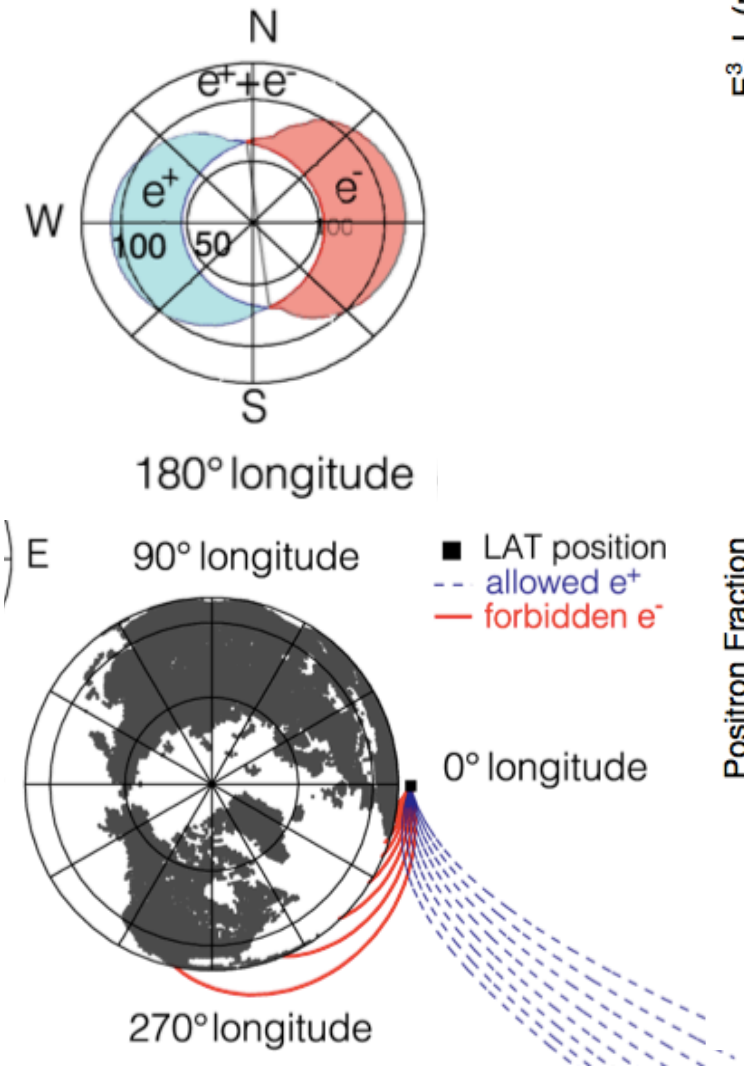


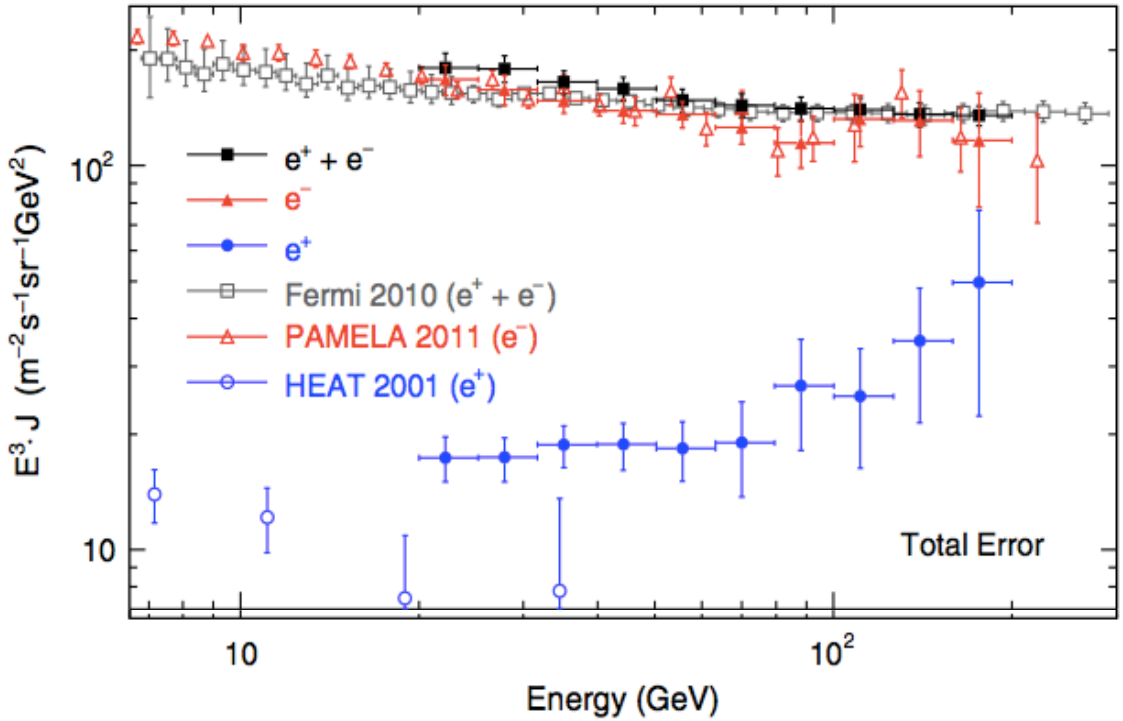


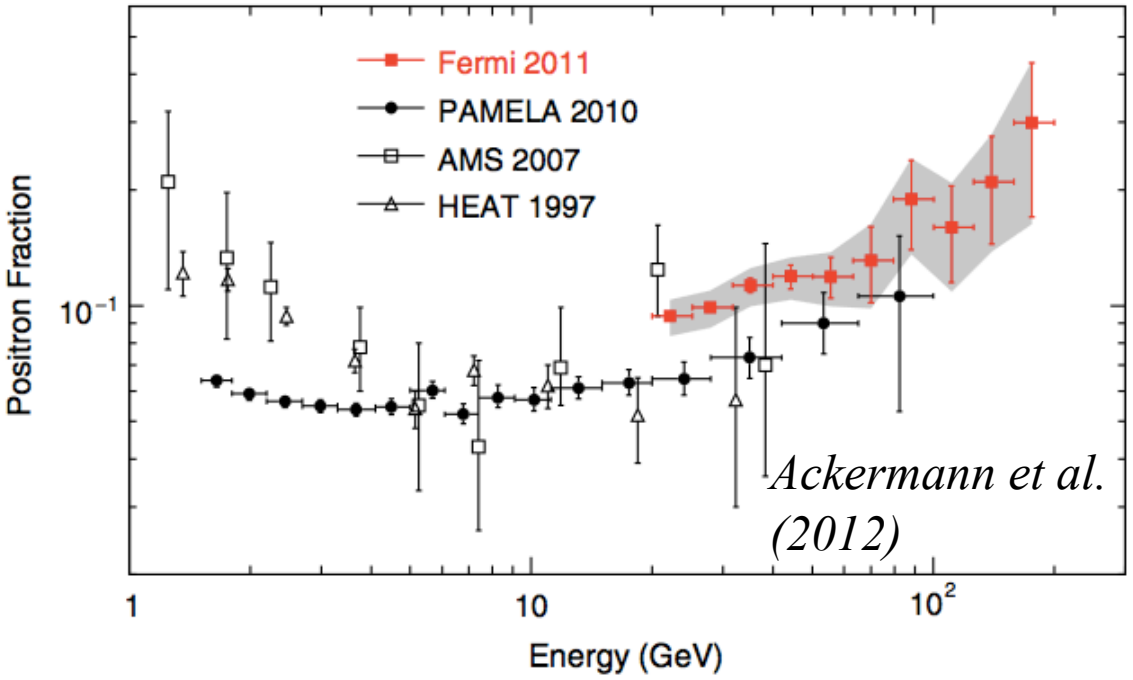
Positron excess seen with PAMELA

Adriani et al (2009)

Further confirmation with Fermi using the Earth's magnetic field

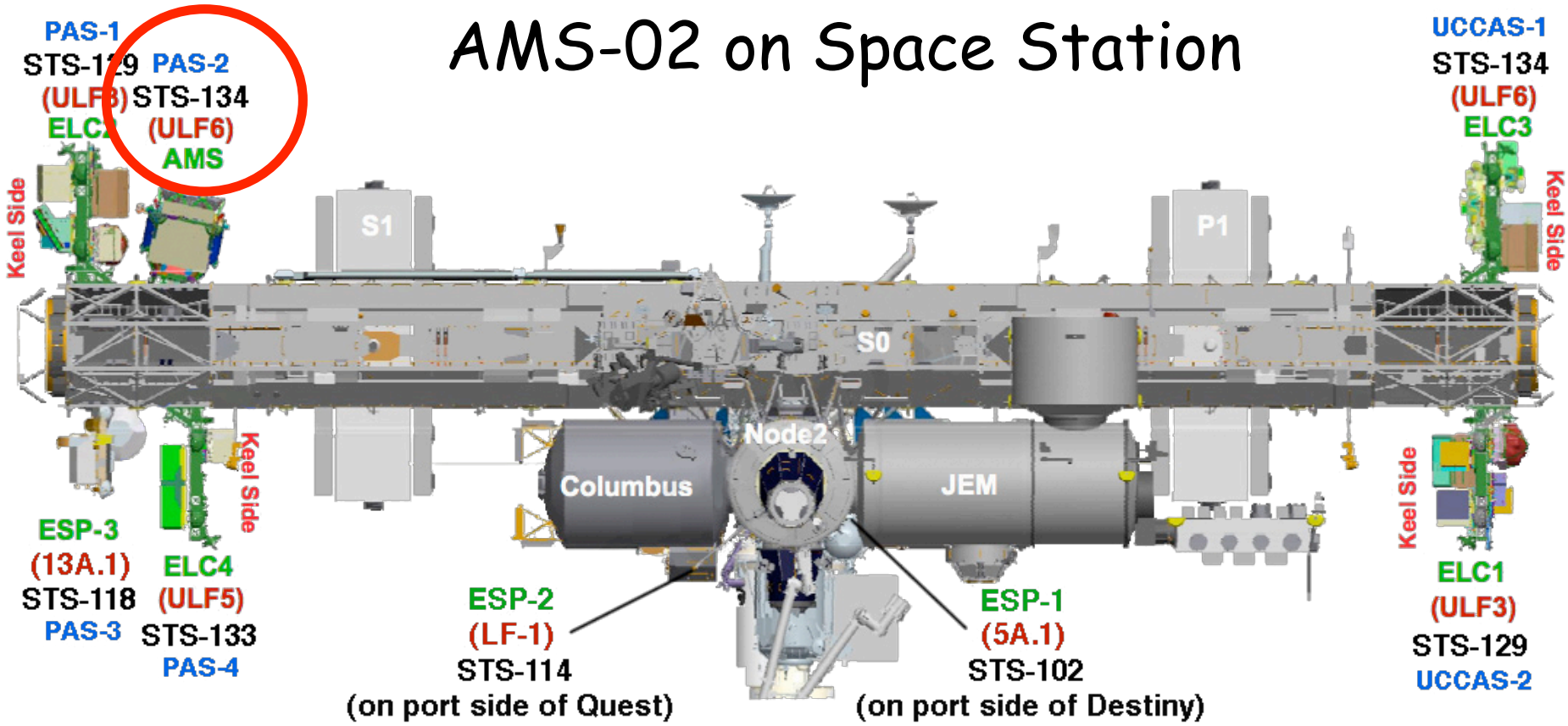






Ackermann et al. (2012)

AMS-02 on Space Station



AMS-01 1998 prototype flown on Shuttle; Data link problems – little data

AMS-02 ~1999 Too much power for a satellite; moved to Space Station

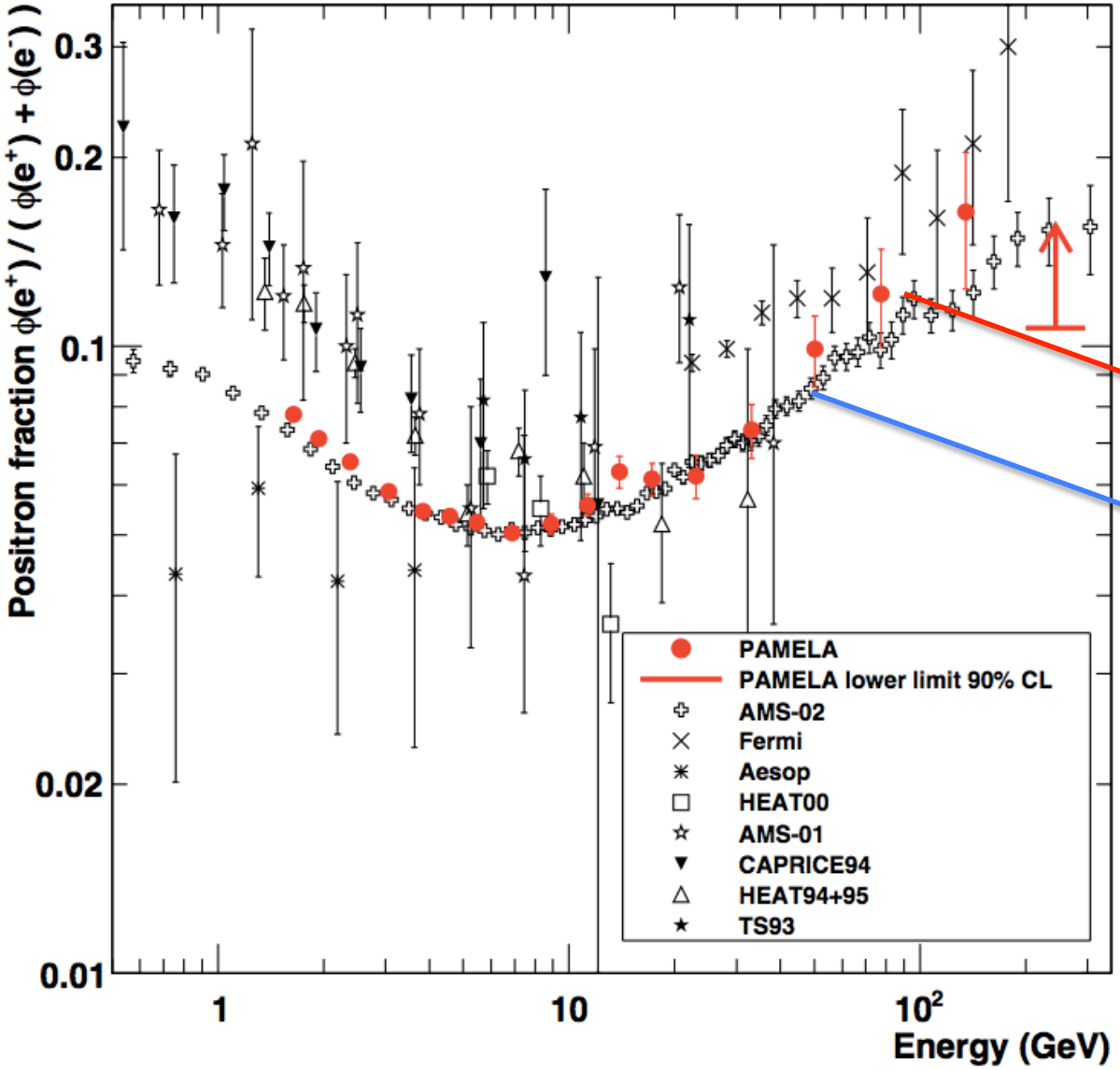
2003 Columbia disaster – no room for launch in revised manifest

2008 Special bill passed by Congress and Senate and signed by Obama to add an extra Shuttle mission to allow AMS-02 to be installed on ISS

2009 Problems with superconducting magnet – replaced with permanent one from AMS-01

2011 Launch

Positron excess confirmed with AMS-02

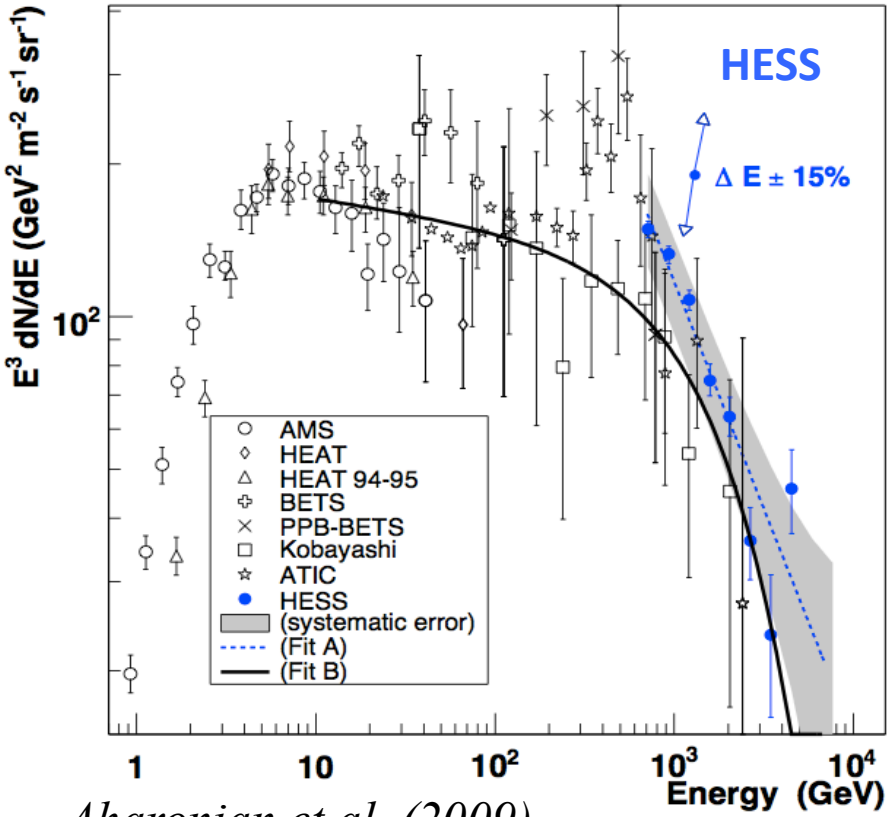


Pamela data

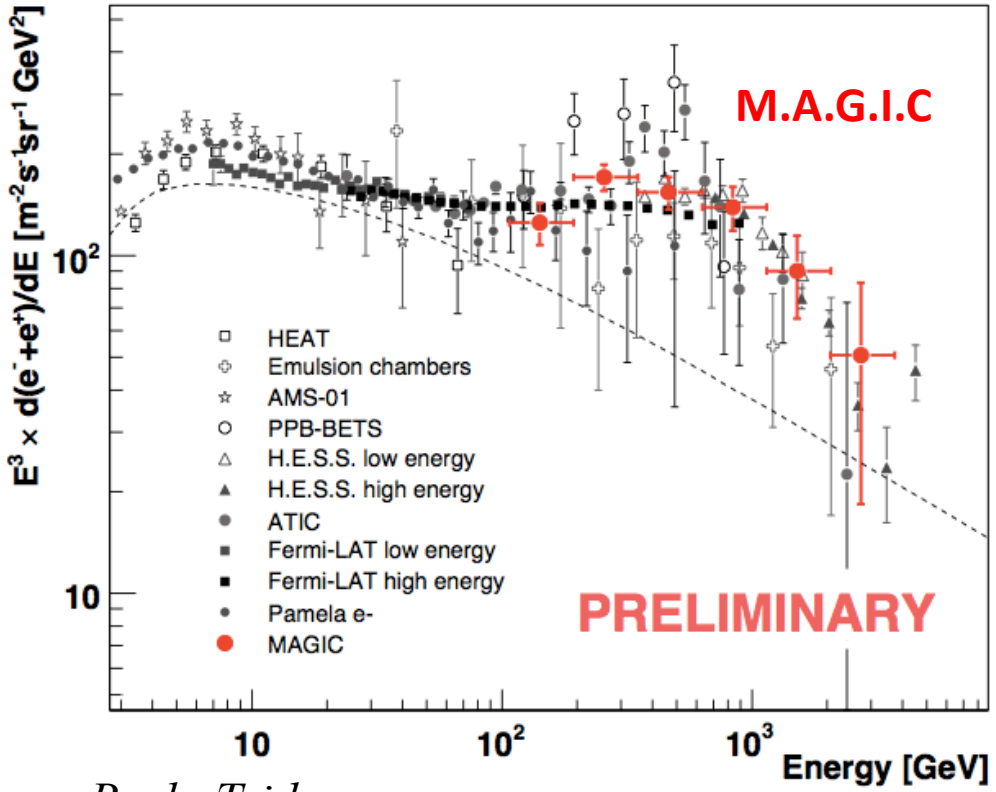
AMS-02 data

Adriani et al (2013)

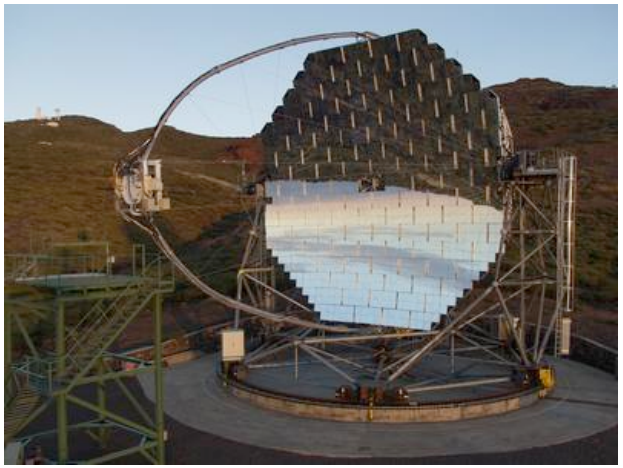
Ground-based experiments cannot distinguish positrons from electrons but confirm an excess in the total



Aharonian et al. (2009)



Borla Tridon et al (2011)



Proposed explanations of the 'Pamela Excess'

1) Nearby Pulsars

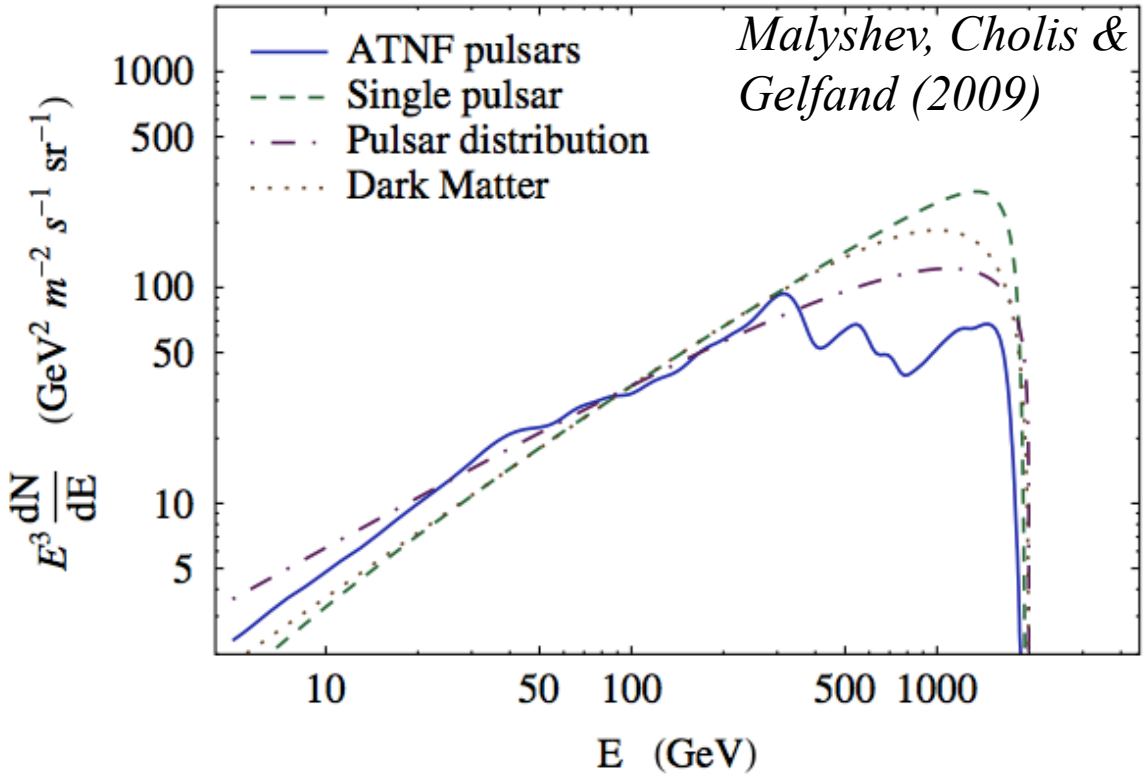
Rotating B field -> → E field

ΔV~ 10^{16} V

Curvature Radn → γ

$\gamma + B \rightarrow e^+ + e^-$

$\gamma + \gamma \rightarrow e^+$



2) Dark Matter annihilation or decay

560 out of 1164 citations of the *Adriani et al (2009)* Nature paper on the Pamela excess contain 'dark' in the title; 761/1164 mention it in the abstract.

Anti Stars; Anti Galaxies; Anti Clusters ?

Dirac in his 1933 Nobel Lecture :

"....One might perhaps think that the same theory could be applied to protons. This would require the possibility of existence of negatively charged protons forming a mirror image of the usual positively charged ones. .

... we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons.

It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods".

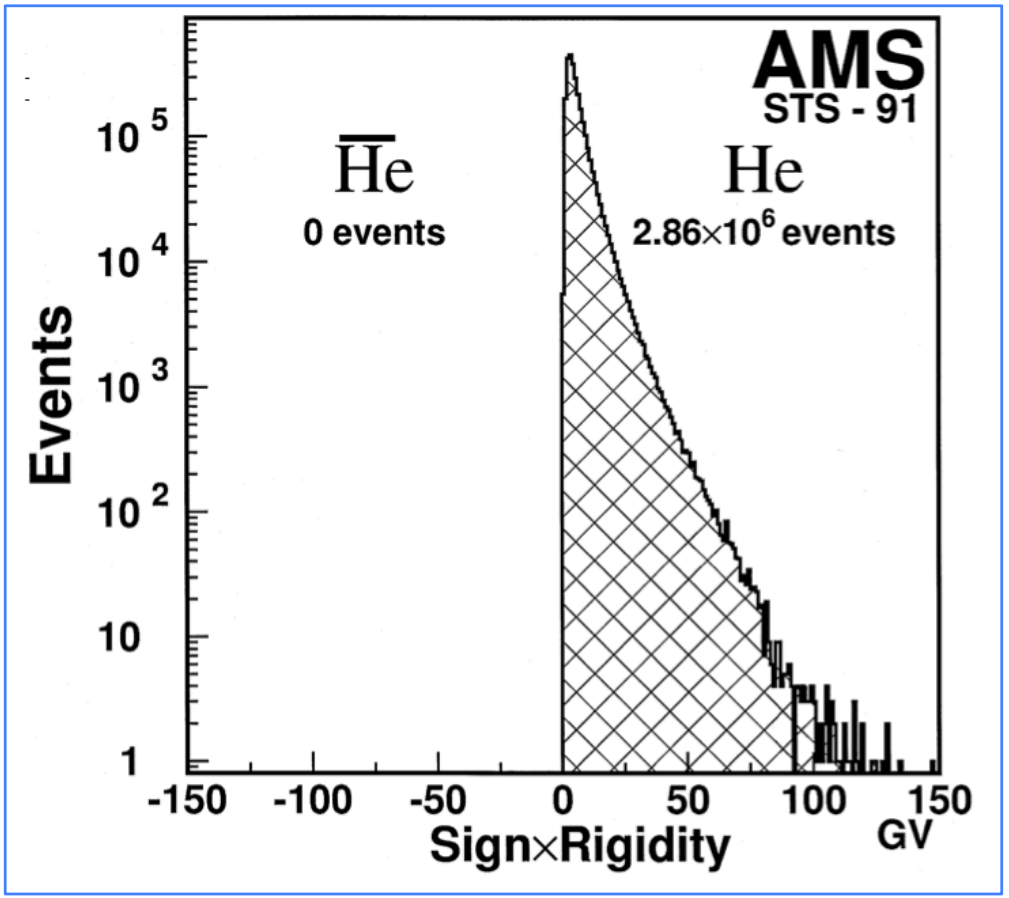
Anti-deuterons – a very small population of secondaries is expected from CR interactions

Consistent with upper limits

A certain detection of even one **anti-Helium** nucleus in CR would be decisive.

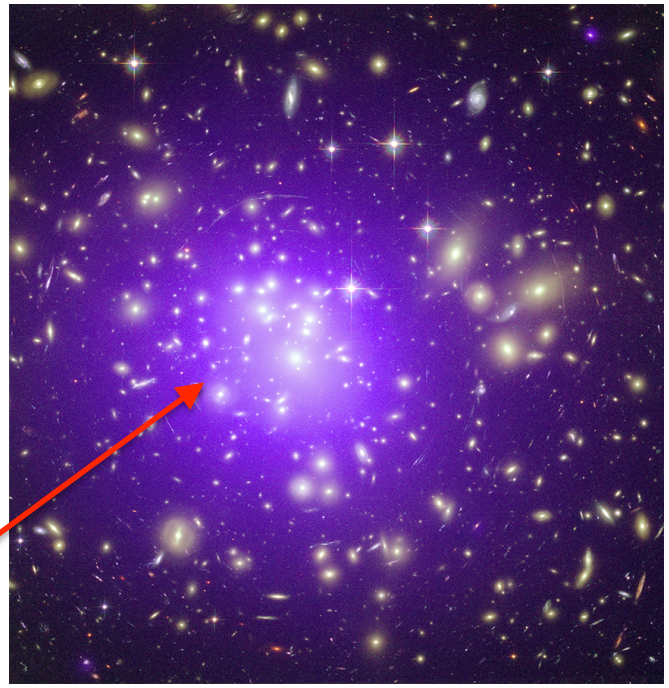
AMS-01 set tight limits $N_{He}/N_{he} < 10^{-6}$

AMS-02 results that are awaited
They should be 1000x more sensitive.



Anti Stars ?

No – at least not in equal numbers
Winds from stars
SuperNova explosions return (anti)matter to the InterStellar Medium
Limits < 1 in 104

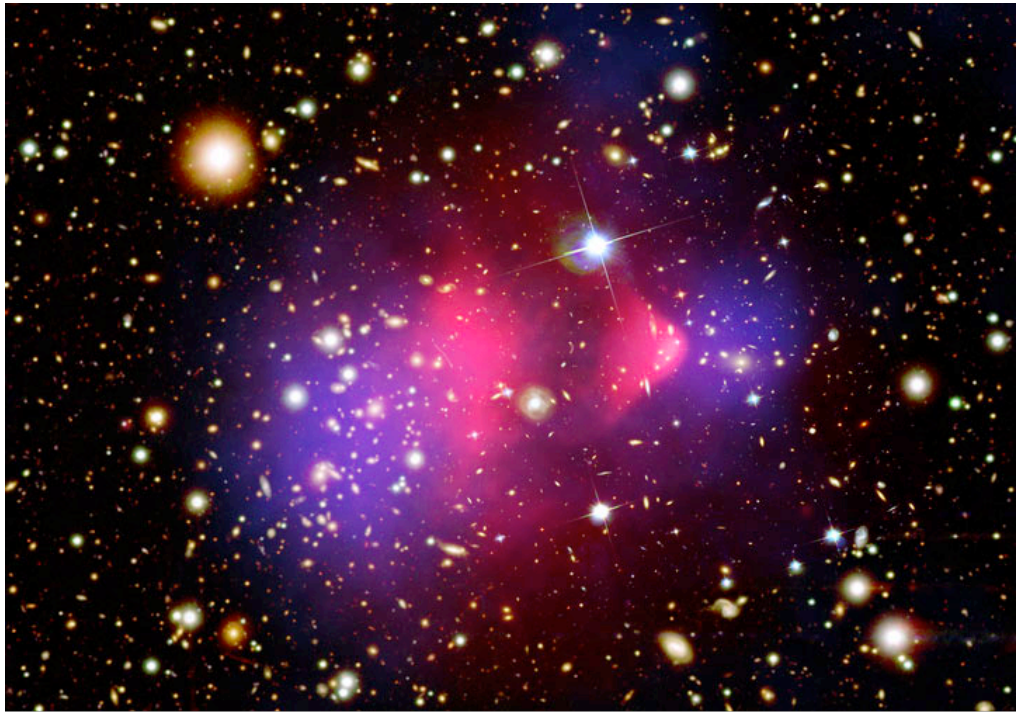


Anti Galaxies ?

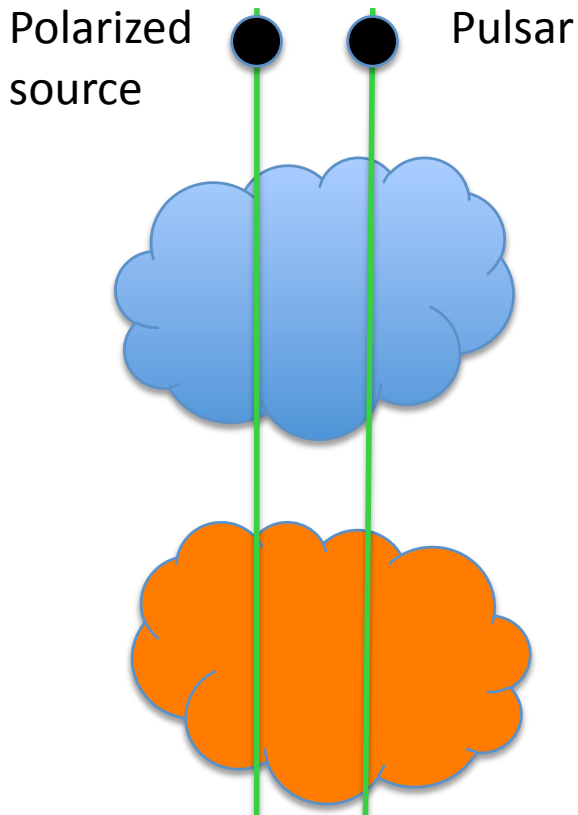
No – at least not in equal numbers
X-ray observations show that there is an InterGalactic medium in clusters that has been processed through stars
No gamma-rays seen

Anti Clusters ?

Difficult to exclude
In one case two colliding clusters cannot have been one matter, one antimatter



In principle, one CAN detect matter / anti-matter mixtures with electromagnetic radiation



Rotation measure

$$\theta \sim \int [n(e^-) - n(e^+)] B_{\|} dl . \lambda^2$$

Dispersion measure

$$\tau \sim \int [n(e^-) + n(e^+)] dl . \lambda^3$$

Gravitational redshift

The gravitational potential of the galaxy is well established from the velocity profile (which shows it to be dominated by dark matter)

For radiation coming from 1 kpc from the centre (an angular offset of 7°), there will be a redshift of 1 part in 10^6.

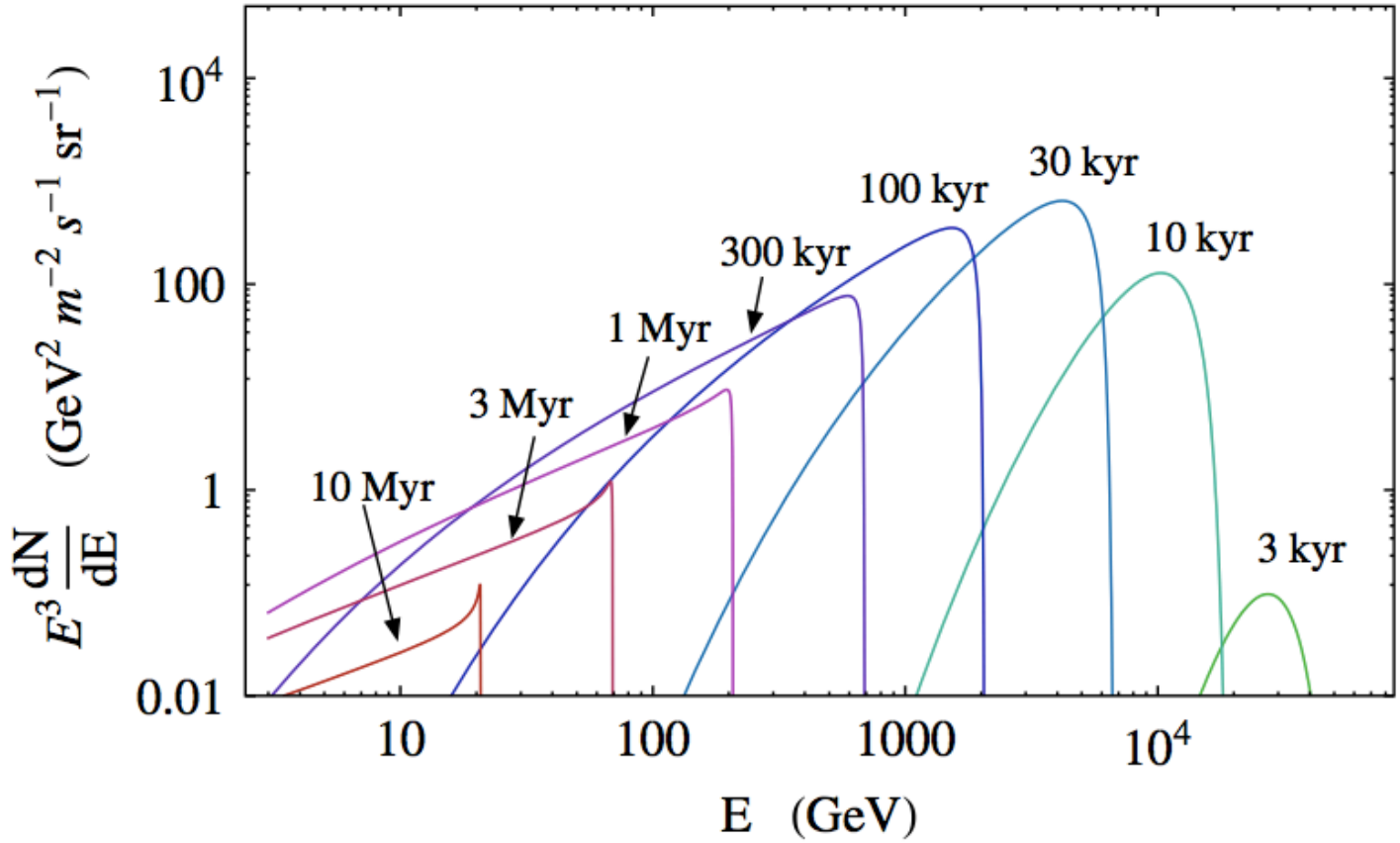
Would negative gravitation mass for positrons mean that 511 keV positronium annihilation radiation would show no such redshift ?

But

1) The effect is small to measure at present
2) The redshift is a GR effect, but GR cannot hold

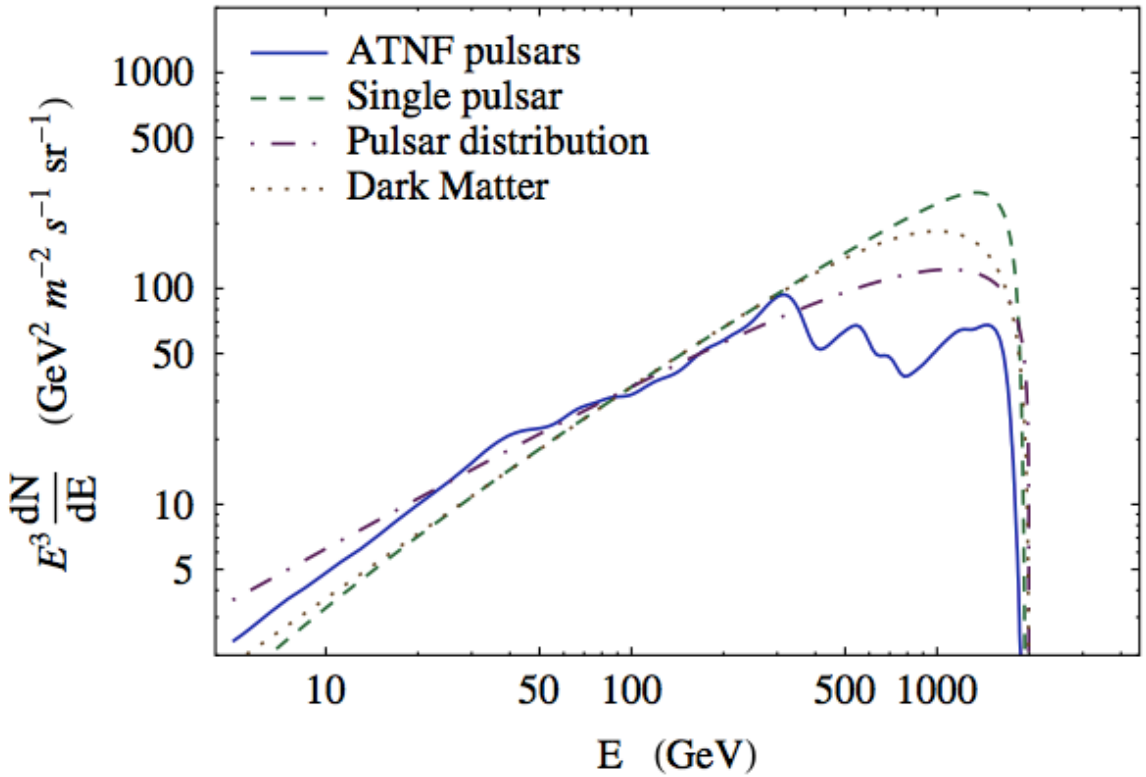
The END

Predicted $e^+ + e^-$ flux from a pulsar at a distance of 1 kpc with $\eta W_0 = 10^{49}$ erg, an injection index n=1.6, and an injection cutoff 10 TeV



Malyshev, Cholis & Gelfand (2009)

Malyshev, Cholis & Gelfand (2009)



e.g. Yin et al. (2013)

	Pulsar	**Age (y)**	**Distance (kpc)**
Geminga	J0633+1746	3.7×10^5	0.25
Monogem	B0656 +14	1.1×10^5	0.28

Fermi/PAMELA excesses and Lesson from DM annihilation/decay

- **In case of stable DM, to explain PAMELA and Fermi excesses one needs**

$$\langle \sigma_{\rm DM} |v_{\rm rel}| \rangle = \mathcal{O}(10^3) \langle \sigma_{\rm DM} |v_{\rm rel}| \rangle_{\rm canonical}$$

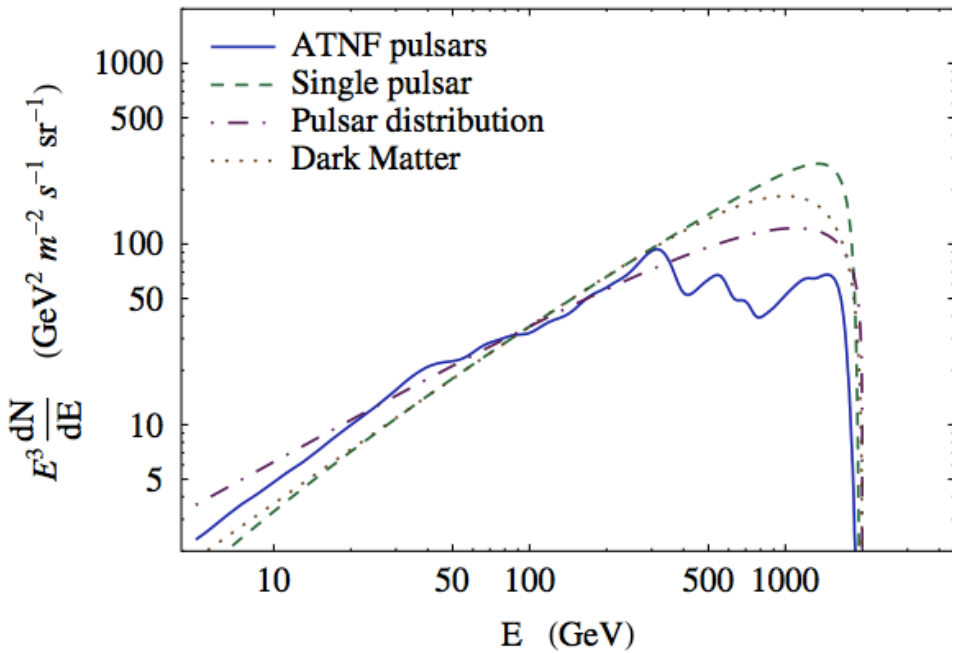
- **In case of unstable DM, to explain PAMELA and Fermi excesses one needs**

$$\tau_{\rm DM} = \mathcal{O}(10^9) \times \tau_0$$

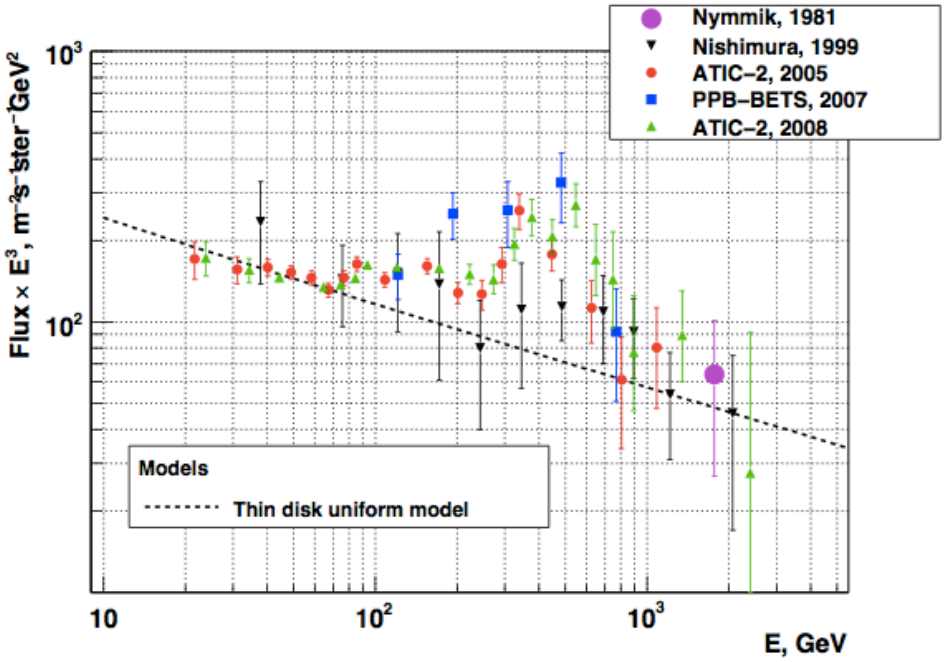
where τ_0 = Age of the Universe.

- **DM should annihilate/decay to leptons and not to hadrons upto 100 GeV (current limit).**

from Sahu (2012)

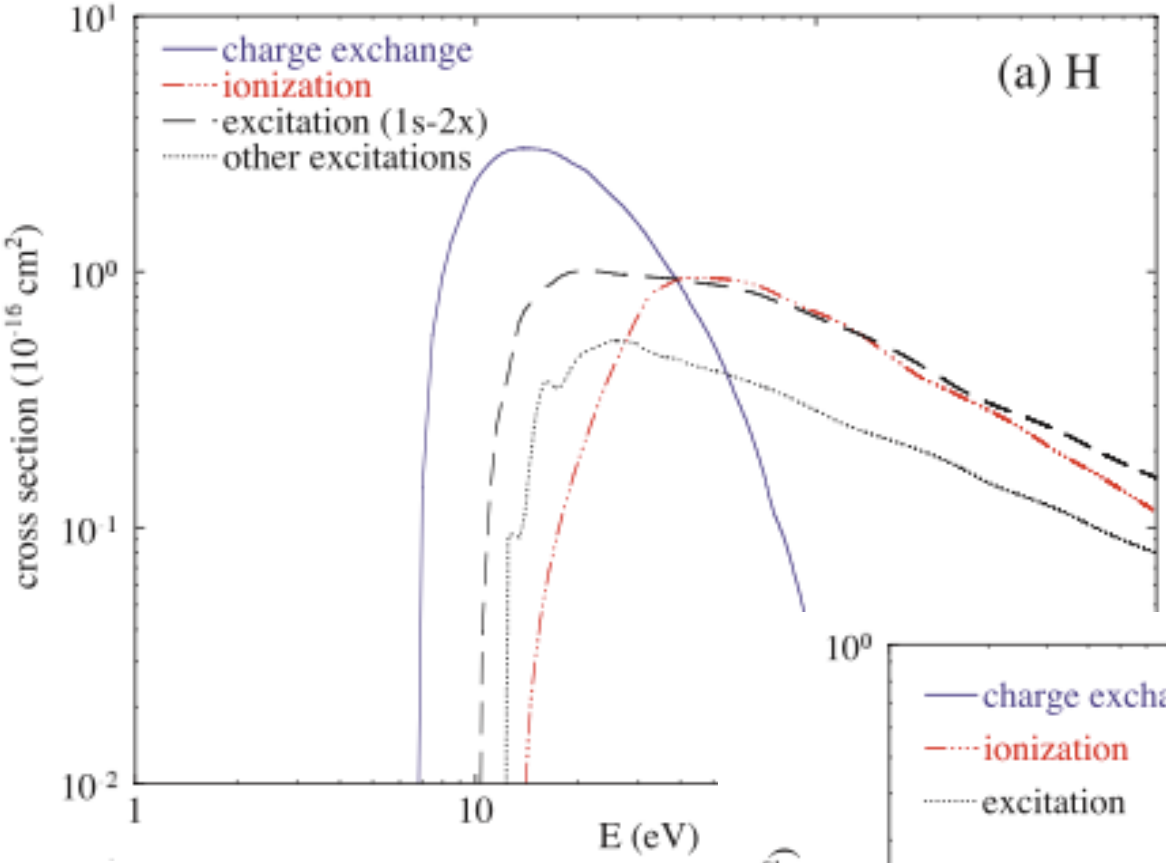


Malyshev, Cholis & Gelfand (2009)

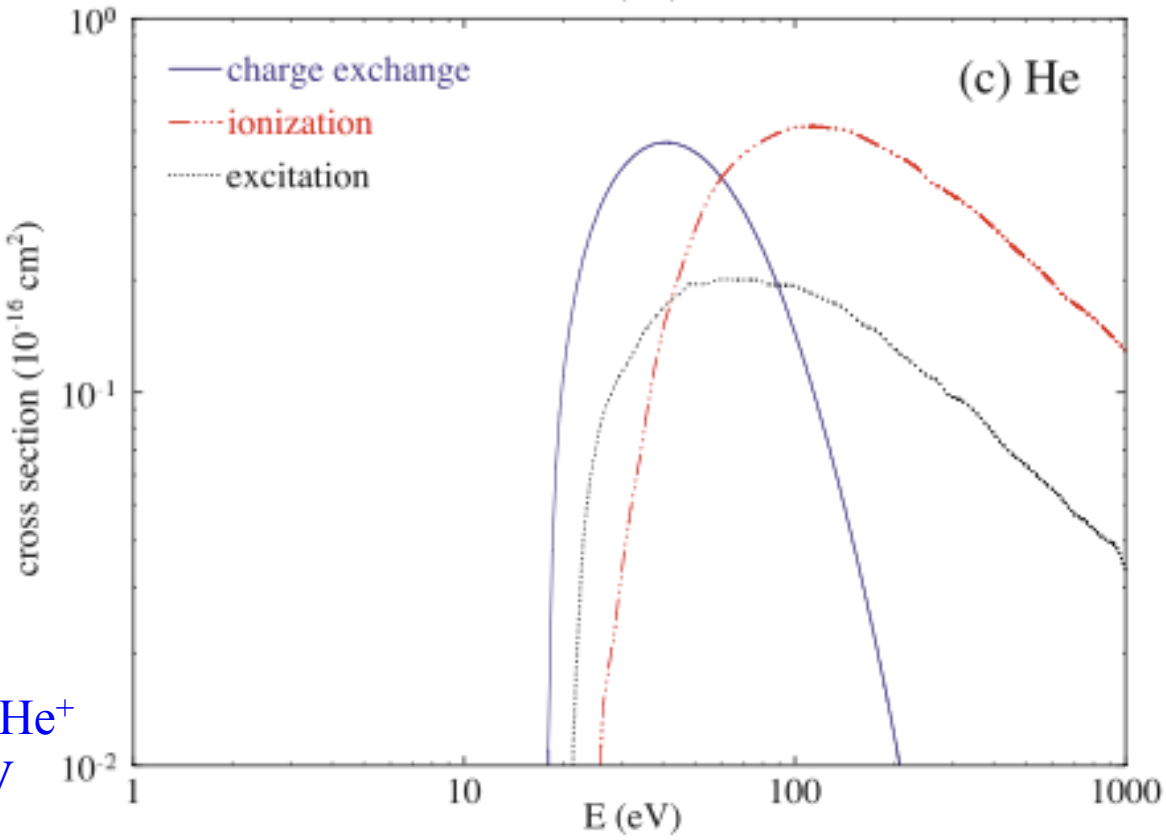


Panov (2013)

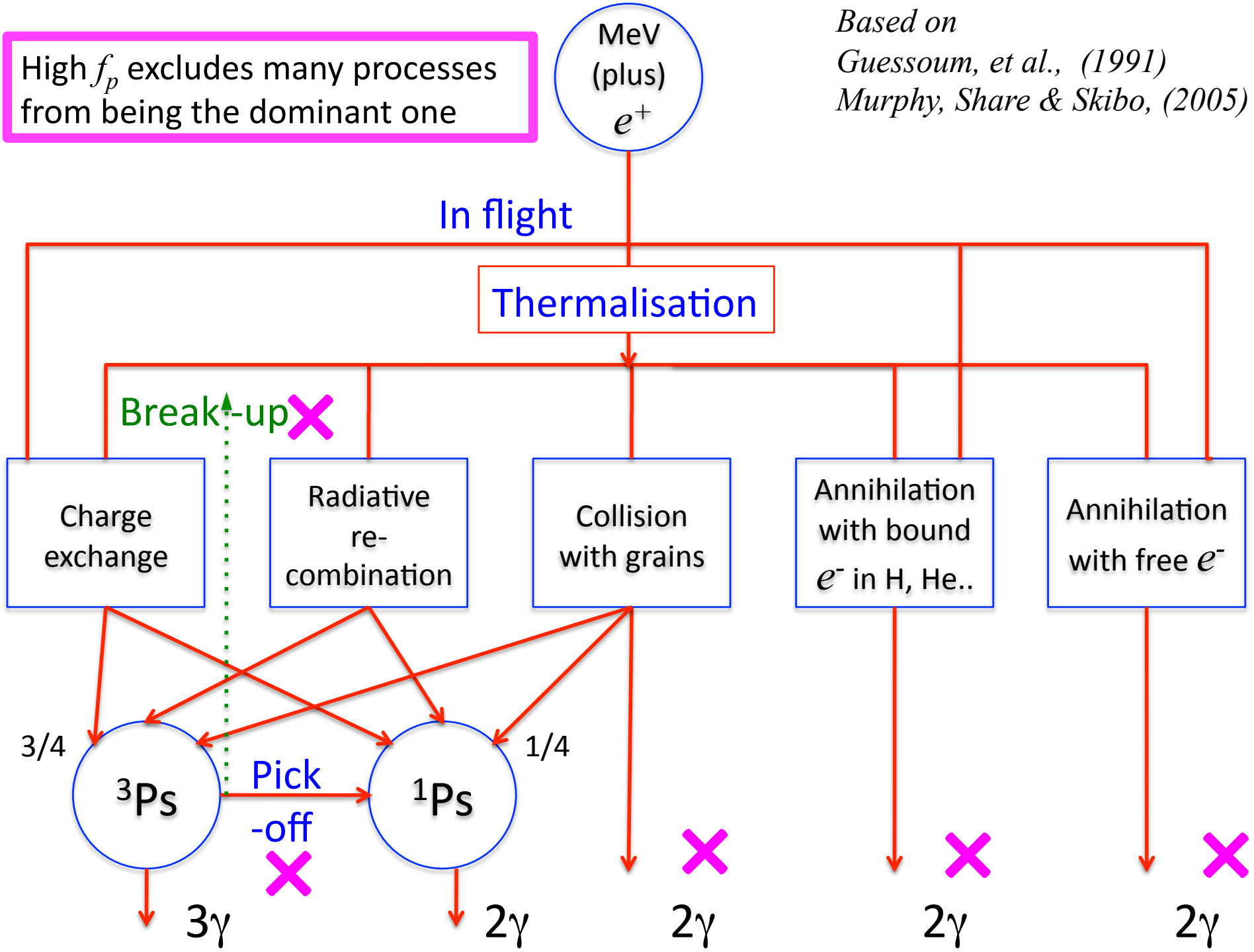
By assuming a distribution of pulsars, or equally by considering dark matter with clumps (`sub-halos') at different distances, one can even explain the features in the total lepton spectrum that may (or may not) have been seen with the ATIC balloon payloads.



$e^+ + H \rightarrow Ps + p$
threshold 6.8 eV

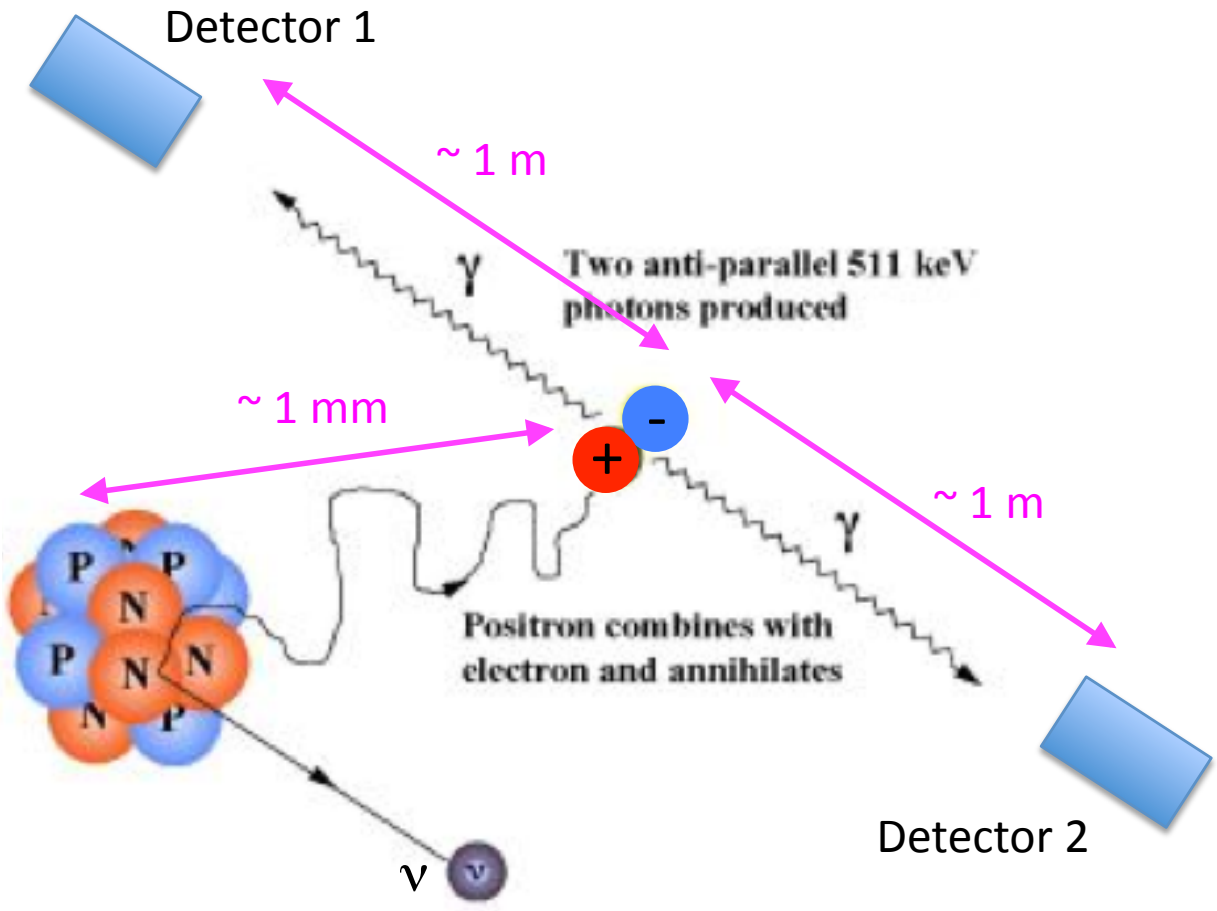


$e^+ + He \rightarrow Ps + He^+$
threshold 17.8 eV

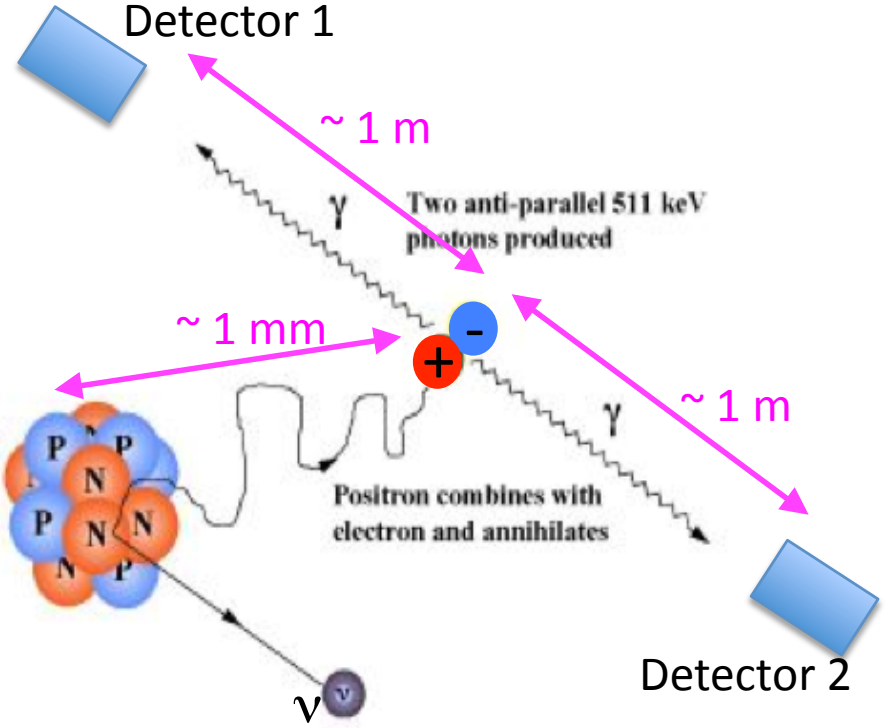


Based on
Guessoum, et al., (1991)
Murphy, Share & Skibo, (2005)

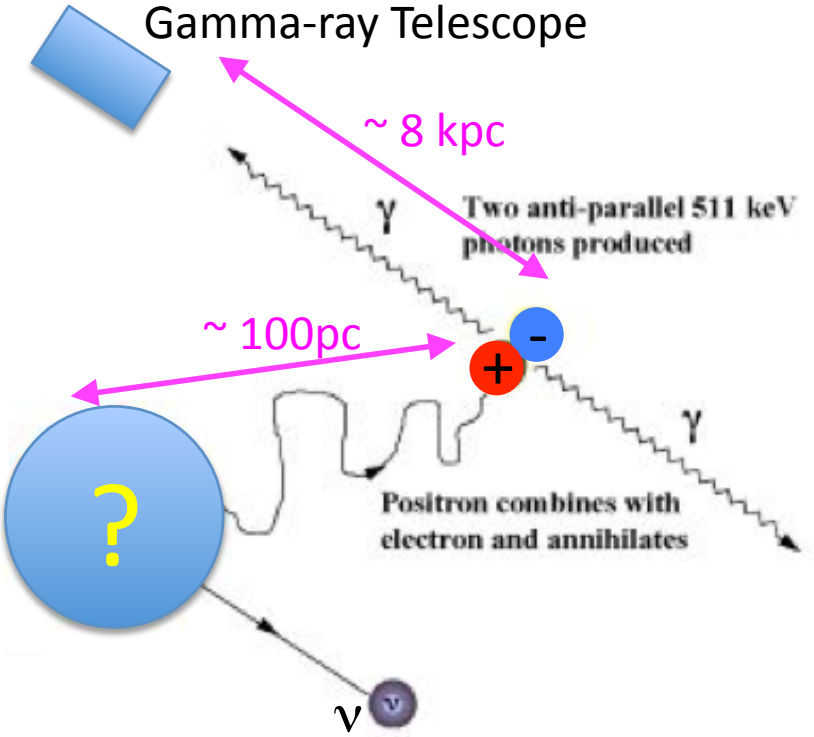
Positron Emission Tomography ('PET scan')



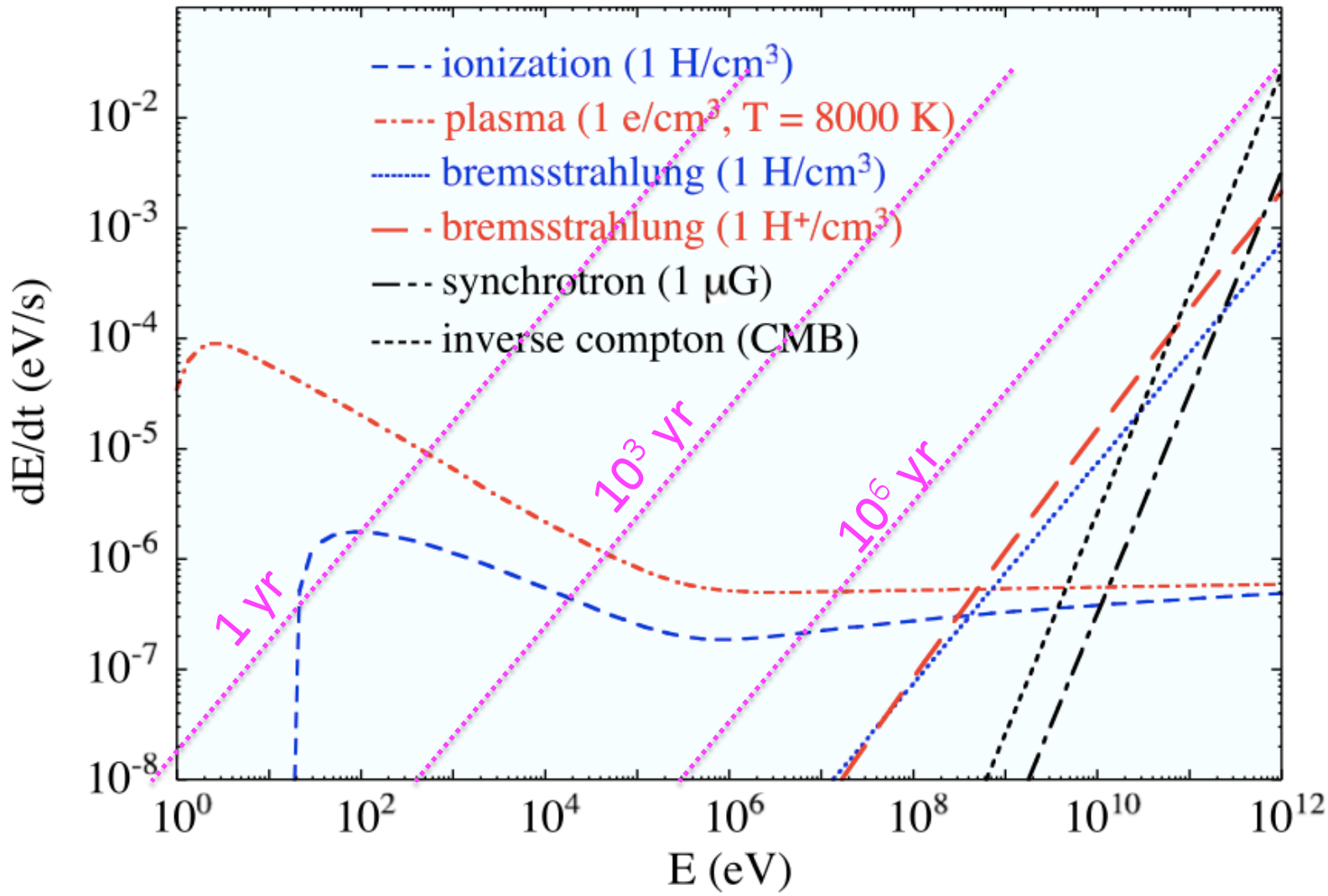
Positron Emission Tomography ('PET scan')



Positron Emission Astronomy



- One knows, with limited precision, on what line the annihilation took place, but not where along it.
- Knowledge of where the positron was produced is limited by its stopping distance



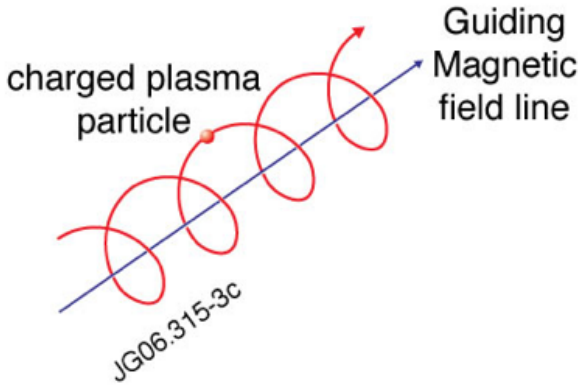
$\tau = E/(dE/dt)$

Prantzos, et al. (2011)

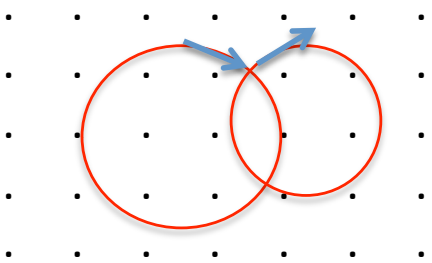
But these are distances along the path

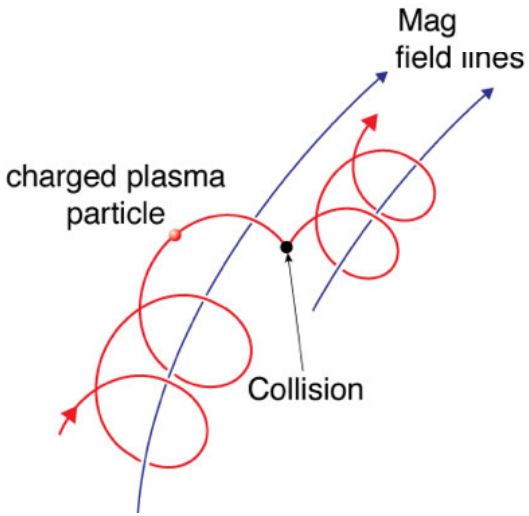
Gyro radius is small

$$10^{-10}\left(\frac{B}{5\ \mu G}\right)\sqrt{\gamma^2-1}\quad pc$$



Pitch angle scattering

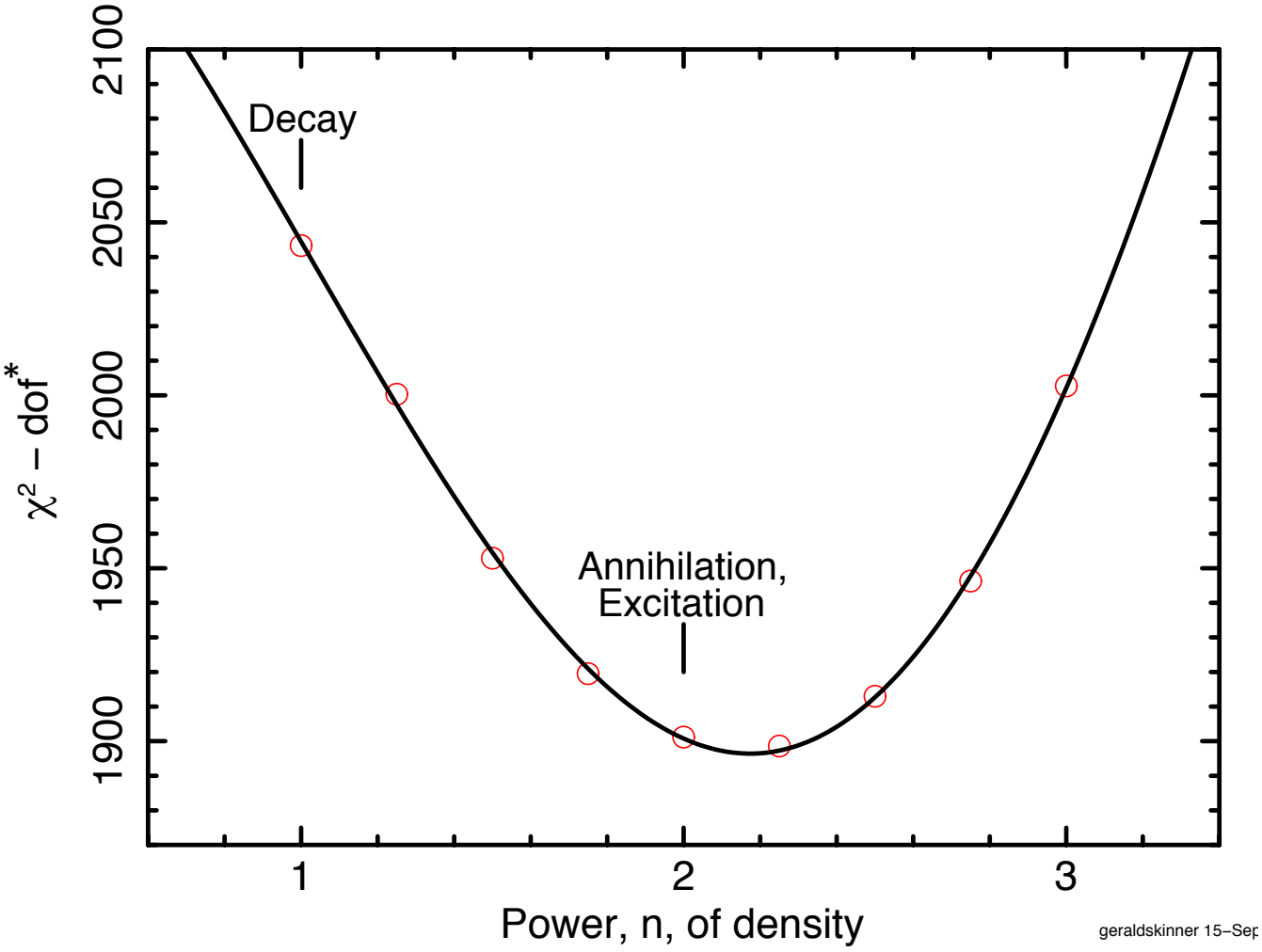




After scattering, particle spirals around a different, but nearby and nearly parallel, field line. But the pitch of the spiral, and hence speed along the line, may be different – even reversed

Diffusion-like process with a random walk along (in tight spiral around) field lines

Fitting a model with a disk from radio-active decay plus a bulge component with $F \propto (\rho_{DM})^n$ and ρ_{DM} based on an NFW dark matter profile



(* 1.2×10^6 dof)

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AN OFF-CENTER DENSITY PEAK IN THE MILKY WAY'S DARK MATTER HALO?

MICHAEL KUHLEN[1], JAVIERA GUEDES[2], ANNALISA PILLEPICH[3], PIERO MADAU[3], AND LUCIO MAYER[4]

"We show that the position of the central dark matter (DM) density peak may be expected to differ from the dynamical center of the Galaxy by several hundred parsecs."

Invoked to explain an offset in the centroid of the possible Fermi 130 GeV line by ~1.5° from the Galactic centre (to negative galactic longitudes).