Cosmic ray "anomalies": some possible causes & implications

Pasquale Dario Serpico

11/01/2016 LPNHE Paris

Cosmic ray "anomalies": some possible causes & implications

won't talk about "biological anomalies"

FROM FANTASTIC FOUR #1

wrongly based on once popular Millikan's theory, or "how to learn history of Physics by reading comics"

Pasquale Dario Serpico

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OUTLINE

- Direct techniques for cosmic ray observations have reached an unprecedented level of precision, unveiling fine-details of the energy spectra (notably spectral breaks and elemental spectra non-universality)
- After reviewing the evidence for new spectral features accumulated by recent experiments, I will discuss the main ideas invoked in their theoretical explanations
- Some implications for the antimatter (positron/antiproton) channels will be highlighted, notably in the context of indirect WIMP dark matter searches (depending on time)

I will only deal with observations which seem to defy expectations about (Galactic) cosmic rays, focusing on direct detection range (rather than EAS/UHECRs) and on charged particles only (neutrinos & photons out of my talk)

For more details and an extensive list of references, see

PS "Possible physics scenarios behind cosmic-ray "anomalies","

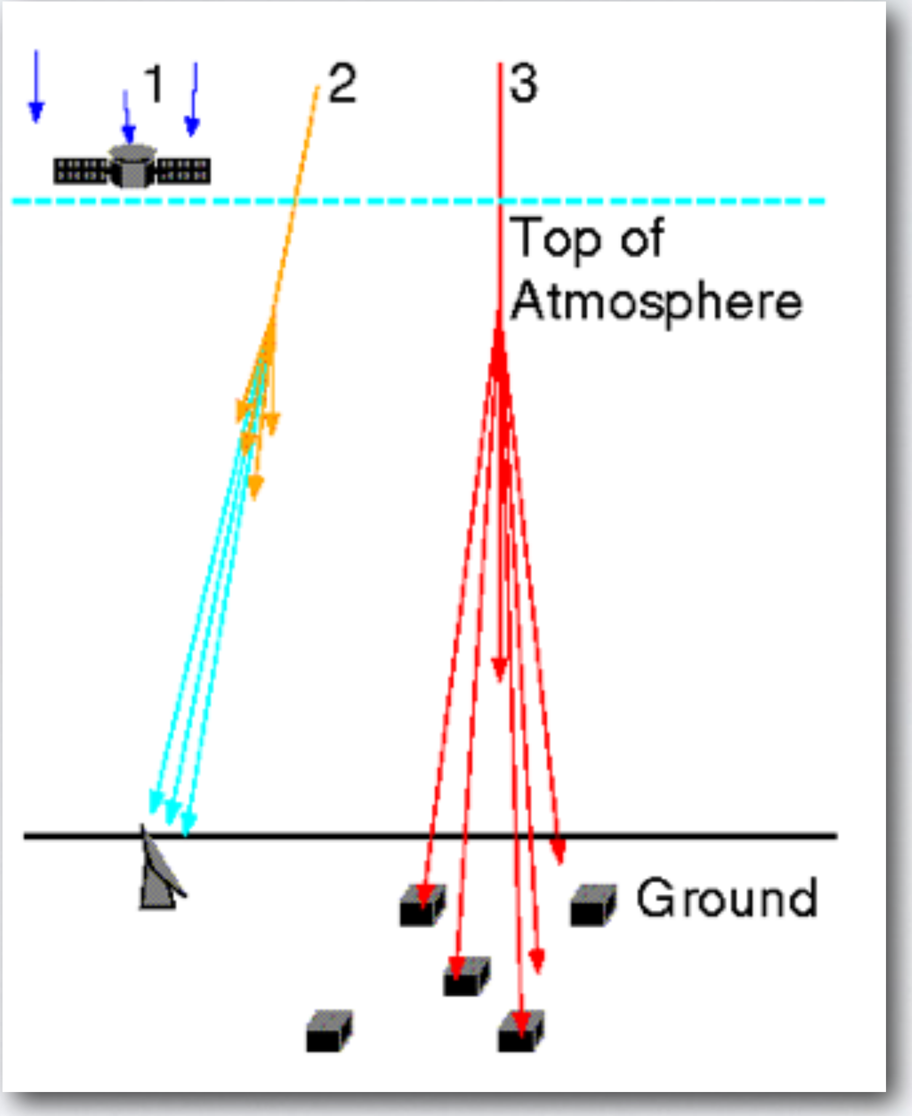
PoS ICRC2015 (2015) [arXiv:1509.04233]

based on an invited Highlight talk at ICRC 2015, The Hague

BACK TO BASICS, FLUXES

Fluxes:

- @ 1 GeV: $\sim$1 particle cm^{-2} s^{-1}
- @ 100 TeV: $\sim$1 particle m^{-2} d^{-1}
- @ 10^{20} eV: $\sim$1 particle km^{-2} century^{-1}



up to ~100 TeV one can use particle detectors flying on balloons or in space, indirect techniques are the only ones viable above that energy

BACK TO BASICS, (DIRECT) DETECTORS

In principle, "ordinary" particle physics detectors can be used to measure the relevant information on CRs: direction, charge, momentum, energy, velocity...

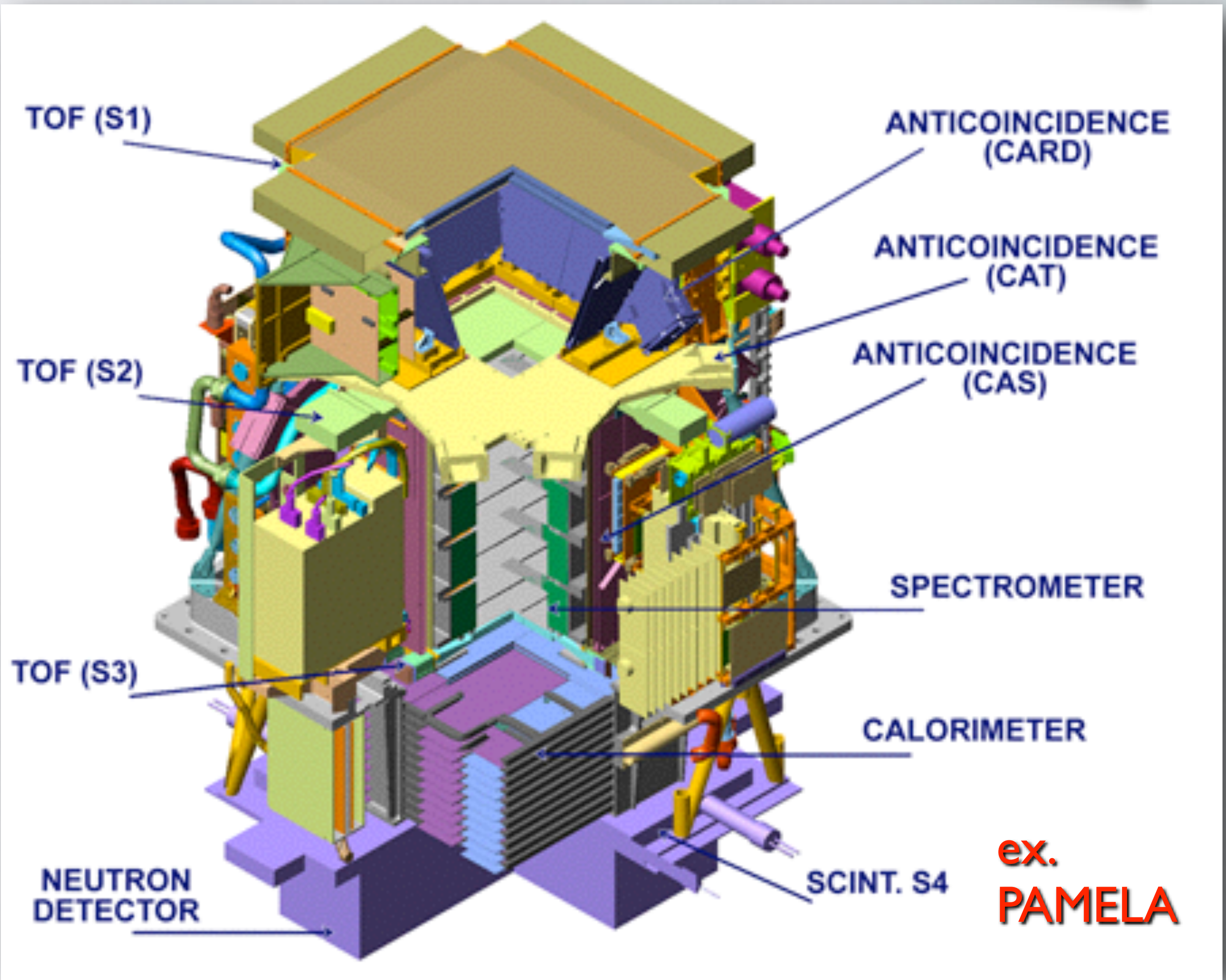
•**spectrometers, magnets & trackers:** determine Q and *p* of the particles

•**Calorimeters:** measure *E* of particles & do particle discrimination.

•**Cherenkov detector:** measure the particle *v* from width of cone

•**Transition radiation detector:** measures the cone opening angle thus the mass of particles

•**Time of flight:** measure the time difference and the velocity



With some difficulties & differences wrt colliders:

- weight and size matter!
- "Specific" backgrounds (for example # e.m. particles << # hadrons),
- Alignment in space (can't go out there to measure...), etc.

BACK TO BASICS, SOME UNITS

- **Rigidity**

Why useful? In magnetic fields, particles of same R behave the same way, useful when collisions are negligible

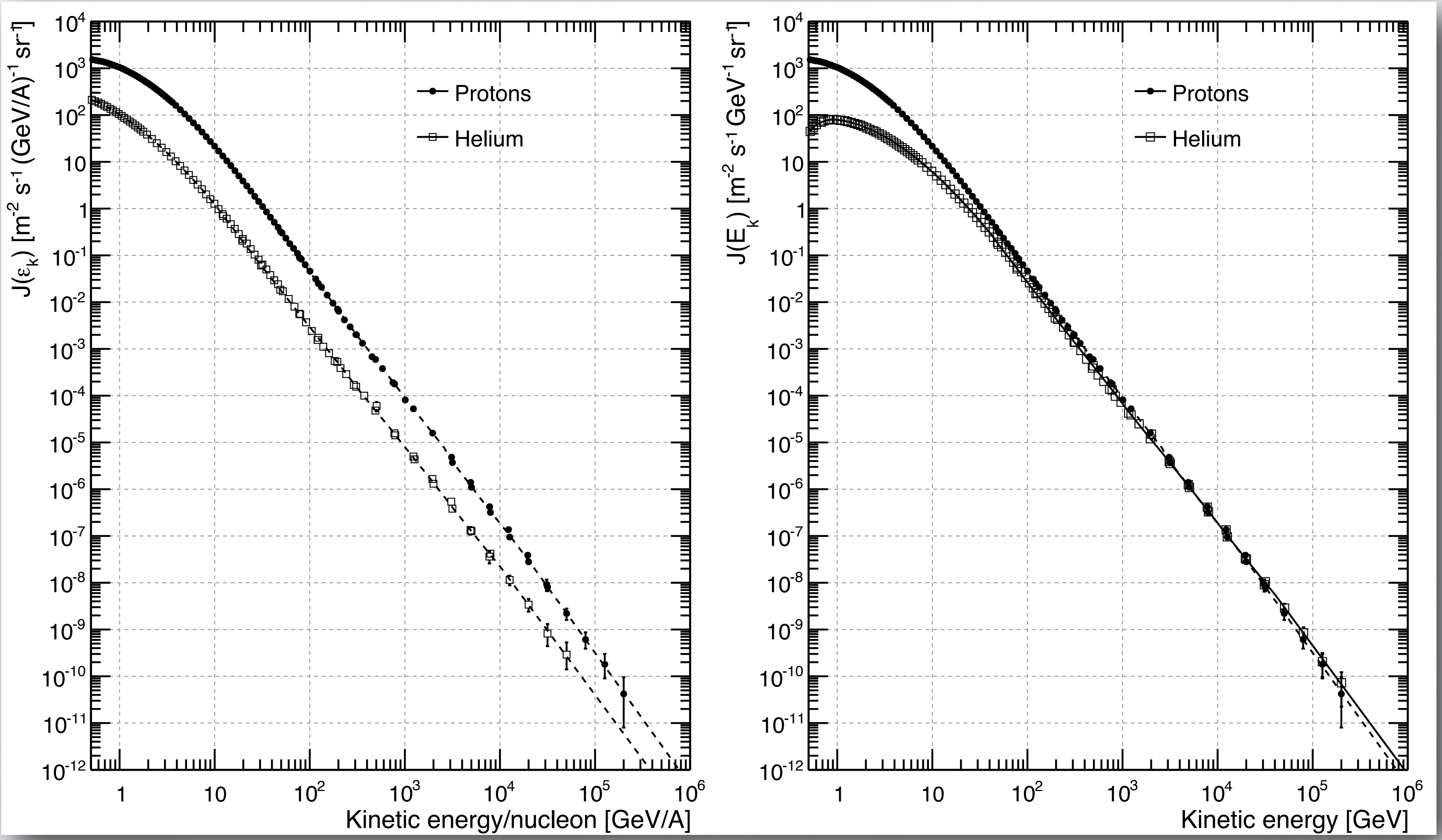
$$\mathcal{R} = \frac{p\,c}{Z\,e}$$

- **(Kinetic) Energy per nucleon**

Why useful? In *spallation* reactions, E_k/A is conserved to very good approximation (CR energies >> nuclear binding energies)

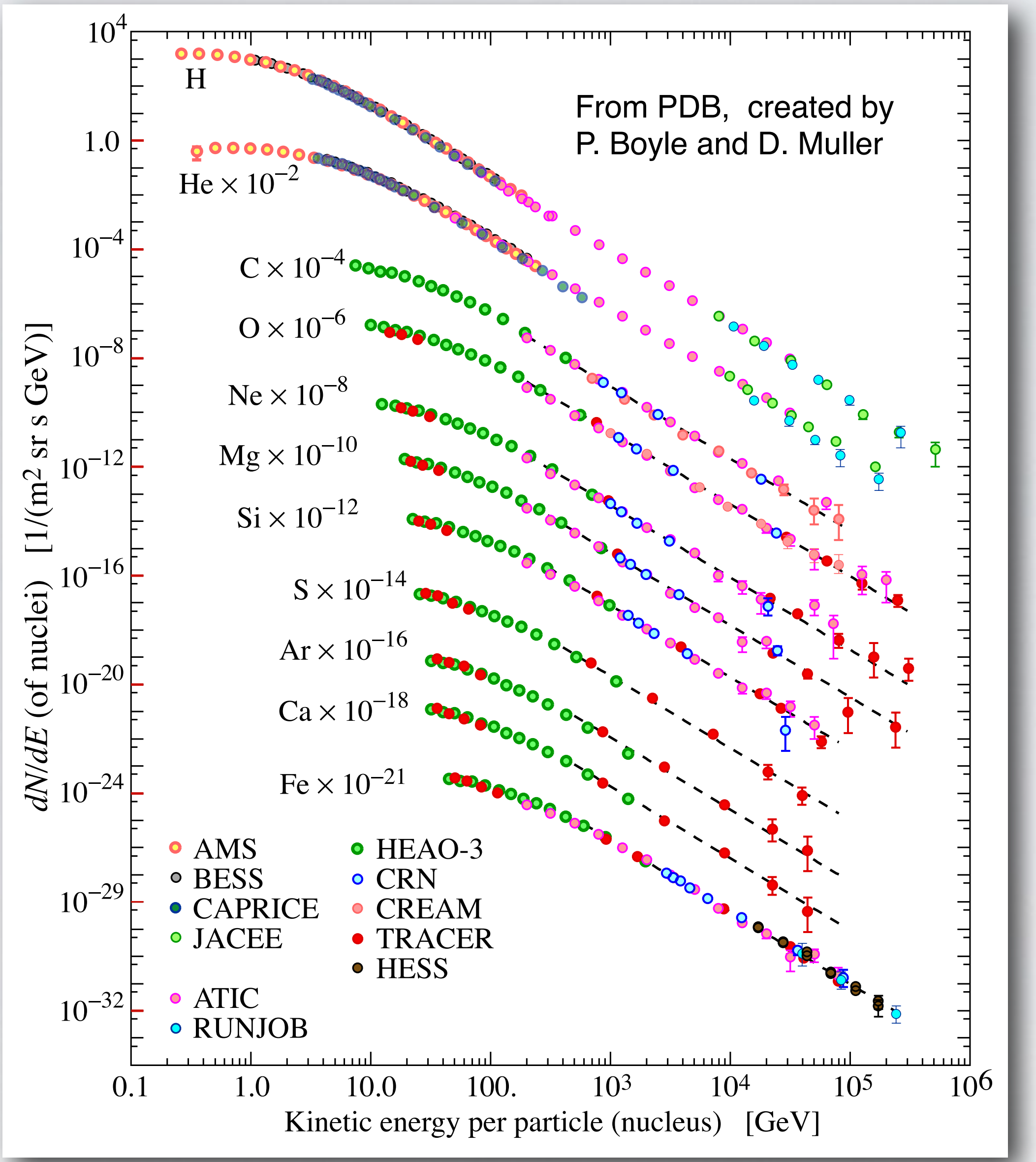
$$\mathcal{E}_k = \frac{E_k}{A}$$

When looking at spectra, beware of units! For a power-law of index Γ $J(E_k) \simeq A^{\Gamma-1} J(\mathcal{E}_k)$



BACK TO BASICS, SPECTRA

Probably the most obvious *expectation* about cosmic rays (0^{th} order picture we teach in CR 101) is that, above a few GeV, they have a **"featureless & universal power-law energy spectra"**



Lots of work rely on/predict e.g. self-similarity (e.g. Fermi Theory, Kolmogorov spectrum...)

Important to test for departures from basic features: may provide clues on ***specific scales & phenomena*** shedding light on non-universal features of *injection, acceleration, escape, propagation*

HISTORICAL ANALOGY

"Perfect" Gas (Clayperon, 1834) $$pV = nRT$$

Universal: valid for low pressure and "warm" gas, no detail of "atomic scales" enters

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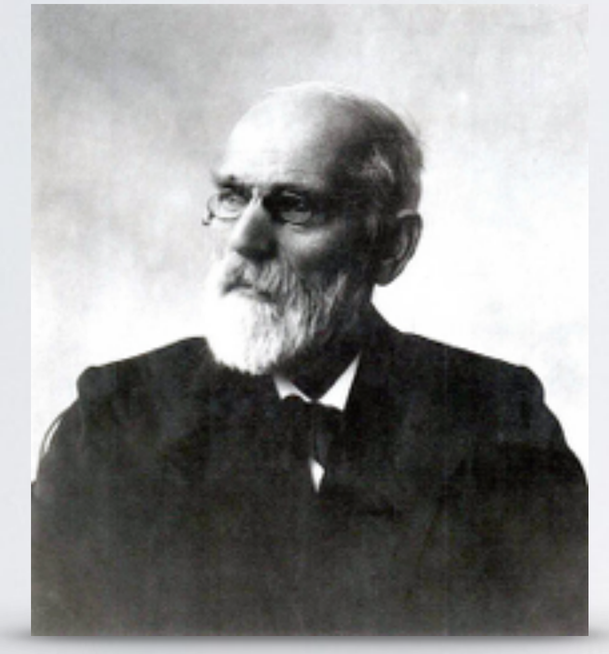
Van der Waals (PhD, 1873)

$$\left(p + \frac{n^2 a}{V^2}\right)(V - n\,b) = n\,R\,T$$

correction for *intermolecular forces*

"Atomic" scales!

correction for *finite molecular size*



Nobel Prize 1910

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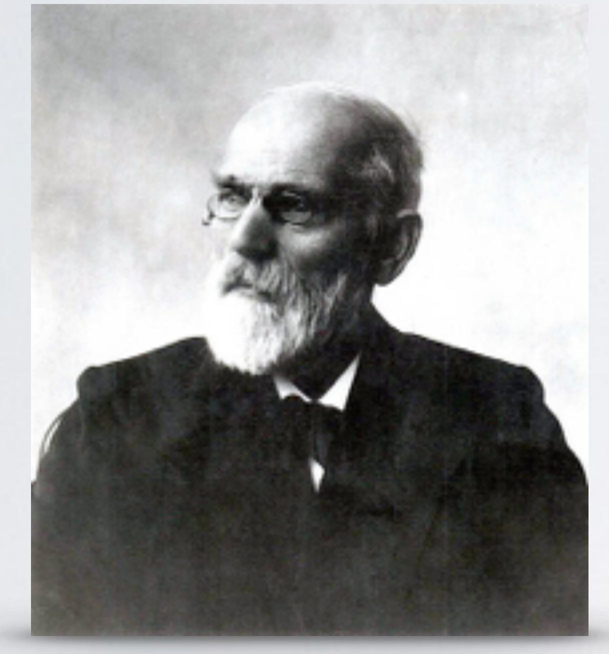

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correction for *intermolecular forces*

"Atomic" scales!

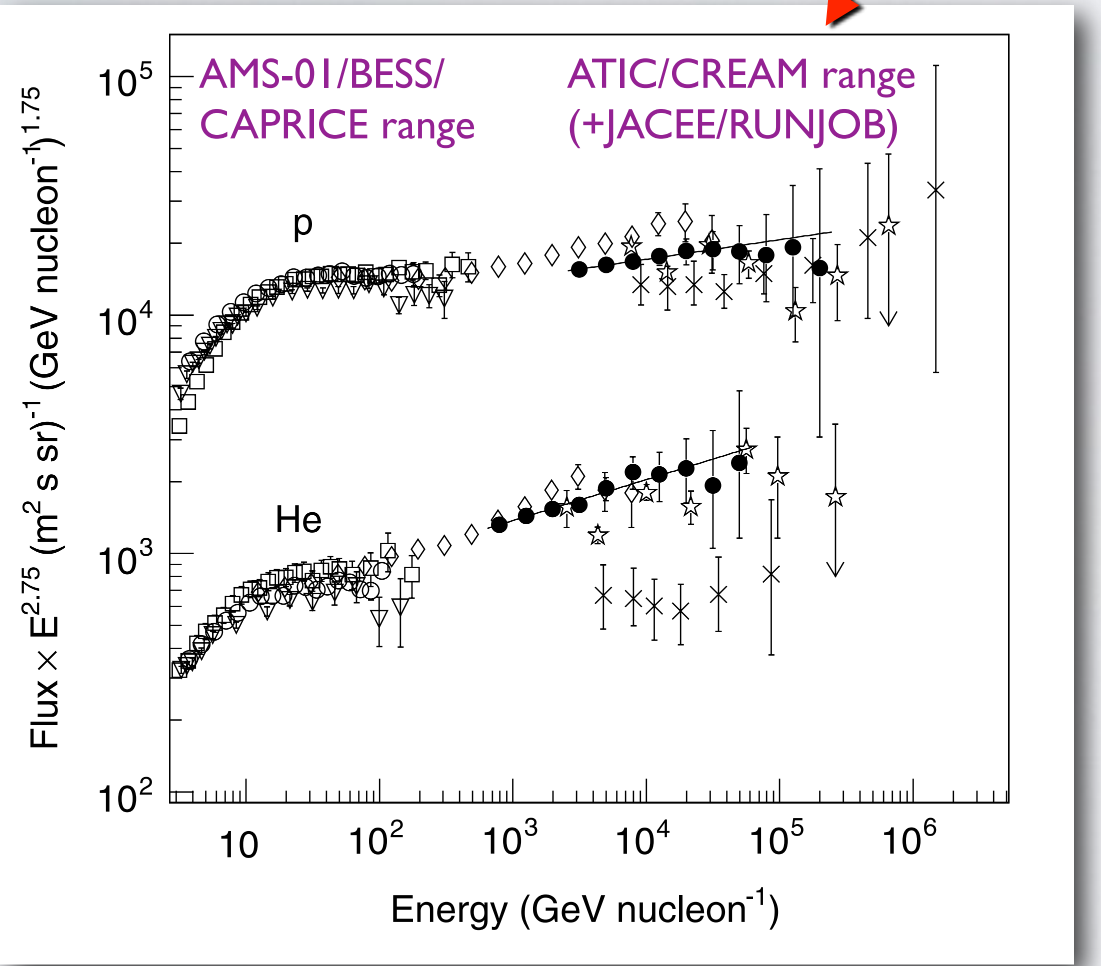
correction for *finite molecular size*

[…] It does not seem to me superfluous, perhaps it is even necessary, to make a general observation […] in all my studies I was quite convinced of the real existence of molecules, that I never regarded them as a figment of my imagination […] When I began my studies I had the feeling that I was almost alone in holding that view […] now I do not think it any exaggeration to state that the real existence of molecules is universally assumed by physicists. Many of those who opposed it most have ultimately been won over, and my theory may have been a contributory factor. And precisely this, I feel, is a step forward

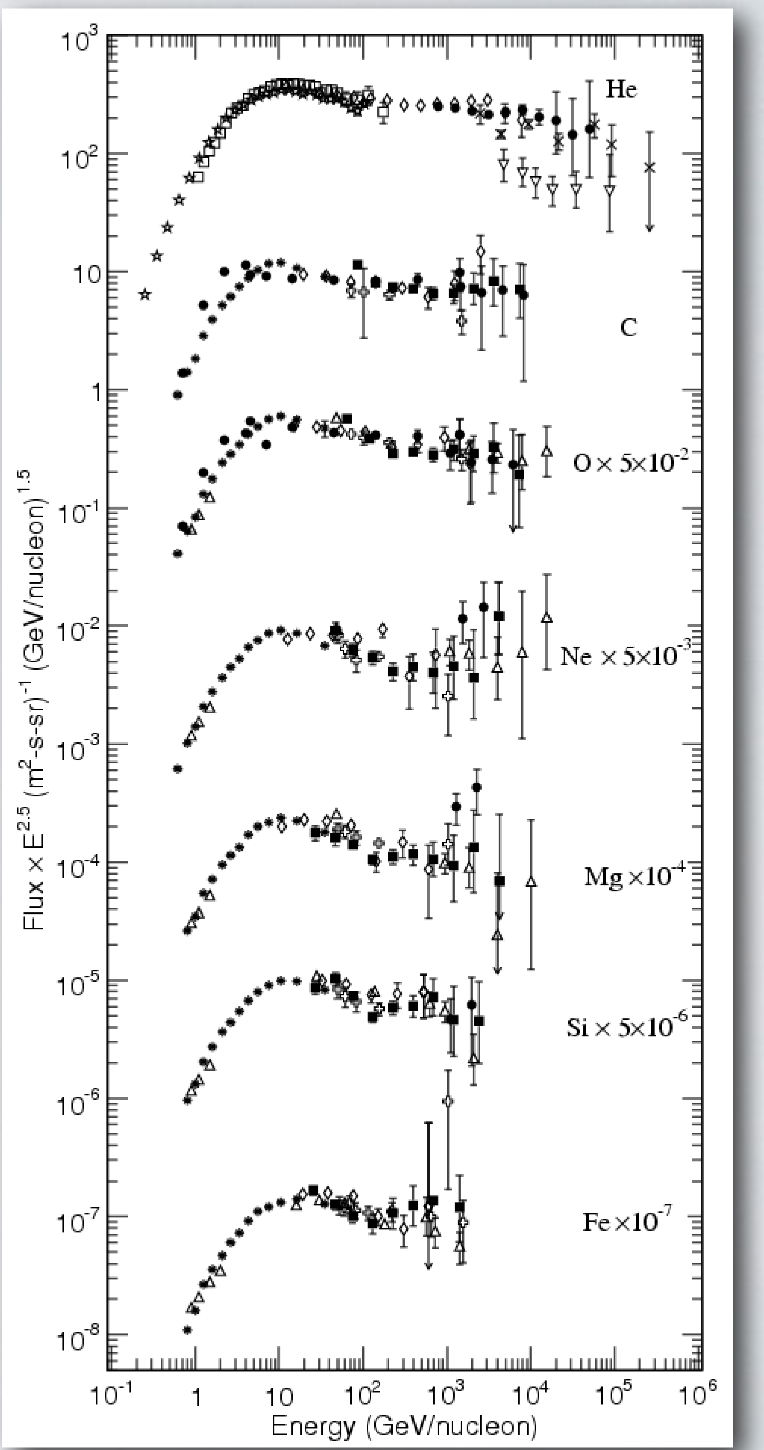
not "mere improvement in fits", but conceptual "step forward"!

HINTS OF POSSIBLE SURPRISES

When the TeV/n range became to be explored with sufficient precision-notably with ATIC-2 (*A. Panov et al 2009, Bull. Russ. Acad. Sci. Phys, 73, 564*) & CREAM (*Y. S. Yoon et al 2011 ApJ 728 122*)-hints of possible departures from extrapolations of lower energies spectra clearly emerging in *p*, He... but also seen in nuclei!



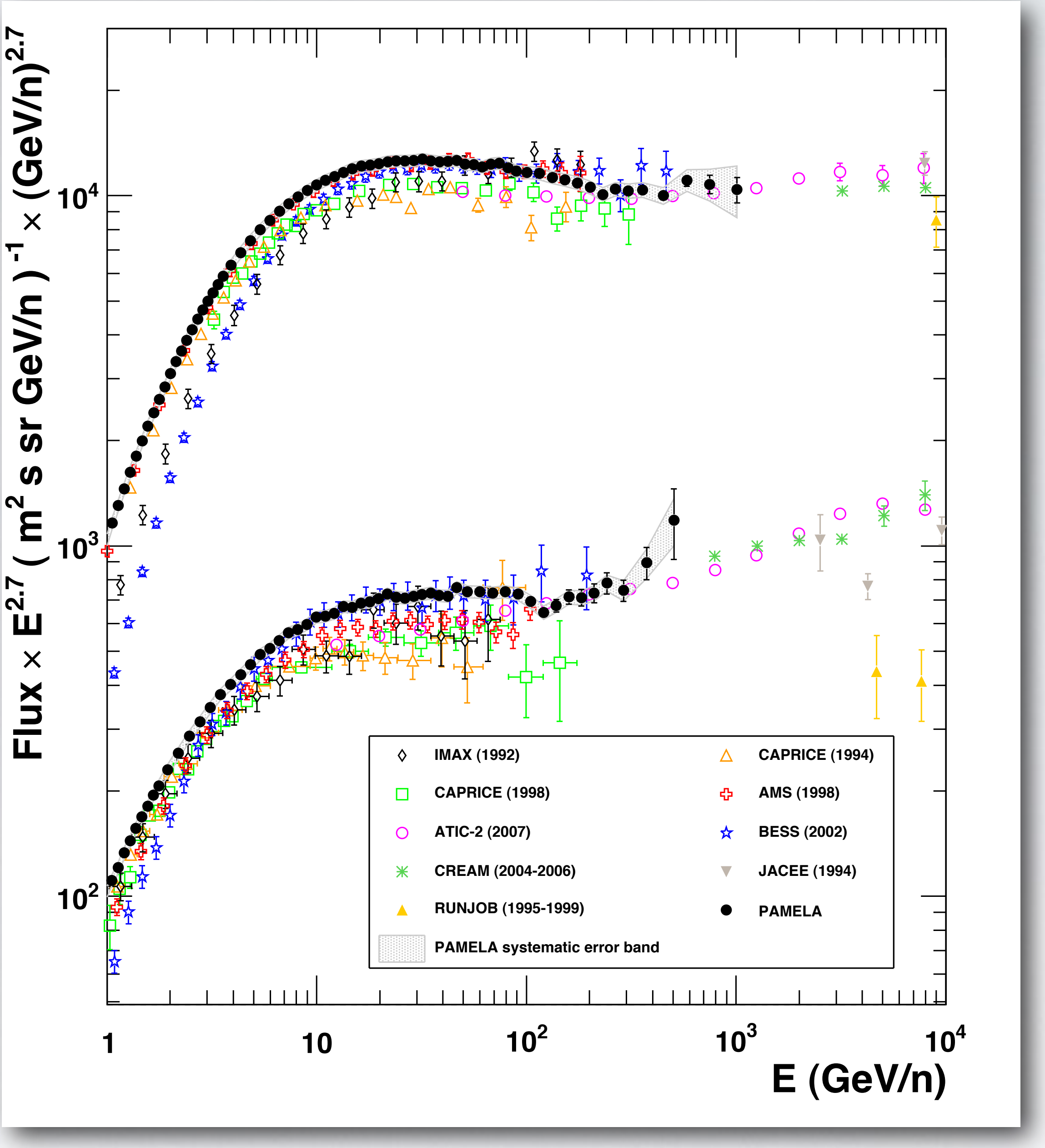
H. S. Ahn et al, ApJ 714 (2010) L89-L93



Yet, conceivable concerns: systematics, possibly related to different experimental technologies?

I ST ANOMALY: BROKEN PL'S BELOW KNEE!

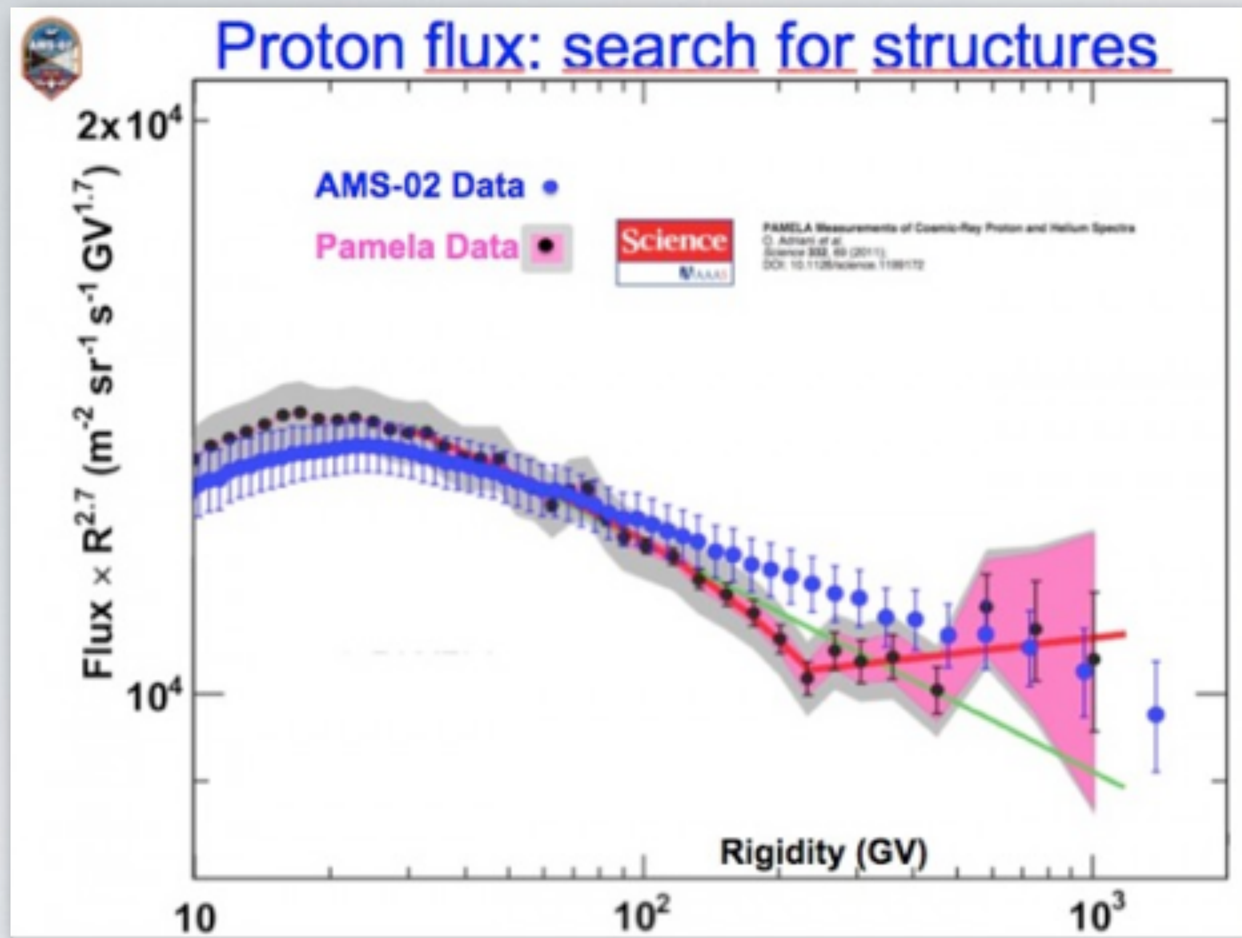
Soon after, PAMELA seemed for the first time to have a glimpse ***at the transition in p & He***



Evidence in a single instrument seemed to settle the issue!

O.Adriani et al.,"PAMELA Measurements of Cosmic-ray Proton and Helium Spectra," Science 332, 69 (2011) [arXiv:1103.4055]

NOT YET! LIKE IN A GOOD THRILLER...



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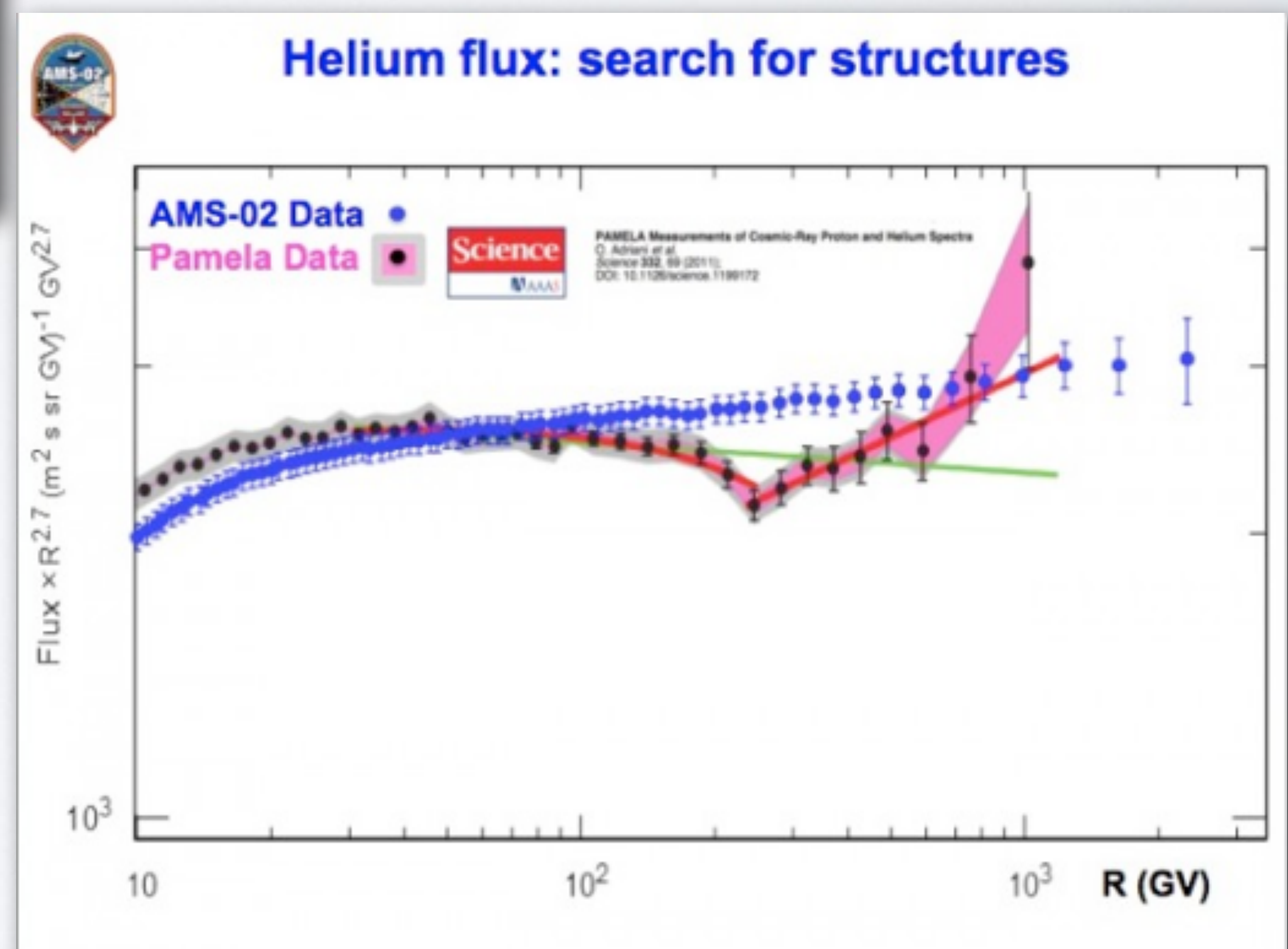

How to make sense of the situation?

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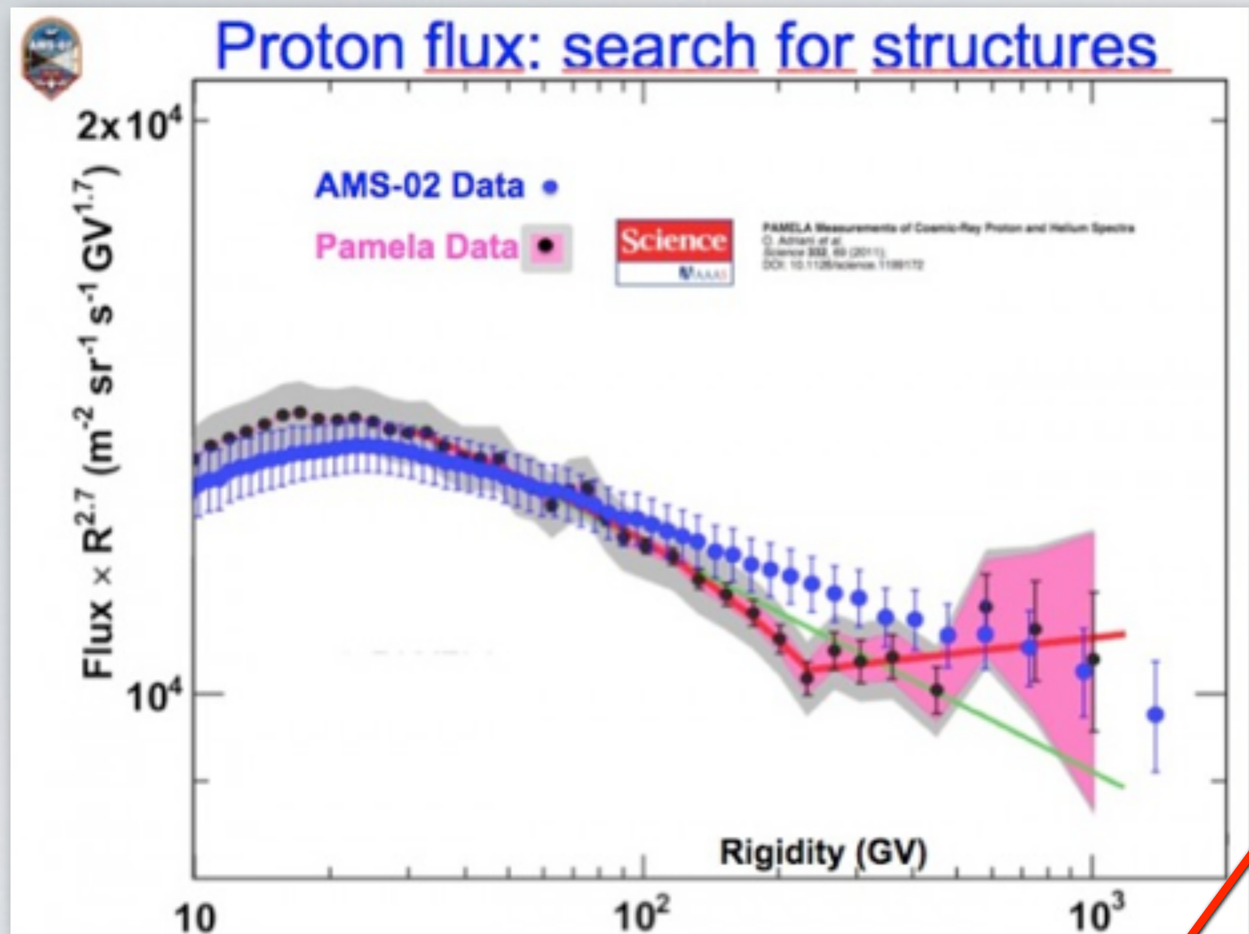

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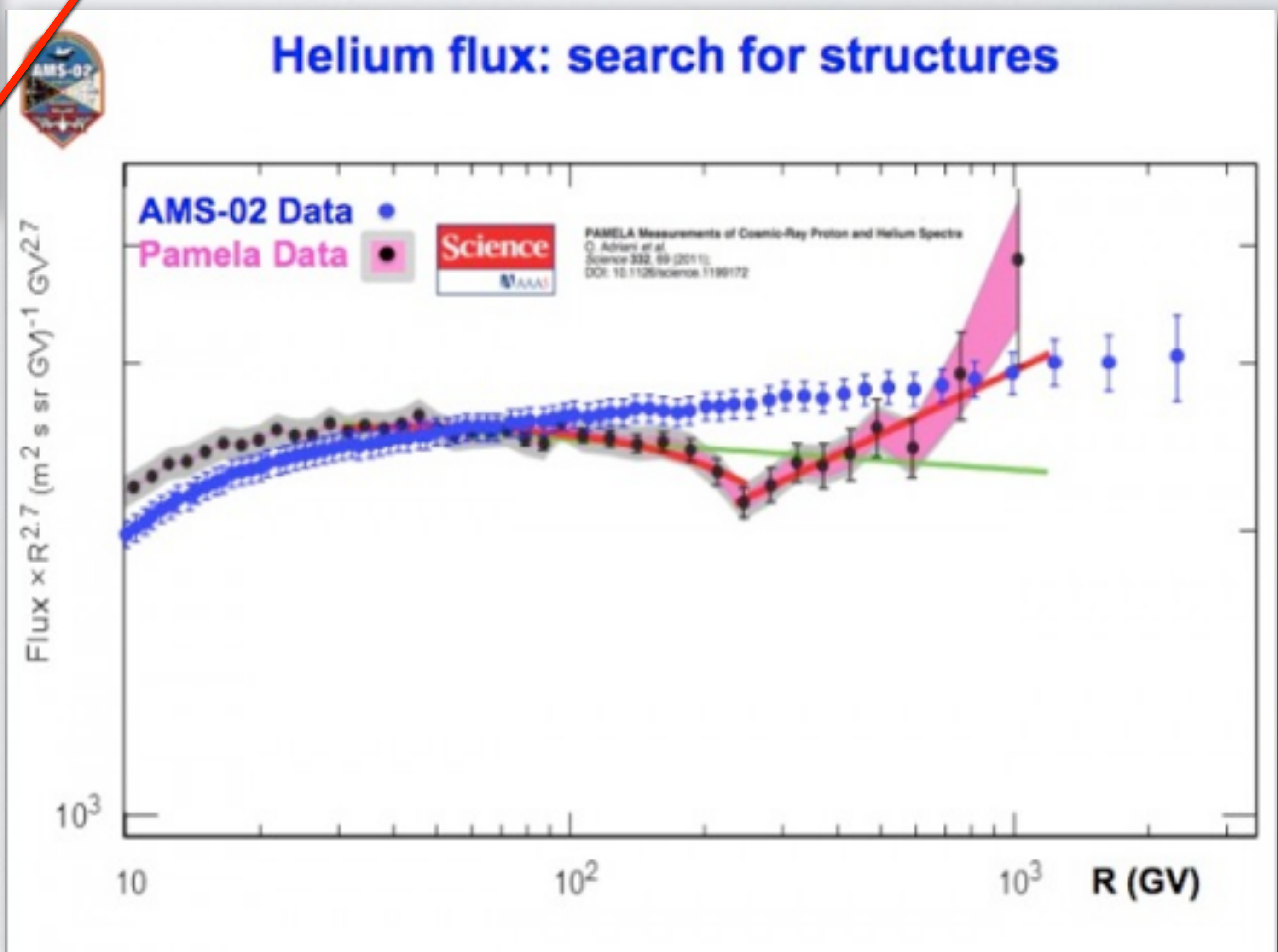
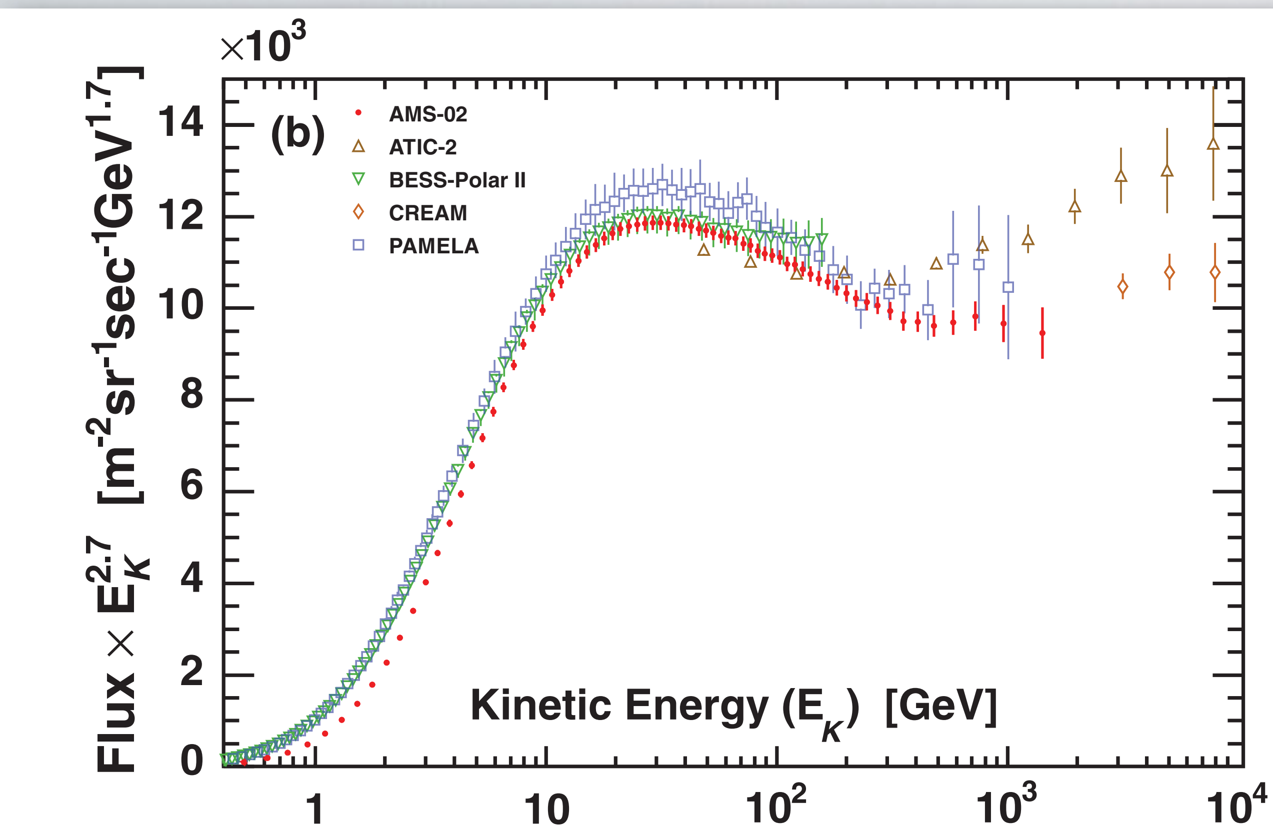


How to make sense of the situation?

FINALLY, HAPPY ENDING



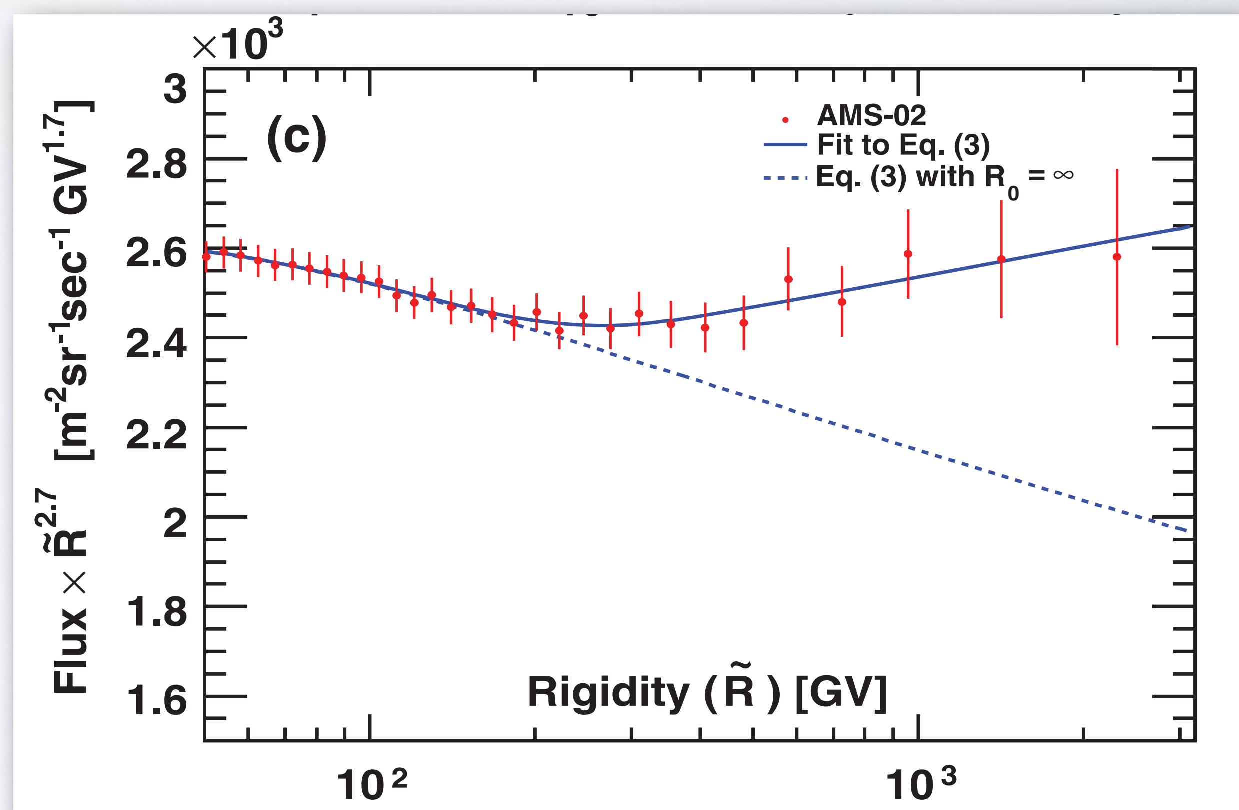
M. Aguilar et al. (AMS Collaboration)
Phys. Rev. Lett. 114, 171103 (2015)

For p, agreement among AMS-02, PAMELA, CREAM (to some extent also quantitatively)

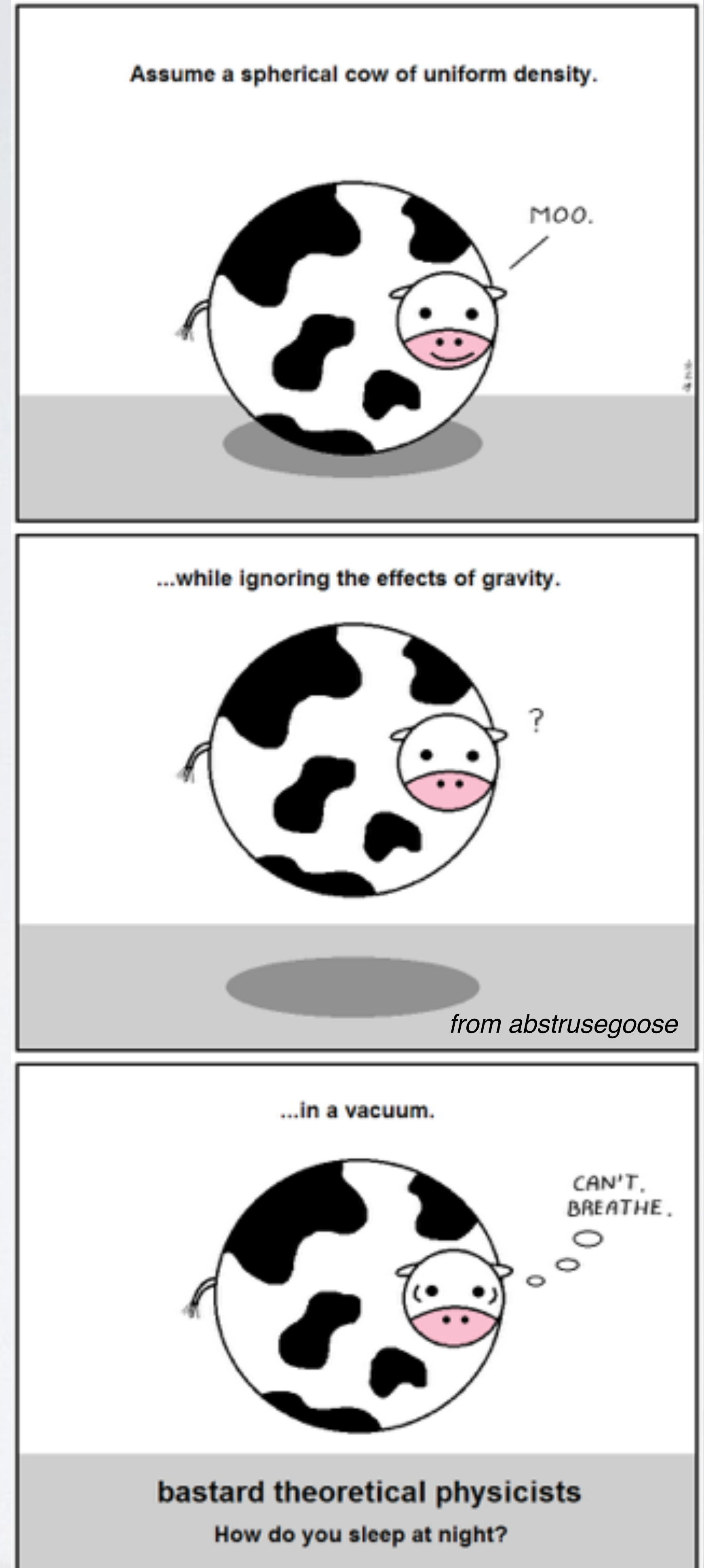
Exp. hardening (AMS)=0.13(~±0.05, sys. dom)

For He, the published analysis agrees at least qualitatively with a change of spectral slope of ~0.12 *(although less prominent than PAMELA reports)*, at a rigidity ~250 GV comparable to the p one

M. Aguilar et al. (AMS Collaboration)
Phys. Rev. Lett. 115, 211101 (2015)



The ball is in the theorists' court!

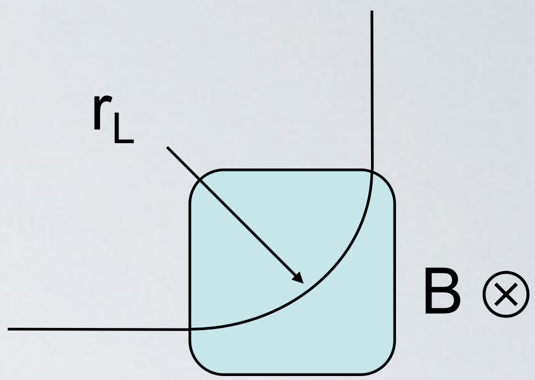


from abstrusegoose

HOW DO CRs PROPAGATE?

Charged particles deflected in a B-field. Their "Larmor Radius" is

$$r_L = \frac{p_\perp}{Z\,e\,B} \approx \frac{1\,\mathrm{pc}}{Z}\left(\frac{p_\perp}{\mathrm{PeV}/c}\right)\left(\frac{1\mu\mathrm{G}}{B}\right)$$



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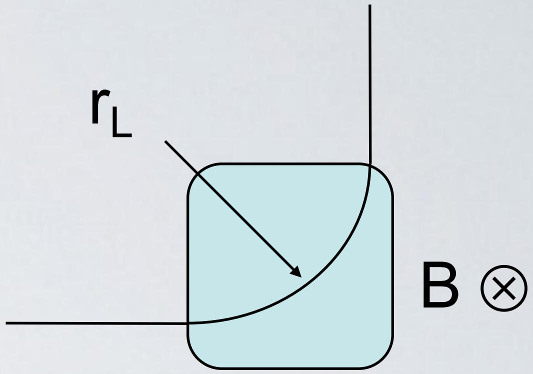

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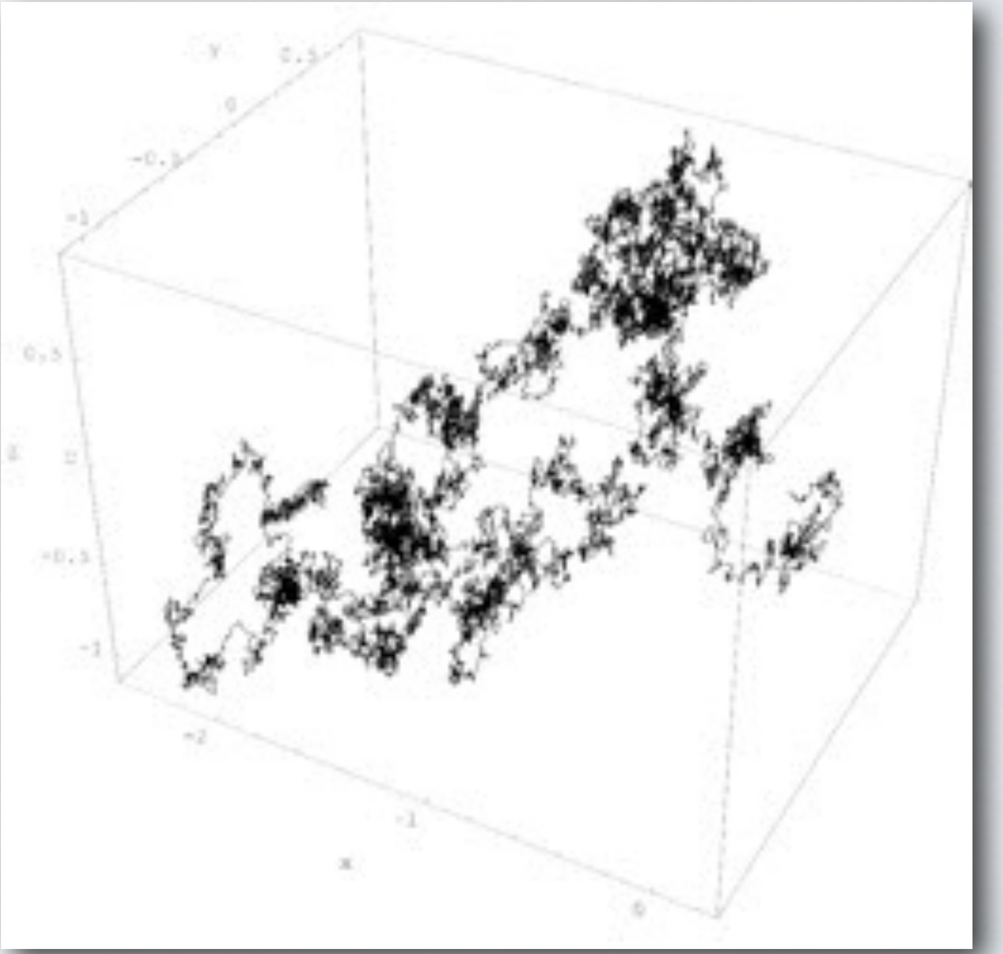
CRs probe thus “small-scale inhomogeneities” in the field, changing direction by what appear “random kicks”, similar to brownian motion



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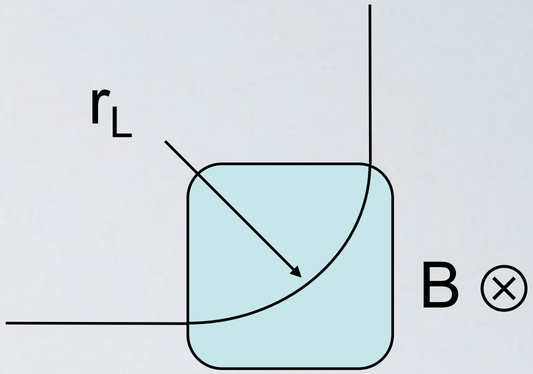

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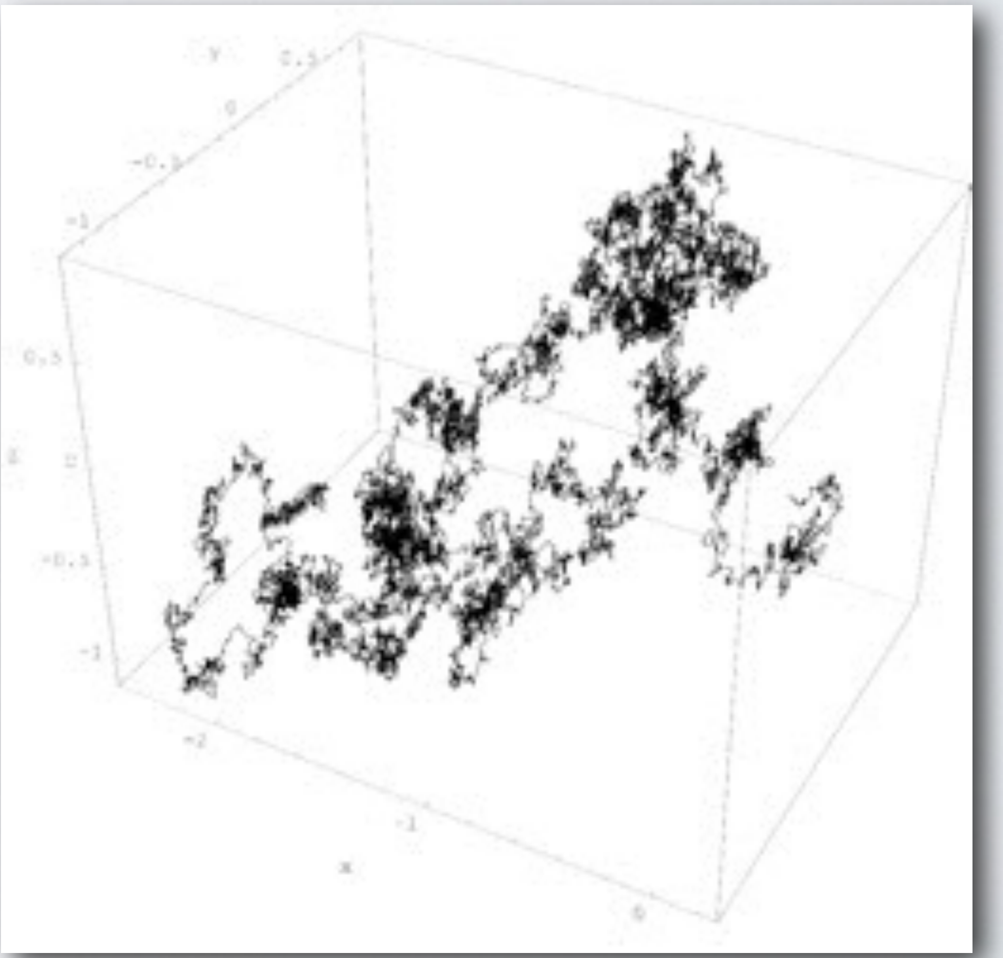

Macroscopically, described as ***diffusion (+ possibly a drift)***

$$\frac{\partial \Phi}{\partial t} + \nabla \cdot \mathbf{J}_\Phi = Q$$

Continuity Equation

$$\mathbf{J}_\Phi = -D(\mathbf{x}, \Phi, E \ldots)\nabla \Phi$$

Fick's law

Let's get a closer look to some properties of this diffusion

ON CR DIFFUSION

If one treats the B-field as regular component B_0 + magnetostatic wave perturbations with an energy power spectrum $\mathcal{E}(k)$, one can prove that the angular diffusion (pitch angle scattering) has a diffusion coefficient depending (~resonantly) on the power stored in perturbation at the wavenumber corresponding to the CR Larmor radius

$$\nu = \left\langle \frac{\Delta\theta^2}{\Delta t} \right\rangle = \frac{\pi}{4} \left(\frac{k_{\rm res}\mathcal{E}(k_{\rm res})}{B_0^2/8\pi} \right) \Omega \qquad \Omega = \frac{q\,B_0}{\gamma\,m\,c} \quad \text{(Larmor Frequency)}$$

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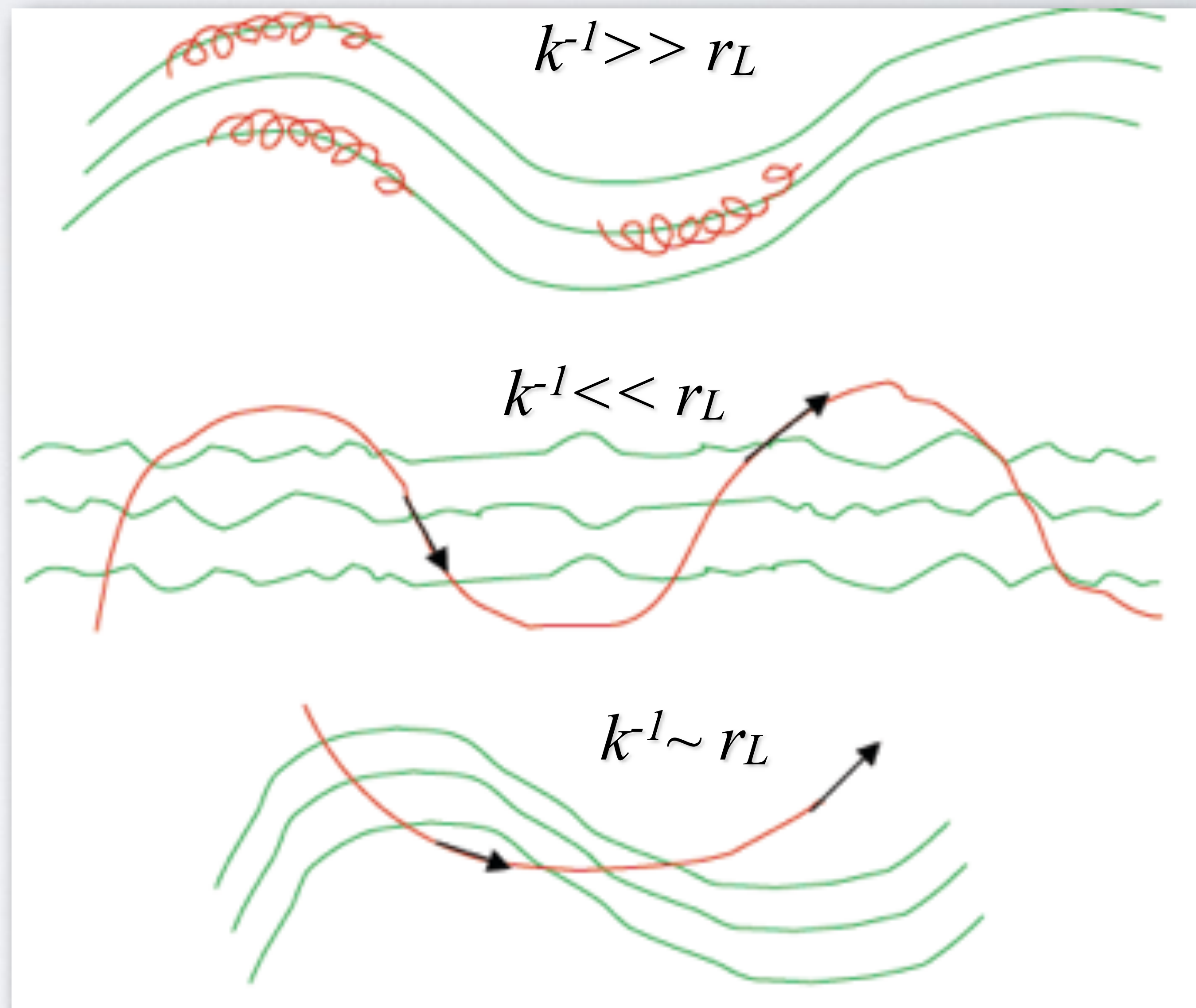
The resonance condition tells us that:

if $k^{-1} >> r_L$ the CRs surf adiabatically the waves,

if $k^{-1} << r_L$ the CRs hardly feel their presence

Each time a resonance occurs, the CR changes pitch angle by $\delta B/B$ with random sign. The spatial diffusion is inversely proportional to ν



STANDARD DESCRIPTION: DIFFUSION-LOSS EQ.

Source term (t, **x**, **p** -dep.)
Includes dec./frag. for heavier nuclei

Spatial 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

momentum diffusion
(not magnetostatic in Lab!)

Fragmentation and decay terms, of "collisional" nature

Could either use Flux Φ or the CR density in phase space *f*

$$\Phi(\mathbf{x}, p, t) \equiv p^2 \int d\Omega_{\mathbf{p}} f(\mathbf{p}) \sim 4\pi\, p^2\, f(p)$$

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For experts: "hybrid frame", momentum in scattering centers frame, position in the lab

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HOW TO DEAL WITH IT? NUMERICAL CODES…

http://galprop.stanford.edu/

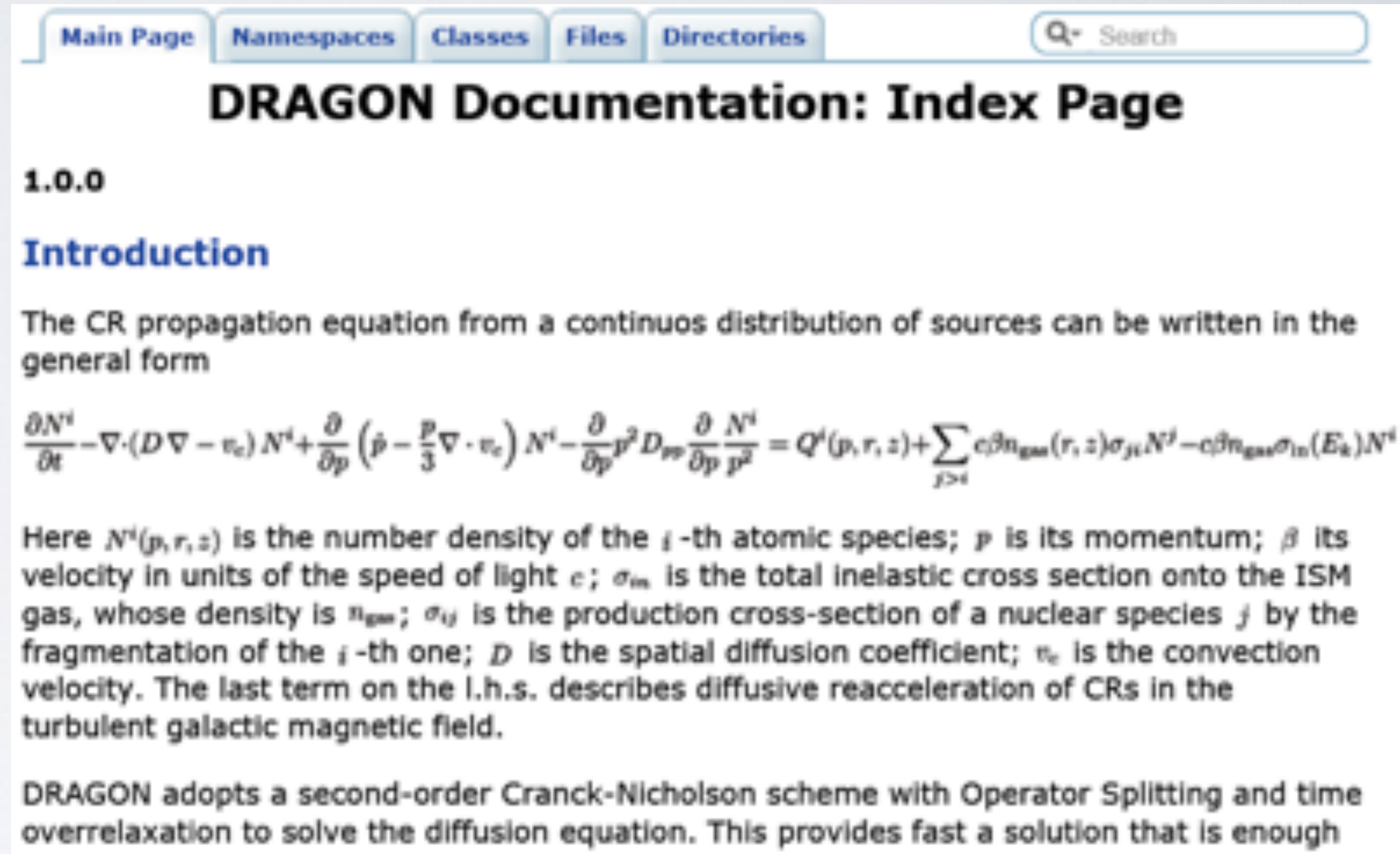
http://www.dragonproject.org/Home.html

http://lpsc.in2p3.fr/usine/

… **but one can grasp main physics with some simplification!**

Most effects relevant only at low energies. <u>**Diffusion & source effects**</u> probably the dominant ones at high-energies

For most observables, "geometry" can be recast in an effective description (after all, we observe ~ isotropic flux!)



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DRAGON Documentation: Index Page

1.0.0

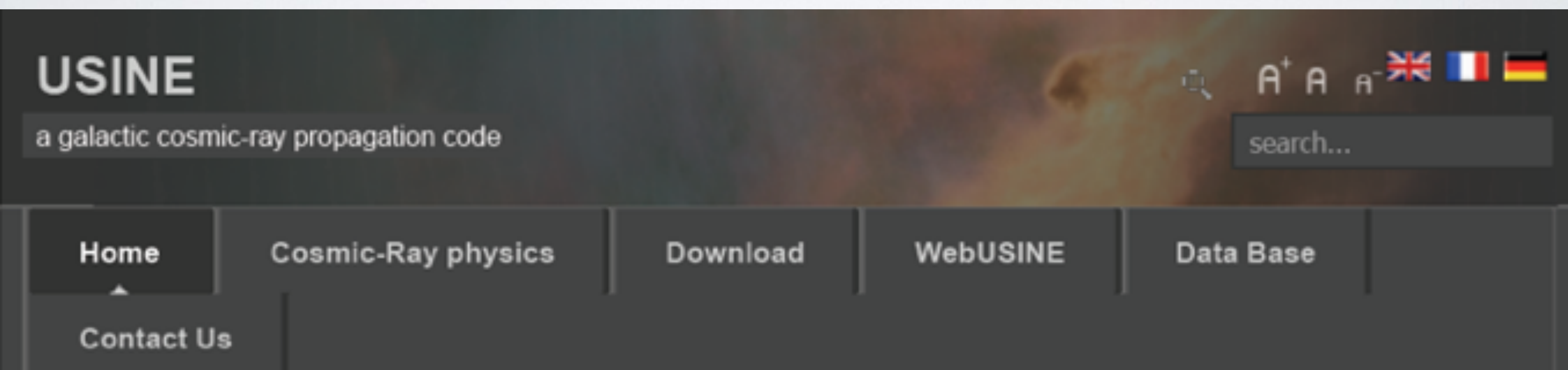
Introduction

The CR propagation equation from a continuos distribution of sources can be written in the general form

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} = Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ji}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

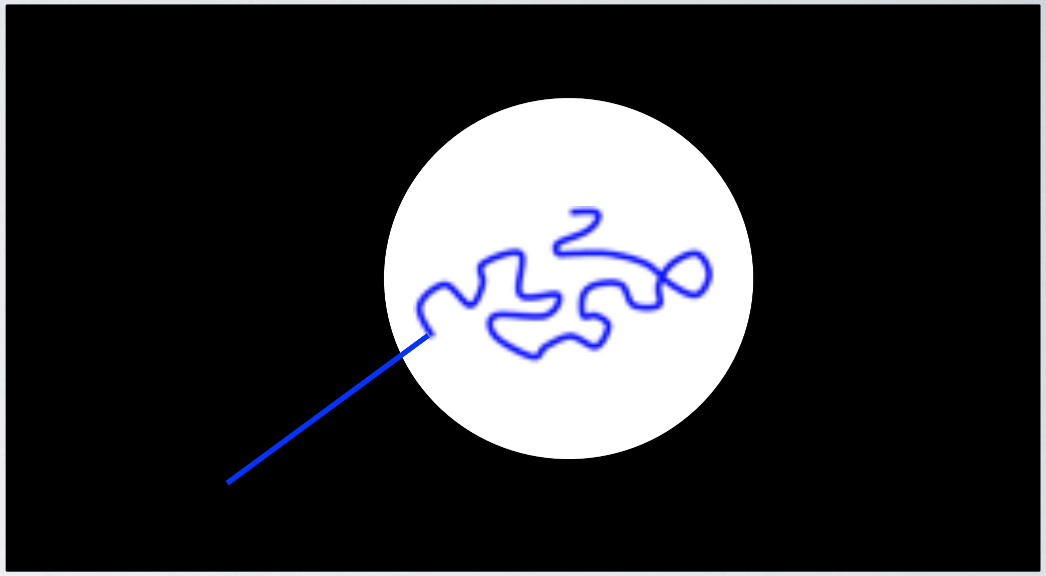
Here $N^i(p,r,z)$ is the number density of the i-th atomic species; p is its momentum; β its velocity in units of the speed of light c; σ_{in} is the total inelastic cross section onto the ISM gas, whose density is n_{gas}; σ_{ij} is the production cross-section of a nuclear species j by the fragmentation of the i-th one; D is the spatial diffusion coefficient; v_c is the convection velocity. The last term on the l.h.s. describes diffusive reacceleration of CRs in the turbulent galactic magnetic field.

DRAGON adopts a second-order Cranck-Nicholson scheme with Operator Splitting and time overrelaxation to solve the diffusion equation. This provides fast a solution that is enough



LEAKY BOX APPROXIMATION

For stationary, homogeneous & isotropic problems & observations at a single location, the diffusion operator can be effectively replaced by an effective "diffusive confinement" time τ_{diff}



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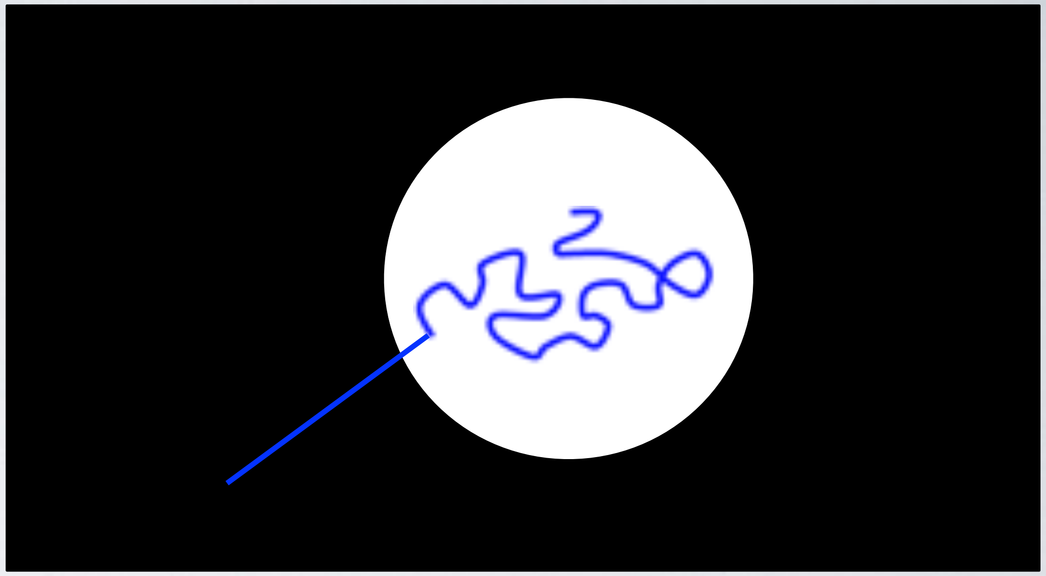


$$\frac{\partial \Phi}{\partial t} - D\nabla^2\Phi = Q \Rightarrow \frac{\partial \Phi}{\partial t} - \frac{\Phi}{\tau_{\mathrm{diff}}(E)} = Q$$

At steady state

$$\Phi = Q(E)\tau_{\mathrm{diff}}(E)$$

If diffusion dominates, we can infer that:

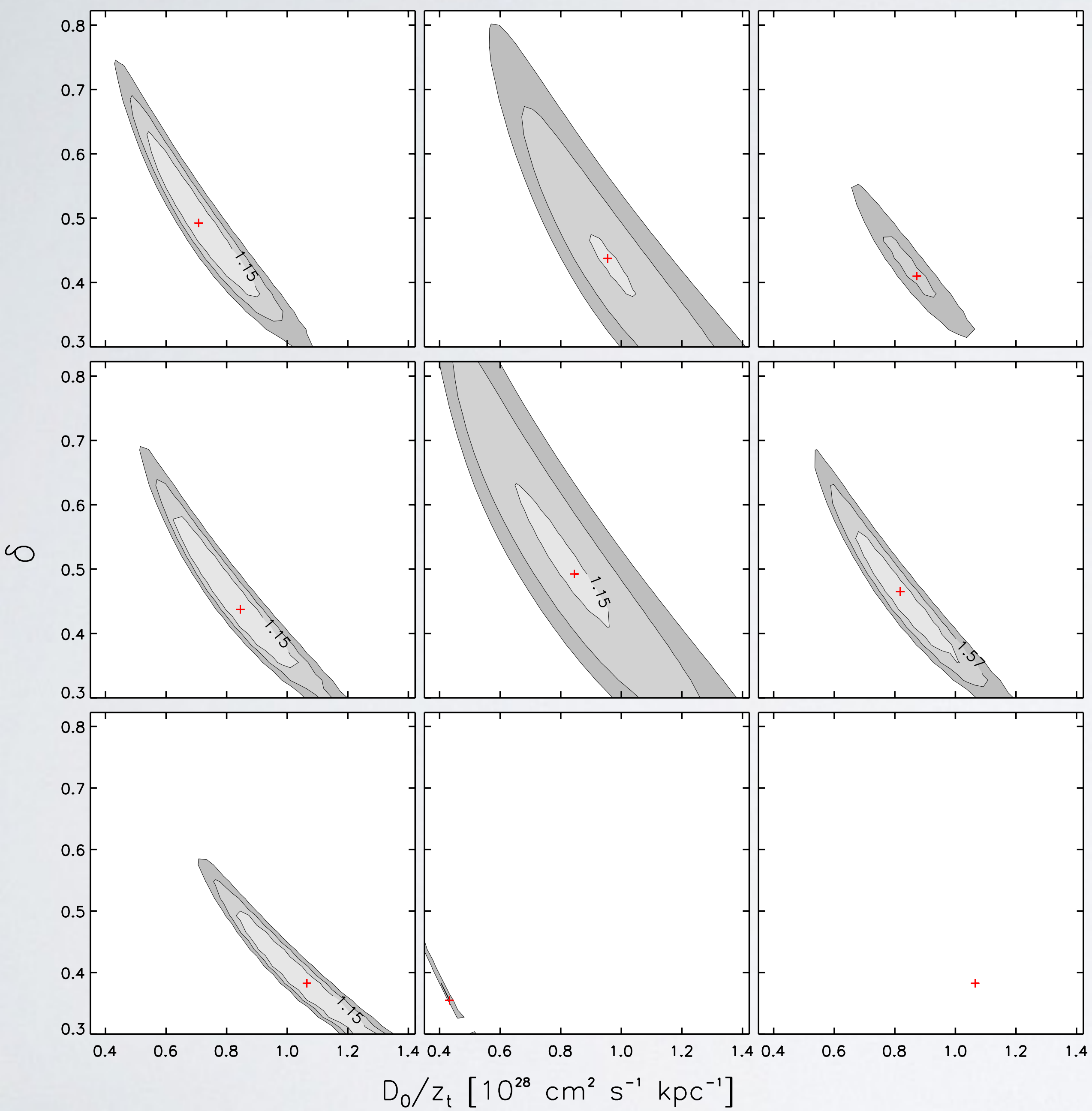
- source spectra are in general different than those CR observed at the Earth
- the (multiplicative) difference should be universal

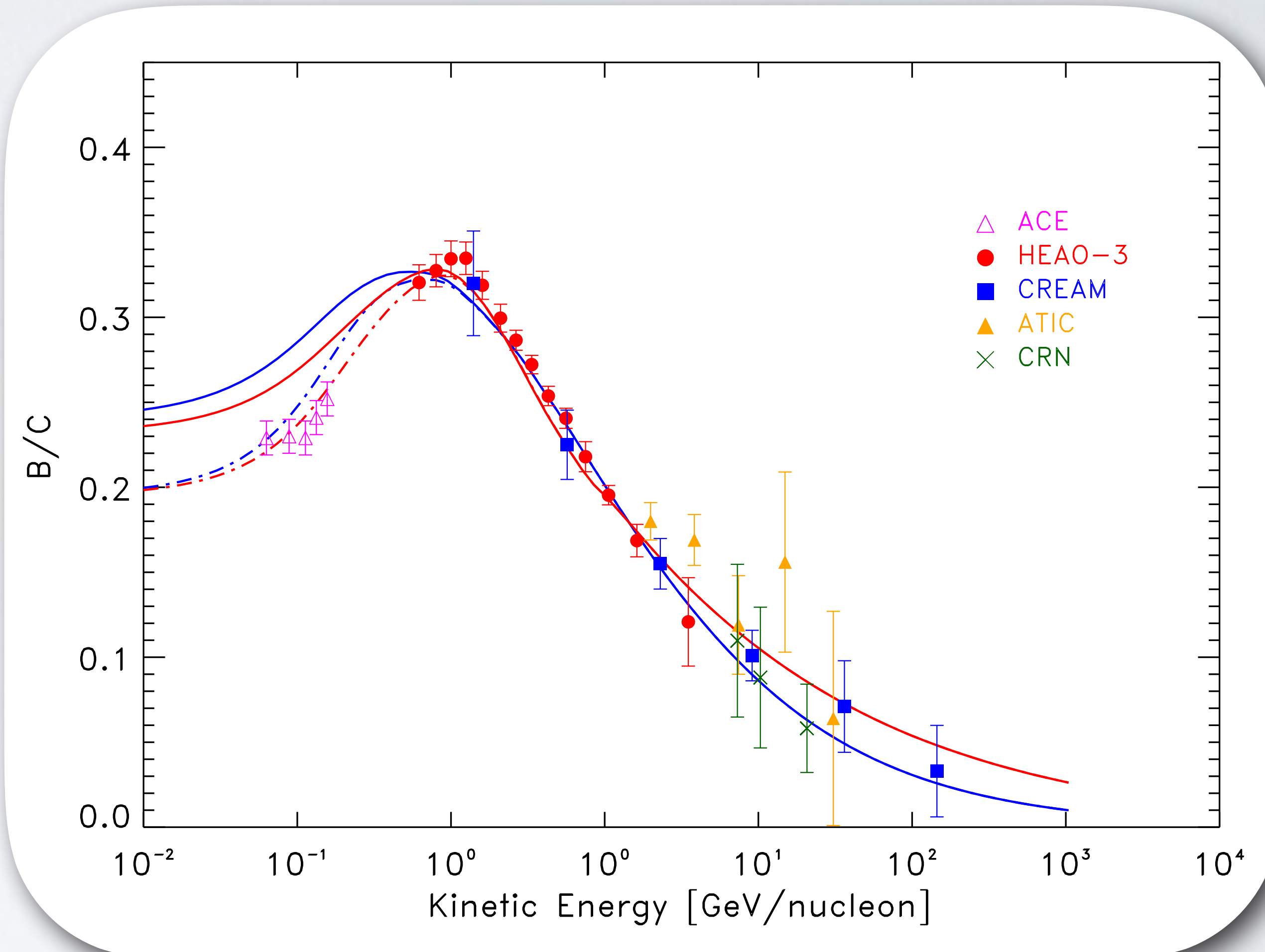
SEC/PRIMARY AS DIAGNOSTICS

If a type of nucleus is not present as primary, but only produced as secondary via collisions (this includes e.g. antiprotons), then

$$\Phi_s = Q_s\,\tau_{\rm diff} \propto \sigma_{p\to s}\Phi_p\tau_{\rm diff}$$

$$\frac{\Phi_s}{\Phi_p} \propto \tau_{\rm diff}(E) \propto D(E)^{-1} \propto E^{\delta}$$





typical empirical fitting form

$$D(R) \simeq 10^{28} \div 10^{29} \left(\frac{R}{3\,\mathrm{GV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

G. Di Bernardo, C. Evoli, D. Gaggero, D. Grasso and L. Maccione, Astropart. Phys. 34, 274 (2010)

COMING BACK TO POSSIBLE SOLUTIONS

I. PROPAGATION

Power-law injection, feature reflects corresponding one in the diffusion coefficient, ***K*** **(naturally account for universality in rigidity)**. Different models differ in what causes the feature in ***K***, **e.g.**

***K* not separable into energy and space variables:**

N.Tomassetti, Astrophys. J. 752, L13 (2012) [arXiv:1204.4492].

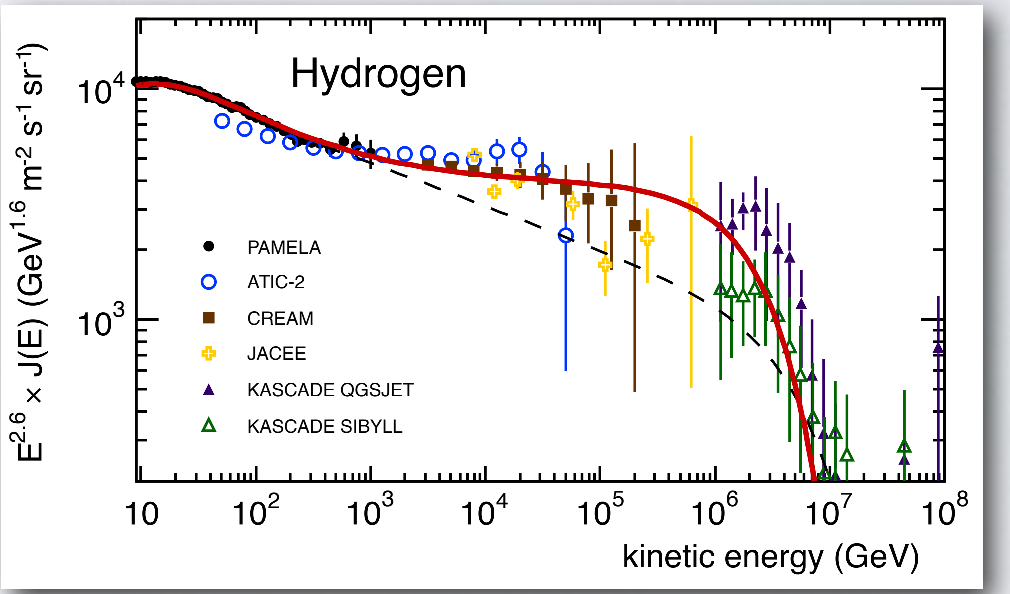
Qualitatively reflecting the fact that that turbulence in the halo (mostly CR-driven) should be different than close to the disk (mostly SNR driven)

$$K(z,\rho) = \begin{cases} k_0 \beta \rho^{\delta} & for\ |z| < \xi L\ (inner\ halo) \\ k_0 \beta \rho^{\delta+\Delta} & for\ |z| > \xi L\ (outer\ halo) \end{cases}$$

Δ ~.55

ξ~0.1

L~5 kpc



Pheno model loosely inspired to arguments raised e.g. in *Erlykin & Wolfendale J.Phys. G28 (2002) 2329-2348*

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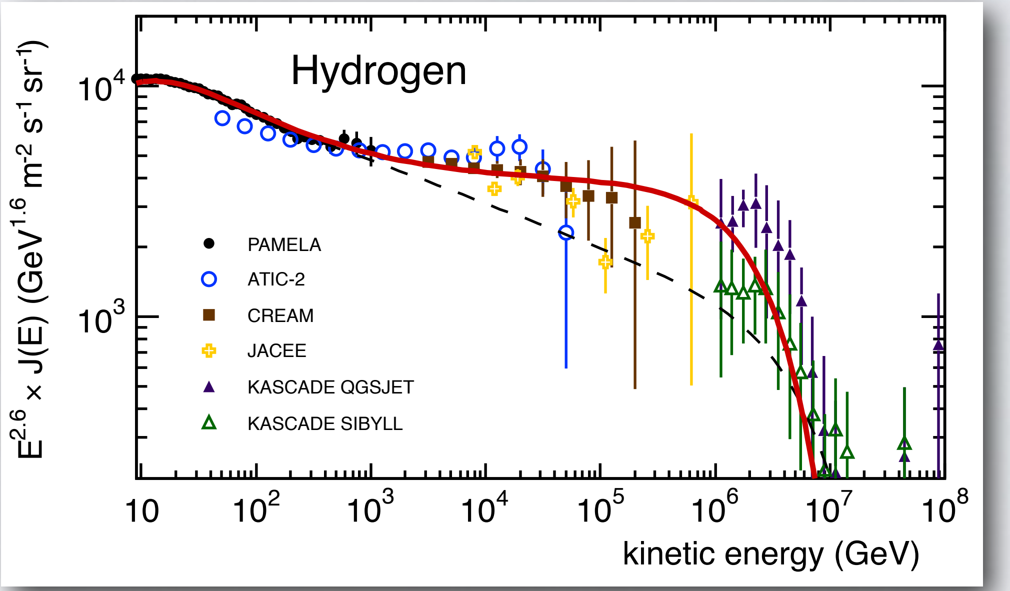


Pheno model loosely inspired to arguments raised e.g. in
Erlykin & Wolfendale J.Phys. G28 (2002) 2329-2348

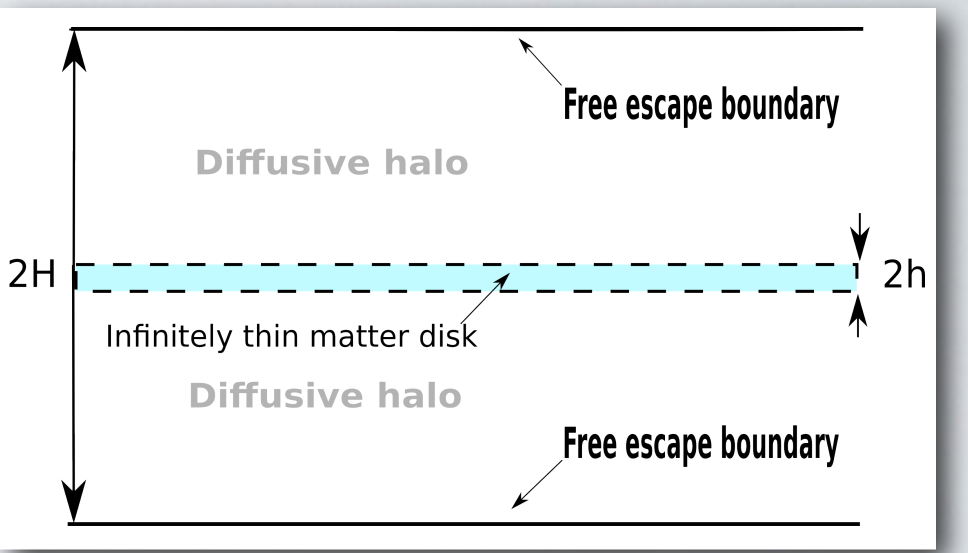
Non-linear coupling of CRs with K:

CR below the break diffuse on waves generated by CRs themselves, above the break onto external turbulence.

P. Blasi, E. Amato, PDS, Phys. Rev. Lett. 109, 061101 (2012) [arXiv:1207.3706].

NON-LINEAR COUPLING: TOY MODEL

"Infinite layer", diffusive halo height H, Galactic-matter disk of infinitesimal thickness, advective wind velocity $v_c \sim v_A$ outgoing.



$$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + v_{\rm A}\frac{\partial f}{\partial z} - \frac{dv_{\rm A}}{dz}\frac{p}{3}\frac{\partial f}{\partial p} = q_{\rm CR}(z,p)$$

Remembering that

$$D(p) = \frac{1}{3}r_L(p)v(p)\left.\frac{1}{k\,W(k)}\right|_{k=qB_0/pc} \qquad \int_{k_0}^{\infty} dk\; W(k) = \eta_B = \frac{\delta B^2}{B_0^2},$$

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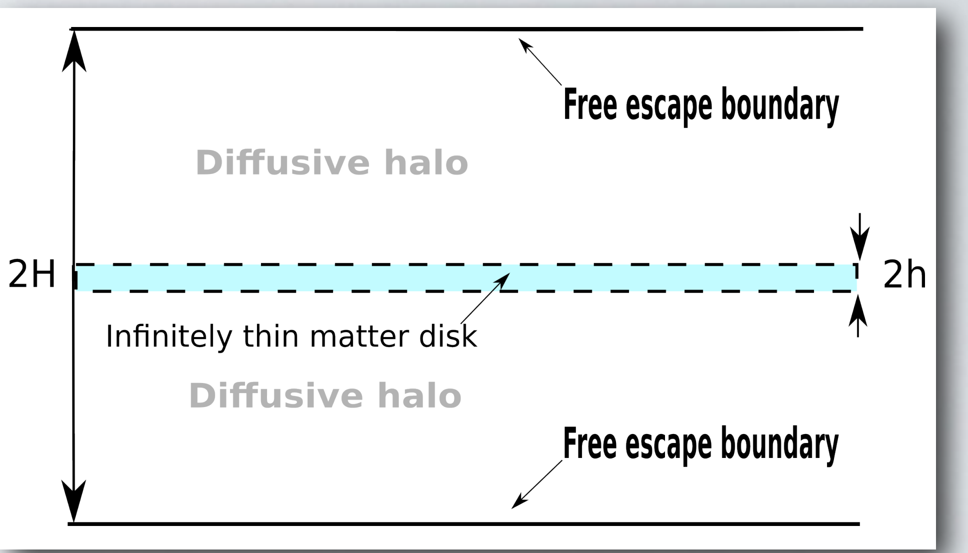

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CR transport eq. solved iteratively with the following one for the waves to which it is coupled

$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \Gamma_{\rm CR}W = q_W(k).$$

External power injected at large scale, e.g. SNRs at ~1/50 pc

$$q_W \propto \delta(k-k_0)$$

Non-linear "wave-wave" coupling → cascade

$$D_{kk} = C_{\rm K} v_{\rm A} k^{7/2} W(k)^{1/2}$$

Streaming instability rate (coupling with CR)

$$\Gamma_{\rm CR}(k) = \frac{16\pi^2}{3}\frac{v_{\rm A}}{k\,W(k)B_0^2}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{p=qB_0/kc}$$

SANITY CHECK

In absence of CR coupling, one finds the well-known Kolmogorov spectrum

$$W_{\rm ext}(k) = (2\eta_B/3k_0)\ (k/k_0)^{-5/3}\ \Theta(k-k_0)$$

the input spectrum of CRs $f_0(p) = A_p(p/m\,c)^{-\gamma_p}$ implies that the NLLD diffusion rate (Γ_{NL}~D_{kk}/k^2) equals the CR instability growth rate (i.e. CR driven waves saturation condition) at

The right transition energy scale

$$E_{\rm tr} = 228\ {\rm GeV}\left(\frac{R_{d,10}^2 H_3^{-1/3}}{\xi_{0.1}E_{51}\mathcal{R}_{30}}\right)^{\frac{3}{2(\gamma_p-4)}} B_{0,\mu}^{\frac{2\gamma_p-5}{2(\gamma_p-4)}}$$

indep. of inj. scale k_0 (depends on level of MDH turbulence, but reasonable η_B~0.08 for k_0~1/50 pc)

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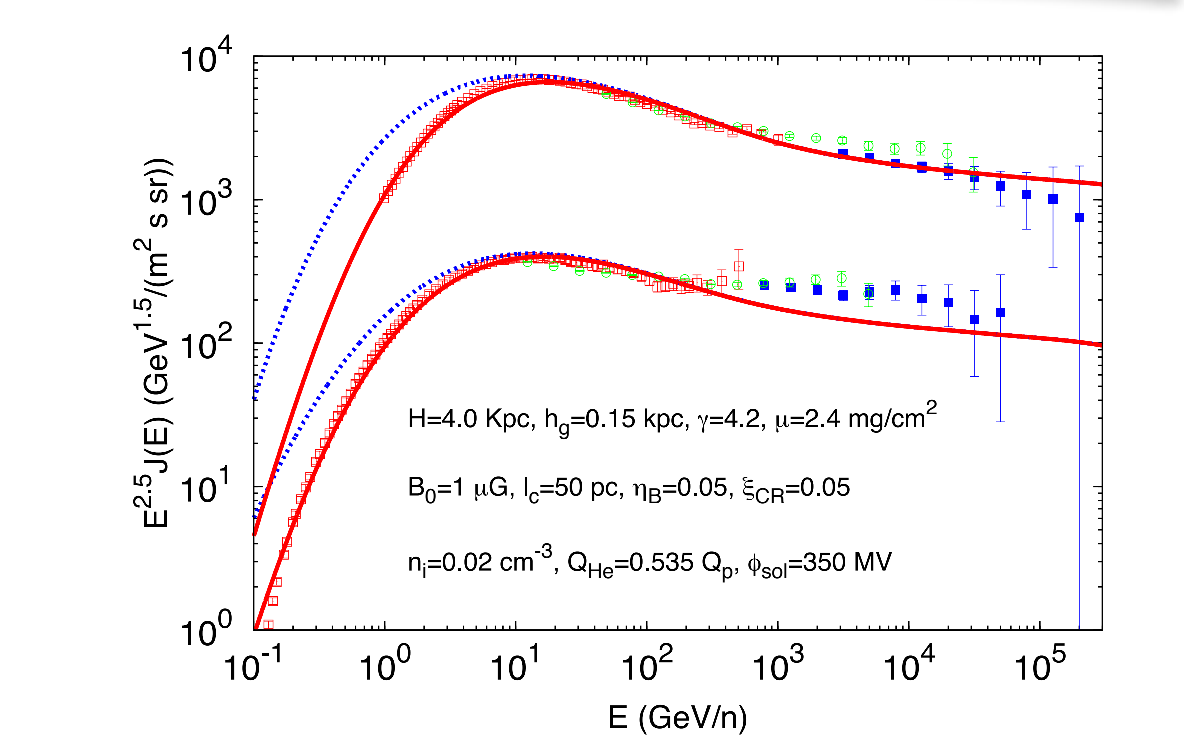
indep. of inj. scale k_0 (depends on level of MDH turbulence, but reasonable η_B~0.08 for k_0~1/50 pc)

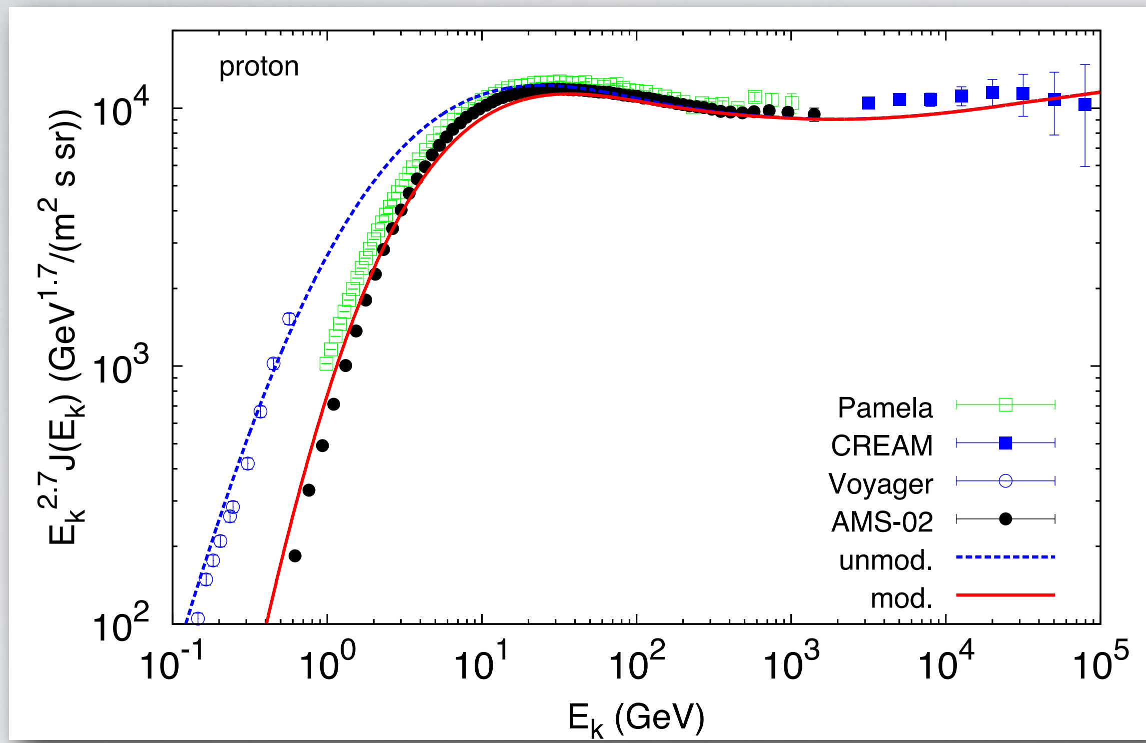
Pheno consequences already worked out a couple of years ago and overall a remarkable agreement with data

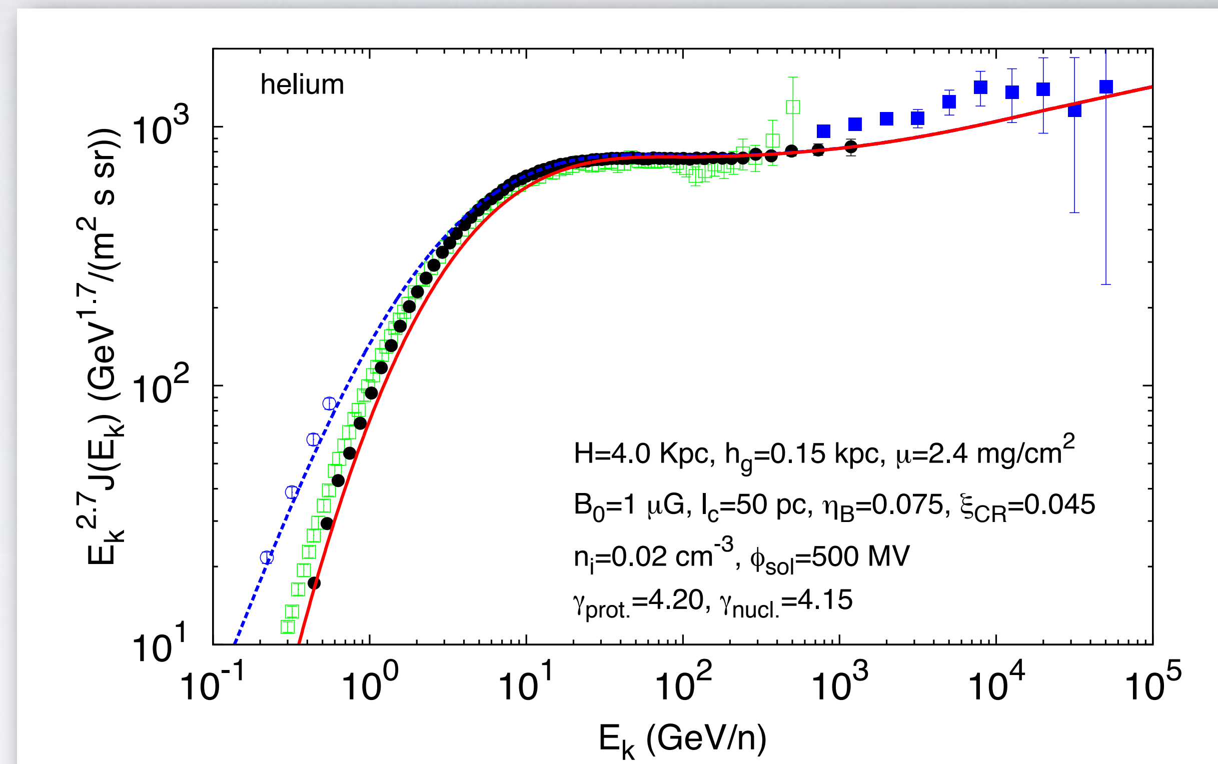
R. Aloisio and P. Blasi, JCAP 1307, 001 (2013) [arXiv:1306.2018]

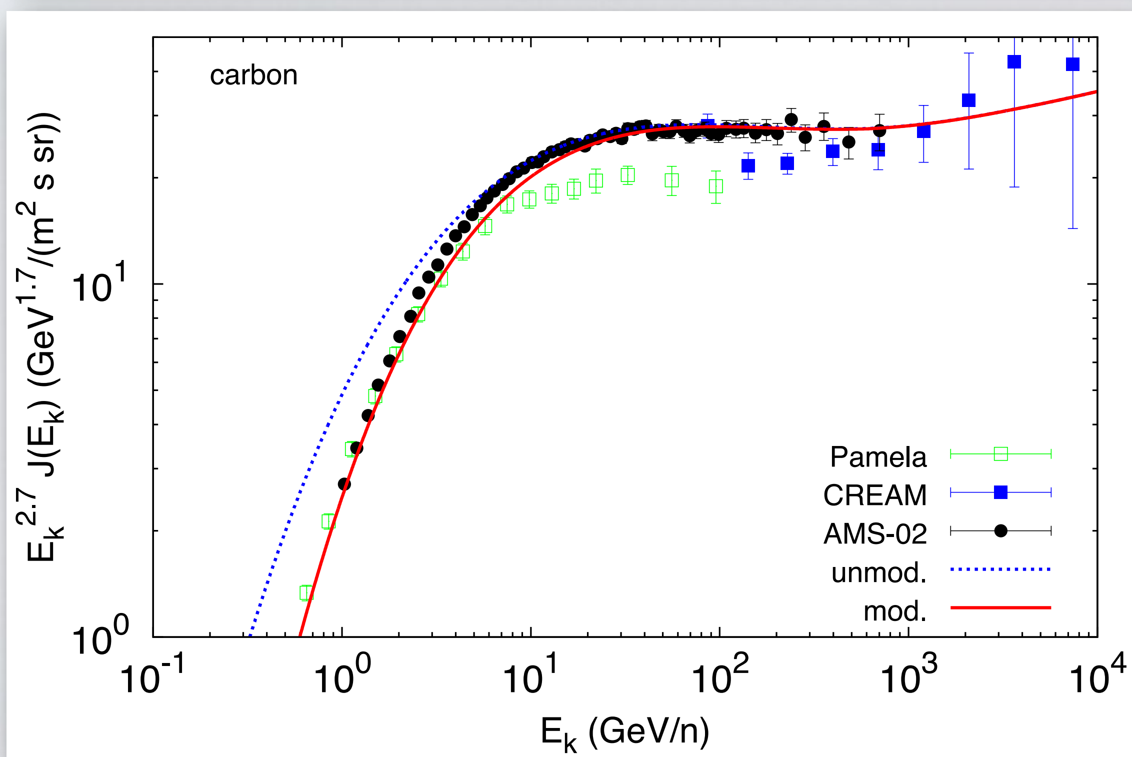


REVISITING THE MODEL

in the light of AMS-02 and Voyager (*E. C. Stone et al.. Science, 341 (2013) 150*) data







despite its simplicity & the low number of free parameters, remarkable level of agreement over 6 decades of energy!

(notably even with the "unmodulated" data at low-E, where transport is essentially advective)

R. Aloisio, P. Blasi and PS,
"Non-linear cosmic ray Galactic transport in the light of AMS-02 and Voyager data,"
A&A 583(2015) A95 [arXiv:1507.00594]

II. AT ACCELERATION SITE

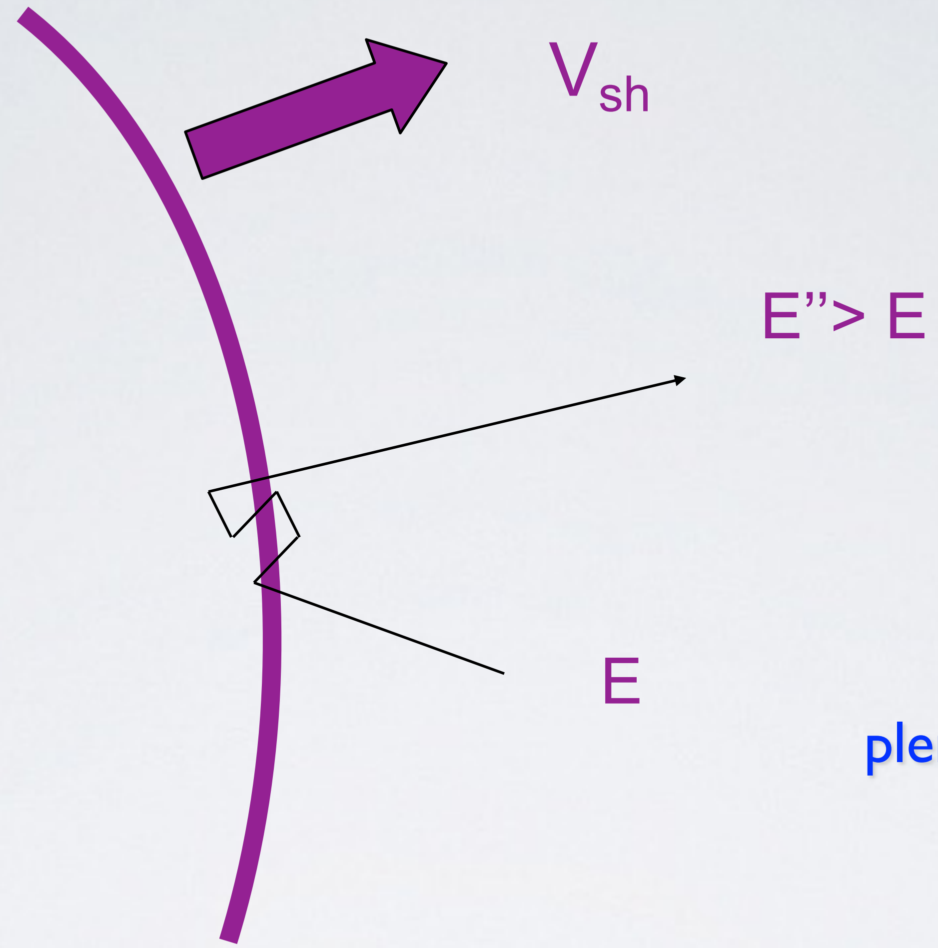
One can play with acceleration population(s), acceleration mechanisms, or escape.

DETOUR ON THE STANDARD THEORY: 1ST ORDER FERMI THEORY OR DIFFUSIVE SHOCK ACCELERATION

A SKETCH

A shock (e.g. from a supernova remnant) can sweep the interstellar medium.

The shock front brings with it magnetic turbulence, causing change of particle momenta



plenty of shocks available in the Galaxy…
(beautiful and numerous enough to regularly sell magazines)

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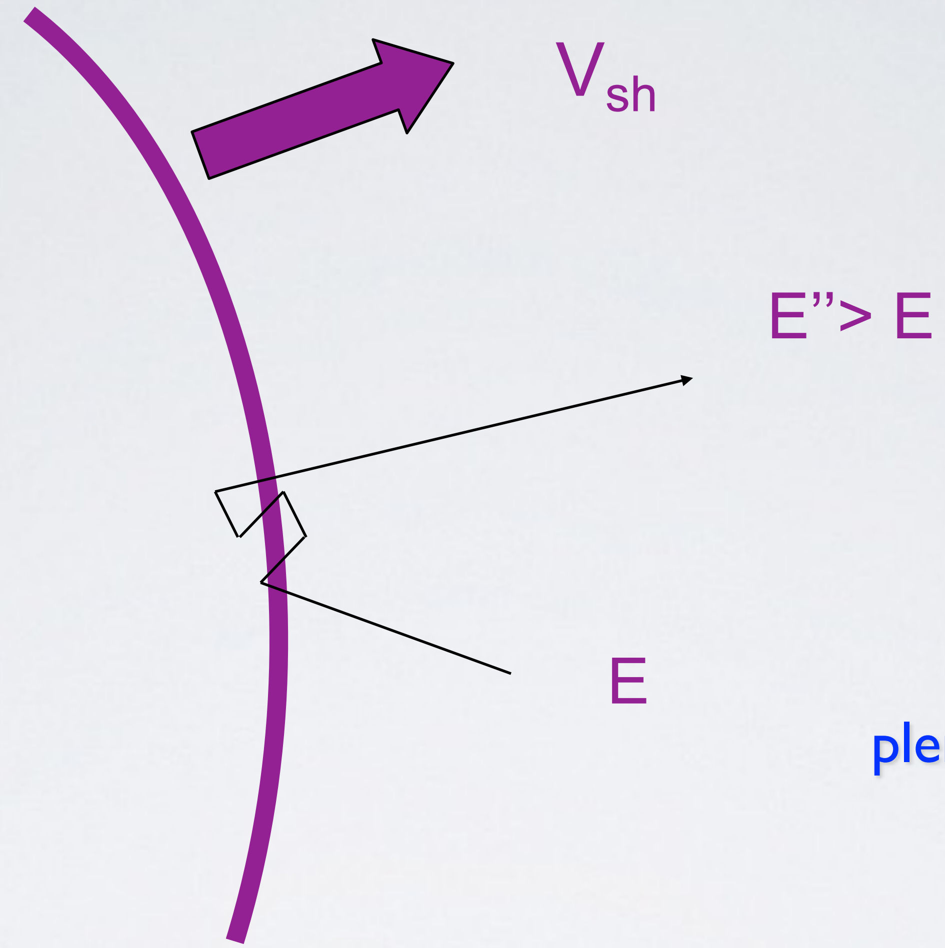

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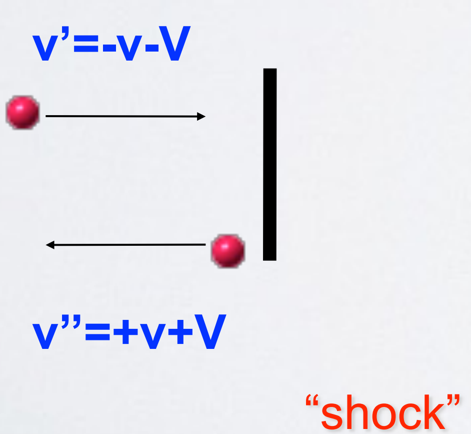
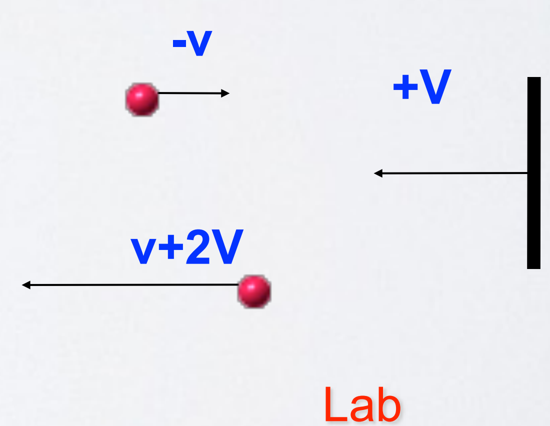
Please note

No gain of energy in the shock frame



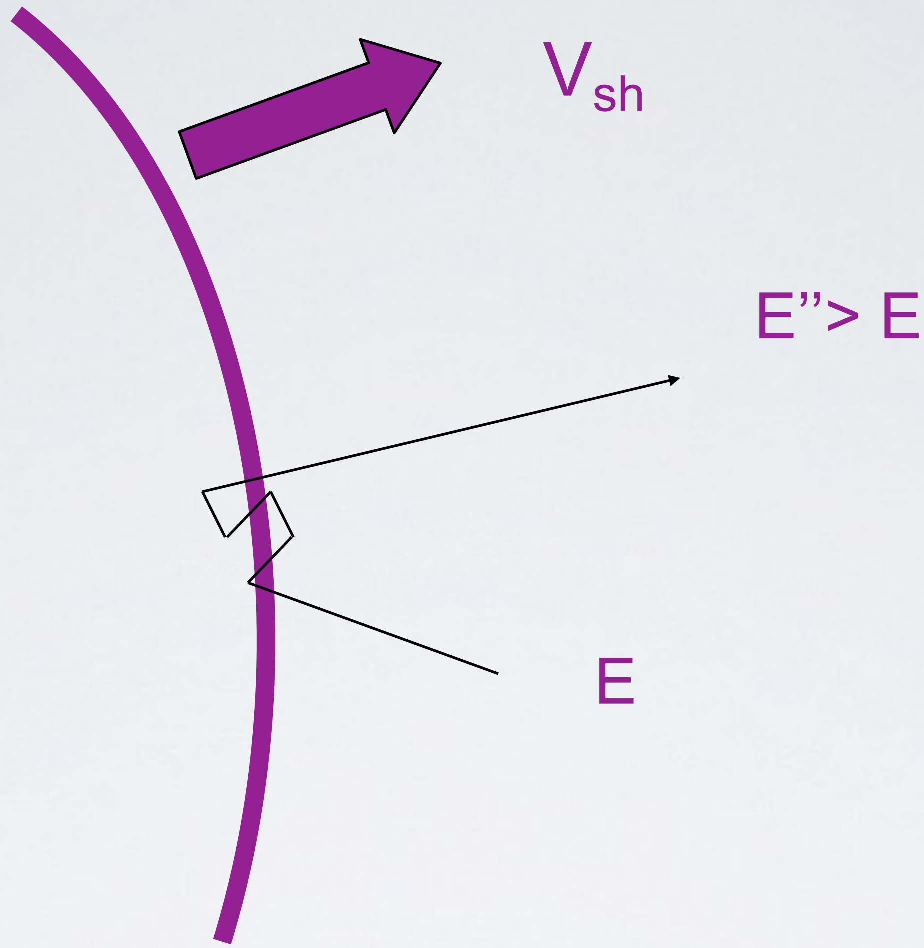
Gain of energy in the Lab frame



When the "mirror" is magnetic, in the Lab there is a moving B-field, i.e. an electric field is available to accelerate the particles wrt the Lab frame

A SKETCH, CONTINUED

Some fraction of particle can enter the shock again… a smaller and smaller fraction of them enters the shock more and more often…



together with the E-independence of the fractional E gain, explains the power-law shape of the spectrum

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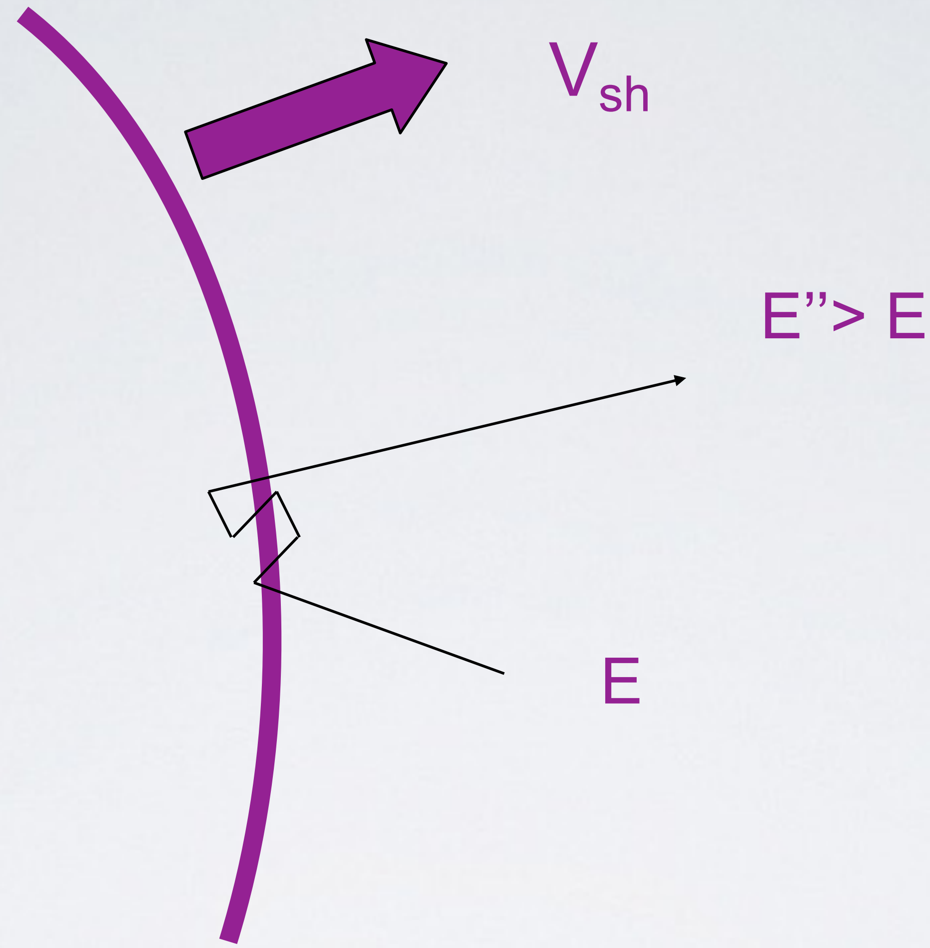


together with the E-independence of the fractional E gain, explains the power-law shape of the spectrum

Good features of the model

I. Acceleration 1st order in the large shock velocity: efficient!

$$\frac{\Delta E}{E} \simeq \frac{V_{\rm sh}}{c} \simeq 10^{-3} - 10^{-2}$$

II. spectral index is universal for strong (M>>1) shocks in ordinary matter (does not depend on chemical composition, for instance)

III. Spectral index value for cumulative E spectra Ok with inferred~1

$$\gamma_I \simeq 1 + \frac{4}{\mathcal{M}^2}$$

IV. estimated E-budget stored in kinetic energy of SNRs ~1 o.o.m. larger than what stored in CRs (efficiency of O(10%) ok)

II. AT ACCELERATION SITE

One can play with acceleration population(s), acceleration mechanisms, or escape. For instance:

- ***"Natural" evolution of Mach number, $\mathscr{M}$,*** within DSA

High-E CR accelerated/escape early on when $\mathscr{M}>>1$, spectral index $\alpha\sim2$, while low-E later when $\mathscr{M}$ is relatively low, α steeper, remembering

$$\alpha = 2\frac{\mathcal{M}^2+1}{\mathcal{M}^2-1}$$

- ***Multiple sources/sites***

E.g. harder high-E component involving OB associations - Superbubbles, explosion of stars into magnetized winds (like Wolf-Rayet), as proposed in the past, e.g.

T. Stanev, P. L. Biermann & T. K. Gaisser, A&A 274, 902 (1993)

E. Parizot et al. A&A 424, 747 (2004)

- ***"Natural" consequence of non-linear DSA***

concavity of spectrum resulting from the nonlinear nature of DSA (but why reflected in escaping particles? Why universality?)

V. Ptuskin, V. Zirakashvili, E. S. Seo, ApJ 763, 47 (2013)

- ***(Weak) reacceleration***

In the sense of *E. Seo & V. Ptuskin, ApJ 431, 705 (1994)*

Associated to the volume of ISM occupied by SNR shocks (mostly old, low $\mathscr{M}$), parameters too extreme? (e.g. p & He spectrum too steep)

S. Thoudam and J. R. Hörandel, A&A. 567, A33 (2014)

Key (common) questions:

how easily reproduce the observed spectral shapes? How universal is the mechanism?

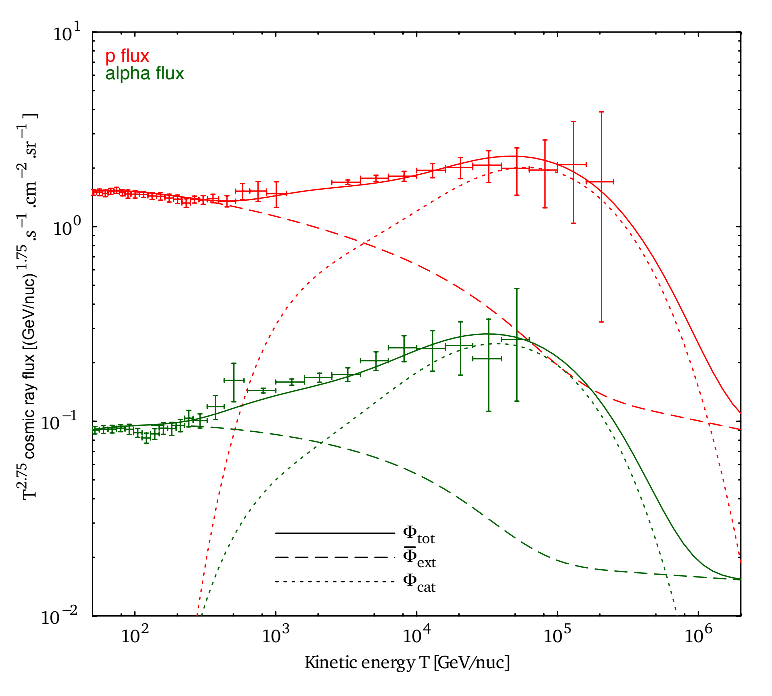
III. DUE TO EFFECT OF LOCAL SOURCES

I.e. hardening due to CR released from local young CR sources, but typically needs fast diffusion and low SN rate, in tension with other observations

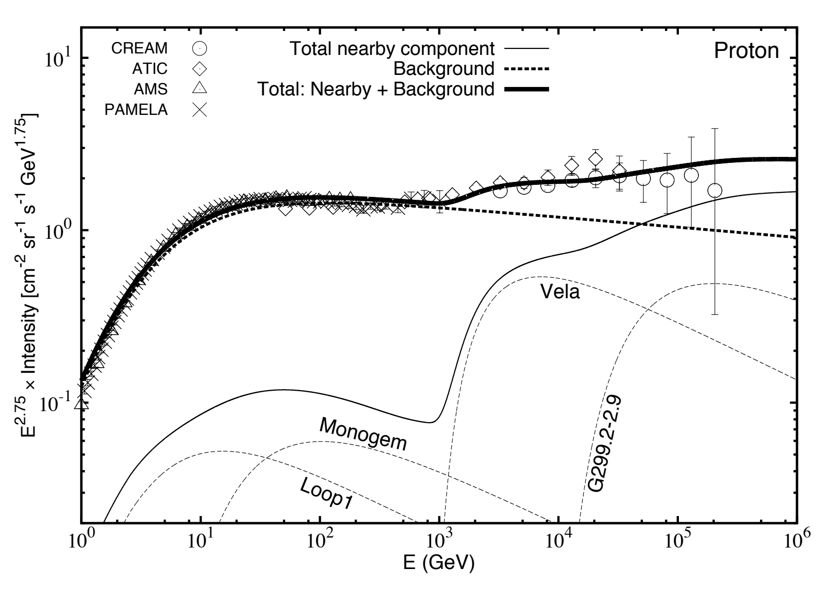
G. Bernard, T. Delahaye, P. Salati & R. Taillet, A&A 544, A92 (2012) [arXiv:1204.6289]

G. Bernard et al. A&A 555, A48 (2013) [arXiv:1207.4670]

W. Liu, P. Salati and X. Chen, Res. Astron. Astrophys. 15, 1 (2015) [arXiv:1405.2835].



S. Thoudam and J. R. Horandel, MNRAS 421, 1209 (2012) [1112.3020] MNRAS 435, 2532 (2013) [1304.1400]



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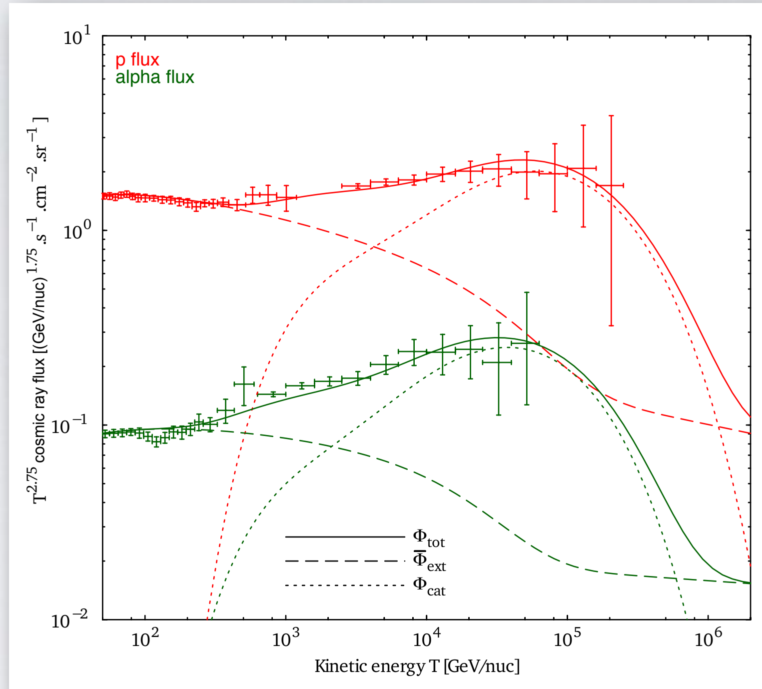
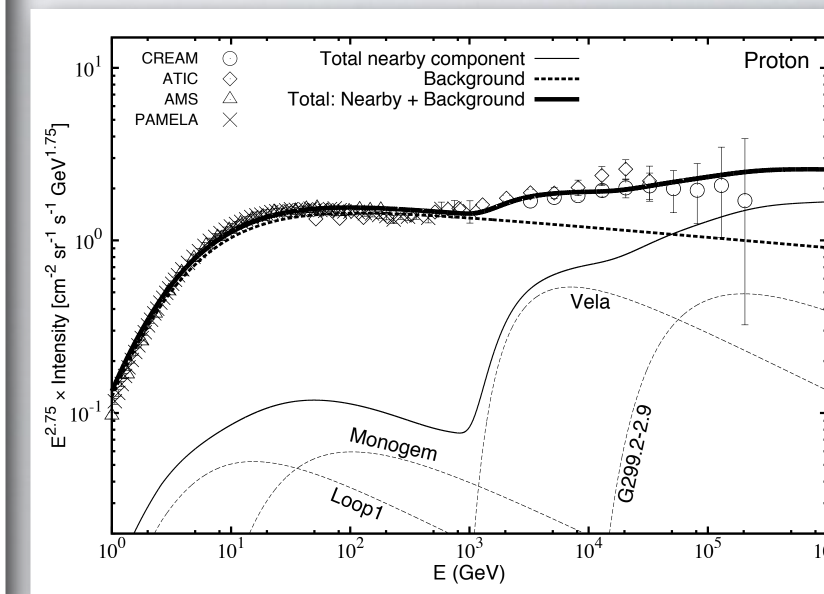
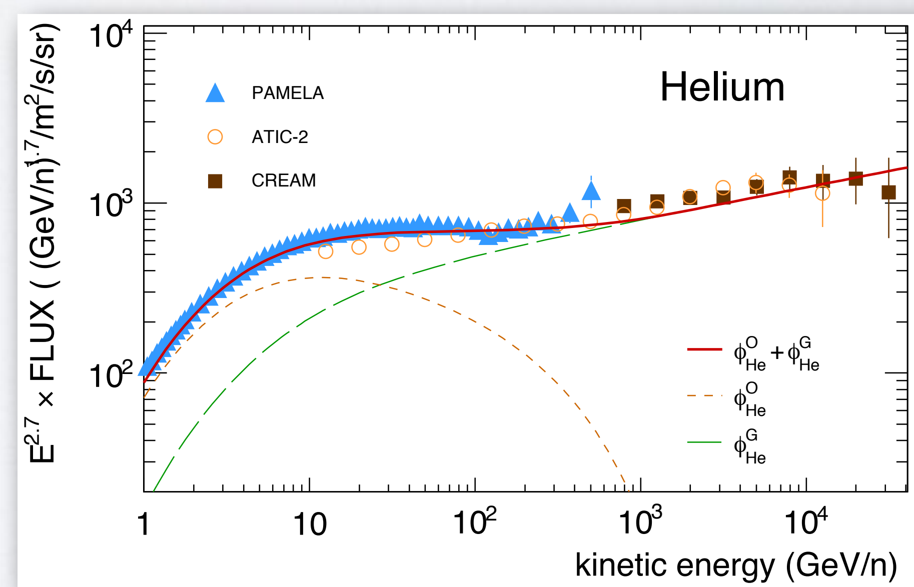


S. Thoudam and J. R. Horandel, MNRAS 421, 1209 (2012) [1112.3020] MNRAS 435, 2532 (2013) [1304.1400]



As another example, it has also been proposed that some "local/old" source contributes at low-E, & overall contribution of young and further away ones dominates at high-E

- **+** Easily allows for a hadronic origin of the e^+ excess
- **-** "breaking" a link, loses predictivity
- **-** how likely is such a configuration? (Not estimated)



N. Tomassetti and F. Donato, ApJ 803, 2, L15 (2015) [arXiv:1502.06150]

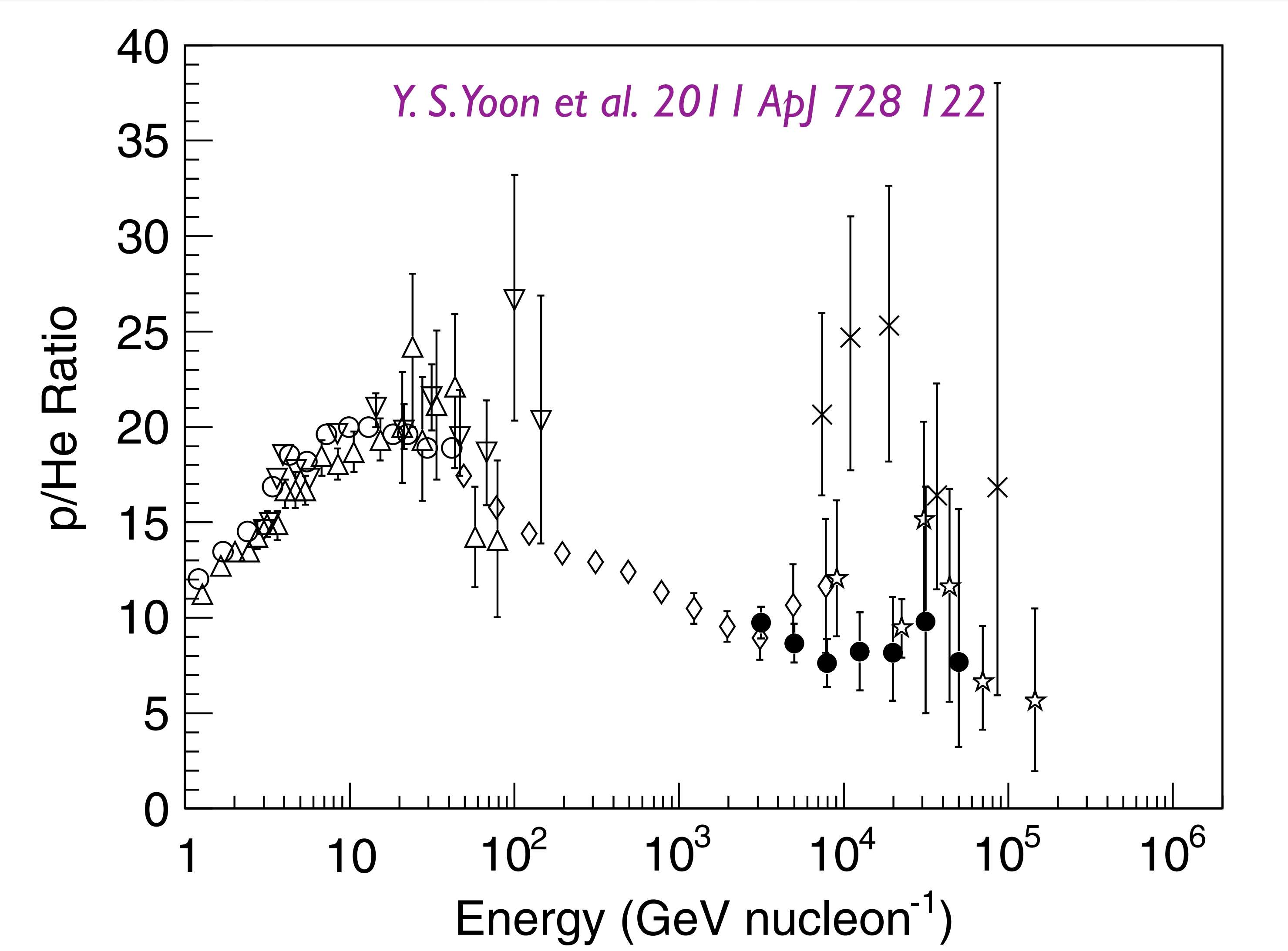
LET ME PAUSE A BIT, IT'S TIME TO INTRODUCE ANOTHER "ANOMALY"...

2^{ND} ANOMALY: NON-UNIVERSALITY

Above O(10) GeV/n, He spectrum ~0.1 harder than the *p* one

ATIC-2 (*Panov, A. D., et al. 2009, Bull. Russ. Acad. Sci. Phys, 73, 564*) and CREAM (*Y. S. Yoon et al. 2011 ApJ 728 122*)

as well older experiments already offering strong indications in that sense...

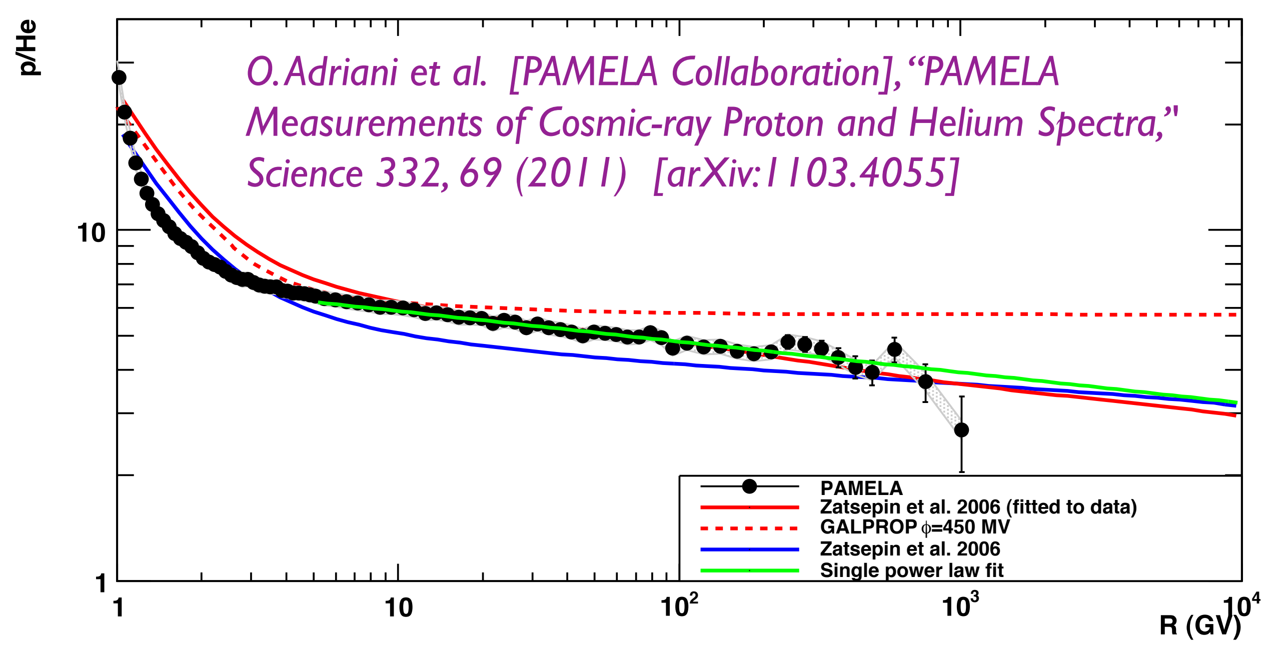


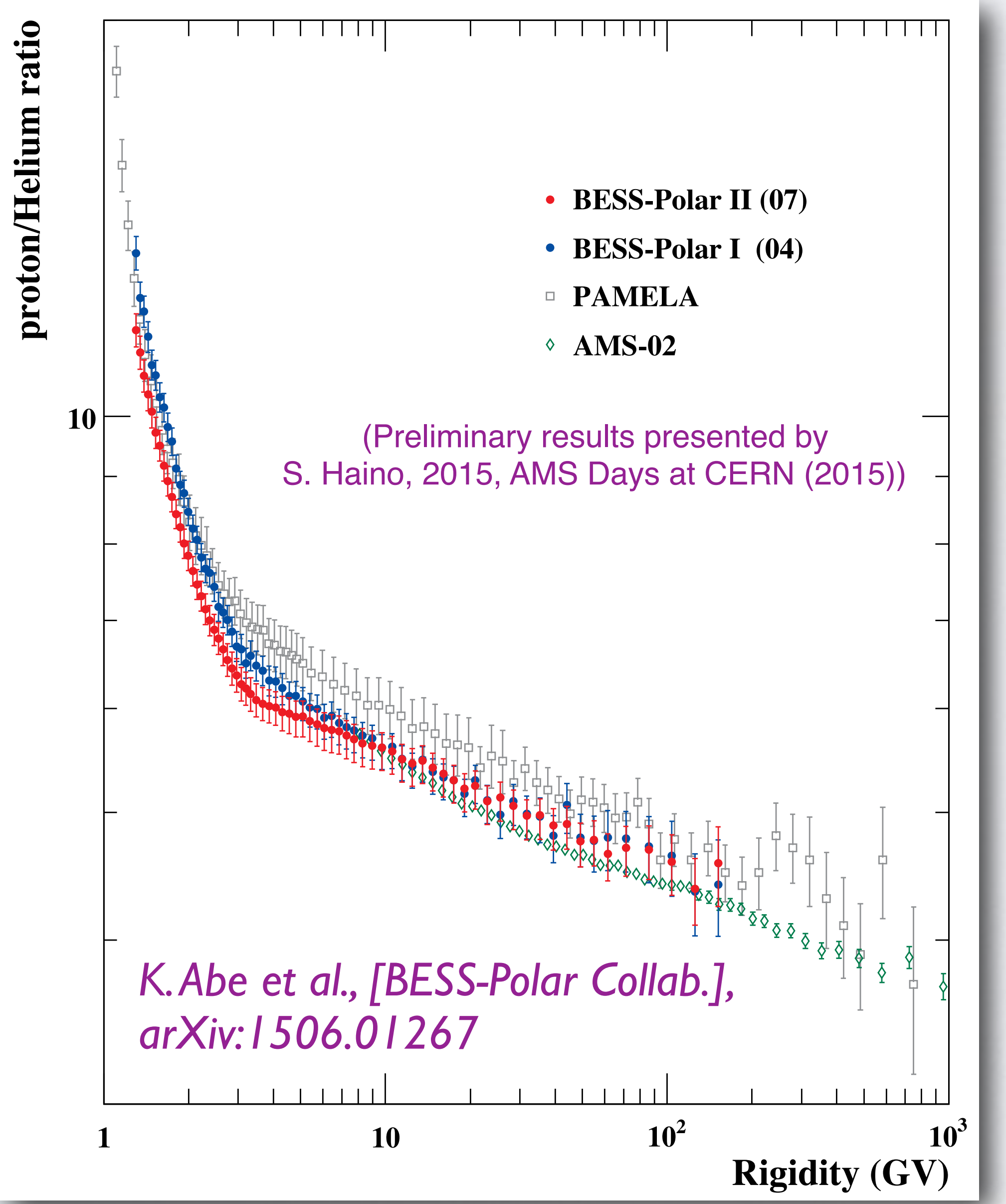
CREAM (filled circles), ATIC-2 (diamonds), CAPRICE94 (upward triangles), CAPRICE98 (downward triangles), LEAP (open circles), JACEE (stars), and RUNJOB (crosses)

NON-UNIVERSALITY, CONT'D

Confidence grew stronger after PAMELA.
By now, conclusively established:

Almost uncontroversial, several experiments in agreement!





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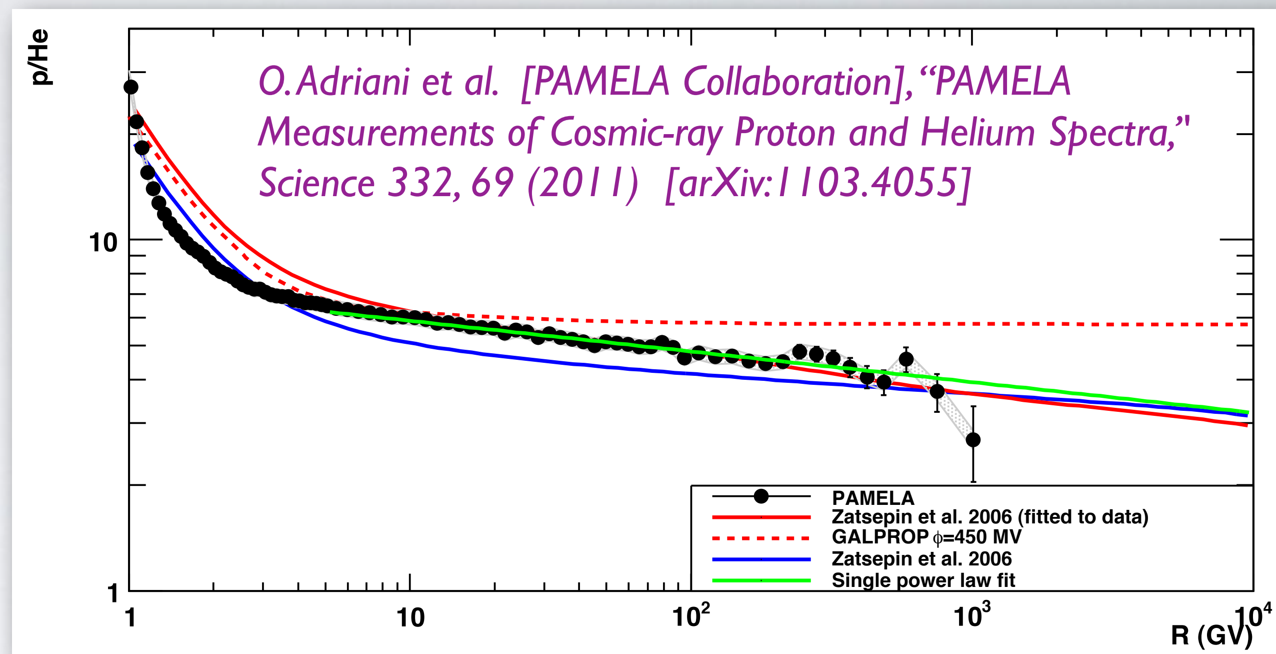
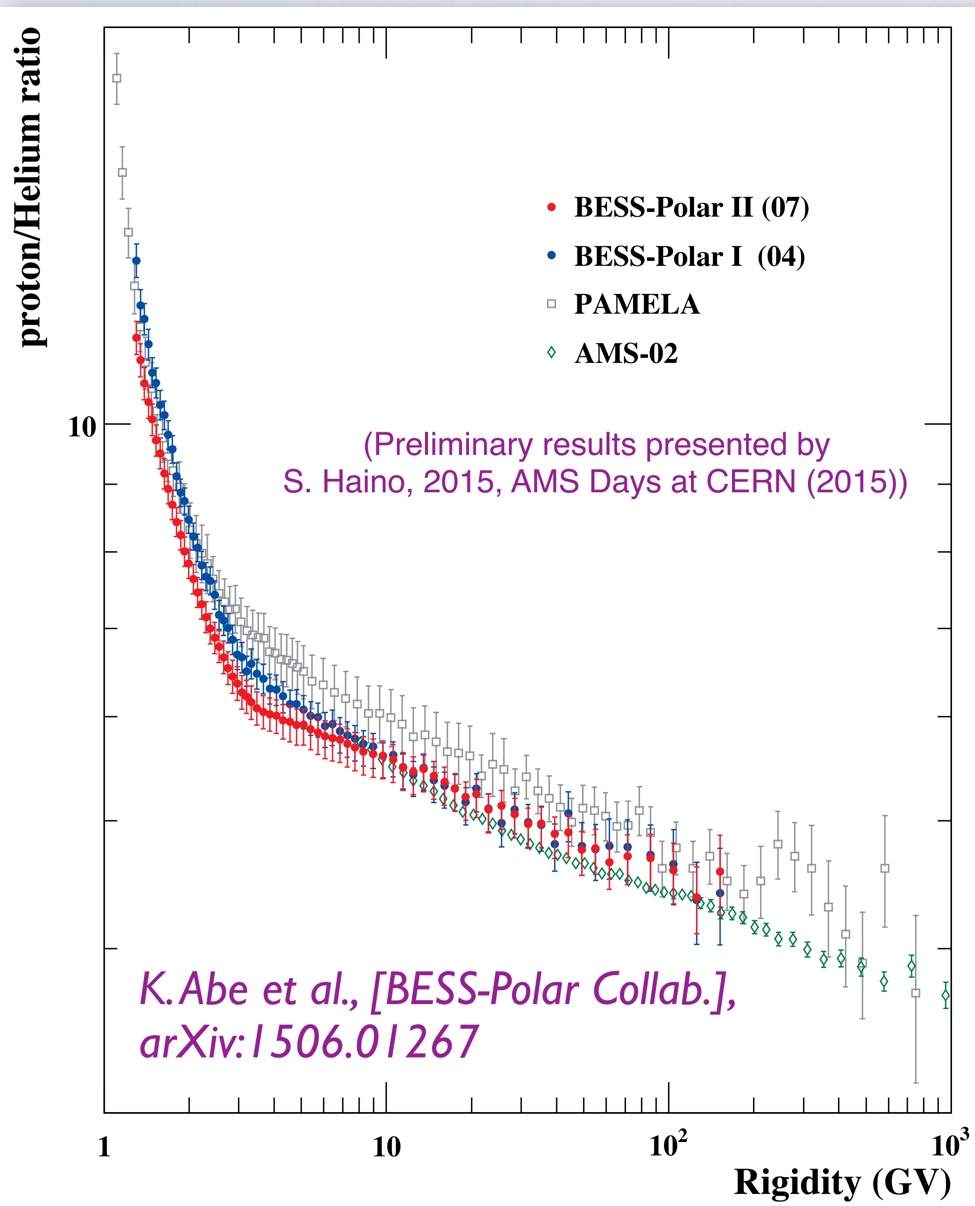
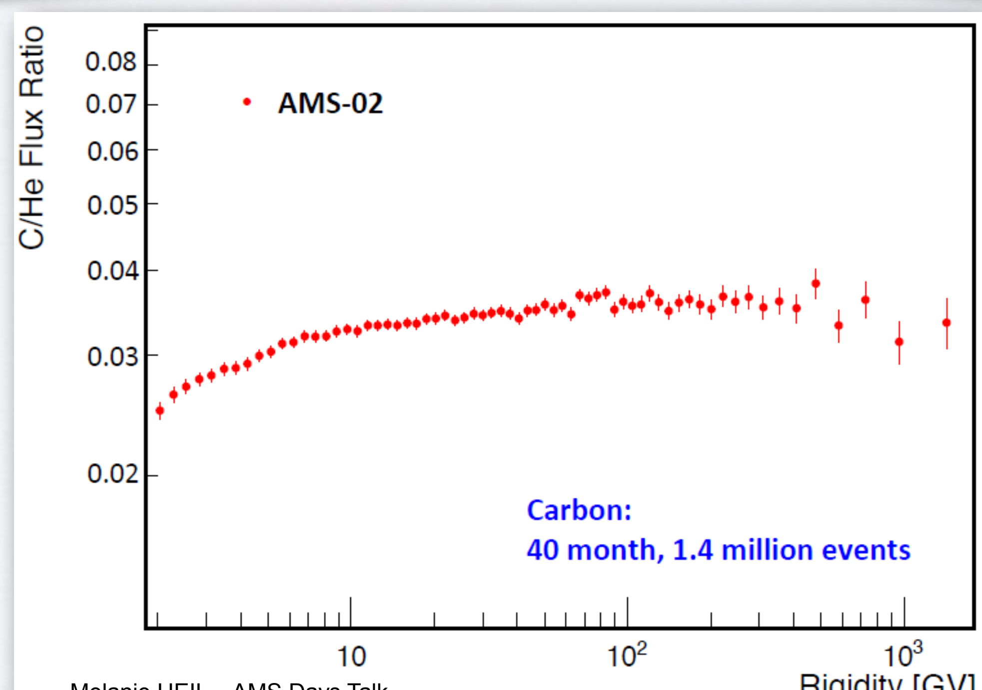


at high-E, harder He spectrum seems to be shared by heavier nuclei (strong hints e.g. from CREAM, being confirmed by AMS-02?)





THE PUZZLE & POSSIBLE SOLUTIONS

Usual acceleration & diffusive propagation mechanisms respond to **rigidity**: should be composition-blind in the *ultra-relativistic regime*

$$\frac{1}{c}\frac{d\vec{\mathscr{R}}}{dt} = \mathbf{E}(\mathbf{r},t) + \frac{\vec{\mathscr{R}} \times \mathbf{B}(\mathbf{r},t)}{\sqrt{\mathscr{R}_0^2 + \mathscr{R}^2}} \qquad \mathscr{R}_0 = Am_pc^2/Ze$$

$$\frac{1}{c}\frac{d\mathbf{r}}{dt} = \frac{\vec{\mathscr{R}}}{\sqrt{\mathscr{R}_0^2 + \mathscr{R}^2}}. \qquad \vec{\mathscr{R}} = \mathbf{p}c/eZ$$

Some solutions proposed (and a few challenges!)

- ***Non-e.m. effects in propagation (spallation?)*** *P. Blasi, E. Amato, JCAP 1201, 010 (2012)*

  Does not seem consistent with parameters for B/C or anti-*p* *A. E. Vladimirov et al. ApJ 752, 68 (2012)*

- ***Different sources/sites***

  Requires special conditions (e.g. break should be propagation-induced to explain universality, in He/metals accelerators need to suppress *p* one & vice versa...) *V. I. Zatsepin, N.V. Sokolskaya, A&A 458, 1 (2006)*

- ***Linked to the "natural" evolution of Mach number, $\mathscr{M}$, within DSA:***

  For <u>some reason</u>, He mostly accelerated "early on" ($\mathscr{M}$>>1) *p*'s "later" ($\mathscr{M}$ is relatively low)

  what is this reason?

PREFERENTIAL "LATE" P ACCELERATION

(Some) possible reasons

- ***Related to the efficiency of injection in the acceleration cycle***

Alfven waves ~ frozen with the shock, dominated by *p*. At same Vs (Mach velocity) He^{++} have twice the *p* gyroradius, more likely to return upstream, more efficiently accelerated. Both *p* and He efficiency declines with *M*, but faster decline for p. expected ⇒ softer spectrum

M. A. Malkov, P. H. Diamond, R. Z. Sagdeev, PRL 108, 081104 (2012)

No "standard theory" for this, further complications due to role of partially ionized atoms (see e.g. G. Morlino, MNRAS 412, 2333–2344 (2011)), and role of grains of dust (D. Ellison, L. Drury and J. Meyer, ApJ 487, 197 (1997) …)

- ***Variable (ionized) He/p concentration in medium swept by shocks***

caused by time-dependent ionization state?

older/weaker shocks propagate in medium where more He is neutral than in strongly ionized environment of young remnant

*L. O. Drury, MNRAS **415**, 1807 (2011)*

"just" reflecting the chemical environment in the sources?

e.g. argued to match environment in superbubbles

Y. Ohira and K. Ioka, ApJ 729, L13 (2011)

Y. Ohira, N. Kawanaka and K. Ioka, arXiv:1506.01196

"spatial" segregation of He vs p

p tend to be in % more abundant "far away" (attained later by the shock)

A. D. Erlykin and A. W. Wolfendale, J. Phys. G 42 (2015) 7, 075201

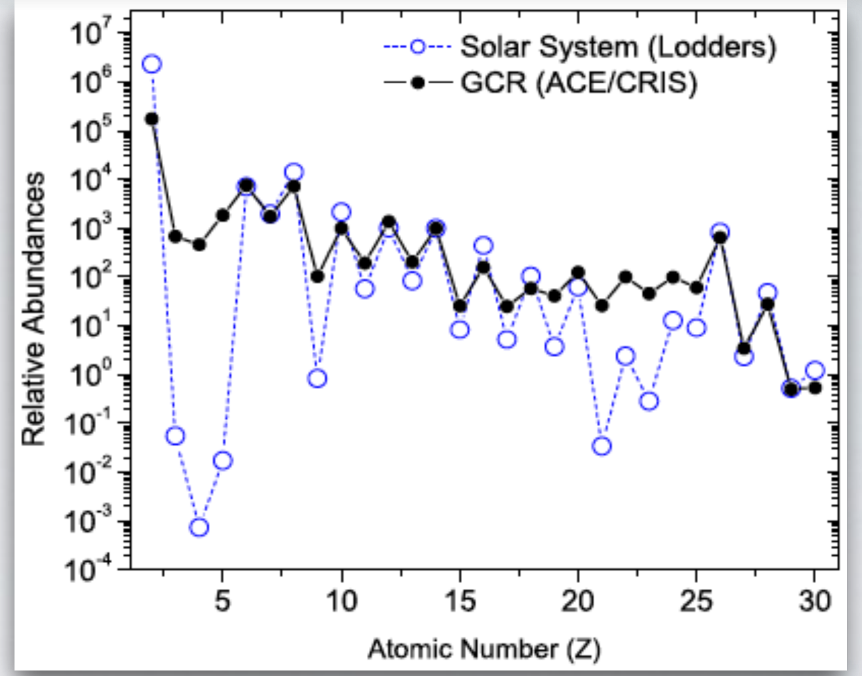
TESTING BREAK MODELS

Main <u>diagnostics: from secondaries</u>, notably (but not exclusively!) B/C

Fragile nuclei such as Li, Be, B… present but in traces in stellar astrophysical environments, while in sizable fractions in CRs:

➡ interpreted as result of spallation of "primary" nuclei, accelerated at sources (e.g. SNRs) during the CR diffusive propagation in the ISM.

While CR are sensitive to both acceleration and propagation effects, the ratio of Secondary/Primary species is used to constrain propagation parameters (assumed insensitive to injection)



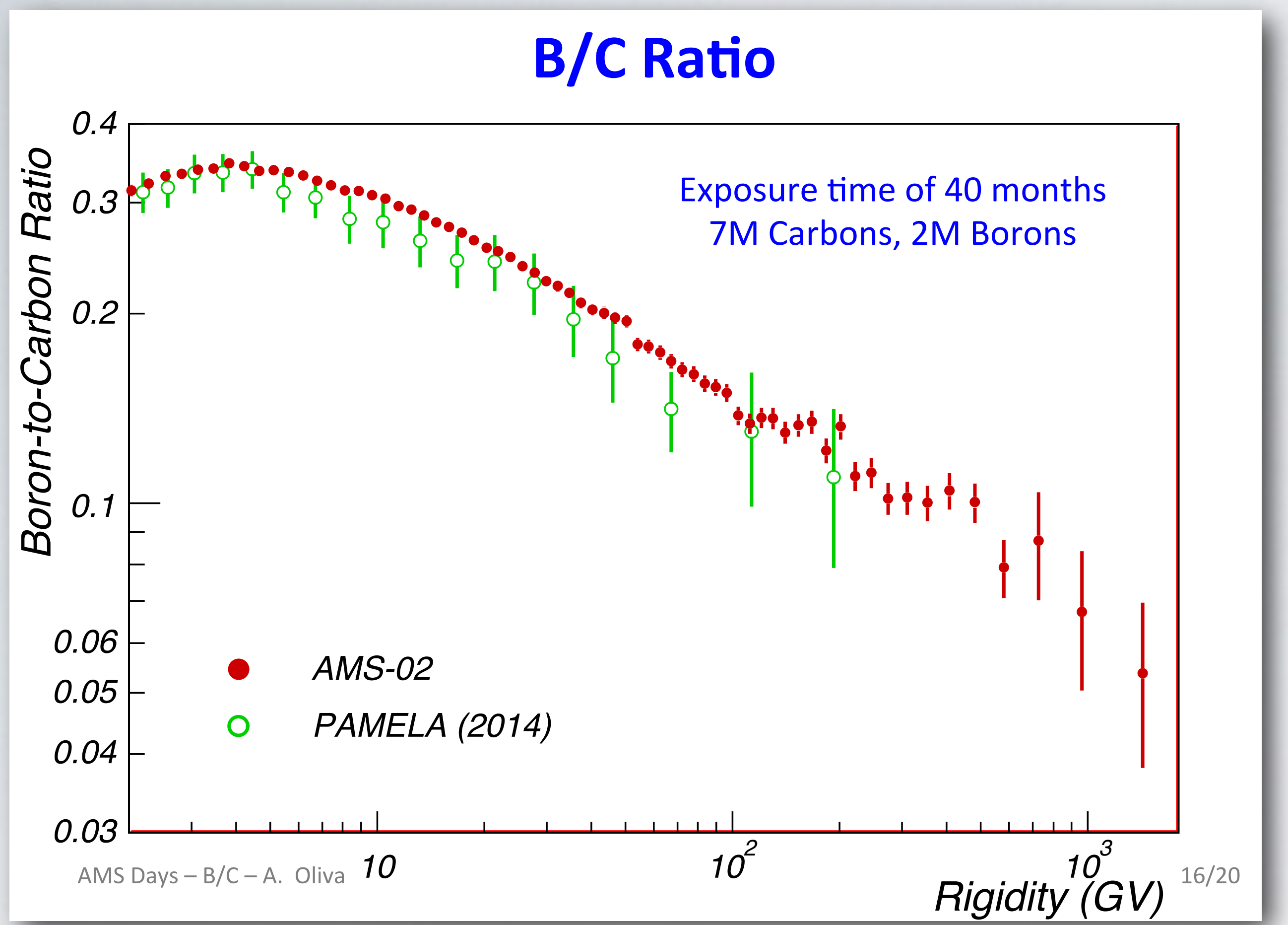
In short:

1) Source origin for the break: no feature expected in secondaries/primaries

2) Propagation origin for the break: should reflect in probes of propagation as B/C (i.e. secondary spectra should show a more pronounced break than primary ones)

3) Local models like the "myriad" one may even obtain a softening of sec/primary, since secondaries are ~ sourced by the "unbroken" average spectrum

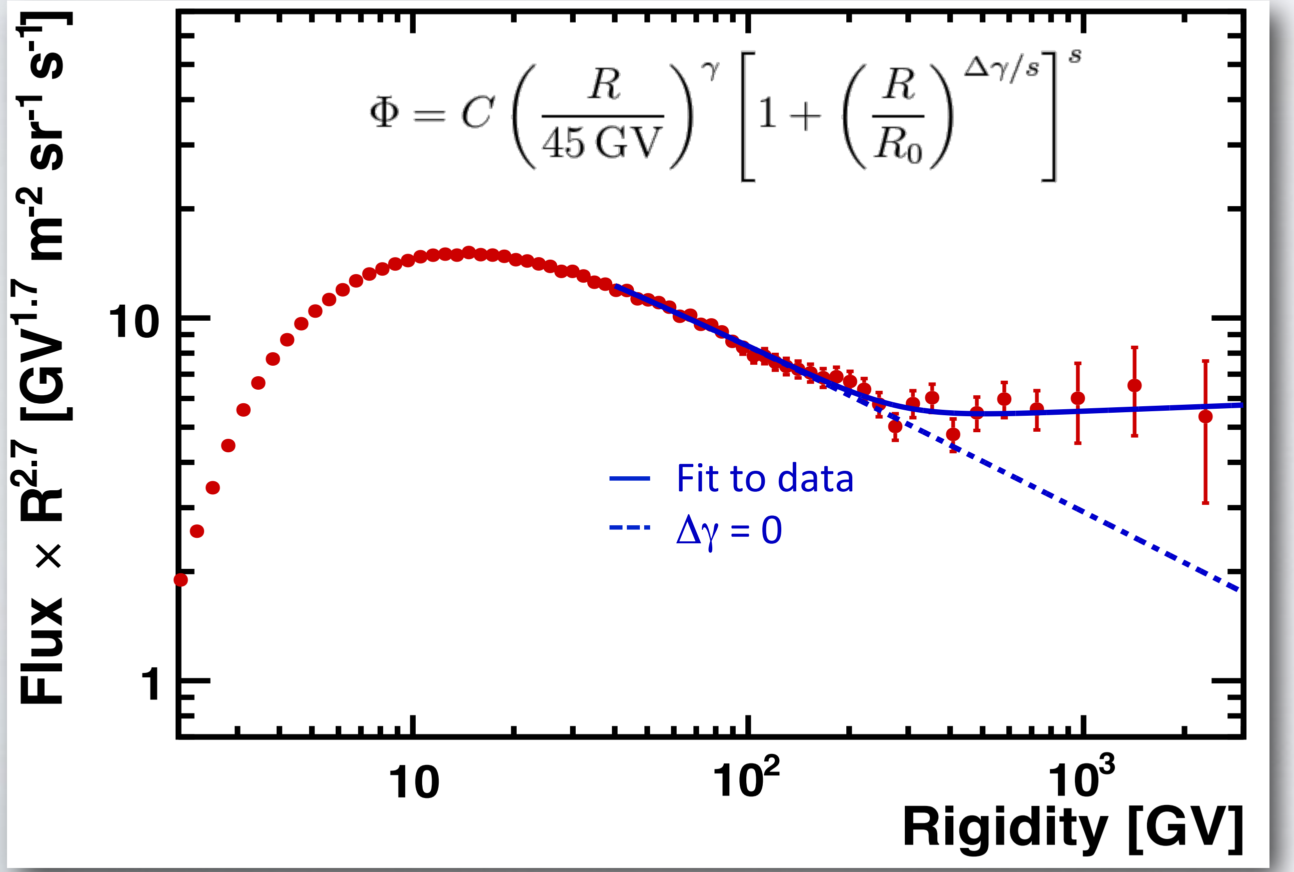
TESTING BREAK MODELS: STATUS



B/C preliminary results do not seem to favour local source effect, surely inconclusive for disentangling propagation vs generic source effects

A. Oliva [AMS Collaboration]

AMS days @ CERN 2015, & ICRC 2015



Qualitative hints for propagation effect from AMS preliminary Lithium data? (Prominent break)

L. Derome [AMS Collaboration]

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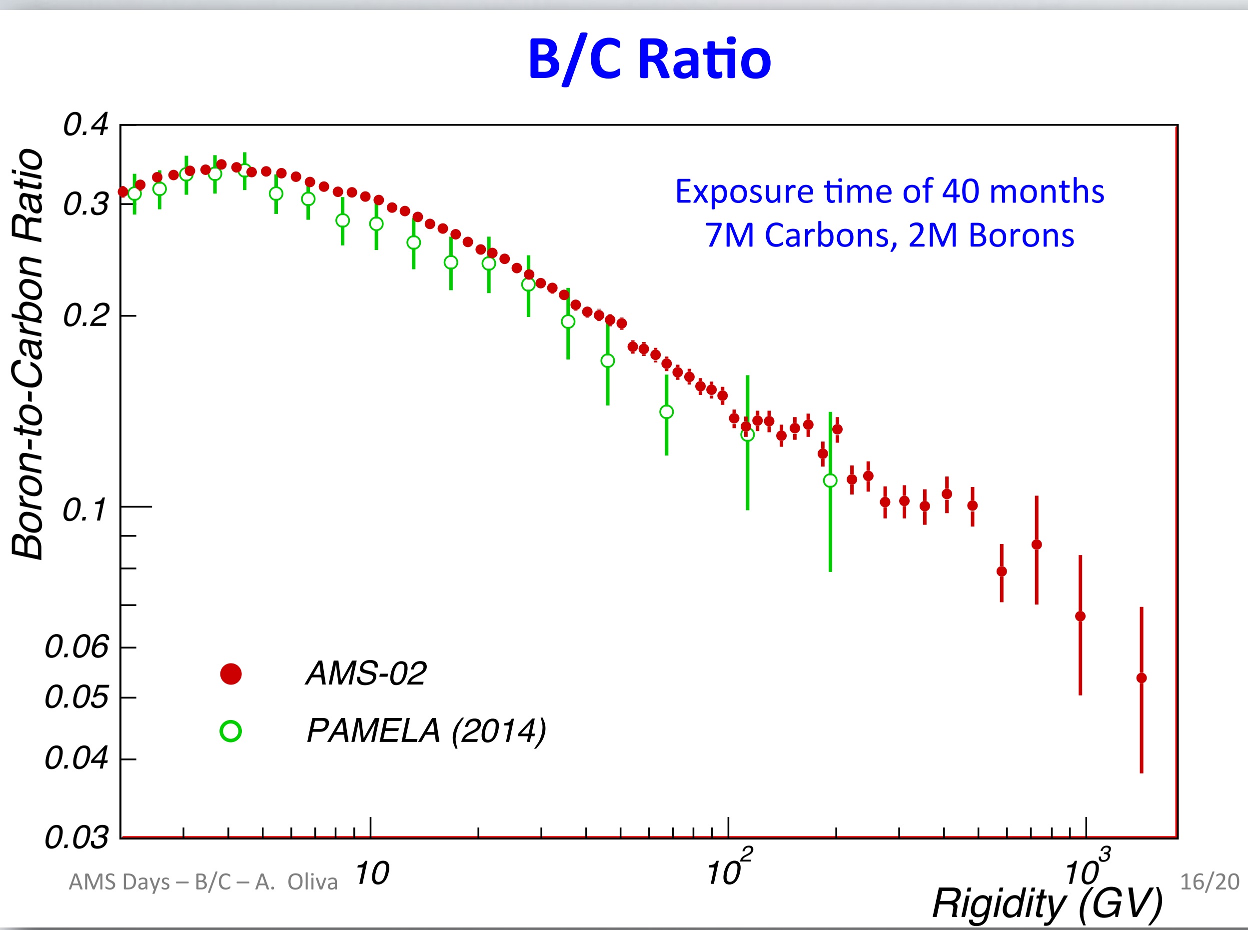

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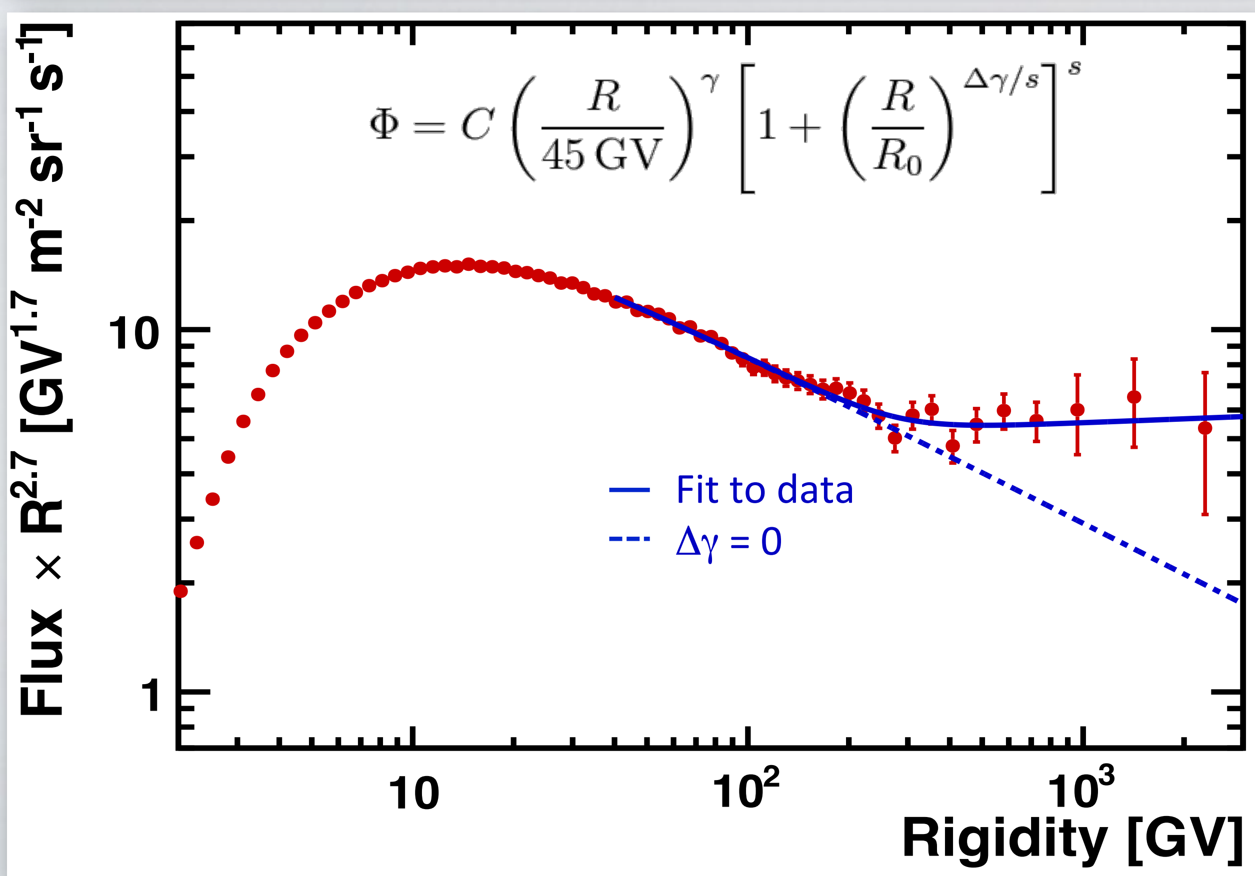

Qualitative hints for propagation effect from AMS preliminary Lithium data? (Prominent break)

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Need O(10%) precision @ 1 TeV/nuc for firm conclusion!

SOME DIFFICULTIES

➡ *Models within the same class (source/propagation) largely degenerate within foreseeable sensitivity*

Obvious, yet true: Possibility to reduce degeneracies in models where links with additional observables are present (multi-messenger approach)

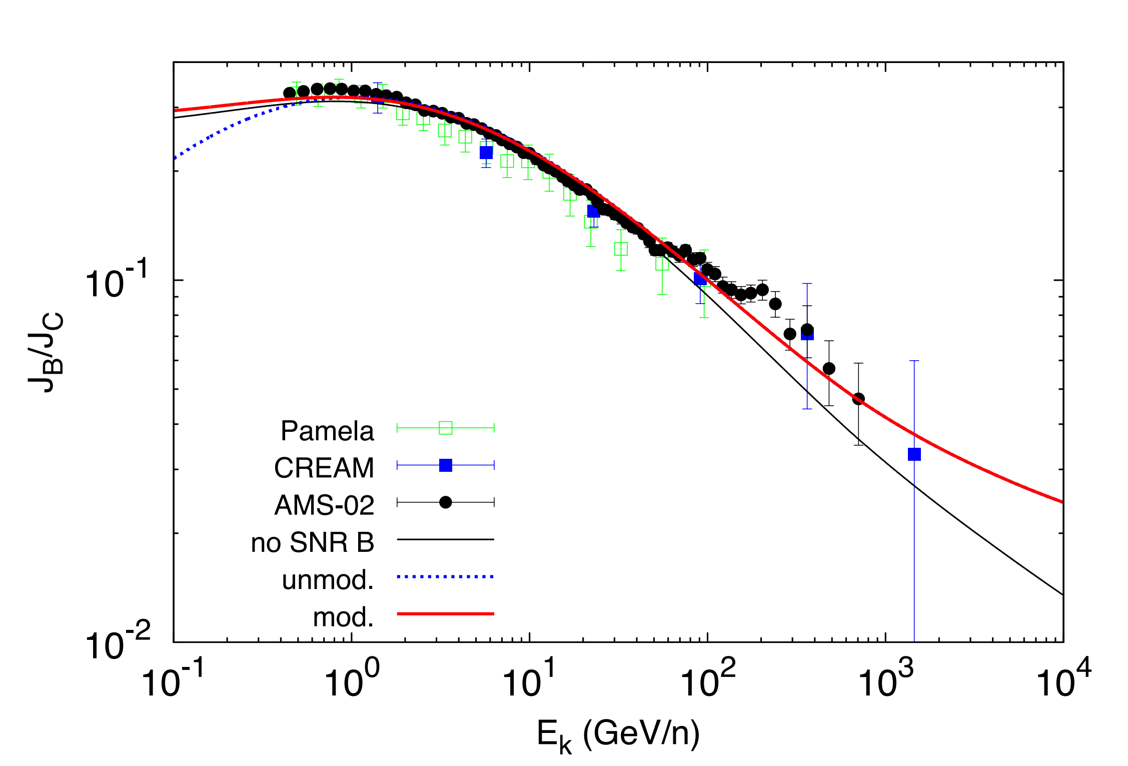
➡ *"Secondary" production at sources become a major concern (must be taken into account)*

High precision data on secondaries (or sec/prim.) in E~0.1-1 TeV/nuc. needed to test source vs. propagation scenarios.

However, easy to estimate than in the same range we expect sizable "secondary" production at the source

$$X_{\rm SNR} \approx 1.4 r_s m_p n_{\rm ISM} c T_{\rm SNR} \approx 0.17\,{\rm g\,cm^{-2}} \frac{n_{\rm ISM}}{\rm cm^{-3}} \frac{T_{\rm SNR}}{2\times 10^4 {\rm yr}}$$

R. Aloisio, P. Blasi and PS, A&A 583 (2015) A95 [1507.00594]



This is a generic conclusion on "theoretical" limitation in extracting propagation parameters from B/C

Y. Genolini, A. Putze, P. Salati, PS A&A 580, A9 (2015) [arXiv:1504.03134]

TESTS OF NON-UNIVERSAL MODELS?

One important diagnostics is the dependence of the feature on the nuclei

Are the spectra of the "metals" the same as He and among themselves?

Good News: AMS should provide some new data soon.

Bad News: Problem may be related to understanding of relative abundances of species of different chemical composition, either poorly understood aspects of injection or of source astrophysics may be involved.

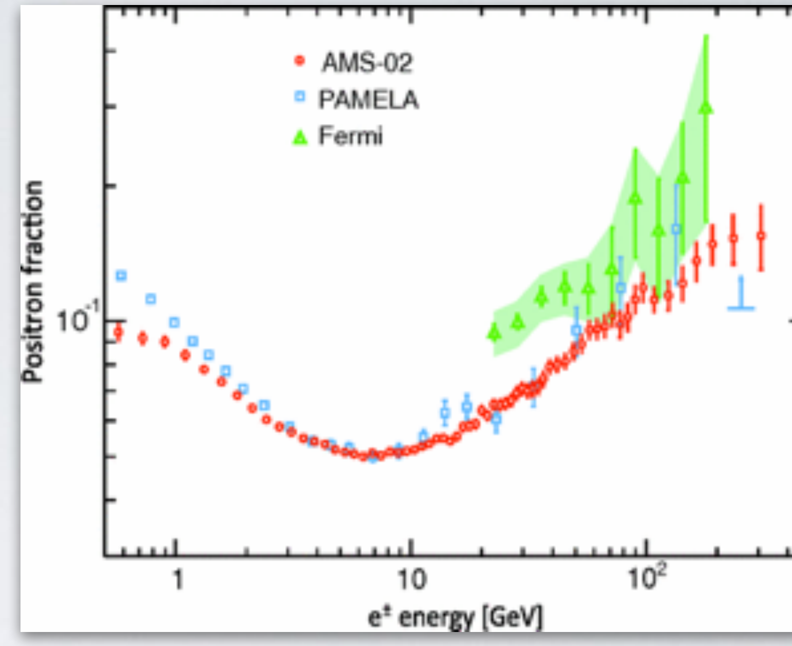
Do not despair, yet! Keep hoping in the future...

Example of futuristic handle: inferring and comparing the "grammage at source" experienced by protons & nuclei (e.g. antiprotons wrt secondary nuclei) could indicate if the main culprit is some environmental condition at accelerator site (as opposed to injection)

THE (BY NOW OLD) POSITRON "EXCESS"

Interesting example of <u>misnomer</u> (or "sociological aspect of the word anomaly"): not the too large number of e^+, rather their energy spectrum that requires an explanation *(if one aims at a coherent modeling of CR fluxes, of course)*

P.S. PRD 79, 021302 (2009)



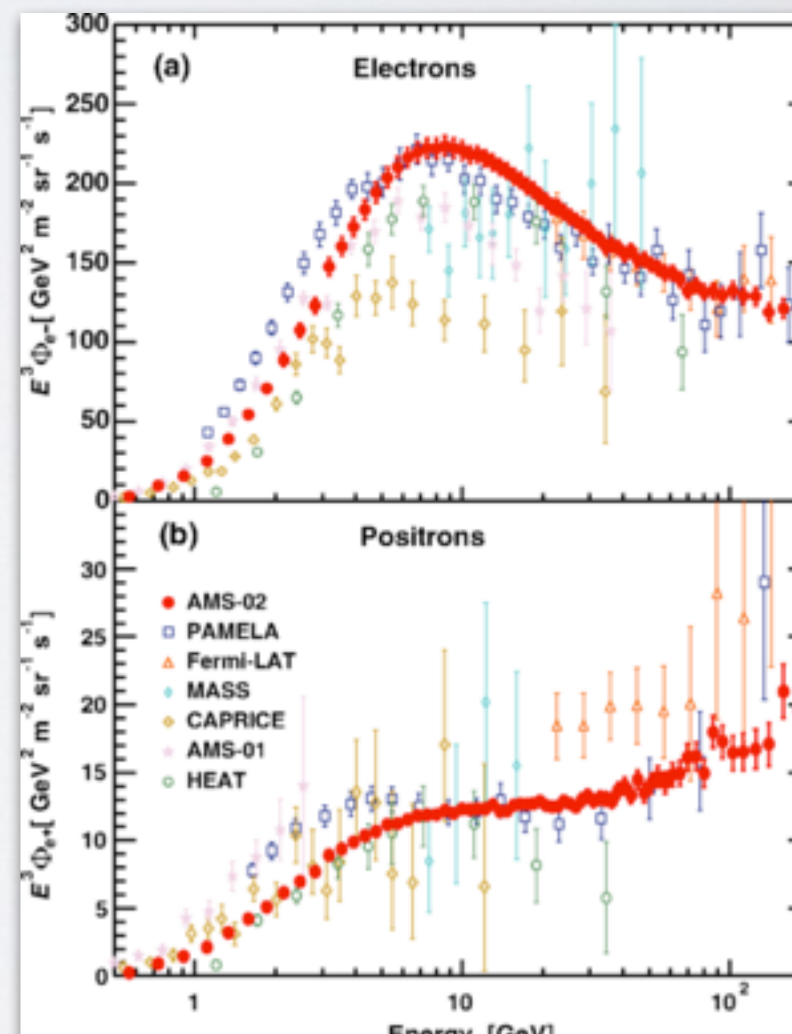
Latest results in this field: AMS-02 publication of fraction (2013), and of both fraction and absolute fluxes of e^+ and e^- (2014), preliminary updated results announced at CERN in 2015

M. Aguilar et al. [AMS Collaboration], PRL 110, 141102 (2013) (e^+ fraction)

L. Accardo et al. [AMS Collaboration], PRL 113, 121101 (2014) (e^+ fraction update)

M. Aguilar et al. [AMS Collaboration], PRL 113, 121102 (2014) (separate e^+ and e^-)

M. Aguilar et al. [AMS Collaboration], PRL113, 221102 (2014) (e^+ + e^-)



Since a few years, I consider the (main) **case closed**: there is *no consistent model* (i.e. compatible with B/C, diffuse gamma-rays, etc.) *which does not require some primary* source of e+

STATUS AND EXPECTATIONS

On Primary source(s):

- must be mostly *astrophysical rather than DM* (to pass multi-messenger constraints, notably from γ's).
- *PWNe are natural candidates* ($e^{\pm}$ producers & accelerators, spectrum at termination shock hard as needed, energetics Ok), but other sources (e.g. SNRs) possible, at least as sub-leading component.
- Local, discrete sources more and more important with E; O(0.1%) anisotropy @ O(100) GeV likely

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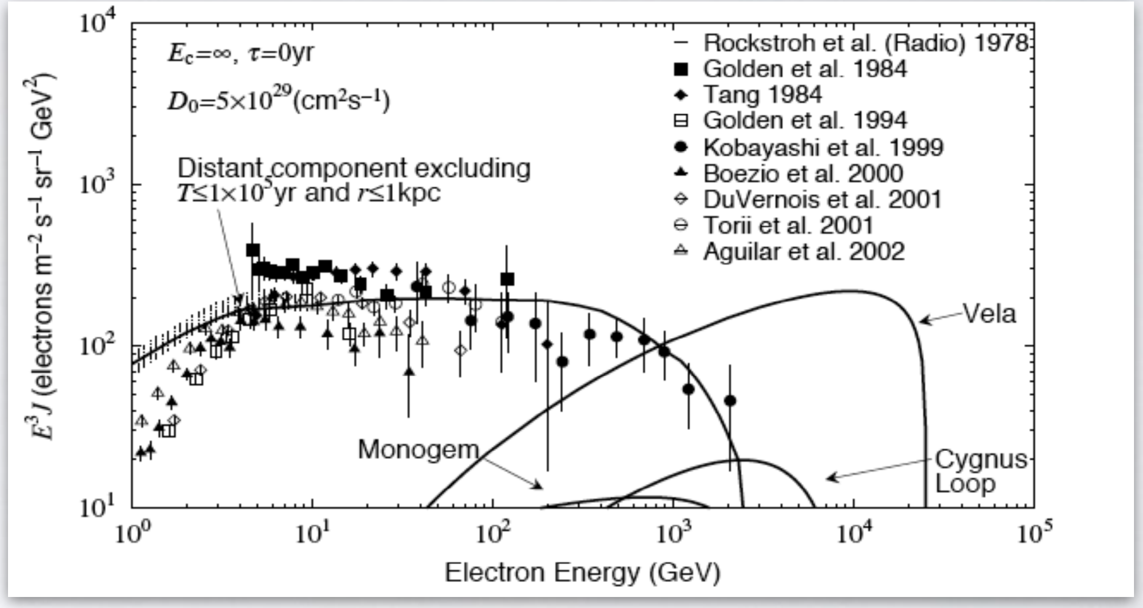
NOTE

several of these aspects already clear well before "good modern data" came in! E.g.

A. M. Atoyan, F. A. Aharonian, and H. J. Völk PRD 52 (1995) 3265

[…] separating the contribution of the local (discrete) source(s) from the contribution of distant sources, it is possible to explain all the locally observed features of the energy spectrum of cosmic ray electrons from sub-GeV to TeV energies. In addition, assuming that the local source produces electrons and positrons in equal amounts, the model allows us to explain also the reported increase of the positron content in the flux above 10 GeV […]

Kobayashi, Komori, Yoshida, Nishimura, ApJ 601, 340 (2004)

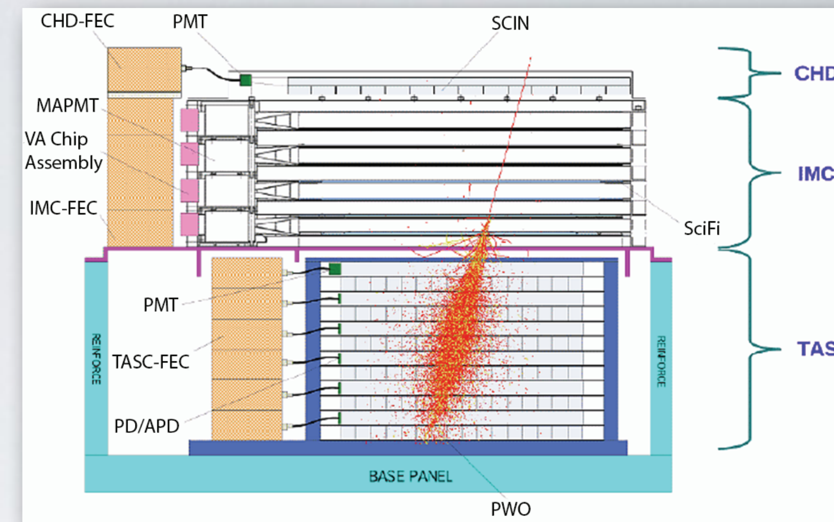


here the **anomaly** would be featureless power-laws! We ***expect*** lepton CR spectra to be "bumpy" at high-energy. (Some indication by IACTs?) e^+ fraction determined by e.g. relative PWN to SNR contribution in the range, turning points expected when exceeding single PWN E_{max}

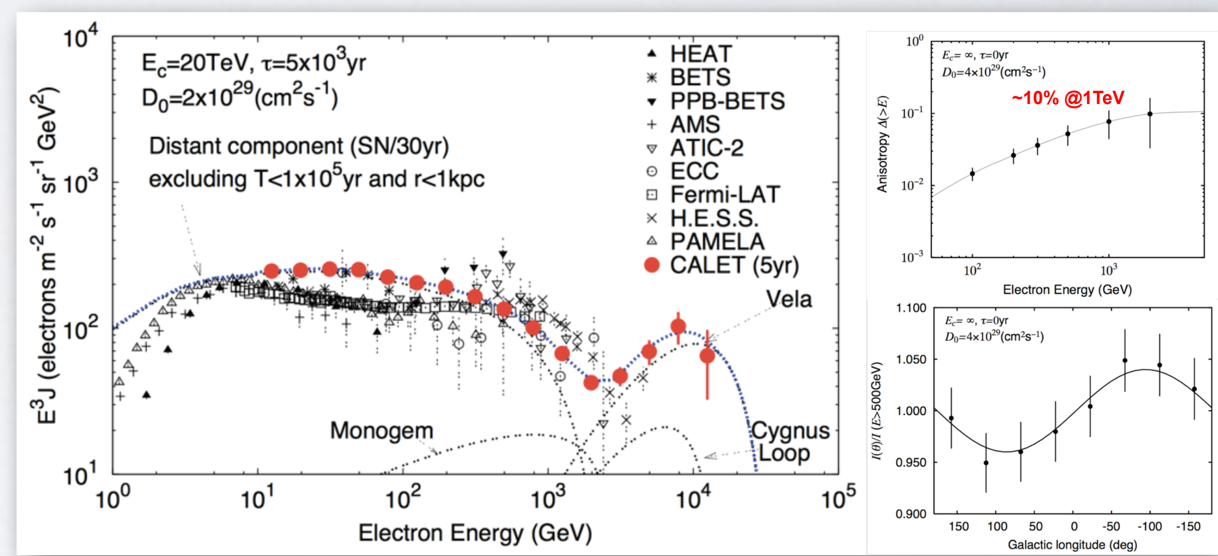
Detecting these features would confirm the standard understanding of CR, not disprove it!

FORTHCOMING NEWS (BESIDES AMS-02)?

CALET is an *all-calorimetric* instrument, with a total thickness equivalent to 30 radiation lengths and 1.3 proton interaction lengths, preceded by a particle identification system



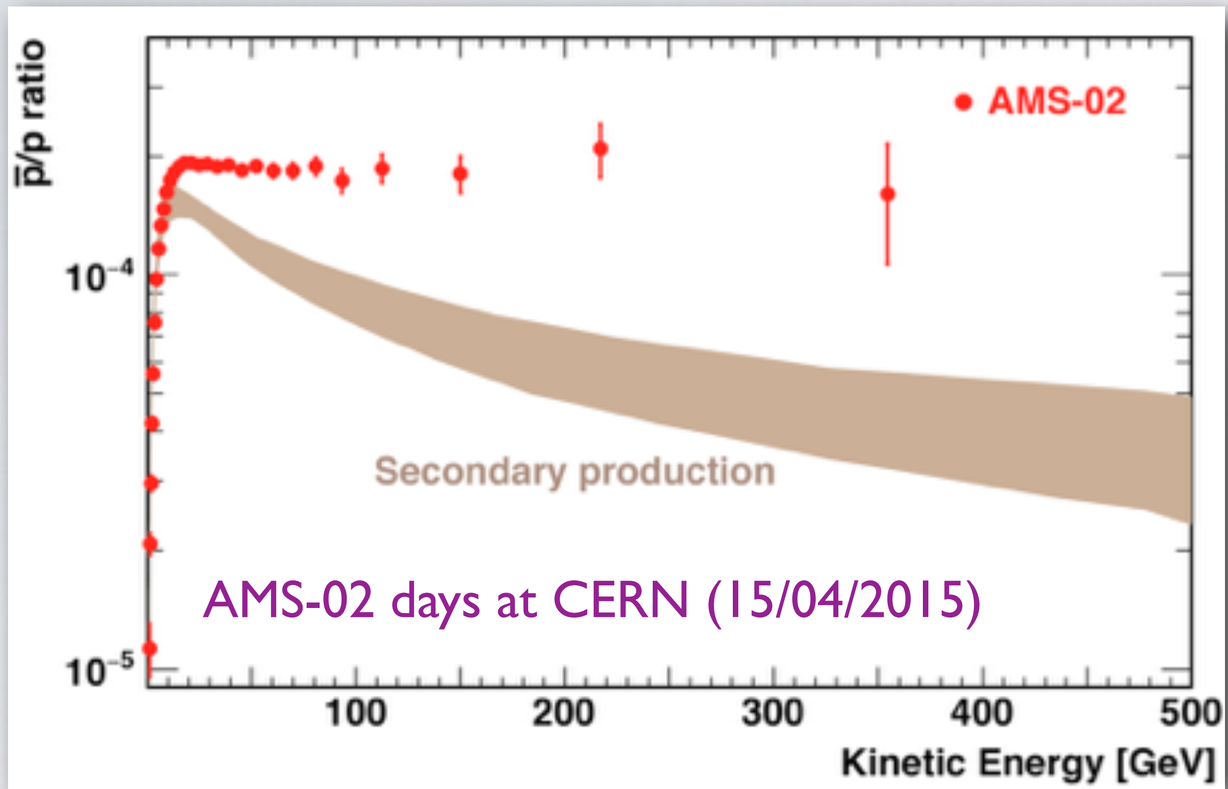
Since end of August 2015, docked at the Japanese module of ISS



The Primary Science for CALET is the investigation of the high energy electron spectrum into the trans-TeV energy range (bumps and anisotropies due to local sources, end of spectrum, DM constraints…) The effective geometrical factor for CALET for high-energy electrons is ≃1200 cm^{2}sr

http://calet.phys.lsu.edu/images/ICRC2015-Torii.pdf preliminary!

AN ANOMALY IN AMS-02 ANTI-P?



By glancing at such a plot, one would naively conclude so!

However: Old predictions cannot be consistently overlapped with points!

preliminary!

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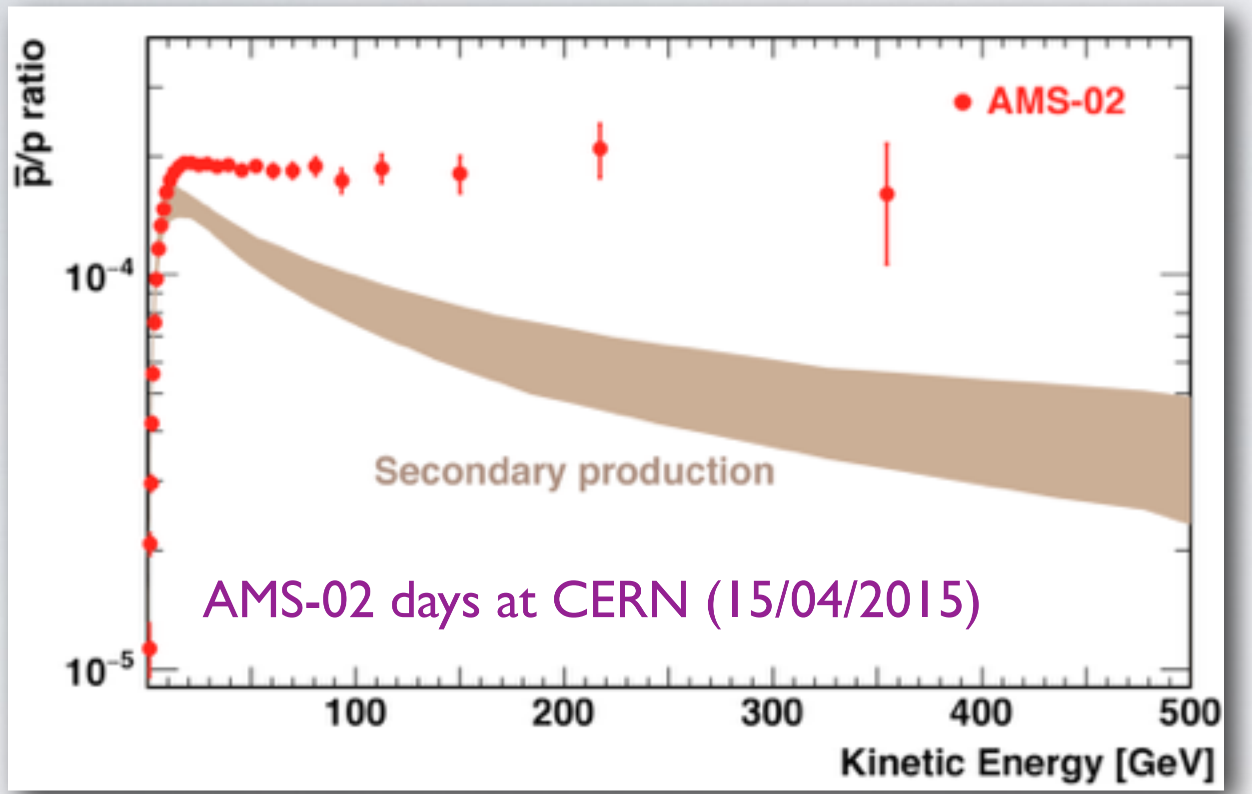


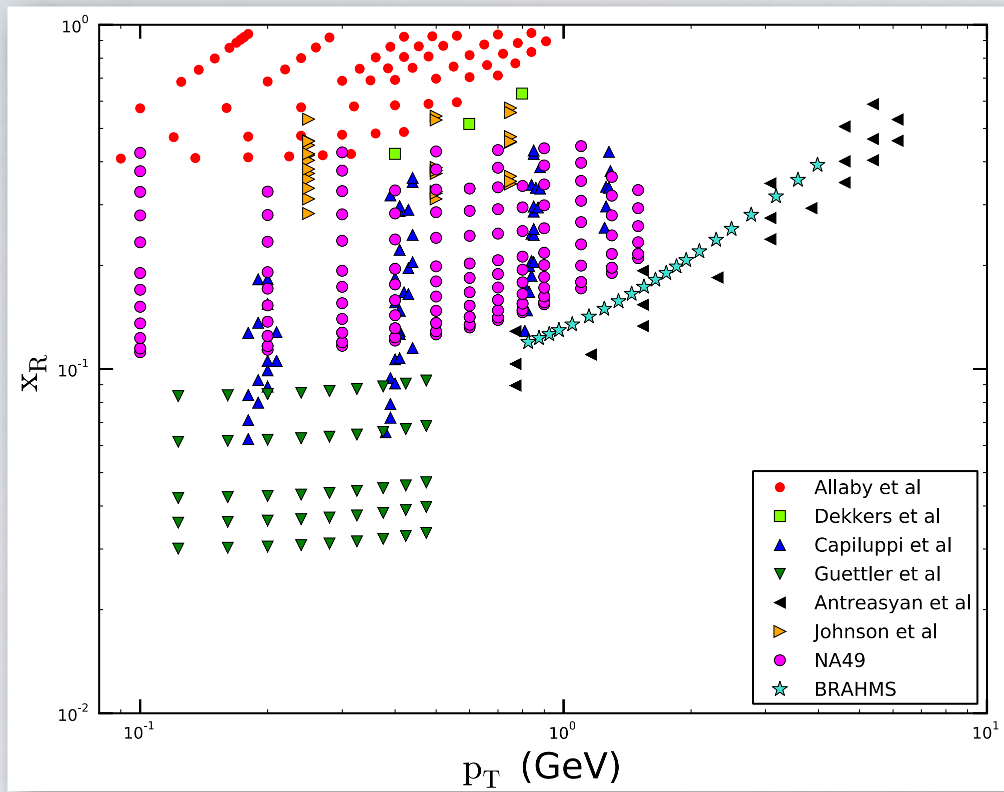
By glancing at such a plot, one would naively conclude so!

However: Old predictions cannot be consistently overlapped with points!

For instance, do not take into account harder p and He fluxes at high-E, a point anticipated in *Donato & PS, PRD 83, 023014 (2011) [arXiv:1010.5679]*

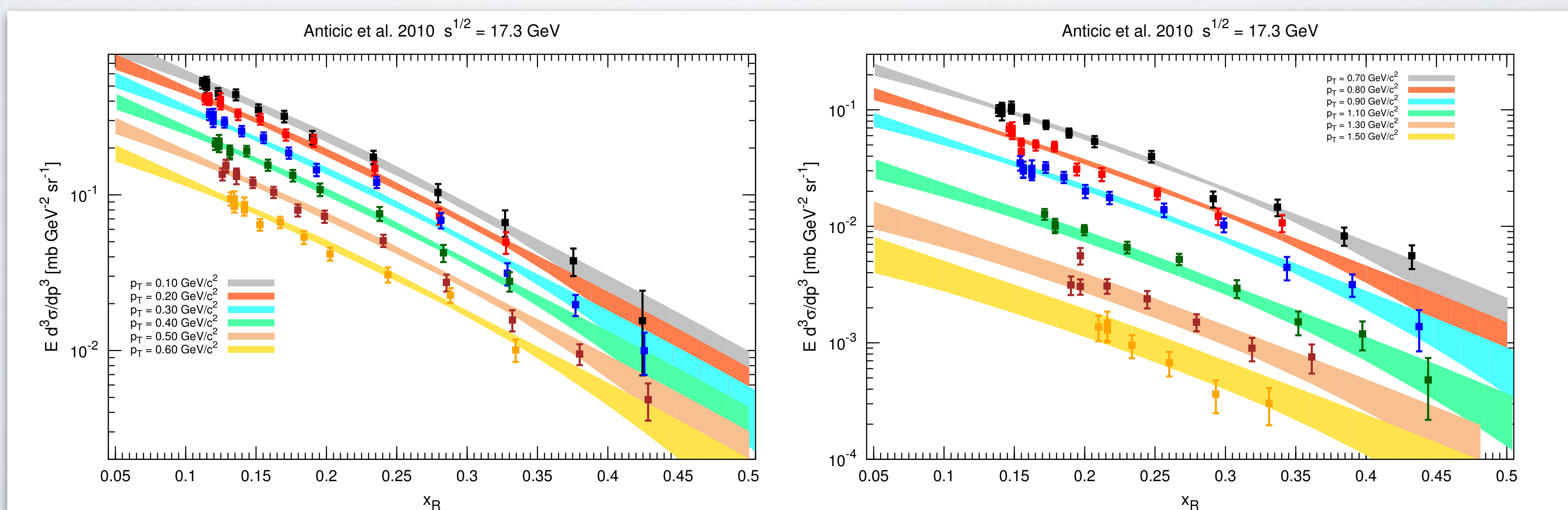
Newer data on anti-p production cross section should be taken into account *Di Mauro, Donato, Goudelis, PS, PRD 90, 085017 (2014)*
Kappl & Winkler, JCAP1409, 051 (2014)

ACCOUNTING FOR NEW X-SEC DATA



Experiment	$\sqrt{s}$ (GeV)	p_T (GeV)	x_R
Dekkers *et al*, CERN 1965 [18]	6.1, 6.7	(0., 0.79)	(0.34, 0.65)
Allaby *et al*, CERN 1970 [19]	6.15	(0.05, 0.90)	(0.40, 0.94)
Capiluppi *et al*, CERN 1974 [20]	23.3, 30.6, 44.6, 53.0, 62.7	(0.18, 1.29)	(0.06, 0.43)
Guettler *et al*, CERN 1976 [21]	23.0, 31.0, 45.0, 53.0, 63.0	(0.12, 0.47)	(0.036, 0.092)
Johnson *et al*, FNAL 1978 [22]	13.8, 19.4, 27.4	(0.25, 0.75)	(0.31, 0.55)
Antreasyan *et al*, FNAL 1979 [23]	19.4, 23.8, 27.4	(0.77, 6.15)	(0.08, 0.58)
BRAHMS, BNL 2008 [13]	200	(0.82, 3.97)	(0.11, 0.39)
NA49, CERN 2010 [14]	17.3	(0.10, 1.50)	(0.11, 0.44)

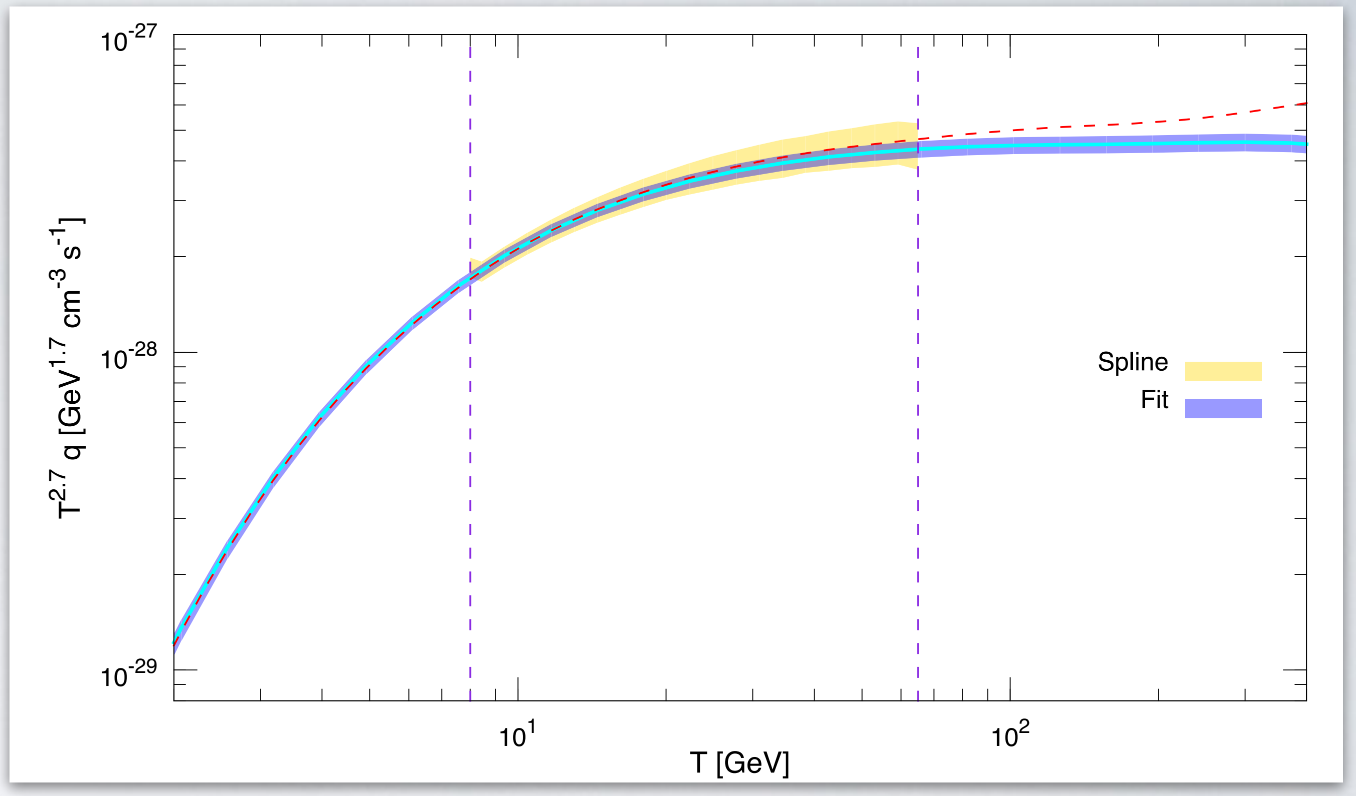
M. di Mauro, F. Donato, A. Goudelis and PS, PRD 90, 085017 (2014)



SOME HIGHLIGHTS

➡ **Tested numerical interpolations vs. theoretically motivated fits**

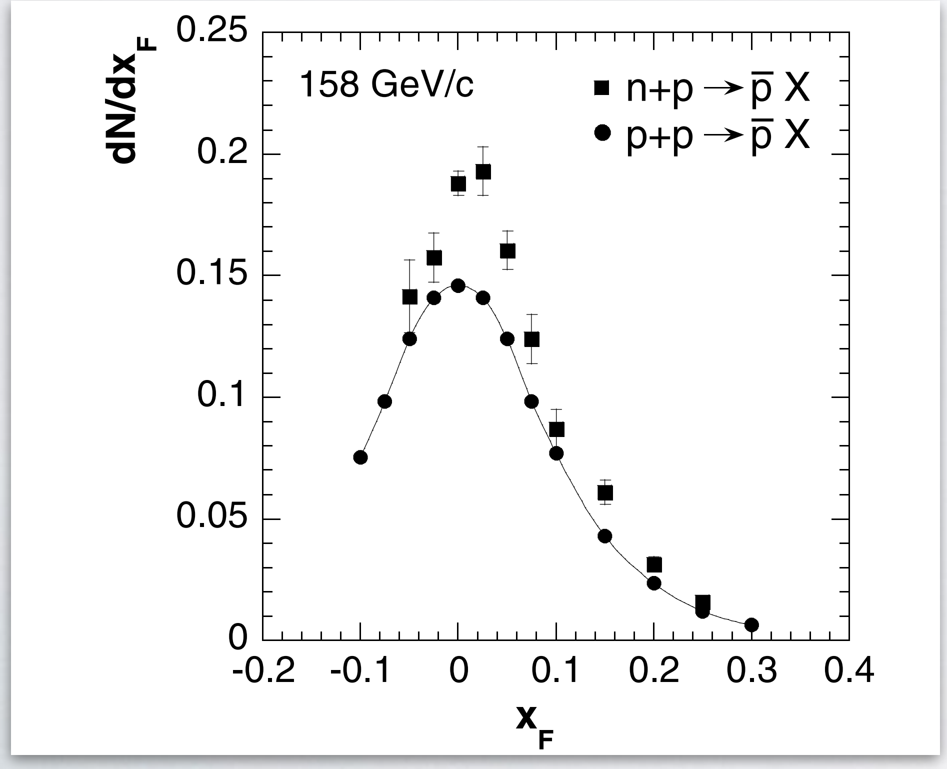
"bias" due to assuming functional form roughly ~3 sigma of statistical error; error grows outside range experimentally tested

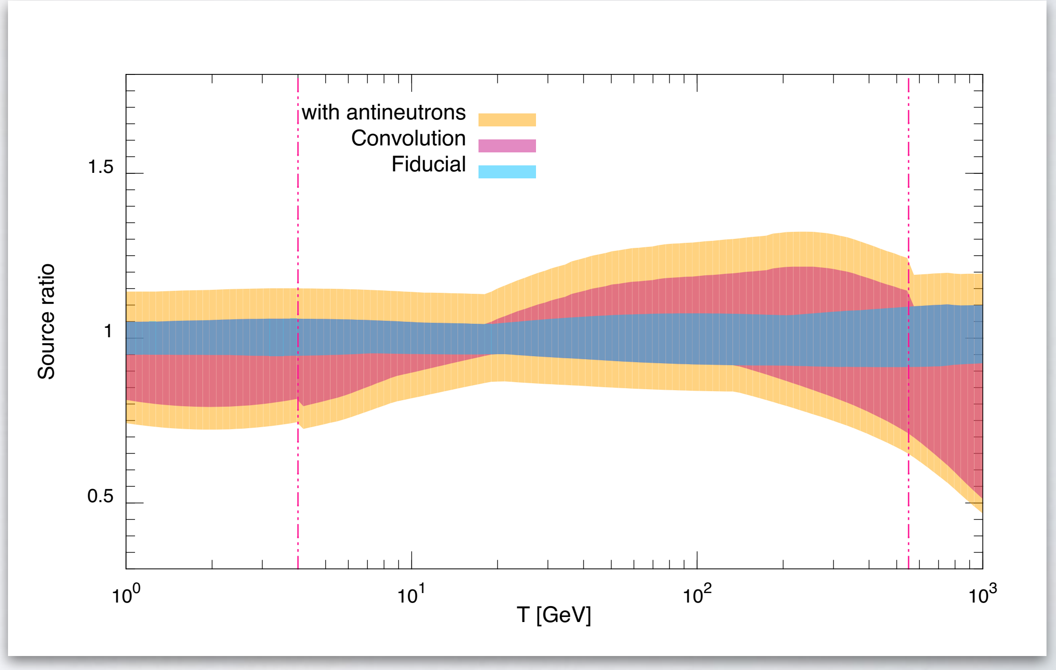


➡ **Important to account for anti-n isospin dependent effect**

In pp reactions, (x-dependent) significant preference of the positively charged p-anti-n combination over anti-p-n !

H. Fischer (NA49 Collaboration), Heavy Ion Phys. 17, 369 (2003)





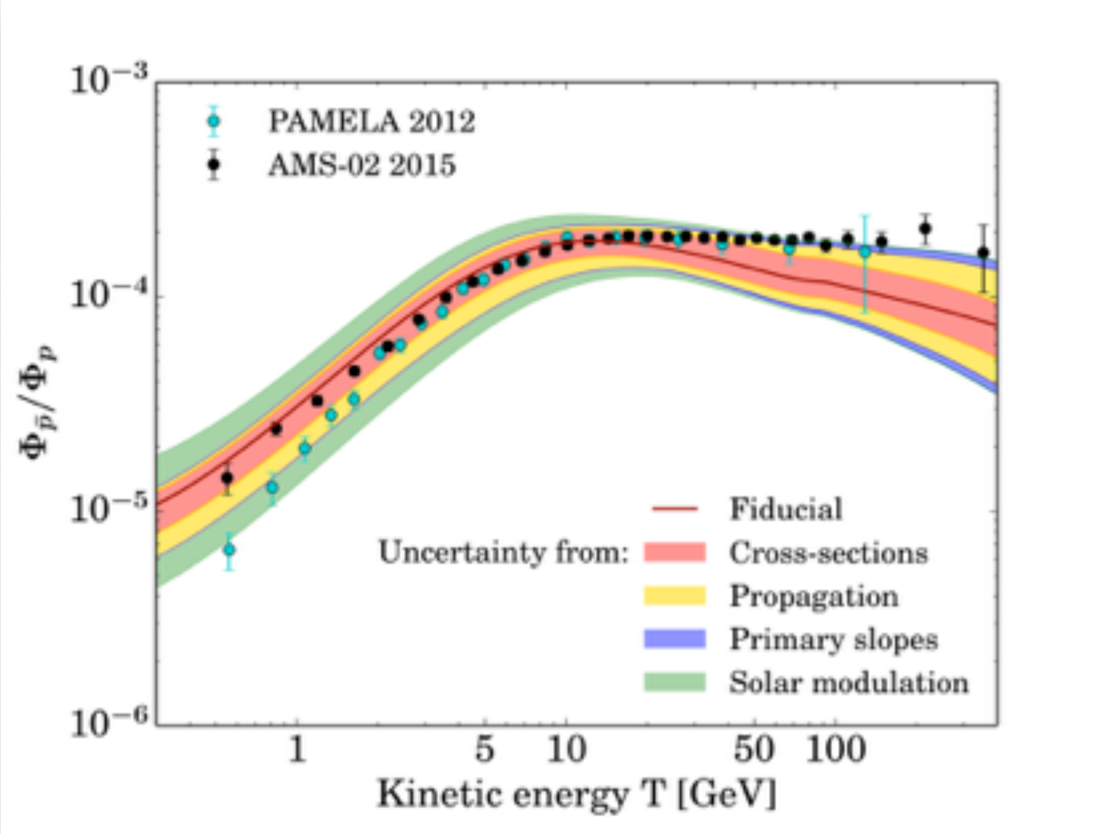
M. di Mauro, F. Donato, A. Goudelis and PS, PRD 90, 085017 (2014)

ALL TOGETHER: MORE REALISTIC COMPARISONS

G. Giesen et al. JCAP 1509, 023 (2015) [1504.04276]

Even within *old propagation models*, once an update is performed of these inputs and realistic account of uncertainties is done... an *"anomaly" is at most marginal*: cannot be unambiguously established.

Models with milder dependence of diffusion coefficient wrt rigidity (like "MAX") preferred



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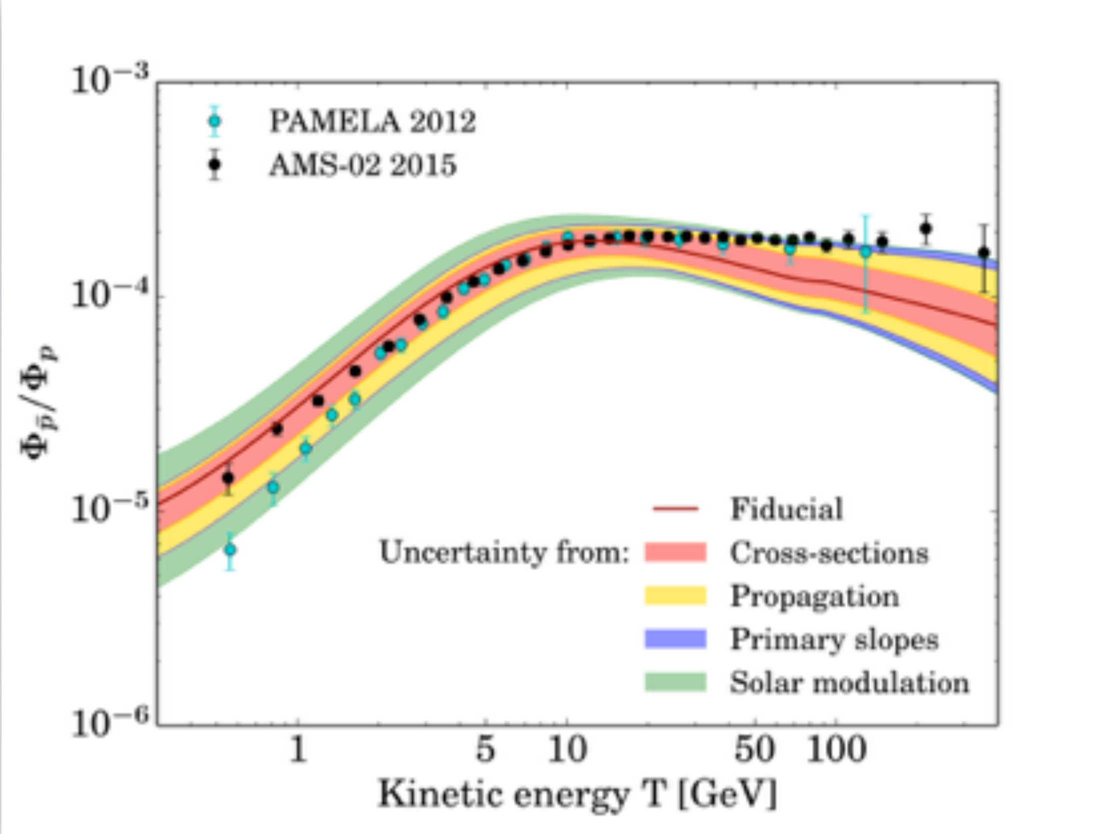


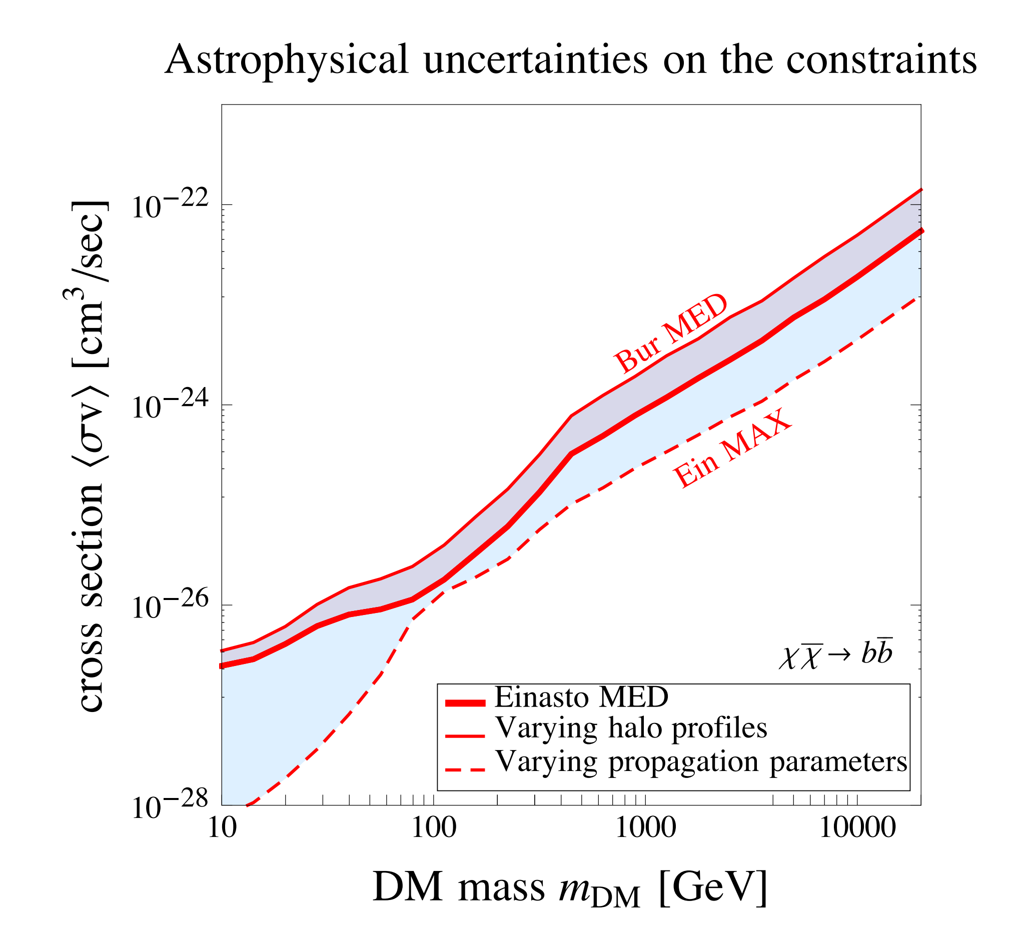
First attempts when updating propagation models with PAMELA & AMS-02 data reach similar conclusions

C. Evoli, D. Gaggero and D. Grasso, arXiv:1504.05175

R. Kappl, A. Reinert and M.W. Winkler, arXiv:1506.04145

Extremely important for Dark Matter constraints!

E.g.: At face value, "surviving" propagation models would independently exclude DM explanation of GC gamma excess



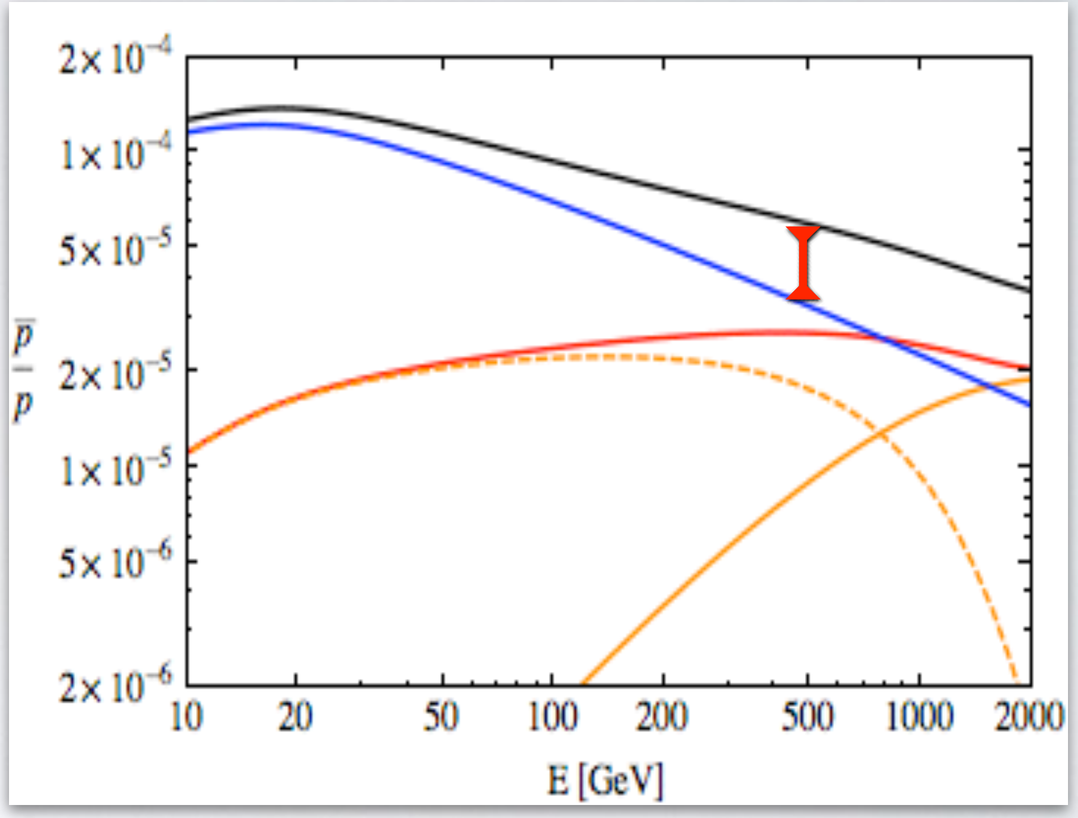
Of course, for a final assessment let's wait for proper analyses of the whole AMS-02 dataset (including, notably, secondary nuclei)

PRIMARY PBAR SOURCES LIKELY!

Just as B/C at high-E could be significantly affected by production at sources, so could anti-p!

Already noted in the past (well before any suspect of anomaly in p-bar was even raised!)

"The good news is that the high-energy range of the antip. spectrum may reveal important constraints on the physics of the CR acceleration sites. The bad news is that it is not straightforward to infer from high energy antip/p-data the propagation parameters [...] our results may change dramatically the perspectives for the detection of DM. An "excess" in the high-energy range of antip/p could not be interpreted anymore uniquely as manifestation of new physics [...]"



P. Blasi and PS, "High-energy antiprotons from old supernova remnants," PRL 103, 081103 (2009) [0904.0871]

Should an antiproton anomaly of this type be measured… don't be so surprised, then!

OTHER ANOMALIES (& PROBES)

Almost all of what I said pertains to locally observed CR fluxes!

If CR in the Galaxy were homogeneously distributed, same fluxes should also apply globally.

But neither CR source distribution nor diffusive propagation expected to be homogeneous!

More difficult & less constrained questions to address, but 2 handles on non-local CR population

Gamma ray flux morphology $$\phi_\gamma \propto \int_{\mathrm{l.o.s.}} \phi_{\mathrm{CR}}\, n_{\mathrm{gas}} \mathrm{d}s$$

Anisotropy $$\mathrm{CR\,(dip.)\,anisotropy} \propto \nabla \phi_{\mathrm{CR}}$$

Perhaps not surprisingly (since linked to things we know relatively little about!)
both associated to long-standing "problems":

gamma-ray gradient problem & anisotropy problem(s)

whose nature & related subjects have lately been investigated a lot, recently

E.g works by C. Evoli, D. Gaggero, D. Grasso, Ahlers, Mertsch, Giacinti…

SOME CONCLUSIONS

Provided that the precision of modern experiments is not illusory *(i.e. systematics are not underestimated)* what is happening in CR physics is a sign of **normal progress** in experimental science, where with higher precision one expects to see "cracks" in the simplest models.

Violation of species **universality and energy-invariant** spectra may be such signs.

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Let me emphasize that this "healthy" progress is rare & extraordinary, for CR physics! When studying CR, I quickly learned an important fact:

"Sec.1.2: Is progress in the cosmic ray field slow?"
It certainly looks like that.

From T. Stanev's "High Energy Cosmic Rays" textbook

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Most pressing issue, in my opinion: to understand how many of these "cracks" are telling us something ***generic*** about CR sources/propagation, and what is instead ***"accidental"*** (e.g. specific position and time of the Galaxy we happen to live at): remember Van der Waals' lesson!

SOME CONCLUSIONS, CONT'D

For sure, more data will help, notably nuclei (both "primary" and "secondary" ones). Understanding the main class in which the solution falls (e.g. source vs. propagation) is probably within reach, but discriminating different models is much more challenging

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Extra tools (multimess. aspects, non-local observables) probably can help but bear in mind the risk of uncontrolled multiplication of parameters

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Antimatter in CR provides extra diagnostic potential, also for DM:

while the one of e^+ is saturating (probably more interesting to see spectral features at high-E in the overall $\mathbf{e^+ + e^-}$) for anti-p significant room for improvement is certainly there, but meaningful studies should wait for release of nuclear data (and, for DM, should seriously account about many sources of uncertainties and astrophysics)

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Merci pour votre attention!