Cosmic ray physics @Southern hemisphere

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Active experiments

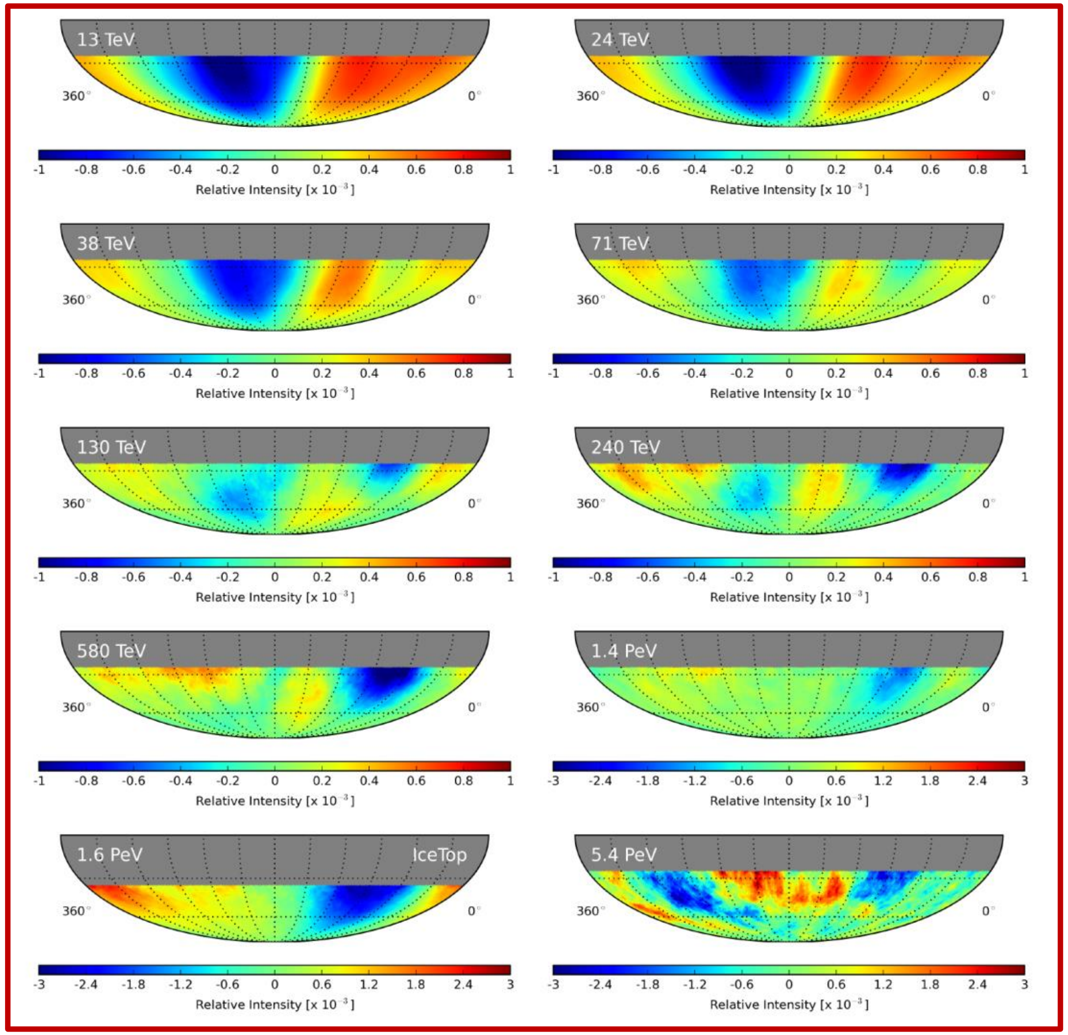
- Northern hemisphere
  - HAWC (4100 m a.s.l., 2×10^4 m^2, WC)
  - TIBET III (4300 m a.s.l., 5×10^4 m^2, Scint.+μ det.)
  - TUNKA/TAIGA (670 m a.s.l., 3×10^6 m^2, Cherenkov + μ det.)
  - LHAASO (from 2019) (4400 m a.s.l., 10^4 m^2 WC + 10^6 m^2 KM2A + WFCTA)
- Southern hemisphere
  - Ice Cube – Ice Top (2830 m a.s.l., 10^6 m^2, Ice tanks)
- Satellite
  - AMS 02
  - ISS-CREAM

- Physics goals depend on the choice of the array surface
  - 10^4 m^2 → Below the knee
  - 10^6 m^2 → Above the knee

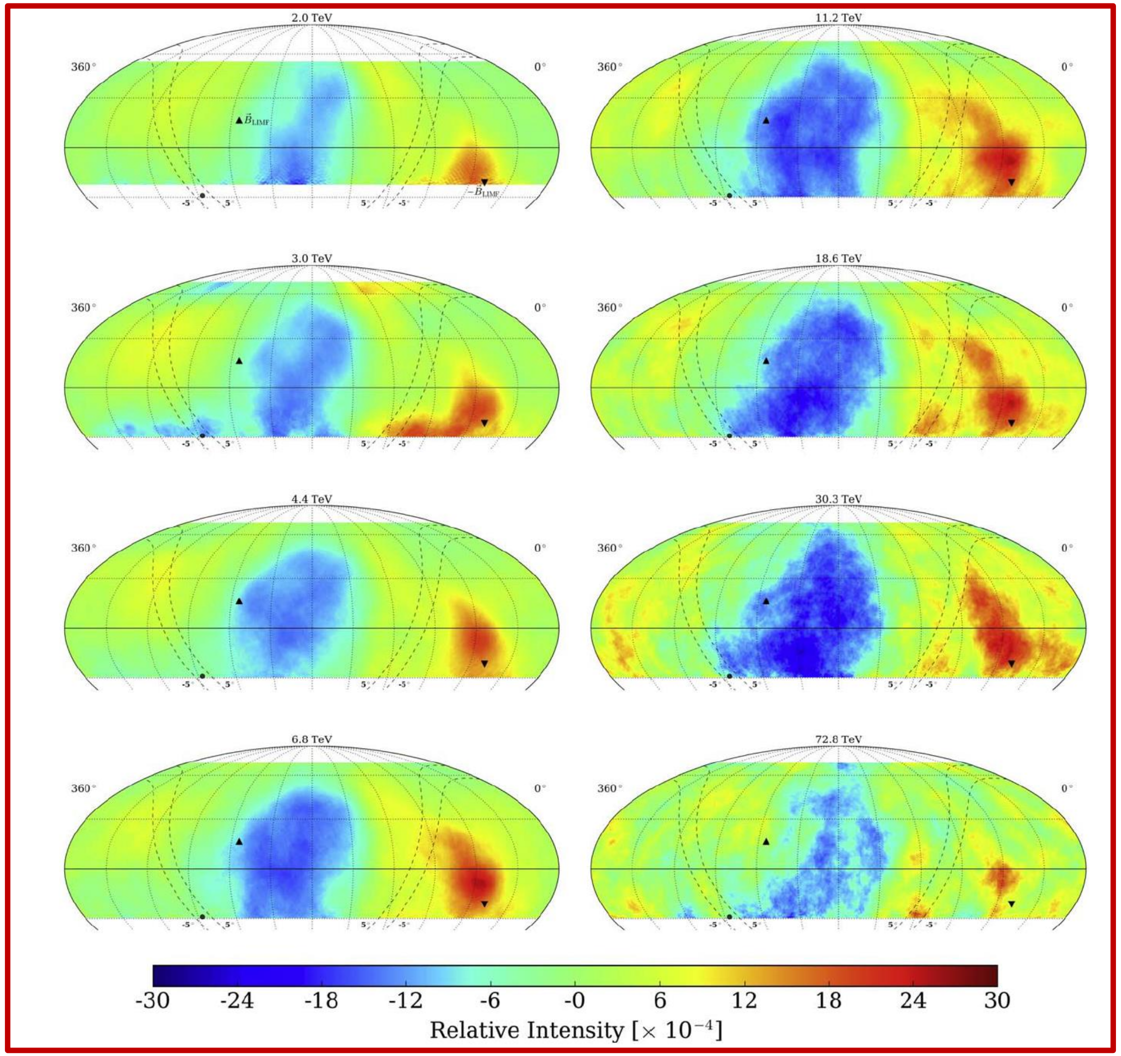
Array design must be driven by the gamma ray sources physics

- In both cases is mandatory:
  - High resolution
  - Event by event mass group classification
- Southern hemisphere
  - Spectrum → Not relevant
  - Anisotropy → Some relevance

Large Scale Anistoropy

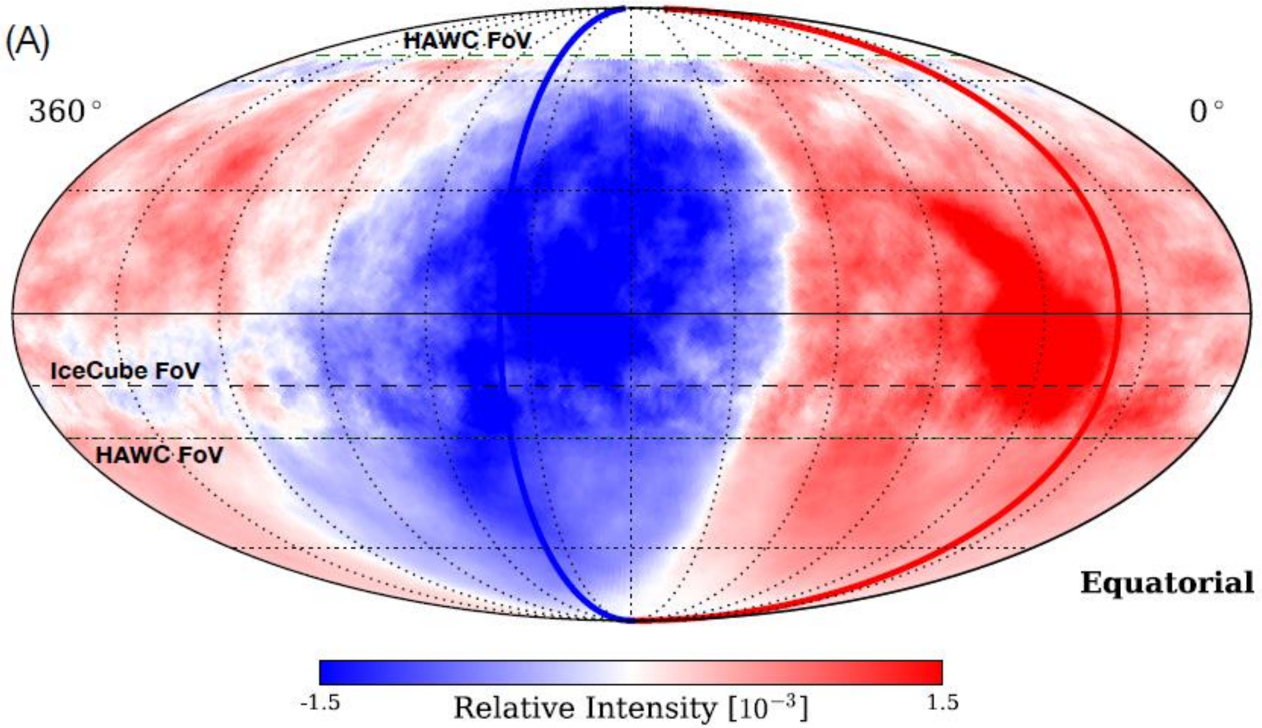


Ice Cube

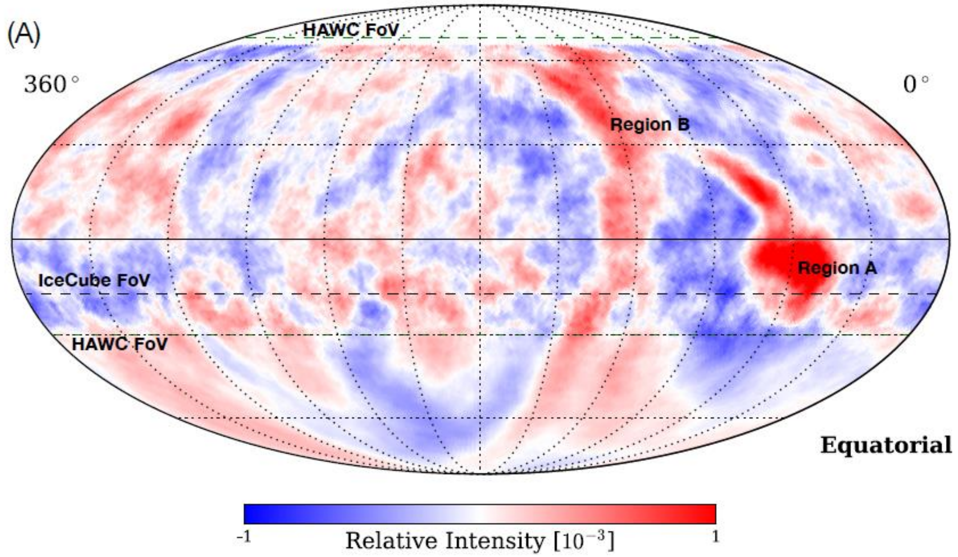


HAWC (ApJ 2018)

Ice Cube & HAWC combined analysis



Relative intensity, median energy 10 TeV



Relative intensity, subtracting the multipole fit from large-scale sky map

Large Scale Anisotropies

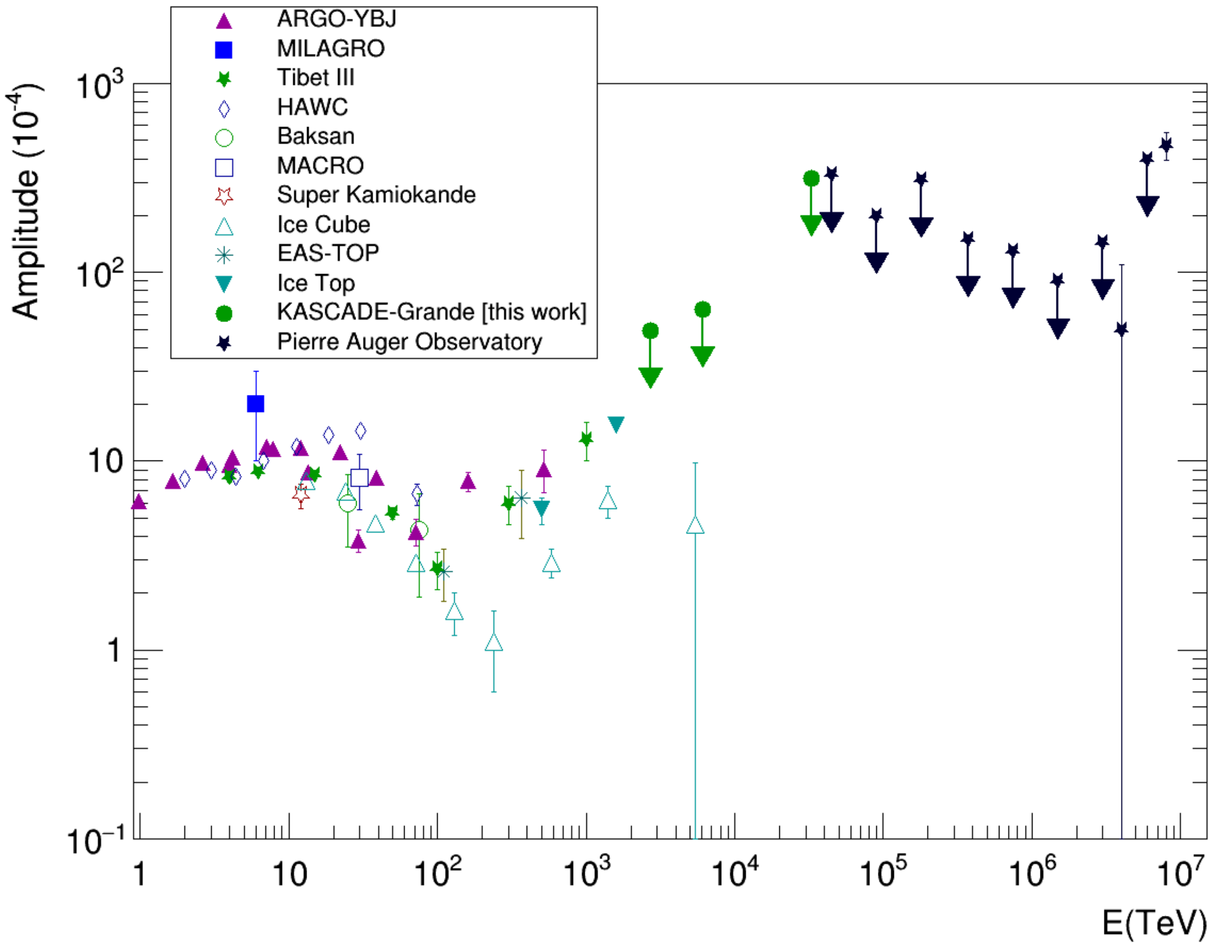
1st Harmonic Amplitude measured at different energies

Hint of a change of the phase for $E>10^{14}$ eV

The phases measured above $5\text{x}10^{14}$ eV are consistent with those obtained by UHE experiments

Hint of an increasing amplitude crossing knee energies

$E > 5\text{x}10^{15}$ eV → only upper limits



Apel et al., ApJ 870, (2019) 91

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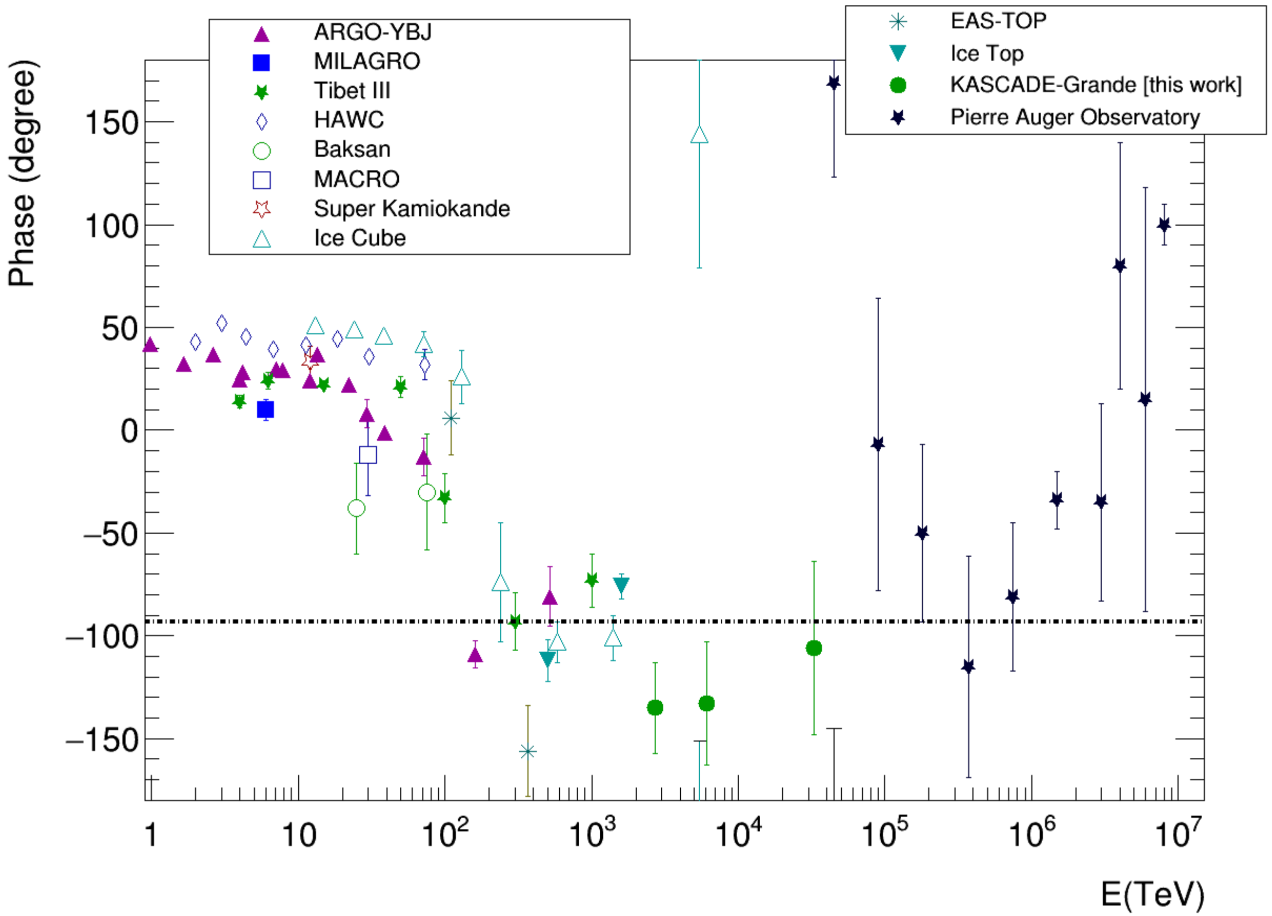


Apel et al., ApJ 870, (2019) 91

- Aartsen et al. (Ice Cube), ApJ 826, 220 (2016)

6.4. *Outlook*

The PeV energy region is not only significant for the energy-dependent cosmic-ray anisotropy; it is also a region where the cosmic-ray energy spectrum shows noticeable fine structure and the chemical composition of the cosmic-ray flux changes (see for example Aartsen et al. (2013c)). In the future, we will focus on a detailed study of possible connections between the arrival direction anisotropy and the energy spectrum and chemical composition of the cosmic-ray flux. The IceTop air shower array has an energy resolution better than 0.1 in $\log_{10}(E/\mathrm{GeV})$ (Abbasi et al. 2013a). IceTop data can thus be used to compare the energy spectrum in regions of excess or deficit flux to the isotropic spectrum. At TeV energies, this type of analysis already showed that the spectrum in excess regions is harder than the overall energy spectrum (Abdo et al. 2008; Bartoli et al. 2013; Abeysekara et al. 2014). With IceTop data, we can search for similar effects at PeV energies. IceTop also has some sensitivity to the chemical composition of the cosmic-ray flux. A study of composition-dependent parameters as a function of sky location could reveal correlations between the anisotropy and the composition of the cosmic-ray flux. In addition, future data will help to extend the IceCube/IceTop measurements to higher energies where they can be compared with results from the KASCADE-Grande experiment in the Northern Hemisphere.

Cosmic ray spectrum

- Below 1014 eV comparison with satellite experiments, relevant for a 104 m2 array
- AMS 02 → p spectrum from 1 GV to 1.8 TV
  → He spectrum from 1.9 GV to 3 TV
- CREAM → roughly up to 100 TeV/n
- Hardening at 200 GeV/n

- HAWC, all particle spectrum: break at 45.7±0.1 TeV (γ 2.49±0.01 → 2.71±0.01)
- ARGO-YBJ: light elements knee at 700±230±70 TeV (γ 2.56±0.05→3.24±0.36)

AMS 02

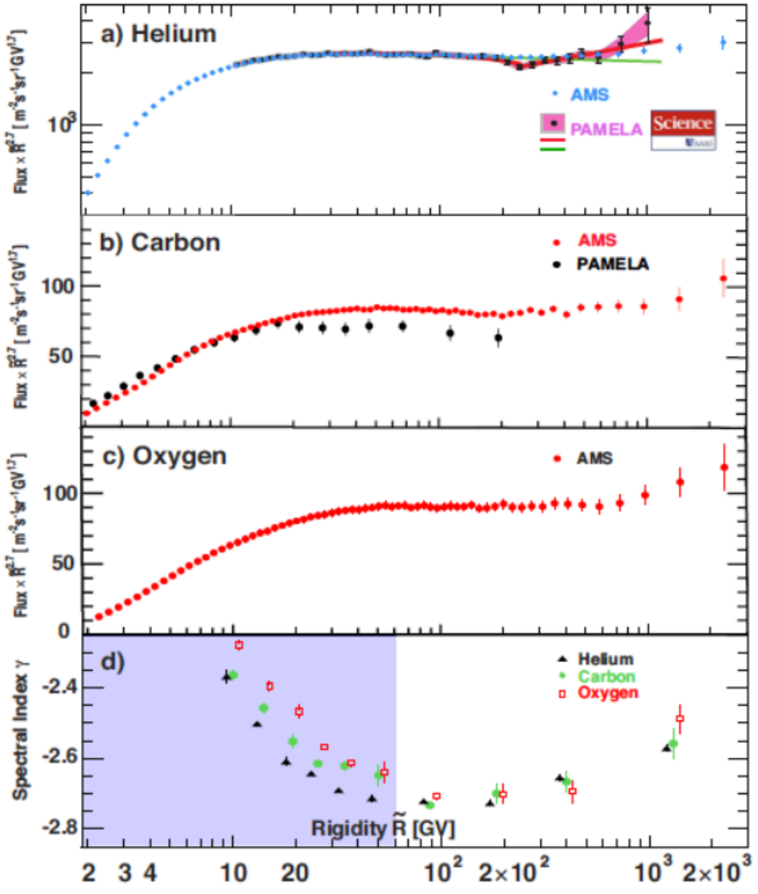


FIG. 1. The AMS (a) helium, (b) carbon, and (c) oxygen fluxes [23] multiplied by $\tilde{R}^{2.7}$ with their total errors as functions of rigidity. Earlier measurements of helium, see Fig. 4 in Ref. [28], and carbon [12] fluxes in rigidity are also shown. (d) The dependence of the helium, carbon, and oxygen spectral indices on rigidity. In (d) , for clarity, the horizontal positions of the helium and oxygen data points are displaced with respect to carbon. As seen, above 60 GV (indicated by the unshaded region) the spectral indices are identical.

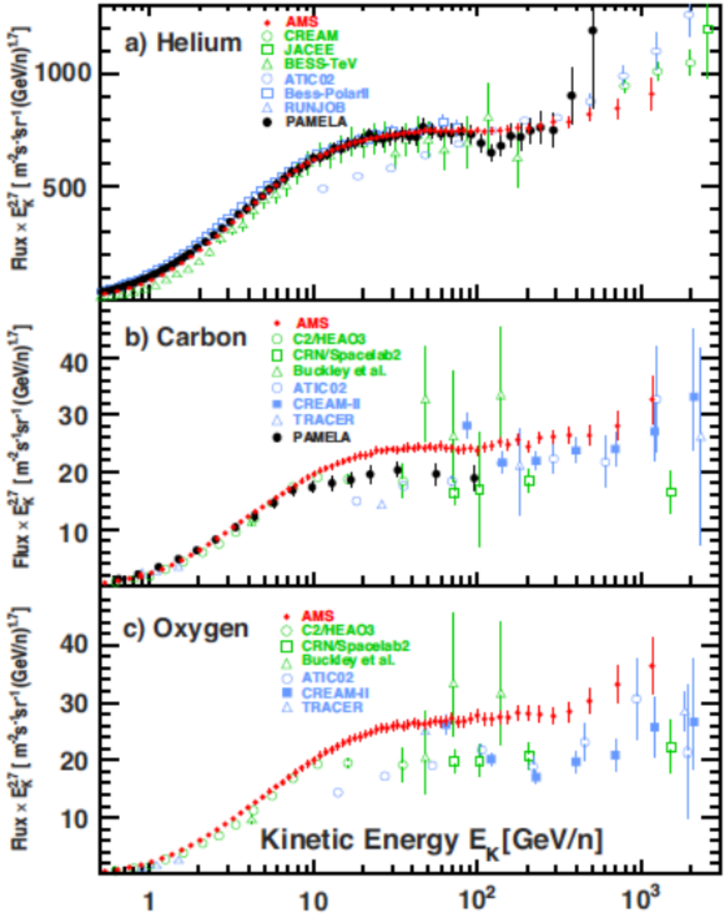
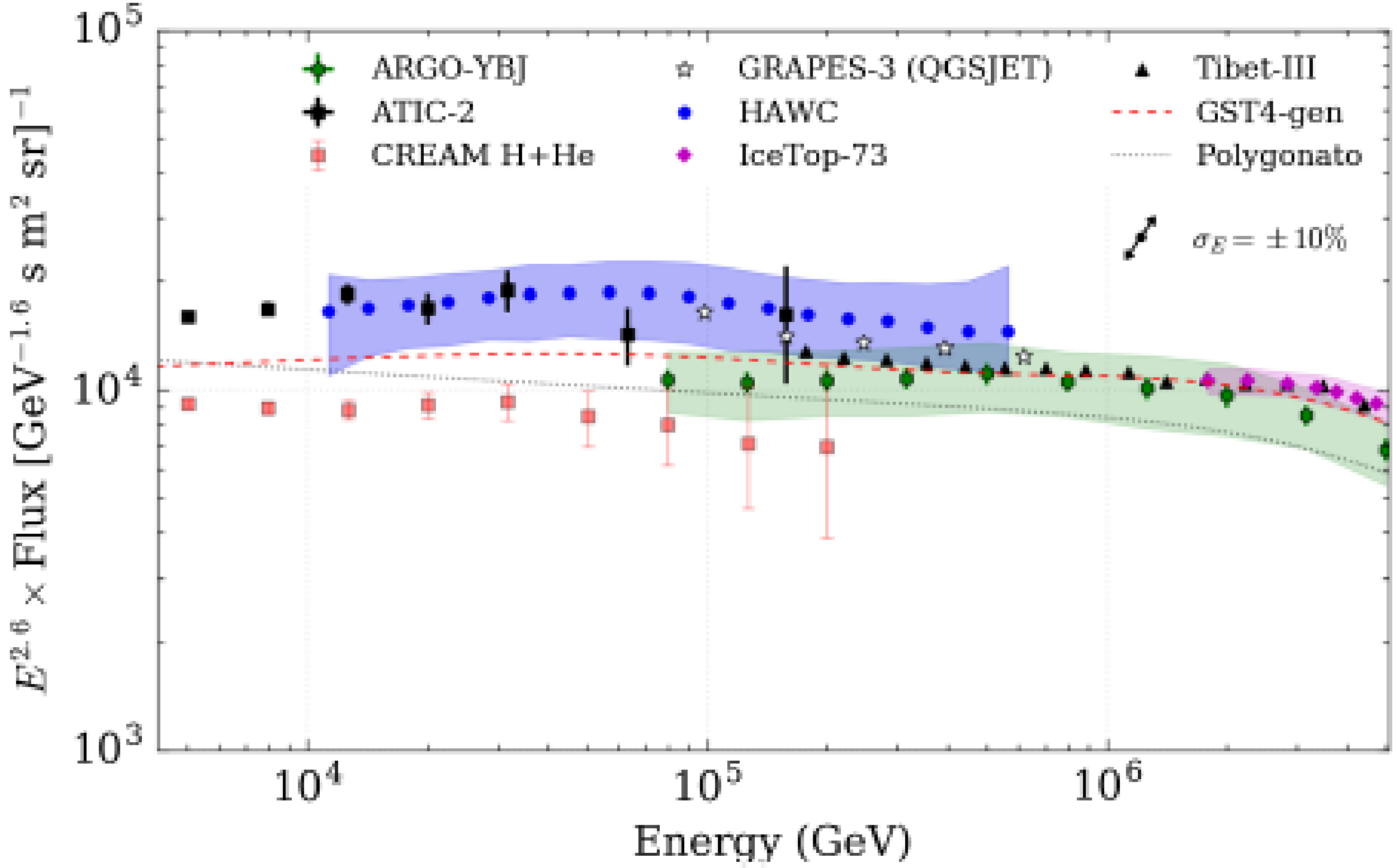


FIG. 2. The AMS (a) helium, (b) carbon and (c) oxygen fluxes as functions of kinetic energy per nucleon E_K multiplied by $E_K^{2.7}$ together with previous measurements [4–12, 28, 30]. For the AMS measurement $E_K = \left(\sqrt{Z^2 R^2 + M^2} - M\right)/A$ where Z, M, and A are the ^{4}He, ^{12}C, or ^{16}O charge, mass, and atomic mass numbers, respectively. Data from other experiments were extracted using [31]

13

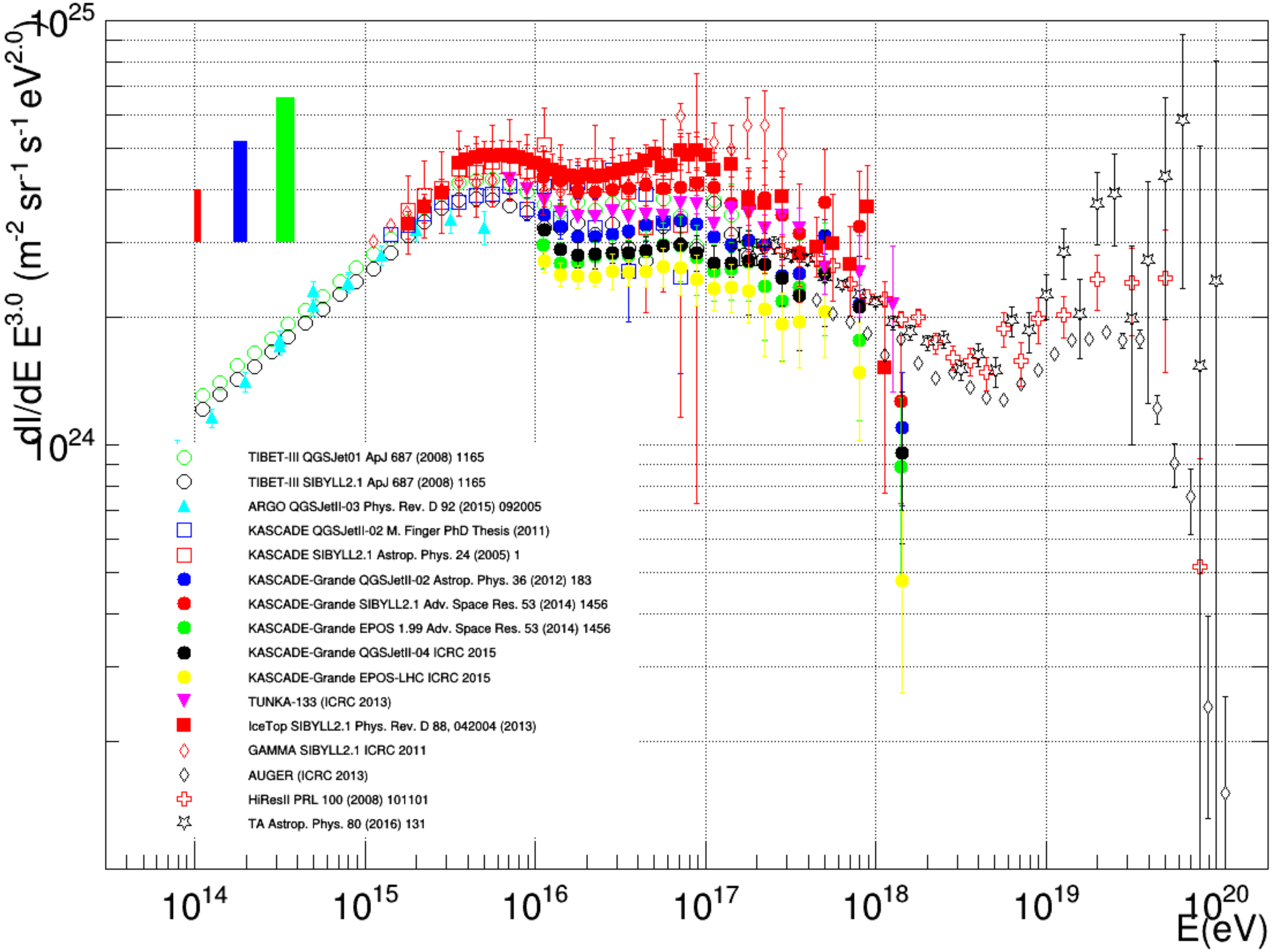


R. Alfaro et al. (HAWC coll.) Phys. Rev. D96, 122001 (2017)

Cosmic ray spectrum

- Above 10^{14} eV comparison with EAS experiments, relevant for a 10^6 m^2 array
- Main limitation of EAS experiments
  - Z sensitivity
  - Systematic errors in the energy calibration
- Knee ≈ $4x10^{15}$ eV, Dip ≈ 10^{16} eV, Second knee ≈ 10^{17} eV
- KASCADE & KASCADE-Grande
  - → light primaries spectrum steepening @knee energy
  - → light primaries spectrum hardening @ 10^{17} eV
  - → heavy primaries spectrum steepening @ $8x10^{16}$ eV
- ARGO-YBJ → light primaries spectrum steepening @ 700 TeV
- Running Experiments
  - Ice Top
  - TUNKA-Grande
  - TALE
- Near Future
  - LHAASO

Primary Spectra Measurements



- Differences, in this plot, due to energy calibrations.
  - 10% E error
  - 20% E error
  - 30% E error
- Better agreement if we compare data calibrated with the same hadronic interaction model.
- Spectral shapes agree

Summary

i. Charged cosmic rays physics around the knee of the primary spectrum still has open (and relevant) questions
ii. To address them we need high resolution measurements and event by event mass group separation
iii. No other future experiments are planned in the southern hemisphere (some relevance for anisotropy measurements)
iv. Main future competitor: LHAASO