ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

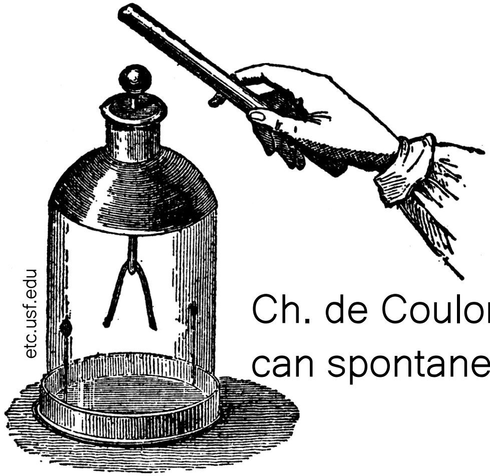
Cosmic rays & extensive air showers

Agnieszka Leszczyńska

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

Credit: Johannes Werthebach/NSF

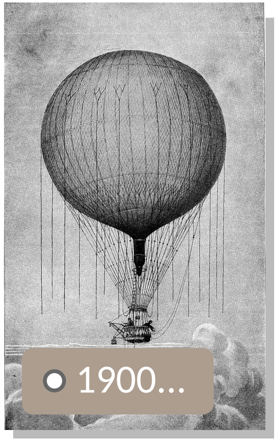
History notes...


etc.usf.edu

18th century

Ch. de Coulomb - electroscope can spontaneously discharge

commons.wikimedia.org



de.wikipedia.org

T. Wulf, A. Gockel and others...

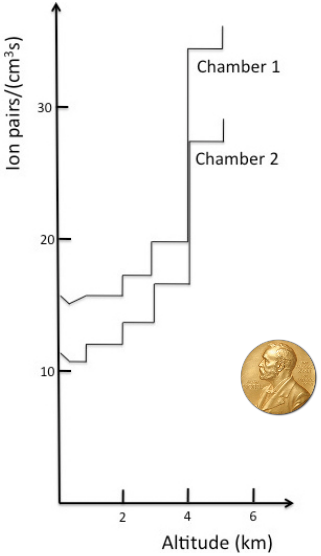
- observations at higher altitudes inconclusive

cerncourier.com

D. Pacini - concluded that radiation causing air ionization is mainly not of terrestrial origin

NYTimes

V. Hess - proved its **extra-terrestrial origin**



https://cds.cern.ch/record/1471207

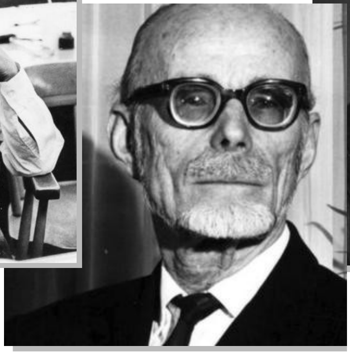
History notes...

DOI: 10.4467/2543702XSHS.18.015.9335

1927

J. Clay, A. Compton - CR intensity depends on latitude and follows geomagnetic field lines

B. Rossi



P. Auger

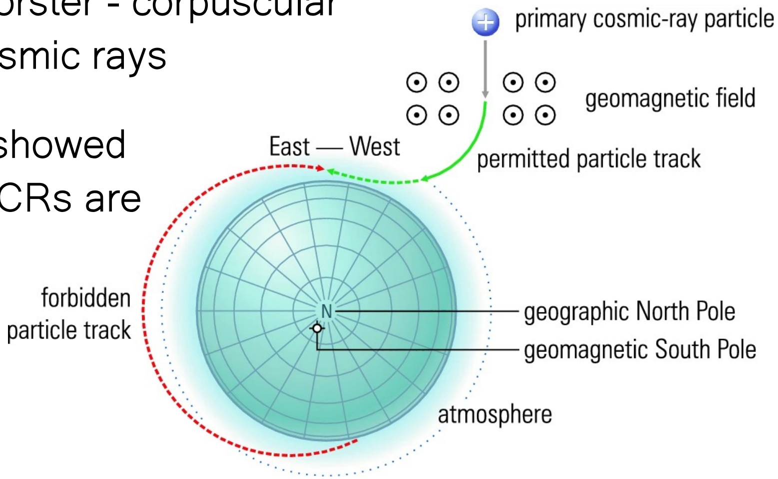
D. Skobeltzyn

1933-1937

Extensive air showers, cosmic rays reach energies around 10^{15} eV

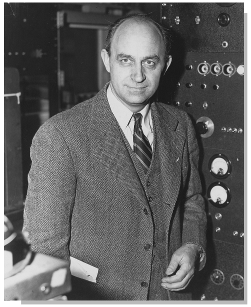
1928 Bothe, Kolhörster - corpuscular nature of cosmic rays

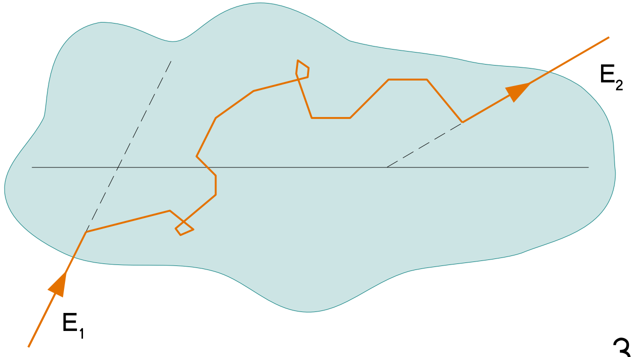
1933 T. Johnson showed East-West effect → CRs are positively charged

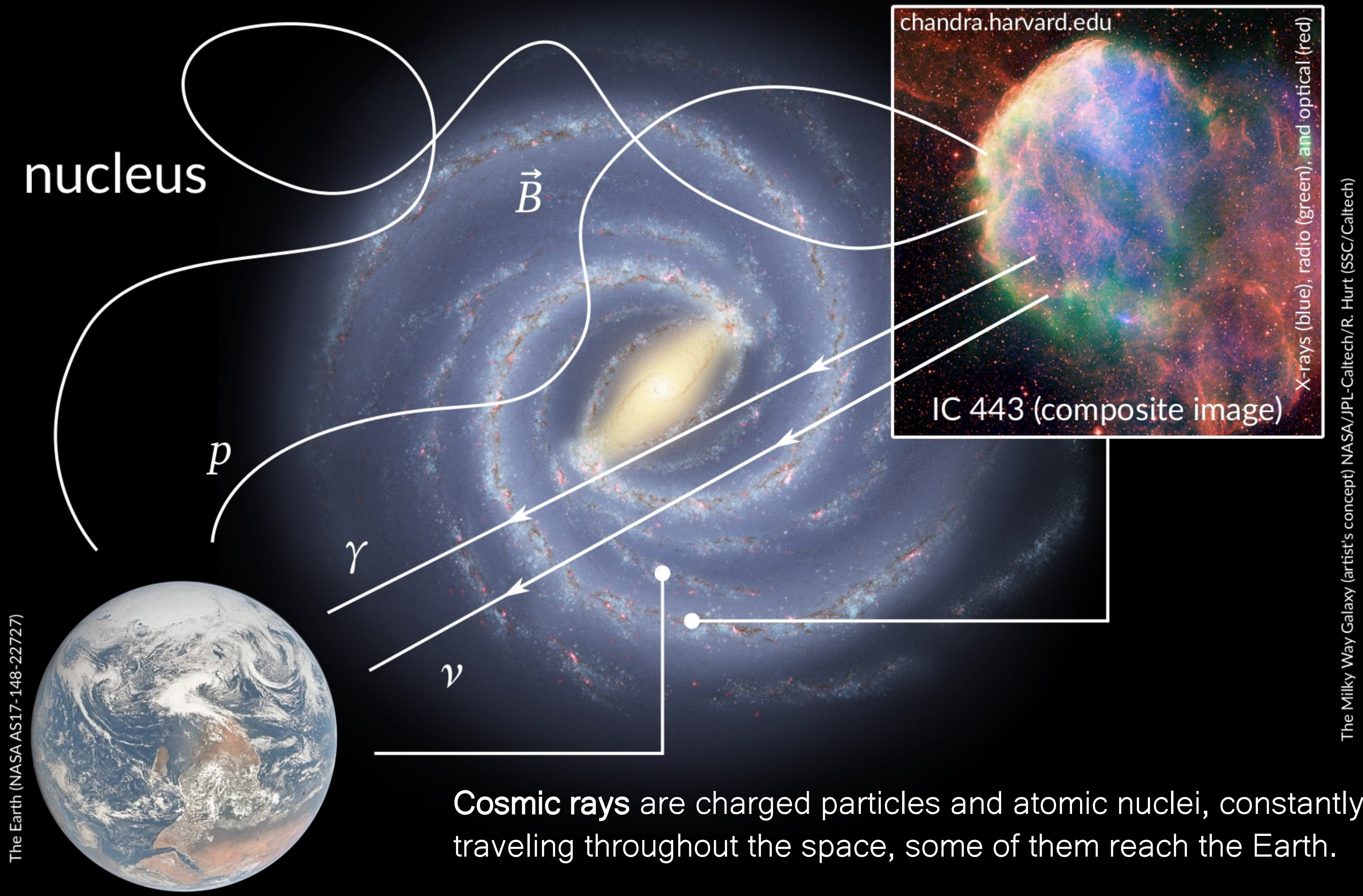


1949

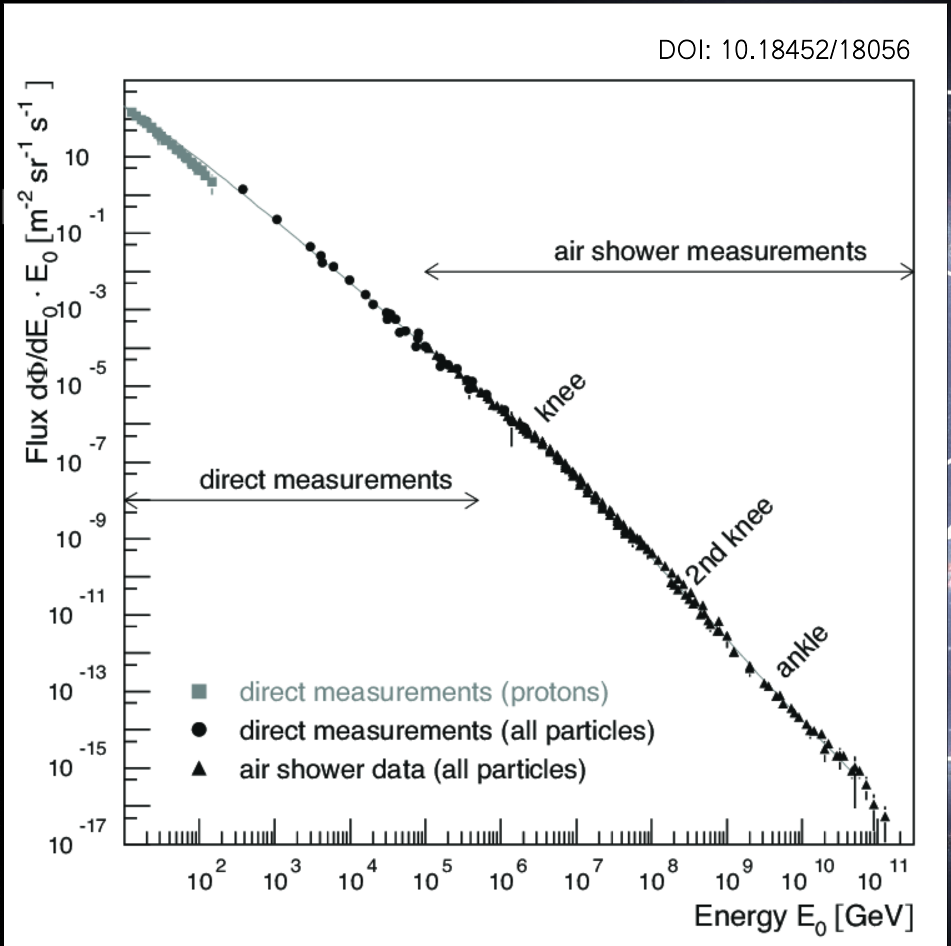
E. Fermi - model of particle acceleration mechanism

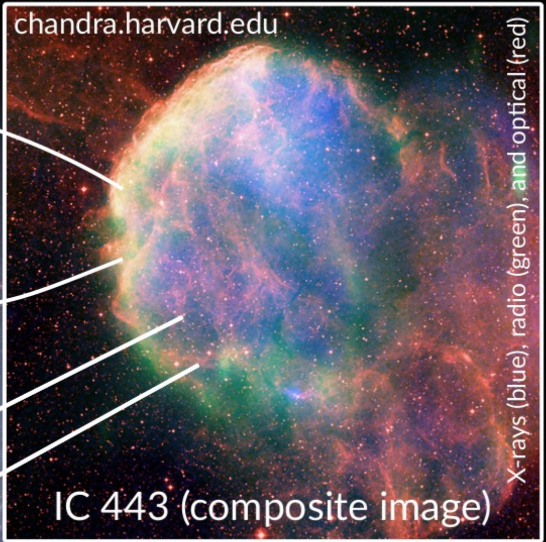


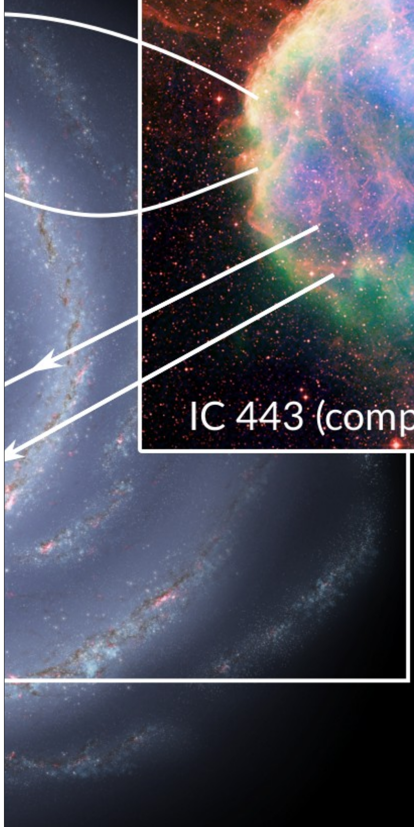




Cosmic rays are charged particles and atomic nuclei, constantly traveling throughout the space, some of them reach the Earth.





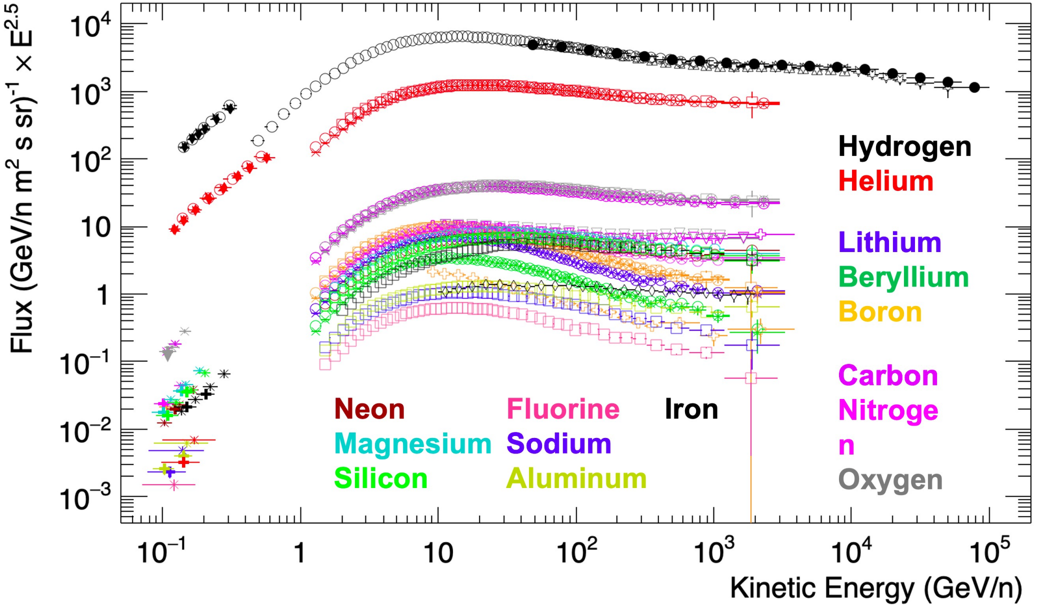


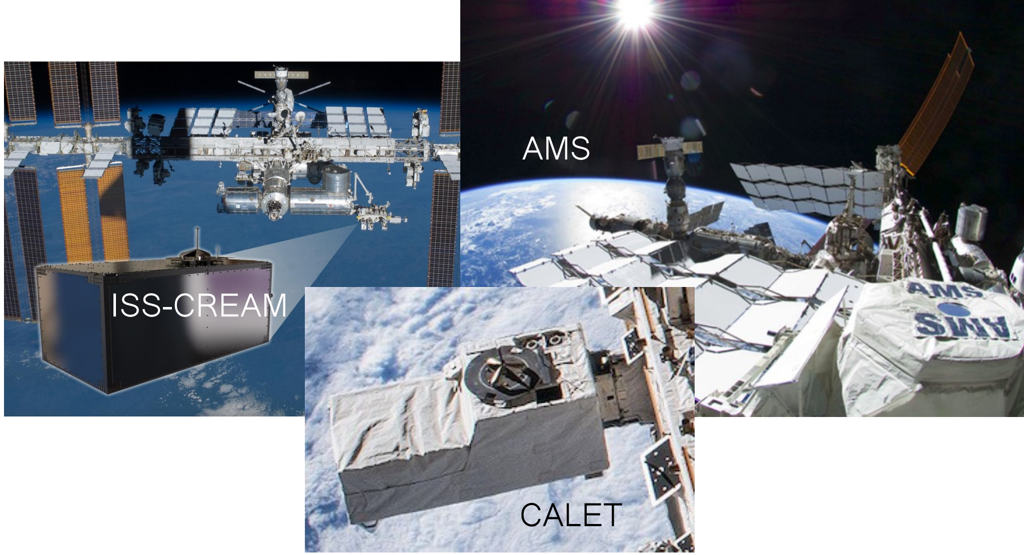
The Milky Way Galaxy (artist's concept) NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

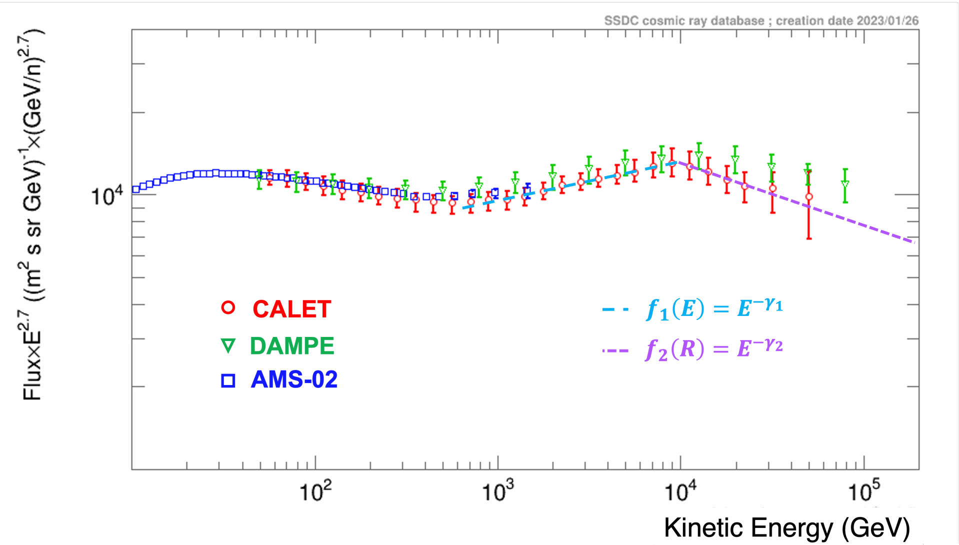
The Earth (NASA AS17-148-22727)

Cosmic rays are charged particles and atomic nuclei, constantly traveling throughout the space, some of them reach the Earth.

Direct measurements







Many excellent observations - still difficult to understand the entire picture

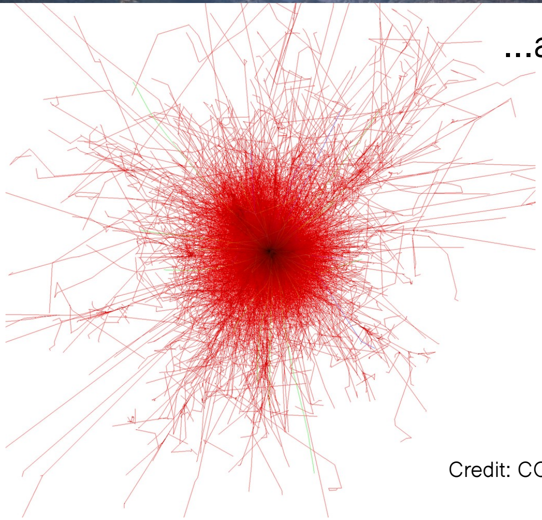
https://doi.org/10.48550/arXiv.2301.10255

Extensive air showers

EAS develops **longitudinally**...

EAS forms a curved disk of particles

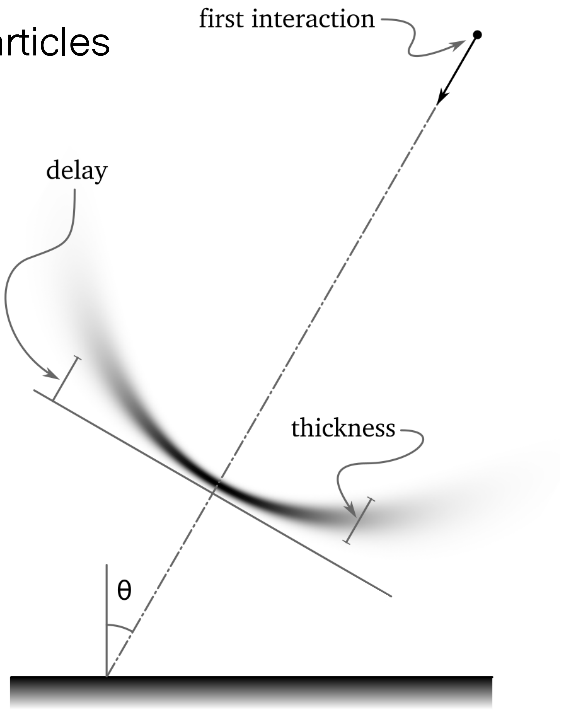
EAS development depends on the CR energy and type, cross section...



...and **laterally**

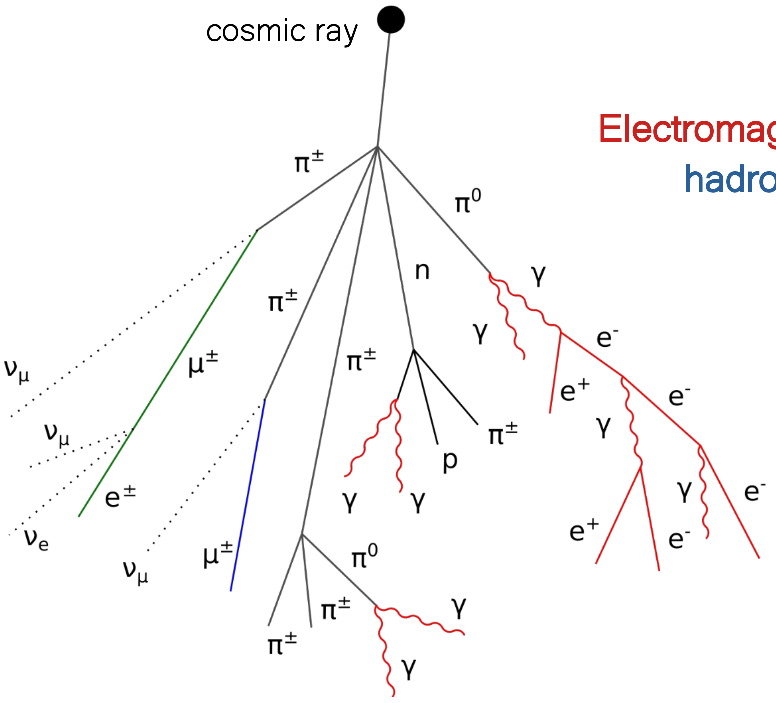
Credit: CORSIKA

Bulk of secondary particles arrive at the ground



Distributions of deposited energy and arrival times carry information about EAS development

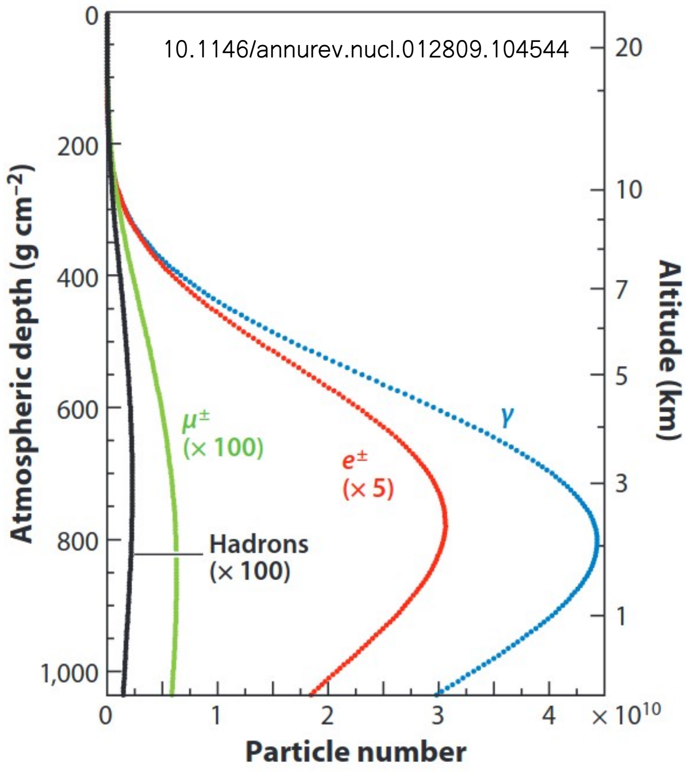
Extensive air showers



Electromagnetic &
hadronic cascades

$$E_o = \xi_c^e N_{max} + \xi_c^\pi N_\mu$$

$$N_\mu(E, A) \propto A (E/A)^\beta$$

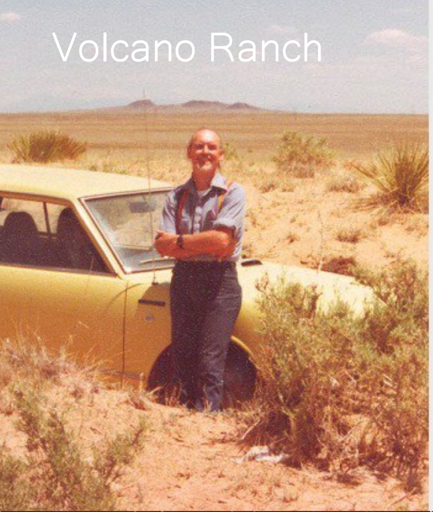


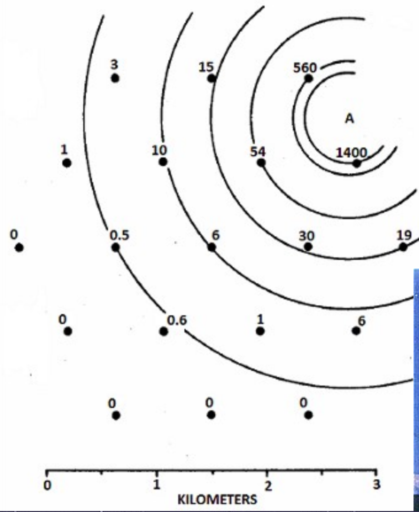
Electromagnetic cascades reliably described

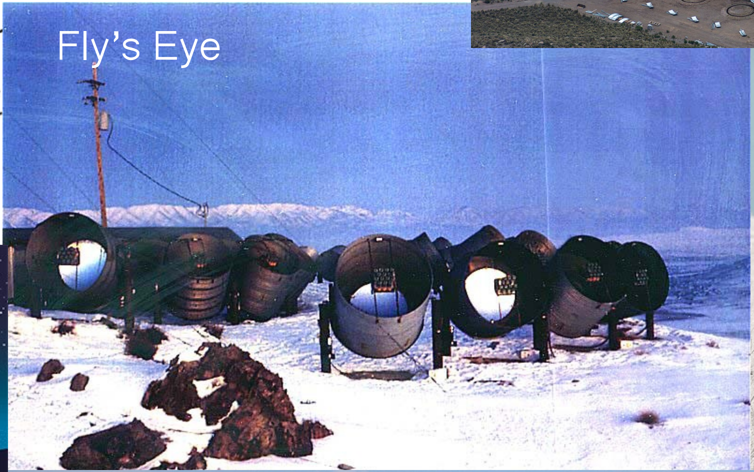
Challenging to describe hadronic cascades:
→ phase-space not probed at accelerators
→ different phenomenological models exist

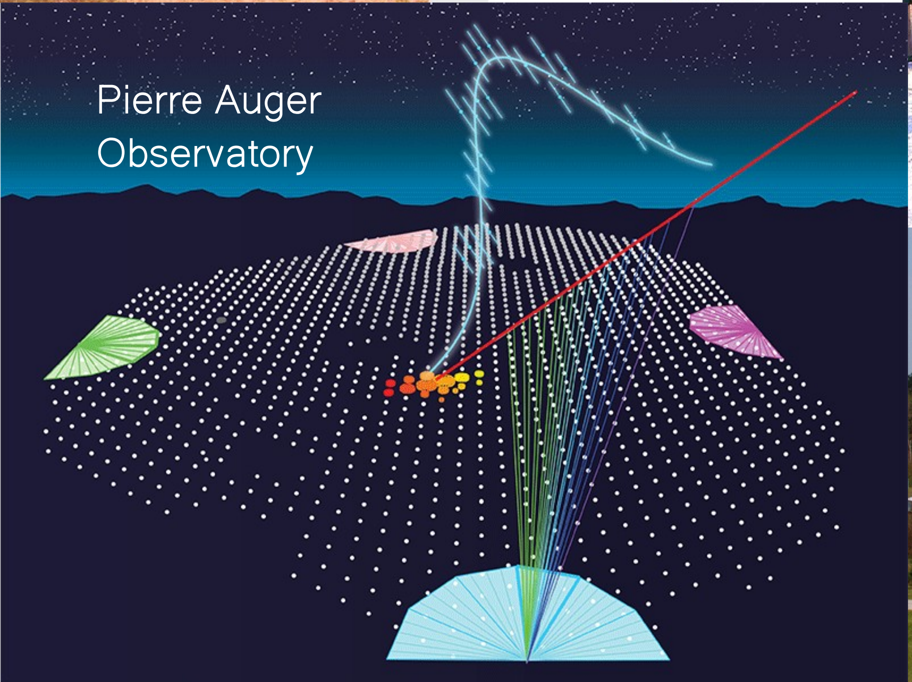
EAS development depends on the CR type
→ determines parameters of the hadronic production

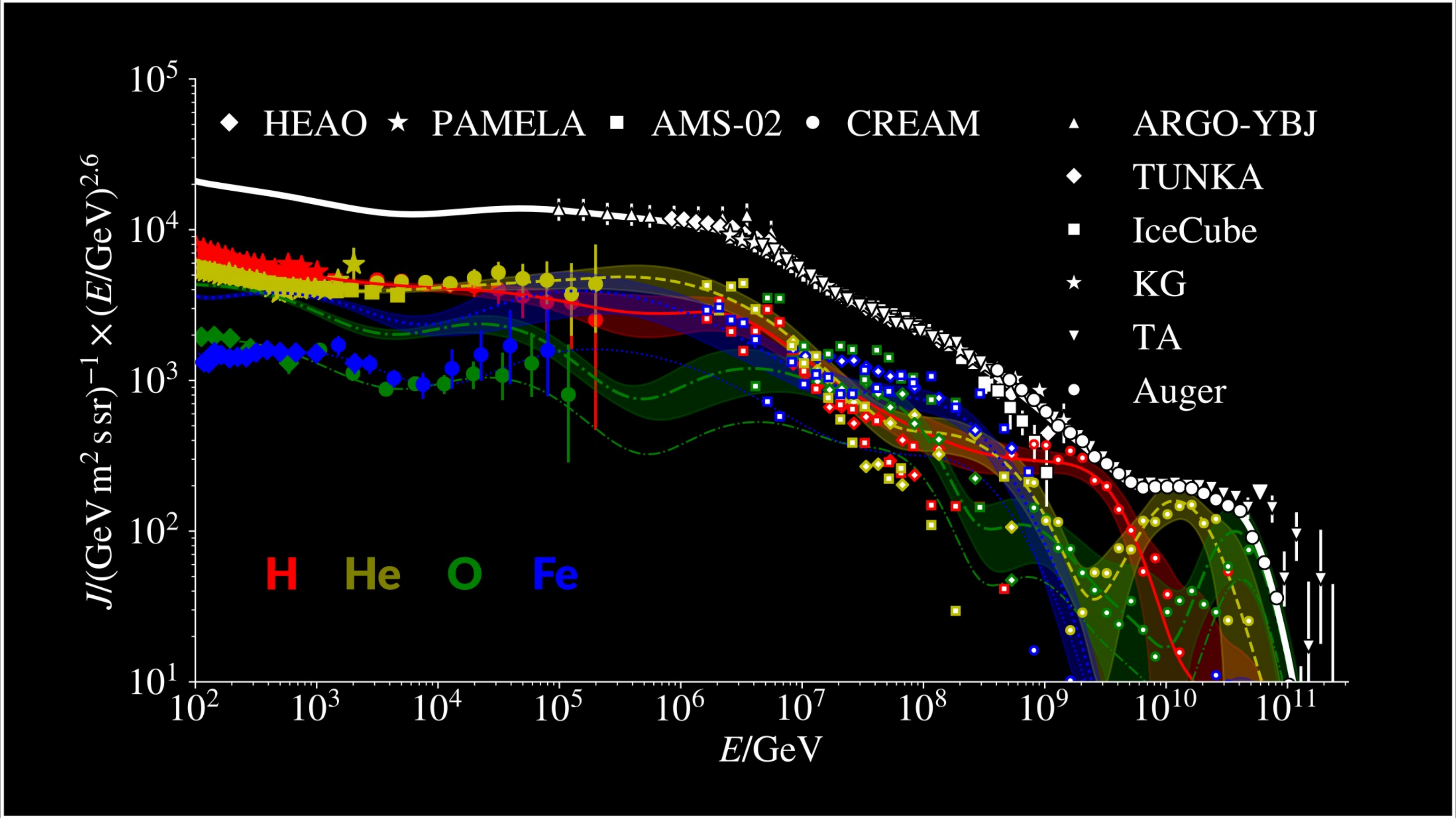
Air showers arrays





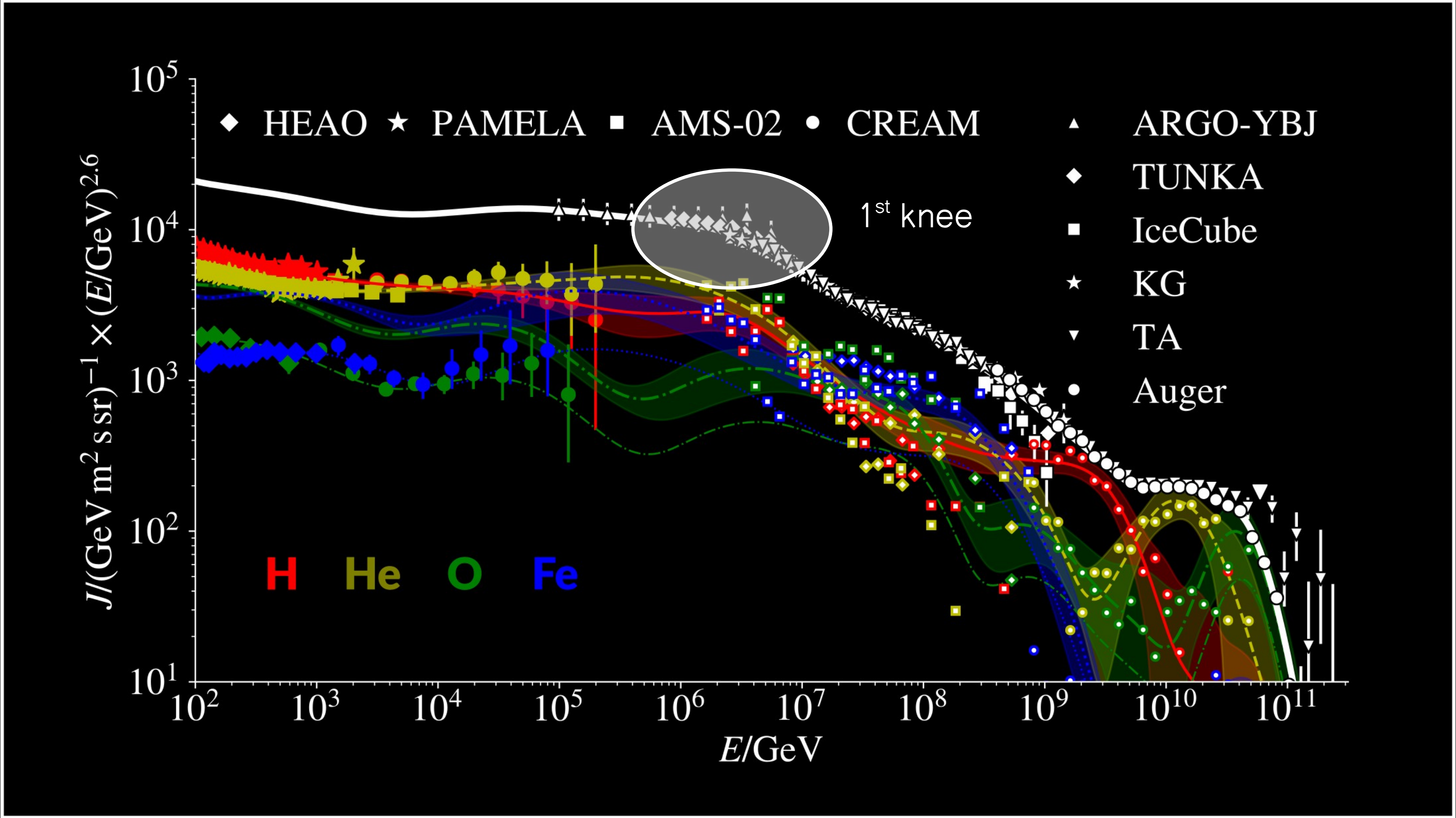




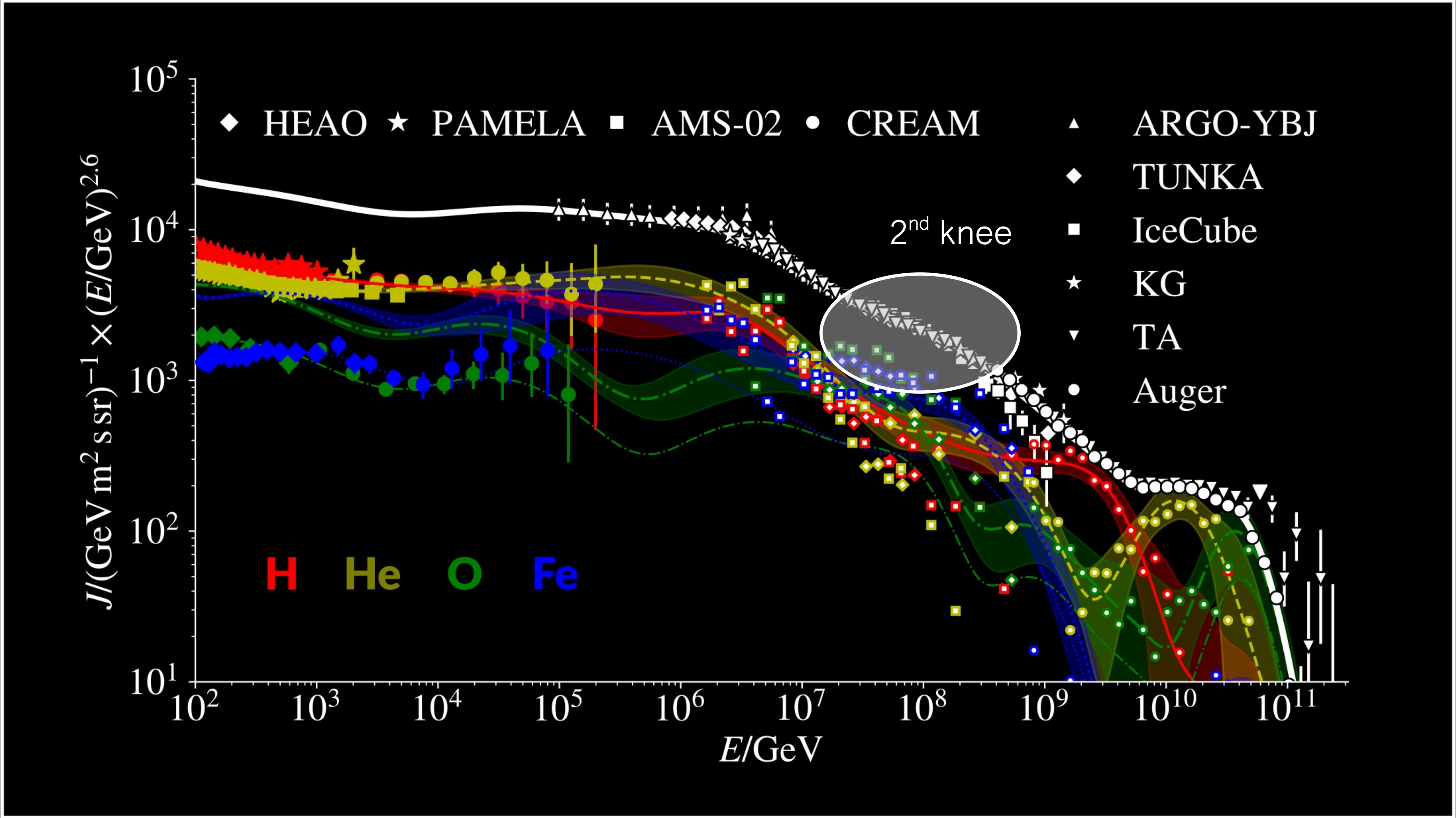


Dembinski et al., EPJ Web Conf. 2019

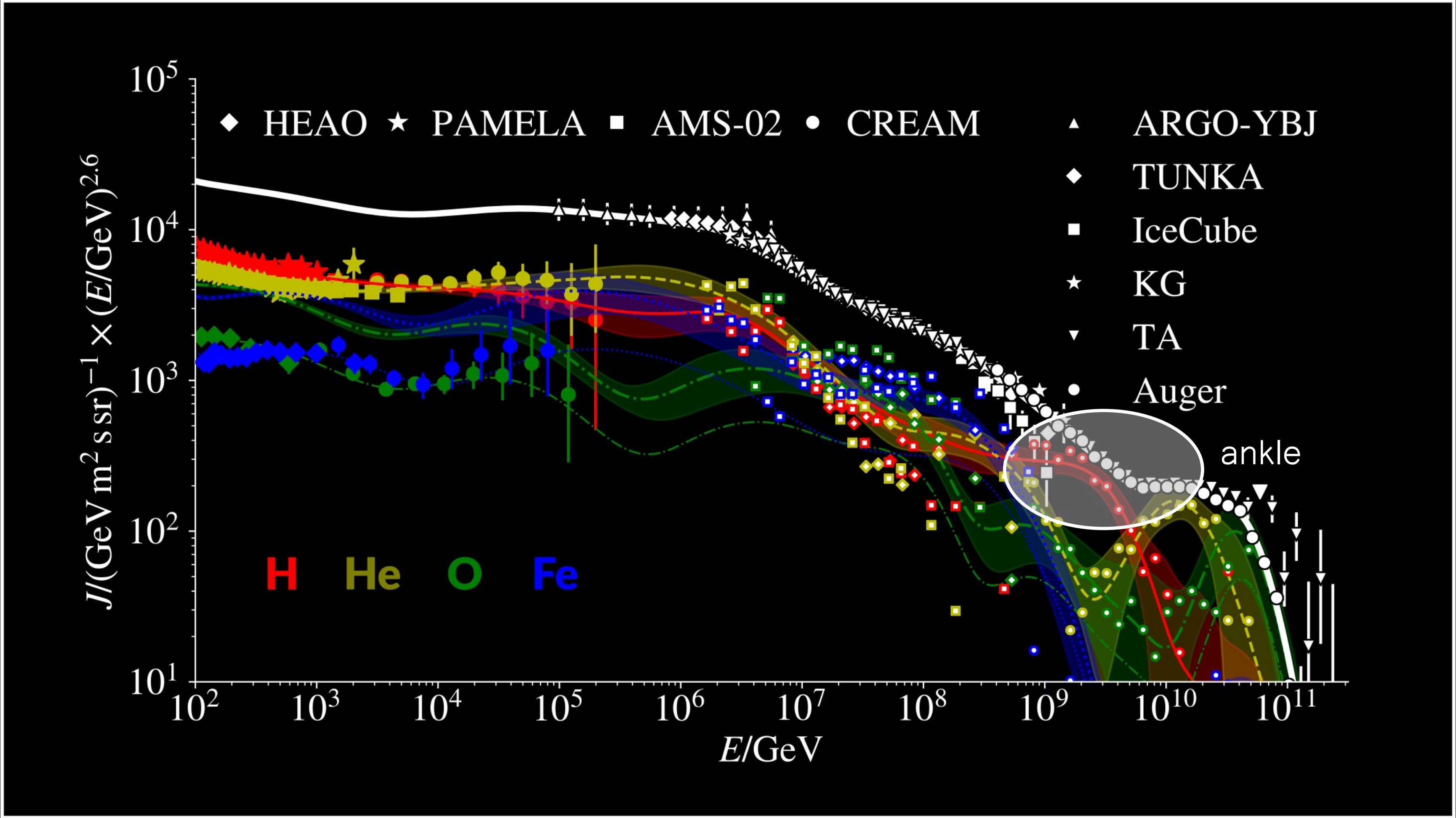
Their origin remains mostly unknown, specially at the high energies and ultra-high energies...



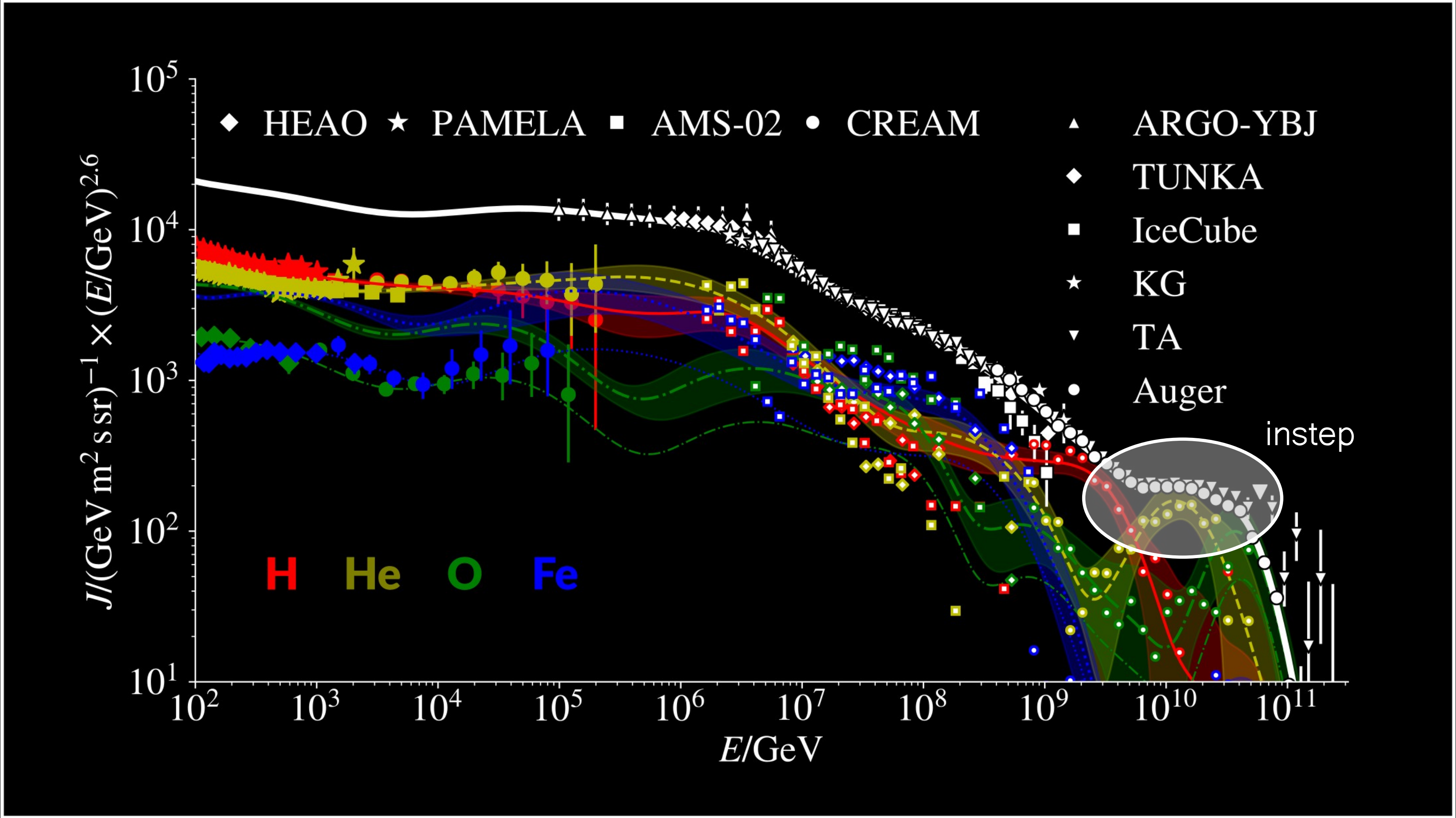
Dembinski et al., EPJ Web Conf. 2019



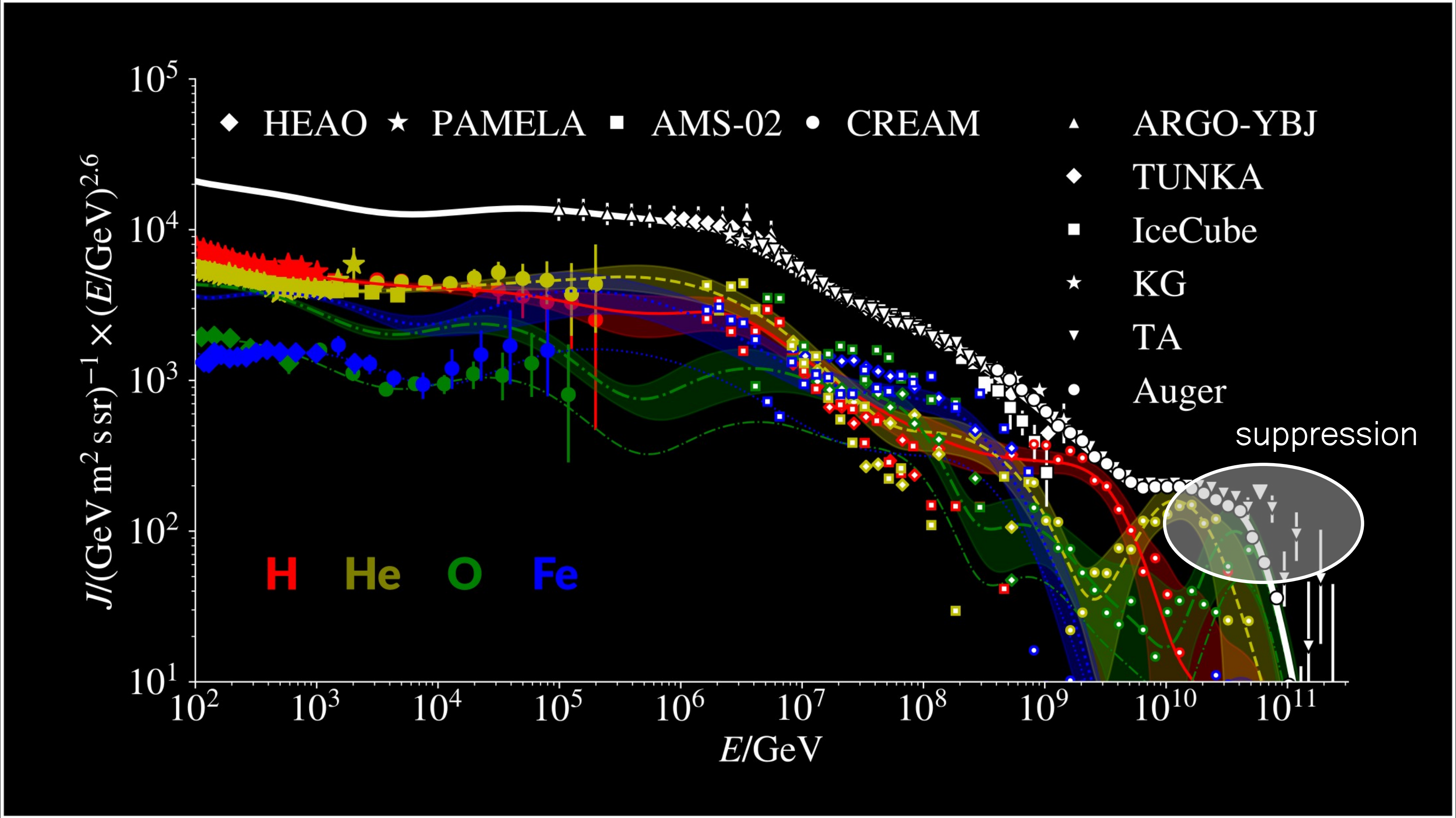
Dembinski et al., EPJ Web Conf. 2019



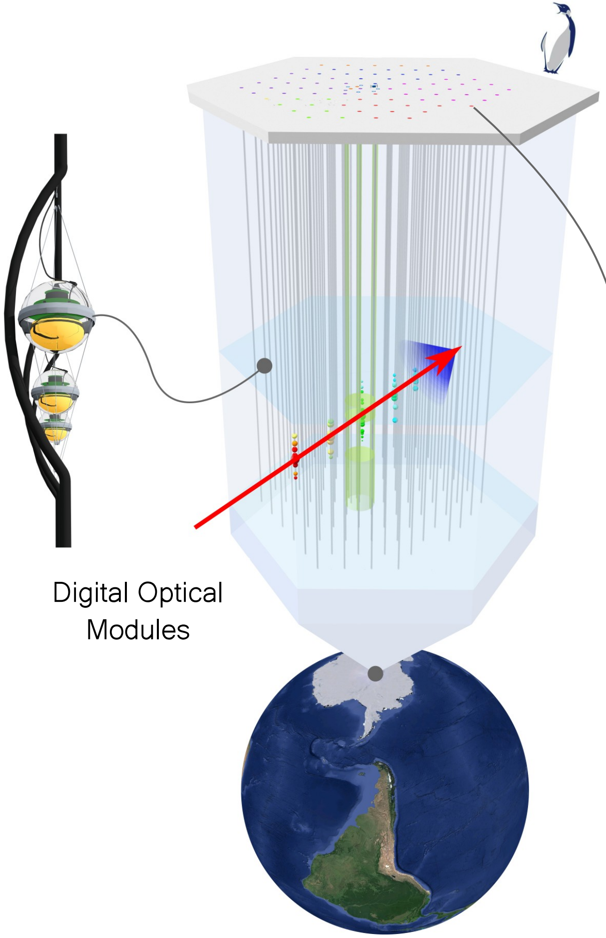
Dembinski et al., EPJ Web Conf. 2019

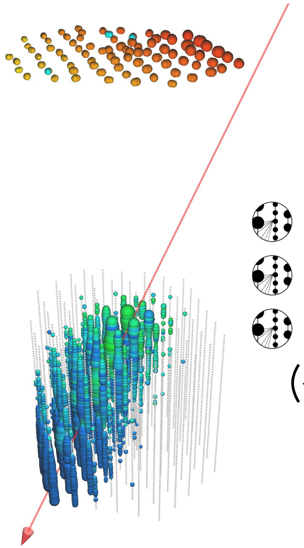


Dembinski et al., EPJ Web Conf. 2019



Dembinski et al., EPJ Web Conf. 2019





IceCube

- Astrophysical neutrinos (~10/year)
- Atmospheric neutrinos from air showers (~10/h)
- **Downgoing muons** (> 300 GeV) from air showers (~3000/s)

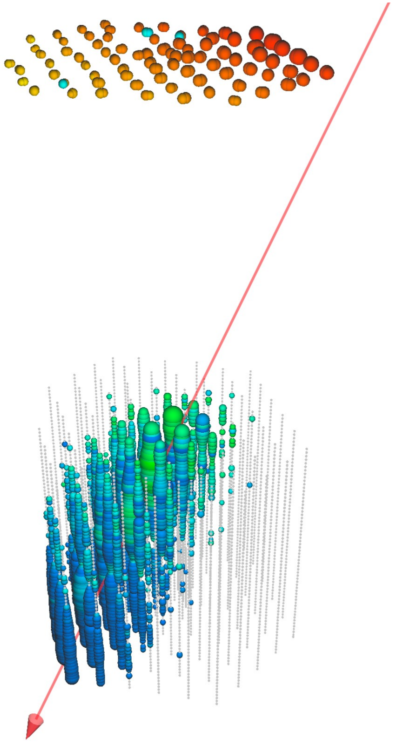
IceTop

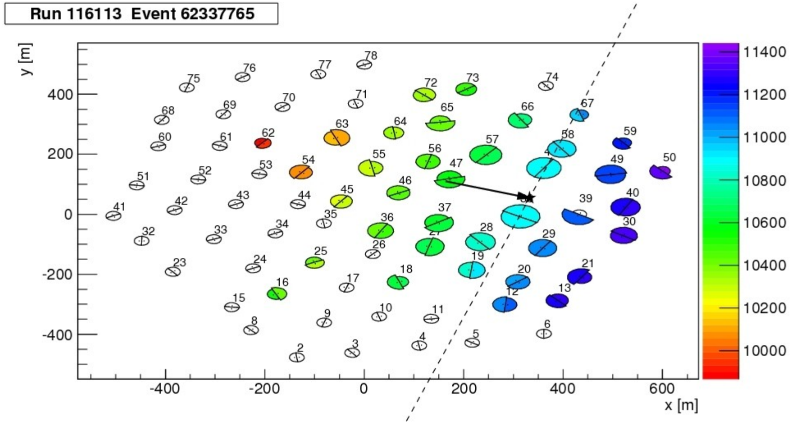
- Indirect measurements of PeV - EeV CR
- CR energy & direction event-by-event + average CR composition

162 ice Cherenkov tanks

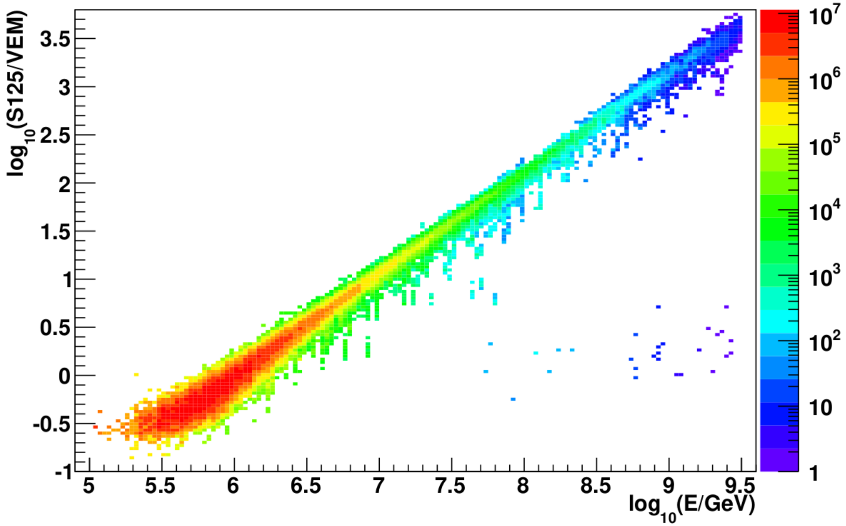
2 optical modules per tank

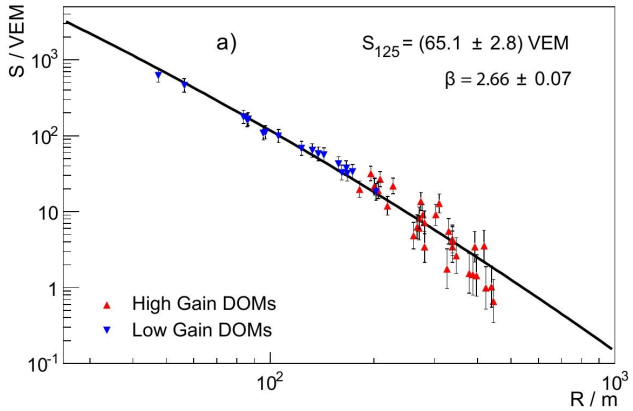
IceTop/IceCube EAS detection





Pure Protons, cosθ>0.95



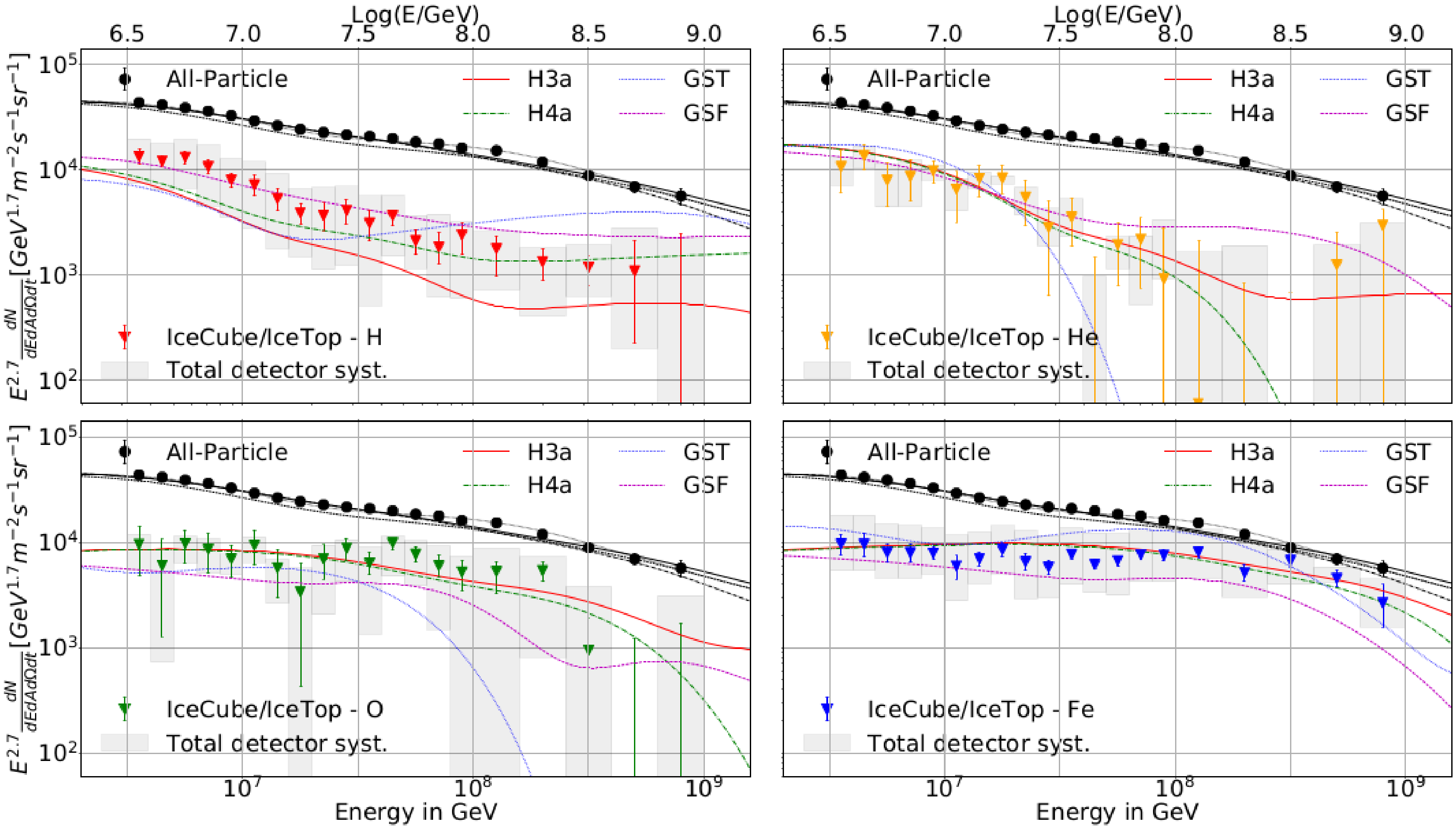


$$S(r)=S_{125} \cdot \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa\cdot\log_{10}(r/125\,\mathrm{m})}$$

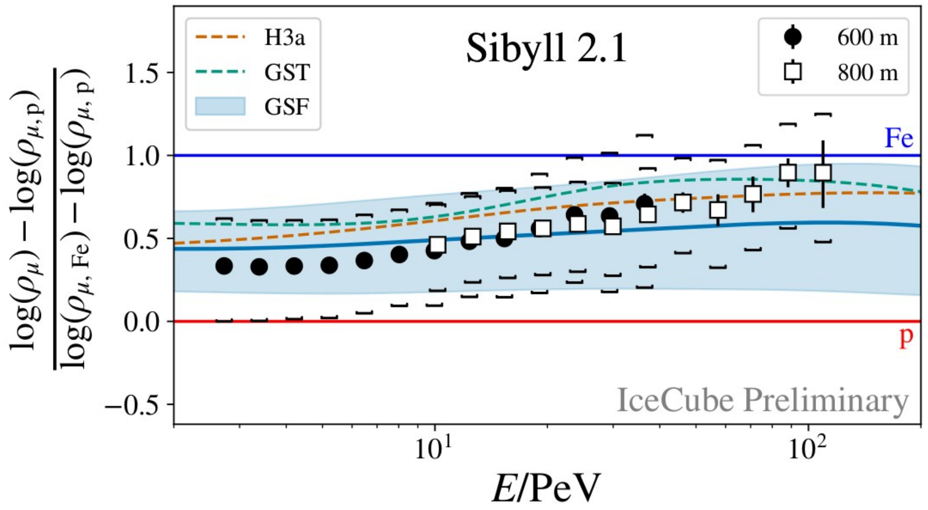
- CR energy reconstructed from lateral signal distributions based on MC
- Lateral shape mildly sensitive to mass

Energy conversion relies on simulations

CR mass composition

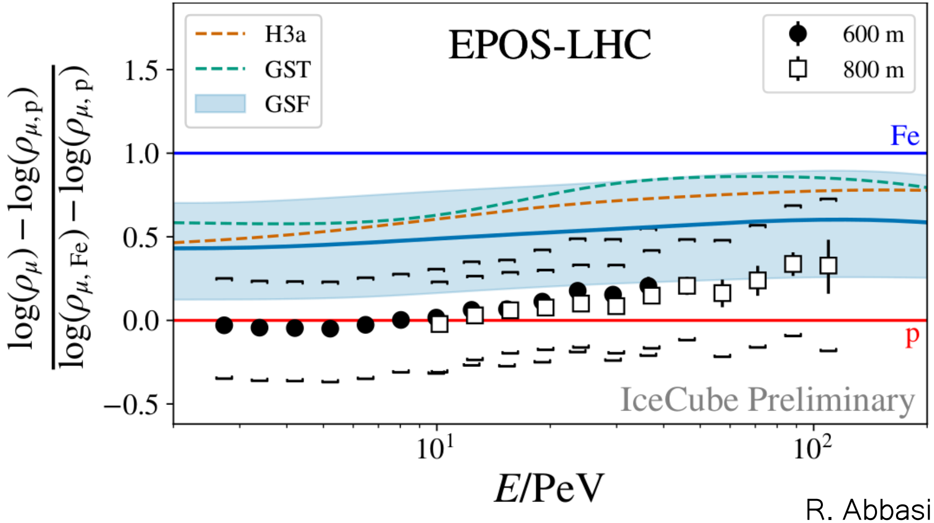


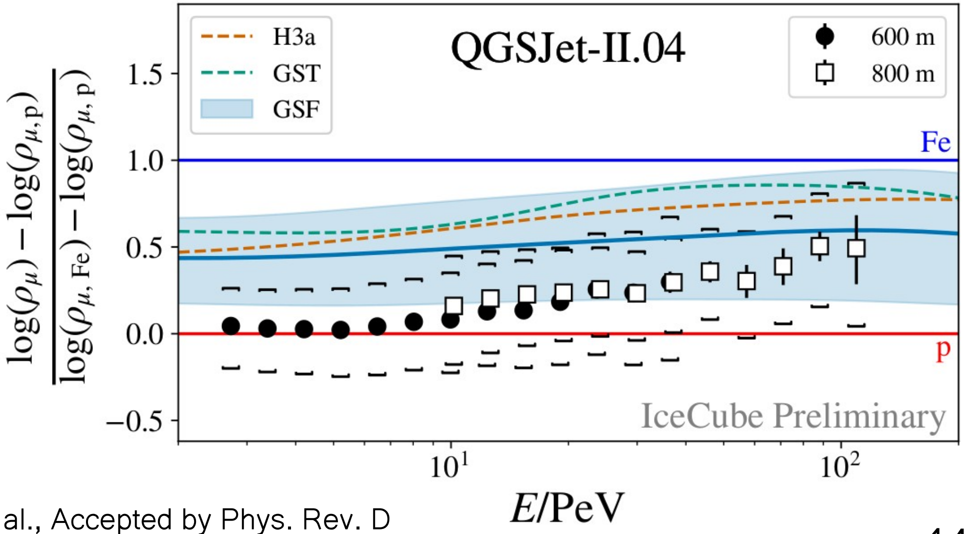
~GeV muons@IceCube



Sibyll 2.1 → no large deviation from the model

Small deviation for QGSJet-II.04 and EPOS-LHC
→ predict more muons → very light masses

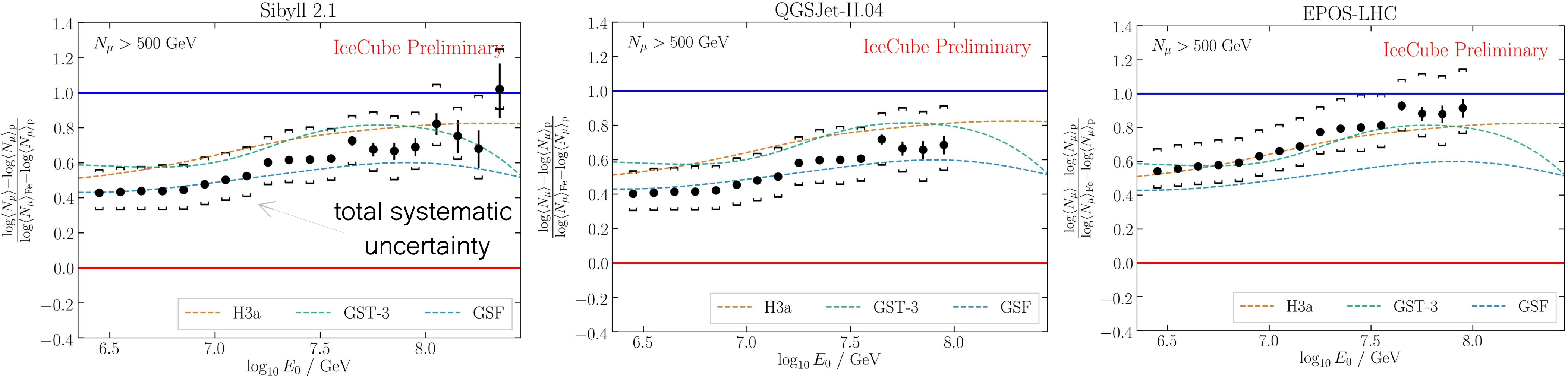




R. Abbasi et al., Accepted by Phys. Rev. D

TeV muons@IceCube

$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

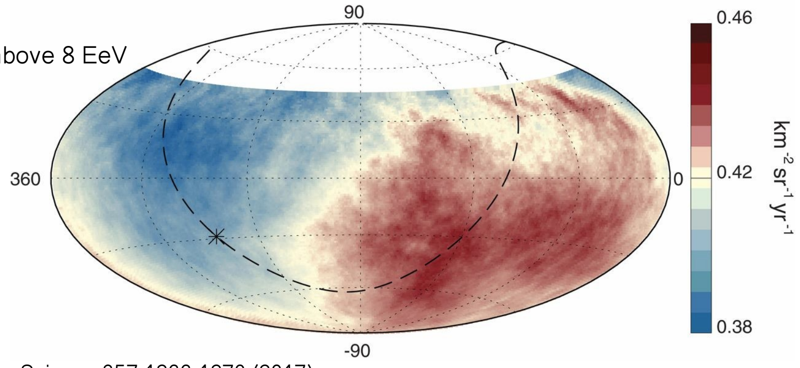


Stef Verpoest, ECRS 2022

Results depend on a chosen hadronic model,
but no significant deviations from the models

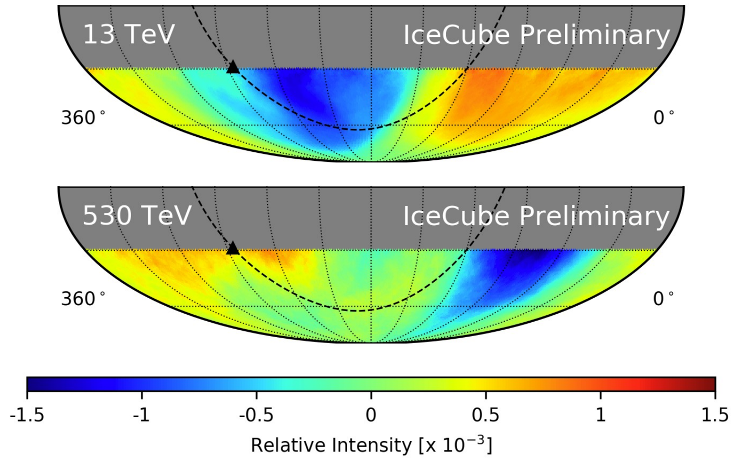
Anisotropy measurements

Pierre Auger Observatory → CR flux



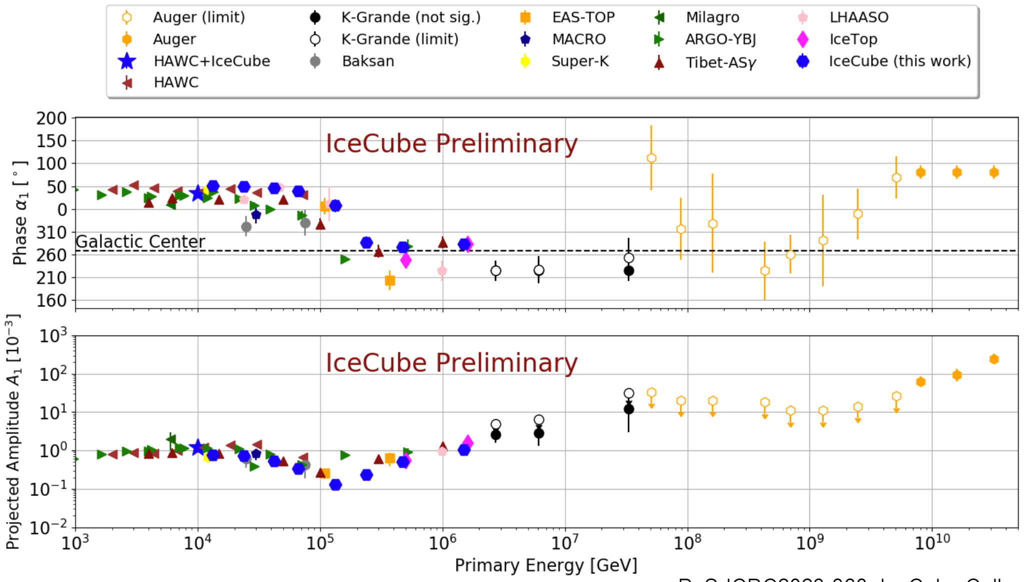
Science 357,1266-1270 (2017)

IceCube Observatory → relative intensity



PoS-ICRC2023-360, IceCube Coll.

Dipole component

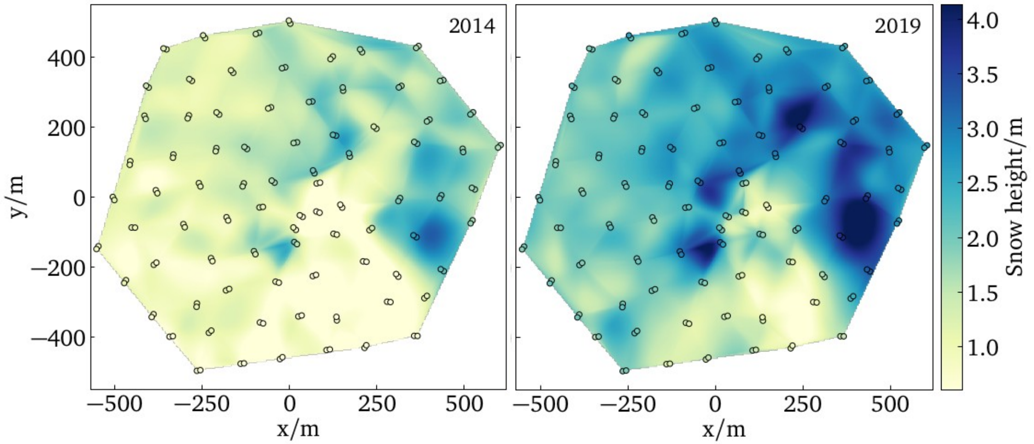


PoS-ICRC2023-360, IceCube Coll.

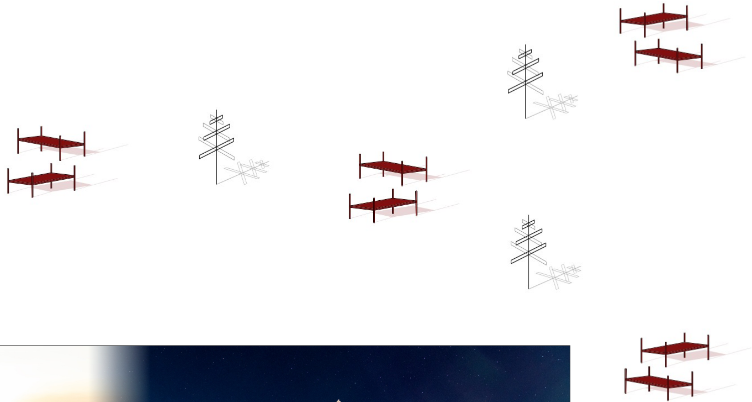
- Strong dipole at UHE → extragalactic origin
- Large- and small-scale structures at lower energies
  → strong energy dependency

Enhancing IceTop

IceTop signals get attenuated due to **snow coverage**
→ increasing energy threshold over time → high uncertainties

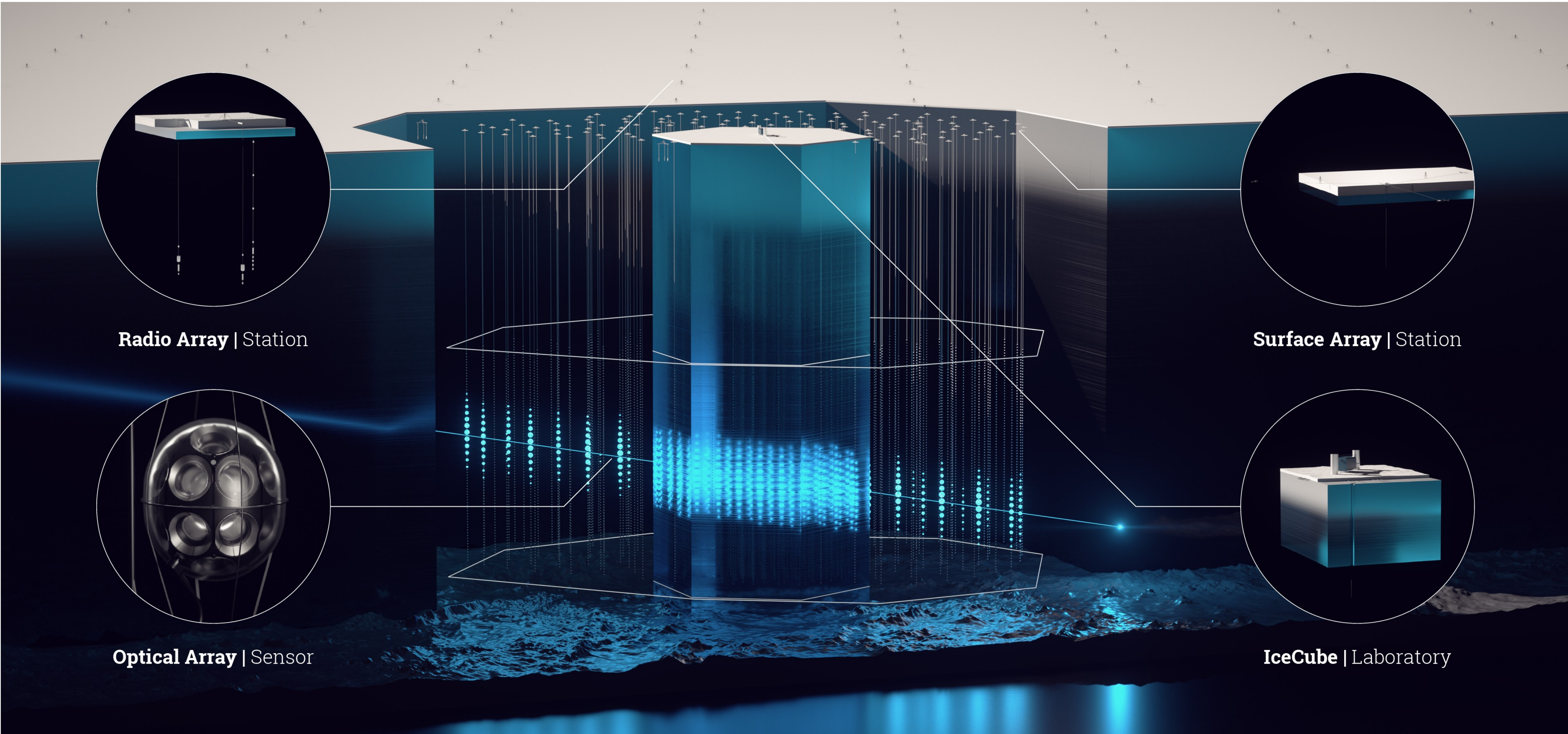


New detection channels



- Elevated scintillator array
  - → lowering the energy threshold
  - → calibration of the snow attenuation
- Elevated radio antennas
  - → very good energy estimation
  - → sensitivity to inclined air showers

Next generation of IceCube



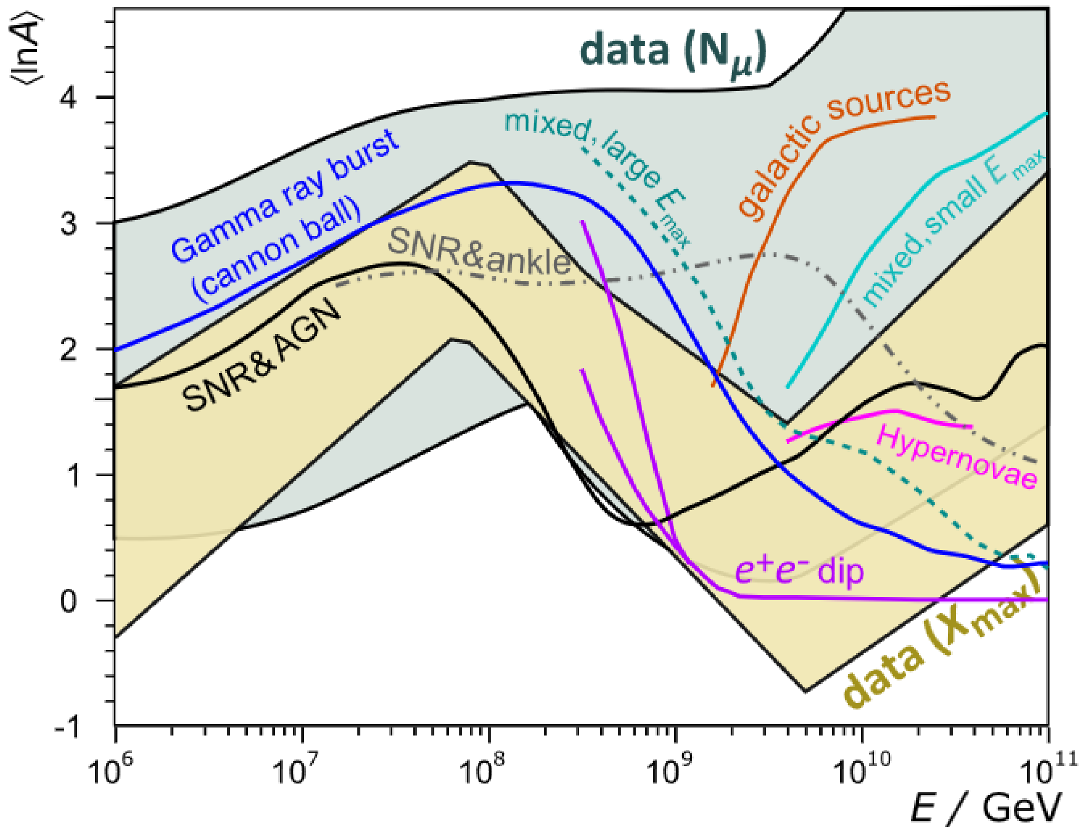
Cosmic ray field

- large progress over decades of ground arrays, balloon & space missions
- more to learn about high-energy Universe and CR sources
- more comprahensive& precise measurements needed

IceCube is a very unique CR detector

- secondaries detected with IceTop
- high-energy muons detected with the in-ice array

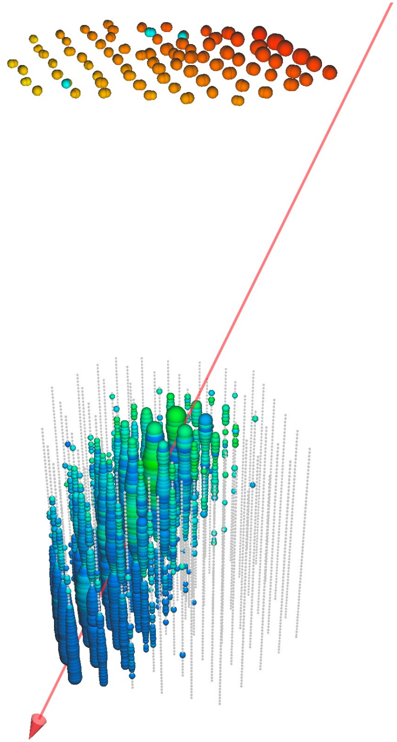
Sources above “the knee”

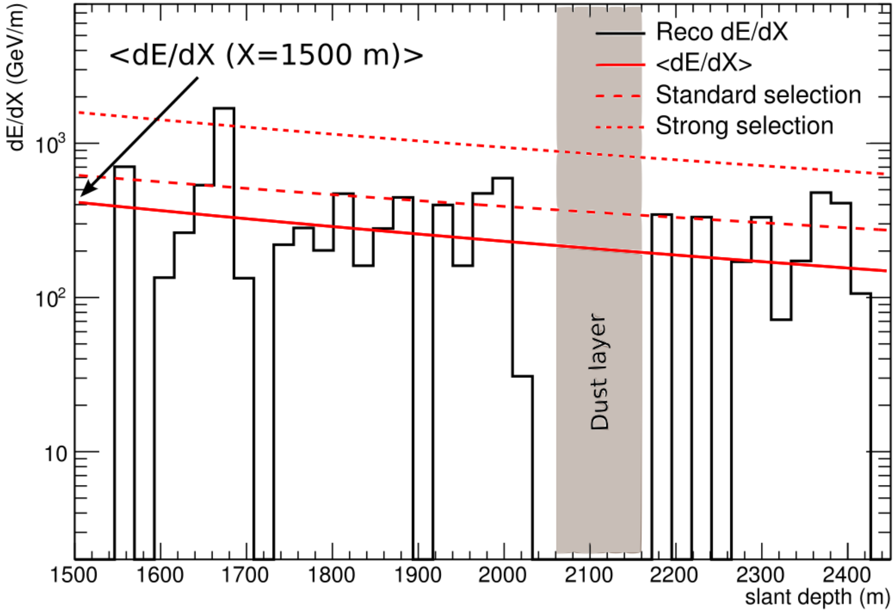


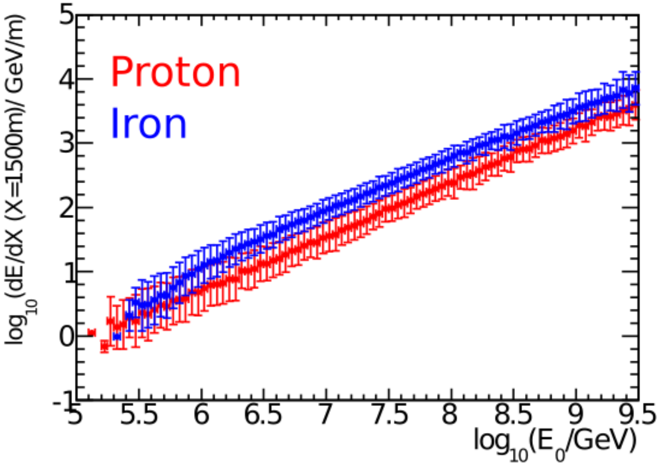
Dembinski et al., EPJ Web Conf. 2019

- Need better estimation of CR composition
- Large uncertainties from hadronic models
- Galactic models only up to PeV
- Transition region?
- Extragalactic sources at the UHE

IceTop/IceCube EAS detection



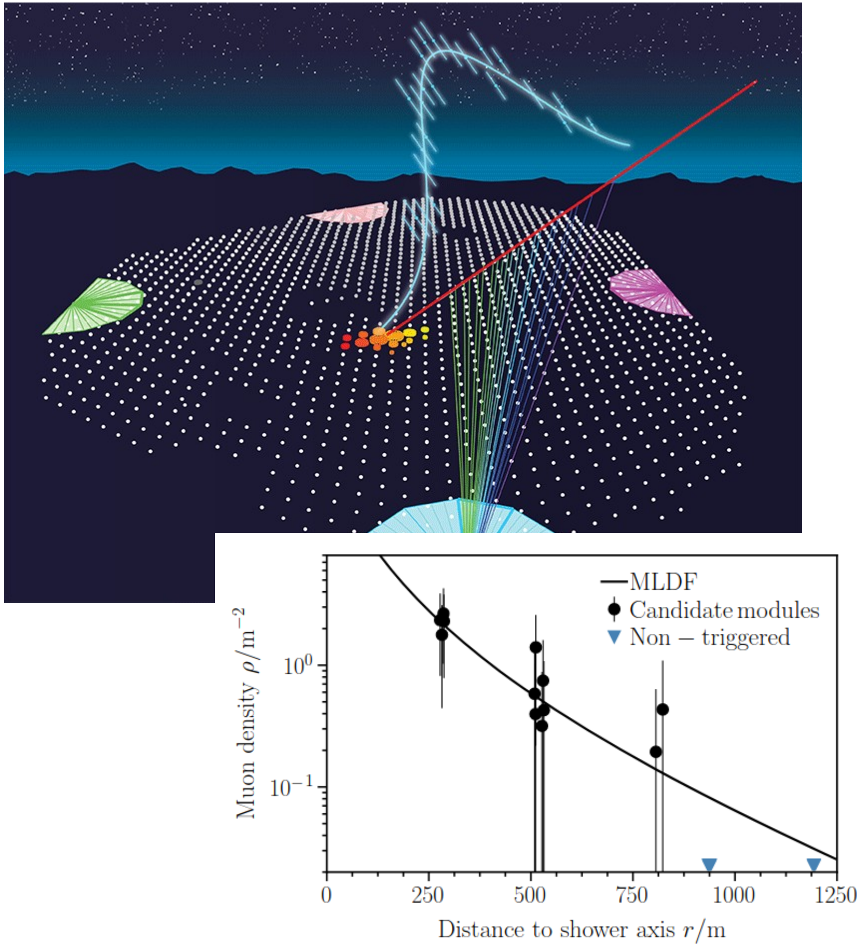




In-ice distribution sensitive to CR mass:

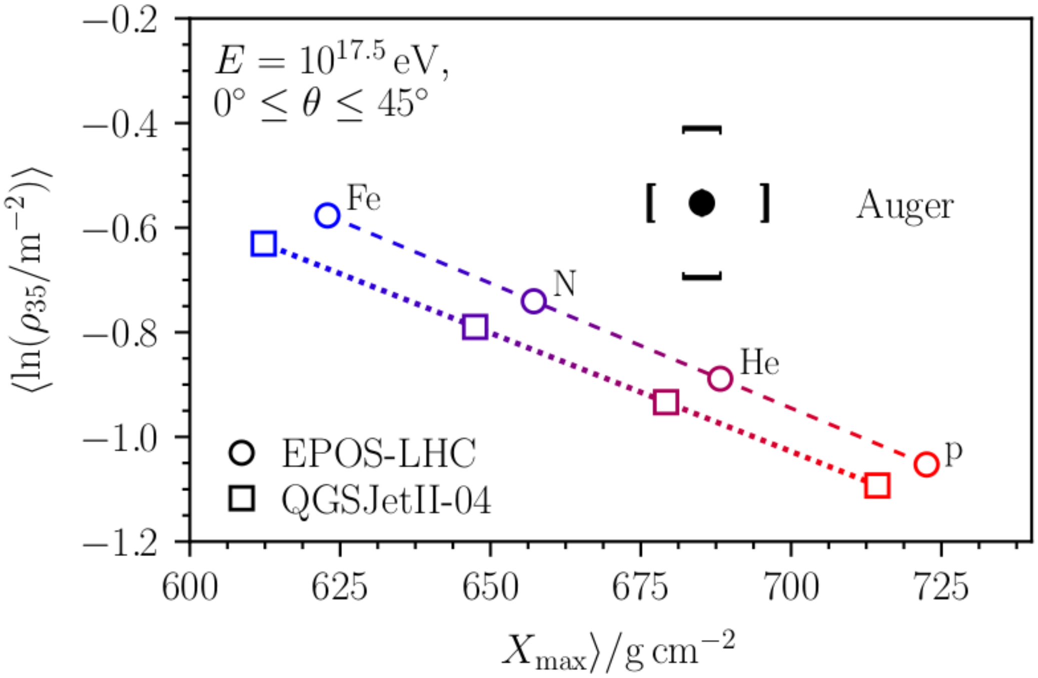
- heavier CR → more muons → more in-ice deposition
- lighter CR → higher-energy muons → local large deposition

Muon puzzle



https://physics.aps.org/articles/v9/125

Discrepancies between EAS muon measurements and model predictions



Pierre Auger Observatory, Eur. Phys. J. C 80, 751 (2020)