Opportunities for Cosmic Ray Science with TAMB(IT)O

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2026/08/18 - TAMBO Collaboration Meeting

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About me

PhD: Ghent University, Belgium

Postdoc: University of Delaware (current)

Recruited by Carlos for cosmic ray experience

- IceCube: muon analysis, surface radio, WG convener
- Auger: deployment of pathfinder radio array *ARISE*

Cosmic Rays

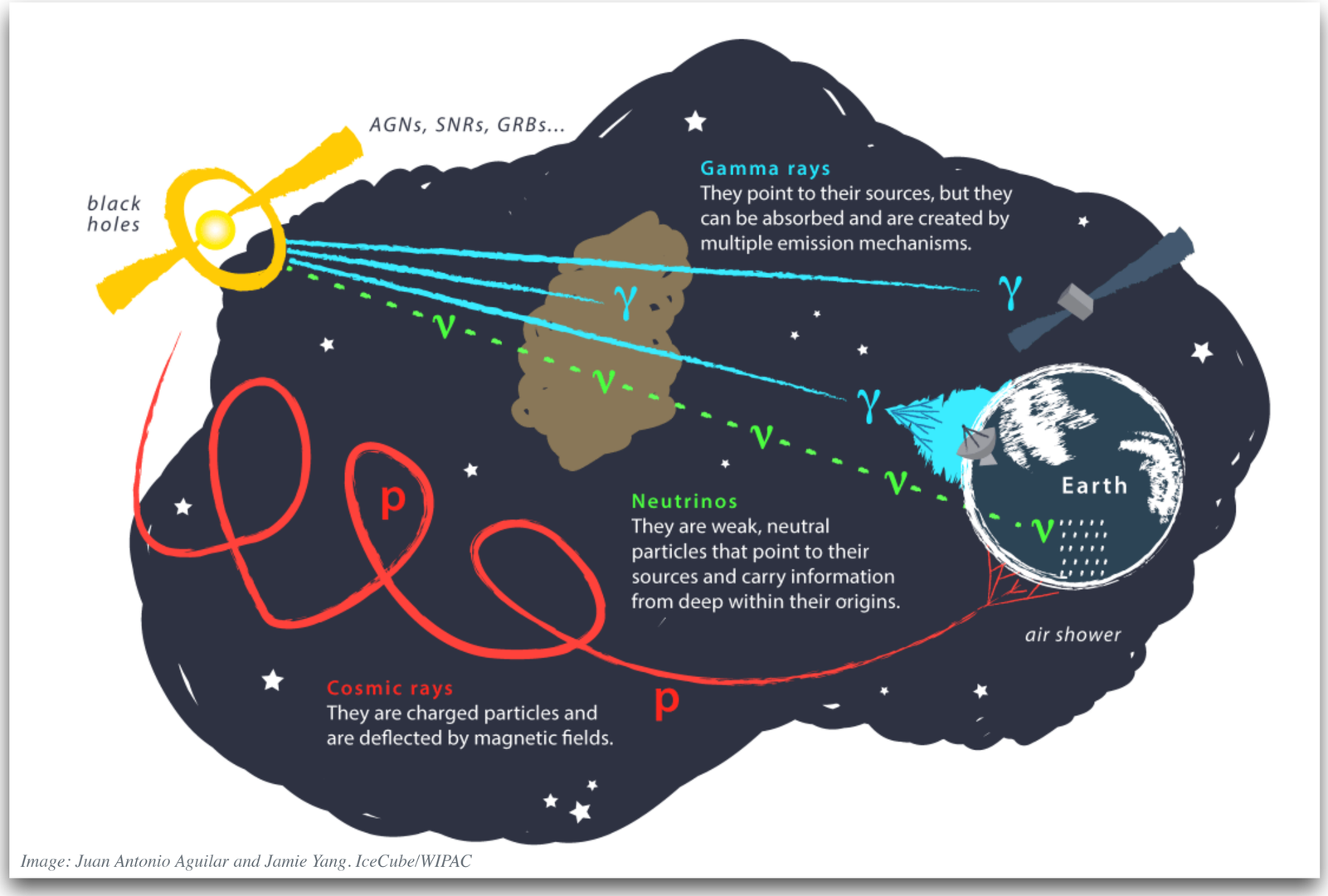
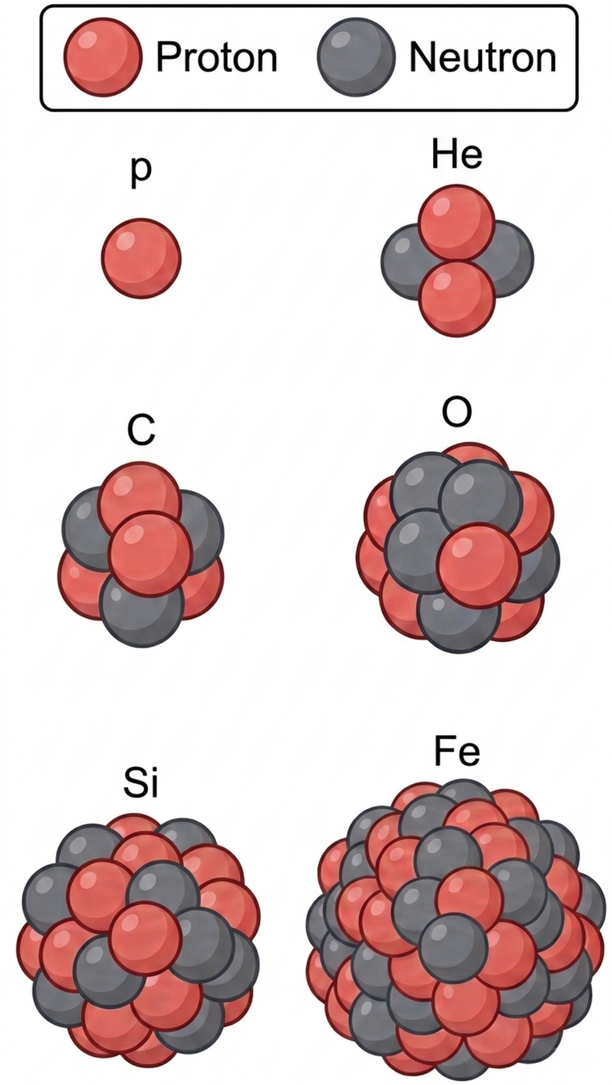
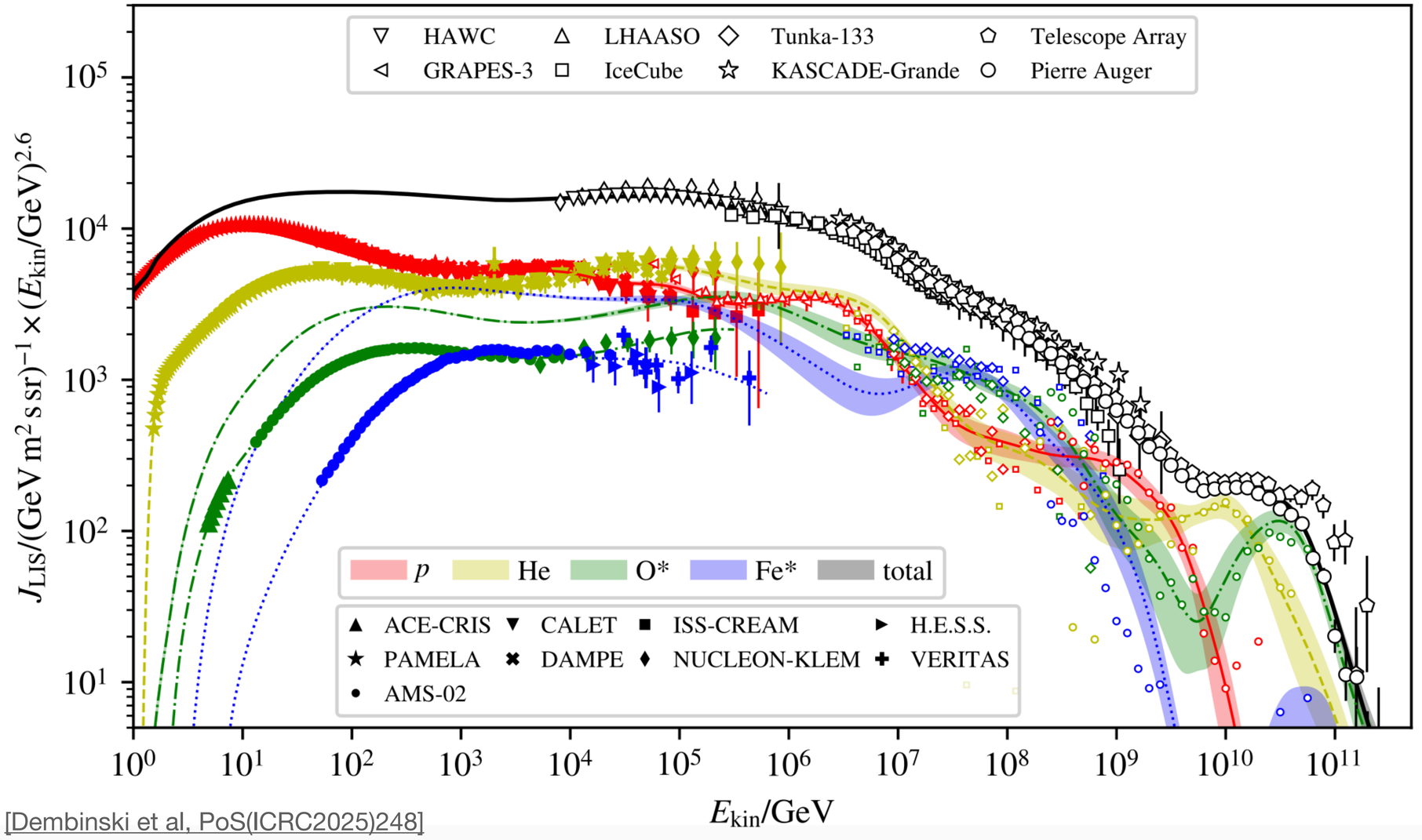


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC



Cosmic Rays

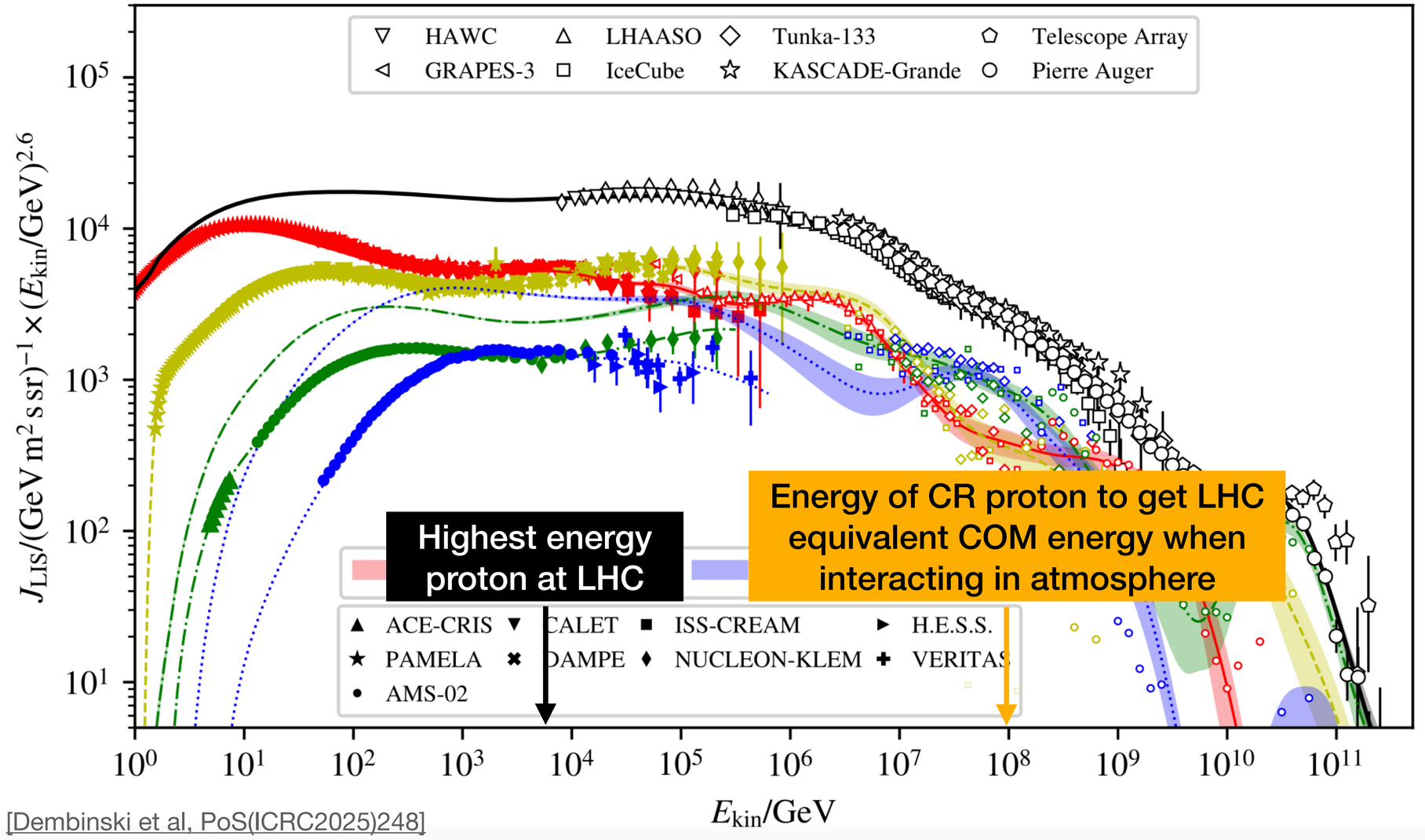


[Dembinski et al, PoS(ICRC2025)248]

Cosmic-ray data landscape

(and Global Spline Fit)

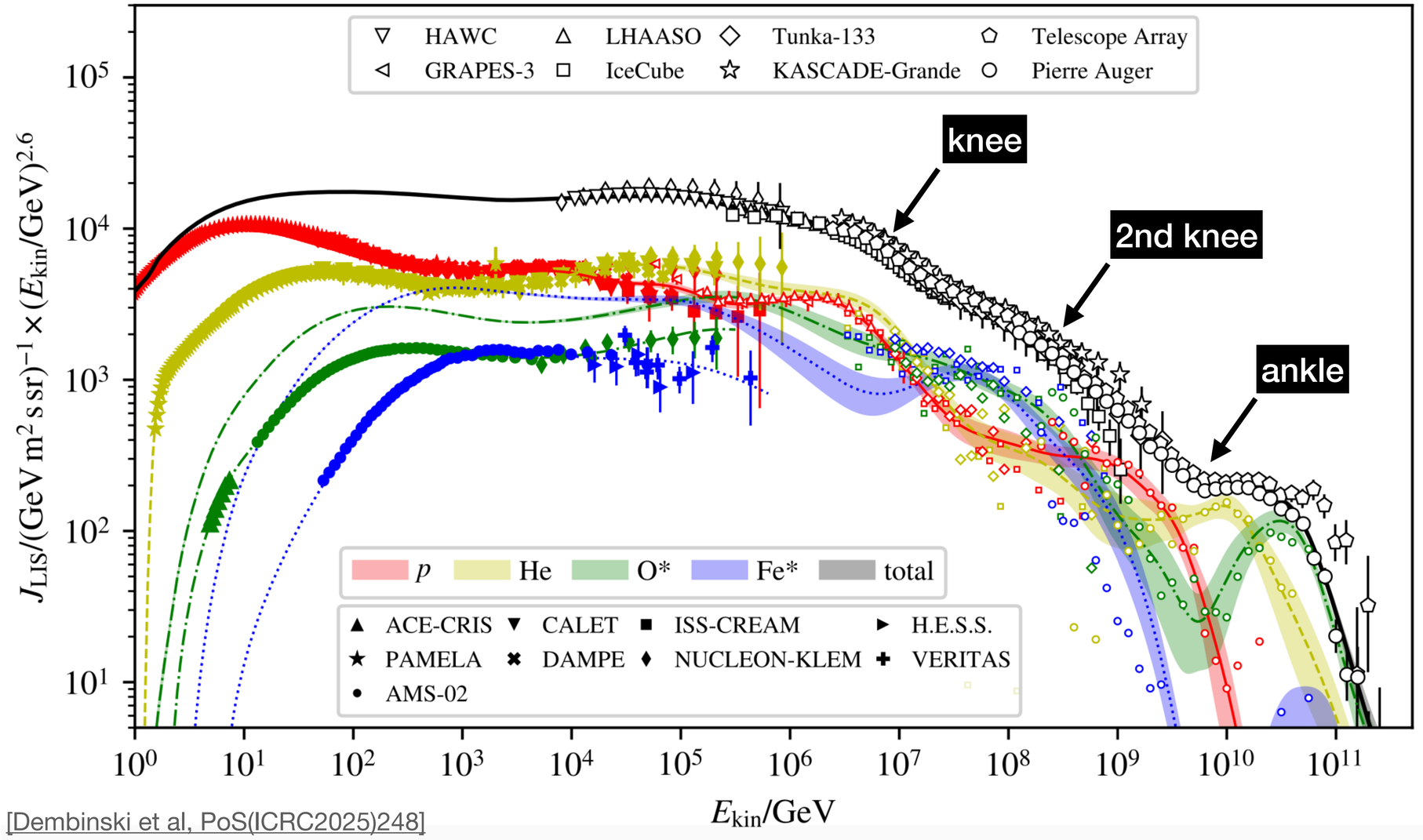
Cosmic Rays



[Dembinski et al, PoS(ICRC2025)248]

- Steeply falling flux
- 11 orders of magnitude in energy
- Highest energy particles in the Universe (> 100 EeV)

Cosmic Rays



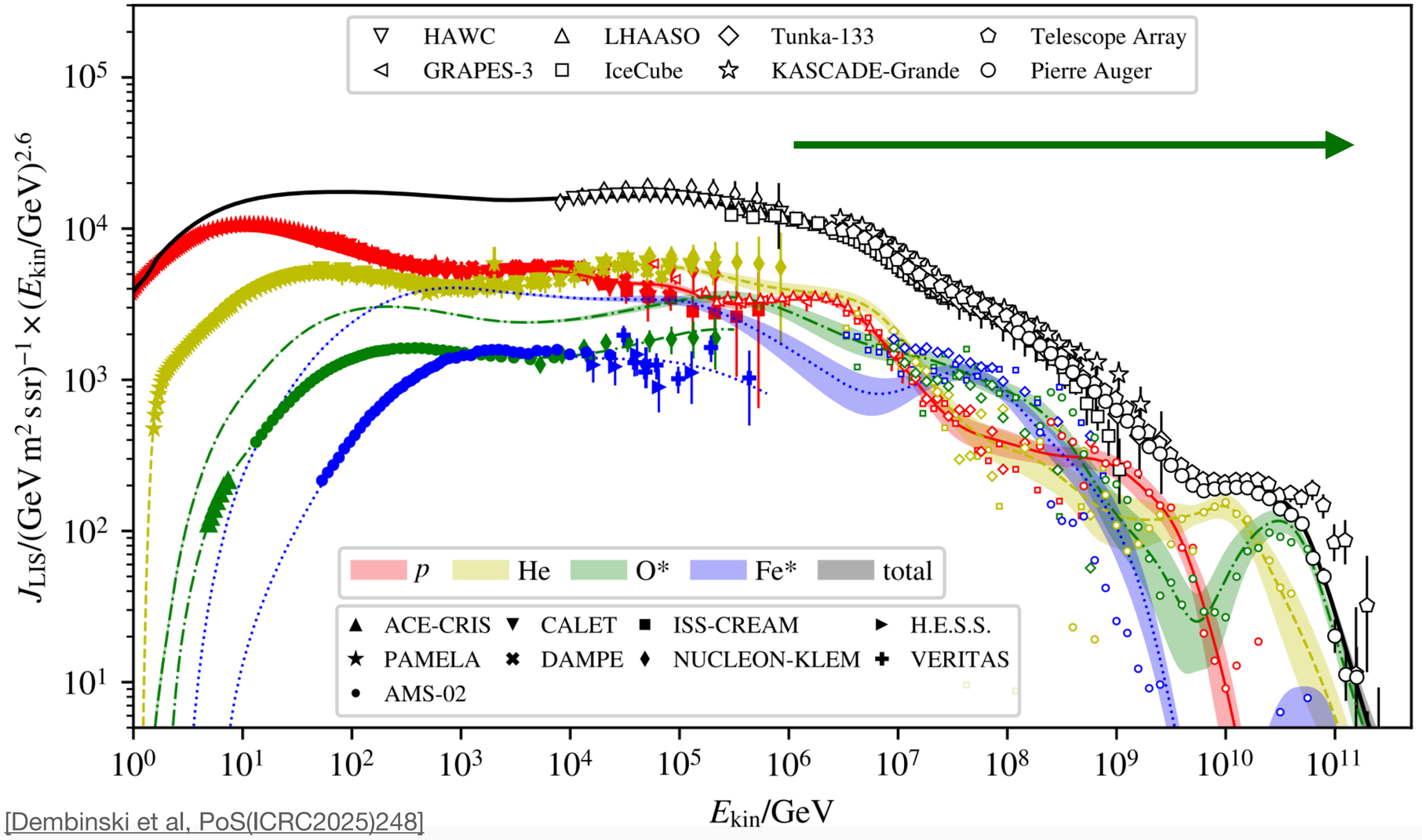
[Dembinski et al, PoS(ICRC2025)248]

Different source populations unknown

Features likely relate to transitions

Transition to extragalactic somewhere above ~100 PeV

Cosmic Rays

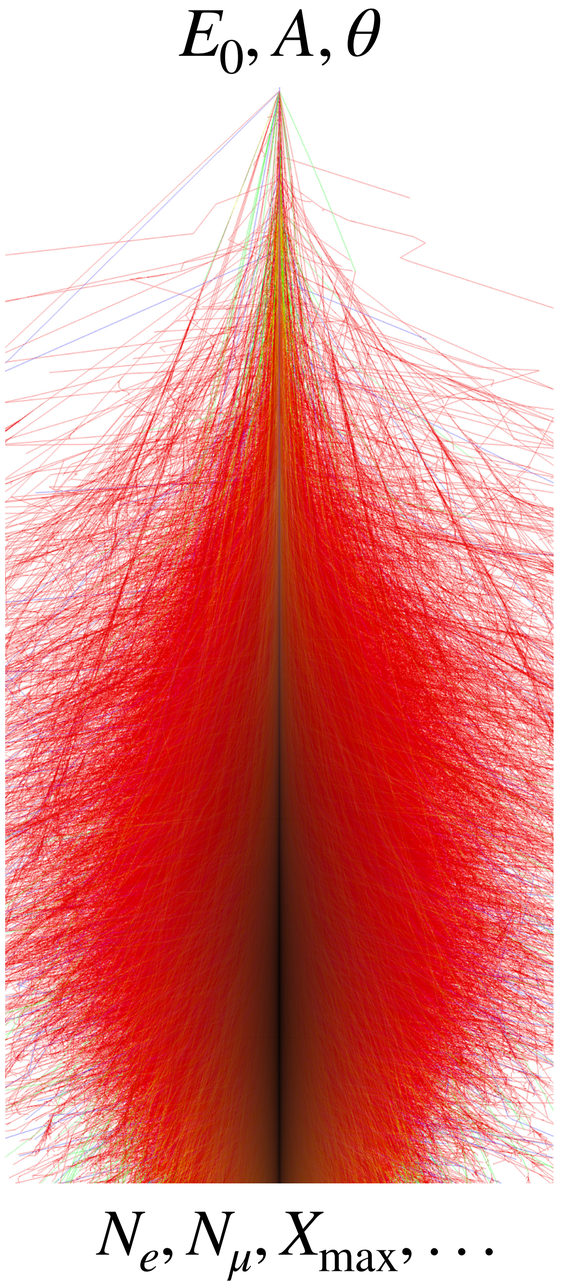


[Dembinski et al, PoS(ICRC2025)248]

Indirect detection with air shower arrays above ~PeV

Air showers

- Efficient way of collecting cosmic rays where flux is low
- "Destroy" a lot of information about the primary nucleus



Air showers

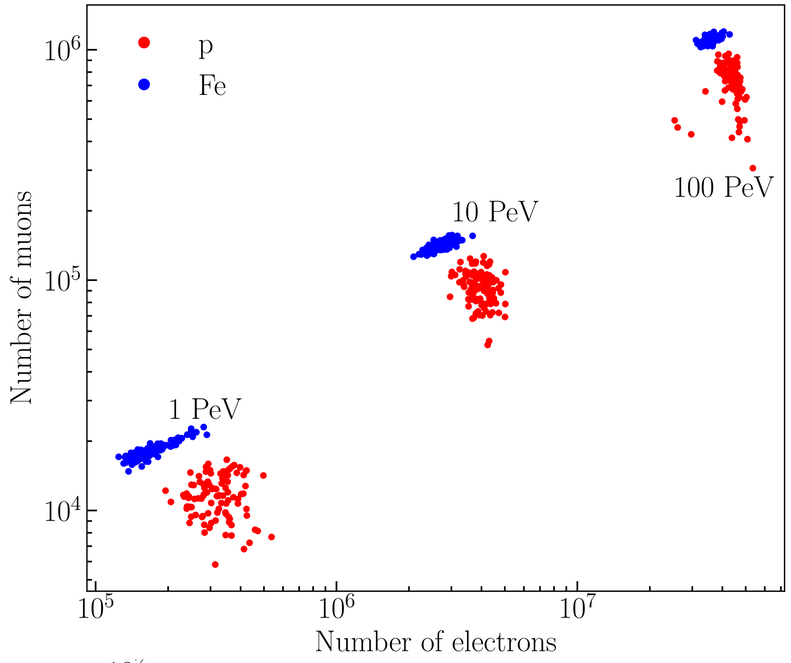
Information about primary mass A mostly from

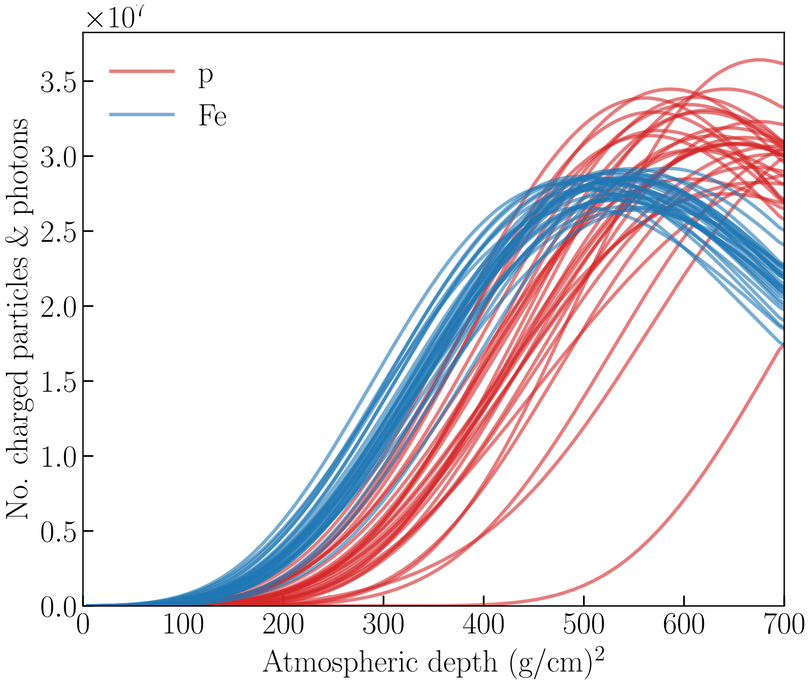
- Number of muons at ground (particle detector arrays)

$$N_\mu \propto A \left(\frac{E_0}{A}\right)^\beta, \quad \beta \approx 0.9$$

- Longitudinal development (fluorescence telescopes, radio antennas)

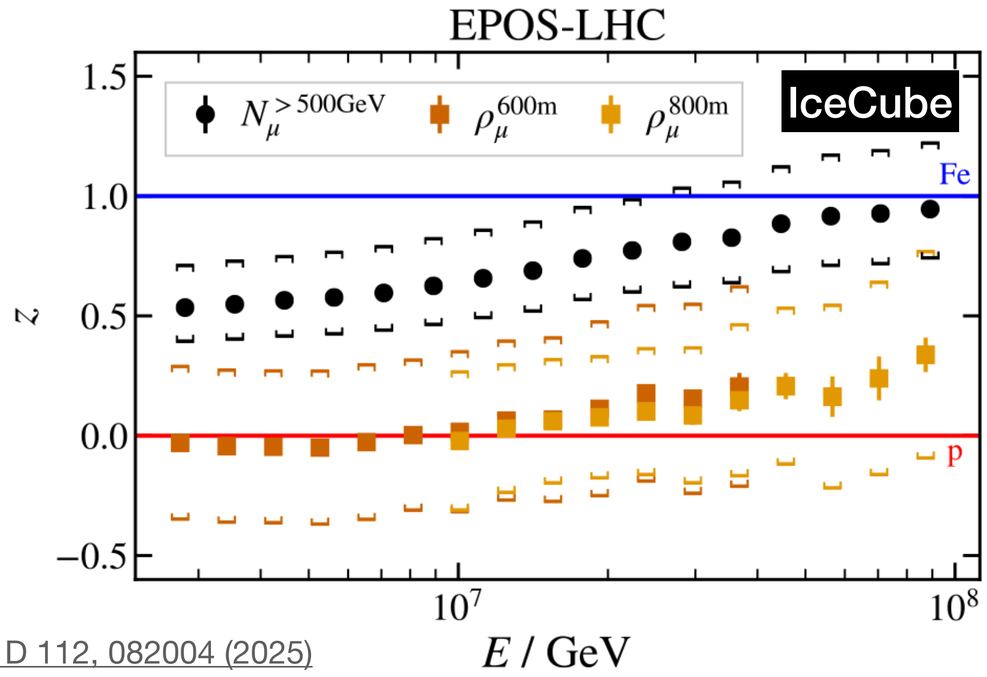
$$X_{\max} \approx a + b \ln \frac{E_0}{A}$$



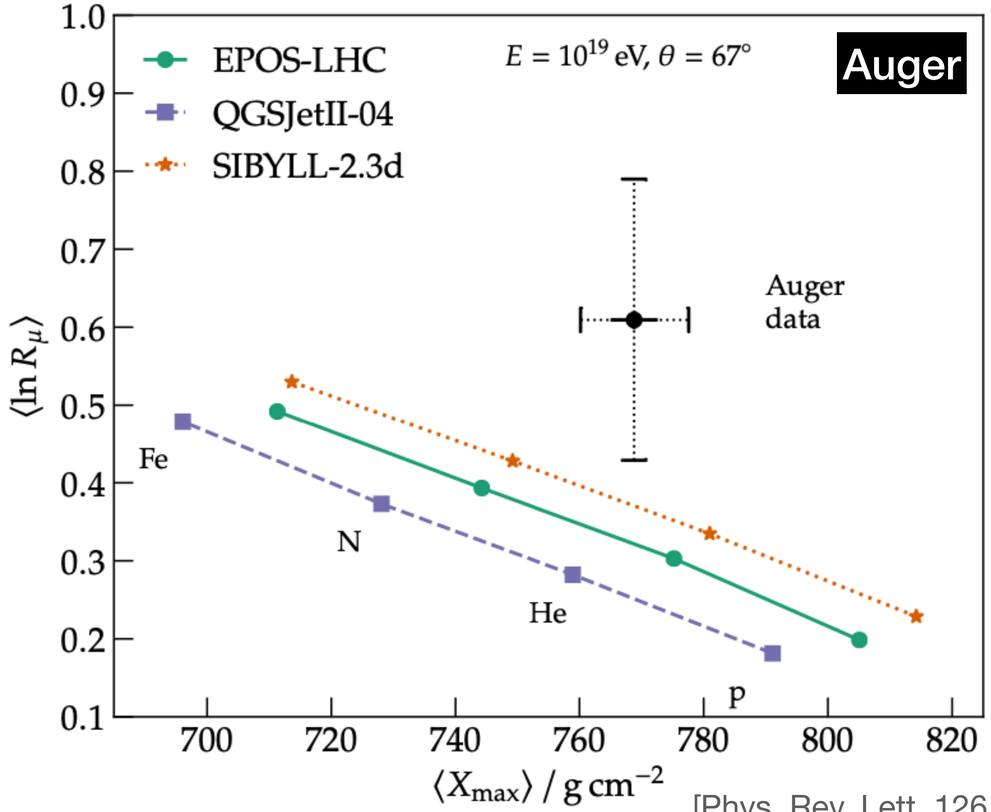


Hadronic interactions & "Muon Puzzle"

- Interpretation of air shower measurements relies on accurate simulations
- Hadronic interaction models extrapolate accelerator measurements in different ways
- Known issues in current models!



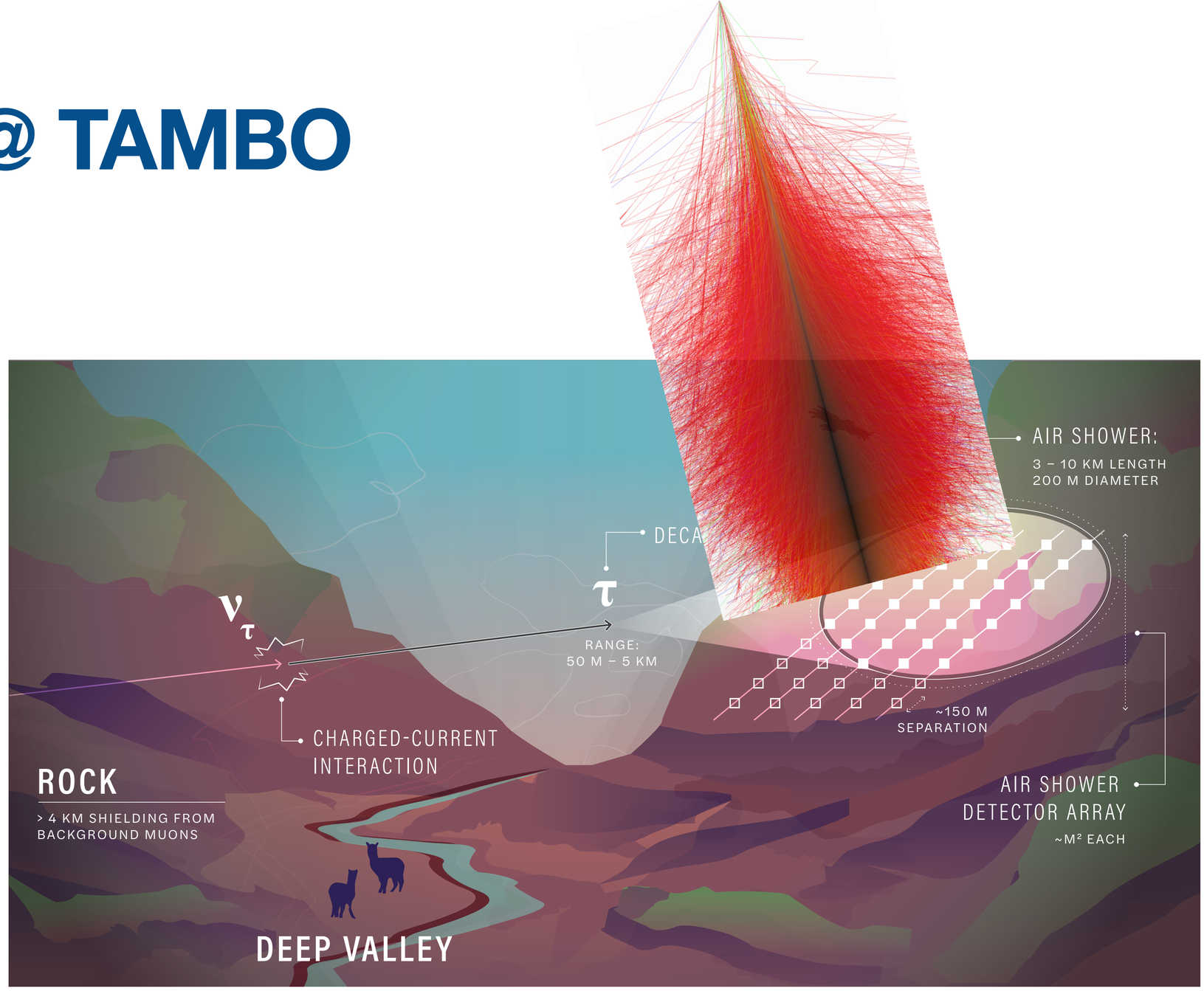
Phys. Rev. D 112, 082004 (2025)



[Phys. Rev. Lett. 126, 152002 (2021)]

Cosmic Rays @ TAMBO

- **Energy spectrum**
- **Mass composition**
- **Shower physics**
- Anisotropy
- Solar physics
- Atmospheric phenomena



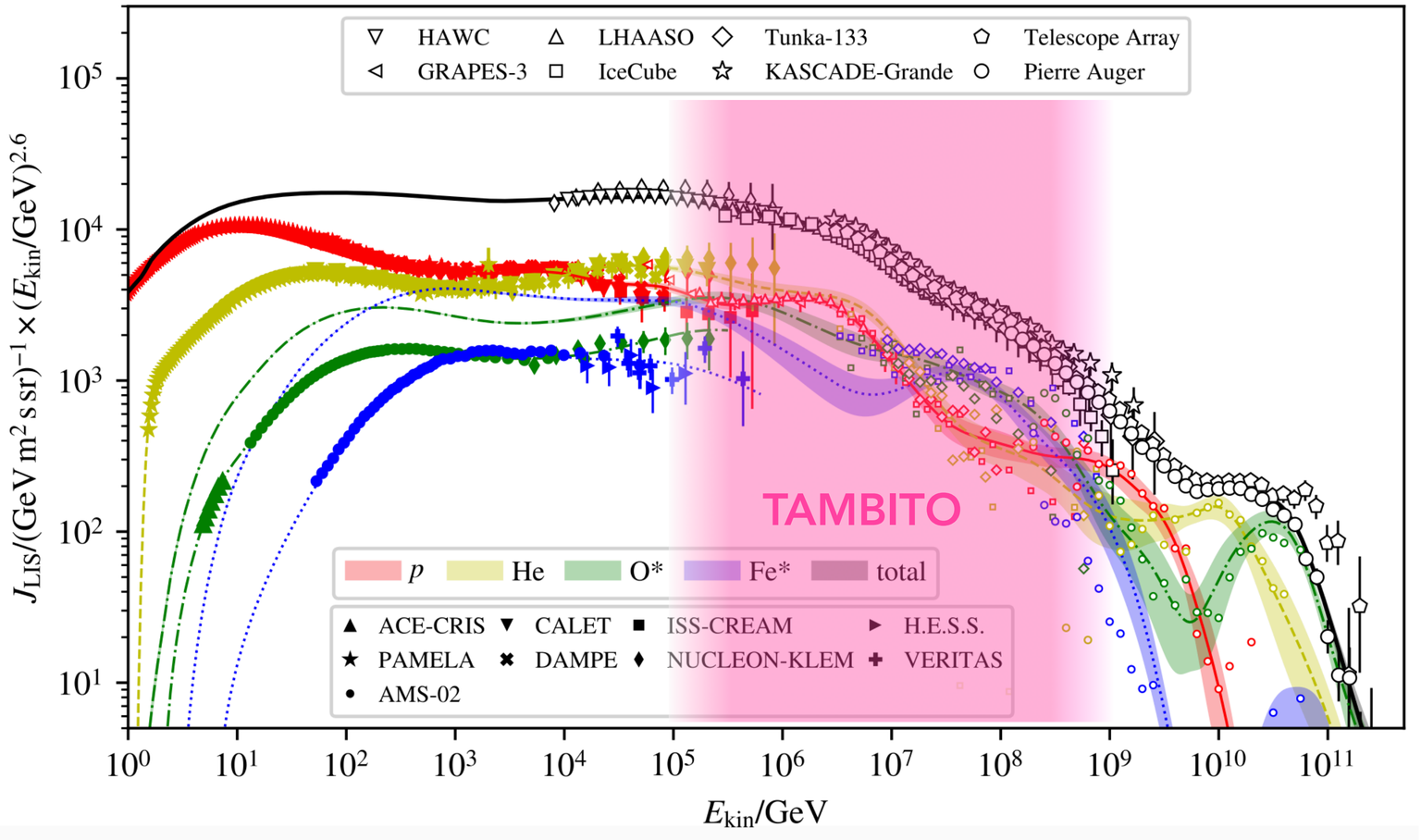
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO)

Cosmic Rays @ TAMBO

Energy threshold set by detector spacing & altitude/ overburden

- expect $\mathcal{O}$(100 TeV - 1 PeV) for vertical showers

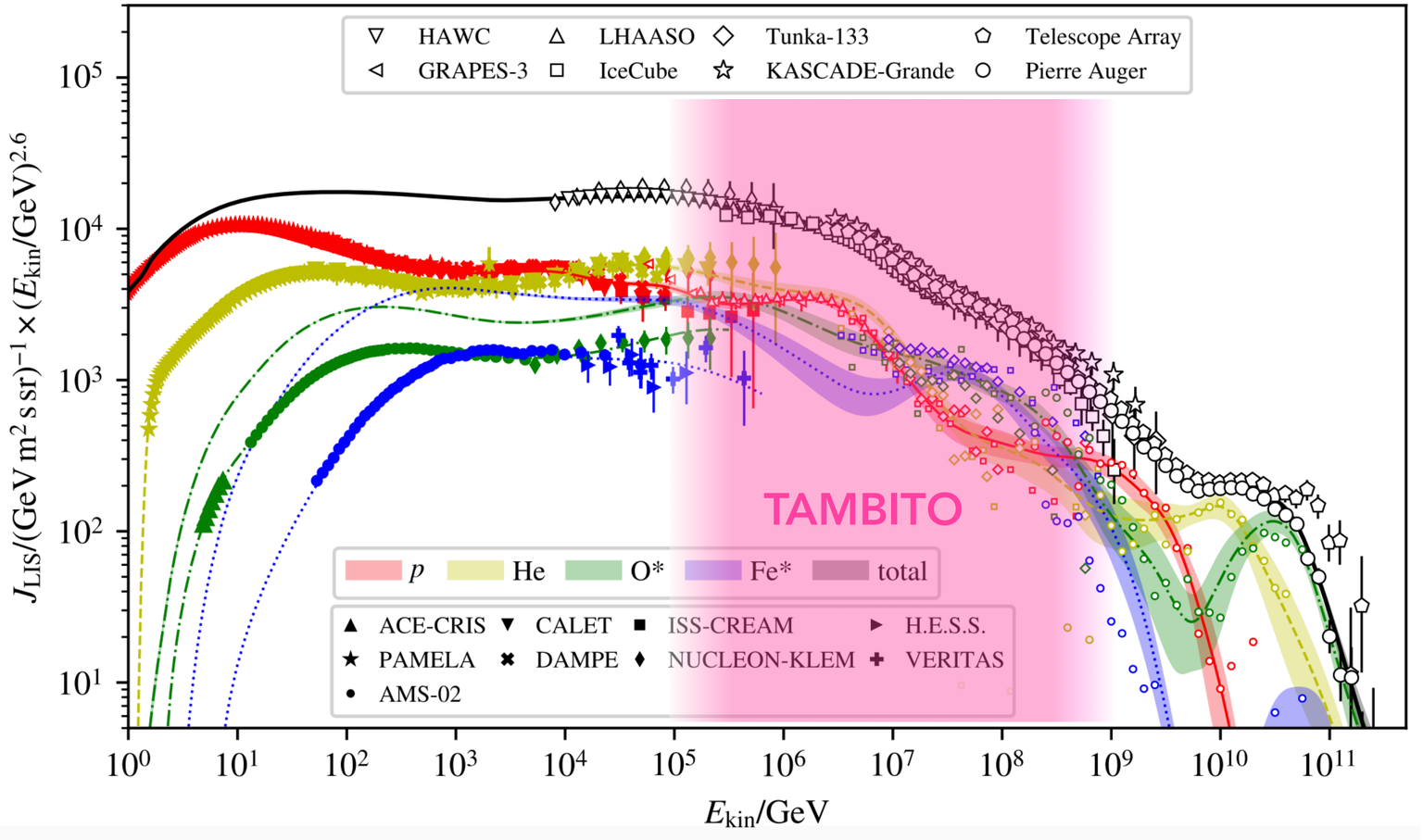
Highest energy ~ statistics given by array size (and possibly detector saturation)



[Dembinski et al, PoS(ICRC2025)248]

Cosmic Rays @ TAMBO: All-particle spectrum

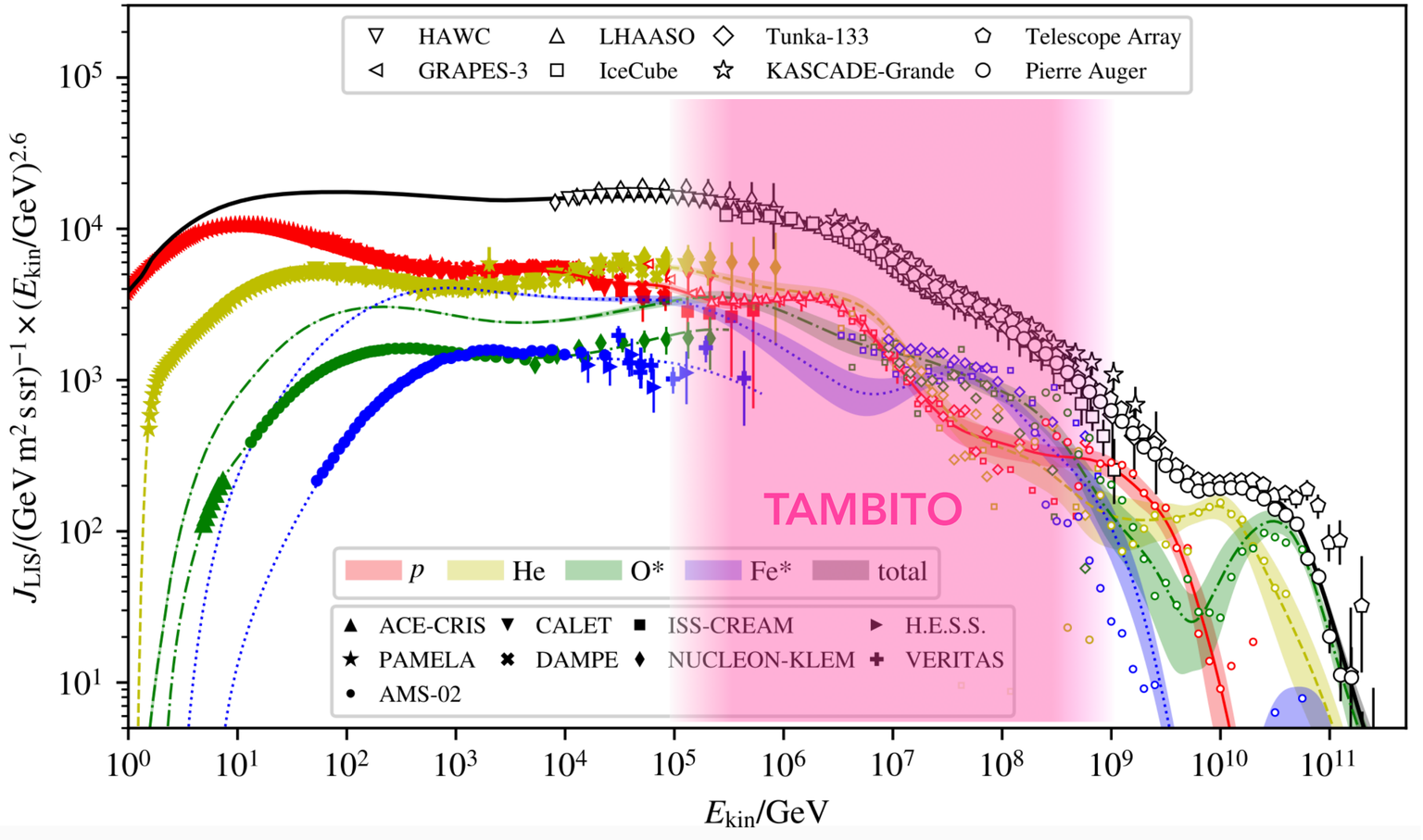
- Cover position of knee and 2nd knee
- Measurement with TAMBITO demonstrates
  - Efficiency
  - Air shower reconstruction
  - Energy estimation



[Dembinski et al, PoS(ICRC2025)248]

Cosmic Rays @ TAMBO: Mass composition

- **Interesting energy range!**
  - Iron knee at $E_{Fe} = 26 \times E_p$?
  - Transition to extragalactic
- 2nd knee composition only constrained by two modern experiments: Tunka-133 and IceCube



[Dembinski et al, PoS(ICRC2025)248]

Cosmic Rays @ TAMBO: Mass composition

Ideally EM/muon separation: limited with scintillators, can be improved by adding:

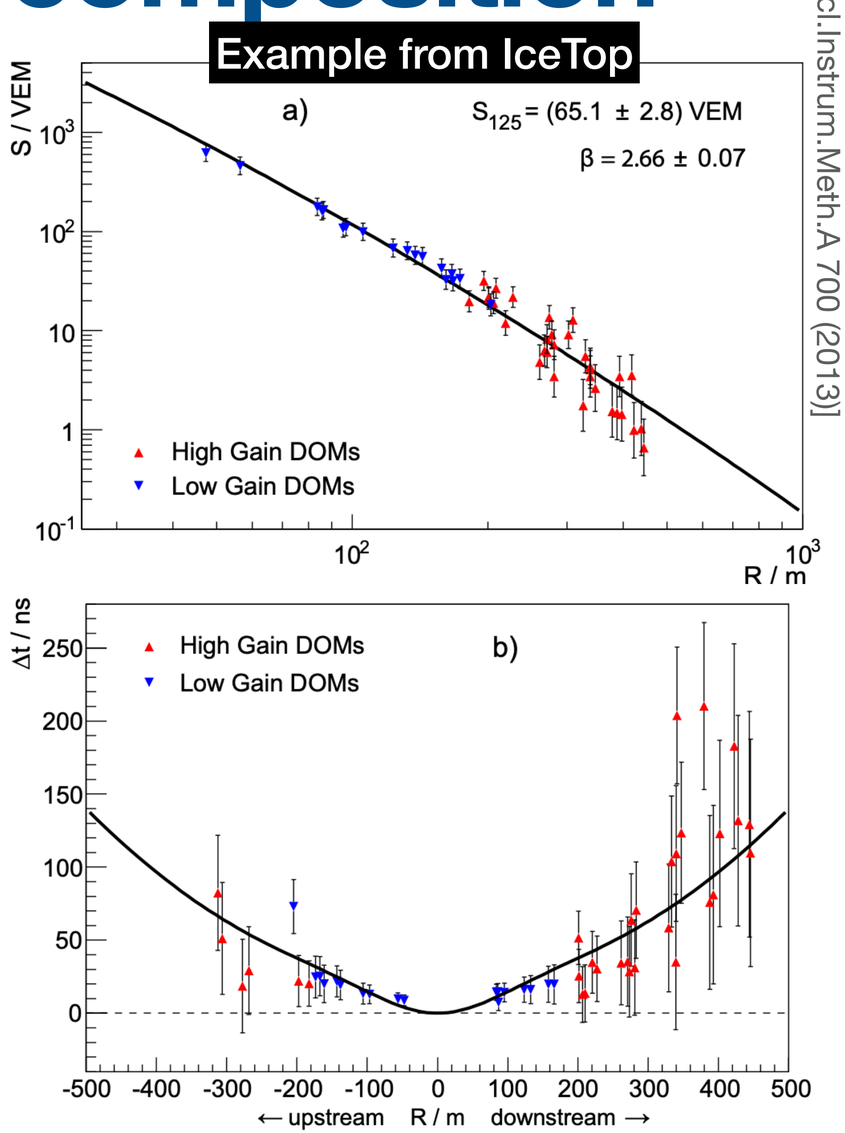
- water tanks
- shielded/buried detectors

Other composition sensitive observables:

- slope of lateral distribution function (charge)
- curvature of shower front (time)
- waveform features, e.g. risetime
- upstream/downstream asymmetry

(GNN classifier could be trained on p & Fe simulations with scintillator-only array to quantify composition sensitivity.)

Example from IceTop

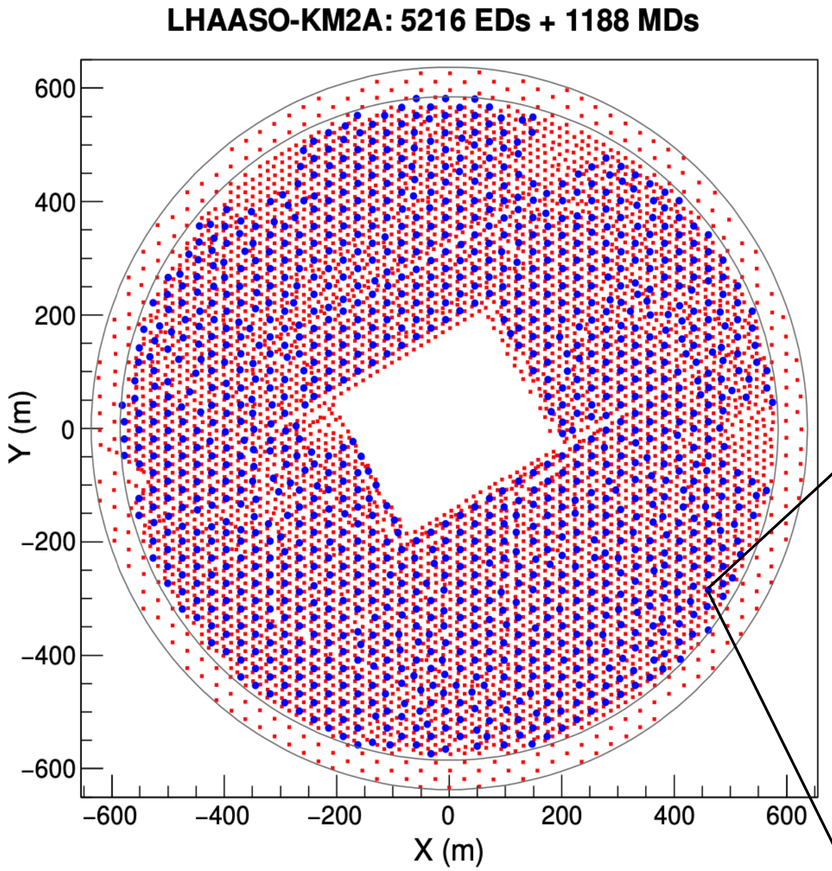


[Nucl.Instrum.Meth.A 700 (2013)]

What else muon separation buys

1. Gamma/hadron separation for gamma ray studies

e.g. buried water tanks @ LHAASO



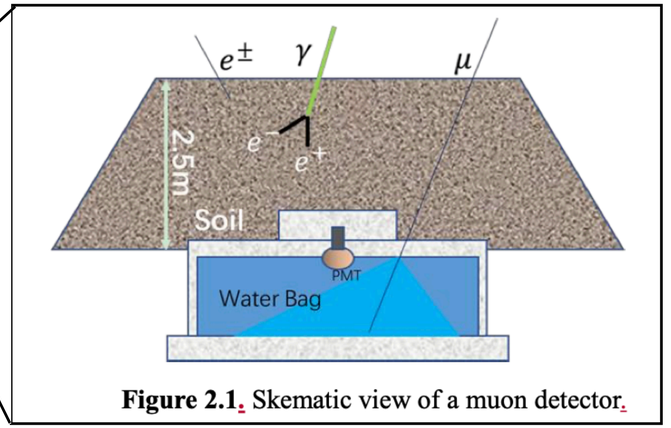
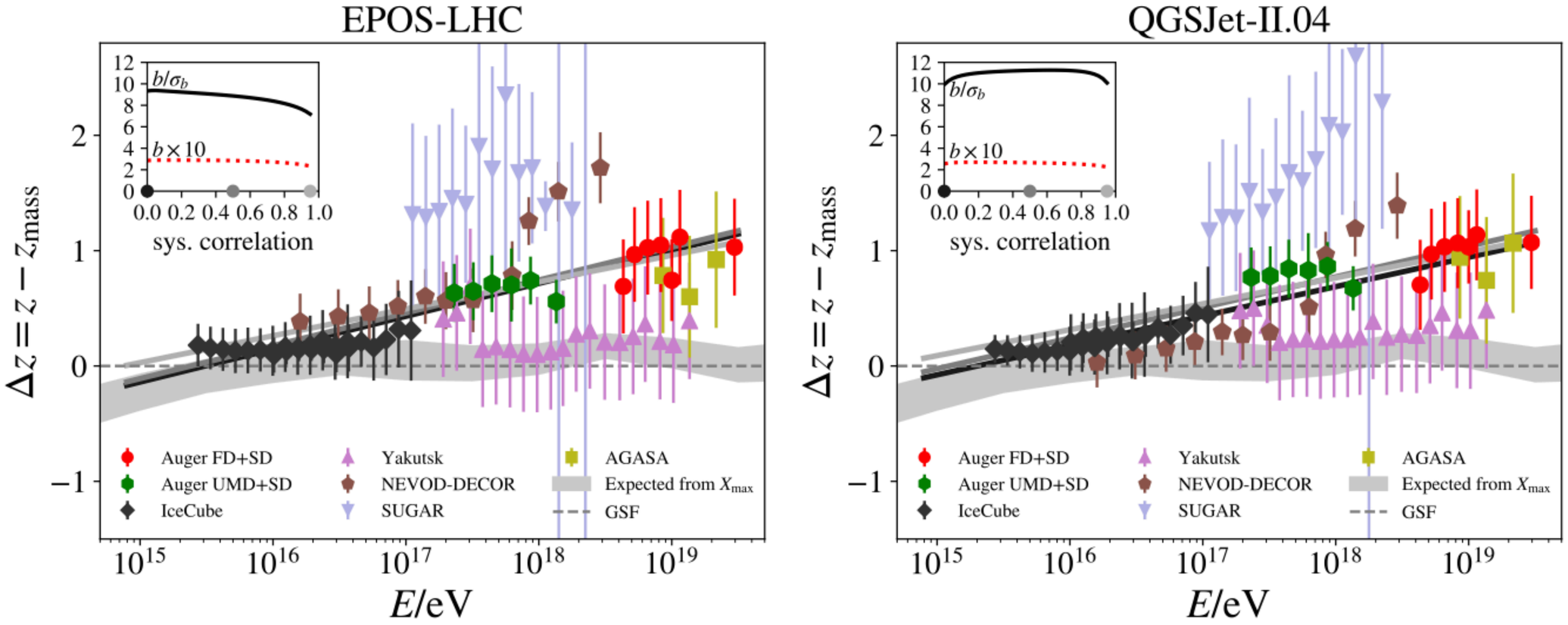


Figure 2.1. Skematic view of a muon detector.

[Radiat.Detect.Technol.Methods 8 (2024) 3] [PoS(ICRC2019)831]

What else muon separation buys

1. Gamma/hadron separation for gamma ray studies
2. Contribute to the Muon Puzzle in the energy range where it "turns on"

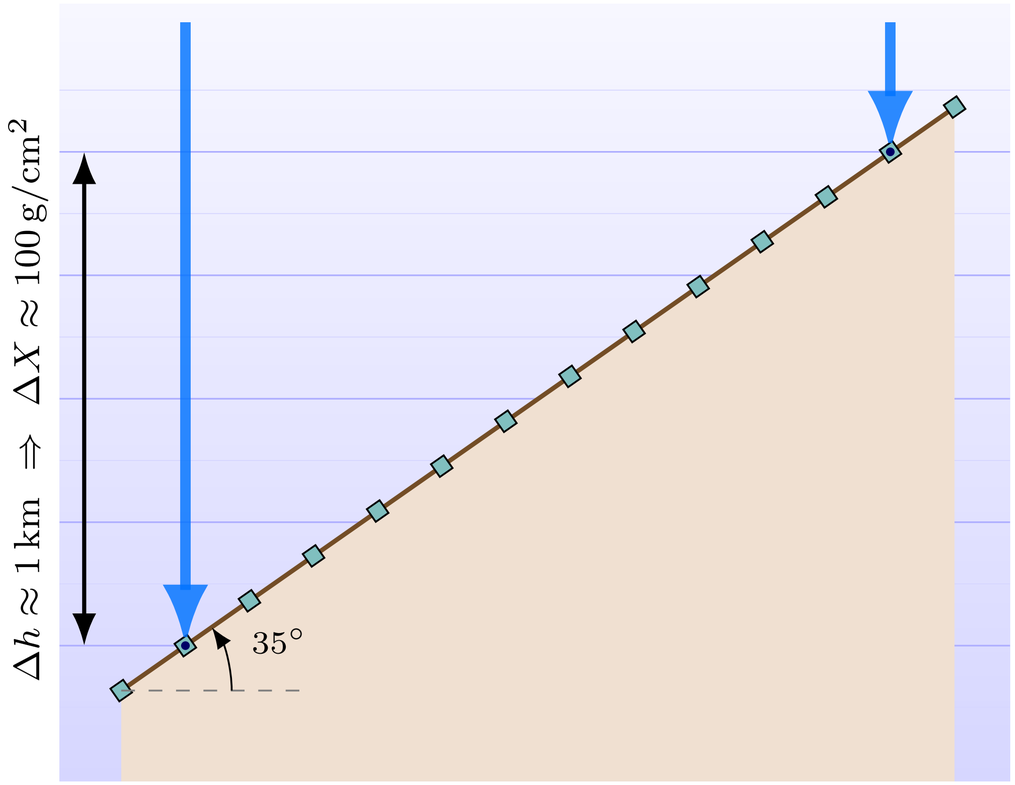


[Astrophys.Space Sci. 367 (2022) 3, 27]

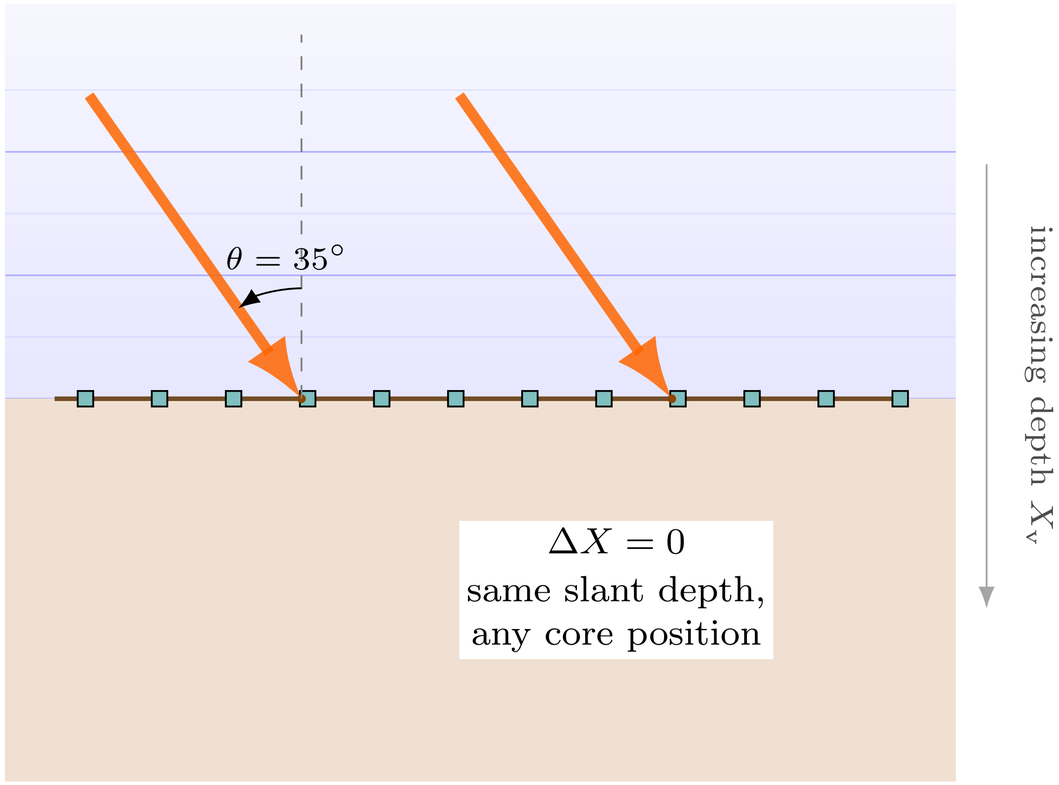
An array on a steep incline: new opportunities?

Not just a rotation! For flat arrays, the amount of matter traversed is decided by the zenith angle.
For an inclined array, these decouple.

(a) sloped array, vertical showers

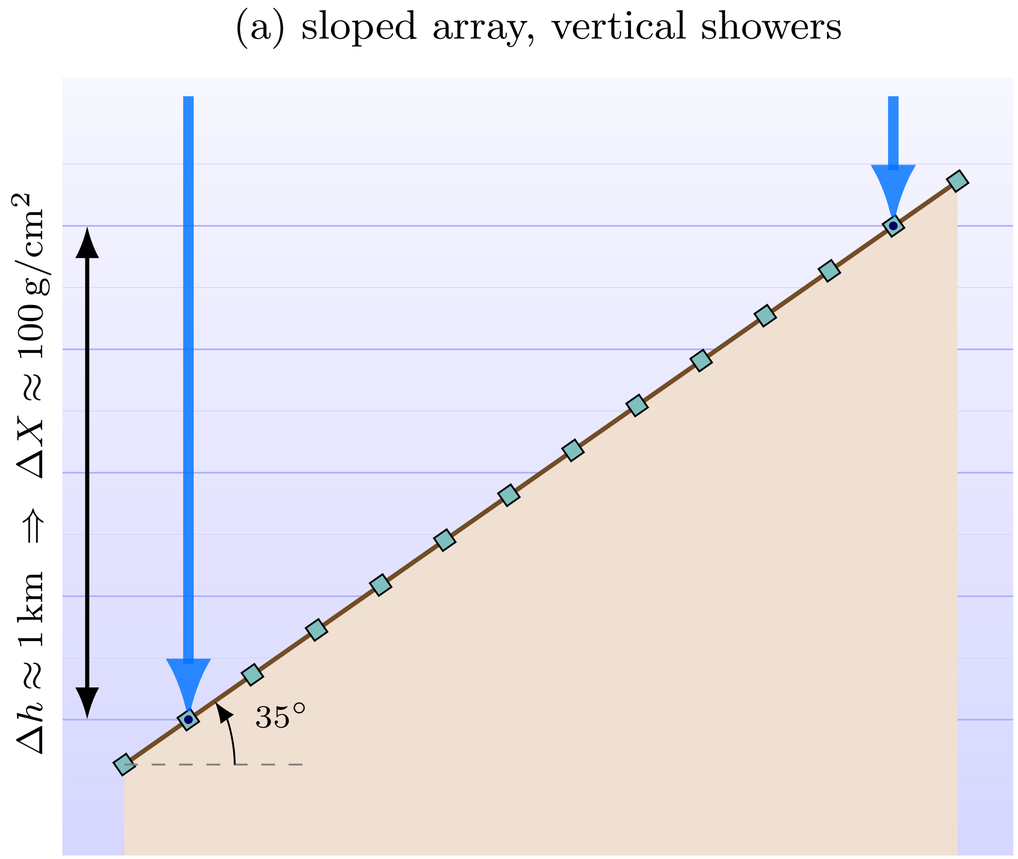


(b) flat array, inclined showers



horizontal lines: iso-depth layers of the stratified atmosphere ($X_\mathrm{v} = \mathrm{const}$)

An array on a steep incline: new opportunities?



- Compare ensembles of showers at fixed zenith but different depth
- Upstream/downstream asymmetry in inclined showers: extra degree of freedom from azimuth
- Observations at different depths can be compared, likely canceling several systematics

→ new ways to test predictions from had. int. models & probe mass composition

Summary & Outlook

- TAMB(IT)O can study the **knee - 2nd knee region** of the cosmic ray spectrum
- The inclined array may provide **new ways of testing longitudinal shower development** and probing mass composition
- Most CR science can likely be improved with increased EM/muon separation