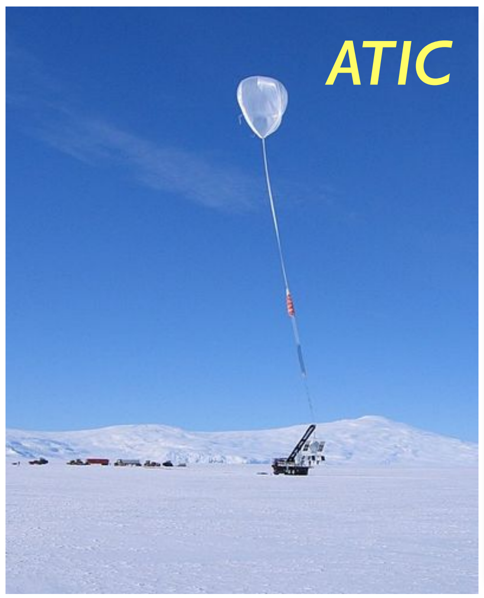
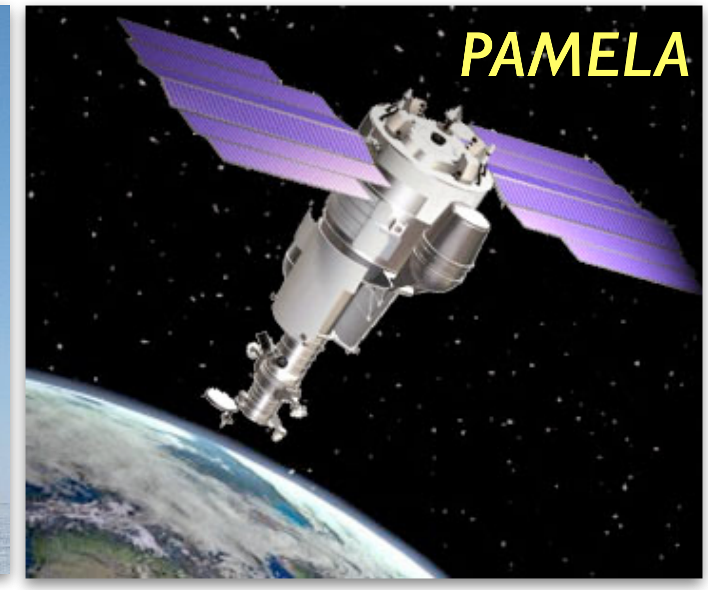
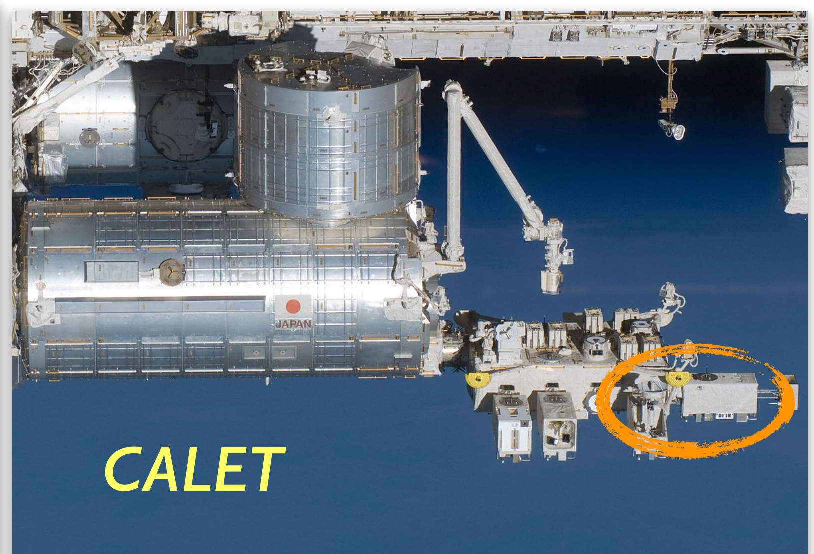
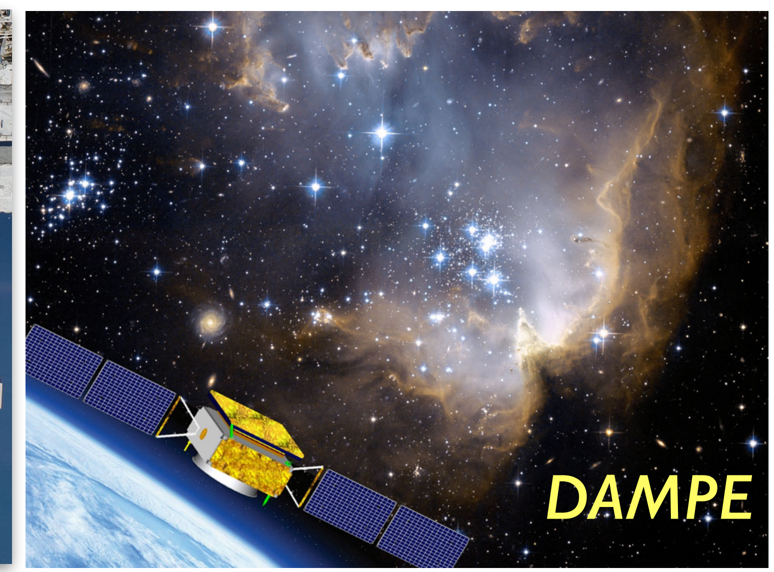
Entering the cosmic ray precision era

***Disclaimer:** I will only deal with (Galactic) cosmic rays & direct detection (no EAS/UHECRs)*









P. D. Serpico (Annecy, France)

IPA 2018 - Oct 12, Cincinnati

Main questions in CR (astro)physics

and main consensual answers (at least for hadrons, and sticking to the "leading order"…)

How is CR acceleration taking place?

Via "diffusive shock acceleration"

In what type of objects?

Predominantly supernova remnants

Where are they located? When did the events happen?

Randomly in the Galaxy, with a size much smaller than typical source-Earth distance, and frequently enough… hence well approximated by a continuum injection term.

How do CRs get to us, after leaving their acceleration sites?

Diffusing into an externally assigned ~ scale-invariant turbulent magnetized medium

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Should we trust them?
Maybe, but that is not the point!

What's great is that we are finally starting to test them!

Some notions about CRs most people believe(d) in

- *We only have access to cosmic ray fluxes "modulated" by heliosphere*
- *Primary fluxes have power-law spectra*
- *Primary spectra have universal (species independent) spectral indices*
- *Positron flux dominated by secondaries*
- *Propagation parameters as dominating uncertainty in theory predictions*

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- *Primary spectra have universal (species independent) spectral indices* ✗
- *Positron flux dominated by secondaries* ✗?
- *Propagation parameters as dominating uncertainty in theory predictions* ✗?

Probably all of them wrong!

Mostly triggered by experimental progress over the past decade

A revisitation and new scrutiny of our (simplest) paradigm is ongoing. Ideally, we would like to match theoretical uncertainties with experimental ones

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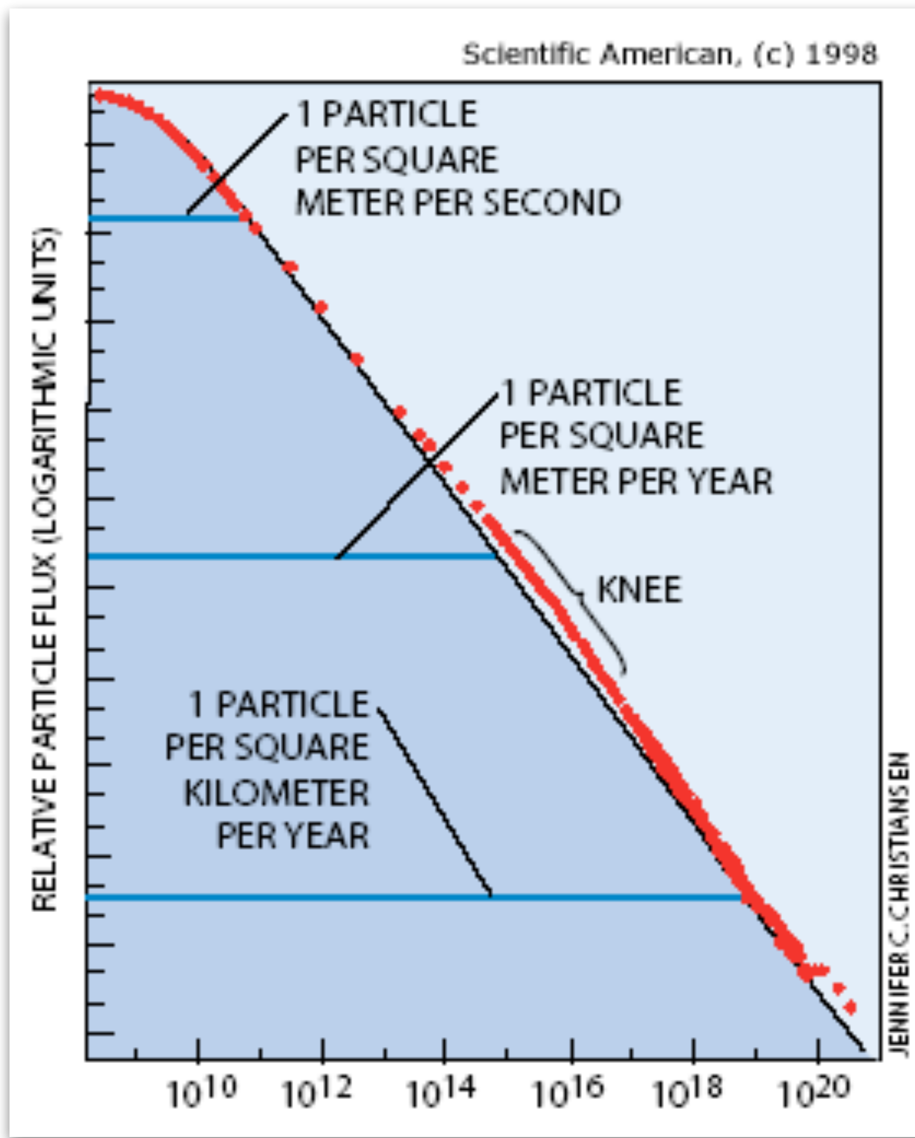
Let me illustrate this theoretical trend with a specific example

Basic consensus: "CRs have power-law spectra"

Probably the most obvious *expectation* about cosmic rays (0th order picture we teach in CR 101) is that, above a few GeV and below the PeV (*Galactic CR regime*) they have

"featureless power-law energy* spectra"

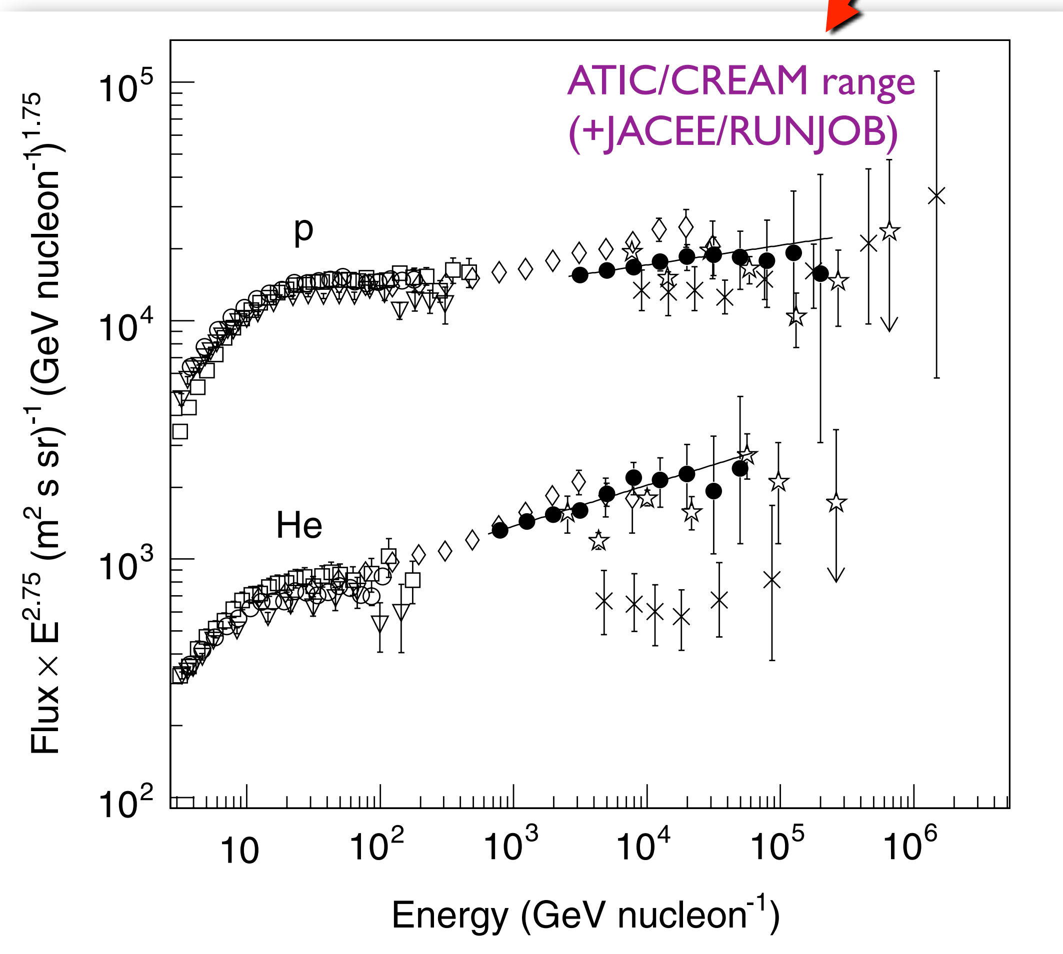


* I will focus on the relativistic regime, hence I won't be pedantic and will often use energy, momentum, and rigidity interchangeably

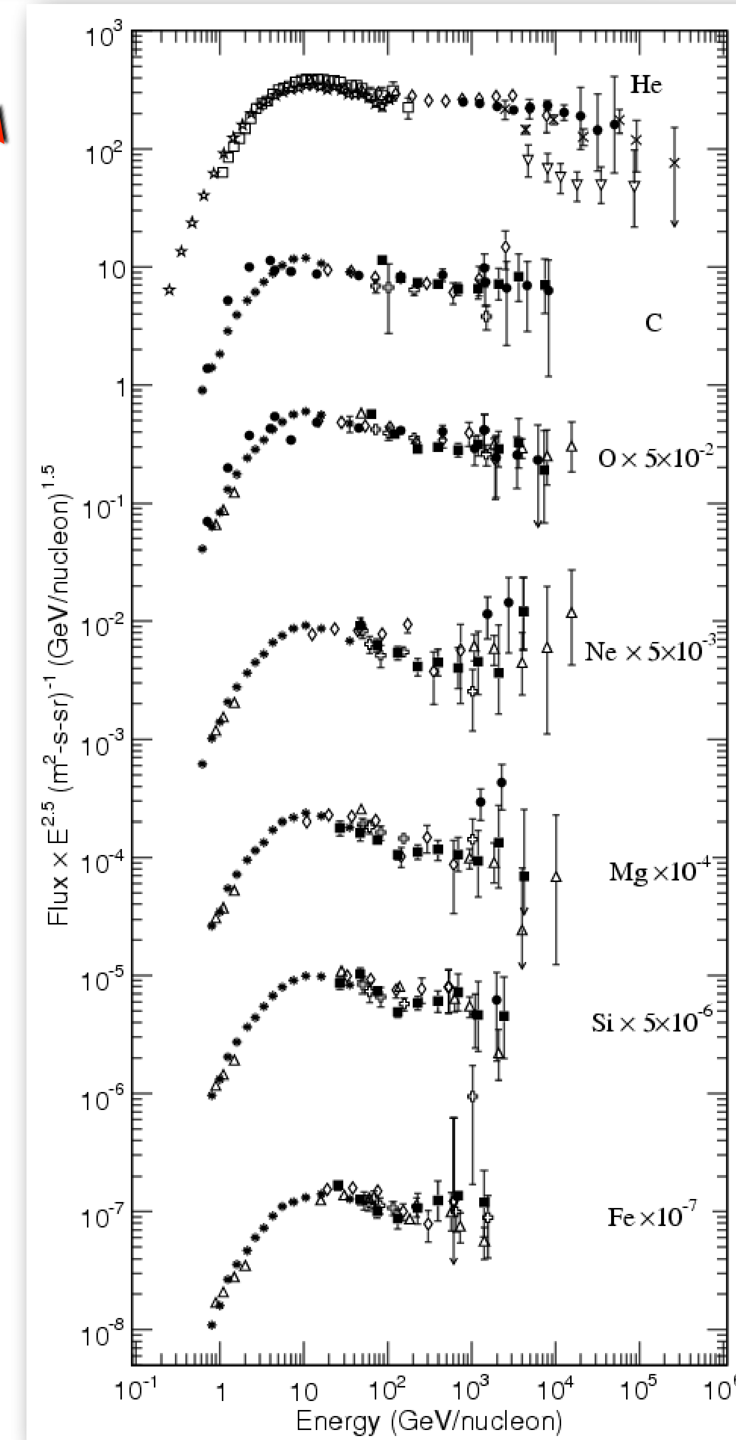
Lots of work rely on/predict e.g. self-similarity (Fermi Theory, Kolmogorov spectrum...)

Cracks in the realm of spherical cows

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!



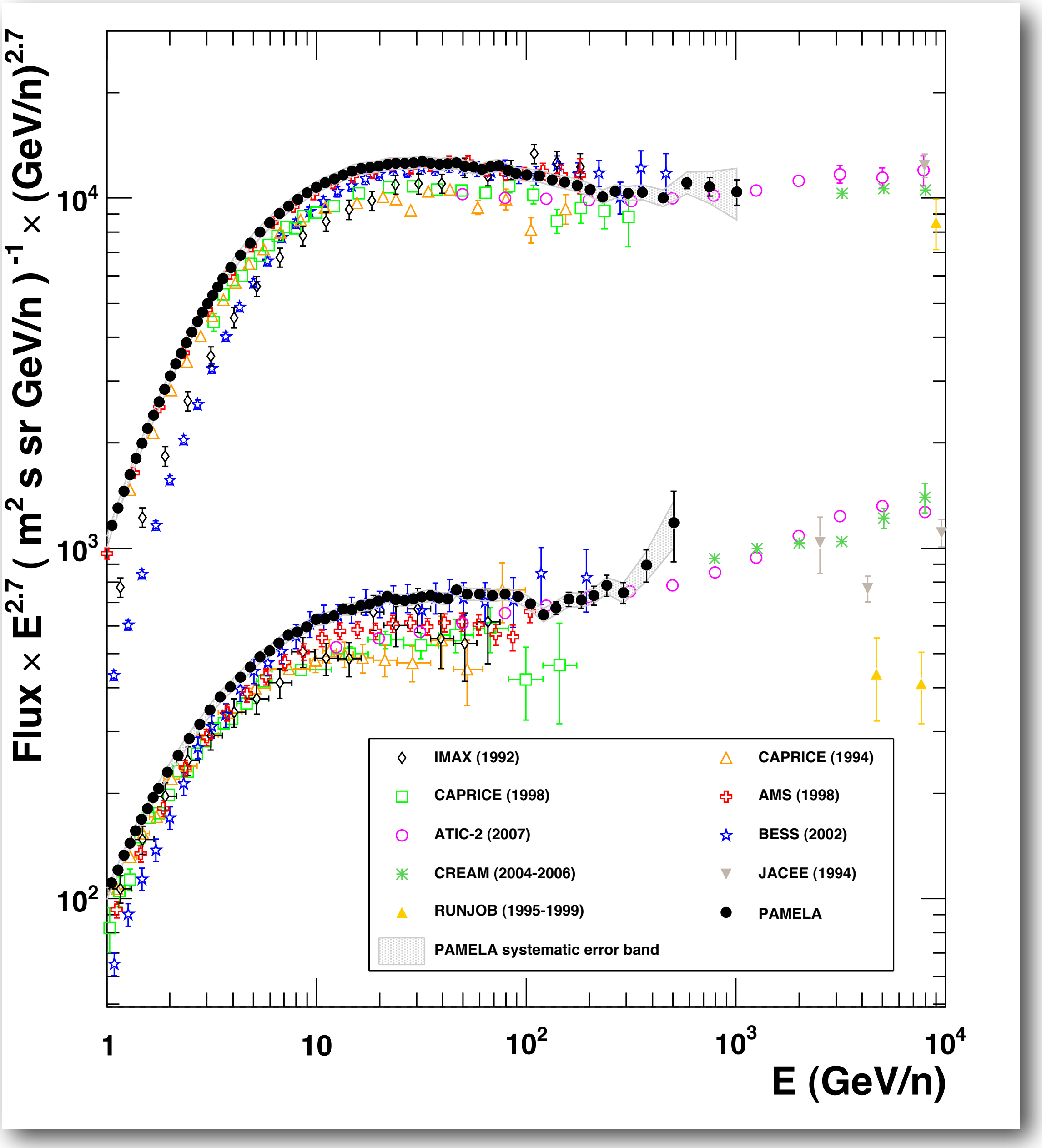
H. S. Ahn et al, ApJ 714 (2010) L89-L93



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

Broken power-laws below the knee!

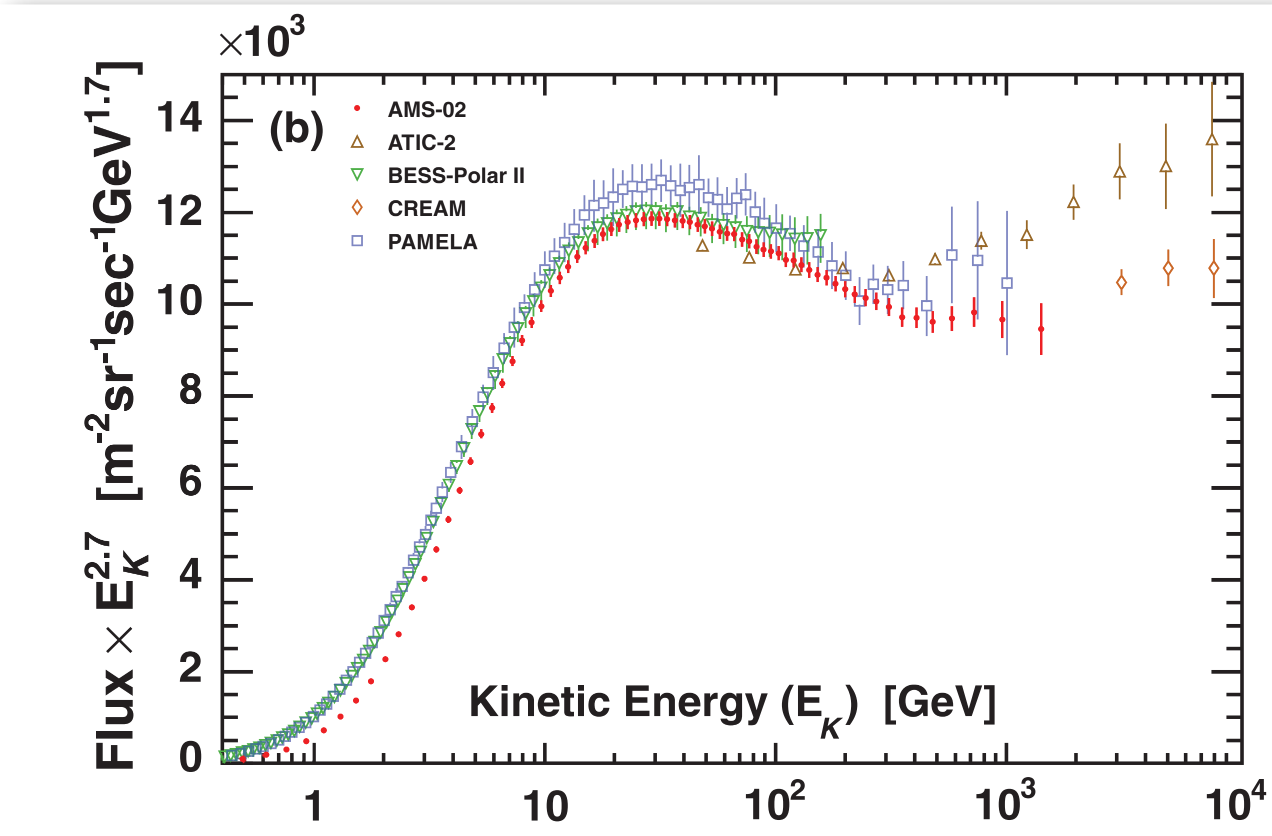
Soon after, PAMELA for the first time directly revealed **the transition in p & He**



Evidence in a single instrument!

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

Eventual confirmation by AMS-02



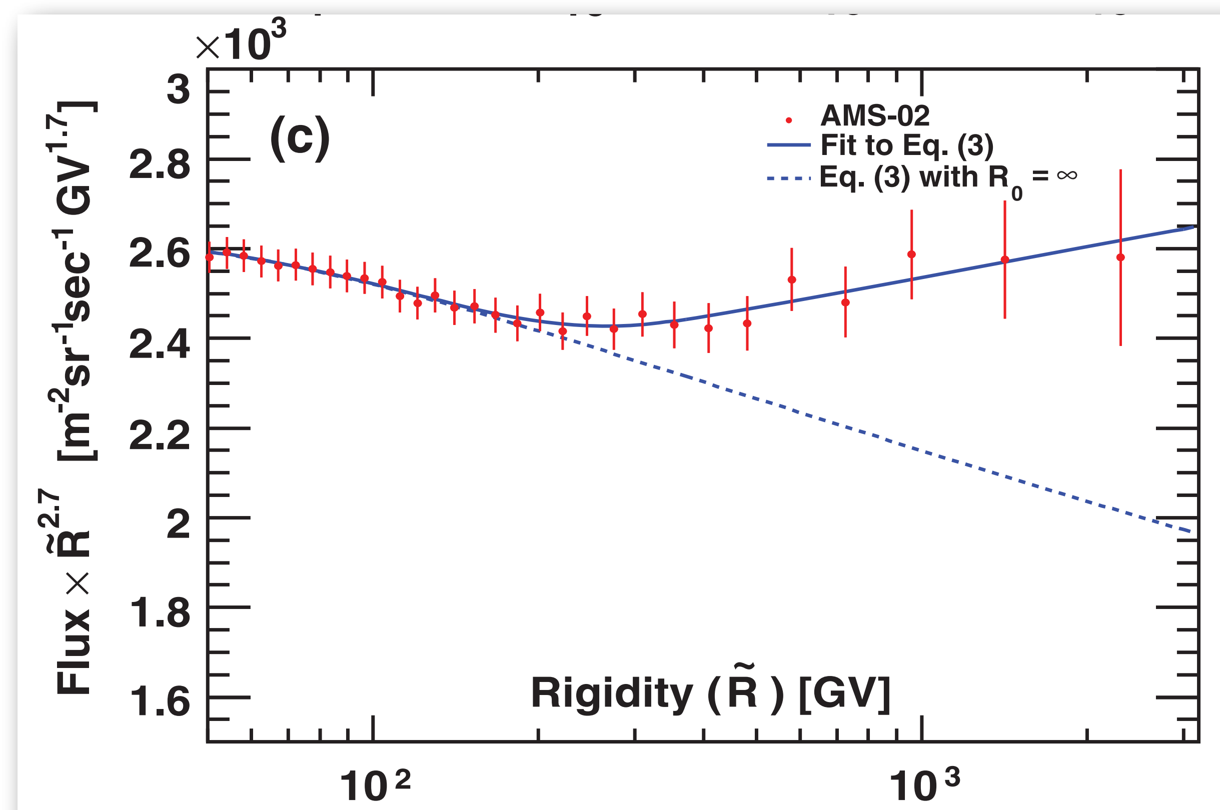
M. Aguilar et al. (AMS Collaboration)
Phys. Rev. Lett. 114, 171103 (2015)

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)

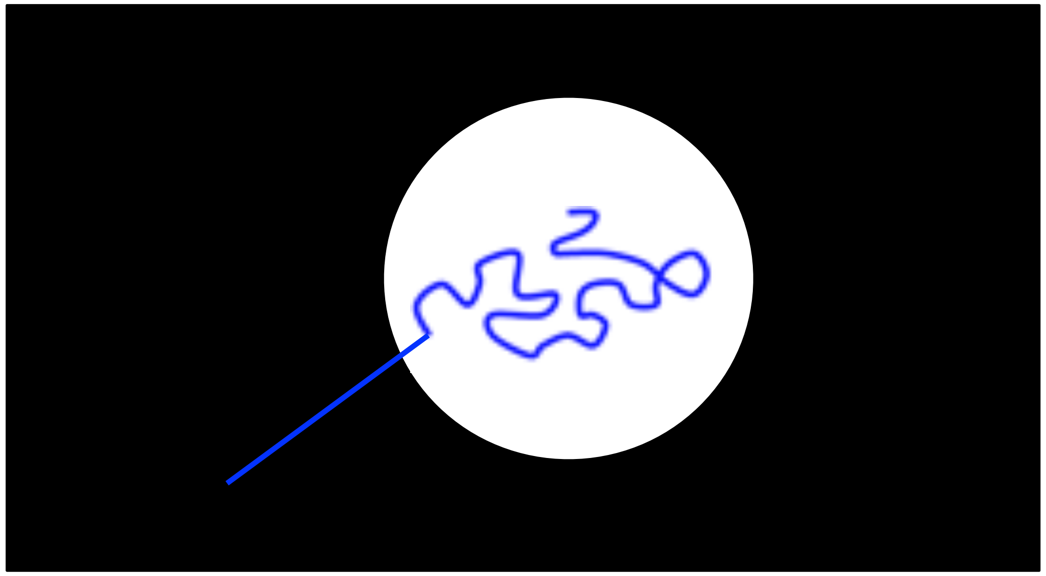


Anything wrong with that?

To assess that, take simplest expectation:

(which, nonetheless, matched data till now…)

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



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

At steady state

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

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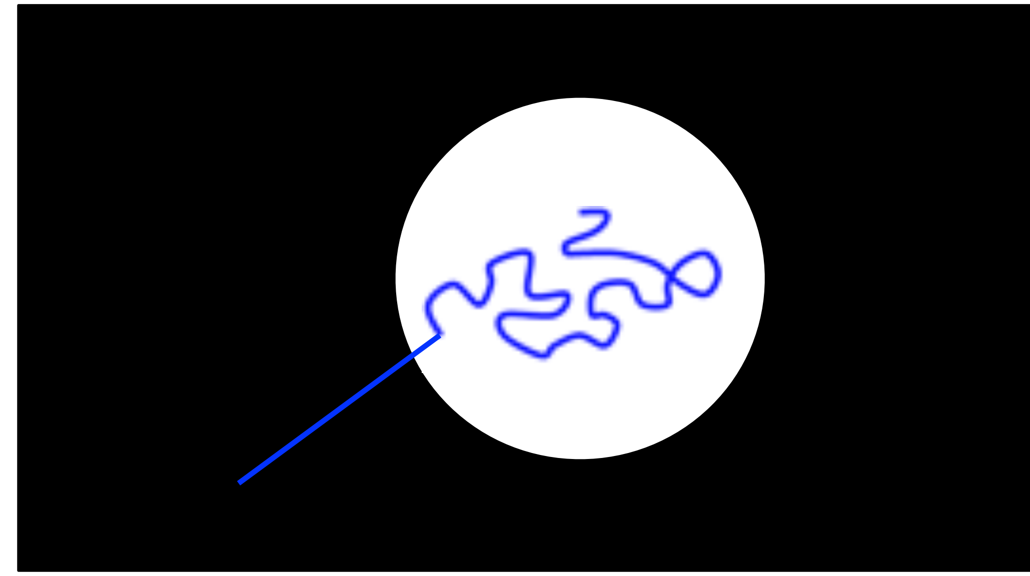

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At steady state

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If both Q and τ~1/K are power-laws… then puzzling!

Naturally suggests (classes of) solutions:

- *Drop K homogeneity (and possibly isotropy)*
- *Drop power-law behaviour in K (**"propagation"**)*
- *Drop power-law behaviour in Q (**"multiple sources, source features"**)*
- *Drop homogeneity in Q (e.g. **"local sources"**)*
- …

I will briefly concentrate on the latter to illustrate some works

Drop homogeneity in Q: local sources

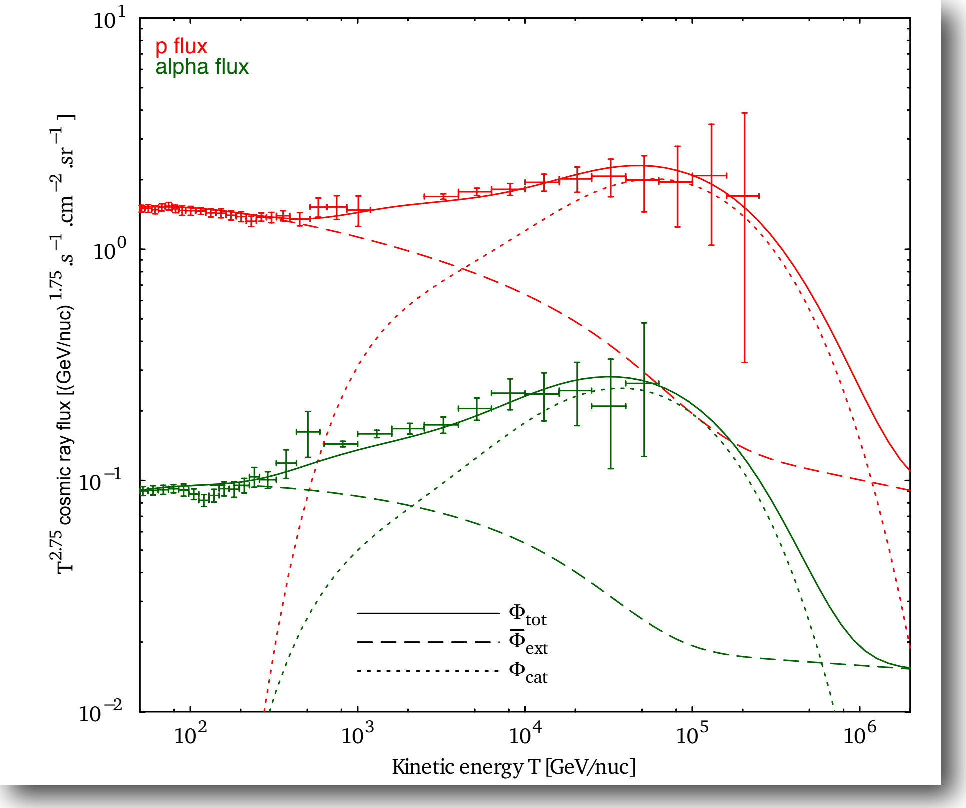
Low-E from average Galactic contribution, hardening due to *local young* sources (treated parametrically or from catalogue). E.g.:

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

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

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

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

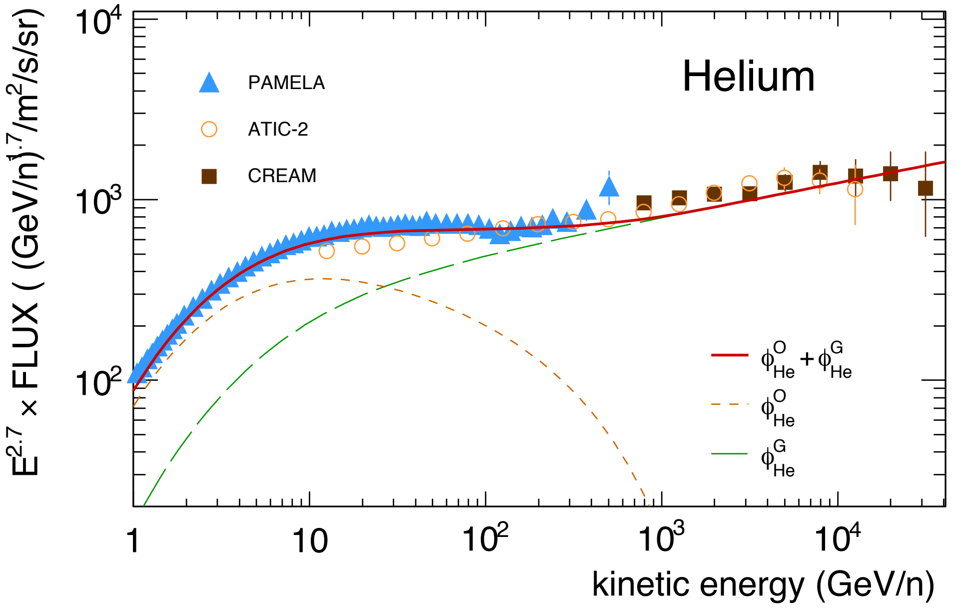


local, old source contributes at low-E & overall contribution of young and further away ones dominates at high-E, like in

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

Or young (~2 Myr) local and steep source at low-E, high-E dominated by average contribution, like in

M. Kachelrieß, A. Neronov, D.V. Semikoz, PRL 115, 181103 (2015) [1504.06472]



(and the list goes on…)

Till recently the *assessment* of these model done "*qualitatively*": (e.g. one typically needs fast diffusion and low supernova rate *in tension with other observations*)

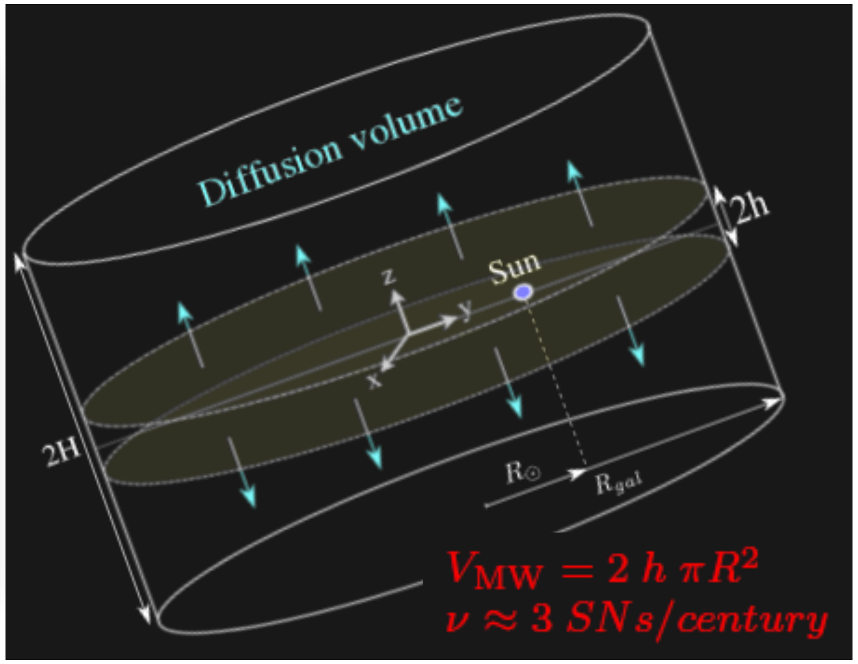
But how likely is the hypothesis in itself, given "Galactic variance"?

A theory for local source effects

Overall flux from N sources $\Psi = \sum_{i=1}^{N} \psi_i$ does not necessarily match "continuum" average $\langle \Psi \rangle = \frac{q\,\nu}{2\pi\,R^2}\frac{h\,H}{K}$

Actual flux obeys prob. distribution obtained as convolution of single pdfs

$$P_N(\Psi) = \int_{\psi_1}\int_{\psi_2}..\int_{\psi_N} p(\psi_1)\,p(\psi_2)..p(\psi_N)\,\delta\left(\sum_i^N \psi_i - \Psi\right)\,\mathrm{d}\psi_1\mathrm{d}\psi_2..\mathrm{d}\psi_N$$



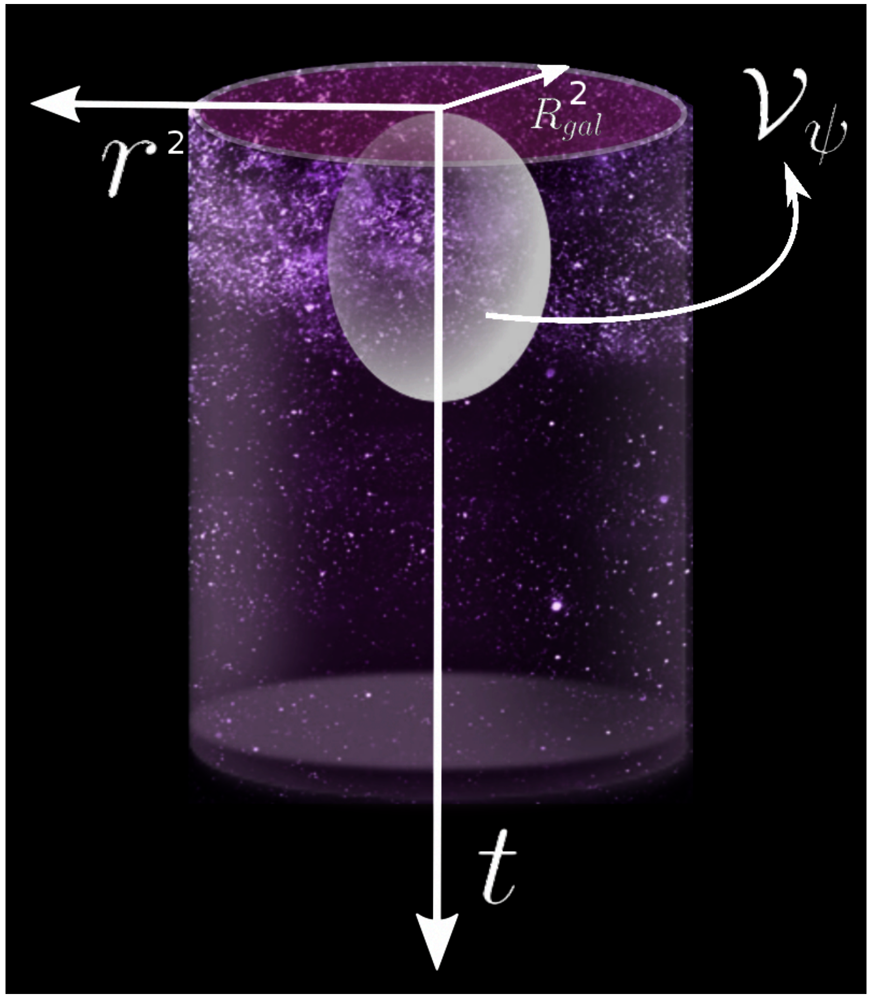
$$\langle \Psi \rangle = N \langle \psi \rangle \qquad \langle \psi \rangle = \int_0^\infty d\psi\, p(\psi)\psi$$

$$p(\psi) = \int_{\mathcal{V}_\psi} \mathrm{d}\mathbf{x}_s\,\mathrm{d}t_s\,\mathcal{D}(\mathbf{x}_s, t_s)$$

normalized distribution in space & time for 1 source

Integration over domain of space & time that gives a flux ψ associated to the diffusive solution

$$\psi = \frac{q}{(4\pi K\tau)^{3/2}}\exp\left(-\frac{d^2}{4K\tau}\right)$$



Y. Génolini, P. Salati, PS, R. Taillet, Astron. Astrophys. 600, A68 (2017) [1610.02010]

A theory for local source effects, II

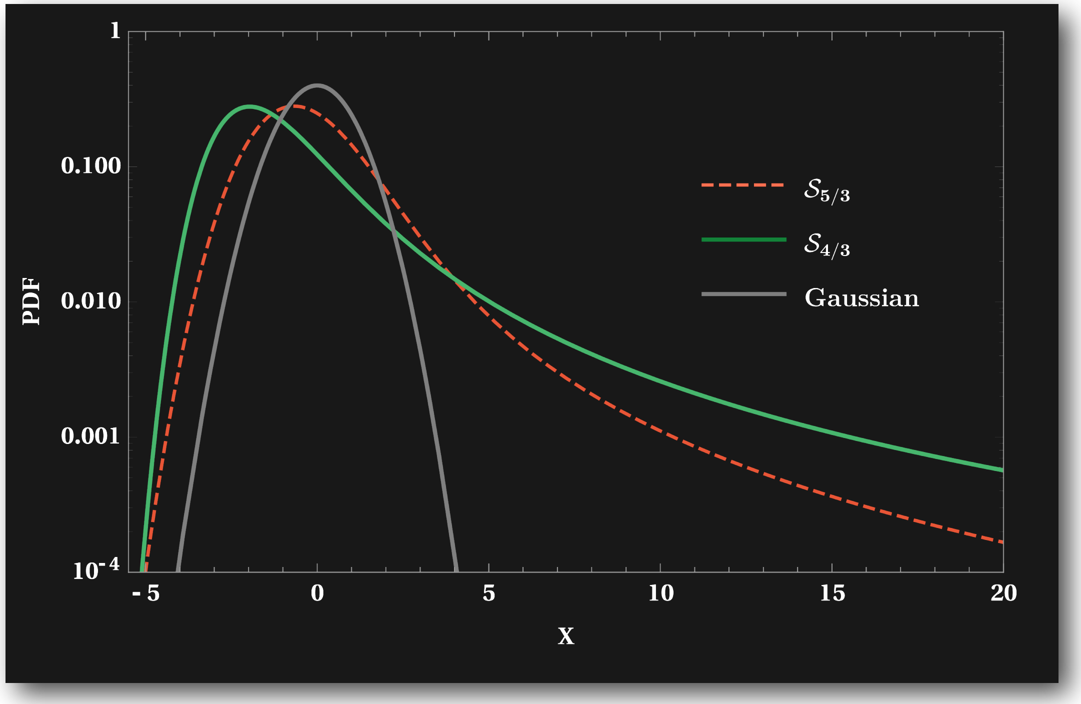
$$\text{At } \psi \gg \langle\psi\rangle\,,\;\; p(\psi) \propto \begin{cases} \psi^{-8/3} & \textit{high-flux/nearby/3D config.} \\ \psi^{-7/3} & \textit{low-flux/far/2D config.} \end{cases}$$

→ *e.g. infinite variance!*

Central Limit Theorem does not apply, fat-tail distributions!

Yet, generalized CLT applies: ***Stable Laws*** characterized by index α=5/3 (3D) or 4/3 (2D) replace Gaussians

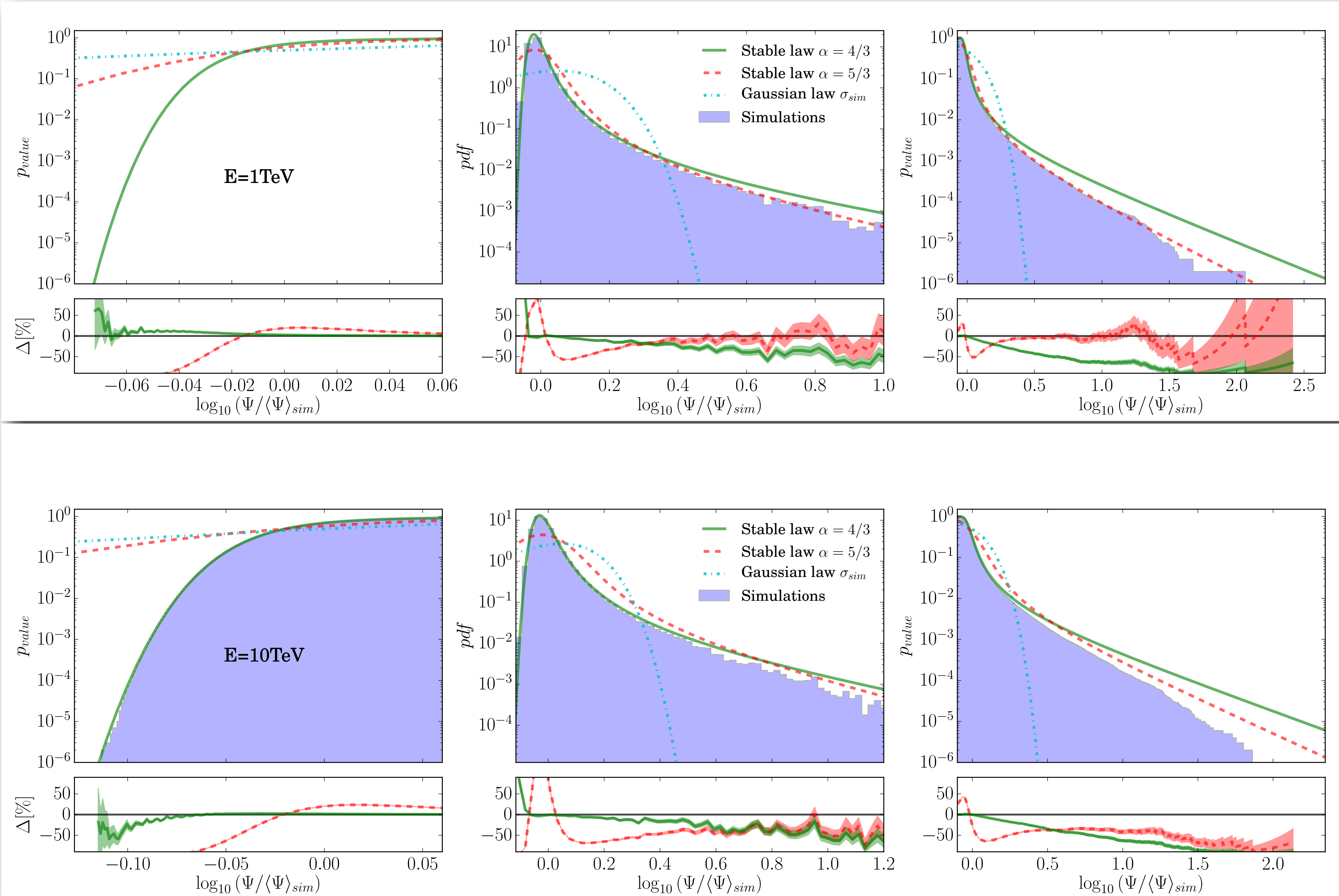
These-known-distributions can then be used to set confidence intervals, compute p-values…



Subtlety: causality in Special Relativity & constraints from "local info" (e.g.:No SN in the Solar System in historical time) still impose maximal flux ϕ_c→ CLT applies, but convergence for $\phi<\phi_c$ attained for a too large *N* compared with what physically interesting (checked via Monte Carlo)

Y. Génolini, P. Salati, PS, R. Taillet, Astron. Astrophys. 600, A68 (2017) [1610.02010]

A theory for local source effects, III



In a range of E and for not to extreme fluctuations, "3D" and "2D" Stable Laws provide a good approximation of the actual distribution obtained by numerical simulations

Y. Génolini, P. Salati, PS, R. Taillet, Astron. Astrophys. 600, A68 (2017) [1610.02010]

A theory for local source effects, IV

Generic consequence:

with current exp. precision, **sizable probability to see deviations from average theory predictions**, even if the model is correct!

Models	PAMELA		AMS02	
Model	50GeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$	1TeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$	50GeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$	1TeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$
MIN	0.15 0.13	0.083 $< 10^{-6}$	0.28 0.63	0.26 0.51
MED	0.047 $< 10^{-6}$	0.014 $< 10^{-6}$	0.16 0.26	0.12 0.0025
MAX	0.009 $< 10^{-6}$	0.0018 $< 10^{-6}$	0.045 $< 10^{-6}$	0.016 $< 10^{-6}$

But does it explain "the break"? Not very likely!

Models	MIN	MED	MAX
Probabilities(Stable law 4/3)	0.031	0.0082	0.0013

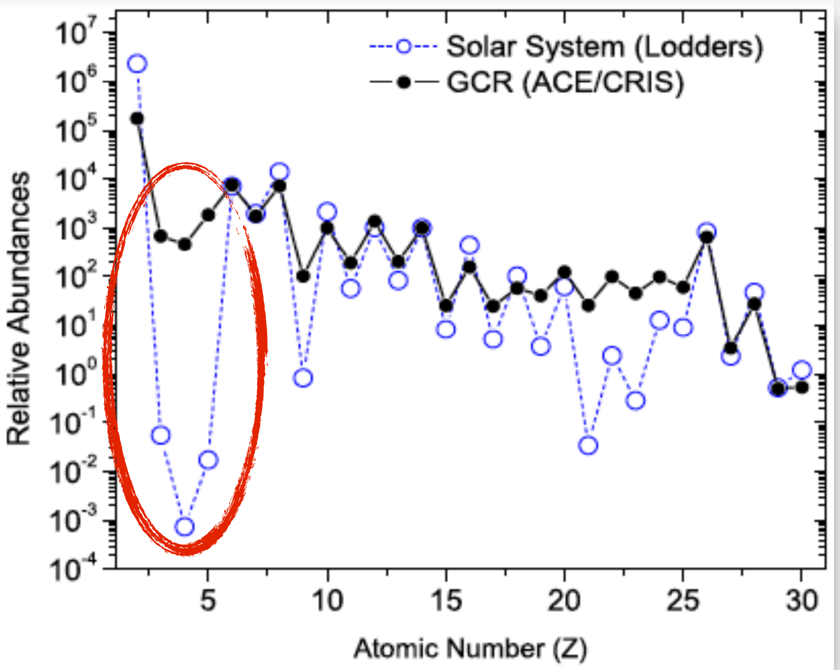
Next on theory wishlist: energy correlations, anisotropies (currently only doable with extensive MC)

Towards a test of break models: secondaries

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)



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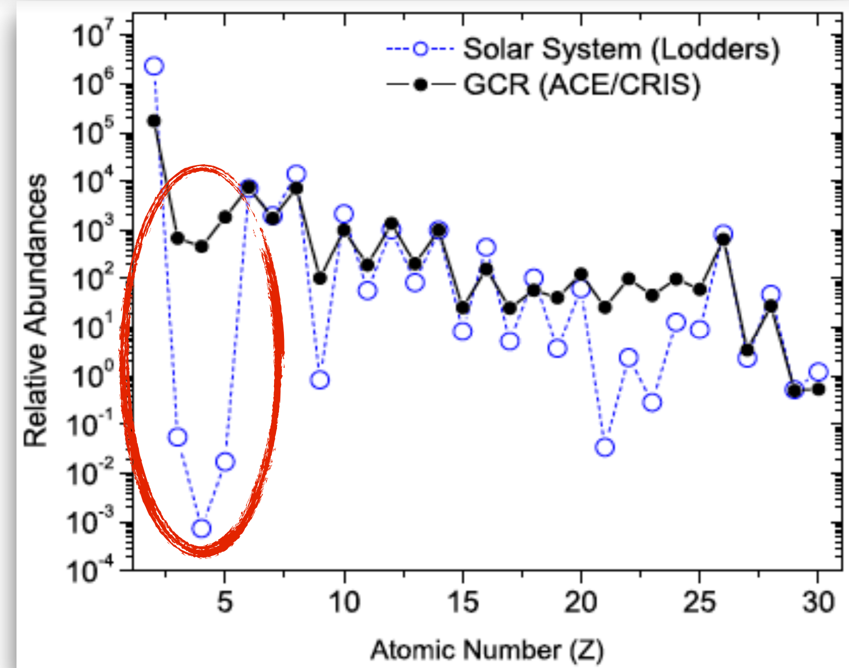


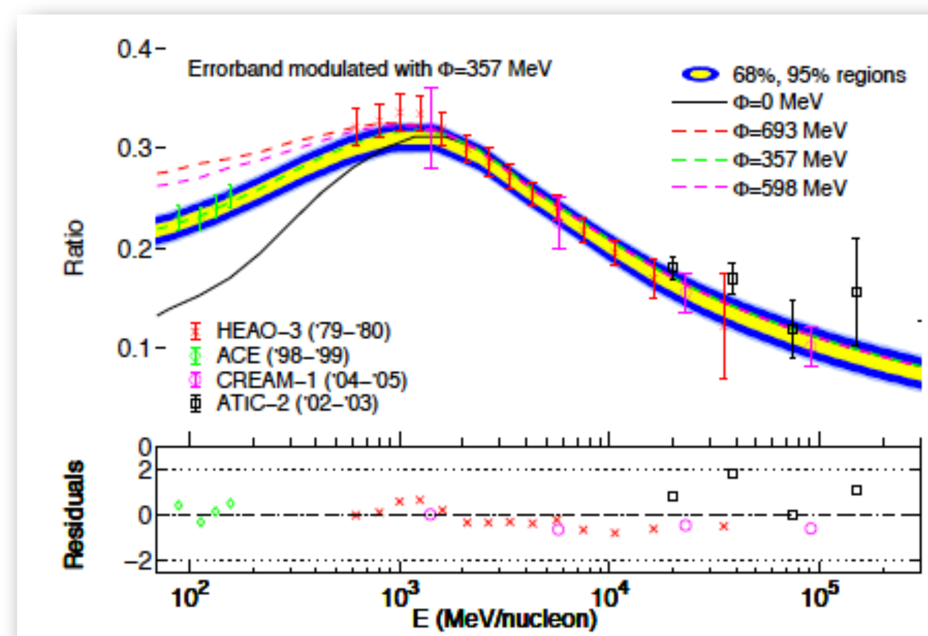
If a type of nucleus is not present as primary, but only produced as secondary via collisions (this includes e.g. Boron) then

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

yielding $$\frac{\Phi_s}{\Phi_p} \propto \tau_{\rm diff}(E) \propto 1/K(E) \propto E^{-\delta}$$ typically inferred from B/C

(modulo uncertainties in the x-section!)

typical fits $$K(R) \sim 10^{28} \div 10^{29}\left(\frac{R}{3\,{\rm GV}}\right)^{0.2\div0.6}\,{\rm cm}^2/{\rm s}$$



see e.g. Trotta, Johannesson, Moskalenko et al. ApJ 729, 106 (2011)

Testing break models

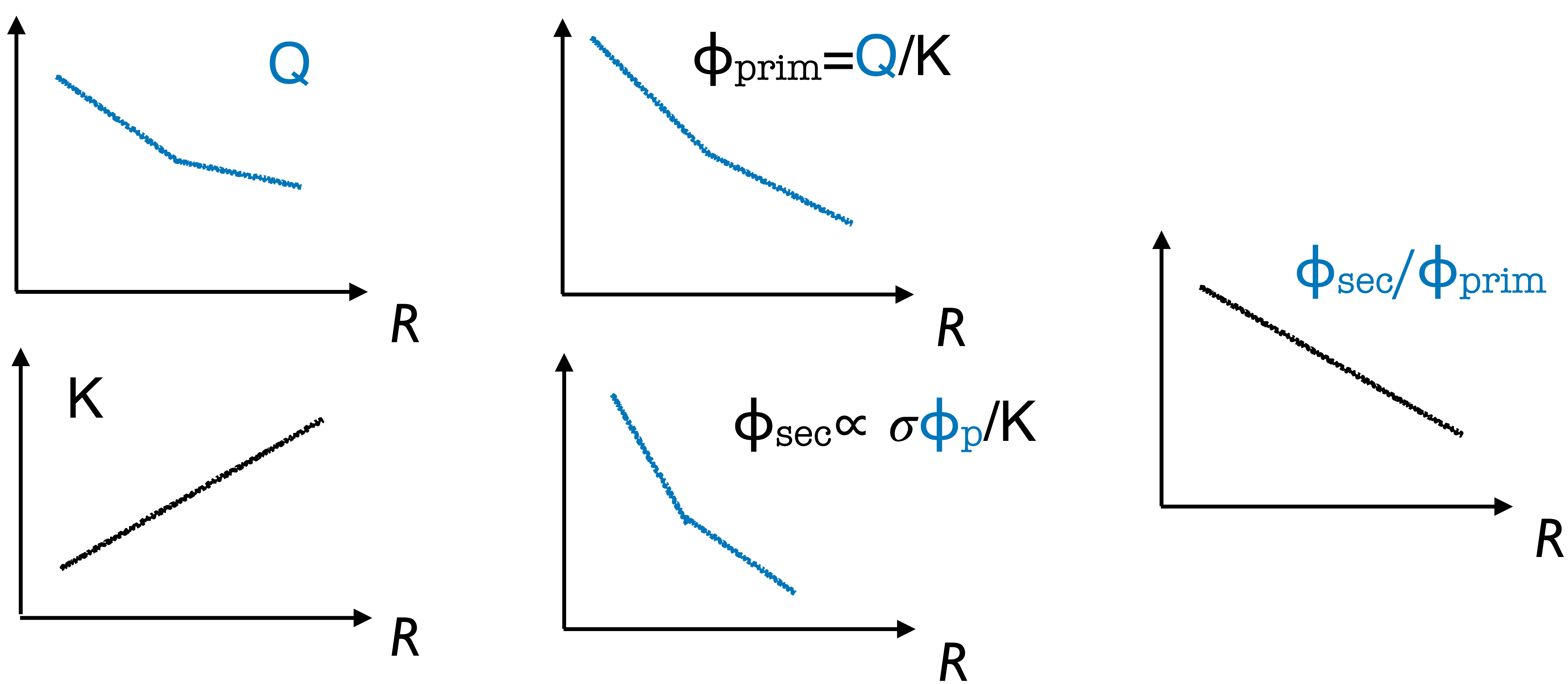
Main <u>diagnostics: from secondaries</u>, notably (but not exclusively!) B/C

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



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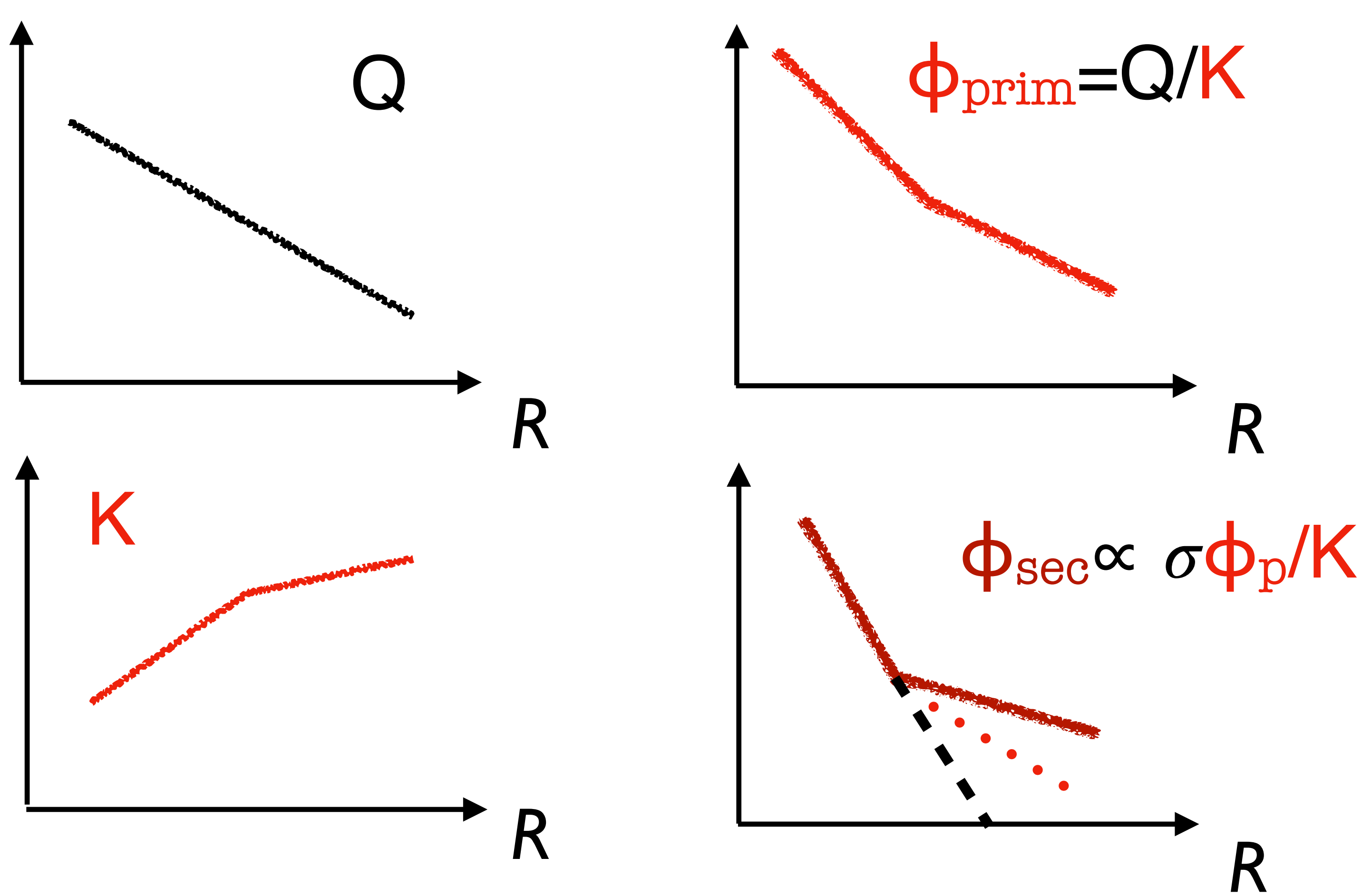
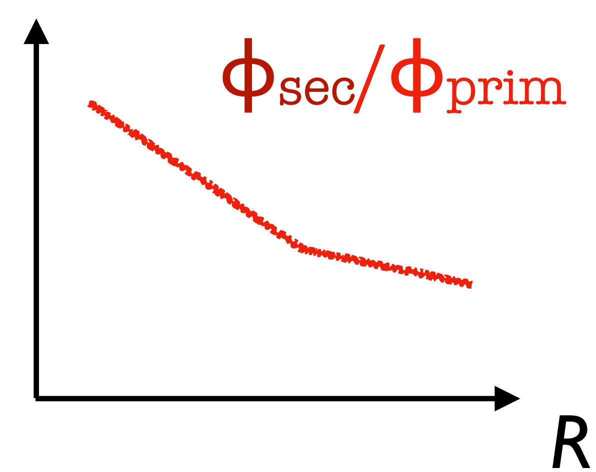


** "distributed reacceleration" would have different features, but does not appear phenomenologically viable*



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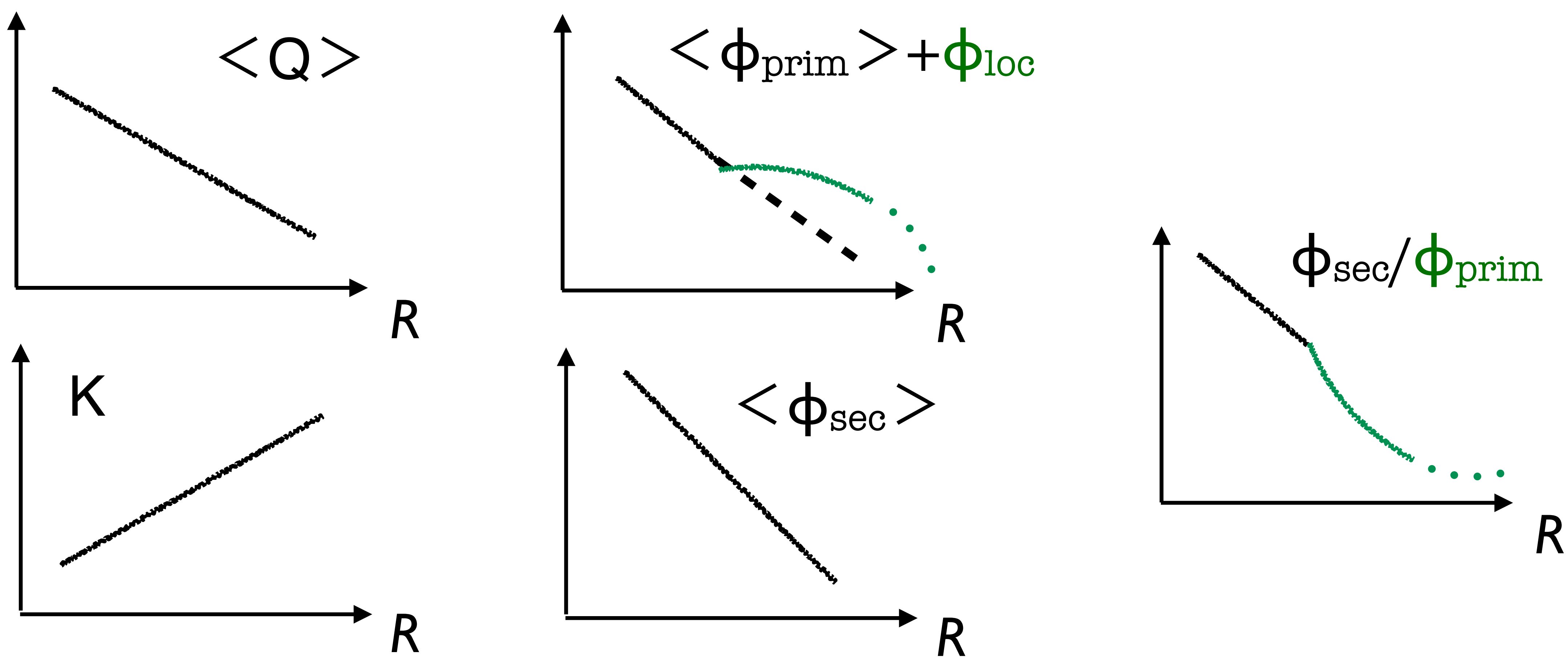
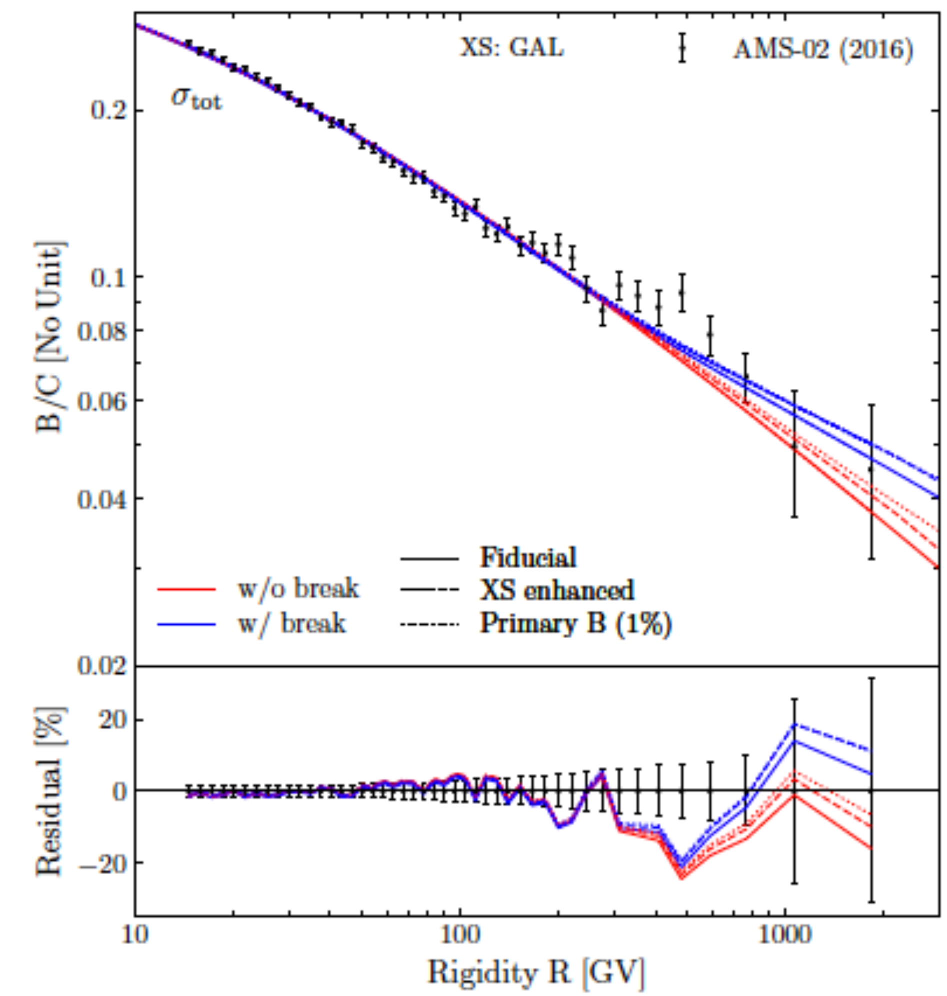


Testing break models: a first analysis

We performed a first *a priori* test in this sense, comparing a baseline model with featureless *K(R)* vs. case with a break *with* parameters fixed by the p & He data

$$K(R) = K_0\,\beta\,(R/\mathrm{GV})^{\delta} \qquad K(R) = K_0\,\beta\,\frac{(R/\mathrm{GV})^{\delta}}{\left\{1+(R/R_b)^{\Delta\delta/s}\right\}^{s}}$$

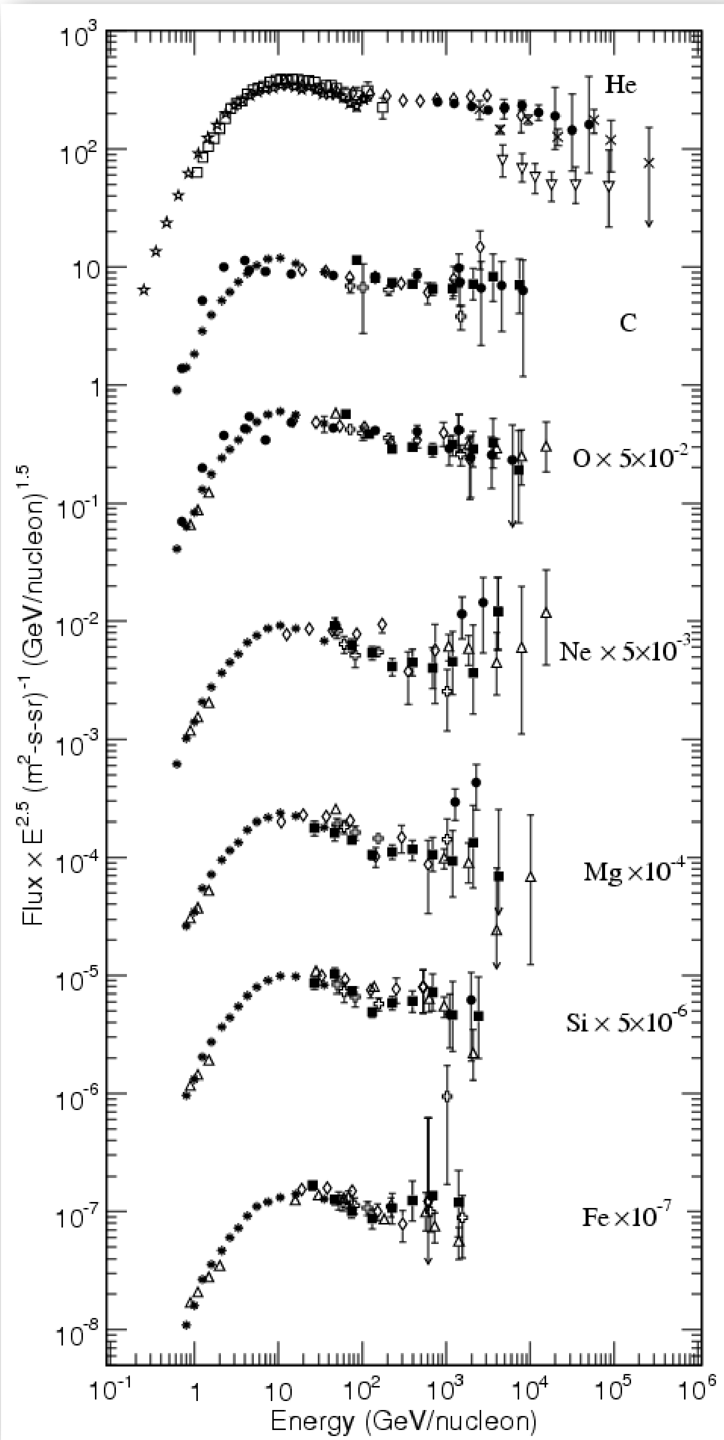
- *Same (limited) number of free parameters*
- *Tested impact of different treatment of AMS-02 systematic errors*
- *Tested impact of x-sec uncertainties as well as flat high-E dependence vs. $\log^2 s$ growth*
- *Tested impact of expected amount of "grammage at the source" (source "secondaries")*



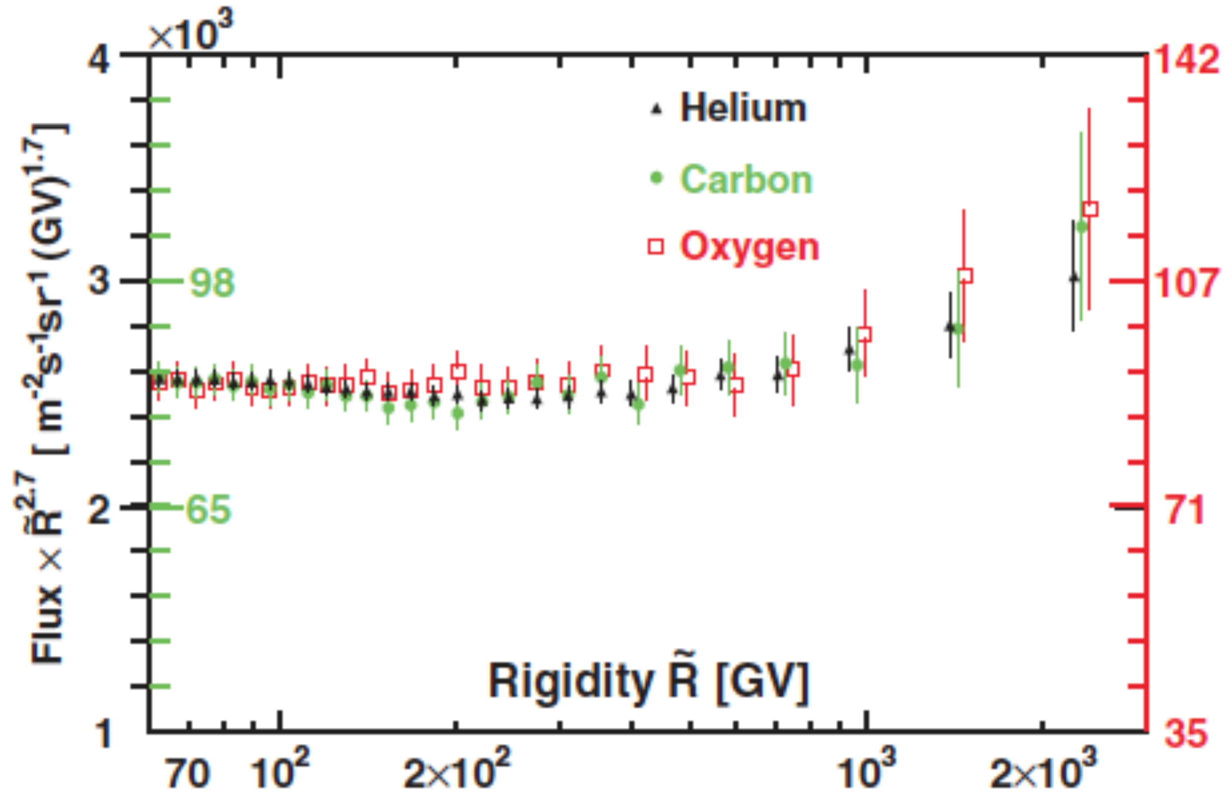
In all cases a ***sizable preference*** for broke K obtained ($\Delta\chi^2$>10)

Y. Génolini, PS, et al. ``Indications for a high-rigidity break in the cosmic-ray diffusion coefficient," Phys. Rev. Lett. 119, 241101 (2017) [1706.09812]

Since then: 1. Clear indications of universality



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



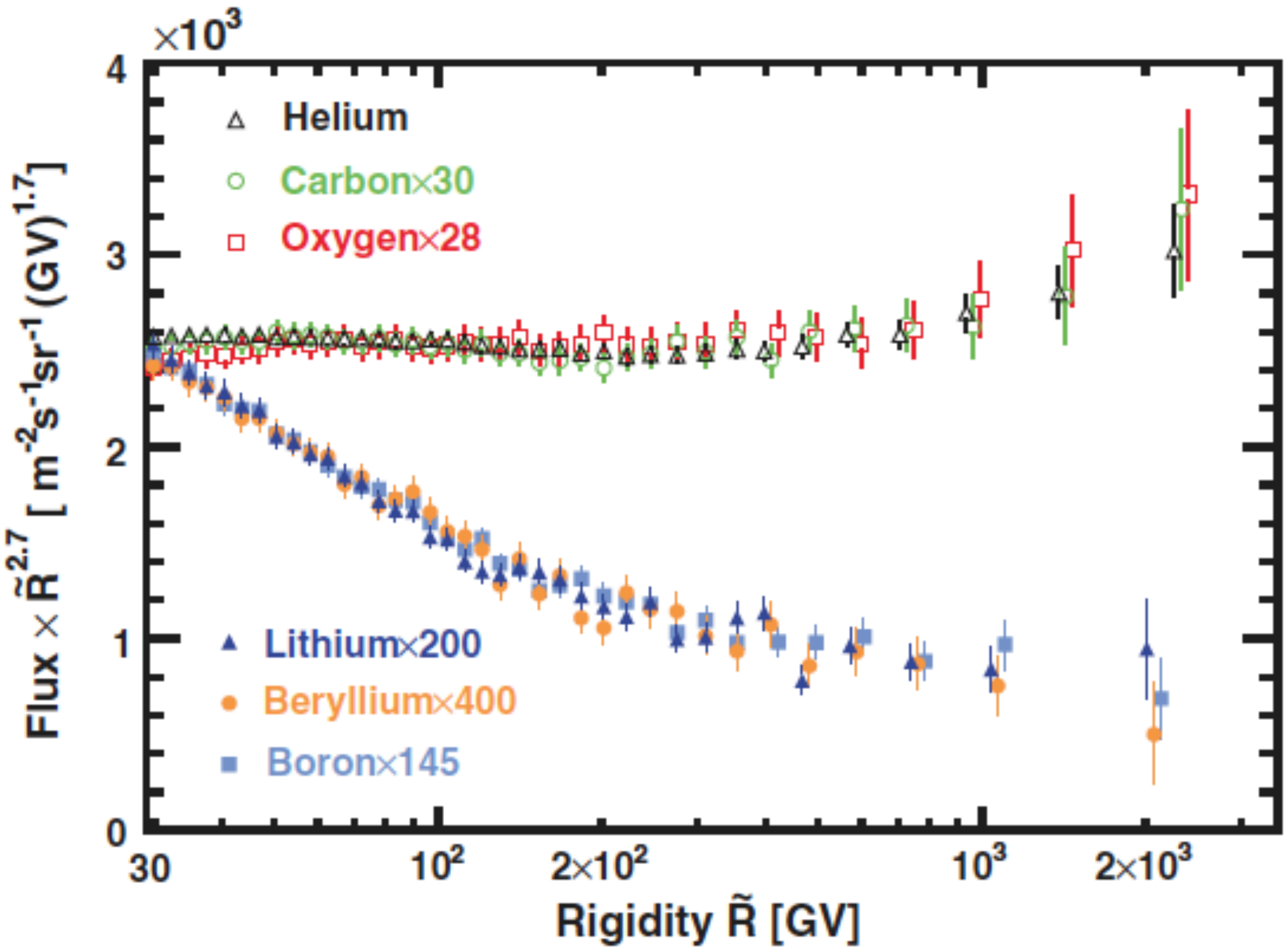
M. Aguilar et al. [AMS-02], "Observation of the Identical Rigidity Dependence of He, C, and O Cosmic Rays at High Rigidities by the Alpha Magnetic Spectrometer on the International Space Station" Phys. Rev. Lett. 119, 251101 (December 2017)

"Above 60 GV, these three spectra have identical rigidity dependence. They all deviate from a single power law above 200 GV and harden in an identical way."

One more prediction of the hypothesis passed

Since then: II. secondaries show more pronounced break

Yet another success!



"All three fluxes have an identical rigidity dependence above 30 GV […]. The three fluxes deviate from a single power law above 200 GV in an identical way. […] Above 200 GV, the secondary cosmic rays harden more than the primary cosmic rays."

M. Aguilar et al., "Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron by the Alpha Magnetic Spectrometer on the International Space Station" Phys. Rev. Lett. 120, 021101 (January 2018)

Some ideas on the causes

Diffusion as responsible for the breaks naturally accounts for universality of primary breaks + larger & universal break in secondaries. Different models for **causes** of the feature in K, e.g.

K not separable into rigidity and space variables:

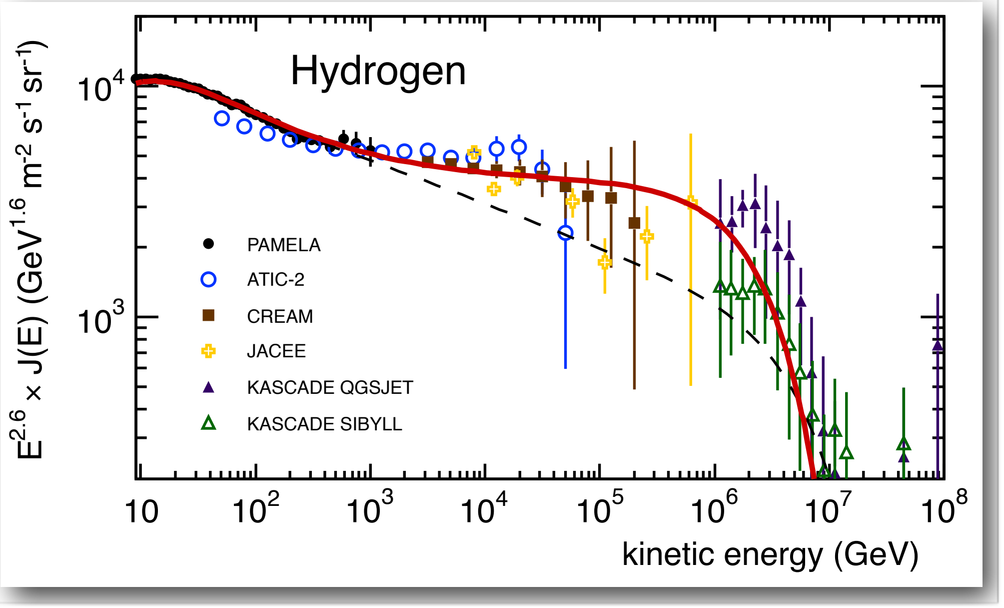
N.Tomassetti, Astrophys. J. 752, L13 (2012) [arXiv:1204.4492].

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

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

$\xi \sim 0.1$

$L \sim 5$ kpc



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

+ Relatively flexible, good fits

- No microscopic understanding of parameter values

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K not separable into rigidity and space variables:

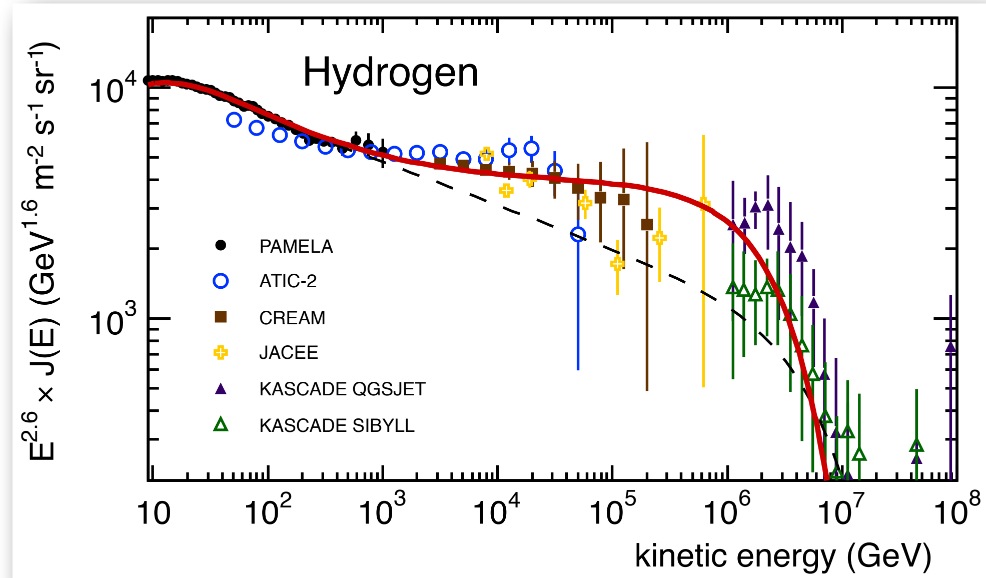
N.Tomassetti, Astrophys. J. 752, L13 (2012) [arXiv:1204.4492].

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

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

ξ~0.1

L~5 kpc



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

- \+ Relatively flexible, good fits
- \- No microscopic understanding of parameter values

Non-linear coupling of CRs with K:

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

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

- \+ Quite constrained, yet acceptable fits
- \- Hard to generalize to higher-K due to nonlinearities

(not mutually exclusive either!)

Associated expectations

Link between source distribution & diffusion coefficient ***(inhomogeneity in K, also radial)***

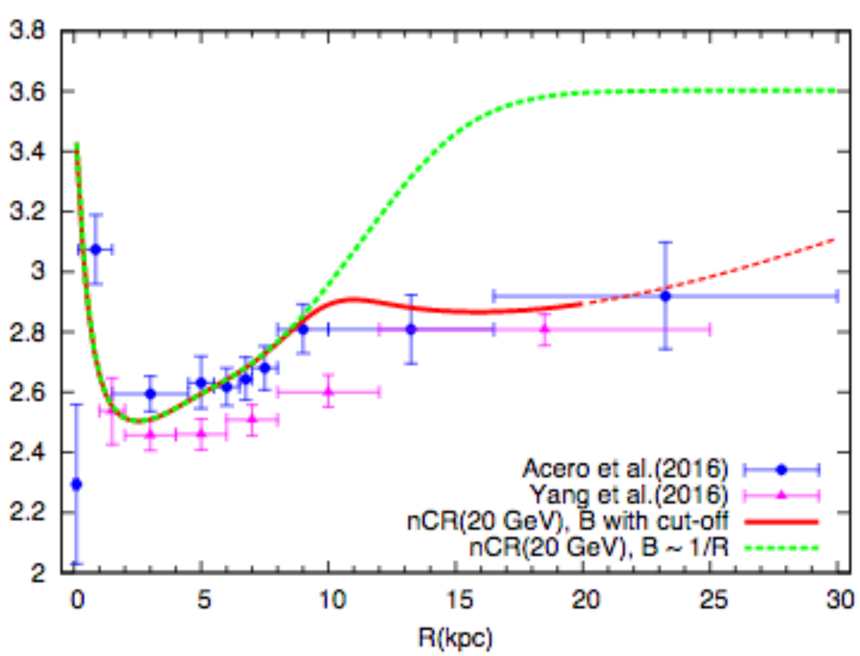
Phenomenological fits show reconciliation of the theory with too shallow gradient in diffuse γ-emission seen by Fermi, & relatively low anisotropy of single diffusion models

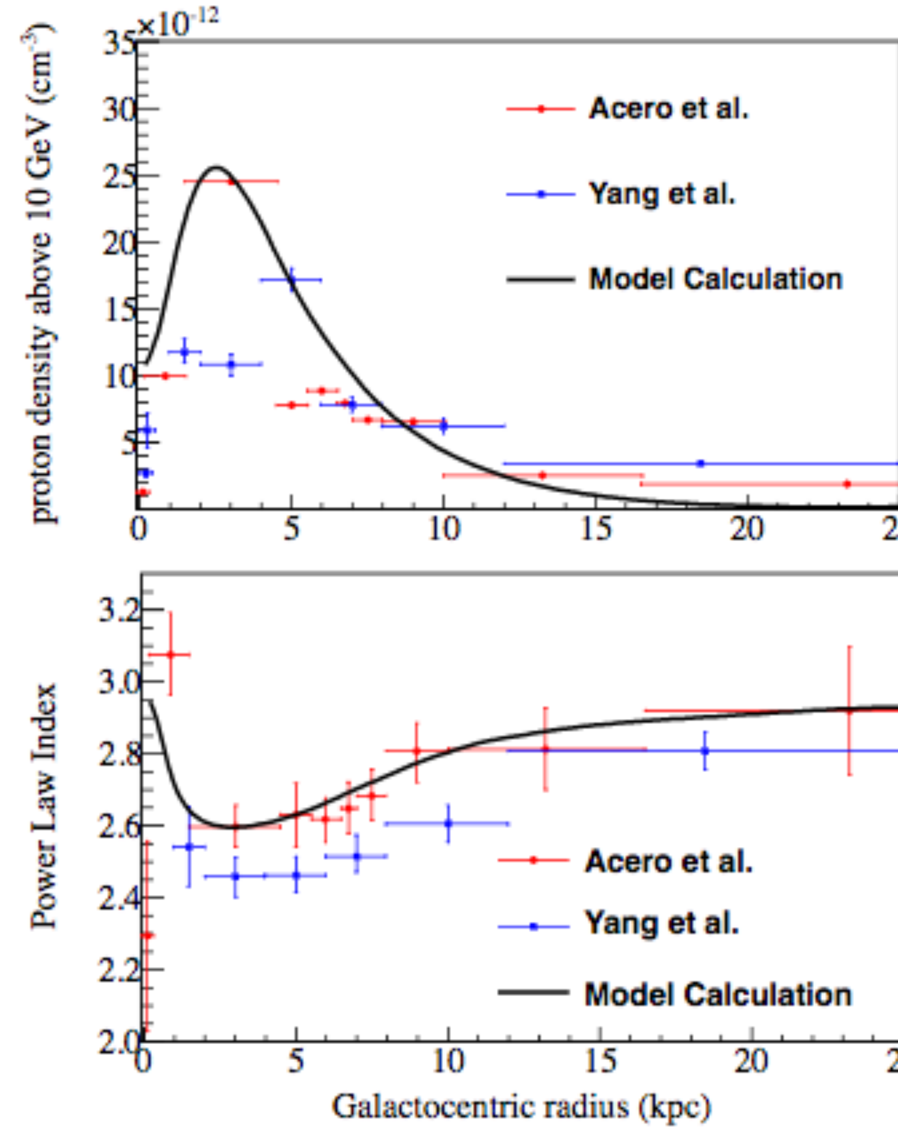
C. Evoli et al., "A common solution to the cosmic ray anisotropy and gradient problems," Phys. Rev. Lett. 108, 211102 (2012) [1203.0570]

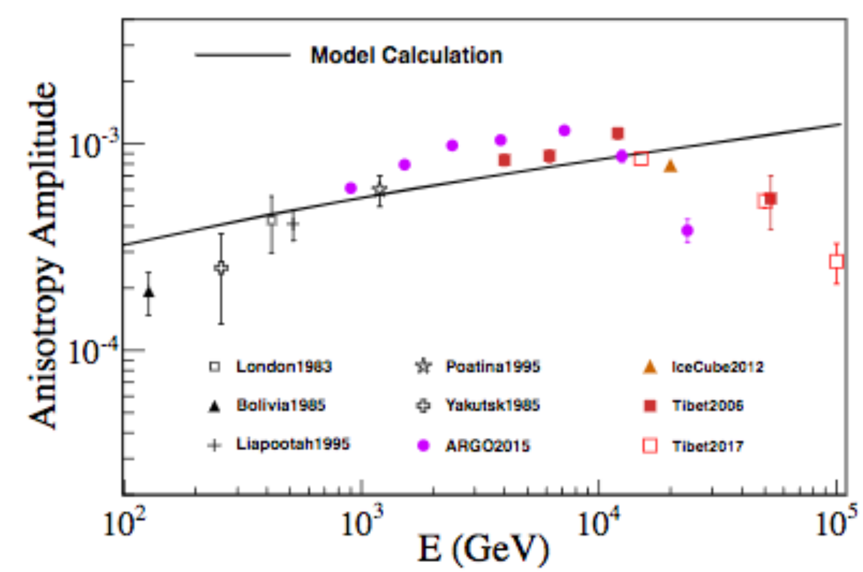
Even recently confirmed within "multi-zone" Tomassetti's model in *Y. Q. Guo and Q.Yuan, 1801.05904 (plots to the right)*

within some approximations, can be reproduced in the non-linear model (regular magnetic field dependence is required)

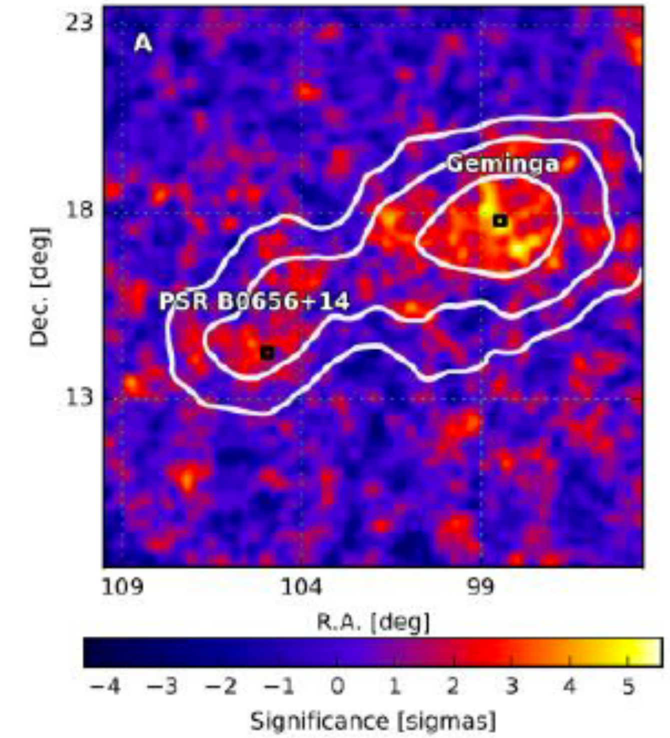
S. Recchia, P. Blasi and G. Morlino, MNRAS 462, L88 (2016)[1604.07682]







Hints from HAWC

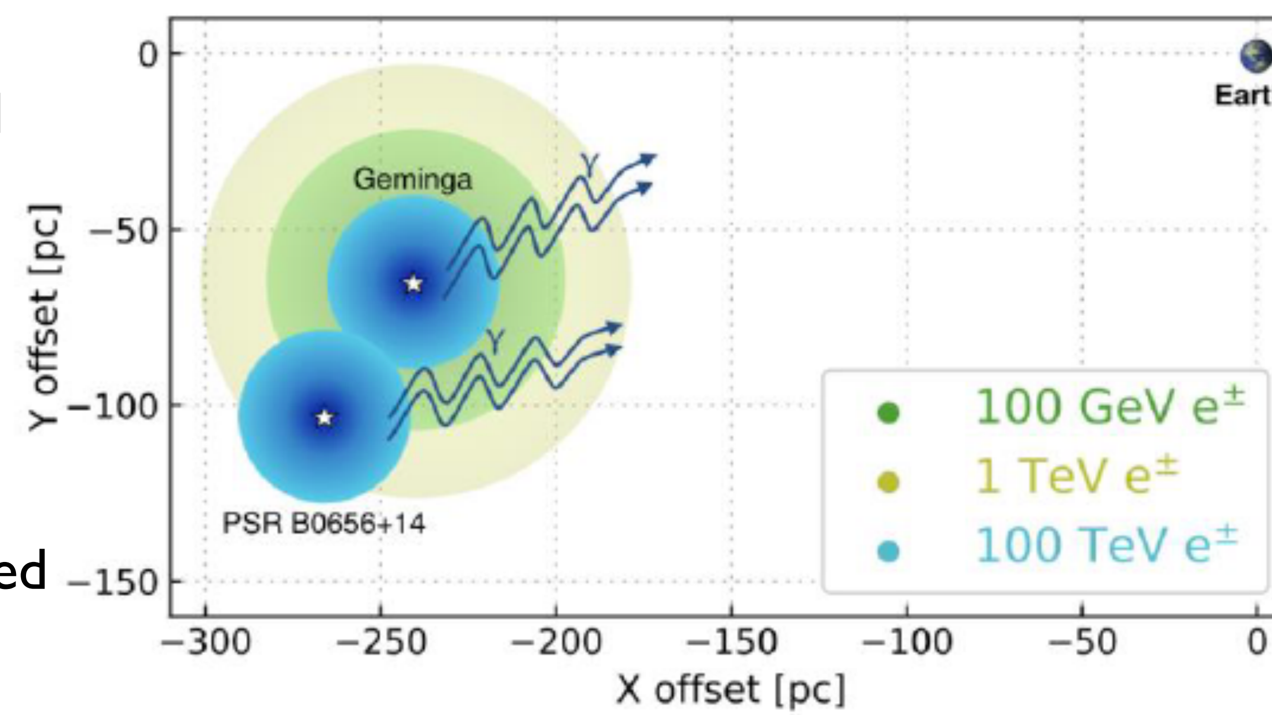


HAWC has detected (not-so-)extended TeV γ-emission around pulsars (PWN)

A. U. Abeysekara et al. [HAWC Collaboration], Science 358, no. 6365, 911 (2017) [1711.06223]

This is most obviously interpreted as a diffusion around pulsars (PWN) much slower (i.e. inefficient) than the ISM average value

S. Profumo et al. "Lessons from HAWC […]" Phys. Rev. D 97, no. 12, 123008 (2018) [1803.09731]



Inhomogeneous, time-dependent models being constructed (also linking these observations to CR e⁺), see e.g.

C. Evoli, T. Linden and G. Morlino, "Self-generated cosmic-ray confinement in TeV halos: Implications for TeV γ-ray emission and the positron excess," Phys. Rev. D 98, no. 6, 063017 (2018) [1807.09263]

Summary and conclusions

The observational improvements have shown the *first cracks in the simplest models* for cosmic ray production/propagation.

κῦδος to our experimental colleagues for their successful efforts!

many ideas proposed for their cause but we face a *double theoretical challenge*:

- to provide a *more refined modeling* (to account for new facts) *AND*
- to *keep theoretical errors under control*, *or* at least *assess them* the newly attained experimental precision becomes worthless

I focused on the case *spectral breaks*, which can be "naturally" explained if we:

- *Drop K homogeneity (and possibly isotropy)*
- *Drop power-law behaviour in K*
- *Drop power-law behaviour in Q*
- *Drop homogeneity (and possibly stationarity, isotropy…) in Q*
- …

Summary and conclusions

My opinion: *finding a model that fits is not the hardest task*, especially with many free parameters! *Better criteria* for judging how worth a model is e.g.:

- *how likely* it is, in a statistical sense? Does it require "anti-copernican" conditions?
- Does it *predict* (as opposed to *postdict*) any feature that we can *test*?

We provided a first estimate of the irreducible ("Galactic variance") *theoretical error due to space-time discreteness of the CR sources* (exact location and times unknown!)

- It is *comparable or even larger than the AMS-02 statistical one*!
- *Alone*, this effect *cannot explain the breaks in p, He* ($p<0.1\%$)

We presented a first attempt to test if AMS-02 *B/C* data prefer a *propagation origin* for the breaks, finding *intriguing hints* in that sense. Numerous further hints are accumulating suggesting the need of a inhomogeneous diffusion coefficient.

More precision & CR species, *extended E-range* will help, but we also need *theory & pheno progress*: e.g. multimessenger perspective (since some fine details could be "accidental", better to explain approximately all channels than precisely one!) & accounting for "non-local" observables (like CR anisotropies or diffuse γ's) can break model degeneracies and bring us closer to an understanding