How well do we understand the properties of Galactic Cosmic Rays Acceleration and Propagation ?

[a critical view]

Thanks for looking a these slides (or this presentation)

If you have comments, questions or criticisms:

contact me !

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INFN Roma "Sapienza"

37th ICRC
Berlin 21st 12-23 July 2021

Part 1.

Galactic Cosmic Ray Propagation

(is the “standard scenario” correct ?)

Part 2.

The Spectra of the Cosmic Ray Accelerators

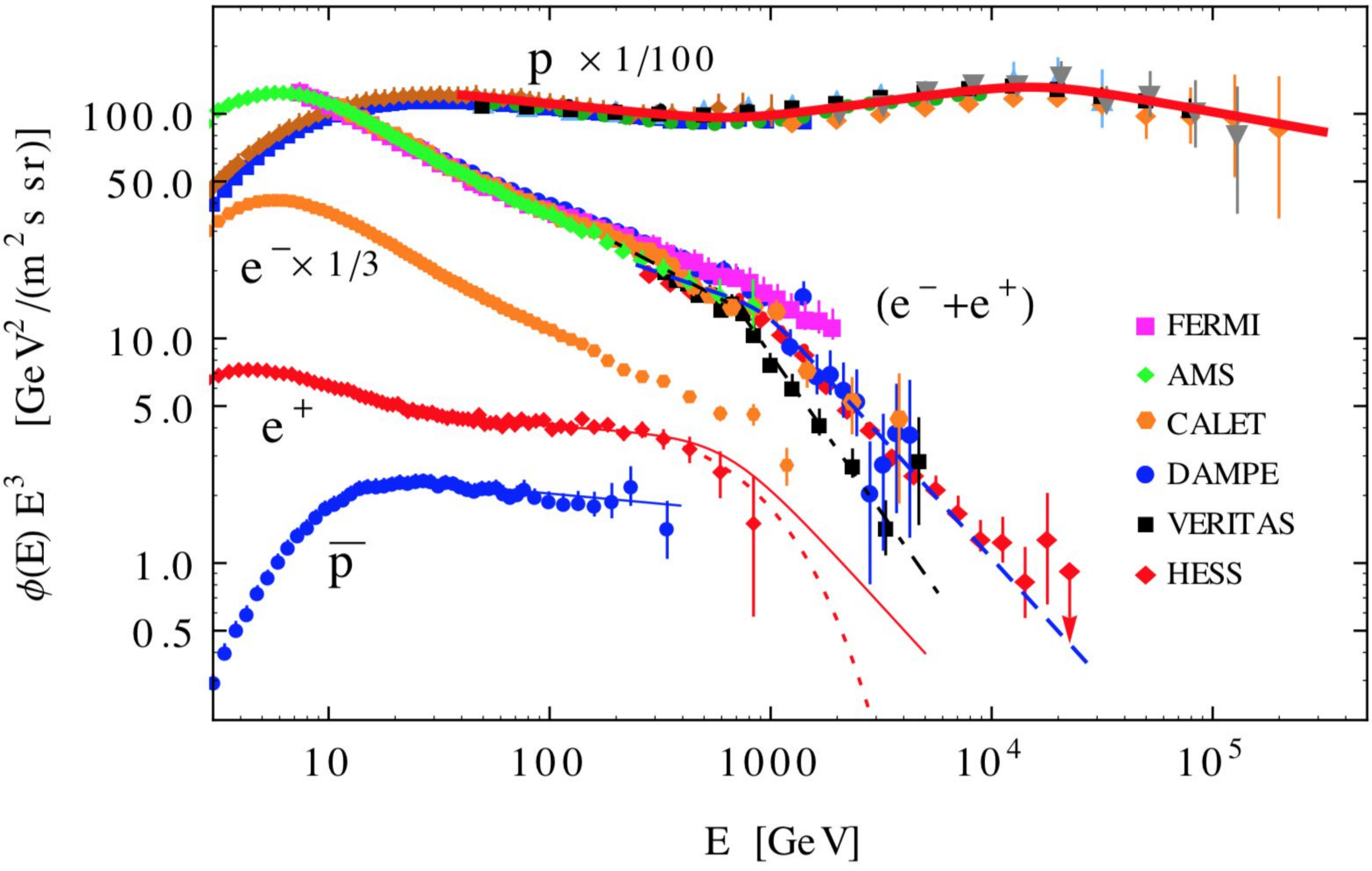
(very “speculative” considerations)

Precision measurements of the
Cosmic Ray Spectra [*at the Earth!*]

$p \quad e^-$

$\overline{p} \quad e^+$

Why these spectral shapes ?



Observable fluxes: Source Spectra + Propagation

$$\phi_j(E, \vec{x}, t)$$

$$q_j(E, \vec{x}, t)$$

Flux of particles of type j

Source spectrum of particles of type j

$$j \in \{p\ ,\ e^-\ ,\ e^+\ ,\ \overline{p}\ ,\ ^3\mathrm{He}\ ,\ ^4\mathrm{He}\ ,\ ^6\mathrm{Li}\ ,\ \ldots\}$$

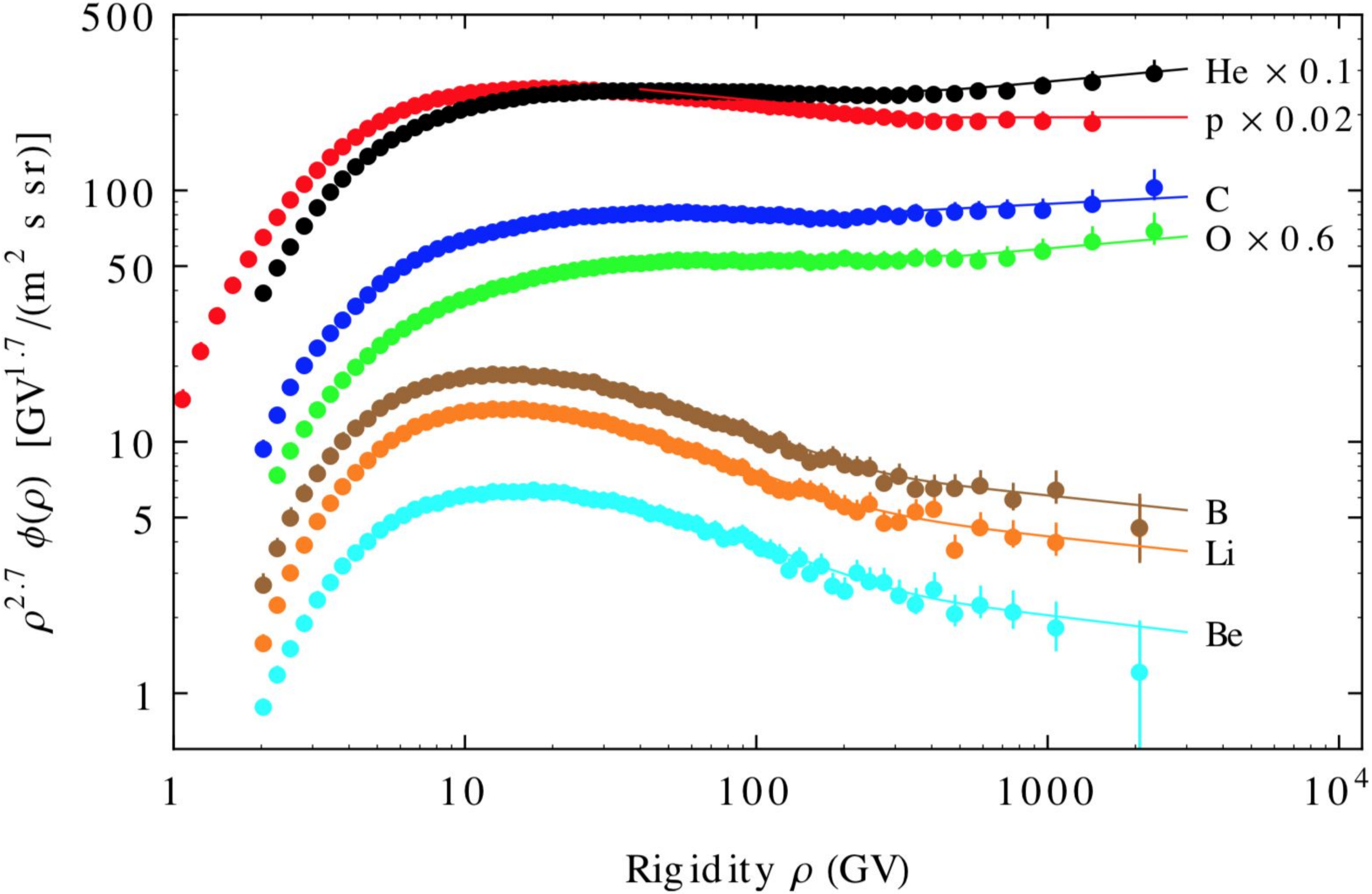
$$\phi_j = q_j \otimes \mathcal{P}_j$$

$$[\mathrm{Flux}]_\mathrm{j} = [\mathrm{Source\ spectrum}]_\mathrm{j} \otimes [\mathrm{Propagation}]_\mathrm{j}$$

Precision measurements of the
Cosmic Ray Spectra [*at the Earth!*]

p
He
C, O
Li, Be, B

Nuclei (AMS02)



"Secondary Nuclei" Li, Be, B

Rare nuclei created in the fragmentation of primary (directly accelerated) more massive nuclei

Some examples:

$$^{12}\mathrm{C} + p \to {}^{10}\mathrm{B} + 2\,p + n$$

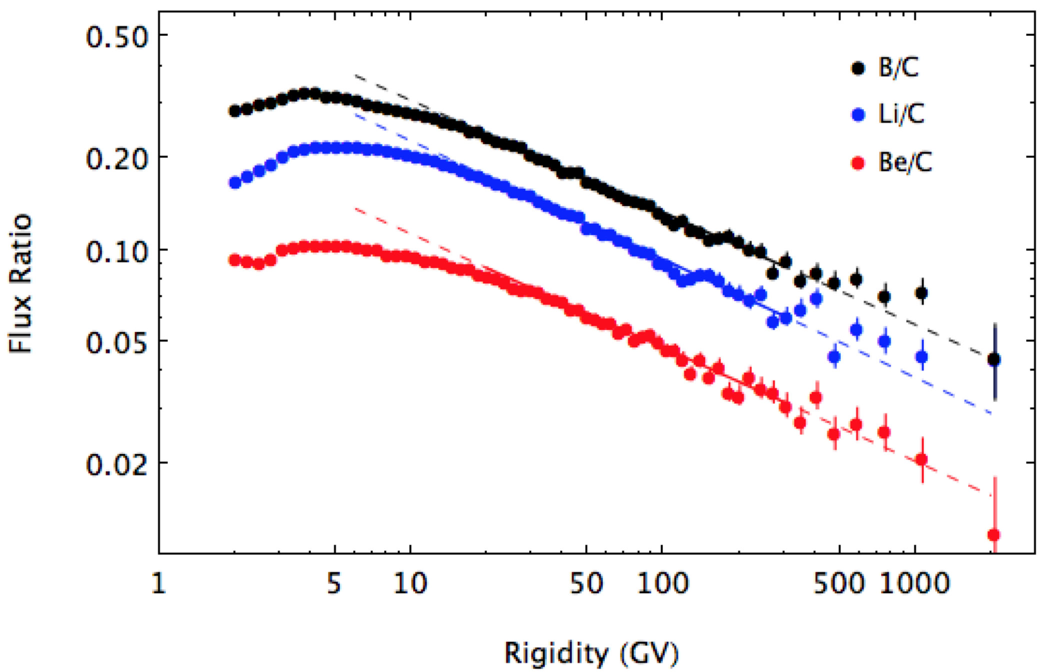
$$^{12}\mathrm{C} + p \to {}^{11}\mathrm{B} + 2\,p$$

$$^{16}\mathrm{O} + p \to {}^{11}\mathrm{B} + {}^{4}\mathrm{He} + 2\,p$$

....

$$\frac{\text{secondary nuclei}}{\text{primary nuclei}} \Longrightarrow$$

"grammage" traversed by the nuclei



The "cornerstone" of the "Standard Scenario"

The study of secondary nuclei allows to infer a *"Grammage"* [column density]

[in the limit of small $\langle X \rangle$]

$$\mathrm{Li} \approx (\mathrm{C} \to \mathrm{Li}) + (\mathrm{N} \to \mathrm{Li}) + (\mathrm{O} \to \mathrm{Li})$$

$$\frac{\mathrm{Li}}{\mathrm{C}} \approx \frac{\langle X \rangle}{m_p} \, \sigma_{\mathrm{C}\to\mathrm{Li}} \left[1 + \frac{\phi(\mathrm{O})}{\phi(\mathrm{C})} \, \frac{\sigma_{\mathrm{O}\to\mathrm{Li}}}{\sigma_{\mathrm{C}\to\mathrm{Li}}} + \frac{\phi(\mathrm{N})}{\phi(\mathrm{C})} \, \frac{\sigma_{\mathrm{N}\to\mathrm{Li}}}{\sigma_{\mathrm{C}\to\mathrm{Li}}} \right]$$

Need cross sections, (take into account absorption ....)
and more in general a *propagation Model* (distribution of X)

Grammage interpretations Rigidity $\rho \gtrsim 5$ GV (best fit, no errors)

1990 HEAO-3 (Leaky Box)

J. J. Engelmann, *et al.* [HEAO–3]
Astron. Astrophys. **233**, 96-111 (1990)

$$\langle X \rangle = 8.6 \, \left(\frac{\rho}{10 \text{ GV}} \right)^{-0.60} \text{ g cm}^{-2}$$

2019 (after AMS02, Diffusion)

C. Evoli, R. Aloisio and P. Blasi,
"Galactic cosmic rays after the AMS-02 observations,"
Phys. Rev. D **99**, no.10, 103023 (2019)

$$\langle X \rangle = 8.4 \, \left(\frac{\rho}{10 \text{ GV}} \right)^{-0.63} \text{ g cm}^{-2}$$

Very desirable to make a "grammage" analysis

IF one assumes that the "grammage" is crucial *ASSUMPTION*
integrated during propagation in interstellar space
Then: one can estimate the CR residence time

$$\langle X \rangle \simeq m_p \; \langle n_{\rm ism} \rangle_{\rm traj} \; c\, T_{\rm age}$$

$$T_{\rm age} \simeq 63 \; \left[\frac{\langle X \rangle}{10 \text{ g cm}^2} \right] \; \left[\frac{\langle n_{\rm ism} \rangle}{0.1 \text{ cm}^{-3}} \right]^{-1} \; \text{Myr}$$

Many works have interpreted the
Secondary nuclei data immediately in terms
of parameters of Galactic Propagation parameters

$H \quad D_0 \quad \delta$

$$T = \frac{H^2}{2D}$$

$$T_{\rm age}(\rho) \simeq 54 \text{ Myr} \left(\frac{\rho}{10 \text{ GV}} \right)^{-0.54}$$

C. Evoli, G. Morlino, P. Blasi and R. Aloisio, Phys. Rev. D **101**, no.2, 023013 (2020)

$$T_{\rm age}(\rho) \simeq 99 \text{ Myr} \left(\frac{\rho}{10 \text{ GV}} \right)^{-0.51 \pm 0.02}$$

N. Weinrich, *et al.* [USINE] Astron. Astrophys. **639**, A131 (2020)

$$T_{\rm age}(\rho) \simeq 38 \text{ Myr} \left(\frac{\rho}{10 \text{ GV}} \right)^{-0.415 \pm 0.025}$$

M. J. Boschini, *et al.* [GALPROP] [arXiv:1911.03108 [astro-ph.HE]].

[........]

Implications of the "Standard Interpretation"

Infer the shape of the source spectra for protons and nuclei
[... softer than Fermi acceleration (?)]

$$E^{-\alpha} \propto E^{-(\alpha_{\rm obs} - \delta)}$$

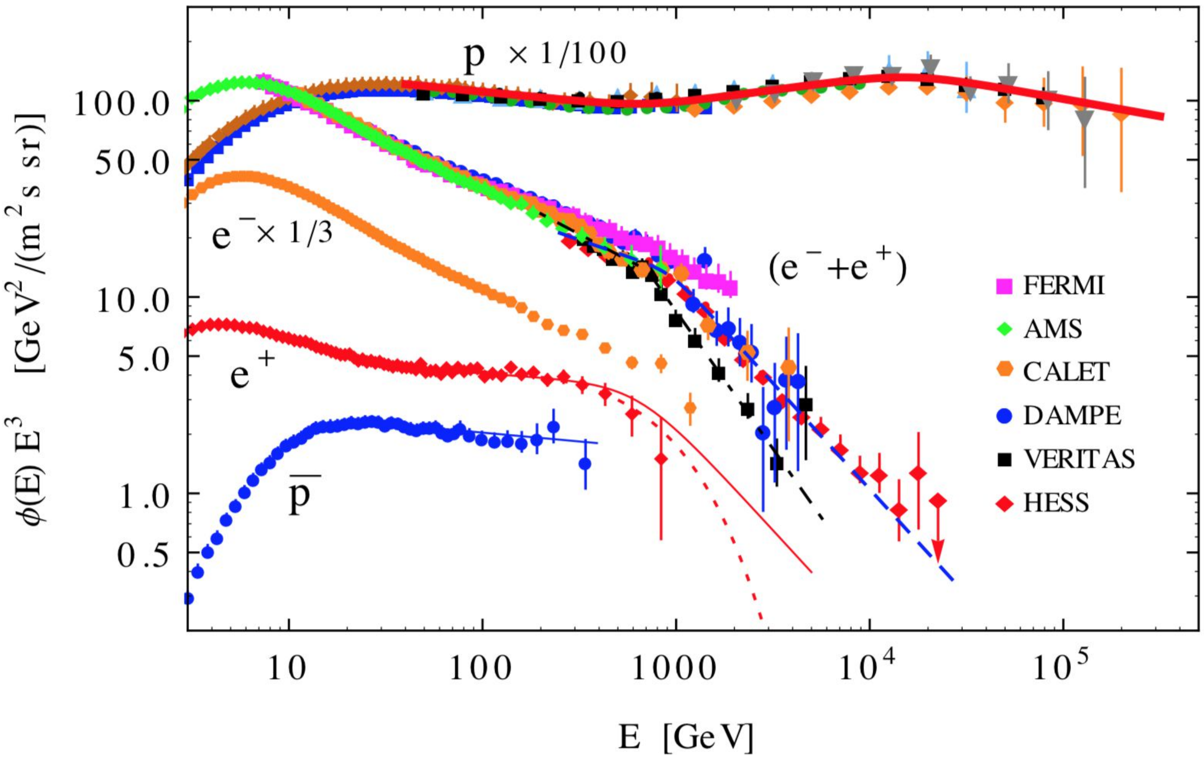
(electron+ positron) Energy Losses important for E > few GeV

$$(\Delta E)_{e^\pm} \approx \left| \frac{dE}{dt} \right|_{e^\pm} T_{\rm age}(E)$$

$<$	E	losses negligible
$\approx$	$E = E^*$	Critical energy
$>$	E	losses dominant

Electrons: Source spectra for protons/electrons are *similar*

Positrons: Secondary Production cannot explain the data
New source is needed [2300 papers.. and counting!]



$E \gtrsim 40$ GeV

Electrons $\dfrac{\phi_{e^-}(E)}{\phi_p(E)} \propto E^{-0.41}$

Difference in shape
is a propagation effect
(source spectra "similar")

Positrons $\dfrac{\phi_{e^+}(E)}{\phi_p(E)} \propto \text{constant}$

New, Hard
positron source

Antiprotons $\dfrac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \text{constant} \approx 2.0$

positrons and antiprotons
"appear" intimately related....

"Conventional mechanism" for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

$$pp \to \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

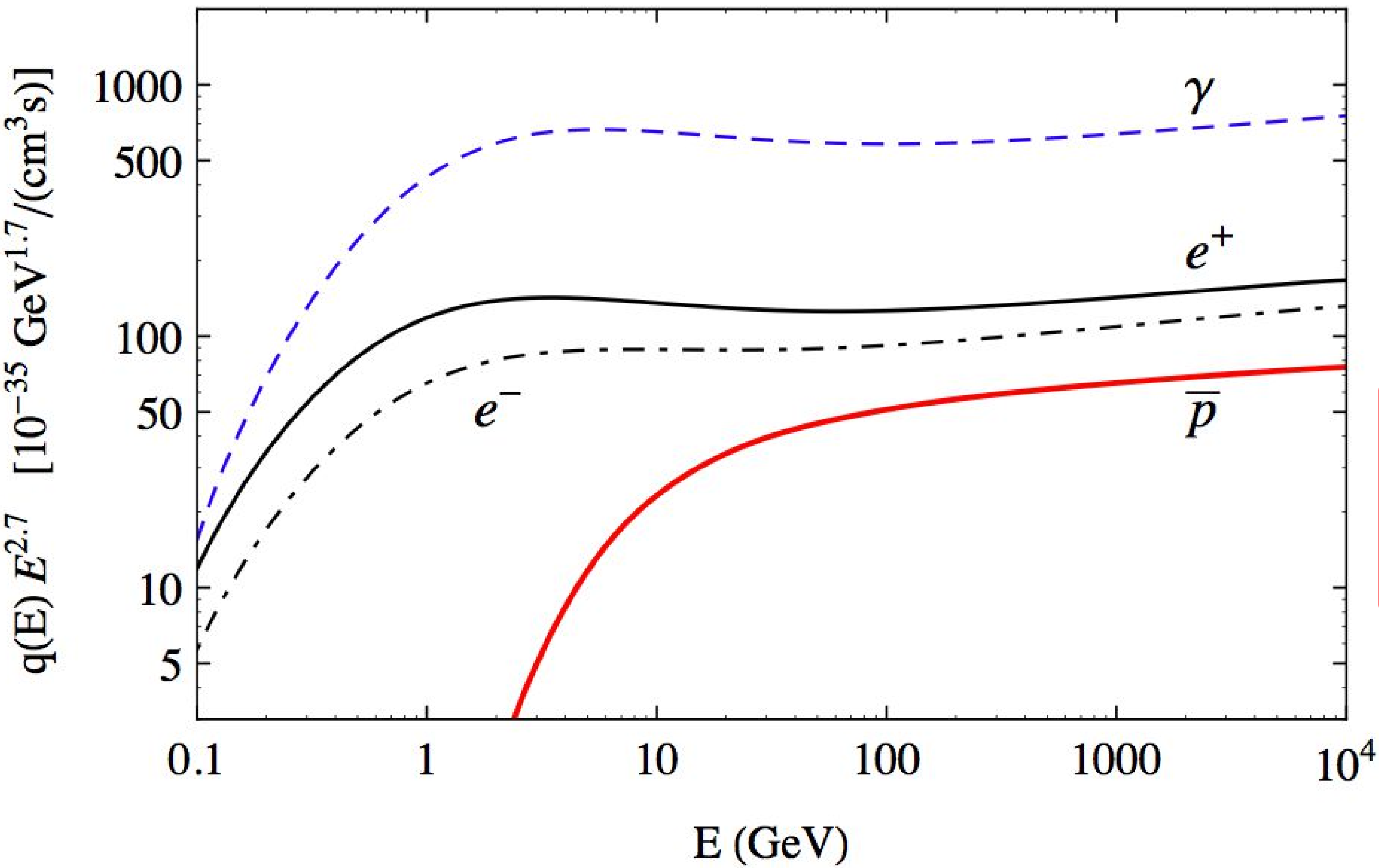
"Standard mechanism" for the generation of positrons and anti-protons

Source spectra can be calculated from a knowledge of the spectra of protons (and other nuclei)

At high energy the Source Spectra of positrons and antiprotons have a power-law shape with same exponent of the interacting CR particles

Rate of production of secondaries

(Interacting CR are those measured at the Earth) $\langle n_{\rm ism} \rangle \simeq 1 \ {\rm cm}^{-3}$



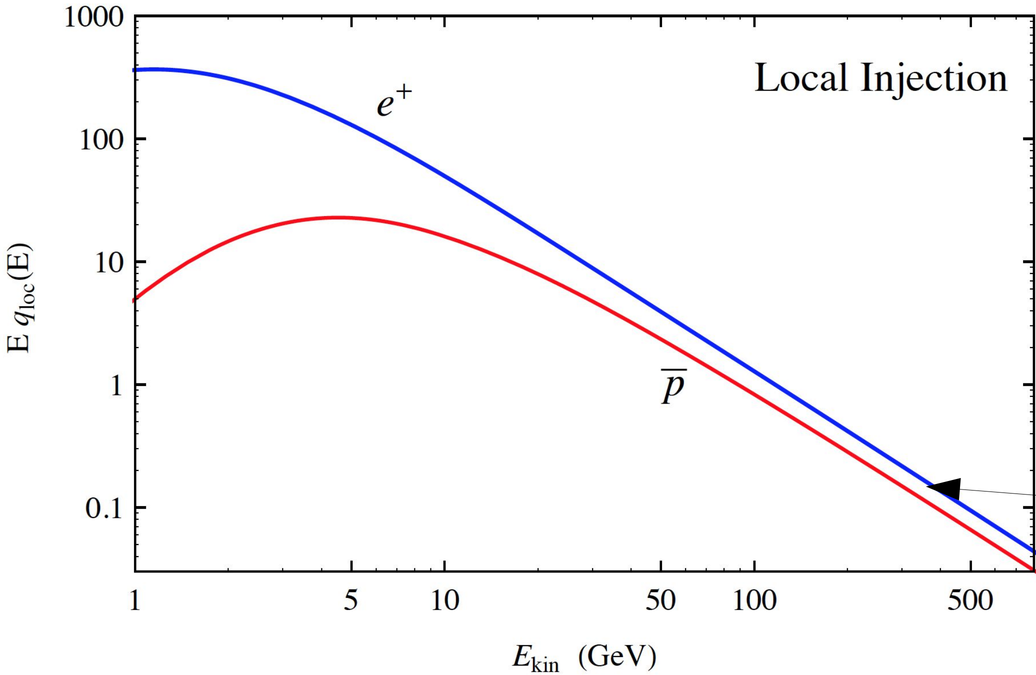
$$\frac{\gamma}{e^+} \approx 5.5$$

$$\frac{e^-}{e^+} \approx 0.8$$

$$\frac{e^+}{\overline{p}} \approx 2.0$$

Different low energy behaviors
(low energy antiproton production suppressed)

Power Law behavior at high energy



"striking" similarity

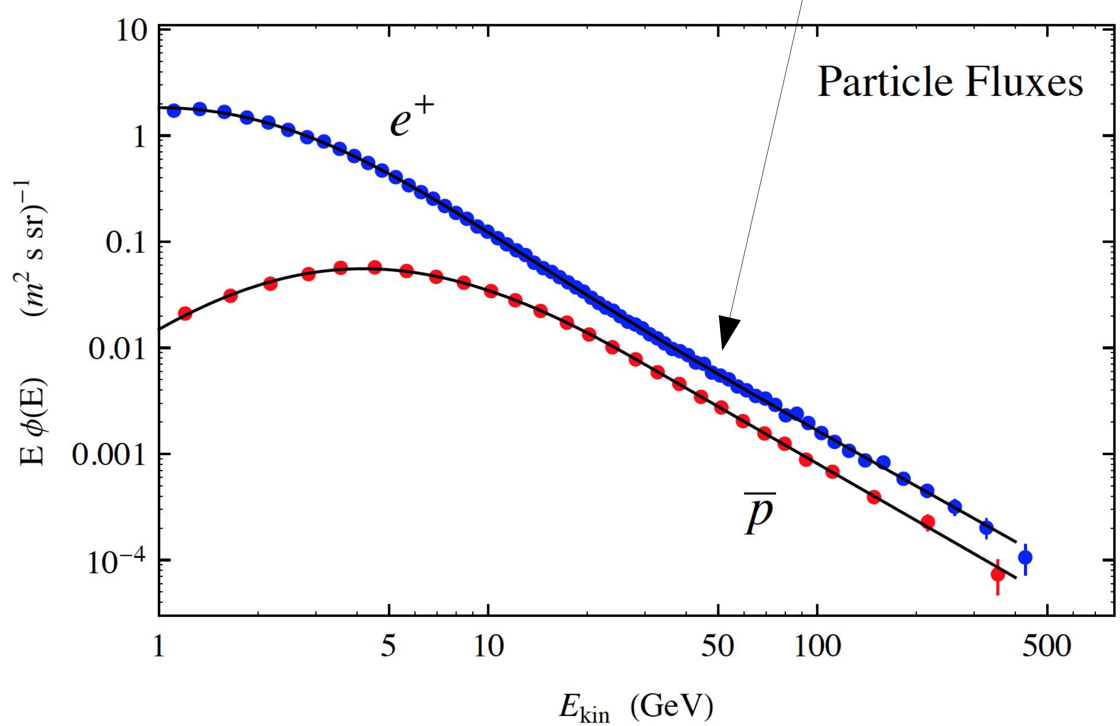
$$E_{kin} \simeq [1, 300] \text{ GeV}$$

$$\left(\frac{e^+}{\overline{p}}\right)_{\text{flux}} \simeq \left(\frac{e^+}{\overline{p}}\right)_{\text{sec. prod.}}$$

power-law shape
ratio ≈ 2

Local production rates of secondaries

intriguing ... but ...
...just a "coincidence" ?



Observed fluxes

(Potential) Problems with the standard interpretation:

[0] Spectrum of positrons too hard

[recognized as a "problem" , but: Exciting Solution: New source !]
(But the existence of this source must be demonstrated !!)

[1] Measurements of abundance Beryllium-10
[Residence time too short]

[2] Spectrum of anti-protons is also too hard.

[3] No clear evidence for the signature of energy losses in the spectra of electrons and positrons.

[4] No-evidence of electron/positron sources E > few TeV

Beryllium Measurements

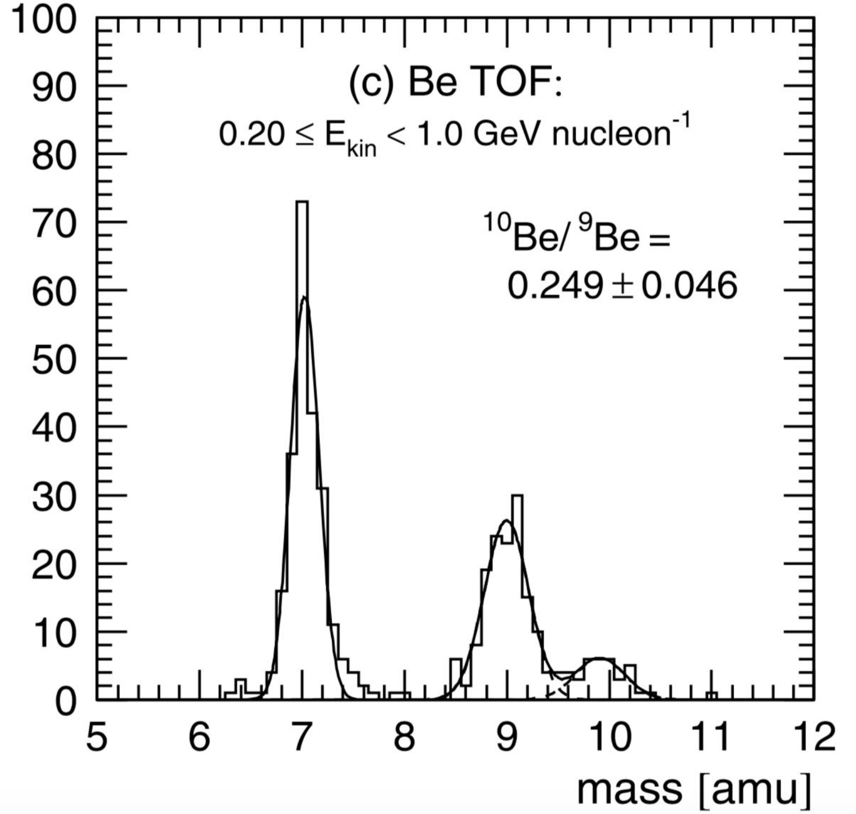
S.P. Ahlen, , *et al.* (SMILI coll.), Astrophys. J. **534**, 757-769 (2000)

T. Hams, *et al.* (ISOMAX Coll.) Astrophys. J. **611**, 892-905 (2004).

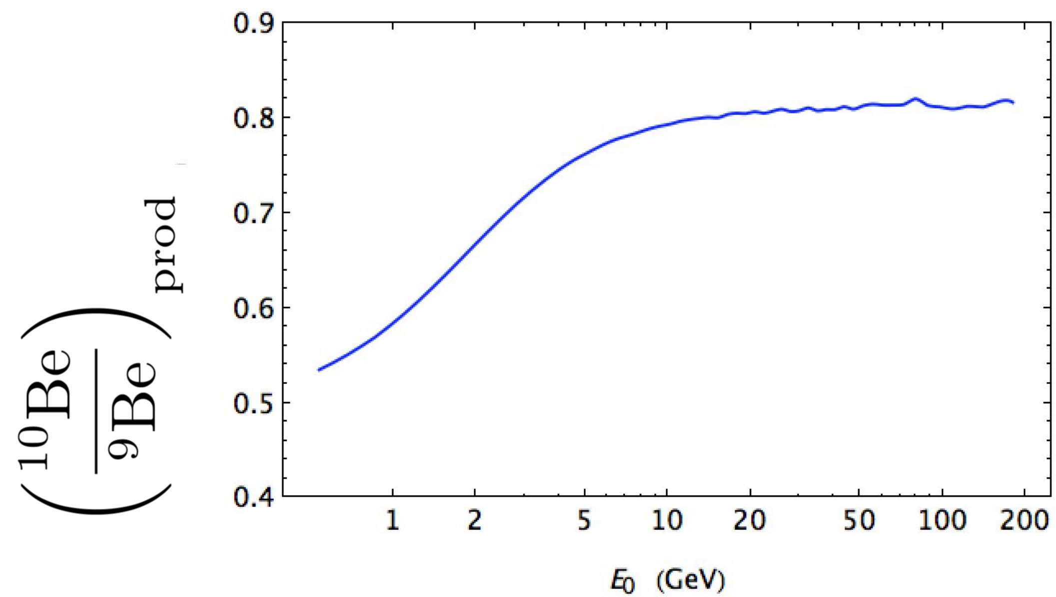
Beryllium 7	Stable in c.r.	(electron capture)
Beryllium 9	Stable	
Beryllium 10	Unstable	"Cosmic Ray clock"

Unstable isotope [Beryllium-10]

$$T_{1/2} = 1.387 \pm 0.012 \text{ Myr}$$



Some measurements of Beryllium-10 suggest a residence time one order of magnitude shorter than the "standard CR propagation model"



Beryllium-10 / Beryllium-9 Ratio calculated [Convoluting AMS02 C, N, O spectra with fragmentation cross sections]

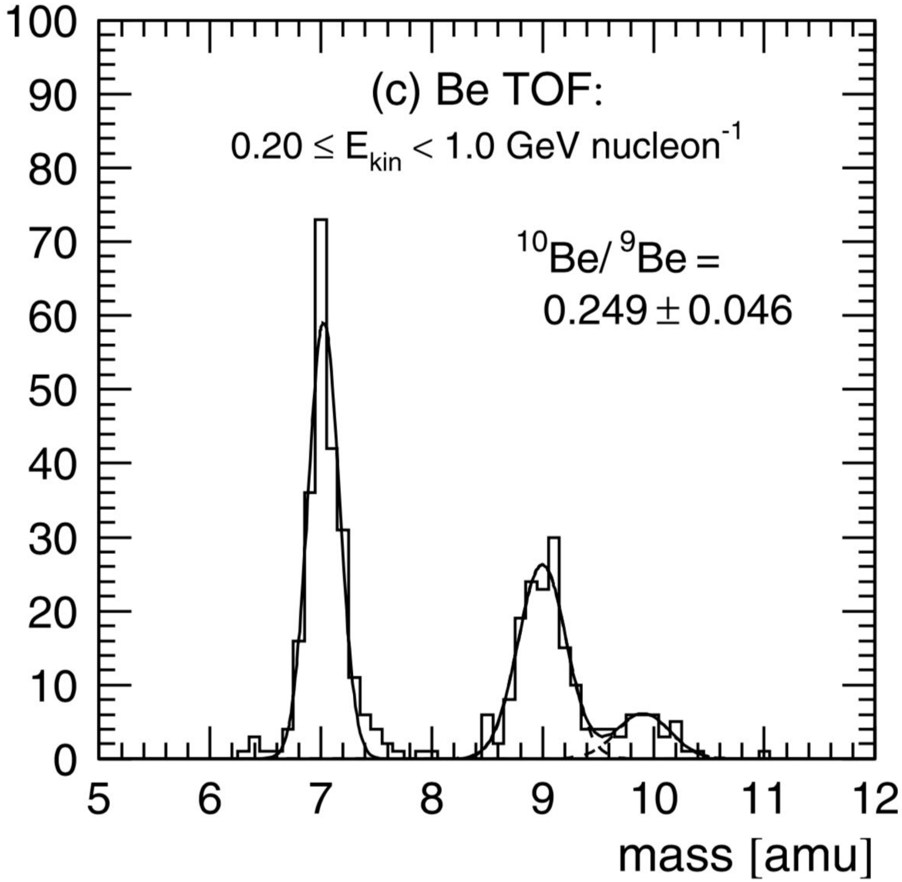
$$\left(\frac{^{10}\mathrm{Be}}{^{9}\mathrm{Be}}\right)_{\rm obs} = \langle P_{\rm surv}(E)\rangle \left(\frac{^{10}\mathrm{Be}}{^{9}\mathrm{Be}}\right)_{\rm prod}$$

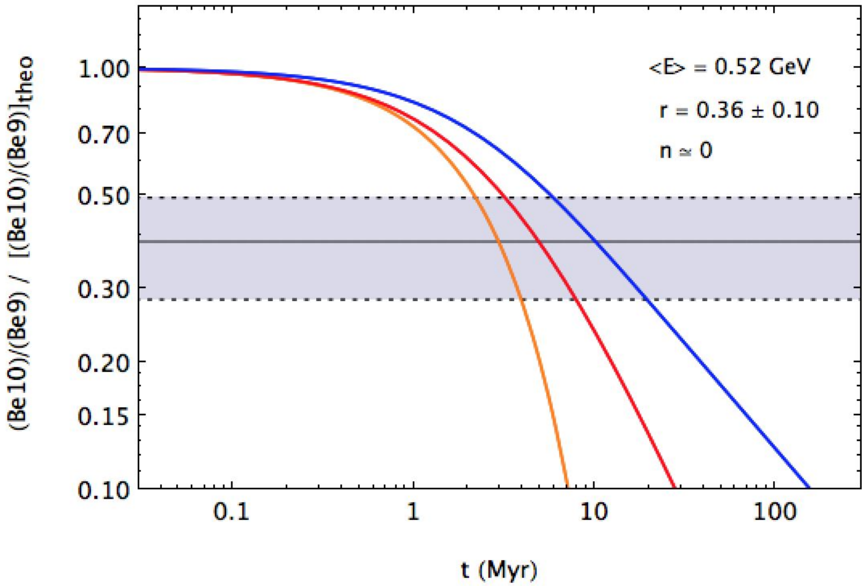
Survival Probability for unstable nucleus

$$\langle P_{\rm surv}(E)\rangle = \int_0^\infty dt\ F[t, \langle t(E)\rangle]\ e^{-t/T_{\rm dec}(E)}$$

Depends on residence time distribution

ISOMAX

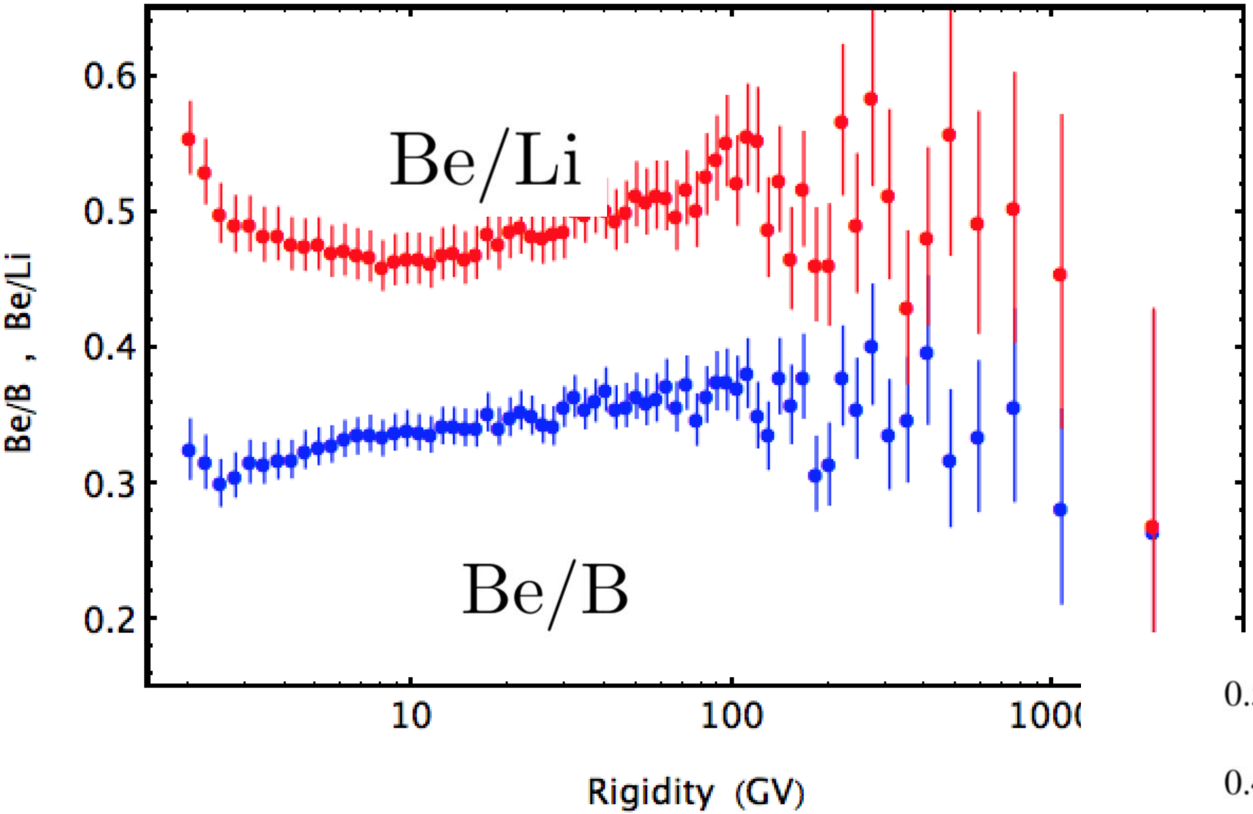




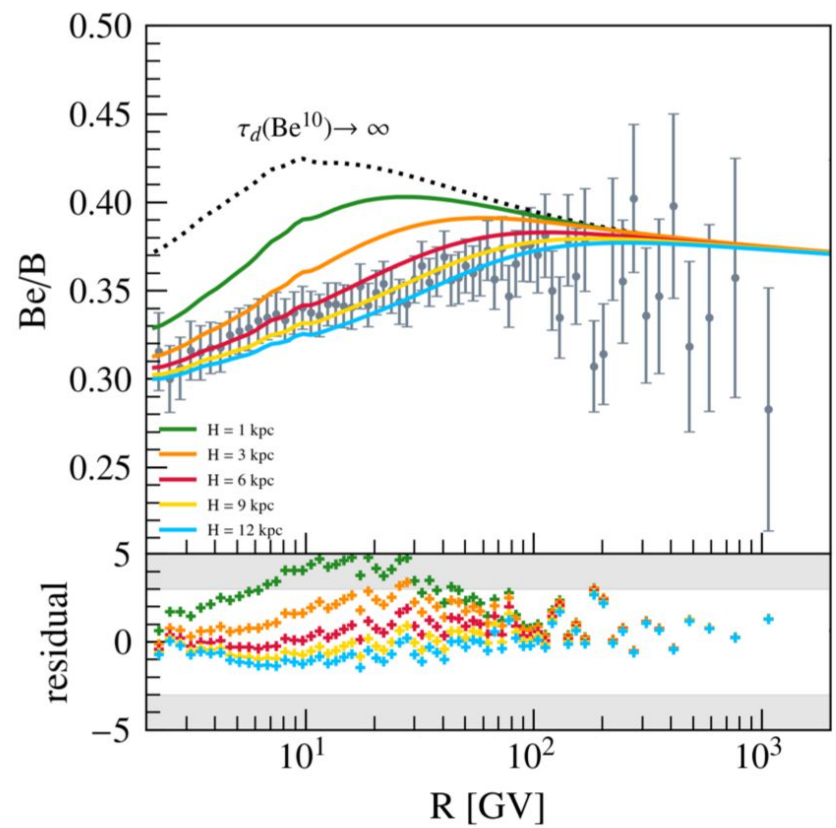
$t_0 = 2.9^{+1.0}_{-0.8}$ Myr Single time

$T = 4.9^{+3.0}_{-1.7}$ Myr Leaky Box

$T_{\rm diff} = 10.1^{+9.4}_{-4.2}$ Myr Diffusion model



C. Evoli, G. Morlino, P. Blasi and R. Aloisio,
"AMS-02 beryllium data and its implication for cosmic ray transport,"
Phys. Rev. D **101**, no.2, 023013 (2020)
[arXiv:1910.04113 [astro-ph.HE]].



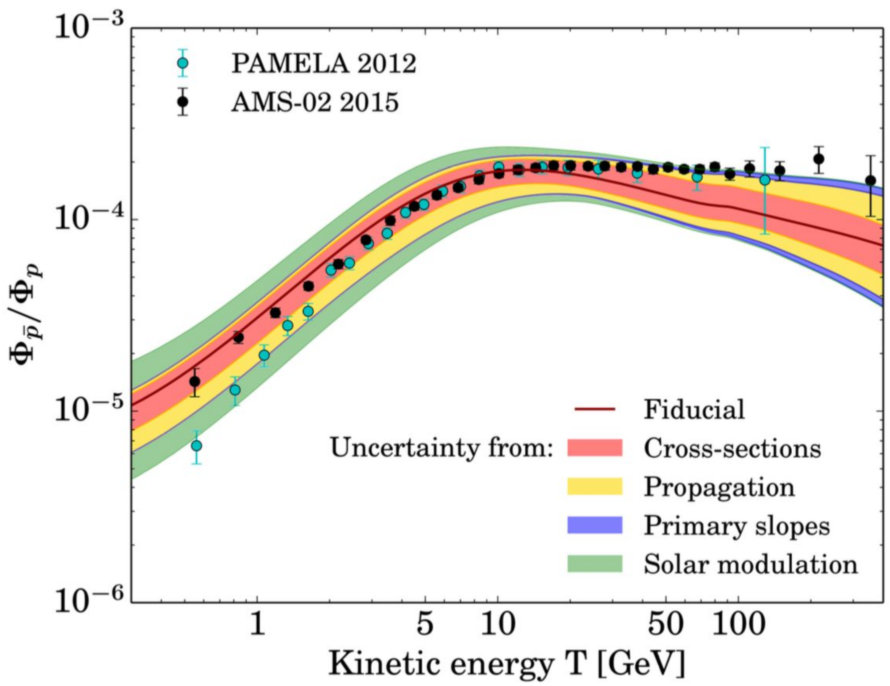
Claim to infer a long beryllium-10 residence time from Be/B ratio.

[Interesting idea …. But:
Very dependent on cross section !]

Anti-proton spectrum

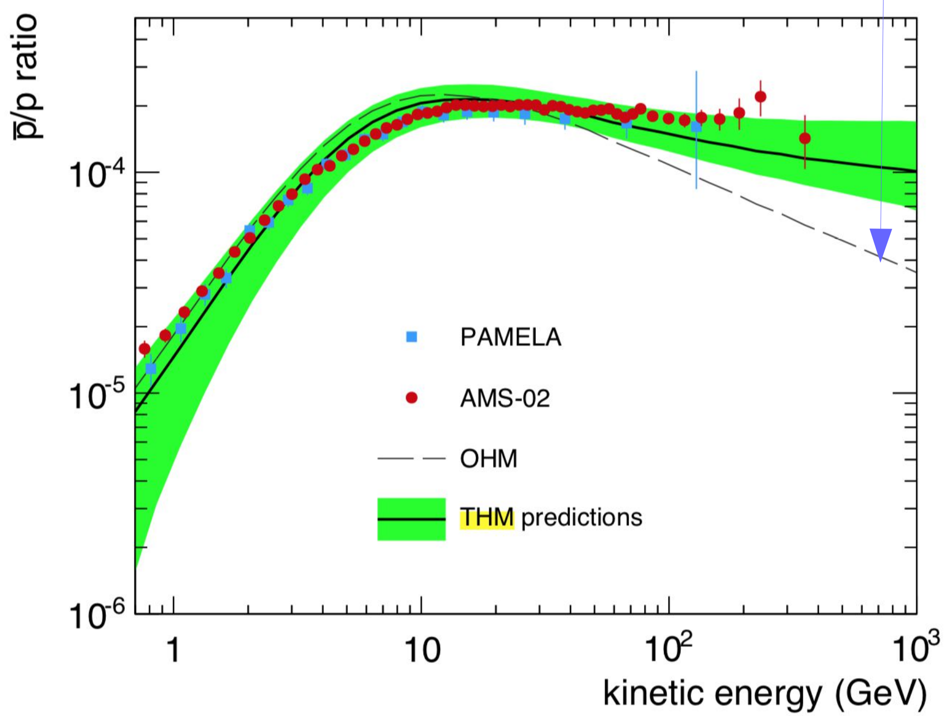
All PREdiction of the antiproton flux
(before the release of the AMS02)
based on the “Standard Propagation Scenario”
and Secondary production mechanism
where significantly softer
than the data at high energy.

All new calculation
(published AFTER the release of the AMS02)
still obtain a spectrum
“significantly” softer that the data



G. Giesen, *et al.*, “AMS-02 antiprotons, at last! Secondary astrophysical component and immediate implications for DM,” JCAP **09**, 023 (2015)
[arXiv:1504.04276 [astro-ph.HE]].

Standard
One Halo Model (OHM)



J. Feng, N. Tomassetti and A. Oliva,
“Bayesian analysis of spatial-dependent cosmic-ray propagation: astrophysical background of antiprotons and positrons,”
Phys. Rev. D **94**, no.12, 123007 (2016)
[arXiv:1610.06182 [astro-ph.HE]].

Interpreting the "Coincidence"

$E_{\rm kin} \simeq [1, 300]$ GeV

$$\left(\frac{e^+}{\overline{p}}\right)_{\rm flux} \simeq \left(\frac{e^+}{\overline{p}}\right)_{\rm sec.\ prod.}$$

There is a simple "natural" explanation:

that *"leaps out of the slide" :*

to suggest an Alternative Model for
CR Galactic Propagaiton

Simple, natural interpretation of the “Coincidence”

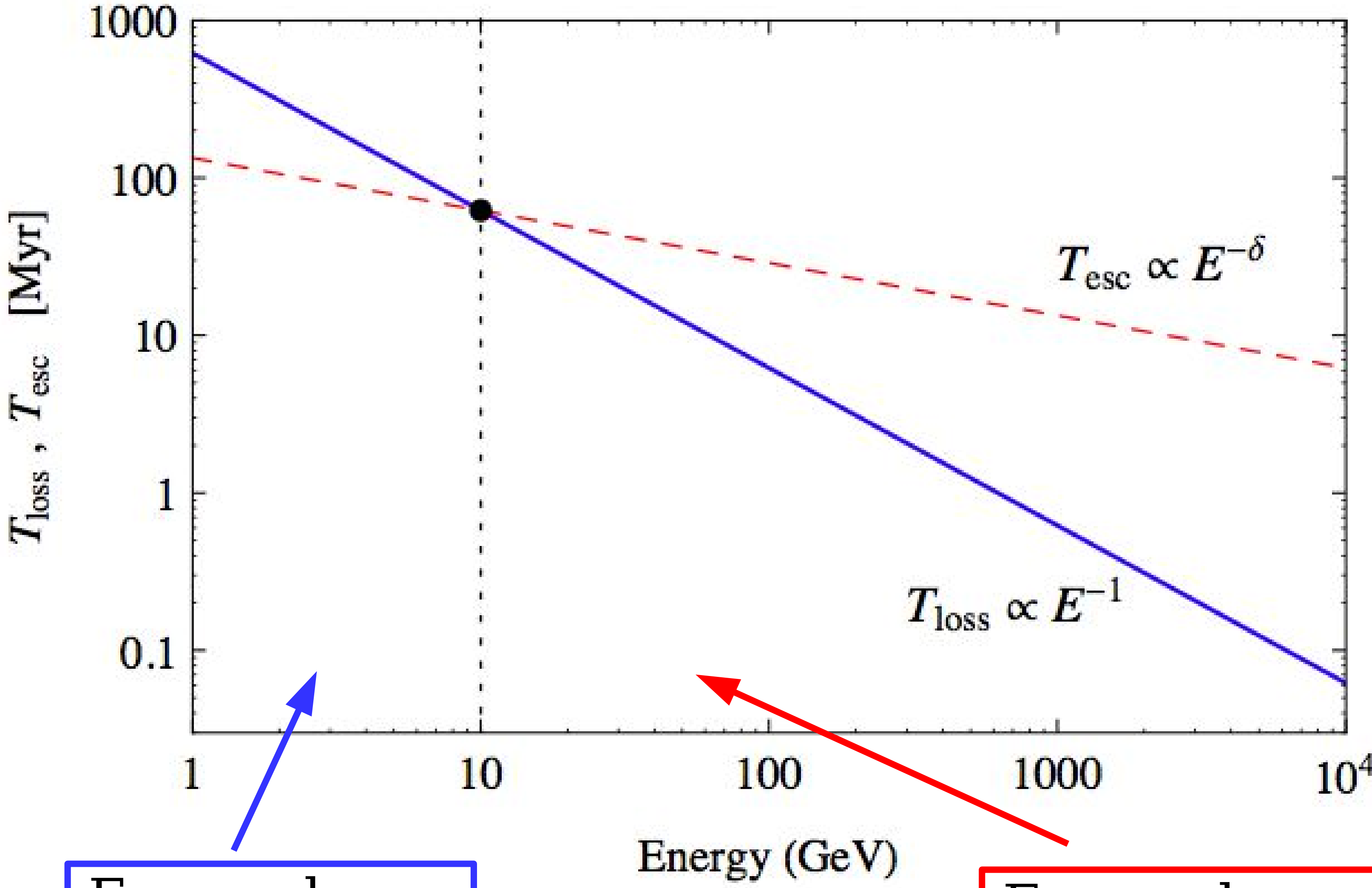
1. The “standard mechanism of secondary production is the main source of the antiparticles (and of the gamma rays)

2. The cosmic rays that generate the antiparticles and the photons have spectra similar to what is observed at the Earth.

3. *The Galactic propagation effects for positrons and antiprotons are approximately equal*

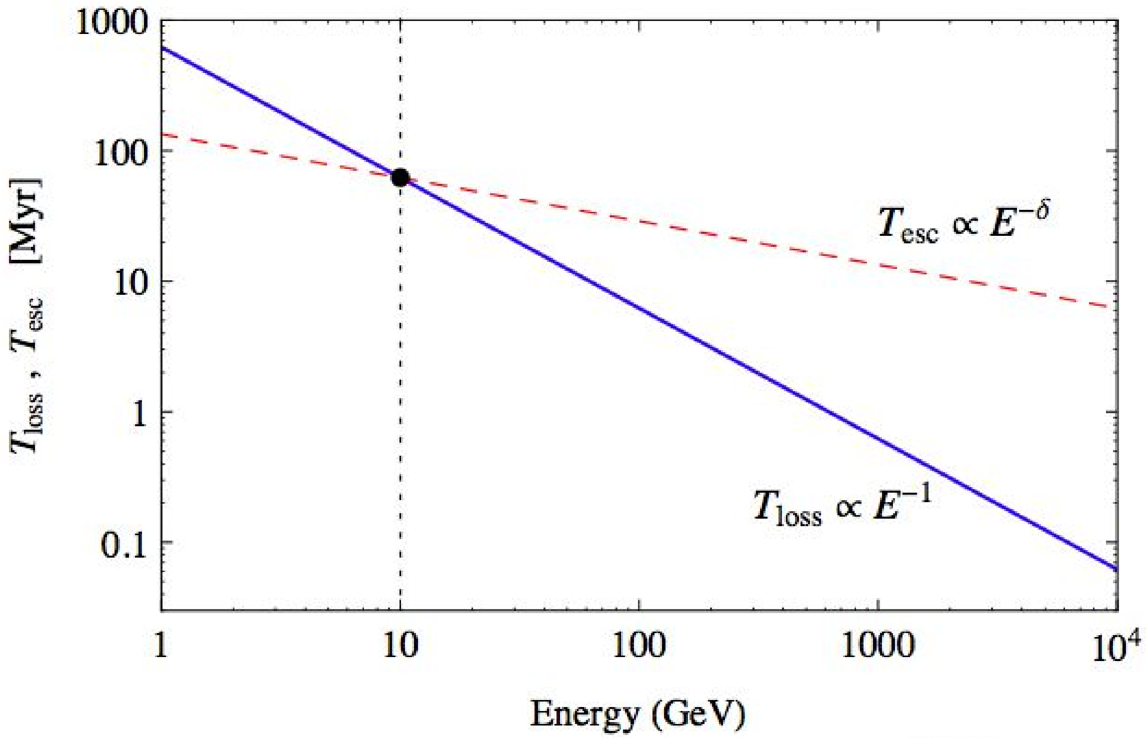
4. The propagation effects have only a weak energy dependence.

Observing the Feature of energy losses in the spectra of electrons and positrons



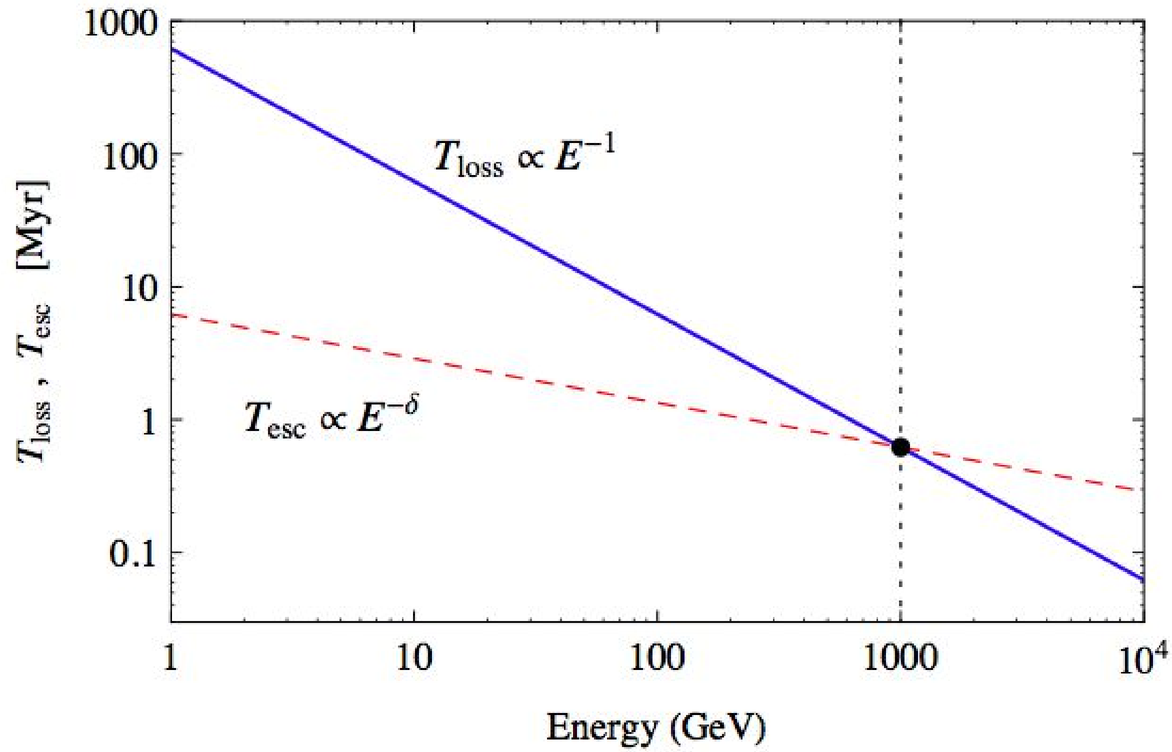
Energy losses negligible

Energy losses significant



"Standard picture"

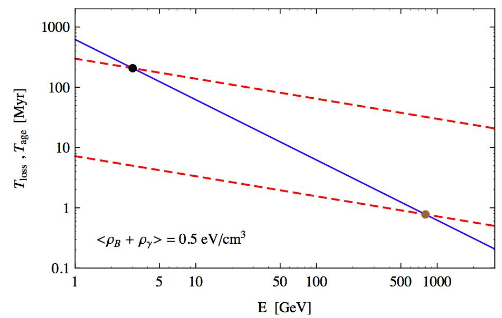
Energy losses important for E > few GeV



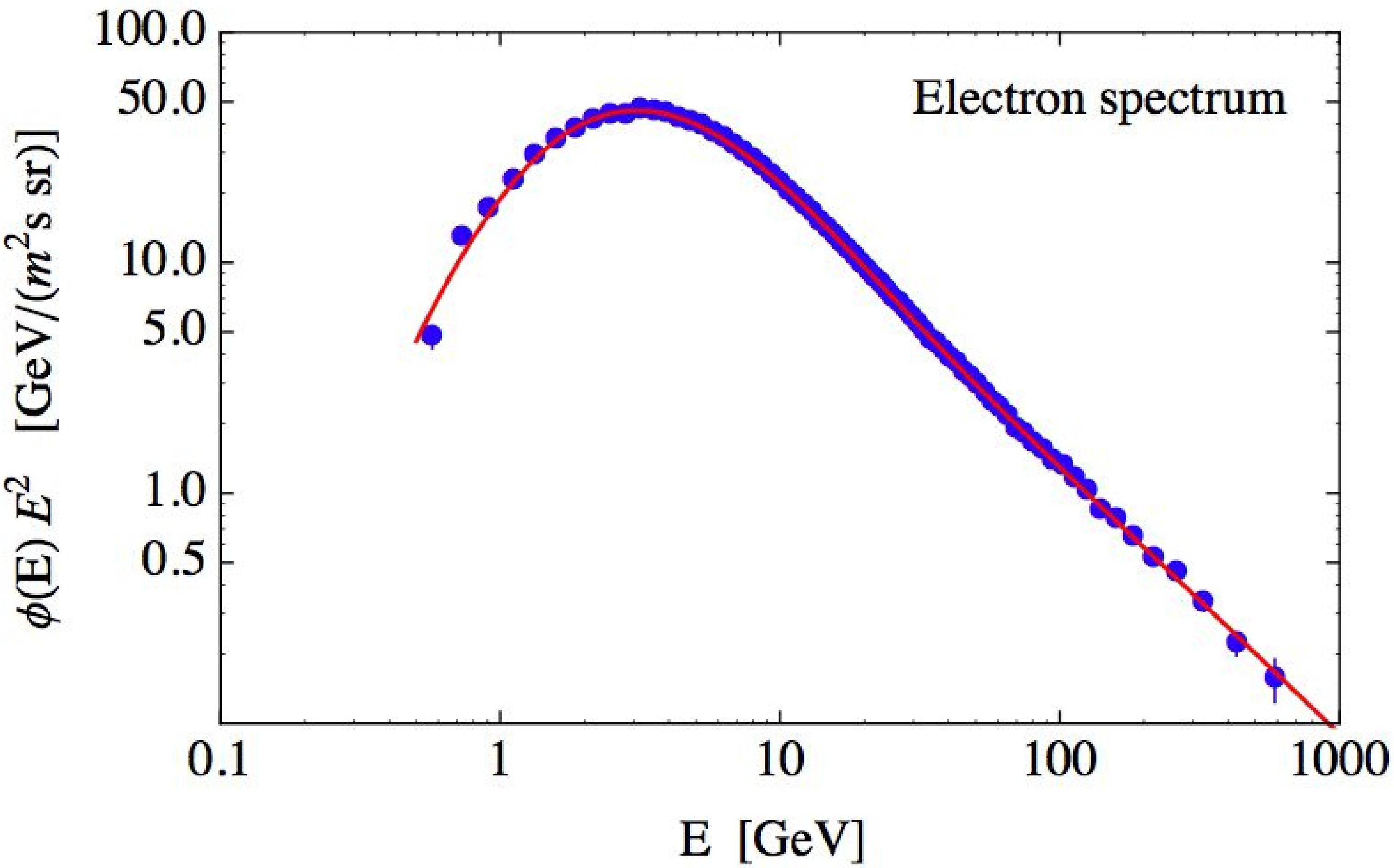
"Alternative picture"

Energy losses become important at E ≈ 1 TeV

Use the electron spectrum
as a *“cosmic ray clock”*



Where is the spectral feature
associated to the critical energy ?



Very smooth
electron
spectrum

Fit =

$K\ E^{-3.17}$

$\otimes$

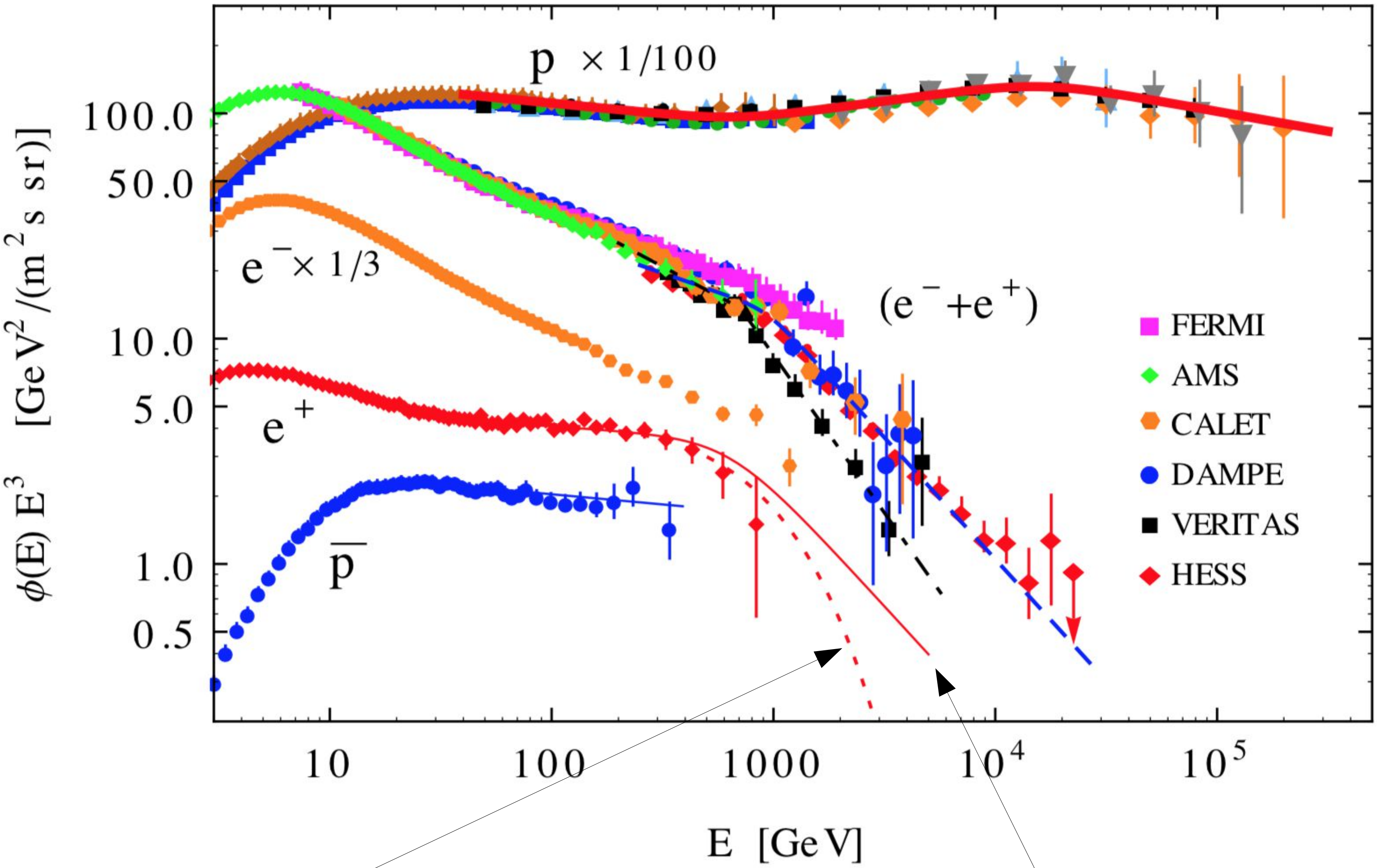
FFA Solar
Modulations
(1.44GeV)]

Problems for the “Alternative Propagation Model”:

1. Need to construct a model of the CR accelerators to explain light/secondary Nuclei.

2. Need to explain the large difference in the shape of the source spectra for p ed e-

3. Need to see somewhere the effect of energy losses for electrons and positrons *[and at (approximately) the same energy]*



Exponential cutoff

Break of two power laws

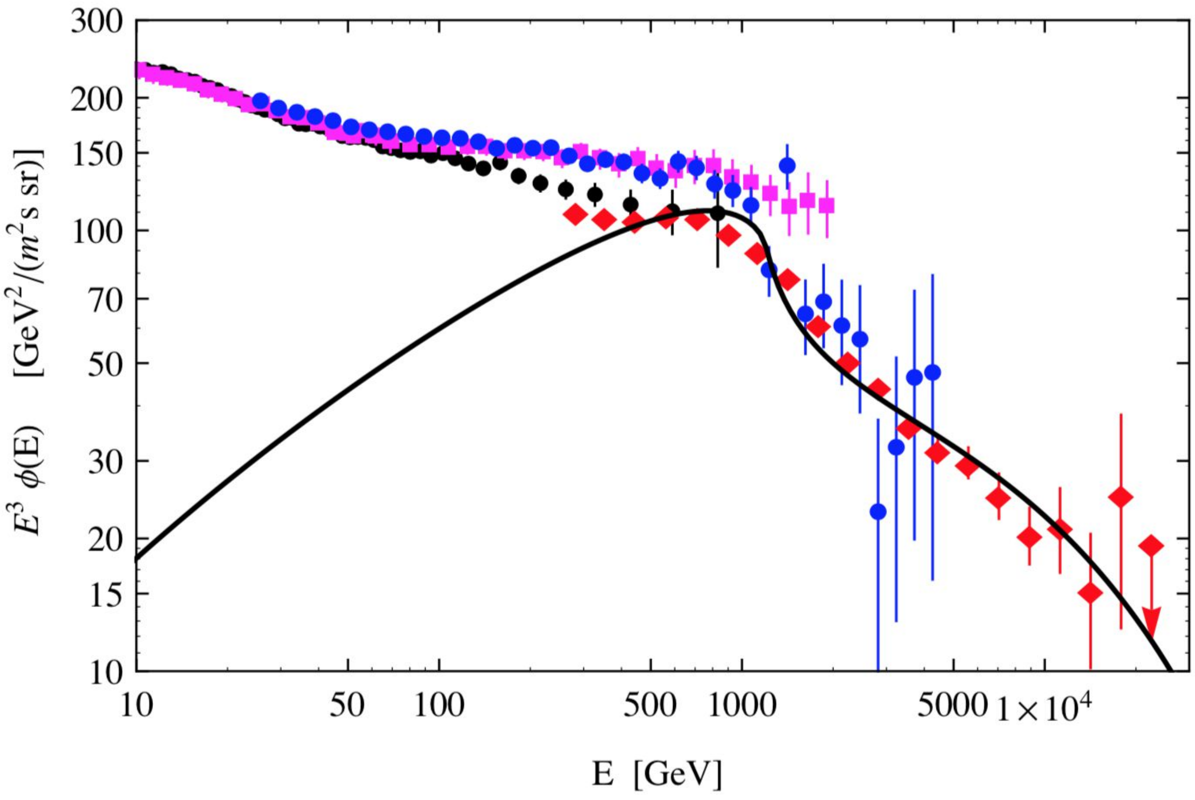
The study of the electron spectrum at high energy, and the search for their sources is also crucial

$$E \gtrsim 1 \text{ TeV}$$

In the “conventional scenario” already at 1 TeV very few sources should contribute to the spectrum.

Spectral and anisotropy signatures should be (or very soon) become visible

In the “alternative scenario” (fast propagation, larger propagation radius) The “granularity effects” should emerge at higher energy (around 10 TeV)



$r = 157$ pc

$t = 260$ kyr

$\tau = 40$ kyr

$\mathcal{E} = 1.1 \times 10^{48}$ erg

S. Recchia, S. Gabici, F. A. Aharonian and J. Vink,
"Local fading accelerator and the
origin of TeV cosmic ray electrons"
Phys. Rev. D **99**, no.10, 103022 (2019)

Model that explains the highest energy electrons
as a single Pulsar "fine-tuned" source
of only electrons (no protons, no positrons)

The Source Spectra of the Cosmic Ray Accelerators

Changing Propagation
change also the CR Source Spectra

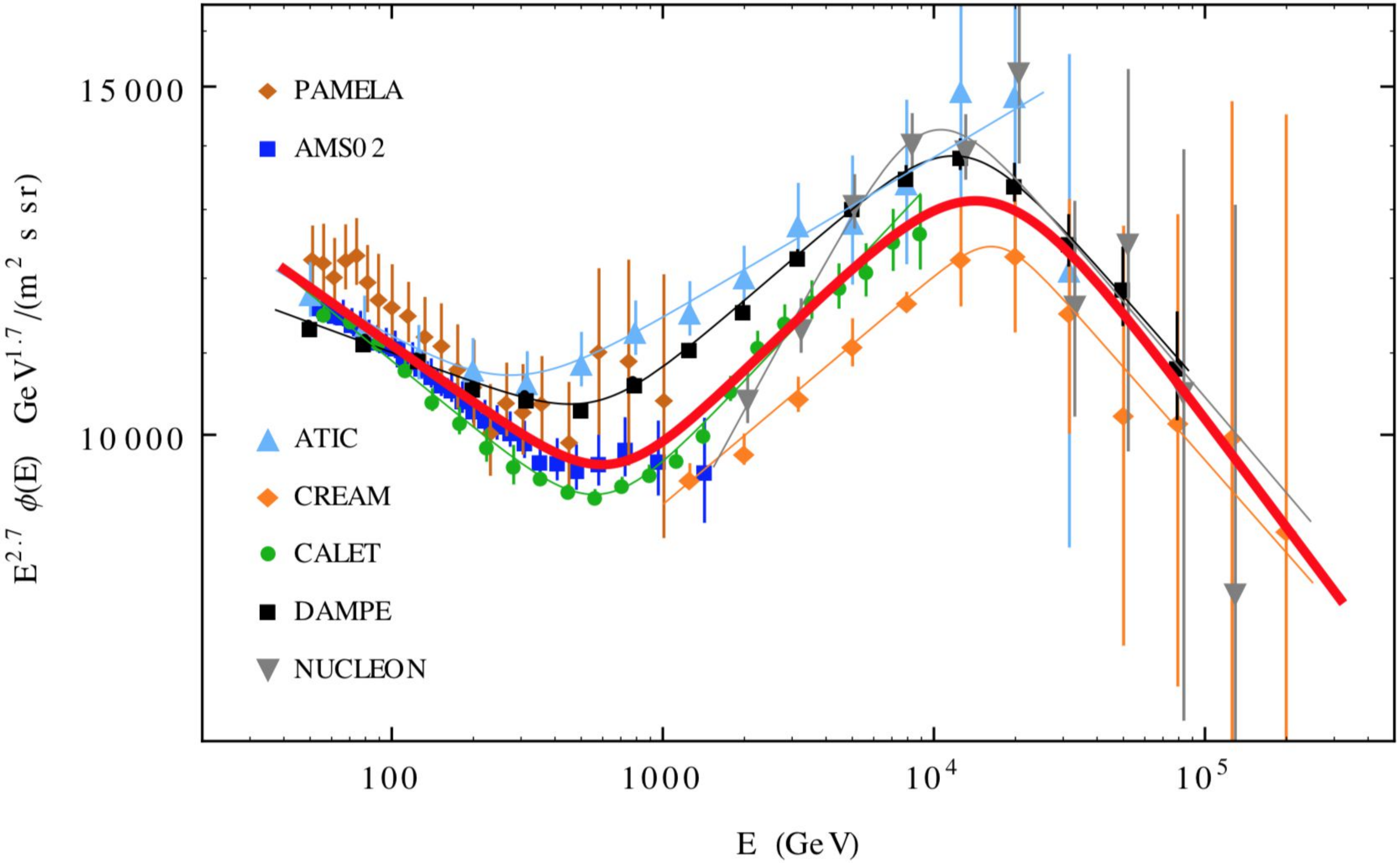
"Alternative Scenario" Requires:

[1.] Very different e- and p Source spectra

[2.] More power for the Accelerators

[3.] Softer Source spectra

The origin of the
Power-Law Spectra of Cosmic Rays
(and its deviations)



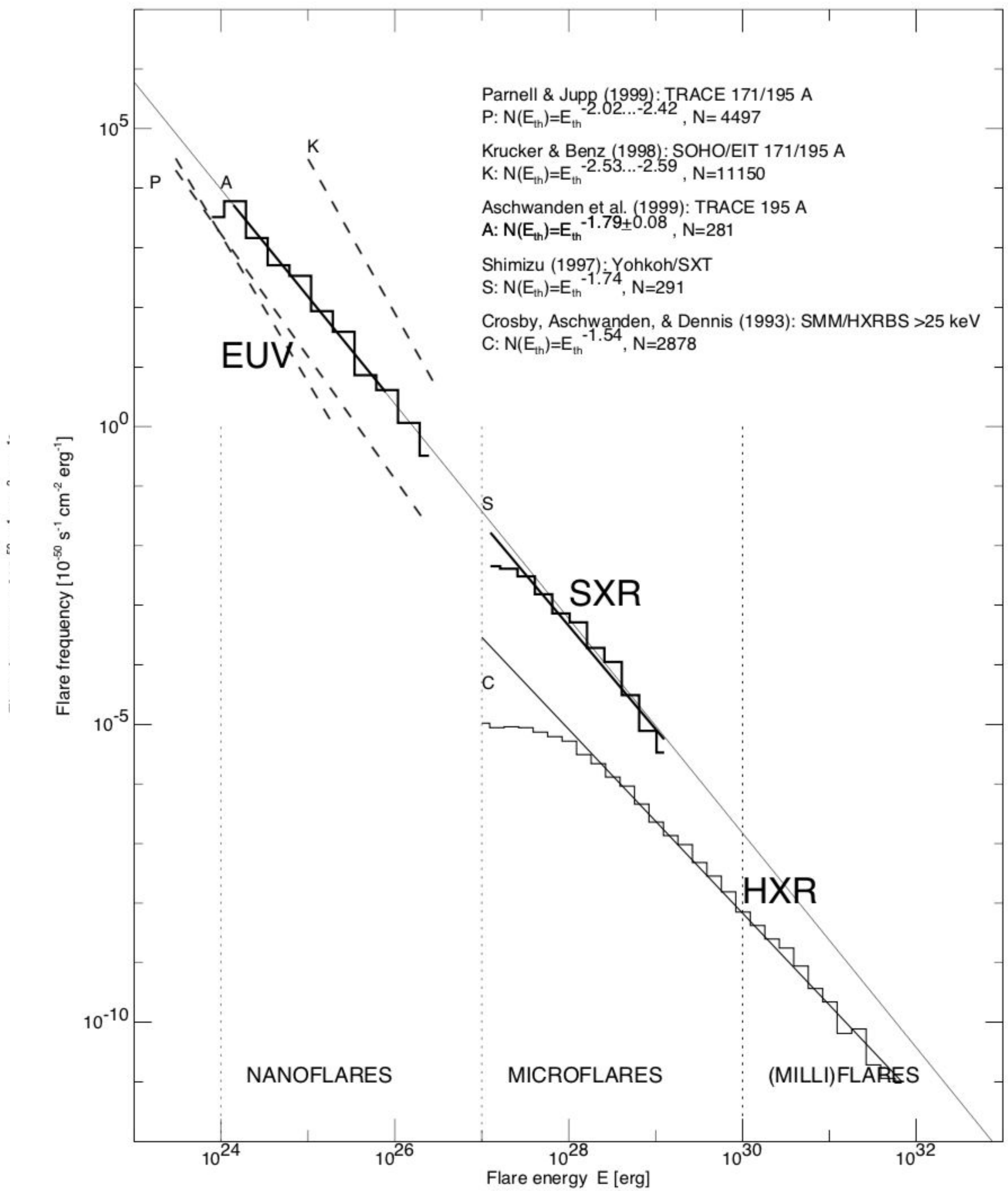
Global fit to to the CR proton flux [PL + Silvia Vernetto astro-ph/1911.01311]

The origin of the
Power-Law Spectra of Cosmic Rays

Fermi Acceleration Mechanism

[universal shape for all sources]

… but perhaps there are other possibilities …



Solar Flares

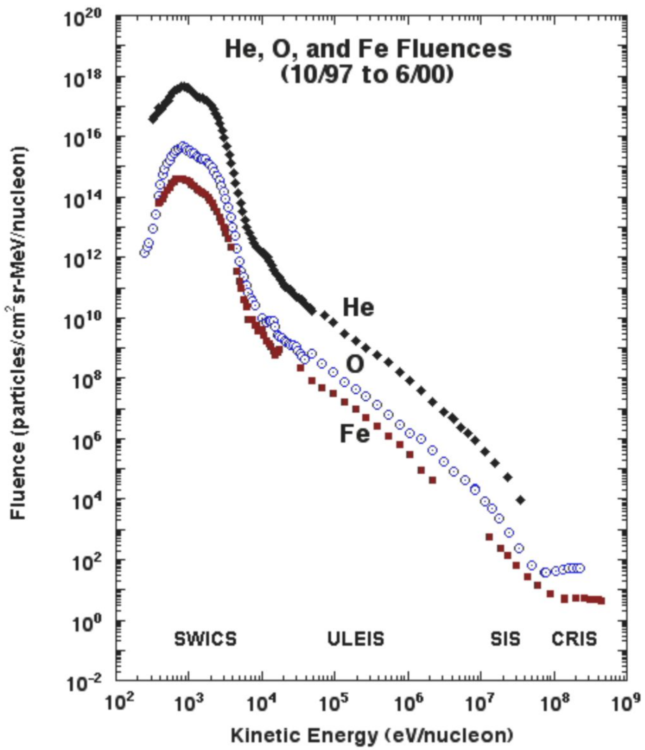
Distribution
(of power-law form)

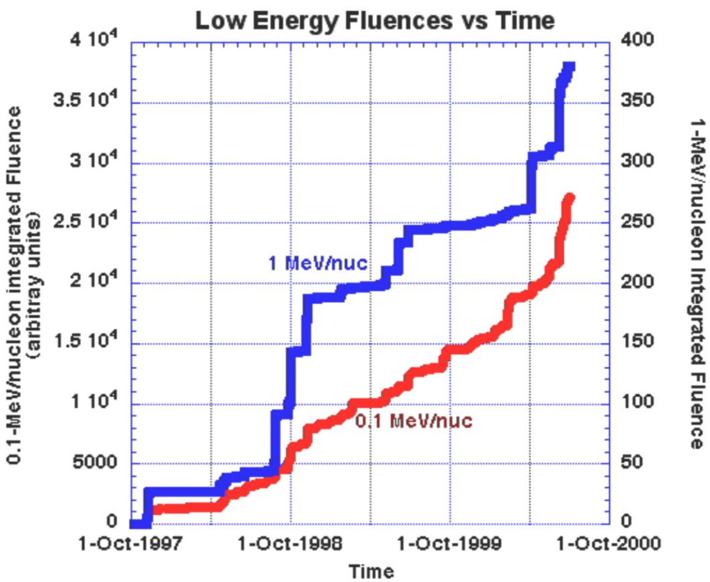
Frequency
versus
Total Released Energy

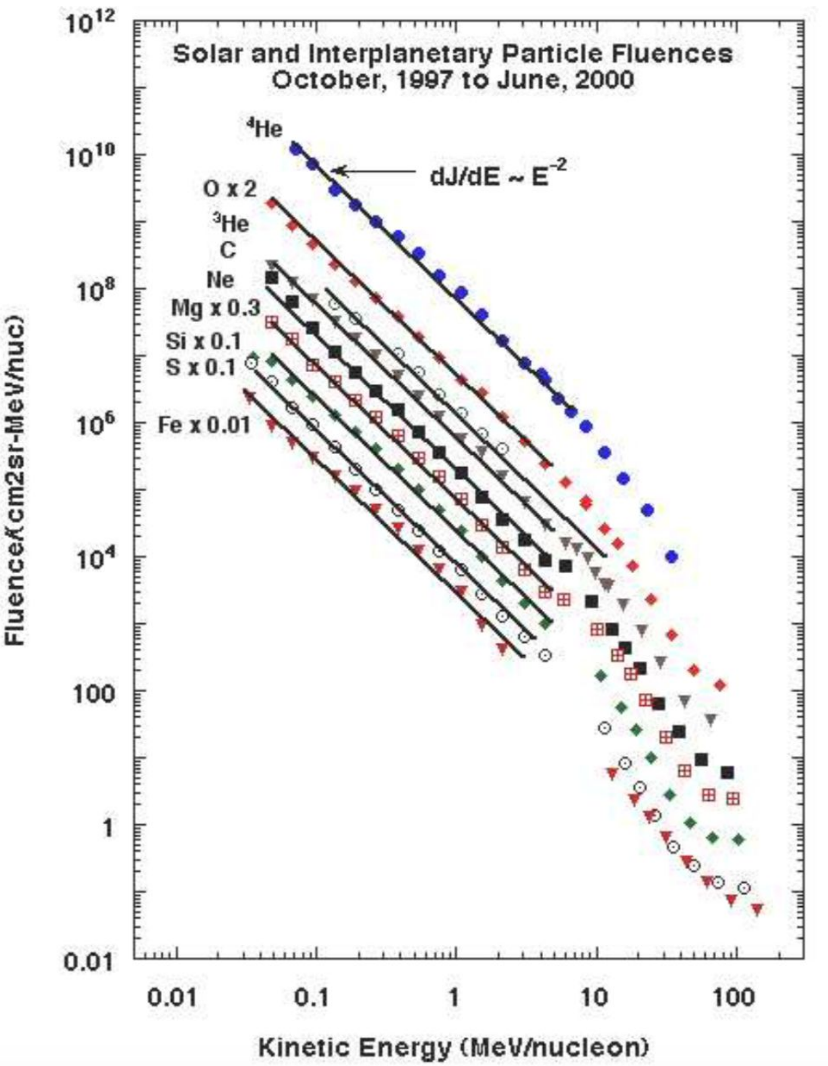
(many small flares
few large flares)

[8 orders of magnitude]

R.A. Mewaldt *et al.*
“Long-Term Fluences of Energetic Particles in the Heliosphere”
27th ICRC Hamburg, (2001).





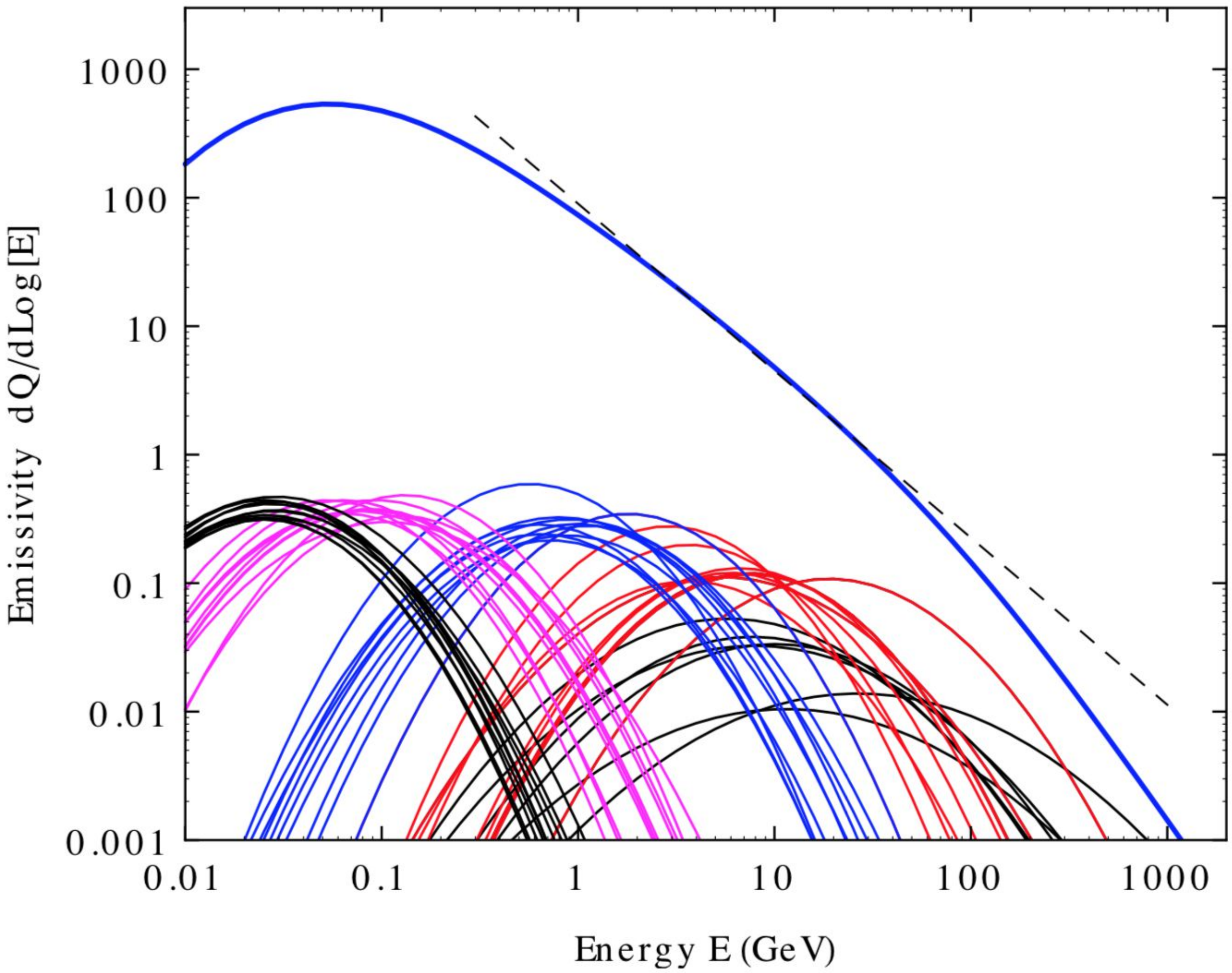


Sum of all Flares
result in a power law shape
[with exponent = 2]

Small flares soft
Large flares hard

Montecarlo “Toy Model” [10^4 sources]

Ensemble of sources with a
power-law distribution in total emitted energy.
emitting Log-parabola (curved spectra) with correlation [Hardness-Total-energy]



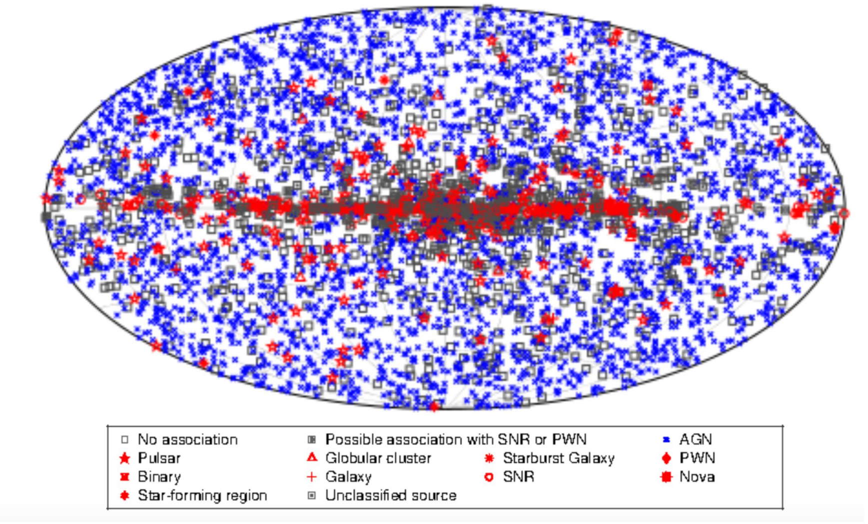
Sum of all sources
has a spectrum
of power law form

P.L.
Astropart.Phys.
(2021).

The 4FGL catalog (5066 sources) gives a "best fit" spectrum for all sources. In one of three functional forms:

Power-Law (3543 sources)

$$\phi_\gamma(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha}$$



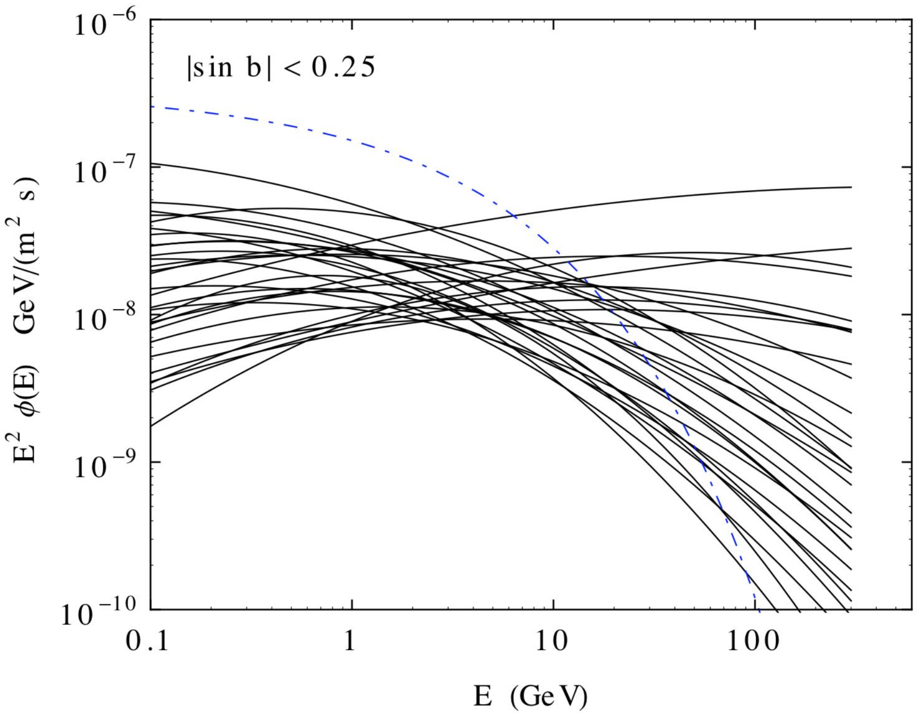
Log-Parabola (1303 sources)

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-(\alpha_0 + \beta \ln E/E_0)}$$

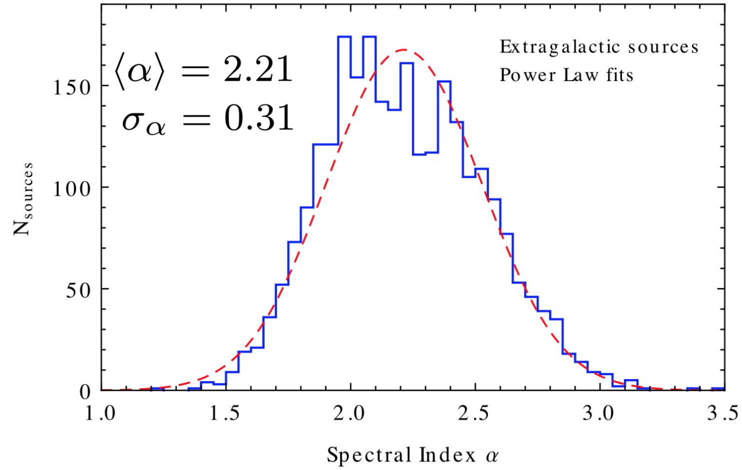
Log-Parabola = *Gaussian in* Log E

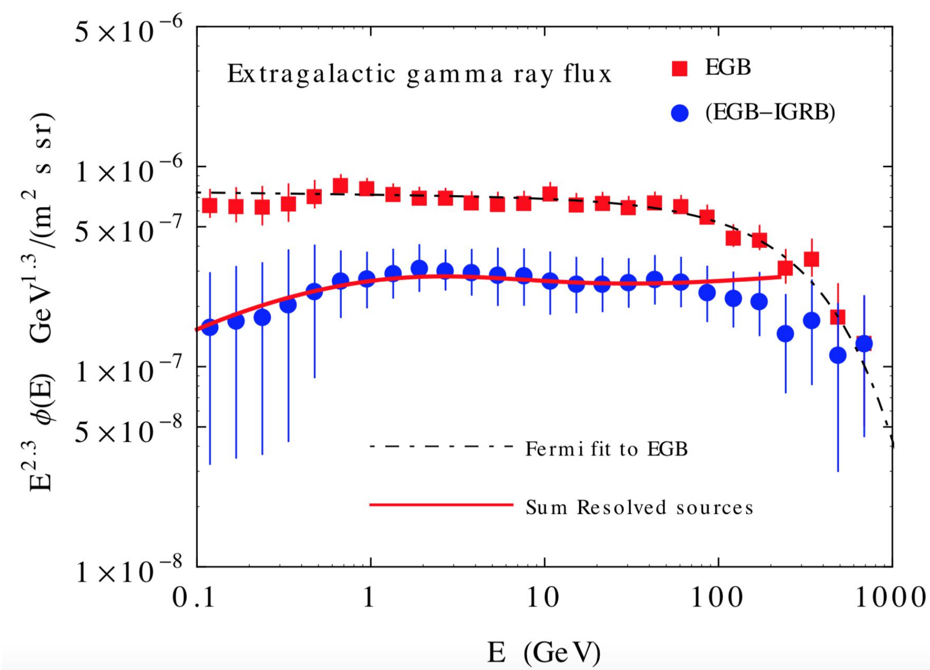
"Cutoff" (218 Pulsars, LMC, 3C 454.3)

Bright sources
have spectra
of log-parabola form

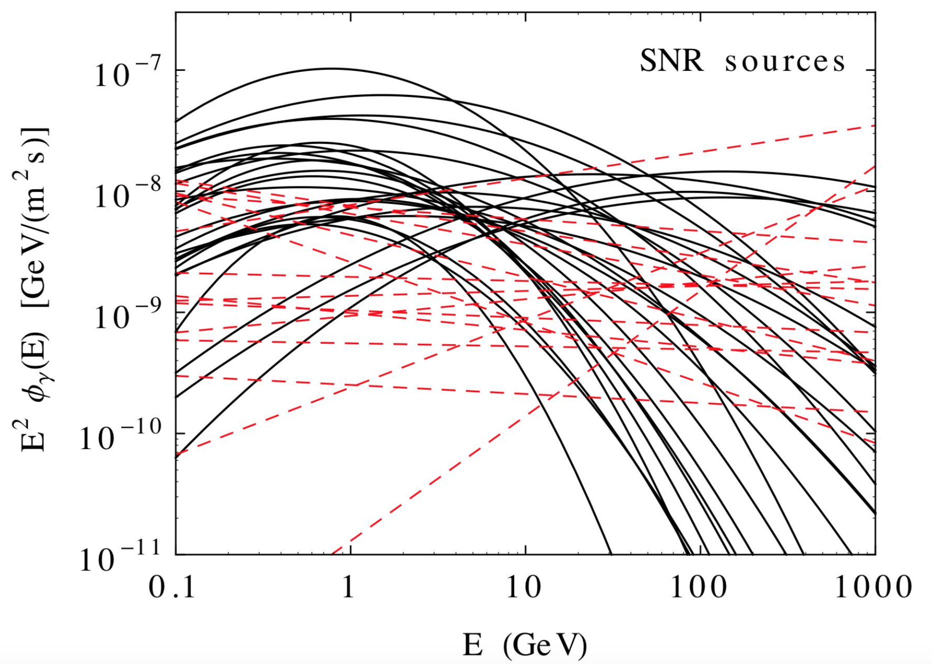


30 brightest extragalactic sources
[3C454.3 + 29 others all log-parabola]





Sum of extragalactic sources
is a power law.



Gamma-Ray spectra from SNR

Very broad range of spectral shapes !

40 Supernova sources in the 4FGL
25 Log-parabola fits
[90.1 % of the flux in the 1-100 GeV range]
15 Power-law fits

Is this consistent with the "standard picture" for Galactic CR acceleration ?
(a) Acceleration in SNR
(b) Power-law spectrum with *unique spectral index*

May be YES.

1. Different ages
2. Different environments

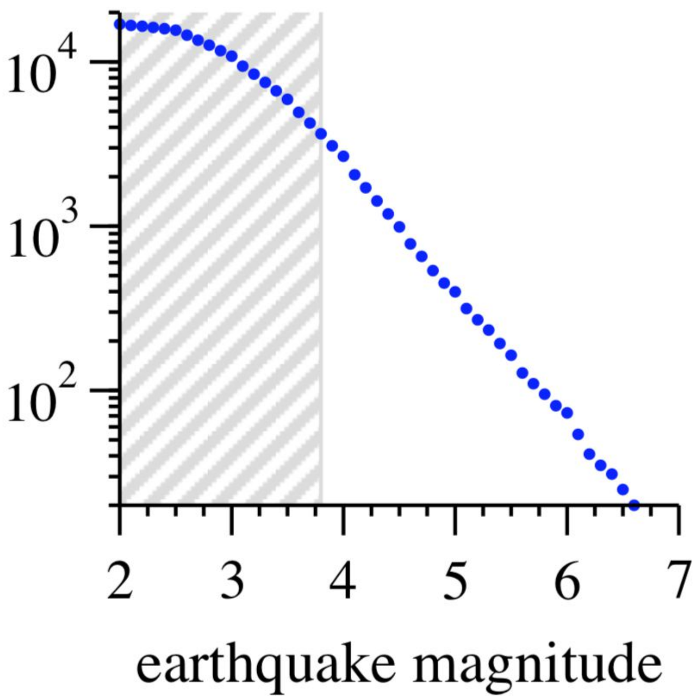
May be NO...

Can the sum of "curved" spectra combine to form a power-law spectrum ?

Power-law distributions

appear widely in a very broad range of fields:
physics, biology, earth and planetary science
economics and finances, social sciences, ...

The origin of power-law behavior has been a topic of debate for more than a century



Gutenberg-Richter law

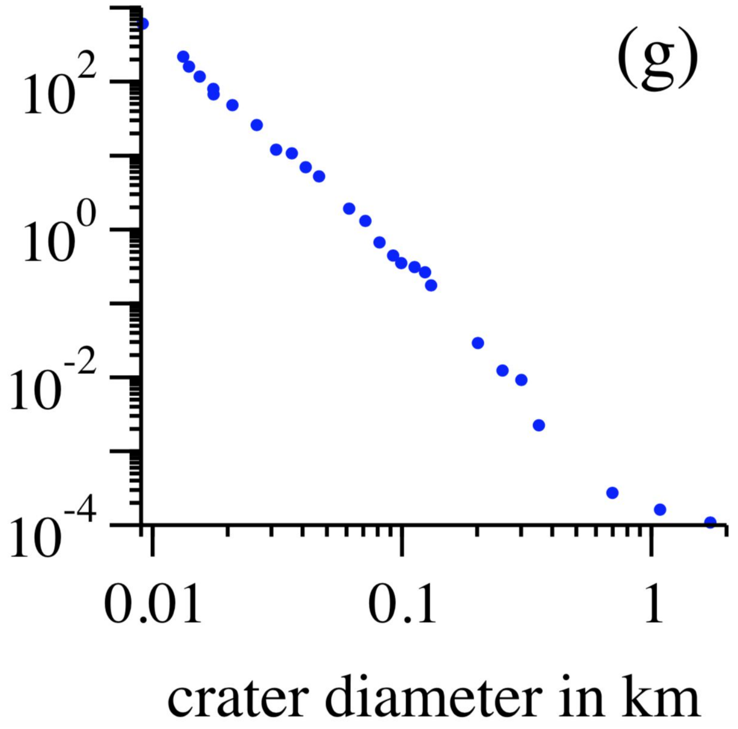
for earthquake frequency
as a function of magnitude

$$\log_{10} N = a - b\, m$$

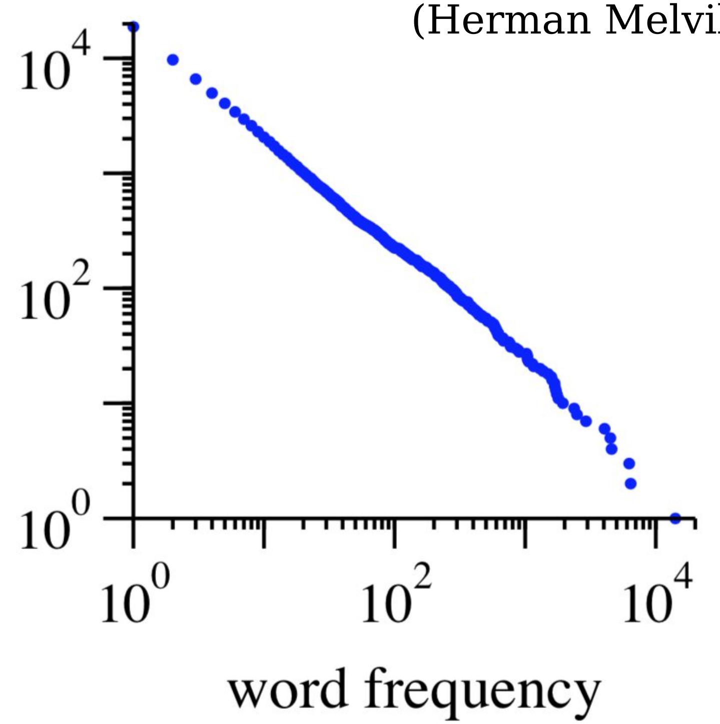
$$dN/d\mathcal{E} \propto \mathcal{E}^{-(b+1)}$$

Earthquakes in California
1910-1992

Cumulative distributions
of Moon craters



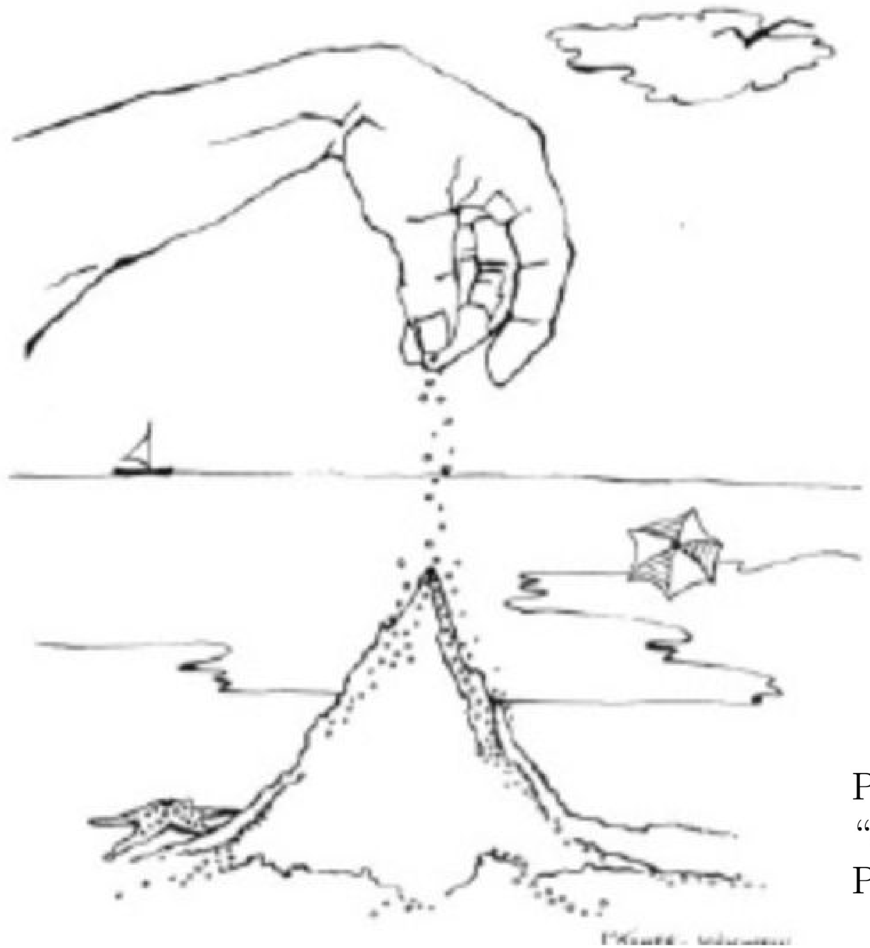
Frequency
of unique words
in Moby Dick
(Herman Melville)



Concept of "Self Organized Criticality"

"Sand Pile"

model



P. Bak, C. Tang and K. Wiesenfeld,
"Self-organized criticality: An Explanation of 1/f noise"
Phys. Rev. Lett. **59**, 381 (1987).

P. Bak, C. Tang and K. Wiesenfeld,
"Self-organized criticality"
Phys. Rev. A **38**, 364 (1988).

Are the concept of “Self Organized Criticality”
relevant for Cosmic Ray Physics
[and for the origin of Galactic CR acceleration] ?

Personal opinion is that this is an intriguing question that deserves to be investigated in depth.

More “concretely"

Do the Cosmic Ray accelerators generate spectra with a “universal spectral shape” (perhaps with only different Maximum energies) or we have a variety of different shapes ?

The Log-Parabola [or LogNormal: a Gaussian in Log E] is spectral shape that appears “everywhere”.
What is its origin and significance ?

I think it is very likely that it is a form that is more than a “ first order approximation” for a curved spectrum, but it is a shape that emerges naturally in many different circumstances [like the Gaussian]

Conclusions

1. The main properties of Galactic Cosmic Rays Propagation have yet been established "beyond doubt".

   Crucial Observations:
   Beryllium-10
   Electrons and positron spectra for E > 1 TeV

2. We are living a
   "Golden Era" in
   High Energy Astrophysics

   but/therefore it possible/desirable to look critically to the fundamental concepts of the field
   [Like the spectra generated by the accelerators].