Cosmic Rays and Extensive Air Showers

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Multi-Messenger Astrophysics
in the era of LHAASO

Online meeting 28th July 2020

Outline:

1. Introduction.
2. Spectral structures below the Knee
3. Measurements of the spectra around the Knee
4. Hadronic Interactions
5. The potential of LHAASO
6. Relation to UHECR
7. Conclusions.

1. INTRODUCTION

Cosmic-Rays in the context of
Multi-messenger Astrophysics

COSMIC RAYS

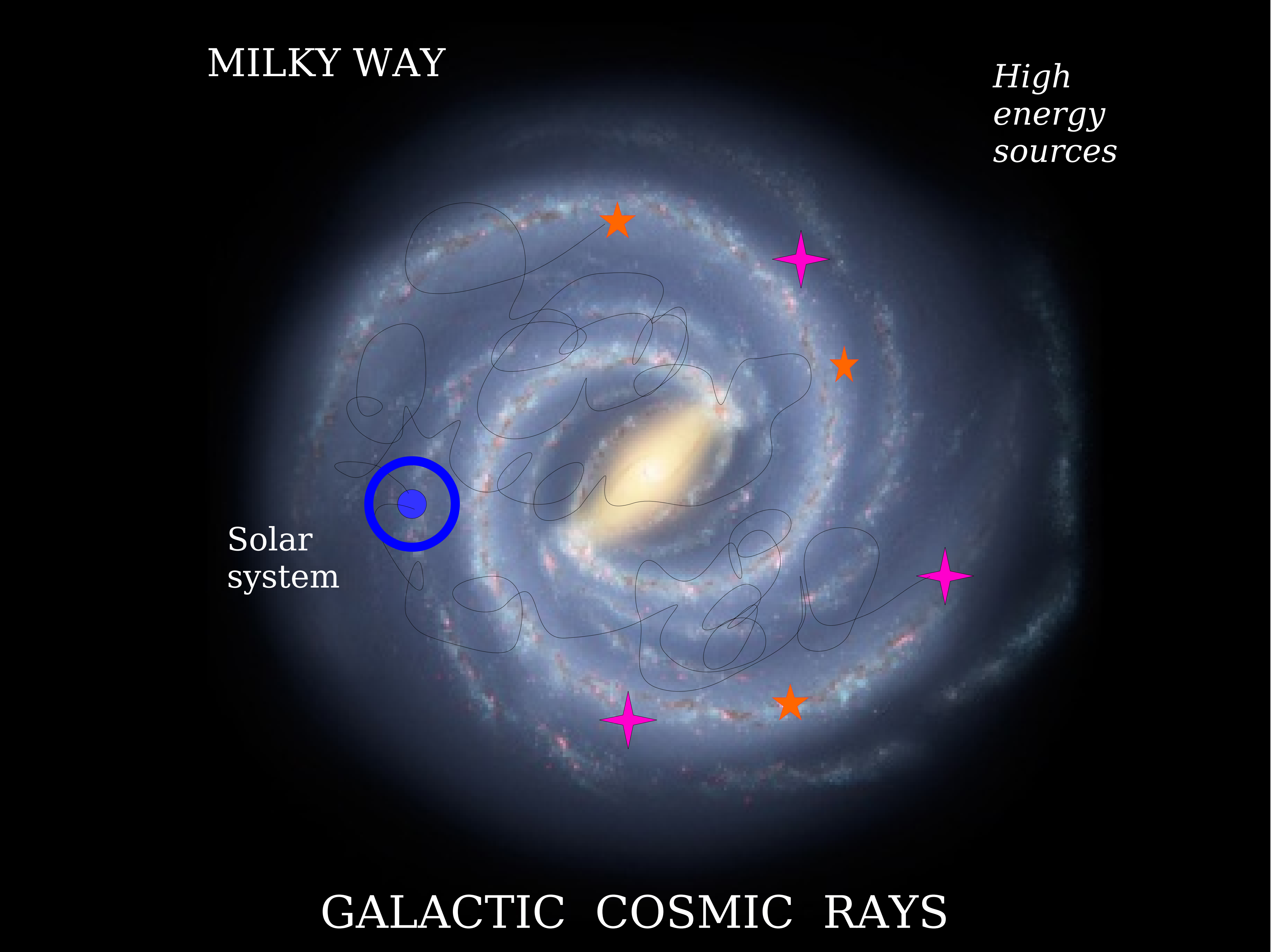
Space and time integrated average of particles generated by many sources in the Galaxy and in the universe, *also shaped by propagation effects*.

Spectra nearly perfectly isotropic $\phi(E,\Omega) \simeq \phi(E)$

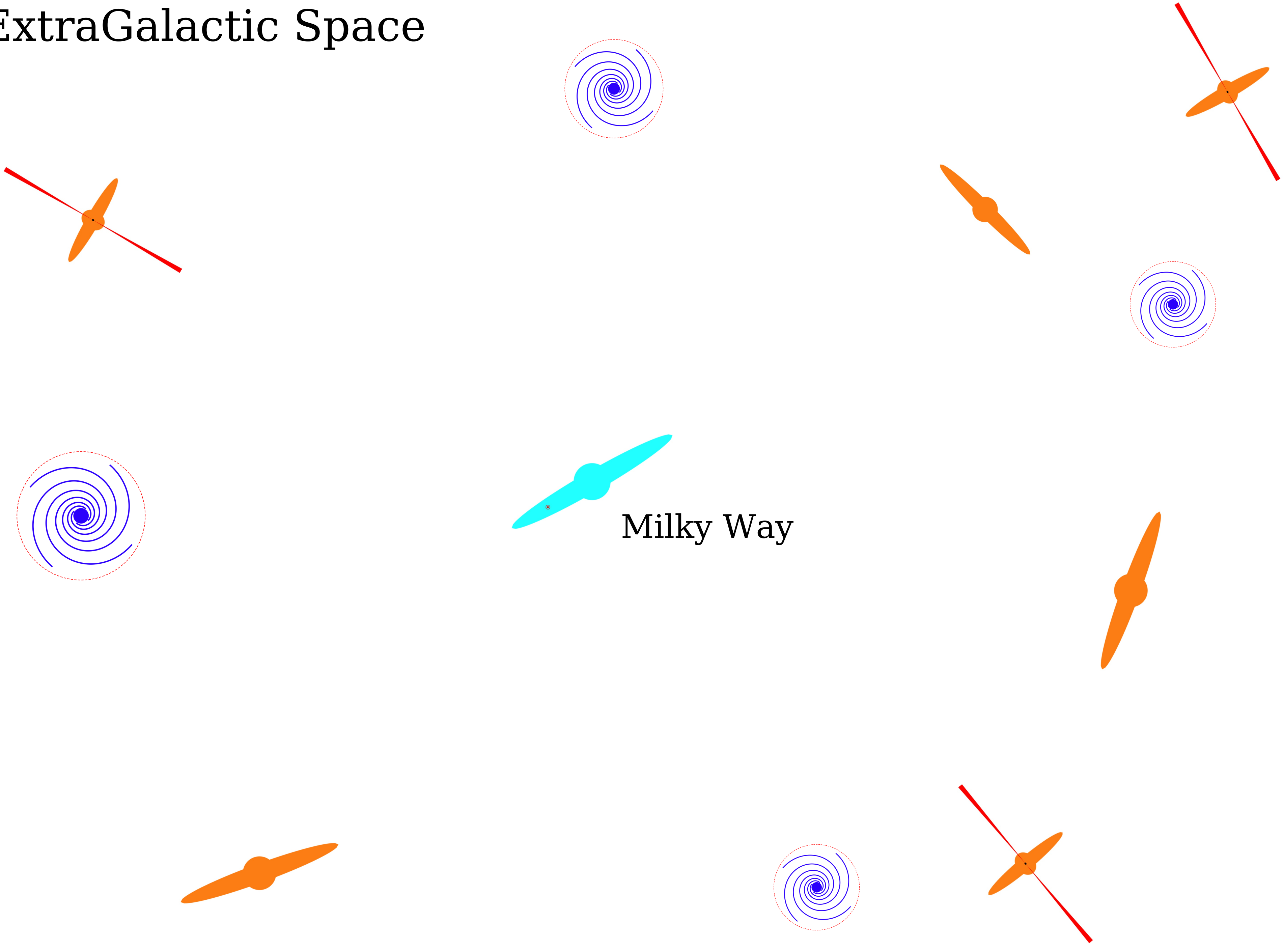
Single point, and (effectively) single time.

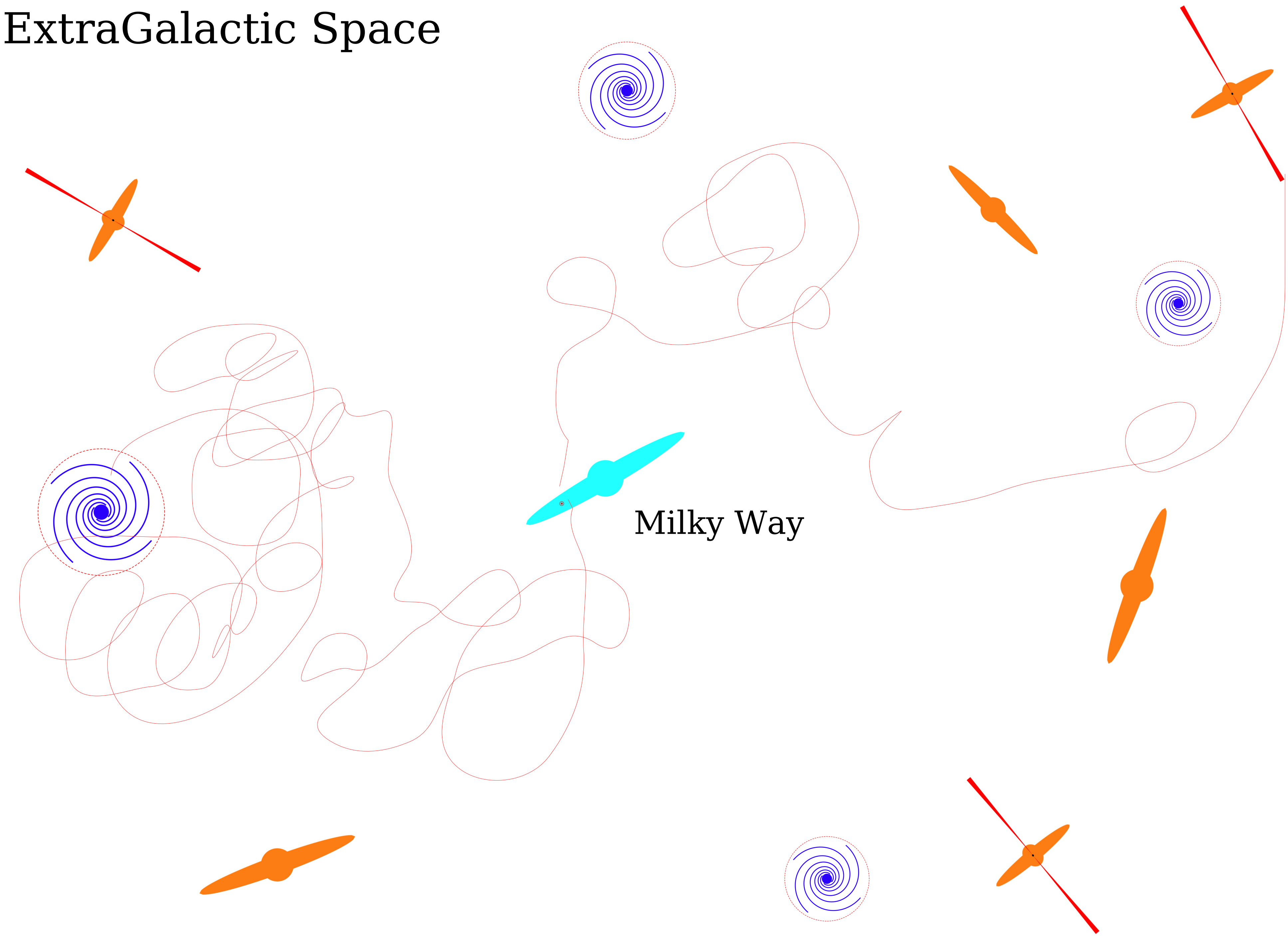
[slow time variations, geological record carries some information]

A *"Local Fog"* that is a terrible nuisance but also carries very important information


MILKY WAY
High energy sources
Solar system
GALACTIC COSMIC RAYS

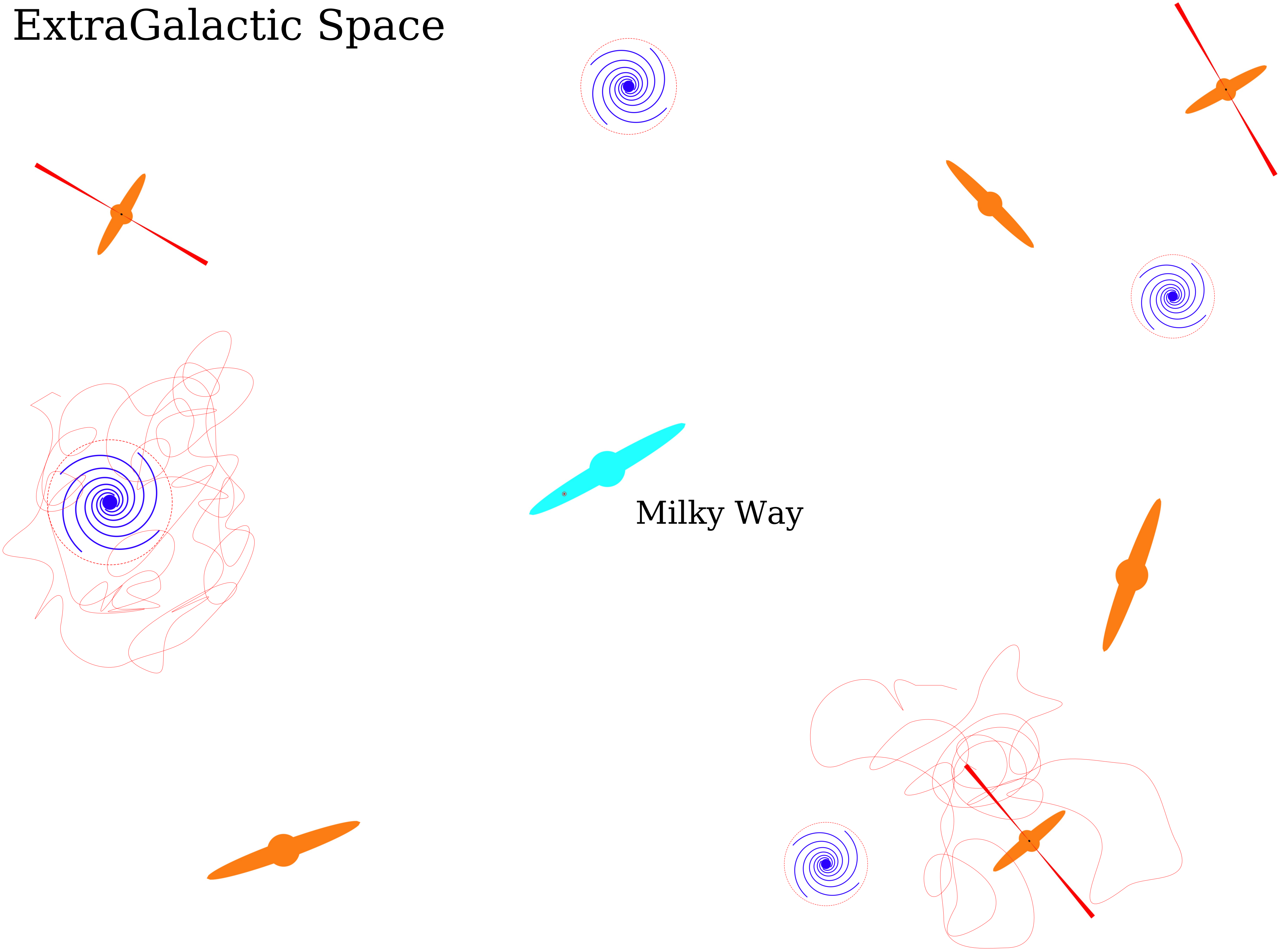
ExtraGalactic Space





Extragalactic Propagation

ExtraGalactic Space



Formation of the Cosmic Ray flux:
divided into two phases:

Injection

[ASTROPHYSICAL SOURCES]

[in interstellar (or intergalactic) space]

Propagation

[from the injection point to the Sun]

Q: is this division really valid ?
A: in most scenarios this is a good subdivision,
but this is a critical point

Very important ambiguity:

Any feature in the shape of the energy spectrum can be attributed to the injection or to propagation.

Most prominent spectral feature
the “Knee” [or better the “Knees”]:

Is it created by Injection or Propagation ?

Galactic Cosmic Rays:

have their origin in sources inside the Milky Way

Extra-Galactic Cosmic Rays

gave their origin in sources outside the Milky Way

Natural to expect that:

Galactic particles dominate the flux at Low energy

Extra-galactic particles dominate the flux at High energy

$$\phi_{\text{galactic}}(E^*) = \phi_{\text{extra galactic}}(E^*)$$

Transition Energy E*

Fundamental *"Boundary Condition"* for
High Energy Astrophysics :

Some sources are capable to accelerate particles
to very high energy:

$$E \sim 10^{20} \text{ eV}$$

Maximum energy for Galactic sources

$$E \sim \text{few} \times 10^{15} \text{ eV}$$

[but perhaps much higher
transition at the "Ankle"]

Fundamental *“Boundary Condition”* for
High Energy Astrophysics :

Some sources are capable to accelerate particles
to very high energy:

$$E \sim 10^{20}\ \mathrm{eV}$$

Extragalactic sky
dominated by Blazars

Do they generate the
highest energy particles ?

Maximum energy for Galactic sources

$$E \sim \mathrm{few} \times 10^{15}\ \mathrm{eV}$$

[but perhaps much higher
transition at the “Ankle”]

Supernova “Paradigm”

Are they the Pevatrons ?

Measurements of the
Cosmic Ray Fluxes at the Earth:

Interpretation
in terms of sources
and propagation

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\quad \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

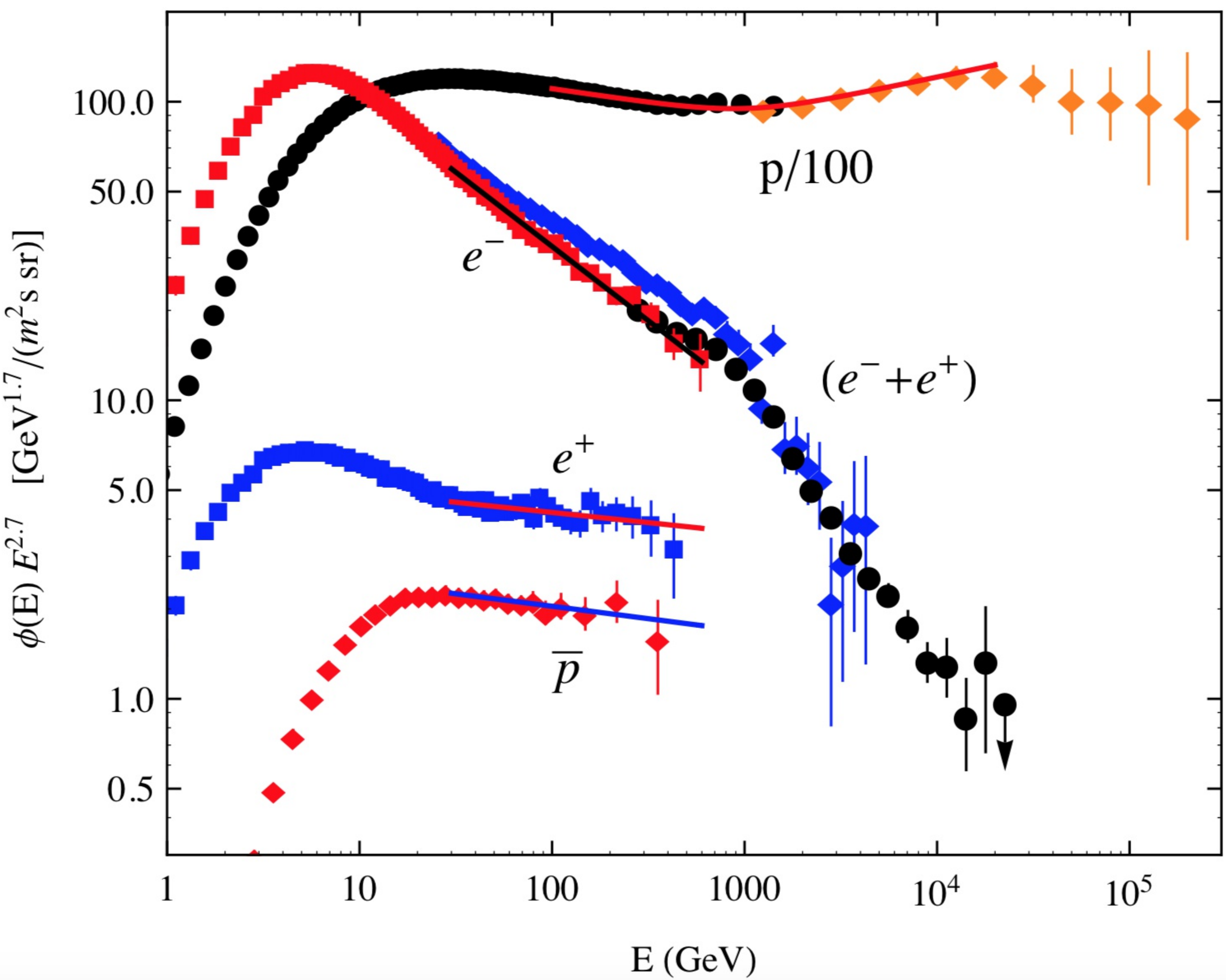
$$\phi_{e^-}(E,\Omega)$$

electrons

$$\phi_{e^+}(E,\Omega)$$

$$\phi_{\overline{p}}(E,\Omega)$$

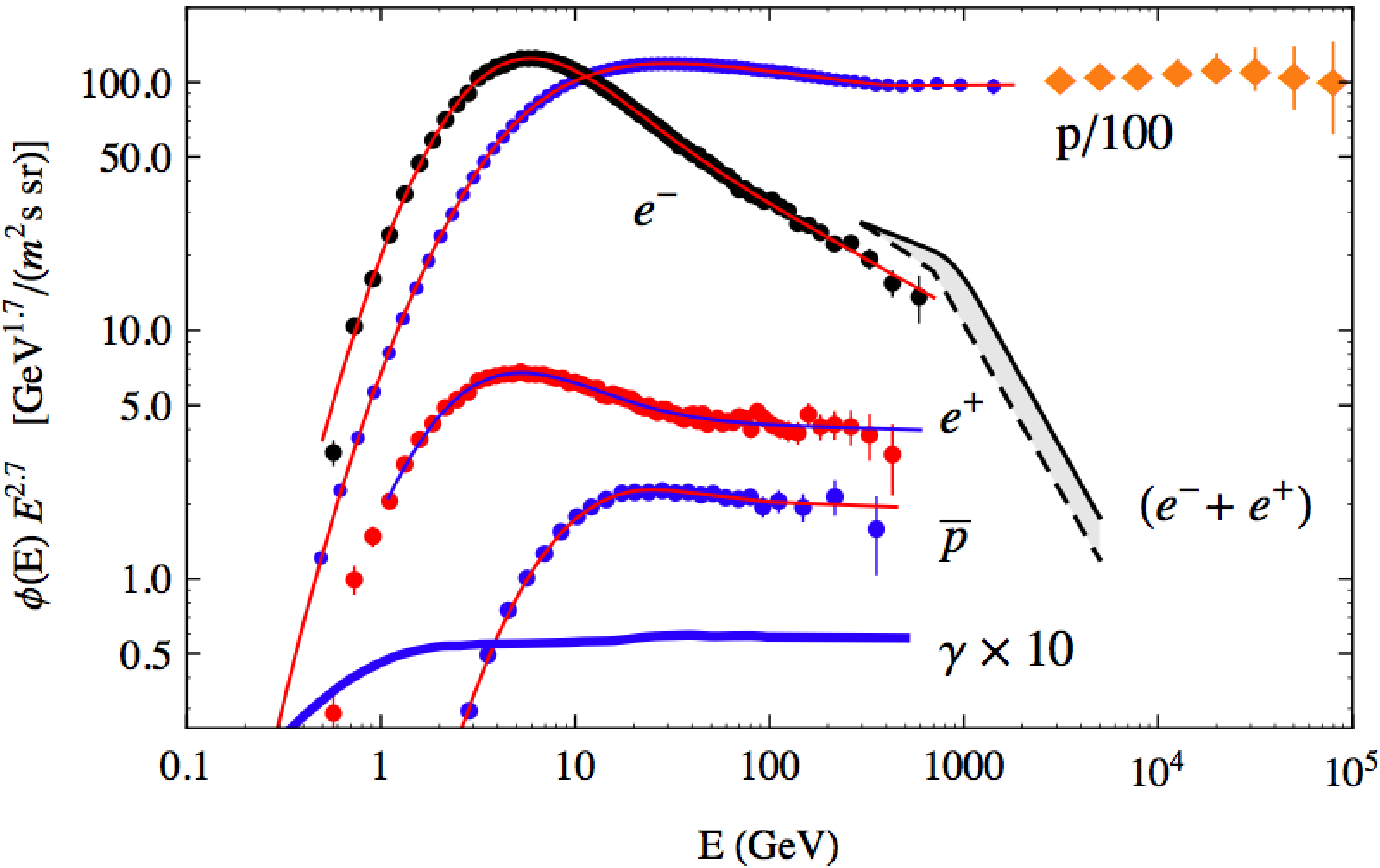
anti-particles



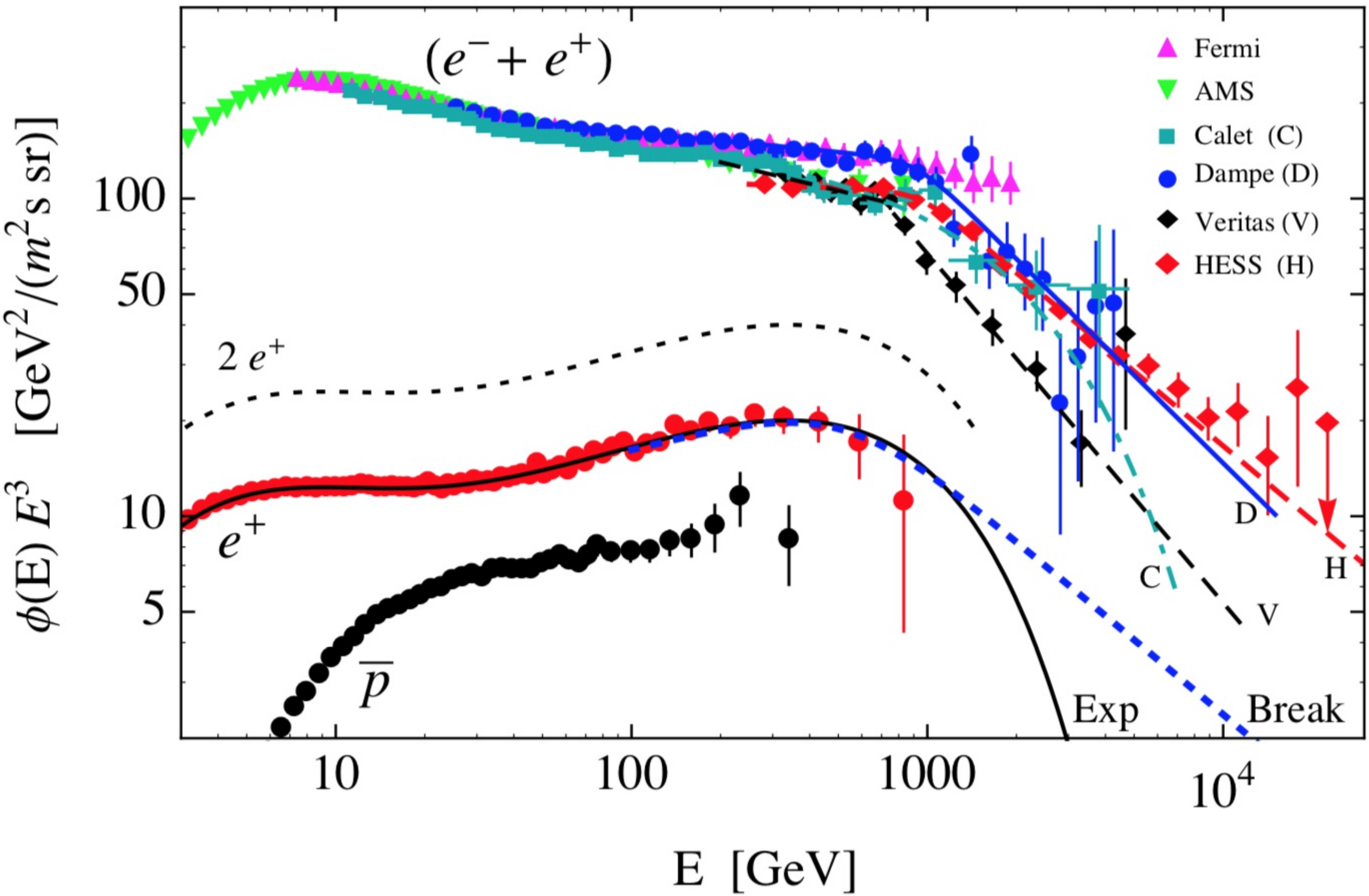
p/100
e^-
$(e^- + e^+)$
e^+
$\overline{p}$
100.0
50.0
10.0
5.0
1.0
0.5
1
10
100
1000
10^4
10^5
$\phi(E)\ E^{2.7}$ [GeV$^{1.7}$/(m^2s sr)]
E (GeV)

Cosmic Ray Spectra $p \quad e^- \quad e^+ \quad \bar{p}$
AMS02

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)



$(e^- + e^+)$
Fermi
AMS
Calet (C)
Dampe (D)
Veritas (V)
HESS (H)
$2\, e^+$
e^+
$\overline{p}$
D
C
V
H
Exp
Break
100
50
10
5
10
100
1000
10^4
$\phi(E)\, E^3$ [$GeV^2/(m^2 s\, sr)$]
E [GeV]

1. The spectra of electrons

Understand CR p/e- co-acceleration in the sources

2. The spectra of positrons and anti-protons.

essential to understand CR propagation.

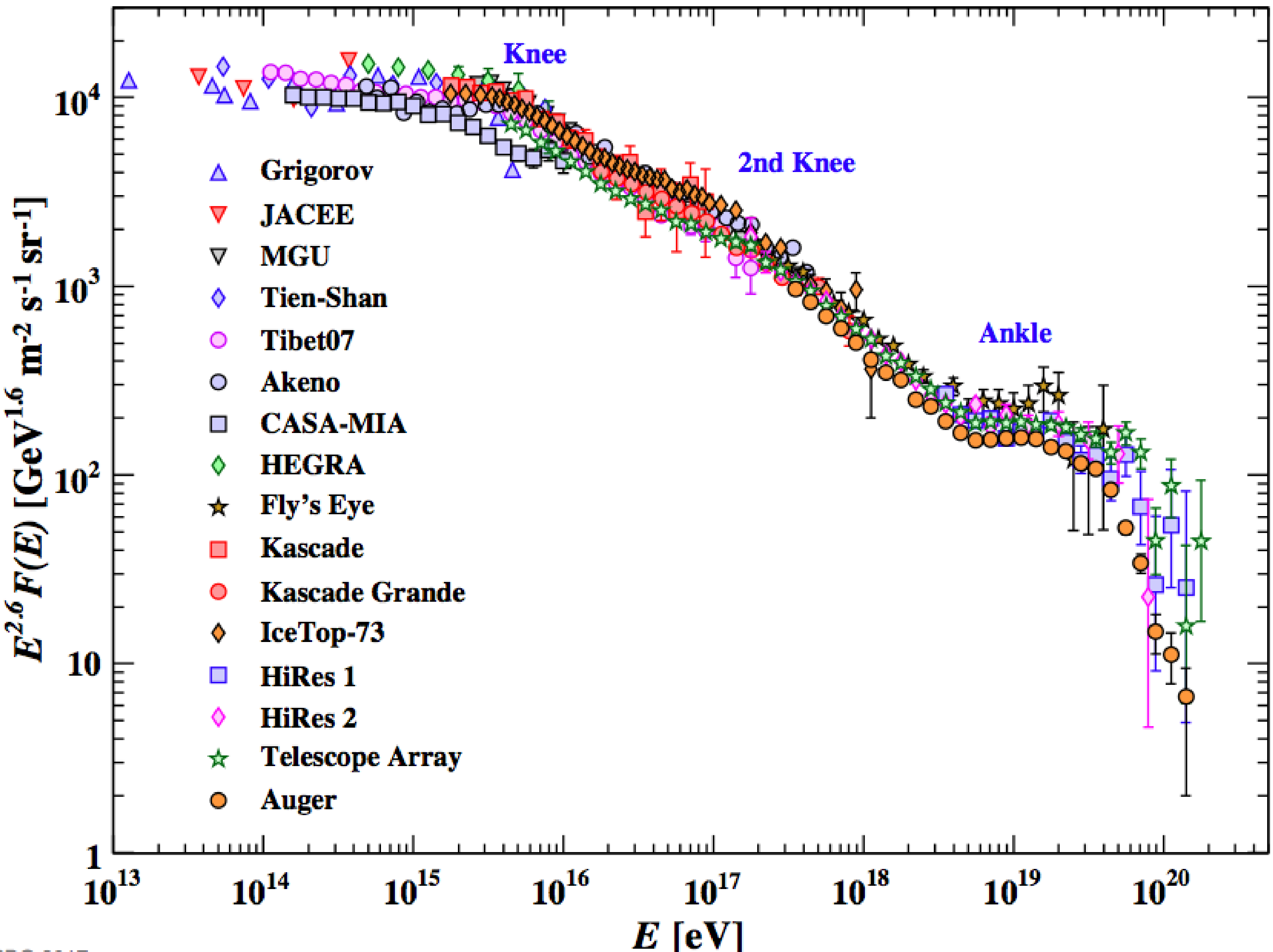
[In my view] finding the solution to
the "positron anomaly" problem
is a crucial problem with deep and broad implications.

2. CR Spectral "Features"

The description of Cosmic Ray Spectra
below the "Knee" as simple power laws
is not valid.

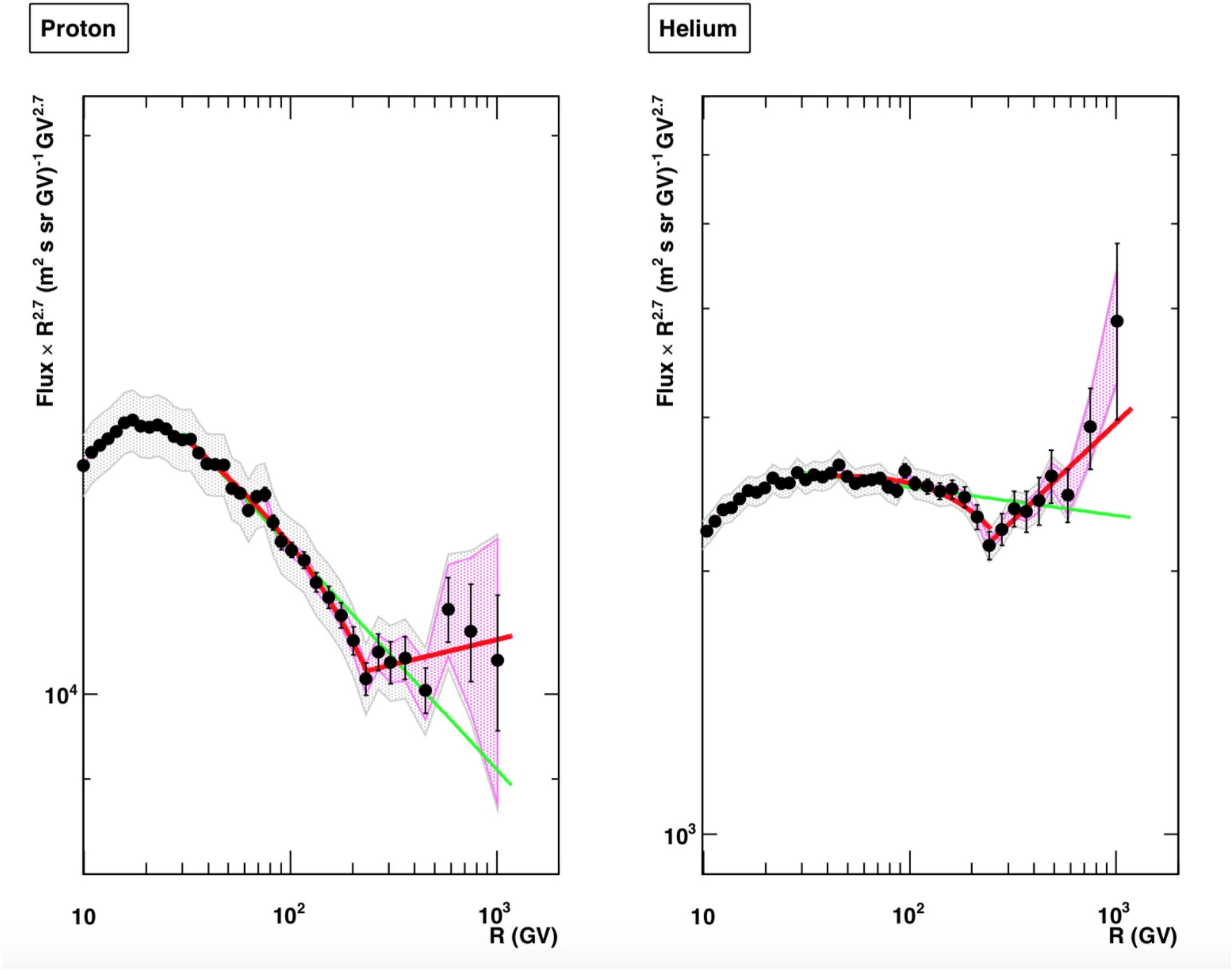
Discovery of spectral features
below the "Knee"

Ultrahigh Energy Cosmic Rays

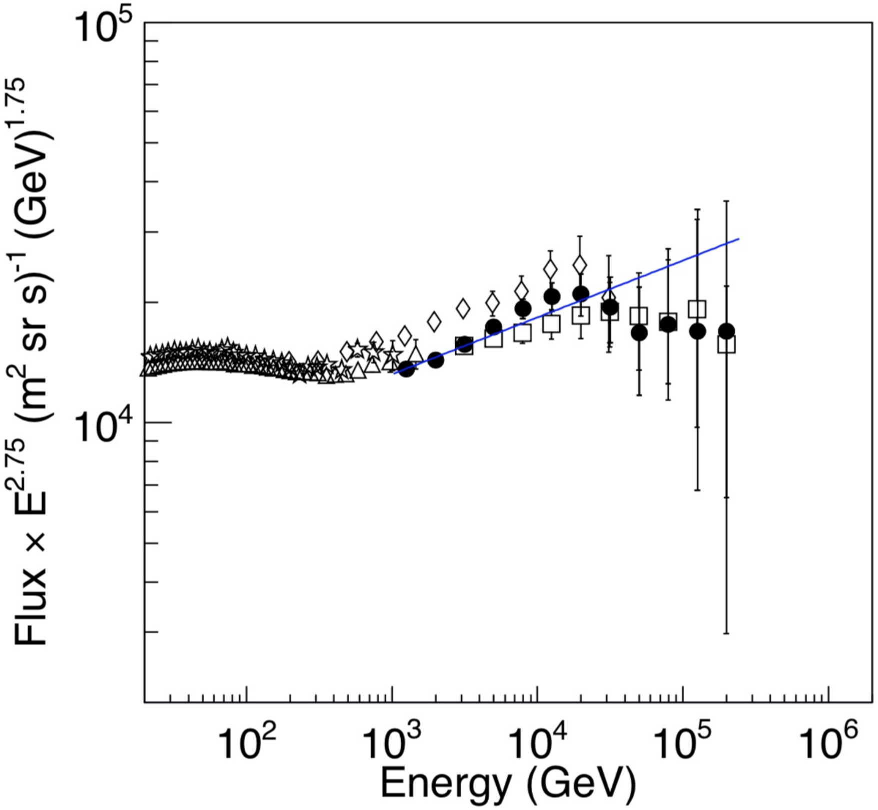


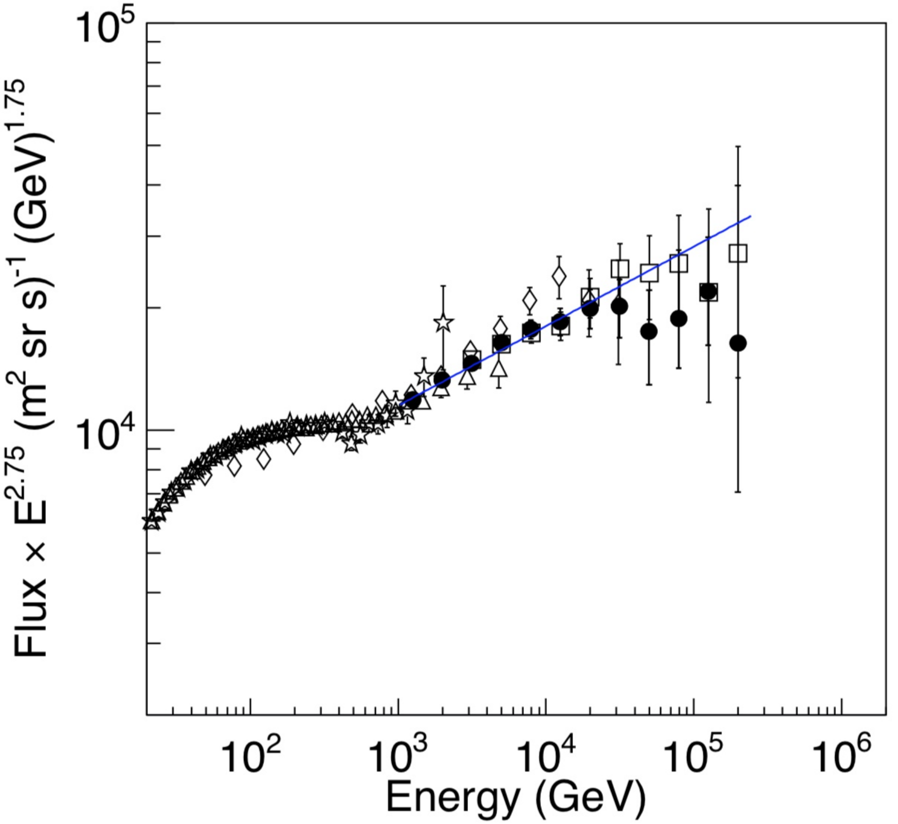
PDG 2017

Pamela Hardening of the proton and Helium spectra



CREAM Measurements of the proton and Helium spectra

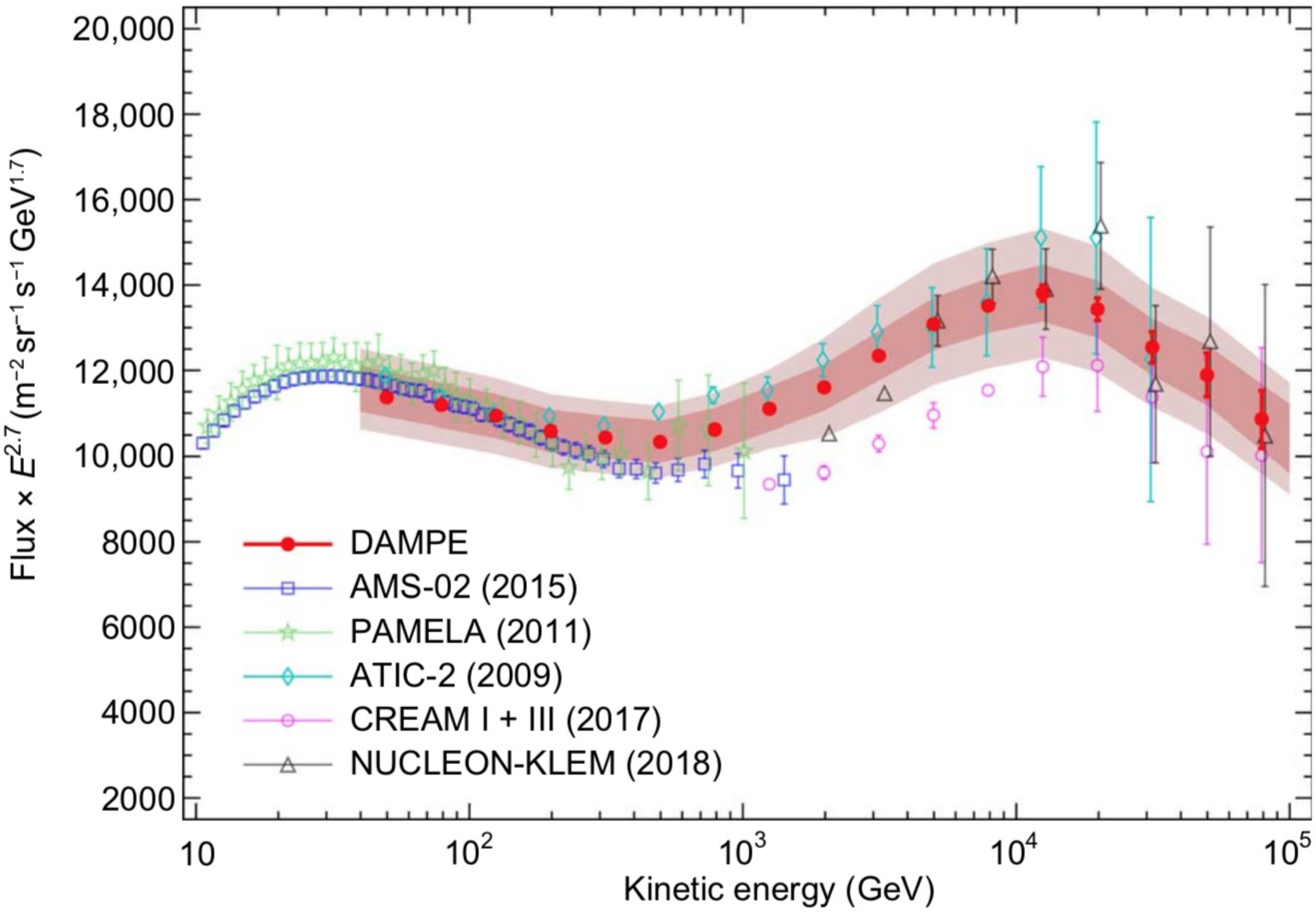




"Hint" of a softening at 10^4 GeV

DAMPE telescope

Clear Observation of the softening in the proton spectrum

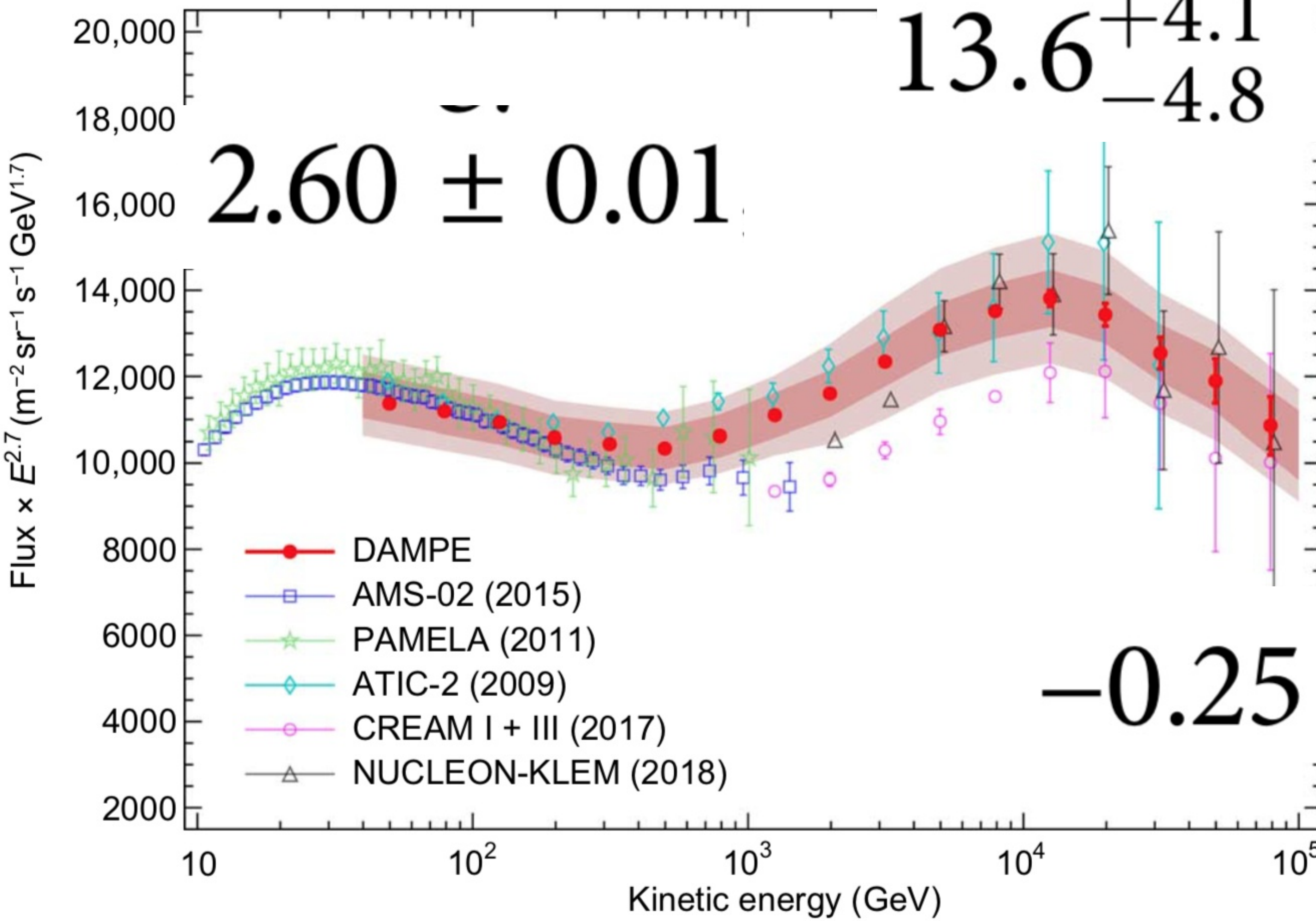


DAMPE telescope

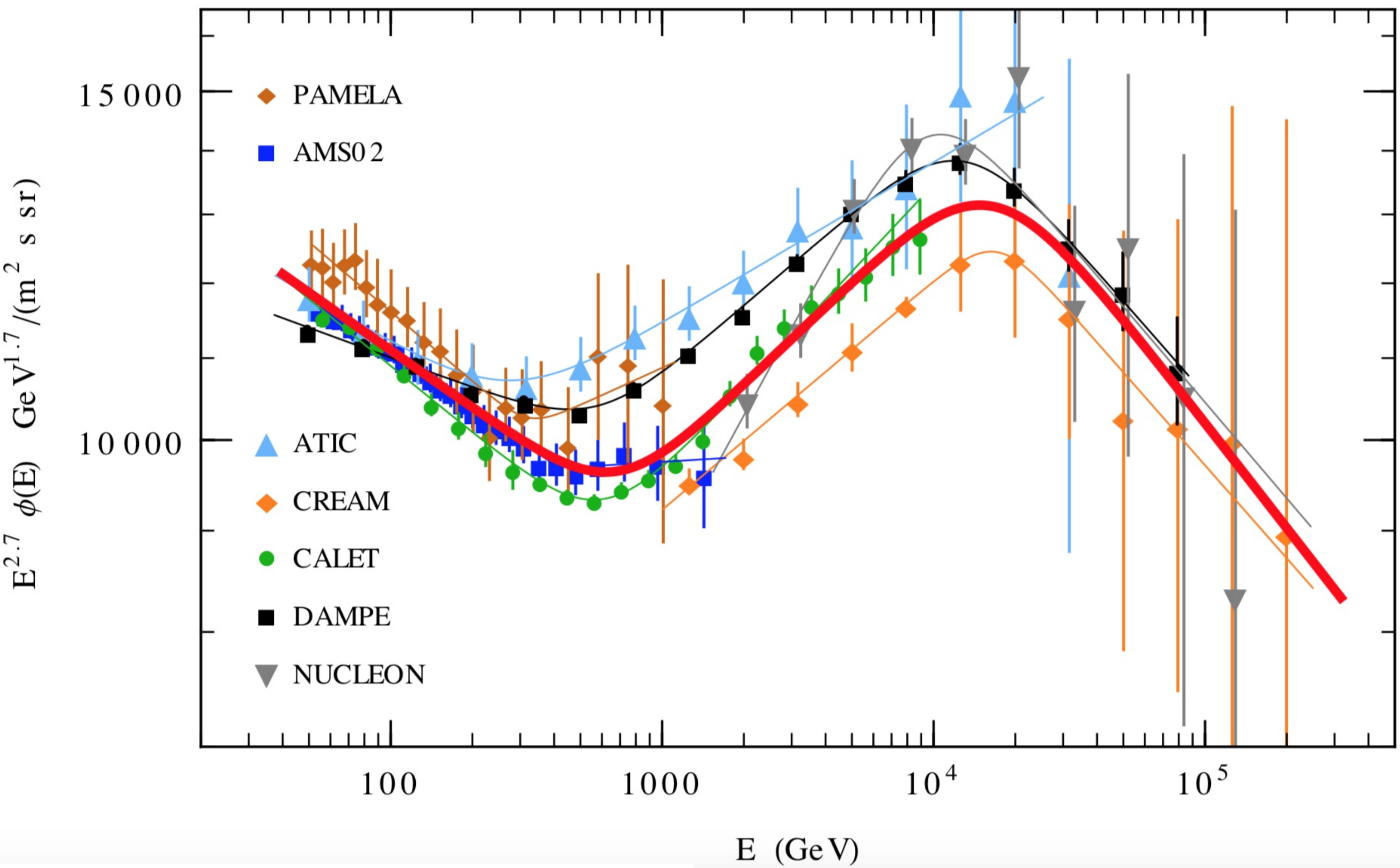
Clear Observation of the softening in the proton spectrum

$13.6^{+4.1}_{-4.8}$ TeV

2.60 ± 0.01

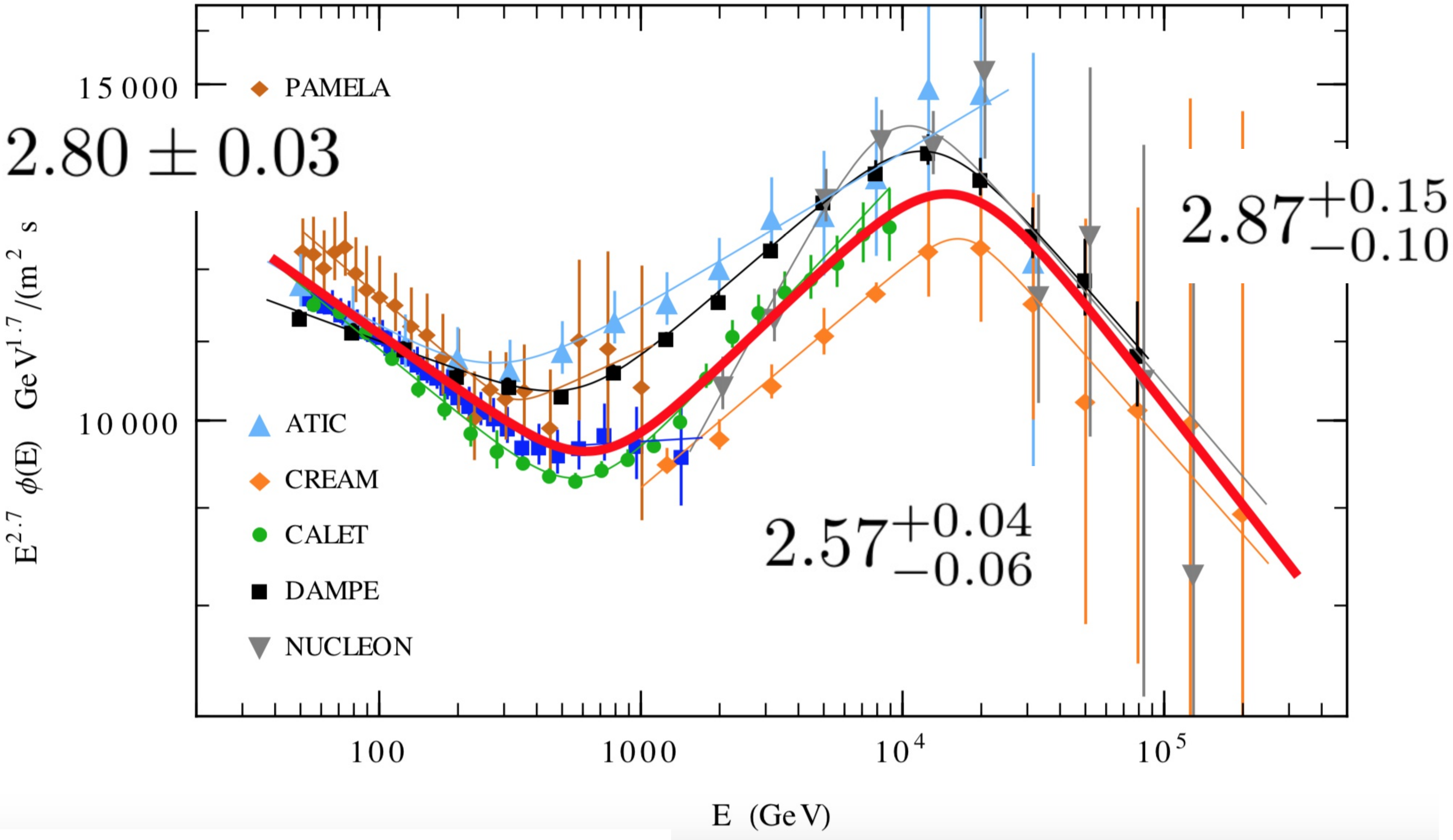


-0.25 ± 0.07



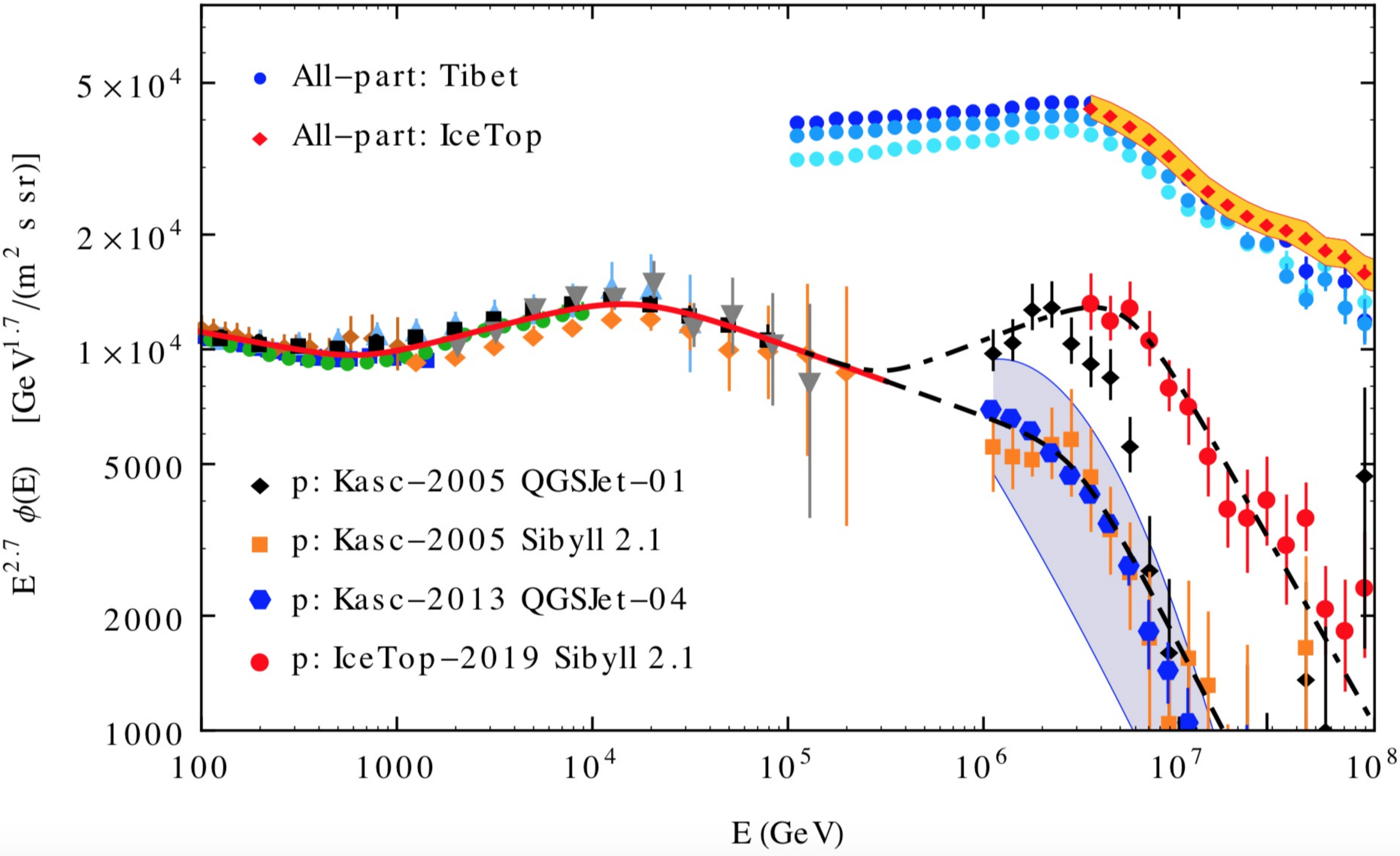
P.L. and Silvia Vernetto,
"The shape of the cosmic ray proton spectrum,"
Astropart. Phys. **120**, 102441 (2020)
[arXiv:1911.01311 [astro-ph.HE]].

Global Fit



P.L. and Silvia Vernetto,
"The shape of the cosmic ray proton spectrum,"
Astropart. Phys. **120**, 102441 (2020)
[arXiv:1911.01311 [astro-ph.HE]].

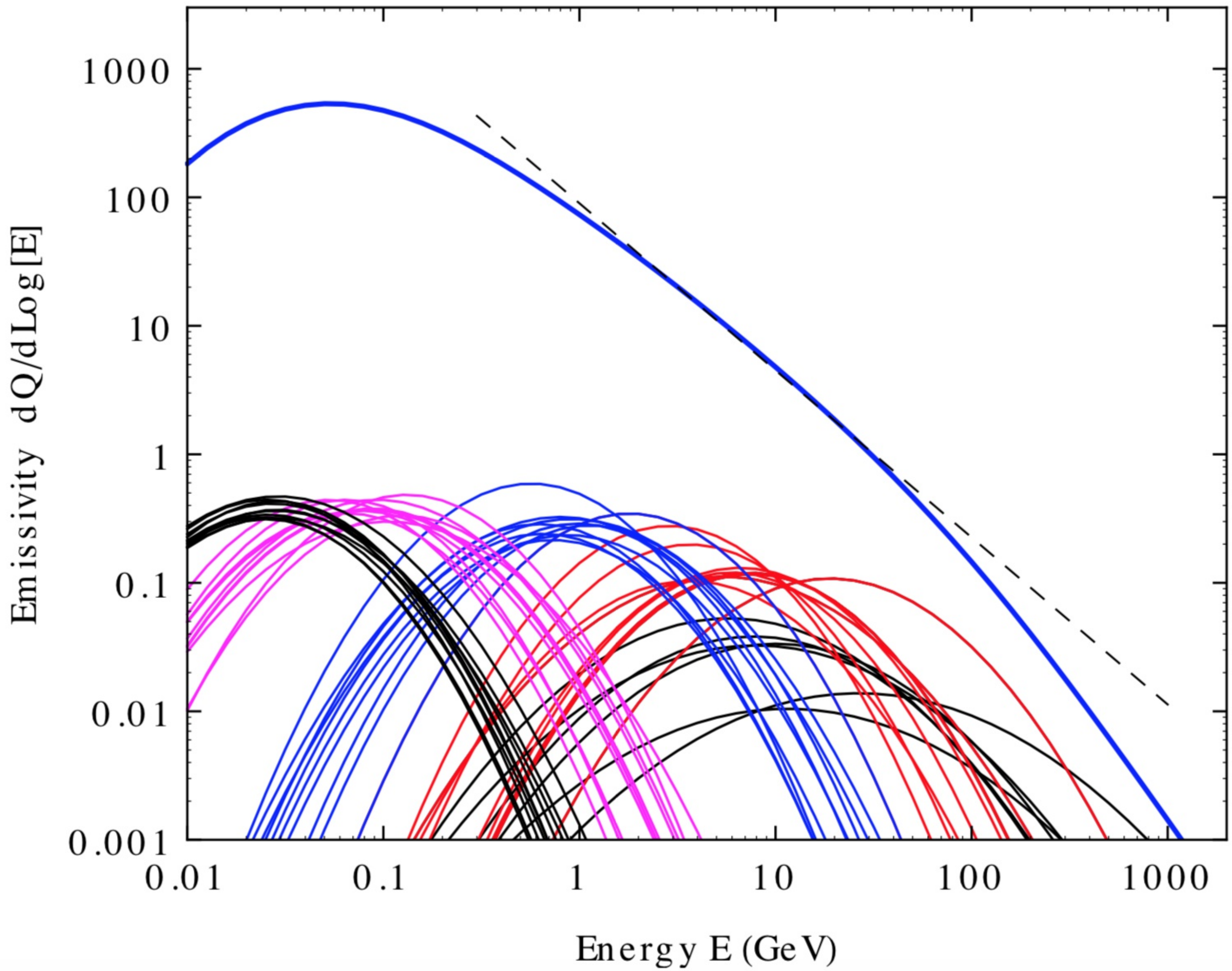
Extrapolation to the region of EAS observations



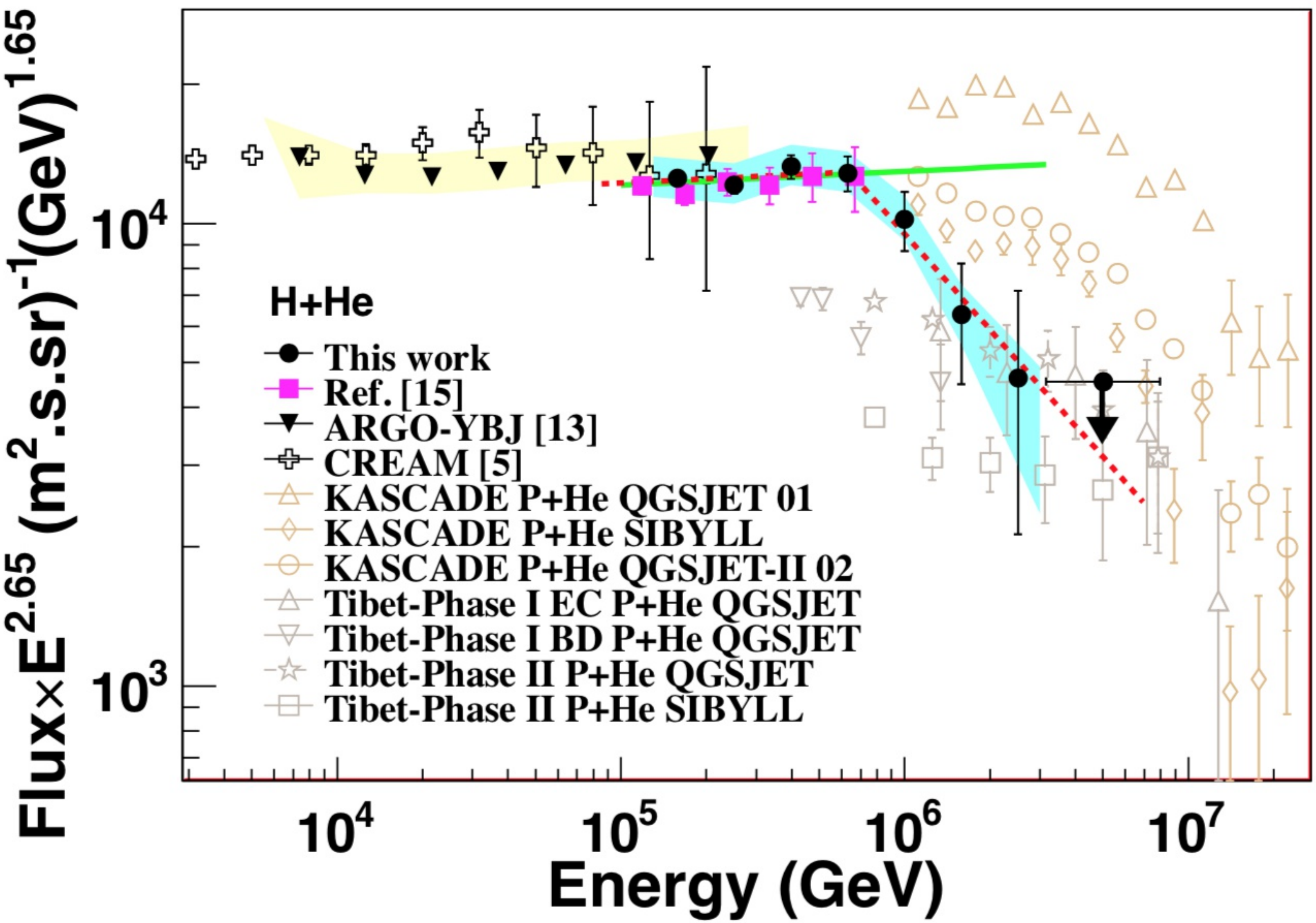
“unorthodox" speculation

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]].



ARGO “light component”Knee



3. Measurements around the "Knee"

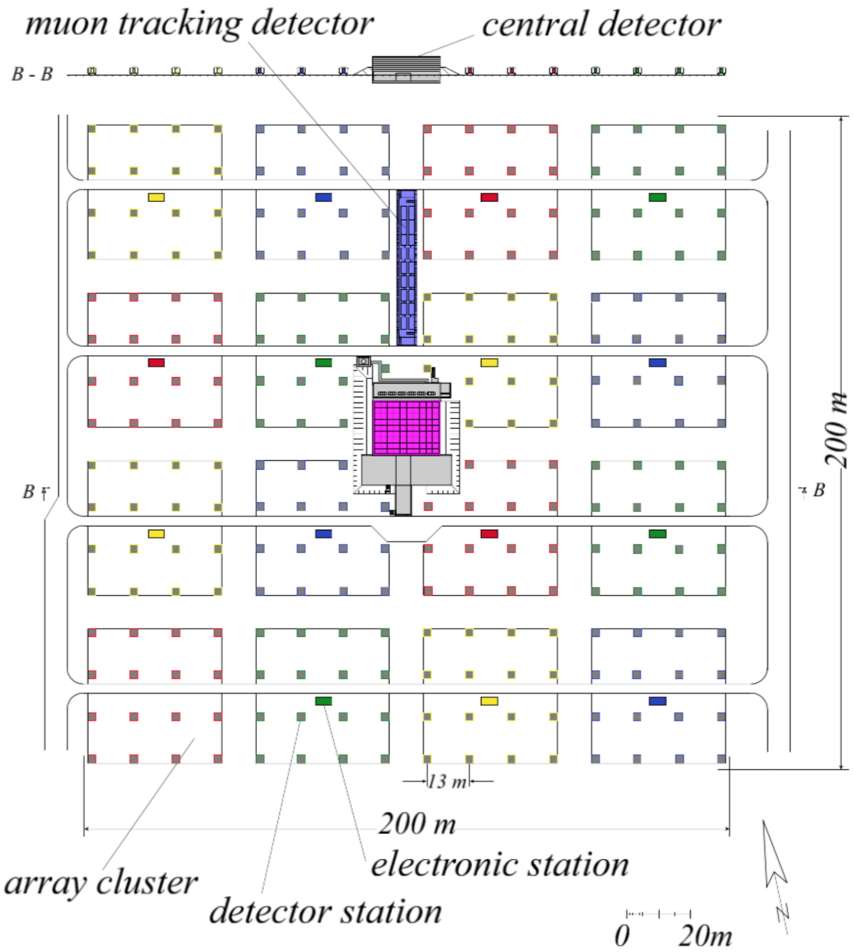
Very large
systematic uncertainties

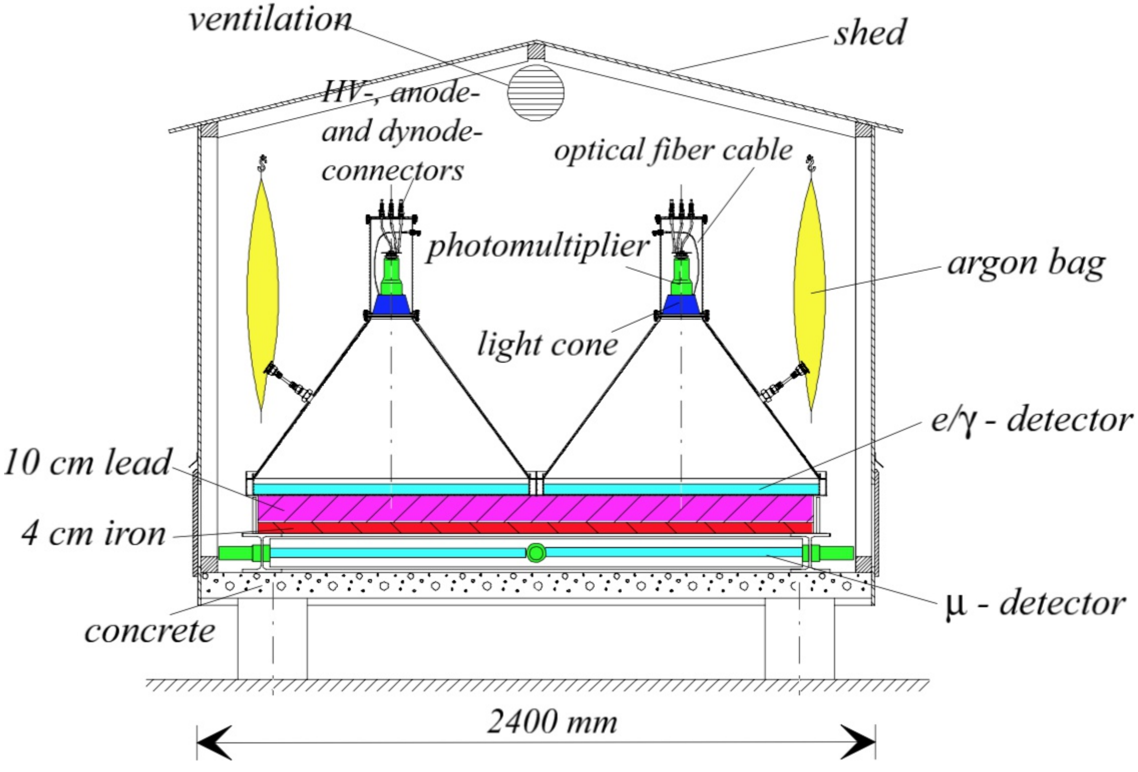
KASCADE Collaboration,
"KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems,"
Astropart. Phys. **24**, 1 (2005)
[astro-ph/0505413].

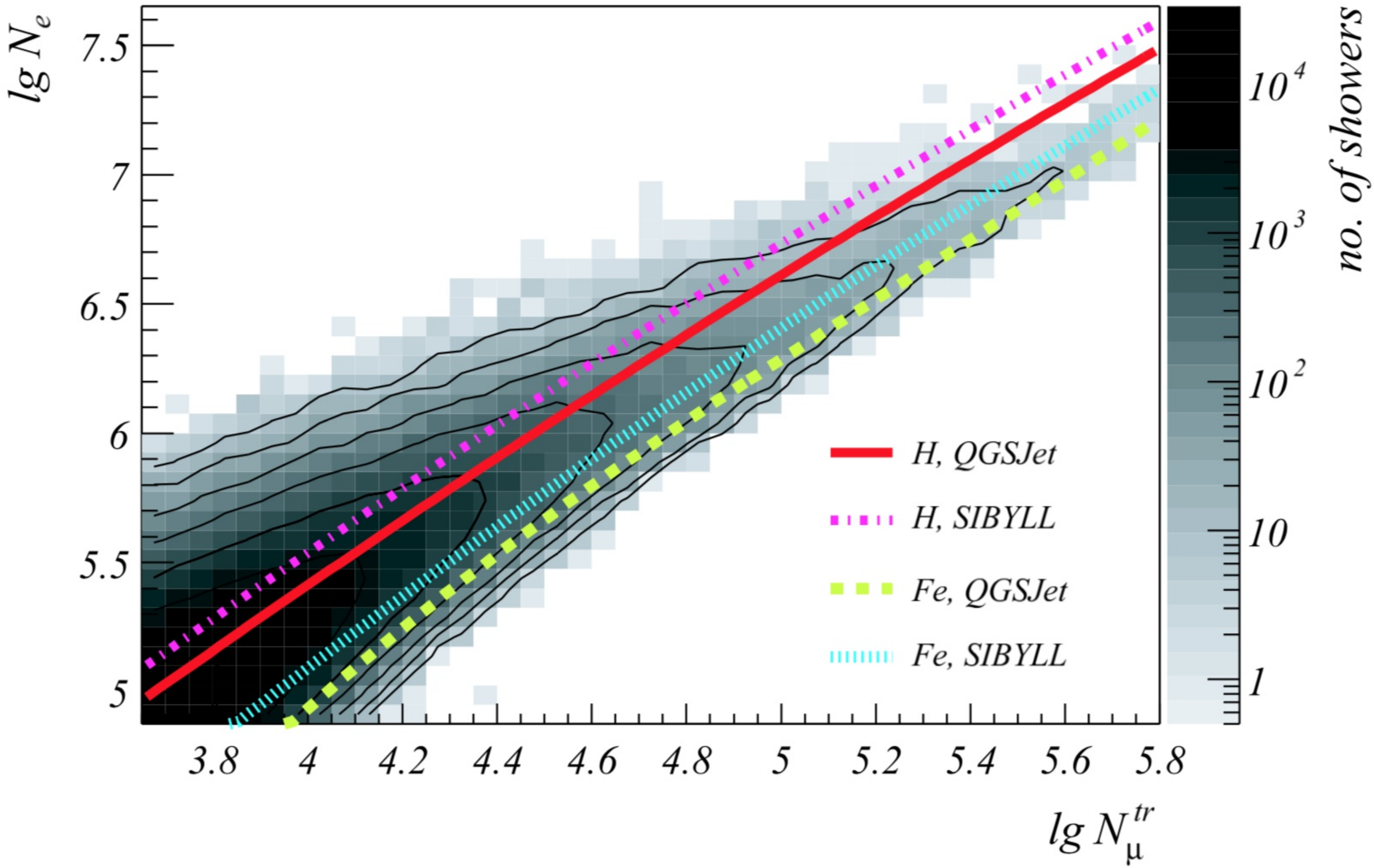
KASCADE-Grande Collaboration,
"KASCADE-Grande measurements of energy spectra for elemental groups of cosmic rays,"
Astropart. Phys. **47**, 54 (2013)
[arXiv:1306.6283 [astro-ph.HE]].

IceCube Collaboration,
"Cosmic ray spectrum and composition from PeV to EeV using 3 years of data from IceTop and IceCube,"
Phys. Rev. D **100**, no.8, 082002 (2019)
[arXiv:1906.04317 [astro-ph.HE]].

The Kascade detector

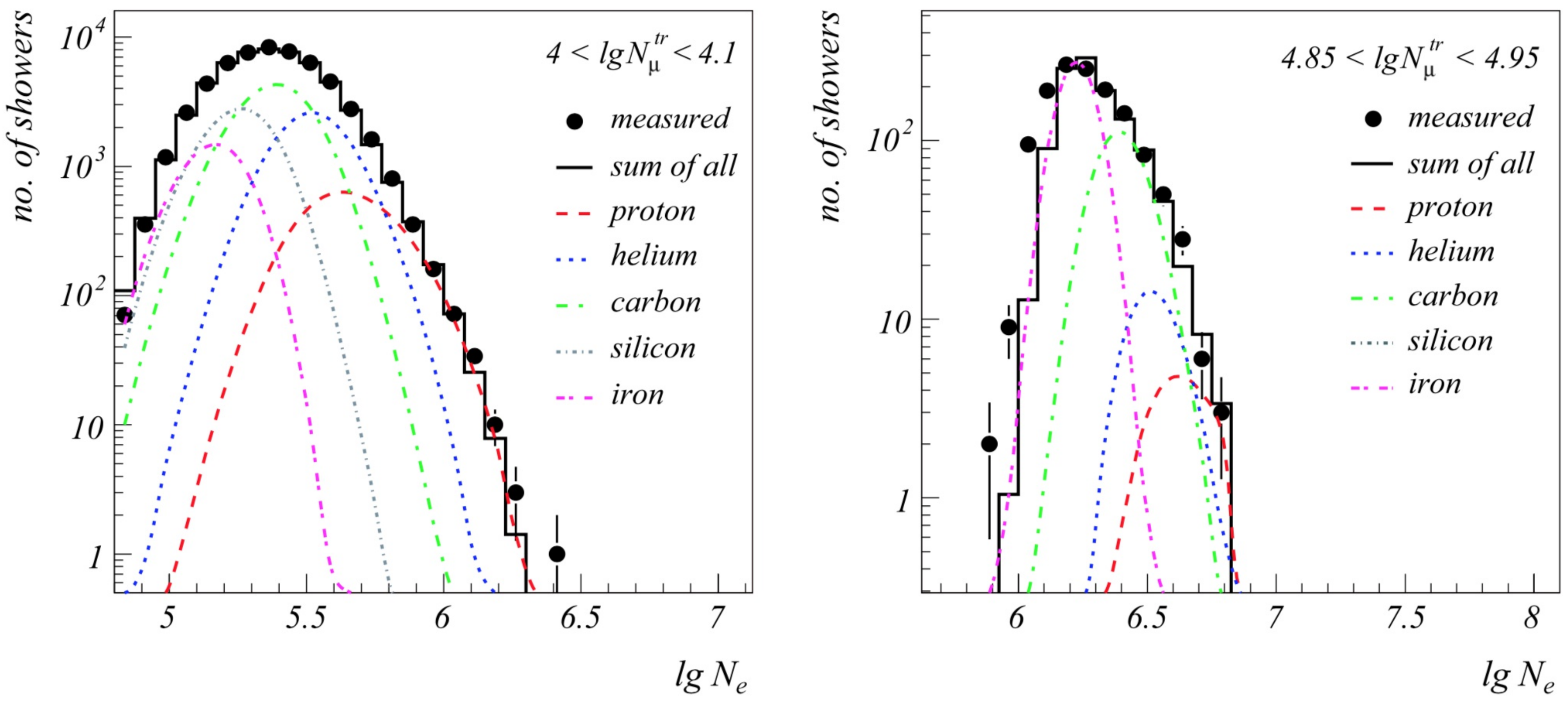




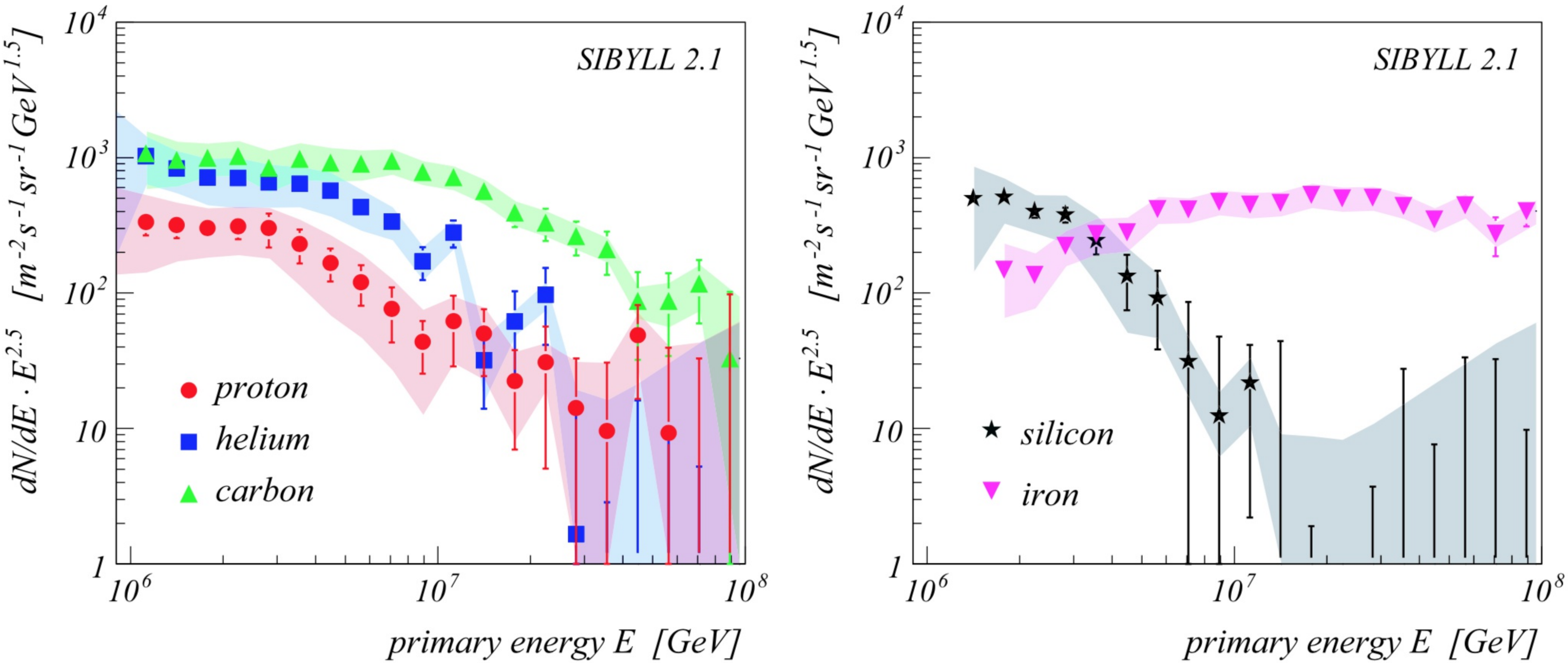


lg N_e
7.5
7
6.5
6
5.5
5
3.8
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
lg N_μ^{tr}
H, QGSJet
H, SIBYLL
Fe, QGSJet
Fe, SIBYLL
no. of showers
10^4
10^3
10^2
10
1

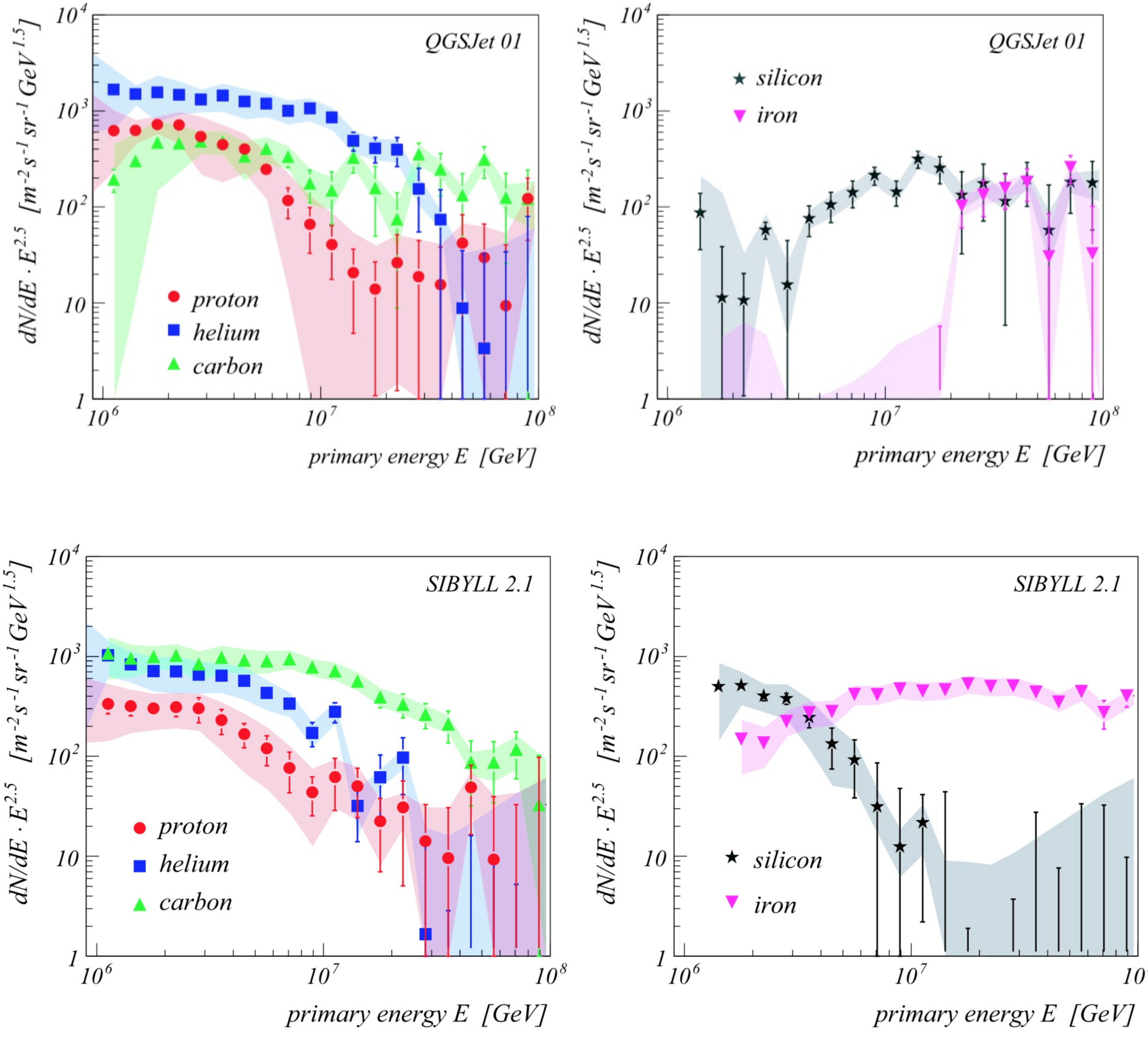
“Unfolding” [Model dependent]

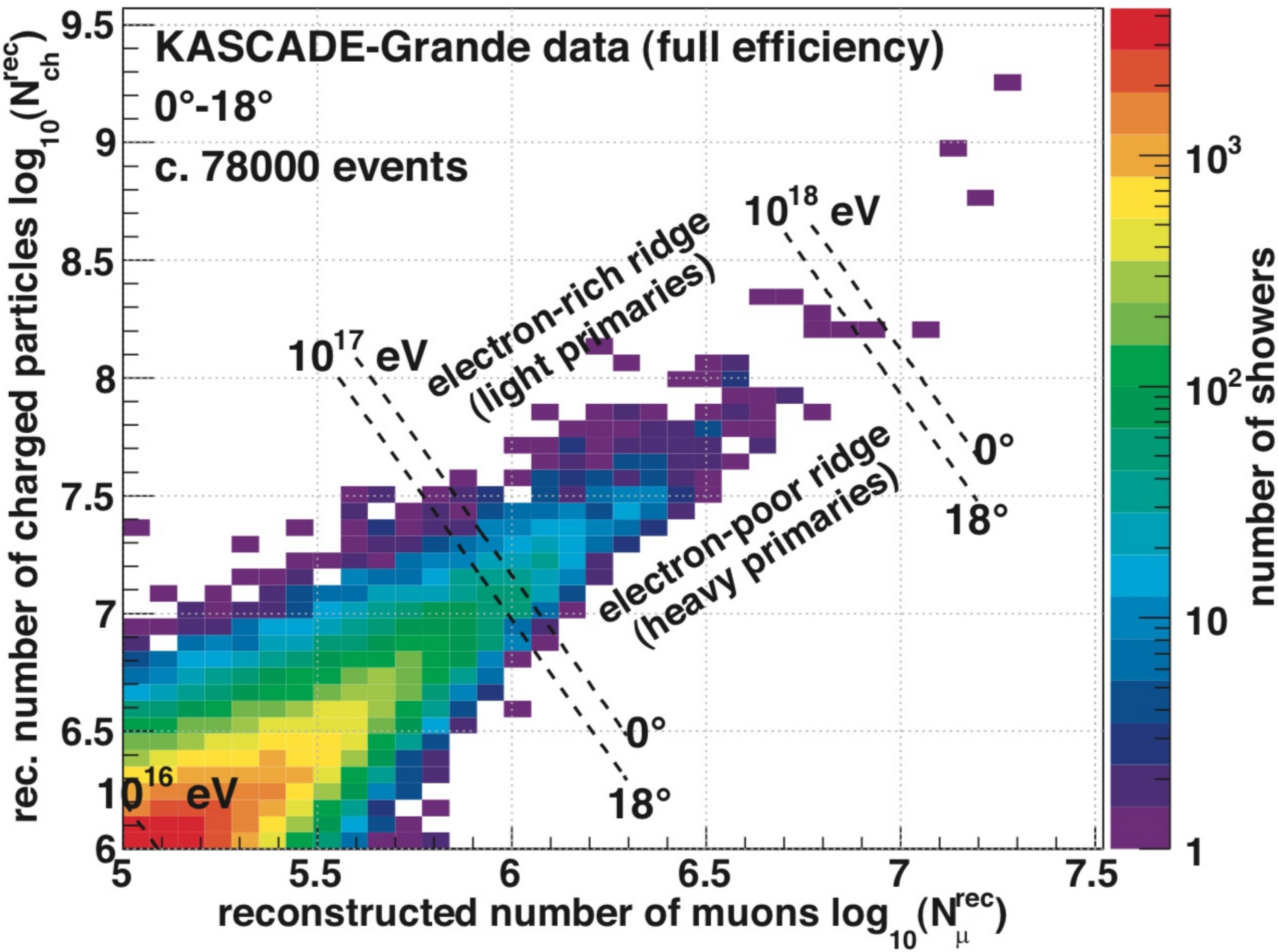


Sibyll-2.1 model

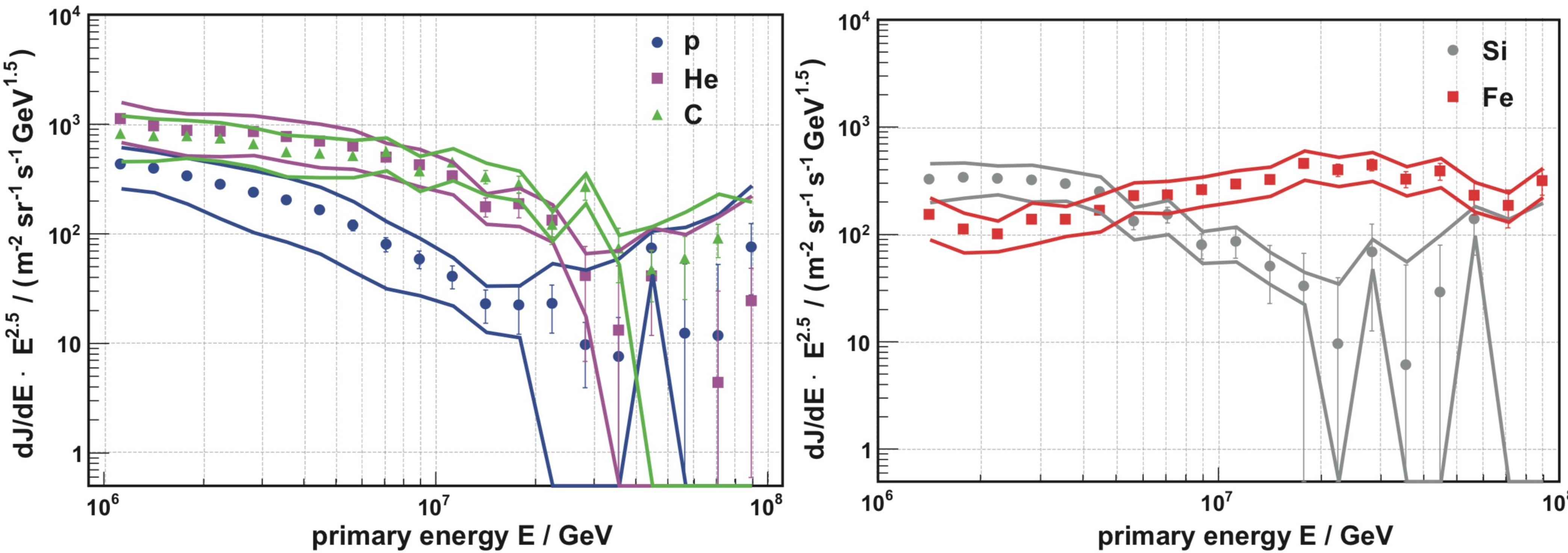


SIBYLL 2.1
dN/dE · E^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
proton
helium
carbon
primary energy E [GeV]
SIBYLL 2.1
silicon
iron


QGSJet 01
proton
helium
carbon
silicon
iron
SIBYLL 2.1
$dN/dE \cdot E^{2.5}$ [$m^{-2} s^{-1} sr^{-1} GeV^{1.5}$]
primary energy E [GeV]



KASCADE-Grande data (full efficiency)
0°-18°
c. 78000 events
10^18 eV
10^17 eV
10^16 eV
electron-rich ridge
(light primaries)
electron-poor ridge
(heavy primaries)
0°
18°
0°
18°
rec. number of charged particles log10(N_ch^rec)
reconstructed number of muons log10(N_μ^rec)
number of showers
9.5
9
8.5
8
7.5
7
6.5
6
5
5.5
6
6.5
7
7.5
10^3
10^2
10
1



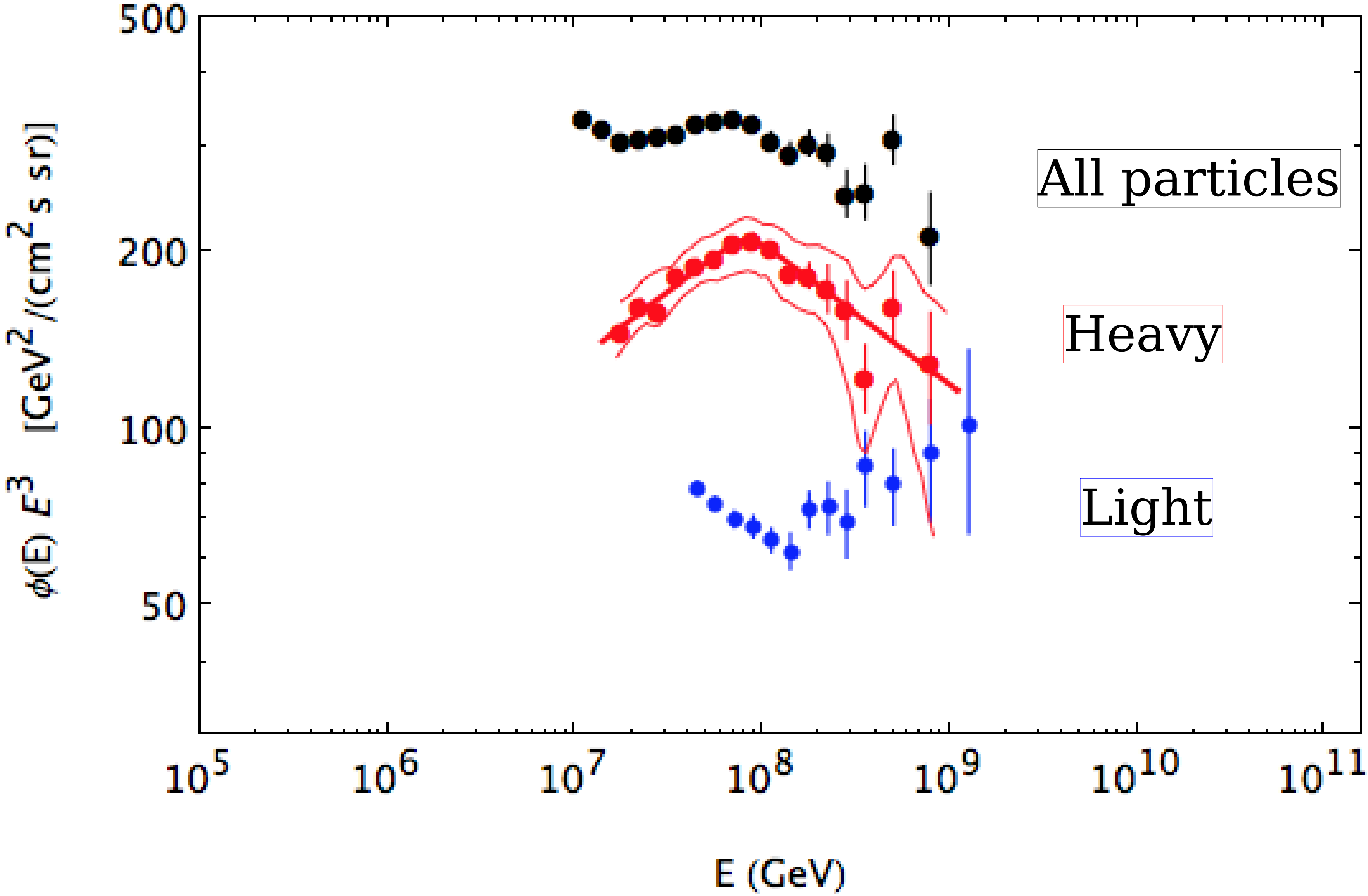
dJ/dE · E^2.5 / (m^-2 sr^-1 s^-1 GeV^1.5)
primary energy E / GeV
p
He
C
Si
Fe

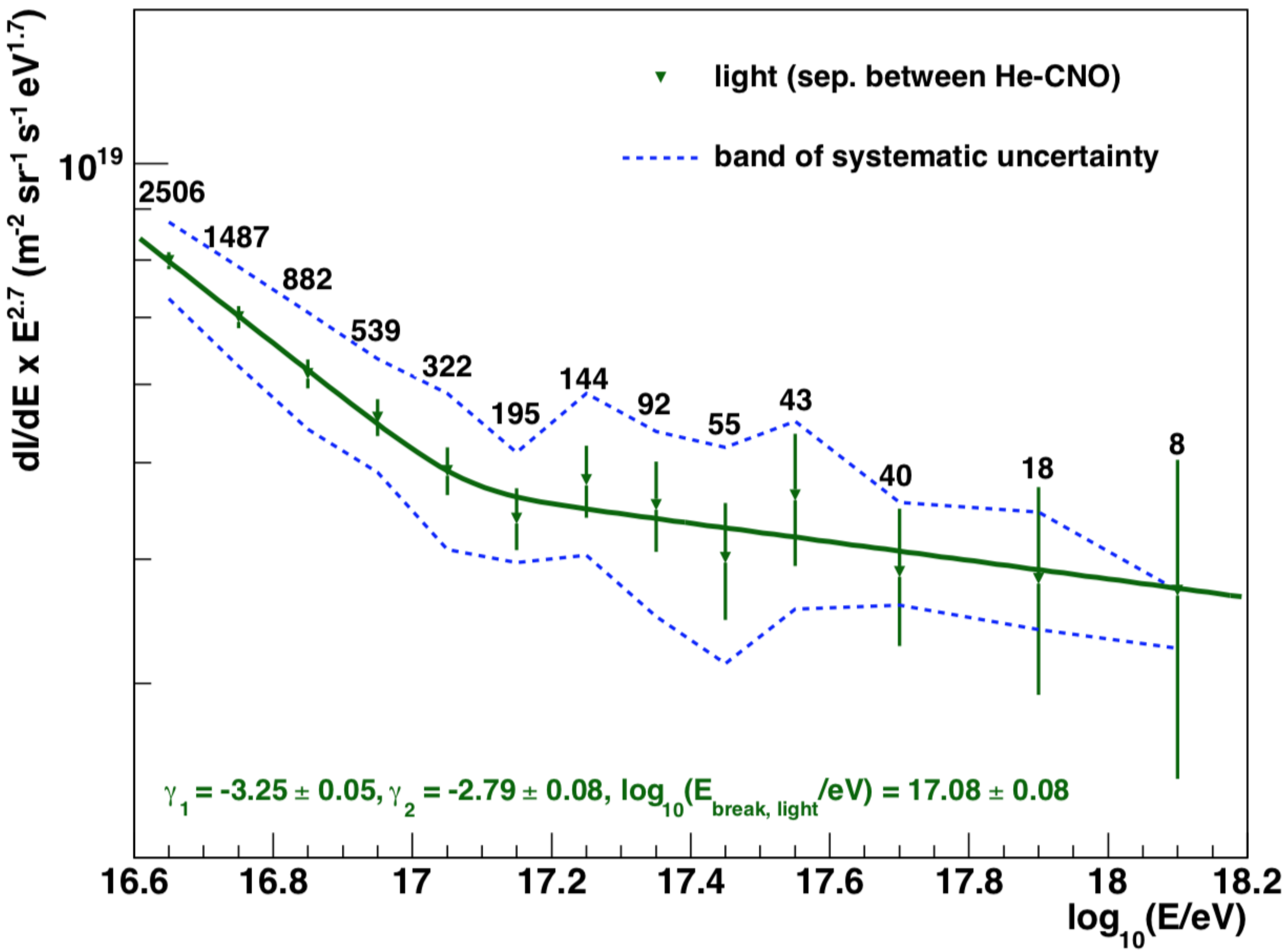
KASCADE-GRANDE Collaboration
"The spectrum of high-energy cosmic rays measured with KASCADE-Grande,"
Astropart. Phys. **36**, 183-194 (2012)

KASCADE-GRANDE Collaboration
"Ankle-like Feature in the Energy Spectrum of Light Elements of Cosmic Rays Observed with KASCADE-Grande,"
Phys. Rev. D **87**, 081101 (2013)
[arXiv:1304.7114 [astro-ph.HE]].

KASCADE-GRANDE Collaboration
"Kneelike structure in the spectrum of the heavy component of cosmic rays observed with KASCADE-Grande,"
Phys. Rev. Lett. **107**, 171104 (2011)
[arXiv:1107.5885 [astro-ph.HE]].

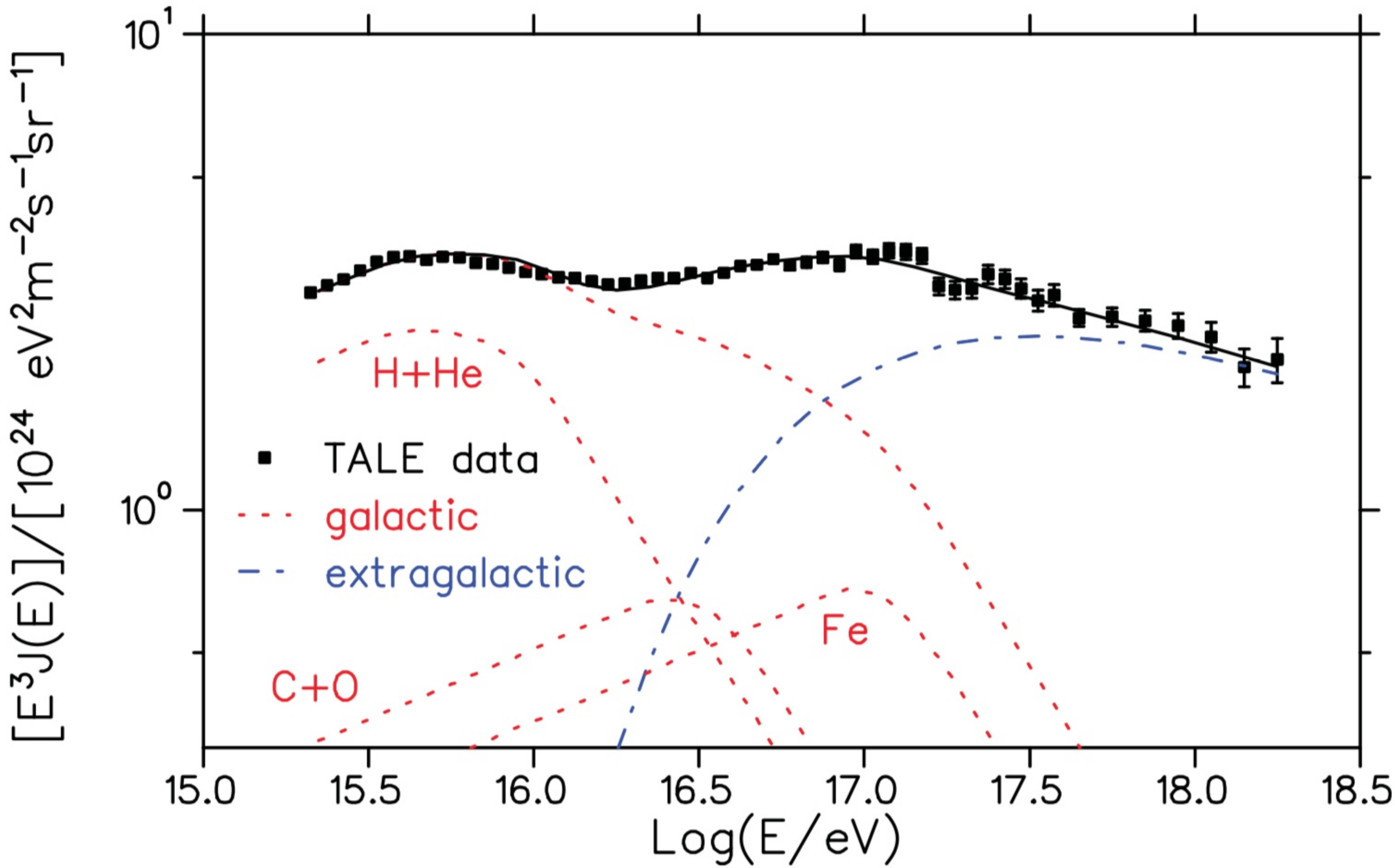
KASCADE-GRANDE Results





light (sep. between He-CNO)
band of systematic uncertainty
10^{19}
2506
1487
882
539
322
195
144
92
55
43
40
18
8
γ_1 = -3.25 ± 0.05, γ_2 = -2.79 ± 0.08, $\log_{10}(E_{break, light}/eV)$ = 17.08 ± 0.08
16.6
16.8
17
17.2
17.4
17.6
17.8
18
18.2
$\log_{10}(E/eV)$
dI/dE x $E^{2.7}$ (m^{-2} sr^{-1} s^{-1} $eV^{1.7}$)

T. Abu-Zayyad *et al.*,
"The Knee and the Second Knee of the Cosmic-Ray Energy Spectrum,"
arXiv:1803.07052 [astro-ph.HE].



Main results of the observations
[Kascade, Kascade-GRANDE, IceTop/IceCube]

[1.] Composition that becomes gradually "heavier"

Simple hypothesis:
Rigidity dependent spectral shapes

$$\phi_Z(E_p\, Z) \propto \phi_p(E_p)$$

This is consistent with the data but not clearly established. Should be verified experimentally

Shape of the spectra should be accurately measured (to allow an understanding of its origin)

[2.] Emergence of a light (proton rich) component

[Auger, TA] $E \approx 10^{18}$ eV composition proton rich

Systematic Uncertainties
in the measurement of the Cosmic Ray Spectra

1. Understand the detector performances

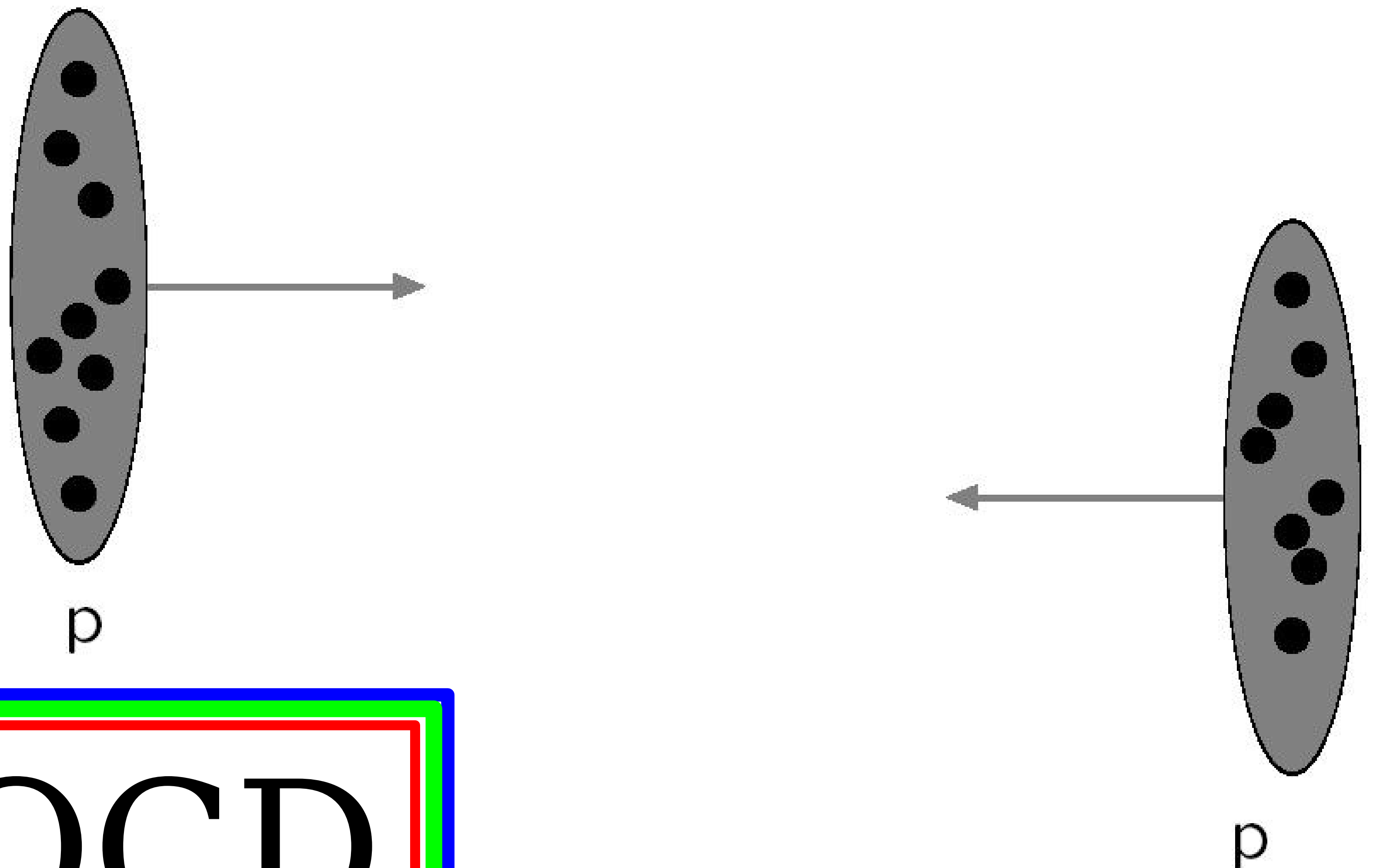
2. Algorithms of analysis

2. Modeling of Shower Development

Hadronic Interactions

"The Dark Side of the
(Particle Physics) Standard Model"

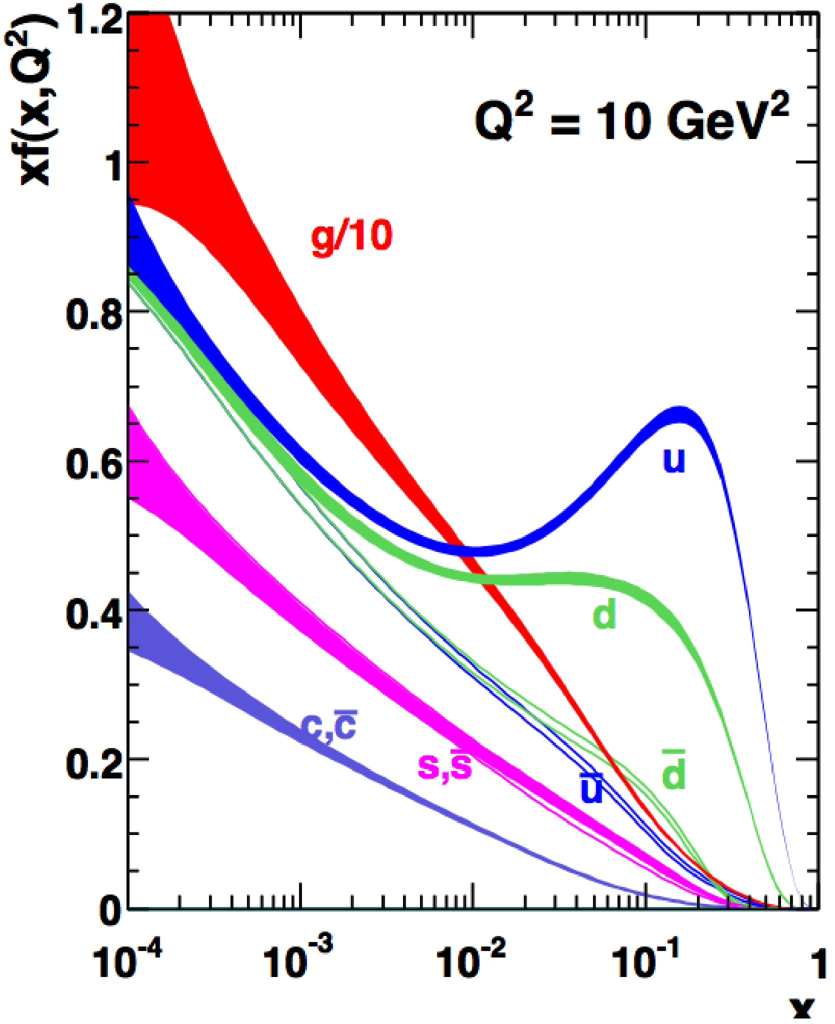
4. Hadronic Interactions

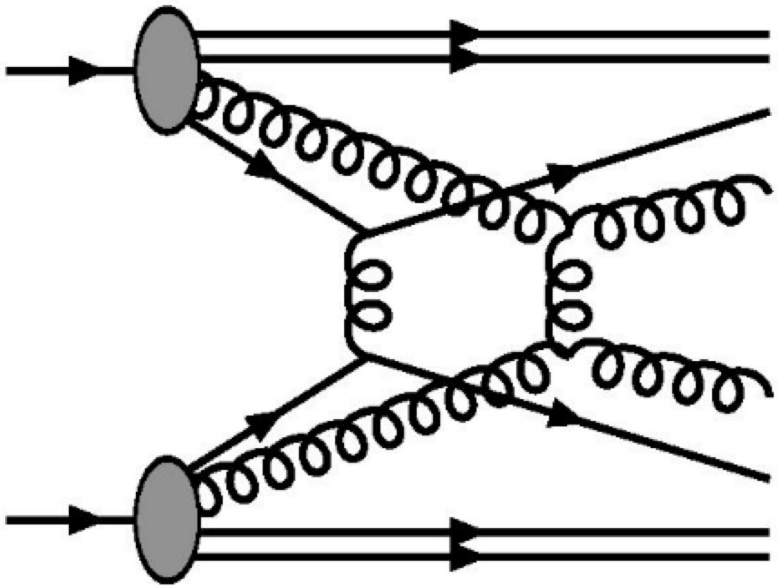


QCD

PDF's
Parton Distribution Functions

Multiple Interactions





$$E_0 = 10^{15} \text{ eV}$$

$$\sqrt{s} = 1.37 \text{ TeV}$$

Tevatron
LHC energy

$$E_0 = 10^{17} \text{ eV}$$

$$\sqrt{s} = 13.7 \text{ TeV}$$

LHC energy

No need for extrapolation in energy,
but systematic uncertainties remain large

Phase space coverage

[very forward region crucial for CR showers
and poorly measured in accelerator experiments]

Nuclear effects

[Little/no data on interactions on nuclear targets
at high energy]

Meson Interactions

[Limited to fixed target interactions]

Lower energy (deeper in the shower development)
interactions known with limited precision
[often old data]

Theoretical understanding remain (very) poor.

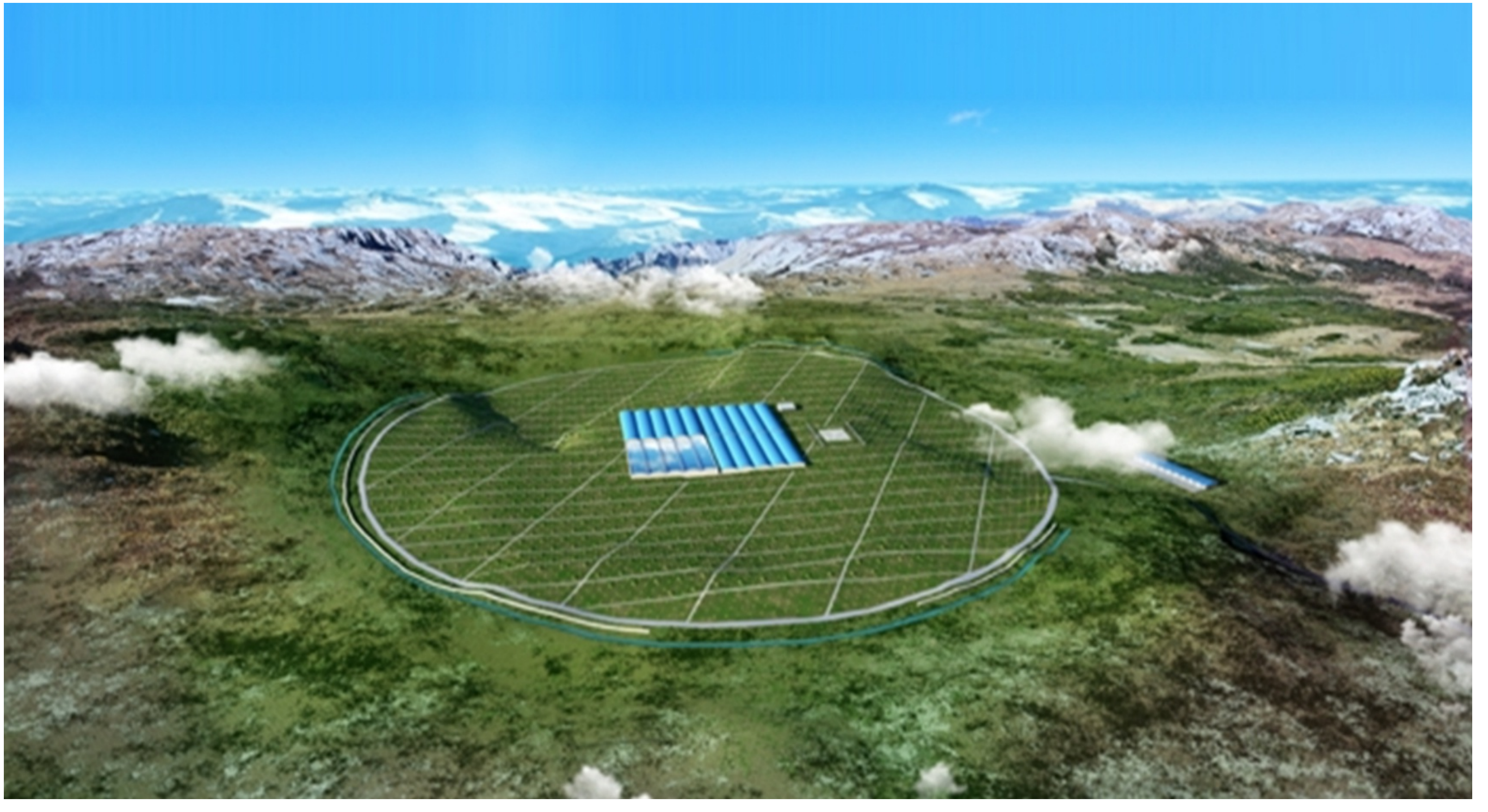
How can we improve ?

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.

5. LHAASO CR observations



Institute of High Energy Physics
Chinese Academy of Sciences

The 10th International Workshop on Air Shower Detection at High Altitudes

Cosmic ray spectral measurement around the knee with LHAASO experiment

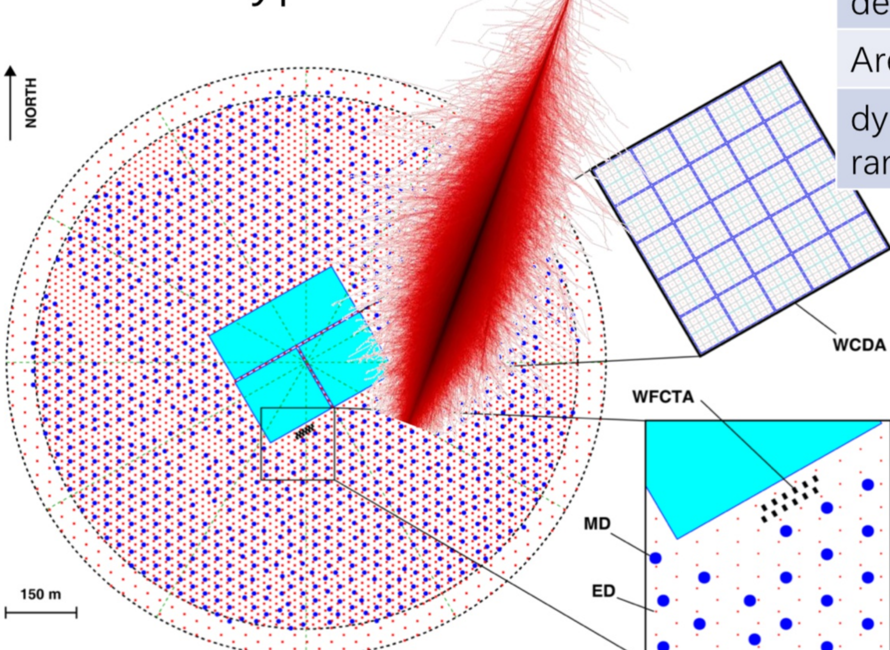
Lingling Ma for LHAASO Collaboration

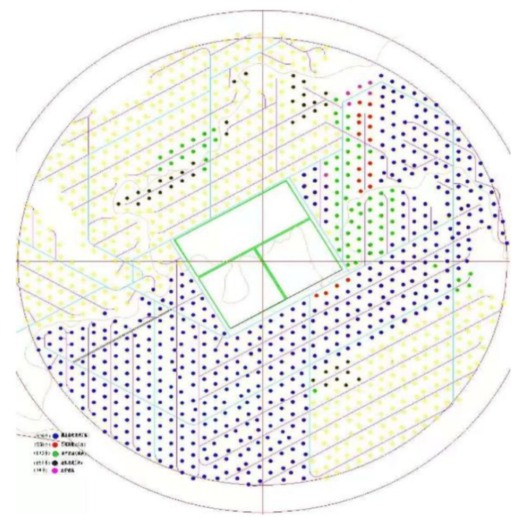
2020.01 Nanjing

Hybrid observations of LHAASO

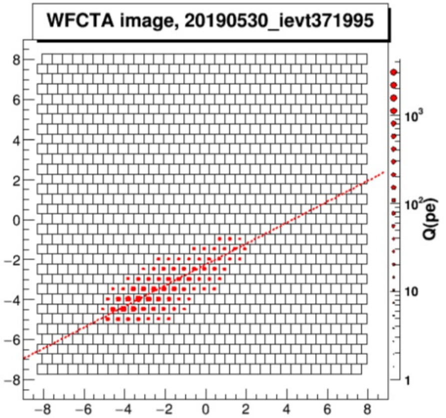
- High Altitude: 4400m
- Multi-type detectors

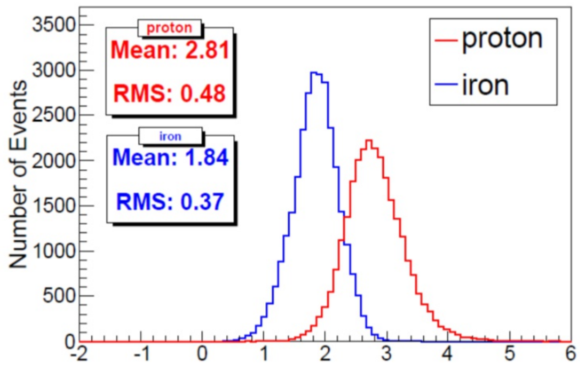
	WCDA WCDA++	KM2A		WFCTA
		EDA	MDA	
NO. of detector	3120cells	5195	1171	20
Area	$3120X25m^2$	$1km^2$	$1km^2$	0.06X20Sr
dynamic range	10TeV ~10PeV	100TeV ~100PeV	100TeV ~100PeV	15TeV ~100PeV



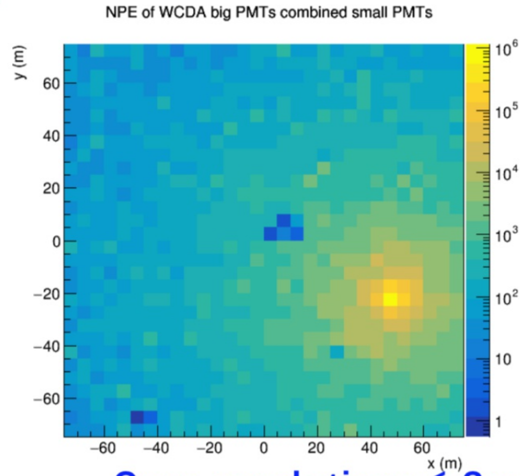


Discrimination variables for composition studies by MC



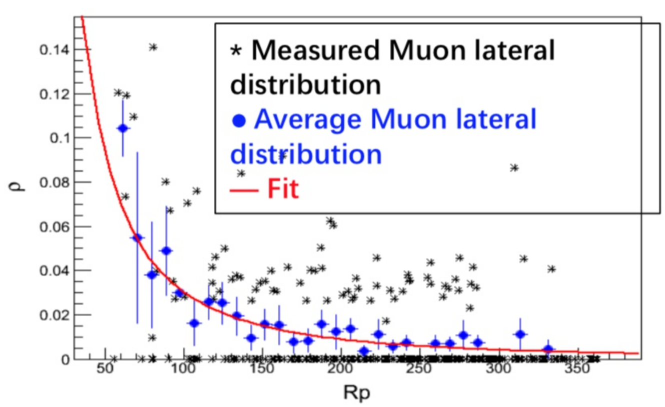


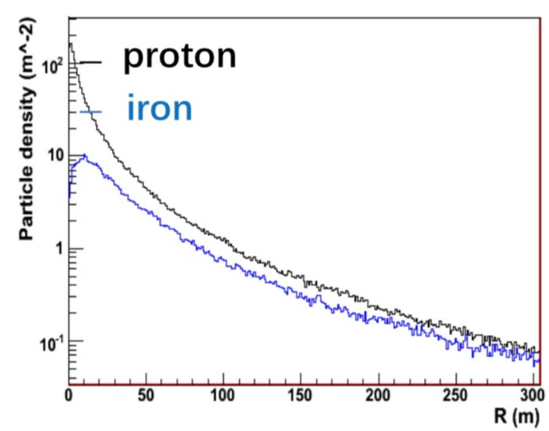
$$P_c = \left(\frac{Length}{Width}\right)\Big|_{normalized}$$



Core resolution: ≤ 3m

- **Length/Width**
- **Dist (related to X_{max})**
- **Particle numbers near the shower core**
- ***Number of muons***



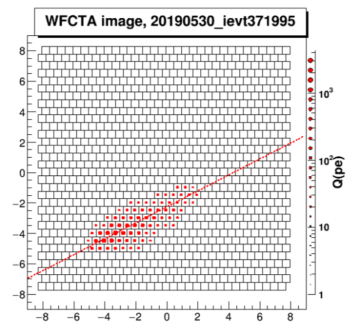


Multi-Component observations of EAS

LHAASO

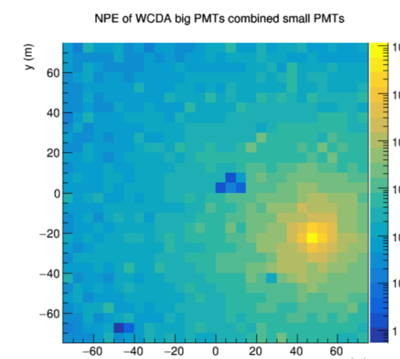
Cherenkov Telescopes (WFCTA)

$N_{p.e.}^{\text{tel}}$ $X_{\max}$ Length, Width



Water Detectors (WCDA)

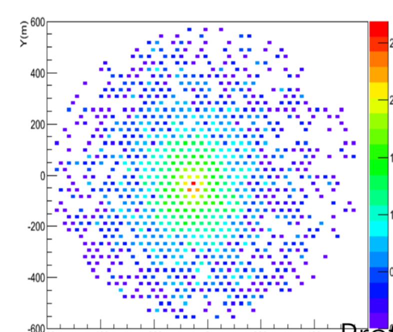
$N_{p.e.}^{\text{water}}$ $N_{\text{core}}^{\text{water}}$



Km2A detector

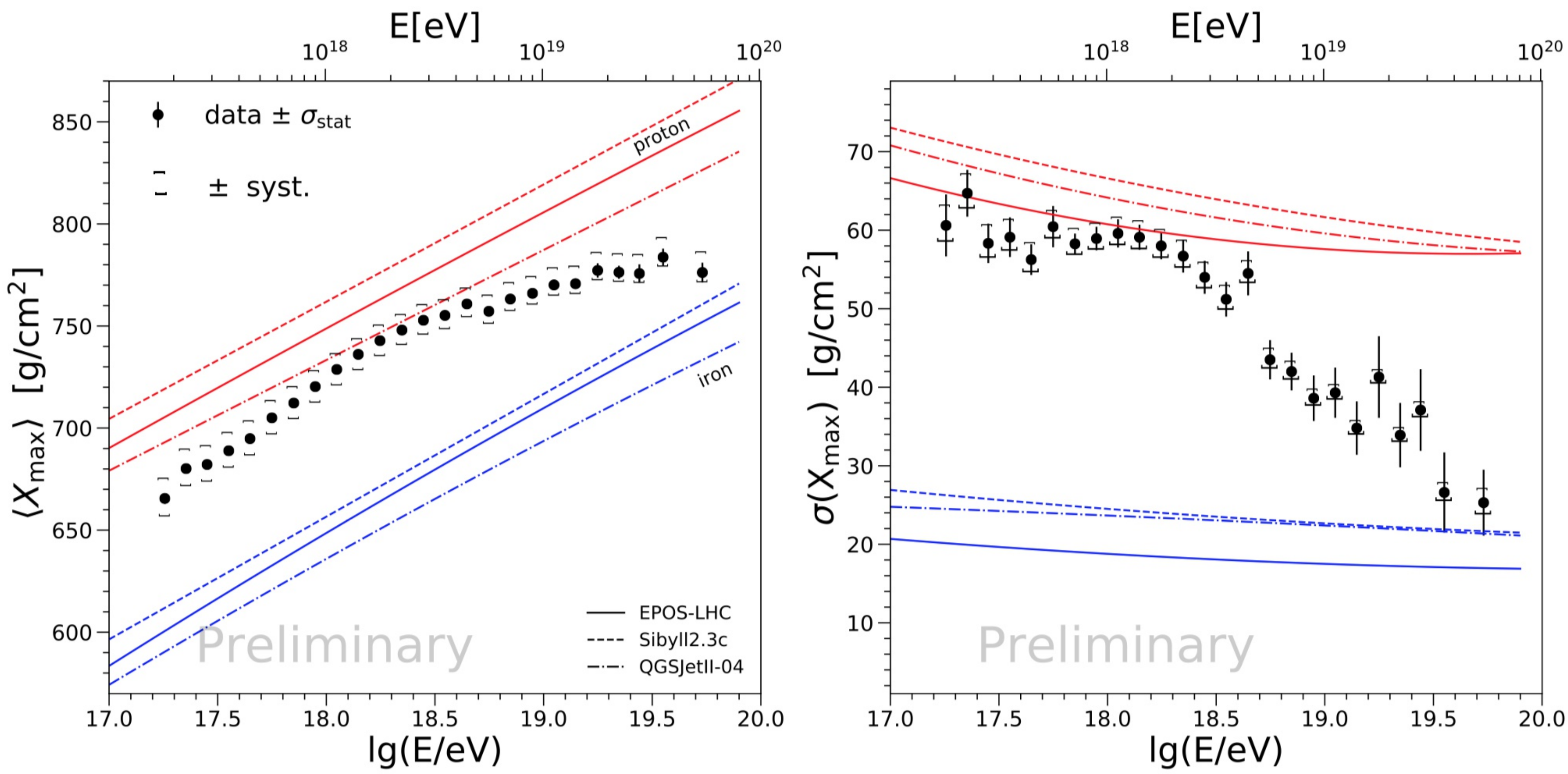
S_{em}^{km2} e.m. signal

N_{μ}^{km2} Muon signal

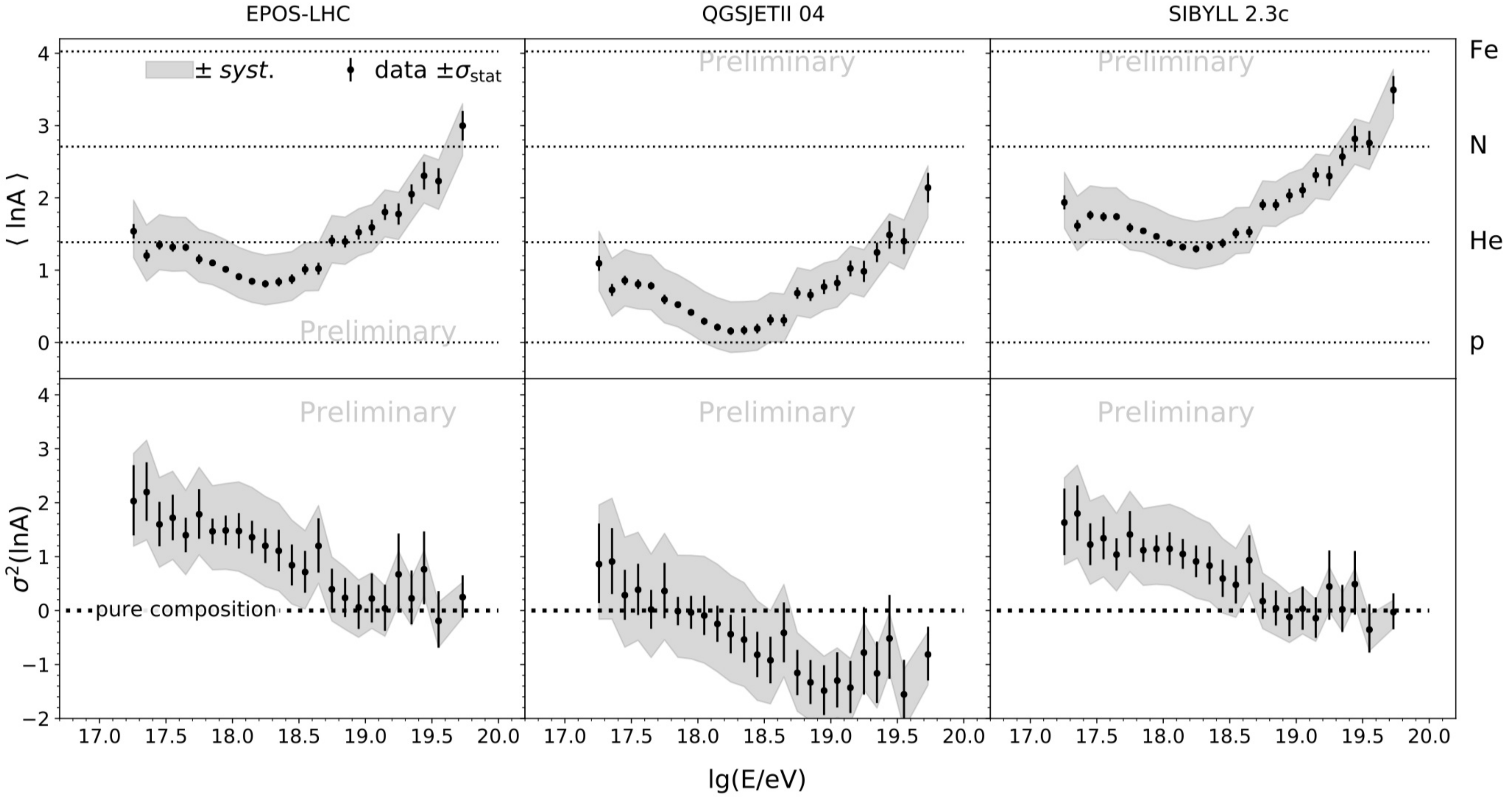


6. Connection to the UHECR

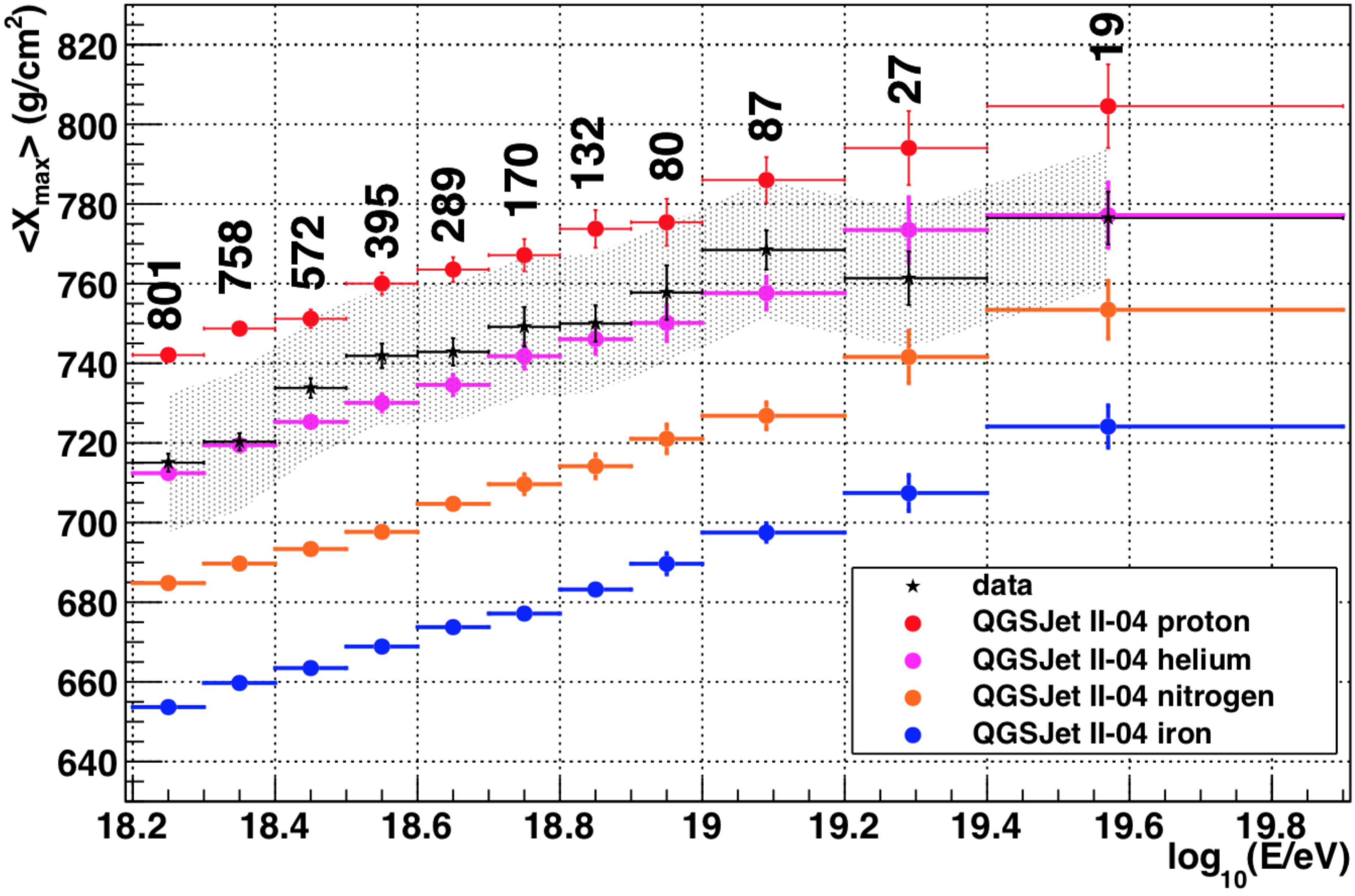
Auger   ICRC-2019



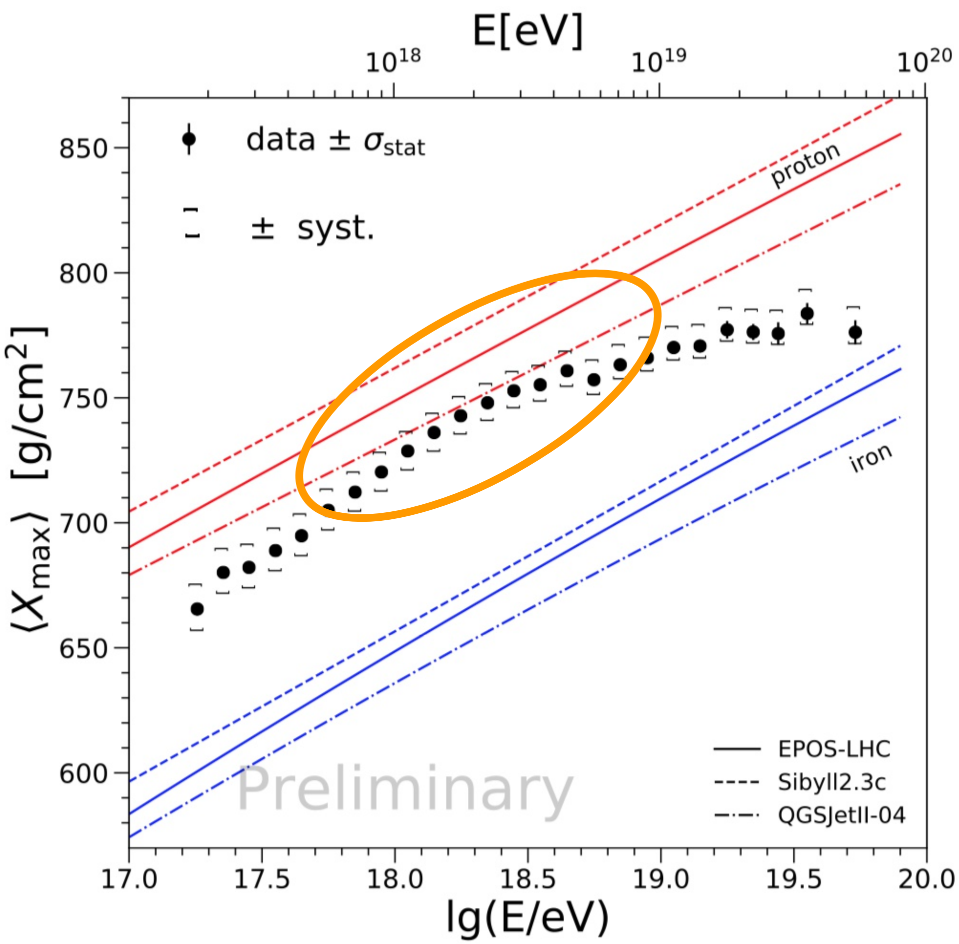
Interpretation in terms of Composition

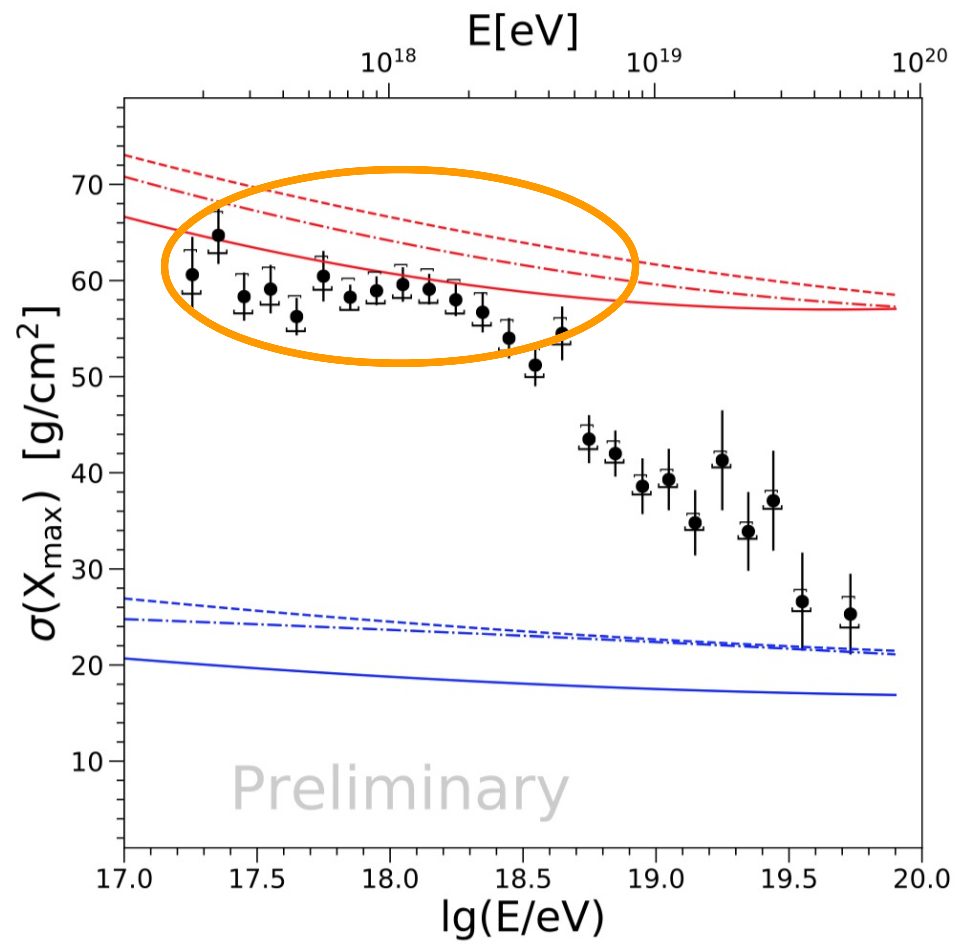


TELESCOPE ARRAY [8.5 Years of Hybrid observations]



Auger ICRC-2019



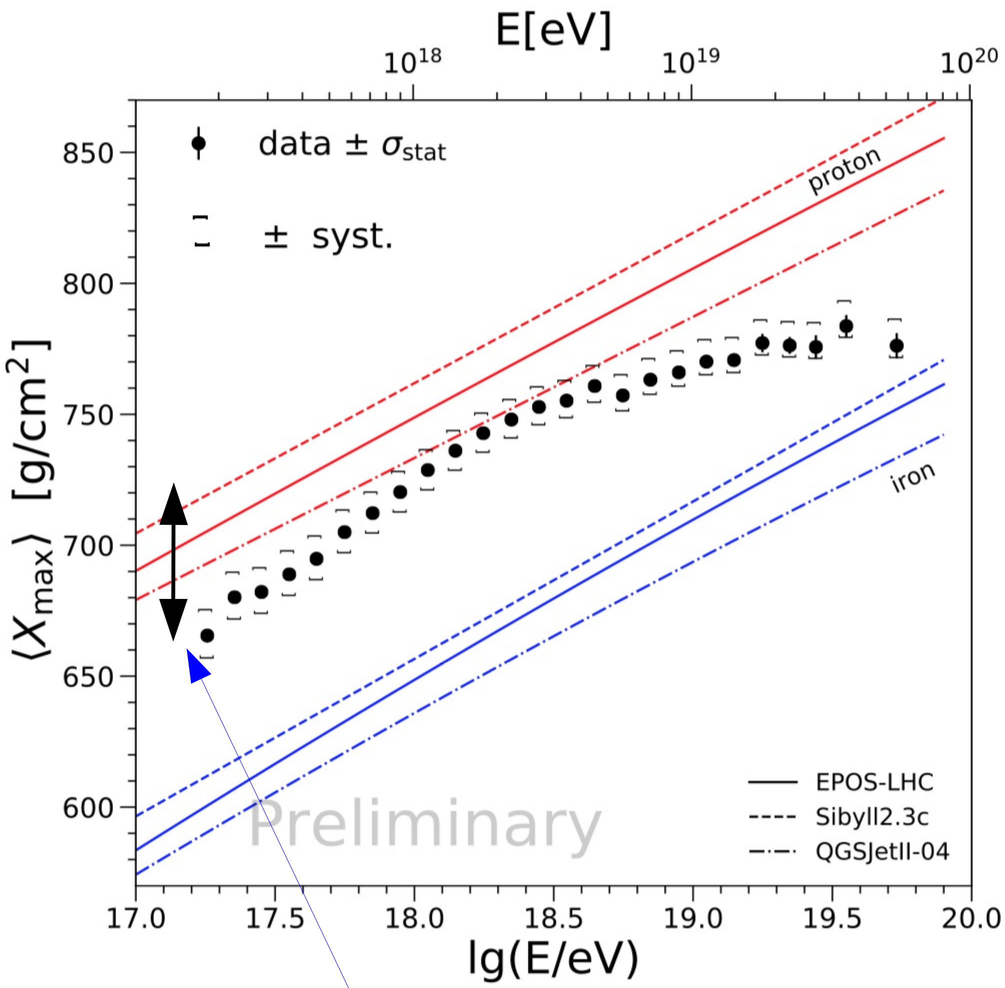


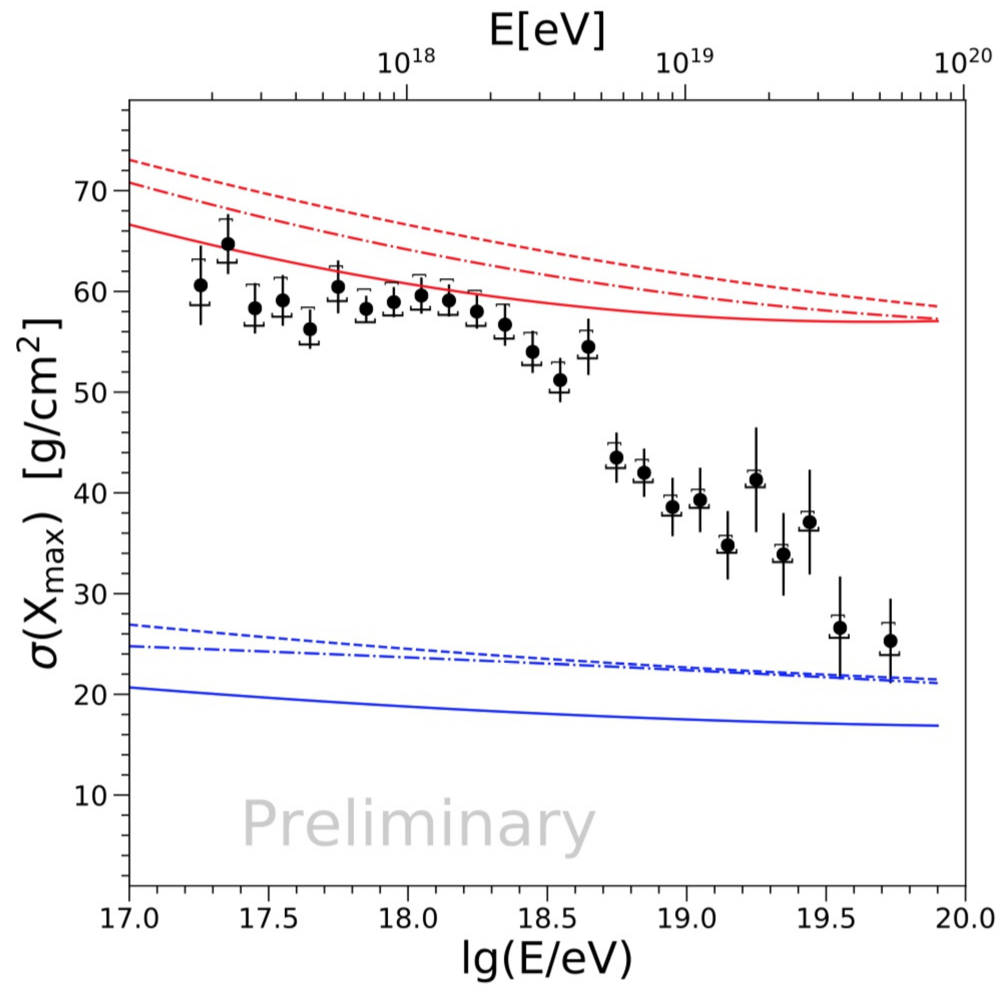
$$E \sim 10^{18} \text{ eV}$$

"Light" composition
(rich in protons). Measurements
of the proton-air cross section

Understand the
"emergence" of this
light component

Auger ICRC-2019

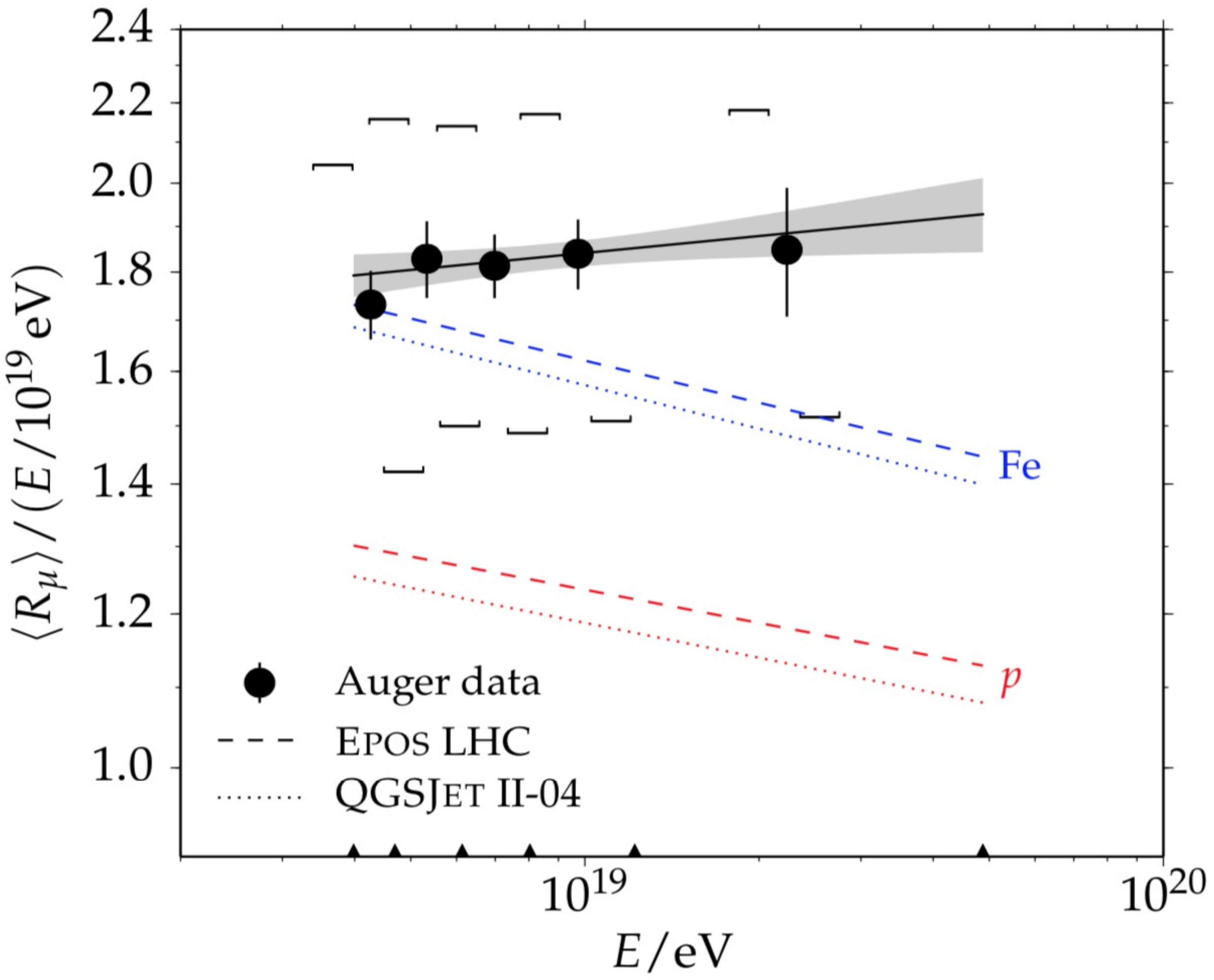


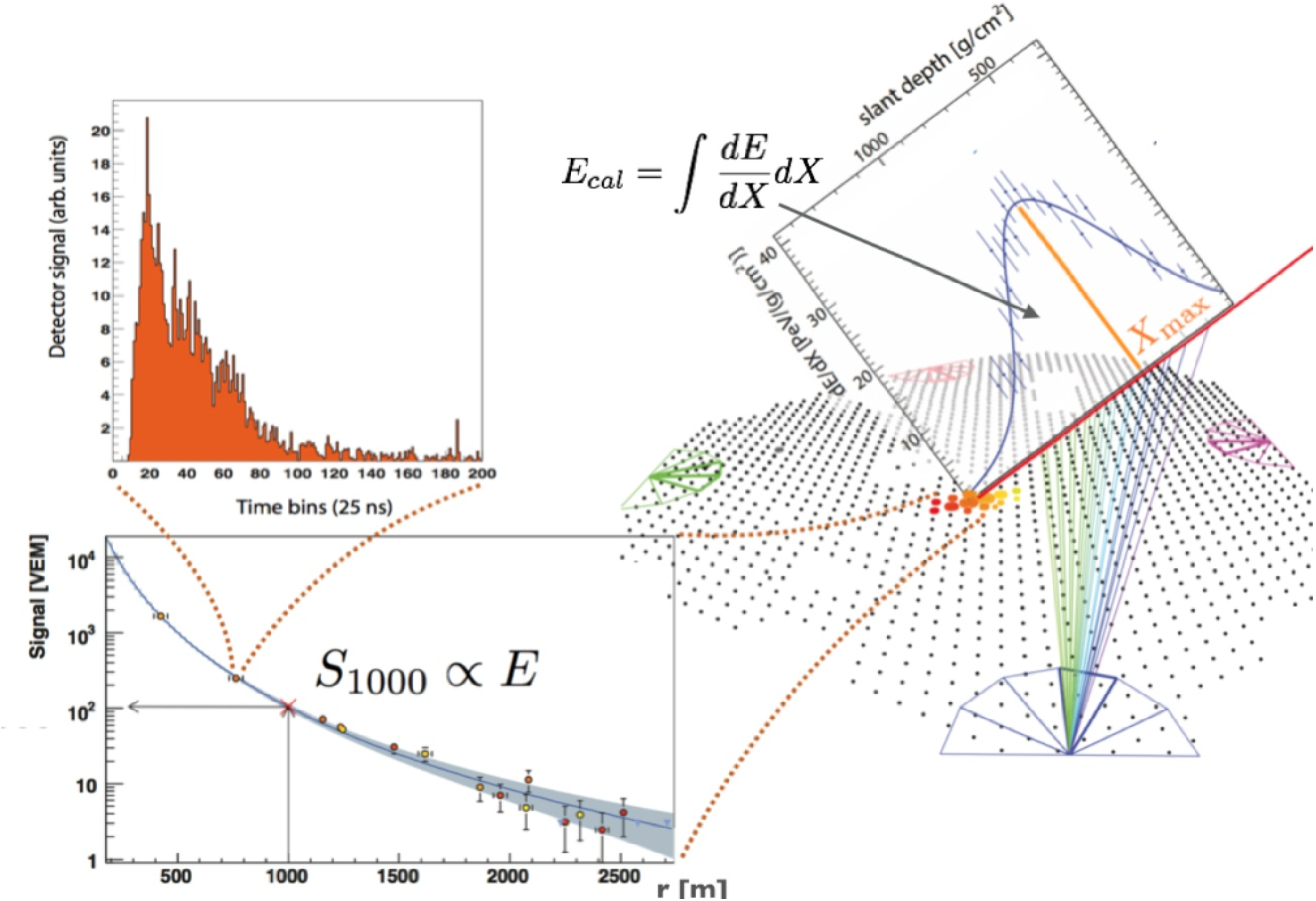


Important “theoretical" uncertainty

The “Muon problem” in UHECR

Auger number of muons in inclined showers

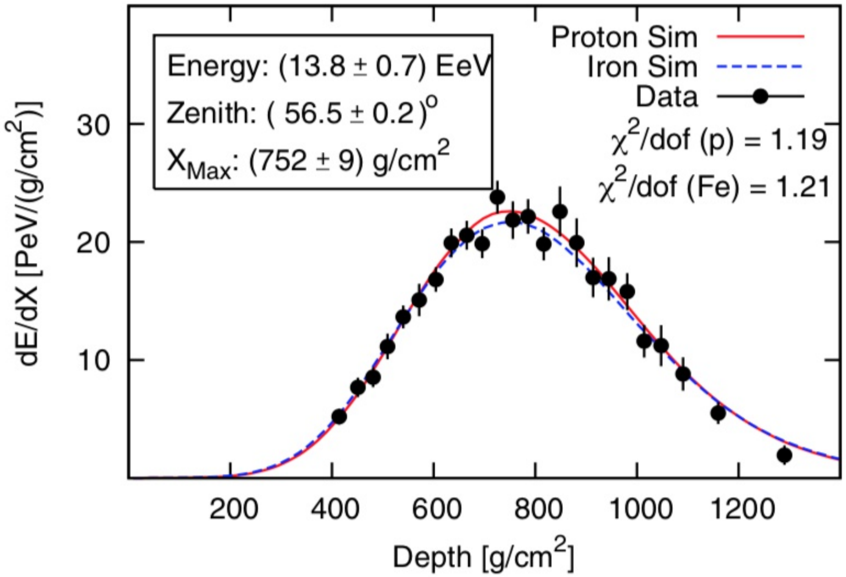


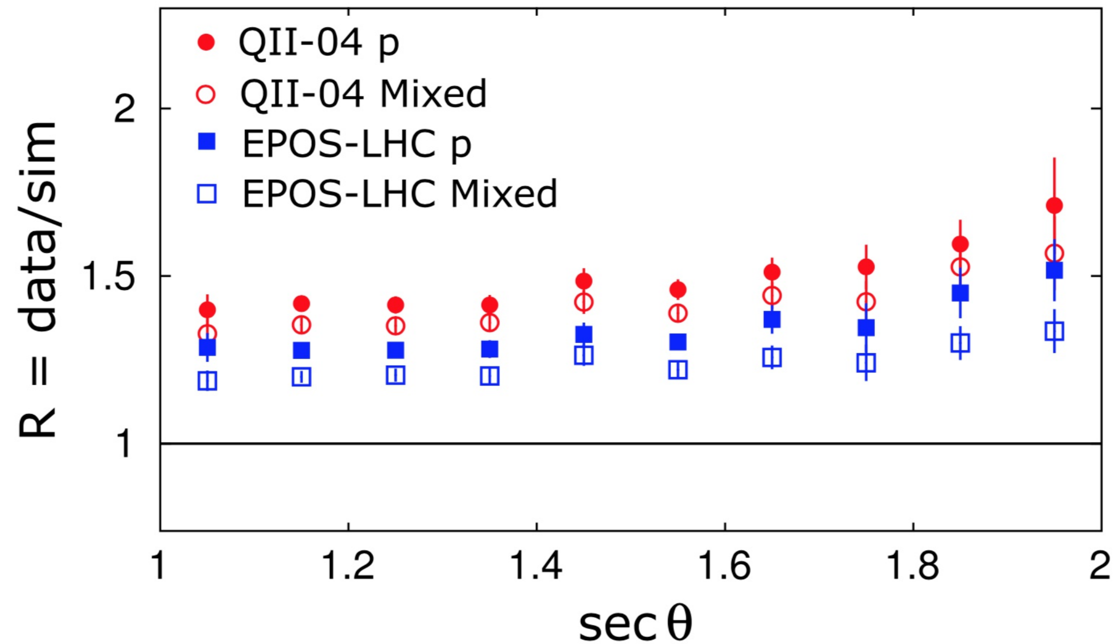


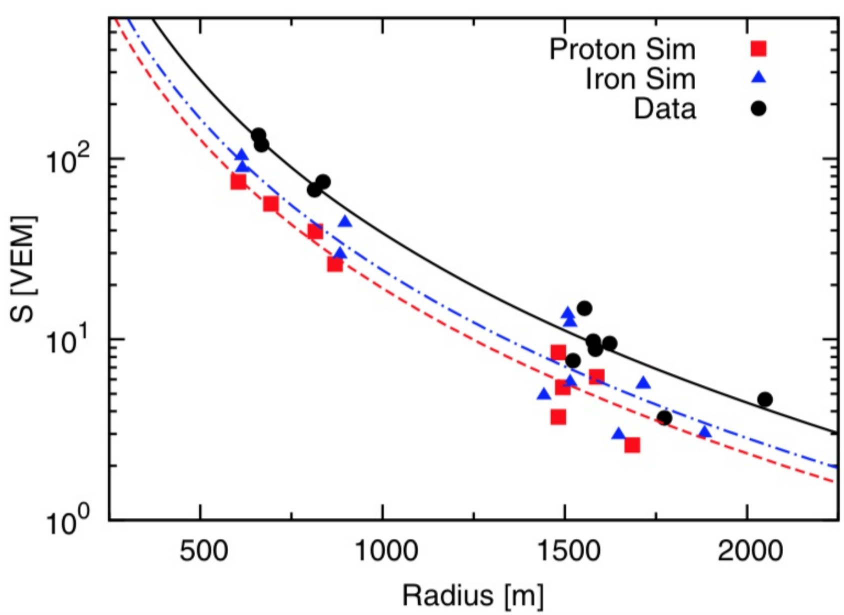
Detector signal (arb. units)
Time bins (25 ns)
Signal [VEM]
r [m]
$S_{1000} \propto E$
$E_{cal} = \int \frac{dE}{dX} dX$
slant depth [g/cm^2]
dE/dX [PeV/(g/cm^2)]
X_{max}

Pierre Auger Collaboration
"Testing Hadronic Interactions at Ultrahigh Energies
with Air Showers Measured by the Pierre Auger Observatory,"
Phys. Rev. Lett. **117**, no.19, 192001 (2016)
[arXiv:1610.08509 [hep-ex]].

$S(1000)$





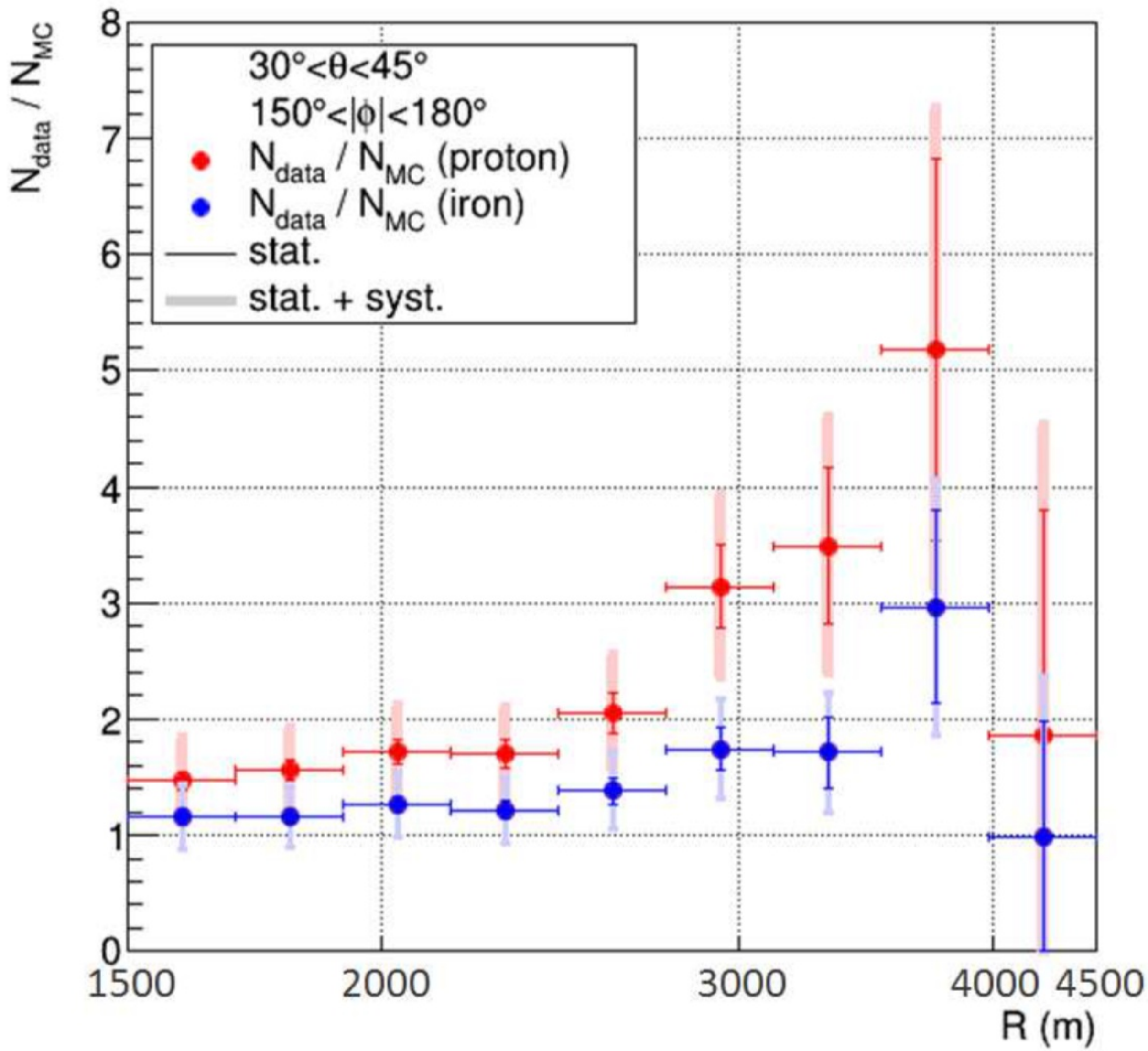


$$\frac{\text{(Average size hadronic shower)}}{\text{(Montecarlo prediction)}}$$

1.33 ± 0.16 EPOS-LHC

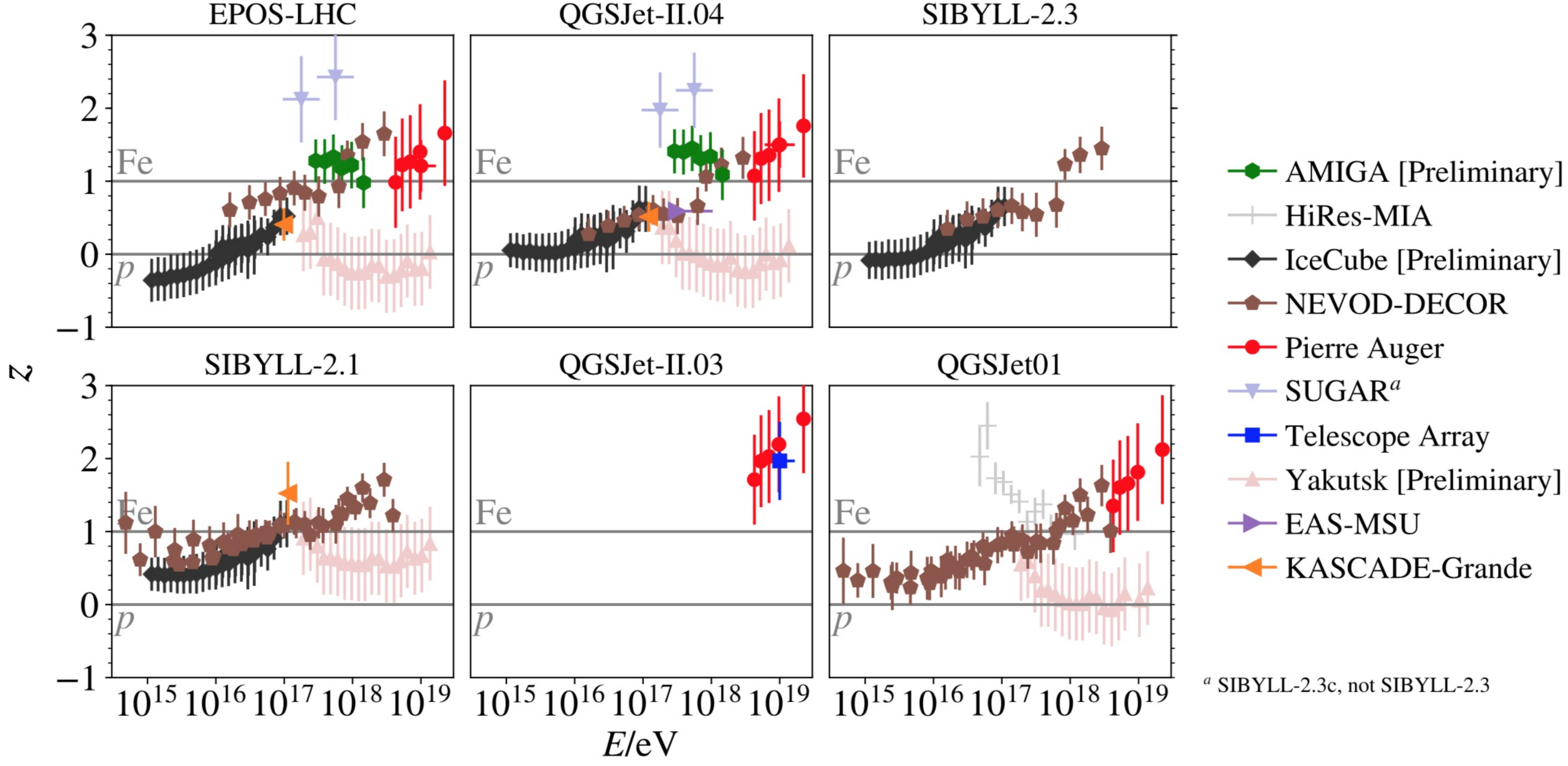
(1.61 ± 0.21) (QGSJetII-04).

Telescope Array Collaboration,
"Study of muons from ultrahigh energy cosmic ray air showers measured with the Telescope Array experiment,"
Phys. Rev. D **98**, no.2, 022002 (2018)
[arXiv:1804.03877 [astro-ph.HE]].

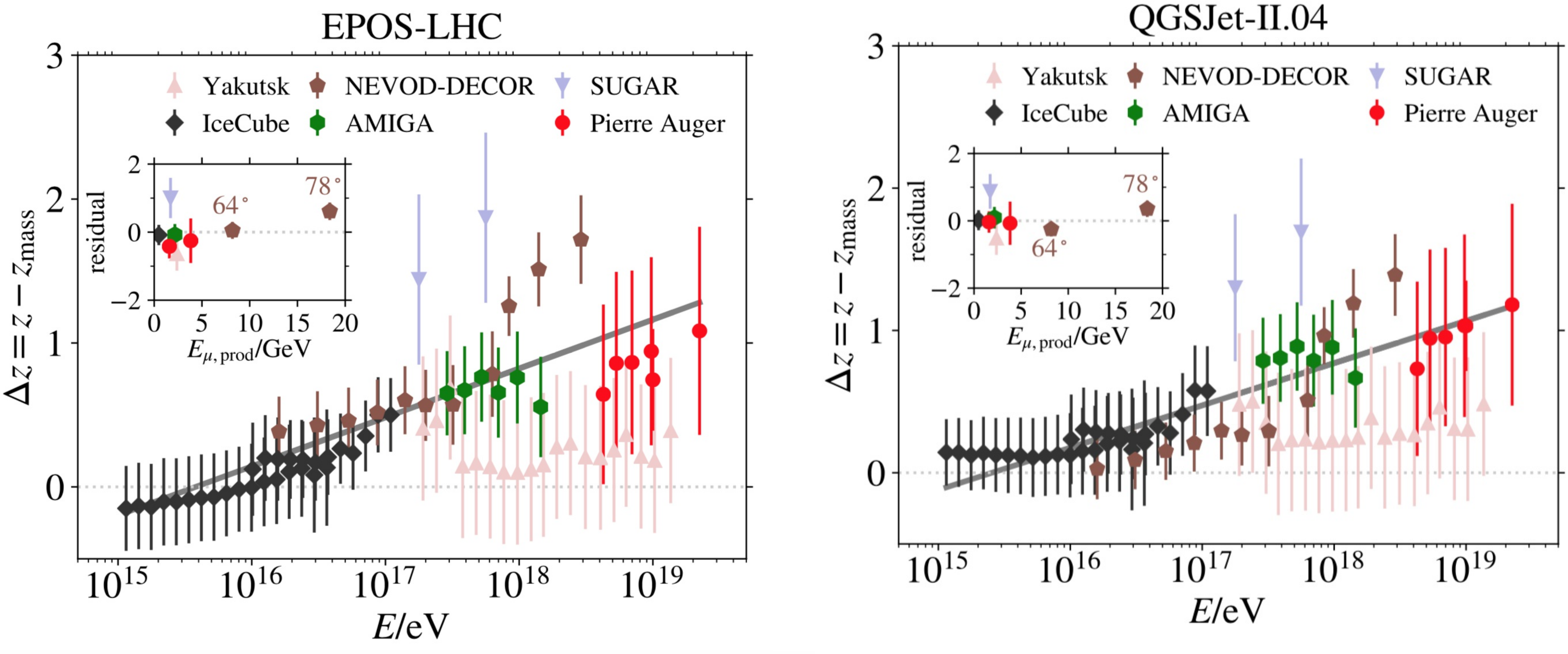


$$z = \frac{\ln(N_\mu{}^{\text{det}}) - \ln(N_\mu{}_p^{\text{det}})}{\ln(N_\mu{}_{\text{Fe}}^{\text{det}}) - \ln(N_\mu{}_p^{\text{det}})}$$

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.

Conclusions

- New measurements of the cosmic ray spectra
in the energy range from direct-observations
up to the "UHECR" region,
with better control of systematic uncertainties
can be of great value to develop our understanding
of the "High Energy Universe".

- LHAASO with its capabilities of multi—component
observations has a great potential to provide
very important measurements.

- To fully exploit this potential it is very desirable
(in fact in my opinion necessary) to invest in an
effort to improve our understanding of hadronic interactions.

    (1) Accelerator Data, (2) Theoretical work,
    (3) CR data "Self-Consistency" ["Bootstrap"]
    with the measurements of different shower components
    (and different experiments)]