Astrophysical sources of CR antimatter

or

How the ignorance of what we know exists affects the chances of unveiling what we think should exist but we're not sure of how to find…

Pasquale D. Serpico

Focus week on Indirect Dark Matter Search, Dec 07 - 11, 2009

IPMU-Tokyo

Outline

- Why are we here?

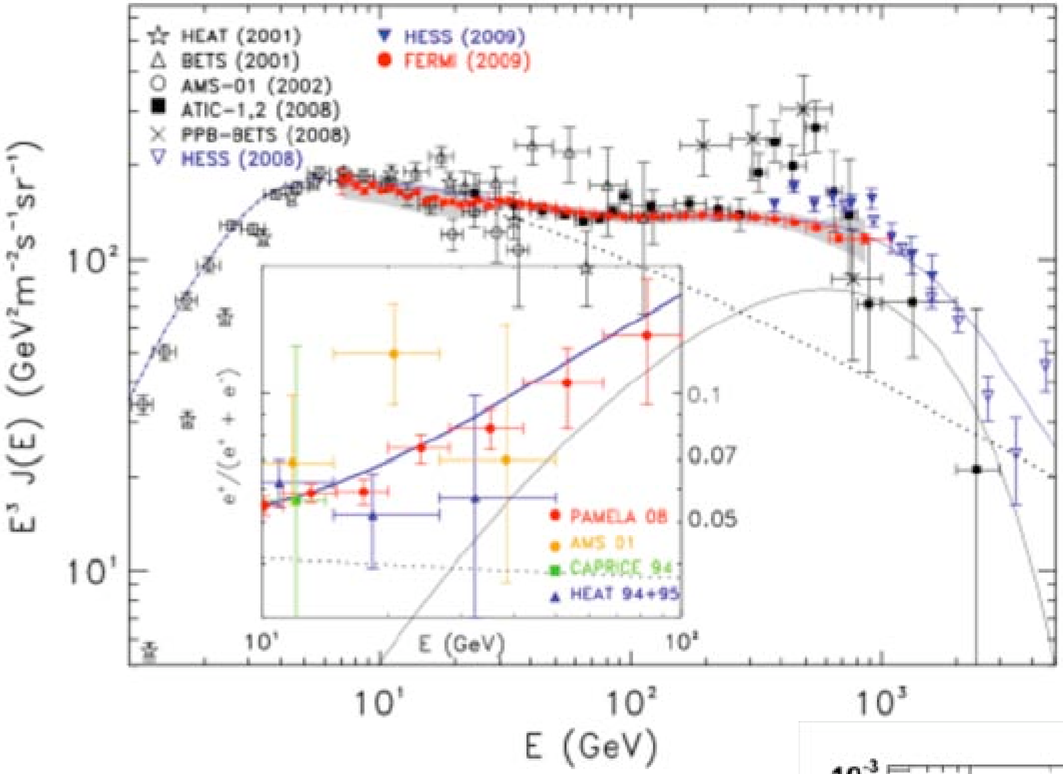
Over the last year, much excitement caused by the PAMELA-ATIC-Fermi CR lepton data. A plethora of interpretations (="usual path": model proposed → test it against data → derive some consequence).

- Part I

I will present some proposals along the above lines requiring only astrophysical sources and properties which are known to exist, but have quantitative uncertainties

- Part II

To <u>discover</u> new physics is in my opinion on a different footing (just like claiming to have discovered a new class of objects from these data!)
I will discuss on more general grounds to what extent it is possible to identify new physics in CRs, and how.



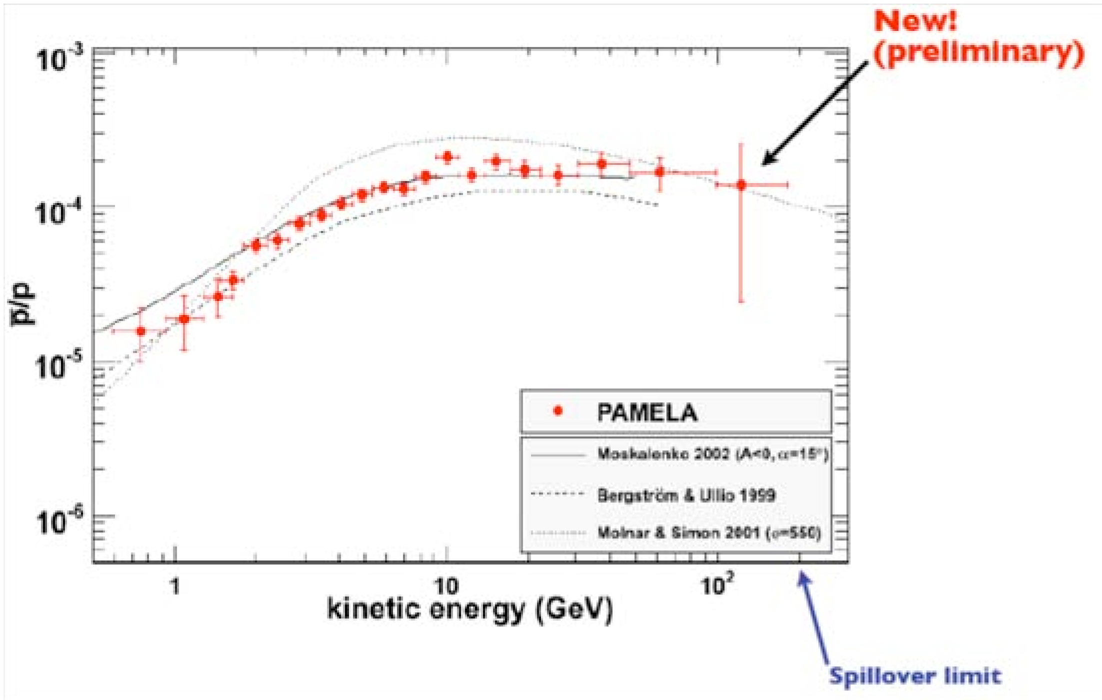
Overall e^-+ e^+ Spectrum
Positron Fraction data

Latronico, Fermi Symposium 2009

Nature 458 (2009) 607
PRL 102 (2009) 181101

Antiproton fraction

PRL 102 (2009) 051101
Pearce, 37th SLAC Summer Institute



Current "philosophy" in CR astrophysics

- Reasonable Ansatz (based on empirical evidence and physical basis) that one can factorize CR production & diffusive propagation problems.

- All species largely share the same propagation parameters: for a given assumption on the sources they can be determined by "overconstrained measurements"

- The source problem is conceptually more difficult to address: intrinsically model-dependent! It relies on some model-building and must be tested via

→ Unique (as far as we know) predictions (e.g. γ-line emission in DM)

→ Not unique, but strongly correlated predictions btw different signals (e.g. links between energy and spectral feature in DM γ-signal)

"My two cents": some considerations on…

Source term (time, space, momentum dep.)
Includes dec./frag. for heavier nuclei

Diffusion

Energy loss

$$\frac{\partial \Phi}{\partial t} = Q + \vec{\nabla} \cdot (D_{sp} \vec{\nabla} \Phi) - \frac{\partial}{\partial p}(\dot{p}\Phi) +$$

Convection velocity

$$+ \frac{\partial}{\partial p}\left[p^2 D_{mom} \frac{\partial (p^{-2}\Phi)}{\partial p}\right] - \vec{\nabla} \cdot (\vec{V}\Phi) + \frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla} \cdot \vec{V})\Phi\right] +$$

$$- \frac{\Phi}{\tau_{frag}} - \frac{\Phi}{\tau_{decay}}$$

Adiabatic flow term

Fragmentation and decay terms
(negligible/vanishing for protons)

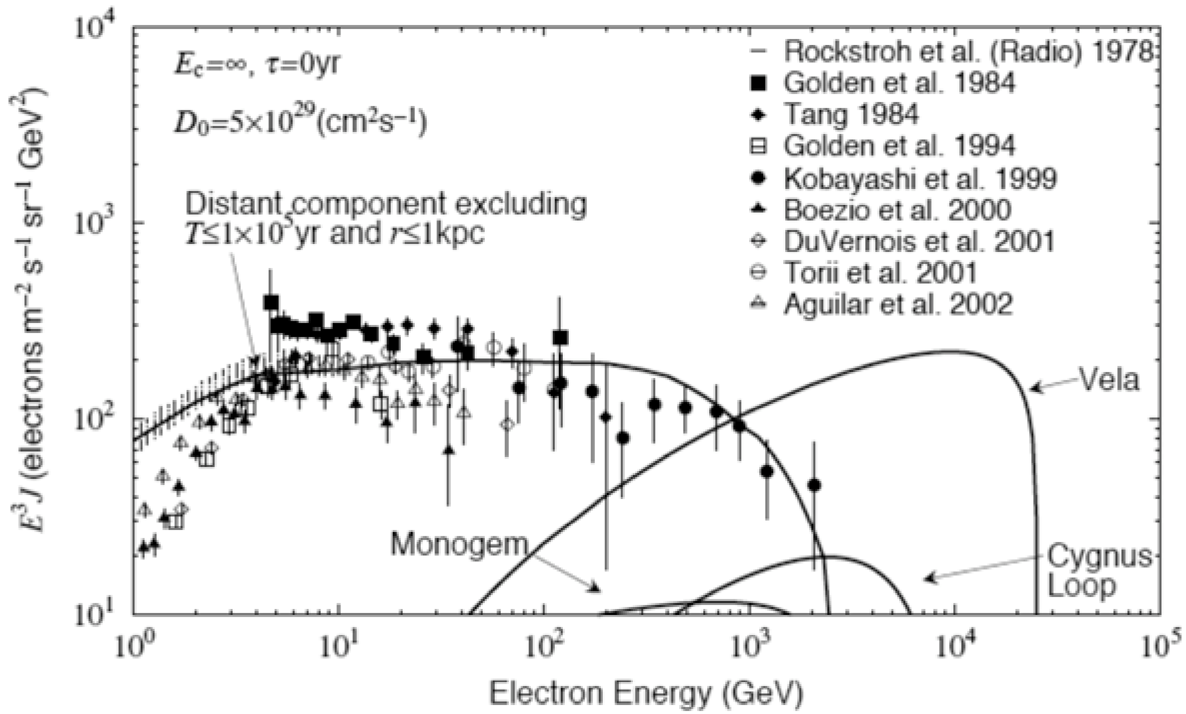
Diffusive reacceleration

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

Why am I caring only about <u>antimatter</u> sources?

Because that's the only possible trouble for astrophysical mechanisms!

Virtually any HE astrophysics object sources relativistic e^-. A plethora of suitable candidates exist to explain "bumps" in the electron flux! SNRs, pulsars, X-ray binaries, etc. (γ,X-ray & radio objects) The astrophysical motivation for "TeV" e^- studies is to explore a range where all but one/few local objects account for the flux



Kobayashi, Komori, Yoshida, Nishimura, "The Most Likely Sources of High Energy Cosmic-Ray Electrons in Supernova Remnants," APJ 601, 340 (2004)

Guaranteed astrophysical sources of antimatter

Spallation of CRs (assume pure matter) on interstellar medium gas

How robustly do we know that?

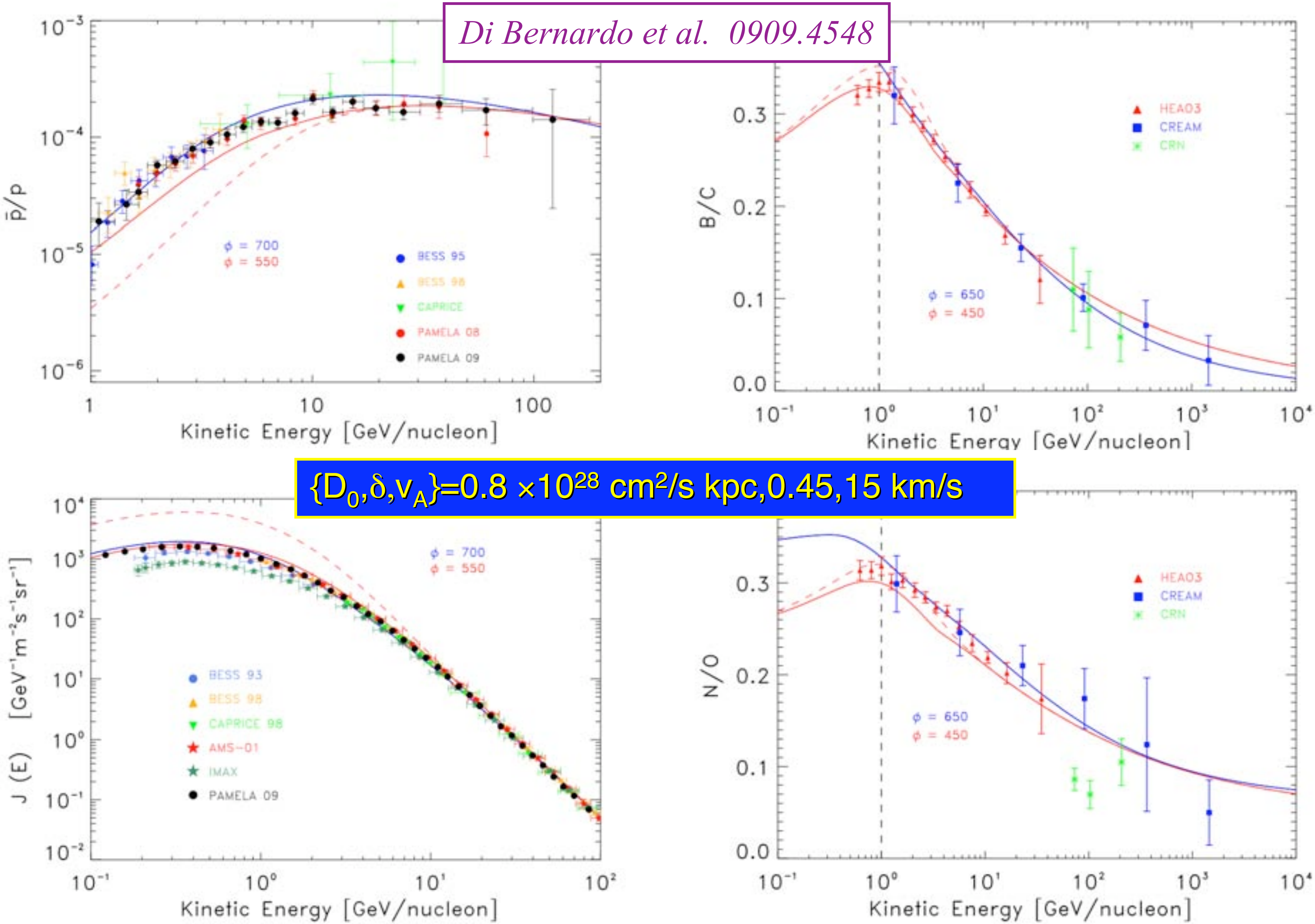
- ✓ We know CR spectra at the Earth, and (assuming known (astro)physics!), that they should be confined diffusively in a magnetized region embedding the MW

- ✓ Propagation parameters constrained by assumed secondary/primary elements (B/C), "chronometers" as ^{10}Be good agreement with properties of the ISM estimated from direct probes.

- ✓ Diffuse gamma-ray data, of course

Toward a consistent framework…

Di Bernardo et al. 0909.4548

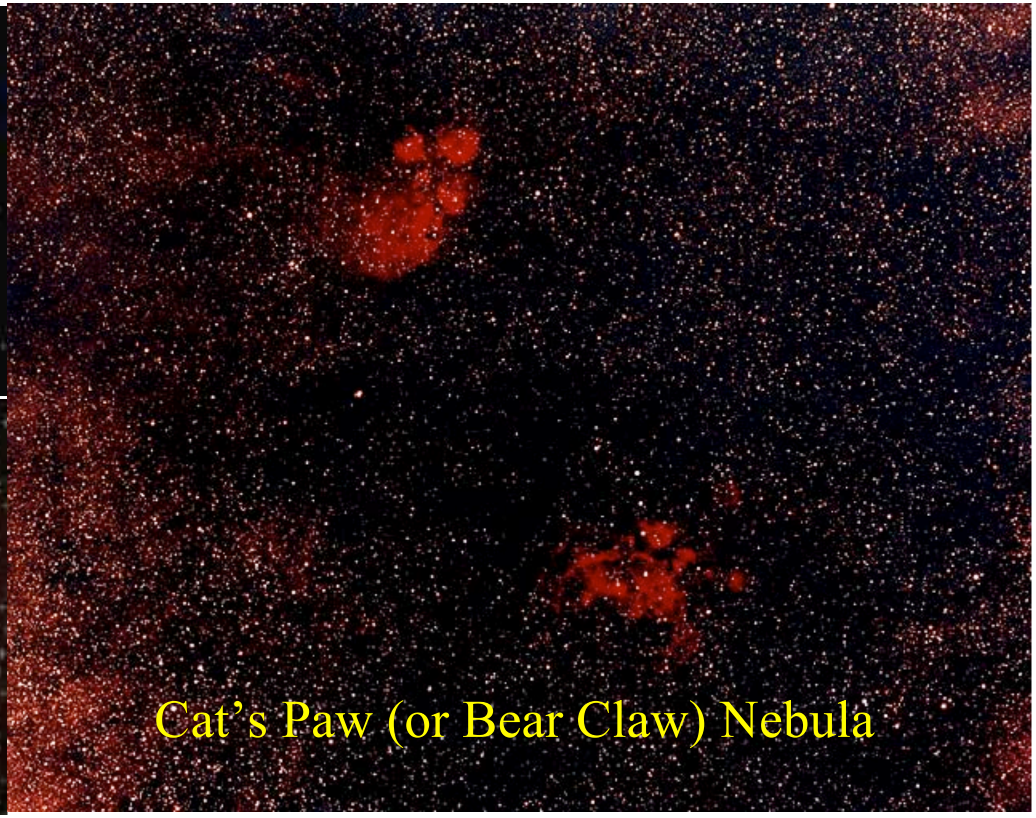


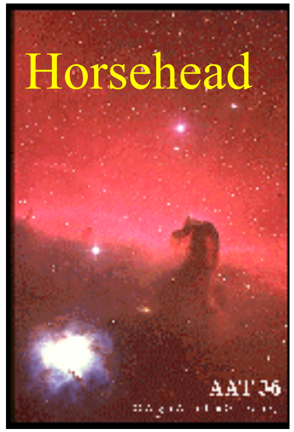
$\{D_0,\delta,v_A\}$=0.8 $\times 10^{28}$ cm^2/s kpc,0.45,15 km/s

"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy."

W. Shakespeare, Hamlet - Scene V

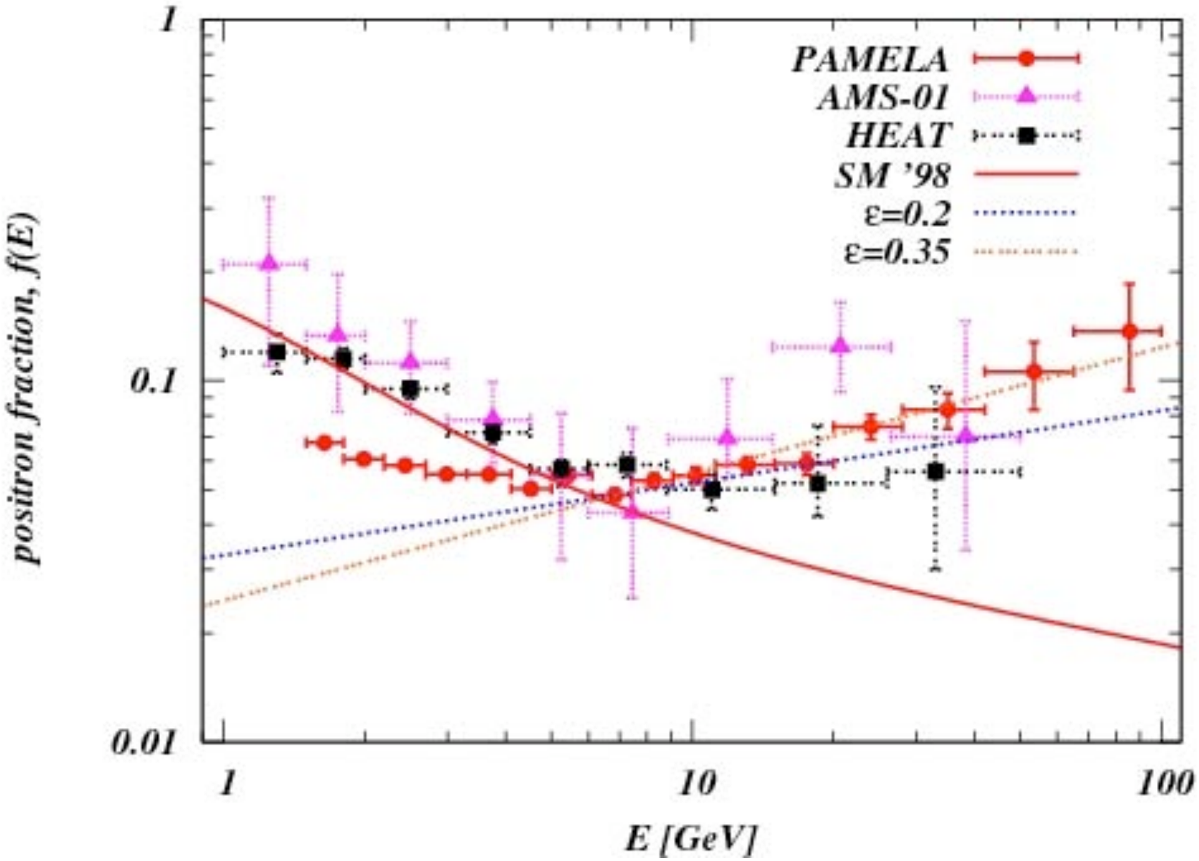
The astrophysical zoo





Why are these data puzzling?

Basically, because in a standard propagation framework the high-E behavior is dictated by $D(E) \sim E^{-\delta}$, with $\delta \sim 0.33-0.7$ e.g. from B/C fits.



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

ELSEVIER

N.B. 1999

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]

Barring:

- systematics (final check by AMS-02, hopefully!)
- and/or fundamental flaw in our understanding of CR propagation

Very, very likely the answer is: Yes

What causes the rise? "Anticopernican" option

"Exceptional object": elsewhere or at another time in the Galaxy we would not see something similar very easily. E.g.:

collisions of CRs from a SNR in a near dense cloud
Y. Fujita, K. Kohri, R. Yamazaki and K. Ioka, arXiv:0903.5298, see also Dogiel, V. A et al (1987), MNRAS, 228, 843

GRB (or μ–quasar event?) happening in our Galactic neighborhood in the last ~ 10^5 yr (~1% chance probability?)
K. Ioka, arXiv:0812.4851

Single pulsar? *Many papers…*

Predict specific features in total e flux, not (yet?) confirmed

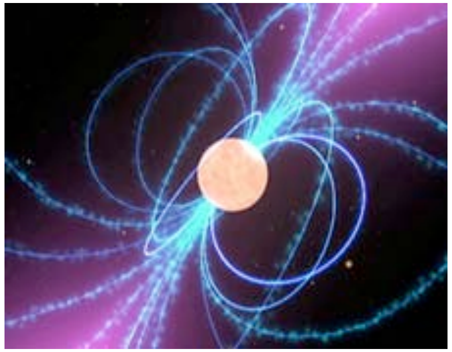
certainly "logical possibilities": but better to invoke exceptional objects only if really needed (otherwise generic conclusions would hardly be reached…)

For example, for the known distribution in space & time of sources and targets, are these contributions really dominant over "diffuse" contributions from all other (known) sources?

What causes the rise?

Dark Matter

- For a given model, spectra “easily” predicted
- Signal requires large enhancement
(non-thermal? Decay? Sommerfeld? Clumps?):
ready to give up the “WIMP miracle”?
- Constrained (excluded?) from anti-p, ν and γ-ray data



Pulsars

- Complex astrophysics, no “robust predictions”
- <u>“Natural” normalization</u>; shape of the signal (?)
- Purely e.m. cascade, explains why no anti-p & no ν

Mature SNRs *(standard source of CRs!!!)*

- In situ production is <u>certain at some level</u>.
- How large hard to calculate reliably a priori,
most likely must be answered observationally.
- Prediction of high-energy feature in p-bar, nuclei

Supernova remnants

The Supernova Remnant Paradigm for CRs

- Galactic Cosmic Rays produced by 1st order Fermi acceleration at SNR shocks ($L_{CR} \approx 0.1 E_{kin,SNR} R_{SN}$, SNR known TeV γ-sources…)
- Power laws $\sim E^{-\gamma}$ generated naturally with $\gamma = 2 + \varepsilon$

(strong/supersonic non-relativistic shock, no-backreaction, perfect gas EOS)

- Spectra observed at the Earth modified by diffusive propagation in the Galaxy (which also isotropizes the flux)+spallation

At steady state source term = loss term

$$Q(E) = \frac{N(E)}{\tau_{escape}(E)} + \frac{N(E)}{\tau_{spall}(E)}$$

$$\tau_{escape}(E) \propto E^{-\delta}$$

$\delta \sim 0.6$ e.g. from B/C

When spallation losses are negligible…

$$N(E) = Q(E)\tau_{escape}(E) \propto E^{-\gamma-\delta}$$

$\gamma + \delta \sim 2.7 \rightarrow \gamma \sim 2.1$, OK with theory!

Maximum Energy from lengthscales and timescales

- The acceleration to energy E takes a finite time $t_A(E) \propto D_A(E) \propto E$
- The accelerators only live a finite time t_L (~10^4 yr for a SNR)
- Energy losses kick in soon or later, with $t_E(E) \sim E^{-1}$
- The system must be able to contain the particle, $s > \lambda_G = p/(Ze\ B)$

From $D_{ISM}(E)$ derived from B/C, $E_{max} \sim$ few GeV!!! ⇒ $D_A(E) \gg D_{ISM}(E)$?!

Are our scenarios completely wrong?
Is "new Physics" required?

Yes, we needed to improve our 0th order astrophysics!

Theoretical Efforts devoted to

- Relax test-particle approximation, ie. backreaction of CRs on the shock
- Self-generation of B-field amplification via streaming instabilities
- Matching analytical insight to simulations and phenomenological applications
- Set the basis for a general theory applicable to shocks with arbitrary speed
- Studying alternative acceleration mechanisms…

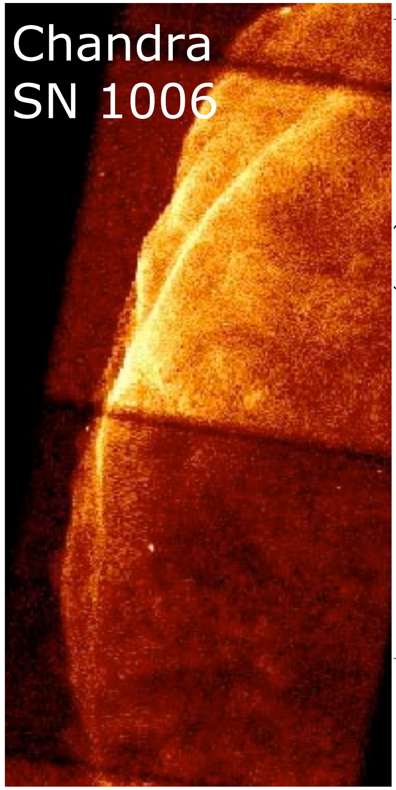
(Aharonian, Amato, Berezhko, Bell, Blasi, Gabici, Drury, Duffy,Lemoine, Malkov, Ptuskin, Schlickeiser, Volk, Zirakashvili, ...)

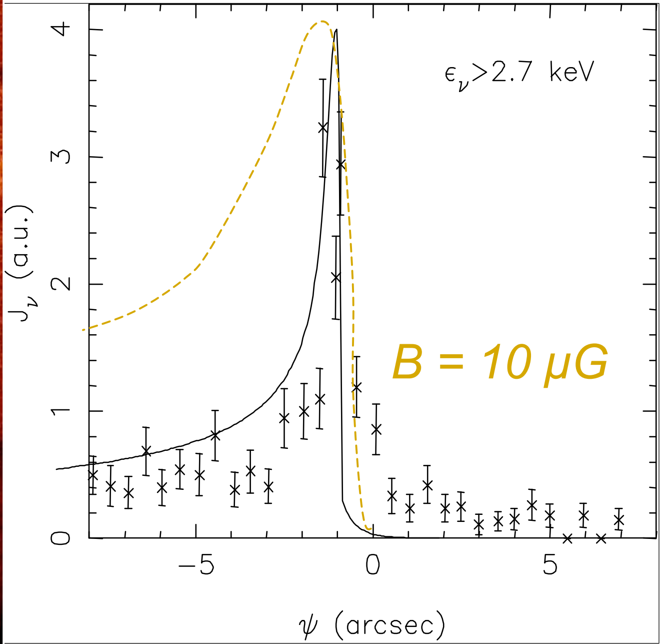
Particular attention has been paid to the *Bell'04,* non-resonant streaming instability where CRs excite MHD modes at scales $\lambda << \lambda_G$.

It seems to allow a fast enough growth rate to "match the data"

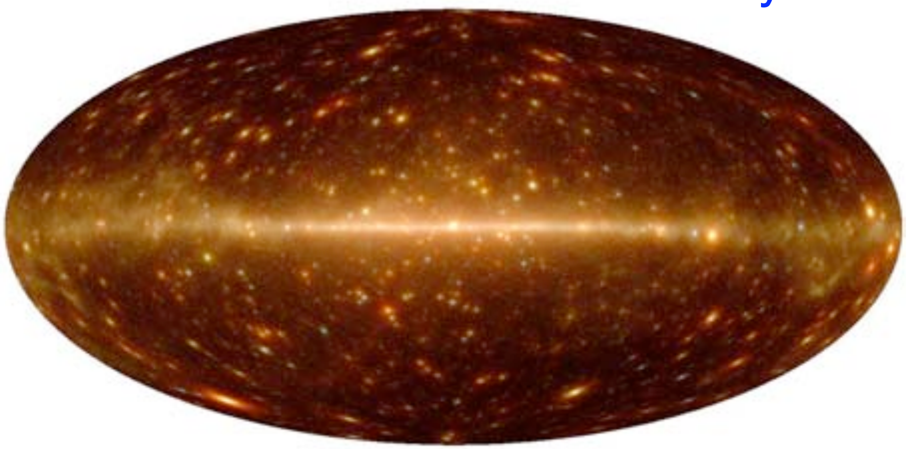
Some of these topics (and other complementary ones)
Subject of the talk by M. Hoshino on Friday

Multiwavelength approach: Yesterday, today, tomorrow





❖ Fermi is mapping the GeV sky



❖ Soon TeV Neutrinos!

Prospective Galactic TeV ν sources

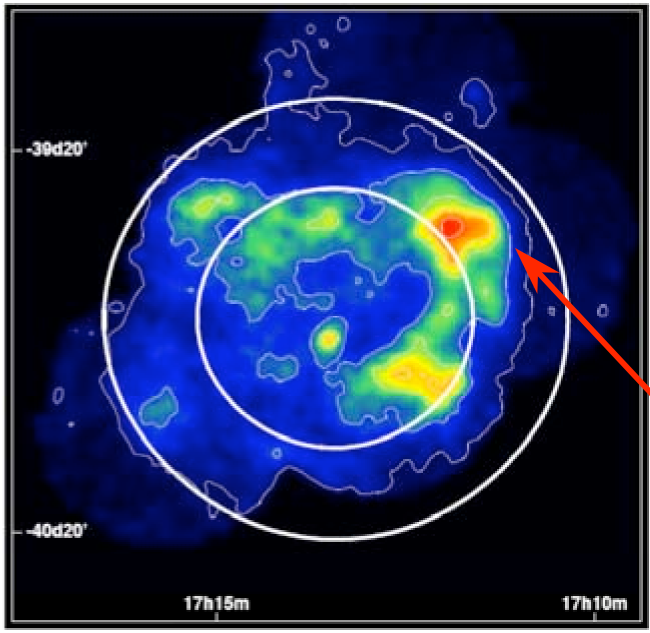
Source	ϕ_γ	Γ	E_ν^{cut} (TeV)	$N_\mu(>1$ TeV)
Vela Jr.	21.0	2.1	10	3.1
(RX J0852.0–4622)			25	4.9
			50	6.1
GC Diffuse	5.2	2.29	20	0.5
			50	0.7
(+ GC Source)			20	0.8
			50	1.0
RX J1713.7–3946	15.0	2.19	50	2.8
	20.4	1.98	6	2.2
Vela X	9.0	1.45	7	4.5
Crab (IceCube)	33.0	2.57	50	2.7
HESS J1514–591	5.7	2.27	25	0.9
			50	1.1
HESS J1616–508	6.0	2.35	10	0.5
			50	0.9
HESS J1632–478	5.5	2.12	10	0.8
			50	1.5
HESS J1634–472	2.0	2.38	10	0.2
			50	0.3
HESS J1640–465	3.0	2.42	10	0.2
			50	0.4
HESS J1745–303	2.5	1.8	10	0.5
			50	1.2

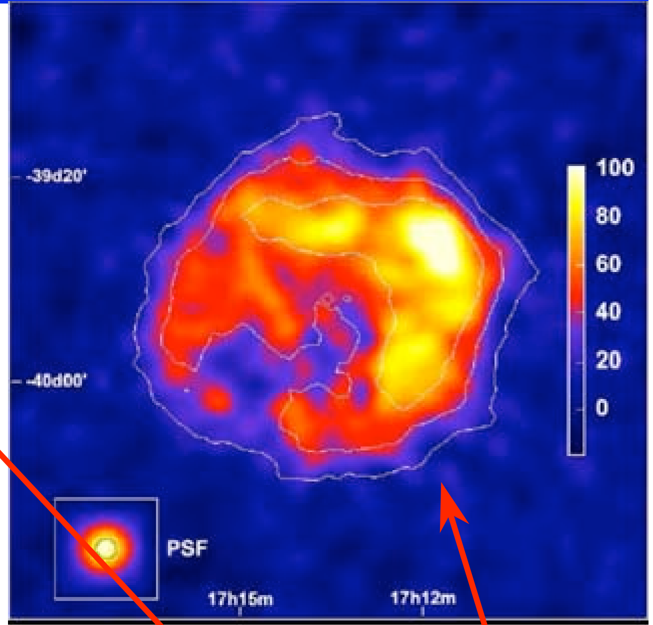
Kistler & Beacom, astro-ph/0607082

Towards a consistent phenomenology

required interior magnetic field
$B = 126\ \mu G >> B_{ISM}$

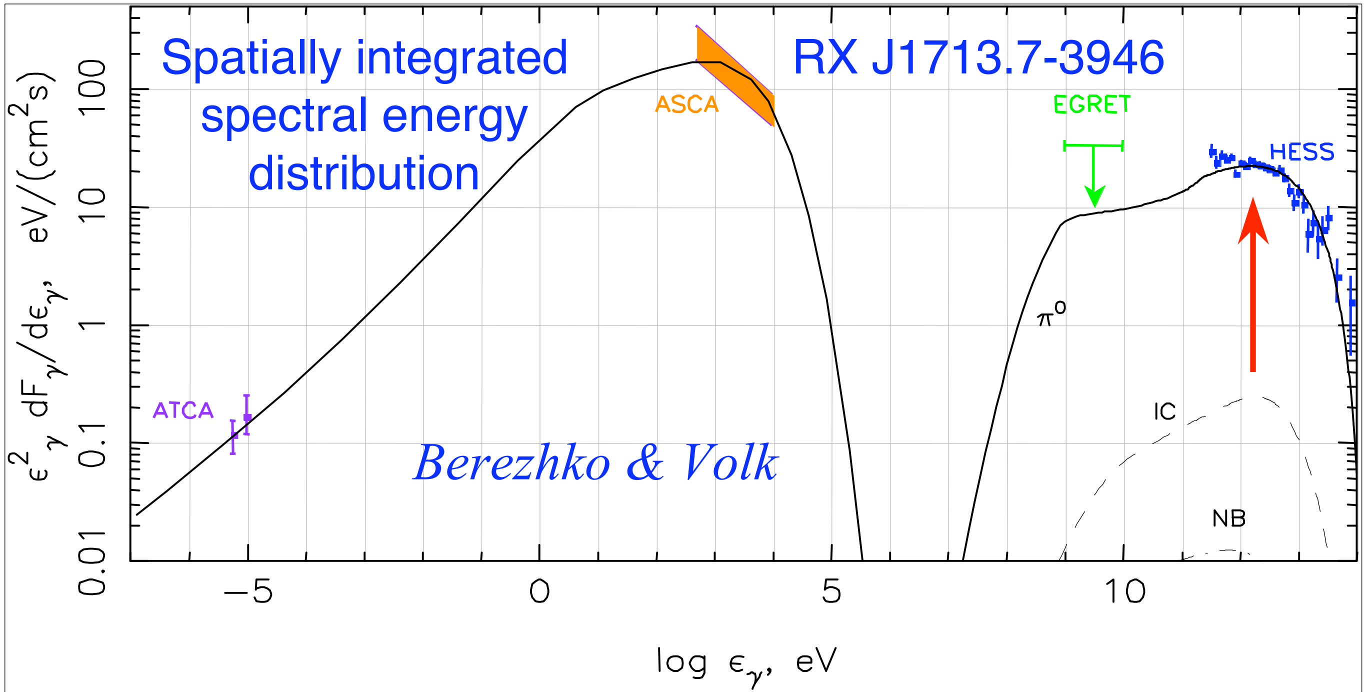
Consistent with filamentary structures revealed by X-rays





X-rays

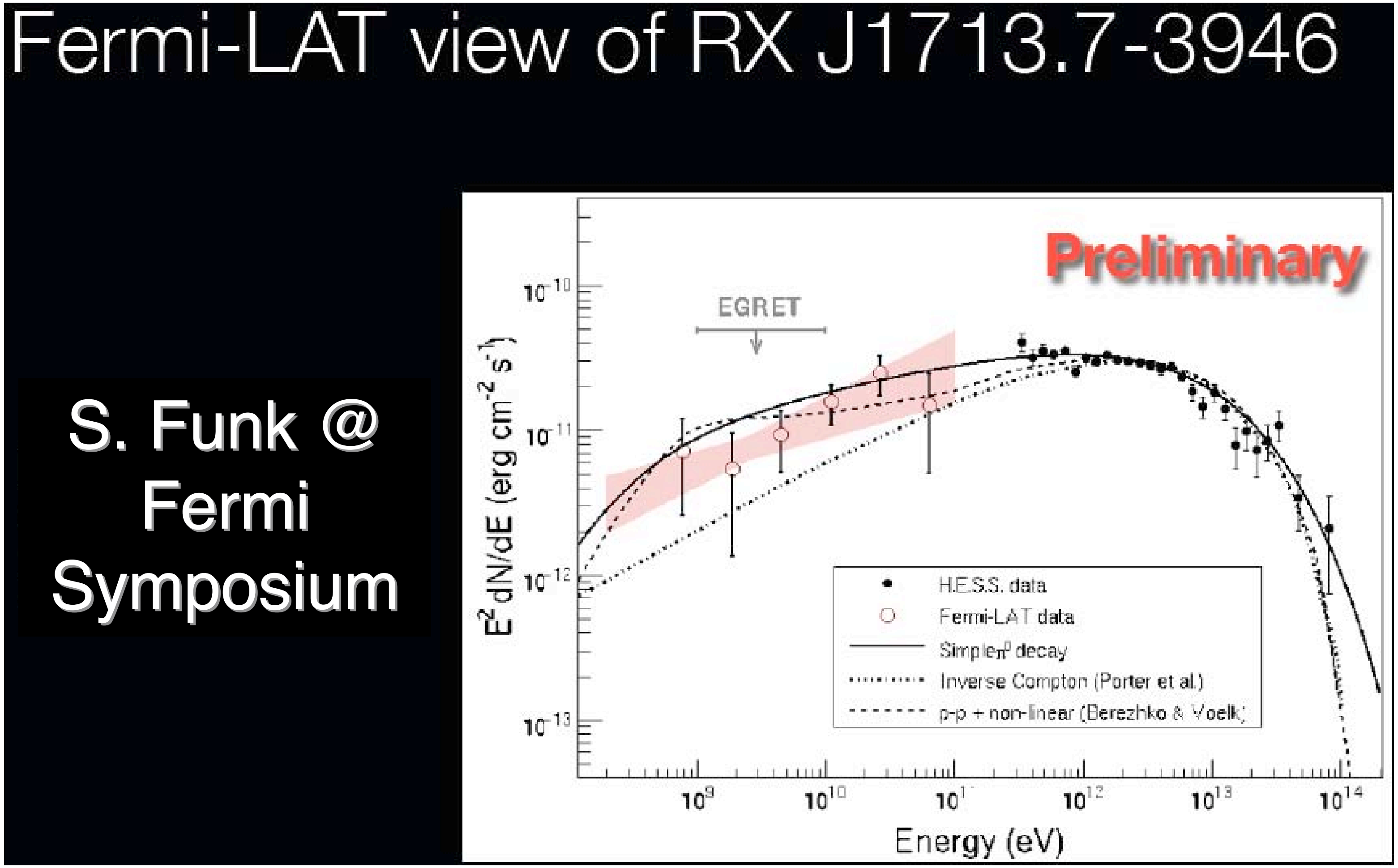
TeV (HESS)



γ from π_0 decay: Hadronic!

Bright perspectives for understanding the bulk of Galactic CRs

Early results from Fermi…



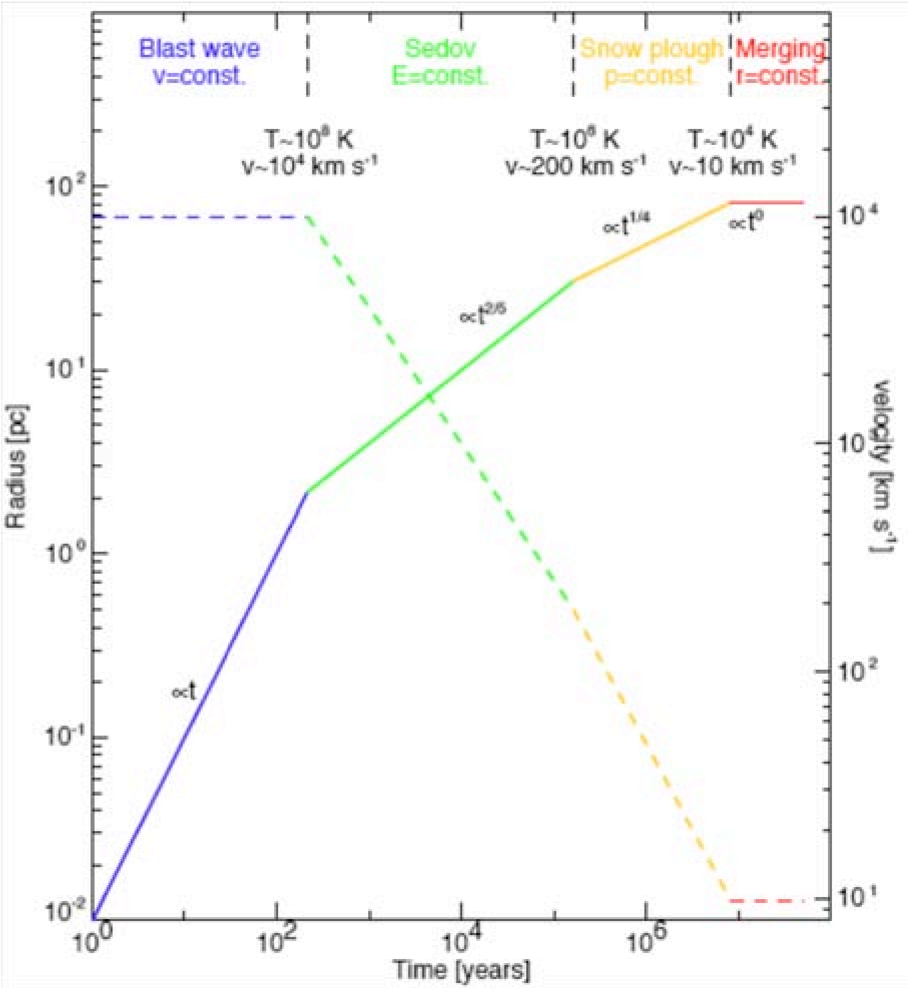
Very preliminary, but

- all points are above leptonic acceleration models
- a couple of them by ">3 σ"
- points fluctuate (within 1-2 σ) around the non-linear hadr. model prediction…

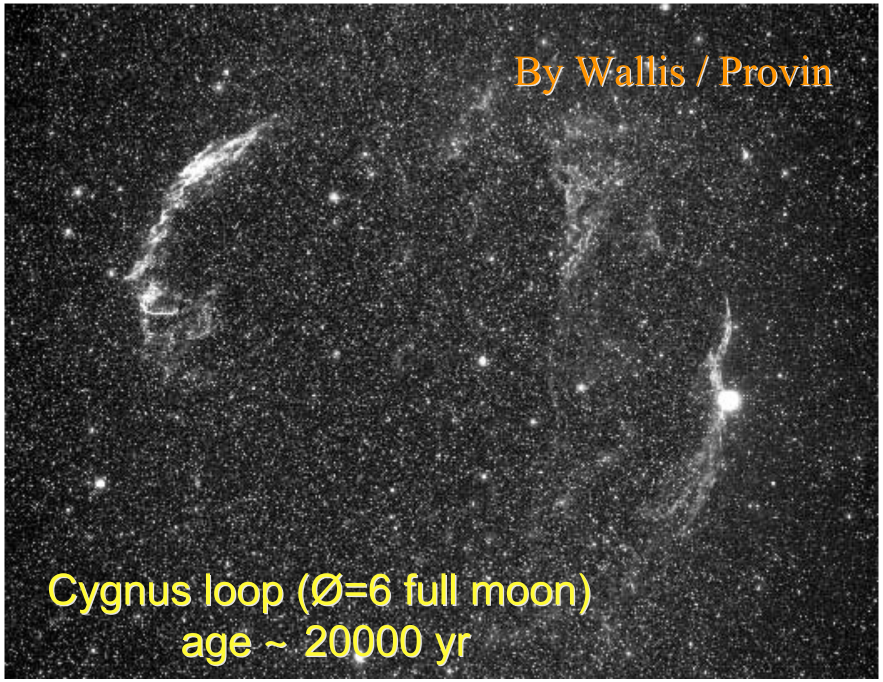
Old Supernova Remnants?

Young SNRs ($\tau_{SN} \lesssim 10^3$ yr) can accelerate Galactic CRs up to the "knee" (few PeV)
But "low energy" (E< TeV) CRs can be accelrated for much longer ($\tau_{SN} > 10^4$ yr)

the bulk of GeV-TeV CRs should come from old (almost invisible?) SNRs!

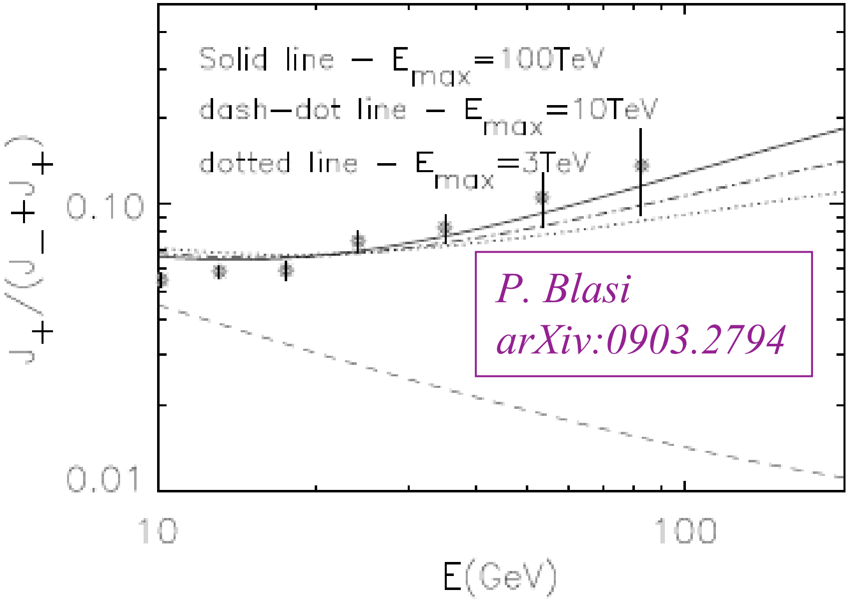


Collisions in the accelerating environment are not crucial for predicting the bulk of CR injection, but are not irrelevant when considering secondaries!



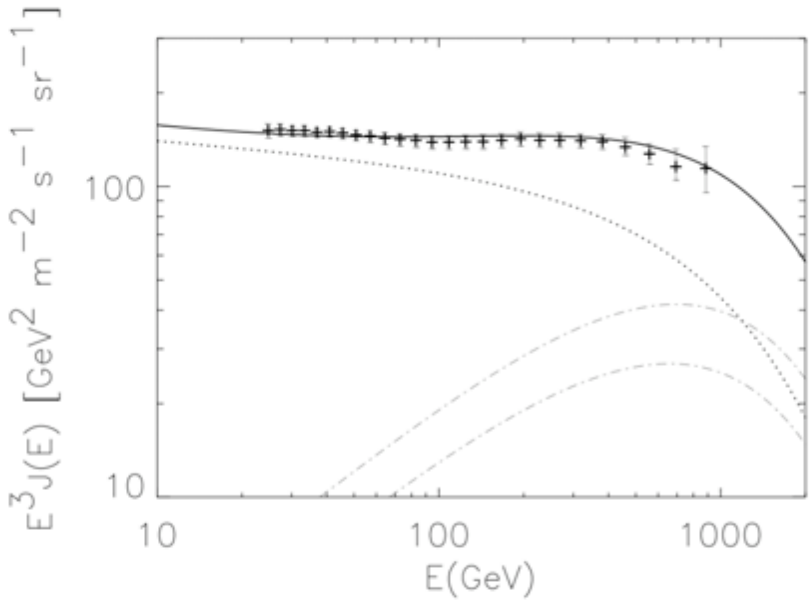
Acceleration of Secondary $e^{\pm}$

- Primary e^- $\sim E^{-\alpha}$, after propagation $\sim E^{-\alpha-\delta}$
- Secondary e^+ and e^- at Earth, produced during CR propagation: $\sim E^{-\alpha-2\delta}$
- Secondary e^+ & e^- in source $\sim E^{-\alpha} + E^{-\alpha+d}$ after propagation $\sim E^{-\alpha-\delta} + E^{-\alpha-\delta+d}$



Positron fraction $\sim a_0\, E^{-\delta} + a_1 + a_2\, E^{d}$ → $\sim n\, r^2 \gamma\, D/\, u^2$ (2 effective par.)

↓ $\sim n\, r\, \tau_{SN}$ (1 effective parameter)



Crucial physics ingredient production in the same region where CRs are accelerated. These e^+e^- have a very flat spectrum!

Universal (unavoidable) effect: strength depends on environment parameters in mature SNRs

For more (technical) details, see P. Mertsch's talk

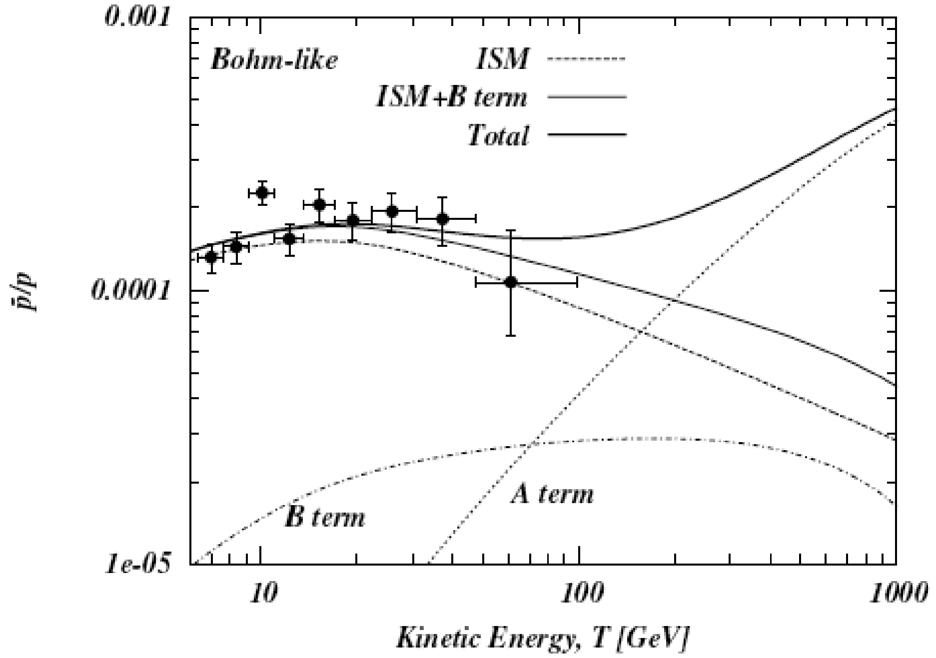
"Primary" antiproton

The same ("hadronic") mechanism produces anti-p!

- ❑ The scenario is consistent with current antiproton data
- ❑ Sharp difference with respect to standard predictions for AMS-02 range

P. Blasi & PS arXiv:0904.0871

(P. Mertsch's talk for extension to nuclei)



- ➢ Implications for astrophysics: info on sources present, but degeneracy propagation/source properties possible!
- ➢ Correlated "rises" in e^+ and anti-p. Troubles for DM searches?

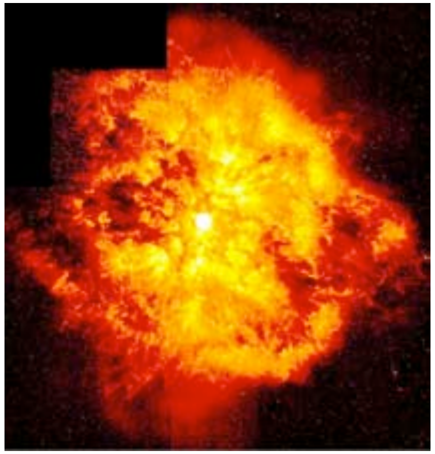
Lesson: astrophysical "backgrounds" to CR antimatter might be not so trivial…
The viability of antimatter for DM searches should rely on robust signatures only!

Enriching the scenario: e^+ blowing in the wind?

It is possible that SNRs from different classes
of progenitors dominate CRs of different type/energy

- Red-Blue SG are very massive stars (M> 15-25 M_{sun}) which typically experience significant mass losses; their SN explosion happens in a (relatively) dense, magnetized and Z-enriched medium (Wolf Rayet stars)

- Theories invoking those objects as responsible for HE tail of Galactic CRs exist since longtime, recently reassessed in relation to positron/electron data



WR 124 (HST)

P.L. Biermann, T. K. Gaisser, T. Stanev astro-ph/9501001;
P. L. Biermann et al., arXiv:0903.4048

Peculiarities:

- detectable HE ν and γ sources? (less sources contribute, more localized…)
- contributions from β^+ nuclei (less anti-p than in baseline "SNR" scenario?)

Pulsars

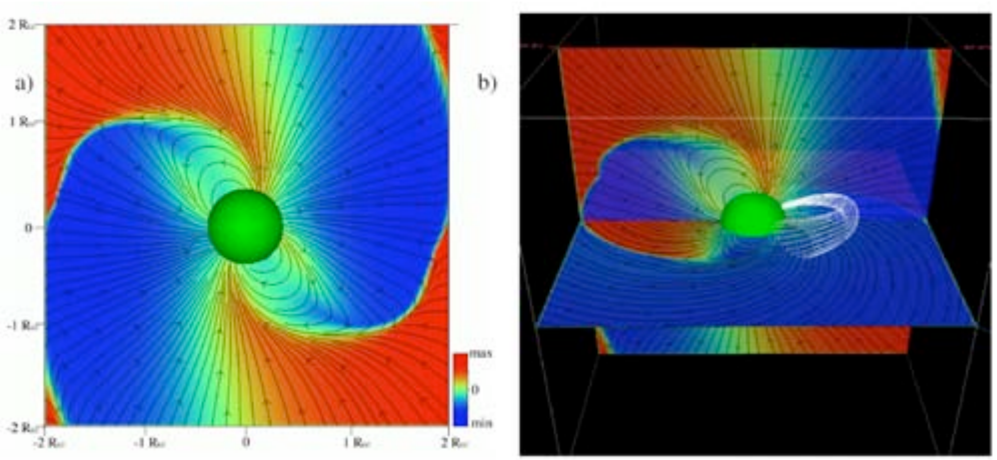
Pulsars

- Magnetized NS with non-aligned rotation and magnetic axes: *Pacini, Gold 1967-68.*

- They lose rotational energy and spin-down through e.m. torques due to large-scale currents in their magnetospheres.

- Only qualitative ideas on their structure: analytic expression exists for the vacuum rotator but real pulsars are not in vacuum since e^{+-} e^{-} are copiously produced due to the high surface electric fields induced by rotation

- One must rely on numerical solutions, which present several challenges.
Very active field in astrophysics:
  - First consistent solution axisymmetric case: *Contopoulos, Kazanas & Fendt (1999)*
  - First time-dependent simulations in 3D: *Spitkovsky (2006).*

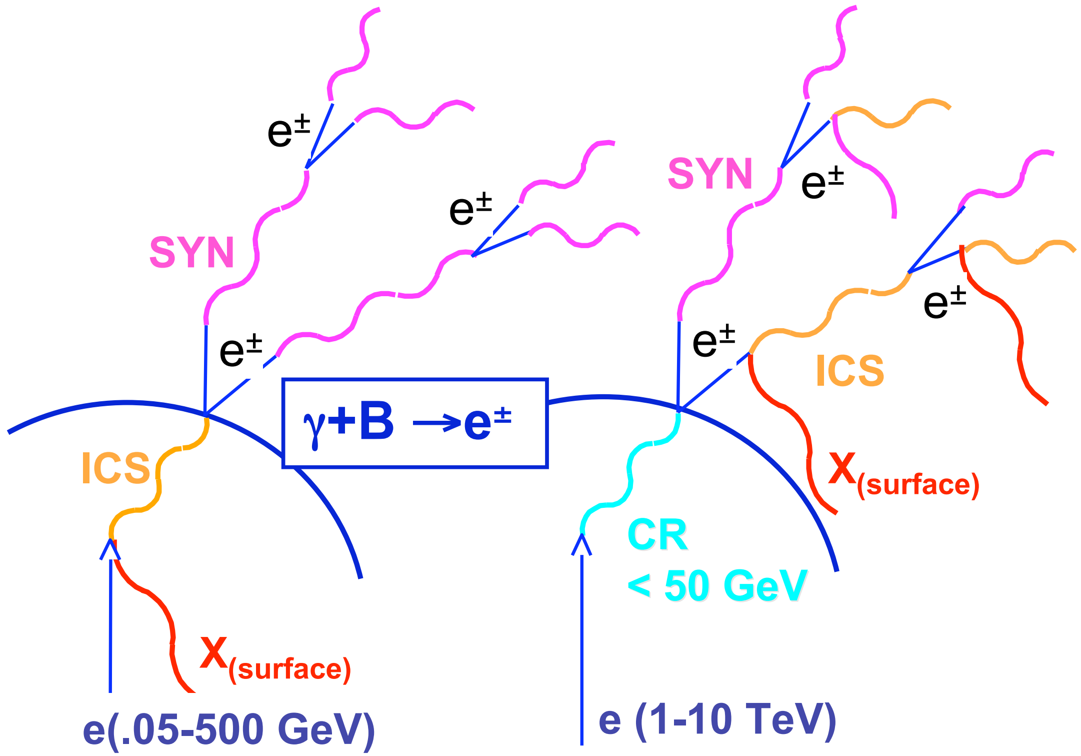


Force-free electrodynamics:

$E \cdot B = 0$ everywhere

No accelerator gaps!

Pulsars: Basics of pair cascade mechanism

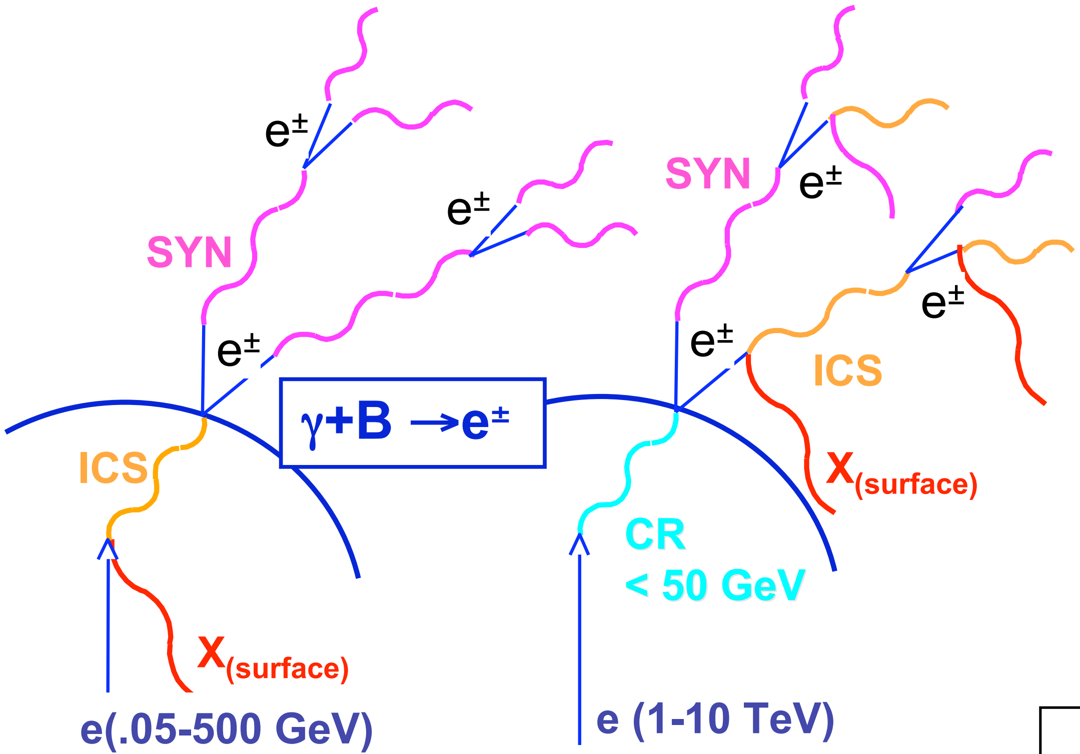


e^+ and e^- are accelerated by $E_{||}$

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

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

Pulsars: Basics of pair cascade mechanism



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

↓

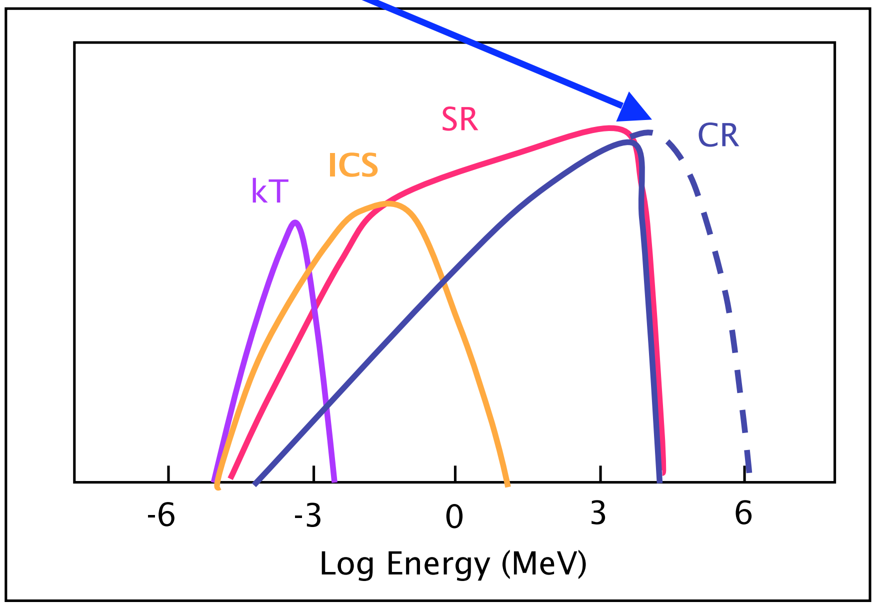
Relativistic e^+/e^- emit γ-rays via synchro-curvature, and IC

↓

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

"Fermi" region!

Profumo's talk



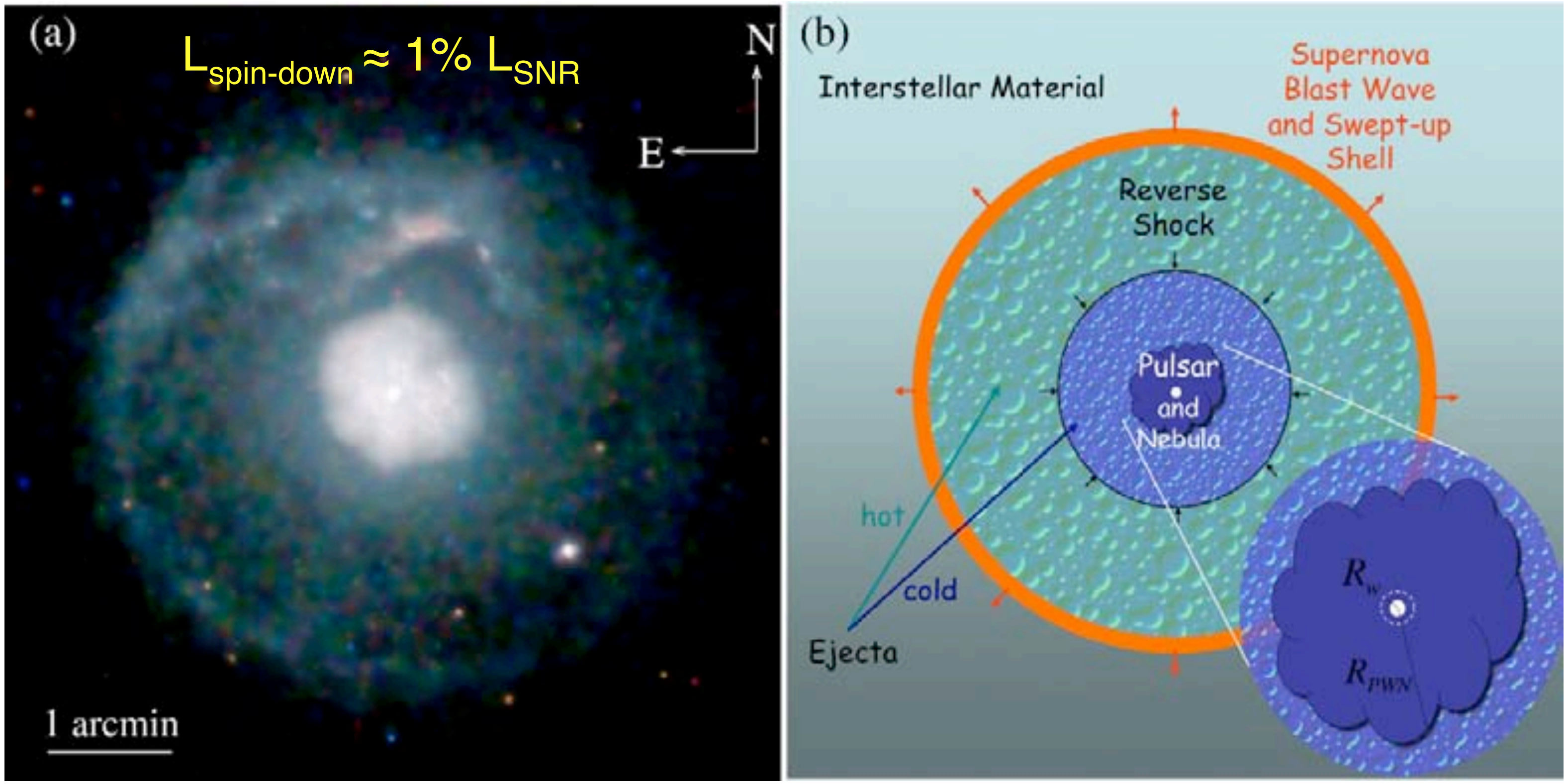
Different models exist depending on location & geometry of "gaps" (where E.B≠0)

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

For details of models, K. Hirotani's talk!

Emission at magnetosphere is not the whole story…

- ✓ Production at magnetosphere: dependence on B,Ω,geometry…
- ✓ Propagation in the PWN, then circumstellar environment: shock reacceleration!
- ✓ Escape in the ISM after the PWN breaks-up, after ~10^5 years



X-ray Chandra image of "composite" SNR G21.5-0.9
(here, no reverse shock of ejecta deceleration moving inward, yet)

Gaensler & Slane
astro-ph/061081

Some Numbers

$$\mathcal{L}_{\rm spindown} = I\Omega\dot{\Omega} = \frac{1}{2} I\Omega_0^2 \frac{1}{\tau_0} \frac{1}{\left(1+\frac{t}{\tau_0}\right)^2} \qquad \tau_0 \sim 10^4\,{\rm yr}$$

$$\dot{E} = b_0\,E^2 \qquad t_{\rm loss}(E) = (b_0\,E)^{-1} \gtrsim \frac{10^5\,{\rm yr}}{E_{\rm TeV}}$$

$$d^2 \simeq 4\,D(E)t \qquad t_{\rm diff} \simeq \frac{d^2}{4\,D(E)} \sim 2\times 10^5\,{\rm yr}\,\frac{d^2_{\rm kpc}}{E^\delta_{100}}$$

✓ Pulsars are "luminous" in photons for a time << than the time needed to produce charged particles reaching us from ~kpc distances (but for very local objects or at very high energies)

✓ For the PAMELA range, we have usually the hierarchy $\tau_0 << t_{PWN} < t_{diff}$ "instantaneous injection approximation". But electrons reaching us are typically emitted by otherwise dim objects!

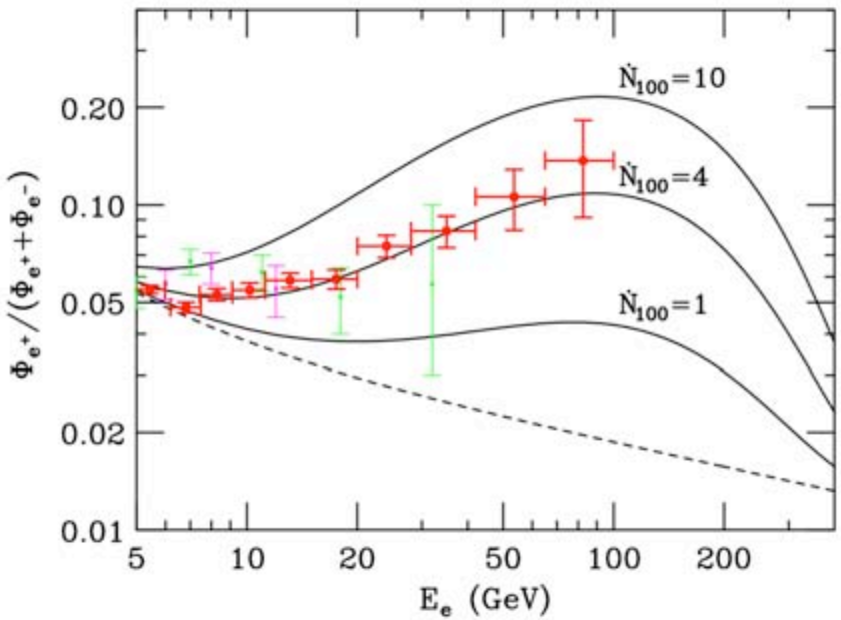
Prediction of a 'population model' of pulsars

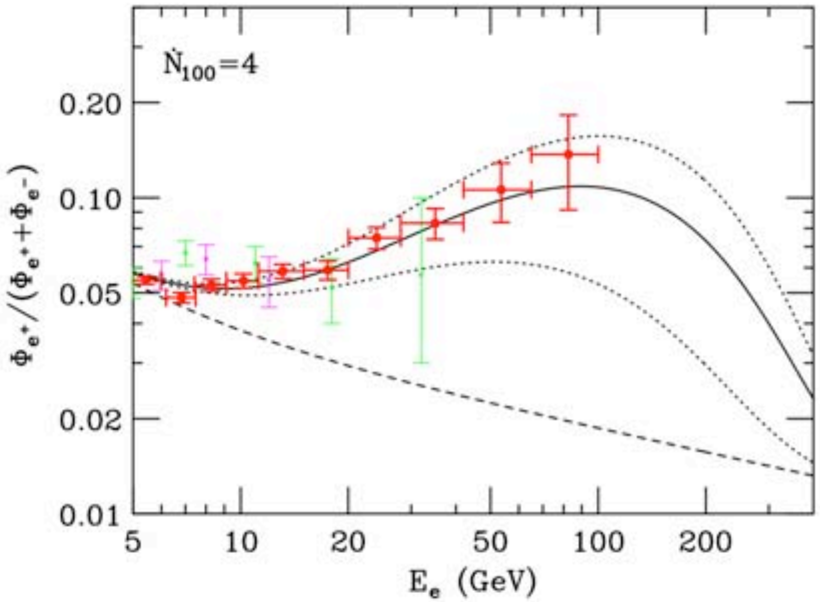
Once fixed a model for the emission (dependence on B, age…) a population study with Galactic population of Pulsars is needed

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

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

Account for Propagation/Energy losses…

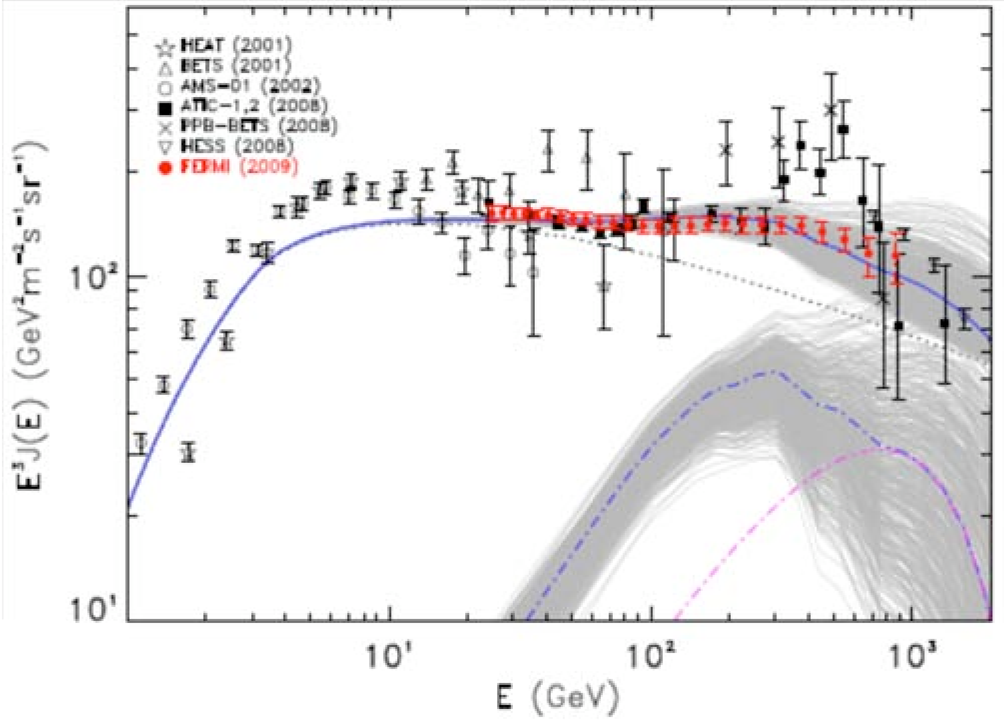


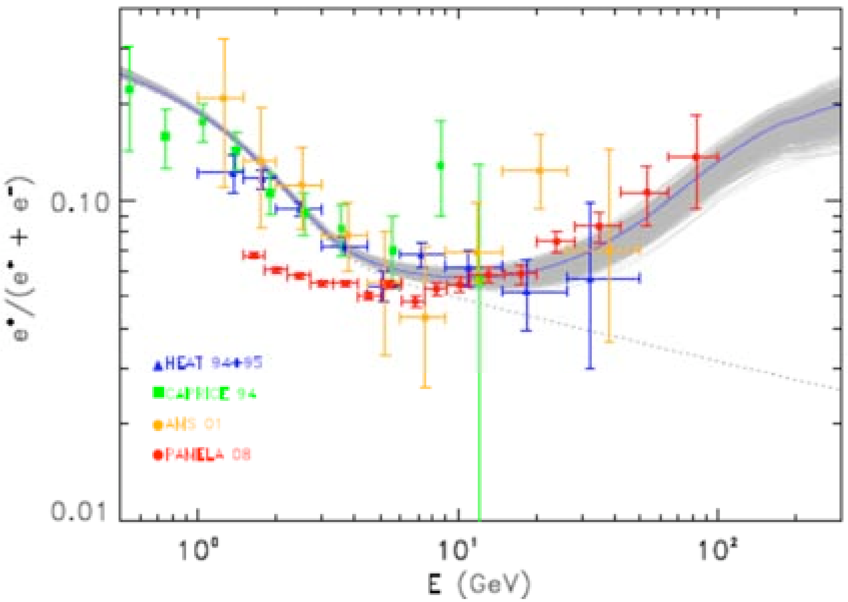


For details: D. Hooper, P. Blasi, PS, arXiv:0810.1527
(old idea, see e.g. F. A. Aharonian, A. M. Atoyan and H. J. Volk A& 95…
revisited on the light of qualitative & quantitative new data)

Contribution of “discrete” sources

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



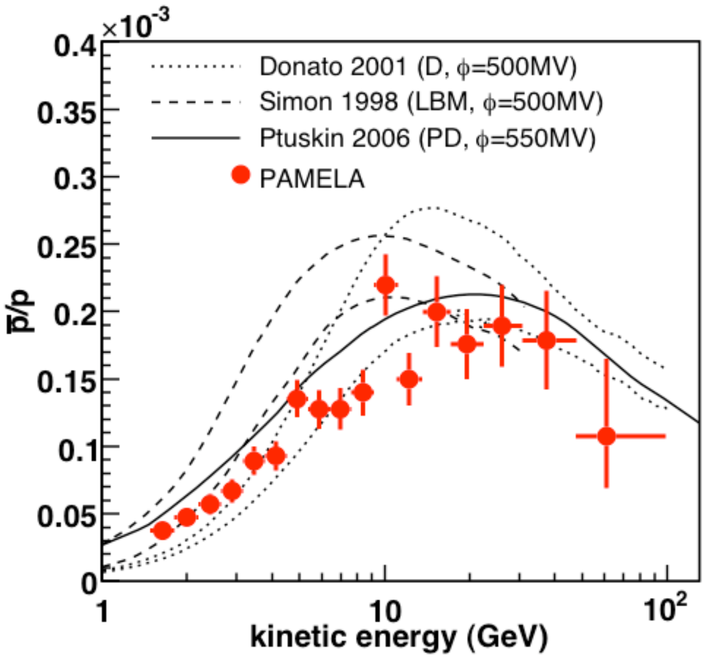


D. Grasso et al. arXiv:0905.0636;
Yuksel, Kistler, Stanev, arXiv:0810.2784;
Profumo, arXiv:0812.4457;
Malyshev, Cholis, Gelfand, arXiv:0903.1310.
Kawanaka, Ioka, Nojiri, arXiv:0903.3782
…

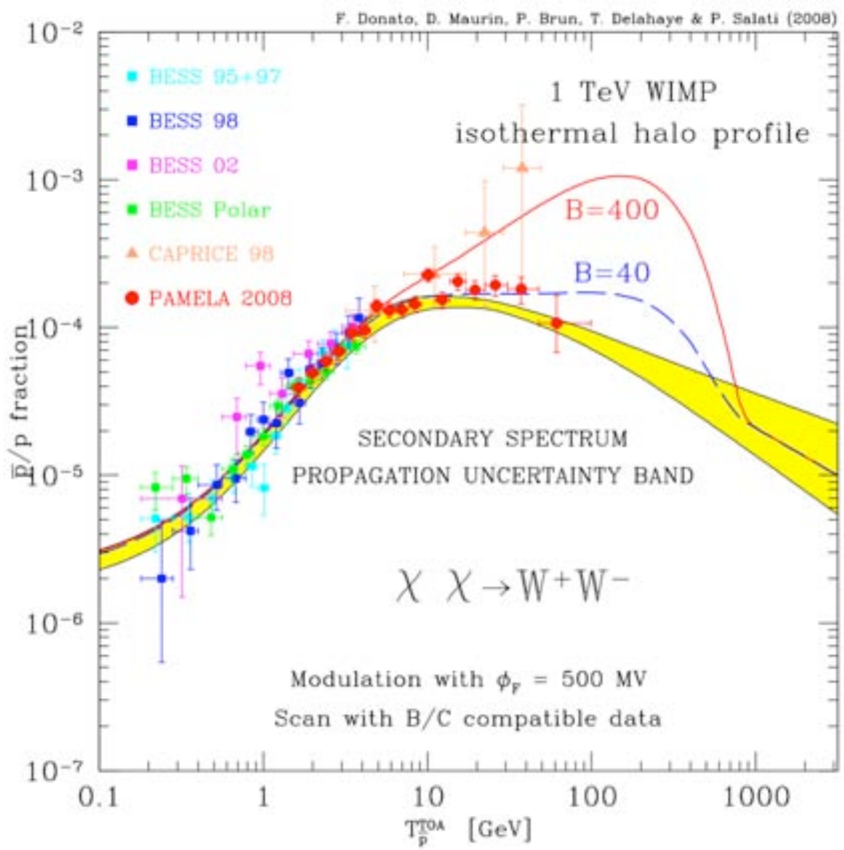
Towards possible test (I)

- ✓ *Antiprotons (& anti-D)*
- ✓ *Possible anisotropy*
- ✓ *Shape of the cutoff in e-flux feature (IACTs?)*
- ✓ *γ-rays: Fermi should find high-latitude diffuse excess vs. unresolved/unidentified point-sources*
- ✓ *…*

- Antiprotons consistent with pure CR spallation background
- Exclude "universal" BF ~ needed to fit e^+
- Fraction for "typical" WIMP annihil. Modes
- hadronic vs. leptonic astrophysical models



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



Towards possible test (II)

✓ *Antiprotons (& anti-D)*

✓ *Possible anisotropy*

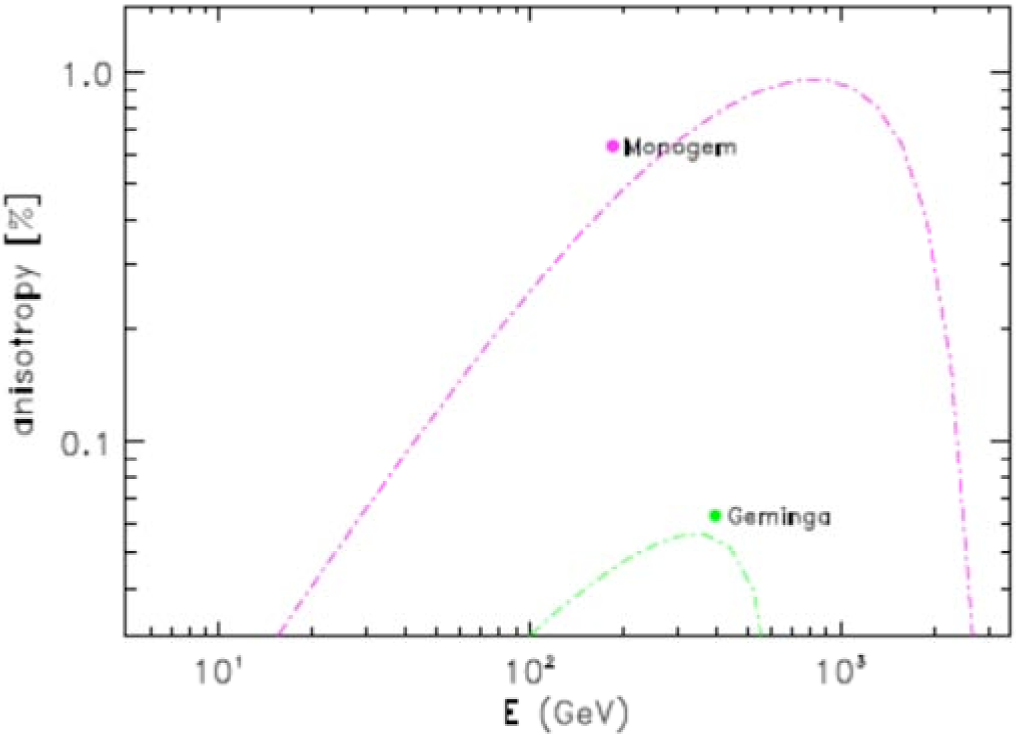
✓ *Shape of the cutoff in e-flux feature (IACTs?)*

✓ *γ-rays: Fermi should find high-latitude diffuse excess vs. unresolved/unidentified point-sources*

✓ *…*

• 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

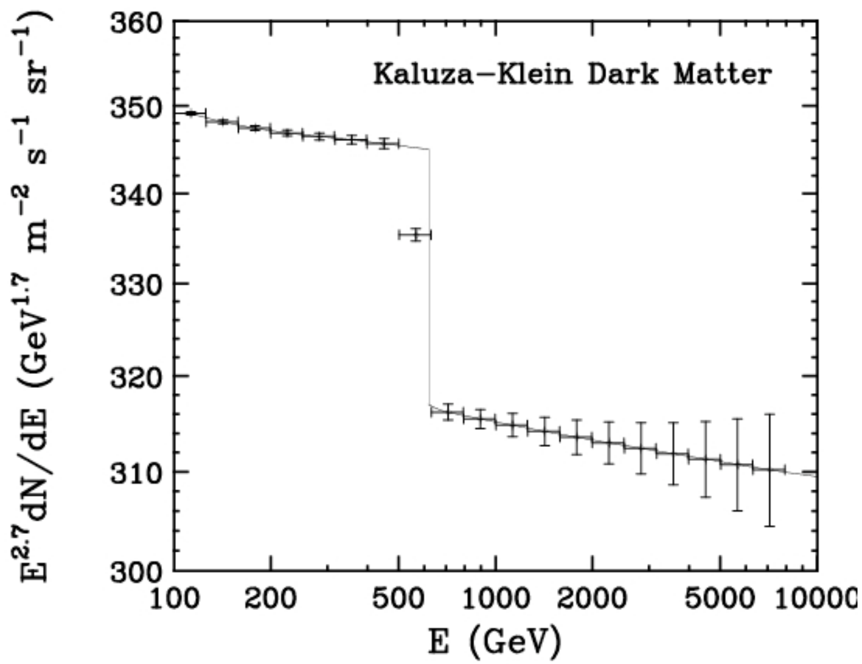
…
I. Buesching et al. arXiv:0804.0220,
D. Hooper, P. Blasi, PS, arXiv:0810.1527,
D. Grasso et al. arXiv:0905.0636
…

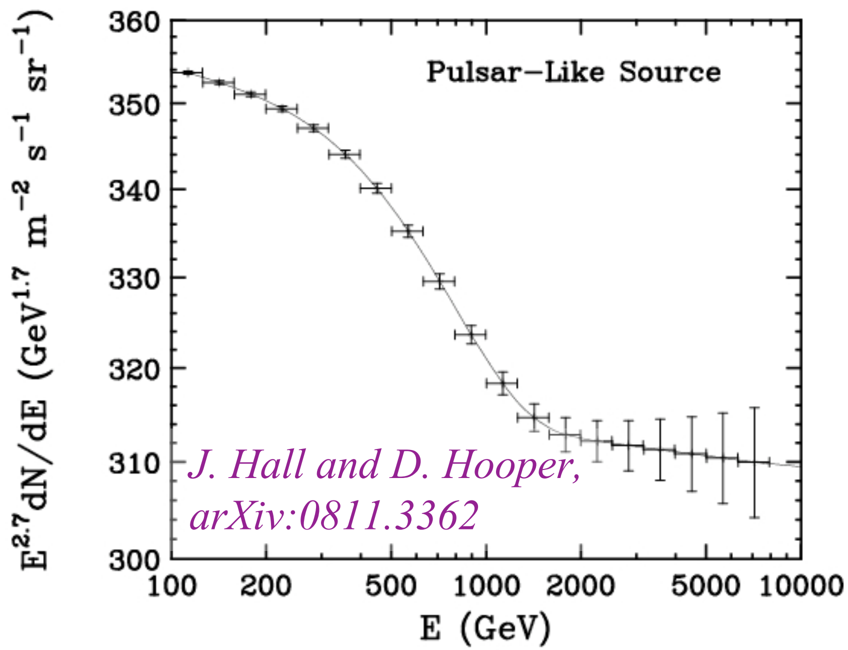


Towards possible test (III)

- ✓ *Antiprotons (& anti-D)*
- ✓ *Possible anisotropy*
- ✓ *Shape of the cutoff in e-flux feature (IACTs?)*
- ✓ *γ-rays: Fermi should find high-latitude diffuse excess vs. unresolved/unidentified point-sources*
- ✓ *…*

- In some DM models (e.g. KK) sharper cutoff, Hard to achieve for astrophysical models. (But the feature can be spoiled by propagation effects, see *M. Pohl, arXiv:0812.1174*)
- "Multiple bump" structure (due to multiple source contributions) could disfavour DM?





J. Hall and D. Hooper, arXiv:0811.3362

Towards possible test (IV)

✓ *Antiprotons (& anti-D)*

✓ *Possible anisotropy*

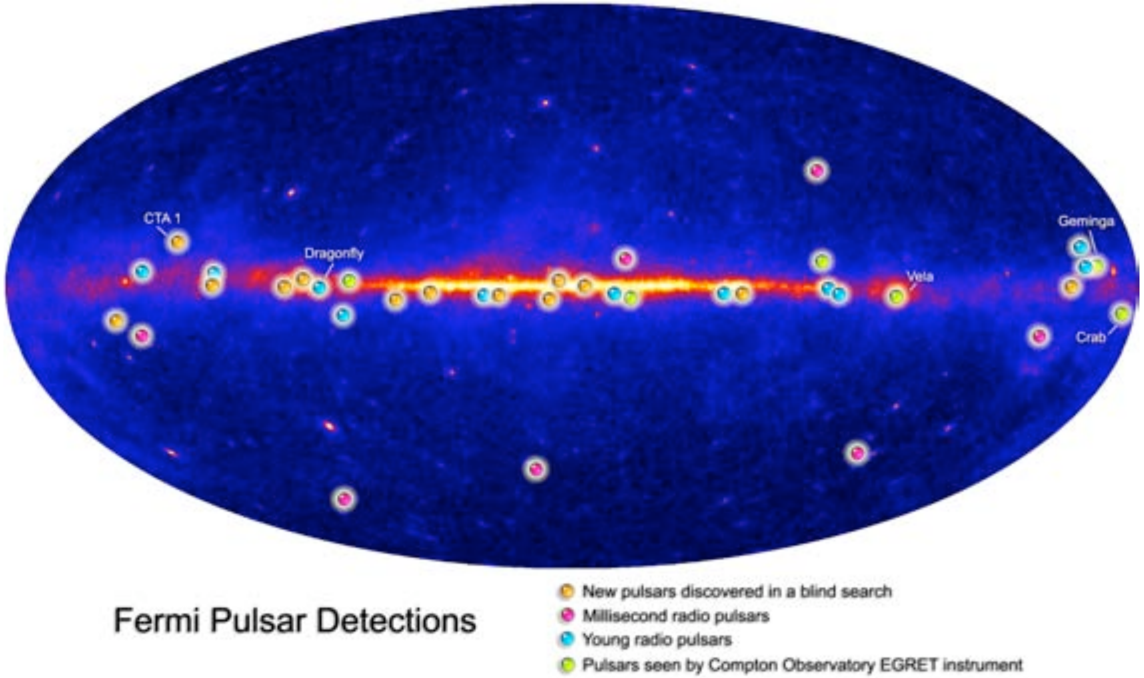
✓ *Shape of the cutoff in e-flux feature (IACTs?)*

✓ *γ-rays: Fermi should find high-latitude diffuse excess vs. unresolved/unidentified point-sources*

✓ …

- 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

More details in Profumo's talk



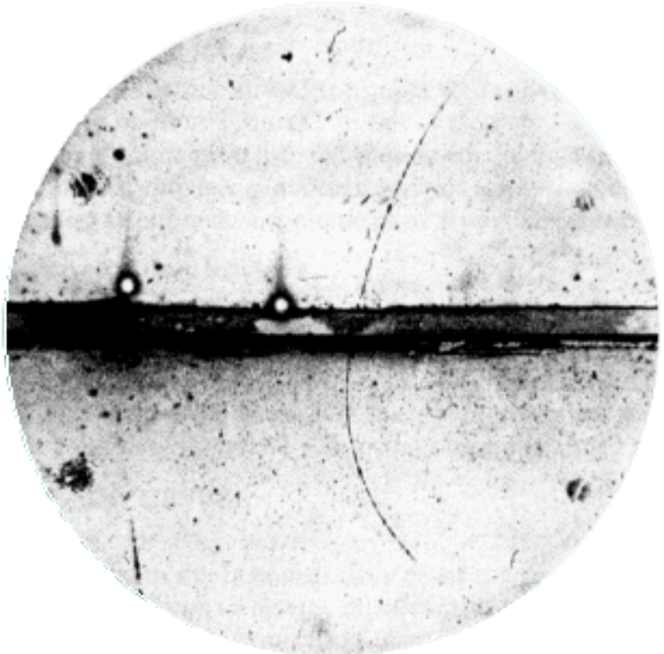
Fermi Pulsar Detections

Can we discover new particles “in the sky”?

Disclaimer: most of what follows reflects my opinion, not necessarily most popular common view

Short answer based on historical records: Yes, we can!

- ✓ Solar spectrum → New "particle" (Helium, 1868 - Lockyer)
- ✓ CRs → Antimatter (e^+ '32)
- ✓ CRs → The "Yukawa Particle" (π '47)
- ✓CRs → "Second Generation" (μ, strange hadrons '30-'50)
- ✓ MeV-GeV ν → neutrino masses, new Physics!



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

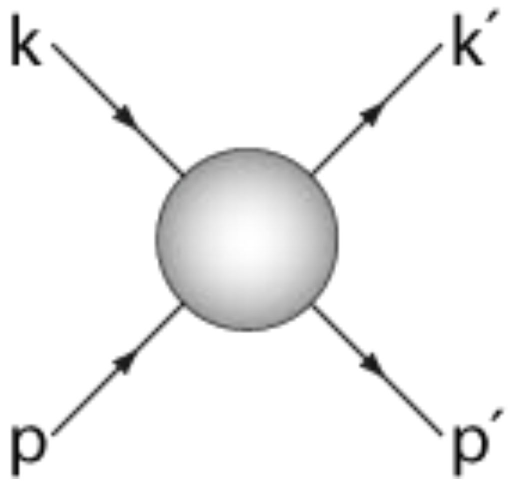
Astrophysicists (APs) vs. particle physicists (PPs)

Be aware of sociological differences!

❖ PPs like studying simple systems, tend to factorize problems, and to exhaust the possible explanations

❖ Astrophysics is a mess: Exhausting logical possibilities is "out of question".
If a simple (even semi-empirical!) model roughly fits a variety of data most APs will be fine with it… and soon dub it "a Standard Model".Now, PPs will interpret the word "Standard" their own way and tend to see "new physics" when new observations might be simply showing that a model is inadequate/incomplete.

Example of this "conflict": shaky ground of standardization of SNIa lightcurve, to be compared with the aim & huge effort of extracting "fundamental" DE parameters to ~1%



Dendera Zodiac, Egypt, ~50 BC

Some rules of the Game

- *In astrophysics,*
"Standard Model"= minimal model accounting for most facts known.
In no case, it is the model following from including all Possible Standard Physics & astrophysical objects

- *In astrophysics,*
# of observables << # of "free parameters" in the problem.
Exactly as in early physics development, identifying the key or simplest variables reproducing the data is a necessity if there is to be progress.

- *Does not mean all astrophysics is "simple" or necessarily an "order of magnitude" science: e.g. for the Solar model, many observables, some precise ones, require hard modeling.*

…How to identify new physics "from the sky"?

✓ Directly detecting "particles that should not exist" (smoking gun)

- Early particle discoveries in CRs
- Non e-type neutrinos in solar ν flux (SNO)
- GeV/TeV γ-ray lines or ν flux from center of Earth/Sun
- anti-He or strangelets in space CR detectors
- Upgoing shower (from ~ Nadir) in EAS detectors at Ultra-High Energies

✓ Understanding some unique quantitative aspects of the signal

- "Solar ν deficit" in radiochemical experiments (contested!): absolute flux based
- ratios of events in the discovery of atmospheric ν osc. (flavour & angular info)
- Spectral & angular properties of gamma-ray radiation (DM vs astro backg.)

✓ Having strongly correlated predictions for different observables

(single signals need not be robust, but the correlation among them can be!)

- Evidence from Hot Big Bang from light nuclides as well as ~3 K radiation.
- "Multiwavelength" or "multimessenger" approach for indirect DM detection

Until now none of the above applies to the PAMELA-ATIC-Fermi data.
But the stage we're going through is not new, just proves that the field is now moving towards a more mature stage: lesson from gamma rays!

A lesson from gamma-ray signatures of DM

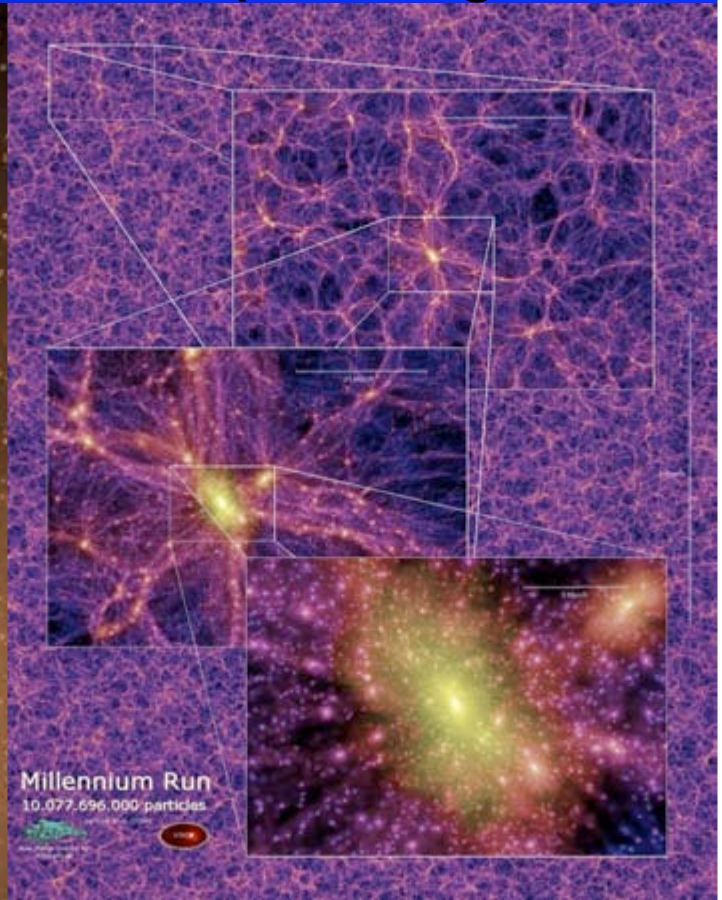
The hierarchical structure formation paradigm

z=0.0

- Primordial fluctuations in DM density led to gravitational collapse. In CDM, structure formed in a hierarchy, from smallest to largest dark matter halos

- When ordinary matter fell into these DM halos, it dissipated heat and collapsed to form stars and galaxies – DM cusps and substructures may persist if not washed out by dynamics

- Simulations suggest that, qualitatively, the largest density is expected at the Galactic Center.



80 kpc

via lactea 234 million particles http://www.ucolick.org/~diemand/vl

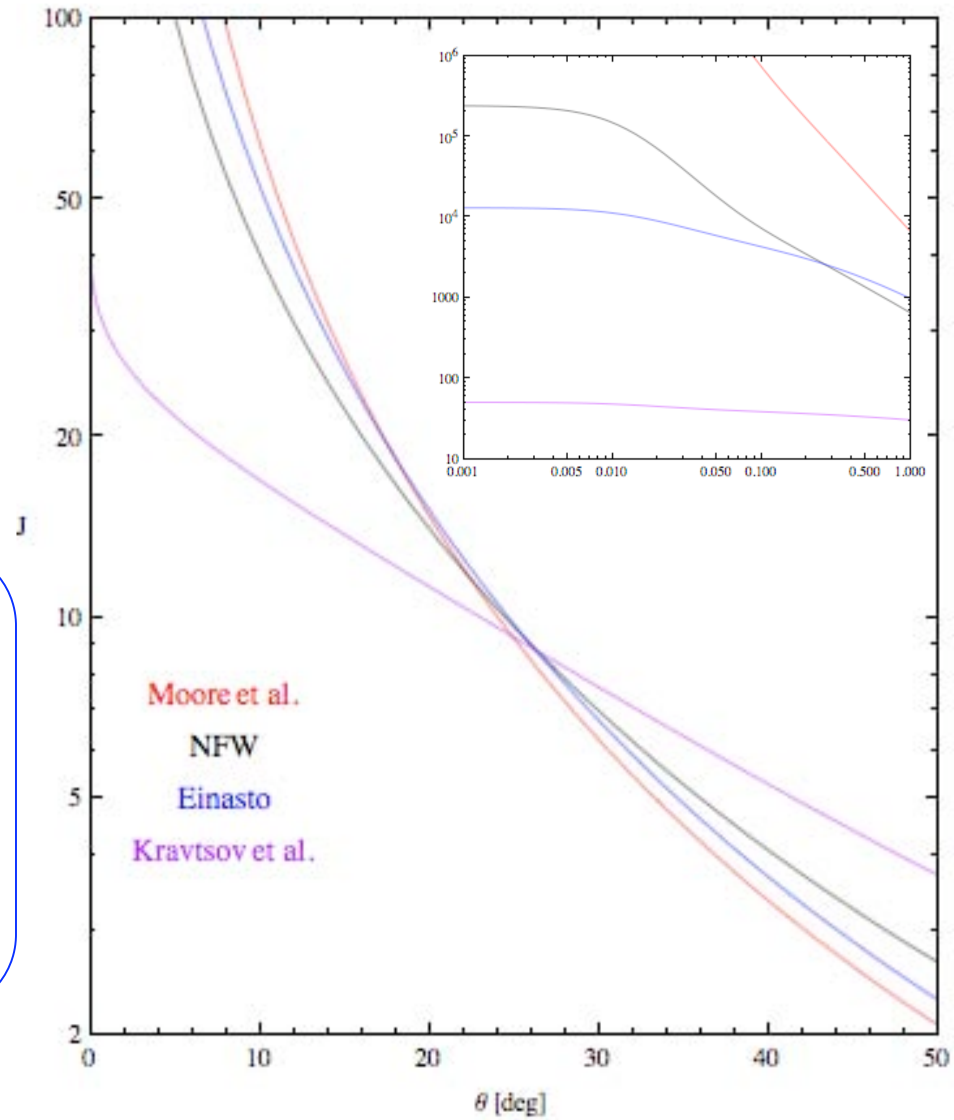
gamma rays from DM annihilation: where to look?

$$\Phi_\gamma(E_\gamma,\Omega) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\int_{\mathrm{los}}\rho^2(\ell,\Omega)\,\mathrm{d}\ell$$

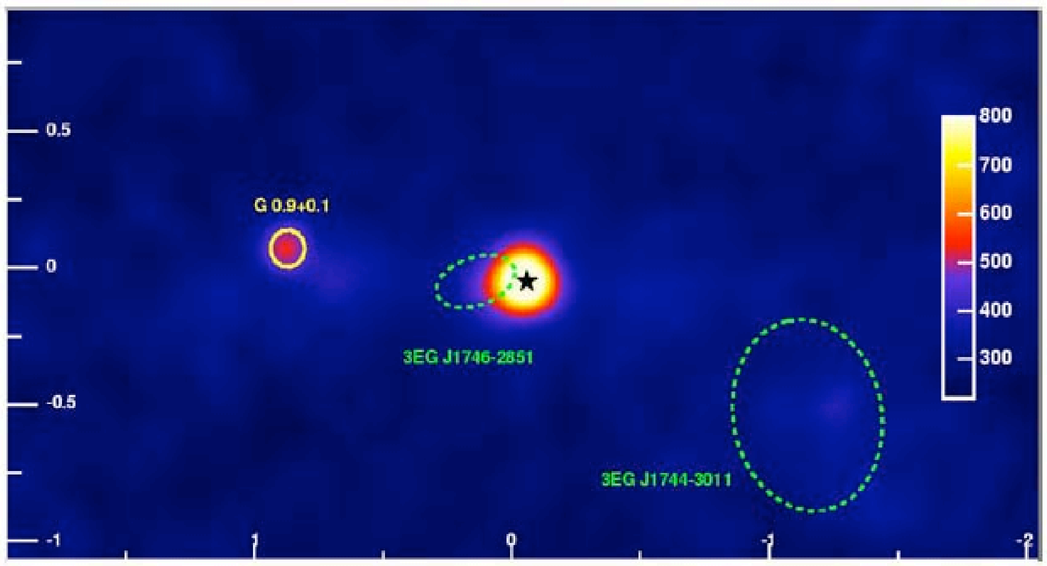
NOTE: This [particle] ⊗ (astro) factorization holds if $<\sigma v>$ is v-independent, which holds for s-wave thermal relic $<\sigma v>$~const~pb

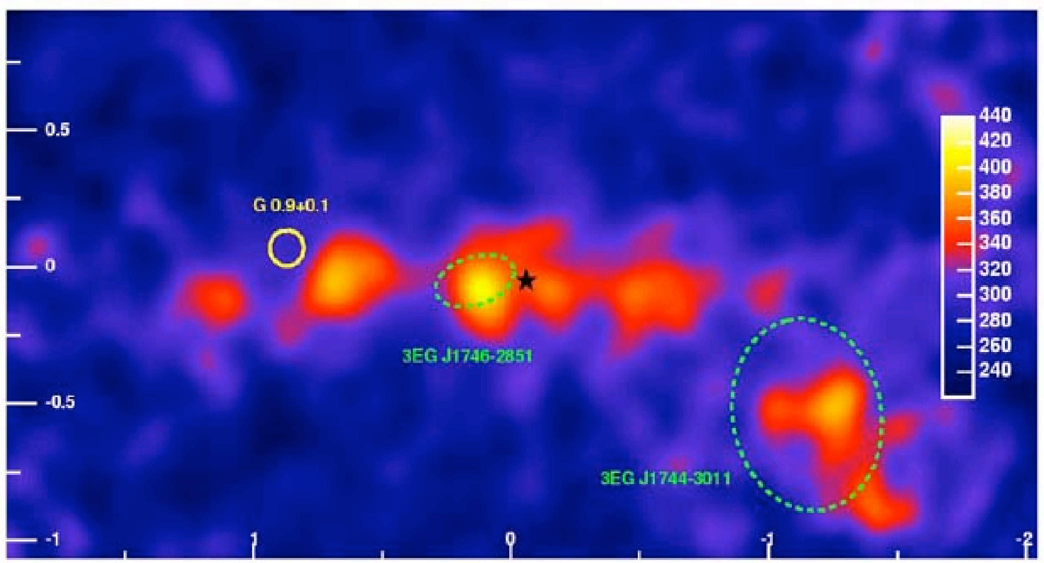
Problem 1:
Even forgetting substructure,
Halo profile towards GC not known!

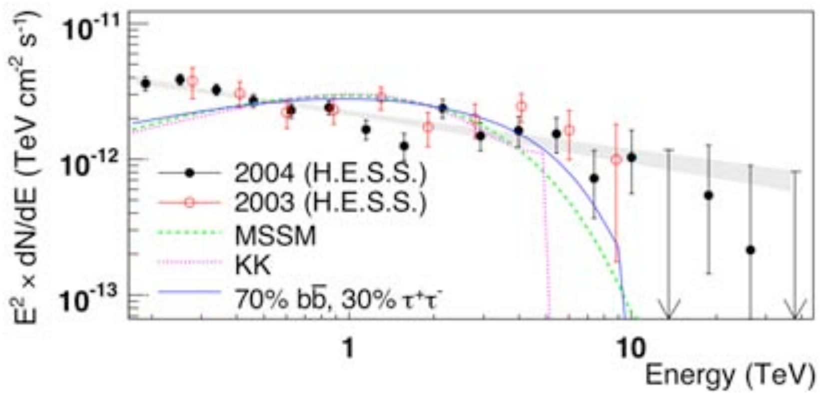
- Unknown role of baryons in modifying the "pure DM" halo shape
- possible effects of specific evolution of our Galaxy (e.g. mergers, central BH evolution, etc.)
- Would not be a problem if a simple "detection" provided a "smoking gun"



EGRET/HESS reveal background from MeV→TeV!







For a Fermi-like instrument, tens of photons from the GC, ≥O(1000) from the whole sky, but…

Problem 2:

Not a background-free detection!

- background-free (?) targets (but low signal, as dwarf galaxies)
- Signal/Background disentanglement strategies

Where most effort has been spent on lately and still is (ask Fermi team)!

Back to searches in CR antimatter…

Compared with γ-rays:

- Does one expect large(r) signals?

This is not *typically* the case.

- Does one know the backgrounds better?

Not really: we cannot identify directly sources producing antimatter, differently from γ & ν!

- Can one reject backgrounds more easily?

Not at all: almost no chance of angular info, simply spectral information, which also includes poorly known propagation effects.

Does this mean that these searches are hopeless/useless?
Not at all!

Rationale behind indirect DM program

As a discovery tool
we search for peculiar signatures, which cannot be (easily) mimicked by astrophysical objects. This is no different from particle physics, where one looks for new particles in the "best channels"!

If no signal is found
One can use indirect constraints (complementary to accelerators) to "motivated particle physics models" (e.g. SUSY in its MSSM incarnation)

If a signal is found in other channels (accelerator/direct detection)
We still *need* indirect detection:

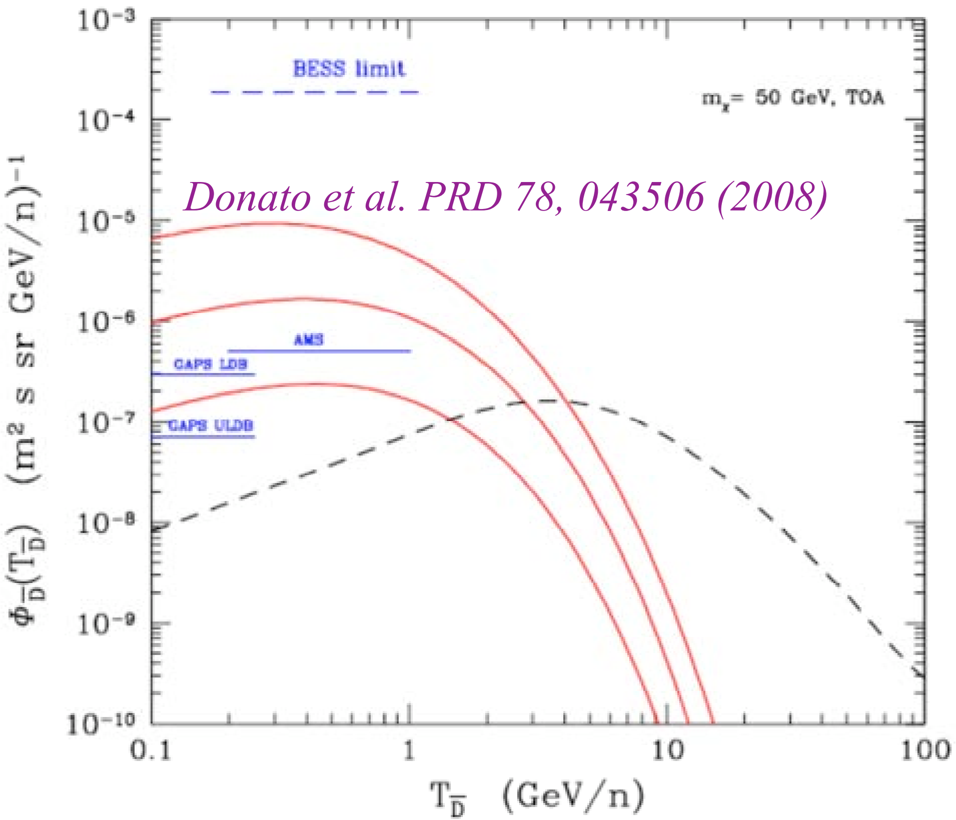
- ✓ To confirm that whatever we find in the Lab is the same "dark stuff" responsible for astrophysical and cosmological observations.
- ✓ To access particle information not otherwise available in the Lab (annihilation cross section or decay time, b.r.'s)
- ✓ to infer cosmological properties of DM (e.g. power spectrum of DM at very small scales) not accessible otherwise.

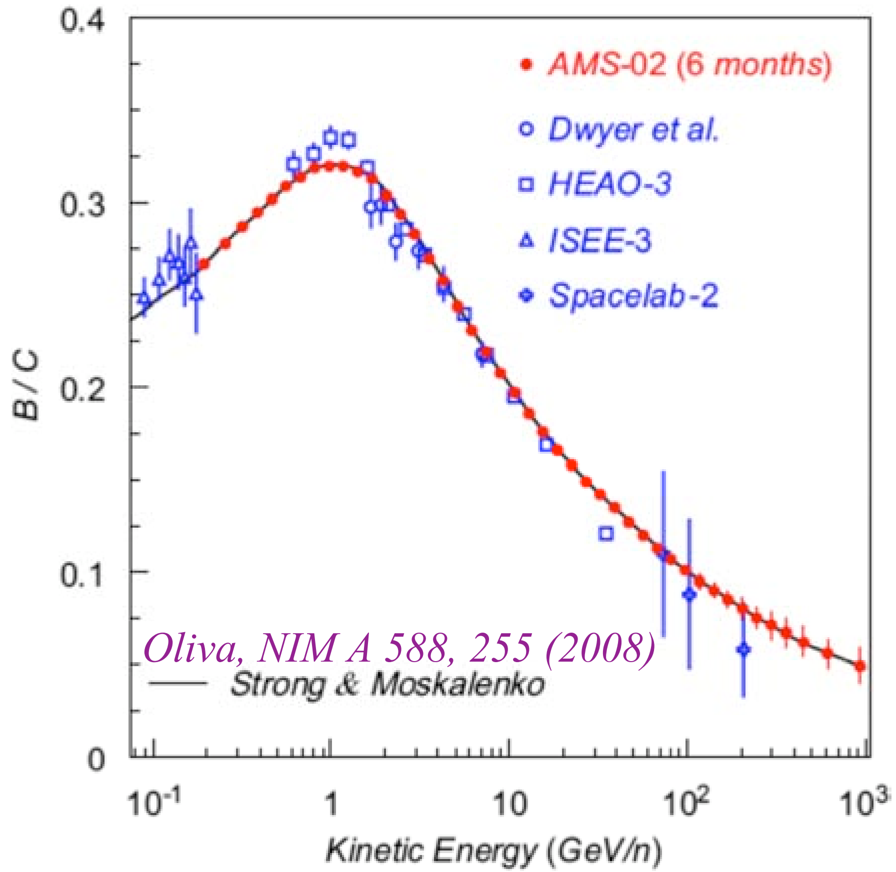
While a posteriori/adjusted fits to the data are very risky, "Consistency Checks"/ constrained searches are much more promising!
After all, the task to discover new particles should be a collider job!

Fortunately, there is some progress in the field…

Before PAMELA, the attitude was that the major uncertainties in antimatter backgr. searches were due to propagation parameters. A large(r) community now appreciates that perhaps a greater limitation comes from lack of knowledge of the sources

In few years, AMS-02 should provide a check of the internal consistency of a simple model of CRs without primary sources of antimatter. The field will be re-defined by high-quality data, extending over a larger dynamical range.





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, recent e^+ e^- data suggest a class of energetic lepton (pair?) producers. Both astrophysical & DM explanations in principle possible.

→ The combined data (p-bar, gammas, electrons, etc.) point likely to astrophysical explanations. Alternatively, to extremely exotic DM properties (exciting?!)

→ In order to assess viability of indirect DM strategy, astrophysical "backgrounds" have to be understood. e^+ e^- are probably the most difficult channel to keep under control, but still important "sanity check" in a multimessenger perspective!

→ Fortunately, other indirect experiments are running/being completed (e.g. IceCube, PAMELA… AMS-02) direct detection is achieving a jump in sensitivity, and LHC will tell us what's really going on at the electroweak scale. Synergy is the key!

Everything we see hides another thing, we always want to see what is hidden by what we see.

R. Magritte

The Promenades of Euclid