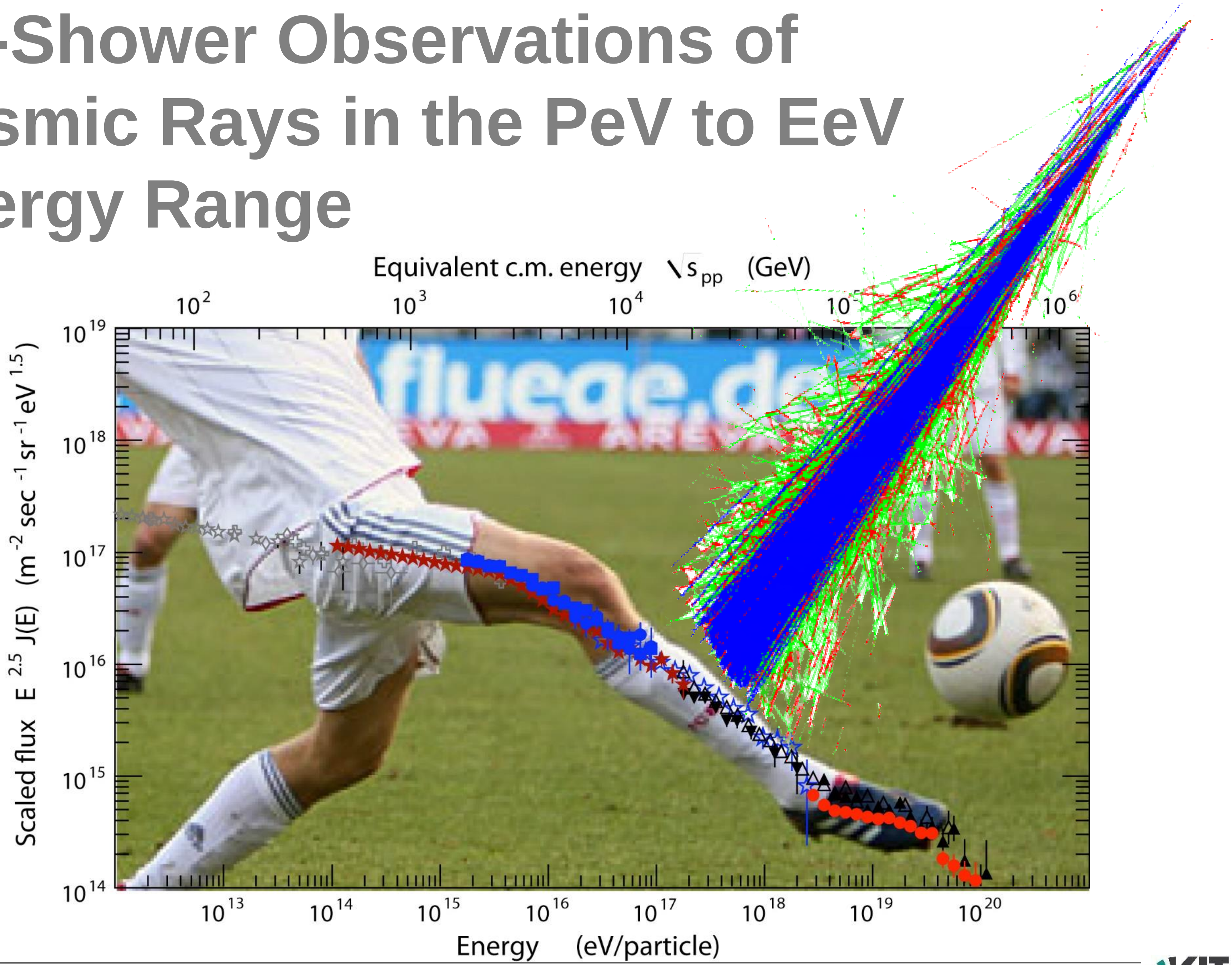
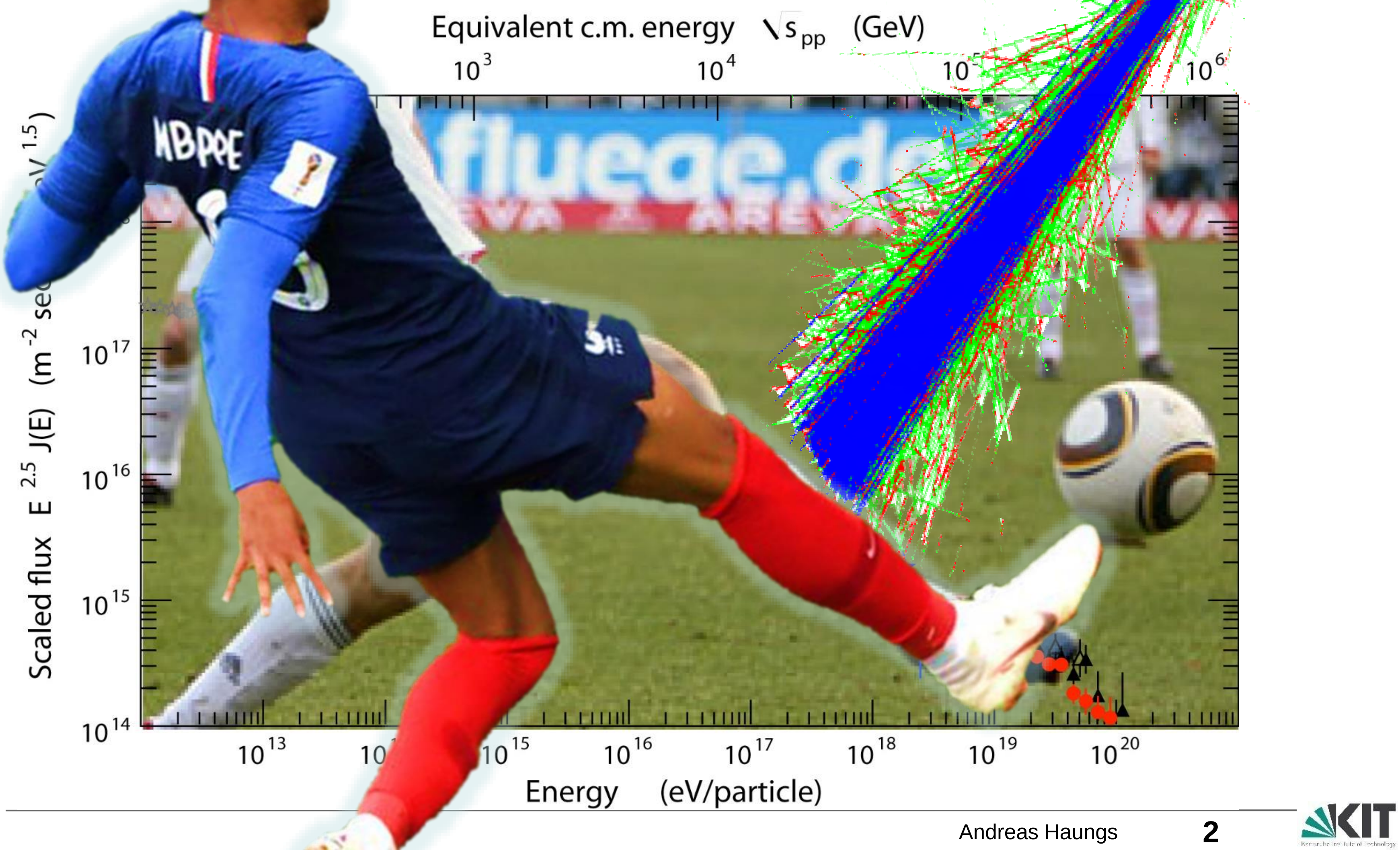
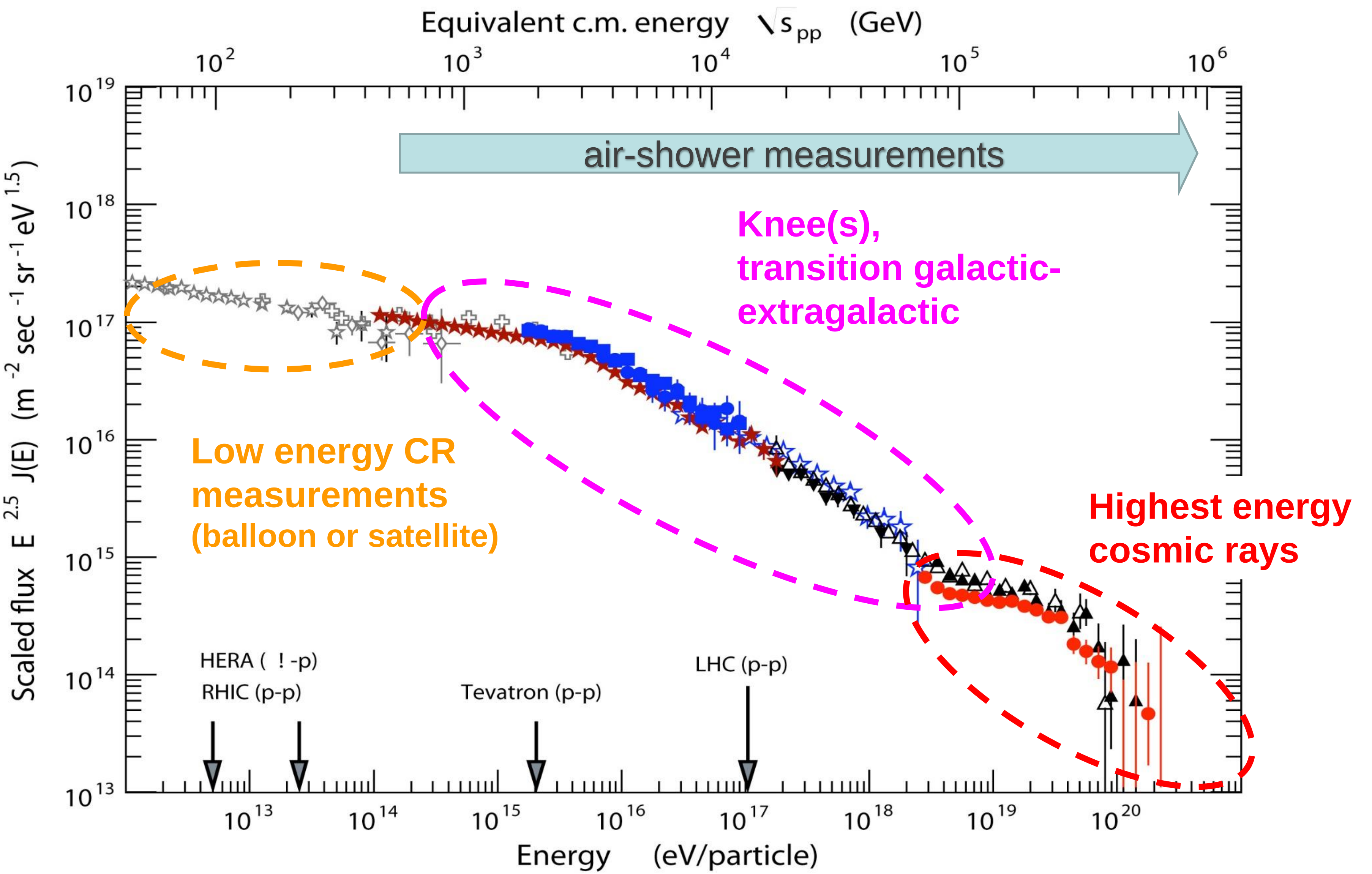
Air-Shower Observations of Cosmic Rays in the PeV to EeV Energy Range



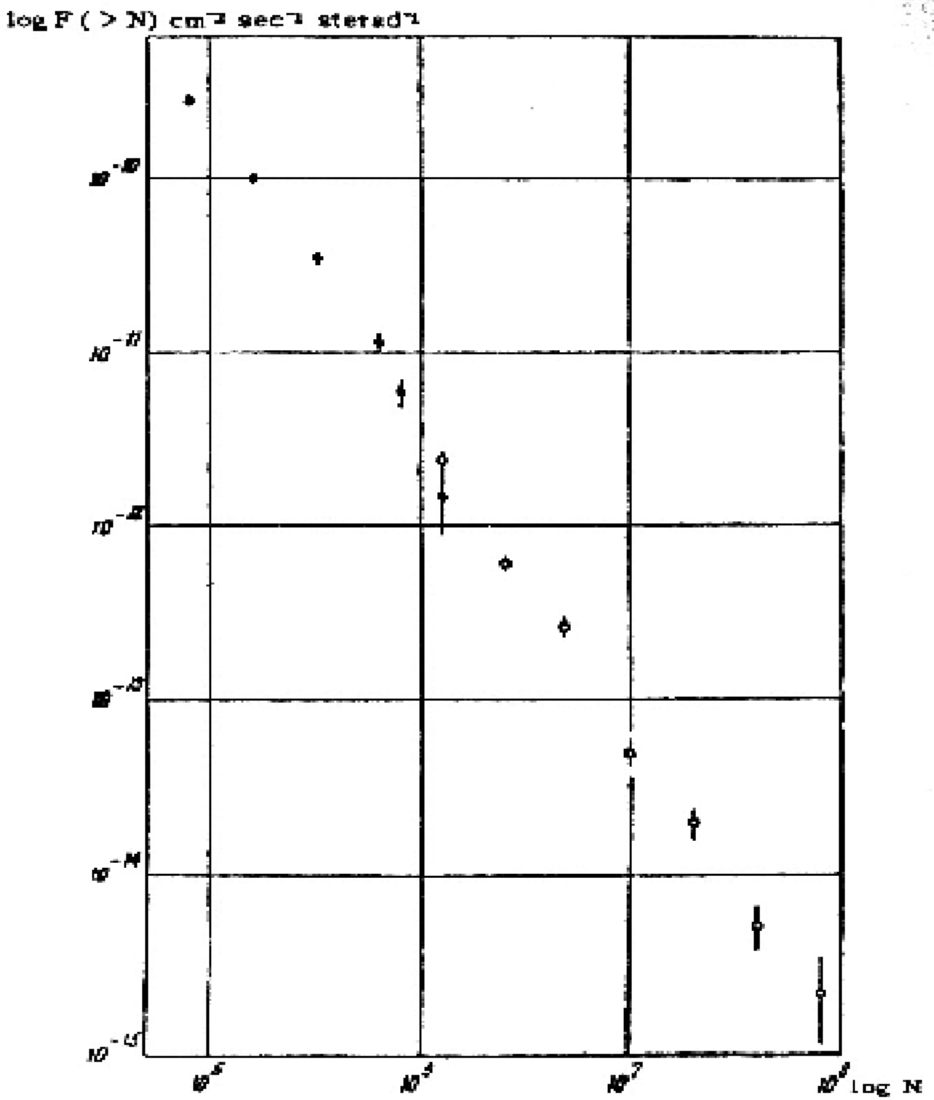
Air-Shower Observations of Cosmic Rays in the PeV to EeV Energy Range



High-energy cosmic ray spectrum



Cosmic Rays: 1958



The "first knee"

G.V.Kulikov & G.B.Khristiansen

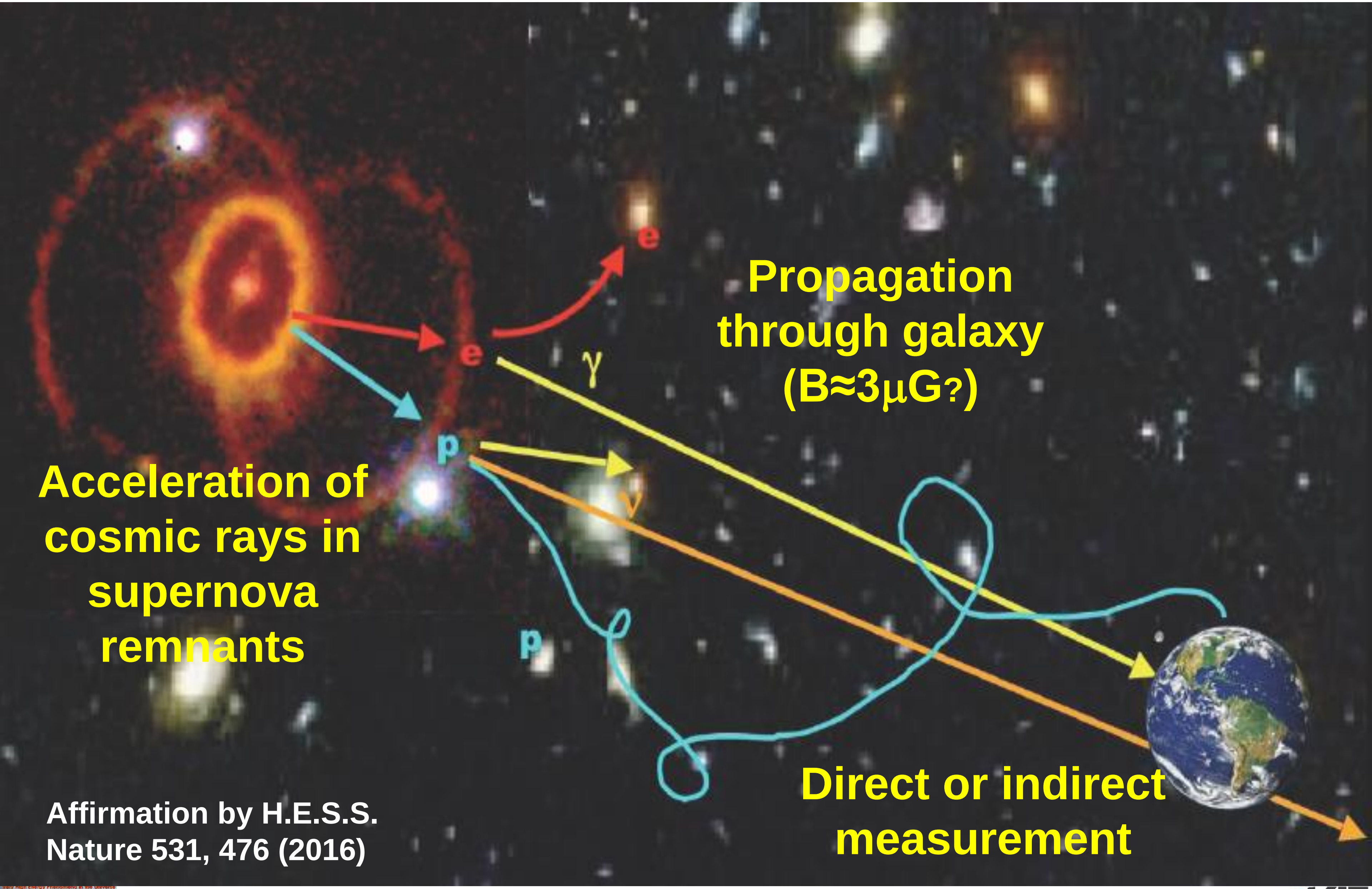
Soviet Physics JETP Volume 35(8), No 3, March 1959

measured N_{ch} spectra

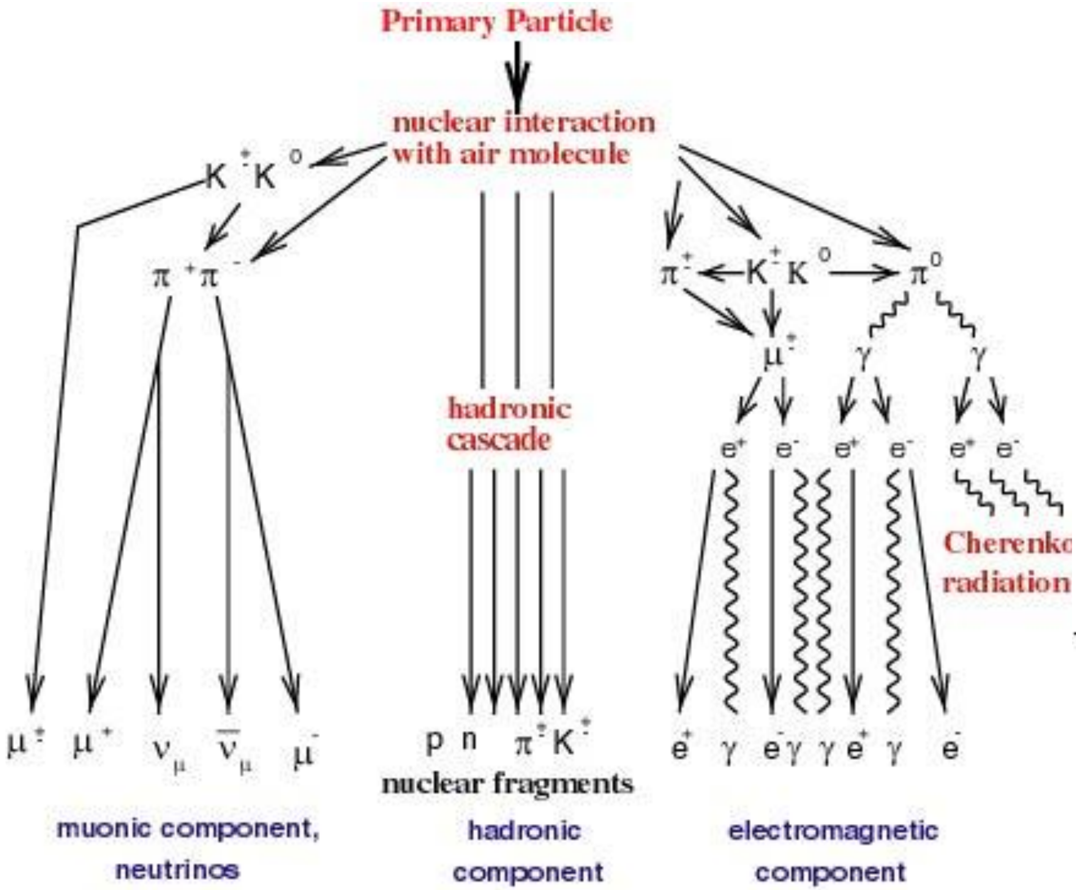
hodoscope counters in a 20x20 m^2 array

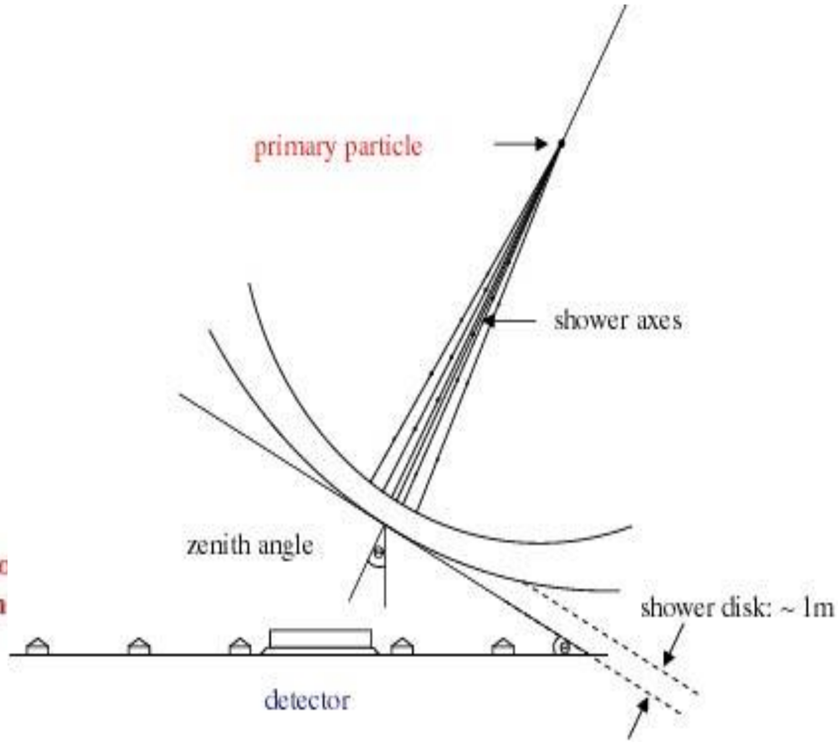
„the observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin"

Galactic cosmic rays



Extensive Air Showers - schematic





~10% **~ 1%** **~90%**

EAS measurement and reconstruction:

- **energy ?**
- **mass ?**
- **arrival directions ?**
- **interaction mechanism ?**

KASCADE

KArlsruhe Shower Core and Array DEtector

- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables: electrons, muons@4 thresholds, hadrons

T.Antoni et al. NIM A513 (2003) 490

KASCADE timeline

- **57 collaborative papers in reviewed journals** (3-4 still in queue, short author list papers not included)
- **56 PhD thesis**
- **86 diploma/master thesis**

2016
Xmax by radio
KCDC

EAS GHz emission
2012
light ankle
CROME

heavy knee
Karlsruhe Air Shower Test Facility
2008

muon production height
proof-of-principle radio detection
Cosmic Revelation

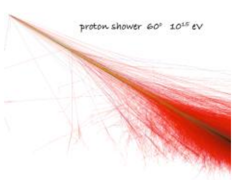
(an)isotropy
2004
γ limit
LOPES

light knee
2000
KASCADE-Grande

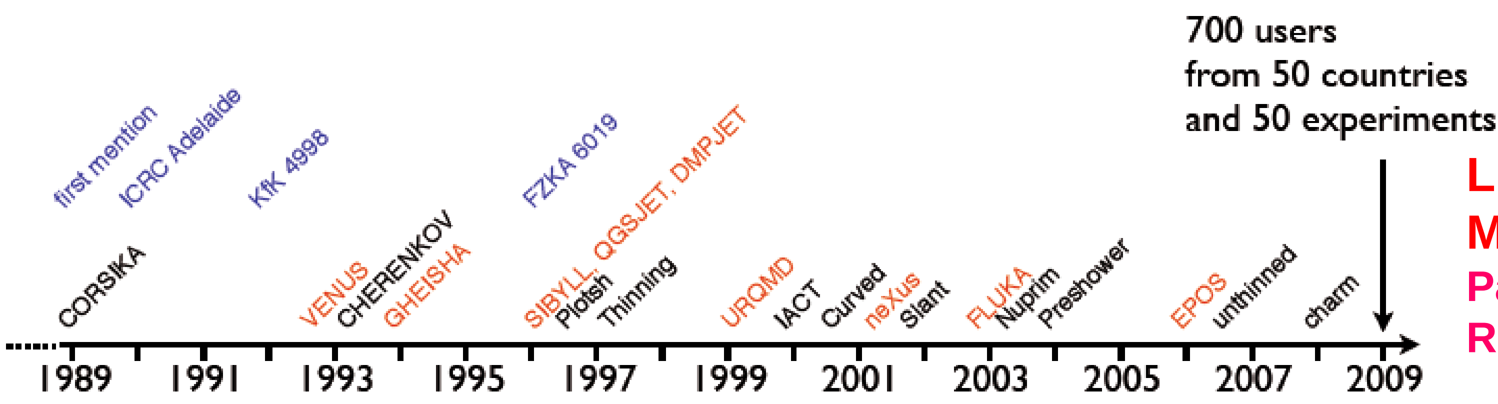
model tests
1996

KASCADE

1989
Proposal
CORSIKA



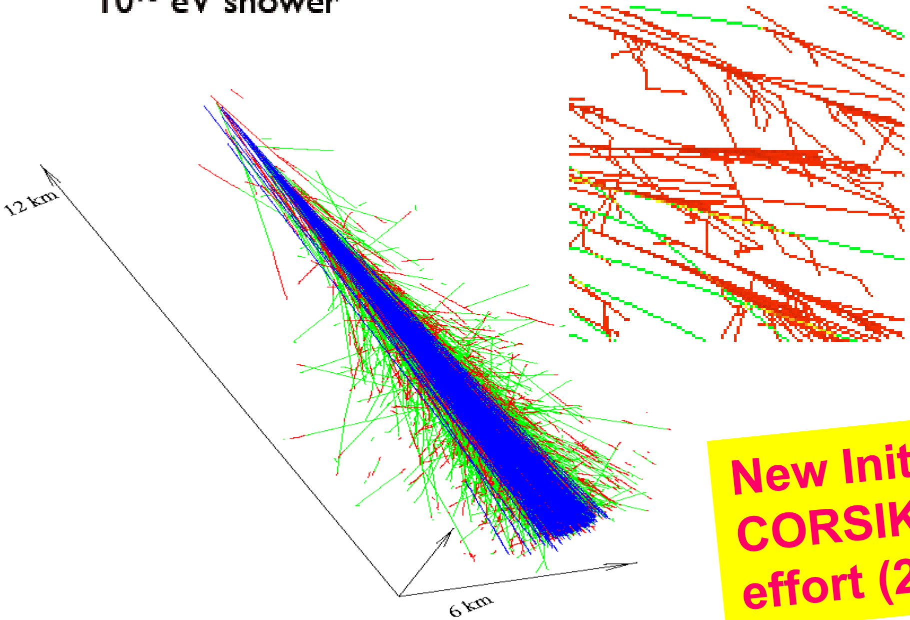
CORSIKA (COsmic Ray SImulations for KAscade)

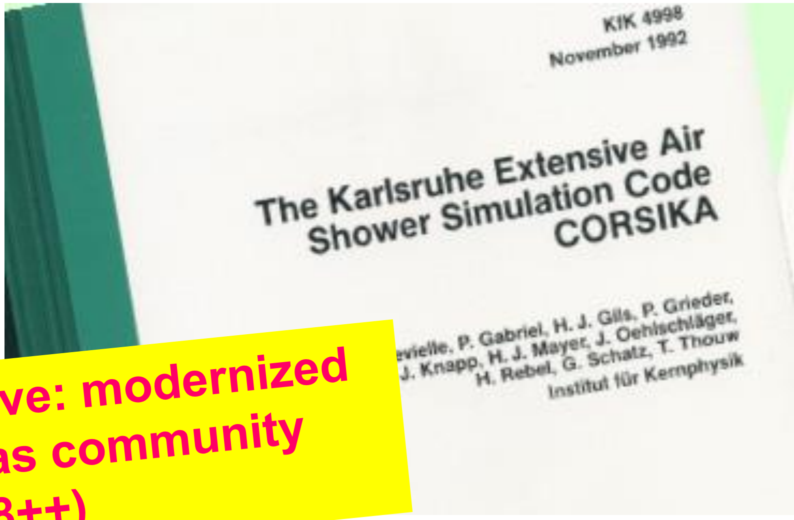


LHC adapted Models
Parallelization
Radio: CoREAS
....

> 1 day per
10^{15} eV shower

< 20 min per
10^{15} eV shower



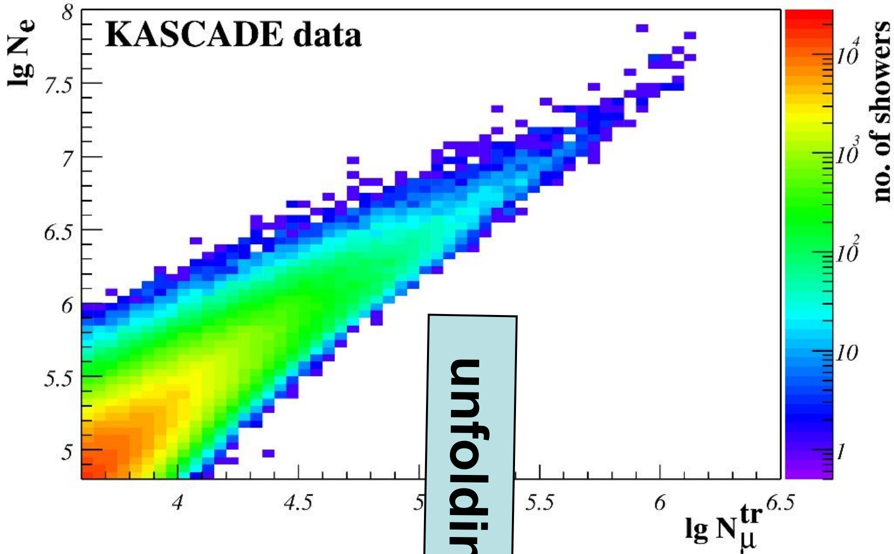


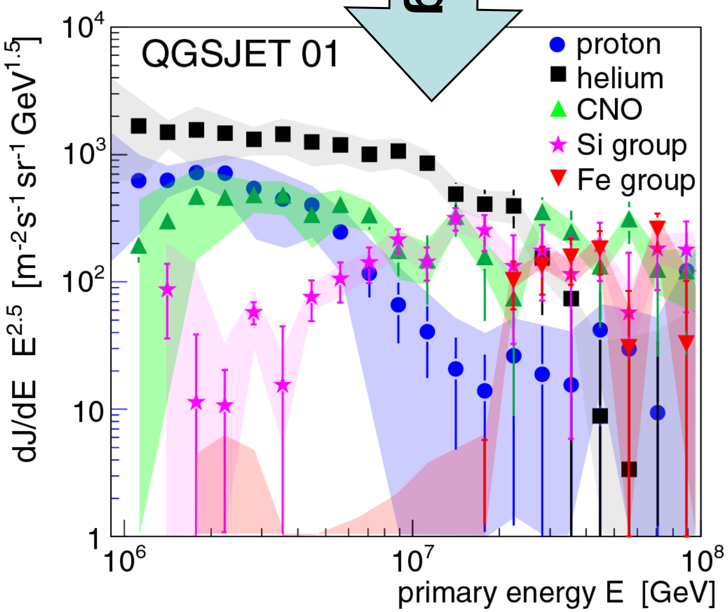
New Initiative: modernized CORSIKA as community effort (2018++)

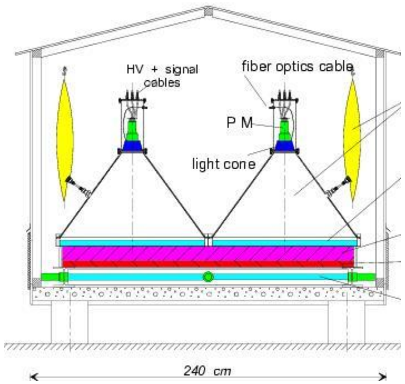
©Johannes Knapp

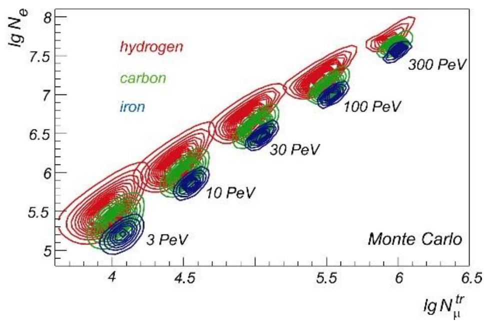
>2000 citations

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

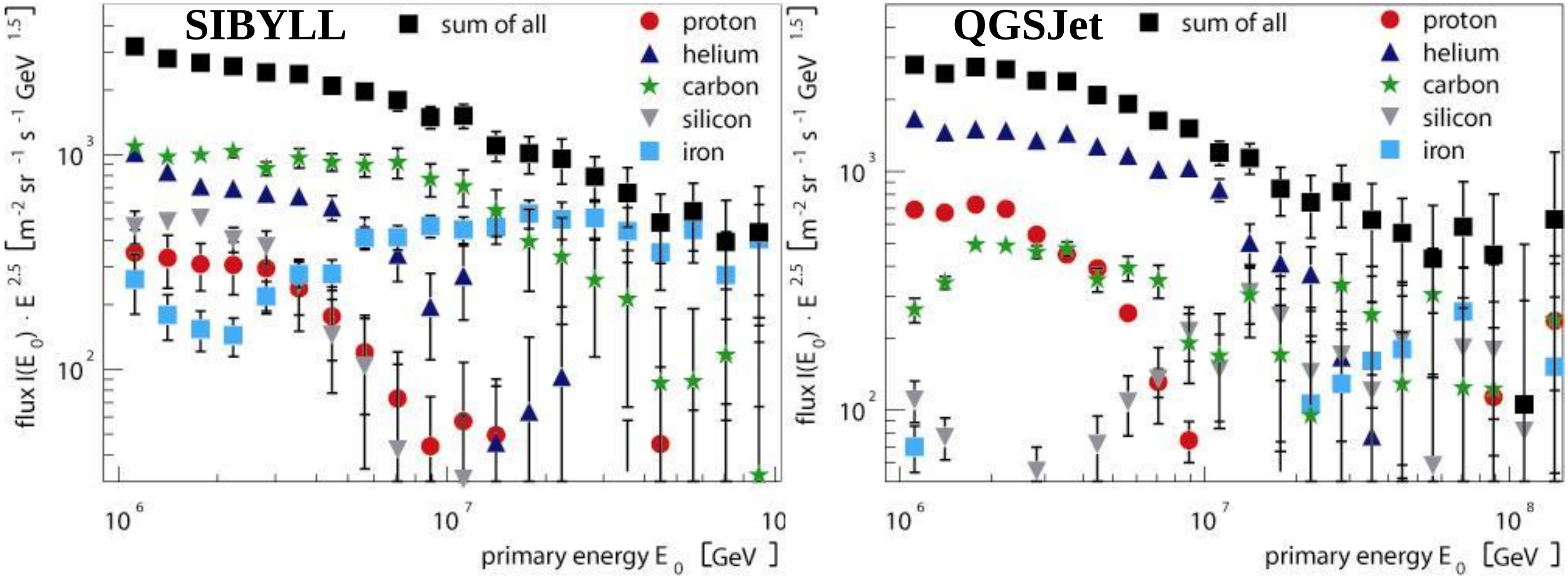
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

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

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

KASCADE: the rigidity knee

- same unfolding but based on different hadronic interaction models embedded in CORSIKA



- all-particle spectrum similar

- general structure similar: knee by light component

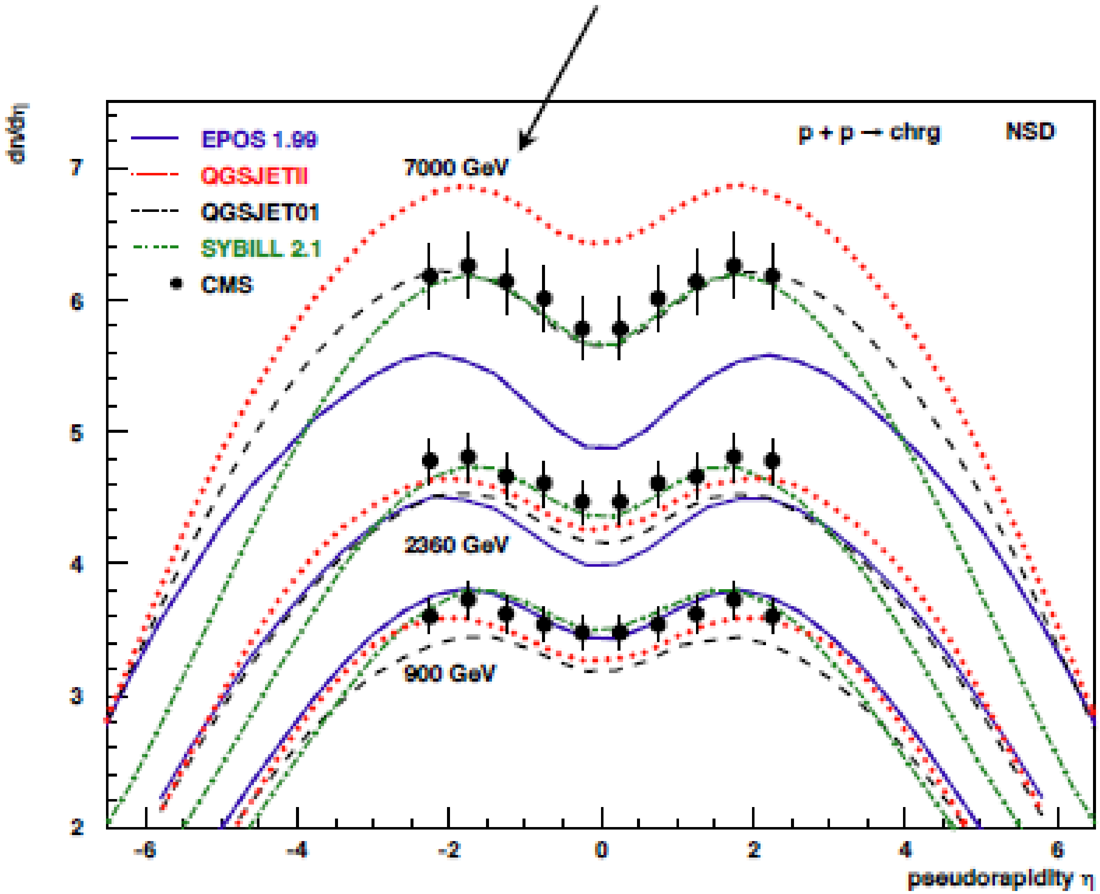
-relative abundances very different **for different high-energy hadronic interaction models**

but for many models: proton not the most dominant component!

KASCADE collaboration, Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86

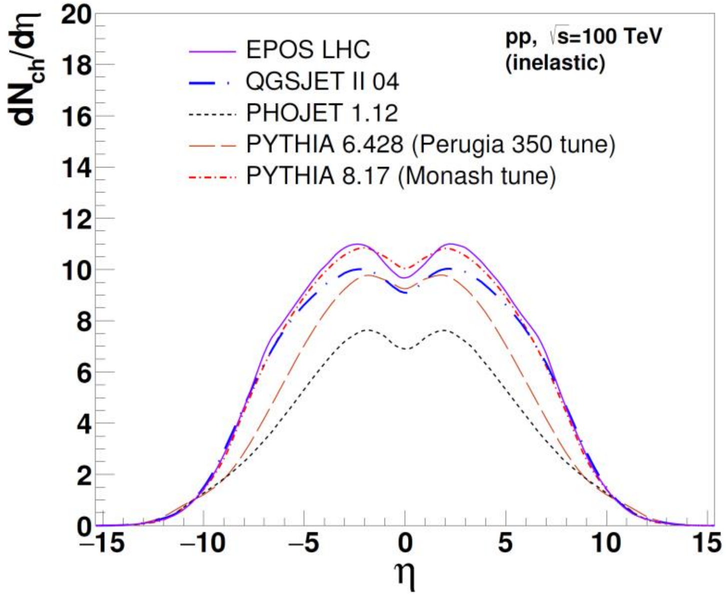
Charged particle distribution in pseudorapidity

Protons: E_{lab} = 3 x 10^{16} eV



Post LHC models

Protons: E_{lab} = 8 x 10^{18} eV

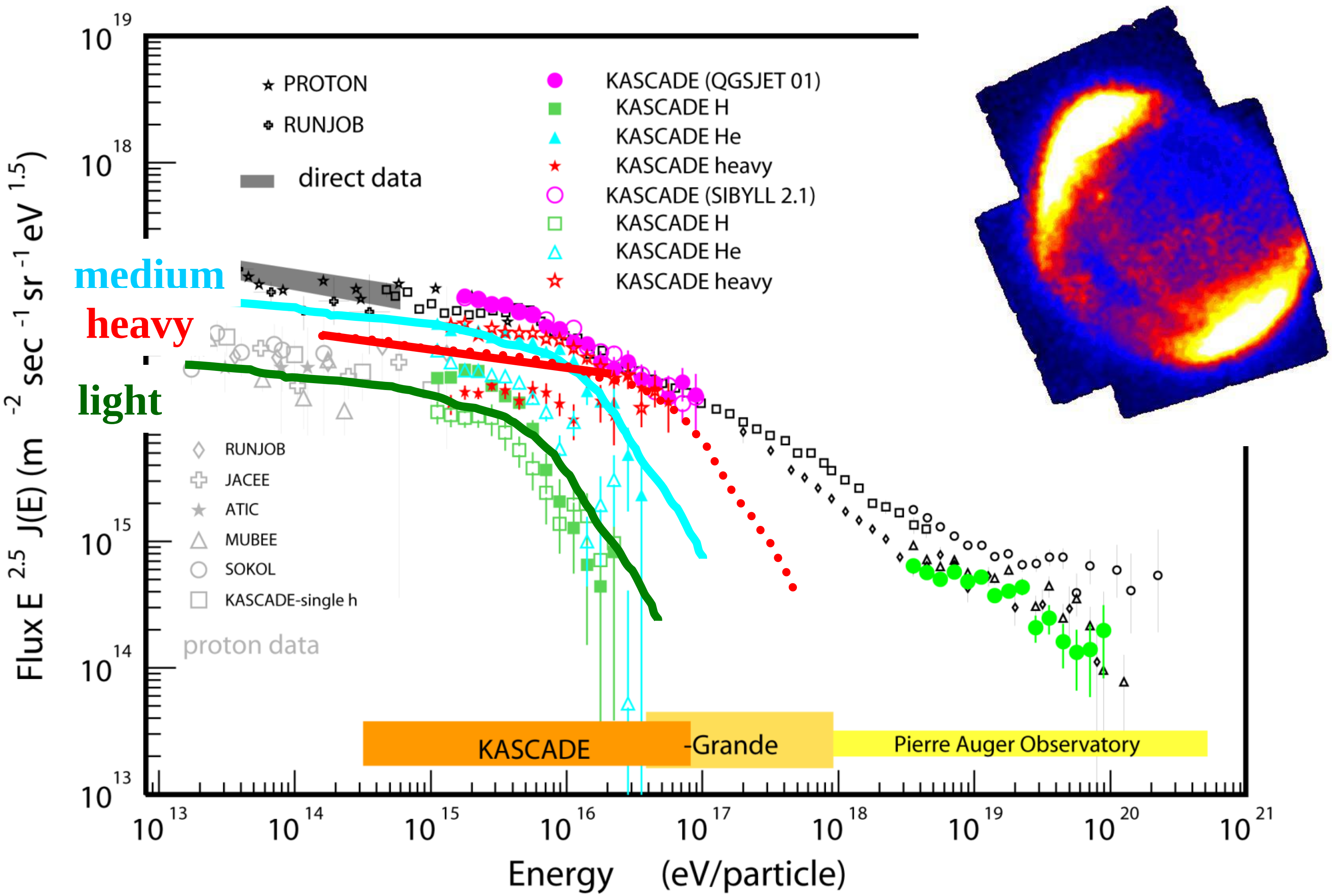


(data from all LHC experiments, CMS shown as example)

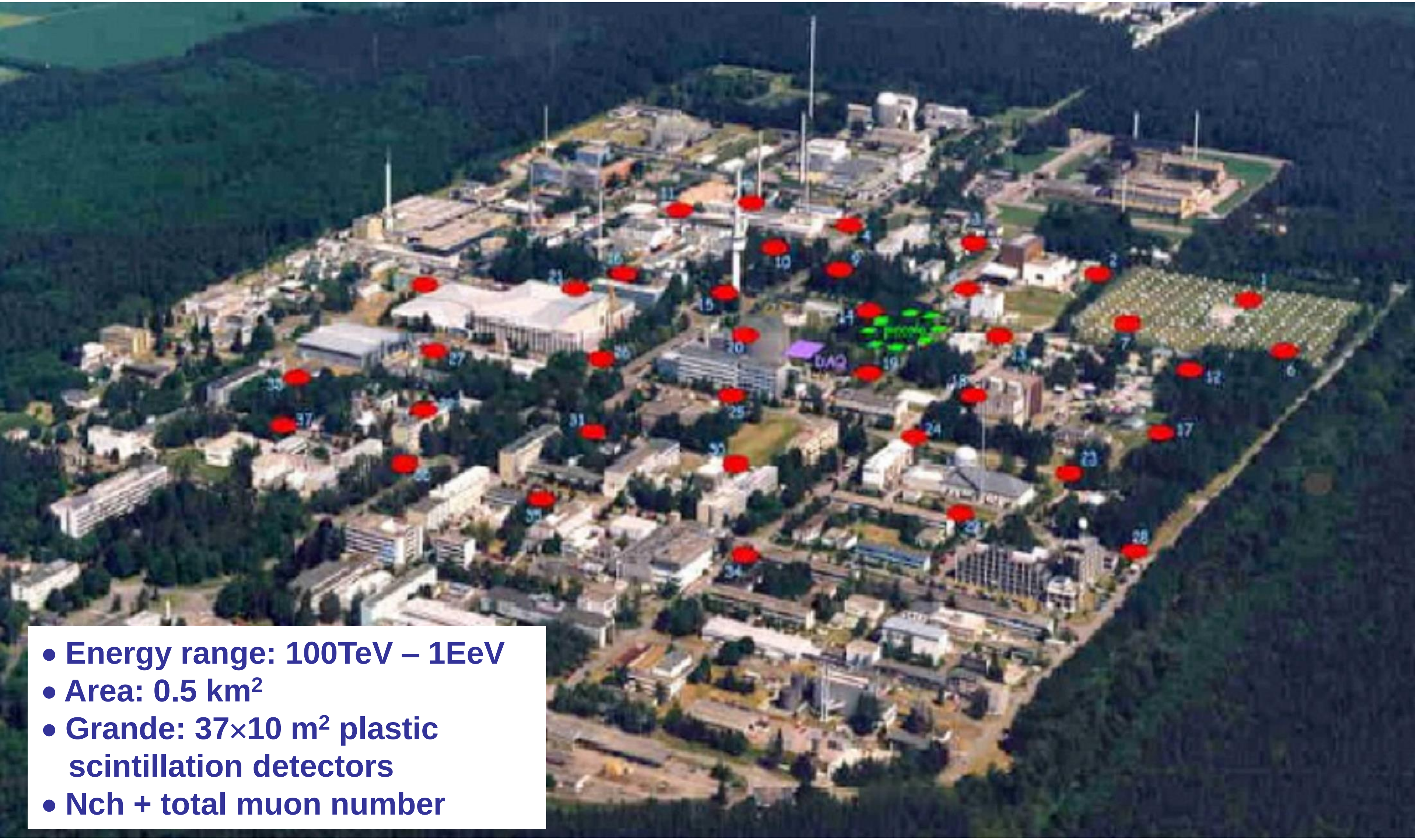
D'Enterria et al., Astropart. Phys. 35, 2011

D'Enterria, Pierog, JHEP 08 (2016) 170

Result KASCADE ➔ Motivation KASCADE-Grande



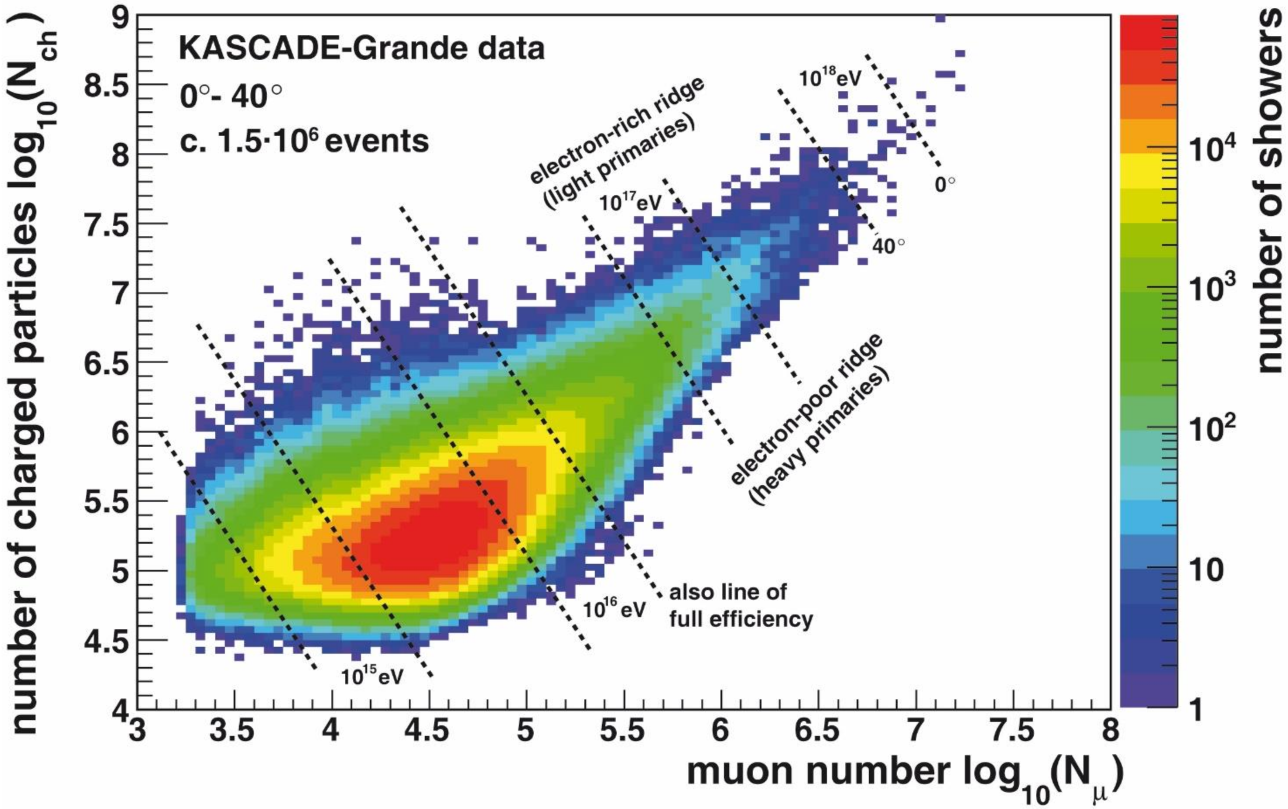
KASCADE-Grande



- **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



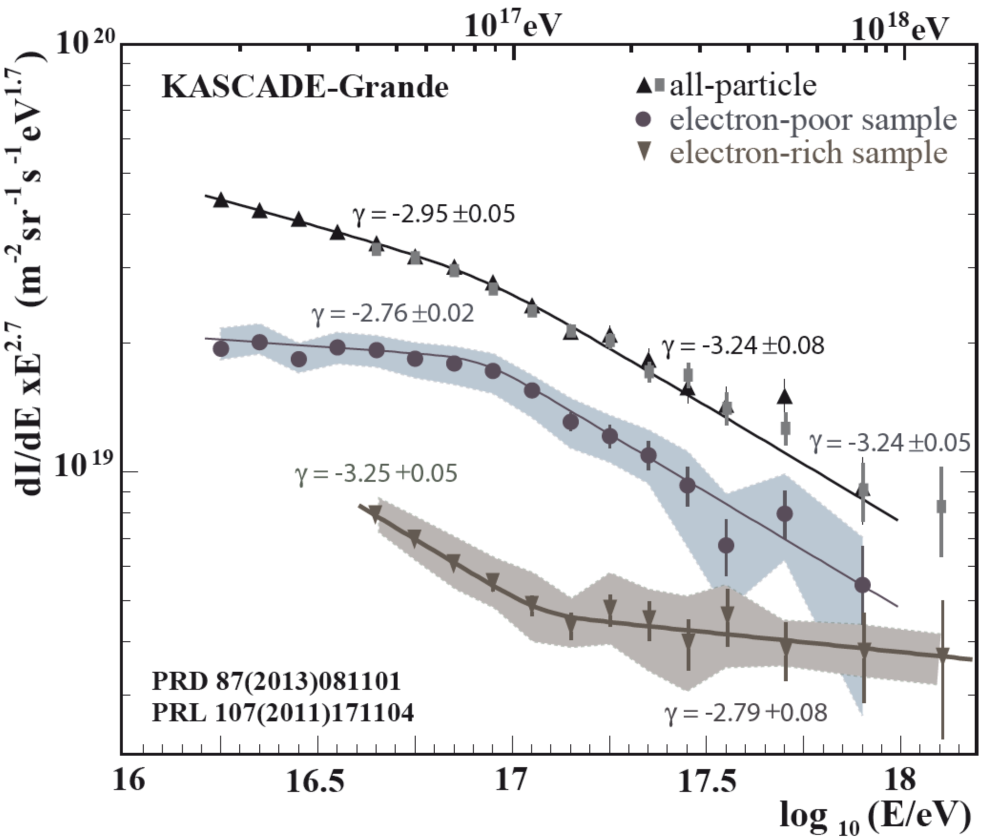
➔ **determination of primary energy**

➔ **separation in “electron-rich” and “electron-poor” event**

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

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

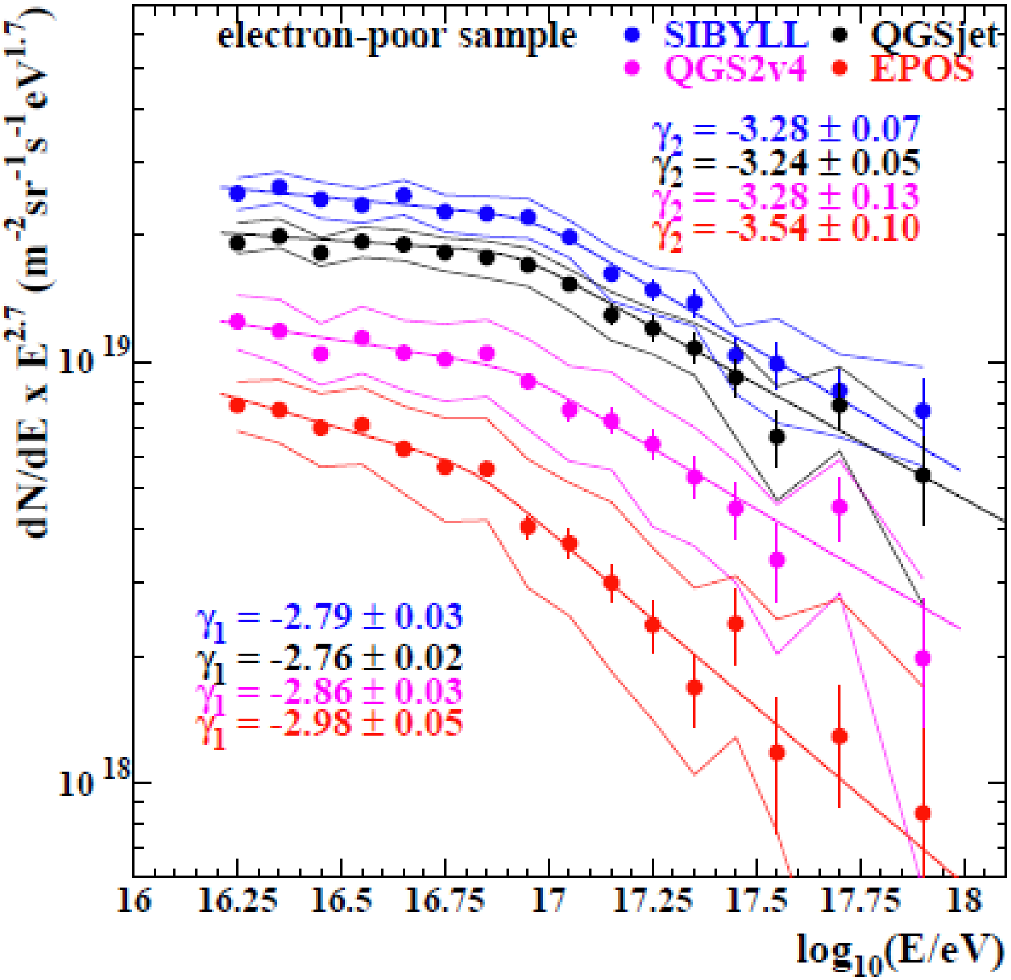
KASCADE-Grande
energy spectra of mass groups



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

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

KASCADE-Grande: model dependence



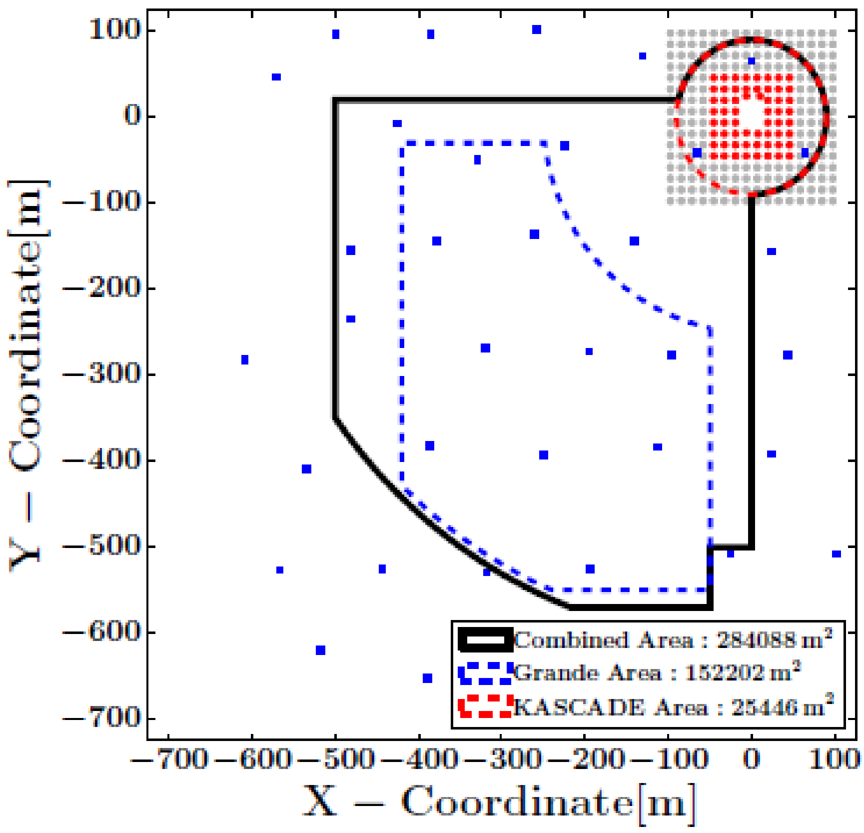
- Spectra of heavy primary induced events

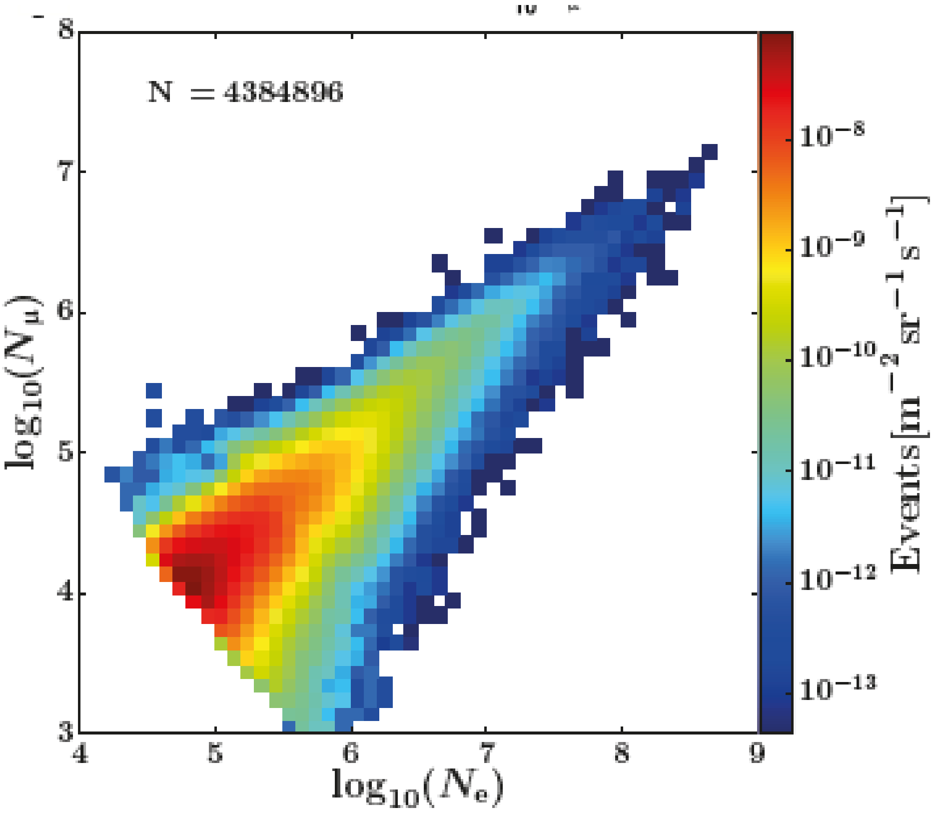
➔ a knee structure at the heavy component

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

Advances in Space Research 53 (2014) 1456

KASCADE-Grande: Combined Analysis





- **for KASCADE: additional stations at larger distances**

➔ higher energies

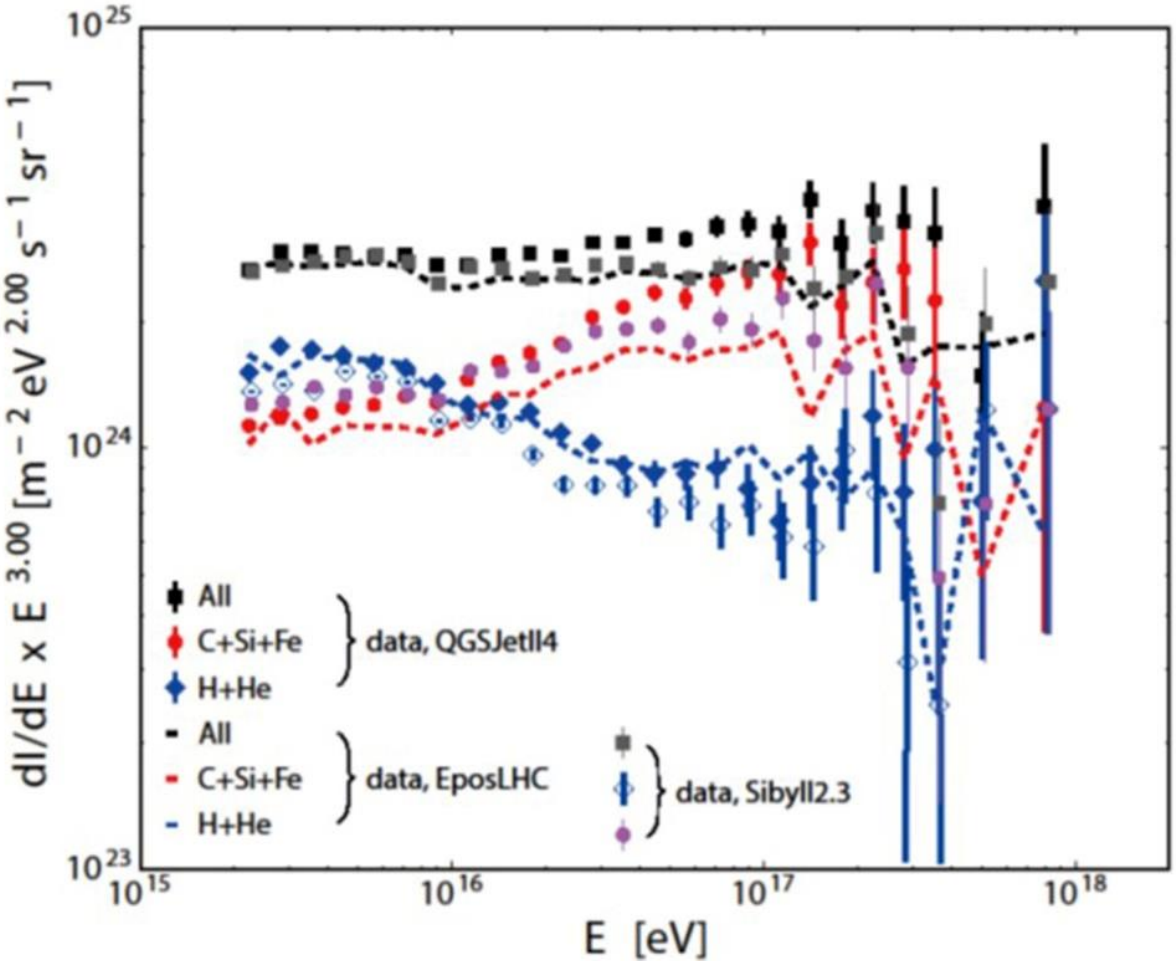
- **for Grande: additional 252 stations**

➔ higher accuracy

Sven Schoo, KIT, PhD 2016

KASCADE-Grande: Combined Analysis

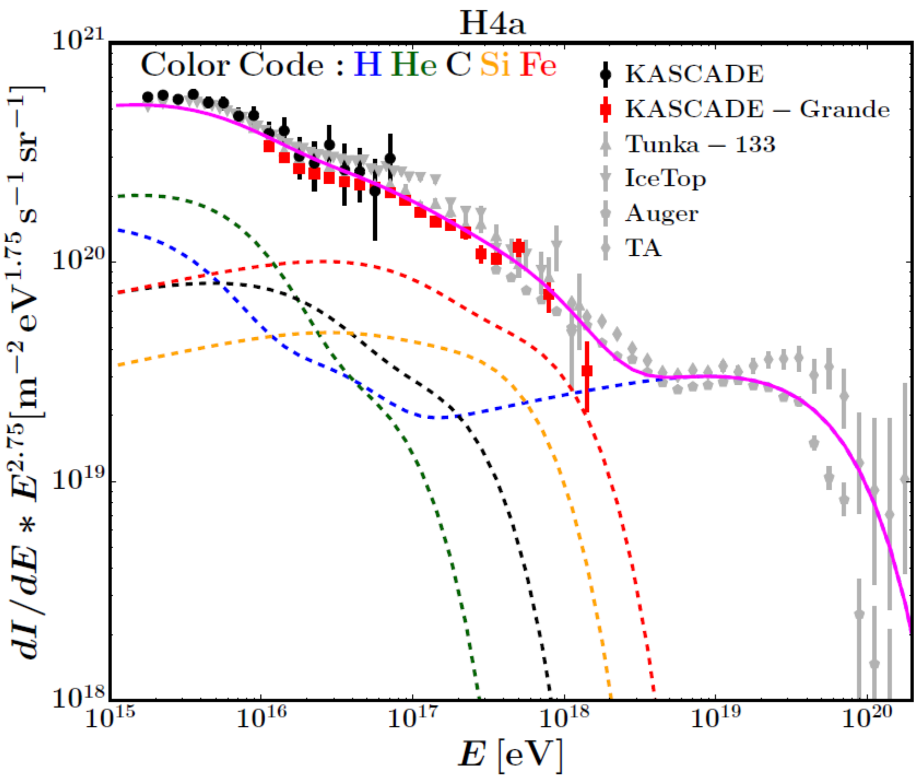
resulting energy spectra based on hadronic interaction models

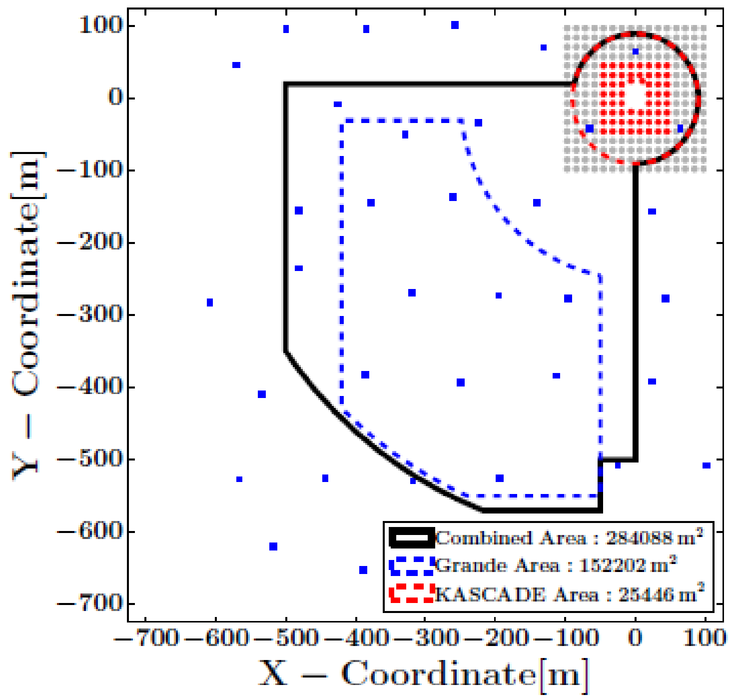


QGSJet-II.04 vs. EPOS-LHC vs. SIBYLL 2.3

- **Post LHC models**
  light primary interactions okay?
  heavy primary interactions show differences

KASCADE-Grande: combined analysis
Check Hadronic Interaction Models



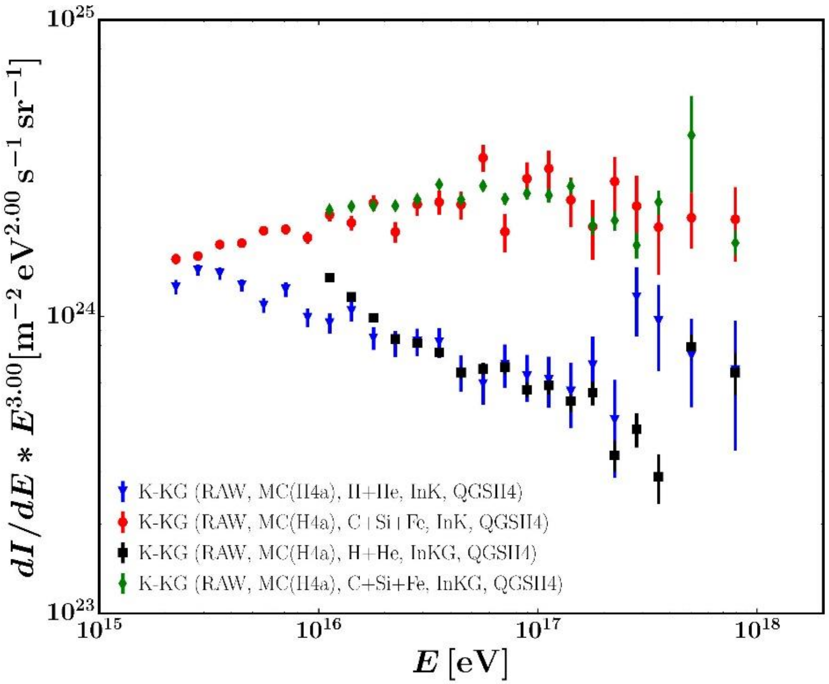


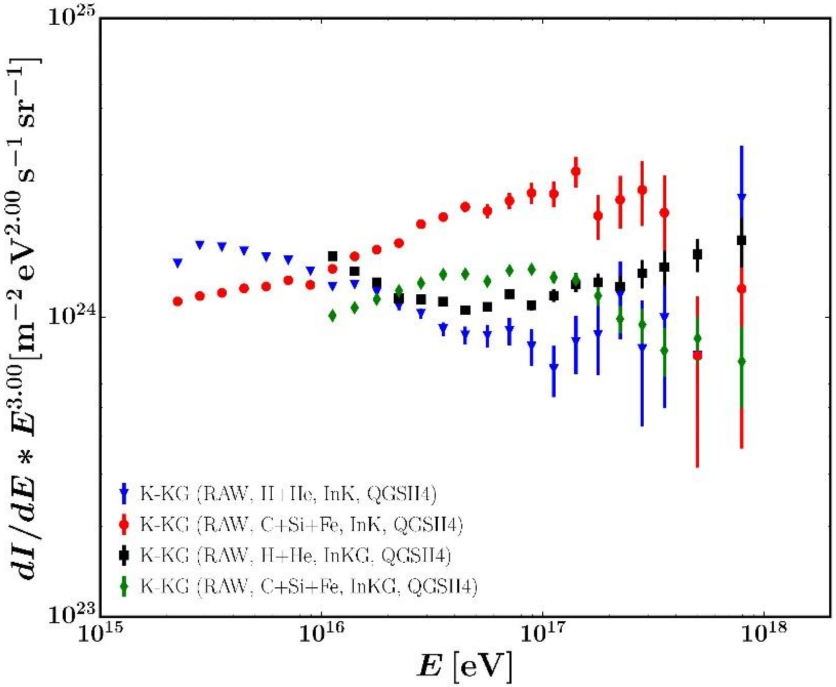
- **assume a composition model: H4a by Tom Gaisser**
- **two selections: core located in KASCADE, core located in Grande**
  ➔ we measure “different” muons

KASCADE-Grande: Combined Analysis

Test of models

QGSJet-II.04

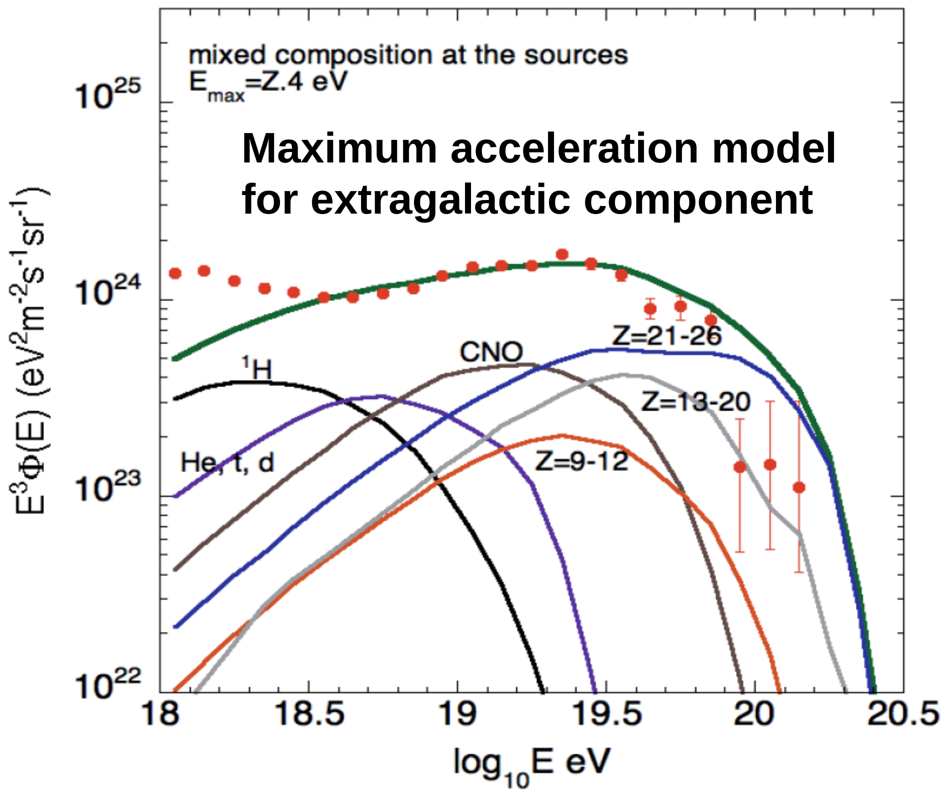


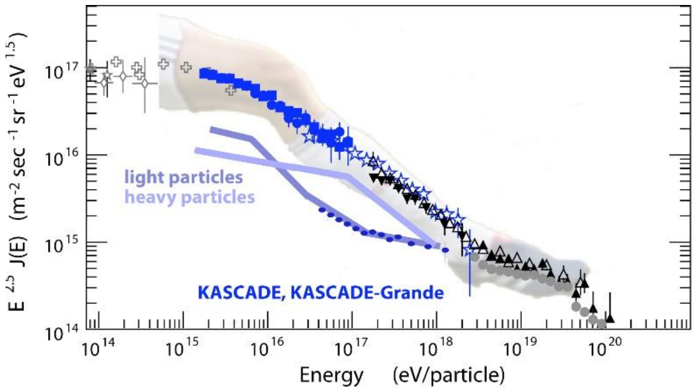


- **One model, but two selections:**
  Simulations okay, but strong differences in data
  (similar result for QGSJet-II.04, EPOS-LHC, SIBYLL 2.3)

➔ Muon component not sufficiently described

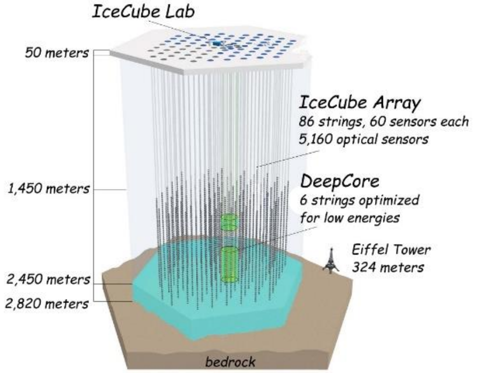
Connection Cosmic Rays and Neutrinos

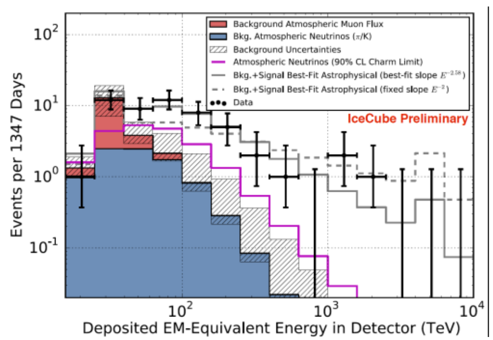




Slope of proton in the model same as slope of "light" spectrum after ankle in KASCADE-Grande

IceCube PeV neutrinos from 100 PeV extragalactic protons?

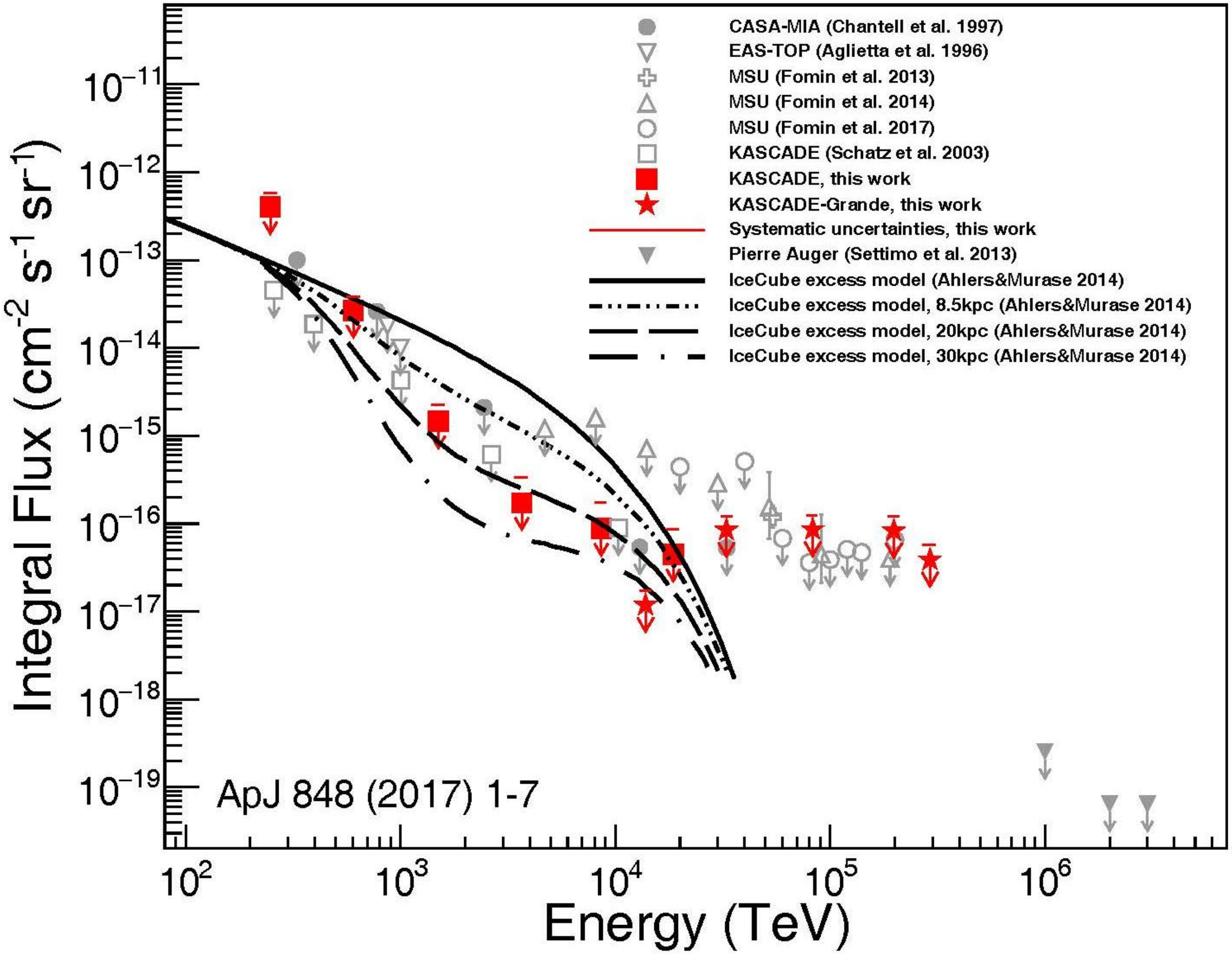




IceCube measured PeV-neutrinos

➔ PeV-ν from IceCube might correspond to 10^{17}eV protons

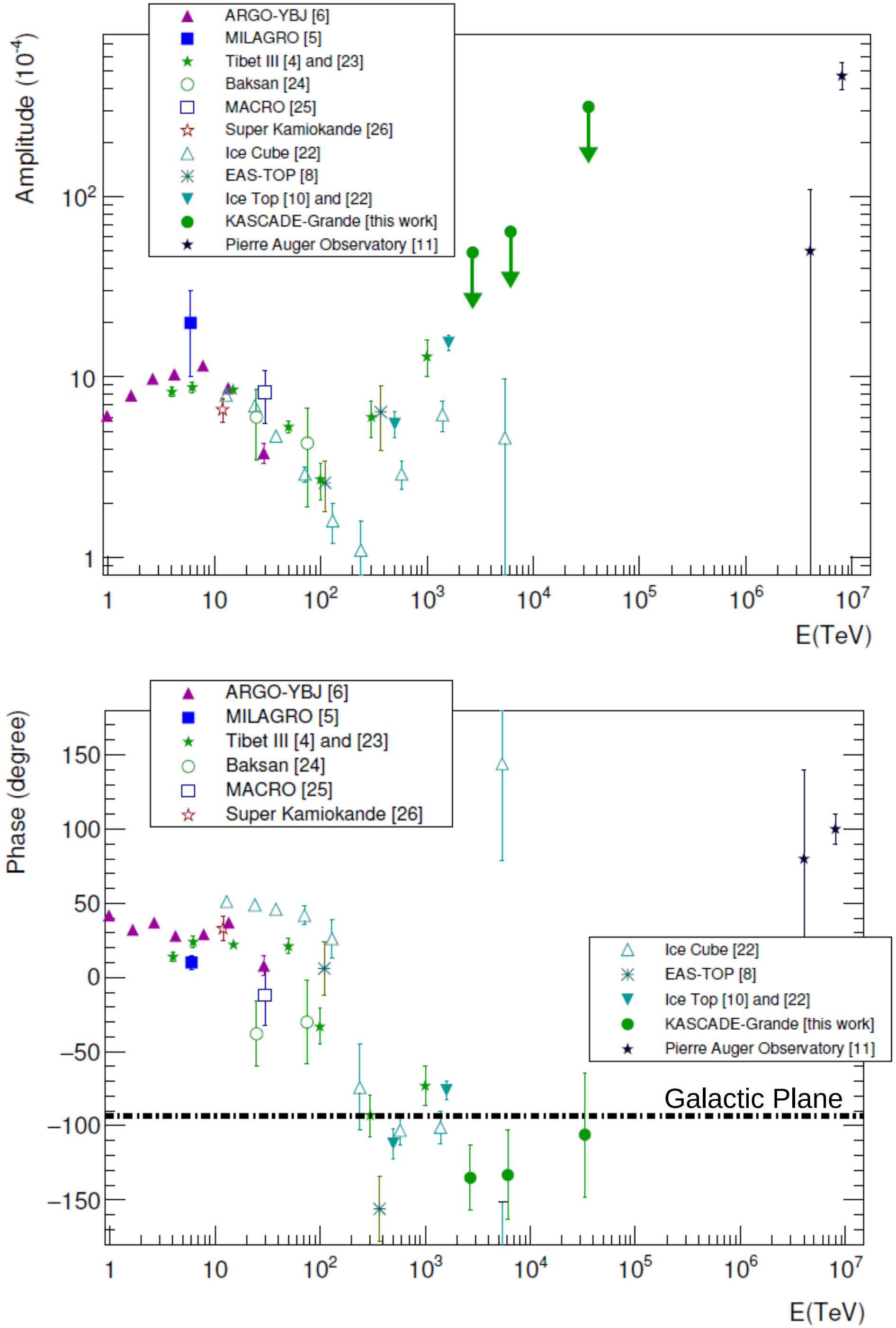
Limits on diffuse Gamma-ray Flux



- **selection of muon-poor events**
- **limits on ratio of primary gammas to hadrons**
- **limits on diffuse Gamma-ray flux constrain the origin of IceCube-neutrinos**

🡐 Reject the model of IceCube excess coming from <20kpc in the Galaxy

Anisotropy



- study large-scale anisotropies by the East-West method

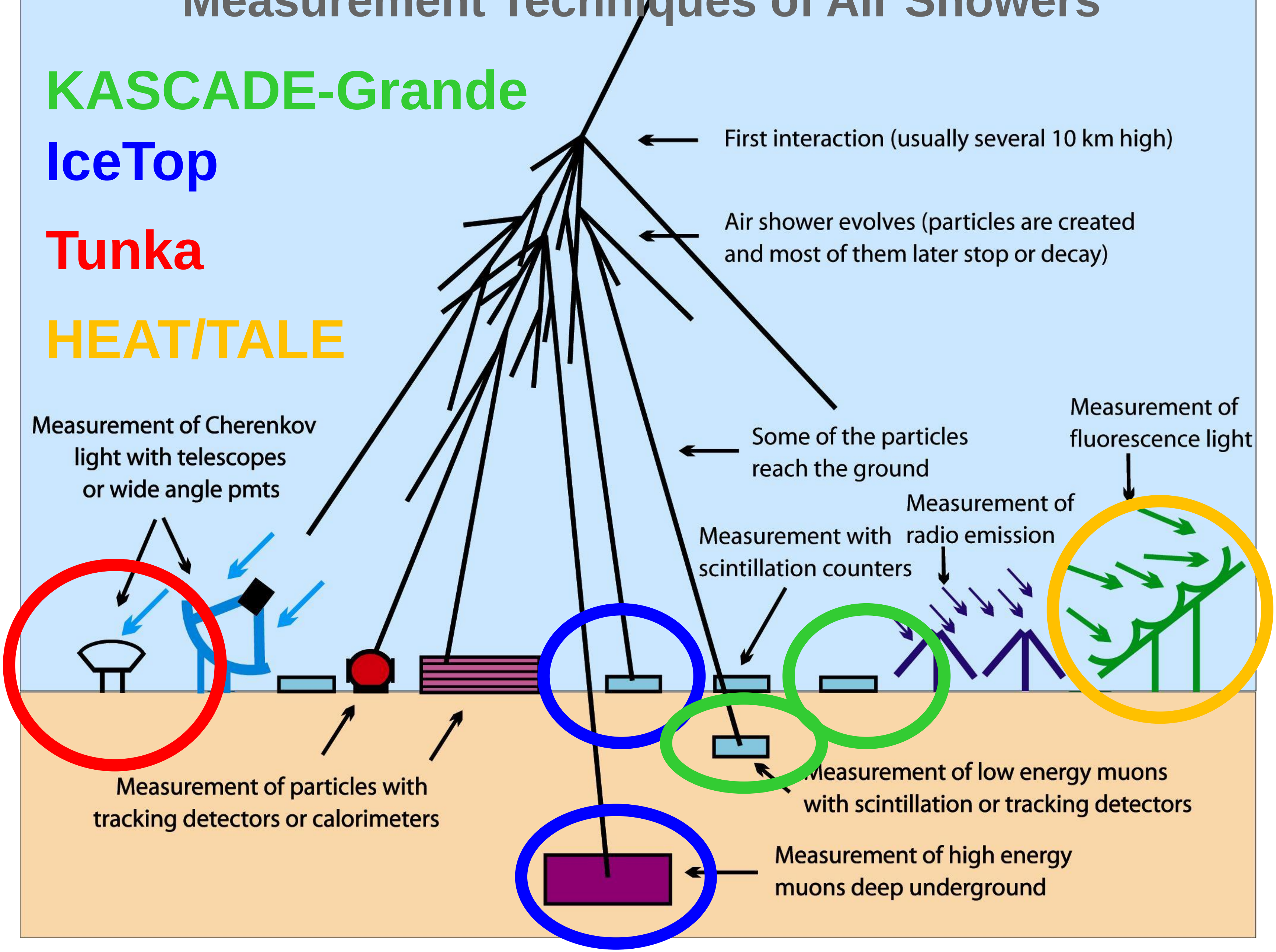
- limits on amplitude

- phase determined

← Confirms flip in phase at around 100 TeV - 1 PeV

A. Chiavassa et al., Nucl.Part.Phys.Proc. 279-281 (2016) 56-62
KASCADE-Grande coll.; in preparation

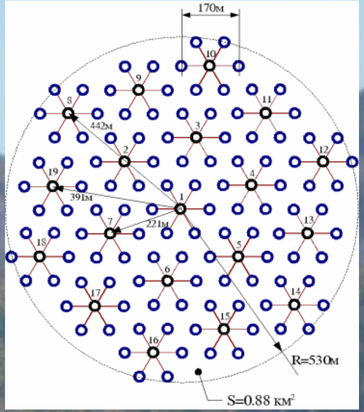
Measurement Techniques of Air Showers



Tunka-133 ➔ TAIGA

light flux at core distance 200 m Q_{200} ~ Energy

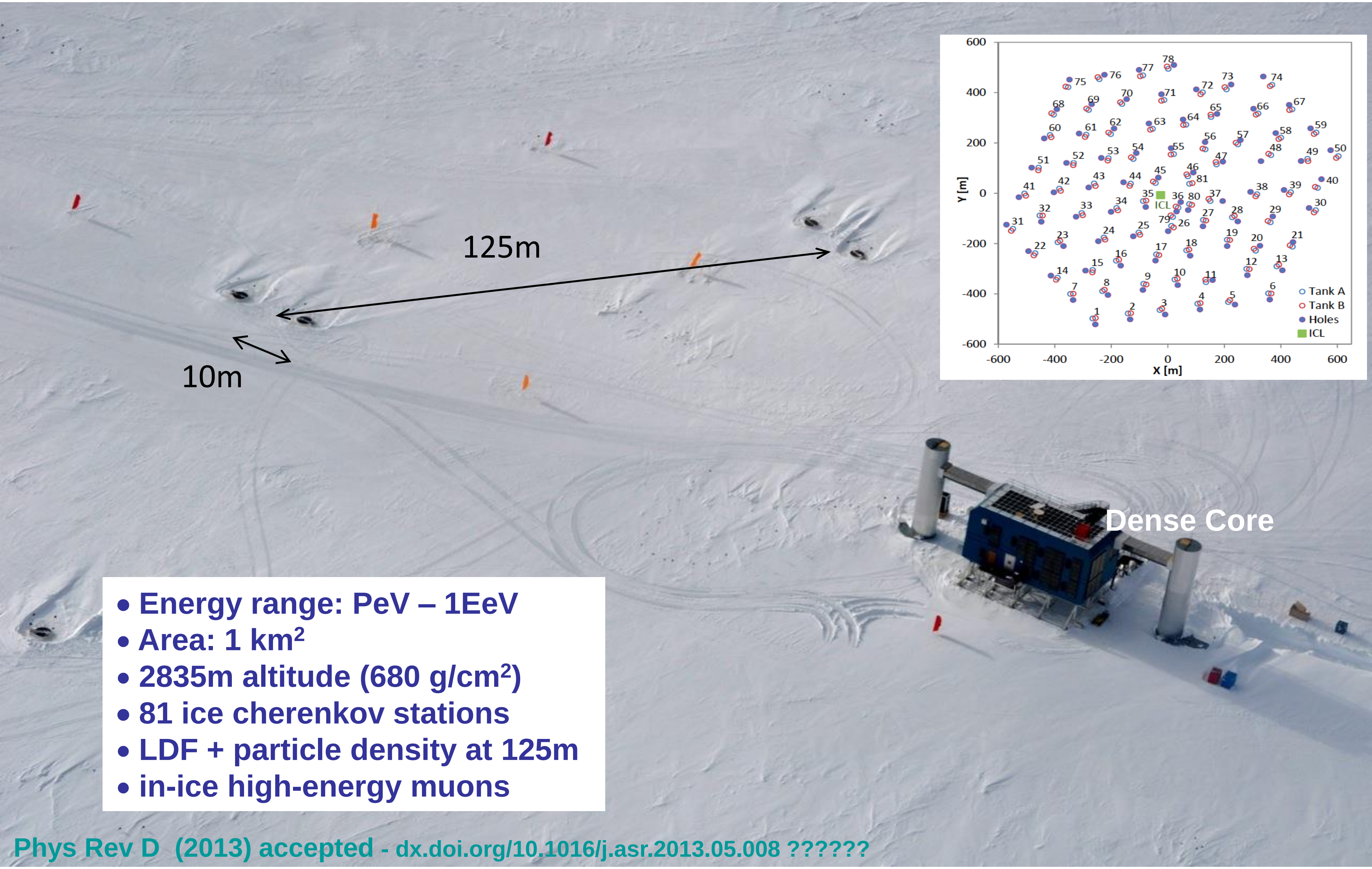
steepness of LDF $P = Q(100)/Q(200)$ ➔ X_{max}



- Energy range: 100TeV – 1EeV
- Area: >1 km^2; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

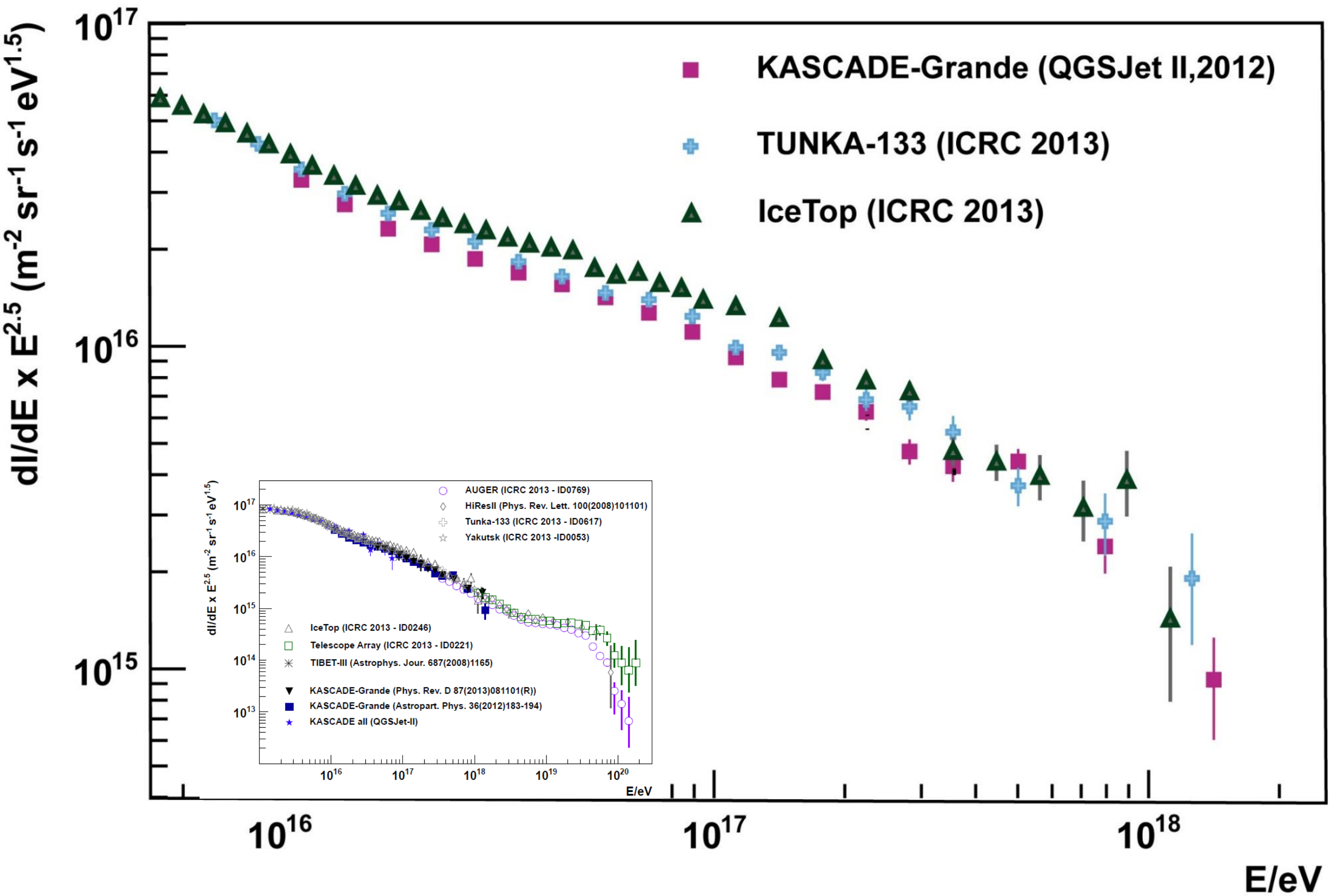
NIM A (2013) accepted - http://dx.doi.org/10.1016/j.nima.2013.09.018

IceTop ➔ Enhancements / IceCube-Gen2



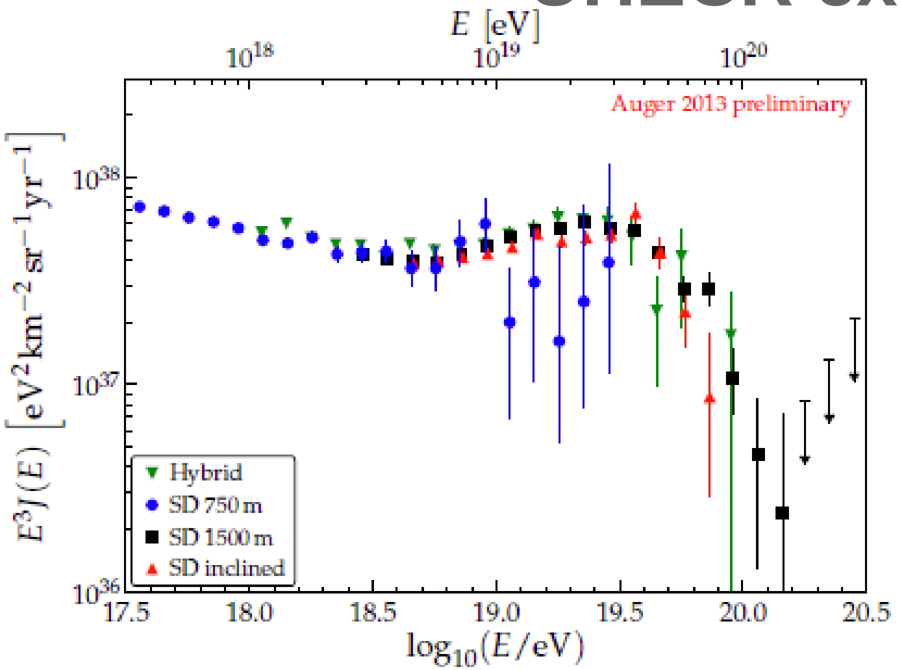
- Energy range: PeV – 1EeV
- Area: 1 km^2
- 2835m altitude (680 g/cm^2)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons

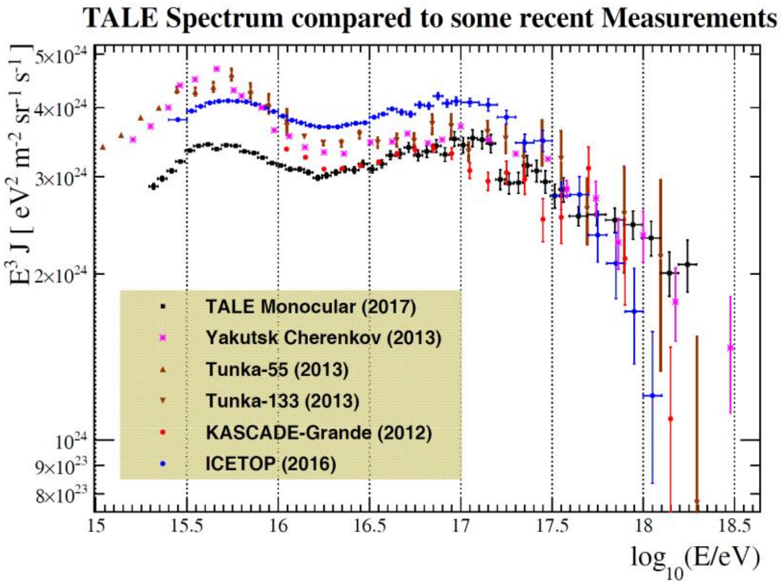
Phys Rev D (2013) accepted - dx.doi.org/10.1016/j.asr.2013.05.008 ??????



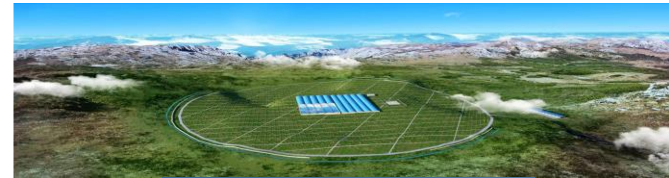
- **Structures of all-particle spectra similar (in the level of 15%)**
- **first composition results are in agreement with KASCADE-Grande**

UHECR experiments





experiments in the knee energy range



- **(Tibet, ARGO) LHAASO**

  CR around knee with multi-detector installation
  China - with participation of France, Italy

- **TAIGA/ Tunka/HiSCORE/Tunka-Taiga-Rex**

  CR around knee and up to ankle with multi-detector installation
  Russia - with participation of Germany, more?

- **IceCube/IceTop – (Gen2)**

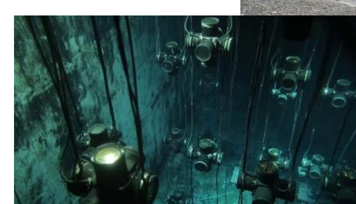
  Ice-Cherenkov array on top of IceCube
  USA – with important European contribution
  Advanced plans for Gen2-surface (veto) array

- **GRAPES**

  KASCADE-like operating array at 2300m altitude
  India - with participation from Japan

- **HAWC**

  High-Altitude Gamma-ray Observatory in Mexico
  Extension with outer trigger for better CR detector



- **NEVOD**

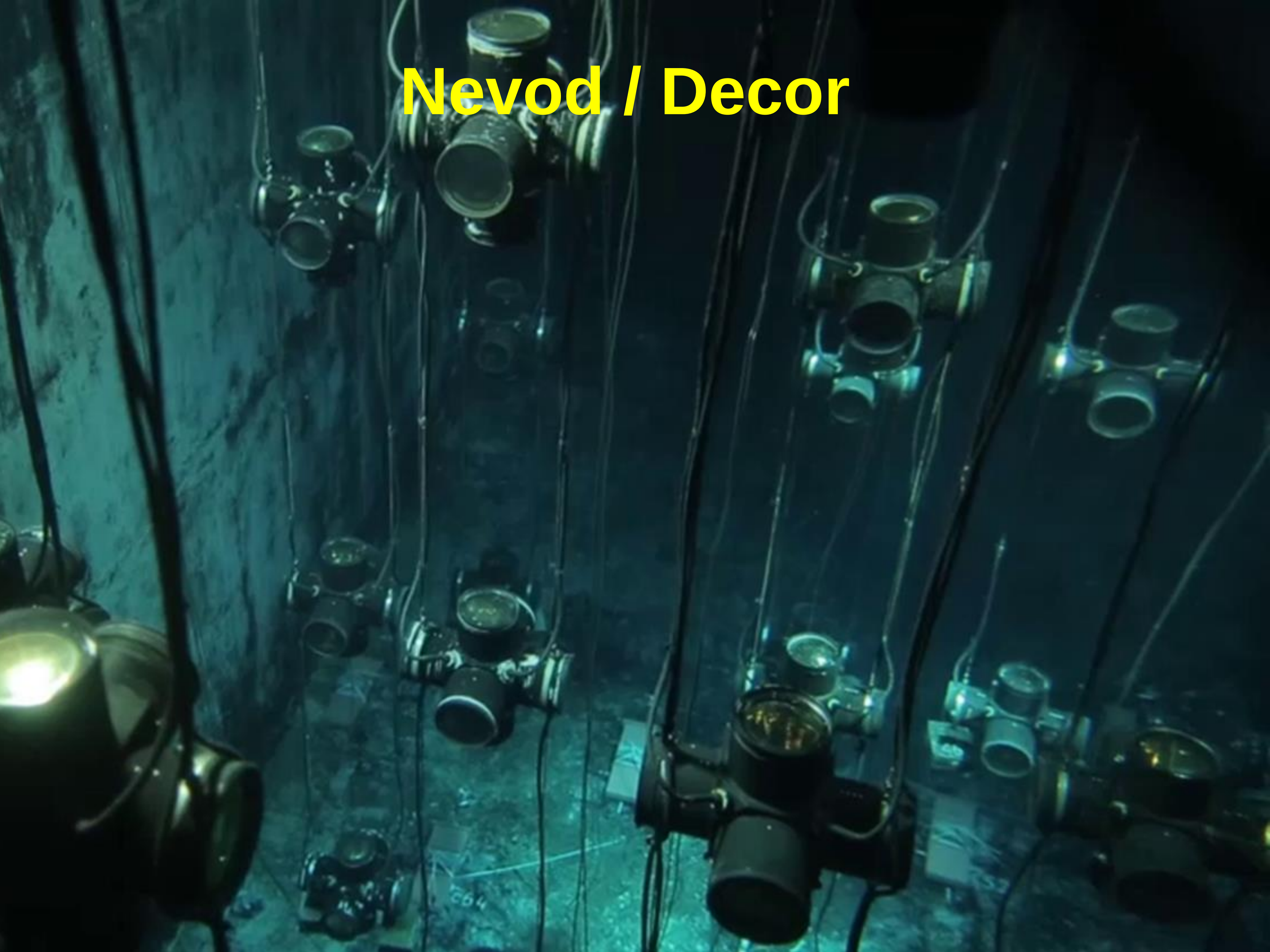
  Nevod / Decor complex now with air shower array

LHAASO

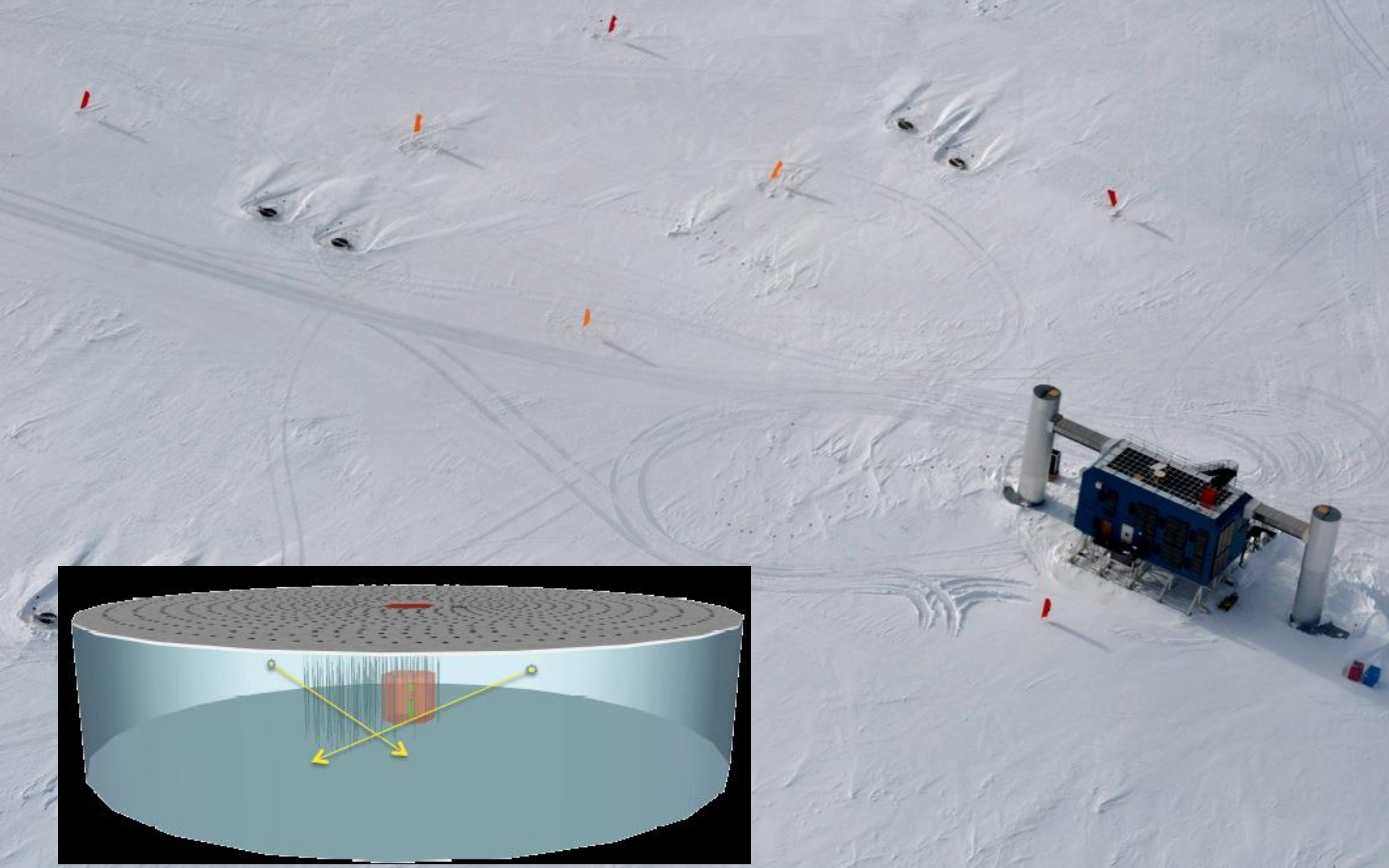
Tunka / Tunka-Rex / HiScore

Andreas Haungs

Nevod / Decor



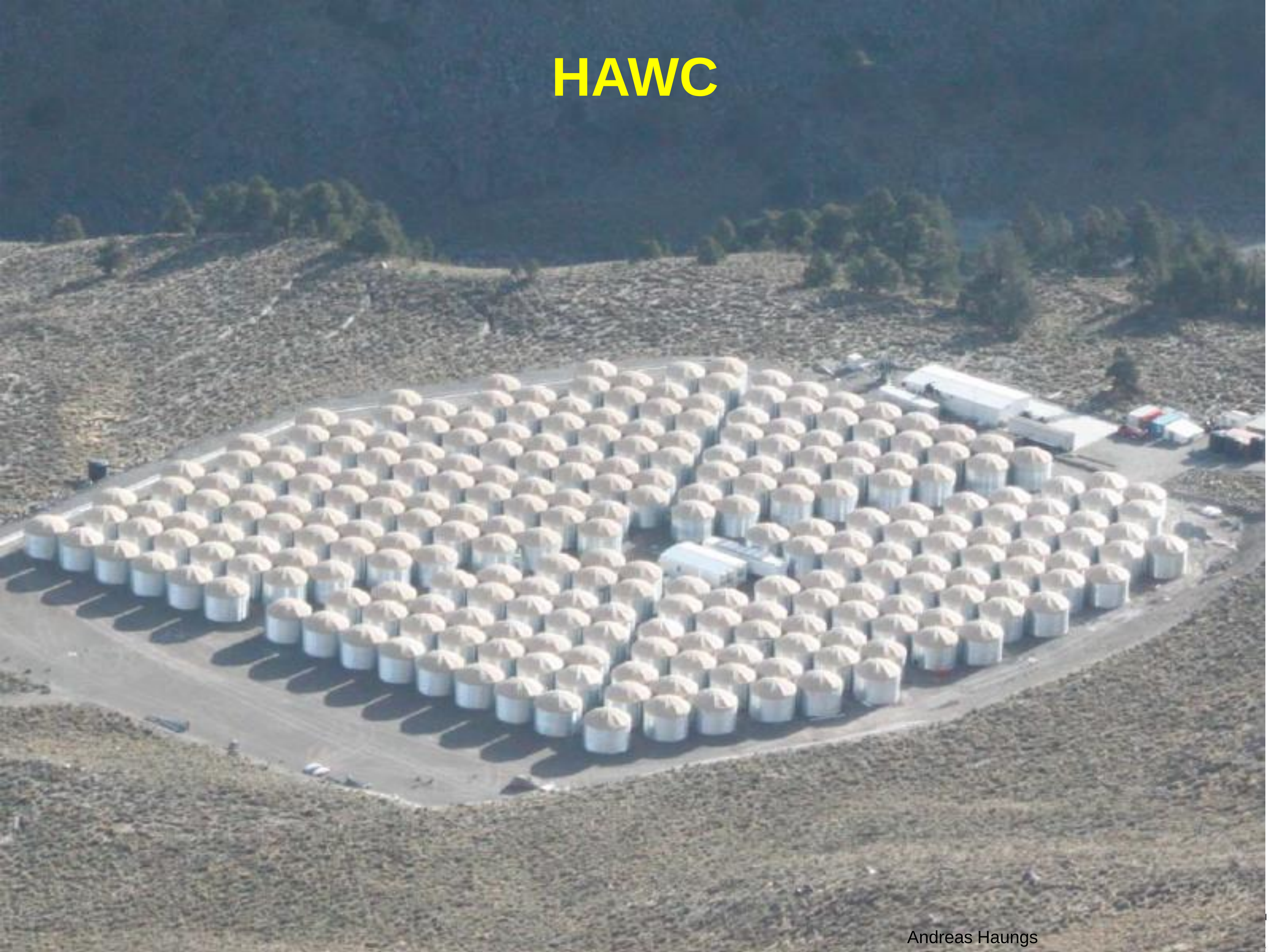
IceCube / IceTop (-Gen2)



GRAPES

Andreas Haungs

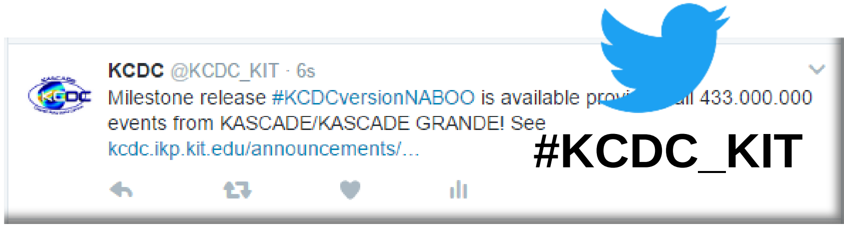
HAWC

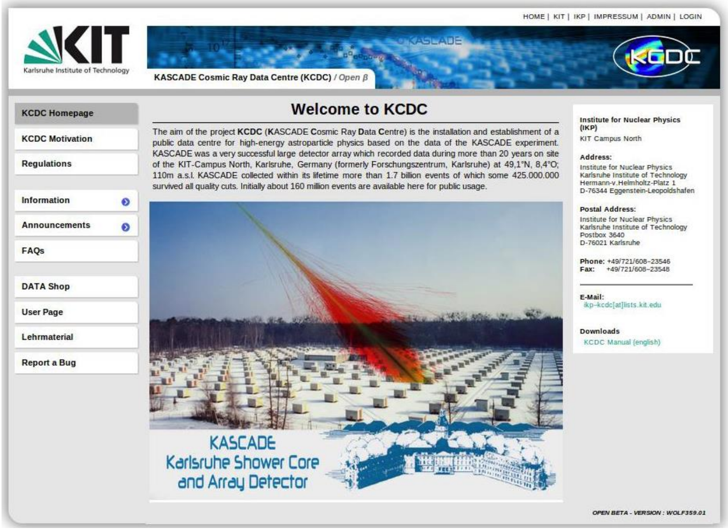



https://kcdc.ikp.kit.edu
KASCADE
KCDC
Cosmic ray Data Centre
Andreas Haungs

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

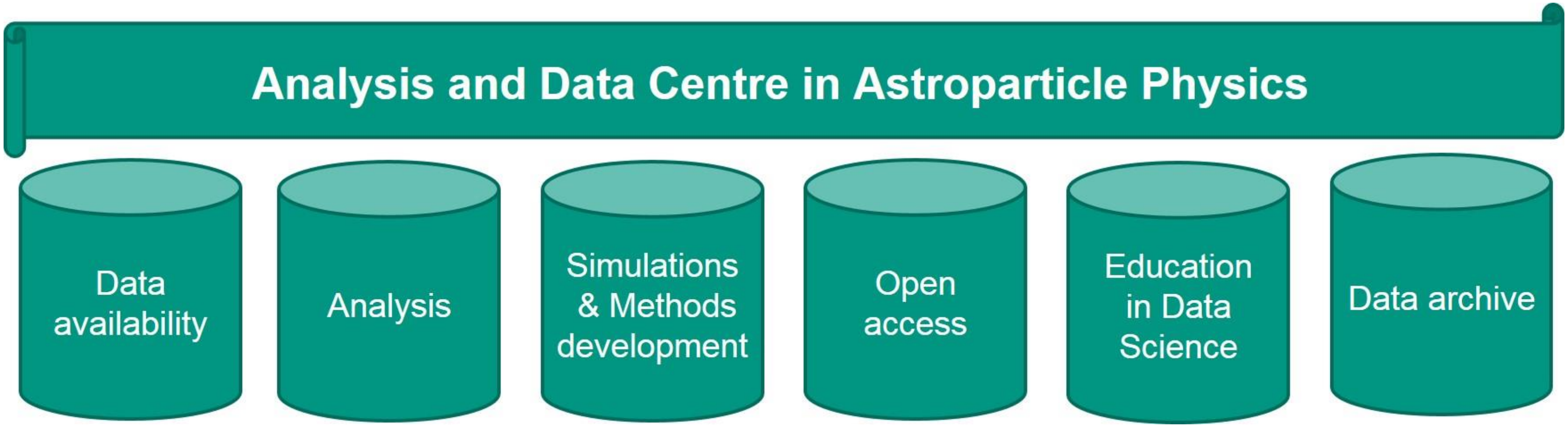
- **KCDC = publishing research data**
  from the KASCADE experiment
- **Motivation and Idea of Open Data:**
  general public has to be able to
  access and use the data
  the data has to be preserved for
  future generations
- **Web portal:**
  providing a modern software solution
  for publishing KASCADE data
  for a general audience
  In a second step: release the software
  as Open Source for free use by
  other experiments
- **Data access:**
  Version NABOO is released (Feb.2017)
  4.3·10^{8} EAS events are available
  including energy deposits
  corresponding simulations
  >90 spectra of EAS experiments





Submitted to: Eur.Phys.J.C (arXiv:1806.05493)

Towards a



Motivation:

- **Astroparticle Physics requests for multi-messenger analyses.**
- **This needs an experiment-overarching platform**
- **High demand in (German and international) community**
- **APP Observatories are globally distributed (no CERN or ESA)**

Important steps:

- **Develop an open science system (based on KCDC and the LHC-Tier environments)**
- **Develop solutions of distributed data storage algorithms and techniques**
- **Allowing community to perform multi-messenger analyses with deep learning methods**
- **Providing platform for public access to scientific data**

Conclusions – open points

- Light and heavy knee established
- Light ankle probably there
- Difficult to compare experiments due to different observables
  what is contribution of MHz-Radio?
- Yet no conclusive result due to insufficient hadronic interaction models
- Continuation in improving hadronic interaction models required
- Still problem: absolute mass scale
- Confrontation of the data with astrophysical models still challenging
- Future: (mass dependent) Anisotropy studies
- Future: Multi-messenger Analyses (cosmic rays, γ-rays, neutrinos)
- IceTop(-Gen2), TAIGA, LHAASO, GRAPES, TALE, PAO, NEVOD, HAWC?
- Global Data Centre for Astroparticle Physics envisaged