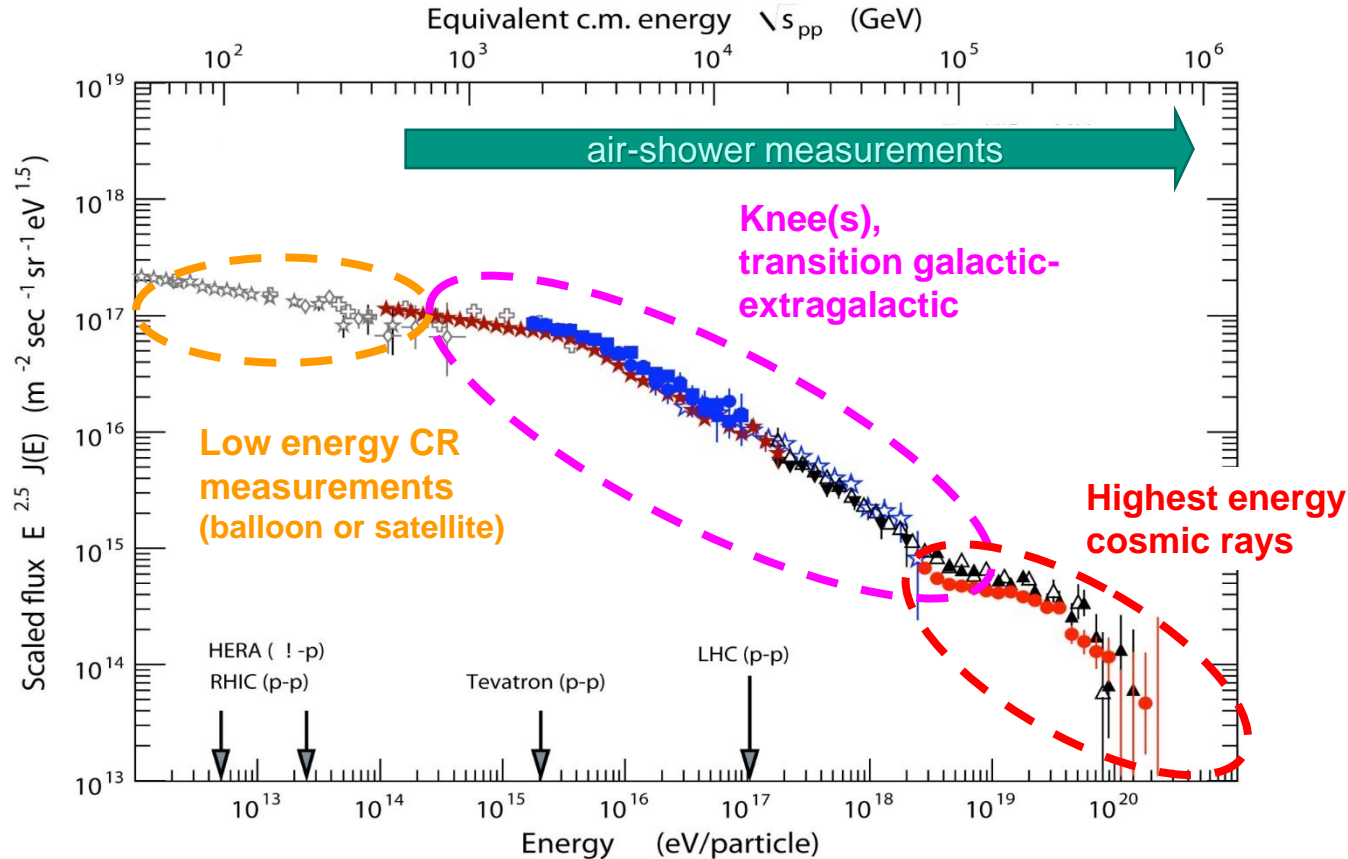


Air-Shower Observations of Cosmic Rays in the PeV to EeV Energy Range

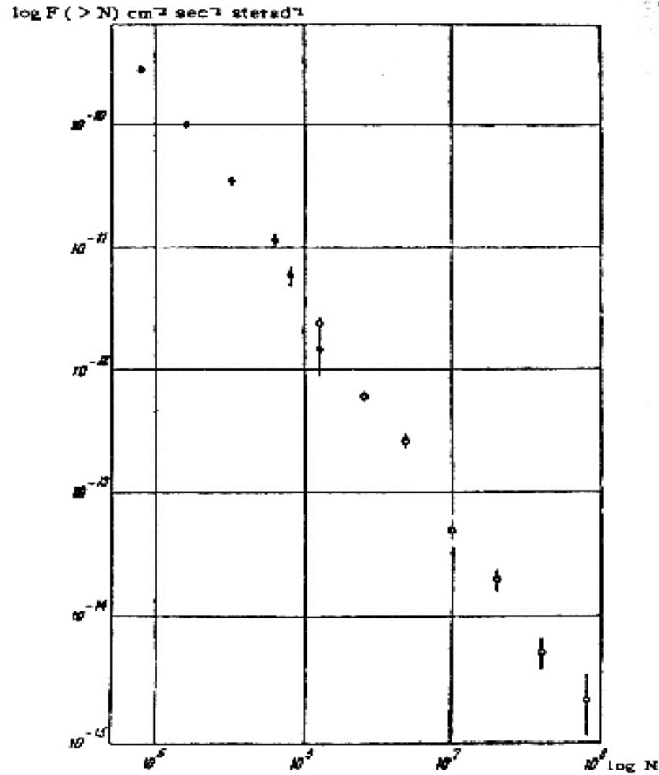
Cosmic Rays and Neutrinos in the Multi-Messenger Era (online conference)
10th December 2020, Andreas Haungs, Institute for Astroparticle Physics



High-energy cosmic ray spectrum



The “first knee”



G.V.Kulikov & G.B.Khristiansen

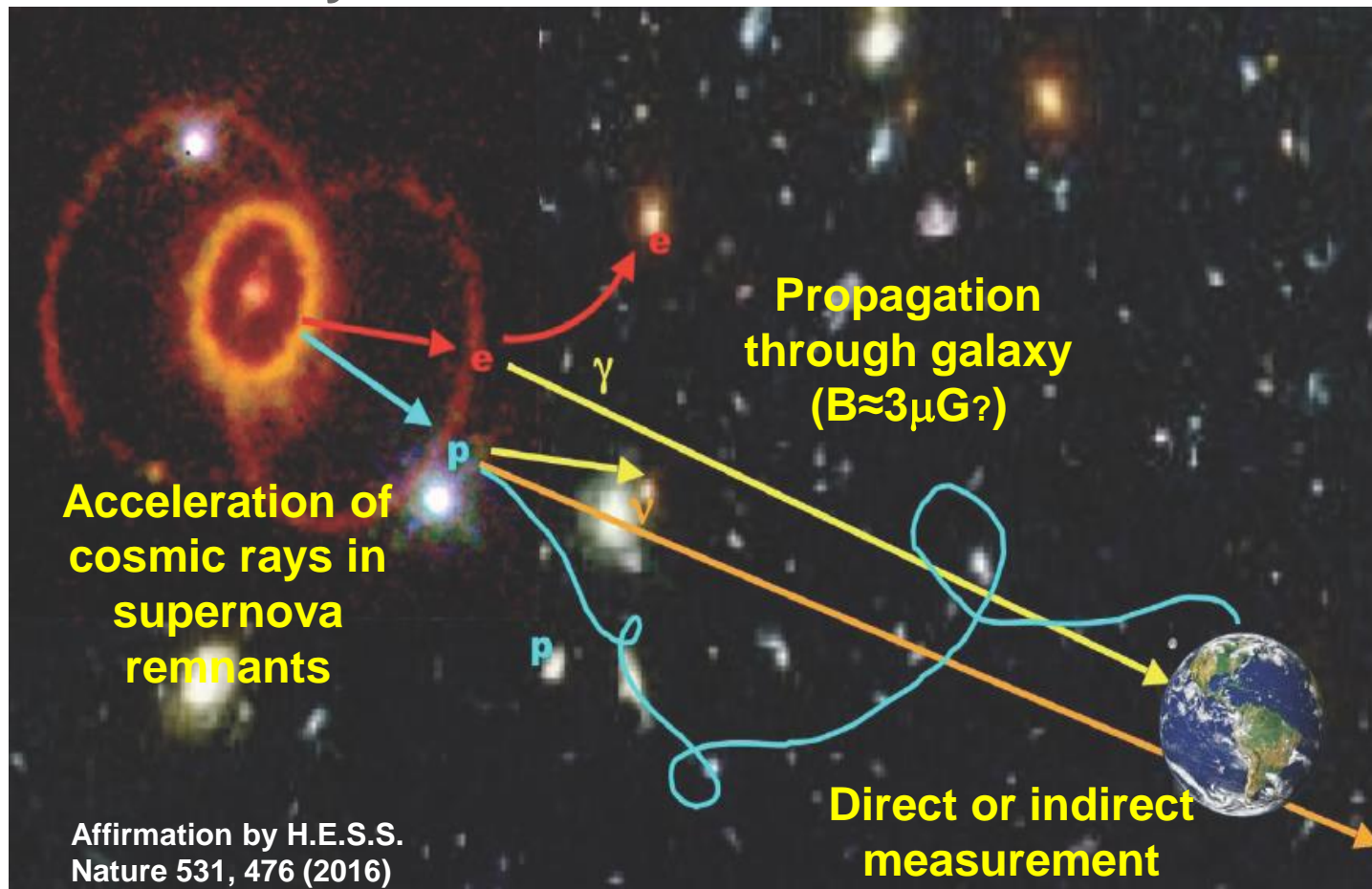
Soviet Physics JETP
3, March 1959

Volume 35(8), No

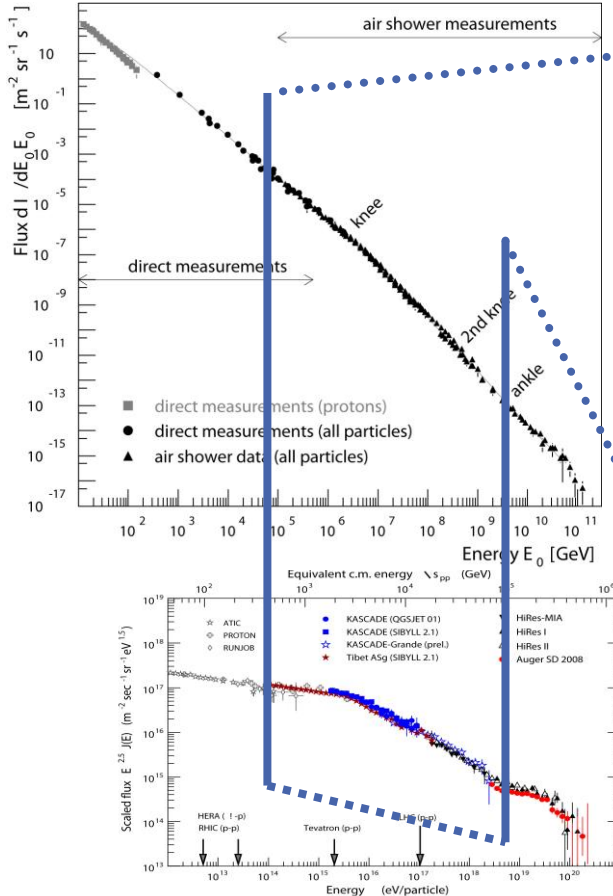
measured N_{ch} spectra

hodoscope counters in a 20x20 m² array

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



Questions to the knee-to-ankle energy range



Overlap direct-indirect measurements?

Hadronic interaction models?

Rigidity dependent knee?

Fine-structures in spectrum?

Composition at knee?

Spectra of individual masses?

Iron knee?

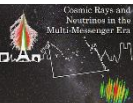
End of Galactic Spectrum?

Second knee?

Transition galactic – xgalactic?

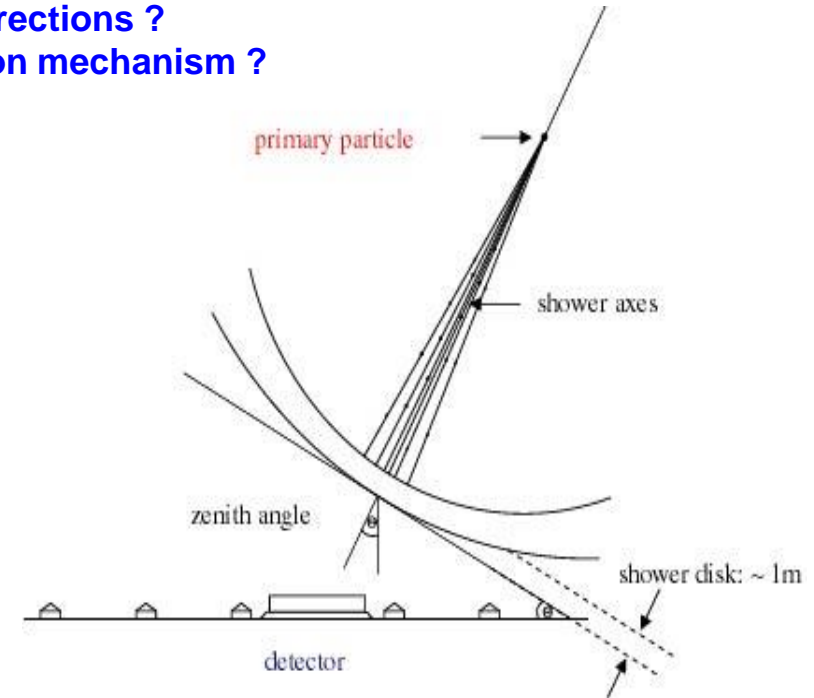
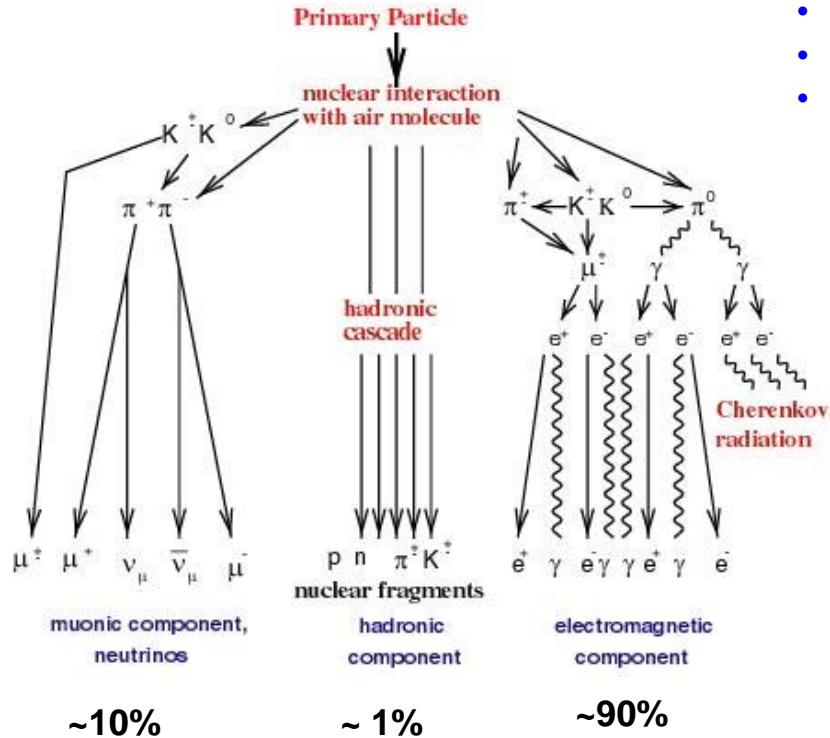
Anisotropy?

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



EAS measurement and reconstruction:

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



Current Experiments 10^{16} - 10^{18} eV

IceTop (IceCube)



KASCADE-Grande



Tunka



LOFAR



Pierre Auger

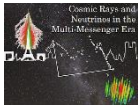
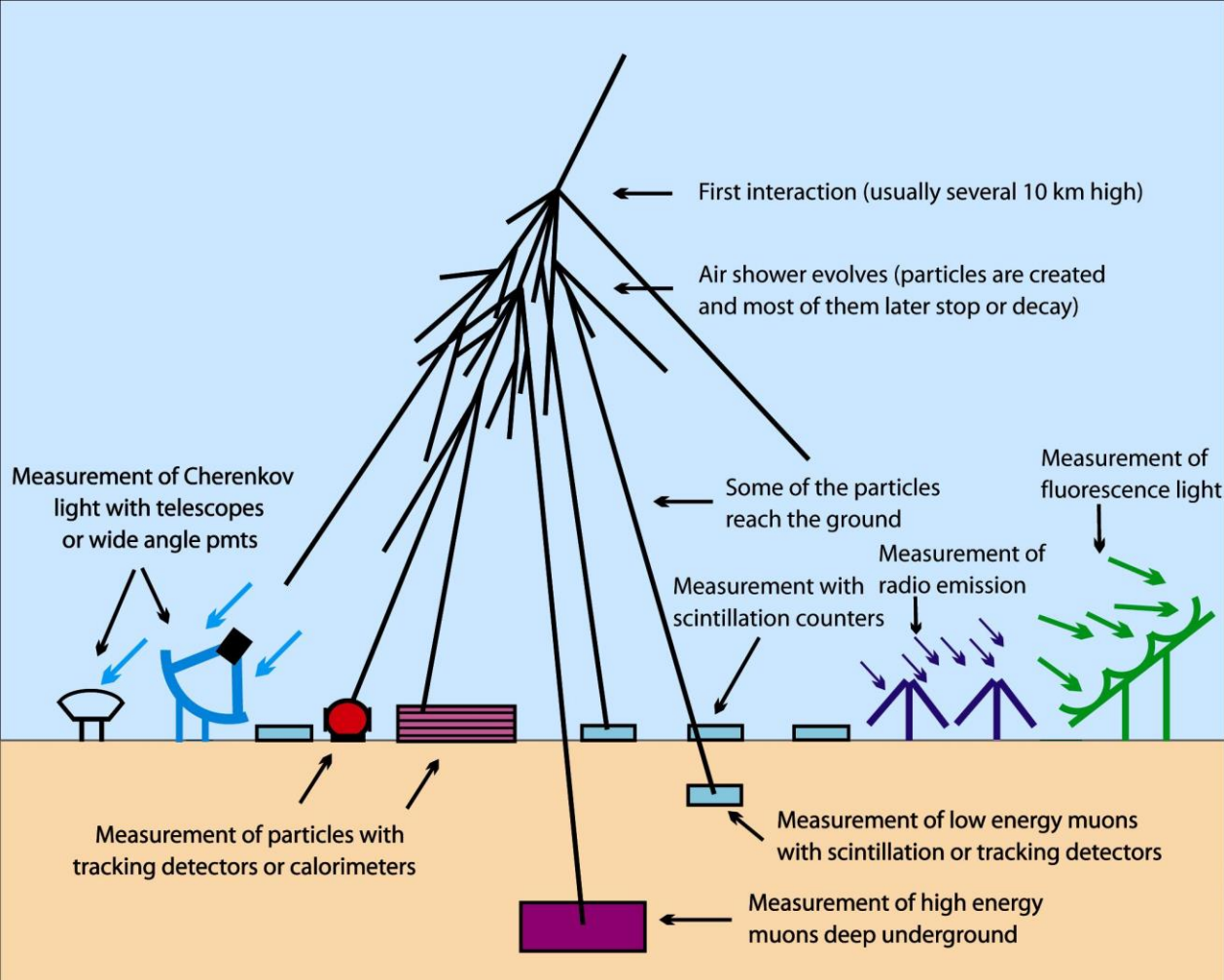


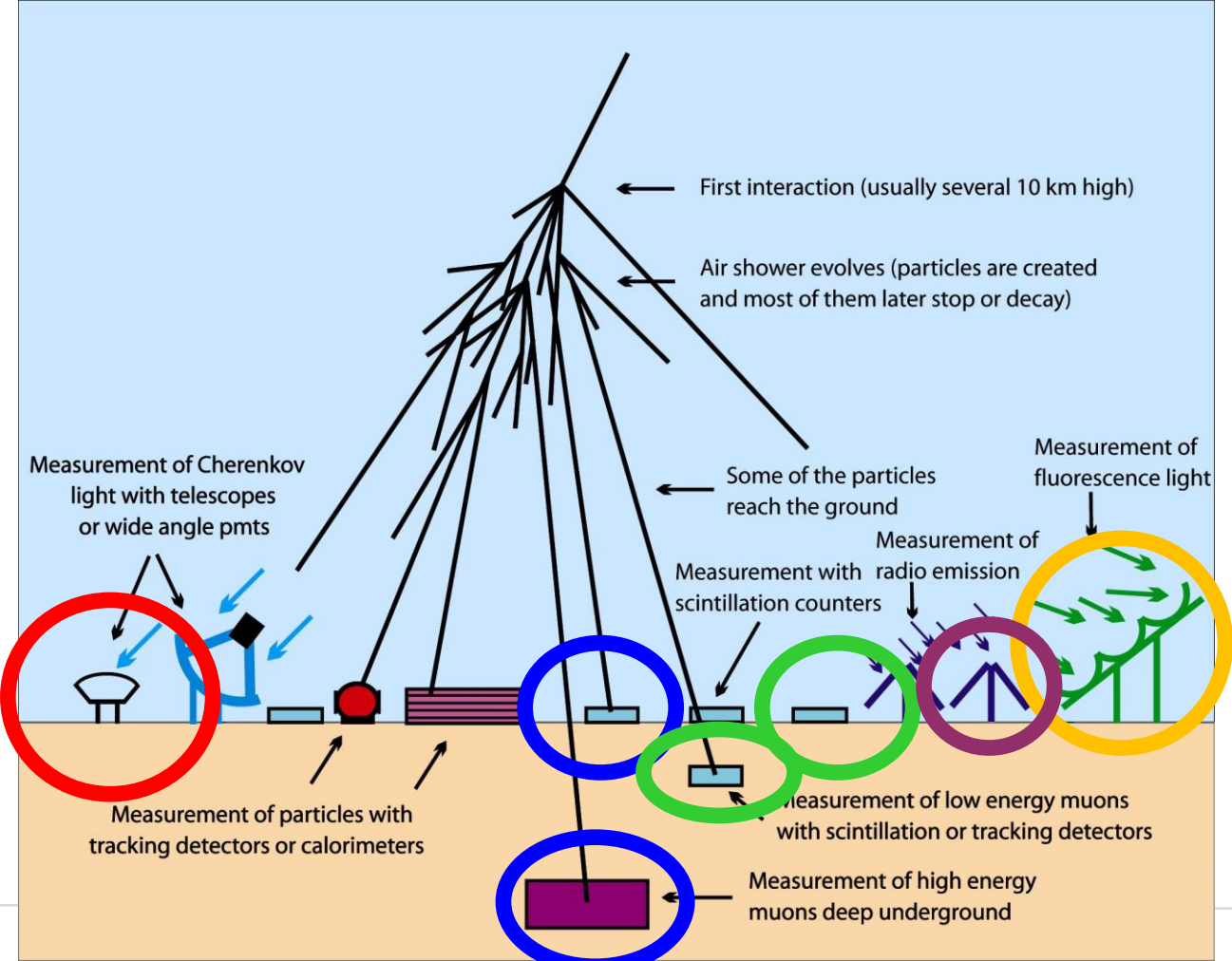
Telescope Array



Nevod





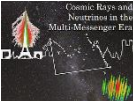


KASCADE-Grande
IceTop

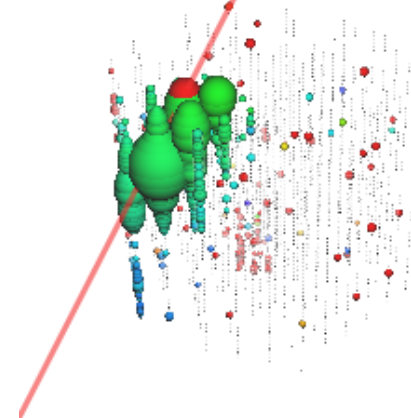
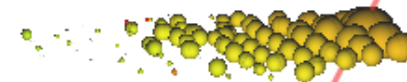
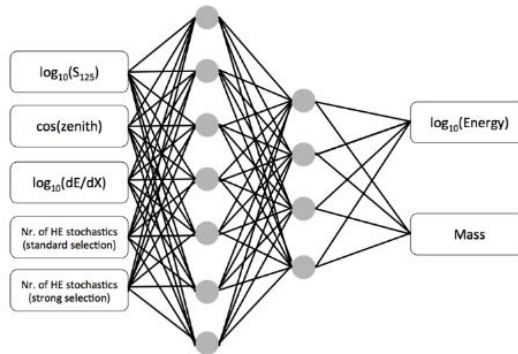
Tunka

HEAT/TALE

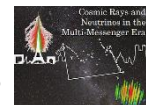
LOFAR, ...

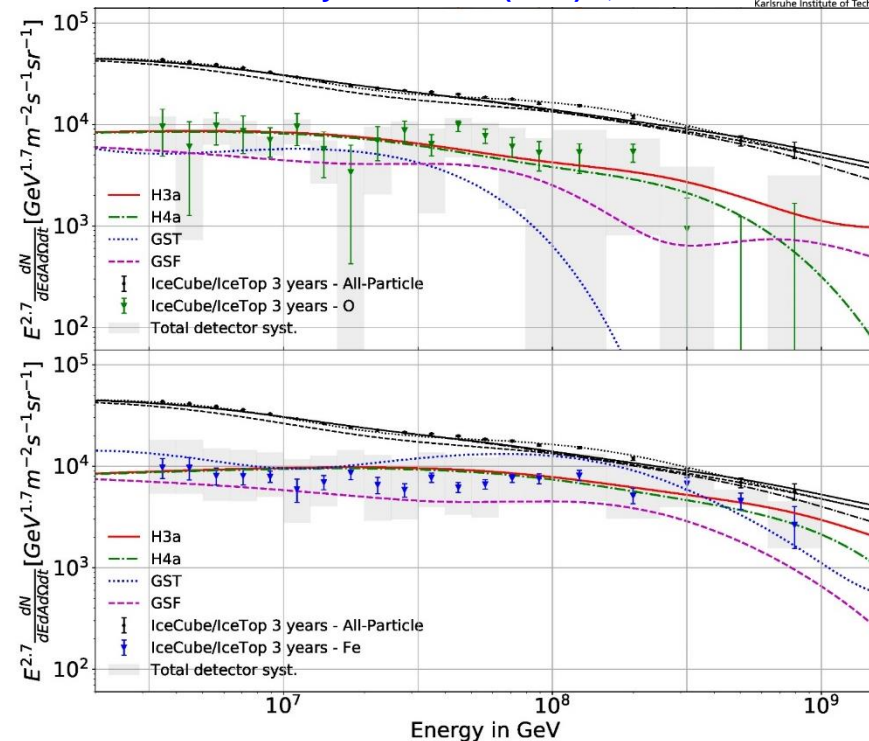
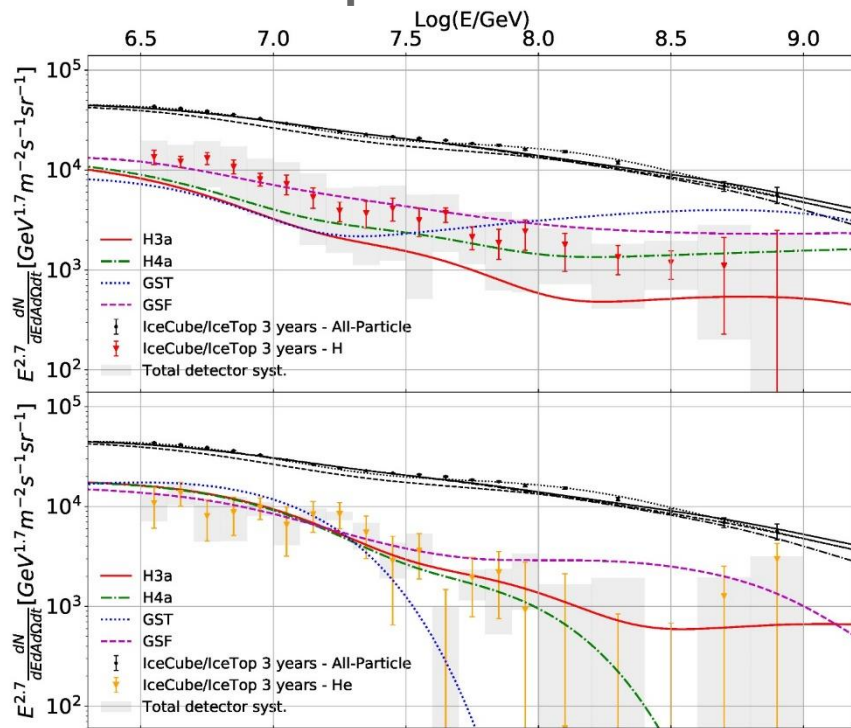


- Energy range: PeV – 1EeV
- Area: 1 km²
- 2835m altitude (680 g/cm²)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muon (bundles)



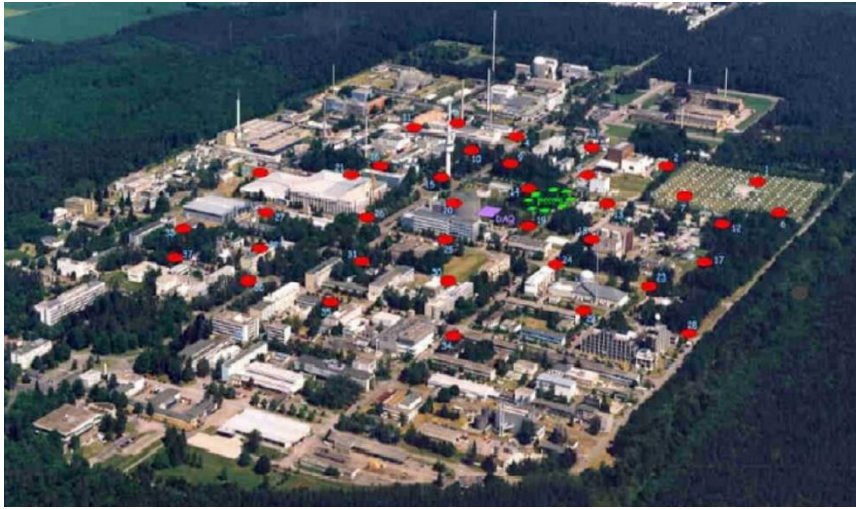
Phys.Rev.D 100 (2019) 8, 082002



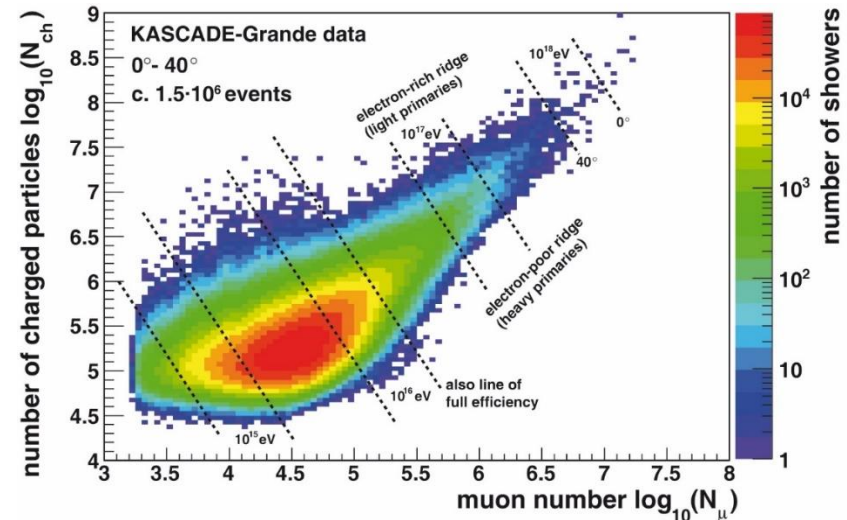


- Confirms structures seen before (light ankle, heavy knee)
- Mass scale model dependent (confirmed by muon density measurements)
- Astrophysical models not really distinguishable

- Energy range: 100TeV – 1EeV
- Area: 0.5 km²
- Grande: 37×10 m² plastic scintillation detectors
- N_{ch} + total muon number

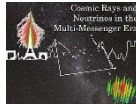


- ➔ determination of primary energy
- ➔ separation in “electron-rich” and “electron-poor” event

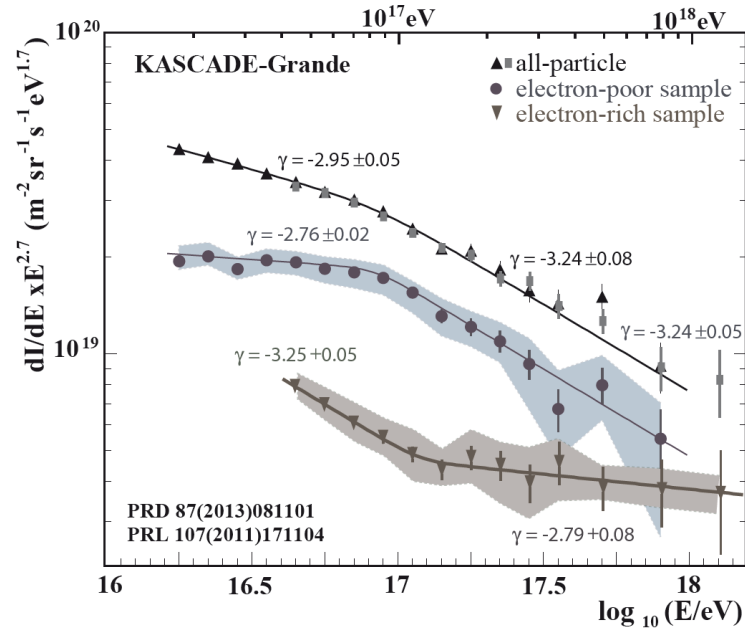


$$\log_{10}(E) = [a_p + (a_{Fe}-a_p) \cdot k] \cdot \log_{10}(N_{ch}) + b_p + (b_{Fe}-b_p) \cdot k$$

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

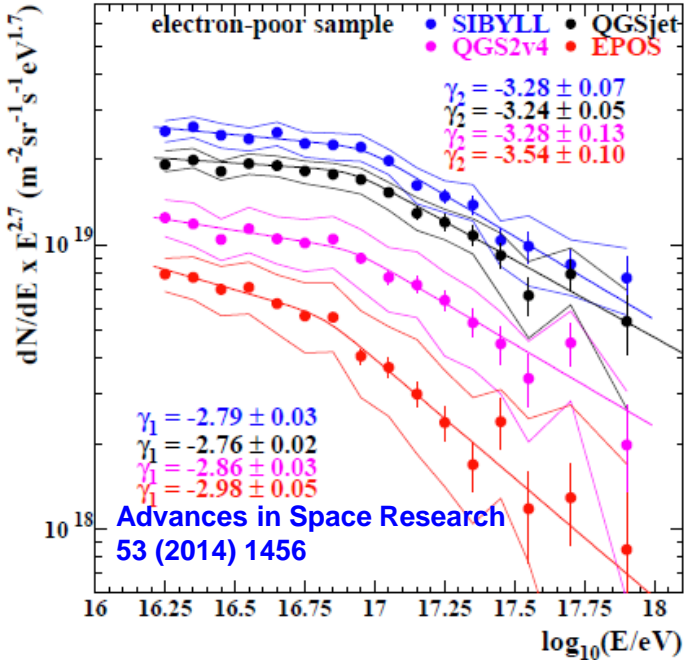


KASCADE-Grande: results

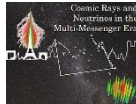


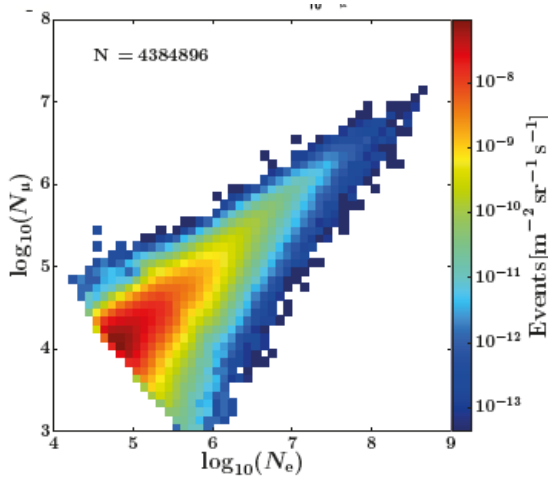
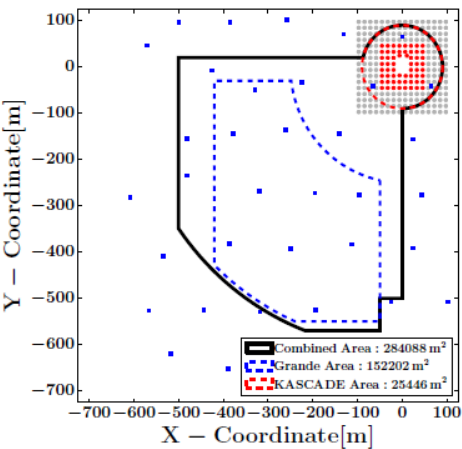
- steepening due to heavy primaries (3.5σ)
- hardening at $10^{17.08} \text{ eV}$ (5.8σ) in light spectrum
- slope change from $\gamma = -3.25$ to $\gamma = -2.79$!

KASCADE-Grande: model dependence

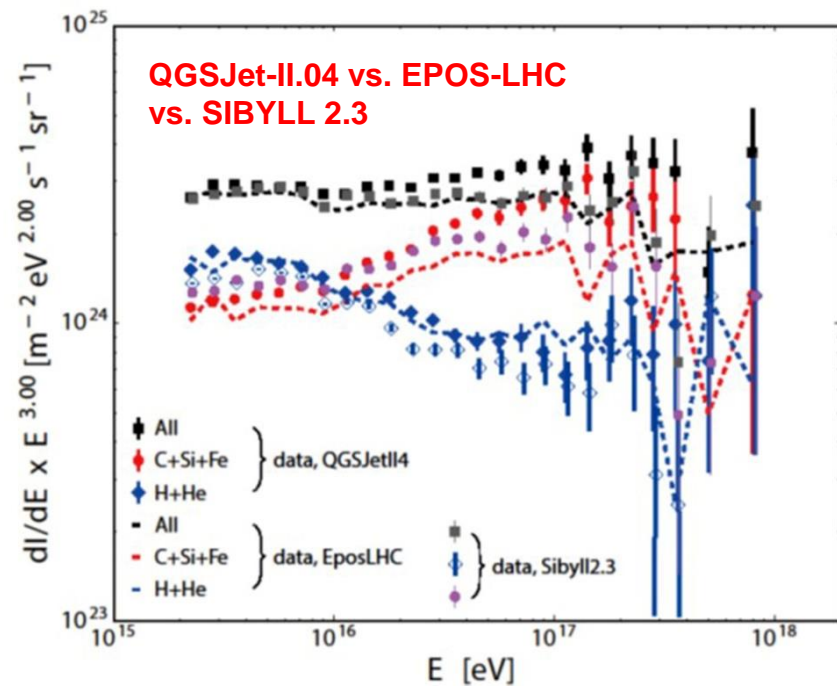


- Spectra of heavy primary induced events
 - knee structure at the heavy component
 - relative abundances different for different high-energy hadronic interaction models

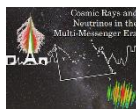


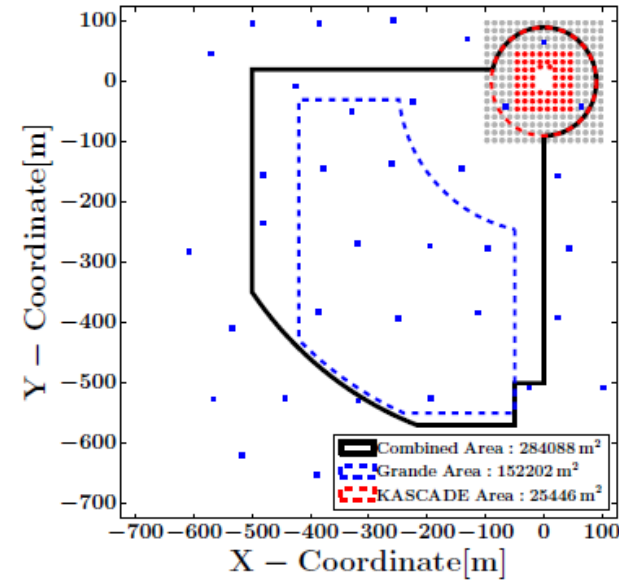
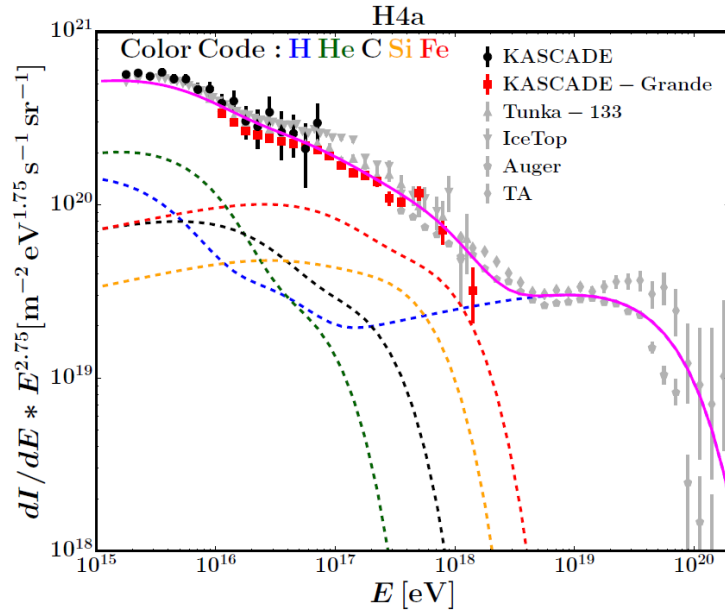


- for KASCADE: additional stations at larger distances
→ higher energies
- for Grande: additional 252 stations
→ higher accuracy

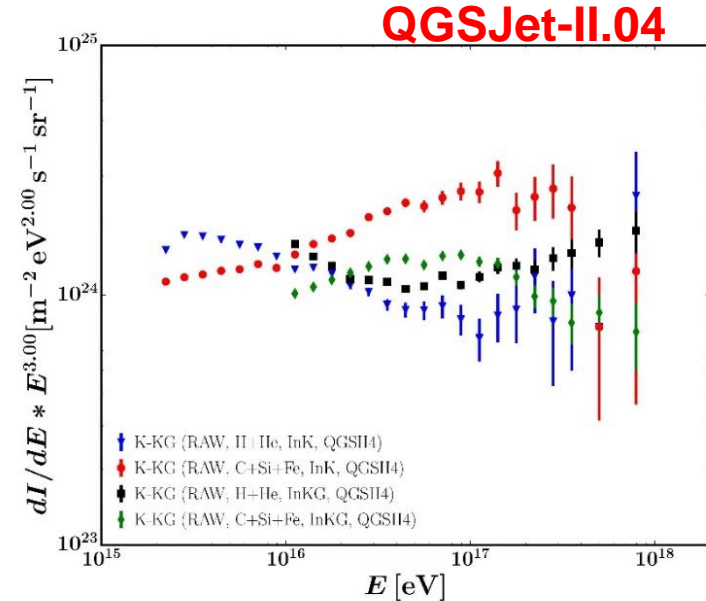
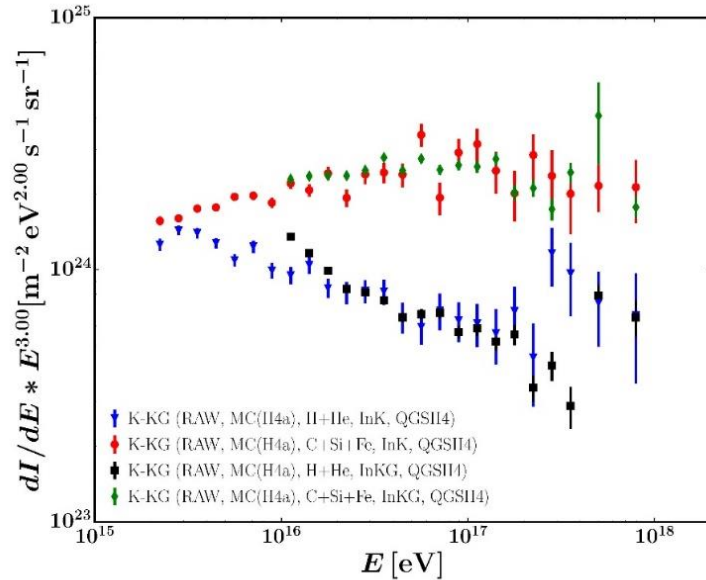


Post LHC models:
light primary interactions okay?
heavy primary interactions show differences



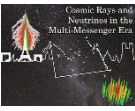


- assume a composition model: H4a by Tom Gaisser
- two selections: core located in KASCADE, core located in Grande
→ we measure “different” muons

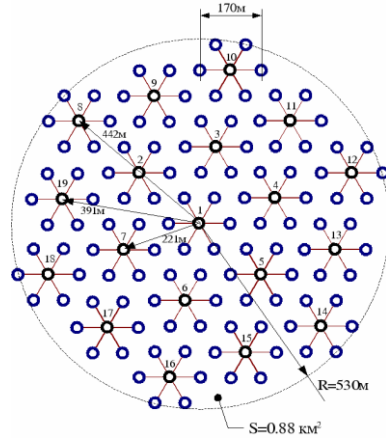


- One model, but two selections:
Simulations okay, but strong differences in data
(similar result for **QGSJet-II.04**, **EPOS-LHC**, **SIBYLL 2.3**)

➔ Muon component not sufficiently described



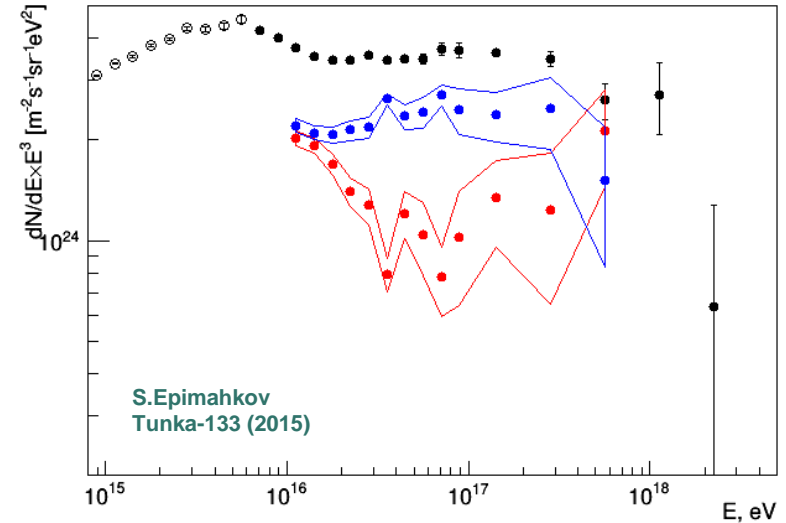
- Energy range: 100TeV – 1EeV
- Area: >1 km²; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters



light flux at core distance 200 m

$Q_{200} \sim \text{Energy}$

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



- The **heavy component** (N+Fe) has a break
- The **light component** starts to rise again above 10¹⁷ eV

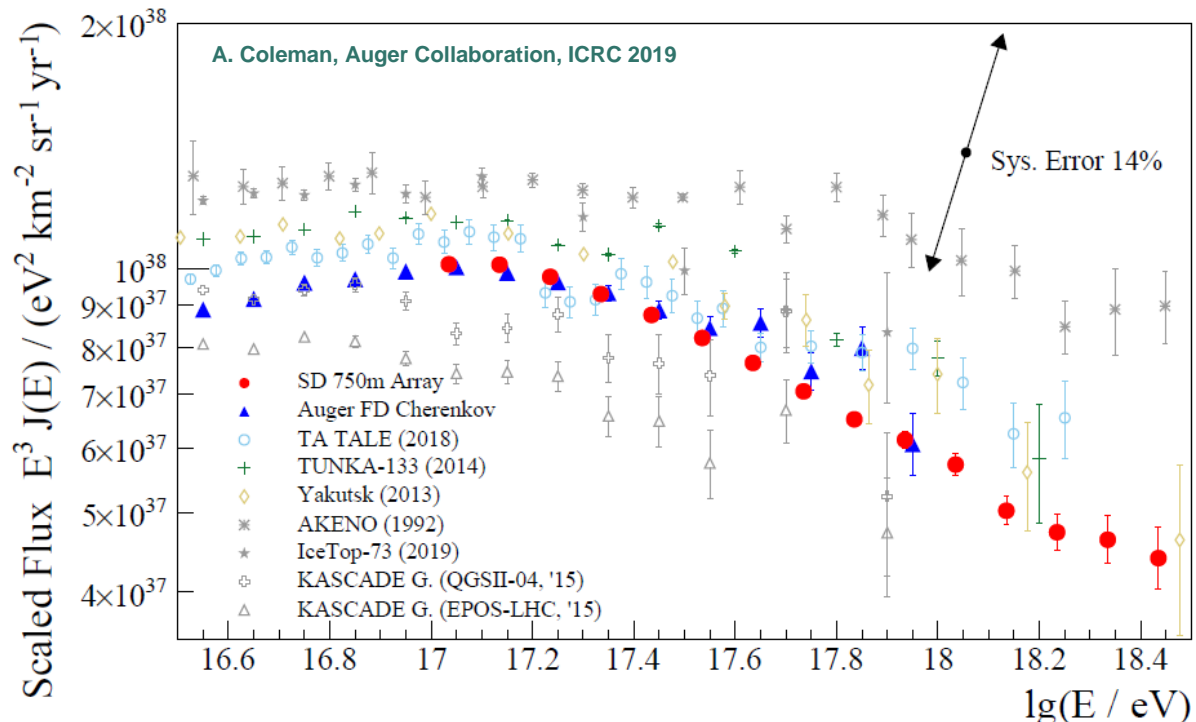
UHECR experiments



Pierre Auger Observatory
→ HEAT/AMIGA/AERA



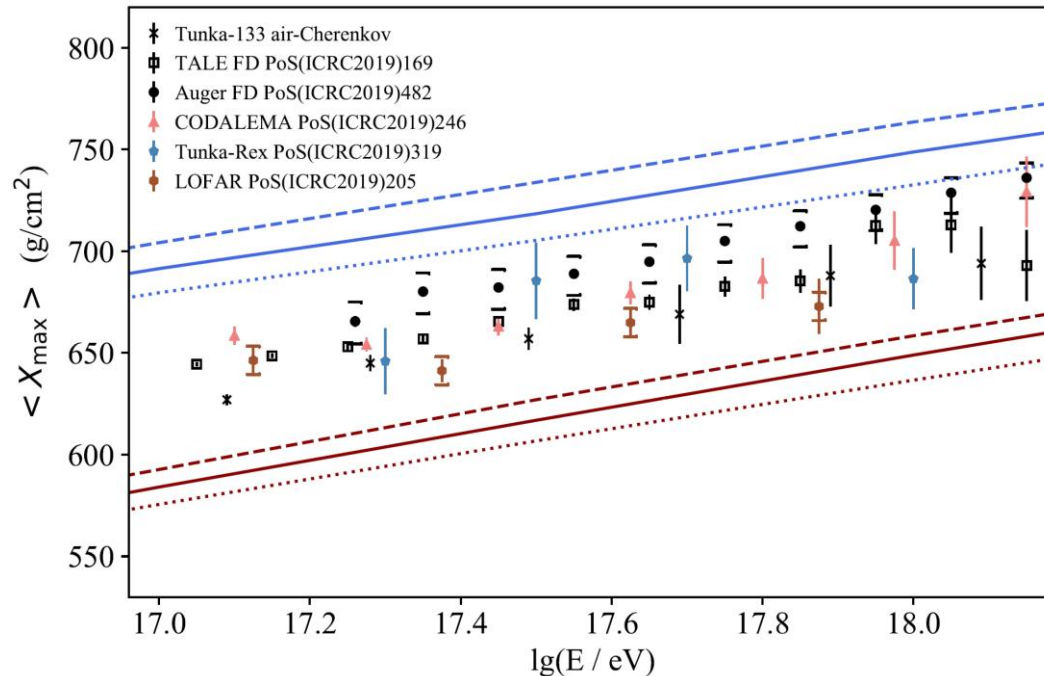
Telescope Array
→ TALE



- Auger HEAT measurements
- Auger Infill measurements
- TALE measurements
- ➔ Knee at $\sim 10^{17}$ eV observed (confirmed) in all-particle spectrum

Radio Experiments

A lot of (promising) progress in X_{\max} determination by radio Experiments



- published already by **LOPES**

PhysRevD 90(2014)062001

Tunka-Rex

PRD 97, 122004 (2018)

LOFAR

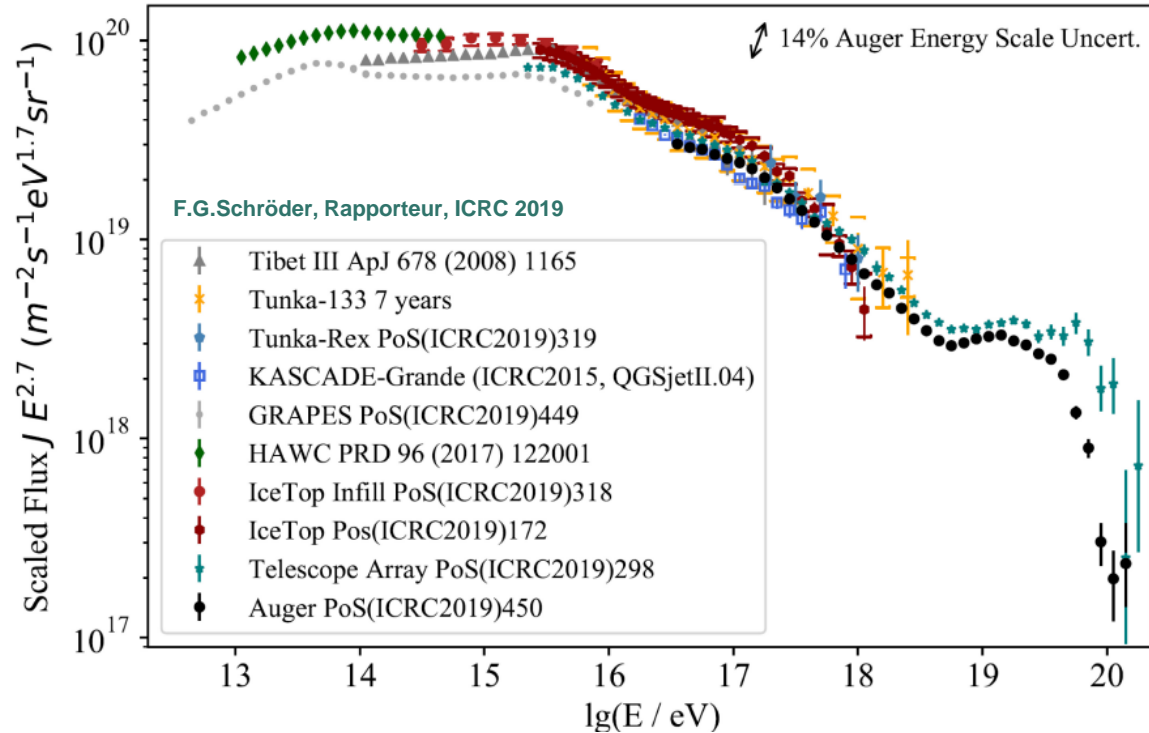
Nature 531(2016)70

- **Auger/AERA promising**

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

➔ Certainly important contribution by the radio experiments

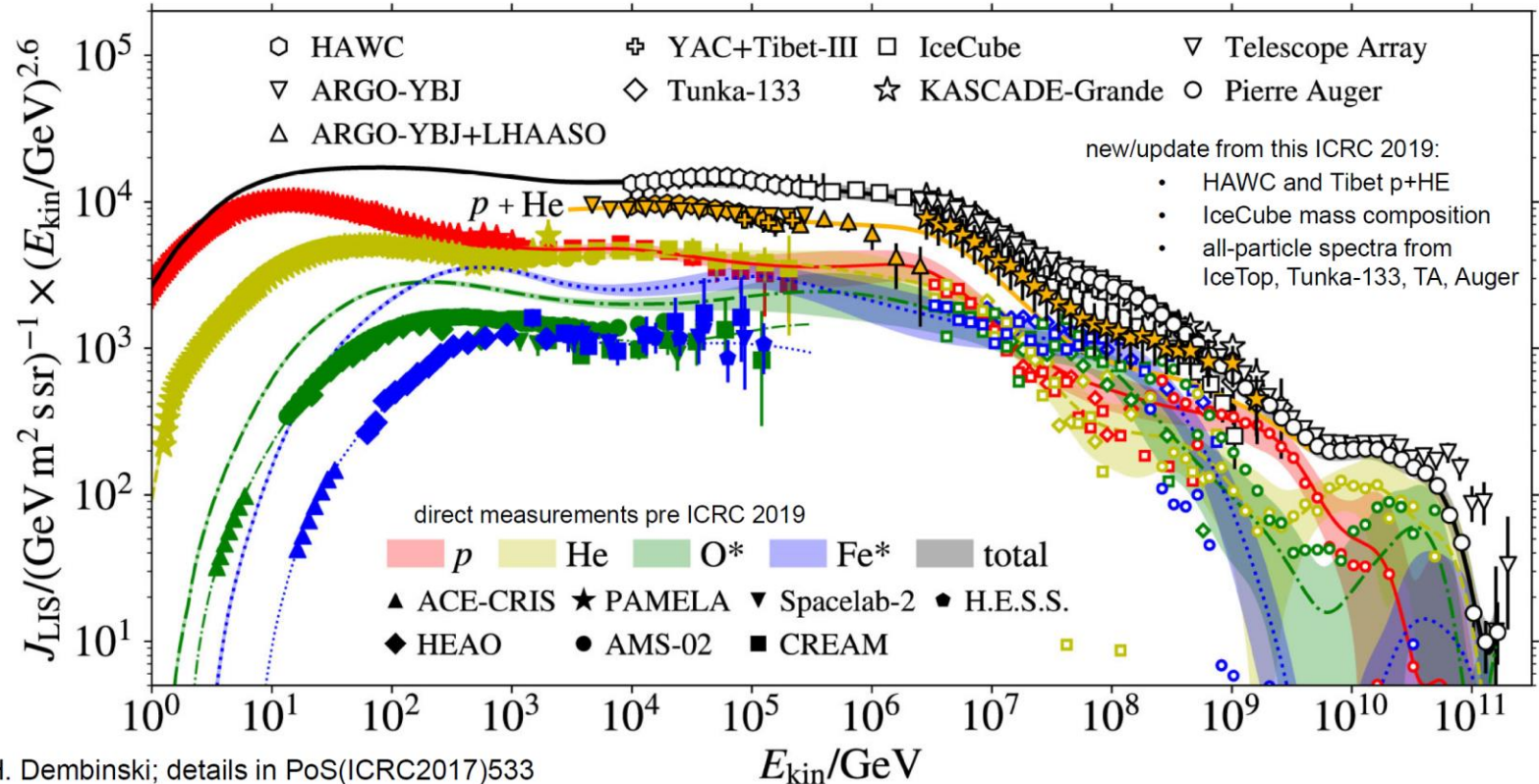
➔ High threshold?

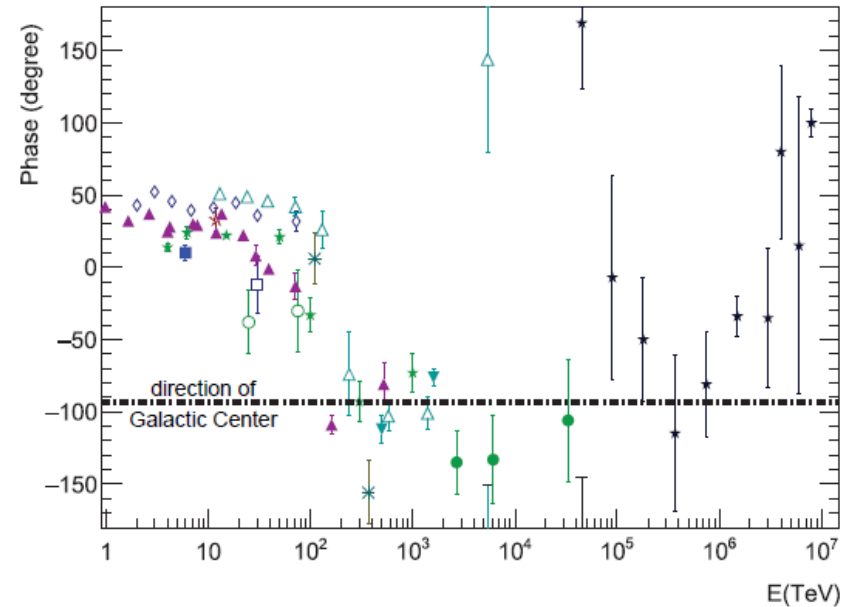
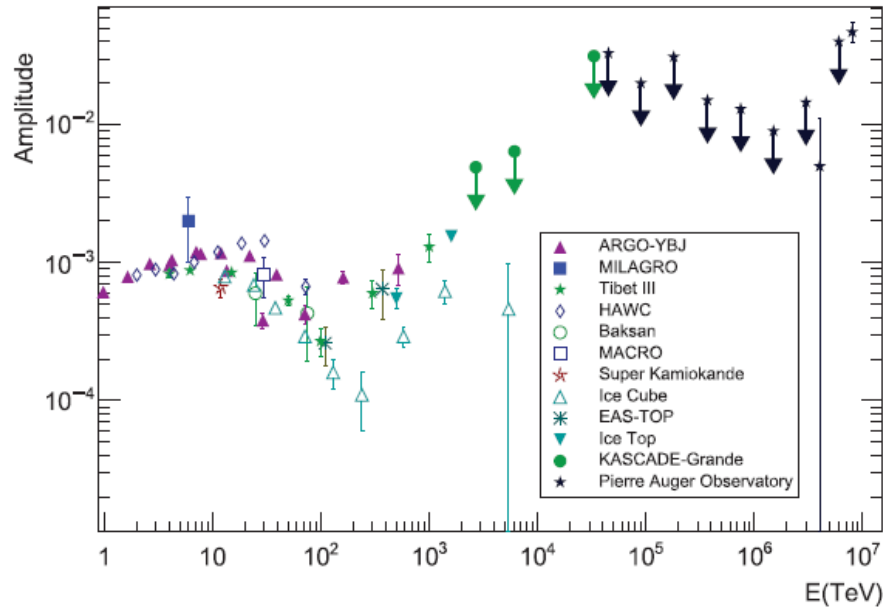


- Structures of all-particle spectra similar (in the level of 15%)
- Composition results are still uncertain

Global Spline Fit (Composition and Energy Spectrum)

Fit of spectra *within experimental uncertainties*, allowing for constant shift in energy scales



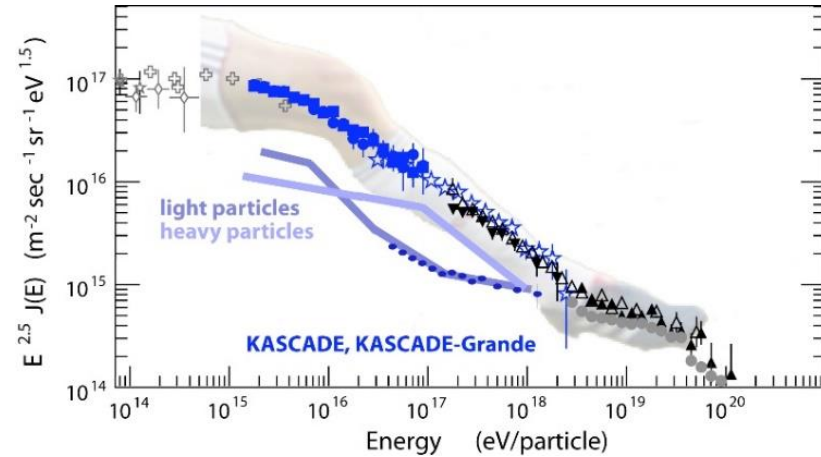
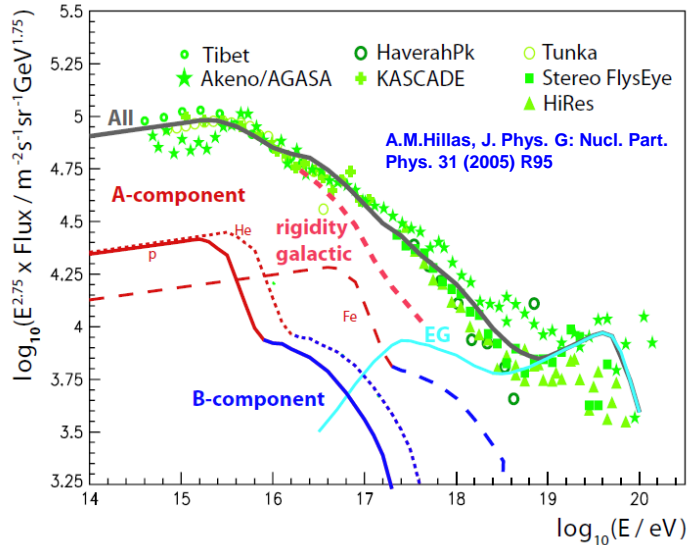


- study of large-scale anisotropies by the East-West method
- limits on amplitude
- phase determined

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

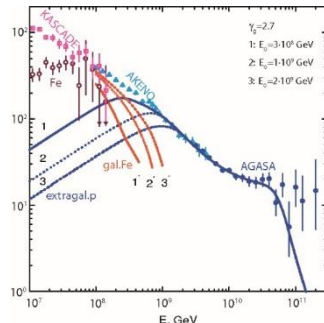
KASCADE-Grande collaboration,
Astrophys.J. 870 (2019) 2, 91

Light and Heavy Knees, Ankles, and Transition

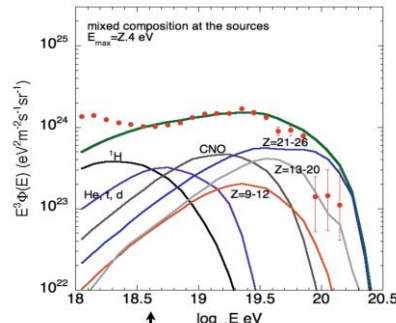


Questions:

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



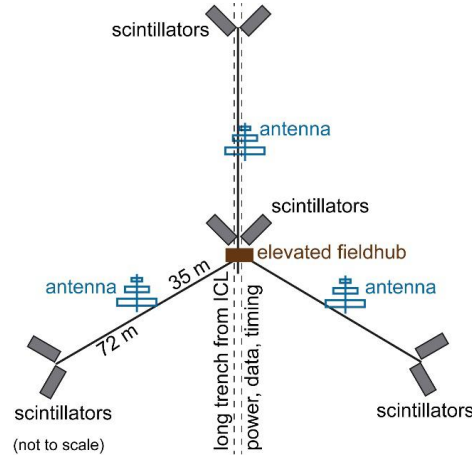
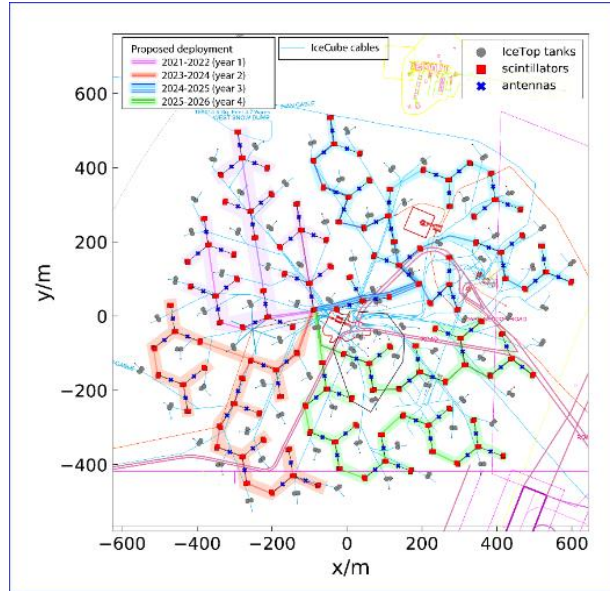
V.Berezinsky, astro-ph/0403477



D.Allard, astro-ph/1111.3290

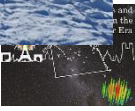
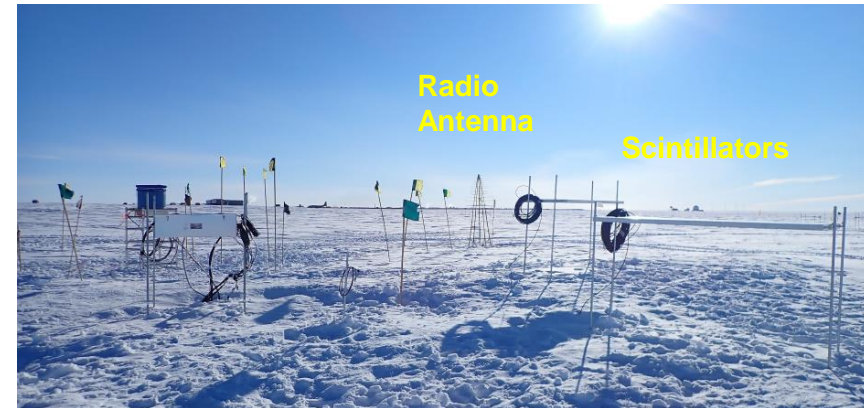


Hybrid Radio Scintillator Enhancement of IceTop (2021-25)



Science Goals:

- Neutrino science (atmospheric background, veto)
- Cosmic ray physics (spectrum, composition, PeV gammas)
- Air shower physics (test hadronic interaction models)
- Technology (pathfinder Gen2)



South Pole October 2020



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



Analysis and Data Center in Astroparticle Physics

Data
availability

Analysis

Simulations
& Methods
development

Real-time
analysis
center

Open
access

Education
in Data
Science

Data
archive

Experiment-Overarching Working Group for the Transition Energy Range

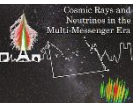
Proposed at UHECR-conference 2018

Target:

- Energy spectrum and composition from knee to ankle
- Systematics by hadronic interaction models
- Comparison with astrophysical models

First steps:

- Formation of the working group (end of 2018?)
 - Comparison and compilation of all currently available results
 - Agreement on a defined set of simulations which will be reconstructed
- ➔ Should be installed now in order to have first activities until next UHECR conference



Snowmass 2021 Contribution: Highest Energy Galactic Cosmic Rays

Scientific Issues:

- The most powerful accelerators of cosmic rays in our Milky Way have not yet been revealed.
- The maximum energies of various possible acceleration mechanisms and sources are uncertain.
- The Galactic-extragalactic transition and several features in the CR energy spectrum are not well understood.

Summary:

The increase in accuracy, exposure and sky coverage provided by all these experiments will bring unprecedented sensitivity to the science questions raised in this LoI. Hence, the contribution of GCR to multimessenger astrophysics will be lifted to a new level providing a real chance finally to discover the most energetic accelerators in our Milky Way.

Snowmass2021 - Letter of Interest

Highest Energy Galactic Cosmic Rays

Thematic Areas: (check all that apply) ☐ ☒

- ☐ (CF1) Dark Matter: Particle Like
- ☐ (CF2) Dark Matter: Wavelike
- ☐ (CF3) Dark Matter: Cosmic Probes
- ☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
- ☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
- ☒ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- ☒ (CF7) Cosmic Probes of Fundamental Physics
- ☒ (EF06) QCD and strong interactions: Hadronic structure and forward QCD

Contact Information:

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Collaborations: All authors are members of one or more of the following collaborations: IceCube Neutrino Observatory, The Telescope Array, The Pierre Auger Observatory, HAWC, Tunka, TAIGA, LHAASO, SWGO, GRAND, GRAPES, KASCADE-Grande

Other LoI: see last page for further to this topic relevant LoI.

Abstract: Investigations of the energy spectrum, mass composition and arrival directions of cosmic rays in the energy range of PeV to EeV are important for understanding the origin of both galactic and extragalactic cosmic rays. The origin of the highest energy Galactic cosmic rays is still not understood, nor is the transition to EeV extragalactic particles. Enhancements of existing air-shower arrays as well as new installations are in progress to achieve measurements with better accuracy and higher statistics. In this Letter of Interest (LoI) the scientific motivation and current results are presented, and the foreseen experimental improvements are discussed. There remain uncertainties in aspects of the physics of air showers in the PeV to EeV energy range, so the effects of using different hadronic interaction models for interpreting air-shower data will also be addressed.

https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF7_CF6-EF0_EF6-094.pdf

Conclusions – open points

- **Light and heavy knee established**
- **Light ankle probably there**
- **Difficult to compare experiments due to different observables (help by radio experiments?)**
- **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: Galactic Multi-Messenger Analyses (cosmic rays, γ -rays, neutrinos)**
- **IceTop(-Gen2), TAIGA, LHAASO, GRAPES, TALE, Auger, NEVOD, HAWC?**
- **Global Data Centre for Astroparticle Physics envisaged**
- **Installation of a UHECR working group: Cosmic-Ray Physics in the Transition Region**