IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Dark matter and cosmic-ray anomalies

6. July 2009

@YITP 「場の理論と弦理論」

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Plan of talk

- 1. Introduction
- 2. Recent observations - PAMELA/ATIC/PPB-BETS/Fermi/H.E.S.S.
- 3. Dark Matter Models
  - Annihilation and decay of dark matter
  - A model
- 4. Conclusion

1. Introduction

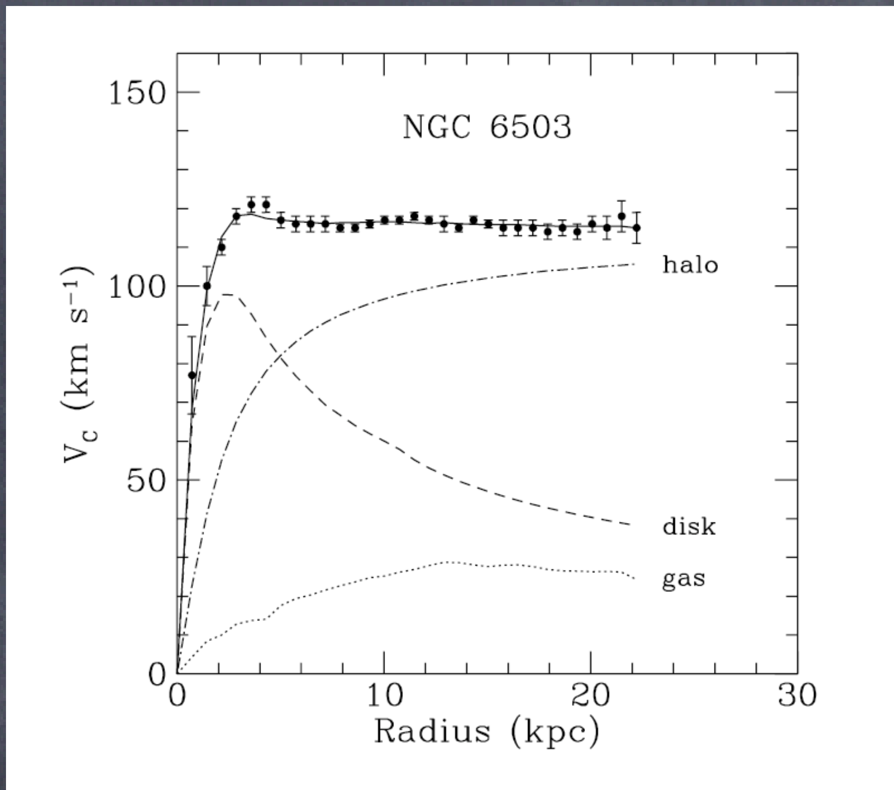
Dark Matter

How can we know the presence of “dark” matter?

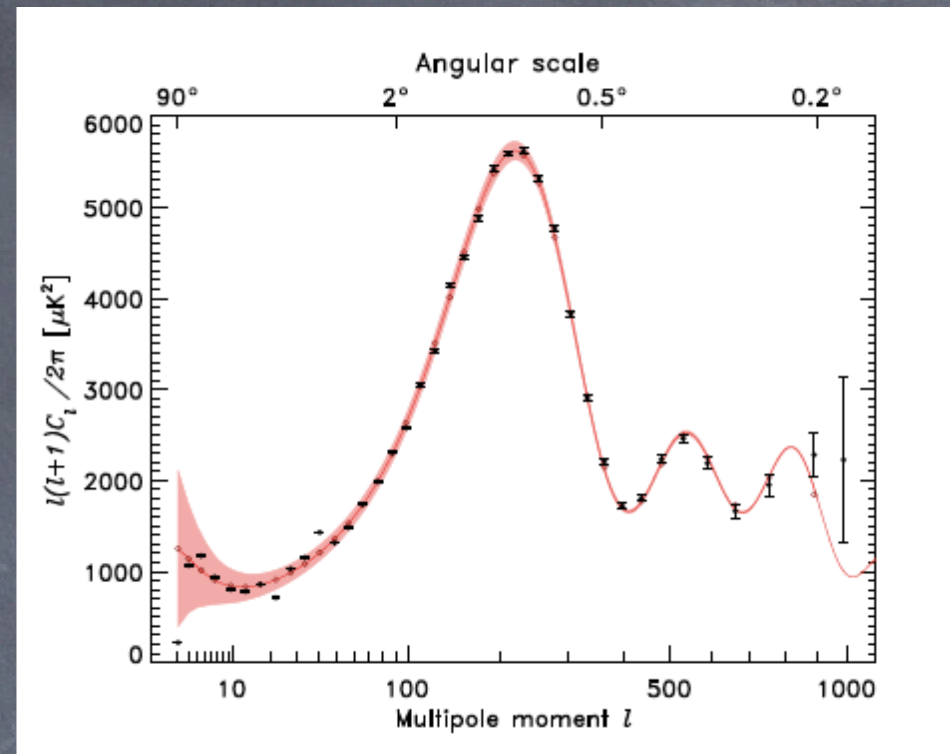
Gravity

It's not just a good idea.
It's the law!

rotation curve

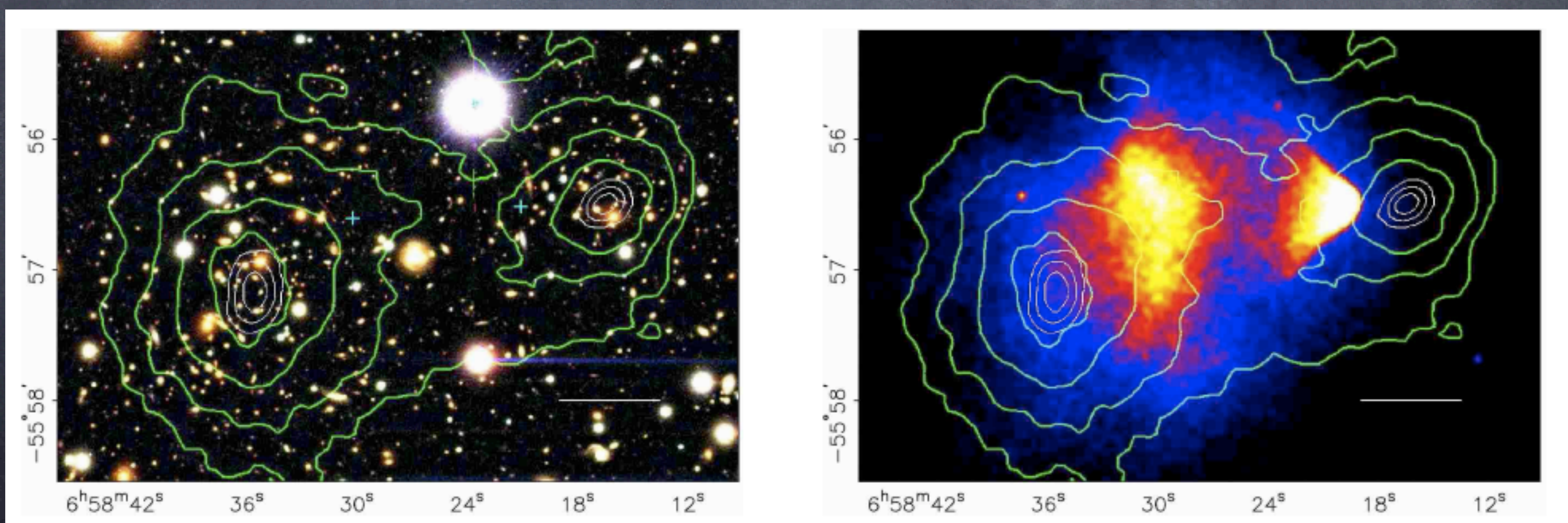


CMB



lensing

Bullet cluster



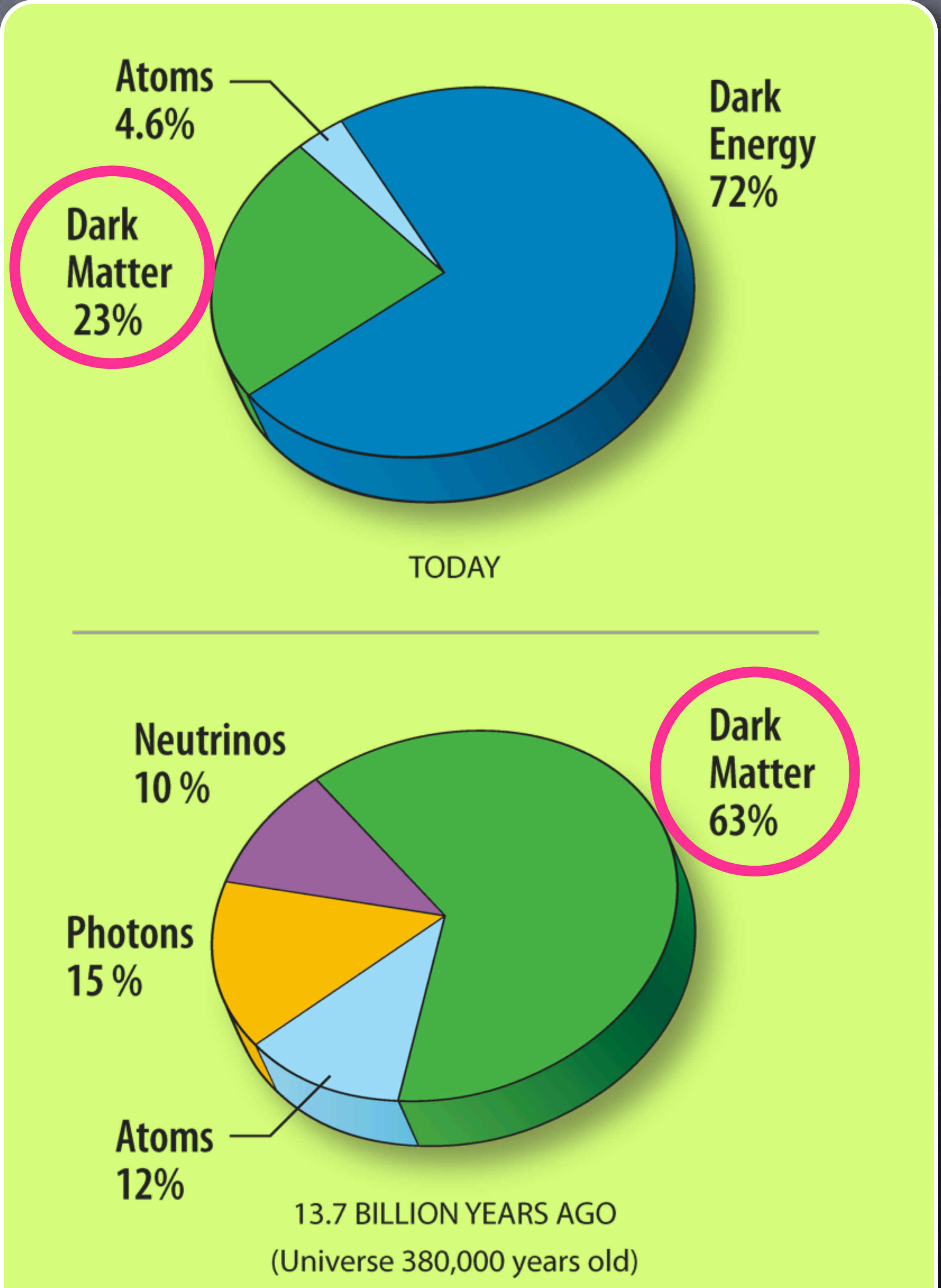
+ large scale structures.

Dark Matter

The presence of DM has been firmly established.

$$\Omega_{DM} \sim 0.2$$

- CMB observation
- Rotation curves
- Structure formation
- Big bang nucleosynthesis



(taken from WMAP webpage)

Dark Matter Candidates

Many

Must be electrically neutral, long-lived and cold.

No DM candidates in SM.

- SUSY

  LSP is long-lived if R-parity is a good symmetry.

  e.g.) neutralino, gravitino, etc. (right-handed sneutrino, axino).

- Little Higgs, UED, etc.

  The lightest T-parity/KK-parity particles

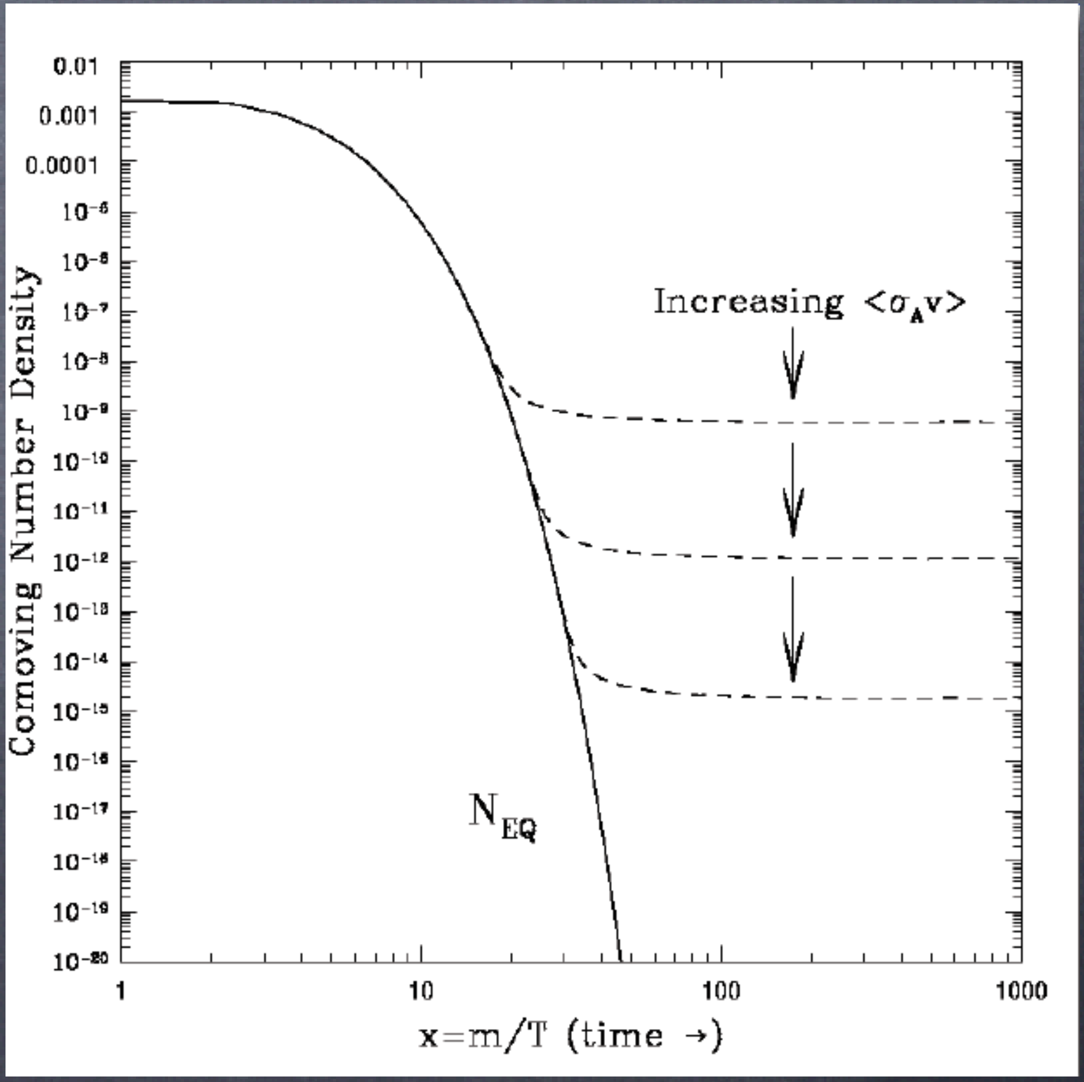
- Others Q-ball, saxion, light moduli, sterile nu, etc...

WIMP ``miracle"?

- Thermal relic abundance of WIMPs of mass O(100)GeV - O(1)TeV is close to the observed DM density.

$$\Omega_{\rm WIMP} = \frac{0.3}{\langle \sigma v \rangle / ({\rm pb})}$$

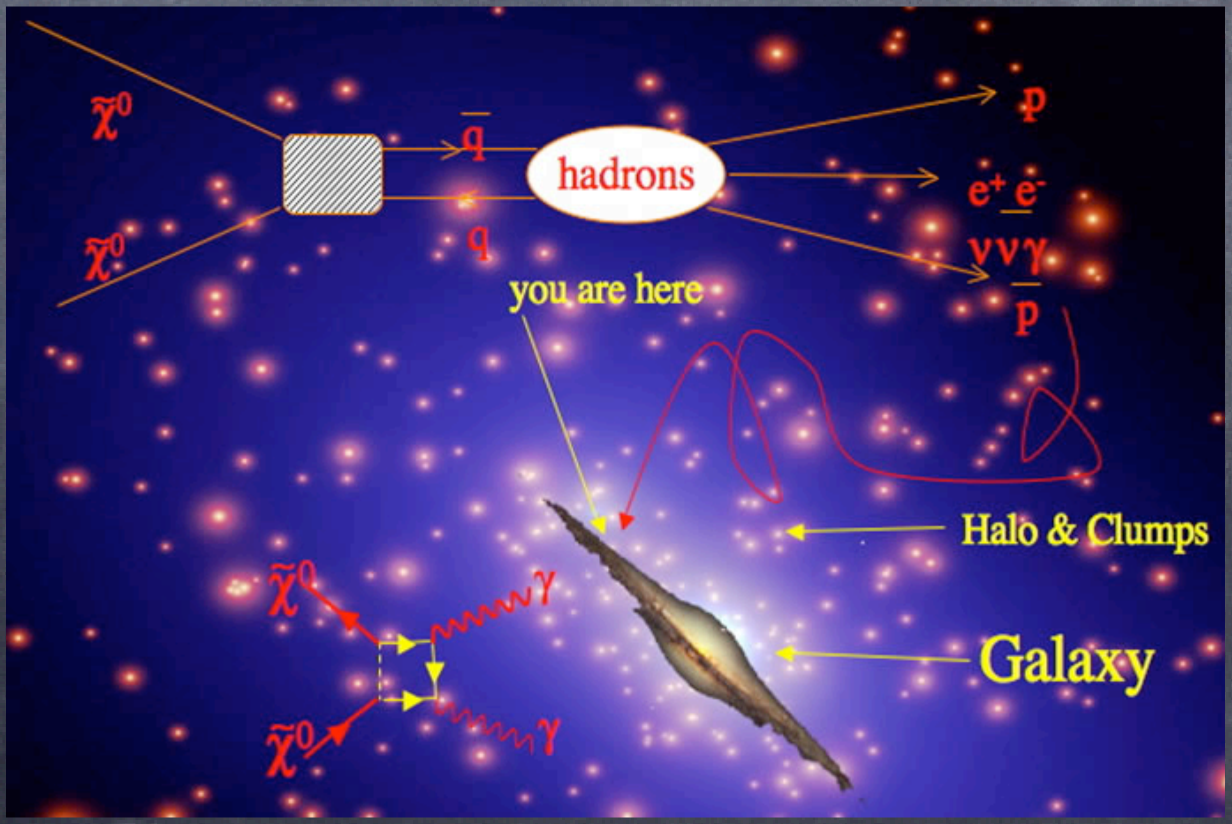
$$\langle \sigma v \rangle_{\rm thermal} \simeq 3 \times 10^{-26}\, {\rm cm}^3/{\rm sec}$$



Sounds reasonable, but it is better keep in mind other possibilities.

Dark matter may not be completely dark.

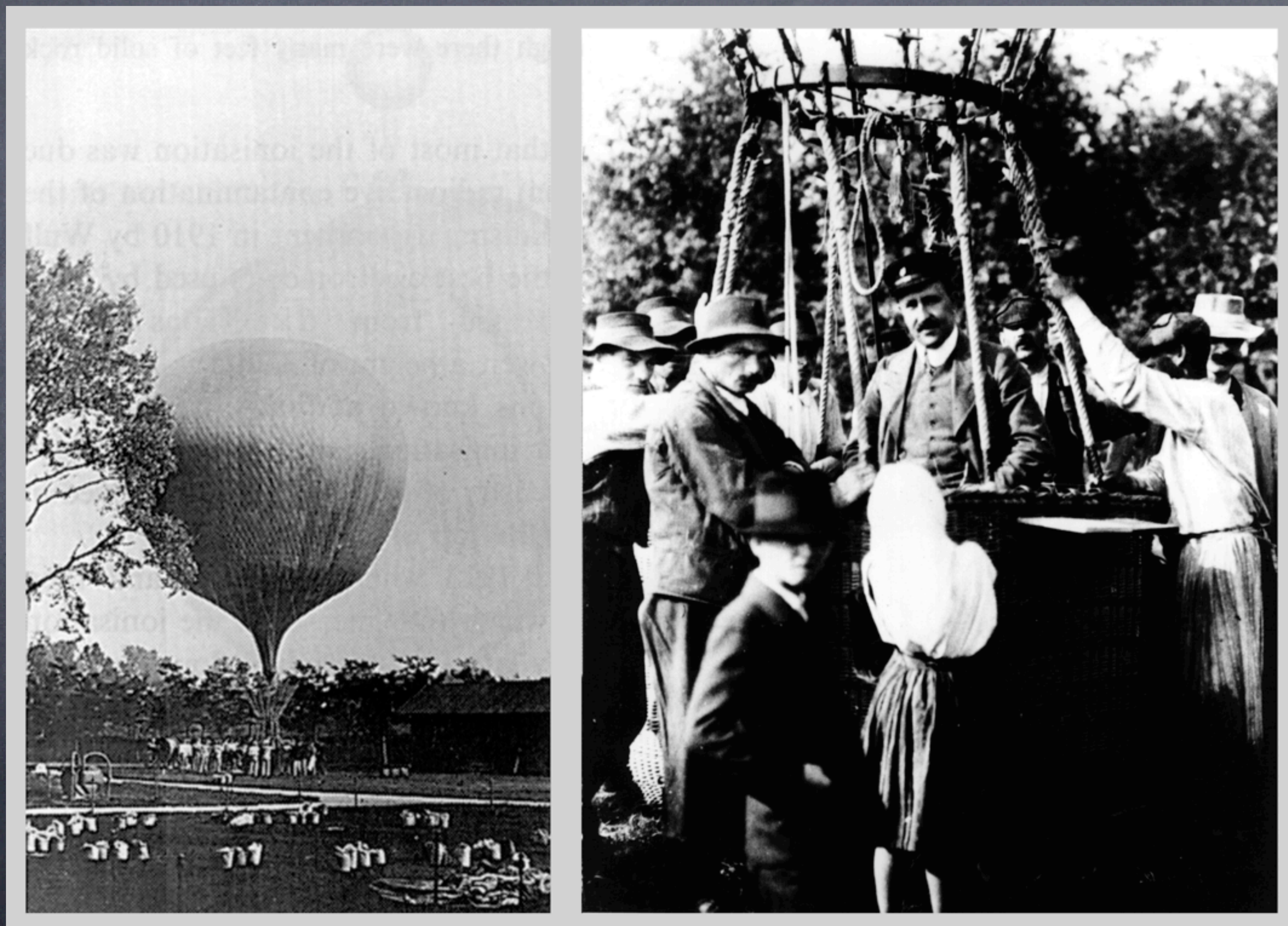
- Collider
- Direct detection
- Indirect search: annihilation/decay of dark matter



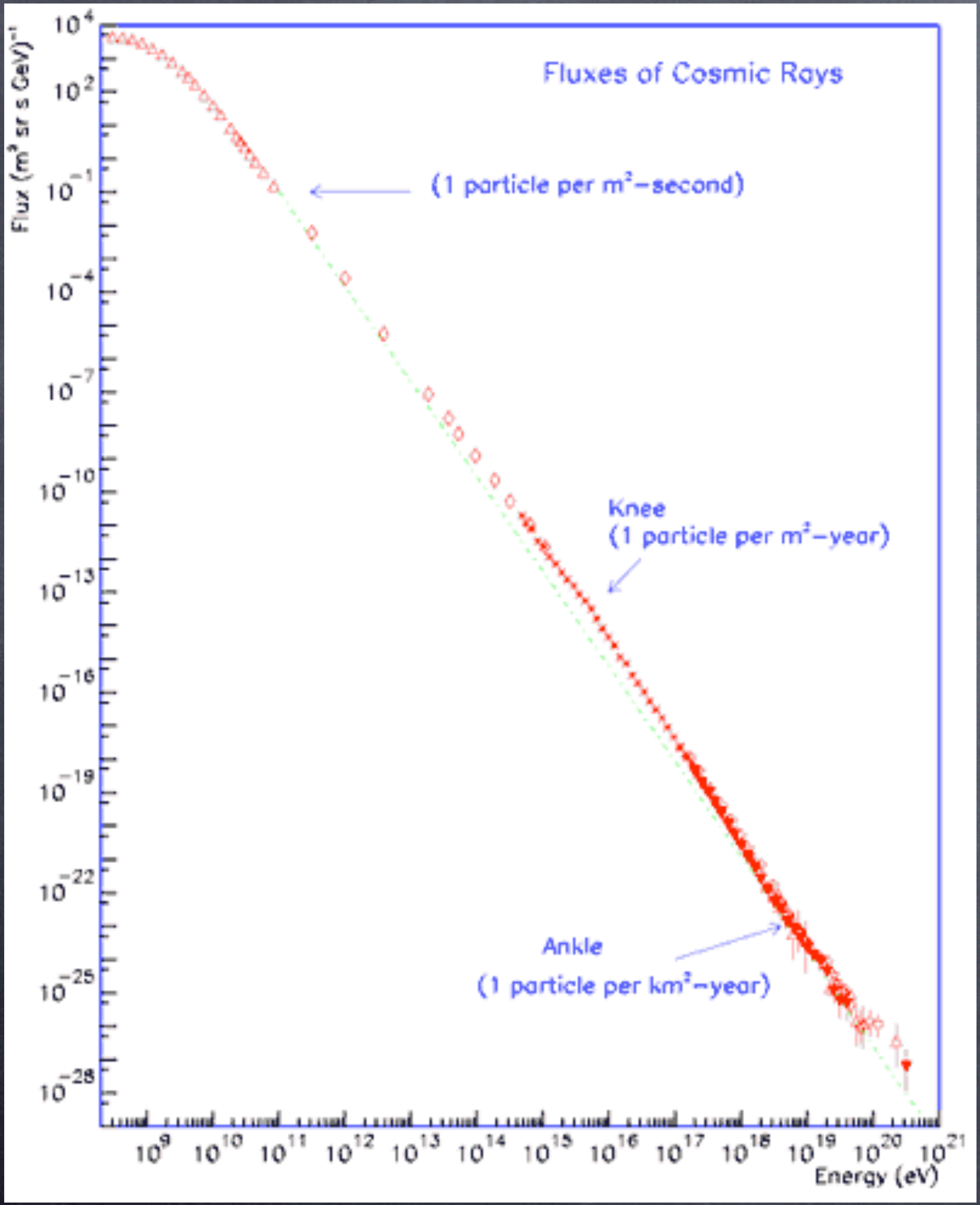
(http://pamela.roma2.infn.it/index.php)

So, what is cosmic-rays?

Cosmic-ray was discovered in 1912 by Victor Hess using the balloon experiment.



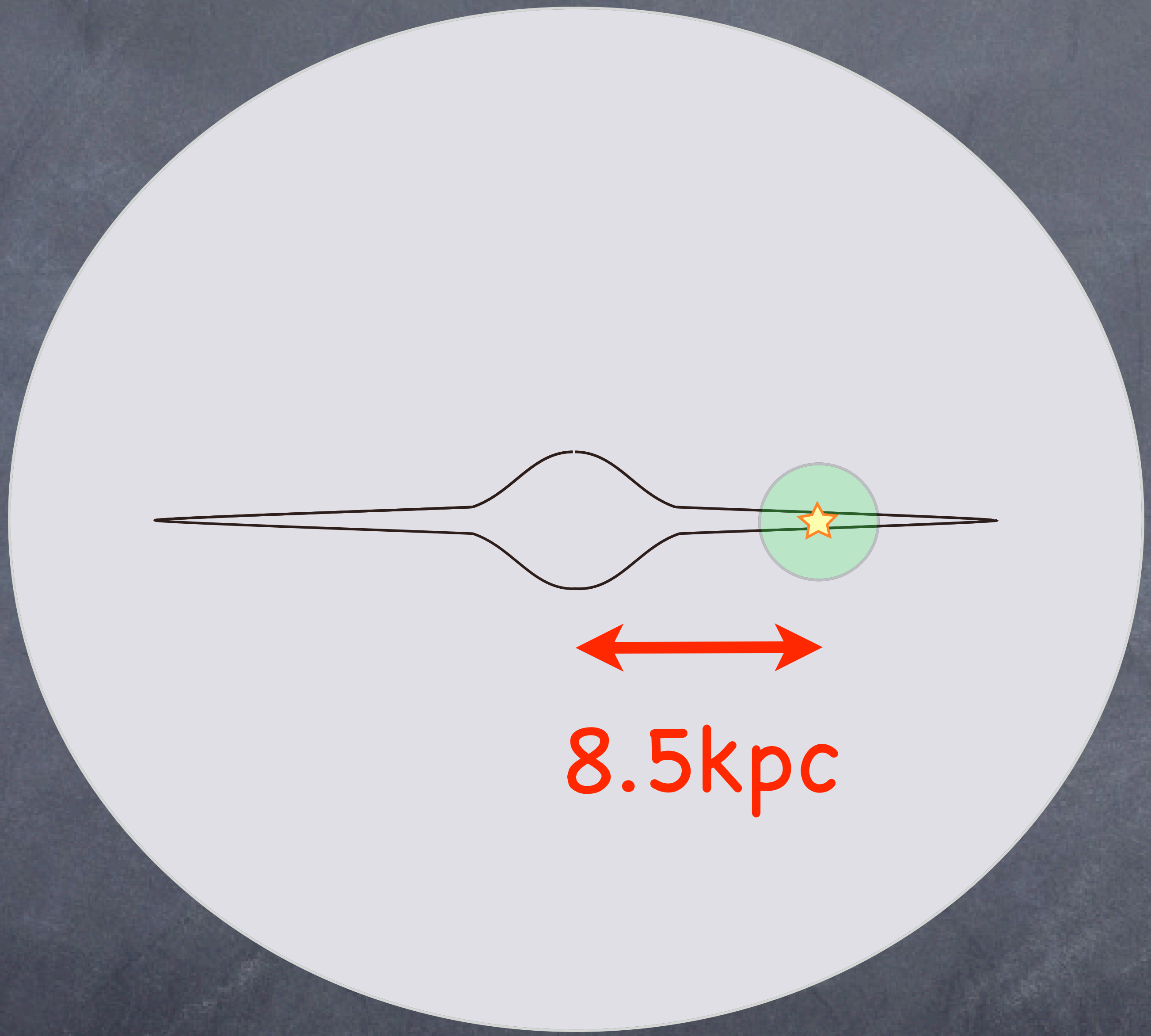
Total cosmic-ray spectrum



Main components: proton (+ alpha)

Heavier nuclei: a few %
Electron: 1-0.1%
Positron: 0.1-0.01%
Antiproton: 0.01%

The cosmic-ray particles diffuse in our Galaxy.



1 pc = 3.26 lyr
= 3×10^{16} m

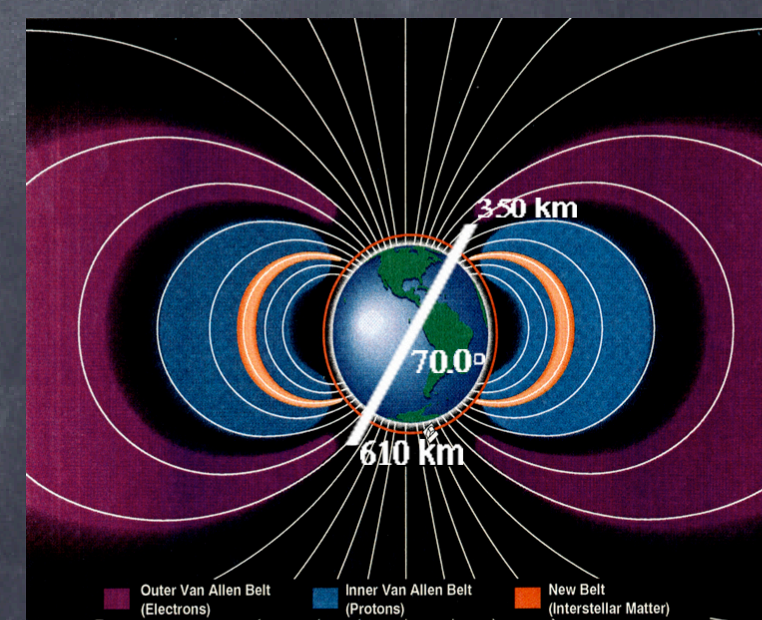
In particular, 1TeV electron/positron loses its most of the energy in 10^5yrs, traveling about 1kpc.

2. PAMELA, ATIC/PPB-BETS, Fermi, and H.E.S.S. results

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

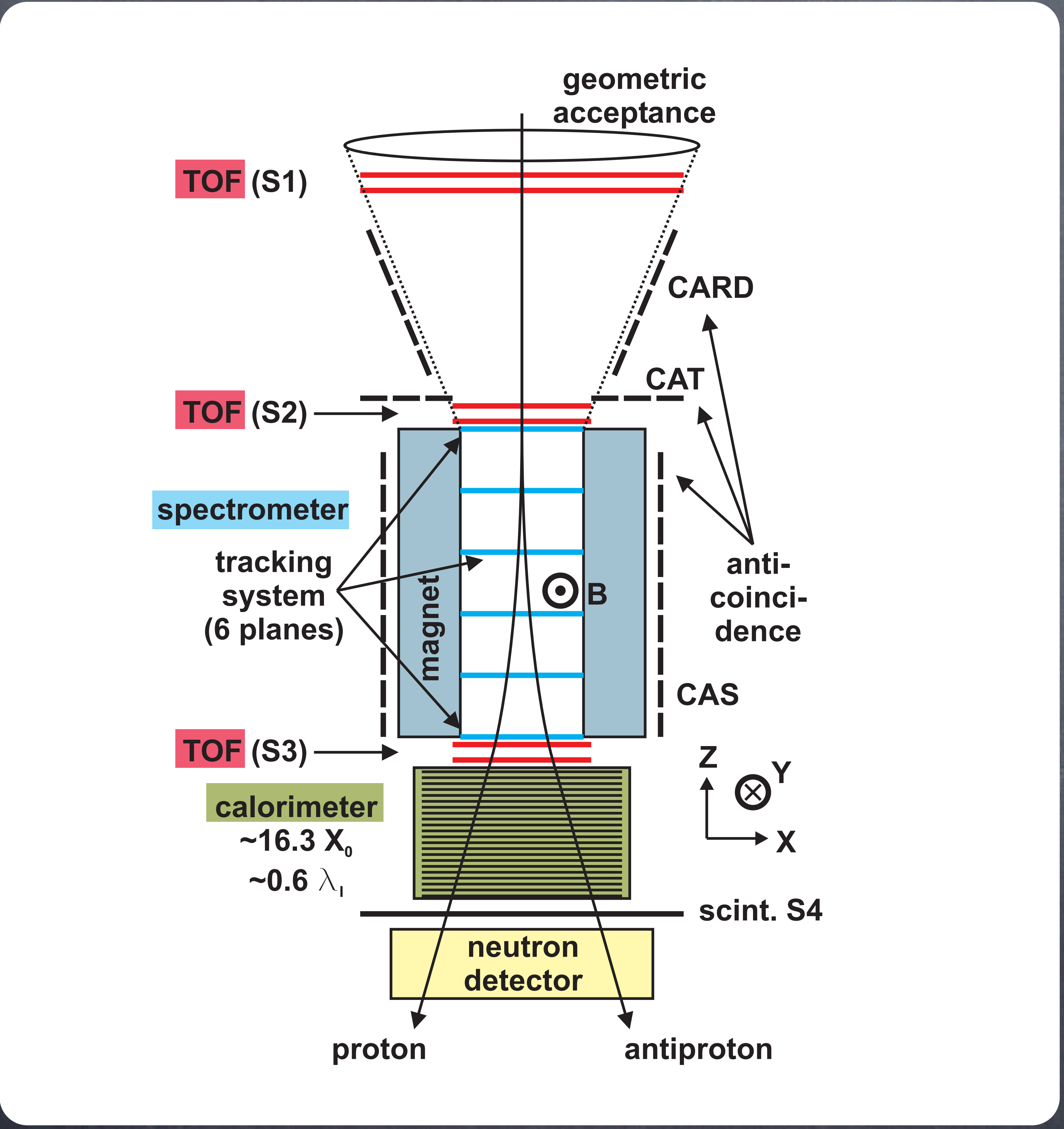
- Launched on the 15th of June 2006.
- An altitude between 350 and 610 Km with an inclination of 70°.
- Expected to operate at least by Dec. 2009 (3 years).



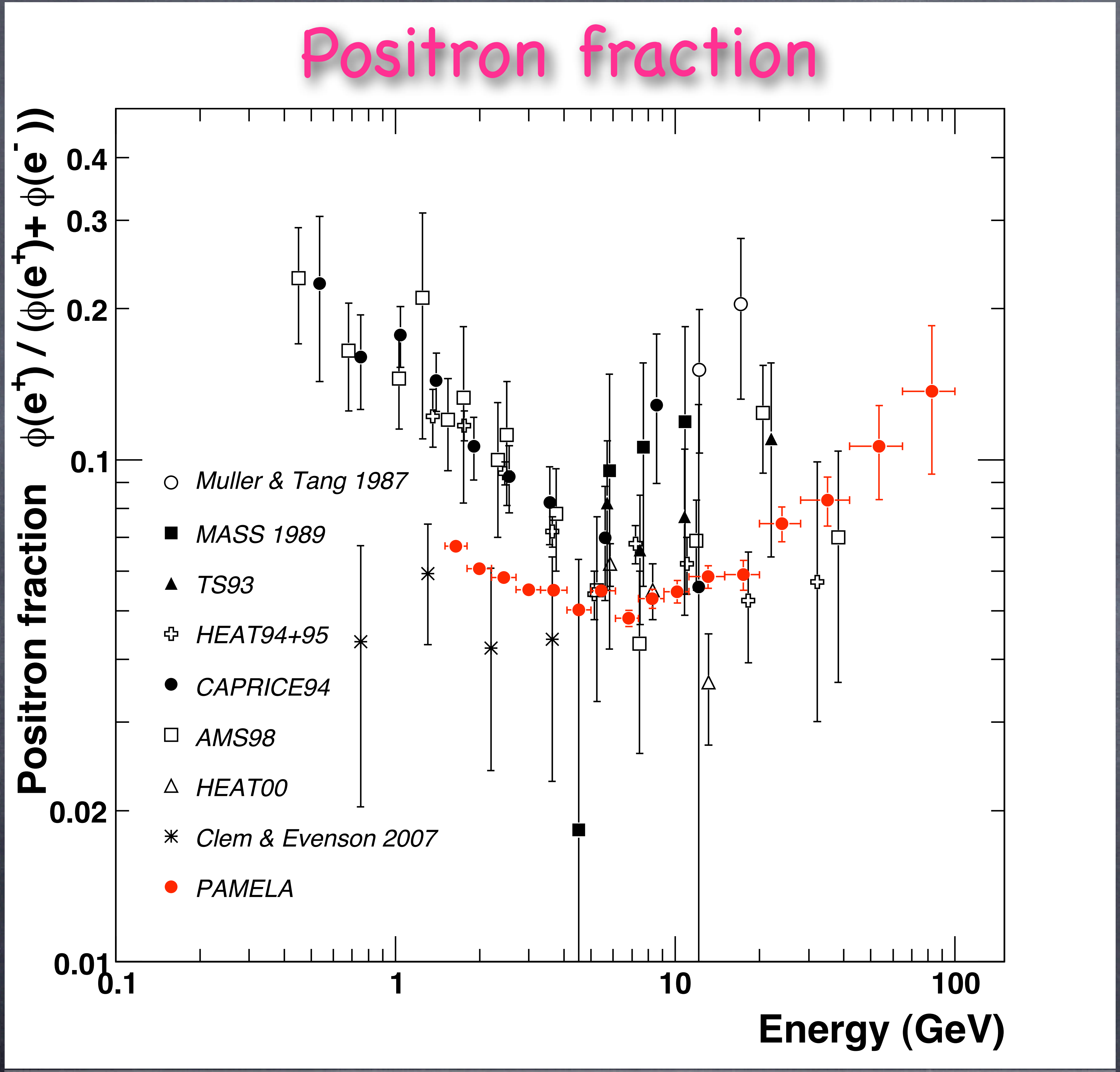
Energy range:

Positron: 50 MeV - 270 GeV

Antiproton: 80 MeV - 190 GeV


geometric
acceptance
TOF (S1)
CARD
CAT
TOF (S2)
spectrometer
tracking
system
(6 planes)
magnet
B
anti-
coinci-
dence
CAS
TOF (S3)
Z
Y
X
calorimeter
~16.3 X0
~0.6 λI
scint. S4
neutron
detector
proton
antiproton

This is what PAMELA observed.

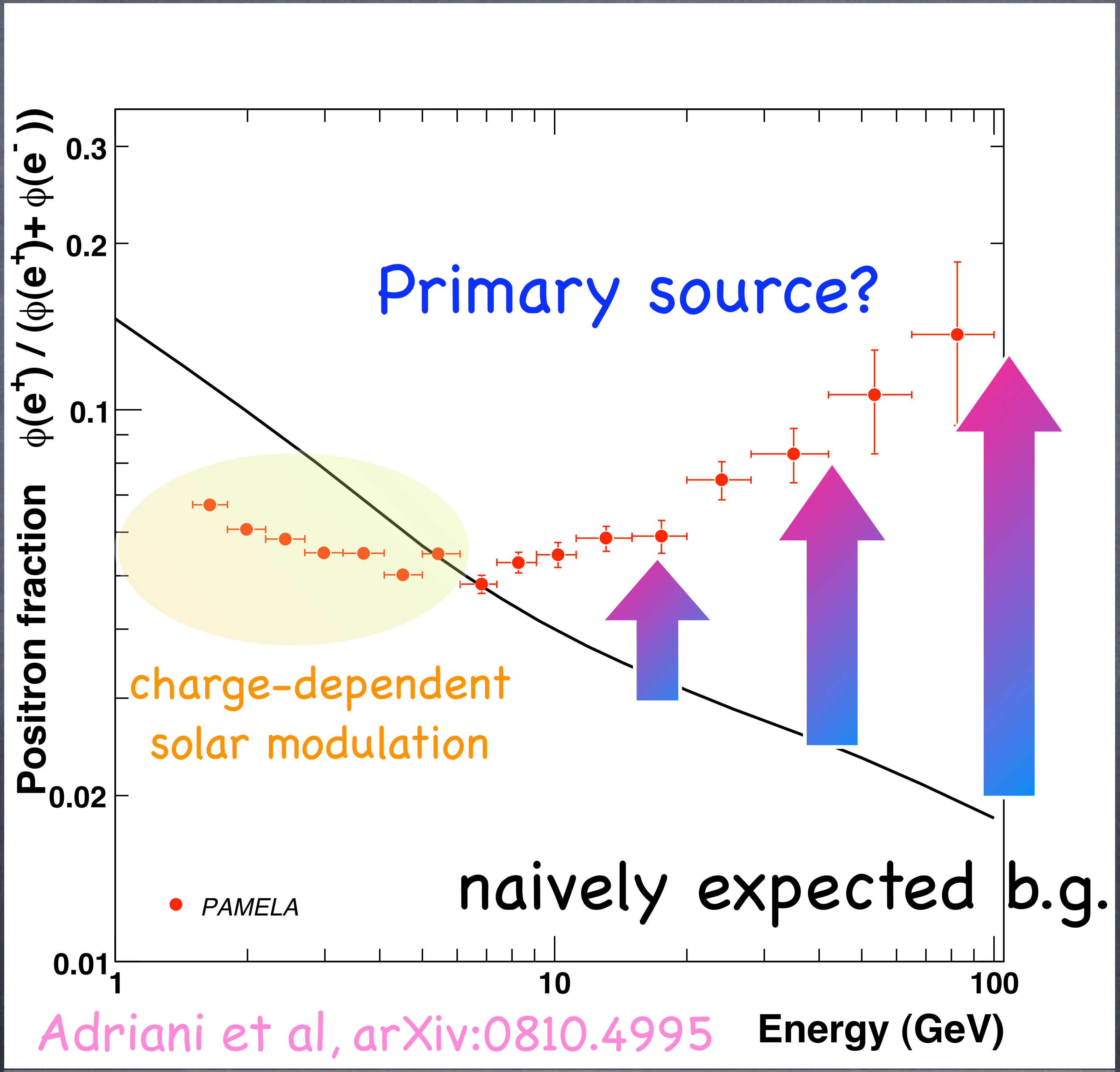


July2006-
Feb. 2008

151,672 e-
9,430 e+
in 1.5-100GeV

Adriani et al, arXiv:0810.4995

PAMELA found an excess in the positron fraction!

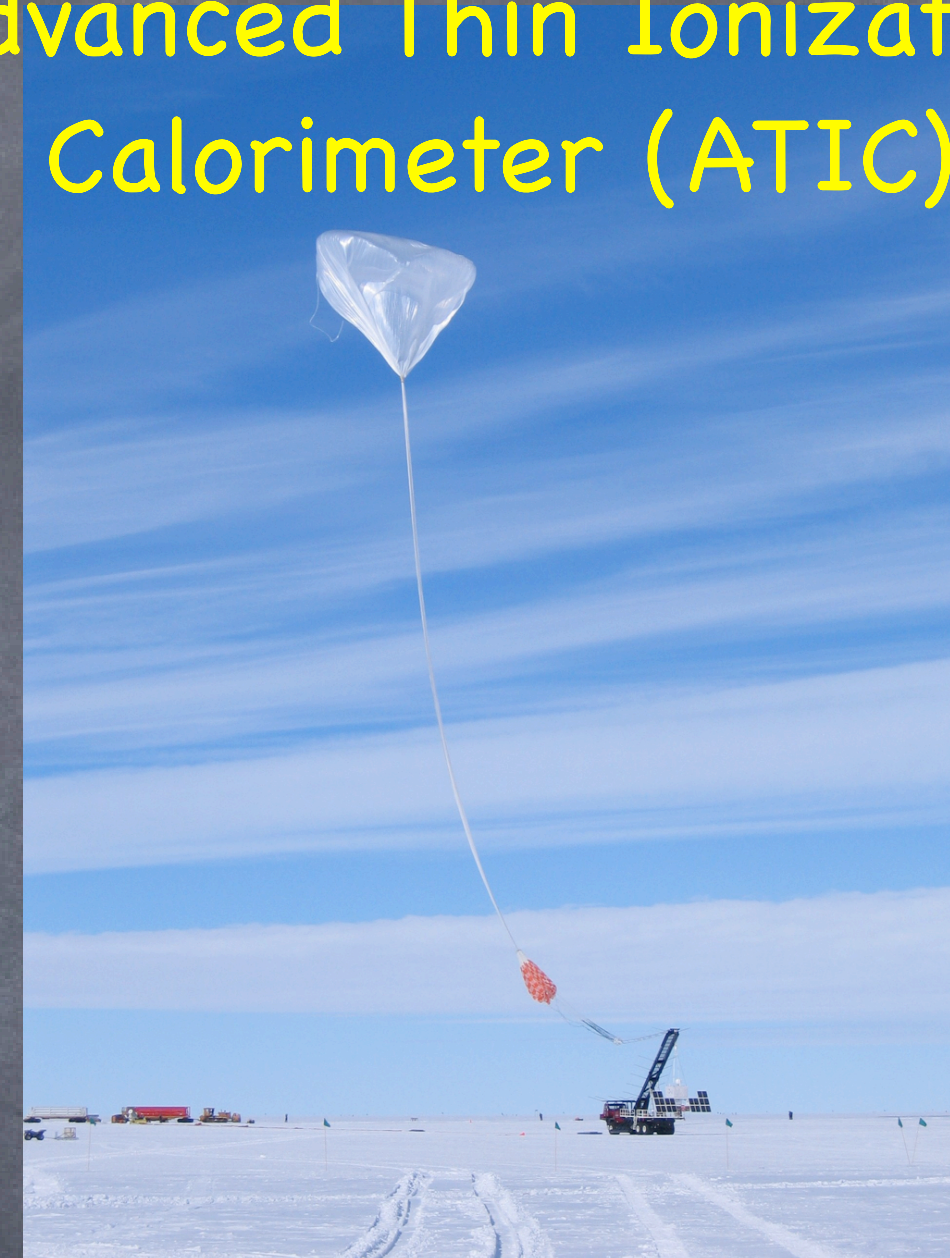


Polar Patrol Balloon (PPB)

PPB-BETS: 2004

http://ppb.nipr.ac.jp/

Advanced Thin Ionization Calorimeter (ATIC)



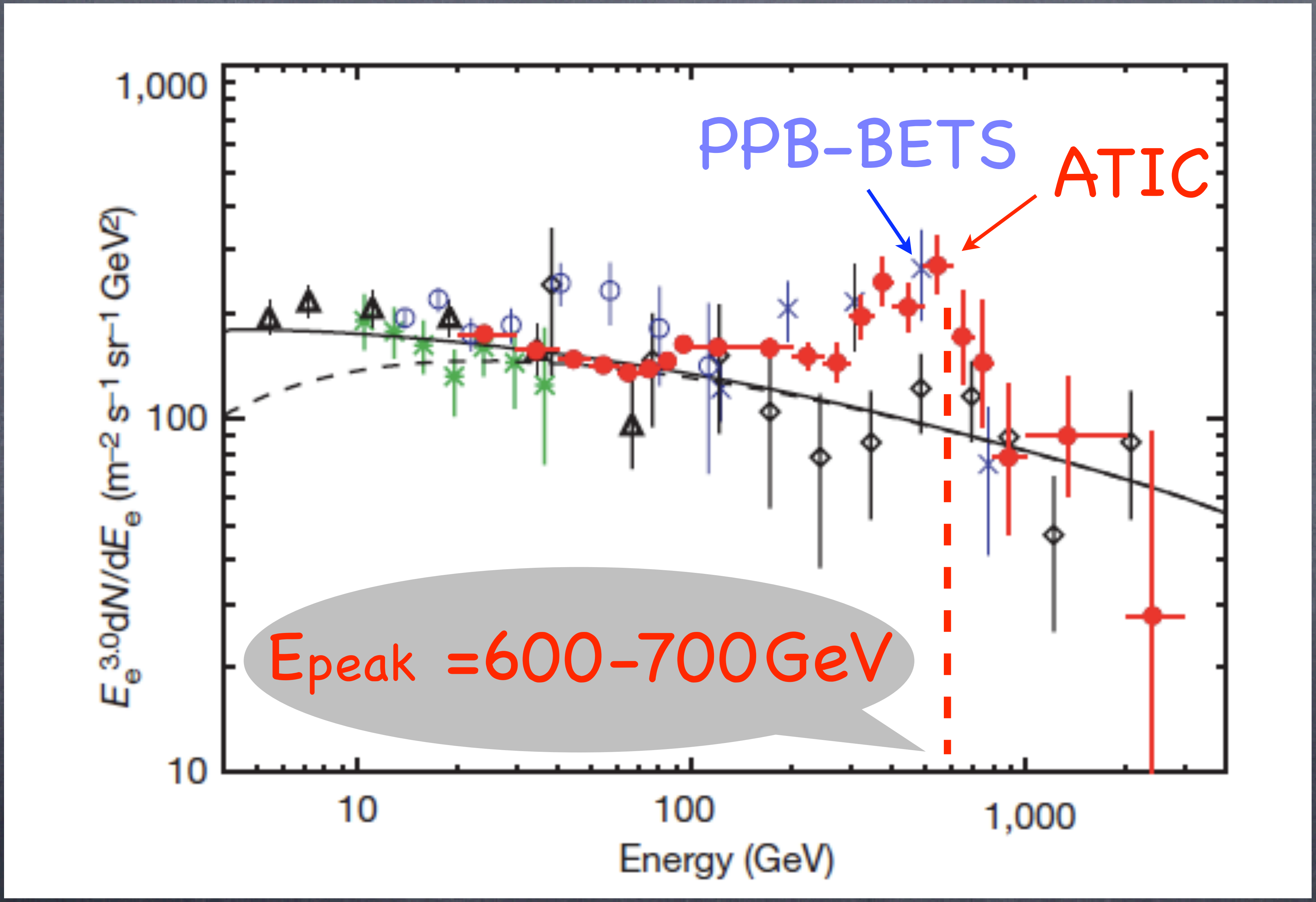
ATIC-1: 2001

ATIC-2: 2003

ATIC-4: 2008

http://atic.phys.lsu.edu/aticweb/index.html

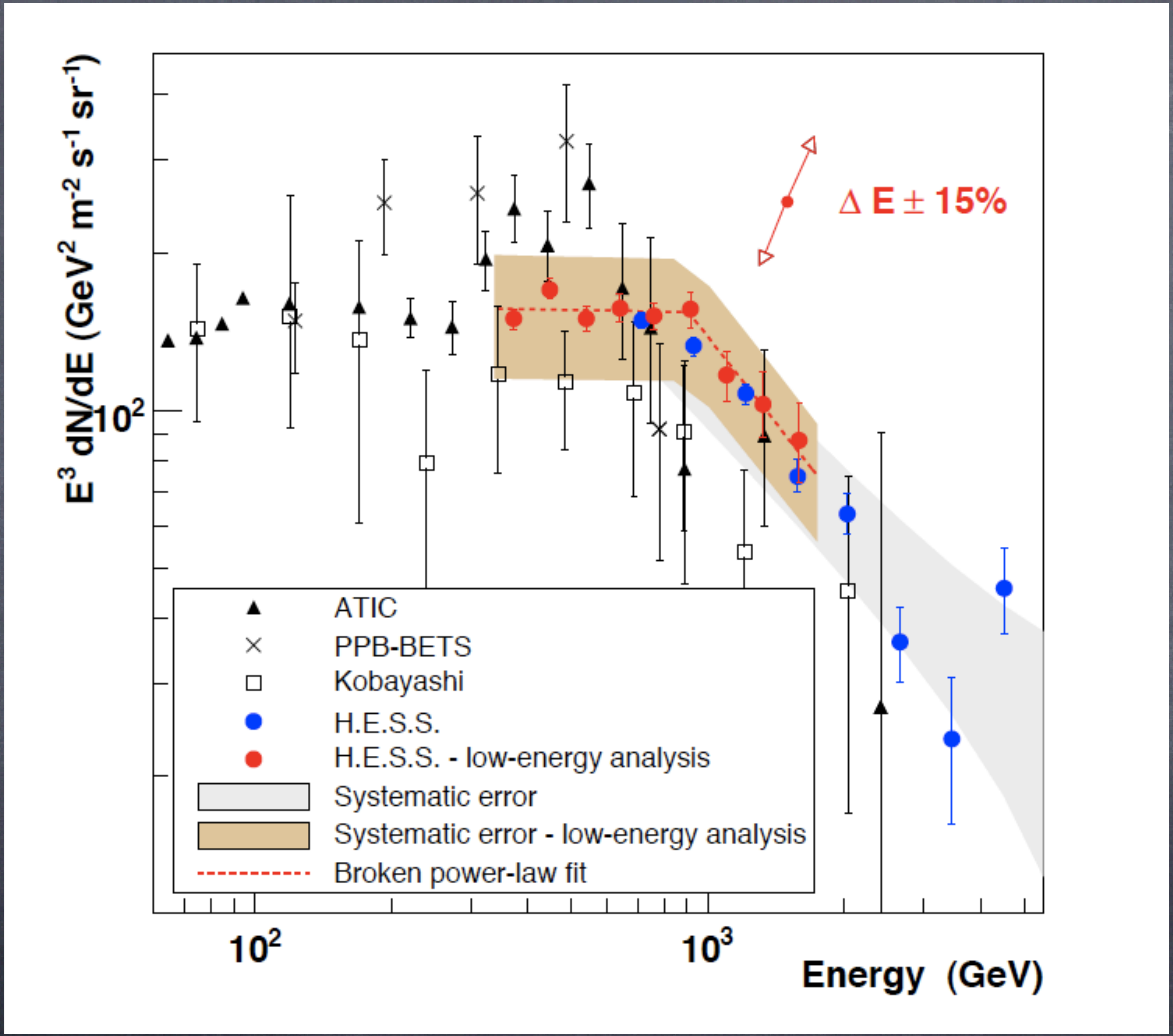
ATIC/PPB-BETS found excess in the ($e^- + e^+$) spectrum



Chang et al, Nature Vol.456 362 2008 [ATIC]
Torii et al, arXiv:0809.0760 [PPB-BETS]

H.E.S.S.

Khomas Highland of Namibia



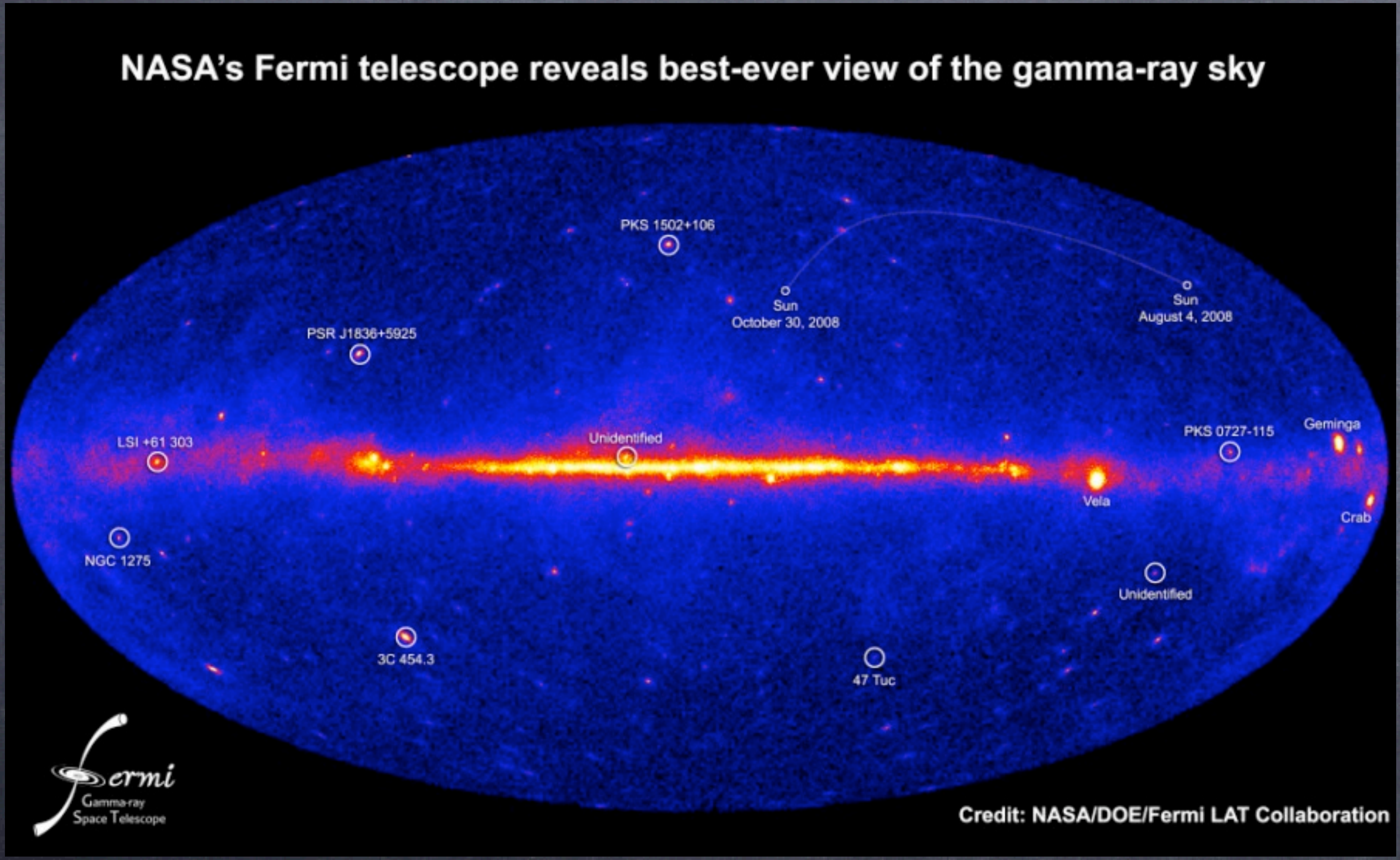
arXiv:0811.3894, 0905.0105

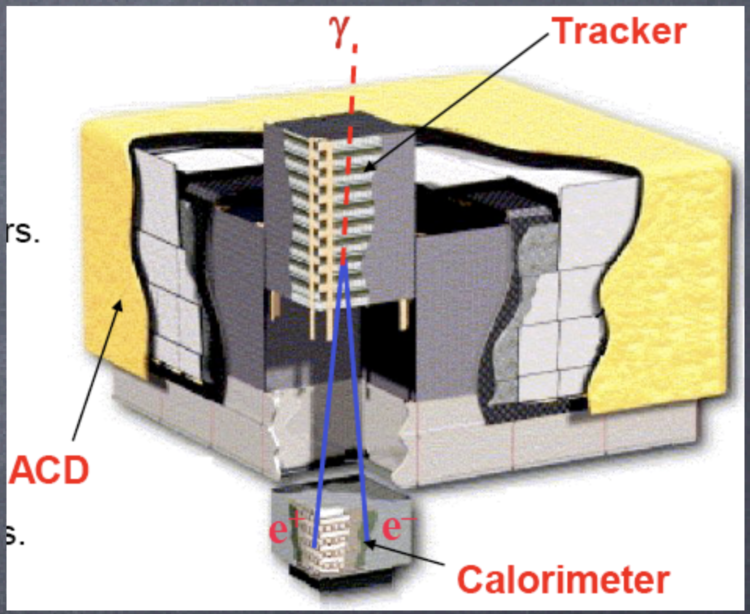
Fermi (formerly GLAST)

Launched on 11th of June, 2008.

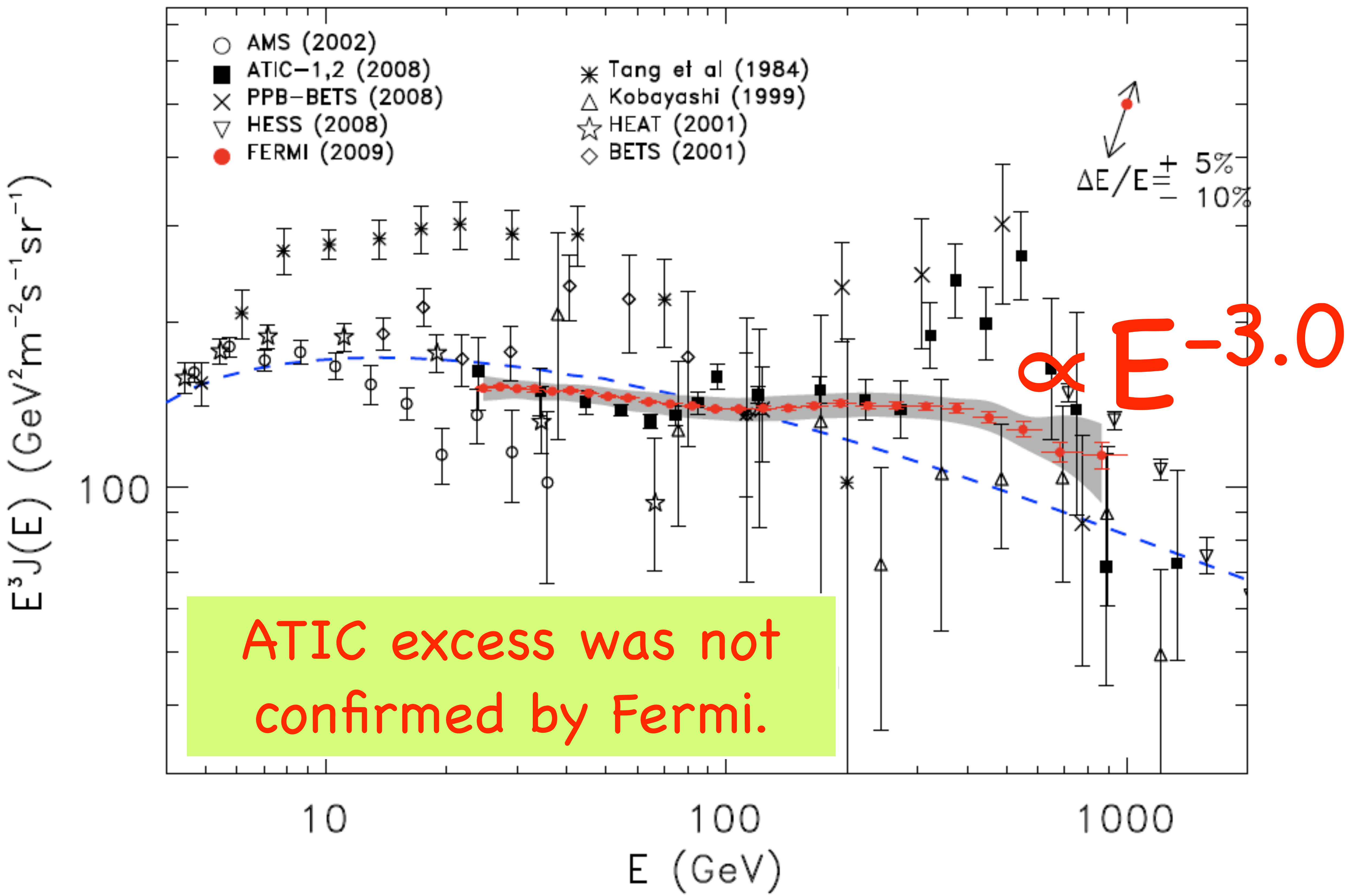
20MeV-300GeV

First-Light sky map with 95 hrs (4 days).





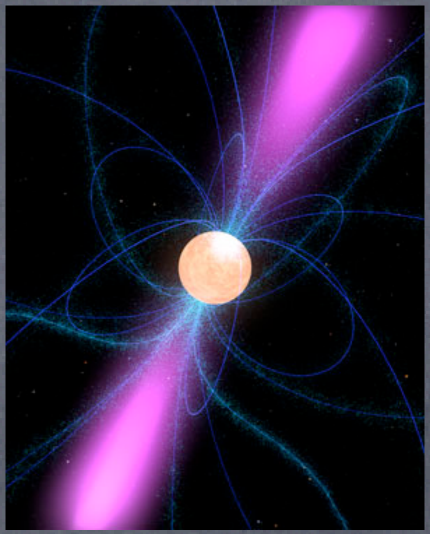
Many point sources will be identified, all the data will be released in next August.



arXiv:0905.0025 [astro-ph.HE]

Combining the PAMELA, Fermi, and H.E.S.S. results, it is likely that there is an excess in the CR $e^{-}+e^{+}$ from several tens GeV up to 1TeV.

Candidates for CR $e^{-}+e^{+}$



- Pulsars
- Modification in propagation or acceleration/production in local SNR
- Dark Matter decay/annihilation

What will be a smoking gun?

- The annihilation/decay of DM is often accompanied with anti-protons, gamma-rays, and neutrinos. The detection through those channels will be indispensable.
- If the positron/electron excess is dominated by a few nearby pulsars, we may be able to observe directional anisotropy of O(0.1-1)%.

Need more data!!

3. Dark Matter Models

Dark matter must account for

1) the observed electron + positron flux

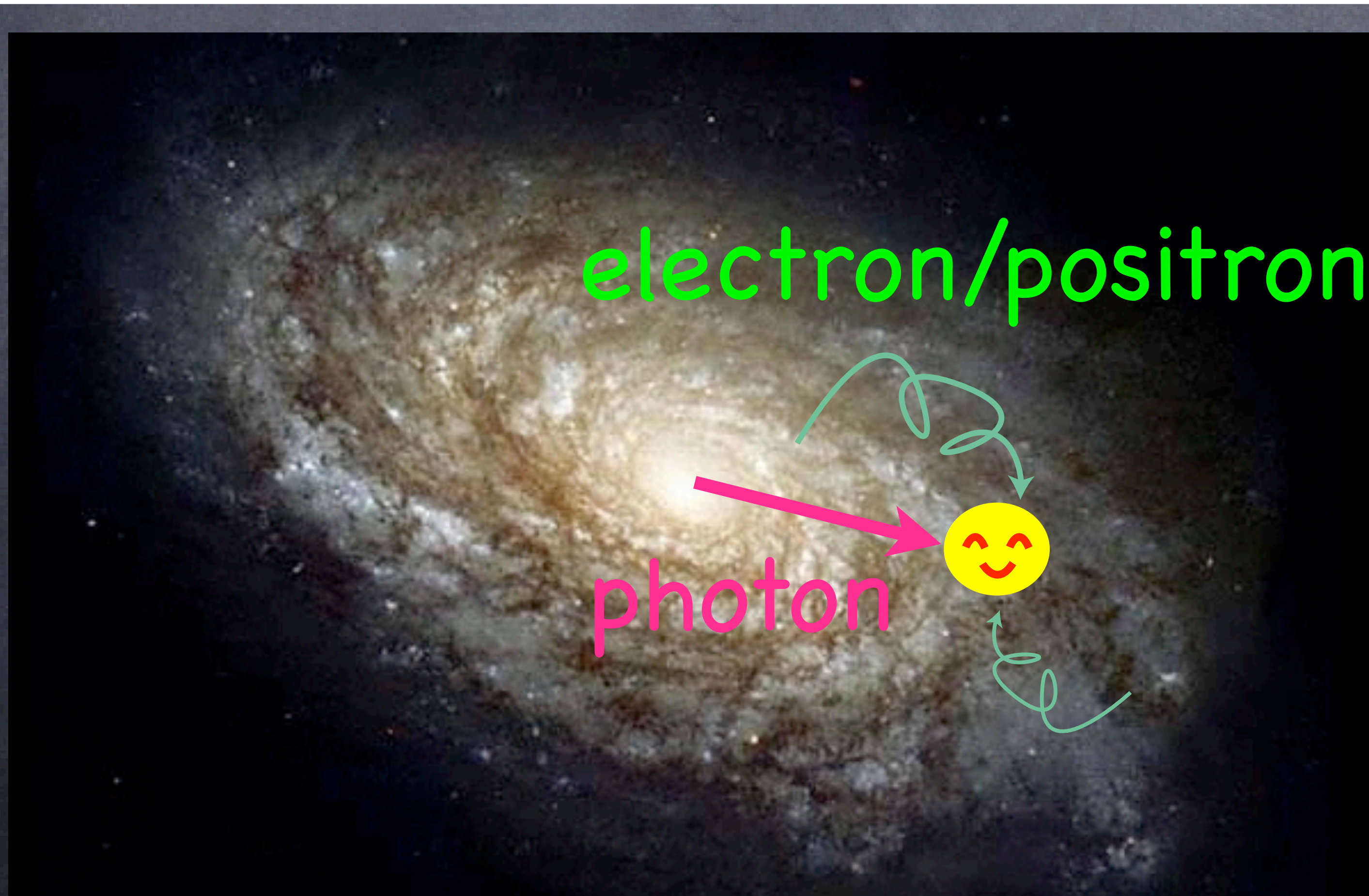
2) while avoiding anti-proton, neutrino, and gamma-ray overproduction.

Electron + Positron flux:

Propagation through the galactic magnetic field is described by a diffusion equation

$$\frac{\partial f_e}{\partial t} = K(E)\nabla^2 f_e(E,x) + \frac{\partial}{\partial E}[b(E) f_e(E,x)] + Q(E,x)$$

diffusion — energy loss — source



Dark Matter → source

Cross-section,
Decay rate

Annihilating DM scenario

The mass should be about 1TeV.

The needed annihilating cross section is

$$\langle \sigma v \rangle \;=\; \mathcal{O}(10^{-23})\,\mathrm{cm}^3/\mathrm{sec}$$

$$\gg \langle \sigma v \rangle_{\mathrm{thermal}} \simeq 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$$

cf. thermal relic abundance:

$$\Omega_{dm} h^2 \sim 0.1 \left(\frac{\langle \sigma v \rangle_{fo}}{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}} \right)^{-1}$$

In the thermal case, some enhancement is necessary.

Or DM may be non-thermally produced.

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Or DM may be non-thermally produced.

Decaying DM scenario

Dark matter particle with

Mass: a few TeV (or heavier)

Lifetime: $\tau \sim 10^{26}\mathrm{sec}$

Insensitive to the clumpy structure.

The longevity of DM may be a puzzle, especially if the mass is above 1TeV.

Annihilating DM scenario

$$\langle \sigma v \rangle \ = \ \mathcal{O}(10^{-23})\,\mathrm{cm}^3/\mathrm{sec}$$

$m \sim 1\,\mathrm{TeV}$
(for unit boost factor)

Decaying DM scenario

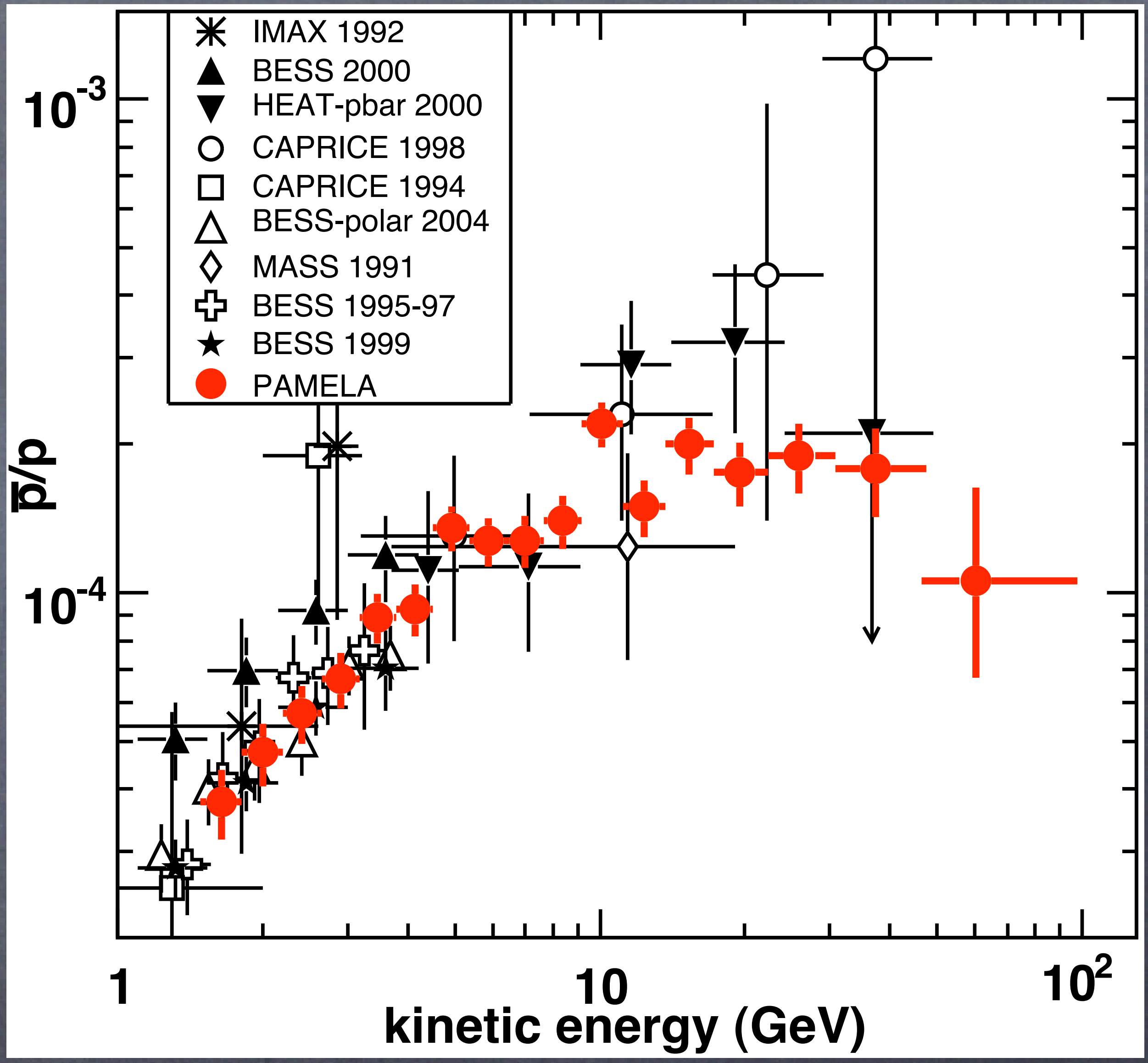
Lifetime: $\tau \sim 10^{26}\mathrm{sec}$

$m \sim$ a few TeV

Rem. One cannot distinguish annihilation and decay from CRE.

No excess in antiprotons

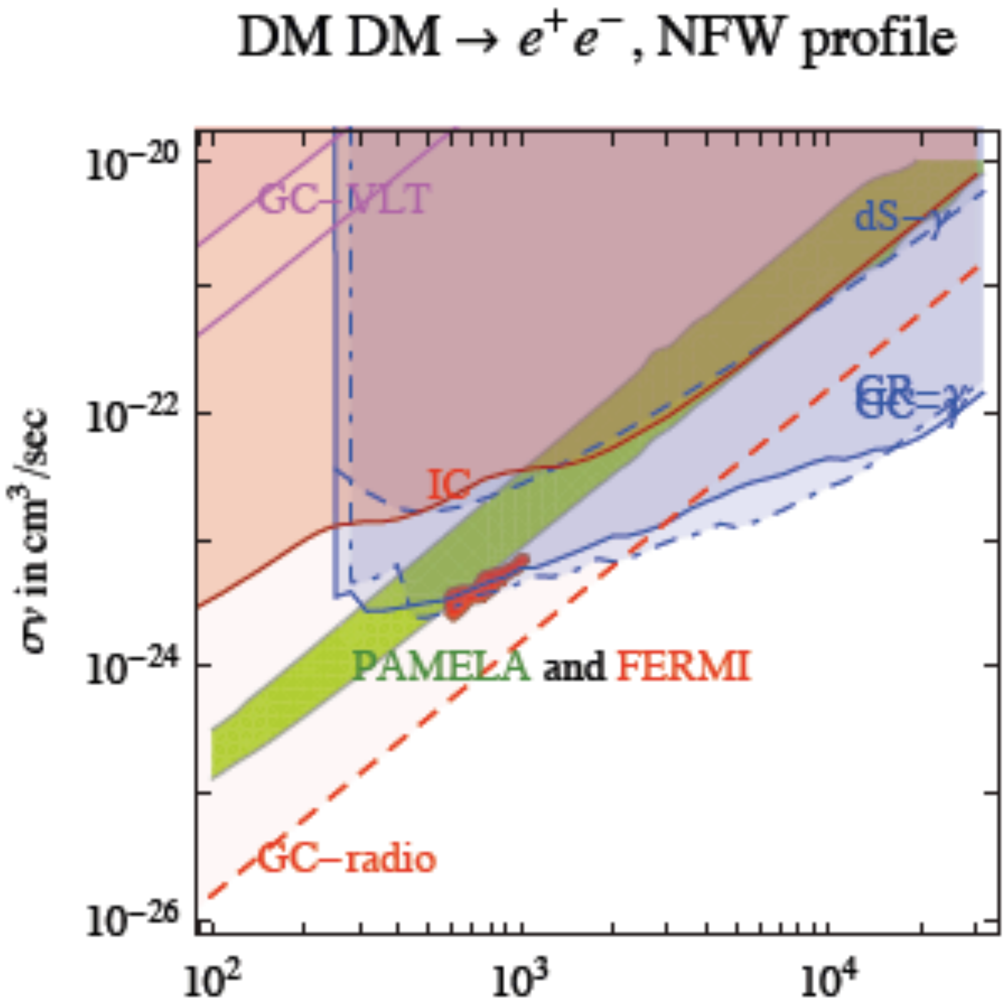
- Quark, W, Z, Higgs productions tend to lead to too many antiprotons.
- Should mainly annihilate/ decay into leptons.

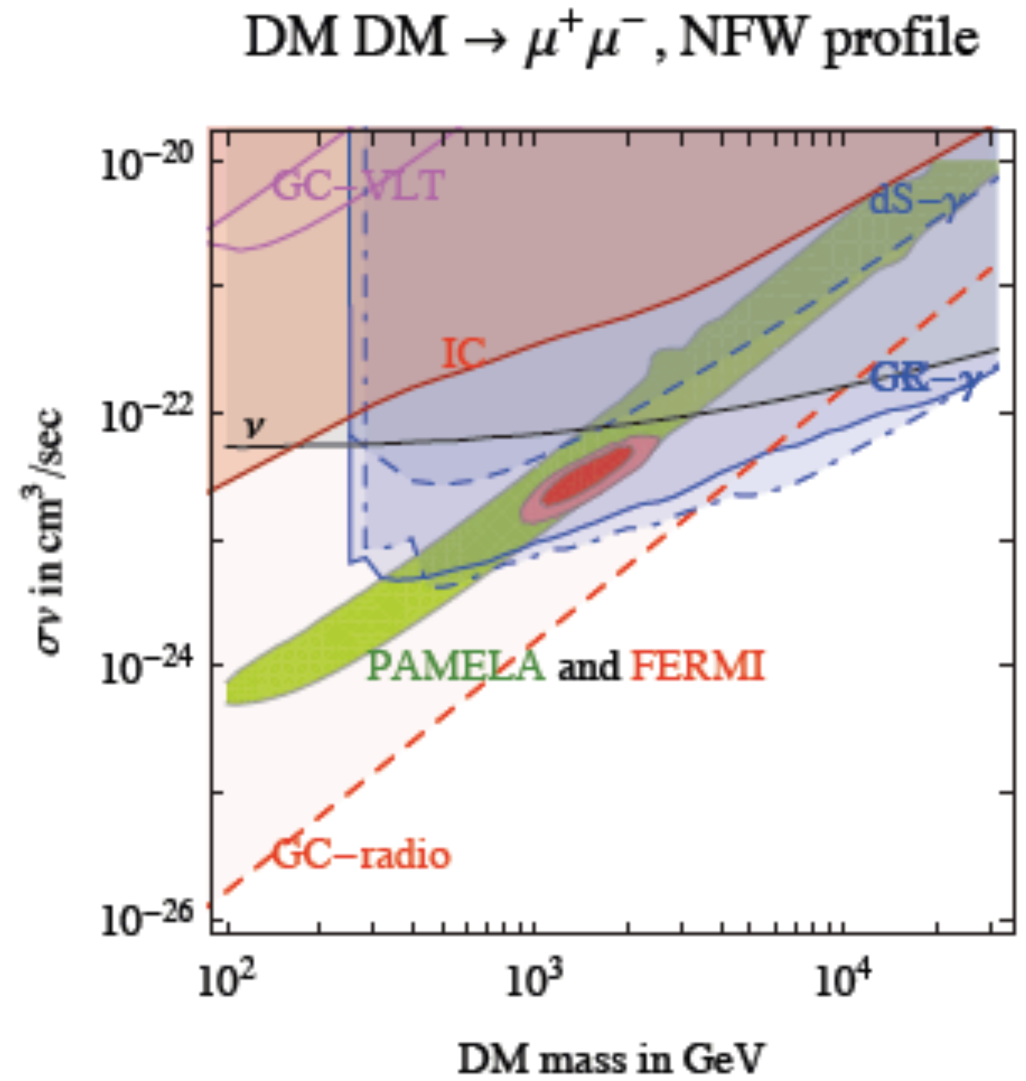


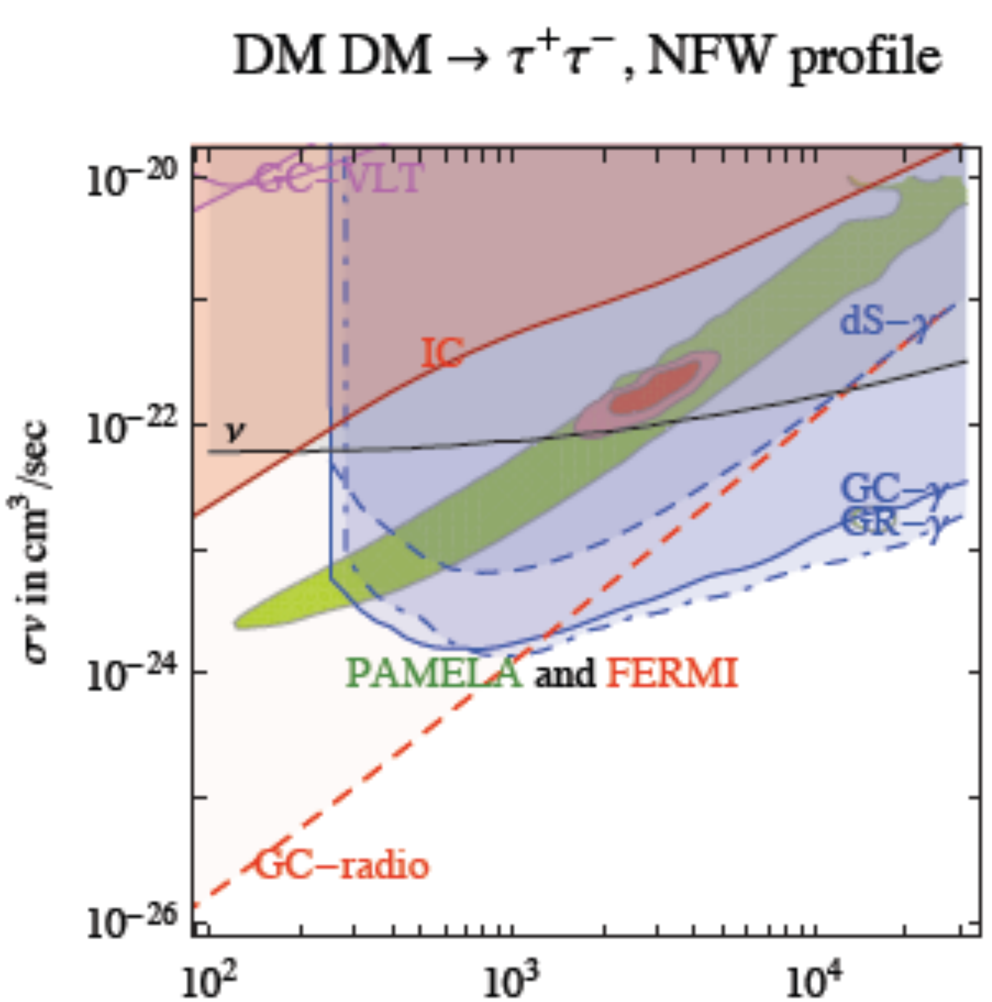
Most of the observed antiprotons are considered to be secondaries.

Adriani et al, arXiv:0810.4994

Model-independent analysis

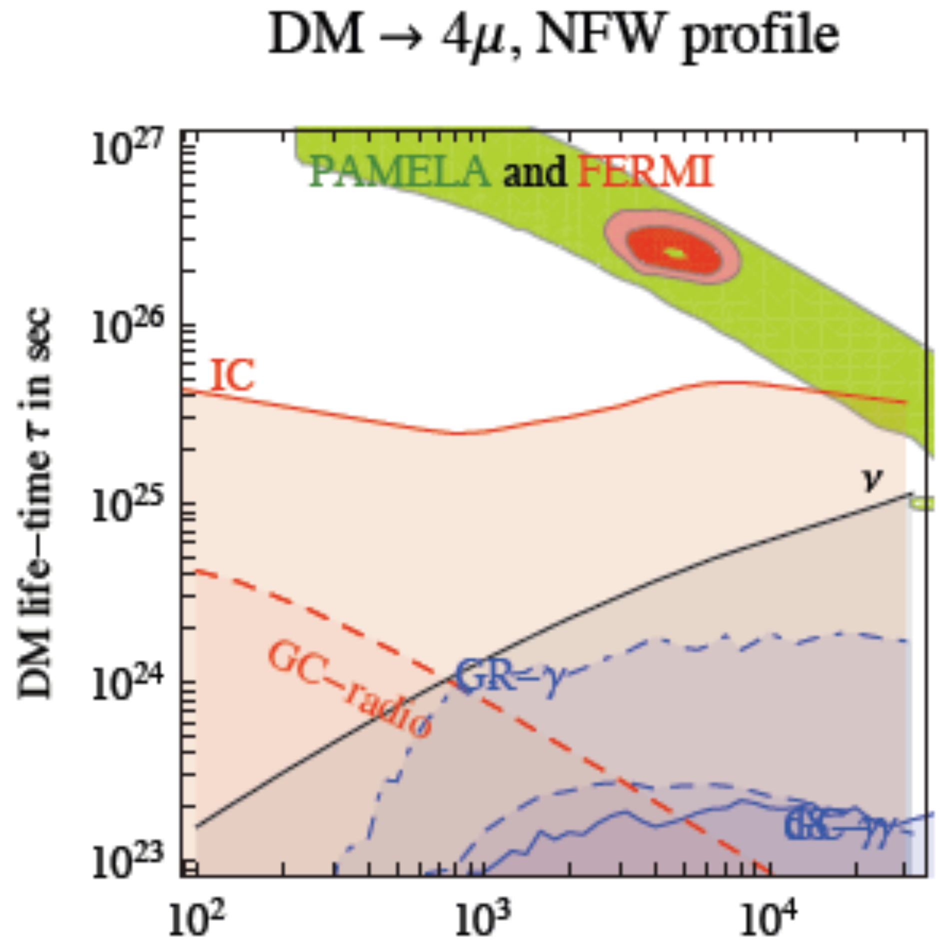


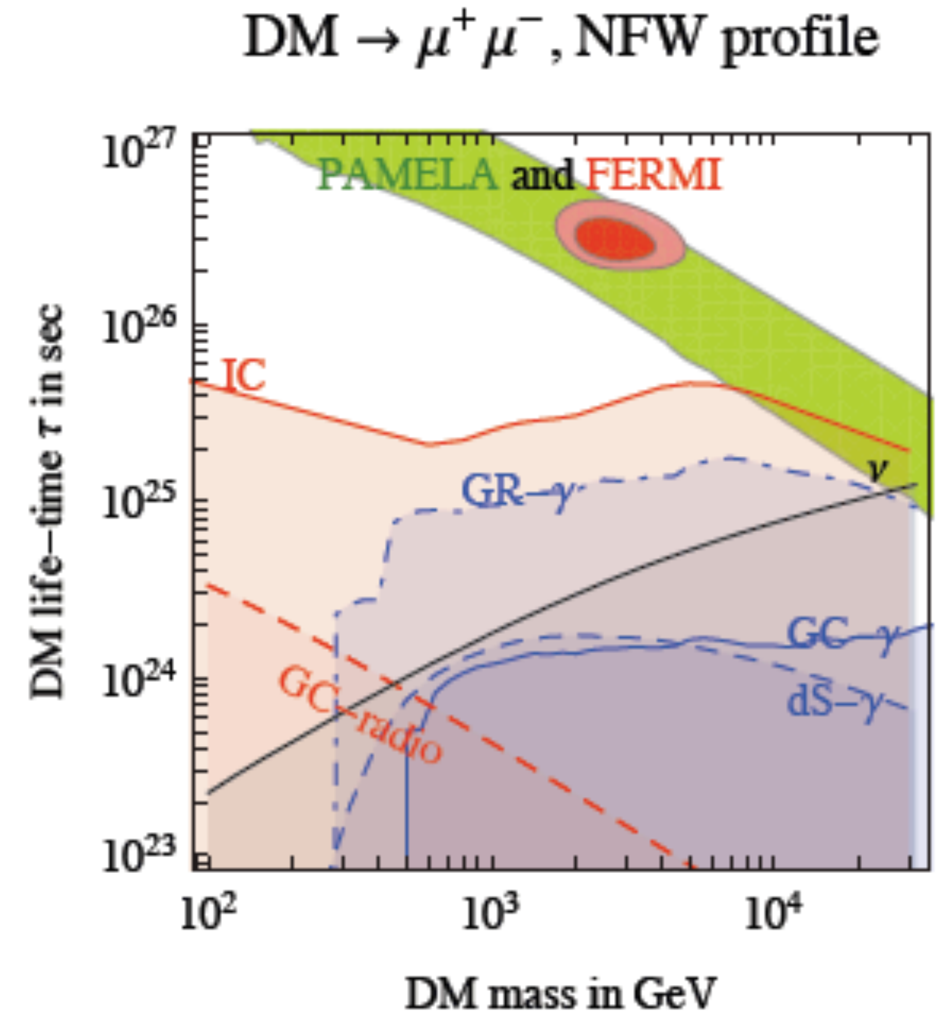


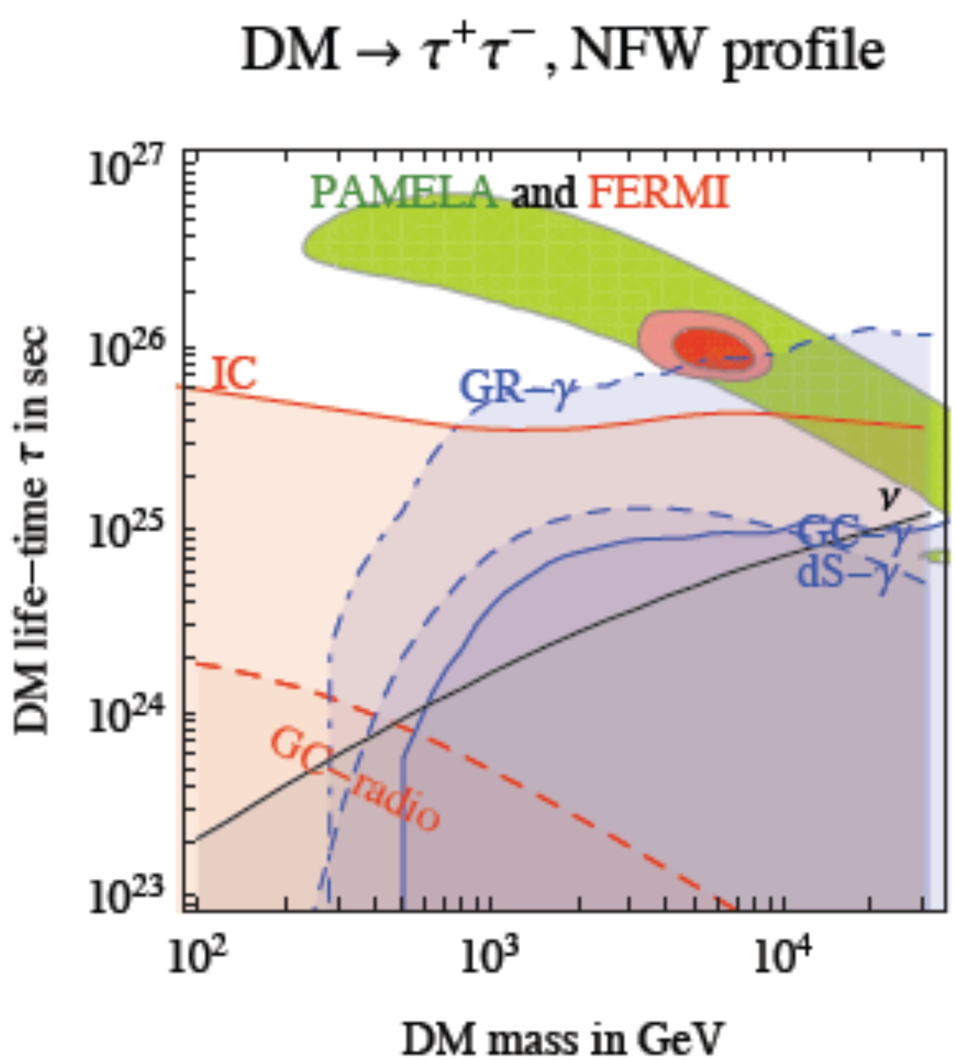


NFW Annihilation

Meade et al, arXiv:0905.0480







NFW Decay

Meade et al, arXiv:0905.0480

- Monochromatic electron production gives a poor fit to the Fermi data. (good for ATIC, though)
- Softer spectrum, e.g. (mu, tau) production is favored by Fermi.
- DM annihilation scenario is disfavored.
- DM decay scenario can satisfy the observational constraints.
- DM mass must be in the TeV scale!

Wino LSP DM

Shirai, FT, Yanagida, arXiv:0905.0388

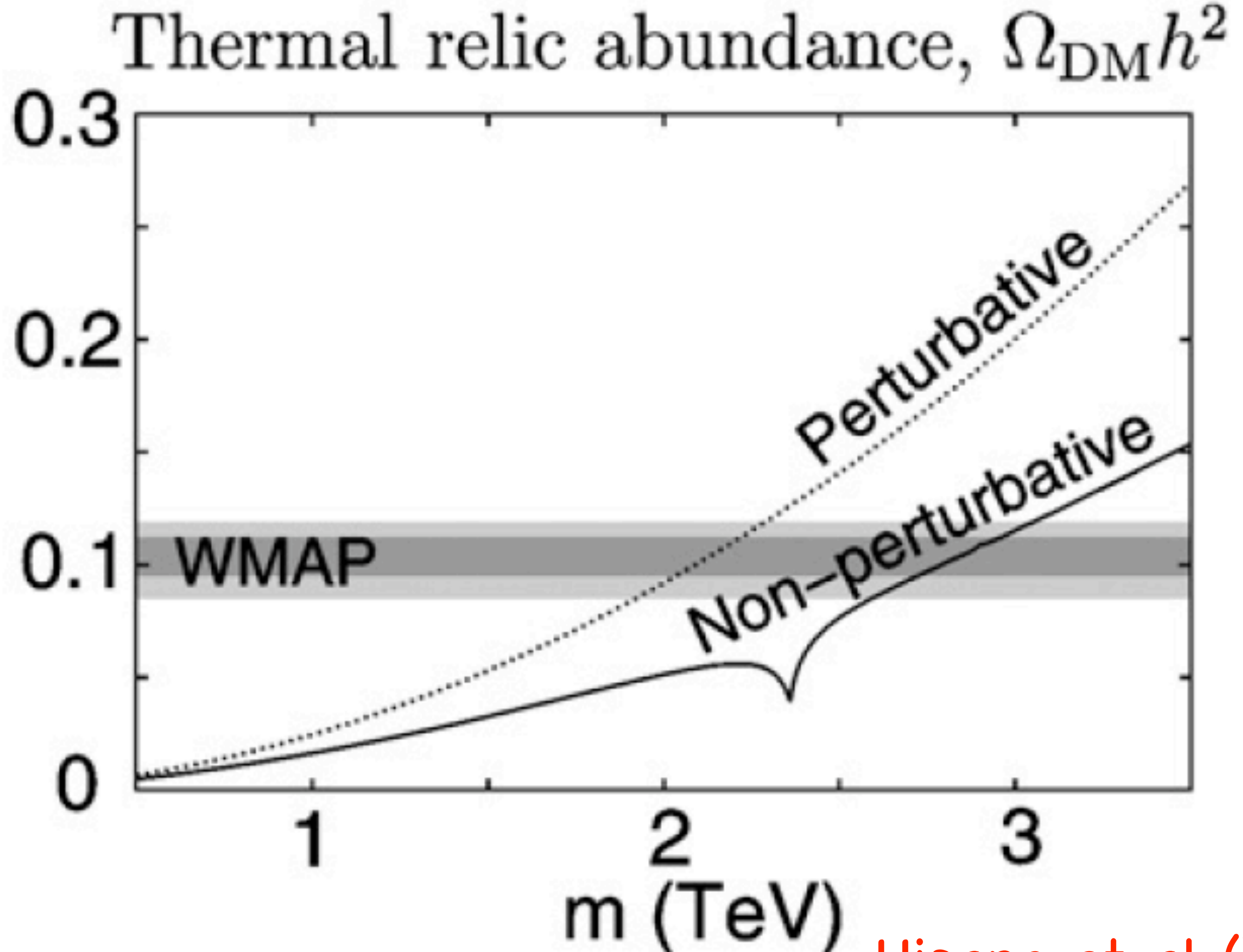
The neutralino LSP scenario is interesting, because thermal relic production can naturally explain the DM abundance.

The lightest neutralino is Bino-, Higgsino-, or Wino-like, or a certain mixture of those.

Let us focus on the **Wino LSP** scenario,

which is realized in anomaly-mediation.

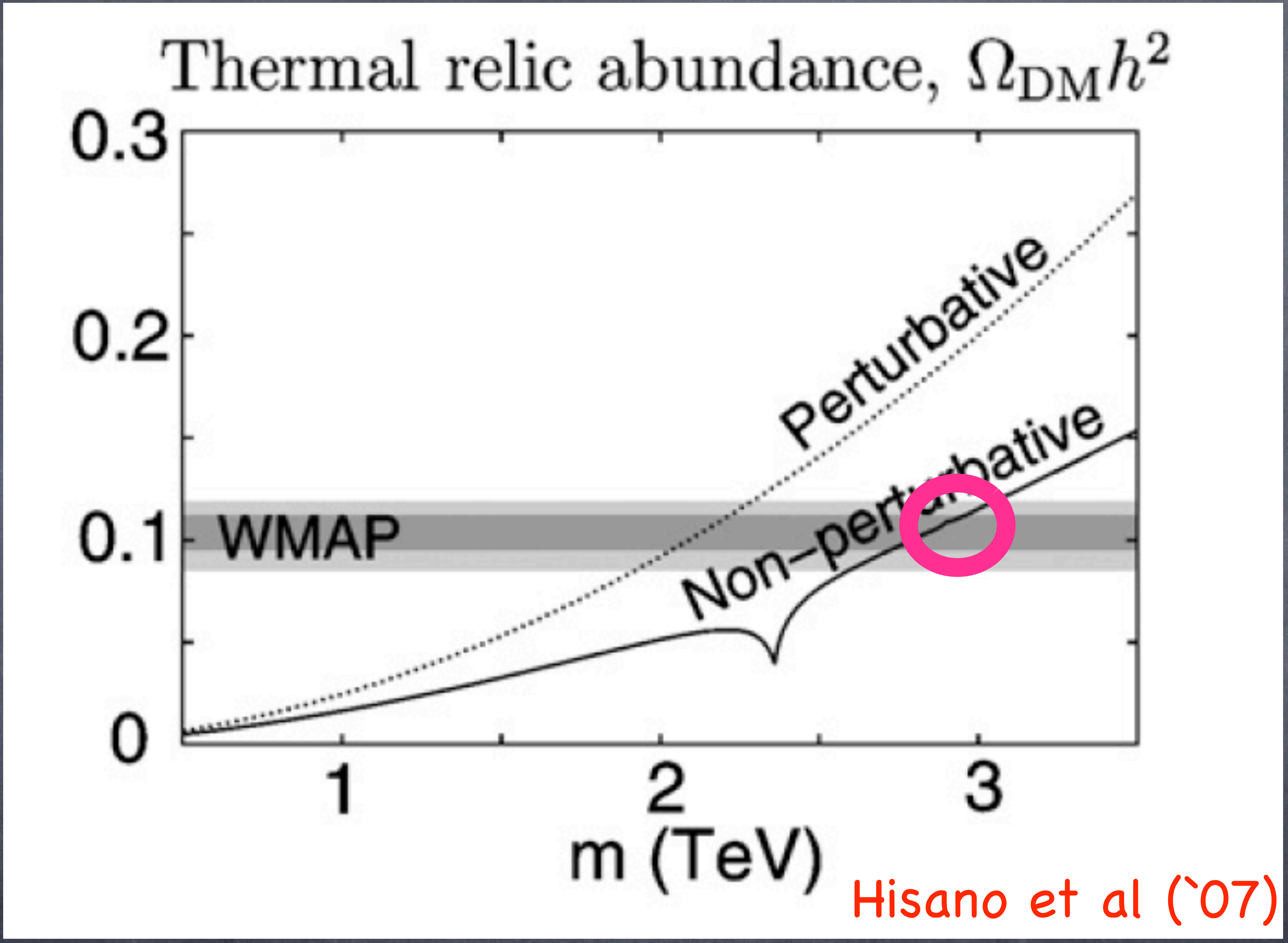
Thermal relic Wino DM



Hisano et al (`07)

$$m_{\tilde{W}} \sim (2.7 - 3)\,\mathrm{TeV}$$

Thermal relic Wino DM



Hisano et al (`07)

$$m_{\tilde{W}} \sim (2.7 - 3)\,\text{TeV}$$

The R-parity must be a good symmetry for the Wino LSP to account for the observed DM.

Is the R-parity an exact symmetry or just an approximate one?

In order to have a (almost) vanishing cosmological constant, the superpotential must have a constant term:

$$W \supset C_0 = m_{3/2} M_P^2$$

The constant term breaks a continuous U(1)R symmetry down to the Z_2 symmetry (R parity).

However, a continuous $U(1)_R$ may not be the symmetry of the theory at high energies.

If the R symmetry in the high energy is a discrete one (e.g. Z_{2k+1}), the R parity is broken by C_0.

As an example, let us consider the case of k = 2,

namely, Z_5 R symmetry.

R-parity violation

	Q	$\bar{u}$	$\bar{d}$	L	$\bar{e}$	H_u	H_d	C_0
R	1	1	1	1	1	0	0	2

In addition to the SM Yukawa interactions, the following operator is allowed by the symmetry.

$$W = \kappa_{ijk}(C_0)^2 \bar{e}_i L_j L_k,$$

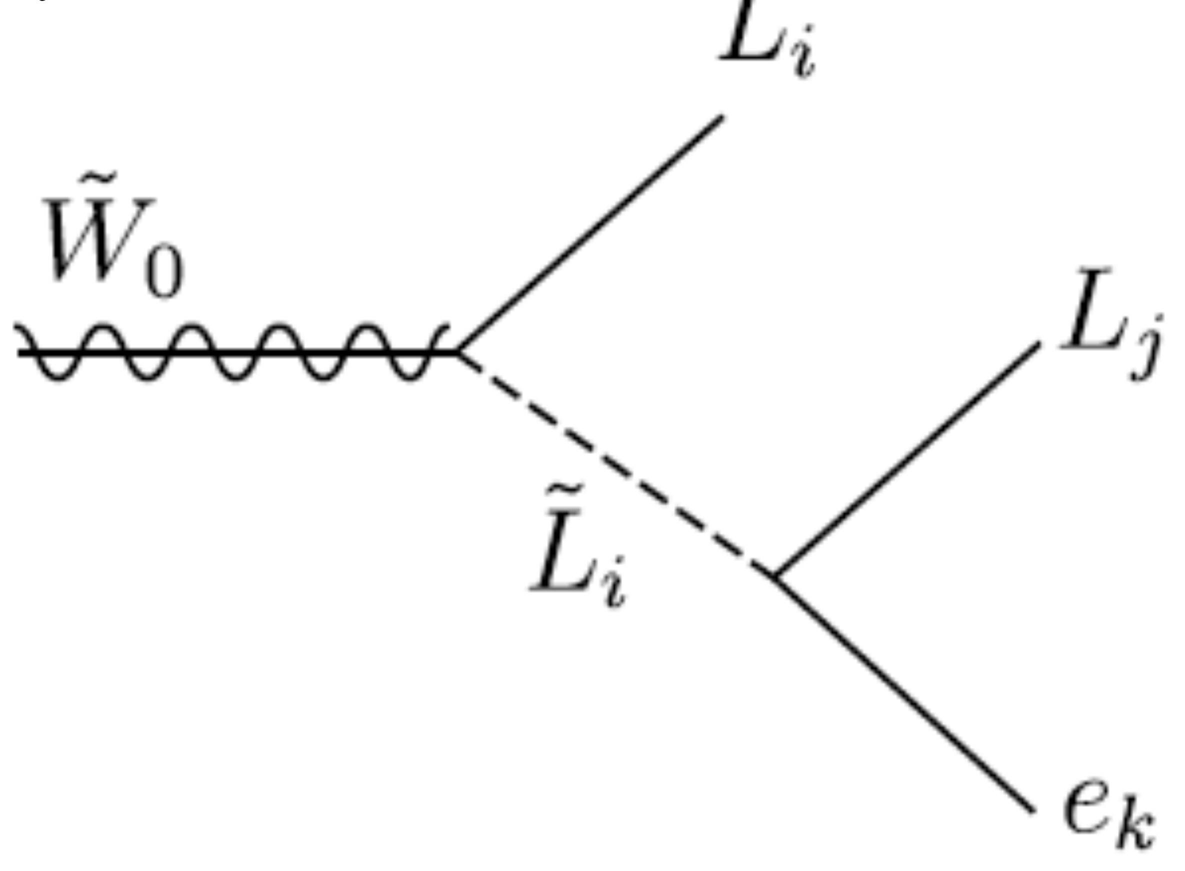
2x2+1+1+1 = 7 ≡ 2 (mod 5)

w/ $\kappa \sim \mathcal{O}(1)$

and similar terms for quark multiplets.

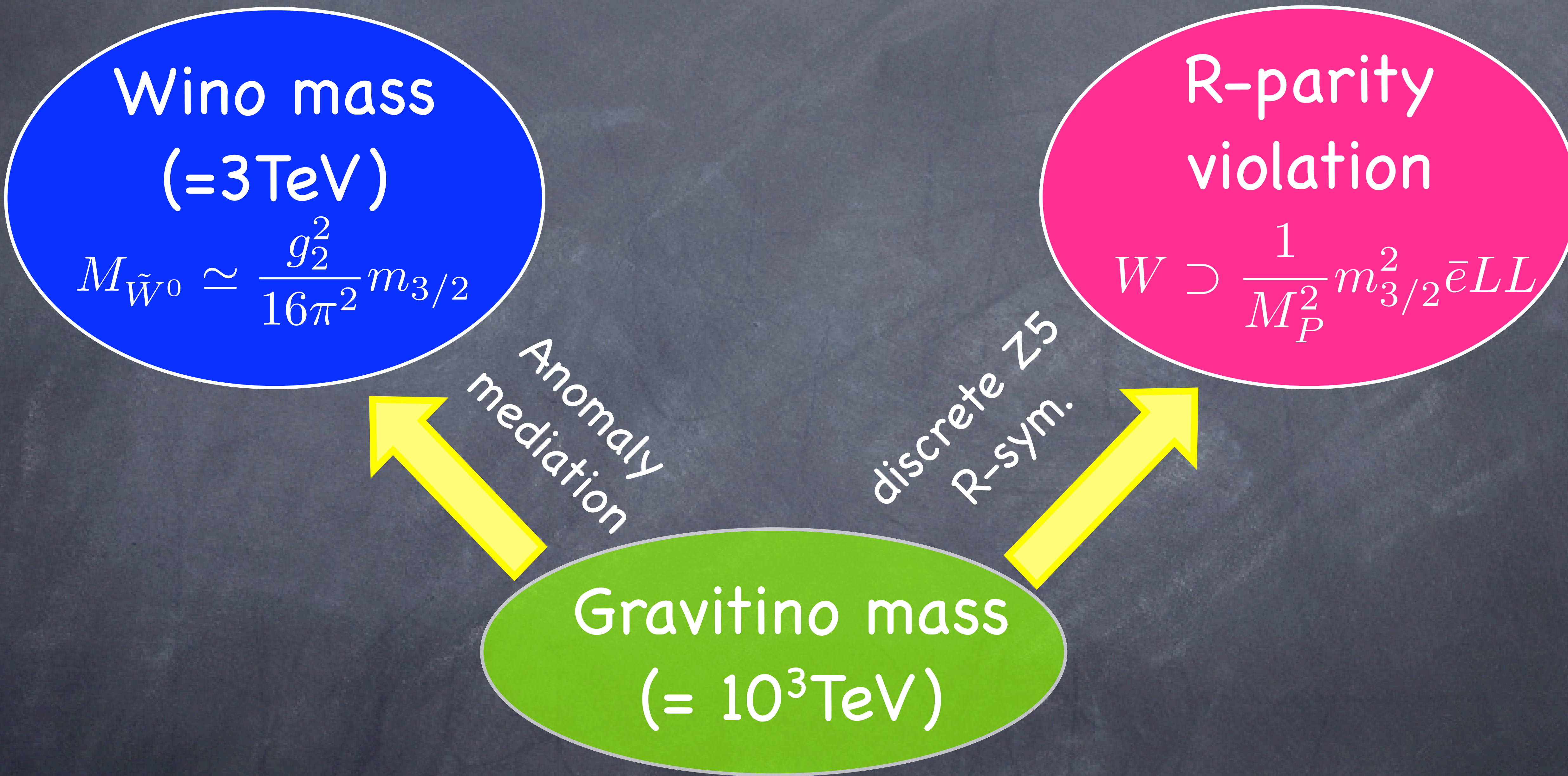
In our model, the Wino DM of mass 3TeV is not absolutely stable, and decays through the R-parity violating operator, eLL.

e.g.)



$$\Gamma \sim (10^{27}\mathrm{sec})^{-1}\,\kappa^2 \left(\frac{m_{3/2}}{10^3\ \mathrm{TeV}}\right)^4 \left(\frac{m_{\widetilde{W}^0}}{3\ \mathrm{TeV}}\right)^5 \left(\frac{m_{\tilde{\ell}}}{5\,\mathrm{TeV}}\right)^{-4},$$

Note that both the Wino mass and the size of the R-parity violation are determined by the gravitino mass.



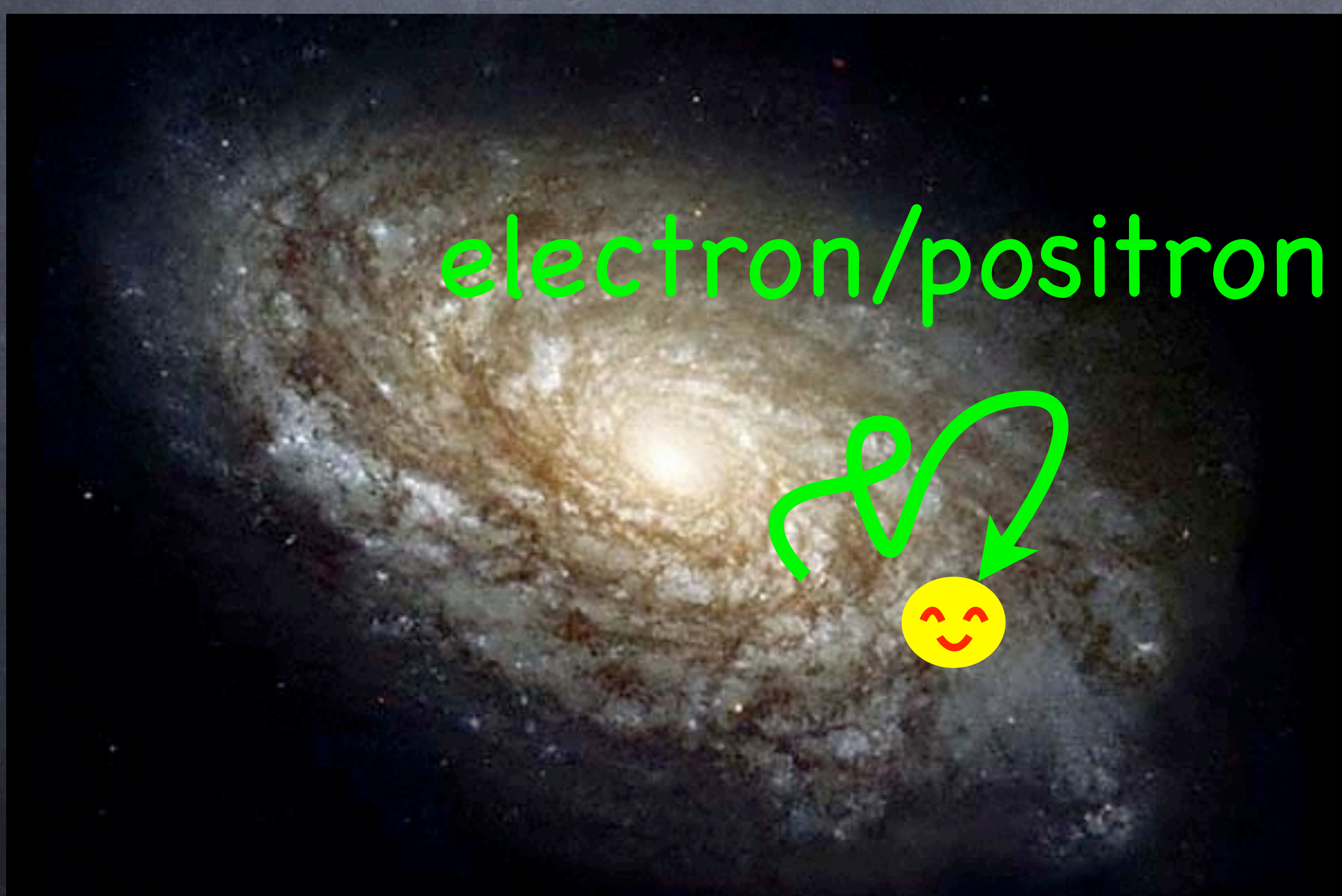
The overall scale is determined by the thermal relic abundance.

Electron + Positron flux:

Propagation through the galactic magnetic field is described by a diffusion equation

$$\frac{\partial f_e}{\partial t} = K(E)\nabla^2 f_e(E,x) + \frac{\partial}{\partial E}[b(E) f_e(E,x)] + Q(E,x)$$

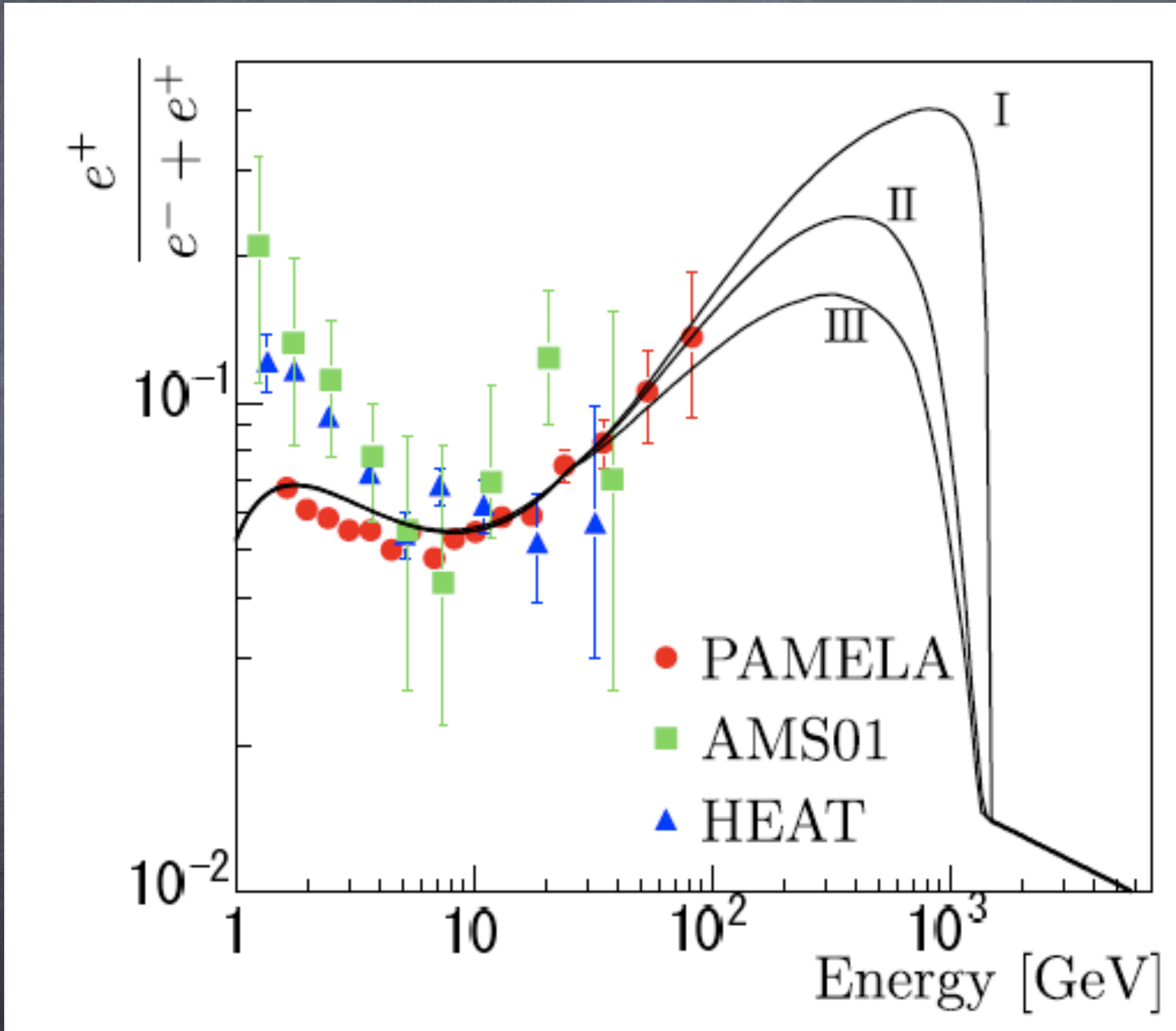
diffusion — energy loss — source



Dark Matter

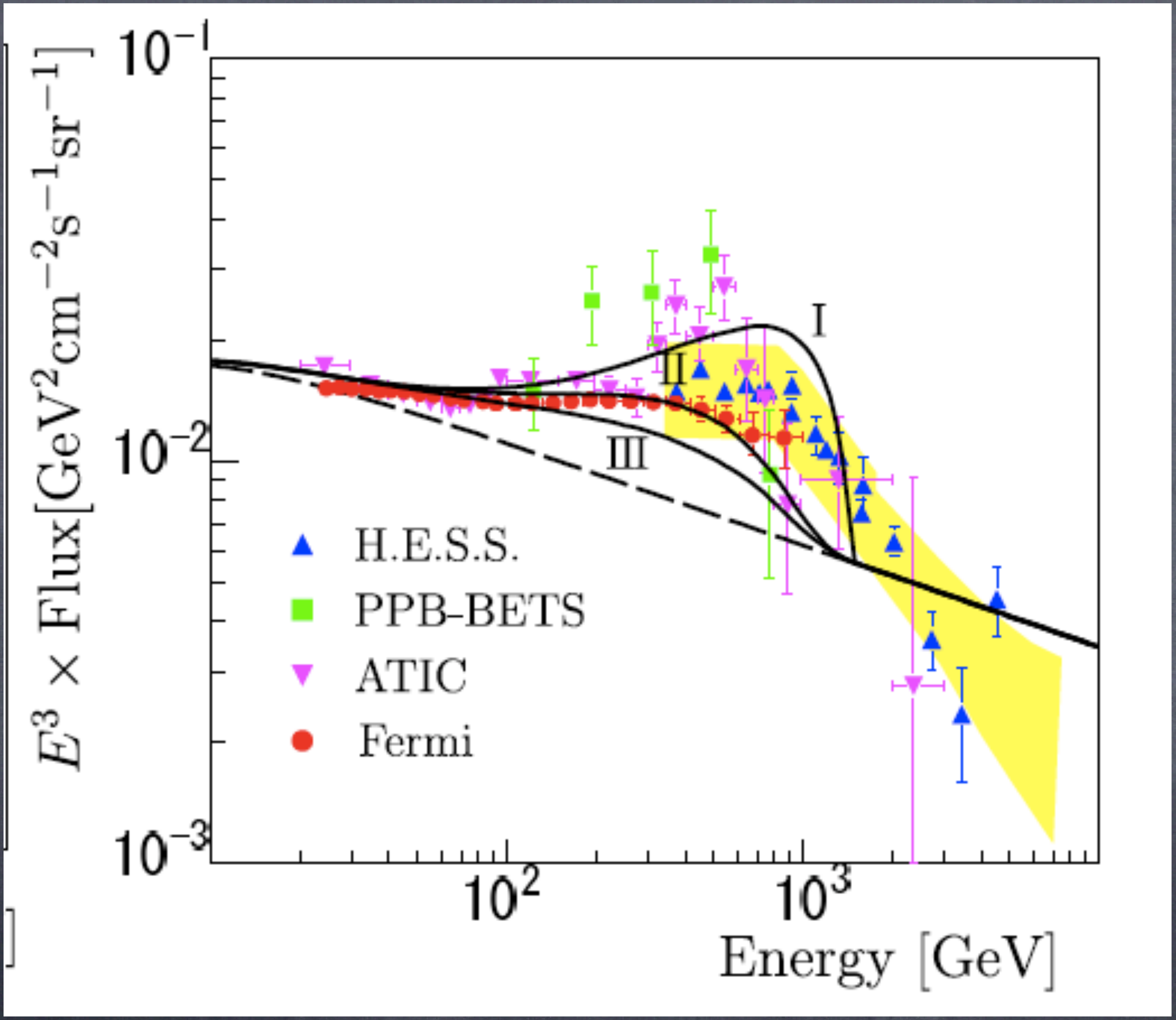
Mass &
Decay rate

The Wino DM decay may account for the observed PAMELA/Fermi excesses in the CR $e^- + e^+$.



(a)

I: $e_1L_2L_3$, II: $e_2L_2L_3$, III: $e_3L_2L_3$



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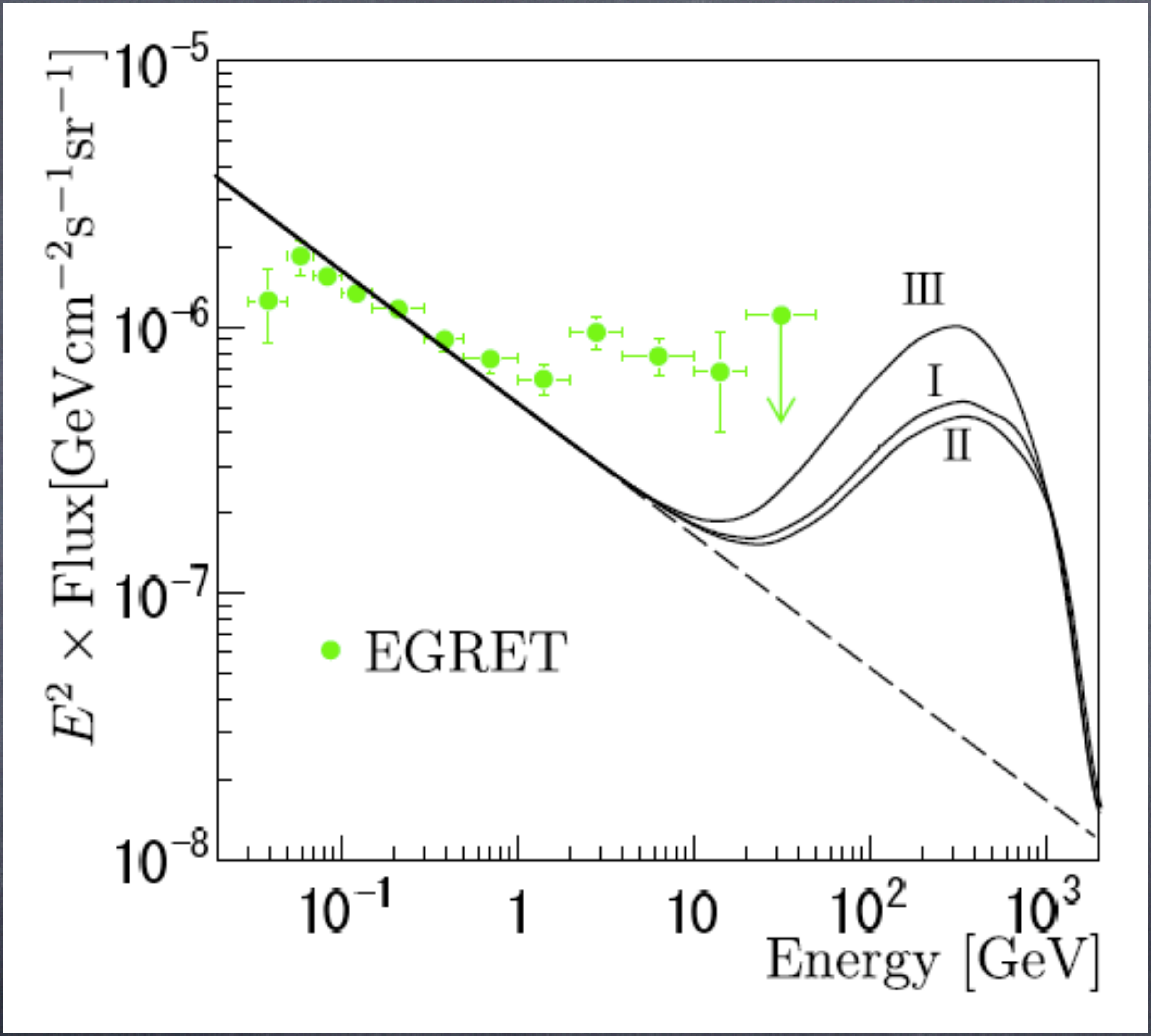


I: $e_1L_2L_3$, II: $e_2L_2L_3$, III: $e_3L_2L_3$

…yet another coincidence??

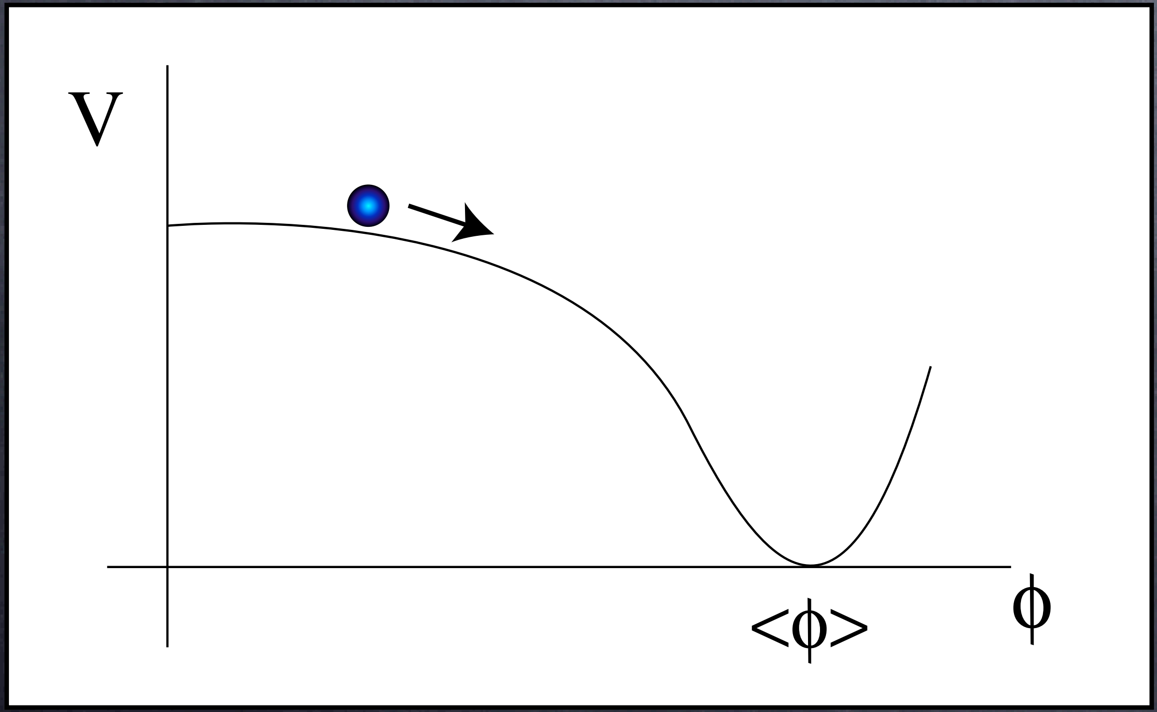
New inflation model with Z_5 R-symmetry

Izawa and Yanagida ,`97

$$K(\phi, \phi^\dagger) = |\phi|^2 + \frac{k}{4}|\phi|^4,$$
$$W(\phi) = v^2\phi - \frac{g}{6}\phi^6.$$

$$R[\phi] = 2 \quad R[\phi^6] = 12 \equiv 2 \pmod 5$$

Consistent with the discrete Z_5 R-symmetry.



$$V(\varphi) \simeq v^4 - \frac{k}{2}v^4\varphi^2 - \frac{g}{2^{\frac{5}{2}-1}}v^2\varphi^5 + \frac{g^2}{2^5}\varphi^{10}$$

Inflaton acquires non-vanishing VEV:

$$\langle\phi\rangle \simeq (v^2/g)^{1/5}$$

The gravitino mass is related to the inflaton parameters!

$$m_{3/2} = W(\phi_0) \simeq \frac{5v^2}{6}\left(\frac{v^2}{g}\right)^{\frac{1}{5}}$$

$$\sim \mathcal{O}(10^6)\,\mathrm{GeV}$$ for $g = \mathcal{O}(1)$

The WMAP normalization δ = 10^{-5} is imposed.

Conclusions

It is likely that the PAMEA and Fermi found an excess in the CR positrons/electrons.

If so, we need to modify the conventional model of CR electron/positron. The possible sources are 1) pulsars; 2) SNR; or 3) Dark Matter.

In the case of DM, other observational channels, especially gamma-ray, could refute/support the scenario.

We have proposed a model based on the discrete Z_5 R symmetry in which R-parity is broken by the constant term in W (= gravitino mass).

The thermal relic Wino DM of mass 3TeV can explain the observed PAMELA/Fermi anomalies in this framework.

The new inflation model based on Z_5 R symmetry can give rise to the gravitino mass of 10^3TeV.

Victor F. Hess

Nobel Lecture, December 12, 1936

``.....It is likely that further research into "showers" and "bursts" of the cosmic rays may possibly lead to the discovery of still more elementary particles, neutrinos and negative protons, of which the existence has been postulated by some theoretical physicists in recent years."