High energy rise in the cosmic ray positron fraction: possible causes

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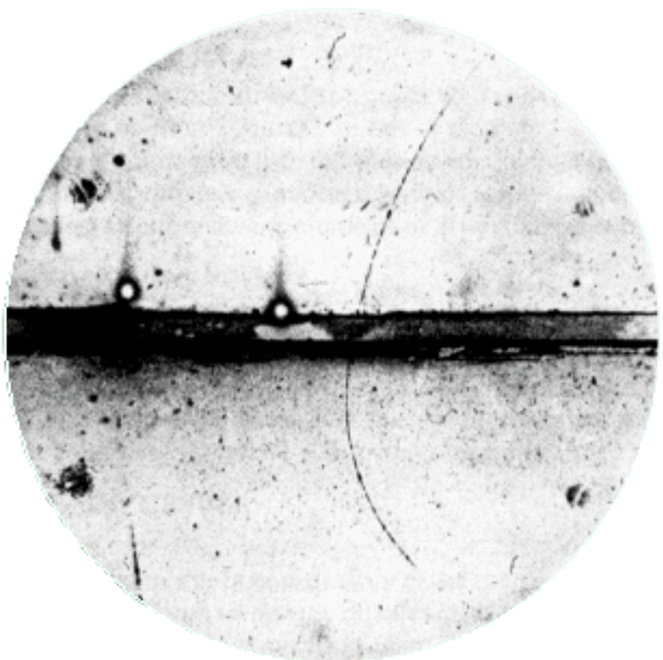
CERN



C.D. ANDERSON → Nobel Prize 1936
Phys. Rev. 43, 491 (1933)

PAMELA → ?!

DM Conference within "New Horizons for Cosmology" - GGI, 9 Feb. 2009

Outline of the talk

- Setting the Stage

→ Generalities on Dark Matter & indirect searches

→ The data

→ Some notions on Galactic Cosmic Rays

- Recent Positron Data: “Model-independent” interpretation

→ I’ll argue that this points to the existence of a primary source!

- Models for the interpretation & way to distinguish between

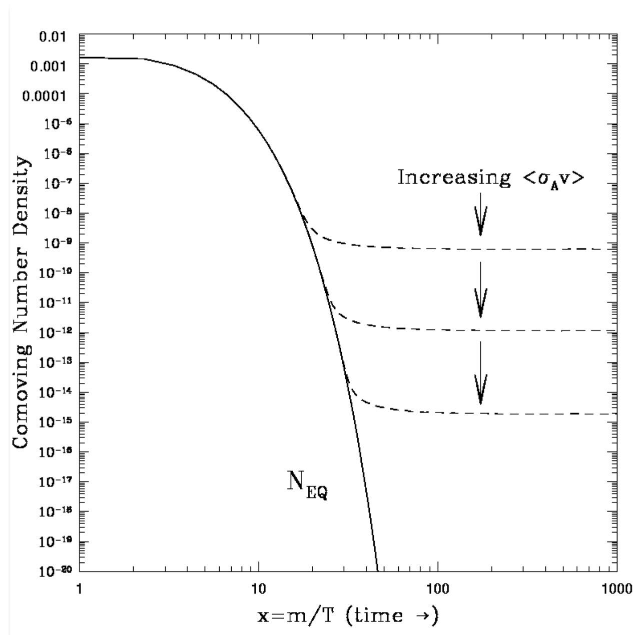
→ Astrophysical explanations (Pulsars?)

→ Dark Matter explanations

- Conclusions

What is DM? WIMPs? A reasonable bet

✓ It's cold (maybe a little warm… but cool)
✓ It's dark (at most weakly interacting with SM particles)
✓ It's non-baryonic (New Physics!)



❖ The Weakly Interacting Massive Particle "miracle"
thermal relic with EW gauge couplings & $m_X \approx 0.01$– 1 TeV matches cosmological requirement, $\Omega_X \approx 0.25$

$$\Omega_{wimp} \sim 0.3 / <\sigma v> (pb)$$

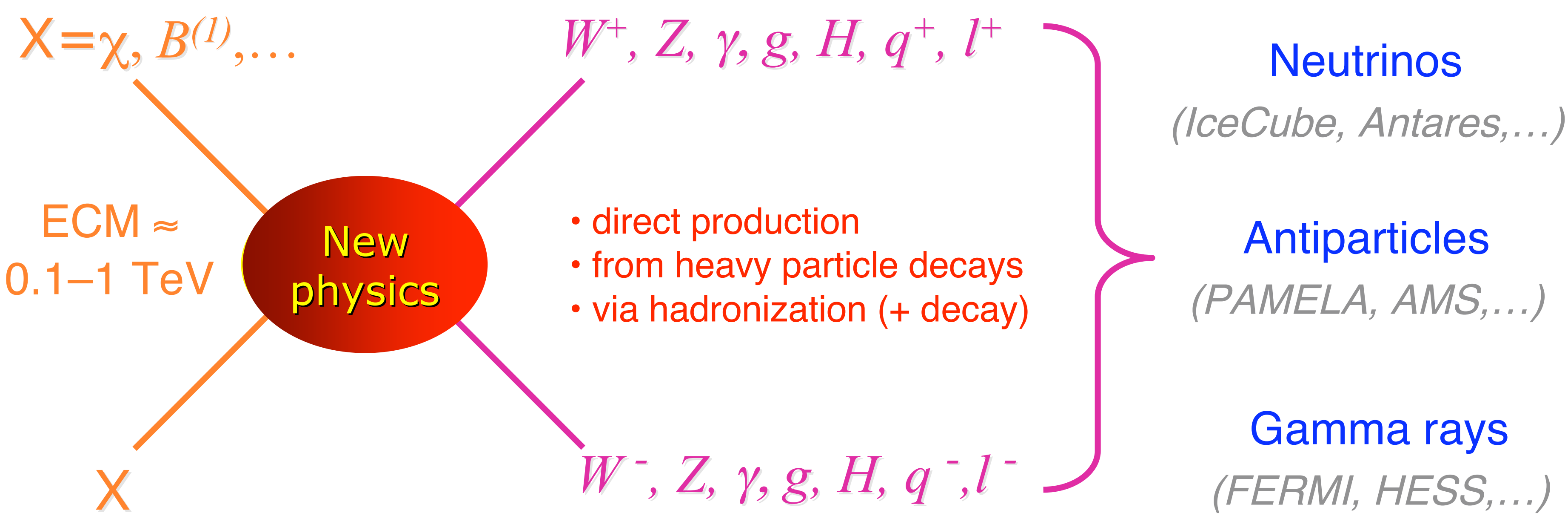
❖ EW scale related with DM?
Possibly, e.g. neutralino in SUSY, KK states in extra-dimension theories
Stability ↔ Discrete Symmetry ↔ Only pair production at Colliders?
(R-parity, K-parity, T-parity…enters EW observables in loops only! Proton stability…)

❖ EW-related candidates have a rich phenomenology
Higher chances of detection via collider, direct, and indirect techniques

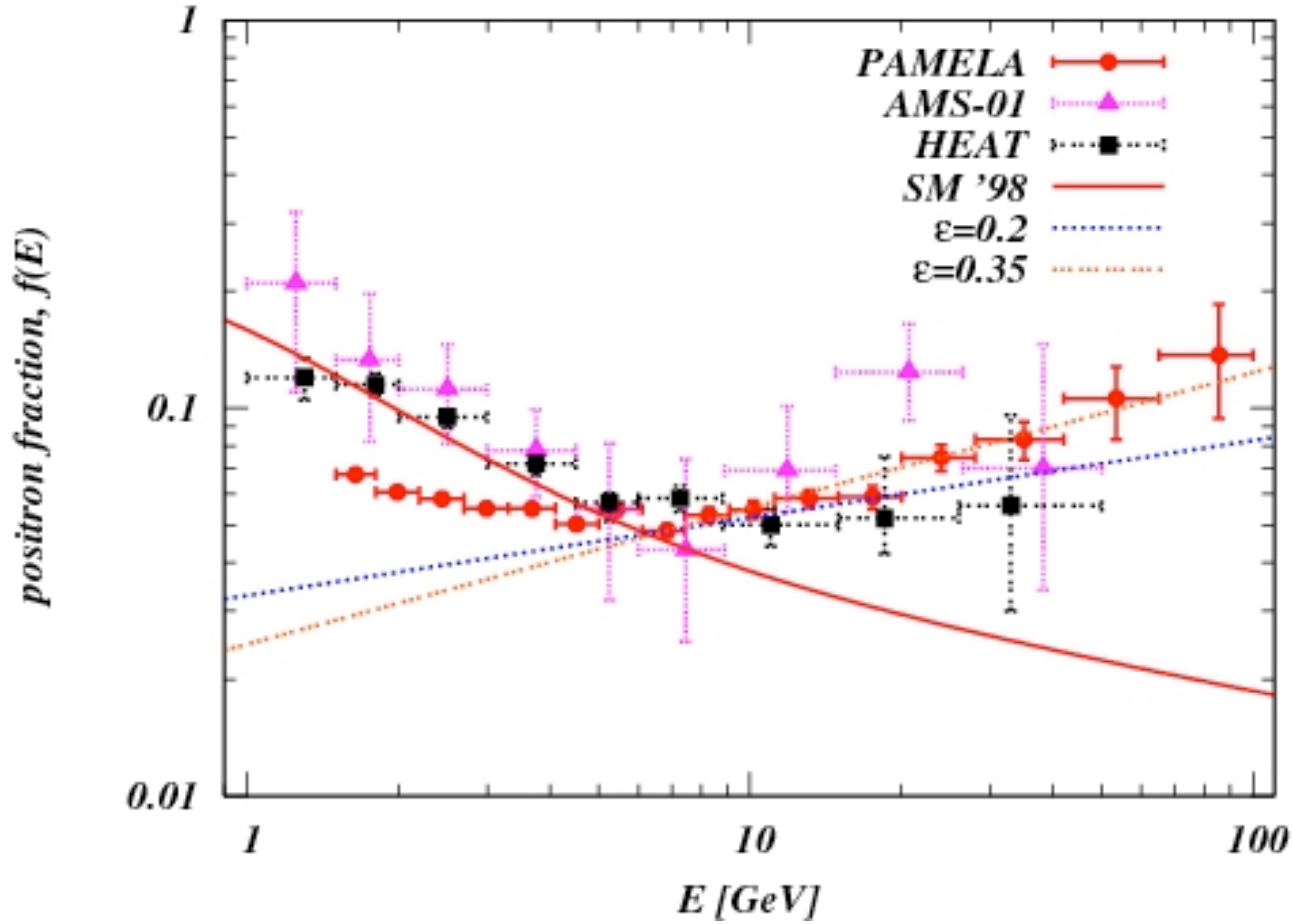
➢ *Warning: keep in mind other possibilities!*
(Axions, SuperHeavy DM, SuperWIMPS, MeV DM, sterile neutrinos…)
They have peculiar signatures and require ad hoc searches

Detection of WIMP Dark Matter

Experiment	*Source*	*Interaction*	*Channel*
Direct	Local (crossing Earth surface)	WIMP-nucleus scattering	Phonons
Indirect	Earth, Sun, Galaxy, Cosmos	WIMP pair annihilation	γ,ν, Antimatter
Collider	Controlled production	WIMP pair production	$\not{E}$



e^+ fraction measurements reveal the following:



Feel free to take pictures….

Diffusion → Leaky box: hadrons

$$\frac{\partial \Phi}{\partial t} = Q - \frac{\Phi}{\tau_{esc}} - \frac{\partial}{\partial p}(\dot{p}\Phi)$$

- For Protons, fair to neglect energy losses and one gets

$$Q_p(E) \propto E^{-\gamma_p} \Rightarrow \Phi_p(E) \propto E^{-\gamma_p} \tau_{esc}(E)$$

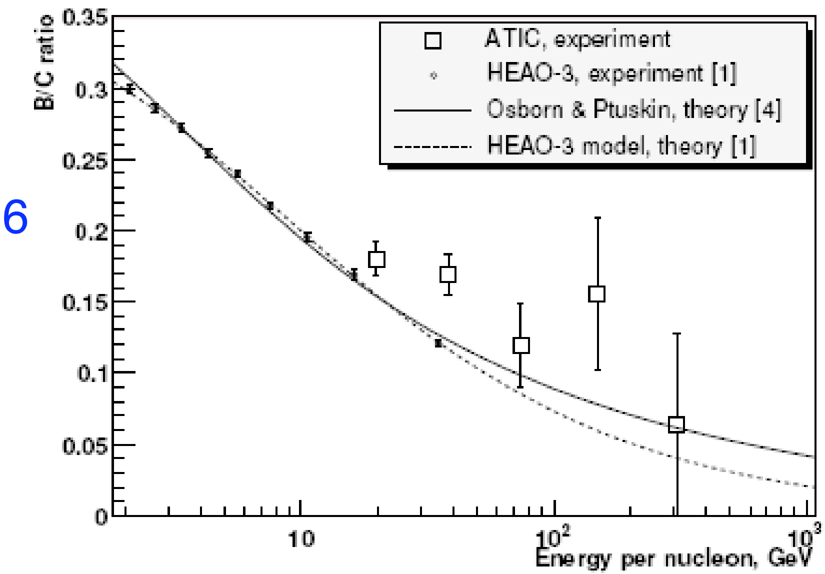
- For pure secondary nuclei (as Boron, produced from Carbon) one gets

$$Q_{\sec}(E) \propto \sigma\, \Phi_{prim}(E) \Rightarrow \Phi_{\sec}(E) \propto \sigma\, \Phi_{prim}(E) \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto D(E)^{-1} \propto E^{-\delta}$$

δ~0.6 e.g. from B/C (and other s/p data).
Non-linear theory & simulations predict δ~0.3-0.6

Note: Unlikely to stay constant to comply with anisotropy bounds at the Knee, possibly declining to ~0.3 at ~100 TeV…
But irrelevant for energy range of interest for e!



Diffusion → Leaky box: leptons & positron fraction

$$\frac{\partial \Phi}{\partial t} = Q - \frac{\Phi}{\tau_{esc}} - \frac{\partial}{\partial p}(\dot{p}\Phi)$$

- For primary electrons, one can deduce by analogy

$$Q_{-}(E) \propto E^{-\gamma_{-}} \Rightarrow \Phi_{-}(E) \propto E^{-[\gamma_{-} + \ell(E)]}$$

- Similarly, for secondary positrons (if cross section~E-independent)

$$Q_{+}(E) \propto \Phi_{p}(E) \Rightarrow \Phi_{+}(E) \propto E^{-[\gamma_{p} + \delta + \ell(E)]}$$

If energy-loss time negligible wrt escape time $\ell(E) \approx \delta$

When radiative energy loss dominate (high energy):
But continous source approximation can break down… $\ell(E) \approx 1$

$$f(E) \equiv \frac{\Phi_{+}}{\Phi_{+} + \Phi_{-}} = \frac{1}{1 + (\Phi_{-}/\Phi_{+})} \approx \frac{1}{1 + kE^{\rho}}$$

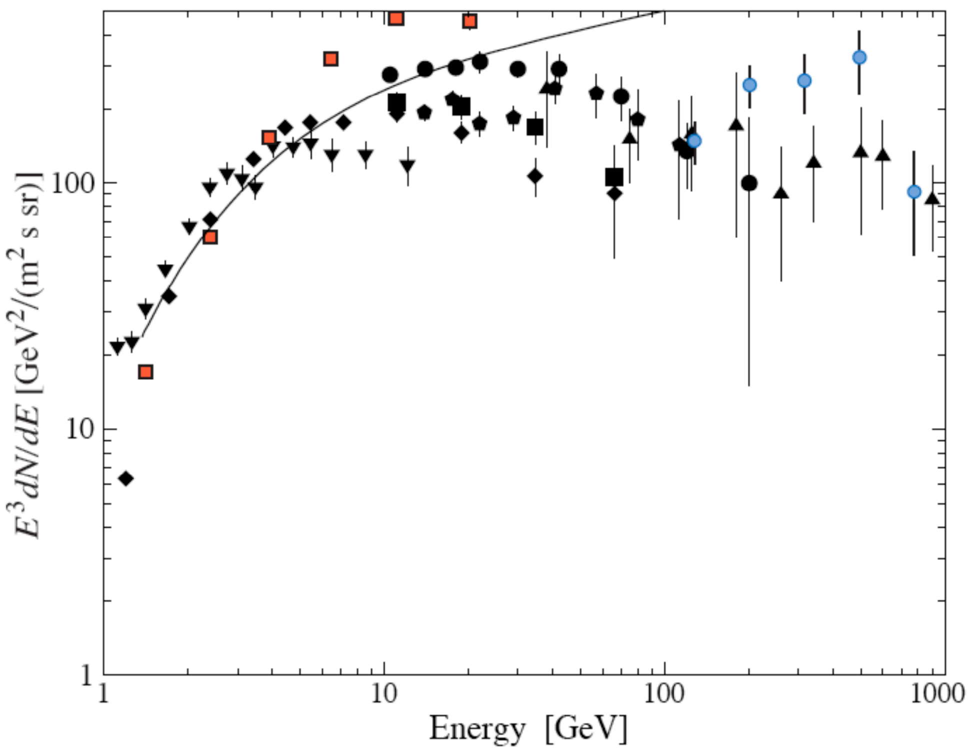
$$\rho = \delta + \gamma_{p} - \gamma_{-}$$

Can we have $\gamma_- > \gamma_p + \delta$? Theoretical argument

As far as we know (e.g. from low-energy data and SNRs phenomenology) most *e* undergo similar acceleration (same site?) as *p.*
For example, when both are subject to diffusion only,

$$\Phi_-(E) \propto \Phi_p(E) \;\; at \;\; E \leq 10 \;\; GeV$$

In this case, $\gamma_- = \gamma_p$ and secondaries have a spectrum harder than primary electrons



Can we have $\gamma_- > \gamma_p + \delta$? Empirical argument

Assume we know nothing about *e* but the observed spectrum (note: this just moves the problem to explain the *e* -spectrum: a new mechanism is now required for *e* !), while we trust secondary calculations because *p* are better measured (and featurless). Even in this case, there is a conflict between *f(E)* and overall *e*-flux.

Hardest self-consistent secondary e^+ spectrum

$$\Phi_+(E) \propto E^{-3.33} \quad at\ E \geq 10\ GeV$$

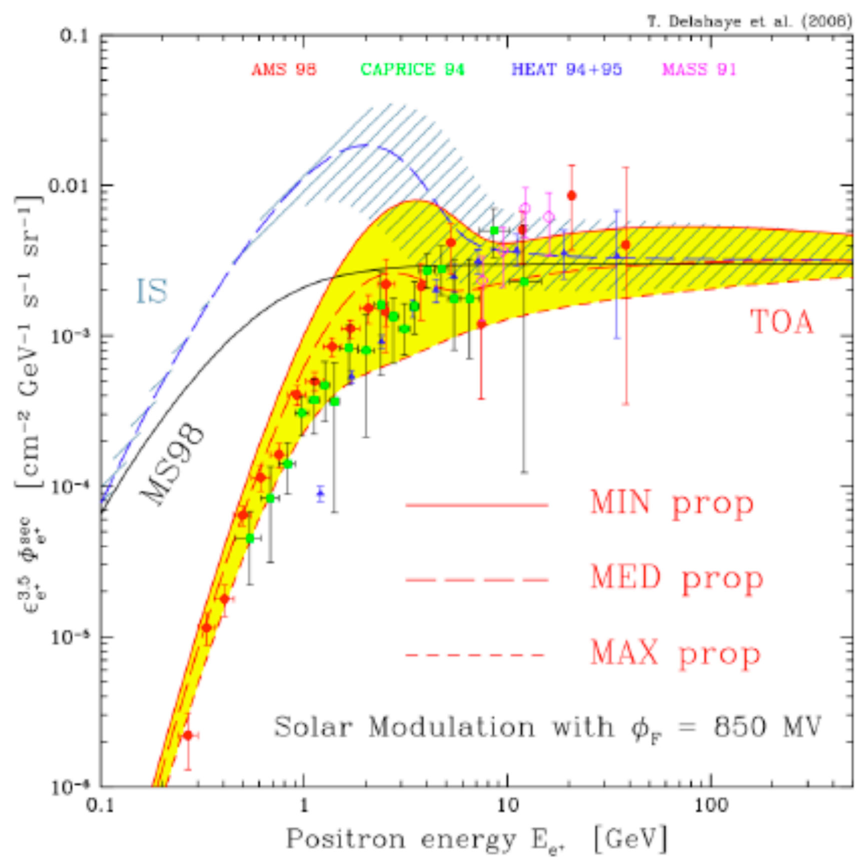
Softest possible spectrum fitting at 3 σ $e^-(+e^+)$ data (not explaining them!)

$$\Phi_e(E) \propto E^{-3.54} \quad at\ E \geq 10\ GeV$$

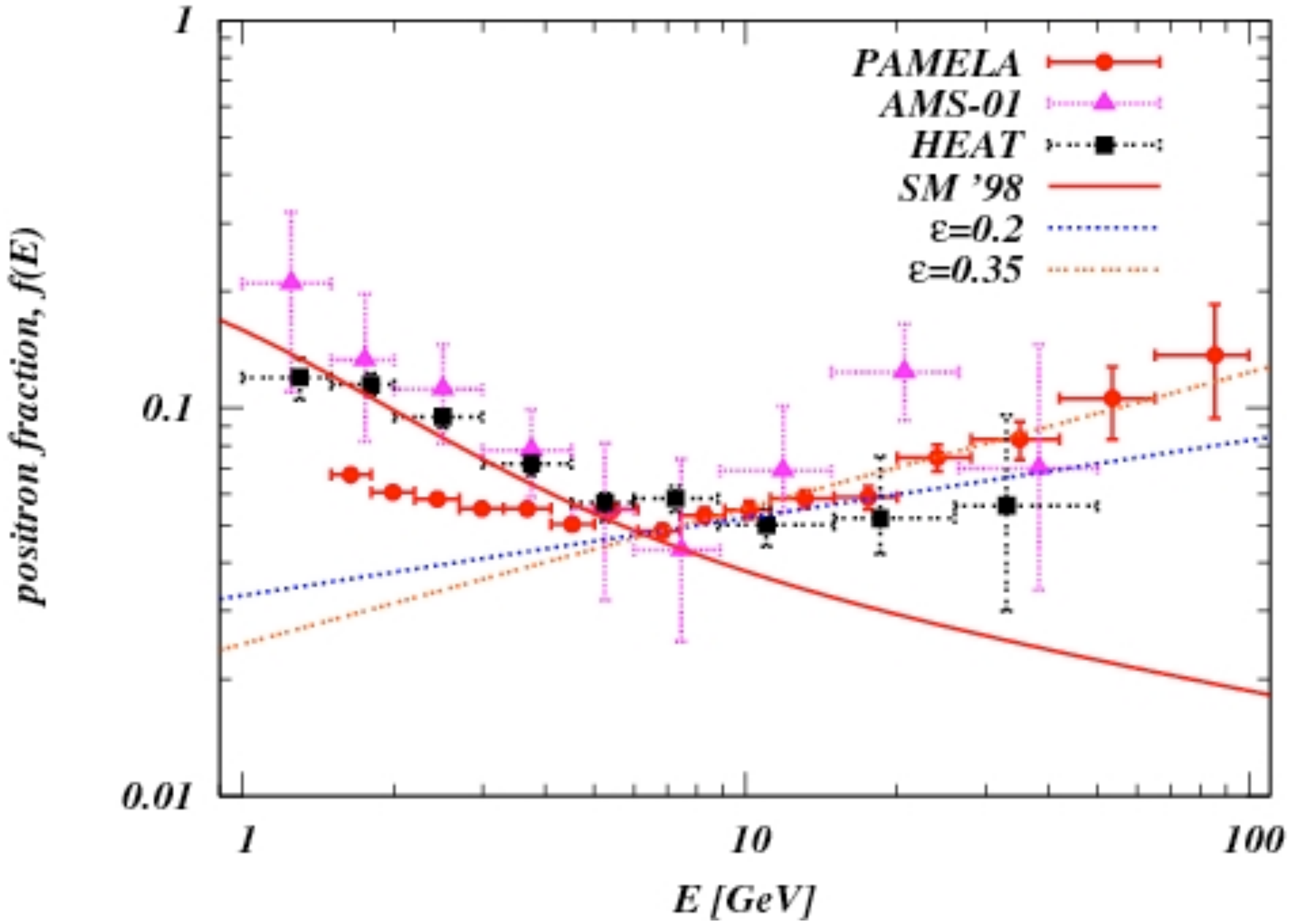
$$\rho > -0.2\ (\rho \approx -0.35\ required)$$

PAMELA preliminary results at this conference point to a "relatively hard " spectrum ~ 3.34!

Delahaye et al. arXiv:0809.5268



The conclusion is:



$$\rho = \delta + \gamma_p - \gamma_- \approx -0.35 < 0 \ \ at \ \ E \geq 7 \ \ GeV$$

Rather than "the excess" over a (more or less robustly estimated) background, it is the slope seen in *f(E)* which seems to imply a new class of e^+ (or more likely e^+e^-) CR "accelerators"!

Possible Loopholes in the previous arguments

- ✓ Rising cross section at high energy.
- ✓ High energy behavior of the e^+ excess over e^- in secondaries of *pp* collisions.
- ✓ Spectral feature in the proton flux responsible for the secondaries.
- ✓ Role of Helium nuclei in secondary production.
- ✓ Difference between local and ISM spectrum of protons.
- ✓ "Anomalous" energy-dependent behaviour of the diffusion coefficient.

Short answer:
None of them capable of explaining the feature

P.S. arXiv:0810.4846 - PRD 79, 021302(R) (2009)

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Astroparticle Physics 11 (1999) 429–435

Astroparticle Physics

www.elsevier.nl/locate/astropart

Cosmic-ray positrons: are there primary sources?

Stéphane Coutu [a,*], Steven W. Barwick [b], James J. Beatty [a], Amit Bhattacharyya [c], Chuck R. Bower [c], Christopher J. Chaput [d,1], Georgia A. de Nolfo [a,2], Michael A. DuVernois [a], Allan Labrador [e], Shawn P. McKee [d], Dietrich Müller [e], James A. Musser [c], Scott L. Nutter [f], Eric Schneider [b], Simon P. Swordy [e], Gregory Tarlé [d], Andrew D. Tomasch [d], Eric Torbet [e,3]

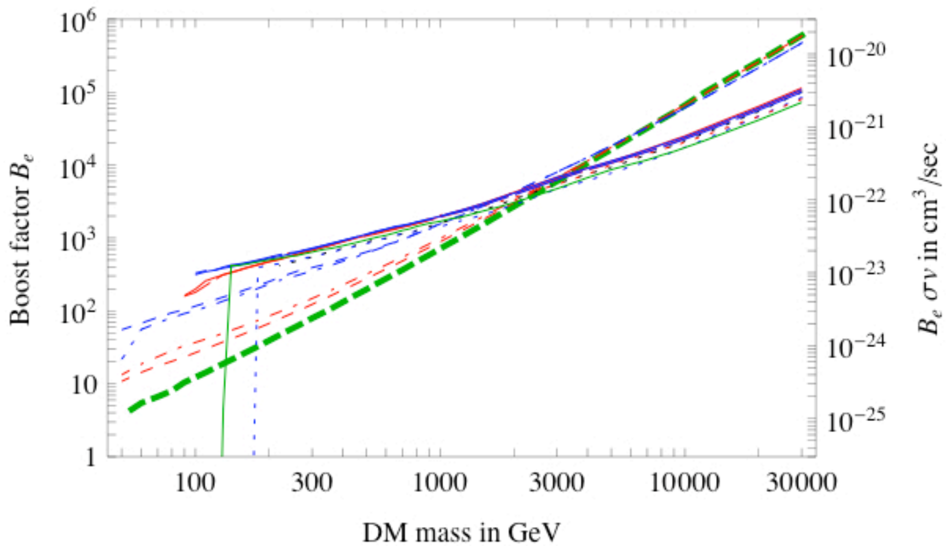
Very, very likely the answer is: Yes

What causes the rise?

Whatever you think of, it is crucial it does not to violate other CR constraints!
(better if it can also account for some other “anomaly”)

Pulsars (μ–quasars or a single GRB possible alternatives?)

- Complex astrophysics, no “robust predictions”
- “Natural” normalization & shape of the signal
- Local sources responsible for ATIC-excess?
- Linked with γ-ray “unidentified sources”?
- Purely e.m. cascade, explains why no p-bar



M. Cirelli et al. arXiv:0809.2409

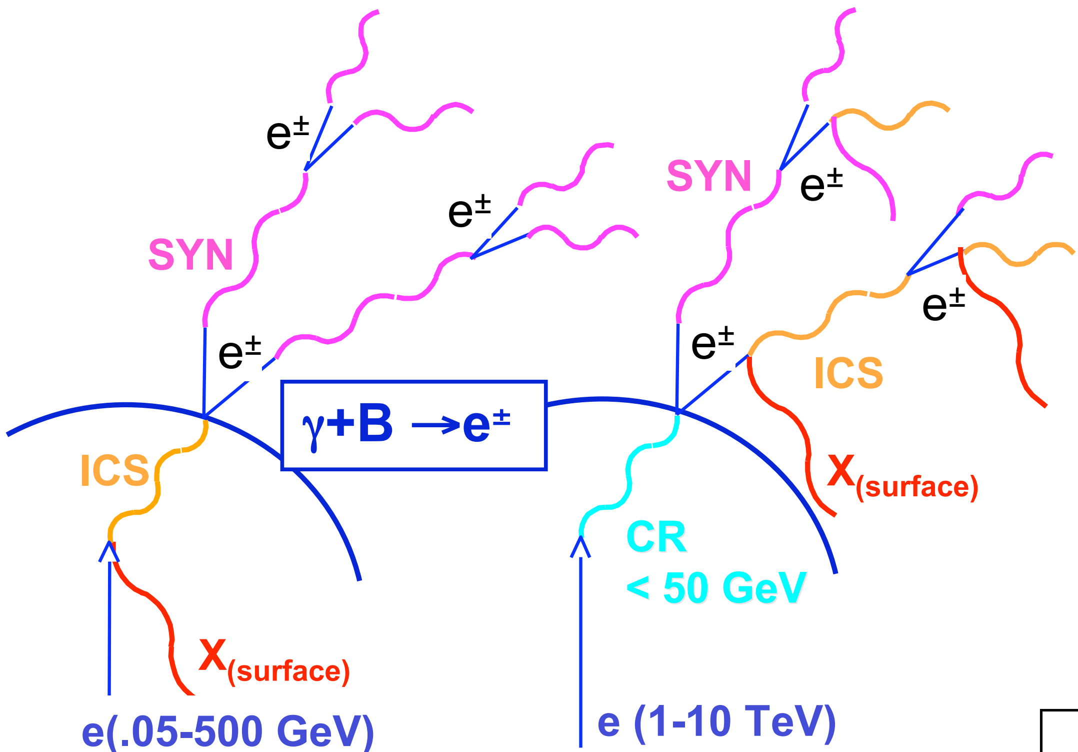
Dark Matter Annihilation

- For a given model, spectra “easily” predicted
- Large Mass (≥TeV) & signal requires large “boost factor” (non-th.? Sommerfeld? Clumps?)
- Constraints from anti-p, ν and γ-ray data

Dark Matter Decay

- Are there “natural” particle physics explanations?
- 2 main free parameters, mass & lifetime, to fit 1-2 spectra: is it predictive?
- Constraints from anti-p and γ-ray data

Pulsars: Basic of pair cascade mechanism



e^+ and e^- are accelerated by $E_{||}$

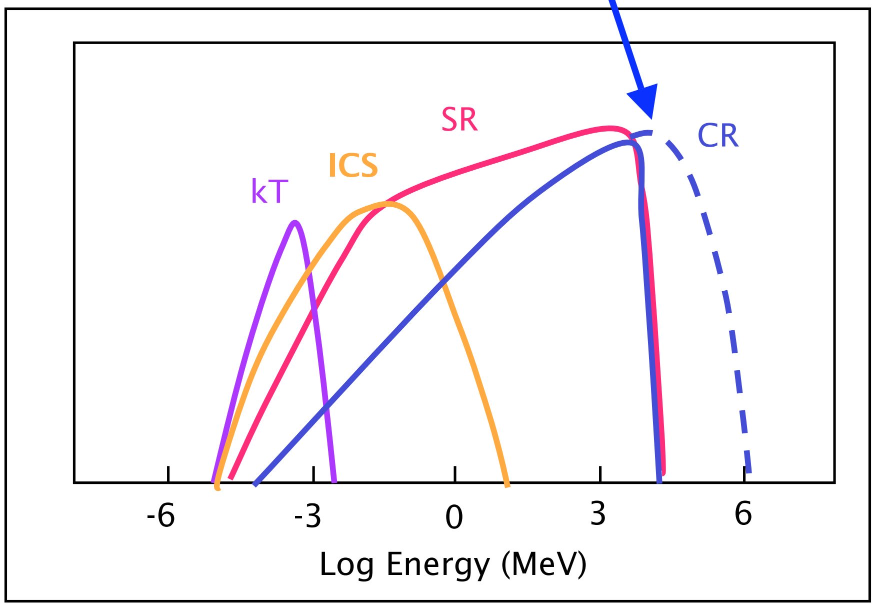
Relativistic e^+/e^- emit γ-rays via synchro-curvature, and IC

γ-rays collide with soft photons/B producing pairs in the accelerator

Different models exist depending on location & geometry of "gaps" (where E.B≠0)

Constrained via γ-ray spectra (possibly high-energy cutoff!), phase-profile, multi-wavelength (radio to γ) constraints.

"Fermi" (GLAST) region!



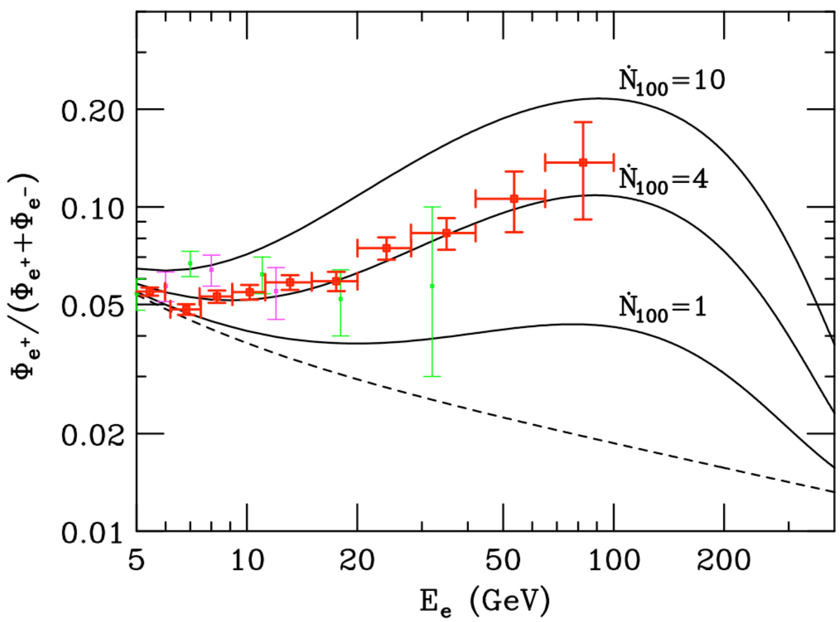
Prediction of a 'population model' of pulsars

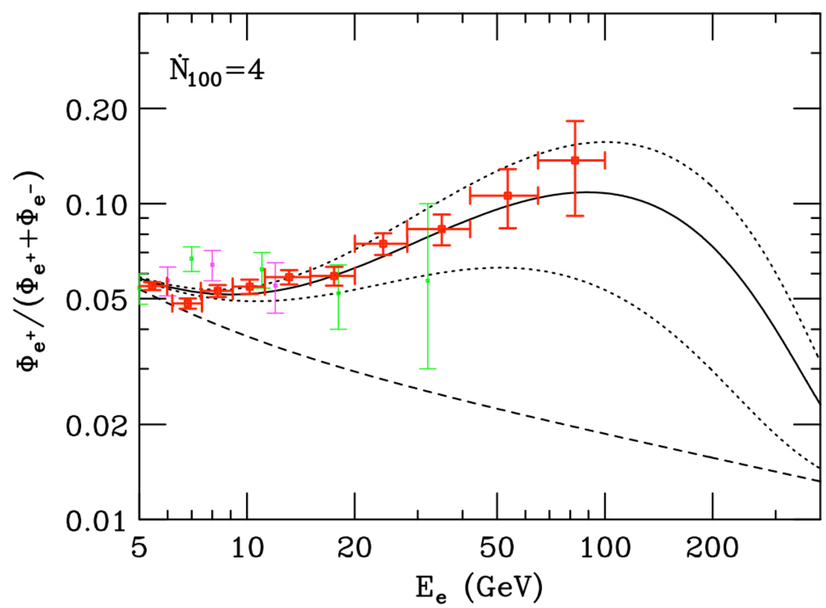
Once fixed a model for the emission (dependence on B, age…) a population study with Galactic population of Pulsars is needed

$$Q(E,\vec{x}) \approx 8.6\times 10^{38}\ \ p(\vec{x})\ \ \dot{N}_{100}\ \ E_{GeV}{}^{-1.6} Exp(-E_{GeV}/80)\ \ GeV^{-1}\ s^{-1}$$

For example: L. Zhang and K. S. Cheng, Astron. Astrophys. 368, 1063-1070 (2001)

Account for Propagation/Energy losses…

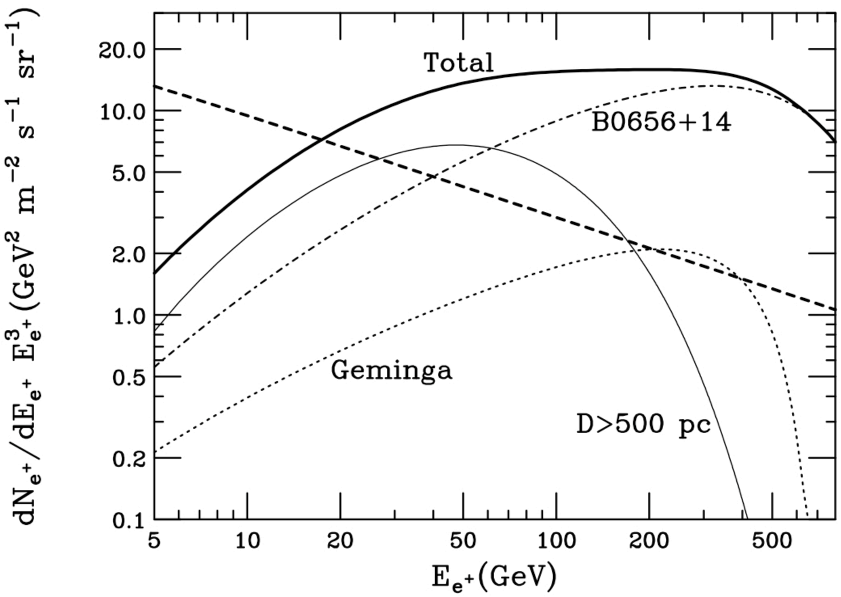


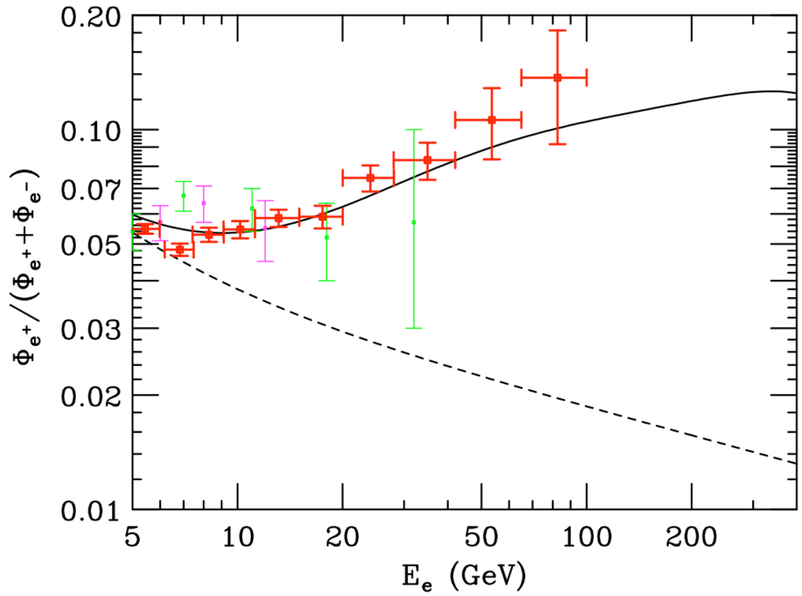


For details: D. Hooper, P. Blasi, PS, JCAP 0901:025 (2009) [arXiv:0810.1527]

Contribution of local sources

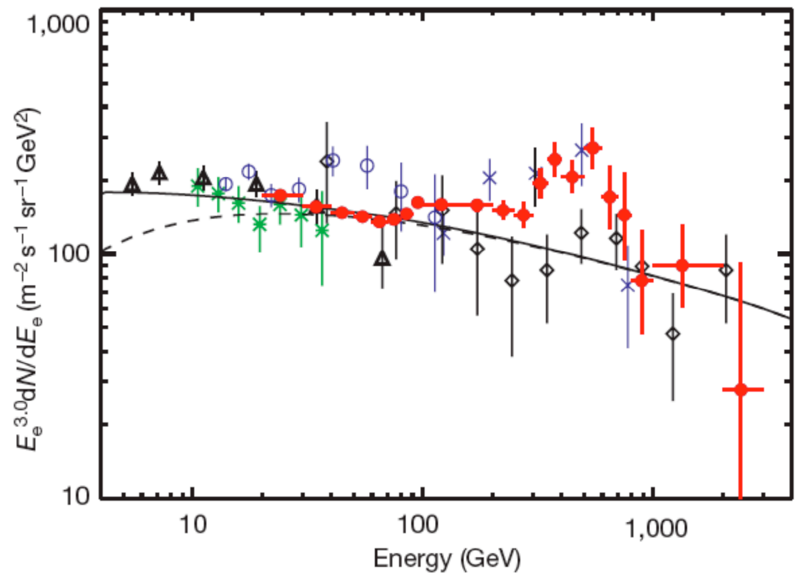
Especially at High Energy (E>50-100 GeV) few prominent sources may give dominant contributions (Geminga, Monogem…)`





Possibility to measure:

- a dipole in the electron flux in Fermi data
- peculiar spectral shape in e^++e^- flux (ATIC-2?)



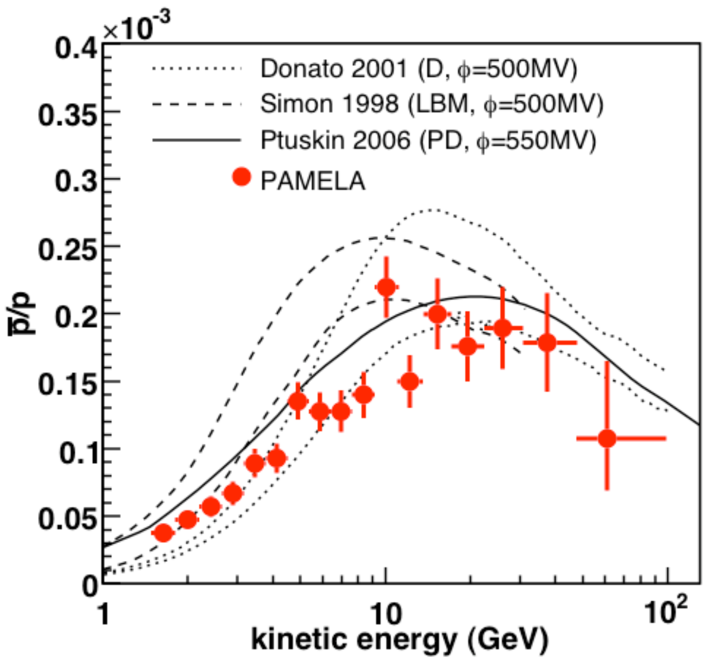
See also S. Profumo arXiv:0812.4457,
H. Yuksel, M. Kistler, T. Stanev, arXiv:0810.2784

Disentangling Pulsars from DM (I)

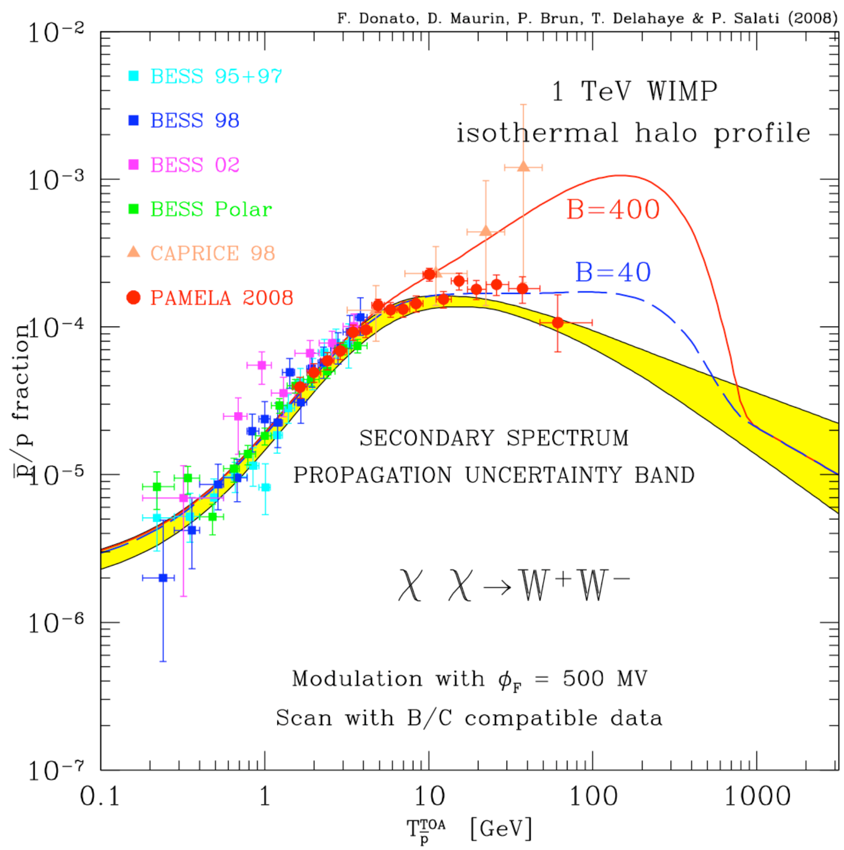
- ✓ *Antiprotons (& anti-D)*
- ✓ *Possible anisotropy*
- ✓ *Shape of the cutoff in e-flux feature (IACTs?)*
- ✓ *γ-rays: Fermi should find diffuse excess (DM) vs. "unresolved/unidentified" point-sources*
- ✓ *Often, new (meta)stable particle at colliders (but troubles for ~TeV hadrophobic particles…)*
- ✓ *Improved ν-bounds from Galactic Center, …*

• Antiprotons consistent with pure CR spallation background
• Exclude "universal" BF ~ needed to fit e^+
• Fraction for "typical" WIMP annihil. modes

(astro-sources predict no anti-p excess)



O. Adriani et al. [PAMELA collab] PRL 102 051101 (2009)



Disentangling Pulsars from DM (II)

✓ *Antiprotons (& anti-D)*

✓ *Possible anisotropy*

✓ *Shape of the cutoff in e-flux feature (IACTs?)*

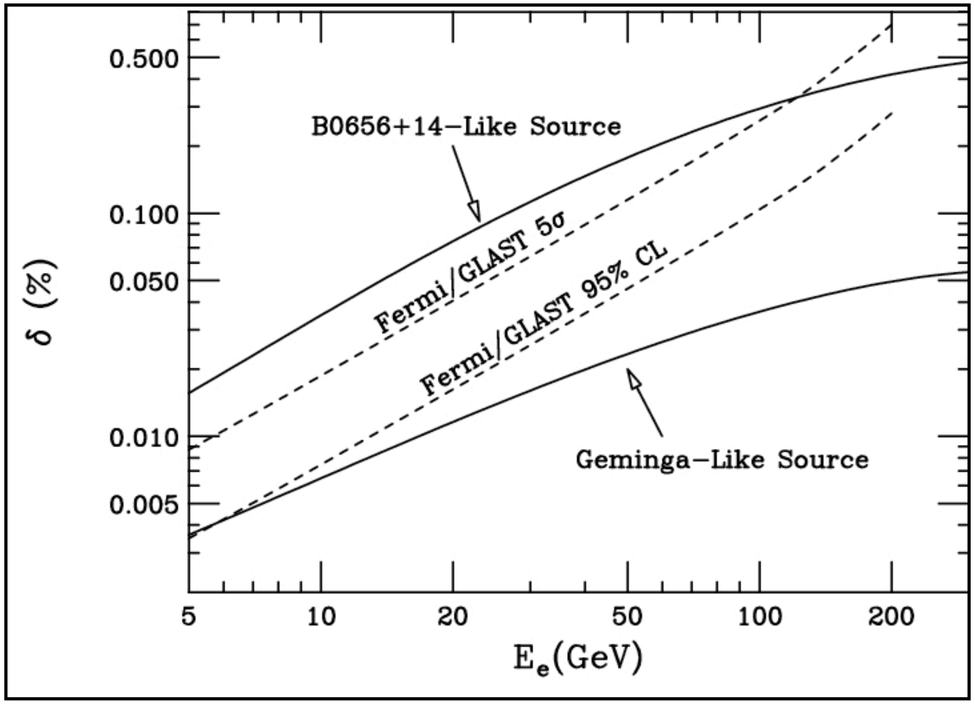
✓ *γ-rays: Fermi should find diffuse excess (DM) vs. "unresolved/unidentified" point-sources*

✓ *Often, new (meta)stable particle at colliders (but troubles for ~TeV hadrophobic particles…)*

✓ *Improved ν-bounds from Galactic Center, …*

- Anisotropy in the total e-flux at ~0.1% level towards Galactic plane for nearby astro sources
- DM could mimic if from "clump", but unlikely oriented towards GP

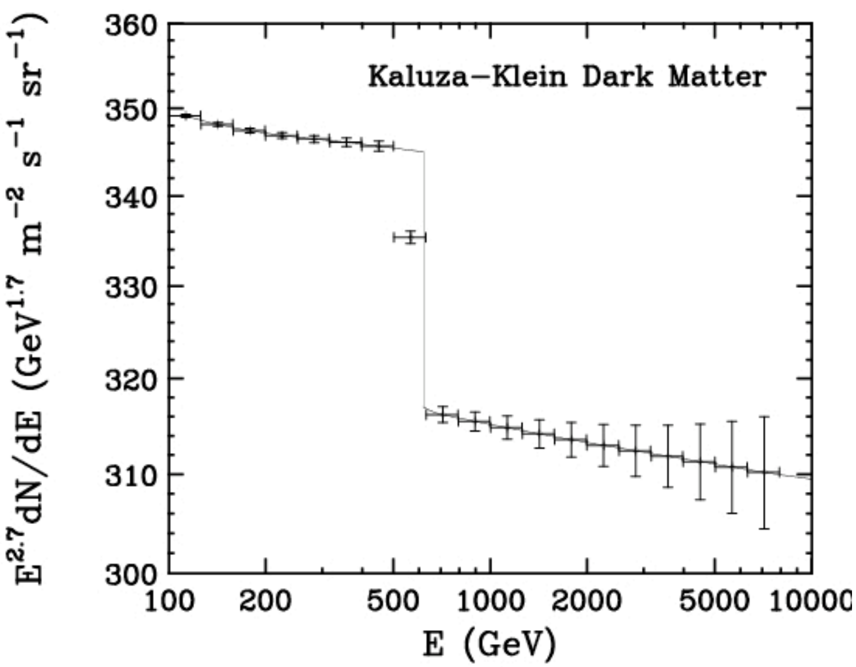
D. Hooper, P. Blasi, PS, JCAP 0901:025 (2009)
I. Buesching et al. arXiv:0804.0220 (APJL)

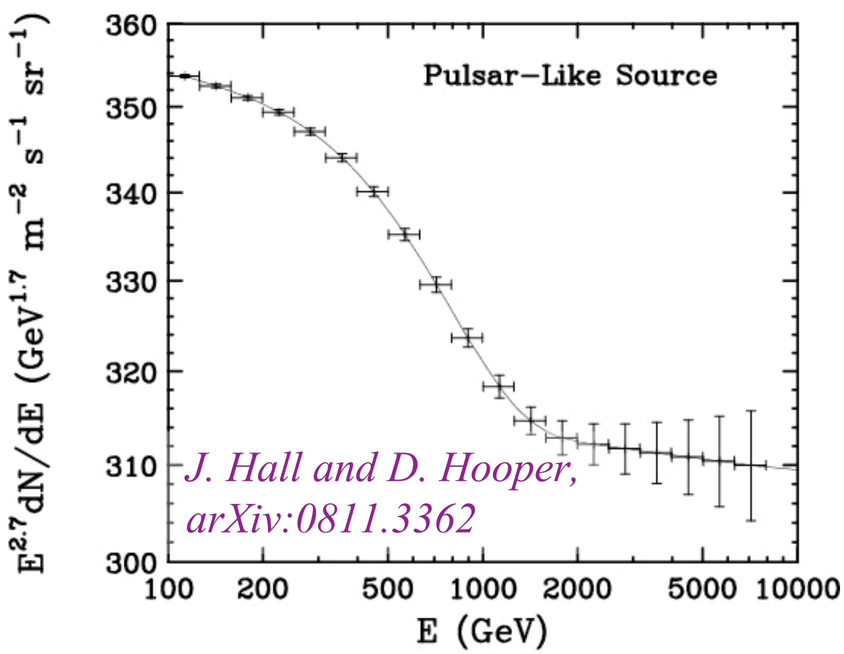


Disentangling Pulsars from DM (III)

- ✓ *Antiprotons (& anti-D)*
- ✓ *Possible anisotropy*
- ✓ *Shape of the cutoff in e-flux feature (IACTs?)*
- ✓ *γ-rays: Fermi should find diffuse excess (DM) vs. "unresolved/unidentified" point-sources*
- ✓ *Often, new (meta)stable particle at colliders (but troubles for ~TeV hadrophobic particles…)*
- ✓ *Improved ν-bounds from Galactic Center, …*

• In some DM models (e.g. KK) sharper cutoff, Harder to achieve for astrophysical models. (But the feature can be spoiled by propagation effects, see *M. Pohl, arXiv:0812.1174*)



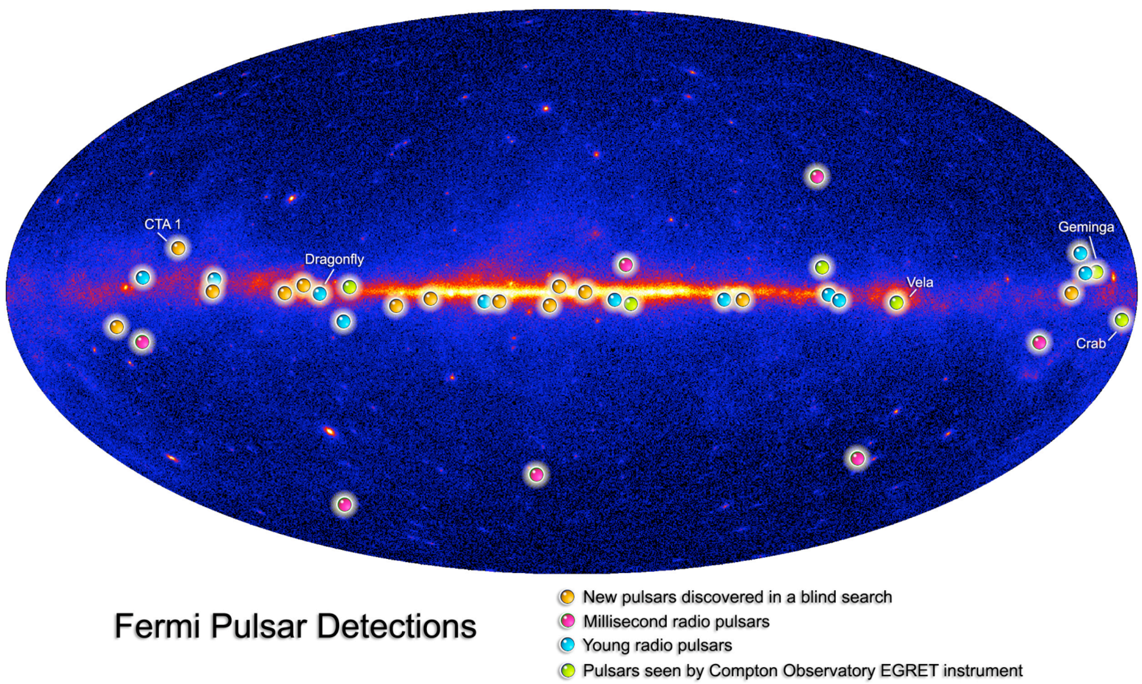


J. Hall and D. Hooper, arXiv:0811.3362

Disentangling Pulsars from DM (IV)

- ✓ *Antiprotons (& anti-D)*
- ✓ *Possible anisotropy*
- ✓ *Shape of the cutoff in e-flux feature (IACTs?)*
- ✓ *γ-rays: Fermi should find diffuse excess (DM) vs. "unresolved/unidentified" point-sources*
- ✓ *Often, new (meta)stable particle at colliders (but troubles for ~TeV hadrophobic particles…)*
- ✓ *Improved ν-bounds from Galactic Center, …*

- Only the youngest and/or nearest pulsars were detectable by EGRET
- Yet ~53 radio pulsars in error circles of EGRET unidentified sources! (~20 plausible counterparts)
- First major Fermi discoveries already in this direction! CTA-1, arXiv:0810.3562; http://www.nasa.gov/mission_pages/GLAST/news/dozen_pulsars.html



Fermi Pulsar Detections

Summary: a new era in High Energy astrophysics

- Wealth of (multi-wavelength) data ⇒ identification of accelerators & their features! *(X-ray detectors…ACTs, MILAGRO, Fermi…PAMELA, Balloons…ν Telescopes)*

- Feedback in CRs-Background field is being understood (e.g. in SNRs): validation of the Standard Model of Galactic Cosmic Rays in Progress!

- Important ‘applications’ to particle physics: atmospheric ν’s, Dark Matter…

- Barring systematics, I argued that recent positron data suggest a class of energetic pair-producers. Both astrophysical & DM explanations possible.

→ The combined data (p-bar, gammas, electrons, etc.) point either to astrophysical explanations (pulsars) or to quite exotic DM properties (exciting?!)

→ Further astrophysical data as well as info from colliders & direct detection experiments important to discriminate between possibilities

- ✓ *Info from other messengers: anti-p, ν, γ*
- ✓ *Spectral shapes of e^-+e^+, e^+, e^-, f_{e+} over larger energy range*
- ✓ *Anisotropies*
- ✓ *Refined astro models especially from Fermi*
- ✓ *Info from colliders & Direct detection (more model dependent)*