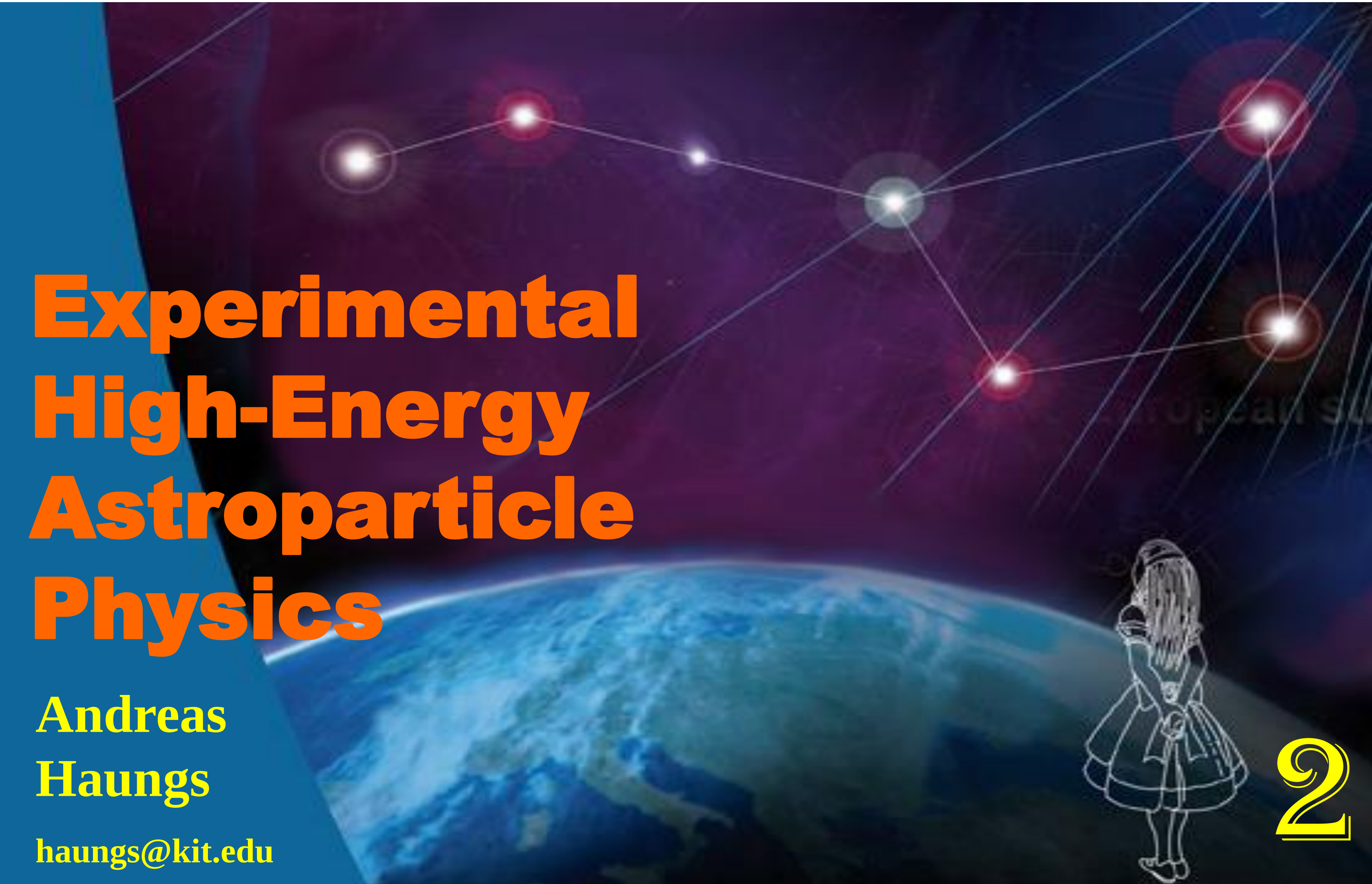
KIT – University of the State of Baden-Württemberg and National Research Center of the Helmholtz Association



Experimental High-Energy Astroparticle Physics

Andreas Haungs

haungs@kit.edu

2

Content:

1. **Introduction in HEAP**
   - **source-acceleration-transport**
   - **short history of cosmic ray research**
   - **extensive air showers**
2. **Ultra-High Energy Cosmic Rays**
   - **KASCADE, KASCADE-Grande and LOPES**
   - **Pierre Auger Observatory, JEM-EUSO**
3. **TeV-Gamma-rays & High-energy Neutrinos**
   - **TeV gamma rays**

     H.E.S.S., MAGIC, CTA
   - **high-energy neutrinos**

     IceCube and KM3Net

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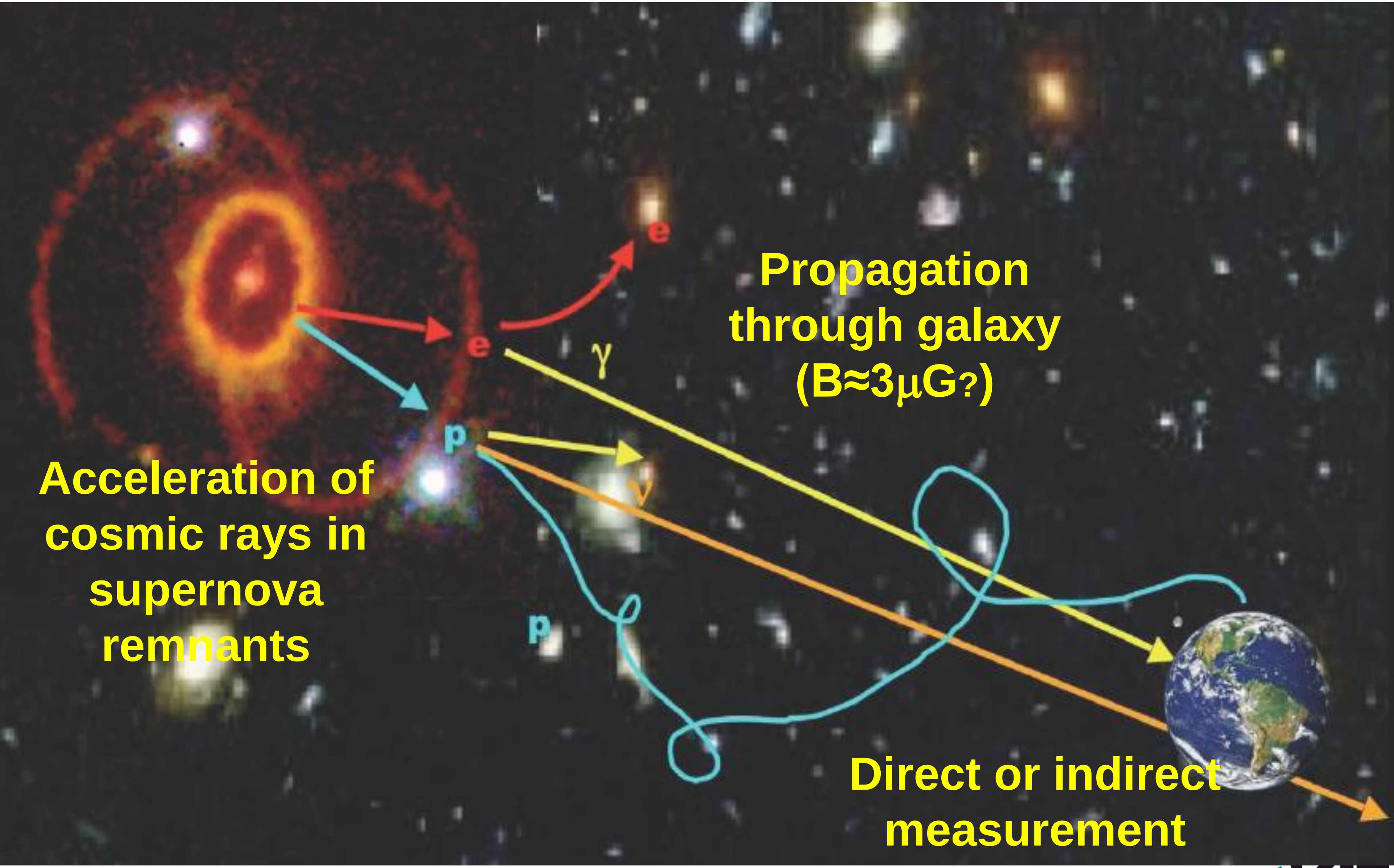
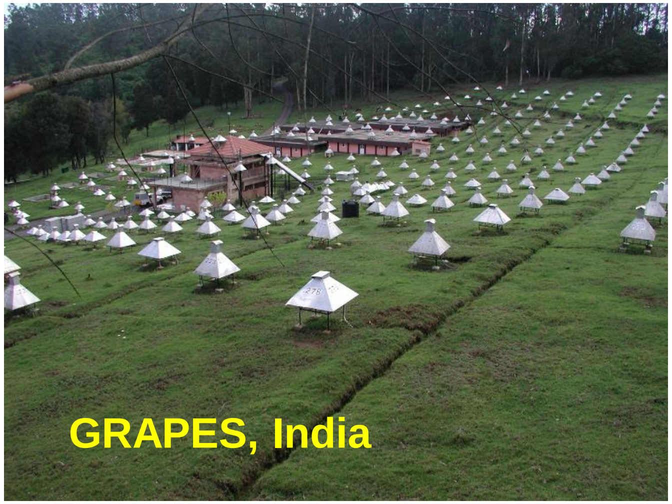
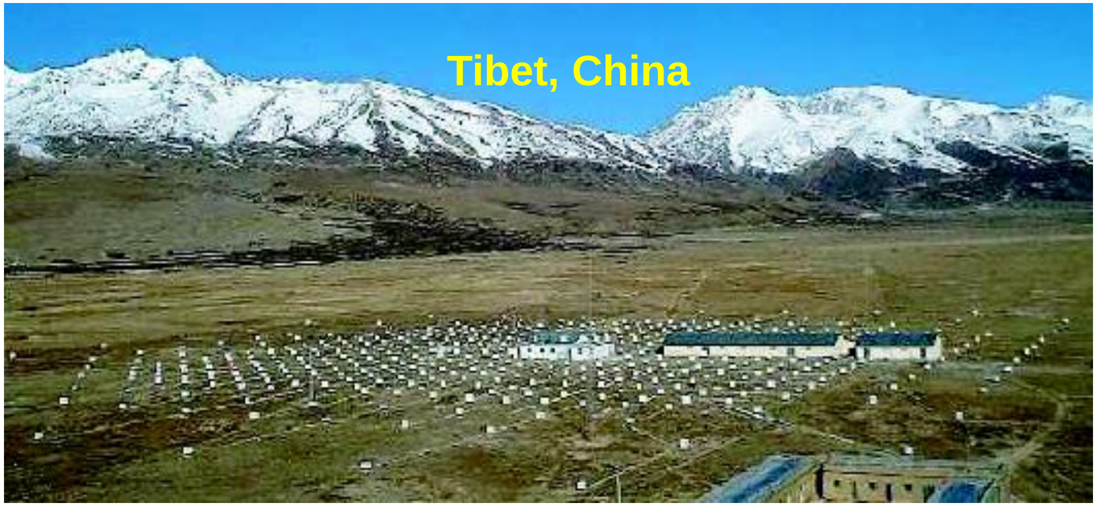
High-Energy Cosmic Ray Investigations with
KASCADE, KASCADE-Grande, and LOPES

Galactic cosmic rays

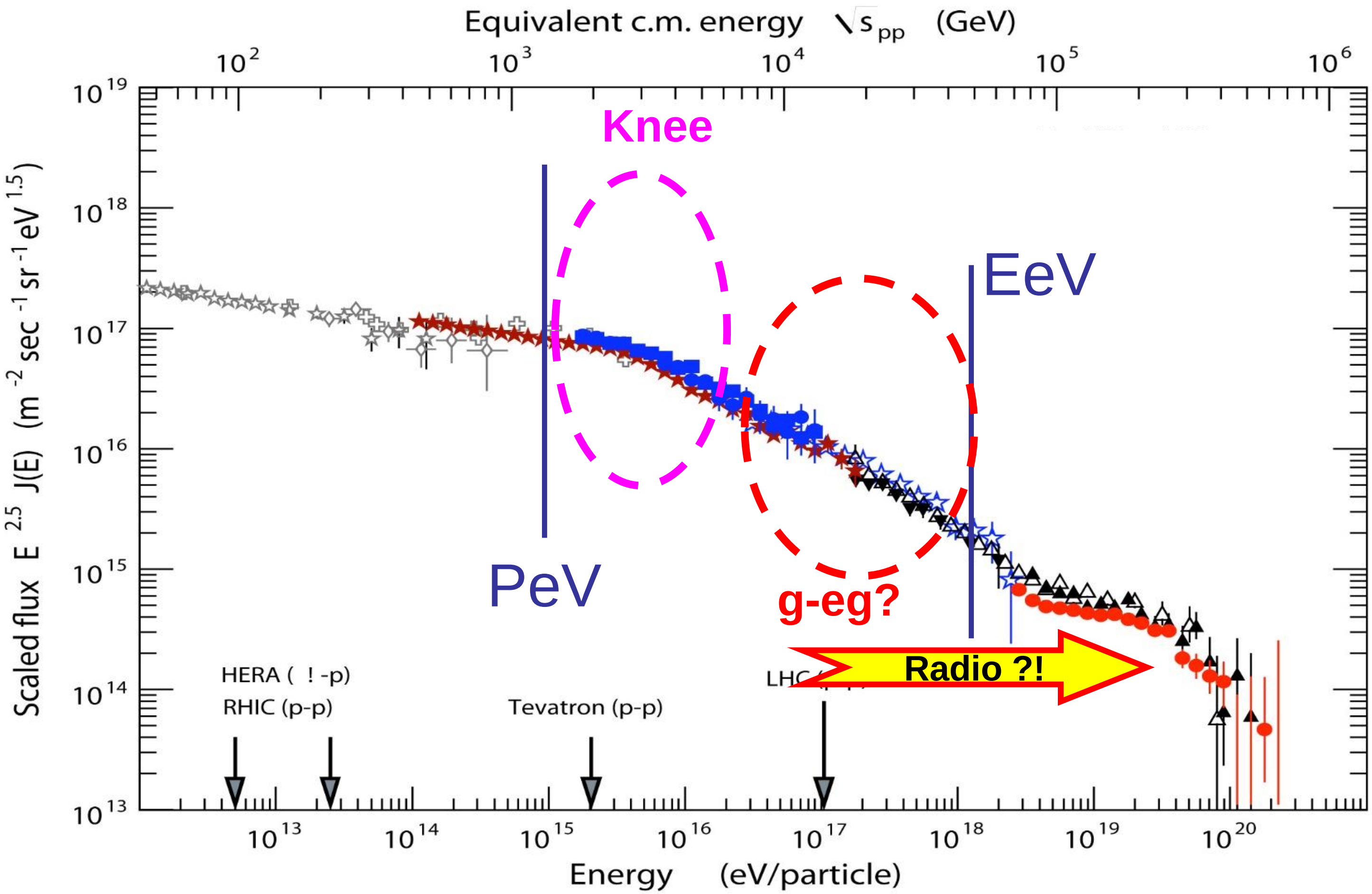


Arrays of particle detectors





Motivation



KASCADE	***10^{15}-10^{17}eV:***	**Origin of the knee?**
KASCADE-Grande	***10^{16}-10^{18}eV:***	**Iron knee (rigidity)?**
		Transition galactic-eg CR?
LOPES	***$10^{16.7}$-10^{18}eV:***	**New detection technique!**

KASCADE timeline

- **51 collaborative papers in reviewed journals** (7 still in queue, short author list papers not included)
- **55 PhD thesis**
- **86 diploma/master thesis**

1992 – 1996 – 2000 – 2004 – 2008 – 2012 – 2016

Xmax by radio

EAS GHz emission

light ankle

heavy knee

muon production height

proof-of-principle radio detection

(an)isotropy

γ limit

light knee

model tests

KCDC

CROME

Karlsruhe Air Shower Test Facility

Cosmic Revelation

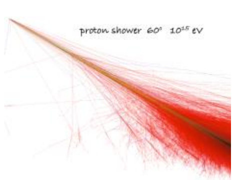
LOPES

KASCADE-Grande

KASCADE

Proposal

CORSIKA



Proposal

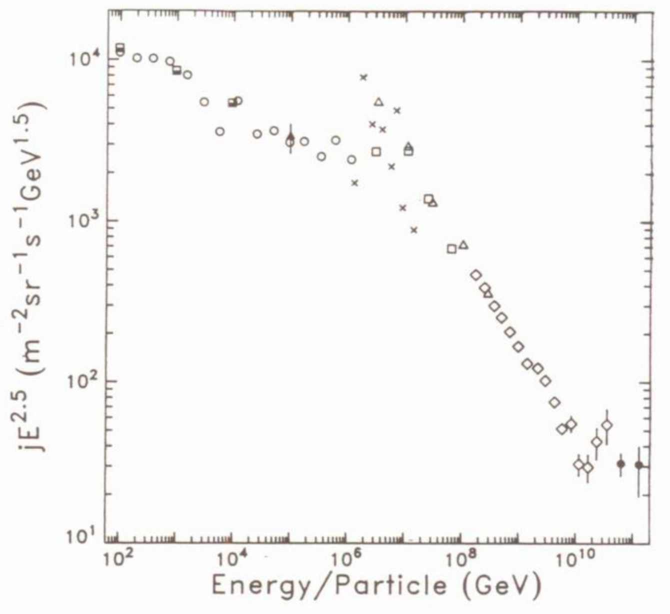
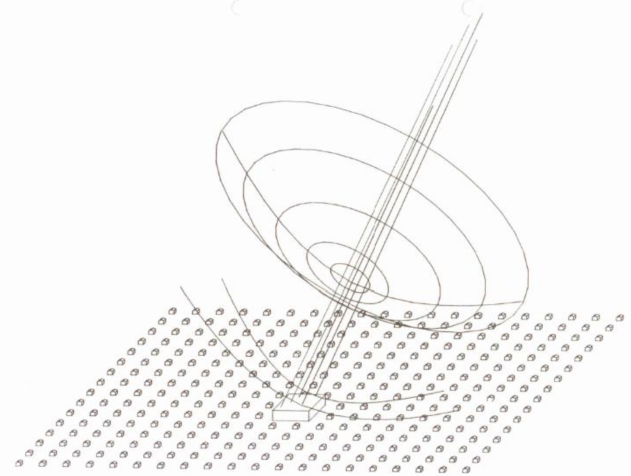


Abb.1: Differentielles Energiespektrum der Höhenstrahlung oberhalb 10^{11} eV. Die Werte des Flusses sind mit $E^{2,5}$ multipliziert, um den starken Abfall in der Darstellung zu reduzieren. Man erkennt deutlich das Abknicken der Kurve zwischen 10^{15} und 10^{16} eV ("Knie") und die große Streuung der Meßwerte in diesem Bereich. (Nach Linsley, 1983).

Konzeptstudie für ein Detektorsystem zur Untersuchung ausgedehnter Luftschauer für Primärenergien zwischen 10^{14} und 10^{17} eV



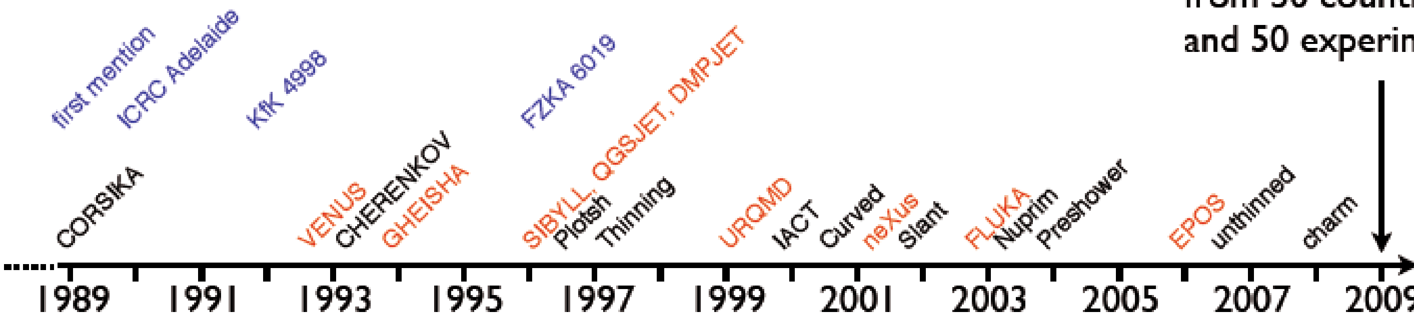
J. Engler, H. J. Gils, D. Heck, W. Heeringa, H. Keim, H. O. Klages, J. Knapp, H. Rebel, G. Schatz, T. Thouw, B. Zeitnitz

Kernforschungszentrum Karlsruhe, Institut für Kernphysik

Juni 1988

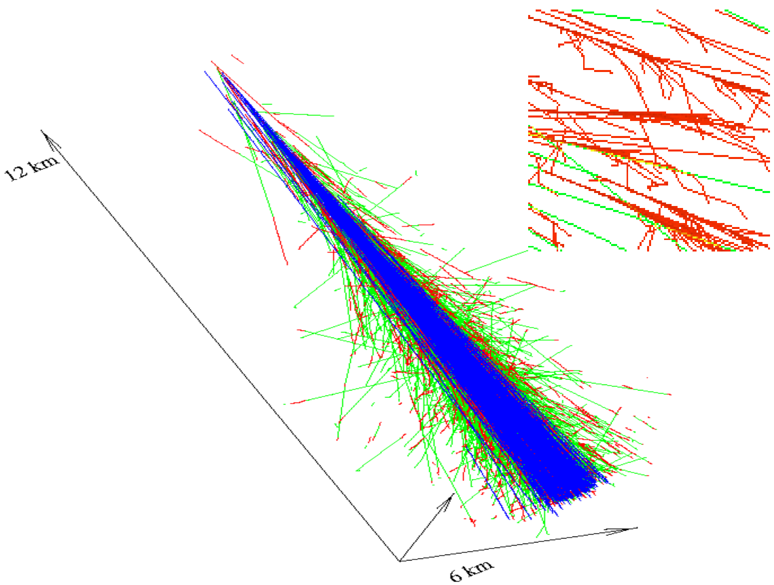
CORSIKA (COsmic Ray SImulations for KAscade)

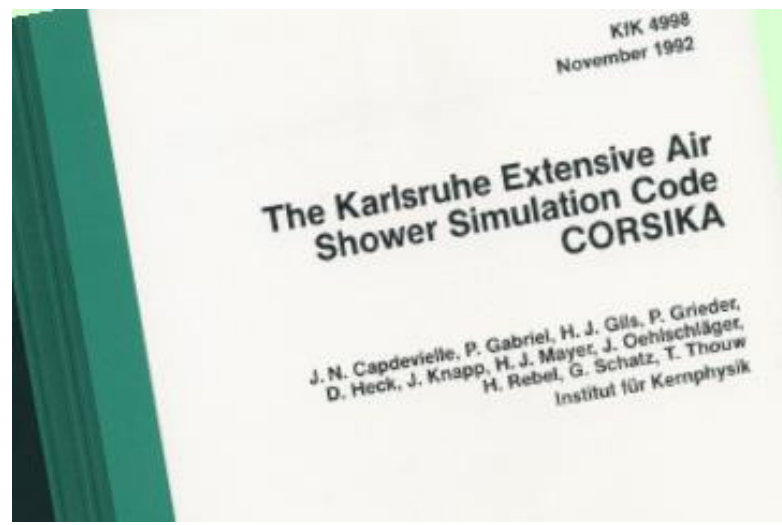
700 users
from 50 countries
and 50 experiments



> 1 day per
10^{15} eV shower

< 20 min per
10^{15} eV shower




KfK 4998
November 1992

The Karlsruhe Extensive Air Shower Simulation Code CORSIKA

J. N. Capdevielle, P. Gabriel, H. J. Gils, P. Grieder, D. Heck, J. Knapp, H. J. Mayer, J. Oehlschläger, H. Rebel, G. Schatz, T. Thouw
Institut für Kernphysik

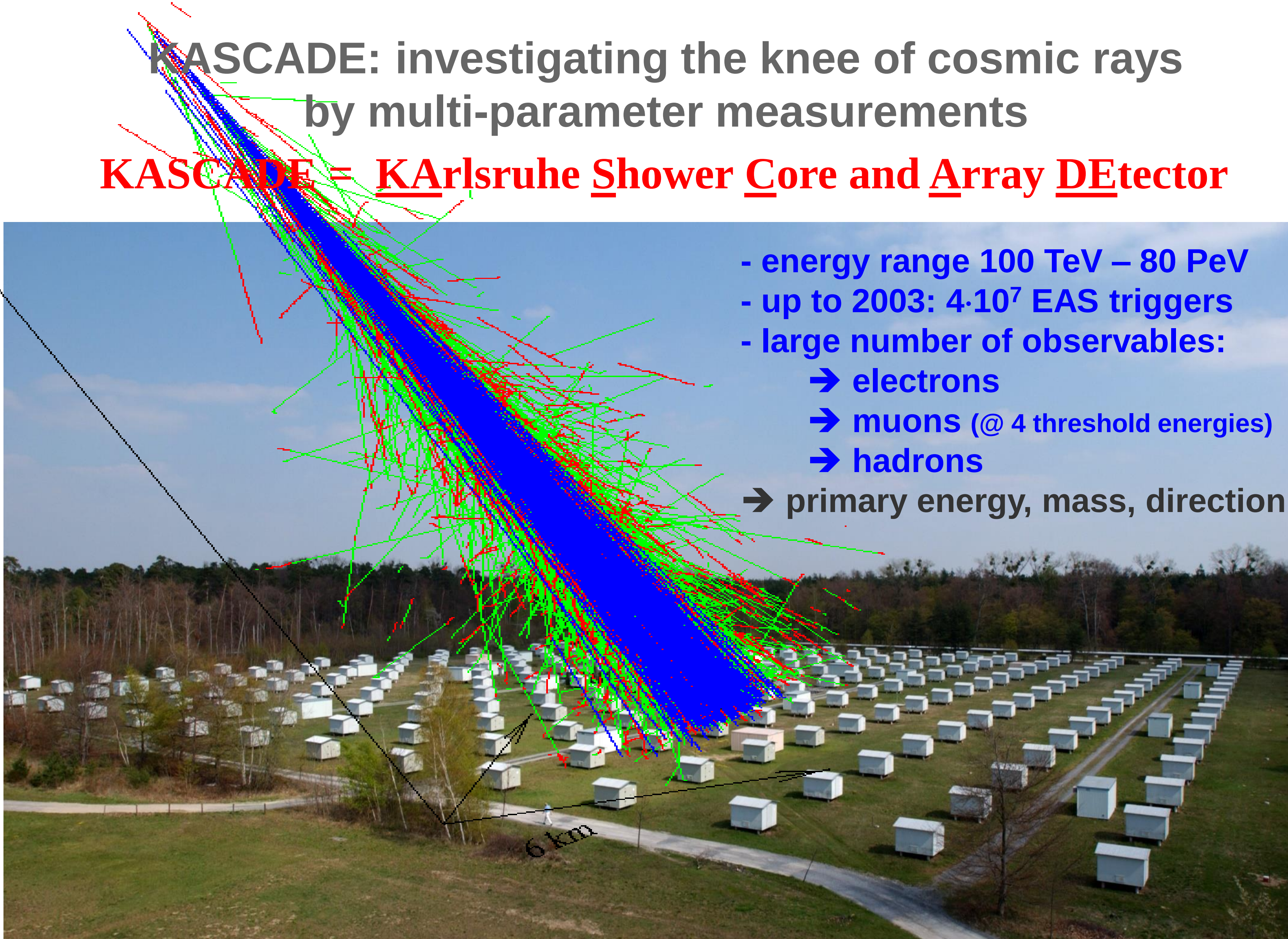
©Johannes Knapp

~1000 citations

KASCADE-Grande

KASCADE: investigating the knee of cosmic rays by multi-parameter measurements

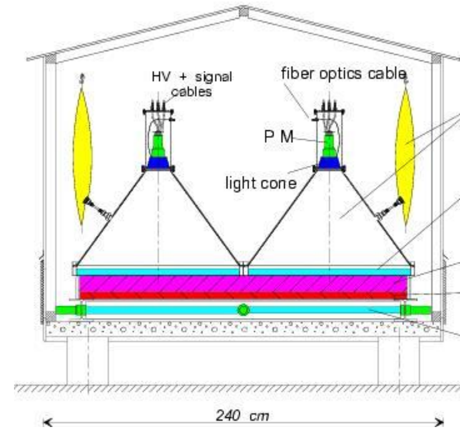
KASCADE = KArlsruhe Shower Core and Array DEtector



- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
  - ➔ electrons
  - ➔ muons (@ 4 threshold energies)
  - ➔ hadrons

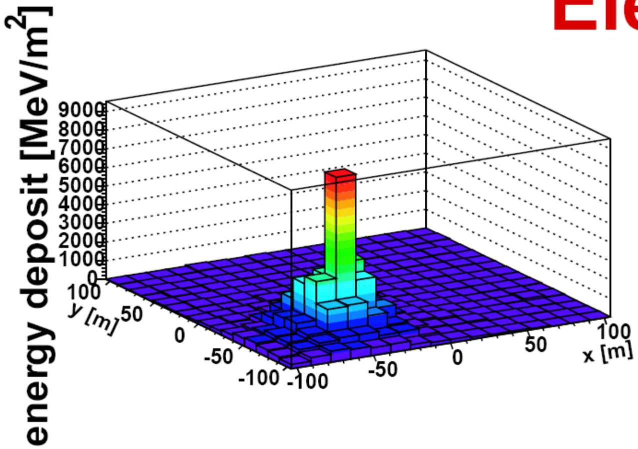
➔ primary energy, mass, direction

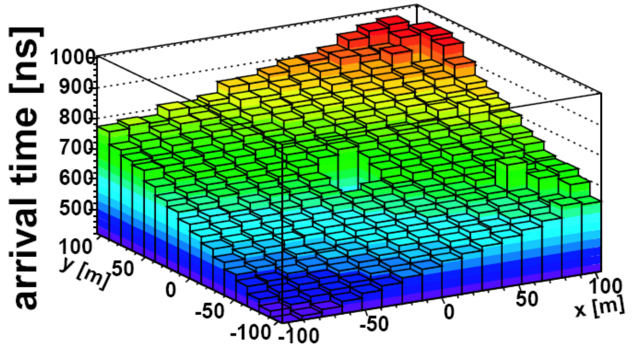
KASCADE



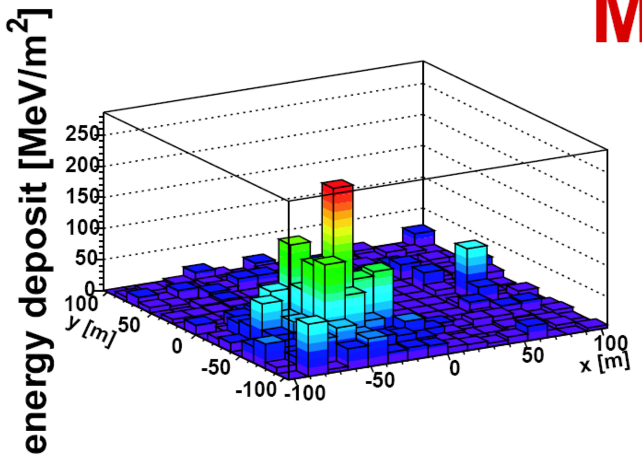
Array

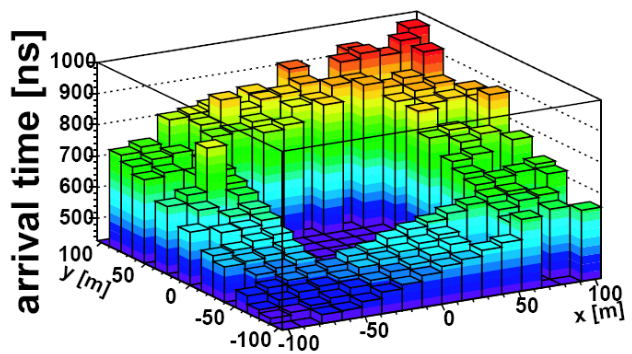
Electrons





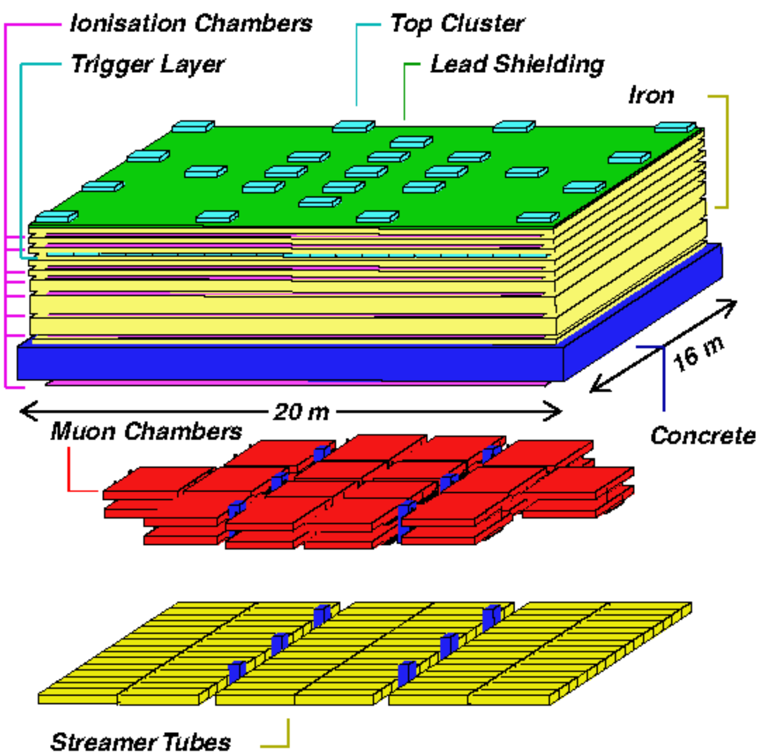
Muons

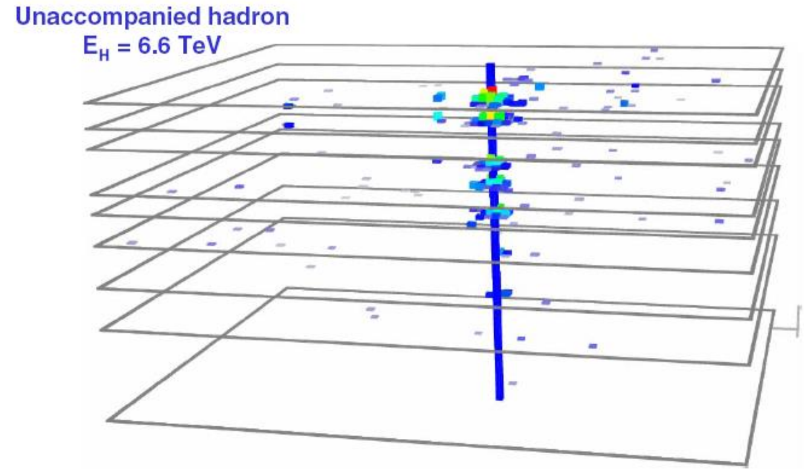




Run 3226, File 2, leve 65041, Ymd 10215, Hms 225810, Neds 250, Npds 138
(Xc,Yc) = (-45.4,-51.0), (Ze,Phi) = (36.7,228.6), log10(Ne)=6.14, log10(Lmuo)=4.66

hadrons in air shower cores

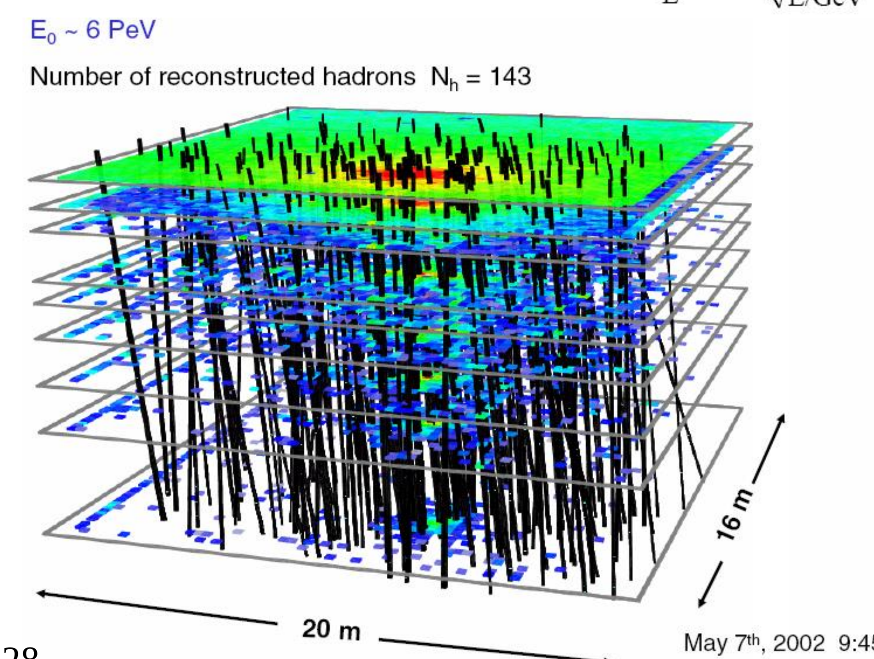




spatial resolution: $\sigma_x \sim 10 - 12$ cm

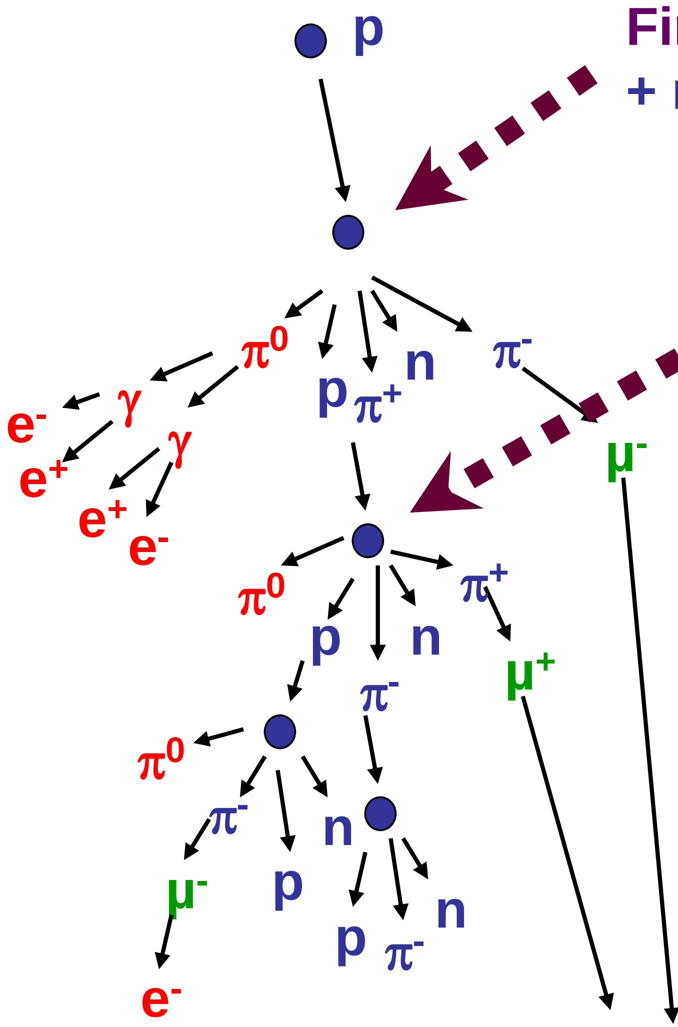
angular resolution: $\sigma_\Theta \sim 1° - 3°$

energy resolution: $\frac{\sigma(E)}{E}[\%] \sim \frac{250}{\sqrt{E/\mathrm{GeV}}}$



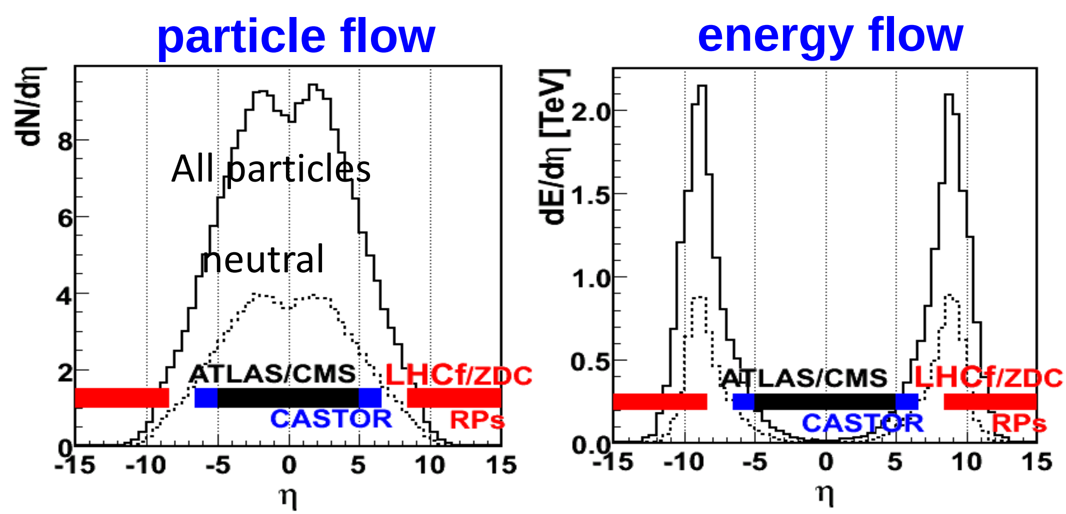
J. Engler et al., Nucl. Instr. Meth. A 427 (1999) 528

Validity of Hadronic Interaction Models

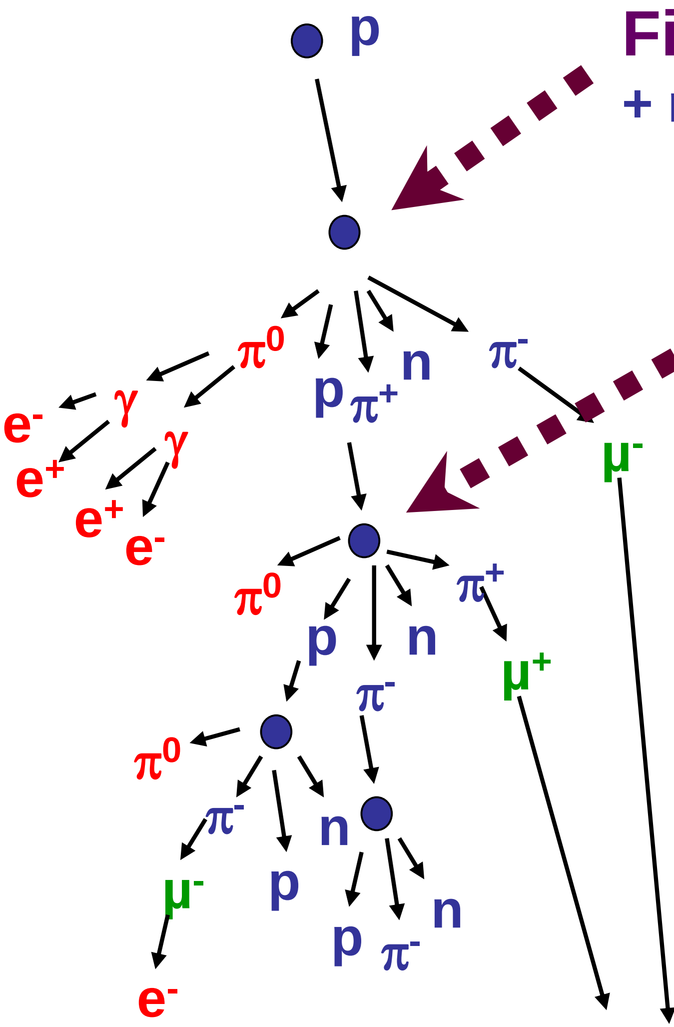


First, high energy interaction: LHC
+ multiparameter measurements EAS

Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS



Validity of Hadronic Interaction Models

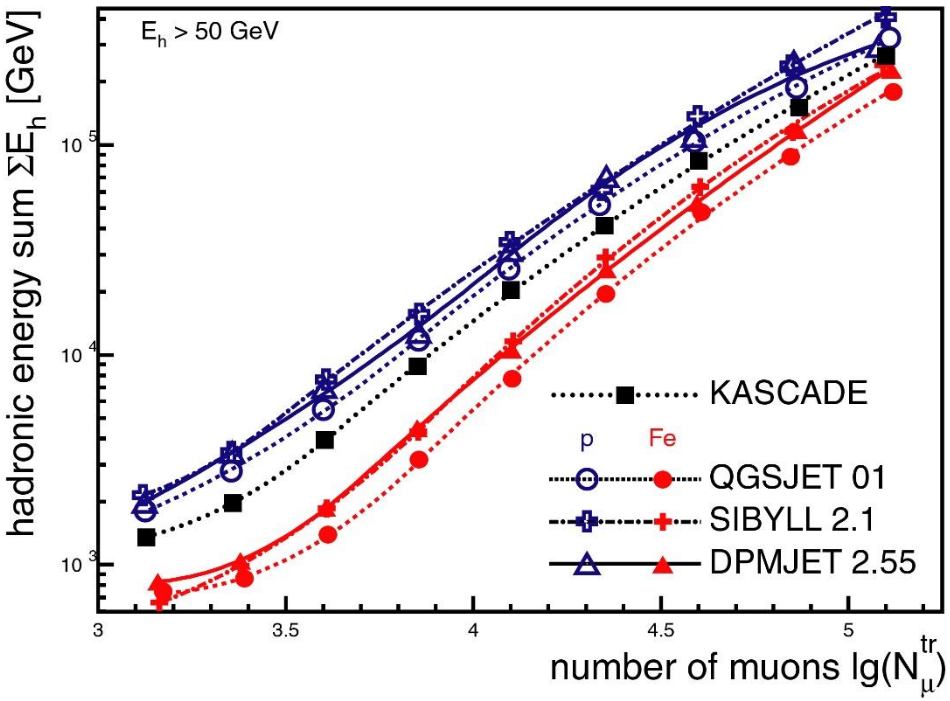


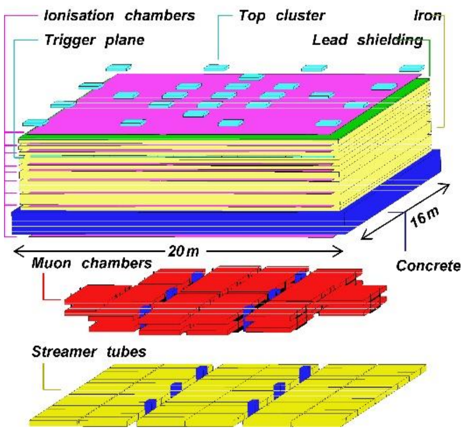
First, high energy interaction: LHC
+ multiparameter measurements EAS

Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS


CORSIKA
air shower simulation code
Fix target experiment:
SHINE (NA61) @ SPS/CERN
LHC experiments:
CMS and CASTOR

KASCADE : sensitivity to hadronic interaction models





Example:
hadrons vs. muons

correlation of observables:

<u>no hadronic interaction model describes data consistently !</u>

➔ tests and tuning of hadronic interaction models !

➔ close co-operation with theoreticians (CORSIKA including interaction models)

➔ e.g.:
- **EPOS 1.6 is not compatible with KASCADE measurements**
- **QGSJET 01and SIBYLL 2.1still most compatible models**

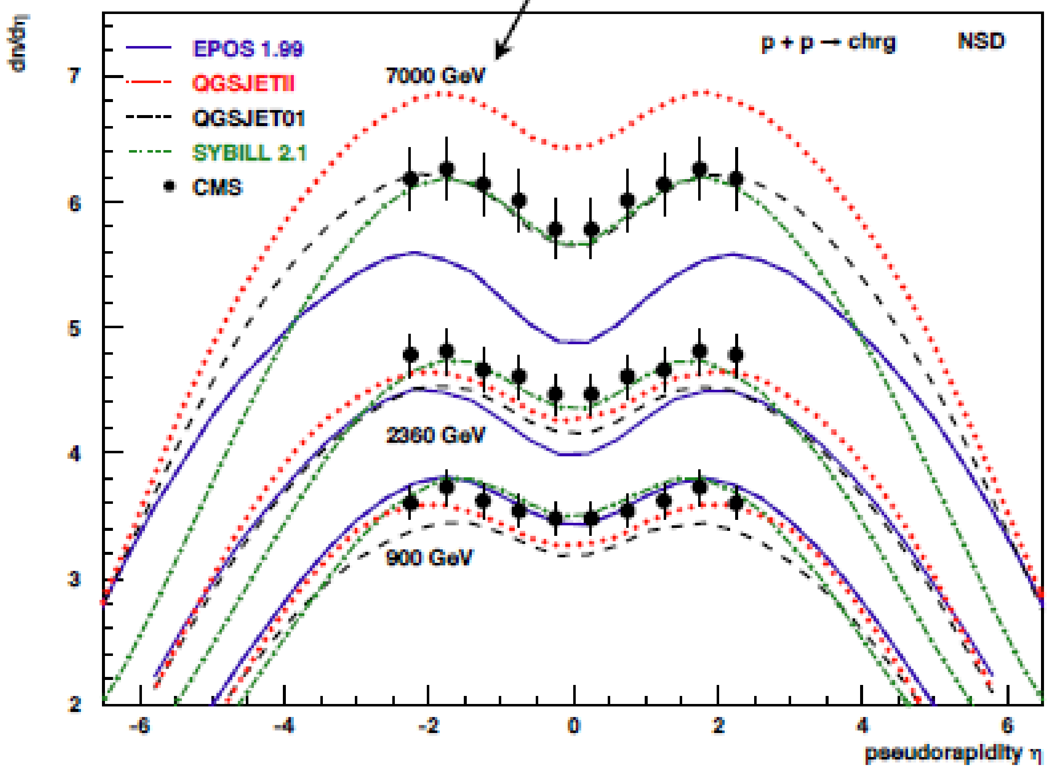
KASCADE collaboration, J Phys G (3 papers: 25(1999)2161; 34(2007)2581; (2009)035201)

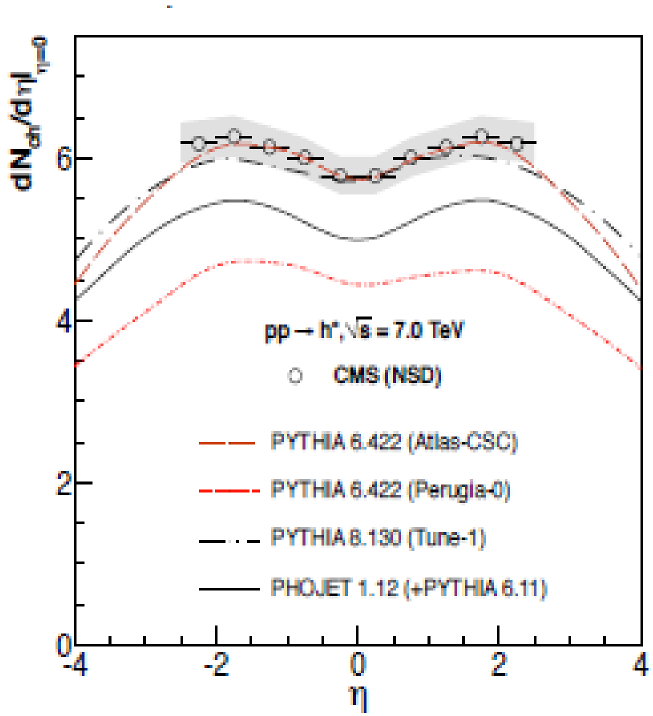
CMS @ LHC

Charged particle distribution in pseudorapidity

Protons: $E_{lab} = 3 \times 10^{16}$ eV

D'Enterria et al., Astropart. Phys. 35, 2011

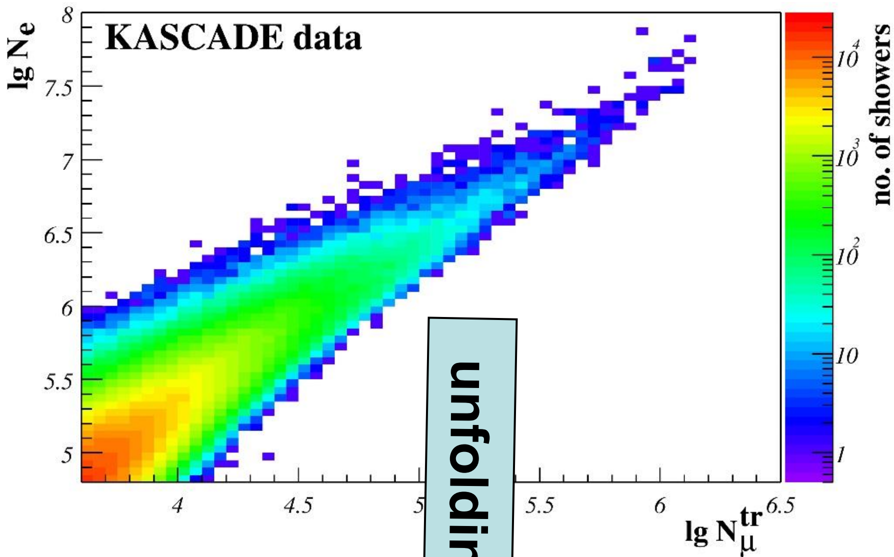


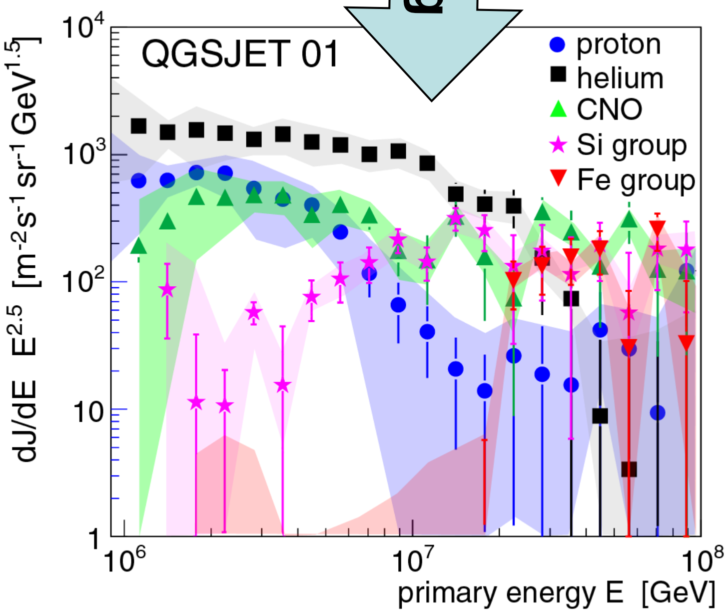


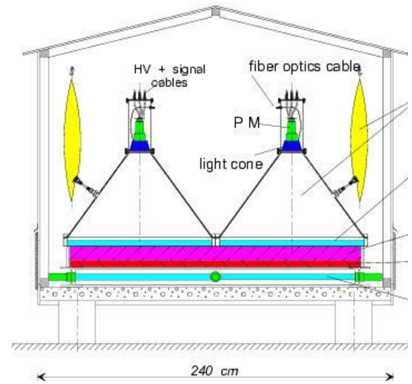
(data from all LHC experiments, CMS shown as example)

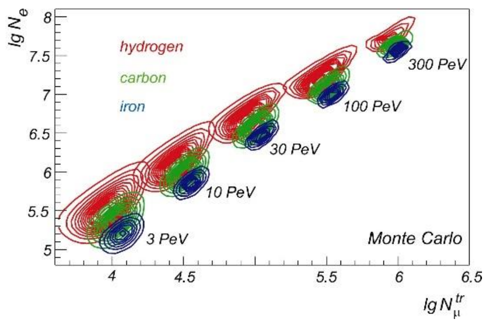
- **Models for air showers typically better in agreement with LHC data**

KASCADE : energy spectra of single mass groups









Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

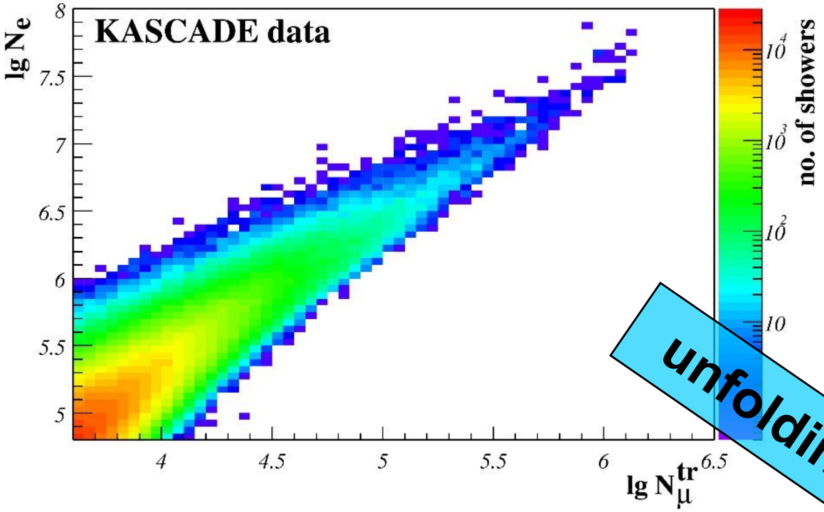
➔ solve the inverse problem

$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

- **kernel function obtained by Monte Carlo simulations (CORSIKA)**
- **contains: shower fluctuations, efficiencies, reconstruction resolution**

KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25

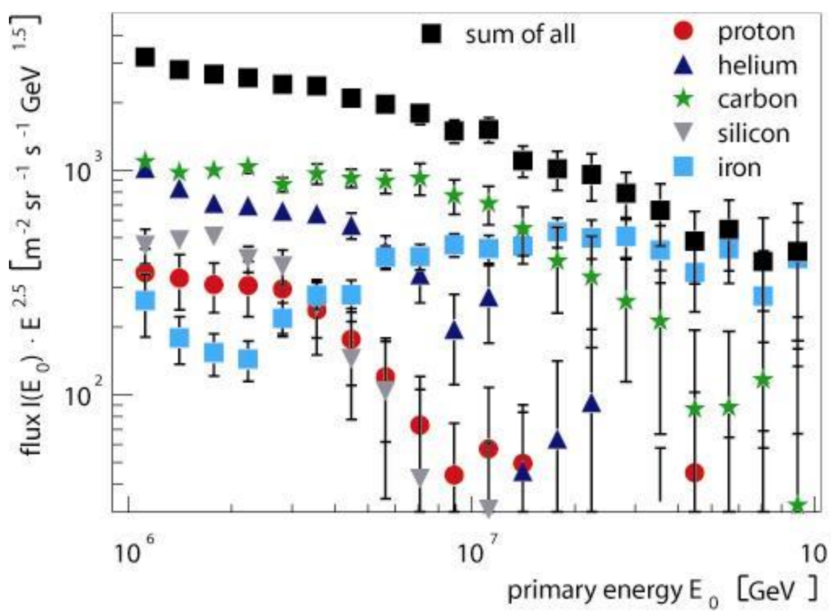
Results of KASCADE:
Energy spectrum & composition



unfolding

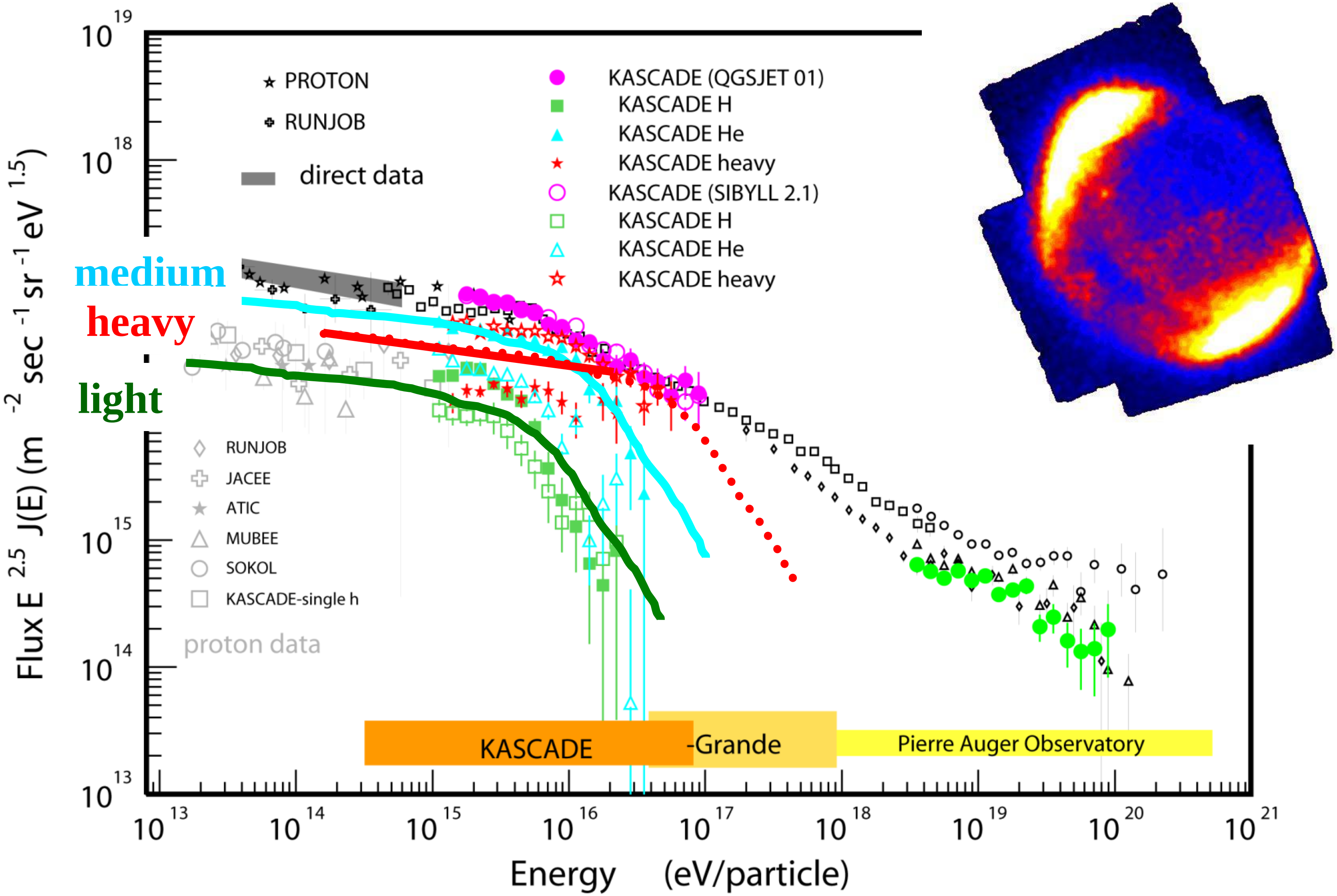
<u>Analysis of 2-dimensional shower size spectrum:</u>

➔energy spectra of single mass groups



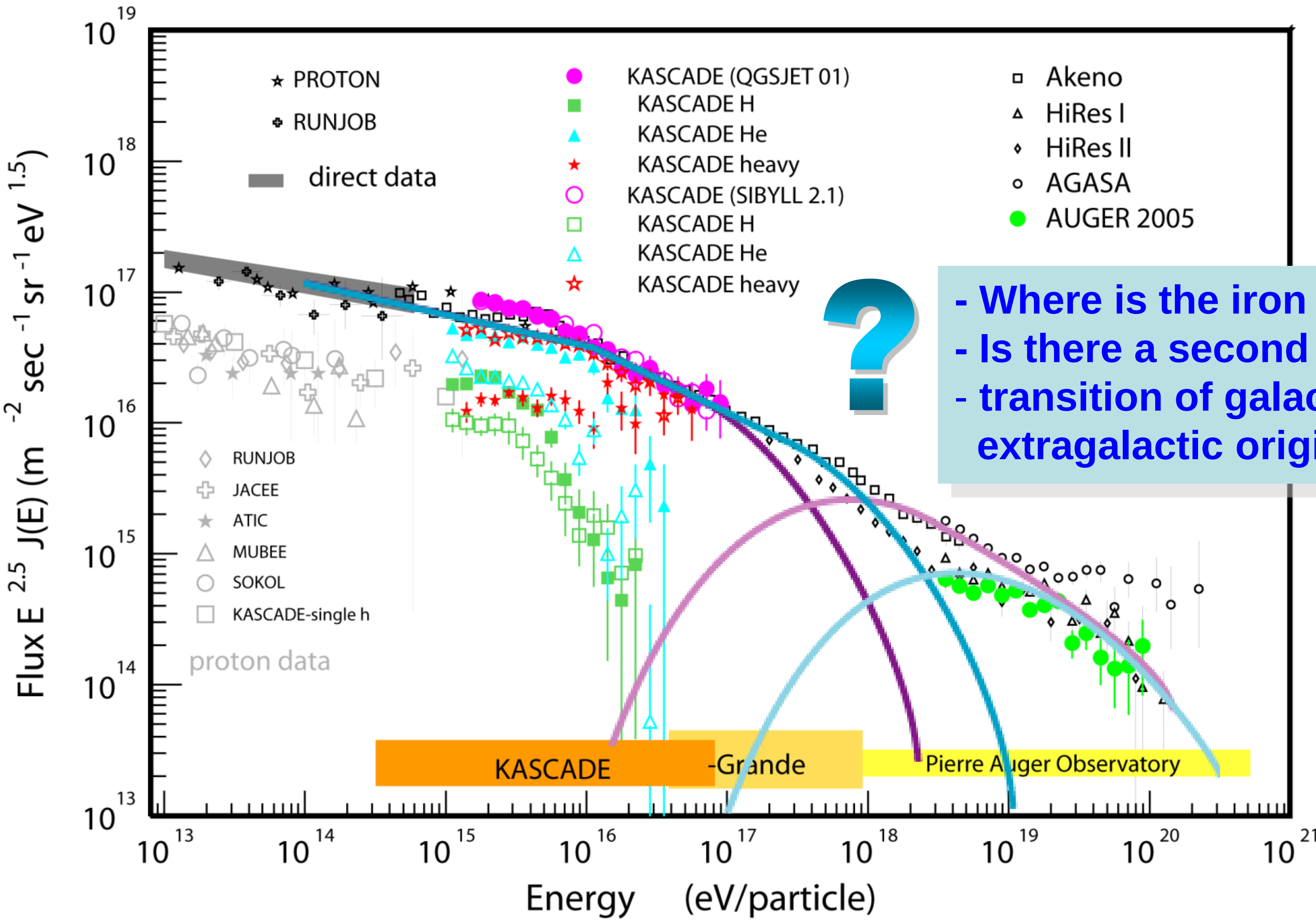
- knee is caused by light elements
- knee positions vary with mass group
- no hadronic interaction model describe data consistently

Result KASCADE ➔ Motivation KASCADE-Grande



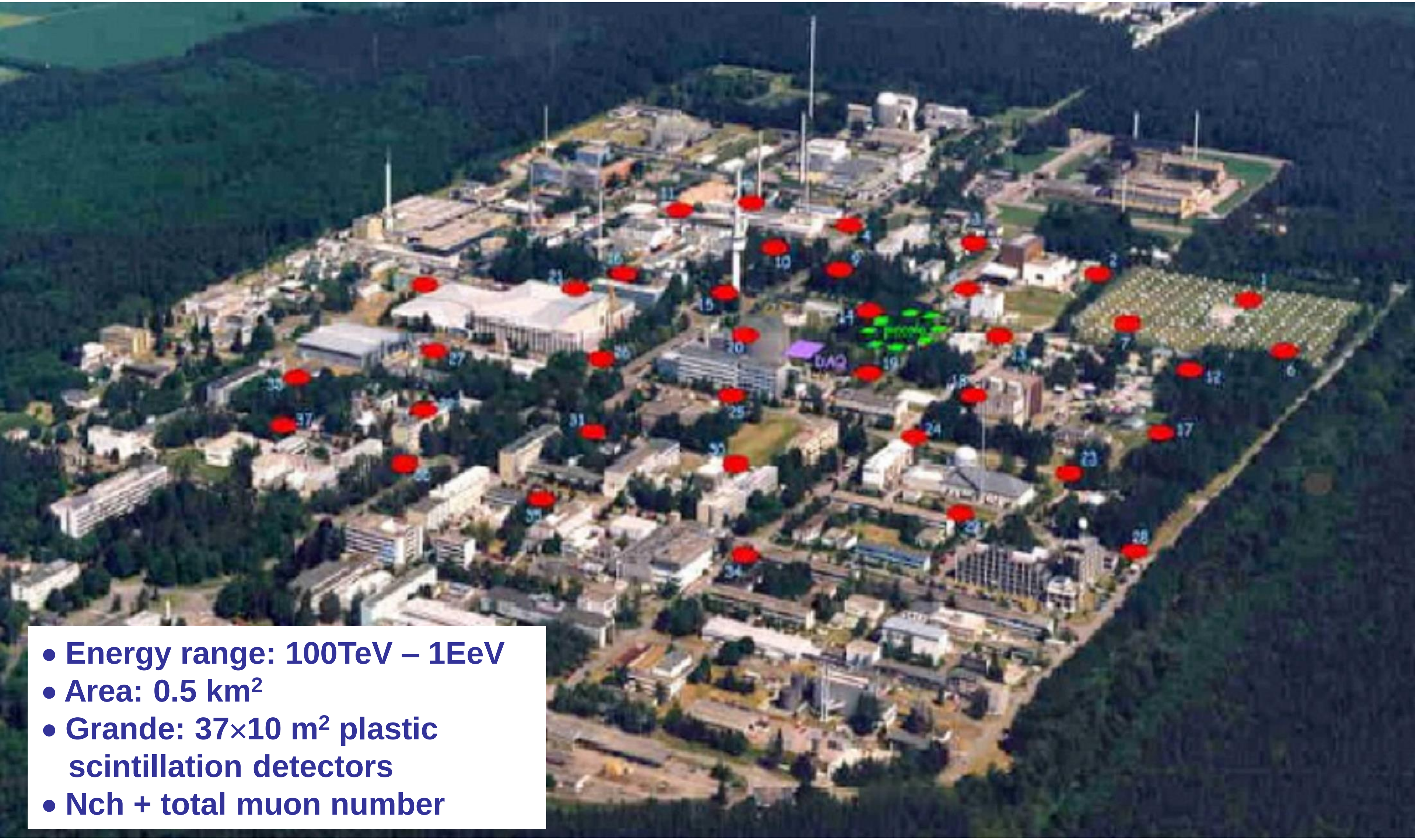
Karlsruhe Institute of Technology

Result KASCADE ➔ Motivation KASCADE-Grande



- Where is the iron knee ?
- Is there a second knee ??
- transition of galactic to extragalactic origin ?

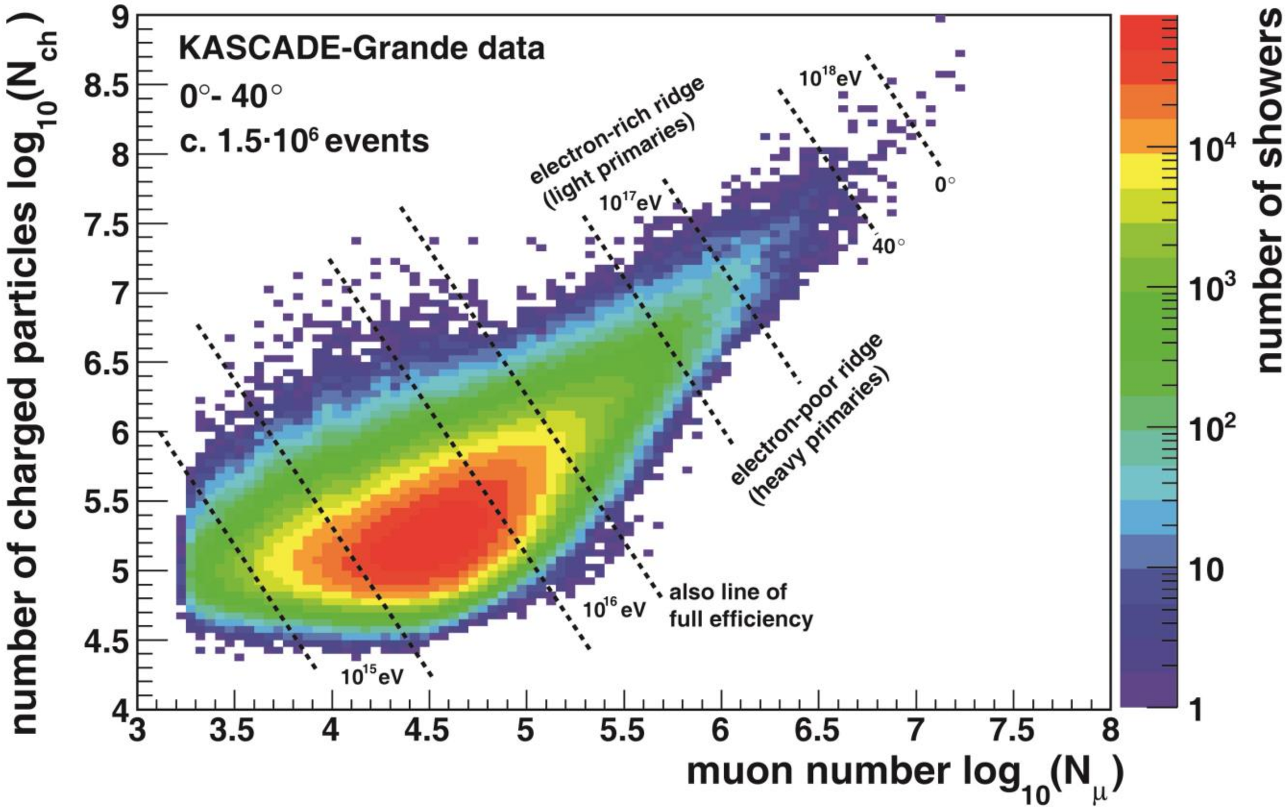
KASCADE-Grande



- **Energy range: 100TeV – 1EeV**
- **Area: 0.5 km^2**
- **Grande: 37×10 m^2 plastic scintillation detectors**
- **Nch + total muon number**

W.D.Apel et al, Nucl.Instr. and Meth. A620 (2010) 202

2-dimensional shower size spectrum



➔ **determination of primary energy**

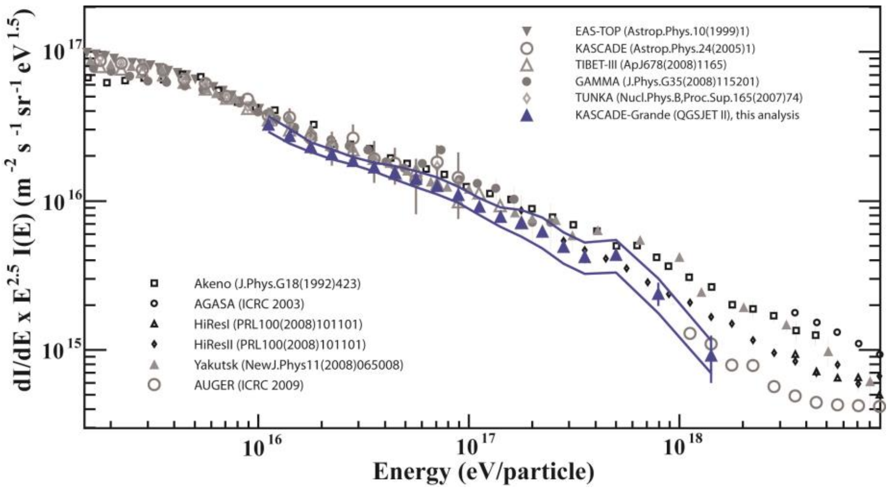
➔ **separation in "electron-rich" and "electron-poor" event**

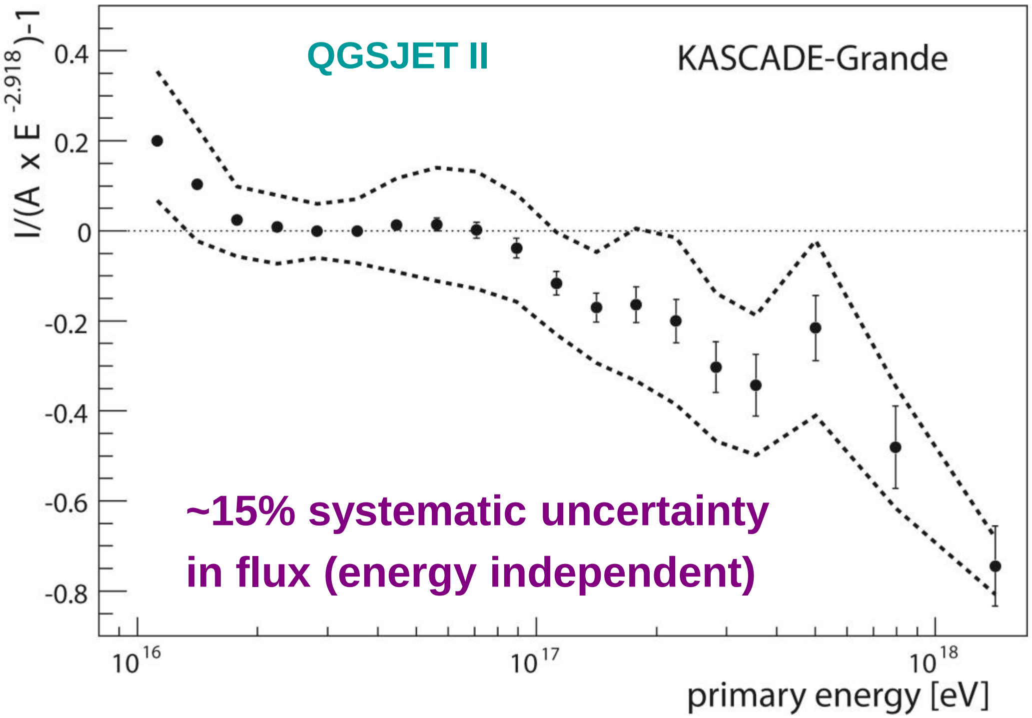
$$\log_{10}(E) = [a_p + (a_{Fe}-a_p)\cdot k] \cdot\log_{10}(N_{ch}) + b_p +(b_{Fe}-b_p)\cdot k$$

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$

KASCADE-Grande
all-particle energy spectrum

Astroparticle Physics 36 (2012) 183





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

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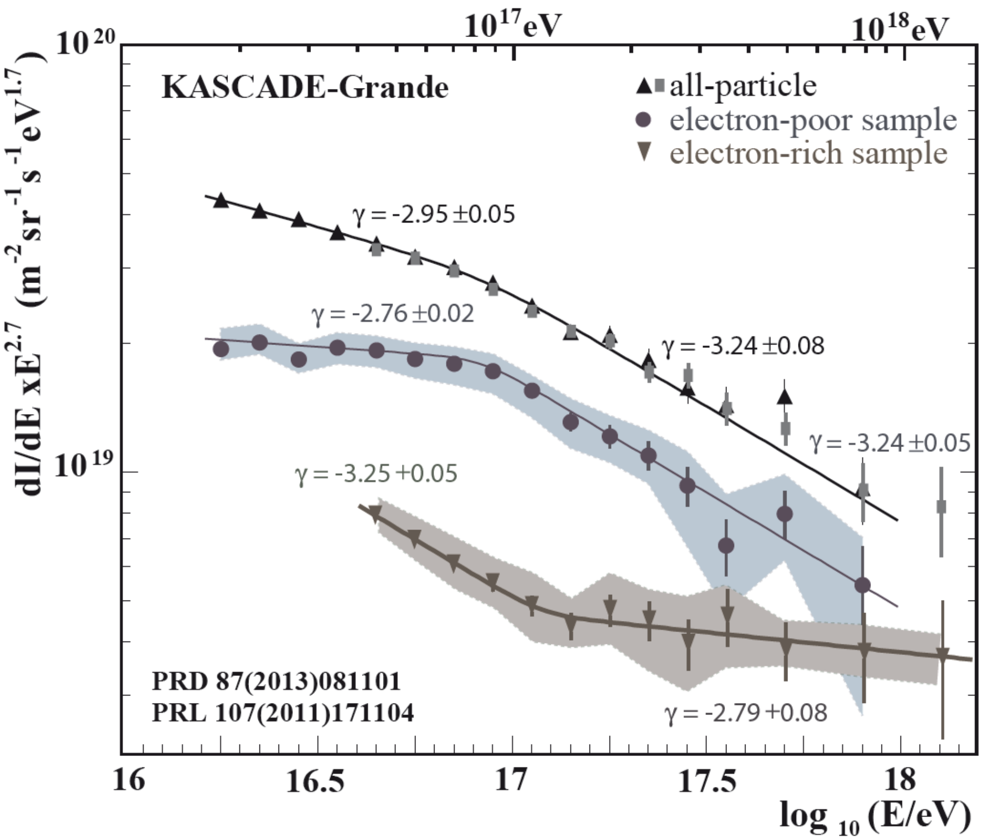
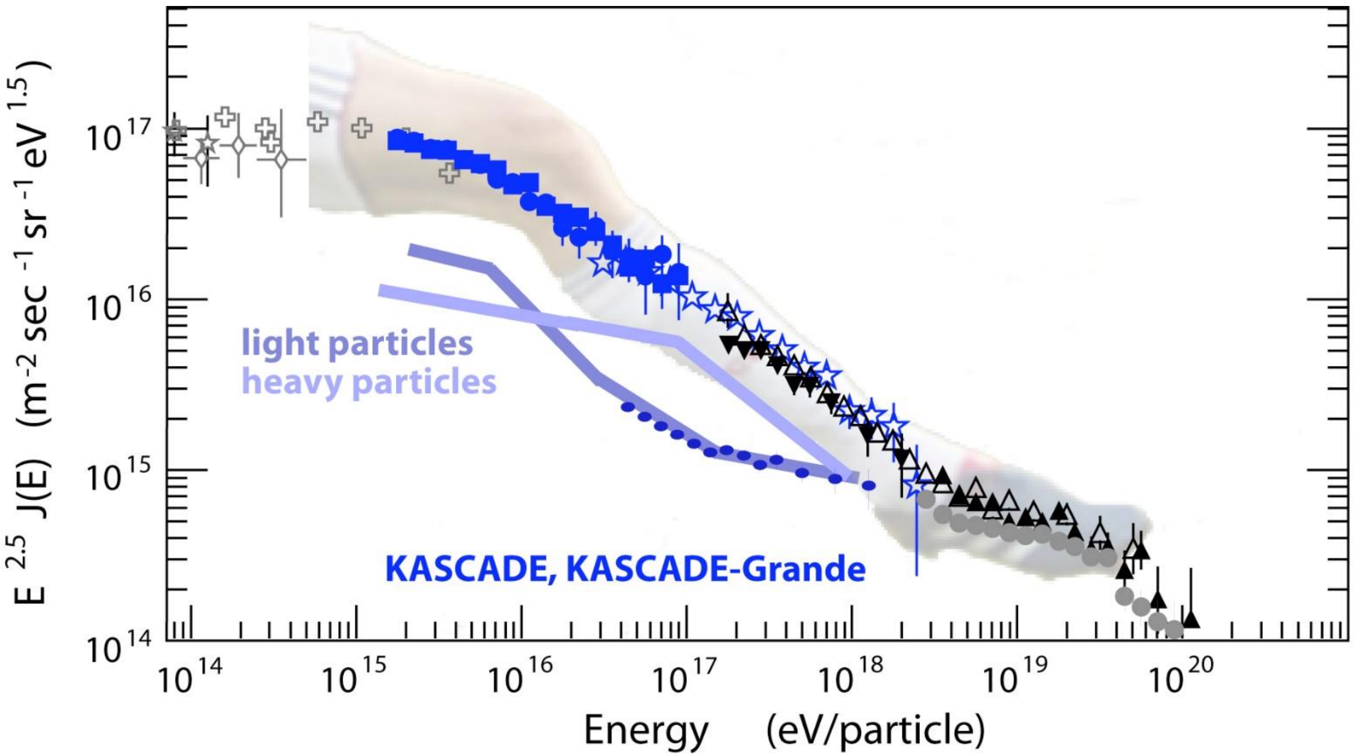
KASCADE-Grande
energy spectra of mass groups



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

Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

Light and Heavy Knees, Ankles, and Transition



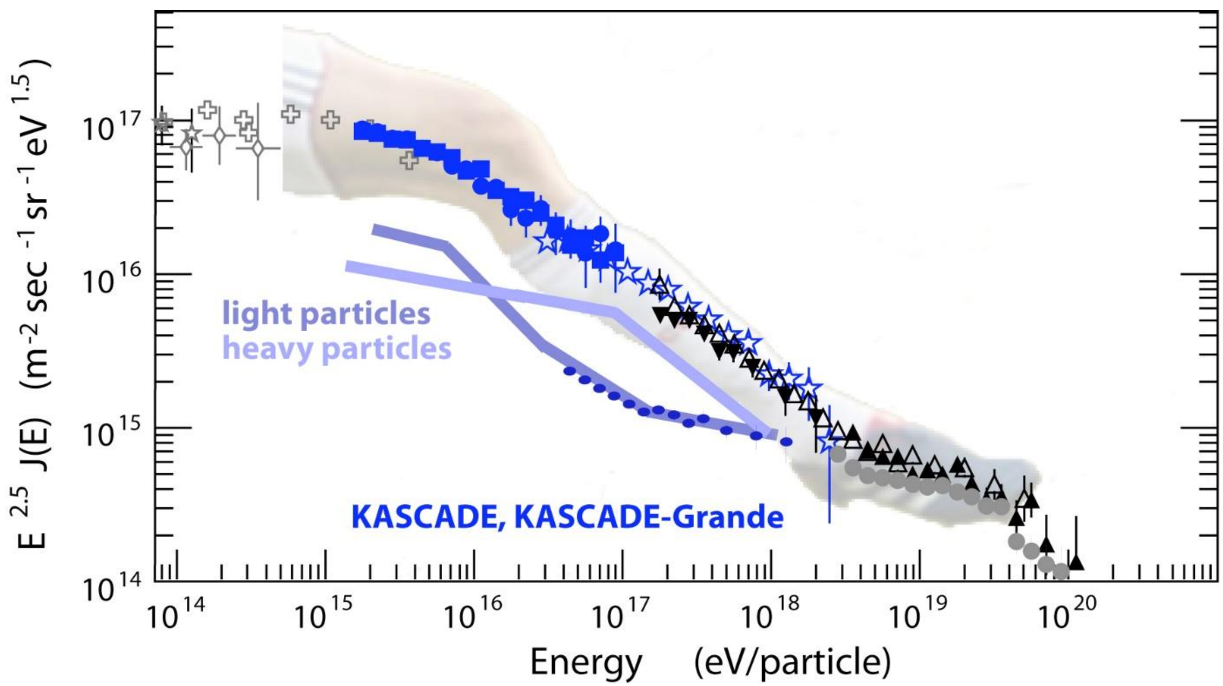
- ➔ **KASCADE: knee of light primaries at ~$3 \cdot 10^{15}$eV**
- ➔ **Hardening at 10^{16}eV due to knee of medium component**
- ➔ **KASCADE-Grande: knee of heavy primaries at ~$9 \cdot 10^{16}$ eV**
- ➔ **heavy knee less distinct compared to light knee**
- ➔ **mixed composition for 10^{15} to ~ $8 \cdot 10^{17}$ eV**
- ➔ **light ankle at $1\text{-}2 \cdot 10^{17}$ eV**

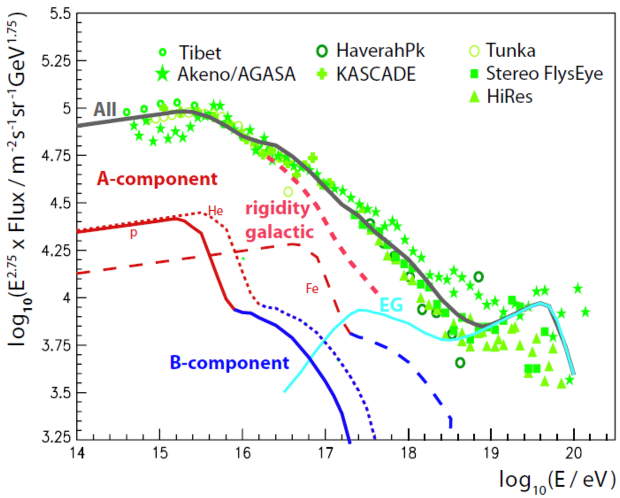
knee position $\propto$ Z

Light and Heavy Knees, Ankles, and Transition

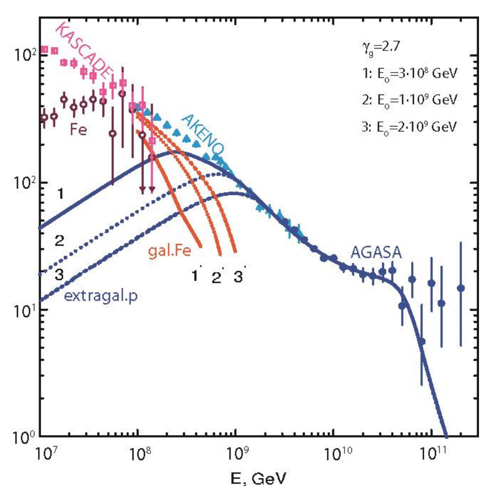
Questions:

- **which astrophysical scenario (model) describes the data?**
- **exact energy and mass scale?**
- **spectral forms?**

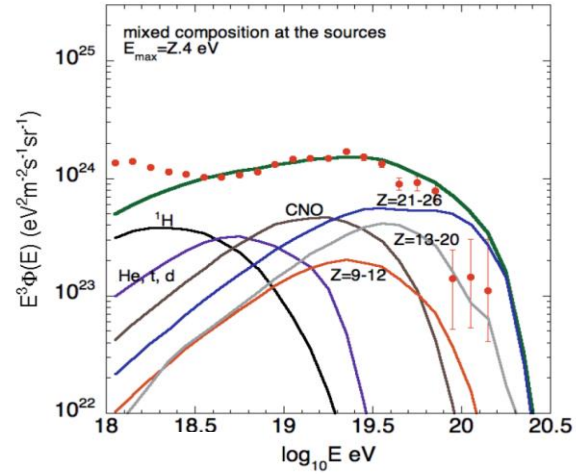




A.M.Hillas, J. Phys. G: Nucl. Part. Phys. 31 (2005) R95



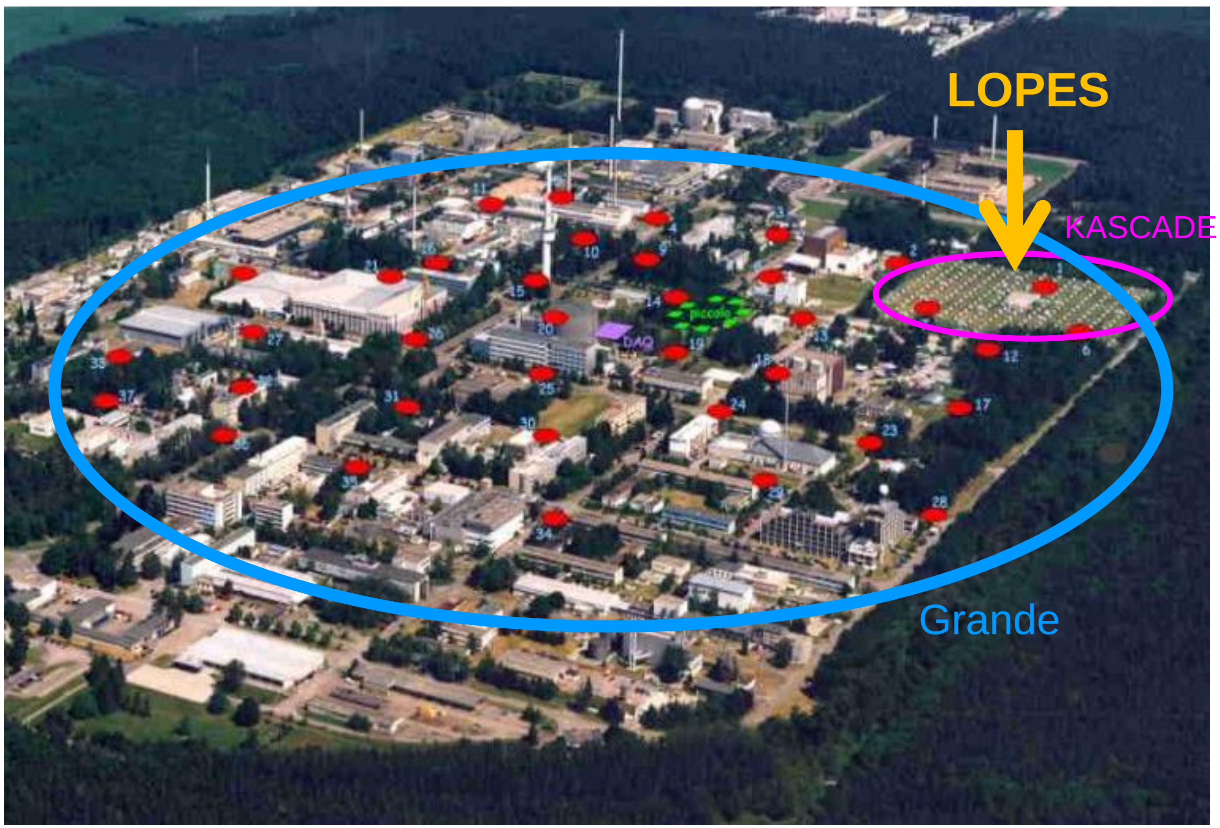
V.Berezinsky, astro-ph/0403477



D.Allard, astro-ph/1111.3290

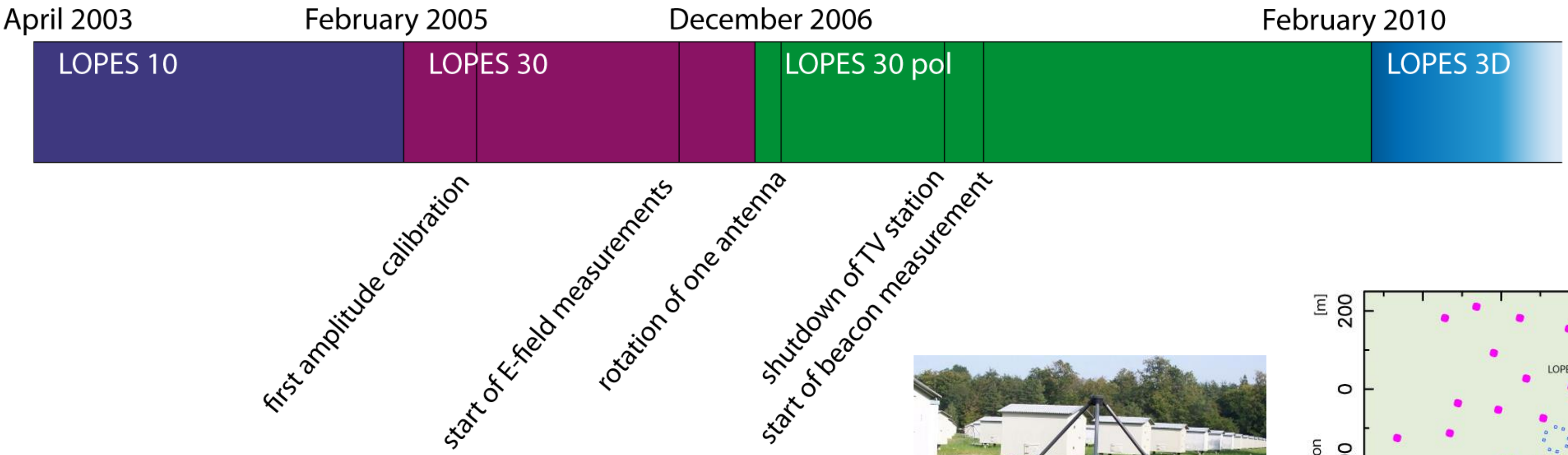
LOPES

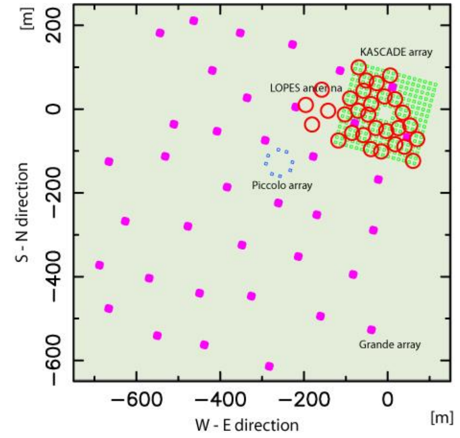
LOPES collaboration:
-) KASCADE-Grande
-) U Nijmegen, NL
-) MPIfR Bonn, D
-) Astron, NL
-) IPE, FZK, D



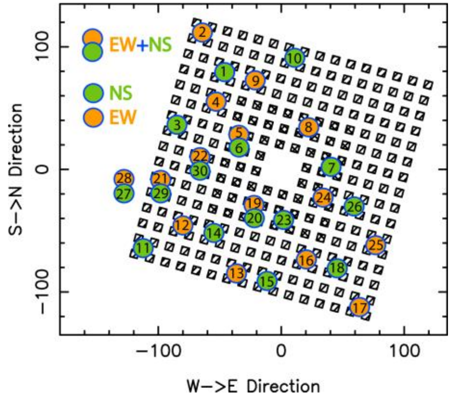
➔Development of a new detection technique!

Evolution of LOPES





- **LOPES 10**
  „proof of principle“
- **LOPES 30 east-west**
  calibration of signal
- **LOPES 30 pol**
  polarization dependencies
- **LOPES 3D**
  complete E-field-vector



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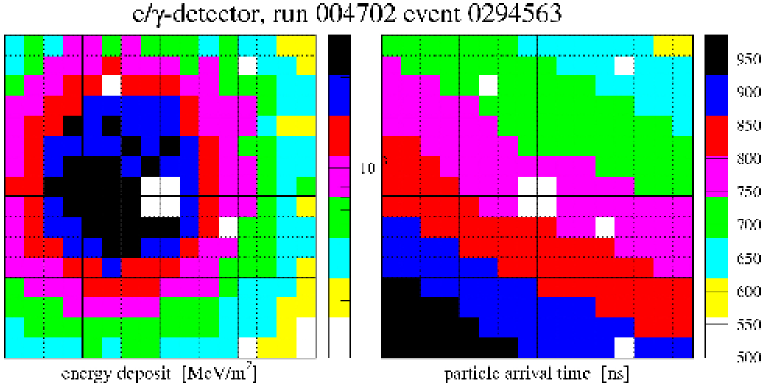
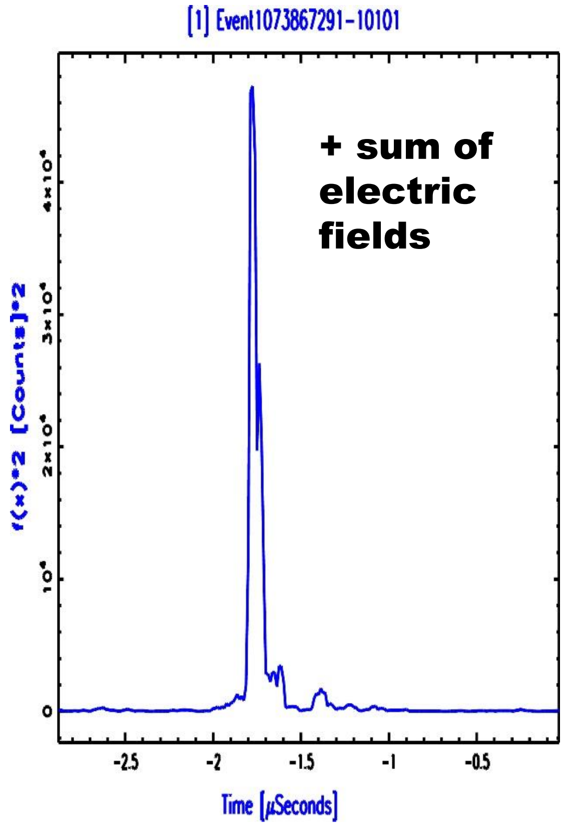
LOPES: Proof of principle

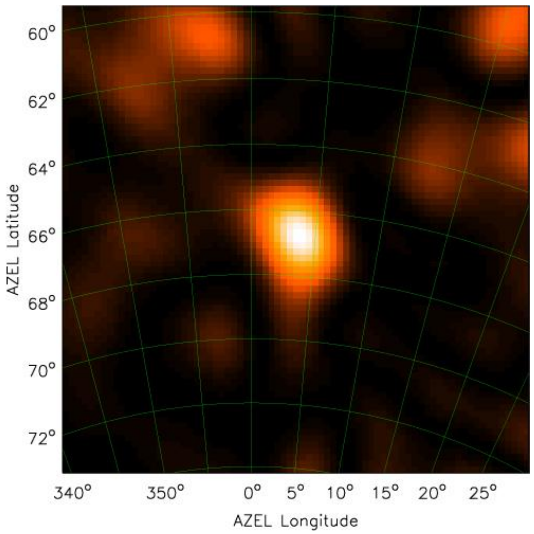
1. KASCADE measurement



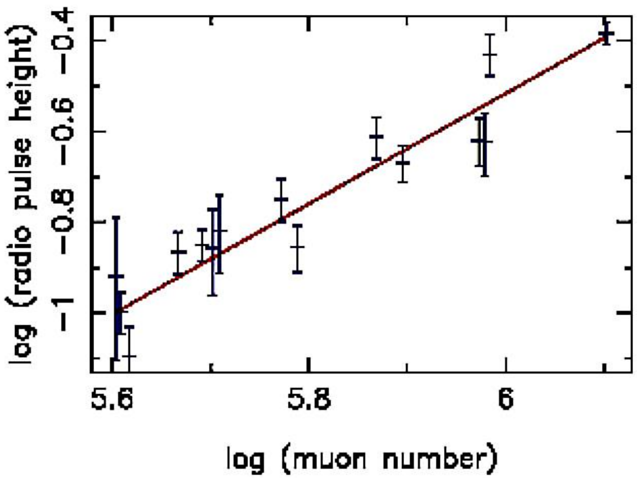
2. Radio data analysis



3. Skymapping



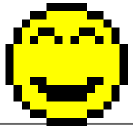
4. Many events



5. Publication

LOPES collaboration, Nature 425 (2005) 313

6. Be happy

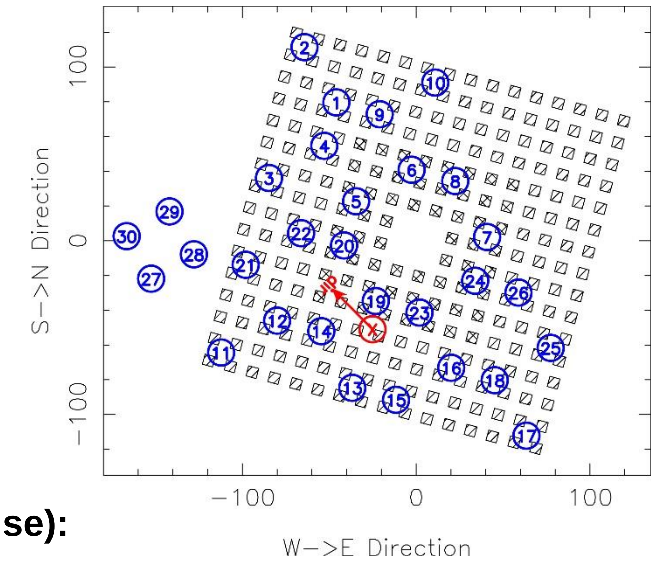


LOPES 30 event example

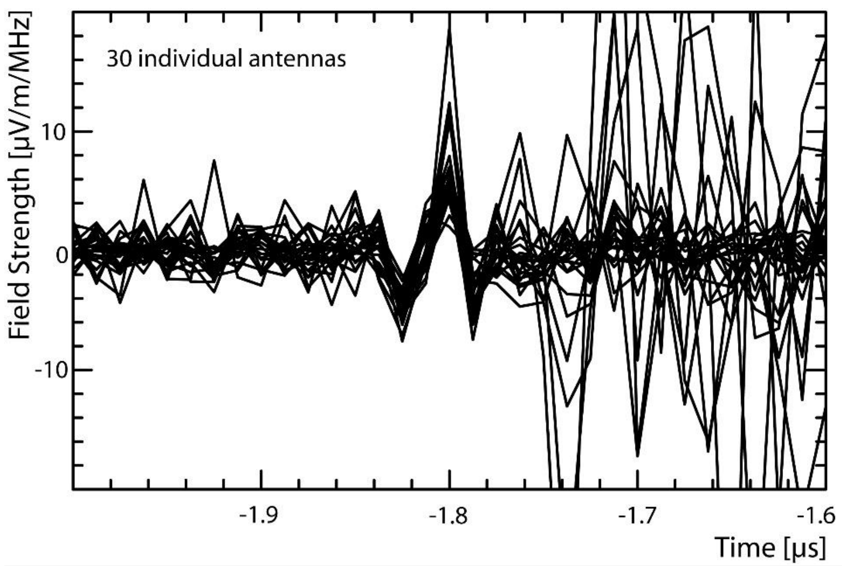
-radio reconstruction inclusive calibration factors of antennas
➔CC-beam value (per event)
➔Field strength (per antenna)

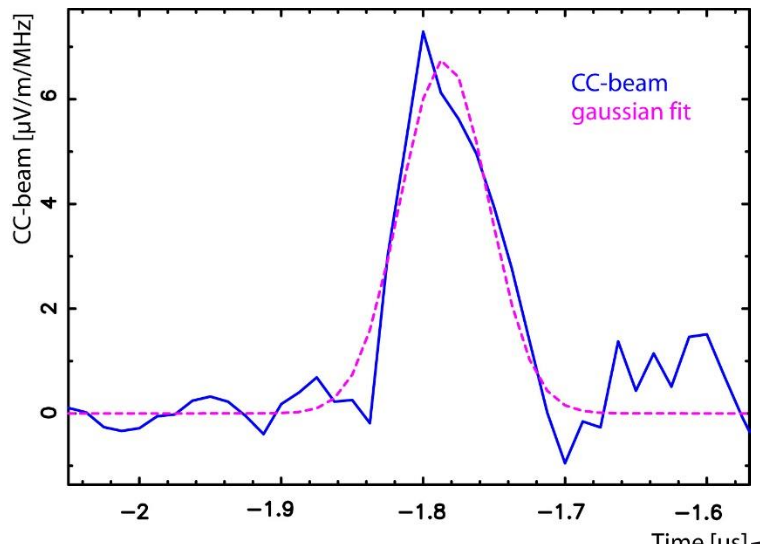
$$cc[t] = \pm\sqrt{\left|\frac{1}{N_{Pairs}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i[t]s_j[t]\right|}$$

(degree of correlation ➔ extract coherent pulse):



Event:
Φ = 15° θ = 306°
core = in KASCADE
$\lg(N_e) \sim 7.4$
$\lg(N_\mu) \sim 6.0$
$E_0 \sim 1.6\cdot10^{17}$ eV





Radio from Air Showers

~3-4000 cosmic ray events unambiguously detected by

LOPES
CODALEMA
Radio Prototypes@Auger
AERA
TREND
ANITA
Tunka-Rex

(and of course the historical experiments, partly re-analyzed: MSU, Yakutsk, e.g.)

➔Now: do we understand the signals?

EAS Radio detection

- **as new CR detection technique established** $E_{threshold} \approx 10^{17}$eV
- **emission mechanism(s) are understood**
- **successful and sensitive to**
  - **primary energy** $\varepsilon \sim E_0^{\gamma}$ $(\gamma \approx 1)$ $\Delta E/E \sim 20\text{-}25\%$
  - **arrival direction** beam forming resolution better 1^o
  - **composition** LDF-slope; wave front $\Delta A/A$ (~ to fluorescence?!)

⇒ ***suitable for hybrid measurements ?*** ***yes!!***

As stand-alone technique? ***will see!!***

Next: AERA@Pierre Auger Observatory / LOFAR / Tunka-Rex /
ANITA-CR optimization / TREND / IceCube surface Radio Array = RASTA / Yakutsk

30 March 2009 – official closure ceremony

Cosmic Revelation

An Art & Science Cooperation

KASCADE

Multi-Detector Setup
for Measuring Extensive Air Showers

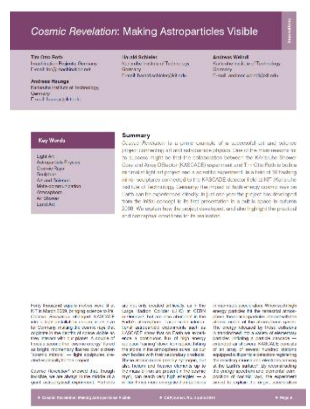
Cosmic Mirror

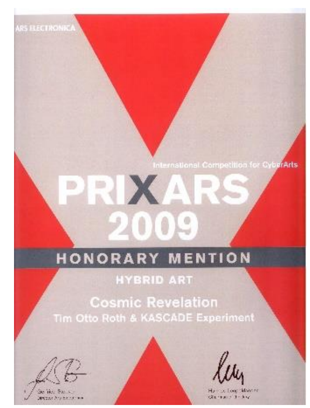
Lightbased Artwork
for Visualisation of Cosmic Rays

Cosmic Revelation

an example of a highly recognized
outreach project at KASCADE

NATURE|Vol 458|16 April 2009





Project is continued: now mainly at art events, exhibitions, etc

More information: Tim Otto Roth's webpage: www.imachination.net

The facility KASCADE-Grande:

LOPES CROME

TAUWER HiSparc Lightning

TAUWER:
Tau Neutrino shower detection

Goal:
Muon/Electron separation sensitivity

Partners:
Univ Roma La Sapienza

HiSPARC:
School project for cosmic ray air shower detection

Goal:
Energy calibration of small EAS

Partners:
NIKHEF Nijmegen/Amsterdam

lightning: Lightning mapping array

Goal: - correlation lightning-EAS
- lightning data for LOPES

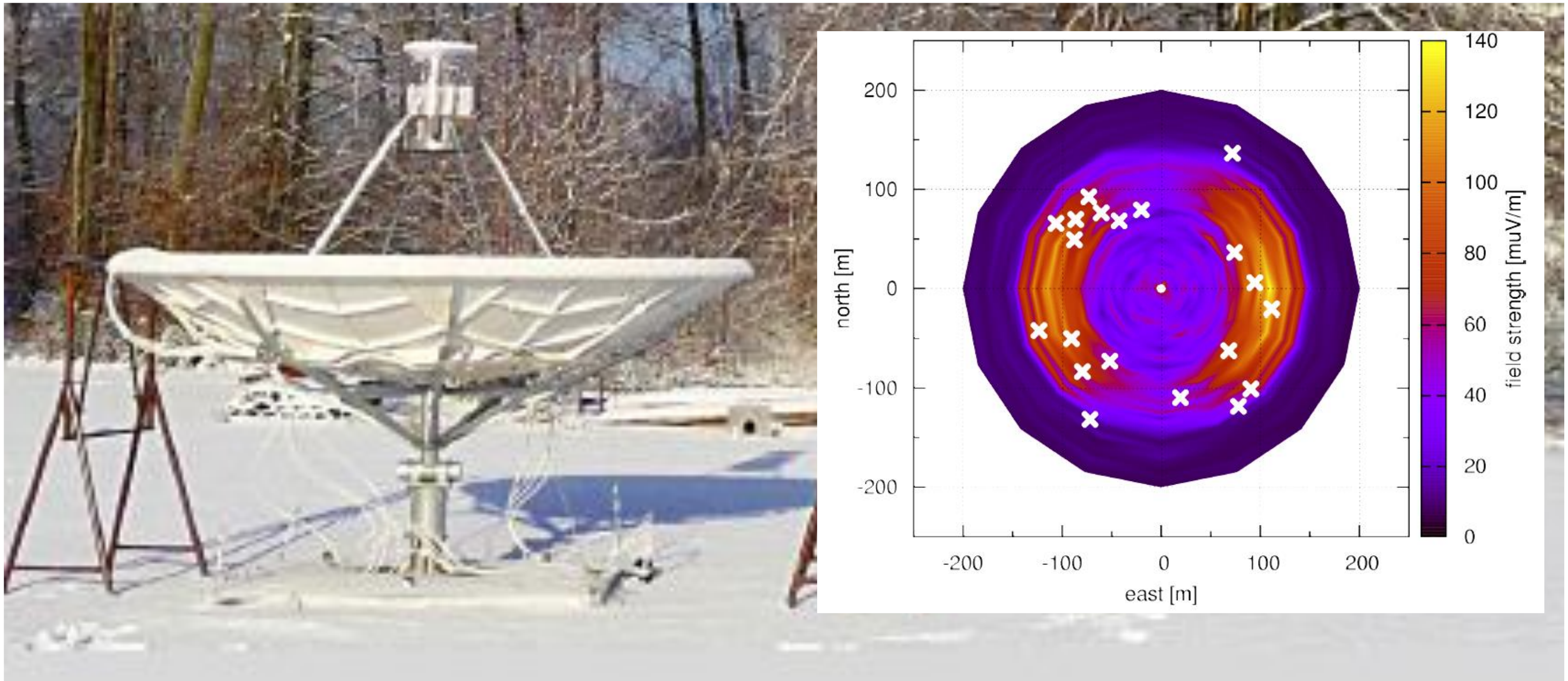
Partners: Paul Krehbiel, US

EAS Radio detection in GHz range: CROME

- **core distances between 80m and 150m**
  ➔ring structure hints towards Cherenkov cone

REAS3 simulations predict such a ring structure in the GHz-frequency range

Iron primary
Total field strength
Simulated with REAS3



F.Werner – CROME; ARENA conf 2012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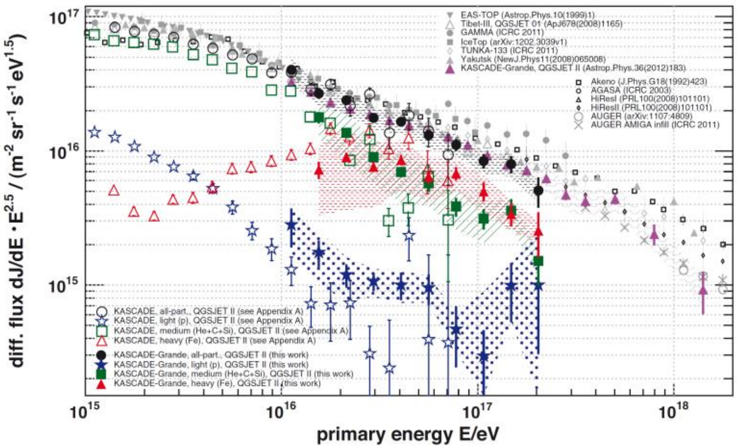
KASCADE-Grande: Next



- **KASCADE + KASCADE-Grande**
  finally closed end 2012
  now dismantled

- **combined analysis**
  for coherent spectrum and
  composition 10^{14}-10^{18} eV

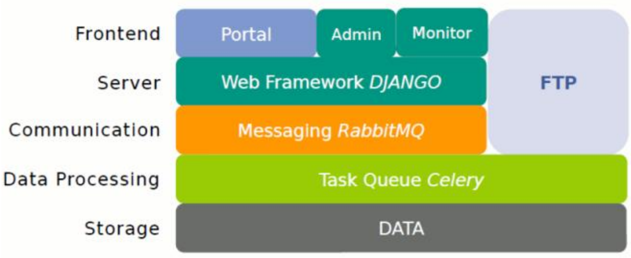


- **detailed data analysis (20y high-quality data)**
  testing hadronic interaction models
  anisotropy studies
  radio (LOPES and CROME)

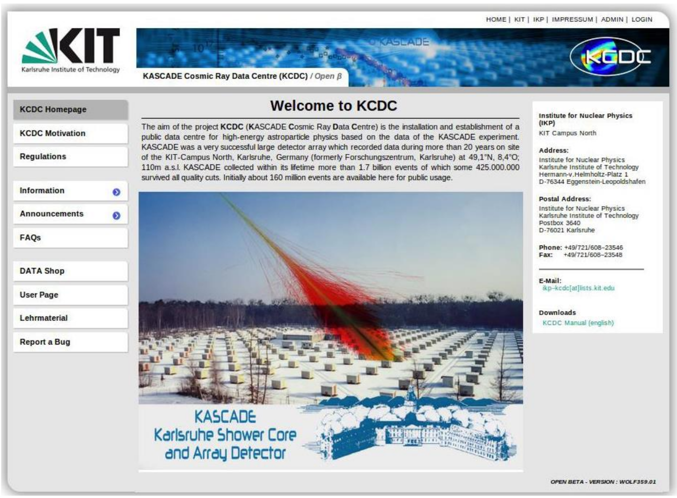
- **KCDC**
  KASCADE Cosmic ray Data Centre

https://kcdc.ikp.kit.edu/

- **KCDC = publishing research data from the KASCADE experiment**
- **Motivation and Idea of Open Data:**
  general public has to be able to access and use the data
  the data has to be preserved for future generations



- **Web portal:**
  providing a modern software solution for publishing KASCADE data for a general audience
  In a second step: release the software as Open Source for free use by other experiments

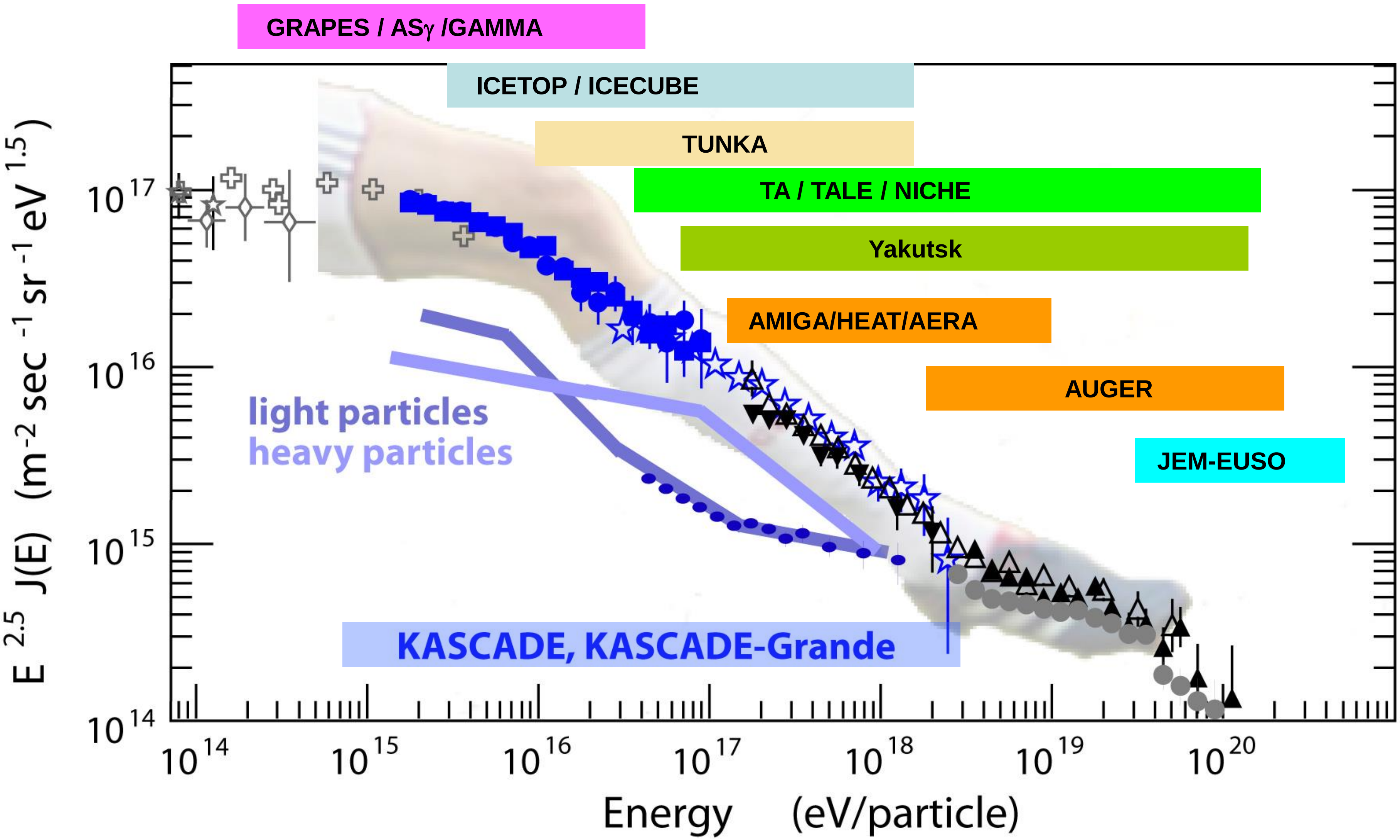


- **Data access:**
  $1.6 \cdot 10^{8}$ EAS events of first data release is now available

KASCADE-Grande: Mission Accomplished !!

open access to research data
https://kcdc.ikp.kit.edu

Summary



answers only by combining all information: stay tuned!

Discussion / Question / Exercise

- **expectations on spectral features in transition region?**
  -
  -
  -
- **ideal accelerator experiment for cosmic ray physics?**
  -
  -
  -
- **why radio could be better than fluorescence?**
  -
  -
  -

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  - **95% duty cycle**
  - **weather independent**
  - **cheaper (larger area)**