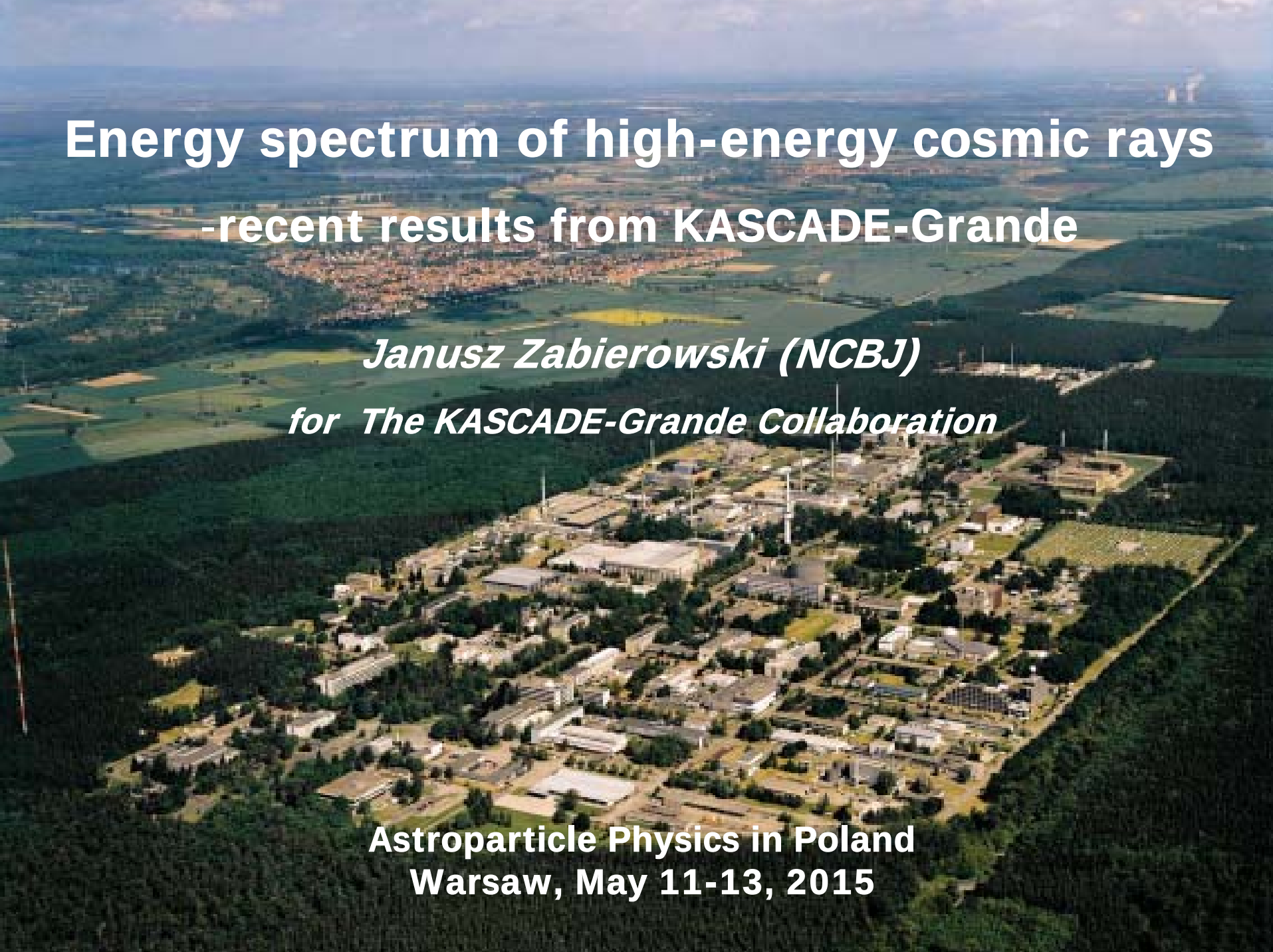
Energy spectrum of high-energy cosmic rays -recent results from KASCADE-Grande

Janusz Zabierowski (NCBJ)

for The KASCADE-Grande Collaboration



Astroparticle Physics in Poland
Warsaw, May 11-13, 2015

Outline

1. 25 years of the experiment at a glance
2. Solving the „knee puzzle” by KASCADE
3. CORSIKA
4. The KASCADE-Grande
5. All-particle CR energy spectrum
   - > heavy „knee”
   - > light „ankle"
6. Summary

Timeline of the KASCADE experiment: 25 years at a glance

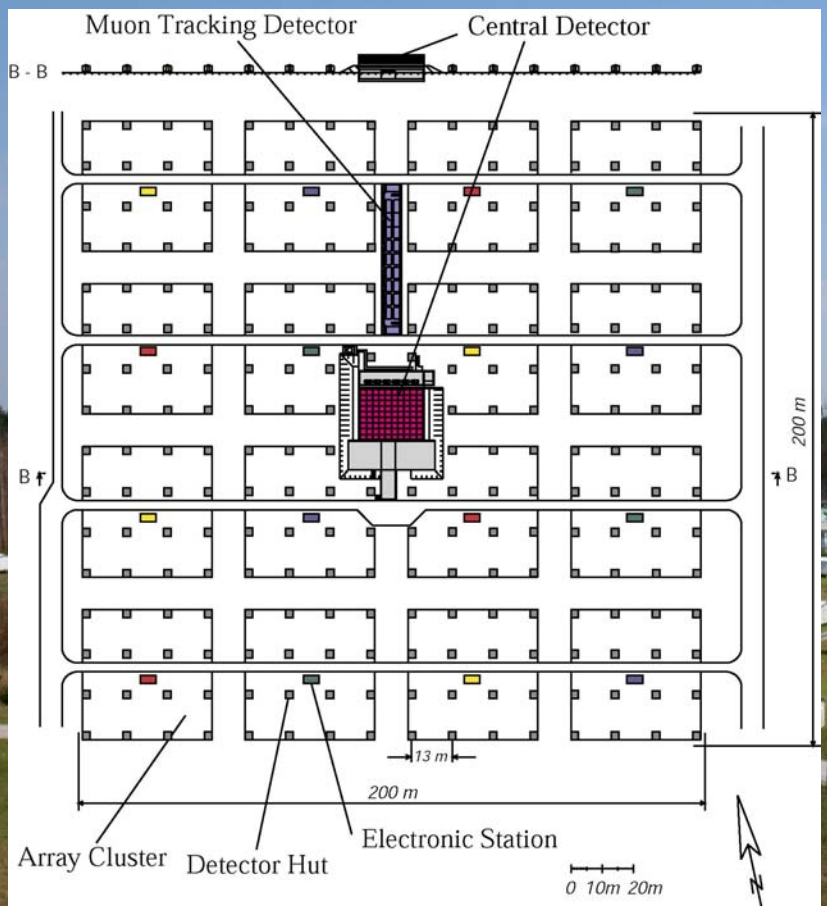
- 53 collaborative papers in reviewed journals (5 still in queue, short author list papers not included)
- 55 PhD thesis (3 Polish)
- 86 diploma/master thesis (1)

1992 Proposal
CORSIKA
1996 KASCADE
2000 model tests
light knee
KASCADE-Grande
2004 γ limit
(an)isotropy
proof-of-principle radio detection
LOPES
2008 muon production height
heavy knee
Karlsruhe Air Shower Test Facility
CROME
2012 light ankle
EAS GHz emission
KCDC
2016 Xmax by radio
Cosmic Revelation

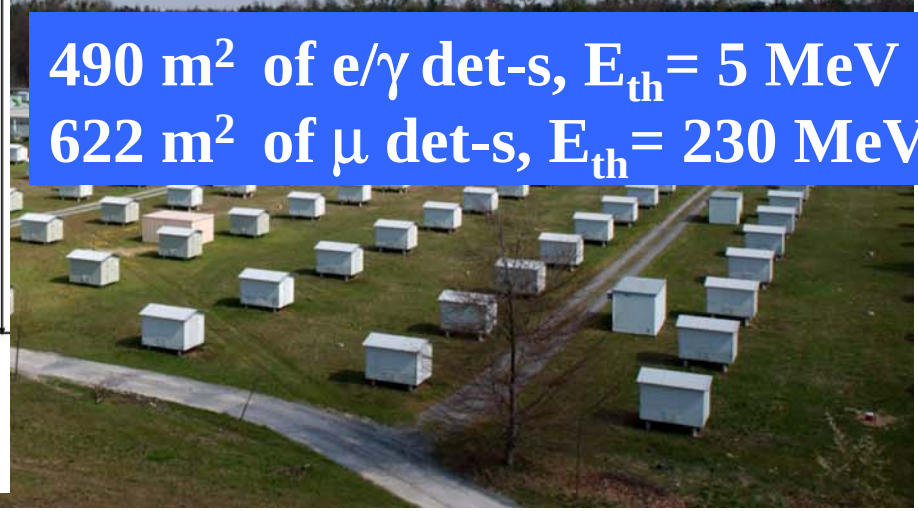
The story has started 25 years ago !

KASCADE := KArlsruhe Shower Core and Array DEtector

multi-parameter measurements on the KNEE

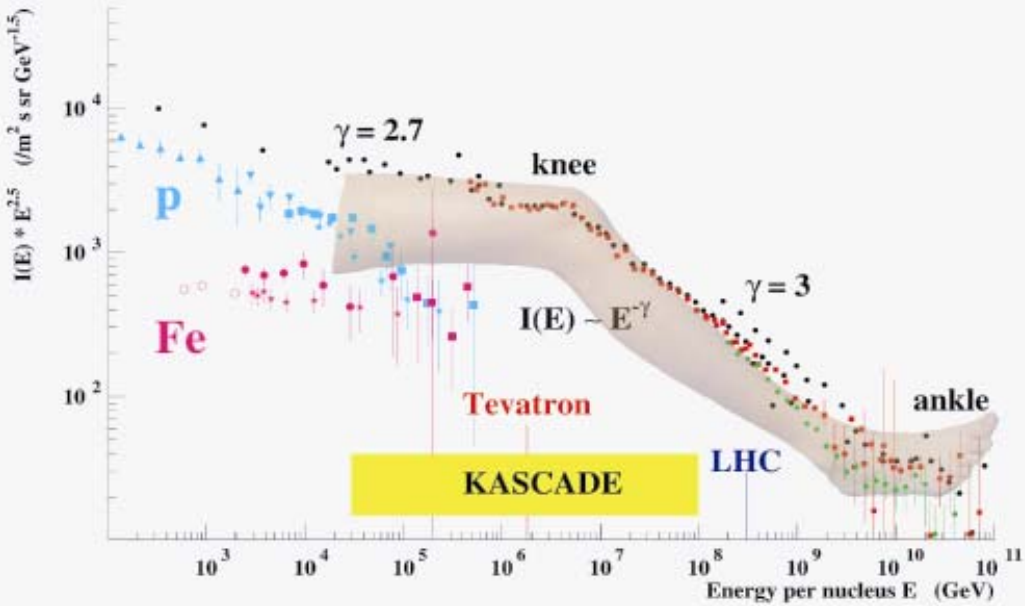


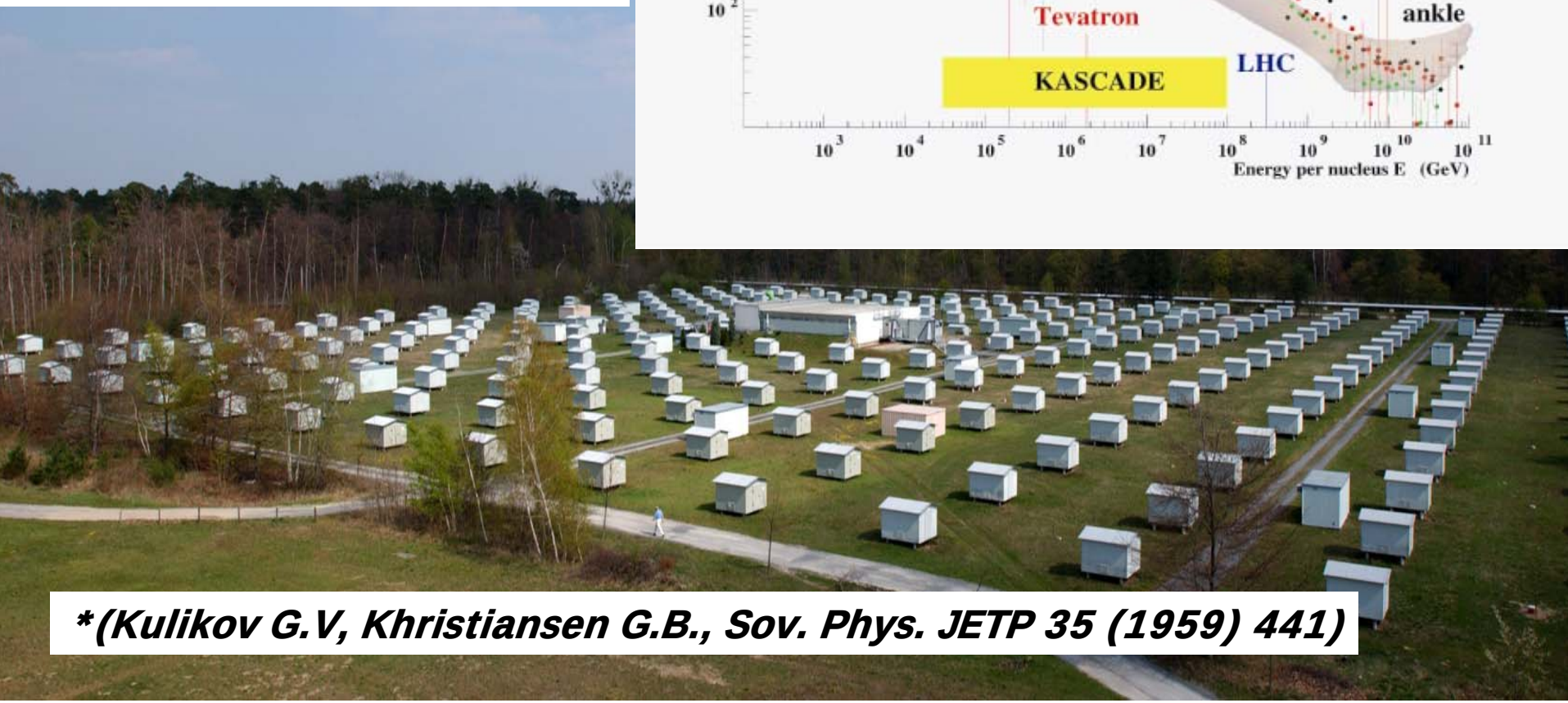
- energy range 100 TeV – 80 PeV
- large number of observables:
  - ➔ electrons
  - ➔ muons (@ 4 threshold energies)
  - ➔ hadrons



490 m^2 of e/γ det-s, E_{th}= 5 MeV
622 m^2 of μ det-s, E_{th}= 230 MeV

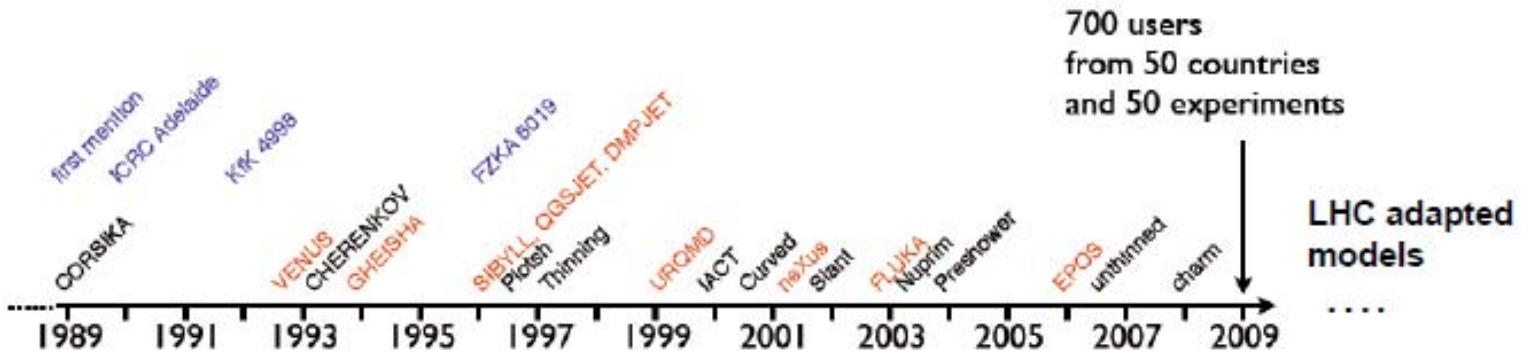
The main task:
to explain the „knee" puzzle* with precise measurements of all shower components





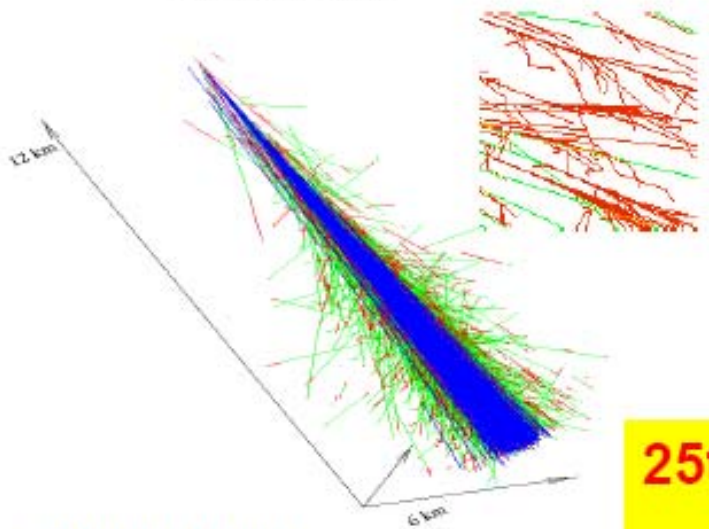
*(Kulikov G.V, Khristiansen G.B., Sov. Phys. JETP 35 (1959) 441)

CORSIKA (COsmic Ray SImulations for KAscade)



> 1 day per
10^{15} eV shower

< 20 min per
10^{15} eV shower



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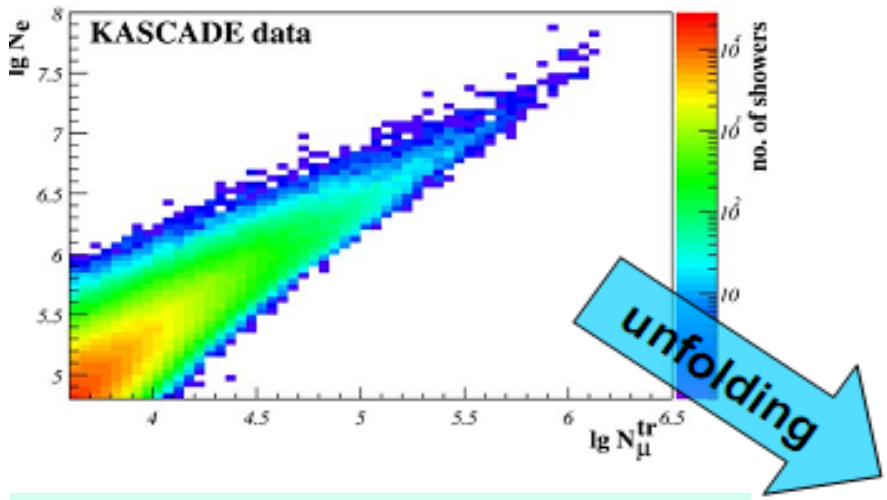
25th anniversary of CORSIKA

~1600 citations

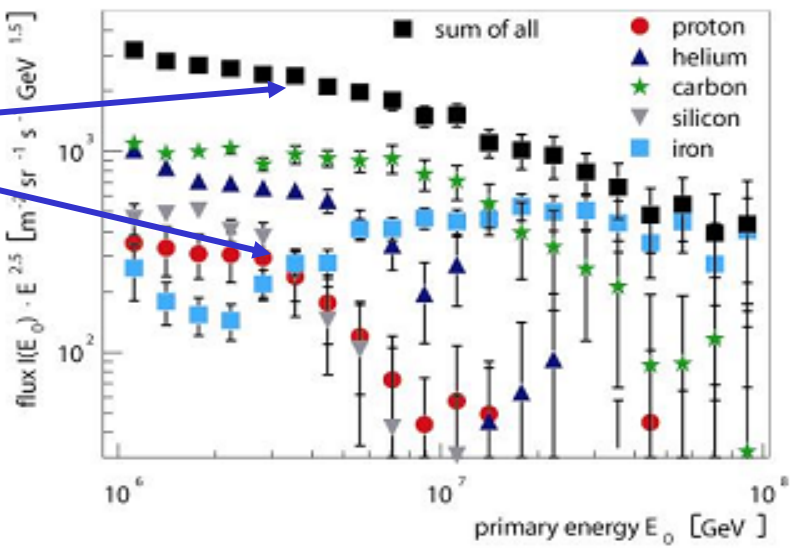
Main Result achieved by 2005 (on the way, many others also):
KASCADE published CR energy spectrum & composition in the knee region *(Astropart. Phys. 24 (2005) 1; ~ 300 citations)*



Analysis of 2-dimensional shower size spectrum:

➔energy spectra of single mass groups

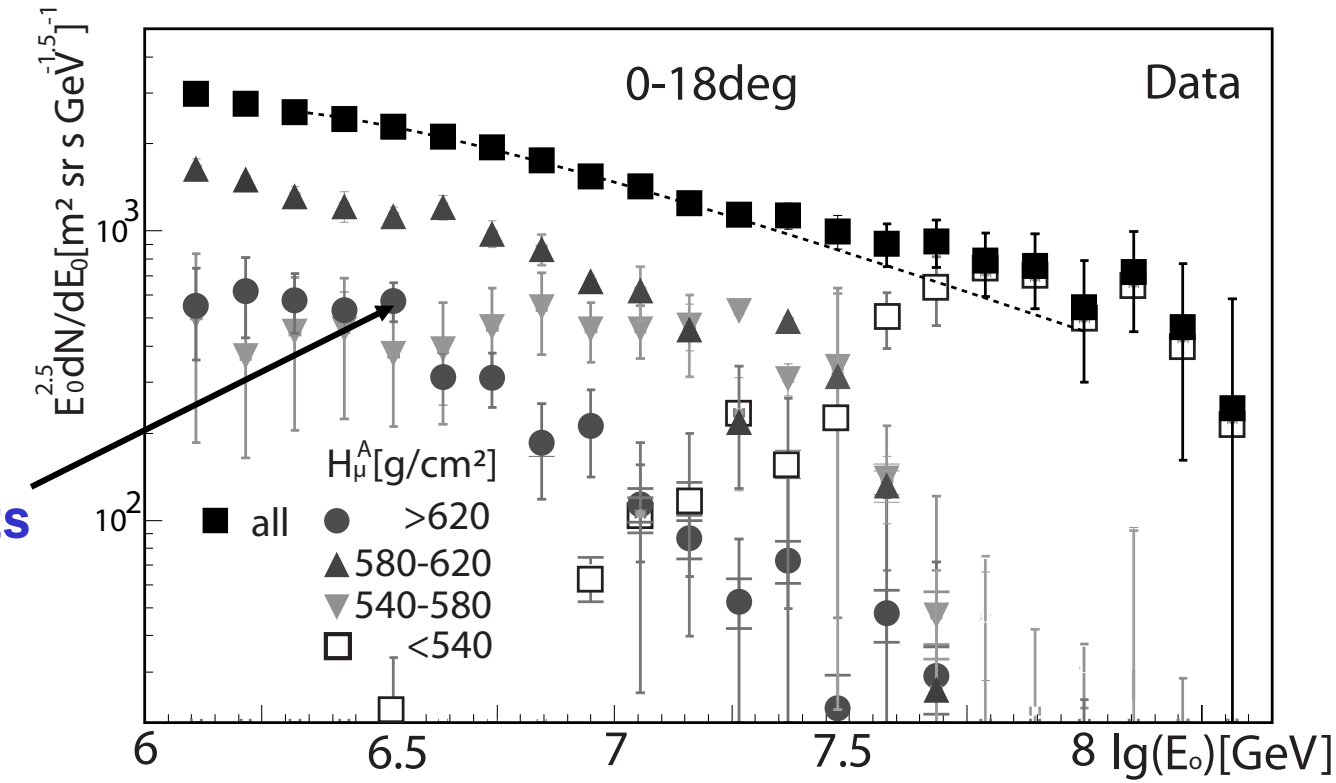
- knee is caused by light elements
- knee positions vary with mass group
- no hadronic interaction model describe data consistently



Investigation of the muon production heights in KASCADE-Grande confirmed conclusions on the knee

(Astropart. Phys. 34 (2011) 476 – 19 citations))

Knee is caused by light elements



Motivation for KASCADE-Grande:

Questions to be answered:

1. Rigidity-dependence (diffusion and/or acceleration)
   or mass-dependence (interaction)
   of the knee position;

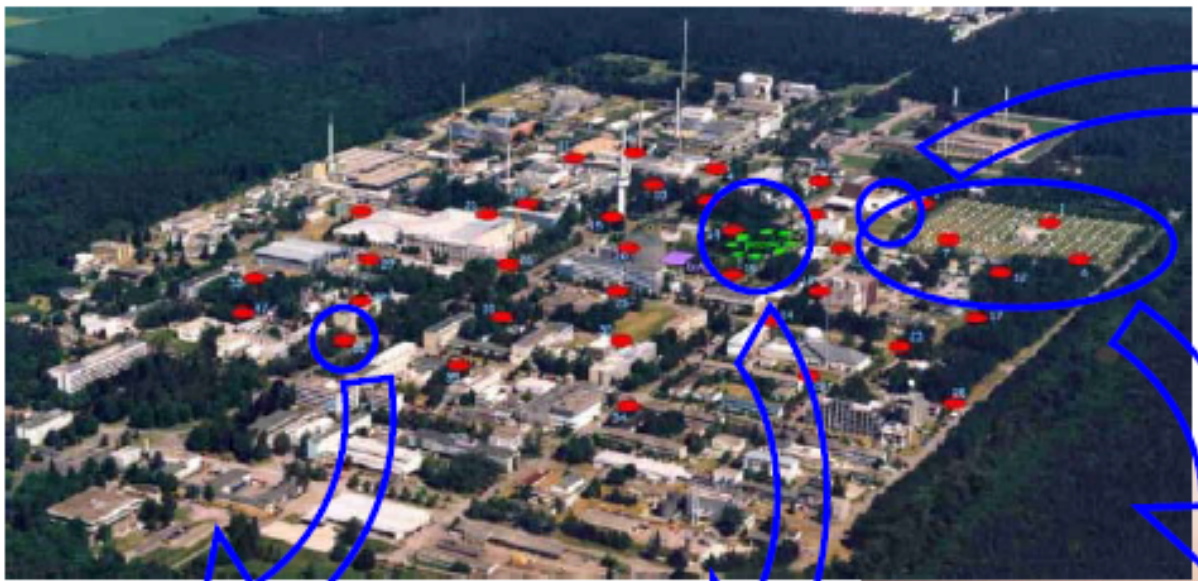
2. Where are the other structures in the spectrum:
   - iron knee ?
   - second knee ?
   - signature of extragalactic component?

Required enlargement of the experiment ~ 10 times to reach 1 EeV primary energies.

KASCADE-Grande

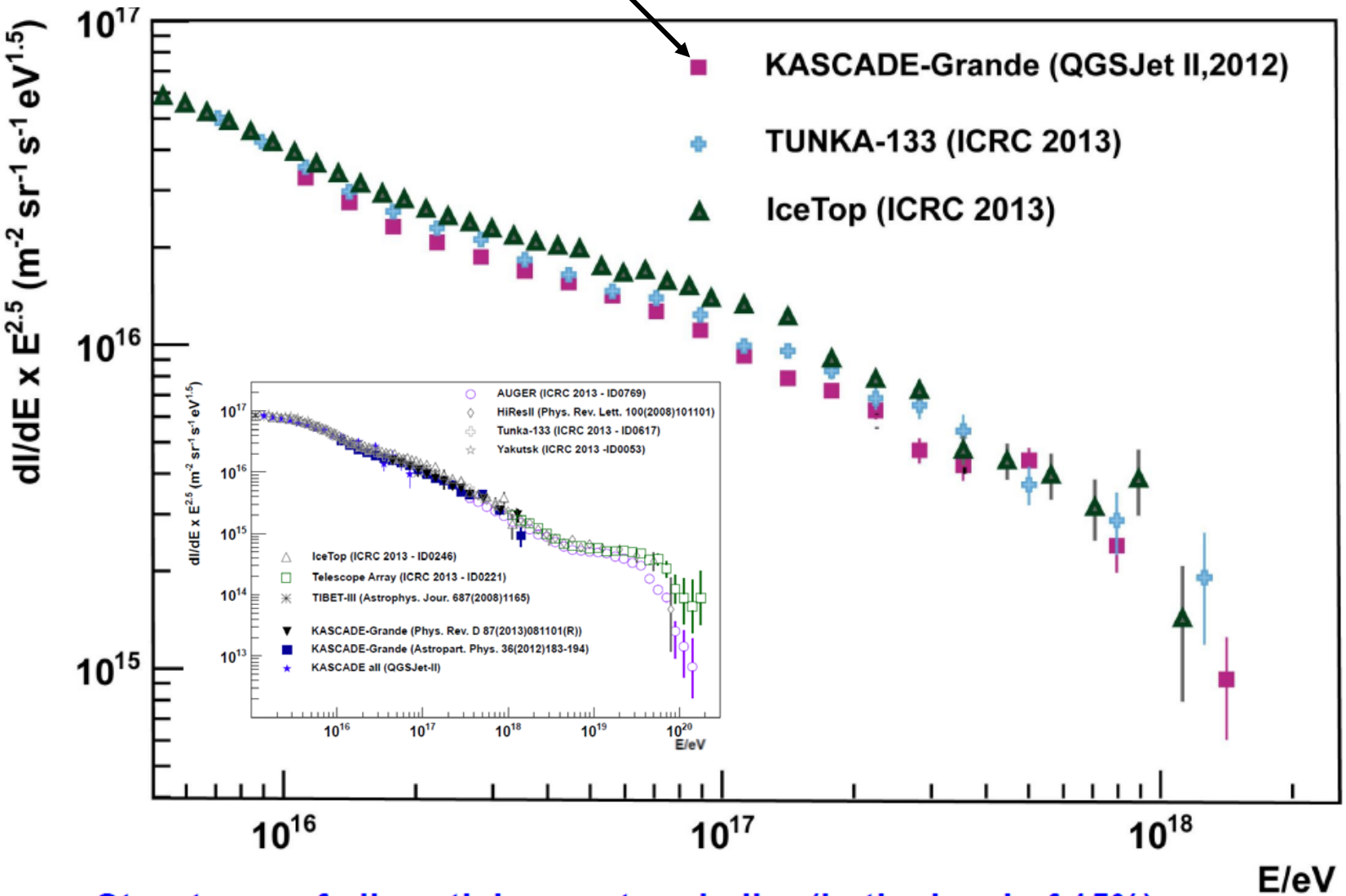
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV



All-particle Cosmic Ray energy spectrum

(Astropart. Phys. 36 (2012)183 – 38 citations)

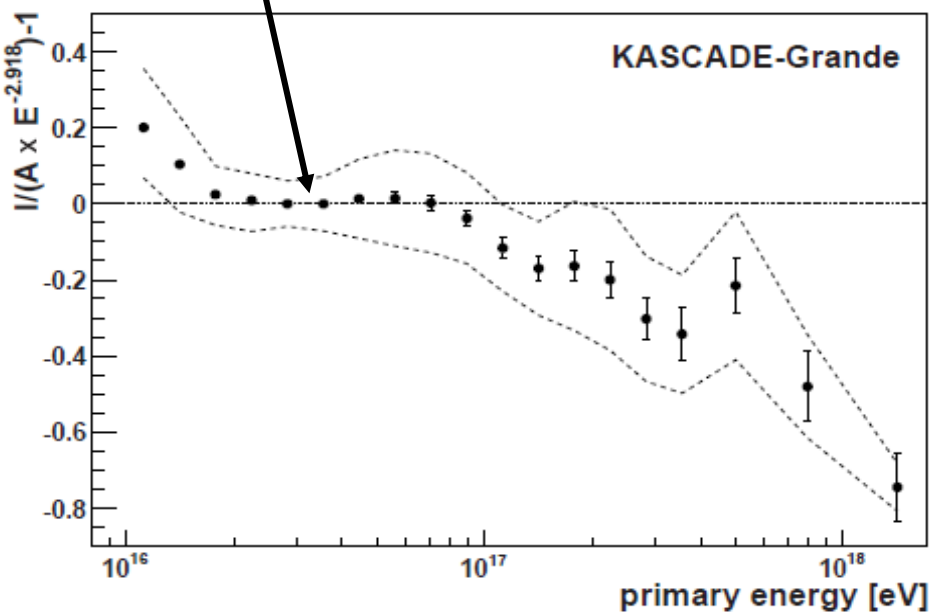


- **Structures of all-particle spectra similar (in the level of 15%)**

All-particle energy spectrum by KASCADE-Grande : observation of a hardening above 10^{16} eV

'Concave' behavior above 10^{16}eV, observed first by KASCADE-Grande.

It is expected when:



Spectrum multiplied with a factor $E^{-2.918}$

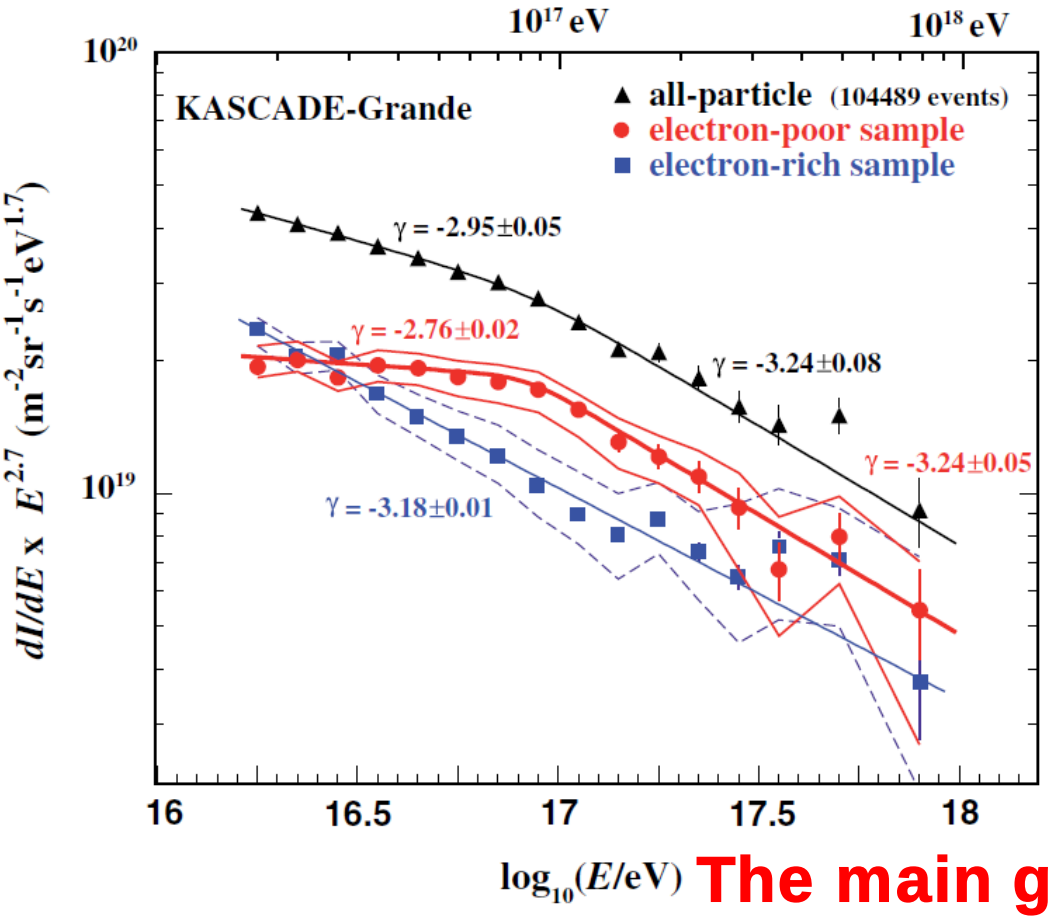
- **A pure rigidity dependence of the galactic cosmic rays is assumed – expected charge dependent steps and hardening is due to the gap in knee positions between the light (H, He and CNO group Z=1-8) and heavy group of primaries.**

or

- **It is the first experimental hint to the proposed by M. Hillas 'component B' of galactic cosmic rays – transition from the one source population to another one.**

Knee-like structure in the spectrum of heavy component of cosmic rays observed with KASCADE-Grande

(Phys. Rev. Lett. 107, 171104 (2011) – 75 citations)



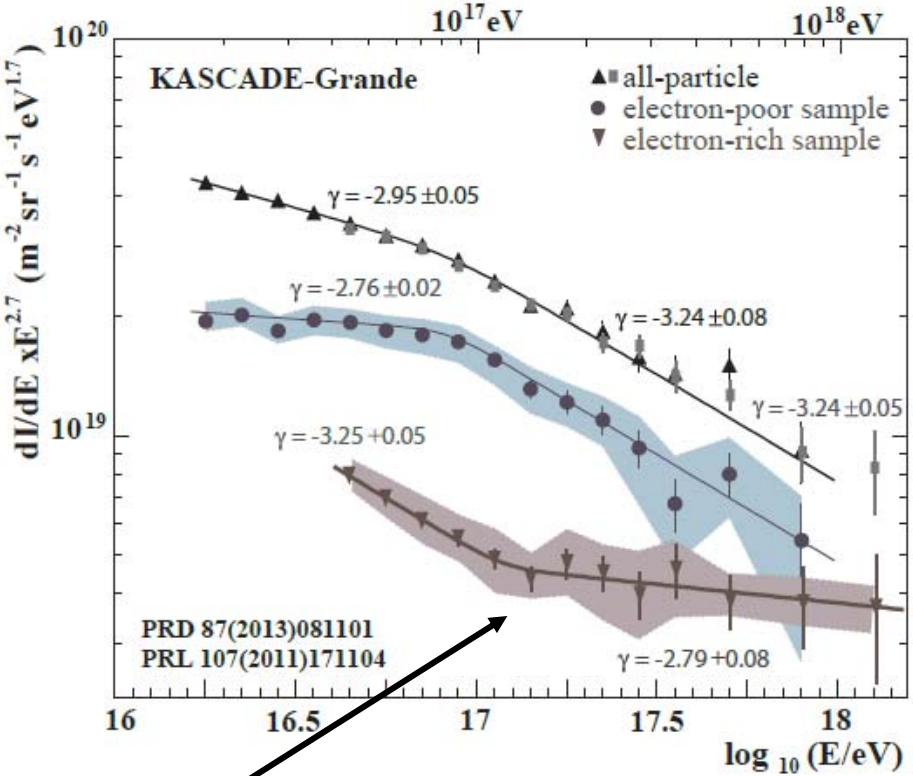
The first evidence of the knee-like break in the spectrum of heavy component at about 8×10^{16} eV.

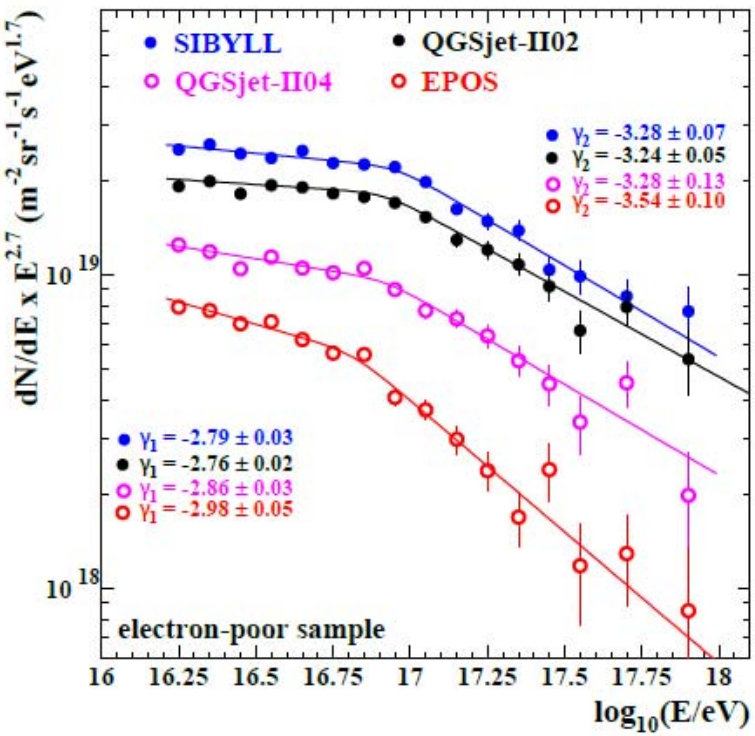
There, the charge dependent knee of primary iron is expected, when the knee at about $3\text{-}5 \times 10^{15}$ eV is assumed to be caused by a decrease in the flux of primary protons.

The main goal of KASCADE-Grande achieved !

Ankle-like feature in the energy spectrum of light elements

(Phys. Rev. D 87, 081101(R) (2013) – 35 citations)

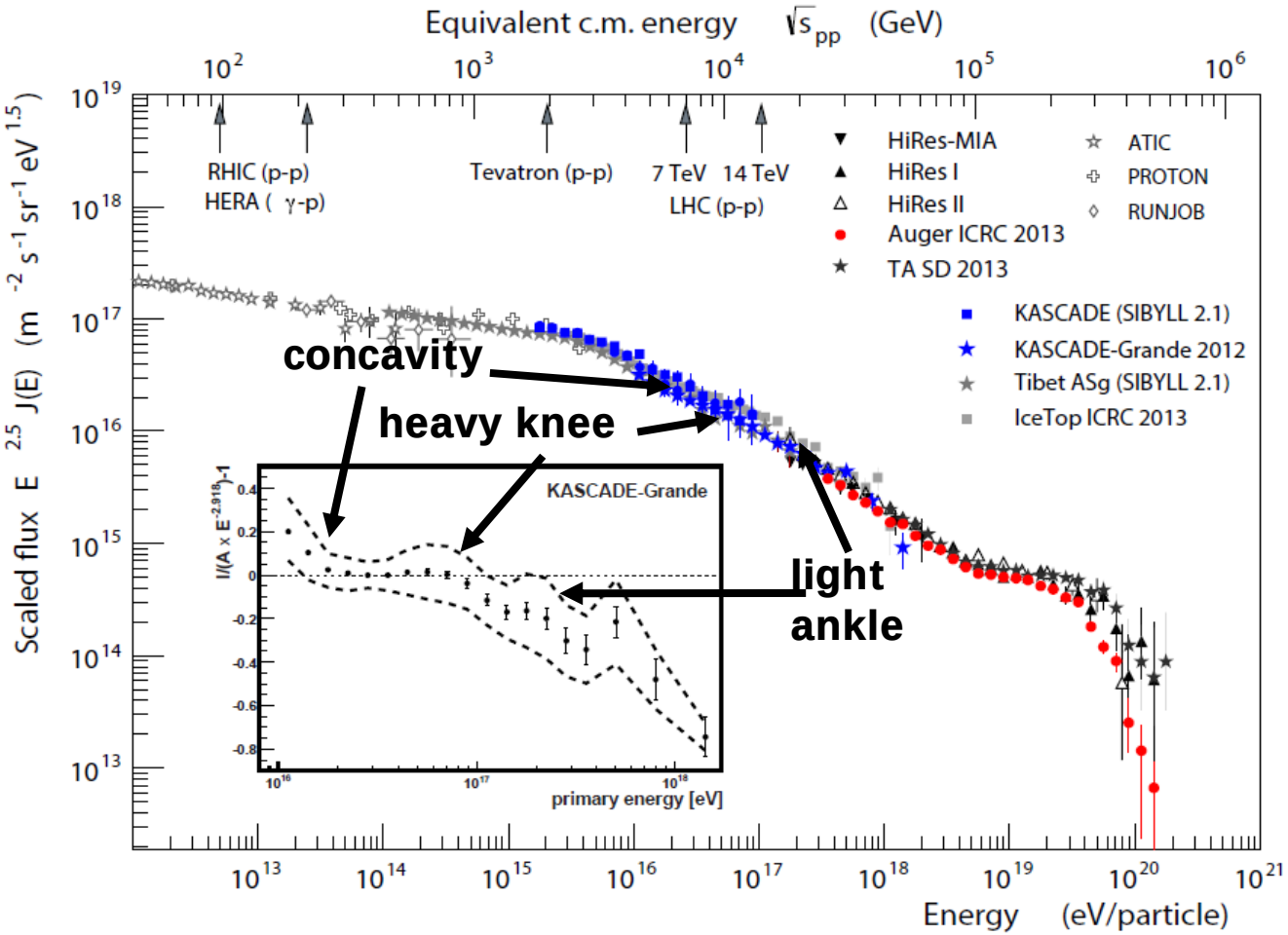




Light ankle at $10^{17.08}$ eV might be the first indication that the transition from the galactic to extragalactic origin of cosmic rays starts already at this energy.

Changes in the spectra of heavy primaries and of light elements are not connected by a bias in the separation or reconstruction, as well as due to dependence on the hadronic interaction model
(W.D.Apel et al. (KASCADE-Grande Coll.), Adv. Space Res. 53 (2014) 1456)

The all-particle energy spectrum obtained with KASCADE and KASCADE-Grande in comparison with results of other experiments

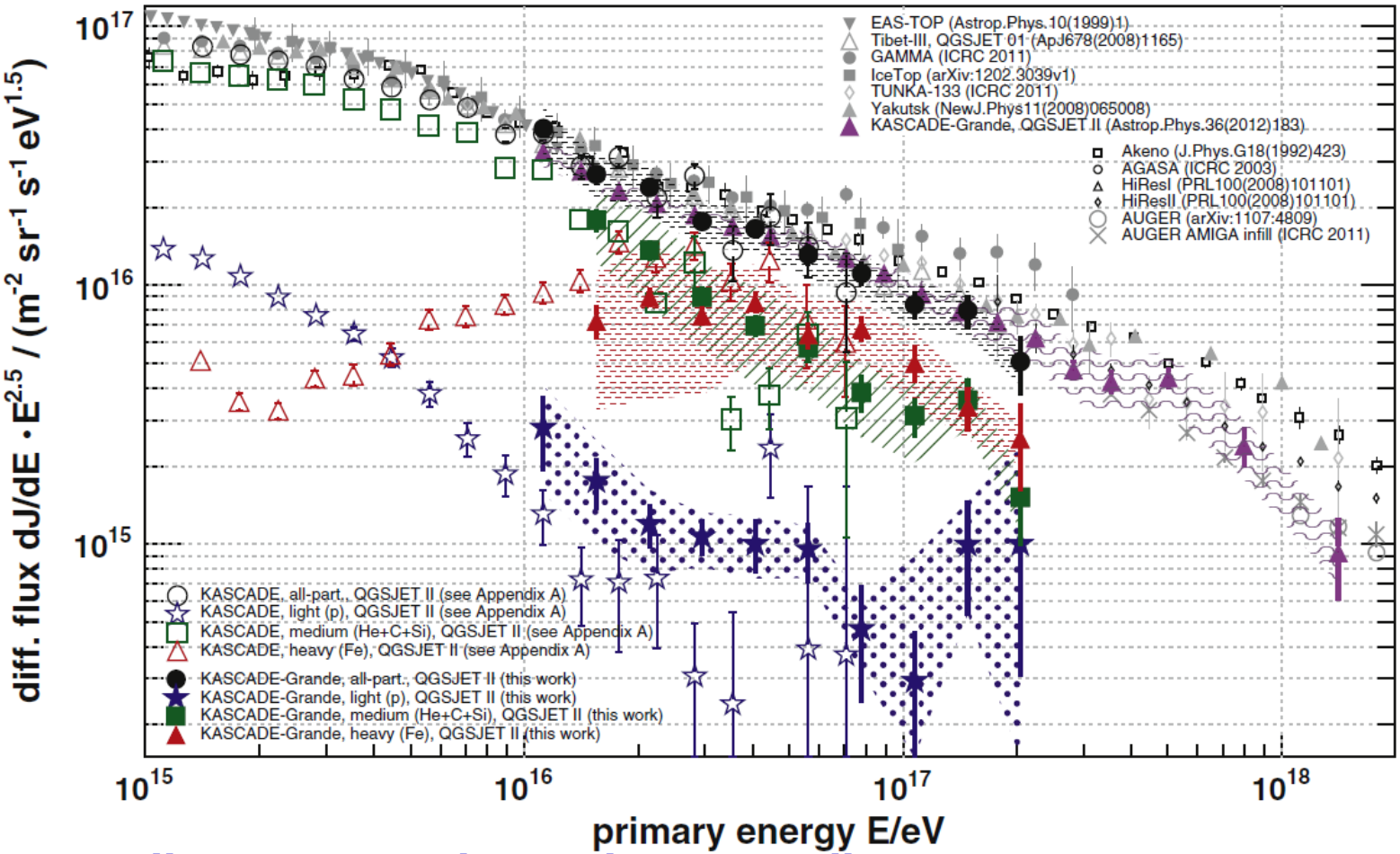


(A. Haungs at al. *Proc.Vulcano Conf. 2014 – Frascati Phys. Ser. Vol.58, p.238*)

Mass composition by KASCADE and KASCADE-Grande

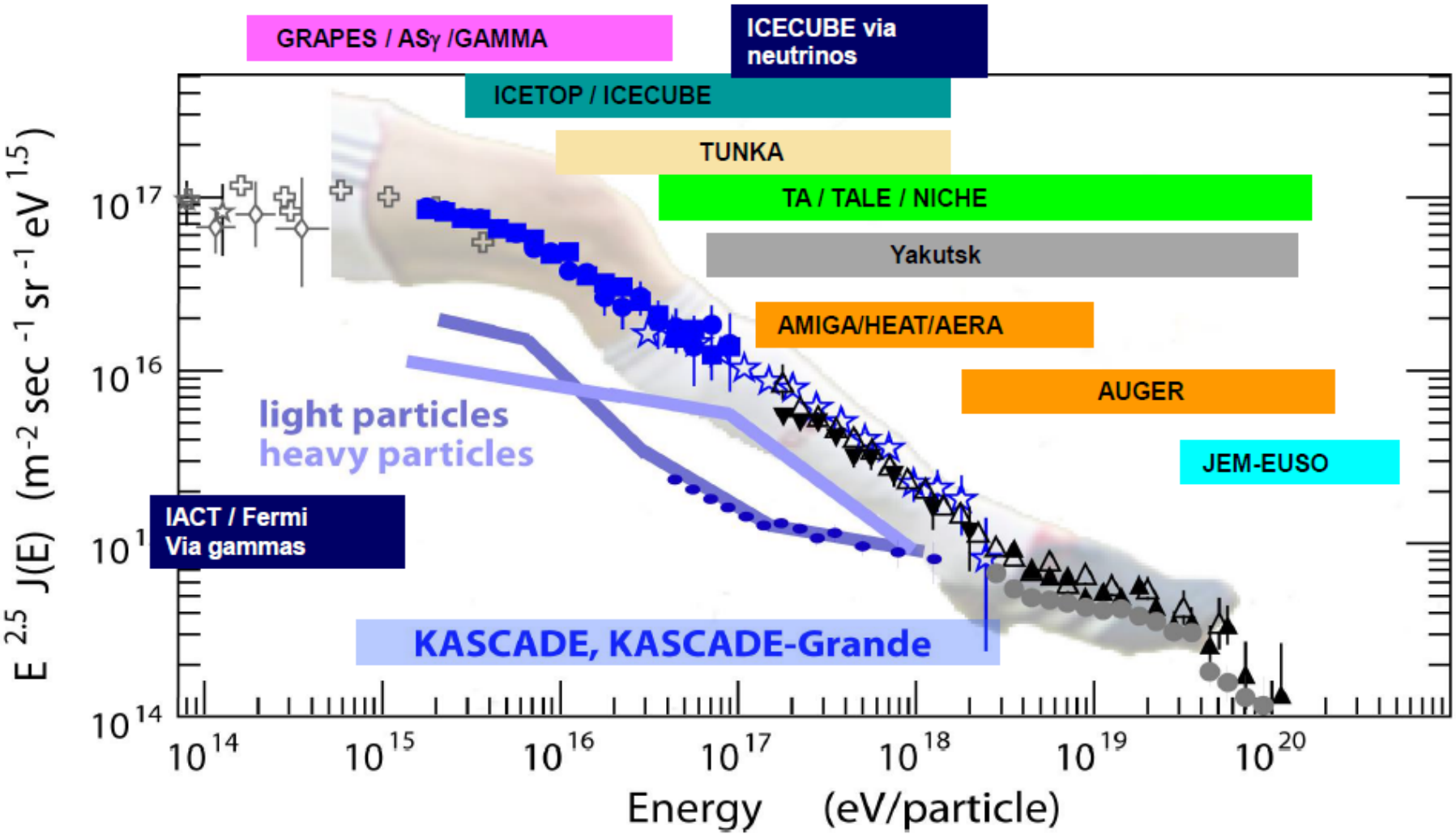
(Astropart. Phys. 47 (2013) 54, – 30 citations)

Spectra of individual mass groups: proton, medium (He+C+Si), iron



- **All spectra overlap and agree well**
- **All three show a knee-like feature**

Current experimental situation on the CR spectrum



….better answers only by combining all information: stay tuned!

SUMMARY 1: Our results confirm the theory

PHYSICAL REVIEW D **91,** 083009 (2015)

Escape model for Galactic cosmic rays and an early extragalactic transition

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[2]*Institutt for fysikk, NTNU, Trondheim, Norway*
[3]*AstroParticle and Cosmology (APC), Paris, France*

The Authors have shown:…

…" that the cosmic ray (CR) knee can be entirely explained by energy-dependent leakage from the Milky Way, with an excellent fit to all existing data, testing this hypotesis by calculating the trajectories of individual CRs in the Galactic magnetic field;"

…" that the CR escape time $\tau_{esc}(E)$ exhibits a knee-like structure around E/Z = few x 10^{15} eV for small coherence lengths of the turbulent magnetic field;"

SUMMARY 1: Our results confirm the theory – cont.

…" that the extragalactic CRs contribute sizable to the subdominant proton flux already for $\geq 2 \times 10^{16}$ eV."

…"the recovery of the proton and helium spectra above $E/Z \sim 10^{16}$ eV in the KASCADE-Grande data is mainly explained by the specific shape of the escape rate $\tau_{esc}(E)$"
(proposed by the Authors in Phys. Rev. D 90, R041302 (2014))

…" that the resulting intensities for different groups of nuclei are consistent with the ones determined by KASCADE and KASCADE-Grande, using simple power laws as injection spectra."

SUMMARY 2: Lessons learned from the 25-years of running the KASCADE facility

It is essential to provide:

- spectra of individual mass groups!!
- multi-parameter EAS measurements to validate hadronic interaction models
- multi-messenger detection (need muons!!?)
- high statistics in a large energy range
  (mainly for composition dependent anisotropy studies)
- the right observation altitude
- room for R&D studies for future, improved technologies
- outreach and public data access

KASCADE-Grande Collaboration

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KIT - Karlsruhe Institute of Technology

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https://web.ikp.kit.edu/KASCADE/

July 2014


KASCADE-Grande
– still alive!!
Thank
You!!

Backup slides

LOPES Collaboration

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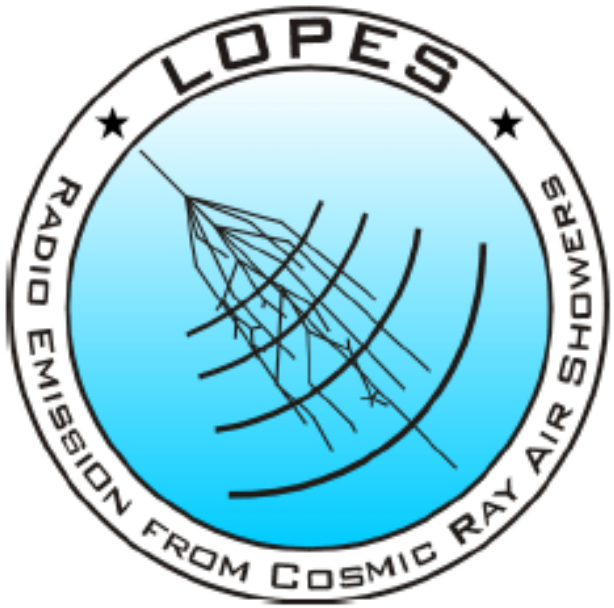

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http://www.lopes-project.org/

PHYSICAL REVIEW D 90, 062001 (2014)

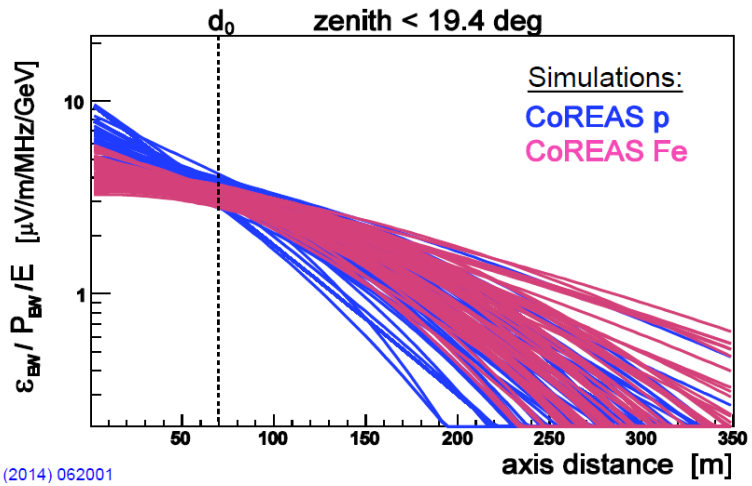
Reconstruction of the energy and depth of maximum of cosmic-ray air showers from LOPES radio measurements

W. D. Apel,[1] J. C. Arteaga-Velazquez,[2] L. Bähren,[3] K. Bekk,[1] M. Bertaina,[4] P. L. Biermann,[5] J. Blümer,[1,6] H. Bozdog,[1] I. M. Brancus,[7] E. Cantoni,[4,8,‡] A. Chiavassa,[4] K. Daumiller,[1] V. de Souza,[9] F. Di Pierro,[4] P. Doll,[1] R. Engel,[1] H. Falcke,[3,10,5] B. Fuchs,[6] D. Fuhrmann,[11,§] H. Gemmeke,[12] C. Grupen,[13] A. Haungs,[1] D. Heck,[1] J. R. Hörandel,[3] A. Horneffer,[5] D. Huber,[6] T. Huege,[1,*] P. G. Isar,[14] K.-H. Kampert,[11] D. Kang,[6] O. Krömer,[12] J. Kuijpers,[3] K. Link,[6] P. Łuczak,[15] M. Ludwig,[6] H. J. Mathes,[1] M. Melissas,[6] C. Morello,[8] J. Oehlschläger,[1] N. Palmieri,[6,†] T. Pierog,[1] J. Rautenberg,[11] H. Rebel,[1] M. Roth,[1] C. Rühle,[12] A. Saftoiu,[7] H. Schieler,[1] A. Schmidt,[12] F. G. Schröder,[1] O. Sima,[16] G. Toma,[7] G. C. Trinchero,[8] A. Weindl,[1] J. Wochele,[1] J. Zabierowski,[15] and J. A. Zensus[5]

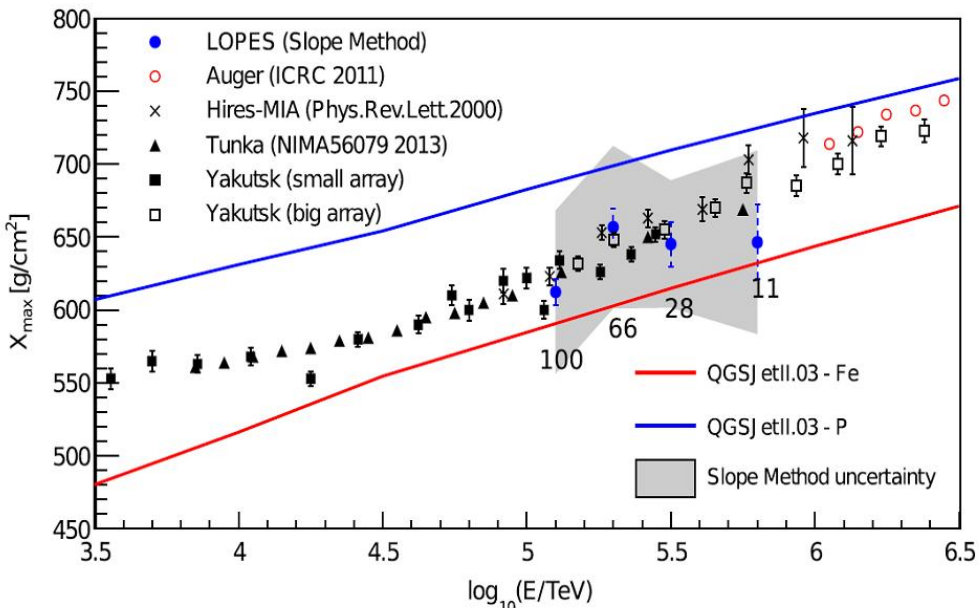
(LOPES Collaboration)

Lateral distribution

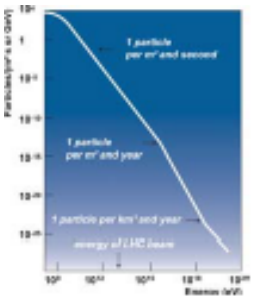
- **Amplitude** at specific distance → **Energy**
- **Slope** or ratio between two distances → **X_{max}**



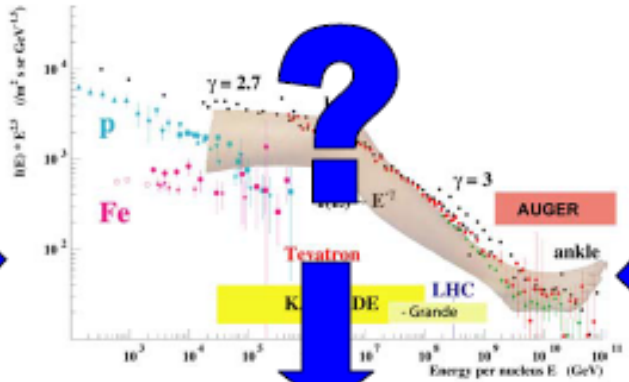
PRD 90 (2014) 062001



The door to wide use of cheap radio-detection technique in EAS research IS OPENED !

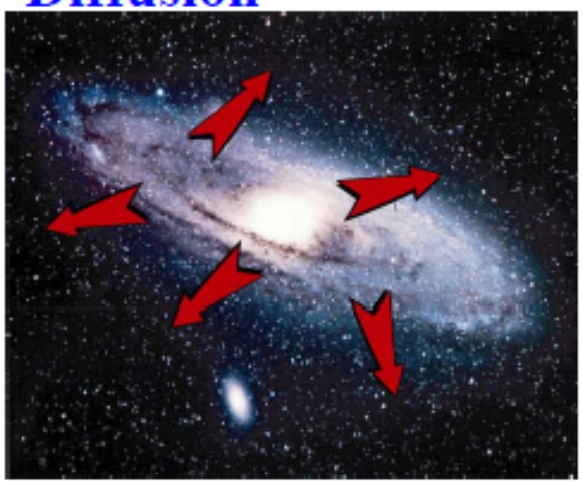


What is the origin of the (first) knee?



various theories:

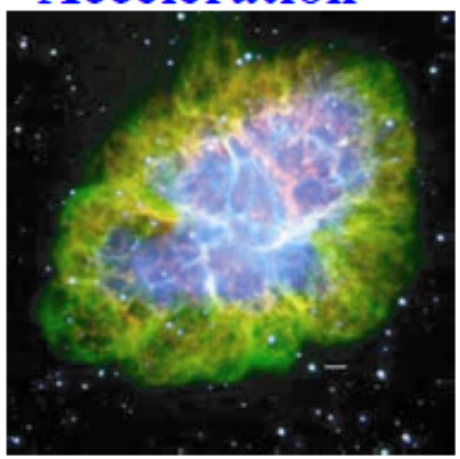
Diffusion



Escape from our Galaxy by diffusion

E(knee) ~ Z

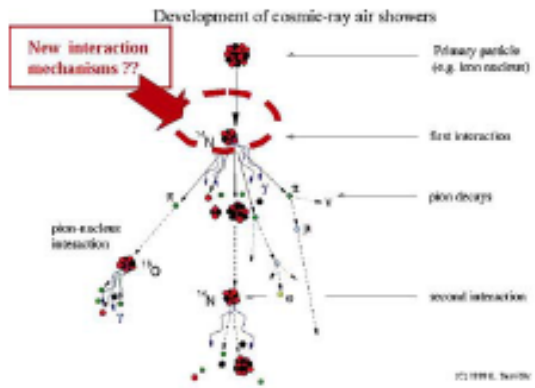
Acceleration



Reach of maximum energy at the acceleration

E(knee) ~ Z

Interaction



Unknown effects of interactions at the air-shower development

E(knee) ~ A