Review of indirect cosmic-ray experiments and the current state of observations

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Universidad Michoacana, Morelia, Mexico

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3. Spectrum and composition
4. E ∈ 1 TeV - 1 PeV
5. E ∈ 1 PeV - 1 EeV
6. E ∈ 1 EeV - 100 EeV
7. Summary

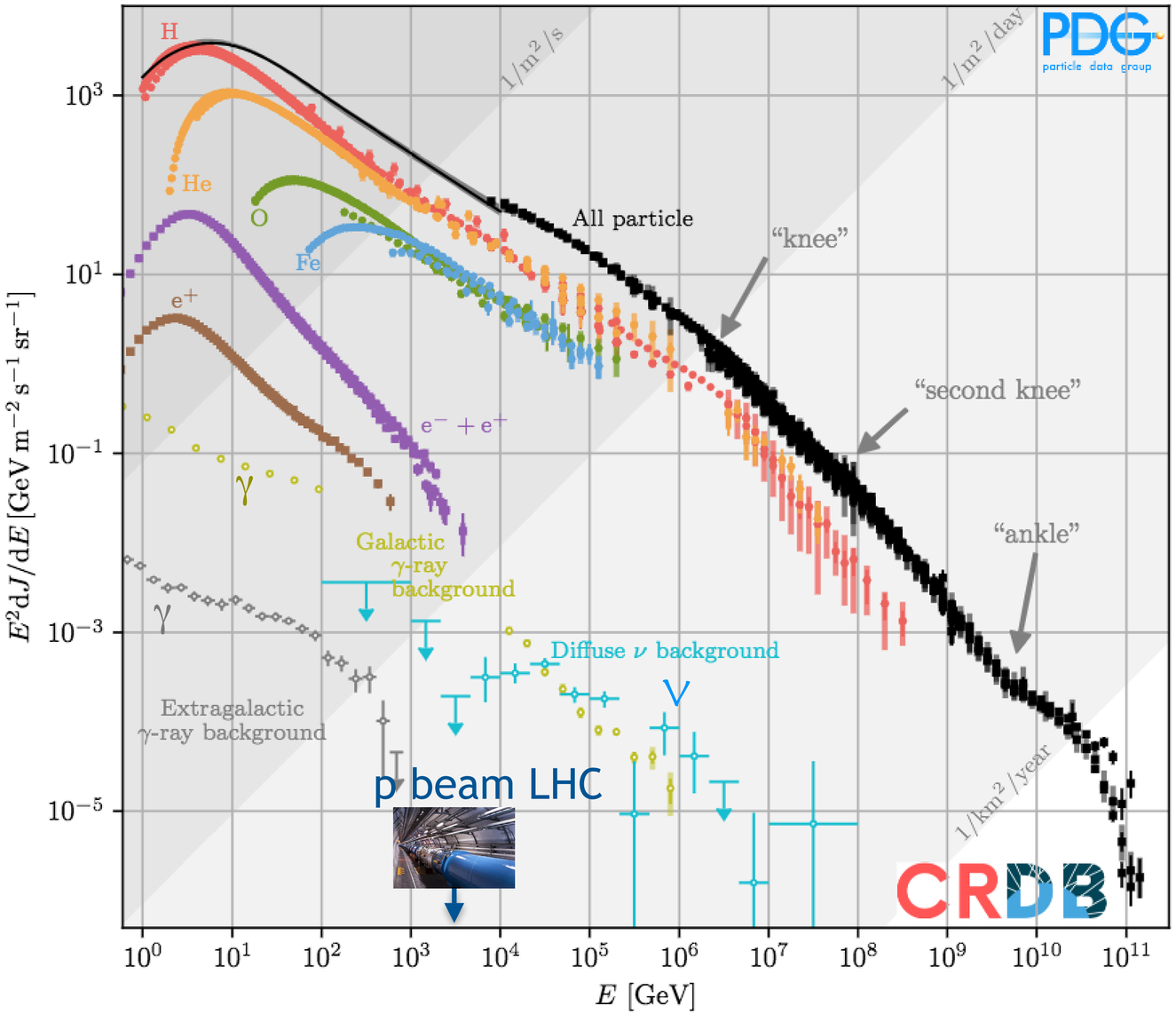
Image: NASA

CRA2026
7th Cosmic Ray Anisotropy Workshop
3 - 6 November, 2026
Monterrey, Nuevo León, México

1) Introduction

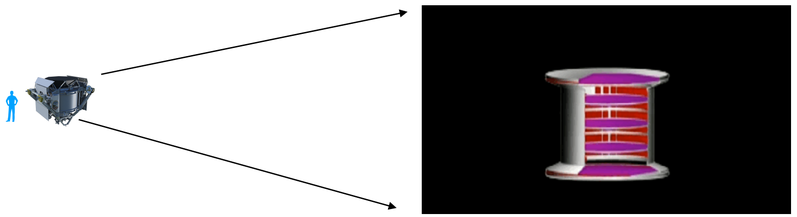
- **Cosmic rays were discovered by V. F. Hess in balloon experiments carried out between 1911 and 1912.** [V. F. Hess et al., Phys. Z. 13 (1912)]
- One of the most energetic forms of extraterrestrial radiation
- **Energies** from 100 MeV to 10^{20} eV.
- Power-law **spectrum:**

  $\Phi(E) = E^{-\gamma}$
- Mainly **composed** of atomic nuclei:
  - Atomic nuclei (99 %):
    H (85%), He (12%), Z ≥3 (3%)
  - e^- (1 %)
  - Traces of antiparticles
    (e^+, $\overline{p}$)



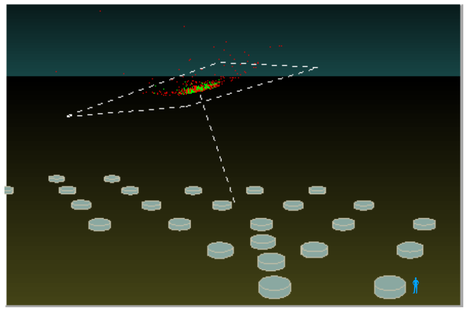
1) Introduction

- **Direct measurements**
  - Detectors on board of airplanes, satellites, balloons, spaceships, space stations.
  - Small detection areas.
  - Direct determination of composition and energy.

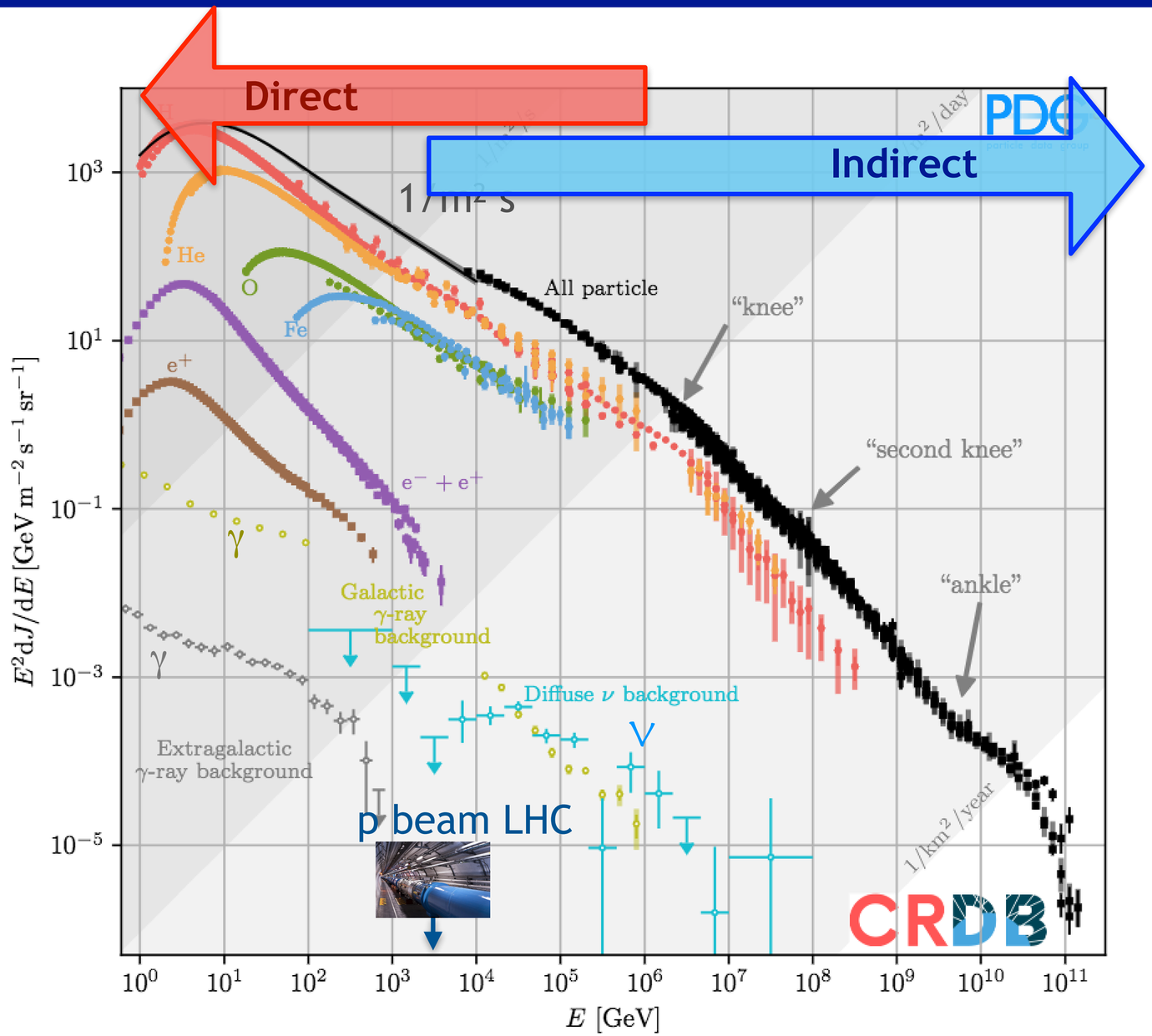


AMS-02 detector

- **Indirect measurements**
  - Detection of extensive air showers.
  - Arrays of particle detectors at ground, optical telescopes in orbit.
  - Large detection areas.
  - Indirect determination of composition.

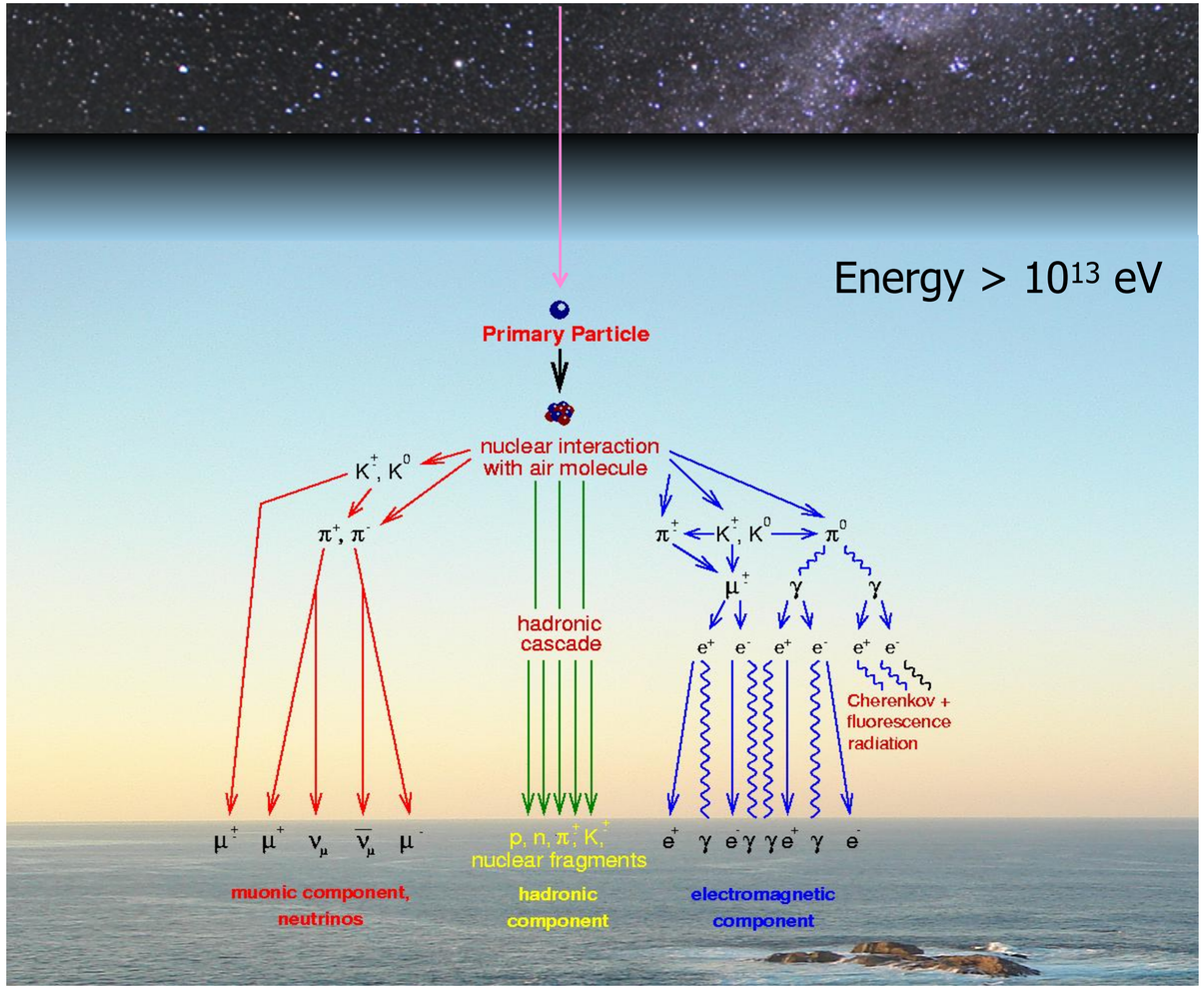


Pierre Auger observatory

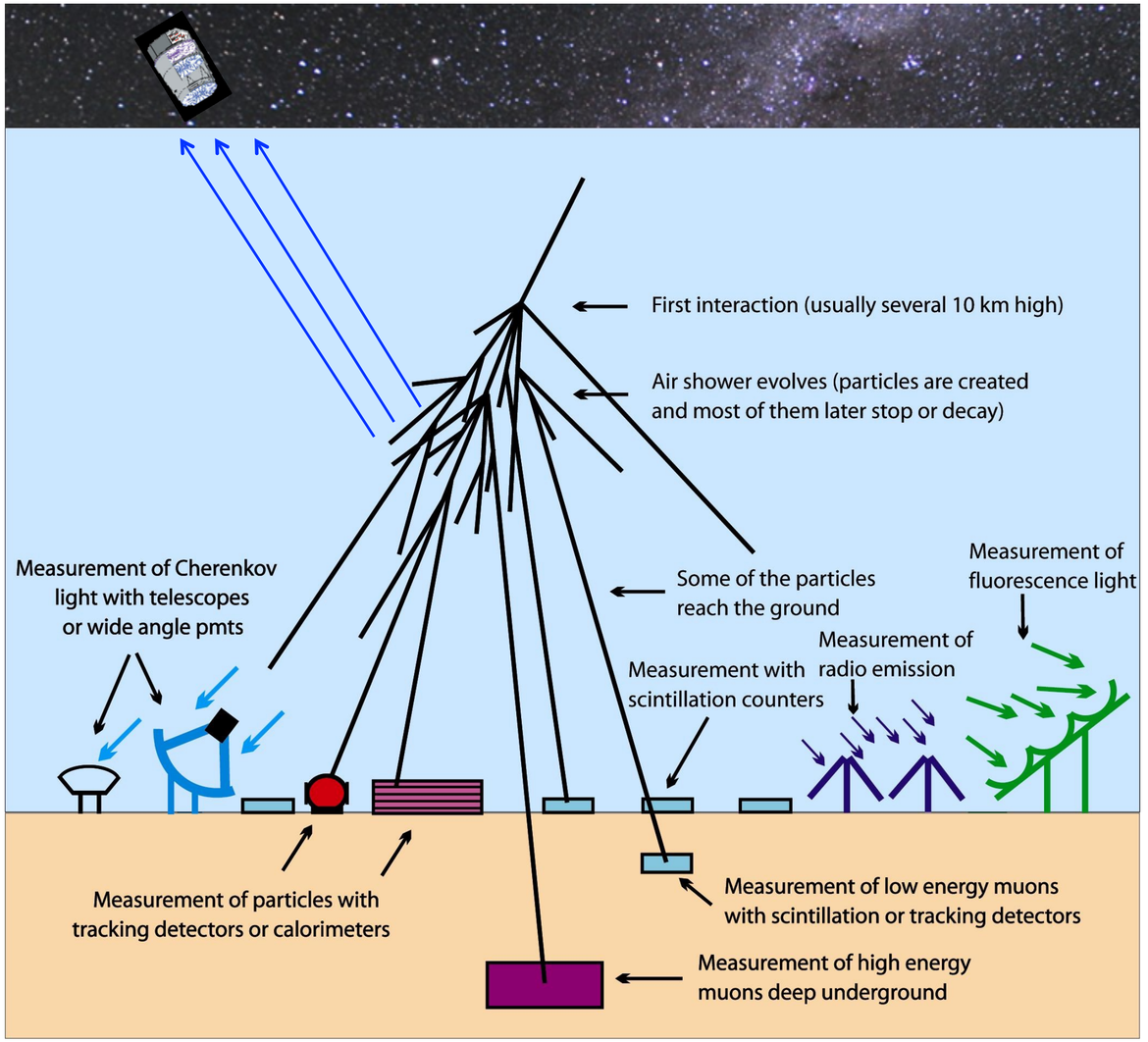


2) Cosmic-ray indirect detection methods

Extensive air showers



CR detection techniques



A. Haungs

2) Cosmic-ray indirect detection methods

EAS experiments



TA, USA



KASCADE-Grande, Germany



TAIGA, Russia



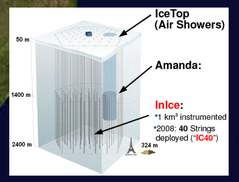
HAWC, Mexico



Alpaquita, Bolivia



Pierre Auger, Argentina



ICETOP, Antartic

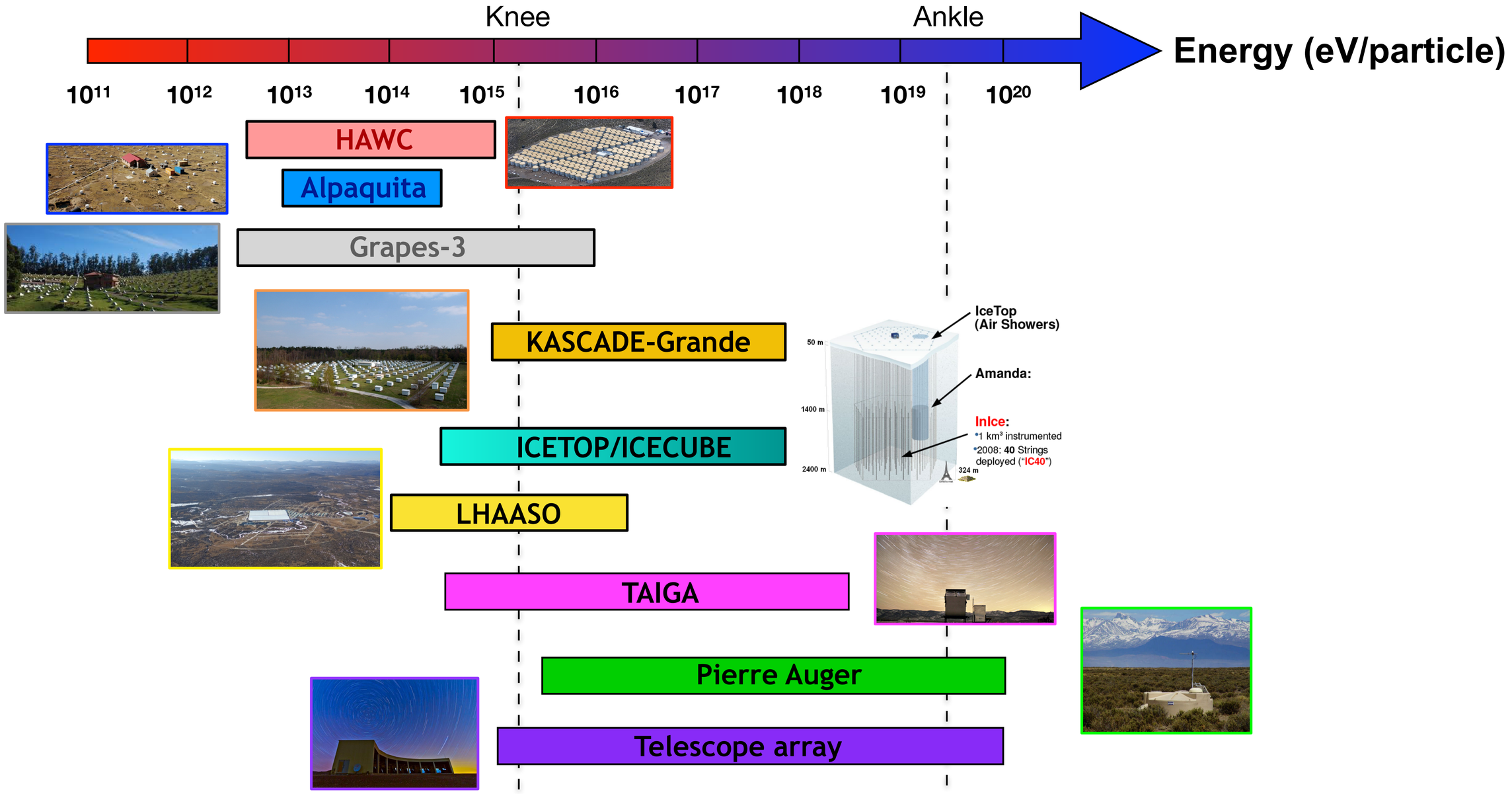


Grapes-3, India



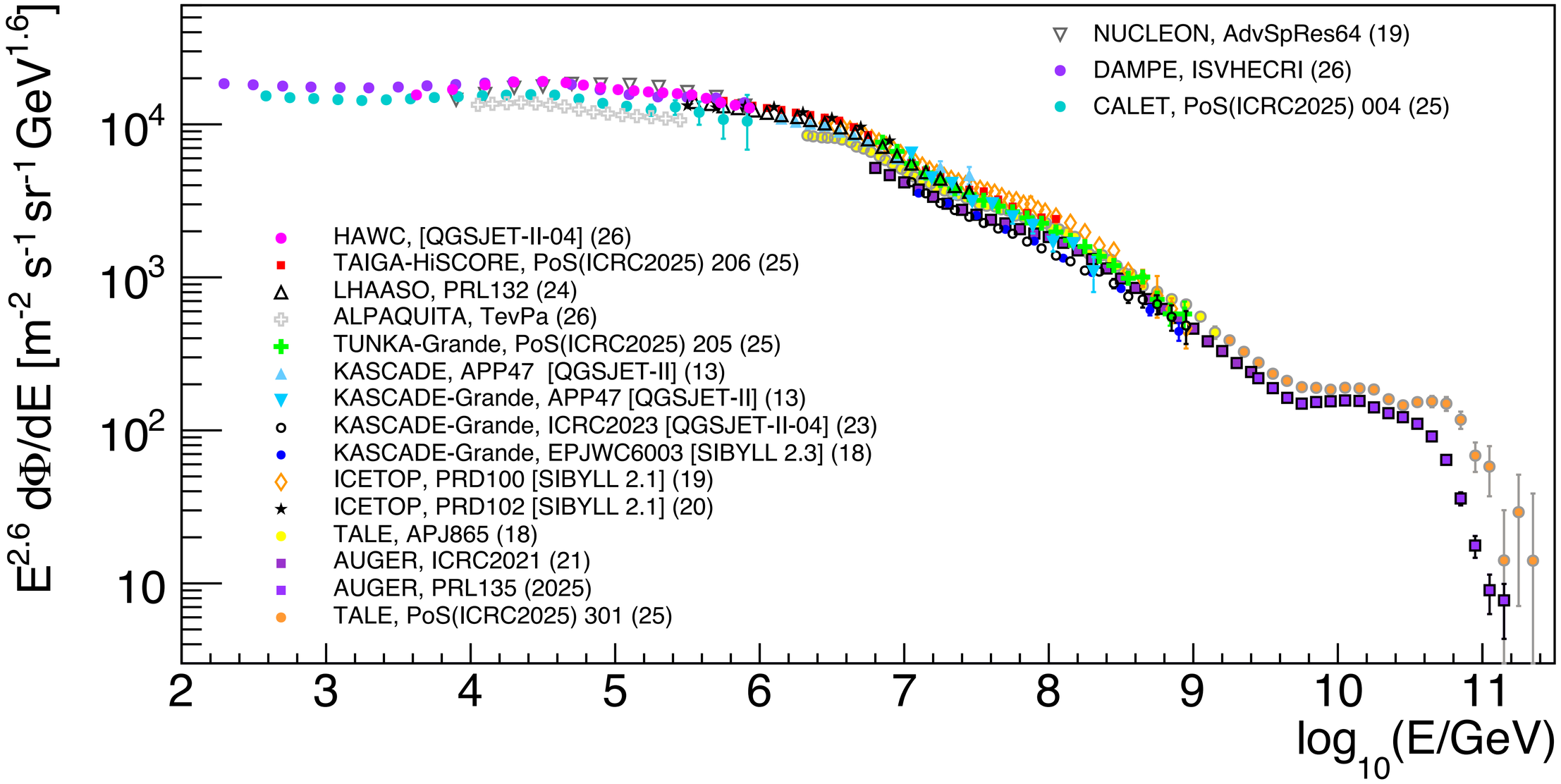
LHAASO, China

2) Cosmic-ray indirect detection methods



3) Cosmic ray spectrum and composition

All-particle



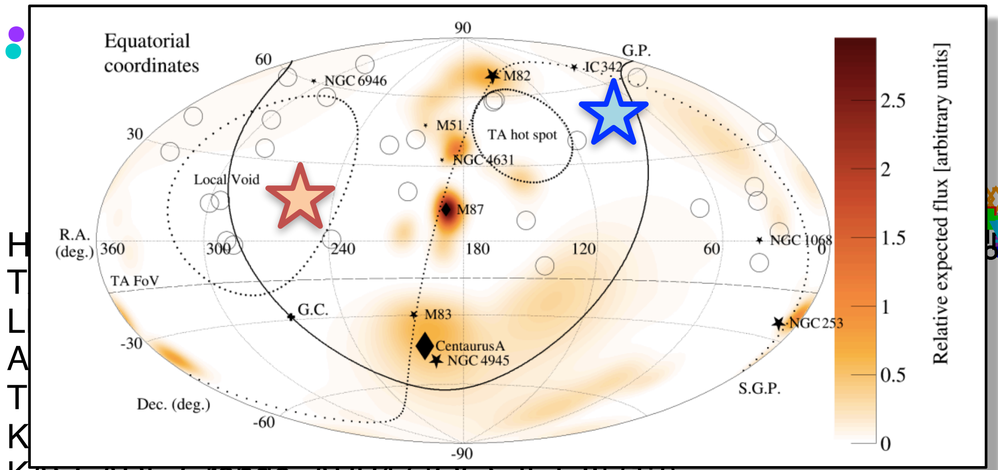
3) Cosmic ray spectrum and composition

[D.J. Bird et al., ApJ 441 (1995)]

All-particle

Highest-energy CR particle:
> E = 3.20 x 10^{20} eV
> Oh-My-God particle
> October 15, 1991, Fly's Eye

[TA Collab., Science 382 (2023)]



$E^{2.6}\, d\Phi/dE$ [$m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{1.6}$]

10^4
10^3
10^2
10

KASCADE-Grande, APP47 [QGSJET-II] (13)
KASCADE-Grande, ICRC2023 [QGSJET-II-04] (23)
KASCADE-Grande, EPJWC6003 [SIBYLL 2.3] (18)
ICETOP, PRD100 [SIBYLL 2.1] (19)
ICETOP, PRD102 [SIBYLL 2.1] (20)
TALE, APJ865 (18)
AUGER, ICRC2021 (21)
AUGER, PRL135 (2025)
TALE, PoS(ICRC2025) 301 (25)

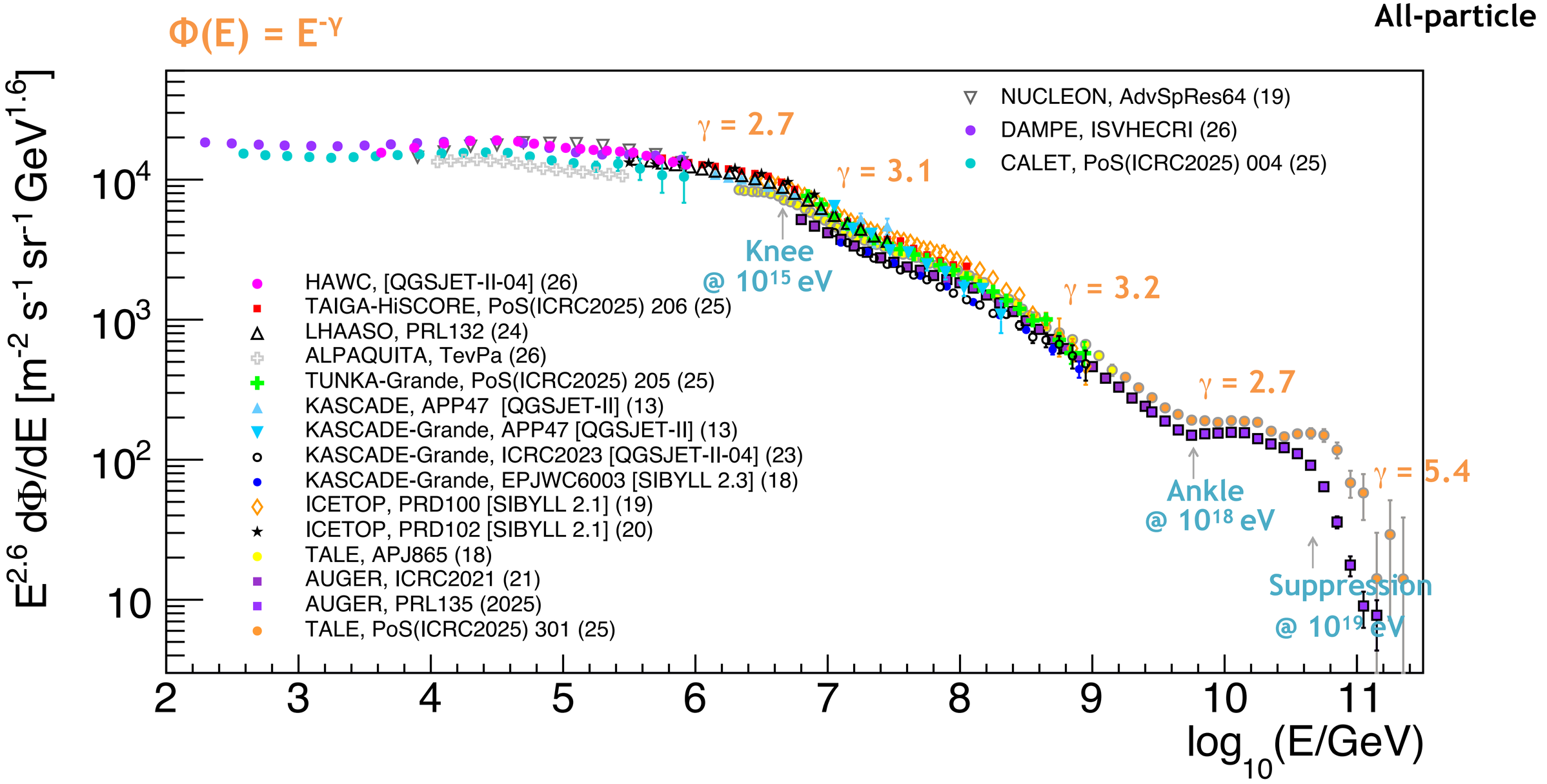
2 3 4 5 6 7 10 11

$\log_{10}(E/GeV)$

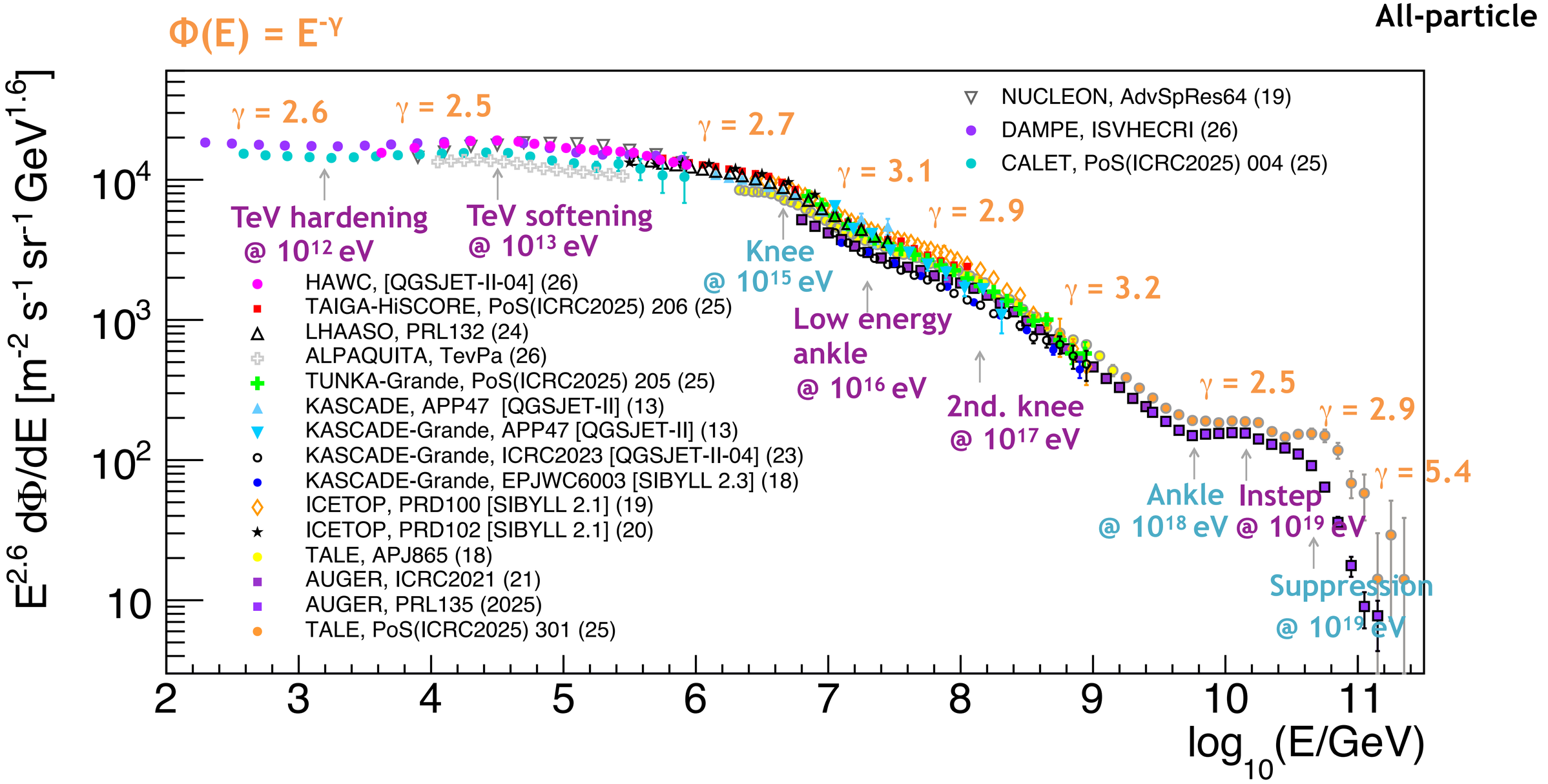
[TA Collab., Science 382 (2023)]

2nd highest-energy CR particle:
> E = 2.44 x 10^{20} eV
> Amaterasu
> May 27, 2021, TA

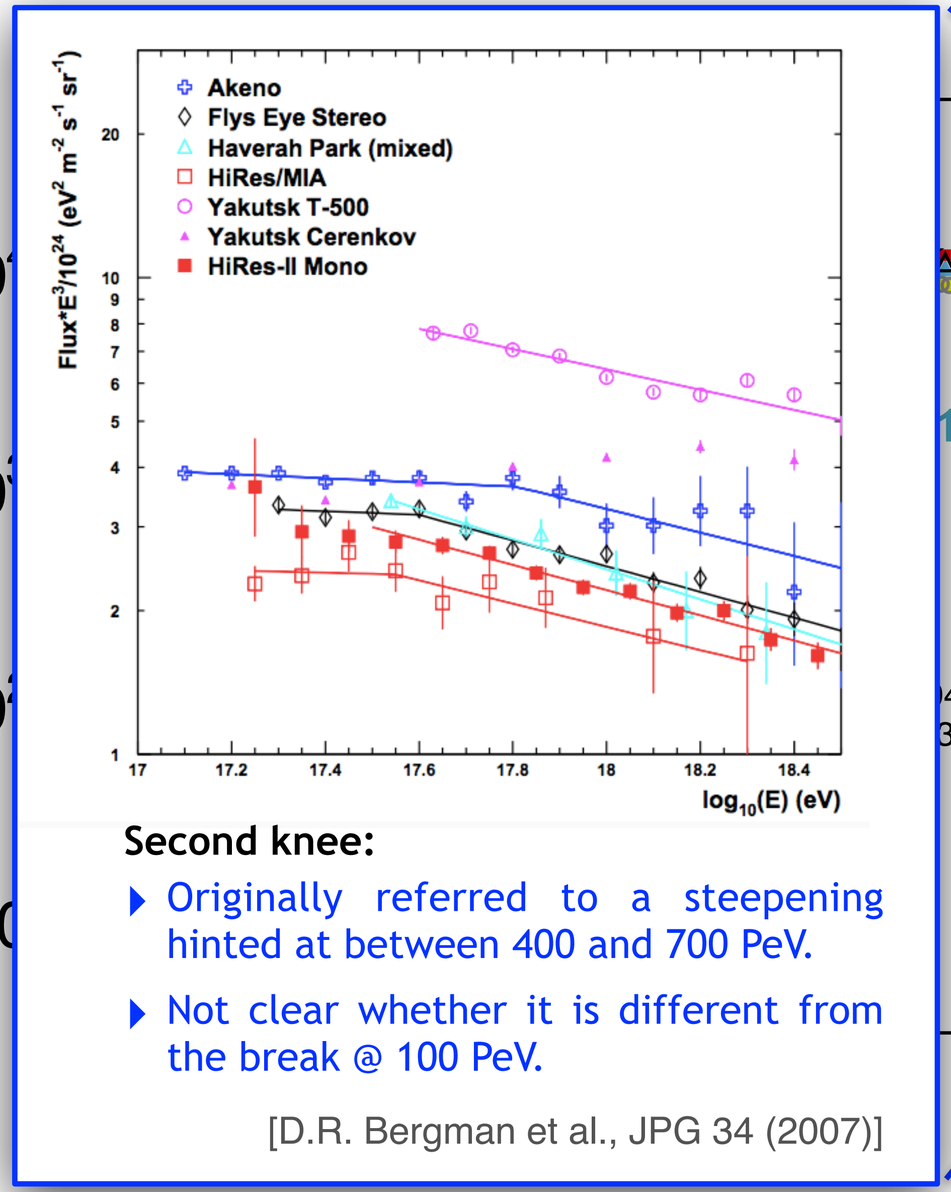
3) Cosmic ray spectrum and composition



3) Cosmic ray spectrum and composition



3) Cosmic ray spectrum and composition



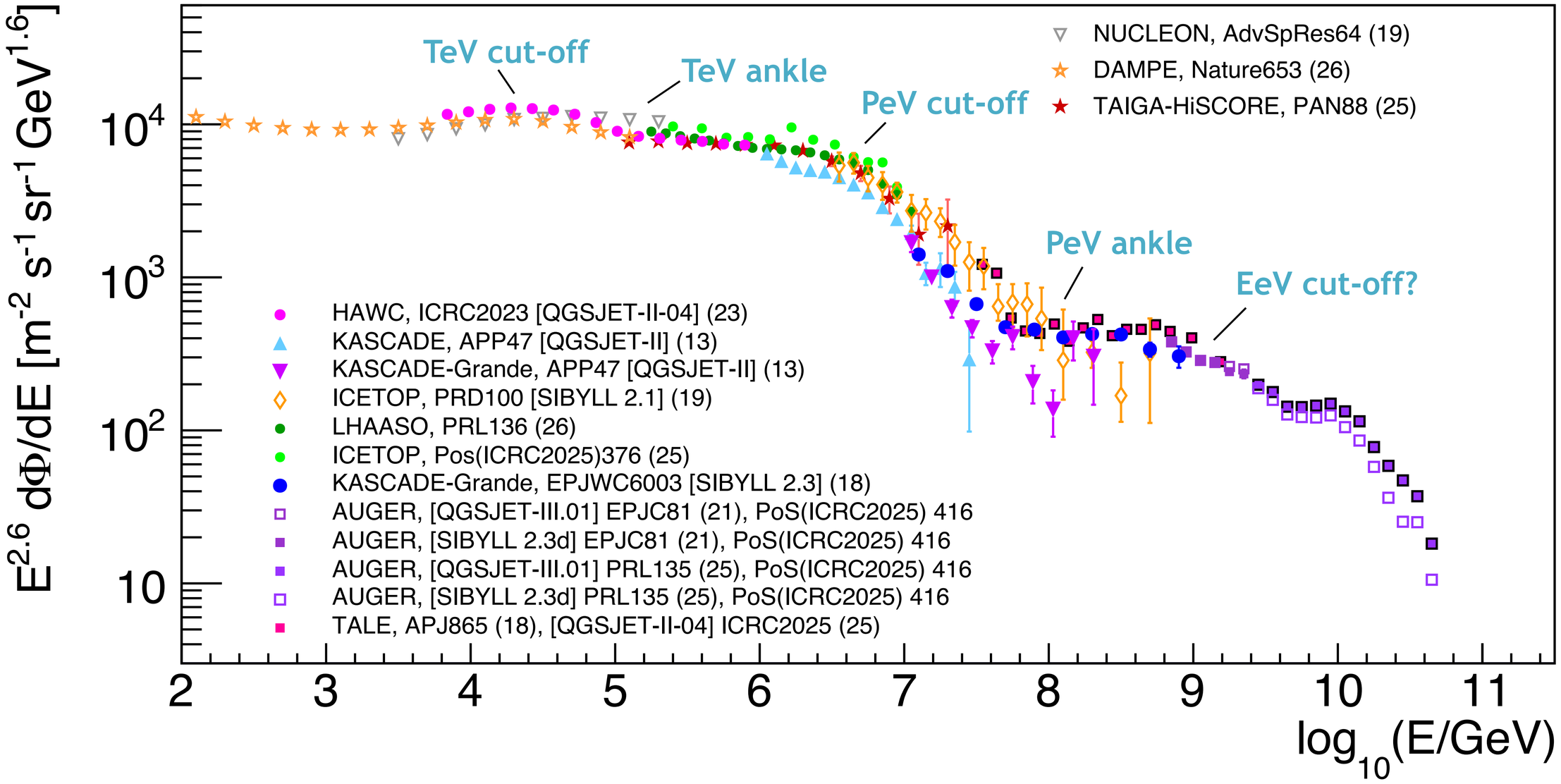
Second knee:

- Originally referred to a steepening hinted at between 400 and 700 PeV.
- Not clear whether it is different from the break @ 100 PeV.

[D.R. Bergman et al., JPG 34 (2007)]

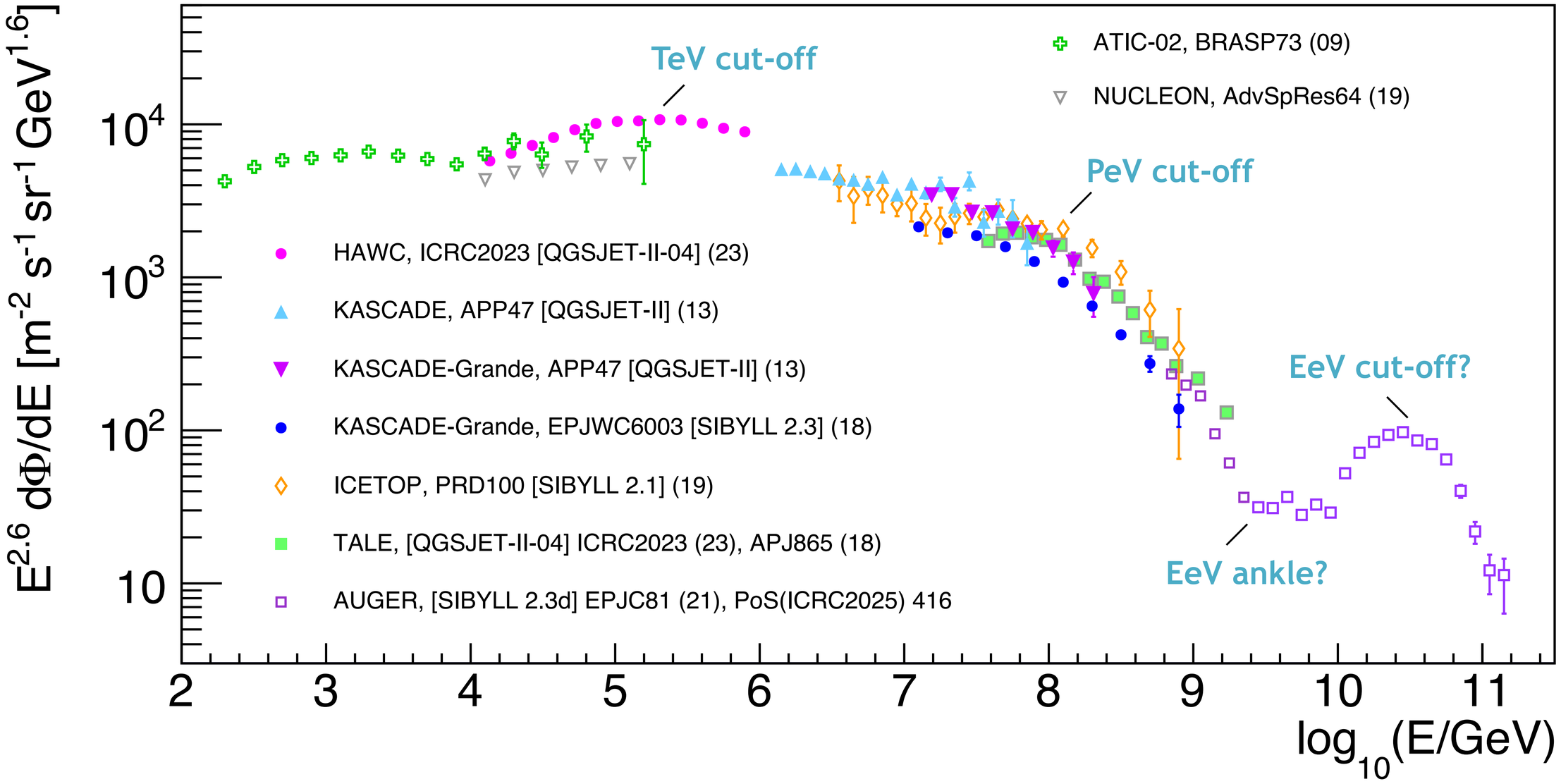
3) Cosmic ray spectrum and composition

Mass composition **H+He**



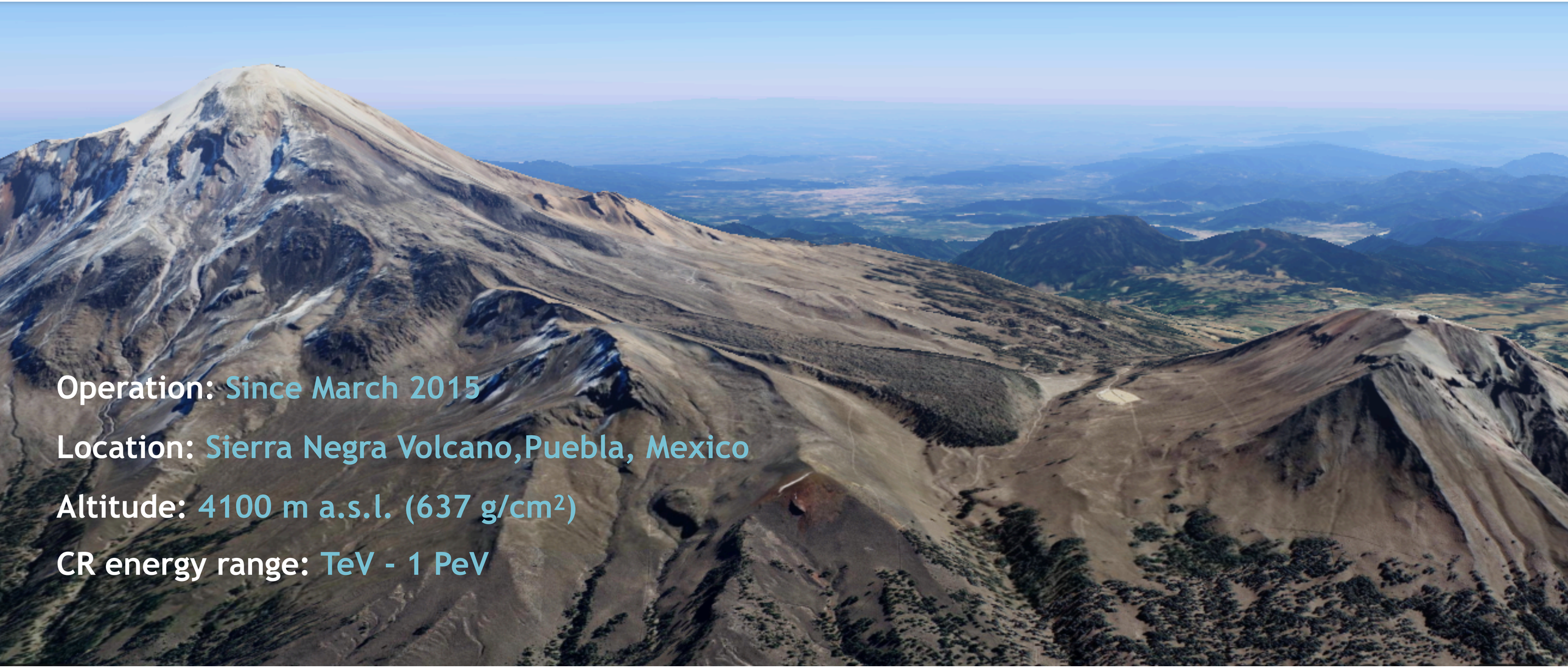
3) Cosmic ray spectrum and composition

Mass composition **Z > 2**



Part 1: 1 TeV - 1 PeV

HAWC observatory



HAWC observatory

- **HAWC central detector:**
  300 water Cherenkov detectors
  1200 PMT's
  150 m x 150 m (22,000 m²)

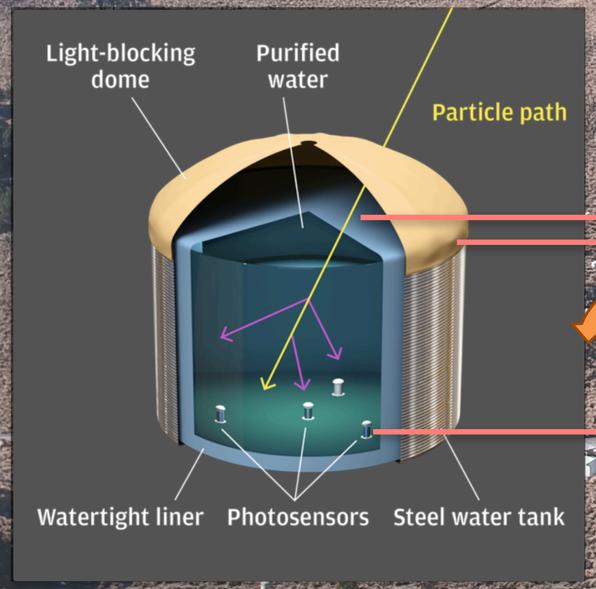
[HAWC Collab., NIMA 1052 (2023)]

Bladder
- Tyvek
- 180,000 L of pure water

Cherenkov detectors
- Steel tanks
- 7.3 m Ø
- 5.4 m high
- 4.5 m water depth









PMT's
- 3 × 8" PMT's
  1.83 m from center
- 1 × 10" PMT's
  At center

- **Outriger detector:**
  345 water Cherenkov detectors
  1200 PMT's
  Within 337 m x 366 m
  A~102,100 m²
  12-18 m separation

[V. Marandon et al., Pos(ICRC2019) 736]



Cherenkov detectors
- Plastic tanks
- 1.55 m Ø
- 1.65 m high
- 1 x 8" PMT

Credit: HAWC Collab.

HAWC observatory

EAS reconstruction from hit times, effective charge, number of PMT's with signal:

- Core location, (X_c, Y_c),
- Arrival direction, θ, ϕ
- Primary energy, E,
- Lateral charge profile, **Qeff(r)**,
- Shower age, …

Lateral age parameter (*s*):

- Fit **Qeff(r)**, event-by-event, with a NKG-like function:

$$f_{ch}(r) = A \cdot (r/r_0)^{s-3} \cdot (1 + r/r_0)^{s-4.5}$$

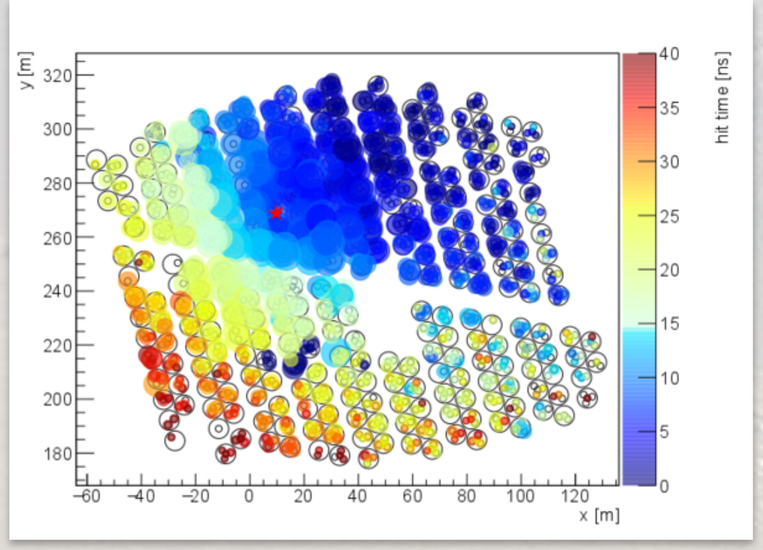
r_0 = 124.21 m

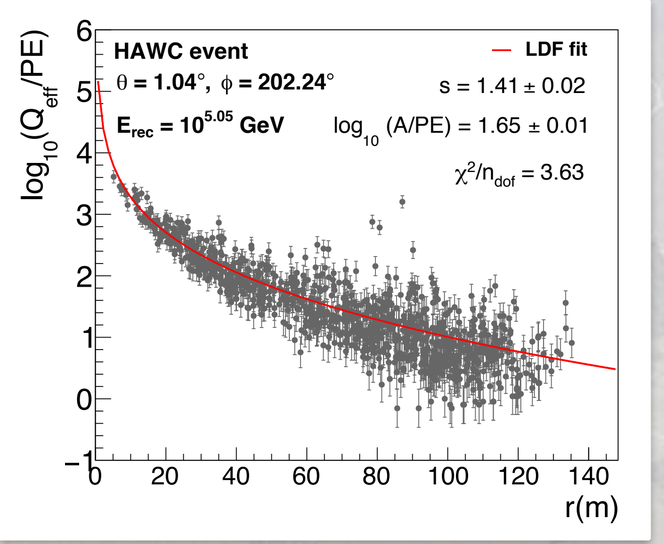
A, ***s*** are free parameters

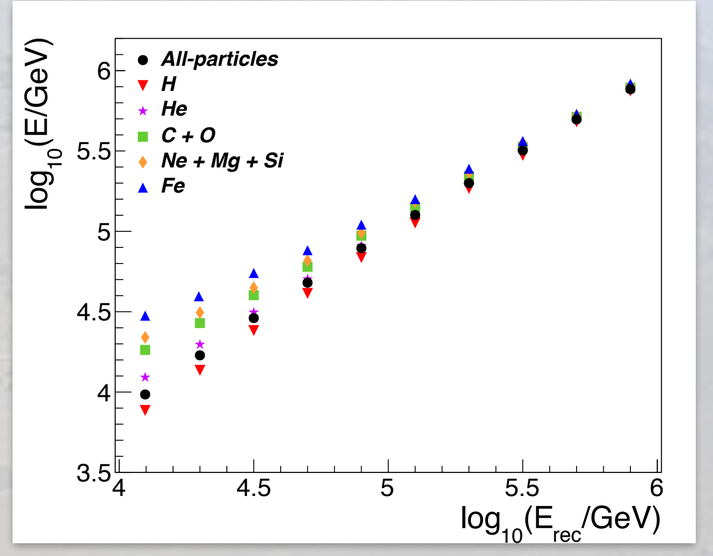
[HAWC Collab., APJ 881 (2019) 134]

Energy estimation

- Maximum likelihood **fit to the Qeff(r)** of an event **with MC templates** of **MC protons**.
- Templates were built with **QGSJet-II-04** for different energy and zenith angle intervals.



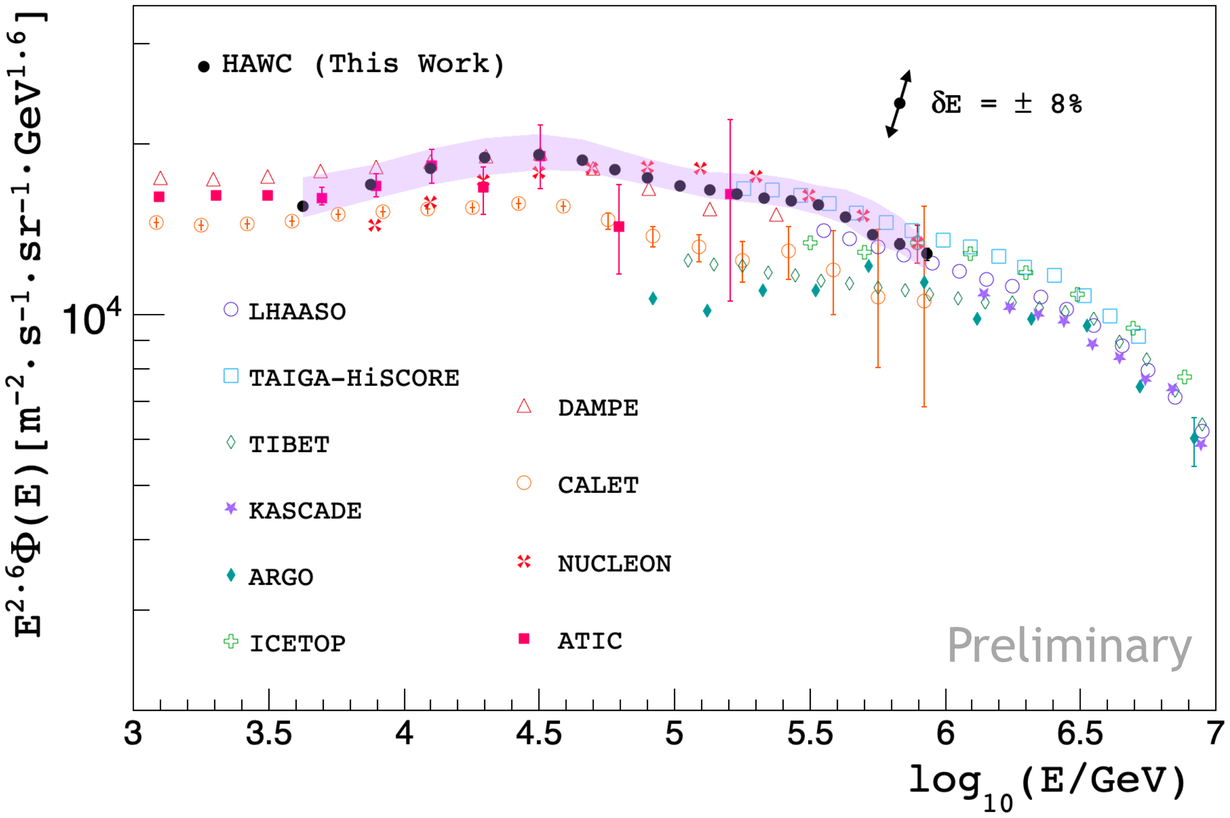




HAWC observatory

All-particle spectrum between 3.9 TeV and 1 PeV

[Paper in progress]



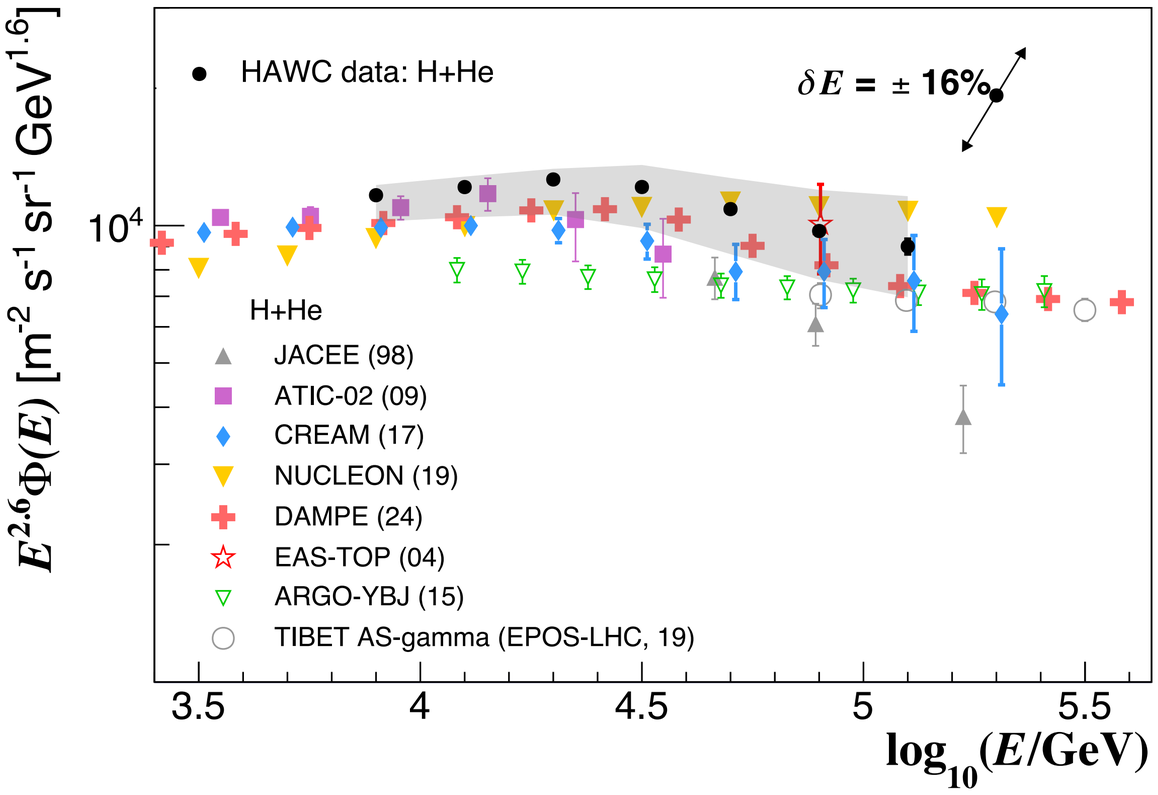
- Spectrum is better described by a broken power law with three breaks rather than with one or two breaks with 5.1σ and 4.1σ, respectively.
- Confirmation of a softening at ~ 30 TeV.
- Discovery of a hardening at ~ 107 TeV.
- Discovery of another softening at ~ 309 TeV.
- Bridge between direct and EAS experiments.

- Effective time ~ 5 years, 1.9 x 10^{11} selected events, $\theta < 35^\circ$.
- Unfolding of energy histogram. Response matrix: QGSJET-II-04.

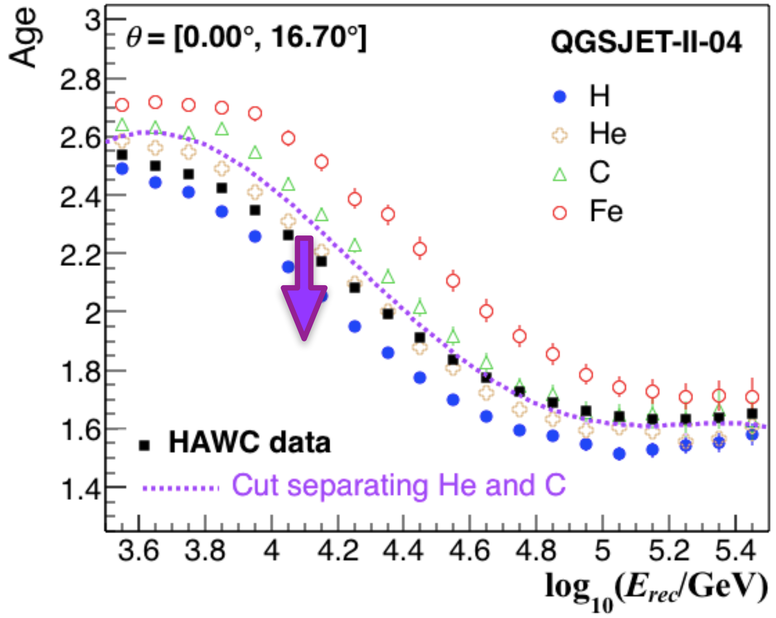
HAWC observatory

H+He energy spectrum from 6 to 158 TeV

[HAWC Collab., PRD 105 **(2022)** 063021]
[HAWC Collab., RMF 61 **(2025)** 261]



- Detection of a softening at 24 TeV with a change from γ=–2.51 to γ=–2.83.
- Observation of feature with 4.1σ of statistical significance.



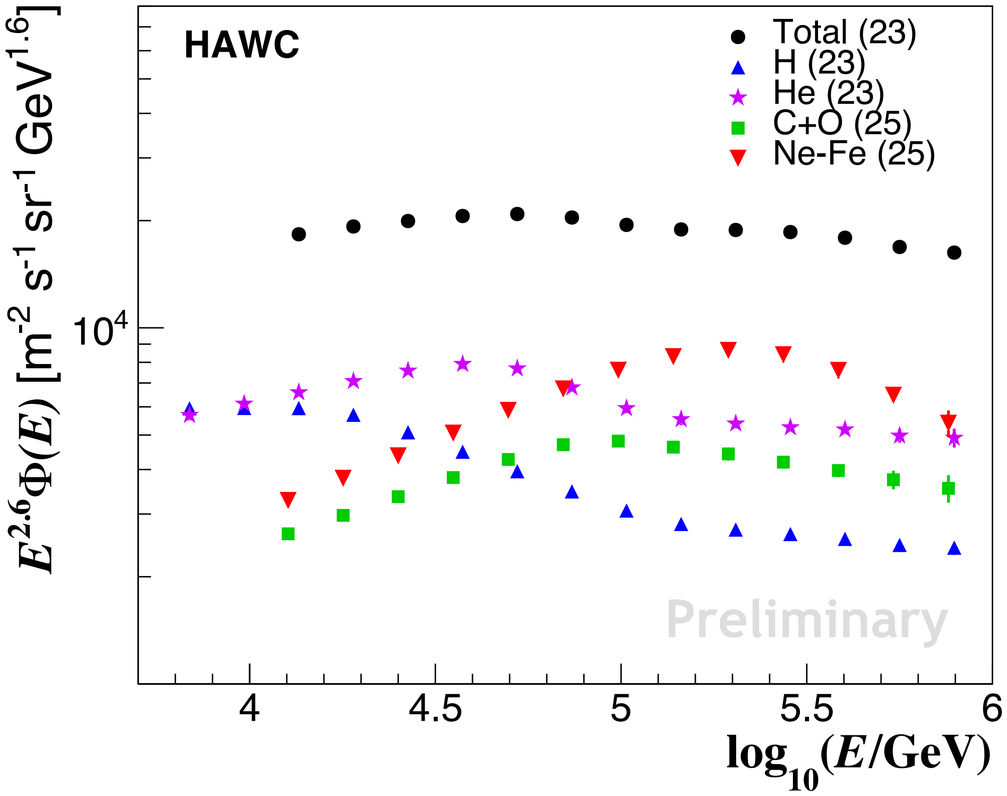
- Effective time ~ 4 years, 9.9 x 10^9 selected events dominated by H+He nuclei (> 82%), θ < 16.7°.
- Unfolding of energy histogram. Response matrix: QGSJET-II-04.

HAWC observatory

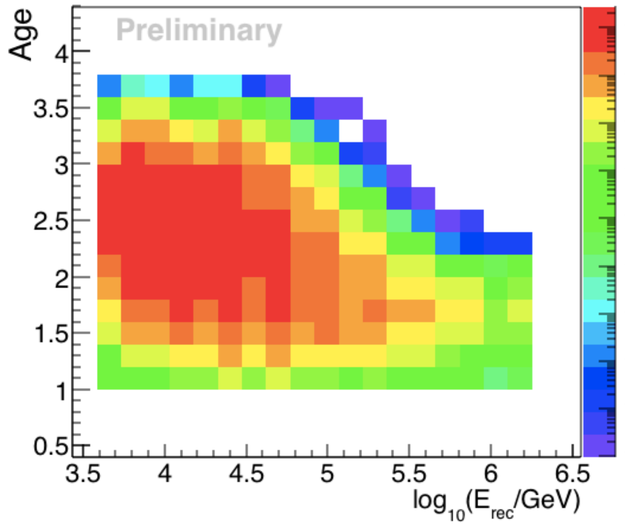
H, He and Heavy (C-Fe) spectra from 10 TeV to 1 PeV

[HAWC Collab., PoS(ICRC2023) 299]

[HAWC Collab., PoS(ICRC2025) 178]



- Mass composition in two decades of energy.
- HAWC data show fine structure (> 3σ, stat):
  - **Softenings** for each mass group, increasing in energy for heavier elements.
    - **H** @ ~ 17 TeV.
    - **He** @ ~ 50 TeV.
    - **C+O** @ ~ 100 TeV.
    - **Ne-Fe** @ ~ 210 TeV.
  - **Hardenings** close to **100 TeV for H and He**.

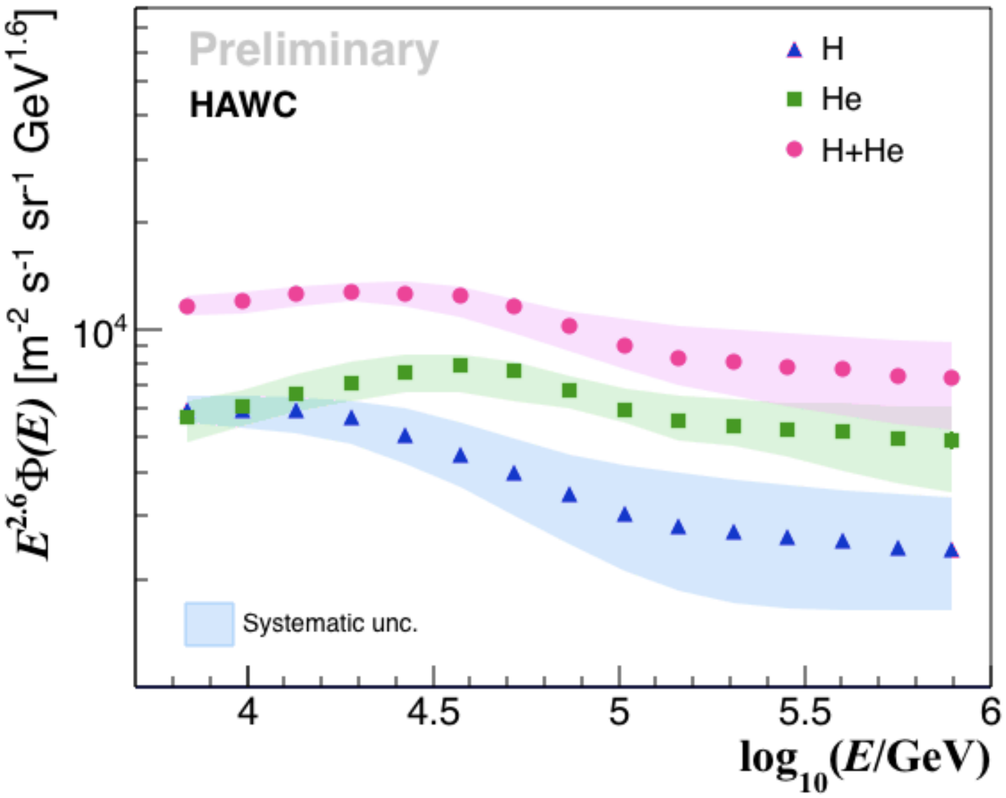


- Effective time ~ 5 years, 37.5 x 10^9 selected events, 20° < θ < 45°.
- Unfolding of 3 mass groups from 2D-histogram for Age vs E_{rec}. Response matrix: QGSJET-II-04.

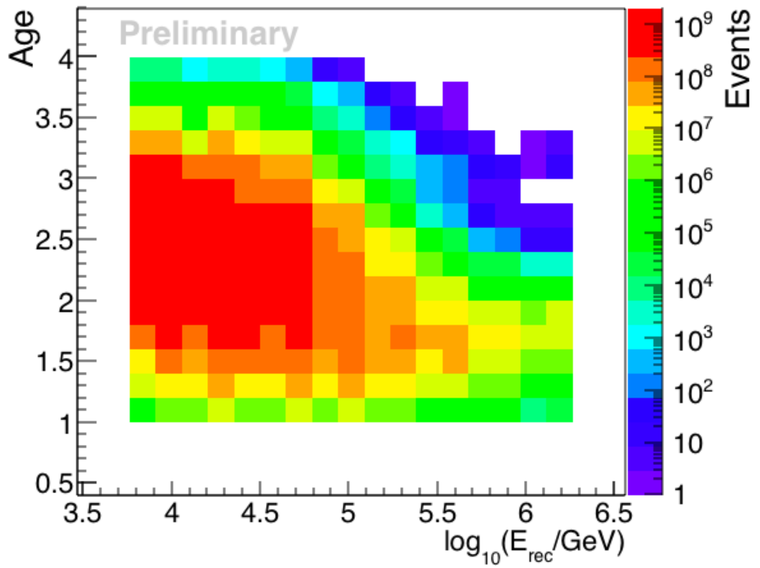
HAWC observatory

H+He spectra from 10 TeV to 1 PeV

[HAWC Collab., PoS(ICRC2023) 299]



- Knee-like feature in spectrum of H+He comes from individual cuts in spectra for H and He.
- Detection of another feature in spectrum of H+He nuclei: Hardening close to 100 TeV.



- Effective time ~ 5 years, 37.5 x 10^9 selected events, 20° < θ < 45°.
- Unfolding of 3 mass groups from 2D-histogram for Age vs E_{rec}. Response matrix: QGSJET-II-04.

ALPAQUITA

Operation: Since 2022

Location: Chacaltaya, Bolivia

Altitude: 4740 m a.s.l. (572 g/cm^2)

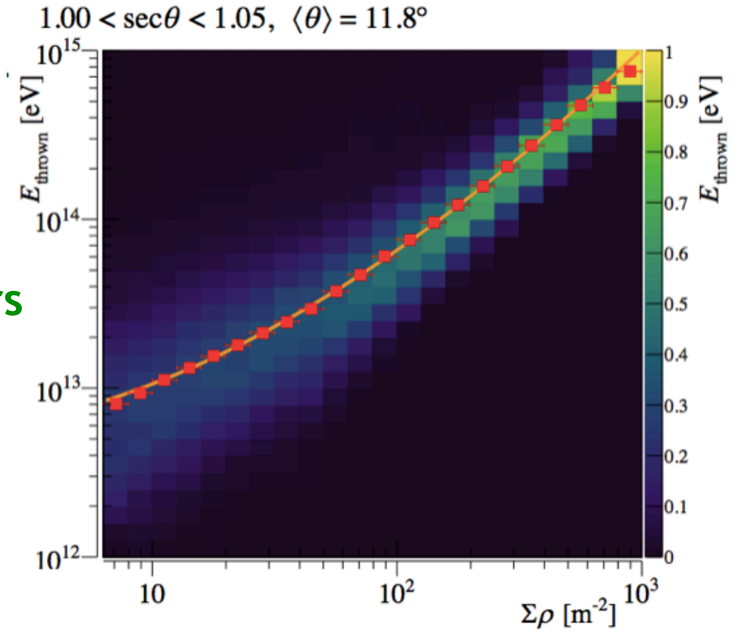
CR energy range: 10 TeV - 300 TeV

[K. Fujita., TeVPA2026]



ALPAQUITA

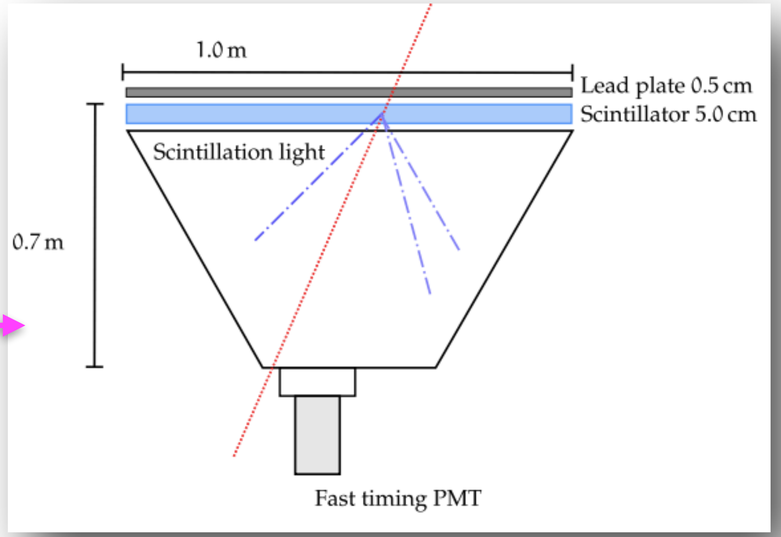
[K. Fujita., TeVPA2026]





- 1/4 surface of ALPACA:
  - 97 plastic scintillator detectors
  - 1 m^2 /detector
  - 15 m separation
  - A = 18450 m^2



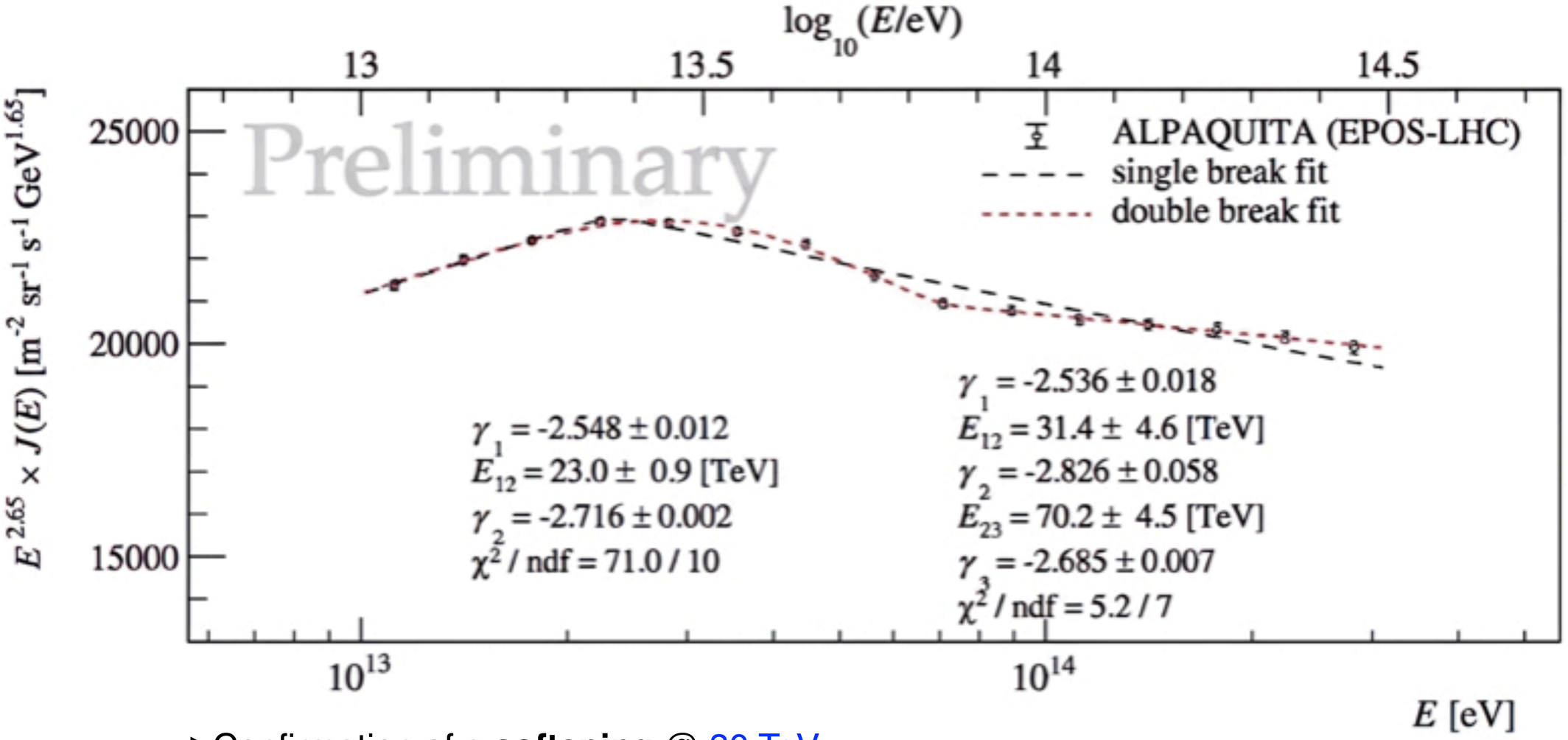


Google Maps

[K. Fujita., TeVPA2026]

[M. Anzorena et al., arXiv:2412.14550 [astro-ph.HE]]

ALPAQUITA



- Confirmation of a **softening** @ 30 TeV.
- Hint for a **hardening** @ 70 TeV.

[K. Fujita., TeVPA2026]

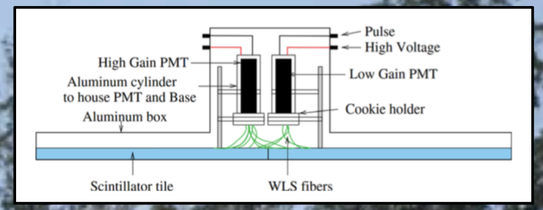
GRAPES-3

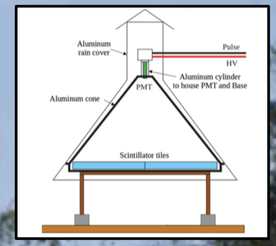


- **Muon telescope:**
  560 m^2
  E_μ^{th} = 1 GeV
  3712 proportional counters
  (Gaseous detector)
  16 muon modules
  Concrete shielding

[Y. Hayashi et al., NIMA 545 (2005)]

[M. Zuberi et al., Eur. Phys. J. C 84 (2024)]





- **Main array:**
  400 plastic scintillator detectors
  1 m^2 /detector (144/256 fiber/cone type)
  8 m separation
  A = 25,000 m^2

[S. K. Gupta et al., NIMA 540 (2005)]

Operation: Since March 2000

Location: Ooty, India

Altitude: 2200 m a.s.l. (790 g/cm^2)

CR energy range: TeV - 10 PeV

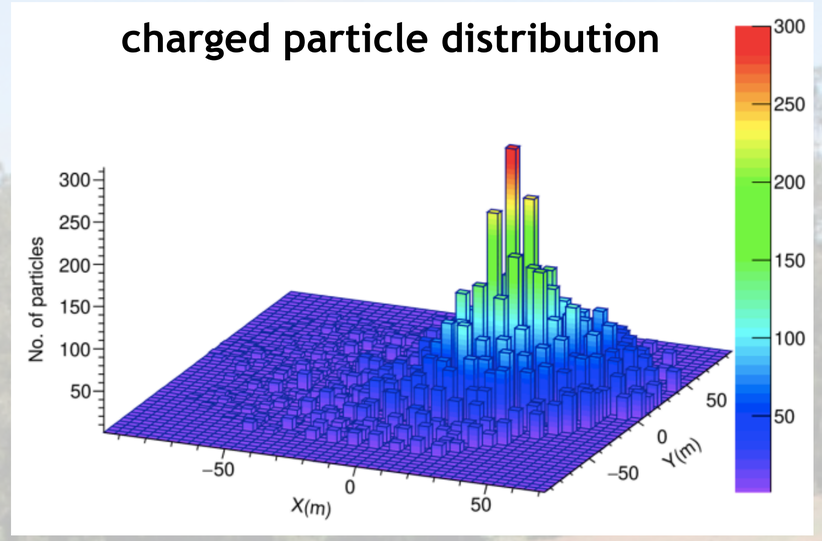
See also Pravata's presentation.

Credit: Hari Adivarekar

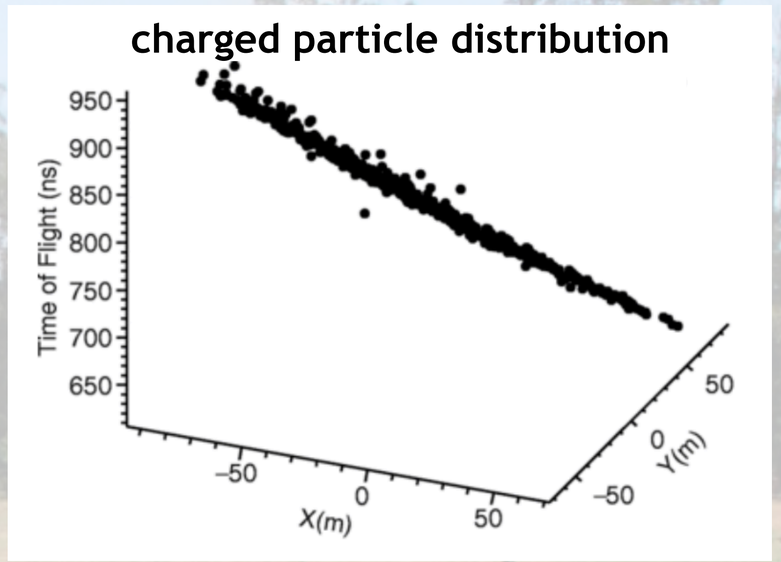
GRAPES-3

EAS reconstruction from arrival times, charged particle distribution, number of particles, muon tracks:

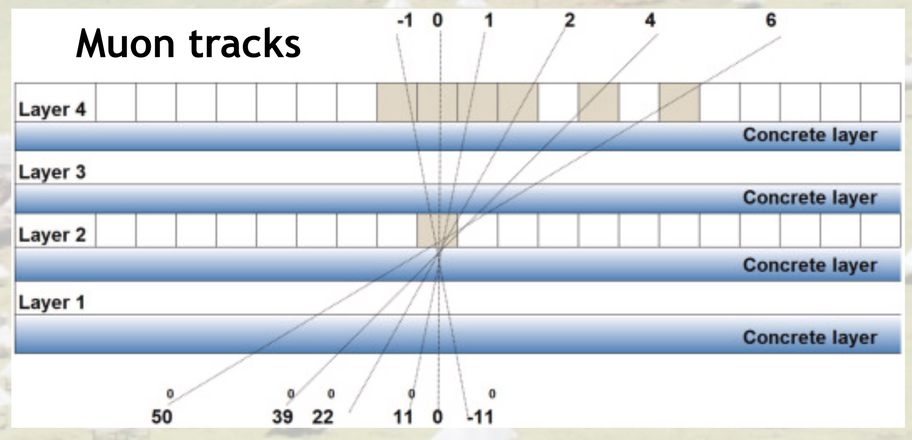
- Core location, (X_c, Y_c),
- Arrival direction, θ, ϕ
- Primary energy, E,
- Lateral charge profile,
- Ne, Nμ…



[B. Hariharan et al., Exp. Astron. 50 (2020)]



Credit: Grapes-3 Collab.



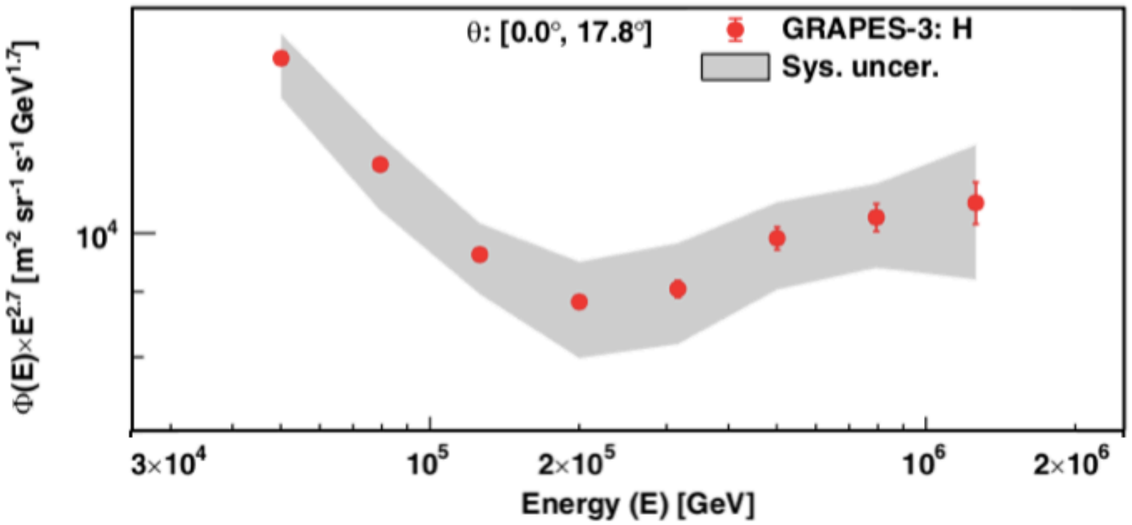
[P. K. Nayak et al., J. Atm. Sol. Terr. Phys. 258 (2024) 106231]

Credit: S. K. Gupta

GRAPES-3

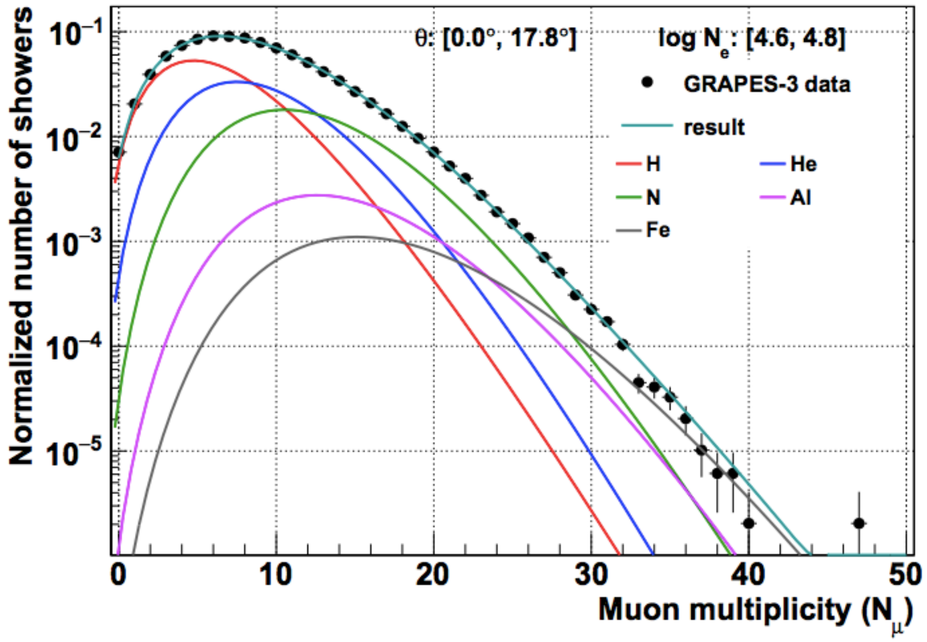
Spectrum of H from 50 TeV to 1.3 PeV

[F. Varsi et al., PRL 132, 051002 (2024)]



- Observation of a hardening at 160 TeV with > 3.2 σ and a change from γ=–3.12 to γ=–2.56.

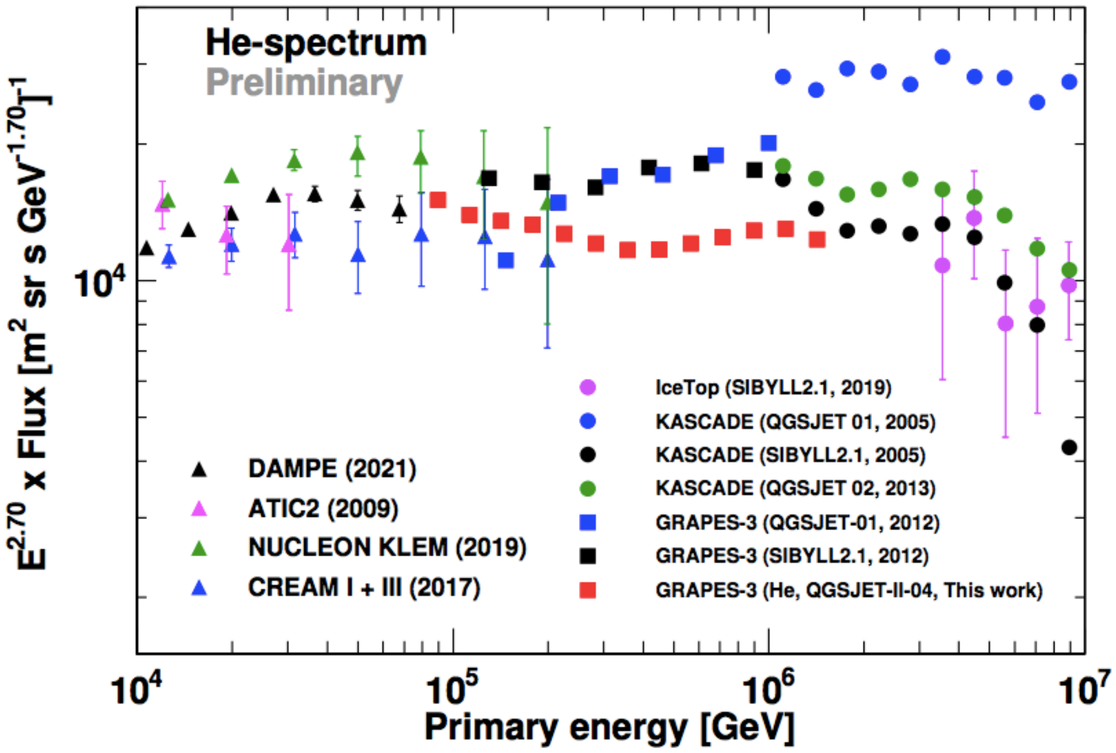
- Mass sensitive parameter
  - Muon multiplicity: Used to obtain relative abundance of H inside shower size (N_e) bins.
- Energy spectrum from unfolding of N_e distribution for H
  - Response matrix using QGSJET-II-04.



GRAPES-3

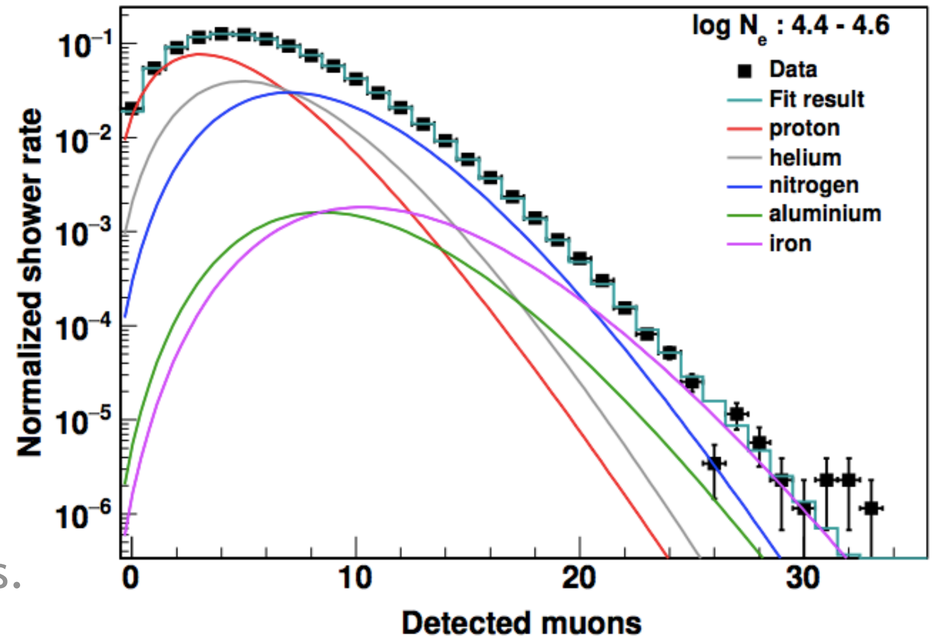
Spectrum of He from 89 TeV to 1.4 PeV

[F. Varsi et al., PoS(ICRC2021) 388 (2021)]



- Hints of a hardening at 400 TeV.

- Mass sensitive parameter
  - Muon multiplicity: Used to obtain relative abundance of H inside shower size (N_e) bins.



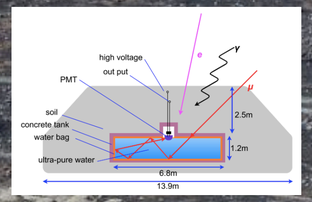
LHAASO
高海拔宇宙线观测站



See also Zhang's presentation.

WCD:
-Water Cherenkov detectors
-3 water ponds
-3120 detector units
-4 m water depth
-78000 m^2

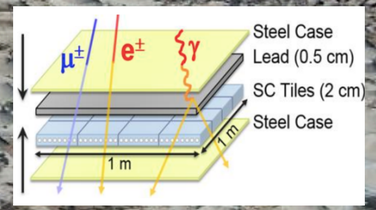
Muon detectors:
- 1188 water Cherenkov detectors
- 36 m^2 x 1.2 m steel tank
- Under 2.5 m of soil
- 1 km^2 array











Operation: Since July 2021

Location: Daocheng,Sichuan, China

Altitude: 4410 m a.s.l. (600 g/cm^2)

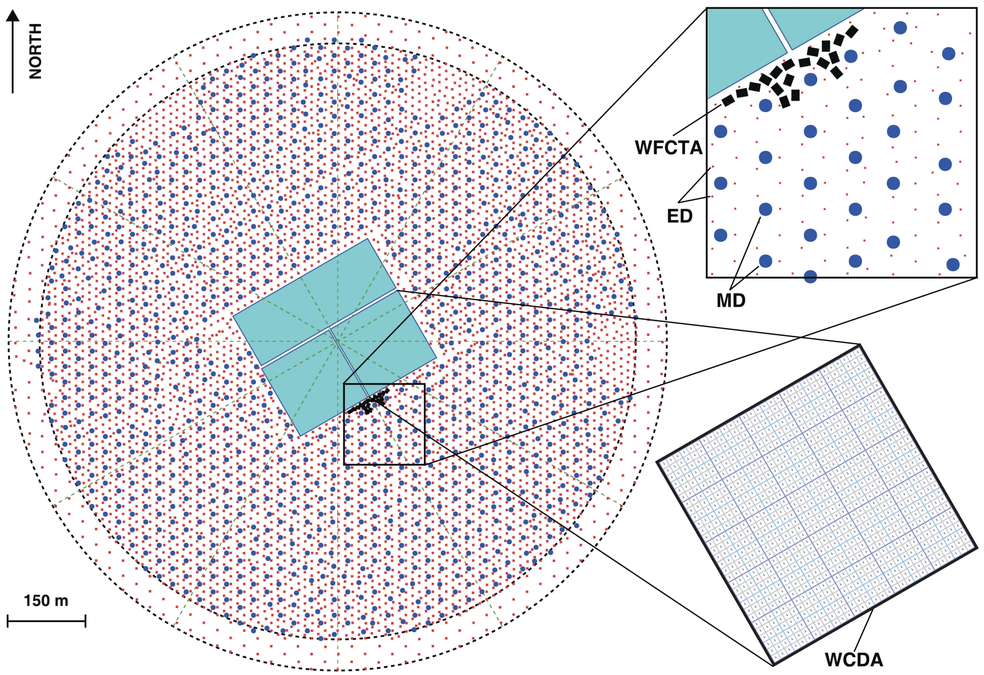
CR energy range: 100 TeV - 10 PeV

[S. Wu et al., PoS(ICRC2023) 010]

WFCTA:
- 18 Cherenkov/FD telescopes
- FOV 16^o x 16^o

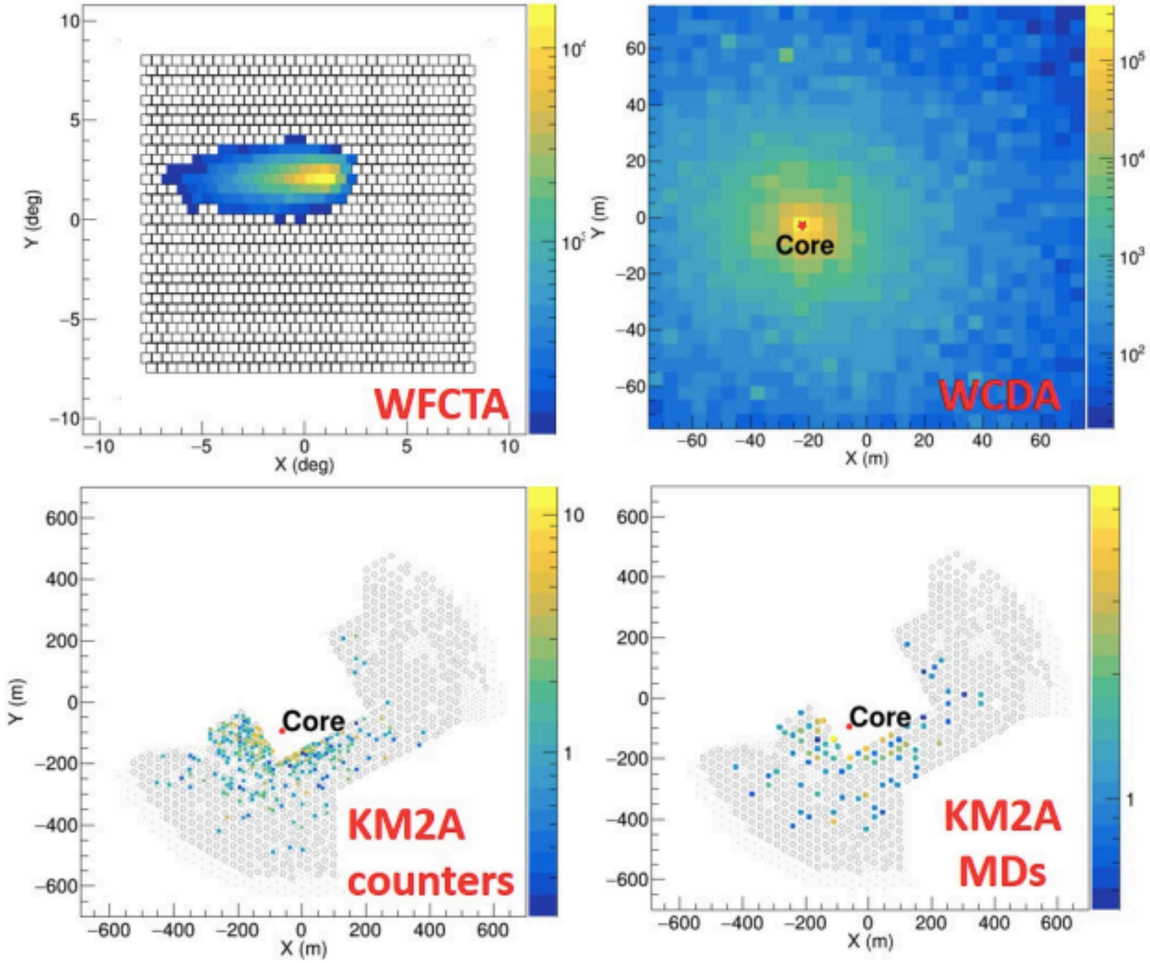
ED:
- 5195 x 1 m^2 e.m. detectors
- Plastic scintillators
- 1.3 km^2 array

[Xin-Hua et al., Chin. Phys. C 46 (2022)]



[Xin-Hua et al., Chin. Phys. C 46 (2022)]

- EAS data: Position and arrival times of charged particles, number of e.m. particles, number of muons, Cherenkov/fluorescence yield.



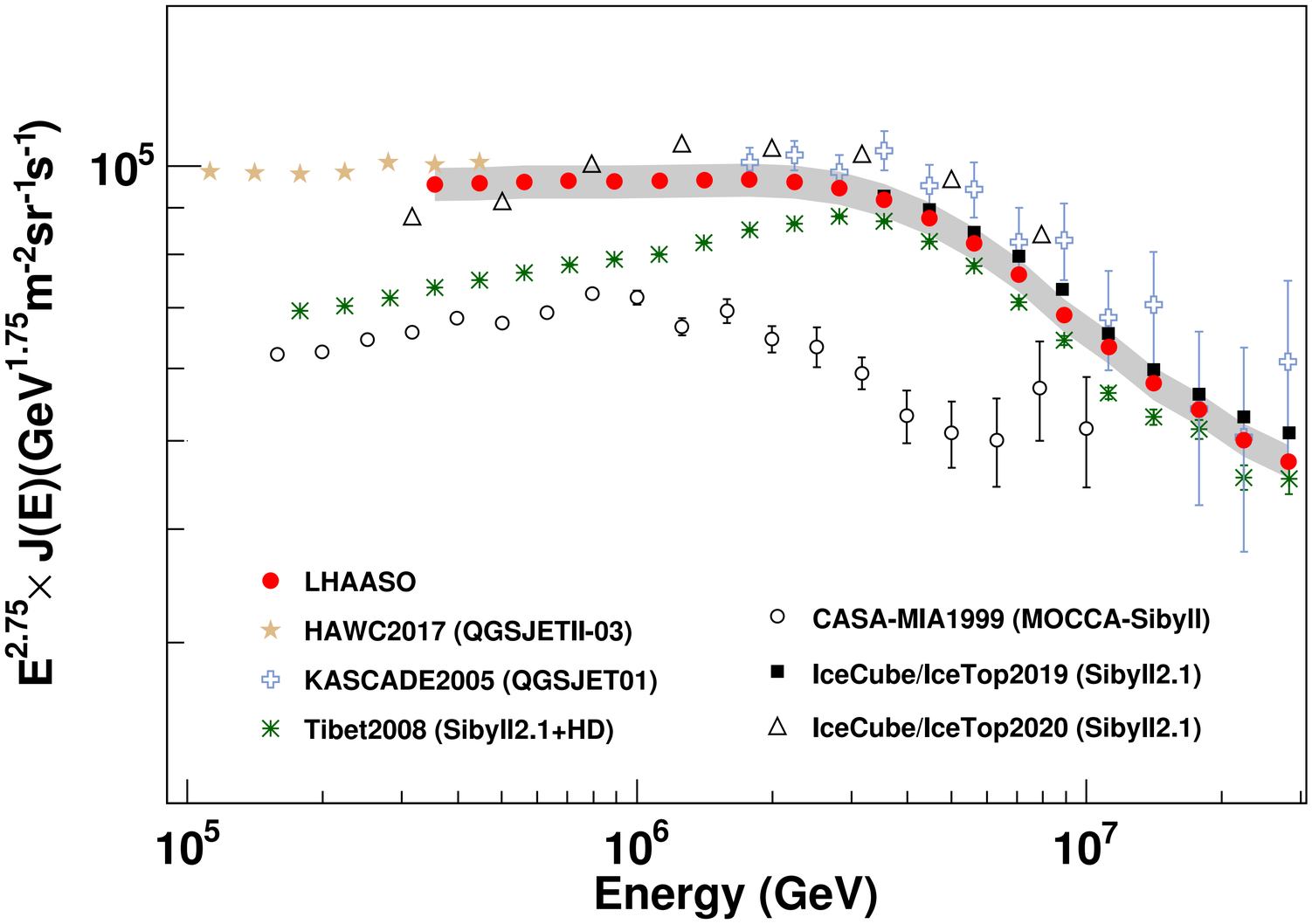
Experimental hybrid event

[Z. Cao et al., EPJ Web of Conf. 280 (2023)]

All-particle spectrum from 300 TeV to 30 PeV

[Z. Cao et al., PRL 132, 131002 (2024)]

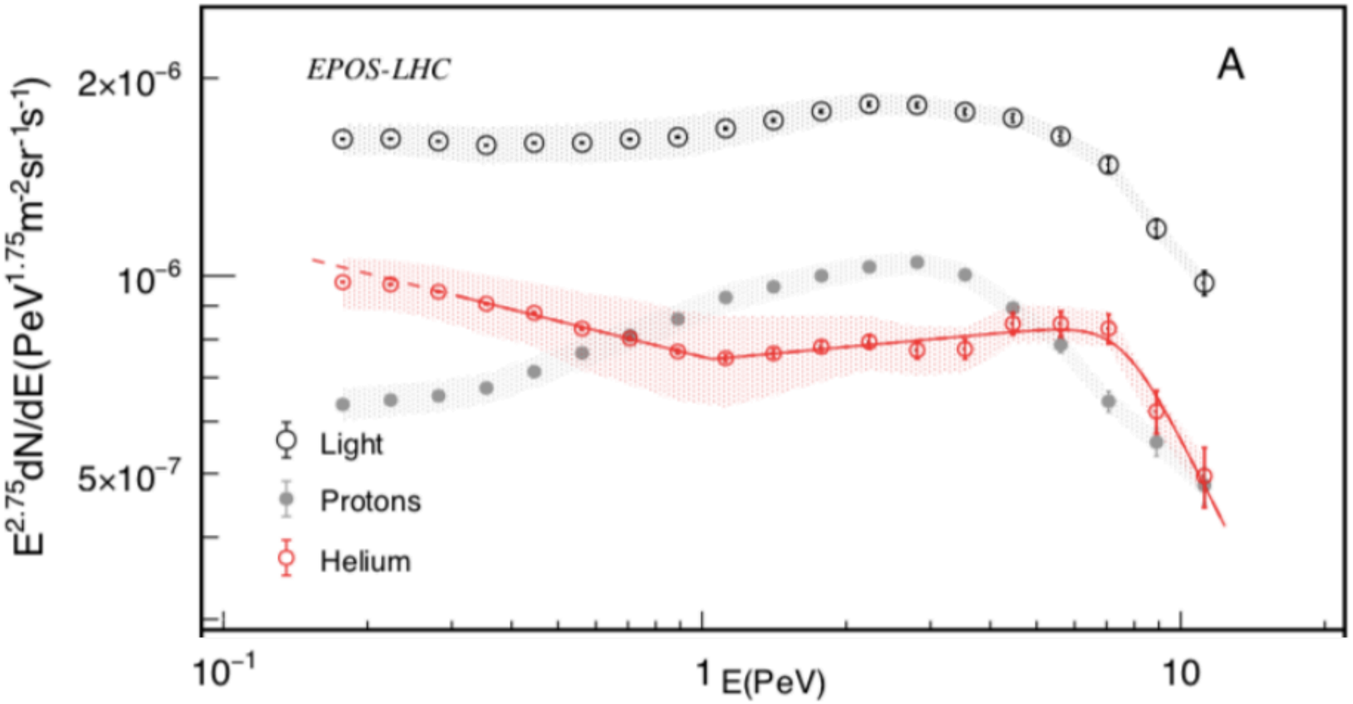
- Estimation of all-particle spectrum in the 300 TeV - 30 PeV region.
- Large statistics and high precision.
- Knee at 3.67 PeV due to a change of spectral index γ from −2.74 to −3.13.



- KM2A data. Energy from N_e and N_μ and MC simulations (mean between different post-LHC models).

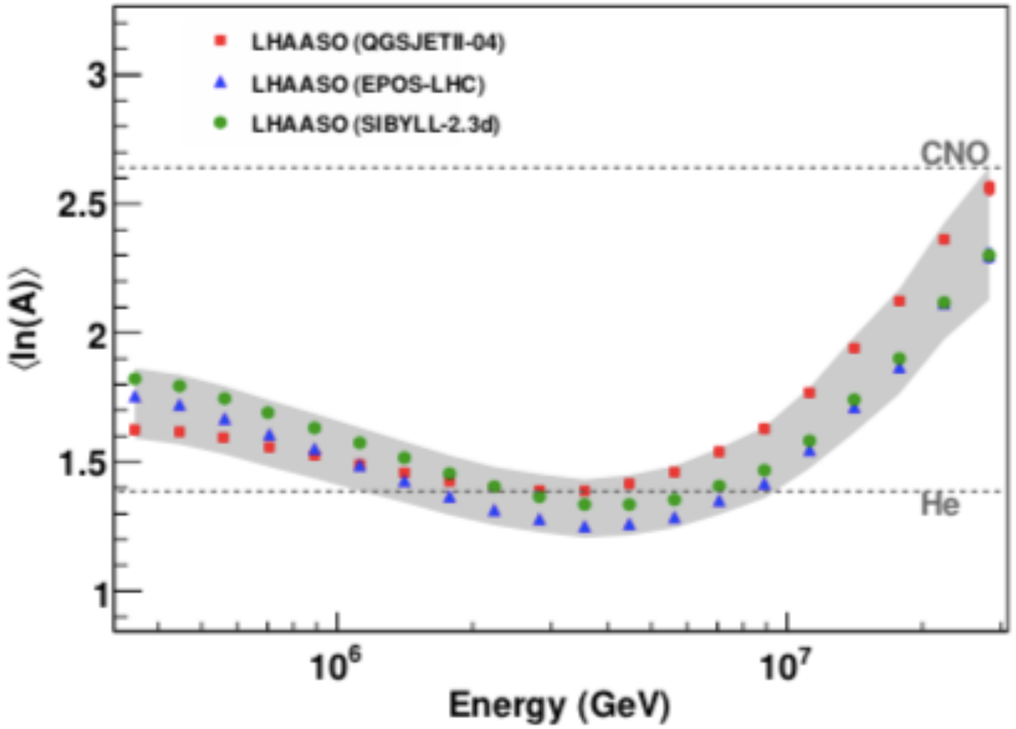
Spectrum of H, He and H+He from 160 TeV to 13 PeV

[Z. Cao et al., PRL 136, 121001 (2026)]



- H spectrum: Hardening @ 350 TeV with Δγ = 0.24
  Knee @ 3.3 PeV with Δγ = -1.00
- He spectrum: Hardening @ 1.1 PeV with Δγ = 0.25 (>12σ)
  Knee @ 7 PeV with Δγ = -1.52 (>6σ)
- KM2A and WFCTA data

[Z. Cao et al., PRL 132, 131002 (2024)]



- Knee dominated by light nuclei
- The proton knee is located at the same position of the all-particle knee.
- WFCTA: Energy calibration.
  N_e, N_μ, Cherenkov image: Mass composition

TAIGA-HiScore



Operation: Since fall 2015

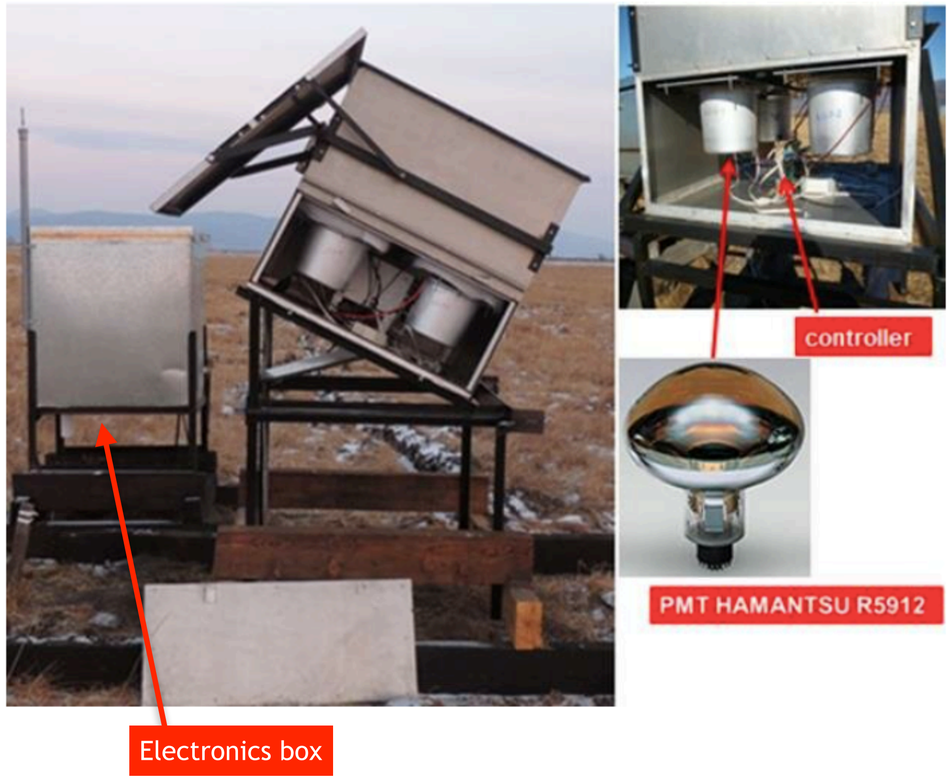
Location: Tunka Valley, **Siberia, Russia**

Altitude: 675 m a.s.l (960 g/cm^2).

CR energy range: 1 TeV - 100 PeV

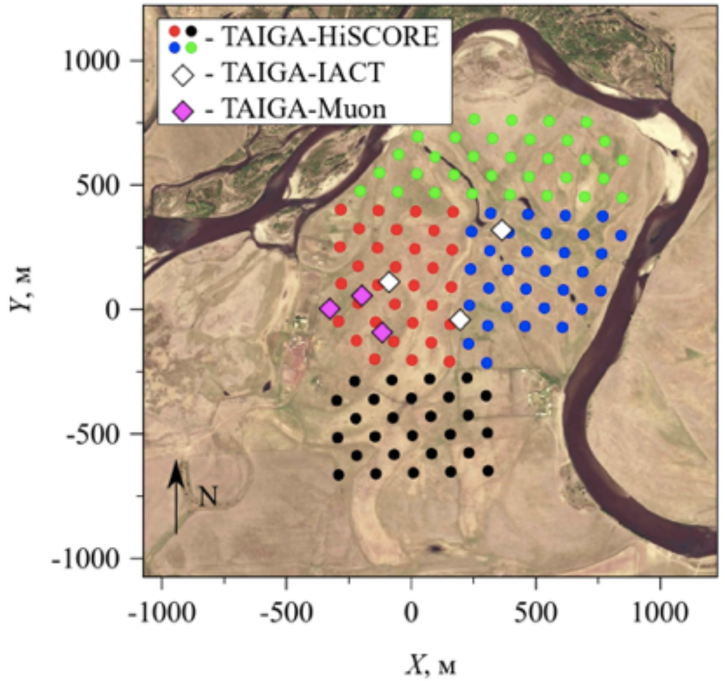
Credit:TAIGA Collab.

TAIGA-HiScore



Credit images:TAIGA Collab.

TAIGA-HiScore
- 120 wide FoV air Cherenkov detectors (non imaging)
- 4 PMTs per station
- 106 m spacing
- 1 km^2
- E > 100 TeV



IACT
- 3 Imaging atmospheric Cherenkov telescopes.
- 4.3 diameter.
- FoV 9.6^o.
- Focal length 4.75 m



[M. Y. Ternovoy et al., PoS (ICRC2025) 206]

[L. Kuzmichev et al., EPJ Web of C. 207 (2019) 03003]

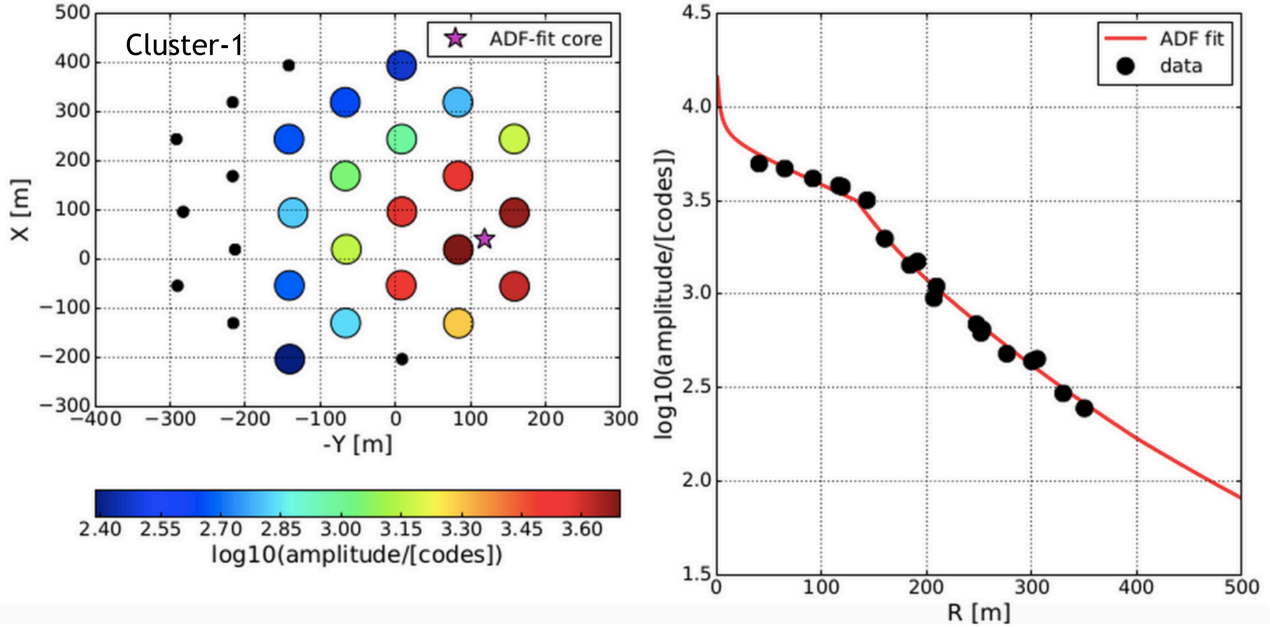
[A. [I. Ivanova et al., SciPost Phys. Proc. 13, 011 (2023)]

TAIGA-HiScore

EAS reconstruction from light pulses (amplitud, pulse area, pulse delay, duration at 0.5 amplitude, arrival times):

- Core location, (X_c, Y_c),
- Arrival direction, θ, ϕ
- Light flux density at 100 and 200 m (Q_{100} & Q_{200})
- Lateral distribution function, **Q(r)**,

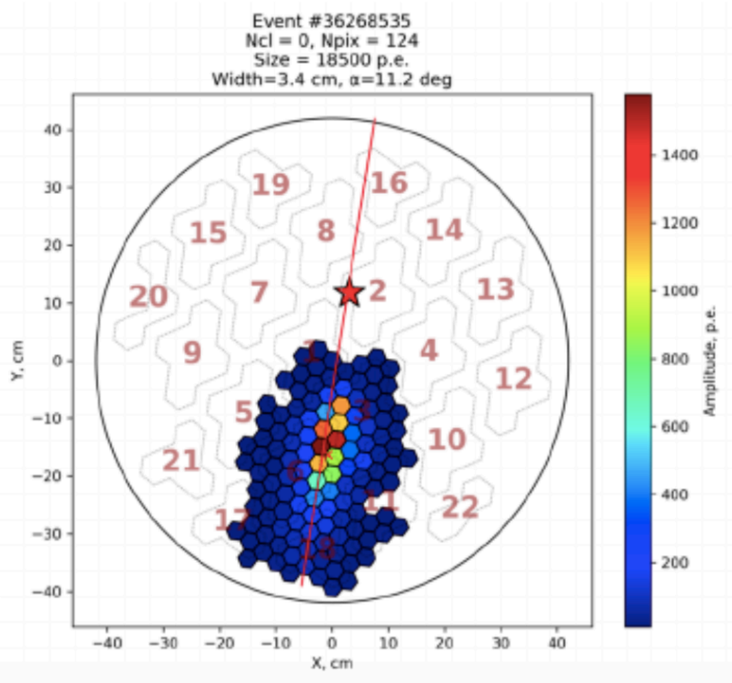
[A. Porelli et al., PoS (ICRC2021) 877]



IACT

Measure width, size (total umber of PEs) and third moment (sharpness of peak) of EAS image ellipse to study mass composition.

[L. Kuzmichev et al., EPJ Web of C. 207 (2019) 03003]



TAIGA-HiScore

Energy estimation

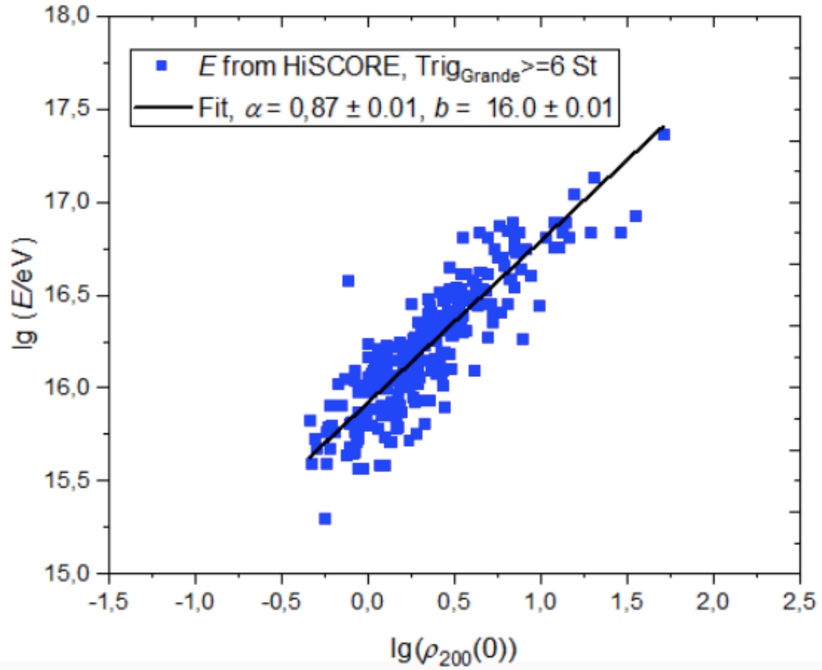
- Based on the light density flux at 100 m and 200 m @ θ = 0°.

$$\lg(E_0/\mathrm{TeV}) = 0.02105 \cdot (\lg(Q_{100}(0^\circ)) + 20.484)^2 - 6.50,$$

$$\lg(E_0/\mathrm{TeV}) = 0.01365 \cdot (\lg(Q_{200}(0^\circ)) + 34.344)^2 - 13.31.$$

- Q_{100}: E = 200 TeV - 3 PeV
- Q_{200}: E > 3 PeV

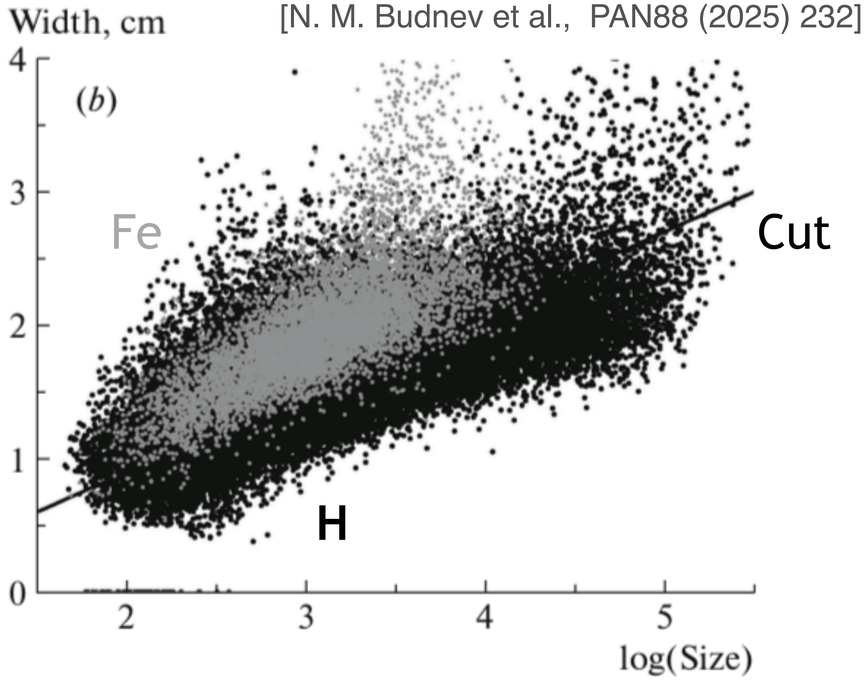
[A. Porelli et al., PoS (ICRC2021) 877]



Mass parameter:

- Use width, size and third moment of EAS image ellipse in IACT as parameters for H+He separation.
- Selection of H+He nuclei:
  Width < a + b log(Size)

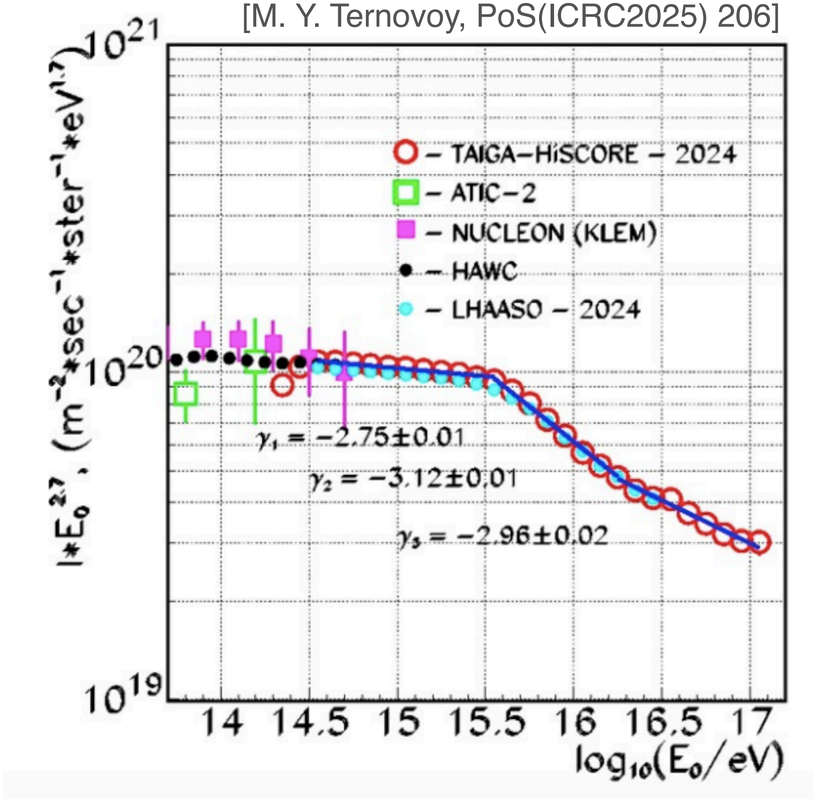
[N. M. Budnev et al., PAN88 (2025) 232]



TAIGA-HiScore

All-particle spectrum between 200 TeV and 100 PeV

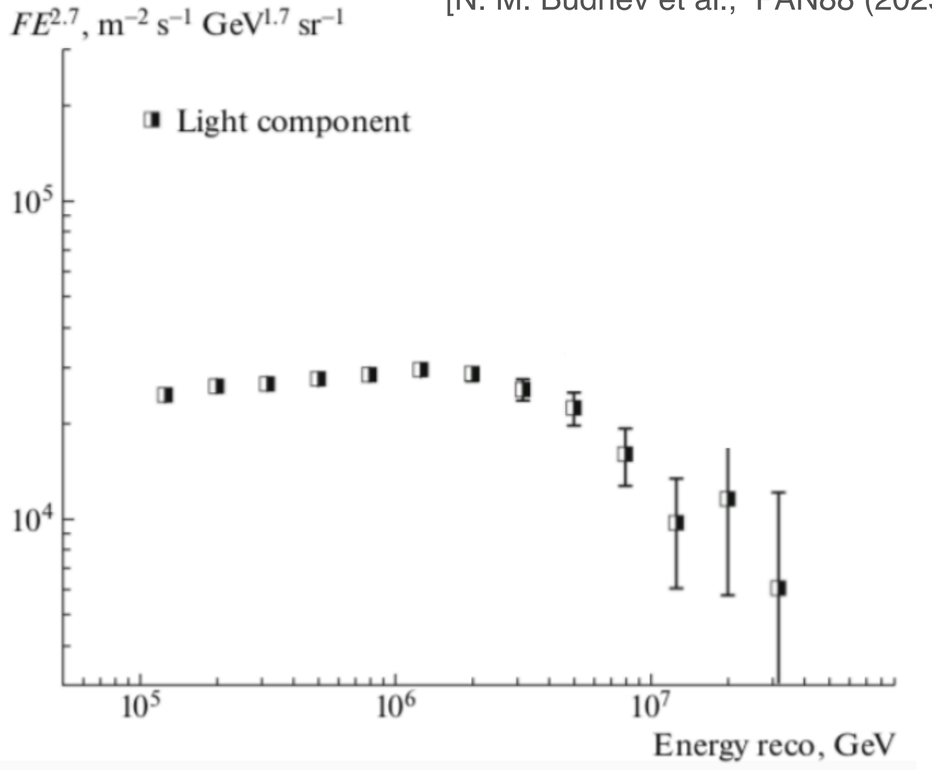
[M. Y. Ternovoy, PoS(ICRC2025) 206]



- Spectrum reaches 200 TeV.
- Knee at 3 PeV.
- Flattening at 20 PeV.

H+He spectrum between 100 TeV and 300 PeV

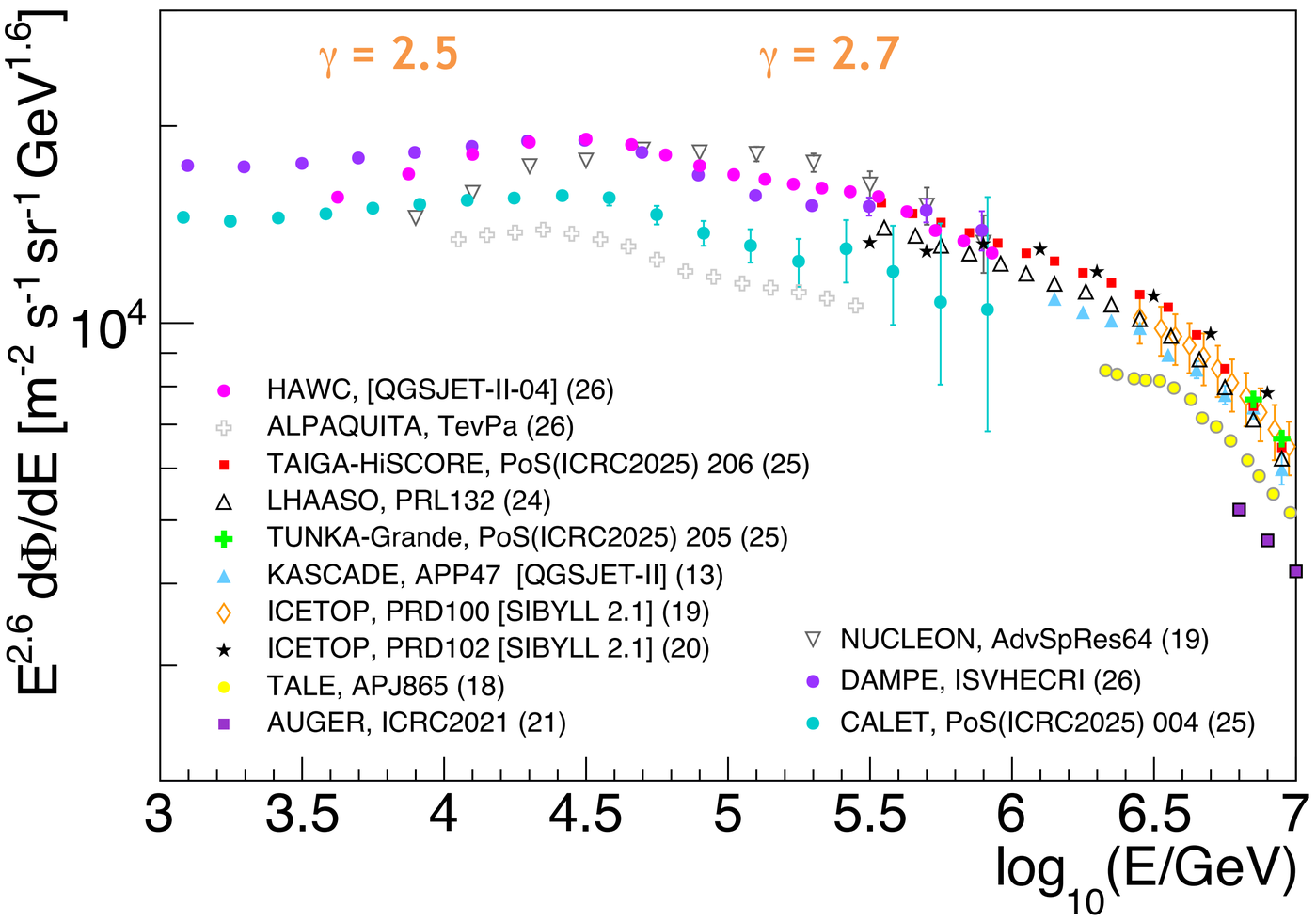
[N. M. Budnev et al., PAN88 (2025) 232]



- H+He cosmic-ray spectrum from 100 TeV.
- Observation of a knee at around 3 PeV.

4) Part 1: 1 TeV - 1 PeV

Total energy spectrum



- **Features:**
  - Steepening

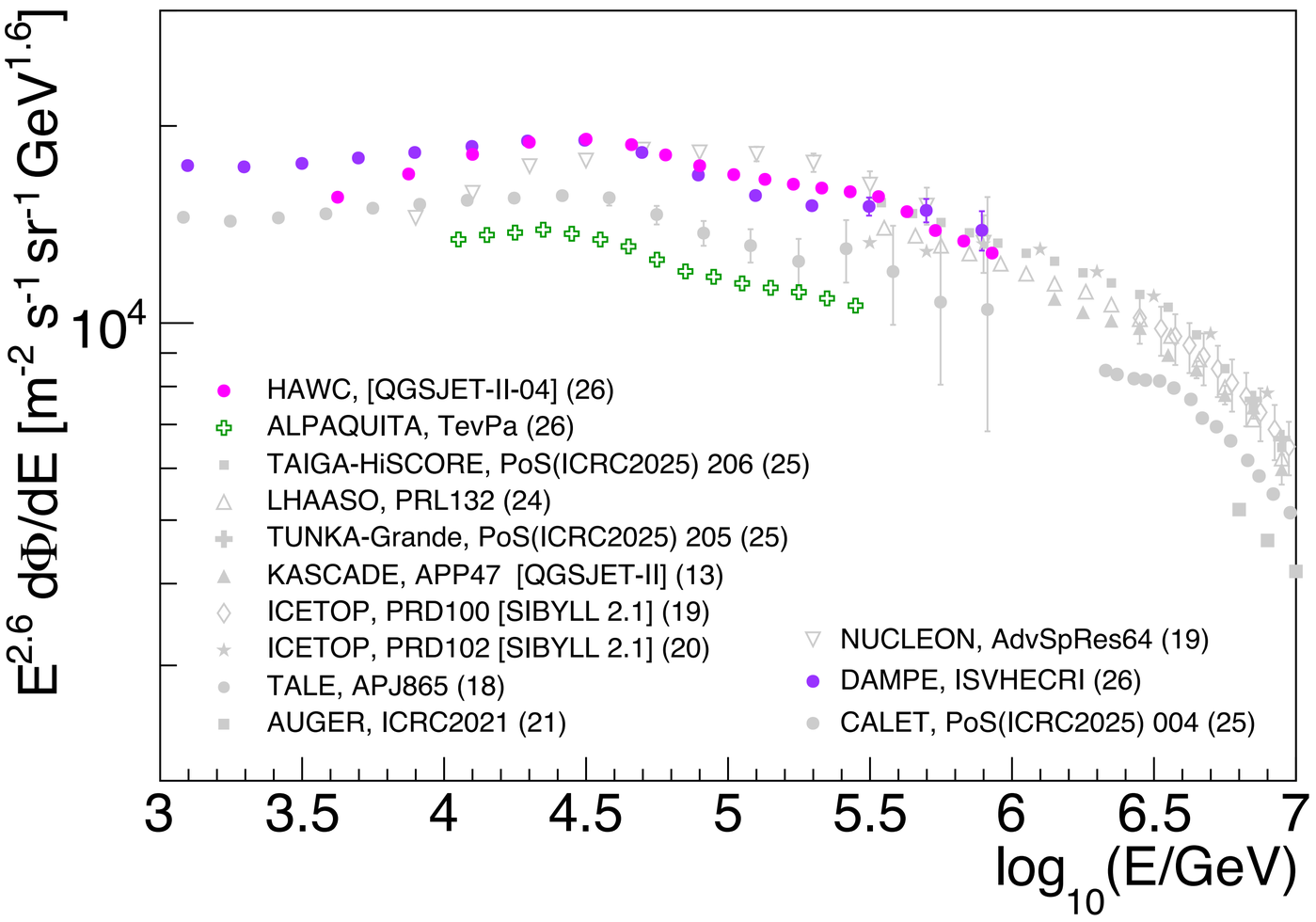
	DAMPE	CALET	HAWC	NUCLEON
E (TeV)	30	30.6	30	79

- Comparisons between direct/indirect experiments are possible between 10 TeV and 1 PeV:
  - Shape of spectra from **modern direct** and **indirect** experiments are in agreement between 10 TeV and 1 PeV.

- Difference between energy scales
  - CALET & DAMPE : **12%**
  - HAWC & CALET :**<14%**
  - HAWC & LHAASO :**< 7%**
  - TAIGA & LHAASO : **5%**
  - HAWC & Alpaquita : **21%**

4) Part 1: 1 TeV - 1 PeV

Total energy spectrum



- **Features:**
  - Hardening

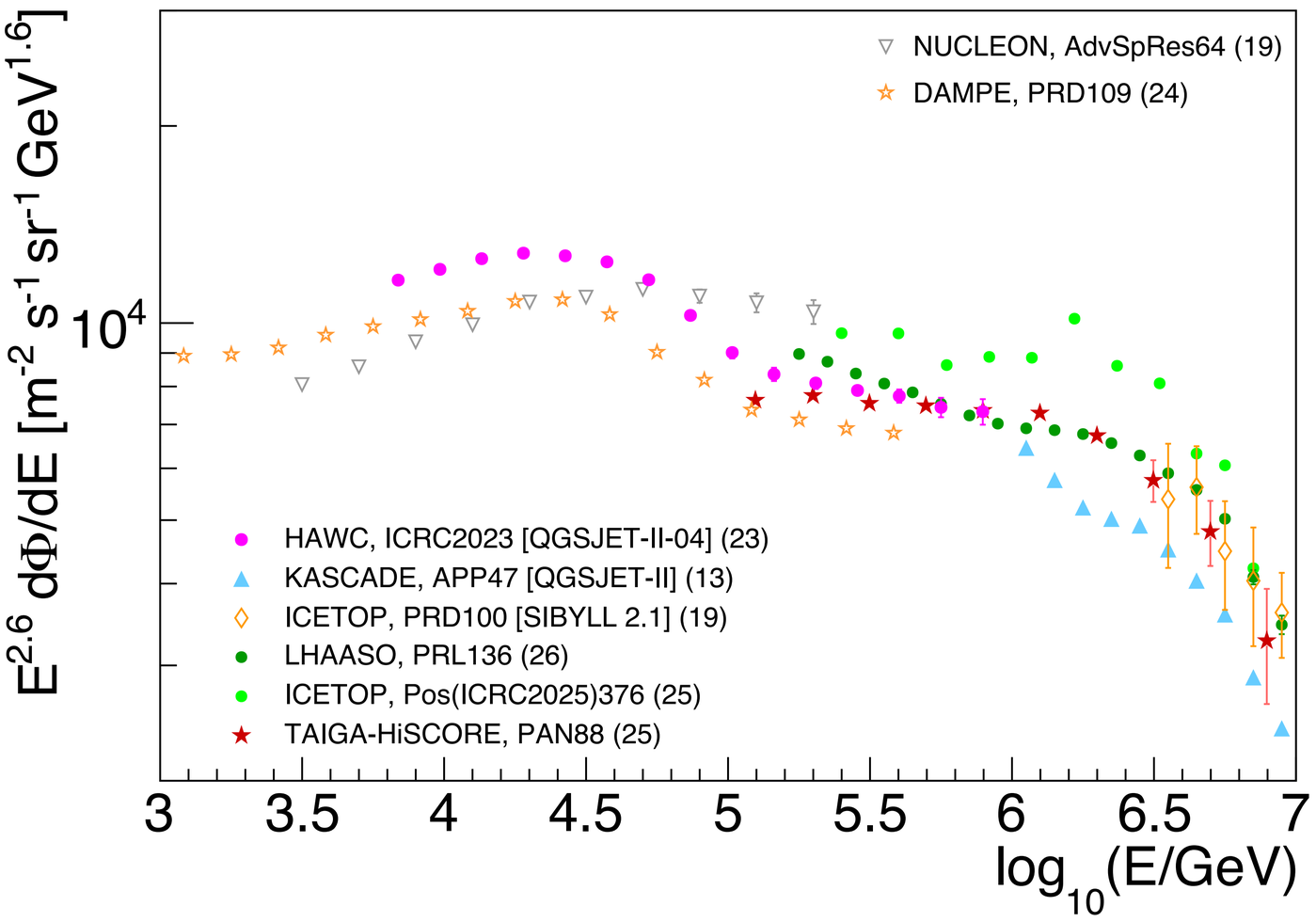
	DAMPE	HAWC	Alpaquita
E (TeV)	158	107	70

  - 2nd softening

	DAMPE	HAWC
E (TeV)	502	309

4) Part 1: 1 TeV - 1 PeV

H+He



- **Features:**
  - Softening

	DAMPE	HAWC
E (TeV)	29	51

- Both DAMPE and HAWC confirms the existence of a TeV softening in the spectrum of H+He.

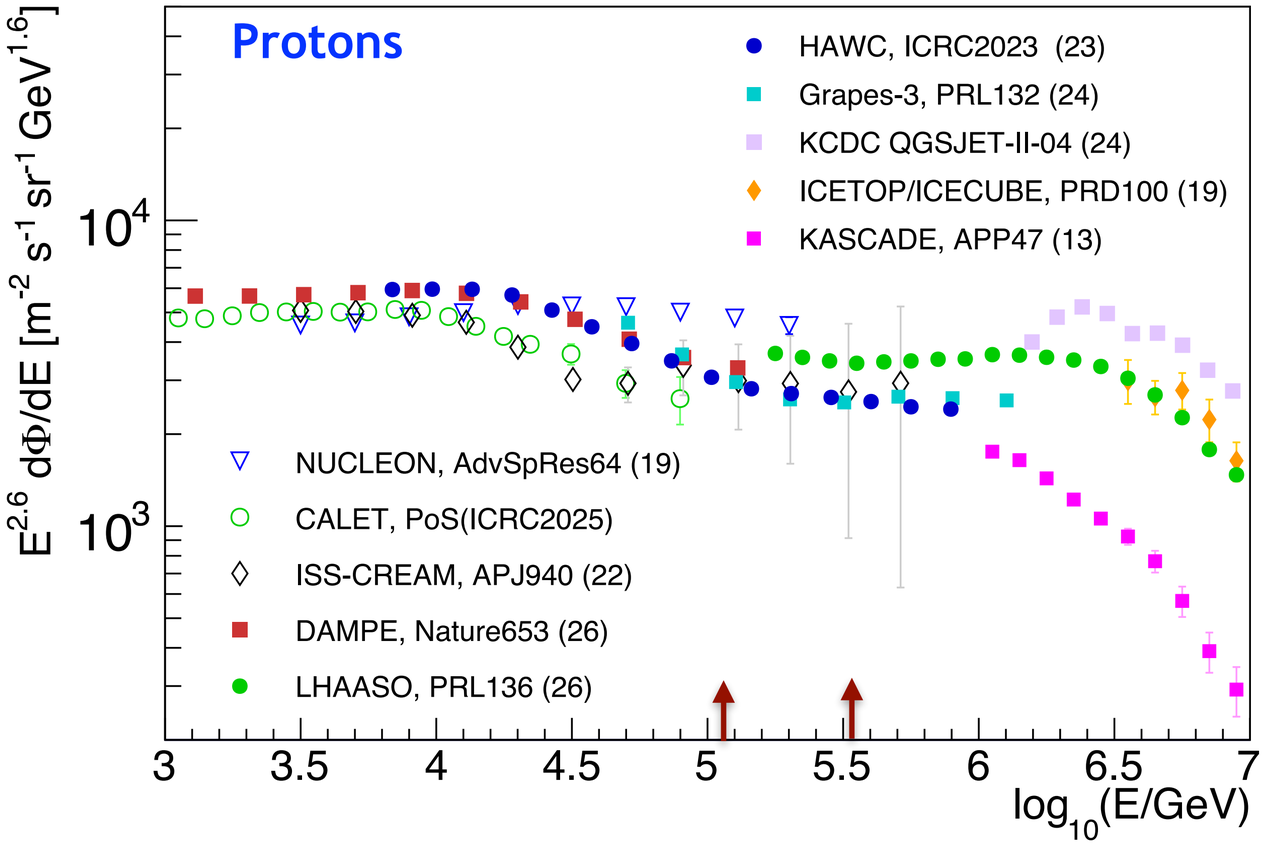
  - Hardening

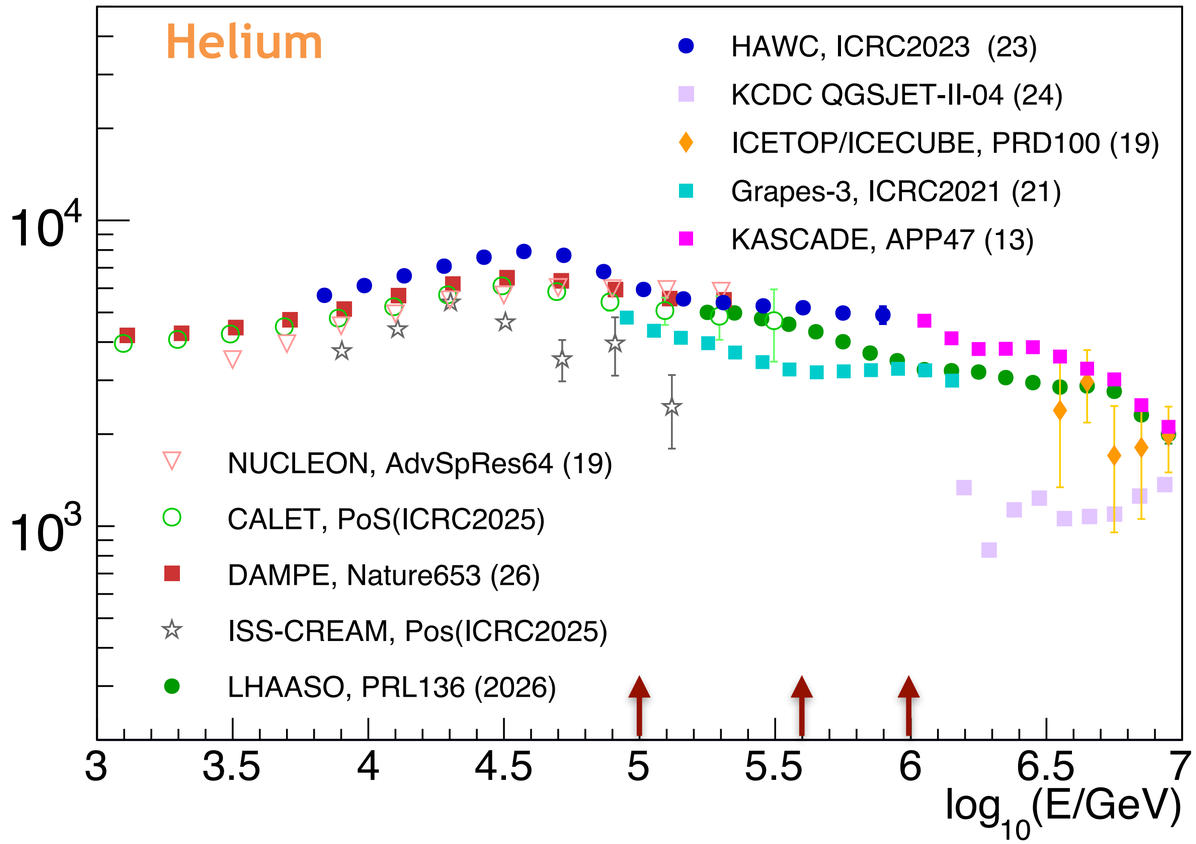
	DAMPE	HAWC	LHAASO
E (TeV)	150	90	1000

- HAWC shows the presence of a TeV hardening, while DAMPE suggest the existence of such structure.

- LHAASO also shows a hardening but at 1 PeV, in disagreement with HAWC and DAMPE. **Is this a new structure or a systematic error?**

4) Part 1: 1 TeV - 1 PeV





- **H and He spectra:** Modern direct and indirect experiments are in agreement in the TeV energy region.
- **HAWC**, **Grapes-3** and **LHAASO** report individual hardenings in spectra of H and He.

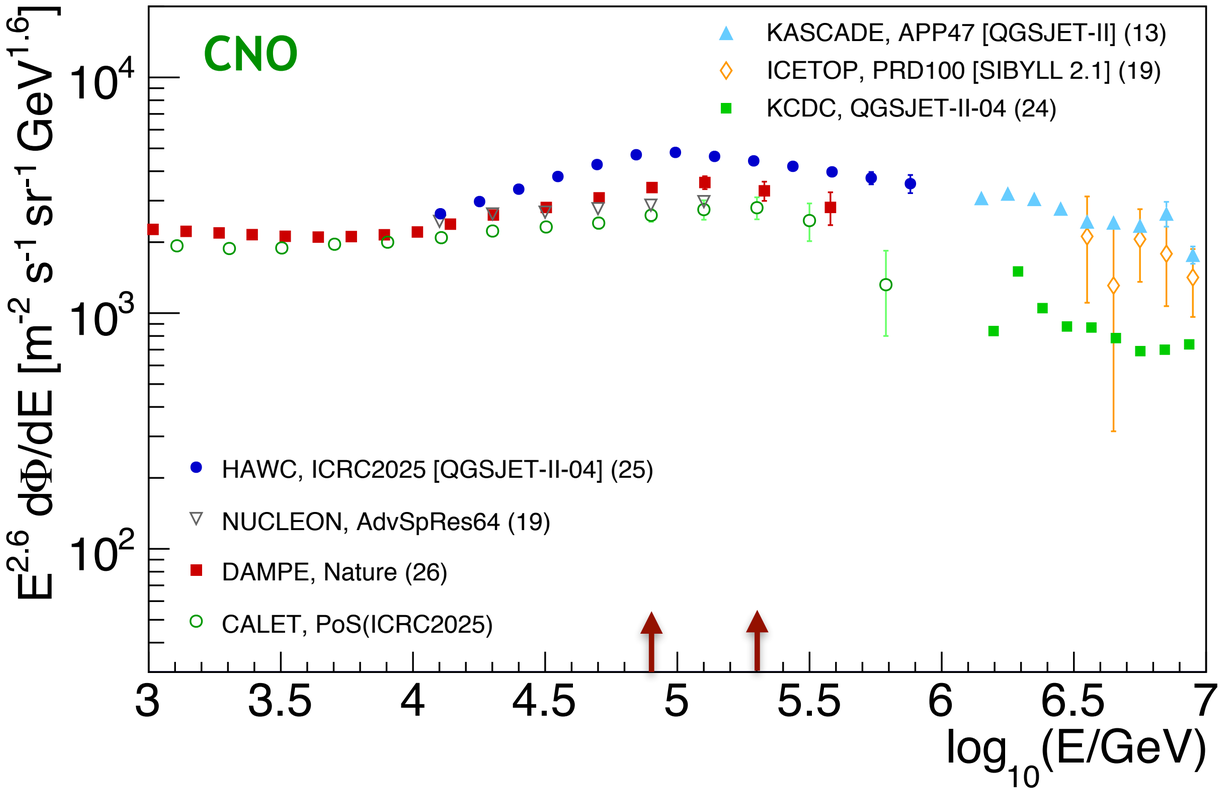
▸ **H: Hardening**

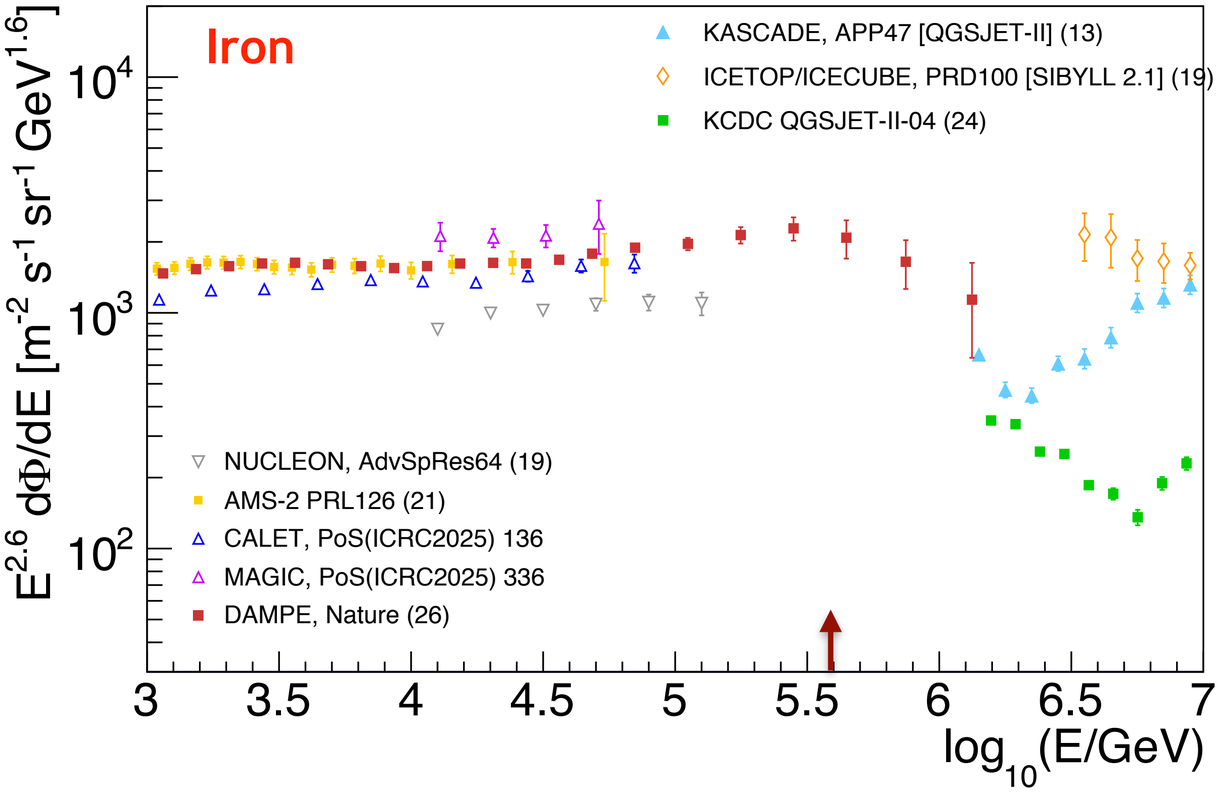
	HAWC	Grapes-3	LHAASO
E (TeV)	114	166	340

▸ **He: Hardening**

	HAWC	Grapes-3	LHAASO
E (TeV)	104	400	1100

4) Part 1: 1 TeV - 1 PeV





CNO: Softening

	HAWC	DAMPE	CALET
E (TeV)	81	134	200

Fe: Hardening

	DAMPE
E (TeV)	390

4) Part 1: 1 TeV - 1 PeV

Interpretations of TeV cosmic-ray data

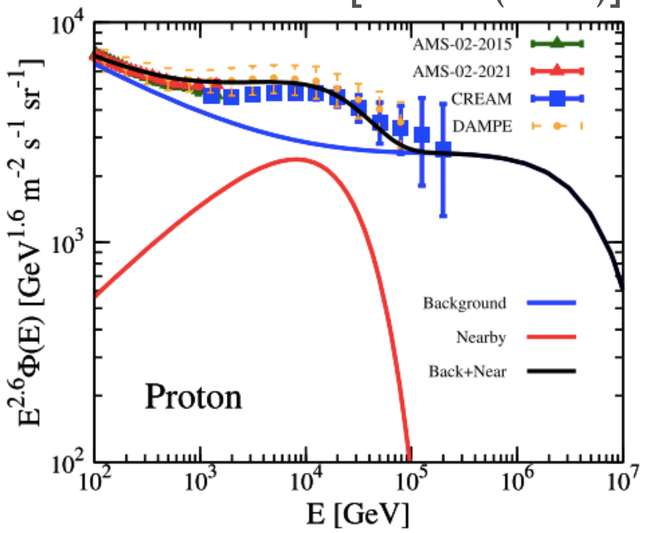
1. Nearby TeV source (d ≤ 500 pc) + Background of PeV CR accelerators

- SNR, Rcut = $\mathcal{O}$(10 TeV), 2 - 3 Myr old, d = 100-200 pc,
  [V. Savchenko et al., APJL809 (15); Kachelriess et al., PRD97 (18)]
- Geminga-like SNR, 340 kyr old, d = 250 - 330 pc
  [DAMPE, Nature (26); P.P. Zhang et al., ApJ 940 (22); C. Yue et al., FP15 (20); W. Liu et al., JCAP10 (19)]

2. New population of TeV sources + Background of PeV CR accelerators

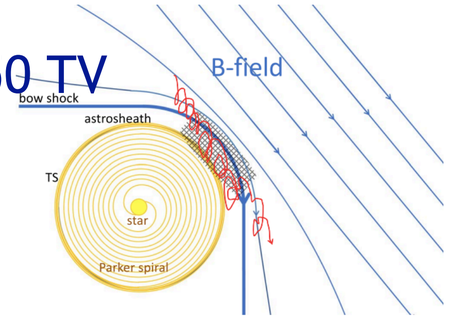
- SNR, Rcut = $\mathcal{O}$(10 TeV), 80-98.48% of majority of SNR
  [S. Recchia et al., A&A692 (24); G. Giacinti et al. (23); C. Yue et al., FP15 (20); V.I. Zatsepin et al., A&A458 (06)]

[W. Liu (2019)]



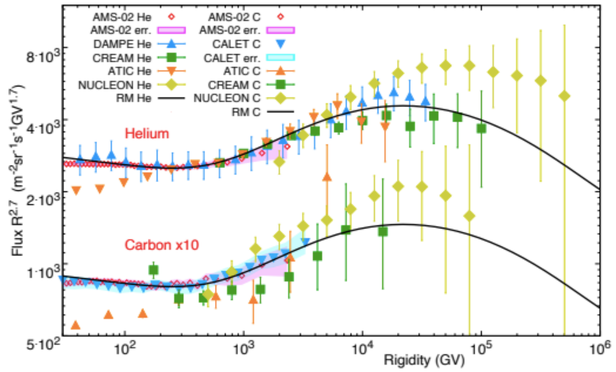
3. Reacceleration in local shock (D = 3- 10 pc)

- Reacceleration of sea of galactic cosmic rays with R < 50 TV
- ε-Eridani (d = 3.2 pc).
  [W.A. Malkov et al., ApJ911 (21); ApJ 933 (22)]



[M.A. Malkov (2022)]

[M.A. Malkov (2022)]



4. Additional effects at source

- Acceleration in reverse shocks.
- P in Type II SNR and A/Z = 2 nuclei in Type I SNR.
  [V. Ptuskin et al., ApJ763 (13)]

Part 2: 1 PeV - 1 EeV

The KASCADE-Grande experiment

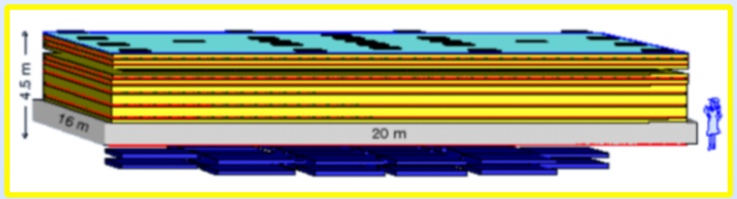
Operation: 1996-2013

Location: Karlsruhe, Germany

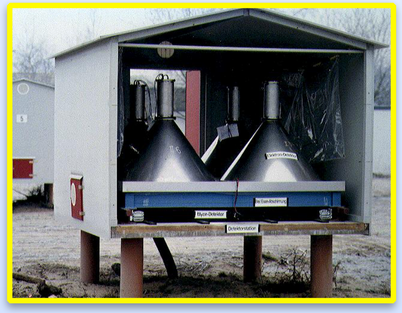
Altitude: 110 m a.s.l. (1022 g/cm²)

CR energy range: 1 PeV - 100 PeV

See also Donghwa's presentation.



Calorimeter
- 320 m² x 4.5 m
- Lead/Fe absorbers/concrete
- Liquid ionization chambers



Scintillation stations
- 60 e/γ stations
- 192 e/γ + μ stations
- μ detectors with 10 cm Pb/4 cm Fe shielding



Muon tracking detector
- Towers of streamer tubes
- 128 m²
- Under Fe plates and sand

KASCADE array:
252 scintillation stations
13 m spacing
200 m x 200 m (40,000 m²)
[T Antoni et al., NIMA 513 (2003)]

Credit: KASCADE-Grande Collab.

The KASCADE-Grande experiment

Operation: 2003 - 2013

CR energy range: 1 PeV - 1 EeV

[W. D. Apel et al., NIMA620 (2010)]



LOPES
- 403- 74 MHz
- 30 dipole antennas
- Distance: 140 m

KASCADE

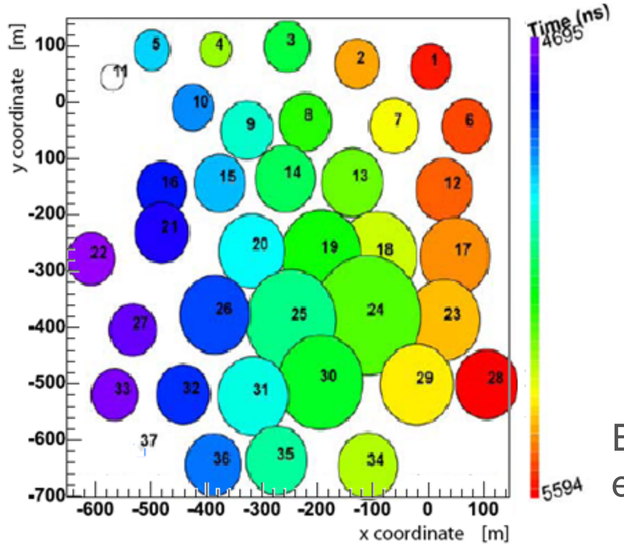
Grande array
- 700 m x 700 m (0.5 km²)
- Plastic scintillating stations
- 37x10 m² detectors
- 140 m separation



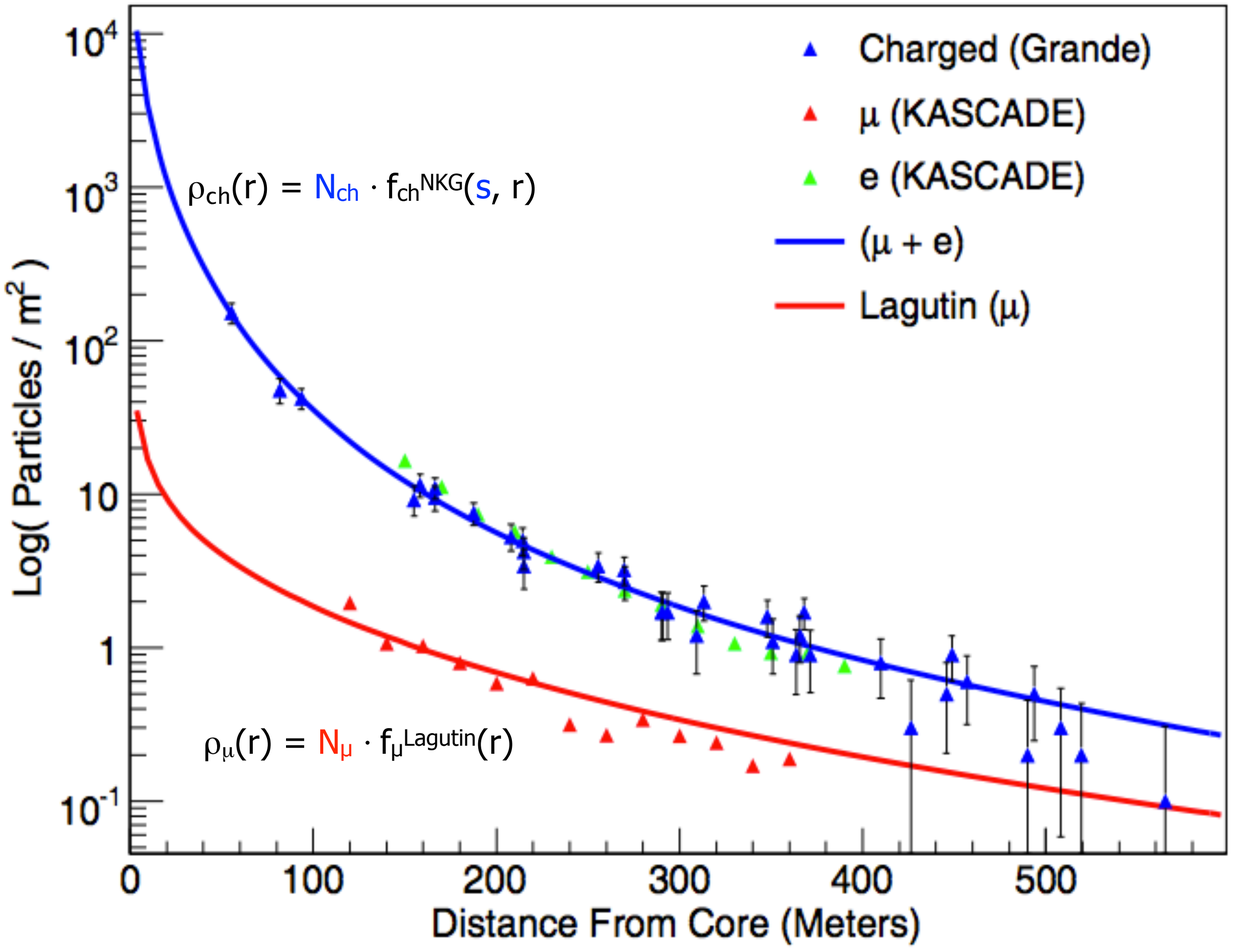
Credit: KASCADE-Grande Collab.

The KASCADE-Grande experiment

Credit: KASCADE-Grande Collab.



Experimental event



- EAS data: Arrival times of EAS particles, number of muons, electrons and charged particles, # stations with signal, ΣE_h, H_μ, η.

- Mass sensitive parameter: $N\mu$.

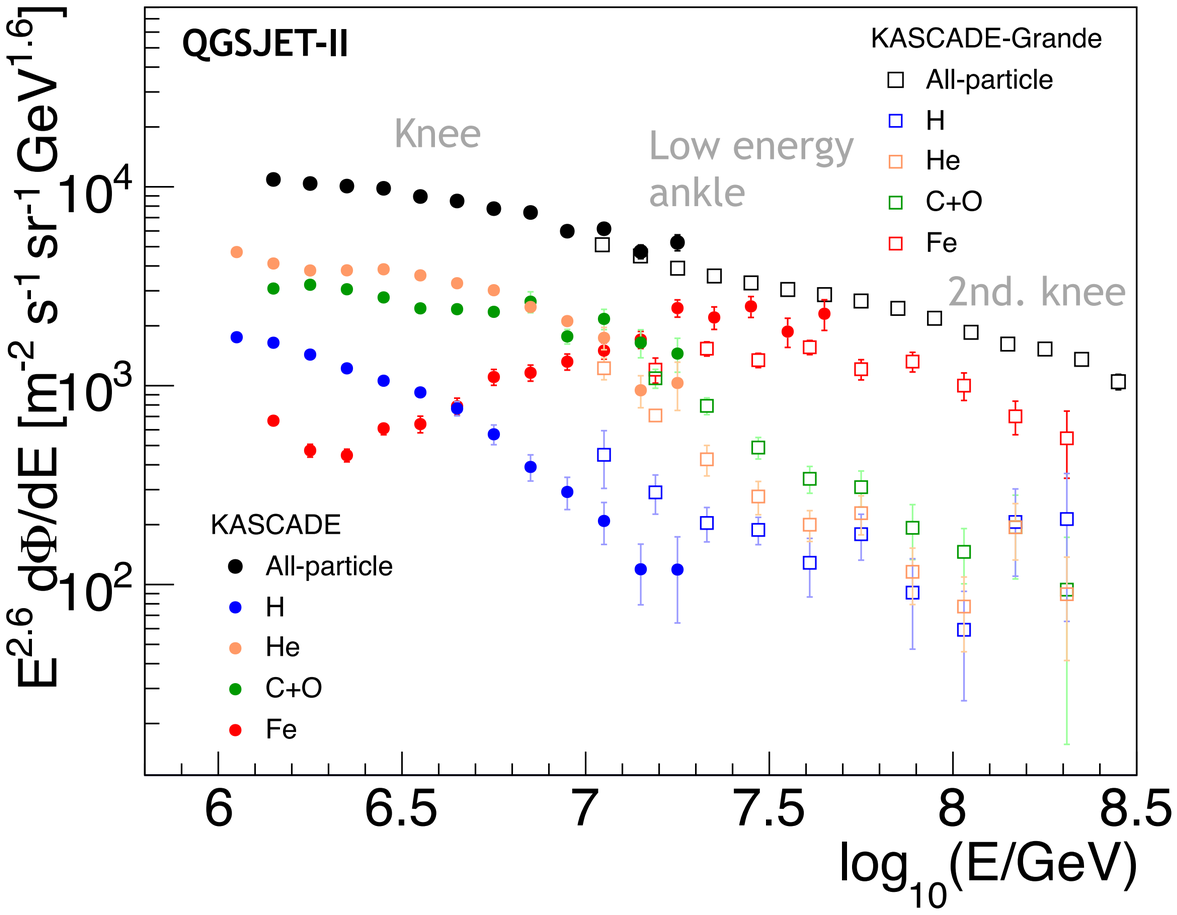
[W. D. Apel et al., NIMA620 (2010)]

The KASCADE-Grande experiment

Elemental spectra from 1 PeV to 1 EeV

[W.D. Apel et al., App 47 (2013) 54]

[W.D. Apel, Astrop. Phys. 36 (2012) 183]



- KASCADE data : N_e - N_μ (E< 100 PeV)
- KASCADE-Grande data: N_{ch} - N_μ (E > 10 PeV)

- Unfolding of elemental spectra of cosmic rays.
- Observation of individual cut-offs in elemental spectra.

Z	Cut-off (10^{15}eV)
H (Z = 1)	4
He (Z = 2)	7
C (Z = 6)	20
Fe (Z = 26)	80

- Position of individual cut-offs: $E^Z_{knee} \approx Z\ E^H_{knee}$

  ⇨ **Supports a rigidity dependent scenario.**

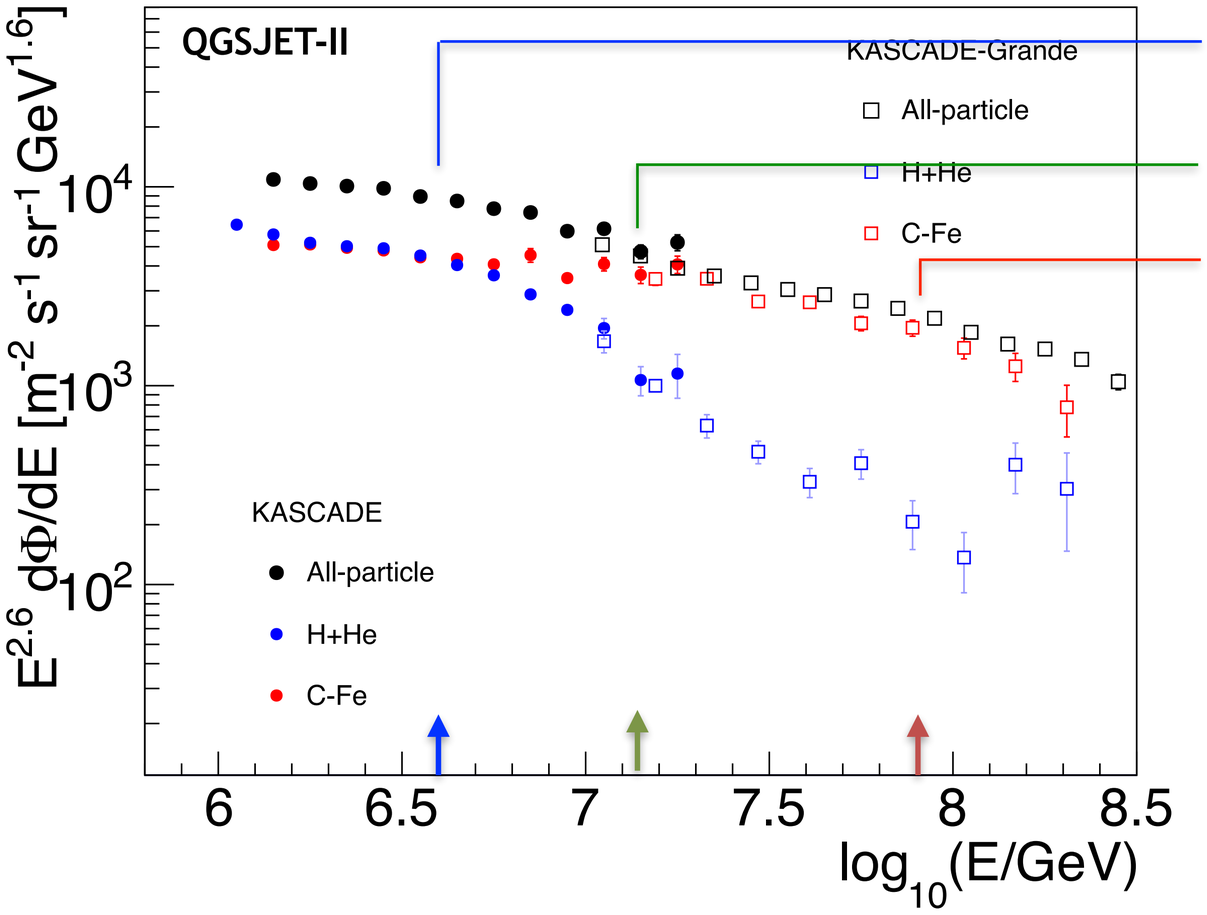
  ⇨ **Confinement losses in magnetic field of source or galaxy.**

The KASCADE-Grande experiment

Elemental spectra from 1 PeV to 1 EeV

[W.D. Apel et al., App 47 (2013) 54]

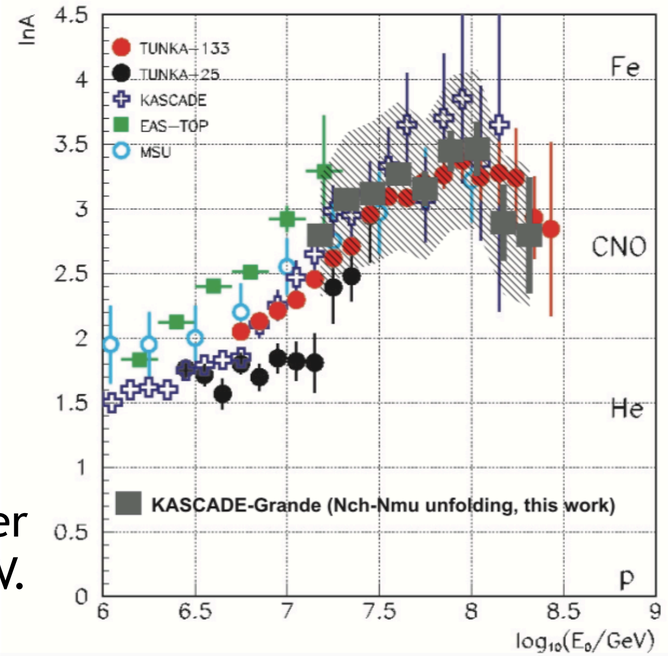
[W.D. Apel, Astrop. Phys. 36 (2012) 183]



- KASCADE data : N_e - N_μ (E< 100 PeV)
- KASCADE-Grande data: N_{ch} - N_μ (E > 10 PeV)

- **Knee** in total spectrum is due to individual **cut-offs in** spectra of **light (H and He) nuclei**.
- **LE ankle** is due to a transition between **light** and **heavy** nuclei.
- **2nd Knee** is produced by **a break in** spectrum of **heavy nuclei**.

Composition becomes heavier up to 100 PeV.

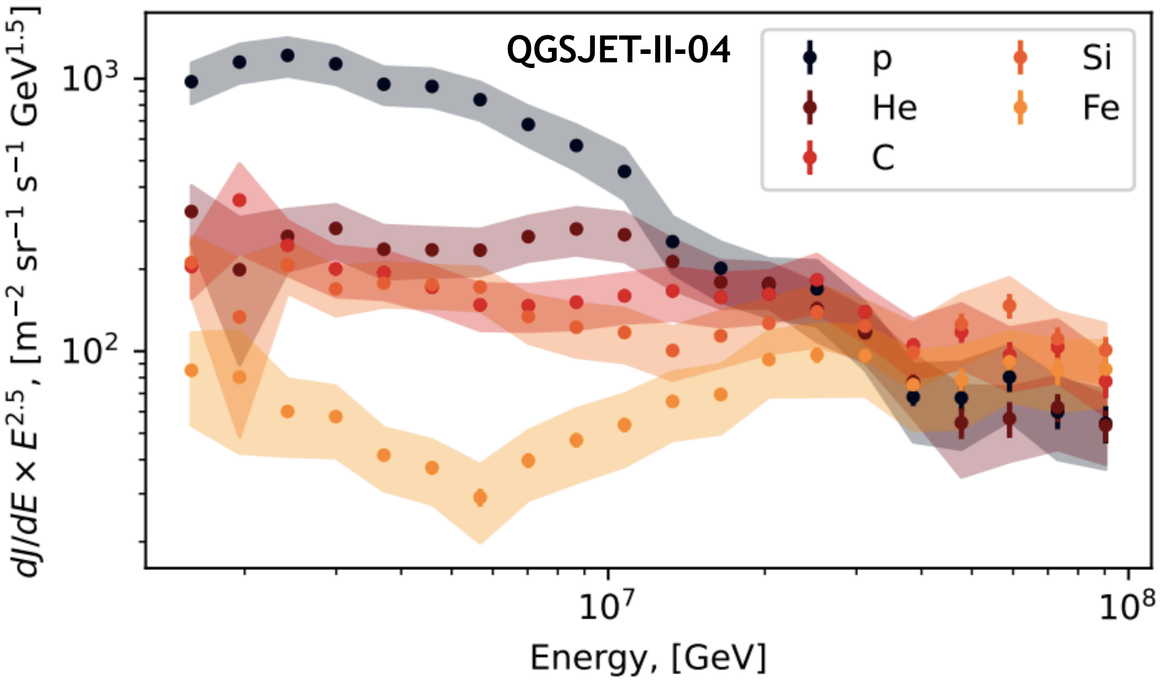


[Tunka-133 Coll., Proc. 32nd ICRC, (2011)]

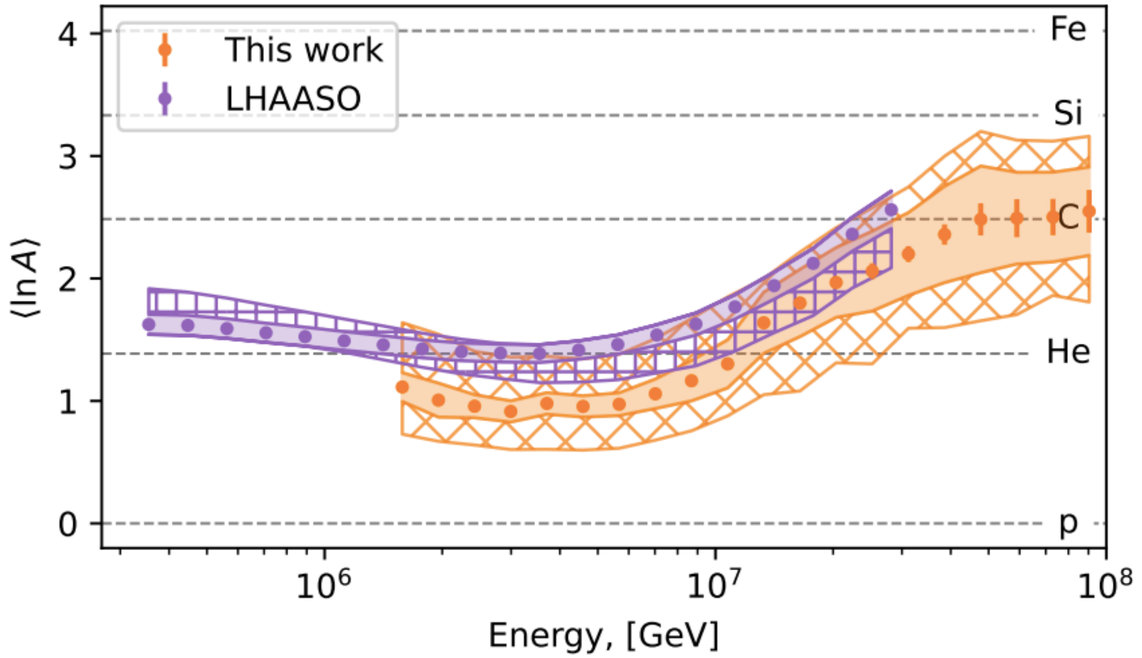
The KASCADE-Grande experiment

Elemental spectra from 1 to 100 PeV

[M. Y. Kuznetsov et al., JCAP 05 (2024) 125]



- H cut-off @ 4.4 PeV (5.2σ).
- He cut-off @ 11 PeV (3.9σ).
- Fe hardening @ 4.5 PeV, which could be a counterpart of the hardening at 100 TeV for protons.



- <lnA> from KASCADE-Grane is in agreement with results of LHAASO, ICETOP and TALE.

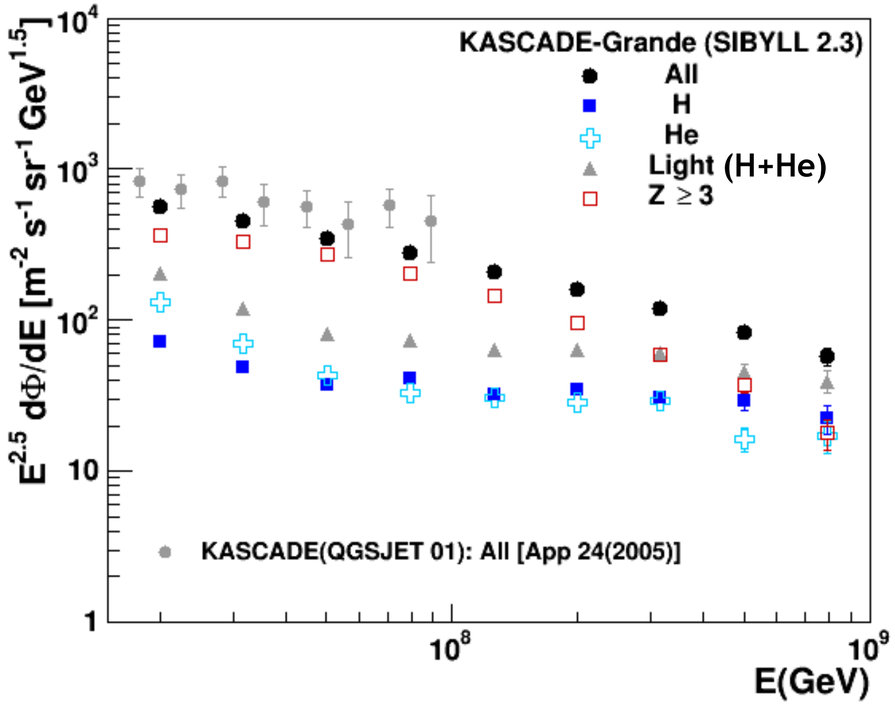
Analysis with KCDC data:
https://kcdc.iap.kit.edu/

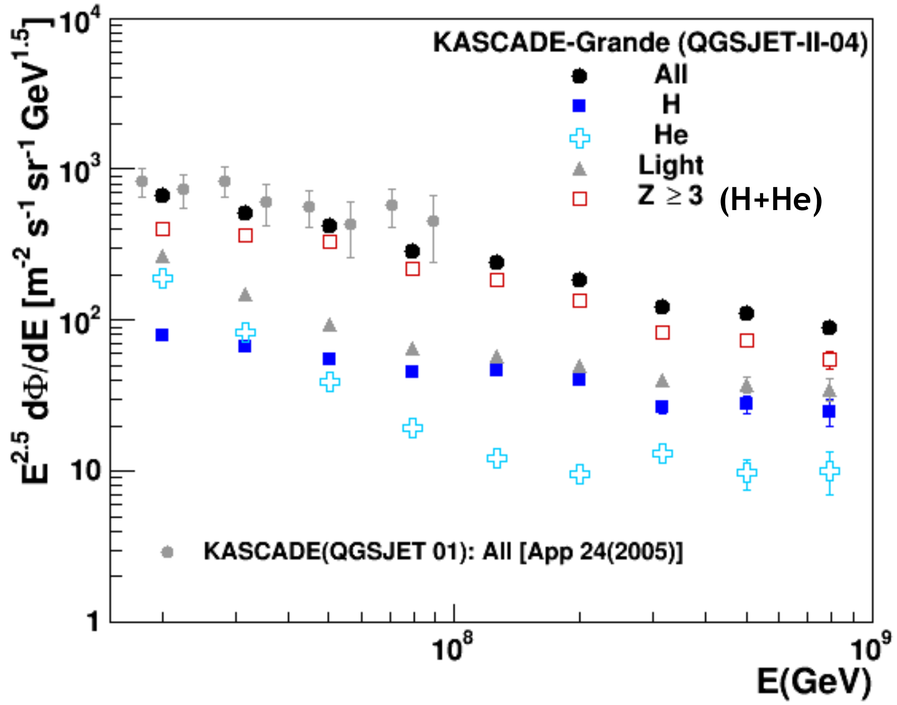
- KASCADE data: N_e, N_μ , zenith, e.m. and muon deposits.

The KASCADE-Grande experiment

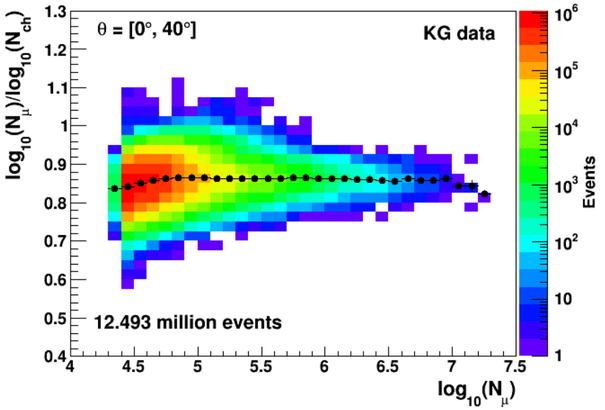
H, He and Heavy spectra from 10 PeV to 1 EeV

[J.C. Arteaga et al., EPJ Web Conf. 208 (2019)]

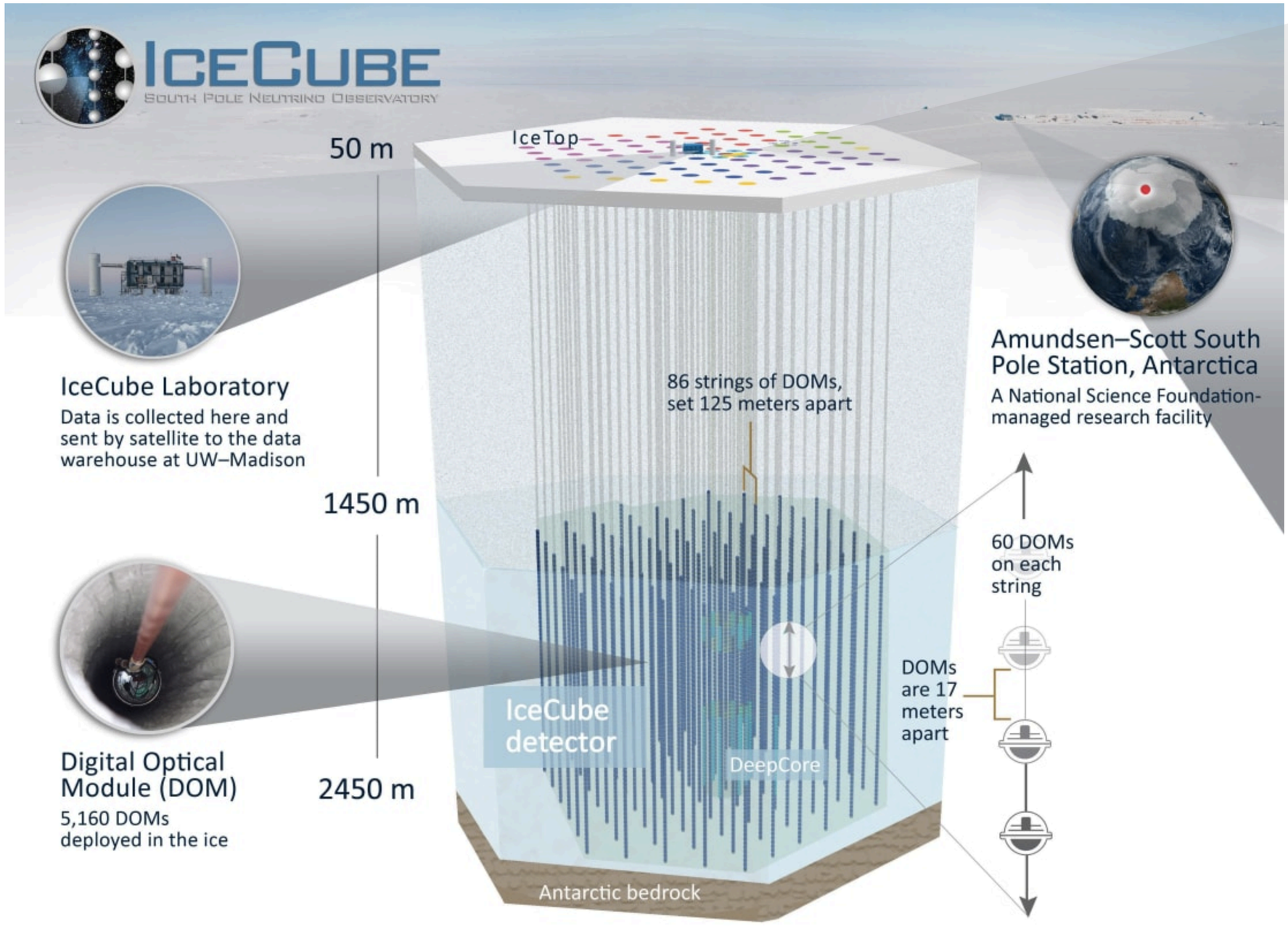


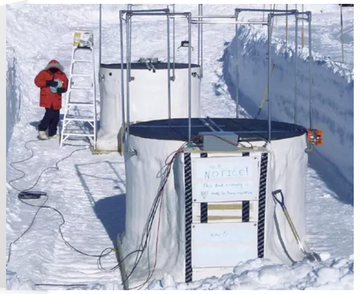


- Elemental spectra from fits to $lg(N_\mu)/lg(N_{ch})$ vs $lg(N_\mu)$ distributions.



- Preliminary analyses show that there seems to exist **hardenings** in individual spectra of H and He between 10 PeV and 100 PeV.
- H+He spectrum seems to have an important fraction of protons for E = 100 PeV - 1 EeV.





IceTop array

- 1 km^2 surface detector
- 81 pairs of ice Cherenkov tanks
- 2 DOMs/tank
- 77 pairs, 125 m spacing (main array)
- 4 pairs, < 50 m spacing (Infill array)

[Icecube Coll., PoS(ICRC2023) 342]

[Icecube Coll., NIMA 700(2013)]

Operation: Since 2010 (final config.)

Location: South Pole

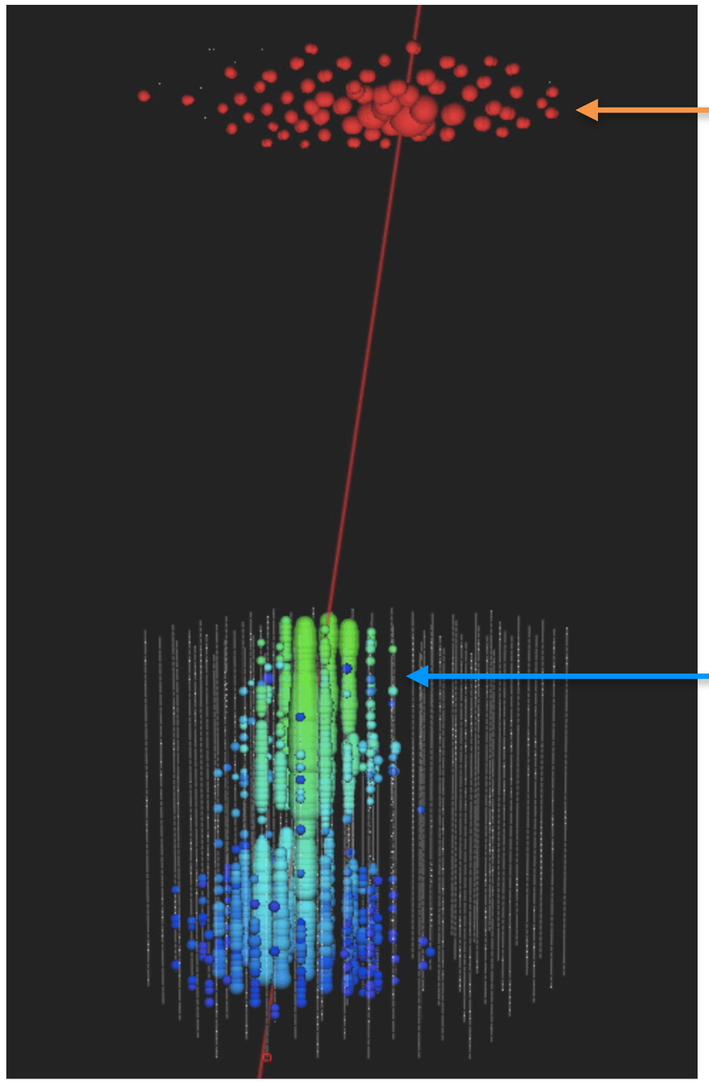
Altitude: 2835 m a.s.l. (680 g/cm^2)

CR energy range: 250 TeV - 1 EeV

Credit: ICECUBE Collaboration

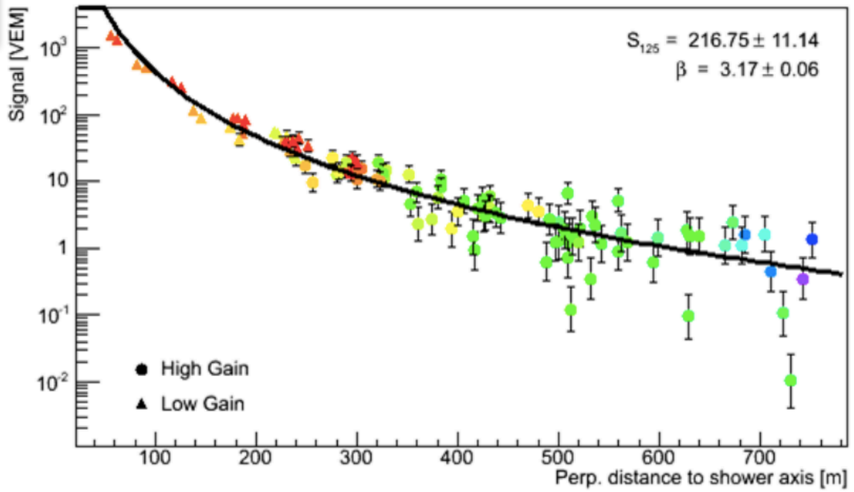
ICECUBE NEUTRINO OBSERVATORY

Credit: ICECUBE Collaboration



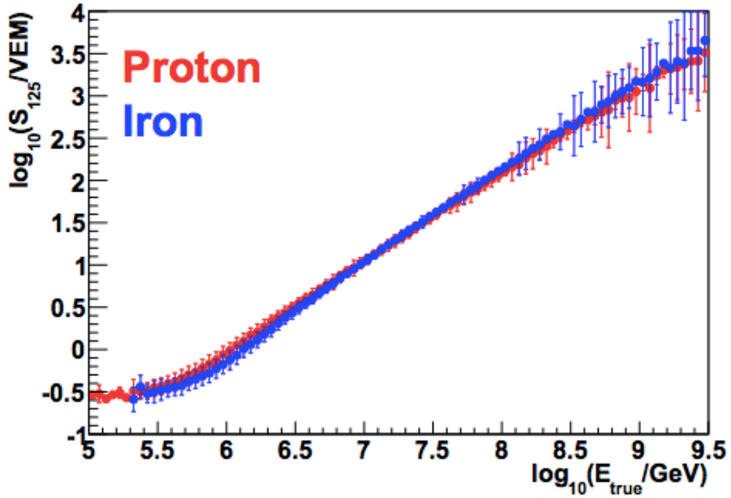
- IceTop data: Arrival times of EAS particles, deposited charge.

$$S = S_{125} \cdot \left(\frac{r}{125\,m}\right)^{-\beta-\kappa\log_{10}\left(\frac{r}{125\,m}\right)},$$

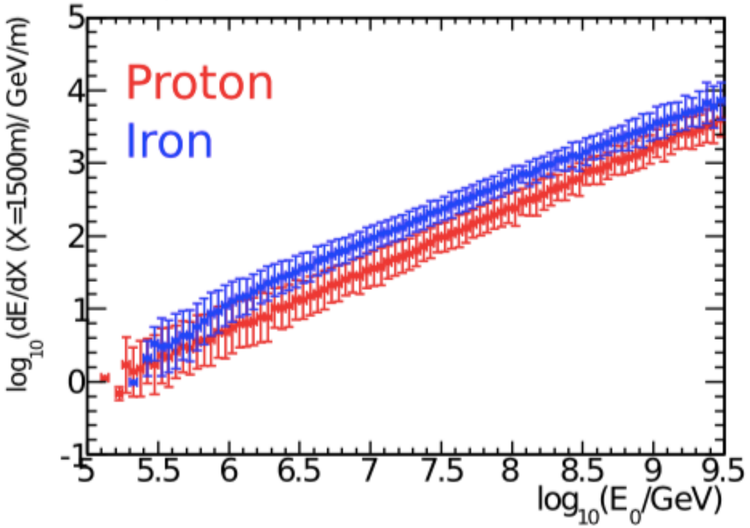


- InIce EAS data: Mean energy loss of HE muon bundles (<dE_μ/dX>), # deviations from the mean (stochastics).

- Energy estimator: S_{125} expected signal at r = 125 m (Small mass dependence).



- Mass sensitive parameters: <dE_μ/dX>, stochastics.



[Icecube Coll., PRD 100 (2019)]

(Icecube Coll., arXiv:1301.6619 **[astro-ph.HE]**)

[Icecube Coll., J. Phys.: Conf. Ser. 718 (2016)]

All-particle energy spectrum

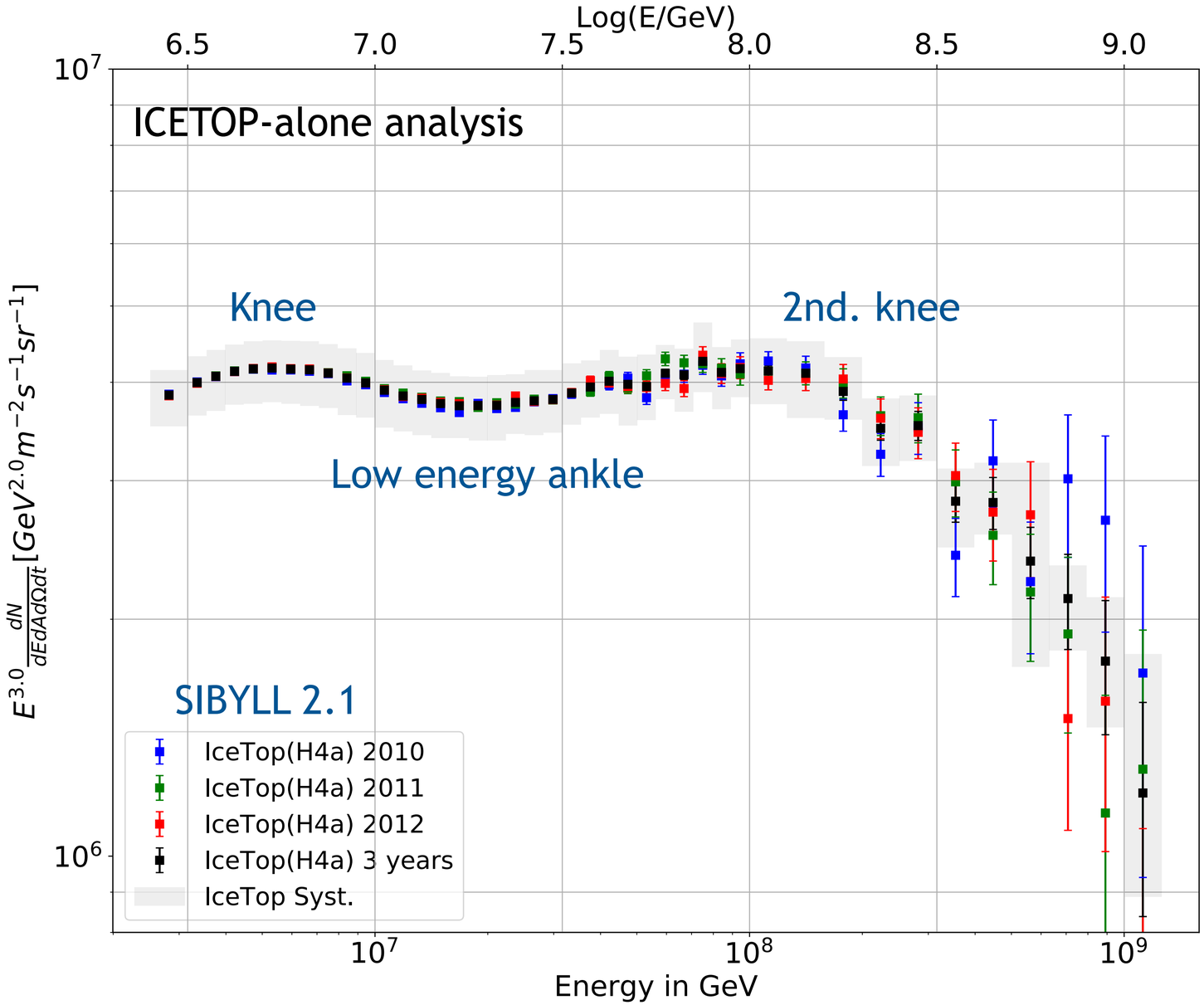
ICETOP-alone analysis

- Unfolding S_{125} distribution.
- Assuming H4a CR composition model.

- Measurements over almost 3 decades of energy.

- Observation of the knee, low energy ankle and 2nd knee.

[Icecube Coll., PRD 100 (2019)]



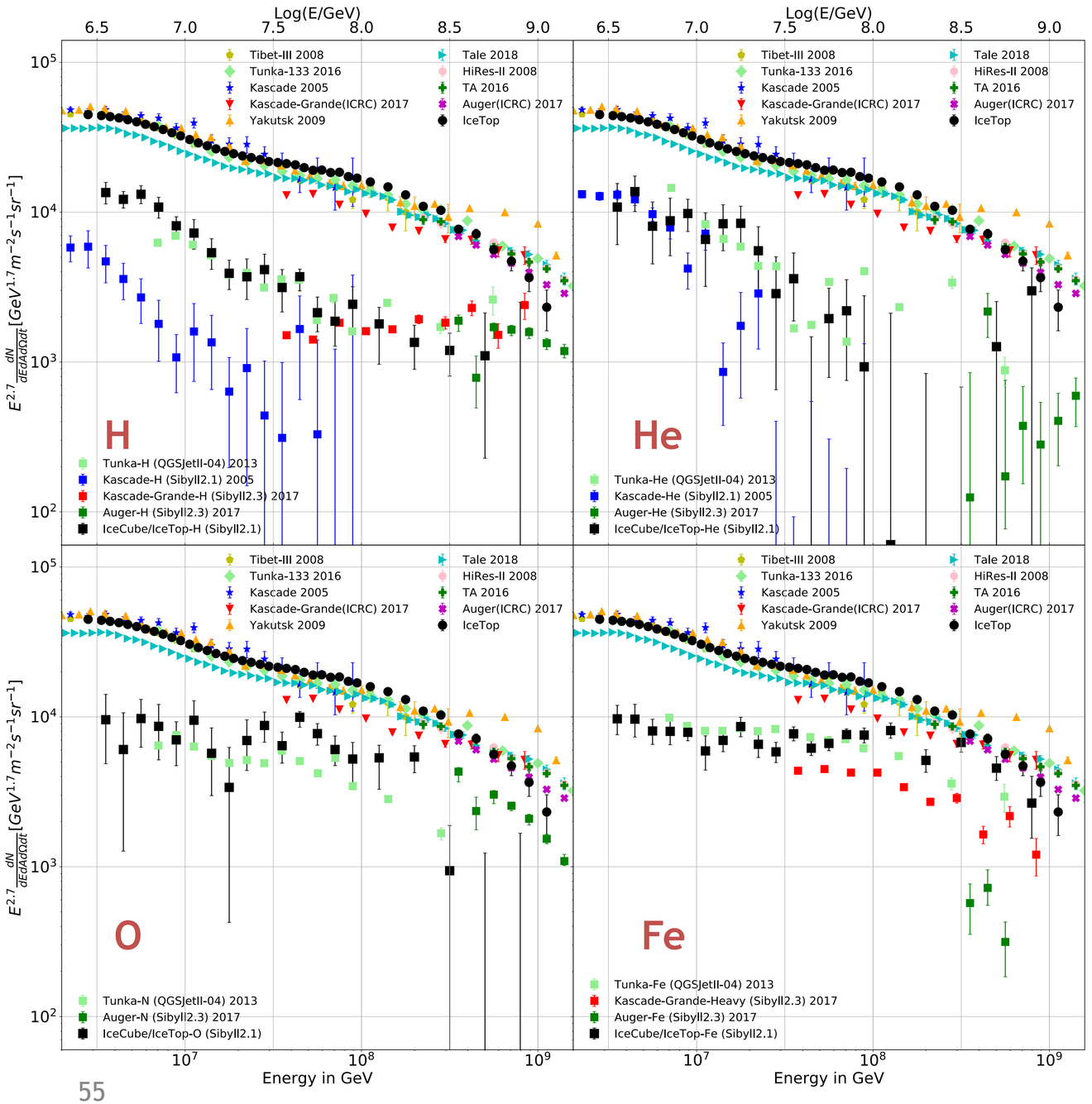
Elemental energy spectra

ICETOP/ICECUBE-combined analysis

- Neural network approach to estimate Mass and E.
- lg(S_{125}), <dE_μ/dX>, stochastics, zenith.

- Separation of H, He, O and Fe groups.
- Larger Fe intensity at HE than data from other experiments.

[Icecube Coll., PRD 100 (2019)]



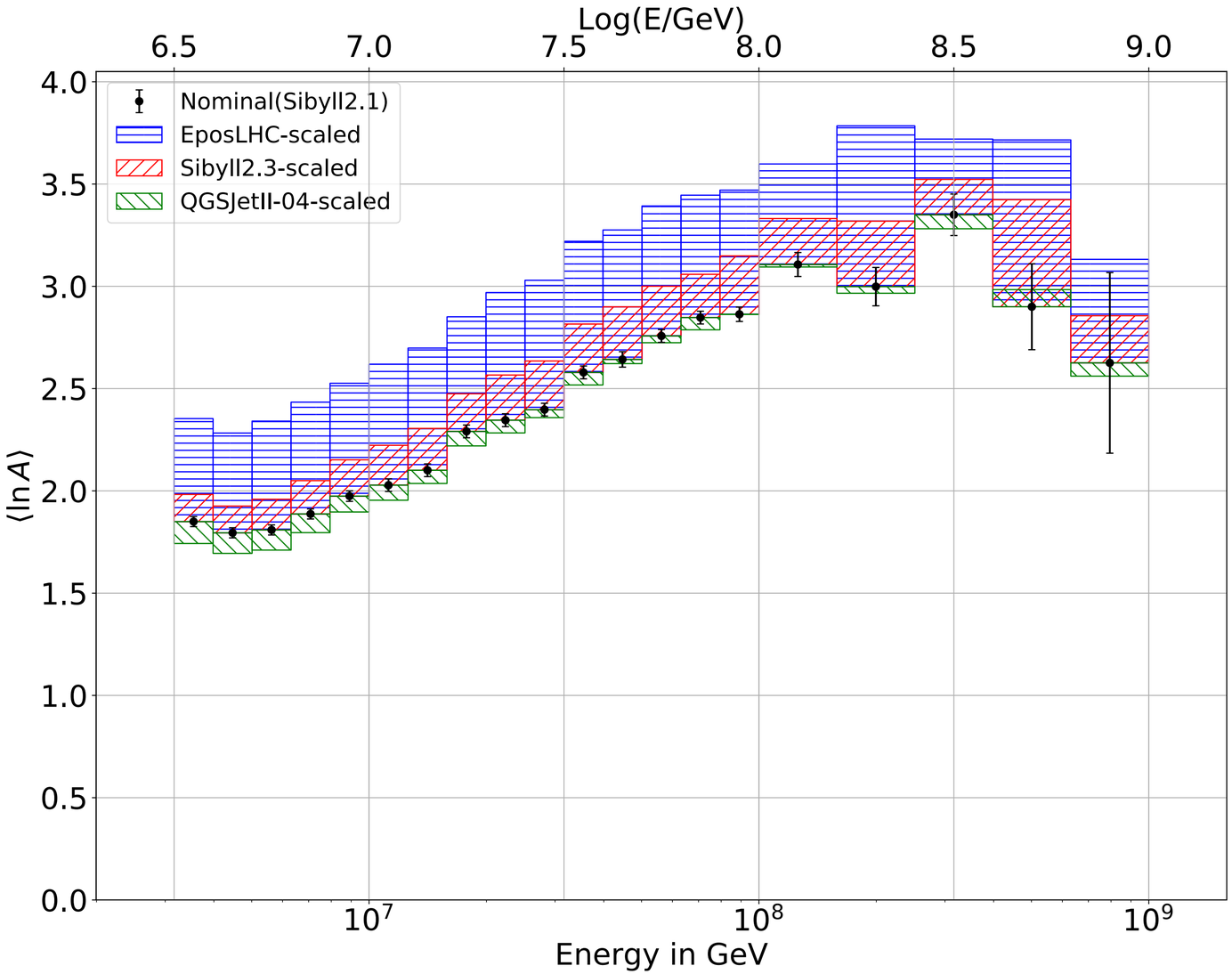
Mean logarithmic mass

ICETOP/ICECUBE-combined analysis

- Composition becomes heavier up to 320 PeV, higher energies than those for KASCADE-Grande.

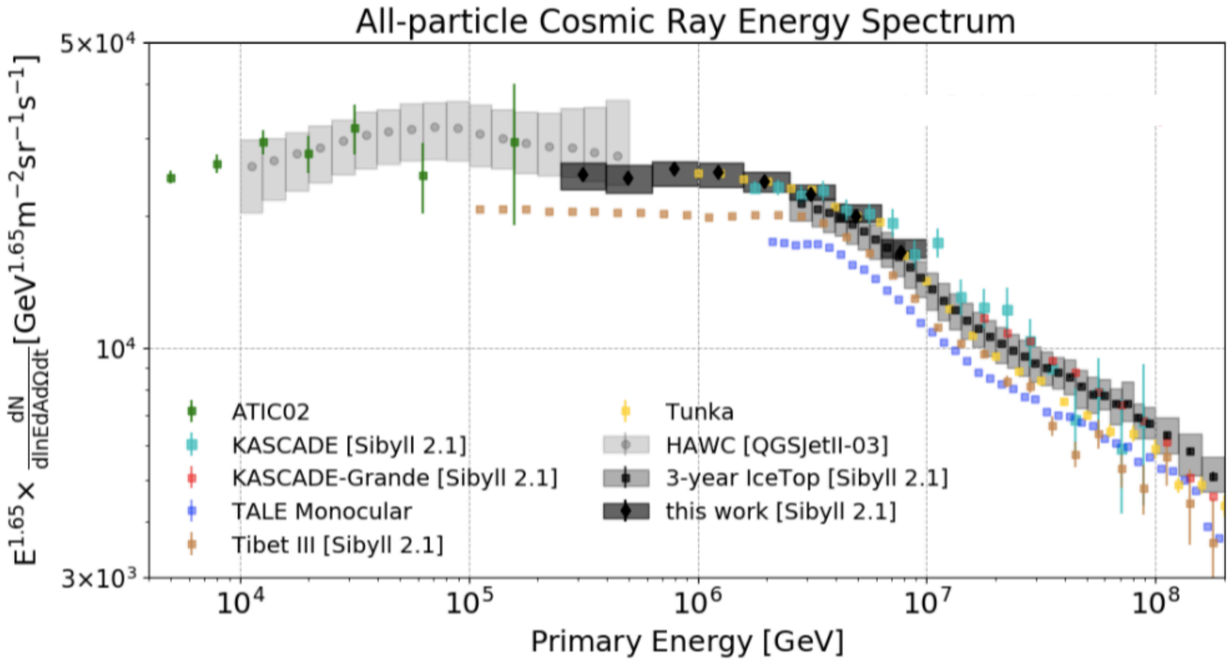
[Icecube Coll., PRD 100 (2019)]

E = 3 PeV - 1 EeV



All-particle spectrum between 250 TeV and 10 PeV

[M. G. Aartsen, PRD 102 (2025) 122001]

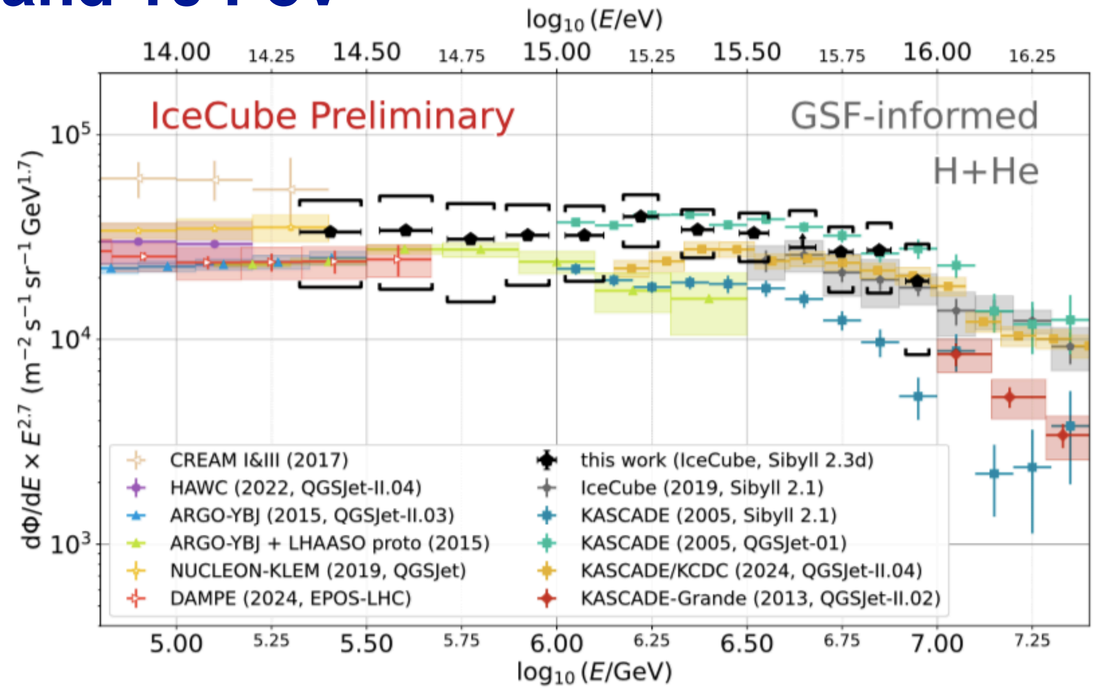


▸ Spectrum reaches 250 TeV.

- Data from infill array. Livetime 330.5 days, 7.4x10^6 events with E > 250 TeV and θ < 26°.
- Random Forest method to get E trained with data on Q(r), Qtot, EAS core, direction, Time of core, etc.

H+He spectrum between 200 TeV and 10 PeV

[ICECUBE Collab., PoS(ICRC2025) 376]



▸ H+He cosmic-ray spectrum from 200 TeV.

- ICECUBE and Infill/main array data. 1 yr DAQ, θ < 30°.
- Neural Network to get E and classify primary. Q(r), Qtot, lg(S_{125}), <dE_μ/dX>.



Credit: V. Lenok et al., PoS(ICRC2021) 421

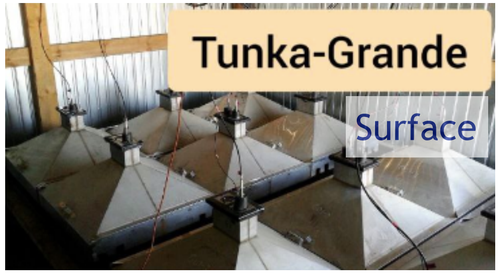
TAIGA



TAIGA-HiScore
- 120 wide FoV air Cherenkov detectors (non imaging)
- 150-200 m spacing
- 1 km^2
- E > 100 TeV

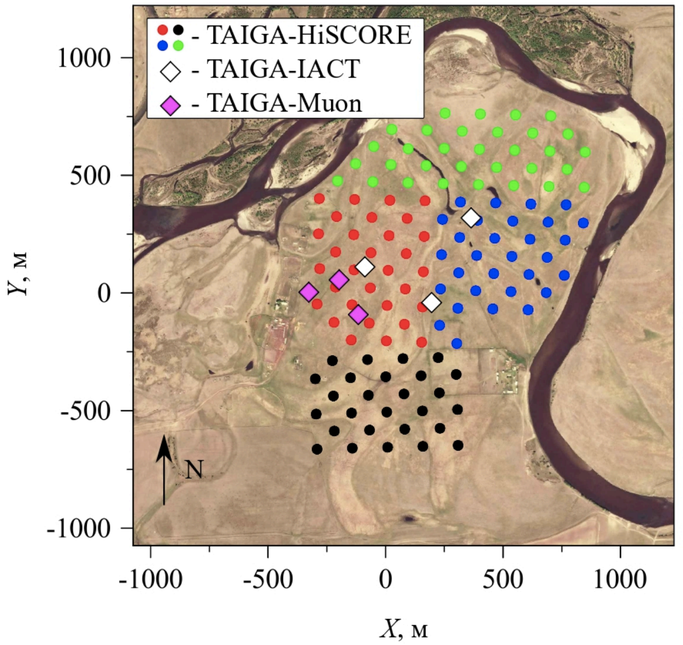


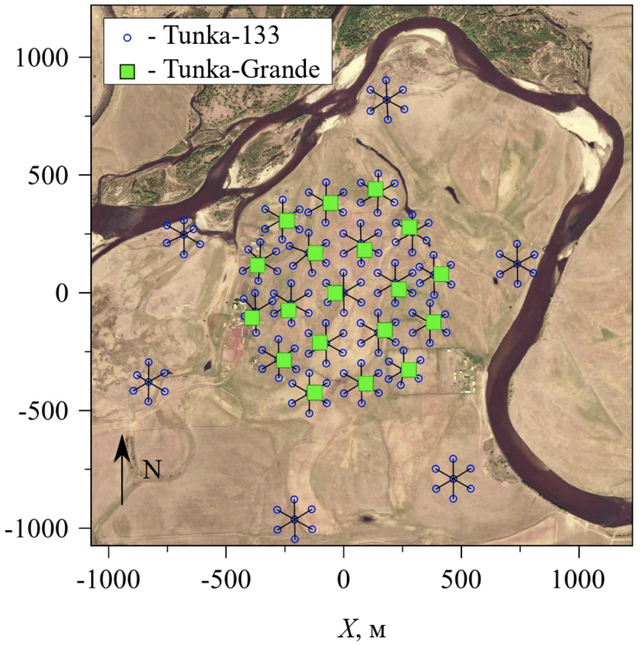
TUNKA-133
- 175 wide FoV air Cherenkov detectors (non imaging)
- 85 m separation
- 3 km^2
- E > 1 PeV





TUNKA-Grande
- 19 plastic scintillator stations.
- Surface +underground detectors
- 200 m spacing
- 0.5 km^2
- E > 10 PeV







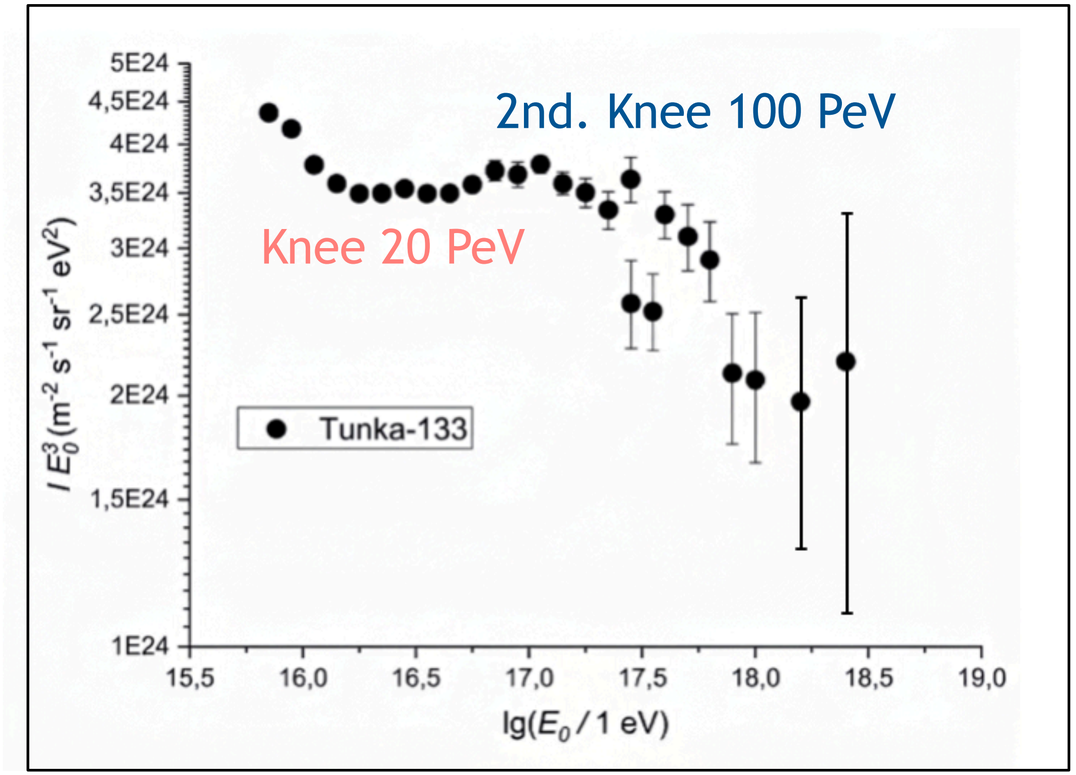
TUNKA-muon
- 3 clusters
- 8 plastic scintillator stations/cluster
- Surface +underground detectors
- 2000 m^2
- LE

[A. I. Ivanova et al., SciPost Phys. Proc. 13, 011 (2023)]
[V. Prosin et al., arXiv:2208.01689 **[astro-ph.HE]**]

Credit images:TAIGA Collab.

Energy spectrum

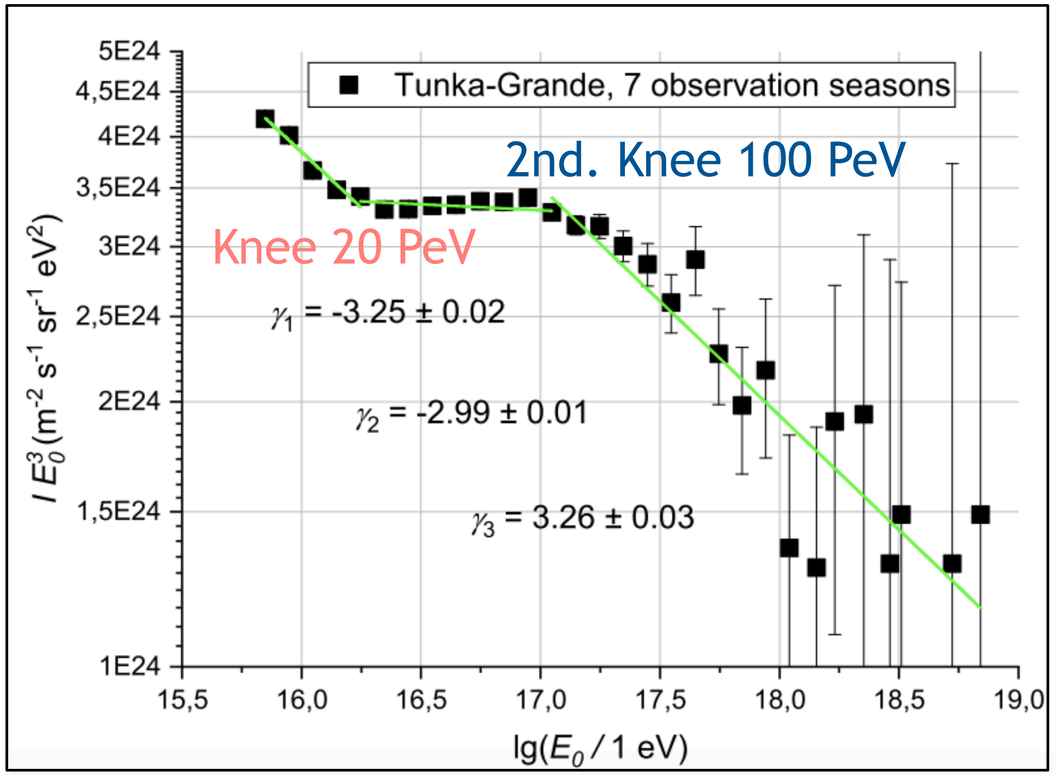
E =100 TeV - 3.2 EeV



Tunka-133

E: Q(200)

[V.V. Prosin et al., Bull. Russ. Acad. Sci. 87 (2023) 1043]



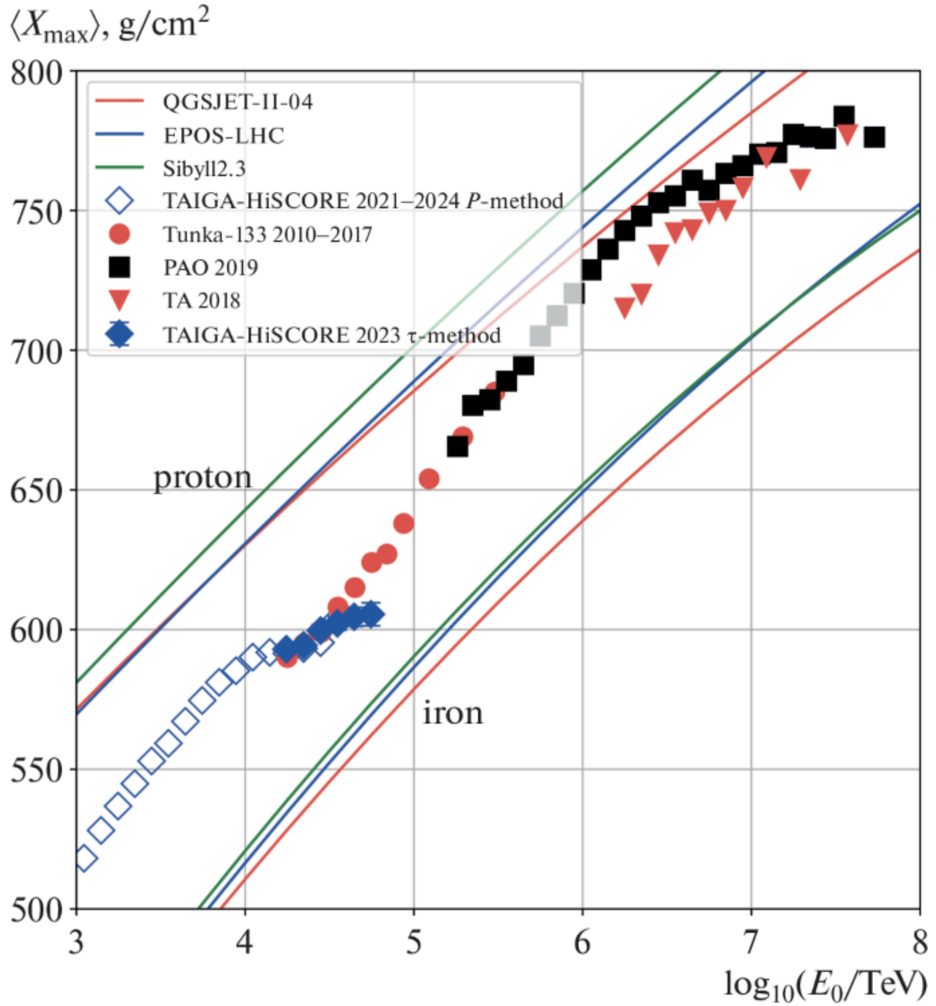
Tunka-Grande

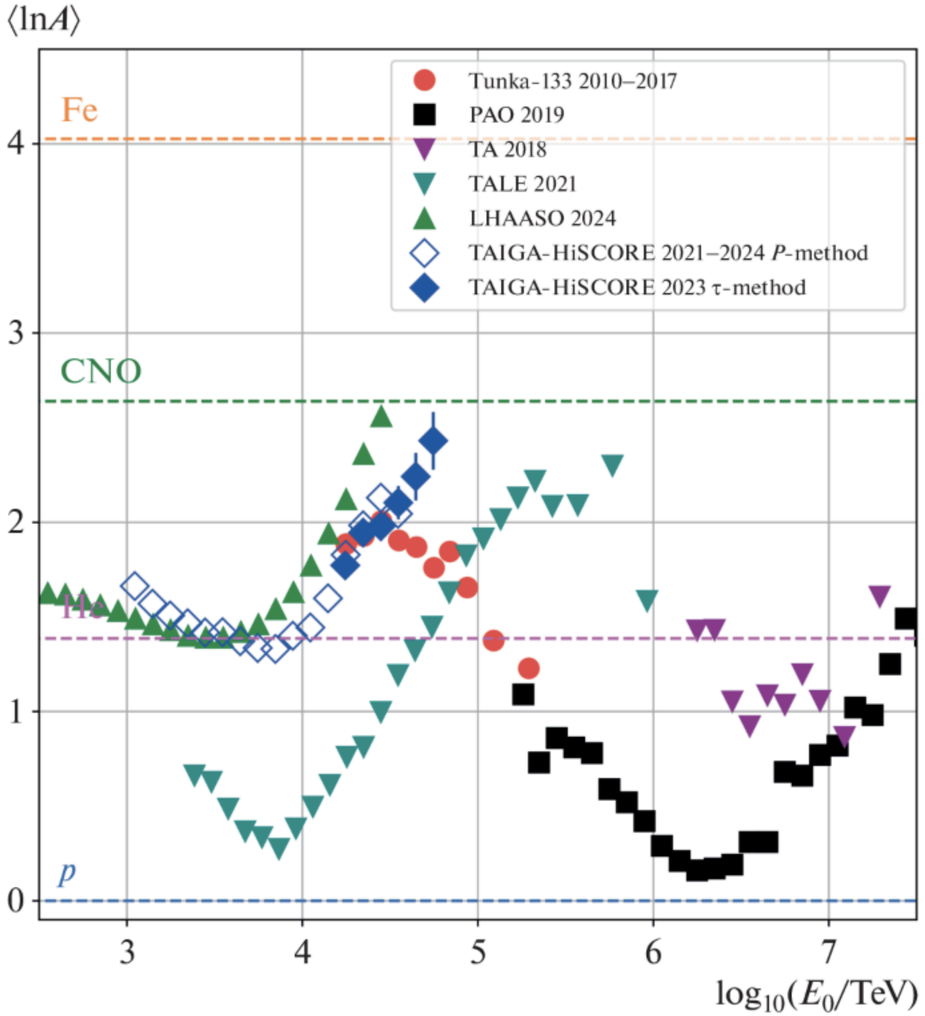
E: ϱ_0(200 m) + empirical formula from Tunka-133/ TAIGA-HiSCORE

[A. I. Ivanova et al., PoS(ICRC2025) 205]

Composition

[M. Yu. Ternovoy et al., Elementary Part. Fields 89 (2026) 89]







Operation: Since 2008 (Full operation)

Location: West desert, Utah, U$A

Altitude: 1400 m a.s.l. (880 g/cm^2)

CR energy range: 2 PeV - 100 EeV

Credit: Ben Stokes

TALE infill
- 50 SD
- 900 m x400 m, 0.36 km^2
- 100 m spacing
- E ≳ 1 PeV

TALE array
- 40 SD, 400 m spacing
- 40 SD, 600 m spacing
- 32 km^2
- E ≳ 10 PeV

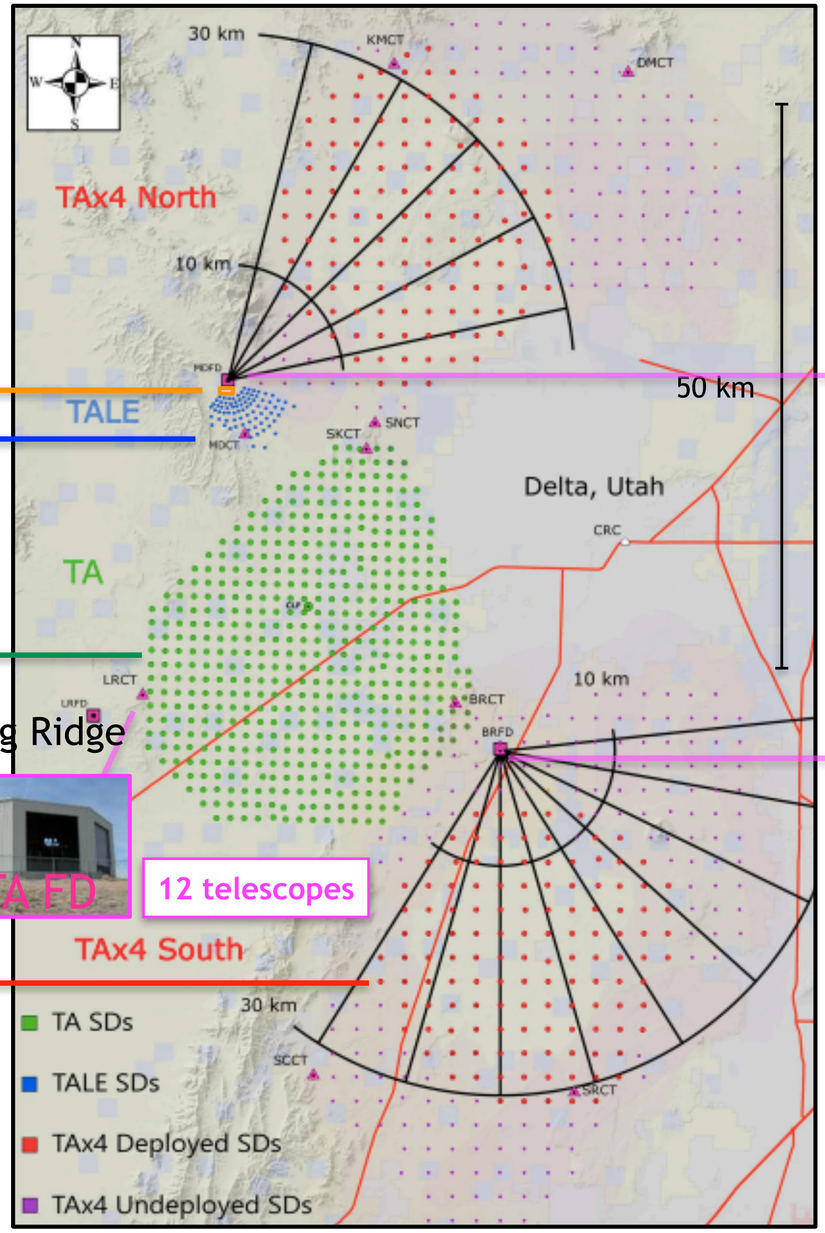


Main array
- 507 plastic scintillator detectors (SD) of 3m^2
- 700 km^2
- 1.2 km spacing
- E > 1.58 EeV

TAx4 array
- 257 SD
- 1000 km^2
- 2.08 km spacing
- E > 20 EeV

[H. Sagawa, SciPost Phys. Proc. 13, 041 (2023)]

[TA Collab., NIMA 1019 (2021)]



[TA Collab.,PoS(ICRC2025) 1410]

Middle Drum



TA FD
- 14 telescopes
- FOV 3^o - 31^o

TALE FD
- 10 telescopes
- FOV 30^o - 57^o



TAx4 FD
- 4 telescopes
- FOV 4^o - 17^o

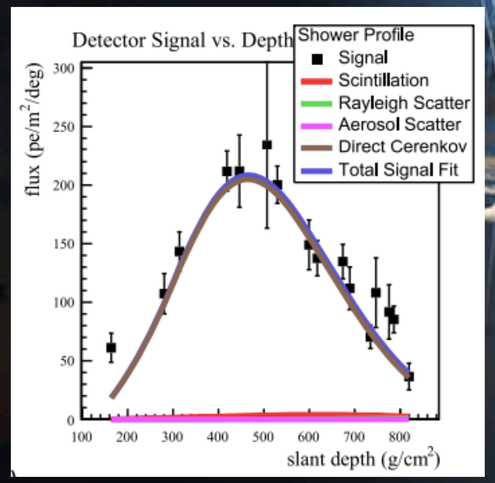
Black rock mesa

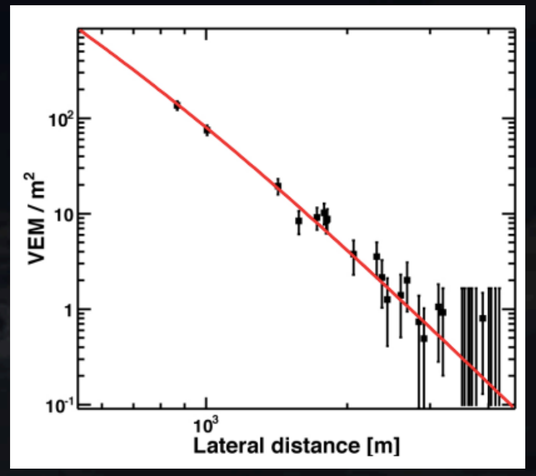


TA FD
- 12 telescopes



TAx4 FD
- 8 telescopes





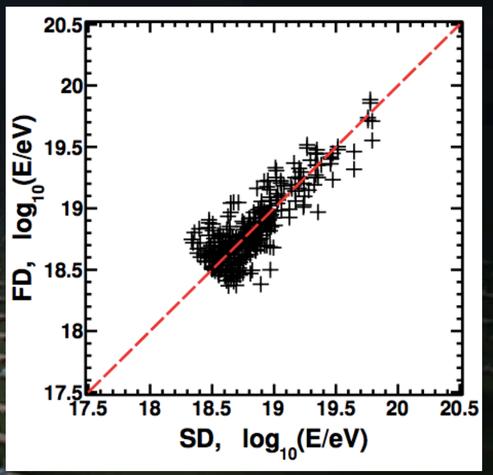
- Mass sensitive parameter:
  - X_{max}, $\sigma(X_{max})$.
- Hybrid/FD energy estimator:
  - Calorimetric: E_{FD}

[TA Collab., ApJ 865 (208)]

[H. Sagawa, SciPost Phys. Proc. 13, 041 (2023)]

EAS data: Arrival times of EAS particles, secondary particles, fluorescence yield and image, Cherenkov yield.

- TA-SD energy estimator:
  - S(800 m): signal at 800 m corrected for atmospheric effects.
  - Use SD+FD empirical formula $E_{FD} = A\,[S_\theta(r_o)]^B$

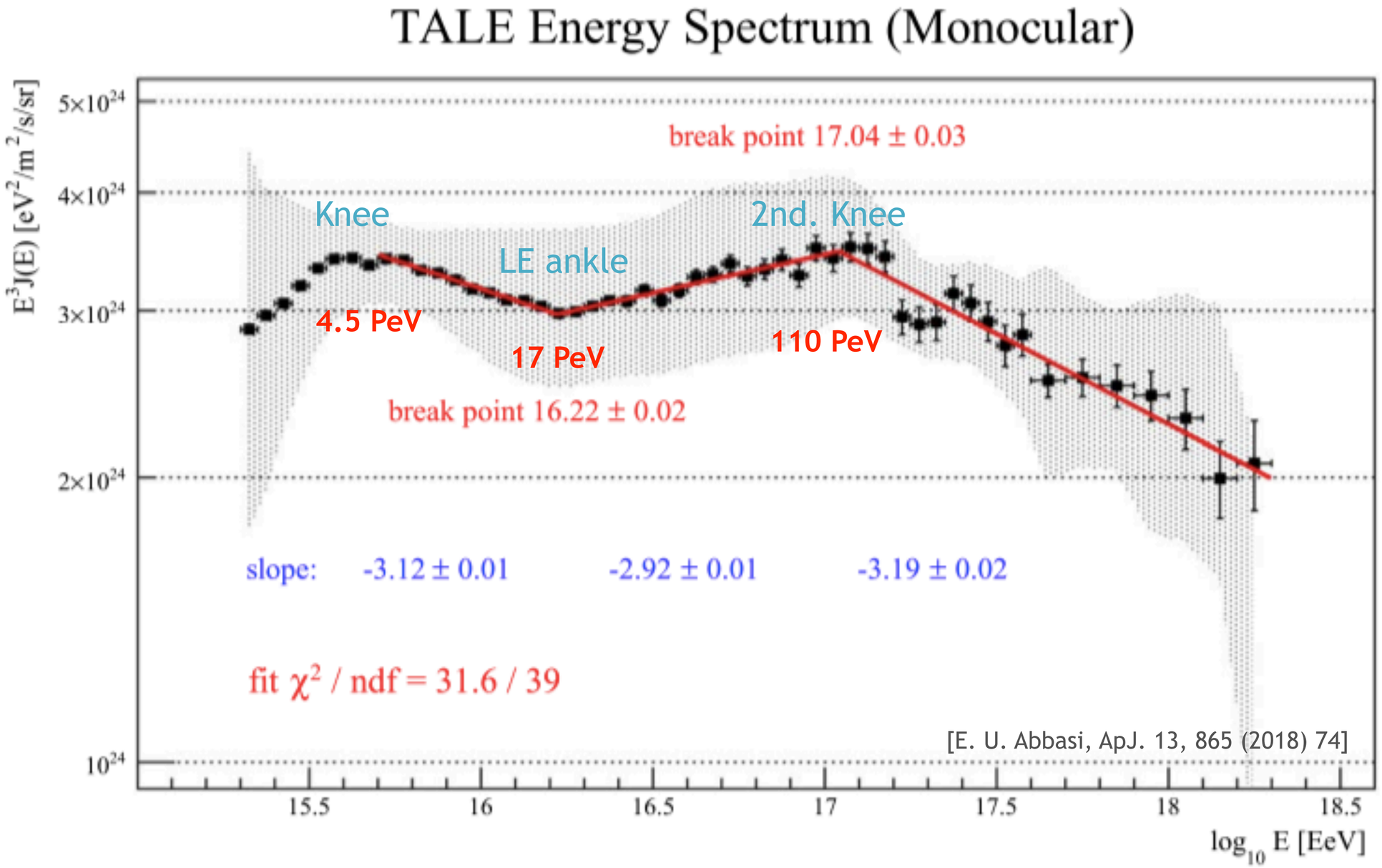


Credit: TA Collab.

[V. Verzi et al., arXiv:1705.09111 **[astro-ph.HE]]**

Energy spectrum

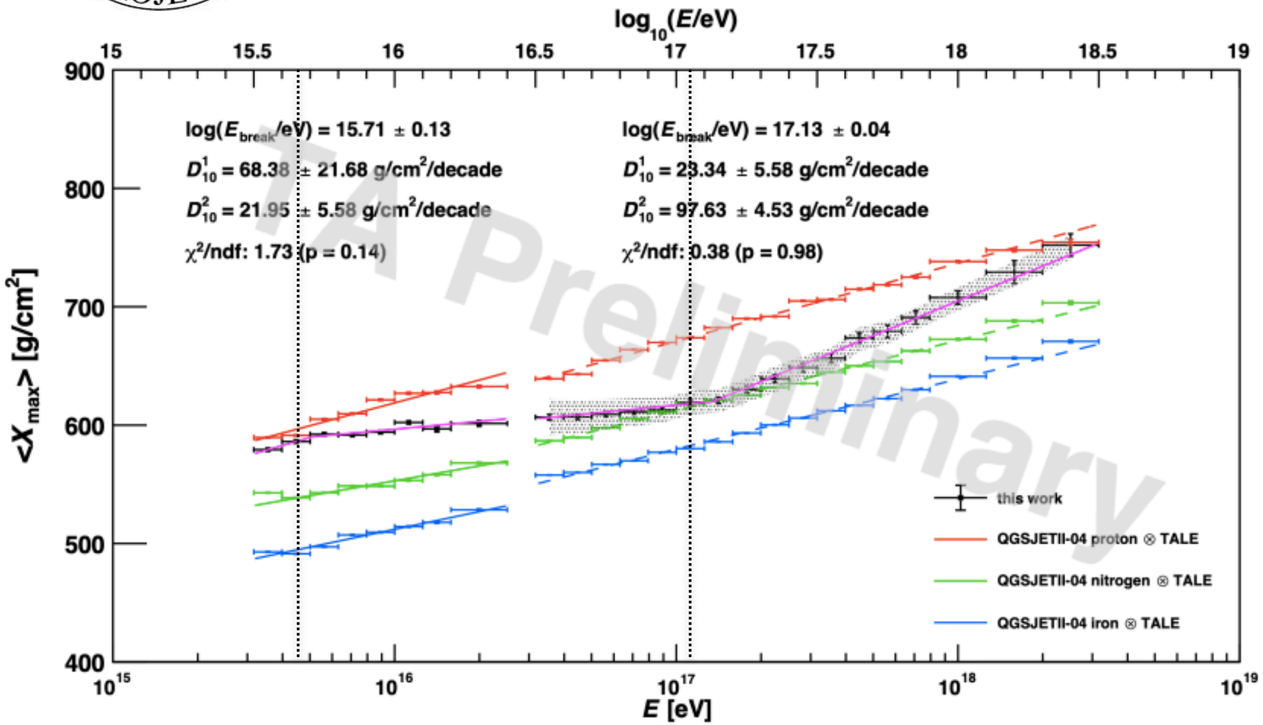
E =2 PeV - 2 EeV

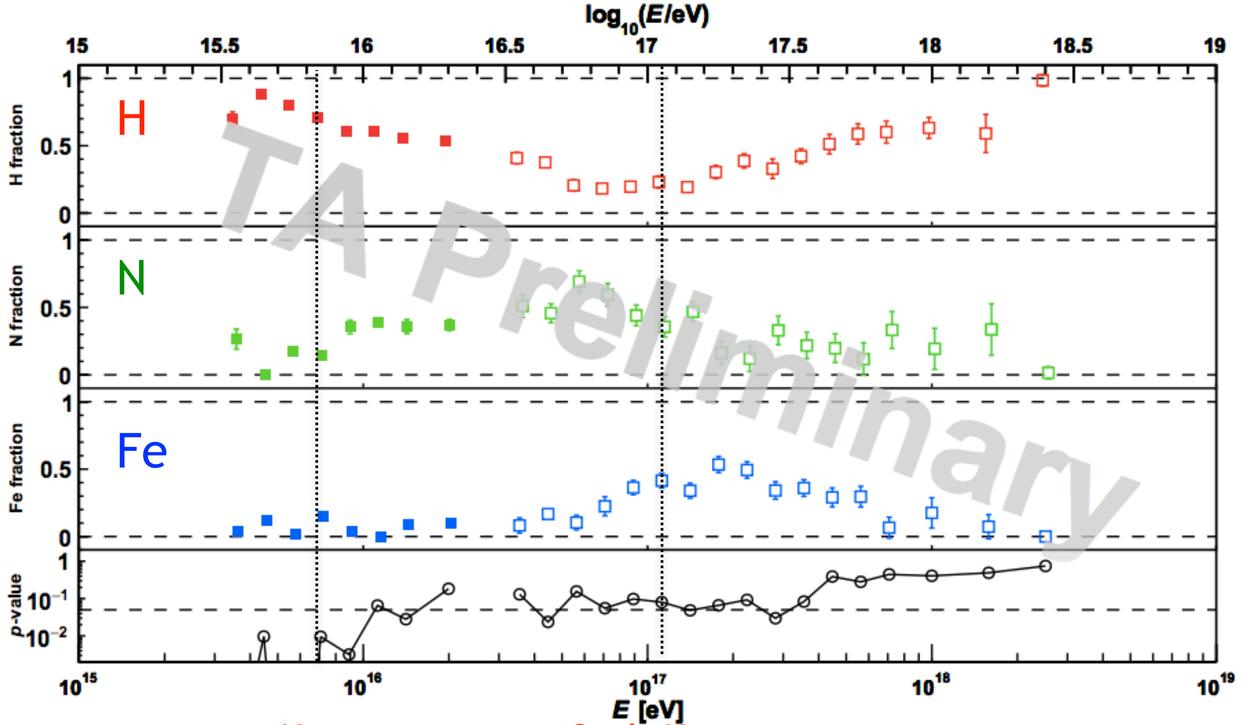


Composition

E =2 PeV - 3 EeV

[TA Collab., PoS(ICRC2025) 261]





Knee 2nd. Knee

Infill-SD+FD TALE-SD+FD

Knee 2nd. Knee

Infill-SD+FD TALE-SD+FD

- Changes in elongation rate are correlated with position of the knee and 2nd knee.

- Light @ 4.5 PeV —> Heavy @ 100 PeV —> Light @ EeV

TALE-SD+FD



Credit: PAO Collaboration

PIERRE AUGER OBSERVATORY

High elevation fluorescence telescope
- 3 telescopes
- FOV 30º - 58º
- E > 100 PeV



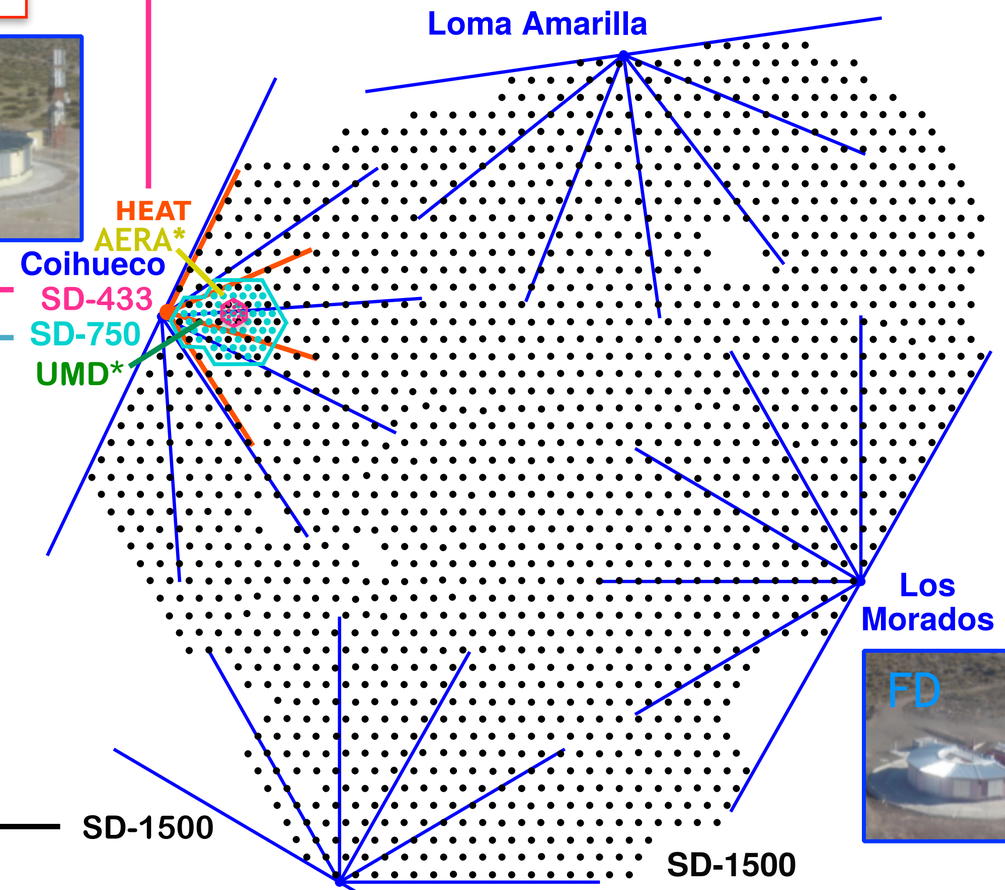


Fluorescence detectors
- 6 telescopes/station
- FOV 0º - 30º
- E > 1 EeV



SD433 array
- 19 WCD
- 2 km²
- 433 m spacing
- E > 63 PeV

SD750 array
- 61 WCD
- 24 km²
- 750 m spacing
- E > 100 PeV



70 [km] 60 50 40 30 0

Hybrid detector 3000 km²



Underground μ detectors
- 53 detectors, 2.3 deep
- Plastic scintillators

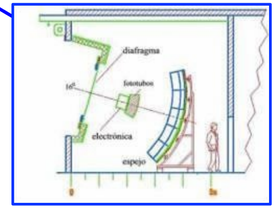


AERA
- 153 radio stations
- 17 km²
- 150 m spacing

Main array
- 1660 water Cherenkov detectors (WCD) with scintillators (SSD) and radio antennas.
- 3000 km²
- 1.5 km spacing
- E > 2.5 EeV







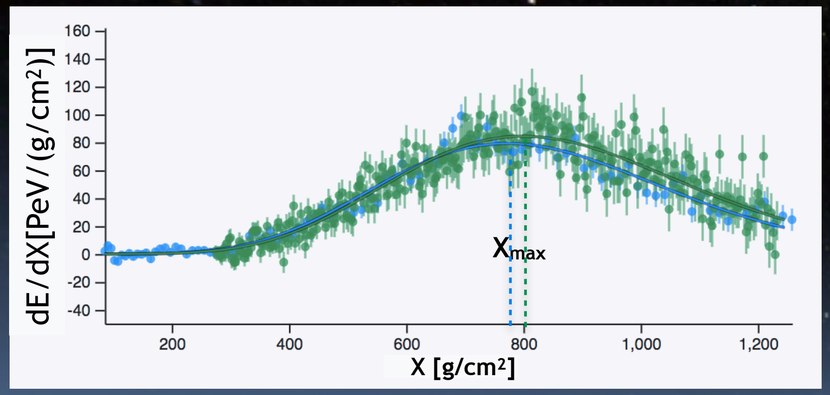
[F. Salamida, PAO Collab., PoS(ICRC2023) 016]

[PAO Collab., Eur. Phys. J. C 81 (2021)]

Credit Images: PAO Collaboration

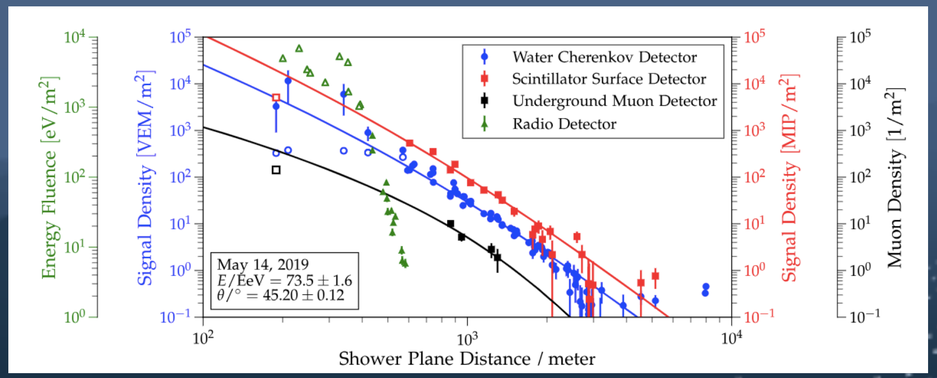
PIERRE AUGER OBSERVATORY

Event ID: 081847986000
Time: 03 Jul 2008 04:06:57
Energy: 56.83 EeV
Number of Stations: 24

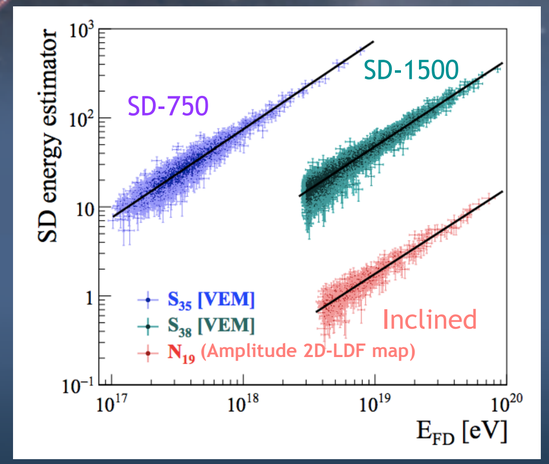


- Mass sensitive parameter:
- X_{max}, $\sigma(X_{max})$, X^{μ}_{max}, rise times ($t_{1/2}$) of WCD signals, azimuthal asymmetries in $t_{1/2}$.
- Hybrid/FD energy estimator:
- Calorimetric: E_{FD} (including missing energy)
  Mass independent

[PAO Collab., JINST 20 (2025) P08002]



[V.Novotny, PoS(ICRC2021) 324]



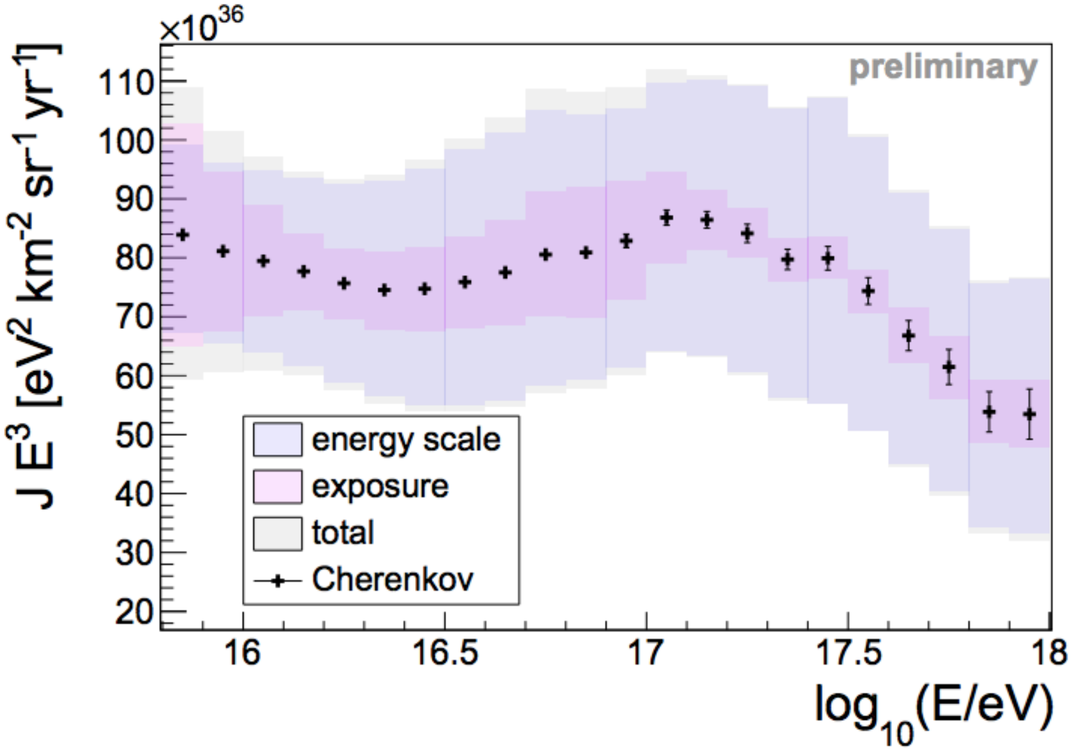
- SD energy estimator:
- $S_\theta(r_o)$: signal at r_o corrected for atmospheric effects to estimate signal at θ
- Use SD+FD empirical formula $E_{FD} = A\,[S_\theta(r_o)]^B$

EAS data: Arrival times of EAS particles, deposited charge, energy fluence in radio, muon density, fluorescence yield and image, Cherenkov yield.

Credit: PAO Collaboration

PIERRE AUGER OBSERVATORY

E = 6 PeV - 1 EeV

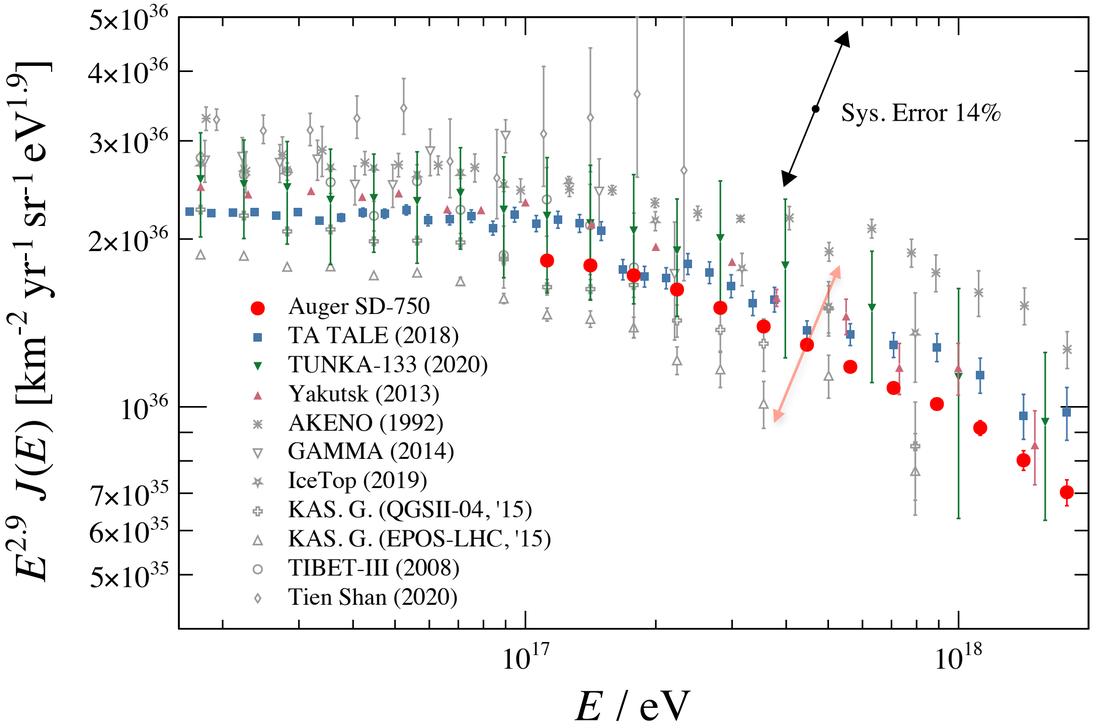


HEAT/COIHUECO: Cherenkov light

- Spectrum over more than 2 decades.
- Low energy ankle @ 28 PeV.
- 2nd knee @ 158 PeV.

[V.Novotny, PoS(ICRC2021) 324]

E = 100 PeV - 25.1 EeV



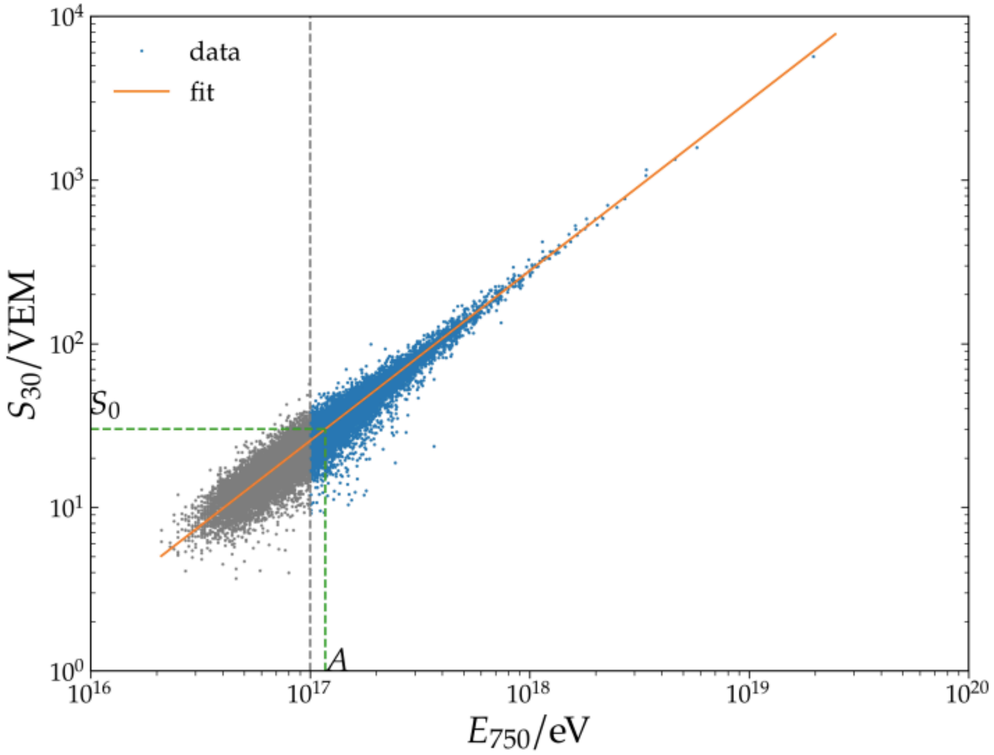
SD-750: S_{35}(450 m)

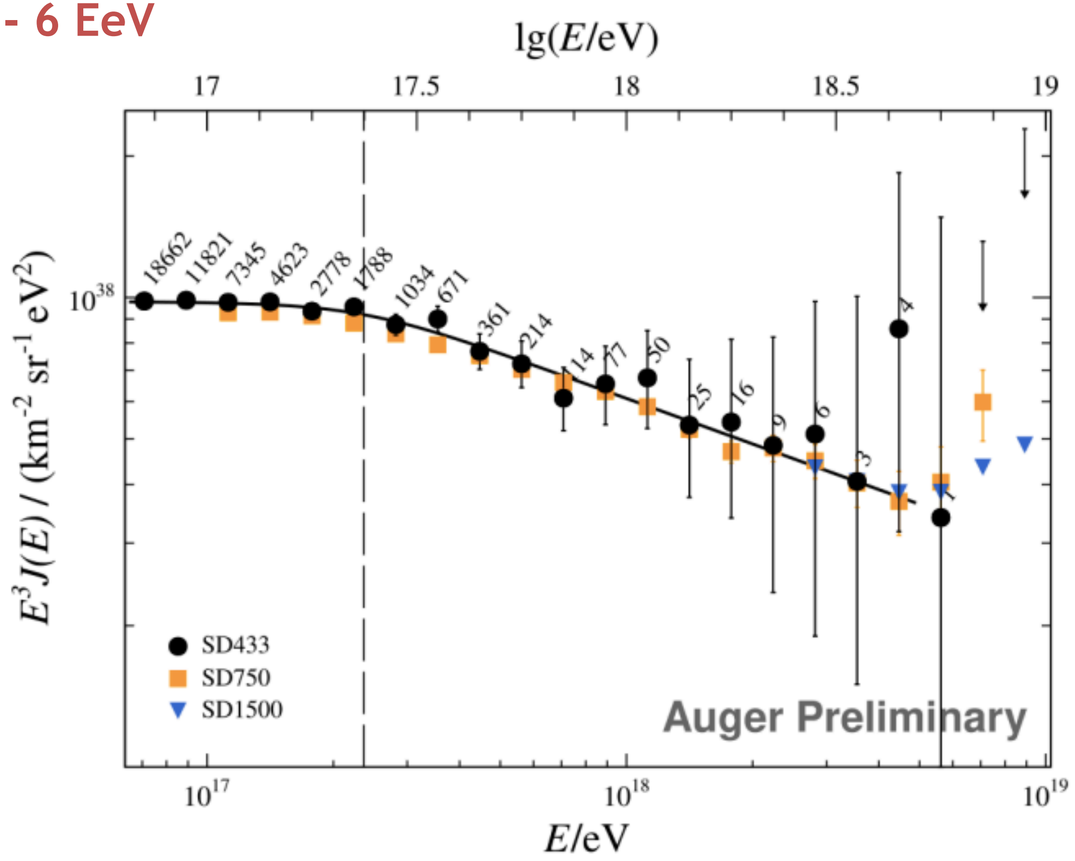
- Width of 2nd. knee is broader than that of the ankle.
- SD-750 and TALE spectra agree well within 6% energy offset.

[PAO Collab., Eur. Phys. J. C 81 (2021)]

PIERRE AUGER OBSERVATORY

E = 60 PeV - 6 EeV





SD-433: S_{30}(300 m)

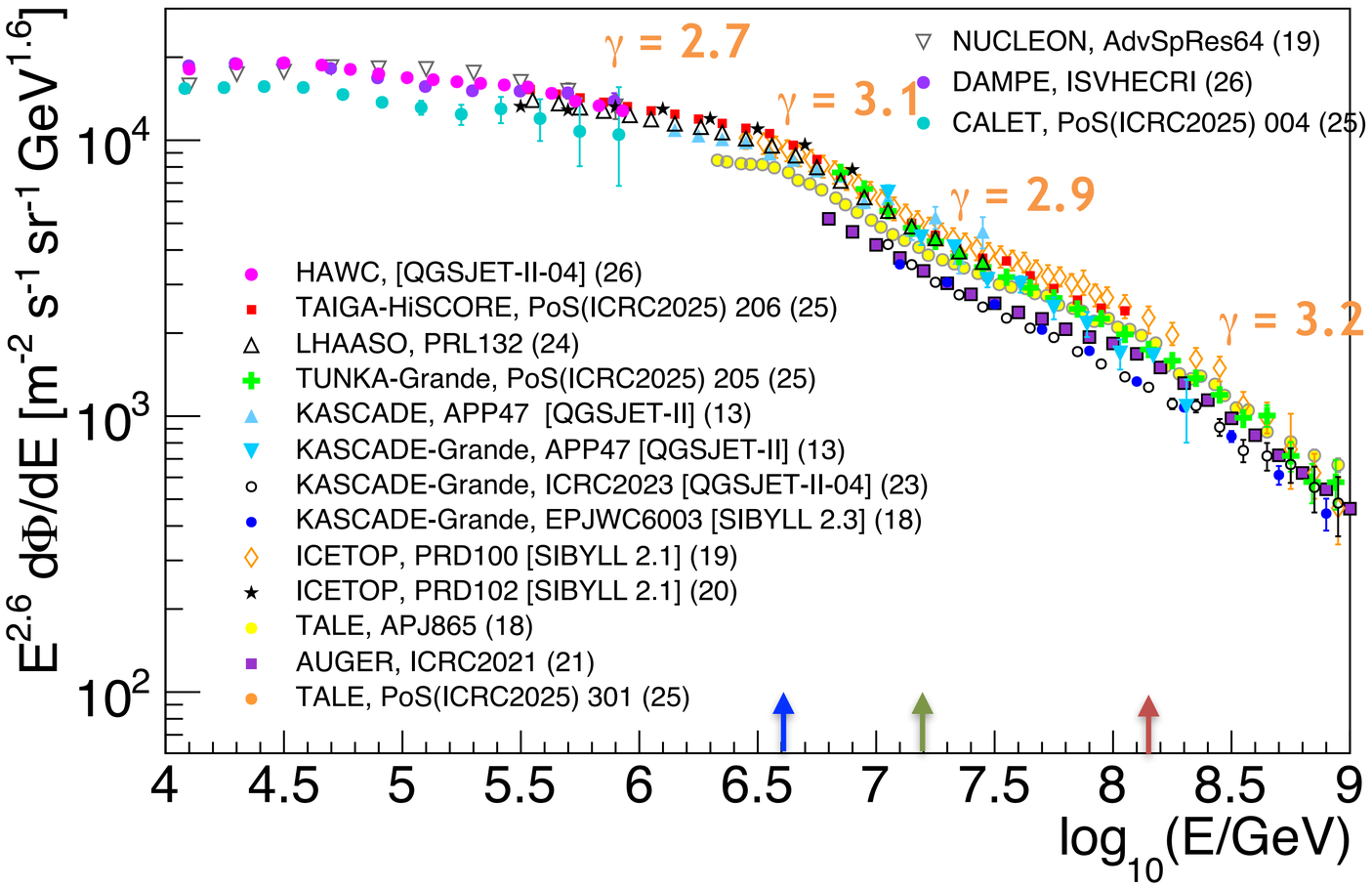
- Energy calibration using coincident events between SD-433 and SD-750 and FD/SD-750 energy calibration.

- In agreement with SD-750 spectrum.
- 2nd knee @ 230 PeV.

[A.Brichetto, PoS(ICRC2023) 398]

5) Part 2: 1 PeV - 1 EeV

Total energy spectrum



- **Features:**
  - **Knee @ E ∈ [3, 5] x 10^{15} eV**
  - **LE ankle @ E ∈ [1, 2] x 10^{16} eV**
  - **2nd Knee @ E ∈ [0.8, 2] x 10^{17} eV**

- LHAASO has determined the knee position with large precision and accuracy:

  ⇨ **E = (3.67 ± 0.05 ± 0.15) x 10^{15} eV**

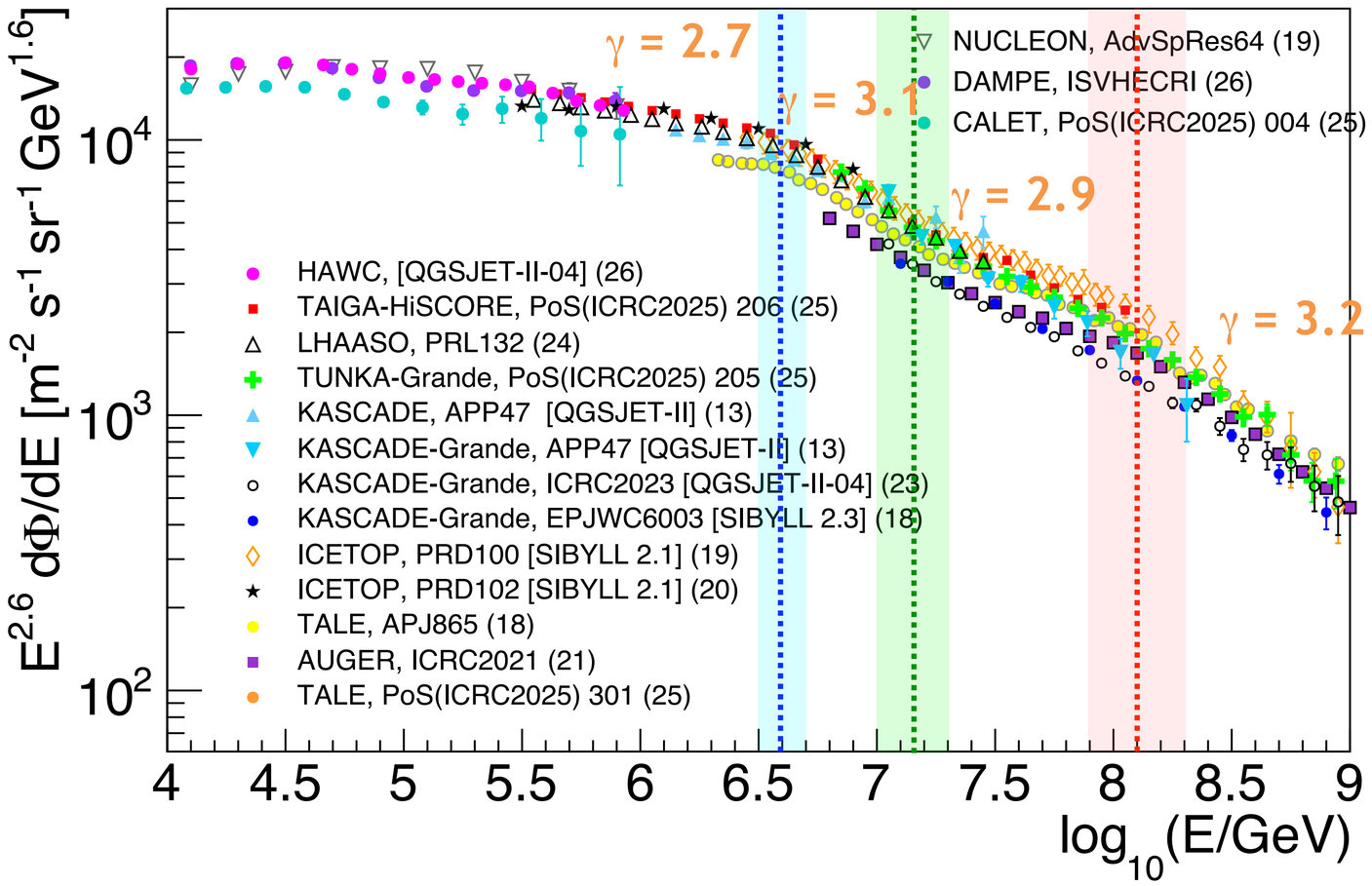
  [Z. Cao et al., PRL 132, (2004) 121002]

- The spectra are in good agreement despite experimental techniques and detector altitudes.

- Difference between energy scales
  - ICECUBE & KASCADE-Grande: < **27%**
  - **TAIGA-HiSCORE & Auger : 20%**
  - **TALE & Auger : 10%**

5) Part 2: 1 PeV - 1 EeV

Total energy spectrum



- **Features:**
  - **Knee @ E ∈ [3, 5] x 10^{15} eV**
  - **LE ankle @ E ∈ [1, 2] x 10^{16} eV**
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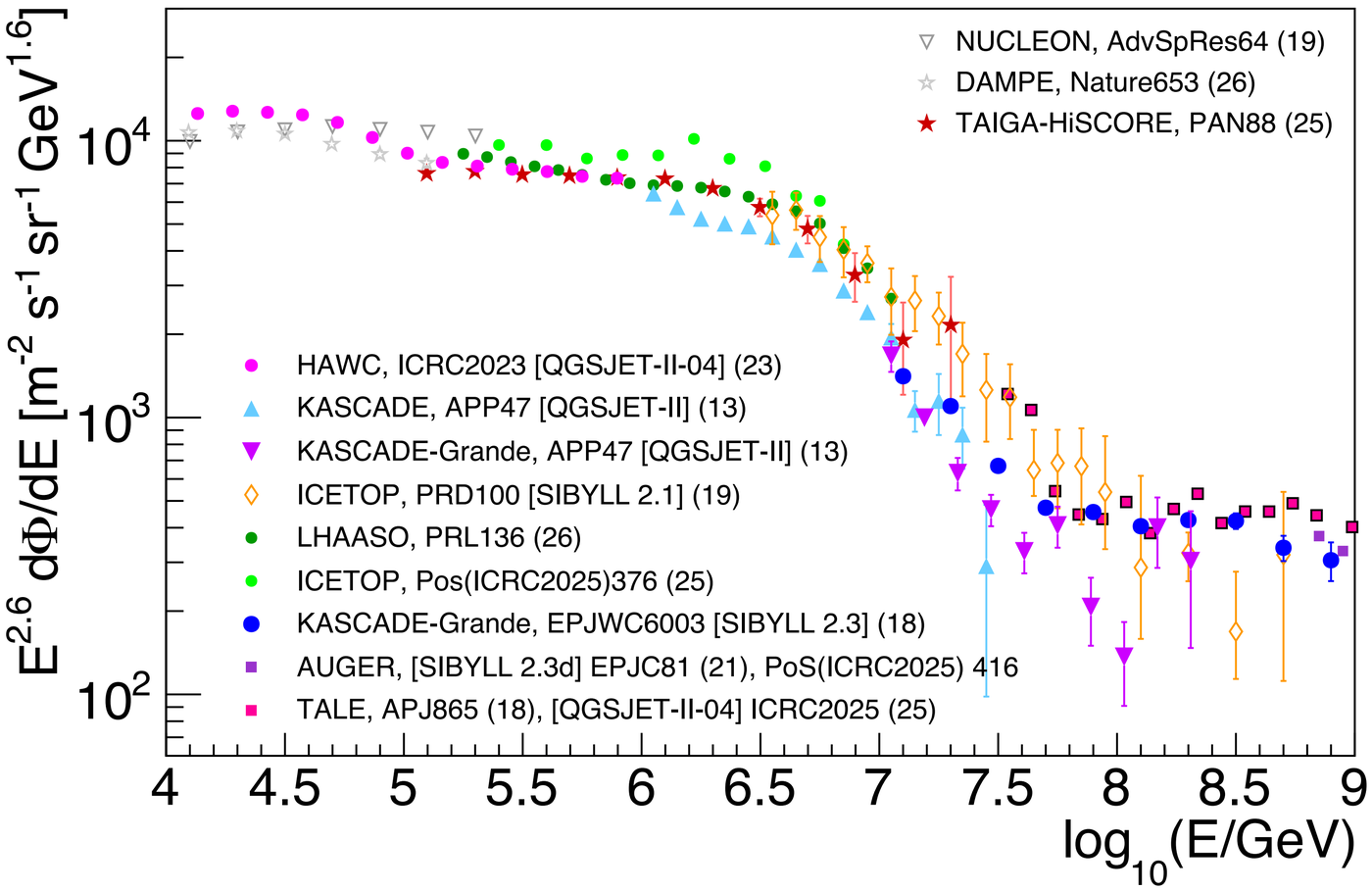
  [Z. Cao et al., PRL 132, (2004) 121002]

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  - **TALE & Auger : 10%**

5) Part 2: 1 PeV - 1 EeV

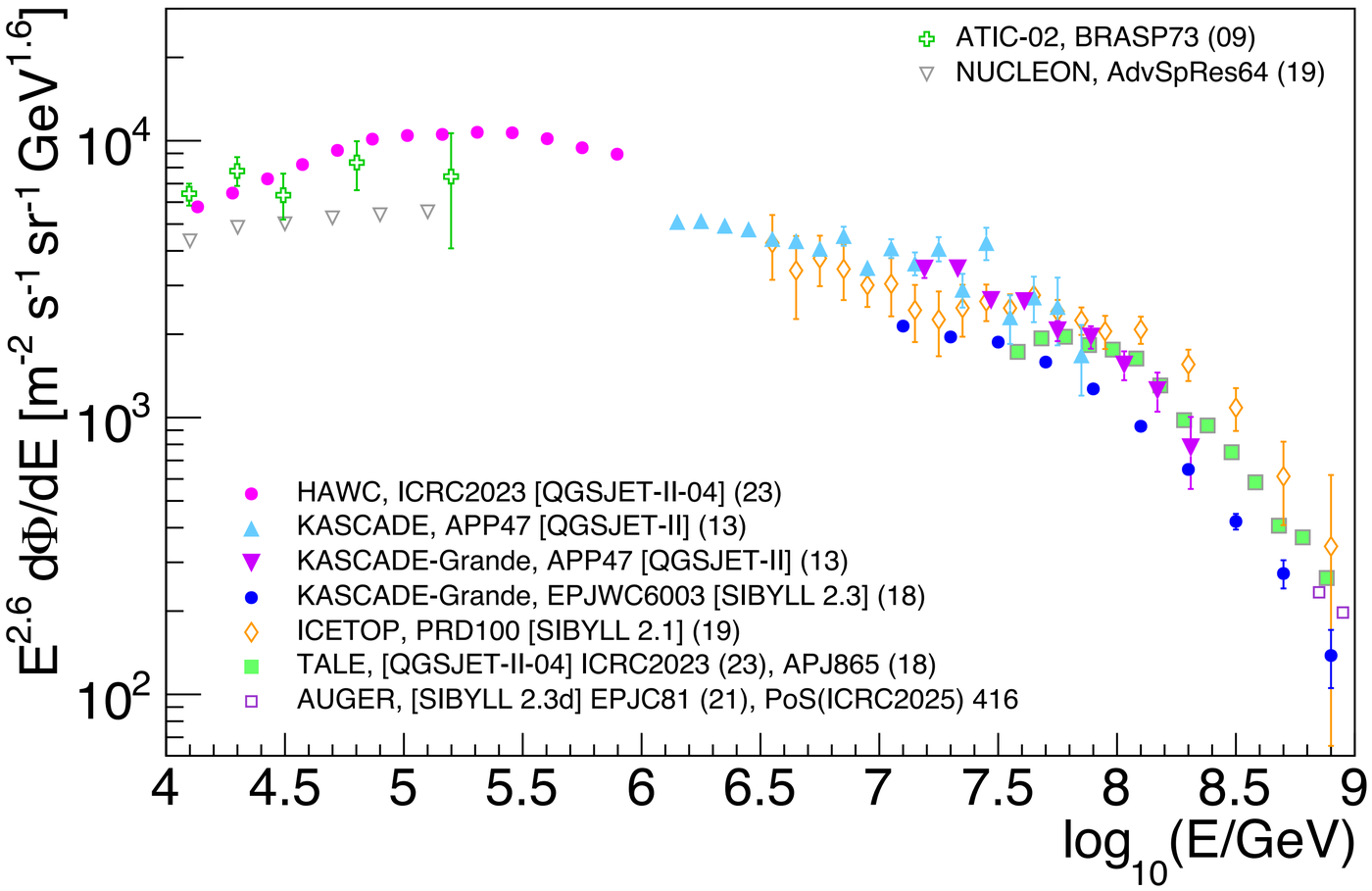
H+He energy spectrum



- **Features:**
  - **PeV knee @ E ∈ [3, 5] x 10^{15} eV**
  - **PeV ankle @ E ∈ [5, 7] x 10^{16} eV**
- The spectra above 1 PeV are in good agreement.
- Difference between energy scales
  - ICETOP & KASCADE :< 29%
  - LHAASO & KASCADE :< 16%
  - TALE & KASCADE-Grande : 38%

5) Part 2: 1 PeV - 1 EeV

H+He energy spectrum

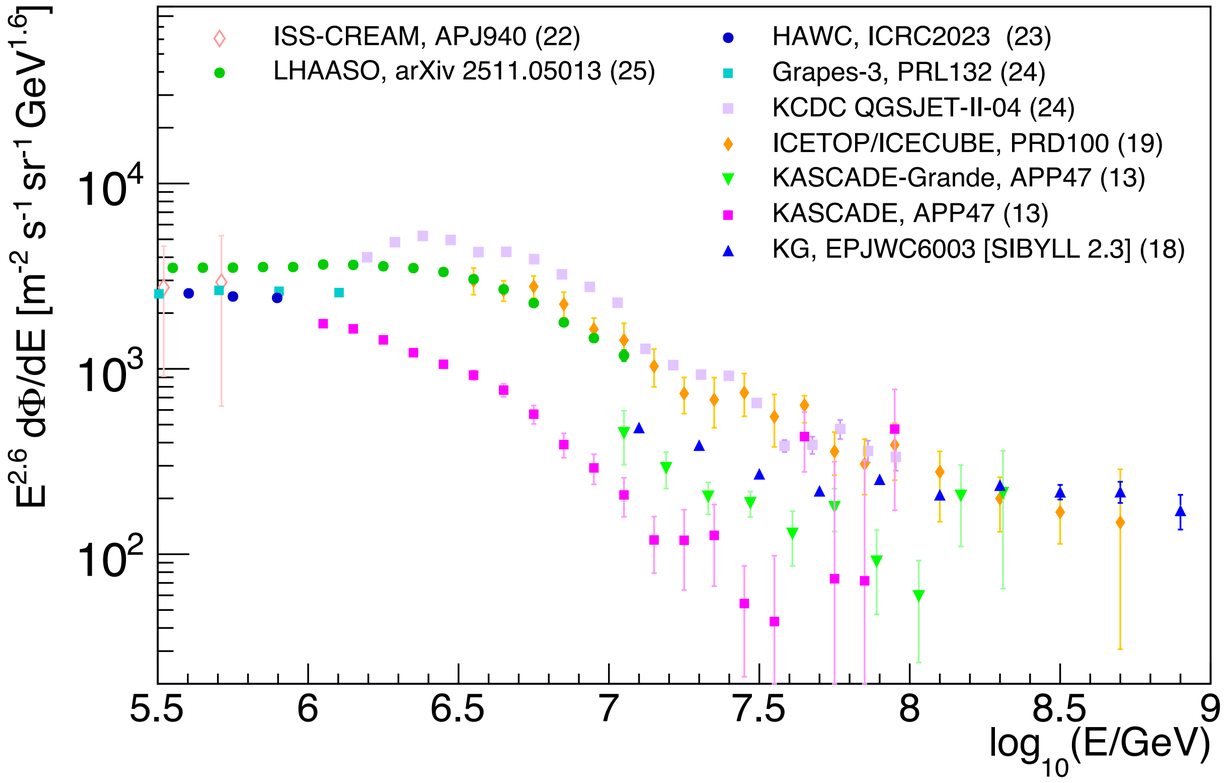


- **Features:**
  - **PeV knee @ E ∈ [0.8, 2] x 10^{17} eV**
- The spectra above 1 PeV are in good agreement.
- Difference between energy scales
  - ICETOP & KASCADE-Grande **:< 30%**
  - **TALE & ICETOP : 16%**

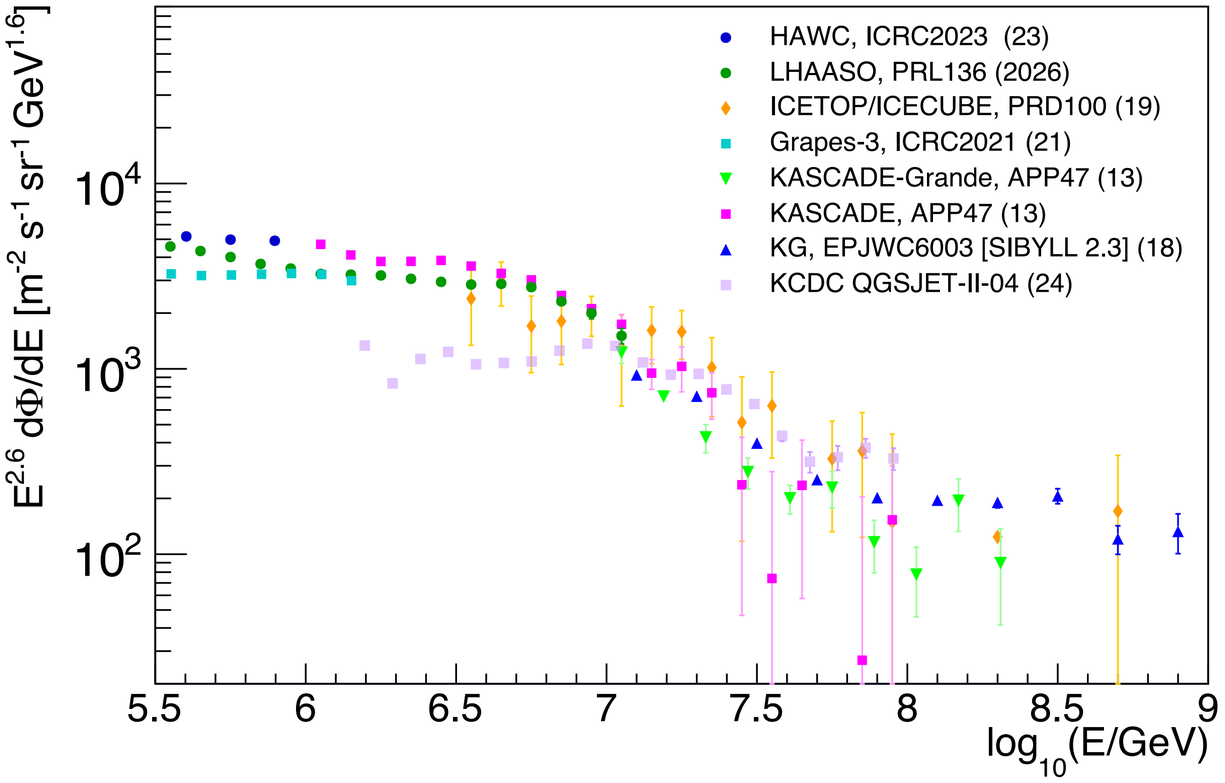
5) Part 2: 1 PeV - 1 EeV

Mass composition

Protons



Helium



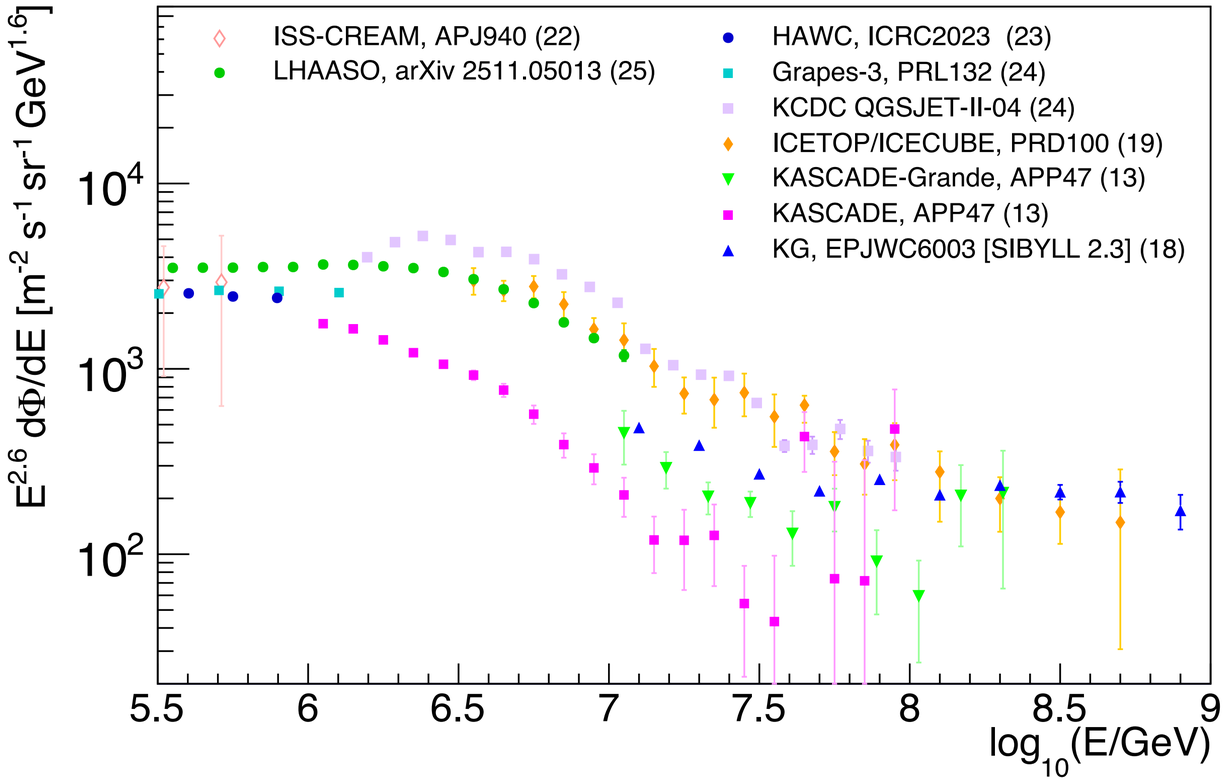
- Different EAS experiments confirm the presence of individual knees in the spectra of H and He cosmic-ray nuclei at PeV energies.

- Differences in magnitude of spectra are still observed.

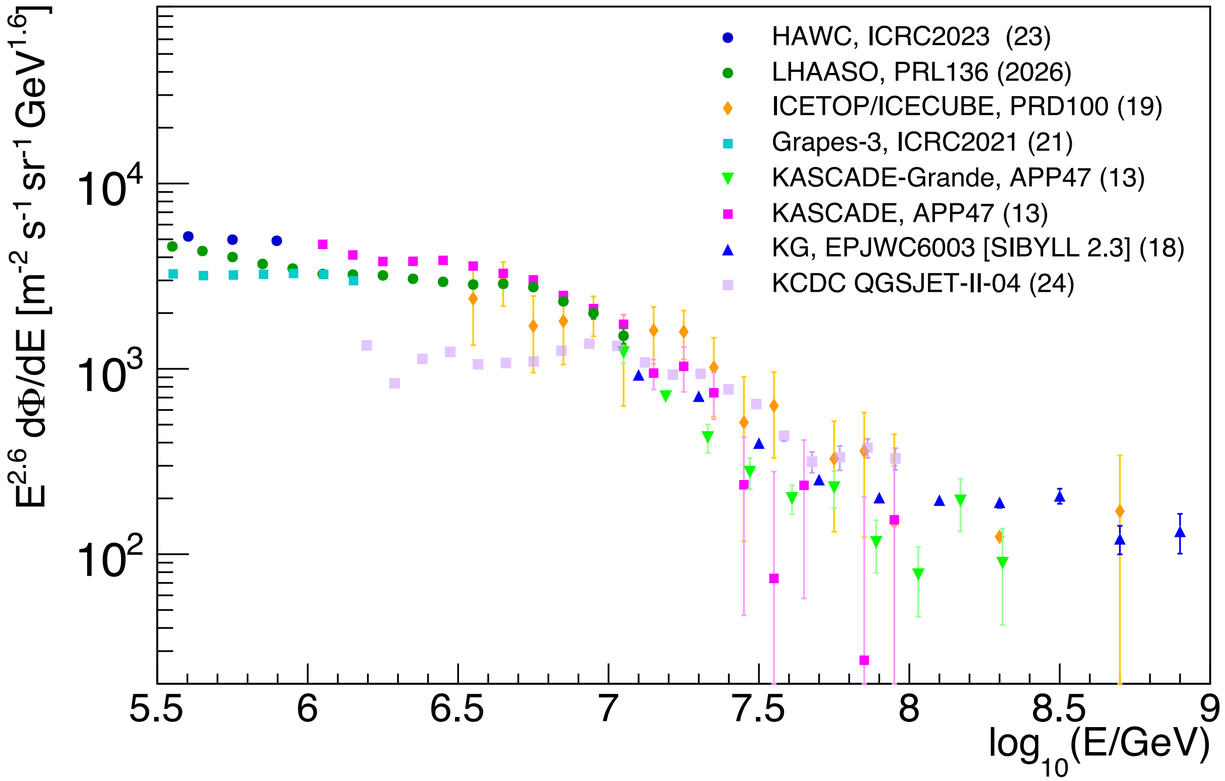
5) Part 2: 1 PeV - 1 EeV

Mass composition

Protons



Helium



- **LHAASO** has recently determined position of the individual knees of H and He with high precision:

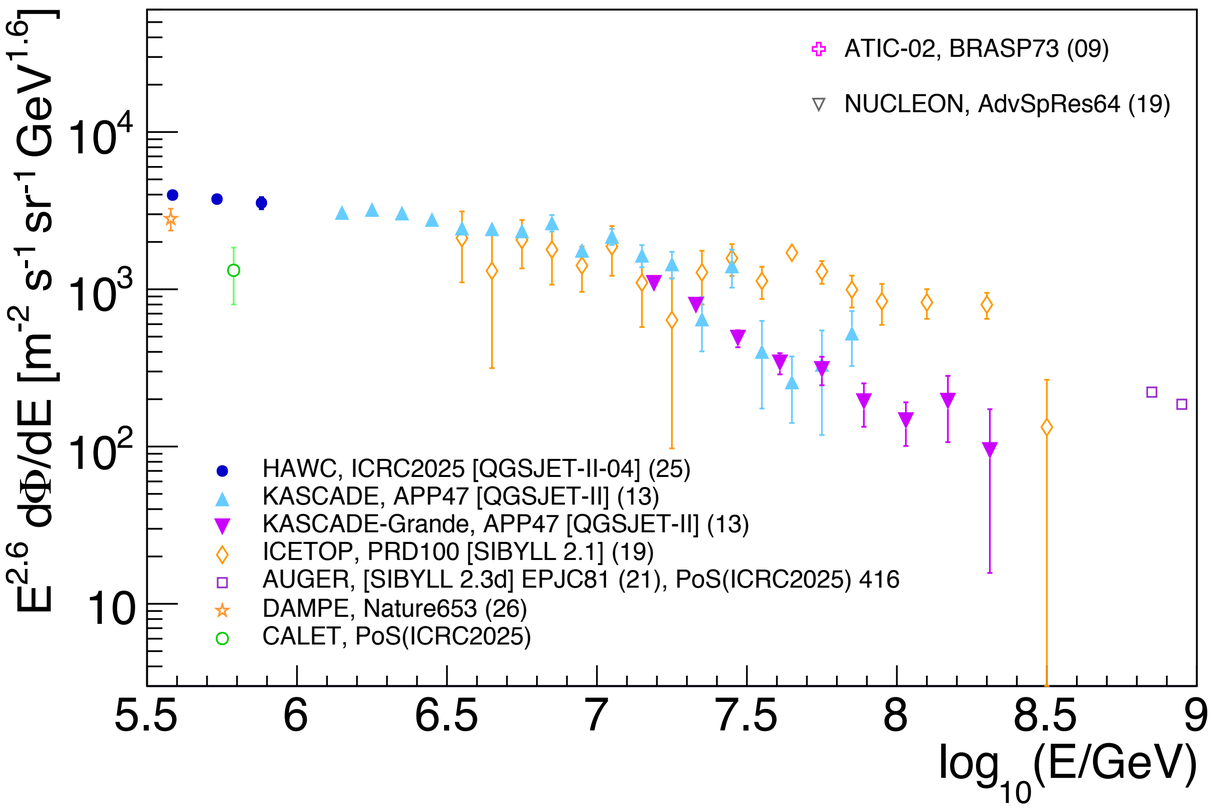
Z	*Knee (10^{15}eV)*
H (Z = 1)	*3.3 ± 0.5*
He (Z = 2)	*7 ± 0.7*

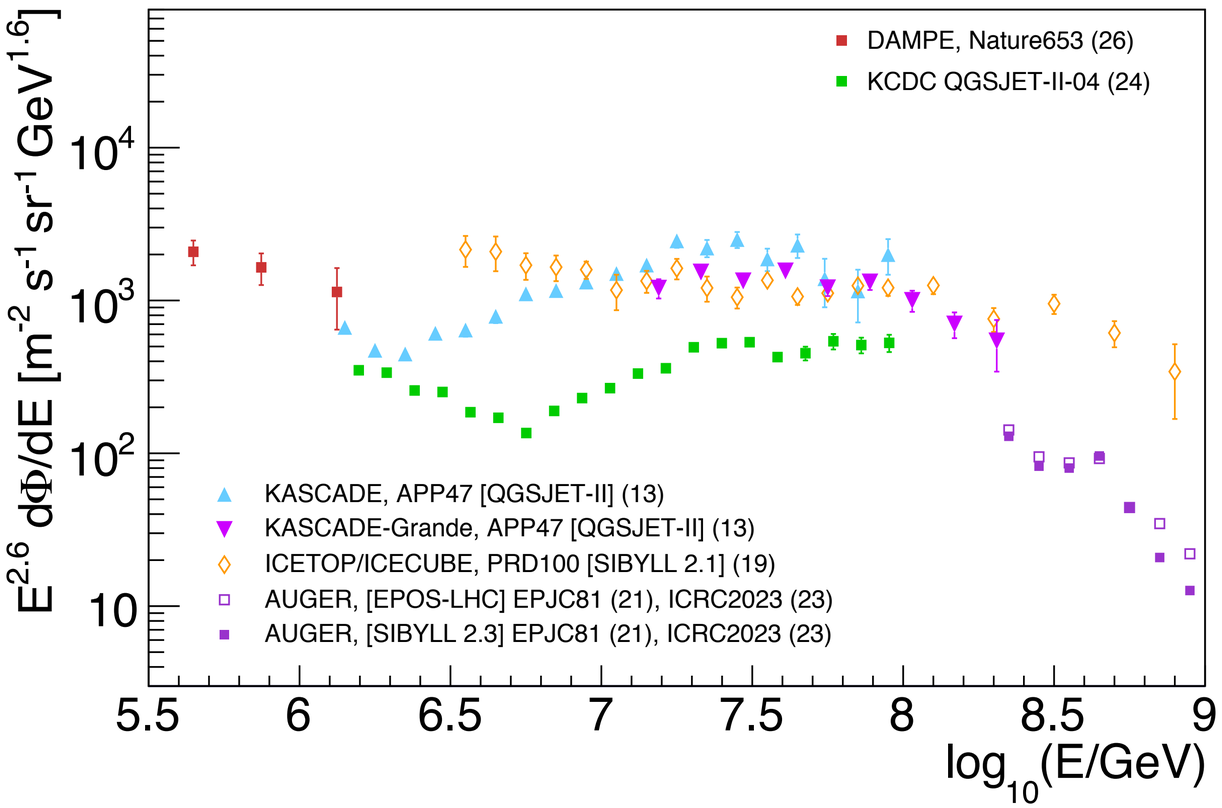
[Z. Cao et al., Sci. Bull. 70 (2025) 4173]

[Z. Cao et al., PRL 136 (2026) 121001]

5) Part 2: 1 PeV - 1 EeV

Mass composition **CNO** **Iron**

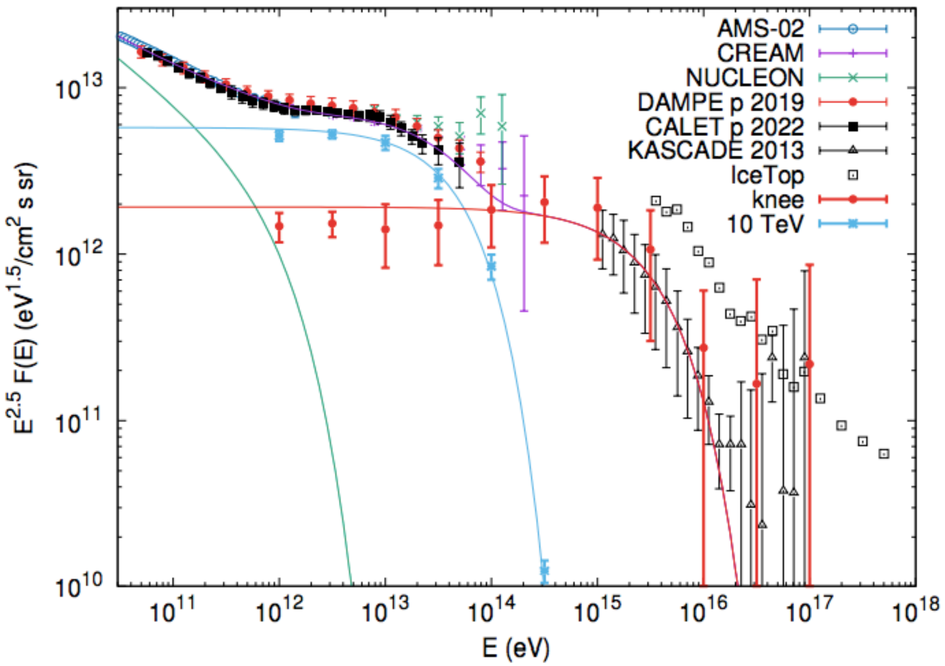




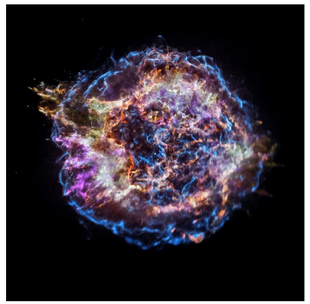
- More detailed measurements of the **CNO** and **Fe** spectra are needed between 1 PeV and 1 EeV.
- Need confirmation of the position of the knee-like structures for these cosmic-ray nuclei.
- How is the transition between TeV and PeV (PeV and EeV) data for these cosmic-ray nuclei?

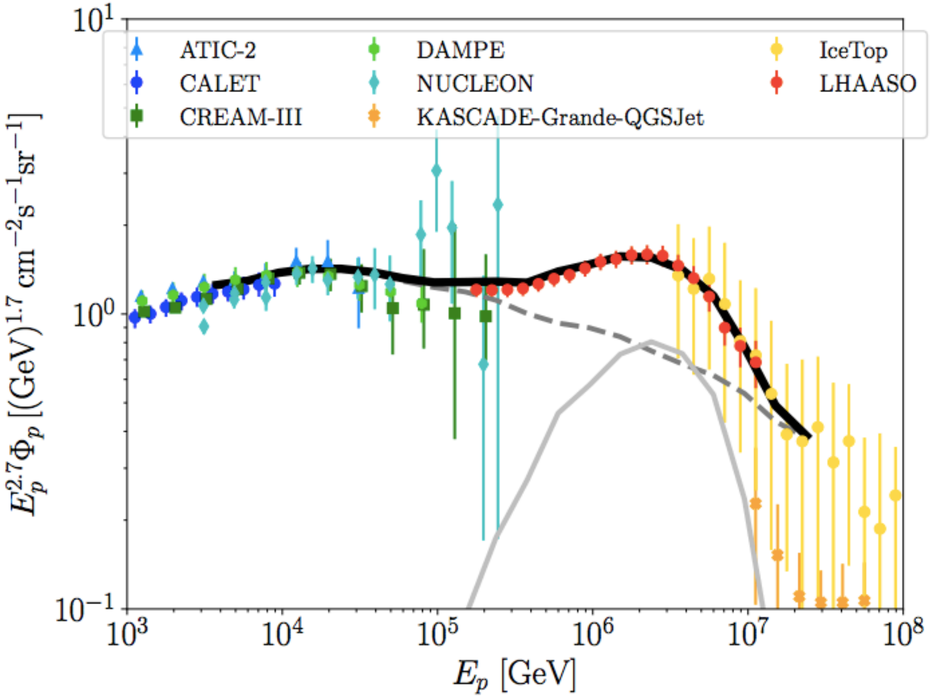
5) Part 2: 1 PeV - 1 EeV

Models to explain formation of the knee

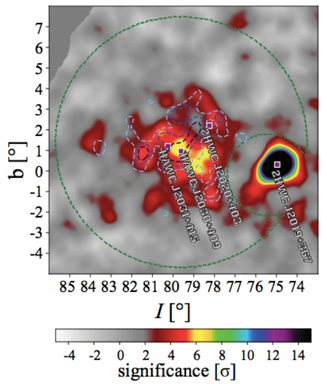


CAS A [NASA]





Cygnus Cocoon [HAWC]

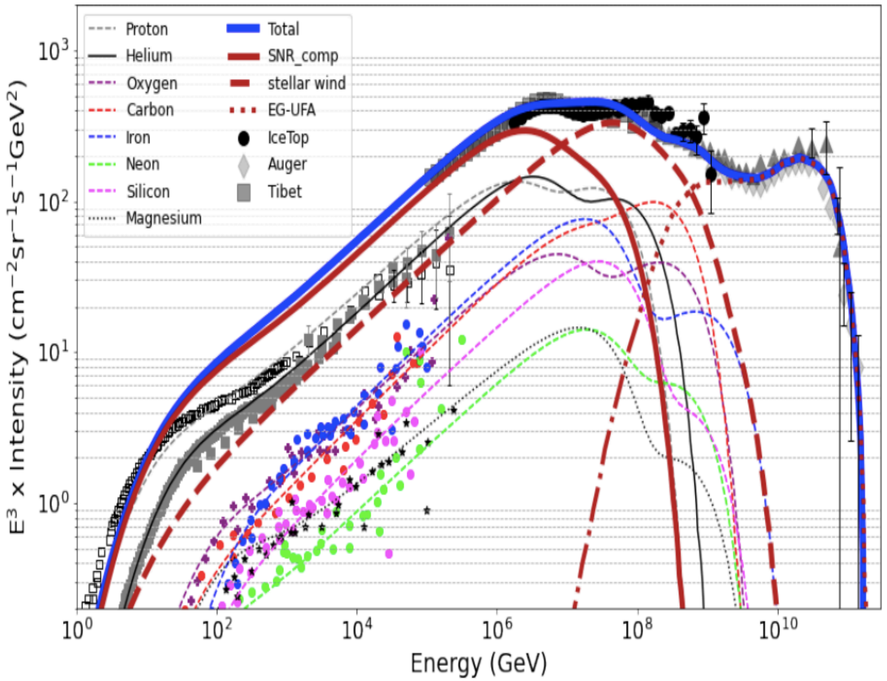


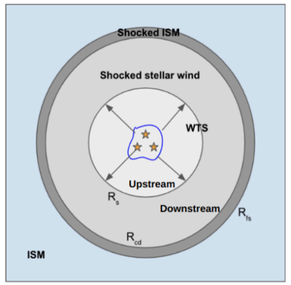
- **PeV SNR sources**
  - [G. Giacinti et al., arXiv:2305.10251 **[astro-ph.HE]]**
    - ✓ 1.6% of majority of SNRs.
    - ✓ Core-Collapse SNe in dense stellar winds [A.R. Bell, MNRAS 431 (13); A. Marcowith, MNRAS 479 (18)]

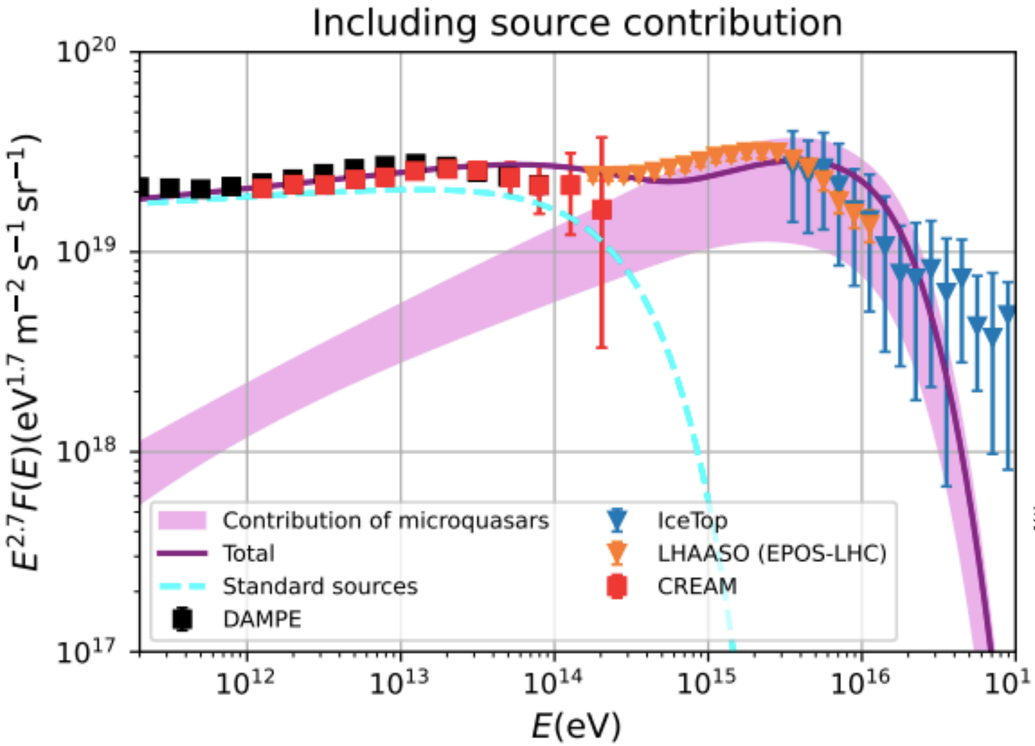
- **Cygnus Cocoon**
  - [K. Fang et al.,ApJL 999 **(26)]**
    - ✓ Knee formed by sources with D ≈ 1 kpc and t = 0.1-1 Myr.
    - ✓ Cygnus Cocoon is a promising candidate, D = 1.4 kpc.

5) Part 2: 1 PeV - 1 EeV

Models to explain formation of the knee

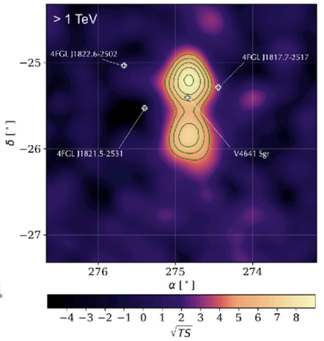






V4641 Sgr

[HAWC]

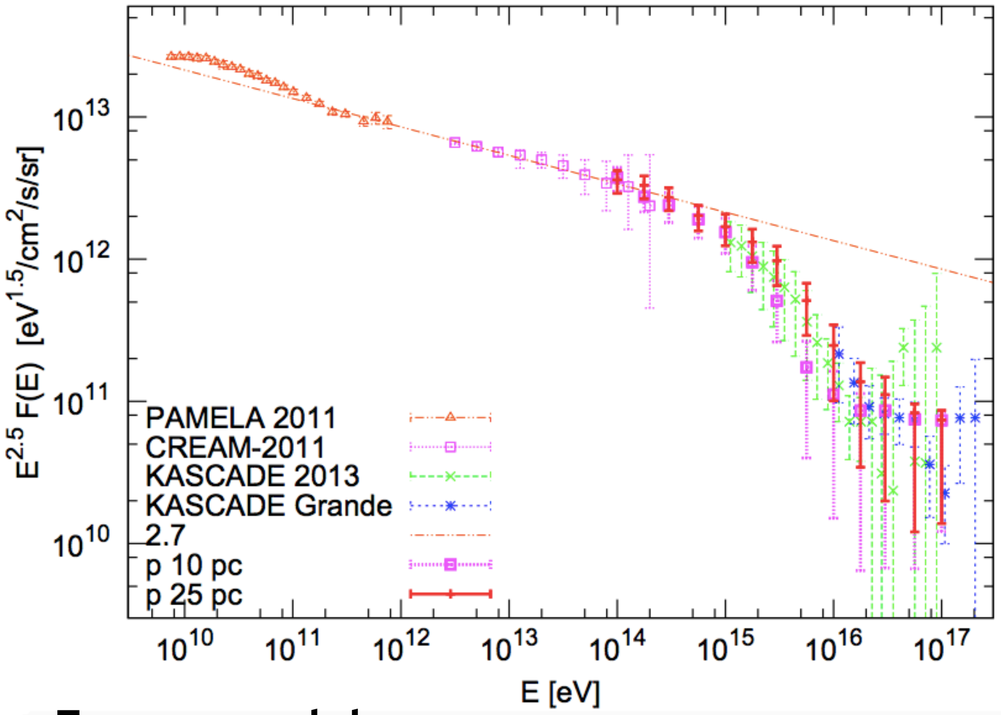


- **SNR + Massive young stellar clusters**
  - [S. Bhadra et al., ApJ961 (24)]
    - ✓ SNR in small clusters: E < 10 PeV.
    - ✓ Star Clusters: E ∈ 10 PeV - 1 EeV.

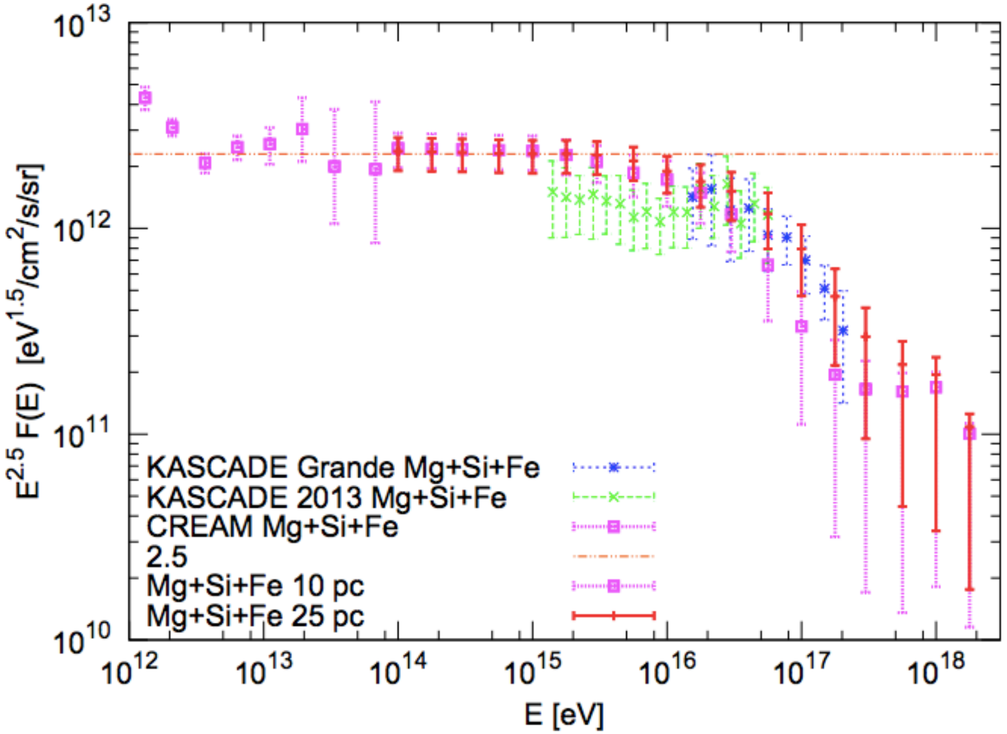
- **Microquasars**
  - [S. Kaci et al., arXiv:2510.01369v1 **[astro-ph.HE]**]
    - ✓ The contribution of ~10 powerful Microquasars in the Milky Way (Acretion ≥ Eddington limit4) can explain CR data.
    - ✓ Jet luminosity L ∈ [10^{39}, 10^{40}] erg/s.

5) Part 2: 1 PeV - 1 EeV

Models to explain formation of the knee



L



- **Escape model**
  - [Giacinti et al., PRD 91 (15)]

✓ Knee is produced by a change in CR diffusion coefficient.
✓ The change is produced @ E where

$\ell_c = L/5$

ℓ_c: Coherent length of turbulent B = 5 pc
L : Larmor radius

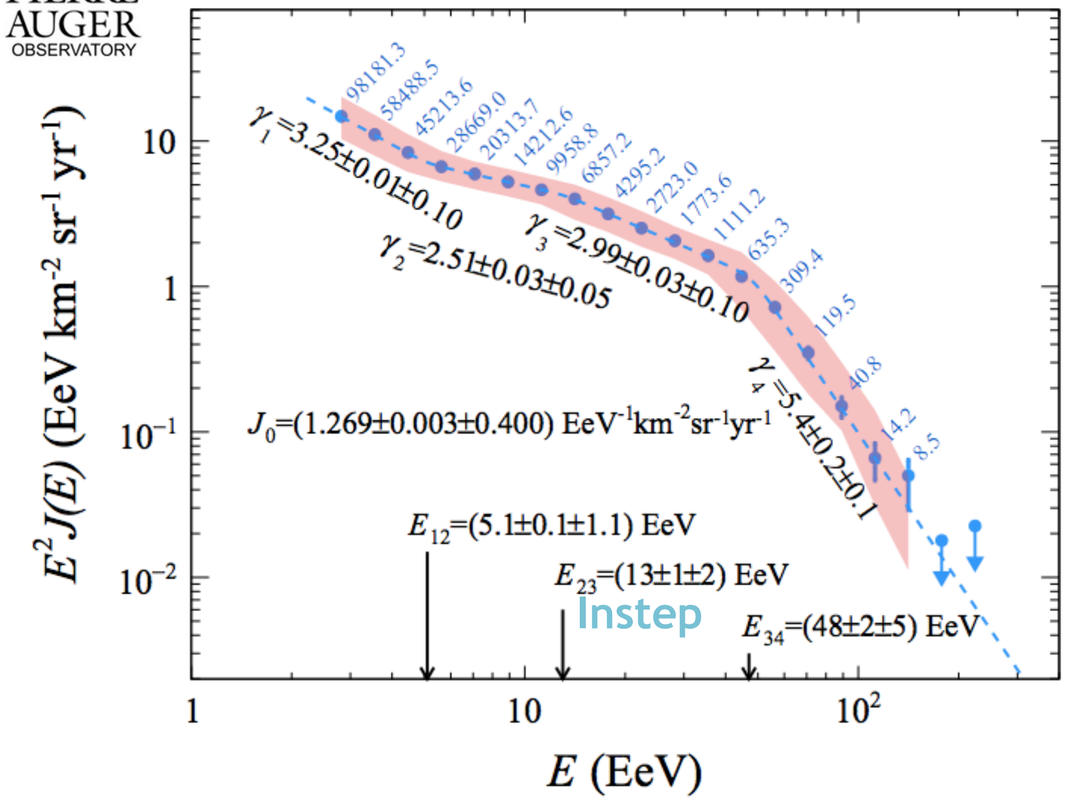
✓ Brms = 0.3 μG
✓Produces also recoveries at 10 PeV in elemental spectrum.

Part 3: 1 EeV - 100 EeV

See also Karen's presentation on UHECR

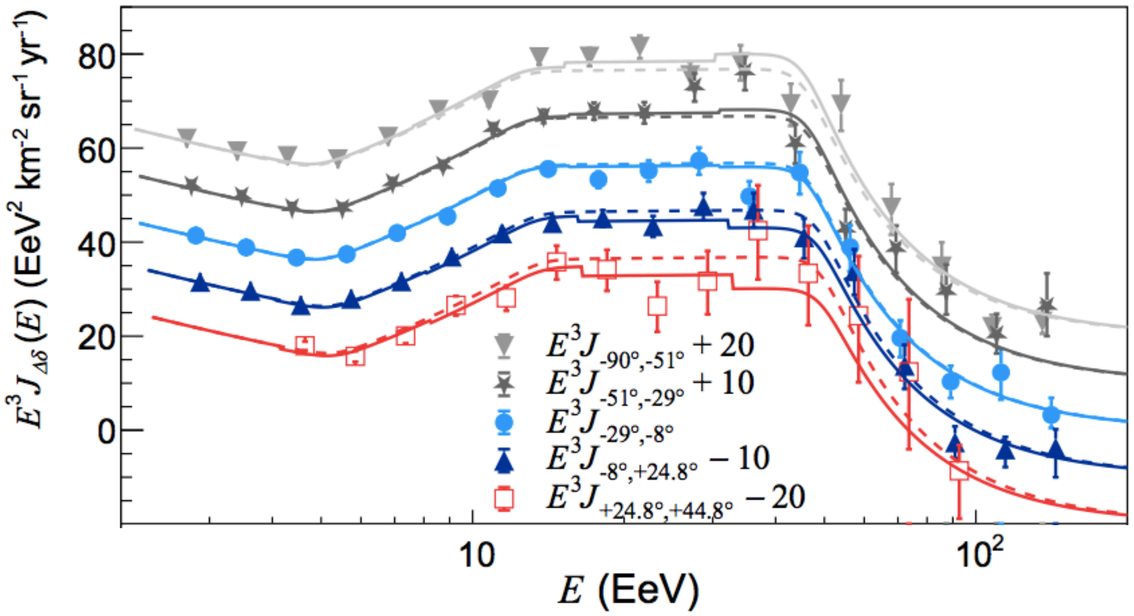

PIERRE
AUGER
OBSERVATORY
Operation: Since 2008 (Inauguration)
Location: Malargüe, Mendoza, Argentina
Altitude: 1400 m a.s.l. (875 g/cm²)
CR energy range: 6 PeV - 100 EeV
Credit: PAO Collaboration

[PAO Collab., PRL 135 (2025) 24]



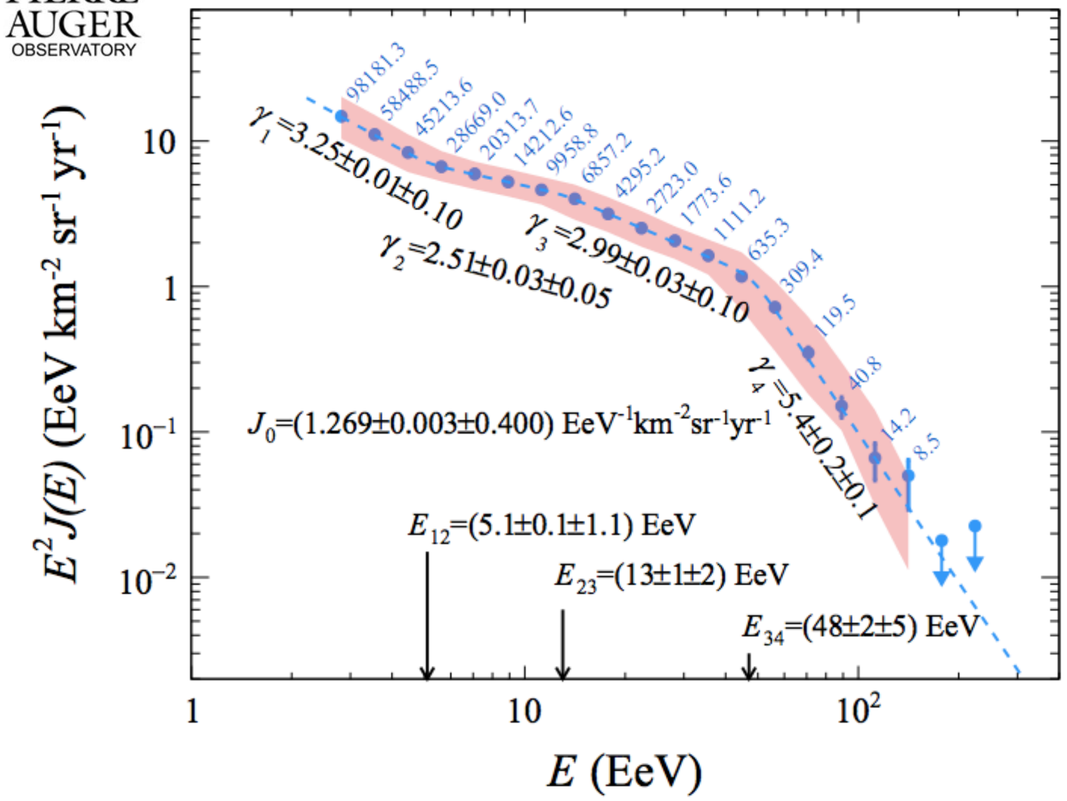
- Total spectrum of CR was obtained for E > 2.5 EeV.
- 19 years of data
- Combined spectrum from events with $0^\circ < \theta < 60^\circ$ and $60^\circ < \theta < 80^\circ$.
- Declination band $-90^\circ < \delta < +44.8^\circ$.
- Instep observed @ 10 EeV with 5σ.

[PAO Collab., PRL 135 (2025) 24]

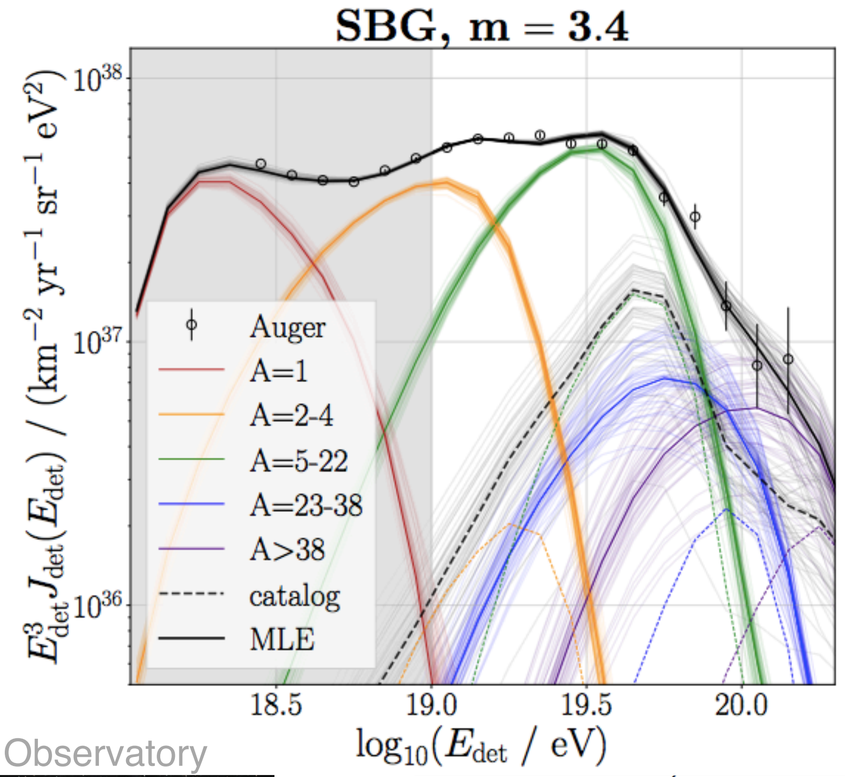


- No declination dependence is observed across the δ range [-84.8°, +24.8°].
- **Instep** is not due to foreground sources.

[PAO Collab., PRL 135 (2025) 24]

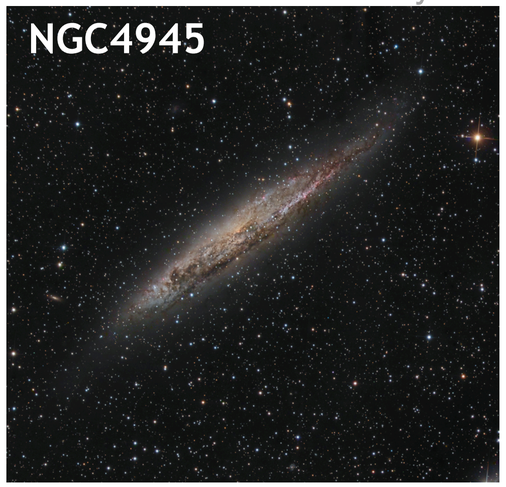


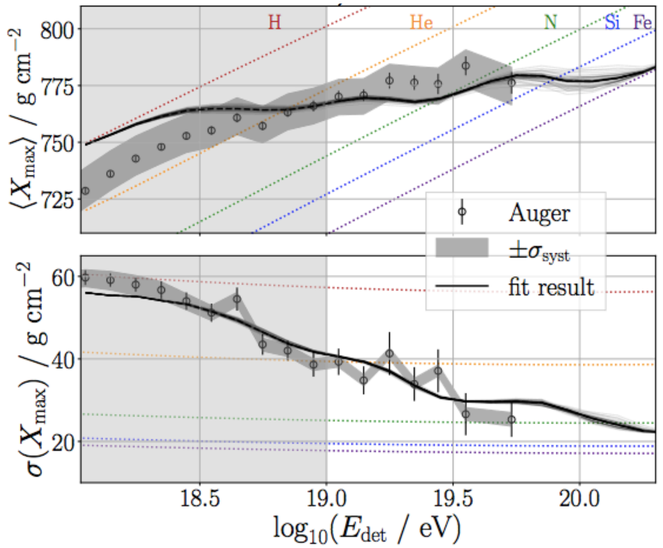
[PAO Collab., PRL 135 (2025) 24]



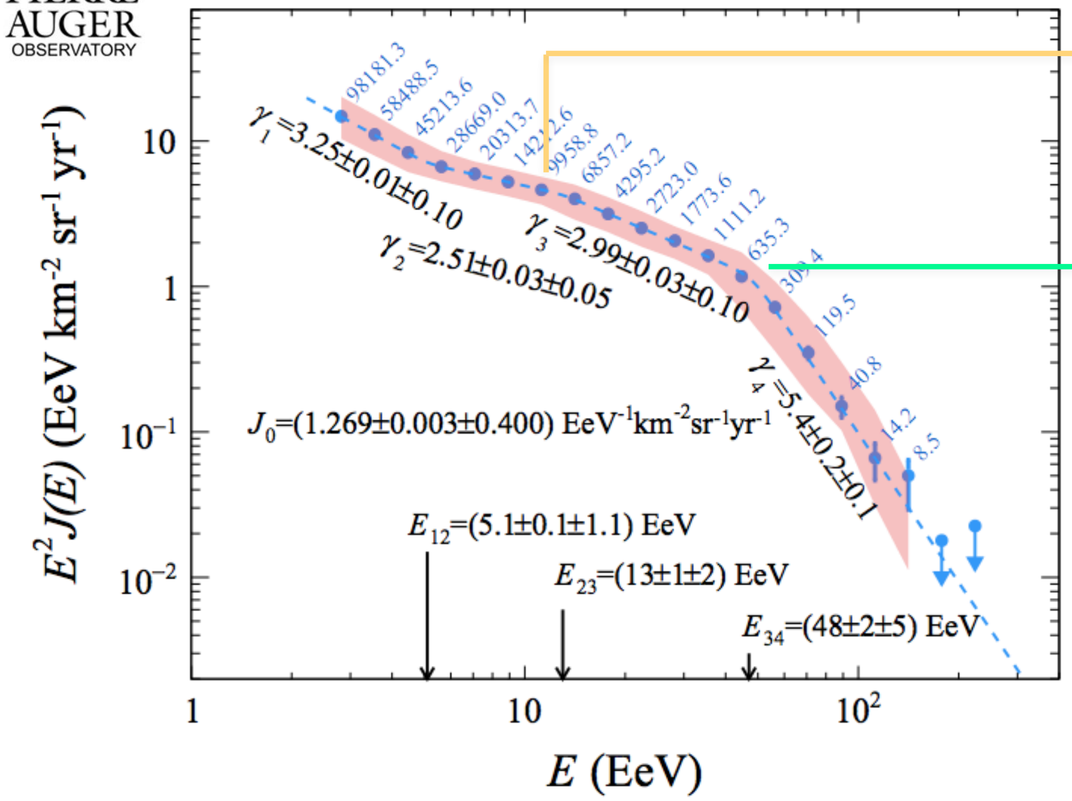
- **Combined fit** to total spectrum, mass composition and arrival directions shows that data can be well described by **Starburst Galaxies** (SBG).
- Strongest SBG: **NGC4945**. Direction and distance almost similar to Centaurus A. 3% contribution to total spectrum @ 40 EeV.

Atacama Observatory

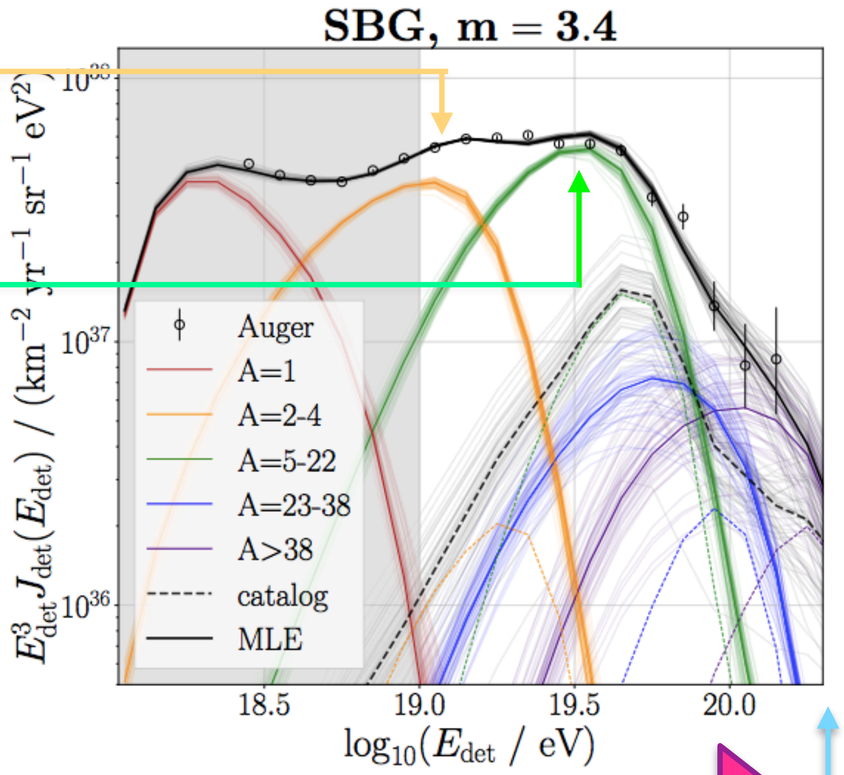




[PAO Collab., PRL 135 (2025) 24]



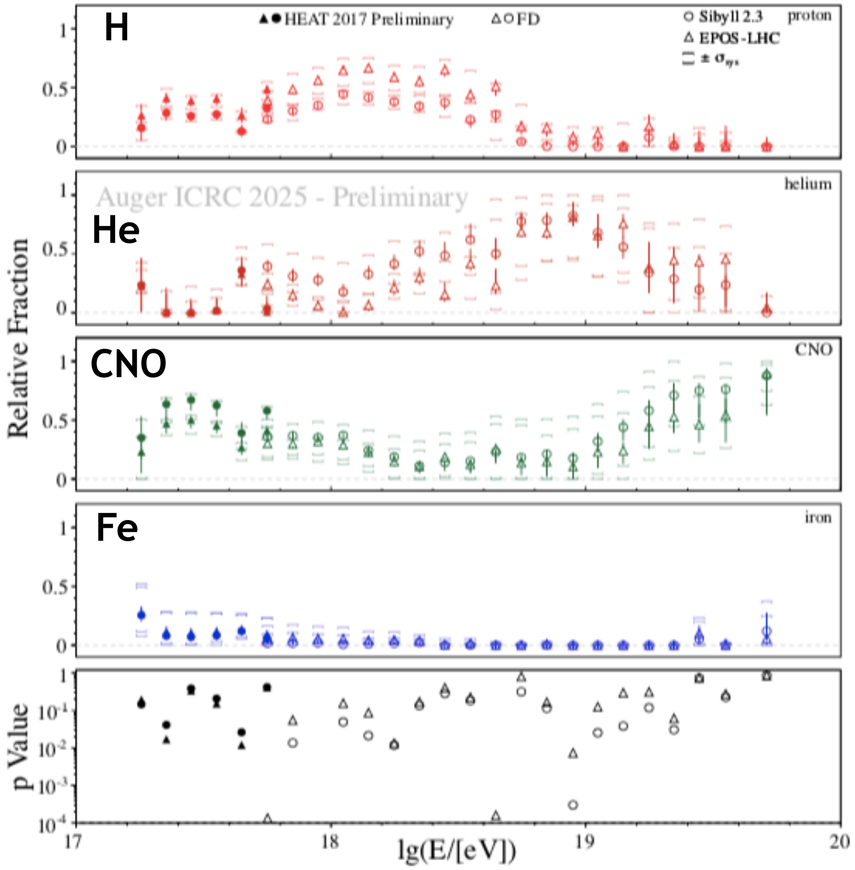
[PAO Collab., PRL 135 (2025) 24]



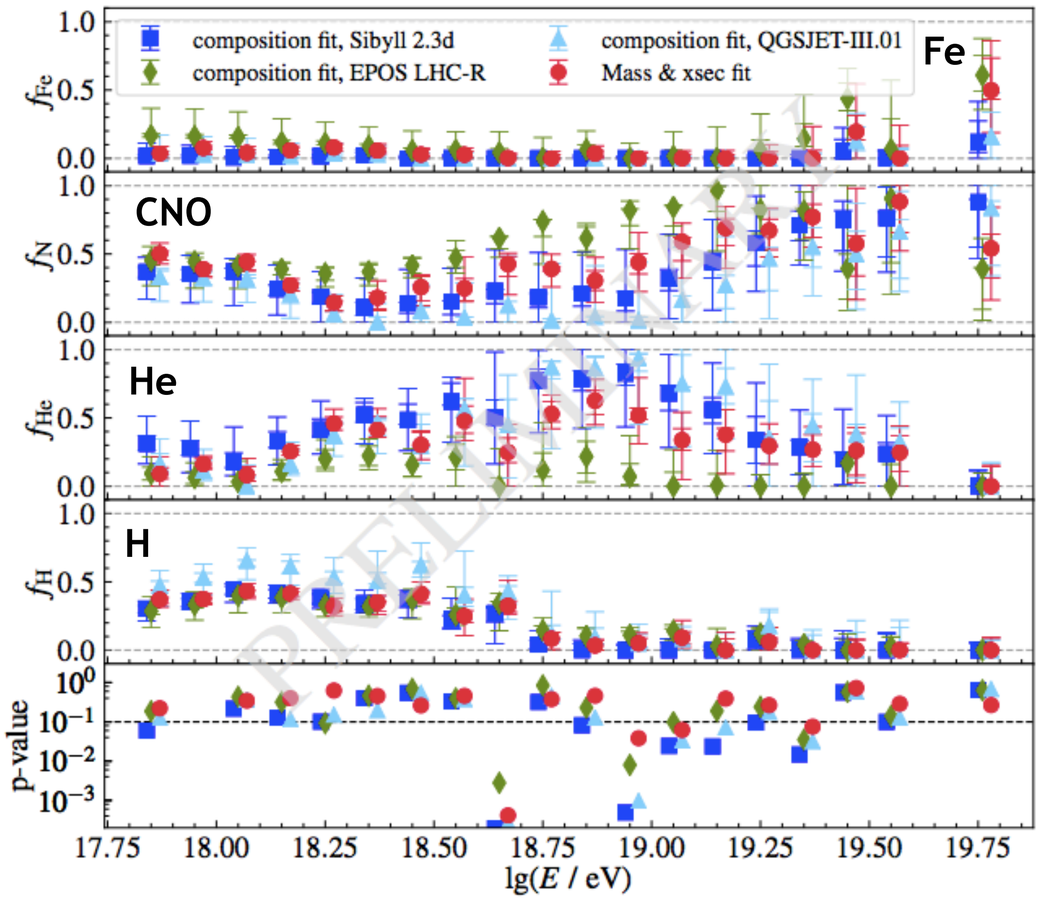
- **Instep** is due to a transition from the He to CNO spectra both from same type of sources.
- Above the **instep**, the CNO component is dominant.
- At the **suppression**, the Si and Fe groups dominate.

Atomic mass grows at higher energies.

Mass composition



[A.A. Halim et al., PoS(ICRC2025) 331]

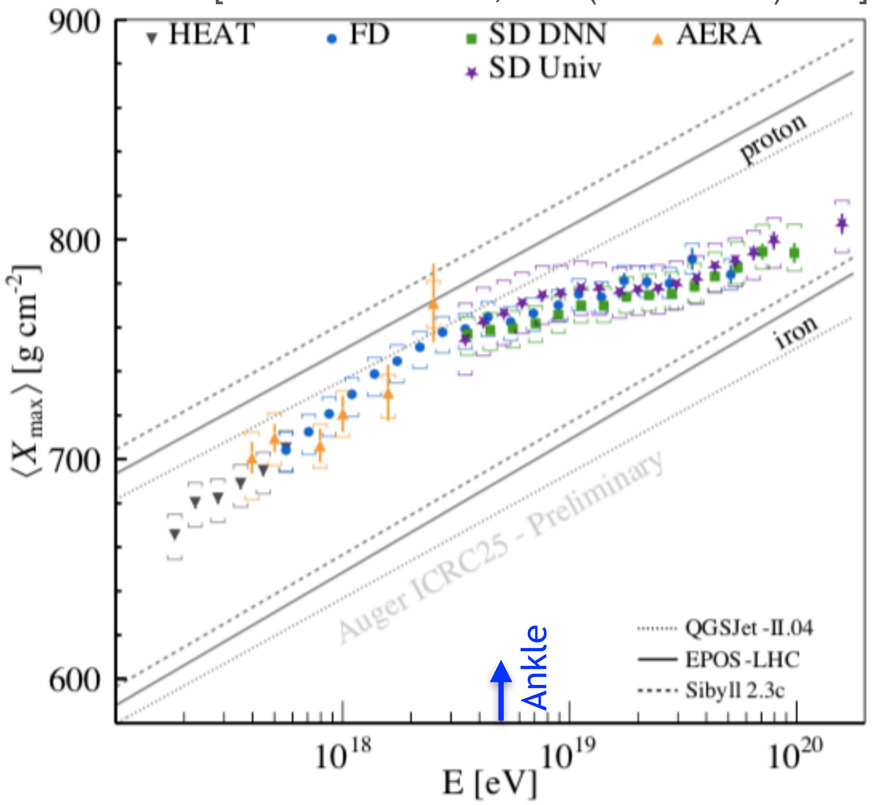


[A.A. Halim et al., PoS(ICRC2025) 416]

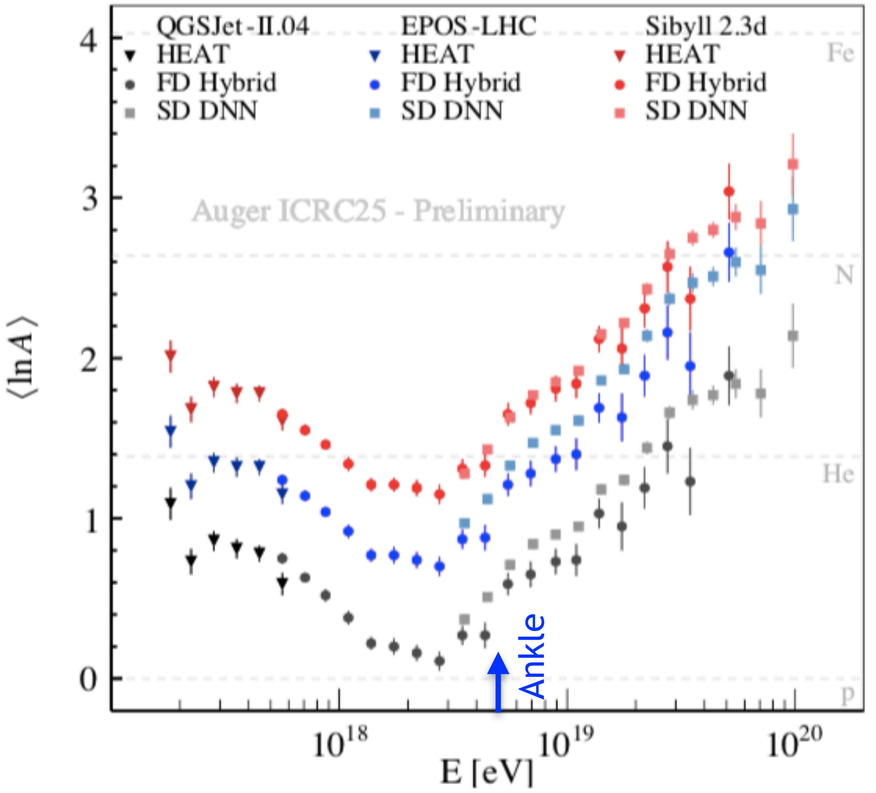
- The relative abundances of **H** and **He** are larger within the [1, 10] EeV energy decade.
- At energies > 10 EeV, the **CNO** mass group becomes more important.

Mass composition

[A.A. Halim et al., PoS(ICRC2025) 331]



[A.A. Halim et al., PoS(ICRC2025) 331]



- At ultra-high energies, cosmic-ray composition seems to be mixed.
- Ankle in cosmic-ray spectrum is not completely dominated by protons.
- At ultra-high energies, composition becomes lighter up to 3 EeV, then it becomes gradually heavier.



Operation: Since 2008 (Full operation)

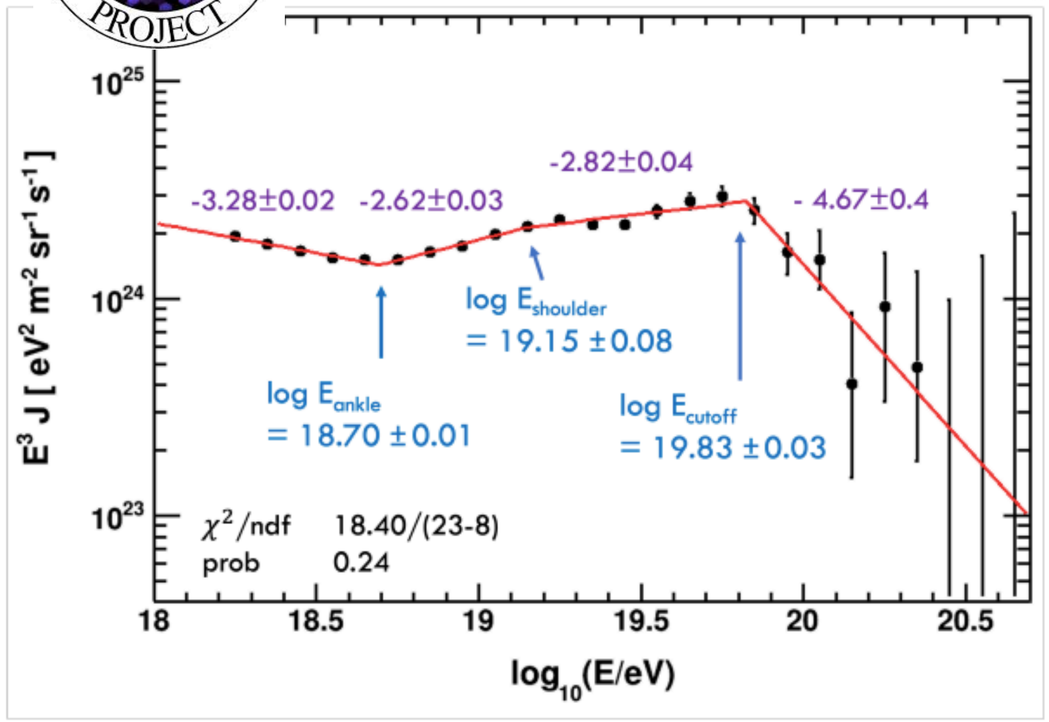
Location: West desert, Utah, USA

Altitude: 1400 m a.s.l. (880 g/cm^2)

CR energy range: 2 PeV - 100 EeV

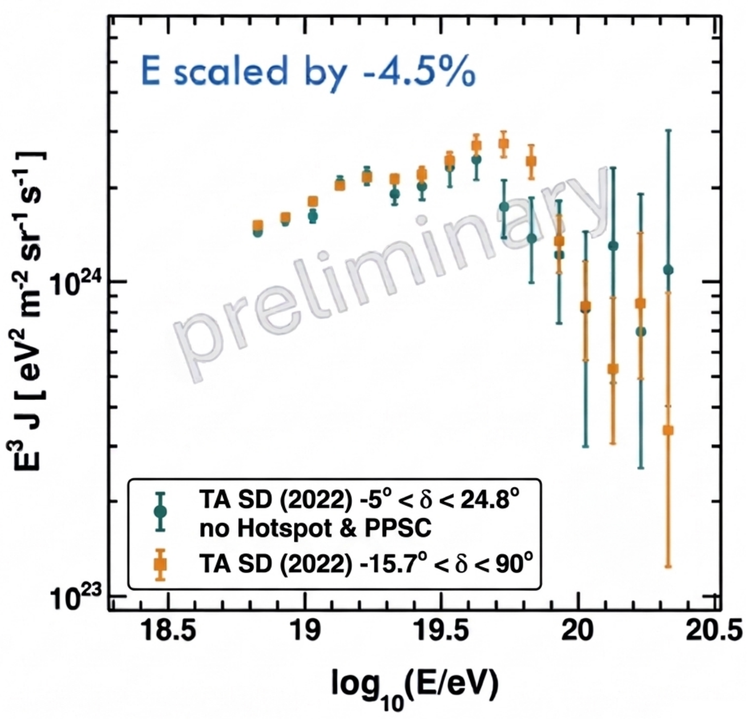
Credit: J. Matthews

[TA Collab., PoS(ICRC2025) 301]

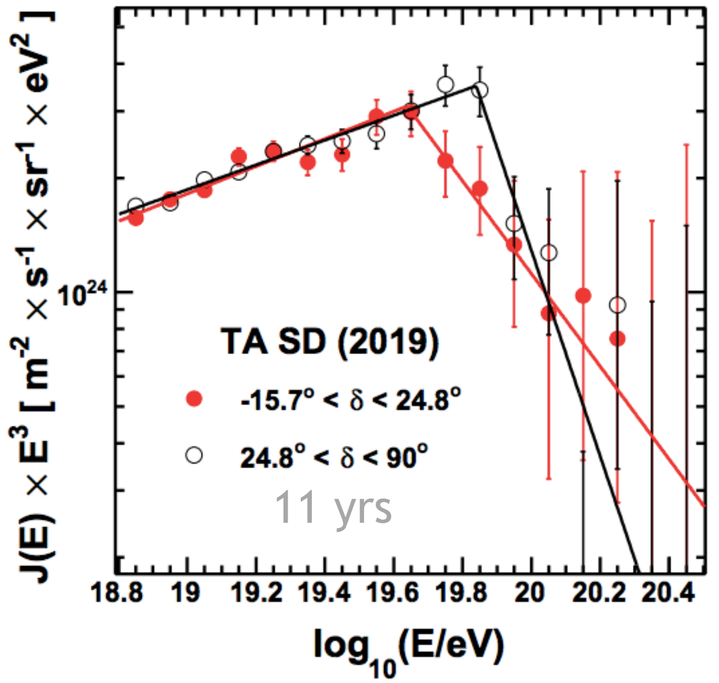


- Total spectrum of CR was obtained for E > 1.6 EeV.
- 16 years of data
- θ < 45°.
- Instep observed @ 13 EeV with 5.2σ.
- Suppression @ 68 EeV with 6.3σ.

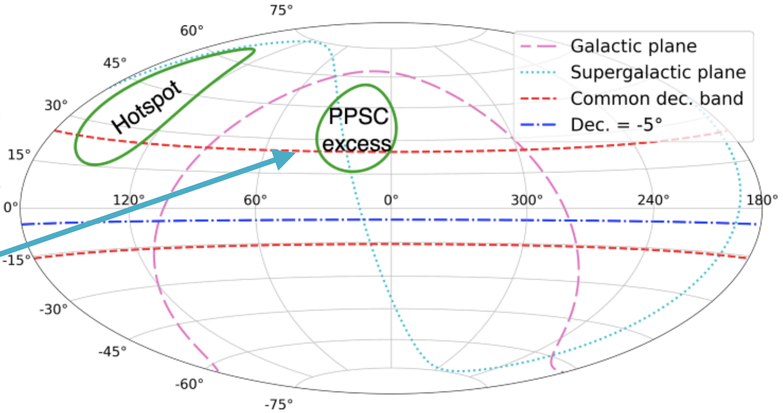
[TA Collab., PoS(ICRC2025) 301]



[TA Collab.,1801.07820 [astro-ph.HE]]



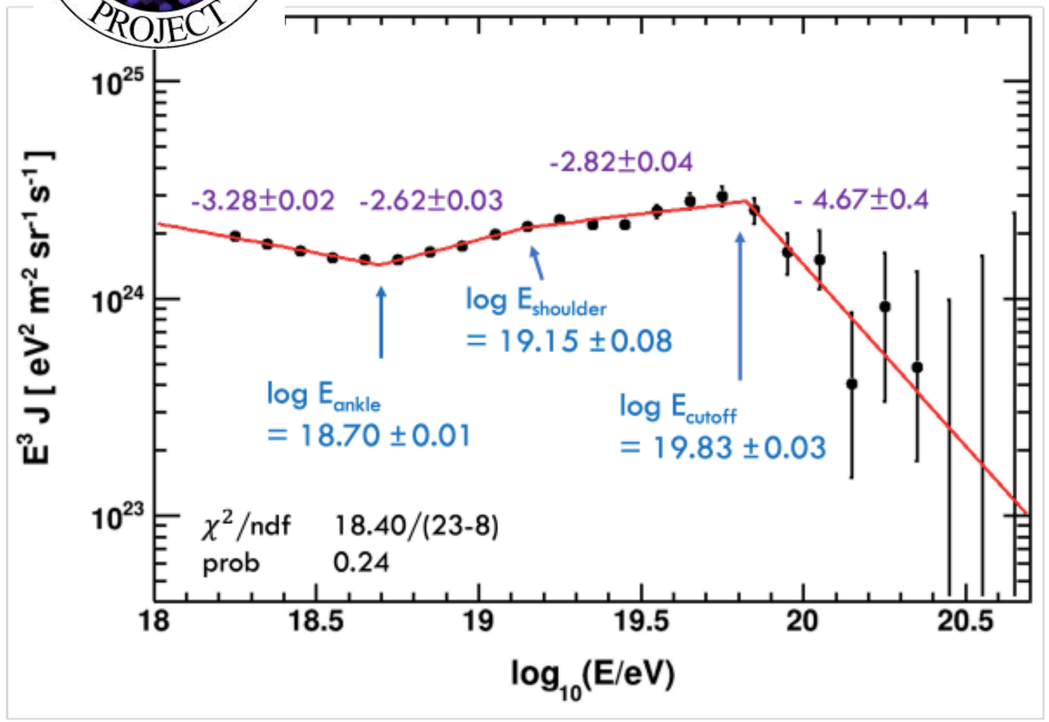
- Declination dependence is observed within the δ range [-15.7°, +90°] (θ < 55° data).



PPSC: Perseus-Pisces supercluster

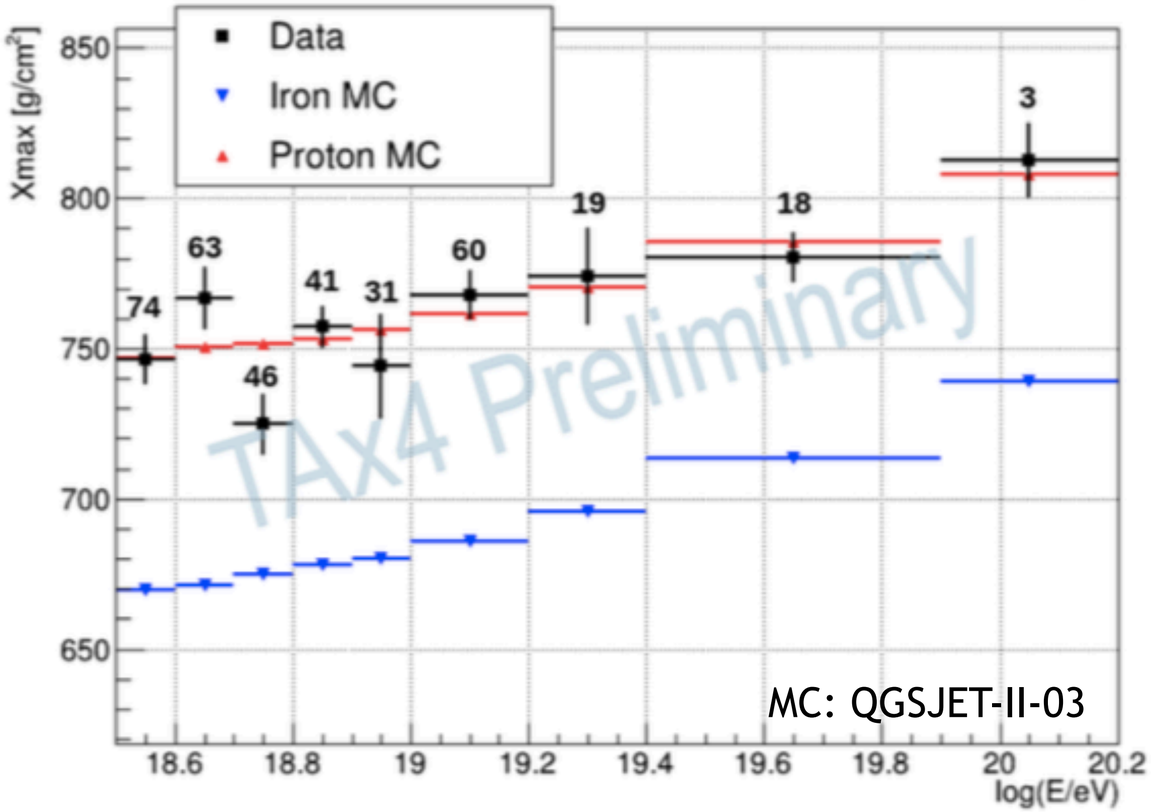
[TA Collab., 2406.08612 [astro-ph.HE]]

[TA Collab., PoS(ICRC2025) 301]



- Total spectrum of CR was obtained for E > 1.6 EeV.
- 16 years of data of TA (SD main array + 3 FD stations).
- θ < 45°.
- Instep observed @ 13 EeV with 5.2σ.
- Suppression @ 68 EeV with 6.3σ.

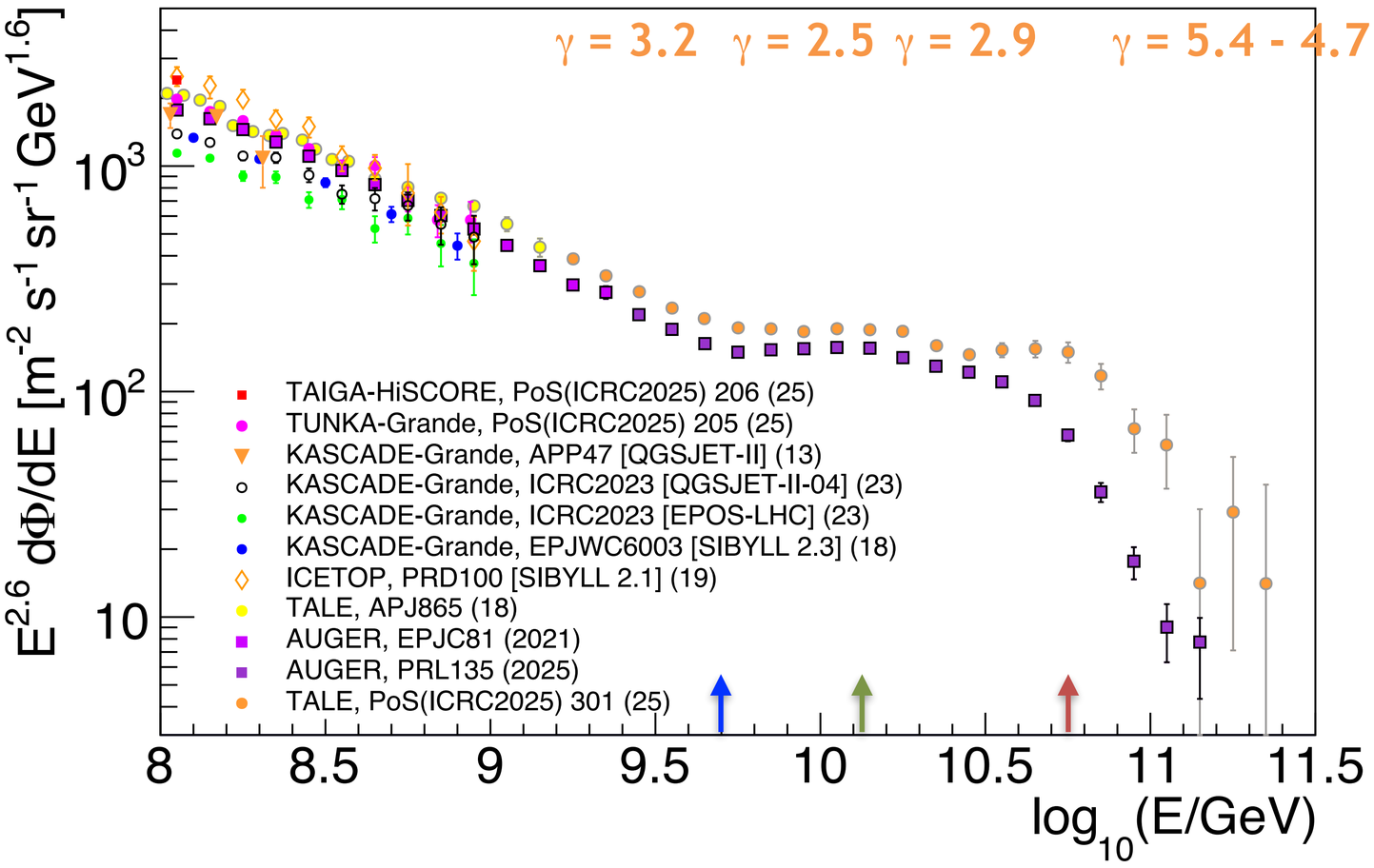
[TA Collab., PoS(ICRC2025) 269]



- TAx4 analysis suggest that light cosmic ray nuclei dominates the spectrum above 3.2 EeV.

6) E ∈ 1 EeV - 100 EeV

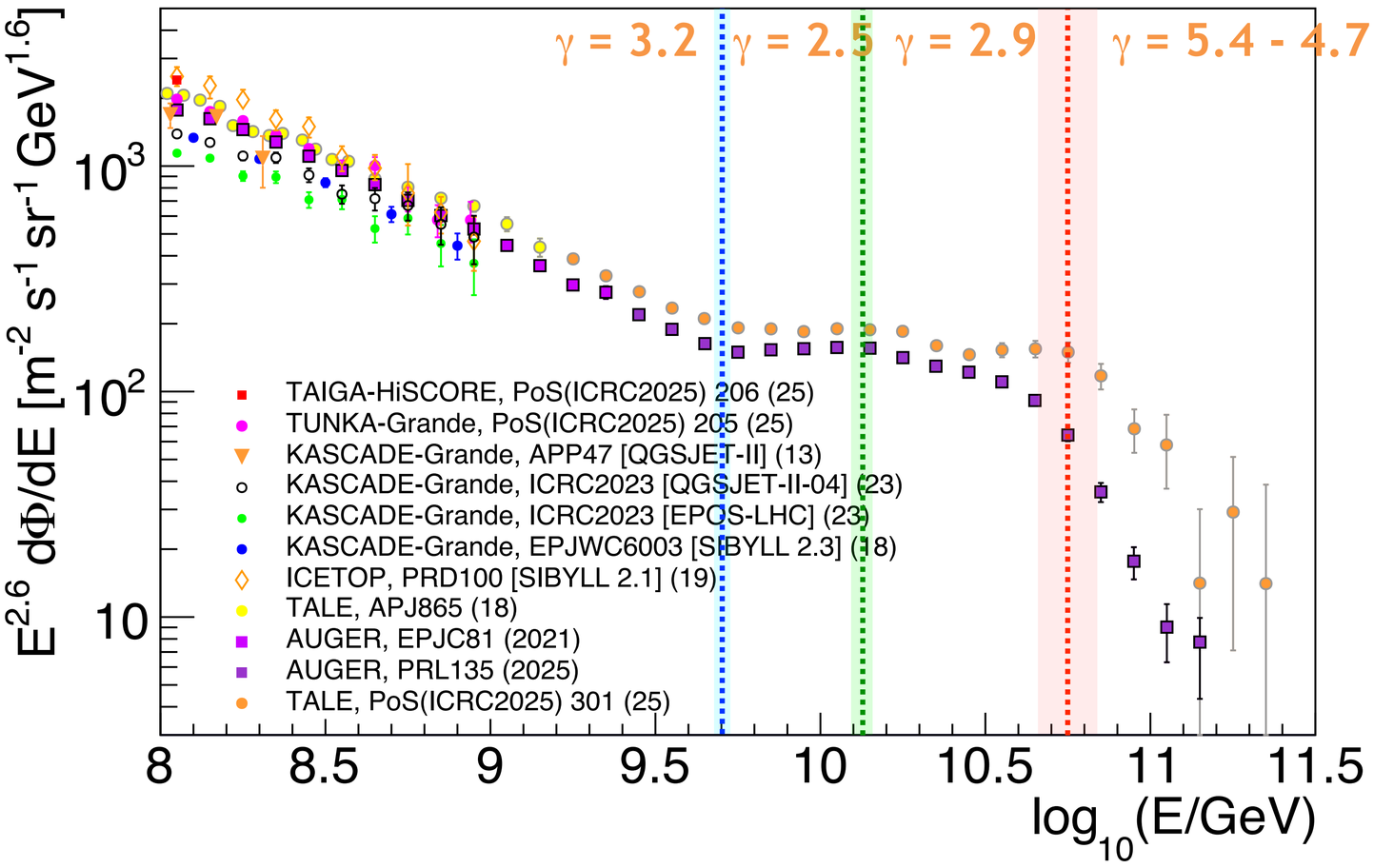
Total energy spectrum



- **Features:**
  - Ankle @ E ∈ [5.0, 5.1] x 10^{18} eV
  - Instep @ E ∈ [13.0, 14.1] x 10^{18} eV
  - Cut-off @ E ∈ [48.0, 67.6] x 10^{18} eV
- Between 2.8 EeV and 10 EeV, spectral shape measured by TA and Auger is in agreement within systematic uncertainties.
- Difference between energy scales for E < 10 EeV:
  - TA & Auger: **11.2%**
- Difference between energy scales for E ≥ 10 EeV:
  - TA & Auger: **16%-20%/Energy decade**

6) E ∈ 1 EeV - 100 EeV

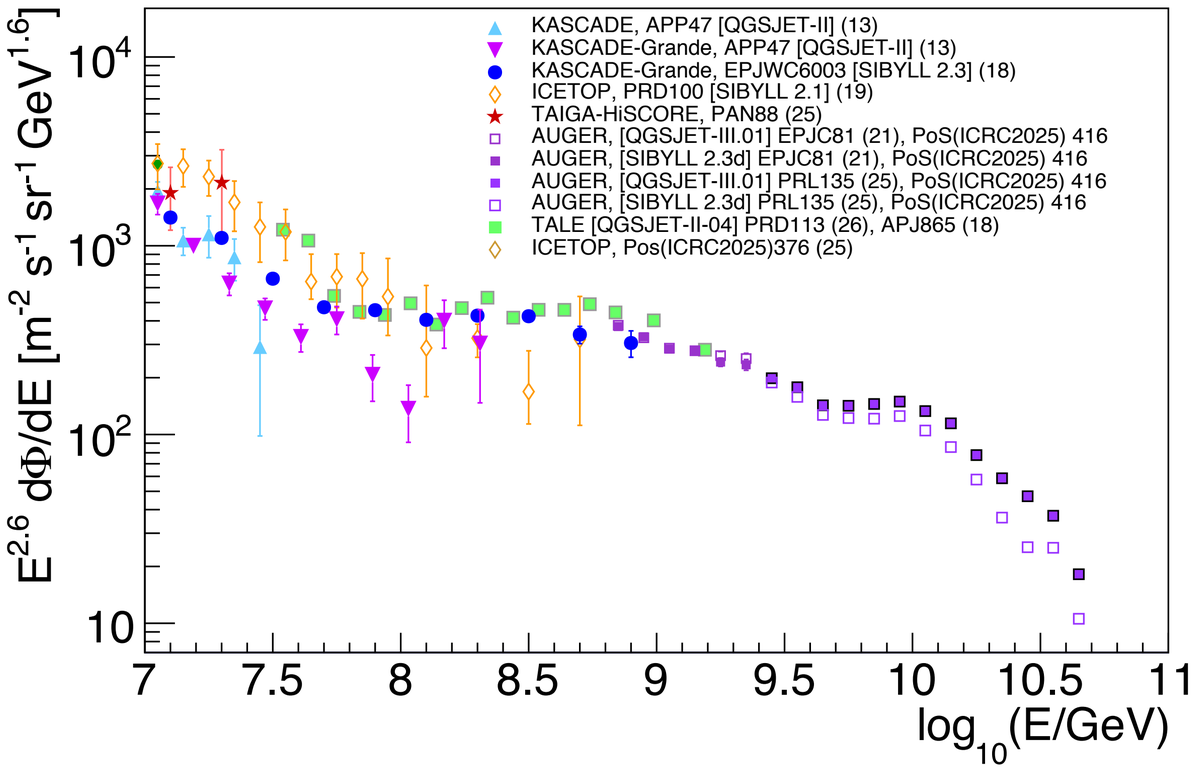
Total energy spectrum



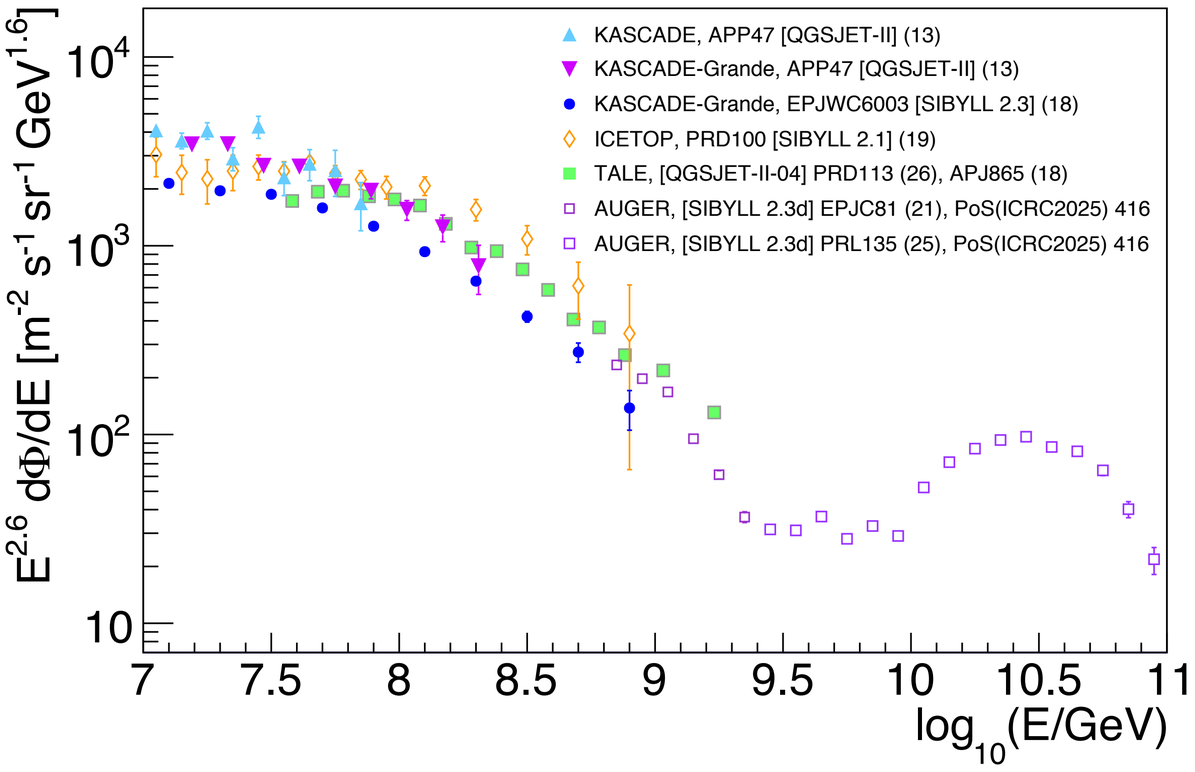
- **Features:**
  - Ankle @ E ∈ [5.0, 5.1] x 10^{18} eV
  - Instep @ E ∈ [13.0, 14.1] x 10^{18} eV
  - Cut-off @ E ∈ [48.0, 67.6] x 10^{18} eV
- Between 2.8 EeV and 10 EeV, spectral shape measured by TA and Auger is in agreement within systematic uncertainties.
- Difference between energy scales for E < 10 EeV:
  - TA & Auger: **11.2%**
- Difference between energy scales for E ≥ 10 EeV:
  - TA & Auger: **16%-20%/Energy decade**

6) E ∈ 1 EeV - 100 EeV

Mass composition



Pierre Auger



- We observe the possible presence of features in the spectra of light and heavy nuclei at ultra-high energies.

6) E ∈ 1 EeV - 100 EeV

- **Extragalactic contribution for E > 100 PeV in the spectrum of light cosmic-ray nuclei?**

Rate of energy production in **Sub-TeV γ-rays de Sub-TeV**, diffuse PeV ν's and ultra-high-energy cosmic rays is of the same order of magnitude: common oirigin?

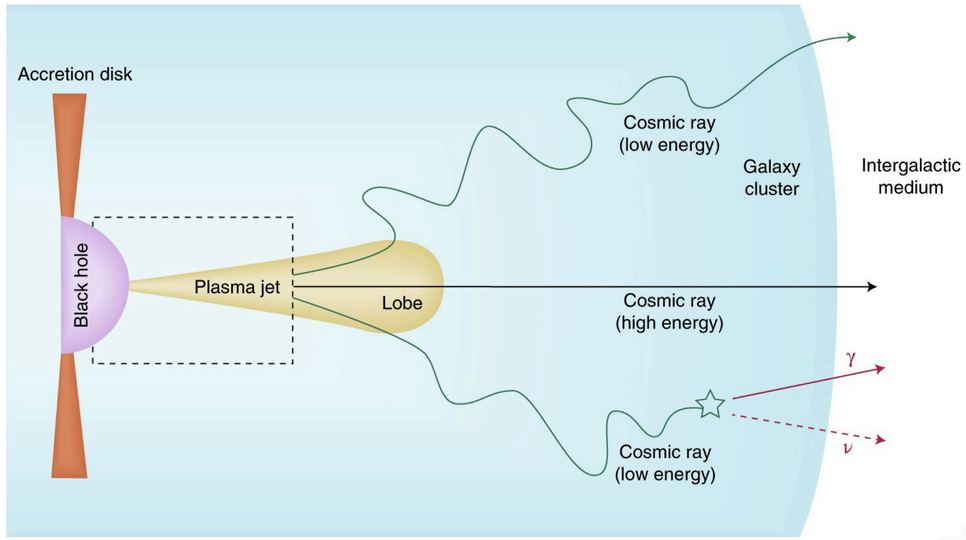
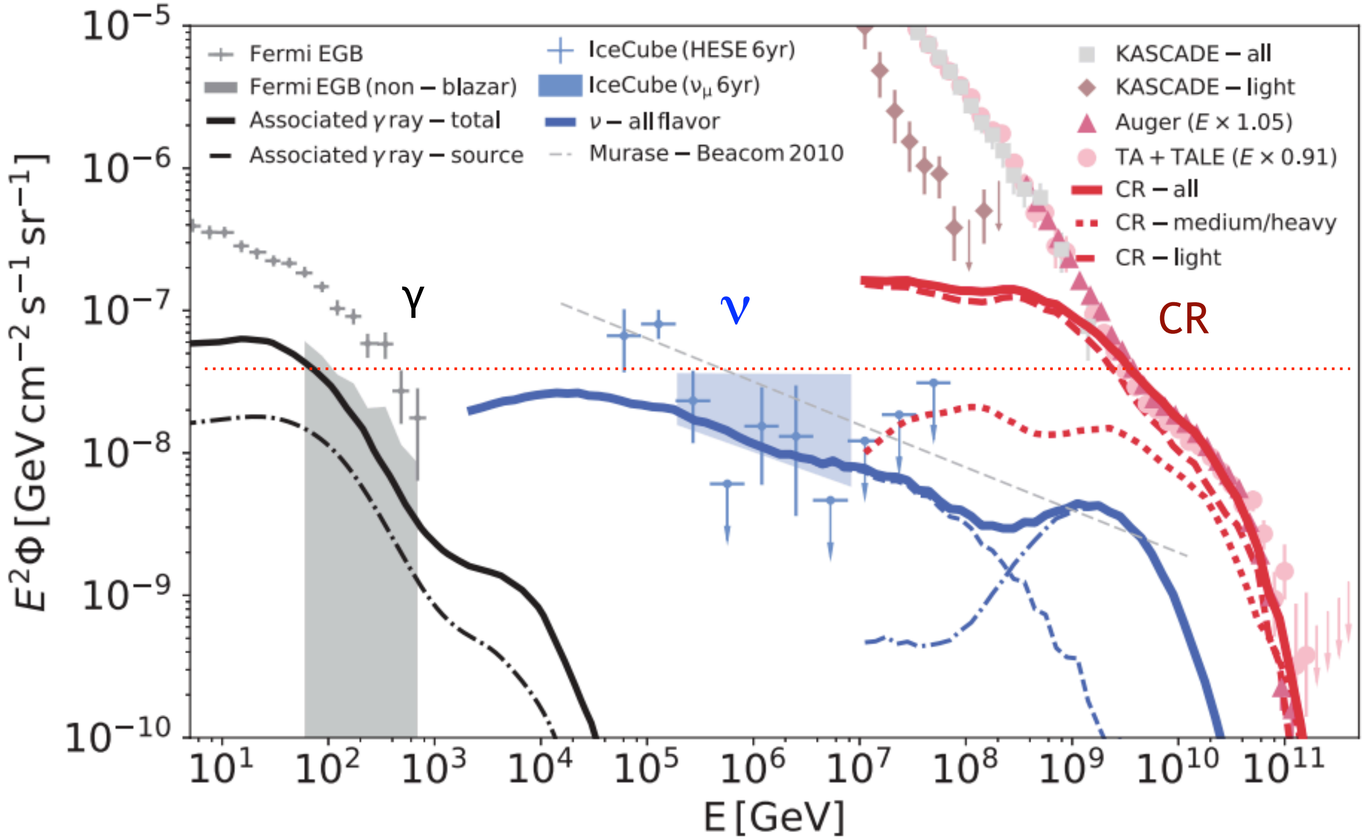


Imagen: J. B. Tjus, Nature Physics 14 (2018)



[K. Murase and K. Fang, Nature Phys. 14 (2018) 396]

[K. Murase and F. W. Stecker, The Encyclopedia of Cosmology (23)]

- RCs (E > 100 PeV): They are produced in **jetted AGN** embedded in galaxy clusters.
- **γ-rays** (sub-TeV) and ν's (PeV): Generated by CR interactions inside the galaxy clusters in which the sources are embedded.

7) Summary

- E ∈ 100 GeV - 1 PeV
  - ⇨ Fine structure has been observed in all-particle spectrum: a 1 TeV hardening and a 10 TeV softening.
  - ⇨ Hardening could be due to propagation effects.
  - ⇨ Softening comes from individual steepenings in the spectra of H and He.
  - ⇨ The steepenings of the elemental spectra of cosmic rays support a Peter's cycle.
  - ⇨ CR origin could be connected with a local and young TeV source, a population of TeV accelerators, etc.

- E ∈ 1 PeV - 1 EeV
  - ⇨ Knee due to depletion of light CR nuclei.
  - ⇨ Second knee produced by steepening in spectrum of heavy CR component.
  - ⇨ Elemental spectra show individual spectra, whose locations support a Peter's cycle.
  - ⇨ The 100 PeV hardening in spectrum of light CR may indicate a possible transition from galactic to extragalactic component.

- E ∈ 1 EeV - 100 EeV
  - ⇨ Extragalactic origin.
  - ⇨ Composition is lighter up to 1 EeV, and becomes heavier at higher energies.
  - ⇨ Energy spectra of elemental mass groups reveals fine structure .

Thank you for your attention!

