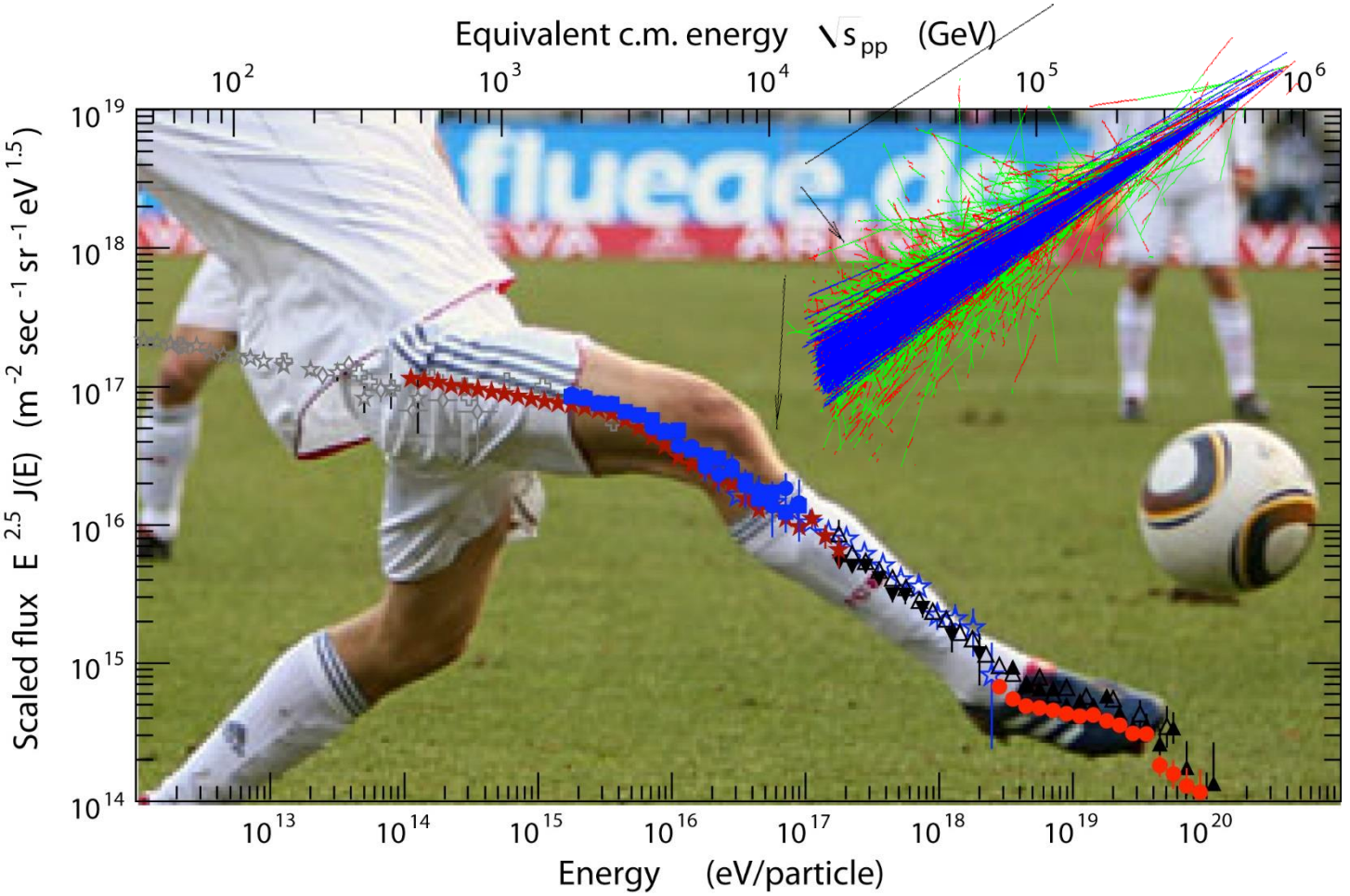
Cosmic Rays….

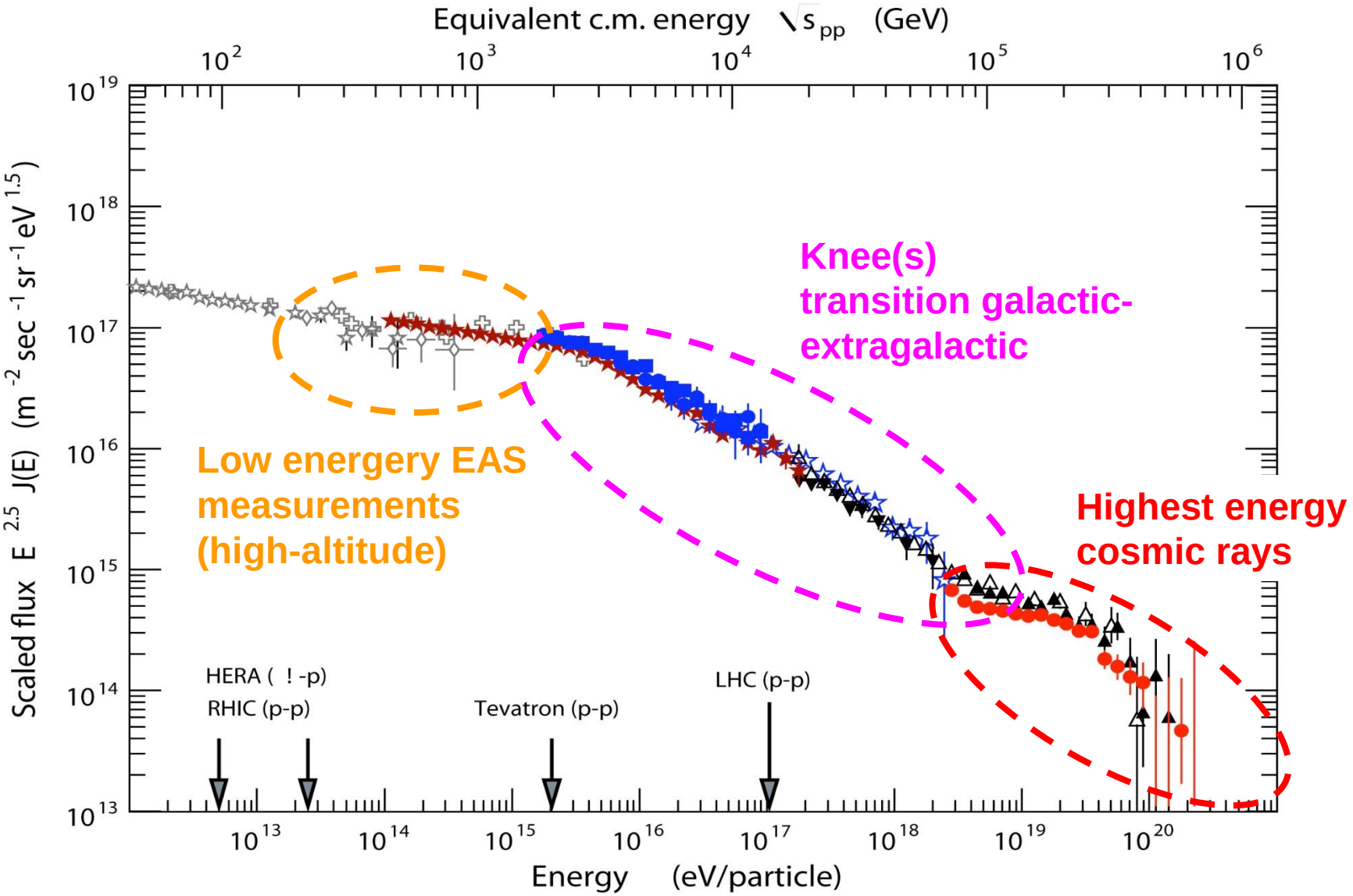
….from PeV to EeV: investigating the knee(s)

KASCADE-Grande….

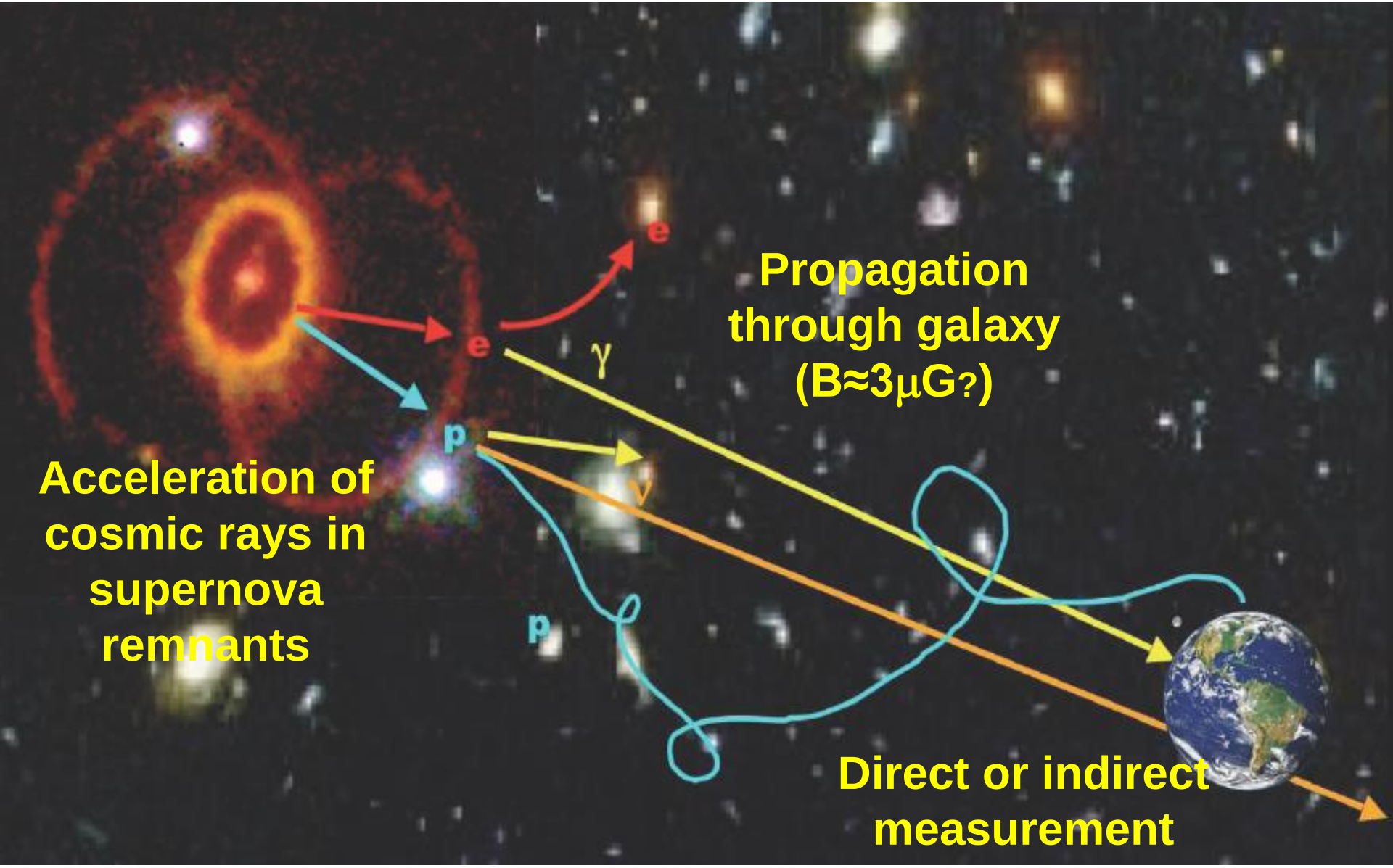
….in the view of the post-LHC hadronic interaction models



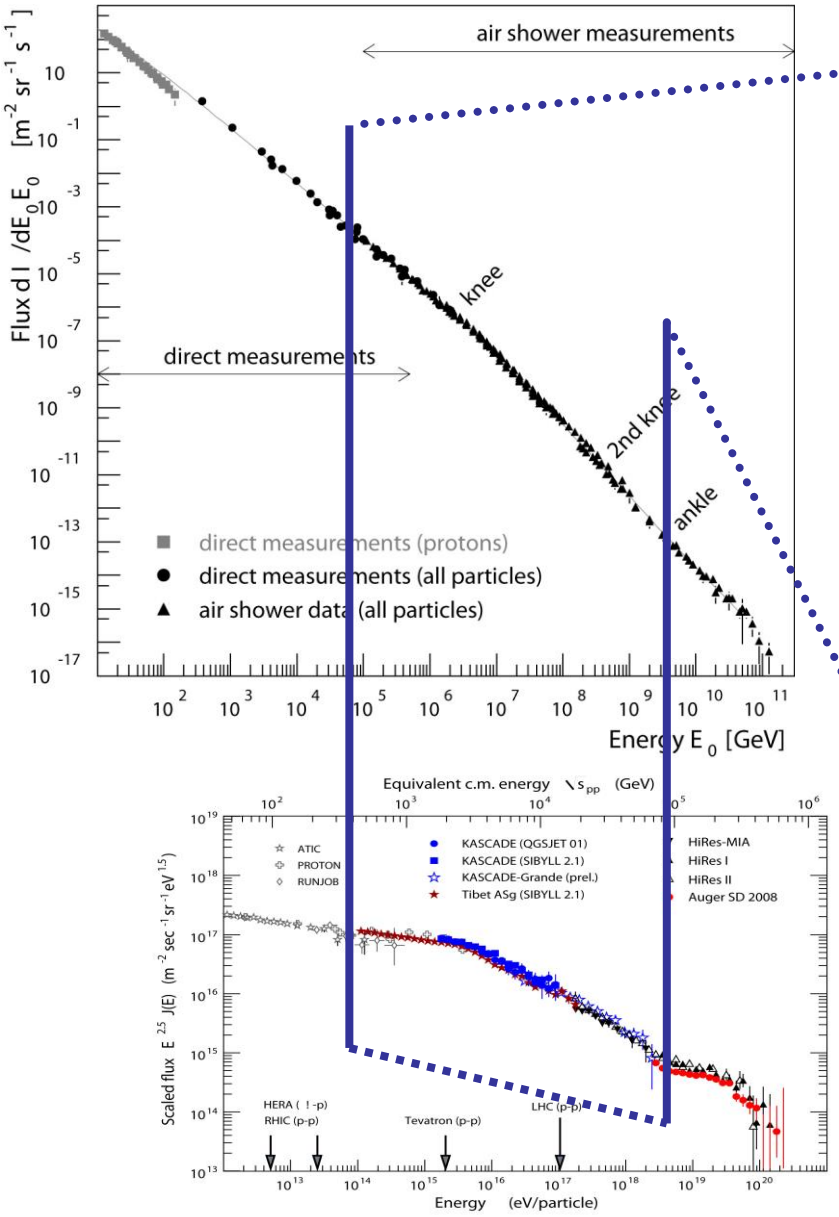
High-energy cosmic ray spectrum



Galactic cosmic rays



Questions to the knee-to-ankle energy range



Overlap direct-indirect measurements?

Hadronic interaction models?

Rigidity dependent knee?

Sharpness of knee?

Composition at knee?

Fine-structures in spectrum?

Iron knee?

End of Galactic Spectrum?

Second knee?

Transition galactic – xgalactic?

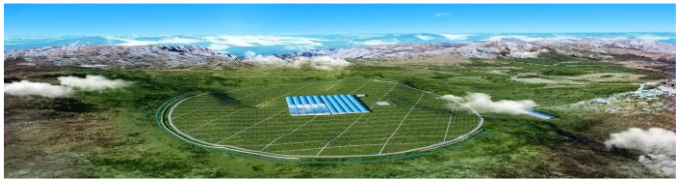
Anisotropy?

Engel, Blümer, Hörandel:
Progress in Particle and Nuclear Physics 63 (2009) 293

experiments in the knee energy range

- HAWC?!

- (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

- KCDC

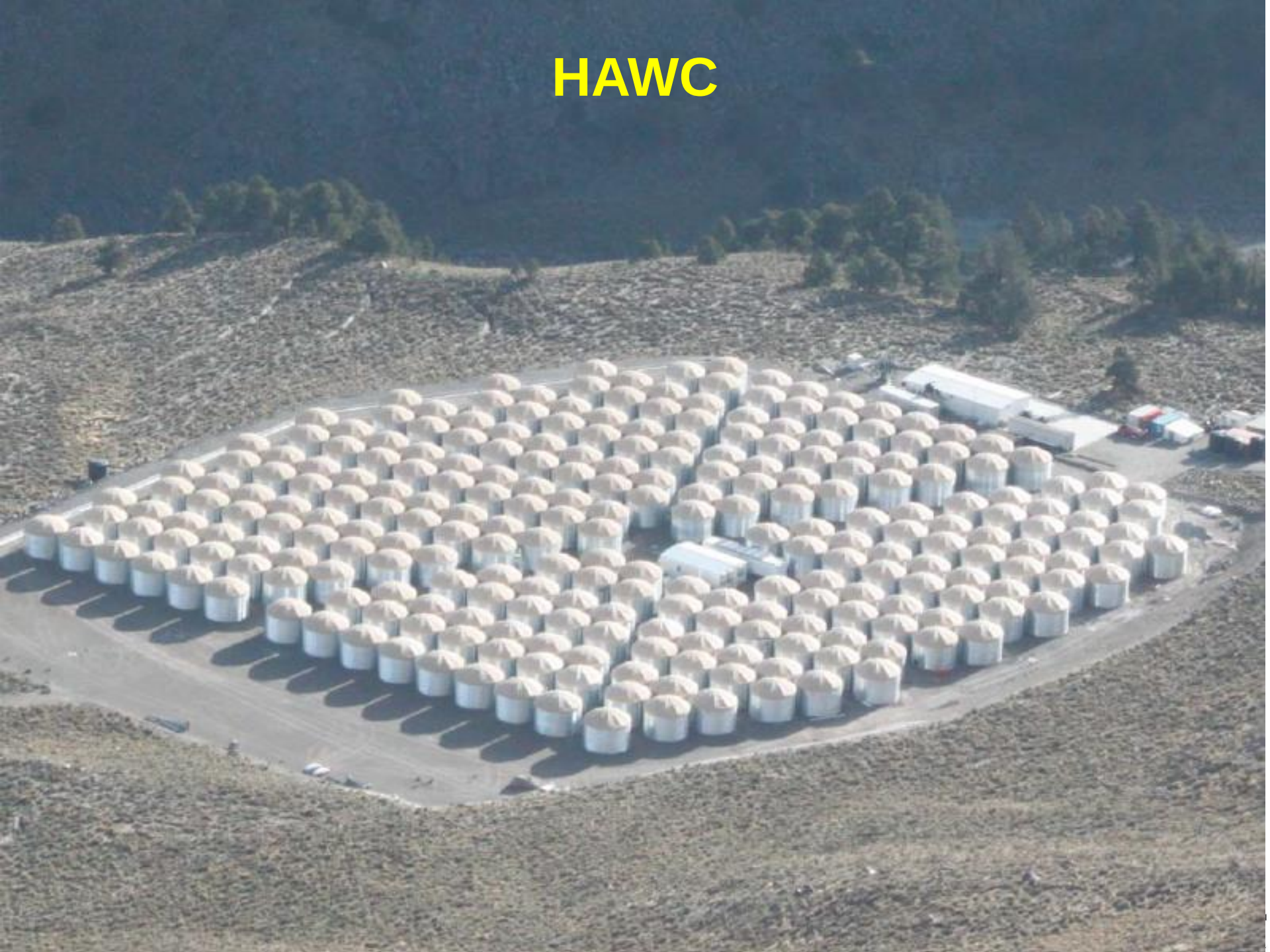
KASCADE Cosmic ray Data Centre for public use
Extension to other experiments foreseen (Auger?)

LHAASO

Tunka / Tunka-Rex / HiScore

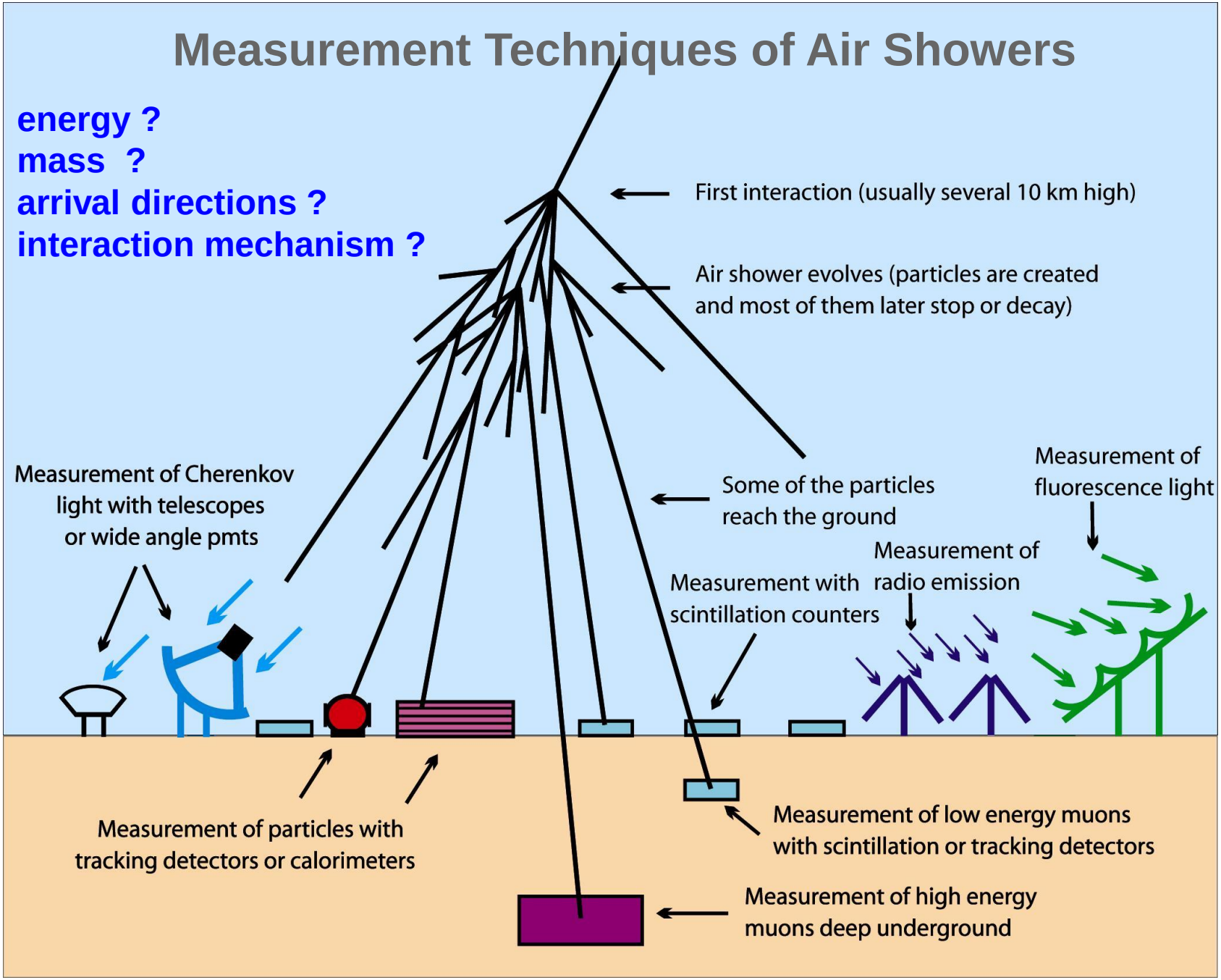
IceCube / IceTop (-Gen2)

GRAPES

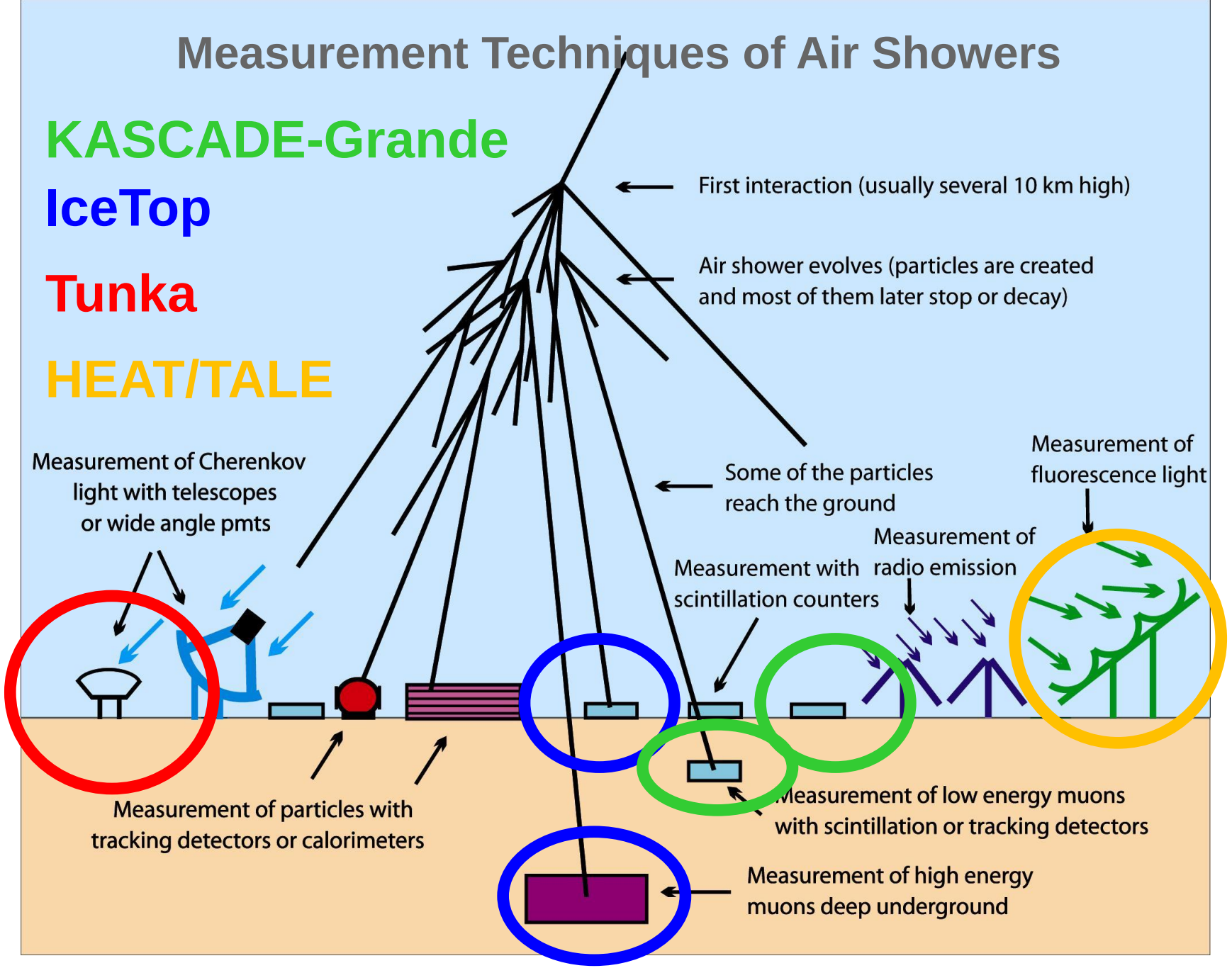

HAWC


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

Measurement Techniques of Air Showers



Measurement Techniques of Air Showers

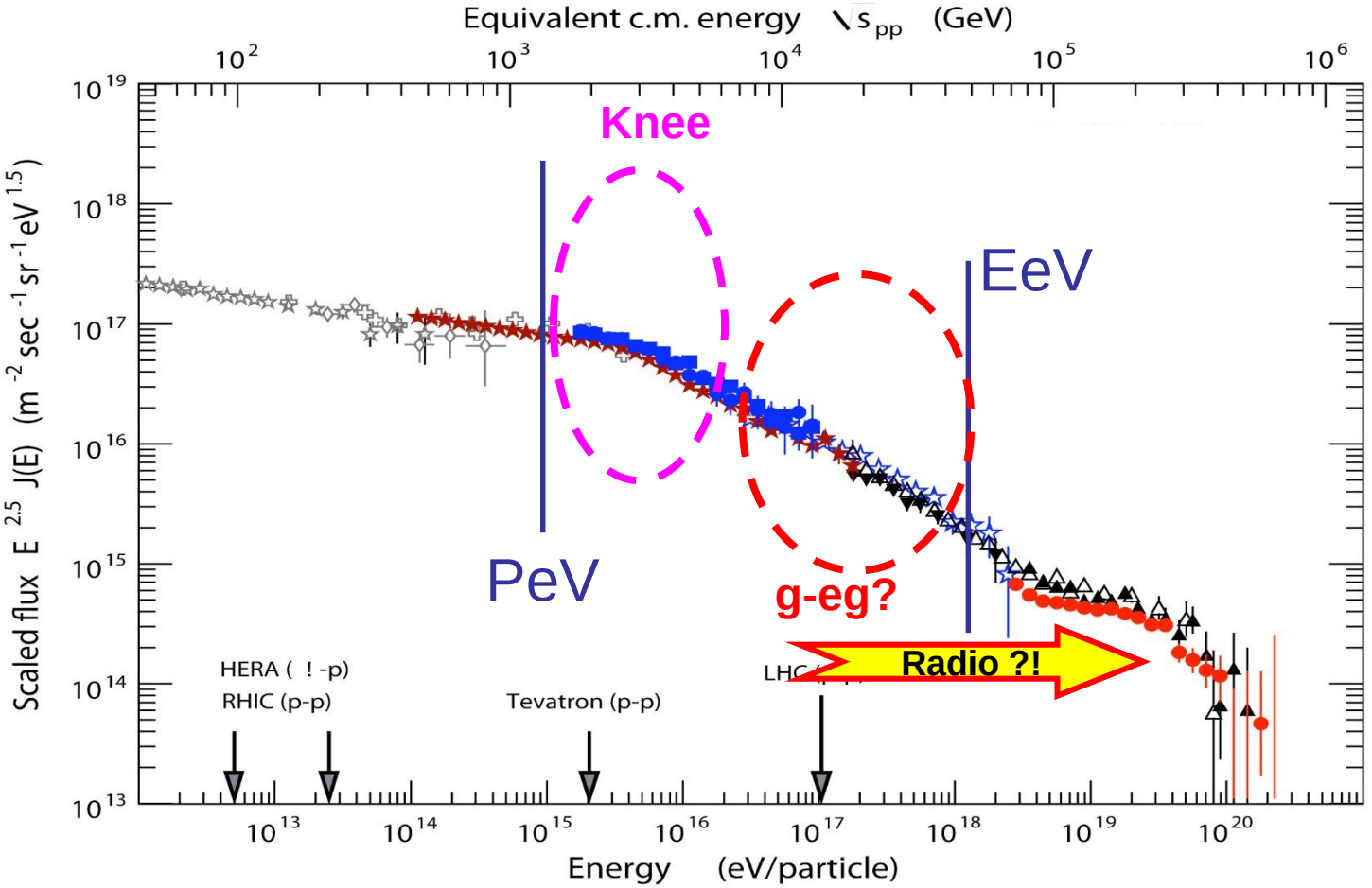


KASCADE

KArlsruhe Shower Core and Array DEtector

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

The physics of the KASCADE facility



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!**

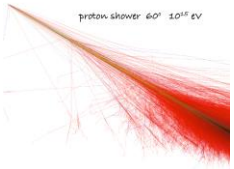
KASCADE timeline

- 56 collaborative papers in reviewed journals (4-5 still in queue, short author list papers not included)
- 56 PhD thesis
- 86 diploma/master thesis

1989 Proposal

1996 CORSIKA

2000 KASCADE



2004 KASCADE-Grande

2008 LOPES

2012 CROME

Karlsruhe Air Shower Test Facility

2016 KCDC

Cosmic Revelation

Xmax by radio

EAS GHz emission

light ankle

heavy knee

muon production height

proof-of-principle radio detection

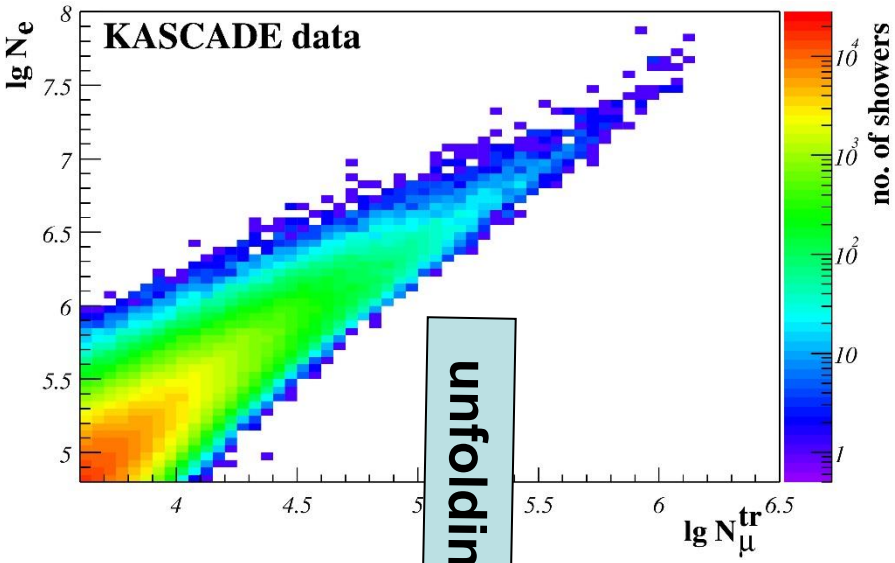
(an)isotropy

γ limit

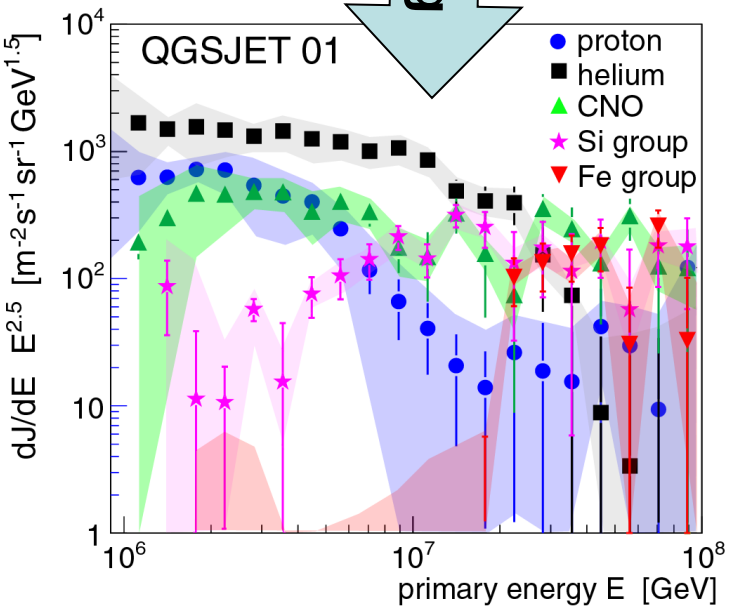
light knee

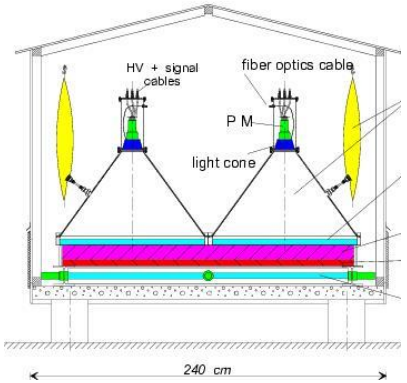
model tests

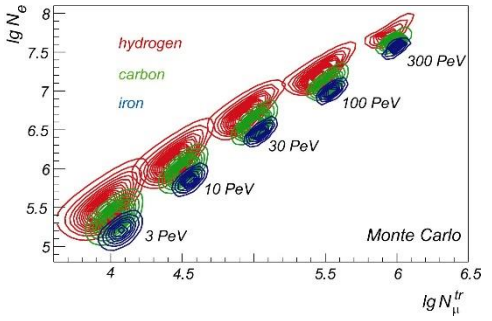
KASCADE : energy spectra of single mass groups



unfolding







Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ solve the inverse problem

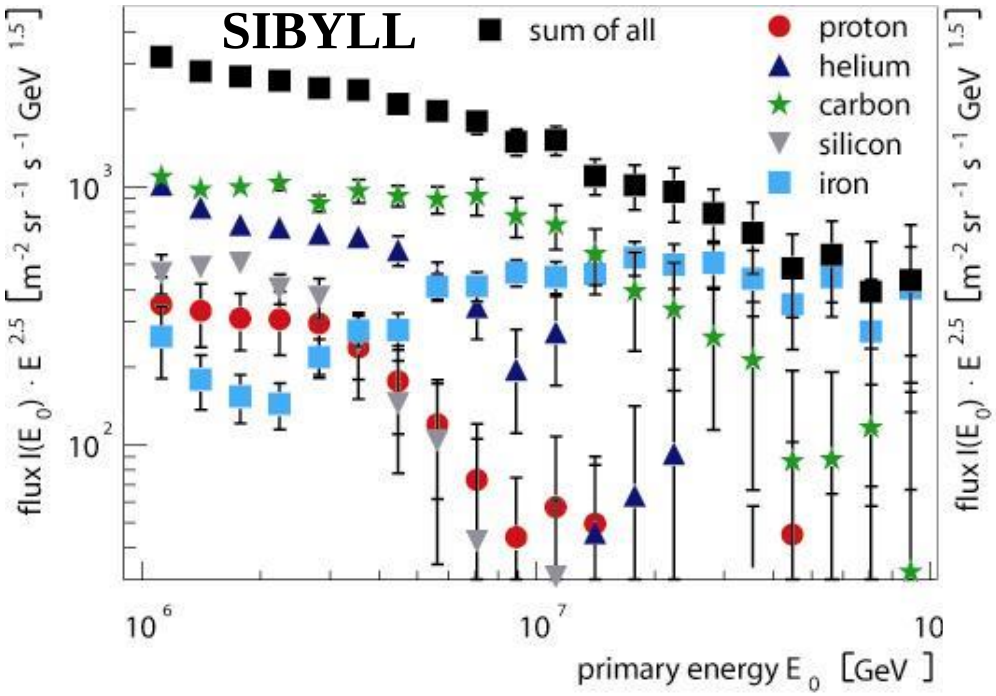
$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

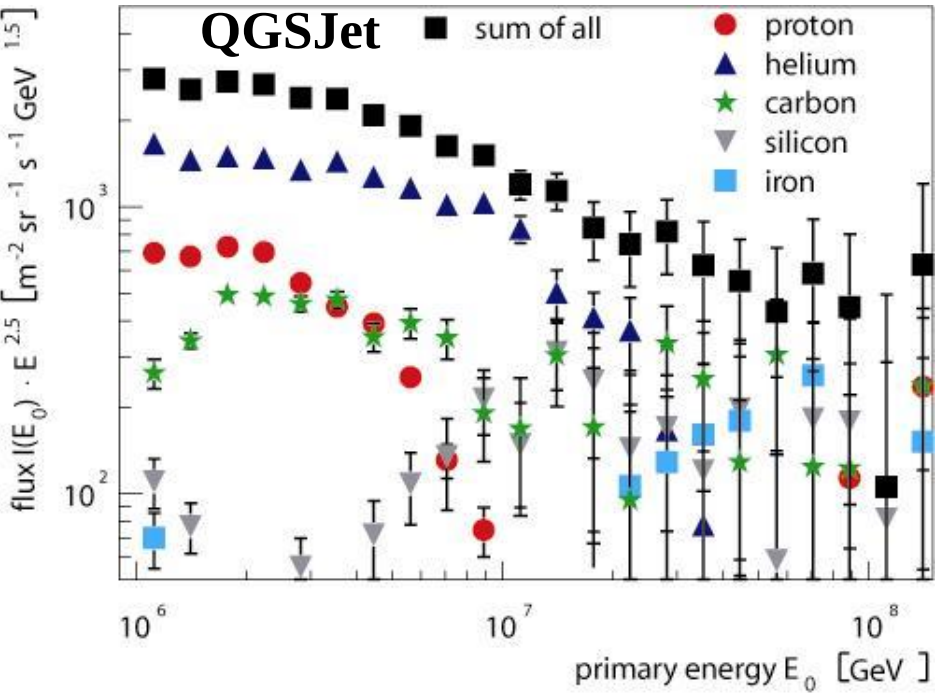
- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

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

KASCADE: the rigidity knee

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

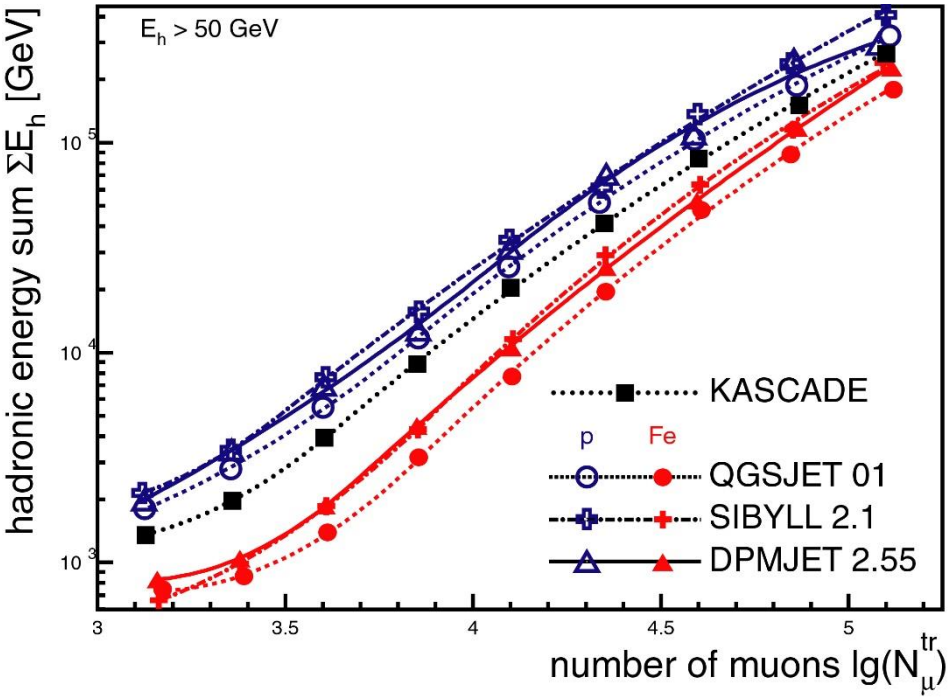


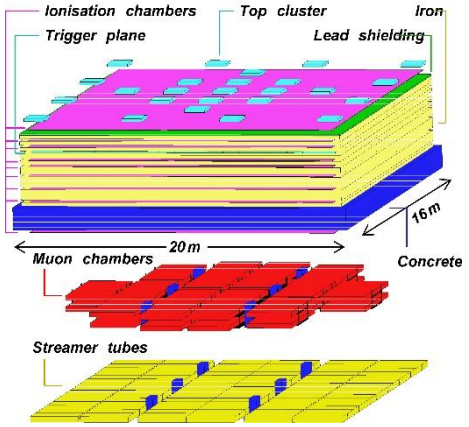


- all-particle spectrum similar
- general structure similar: knee by light component
-relative abundances very different for different high-energy hadronic interaction models
but for many models: proton not the most dominant component!

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

KASCADE : sensitivity to hadronic interaction models



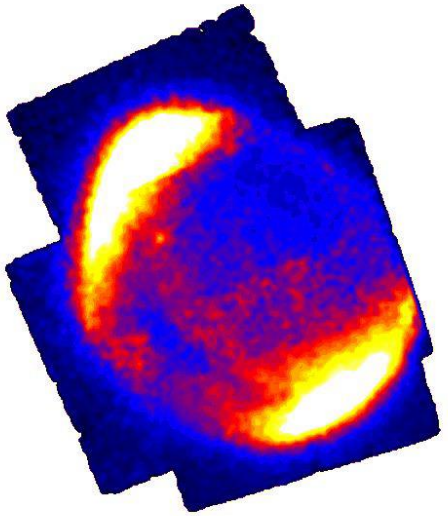


Example:
hadrons vs. muons

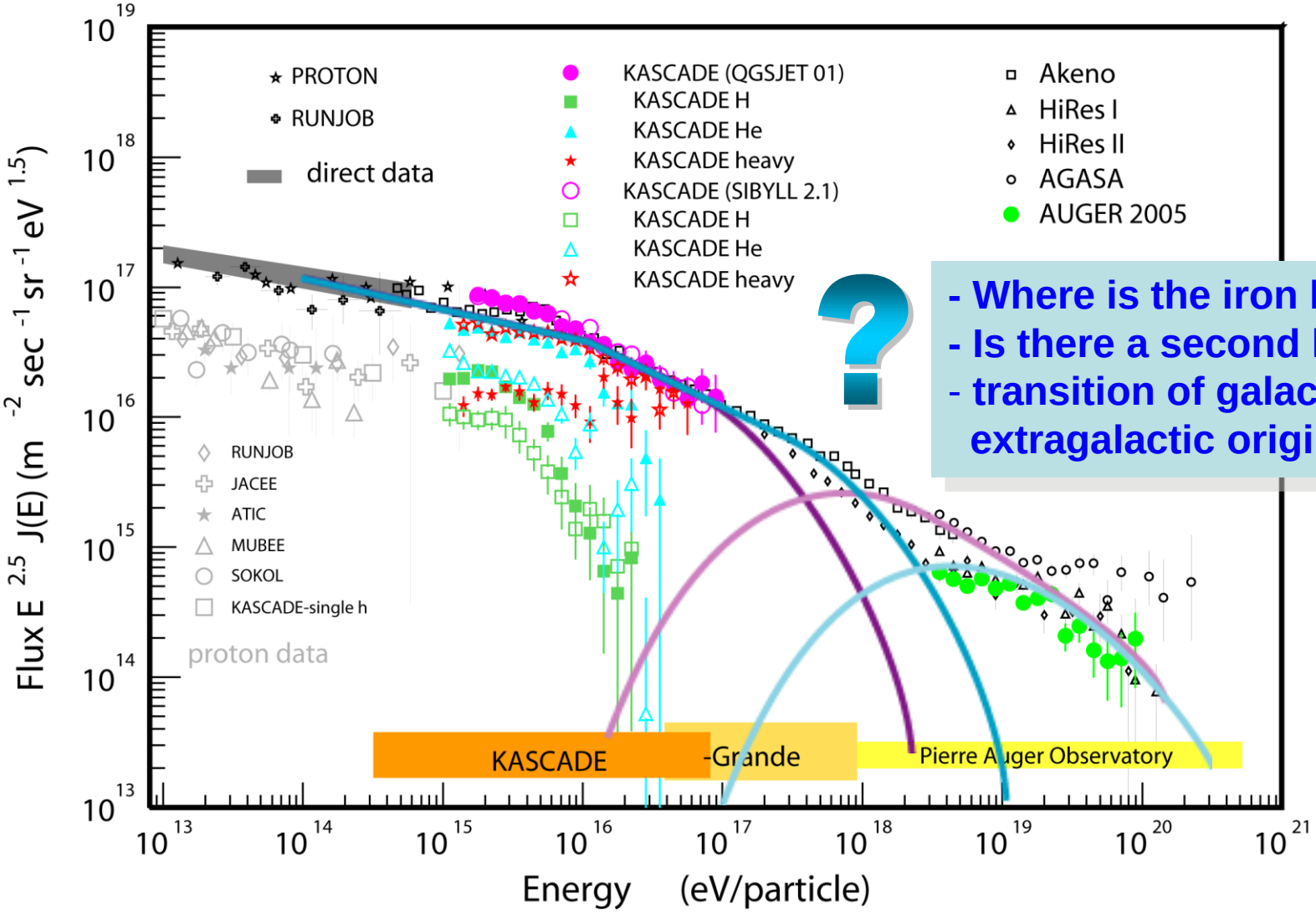
correlation of observables:
no hadronic interaction model describes data consistently !
➔ tests and tuning of hadronic interaction models !
➔ close co-operation with theoreticians (CORSIKA including interaction models)
➔ e.g.:
- **EPOS 1.6 is not compatible with KASCADE measurements**
- **QGSJET 01and SIBYLL 2.1still most compatible models**

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

Result KASCADE ➔ Motivation KASCADE-Grande



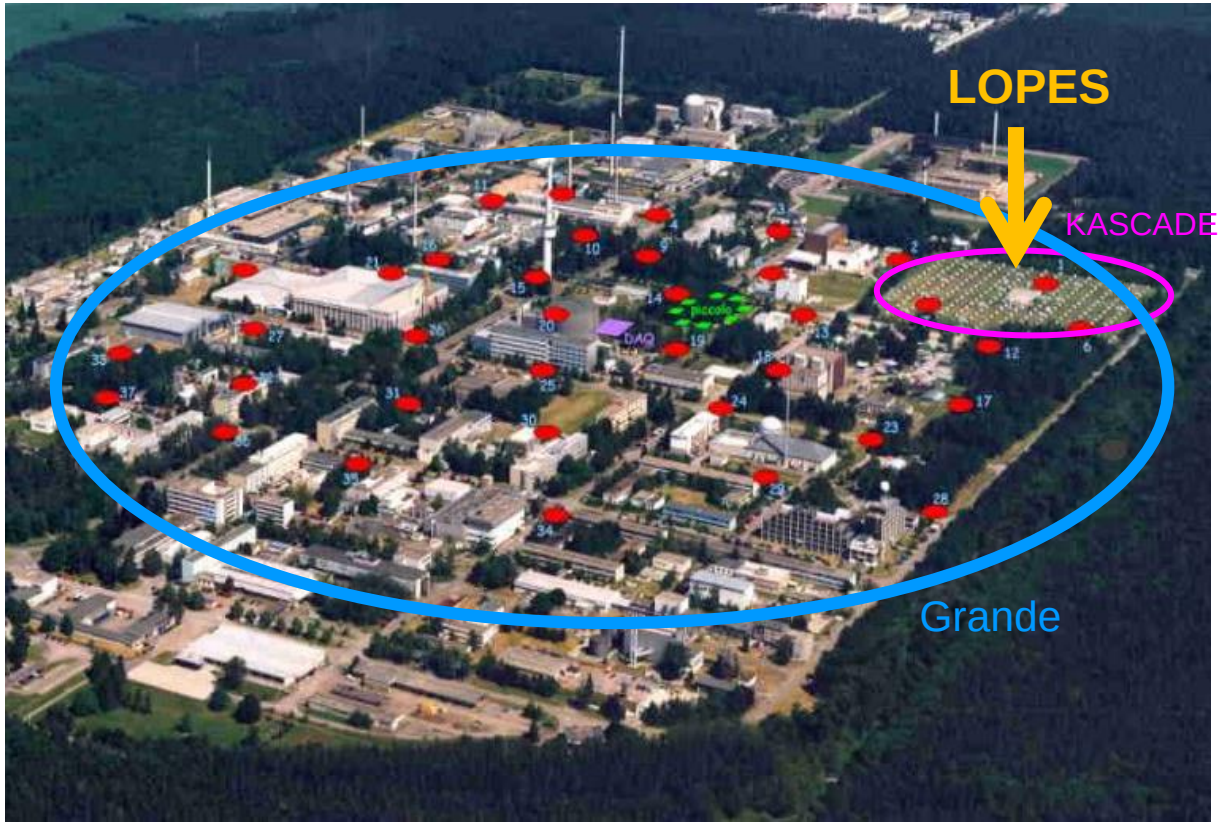
Result KASCADE ➔ Motivation KASCADE-Grande



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

LOPES

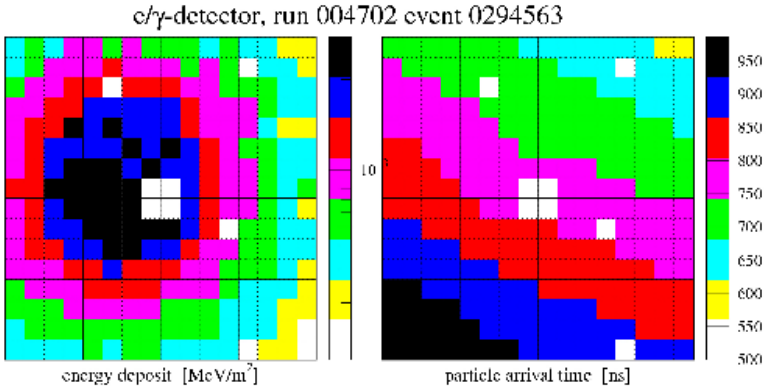
LOPES collaboration:
-) KASCADE-Grande
-) U Nijmegen, NL
-) MPIfR Bonn, D
-) Astron, NL
-) IPE, FZK, D



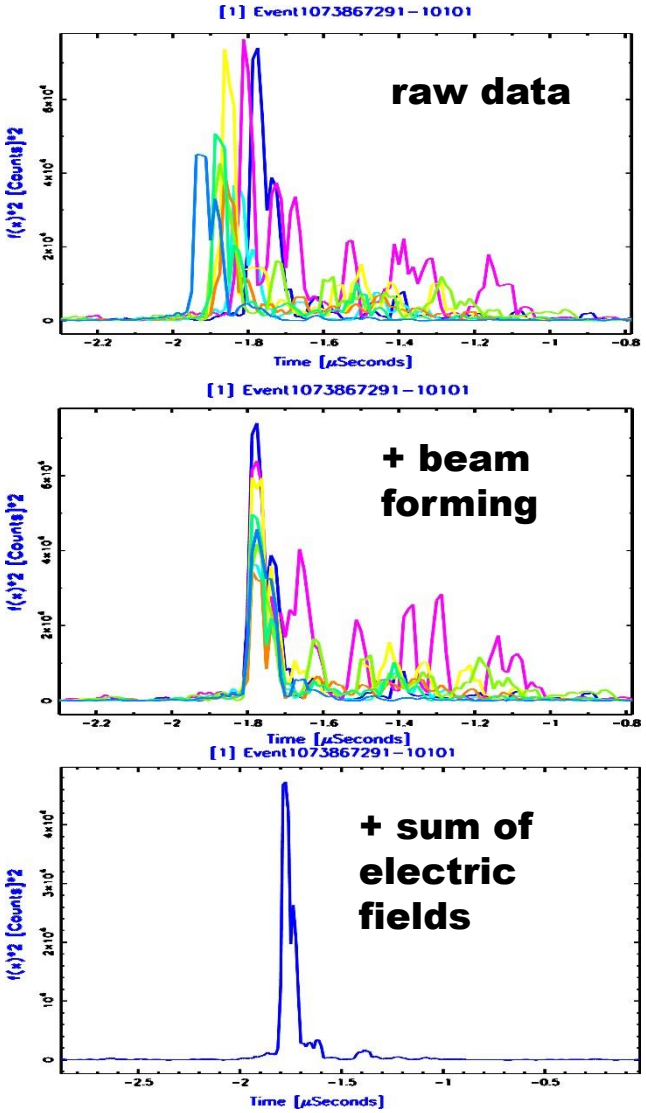
➔Development of a new detection technique!

LOPES: Proof of principle

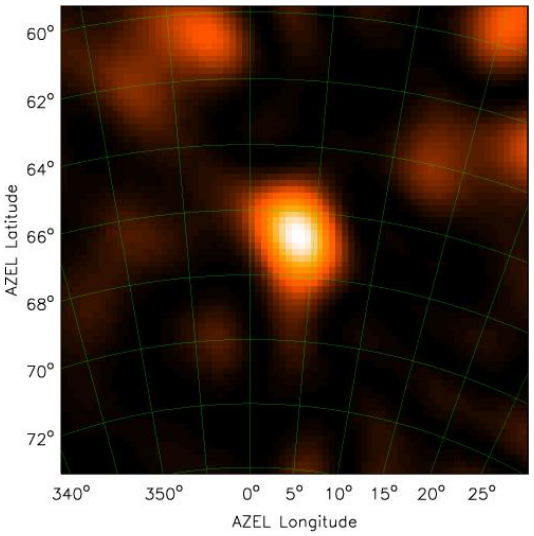
1. KASCADE measurement



2. Radio data analysis

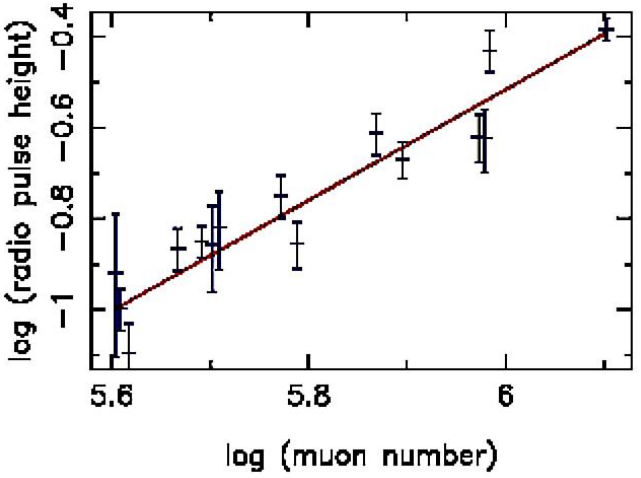


3. Skymapping



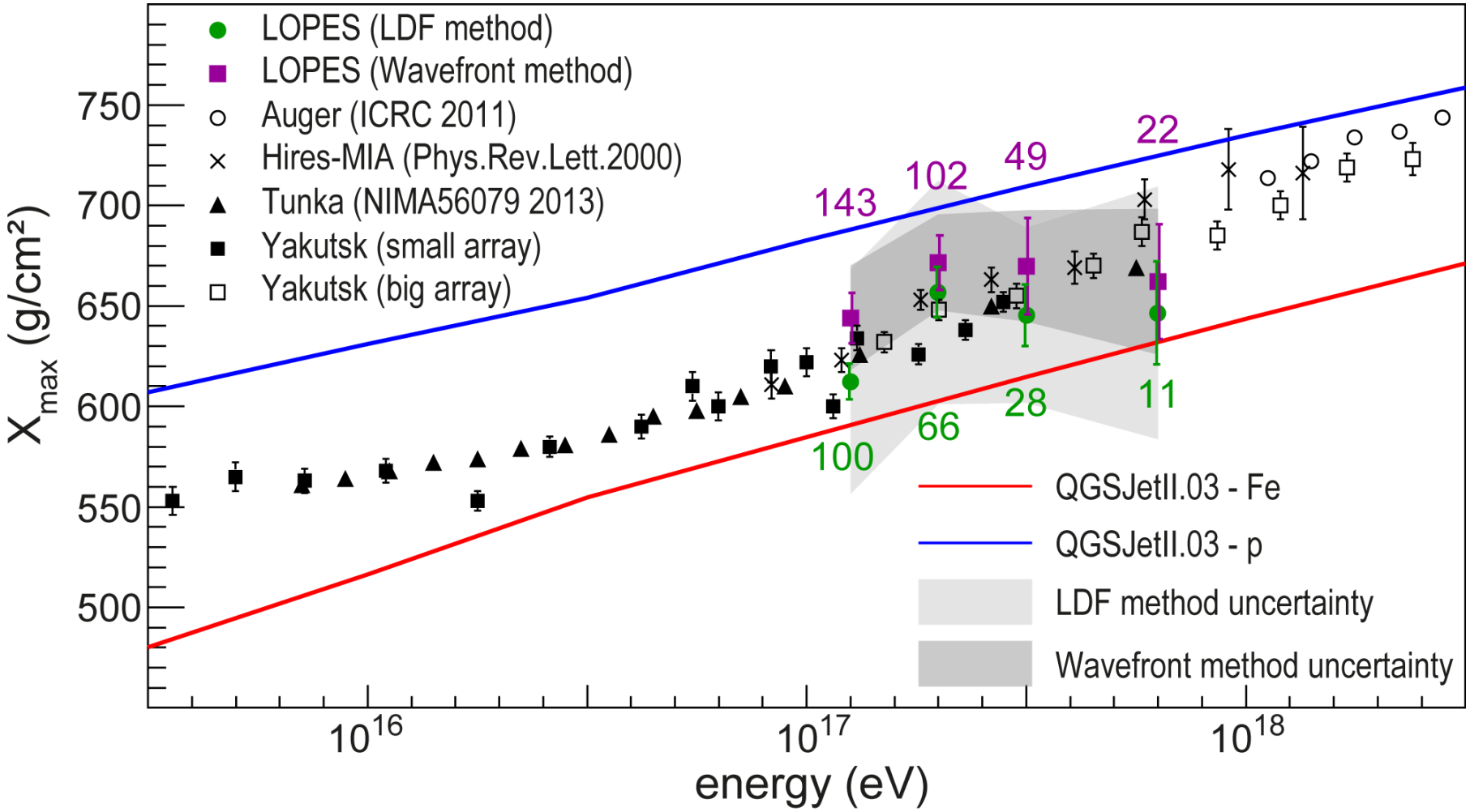
4. Many events

meanwhile >500 events



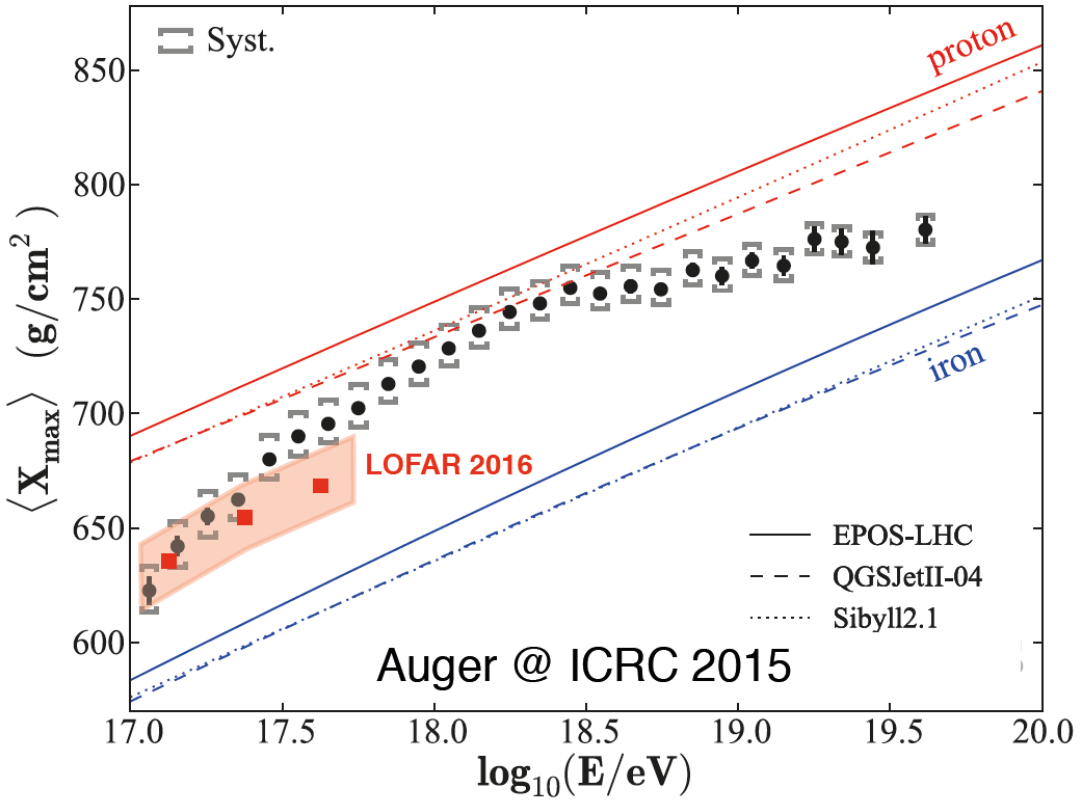
LOPES collaboration, Nature 425 (2005) 313

Composition measurements by LOPES



Xmax / Composition by Radio

A lot of (promising) progress in Xmax determination by radio Experiments



- **published already by**

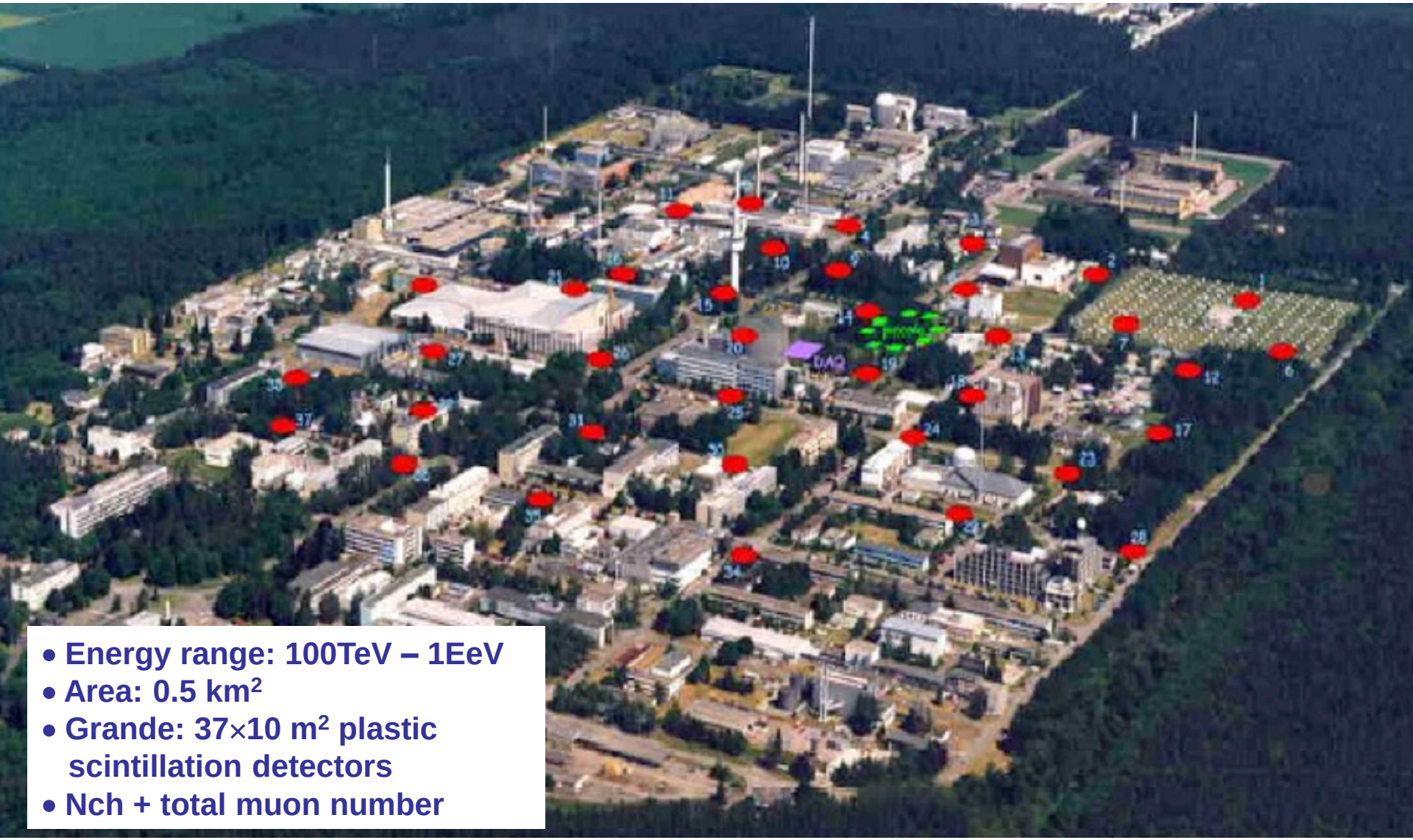
LOPES
PhysRevD 90(2014)062001
Tunka-Rex
JCAP 01(2016)052
LOFAR
Nature 531(2016)70

- **Auger/AERA promising**

- **Higher energy**
- **More accurate EAS**
- **Calibration**
- **Various methods**

➔ **Interpretation debatable:** “Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ eV, our measurements indicate the existence of an additional galactic component to account for the light composition we measured…..” (LOFAR@Nature)

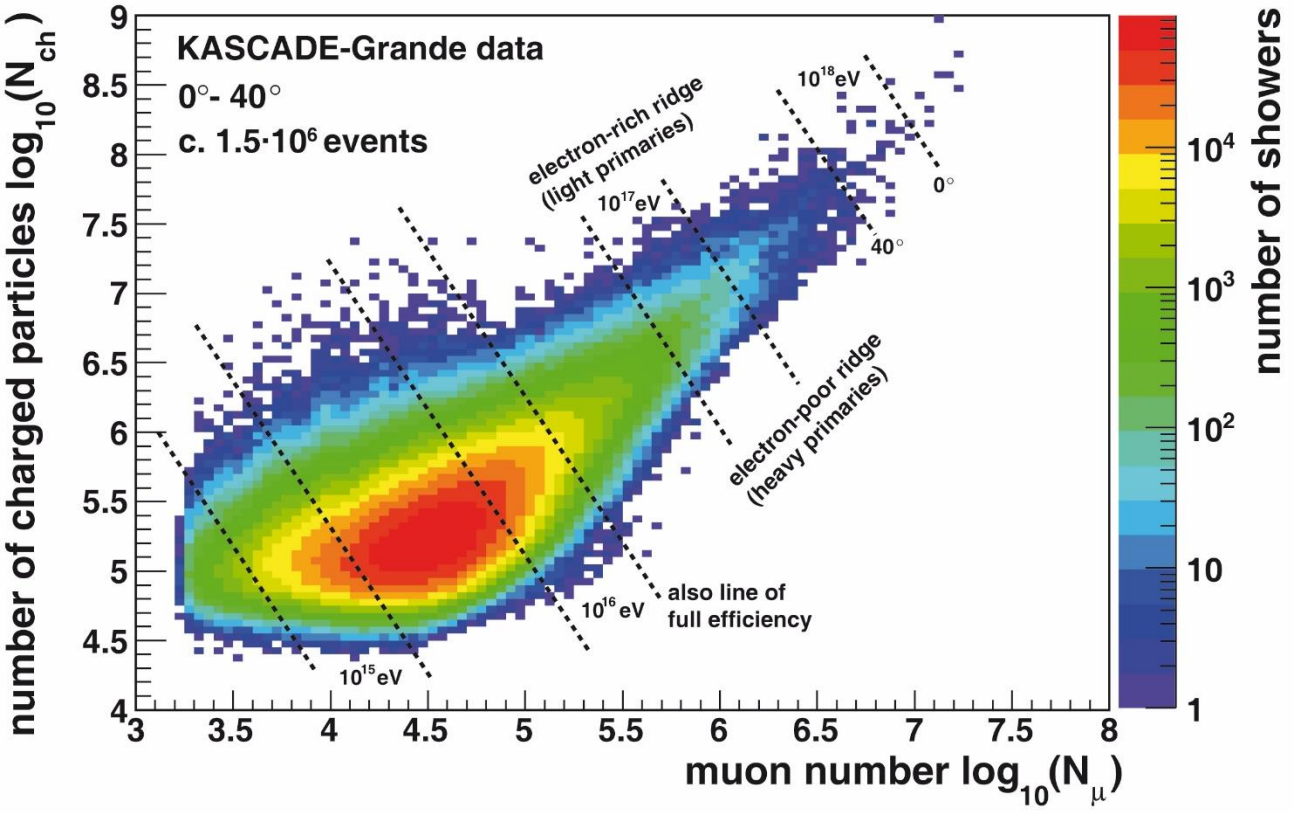
KASCADE-Grande



- 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



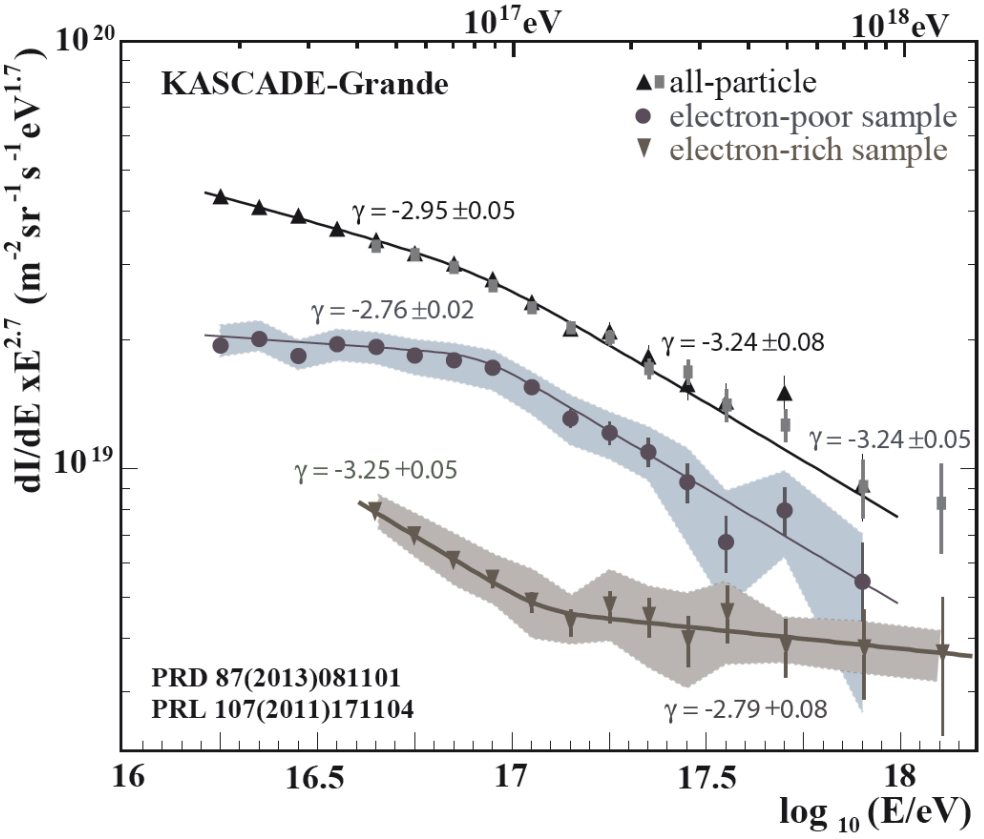
➔ **determination of primary energy**

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

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

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

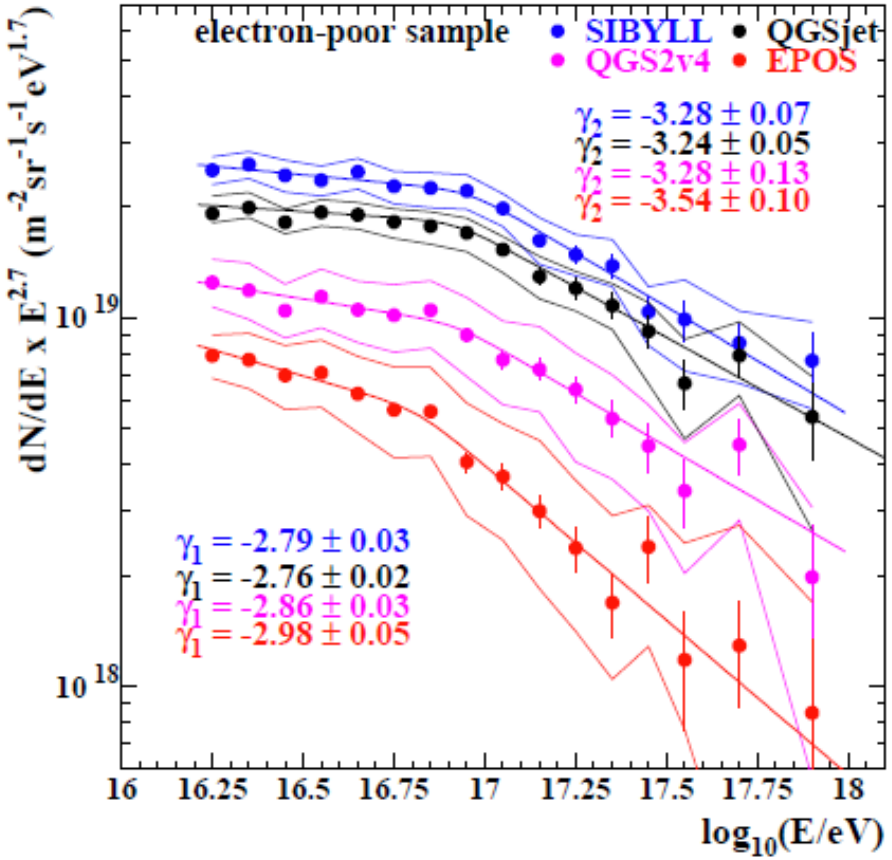
KASCADE-Grande
energy spectra of mass groups

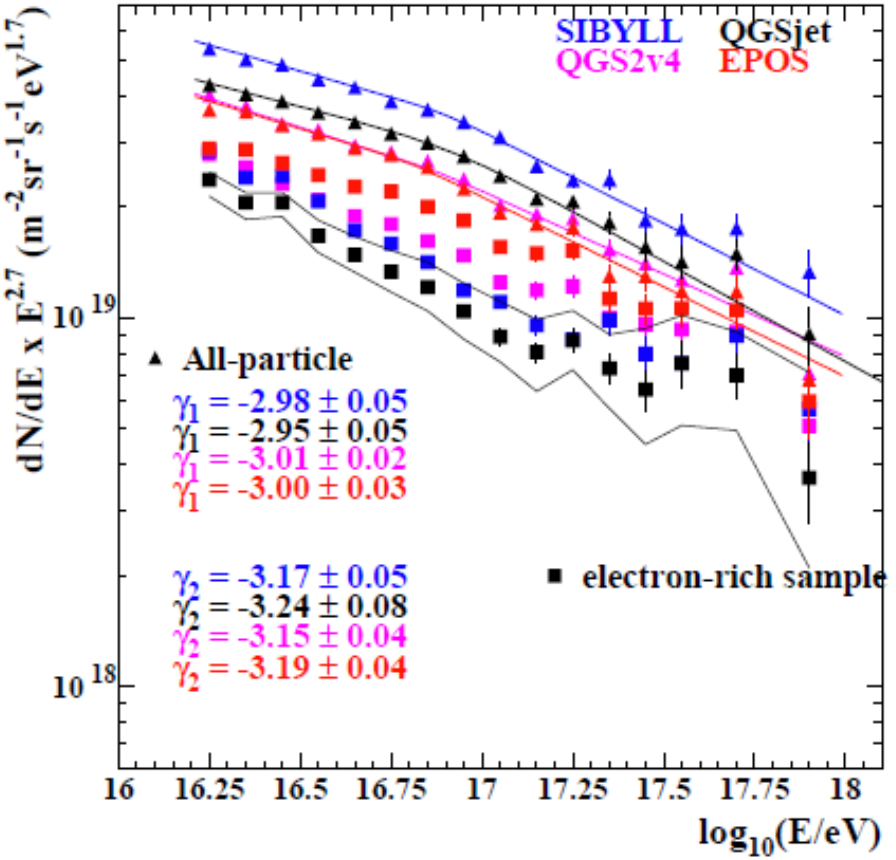


- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**
- **slope change from γ = -3.25 to γ = -2.79!**

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

KASCADE-Grande: model dependence





- Structures of all-particle, heavy and light spectra similar

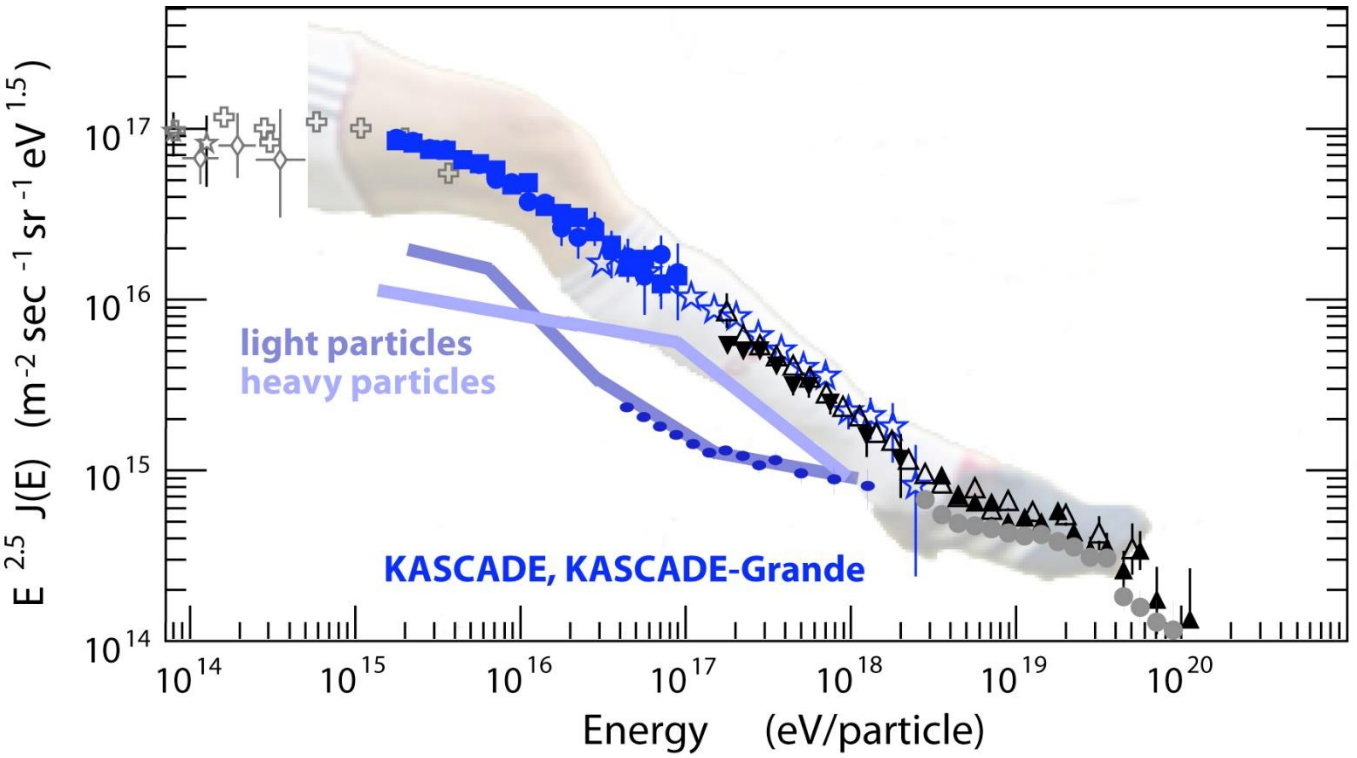
➔ knee by light component and heavy component; ankle by light component

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

Advances in Space Research 53 (2014) 1456

30 March 2009 – official closure ceremony

Light and Heavy Knees, Ankles, and Transition



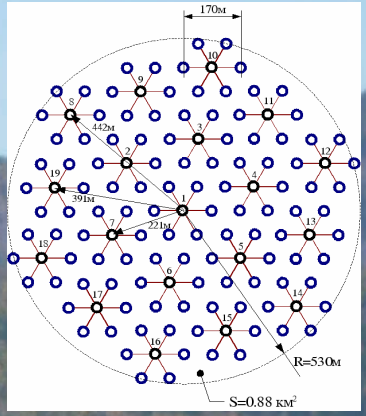
- ➔ **KASCADE: knee of light primaries at ~3·10^{15}eV**
- ➔ **Hardening at 10^{16}eV due to knee of medium component**
- ➔ **KASCADE-Grande: knee of heavy primaries at ~9·10^{16} eV**
- ➔ **heavy knee less distinct compared to light knee**
- ➔ **mixed composition for 10^{15} to ~ 8·10^{17} eV**
- ➔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

knee positions $\propto Z$

Tunka-133

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

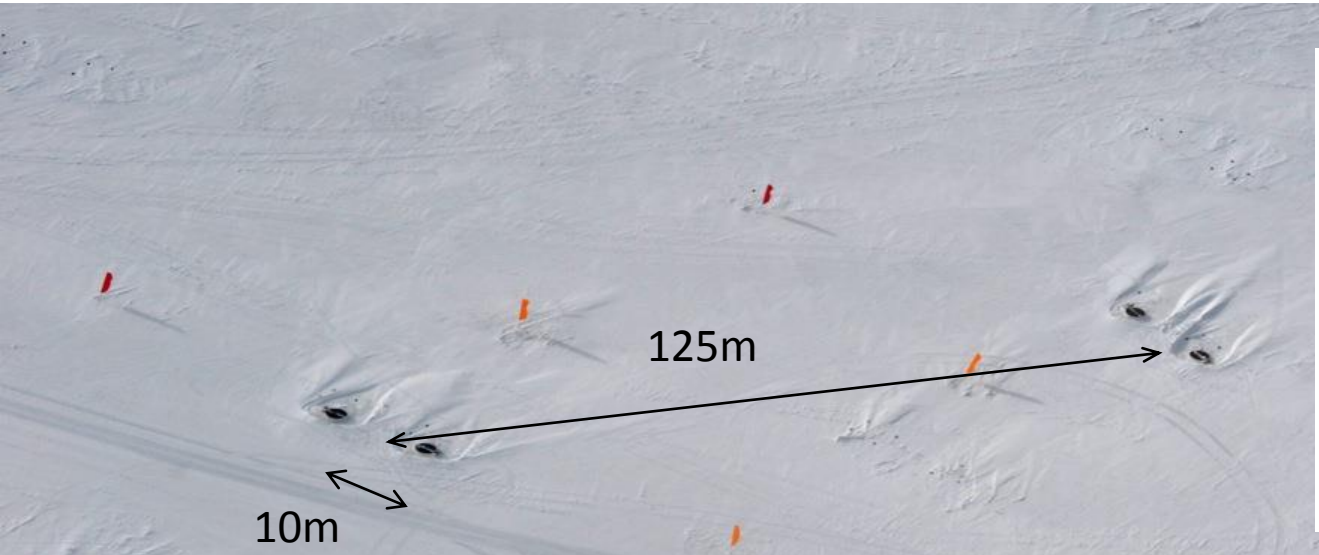
steepness of LDF P = Q(100)/Q(200) ➔ X_{max}

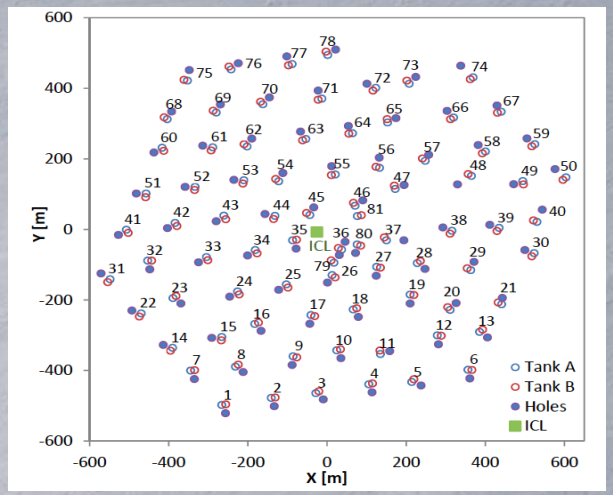


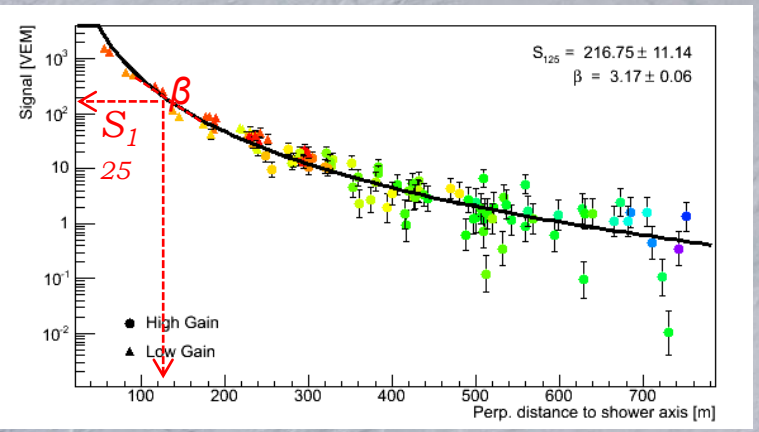
- Energy range: 100TeV – 1EeV
- Area: >1 km²; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

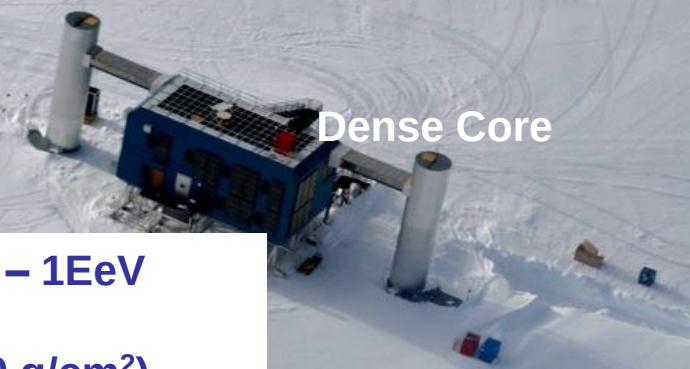
NIM A (2013) accepted - http://dx.doi.org/10.1016/j.nima.2013.09.018

IceTop





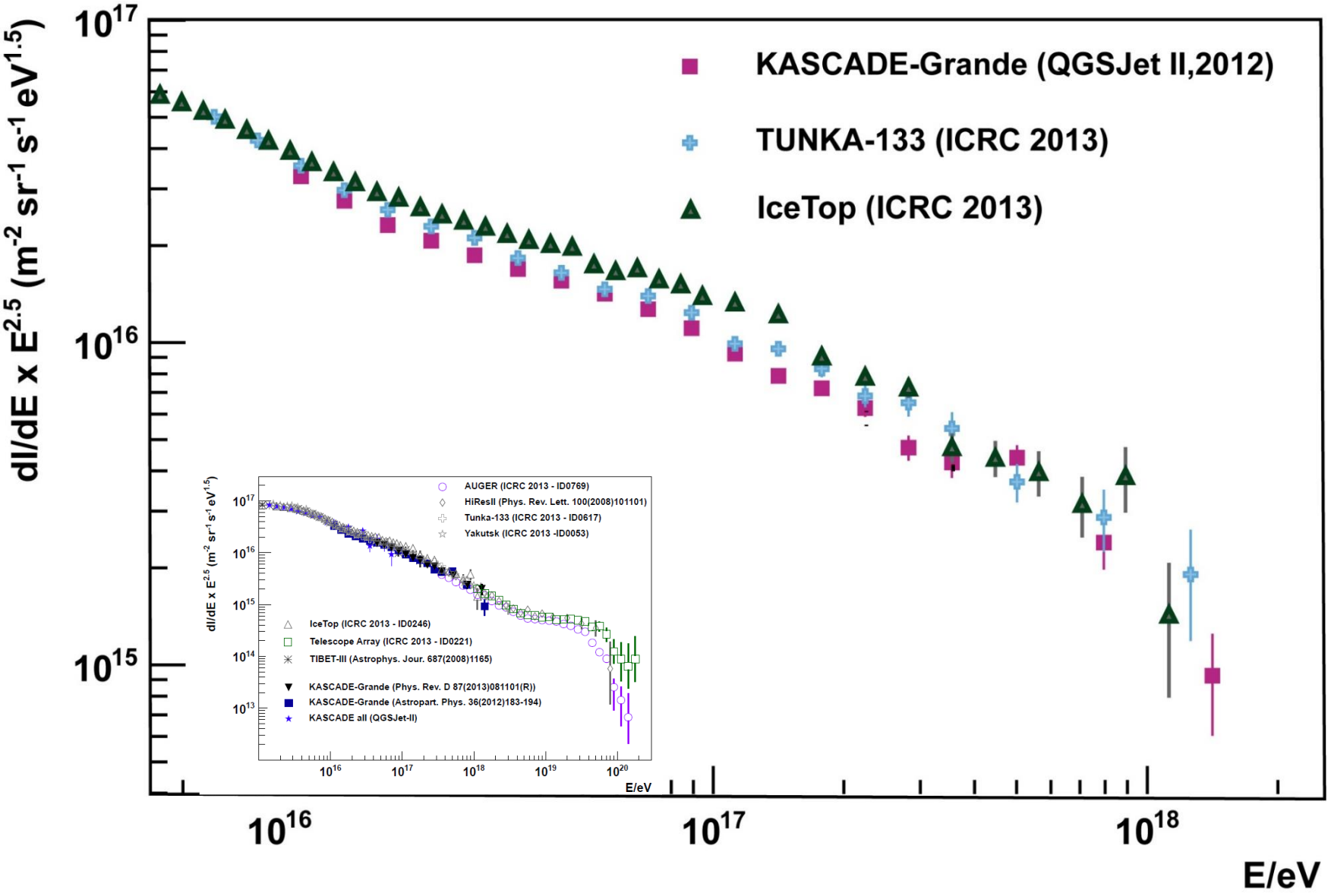




Dense Core

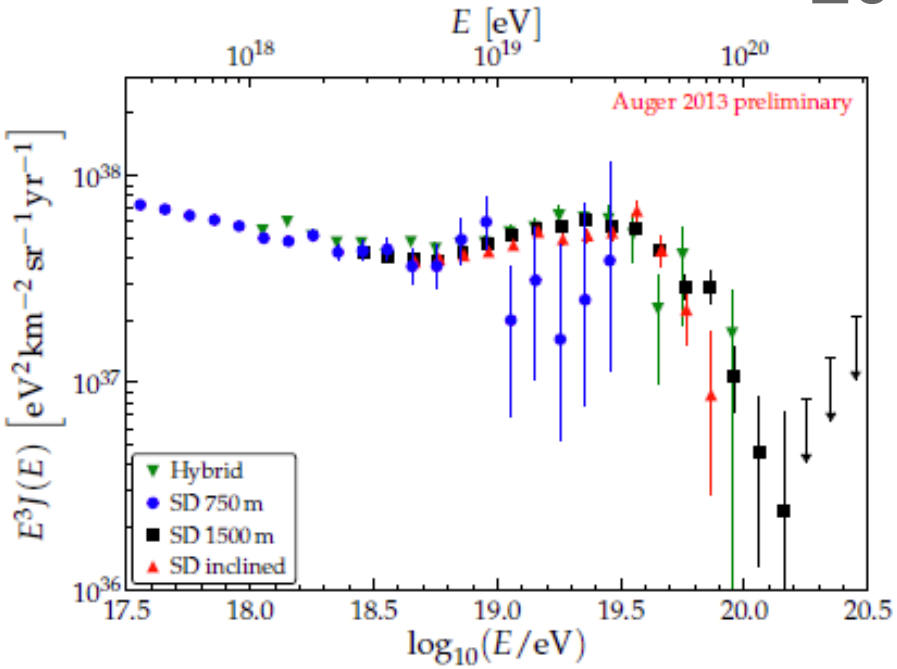
- Energy range: PeV – 1EeV
- Area: 1 km^2
- 2835m altitude (680 g/cm^2)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons

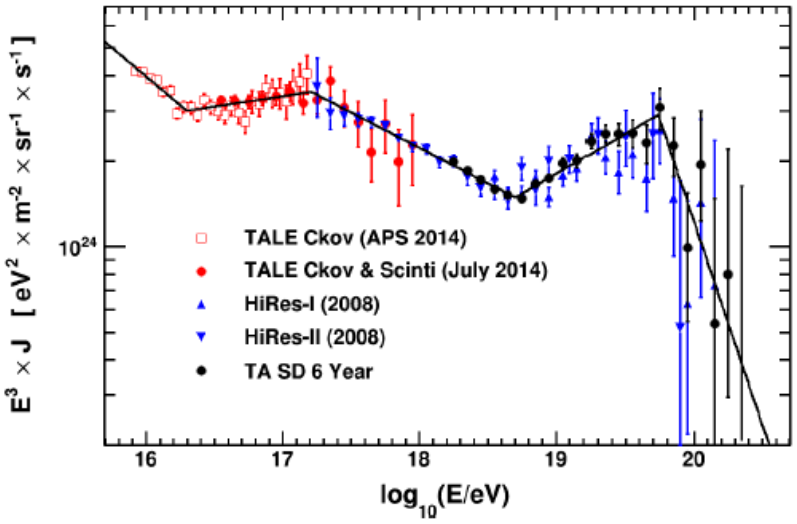
Phys Rev D (2013) accepted - dx.doi.org/10.1016/j.asr.2013.05.008 ??????



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

2015

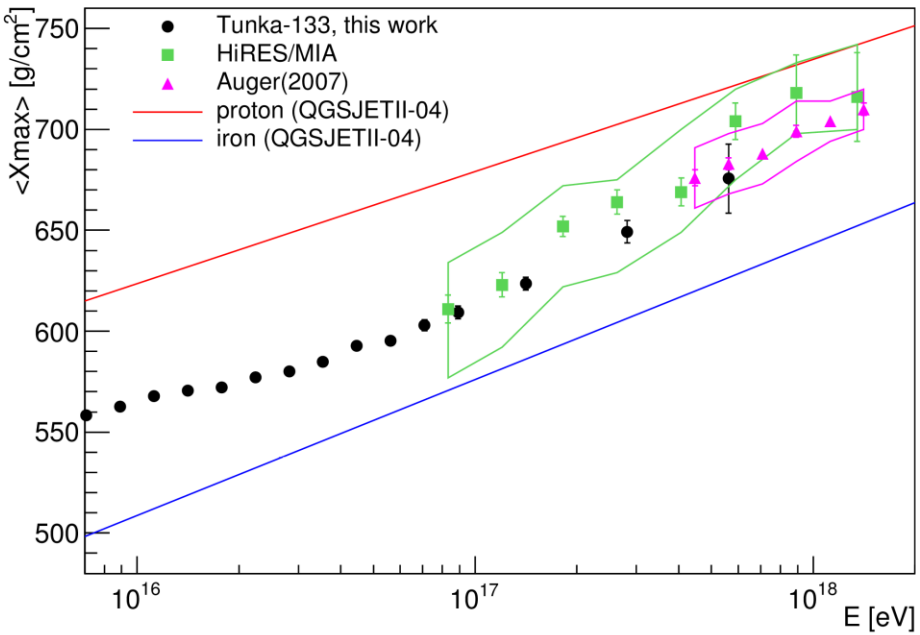

E [eV]
10^18
10^19
10^20
Auger 2013 preliminary
10^38
10^37
10^36
E^3J(E) [eV^2 km^-2 sr^-1 yr^-1]
Hybrid
SD 750 m
SD 1500 m
SD inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log10(E/eV)

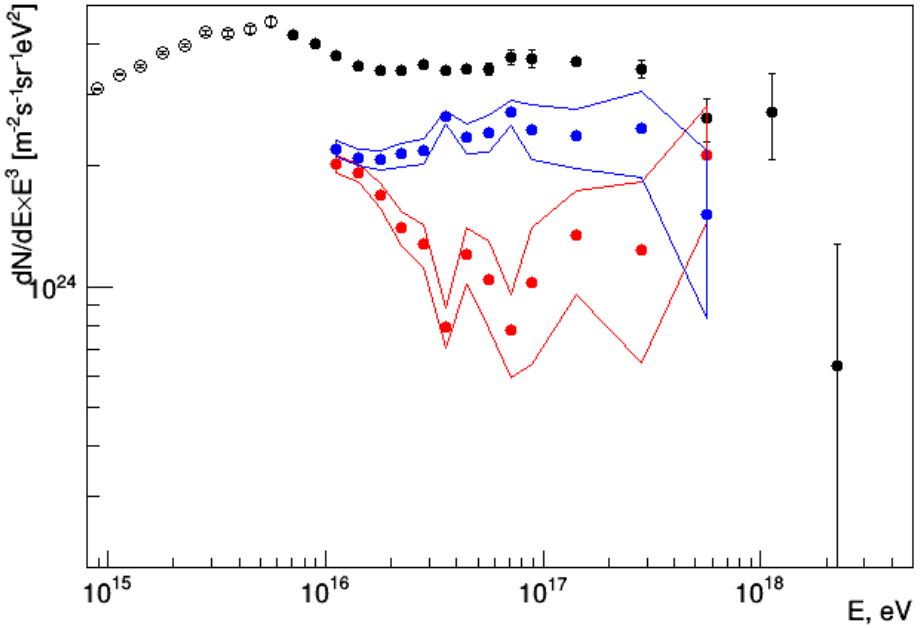

E^3 × J [eV^2 × m^-2 × sr^-1 × s^-1]
10^24
TALE Ckov (APS 2014)
TALE Ckov & Scinti (July 2014)
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year
16
17
18
19
20
log10(E/eV)


Pierre Auger
Observatory


Telescope Array

Tunka-133 Composition

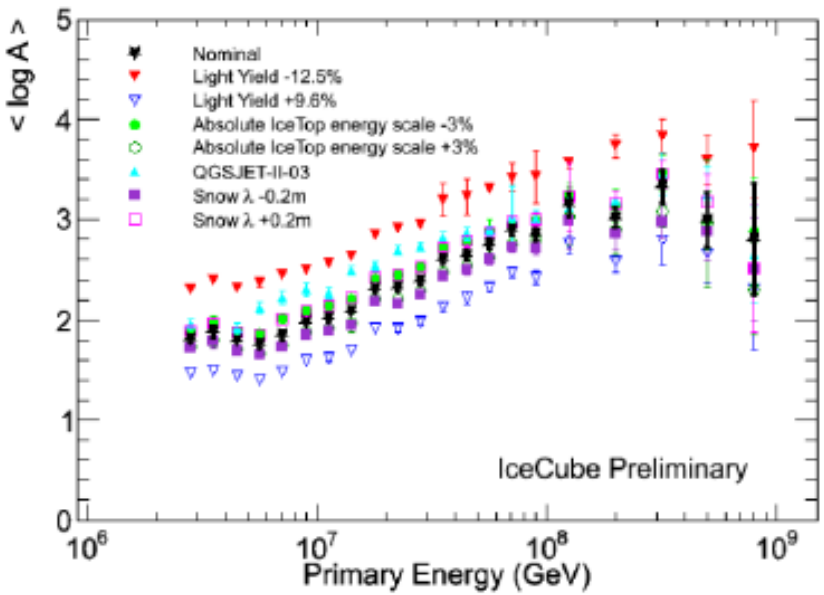


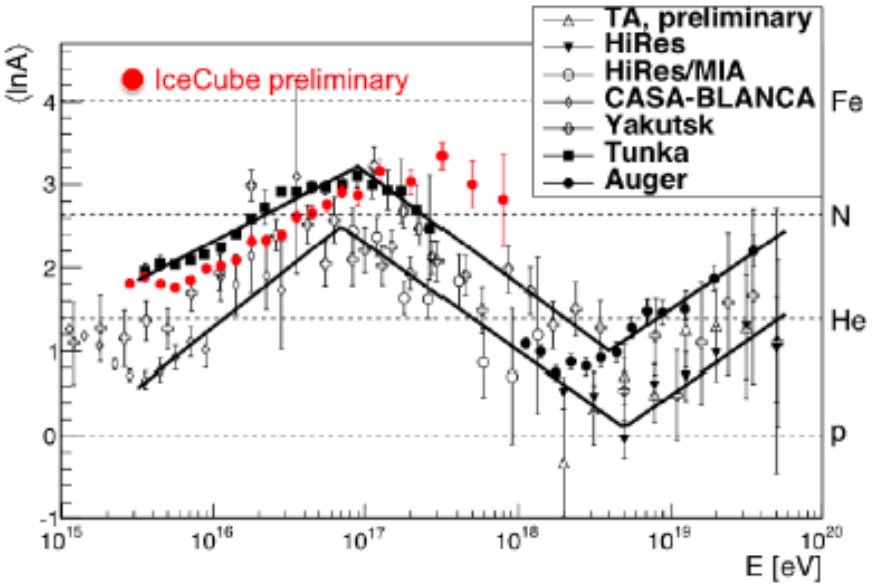


- **The heavy component (N+Fe) has a break at 10^{17} eV, reaching a fraction value of 80%**
- **The light component starts to rise again above 10^{17} eV**
- **Up to now we cannot confirm the sharp decrease of <ln A> seen by KASCADE and the high <ln A> at 10^{17} eV**

S.Epimahkov
Tunka-133 (2015)

IceTop+IceCube: Composition



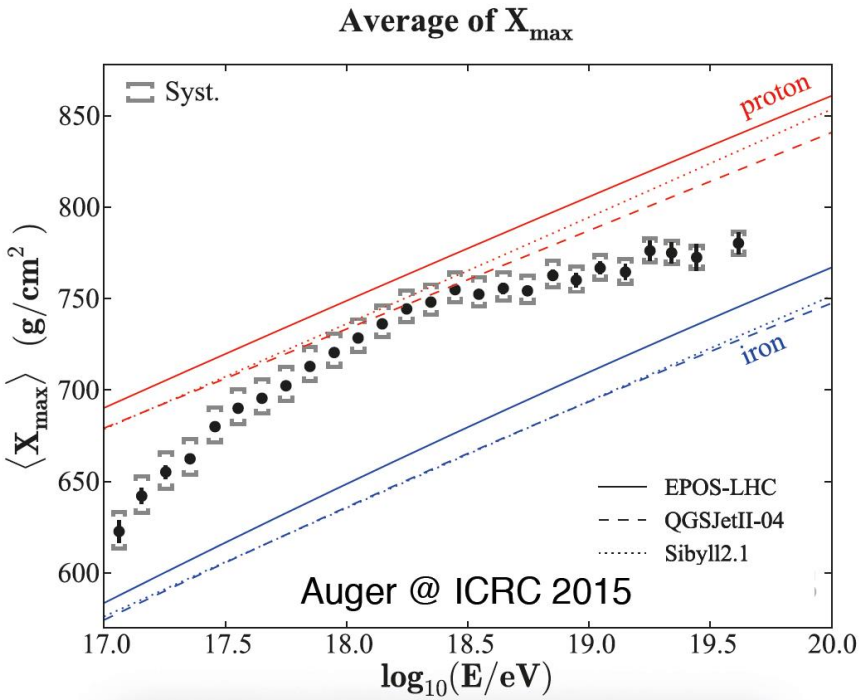


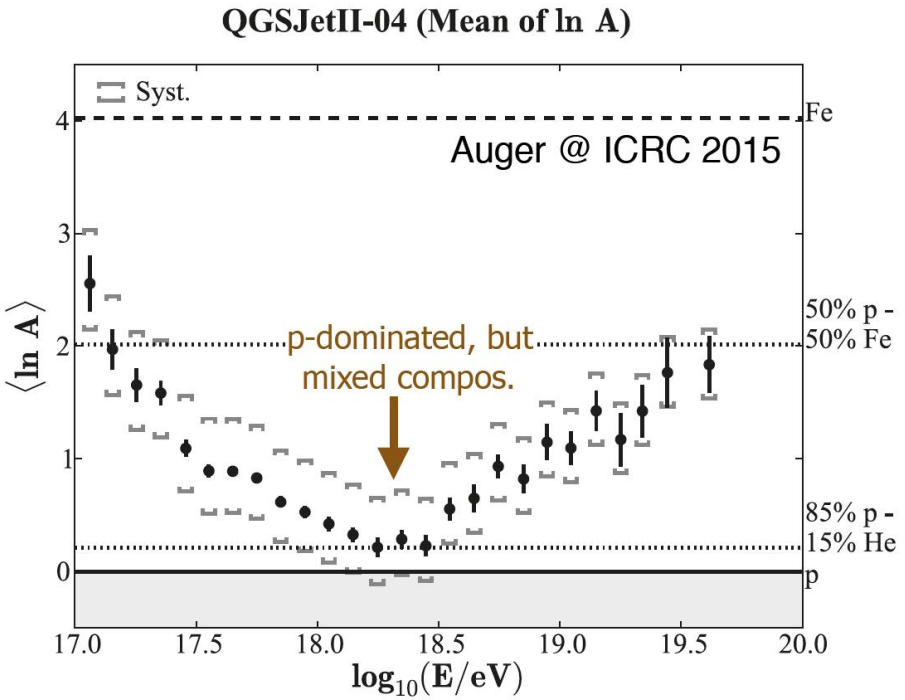
- Energy dependence of <ln(A)> from the coincident analysis and its systematic effects
- The combined IceTop-IceCube analysis shows a clear trend toward heavy primaries in average <ln(A)>
- The heavy knee is at higher energies and above the models

Gaisser, Nucl. Phys. B Proc. Supp. (2016) 1-9

HEAT (2015)

Auger Collaboration, ICRC2015, arXiv:1509.03732





Auger; arXiv:1509.03732, subm. to PRD

Correlations of Xmax and shower-size

⇒ mixed composition at ankle, i.e. no pure p-beam

⇒ dip-model (e+e- pair prod. in CMB) ruled out

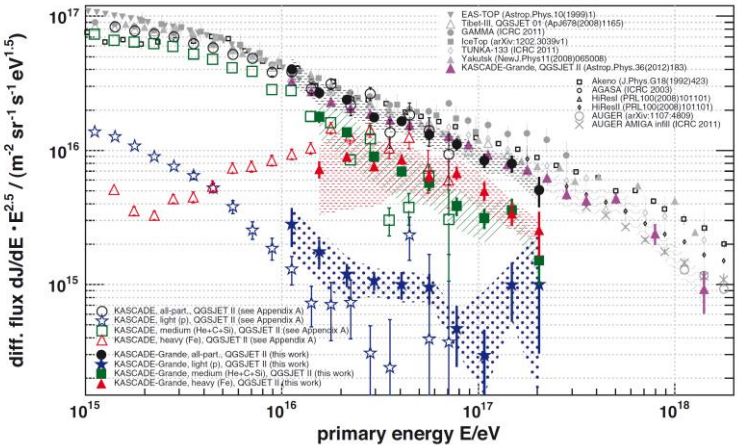
Kampert, 2016
Auger Collaboration

KASCADE-Grande: Next

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



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

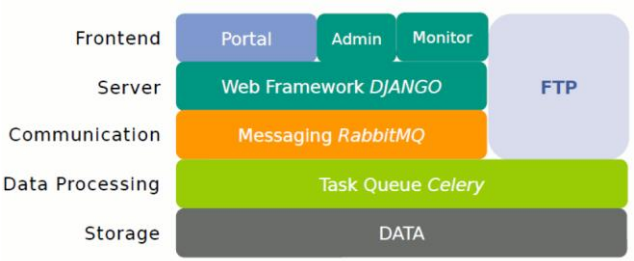


- **detailed data analysis (20y high-quality data)**
  - **testing hadronic interaction models**
  - **anisotropy studies**
  - **radio (LOPES and CROME)**

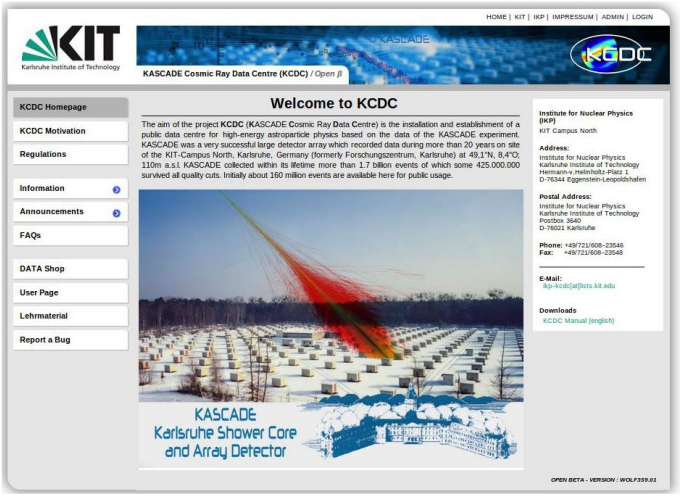
- **KCDC**
  - **KASCADE Cosmic ray Data Centre**

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

Paper in preparation

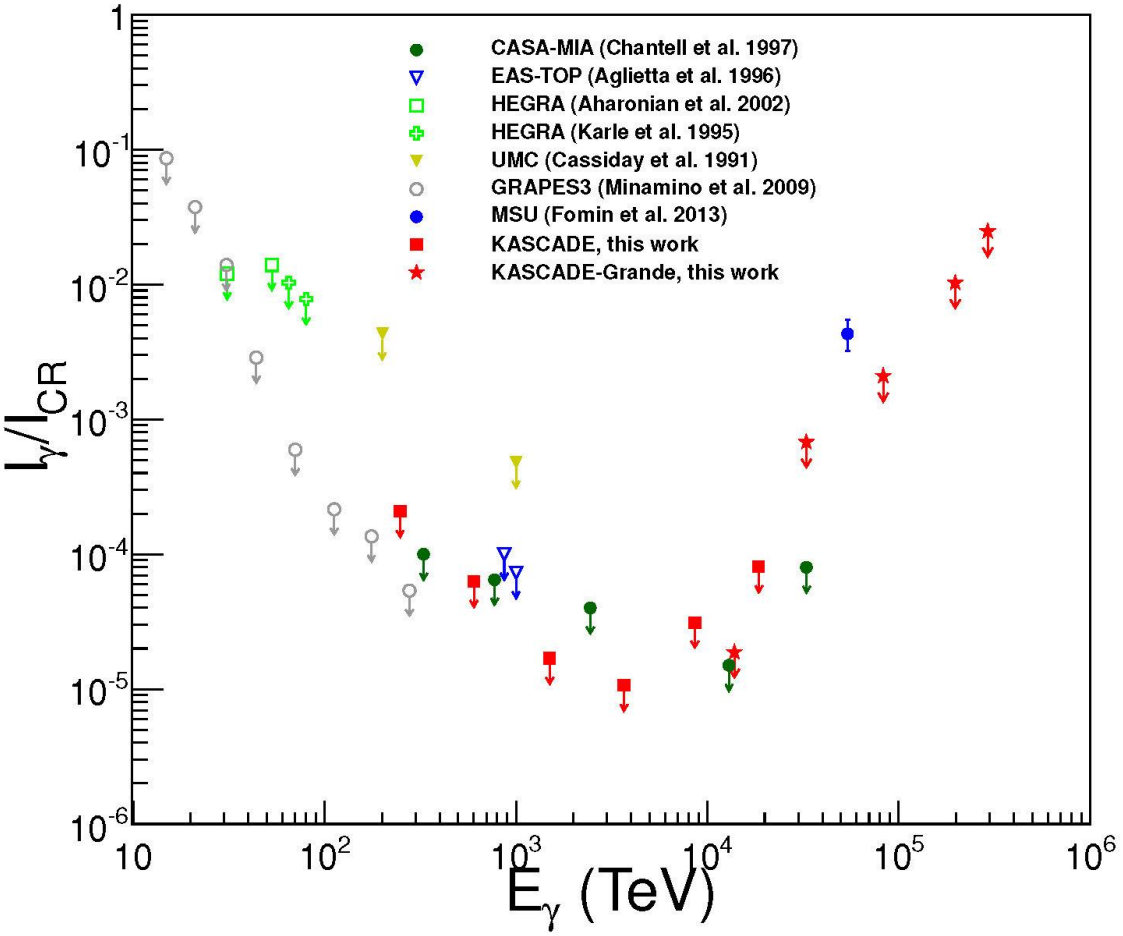
KASCADE-Grande: Mission Accomplished !!

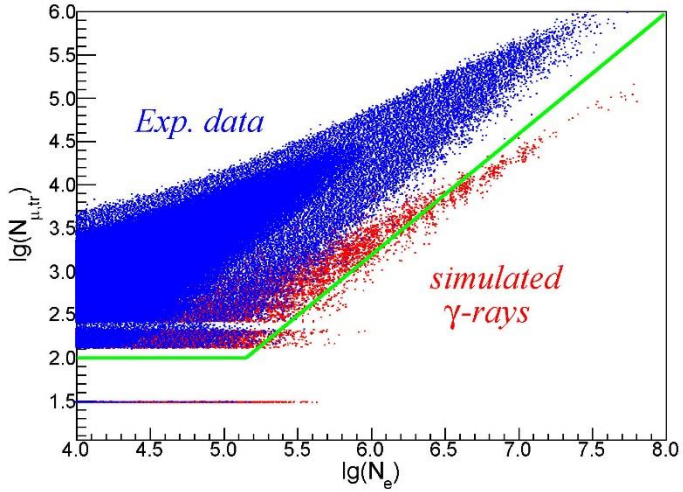
open access to research data
https://kcdc.ikp.kit.edu

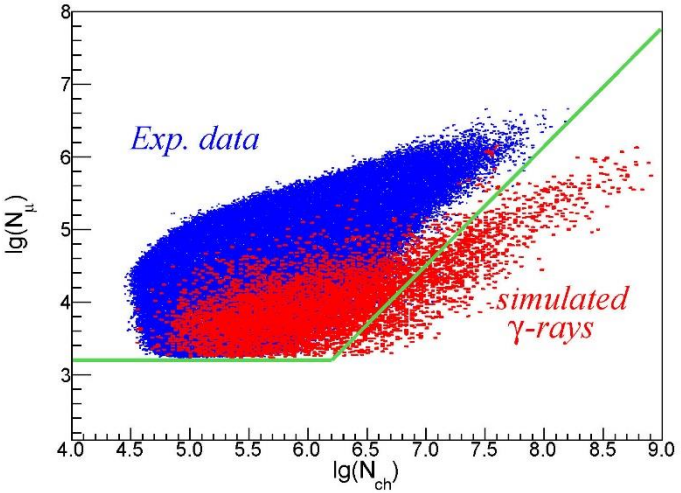
KASCADE-Grande: Mission Accomplished !!

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

Ratio of diffuse Gamma-ray Flux to cosmic ray flux



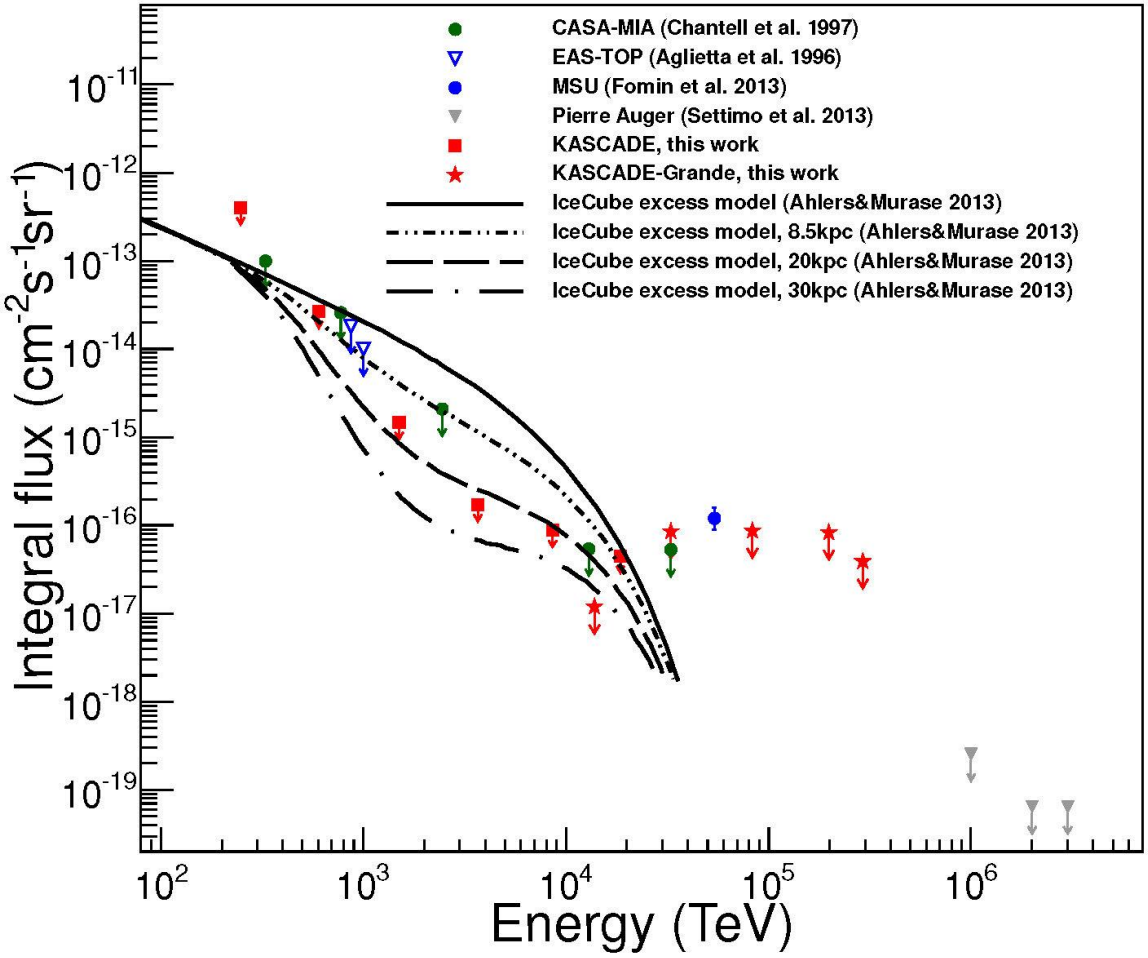




- **obtained by looking for muon-poor air shower**

Paper submitted
Analysis by Donghwa Kang

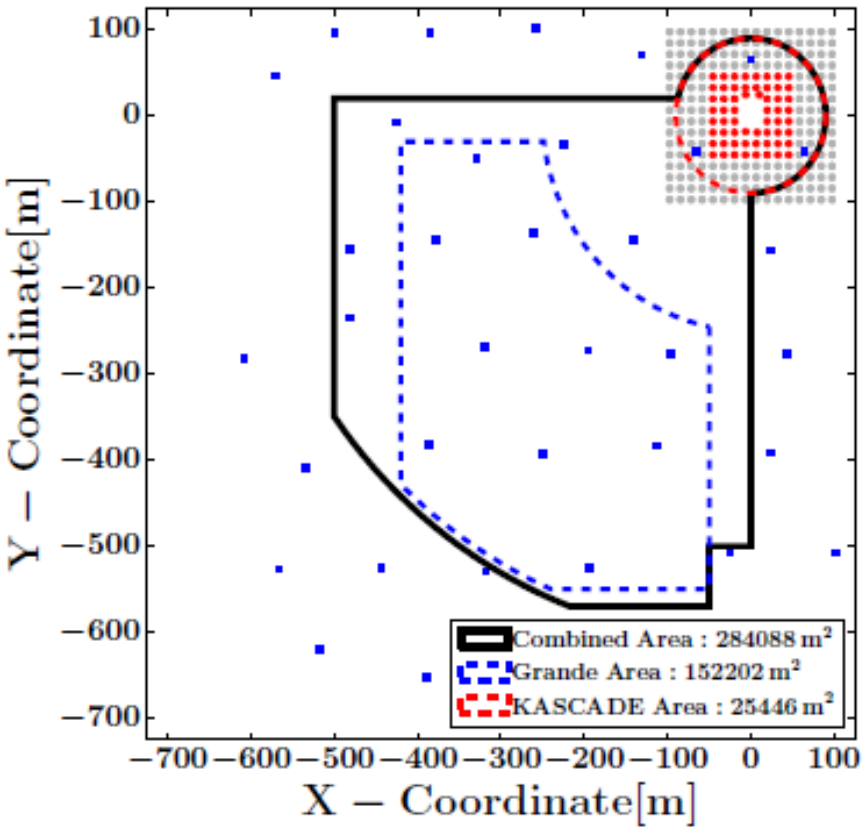
Limits on diffuse Gamma-ray Flux

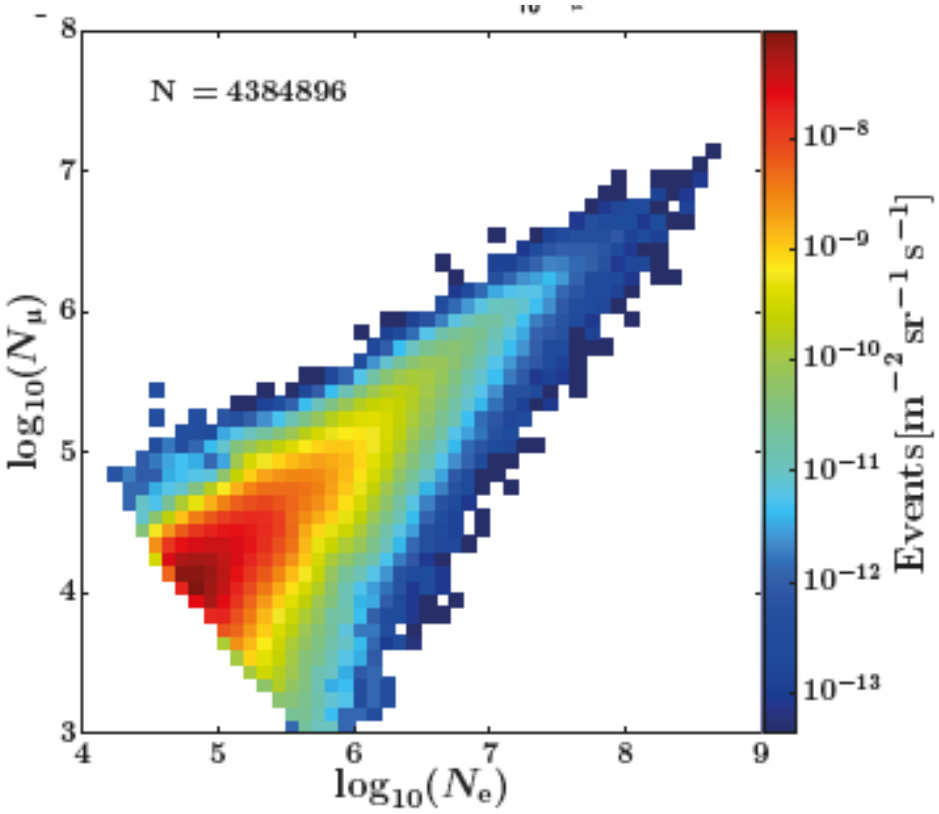


- **limits on diffuse Gamma-ray flux constrain the origin of IceCube-neutrinos**

← Reject the model of IceCube excess coming from <20kpc in the galaxy

KASCADE-Grande: Combined Analysis

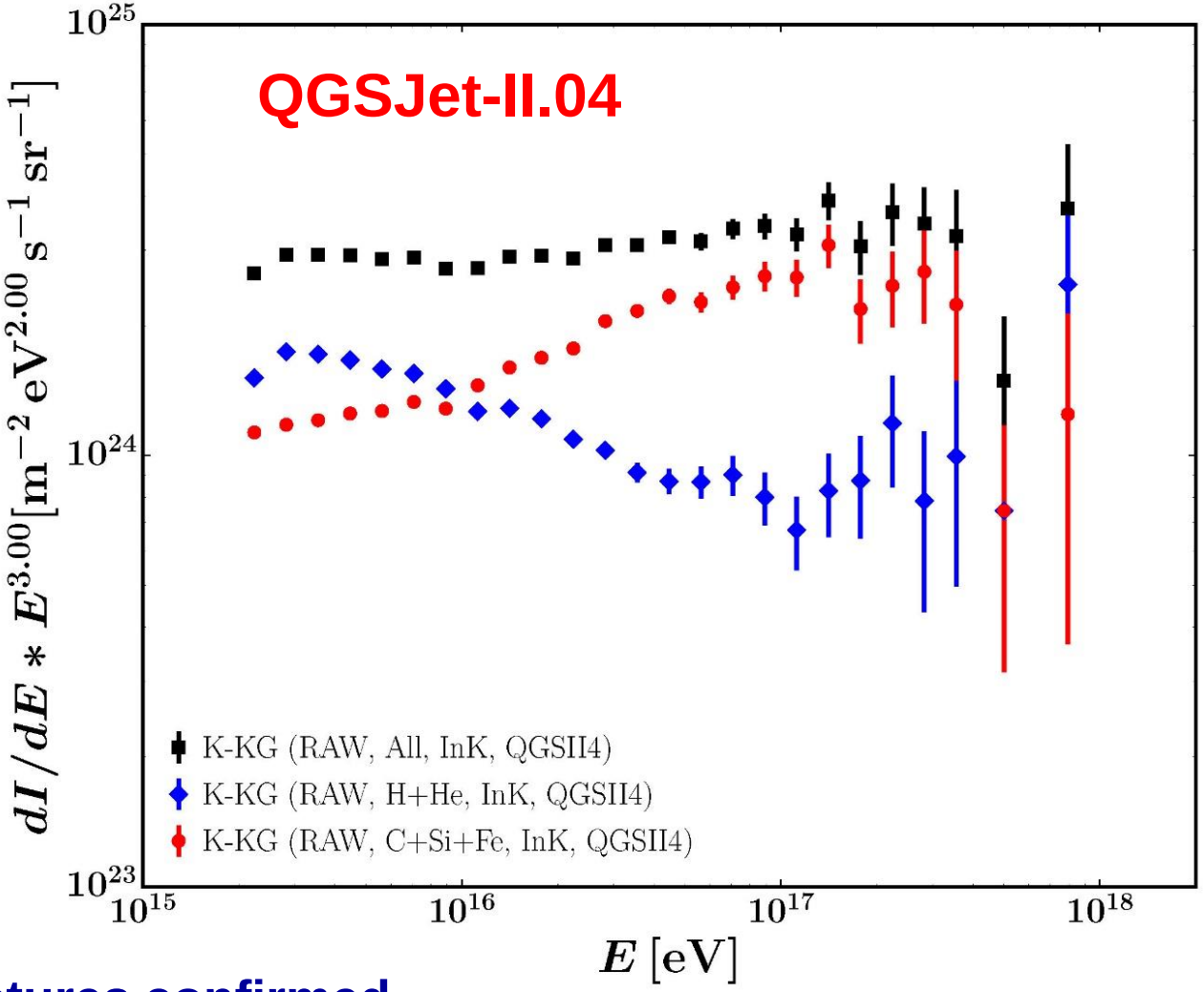




- **for KASCADE: additional stations at larger distances**
  ➔ higher energies
- **for Grande: additional 252 stations**
  ➔ higher accuracy

Analysis by Sven Schoo

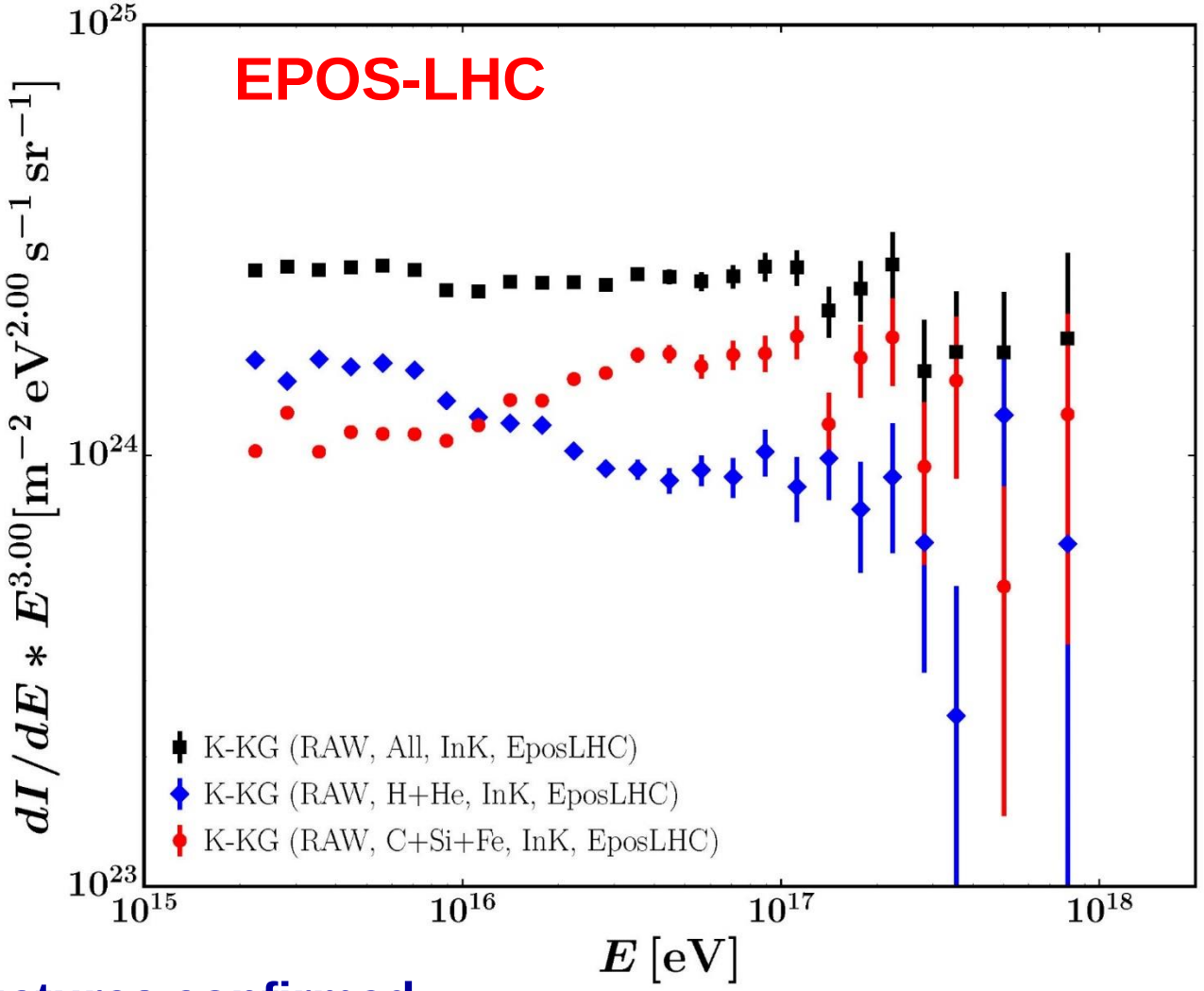
KASCADE-Grande: Combined Analysis resulting energy spectra



- **all structures confirmed**

Spectra not corrected for uncertainties

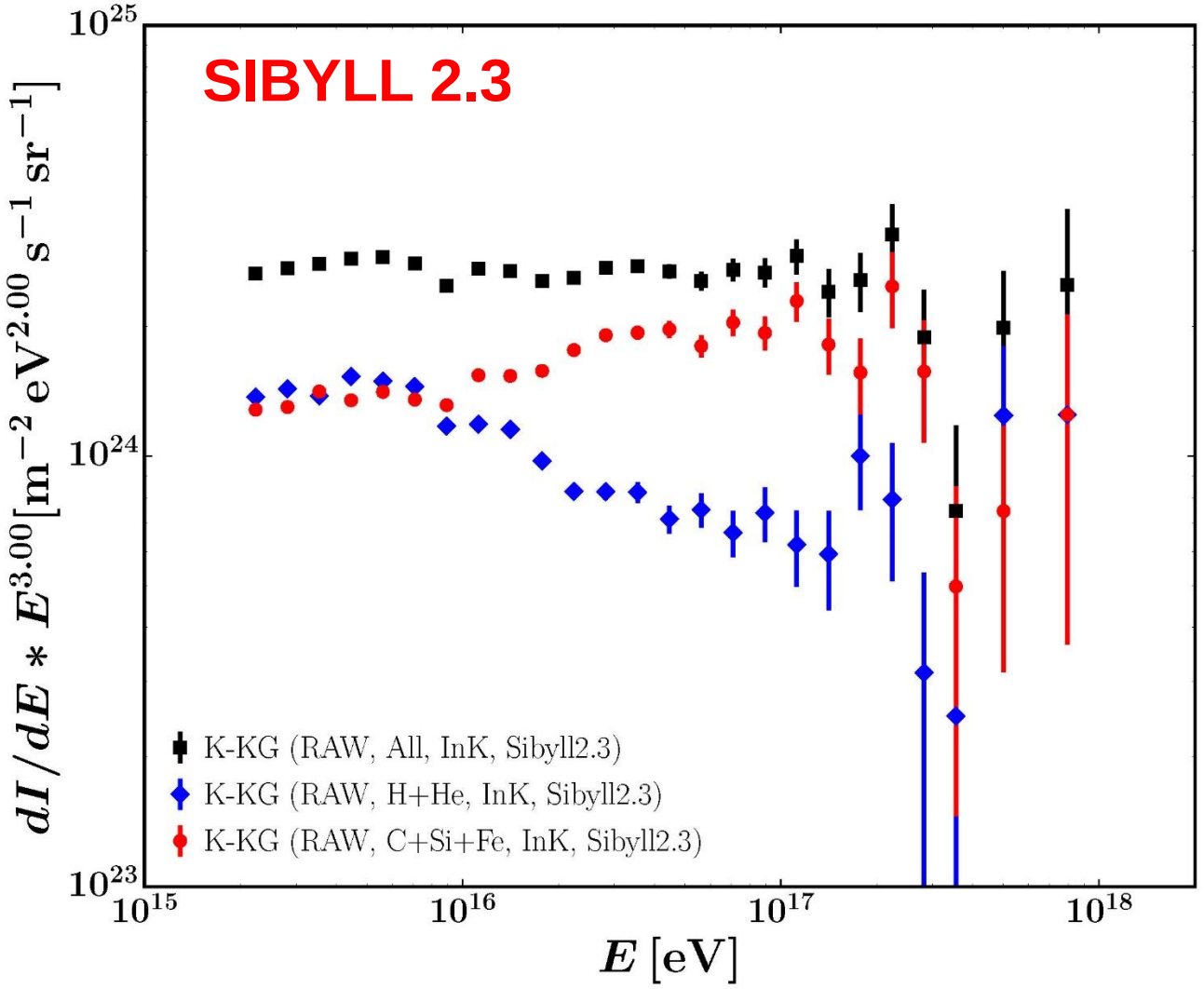
KASCADE-Grande: Combined Analysis resulting energy spectra



- **all structures confirmed**

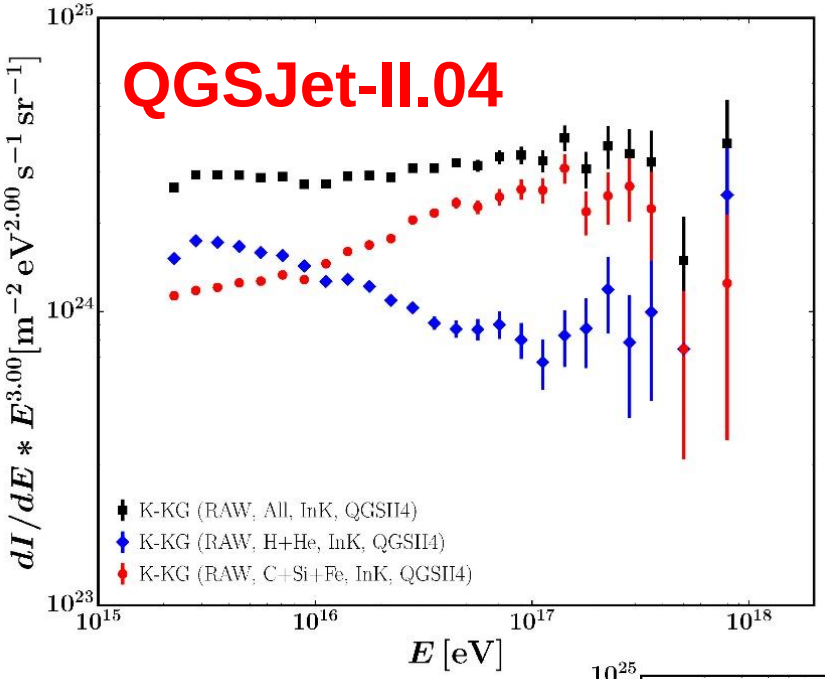
Spectra not corrected for uncertainties

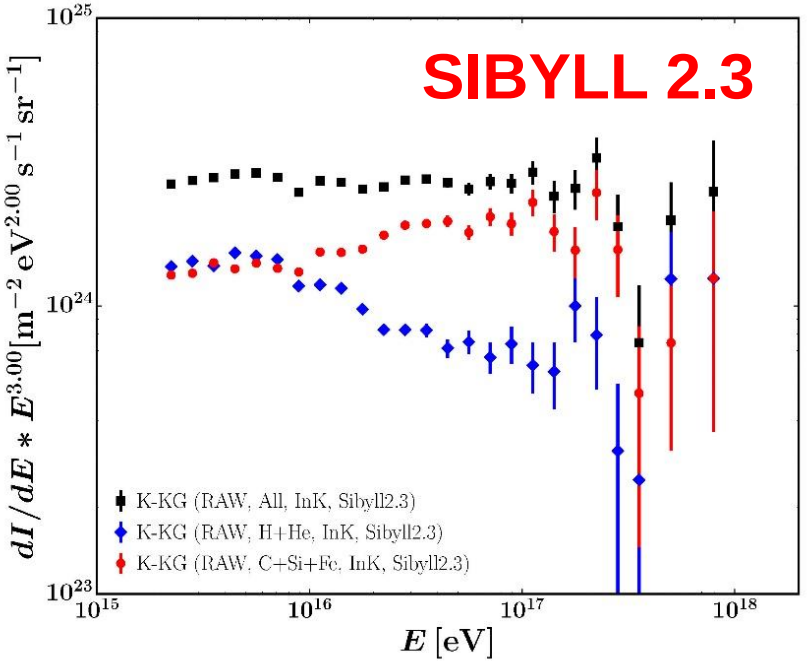
KASCADE-Grande: Combined Analysis resulting energy spectra

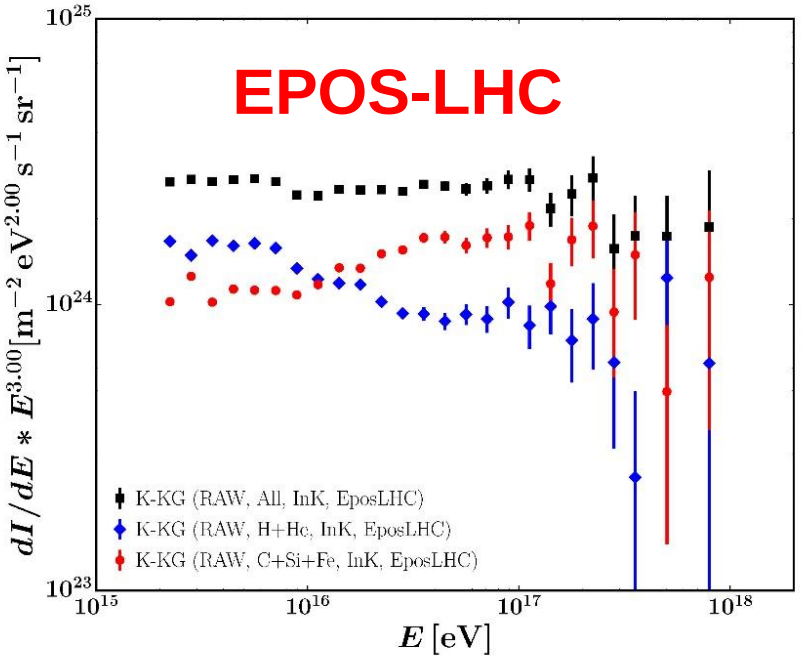


- **all structures confirmed**

Spectra not corrected for uncertainties



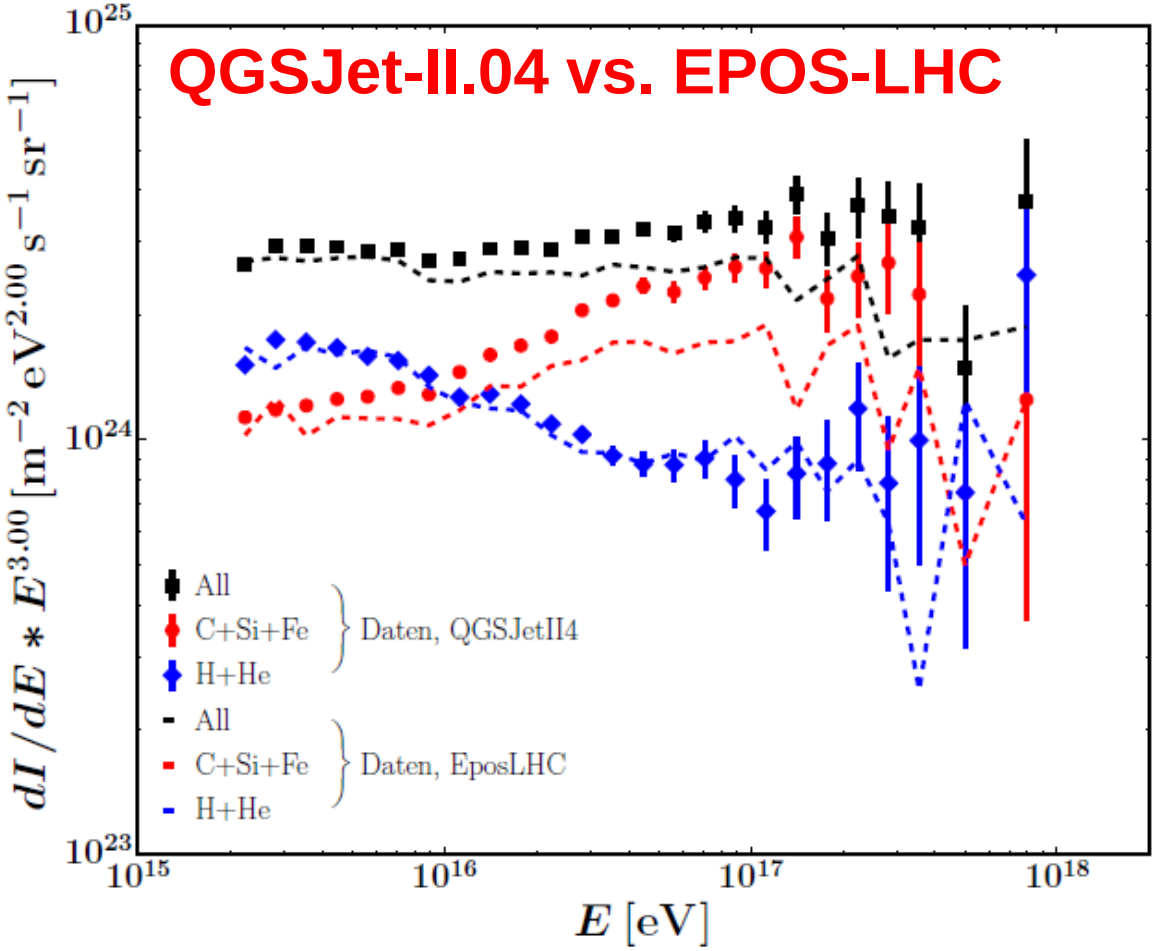




- **structures confirmed**
- **all particle spectrum good agreement**
- **relative abundance of light and heavy quite different**

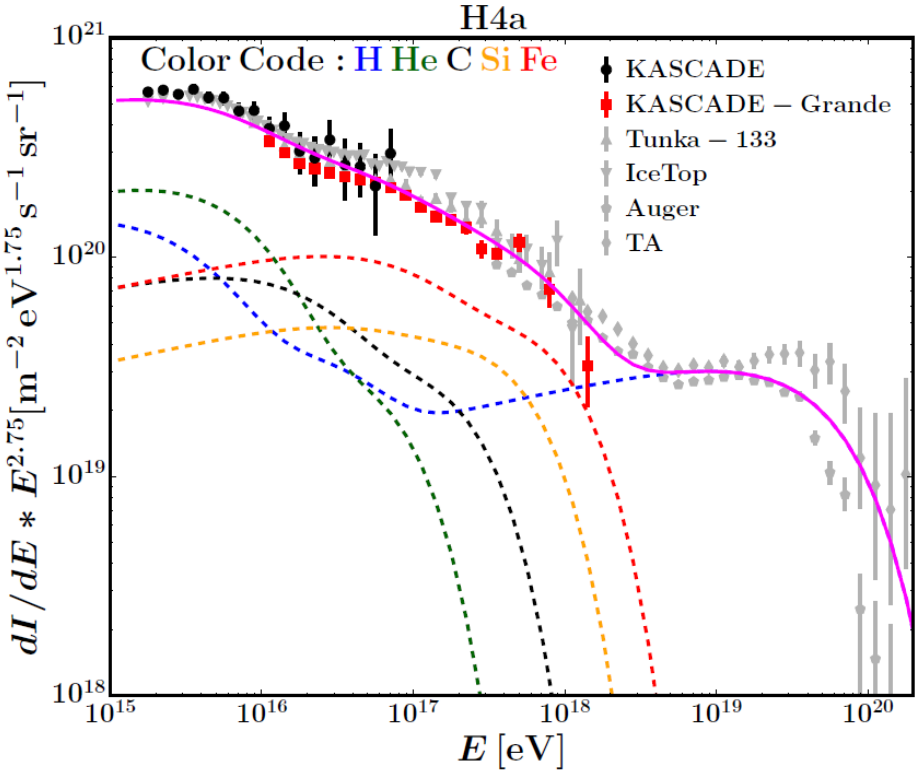
KASCADE-Grande: Combined Analysis

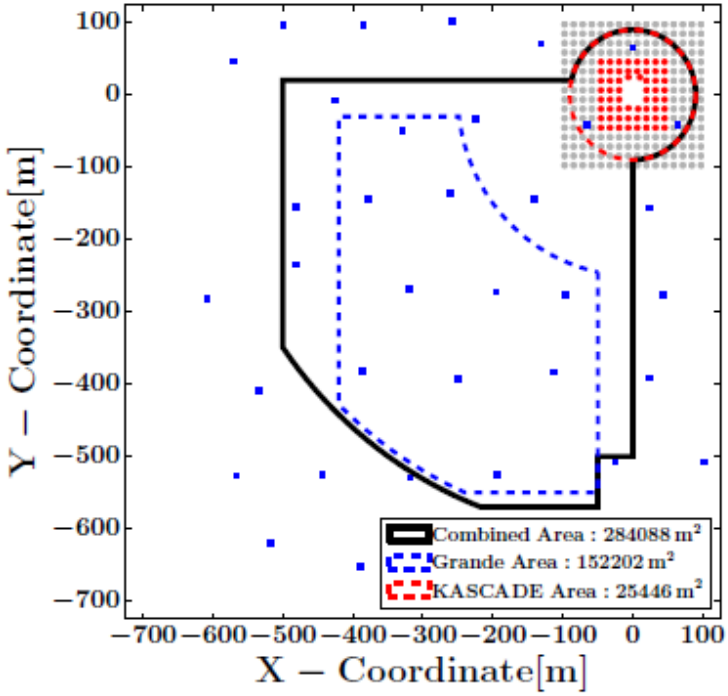
resulting energy spectra based on two hadronic interaction models



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

KASCADE-Grande: combined analysis
Check Hadronic Interaction Models





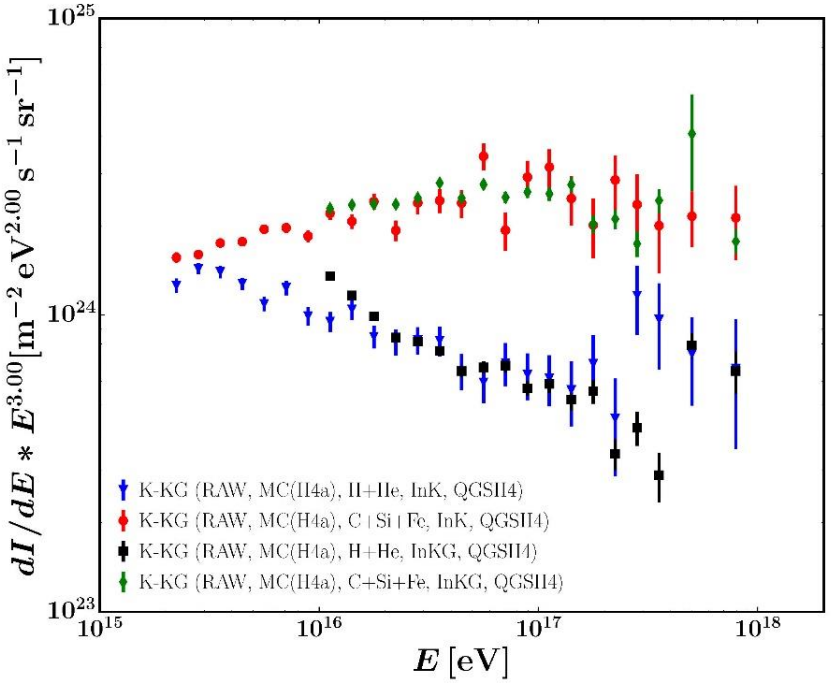
- **assume a composition model: H4a by Tom Gaisser**

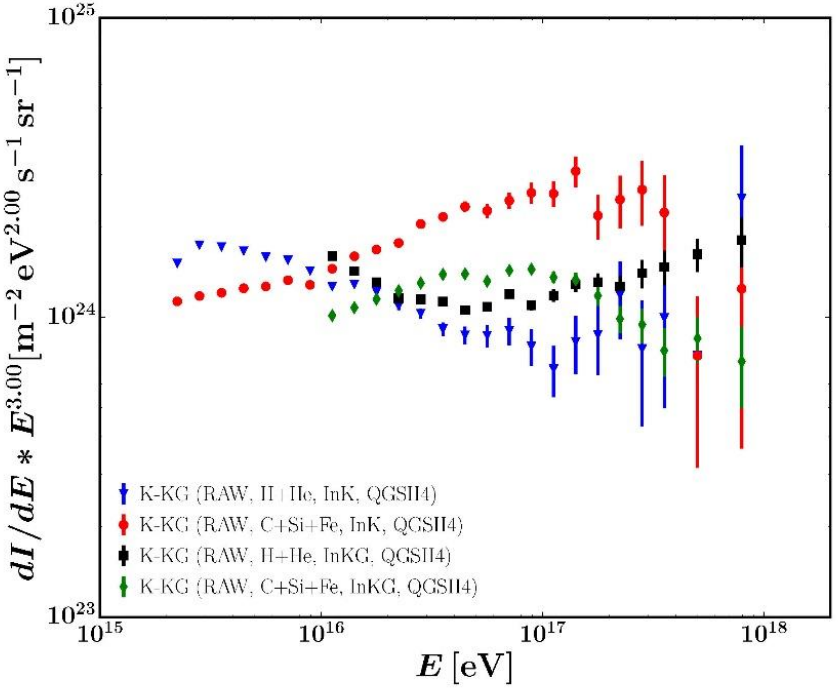
- **two selections: core located in KASCADE, core located in Grande**
  ➔ we measure “different” muons

KASCADE-Grande: Combined Analysis

Test of models

QGSJet-II.04





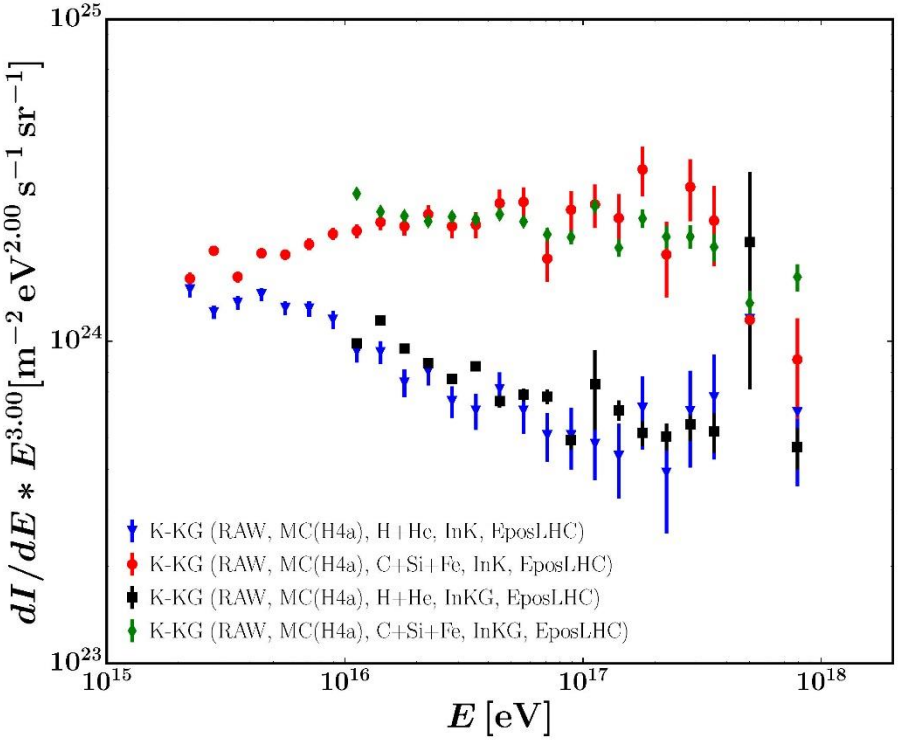
- **One model, but two selections:**
  Simulations okay, but for the data strong differences

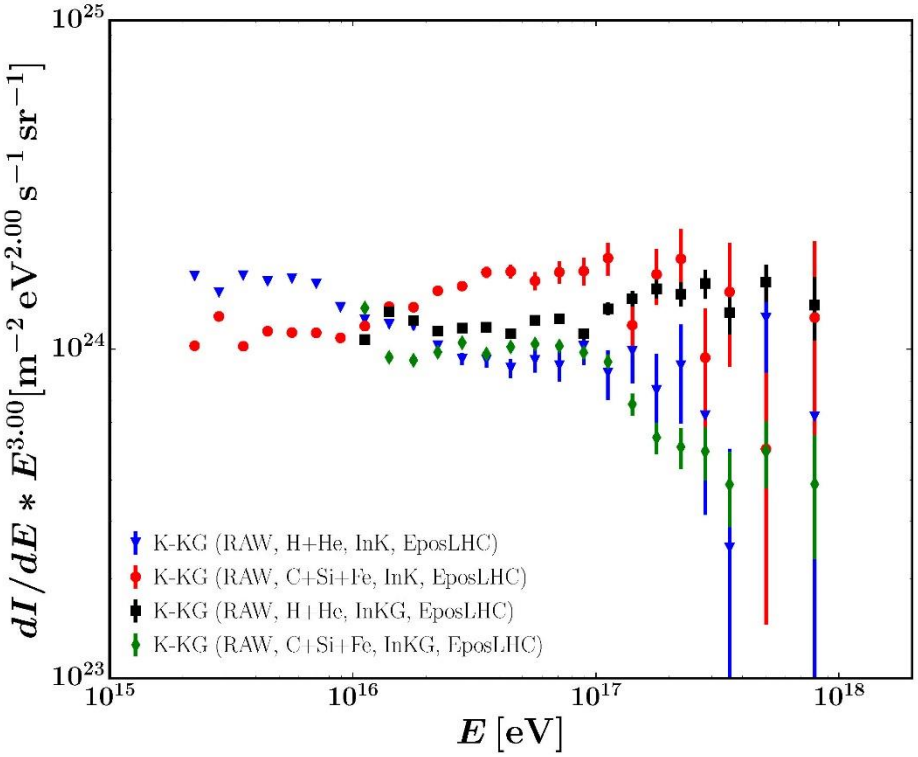
➔ **Muon component not sufficiently described**

KASCADE-Grande: Combined Analysis

Test of models

EPOS-LHC





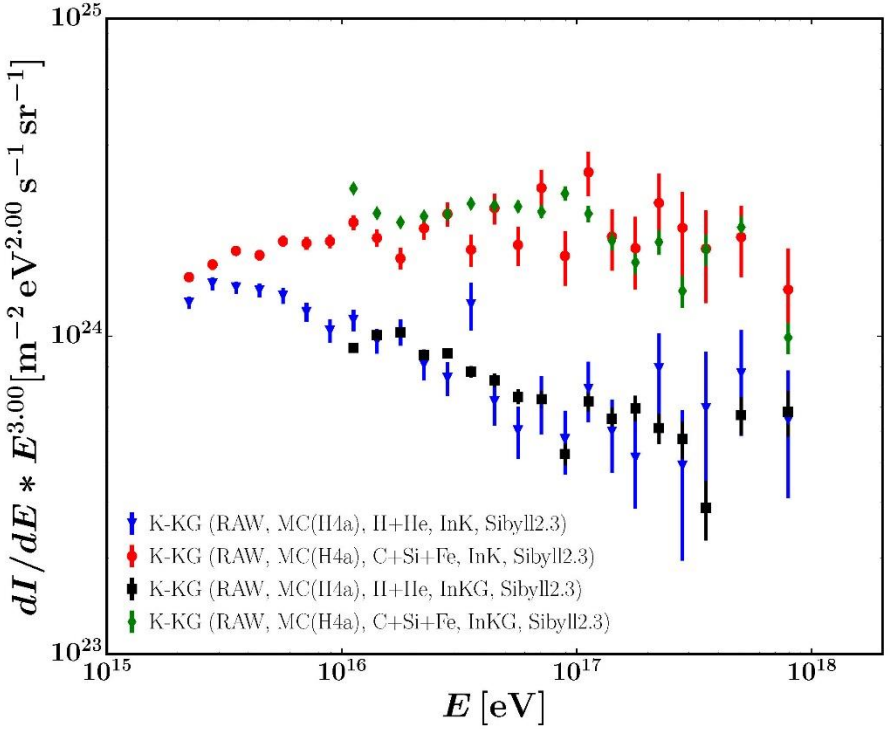
- **One model, but two selections:**
  Simulations okay, but for the data strong differences

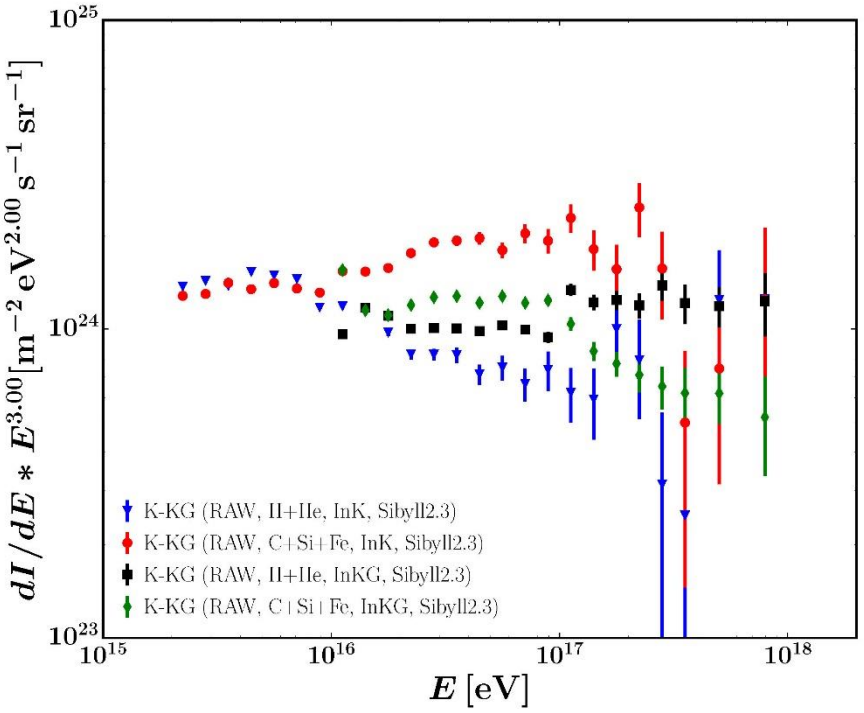
➔ **Muon component not sufficiently described**

KASCADE-Grande: Combined Analysis

Test of models

SIBYLL 2.3



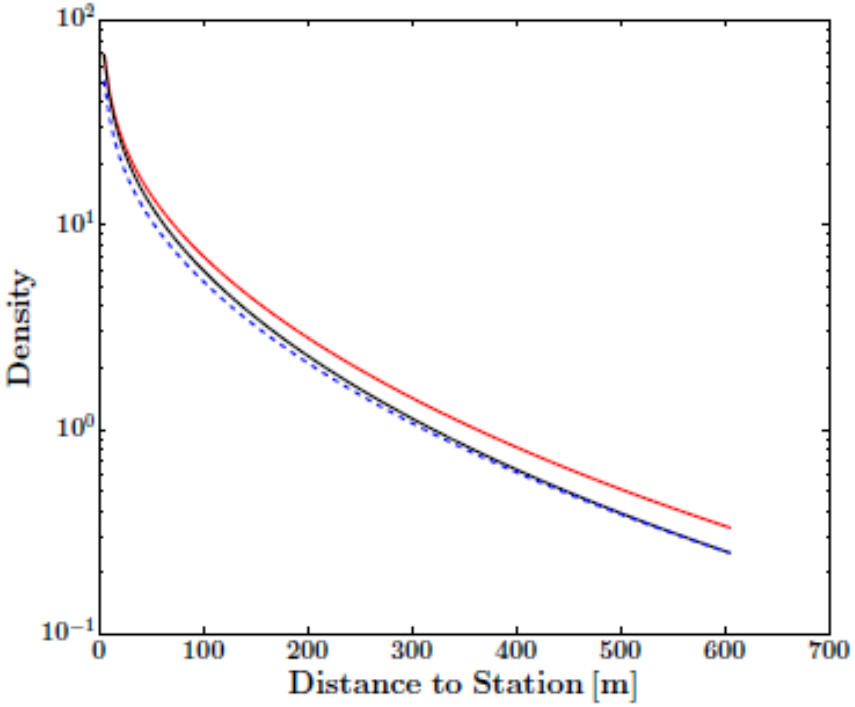


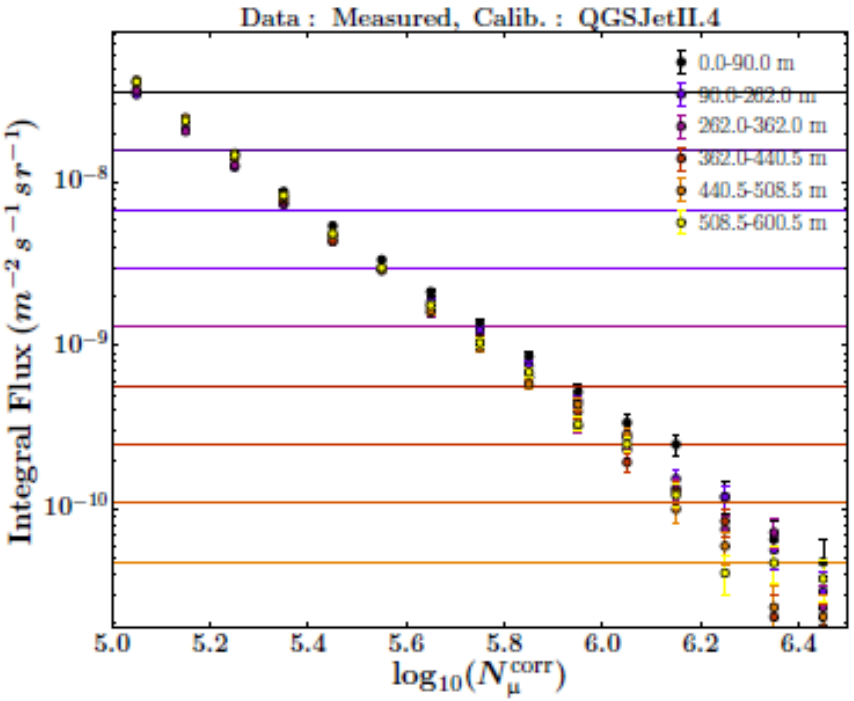
- **One model, but two selections:**
  Simulations okay, but for the data strong differences

➔ **Muon component not sufficiently described**

KASCADE-Grande: Combined Analysis

Test of models





Slope is parametrized with N_e, but fixed and too flat

Distance range covered by Muon detectors limited

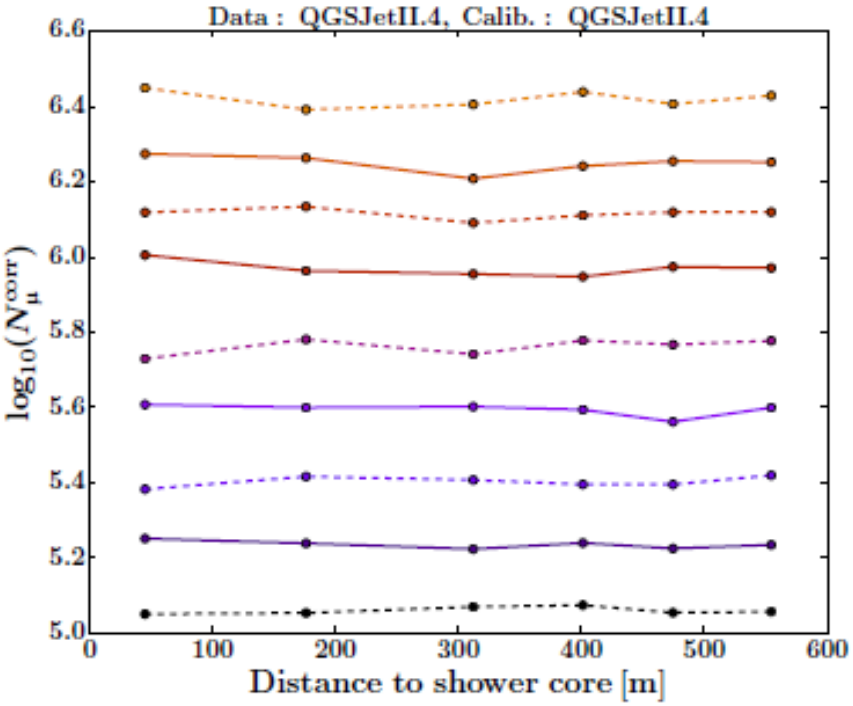
If core within KASCADE → too many muons.

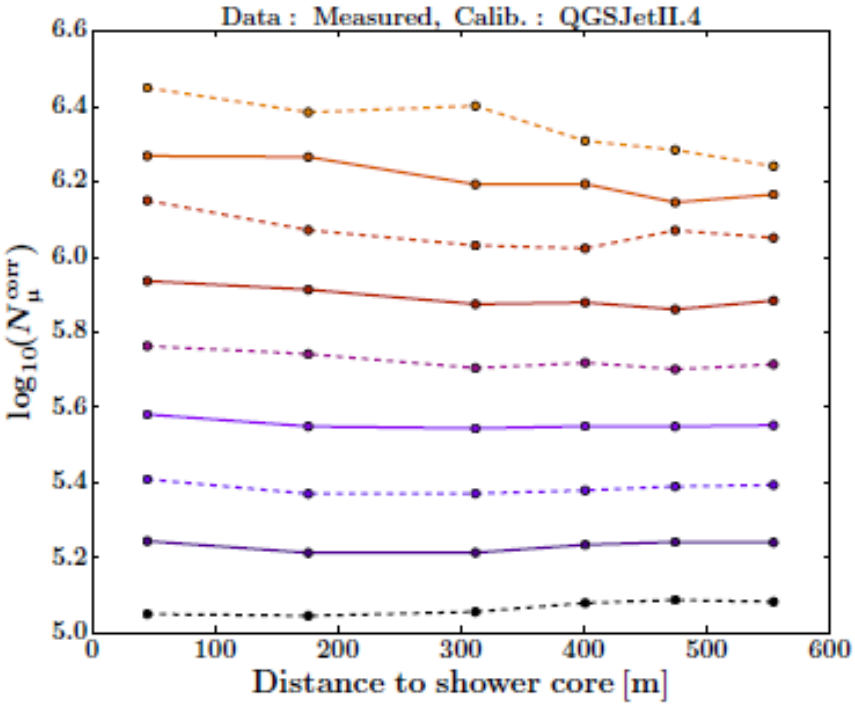
If core within Grande → too few muons.

Crosscheck using "Constant Intensity"

Sven Schoo

KASCADE-Grande: Combined Analysis
Test of models





Number of muons relatively constant for simulations

Number of muons corresponding to same intensity drops for measured data towards higher energies

Can be used to mitigate effect, however, more accurate MC needed

Sven Schoo

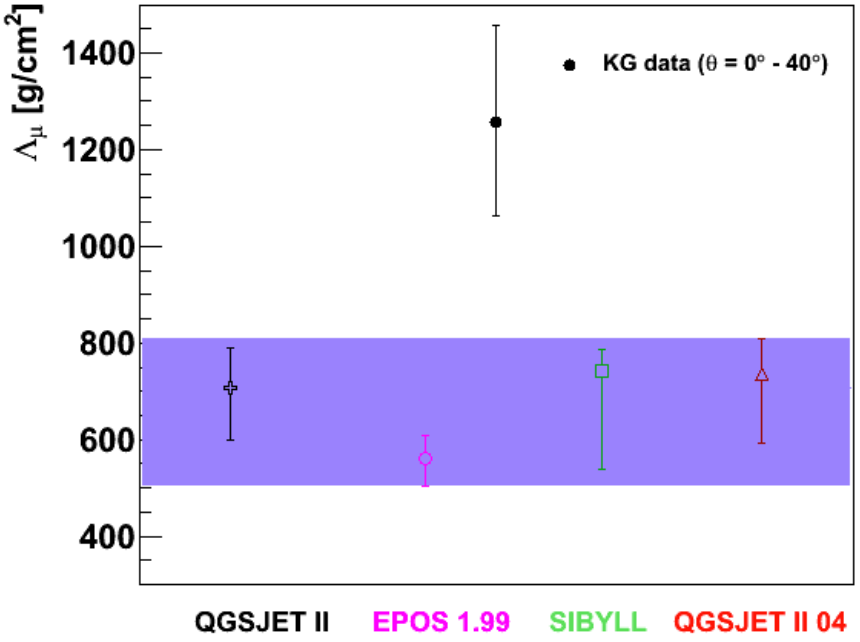
KASCADE-Grande: Muon Attenuation Length

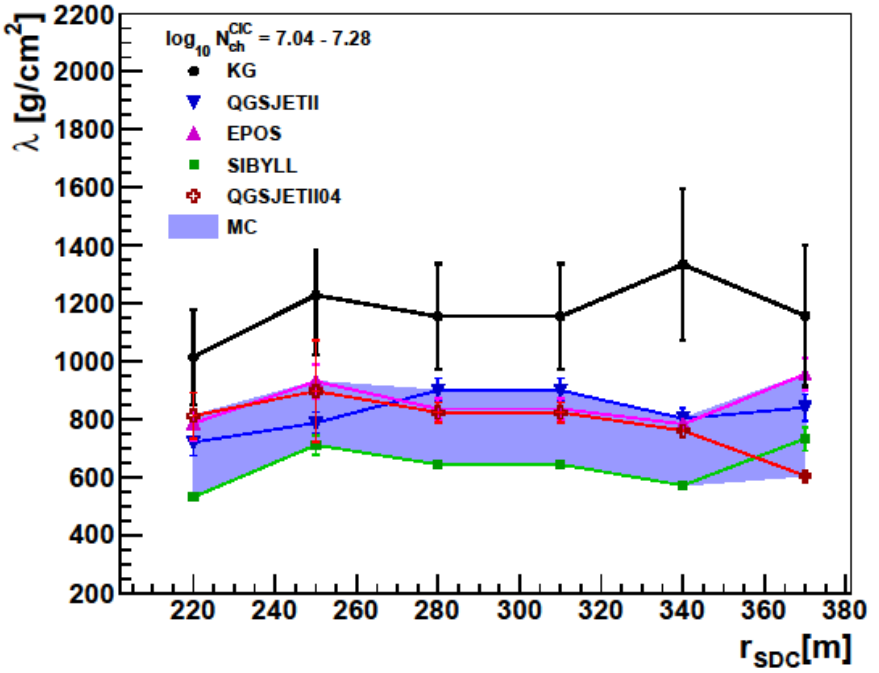
total muon number

$$N_\mu = N_{\mu,0} \exp[- X_0 \sec(\theta) / \Lambda_\mu]$$

local muon density

$$\rho_\mu(r) = \rho_{\mu,0}(r) \exp[- X_0 \sec(\theta) / \lambda_\mu(r)]$$





attenuation length measured is different from the predictions of Monte Carlo

➔ observed evolution of the muon content of EAS in the atmosphere is not described by the hadronic interaction models

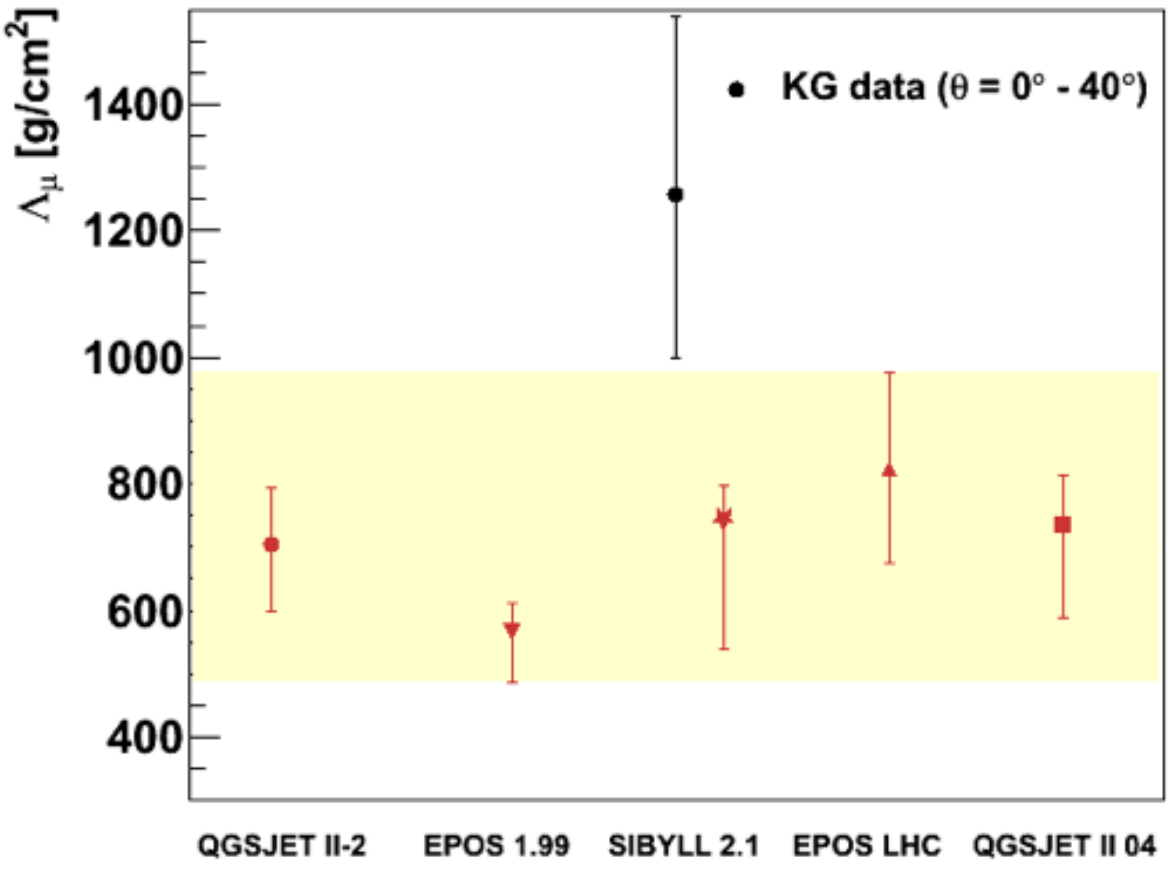
➔ influences absolute energy and mass scale, but not spectral features

KASCADE-Grande, ICRC 2013 #0772, paper in preparation

Juan Carlos Arteaga

KASCADE-Grande: Muon Attenuation Length

total muon number : $N_\mu = N_{\mu,0} \exp[- X_0 \sec(\theta) / \Lambda_\mu]$

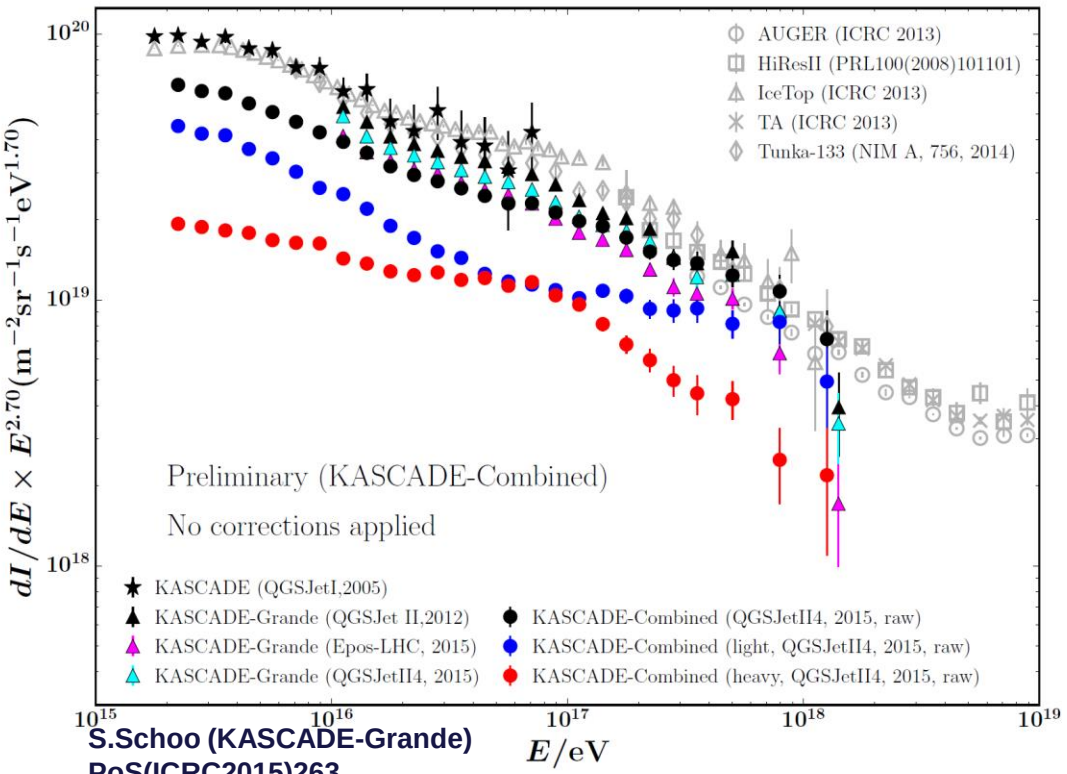


Post-LHC models are presently under investigation
EPOS-LHC looks a bit more promising

Juan Carlos Arteaga

Conclusion combined analysis:

All particle, light and heavy spectra for 3 orders of magnitude



S.Schoo (KASCADE-Grande)
PoS(ICRC2015)263

Paper in preparation
Analysis by Sven Schoo

- **Structures of spectra confirmed**
- **H4a model probably not far away from real composition**
- **Models still do not agree to each other and to data**
- **Light component seems to agree better than heavy**
- **Problem probably in the muons (known due to special selection)**
- **Around 10^{15} eV still (again) no clear picture**

Discussion

Points to discuss:

- Light and heavy knee established
- Light ankle probably there
- Difficult to compare experiments due to different observables
  what is contribution of MHz-Radio?
- KASCADE-Grande combined:
  no conclusive result as models still not describe reality
- New models at lower energy (before the knee)???
- Still problem: absolute mass scale
- Will be something new by IceTop / Tunka-133 data analysis?
- LHAASO, GRAPES, TAIGA, TALE, HEAT, Auger-Infill, LOFAR, HAWC?
- ….

Lessons learned from the >25-years 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

Institut für Kernphysik & Institut für Experimentelle Kernphysik
KIT - Karlsruhe Institute of Technology

W.D.Apel, K.Bekk, J.Blümer, H.Bozdog, F.Cossavella, K.Daumiller, P.Doll, R.Engel, J.Engler, M.Finger, B.Fuchs, H.J.Gils, A.Haungs, D.Heck, D.Huber, T.Huege, D.Kang, H.O.Klages, K.Link, M.Ludwig, H.-J.Mathes, H.J.Mayer, M.Melissas, J.Milke, J.Oehlschläger, N.Palmieri, T.Pierog, H.Rebel, M.Roth, H.Schieler, S.Schoo, F.G.Schröder, H.Ulrich, A.Weindl, J.Wochele, M.Wommer

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Morelia, Mexico
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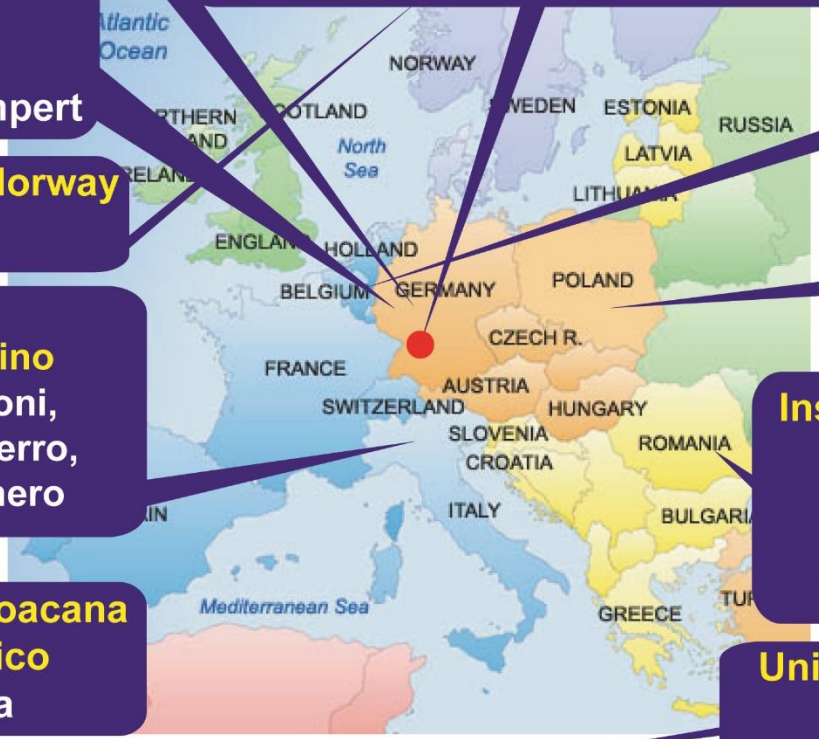

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http://www-ik.fzk.de/KASCADE-Grande/

email spokesperson: haungs@kit.edu

KASCADE:
Contribution to most important question!

©Claus Grupen

Still better understanding of extensive air showers by improved hadronic interaction models are needed to answer this question

Hopefully not another 100 years (since V.Hess) or even 25 years (since KASCADE) needed to finally answer this question