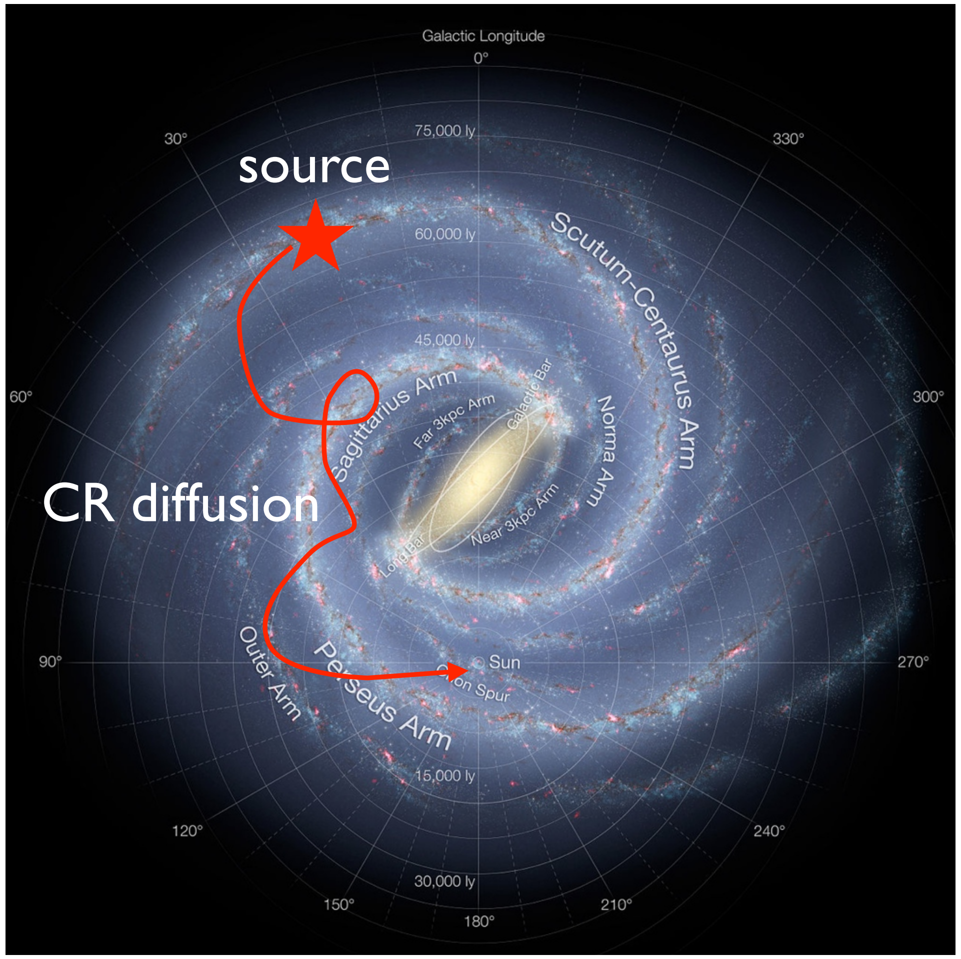
Outline

- *Galactic Cosmic Rays: the standard model*
- *Detection of Cosmic Rays at ground*
- *The energy spectrum of Galactic Cosmic Rays*
- *The knee at $\approx 4 \times 10^{15}$ eV*
- *Elemental composition in the knee energy region*
- *Outlook to the future*

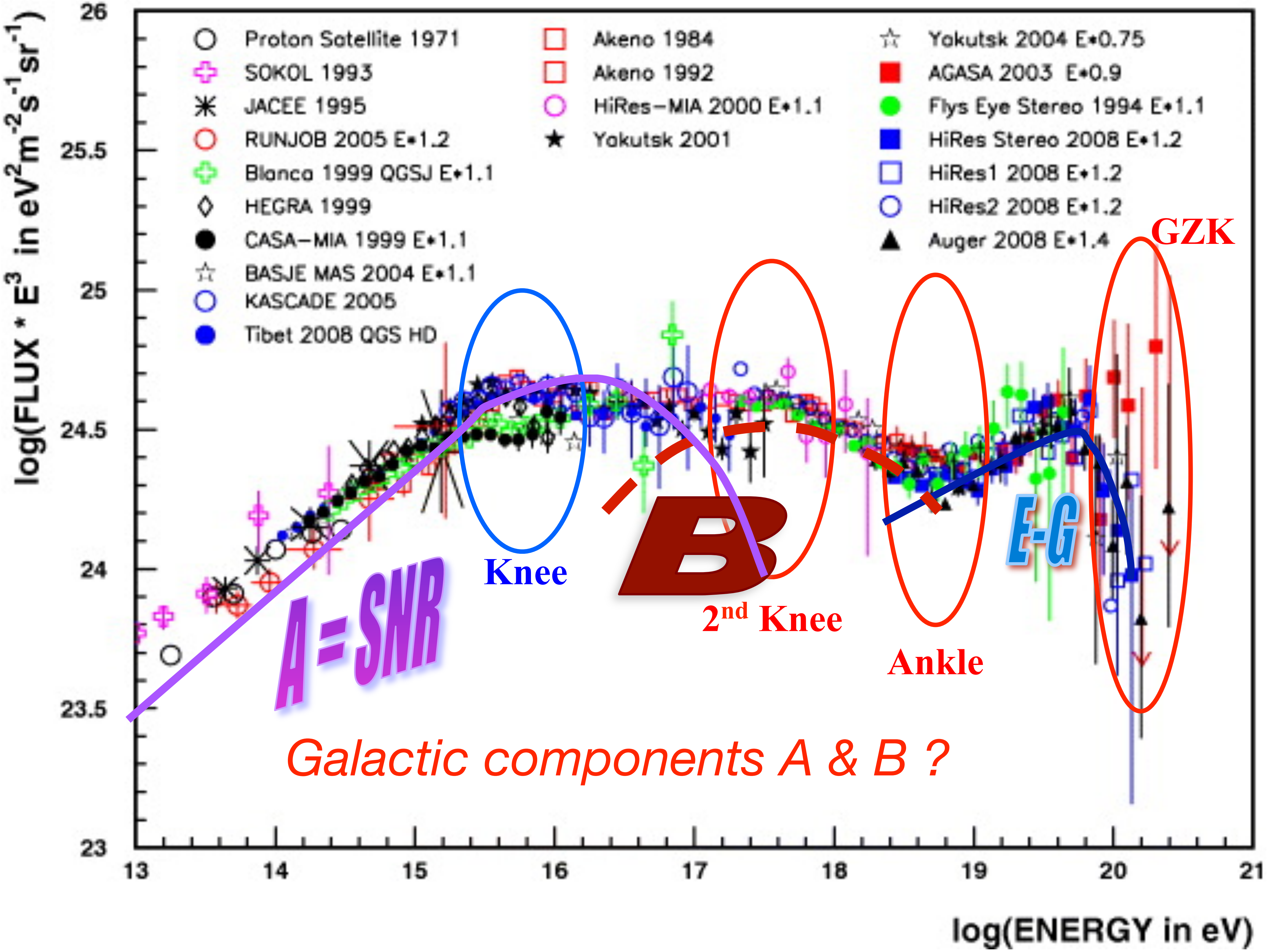
Galactic Cosmic Rays



- CRs below 10^{17} eV are predominantly Galactic.
- *Standard paradigm*: Galactic CRs accelerated in SuperNova Remnants
- Galactic CRs via *diffusive* shock acceleration ?
  $n_{CR} \propto E^{-\gamma}$ (at source)
- Energy-dependent *diffusion* through Galaxy
  $n_{CR} \propto E^{-\gamma-\delta}$ (observed)
- Galactic CRs are scrambled by galactic magnetic field over very long time
  ➜ arrival direction *mostly isotropic*
- Transition to extragalactic CRs occurs somewhere between 10^{17} and 10^{19} eV

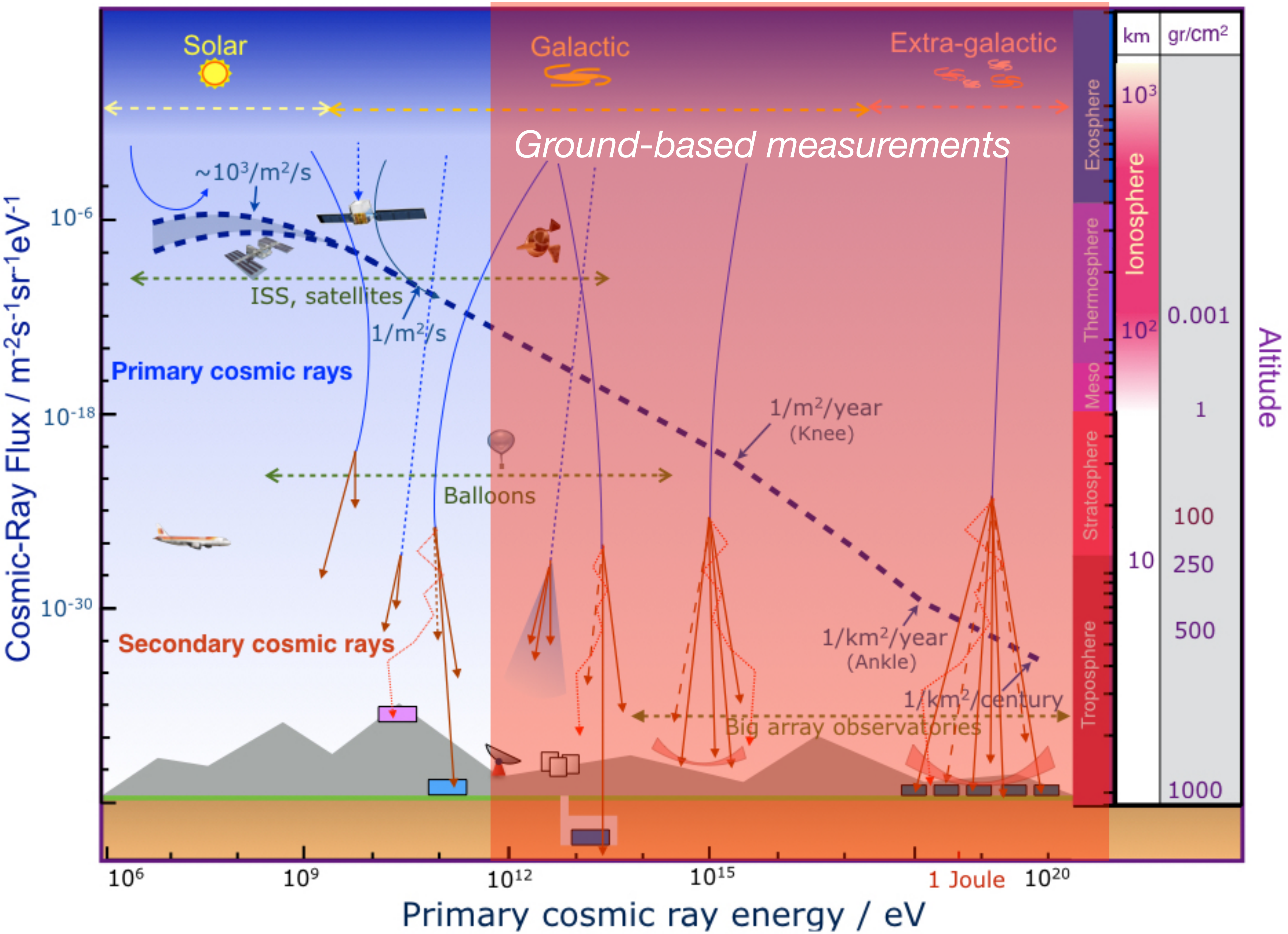
The main open questions in the SNR paradigm are: *(1) the total amount of energy channeled into relativistic particles; (2) the final spectrum injected into the ISM; (3) the maximum energy of accelerated particles.*

All-particle energy spectrum



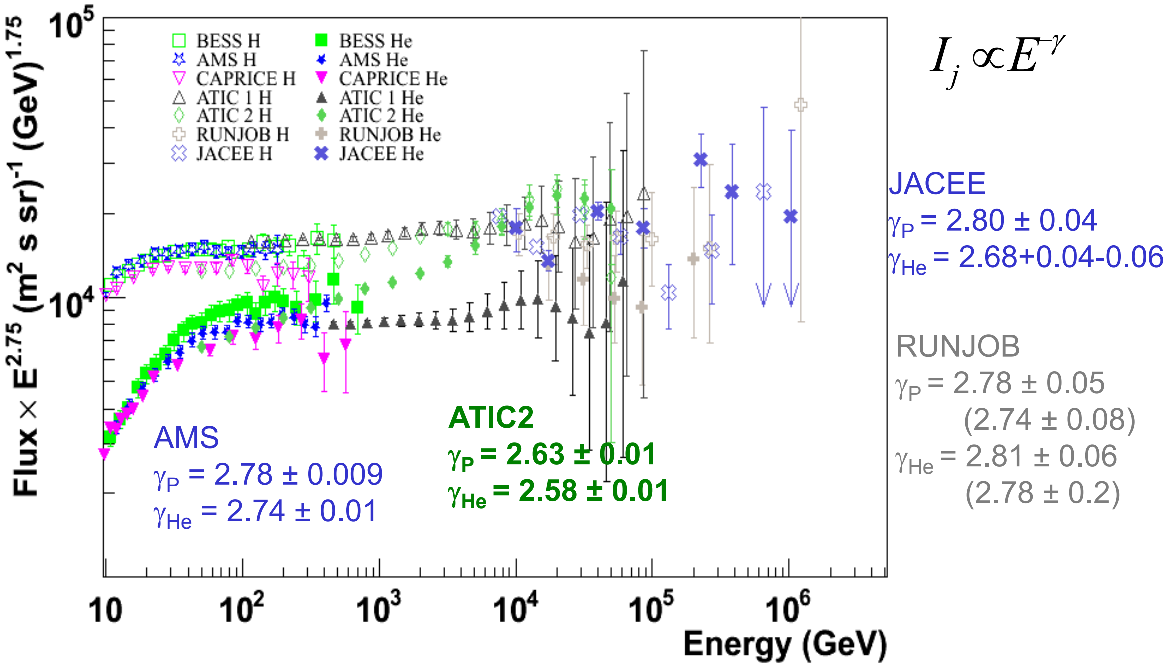
Galactic components A & B ?

Cosmic Ray detection



Charge resolved energy spectra

Until recently the *paradigm* was that all the primary GCR nuclei were essentially just *one feature-less power law* between a few GeV per nucleon and the “knee".

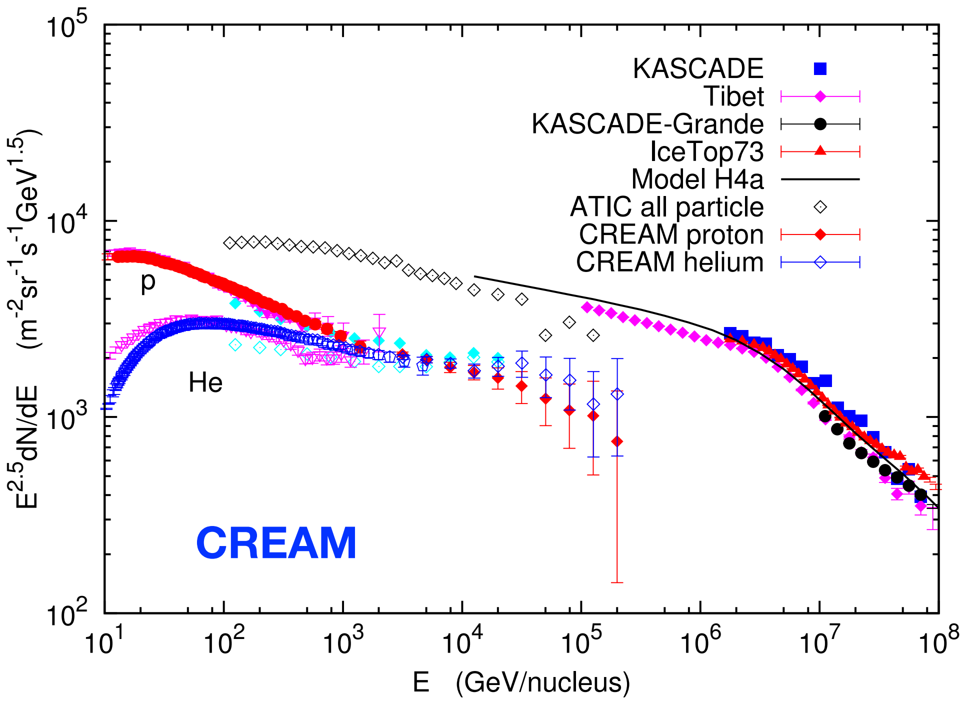


$$I_j \propto E^{-\gamma}$$

But ATIC, CREAM, Pamela and AMS02 showed that

★ The *proton* spectrum is distinctly *softer than* that of *Helium* (and possibly other heavy elements) at all energies.

★ Both spectra show a break and a *spectral hardening* at around a rigidity of *200 GV*.



The *harder helium spectrum* has the interesting consequence that by the time one gets to the "knee" energies it *dominates hydrogen in the all-particle* energy spectrum.

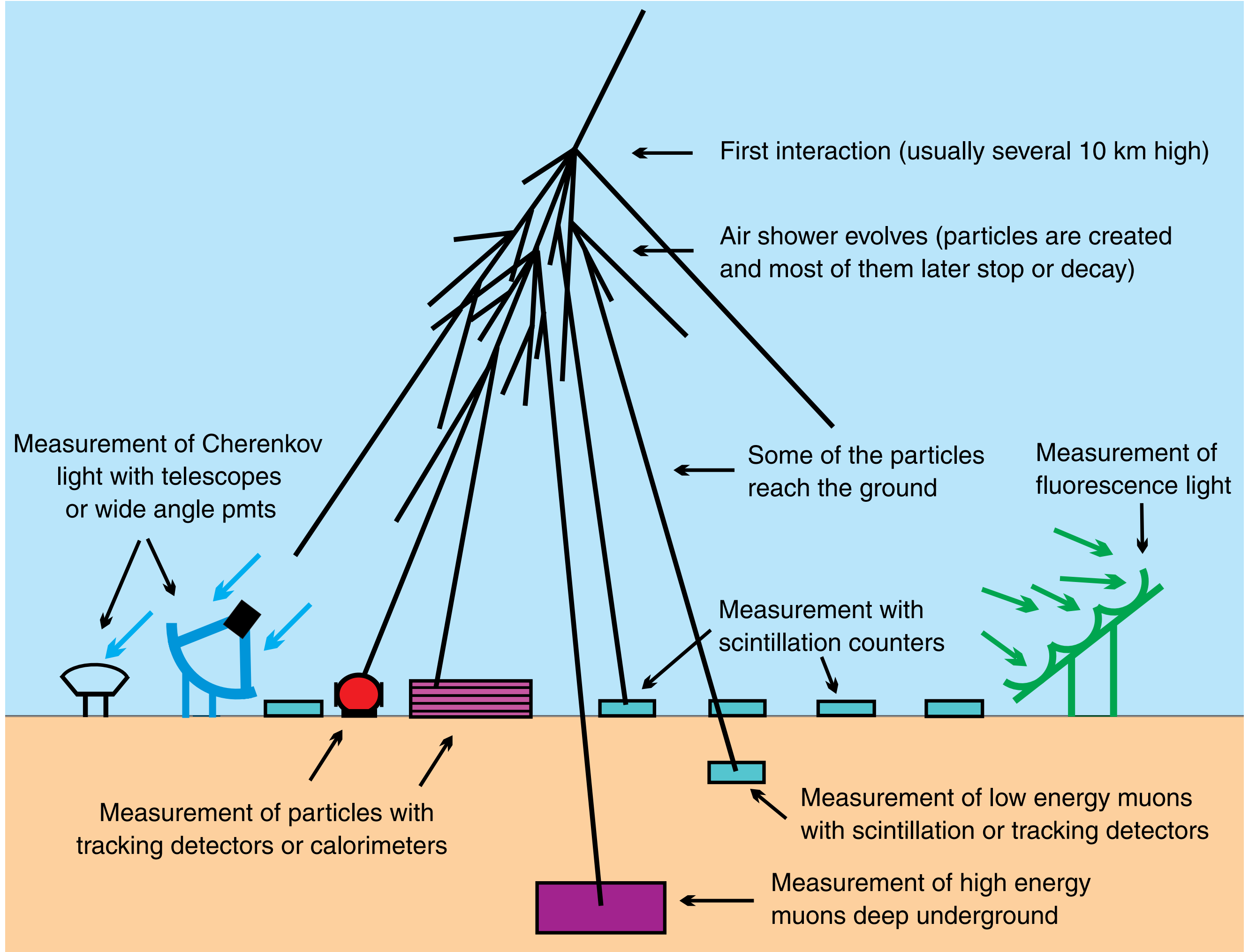
Thus *the "knee" in the all-particle spectrum is actually predominantly a Helium and CNO knee,* and it is possible that the proton spectrum cuts off significantly before.

Drury, ICRC2017, arXiv:1708.08858

All the experimental evidences for a knee feature in the primary CR spectrum *are of indirect kind*, i.e., are based on the reconstruction and interpretation of EAS observables.

EAS measurement

The major observables of EAS at ground are: electron-photon, muon and hadron components, Cherenkov photons, nitrogen fluorescence, radio emission.



With ground-based arrays we observe only the developed status of the EAS at the observation level of the detectors: *sampling calorimeter*

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

From the observables registered there, that means from the total number *(size)* of the various particle components, the *lateral distributions* and eventually the *arrival time profiles* of the shower disk, we have to deduce the properties of the primary particle.

Observation of Cherenkov photons/nitrogen fluorescence allows the study of EAS longitudinal profile: *homogeneous calorimeter*

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

How to obtain the energy spectrum…

…in ground-based experiments ?

Measure the spectrum in one observable and make a conversion to the energy spectrum

The results are displayed as a function of the total energy per particle with the so-called *”all-particle” energy spectrum*, i.e., *as a function of the total energy per nucleus, and not per nucleon*.

Problems: Monte Carlo dependency very large !! Chemical Composition ??

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

More than one observable is needed.... unfolding of model and composition

Use some *mass sensitive observables* for the estimation of the composition and other observables for the energy estimation.

Because of the *reduced resolution in the measurement of the primary mass*, the air shower arrays typically separate events as *“proton-like"* or *"iron-like"*, with results which critically depend on MC predictions.

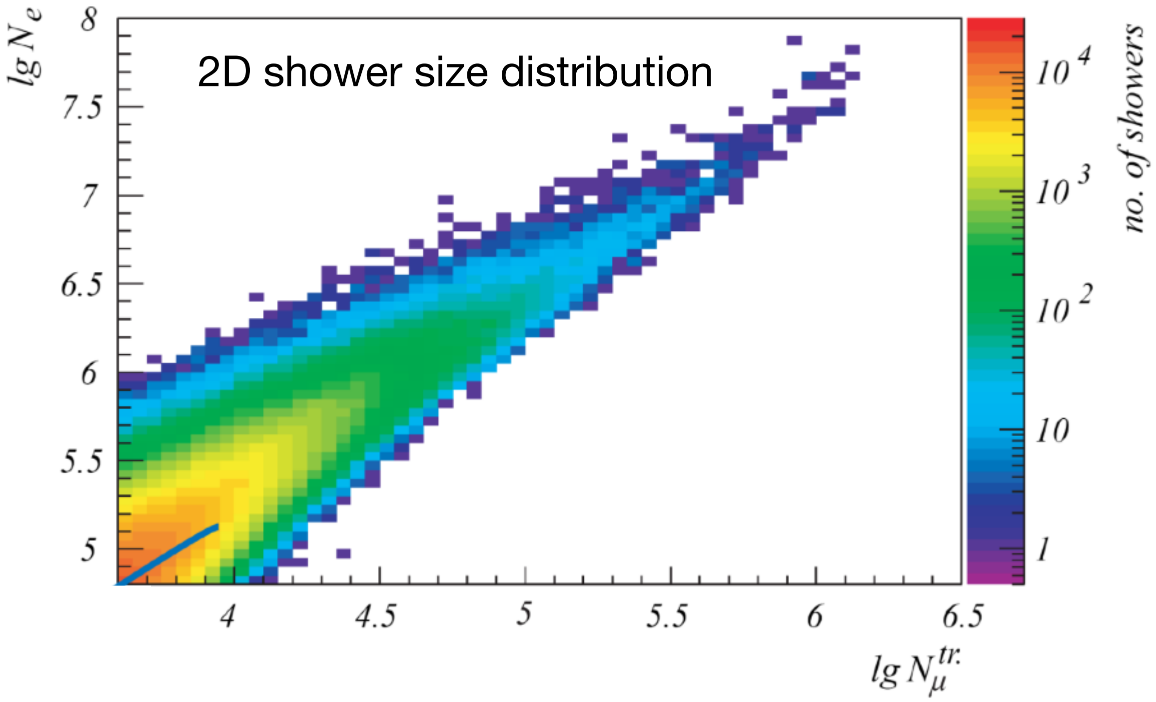
The KASCADE experiment for the first time claimed the capability to reconstruct the energy spectra of *5 mass groups: p, He, CNO, MgSi, Fe.*

How do we measure composition at ground ?

At least *two orthogonal measurements* are needed to estimate the *energy* and *mass* of the primary CR.

And a *third* to test *hadronic interaction models*.

Measuring electron and muon numbers (and their fluctuations) simultaneously at ground has become the first and most commonly employed technique applied to infer the cosmic ray composition from EAS data.



Frequency of showers dependent of 2 observables

In standard EAS experiments the lateral distributions of the particles are sampled by *more or less regular arrangements of a large number of detectors which cover only a small fraction of the total area.*

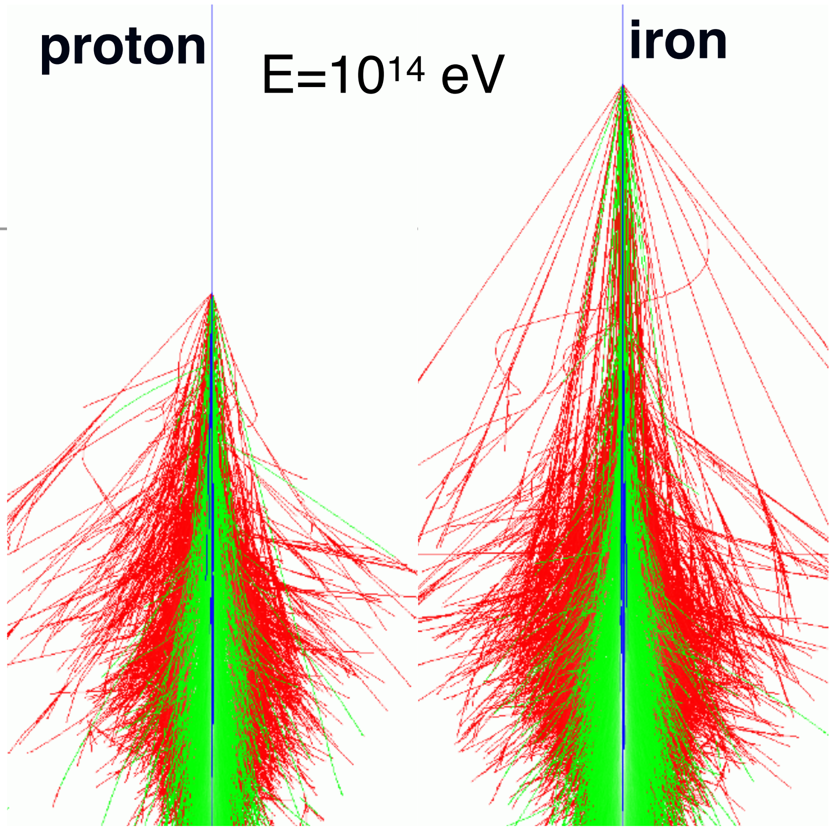
coverage factor (sensitive area/instrumented area) ≈ 10^{-3} - 10^{-2}

This sampling allows us to extrapolate the *size* (total particle numbers), but is an *additional source of instrumental fluctuations* which add to the large spread resulting from the inherent statistical fluctuations due to the stochastic shower development in the atmosphere.

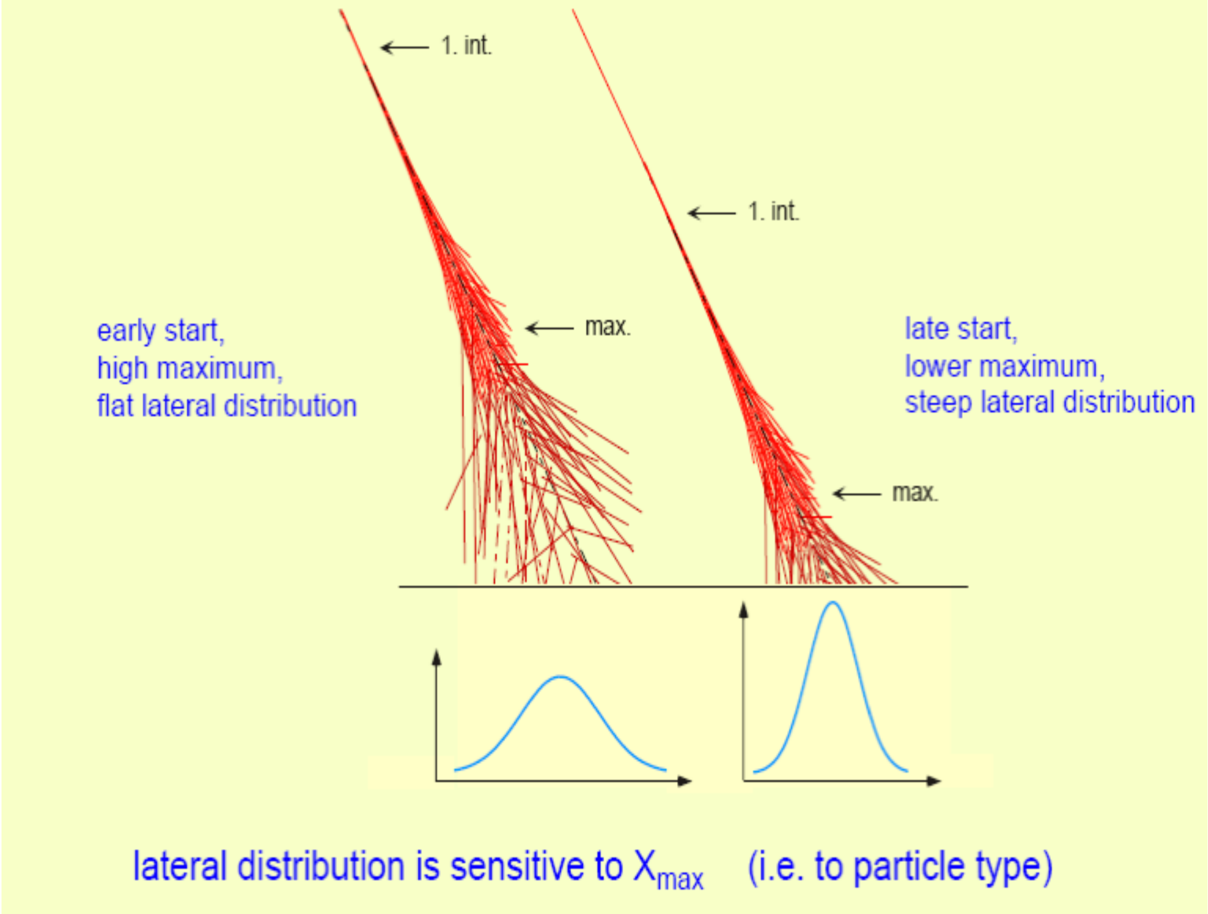
This is especially true for *muons* extending to several hundred metres

Mass discrimination

The different approaches to investigate the elemental composition are commonly based on the fact that *inelastic cross section of the nucleus of mass A is proportional to $A^{2/3}$*, which leads to the long interaction mean free path (m.f.p.) of protons and short m.f.p. of nuclei.



Lateral Distribution



lateral distribution is sensitive to X_{max} (i.e. to particle type)

Different first interaction atmospheric depth
➜ *different lateral distribution*

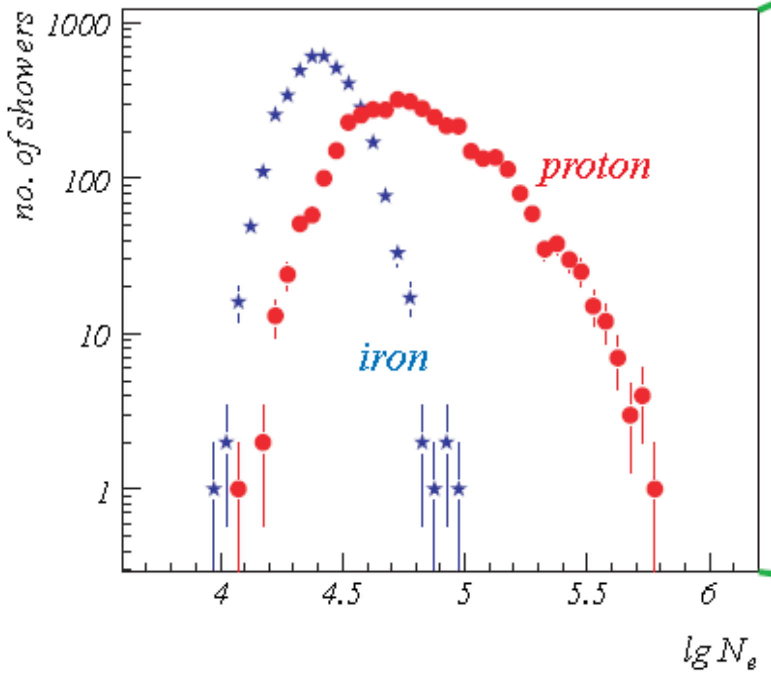
Nuclei develop higher in atmosphere (smaller X_{max}) than protons producing flatter lateral distributions.

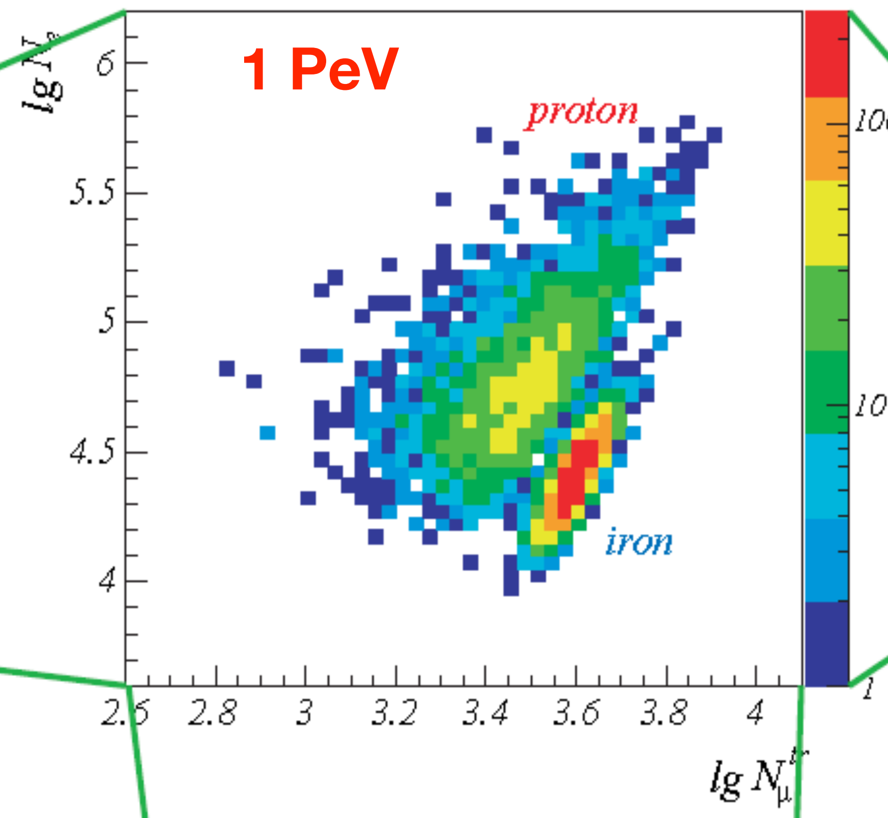
Increasing the mass A

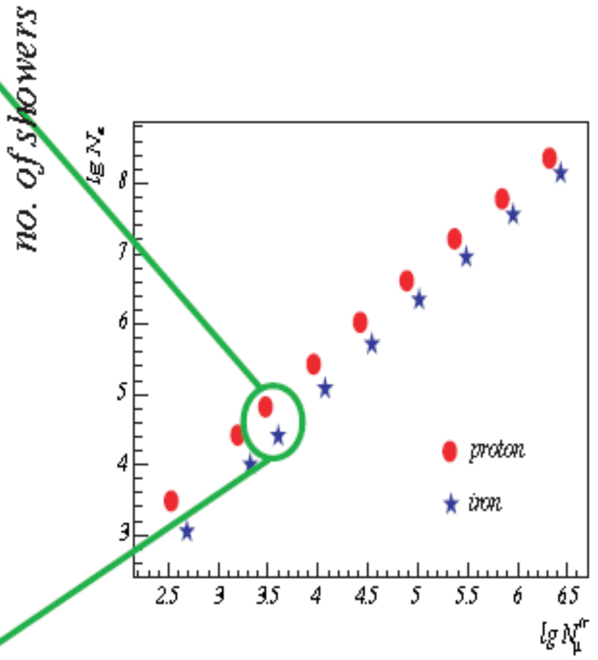
- ★ More secondary particles with less energy
  ➜ less electrons (after max), more μ
- ★ Surviving hadrons have less energy
- ★ Larger deflection angles → flatter lateral distributions of secondary particles

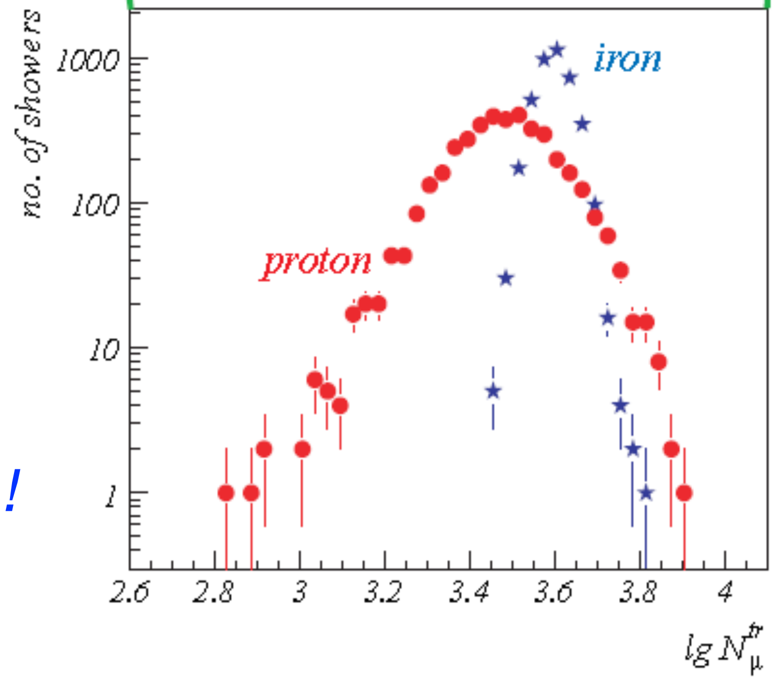
Showers by nuclei dissipate their energy faster than protons, thus having shallower (smaller) X_{max} .

Understanding fluctuations









mean values are not precise enough, distributions needed !

Intrinsic shower to shower fluctuations limit mass resolution !

simulations here:

1 PeV, 0-18 degrees,
CORSIKA V. 6.018
QGSJet 01
GHEISHA

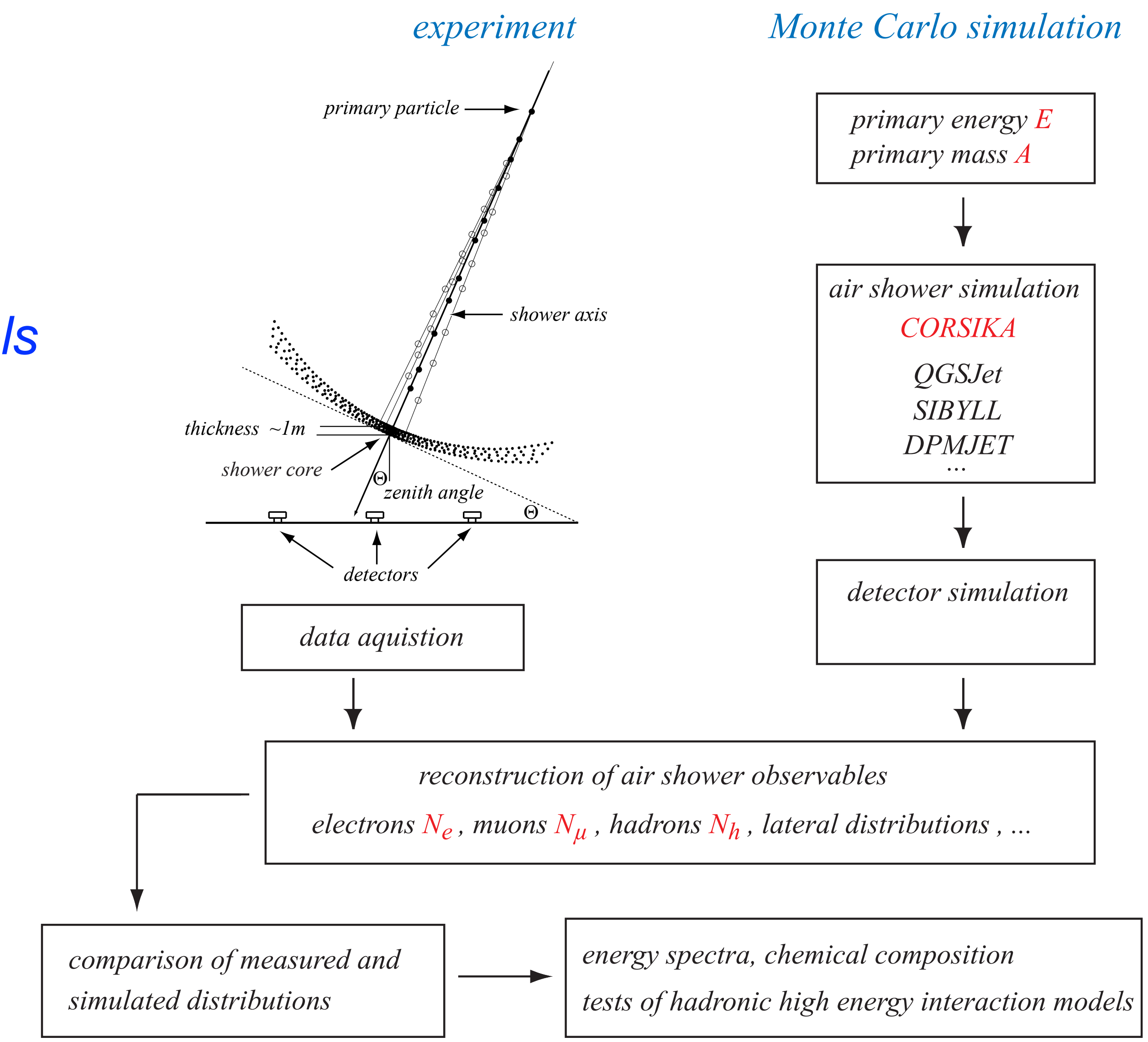
Typical EAS analysis

Assume — *Flux, elemental composition*
hadronic & e.m. interaction models
atmospheric parameters

Model — *Shower development*
detector response
measurement procedures
reconstruction

Obtain — *Fully inclusive simulated spectra*
as they are measured

Compare — *Experimental data and simulations*



experiment — *Monte Carlo simulation*

primary energy E
primary mass A

air shower simulation
CORSIKA
QGSJet
SIBYLL
DPMJET
...

detector simulation

data aquistion

reconstruction of air shower observables
electrons N_e, muons N_μ, hadrons N_h, lateral distributions, ...

comparison of measured and simulated distributions

energy spectra, chemical composition
tests of hadronic high energy interaction models

➡ *Perform a* ***Consistency Check !***

Find a combination of primary spectrum & composition and hadronic interaction for a consistent description of all experimental results

Iterative process to understand CR physics and air shower development simultaneously

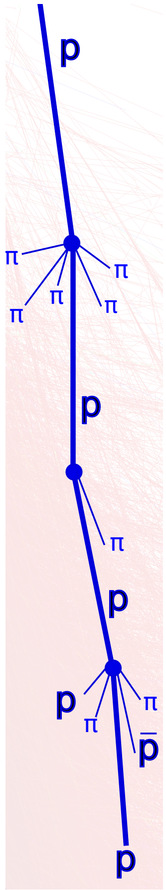
in case of discrepancy: *difficult to identify origin !*
in case of agreement: *is parameters combination unique ?*

Intrinsic ambiguity

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

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

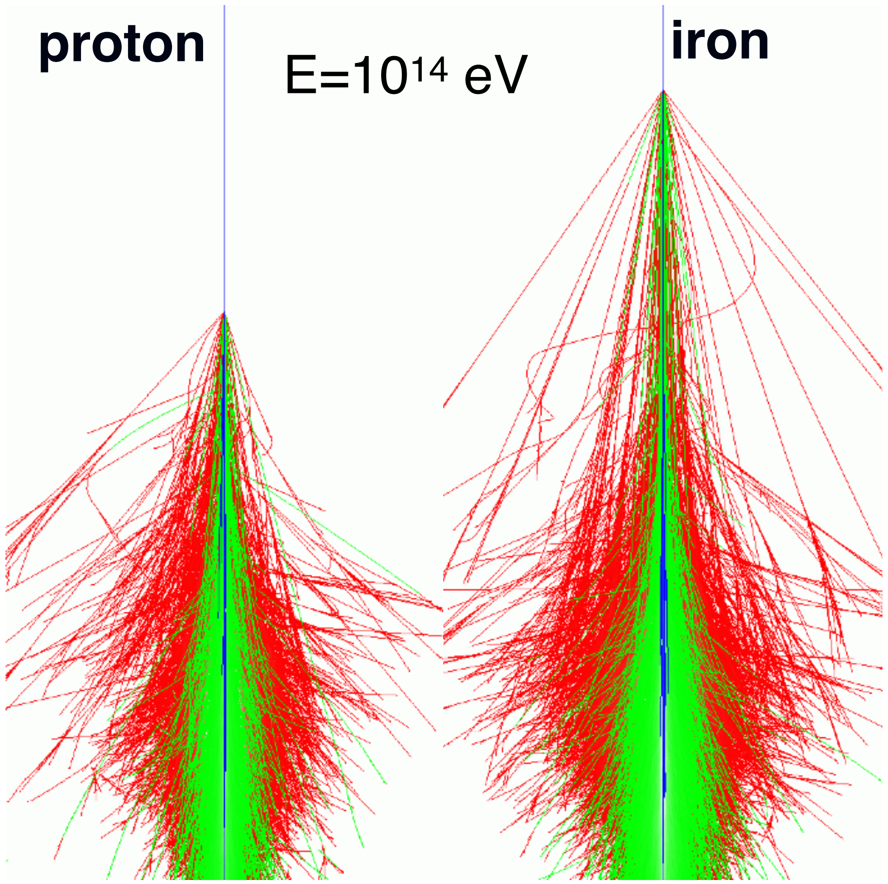


Crucial for shower development

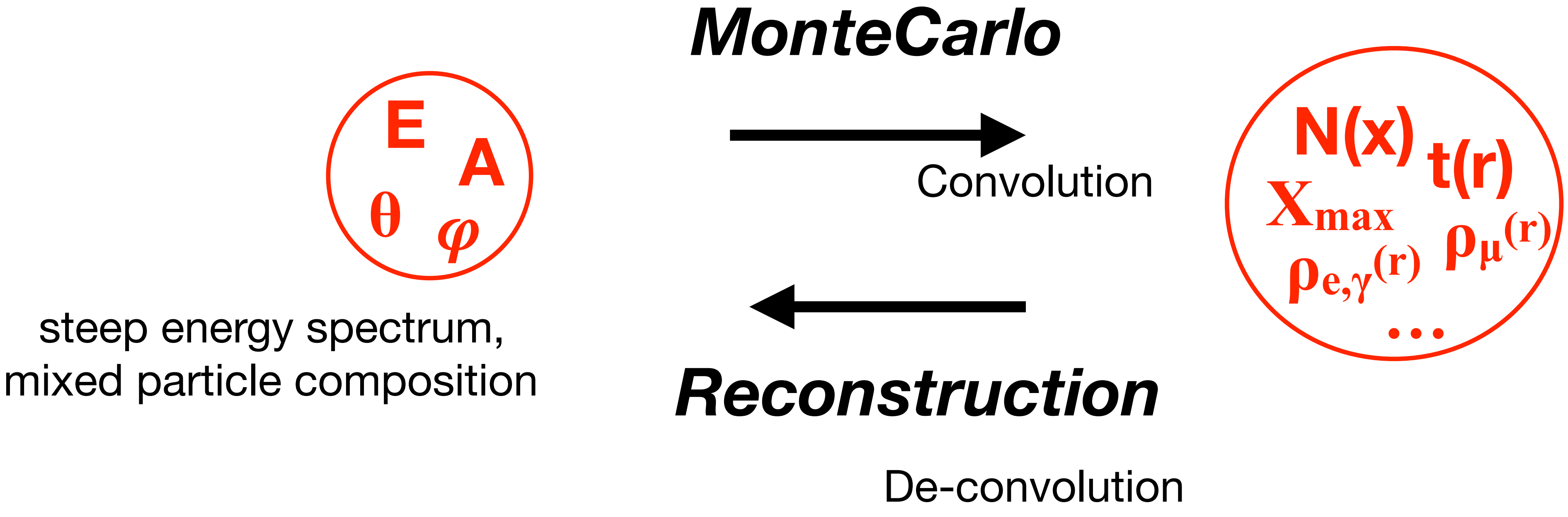
1. the behaviour of the *inelasticity K*, the fraction of the primary energy converted into secondaries
2. the *inelastic cross sections*

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

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



The problem of the reconstruction



E A θ φ

steep energy spectrum,
mixed particle composition

MonteCarlo

Convolution

Reconstruction

De-convolution

$N(x)$ $t(r)$ X_{max} $\rho_{e,\gamma}(r)$ $\rho_{\mu}(r)$ ...

What is the best estimate for
θ, φ, E, A
given the set of measurements

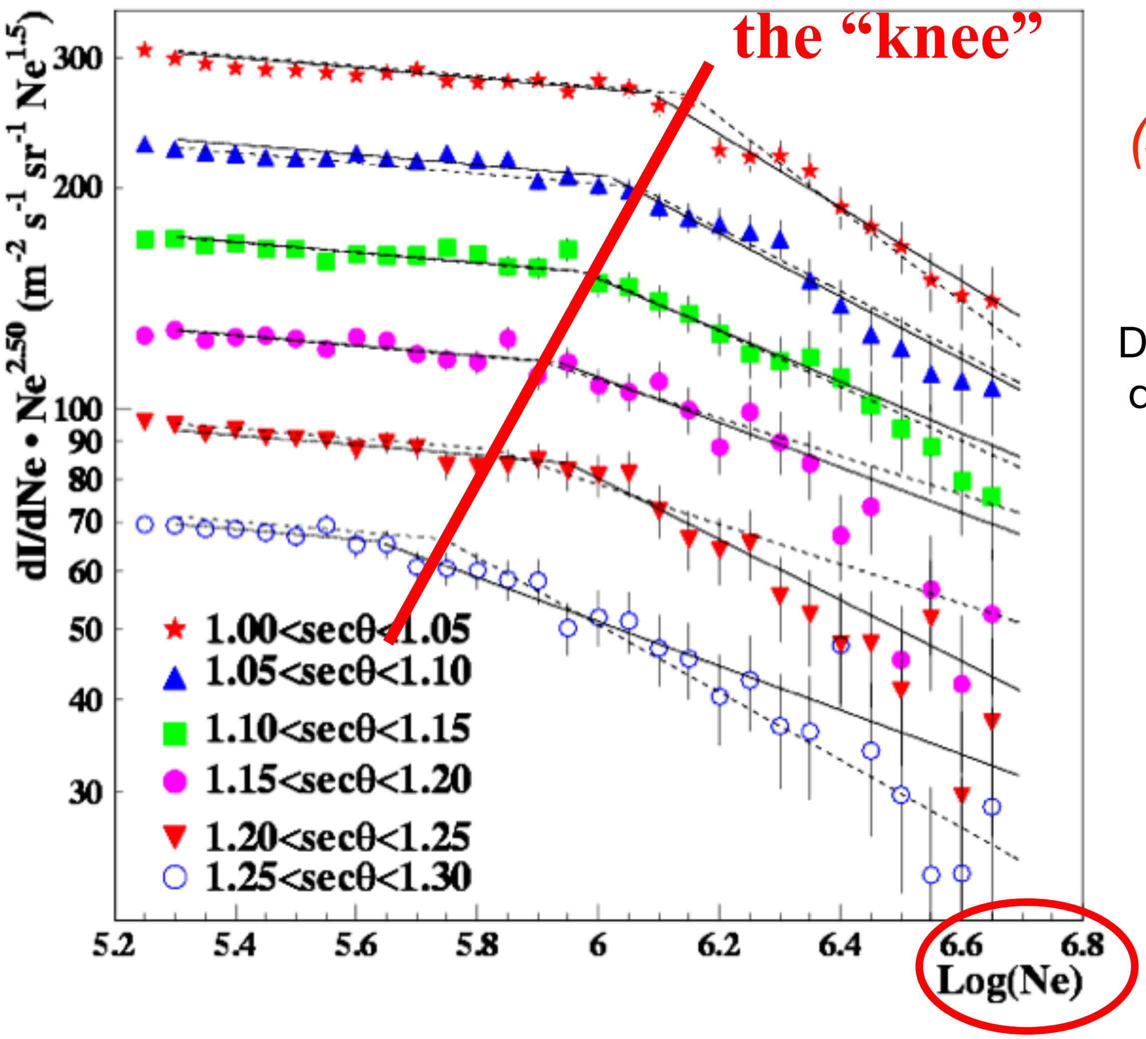
$N(x), t(r), X_{max}, \rho_{\mu}, \rho_{e,\gamma}, \ldots ?$

In principle, numerical simulations can perform a
perfect convolution
of *many inter-dependent sub-processes* to *one large and complex process.*

Shower Size Spectrum

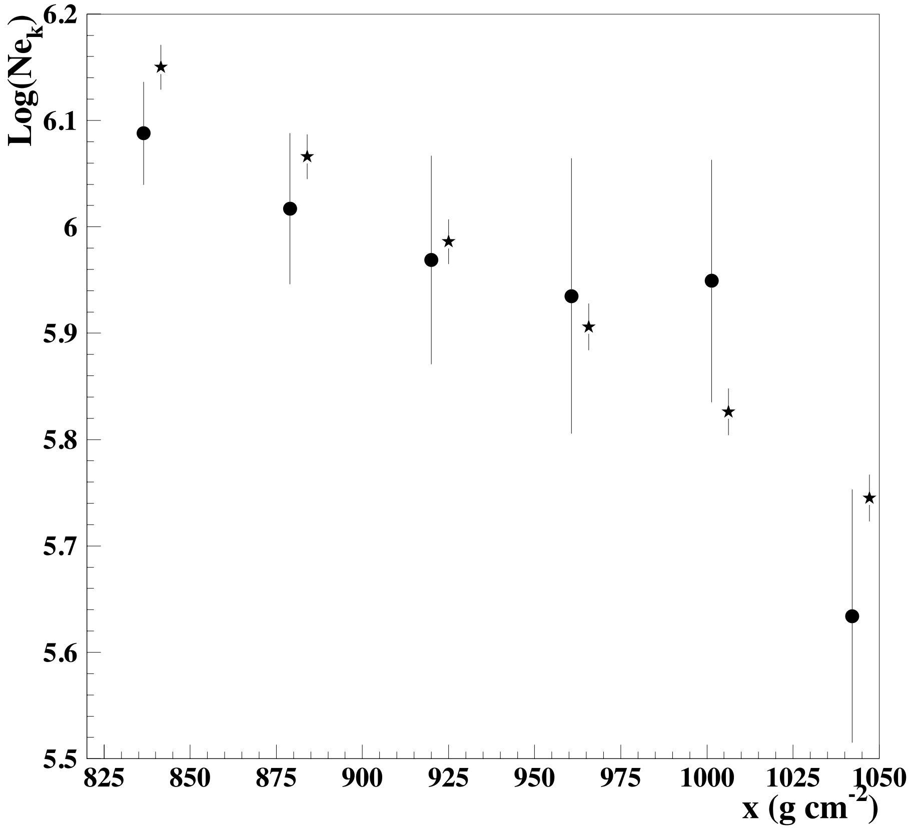
Integration of the Lateral Density Function ➜ shower size

The reconstructed total number of charged particles (shower size) is the main observable of EAS at ground.



Differential shower size spectra measured at different atmospheric depths by ***EAS-TOP***.

Dependence of the size value of the knee on the atmospheric depth.



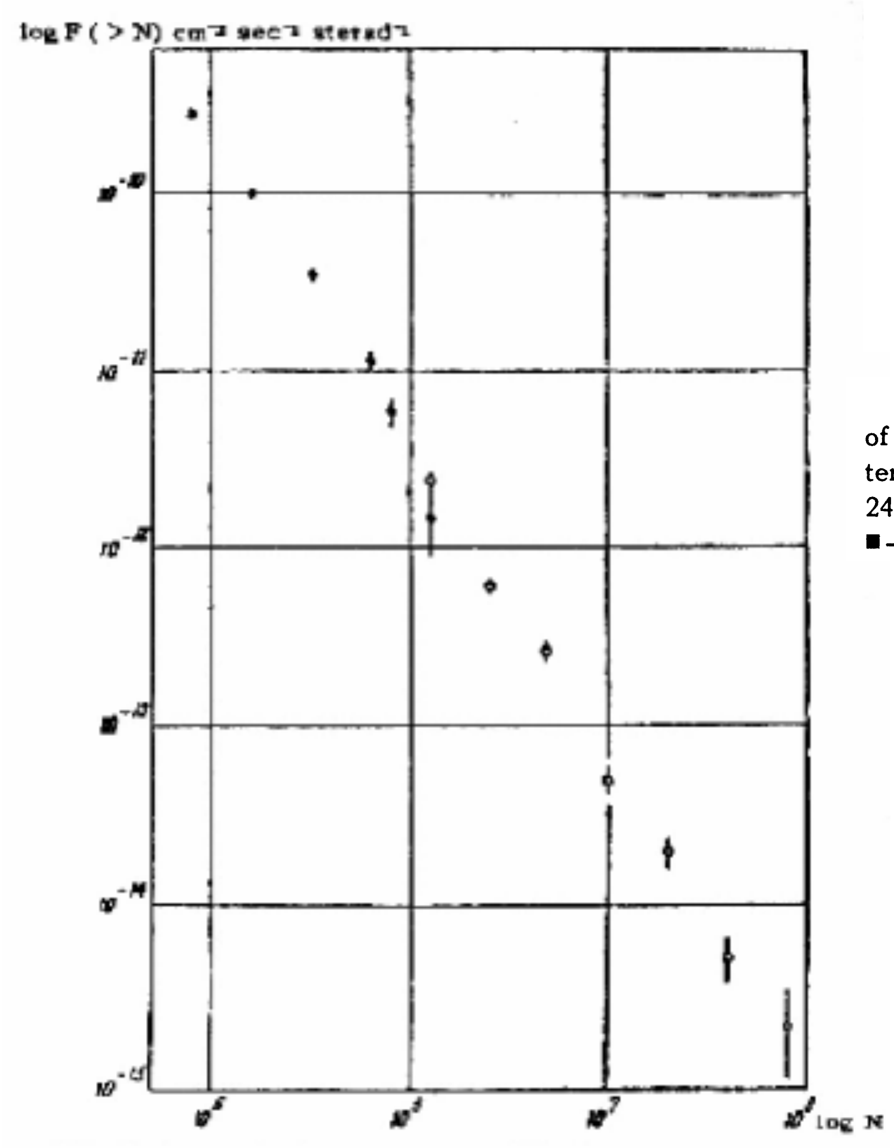
The shower size at the knee $N_{e,k}$ decreases with increasing atmospheric depth with an attenuation length

$$N_{ek}(\theta) = N_{ek}(0)\cdot\exp[-X_0/\Lambda_k\cdot\sec\theta], \qquad \Lambda_k = 257\pm80 \text{ g/cm}^2$$

according to the hypothesis of a knee occurring at fixed primary energy.

The ‘*knee*’ in the CR size spectrum

In 1959 Kulikov & Khristiansen discovered a ‘*knee*’ in the size spectrum of charged particles



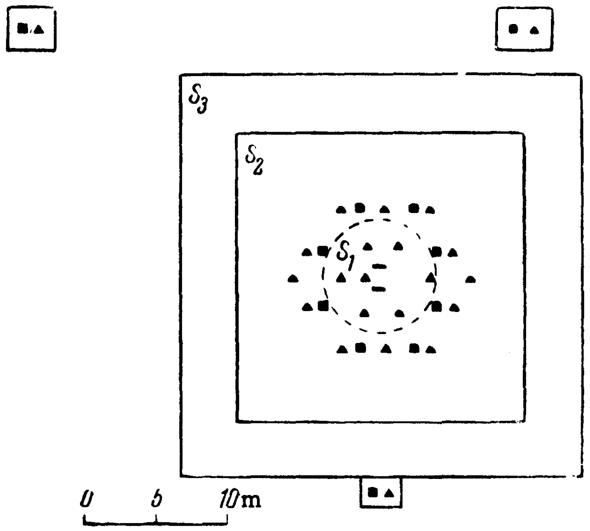
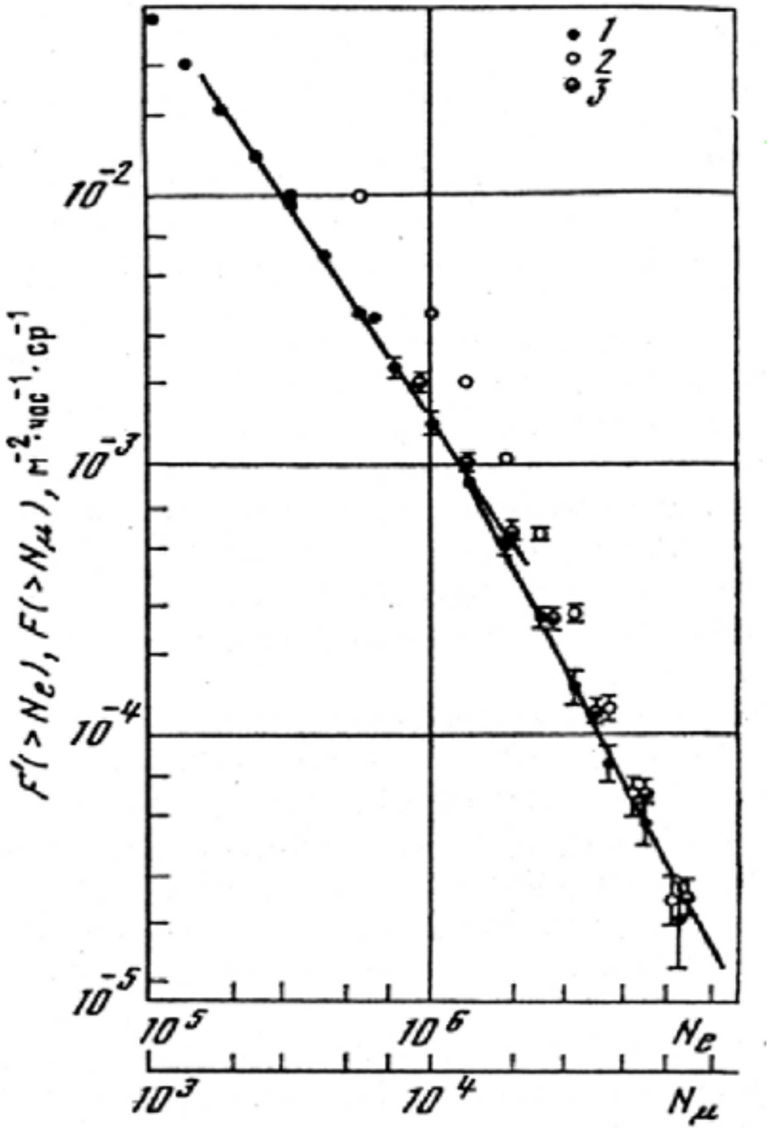


FIG. 1. Diagram of the hodoscope array used for the study of the size spectrum of EAS. ■– group of 24 hodoscope counters, 330 cm² in area each: ▲– group of 48 hodoscope counters 24 of area of 100 cm² each, and 24 of area of 24 cm² each, ■– master groups.

In 1979 the Tien-Shan experiment observed a similar feature in the size spectrum of muons



“It is evident that the particles with $E\geq10^{16}$ eV may have a metagalactic origin.
The observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin.”

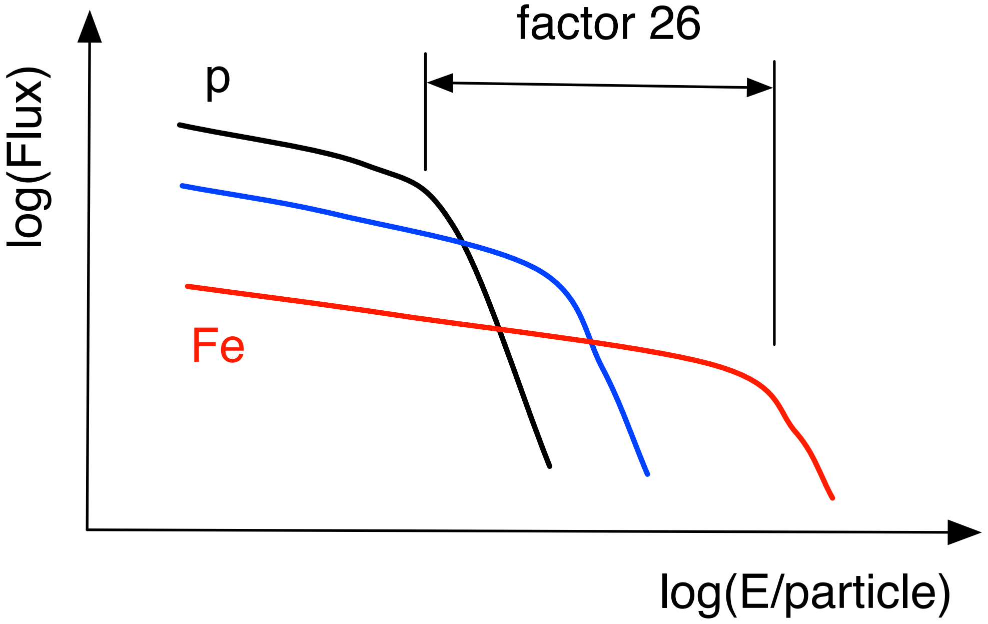
Kulikov & Khristiansen, JETP 35 (1959) 441

The origin of the *'knee'*

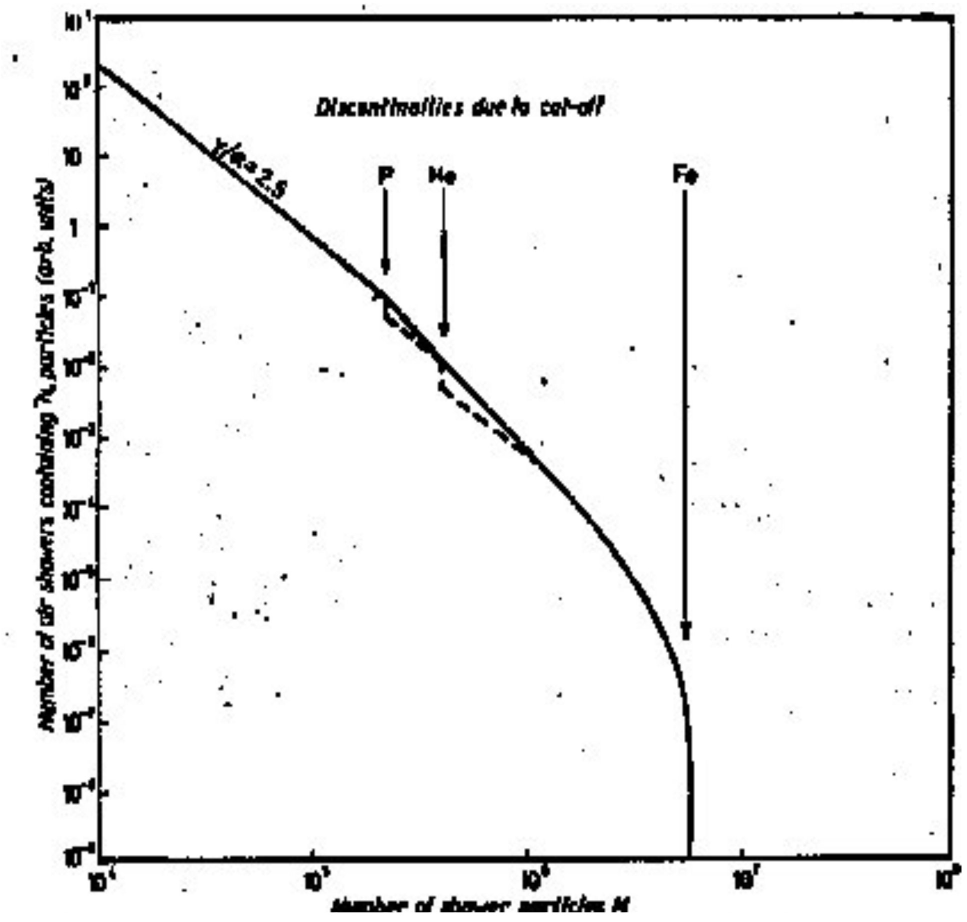
In 1961 B. Peters postulated a *rigidity cutoff model.*

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

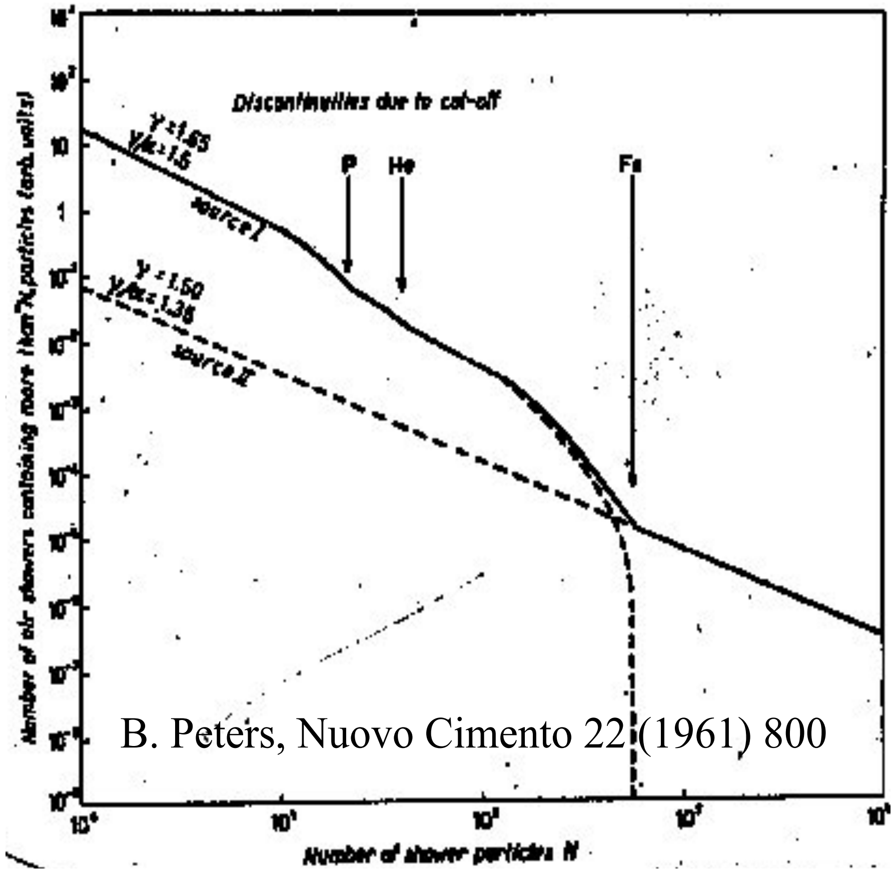
gyro-radius = Pc / ZeB ≡ R (rigidity) / B
➜ E_{total} (knee) ~ Z × R(knee)



Peters cycle: *systematic increase of < A > approaching E_{max}*



<A> should begin to decrease again for E > 30 x E_{knee}



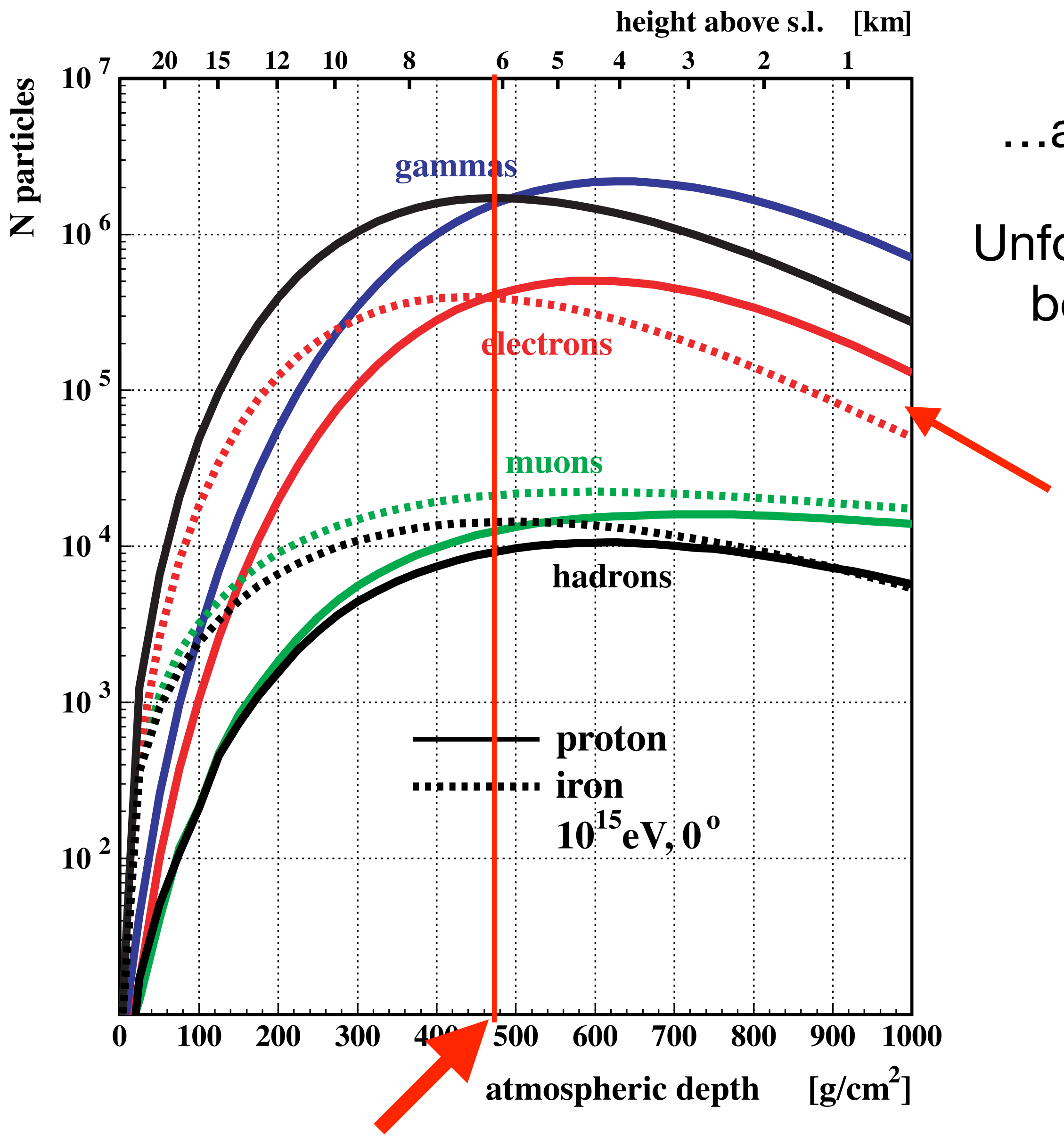
B. Peters, Nuovo Cimento 22 (1961) 800

Conversion Size - Energy

Why the shower size to reconstruct the primary energy ?

The number of electrons *at shower maximum* is nearly *independent on the primary mass !*

$$\boxed{N^A_{e,\max} \approx N^p_{e,\max}}$$



High Altitude > 5000 m asl !!!

…and fluctuations in the max region are reduced !

Unfortunately, the experimental situation is more complicated, because *surface detectors do not observe the number of electrons at shower maximum !*

Since heavy primaries reach their shower max at smaller depths than light ones, the number of electrons on ground is expected to be composition sensitive, with a larger electron number for air showers initiated by light primaries.

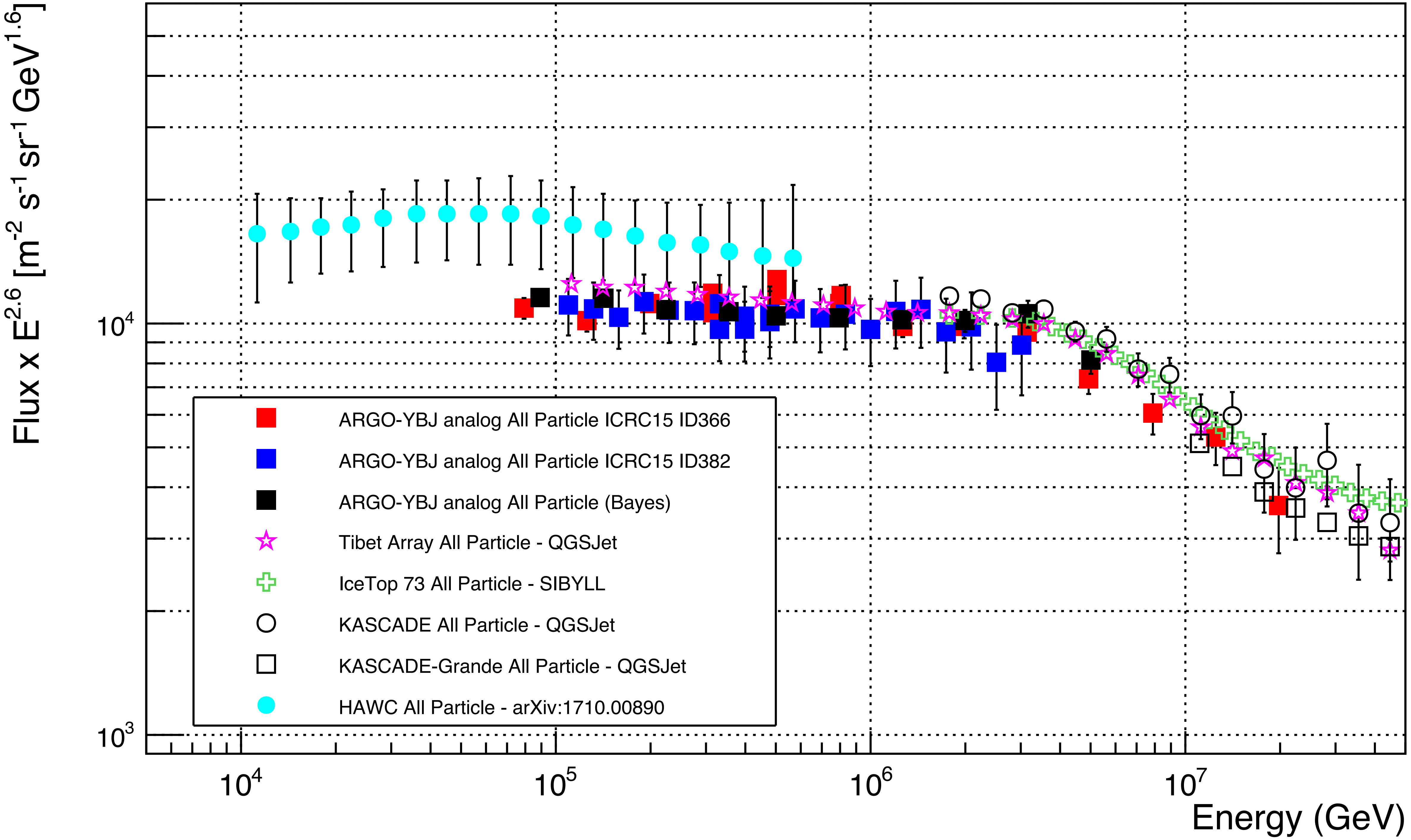
$$Ne(E_0, A) = \alpha(A) \cdot E^{\beta(A)}$$

where $\alpha(A) = 197.5 \cdot A^{-0.521}$, and $\beta(A) = 1.107 \cdot A^{0.035}$

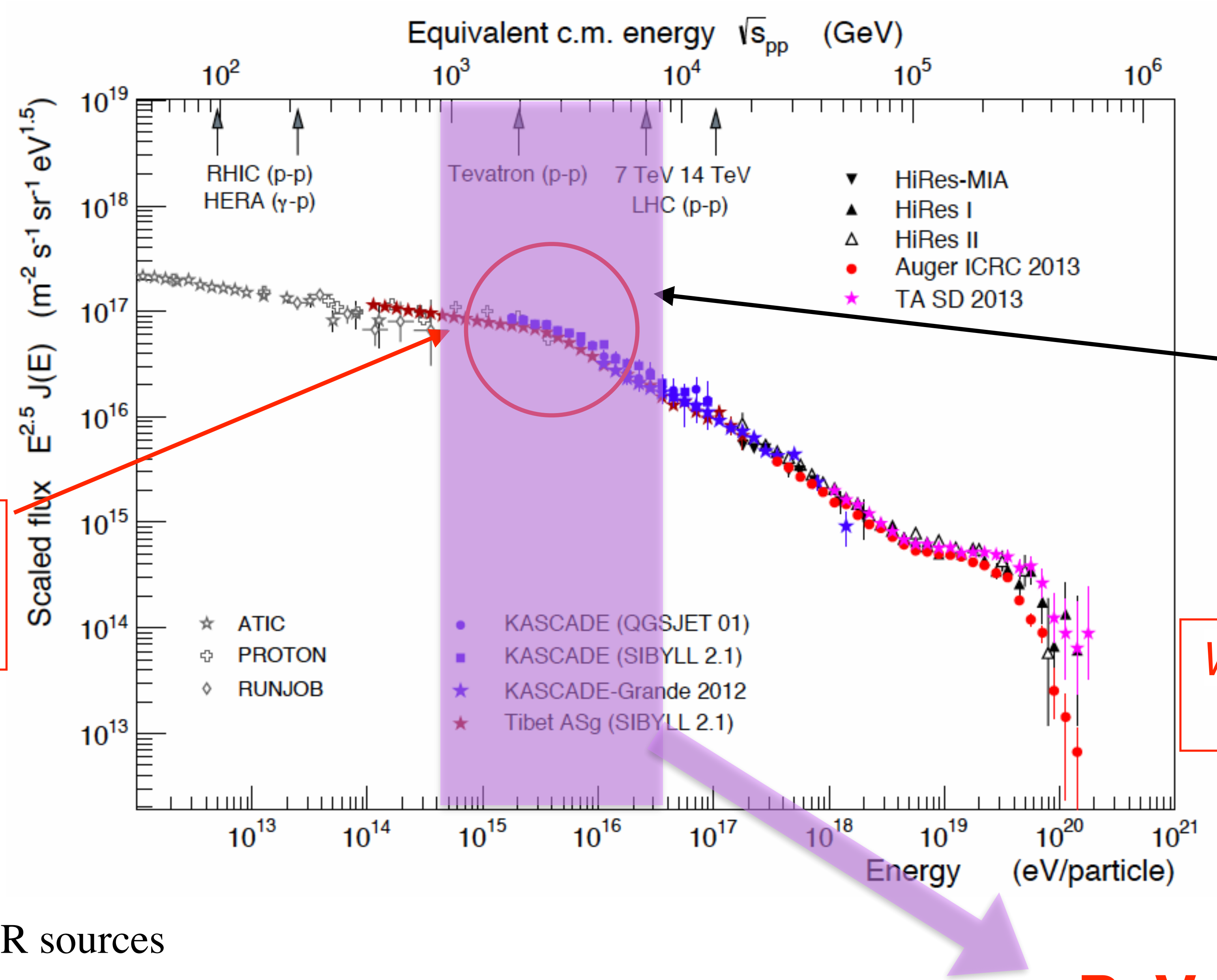
To recover primary energy we must assume a given composition but we want to measure it
➜ degeneracy !

All-particle energy spectrum

After conversion of size in energy assuming a given elemental composition we obtain the all-particle energy spectrum



The ‘*knee*’ in the CR energy spectrum



CR knee @ few PeV’s
Something must
happen here...

We’d like CR sources
to accelerate (at least)
up to that energy

We would like SNRs to be CR PeVatrons…!

PeV Cosmic Rays
Photons > 100 TeV !

Hadronic emission: CR sources

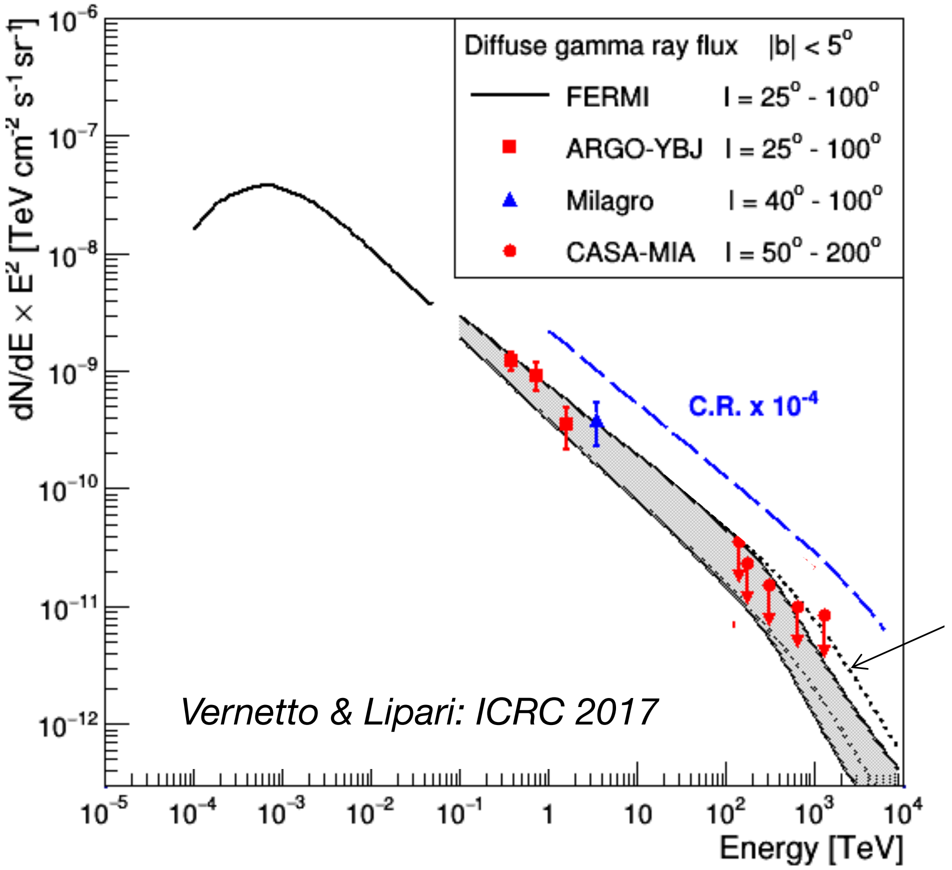
$$\begin{aligned} p\ (p,\ \gamma) &\longrightarrow \pi^0 + rest \\ &\qquad \hookrightarrow \gamma\gamma \end{aligned}$$

Gammas from Galactic Cosmic Rays: $E_\gamma \sim E_{CR}/10$

Knee as end of Galactic population ?

Understanding the origin of the "knee" is the key for a comprehensive theory of the origin of CRs up to the highest observed energies.

In fact, the knee is connected with the issue of the end of the Galactic CR spectrum and the transition from Galactic to extra-galactic CRs.



Vernetto & Lipari: ICRC 2017

★ *Rigidity* models can be *rigidity-acceleration* models or *rigidity-confinement* models

- *Accelerator feature*: maximum energy of acceleration ➜ implies that all accelerators are similar: *source property !*
- *Structure generated by propagation:* ➜ we should observe a *knee that is potentially dependent on location*, because the propagation properties depend on position in the Galaxy ➜ the (main) Galactic CR accelerators must be capable to accelerate to much higher energy.

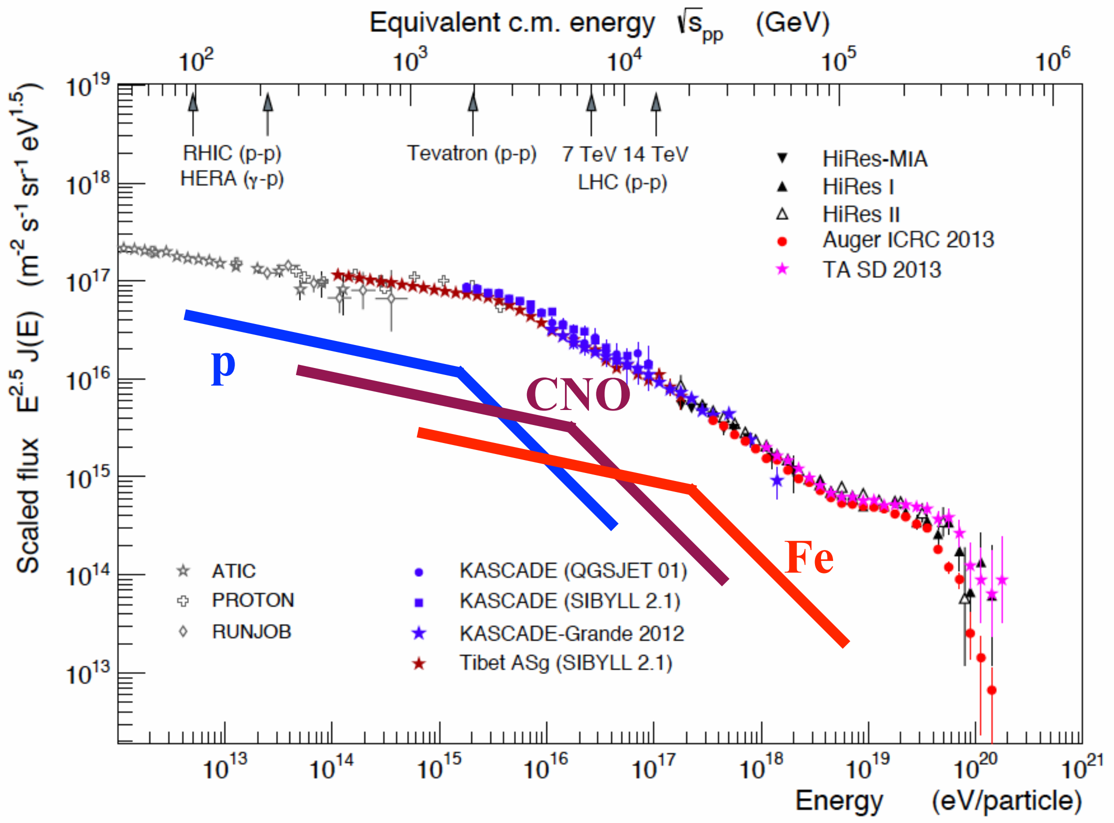
If the "knee" is a *propagation effect*, the Galaxy contains *"super-PeVatrons"* and the study of these objects requires *Gamma-Ray Astronomy at Very High Energy* (100 - 1000 TeV).

➜ Strong interest in the PeV gamma ray (and neutrino) astronomy.

Approaching the '*knee*'

The standard model (mainly driven by KASCADE results):

- Knee attributed to light (proton, helium) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge $E_Z = Z \times 4$ PeV
- The sum of the flux of all elements with their individual cut-offs makes up the all-particle spectrum.
- Not only does the spectrum become steeper due to such a cutoff but also heavier.



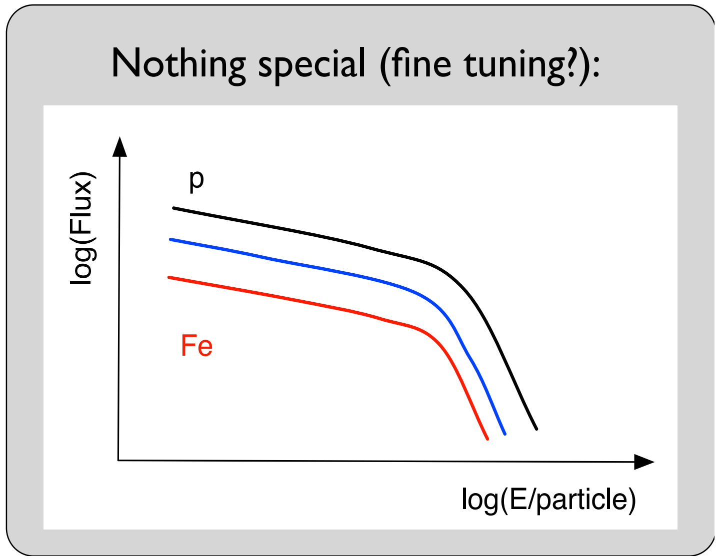
Determining elemental composition in the knee energy region is crucial to understand where Galactic CR spectrum ends

If the mass of the knee is *light* according to the standard model
➜ Galactic CR spectrum is expected to end around 10^{17} eV

If the composition at the knee is *heavier* due to CNO / MgSi
➜ we have a problem !

Understanding the origin of the knee

Different models to explain the ‘knee’ and different signatures…

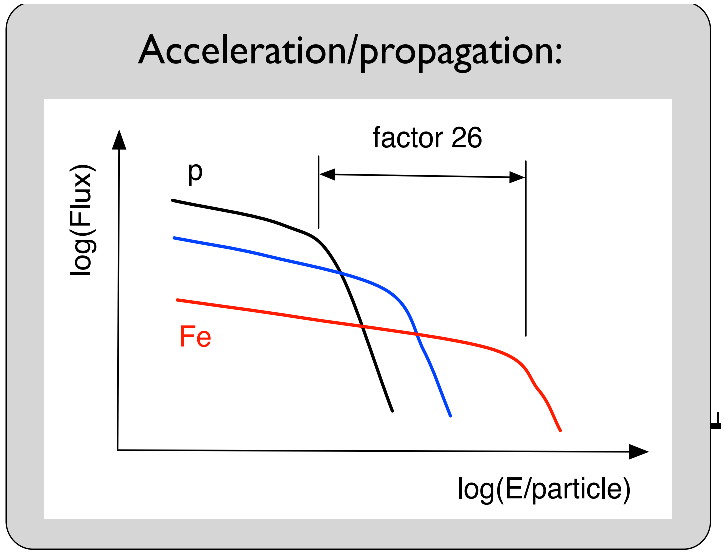


- ***Nothing special***
  Fine tuning ?

- ***Acceleration in SNRs:***
  finite lifetime of shock $E_{max} = Z \cdot 10^{15}$ eV

→

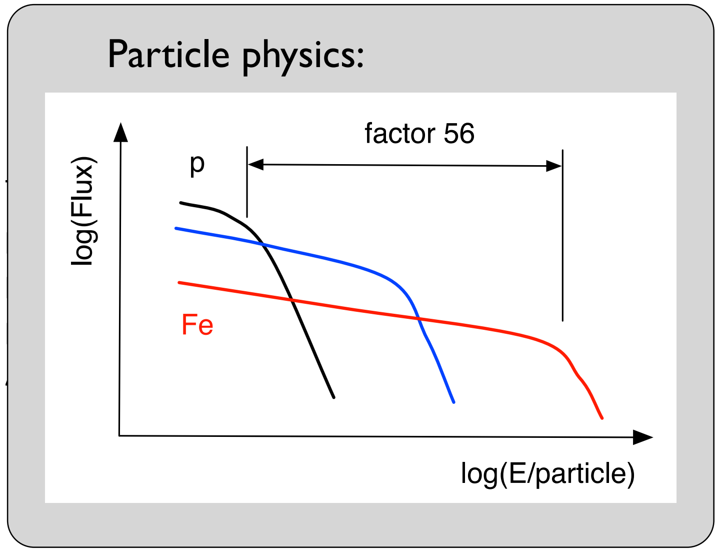
- *Eknee ∝ Z*
- No anisotropy change across the knee region



- ***Diffusion process:***
  probability of escape from Galaxy = f(Z)

→

- *Eknee ∝ Z*
- Anisotropy ∝ E^{δ}



- ***Interaction with bkg particles:***
  Photo-disintegration, etc.
- ***Change in particle interaction***

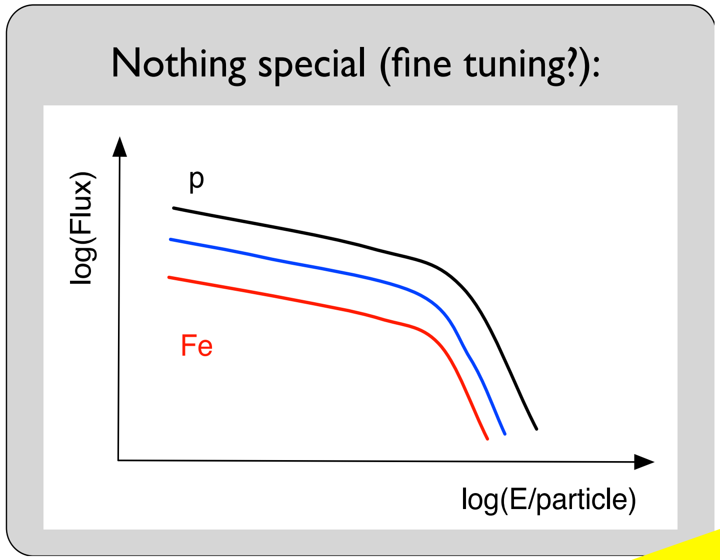
→

- *Eknee ∝ A*

Key elements: *mass composition* and *anisotropy* across the knee

Understanding the origin of the knee

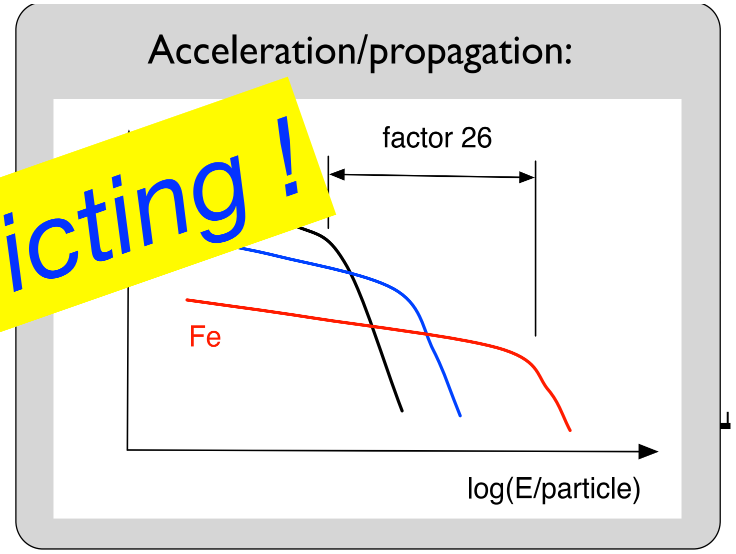
Different models to explain the 'knee' and different signatures…


Nothing special (fine tuning?):

- ***Nothing special***
  Fine tuning ?

- ***Acceleration in SNRs:***
  finite lifetime of shock $E_{max} = Z \cdot 10^{15}$ eV

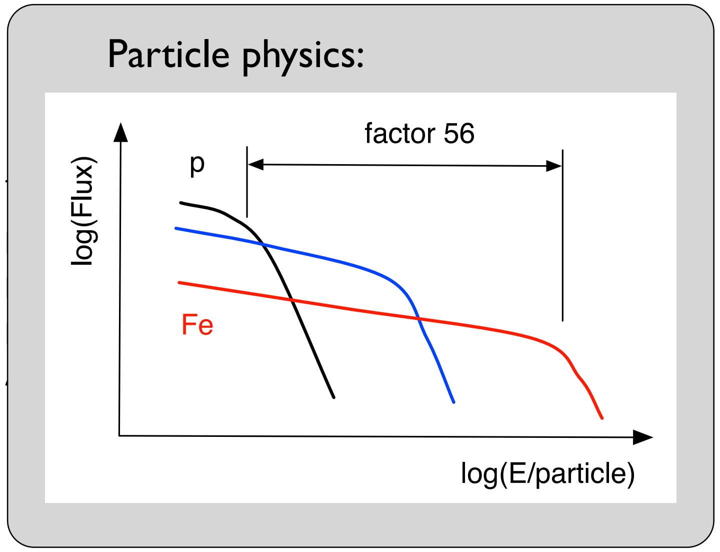
  - *Eknee ∝ Z*
  - No [illegible] nge
    [illegible] knee region


Acceleration/propagation:

- ***Diffusion process:***
  probability of escape fr [illegible])

  - *Eknee ∝ Z*
  - Anisotropy ∝ E^{δ}

Experimental results still conflicting !


Particle physics:

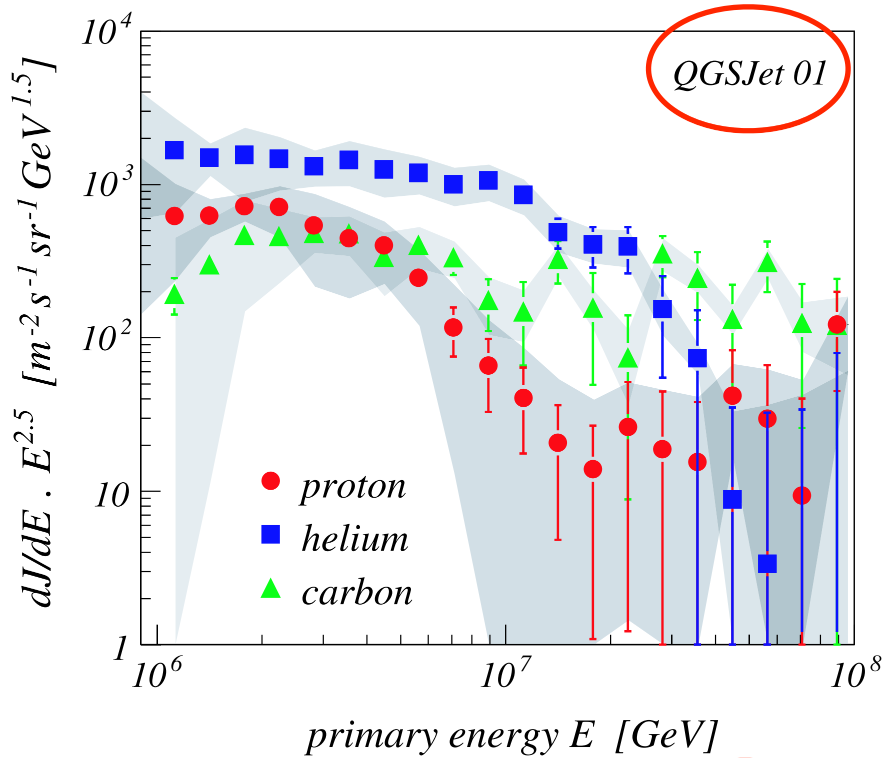
- ***Interaction with bkg particles:***
  Photo-disintegration, etc.
- ***Change in particle interaction***

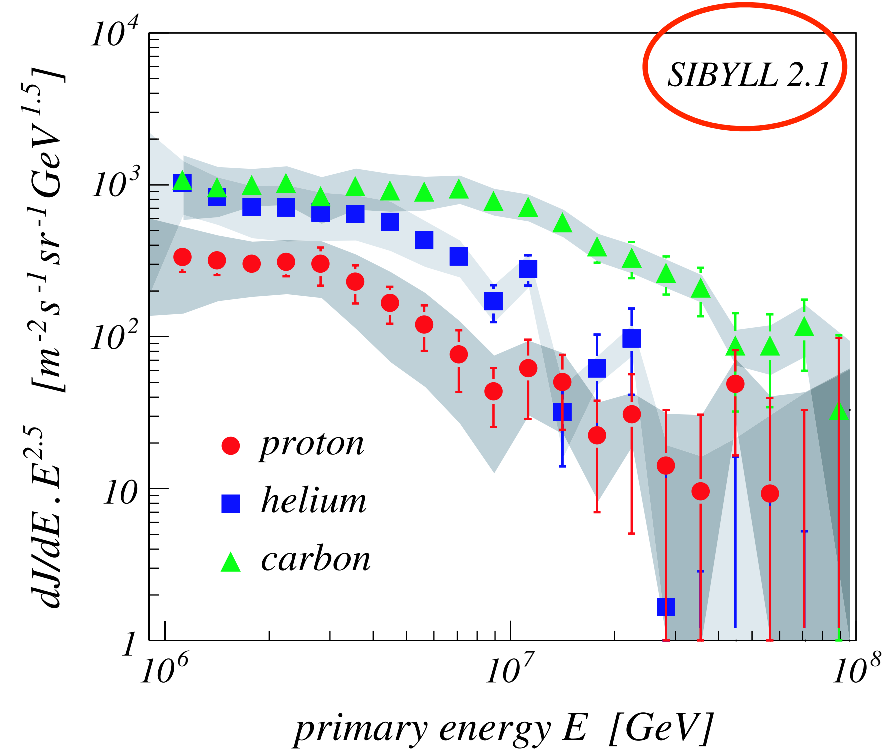
  - *Eknee ∝ A*

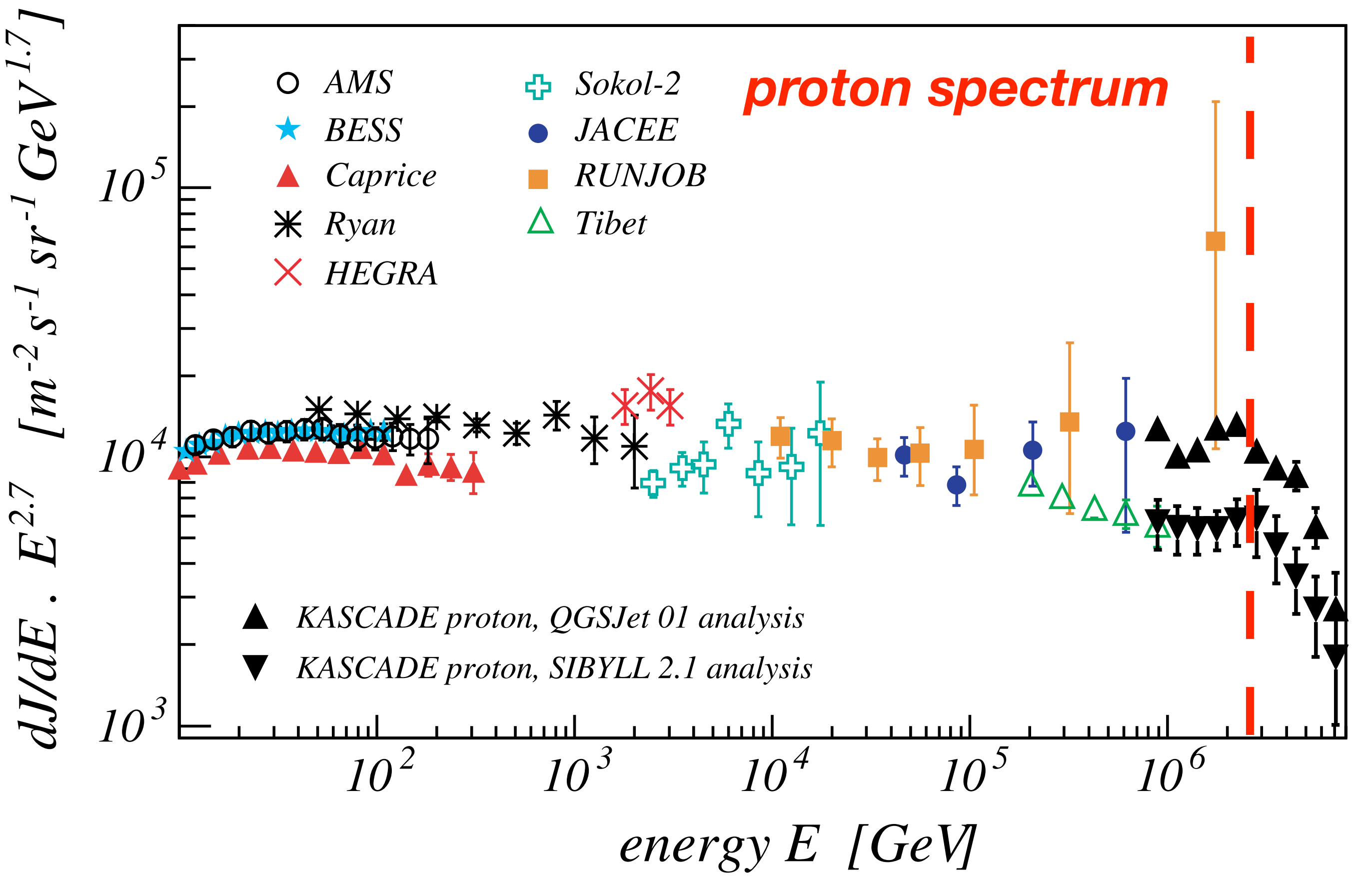
Key elements: *mass composition* and *anisotropy* across the knee

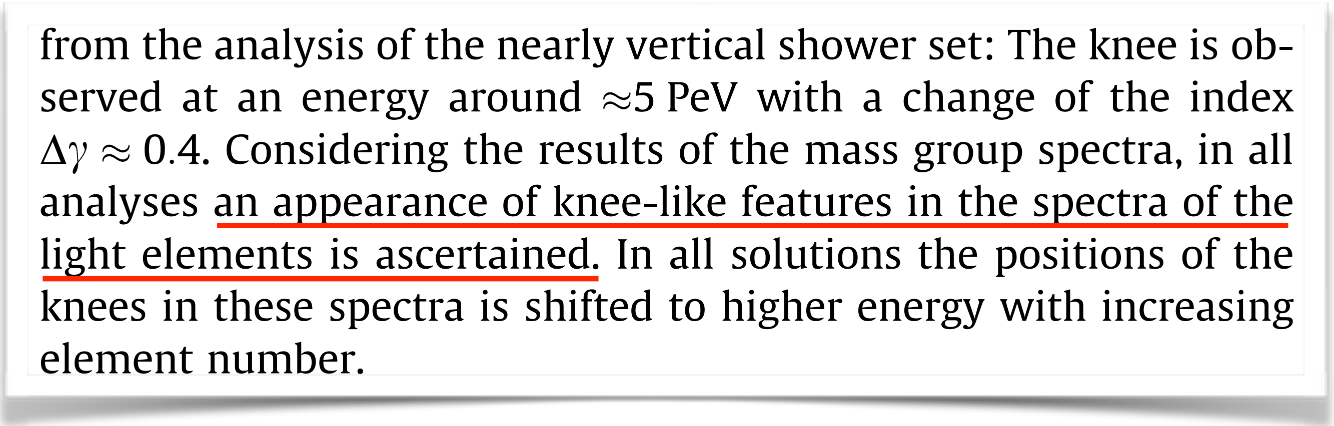
Composition at the knee: KASCADE

The knee in the all-particle spectrum is due to the bending of the light (proton) component







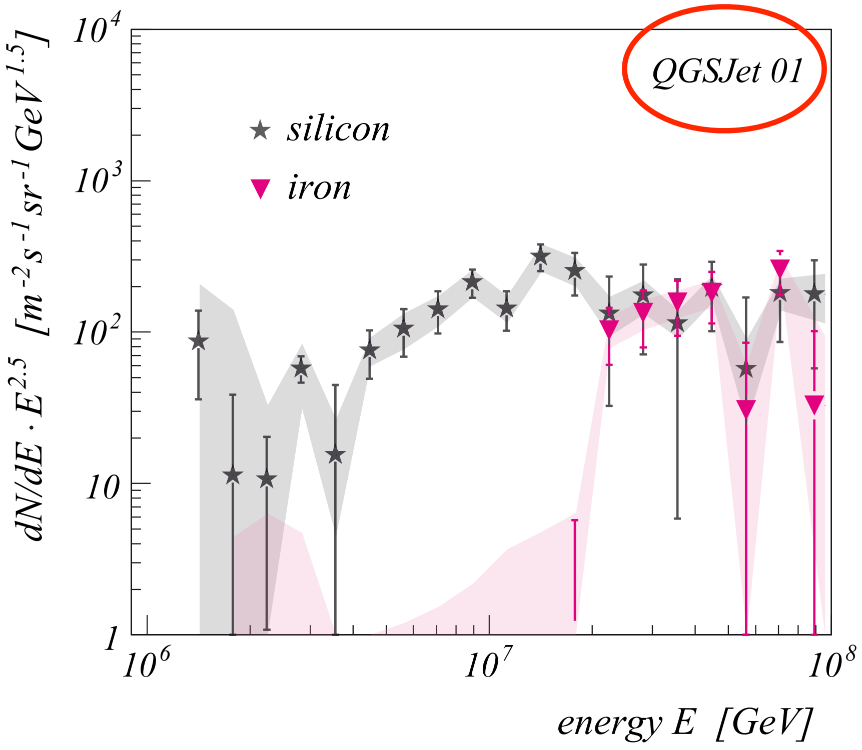


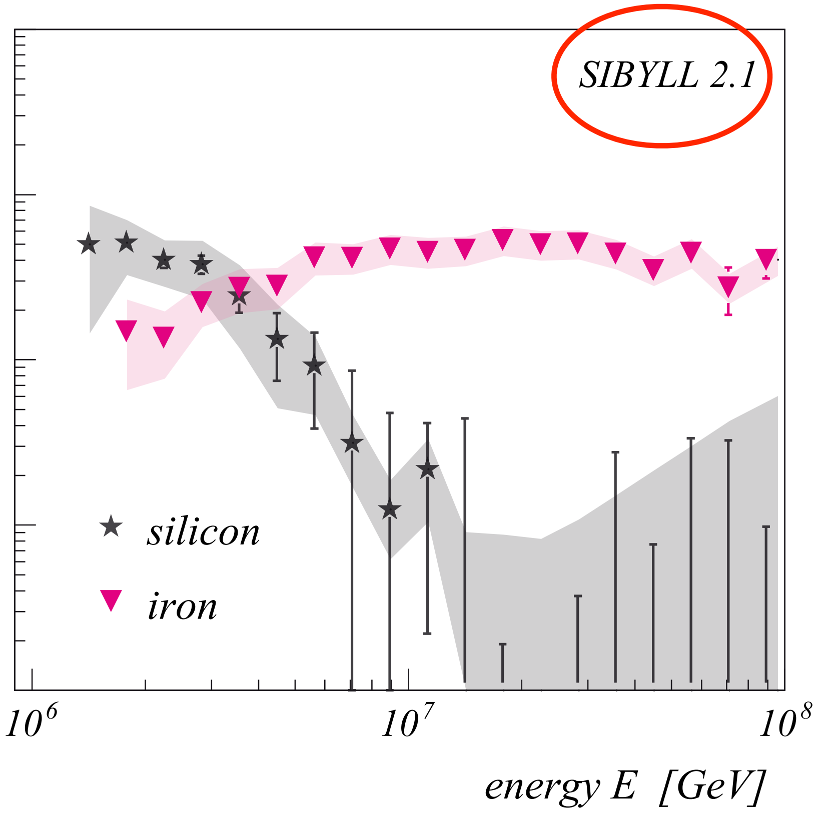
from the analysis of the nearly vertical shower set: The knee is observed at an energy around ≈ 5 PeV with a change of the index $\Delta\gamma \approx 0.4$. Considering the results of the mass group spectra, in all analyses an appearance of knee-like features in the spectra of the light elements is ascertained. In all solutions the positions of the knees in these spectra is shifted to higher energy with increasing element number.

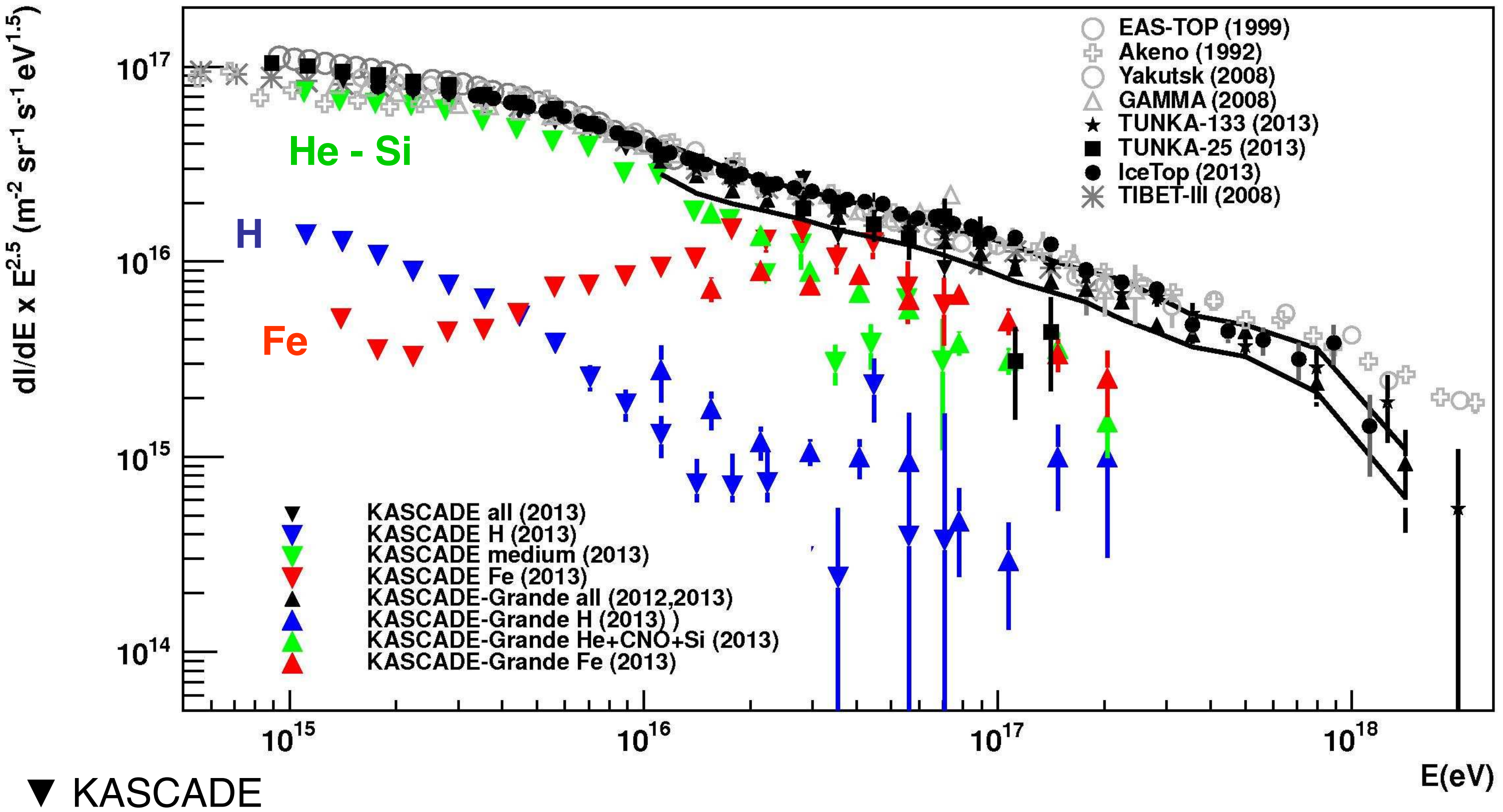
sea level

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

Composition at the knee: KASCADE







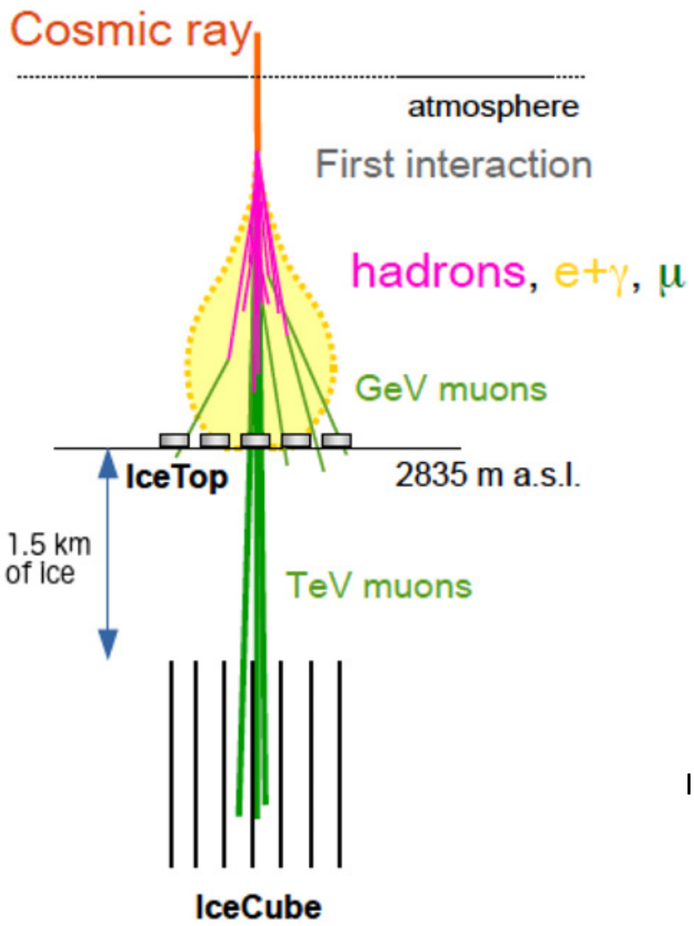
▼ KASCADE
▲ KASCADE-Grande

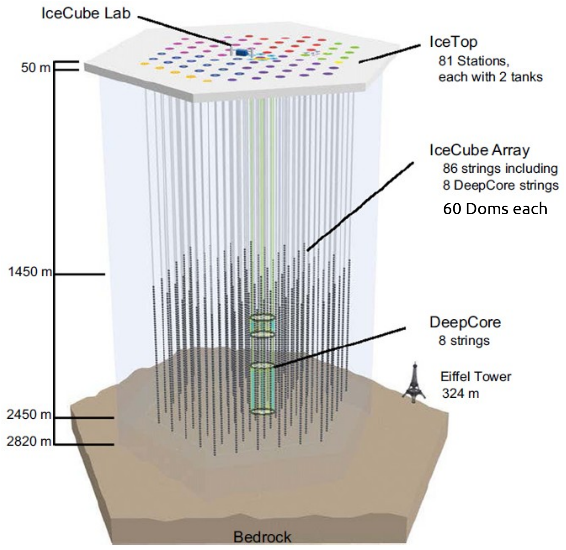
The knee in the all-particle spectrum is due to the bending of the light (proton) component

Helium or carbon the most abundant element at knee

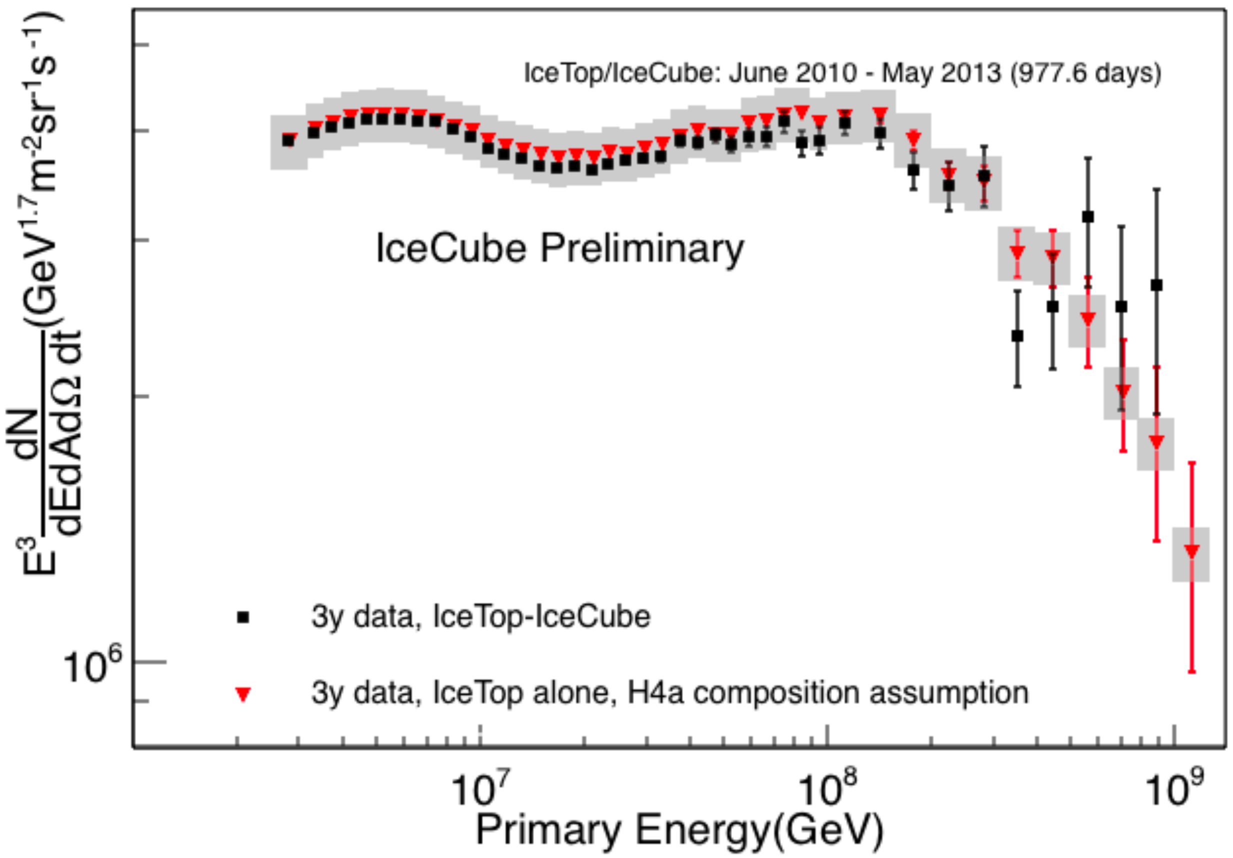
Energy threshold ≈ PeV

Composition at the knee: IceCube





IceTop	KASCADE-Grande
1 km^2 covered area	0.5 km^2
125 m spacing	137 m
2835 m a.s.l. 680 gcm^{-2}	1000 gcm^{-2}



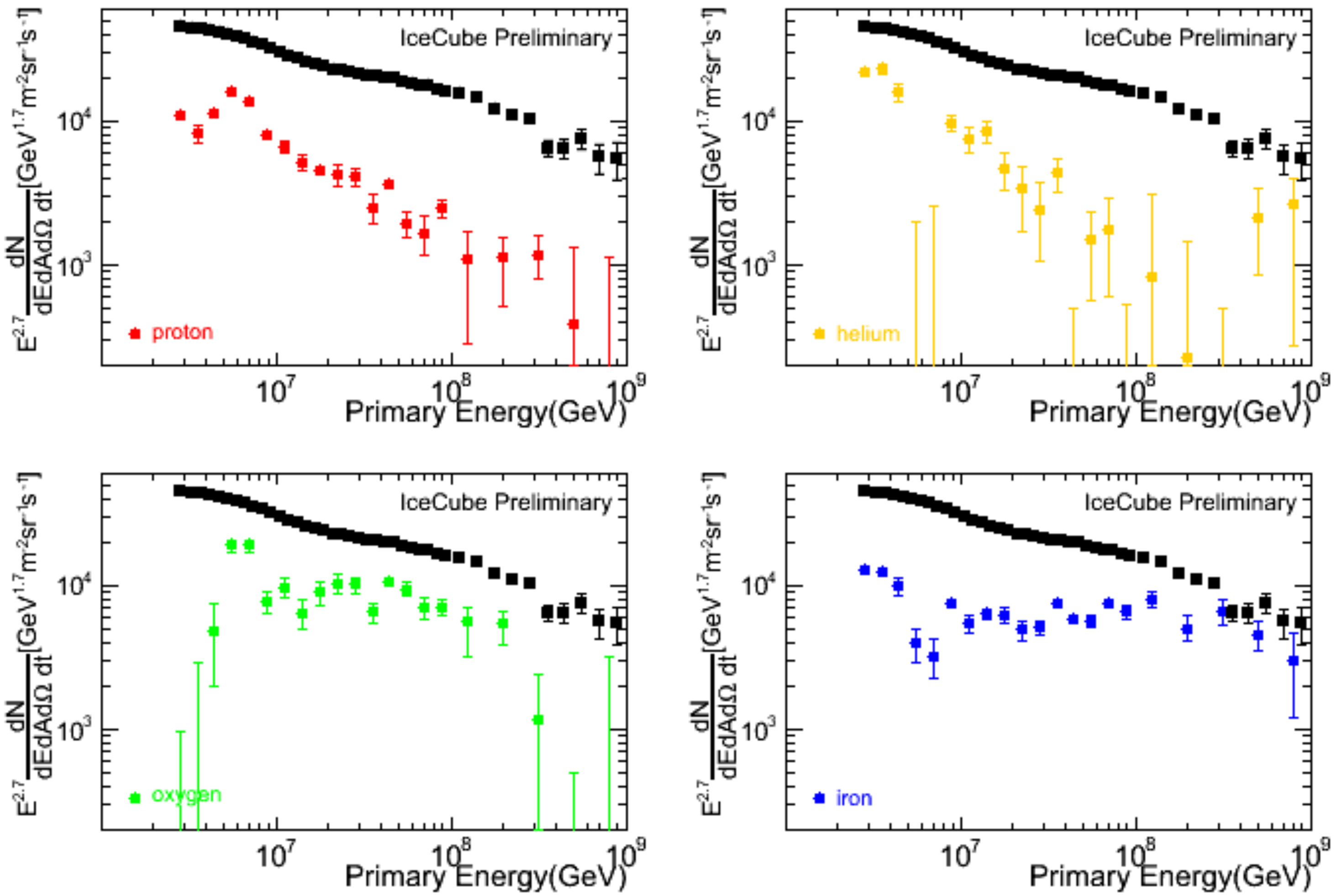
Energy threshold ≈ few PeV

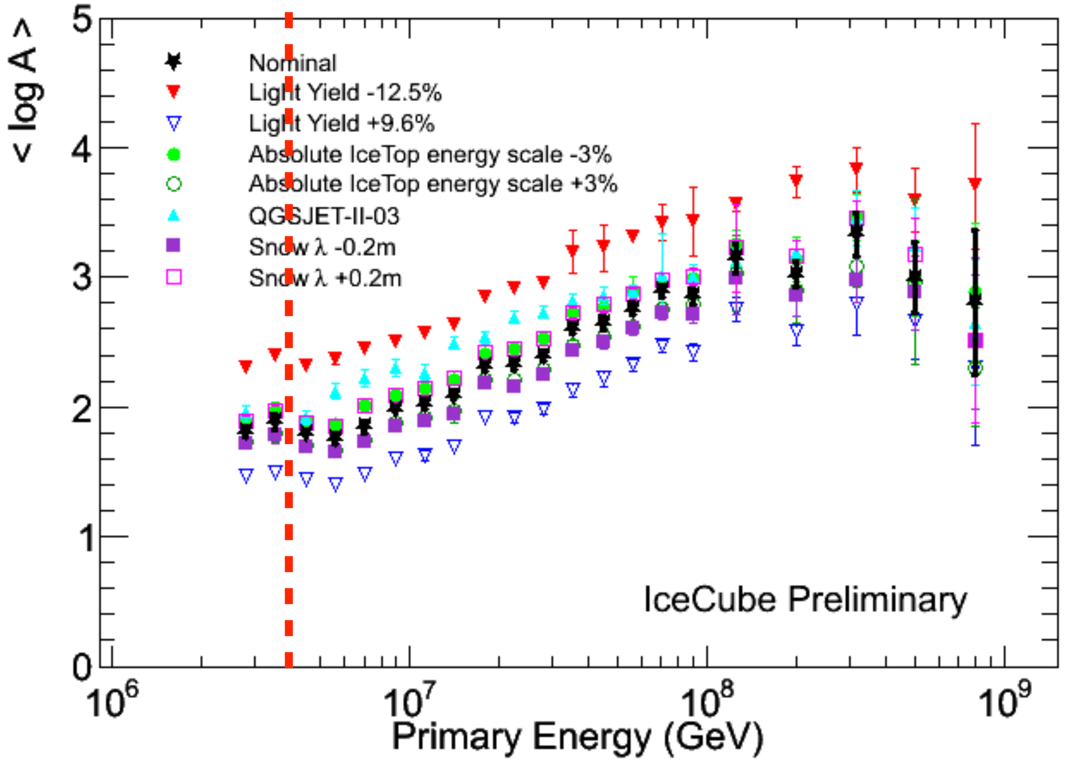
The *CR flux* is measured with the *surface signal*

The *mass composttion* is extracted from the *energy loss of TeV muons* observed in the deep ice in coincidence with signals at the surface

Both the IceTop-alone and IceTop-IceCube coincidence analyses show a *hardening* of the spectrum at *around 20 PeV* and a *softening* again *past 100 PeV*.

Composition at the knee: IceCube





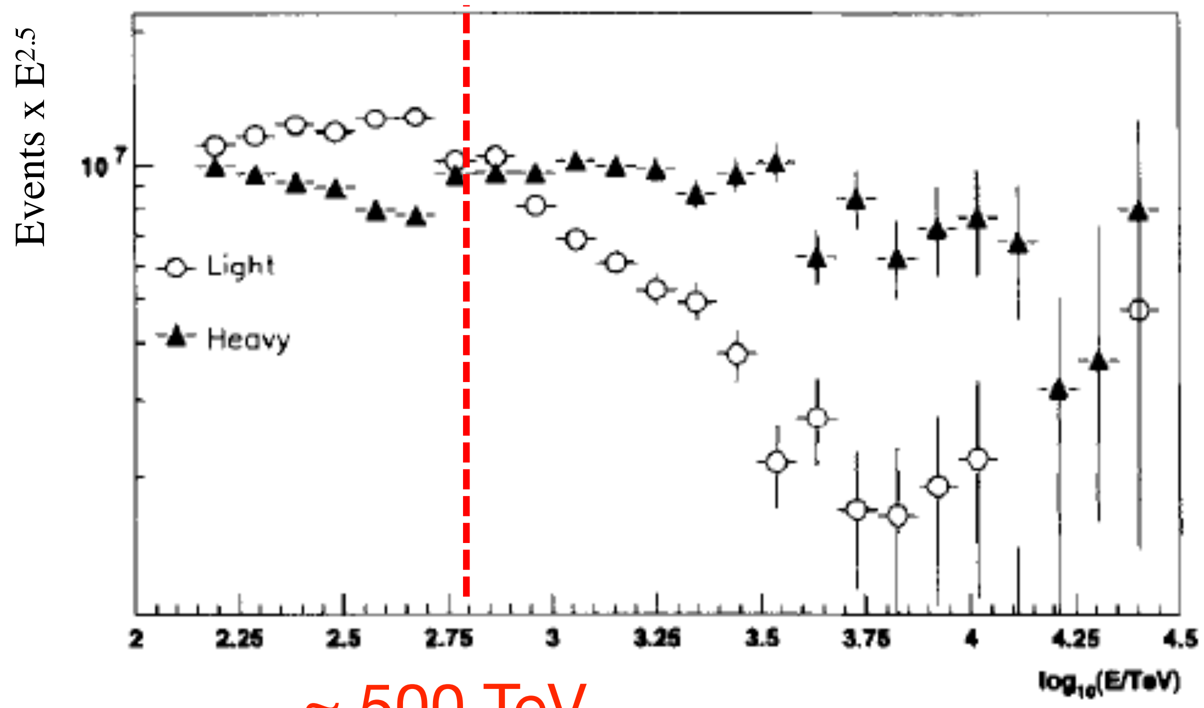
EPJ Web Conf. 145 (2017) 01003

IceCube observes *an initially light composition that becomes increasingly heavy as the energy increases, then stabilizes around 100 PeV.*

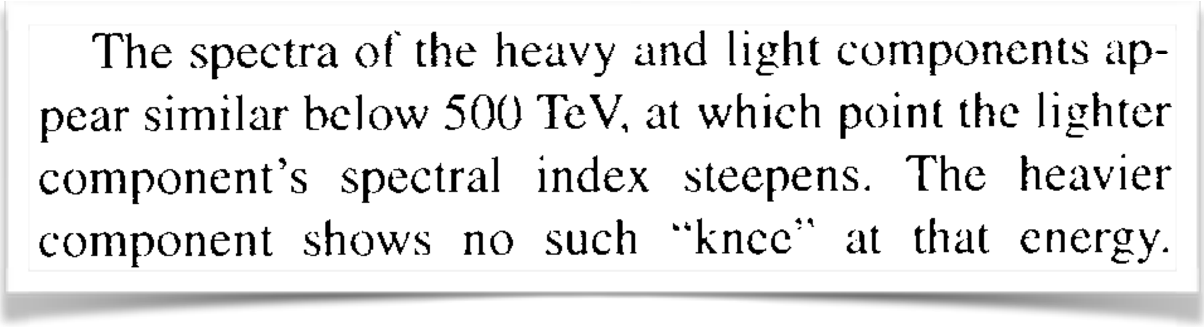
The measurement indicates a *heavier composition around 1 EeV than measurements from Auger* based on the depth of shower maximum.

A sudden drop in the helium and iron spectra around 6 PeV is observed, with corresponding elevated levels of proton and oxygen. This feature is under intense study. The most likely explanation is a statistical fluctuation.

Composition at the knee: CASA-MIA



≈ 500 TeV



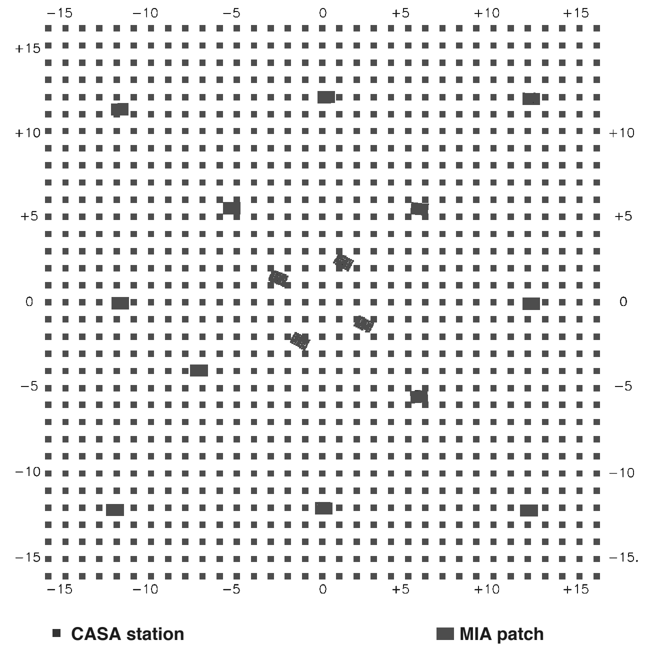
The spectra of the heavy and light components appear similar below 500 TeV, at which point the lighter component's spectral index steepens. The heavier component shows no such "knee" at that energy.

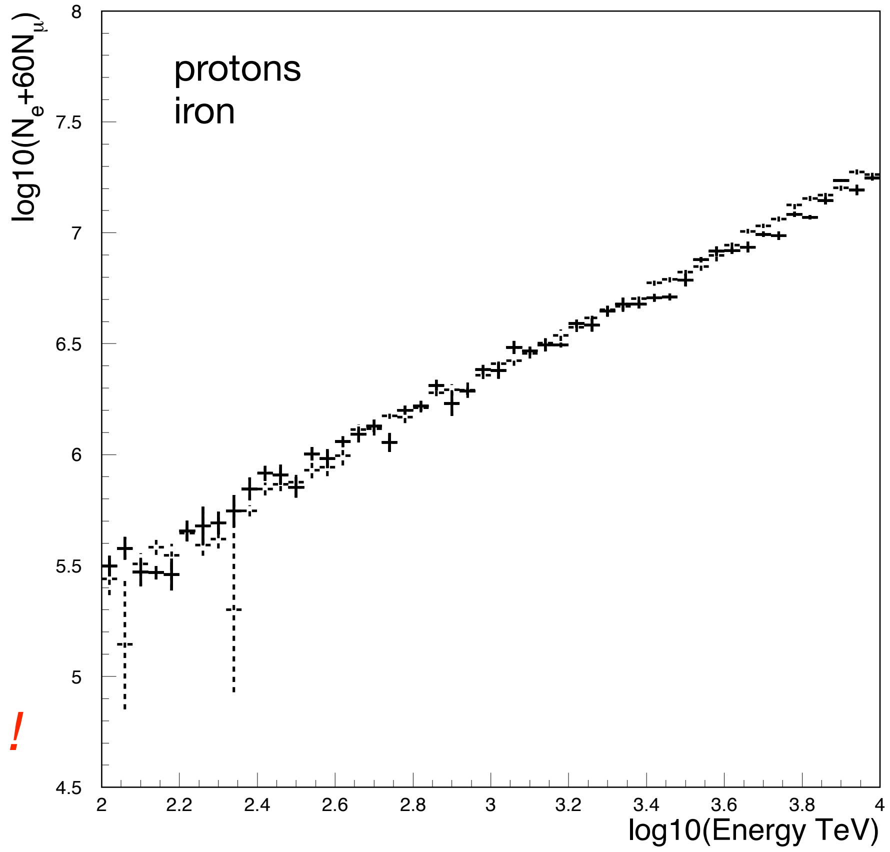
Astroparticle Physics 12 (1999) 1–17

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

The energy reconstruction is *compositionally independent !*

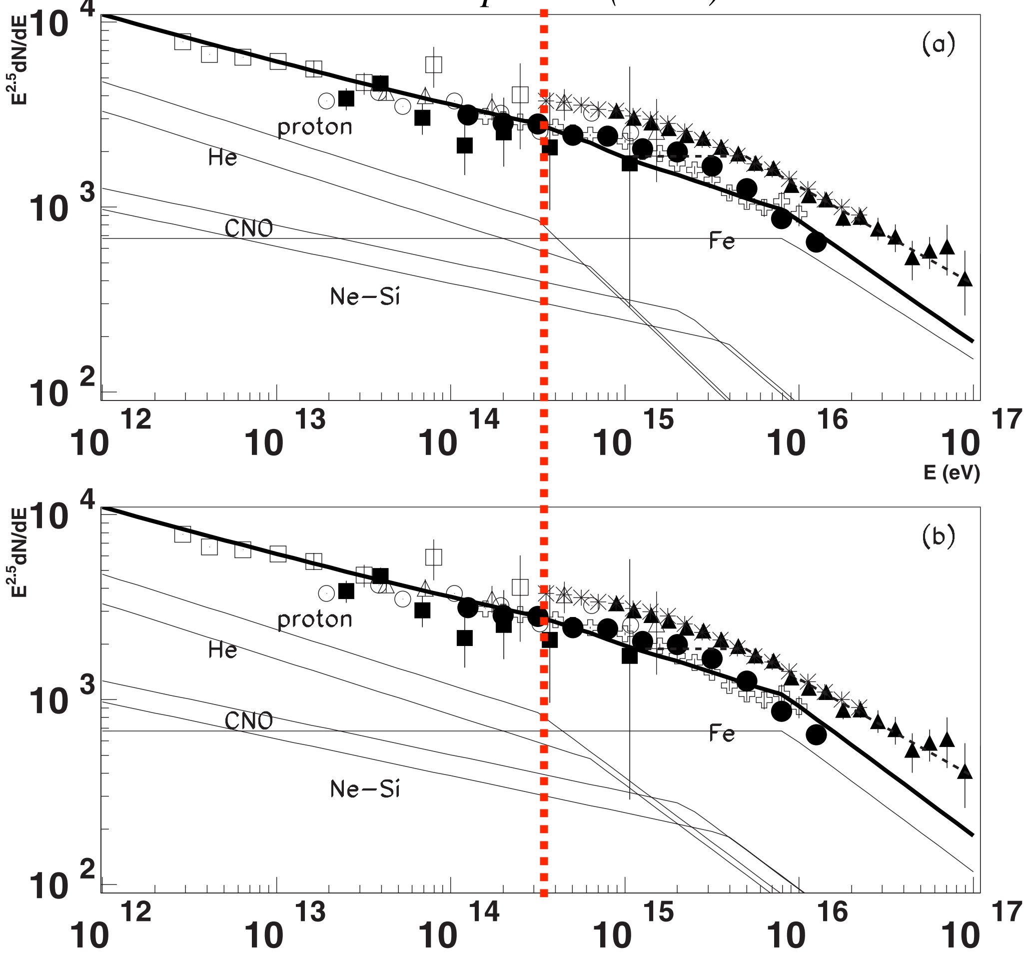
1400 m asl





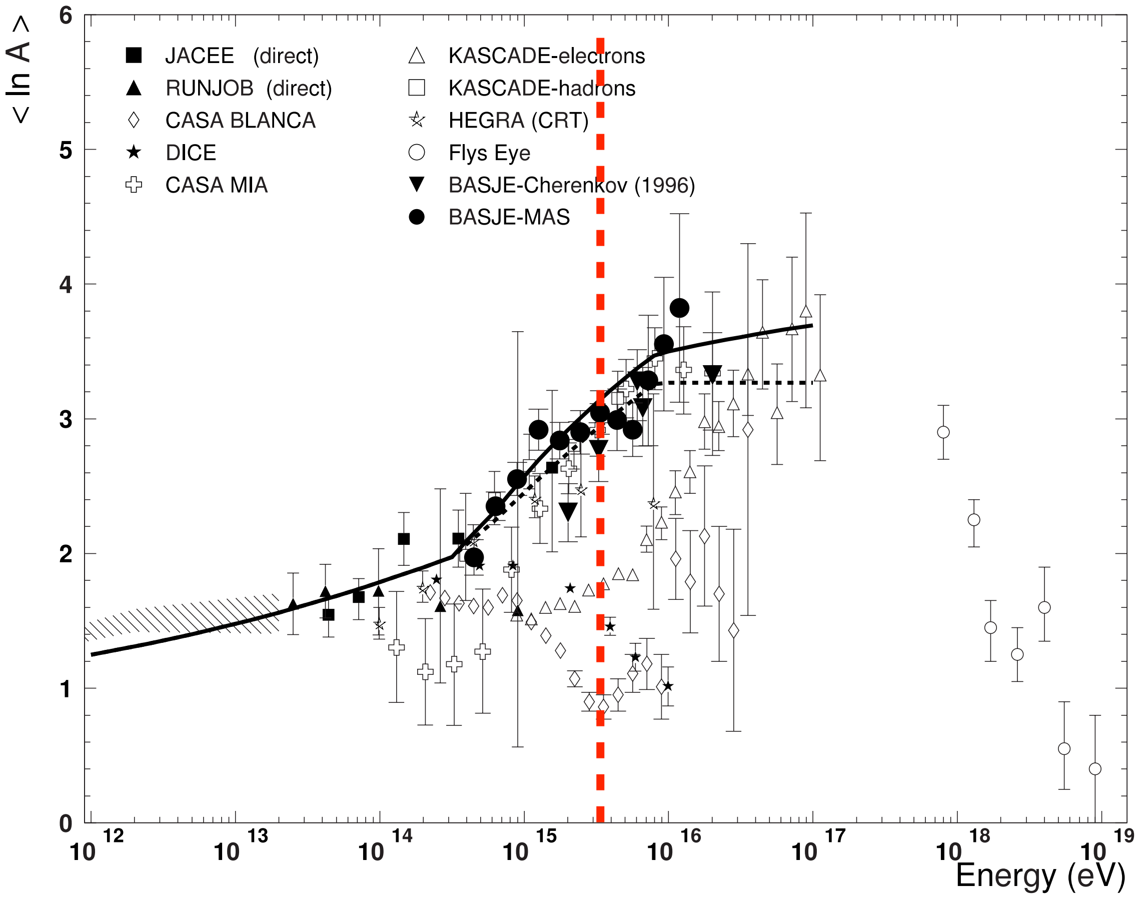
Composition at the knee: BASJE - MAS

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.

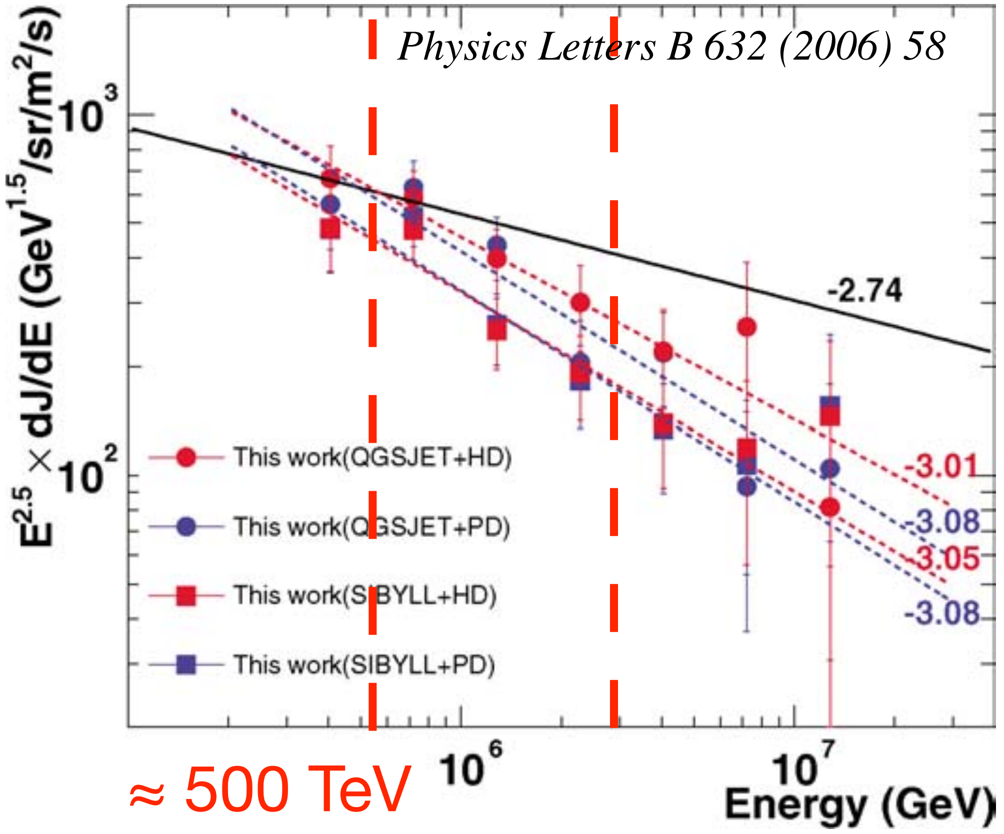


Finally, we conclude that the actual model suggests that the dominant component above 10^{15} eV is heavy and that the $\langle \ln A \rangle$ increases with the energy to about 3.5 at 10^{16} eV.

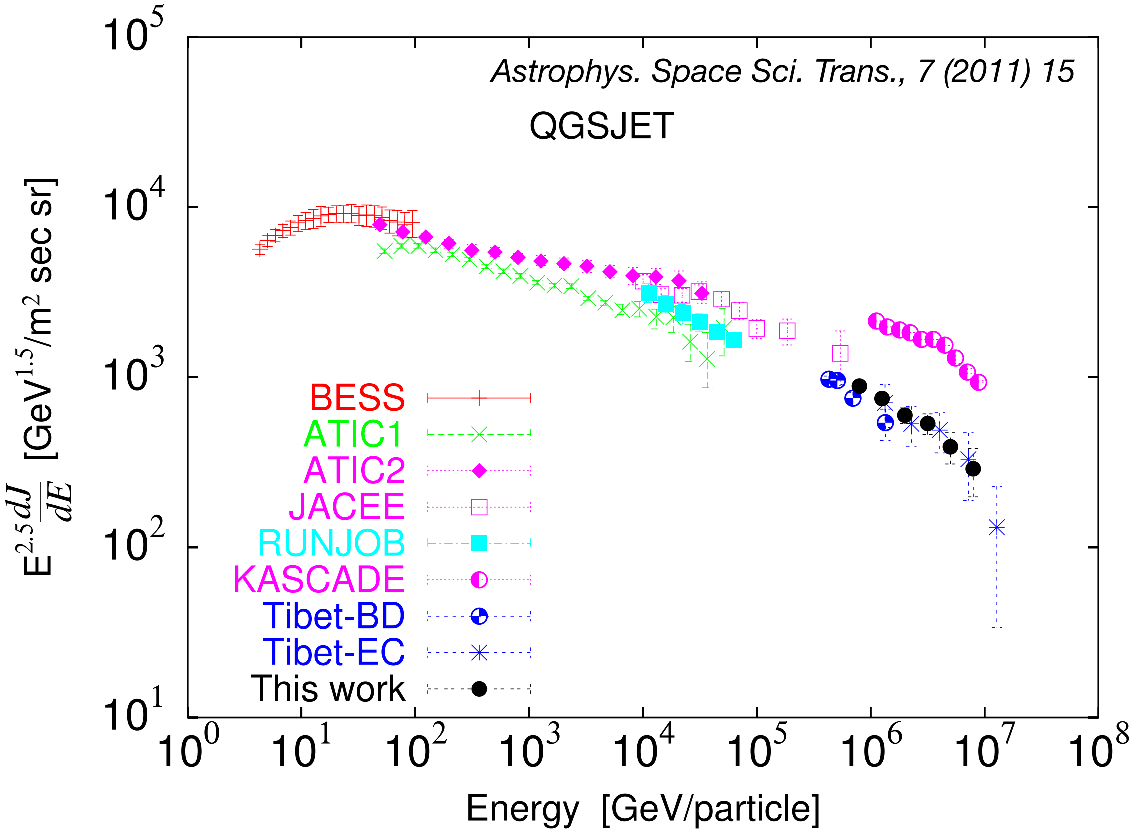
Chacaltaya 5200 m asl

Composition at the knee: Tibet ASγ

Tibet 4300 m asl


Physics Letters B 632 (2006) 58

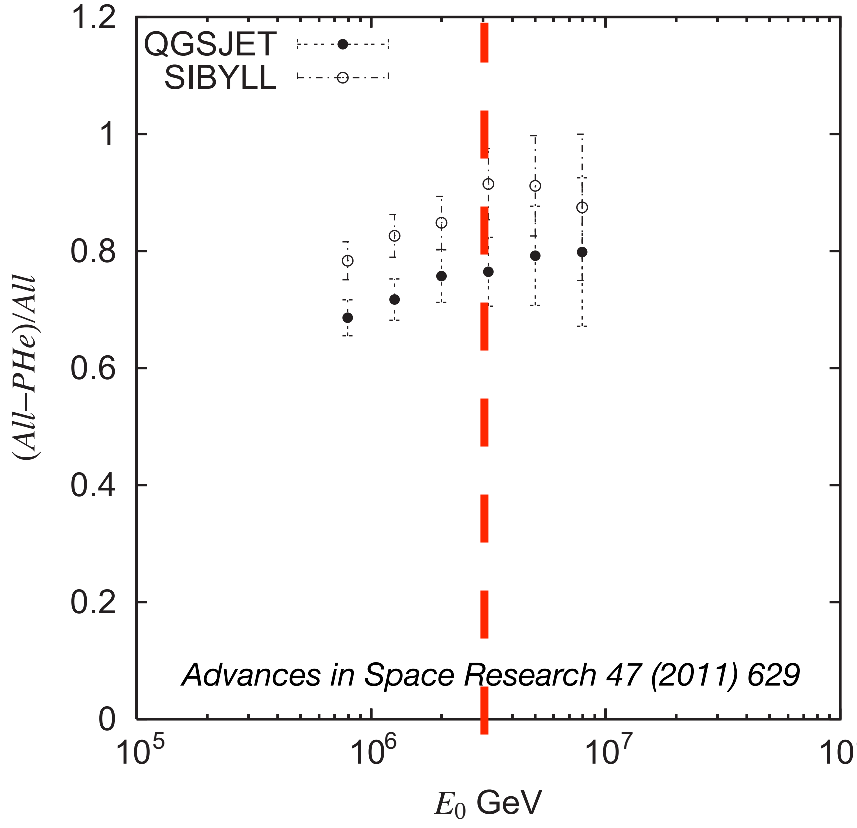
≈ 500 TeV


Astrophys. Space Sci. Trans., 7 (2011) 15

(1) The power index is steeper than that of all-particle spectrum before the knee, suggesting that *the light component has the break point at lower energy than the knee.*

(2) The fraction of the light component to the all-particles is less than 30% which tells that *the main component responsible for the knee structure is heavier than helium.*

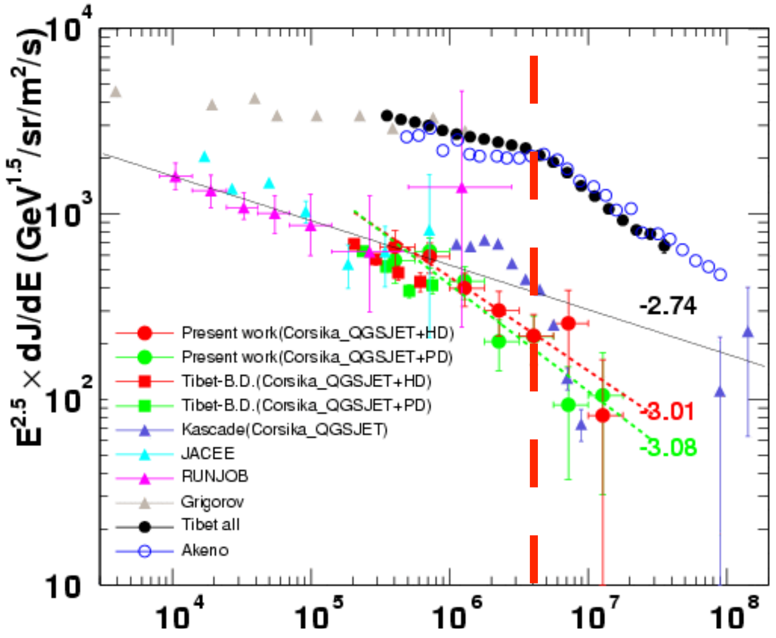
Astrophys. Space Sci. Trans., 7 (2011) 15

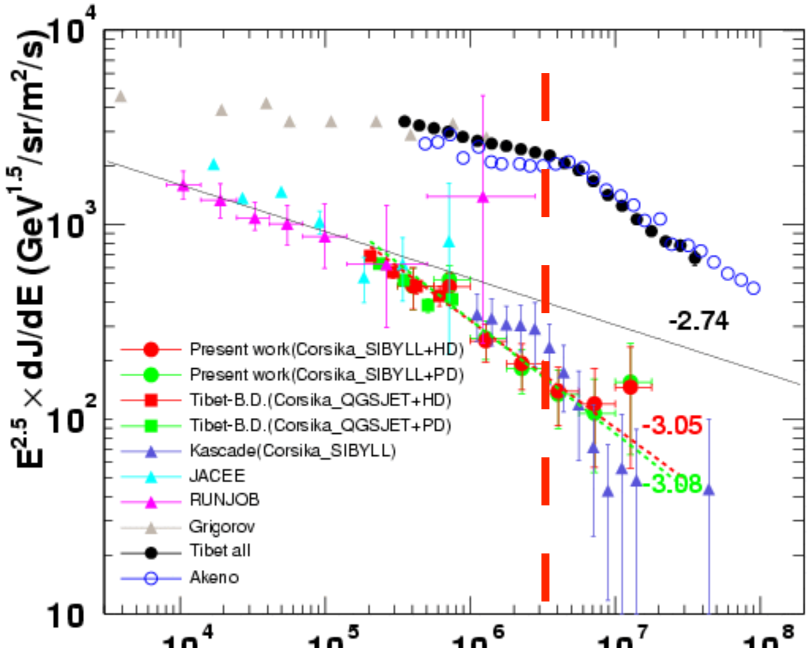

Advances in Space Research 47 (2011) 629

Composition at the knee: Tibet ASγ

CORSIKA QGSJET

CORSIKA_SIBYLL

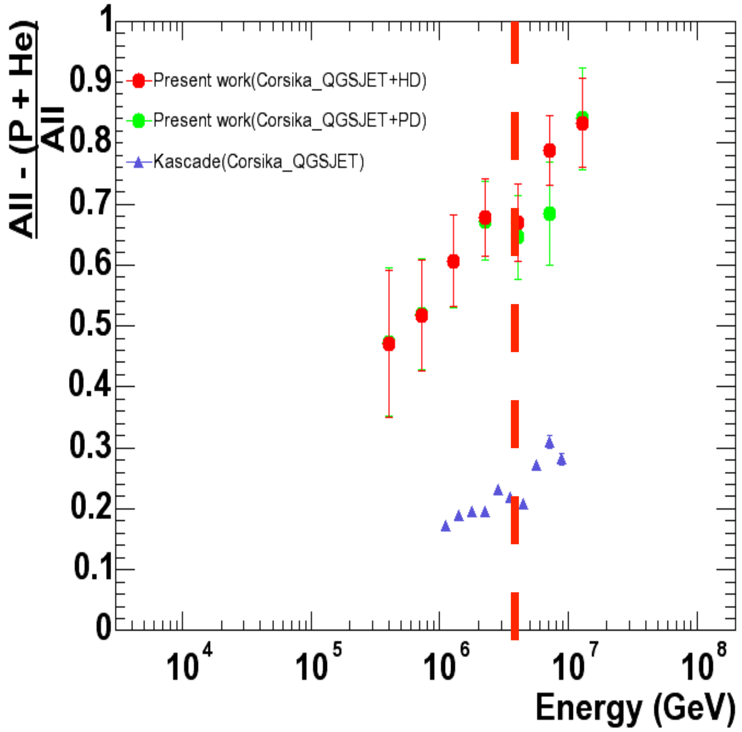


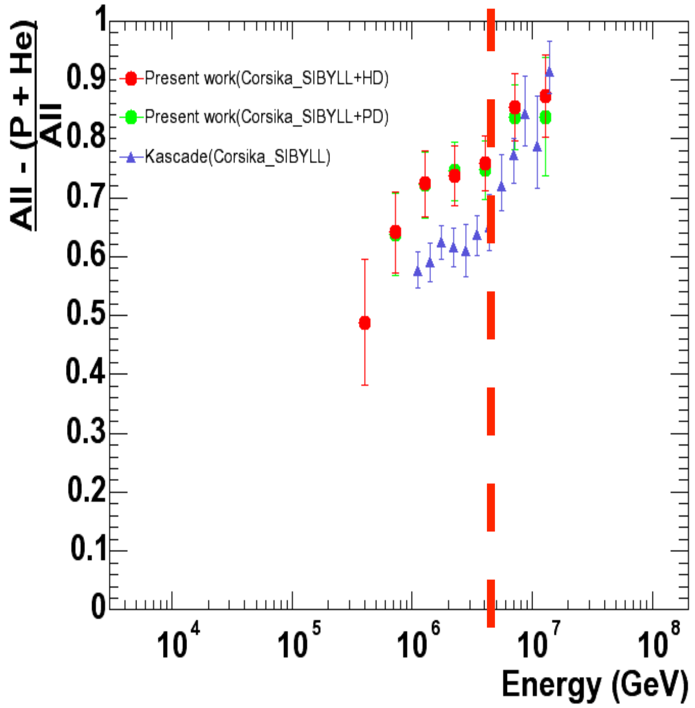


Proton

Small model dependence

(30 %)



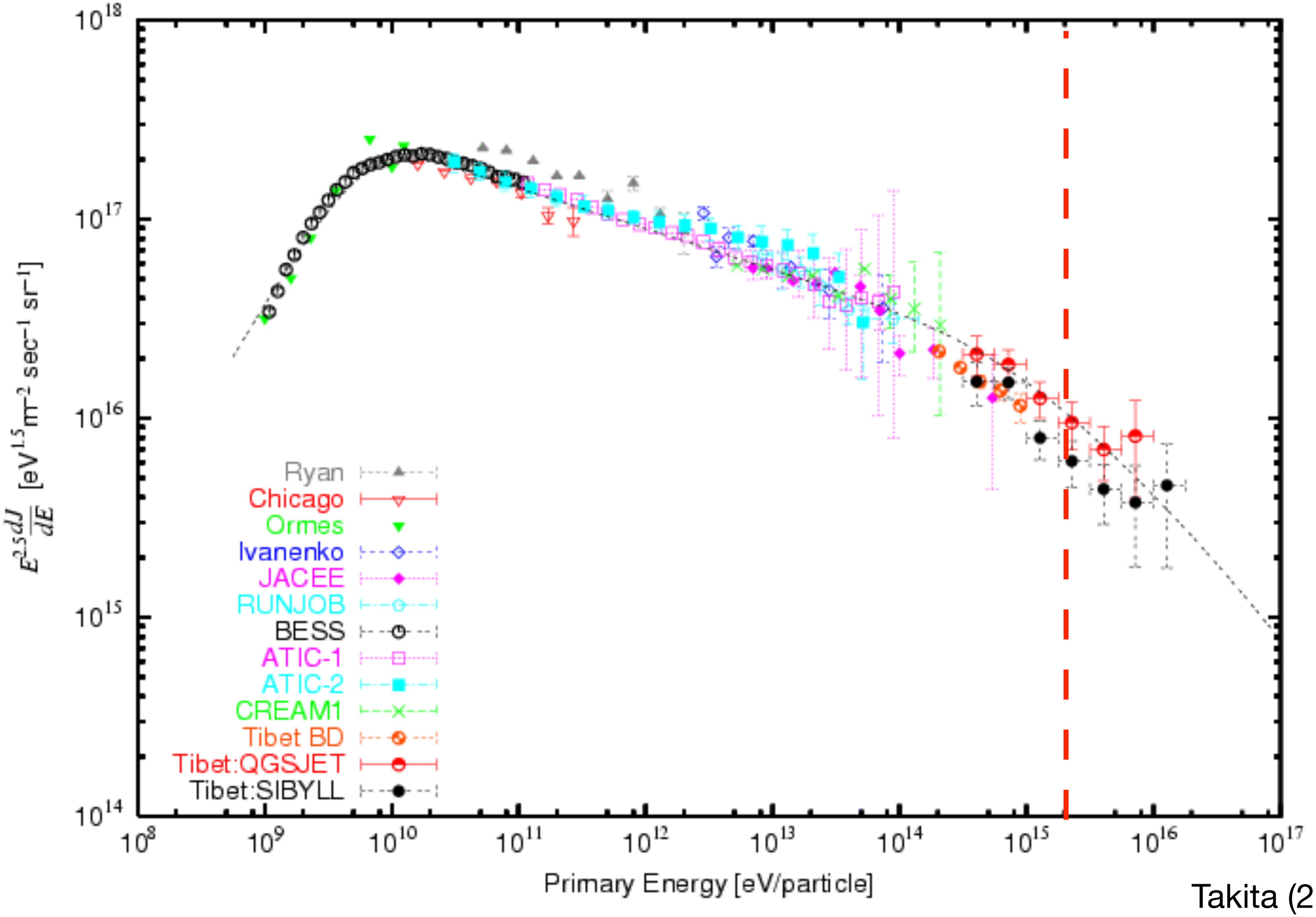


$$\frac{\text{All} - (\text{p+He})}{\text{All}}$$

Takita (2013)

Proton Spectrum

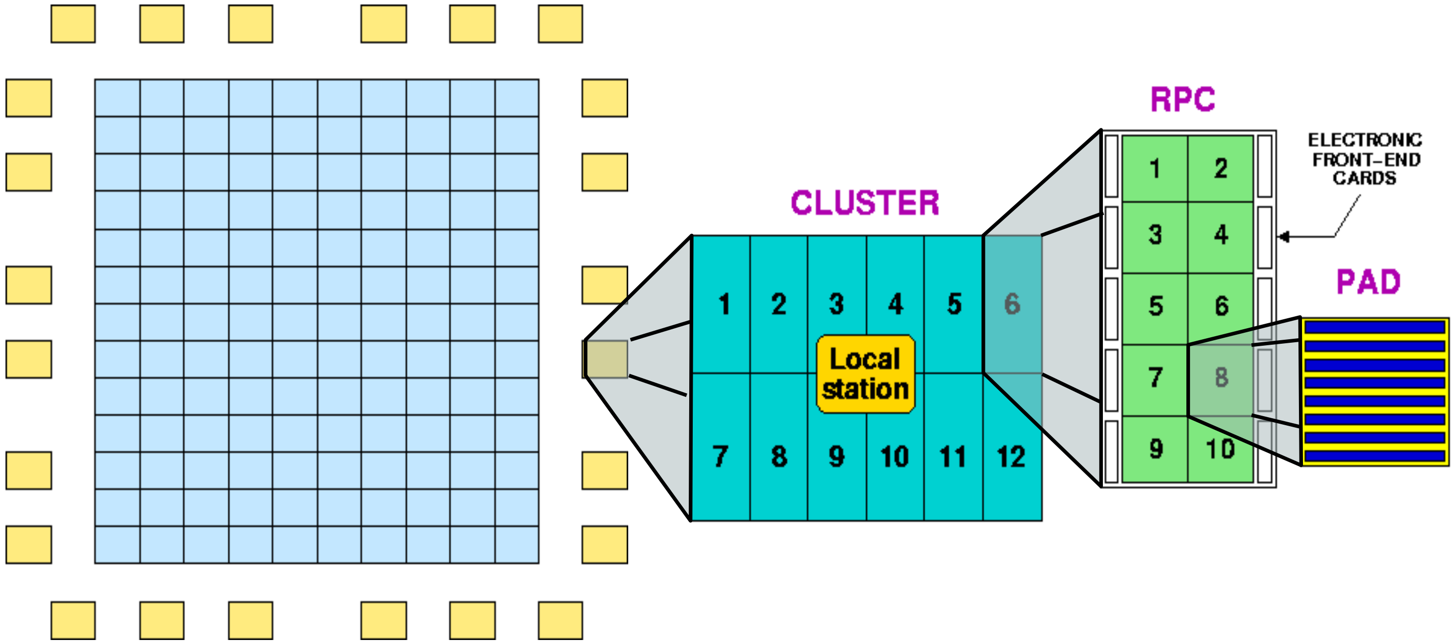
Direct measurement and Tibet ASγ combined



Takita (2013)

The ARGO-YBJ experiment

ARGO-YBJ is a telescope optimized for the detection of small size air showers



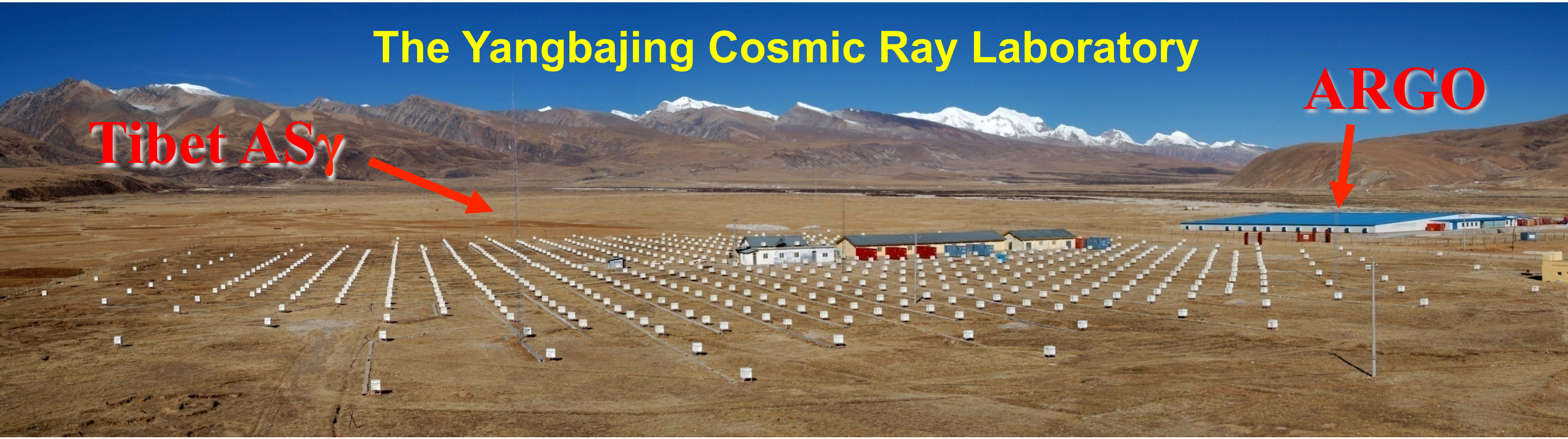
INFN IHEP/CAS

Longitude: 90° 31’ 50” East
Latitude: 30° 06’ 38” North

90 km North from Lhasa (Tibet)

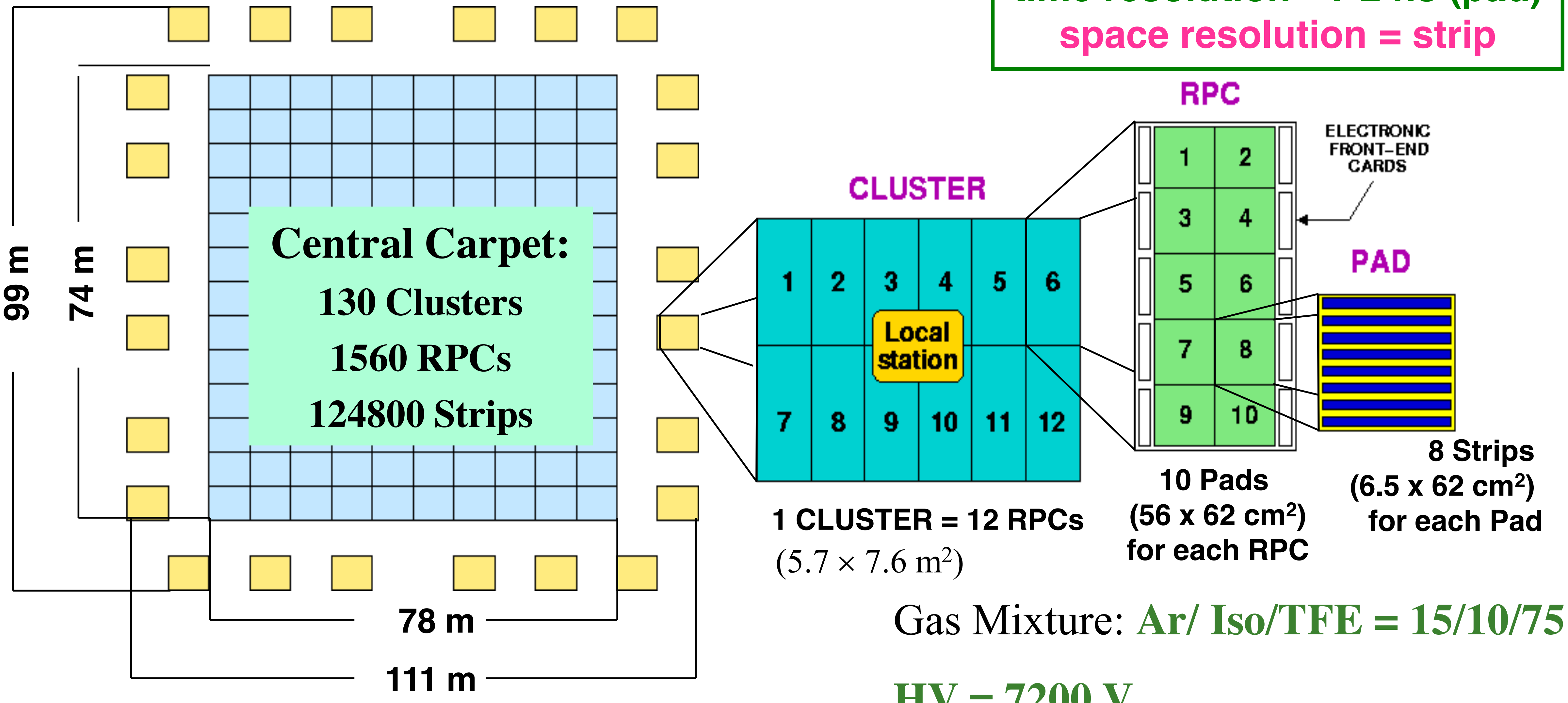
4300 m above sea level
$\sim 600\ \mathrm{g/cm^2}$

The Yangbajing Cosmic Ray Laboratory



The ARGO-YBJ layout

time resolution ~1-2 ns (pad)
space resolution = strip



Central Carpet:
130 Clusters
1560 RPCs
124800 Strips

1 CLUSTER = 12 RPCs
(5.7 × 7.6 m²)

10 Pads
(56 x 62 cm²)
for each RPC

8 Strips
(6.5 x 62 cm²)
for each Pad

Gas Mixture: **Ar/ Iso/TFE = 15/10/75**

HV = 7200 V

Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m²)
+ sampling guard ring (6700 m² in total)

The basic concepts

…for an unconventional air shower detector

❖ HIGH ALTITUDE SITE
(YBJ - Tibet 4300 m asl - 600 g/cm2)

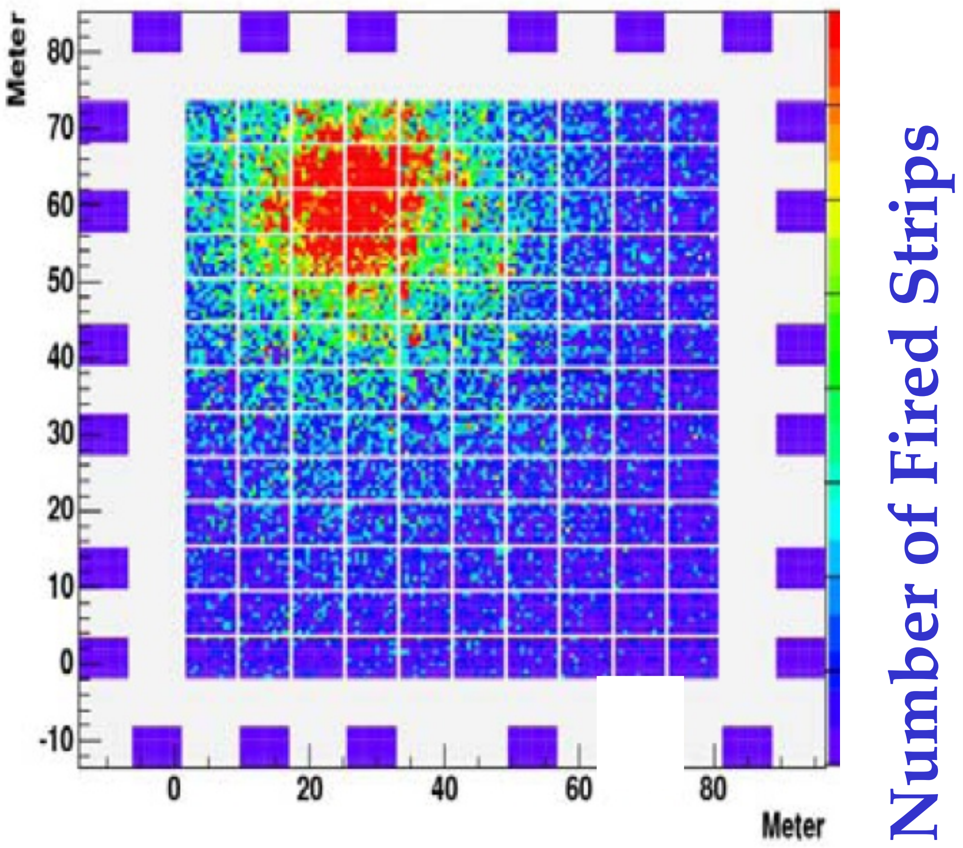
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

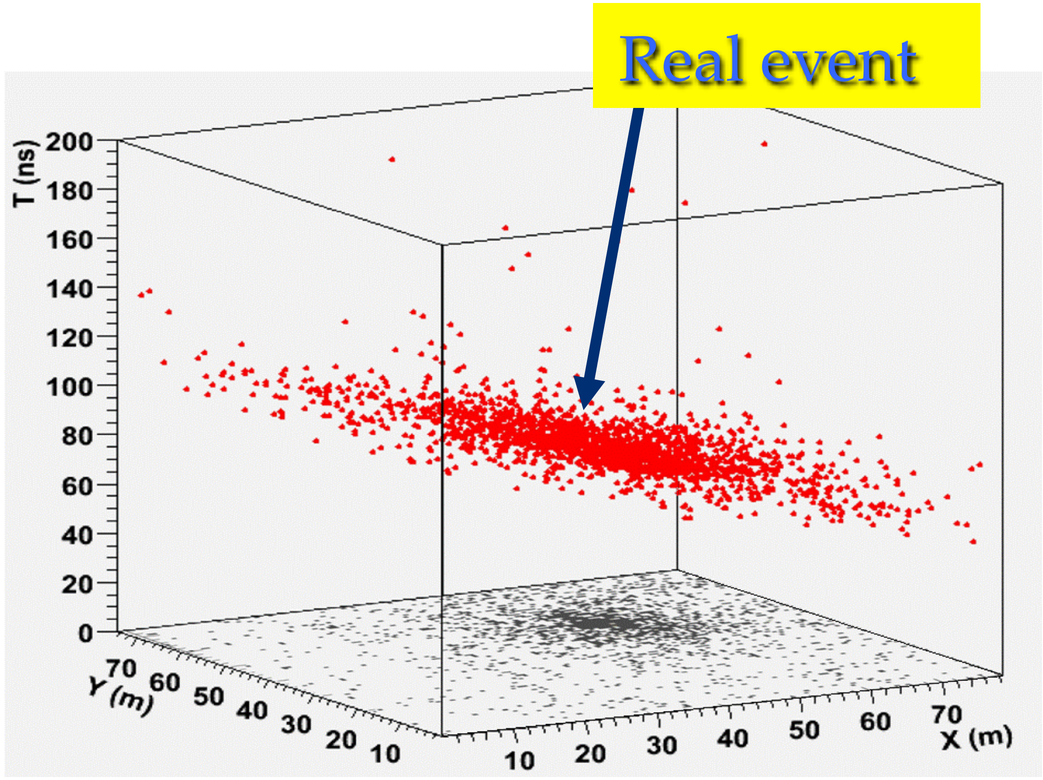
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

Space pixels: 146,880 strips (7×62 cm^2)
Time pixels: 18,360 pads (56×62 cm^2)

… in order to

- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV





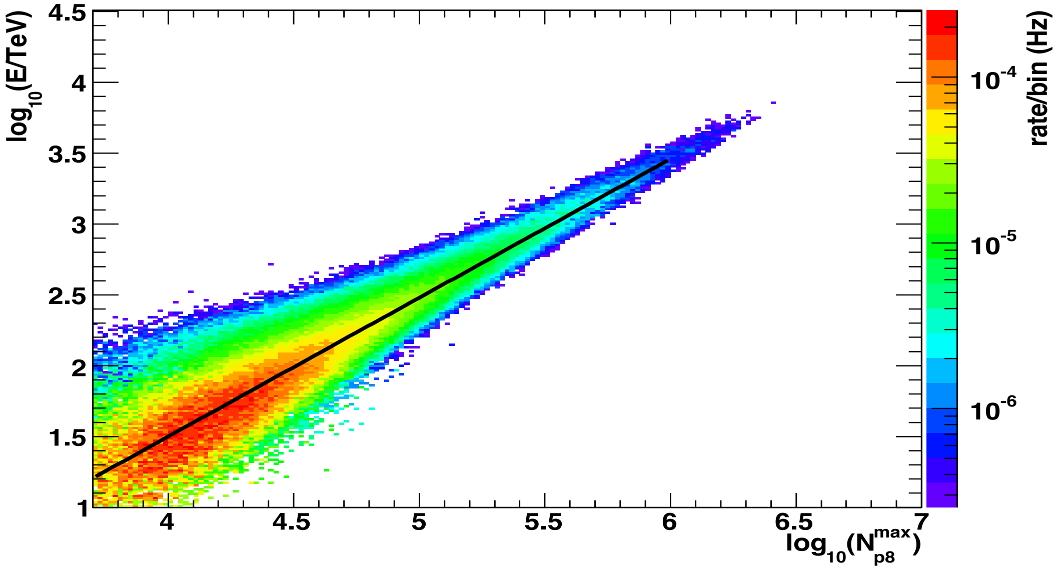
Selection of p+He component by ARGO-YBJ

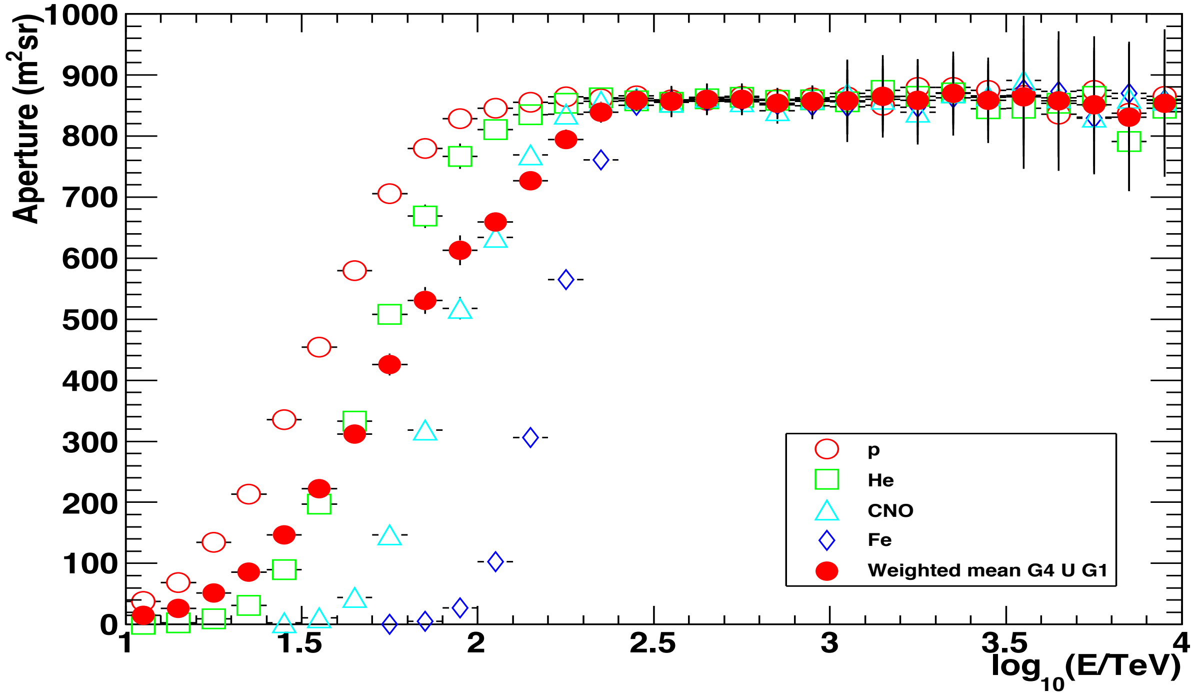
- Selection of (p+He)-induced showers in ARGO-YBJ: **NOT** by means of an unfolding procedure after the measurement of electronic and muonic sizes, but on an *event-by-event basis exploiting showers topology*, i.e. the lateral distribution of charged secondary particles.

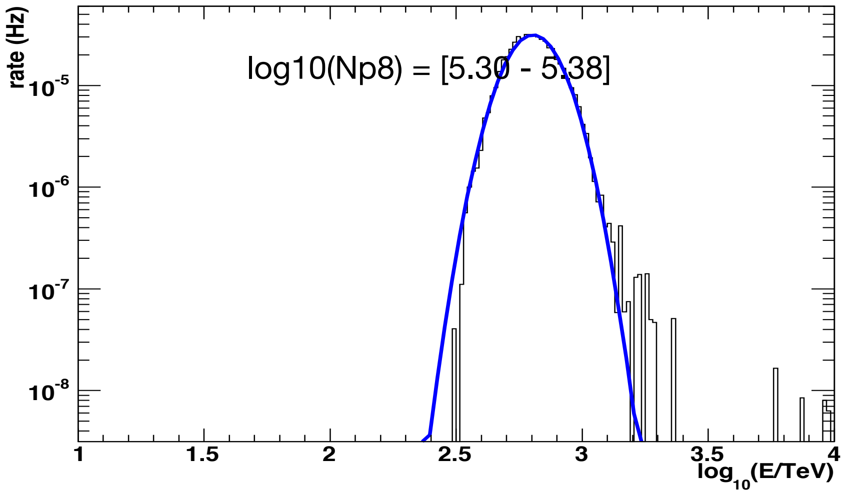
- Energy reconstruction is based on the N_p^{8m} parameter: the *number of particle within 8 m from the shower core position.*

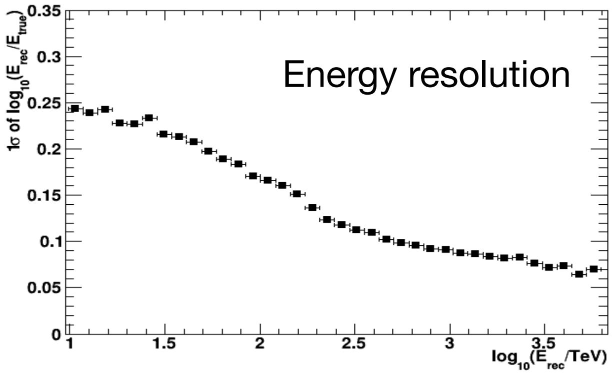
This truncated size is

  - well correlated with primary energy
  - not biased by finite detector effects
  - weakly affected by shower fluctuations









Wide Field of View Cherenkov Telescopes

The goal: measurement of the CR energy spectrum and composition in the range 10^{13} - 10^{18} eV

Why Wide FoV Cherenkov telescopes at high altitude ?

High altitude

(1) Measure EASs near maximum development points to reduce fluctuations.

(2) Use an unbiased trigger threshold for heavy components of primaries.

(3) Low energy threshold and wide energy range (10^{13} → 10^{18} eV).

Cherenkov signal

(4) Measure the electromagnetic component which is less dependent on hadronic interaction models than the muon component.

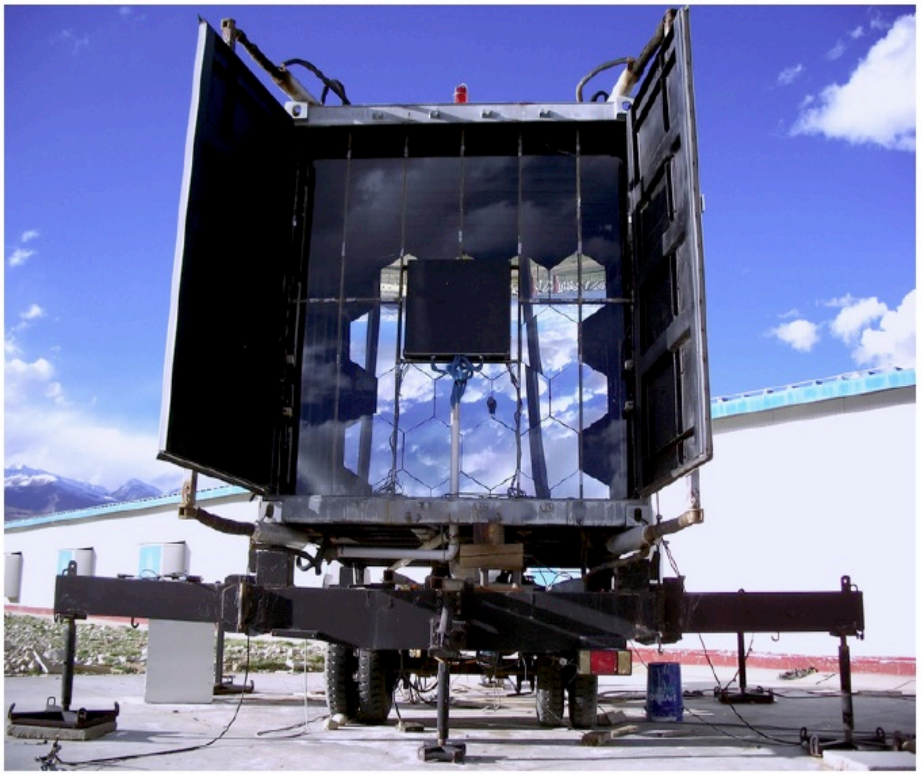
(5) Good separation capability between the different masses.

(6) Good energy resolution (≈20%).

Chin. Phys. C 38, 045001 (2014)
Phys. Rev. D 92, 092005 (2015)

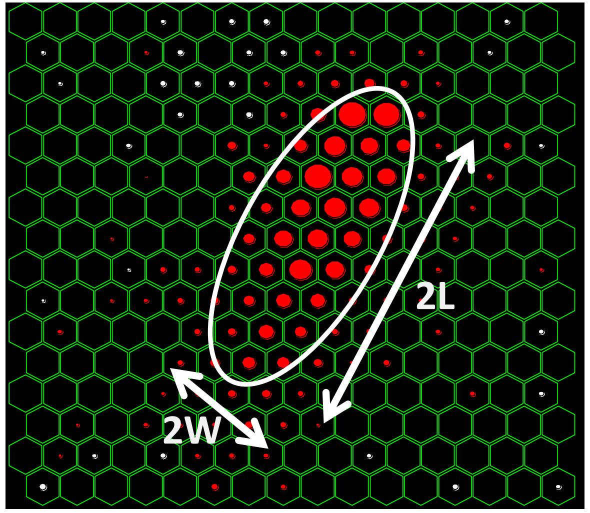
First example of *hybrid measurement*: Cherenkov telescope + EAS array (ARGO-YBJ)

ARGO-YBJ + WFCTA



A prototype of the future LHAASO telescopes has been operated in combination with ARGO-YBJ

- 4.7 m² spherical mirror composed of 20 hexagon-shaped segments
- 256 PMTs (16 × 16 array)
- 40 mm Photonis hexagonal PMTs (XP3062/FL)
- pixel size 1°
- FOV: 14° × 14°
- Elevation angle: 60°



❖ *ARGO-YBJ:* core reconstruction & lateral distribution in the core region

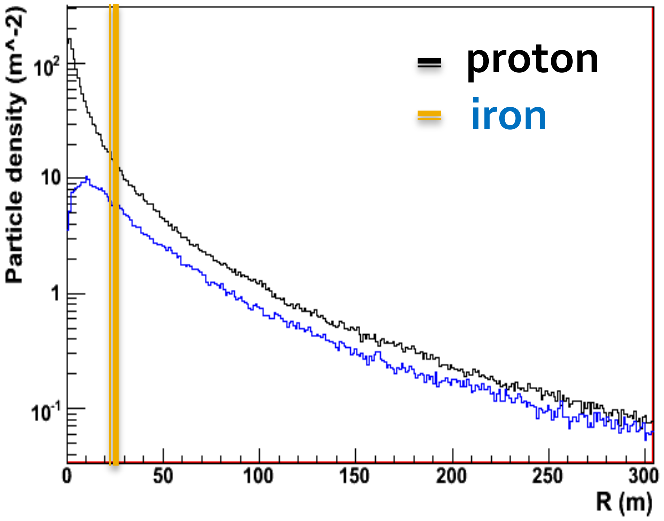
→ mass sensitive

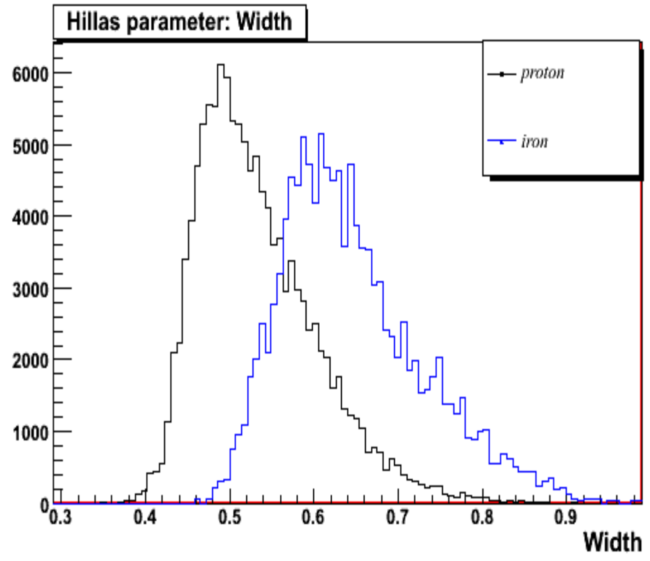
❖ *Cherenkov telescope:* longitudinal information

Hillas parameters → mass sensitive

- angular resolution: 0.2°
- shower core position resolution: 2 m

Phys. Rev. D 92, 092005 (2015)





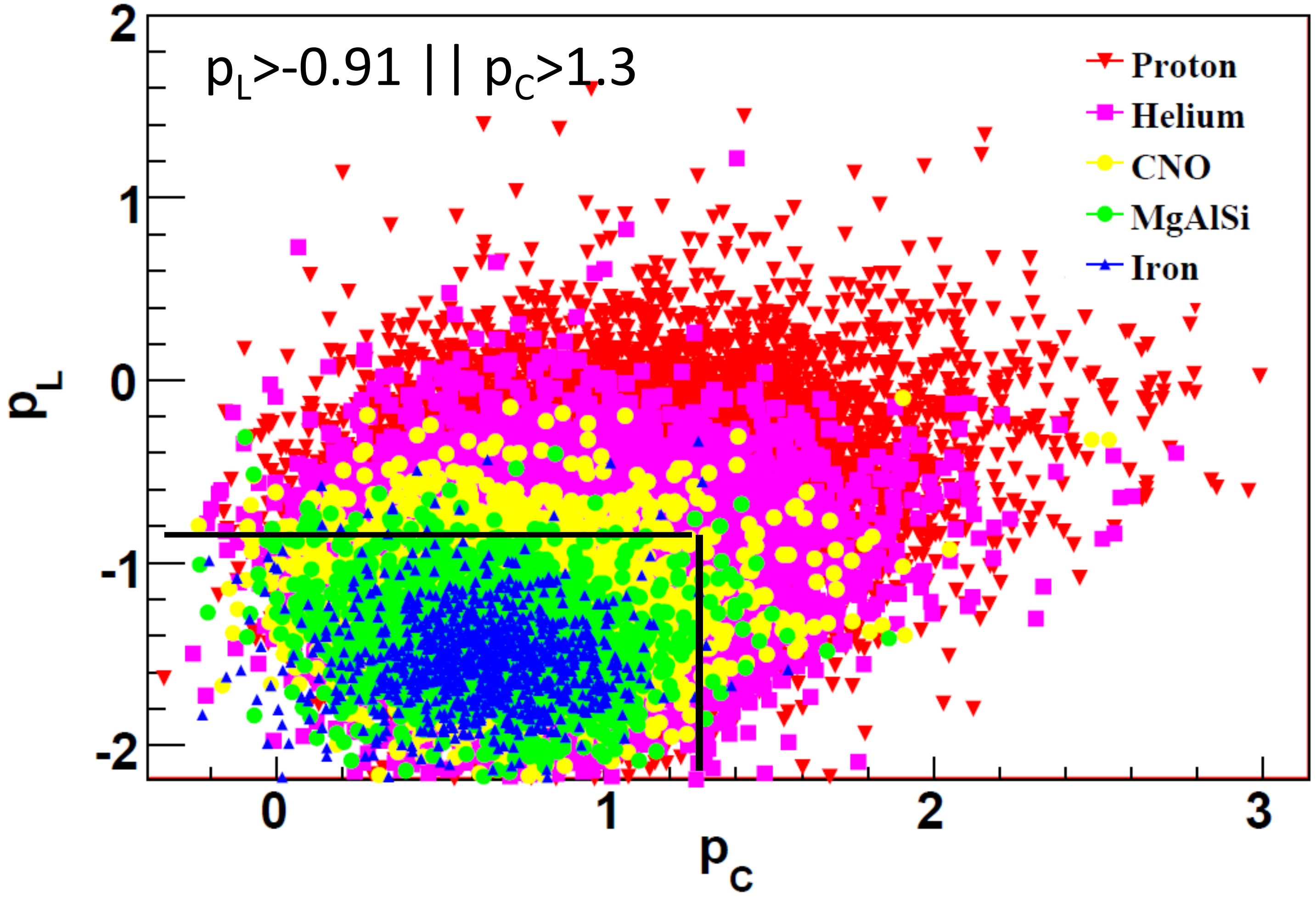
Light component (p + He) selection

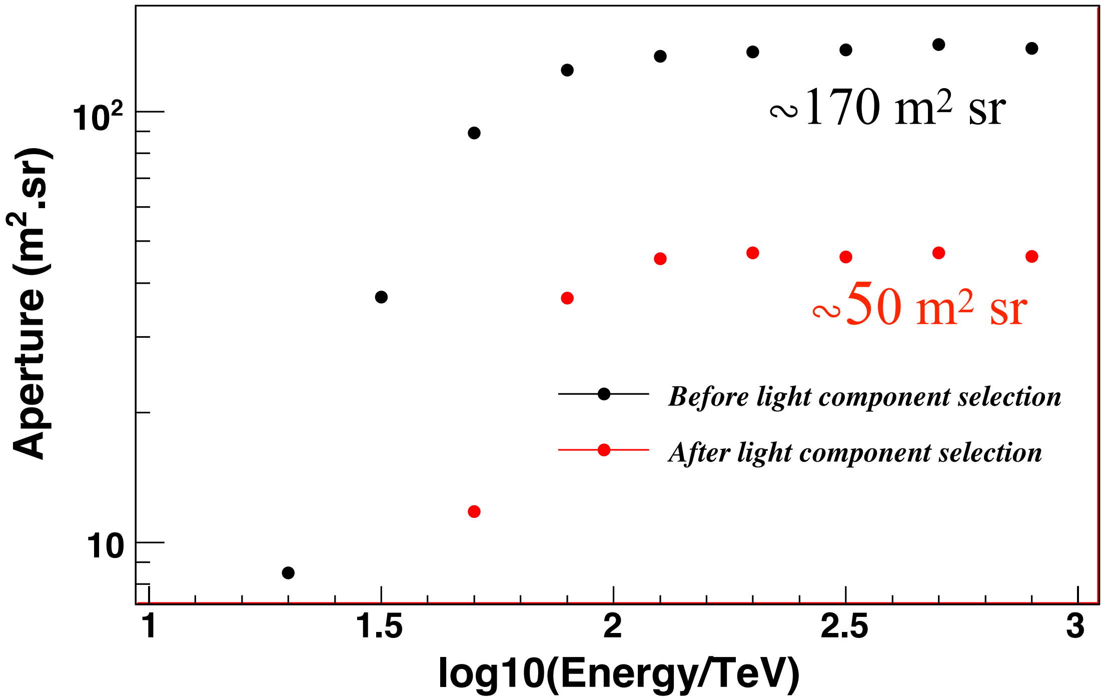
- Contamination of heavier component < 5 %
- Energy resolution: ~25% constant with energy
- Uncertainty : ~25% on flux

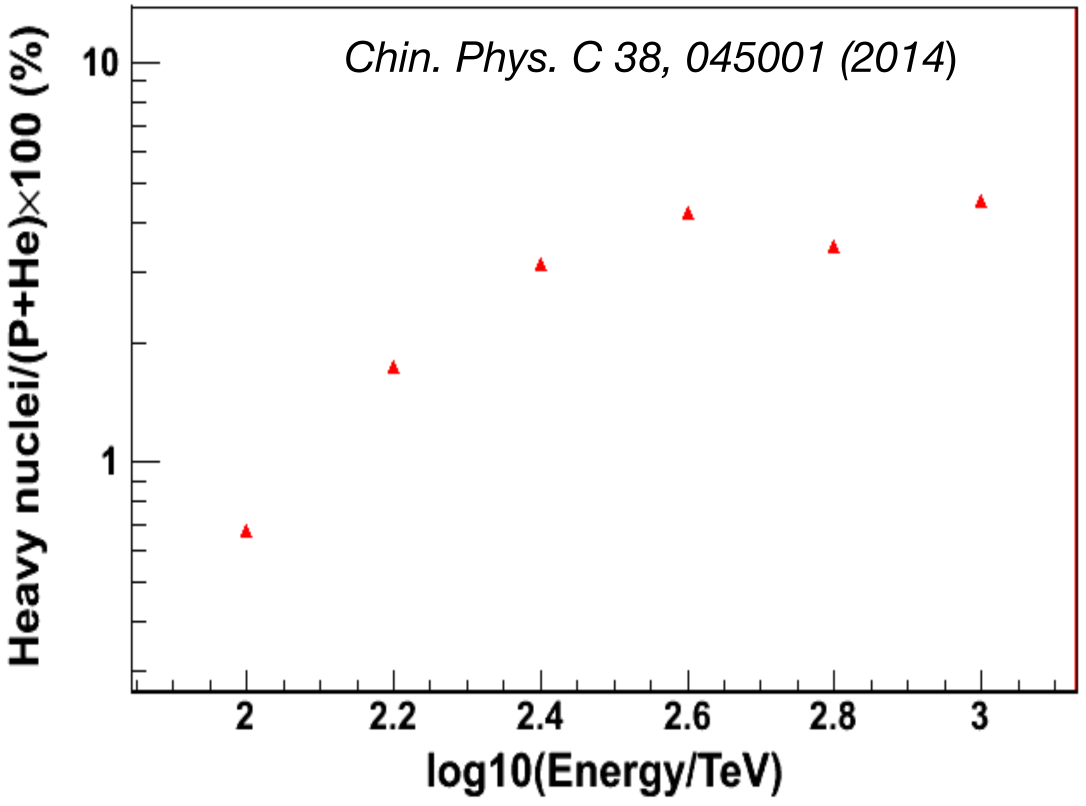
$$p_L = log_{10}(N_{max}) - 1.44 \cdot log_{10}(E_{rec}/TeV)$$

$$p_C = L/W - 0.0091(R_p/1\,m) - 0.14 \cdot log_{10}(E_{rec}/TeV)$$

Events for which $p_L \leq -0.91$ and $p_C \leq 1.3$ are rejected

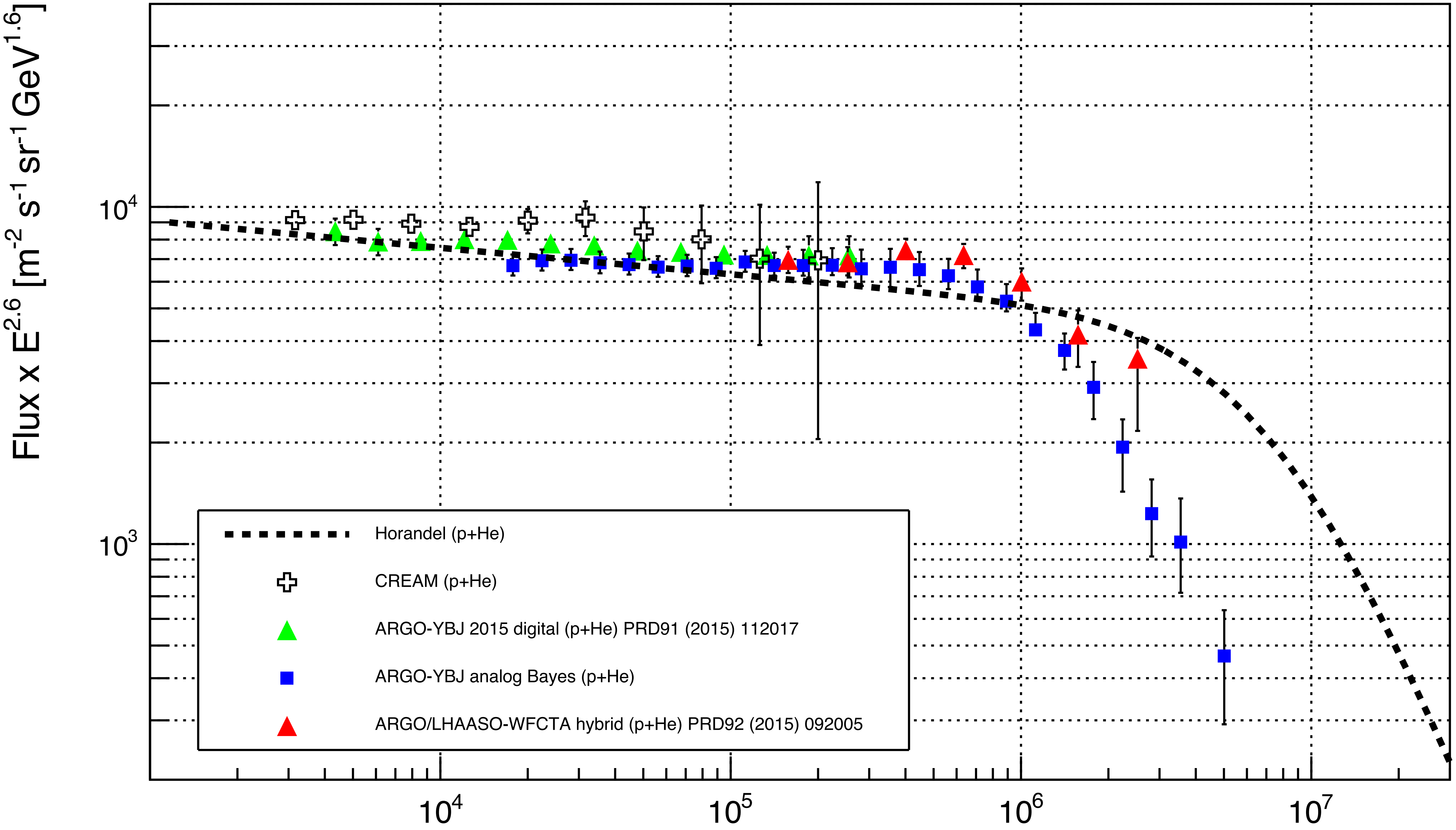






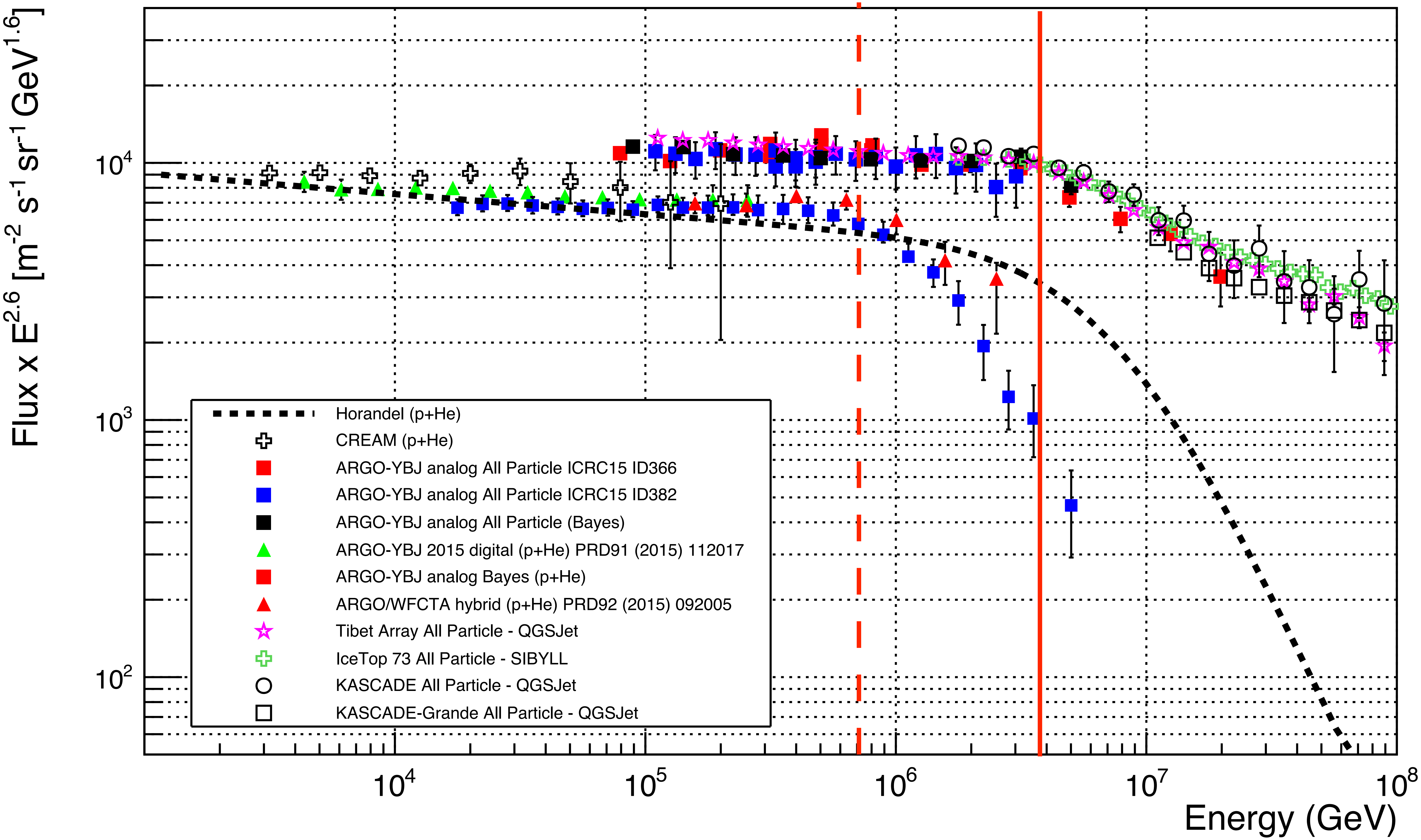
Composition at the knee: ARGO-YBJ

ARGO-YBJ reports evidence for a proton knee starting at about 700 TeV



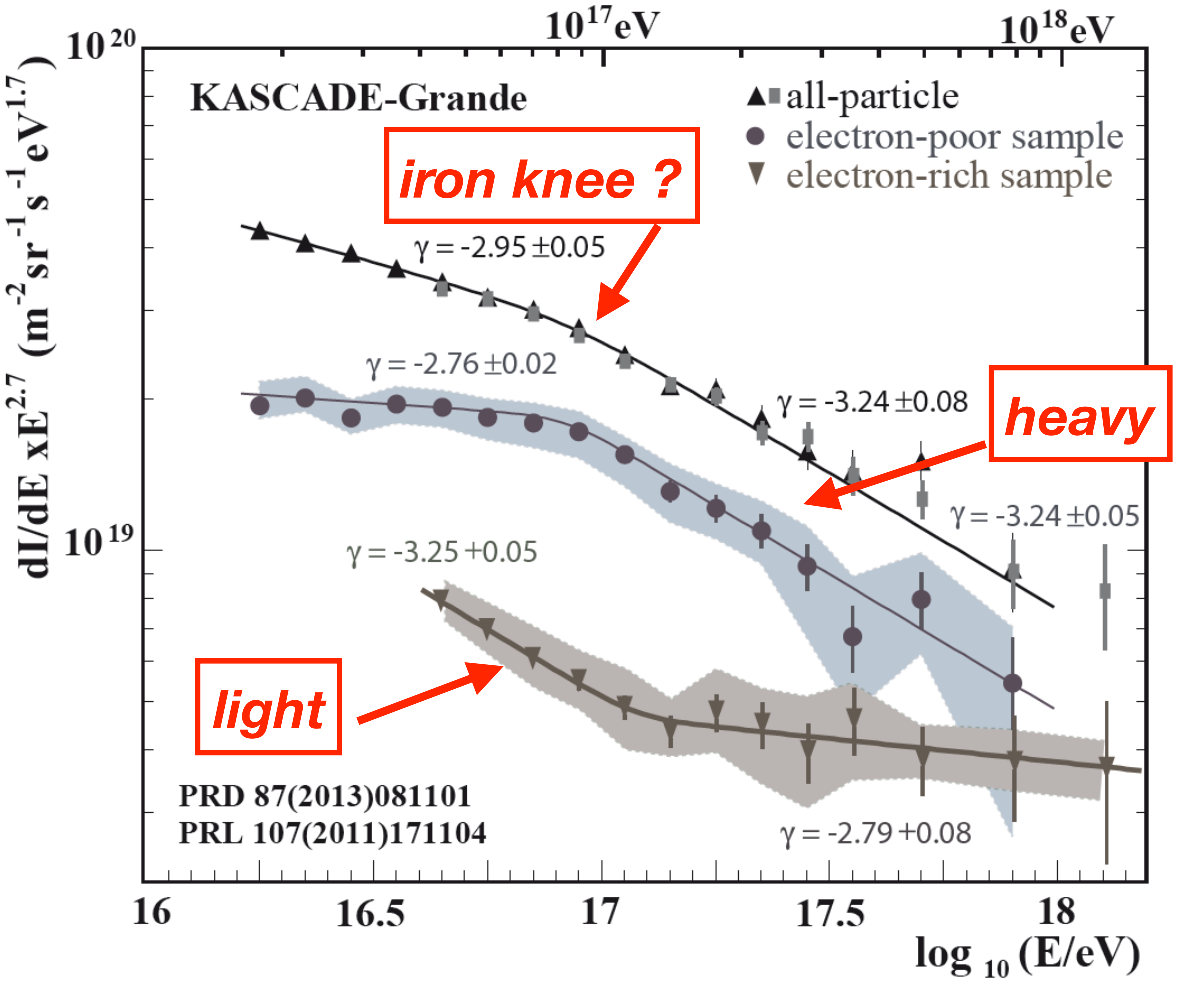
Tibet 4300 m asl

The overall picture

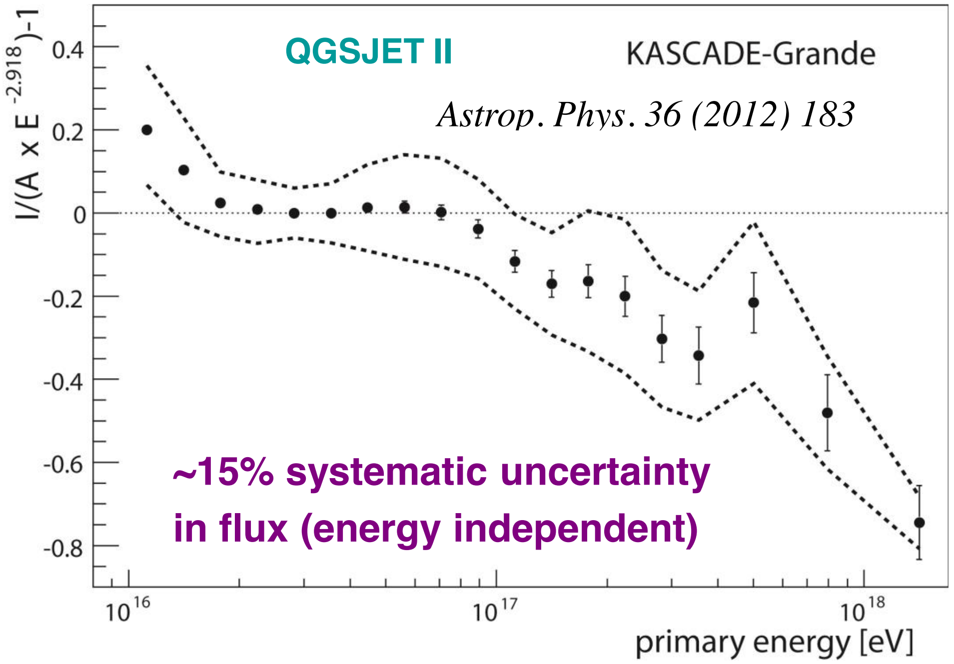


Energy spectrum above the *'knee'*

- spectrum all-particle above the knee *not a single power law*
- hardening of the spectrum above 10^{16}eV
- *steepening* close to *10^{17}eV* (2.1 σ)



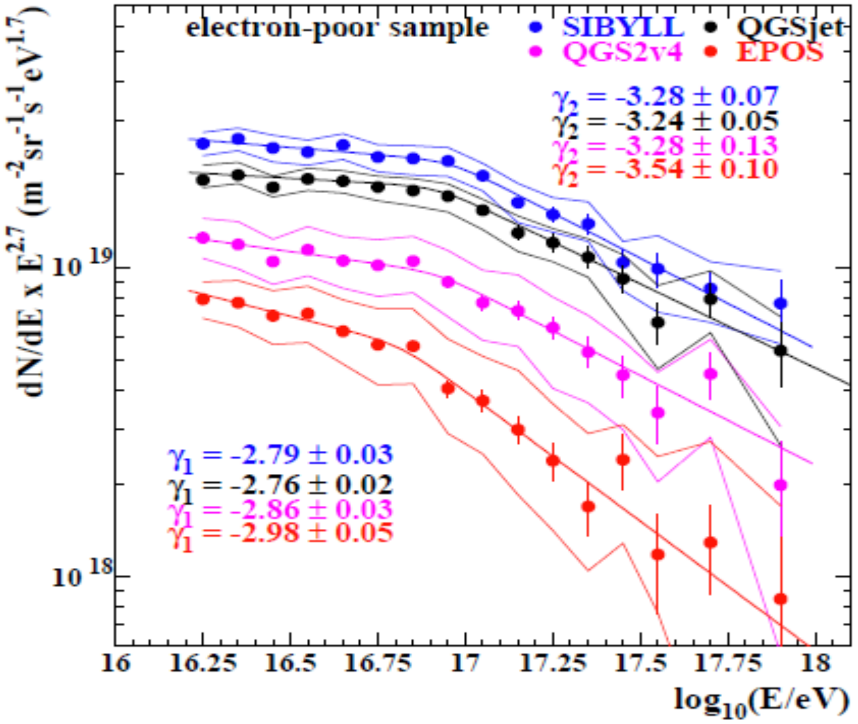
PRD 87(2013)081101
PRL 107(2011)171104



Astrop. Phys. 36 (2012) 183

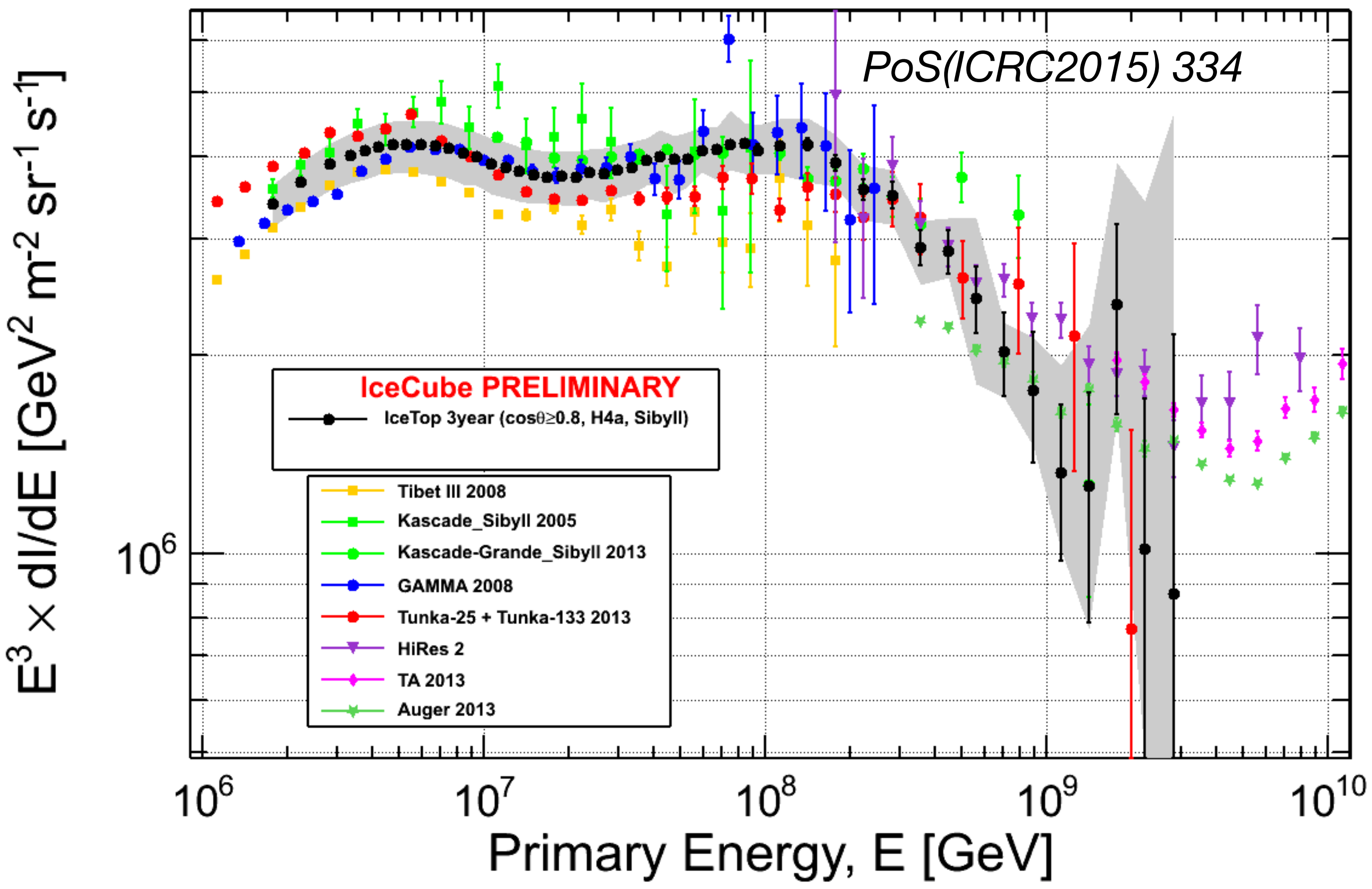
- *relative abundances different* for different high-energy hadronic interaction models

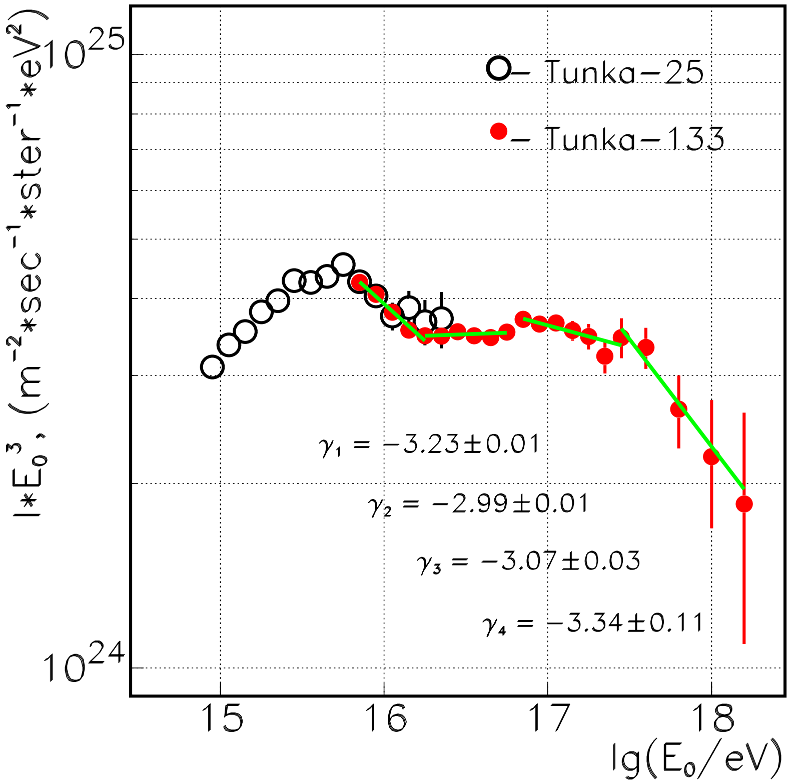
Adv. Sp. Res. 53 (2014) 1456



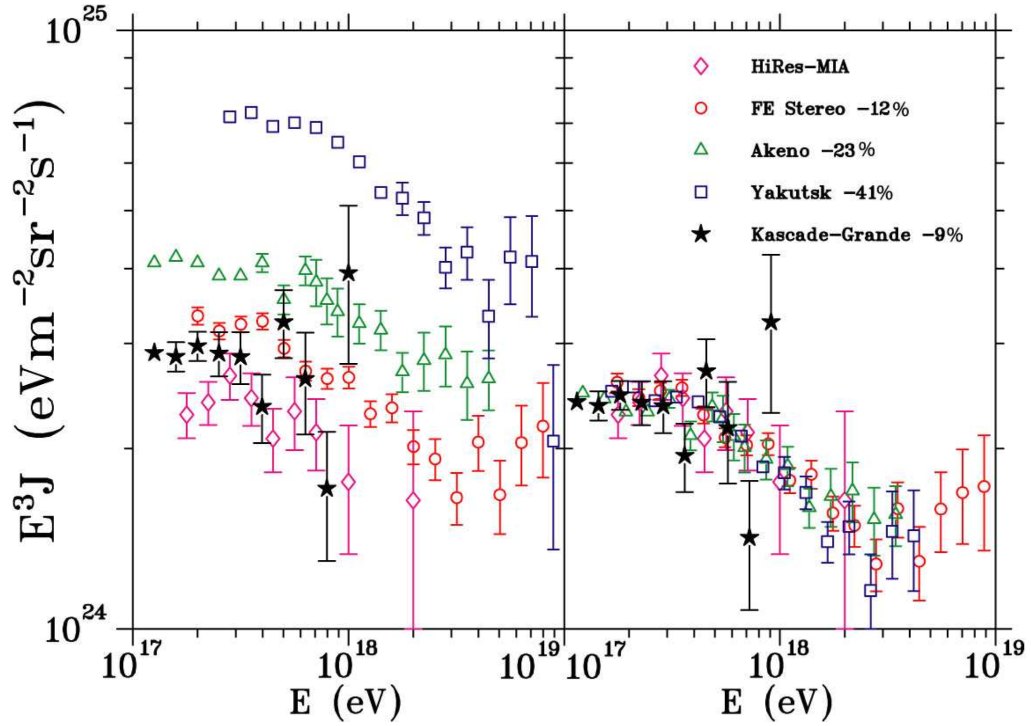
- *steepening due to heavy primaries* (3.5 σ)
- hardening at $10^{17.08}$ eV (5.8 σ) in light spectrum
- light slope change from γ = -3.25 to γ = -2.79 !

The second ‘knee'



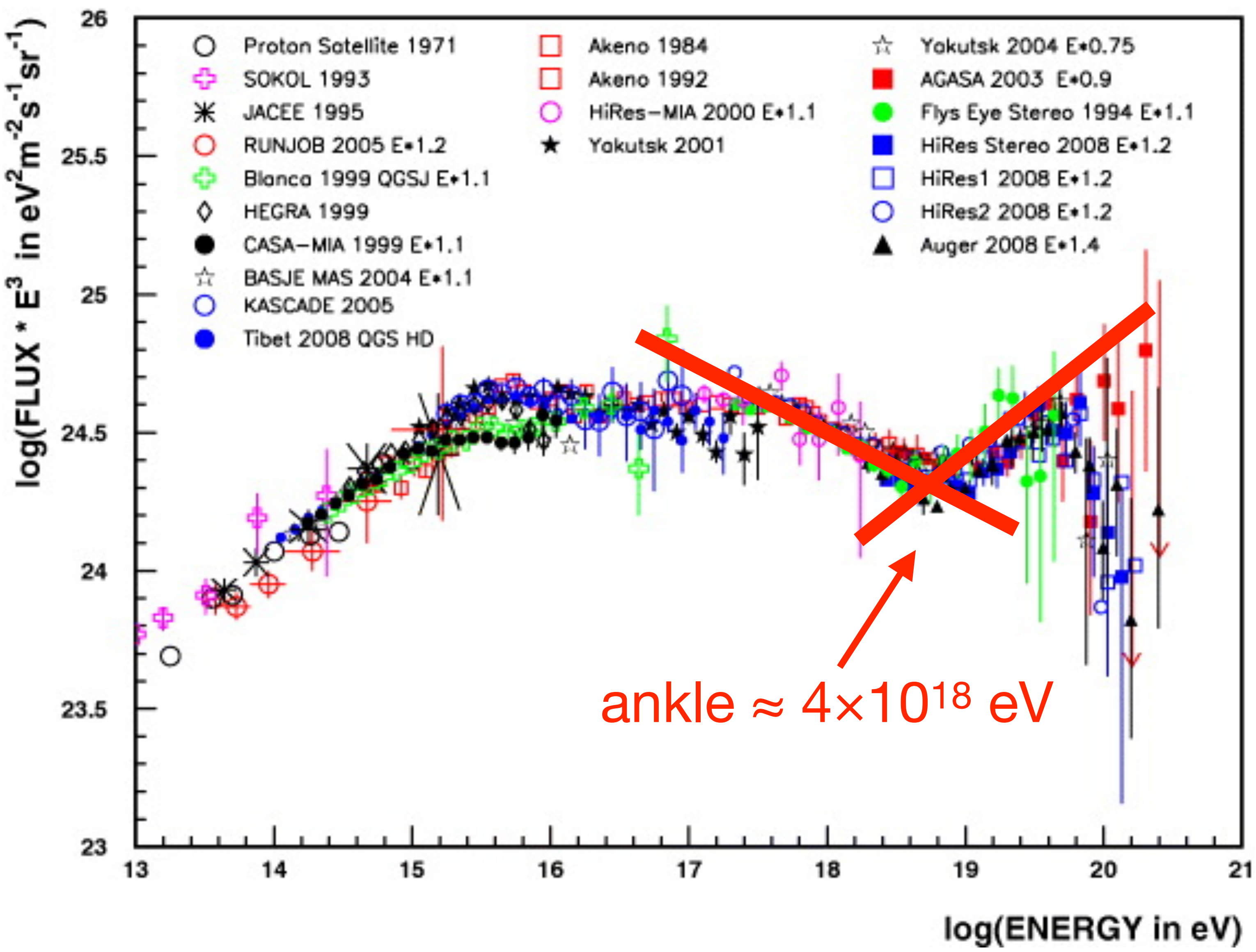


- Deviation from power law established
- *Second ‘knee' around 100 PeV well confirmed by at least 3 experiments.*
- *Knee of heavy component ?*
- Recovery of light (proton ?) component ?

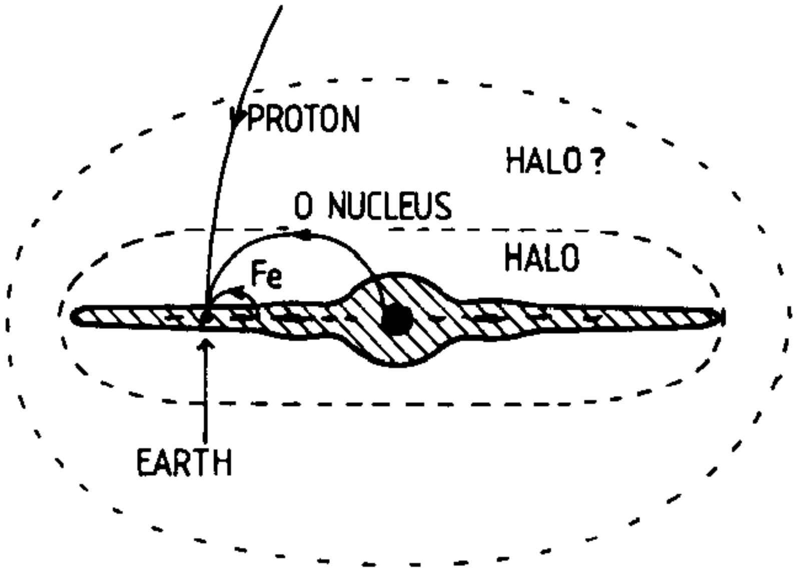


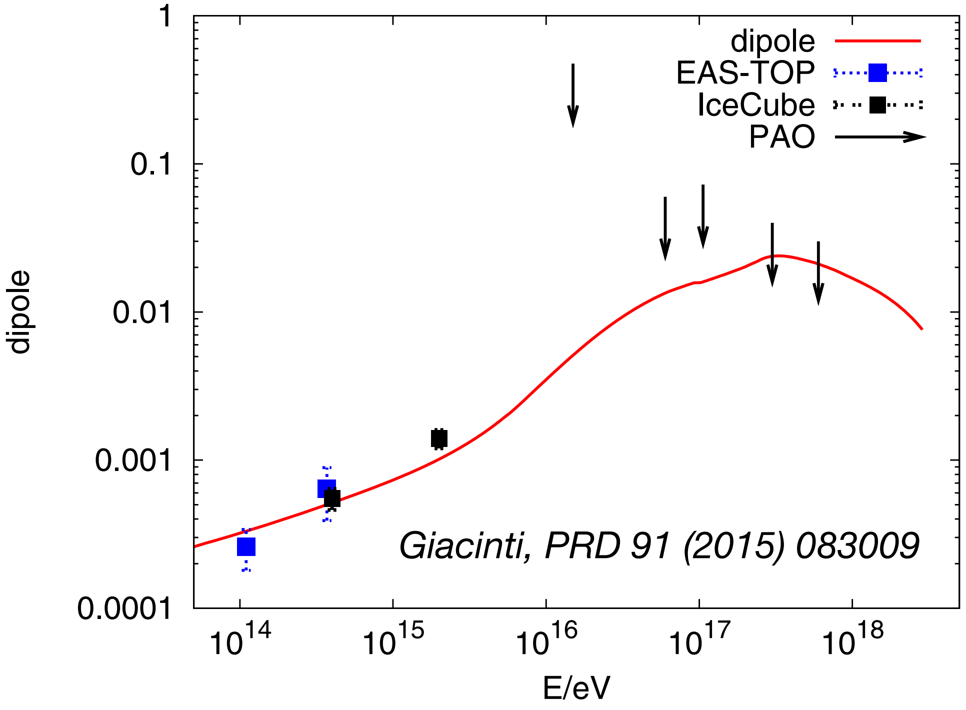
Telescope Array Low Energy Extension (TALE)

From galactic to extragalactic cosmic rays



ankle ≈ 4×10^{18} eV





Giacinti, PRD 91 (2015) 083009

most natural solution ➜ ankle
steep + hard component

The *dipole phase* is expected to change between 10^{17} and 3 × 10^{18} eV, i.e. the energy range of the transition from Galactic to extragalactic CRs.
Such a behavior corresponds to the one observed, providing thus *additional evidence for a transition from Galactic to extragalactic CRs* in this energy region.

Summary

- *A non-trivial picture of Cosmic Rays is emerging from recent data.*

- Many deviations from the common paradigm of power-law found
- None of these important features clearly understood

- The most important feature is the "*knee*" at a few PeV: *the origin of the knee is the main open problem in Cosmic Ray Physics.*

- Understanding *the origin of the "knee"* is *the key* for a comprehensive theory of the origin of CRs up to the highest observed energies.

- In fact, the *knee* is connected with the issue of the *end of the Galactic CR spectrum* and the transition from Galactic to extra-galactic CRs.

- Determining *elemental composition at the knee is crucial to understand where Galactic CR spectrum ends*

What's next ?

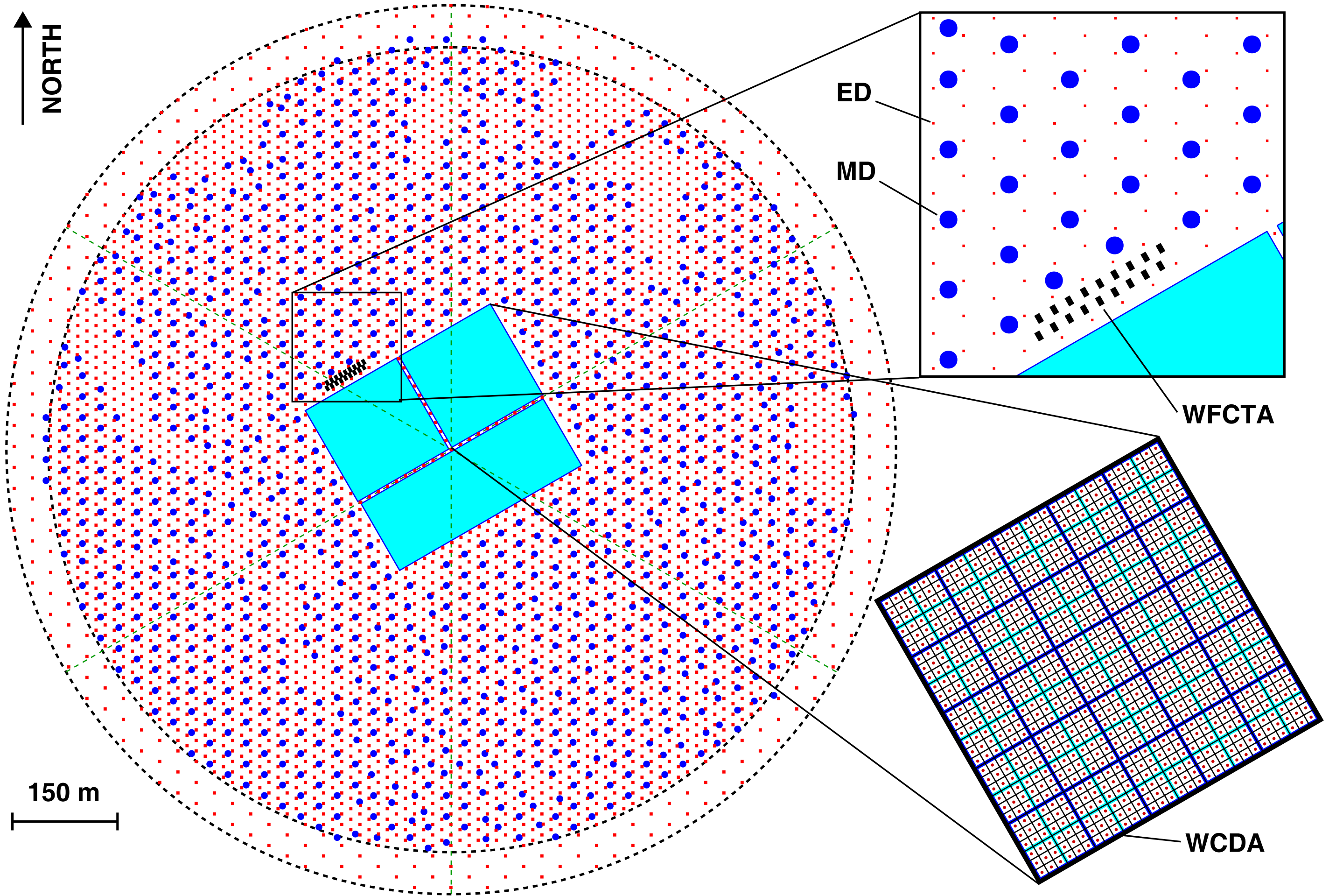
- High statistics measurement of energy spectra of different nuclei up to 10^{18} eV

- Evolution of the anisotropy across the knee separately for different primary masses

- Right altitude: close to the shower maximum ➜ > 4000 m asl

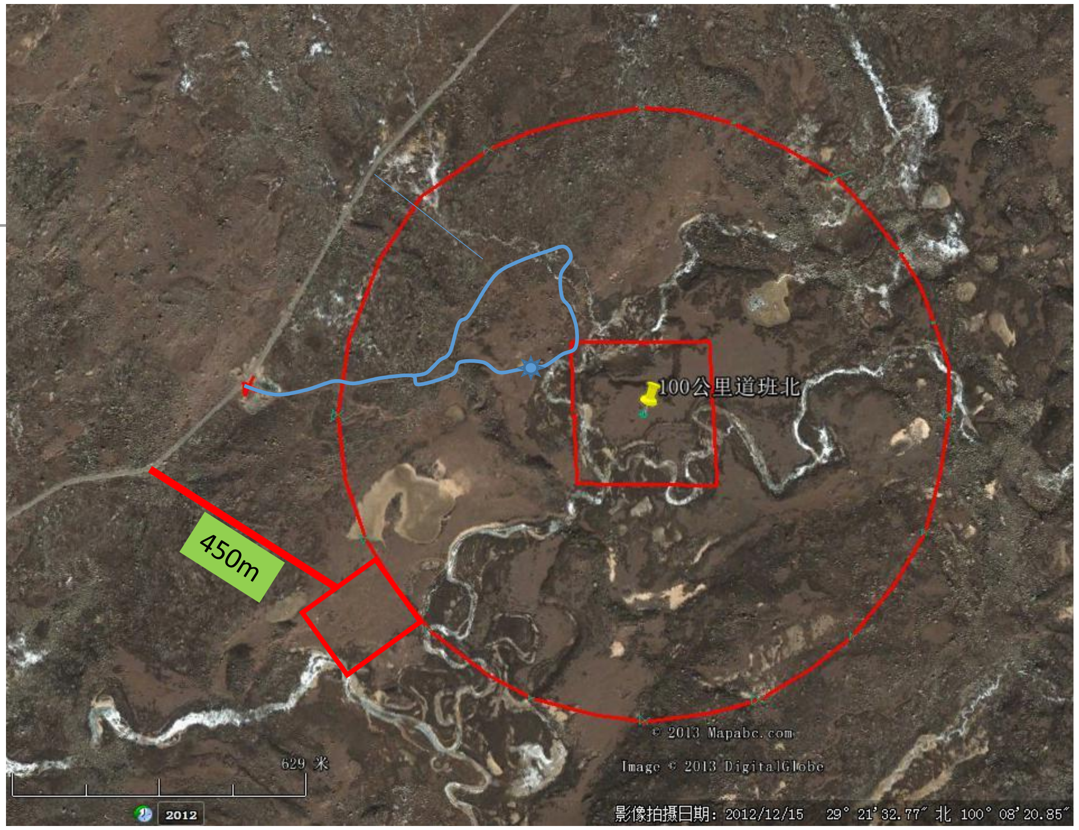
Outlook to the future: LHAASO

- 1.3 km² array, including 5195 scintillator detectors 1 m² each, with 15 m spacing.
- An overlapping 1 km² array of 1171, underground water Cherenkov tanks 36 m² each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m²).



- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m².
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.
- Neutron detectors

The LHAASO site

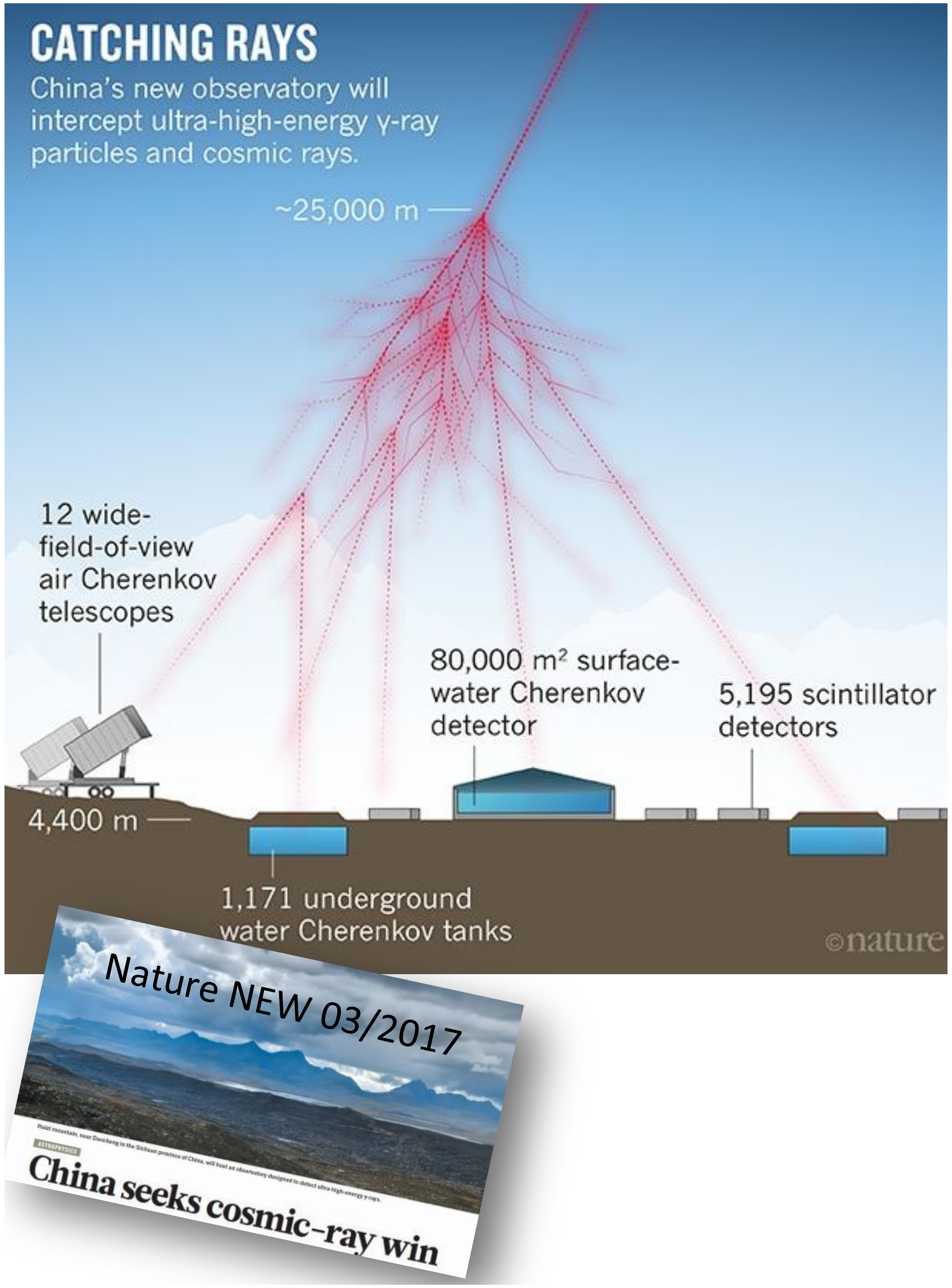


The experiment is located at 4400 m asl (600 g/cm²) in the Haizishan (Lakes' Mountain) site, Sichuan province

Coordinates: 29° 21' 31'' N, 100° 08' 15'' E

700 km to Chengdu
50 km to Daocheng City (3700 m asl, guest house)
10 km to the highest airport in the world

Status of the experiment



Nature NEW 03/2017

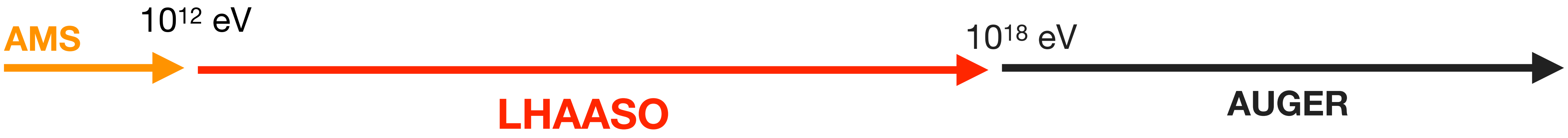
China seeks cosmic-ray win

- ★ The first pond (HAWC-like) will be completed by the end of 2017 and instrumented in 2018.
- ★ 1/4 of the experiment in commissioning by the end of 2018 (sensitivity better than HAWC):
  - 6 WFCTA telescopes
  - 22,500 m^2 water Cherenkov detector
  - ≈200 muon detectors
- ★ Completion of the installation in 2021.

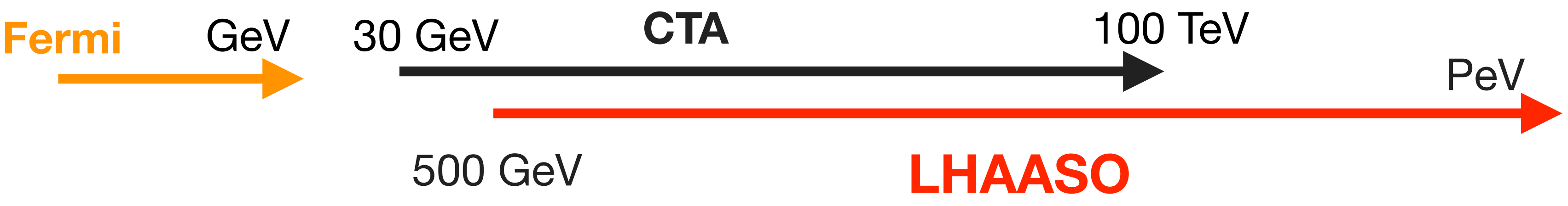
LHAASO: from γ-Ray Astronomy to Cosmic Rays

LHAASO is an experiment able of acting simultaneously
as a Cosmic Ray Detector and a Gamma Ray Telescope

- ✤ Cosmic Ray Physics ($10^{12} \rightarrow 10^{18}$ eV): precluded to Cherenkov Telescopes
  - CR energy spectrum
  - Elemental composition
  - Anisotropy



- ✤ Gamma-Ray Astronomy ($10^{11} \rightarrow 10^{15}$ eV): full sky continuous monitoring
  - Complementary with CTA below 20 TeV, with better sensitivity at higher energies and for flaring emission (GRBs), unbiased all-sky survey, extended and diffuse emission.
  - Searching for *PeVatrons* (→ neutrino sources)



LHAASO vs other EAS arrays

Experiment	Altitude (m)	e.m. Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO	4410	5.2×10^3	1.3×10^6	4×10^{-3}
TIBET ASγ	4300	380	3.7×10^4	10^{-2}
IceTop	2835	4.2×10^2	10^6	4×10^{-4}
ARGO-YBJ	4300	6700	11,000	0.93 (central carpet)
KASCADE	110	5×10^2	4×10^4	1.2×10^{-2}
KASCADE-Grande	110	370	5×10^5	7×10^{-4}
CASA-MIA	1450	1.6×10^3	2.3×10^5	7×10^{-3}

		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 will operate with a coverage similar to KASCADE (about %) over a much larger effective area.
- ✓ The detection area of muon detectors is about 70 times larger than KASCADE (coverage 5%) !
- ✓ Redundancy: different detectors to study hadronic models dependence

(✦) Muon detector area: 4.2×10^4 m^2 + 8×10^4 m^2 (WCDA)