Astrophysical sources of CR (anti)matter

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

Cosmic Ray backgrounds in Dark Matter Searches, Jan 25 - 27, 2010
AlbaNova-Stockholm

Outline

- Introduction. Why are we here? Because of the unknwown unknown

Over the last year, much excitement caused by the PAMELA-ATIC-Fermi CR lepton data, with a plethora of Dark Matter interpretations

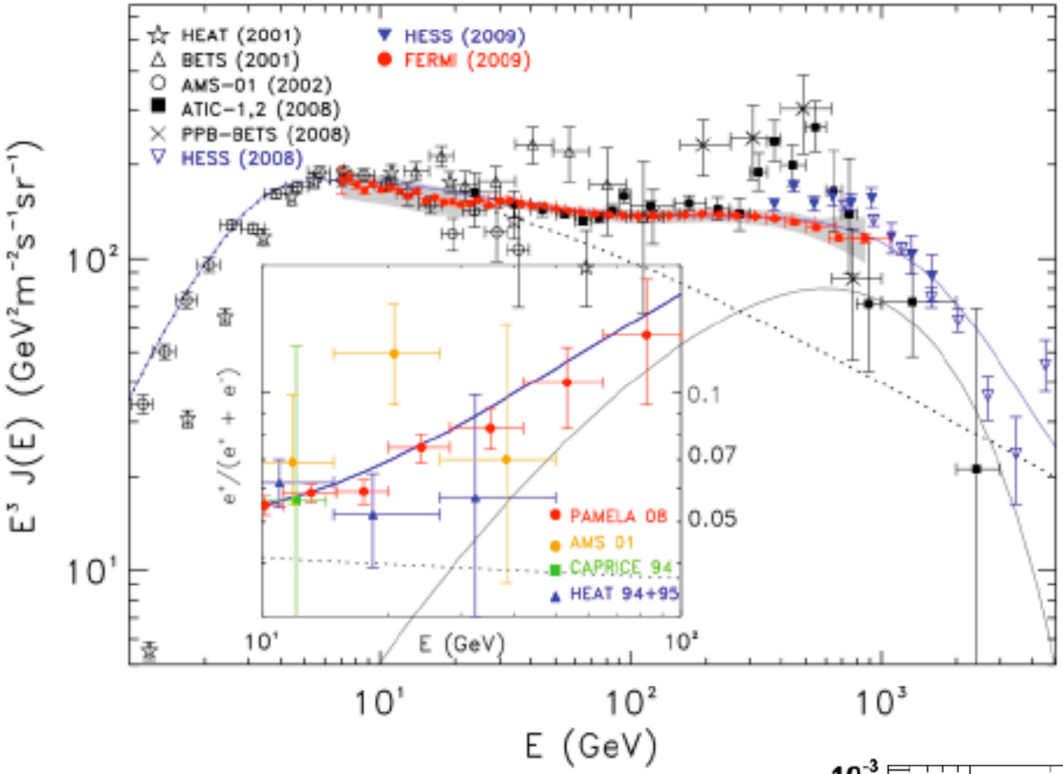
- Part I. the (un)known knowns

In the first part, will discuss a few things we know (but apparently some people not so well…) on electron spectra and antimatter in CRs.

- Part II. the known unknowns: Astrophysical sources of antimatter in CRs

Sources whose existence is not in doubt, but whose contribution to CRs is a though quantitative issue! In particular, SNRs, Pulsars (or, rather, PWN) (Note: astro stuff which is not explicitly given as Galprop output, simply because it is not an input in first place!)

- Conclusions



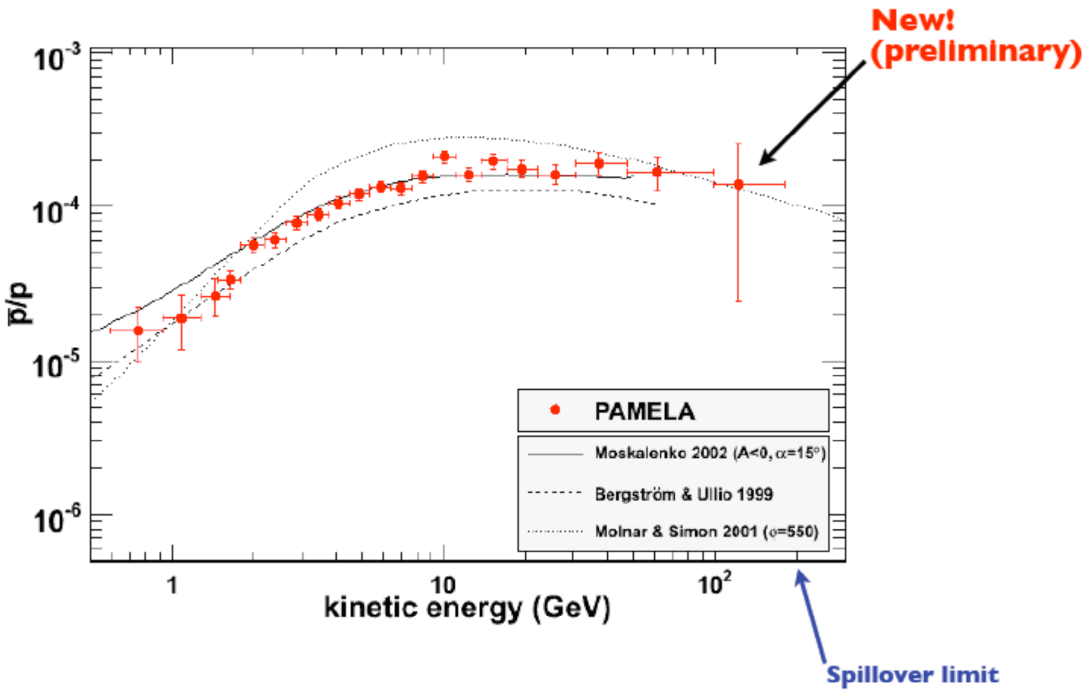
Overall e^-+ e^+ Spectrum
Positron Fraction data

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

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

(a few words on)
the electron spectrum

Why one does not expect a power-law spectrum

Even assuming pure power-laws at injection, features expected!

Pure Energy-loss effects

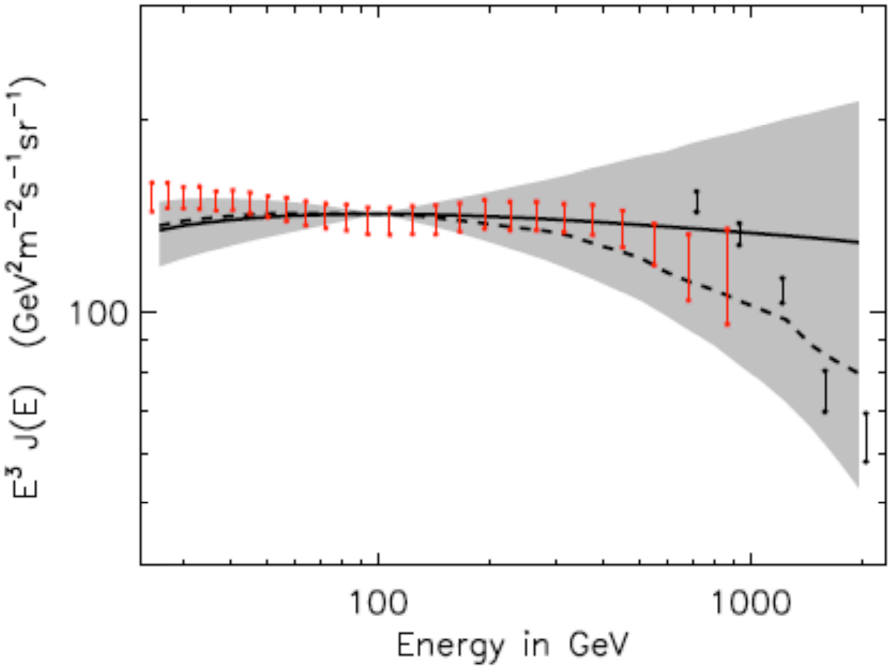
e.g. Klein-Nishina suppression of the IC cooling rate, important at E~TeV.

Stawarz, Petrosian, & Blandford, arXiv:0908.1094

Inhomogeneities

- Stochasticity (rms distance <~ E-loss volume)
- Inhomogeneous distribution of sources, e.g. large arm/interarm difference in SN rate

D. Grasso et al. arXiv:0905.0636;
Shaviv, Nakar, Piran PRL 103, 111302 (2009)



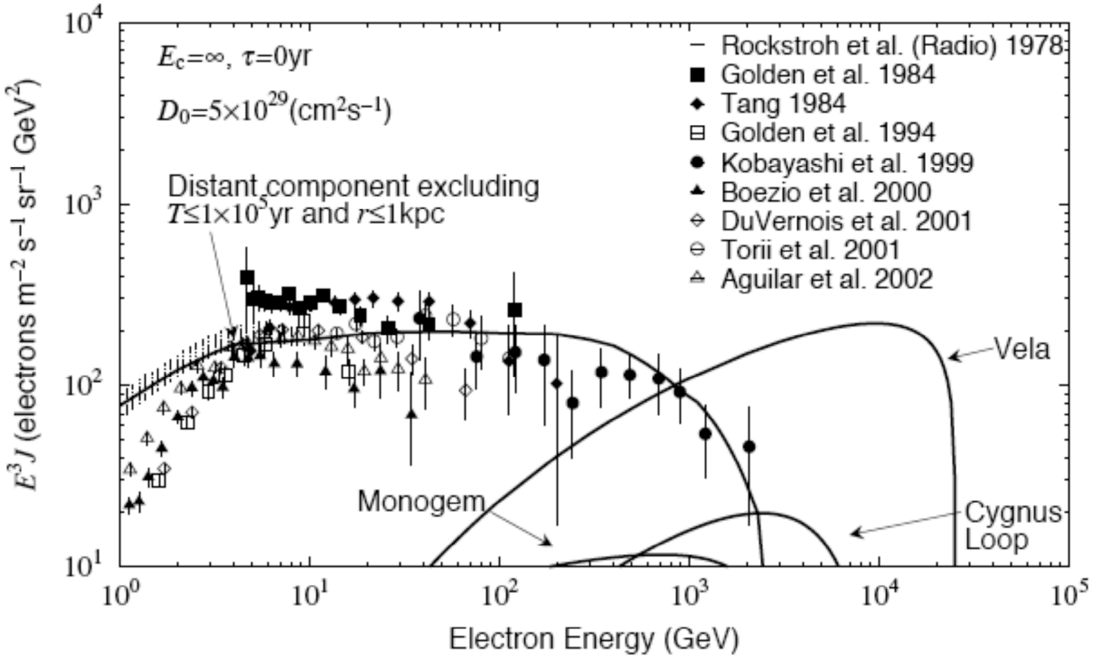
Many Sources and source types!

Virtually any HE astrophysics object sources relativistic e^-. Many spectra measured, at some level their overlap must yield spectral features.

Interest for TeV electrons is astrophysical!

- 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

Possibly Fermi hint for a "bump" welcome & interesting, not unexpected



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?

✓ From CR spectra at the Earth, assuming (from 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.

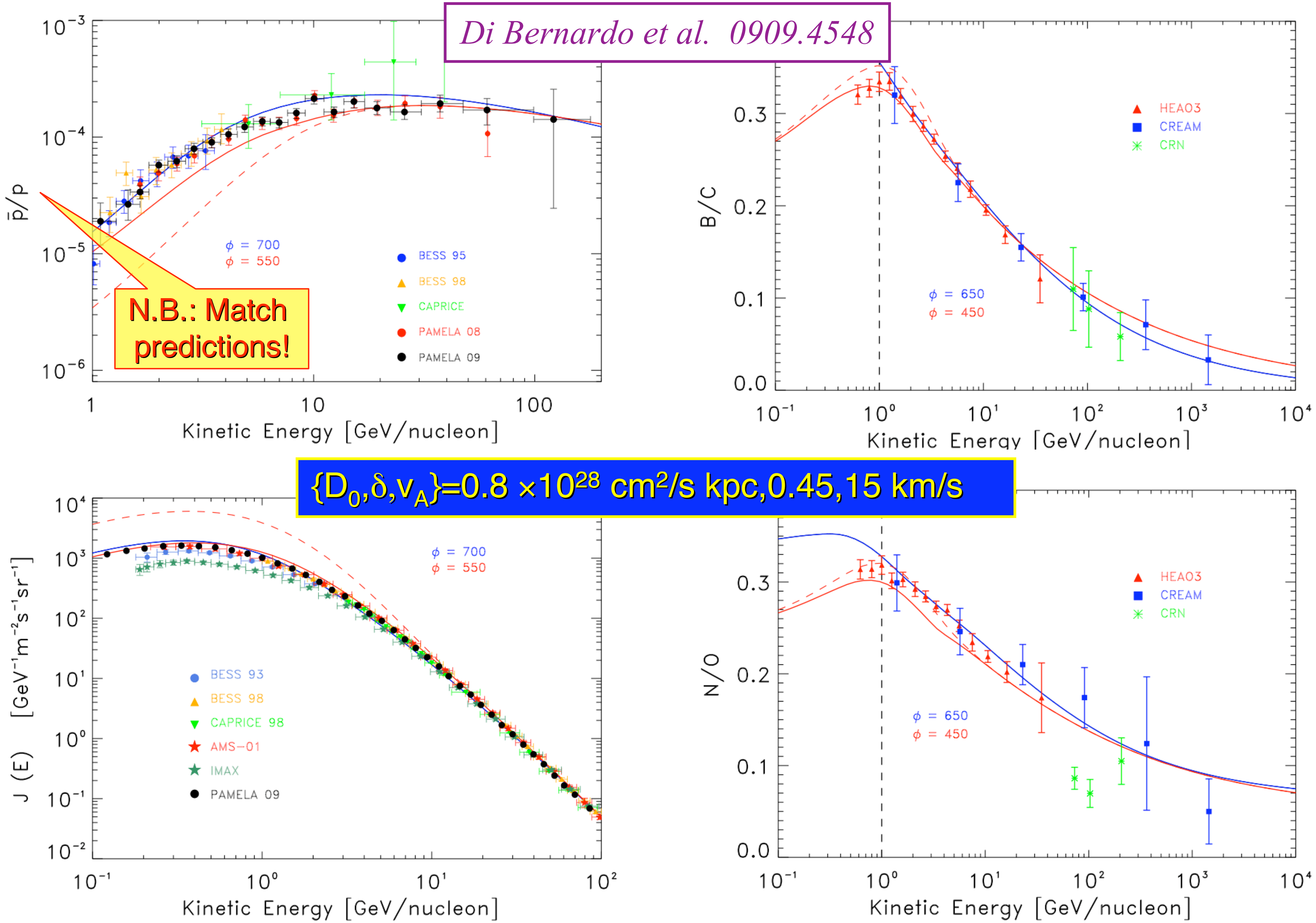
✓ Diffuse gamma-ray data, of course!
(Waiting for an explicit Fermi collaboration constraint on diffusive halo height)

Nota Bene:
"DM fits" to positron data include usually astrophysical sources of background for the positron fraction and assume propagation parameters for DM-produced leptons.

This automatically implies a relevant associated astrophysical "background" e.g. in antiproton and diffuse gamma-ray data which cannot be neglected for <u>predictions</u> of the associated channels.

Toward a consistent framework…

Di Bernardo et al. 0909.4548

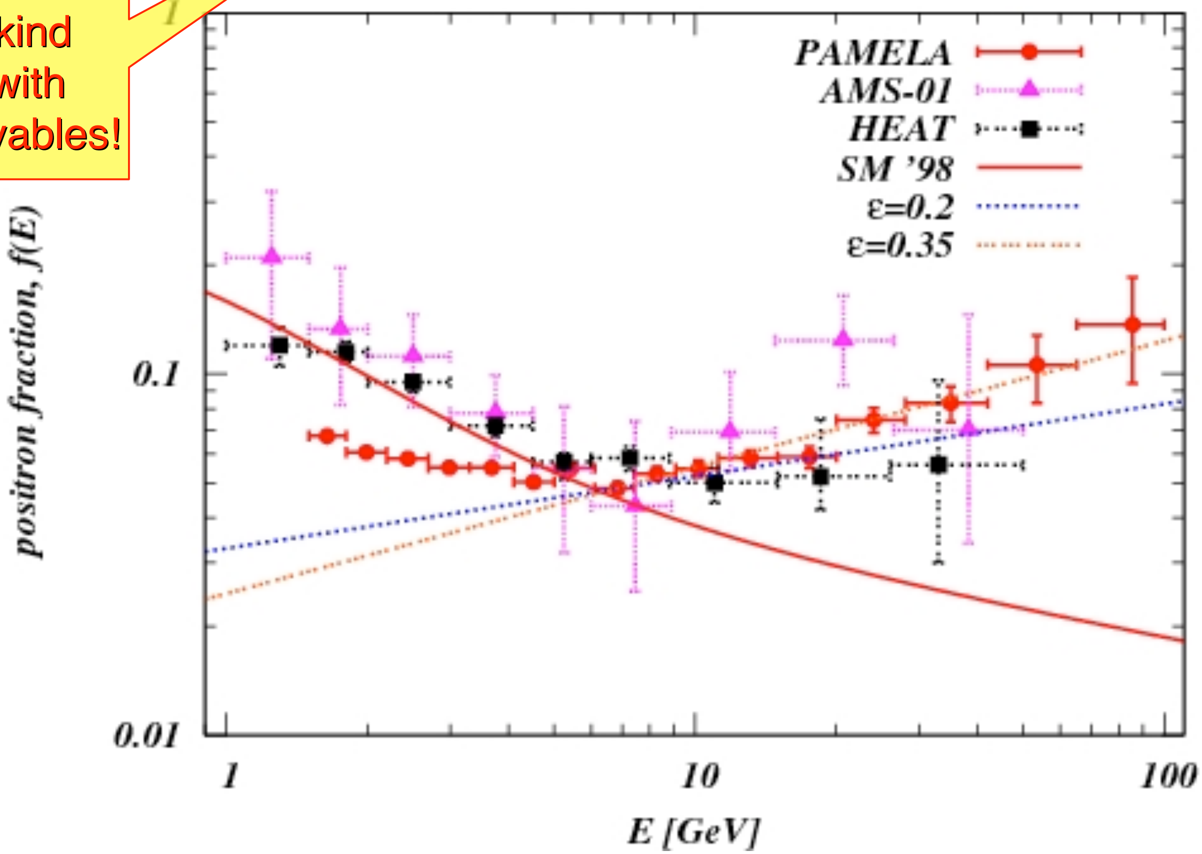


$\{D_0,\delta,v_A\}$=0.8 ×10^{28} cm^2/s kpc,0.45,15 km/s

Why are positron fraction 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.

i.e. of the kind agreeing with other observables!



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(s) or position: 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

Large arm/interarm difference in SN rate + powerful local objects *Shaviv, Nakar, Piran PRL 103, 111302 (2009)*

Single pulsar? *Many papers…*

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

Consistency with other probes, like pbar,γ...?

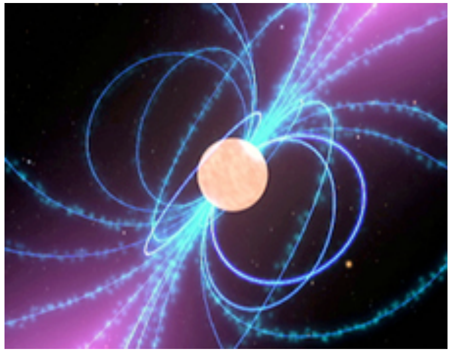
certainly “logical possibilities”: but exceptional objects/special inhomogeneities are also a killing argument (generic conclusions would hardly be reached)

Are we sure we *need* this? 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?

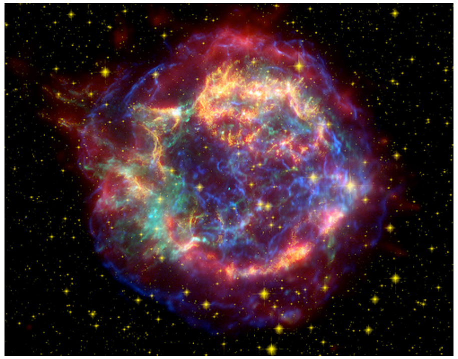
Dark Matter

- 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”
- “Natural” normalization; 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 certain at some level.
- 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

SNR known leptonic CR accelerators (radio, X-ray, γ-rays…). Also Hadronic?

- Galactic CRs via 1st order Fermi accel. at SNR shocks ($L_{CR} \approx 0.1 E_{kin,SNR} R_{SN}$)
- 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

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

$$\tau_{escape}(E) \propto E^{-\delta}$$ δ~0.6 e.g. from B/C

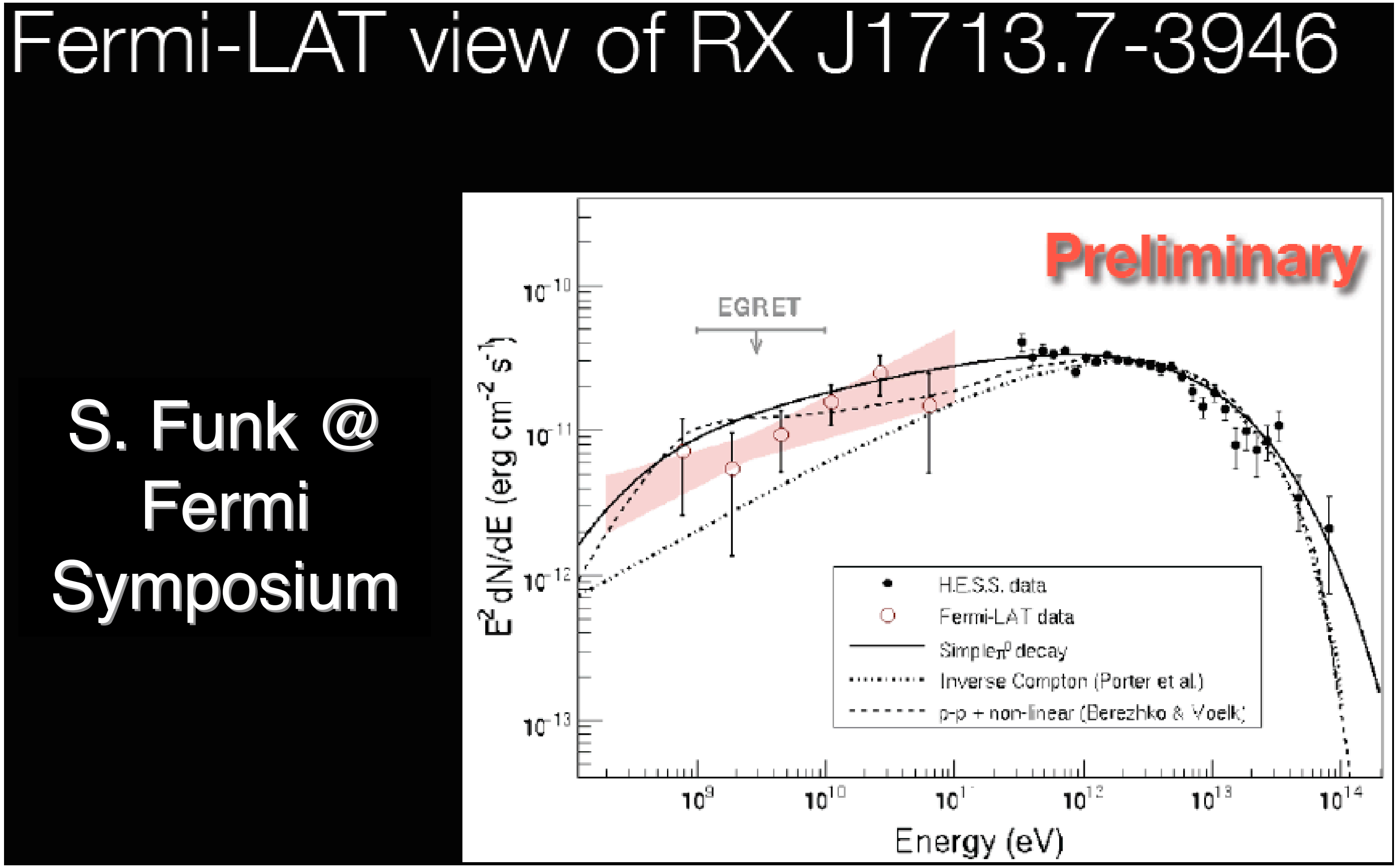
When spallation losses are negligible…

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

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

(too simple, actually…)

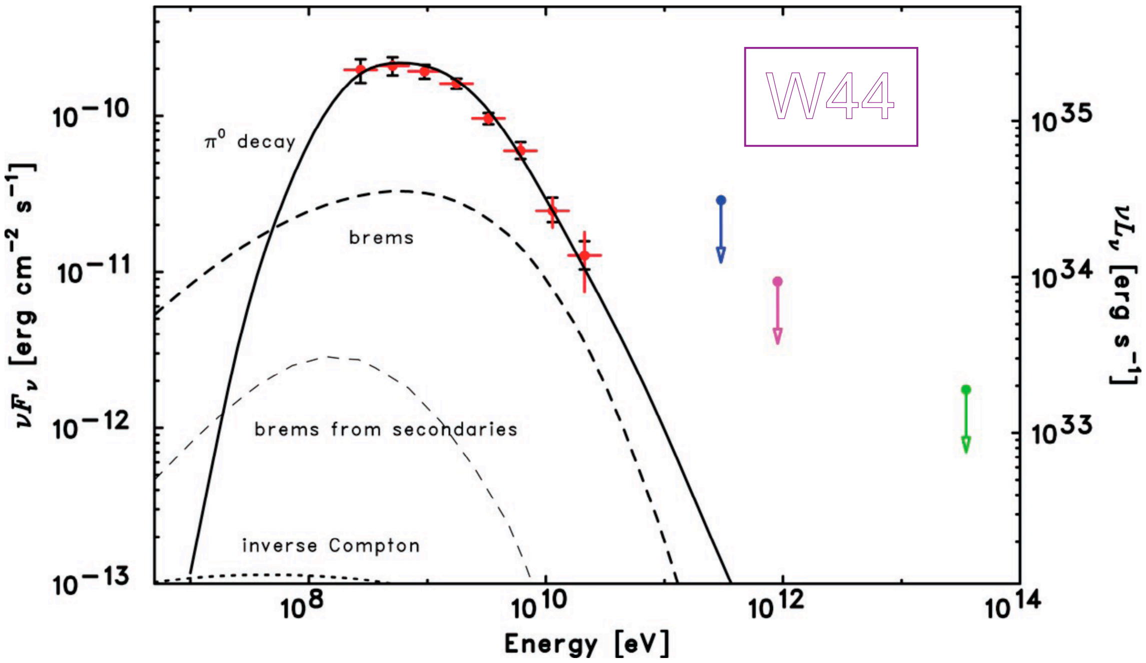
Early results from Fermi (I)



Very preliminary, but

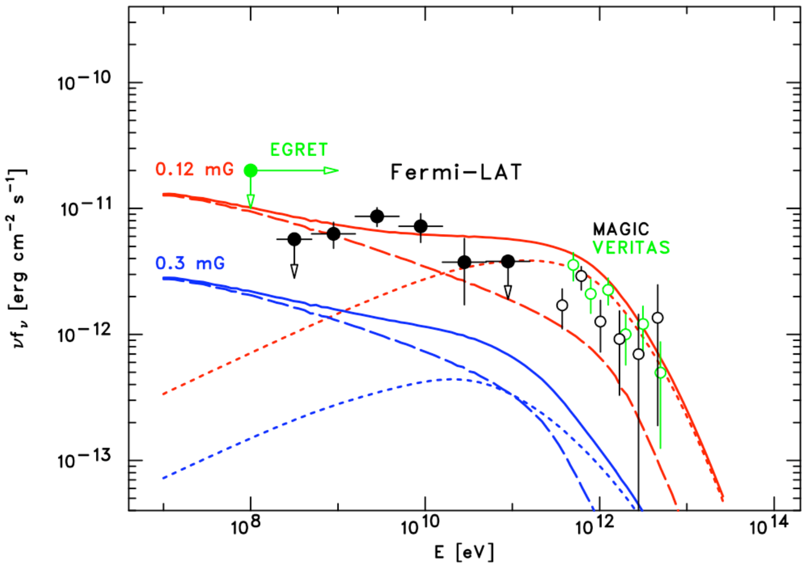
- all sub-TeV points are above leptonic acceleration models
- several of them by “>3 σ”
- points fluctuate (within 1-2 σ) around the non-linear hadr. model prediction…

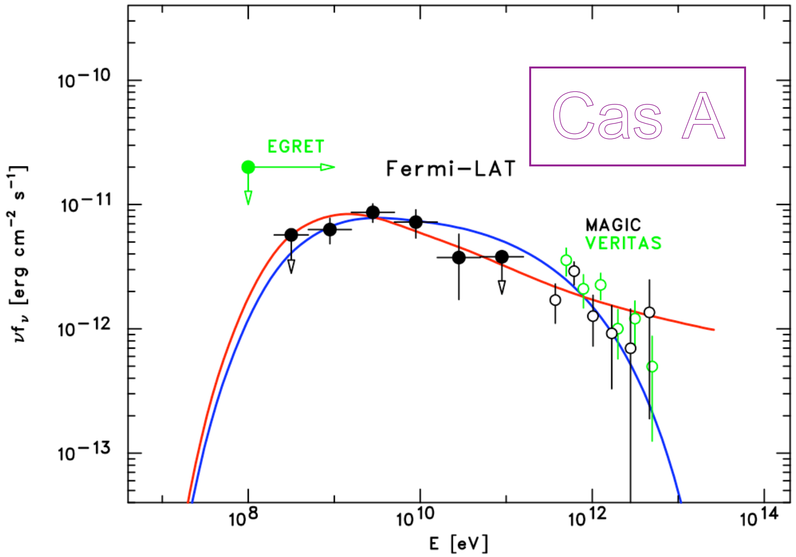
Early results from Fermi (II)



A. Abdo et al.
Science (Express)
January 7, 2010

S. Funk e Y. Uchiyama,
arXiv:1001.1419 ApJL in press

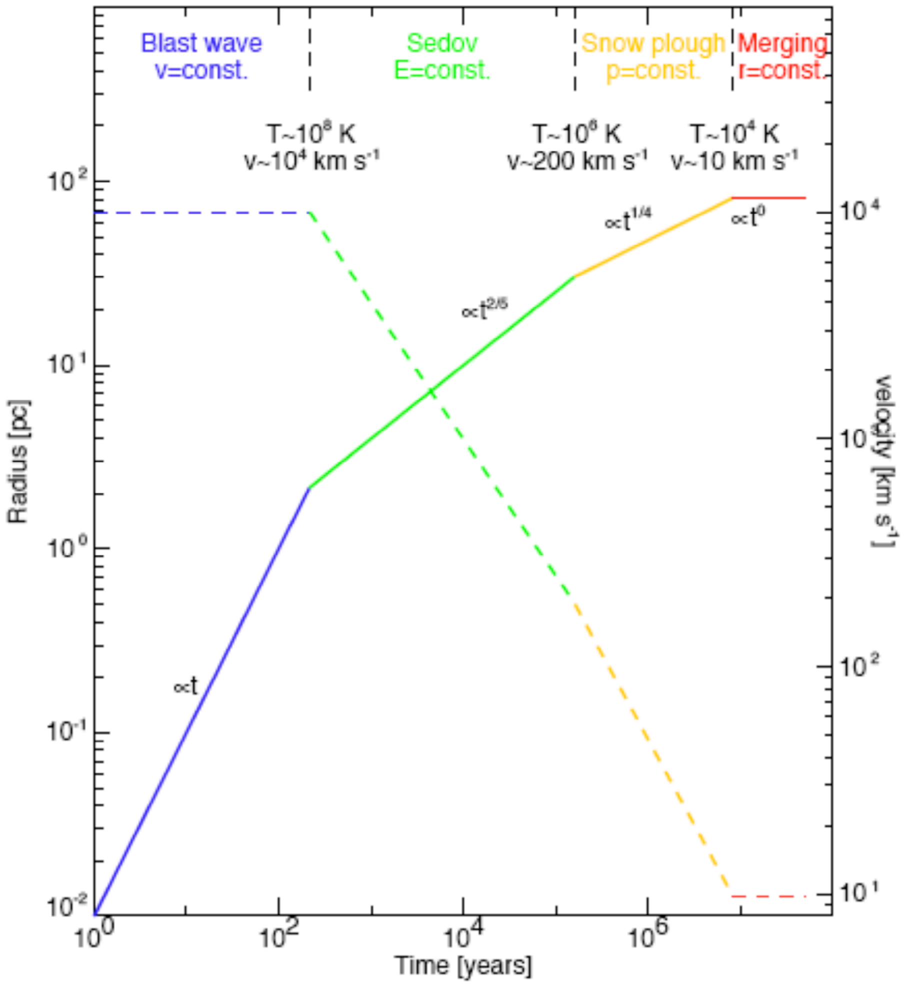




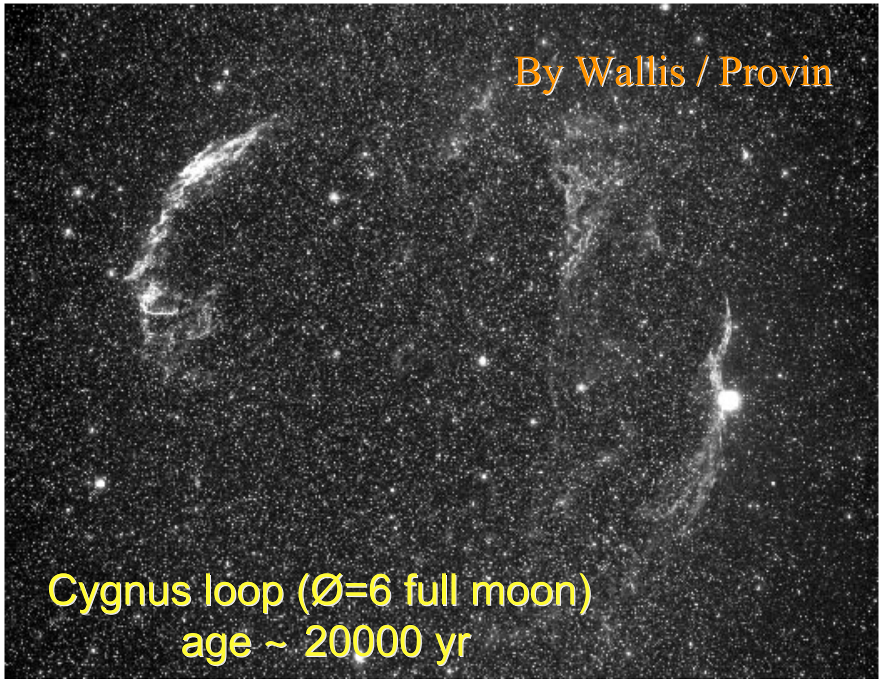
Old Supernova Remnants?

Young SNRs ($\tau_{SN} \sim 10^3$ yr) can accelerate Galactic CRs up to the “knee” (few PeV)
But “low energy” (E< TeV) CRs can be accelerated for much longer ($\tau_{SNR} > 10^5$ 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!



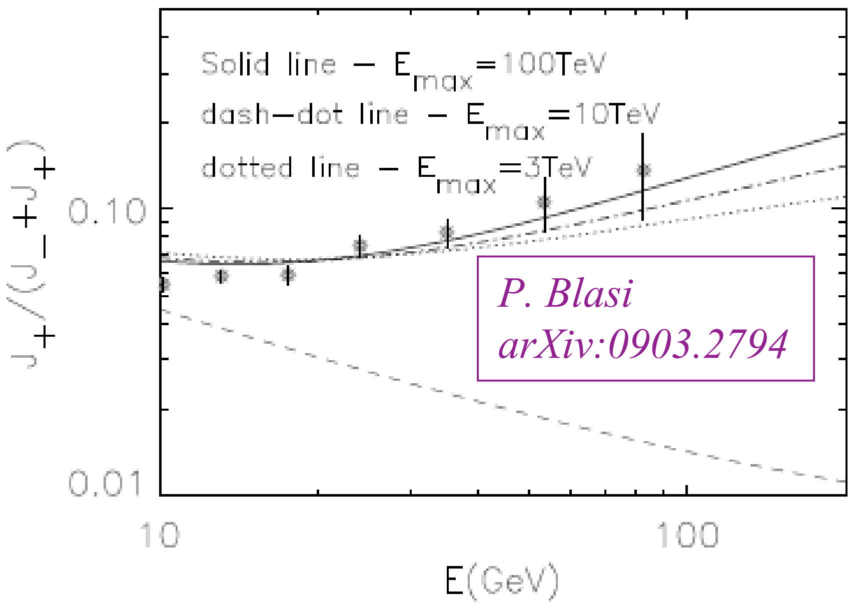
Acceleration of Secondary $e^{\pm}$

- 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 $\sim E^{-\alpha-\delta} + E^{-\alpha-\delta+d}$

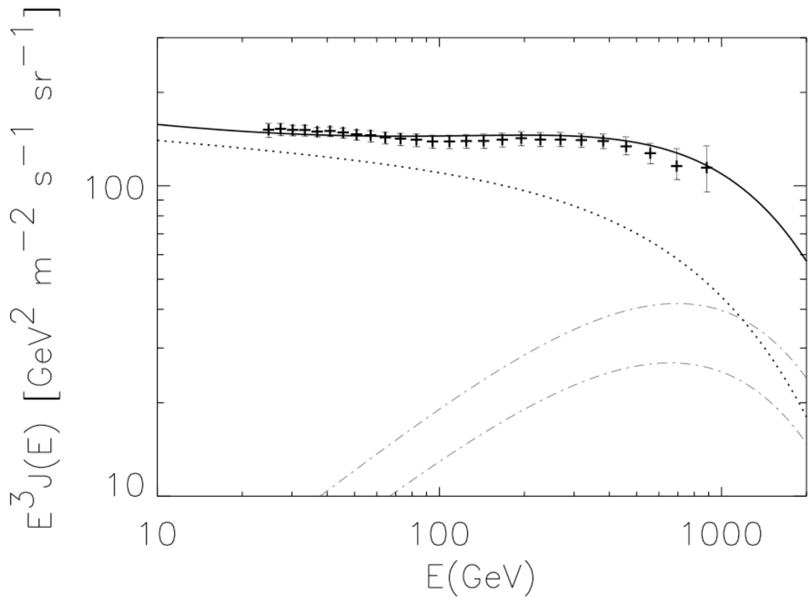
Positron fraction
$\sim a_0\, E^{-\delta} + a_1 + a_2\, E^d$

→ $\sim n\, r^2 \gamma\, D/\, u^2$ (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!

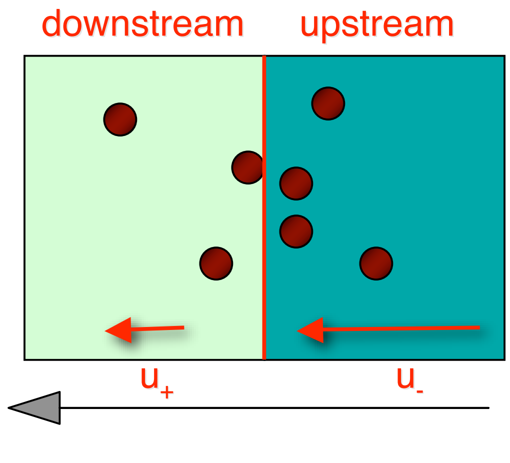


Universal (unavoidable) effect: strength depends on environment parameters in mature SNRs

DSA with Secondaries

Acceleration determined by compression ratio

$$r = \frac{u_-}{u_+} = \frac{n_+}{n_-}$$



The transport equation

$$u\frac{\partial f_{e^\pm}}{\partial x} = D\frac{\partial^2 f_{e^\pm}}{\partial x^2} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f_{e^\pm}}{\partial p} + q_{e^\pm}$$

subject to the boundary conditions

$$\lim_{x\to-\infty} f_{e^\pm} = 0, \quad \lim_{x\to+\infty} |f_{e^\pm}| \neq \infty$$

has the solution

$$f^0_{e^\pm}(x,p) = \begin{cases} f^0_{e^\pm}(p)\exp(u_- x/D) & \text{for } x<0 \\ f^0_{e^\pm}(p) + \frac{q_{e^\pm}(x=0)}{u_+}x & \text{for } x>0 \end{cases}$$

where

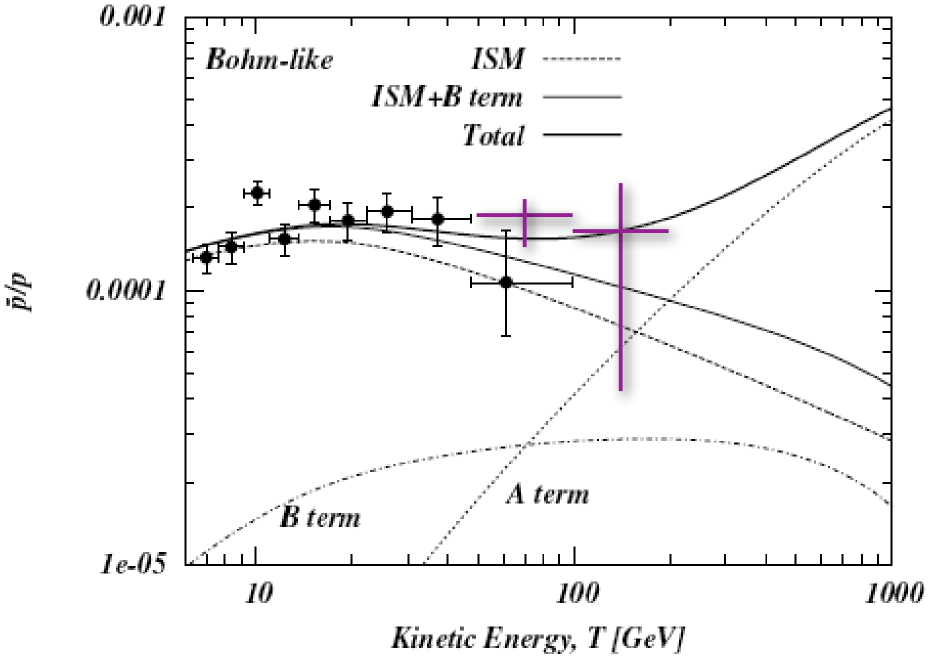
$$f^0_{e^\pm}(p) = \gamma(1+r^2)\int_0^p \frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^\gamma \frac{q_{e^\pm}(x=0)D(p')}{u_-^2} \qquad D(p) \propto p^d$$

“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



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

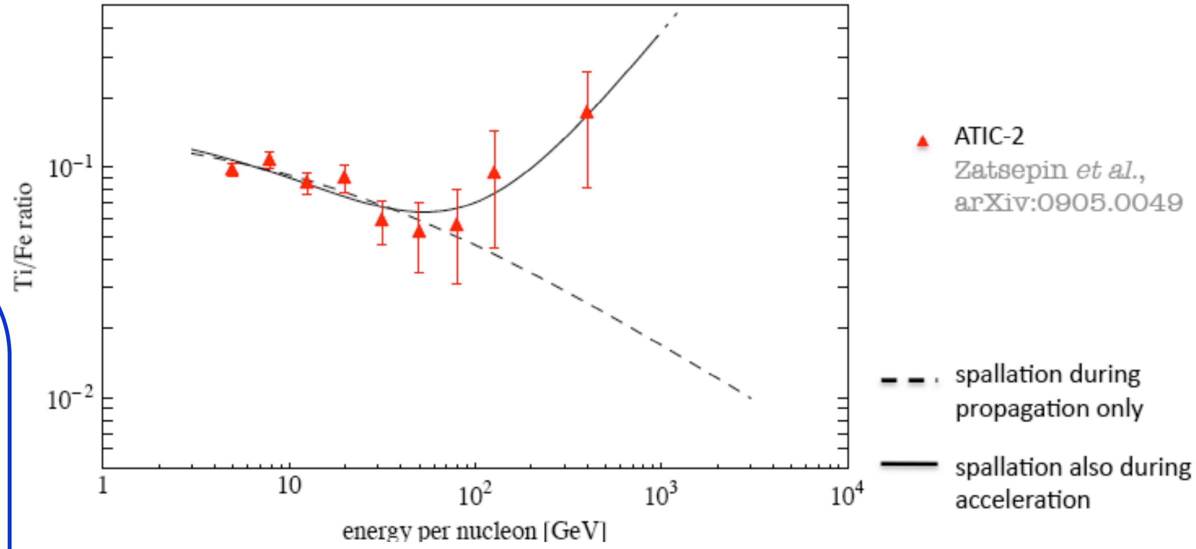
Lesson: astrophysical “backgrounds” to CR antimatter might be not so trivial…
The viability of antimatter for DM searches should rely on robust signatures only!

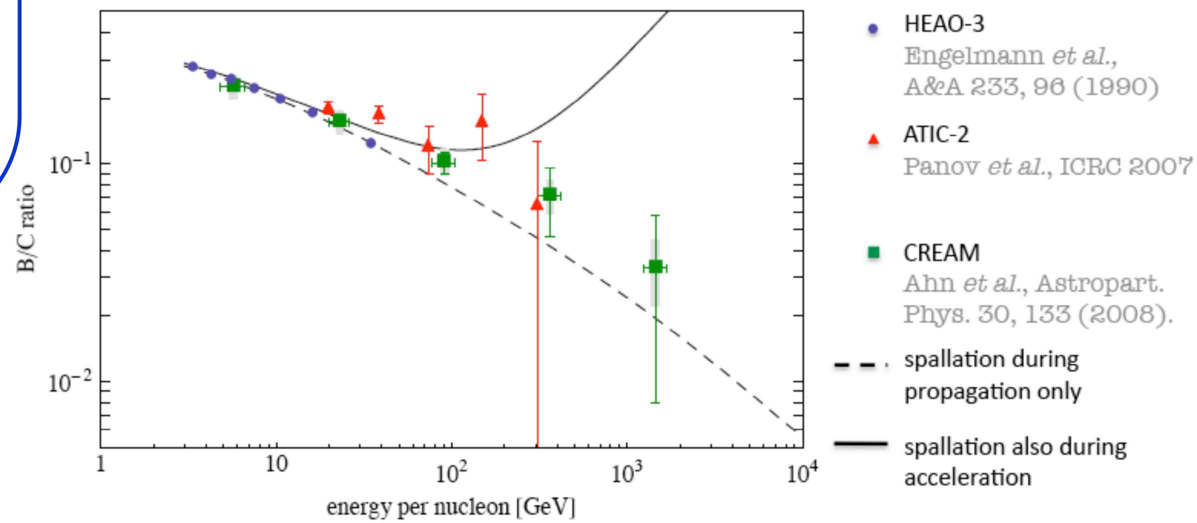
Similar effect for secondary/primary nuclei

Mertsch & Sarkar
arXiv:0905.3152

- some CR nucleosynthesis data (Ne) might suggest that the bulk of nuclei and of p are not necessarily accelerated in the same medium.
- Clearly we need better measurements and over a larger dynamical range
- Endopint issue?

task for AMS-02



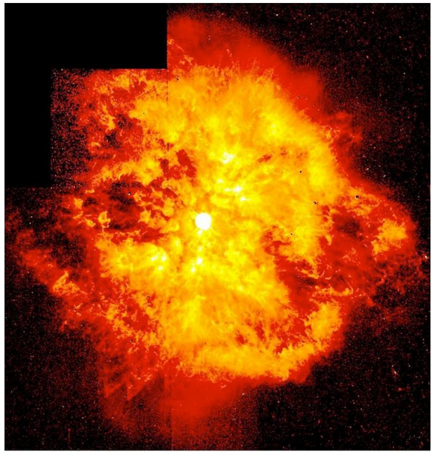


Enriching the scenario: e^+ blowing in the wind?

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

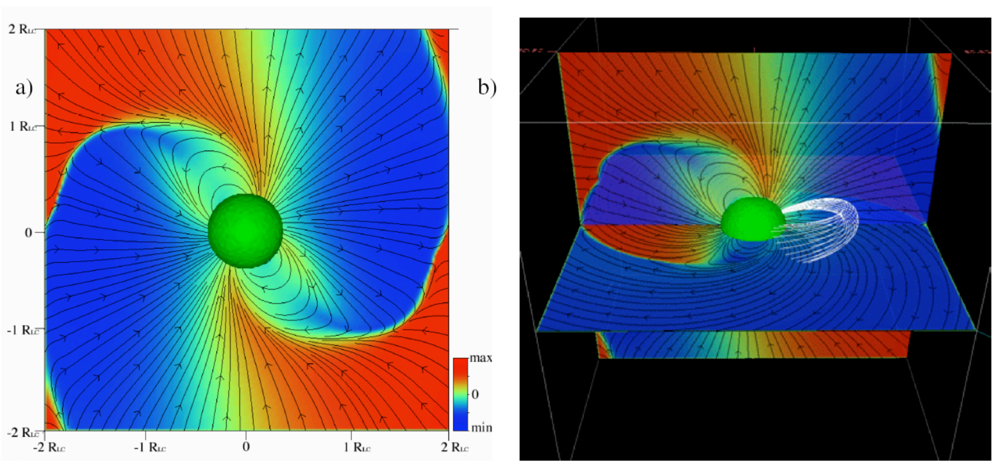
Pulsars

- 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).*

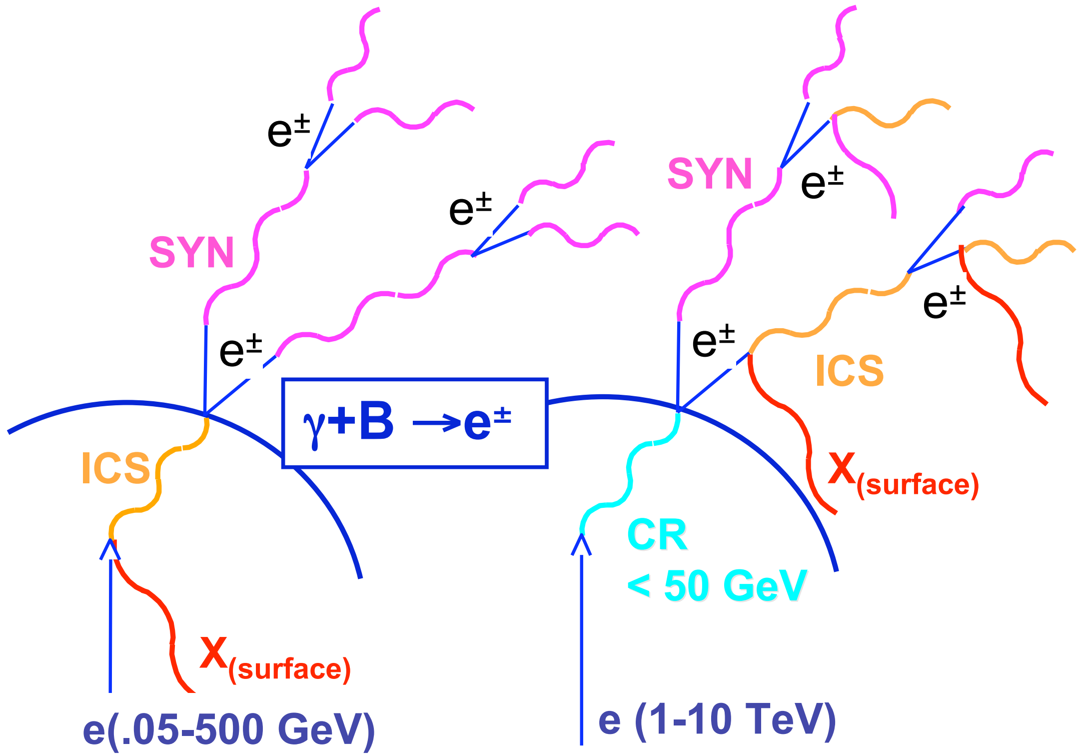


Force-free electrodynamics:

$E \cdot B = 0$ everywhere

No accelerator gaps!

Pulsars: Basics of pair cascade mechanism



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

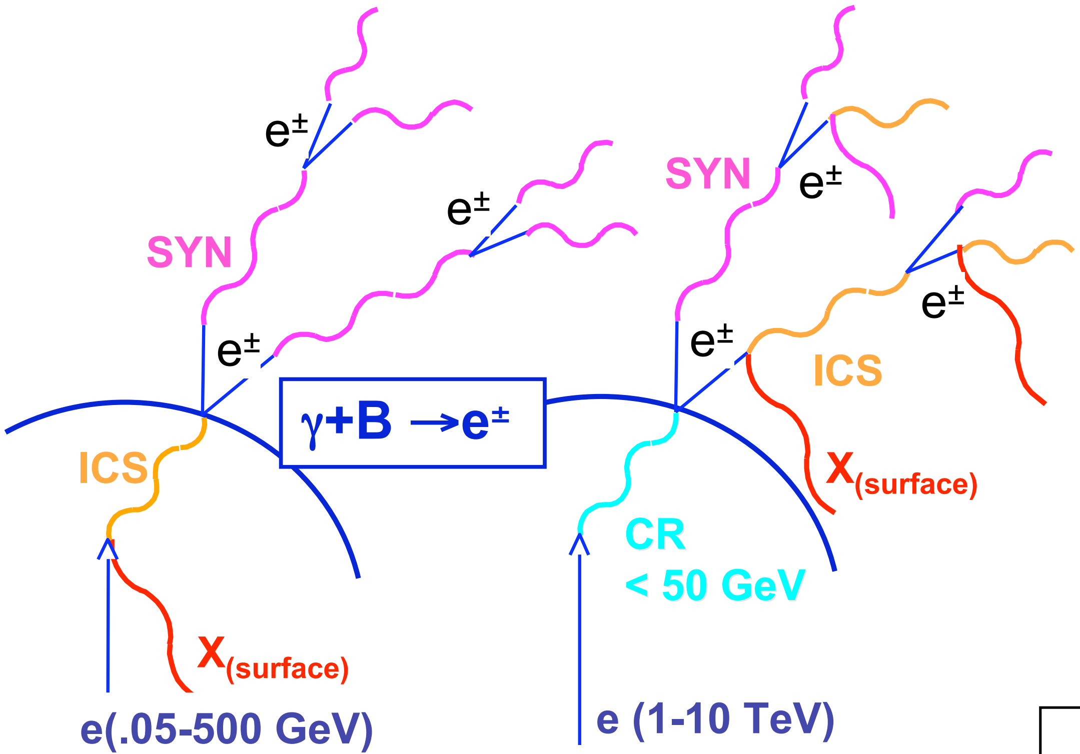
↓

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



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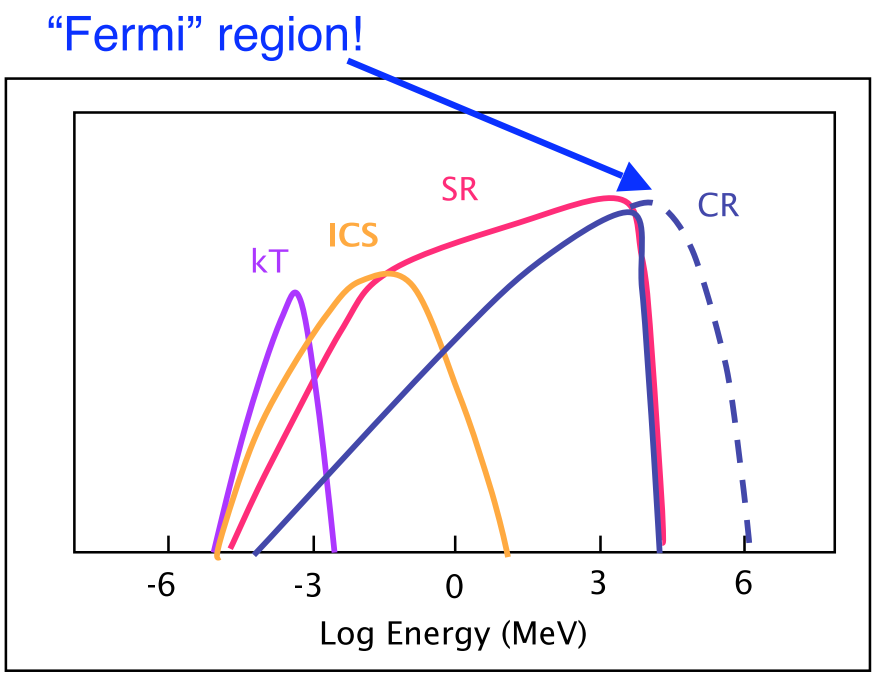
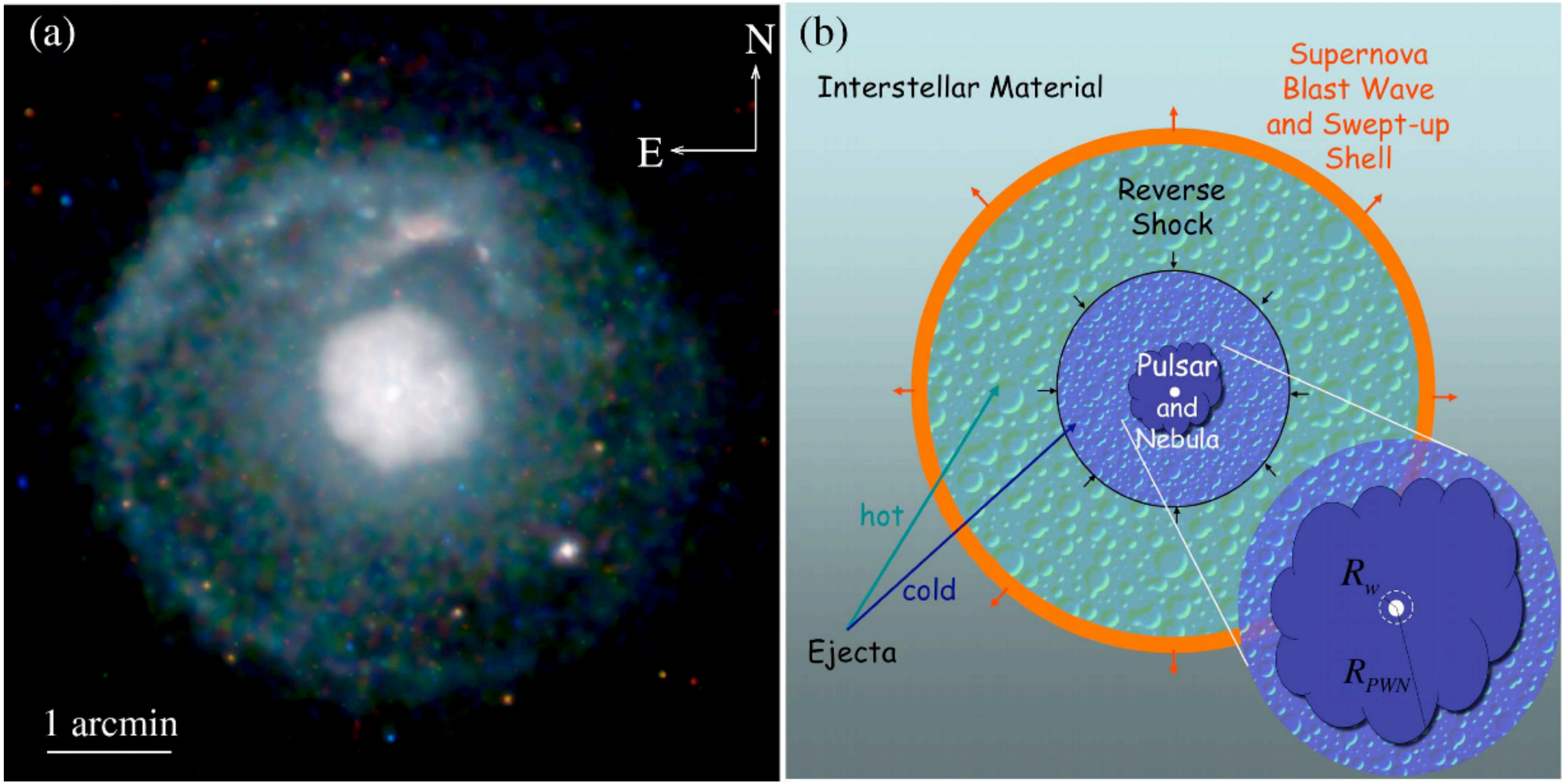
Different models exist depending on location & geometry of "gaps" (where E.B≠0)

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



But there's more than the initial injection!



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

Emission at magnetosphere is not the whole story!

✓ Wind $e^{\pm}$ produced at inner magnetosphere (d< 40 km), via $L_{spin\text{-}down} \approx 1\% \ L_{SNR}$
Region responsible for the pulsed radio emission (but negligible in E-budget!)

✓ Outer magnetosphere (d~ 1000 km) implied in pulsed X and γ emission,
O(1% $L_{spin\text{-}down}$) 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

Note:

- At the magnetosphere the injection of the $e^{\pm}$ eventually escaping the PWN takes place, but radio, X or γ data do not reflect spectral/energetics properties we are interested in: mostly diagnostics tools to understand these objects!

- The (re)acceleration taking place in the PWN until the escape in the ISM is mostly a theoretical subject.

Some Numbers

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

$$\tau_0 \sim 10^4\,{\rm yr}$$

$$\dot{E} = b_0\, E^2$$

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

$$d^2 \simeq 4\, D(E) t$$

$$t_{\rm diff} \simeq \frac{d^2}{4\, D(E)} \sim 2 \times 10^5\,{\rm yr}\, \frac{d_{\rm kpc}^2}{E_{100}^\delta}$$

✓ 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! Theoretical (rather than empirical) arguments must be used to fit the data!

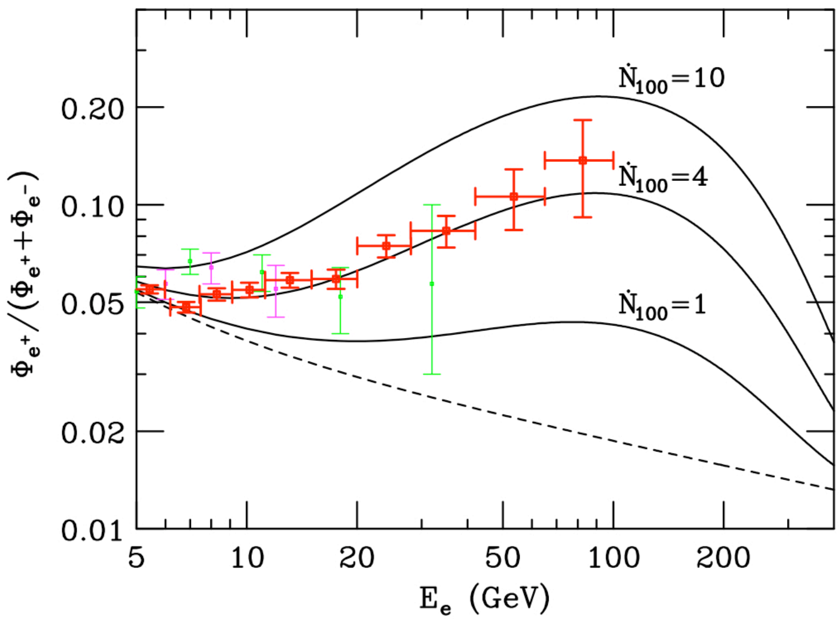
Prediction of a 'population model' of pulsars

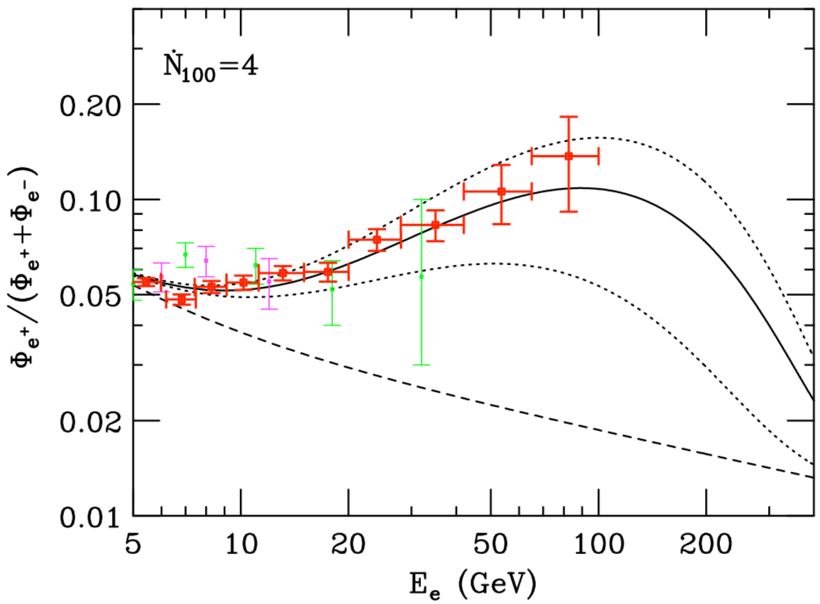
Once fixed a model for the emission (dependence on B, age…) a population study with Galactic population of Pulsars is needed

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

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

Account for Propagation/Energy losses…



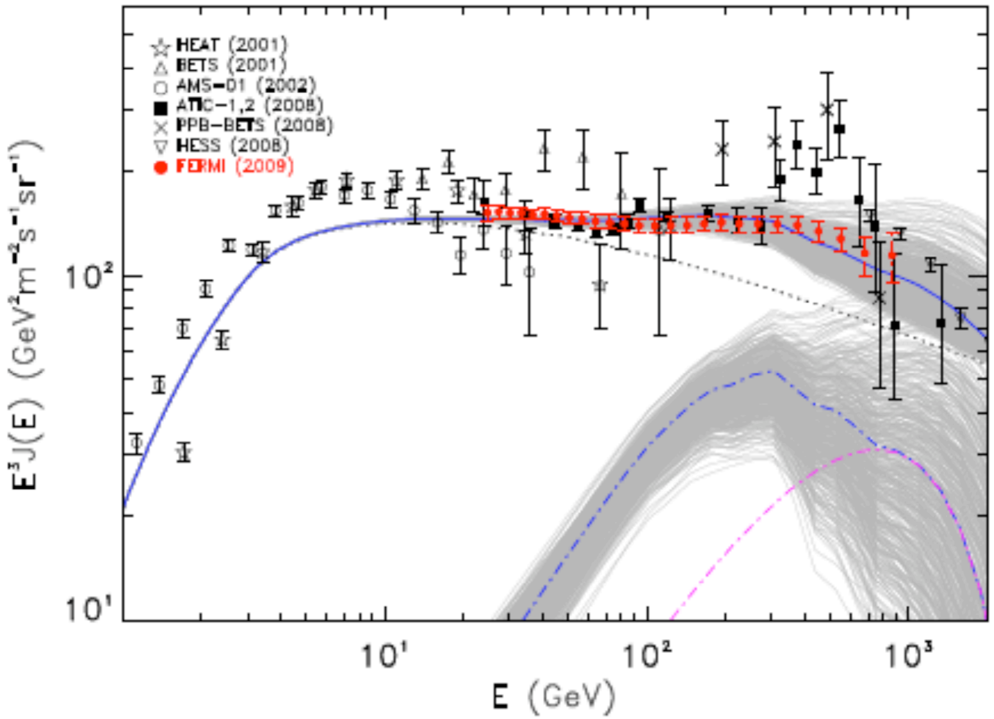


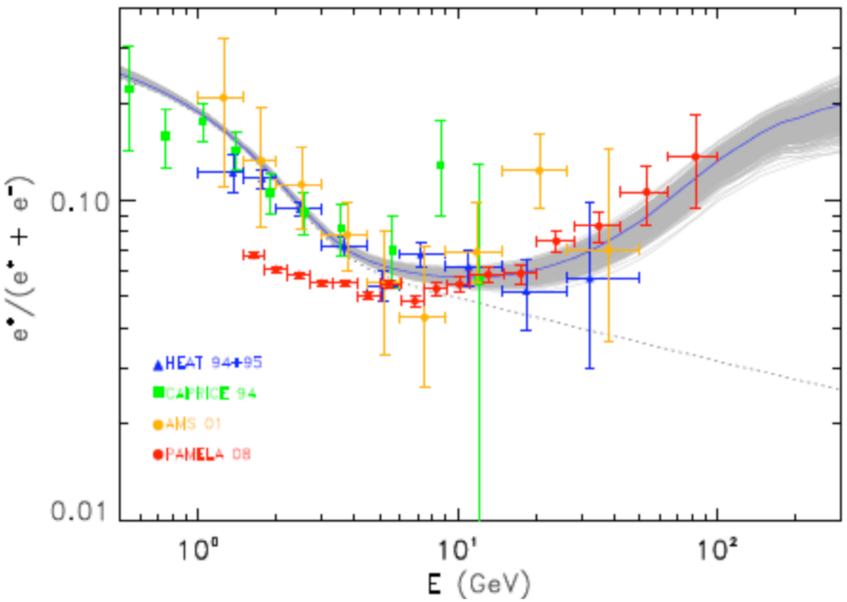
For details: D. Hooper, P. Blasi, PS, arXiv:0810.1527
(old idea, see e.g. F. A. Aharonian, A. M. Atoyan and H. J. Volk A& 95…
revisited on the light of qualitative & quantitative new data)

Contribution of local, “discrete” sources

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

Local contribution is crucial for Fermi E-range, rather than (most) PAMELA





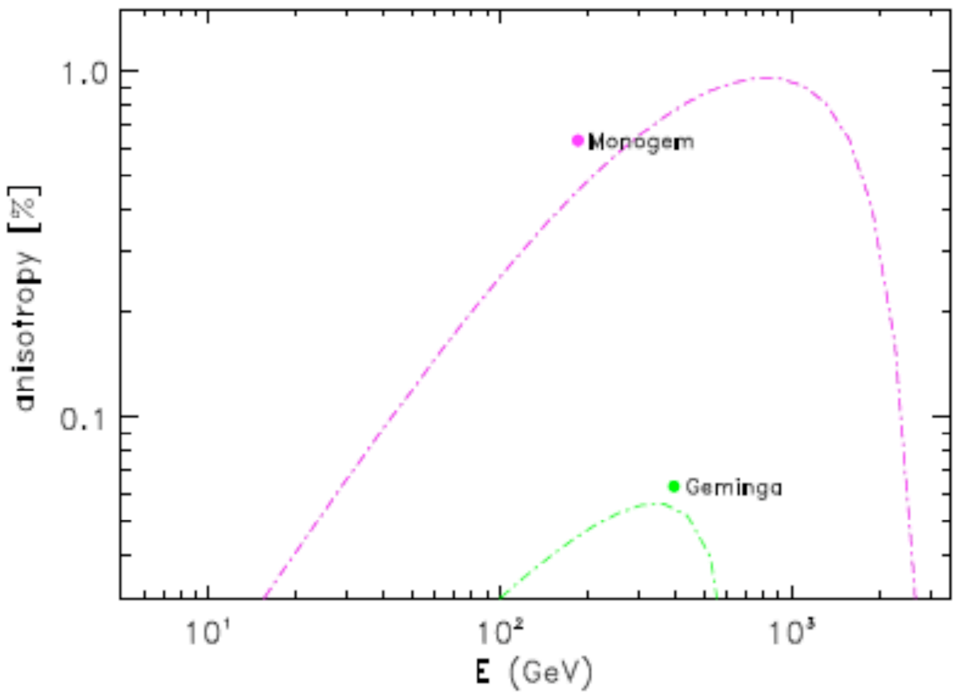
D. Grasso et al. arXiv:0905.0636;
Yuksel, Kistler, Stanev, arXiv:0810.2784;
Profumo, arXiv:0812.4457;
Malyshev, Cholis, Gelfand, arXiv:0903.1310.
Kawanaka, Ioka, Nojiri, arXiv:0903.3782
…

A measurable anisotropy as diagnostics?

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

- Anisotropy dipole in the total e-flux >~0.1% level towards some nearby astrophysical sources

- DM could mimic if from "clump", but unlikely oriented towards GP



Problems:

- Experimentally challenging (easily affected by unaccounted to systematics)
- Do we know enough about intrinsic CR anisotropy? (TeV results by Tibet, MILAGRO, SK)
- Possible degeneracy with magnetic-induced effects: E-dependence should be used!

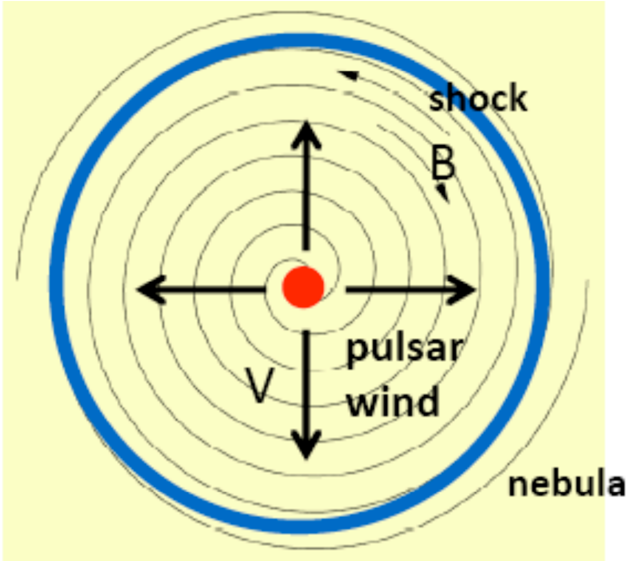
How ‘reasonable’ is the hard PWN spectrum?

DSA paradigm: non-relativistic, strong, parallel shocks in ordinary, ion-e^- medium predicts $E^{-2.\varepsilon}$ spectrum, but has a problem to reach E_{max}~PeV, solvable via

- B field amplification *(X-ray confirmed!)*
- non-linear shock modification (backreaction)

But PWN have a relativistic, oblique (⊥?) shock in a medium filled with pairs!
Diffusion across B line difficult ⇒ no DSA, i.e. no “standard” or generic model

Energetics constraint from data normalization seems OK (O(10%) efficiency, does not violate any bound), spectrum ~$E^{-1.5}$ hard to predict, not necessarily “unreasonable” :
Hard to predict ≠ Hard to obtain in Nature!
(e.g. many AGN show harder than DSA-theory spectra…)



Possible models may be

- Shock Surfing Acceleration

“stays at the shock” due to shock front fine structure

- Wakefield Acceleration

acceleration by radiation pressure

- Resonant Cyclotron Acceleration

See e.g. Hoshino’s talk @IPMU, 12/2009

Both hard spectra and high efficiency possible!

- 3-component plasma of e^-, e^+, p (very different in mass!)

$$\rho \equiv \frac{m_p}{m_e} = 100$$

- Rich in pairs

$$\nu \equiv \frac{n_p}{n_e} < 1$$

- Energy dominated by p-component

$$\eta \equiv \frac{E_{\mathrm{tot},p}}{E_{\mathrm{tot},e}} > 1$$

Particle-in-cell simulation find hard spectra (1<index<2), high efficiency (1-30%), preferential acceleration of e^+ (the higher ρ and η, the better). E.g., 30% efficiency for η~5.25

Amato and Arons, ApJ 653 (2006) 325

- Acceleration happens via resonant absorption of magnetosonic waves by pairs, whose frequencies are harmonics of the proton cyclotron frequency.
- Preferential e^+ acceleration due to helicity matching with dominant proton generated wave spectrum
- $E_{\mathrm{max}} \simeq \frac{m_p}{m_e} E_{\mathrm{inj}}$ *Hoshino & Arons, Physics of Fluids B, 3 (1991) 818*

Conclusions

a new era in High Energy astrophysics

- Barring systematics, recent e^+ e^- data suggest a class of energetic lepton (pair?) producers. Both astrophysical & DM explanations *in principle* possible, but combined data (p-bar, γ's, electrons, etc.) point likely to astrophysical explanations. Alternatively, to extremely exotic DM properties (exciting?!)

- 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.

- Fortunately, other indirect experiments are running/being completed (e.g. Fermi, IceCube, PAMELA… AMS-02): checks of the internal consistency of CR models is ongoing with high-quality data, extending over a larger dynamical range.

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- For DM searches, I believe that we are not yet in the stage of "fitting" data with models. Rather we should worry first to obtain firm discovery of a WIMP DM. PAMELA/Fermi data rather suggest that $e^+ e^-$ are not particularly suitable for DM discovery, since their background is the most difficult to keep under control!

- While clean discovery via this channel is challenging, it still provides an important "sanity check" in a multimessenger perspective. Direct detection is achieving a jump in sensitivity, LHC will tell us what's really going on at the EW 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