Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TOR VERGATA

Indirect measurements of Galactic Cosmic Rays: open problems and perspectives

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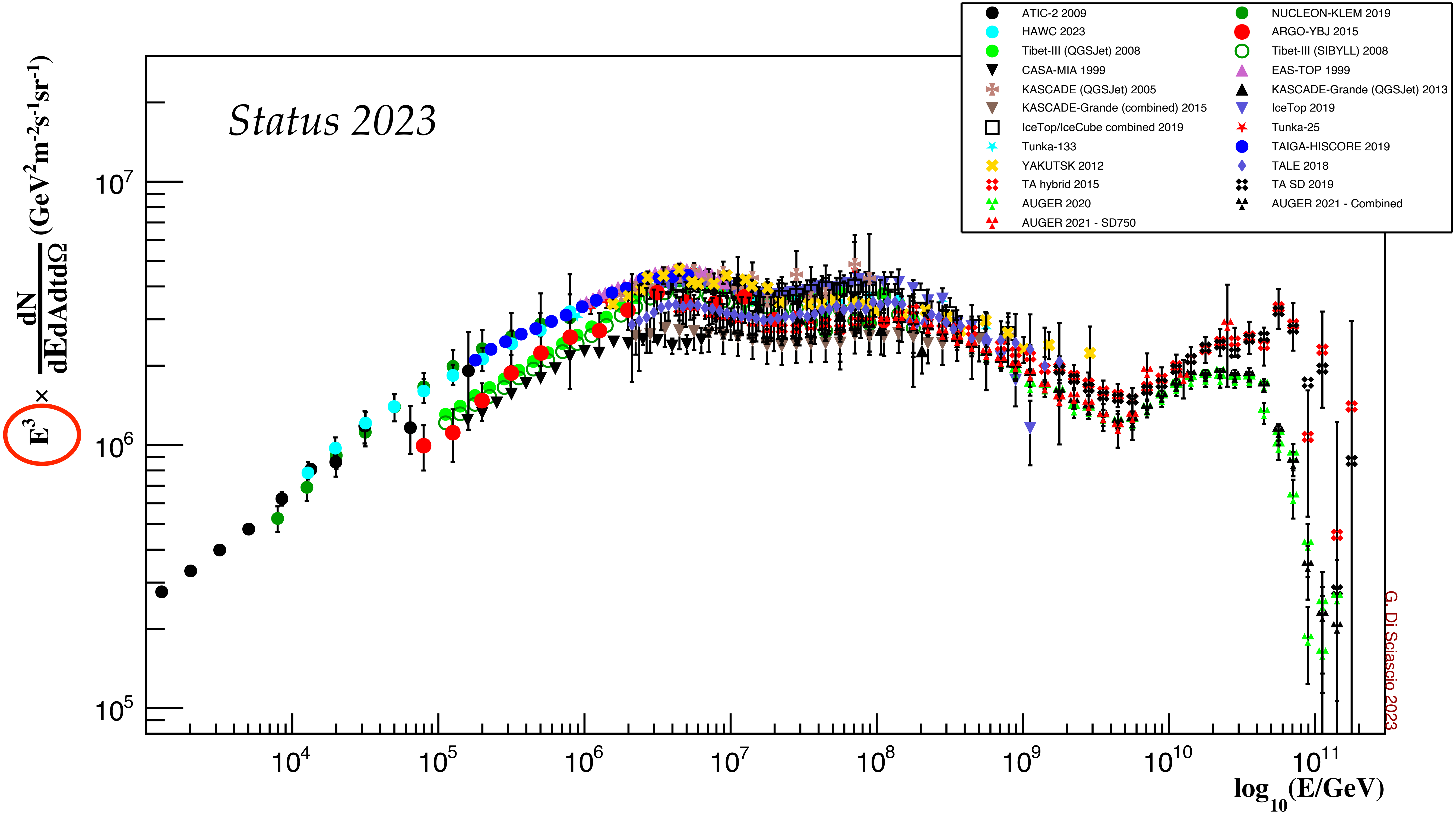
CRA 2023
sixth Cosmic Ray Anisotropy Workshop

May 16-19, 2023
Loyola University - Chicago

All-particle Energy Spectrum



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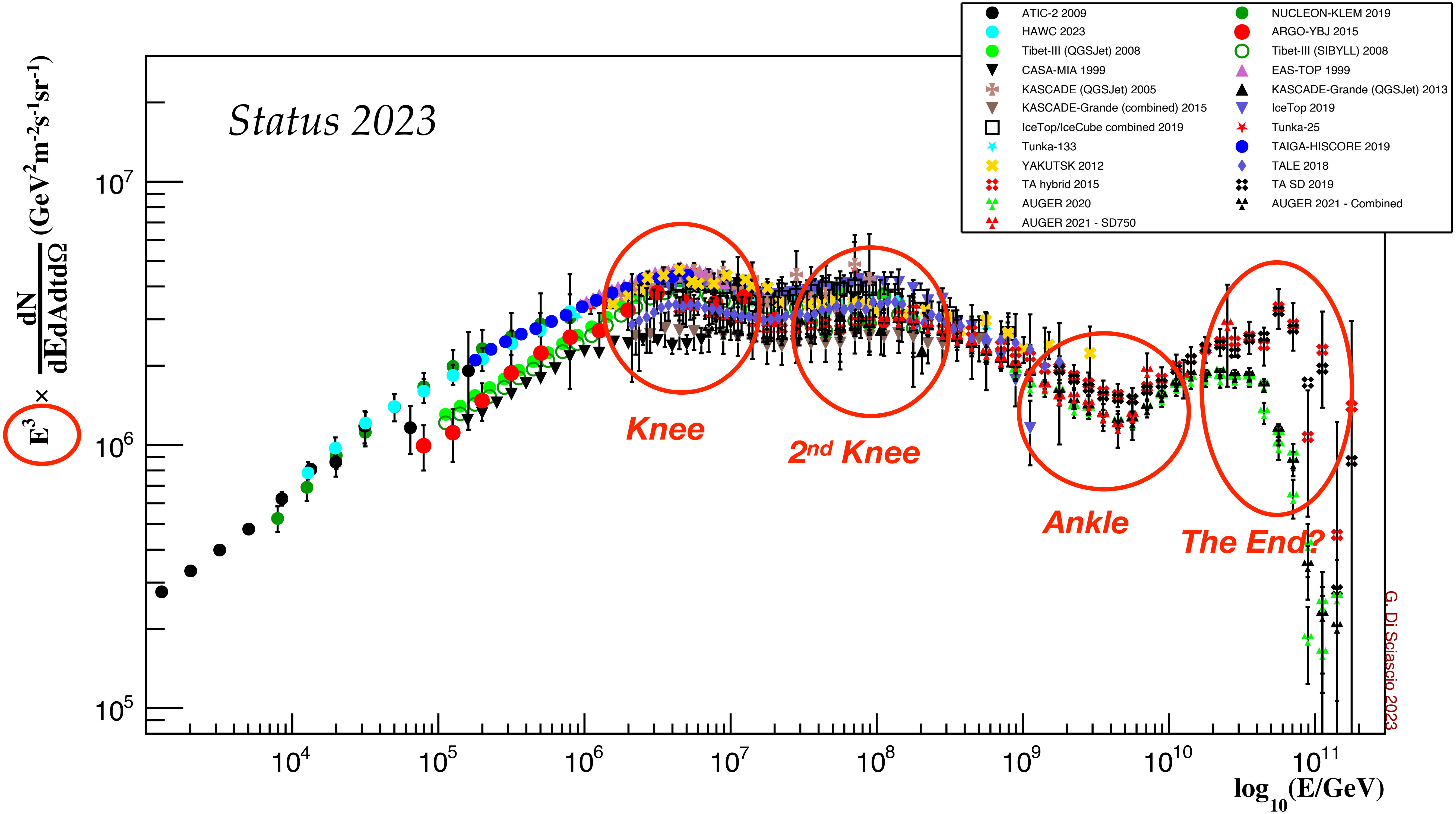
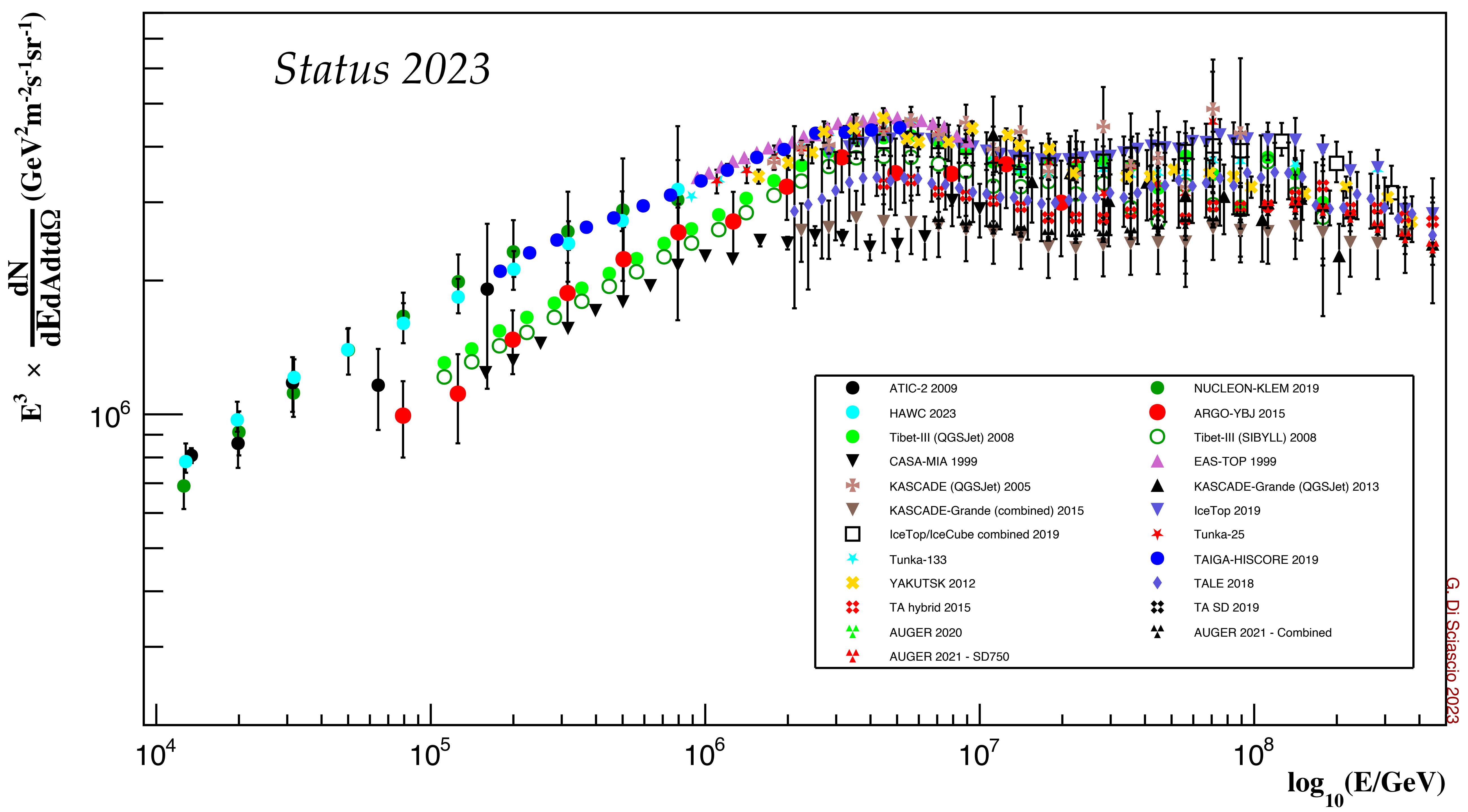


A closer look to the knee region



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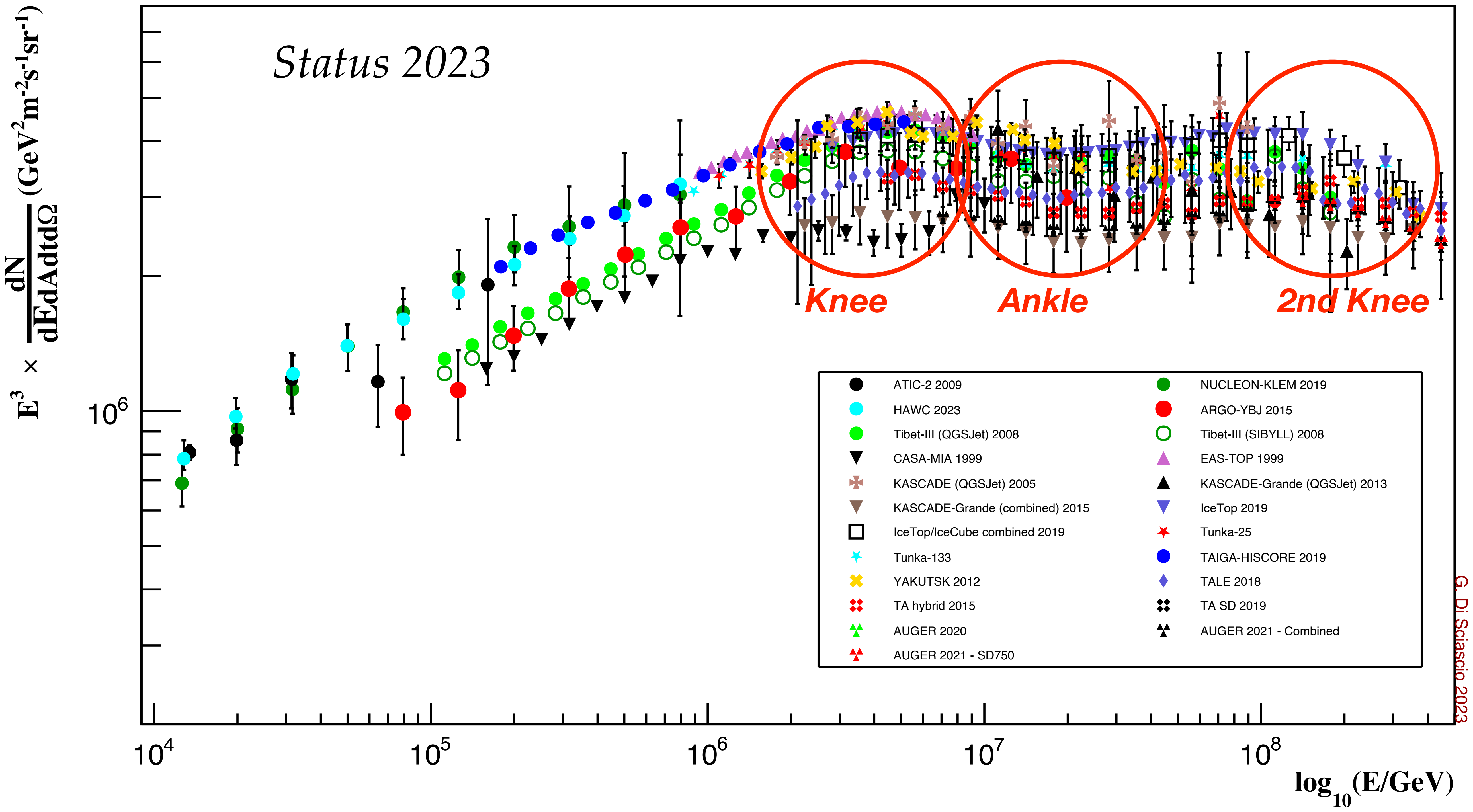
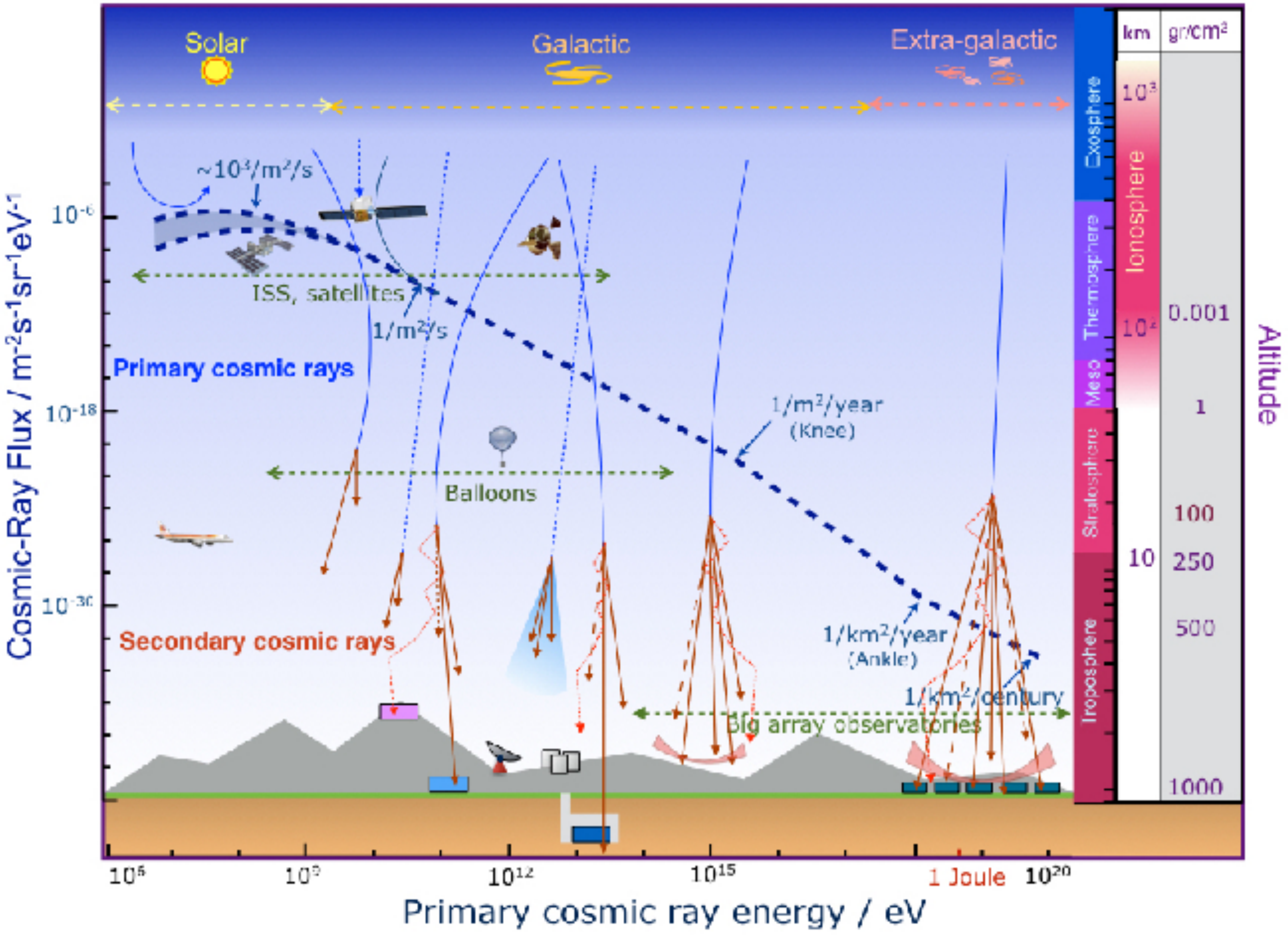


Open questions in Cosmic Ray Physics

Much of CR research in the past century has been devoted to answering a set of classical questions:

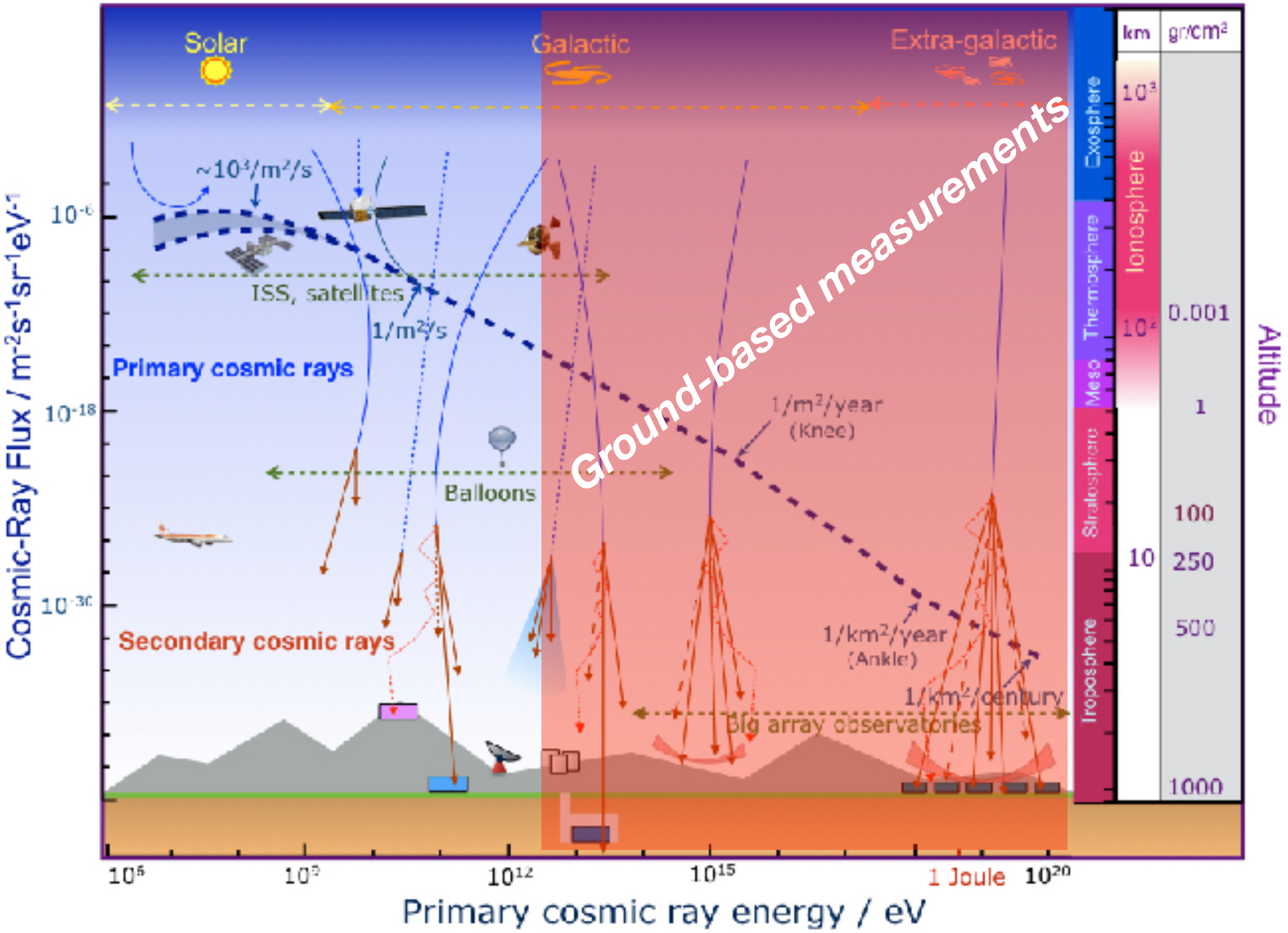
- ✓ Which ***classes of sources*** contribute to the CR flux in different energy ranges? How many types of sources provide a significant contribution to the overall CR flux?
- ✓ What is the ***elemental composition*** of CRs as a function of the energy?
- ✓ Is the ***knee*** due to ***a limit in SNR acceleration***? Does it depend on the particle rigidity? How can we explain the ***second knee***?
- ✓ Which are the relevant processes responsible for CR ***propagation/confinement*** in the Galaxy?
- ✓ Where is the ***transition between Galactic and EG-CRs?*** How can we explain the ***ankle***?
- ✓ Which sources are capable of reaching the ***highest particle energies and how***?

Cosmic Ray detection



≈ 11 decades

Cosmic Ray detection



≈ 11 decades

N_{evts} = ***Flux*** × ***Area*** × ***Time***

small given by nature

≈1 m² for satellite exp

≈5 yrs

According to the flux and the physics line different platforms and detection techniques can be adopted

Detector size limits the smallest measurable flux !

Direct measurements up to *≈100 TeV/n*

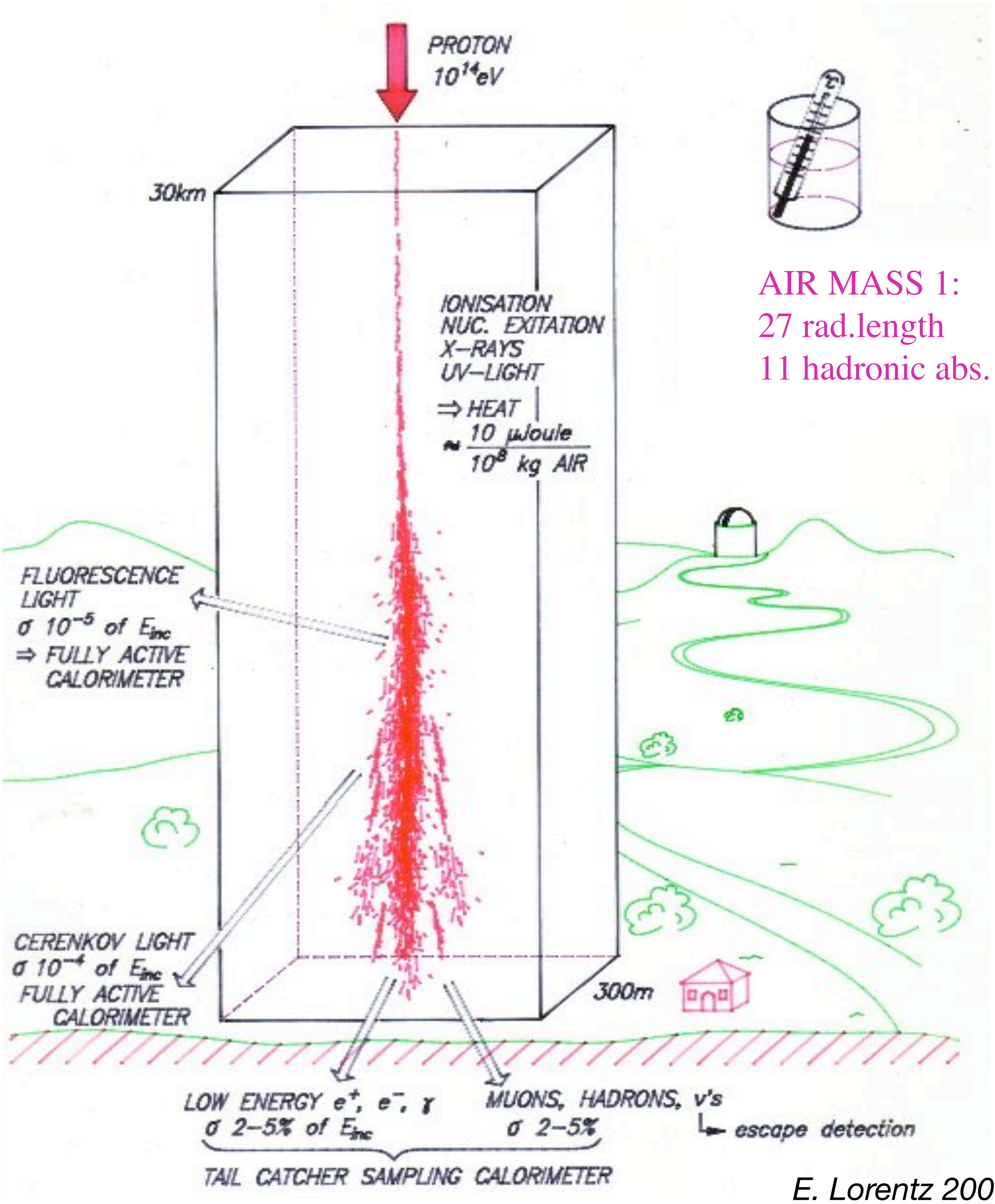
The challenge of EAS detection

The ultimate aim of EAS detection is the identification of the primary CR in terms of

Mass / Charge
Energy
Arrival direction

We are dealing with an INDIRECT measurement of Cosmic Rays

To infer the properties of the primary particle one needs to detect EAS as precisely as possible (with multi-component experiments)



AIR MASS 1:
27 rad.length
11 hadronic abs. length

E. Lorentz 2005

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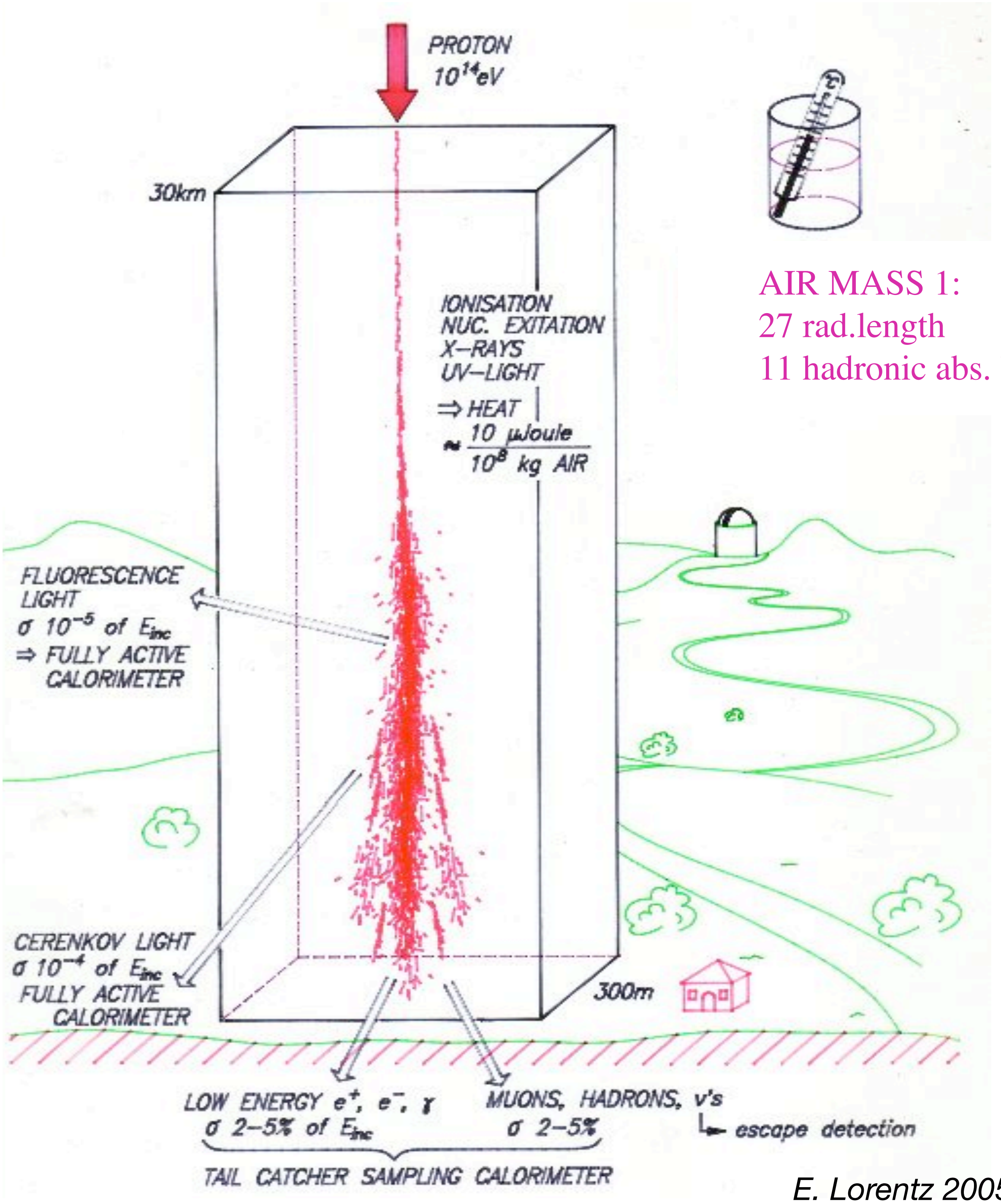
Astrophysical interpretation limited by description of interactions in the atmosphere



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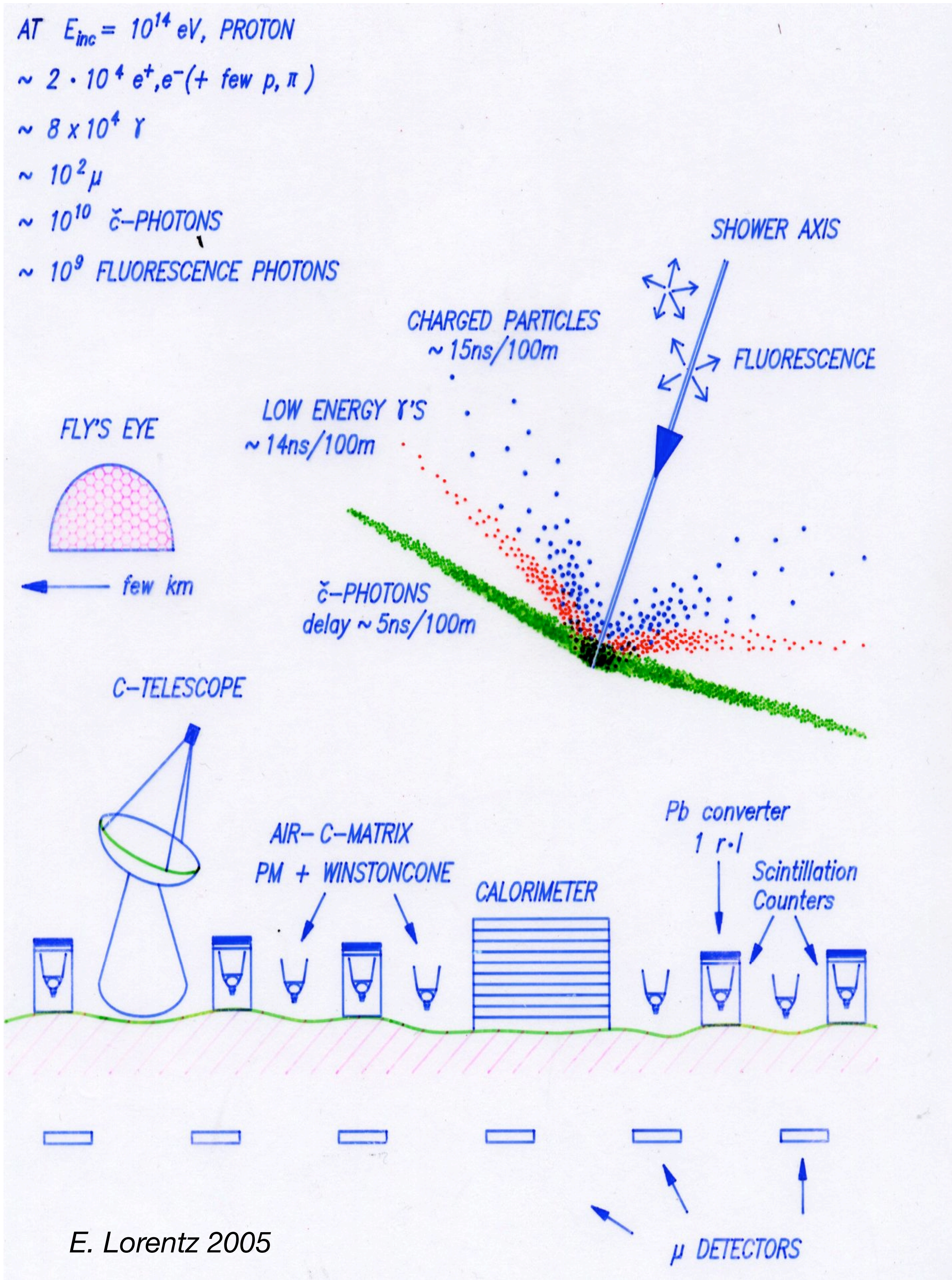
Different detectors for different observables



E. Lorentz 2005

Different detectors for different observables

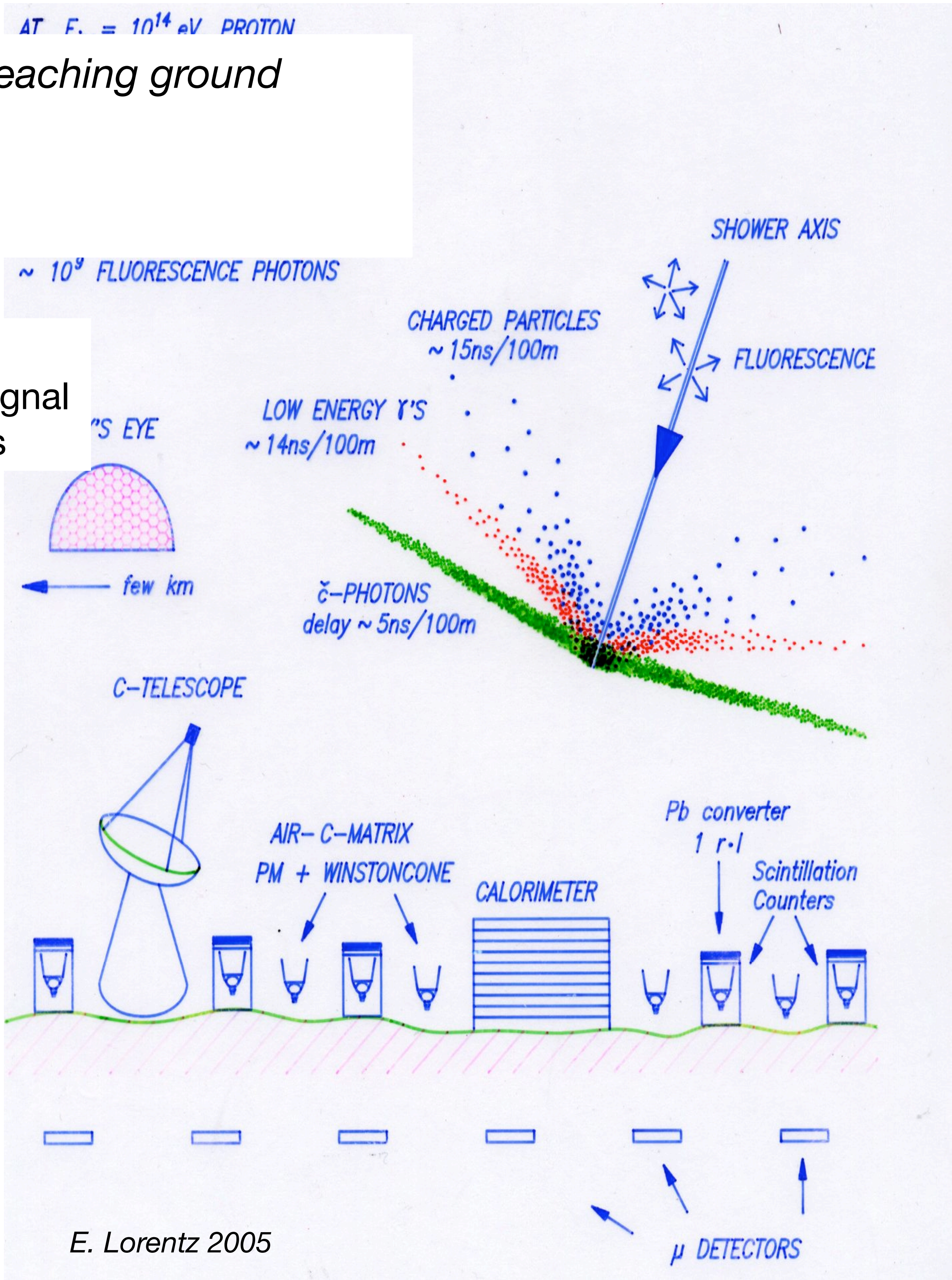
1. *Ground-based arrays*: sample *shower tail particles reaching ground*

➜ ***Tail Catcher Sampling Calorimeter***
(in HEP detector language)

Atmosphere: the absorber
Detector at ground: the device to measure a (poor) calorimetric signal
➜ signal about *direction* and *energy* from the shower tail particles

★ large shower-to-shower fluctuations

★ large geometric acceptance and
high duty cycle (≈100%)



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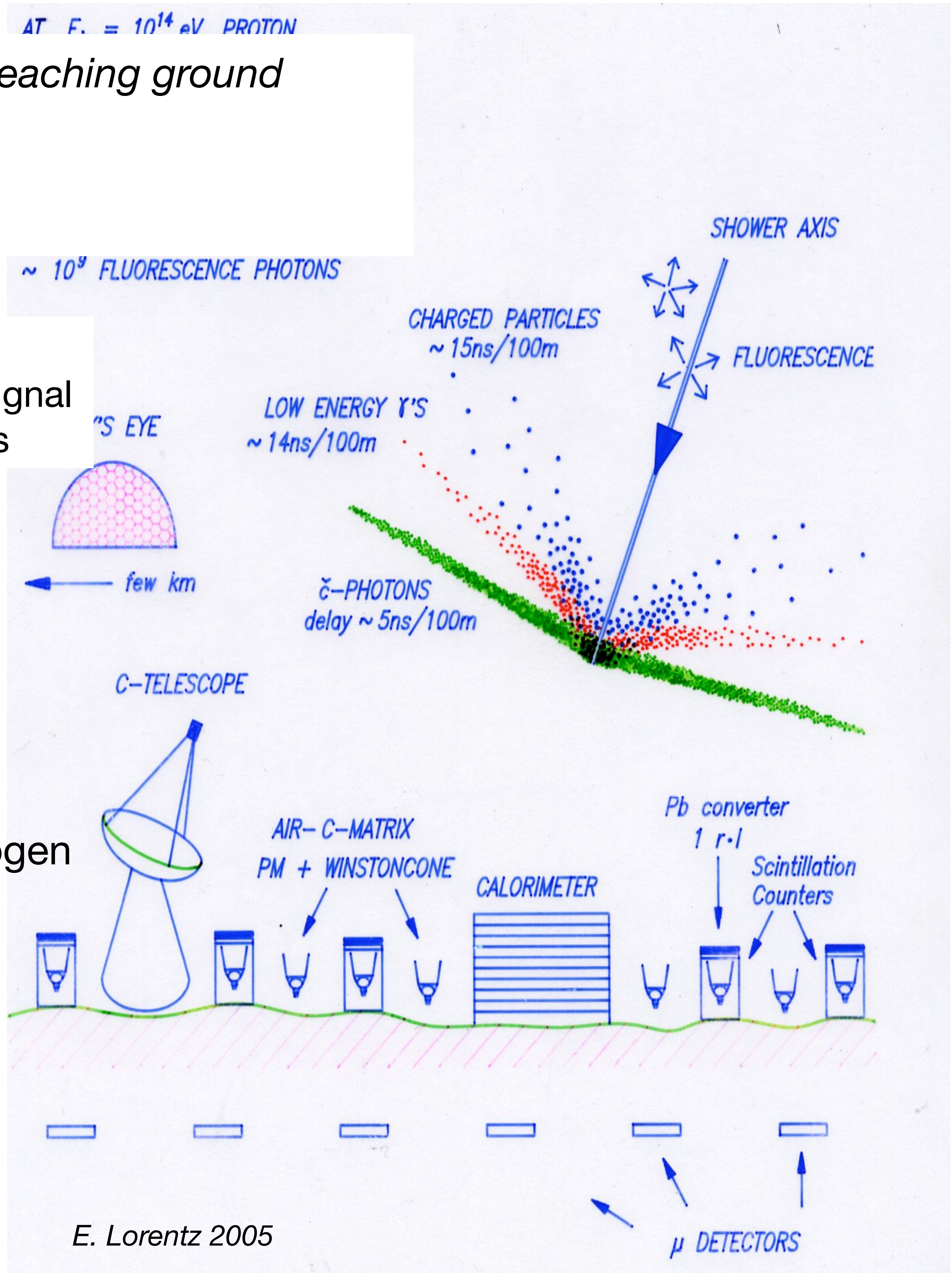
- ★ large shower-to-shower fluctuations
- ★ large geometric acceptance and high duty cycle (≈100%)

2. *Telescopes*: observation of Cherenkov photons/nitrogen fluorescence allows the study of EAS longitudinal profile

➜ ***Homogeneous Calorimeter***

- ★ low duty cycle (≈10-15%)
- ★ good energy resolution



E. Lorentz 2005

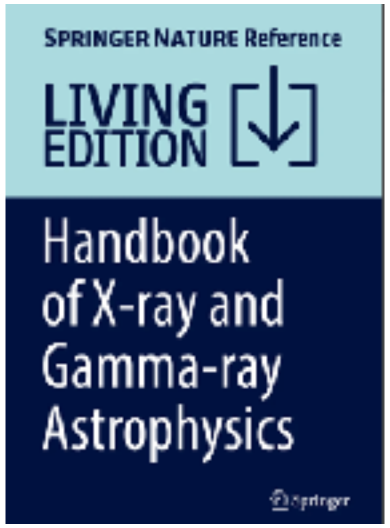
Detection of showers with arrays

From an experimental point of view, the sampling of secondary particles at ground can be realized with ***two different approaches***

(1) ***Particle Counting***. A measurement is carried out with thin (« 1 radiation length) counters providing ***a signal proportional to the number of charged particles*** (as an example, plastic scintillators or RPCs). The typical detection threshold is in the keV energy range.

(2) ***Calorimetry***. ***A signal proportional to the total incident energy of electromagnetic particles*** is collected by a thick (many radiation lengths) detector. An example is a detector constituted by many radiation lengths of water to exploit the Cherenkov emission of secondary shower particles. The Cherenkov threshold for electrons in water is 0.8 MeV and the light yield ≈320 photons/cm or ≈160 photons/MeV emitted at 41°.

"Detecting gamma-rays with moderate resolution and large field of view: Particle detector arrays and water Cherenkov technique"
Michael A. DuVernois, Giuseppe Di Sciascio
Chapter for "Handbook of X-ray and Gamma-ray Astrophysics" (Eds. C. Bambi and A. Santangelo, Springer Singapore) arXiv:2211.04932



Mass-sensitive EAS observables

Strictly speaking, ***no air shower experiment measures the primary composition of CRs.***

We have different mass-sensitive EAS observables

✦ Particle numbers at ground

- electrons
- muons (also underground)
- hadrons

- *the electron-to-muon number ratio*
- *the arrival time distribution*
- *the curvature of the shower front*
- *the slope of the lateral distribution*
- *shower core density*
- *underground muons*
- *muon fluctuations*
- …

$E > 10^{13}$ eV

✦ Cherenkov light $10^{14} < E < 10^{16}$ eV

✦ Fluorescence light $E > 10^{17}$ eV

✦ Radio signals $E > 10^{17}$ eV

Mass Resolution in EAS measurements

A resolution of one unit in lnA in principle allows to reconstruct 4 (or 5 ?) different mass groups: p, He, CNO, MgSi (?) and Fe.

According to the Heitler-Matthews toy model we can evaluate the mass resolution in EAS measurements (Horandel 2007, Di Sciascio 2022)

- ***Electron-muon ratio***

$$\lg\left(\frac{N_e}{N_\mu}\right) = C - 0.065 \cdot \ln A$$

Typical uncertainty

$$\frac{\Delta(N_e/N_\mu)}{N_e/N_\mu} \sim 0.15\left[\frac{\Delta A}{A}\right] \rightarrow$$

$$\Delta\left(\frac{N_e}{N_\mu}\right) \approx 15\% - 20\,\%$$

Expected mass resolution

4 to 5 mass groups
p, He, CNO, (MgSi), Fe

- ***Depth of shower maximum***

$$X^A_{max} = X^p_{max} - X_0 \cdot \ln A$$

Radiation length $X_0 \sim 37\ \ g/cm^2$

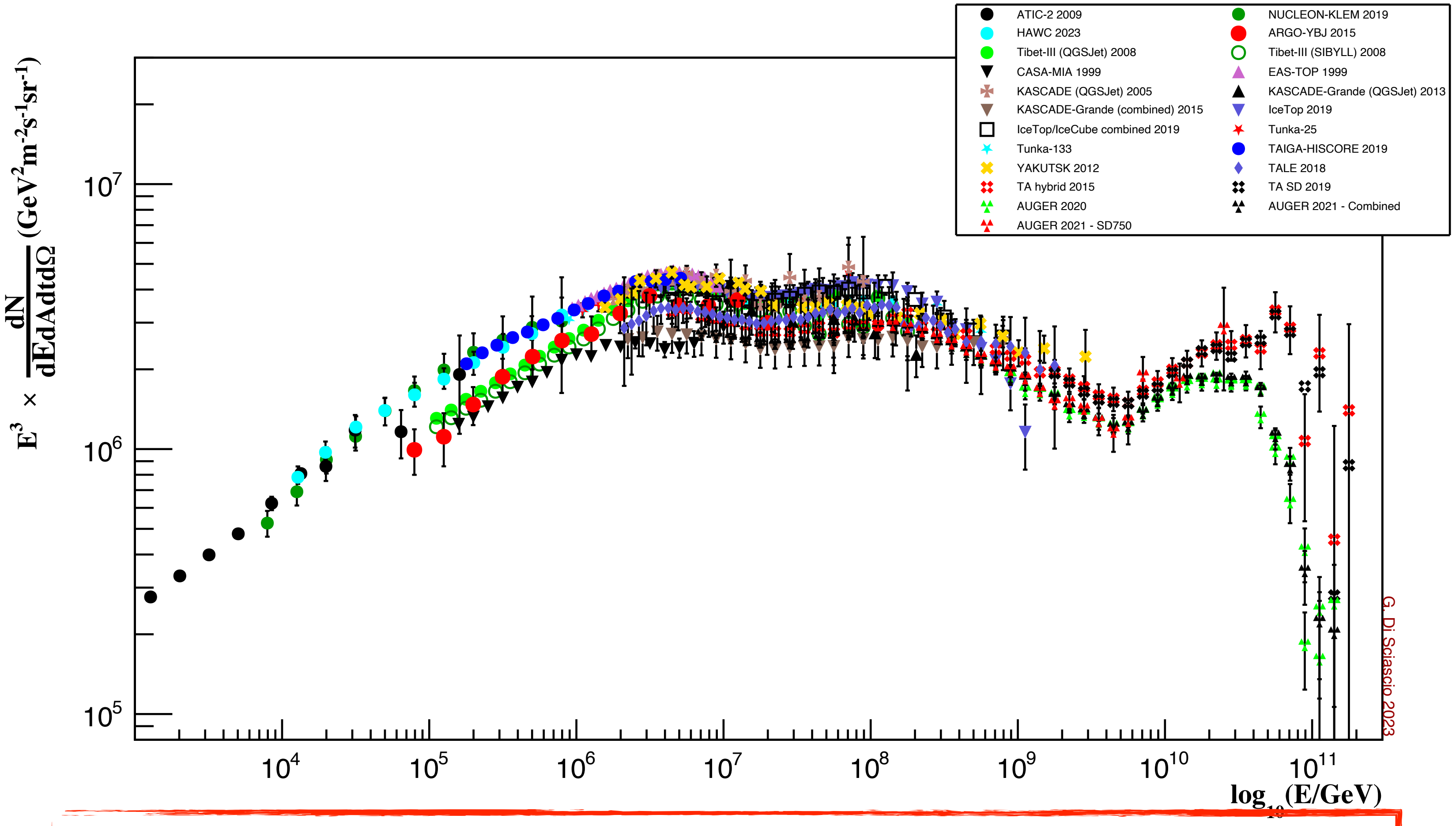
Typical uncertainty

$$\Delta X_{max} \simeq 20\ \ g/cm^2$$

Expected mass resolution

$$\Delta \ln A \approx 1$$

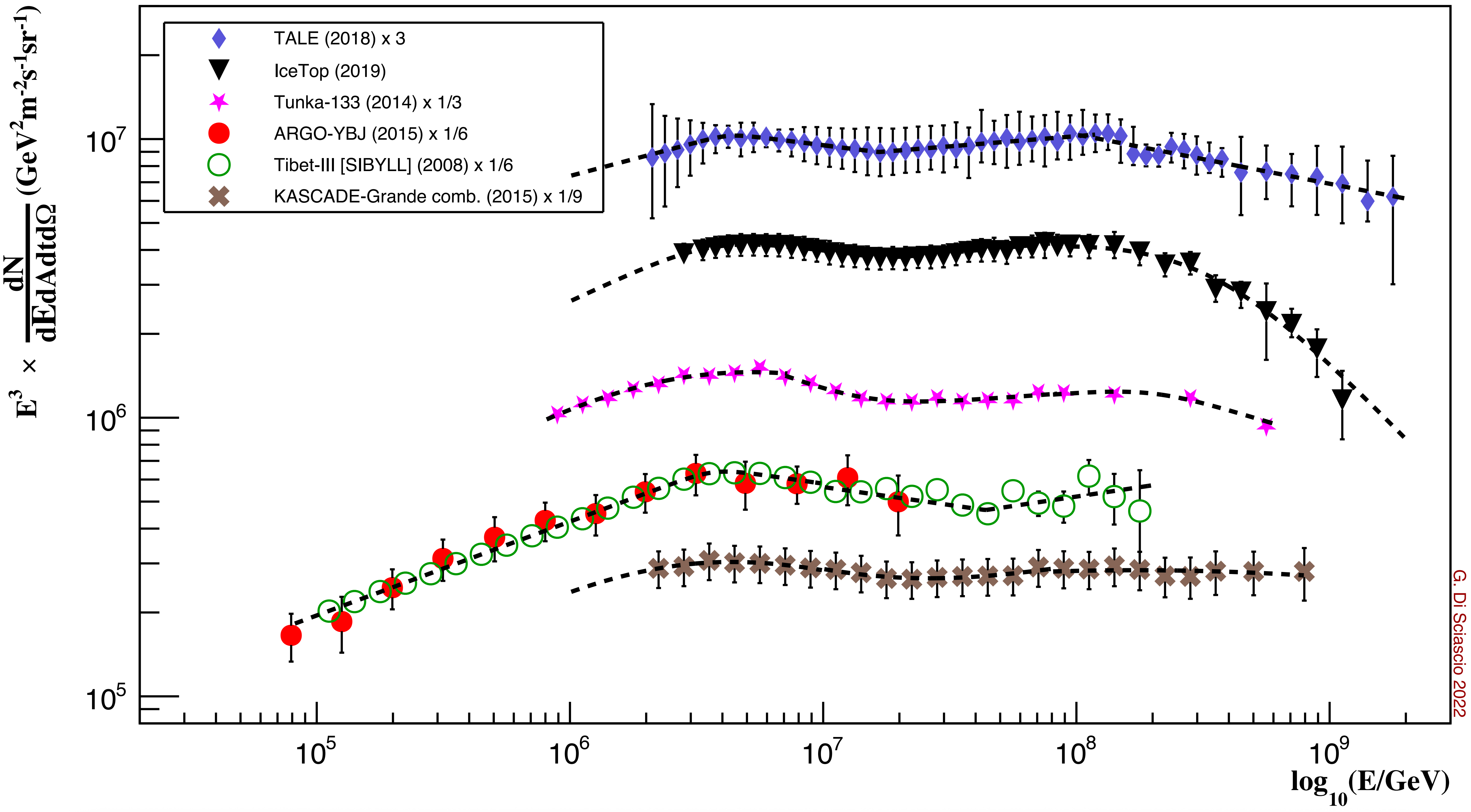
A description of the CR energy spectrum



$$\phi(E) = K_0 \left(\frac{E}{E_0}\right)^{-\alpha_1} \left[1 + \left(\frac{E}{E_b}\right)^{\frac{1}{w}}\right]^{-(\alpha_2-\alpha_1)\,w}$$

The absolute flux K_0 and the spectral index α_1 quantify the power law. The flux above the cut-off energy E_b is modeled by a second and steeper power law. The parameters α_2, the slope beyond the knee, and $w > 0$, the smoothness of the transition from the first to the second power law, characterize the change in the spectrum at the cut-off energy. A value $w = 0$ corresponds to a steep transition that soften with increasing values$^?$.

All-particle energy spectrum: the knee region



The most detailed observation of the knee region comes from ARGO-YBJ and Tibet ASγ

Fits to the all-particle spectra in the knee region

Table 1: Fits to the all–particle CR spectra in the energy range $8 \cdot 10^4$ to $2 \cdot 10^9$ GeV.

(a) Parameters for the first Knee.

Experiment	E_{b1} (PeV)	α_1	α_2	w_1
TALE	4.26 ± 1.65	2.76 ± 0.18	3.11 ± 0.07	0.07 ± 0.18
IceTop	3.30 ± 1.23	2.48 ± 0.08	3.12 ± 0.12	0.30 ± 0.46
Tunka–133	4.18 ± 0.83	2.76 ± 0.09	3.20 ± 0.04	0.15 ± 0.16
ARGO–YBJ/Tibet ASγ	3.72 ± 0.03	2.66 ± 0.01	3.13 ± 0.01	0.11 ± 0.01
Kascade–Grande	2.10 ± 0.87	2.47 ± 0.04	3.16 ± 0.14	0.60 ± 0.51

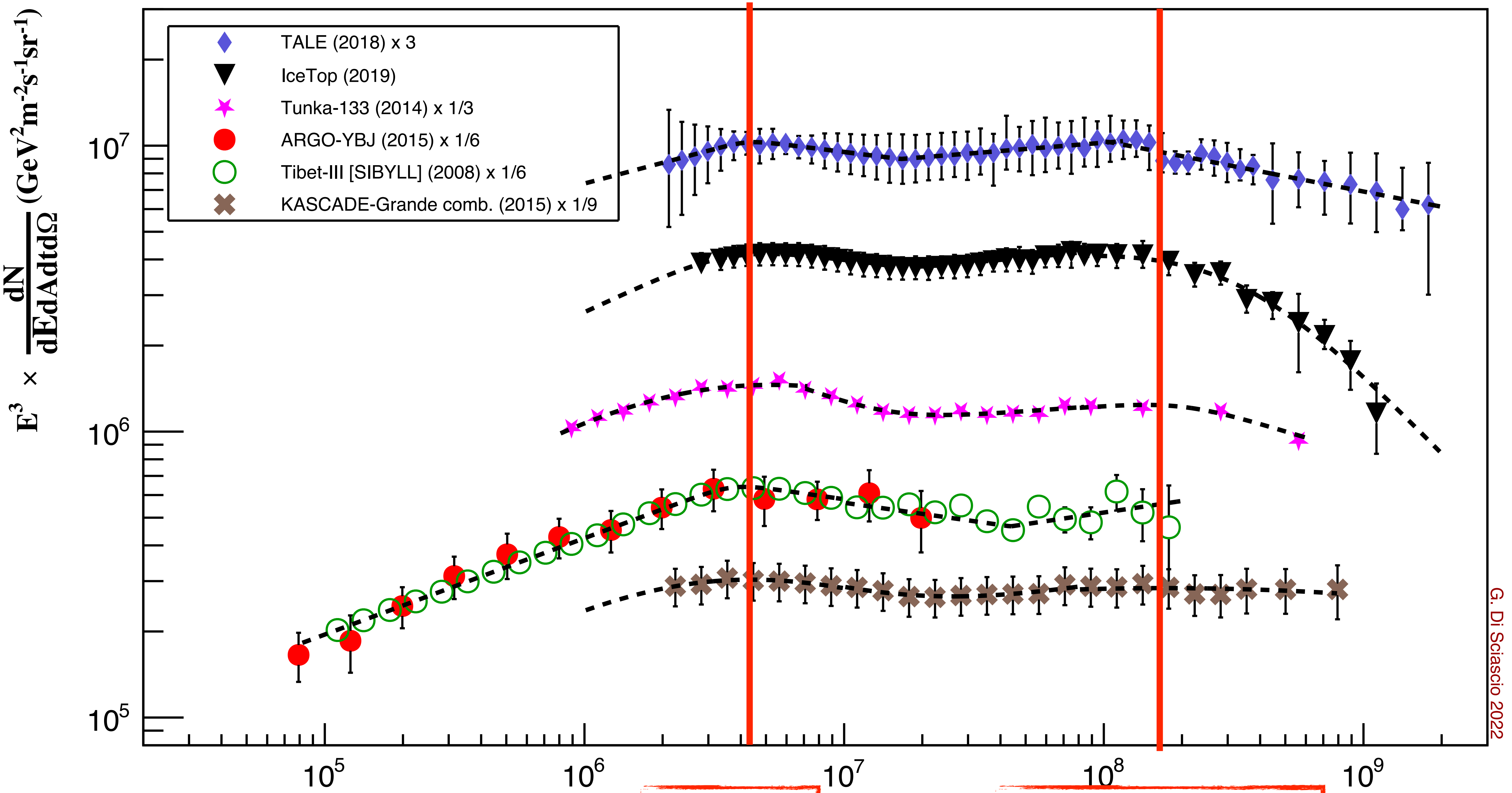
(b) Parameters for the ankle feature.

Experiment	E_{b2} (PeV)	α_2	α_3	w_2
TALE	16.61 ± 8.36	3.11 ± 0.05	2.93 ± 0.05	0.07 ± 0.05
IceTop	18.66 ± 6.65	3.12 ± 0.12	2.92 ± 0.05	0.05 ± 0.05
Tunka–133	18.70 ± 3.88	3.20 ± 0.04	2.96 ± 0.05	0.17 ± 0.45
ARGO–YBJ/Tibet ASγ	43.8 ± 4.81	3.13 ± 0.01	2.86 ± 0.05	0.01 ± 0.01
Kascade–Grande	18.01 ± 17.4	3.16 ± 0.14	2.83 ± 0.45	0.66 ± 1.74

(c) Parameters for the second Knee.

Experiment	E_{b3} (PeV)	α_3	α_4	w_3
TALE	104.5 ± 40.0	2.93 ± 0.05	3.18 ± 0.06	0.02 ± 0.02
IceTop	168.4 ± 17.4	2.92 ± 0.05	3.50 ± 0.40	0.25 ± 0.16
Tunka–133	238.2 ± 56.8	2.96 ± 0.05	3.34 ± 0.19	0.05 ± 0.50
Kascade–Grande	274.5 ± 122	2.83 ± 0.45	3.20 ± 0.13	2.47 ± 0.97

The knee region



≈ 4 PeV

≈ 100 - 200 PeV

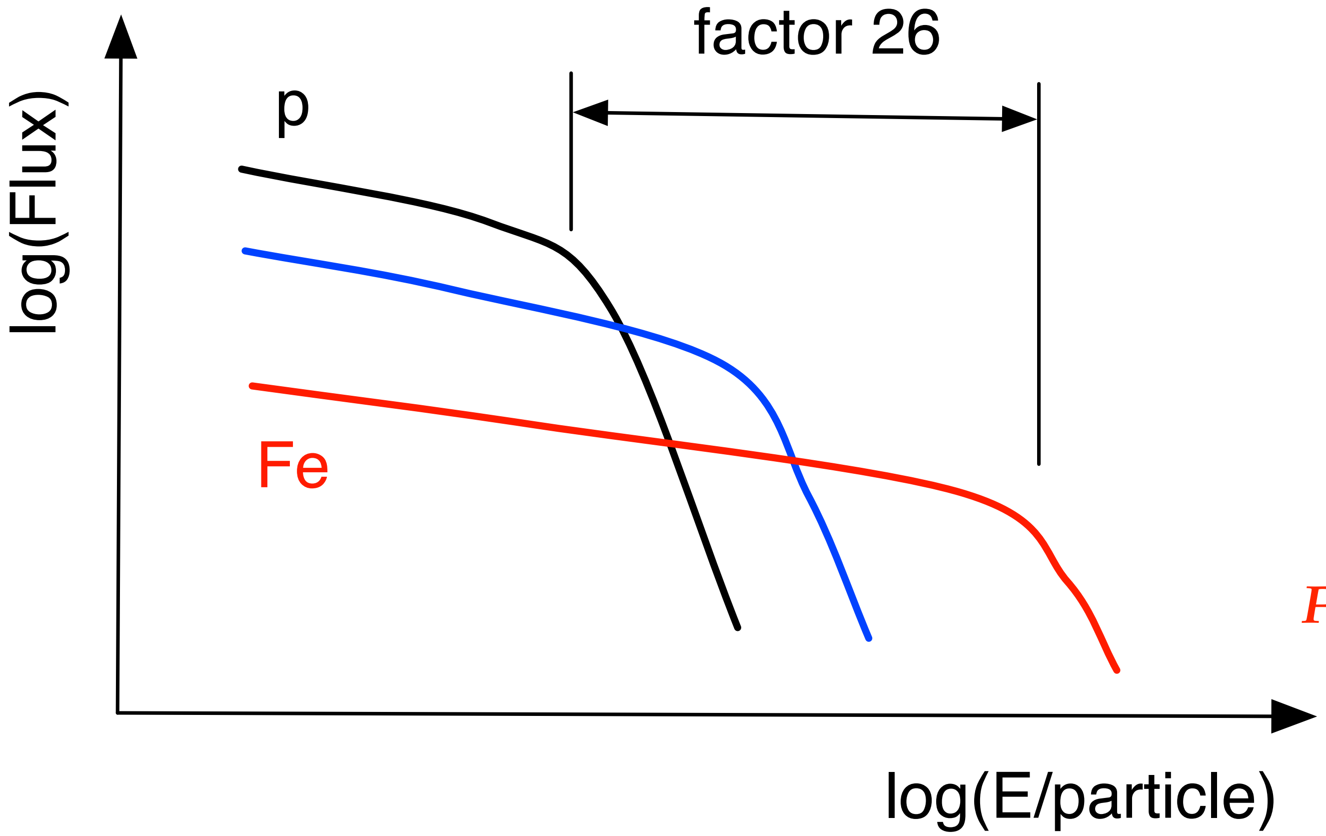
The origin of the 'knee'

In ***1961 B. Peters*** postulated a ***rigidity cutoff model.***

B. Peters, Nuovo Cimento 22 (1961) 800

$$\boxed{E_{max} \approx Ze \cdot L \cdot B}$$

$$\boxed{\rightarrow E_{total}\,(knee) \sim Z \times R(knee)}$$



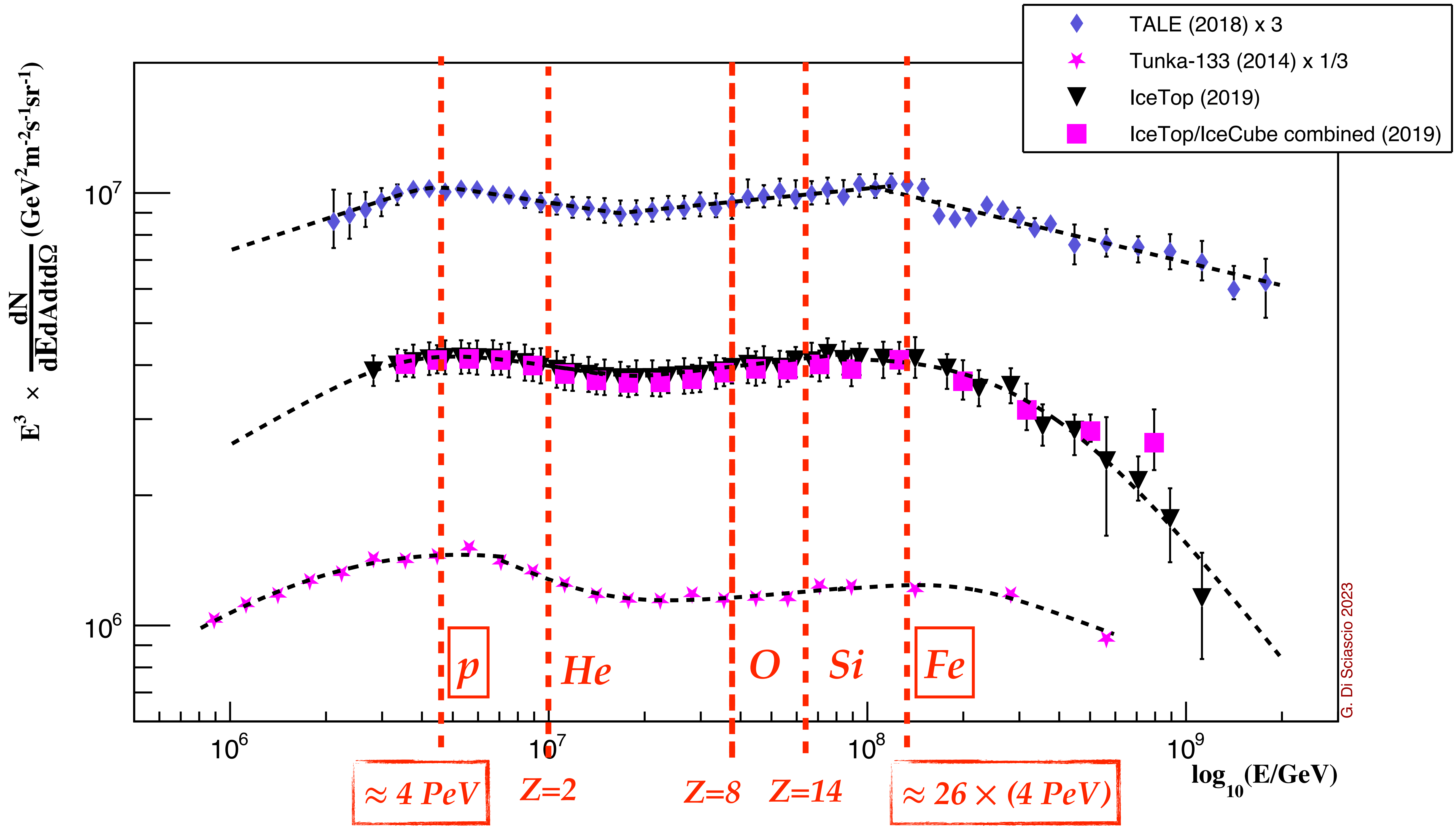
If ***E_{max} depends on B*** then p disappear first, then He, C, O, etc

$$\boxed{R_L(\text{p}, \text{E}) = R_L(\text{Fe}, \mathbf{26\ E})}$$

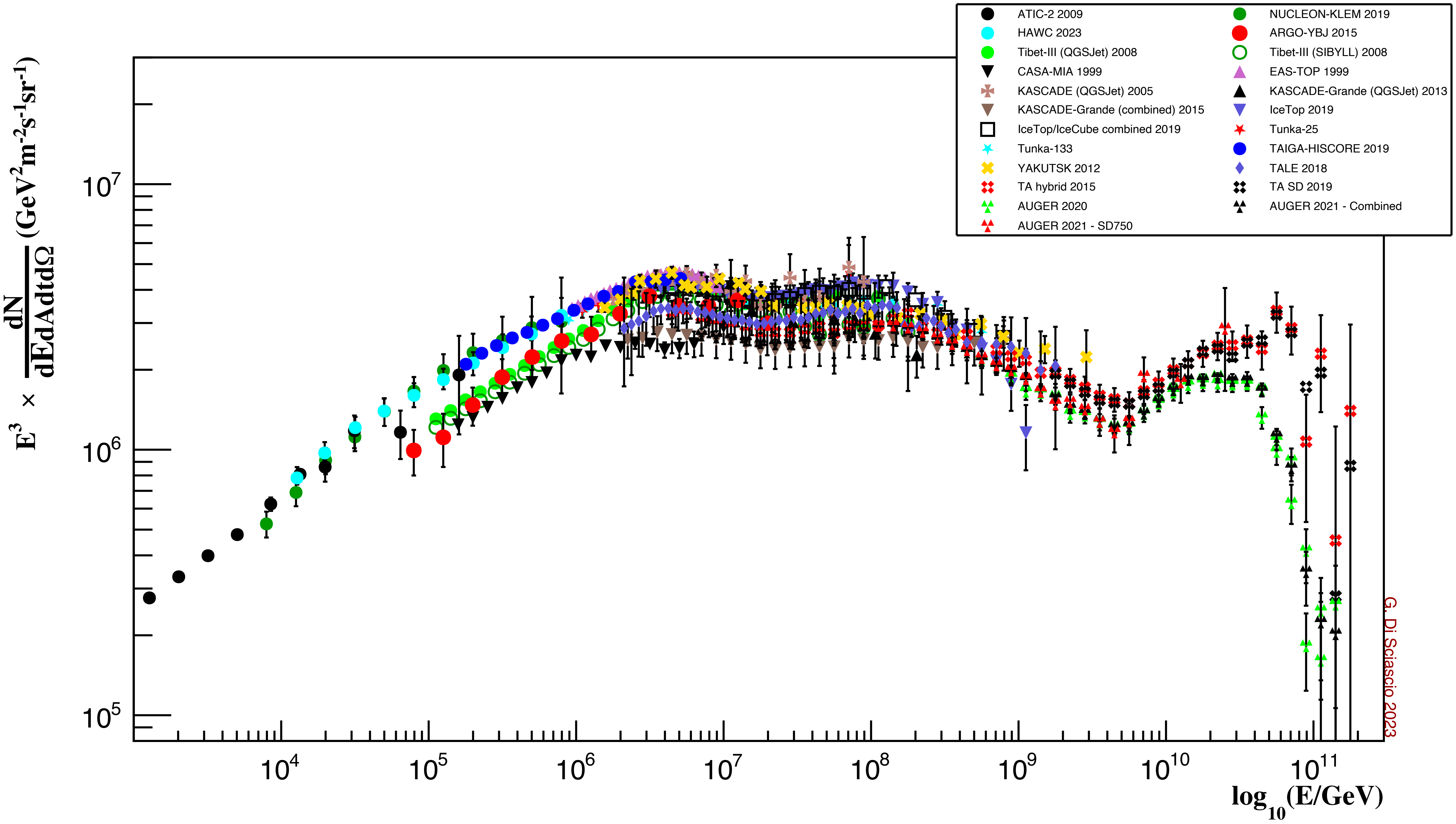
Fe confined longer ➜ accelerated to higher energies

- Not only does the spectrum become steeper due to such a cutoff but also heavier
- <A> should begin to decrease again for E > 30 x E_{knee} ≈ 100 PeV → 2nd knee??

A Rigidity Cutoff model?



The standard model of Galactic CRs



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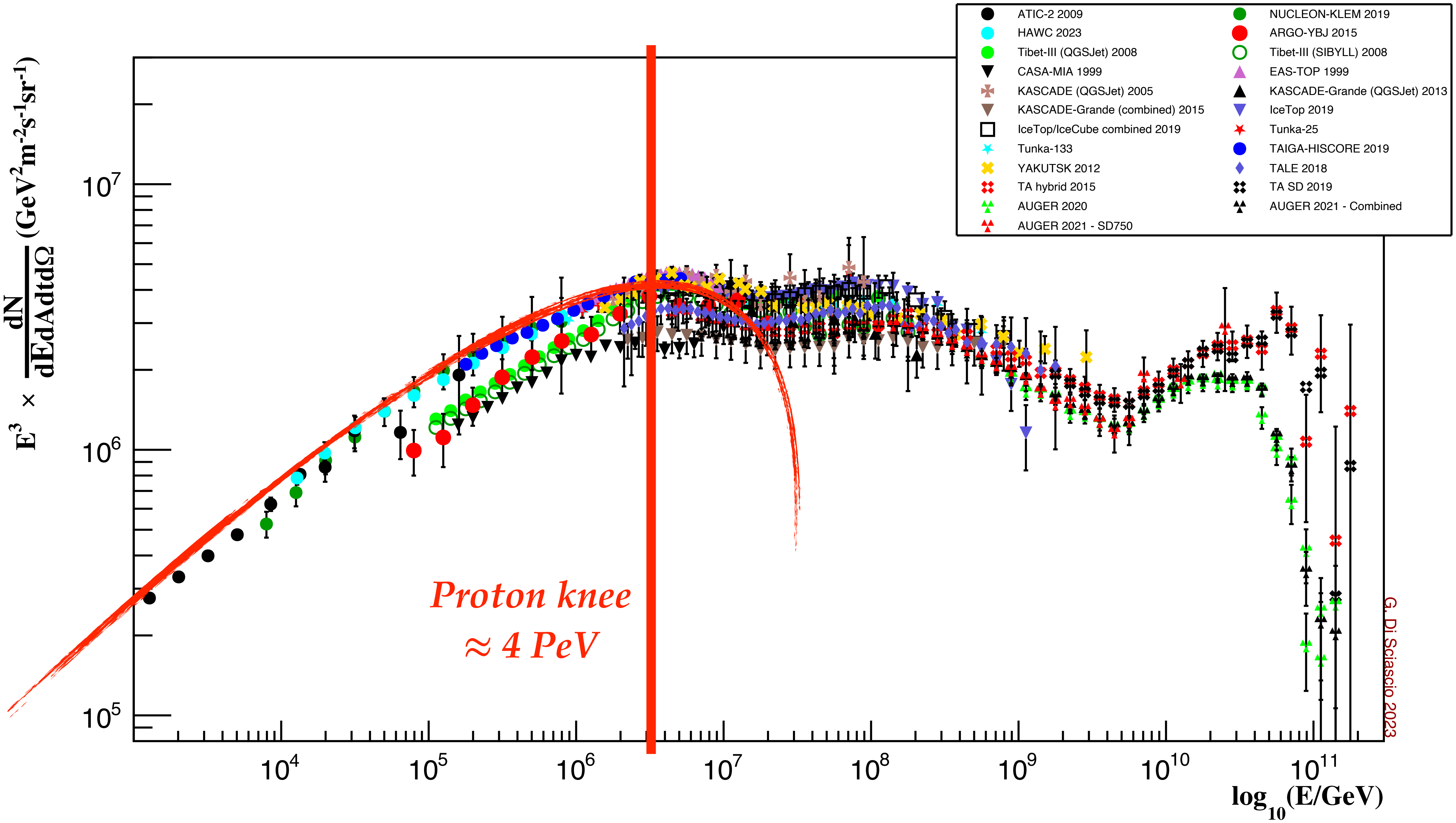
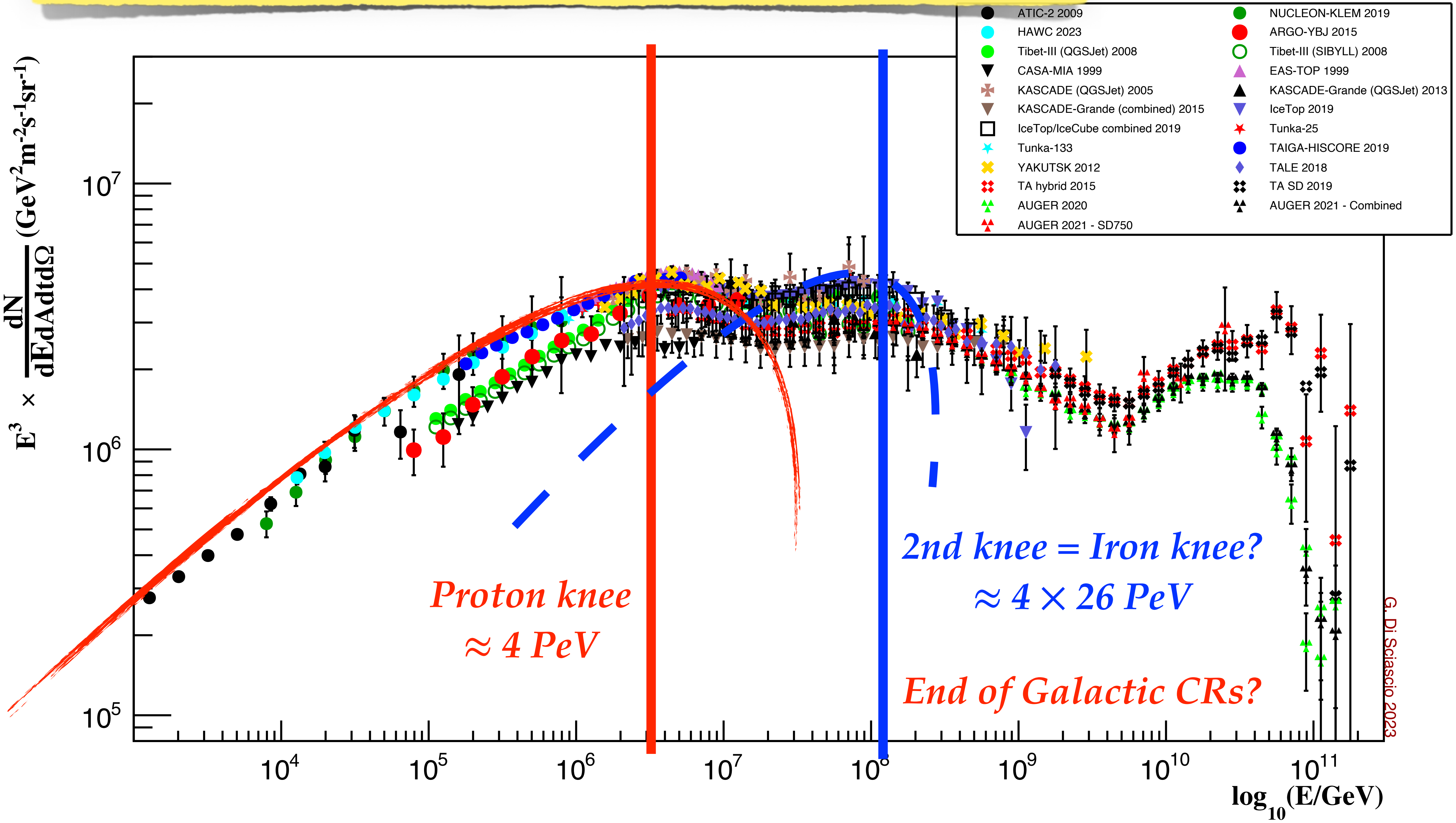


Proton knee
≈ 4 PeV

The standard model of Galactic CRs

Determining elemental composition in the knee energy region is crucial to understand where Galactic CR spectrum ends.



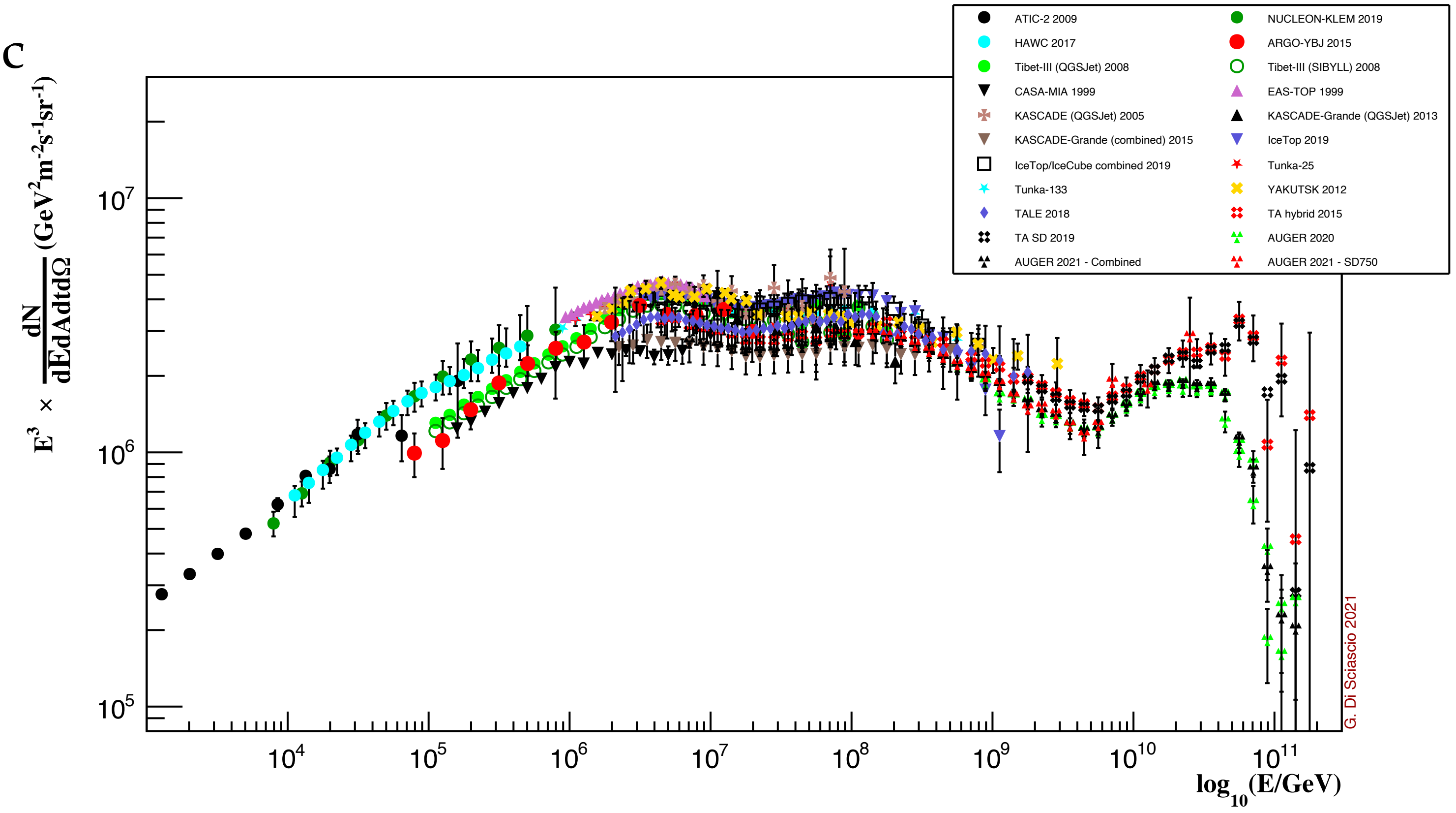
Proton knee
≈ 4 PeV

2nd knee = Iron knee?
≈ 4 × 26 PeV

End of Galactic CRs?

Galactic CRs: mainstream interpretation

- All-particle knee at about 4 PeV caused by *cut-off for light elements (p, He)*
- CRs below 10^{17} eV are predominantly Galactic



- *Standard paradigm*: Galactic CRs accelerated in SN shocks via 1^0 order Fermi mechanism
- Somehow released into the ISM, CRs are *diffusively confined* within a magnetized *Galactic halo*
- CRs reside from some time before escaping the Galaxy
- Galactic CRs are scrambled by galactic magnetic field over very long time ➜ arrival direction *mostly isotropic*

The *knee*
- ✓ Acceleration limits in galactic sources (Hillas, 2005)
- ✓ Escape increasing of particle from the Galaxy (Giacinti, 2014, 2015)

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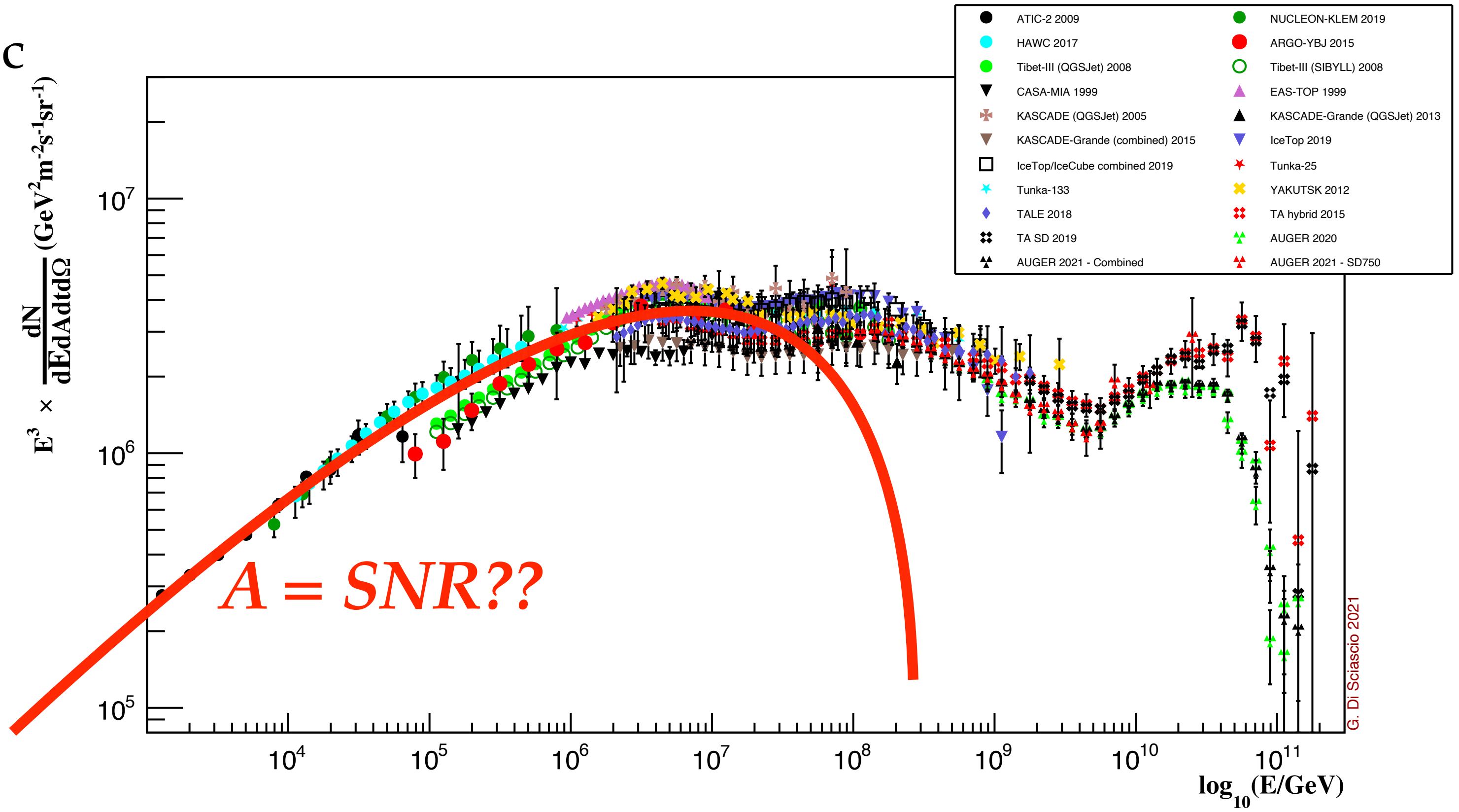

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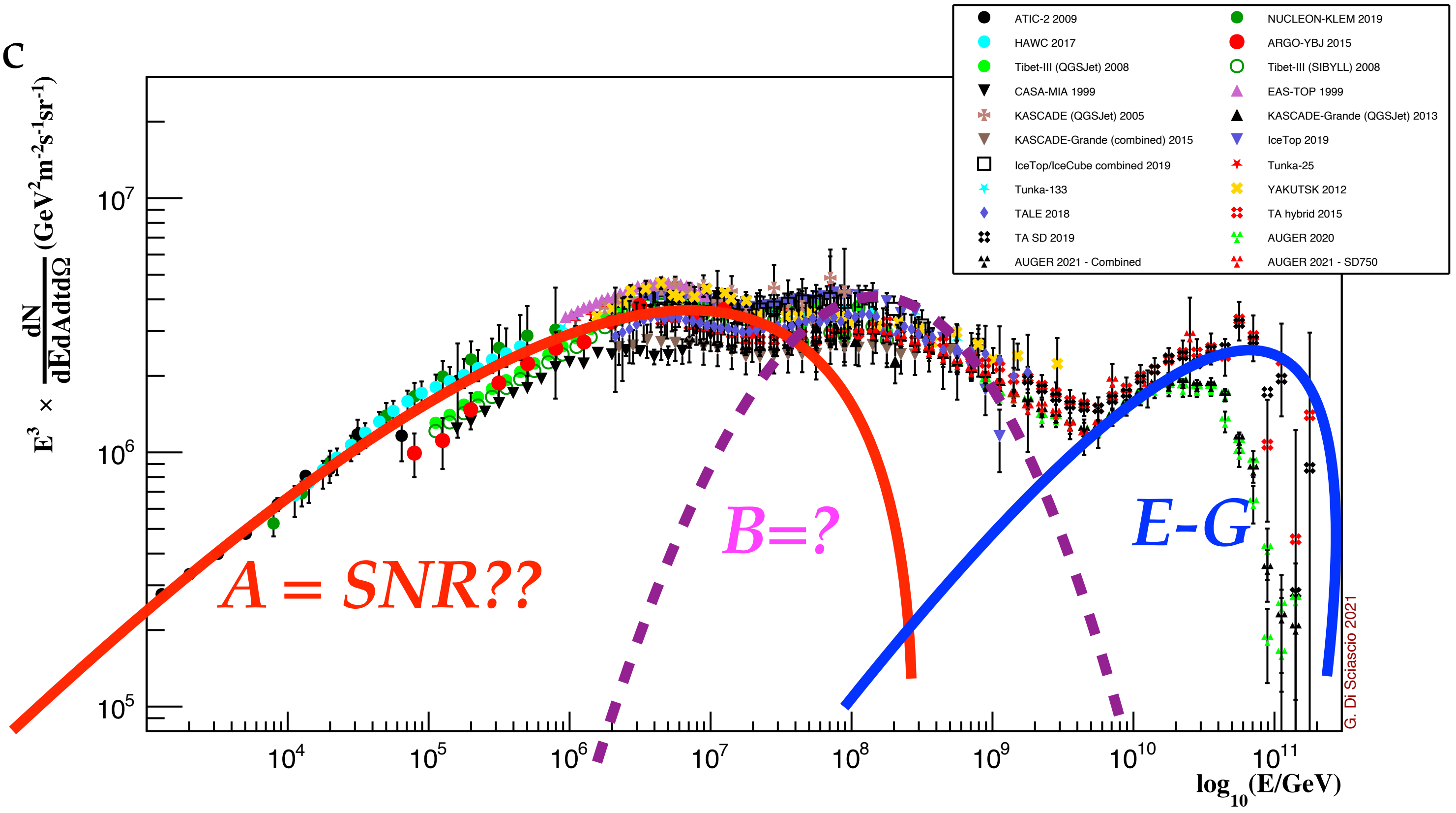

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The *knee*

✓ Acceleration limits in galactic sources (Hillas, 2005)
✓ Escape increasing of particle from the Galaxy (Giacinti, 2014, 2015)

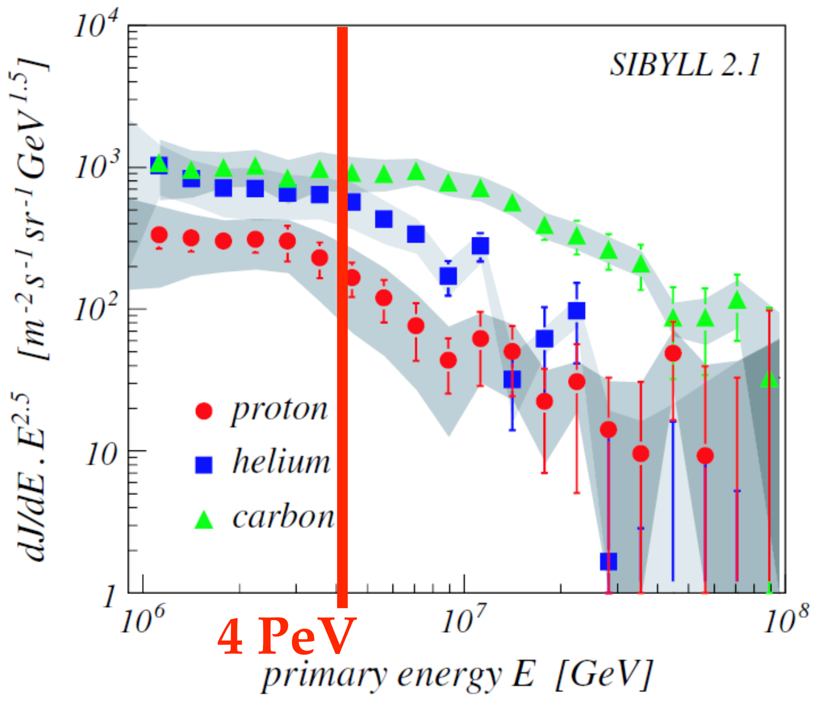
- *2nd galactic component* at ~10^{17} eV?
- Transition to *extragalactic* CRs occurs somewhere between 10^{17} and 10^{19} eV

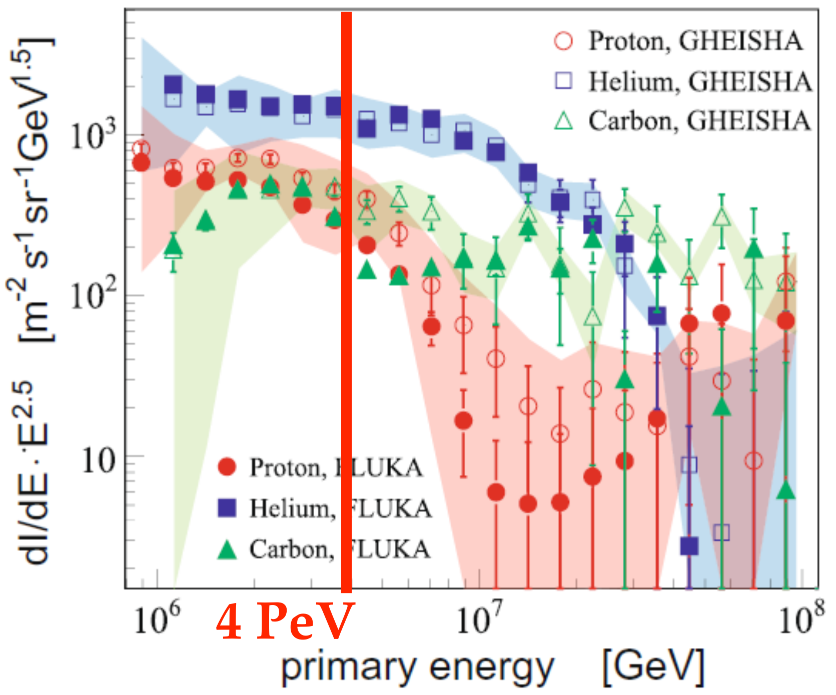
KASCADE results

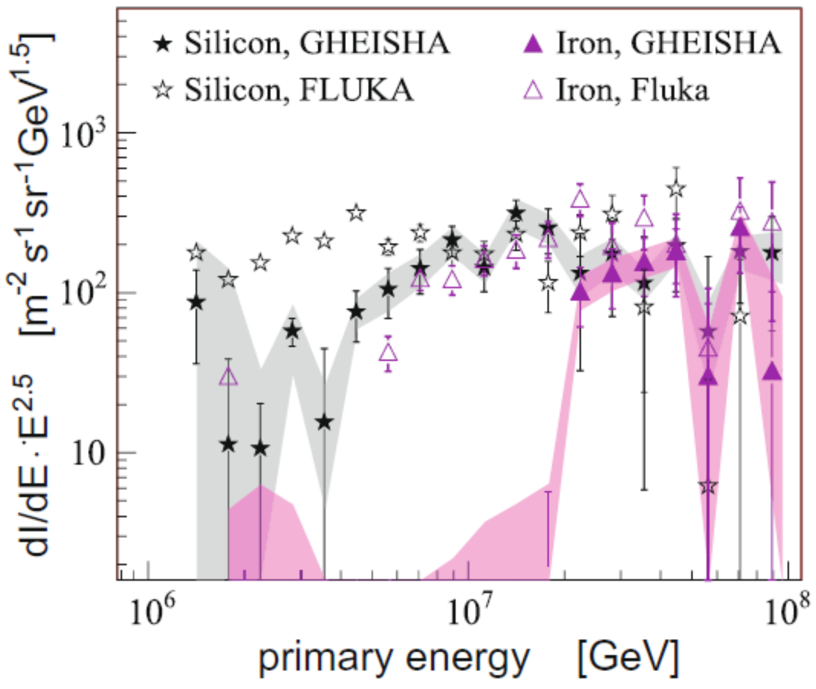
✓ Knee caused by cut-off for light elements
✓ Knee energy increases with primary mass
✓ Fe knee not observed
✓ Strong indication for a rigidity-dependent knee

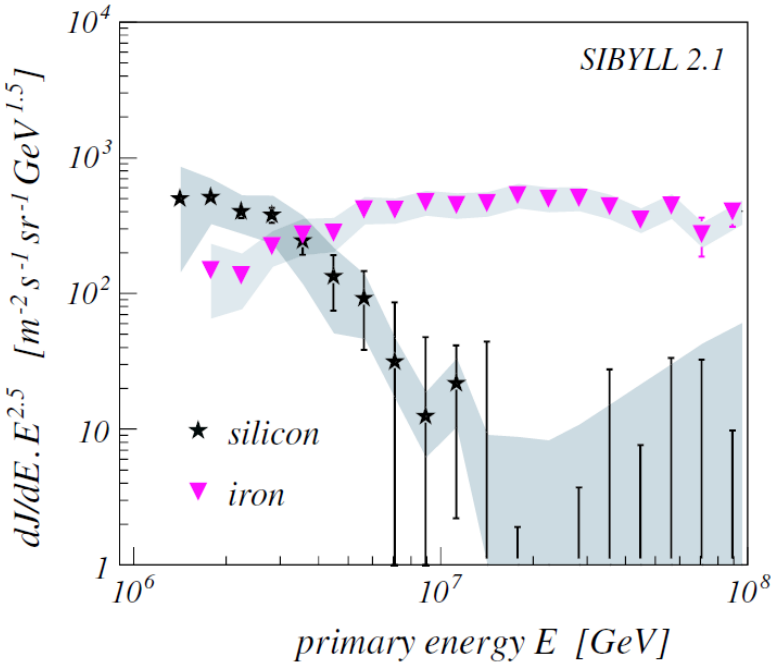
Fluxes depend on the high energy hadronic interaction models

- QGSJet ➜ He more abundant element at the knee
- SIBYLL 2.1 ➜ C more abundant element at the knee



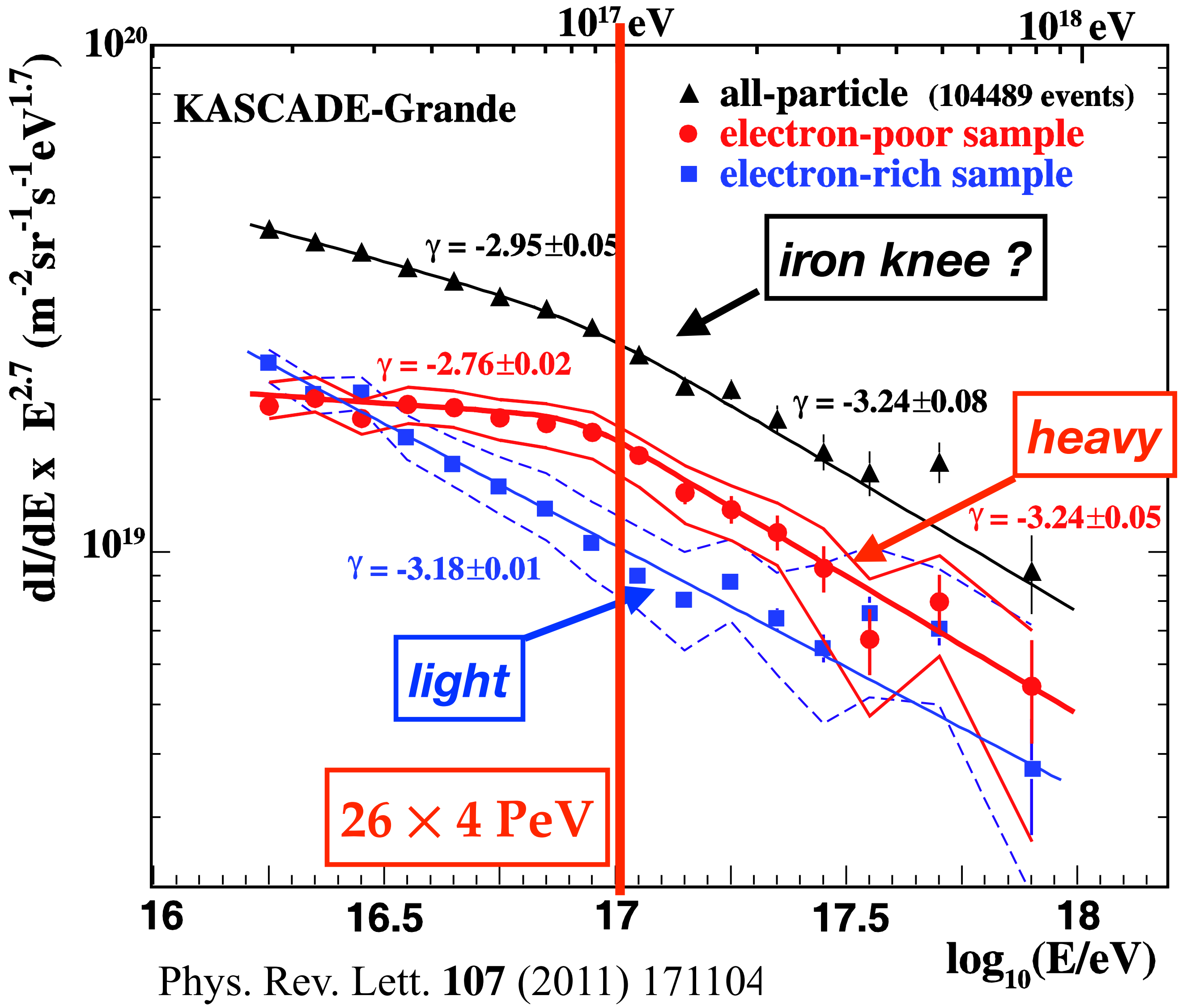






Astroparticle Physics **24** (2005) 1
Astroparticle Physics **31** (2009) 86

Kascade-Grande: Iron knee ?

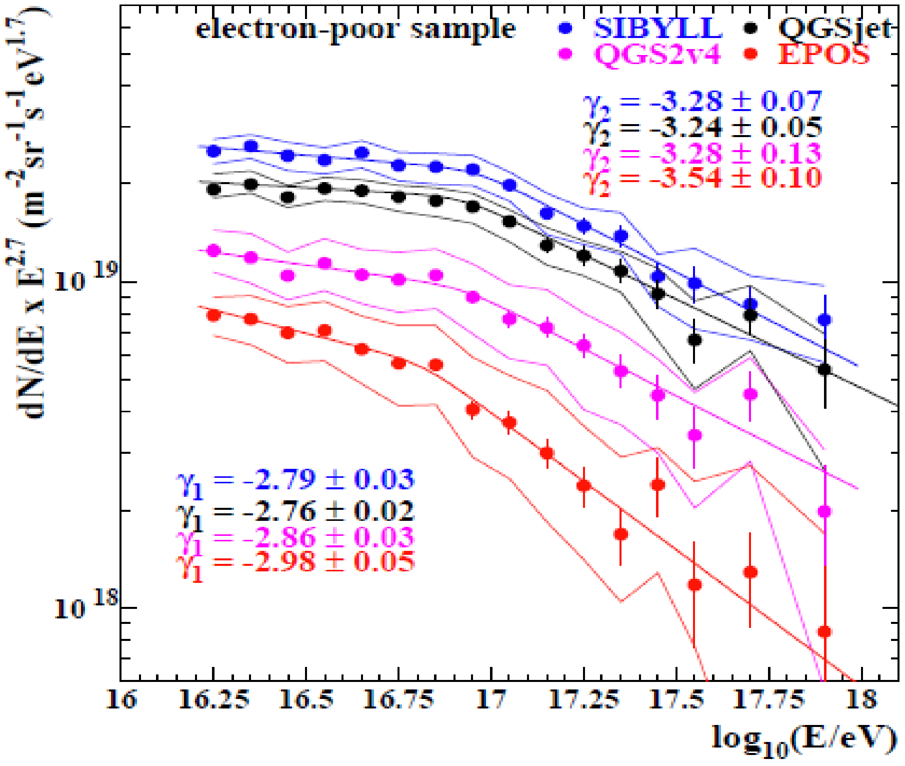


Phys. Rev. Lett. **107** (2011) 171104

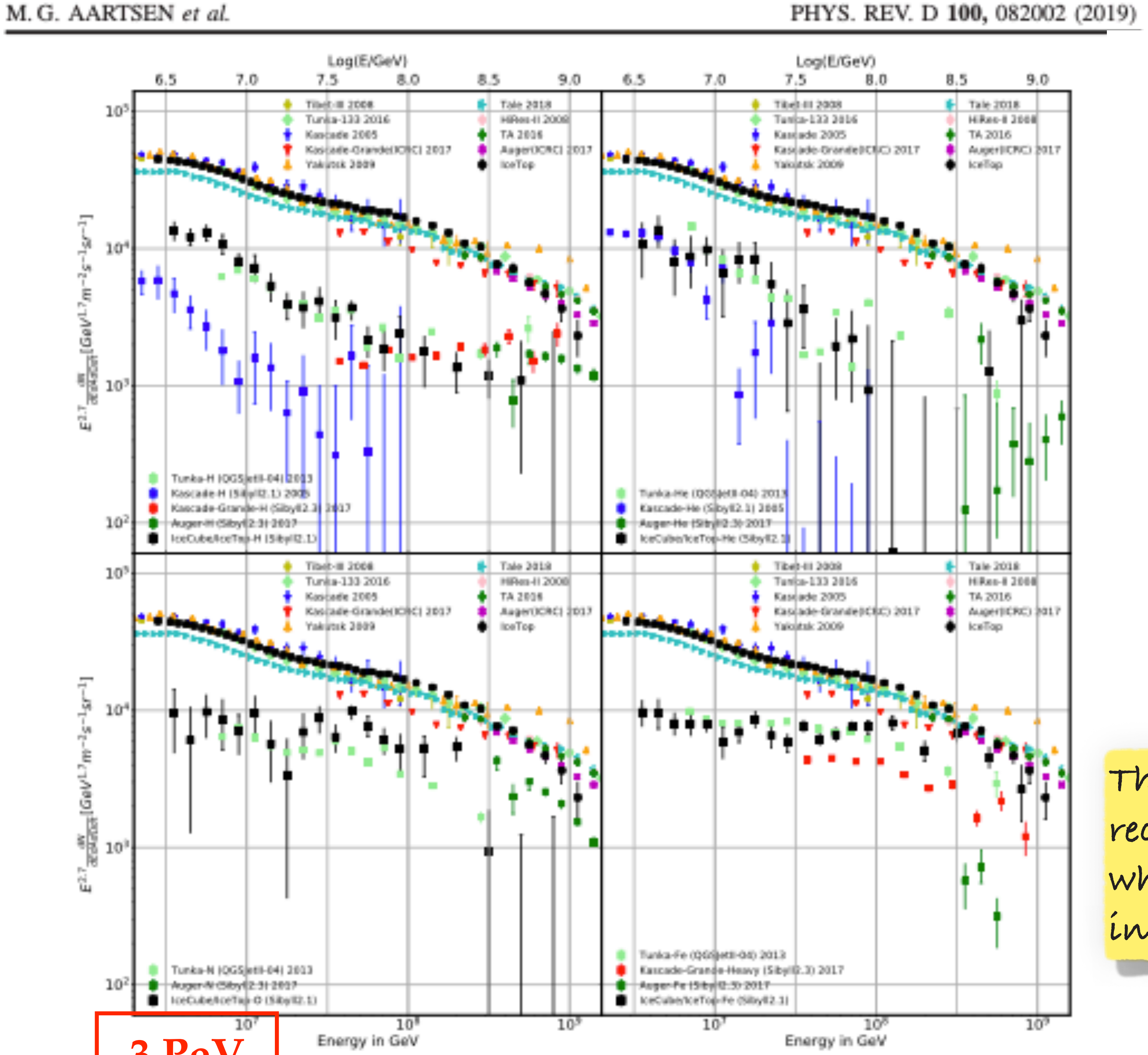
$$\gamma_1 = -2.76 \pm 0.02 \quad E_b = 10^{16.92 \pm 0.04}\ \text{eV}$$
$$\gamma_2 = -3.24 \pm 0.05$$

- Spectrum of the electron poor sample: $k > (k_C + k_{Si})/2$ → steepening observed with 3.5 σ significance
- Spectrum of electron rich events
  → can be described by a single power law
  → hints of a hardening above 10^{17} eV
- relative abundances different for different high-energy hadronic interaction models

Adv. Sp. Res. 53 (2014) 1456

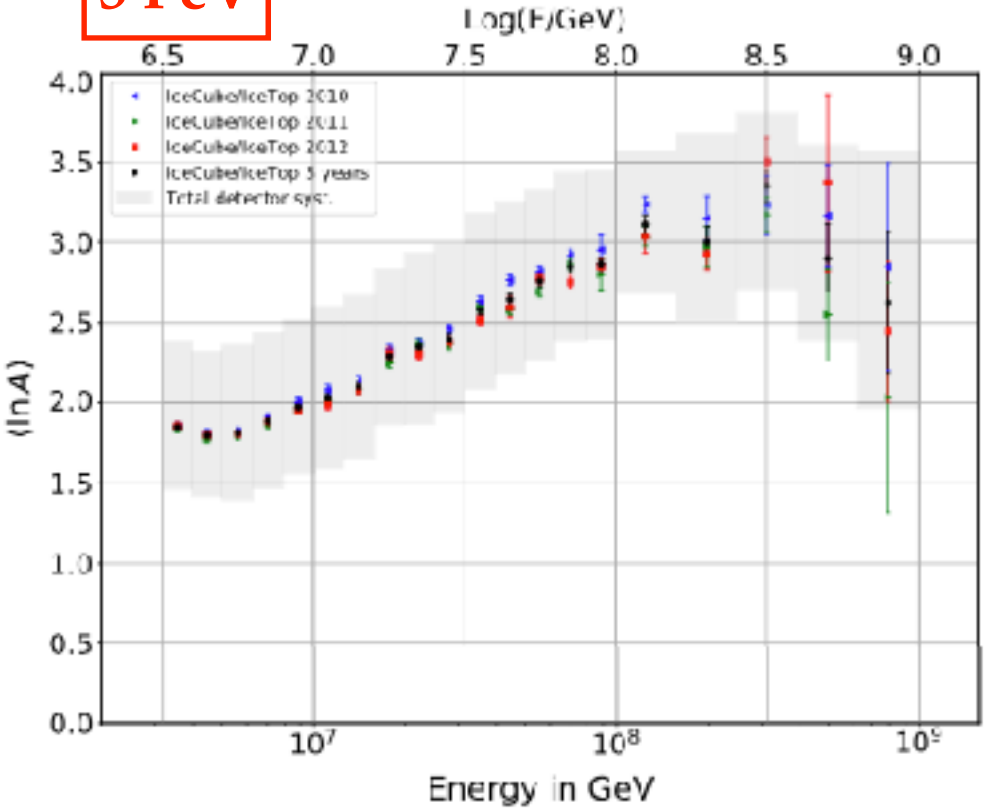


IceTop + IceCube


M. G. AARTSEN *et al.* PHYS. REV. D **100**, 082002 (2019)

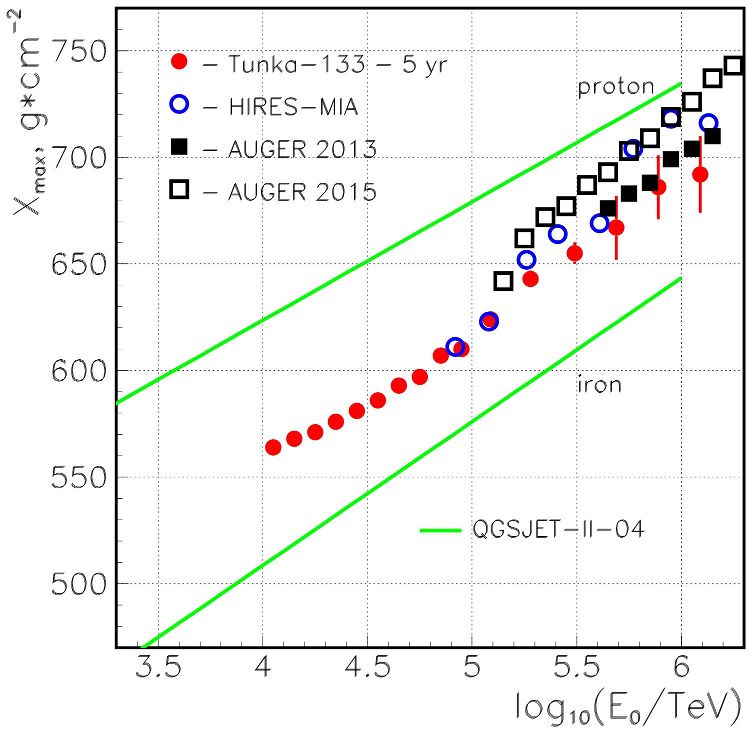
3 PeV

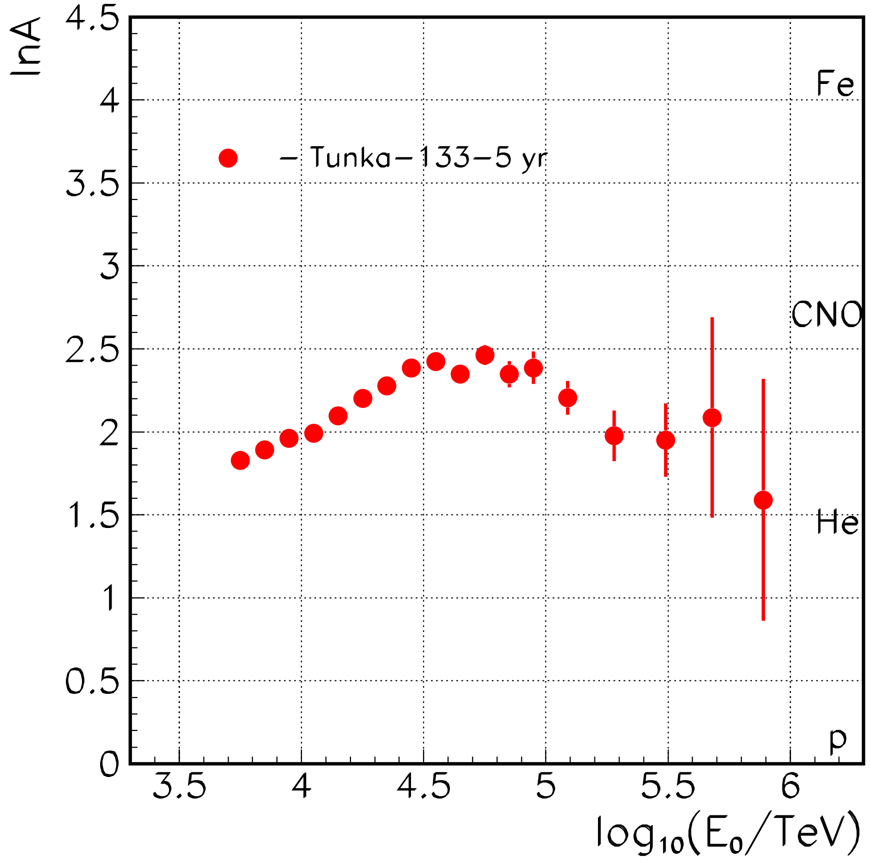
3 PeV

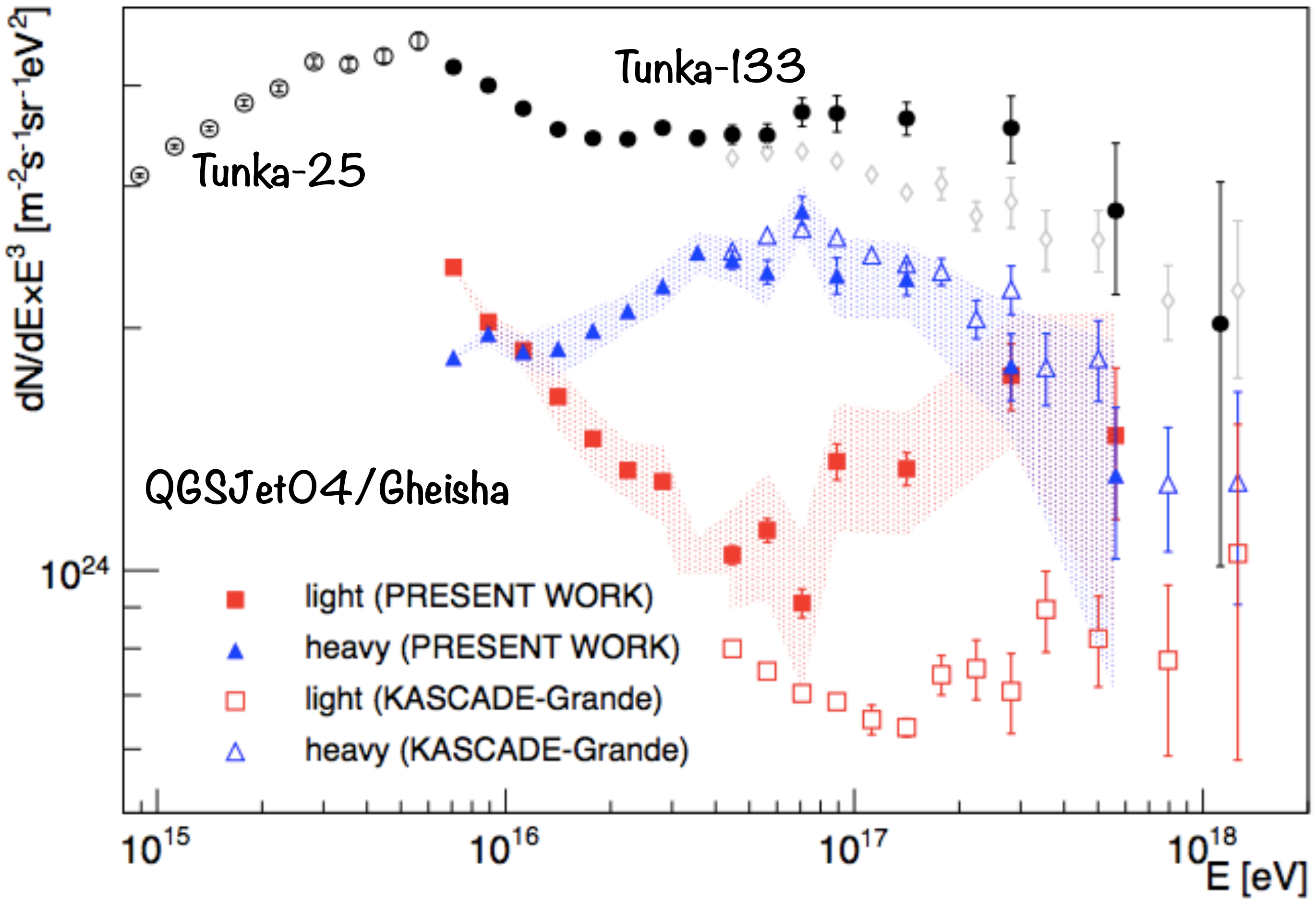


The elemental spectra results agree well with the recent H3a and H4a phenomenological models in which heavier elements retain a harder spectral index to higher energies.

TUNKA-133: Elemental Composition







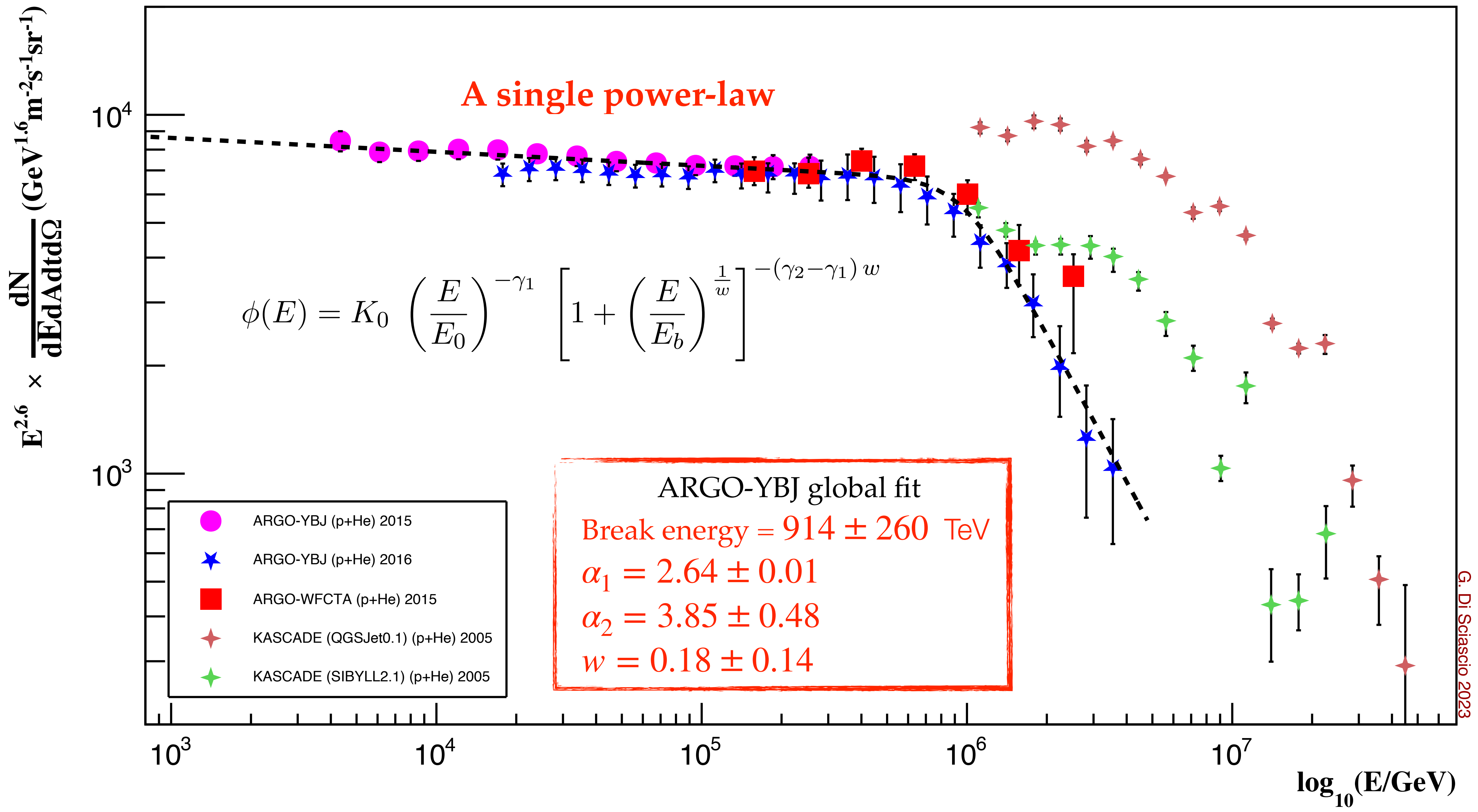
- ✓ Knee: p, He
- ✓ Heavy knee at $\sim 7 \cdot 10^{16}$ eV, light component growing above $\sim 4-5 \cdot 10^{16}$ eV
- ✓ Mean mass getting heavier up to $\sim 10^{17}$ eV, then lighter again

Is that all?

The ARGO-YBJ (p+He) knee

ARGO-YBJ: the only experiment with (p+He) data in the range TeV - 5 PeV

→ clear observation of a knee both with array and a wide FoV Cherenkov Telescope



A single power-law

$$\phi(E) = K_0 \left(\frac{E}{E_0}\right)^{-\gamma_1}\left[1+\left(\frac{E}{E_b}\right)^{\frac{1}{w}}\right]^{-(\gamma_2-\gamma_1)\,w}$$

ARGO-YBJ global fit

Break energy = 914 ± 260 TeV

$\alpha_1 = 2.64 \pm 0.01$

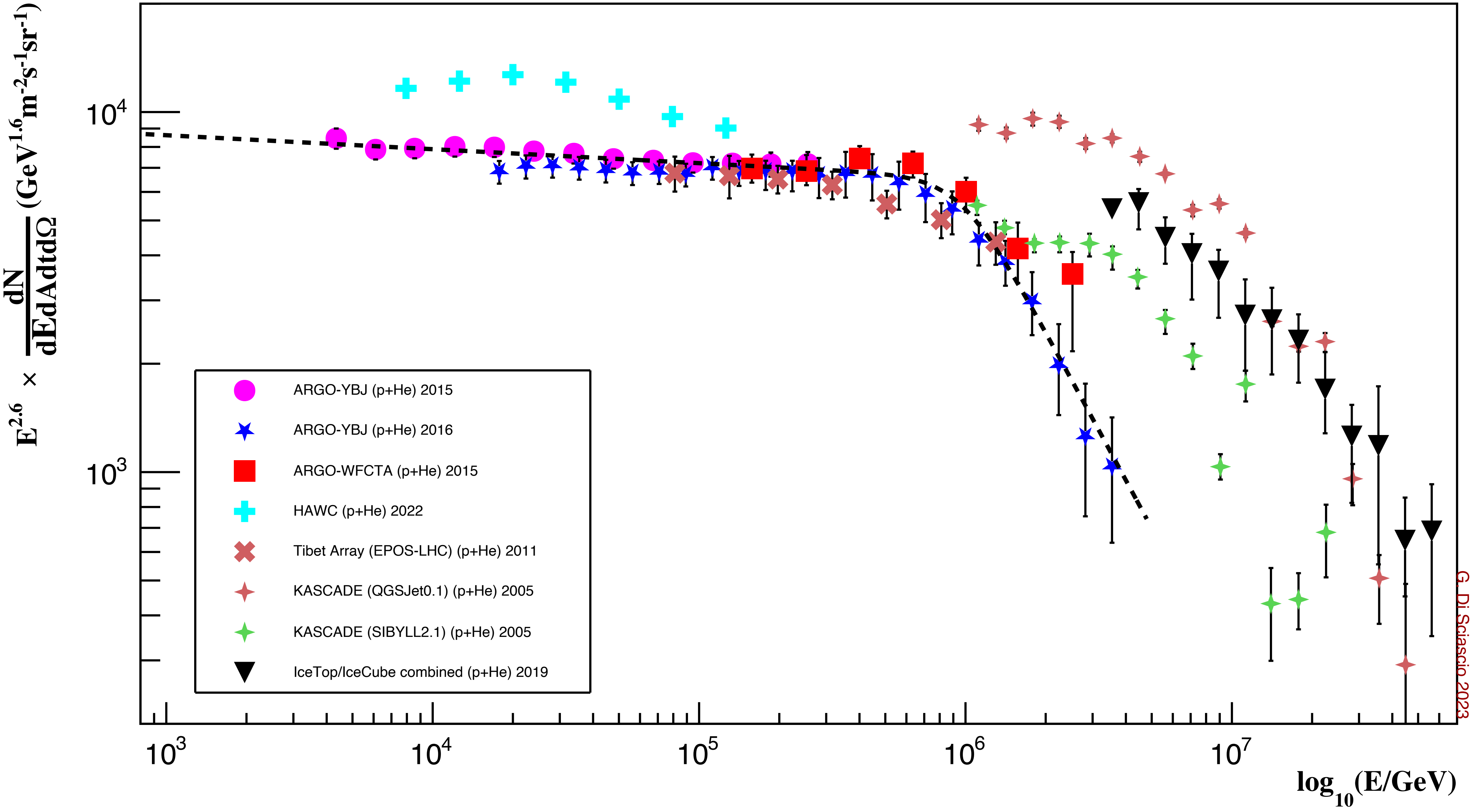
$\alpha_2 = 3.85 \pm 0.48$

$w = 0.18 \pm 0.14$

p+He: indirect measurements

- ✓ ARGO-YBJ and TIBET ASγ: single power law E<500 TeV
- ✓ HAWC: deviation from single power law?

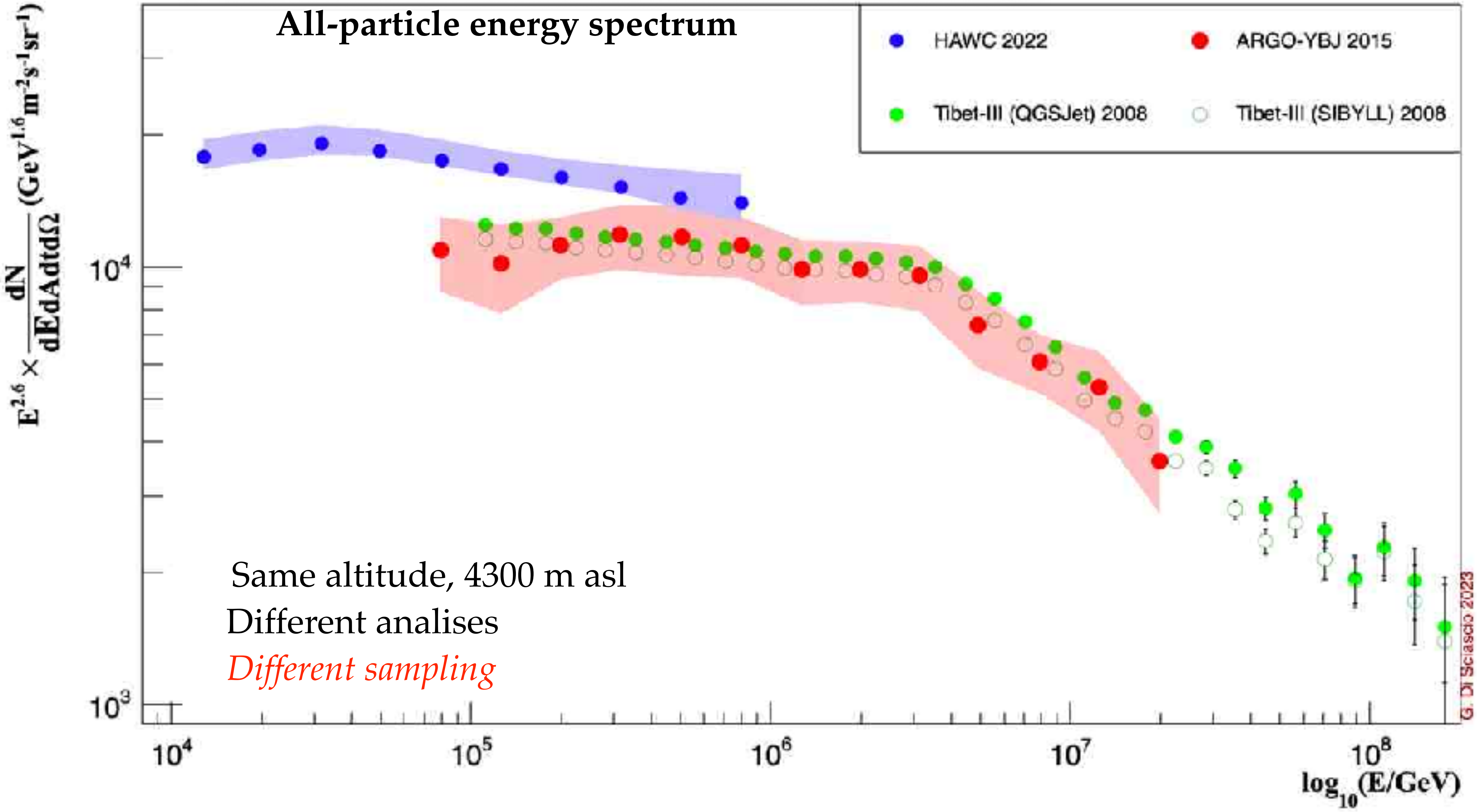
- ✓ ARGO-YBJ and TIBET ASγ: light knee below the PeV
- ✓ KASCADE: light knee at about 4 PeV



HAWC vs ARGO-YBJ/TIBET ASγ

✓ HAWC: deviation from single power-law

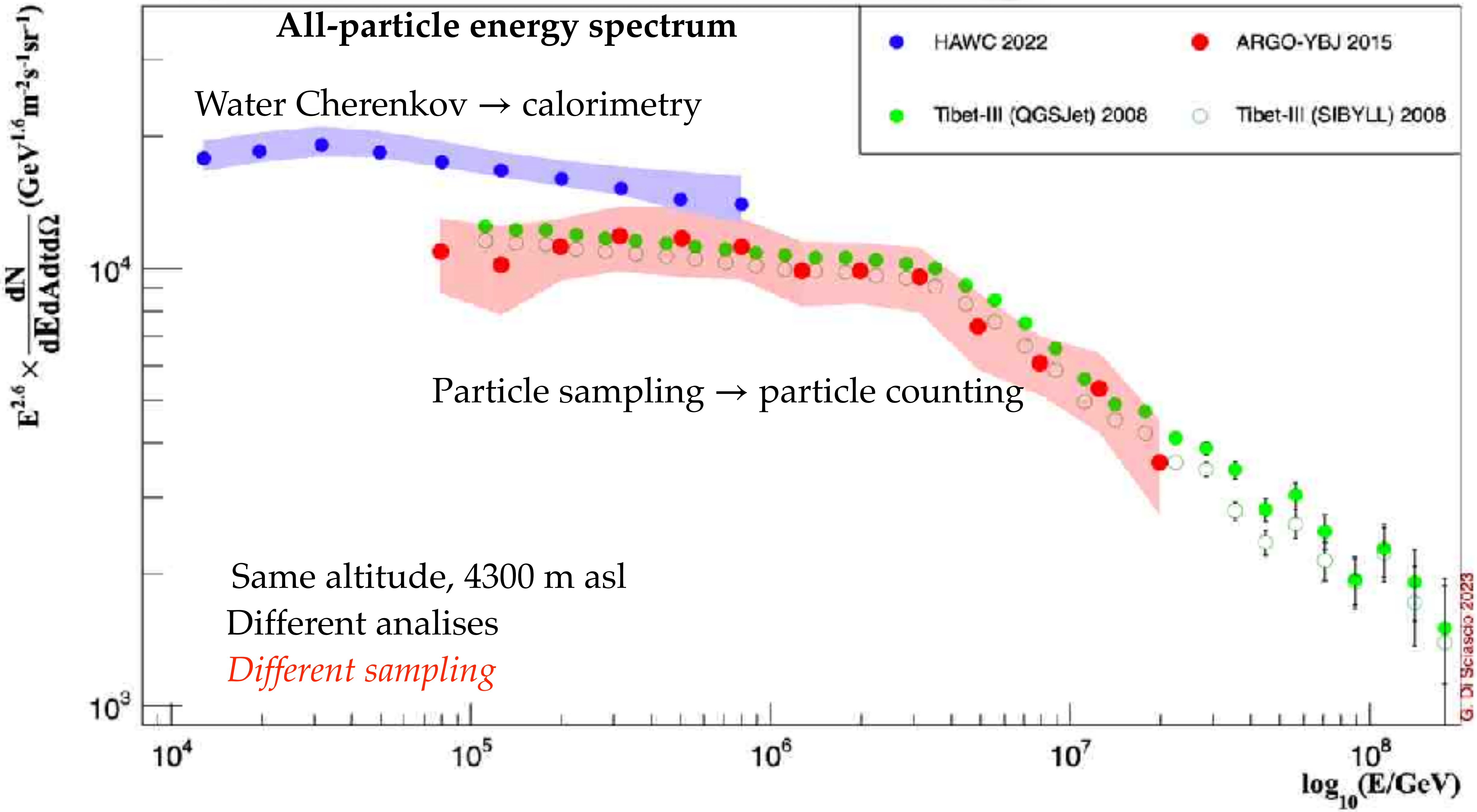
✓ ARGO-YBJ and TIBET ASγ: single power-law



Same altitude, 4300 m asl
Different analises
Different sampling

HAWC vs ARGO-YBJ/TIBET ASγ

- ✓ HAWC: deviation from single power-law
- ✓ ARGO-YBJ and TIBET ASγ: single power-law



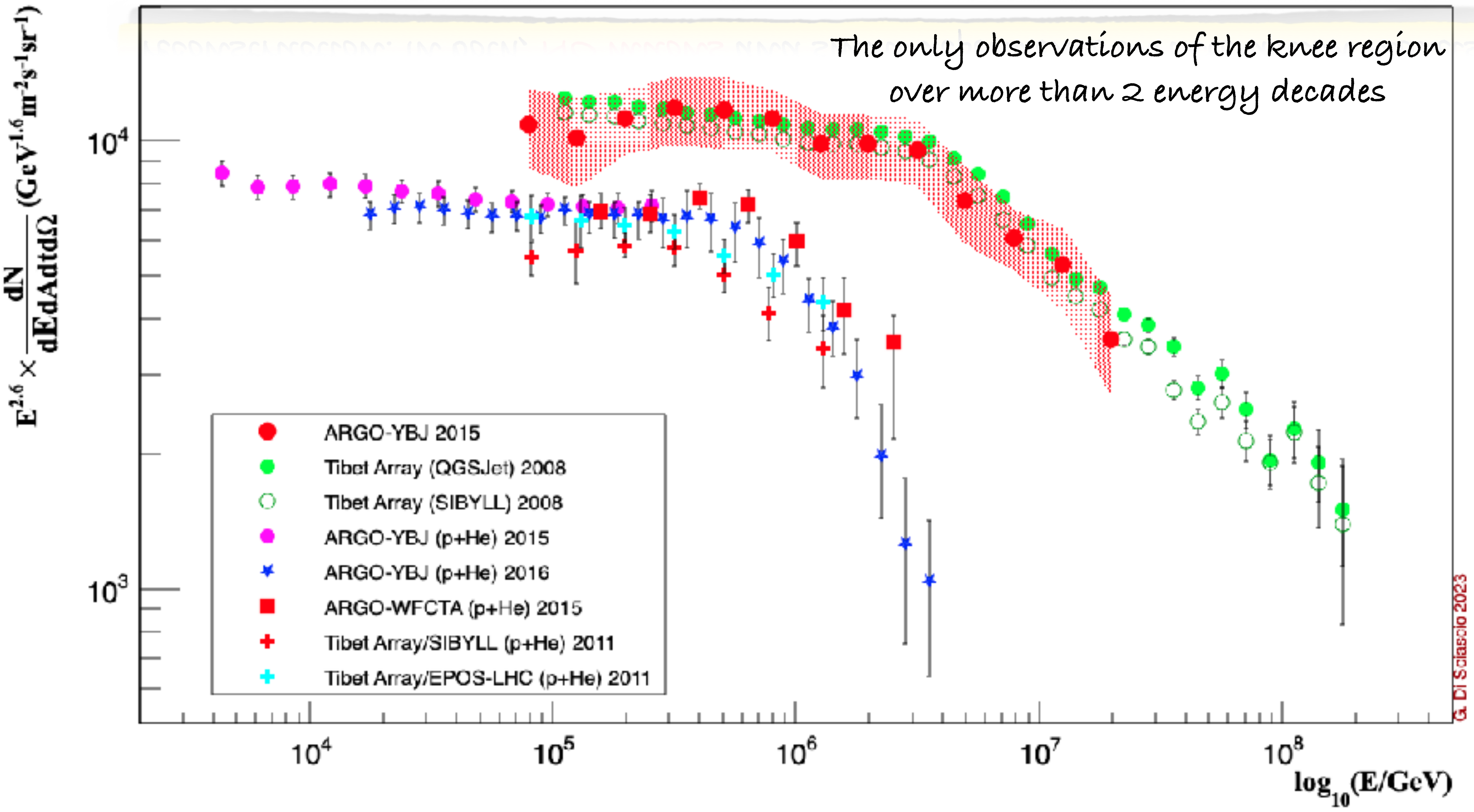
Water Cherenkov → calorimetry

Particle sampling → particle counting

Same altitude, 4300 m asl
Different analises
Different sampling

The light knee: ARGO-YBJ and Tibet Array

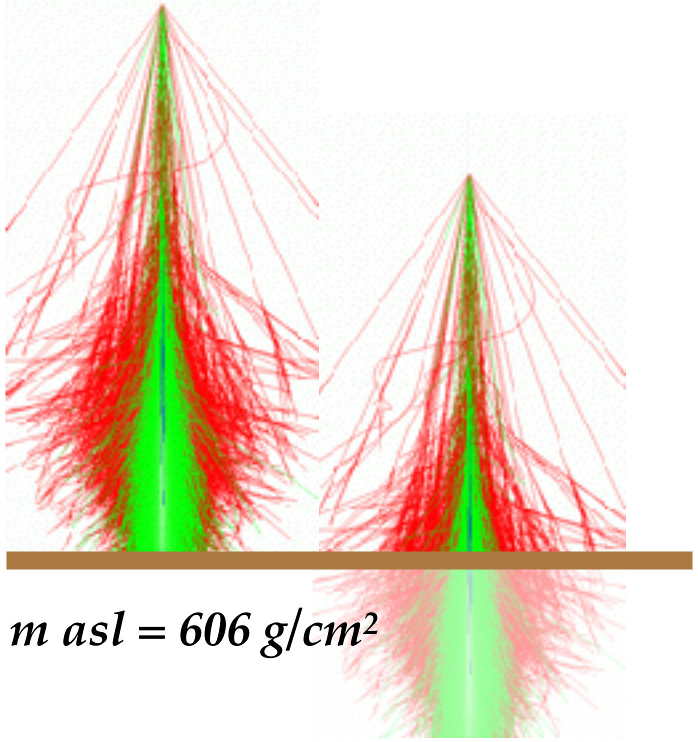
Same altitude but different detectors, layouts, observables (shower core), reconstruction. In both, NO muons and small dependence on interaction models



The only observations of the knee region over more than 2 energy decades

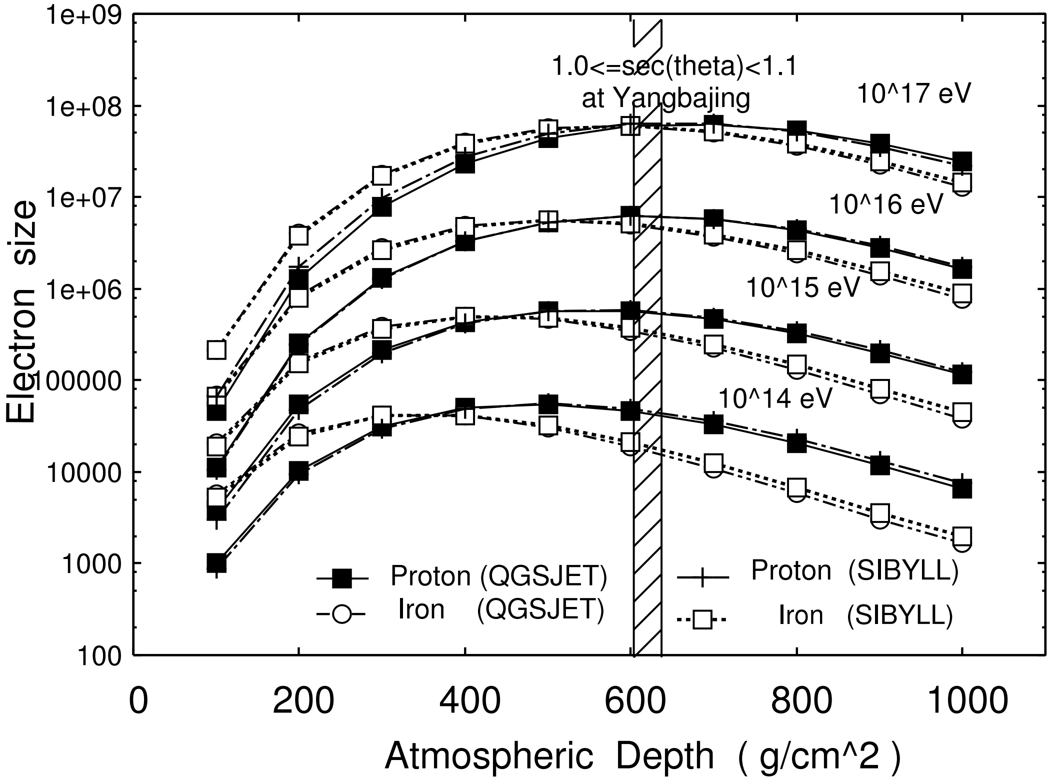
High altitude measurements

Shower sampling before the max?

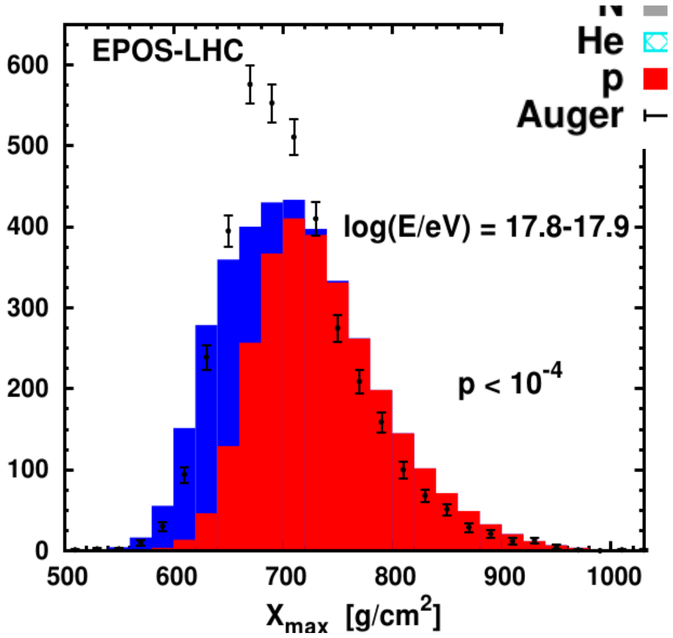


ARGO-YBJ
Tibet ASγ
HAWC
LHAASO

4300 m asl = 606 g/cm²

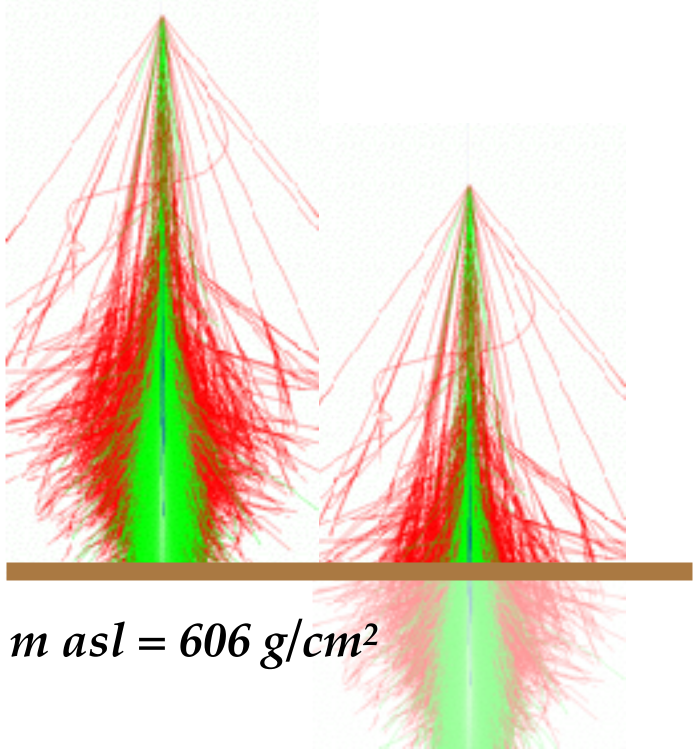


shower maximum for protons has large fluctuations



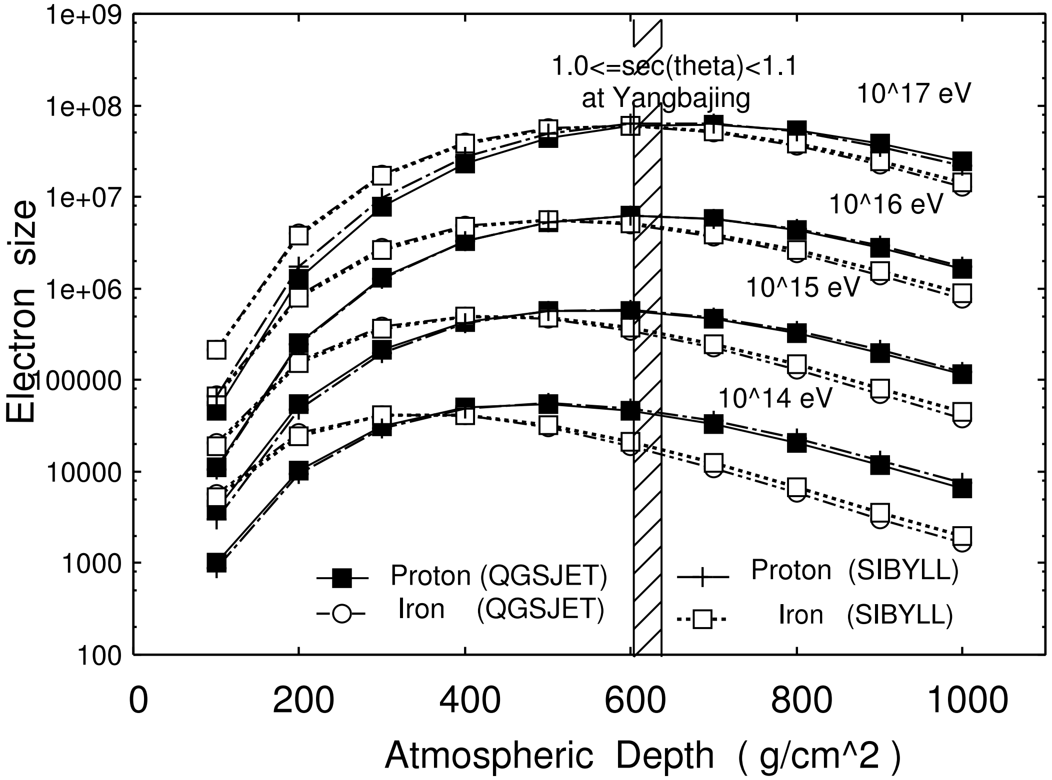
High altitude measurements

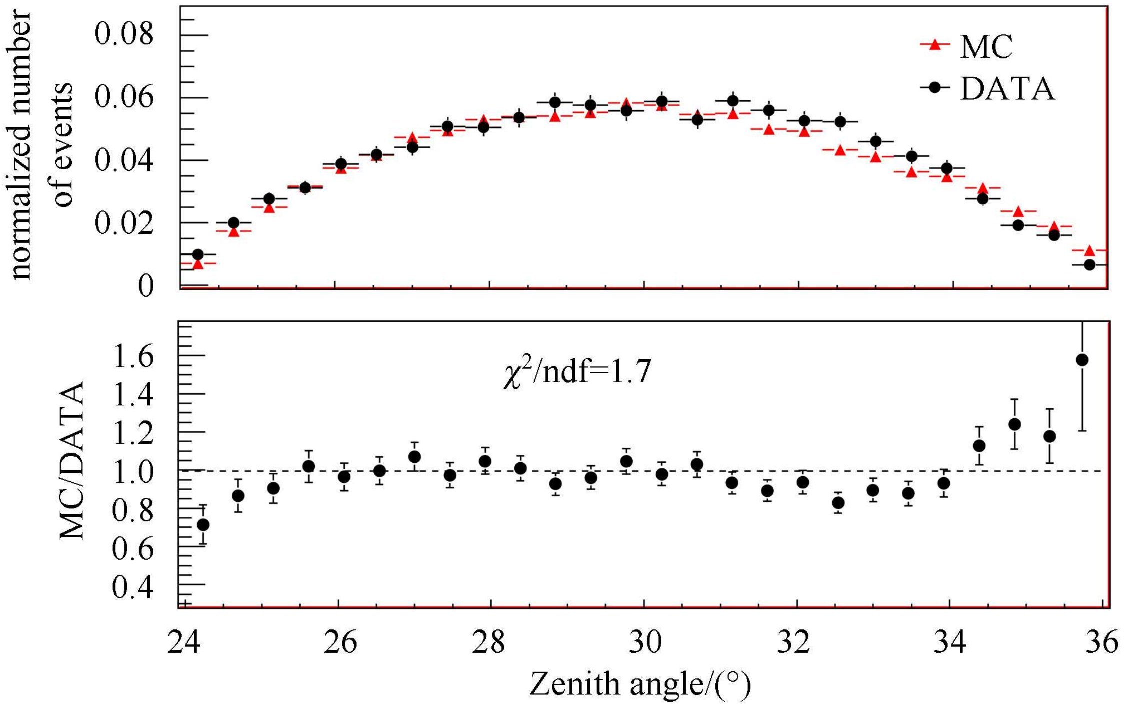
Shower sampling before the max?



ARGO-YBJ
Tibet ASγ
HAWC
LHAASO

4300 m asl = 606 g/cm²

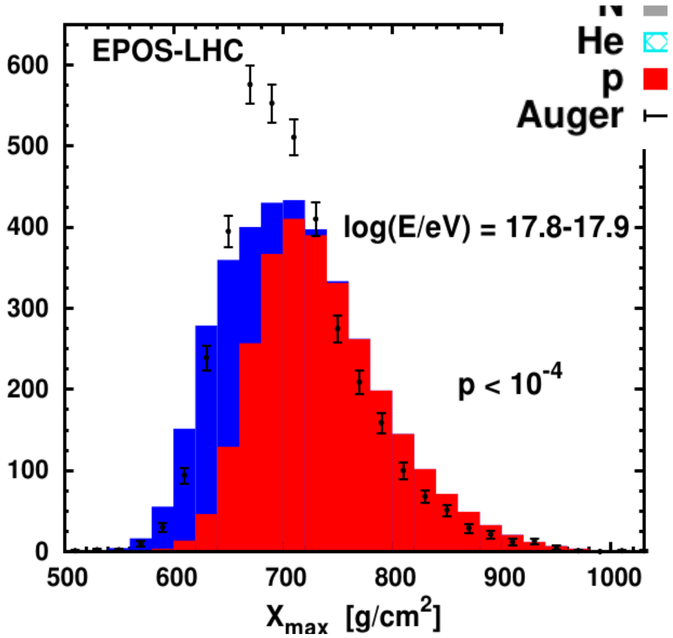




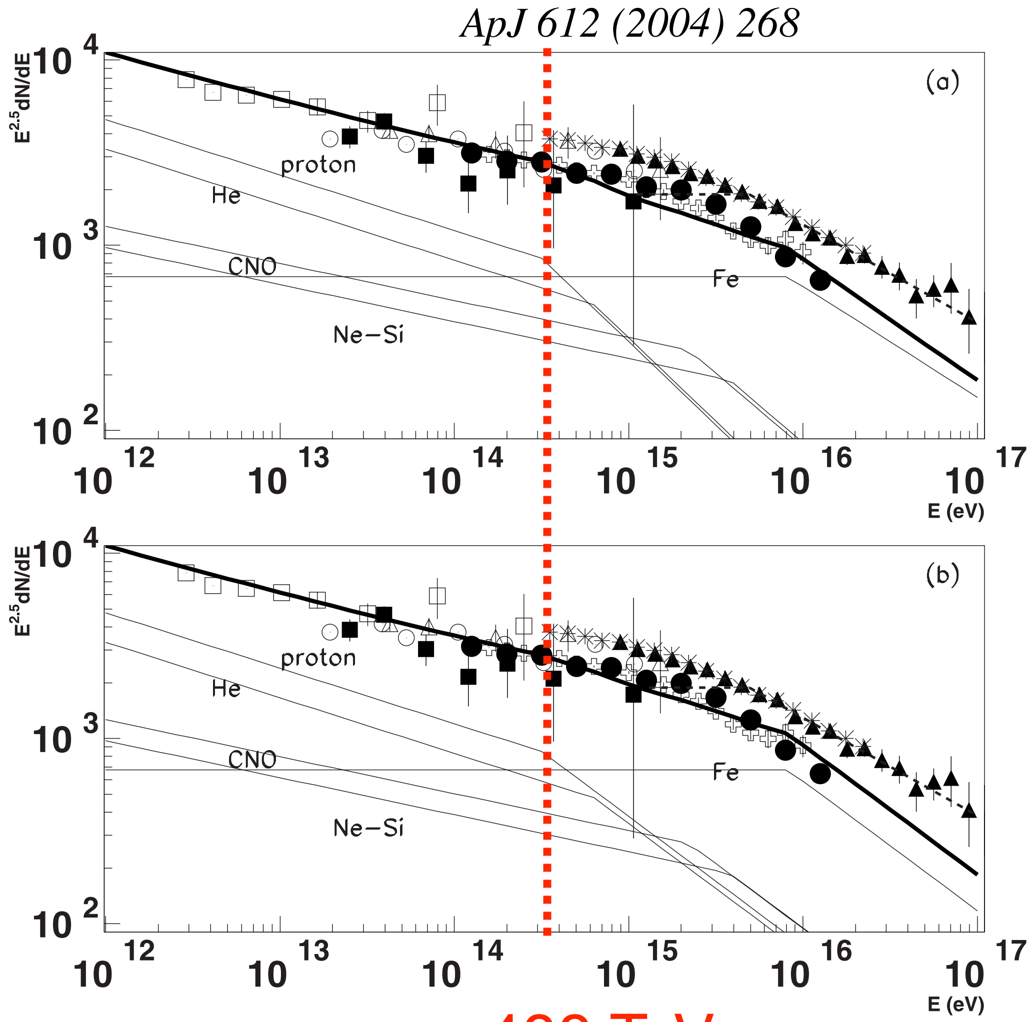
ARGO-YBJ distributions for simulated and observed events

≈ 700 g/cm²

shower maximum for protons has large fluctuations

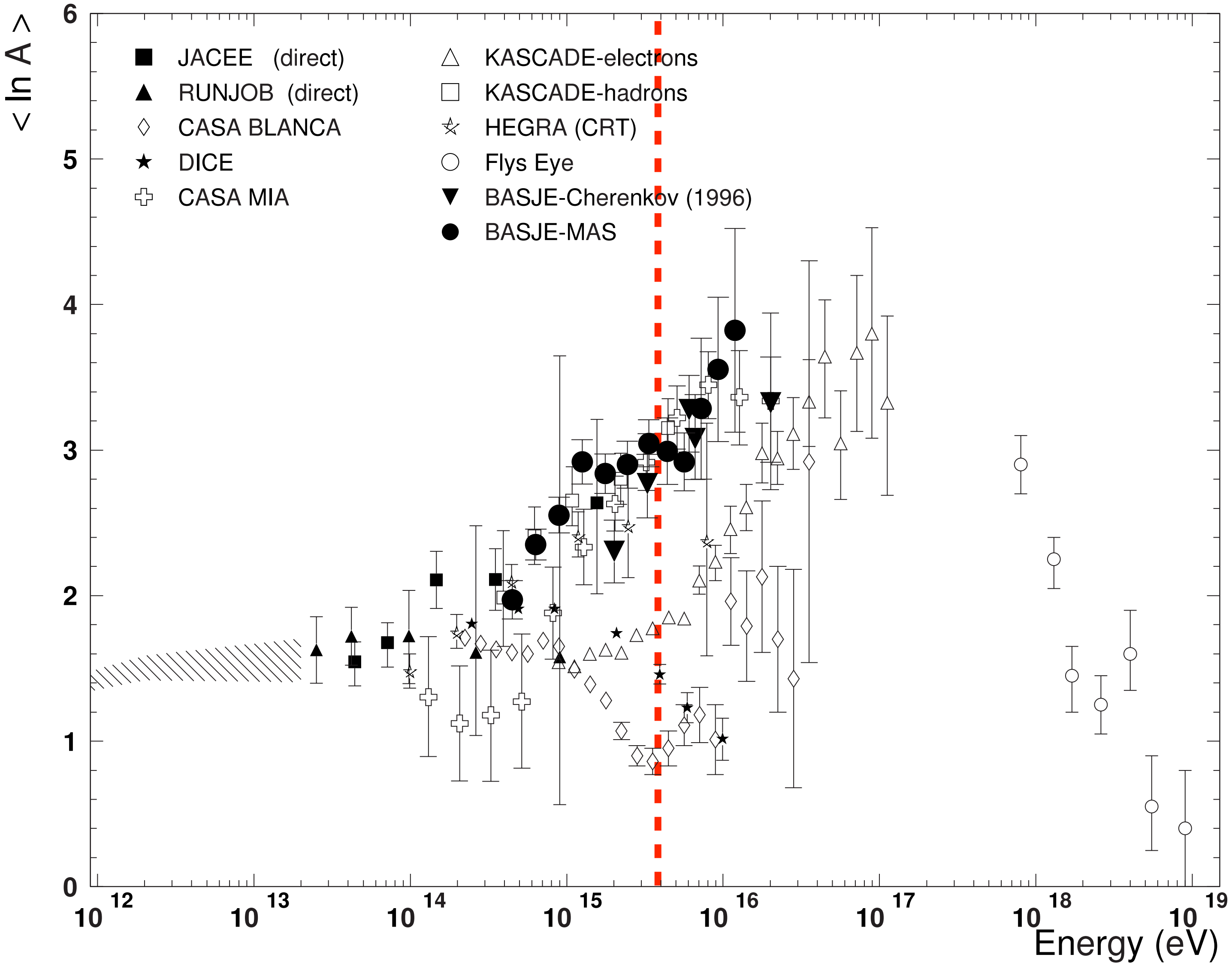


Composition at the knee: BASJE - MAS



ApJ 612 (2004) 268

≈ 400 TeV

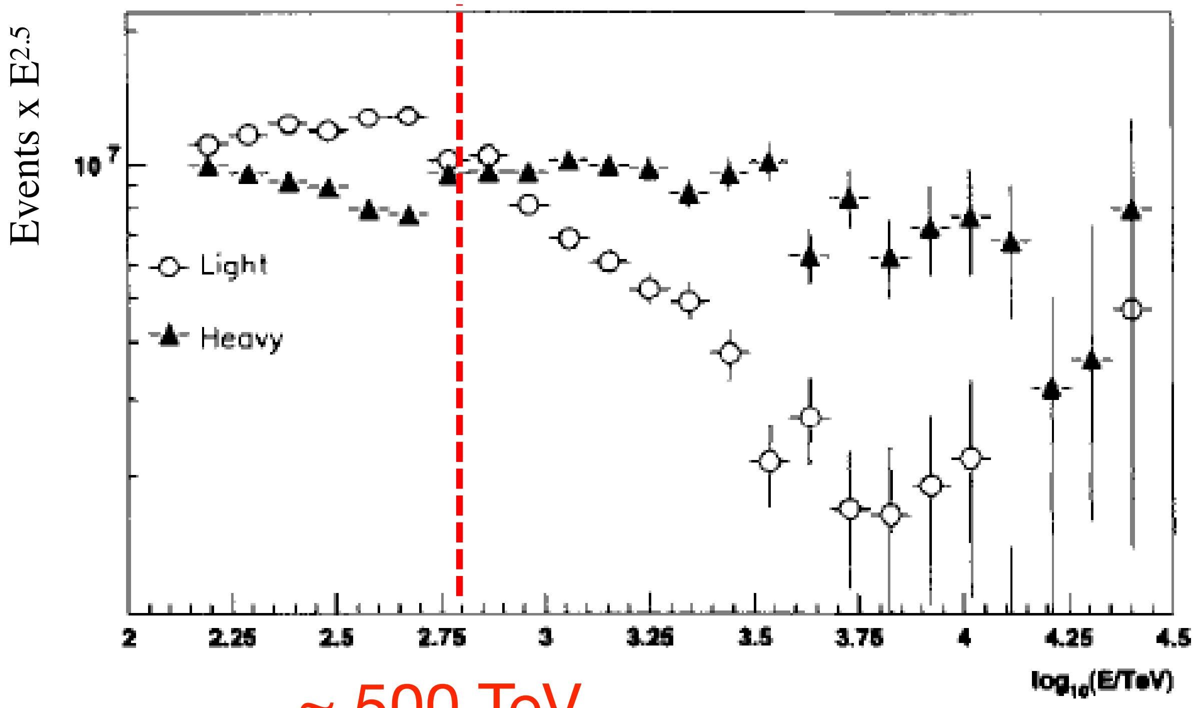


The measured $\langle \ln A \rangle$ increases with energy over the energy range of $10^{14.5}-10^{16}$ eV. This is consistent with our former Cerenkov light observations and the measurements by some other groups. The observed $\langle \ln A \rangle$ is consistent with the expected features of a model in which the energy spectrum of each component is steepened at a fixed rigidity of $10^{14.5}$ V.

Finally, we conclude that the actual model suggests that the dominant component above 10^{15} eV is heavy and that the $\langle \ln A \rangle$ increases with the energy to about 3.5 at 10^{16} eV.

Chacaltaya, 5200 m asl

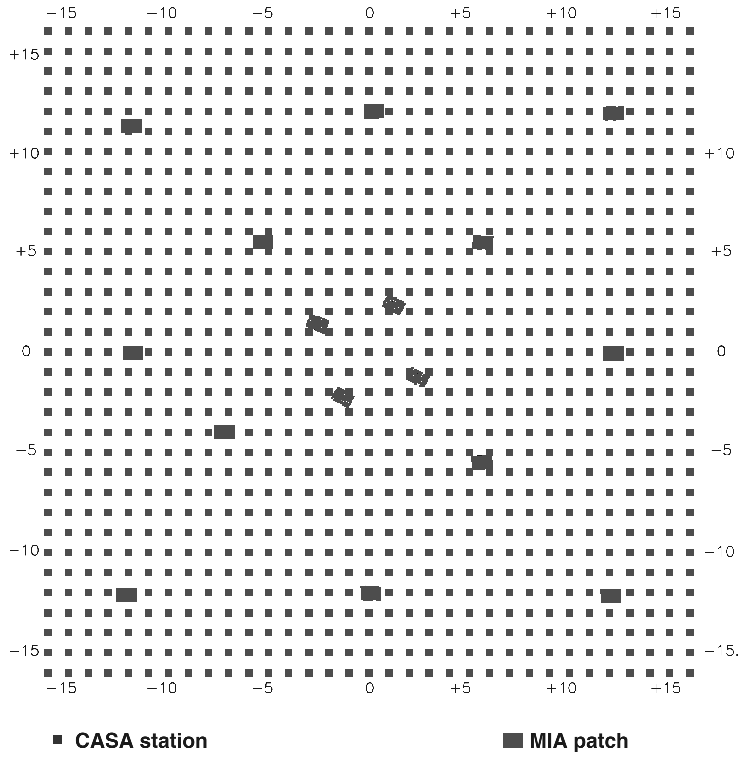
Composition at the knee: CASA-MIA



Energy threshold ≈100 TeV

≈ 500 TeV

1400 m asl

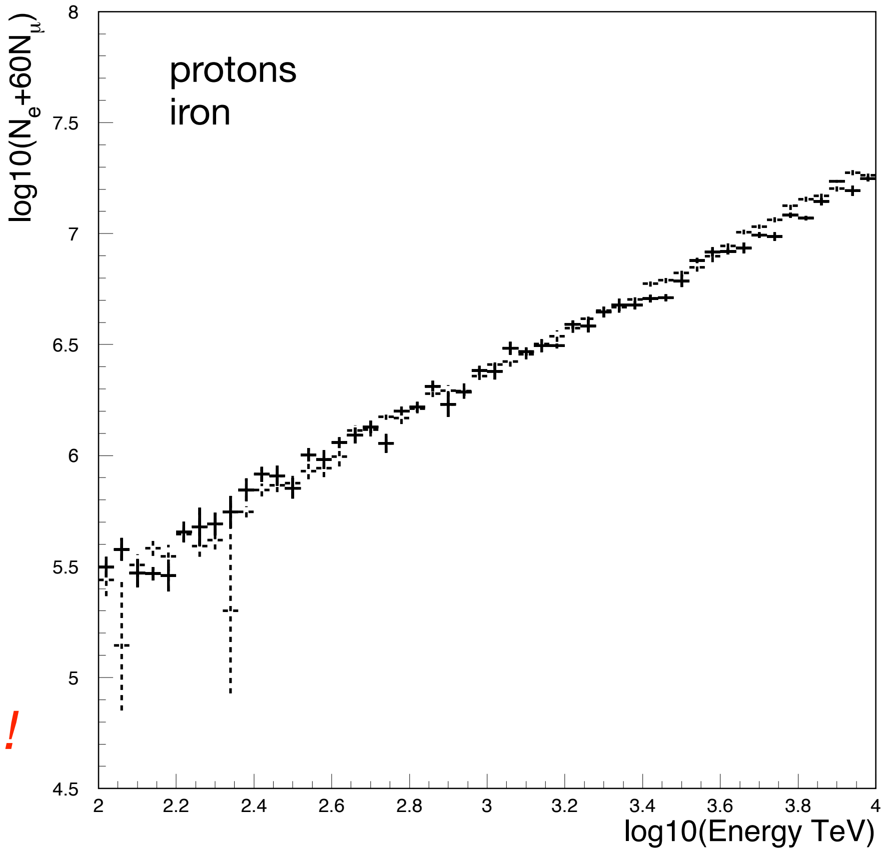


> The spectra of the heavy and light components appear similar below 500 TeV, at which point the lighter component's spectral index steepens. The heavier component shows no such "knee" at that energy.

Astroparticle Physics 12 (1999) 1–17

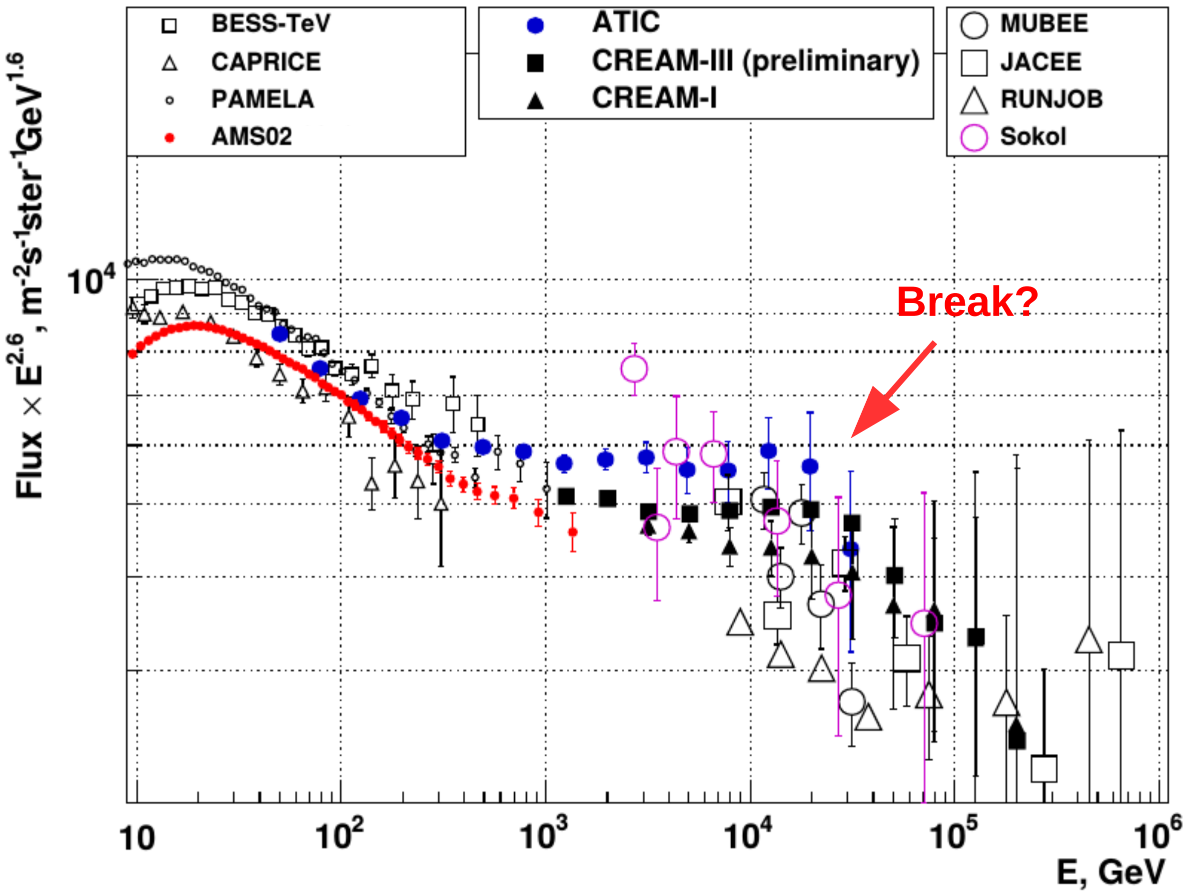
$$\boxed{E_0 \approx A + B \cdot (N_e + K \cdot N_\mu)}$$

The energy reconstruction is *compositionally independent !*



NUCLEON

NUCLEON: A new universal cosmic-ray knee near the magnetic rigidity 10 TV. Universality means the same position of the knee in the magnetic rigidity scale for all groups of nuclei. This new cosmic ray "knee" is probably connected with the limit of acceleration of cosmic rays by some generic or nearby source of cosmic rays.



A compilation of the data on *proton spectrum* before NUCLEON

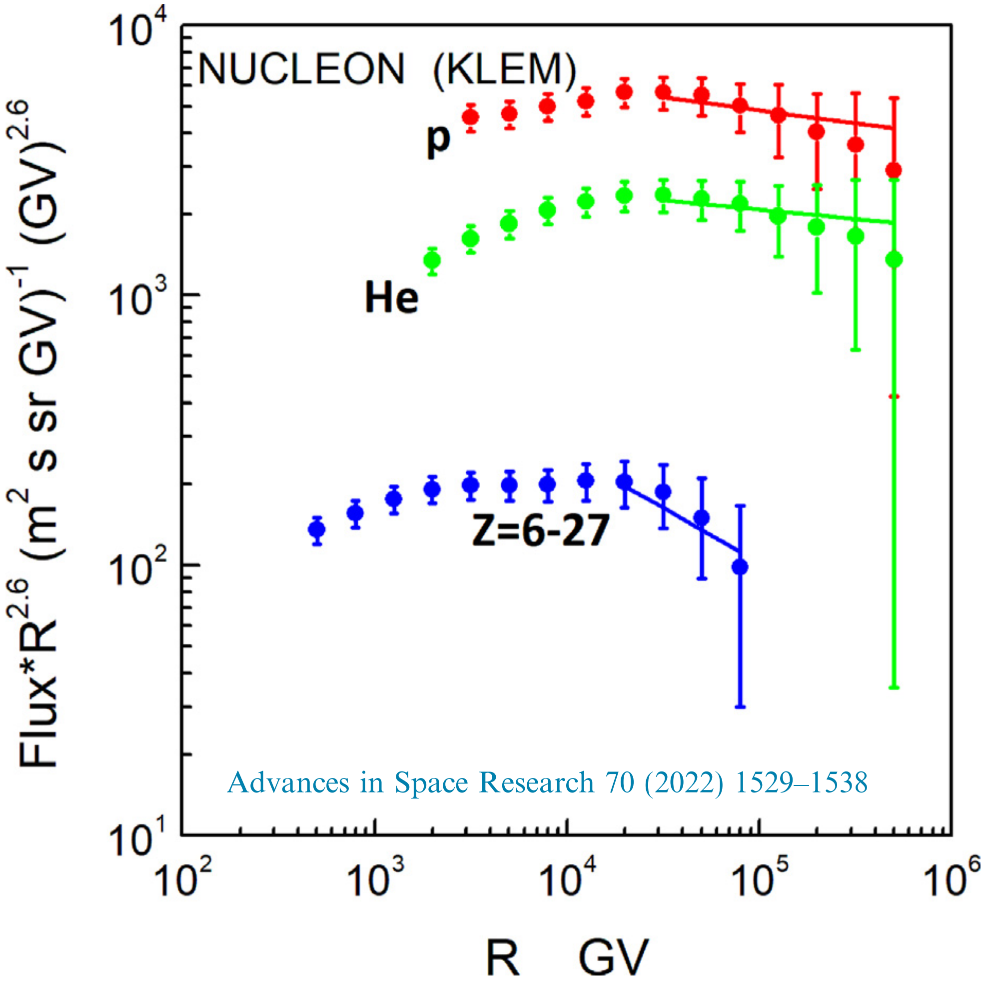


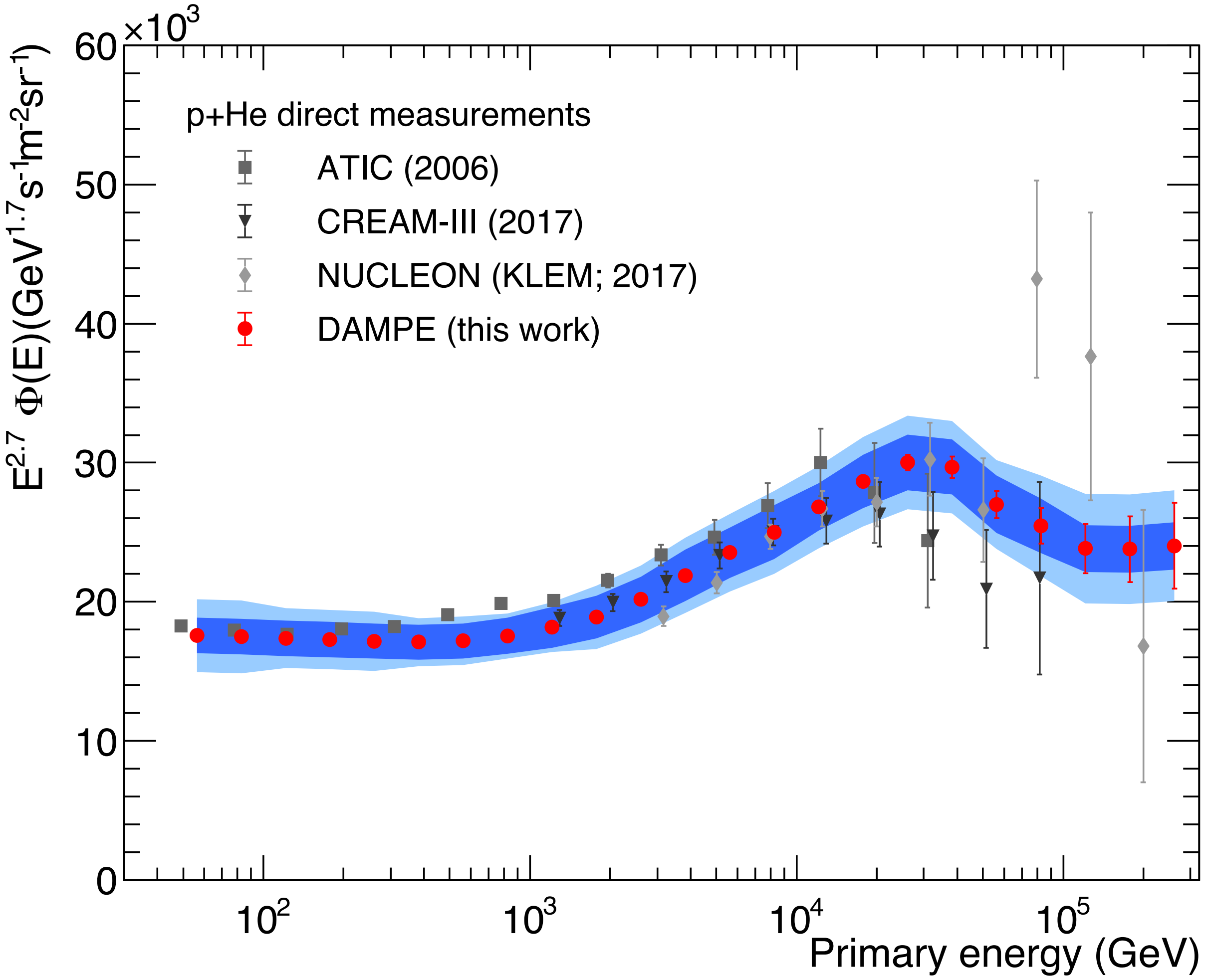
Fig. 5. The magnetic rigidities spectra fitted by a power function after the "knee".

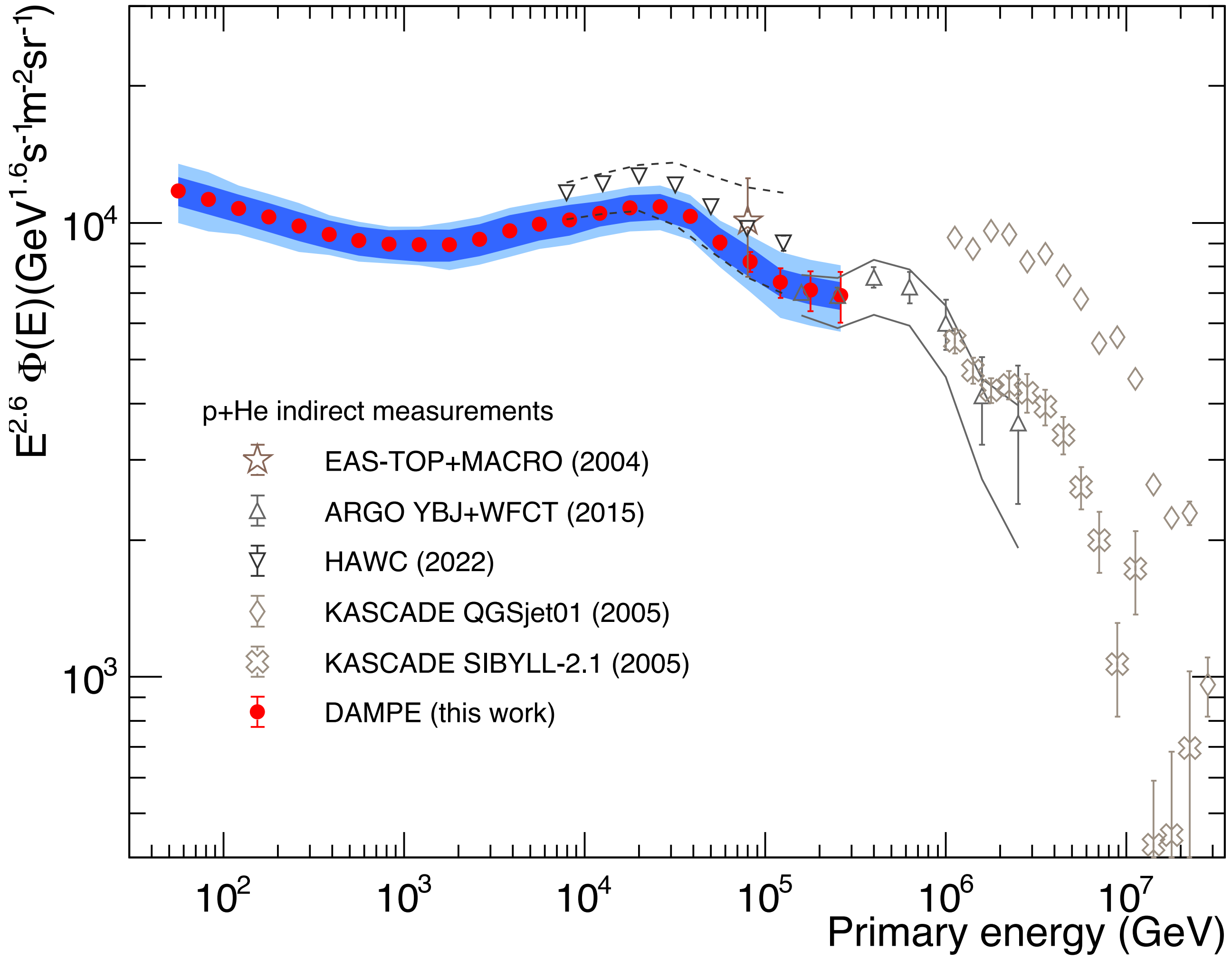
DAMPE: p+He between 46 GeV and 316 TeV

Deviation from a single power-law

Hardening at ~600 GeV with a softening at ~29 TeV with a significance of 6.6 σ

Possible second hardening at ~150 TeV

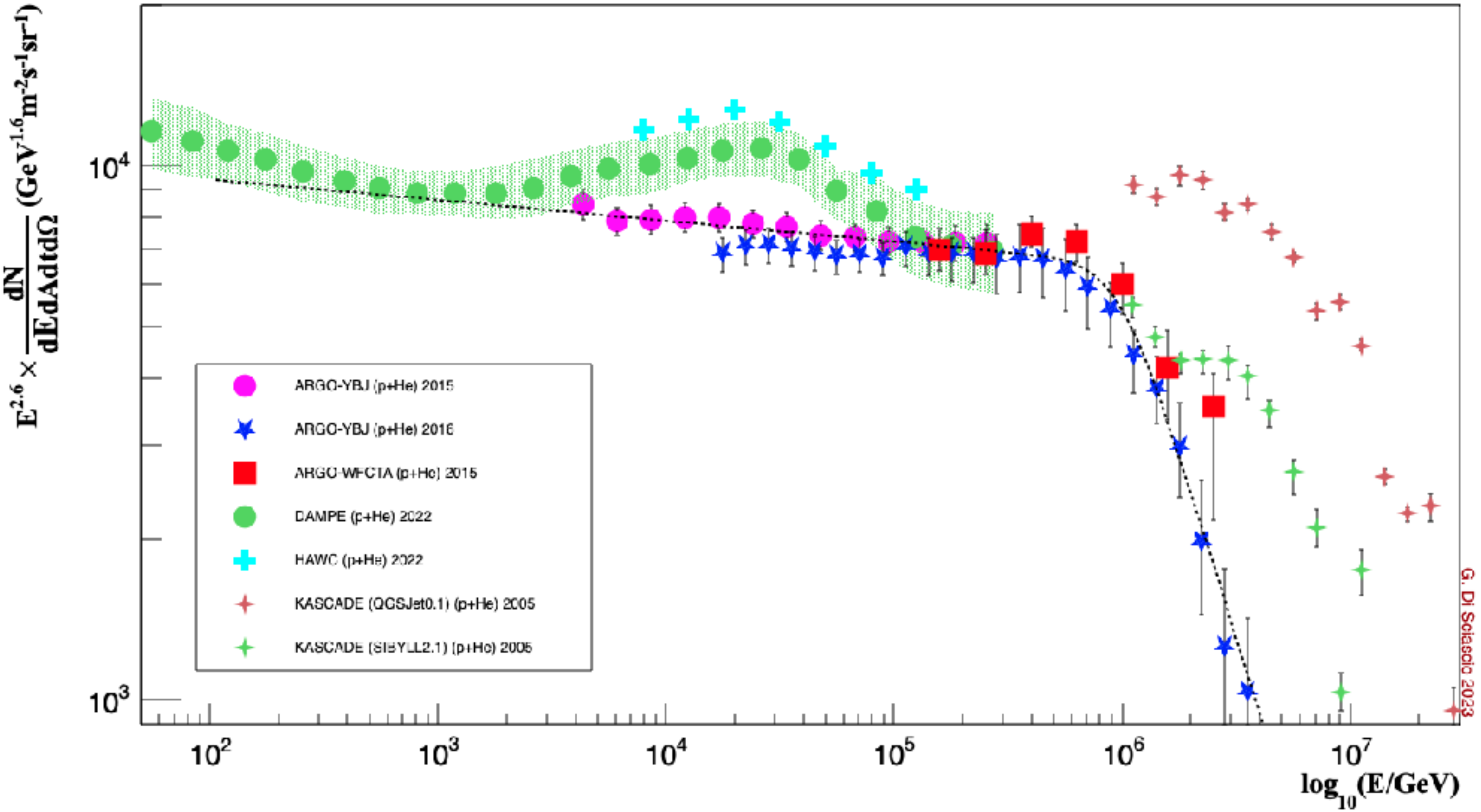




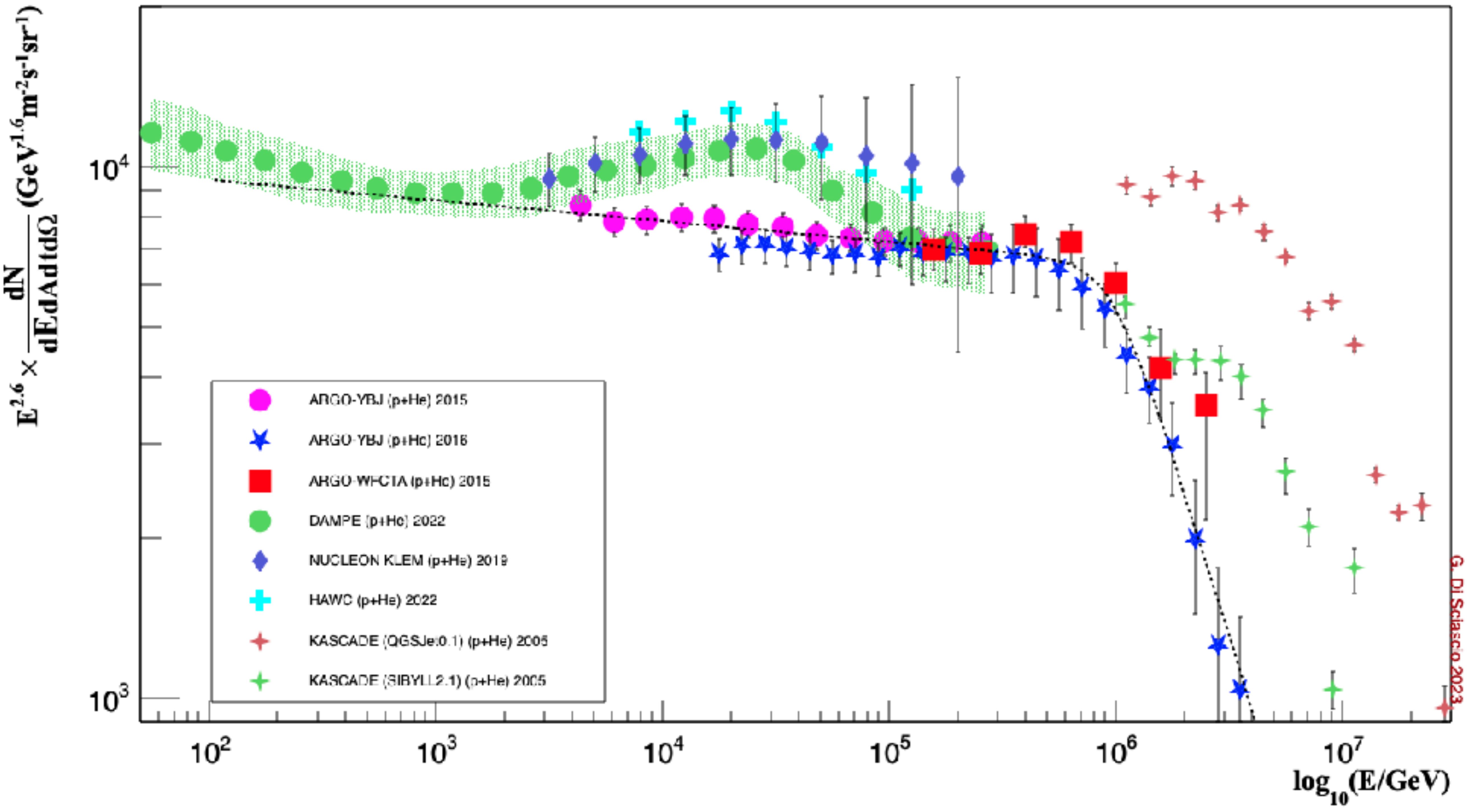
arXiv:2304.00137

p+He: DAMPE vs ARGO-YBJ and HAWC

Conflicting results in the 10 - 100 TeV range

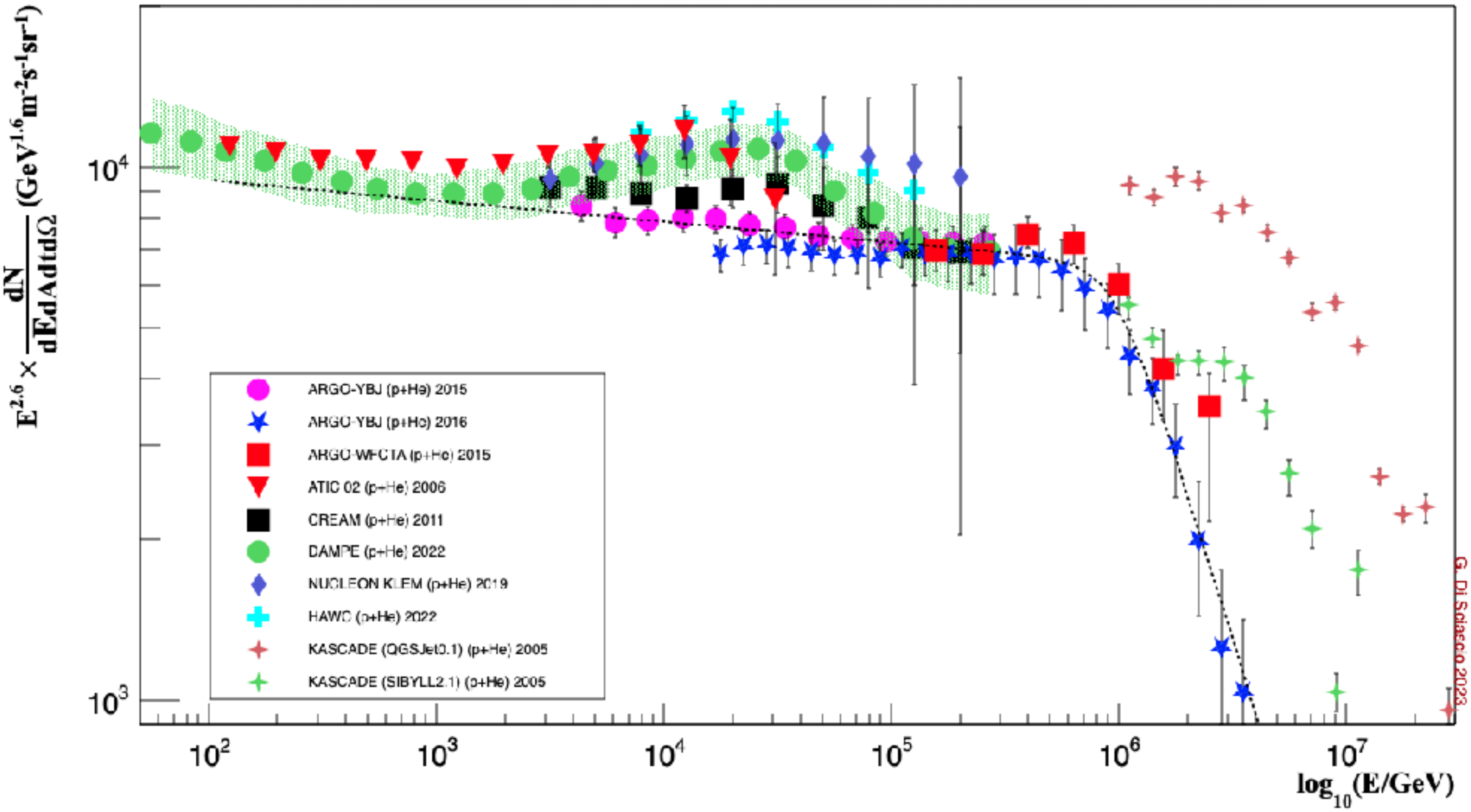


p+He: DAMPE and NUCLEON



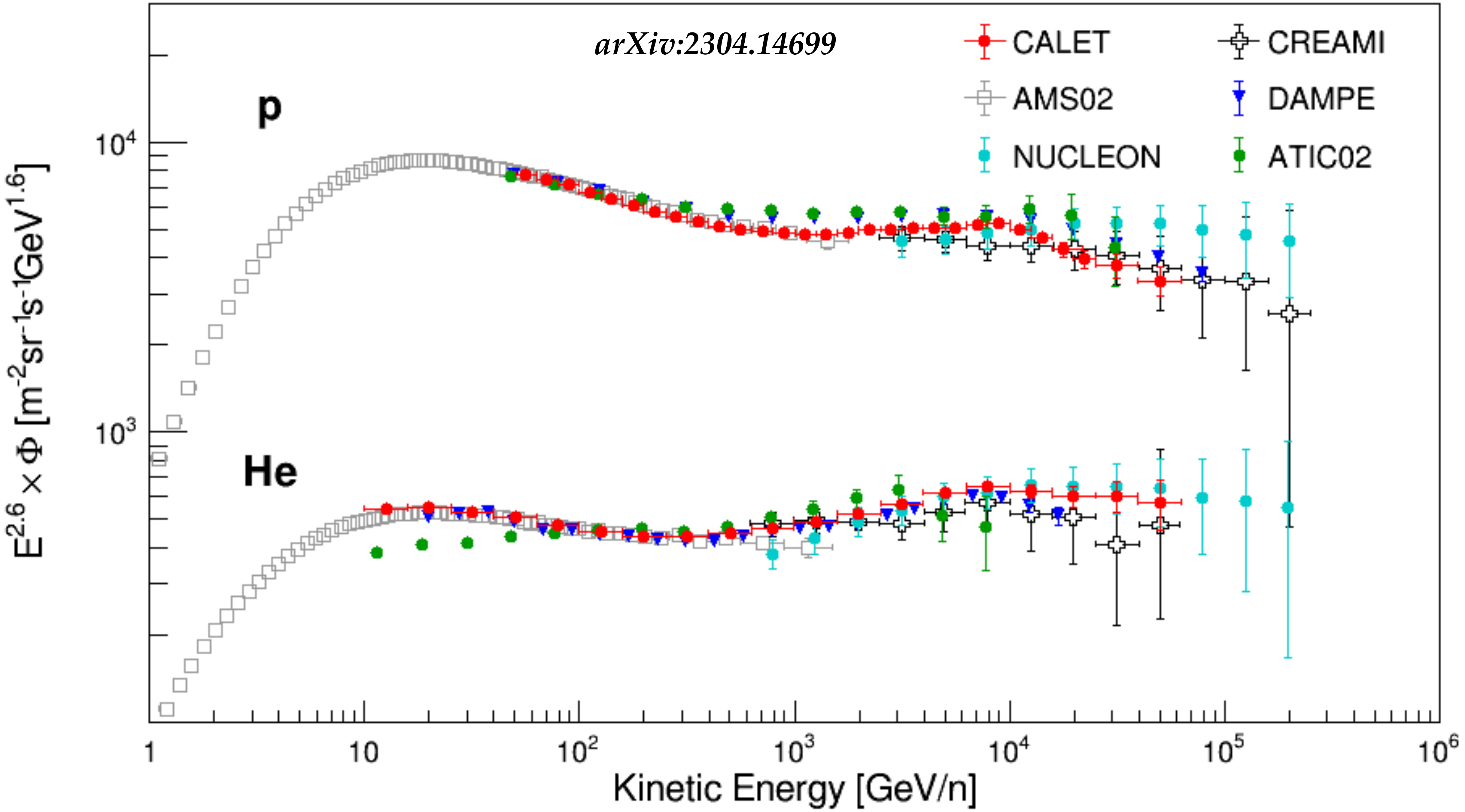
p+He: direct vs indirect measurements

Deviation from a single power-law in the 10 - 100 TeV range?



CALET 2023

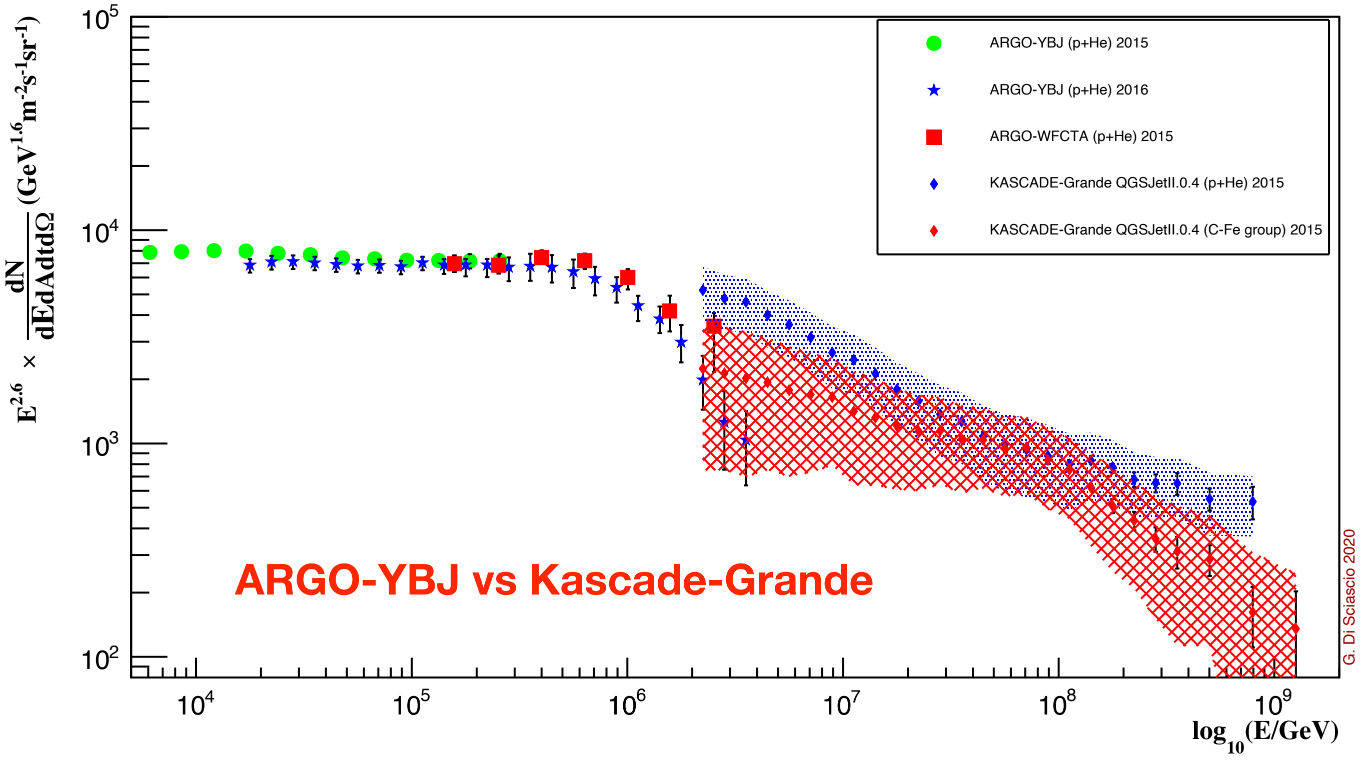
Deviation from a single power-law at 8 σ level

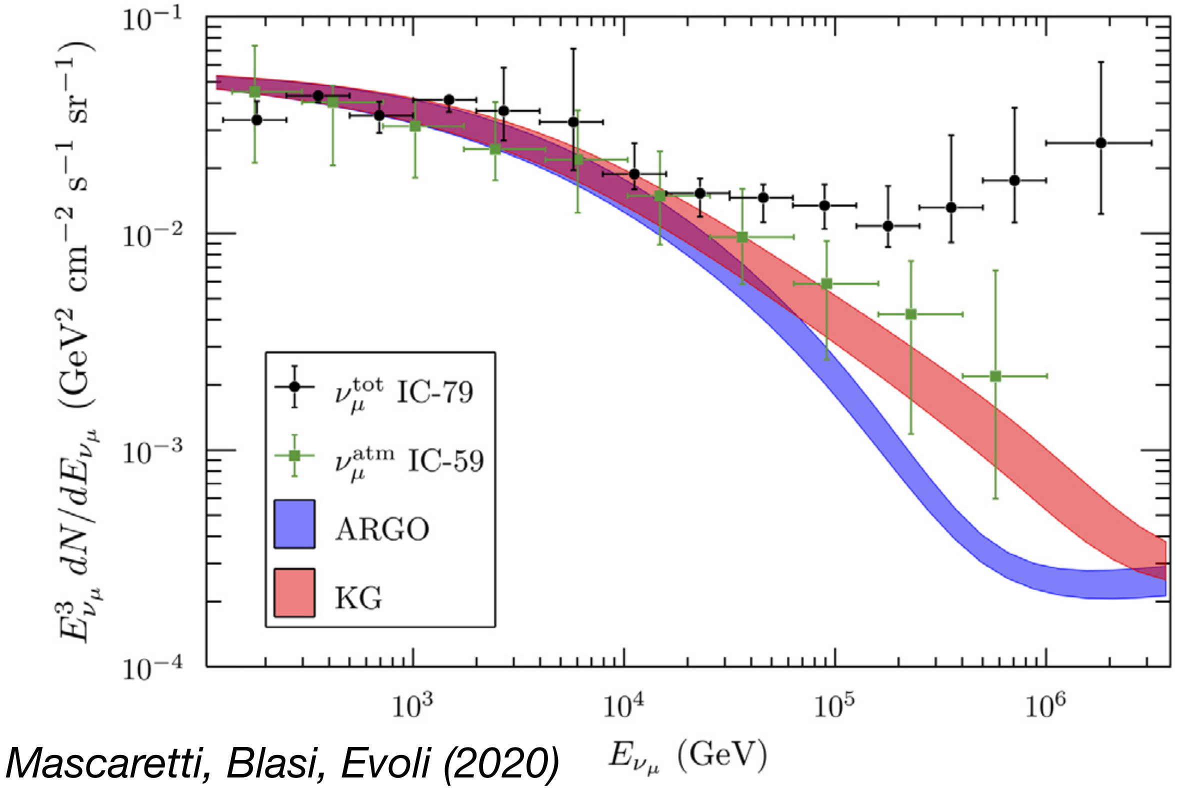


Knees and atmospheric neutrinos

The flux of atmospheric neutrinos is sensitive to the spectrum of parent cosmic rays.

“A clear distinction between an ARGO-like and a KASCADE-like knee seems possible at energies ***≥100 TeV*** if the atmospheric neutrinos could be properly tagged.”



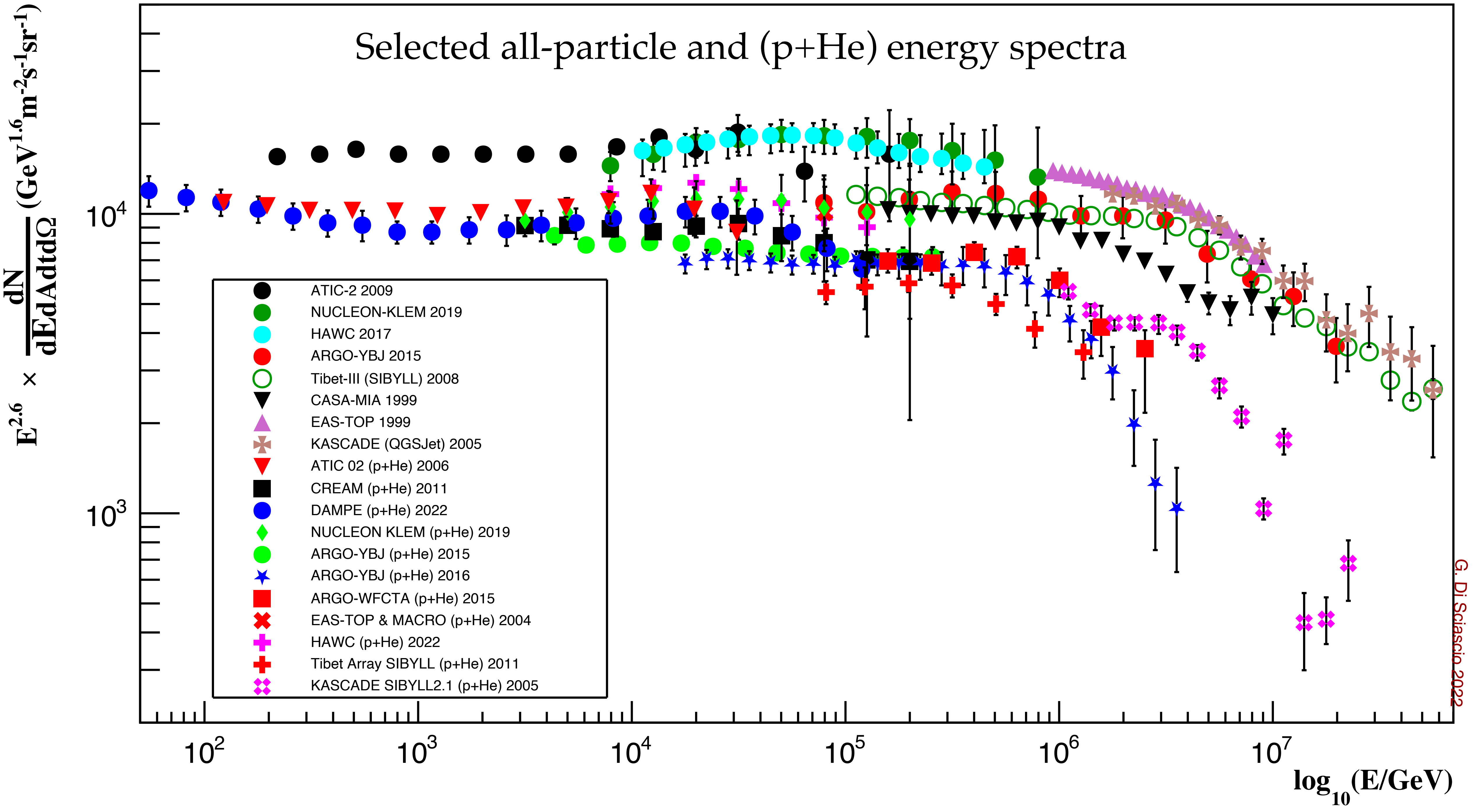


Mascaretti, Blasi, Evoli (2020)

“Unfortunately this is also the energy region where the total neutrino flux detected by IceCube departs from the existing predictions for atmospheric neutrinos. This is usually interpreted as the onset of a neutrino component having an astrophysical origin. So far, the sources of such neutrinos remain unknown.”

"Current experimental uncertainties do not allow to draw firm conclusions."

Knee region: quite confusing situation



Each experiment can find compatible measurements!

Why conflicting results?

- Experiments located at different altitudes: sea level ➜ 5200 m asl
- Different detectors and layout
- Different coverage ➜ different sampling capability/fluctuations
- Different energy threshold ➜ calibration absolute energy scale
- Different role of fluctuations which limit mass resolution
- Different energy resolution ➜ better close to the shower max
- Different observables to infere the elemental composition
- Different reconstruction procedures
- …

Electron & Muon counting

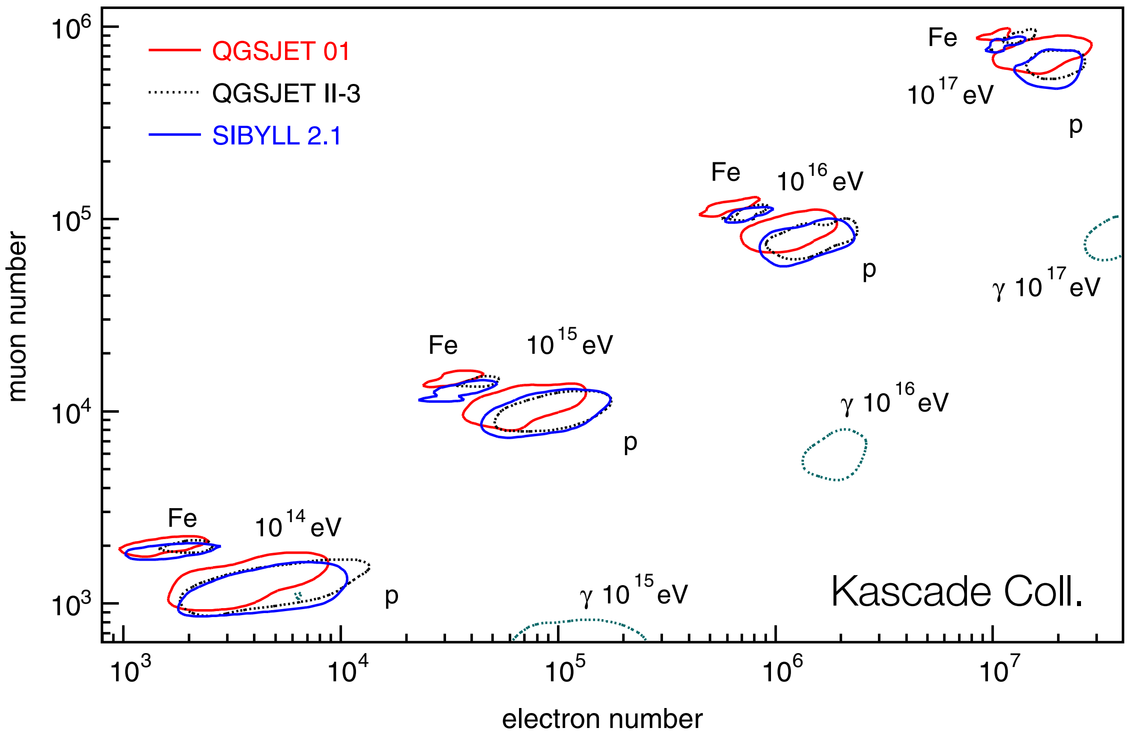
The *first method* to investigate the composition of CRs dates back in ***1962*** when *J. Linsley, L. Scarsi and B. Rossi* working at MIT Volcano Ranch Station suggested for the first time that muons are a mass-sensitive observable after the observation of a ***muon/electron correlation***: $N_\mu \sim A^{1-\alpha} \cdot (N_e)^\alpha$

- ***Problem:*** N_e and N_μ depend on Energy and Mass and atmospheric depth!

$$\boxed{N(E_o, A) = \alpha(A) \cdot E^{\beta(A)}}$$

Want to know E ➞ need to know A!
Want to know A ➞ need to know E!

Both electron and muon numbers scatter considerably.



Primary energy and elemental composition: an entangled problem!!!

Exact relations to be taken from EAS simulation ***assuming*** a given elemental composition and an interaction model

EAS analysis of CR data ➞ *Disentanglement of the threefold problem*: **E, A, interaction**

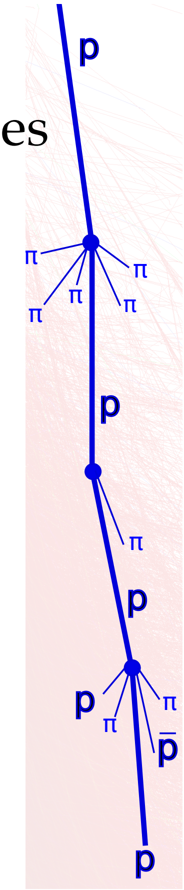
Intrinsic ambiguity

There is an ***intrinsic ambiguity in the interpretation of CR data.***
The ambiguity is governed by our poor understanding of two basic elements:

(a) the ***shower development***
(b) the ***composition*** of the primary CR spectrum, i.e., the mass number A of the primary particles

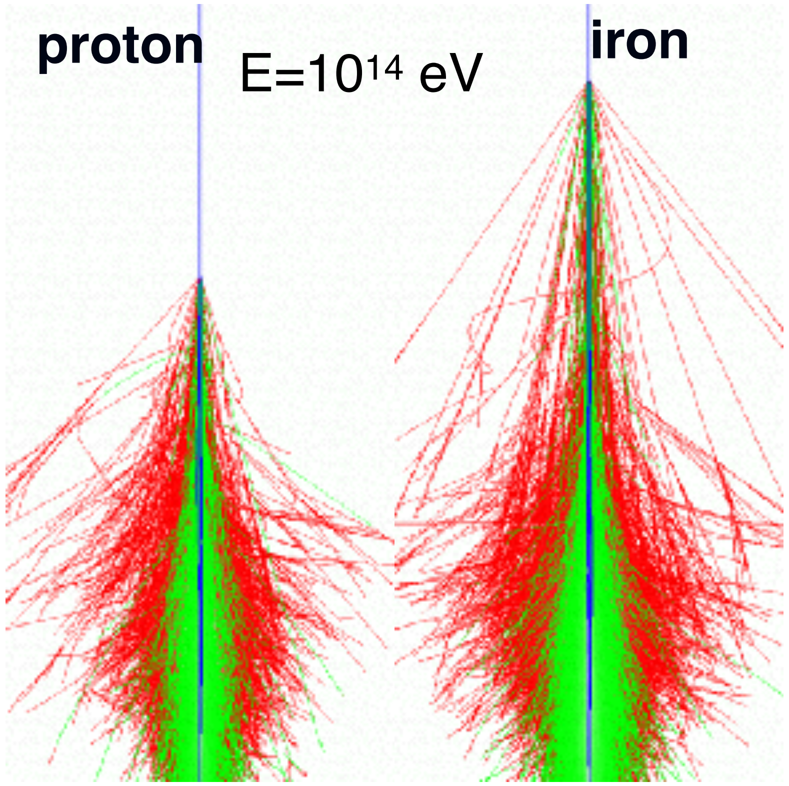
Crucial for shower development

1. the behaviour of the ***inelasticity K***, the fraction of the primary energy converted into secondaries
2. the ***inelastic cross sections***



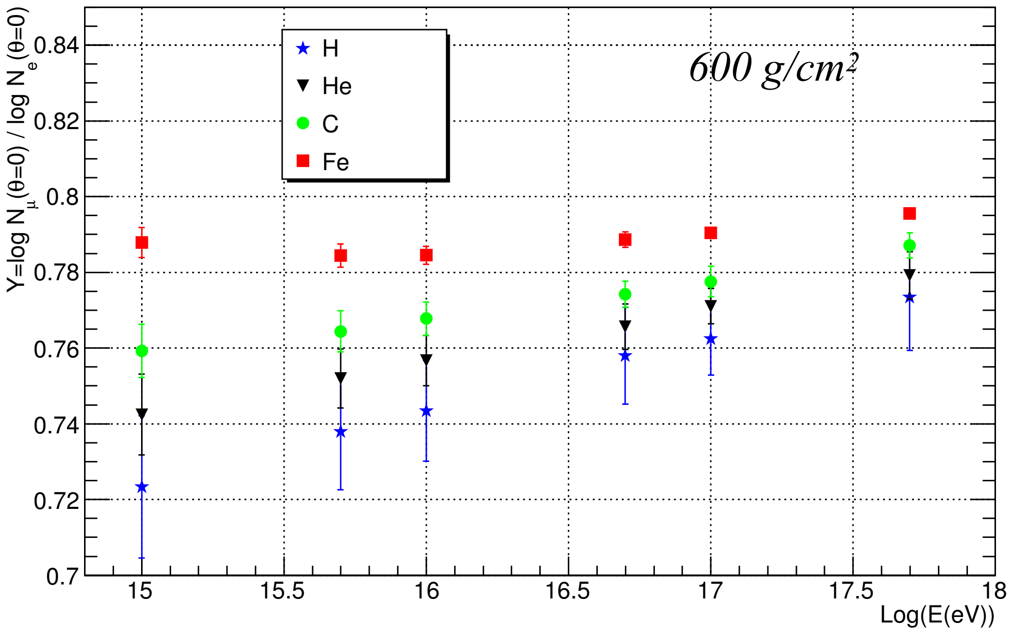
large cross-sections
high inelasticity
large mass A
} *short* showers

small cross-sections
low inelasticity
small mass A
} *long* showers



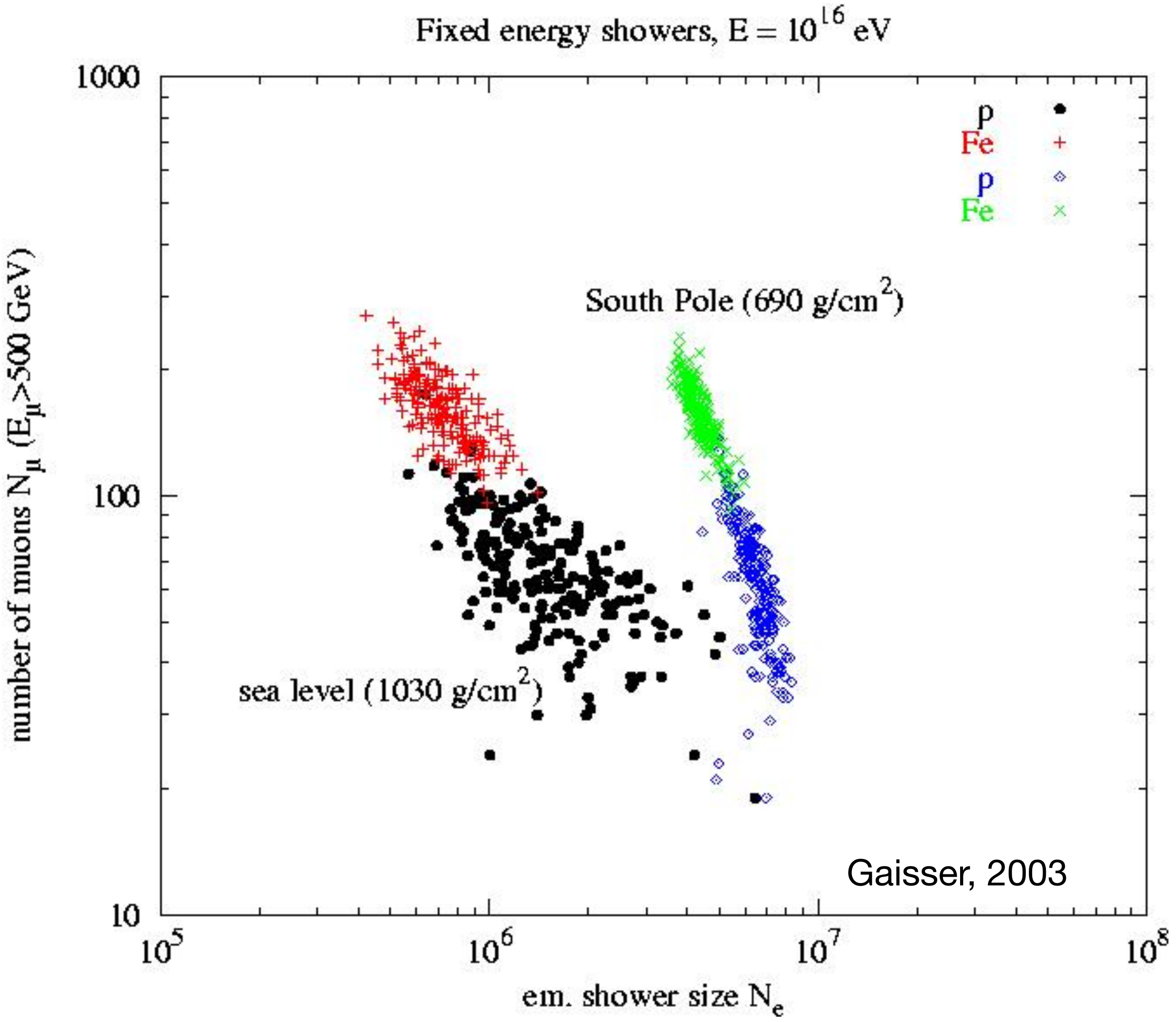
Fluctuations in N_e, N_μ at two depths

The ***intrinsic fluctuations of shower development*** and the additional scattering introduced by the limited sampling of shower particles at the observation level are typically ***larger than the mean differences between showers initiated by different types of primaries.***



Shower-to-shower fluctuations limit the mass resolution of detector located deep in the atmosphere!

Both electron and muon numbers scatter considerably.

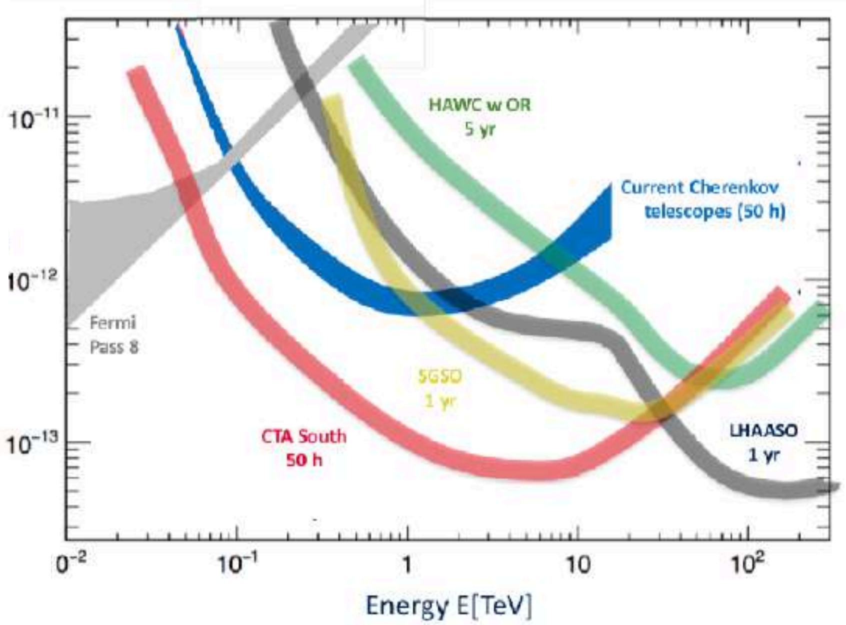


Gaisser, 2003

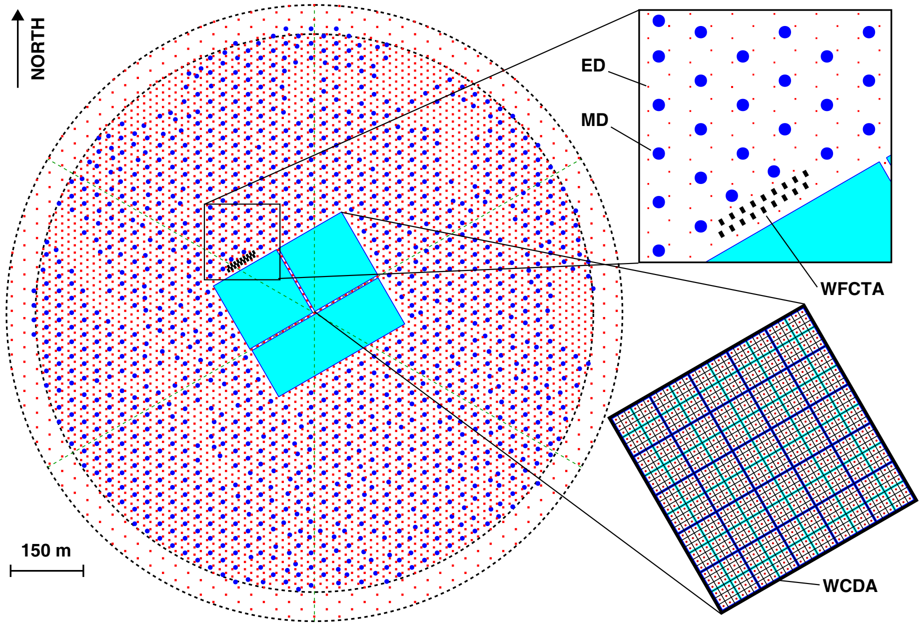
High altitude crucial to improve mass and energy resolution for the knee energy region

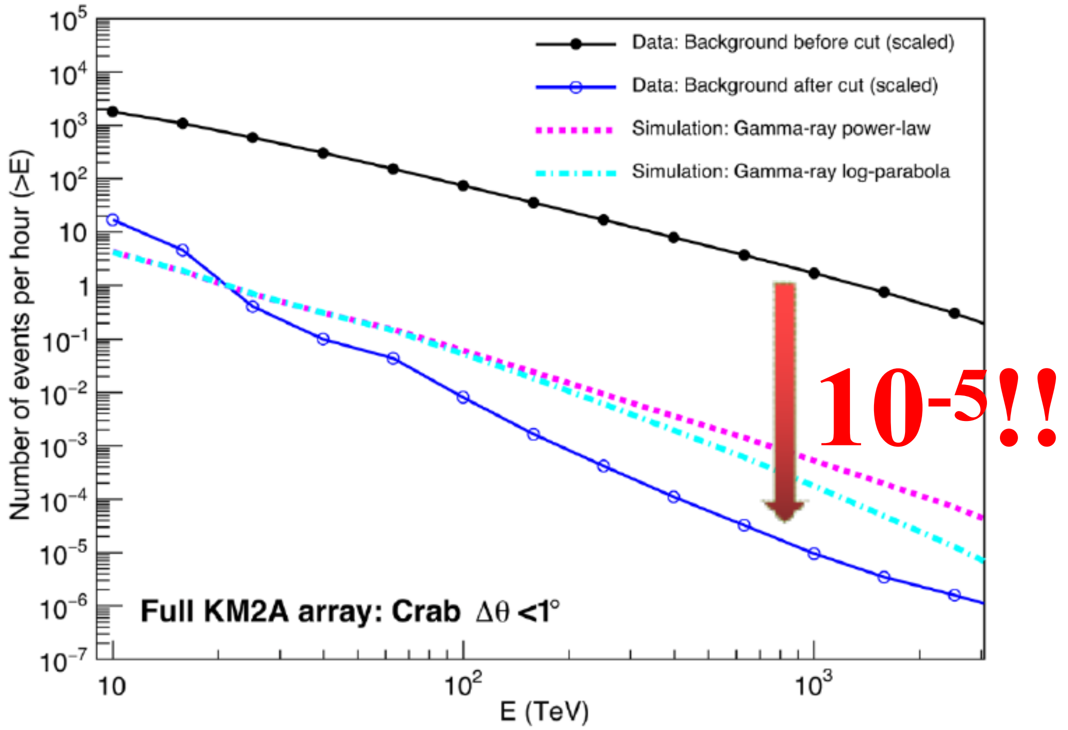
What's next? LHAASO

flux sensitivity νF_ν : erg/cm^{2}s



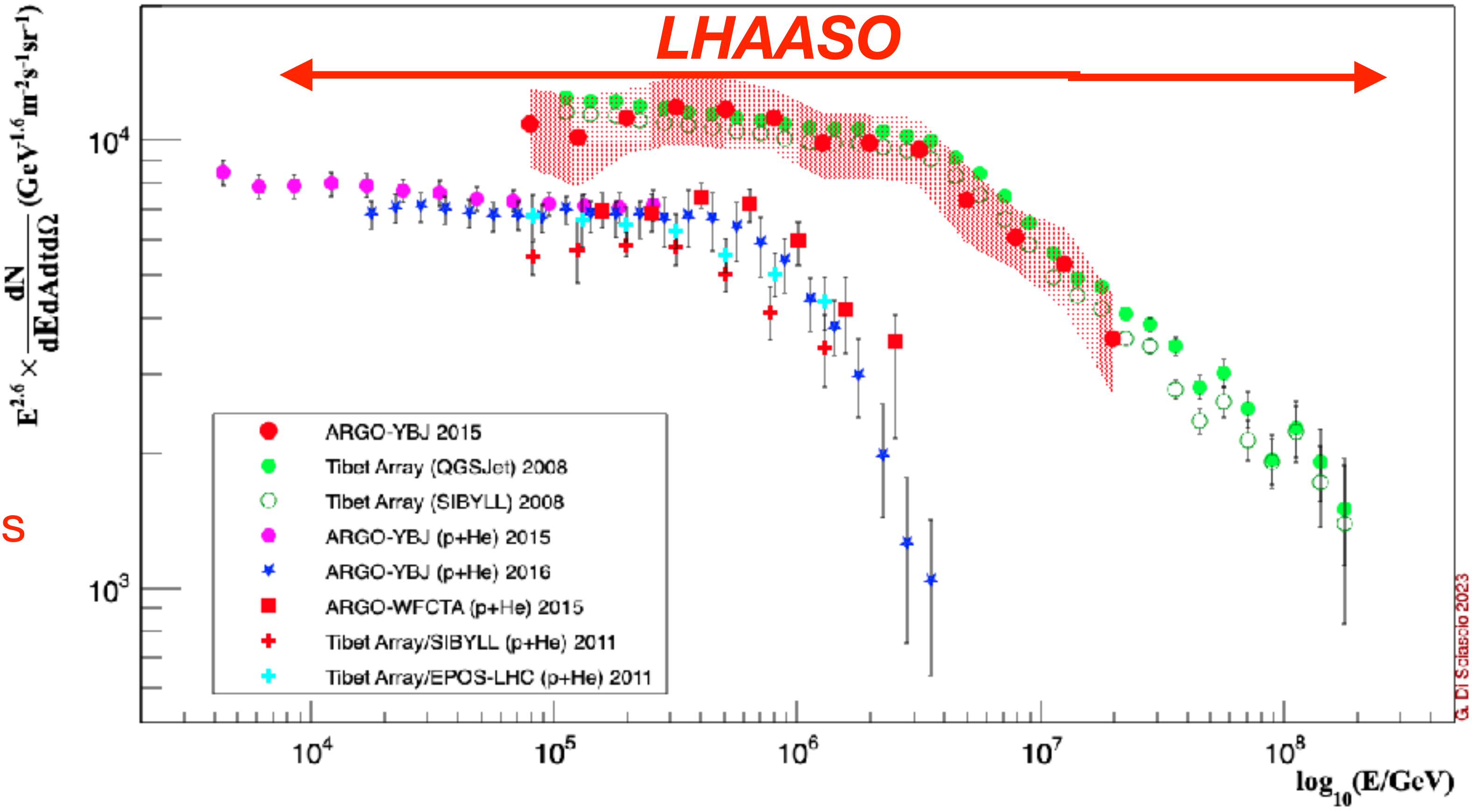
LHAASO ***opened the PeV gamma-sky to observations*** for the first time!





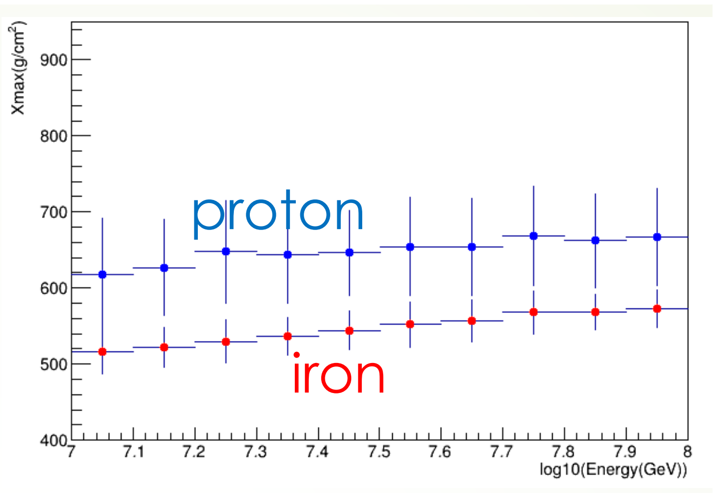
LHAASO: a multi-component experiment

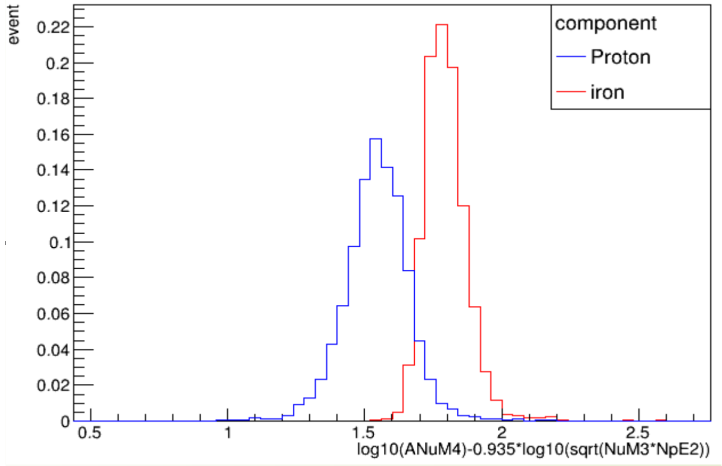
To fill the gap in the CR detection between the low and the very high energy ranges with a single experiment.

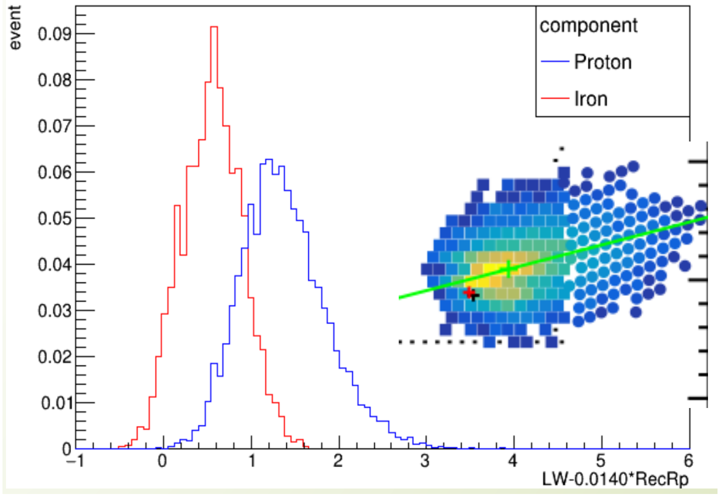


Multi-component strategy to measure light and heavy knees

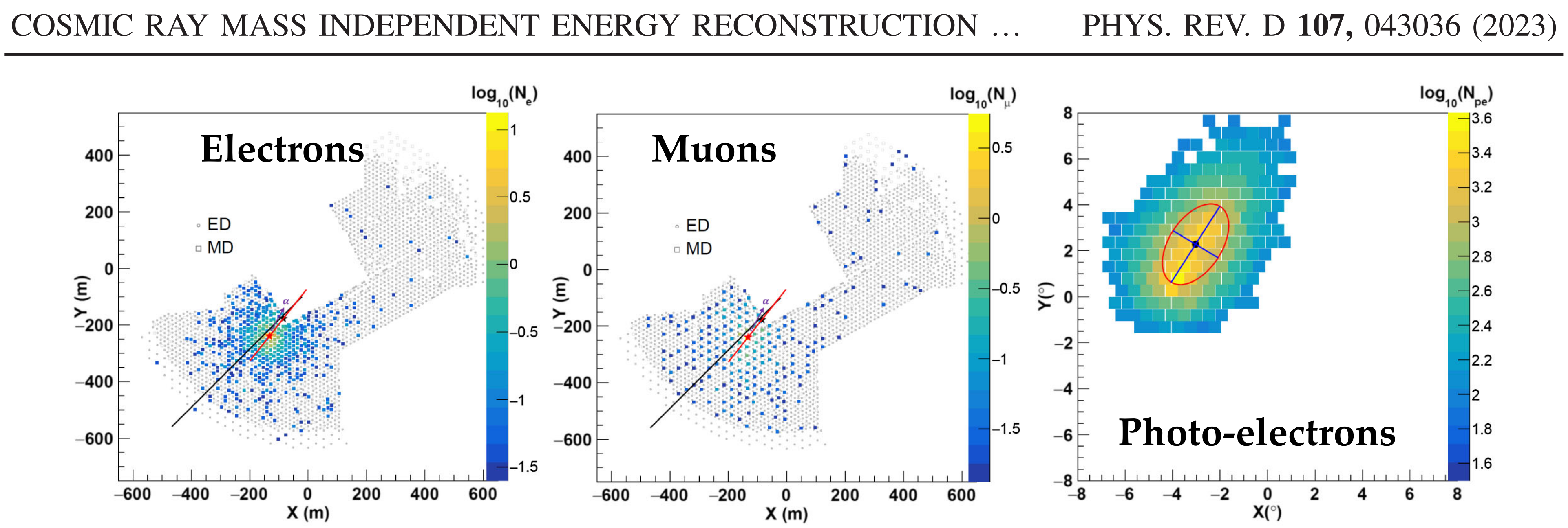
- Water Cherenkov Detector Array
- Scintillator Array
- Muon Detector Array
- 18 Cherenkov/Fluorescence Telescopes
- Neutron (Hadron) Detectors





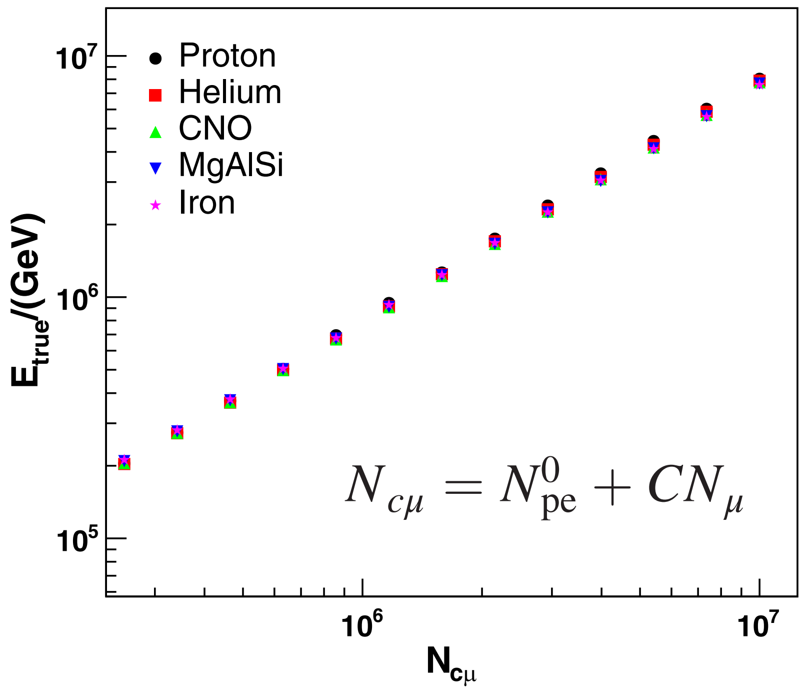


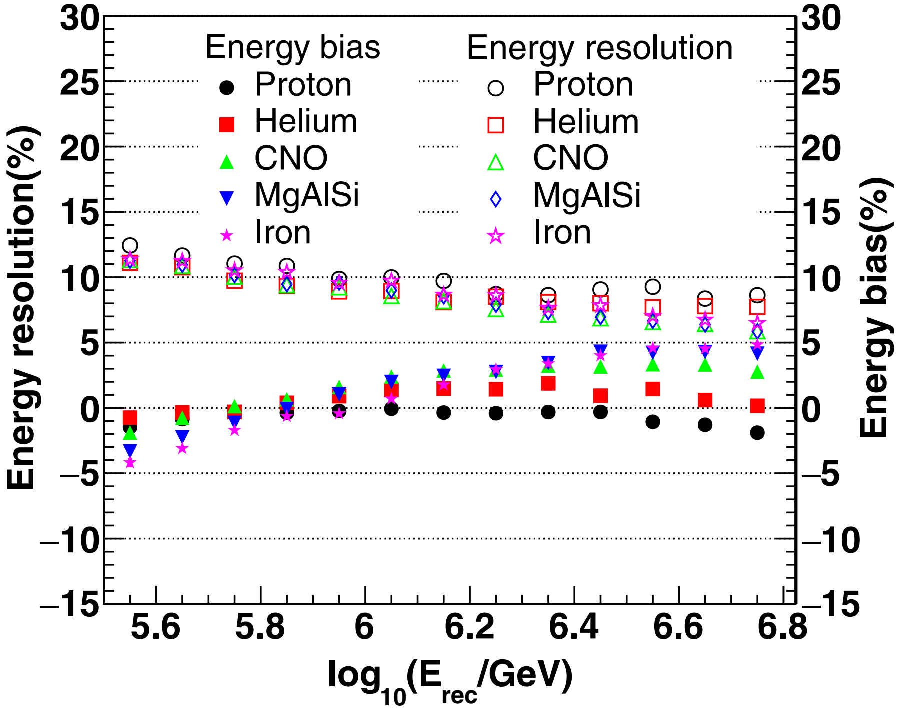
Cosmic Ray Physics with LHAASO



COSMIC RAY MASS INDEPENDENT ENERGY RECONSTRUCTION … PHYS. REV. D **107,** 043036 (2023)

Combined event observed with KM2A and WFCTA

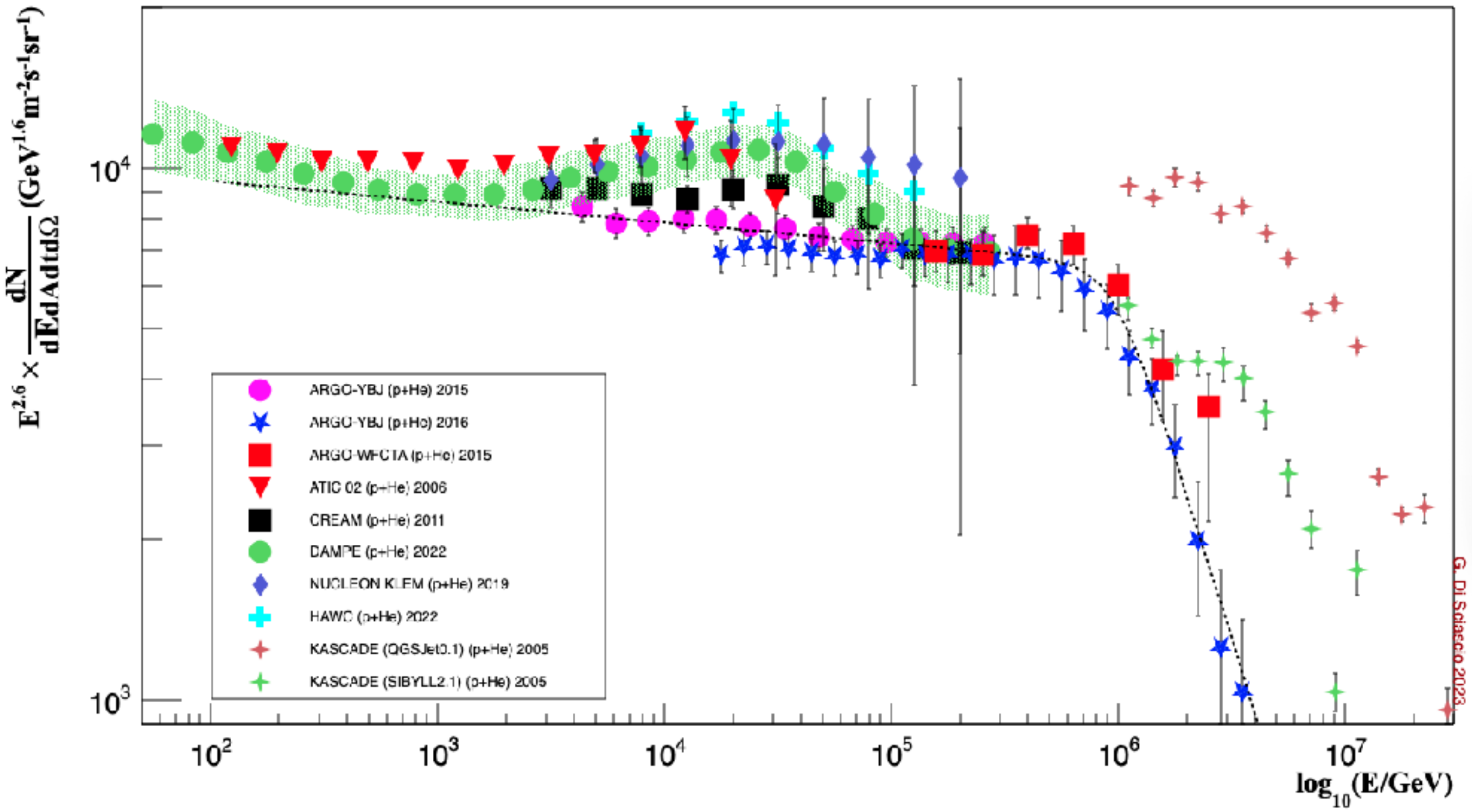




Some conclusions from data

1. Knee energy region

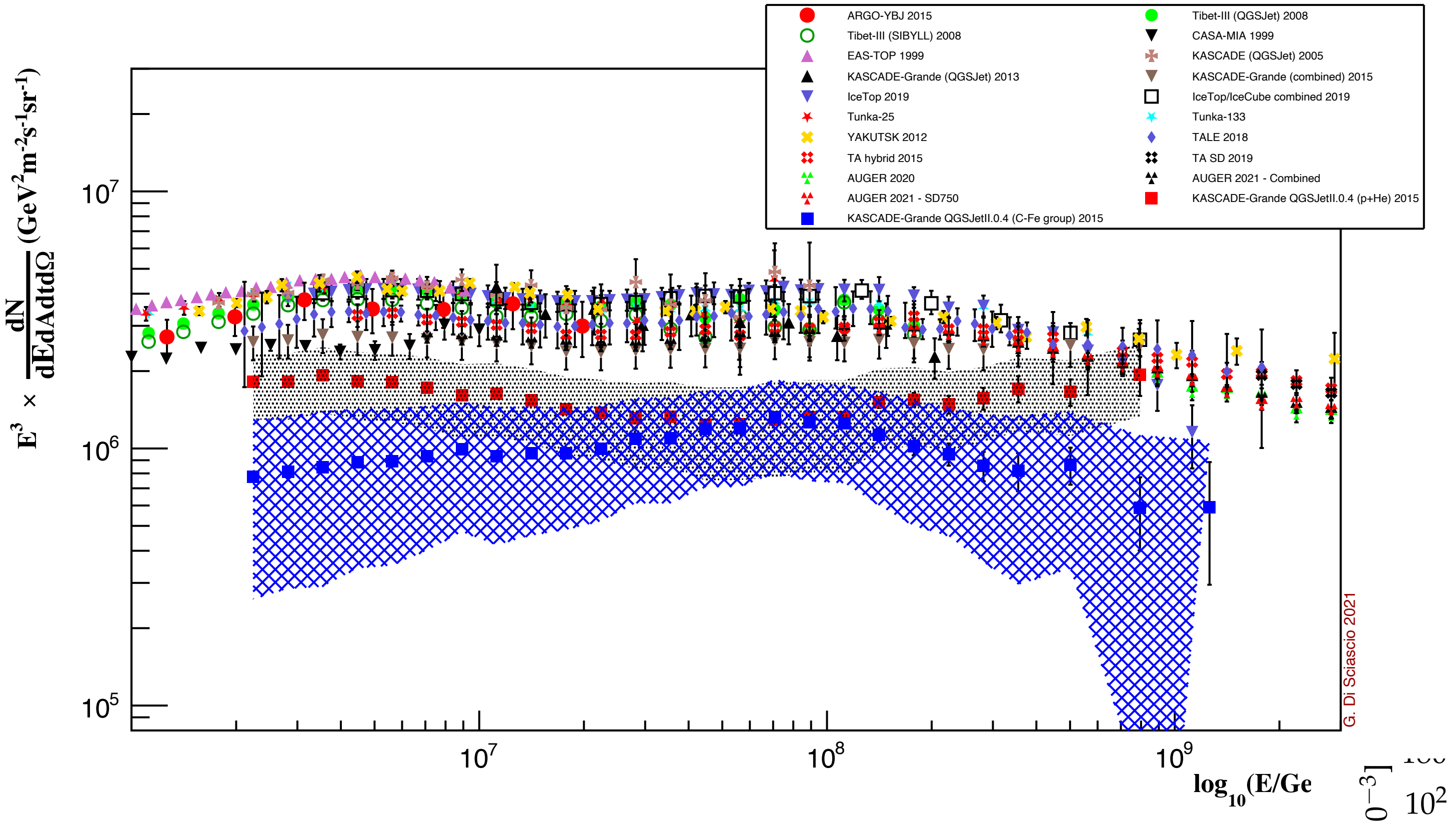
- ✓ all experiments observe an all-particle knee at ~4 • 10^{15} eV
- ✓ Composition at knee controversial: light component knee ~500 TeV (Tibet Array), ~800 TeV (ARGO-YBJ) a factor ~4-5 lower than Kascade
- ✓ Possible deviation from a single power-law in the 10 - 100 TeV range reported by HAWC and direct measurements



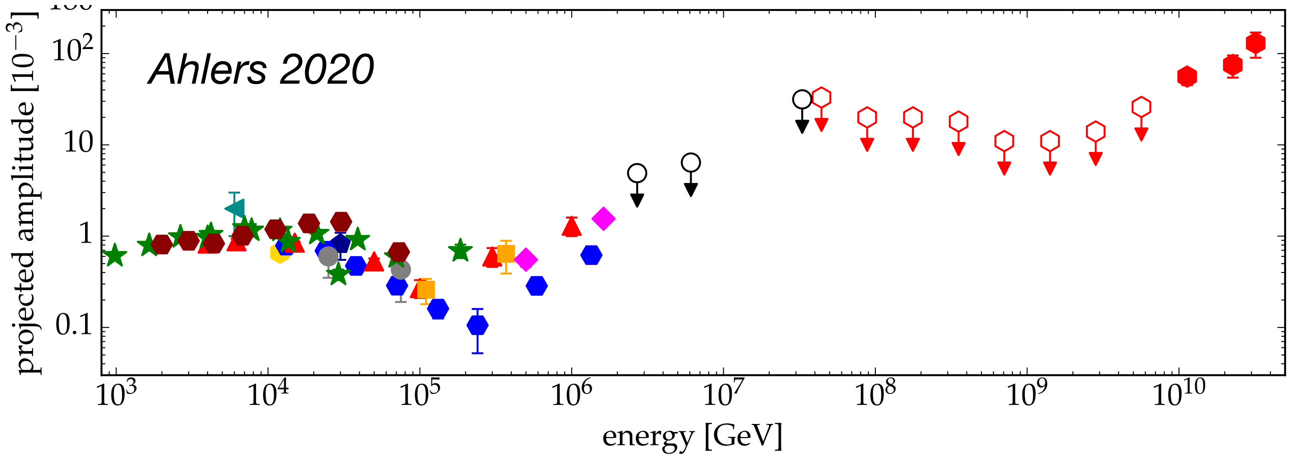
- ✓ 10^{-3} - 10^{-4} LSA amplitudes found at TeV energies.
- ✓ 10^{-4} MSA amplitudes at TeV energies
- ✓ Dramatic phase-flip around ≈100 TeV.

Some conclusions from data

2. Transition region: 10^{16} - 10^{18} eV



- ✓ good agreement of all experiments within systematics
- ✓ good superposition with UHE arrays
- ✓ concave region above $2 \cdot 10^{16}$ eV
- ✓ steepening ~10^{17} eV
- ✓ 2nd galactic component at ~10^{17} eV?



According to Kascade-Grande results

- ✓ evidence for a heavy knee at ~ 10^{17} eV
- ✓ ankle-like feature of the light component above 10^{17} eV

between 10^{16} and 10^{18} eV dipole smaller than ~10^{-2}

Conclusions

The position of the ***proton knee*** is of the crucial importance for the description of the Galactic CRs component(s) and to identify the ***transition from Galactic to extragalactic CRs***.

Data are still conflicting: different measurements suggest rather different scenarios

- A proton knee at about 800 TeV (ARGO-YBJ, Tibet Array, BASJE-MAS, CASA-MIA)
- A proton knee at few PeV (KASCADE, KASCADE-Grande, TUNKA, IceTop)
- Deviation from a single power-law in the 10-100 TeV range?

The *LHAASO experiment* will investigate a wide energy range ($10^{13} \rightarrow 10^{17}$ eV) studying CR physics at extreme altitude with a multi-component strategy.

The energy resolution for the light component was better than 10% with an energy bias of less than 1% at ≈1 PeV.

The recent detections by LHAASO **directly demonstrate the presence of electron and proton PeVatrons in the Milky Way**

Are the galactic proton PeVatrons linked to SNRs or YMCs or Sgr A* or all of of them?

- *observations with LHAASO, eRosita, CTA and SWGO will tell us*

Different detectors, altitudes and range

Experiment	g/cm^2	Detector	ΔE (eV)	e.m. Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
ARGO-YBJ	606	RPC/hybrid	$3 \cdot 10^{11} - 10^{16}$	6700	11,000	0.93 (central carpet)
BASJE-MAS	550	scint./muon	$6 \cdot 10^{12} - 3.5 \cdot 10^{16}$		10^4	
TIBET ASγ	606	scint./burst det.	$5 \cdot 10^{13} - 10^{17}$	380	3.7×10^4	10^{-2}
CASA-MIA	860	scint./muon	$10^{14} - 3.5 \cdot 10^{16}$	1.6×10^3	2.3×10^5	7×10^{-3}
KASCADE	1020	scint./mu/had	$2 - 90 \cdot 10^{15}$	5×10^2	4×10^4	1.2×10^{-2}
KASCADE-Grande	1020	scint./mu/had	$10^{16} - 10^{18}$	370	5×10^5	7×10^{-4}
Tunka	900	open Cher. det.	$3\cdot10^{15} - 3 \cdot 10^{18}$	-	10^6	-
IceTop	680	ice Cher. det.	$10^{16} - 10^{18}$	4.2×10^2	10^6	4×10^{-4}
LHAASO	600	Water C scintill/muon/hadron Wide FoV Cher. Tel.	$10^{12} - 10^{17}$	5.2×10^3	1.3×10^6	4×10^{-3} (KM2A)

		μ Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO	4410	4.2×10^4	10^6	4.4×10^{-2}
TIBET ASγ	4300	4.5×10^3	3.7×10^4	1.2×10^{-1}
KASCADE	110	6×10^2	4×10^4	1.5×10^{-2}
CASA-MIA	1450	2.5×10^3	2.3×10^5	1.1×10^{-2}

- LHAASO Muon detector area: 4.2 x 10^4 m^2 + 8 x 10^4 m^2 (WCDA) ≈ *10^5 m^2* !!!

All-particle energy spectrum