Cosmic Rays around the Knee - Composition and Latest Results

Donghwa Kang
Karlsruhe Institute of Technology

Karlsruher Institut für Technologie

HONEST, November 29 – December 1, 2022, Online

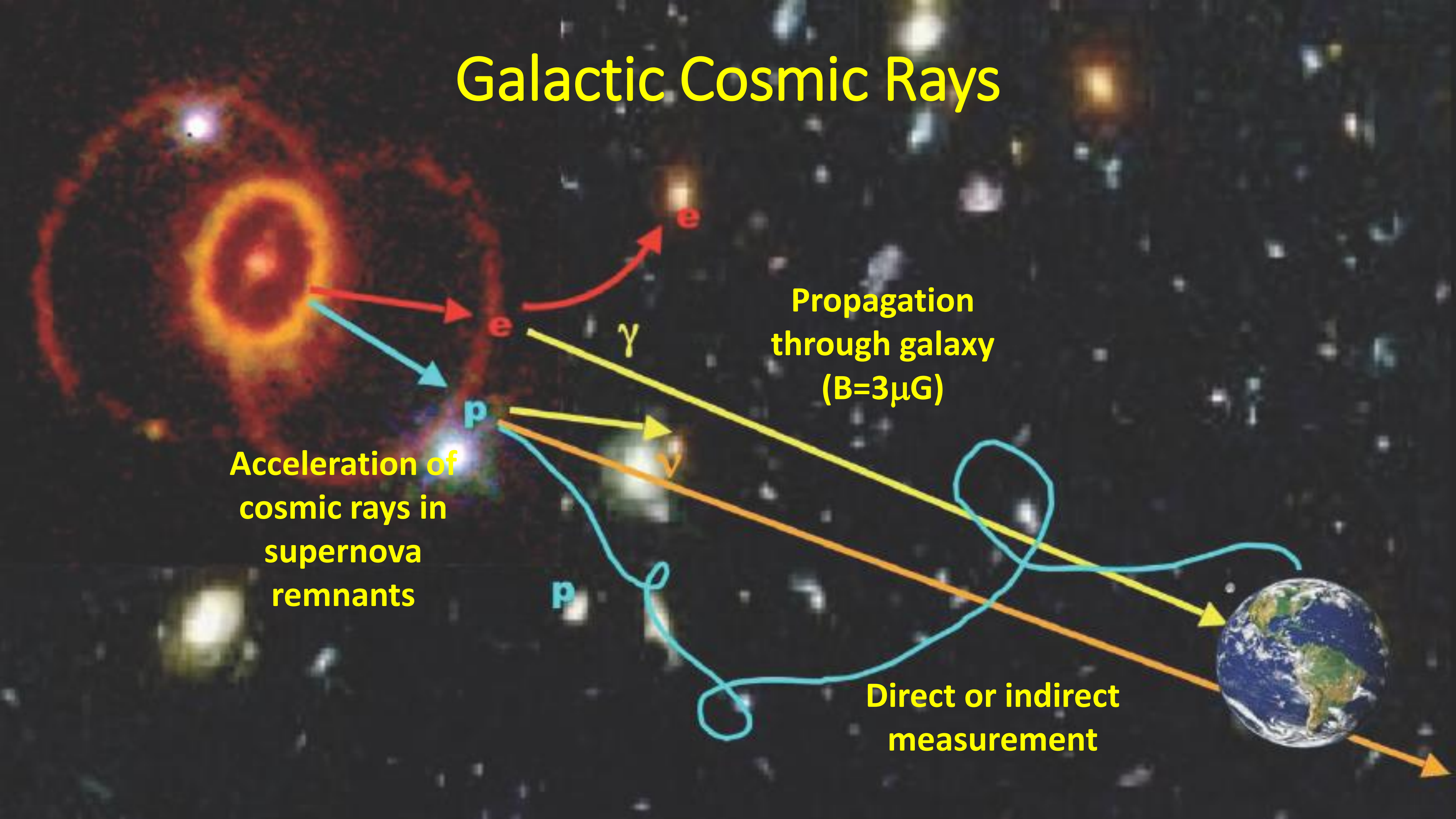
Contents

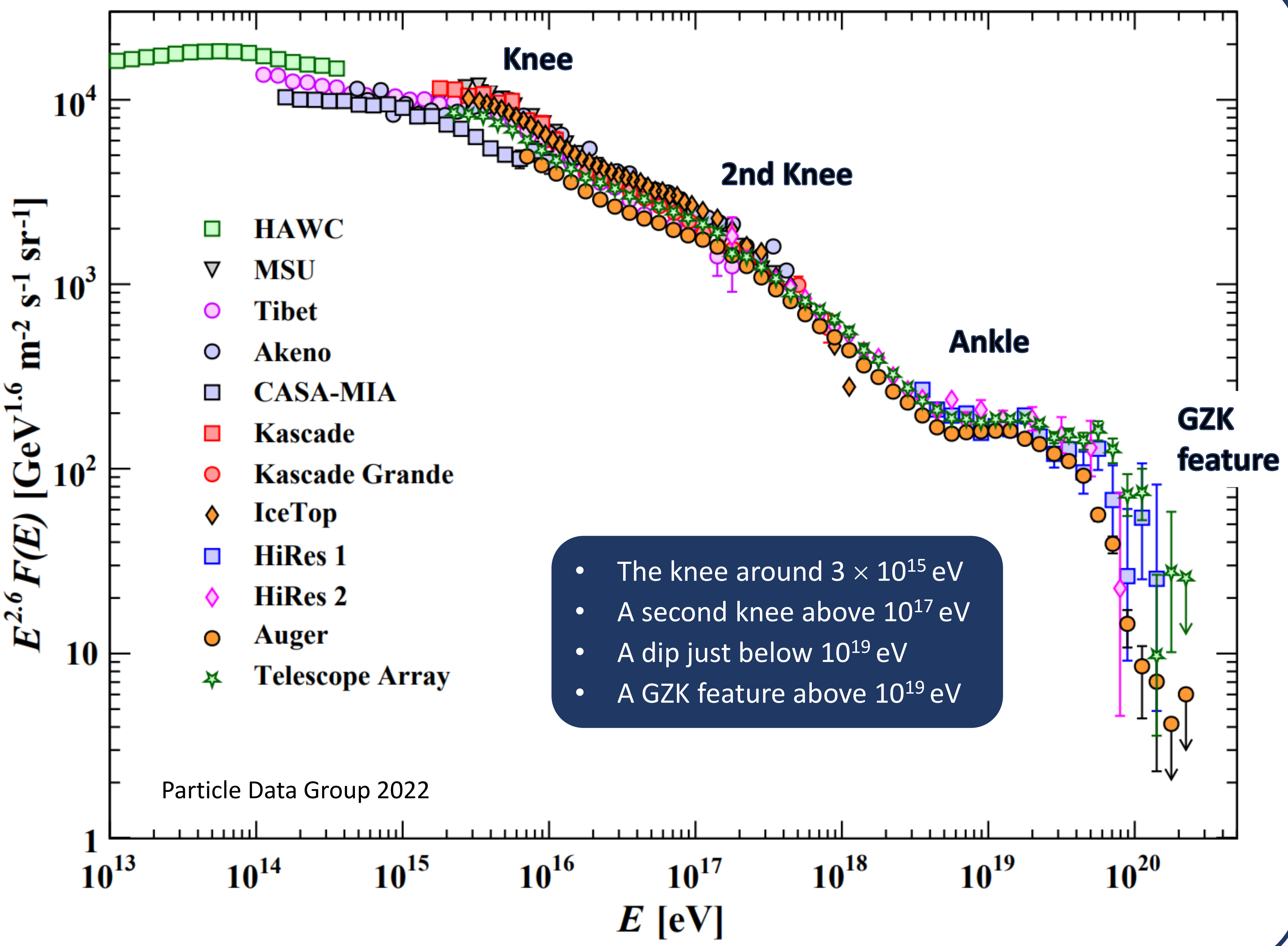
- Introduction

- Selected science results on galactic cosmic rays:
  - all-particle energy spectrum
  - elemental composition
  - anisotropy of arrival direction

- **Extensive Air Shower (EAS)** measurements of PeV to EeV:
  - knee and transition region: **KASCADE**, **KASCADE-Grande**, Tunka, **IceTop/IceCube**
  - LHAASO, HAWC: primarily gamma-ray experiments, but also measure CRs at lower energies
  - TA Low Energy Extension: **TALE**
  - Lower energy extension of the **Pierre Auger** Observatory

Galactic Cosmic Rays

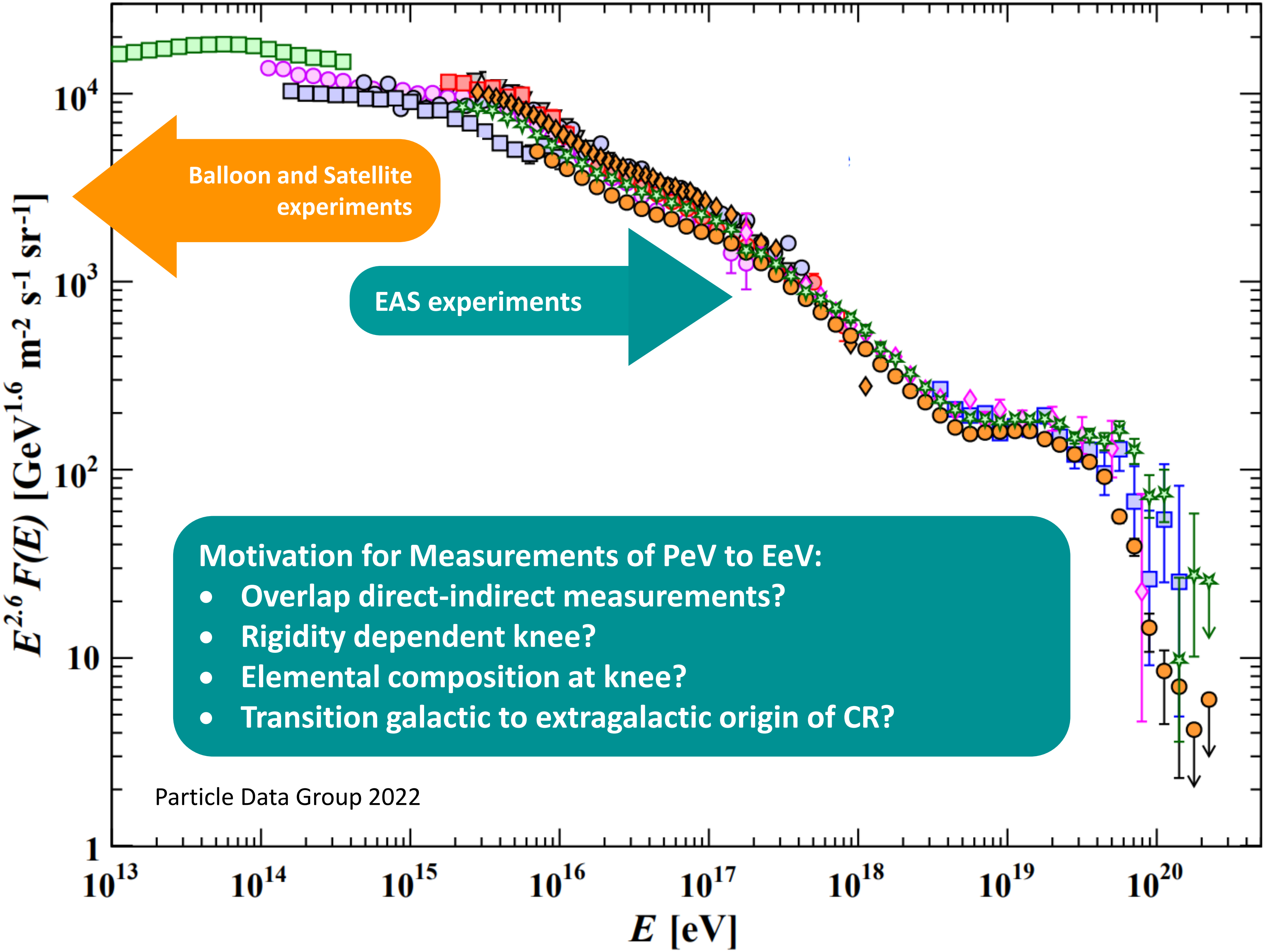




- The knee around 3×10^{15} eV
- A second knee above 10^{17} eV
- A dip just below 10^{19} eV
- A GZK feature above 10^{19} eV

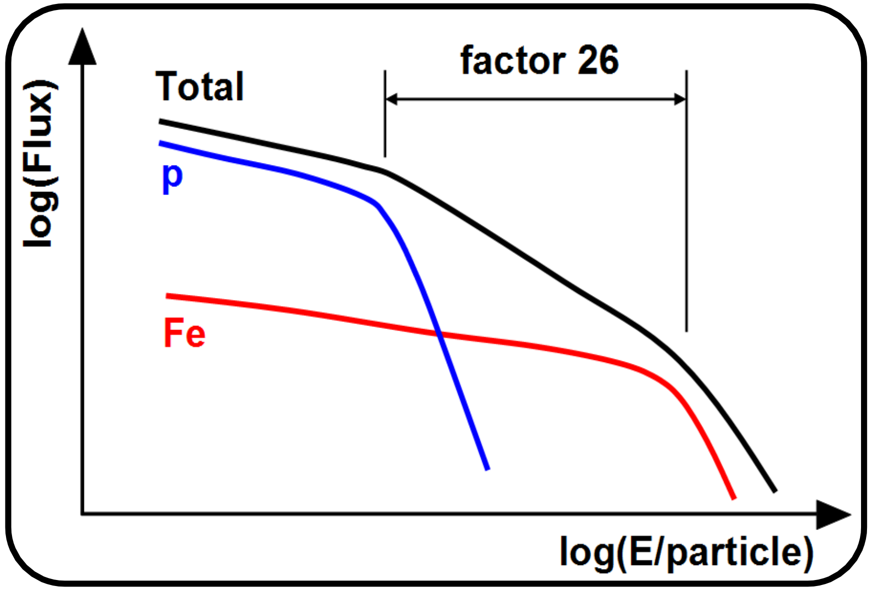
Accelerlation and magnetic confinement:
$E_{max} \sim R \times B \times Z$

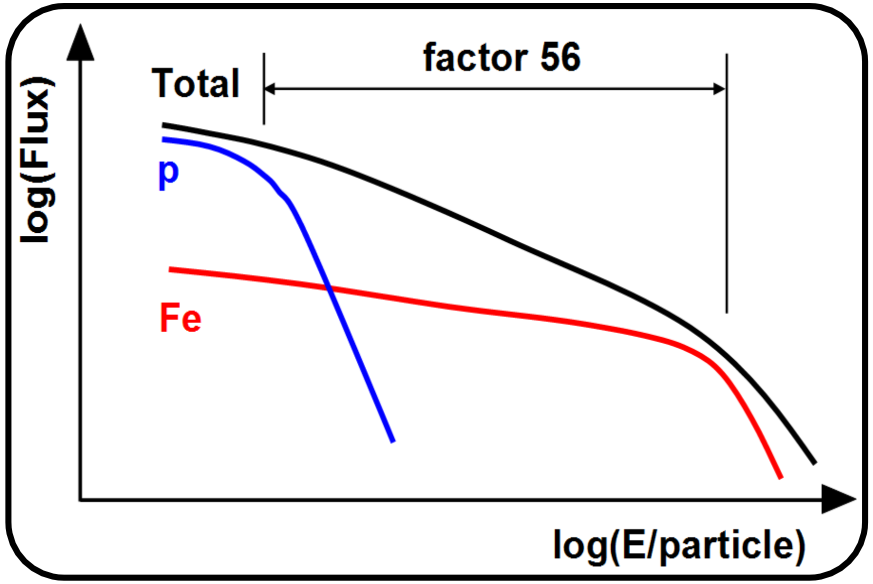
Are these feature caused by the CR sources, or are they an effect of propagation?



Balloon and Satellite experiments
EAS experiments
Motivation for Measurements of PeV to EeV:
• Overlap direct-indirect measurements?
• Rigidity dependent knee?
• Elemental composition at knee?
• Transition galactic to extragalactic origin of CR?
Particle Data Group 2022
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]

Cosmic Rays at the Knee





Rigidity dependent cut-off: $E_{max} \sim Z$

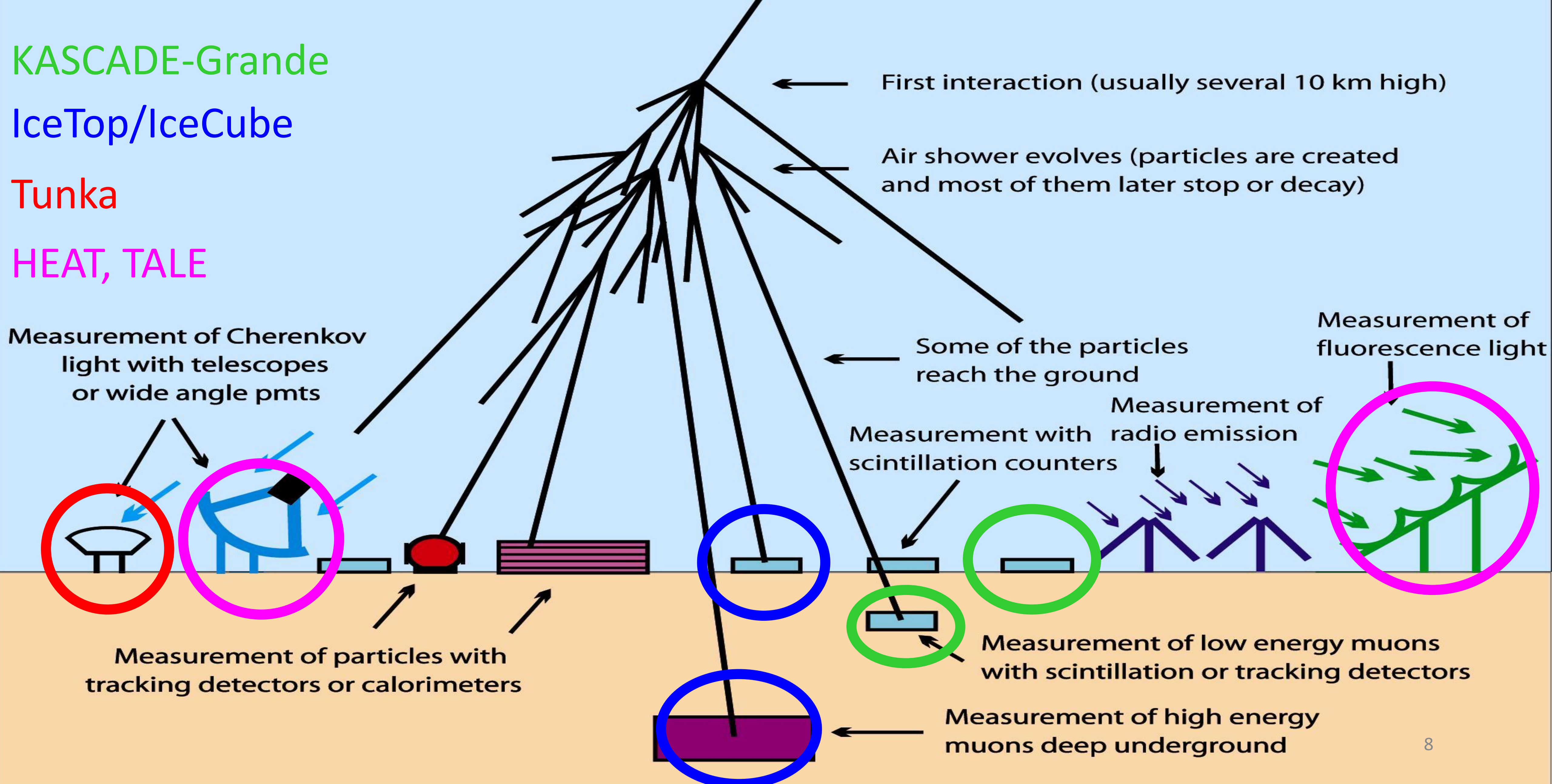
- Acceleration/propagation depends on B: r_{gyro} = R / B with rigidity of R = E / Ze $\rightarrow E_c(Z) \sim Z R_c$
- Shock acceleration ($r_{SNR} \sim$ parsec): $E_{max} \sim Z \times 10^{15}$ eV, $1 \leq Z \leq 26$ (p to Fe)
- Slope change should occur within factor of 30 in energy

Mass dependent cut-off: $E_{max} \sim A$

- Interaction with background particles (photons, neutrinos)
- New particle physics in the atmosphere?

Present Experiments $10^{16} – 10^{18}$ eV

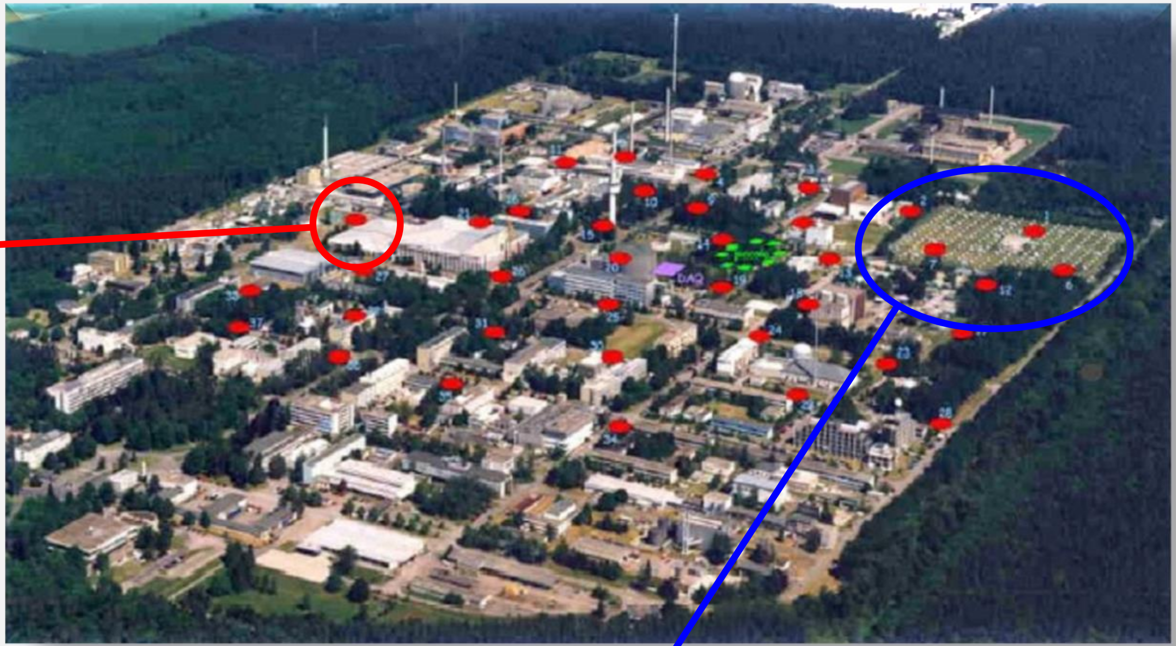
Measurement Techniques of Air Showers



KArlsruhe Shower Core and Array DEtector + Grande

Nucl. Instr. and Meth. A620 (2010) 202

- 10 PeV – 1 EeV
- 0.5 km^2
- 37 stations (each 10 m^2)

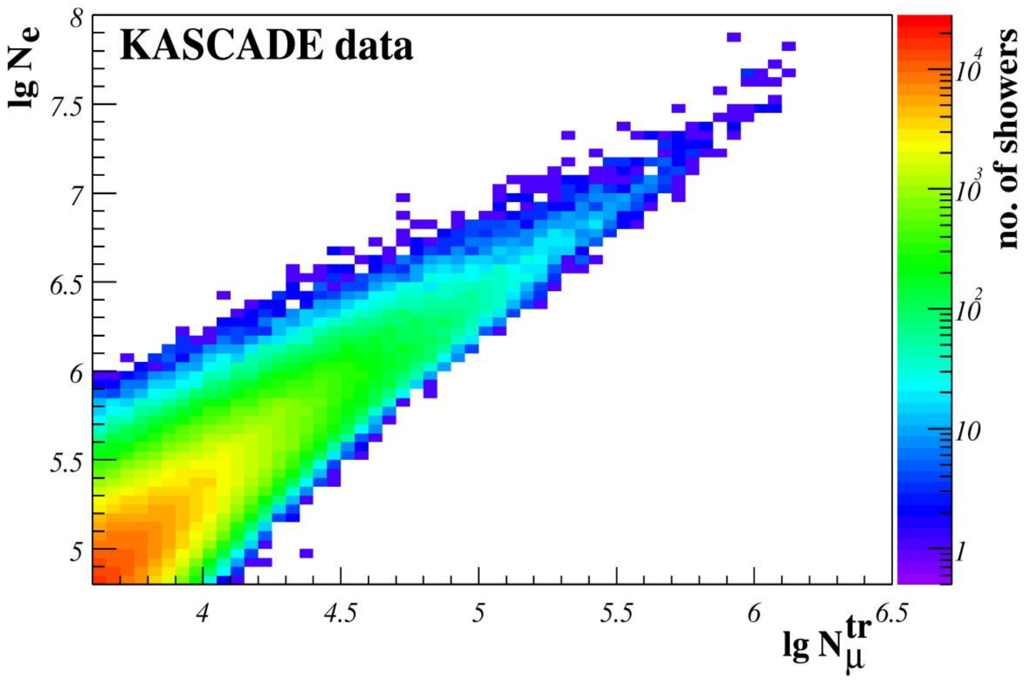


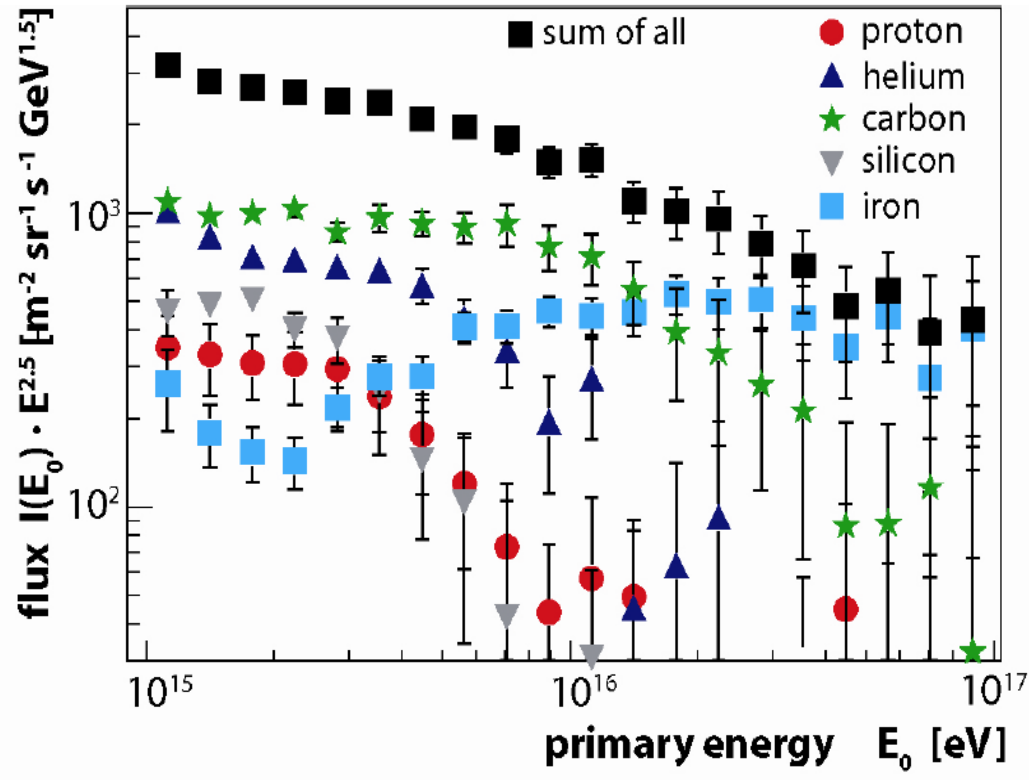
Successfully completed data acquisition at the end of 2013

Data from more than 20 years of measurements are now available for public usage

- 100TeV – 80PeV
- 252 scintillation detector stations
- Large number of observables

KASCADE: Energy Spectra of Single Mass Groups





Searched: Energy and Mass of the cosmic ray particles

Given: N_e and N_μ for each single event $\rightarrow$ solve the inverse problem

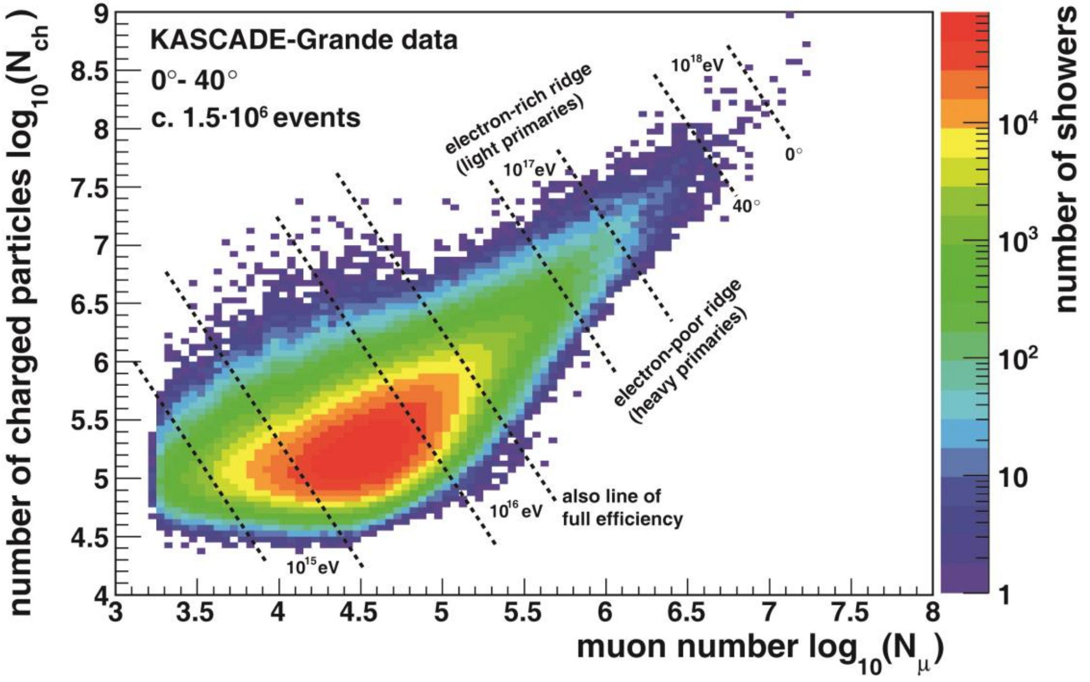
$$\frac{dJ}{d\lg N_e d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

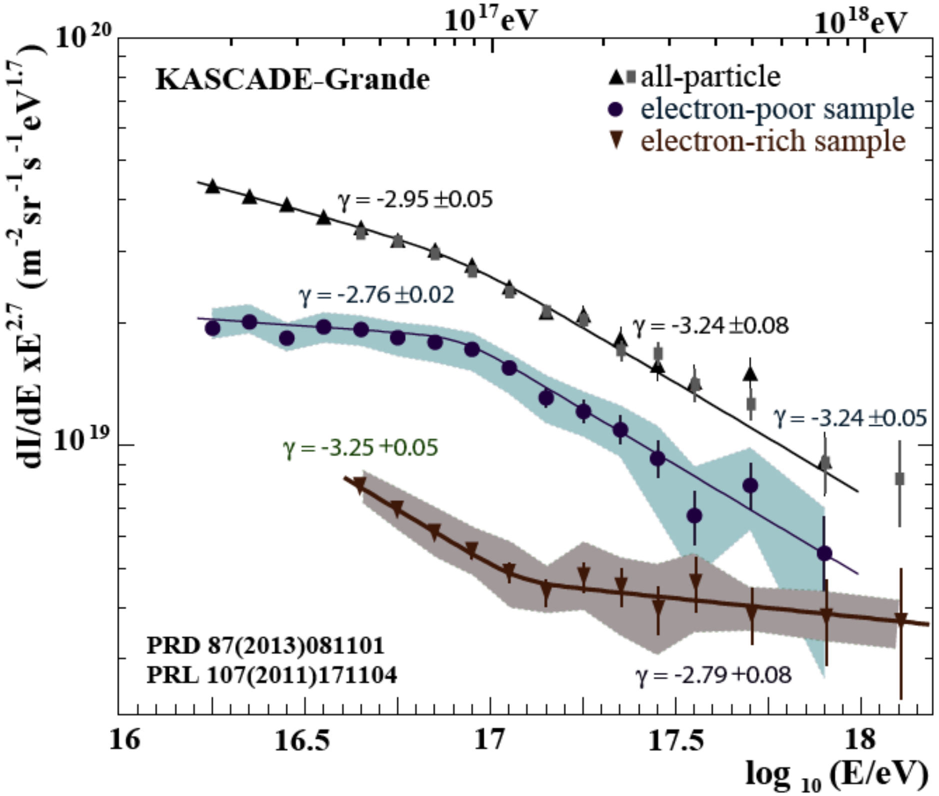
- Kernel function obtained by Monte Carlo simulations (CORSIKA)
- Contains: shower fluctuations, efficiencies, reconstruction resolution

- Knee caused by light primaries at ~ $3 \cdot 10^{15}$ eV (He dominant)
- Relative abundancies depend strongly on high energy interaction model

Astropart. Phys. 24 (2005) 1-25

KASCADE-Grande: Energy and Elemental Composition





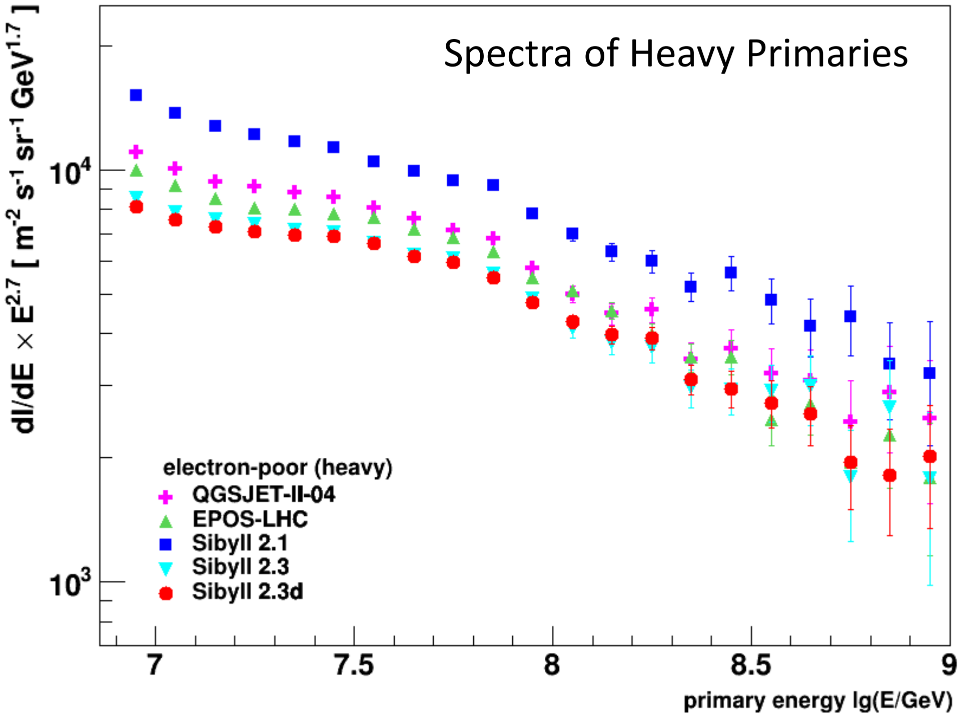
- 2-dim. shower size distribution → determination of primary energy
- Separation in *electron-rich* and *electron-poor* events

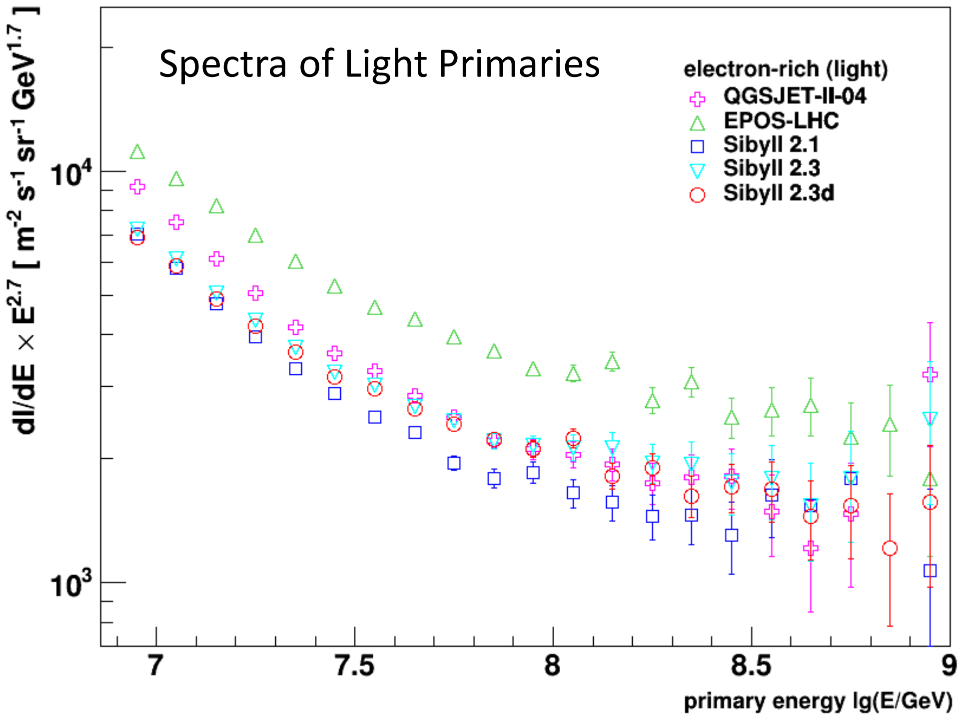
$$\log_{10}(E/\mathrm{GeV}) = [a_H + (a_{Fe} - a_H)\cdot k]\cdot \log_{10}(N_{ch}) + b_H + (b_{Fe} - b_H)\cdot k$$

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

- Spectra of individual mass groups
- Steepening close to 10^{17}eV (2.1σ) in all-particle spectrum
- 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 $\gamma = -2.79$
- Mixed composition for 10^{15} to ~ 10^{18} eV

KASCADE-Grande: Model Dependence

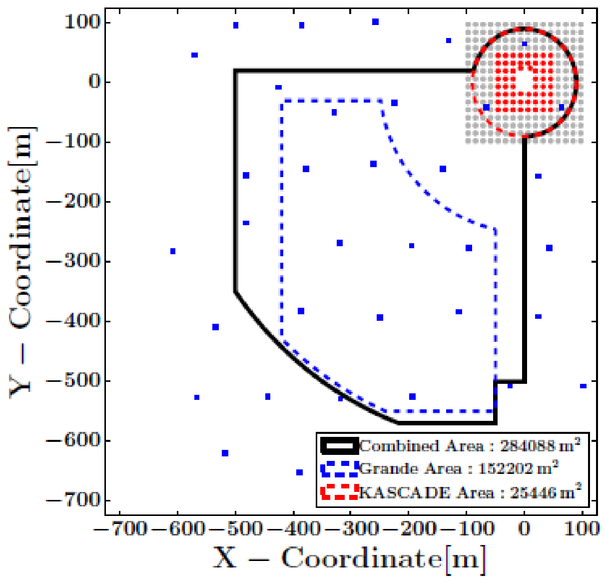


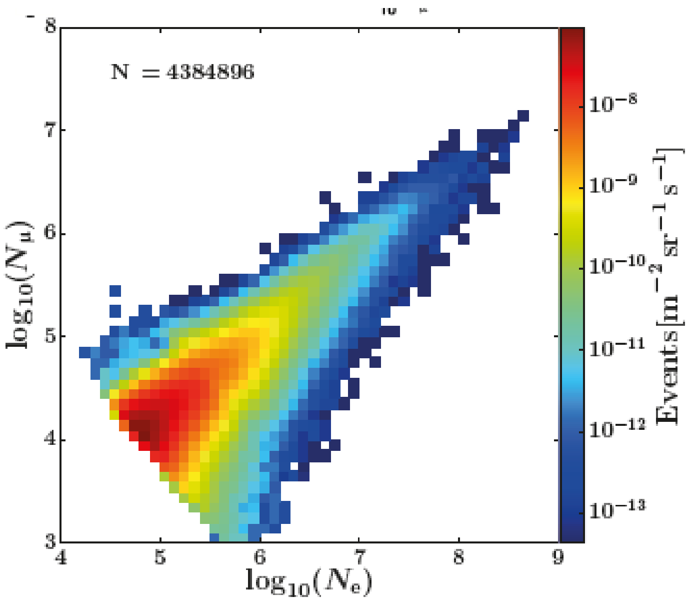


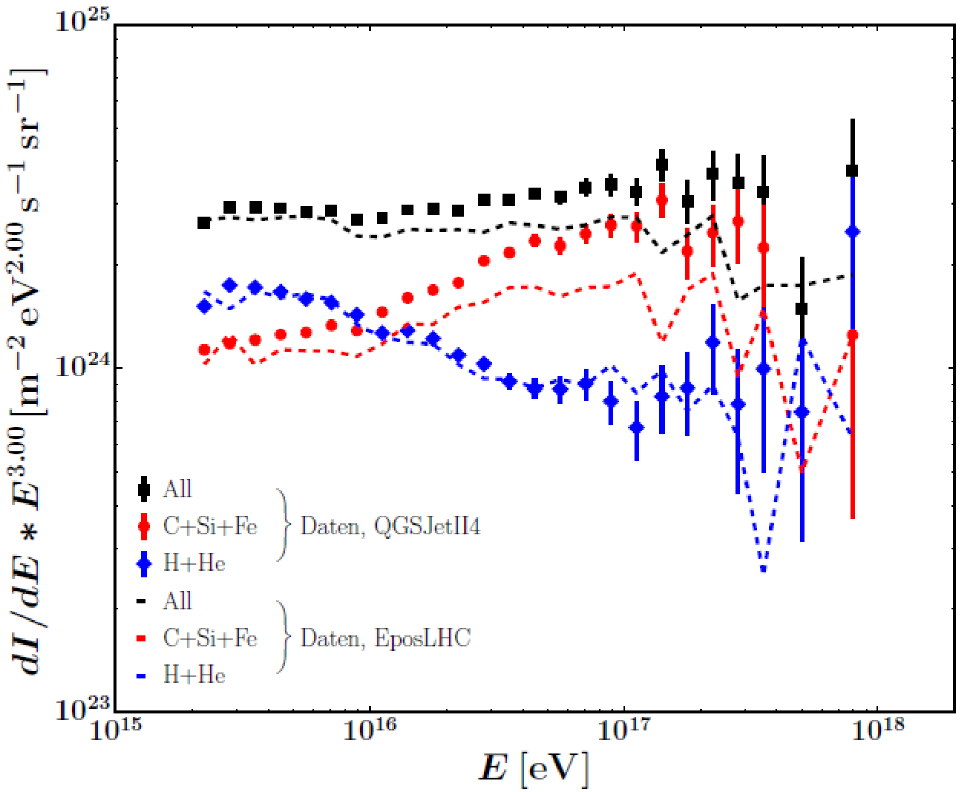
- Testing hadronic interaction models based on shower size
- Structures of all-particle, heavy and light spectra similar → knee by heavy component; hardening by light component
- Sibyll 2.3d: lowest flux of heavy primaries of all models, smooth change of the spectral slope
- Relative abundances different for different high-energy hadronic interaction models
- Estimation of systematic uncertainties is in progress (expected to be ~20%)

PoS(ICRC2021)313, Work in progress

KASCADE-Grande: Combined Analysis



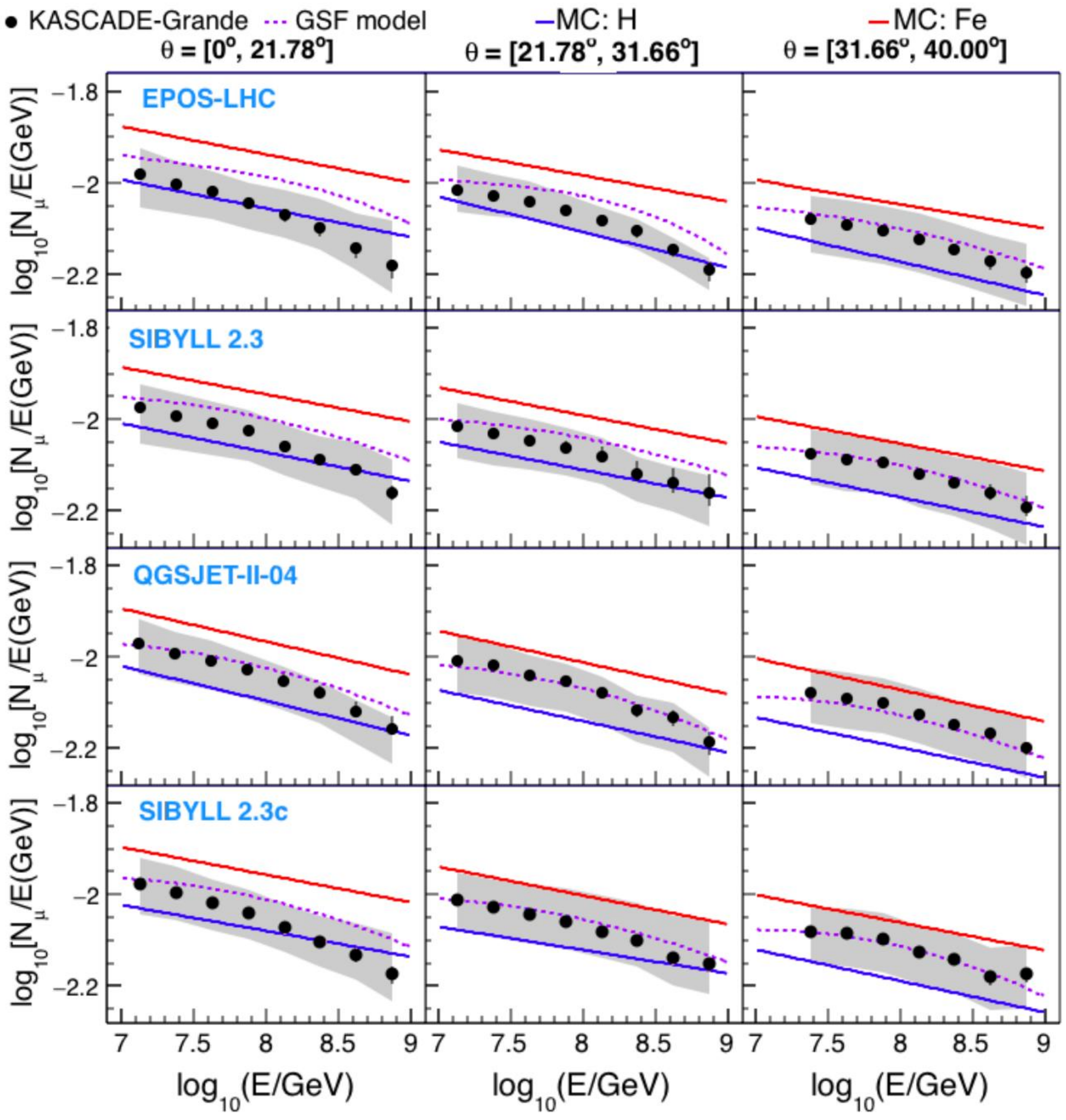




- For KASCADE: additional stations at larger distances → higher energies
- For Grande: additional 252 stations → higher accuracy

- Light primary interactions okay?
- Heavy primary interactions show differences ← Muon component not sufficiently described (Distance from shower core covered by muon detectors limited)

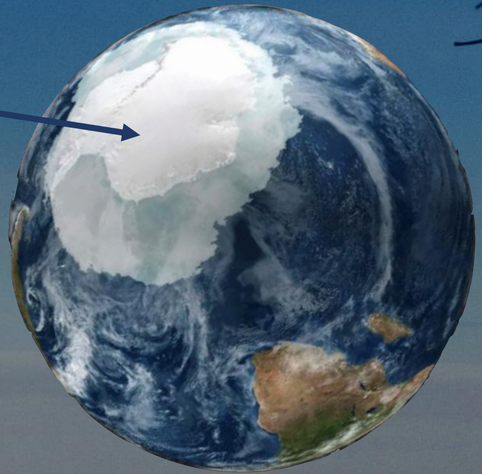
KASCADE-Grande: Muon Contnet



- None of the high-energy interaction models is able to describe consistently the total muon number (Nμ) of EAS measured by KASCADE-Grande at different zenith angles and energies
- Predictions of EPOS-LHC, Sibyll 2.3 and Sibyll 2.3c on Nμ for primary energies between 100PeV and 1EeV are above the KASCADE-Grande data for vertical showers
- Better agreement for inclined EAS close to 40°
- For vertical showers, hadronic interaction models seem to produce more muons
- Observed anomalies could imply that the energy spectrum of muons from real EAS at production site for a given primary energy is higher than the predicted models

PoS(ICRC2021)376, Work in progress

IceTop/IceCube at the South Pole



- Cosmic ray energies from 1 PeV to 1 EeV
- 2835 m a.s.l. 680 g/cm^2
- 81 stations with 2 tanks each (2 DOMs per tank)
- Angular resolution $\sim 1^\circ$
- Timing resolution 3ns
- Energy resolution 0.1 in $\log_{10}(E/\mathrm{GeV})$

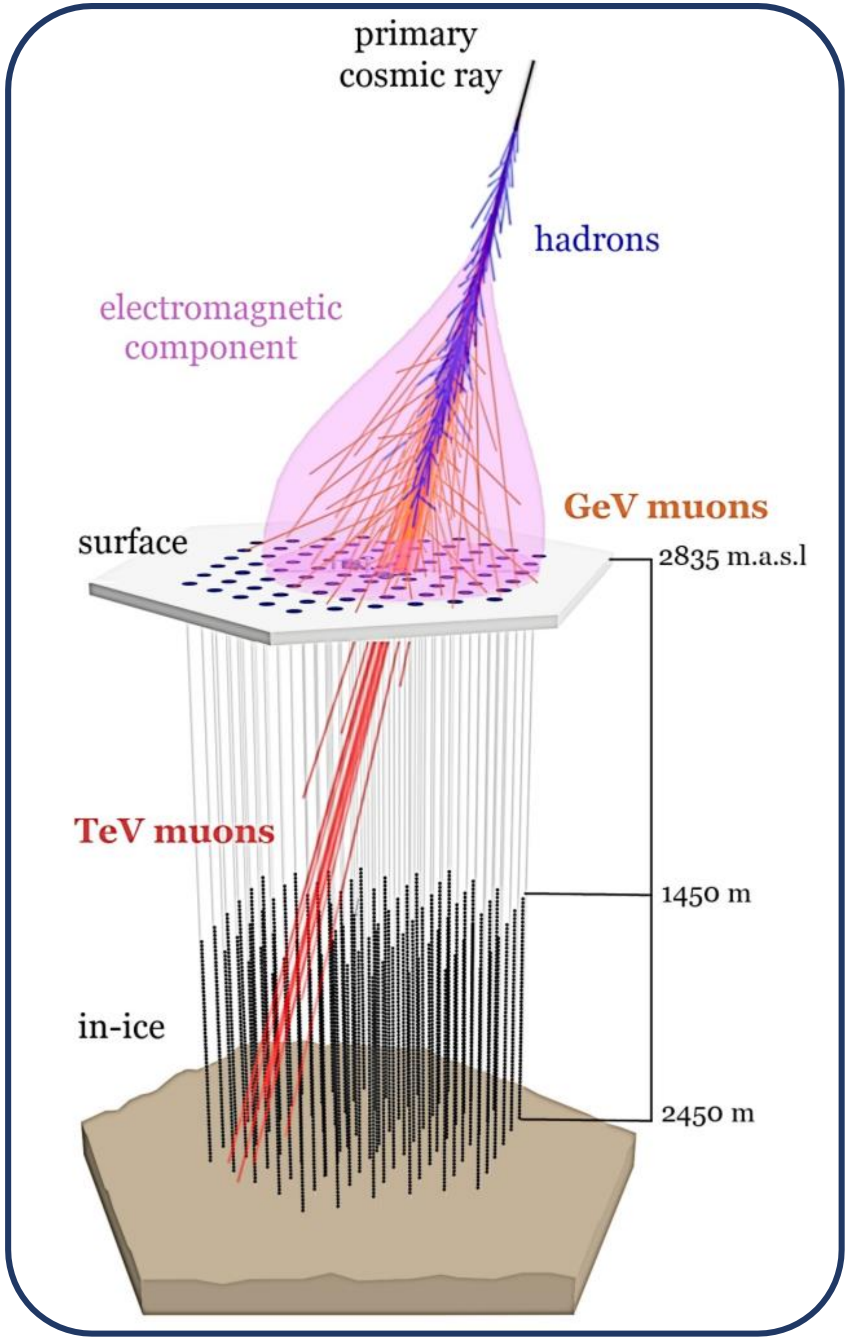


Image: PoS(ICRC2021)357

Cosmic Ray Physics

A three-dimensional cosmic ray detector:

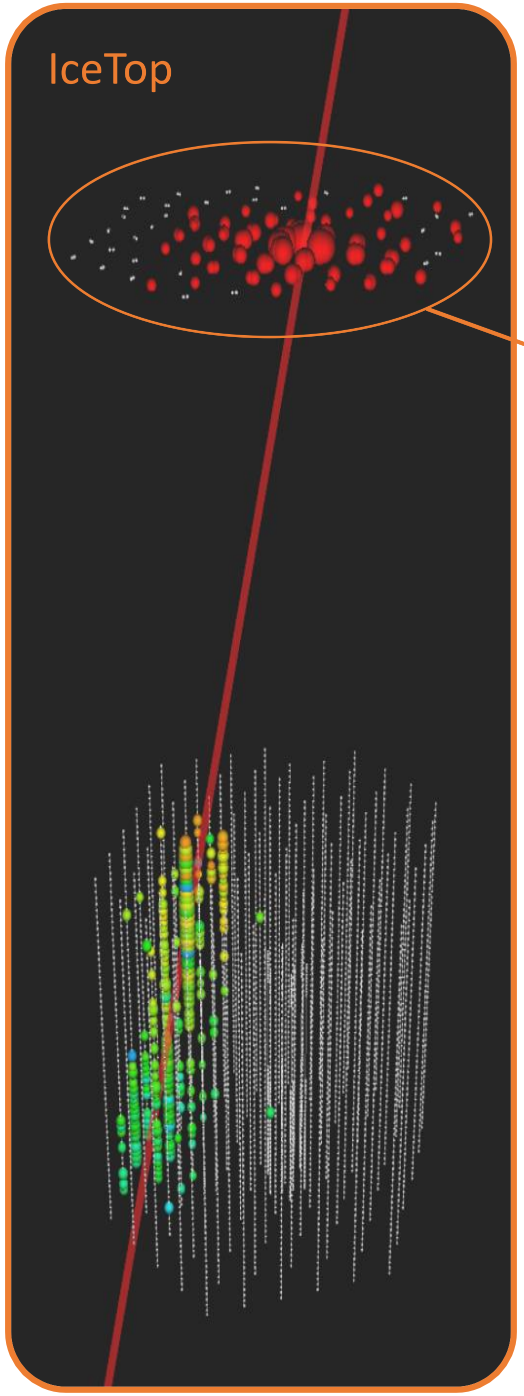
IceTop 1 km^2 surface air shower array

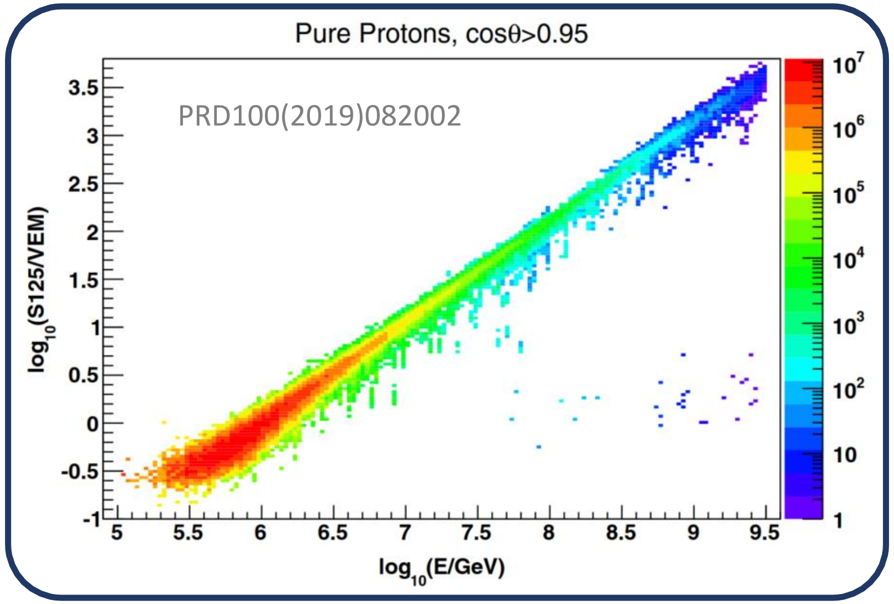
- Cosmic ray energy and direction
- Measure electromagnetic and low energy muon components of air shower ($E_\mu \sim 1$ GeV, GeV muons)

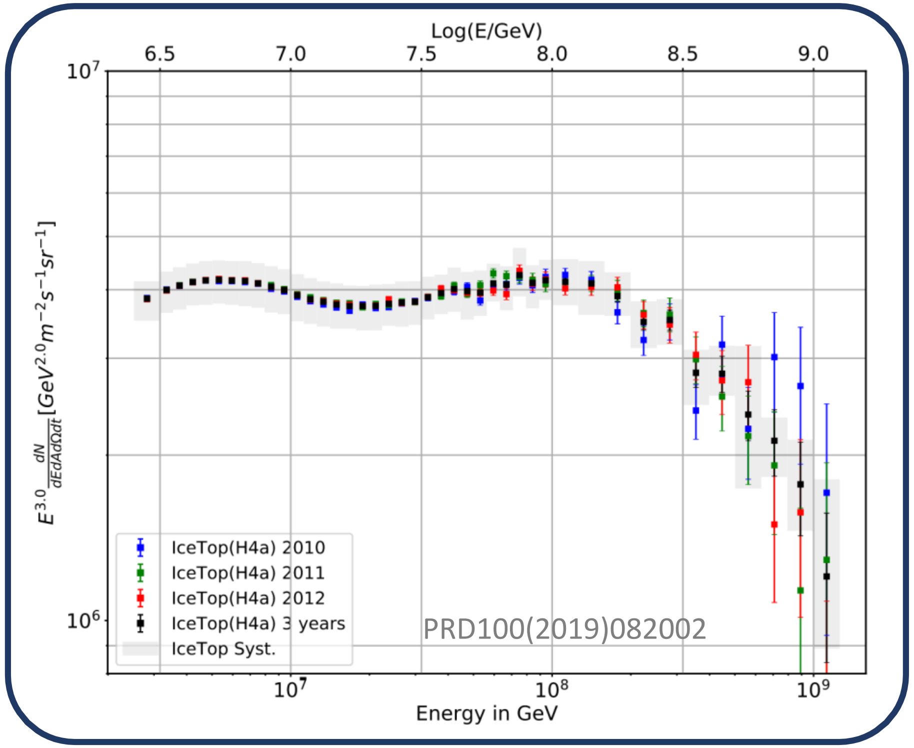
IceCube 1 km^3 in-ice array

- Measure high energy muon component of air shower ($E_\mu > 400$ GeV, TeV muons)
- Track/bundle reconstruction
- Deposited energy along the track dE/dX

Energy Spectrum (IceTop-alone)



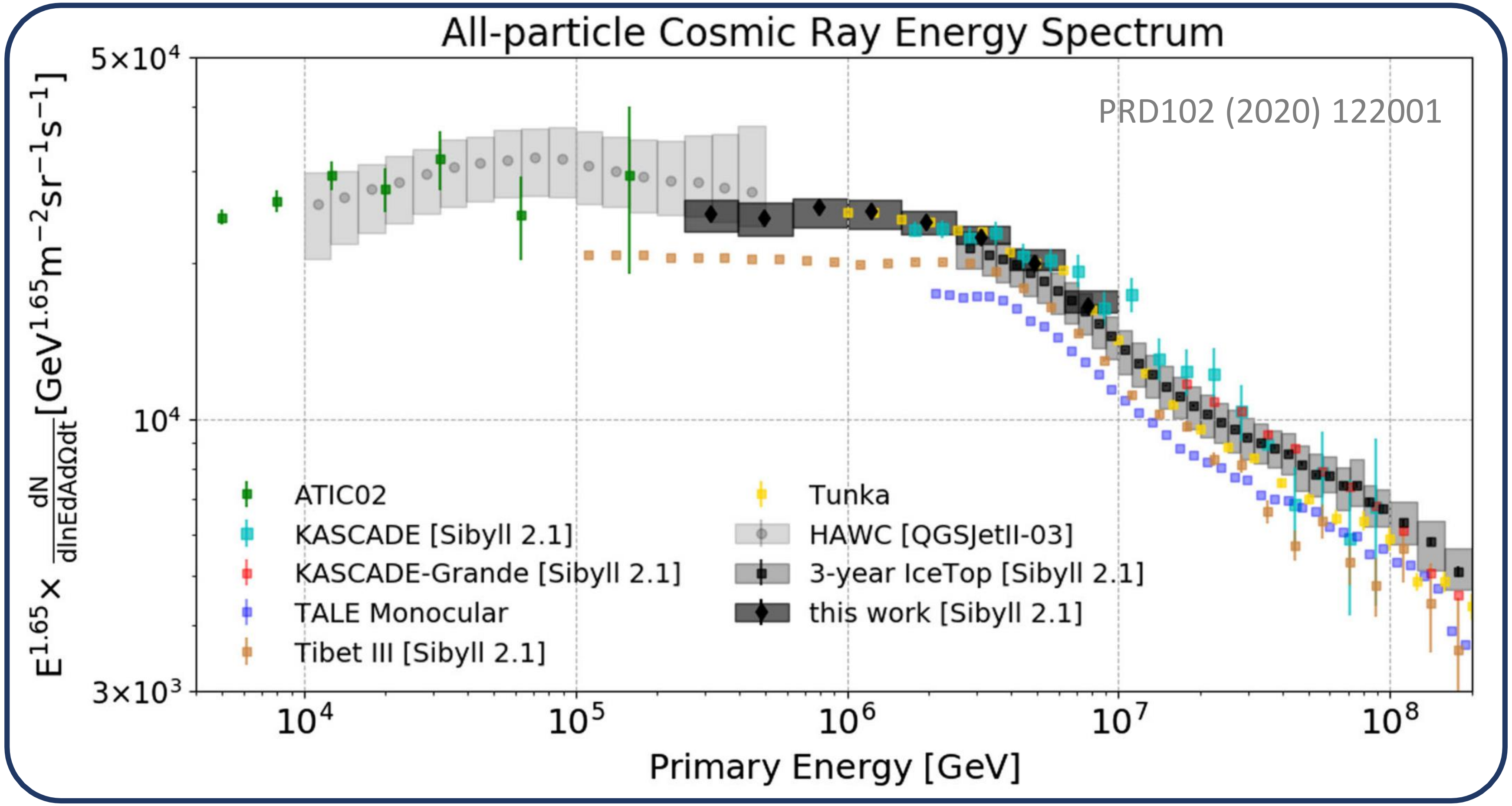




- Lateral Distribution Function (LDF):
  $$S(r) = S_{125} \cdot \left(\frac{r}{125\ \mathrm{m}}\right)^{-\beta-\kappa\cdot\log(r/125\mathrm{m})}$$
- IceTop energy proxy S_{125} in Vertical Equivalent Muons (VEM)
- Nearly composition independent
- Energy calibration based on MC with Sibyll 2.1 and H4a
- Snow depth taken into account
- Quality cuts and full efficiency

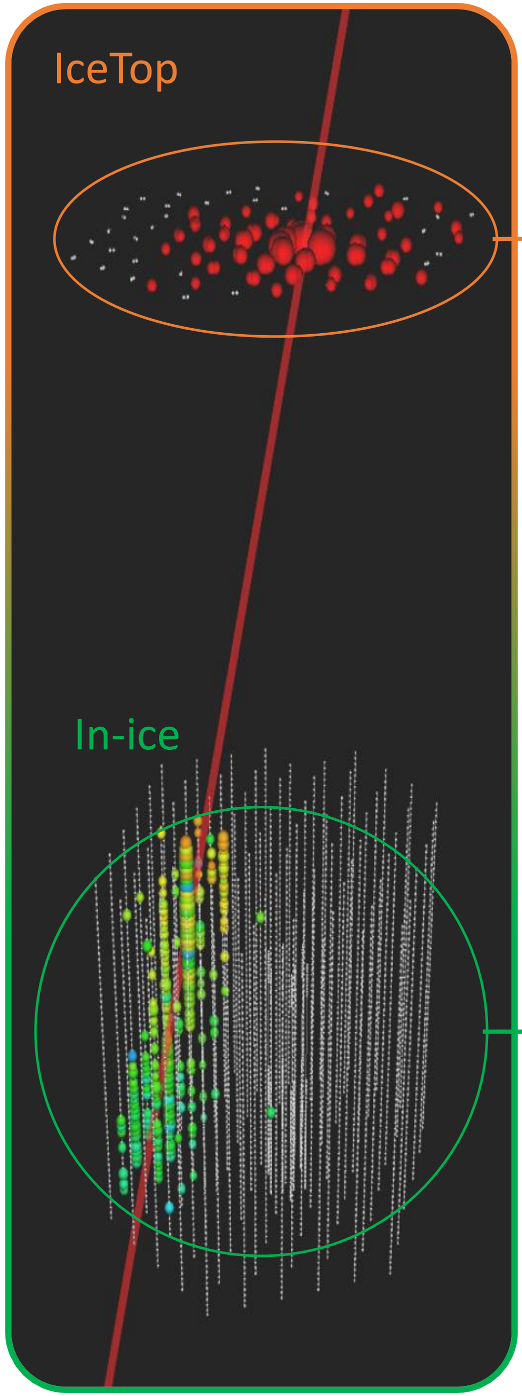
- 3 years of data (May 2010 to June 2013)
- About $5 \cdot 10^7$ selected events
- Dataset divided into individual years shows strong agreement
- Systematic uncertainties ~ 10%

Low Energy Spectrum (IceTop-alone)



- Latest results: Extension to low energies
  - Lower threshold by using IceTop infill area (250 TeV – 10 PeV)
  - LDF fit impracticable → Random Forest (RF) regressions for shower reconstruction
  - Connecting to direct measurements, overlap with HAWC
  - Overlapping region with 3-year IceTop result → Knee structure visible
  - Large systematic uncertainties due to composition, unfolding, atmosphere

Coincident Analysis: Spectrum and Composition

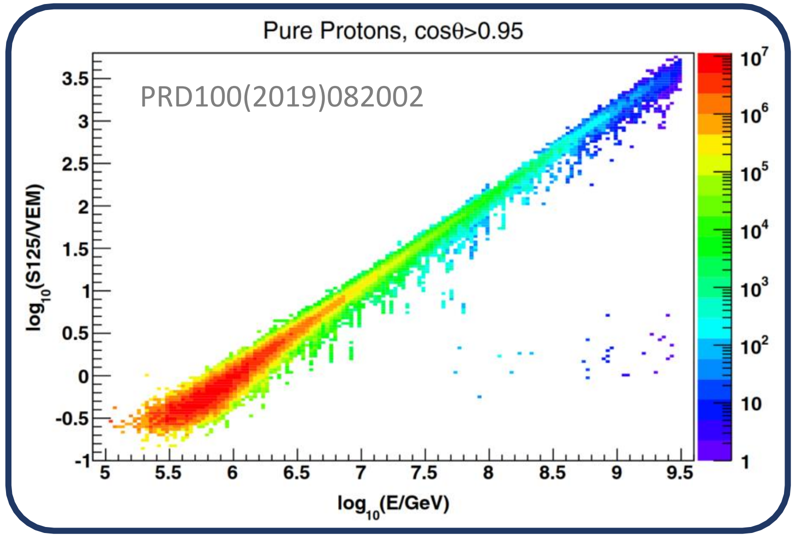


Electromagnetic component of shower:

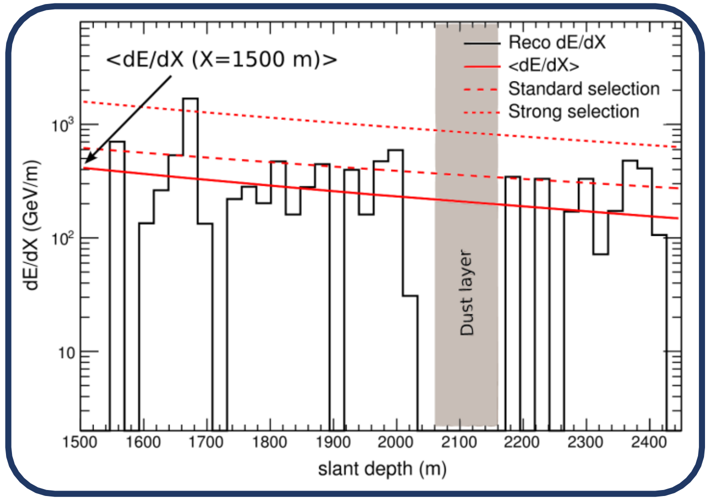
- IceTop energy proxy S_{125}
- Nearly composition independent

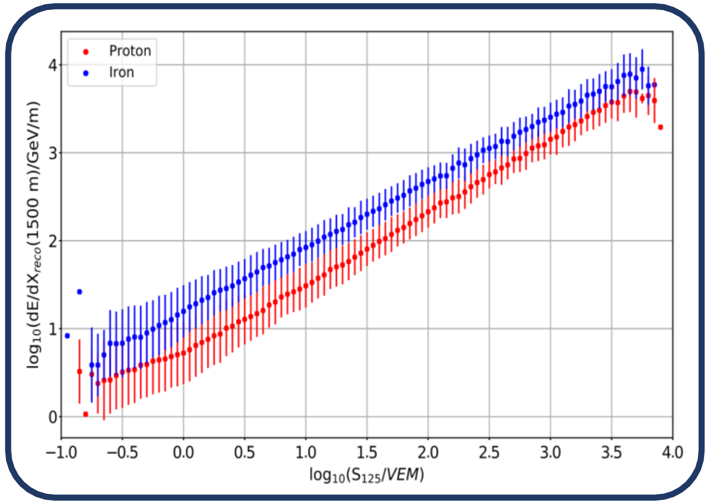
High-energy muons (>400 GeV):

- Energy loss (dE/dX) at fixed slant depth (X=1500m) in the glacial ice
- Strong composition sensitivity



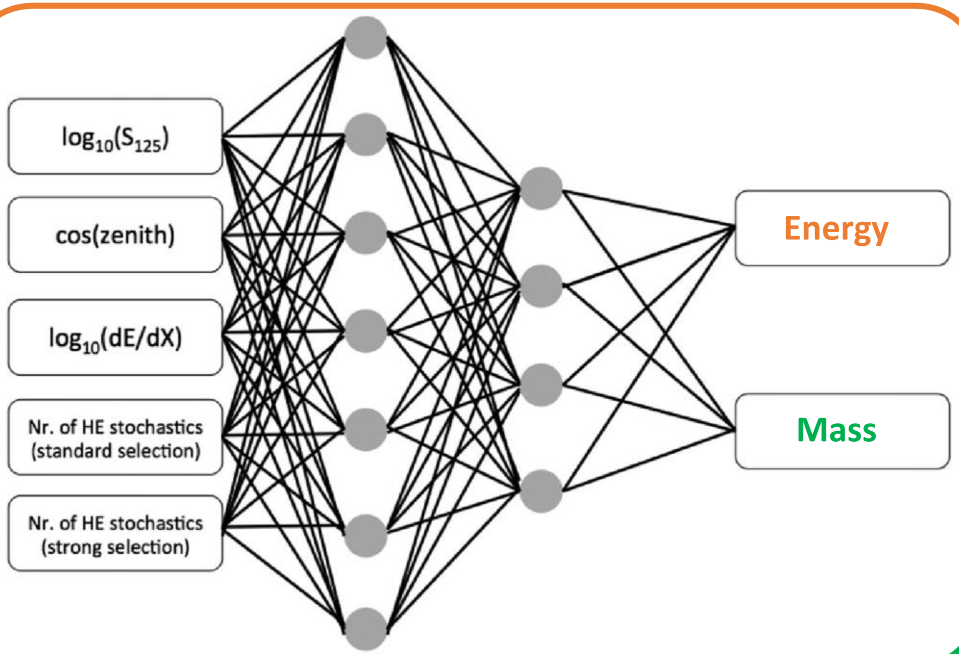
PRD100(2019)082002



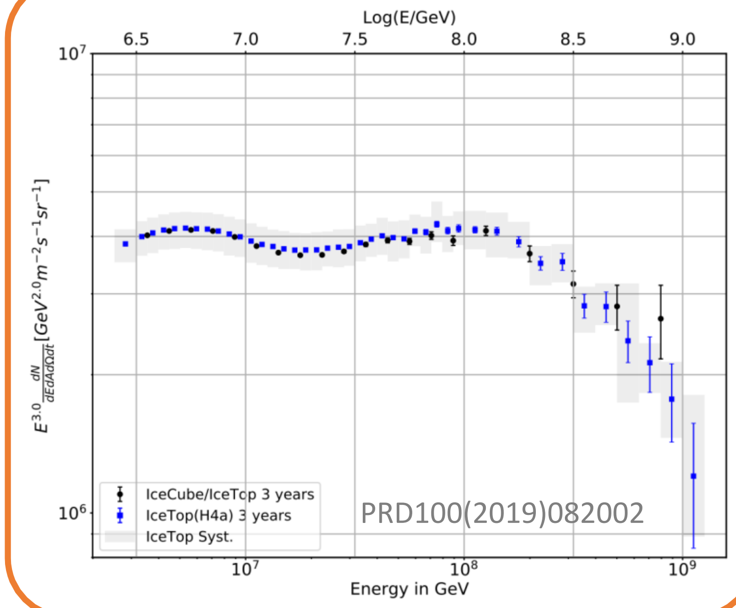


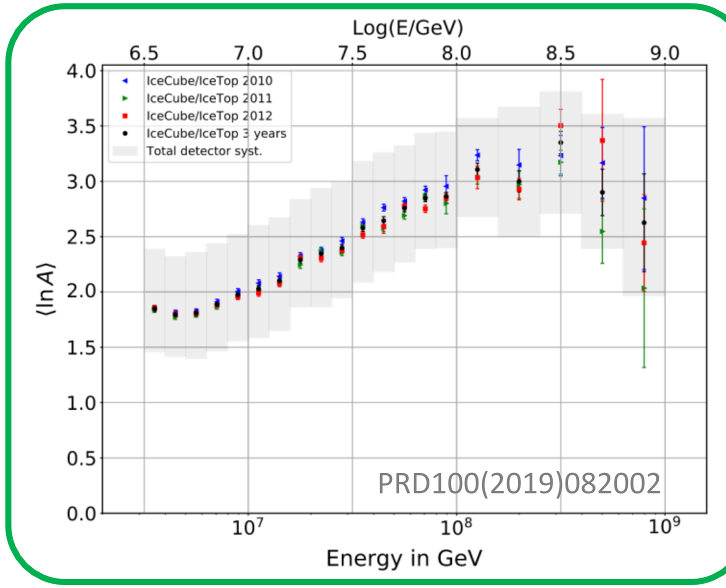
Spectrum and Composition

Use Neural Network to directly reconstruct energy → Coincident energy spectrum



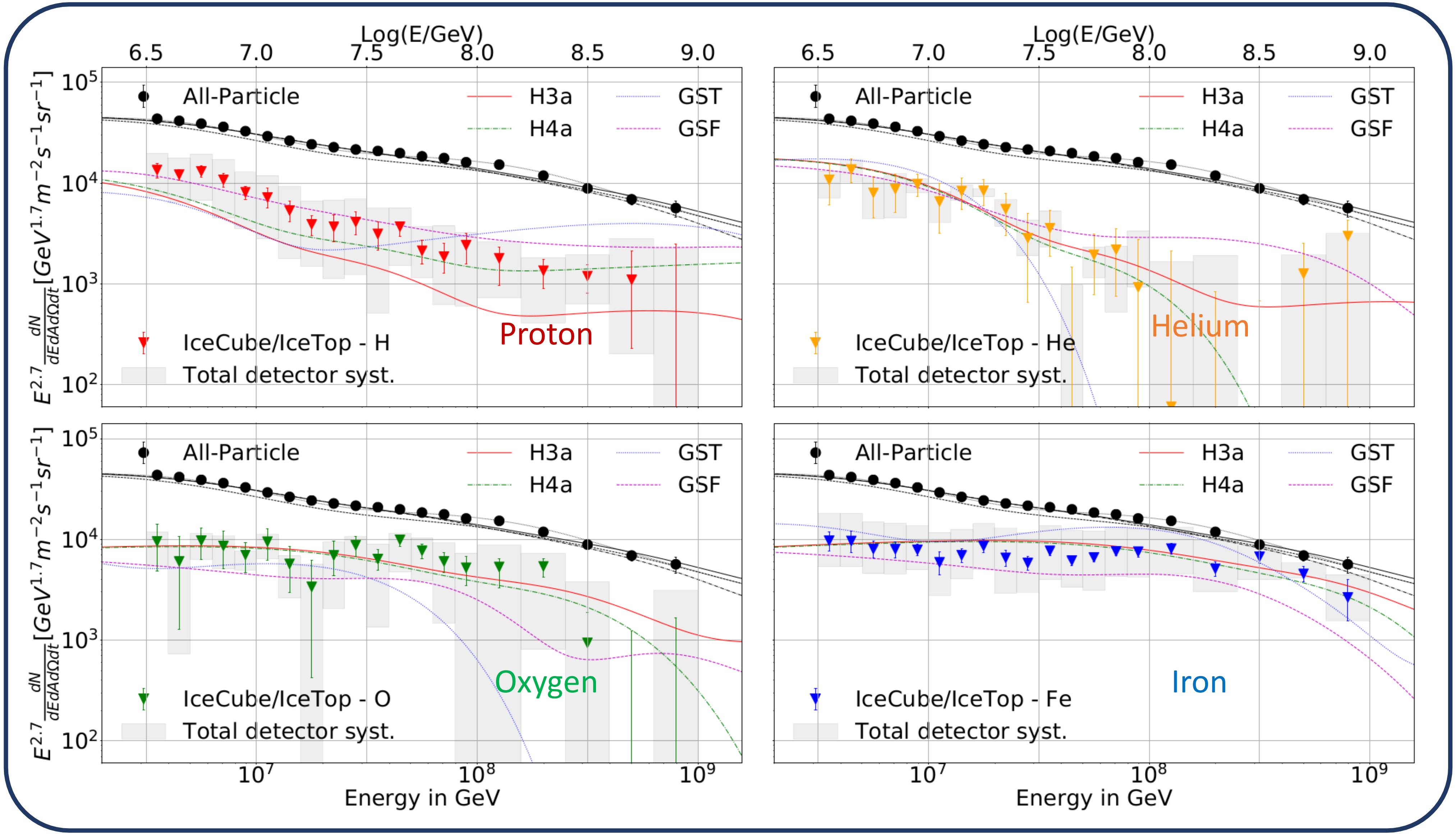
Event by event mass classification is not possible → Analyze mass as a function of energy on a statistical basis





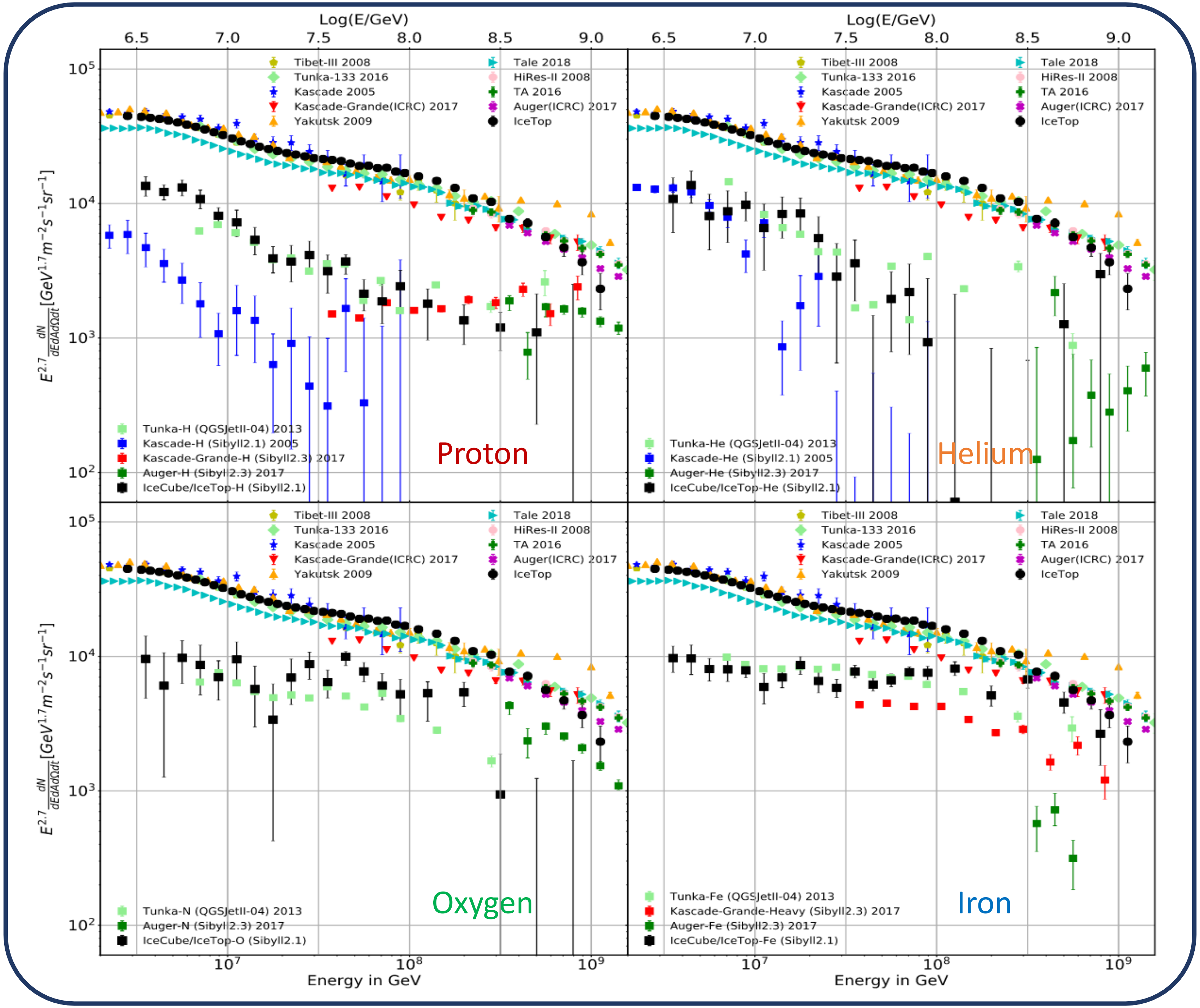
- Same dataset as IceTop-alone analysis
- Agreement with IceTop-alone spectrum
- Coincidence requirement gives composition analysis fewer events and smaller energy range than IceTop-alone analysis

- Mean log mass <lnA> derived from the individual fractions which best fit the NN mass output
- Combined systematic uncertainties of the IceTop and in-ice detectors for coincident analysis:
  - Energy scale ~ 3%
  - In-ice light yield ~ 10%
  - Snow accumulation ~ ±2m



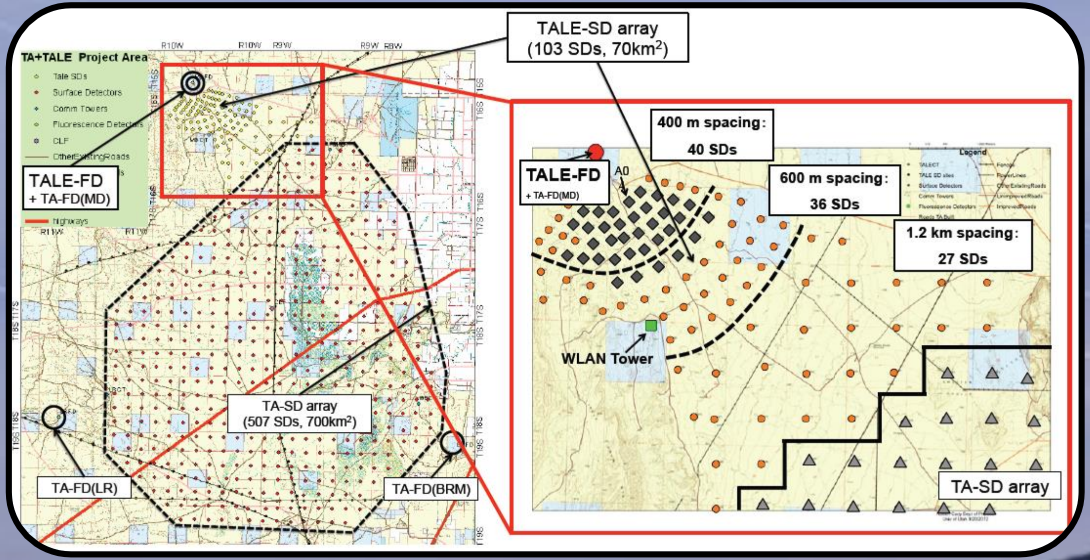
- Each of the four individual fractions from the NN mass output is translated into an individual spectrum
- Composition becomes heavier with increasing energy up to 10^8 GeV
- Agreement with models within statistical and systematic uncertainty

PRD100(2019)082002



- Comparison of the all-particle and composition spectra of the four elemental groups H, He, O, and Fe based on Sibyll 2.1
- Individual elemental fluxes across a wider range in energy than any previous experiment
- The knee energy increasing as mass increases
- Differences in how different experiments handle the intermediate elements may lead to some systematic differences in flux measurements

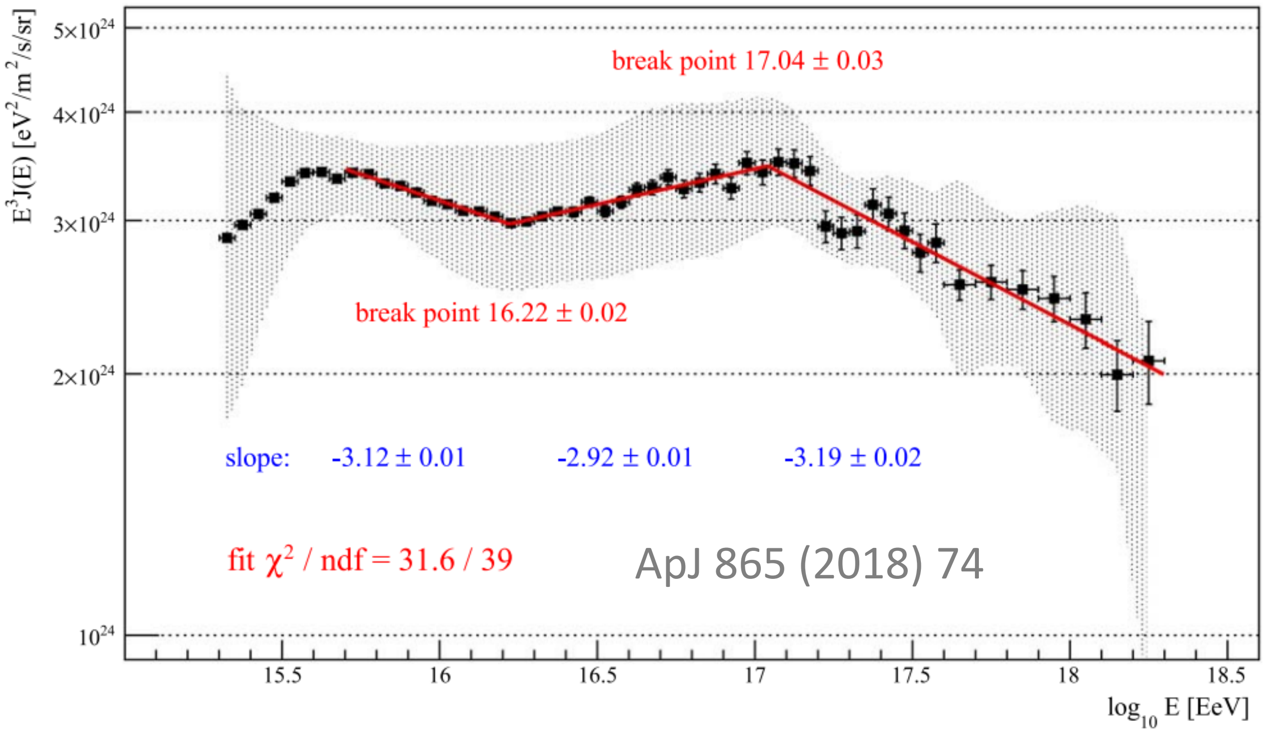
PRD100(2019)082002

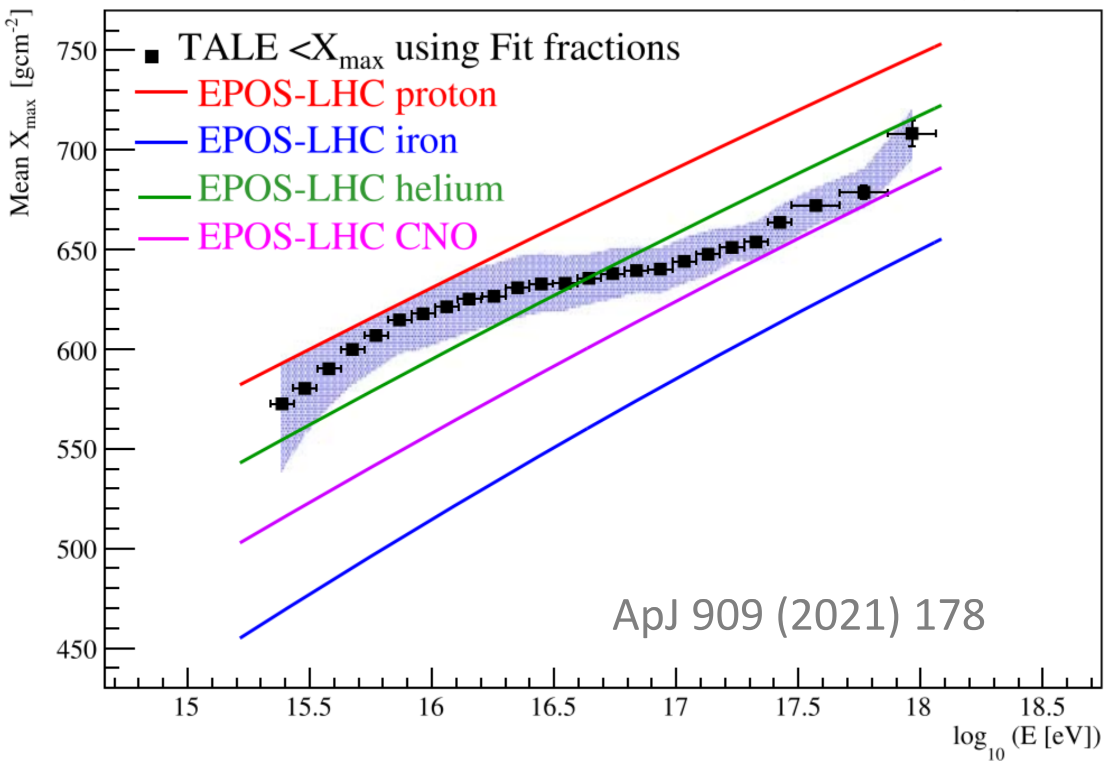


TA Low Energy Extension (TALE)

- 10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies
- Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)

TALE: Energy Spectrum and Mass Composition

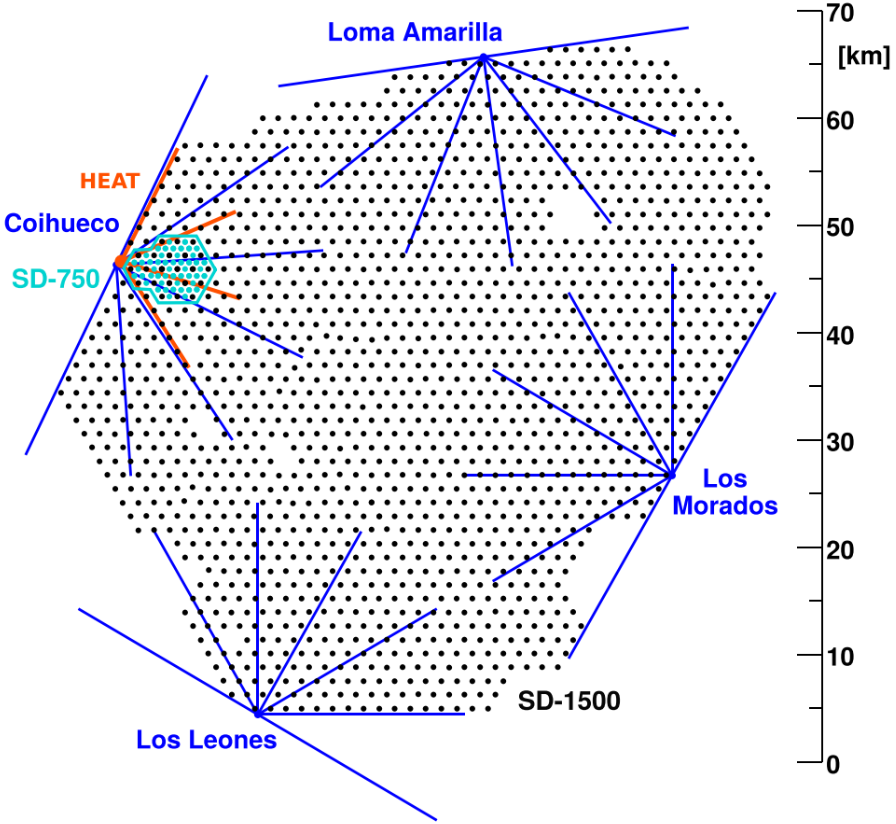




- Updated cosmic ray energy spectrum measured by TALE FD using the mass composition data set
- Broken power-law filt to the cosmic-ray energy spectrum
- Two features: a low energy ankle at $10^{16.22}$ eV and a second knee at $10^{17.04}$ eV

- Composition is getting heavier, followed by a change at an energy of ~ $10^{17.04}$ eV
- It shows a light composition of mostly protons and helium at the lower energies, becoming more mixed near $10^{17.04}$ eV

The Pierre Auger Observatory



Fluorescence Detector (FD)
Detection of fluorescence emitted in atmosphere by CR shower

Surface Detector (SD)
Detection of secondary particles on ground

Surface detector

- 1500 m array: 1600 detectors, 3000 km^2, 1500m grid, E > 2.5 EeV
- **750 m array: 61 detectors, 24 km^2, 750m grid, E > 0.1 EeV → Low energy extension**

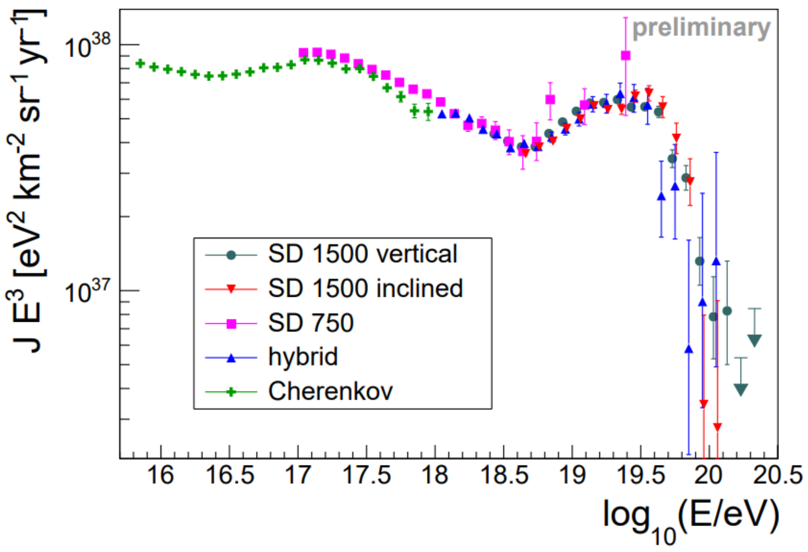
Fluorescense detector

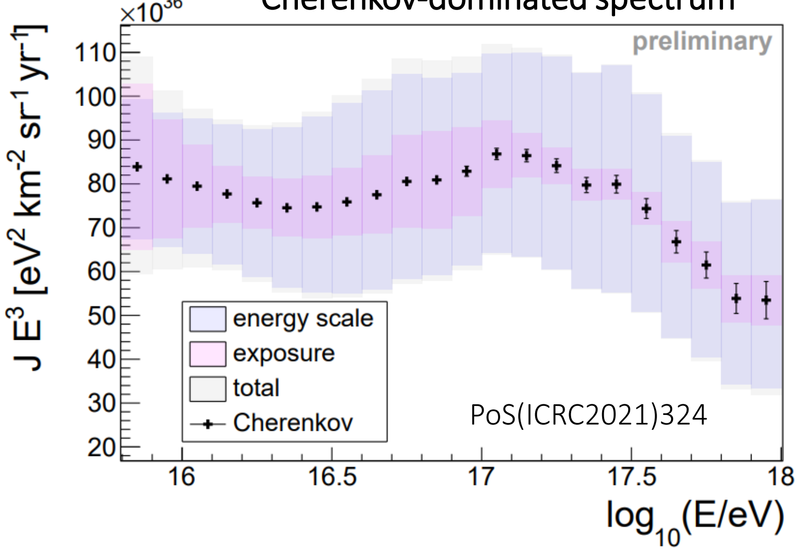
- 24 telescopes: 4 buildings, Elevation up to 30°, E > 1 EeV
- **3 additional telescopes (HEAT), Elevation 30-60°, E > 0.1 EeV**

AERA

- 153 radio antennas: 17 km^2, 30-80 MHz, E > 0.1EeV

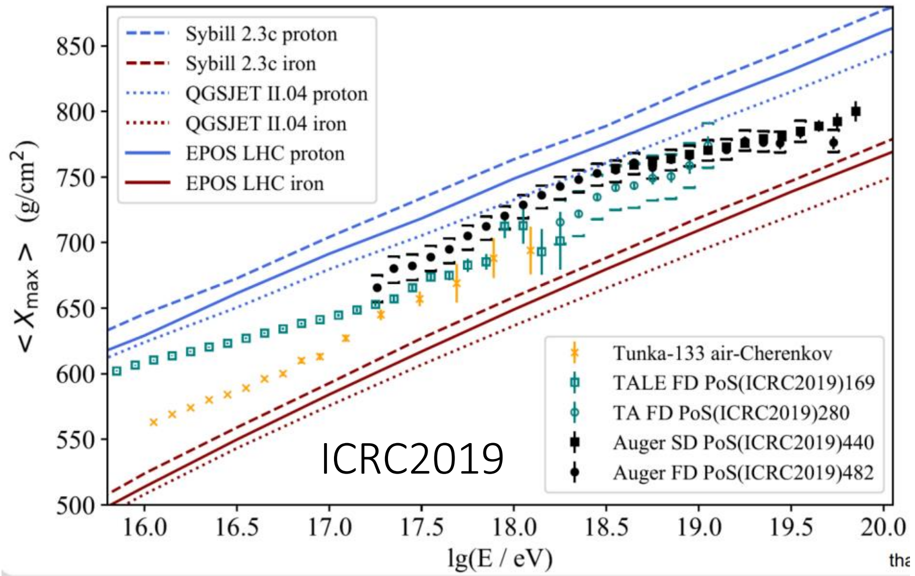
Auger: Energy Spectrum and Mass Composition





Low-energy showers with FD

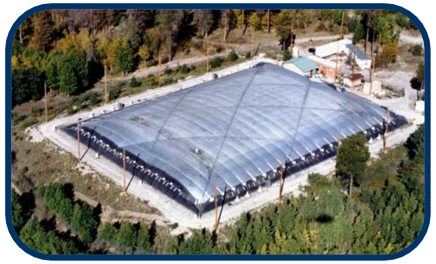
- Large Cherenkov light fraction
- Profile-constrained geometry fit
- Energy scale uncertainty – 15% for Cherenkov



- Mean of the shower maxima indicate a composition becoming lighter up to $\sim 10^{18.3}$ eV
- Transition from light to heavier primaries above $\sim 10^{18.3}$ eV
- Mass composition below 0.1 EeV to be studied
- TALE bias not fully known
- Tunka-133 biases and systematics not fully known

Cosmic Ray Anisotropy

Milagro (2000-2008)



HAWC (2013-present)

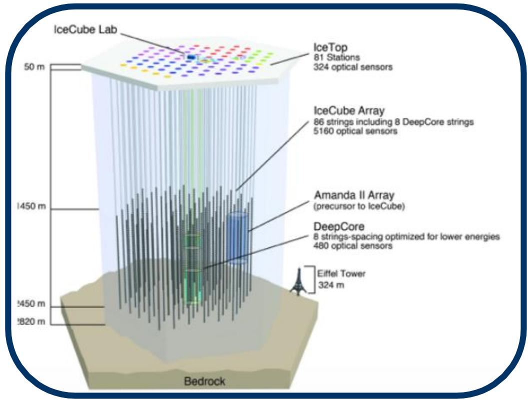
Tibet-ASγ (1997-2009)

ARGO-YBJ (2007-2015)

ESA-TOP

KASCADE
KASCADE-Grande

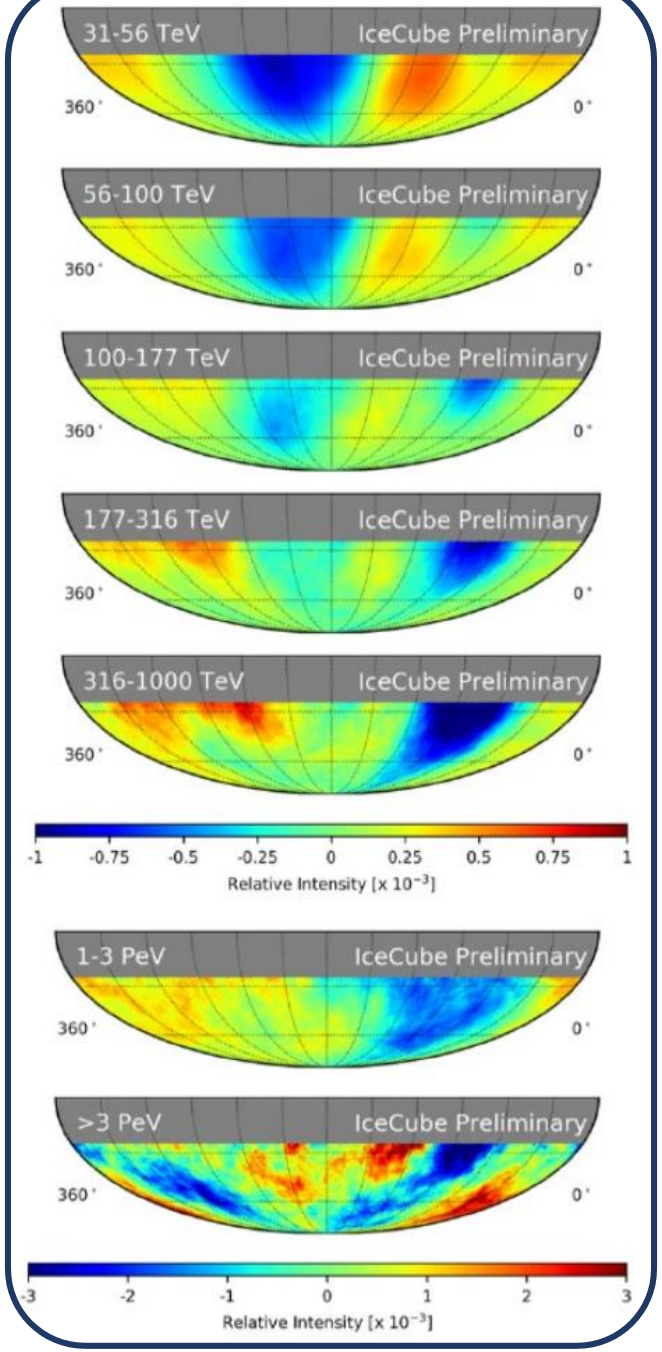
IceCube/IceTop (2007-present)



- Theoretical modes predict an anisotropy in the distribution of arrival directions of cosmic rays that results from distribution of sources in the Galaxy and diffusive propagation of these particles
- Anisotropy in the arrival directions of cosmic rays has been observed by a number of underground and surface detectors
- Total energy range covered: ~ 10 GeV to ~ 10 EeV
- Large-scale structure: 10^{-3} relative intensity
- Small-scale structure: 10^{-4} relative intensity with angular size of 10° – 30°

IceCube Cosmic Ray Anisotropy (10 TeV – 5 PeV)

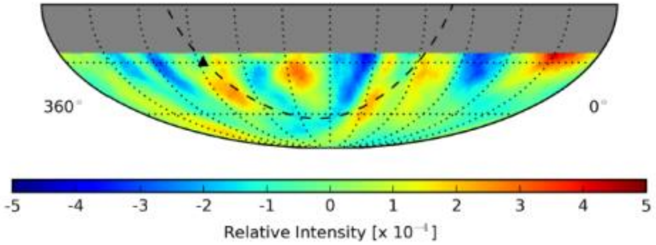
Energy dependence in southern hemisphere



PoS(ICRC2021)320

IceCube, APJ 826 (2016)
IceCube, APJ 765 (2013)

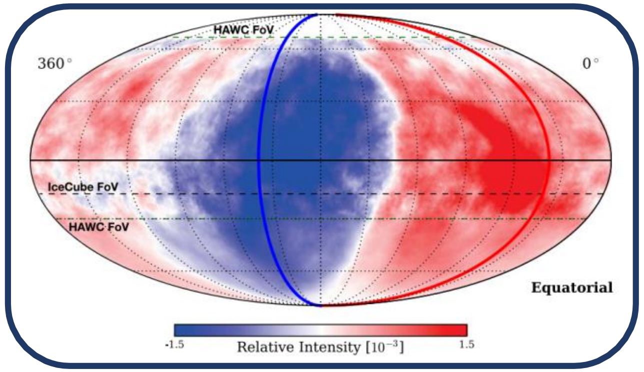
- Dominant dipole at large scale (10^{-3})
- Significant small scale structure (10^{-4})



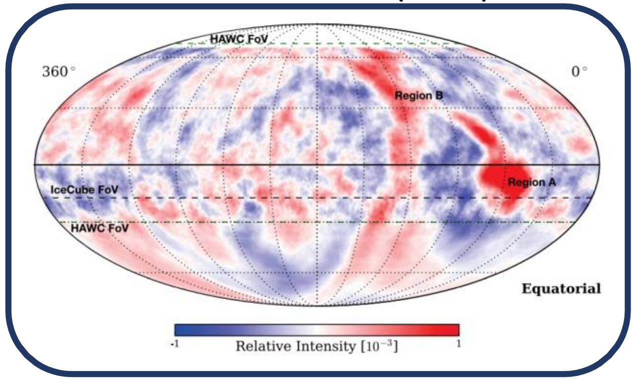
- Cosmic ray anisotropy depends on primary energy
- **Large scale changes structure above 100 TeV**
- Magnetic effects at larger distances with increasing energy
- Note: cosmic ray mass composition changes as well vs. energy

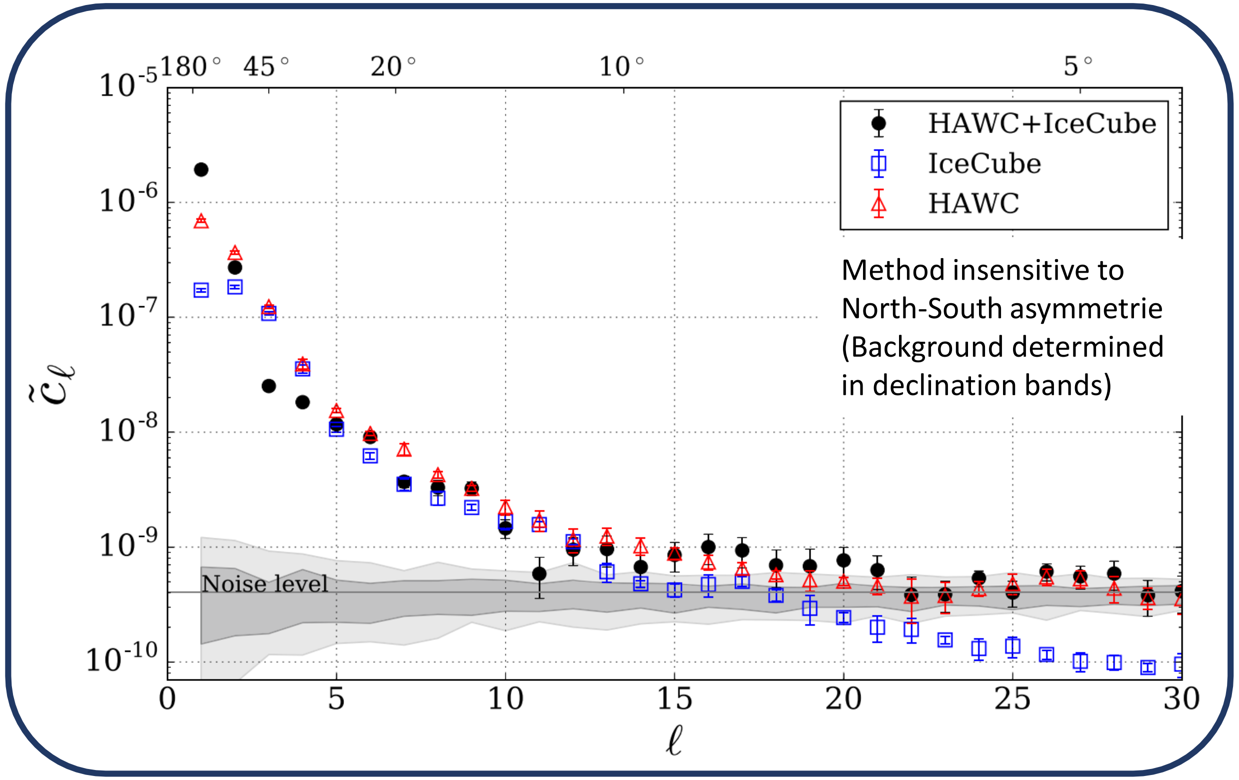
IceCube/HAWC All-Sky Anisotropy at 10 TeV

Large scale



Small scale ($l \geq 3$)



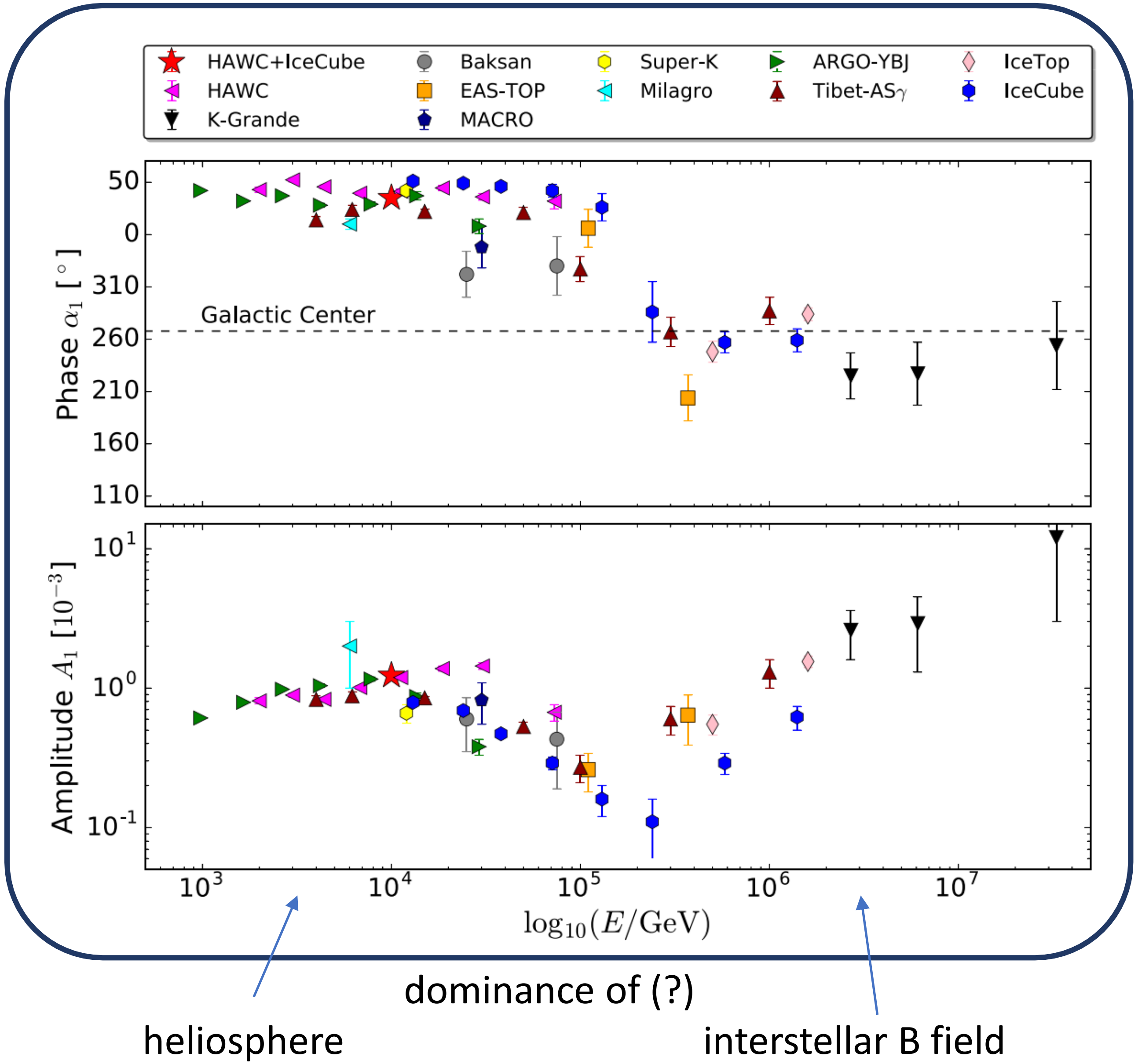


IceCube & HAWC, Astrophys. J. 871 (2019) 96

Joint analysis of data from IceCube and HAWC: First all-sky cosmic-ray data set at 10 TeV

- Relative intensity maps at 10 TeV
- Decomposition of relative intensity into spherical harmonics → angular power spectrum
- Individual measurements show differences due to partial sky coverage
- All-sky measurement removes these biases of the power spectrum
- Noise level dominated by limited statistics for HAWC

IceCube/HAWC All-Sky Anisotropy at 10 TeV



- Dipole phase: α = (38.4 ± 0.3)°
- Dipole amplitude: A = $(1.17 \pm 0.01)\cdot 10^{-3}$
- Systematic uncertainties:
  Δα ~ 2.6° , ΔA ~ $0.006\cdot 10^{-3}$
- Phase shift of dipole around 150 TeV
- Turning point of amplitude at ~10 TeV (transition heliosphere – interstellar magnetic field?)
- Details of effects of magnetic fields need all-sky analyses

Future Projects and Upgrades

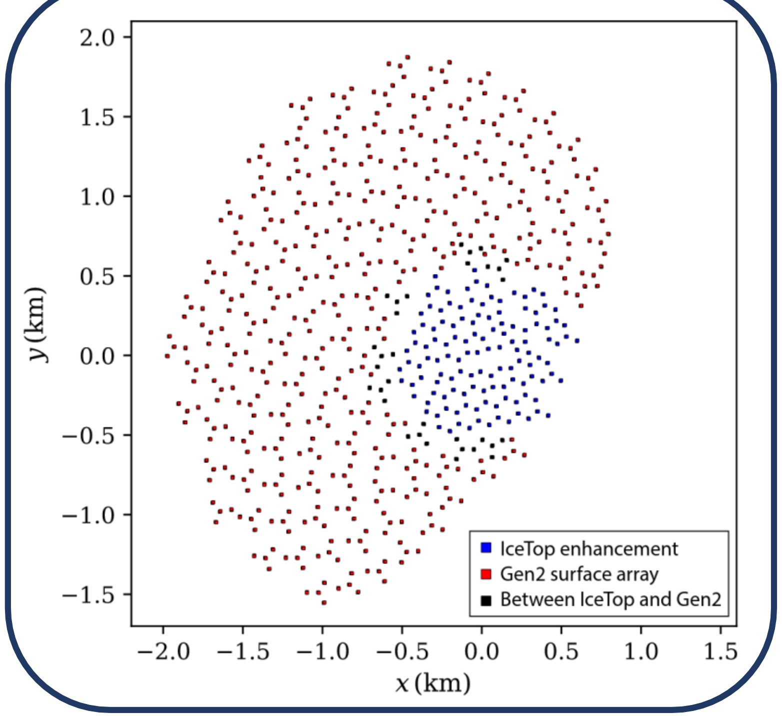
- Increasing overlap with direct measurements from TeV to PeV, e.g. DAMPE, NUCLEON
  - It will help to understand systematic uncertainties in interpretation of measurements of air-shower array

- AugerPrime: Upgrade of the Pierre Auger Observatory
  - Improve quality of surface array with scintillators and radio antennas, underground muon detectors, better electronics
  - Enables event-by-event mass discrimination

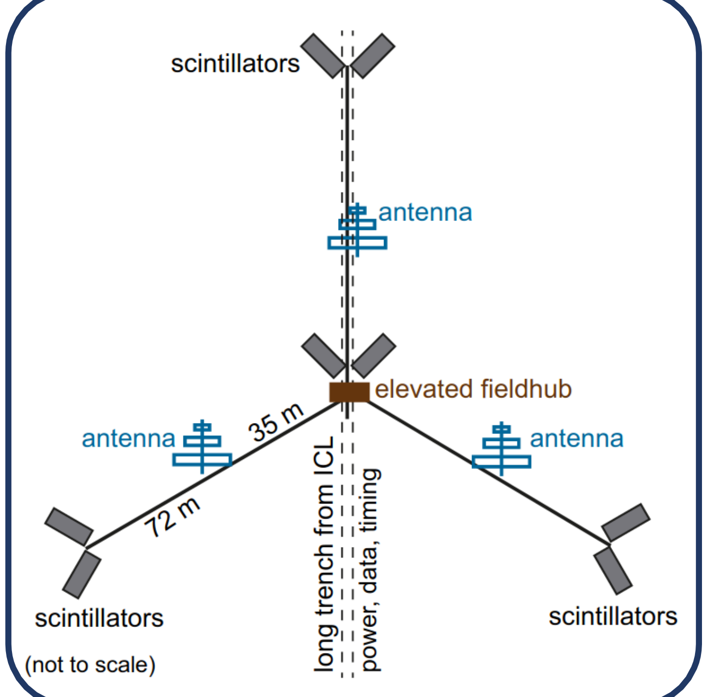
- Telescope Array: Upgrades
  - Lower energies ($E < 10^{15.5}$ eV): TALE SD array complementing NICHE and FD

- IceTop hybrid surface detector enhancement

IceTop: Hybrid Surface Detector Enhancement



PoS(ICRC2021)407



4 pairs of scintillation detectors + 3 antennas

Complete prototype station since 2020

Science goals:
- Improve systematics due to snow coverage
- Improve cosmic ray veto for neutrino detection
- Improve mass composition measurements
- Composition dependent anisotropy studies
- Improve PeV gamma ray search
- Validate hadronic interaction models

A multi-detector IceTop enhancement by adding to IceTop Cherenkov tanks:
- Scintillation detector panels
- Radio antennas

Concluding Comments

- Sources of the most energetic galactic and extragalactic cosmic rays still unknown, however, experimental data in the knee region mostly consistent within uncertainties: Mass composition, Energy spectrum, Anisotropy, ...
- Results sometimes limited by statistics, but often limited by accuracy: Hadronic interaction models and systematic uncertainties
- Bright future with detector upgrades for multi-hybrid measurements!