PeV Cosmic Rays: measurements and interpretation

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Seminars of CDHY Initiative

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Outline:

1. General Introduction

2. Air Shower Measurements of Cosmic Ray spectra

3. LHAASO WFCTA measurements of protons and Helium

4. Comparing the Proton and Helium spectra

5. The “Multiple-classes of sources” ansatz
   for spectral features

6. Local sources

7. Fluctuations and the “Statistical Soup” ansatz

8. The CR spectra above the Knee

9. Conclusions.

COSMIC RAYS

Ensemble of *Relativistic charged particles*
generated by many sources in the Galaxy and the Universe.

Their directions are scrambled by magnetic fields.

Particles observed at one point and at one epoch
have been generated in many points and at different times
The observable spectra are therefore
shaped by their sources and by propagation effects.

They form a *"Local Fog"* that is a terrible nuisance
for gamma and neutrino astronomy
but they also carry very important information
about high energy sources in the Galaxy and the Universe

Three main Cosmic Ray populations

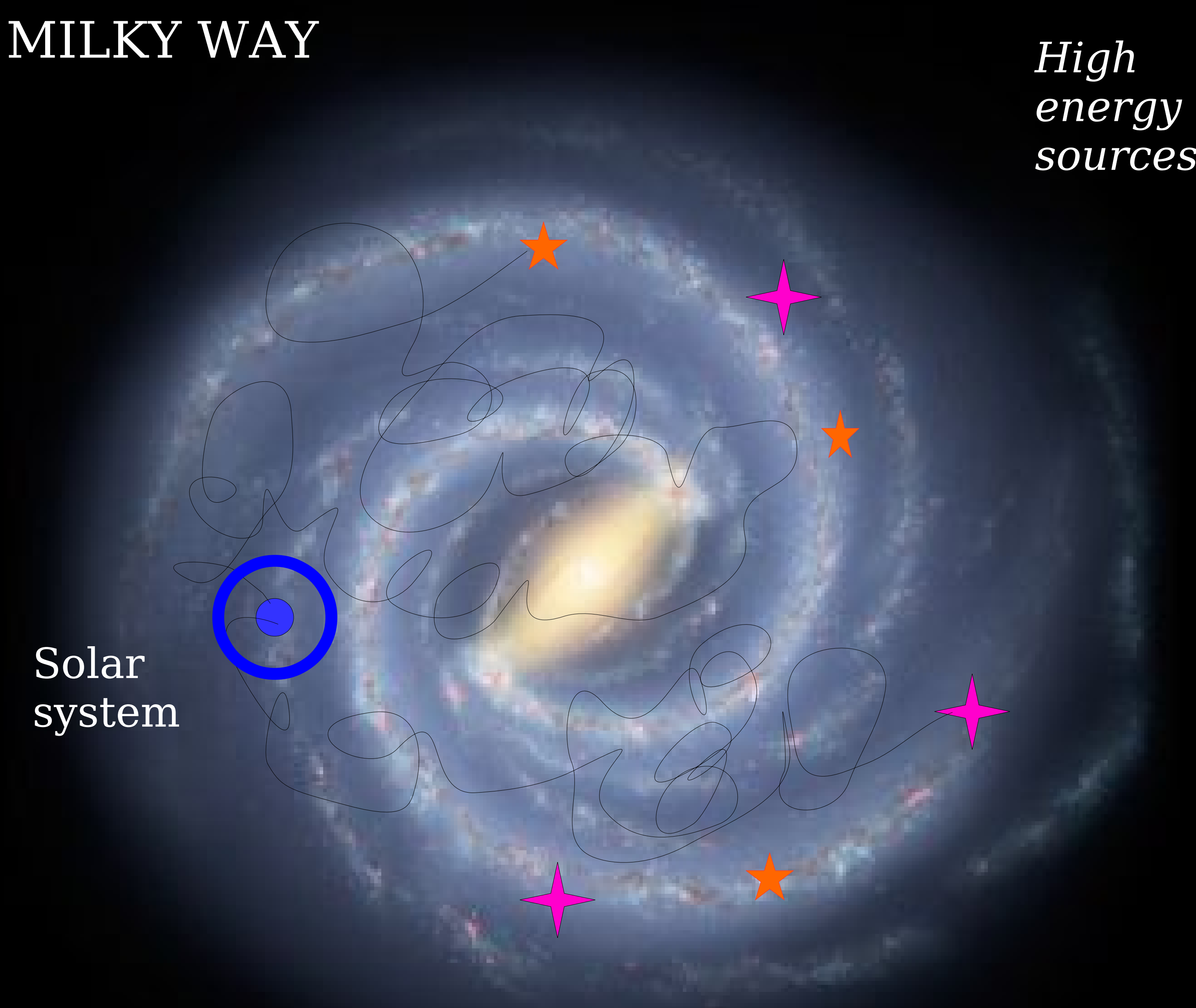
Solar articles
[accelerated in the Sun]

Clear separation
(spectrum shape
and directions)

Galactic Particles
[produced on the Milky Way]

Separating these
components is
an open problem
of crucial importance

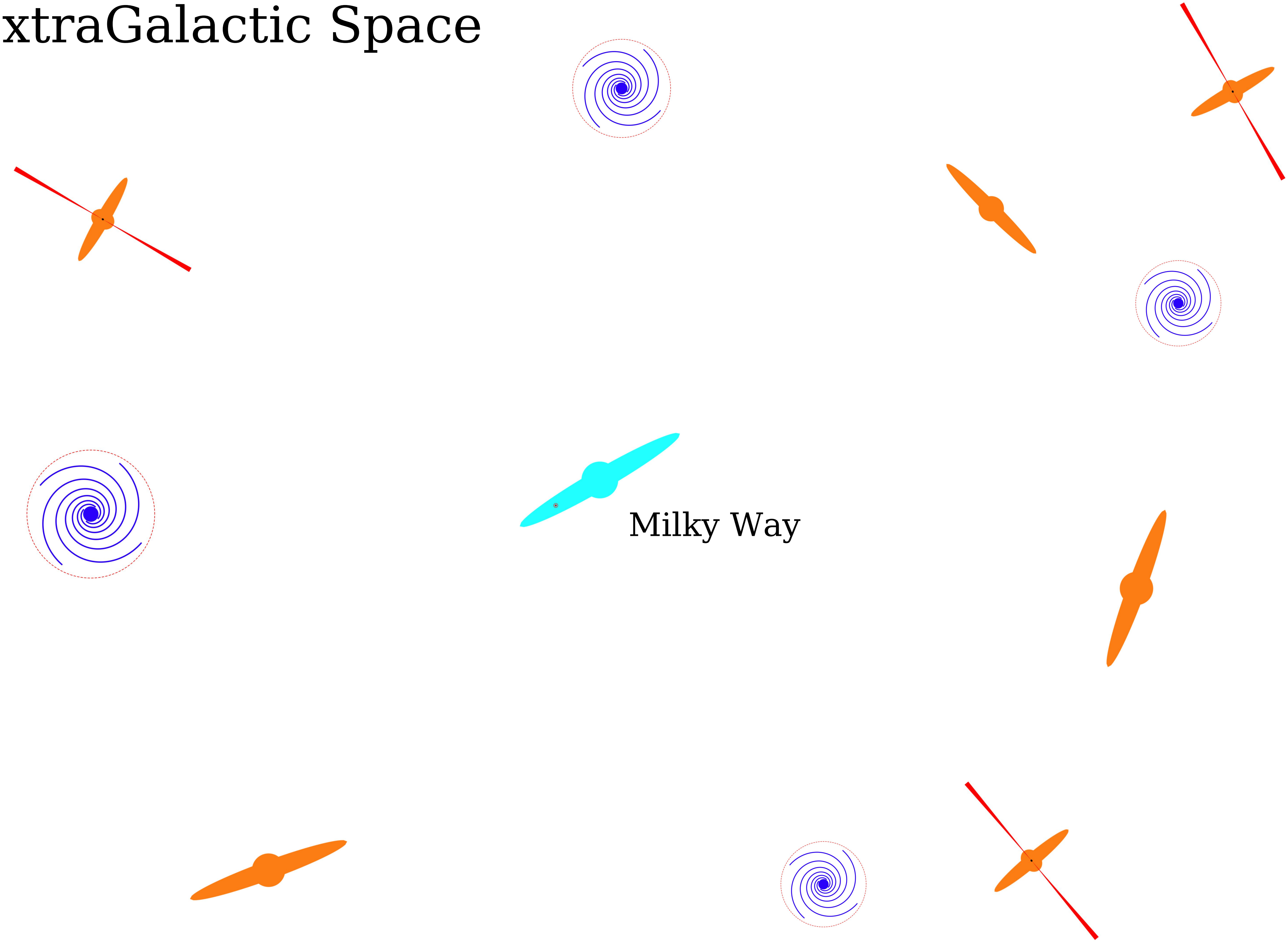
Extra-galactic particles
[produced outside the Galaxy]



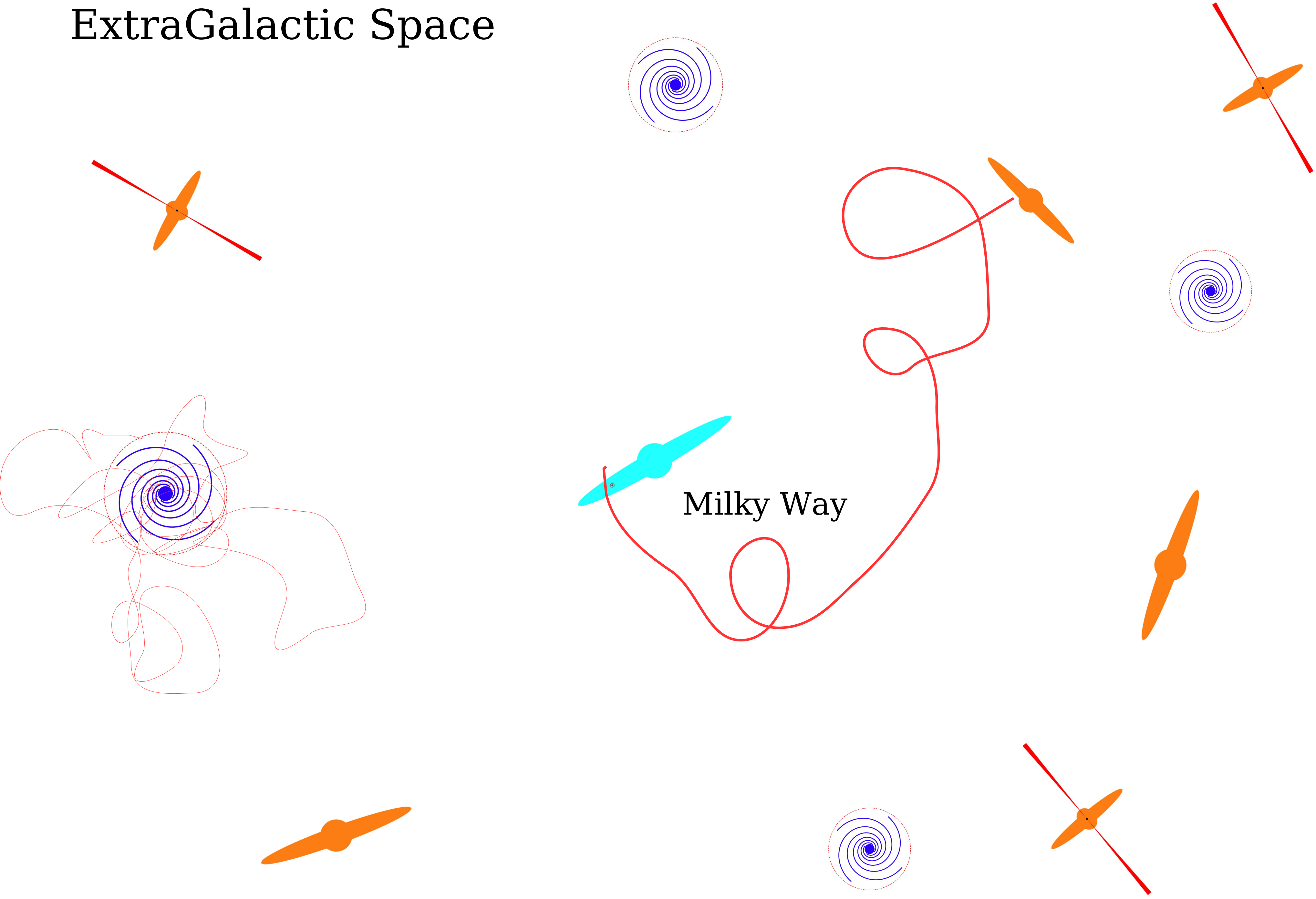
GALACTIC COSMIC RAYS

understanding of Galactic Magnetic fields crucial

ExtraGalactic Space



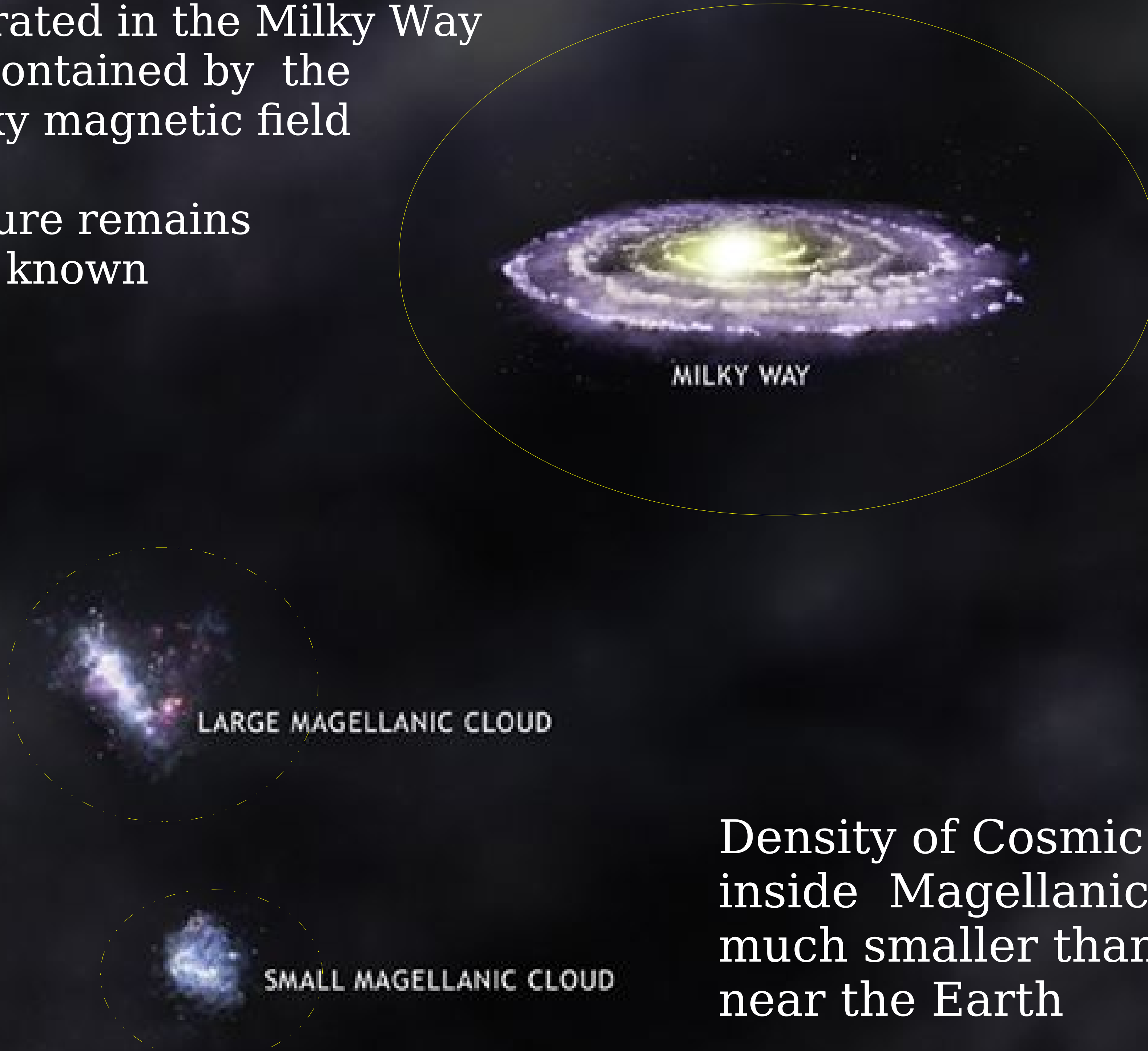
ExtraGalactic Space



Understanding of Extragalactic magnetic field crucial

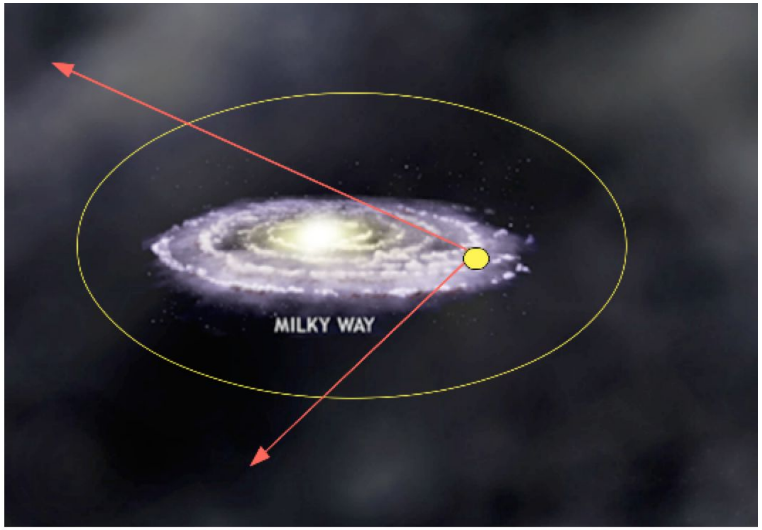
“Bubble” of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

Structure remains poorly known



Density of Cosmic Rays inside Magellanic Clouds much smaller than near the Earth

Study of the Galactic Diffuse gamma-ray and neutrino fluxes



absorption

$$\phi_\gamma(E,\Omega) = \frac{1}{4\pi}\int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell\,\hat{\Omega}]\; e^{-\tau_\gamma(E,\Omega,\ell)}$$

$$\phi_\nu(E,\Omega) = \frac{1}{4\pi}\int_0^\infty d\ell \; q_\nu[E, \vec{x}_\odot + \ell\,\hat{\Omega}]$$

Calculation of “interstellar” gamma-ray emission:
leading (proton-proton) term (for hadronic mechanism):

$$q_\gamma^{(pp)}(E_\gamma, \vec{x}) = n_p^{\rm ism}(\vec{x}) \times$$

$$\times \int_{E_\gamma}^{\infty} dE_p \, [4\,\pi\, \phi_p(E_p, \vec{x})] \, \sigma_{pp}(E_p) \frac{dN_{pp\to\gamma}}{dE_\gamma}(E_\gamma, E_p)$$

Gas density in the Milky Way

Hadronic Interactions

Spectra of cosmic rays in all points of the Galaxy

Study Cosmic Rays in all the Galaxy

Most models for Galactic Cosmic Rays assume:

Factorization (of energy and space dependences) of the CR spectra

$$\phi_p(E, \vec{x}) = \phi_p^{\rm loc}(E) \times f_{\rm space}(\vec{x})$$

All points of the Galaxy contain CR populations with spectra of the same *shape*

Equivalently:
Cosmic rays of all energies have equal (normalized) spatial distributions.

This result emerges under some (questionable) assumptions:

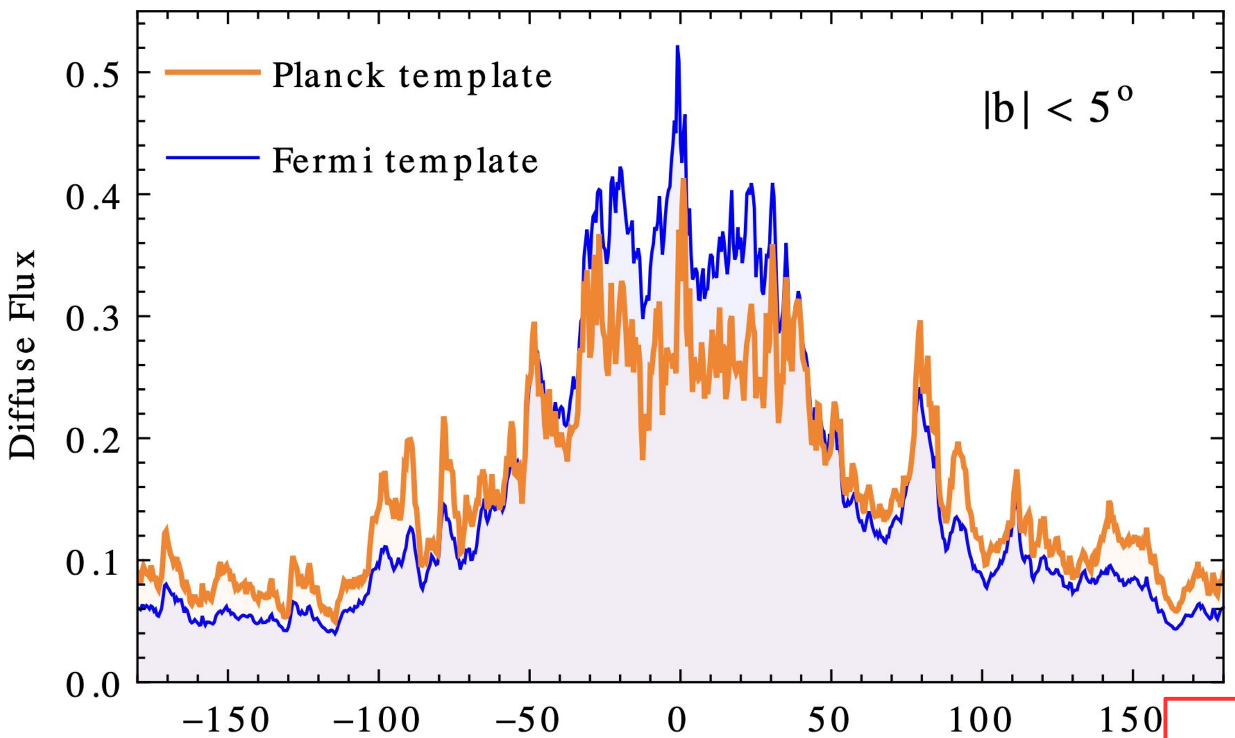
- Equal CR source spectra in all of the Galaxy.
- Diffusion models with factorized rigidity / space dependences

Study experimentally is of crucial importance

Galactic Longitude distribution (for |b| < 5 degrees) of:

[Blue] Planck Dust map (traces gas column density)

[Orange] Fermi template (12 GeV) [traces emission column density]



Galactic Longitude (degrees)

P.L. & Silvia Vernetto
astro-ph/2509.09028
(PRD to appear)

Blue > Orange
towards Galactic Center

Orange > Blue
towards Outer Galaxy

Distributions normalized to the same area

Gradient in the CR density. In first approximation energy independent

$$N_{\rm cr}(r) \propto e^{-\lambda_{\rm cr}\, r}$$

"best fit"
(qualitative)

$$\lambda_{\rm cr} \simeq 0.16 \ \ {\rm kpc}^{-1}$$

[half density length = 4.3 Kpc]

Note: The question if the CR spectral shape
is independent from position in the Milky Way
remains *controversial*, and is of *great importance*.

Three possible mechanisms can
generate a space dependence of the CR spectra.

[1.] Existence of near, young CR *"local" sources*
(several papers discuss the CR "Knee" as a local effect)

[2.] Propagation/ Acceleration models that
are more "complex" than the |standard model"
and result in different spectral distortions in
different points of the Milky Way. (several papers).

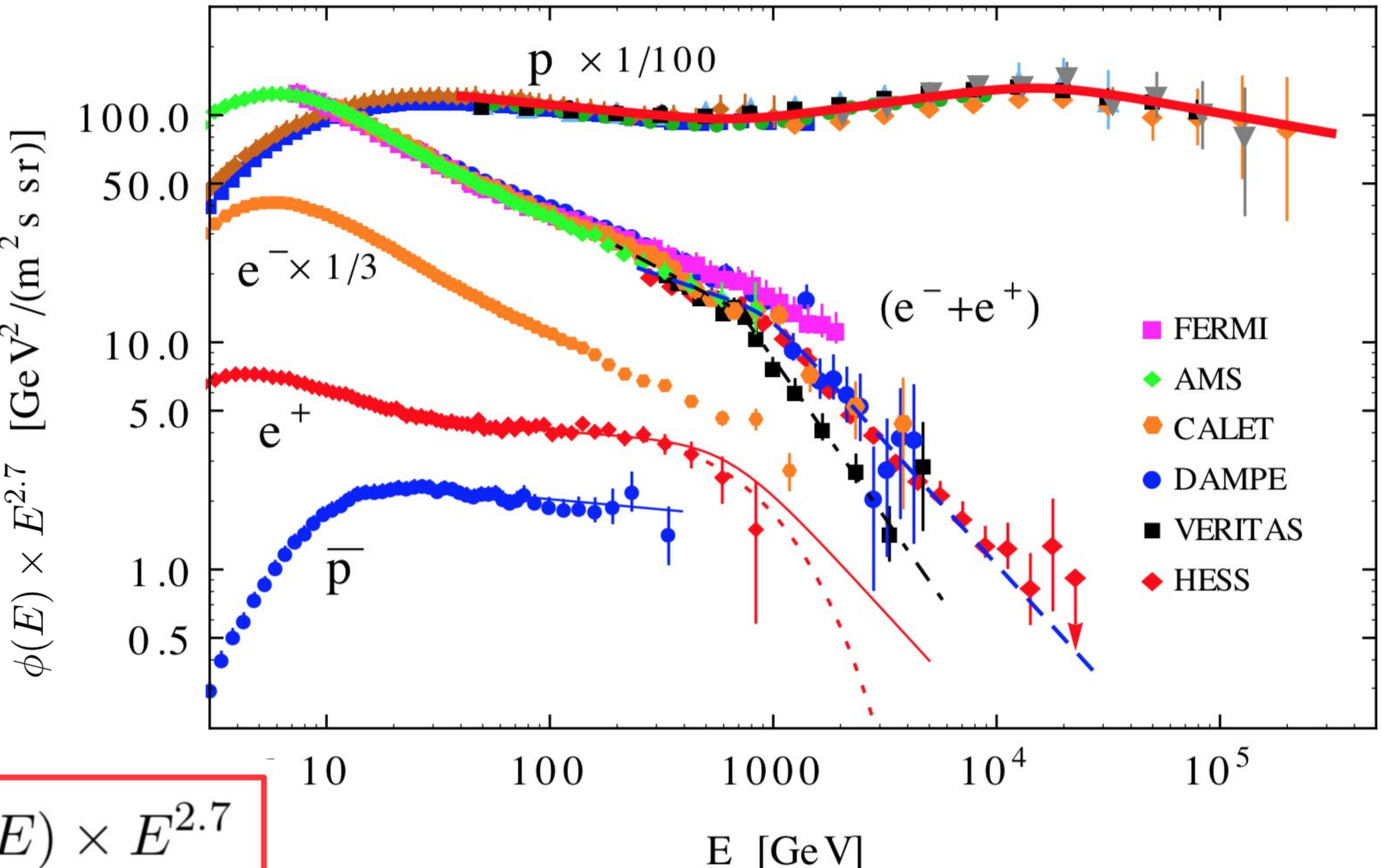
[3.] Extragalactic cosmic rays
(that enter the Milky Way from the outside)
are likely to have a different space distribution than Galactic ones.

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

$p \quad e^-$

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

Comparing the shapes of the different spectra is of fundamental importance



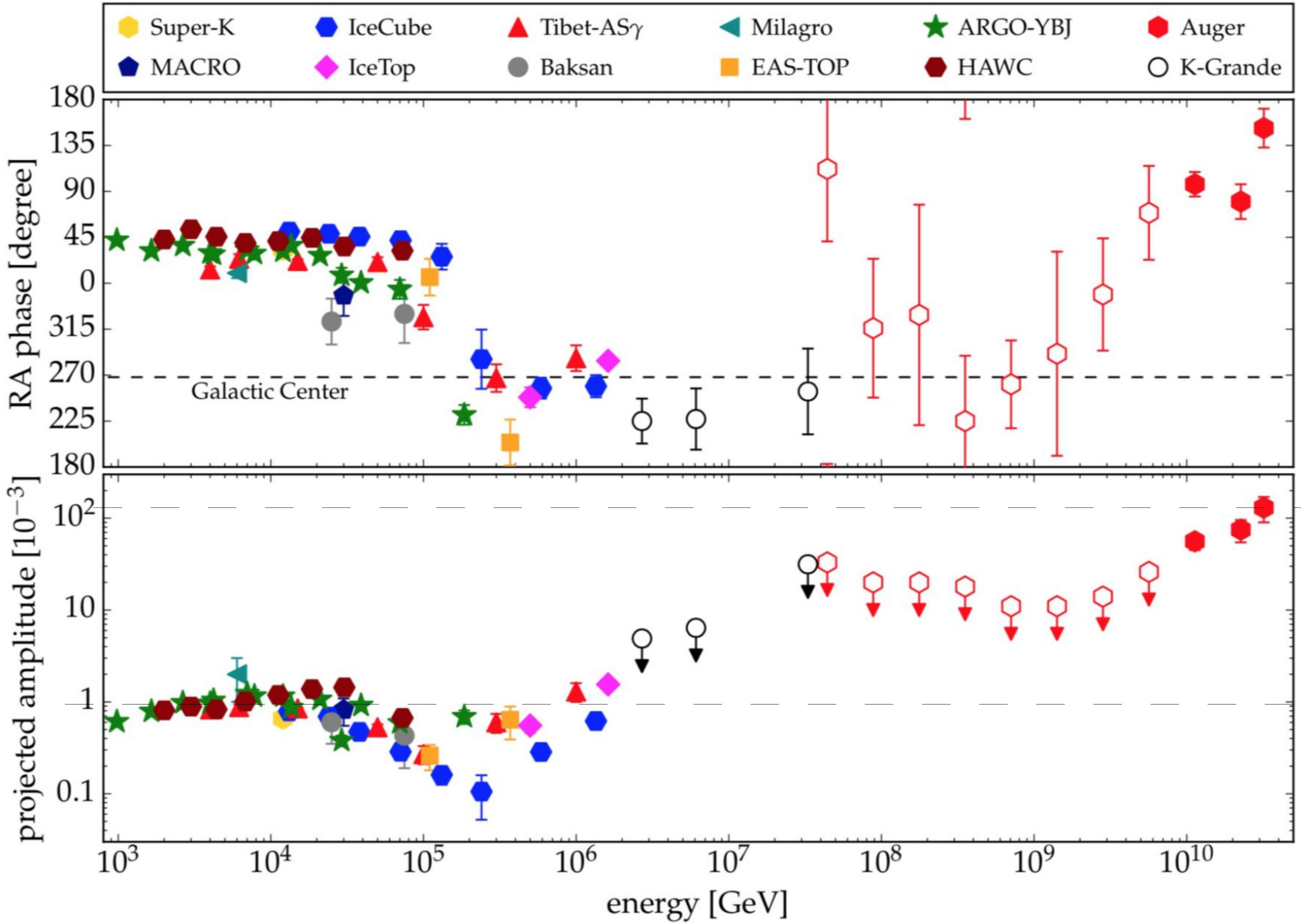
$\phi(E) \times E^{2.7}$

Large scale CR Anisotropy

amplitude and Phase of *Dipole*

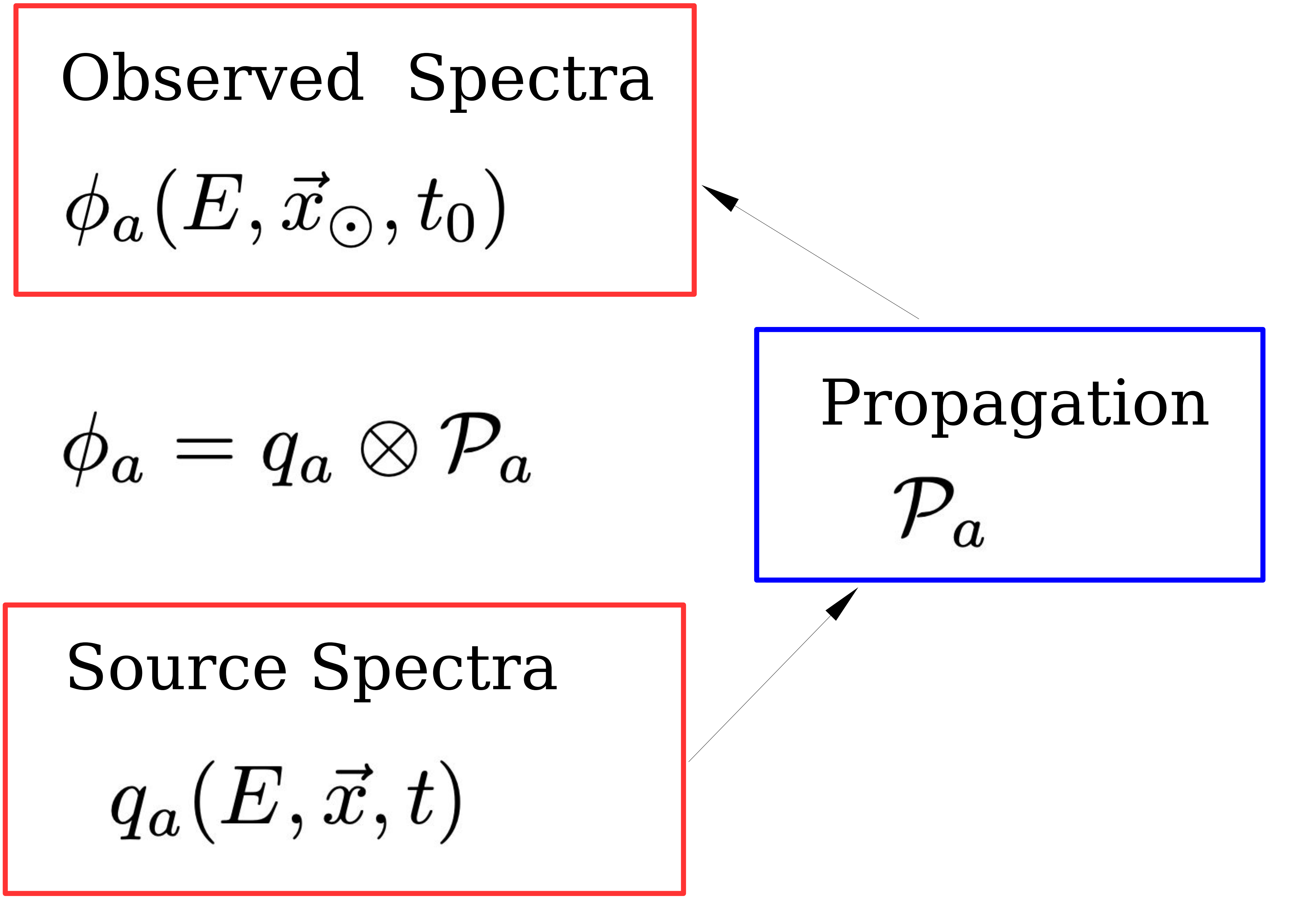
$$\phi(\Omega) = \phi_0 + \hat{n} \cdot \hat{d}\, \phi_1$$

$$\phi_0 + \cos\theta\, \phi_1$$



1/10

1/1000.

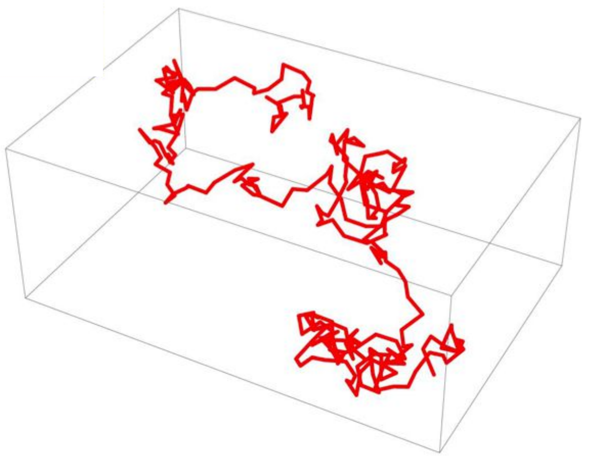


Observed Spectra
$\phi_a(E, \vec{x}_\odot, t_0)$
$\phi_a = q_a \otimes \mathcal{P}_a$
Propagation
$\mathcal{P}_a$
Source Spectra
$q_a(E, \vec{x}, t)$

Modeling Cosmic Ray Propagation in the Milky Way magnetic field

1951 Giuseppe Cocconi [Phys. Rev. 83 (1951)]

"On the Origin of Cosmic Radiation"



The main "sink" for cosmic ray is escape from the Galaxy.

First *Diffusion Model*

[a spherical Galaxy with absorbing boundaries]

Sources as "cosmic ray stars"

1954 Phillip Morrison , Stanislaw Olbert, Bruno Rossi

[Phys. Rev. 94 (1954)] "*The Origin of Cosmic Rays*"

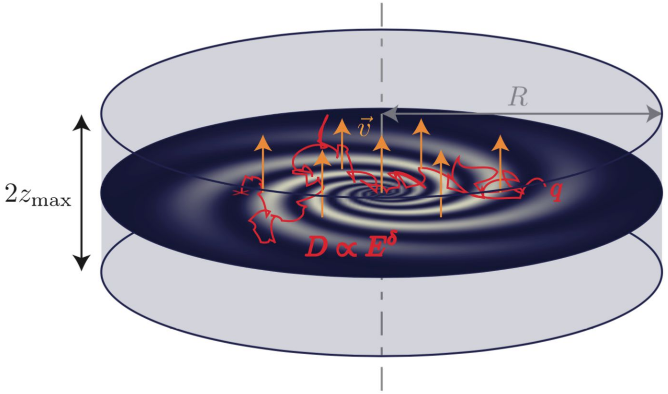
Diffusion Model for Cosmic Rays

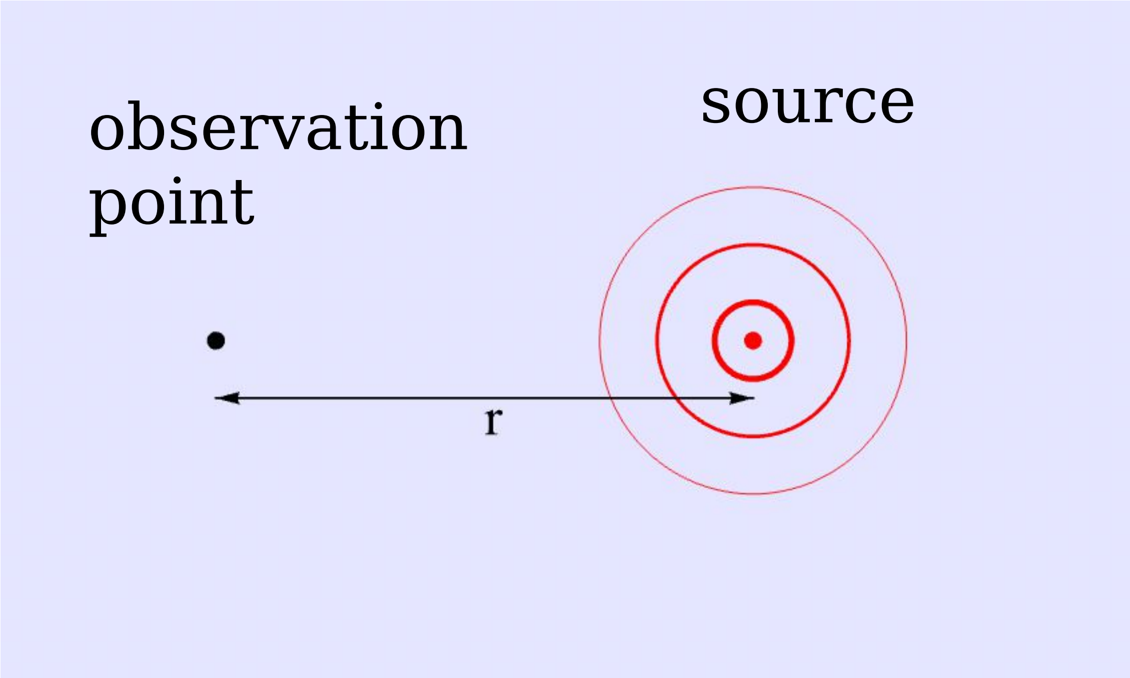
with the main elements of current mo

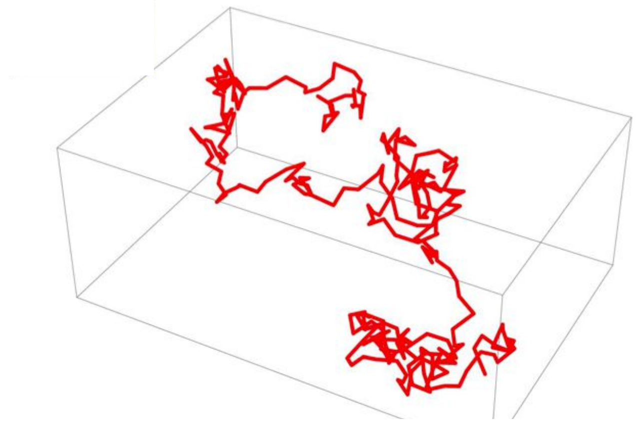
[Cylindrical Galaxy,

absorbing boundaries,

sources distributed in the disk]







$$R^2(t) = 2\,D(E)\,t$$

Isotropic diffusion in a homogeneous medium. no boundaries.

"Burst like" emission from a point:

3D Gaussian with radius $R \propto \sqrt{t}$

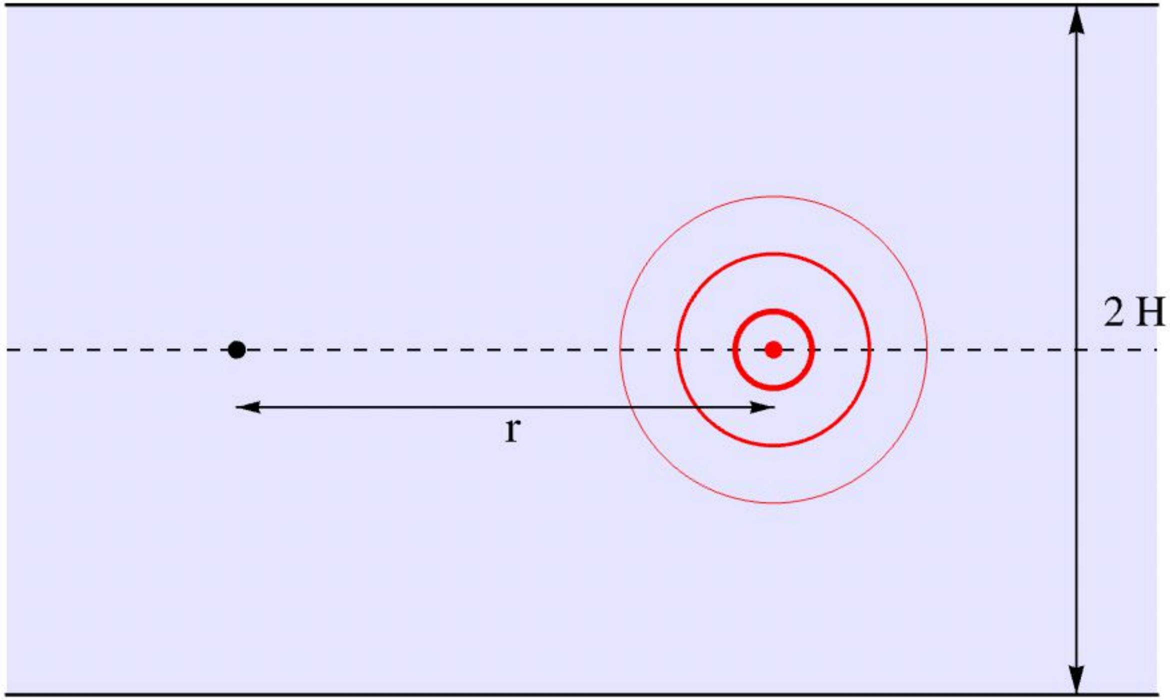
$$\mathcal{P}(r,t) = \frac{1}{(2\pi)^{3/2}}\,\frac{1}{R^3(t)}\,\exp\left[-\frac{r^2}{2\,R^2(t)}\right]$$

Constant source:

$$\int_0^\infty dt\,\mathcal{P}(r,t) = \frac{1}{2\pi\,D(E)\,r}$$

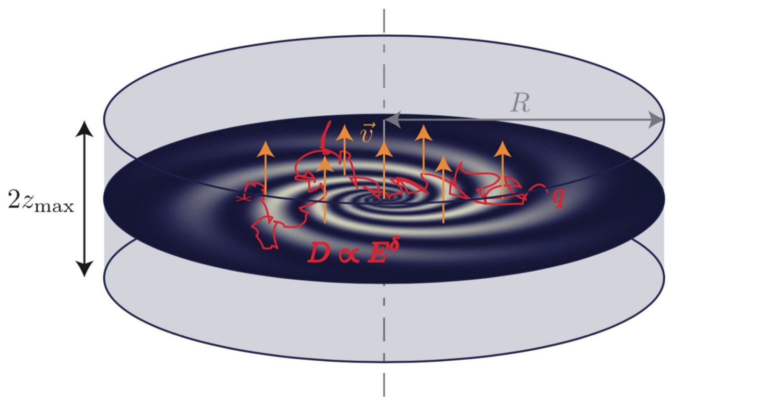
Spectral distortion

$$q(E) \to \frac{q(E)}{D(E)}$$



Introduce boundaries

Limit of very large radius



Burst-like source

$$\mathcal{P}(r,t) = \frac{1}{(2\pi)^{3/2}} \frac{1}{R^3(t)} \exp\left[-\frac{r^2}{2\,R^2(t)}\right] F_{\rm esc}\left(\frac{R^2(t)}{H^2}\right)$$

Constant source

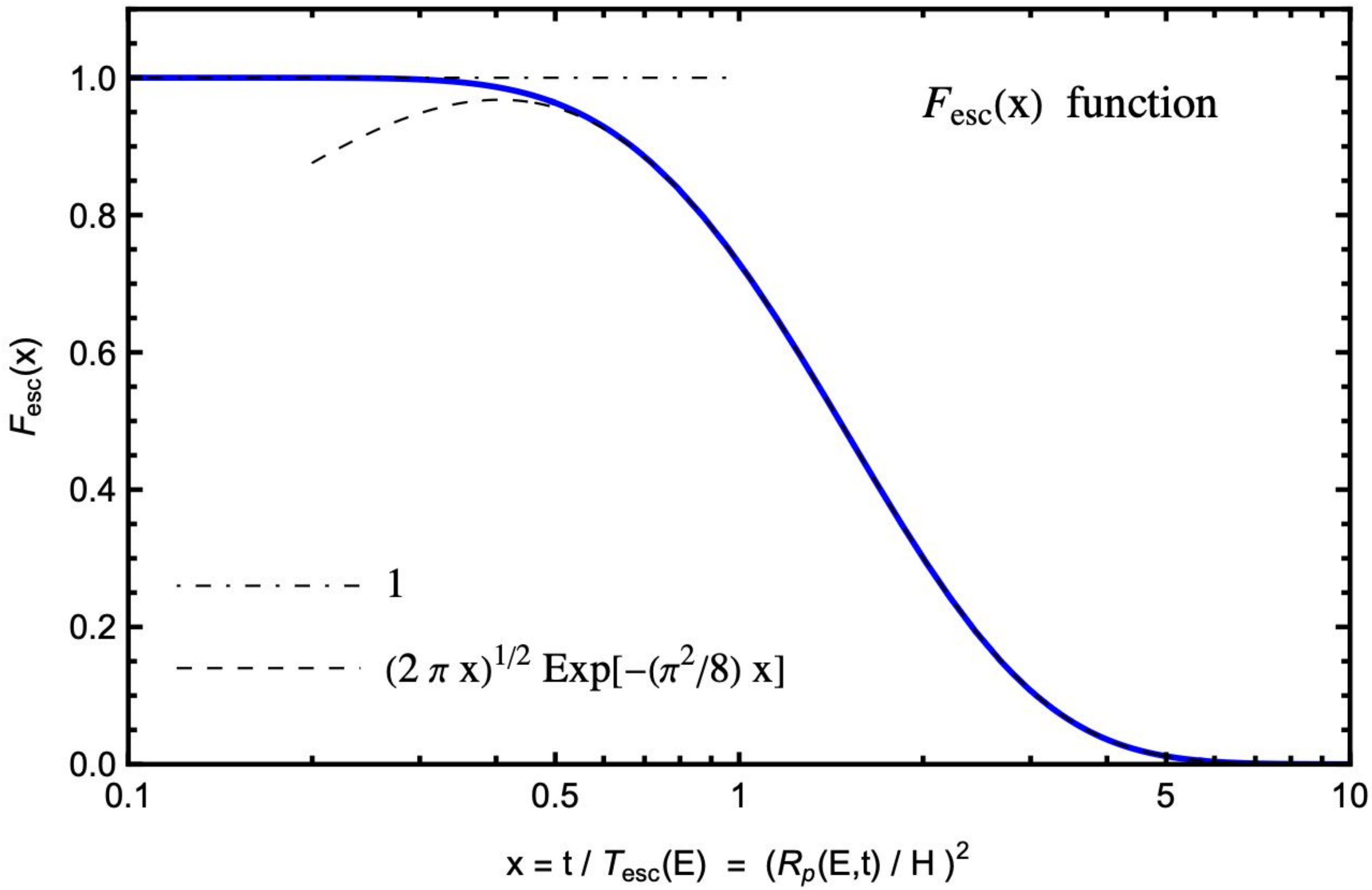
$$n(r) = \frac{1}{2\pi\, D\, r} G_{\rm esc}\left(\frac{r}{H}\right)$$

Exponential cutoff

Spectral distortion

$$q(E) \rightarrow \frac{q(E)}{D(E)}$$

Distortion of the gaussian due to escape



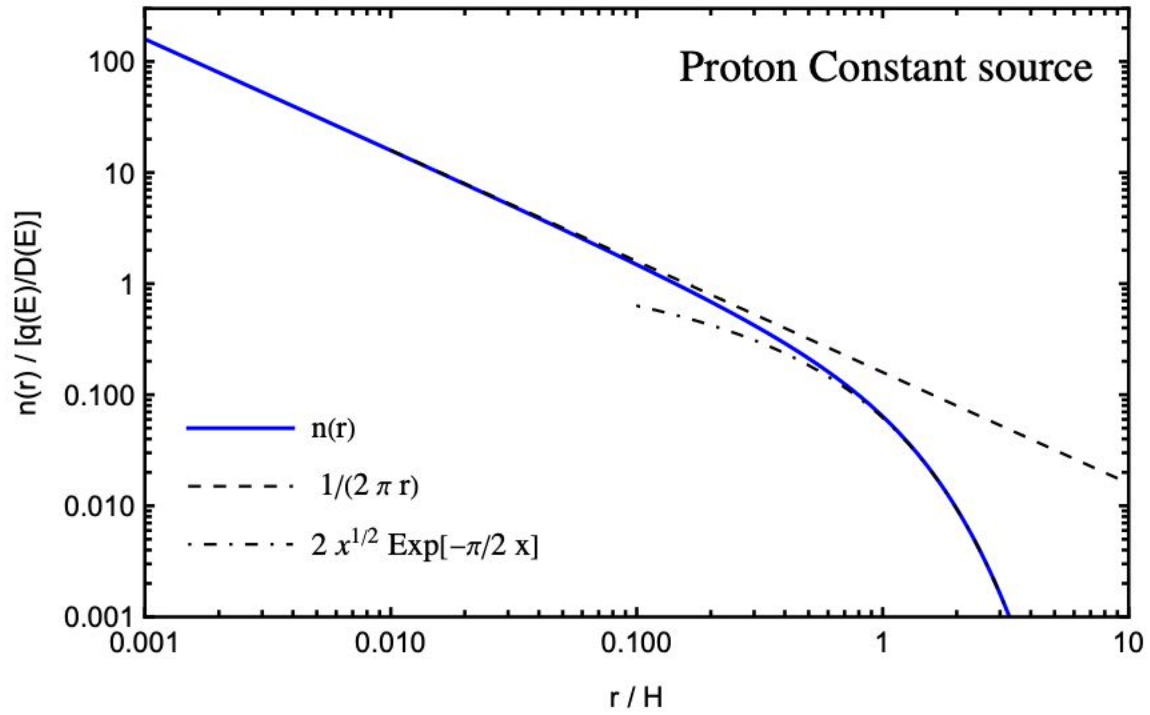
$$\tau = \frac{R^2(t)}{H^2} = \frac{2D\,t}{H^2} = \frac{t}{T_{\rm esc}}$$

$$F_{\rm esc}(\tau) = \theta_3(0, e^{-8/\tau} - \theta_2(0, e^{-8/x}) \; = \begin{cases} 1 & \text{for } \; 0 \leq \tau \lesssim 0.5 \\ \sqrt{2\pi\tau}\, \exp[-\pi^2/8\,\tau] & \text{for } \; \tau \gtrsim 0.5 \end{cases}$$

(Jacobi theta function)

Constant source

$$n(r) = \frac{1}{2\pi D r} G_{\rm esc}\left(\frac{r}{H}\right)$$



Spectral distortion

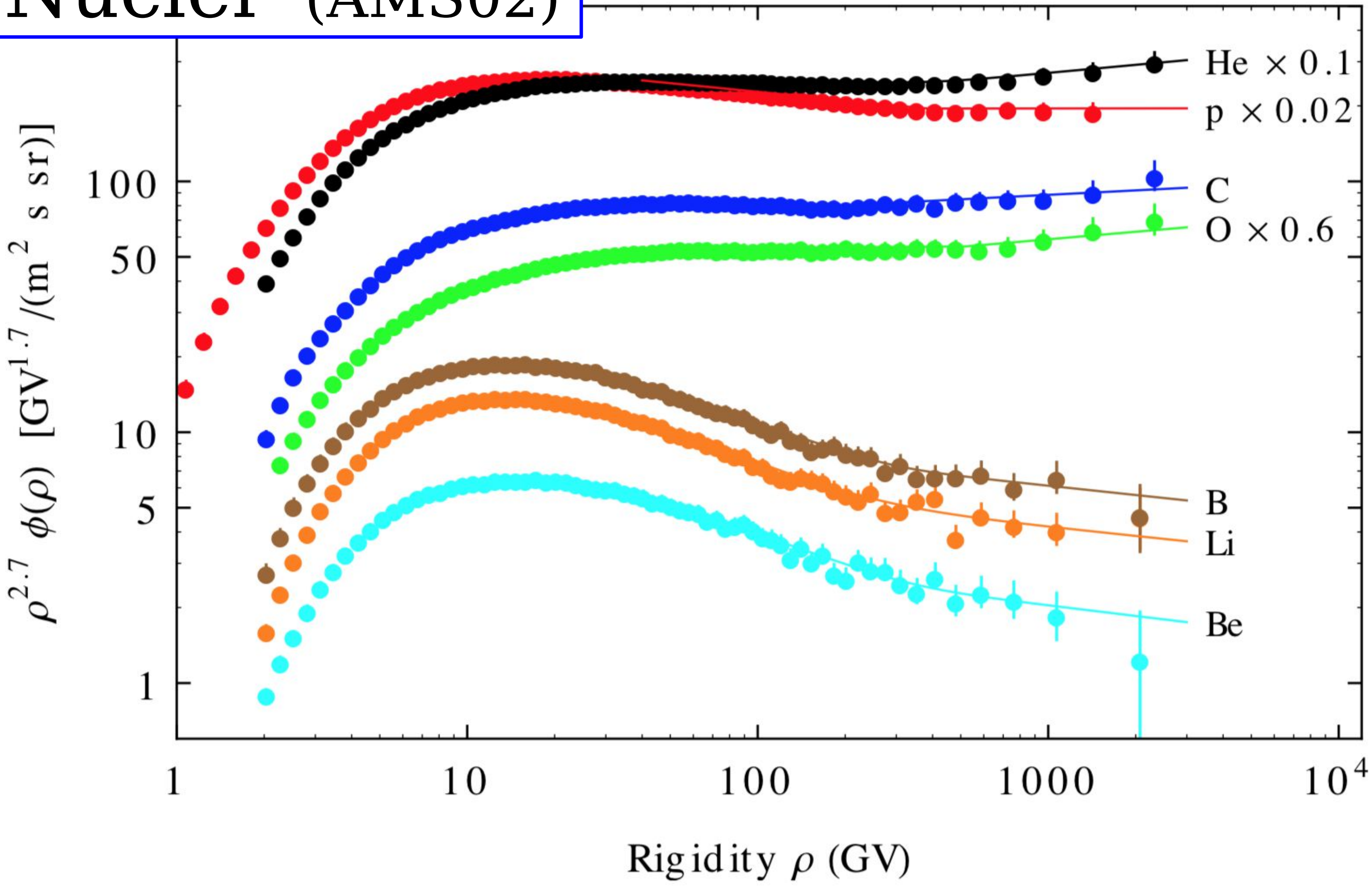
$$q(E) \to \frac{q(E)}{D(E)}$$

$$G_{\rm esc}(x) = \begin{cases} 1 & \text{for} \quad x \ll 1 \\ 2\sqrt{x}\,\exp[-\pi/2\,x] & \text{for} \quad x \gg 1 \end{cases}$$

“Standard Propagation Model"

Based on the interpretation of the spectra of the Secondary Nuclei [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:

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

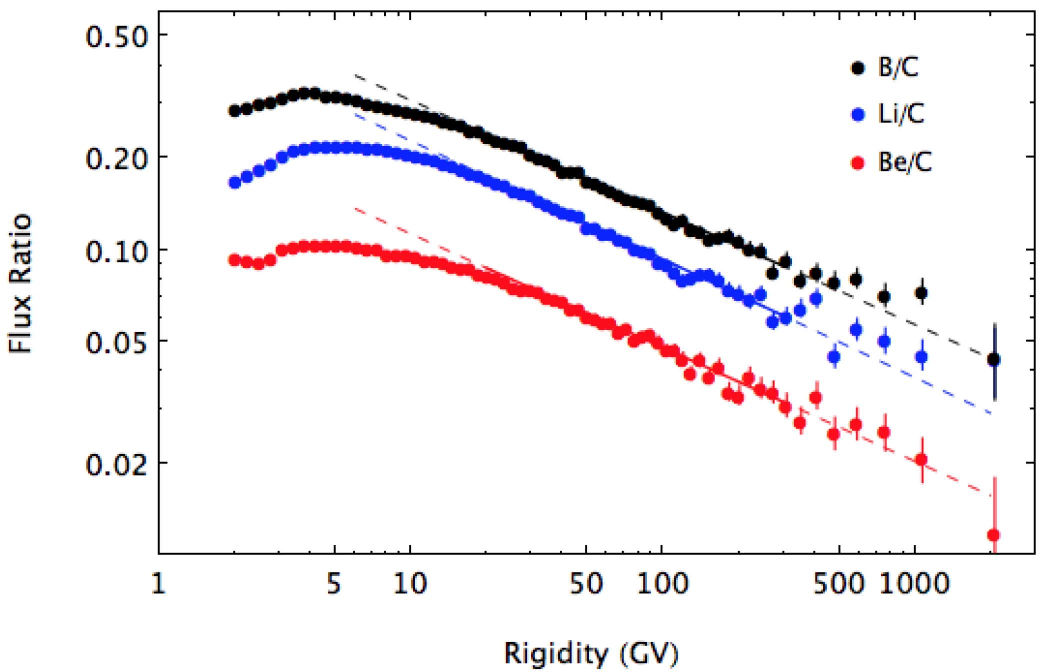
$$^{12}\mathrm{C} + p \to {}^{11}\mathrm{B} + 2\,p$$

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

....

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

"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)

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

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)

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

Very desirable to make a "grammage" analysis

IF one assumes that the "grammage" is *integrated during propagation in interstellar space*

crucial *ASSUMPTION*

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]].

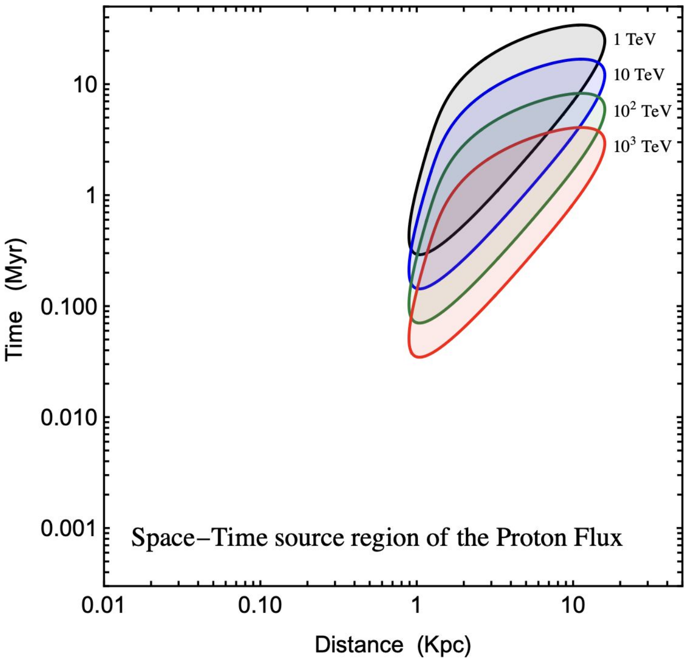
[........]

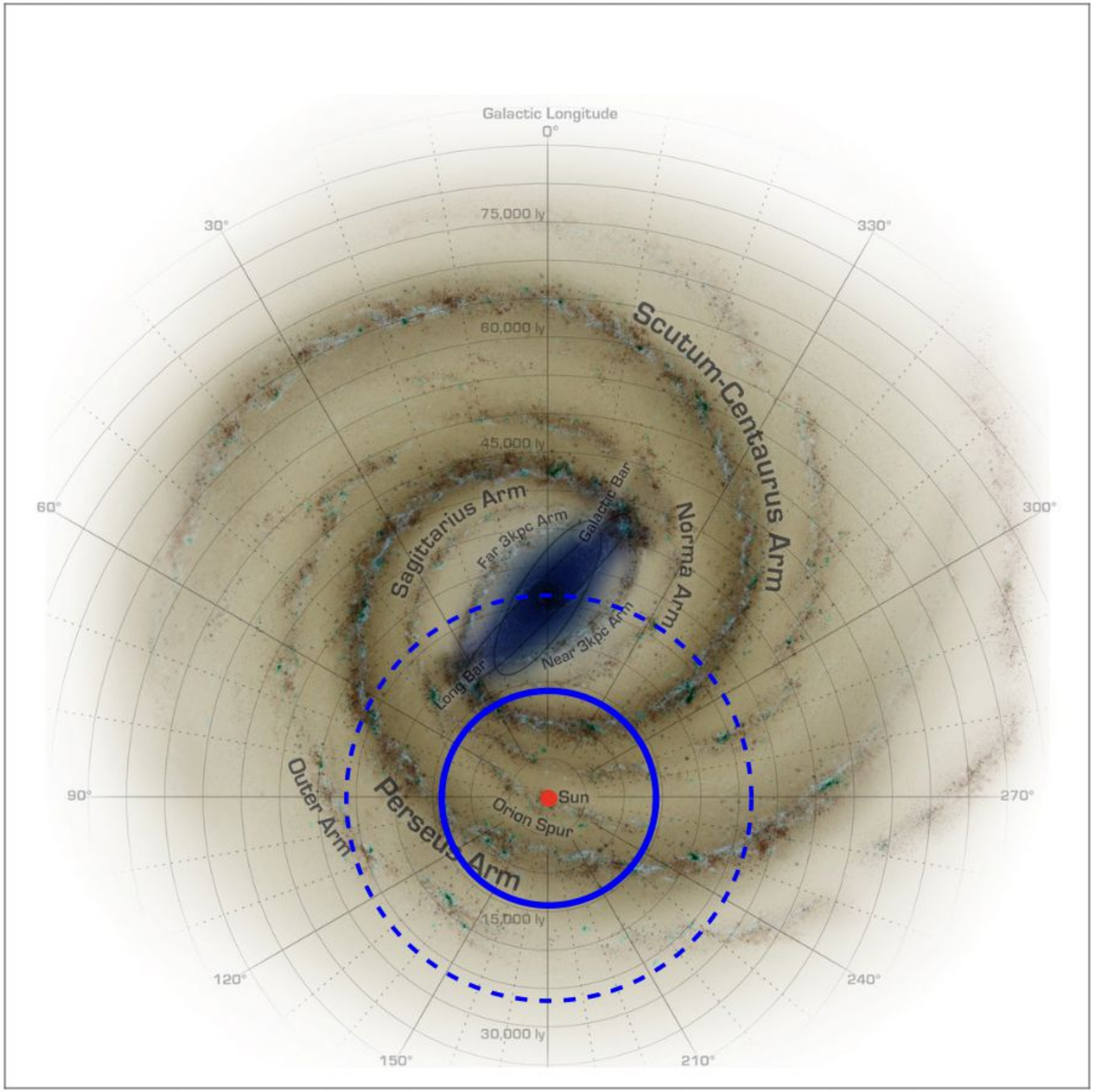
Space region that is the source of the *proton* flux

Standard diffusion model. Halo = 4.5 Kpc

Solid line: r = H

Dashed line: 90% of flux





Electron/Positron Propagation

Much larger
Rate of Energy Loss

$$-\frac{dE}{dt} \propto \frac{q^4}{m^4} E^2$$

Dominant Radiative processes

- Synchrotron,
- Compton scattering on Radiation fields

$$-\frac{dE}{dt} \simeq \frac{4}{3}\sigma_{\text{Th}} c \left[\rho_B + \rho_\gamma^*(E)\right] \frac{E^2}{m_e^2}$$

energy density in magnetic field

energy density in radiation $E\,\varepsilon \lesssim m_e^2$

Energy losses

[synchrotron, Compton scattering]
strongly depend on the particle mass

$$T_{\rm esc} \approx 50 \left(\frac{E}{\rm GeV}\right)^{-0.5} \ {\rm Myr}$$

Escape time from secondary nuclei

Characteristic time
for energy loss

$$T_{\rm loss}(E) \simeq \frac{E}{|dE/dt(E)|}$$

Energy loss becomes the dominant "sink" mechanism above a minimum energy

$$T_{\rm loss}(E) = \frac{E}{|dE/dt|} \simeq \frac{3\, m_e^2}{4\, c\, \sigma_{\rm Th} \, \langle \rho_B + \rho_\gamma^*(E) \rangle \ E}$$

$$\simeq 621.6 \left(\frac{\rm GeV}{E}\right) \left(\frac{0.5 \ {\rm eV/cm^3}}{\rho}\right) \ {\rm Myr}$$

$$\rho_b = \frac{B^2}{8\,\pi} :\simeq 0.22 \left(\frac{B}{3 \ \mu{\rm G}}\right)^2 \ \frac{\rm eV}{\rm cm^3}$$

$$\rho_{\rm CMBR} \simeq 0.26 \ \frac{\rm eV}{\rm cm^3}$$

Implications of the “Standard Interpretation”

Infer the shape of the source spectra for protons and nuclei

[... softer than Fermi acceleration (?)]

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

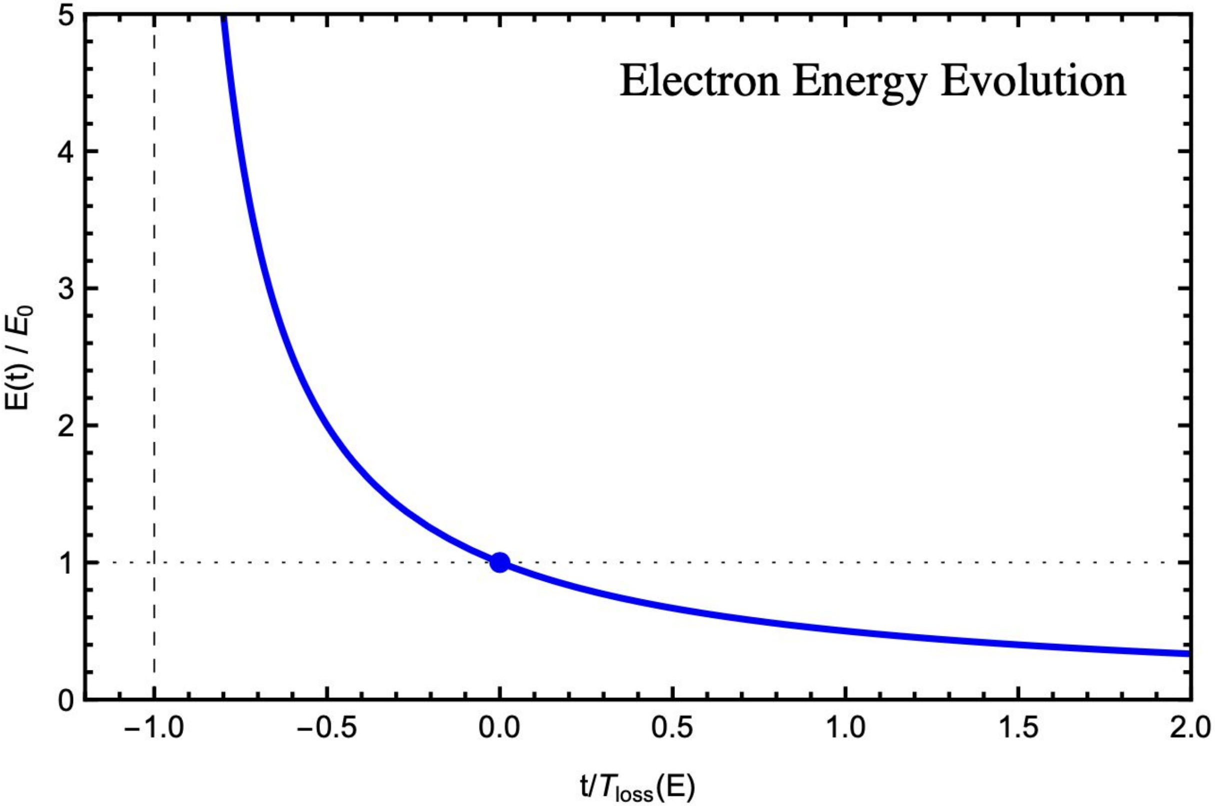
(electron+ positron) Energy Losses important for E > few GeV

$$(\Delta E)_{e^\pm} \approx \left|\frac{dE}{dt}\right|_{e^\pm} T_{\rm age}(E) \quad \begin{array}{ll} < E & \text{losses negligible} \\ \approx E = E^* & \text{Critical energy} \\ > E & \text{losses dominant} \end{array}$$

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

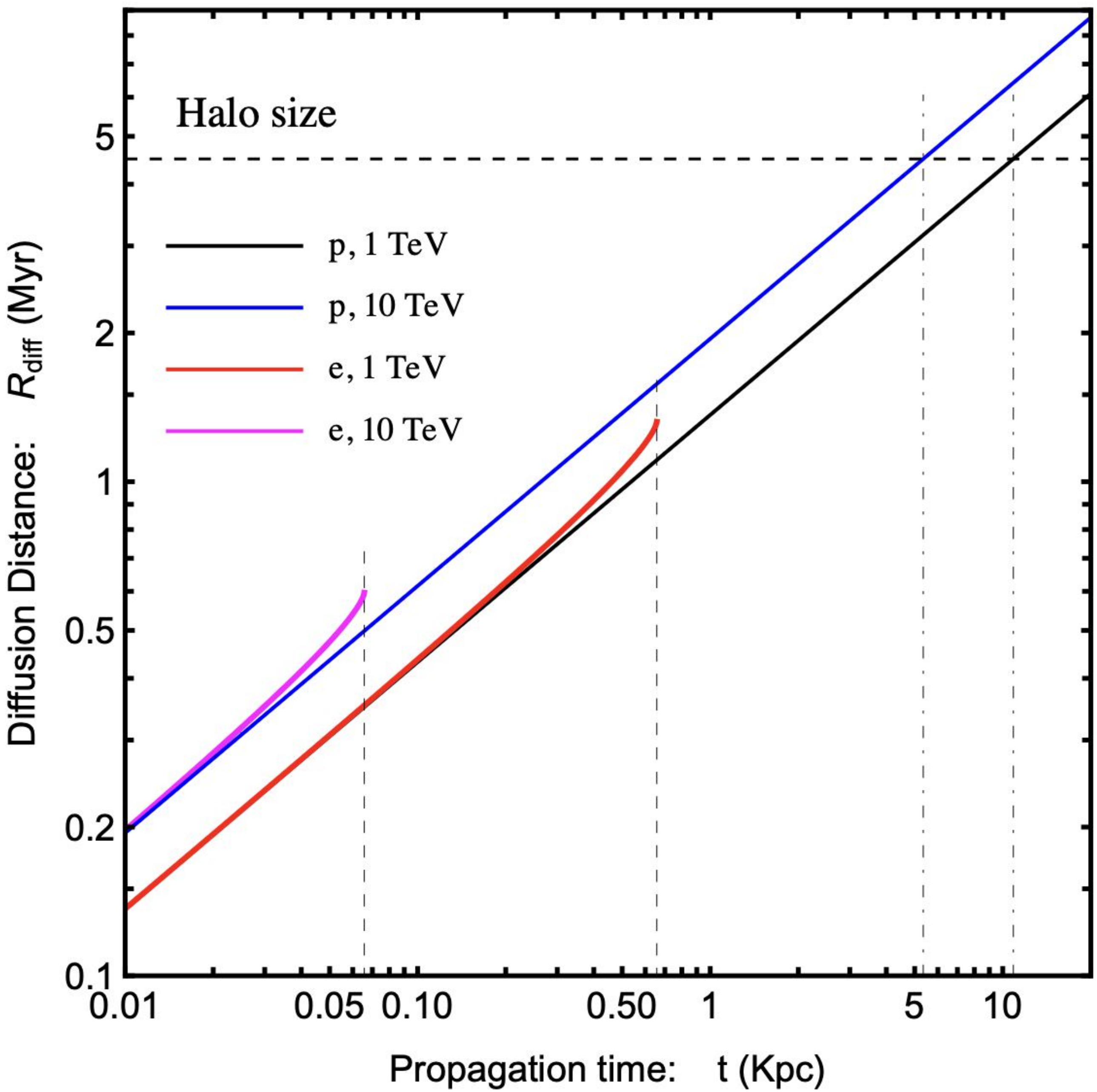
Positrons: Secondary Production cannot explain the data

New source is needed [2500 papers.. and counting!]



$$E_i(E,t) = \frac{E}{1 - b\,E\,t} = \frac{E}{1 - \tau_e}$$

$$\tau_e = \frac{t}{T_{\text{loss}}(E)} \qquad\qquad T_{\text{loss}}(E) = \frac{1}{b\,E}$$

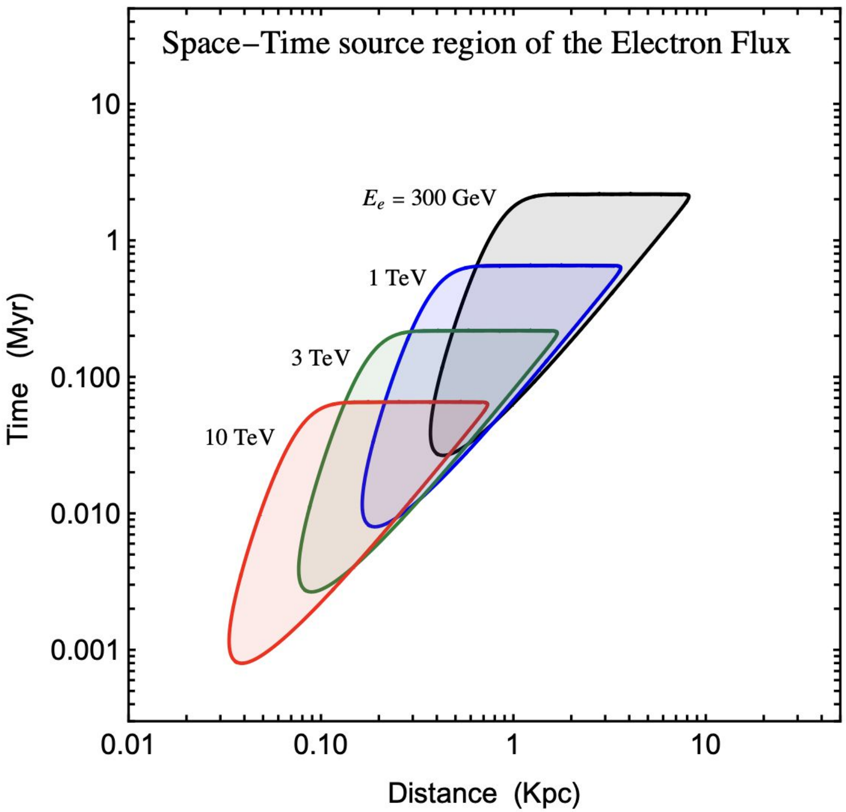


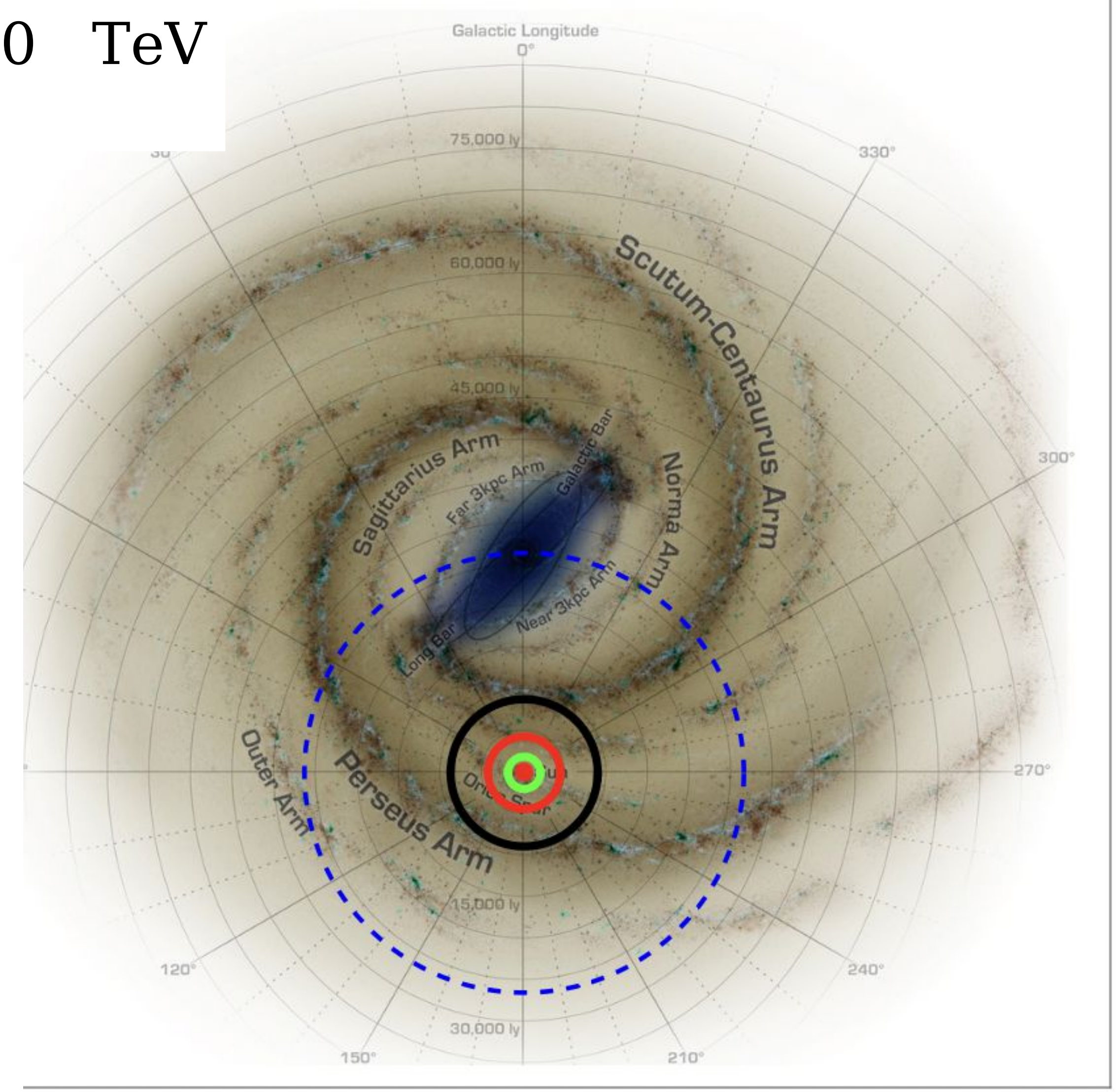
Halo size
p, 1 TeV
p, 10 TeV
e, 1 TeV
e, 10 TeV
Diffusion Distance: R_{diff} (Myr)
Propagation time: t (Kpc)
0.1
0.2
0.5
1
2
5
0.01
0.05
0.10
0.50
1
5
10

Space region that is the source of the *Electron* flux
Standard diffusion model.

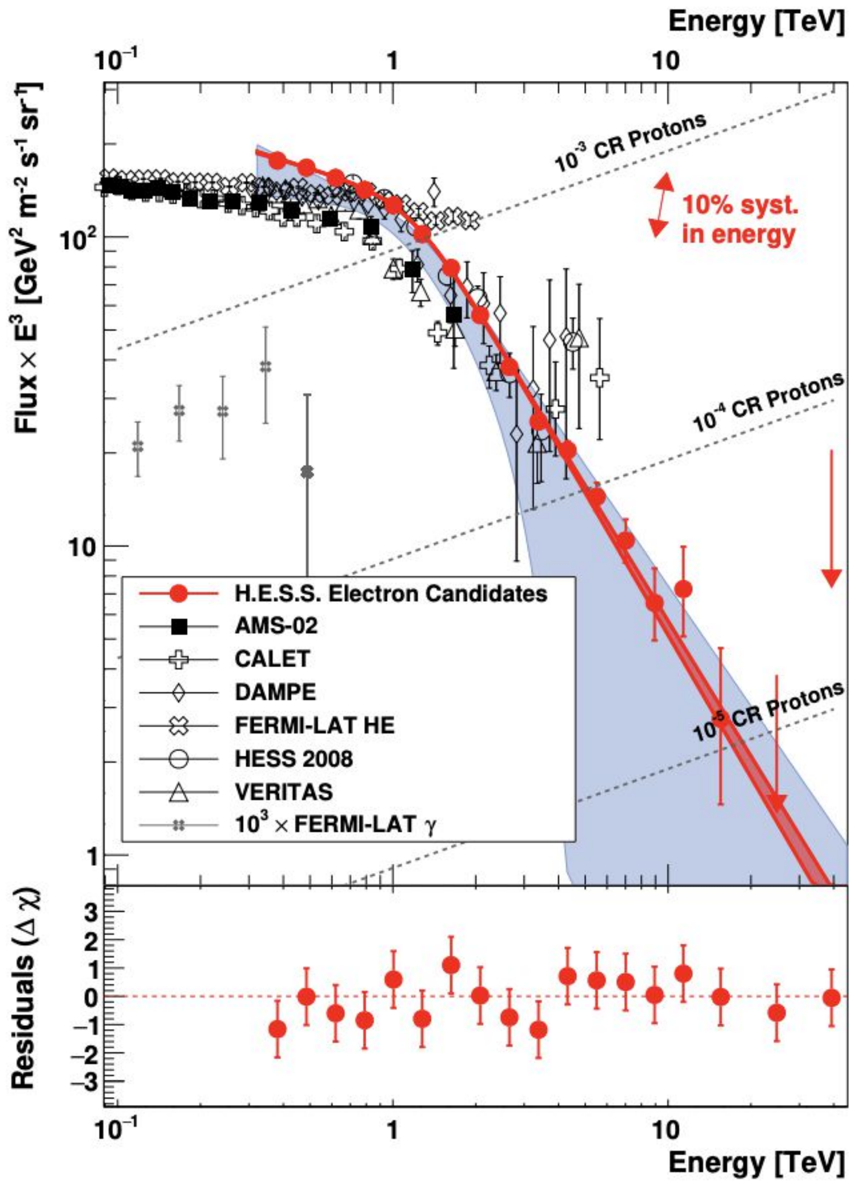
Halo = 4.5 Kpc

0.1 TeV
1 TeV
10 TeV





Electron Spectrum
HESS telescope



The estimate of the size of the diffusion coefficient and of its rigidity dependence are obviously crucially important because they determine:

[1] The Power of the CR sources that is required to generate the pbserved CR population

[2] Determines the shape of the source spectra generated by the CR accelerators

The "standard Propagation Model" based on the interpretation of the spectra of Secondary Nuclei (Li/Be/B) is very broadly but not universally accepted.

It will fail at very high energy (when diffusion will cease to be a valid approximation, and the structure of the regular magnetic field will likely control the propagation. A problem that needs to be addressed.

Three “Problems” suggest the possibility that the confinement time of CR is (approximately) one order of magnitude shorter (and accordingly the CR power is larger),

And that the rigidity dependence of the confinement time is weaker.

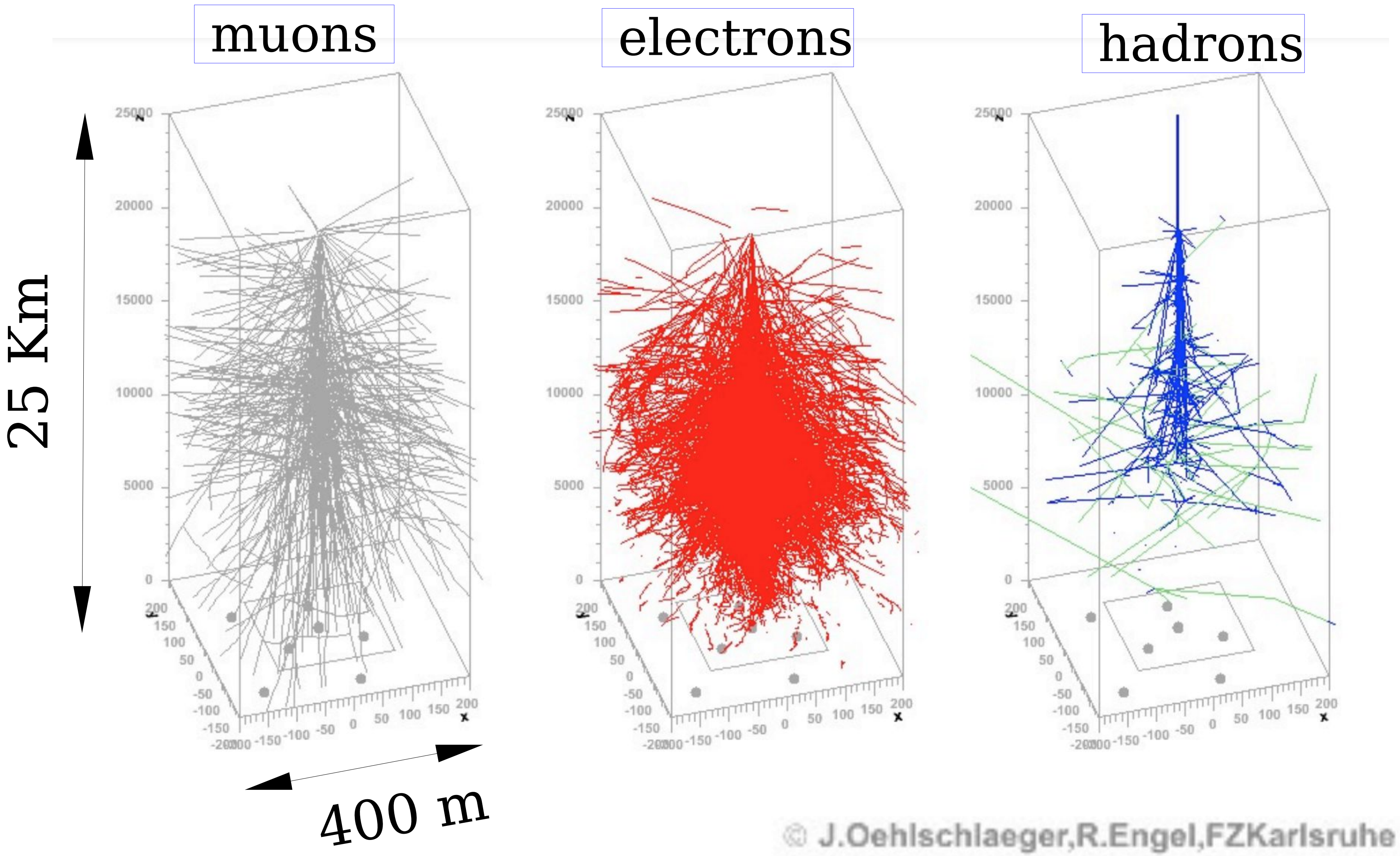
[a] The positron and antiproton spectra

[b] The Beryllium isotopic ratio

[c] The smoothness of the (e+ e-) spectra

For discussion and references:
PoS ICRC2021 (2021) 169
https://pos.sissa.it/395/169

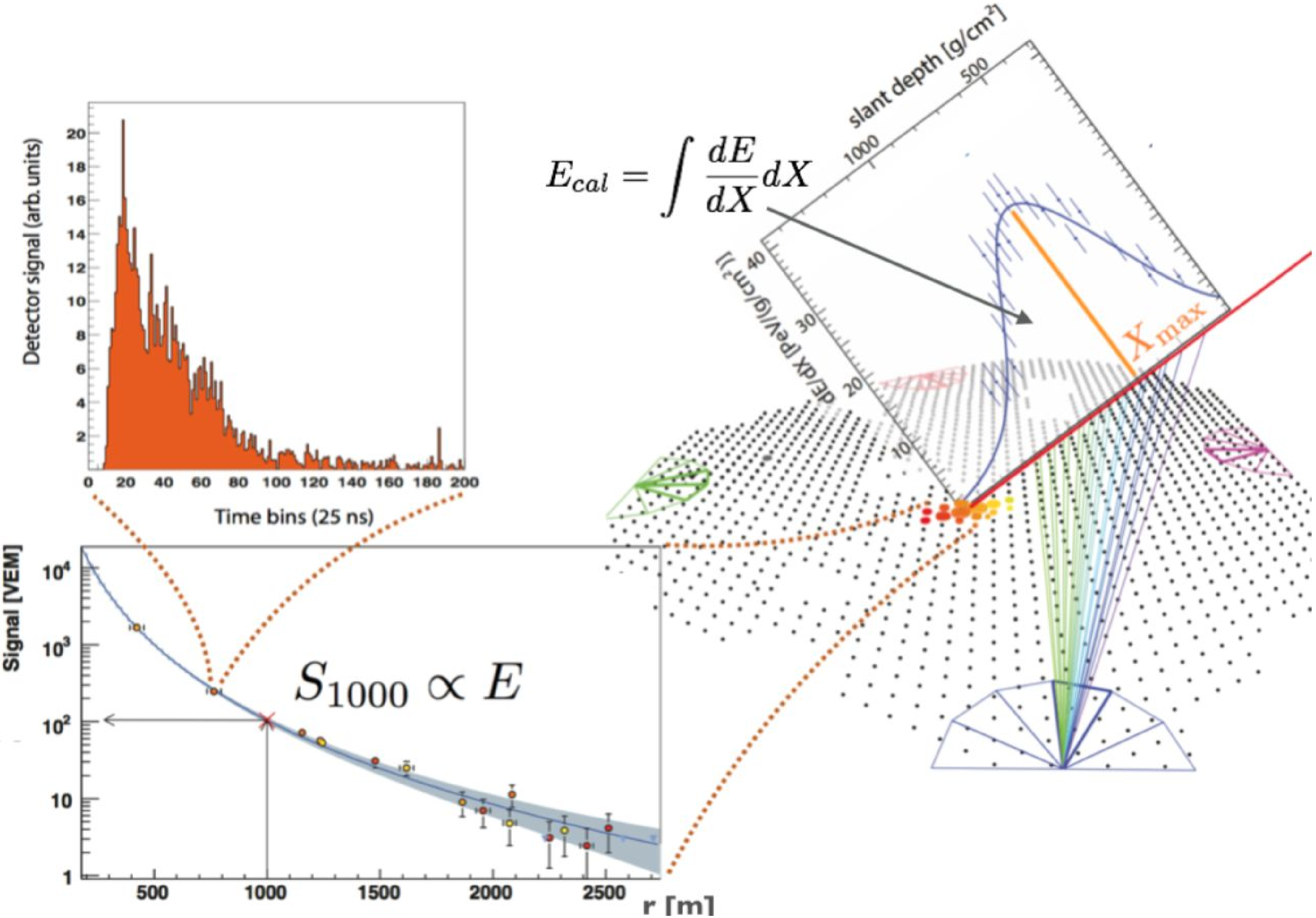
Air Shower Measurements of the Cosmic Ray Spectra

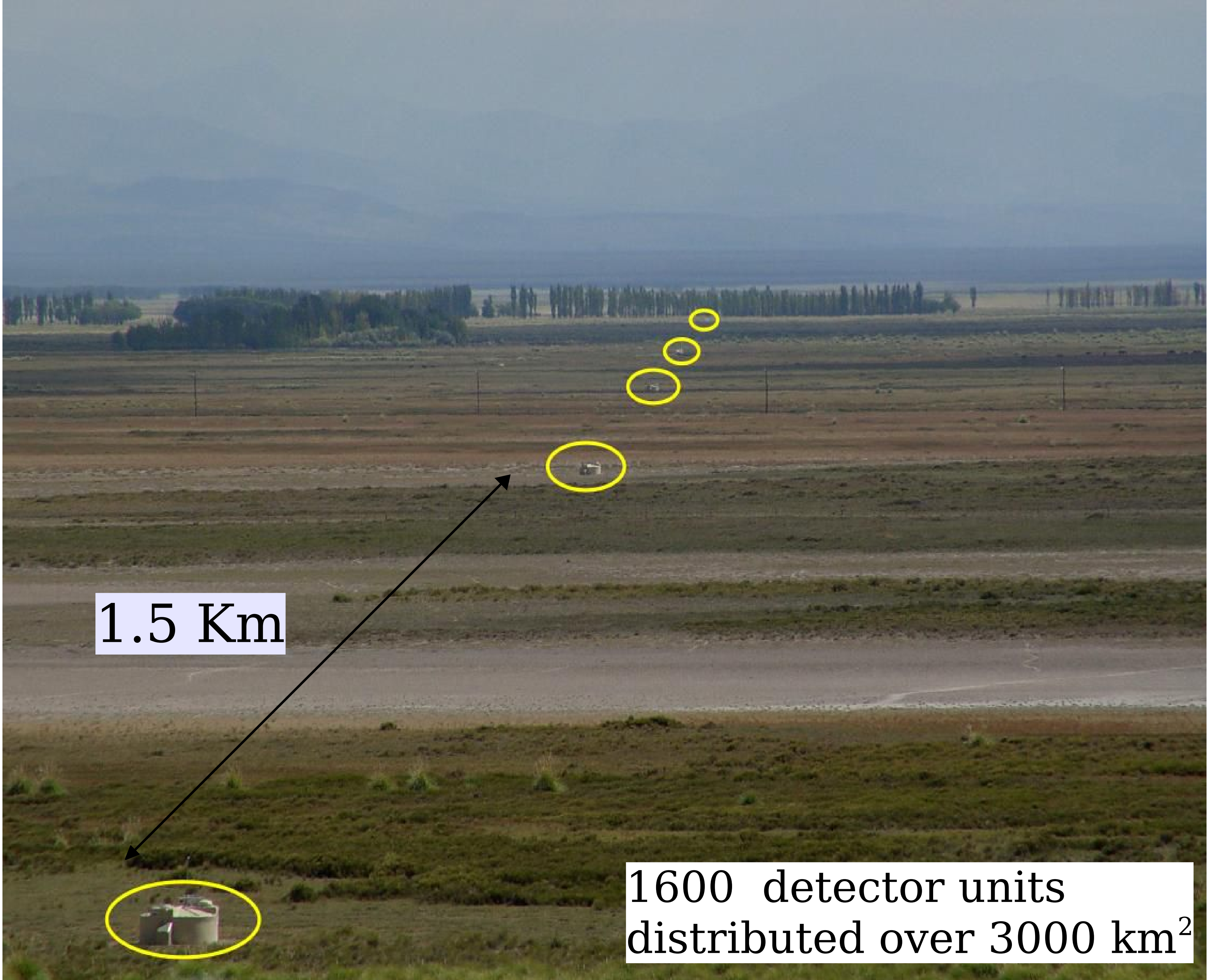


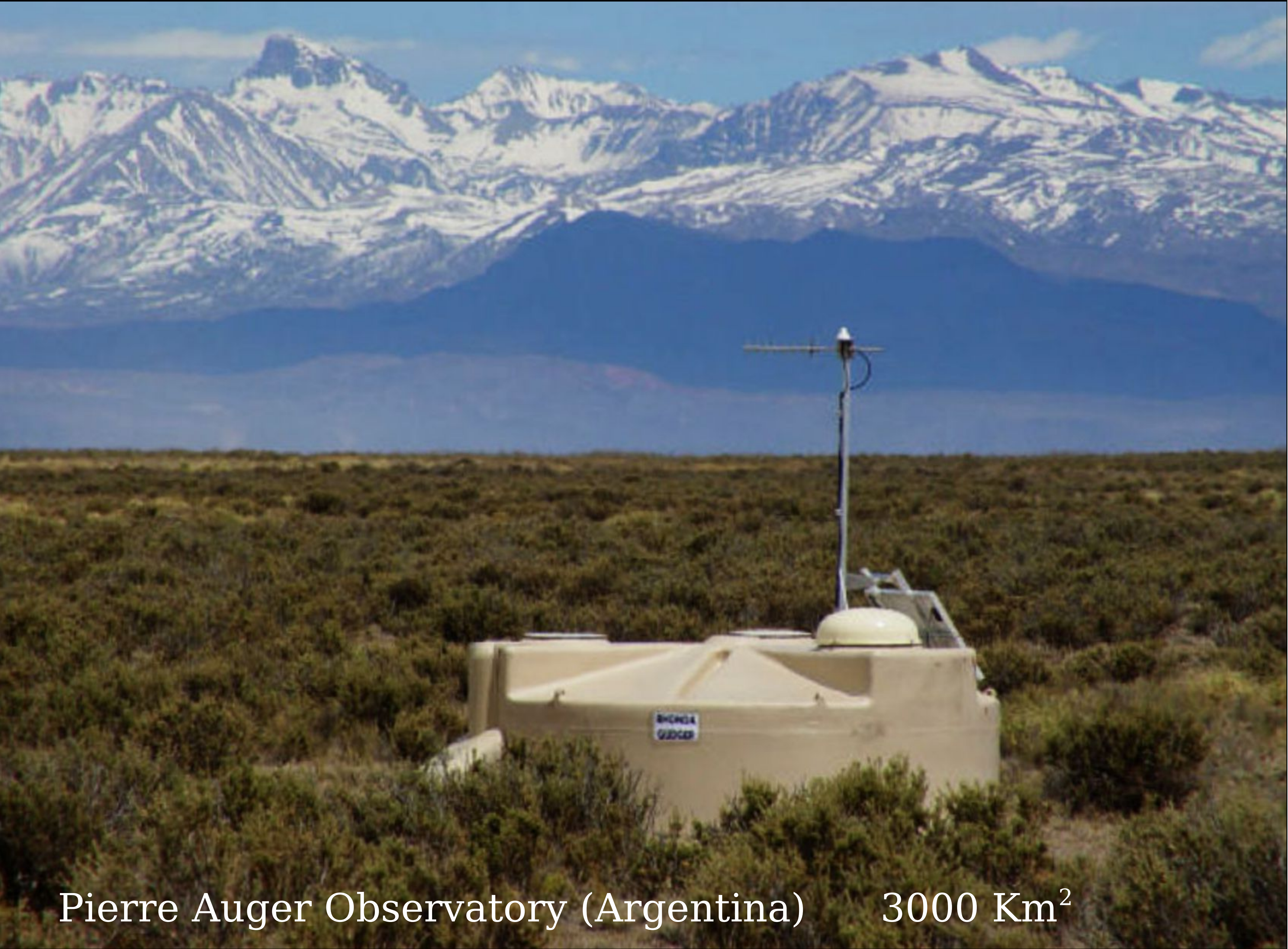
Computer Simulation of a proton shower (10^{13} eV)
[3 images of the same shower for 3 particle types]


GRAPES
Ooty - INDIA - 2200 metri

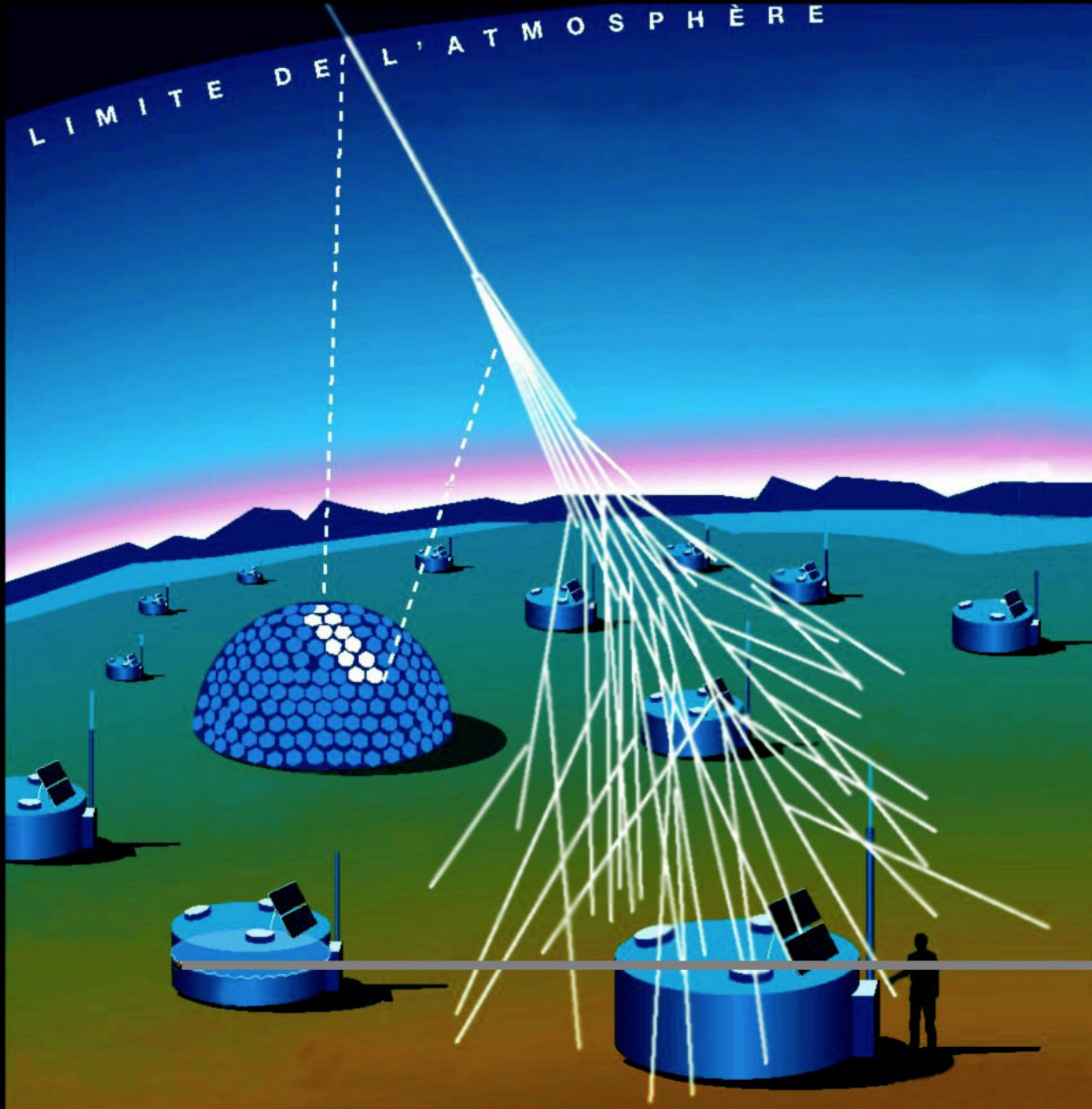
Auger Muon Energy measurement



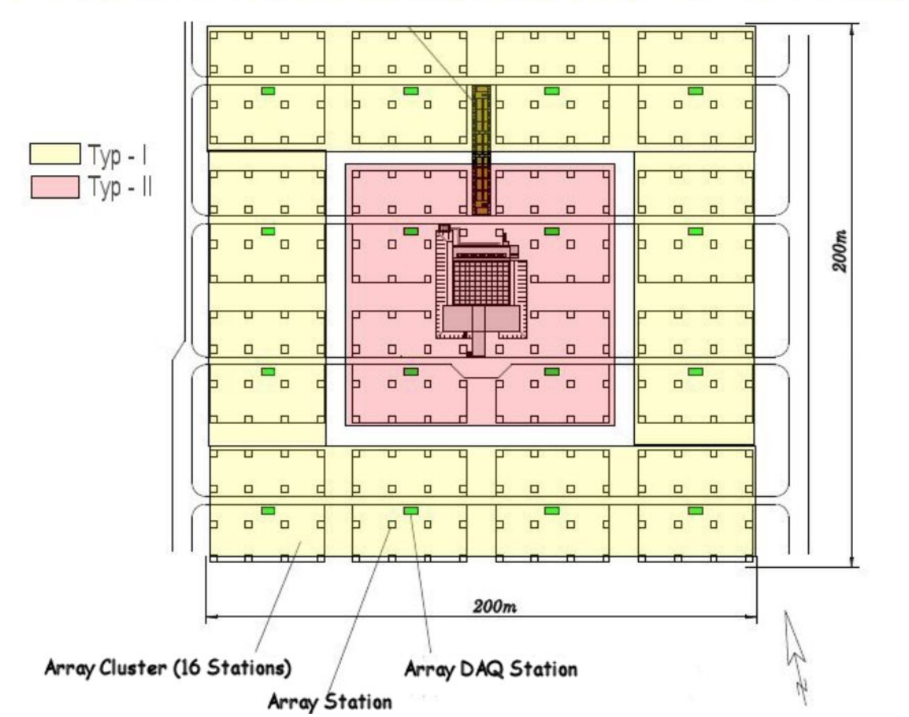

1.5 Km
1600 detector units
distributed over 3000 km2



Pierre Auger Observatory (Argentina) 3000 Km^2

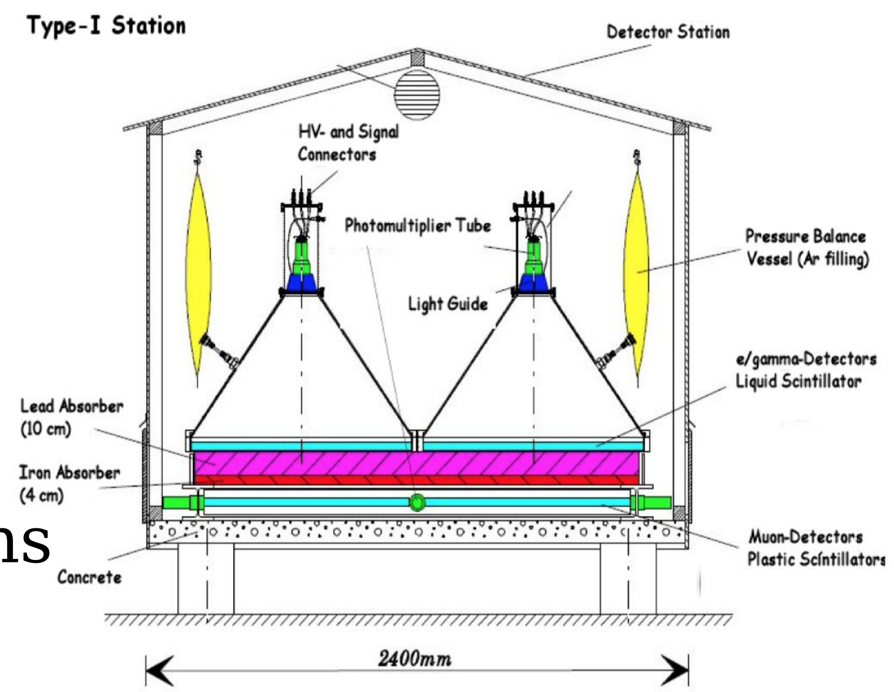

LIMITE DE L'ATMOSPHÈRE

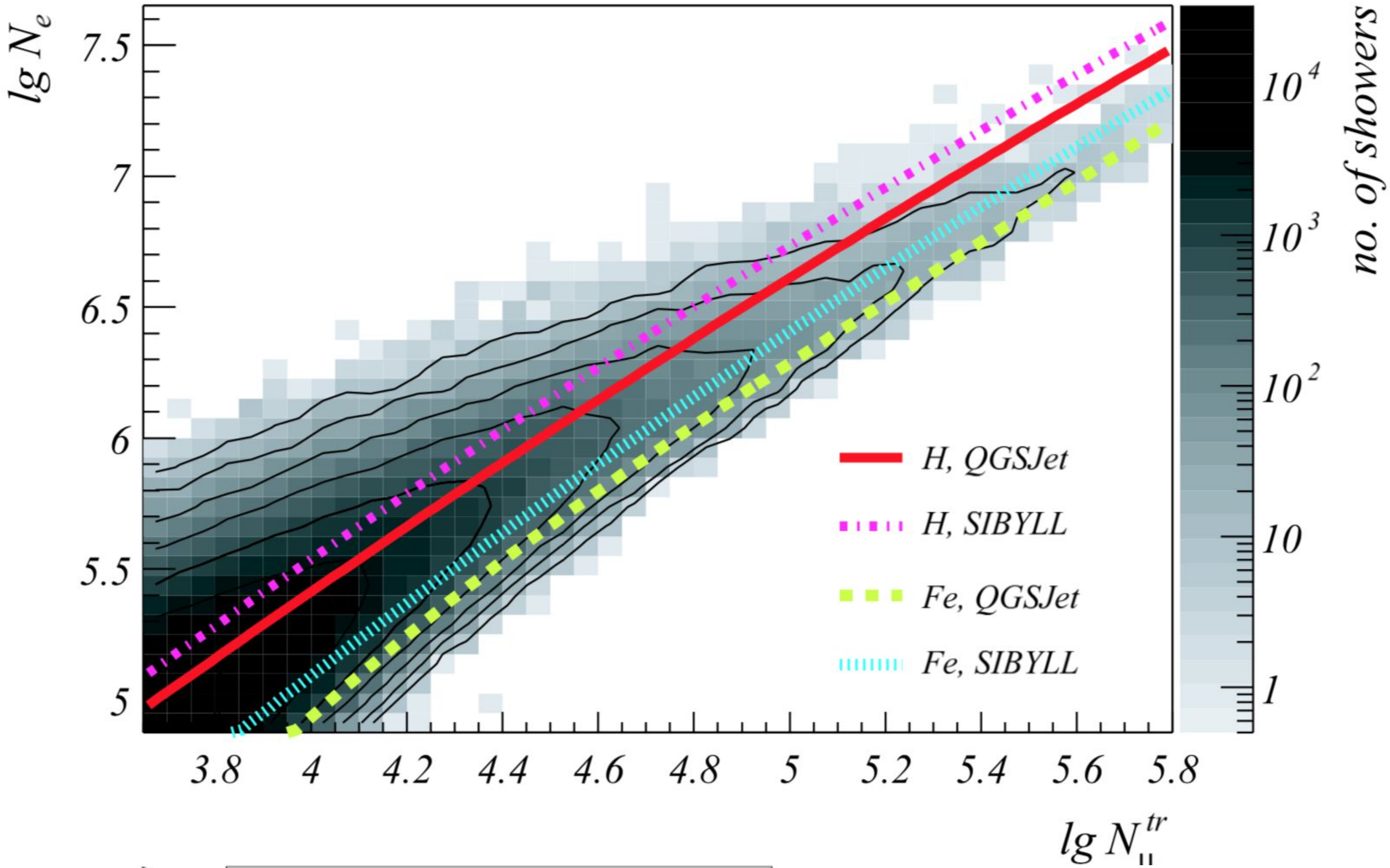
Kascade [Sea level, 200 x 200 m2]



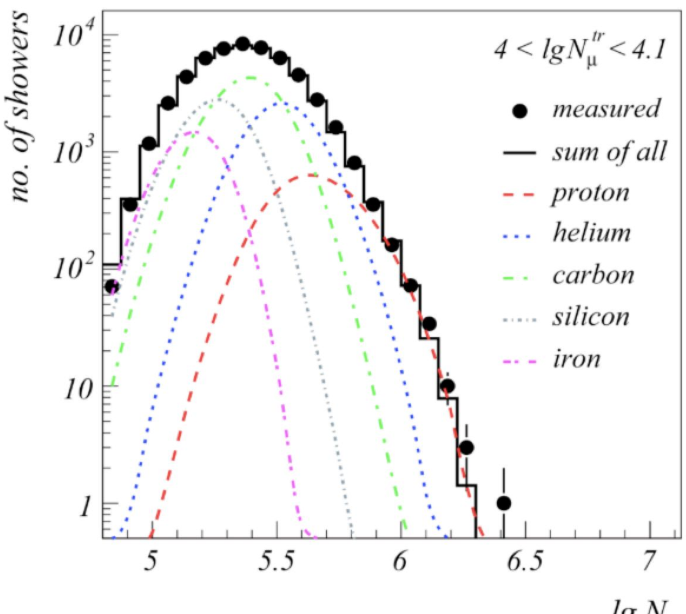
e.m.

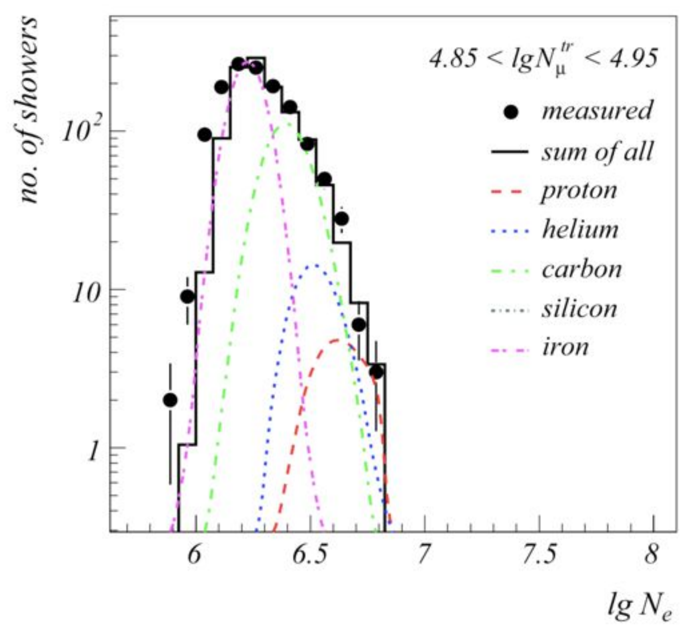
muons





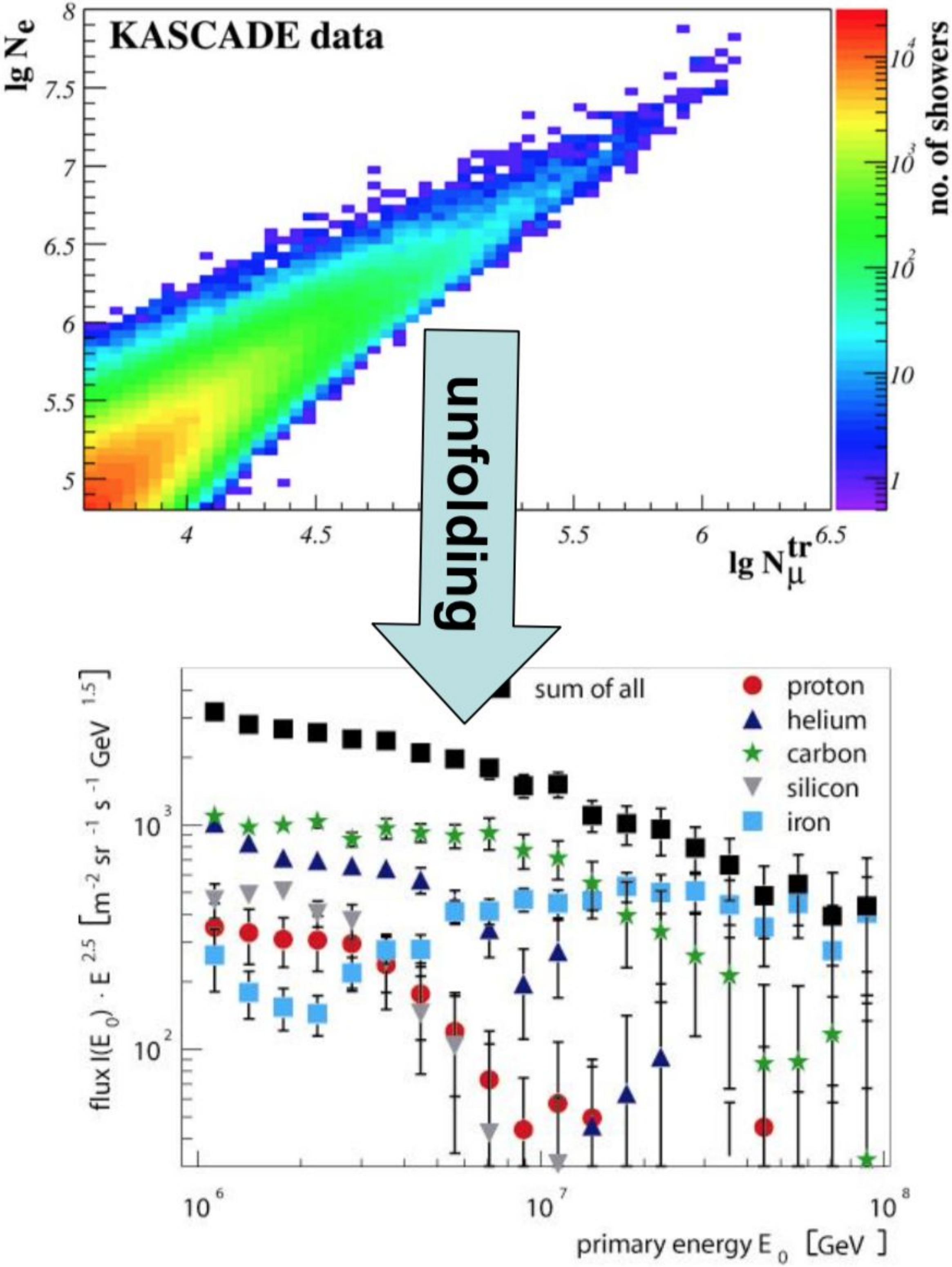
“Unfolding method”





Hadronic Interaction Model

Sibyll-2.1 model



2 Components

e.m. size
Muons

$$\{\log N_e, \log N_\mu\}$$

Shower Modeling

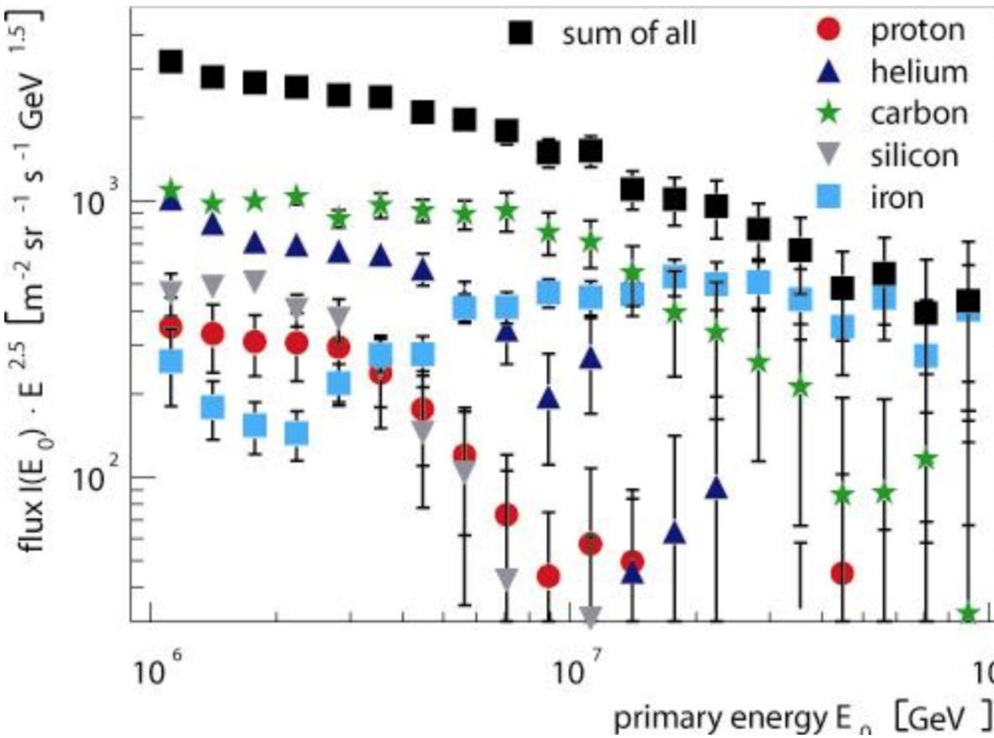
$$\{E\ ,\ A\}$$

Energy and Mass

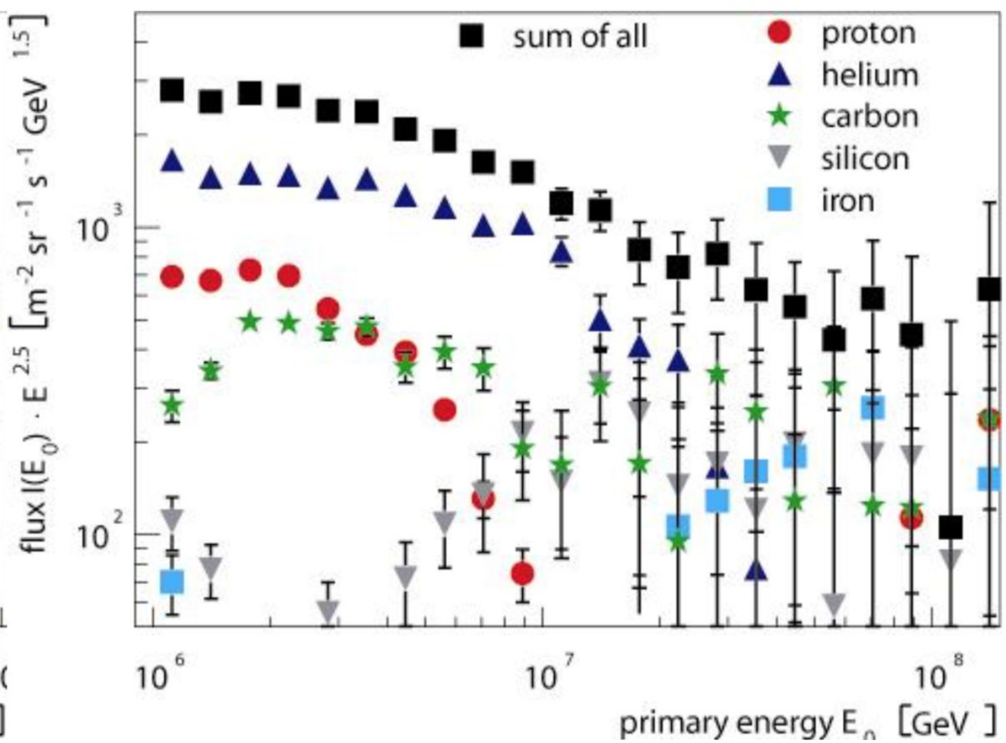
"*KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems*"

[Astroparticle Physics 24, 1 (2005)]

SIBYLL



QGSJet

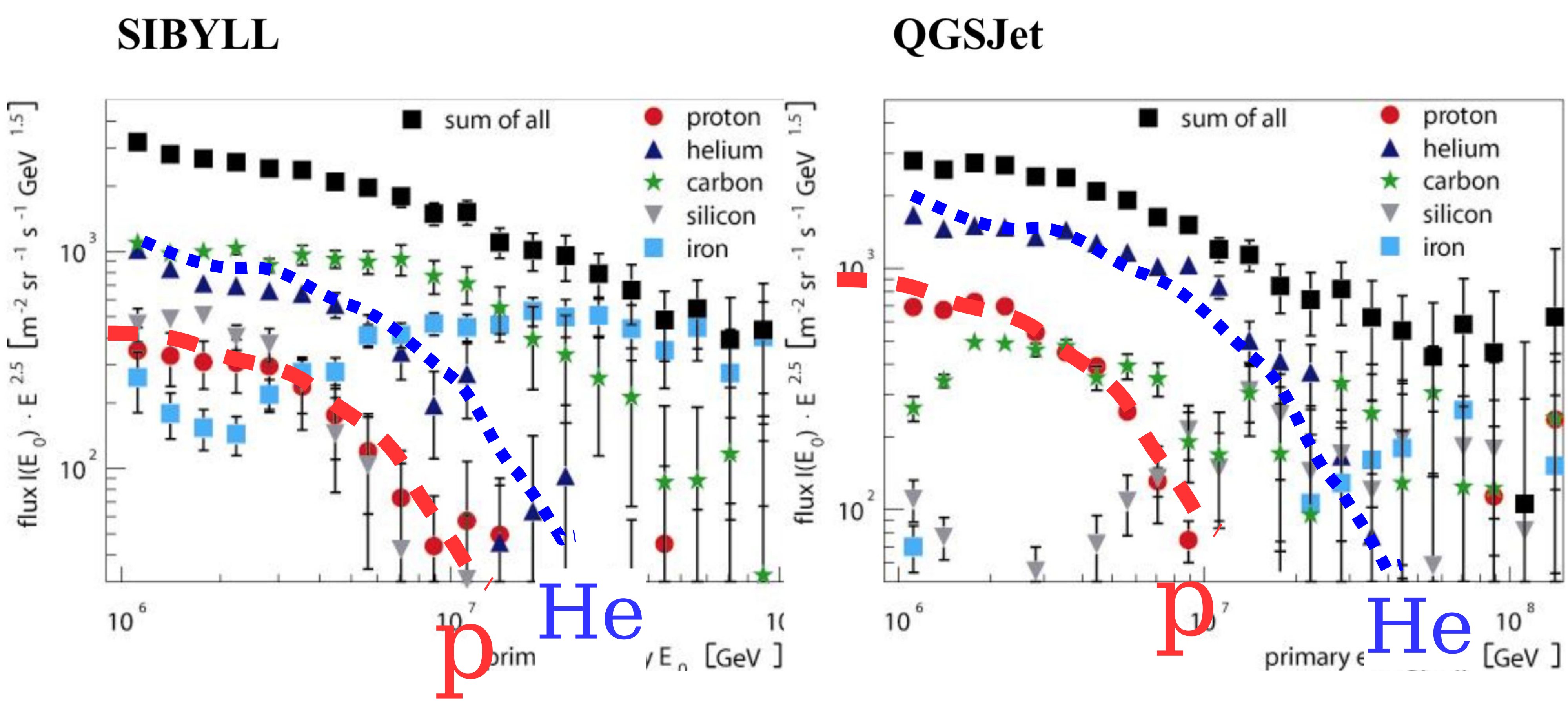


Data consistent (roughly) with the concept of sequence (cycle) of structures proportional to Z

Systematic uncertainties remain significant

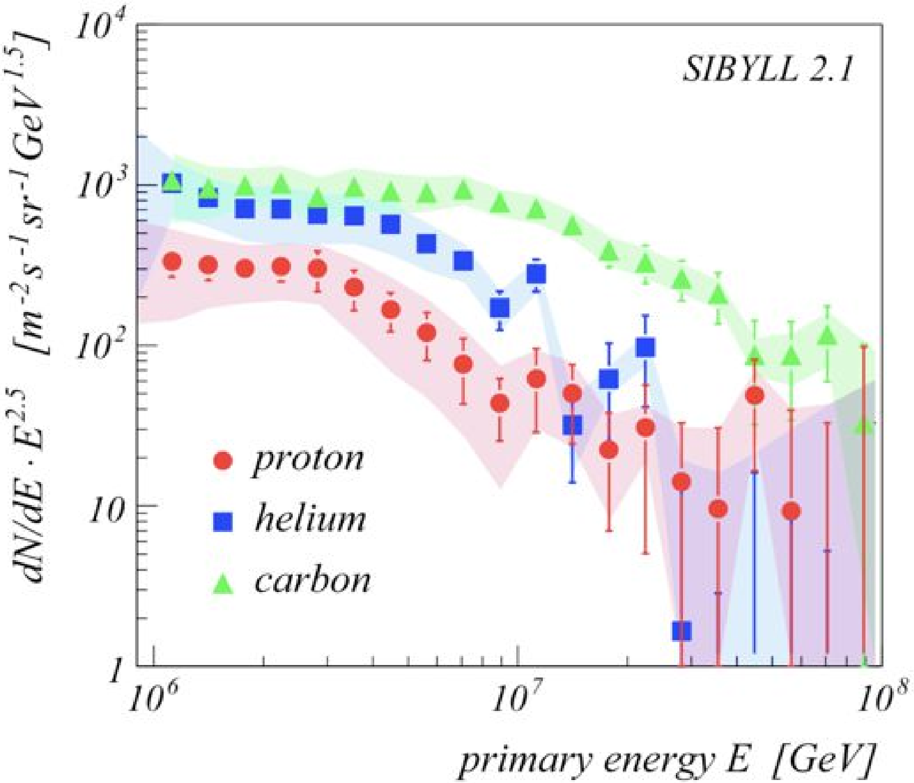
"*KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems*"

[Astroparticle Physics 24, 1 (2005)]

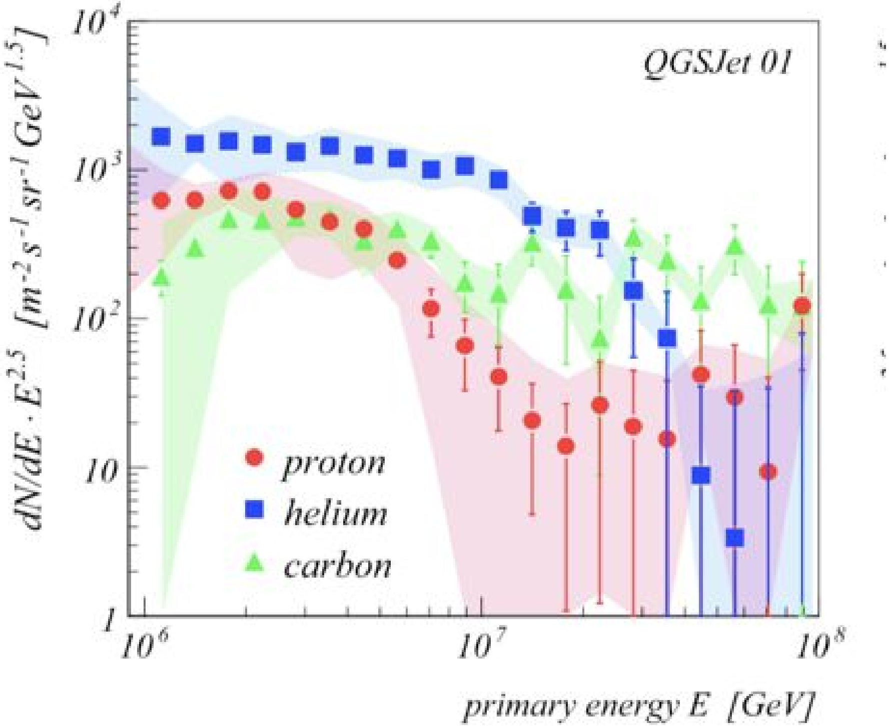


Data consistent (roughly) with the concept of sequence (cycle) of structures proportional to Z

Systematic uncertainties remain significant



Sibyll-2.1



QGSJet-01

Very large systematic errors in obtaining the spectra

Abstract of Kascade paper:

A composition analysis of KASCADE air shower data is performed by means of unfolding the two-dimensional frequency spectrum of electron and muon numbers. Aim of the analysis is the determination of energy spectra for elemental groups representing the chemical composition of primary cosmic rays.

Since such an analysis depends crucially on simulations of air showers the two different hadronic interaction models QGSJet and SIBYLL are used for their generation.

The resulting primary energy spectra show that the knee in the all particle spectrum is due to a steepening of the spectra of light elements

but, also, that neither of the two simulation sets is able to describe the measured data consistently over the whole energy range with discrepancies appearing in different energy region

LHAASO telescope

[4400 m.a.s.l.]

Large area [1 km2]

Excellent muon measurement.

Three Arrays

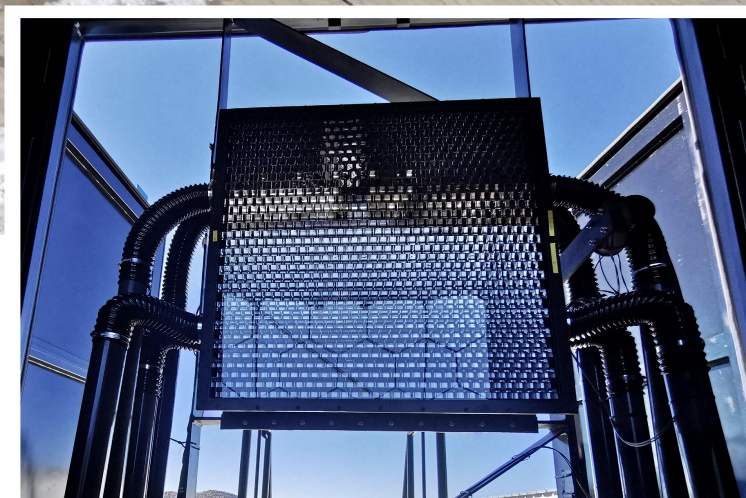
WCDA
Km2A

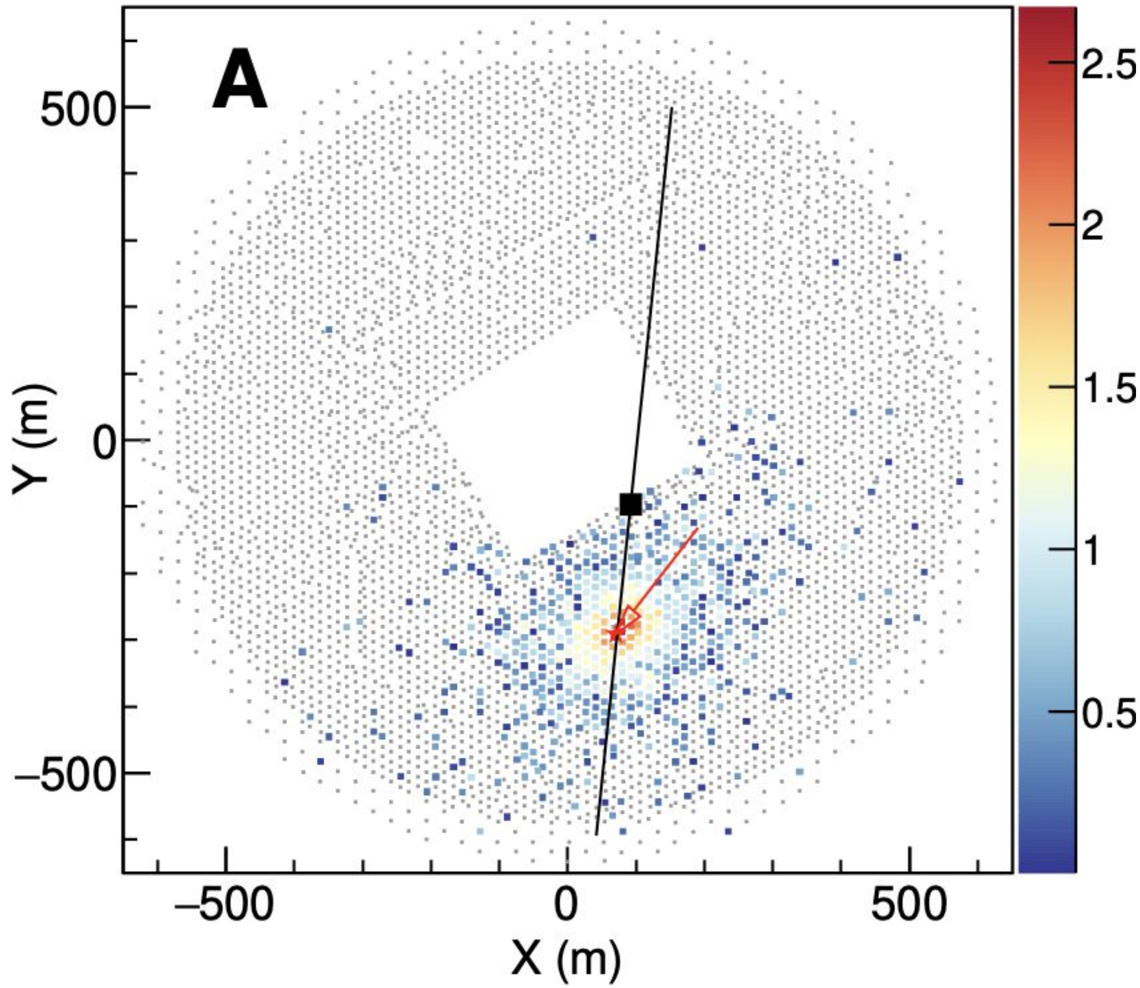
WFCTA

WFCTA Telescopes

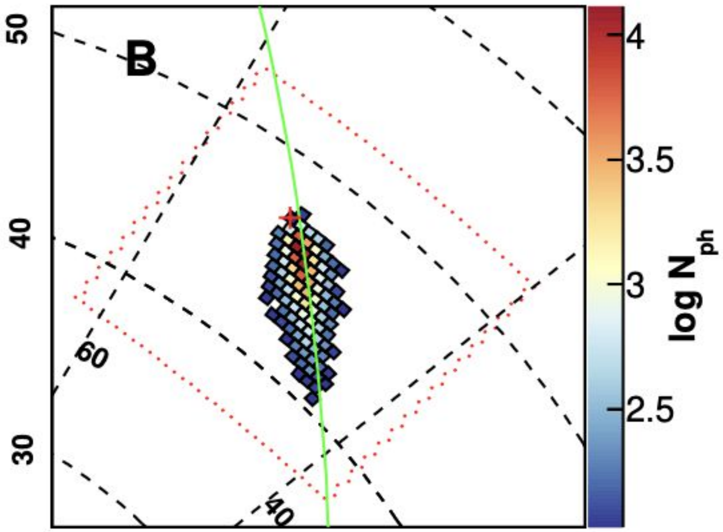
18 Telescopes $16^\circ \times 16^\circ$

$32 \times 32 = 1024$ SiPM $0.5^\circ \times 0.5^\circ$





Surface Detector

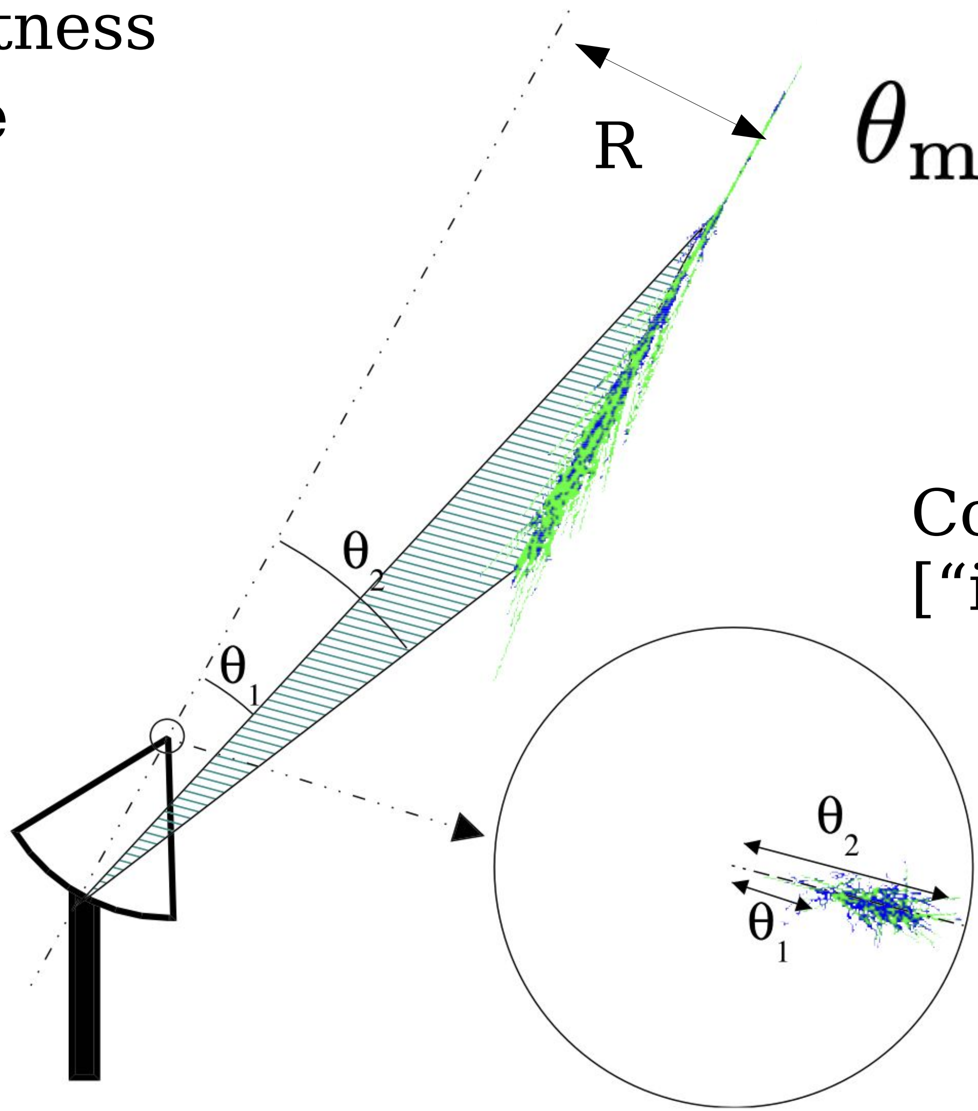


Cherenkov image

Cherenkov image
of a shower

Brightness

Shape



N_γ^{Ch} Total number of Cherenkov photons in image

θ_{max} Angle of maximum of image with respect to the primary particle direction

Correct for geometry
[“impact parameter R]

$$\theta_{\mathrm{max}} \longrightarrow X_{\mathrm{max}}$$

Problem of Air Shower measurements:

Estimate $\{E\ ,\ A\}$

from Shower Observables

Information of the shower:
Combine Surface detector with Cherenkov image

Surface detector

N_e Electromagnetic component

N_μ Muon Component

Cherenkov Image

N_γ^{Ch} Brightness

X_{max} Shape

Acceptance of the WFCTA telescopes:

$$A \simeq 18 \times \Delta\Omega \times [\pi\, R^2_{p,\max}] \simeq 75,000 \text{ m}^2\text{sr}$$

$\Delta\Omega \approx 8^\circ \times 8^\circ \simeq 0.019$ sr

Acceptance constant
above 0.2 PeV

$R_{p,\max} \simeq 250$ m

Observation time reduced because
of requirements of sky darkness + clarity [0.20]

Km2A only observations have lower "quality"
but also much higher acceptance. Nicely complementary

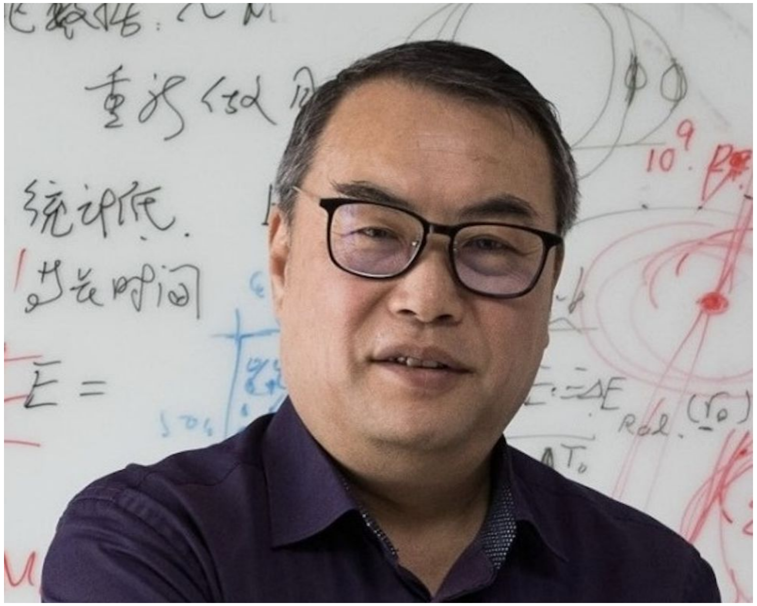
Two recent papers of the LHAASO collaboration
on the proton and Helium spectra $E = 0.158 - 12$ PeV
have obtained resulys of much improved quality

Z. Cao *et al.* [LHAASO],
"Precise measurements of the cosmic ray proton energy spectrum in the "knee" region"
Sci. Bull. **70**, 4173-4180 (2025)
doi:10.1016/j.scib.2025.10.048
[arXiv:2505.14447 [astro-ph.HE]].

Z. Cao *et al.* [LHAASO],
"Precise Measurement of the Cosmic Ray Helium Spectrum above 0.1 PeV"
Phys. Rev. Lett. **136**, no.12, 121001 (2026)
doi:10.1103/d838-49gt
[arXiv:2511.05013 [astro-ph.HE]].

A detailed discussion of the measurement method
(that is innovative and interesting)
will not be given here [also I'm not competent to do it]

but let me give credit to the corresponding authors.
(contact them for details)

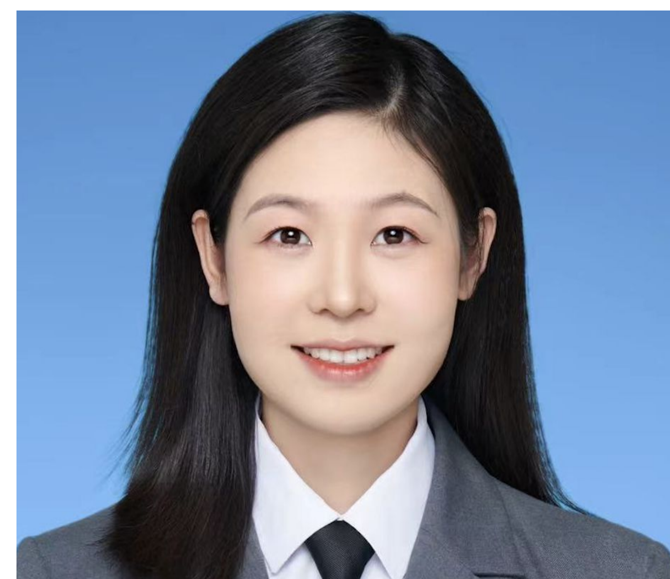


Cao Zhen [spokeperson]

Zhang ShouShan

You ZhiYong

Ma LingLing



Wang LiPing

Fixed A
Increase E

- N_μ $\uparrow$
- N_e $\uparrow$
- N_γ^{Ch} $\uparrow$
- X_{max} $\uparrow$

Fixed E
Increase A

- N_μ $\uparrow$
- N_e $\downarrow$
- N_γ^{Ch} $\downarrow$
- X_{max} $\downarrow$

surface detector (N_μ, N_e)

WFCTA telescopes (N_γ^{Ch}, X_{max})

The combination of a quasi-calorimetric energy measurement with surface information allows very good energy resolution, and better mass – estimate

LHAASO analysis method is two steps

Method is two steps:

[1.] Obtain a measurement of the energy that is in good approximation independent from the mass number A, and has very good resolution

$$N_\gamma^{\mathrm{Ch}} \ , \ N_\mu \ , \ N_e$$

[2.] Construct a Mass-sensitive parameter that combines the measurements

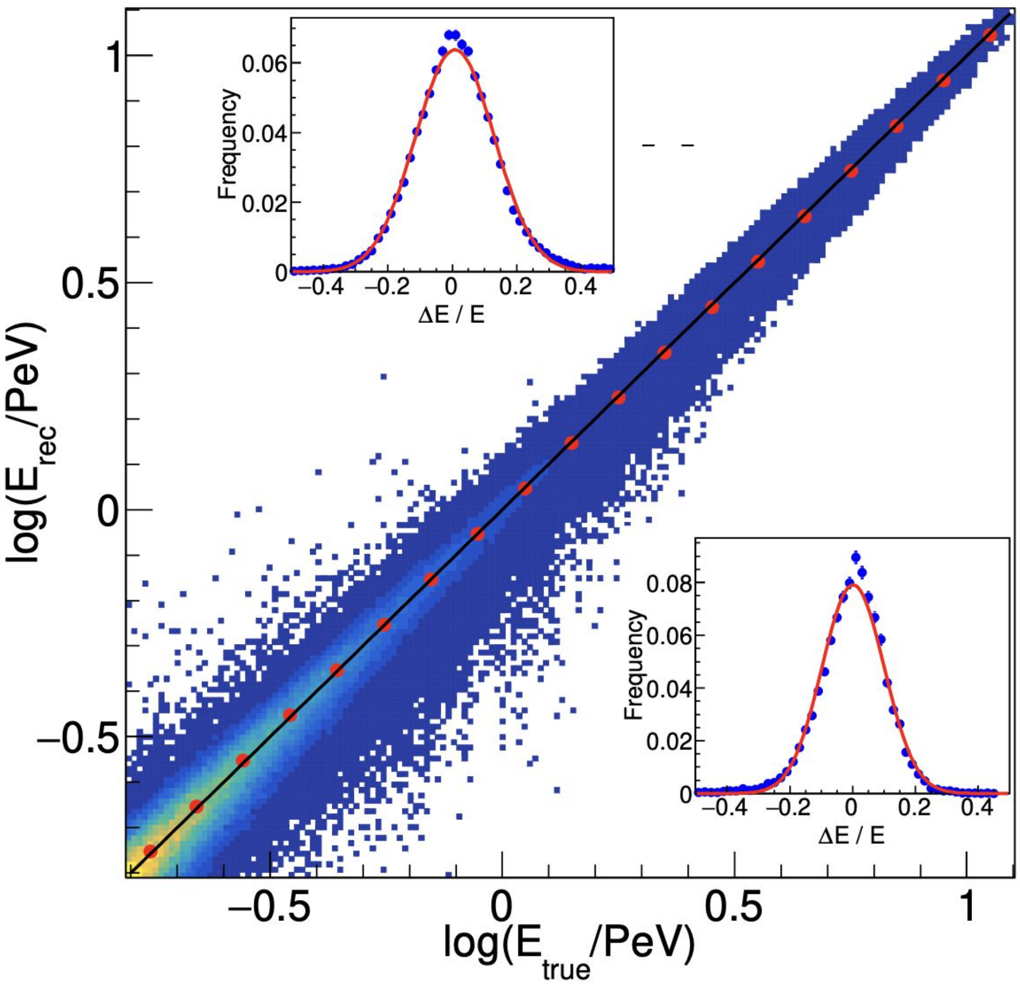
$$\theta_{\mathrm{max}} \ , \ N_\mu \ , \ N_e$$

This allows to select "high purity" samples

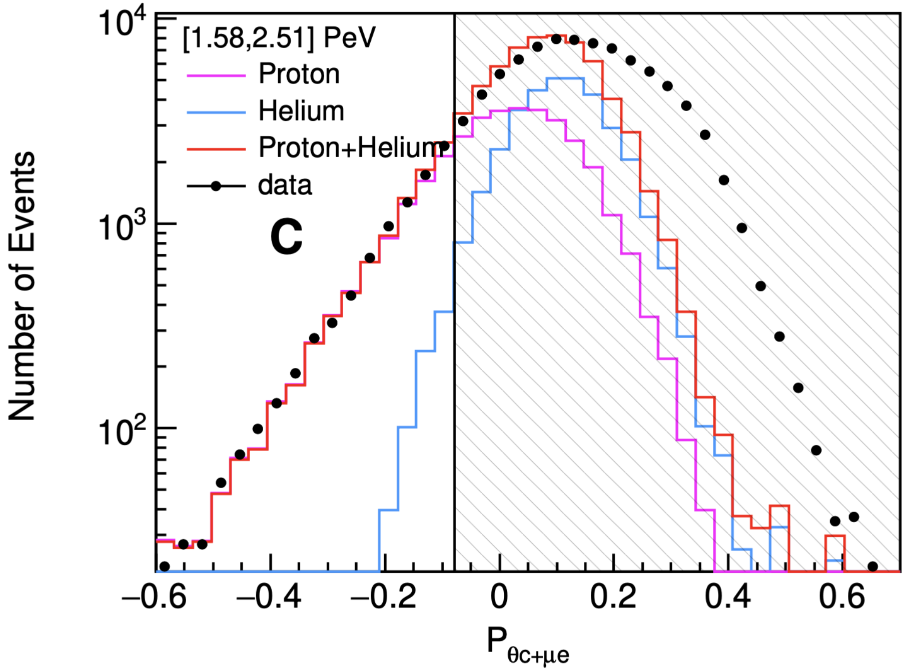
of p [muon poor, penetrating showers]

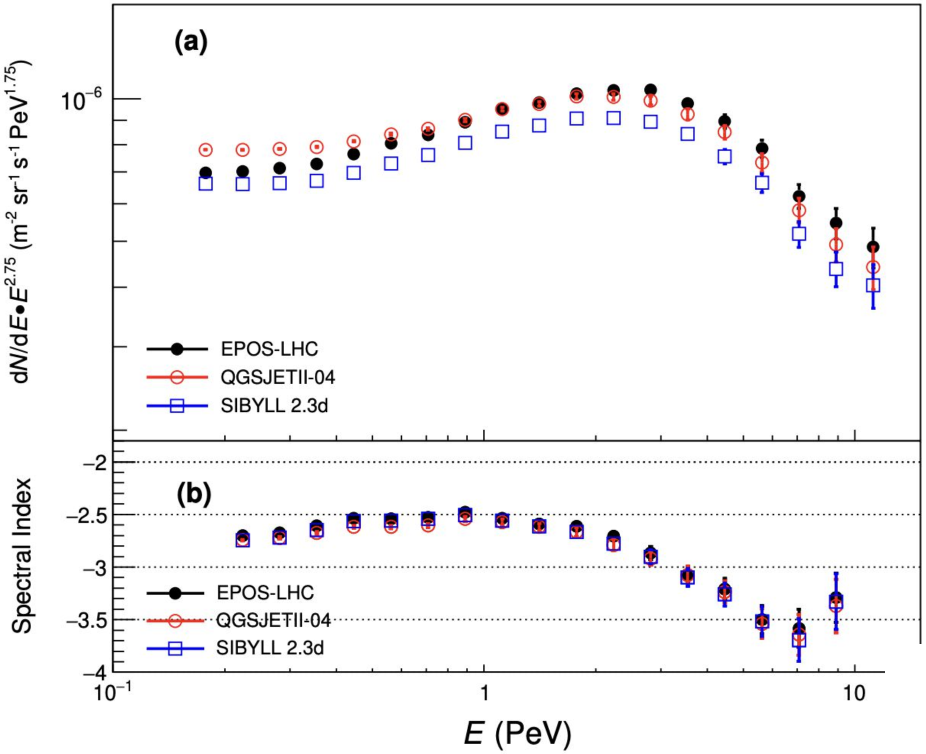
He [more muons, less penetrating]

Energy resolution

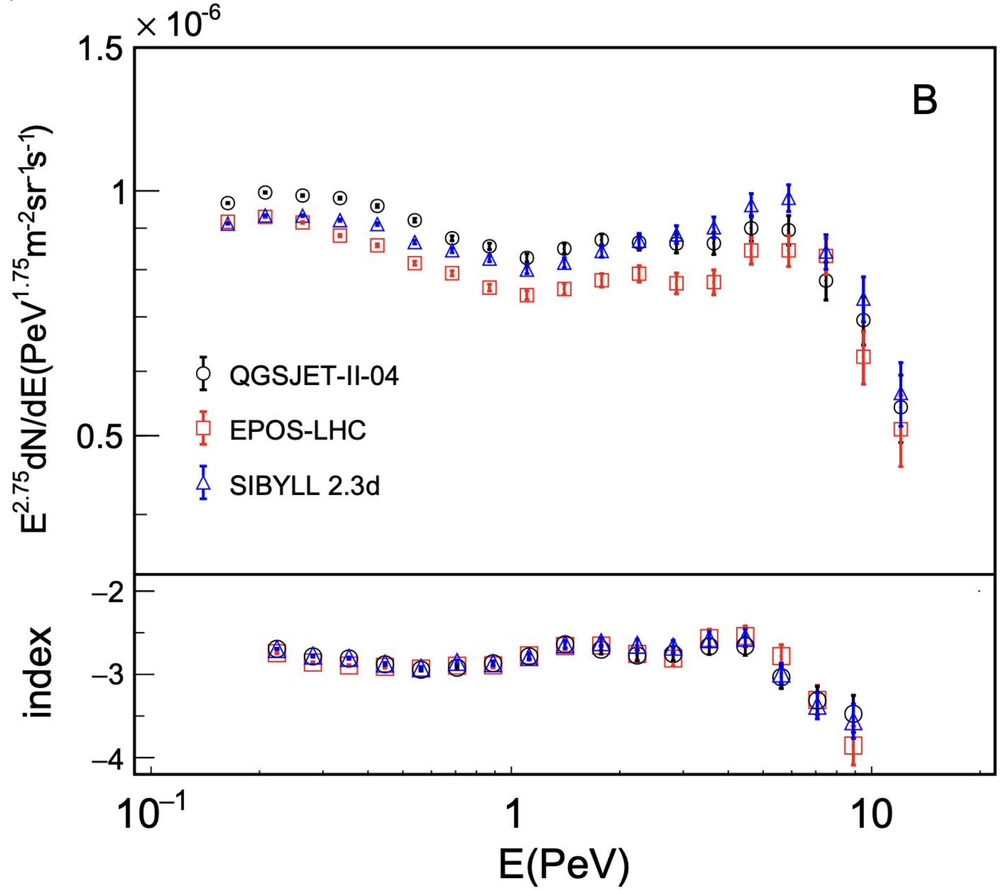


Mass selection





Proton Spectrum

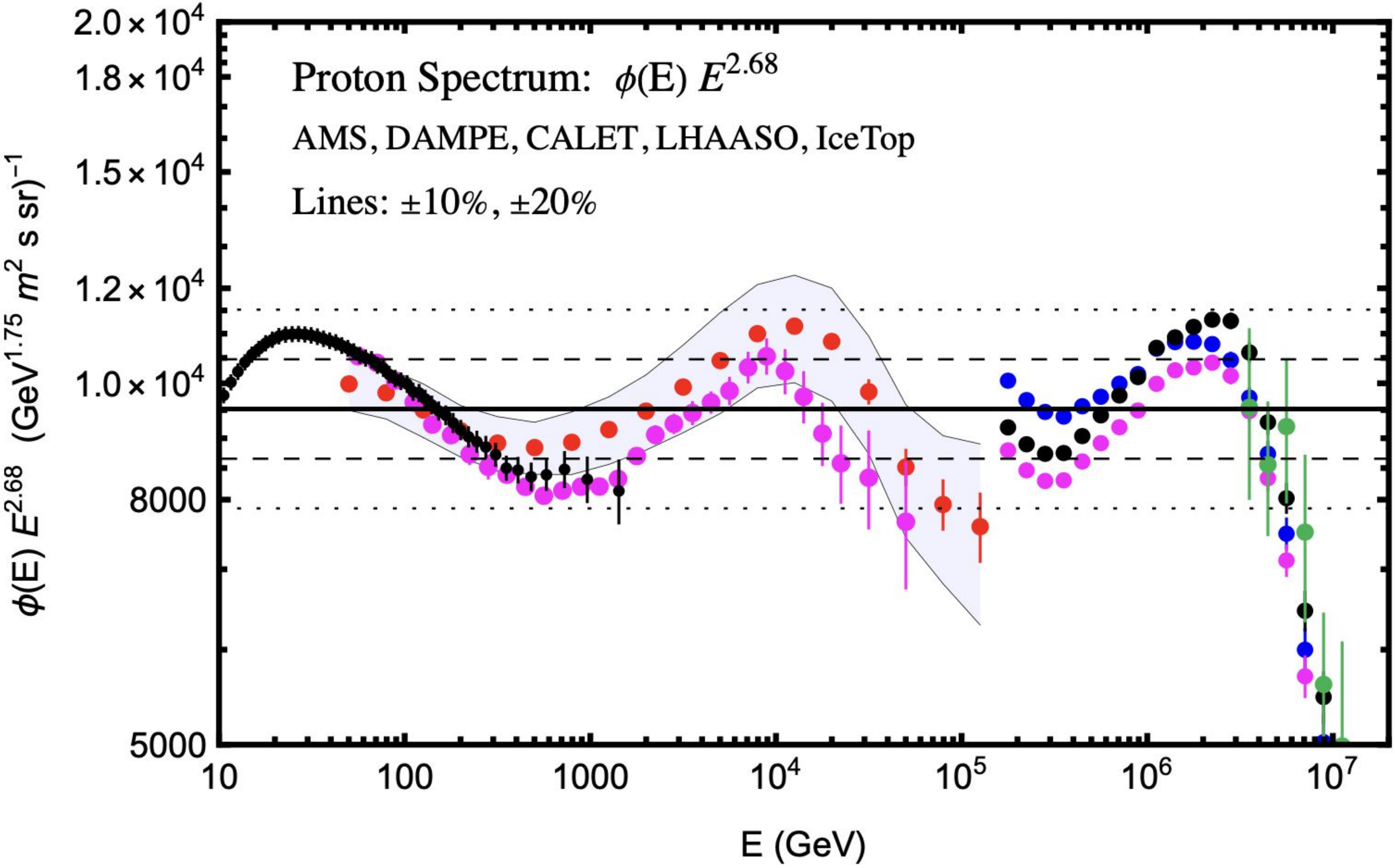


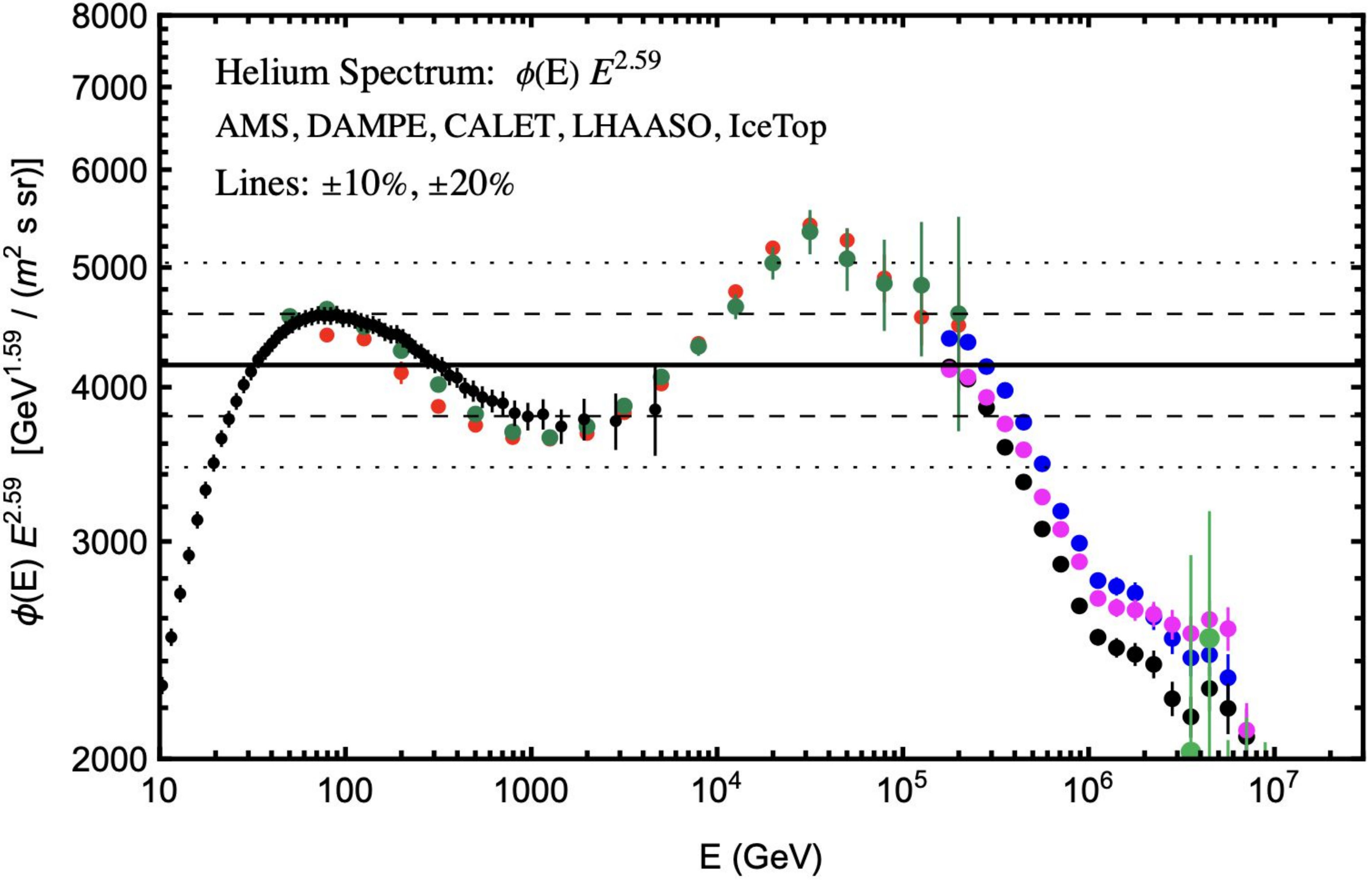
Helium Spectrum

Proton Spectrum

AMS: combined errors

Other experiments: only statistical errors

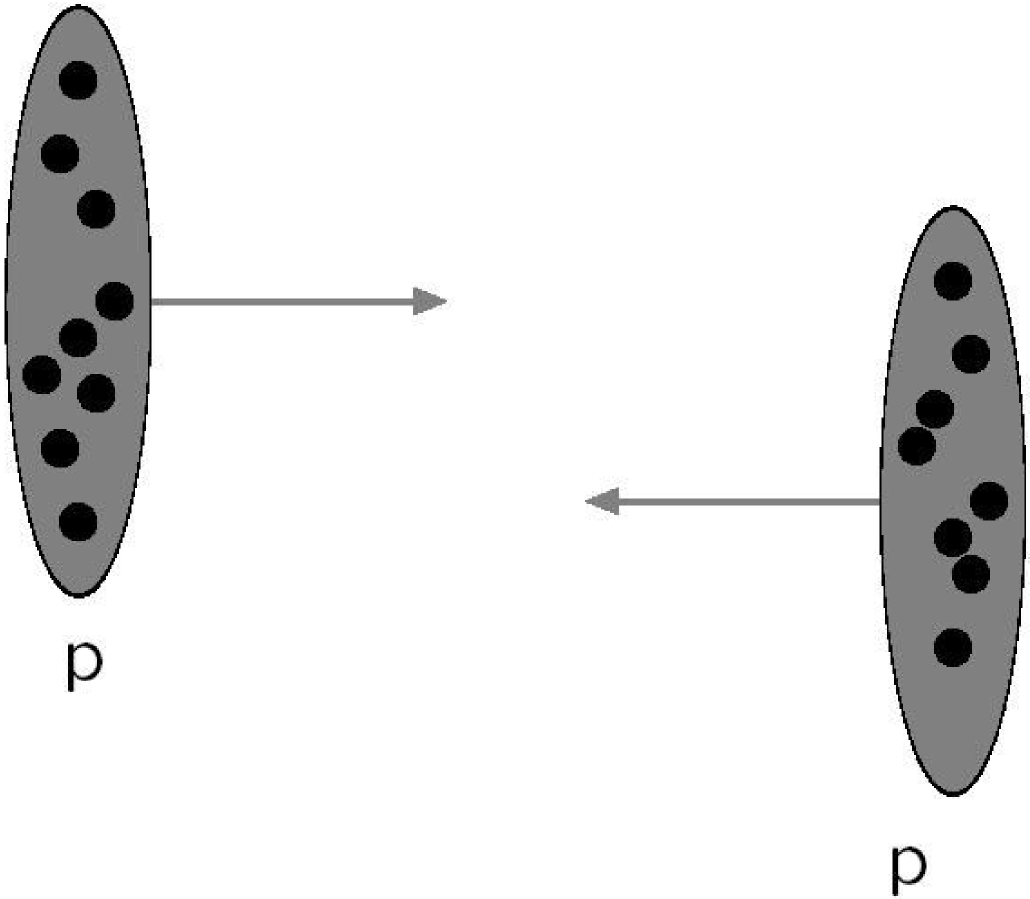




Helium Spectrum: ϕ(E) $E^{2.59}$
AMS, DAMPE, CALET, LHAASO, IceTop
Lines: ±10%, ±20%
ϕ(E) $E^{2.59}$ [GeV$^{1.59}$ / (m^2 s sr)]
E (GeV)
8000
7000
6000
5000
4000
3000
2000
10
100
1000
10^4
10^5
10^6
10^7

Hadronic Interactions

Dominant source of
systematic uncertainty



protons are
composite
objects that
contain many
“partons"

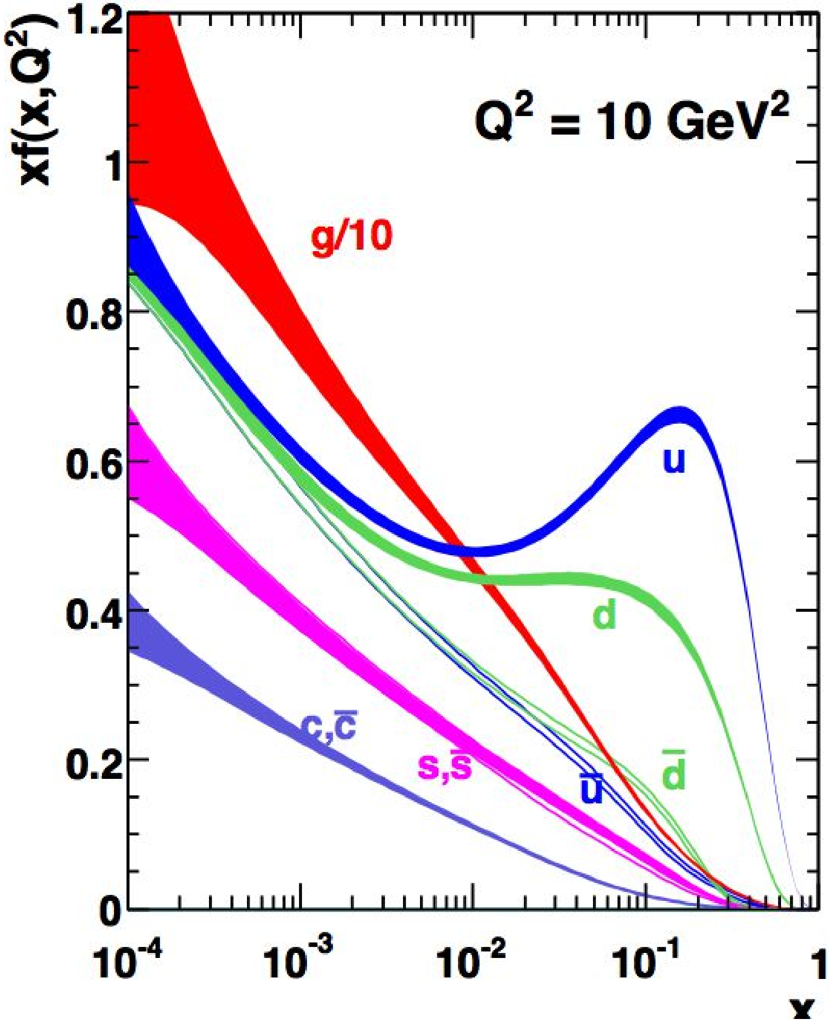
QCD

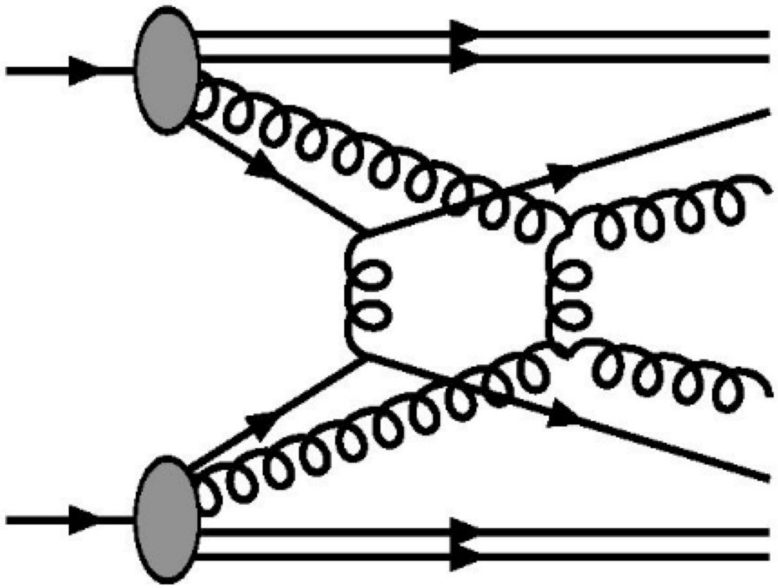
ASYMPTOTIC FREEDOM
QUARK and GLUON CONFINEMENT

“The Dark side of the Standard Model"

PDF's
Parton Distribution Functions

Multiple Interactions





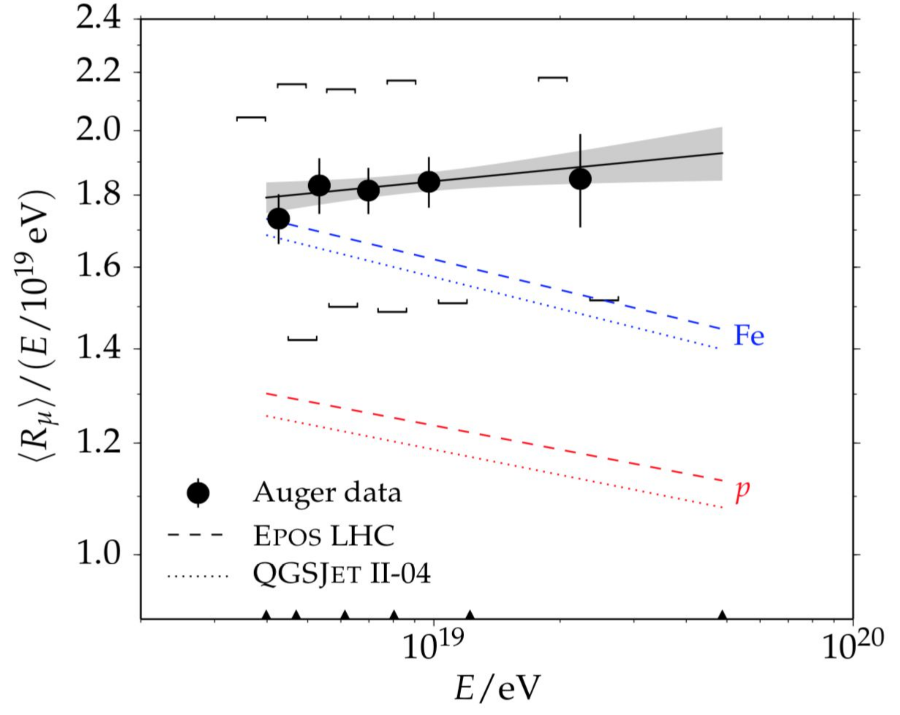
We know the "fundamental Lagrangian" that describes
the strong interaction [SU(3) – QCD] in terms
of elementary fields (quarks and gluons),
Because of *"Asymptotic Freedom"* we can calculate
in perturbation theory hard scattering processes

… But we cannot calculate from first principles
"soft processes" like multi-particles production
in hadron-hadron collisions.

*A precise description of hadronic interactions
is however necessary to model CR shower development
and existing Montecarlo models use theoretical
ideas and various methods to extrapolate from
data obtained in accelerator experiments.*

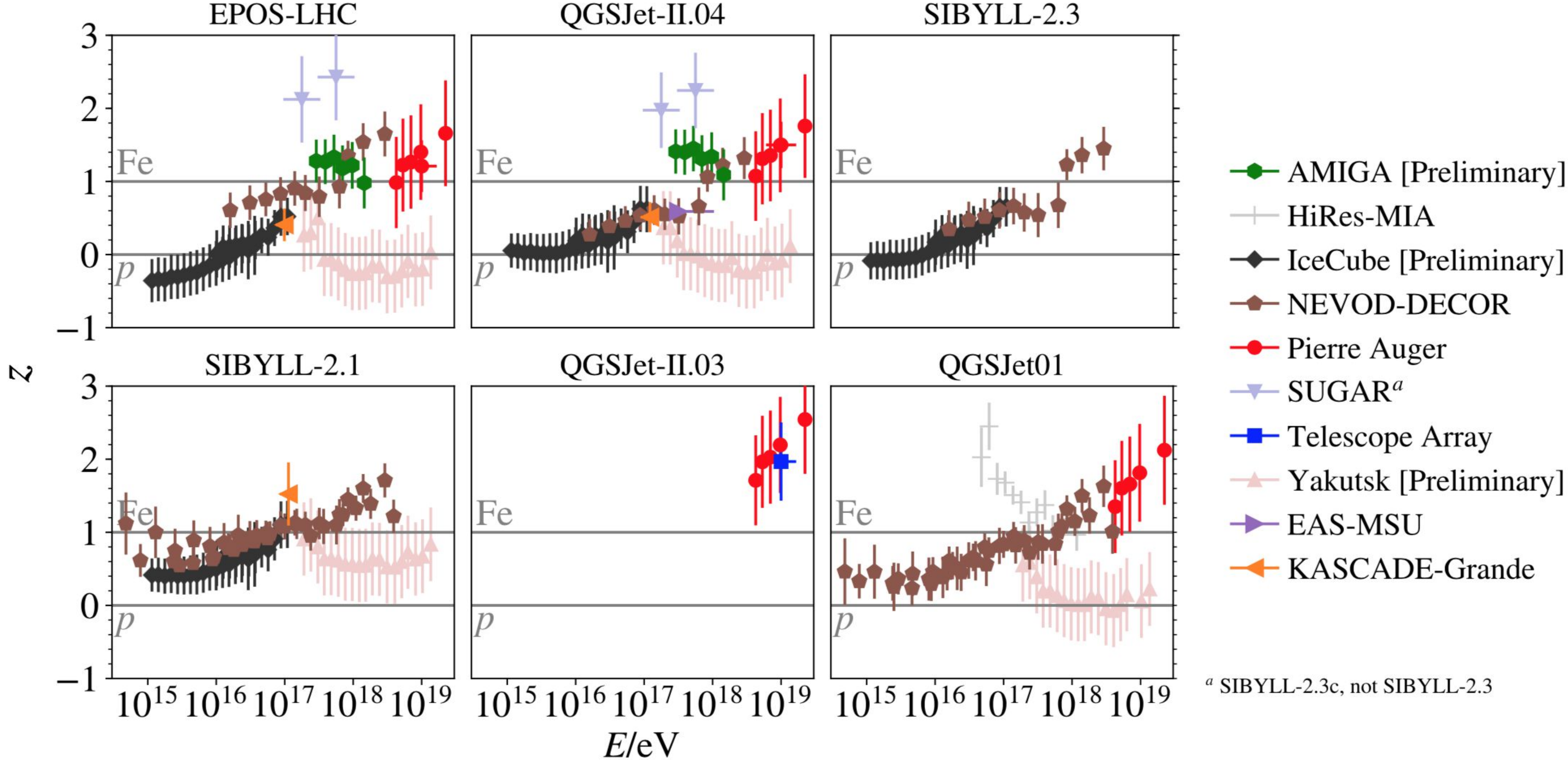
Uncertainties in the description of hadronic interactions remain the dominant source of systematic uncertainty in Air-Shower measurements of Cosmic-Ray spectra.

It is also known that the current models have flaws and do not describe correctly all shower propeties
The so called *“Muon Problem”*
(deficit of muons in the predictions)

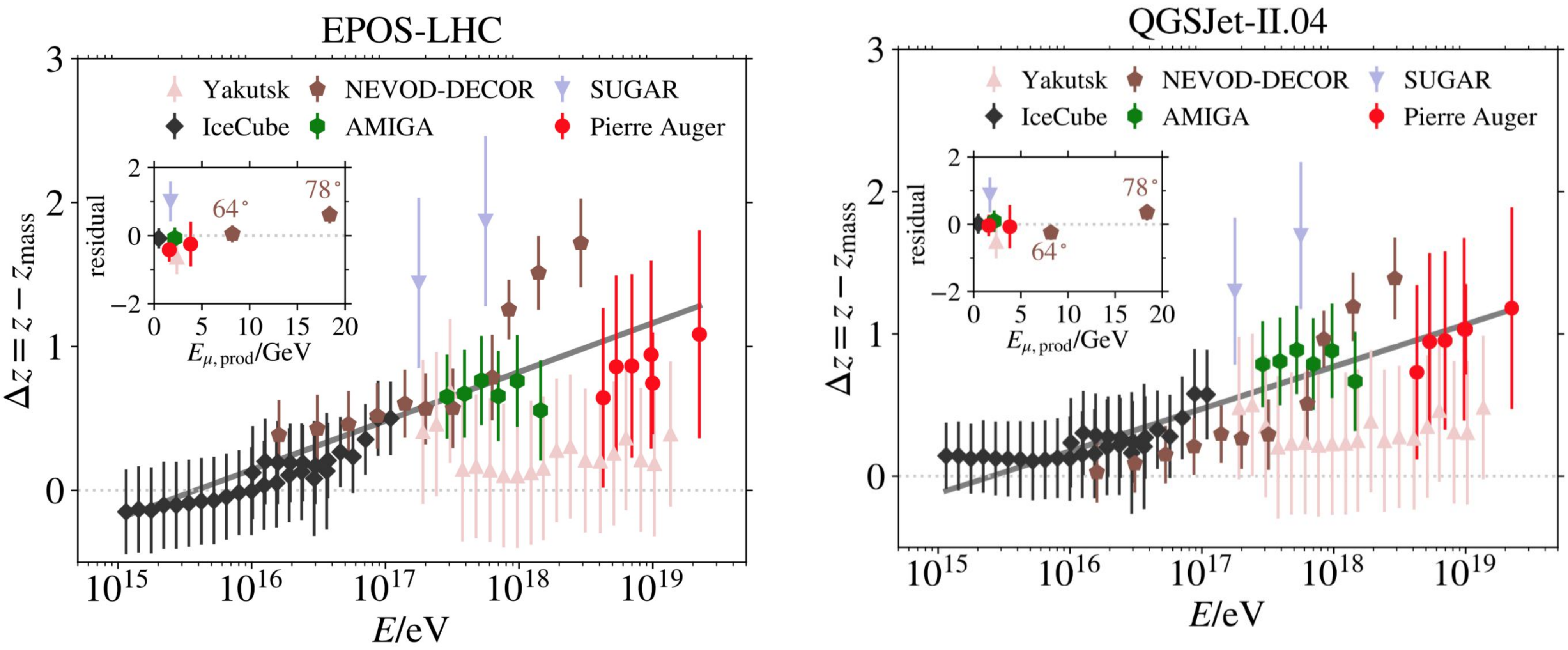


$$z = \frac{\ln(N_\mu{}^{\text{det}}) - \ln(N_\mu{}_p^{\text{det}})}{\ln(N_\mu{}_{\text{Fe}}^{\text{det}}) - \ln(N_\mu{}_p^{\text{det}})}$$

L. Cazon for [EAS-MSU, IceCube, KASCADE Grande, NEVOD-DECOR, Pierre Auger, SUGAR and Telescope Array], "Working Group Report on the Combined Analysis of Muon Density Measurements from Eight Air Shower Experiments," PoS **ICRC2019**, 214 (2020) [arXiv:2001.07508 [astro-ph.HE]].



Energy dependence of the “muon anomaly”



This type of studies can receive a great boost from the (multi-component) data of LHAASO.

How can we improve ?

1. Program of experimental studies
   at accelerators
   (including “lower energy”)

2. Theoretical efforts
   (Deeper understanding)
   (Development of better Montecarlo codes)

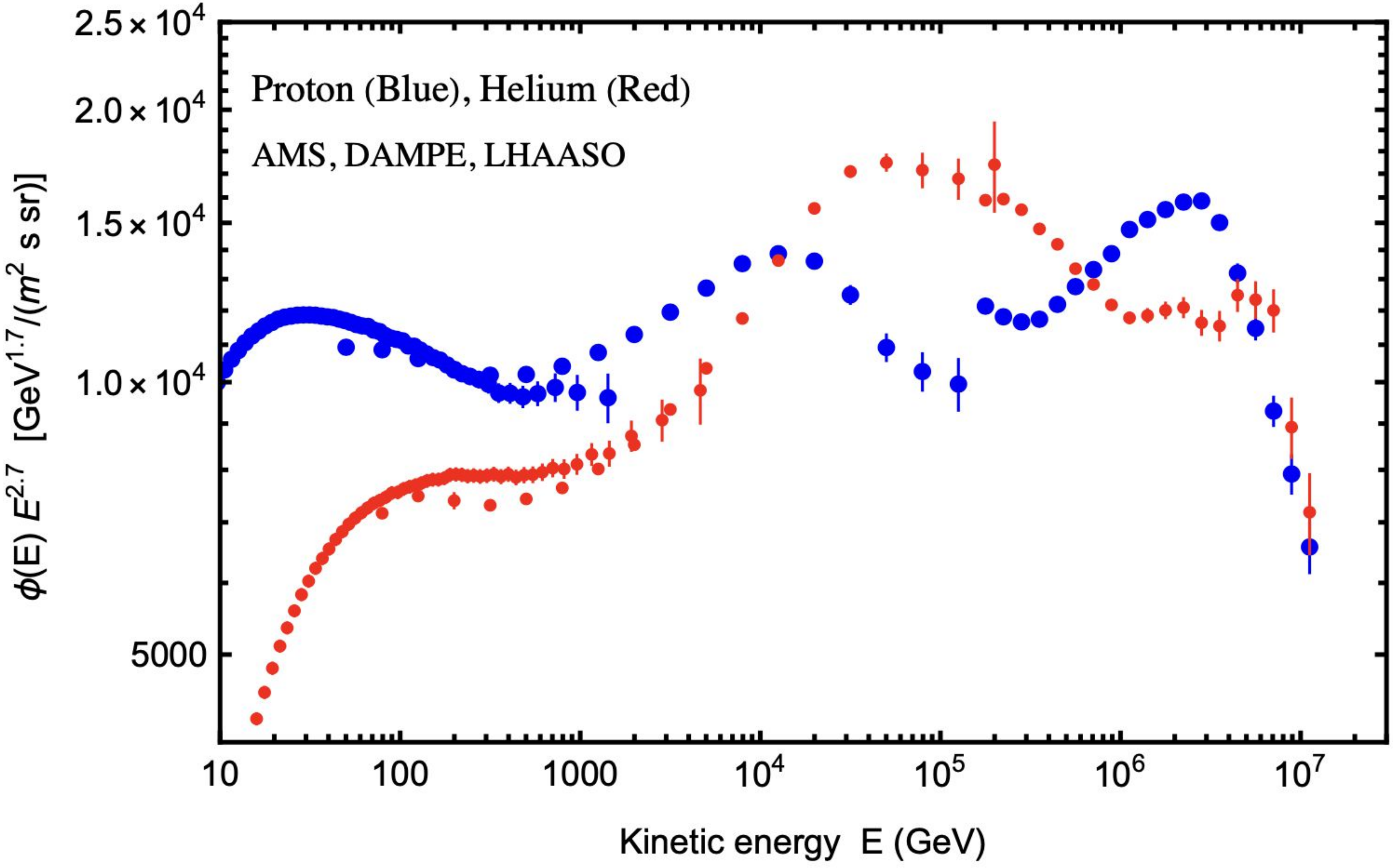
3. Self-consistency studies
   of Cosmic Rays Observations.

Comparing the Proton and Helium spectra

(and the spectra of other nuclear species)

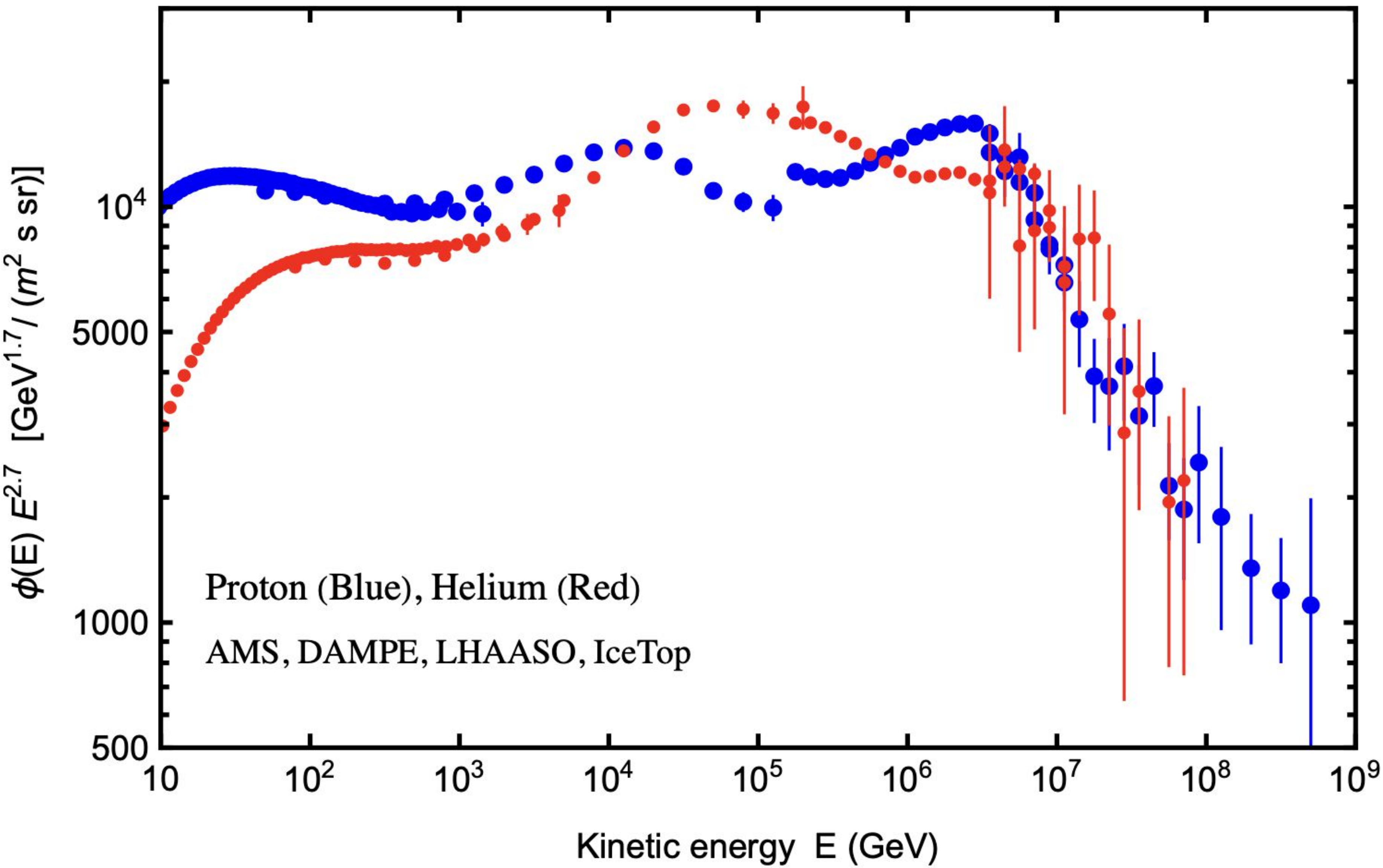
Spectra as a function of Kinetic Energy

Note the three “crossing” of the two spectra)

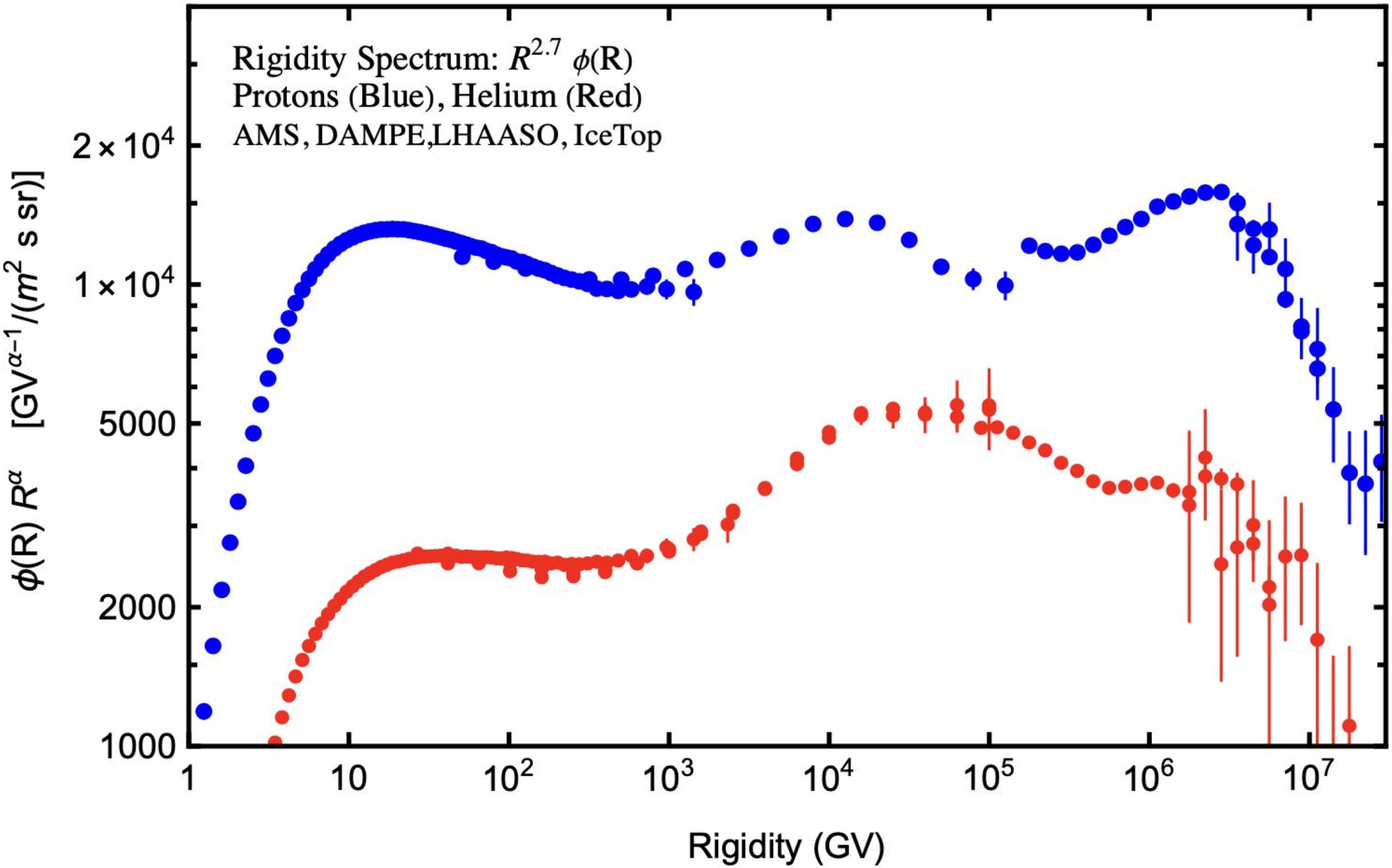


Spectra as a function of Kinetic Energy

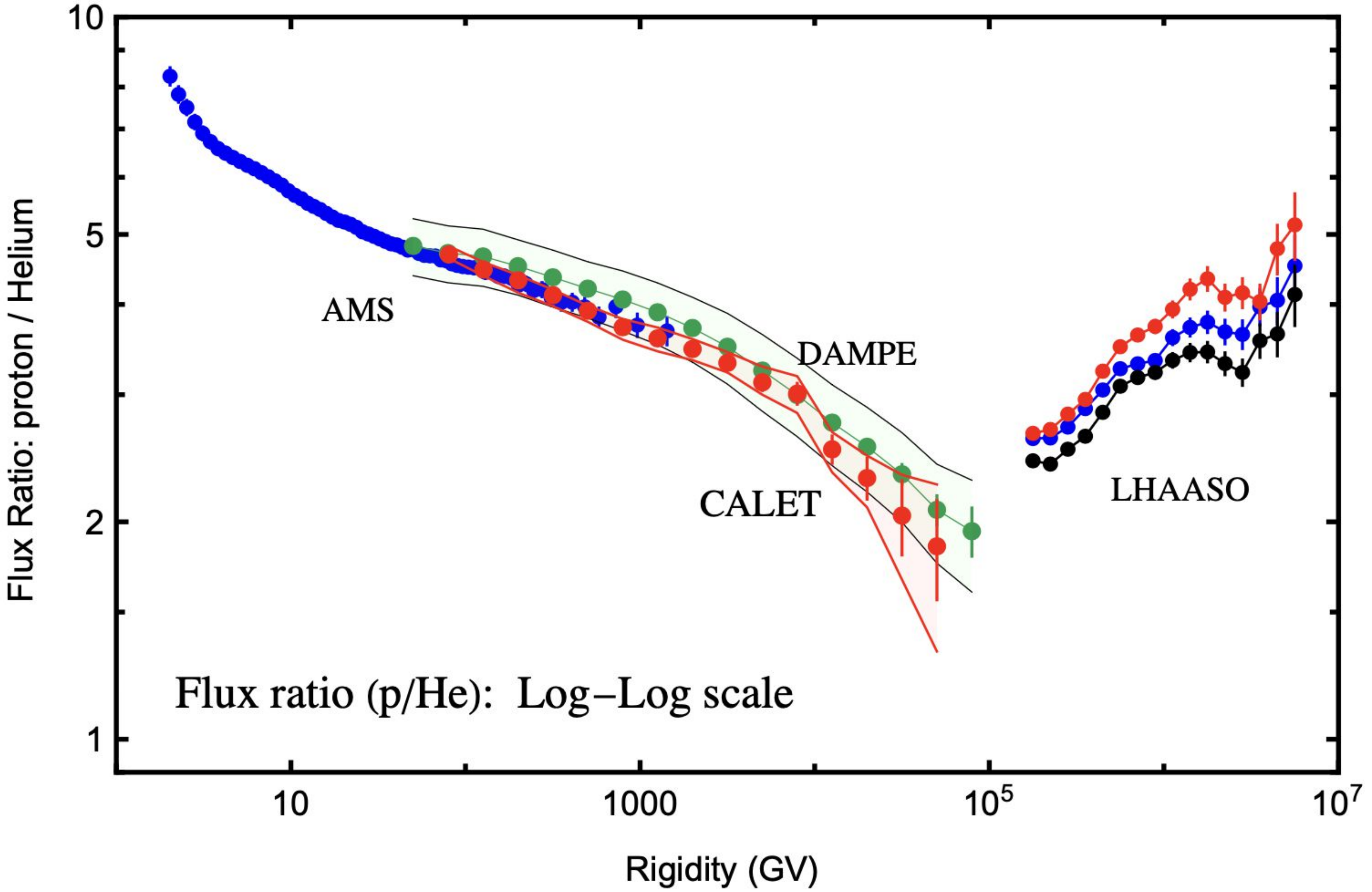
(also inclide IceTop very high energy data (above Knee)



Spectra in *Rigidity*



Ratio proton /Helium in Rigidity



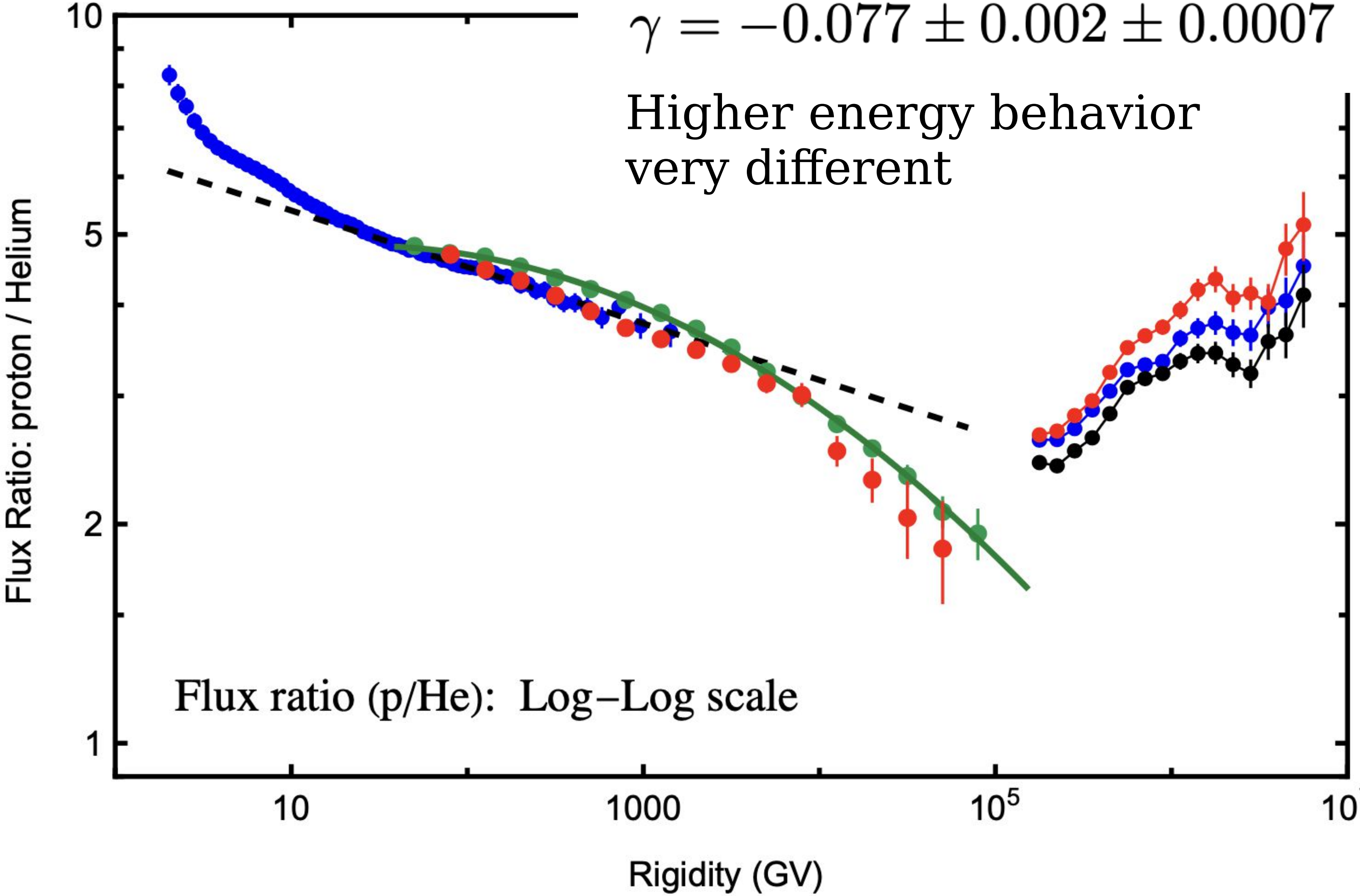
Ratio p/Helium

AMS fit
R>45 GV

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

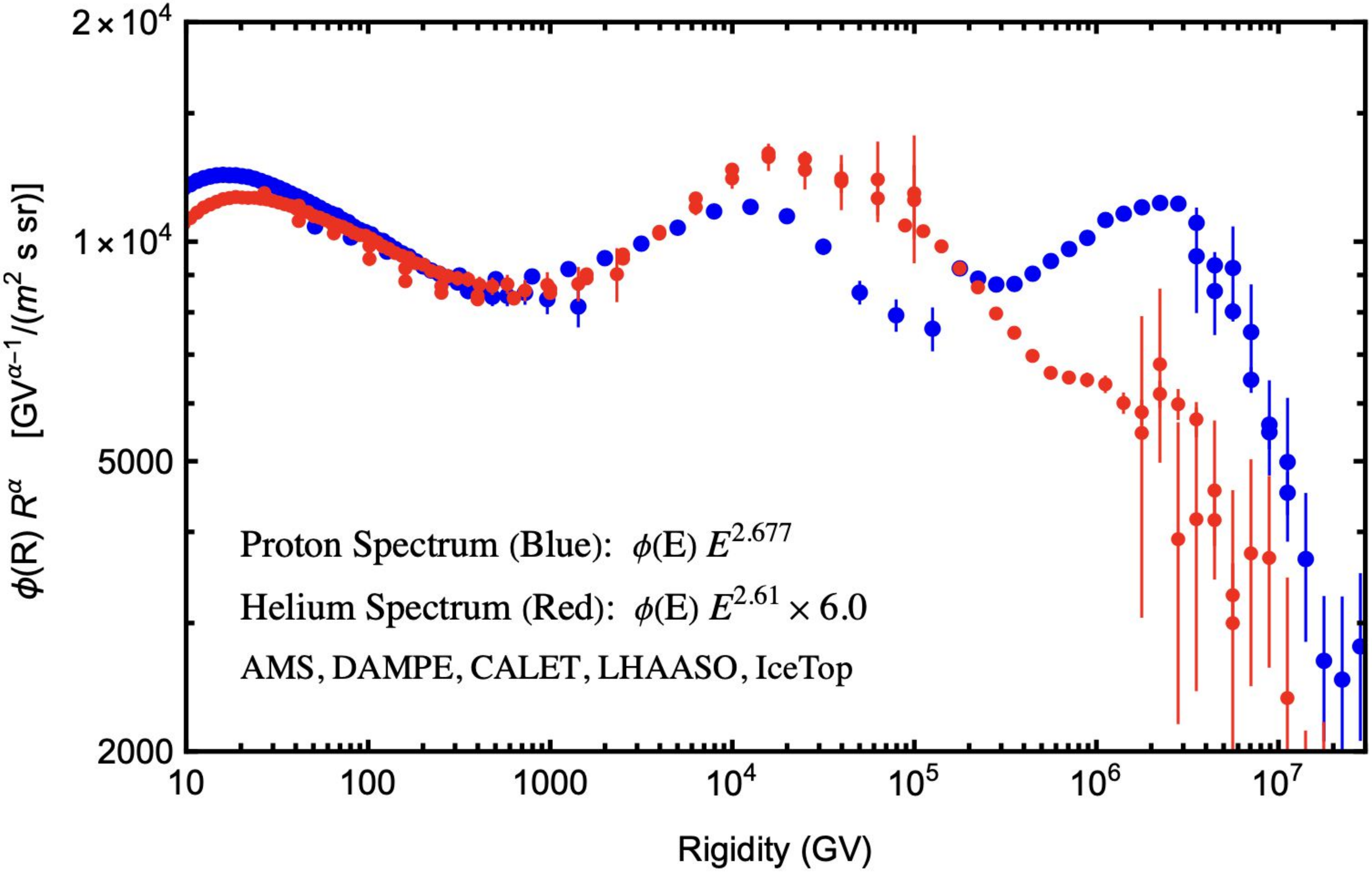
$$\gamma = -0.077 \pm 0.002 \pm 0.0007$$

Higher energy behavior
very different



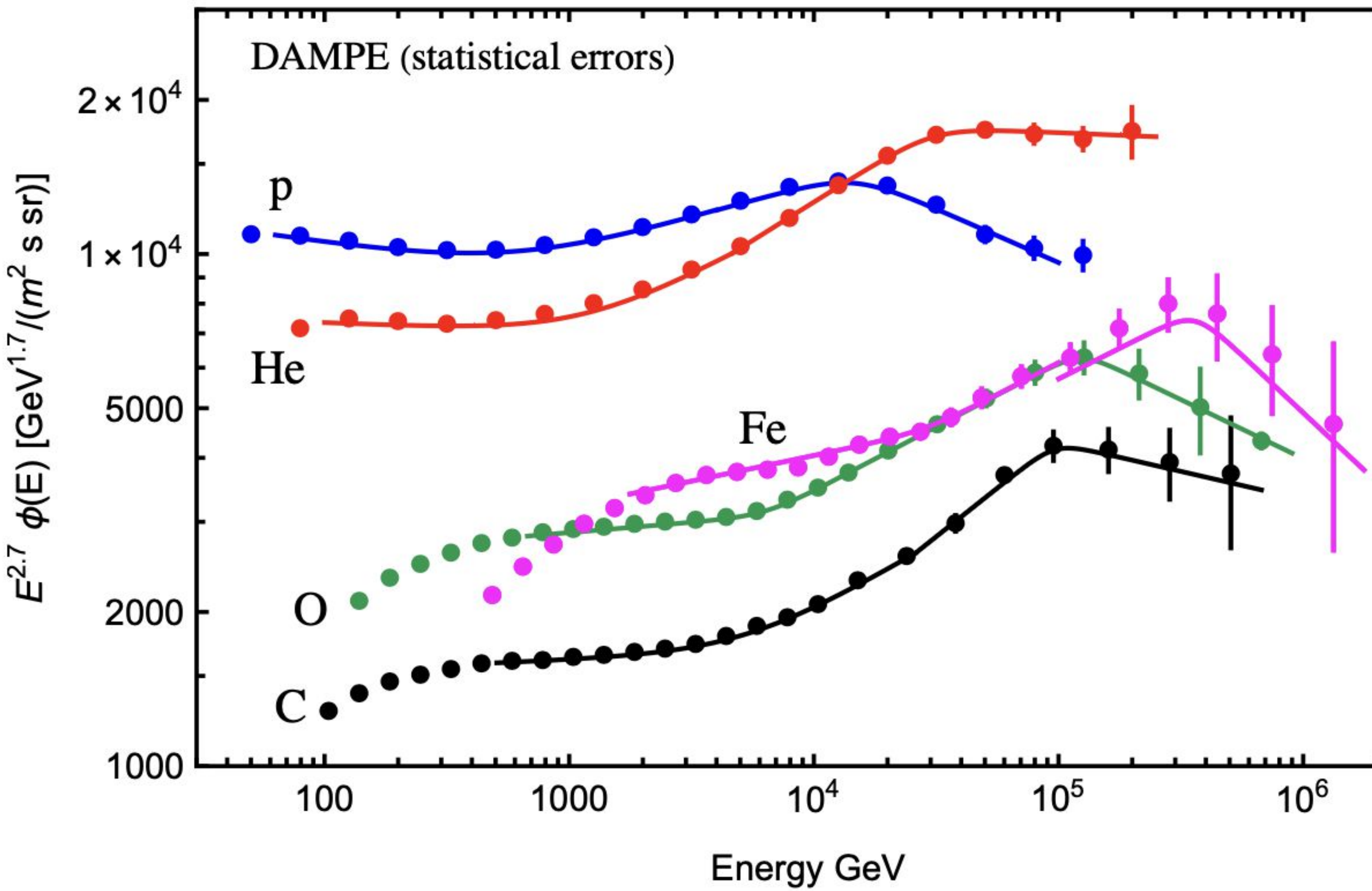
proton/Helium ratio as a function of Rigidity

Note: Different "distortion factors" for p *and* He



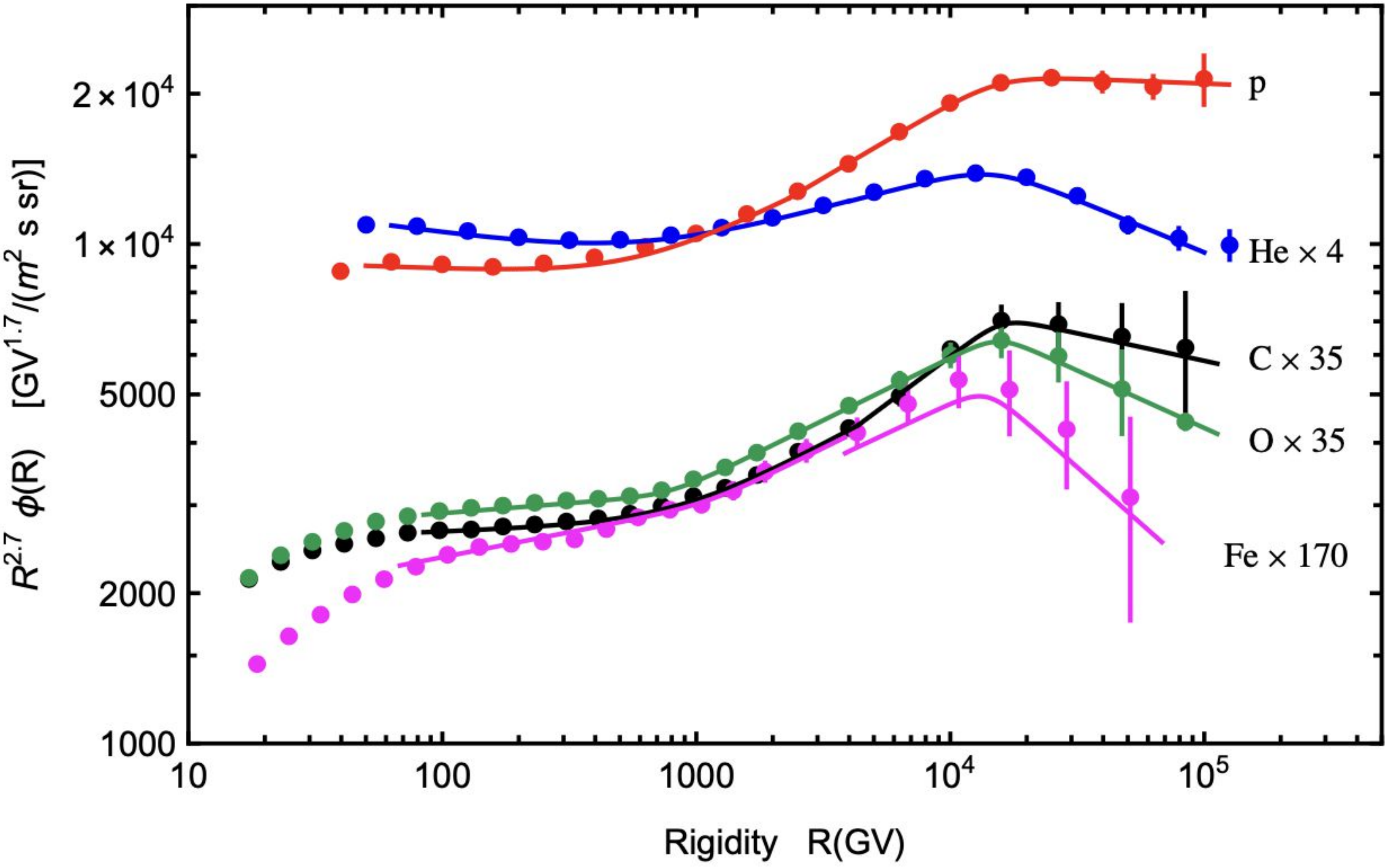
DAMPE spectra of different elements
astro-ph/ 2511.05409

"Charge-dependent spectral softenings of primary cosmic-rays from proton to iron below the knee"

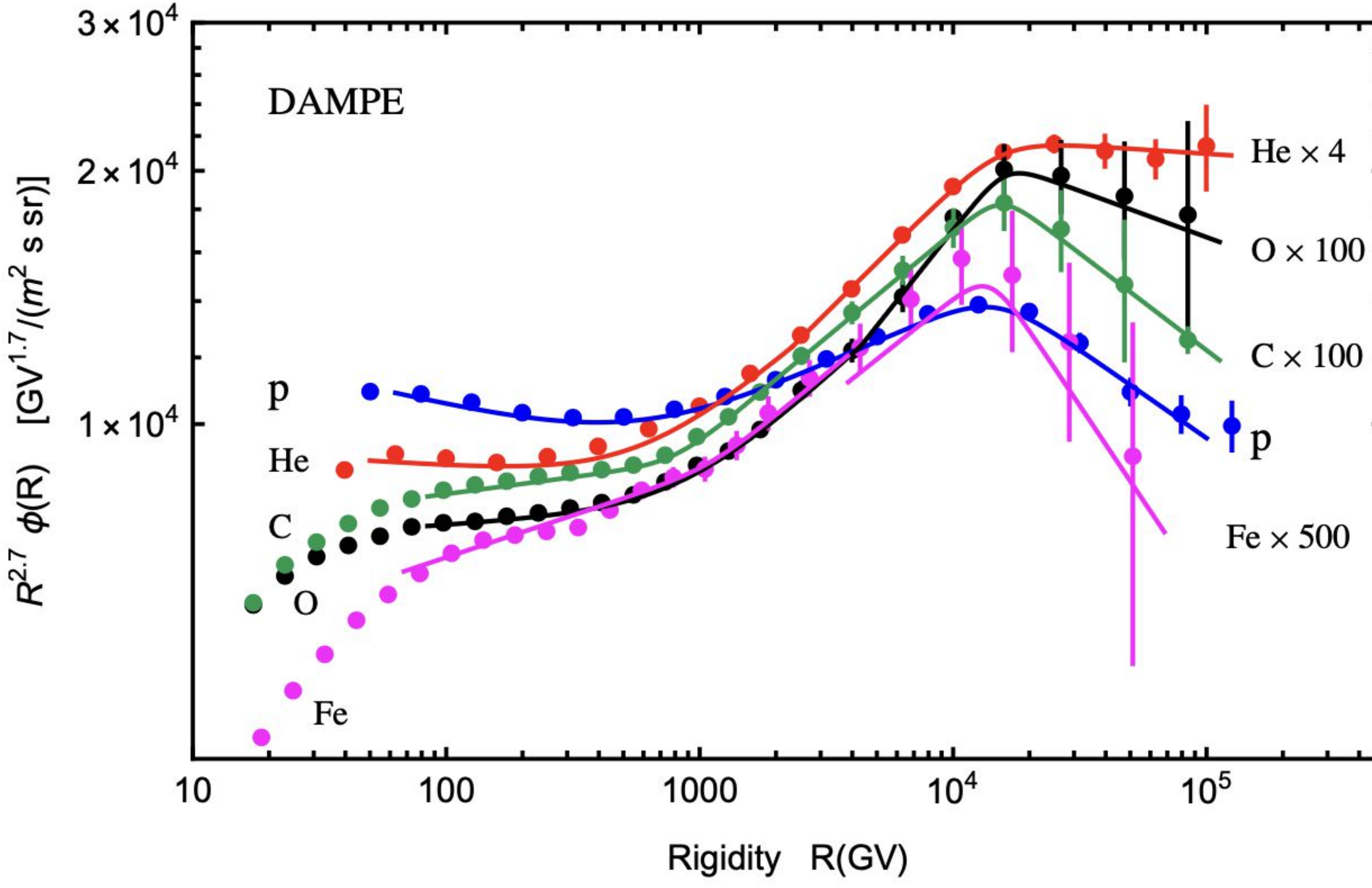


Replot DAMPE data as a function of Rigidity

How well are the features Rigidity dependent ?



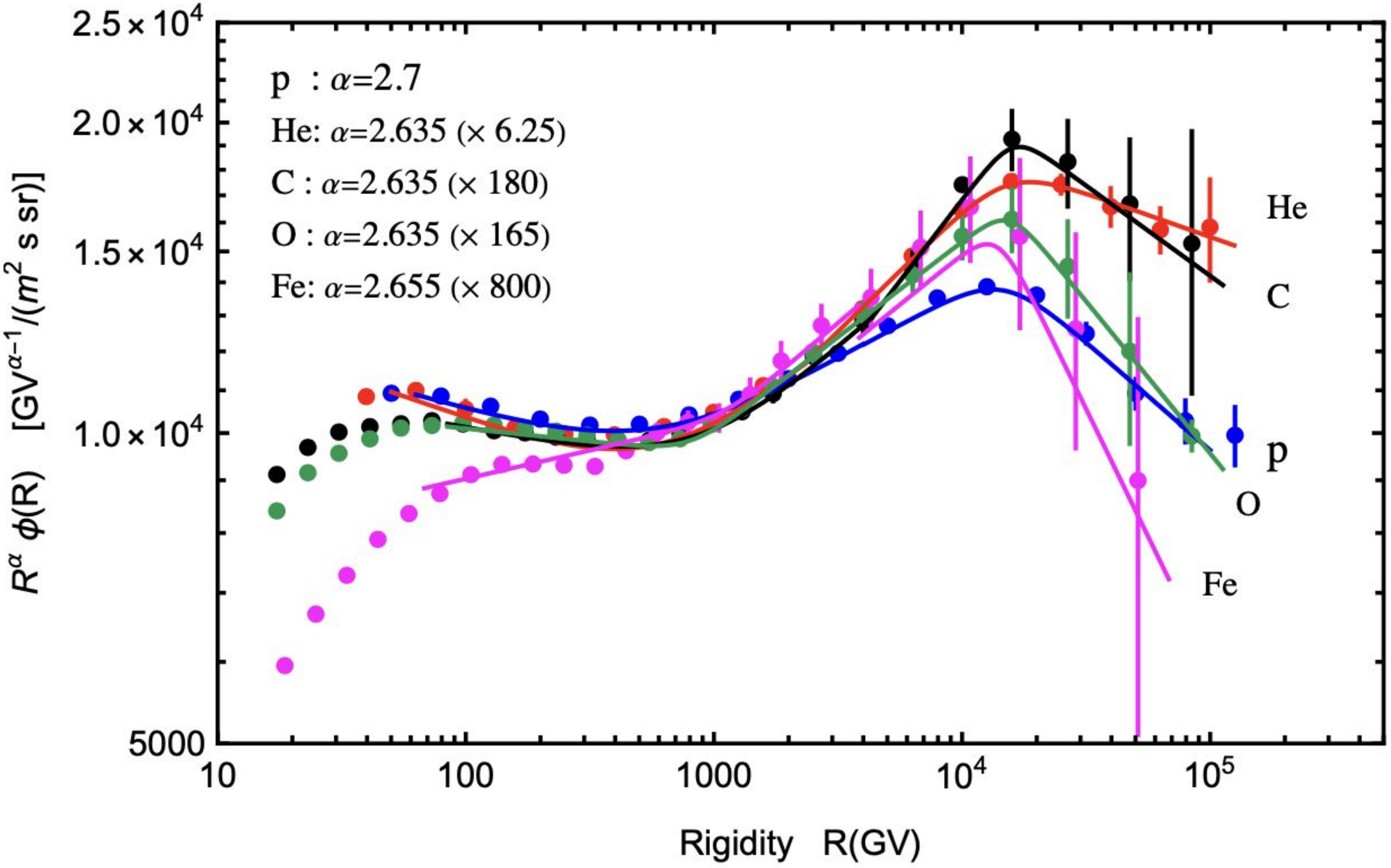
Replot DAMPE data as a function of Rigidity
[closer in absolute normalization]



Replot DAMPE data as a function of Rigidity

with *different distortion factors* E^α

(*and different absolute normalizations)*



Structure of the softening appear 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

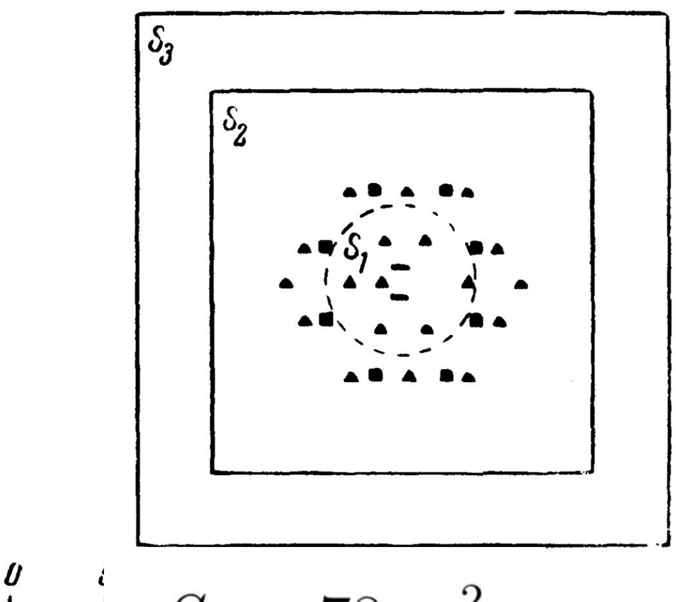
$$E_{b,a} = Z \, E_{b,p}$$

cutoffs $\propto Z$

Kulikov, Khristansen
JETP 35, 635 (1958)

Moscow State University
Cosmic Ray Telescope

Observation of a “break”
in the size spectrum

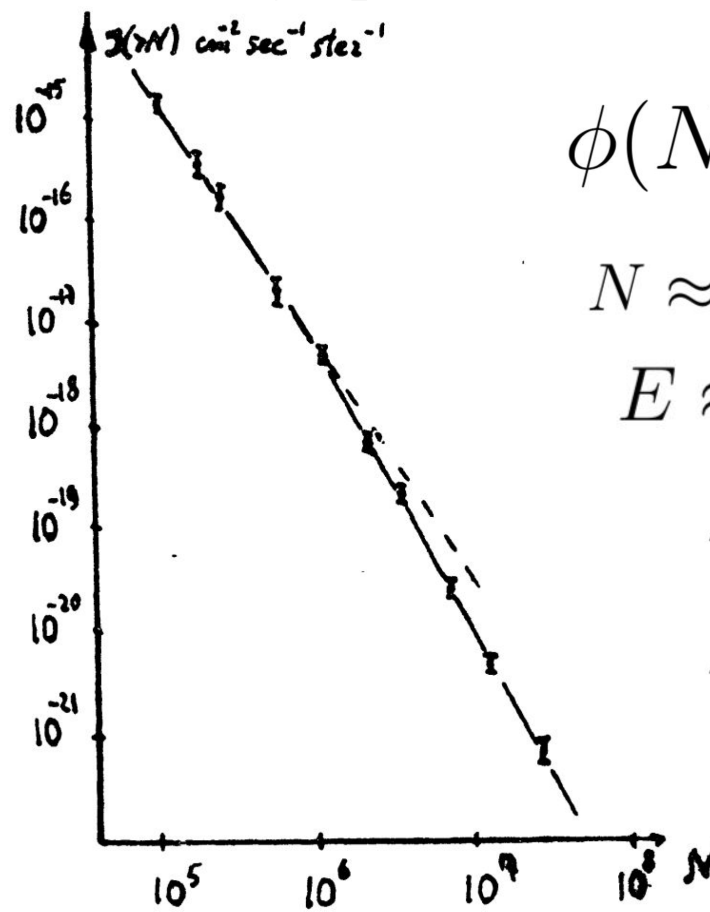


$S_1 = 78\ \mathrm{m}^2$

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

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

ICRC Jaipur (1963)



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

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

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

$$\gamma_1 = 1.4 \pm 0.1$$

$$\gamma_2 = 1.9 \pm 0.1$$

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

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

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

$$\gamma_0 \approx 1.5$$

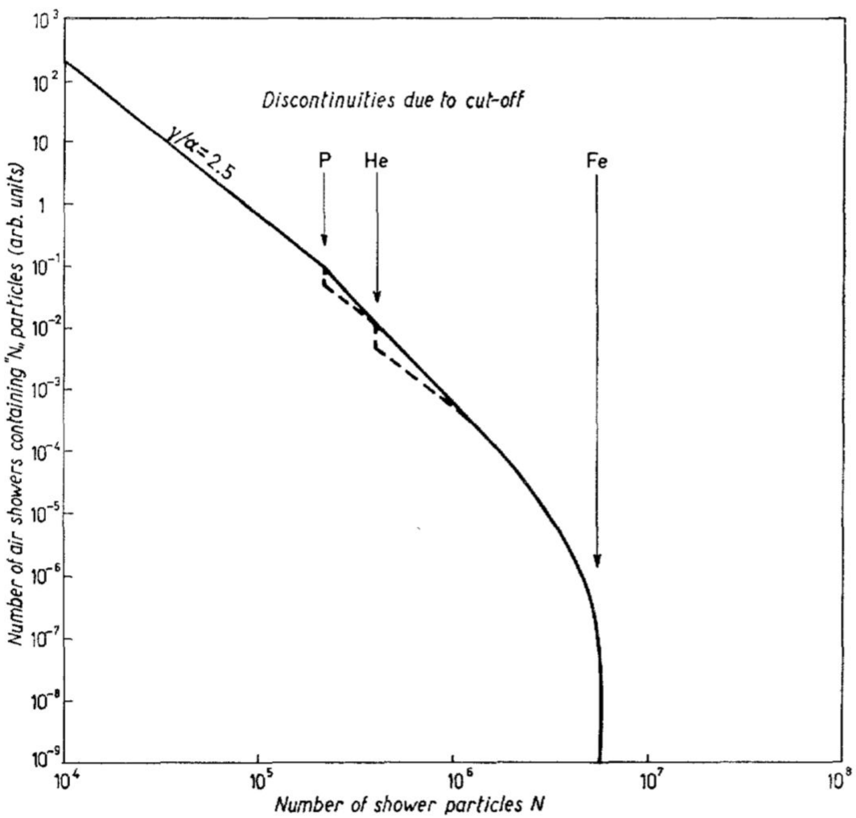
$$\phi(E) \propto \frac{q(E)}{D(E)}$$

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

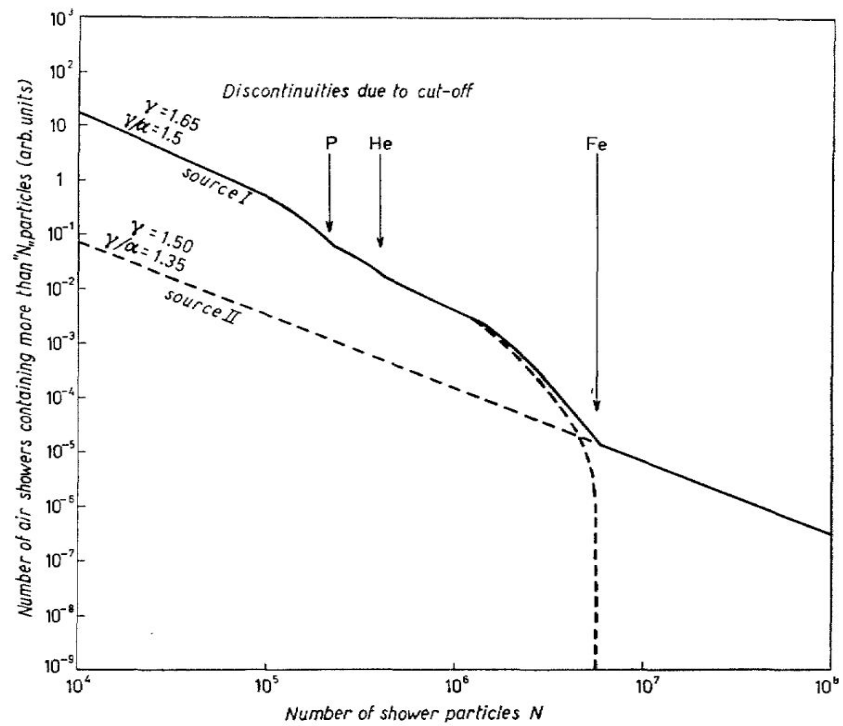
$$D \propto E^{0.2} \quad E \lesssim 10^{15} \text{ eV}$$

$$D \propto E^{0.7} \quad E \gtrsim 10^{15} \text{ eV}$$

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

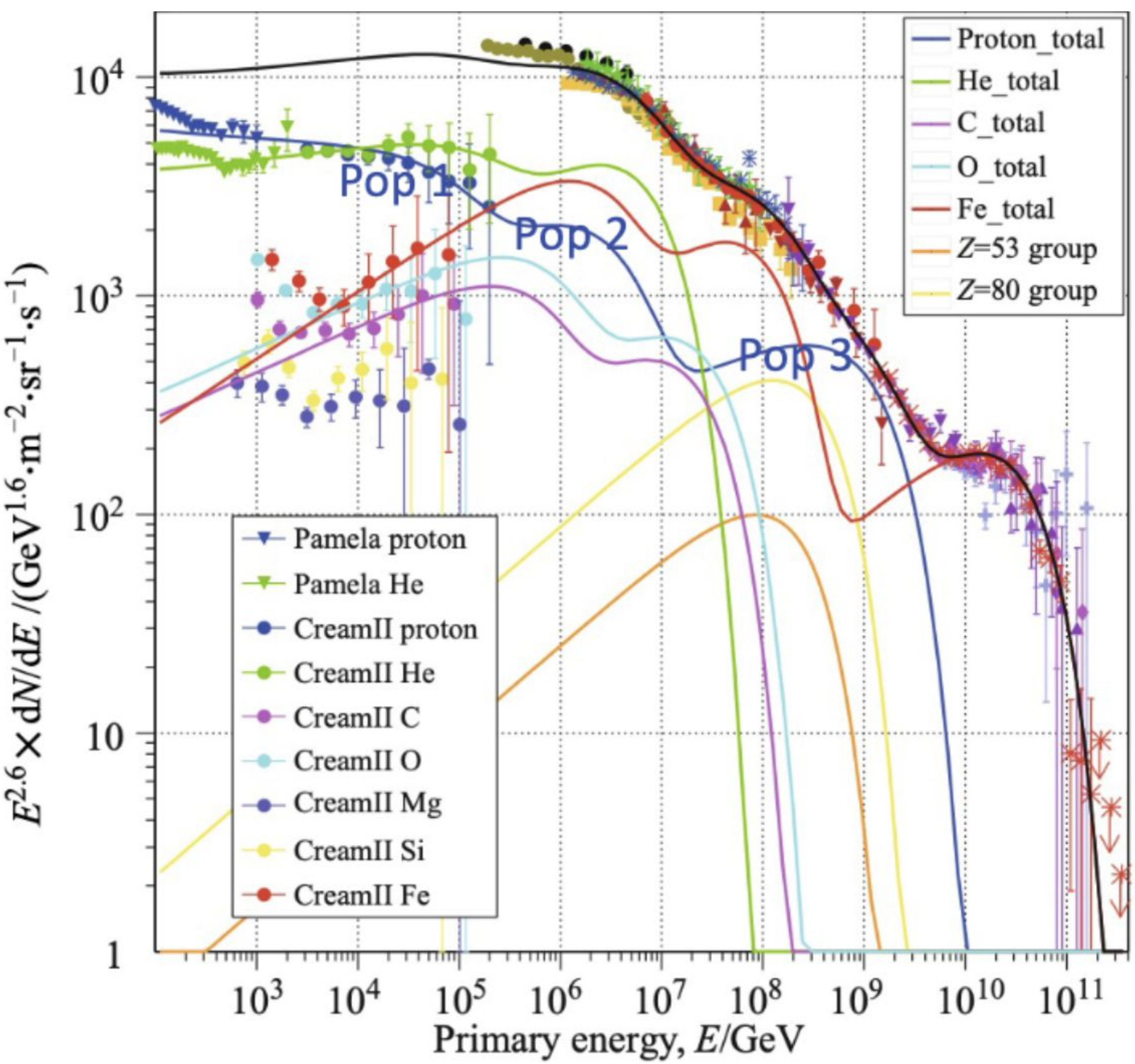


Combination of two
(classes of) sources

Tom Gaisser called these
“Peters's cycles”

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

The “multiple source-classes” Ansatz [“educated guess”]

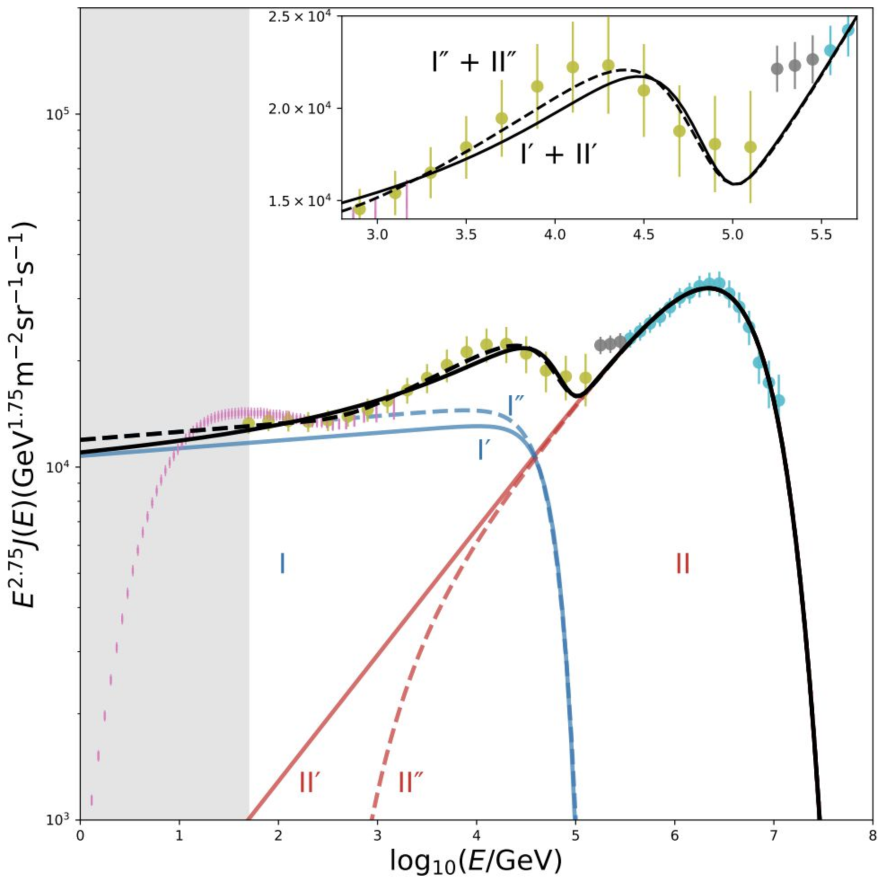
The idea is that cosmic ray accelerators can be divided in different classes [for example SNR and microquasars] that release in interstellar space cosmic ray populations with *(in good approximation)* *equal spectral shape*

In particular they must have a power law form with:
the *same spectral-index*
the same break-energy.
These features are then reflected in the combined CR spectrum.

This idea is the basis of the Gaisser/Stanev/Tilav [GST2013] description of the CR spectra, and has been adopted and extended by several other authors.

A recent example of this idea is the paper of Felix Aharonian and Bing Zhang: [astro-ph/2602.08223]

"A Minimal Interpretation of the Galactic Cosmic-Ray Spectrum from GeV to PeV Energies"



[The paper does not address the helium (and other nuclei) spectrum]

The main problem I find with this idea
is that it is not simple to demonstrate that
several objects [for example SNR] generate
the same spectral shape.

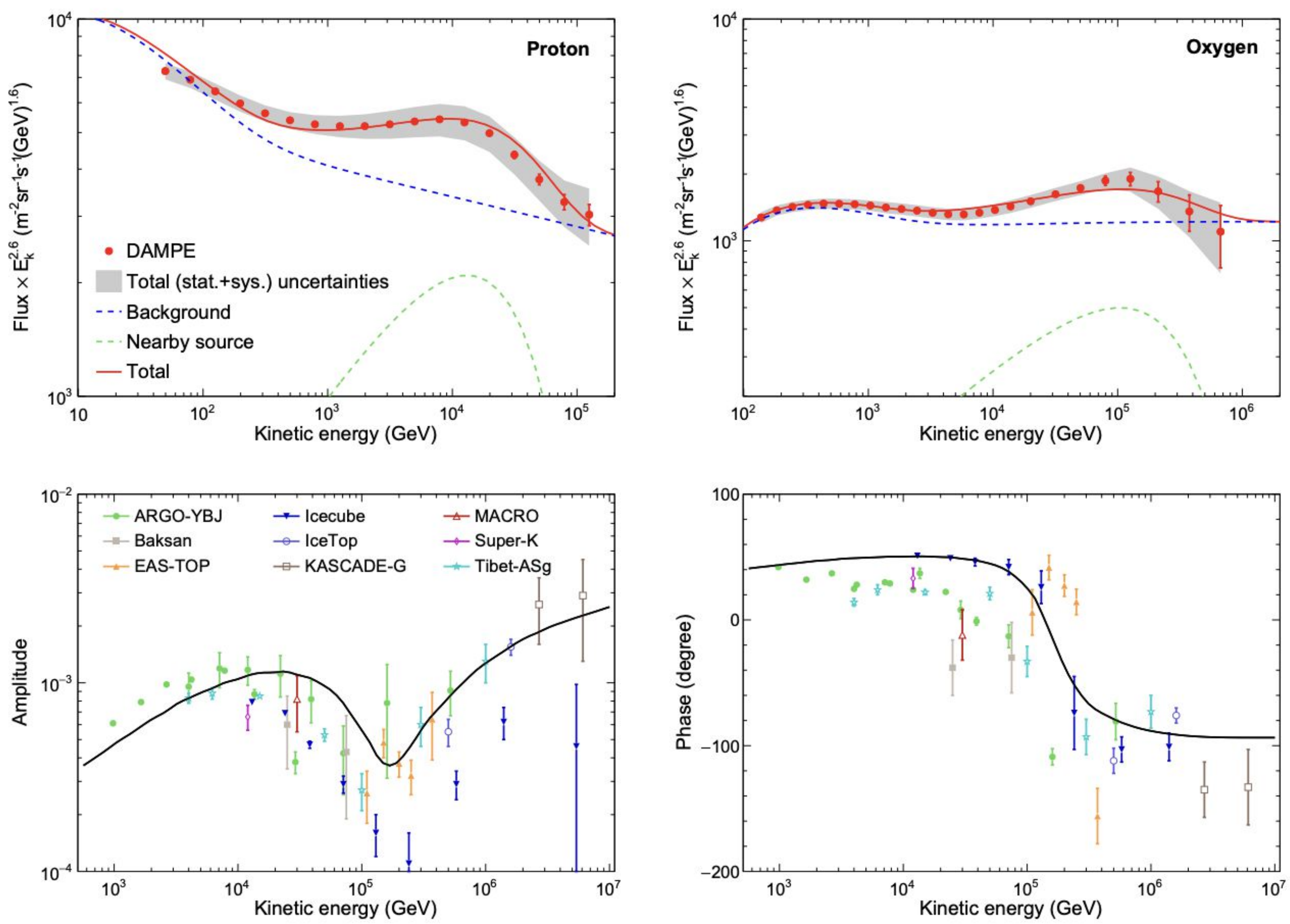
For SNR this idea has been discussed by Michael Hillas
that argues that this could be the case.

The "multiple source classes" hypothesis
requires confirmation by observations
and theoretical modeling of the sources

[Relate the gamma-ray and neutrino emissions
from active sources in the Galaxy
to the (time integrated) release of Cosmic Rays
[A very difficult but fundamental task]

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

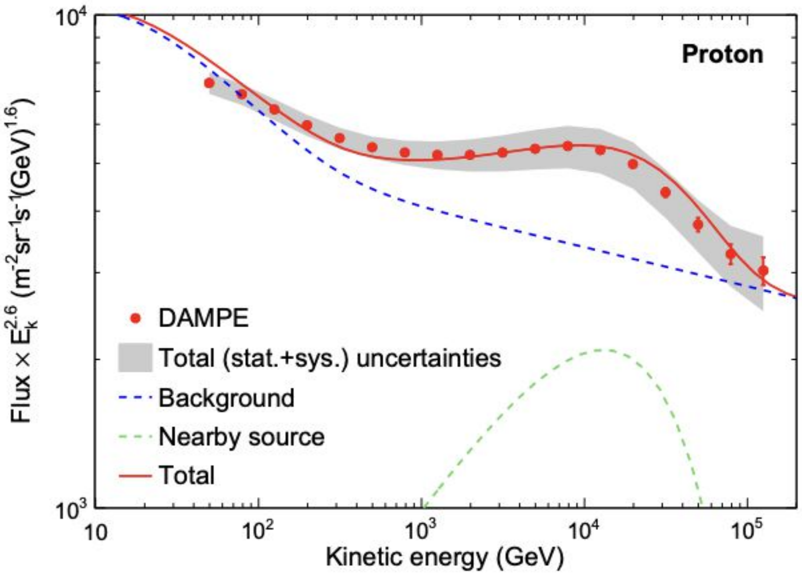
This idea has been adopted by many authors
[and is given as the most likely interpretation in the DAMPE paper]



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

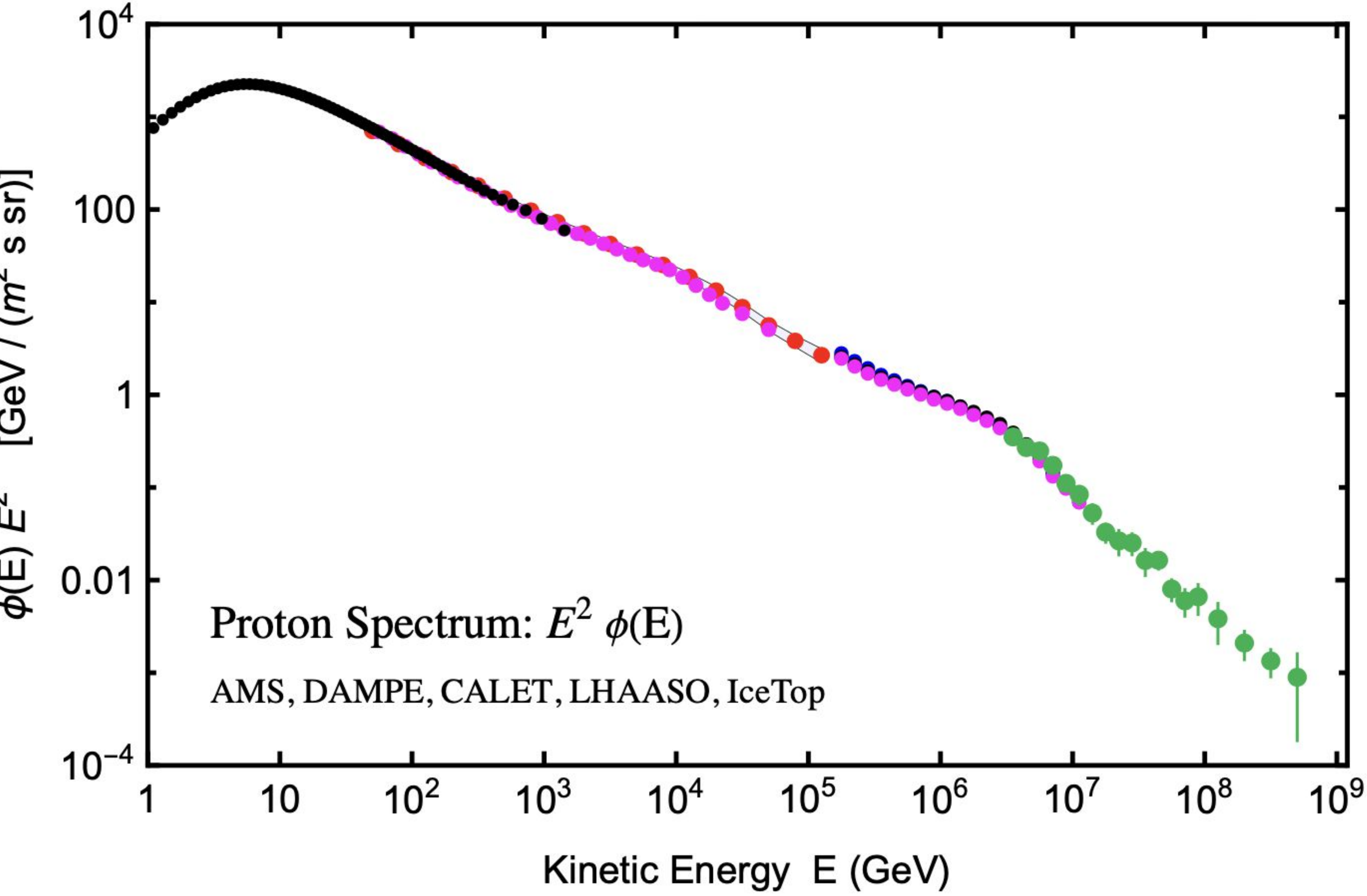
A “very ugly” alternative explanation for some of the features.

The *“Statistical soup”* ansatz

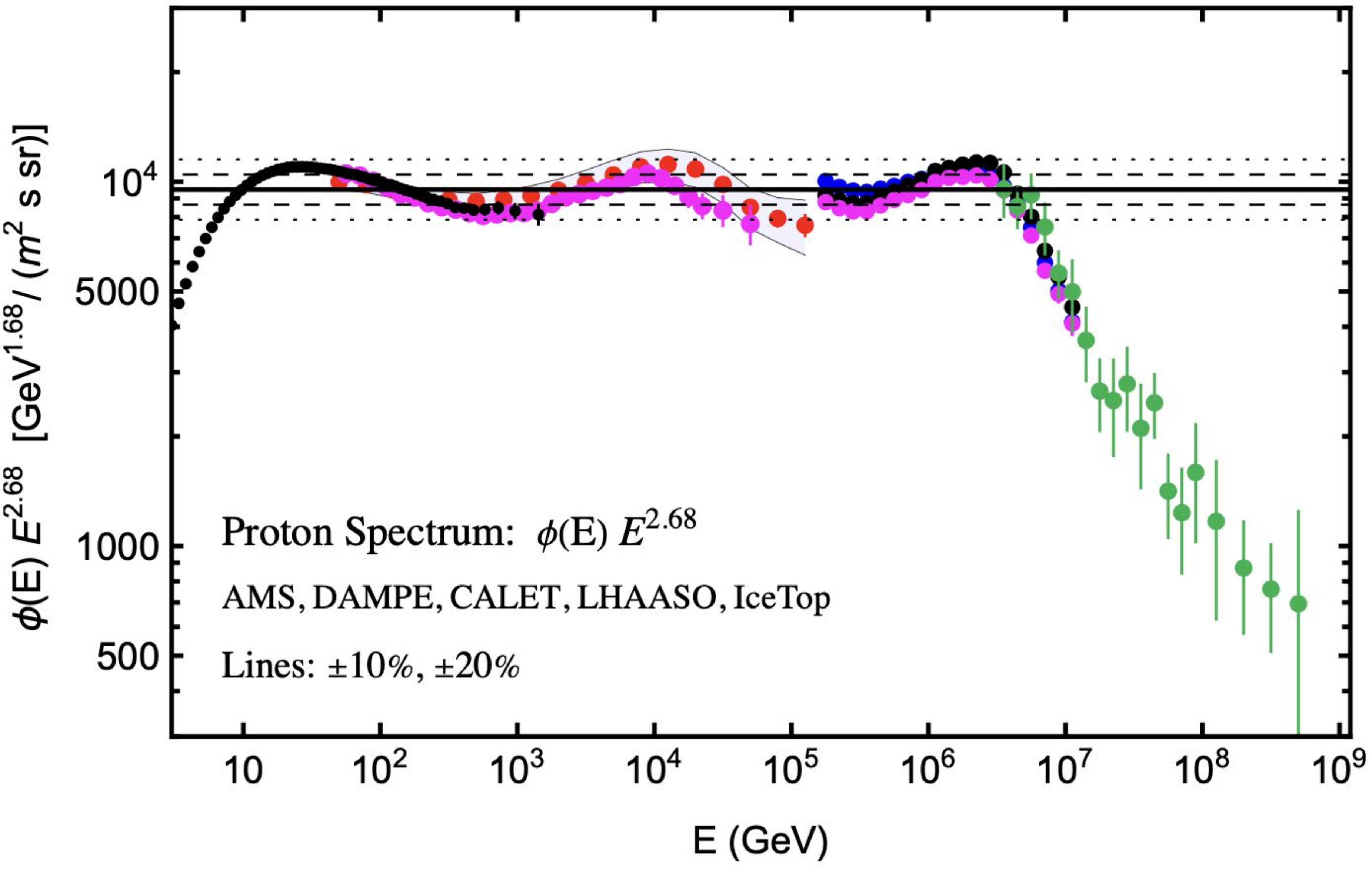
The name was given by Silvia Vernetto
and has a “derogatory” (critical) intention

The idea is that the power-law form of the Cosmic ray Spectrum does not emerge from one (or few) universal spectra, but is a combination of many components, that combine to form only approximately a power law.

Proton spectrum



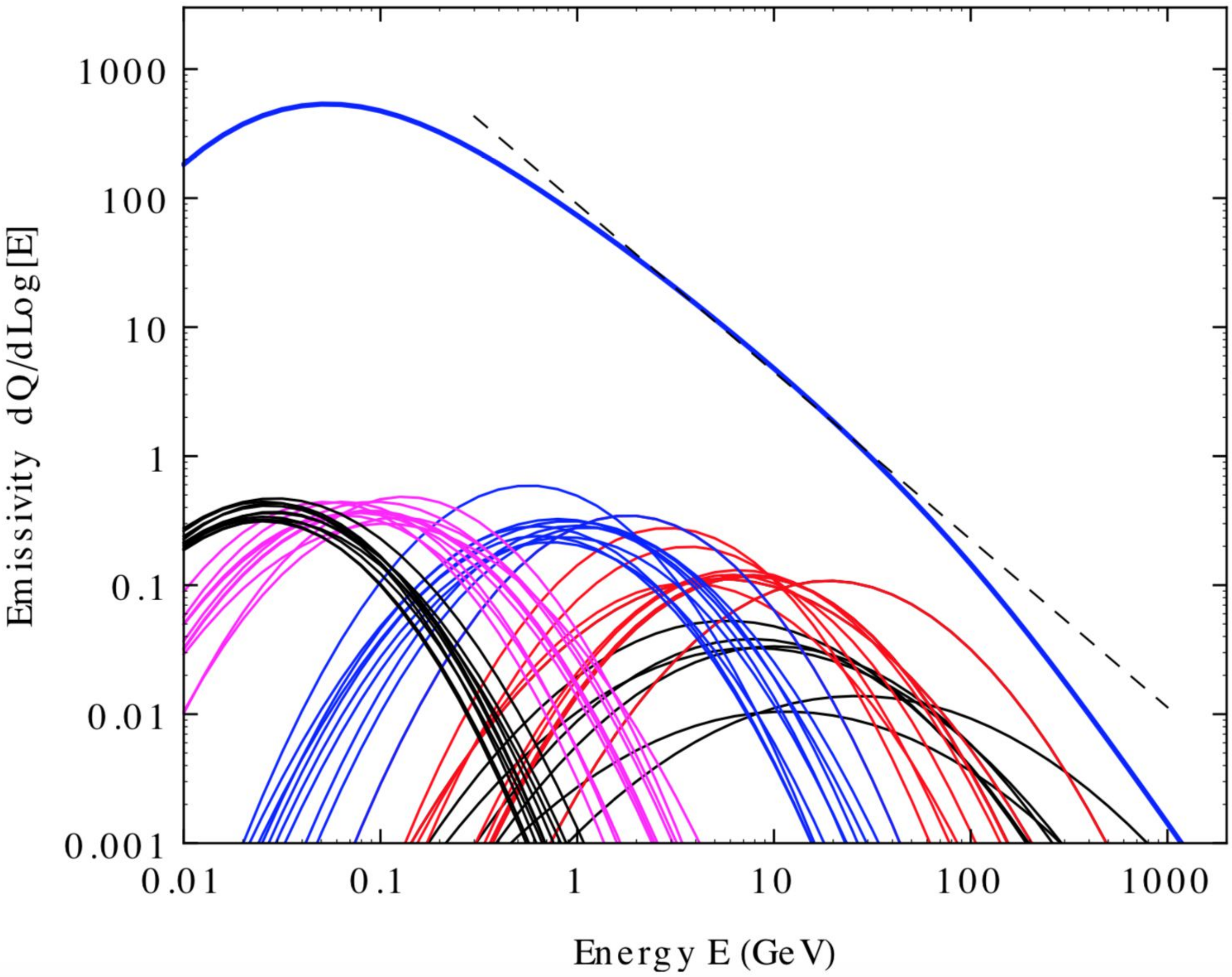
Proton spectrum:
+- 20% deviations over 6 order of magnitude in energy



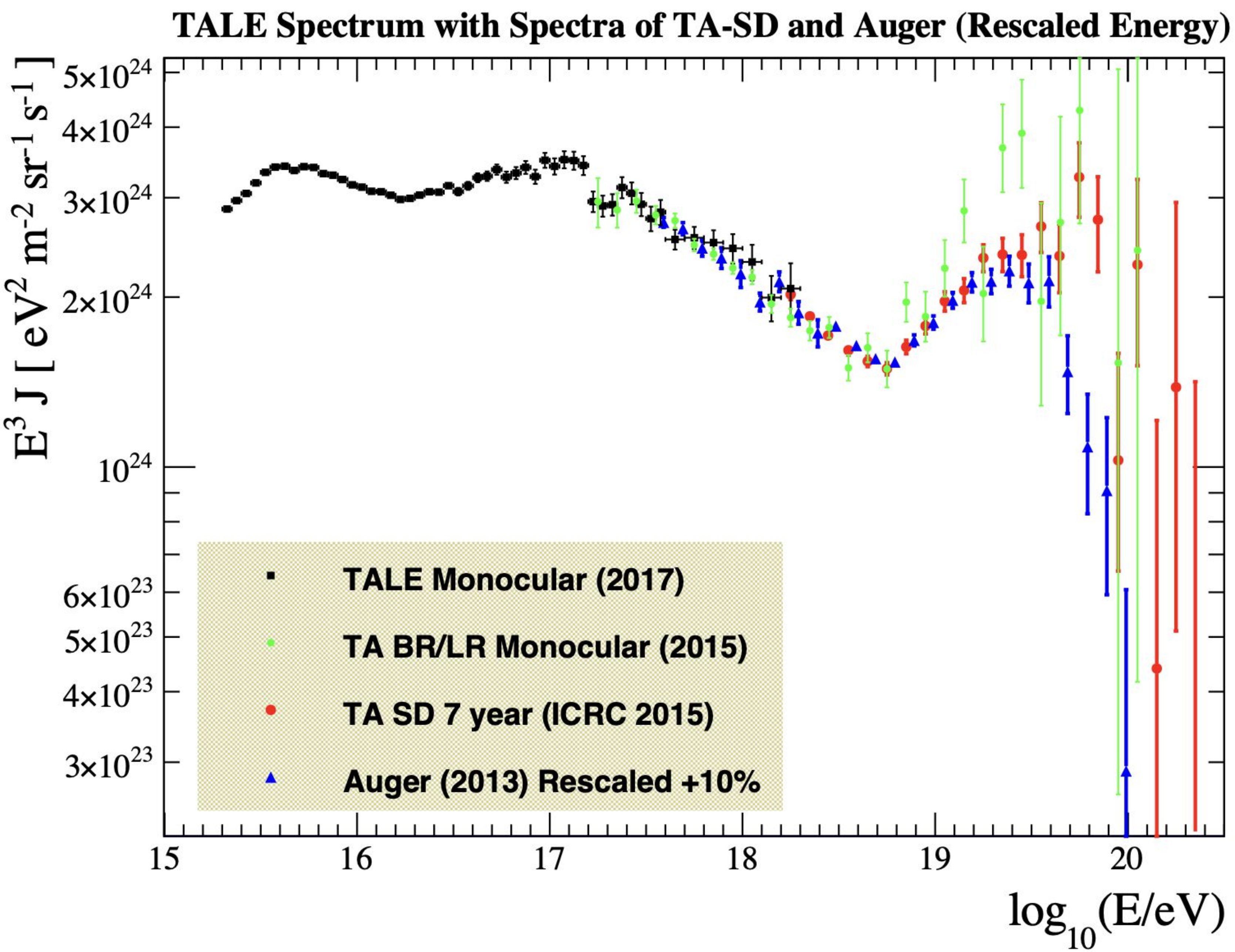
“unorthodox" speculation

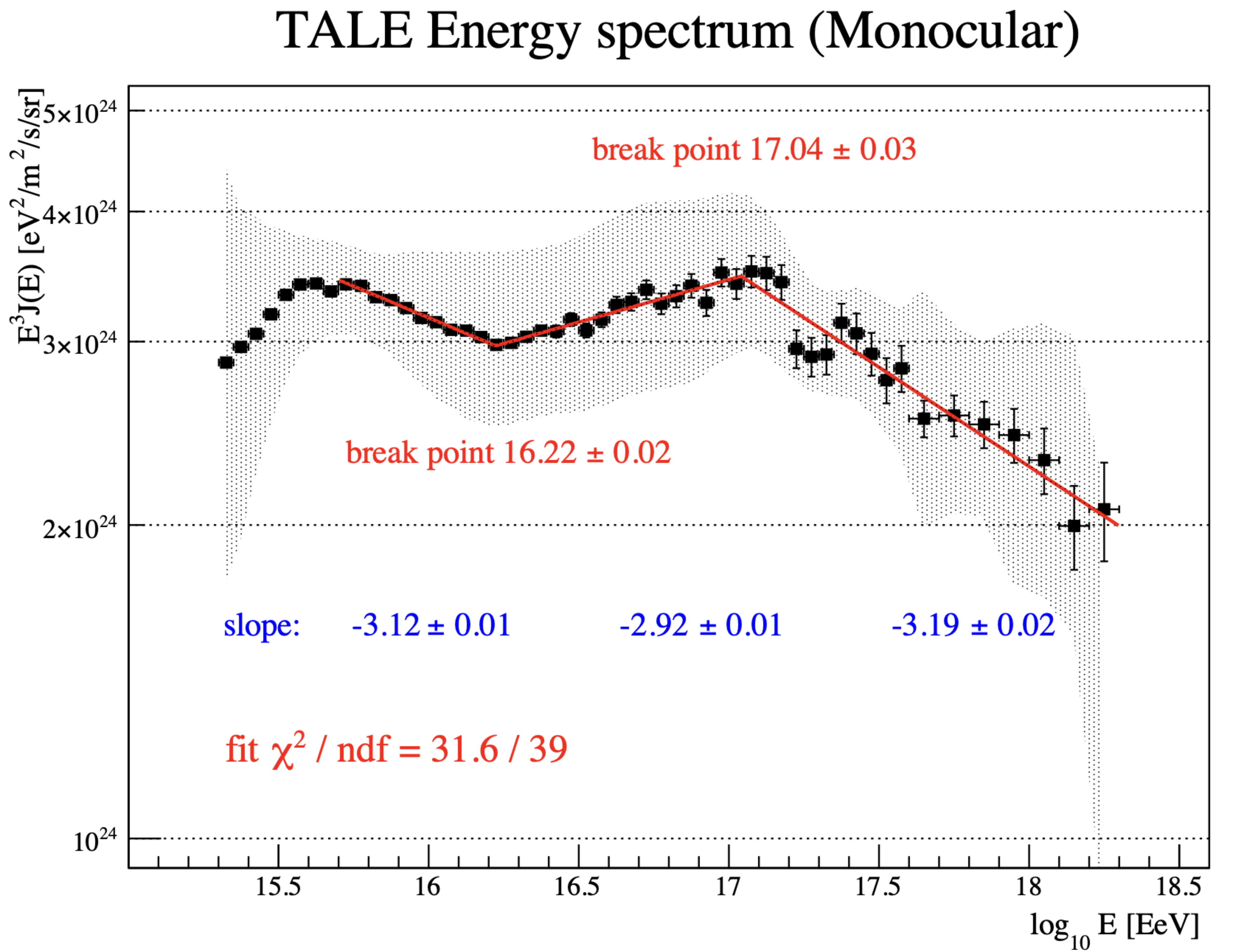
CR spectrum formed by components
that have different (log—parabola) form

Paolo Lipari,
“The origin of the power-law form of the extragalactic gamma-ray flux,”
[arXiv:2001.00982 [astro-ph.HE]].



The CR spectrum above the Knee.

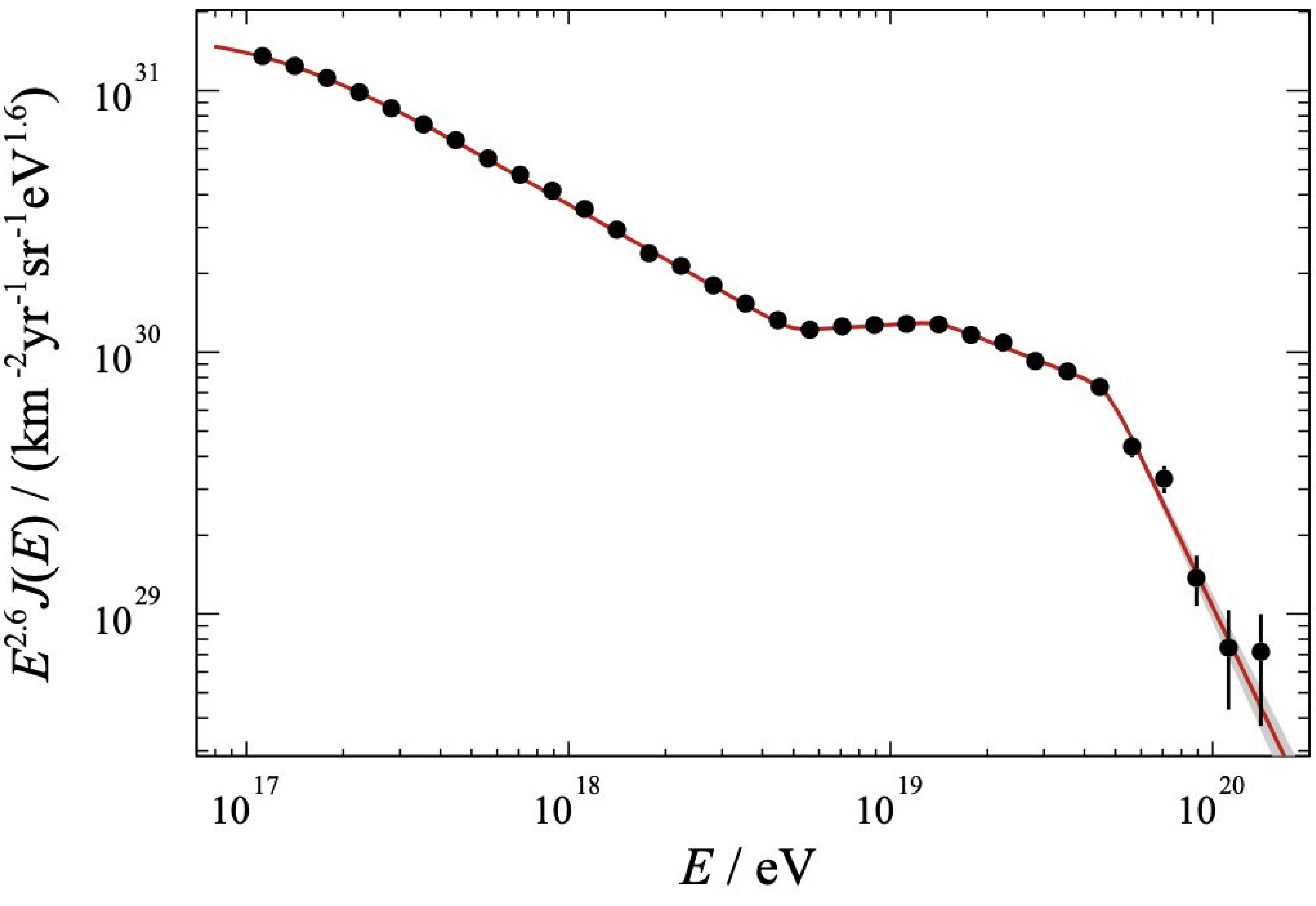




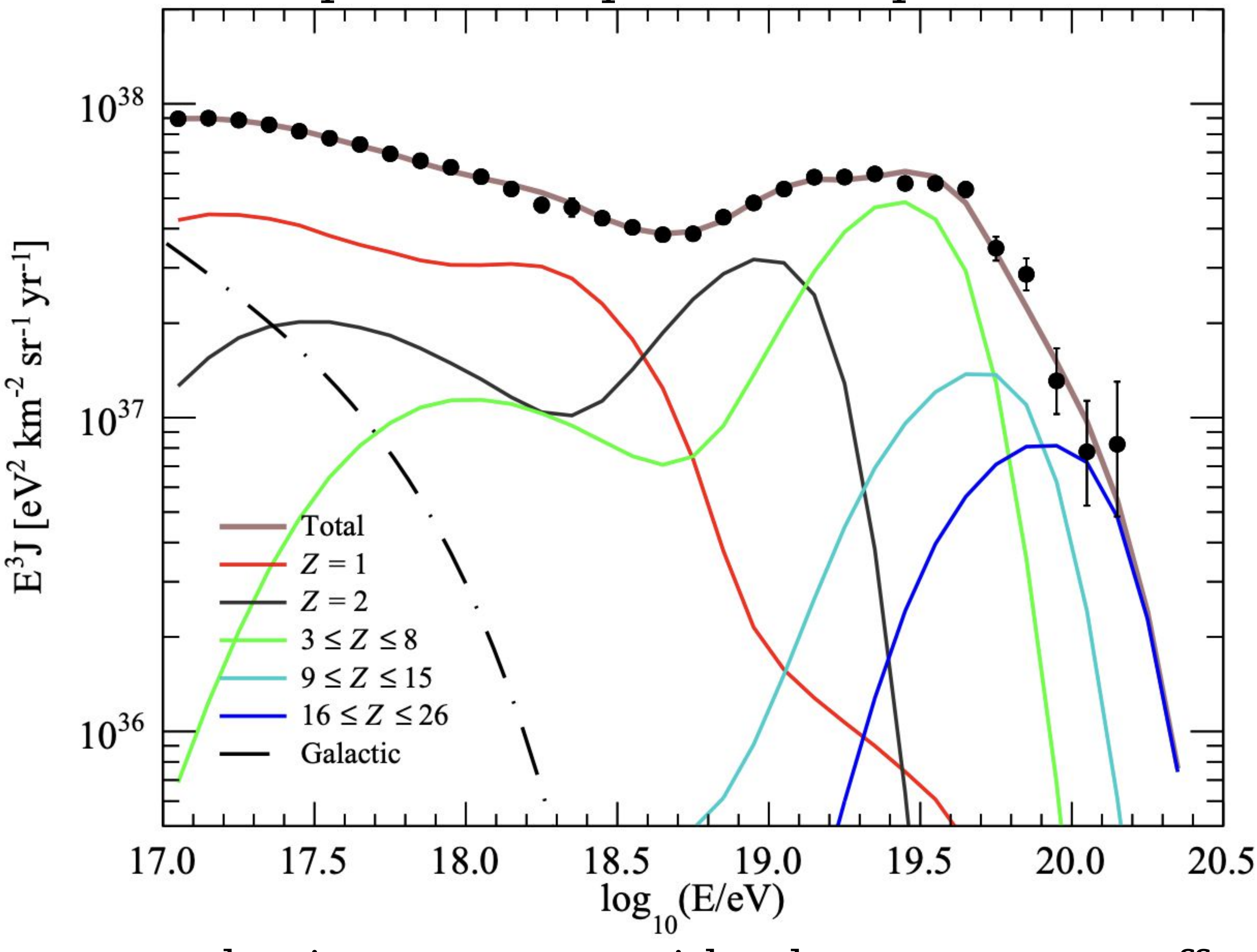
TALE Energy spectrum (Monocular)
E^3J(E) [eV^2/m^2/s/sr]
5×10^24
4×10^24
3×10^24
2×10^24
10^24
break point 17.04 ± 0.03
break point 16.22 ± 0.02
slope: -3.12 ± 0.01
-2.92 ± 0.01
-3.19 ± 0.02
fit χ^2 / ndf = 31.6 / 39
15.5
16
16.5
17
17.5
18
18.5
log_10 E [EeV]

Auger energy Spectrum [Above the 2nd Knee]

Additional structure above the Ankle (composition dependent)



Esteban Roulet for the Auger Collaboration [ICRC2025]
Interpretation of spectral shape and composition,



Two extra-galactic component with a low-energy cutoff
(due to Galactic Magnetic field) + Galactic component

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	2nd 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