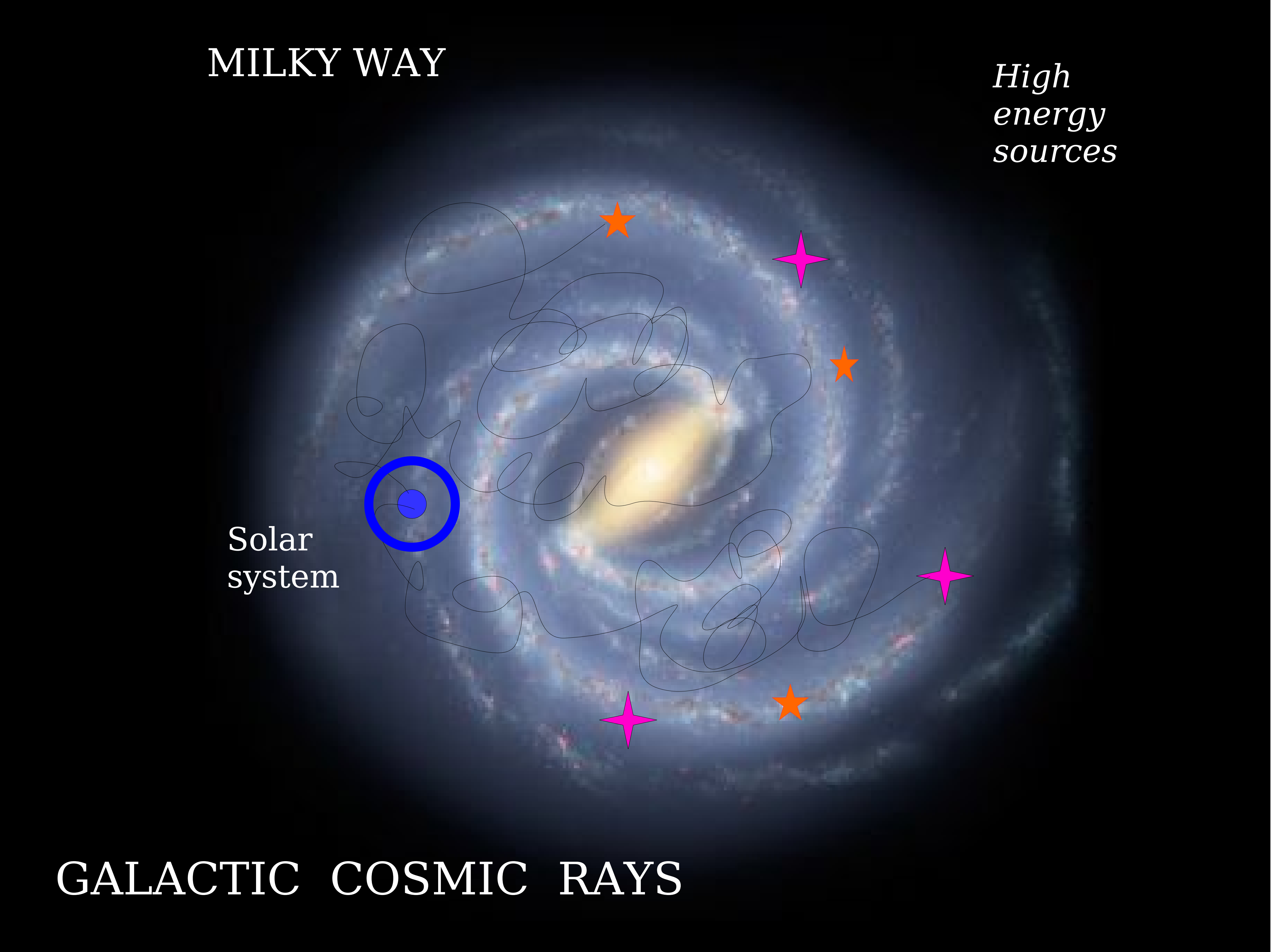
Interpretation of the Protons and Helium-nuclei Cosmic-Ray spectra

Paolo Lipari, INFN Roma "Sapienza"

"The Multimessenger Sky
at Extreme Energies"

Trieste 8th September 2026


MILKY WAY
High energy sources
Solar system
GALACTIC COSMIC RAYS

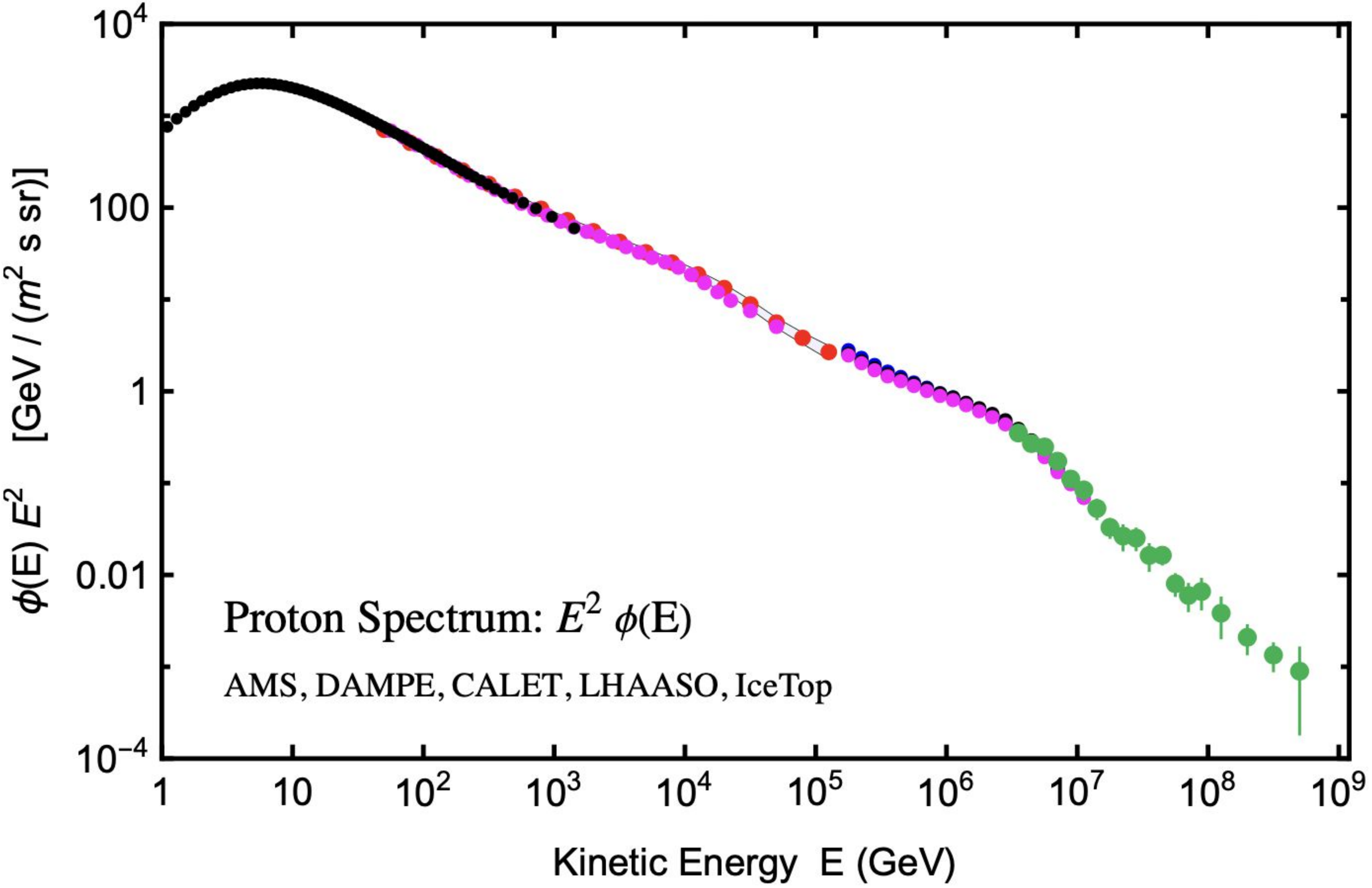
Precision Measurements
of the spectra of protons and helium nuclei
ave revealed the existence of “features”
(deviations from a simple power-law form).

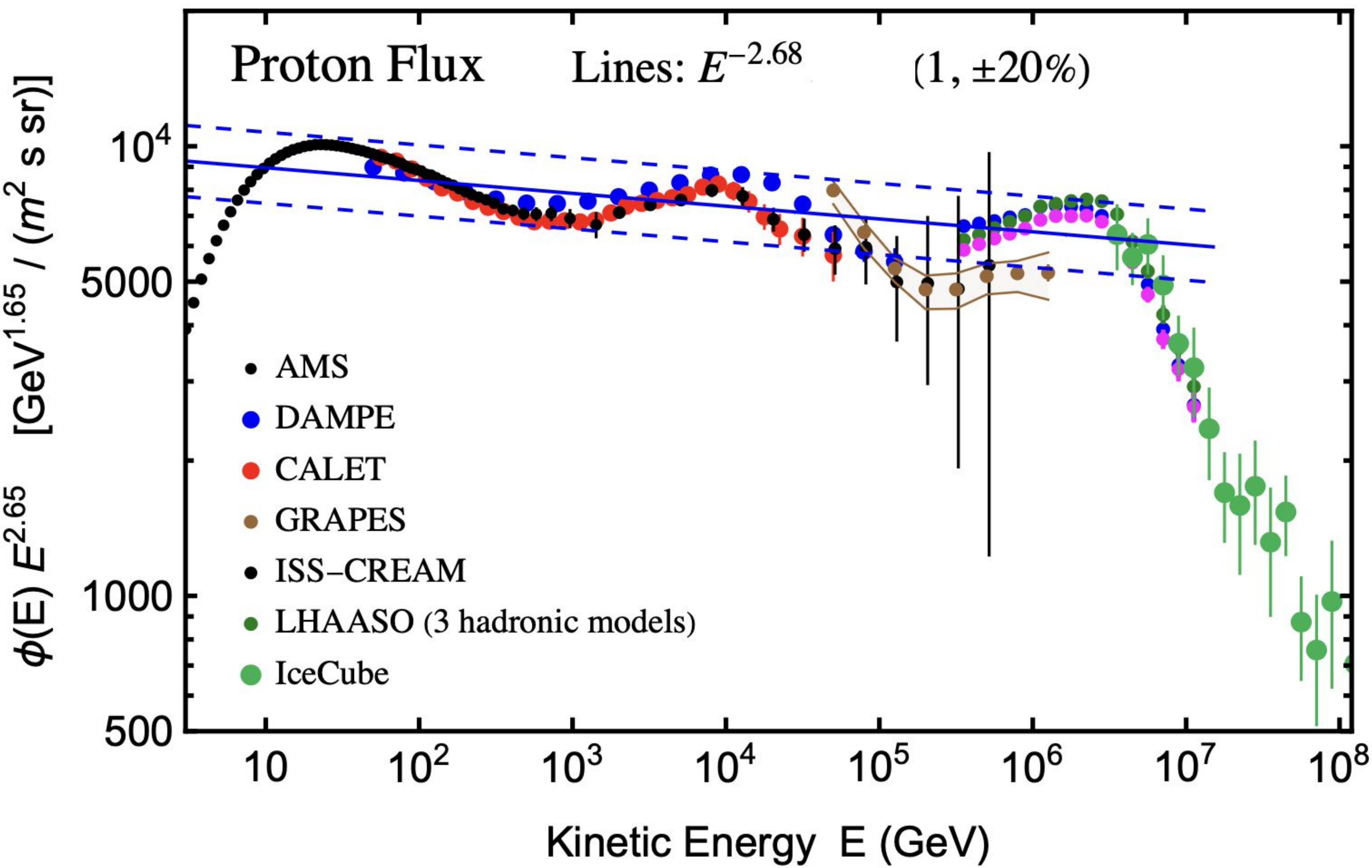
What it is their origin ?

Why are the shapes of the spectra of

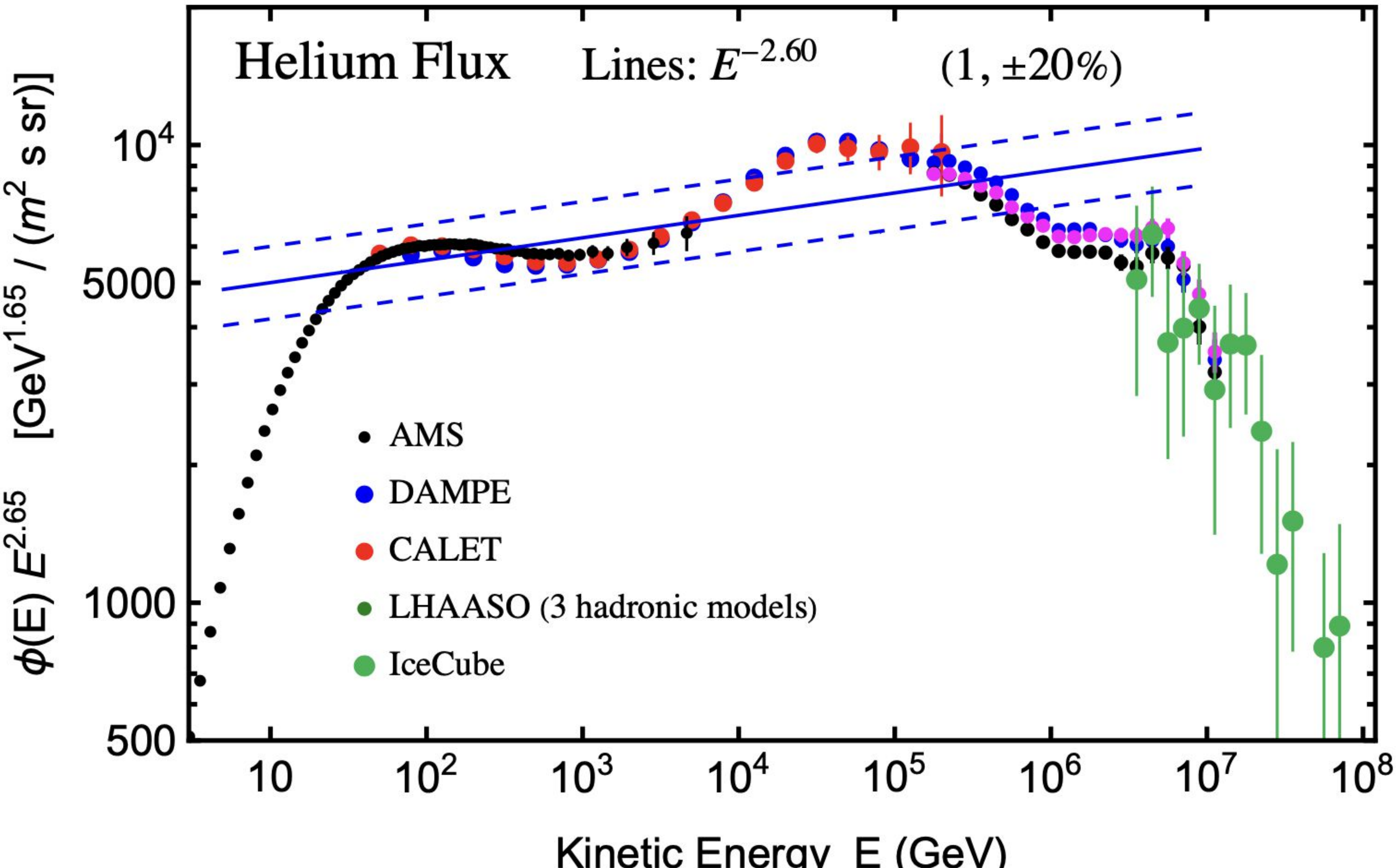
protons and Helium different ?

Proton spectrum




Proton Flux
Lines: $E^{-2.68}$
$(1, \pm 20\%)$
10^4
5000
1000
500
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
$\phi(E)\ E^{2.65}$ [GeV$^{1.65}$ / (m^2 s sr)]
Kinetic Energy E (GeV)
AMS
DAMPE
CALET
GRAPES
ISS–CREAM
LHAASO (3 hadronic models)
IceCube

Helium Flux



Helium Flux
Lines: $E^{-2.60}$
$(1, \pm 20\%)$
$\phi(E)\ E^{2.65}$ [GeV$^{1.65}$ / (m^2 s sr)]
10^4
5000
1000
500
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Kinetic Energy E (GeV)
AMS
DAMPE
CALET
LHAASO (3 hadronic models)
IceCube

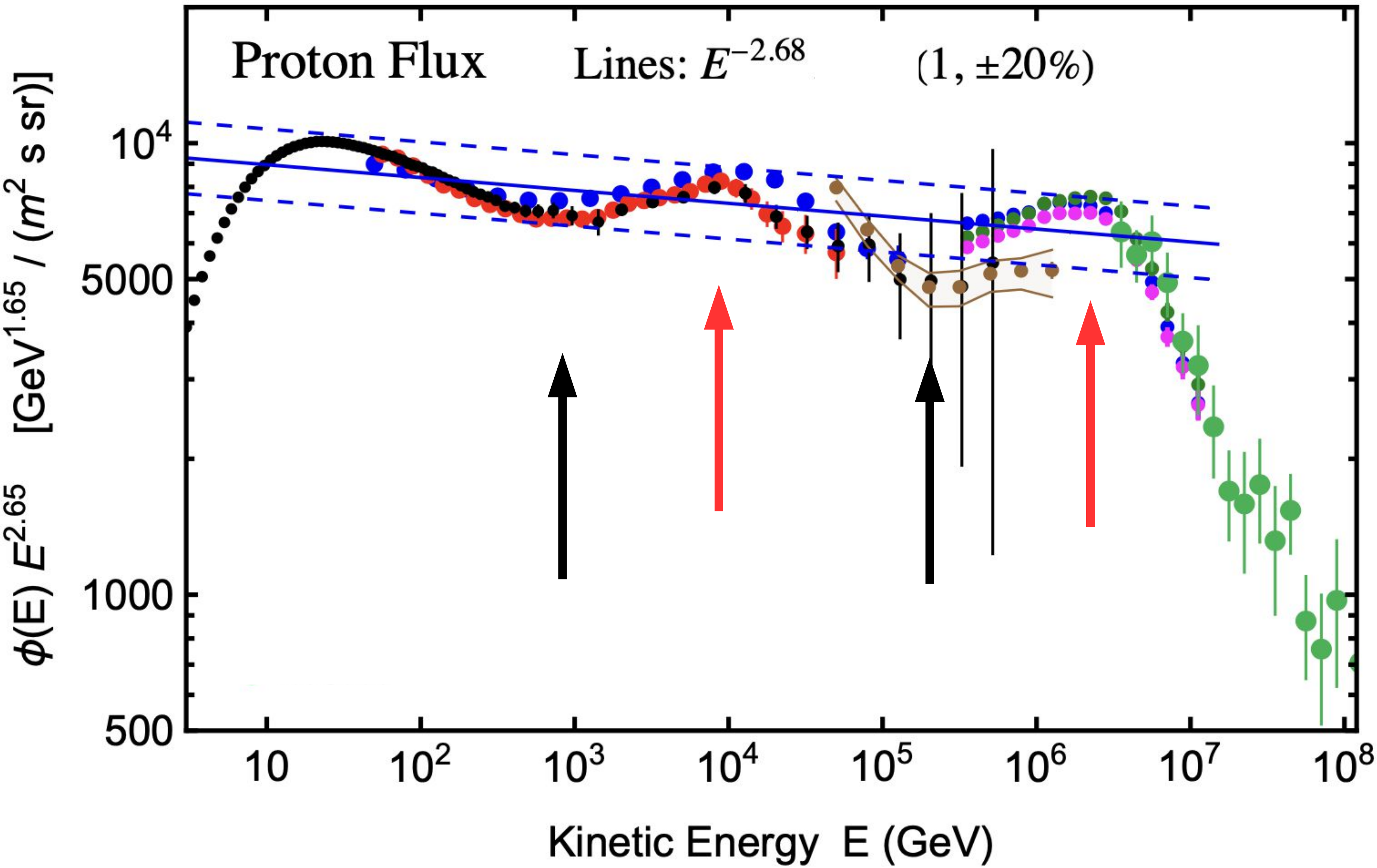
Phenomenogical fit to the data:

Sequence of Breaks

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma_0} \prod_{j=1}^{N_b} \left[1 - \left(\frac{E}{E_{b,j}}\right)^{1/w_j}\right]^{-(\Gamma_j - \Gamma_{j-1})\, w_j}$$

Proton spectrum : 4 breaks

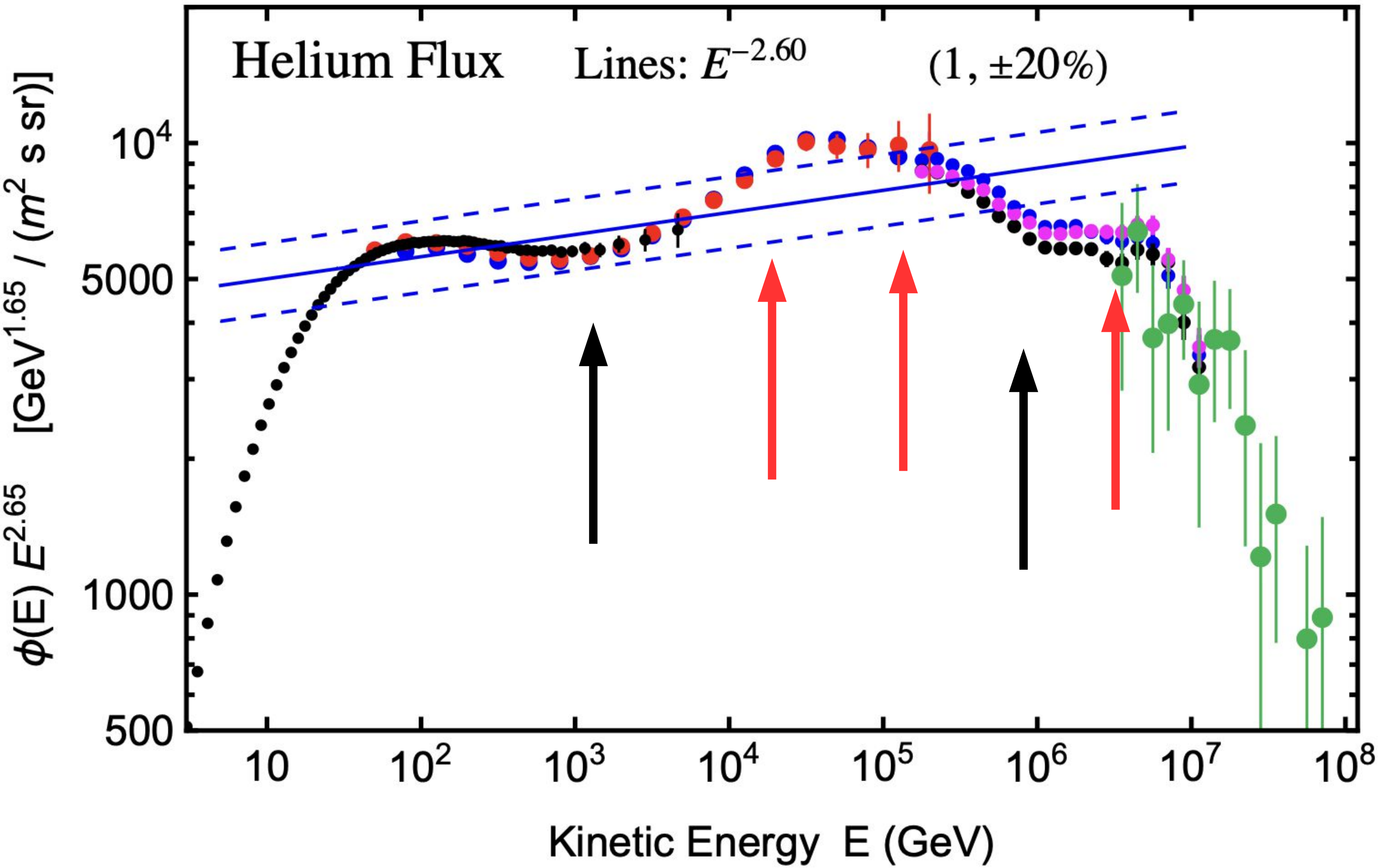
Helium spectrum: 5 breaks



4 features (2 hardenings, 2 softenings)

Helium Flux

[5 features 2 hardenings
3 softenings]



Protons, Helium Energy Spectra

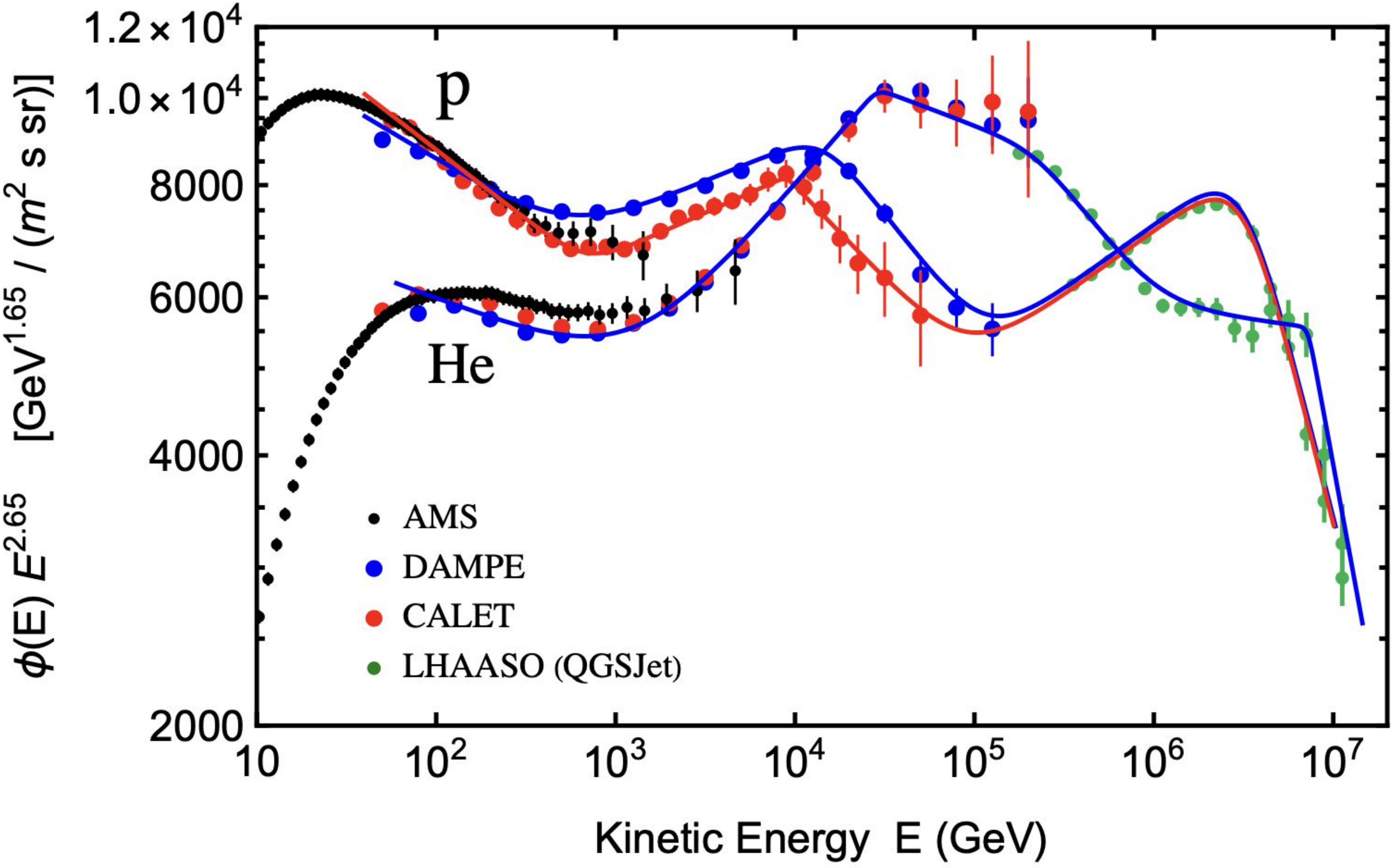
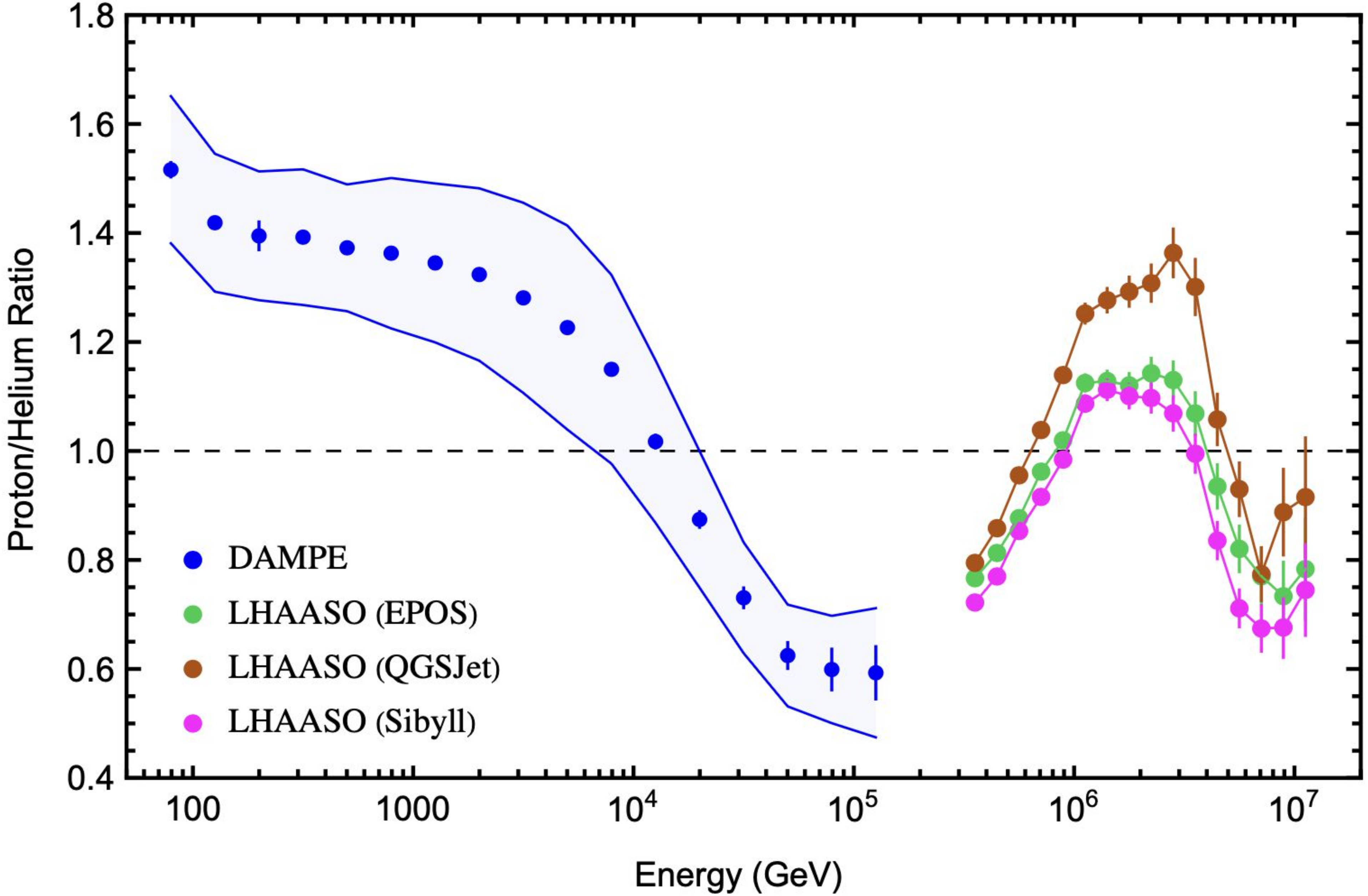


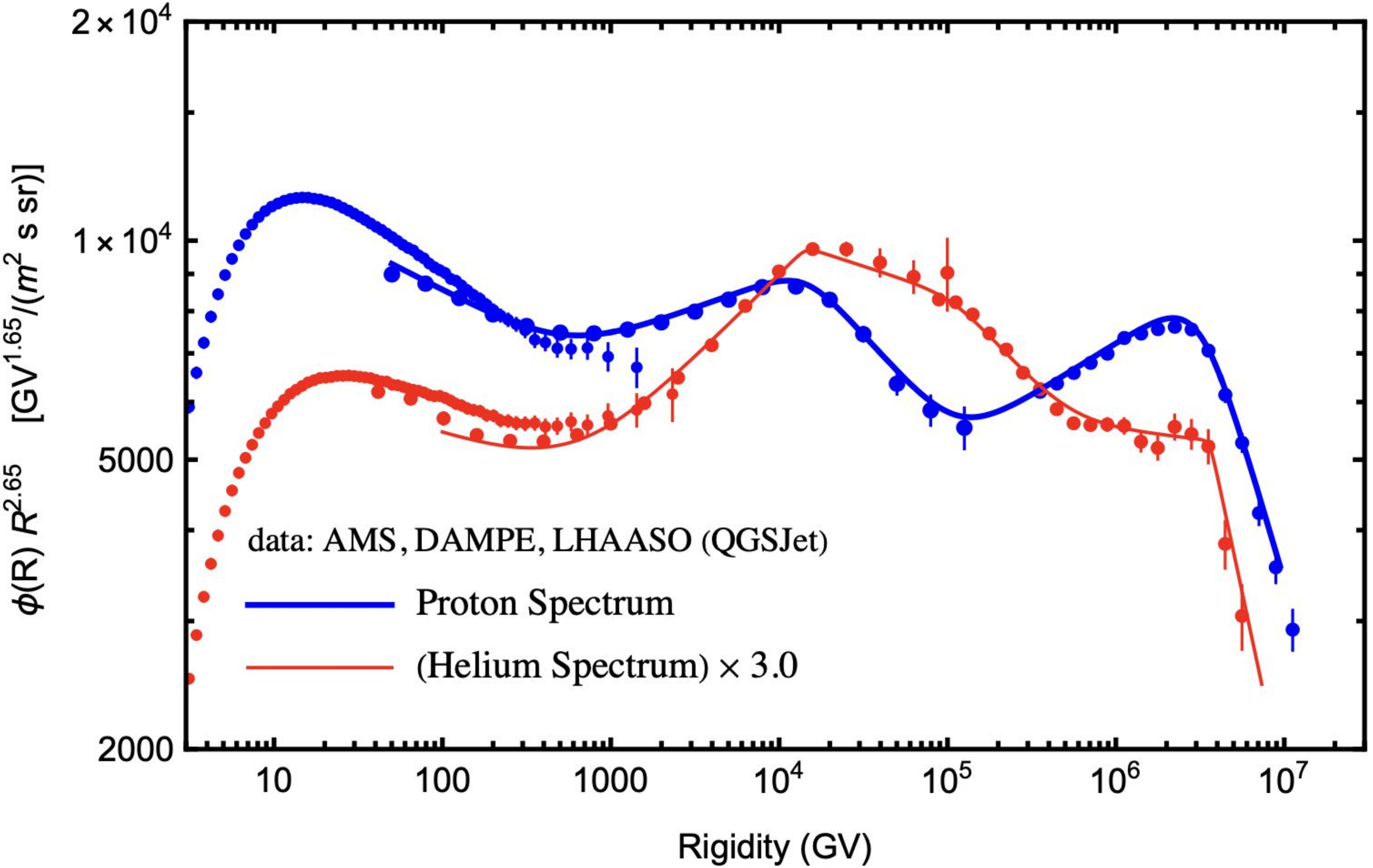
Table of Fit patameters [DAMPE + LHAASO]

	Proton Flux			Helium Flux		
b	$\log_{10}[\mathcal{R}_b]$	γ_b	w_b	$\log_{10}[\mathcal{R}_b]$	γ_b	w_b
0	–	2.75 ± 0.01	–	–	2.73 ± 0.01	–
1	2.81 ± 0.01	2.57 ± 0.01	0.45 ± 0.02	2.89 ± 0.02	2.42 ± 0.01	0.55 ± 0.02
2	4.15 ± 0.01	2.91 ± 0.01	0.2 ± 0.1	4.16 ± 0.01	2.72 ± 0.01	$\lesssim 0.18$
3	5.06 ± 0.01	2.50 ± 0.01	$0.3^{+0.1}_{-0.2}$	5.03 ± 0.02	2.91 ± 0.01	0.23 ± 0.03
4	–	–	–	5.71 ± 0.05	2.68 ± 0.03	0.34 ± 0.10
5	6.50 ± 0.02	3.4 ± 0.1	0.21 ± 0.04	6.56 ± 0.06	3.7 ± 0.5	≤ 0.12
	$\log_{10}[\phi_0\ (\mathrm{m}^2\ \mathrm{s\ sr\ GeV})^{-1}]$			$\log_{10}[\phi_0\ (\mathrm{m}^2\ \mathrm{s\ sr\ GeV})^{-1}]$		
	-2.20 ± 0.01			-2.86 ± 0.01		

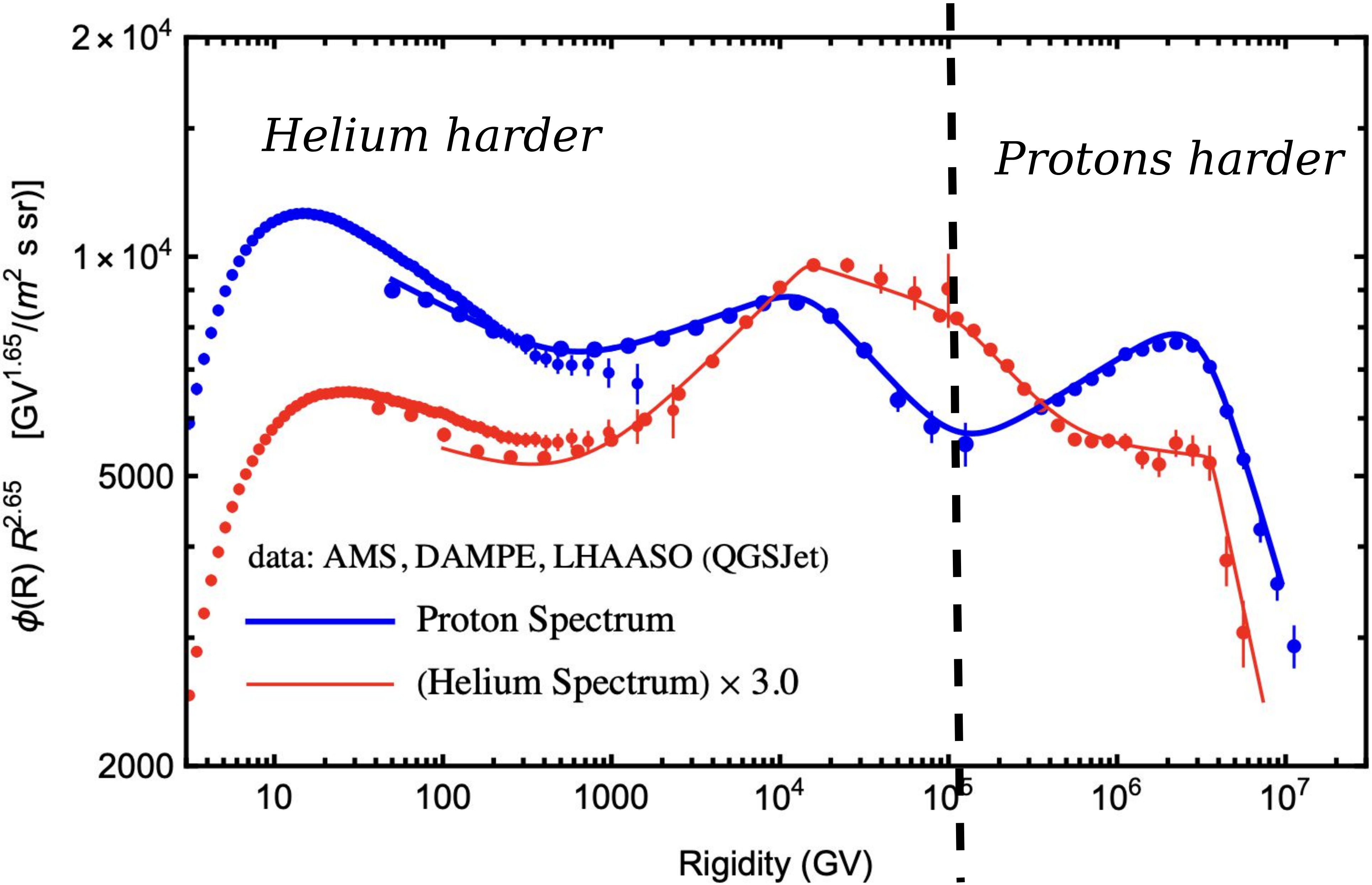
p/He Ratio as a function of Energy



Protons, Helium Rigidity Spectra



Protons, Helium Rigidity Spectra



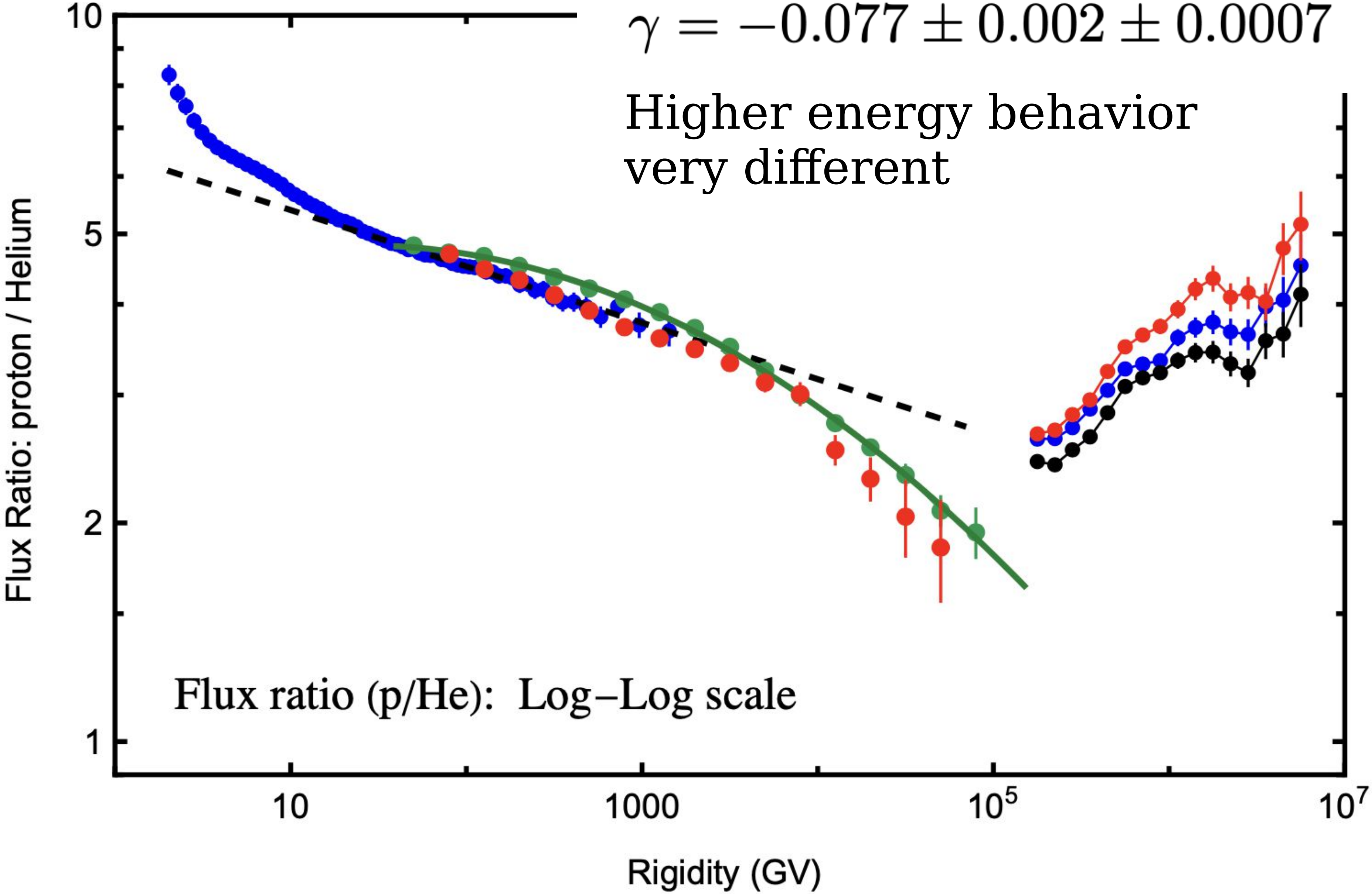
Ratio p/Helium

AMS fit
R>45 GV

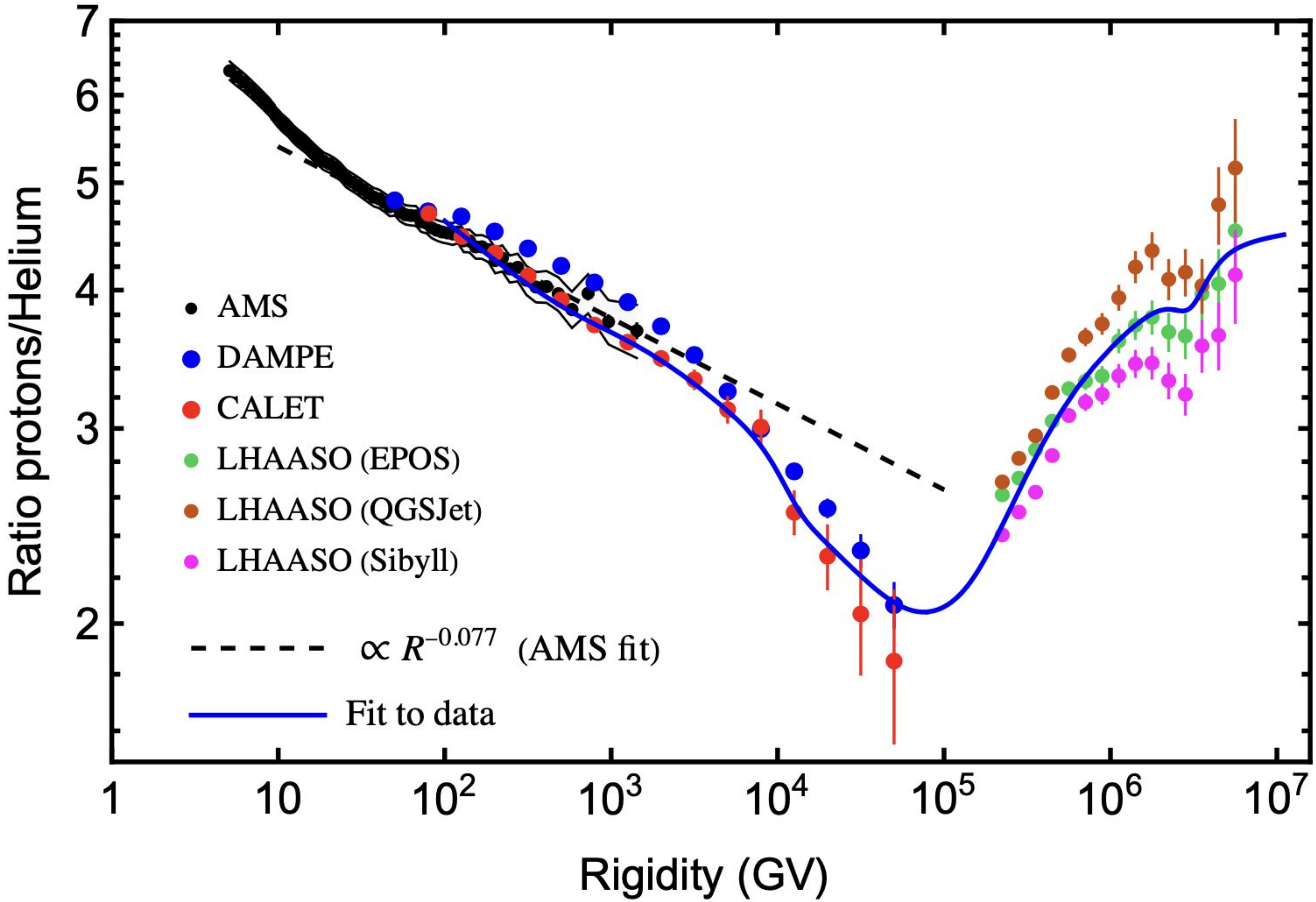
$$\frac{p}{\mathrm{He}} \propto R^{\gamma}$$

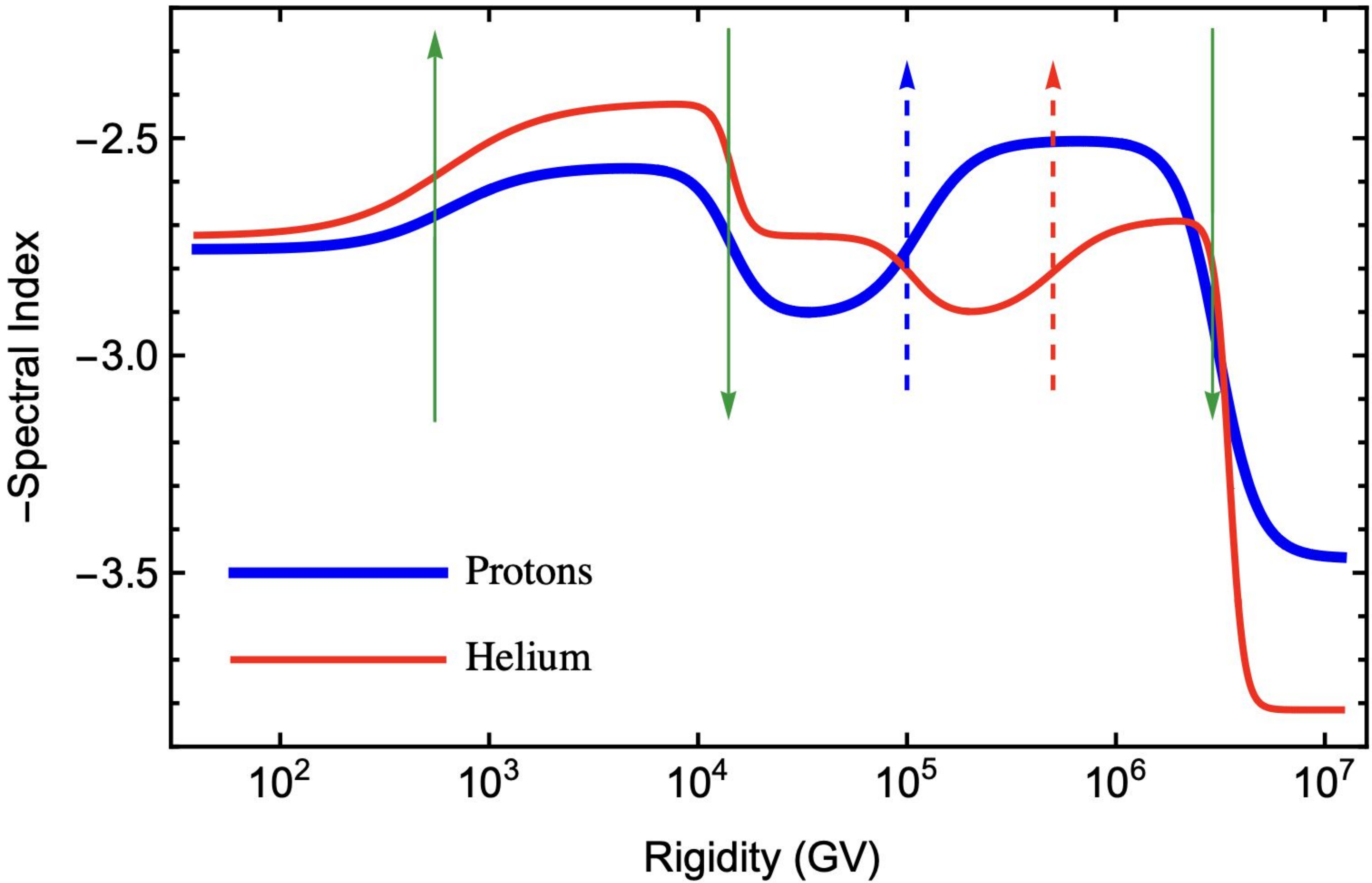
$$\gamma = -0.077 \pm 0.002 \pm 0.0007$$

Higher energy behavior
very different



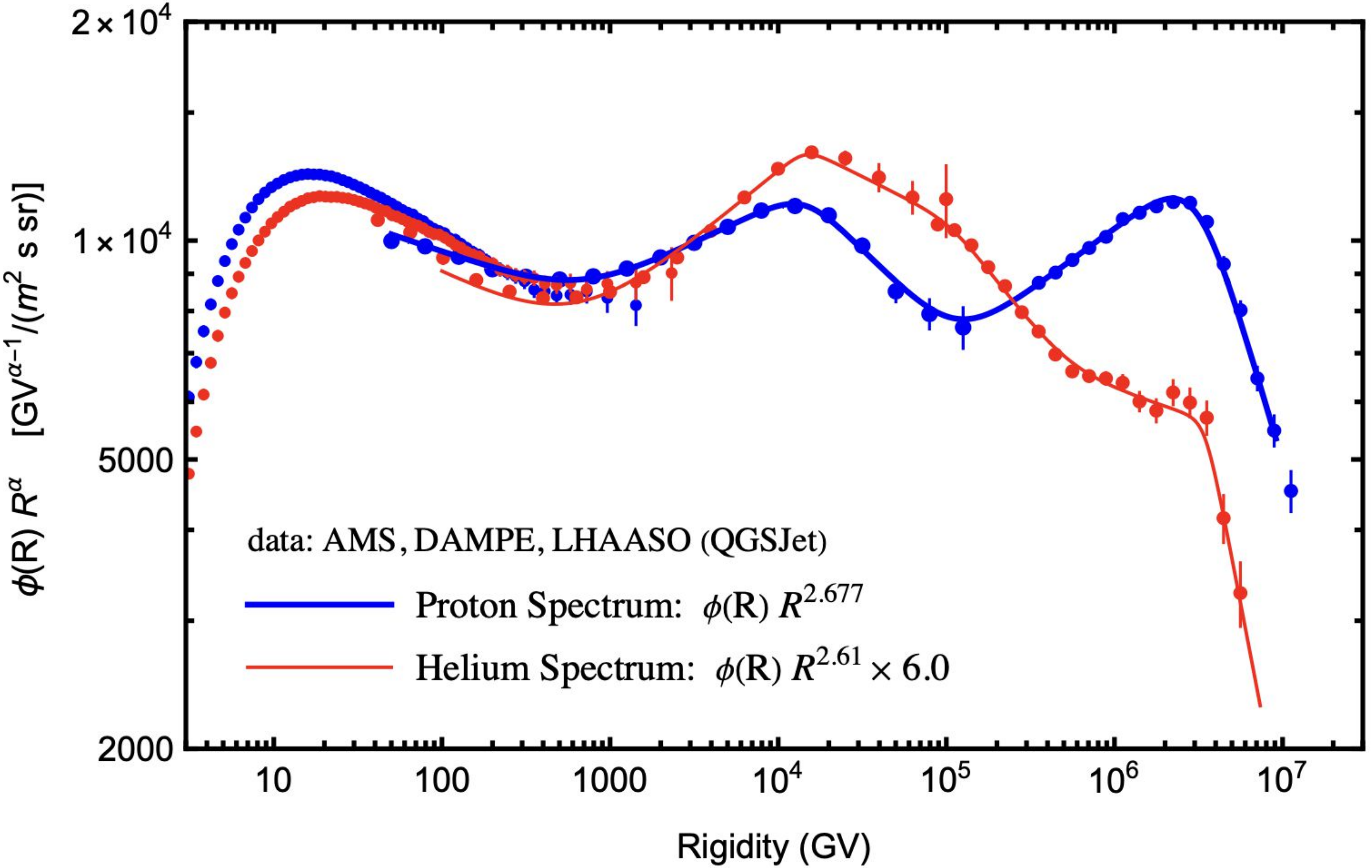
p/He ratio as a function of Rigidity





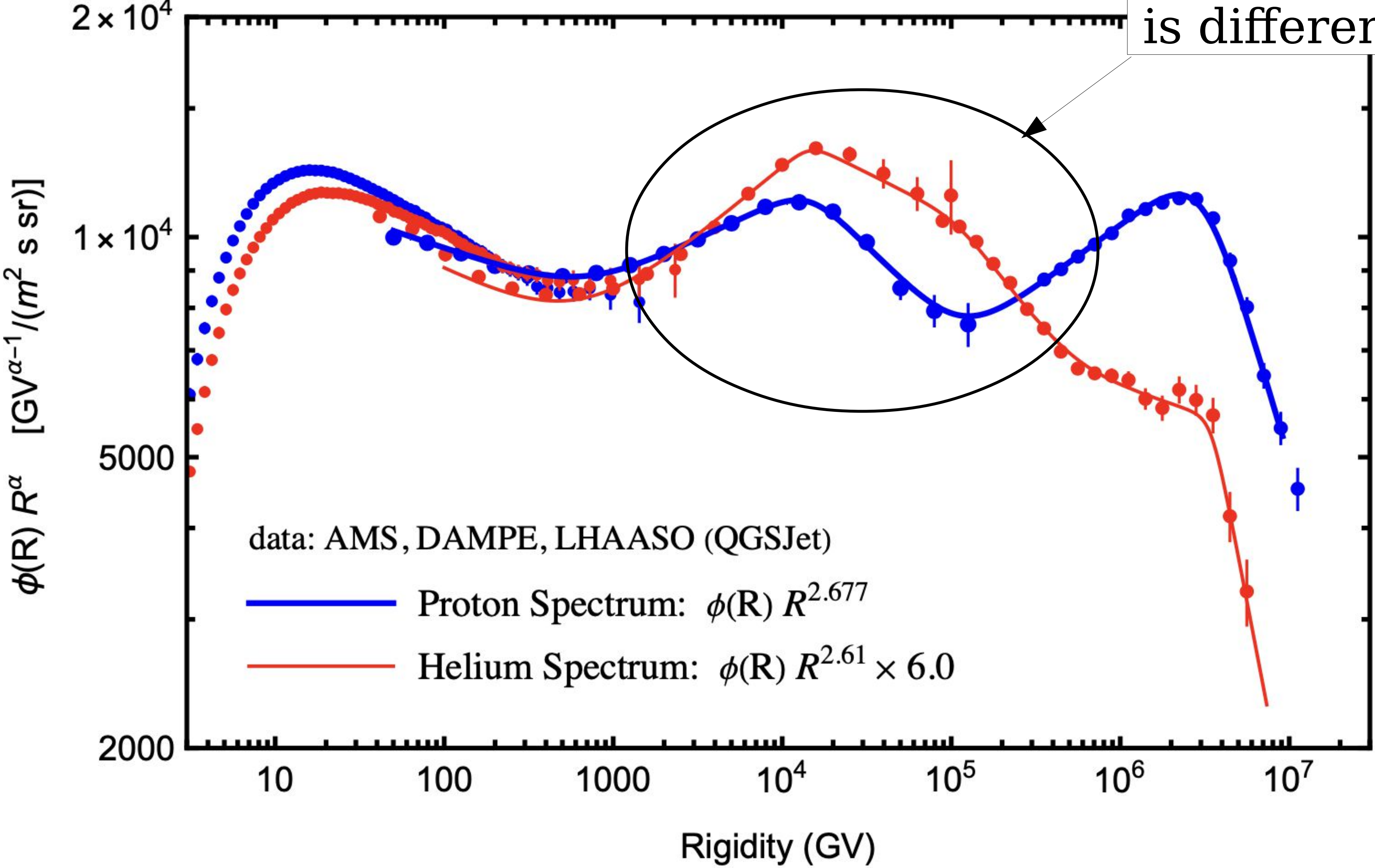
−2.5
−3.0
−3.5
–Spectral Index
Protons
Helium
10^2
10^3
10^4
10^5
10^6
10^7
Rigidity (GV)

Protons, Helium Rigidity Spectra (different factors)

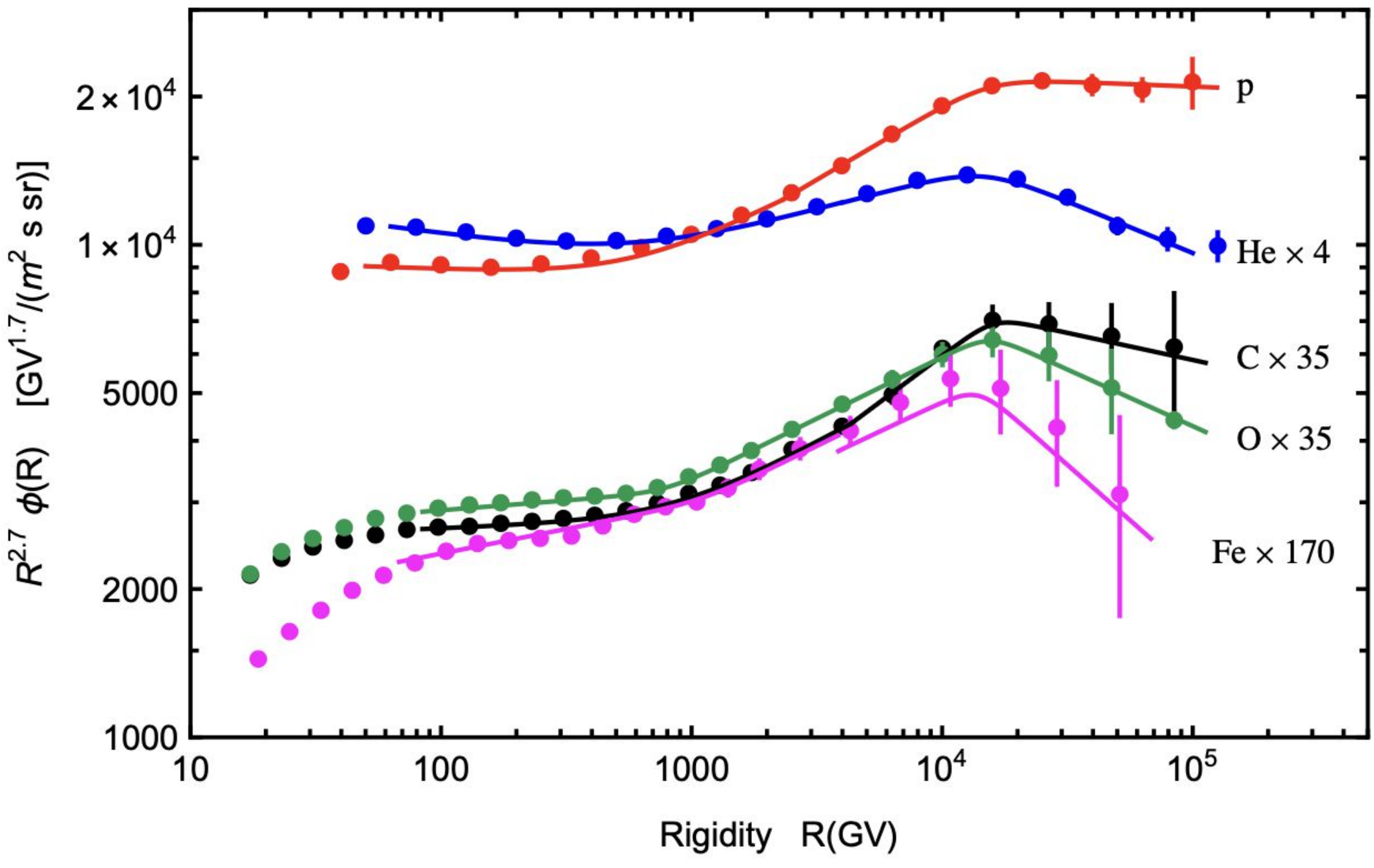


Protons, Helium Rigidity Spectra (different factors)

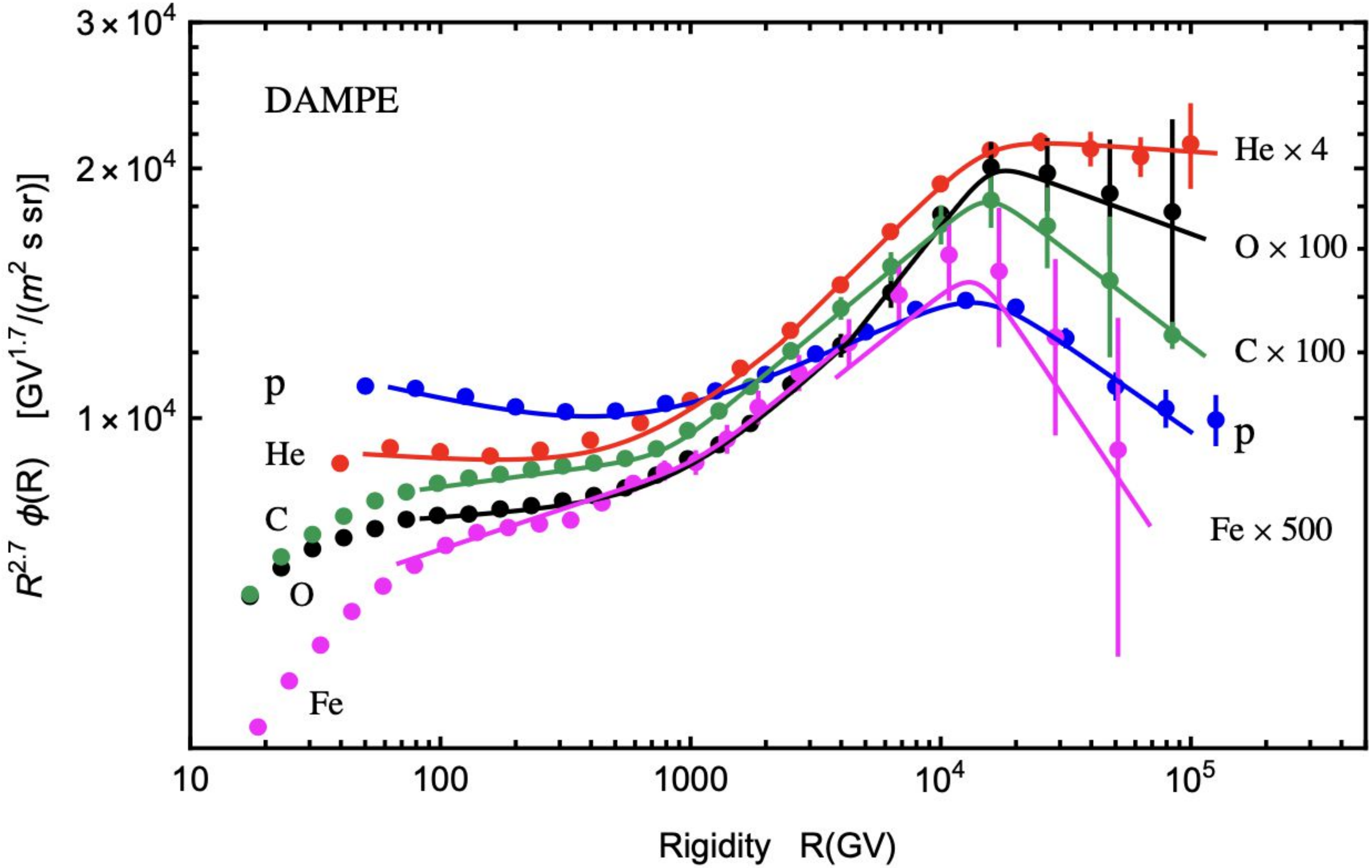
structure of this “bump” is different



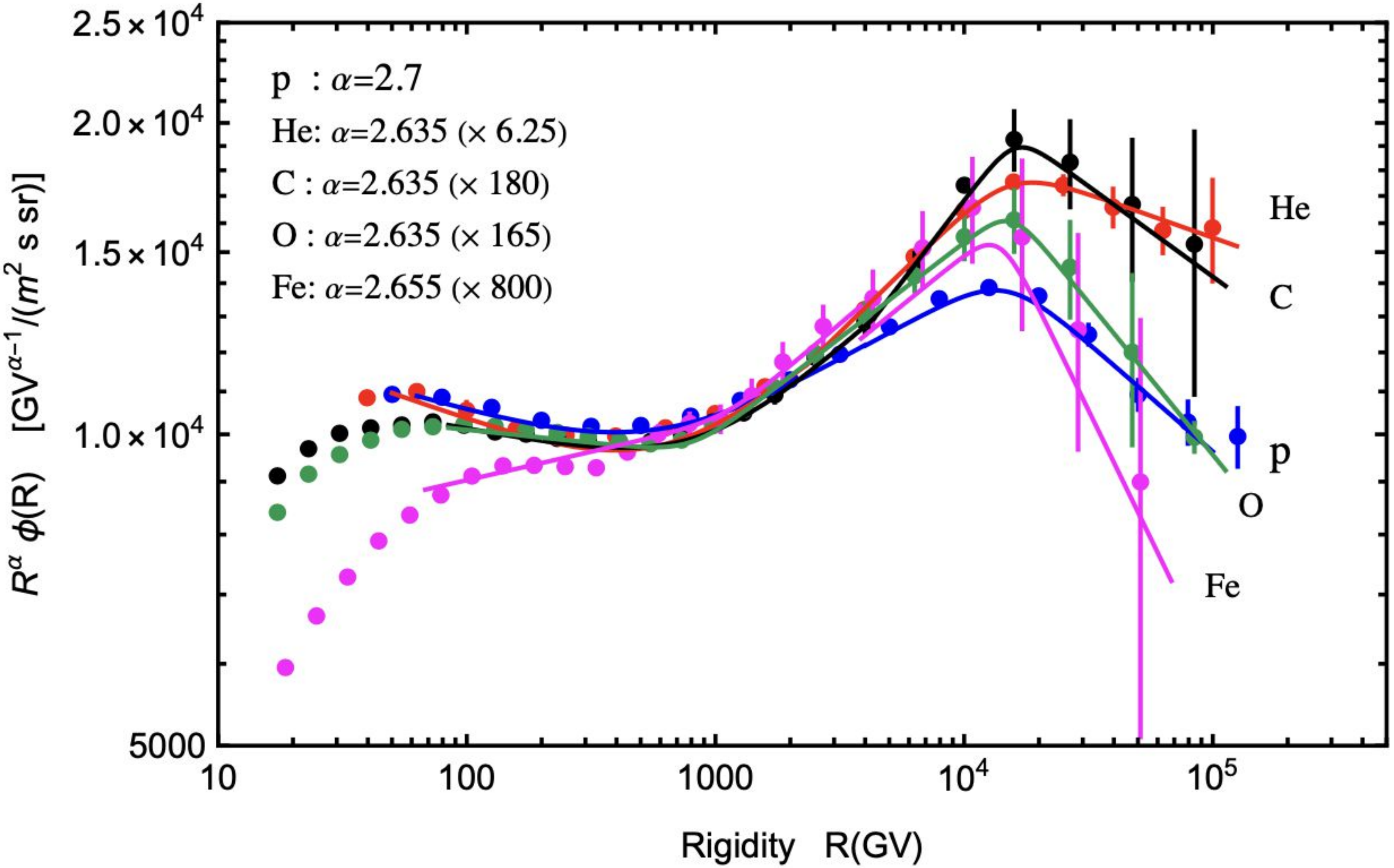
Replot DAMPE data as a function of Rigidity



Replot DAMPE data as a function of Rigidity
[closer in absolute normalization]



Replot DAMPE data as a function of Rigidity
with different factors E^{α}
(and different absolute normalizations)



Structure of the softening quite different

Possible Origin of the Spectral structures.

There is a crucial assumptions that is common to most (in fact nearly all) models that discuss "features" [deviations from a simple power-law form] in the cosmic ray spectra:

The emission spectra generated by [a single class of] CR accelerators have a simple power law shape with a cutoff (of exponential or quasi/exponential form)

$$q_a(E) \propto q_{0,a} \; E^{-\alpha} \; \exp\left[-\frac{E}{E_{b,a}}\right]$$

[If] the spectra [for nuclei] are *Rigidity dependent:*

α "universal" slope

$$E_{b,a} = Z \, E_{b,p}$$

cutoffs $\propto Z$

The Multiple source-class Hypothesis

$$\phi_Z(E) = \sum_{C \in \text{classes}} \phi_{Z,C}(E)$$

$$= \sum_{C \in \text{classes}} K_{Z,C} \left(\frac{E}{E_0}\right)^{-\Gamma_{Z,C}} \exp\left[-\frac{E}{Z\, E_{p,C}^{\text{cut}}}\right]$$

Gaisser, Stanev, Tilav [2013]

The Cosmic-Ray sources release in interstellar space spectra with the form of power-law with a high energy cutoff.

Propagation for stationary sources results in spectral a distortion that is a power-law in rigidity.

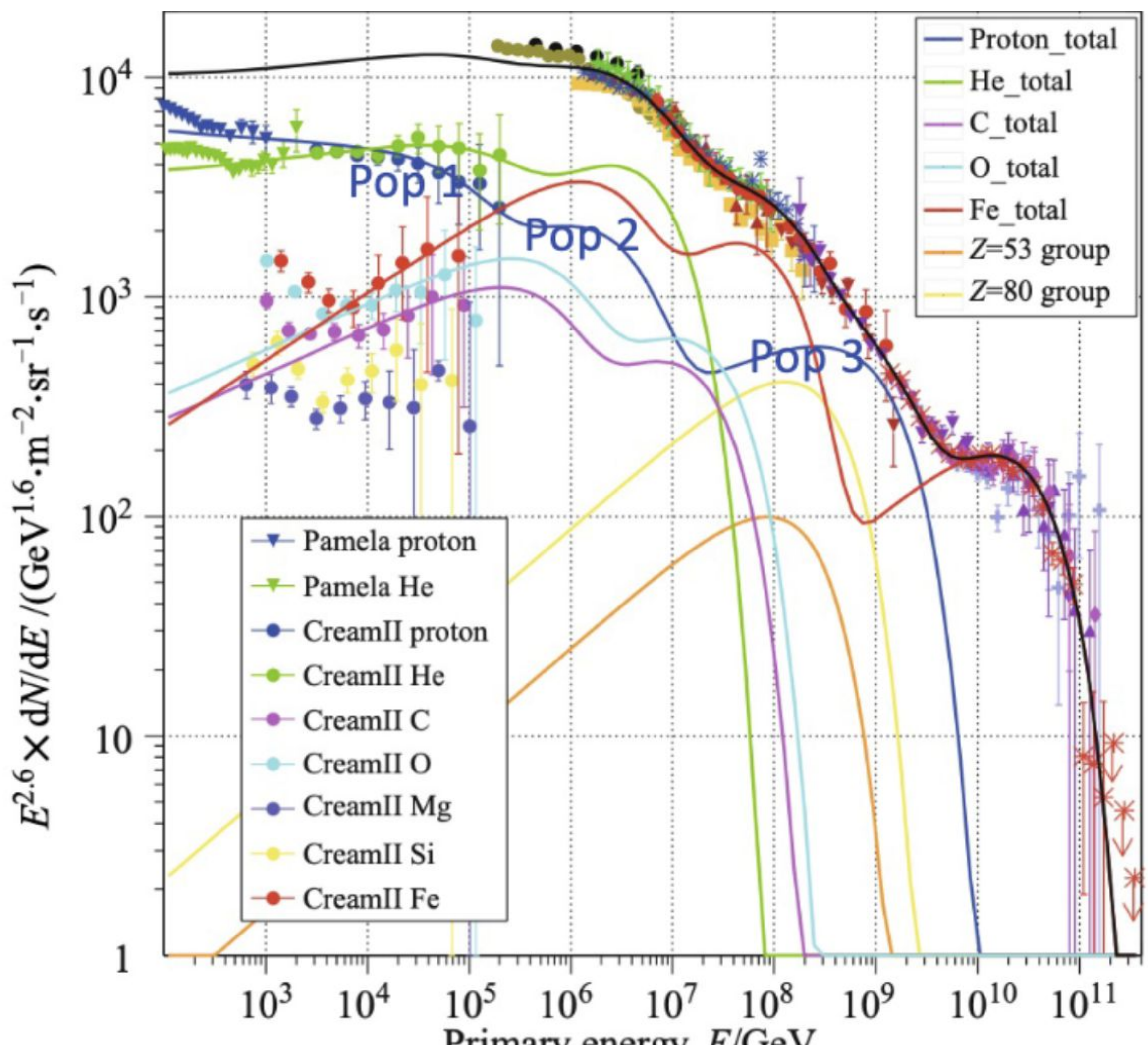
$$\phi(E) \propto \frac{Q(E)}{D(\mathcal{R})}$$

The observable spectra are therefore a power-law with a high energy cutoff

Possibility of "Local" (transient) sources [propagation effects encodes position+ age]

The idea that several classes of sources
that form different "Peters's cycles"
[characterized by different slopes and cutoffs]
was developed by Tom Gaisser, Todor Stanev and Serap Tilav
in an influential paper addressing the high energy CR spectra

Gaisser, Front. Phys., 2013, 8(6): 748–758 (2013)



4 CR population
with different
(Z-proportional)
break energies

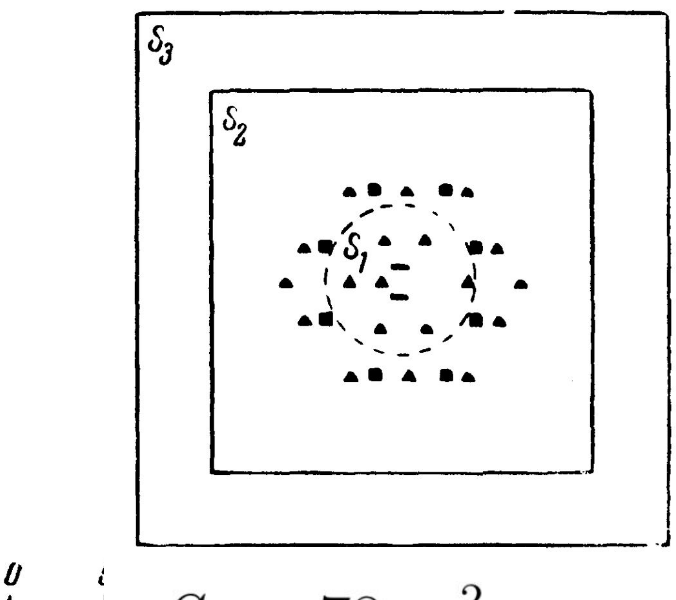
120 TeV
4 PeV (knee)
1.5 EeV
40 EeV ("HE cutoff")

Note:
must allow the slopes
of different elements
to be not identical

Kulikov, Khristansen
JETP 35, 635 (1958)

Moscow State University
Cosmic Ray Telescope

Observation of a “break”
in the size spectrum

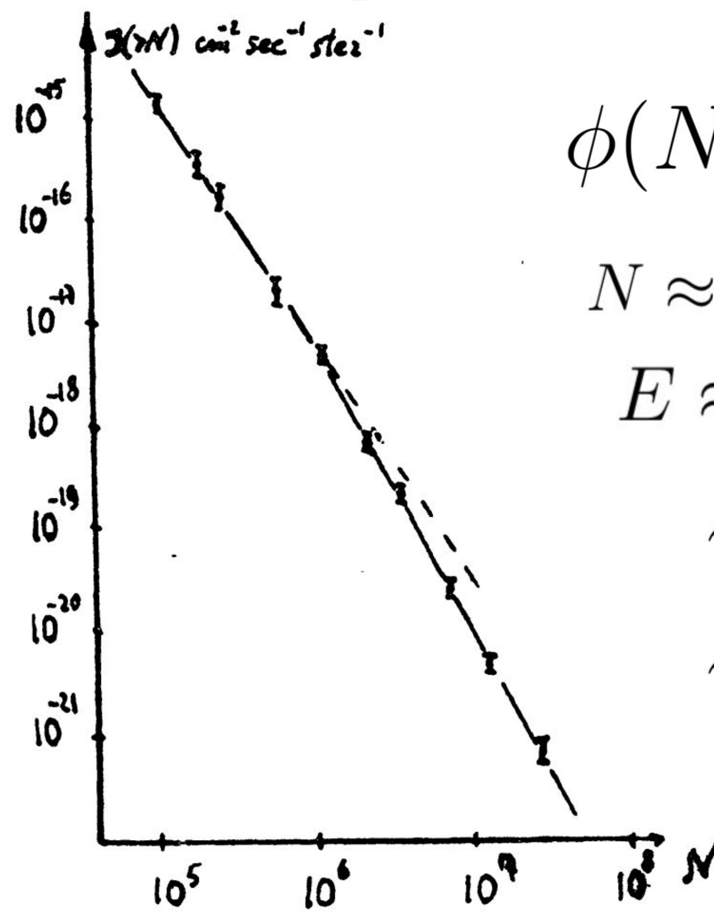


$S_1 = 78 \text{ m}^2$

$S_2 = 400 \text{ m}^2$

$S_3 = 576 \text{ m}^2$

ICRC Jaipur (1963)



$$\phi(N) \propto N^{-(\gamma+1)}$$

$$N \approx 3 \times 10^6$$

$$E \approx 10^{15} \text{ eV}$$

$$\gamma_1 = 1.4 \pm 0.1$$

$$\gamma_2 = 1.9 \pm 0.1$$

Interpretation offered in 1963
[Moscow State University group]

Propagation effect:

Change in the energy (rigidity) dependence of Diffusion coefficient

"The energetic spectrum and composition of the cosmic rays produced by the sources remain unchanged over the whole of primary energy"

Diffusion Model

$$\langle X \rangle \approx 9 \ \mathrm{g\,cm^{-2}}$$

$$q(E) \propto E^{-(\gamma_0+1)}$$

$$\gamma_0 \approx 1.5$$

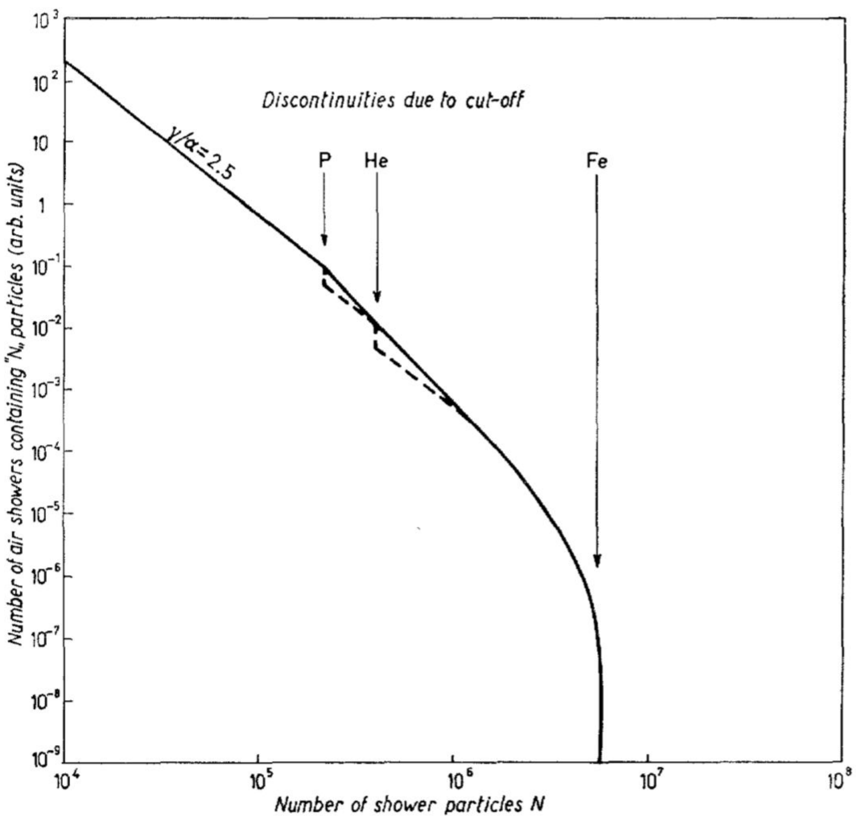
$$\phi(E) \propto \frac{q(E)}{D(E)}$$

$$D(E) \propto E^{\delta}$$

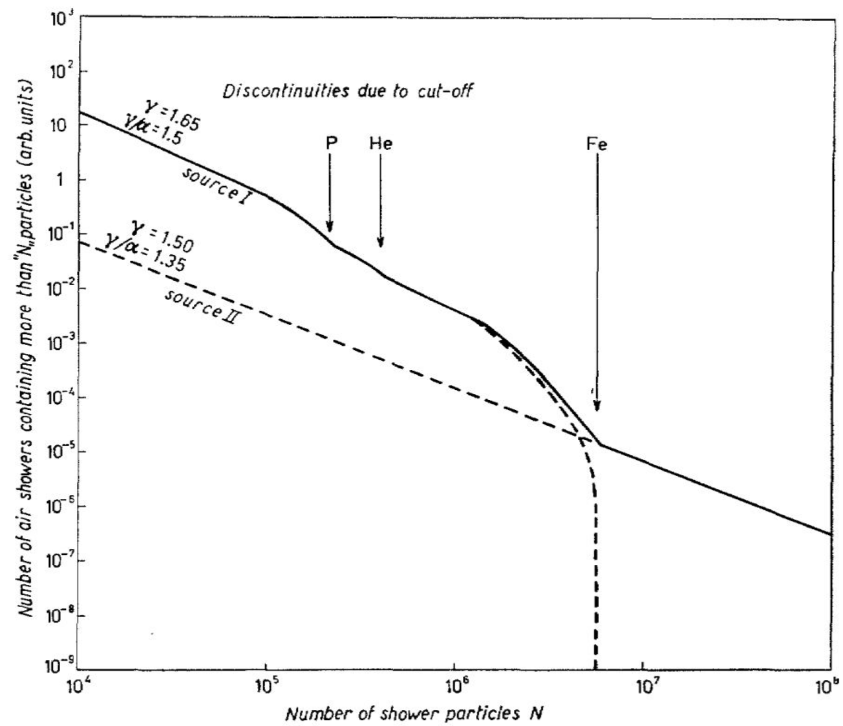
$$D \propto E^{0.2} \qquad E \lesssim 10^{15} \ \mathrm{eV}$$

$$D \propto E^{0.7} \qquad E \gtrsim 10^{15} \ \mathrm{eV}$$

This idea was initially developed by Peters
(Il Nuovo Cimento 1961)
Very soon after the discovery of the Cosmic Ray Knee



Softening generated by
sharp cutoffs at same rigidity
for all nuclear components
[cutoff energy proportional to Z]
will appear a smooth softening



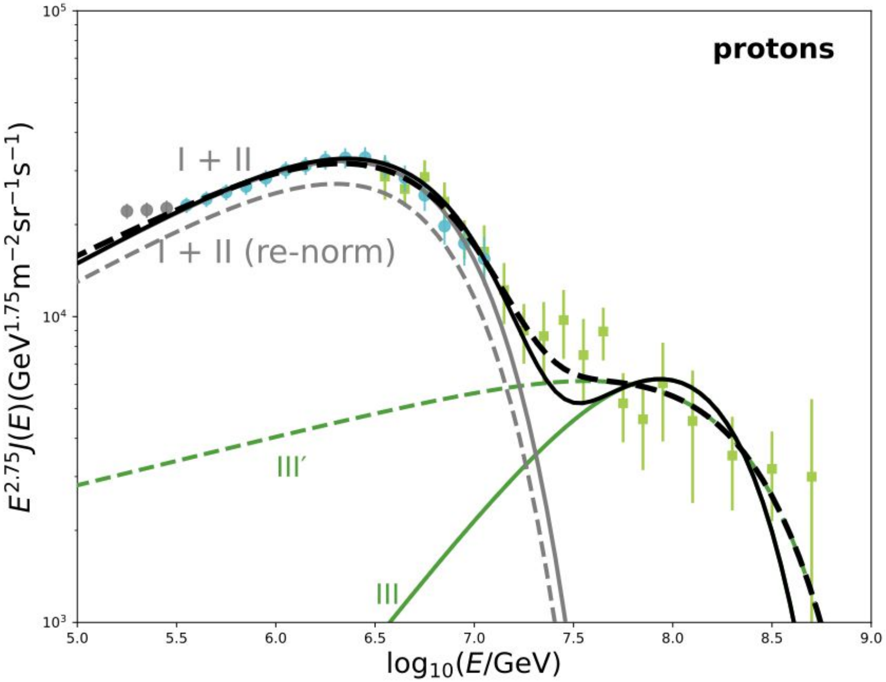
Combination of two
(classes of)   sources

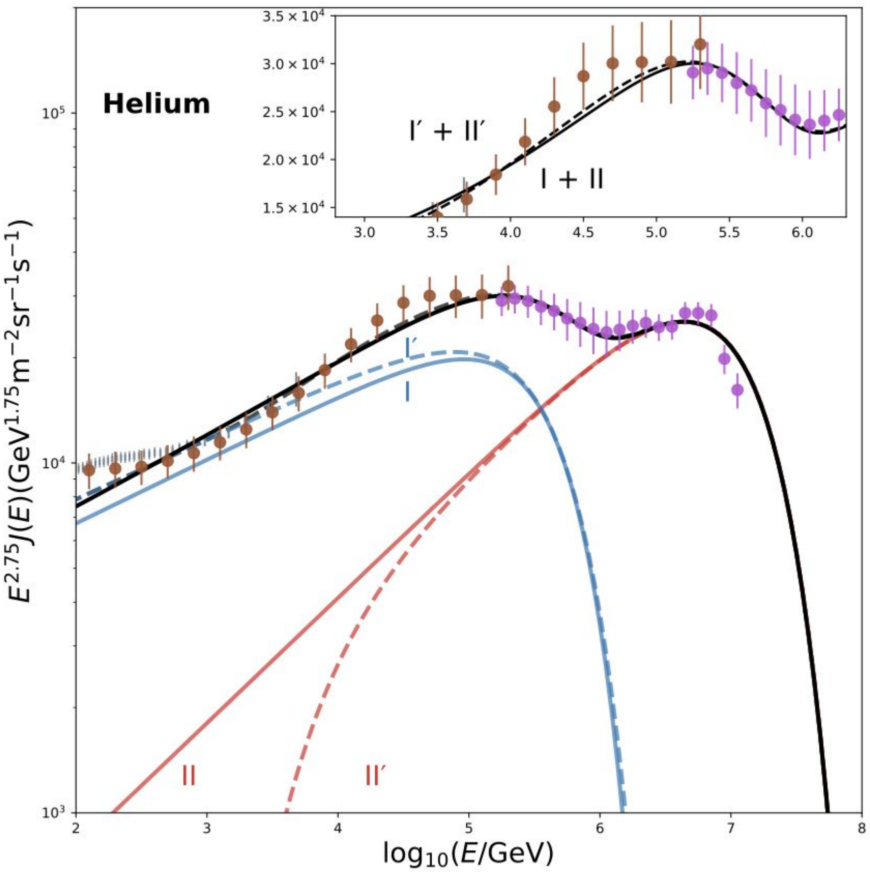
Tom Gaisser called these
“Peters's cycles”

Felix Aharonian and Bing Theodore Zhang.

A Minimal Interpretation of the Galactic Cosmic-Ray Proton and Helium Spectra from GeV to PeV Energies.

Astrophys. J., 1006(2):211, 2026.





Two classes of sources possibly: [SNR, microquasars]

Table 1. Fit parameters for the two-component CR proton model

Model	A ($\mathrm{GeV}^{1.75}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$)	Γ	E_0 (TeV)	β	$E_{\min}$ (TeV)
First component					
I	14500^{+2500}_{-1900}	2.73 ± 0.02	68^{+18}_{-14}	$2.55^{+1.32}_{-0.90}$	$\cdots$
I′	16200^{+4200}_{-2700}	$2.73^{+0.02}_{-0.03}$	63^{+16}_{-12}	$2.18^{+1.31}_{-0.74}$	$\cdots$
Second component					
II	34700 ± 1600	2.39 ± 0.05	6200^{+900}_{-800}	1 (fixed)	$\cdots$
II′	34700 (fixed)	2.39 (fixed)	6200 (fixed)	1 (fixed)	$0.89^{+1.30}_{-0.57}$

Table 3. Fit parameters for the two-component CR helium model

Model	A ($\mathrm{GeV}^{1.75}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$)	Γ	E_0 (TeV)	β	$E_{\min}$ (TeV)
First component					
I	36300^{+7400}_{-6100}	$2.57^{+0.02}_{-0.03}$	468^{+95}_{-88}	$1.12^{+0.33}_{-0.26}$	$\cdots$
I′	38000^{+9900}_{-7100}	2.58 ± 0.03	447^{+103}_{-100}	$1.03^{+0.33}_{-0.23}$	$4.37^{+5.87}_{-2.82}$
Second component					
II	21500	$\cdots$	12400 (fixed)	$\cdots$	$\cdots$
II′	21500	$\cdots$	12400 (fixed)	$\cdots$	$5.62^{+5.60}_{-2.81}$

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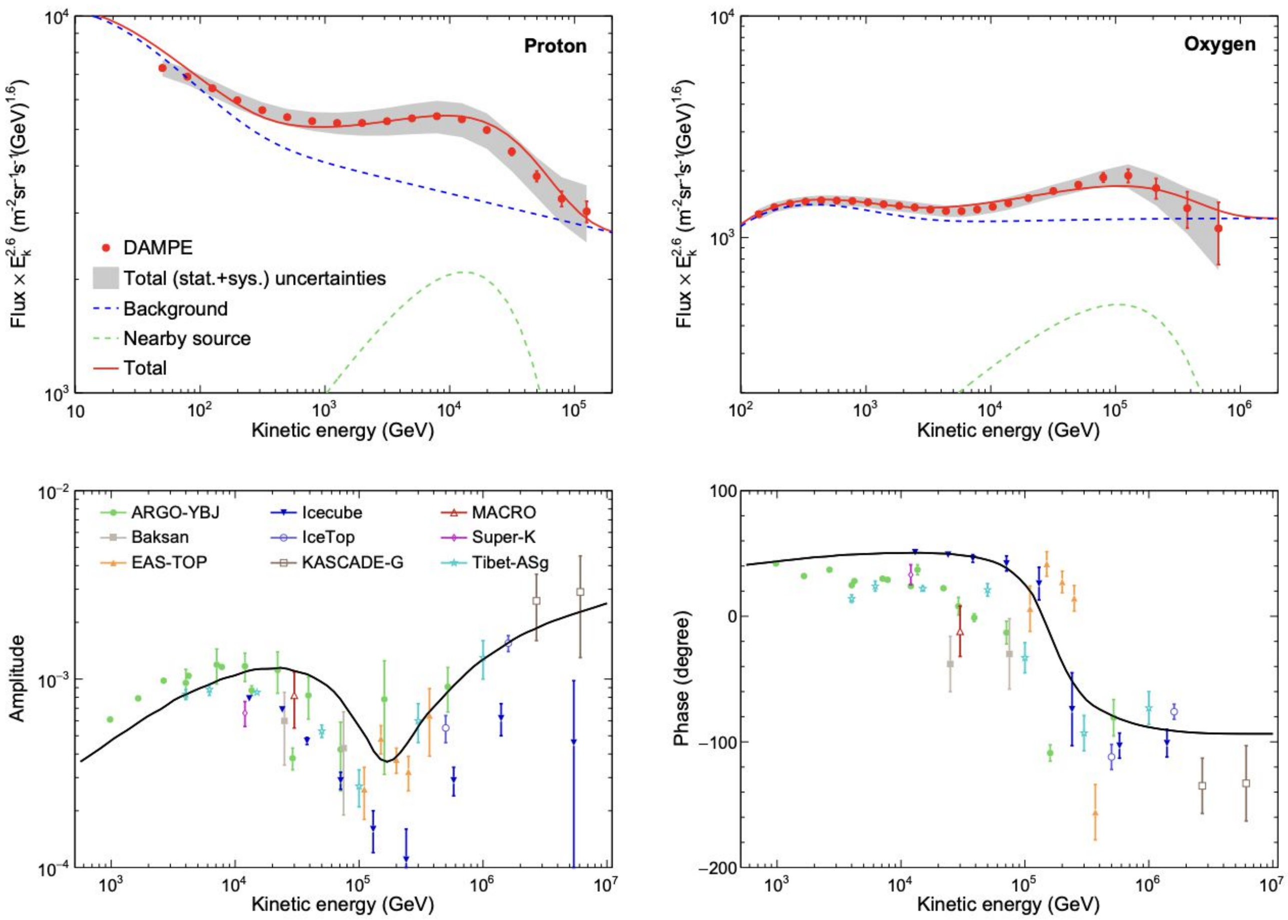
II	21500	$\cdots$	12400 (fixed)	$\cdots$	$\cdots$
II′	21500	$\cdots$	12400 (fixed)	$\cdots$	$5.62^{+5.60}_{-2.81}$

Another idea adopted by many authors is the inclusion of a near *“local source”*

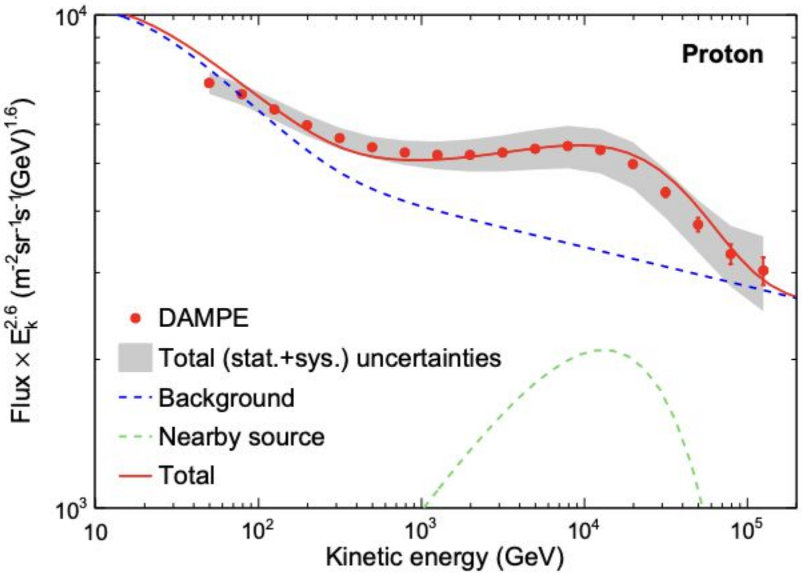
This idea has been adopted by many authors
[and is given as the most likely interpretation in the DAMPE paper]



Anisotropy

The “local source” hypothesis clearly requires to identify the source.

Im my opinion it suffers by some “fine tuning” to reproduce the spectrum

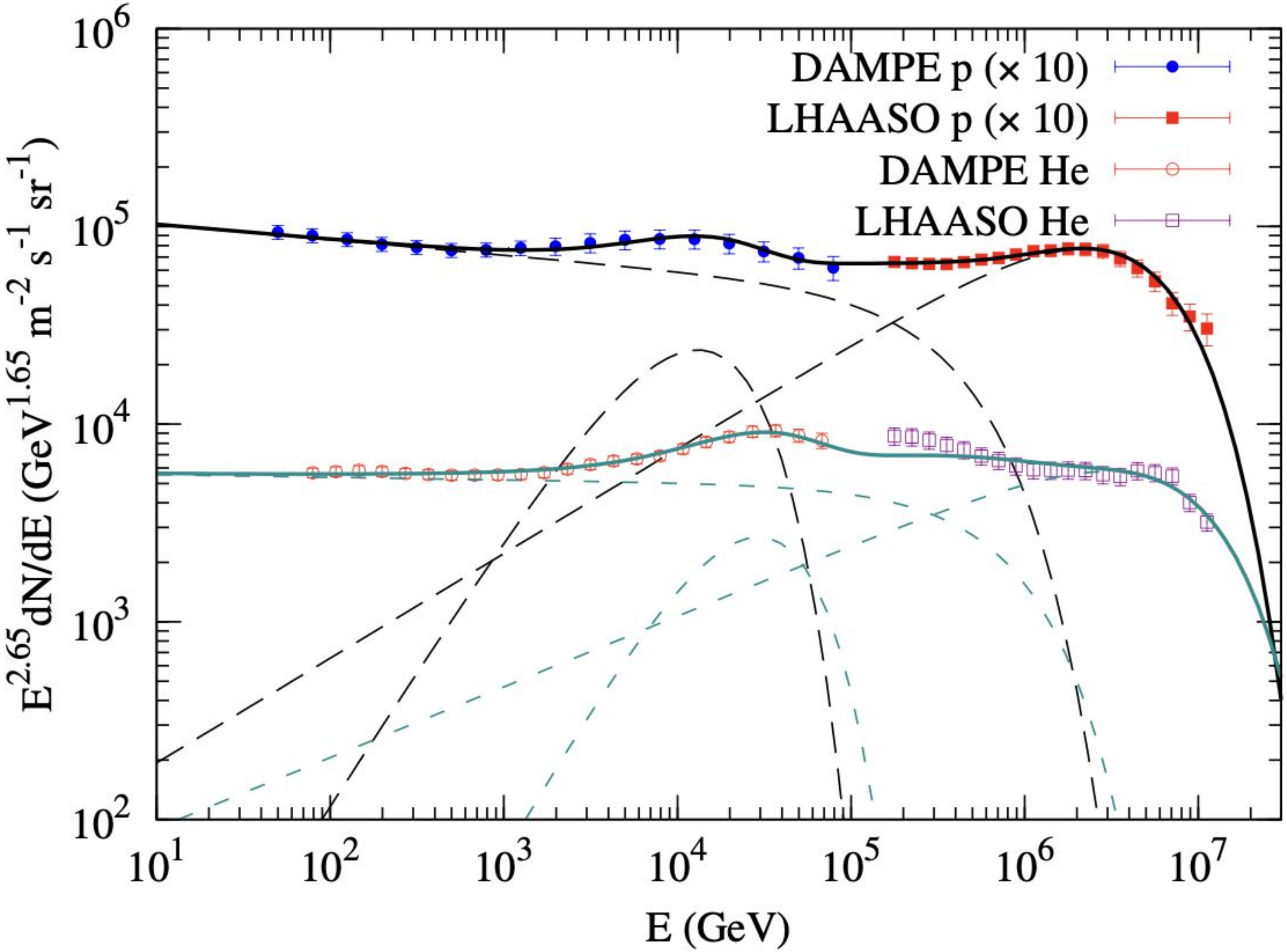


This the maximum energy of the “local source"

Adjust the slope to fit the data

Qiang Yuan
Implication of multiple source populations of Galactic cosmic rays from proton and helium spectra.
Phys. Rev. D, 113(12):123037, 2026.

2 “background” components
1 “Local” source



Improved fit: Two local sources

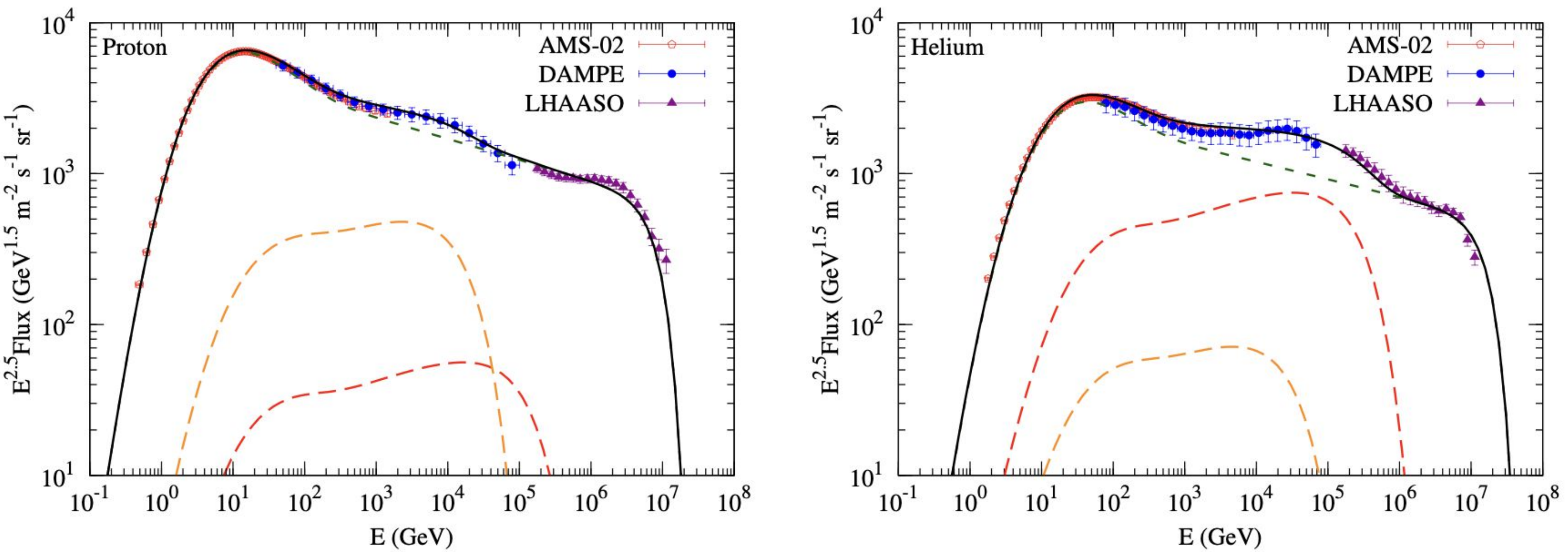


FIG. 4: Model results of the proton and helium spectra assuming the contribution from background sources (green short-dashed) and two local sources (long-dashed). Solid lines show the total fluxes. The solar modulation potential is 600 MV.

TABLE III: Spectral index, cutoff rigidity, kinetic energies of protons and helium nuclei above 1 GeV of the local source(s).

	$\alpha_{\rm loc}$	$\mathcal{R}_c^{\rm loc}$ (TV)	$W_{\rm p}$ (> 1 GeV) (10^{50} erg)	$W_{\rm He}$ (> 1 GeV) (10^{50} erg)
1 src (1 bkg)	2.10	120	1.0	1.8
2 src (1 bkg)	2.10	15	2.0	0.2
	2.10	120	0.2	1.8
1 src (2 bkg)	2.10	25	2.5	0.7

Two local sources

One proton rich
Lower cutoff

One helium rich
Higher cutoff

Problems for the "Multi-component models"

[1a] Difficult to have CR sources that
produce spectra of equal shape
[equal slopes and equal cutoffs]
(Are the acceleration spectra "universal"(or not) "?)

[1b] Why are the spectral shapes
of protons and Helium (and other nuclei) different ?
(*Is acceleration Rigidity dependent (or not) ?)*

[2] The gamma-ray sources show a large variety
of spectral shapes, suggesting that they can contain
cosmic-ray populations of very different shapes.

[3] Is there a "fine-tuning" problem
(Why are the features so "subtle"?)

Spectrum from the ensemble if
of sources in one class

$$Q(E) = \sum q_j(E)$$

Assume the individual sources have
a power-law form with exponential cutoff

$$q_j(E) = q_{0,j} \left(\frac{E}{E_0}\right)^{-\Gamma_j}$$

Range where the cutoff is negligible

$$Q(E) = \sum q_j(E)$$

$$\simeq \int d\Gamma \int dq_0 \boxed{\frac{d^2 N_s}{dq_0\, d\Gamma}} q_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma}$$

distribution of slope
(and normalization)

$$Q(E) = \sum q_j(E)$$

$$\simeq \int d\Gamma \boxed{\int dq_0 \; \frac{d^2 N_s}{dq_0 \, d\Gamma} \; q_0} \cdot \left(\frac{E}{E_0}\right)^{-\Gamma}$$

$$\boxed{\frac{Q_0}{\sqrt{2\pi}\,\sigma_\gamma} \; \exp\left[-\frac{(\Gamma - \Gamma_0)^2}{2\,\sigma_\gamma^2}\right]}$$

Assume a Gaussian distribution
of slopes (with average and width)

$$Q(E) = \sum q_j(E)$$

$$\simeq \int d\Gamma \boxed{\int dq_0 \; \frac{d^2 N_s}{dq_0\, d\Gamma}\; q_0} \cdot \left(\frac{E}{E_0}\right)^{-\Gamma}$$

$$\boxed{\frac{Q_0}{\sqrt{2\pi}\,\sigma_\gamma}\; \exp\left[-\frac{(\Gamma-\Gamma_0)^2}{2\,\sigma_\gamma^2}\right]}$$

Solution:

$$\boxed{Q(E) = Q_0\; \left(\frac{E}{E_0}\right)^{-\Gamma_0+\sigma_\gamma^2/2\;\ln(E/E_0)}}$$

$$\frac{dQ}{d\Gamma}(\Gamma, E_0) = \int dq_0 \; \frac{d^2 N_s}{dq_0 \, d\Gamma} \; q_0 \simeq \frac{Q_0}{\sqrt{2\pi}\, \sigma_\gamma} \; \exp\left[- \frac{(\Gamma - \Gamma_0)^2}{2\, \sigma_\gamma^2} \right]$$

$$\frac{dQ}{d\Gamma}(\Gamma, E) = \frac{Q(E)}{\sqrt{2\pi}\, \sigma_\gamma} \; \exp\left[- \frac{(\Gamma - \langle \Gamma(E) \rangle)^2}{2\, \sigma_\gamma^2} \right]$$

The distribution of slopes
is at all energies a gaussian of constant width
(with an average that decreases linearly with Log[E])

The cumulative flux from the ensemble of individual fluxes that are all power—law with a gaussian distribution of slopes is:

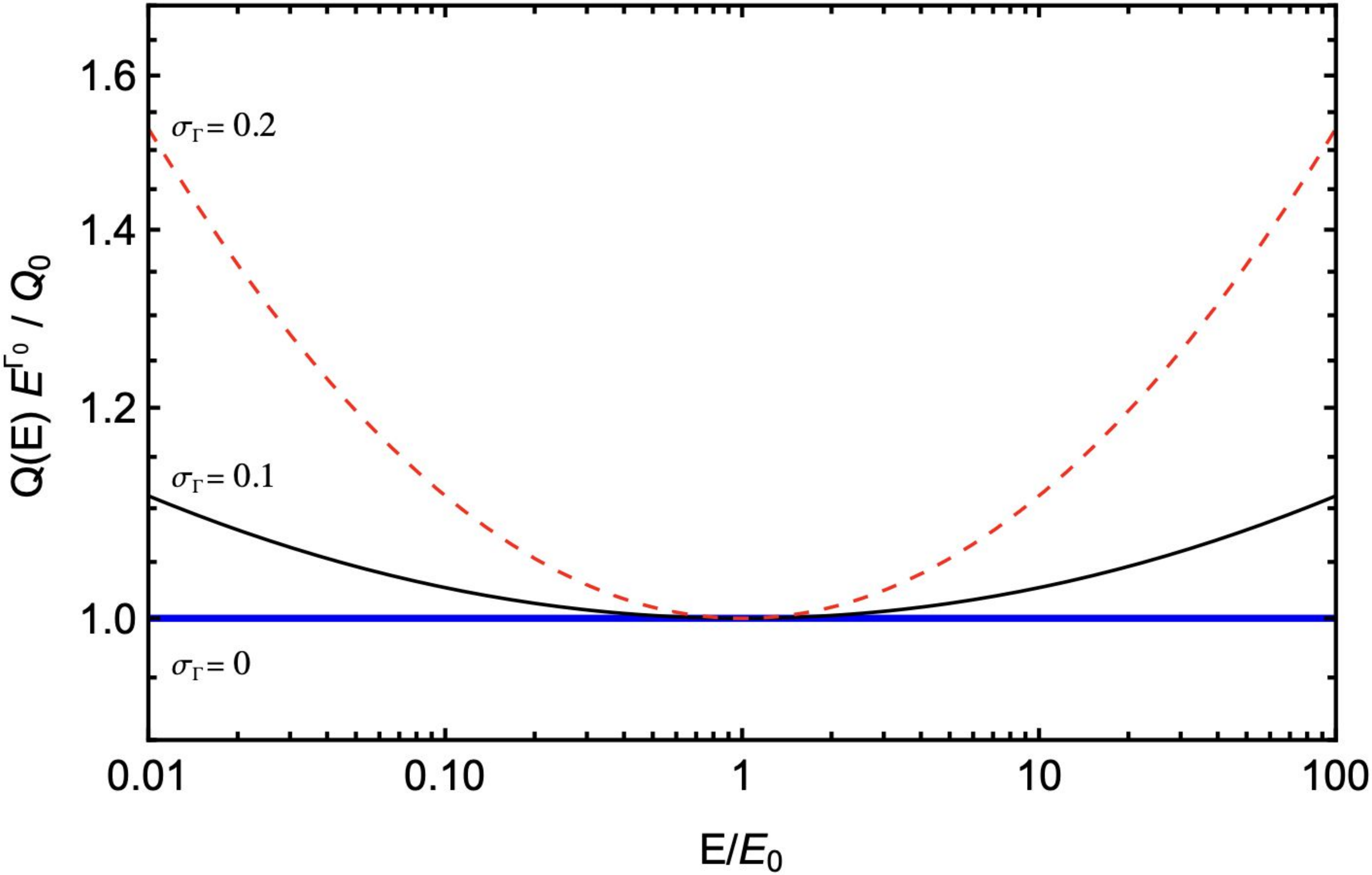
$$Q(E) = Q_0 \left(\frac{E}{E_0}\right)^{-\Gamma_0+\sigma_\gamma^2/2\ \ln(E/E_0)}$$

is a logparabola spectrum with curvature:

$$\beta = -\sigma_\Gamma^2/2.$$

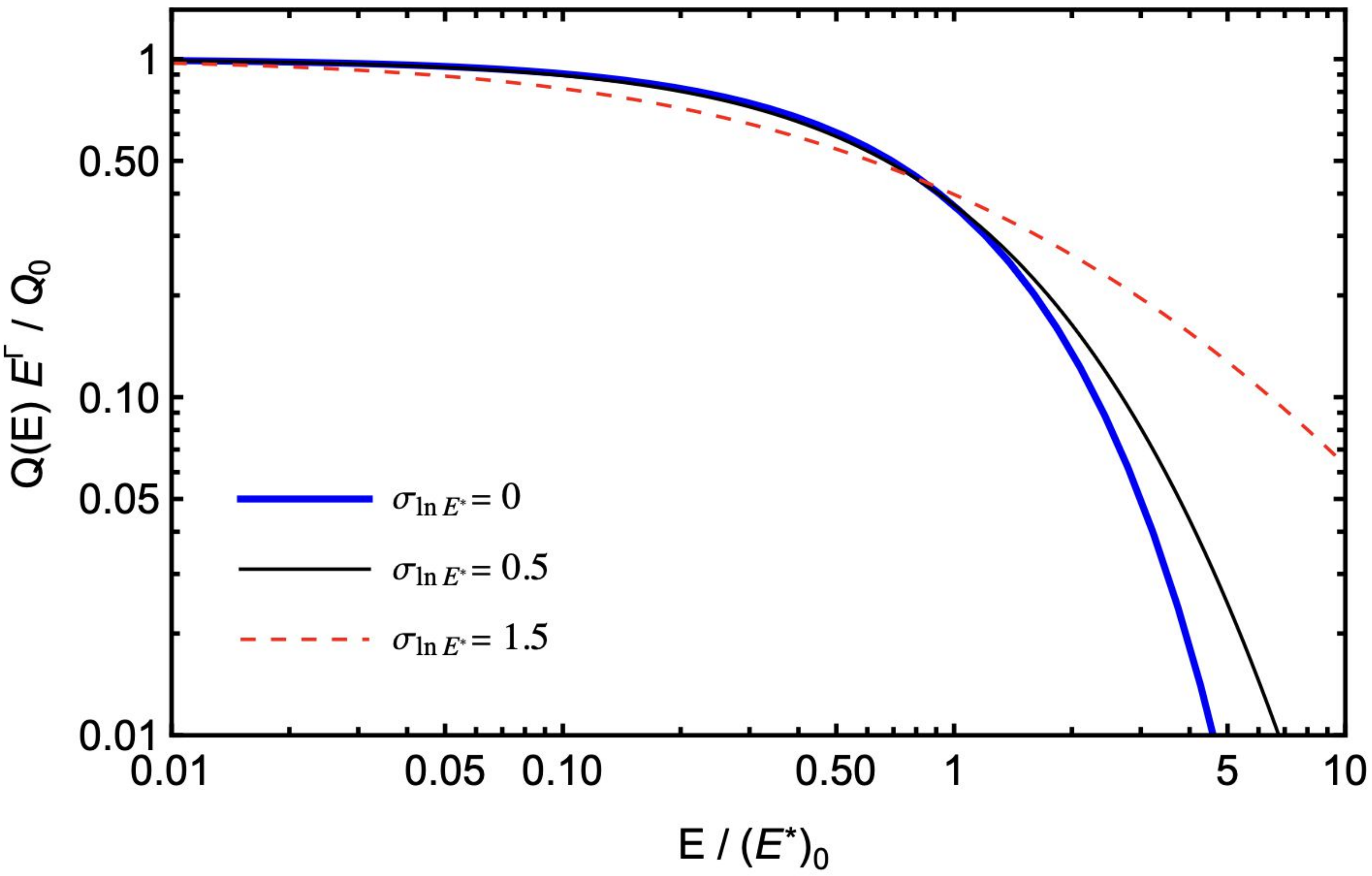
$$\Gamma_Q(E) = \Gamma_0 - \sigma_\gamma^2\ \ln(E/E_0)$$

$$\Gamma_Q(E) = \Gamma_0 - \sigma_\gamma^2 \ln(E/E_0)$$



Limits on the spectrum curvature → Limits on width of slope distribution

Exponential cutoffs of individual sources



To obtain a sharp cutoff in a the (cumulative) source spectrum you need a very narrow distribution of cutoff in the individual sources.

Is acceleration Rigidity Dependent ?

If acceleration is rigidity dependent
then spectra of different elements
(with form of power-law with high energy cutoff)
should have:

[a] Equal slopes

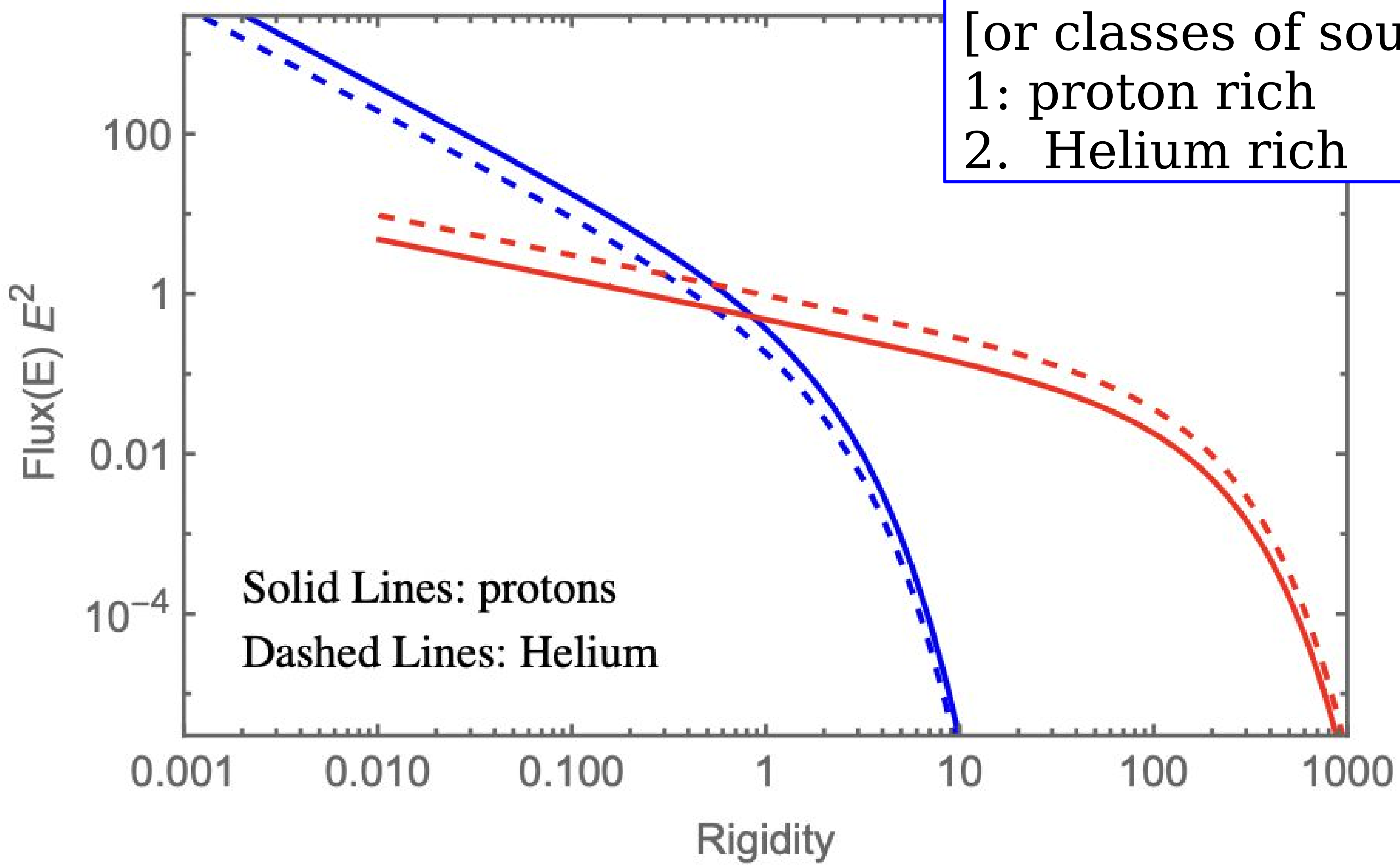
[b] Equal cutoffs in Rigidity

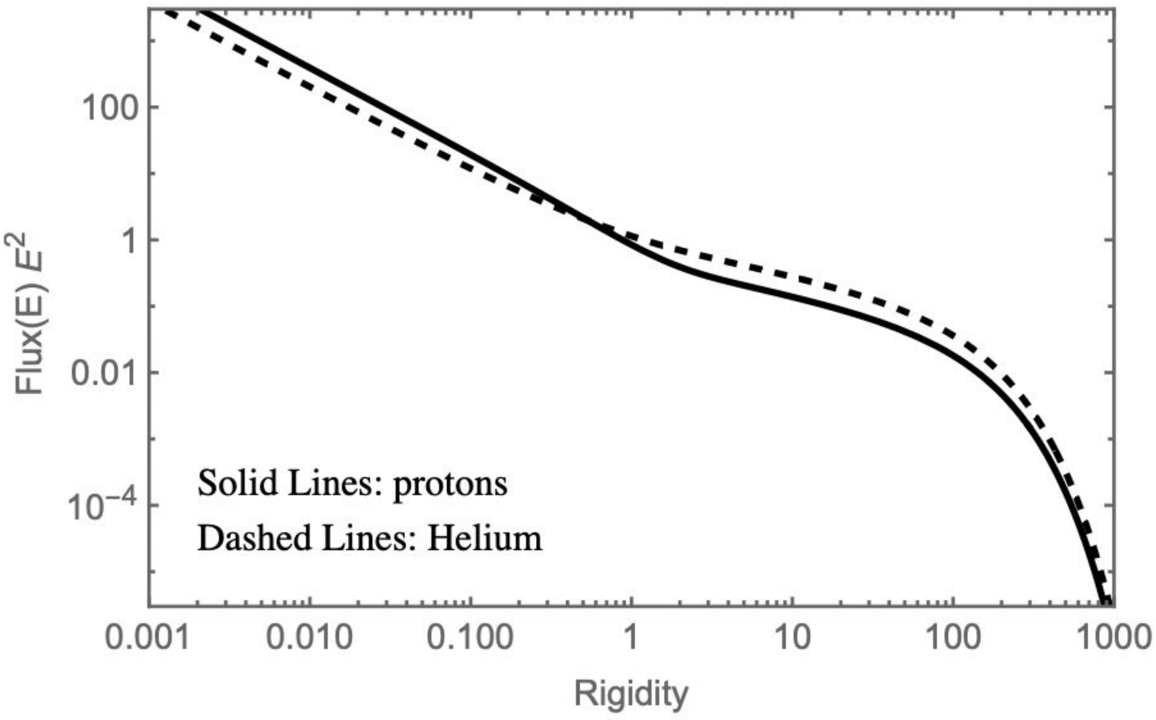
But the slopes of protons and Helium are different
(and perhaps also the cutoffs). Why ?

Do we have to abandon the idea of
Rigidity-independent acceleration ?

The proton/Helium ratio and
the “Rigidity-dependent Acceleration:

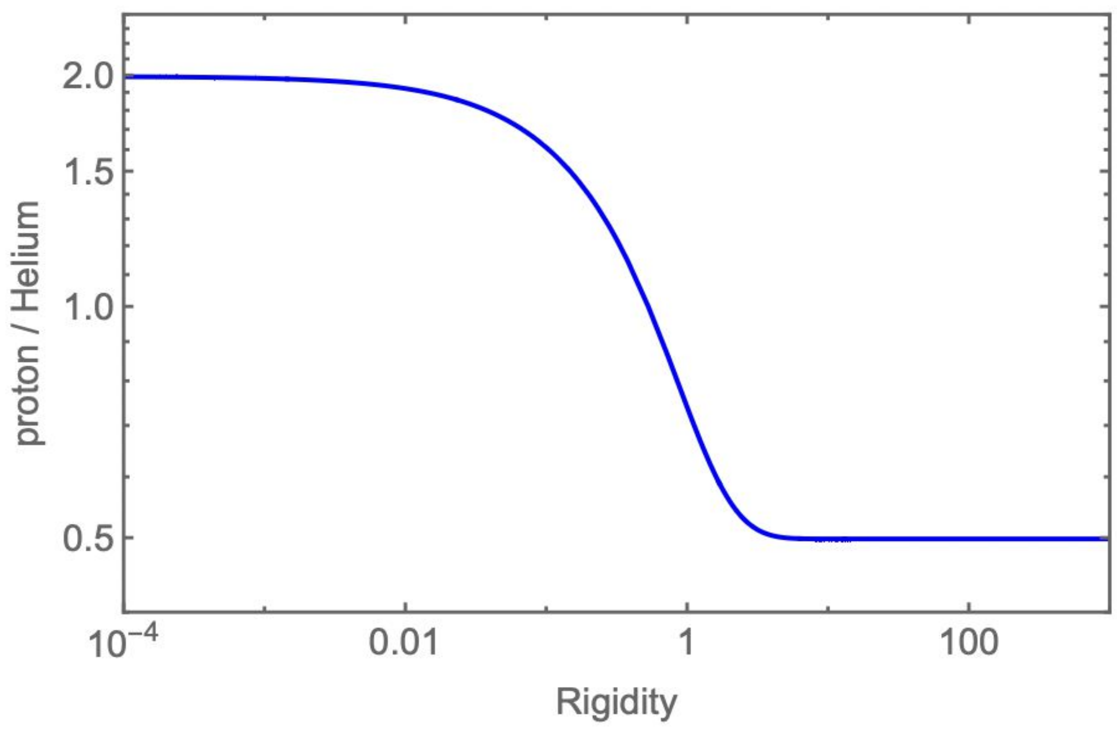
two sources
[or classes of sources]
1: proton rich
2. Helium rich





Combined flux

(summing
components)



Proton / Helium Ratio

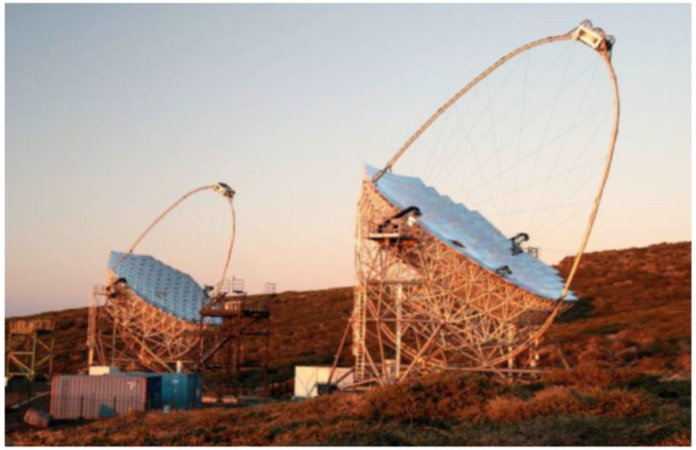
Ratio is constant when the spectrum are power-laws

Changes when the spectra are curved

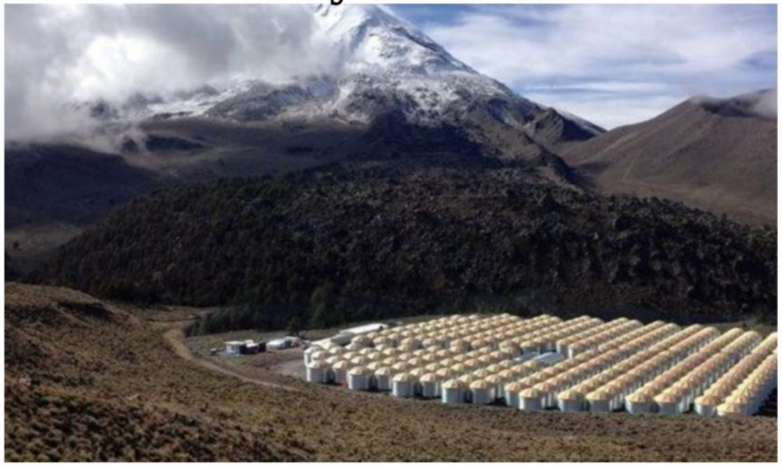
Gamma-ray source catalogs

Space $E_\gamma \simeq 0.1 \div 1000$ GeV

Cherenkov $E_\gamma \simeq 0.1 \div 100$ TeV



Ground Arrays



$E_\gamma \lesssim 30$ PeV LHAASO

Catalogs of gamma-ray sources

1. Fermi-LAT [7195 sources E > 100 MeV]
   4th General Catalog (Data Release 4) 4FGL-DR4

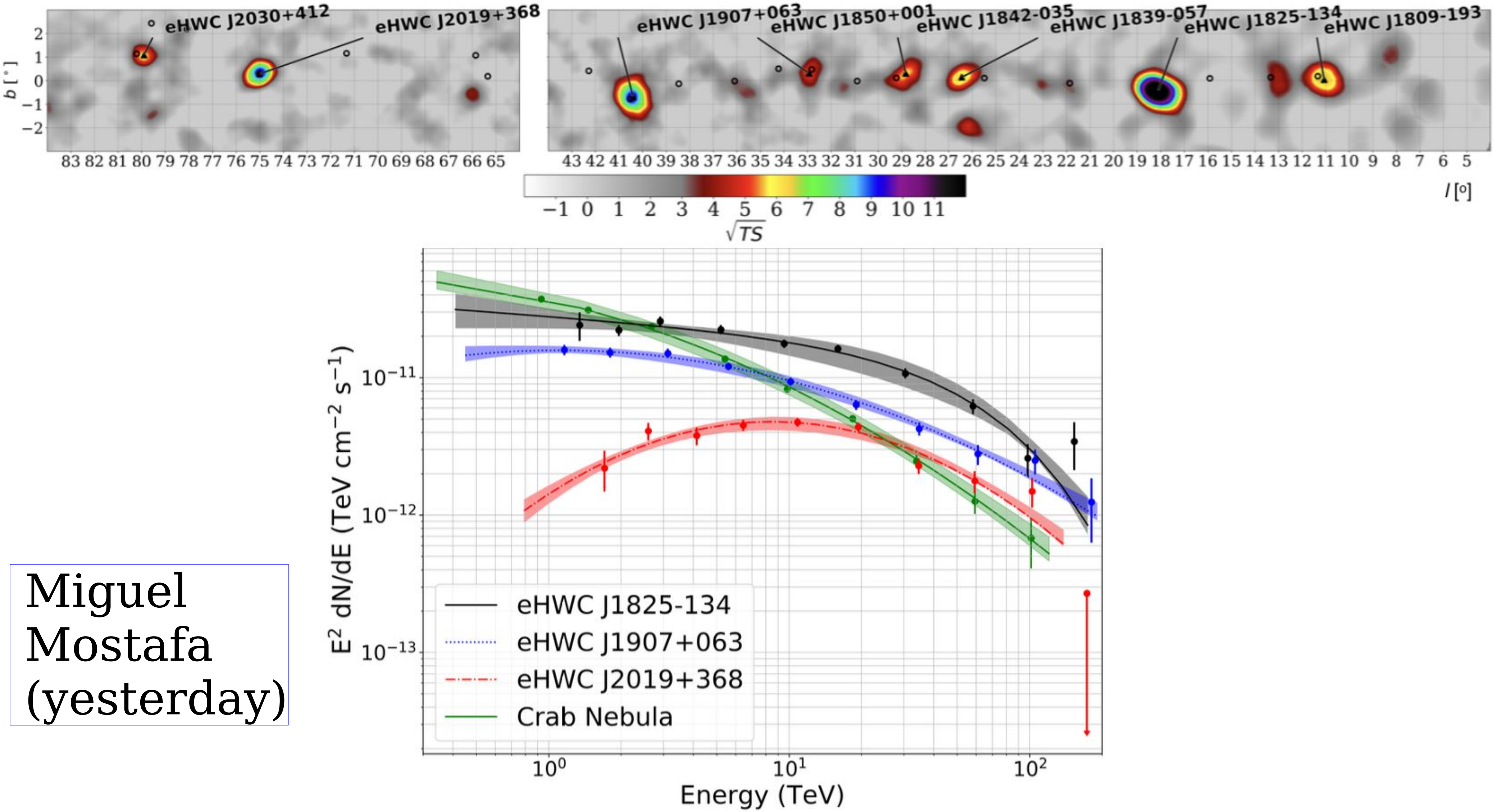
2. HESS Galactic Plane Survey [78 sources]
   $|b| < 3^\circ$ $\quad -110^\circ \le \ell \le +65^\circ$

3. HAWC 4th Catalog [88 sources]

4. LHAASO 1st Catalog [90 sources (WCDA + KM2A)]
   4a LHAASO WCDA [69 sources]
   4b LHAASO KM2A [75 sources]

Catalog of γ-ray Sources above 56 TeV

- Significance map ($E > 56$ TeV, 0.5° hypothesis)



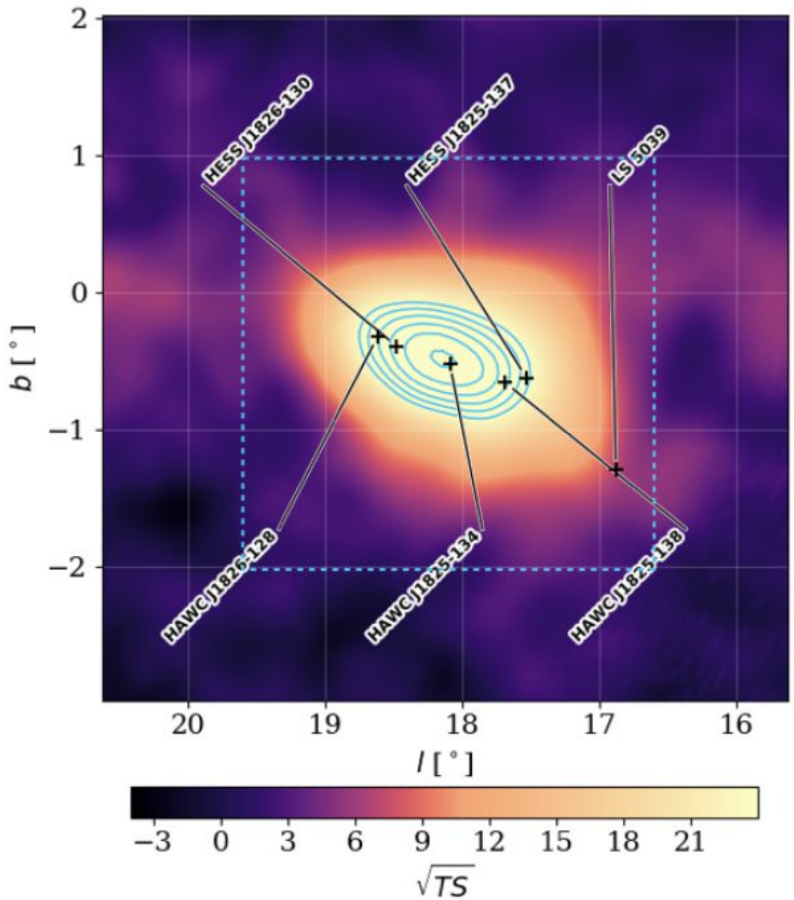
Miguel Mostafa (yesterday)

HE Catalog, HAWC Collaboration: *PRL* **124** (2020) 021102

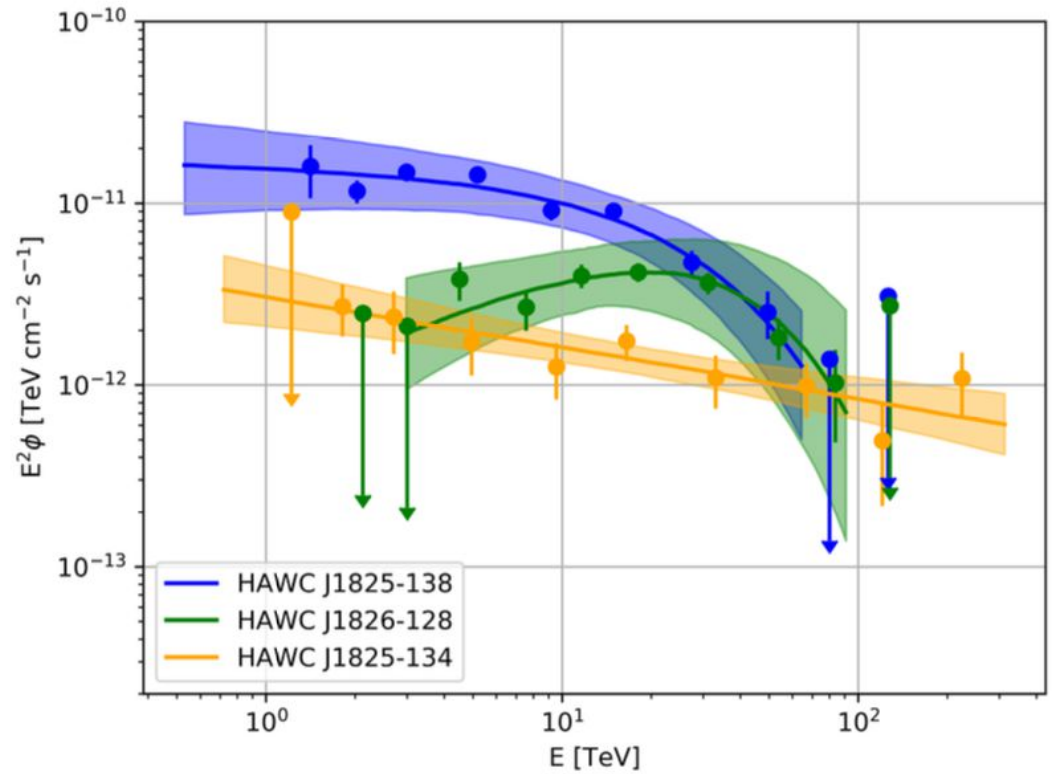
Evidence of 200 TeV γ rays

- eHWC J1825-134

Miguel Mostafa (yesterday)



Significance map



SED from HAWC data

HAWC J1825-134, HAWC Collaboration: *ApJL* **907** (2021) L30

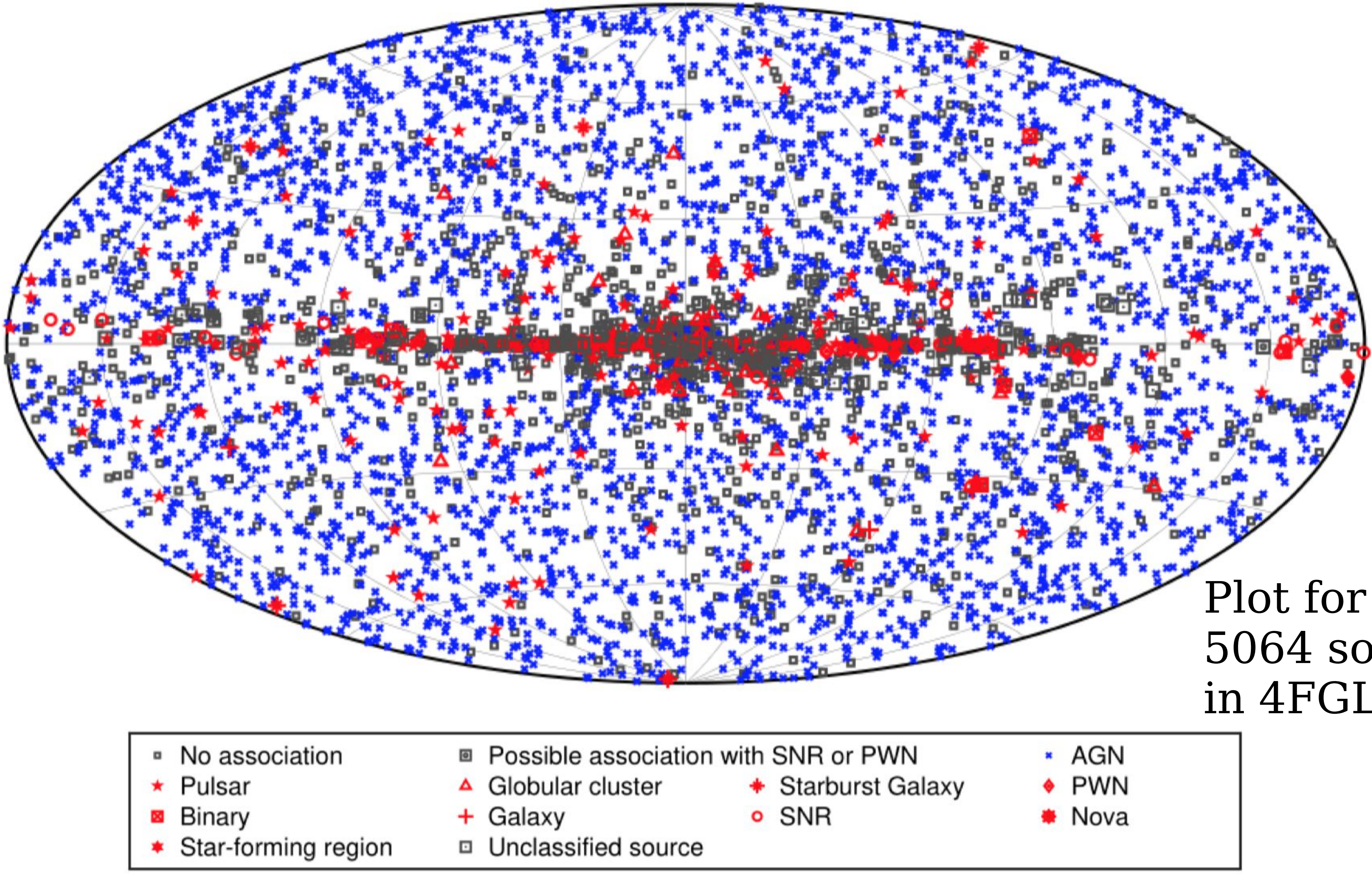
The gamma-ray sources have many different spectral shapes !

Does this mean that the accelerate populations of cosmic rays with different spectral shapes ?

Of course this is not necessary
(for may reasons)

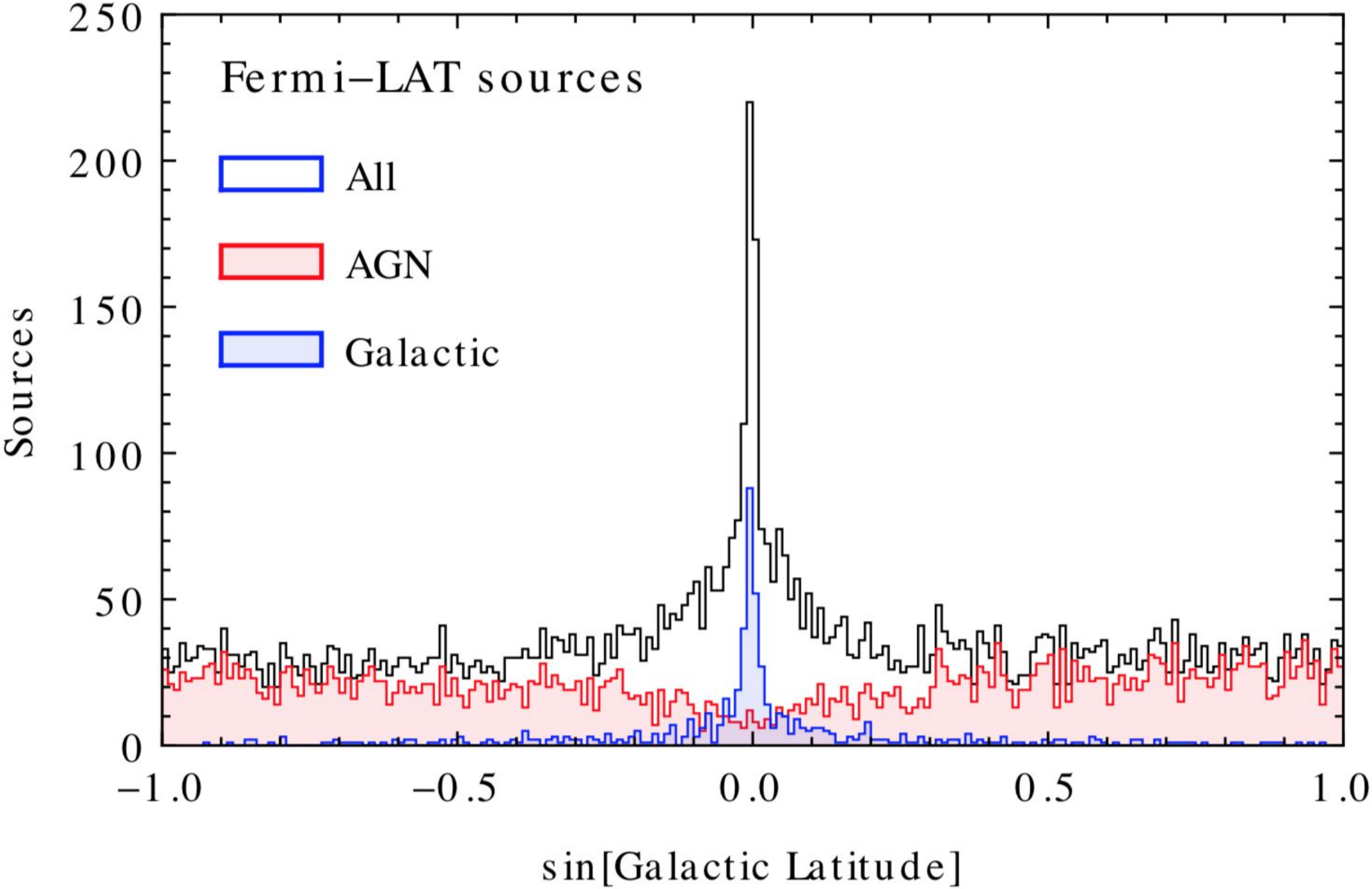
But: It is not easy to reconcile this large variety of spectral shapes with the idea of a well defined spectral shape for the [time integrated] cosmic ray output,.

FERMI 4th General Catalog 4FGL-DR4 (7195 sources)



Plot for 5064 source in 4FGL

Fermi-LAT catalog Galactic Latitude Distribution



Classification of Fermi-LAT sources

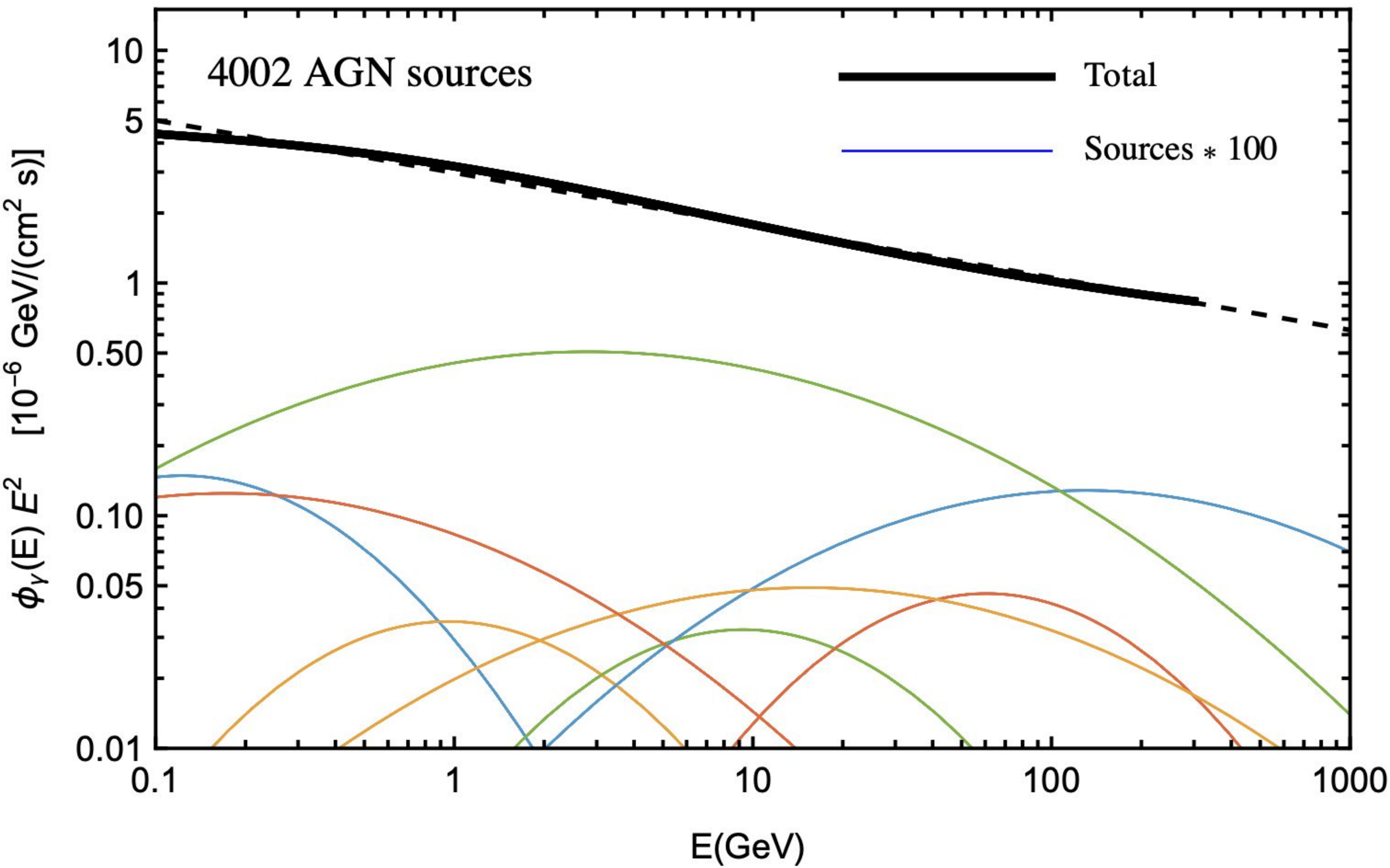
25 classes of objects in catalog.

[+ firmly identified, and associated e.g. PSR, psr]

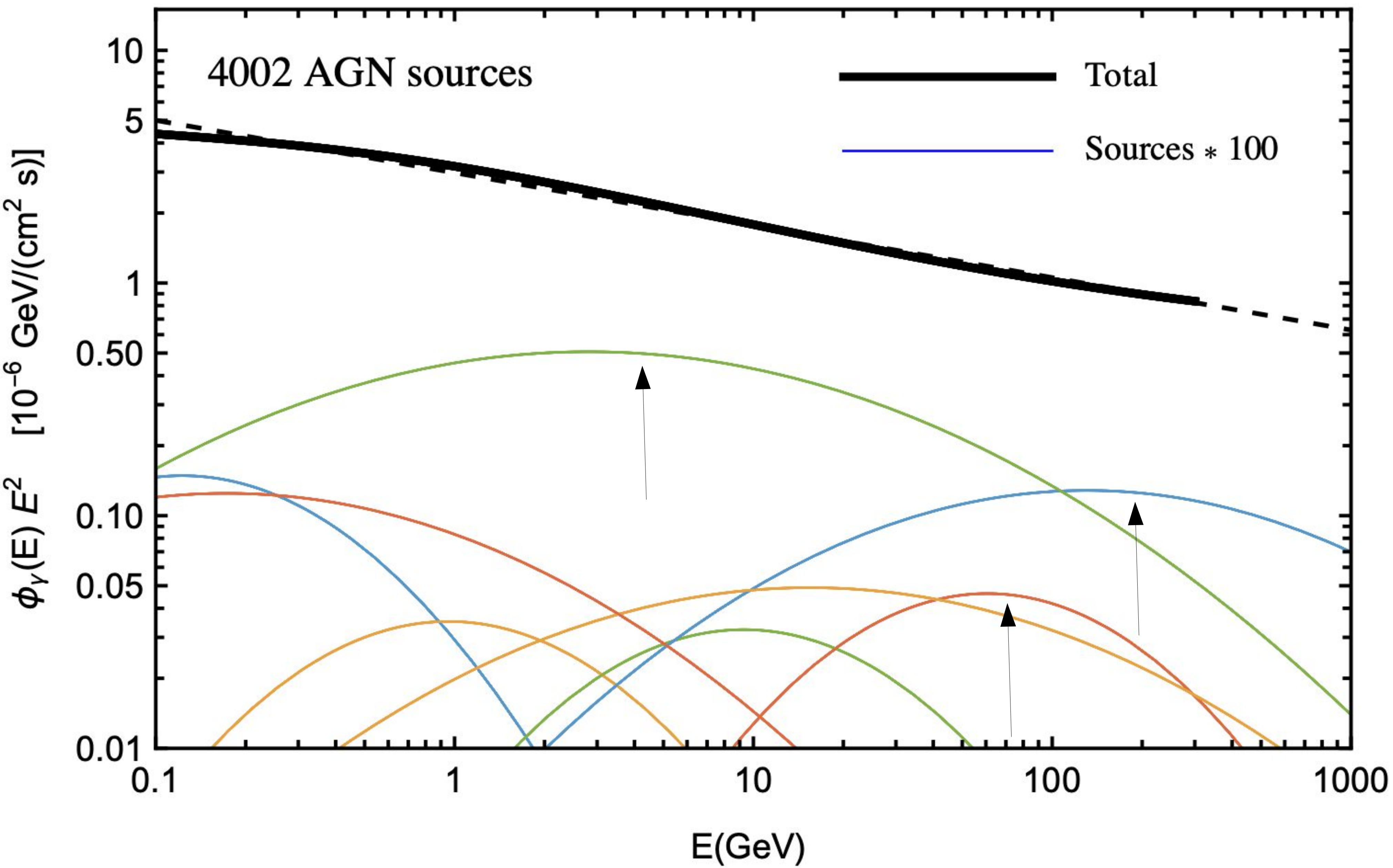
Galactic sources:	0.082	
Pulsars, SNR, PWN, Binary systems	588	[8 (Novae)]
Extra-Galactic sources:	0.56	
AGN, Galaxies	4028	
Do not know	0.36	
Unassociated / Unknown	2577	

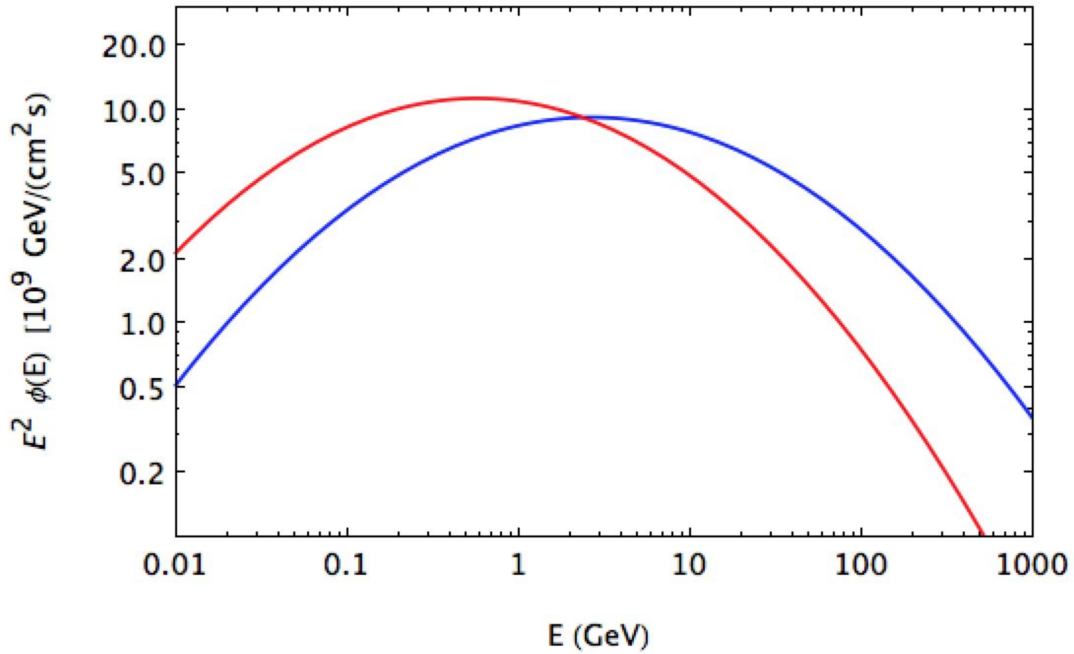
Sum of all fits to AGN sources

Power- law
with < 7% deviations



Sum of all fits to AGN sources





LogParabola Spectra

Fermi LAT parametrization

$$\phi(E) = K_0 \left(\frac{E}{E_0}\right)^{-(\alpha_0 + \beta \ln E/E_0)}$$

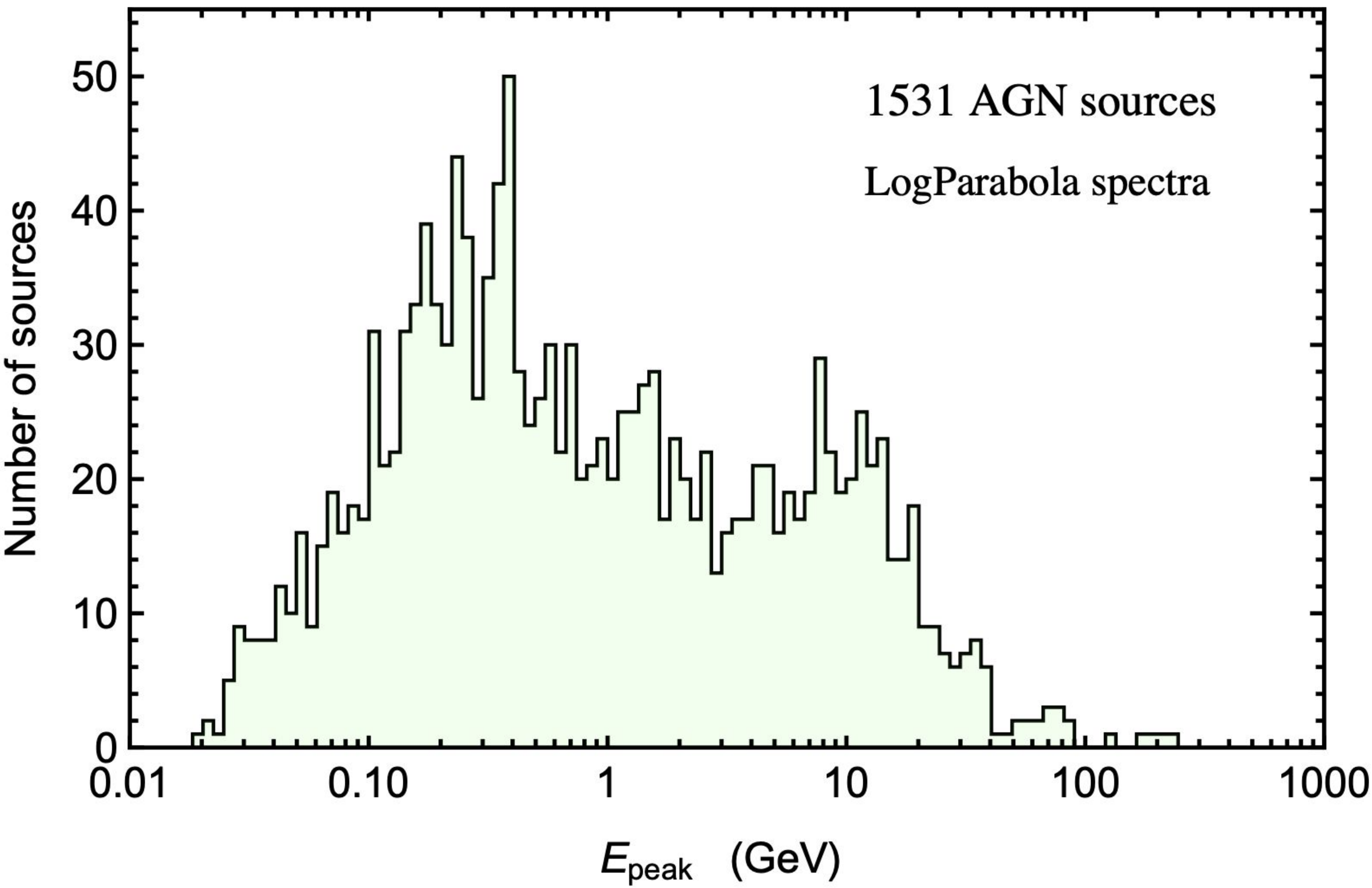
$$\alpha(E) = \alpha_0 + 2\beta \ln \frac{E}{E_0}$$

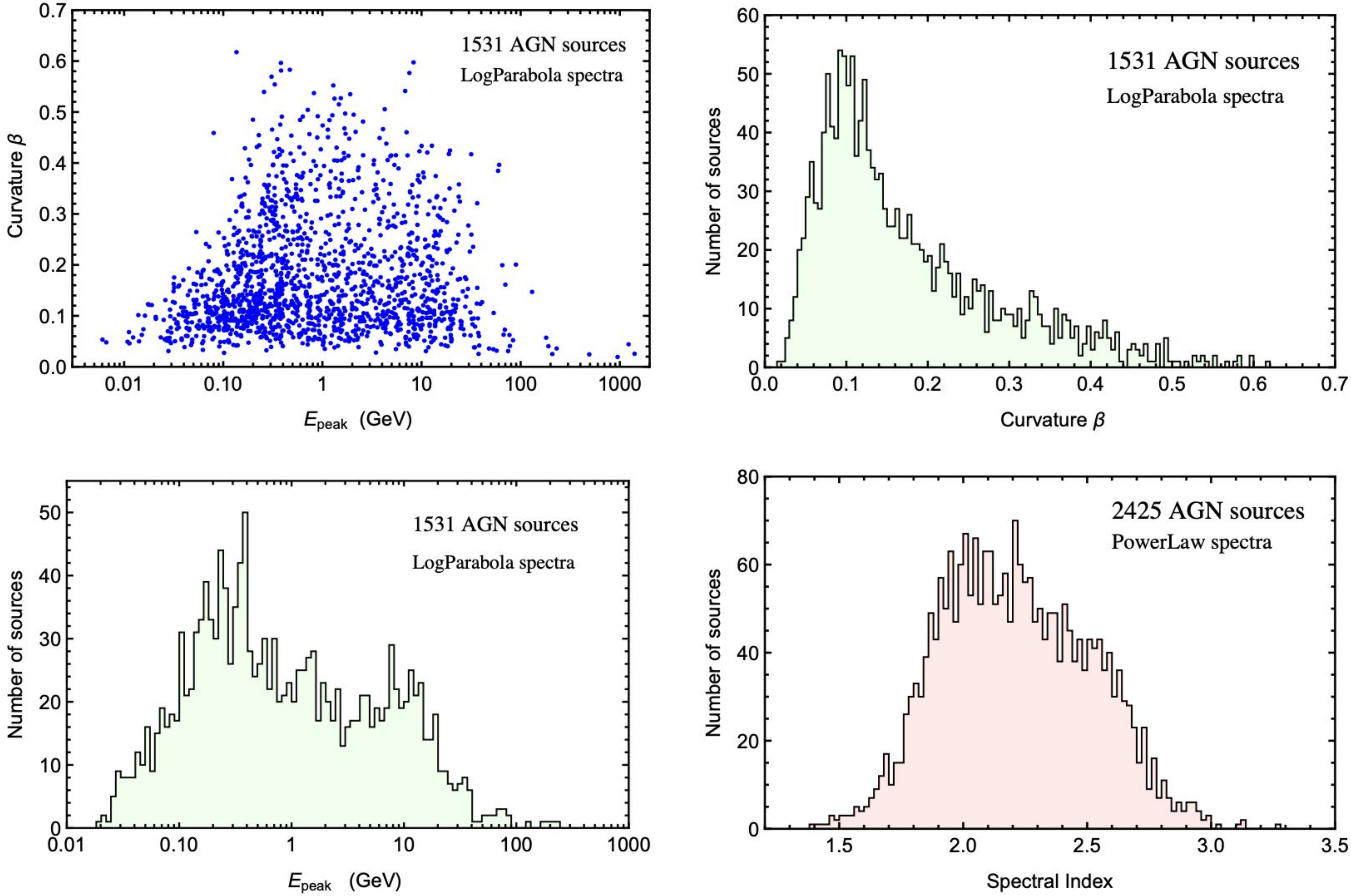
New parametrization: Critical Energy E^*

Position of maximum of SED

$$\phi(E) = K^* \left(\frac{E}{E^*}\right)^{-(2 + \beta \ln E/E^*)}$$

$$\boxed{\alpha(E) = 2 + 2\beta \ln \frac{E}{E^*}}$$


1531 AGN sources
LogParabola spectra
Number of sources
0
10
20
30
40
50
0.01
0.10
1
10
100
1000
$E_{\rm peak}$ (GeV)


1531 AGN sources
LogParabola spectra
Curvature β
E_{peak} (GeV)
Number of sources
Curvature β
2425 AGN sources
PowerLaw spectra
Spectral Index

How an ensemble of curved spectra can result in power-law form.

Example of Log-parabola spectra

$$q_j(E) = \sqrt{\frac{\beta_j}{\pi}} \; \frac{\mathcal{E}_j}{(E_j^*)^2} \; \left(\frac{E}{E_j^*} \right)^{-2-\beta_j \; \ln(E/E_j^*)}$$

$$= \frac{\mathcal{E}_j}{(E_j^*)^2} \; \overline{q} \left(\frac{E}{E_j^*}, \beta_j \right)$$

Spectral shape has a characteristic energy

Normalization [Total energy of emission]

$$\int dE \; E \; q_j(E) = \mathcal{E}_j$$

Combining spectra of different forms
(different characteristic energy E*)

$$Q(E) = \frac{1}{T_s} \int \frac{dE^*}{(E^*)^2} \int d\mathcal{E} \; \frac{dN_s}{d\mathcal{E}\, dE^*} \; \mathcal{E} \; \overline{q} \left(\frac{E}{E^*} \right)$$

$$\frac{dL_{CR}}{dE^*} = \frac{1}{T_s} \int d\mathcal{E} \; \mathcal{E} \; \frac{dN_s}{d\mathcal{E}\, dE^*}$$

The distribution of E* is a power-law

$$\frac{dL_{CR}}{dE^*} = k_p \, \frac{L_{\rm cr}}{E_0} \, \left(\frac{E^*}{E_0} \right)^{-p}$$

Sources
that have higher E*
are less abundant
(release less energy)

$$Q(E) = \int \frac{dE^*}{(E^*)^2} \frac{dL_{CR}}{dE^*} \bar{q}\left(\frac{E}{E^*}\right)$$

$$\frac{dL_{CR}}{dE^*} = k_p \frac{L_{\rm cr}}{E_0} \left(\frac{E^*}{E_0}\right)^{-p}$$

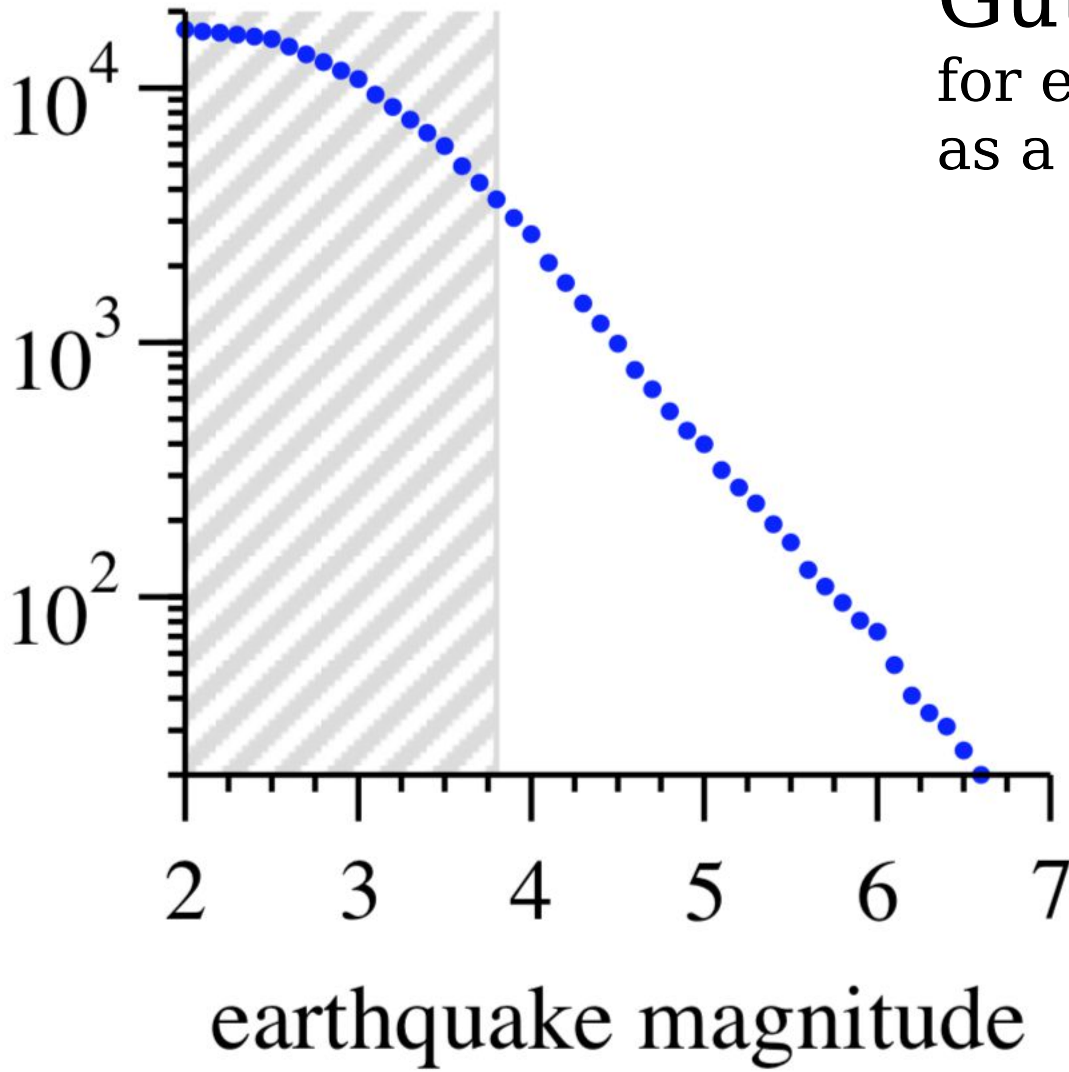
$$\boxed{Q(E) = Q_0 \frac{L_{\rm cr}}{E_0^2} \left(\frac{E}{E_0}\right)^{-(p+1)}}$$

The slope of the source spectra is related to the correlation between power of sources and spectral shape

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

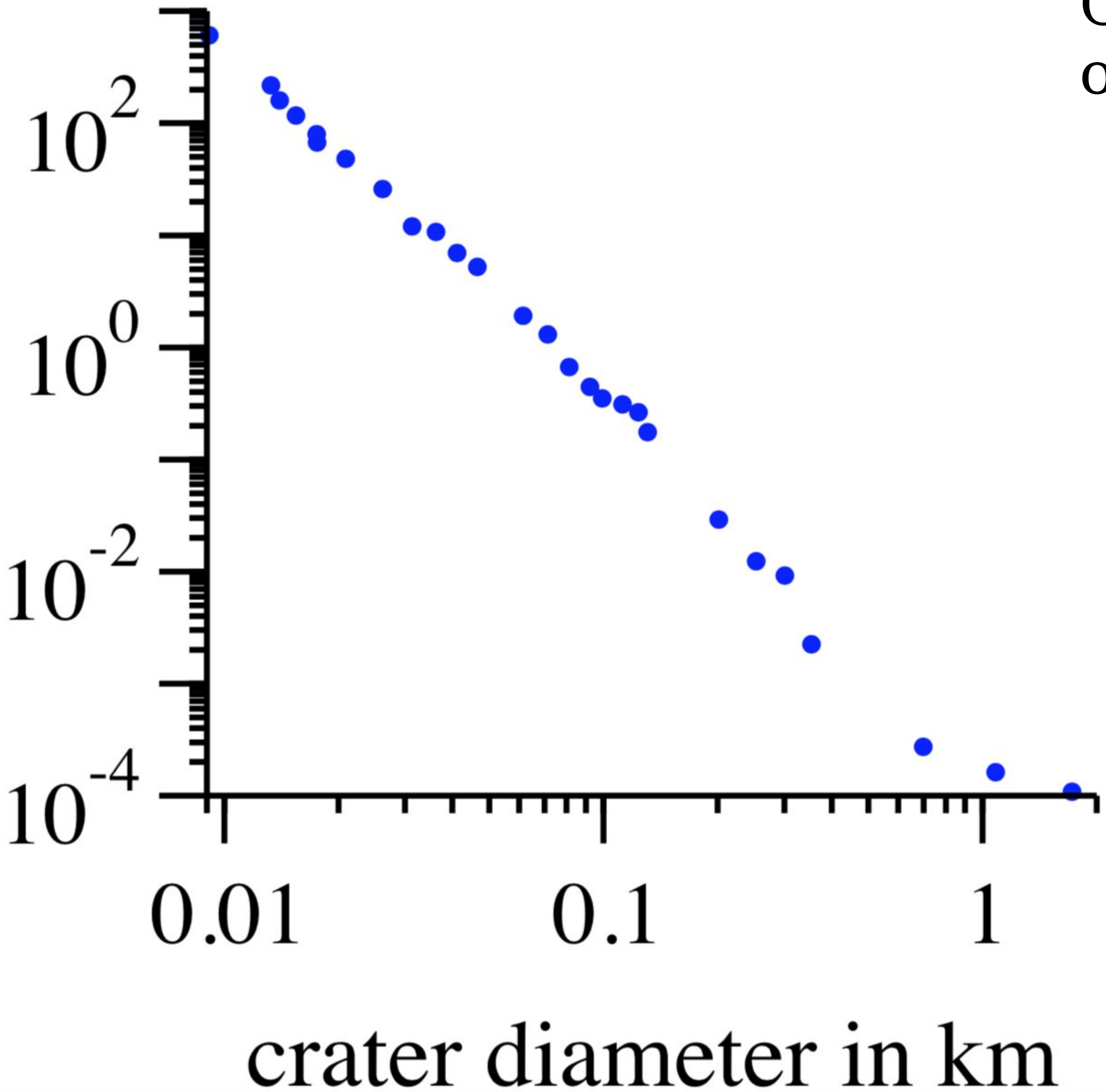
$$\log_{10} N = a - b\, m$$

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

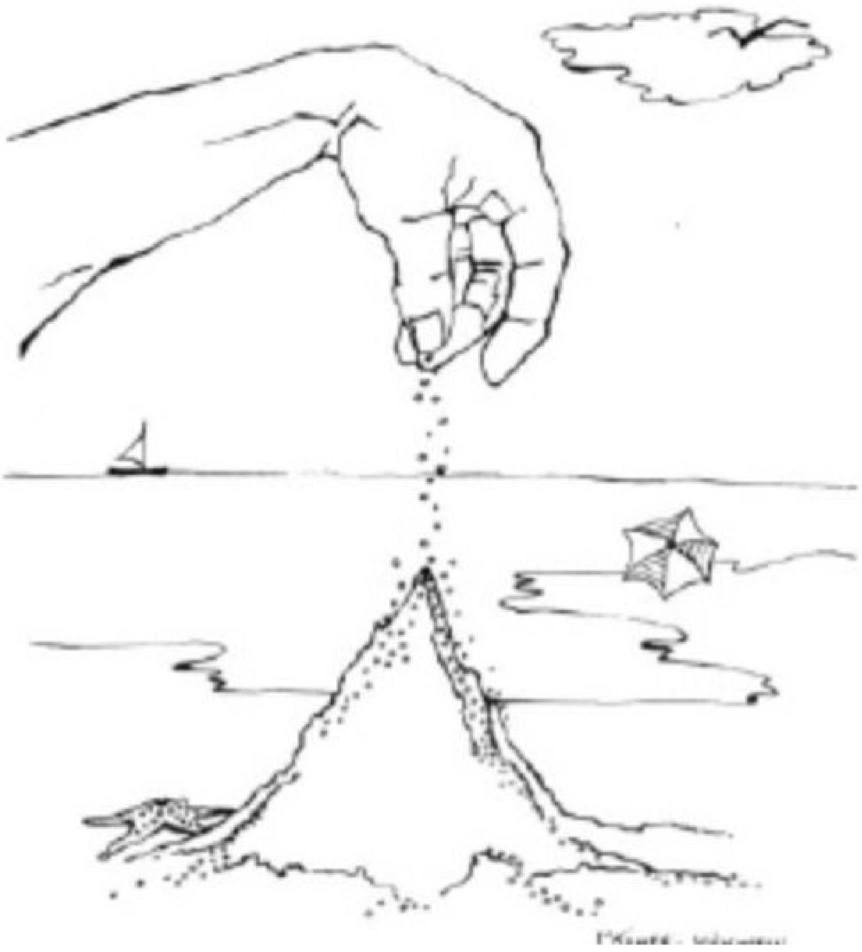
Earthquakes in California
1910-1992

M.E.J. Newman
"Power–laws, Pareto distributions and Zipf's law"
Contemporary Physics **46**, 323 (2005)
arXiv:cond-mat/0412004 [cond-mat.stat-mech]

Cumulative distributions of Moon craters



Concept of "Self Organized Criticality"

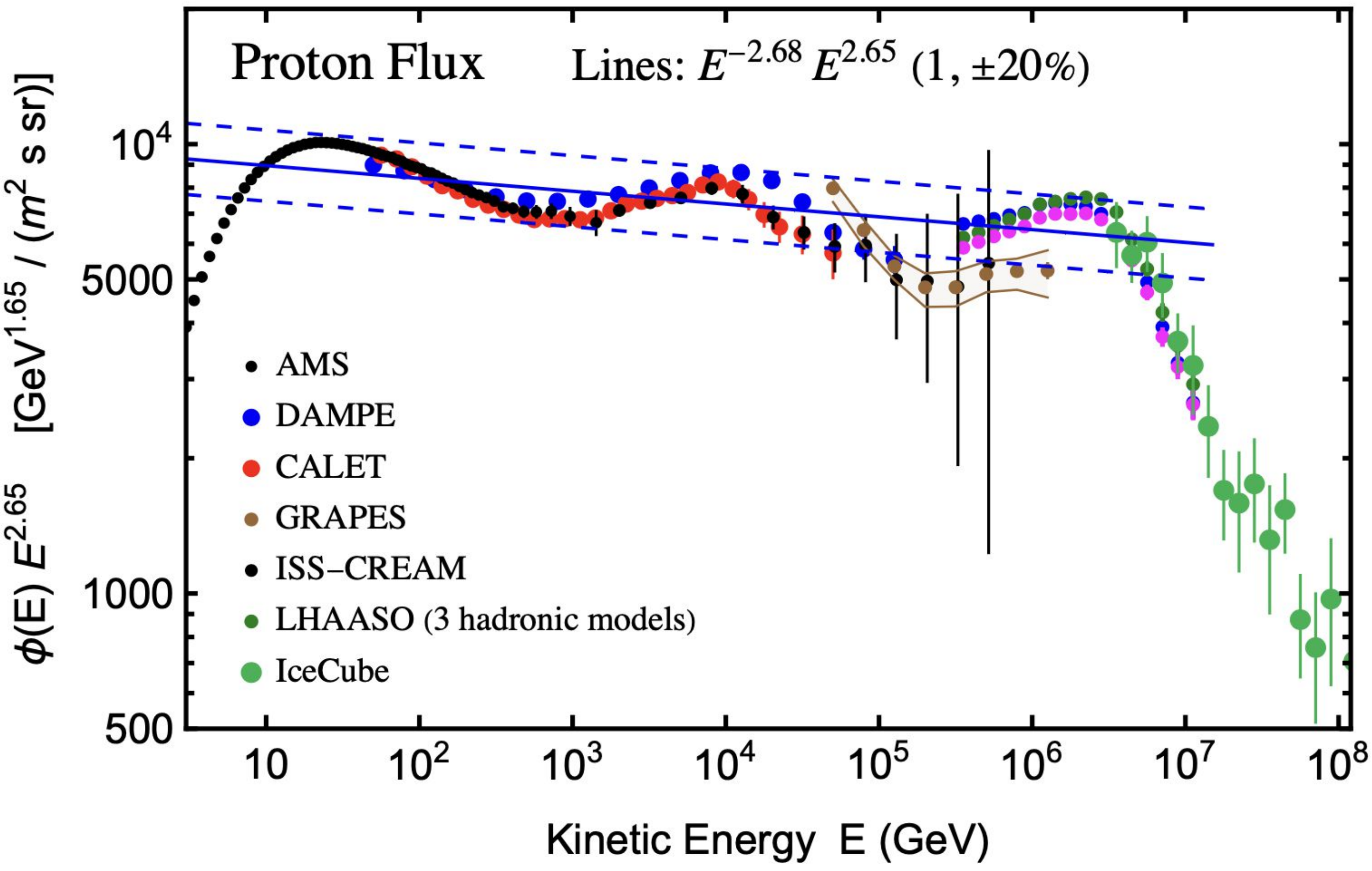


"Sand Pile"
model

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).

Why are the spectral features so "subtle"



Deviations of ±20% on a power-law

Timeline:

1958 Knee
2011 Pamela Hardening (200 GeV)
2019 proton softening 10 TeV
2024 proton hardening 100 TeV

Can the spectral features be
"statistical fluctuations" on a power-law spectrum ?

These fluctuations are too large for
standard multi-components model
but fluctuations of this order could be possible in
a "multi-shape"scenario as outlined before.

The "dramatically" different behavior of the
proton/Helium ratio below and above 100 TeV
does suggest the existence of two different classes\
[Or perhaps the onset of a new phenomenon
(for example: helium photo-disintegration)]

Question:

More precise measurements of the spectra
are going to reveal more (more subtle) structures ?

In the “multi-shape” scenario
the answer is yes !
(effect of fluctuations).

In “standard” multi-component models
the answer is less clear.
One expects possible deviations from
a power-law shape for different effects
both in acceleration and in propagation.

Conclusions

part-1

- Remarkable improvement in the direct measurements of the cosmic ray spectra (detectors in space) with measurements that extend to ~ few 100 TeV

- Great progress in the measurements of CR spectra (for separate elements) in Air-Shower experiments [LHAASO detector]
  Use of Cherenkov telescopes a new attractive method.

- Multi-component measurements of Air shower reduces the dependence on hadronic interaction models.
  But improvements in the models is desirable and possible
  "Threefold approach:
  - Theory,
  - Accelerator Data [LHC+lower energies]
  - Self consistency of CR experiments

Conclusions

part-2

- Measurements of higher precision reveal that the CR spectra have a rich structure with "features" [deviations from a simple power-law form].

Knee				Ankle	Cutoff
hard-1 soft hard2		hard-3	2^{nd} knee		structure

- The interpretation of these features remain an open problem
  - Multiple source-classes ansatz
  - Possible role of "local sources"
  - "Statistical soup" idea [fluctuations due to a broad range of spectral shapes]
- These ideas need to be confirmed by a study of the gamma-ray and neutrino emissions from these sources
- Understanding the Galactic/extragalactic transition is crucial
- Improvement of the propagation models (and structure of the CR halo) especially at very high energy very important