Cosmic Ray Measurements with IceCube and their Connection to UHECRs

Cosmic Rays in the Multi-Messenger Era 2024

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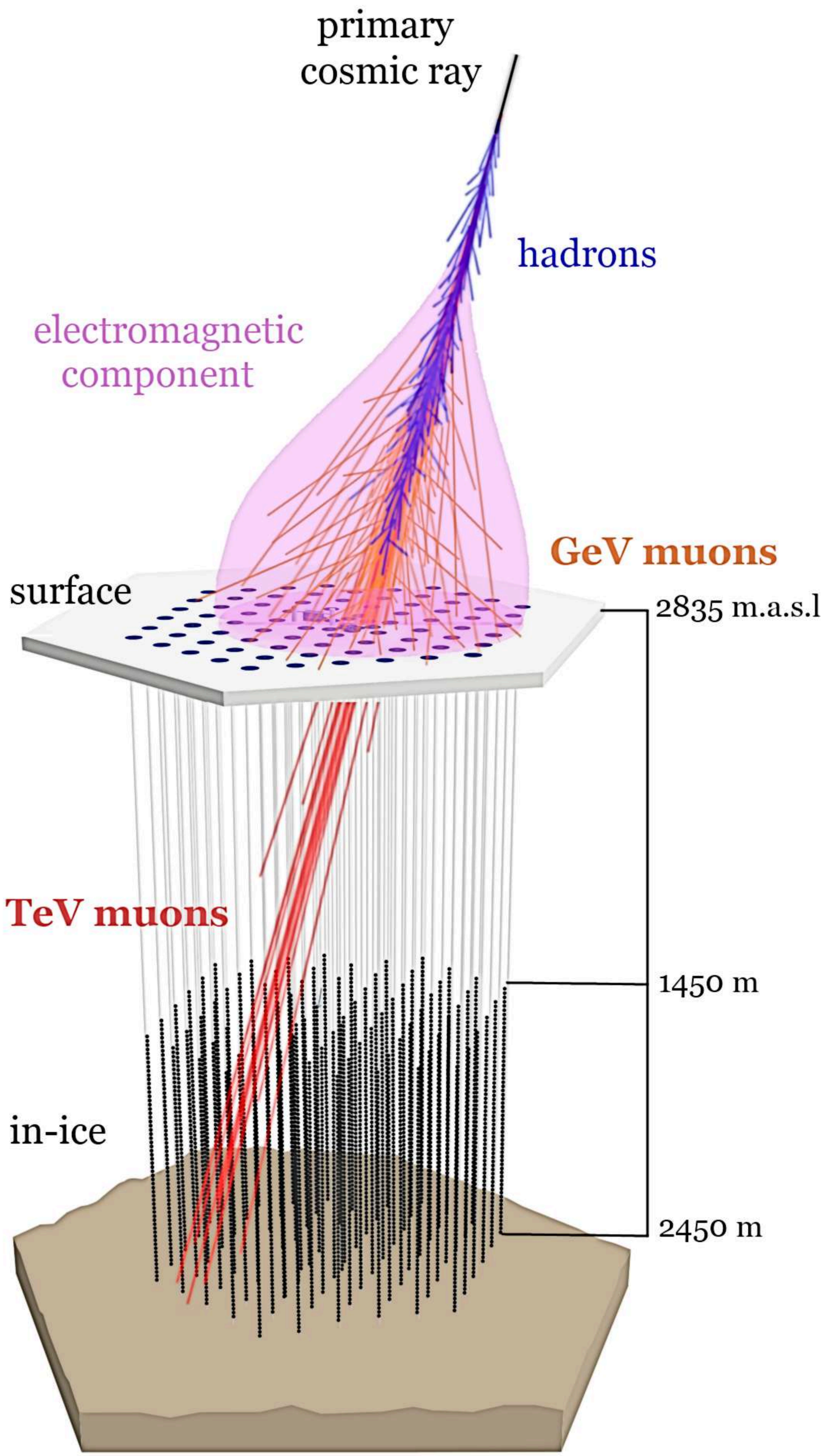
University of Utah, USA

ICECUBE
South Pole Neutrino Observatory

THE UNIVERSITY OF UTAH

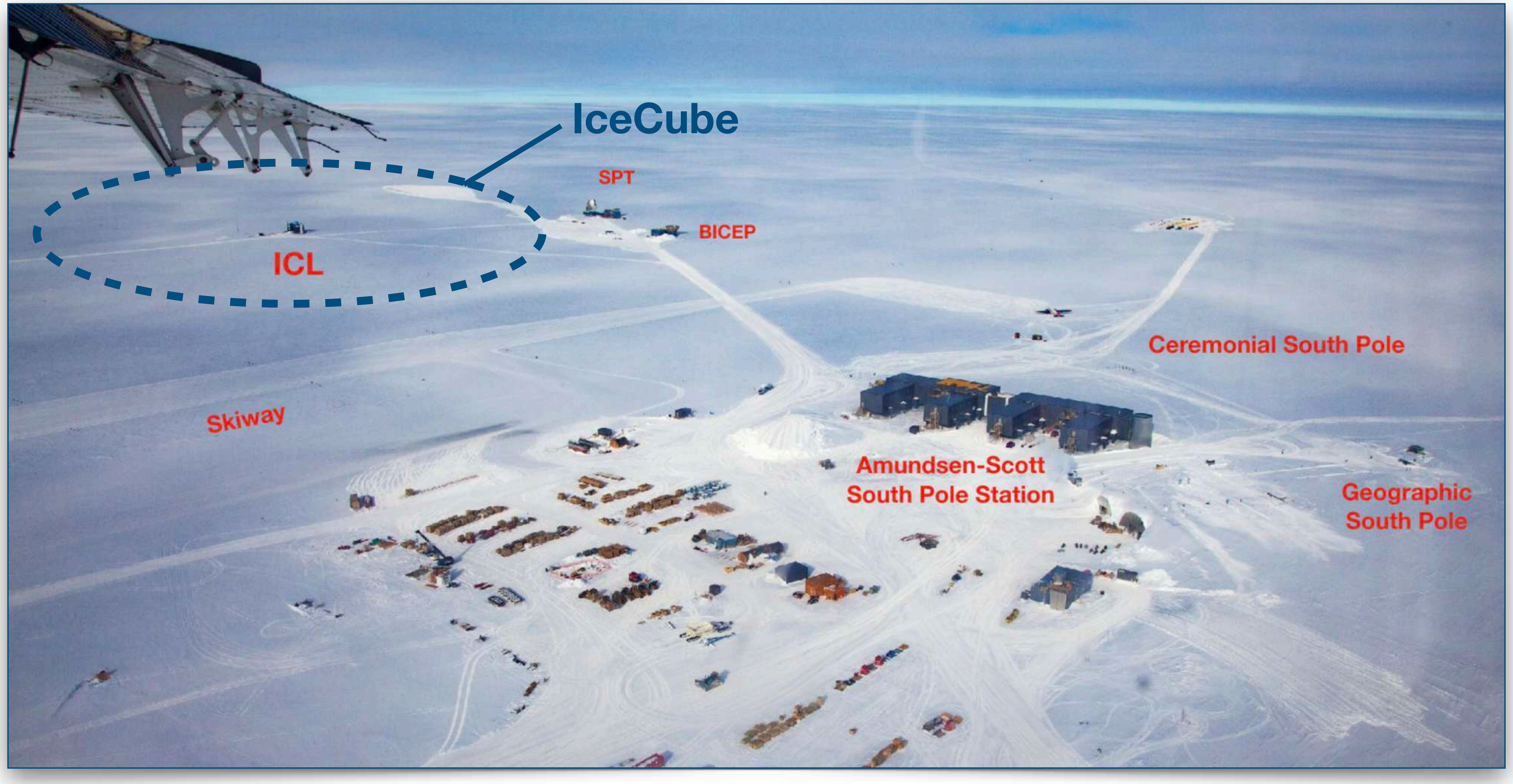
Outline

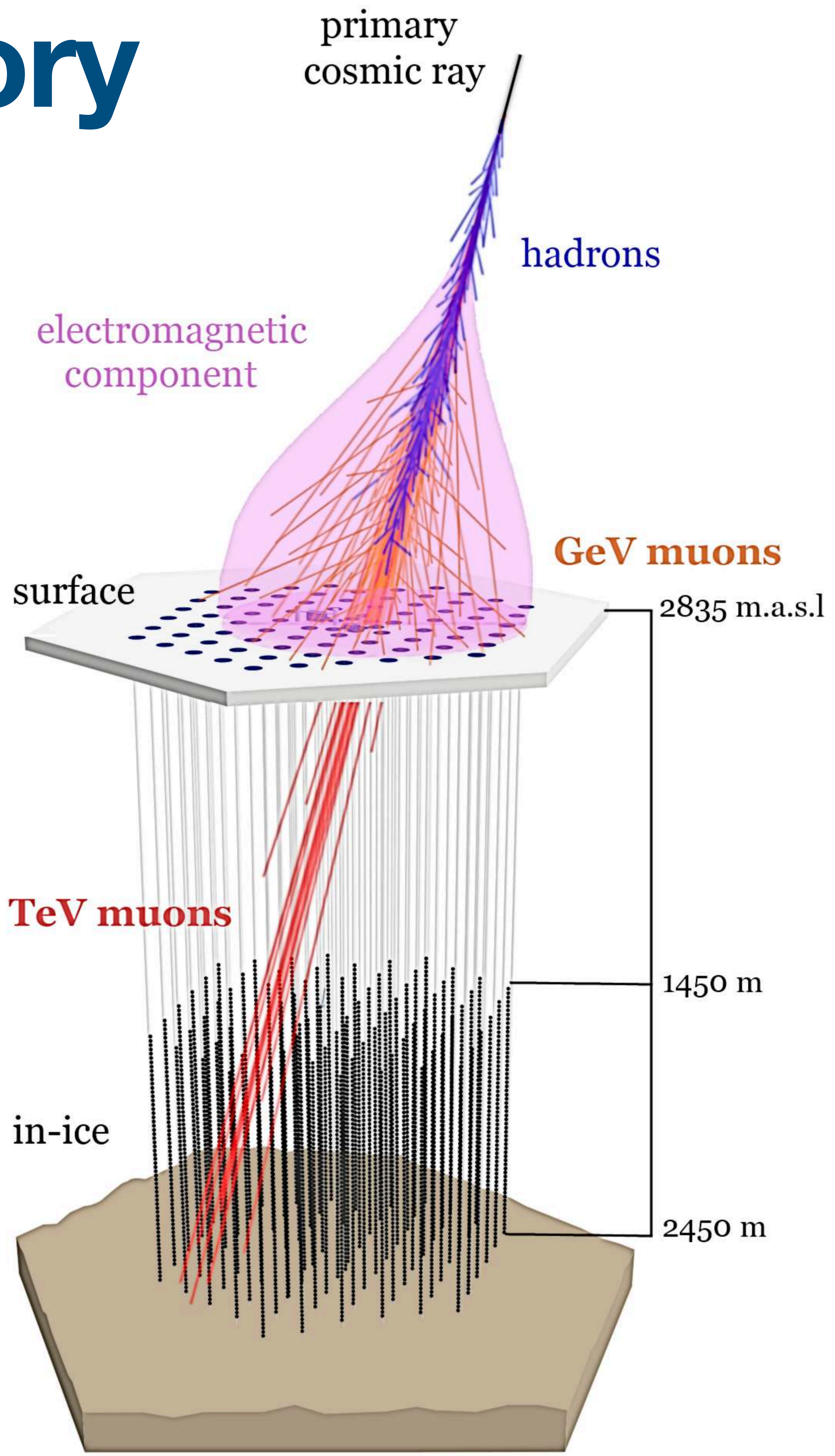
- The IceCube Neutrino Observatory
- (Selected) Cosmic Ray Measurements
  - Spectrum
  - Composition
  - Anisotropy
- Future Measurements at the South Pole



The IceCube Neutrino Observatory

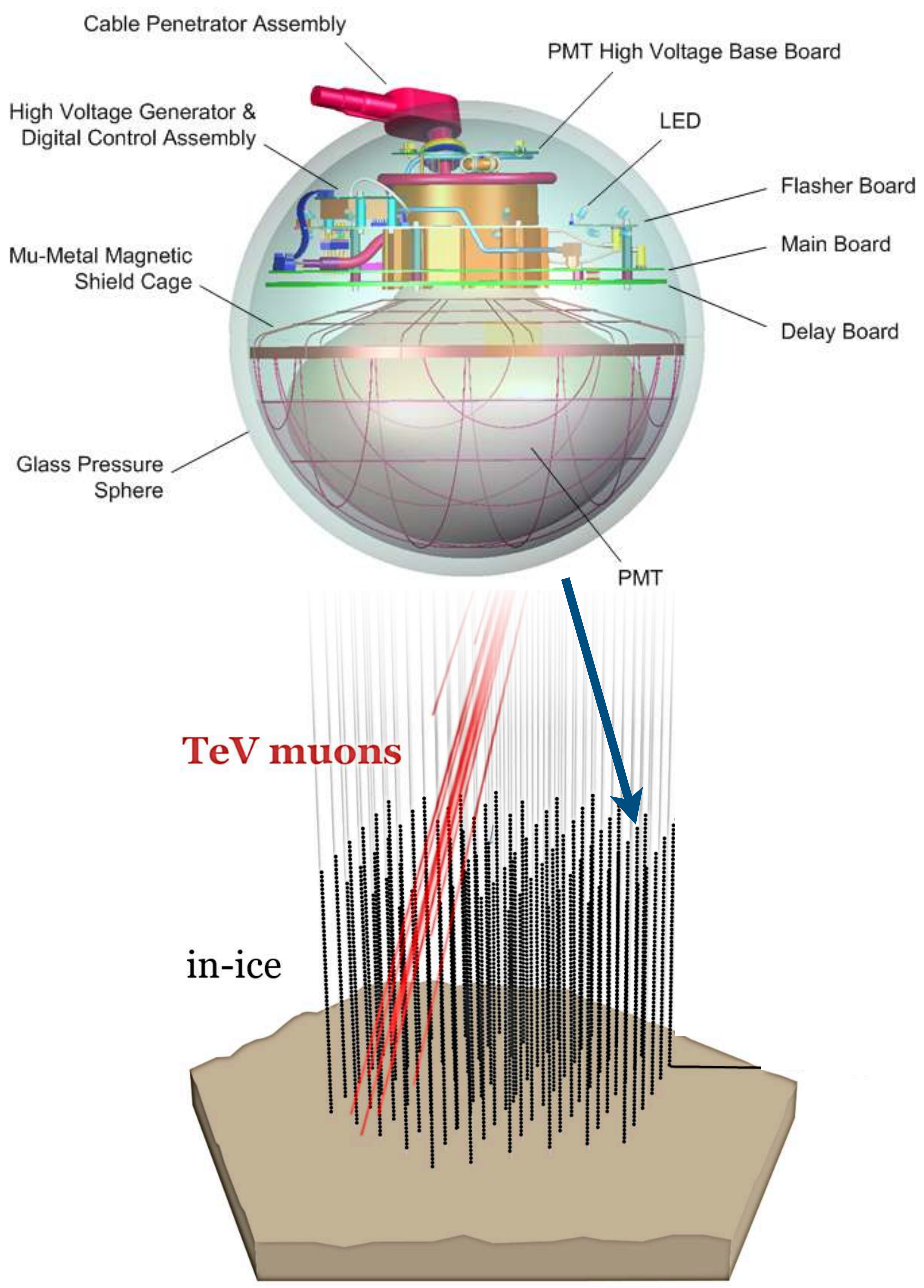
- Hybrid cubic-kilometer Cherenkov detector at South Pole
  - Surface detector at 2835 m.a.s.l (~690g/cm^2)
  - In-ice detector at depths between 1450 m and 2450 m





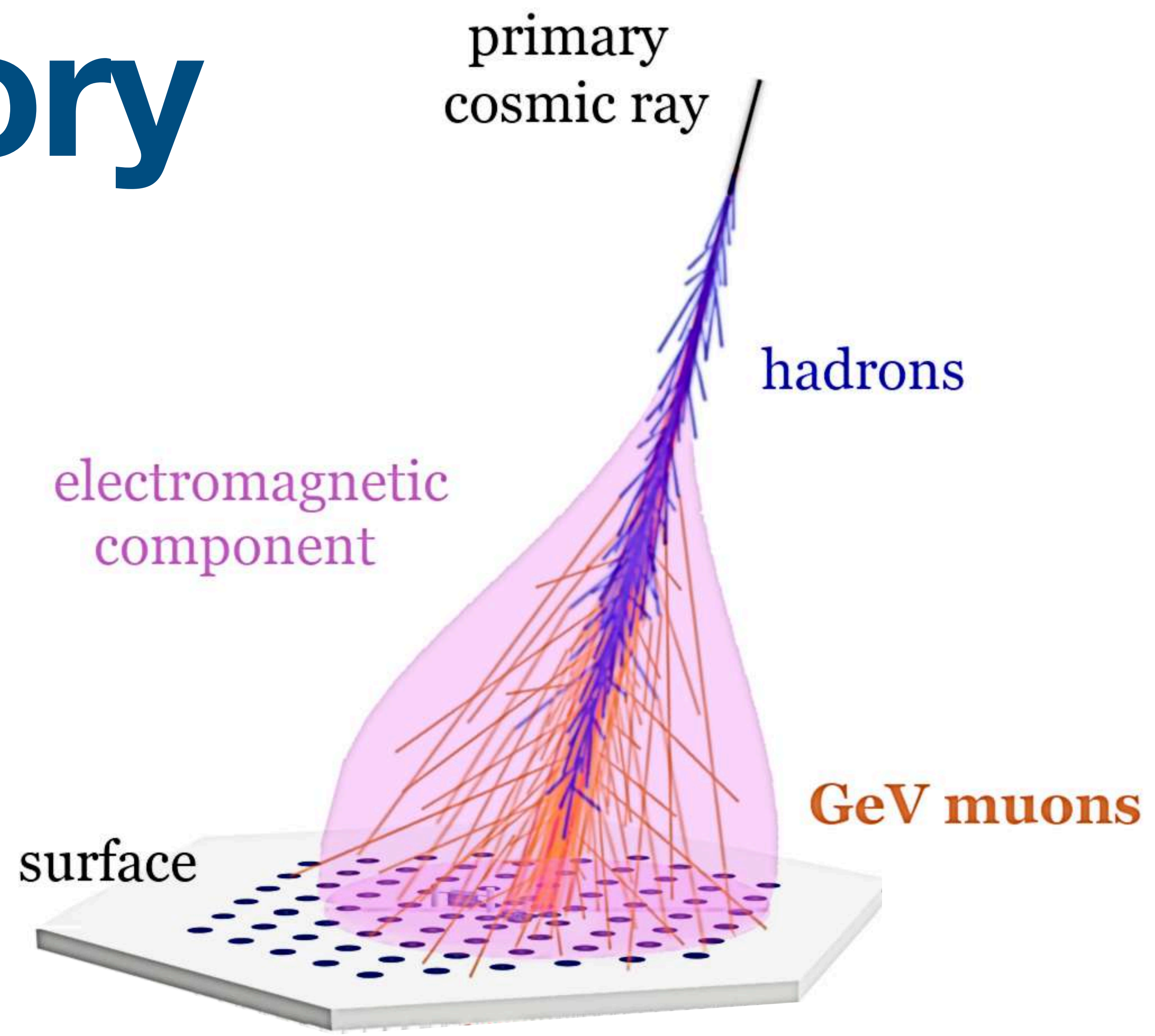
The IceCube Neutrino Observatory

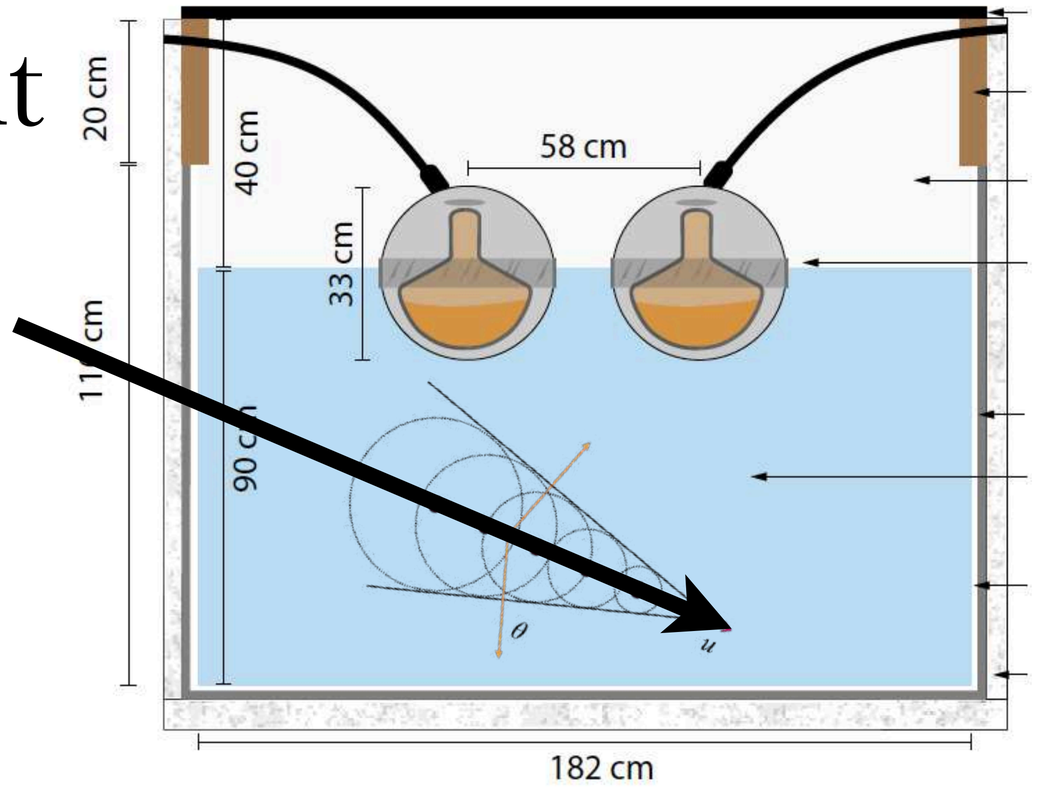
- <u>1 km^3 in-ice Cherenkov detector:</u>
  - 86 strings with grid spacing of ~125 m
  - 5100+ Digital Optical Modules (DOMs)
  - High-energy muons above ~500 GeV ("TeV muons")

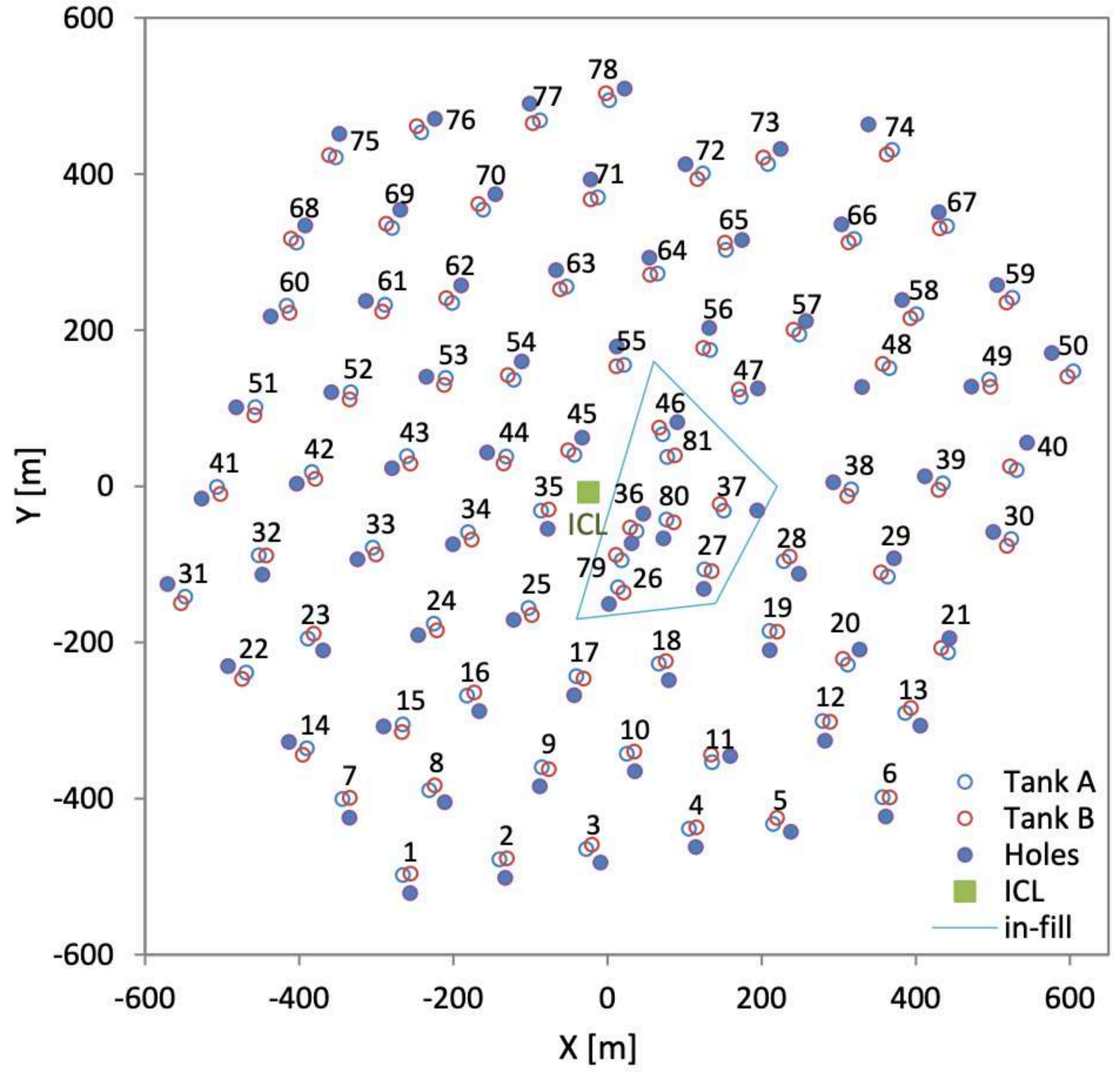


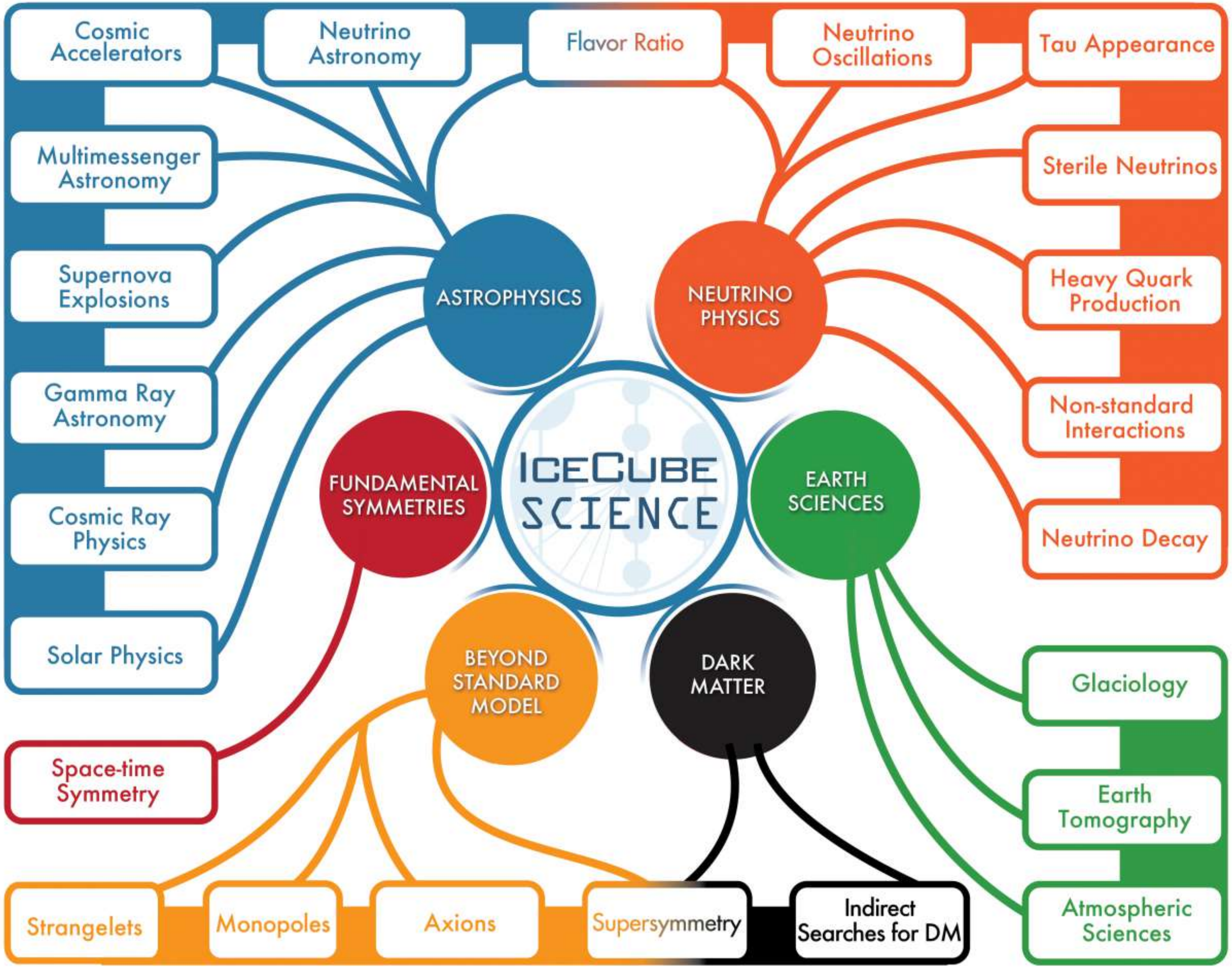
The IceCube Neutrino Observatory

- 1 km^3 in-ice Cherenkov detector:
  - 86 strings with grid spacing of ~125 m
  - 5100+ Digital Optical Modules (DOMs)
  - High-energy muons above ~500 GeV ("TeV muons")
- 1 km^2 surface detector, IceTop:
  - 81 stations with grid spacing of ~125 m
  - Each station: 2 tanks (each tank: 2 DOMs)
  - Electromagnetic air shower component
  - GeV muon content in air showers
  - Cosmic rays energies between 250 TeV and ~1 EeV





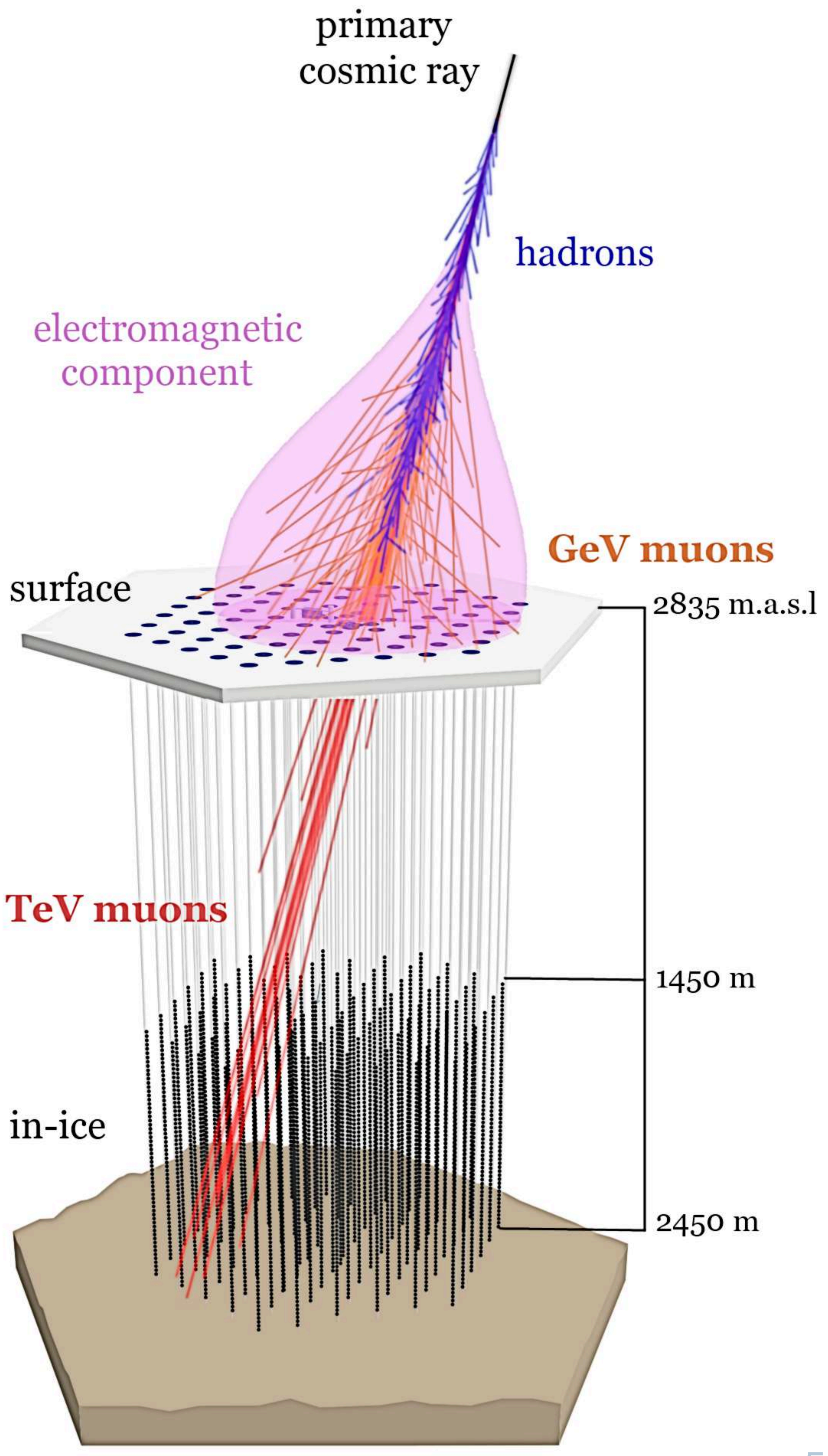




- See also talks by
  - Erin O'Sullivan
  - Francis Halzen
  - Naoko Kurahashi
  - Marcos Santander
  - Carlos Argüelles
  - …others…
  - + posters
- This talk:
  - Cosmic Rays!

Cosmic Ray Measurements

- Hybrid cubic-kilometer particle detector at South Pole
- <u>Surface detector:</u>
  - Electromagnetic air shower component
  - Low-energy (~GeV) muon content
- <u>In-ice detector:</u>
  - High-energy (~TeV) muon content
- Coincident cosmic ray measurements!
- Ideal facility to study cosmic rays!



Cosmic Ray Spectrum

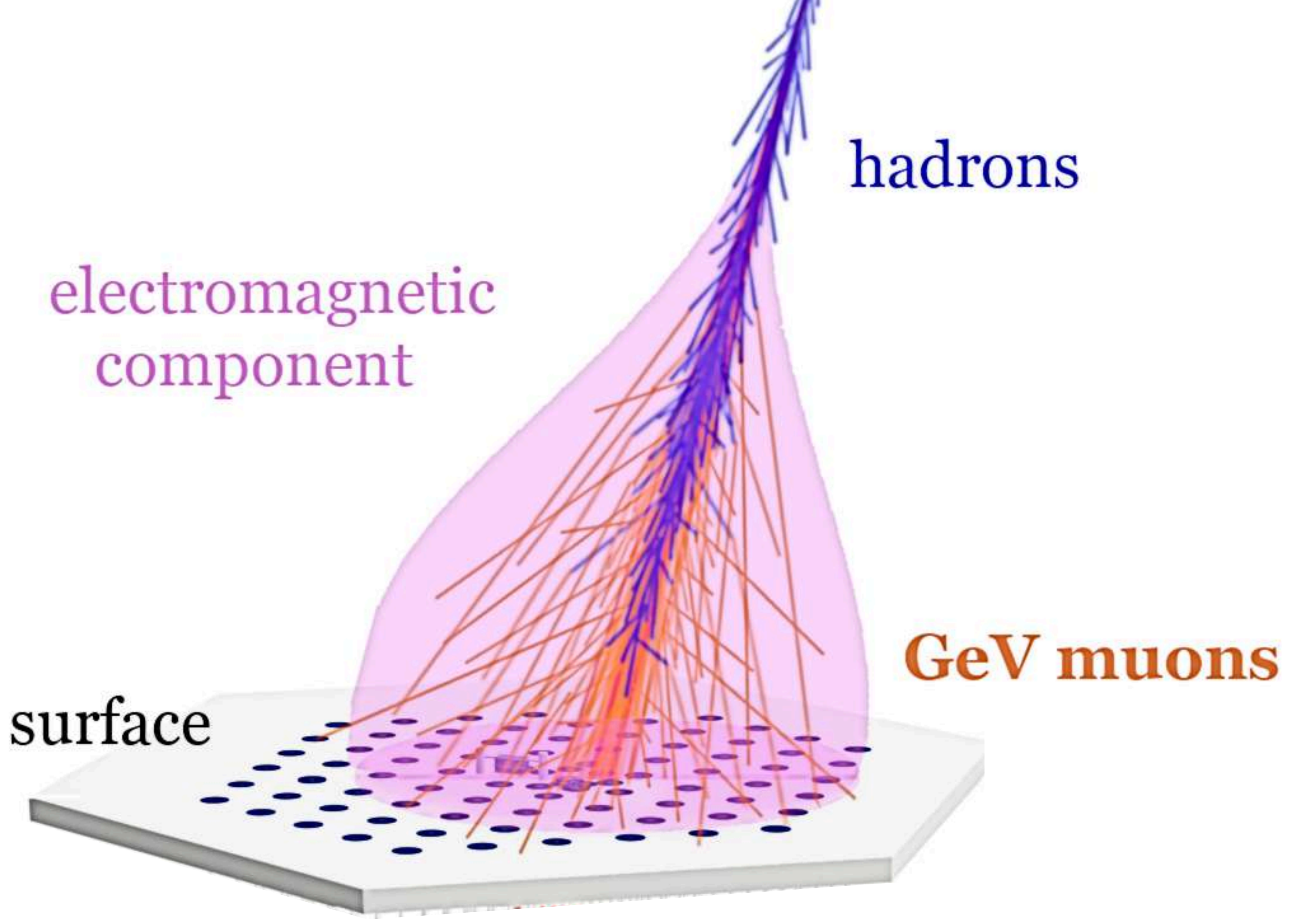
credit: IceCube/NSF

Cosmic Ray Spectrum

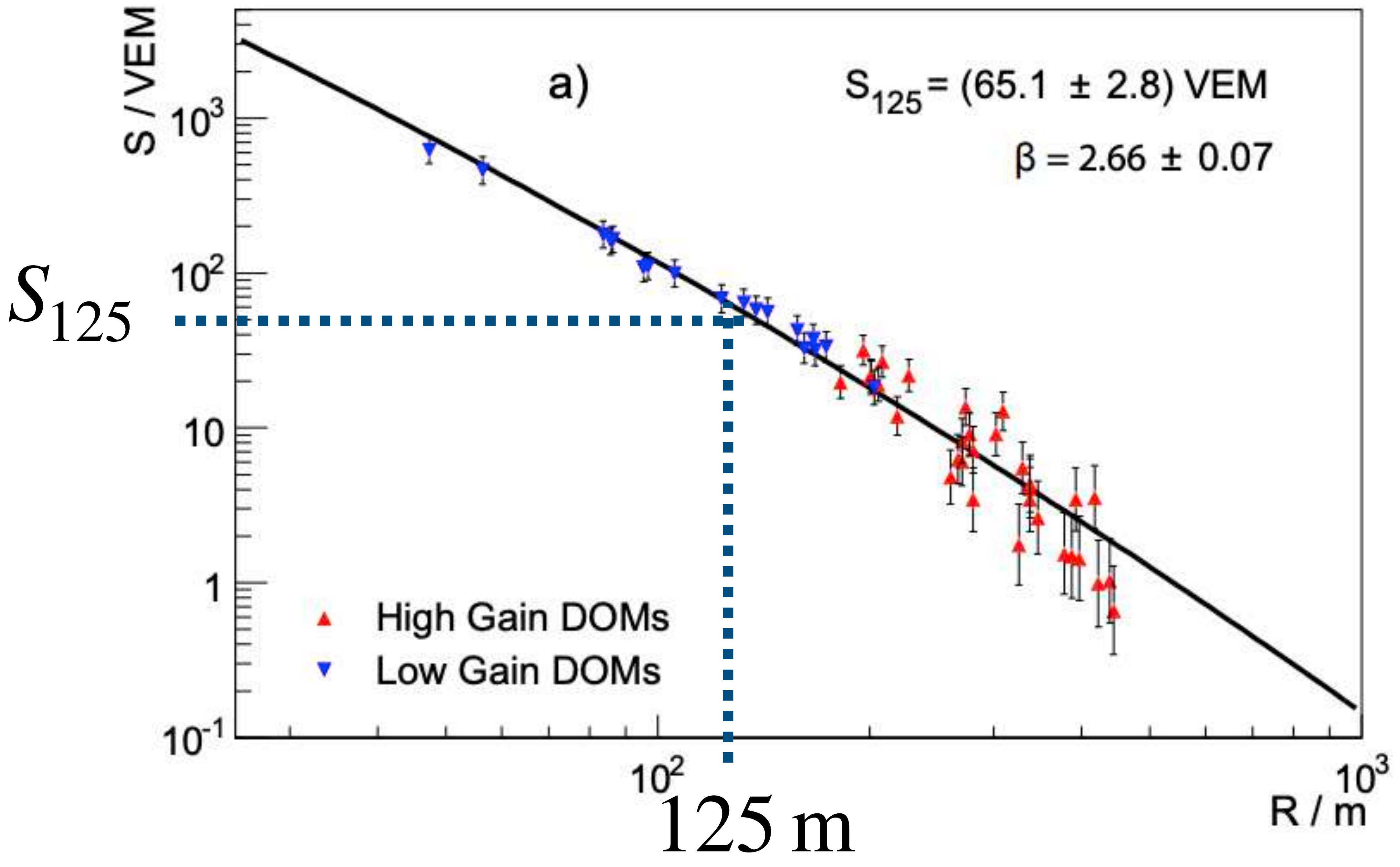
- Cosmic ray energy determined from surface signals (only)
- Lateral Distribution Function (LDF)

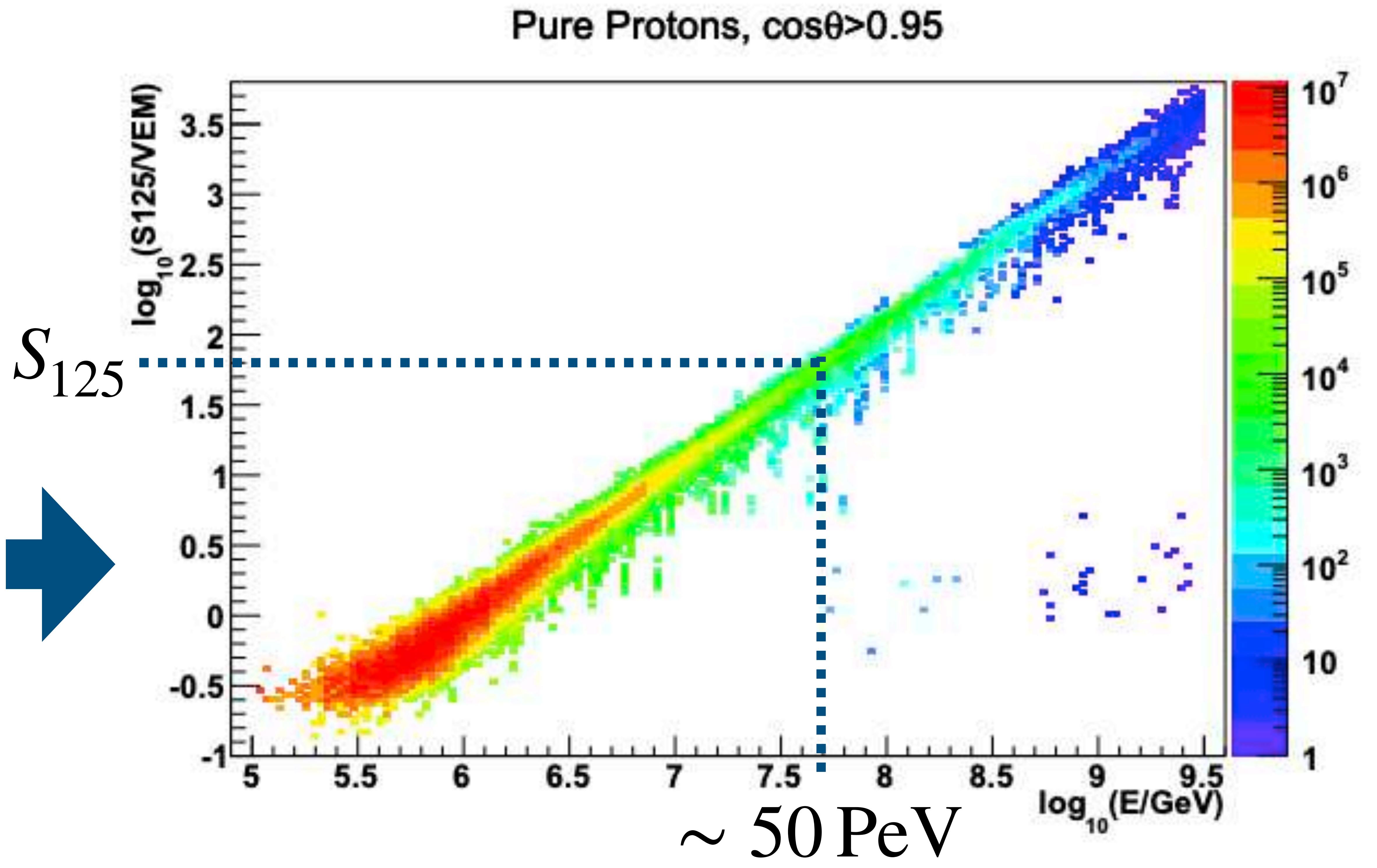
$$S(r) = S_{125} \cdot \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa\cdot\log_{10}(1/125\,\mathrm{m})}$$

- Shower size S_{125} (air shower energy), slope parameter β



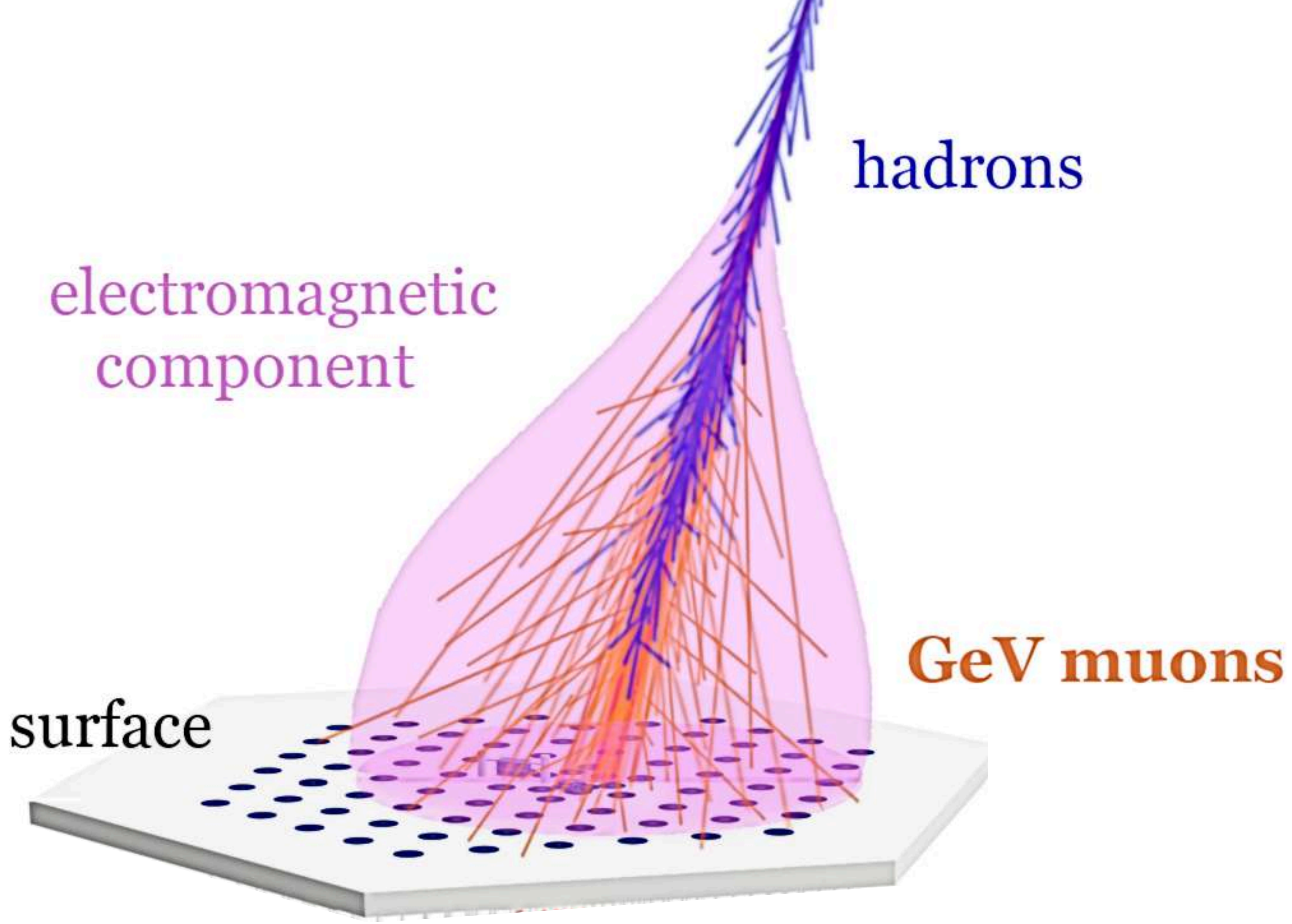
[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]

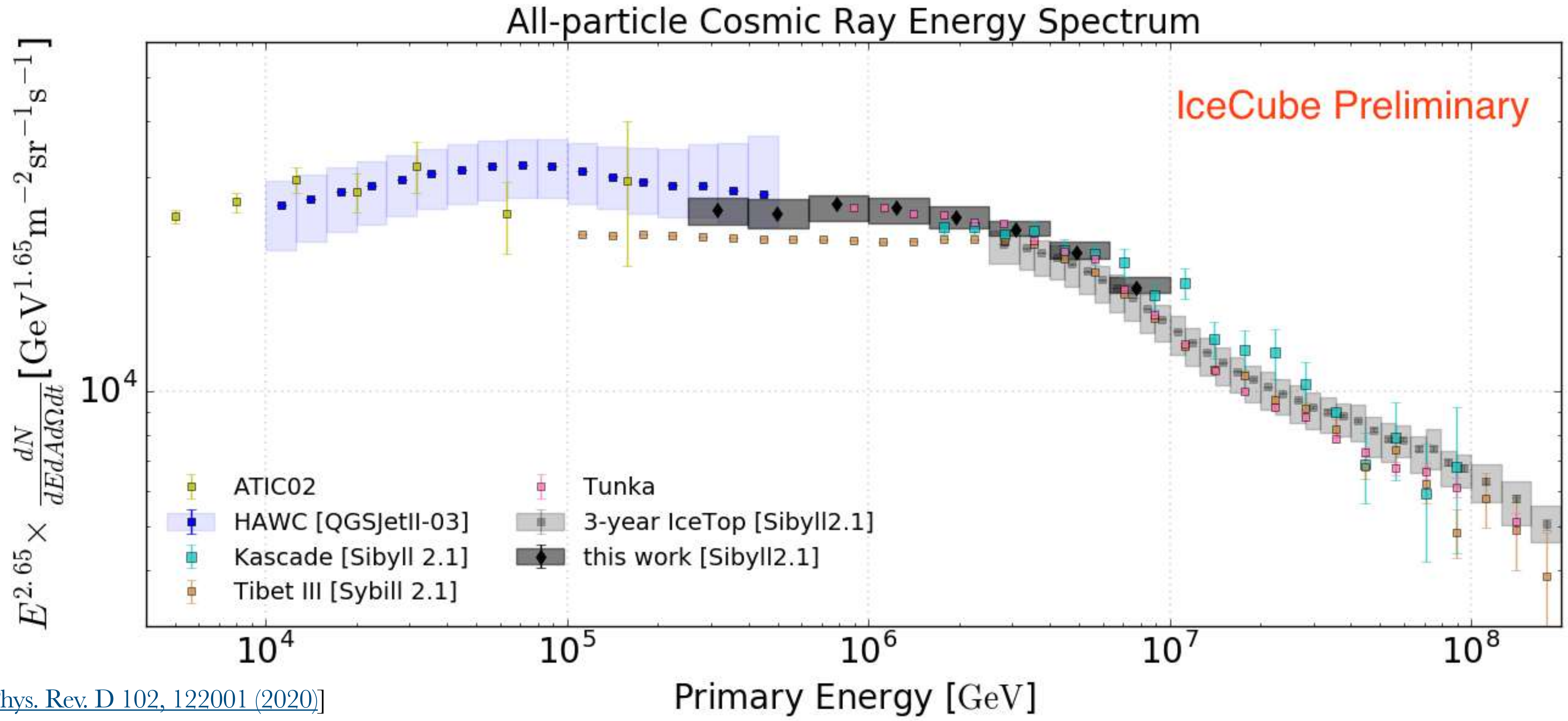




Cosmic Ray Spectrum

- Reconstruction of cosmic ray energy based on LDF fit between ~1 PeV and ~1 EeV (3 years of data)
- Machine learning techniques to extend spectrum down to 250 TeV (1 year of data)

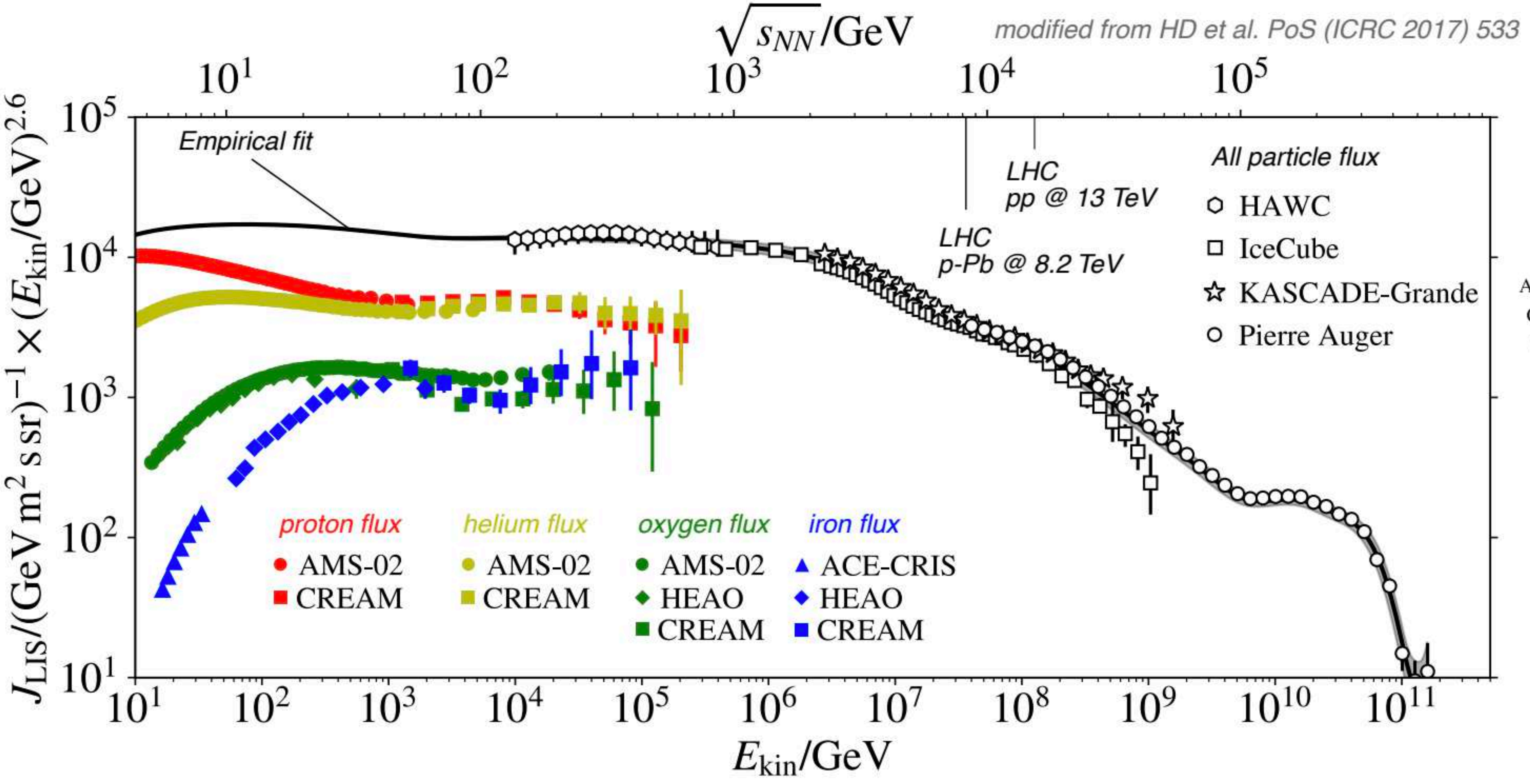


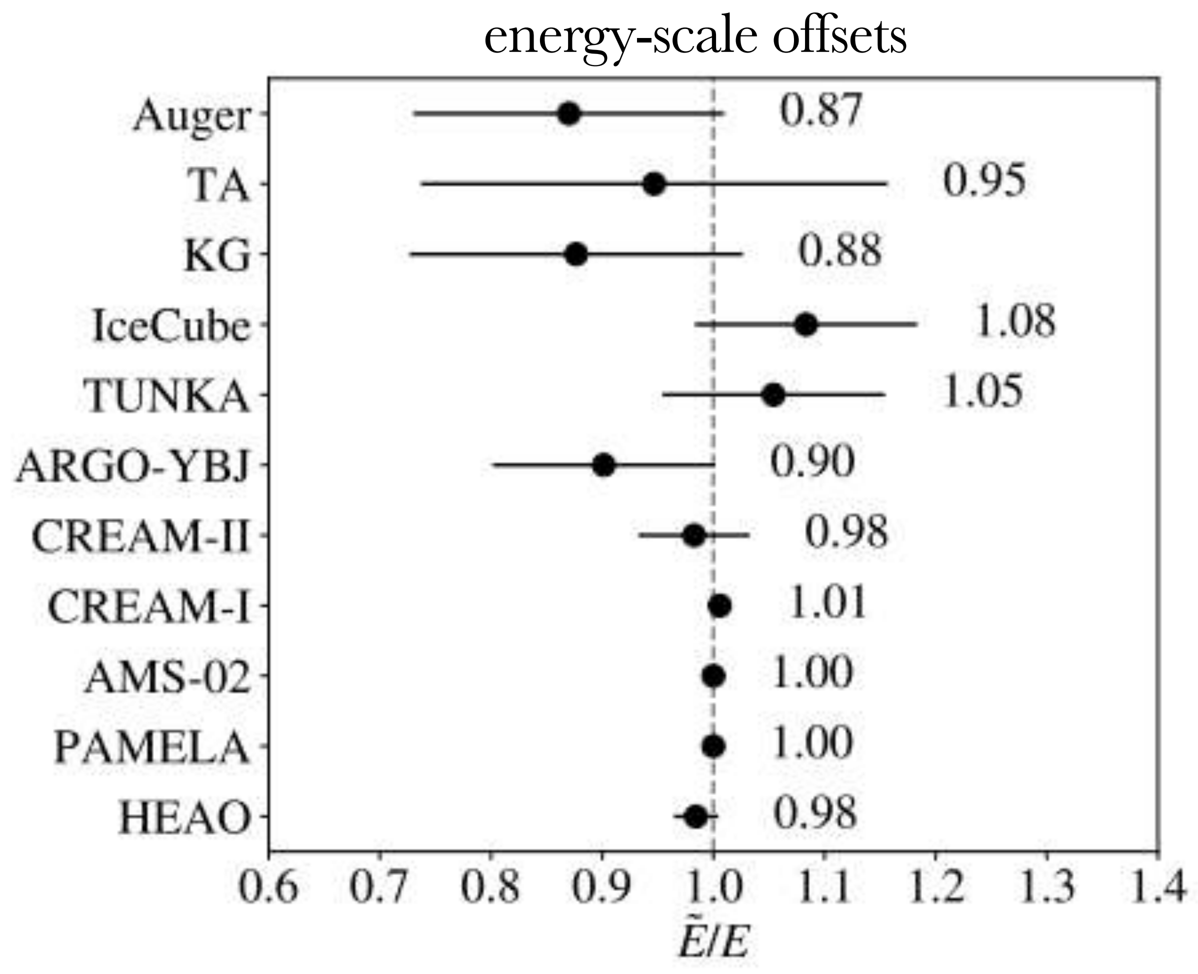


[IceCube Collaboration, Phys. Rev. D 102, 122001 (2020)]
[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]

Cosmic Ray Spectrum

- Comparison with other measurements (GSF 2017)





modified from [H. Dembinski et al., PoS(ICRC2017)533]

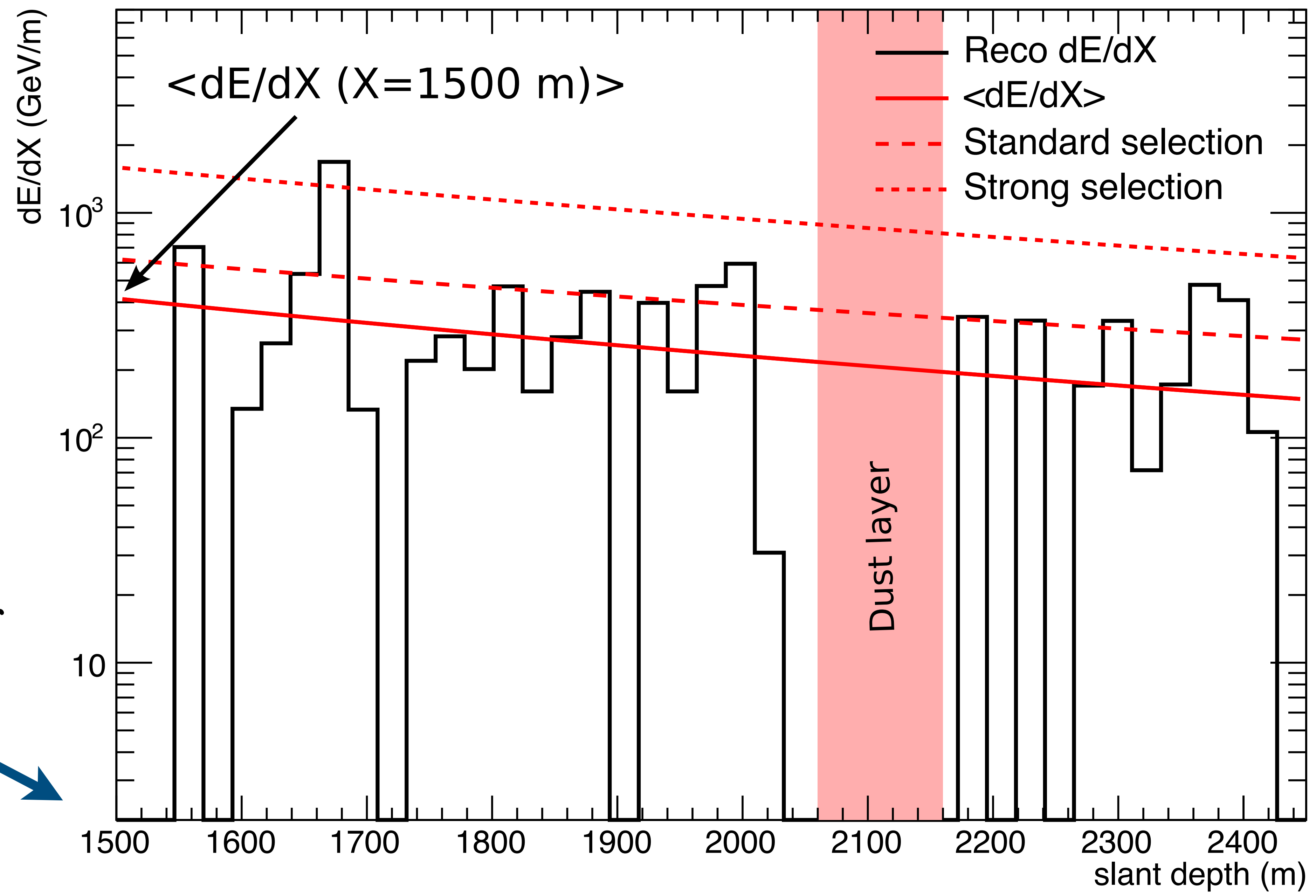
Cosmic Ray Composition

credit: IceCube/NSF

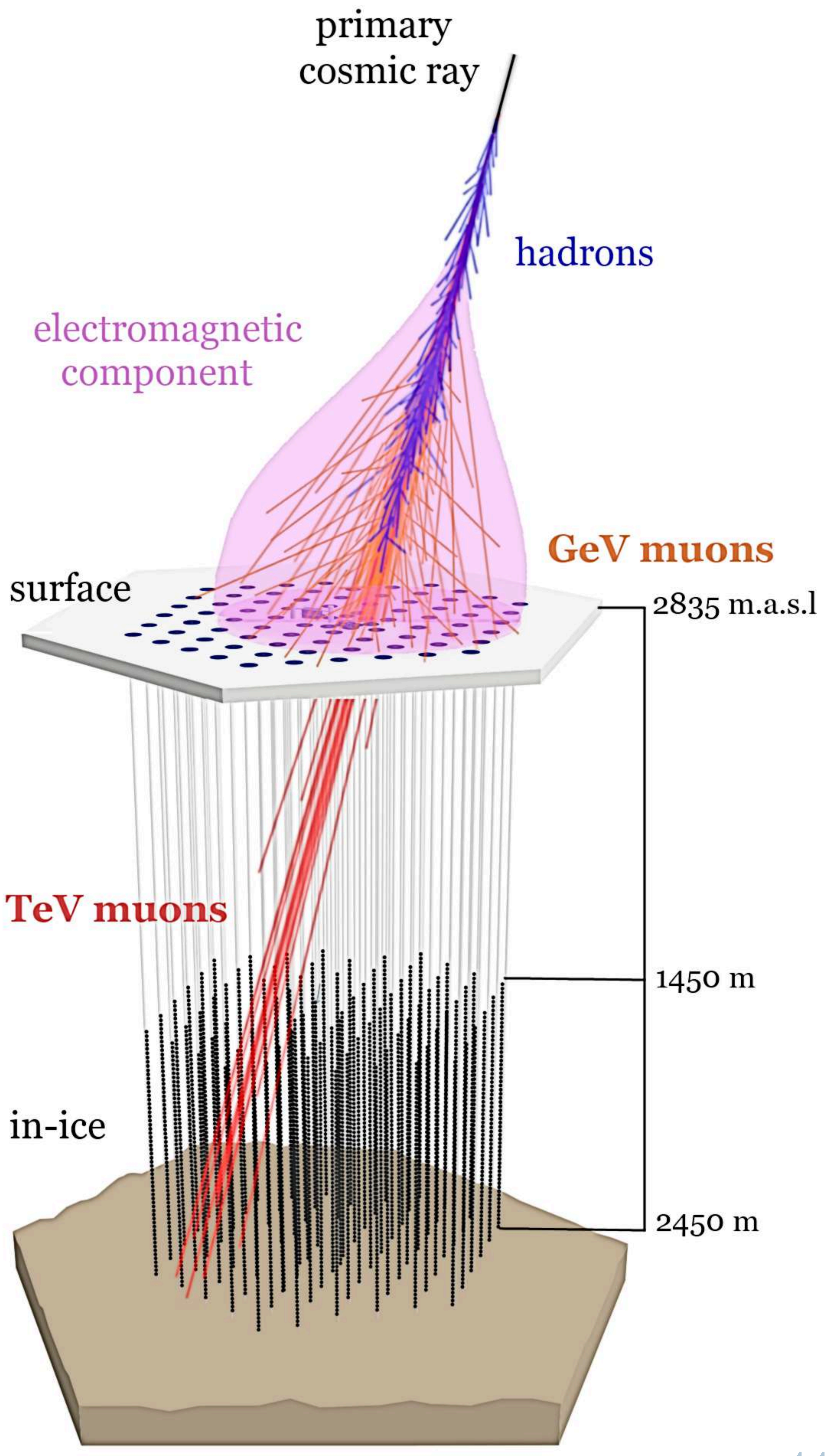
Cosmic Ray Mass Composition

- The number of muons produces in air showers. depends on the mass of the primary cosmic ray
- Using IceTop and the in-ice detector IceCube can measure the cosmic ray energy and mass composition!
- TeV muon number estimated from the fluctuations of the deposited light yield

top of the in-ice detector

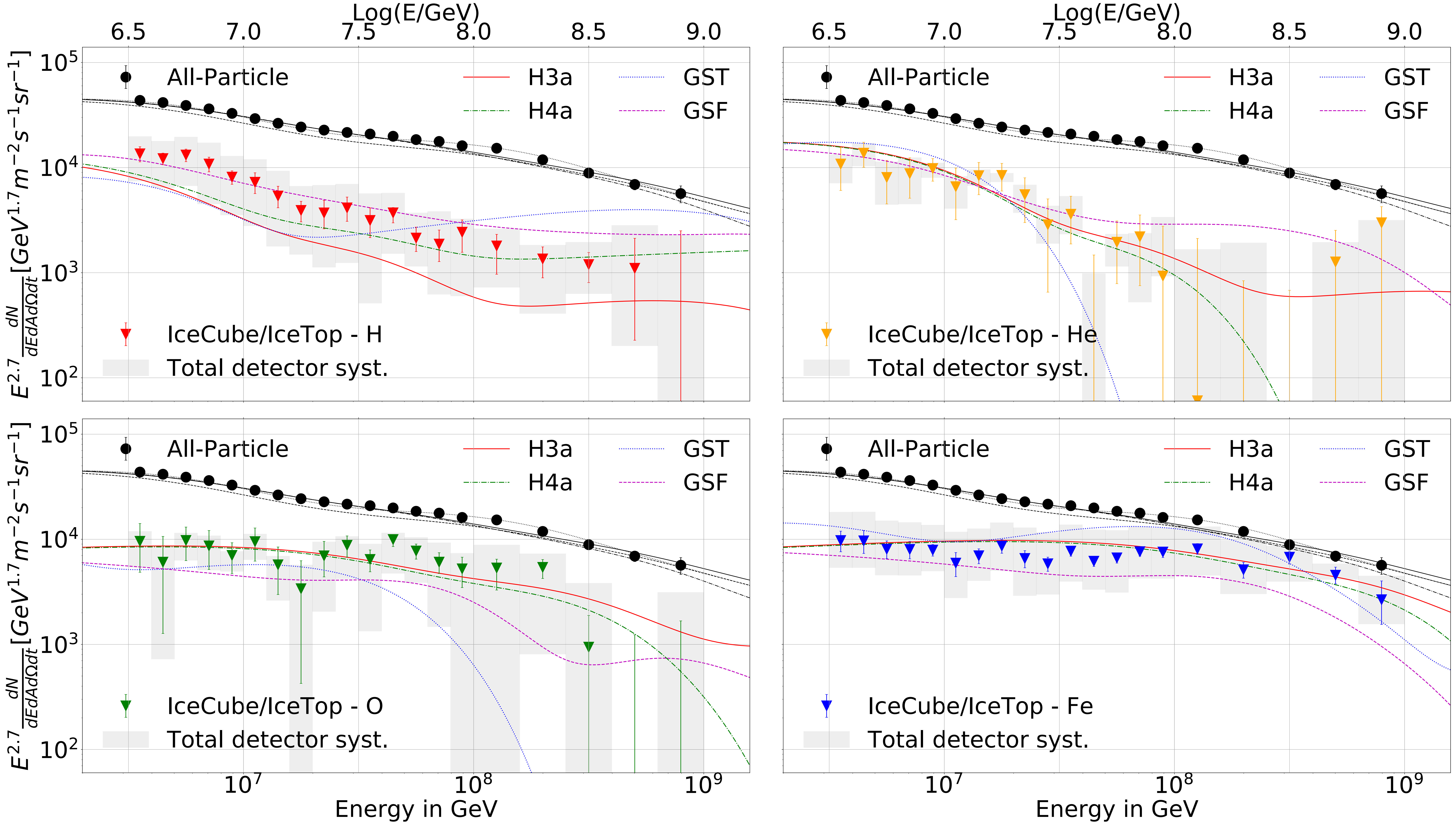


bottom of the in-ice detector



Cosmic Ray Mass Composition

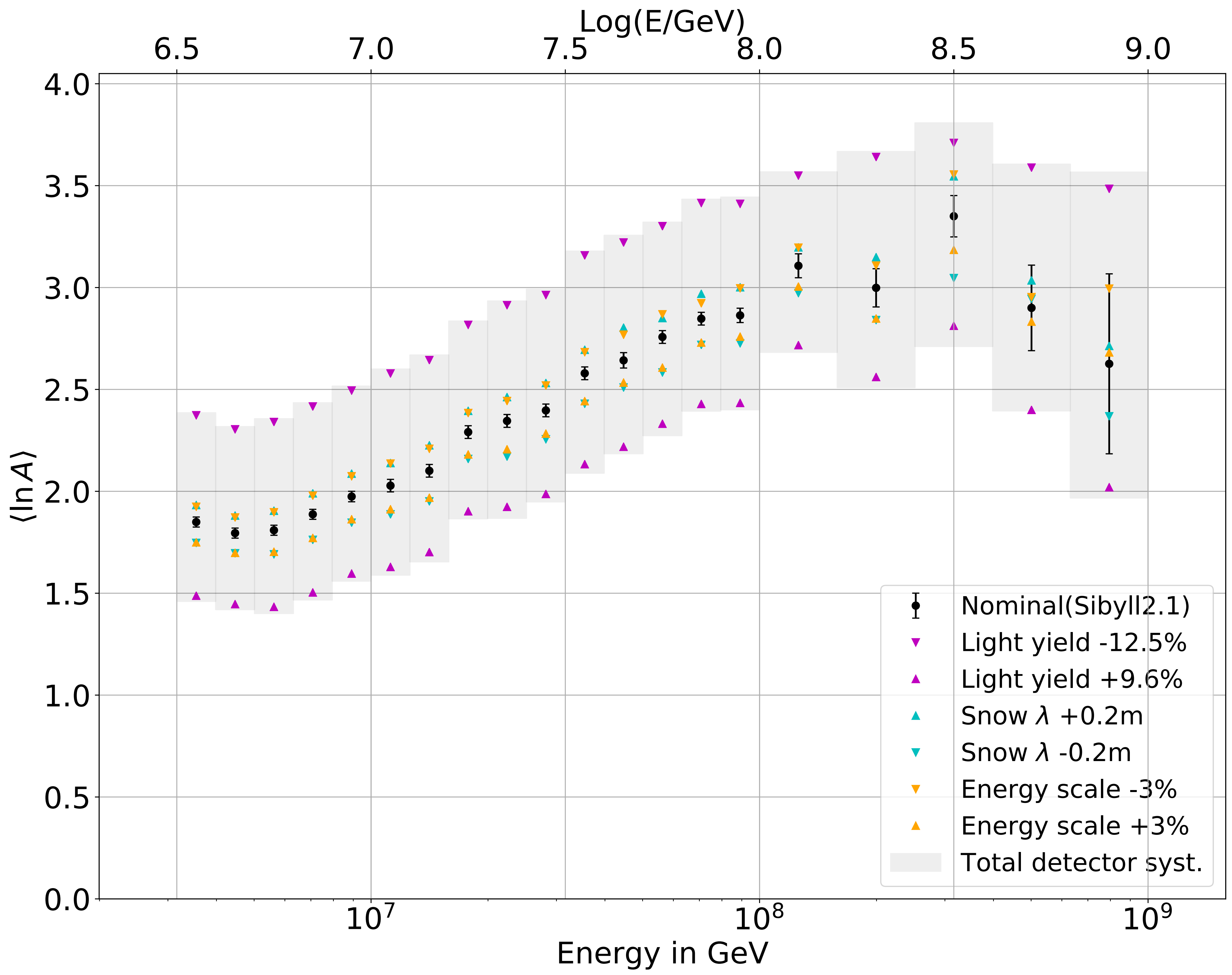
- Machine learning analysis based on neutral network and template fits (3 years of data)



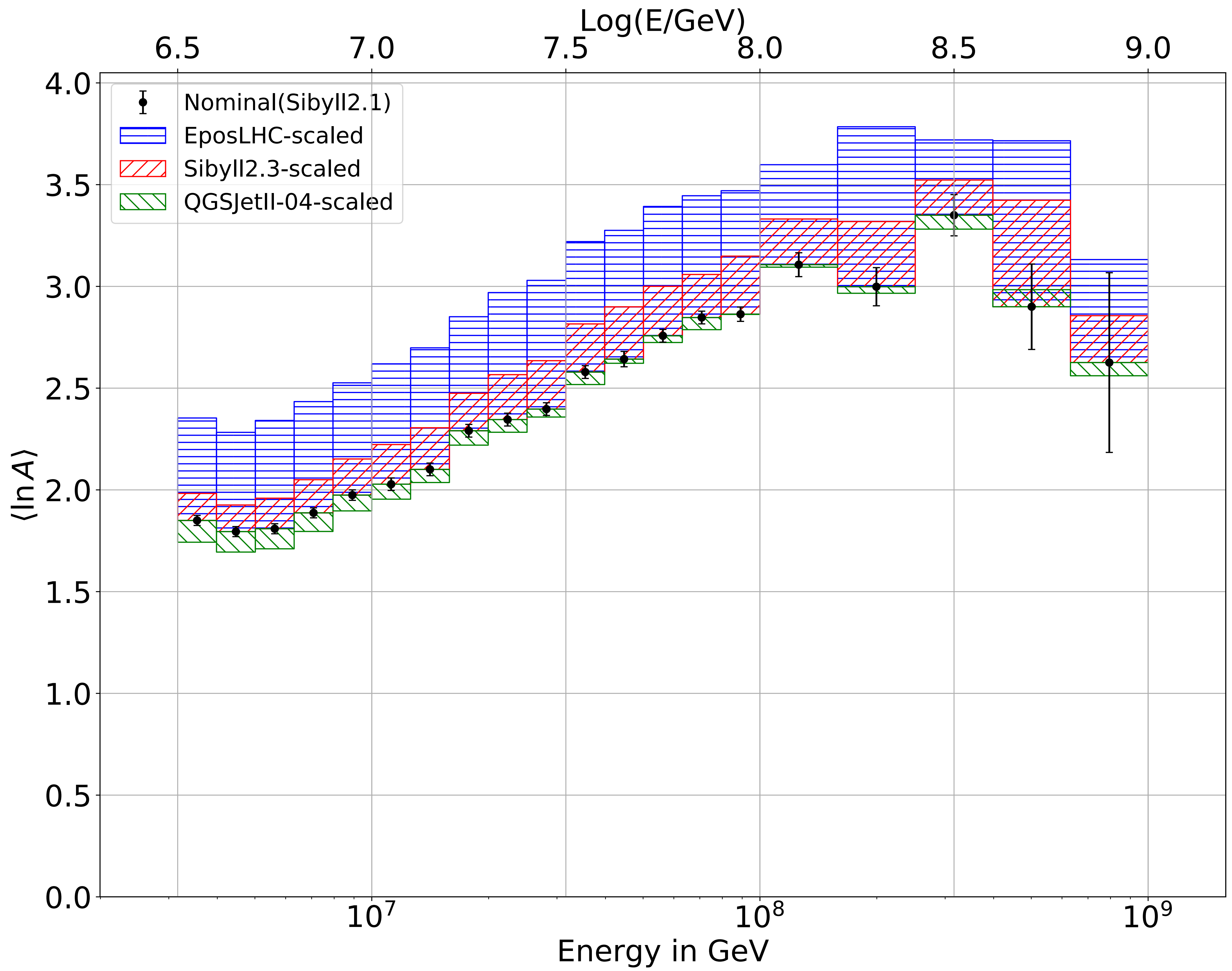
[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]

Cosmic Ray Mass Composition

- ⟨ln A⟩ with syst. errors (except hadr. model):



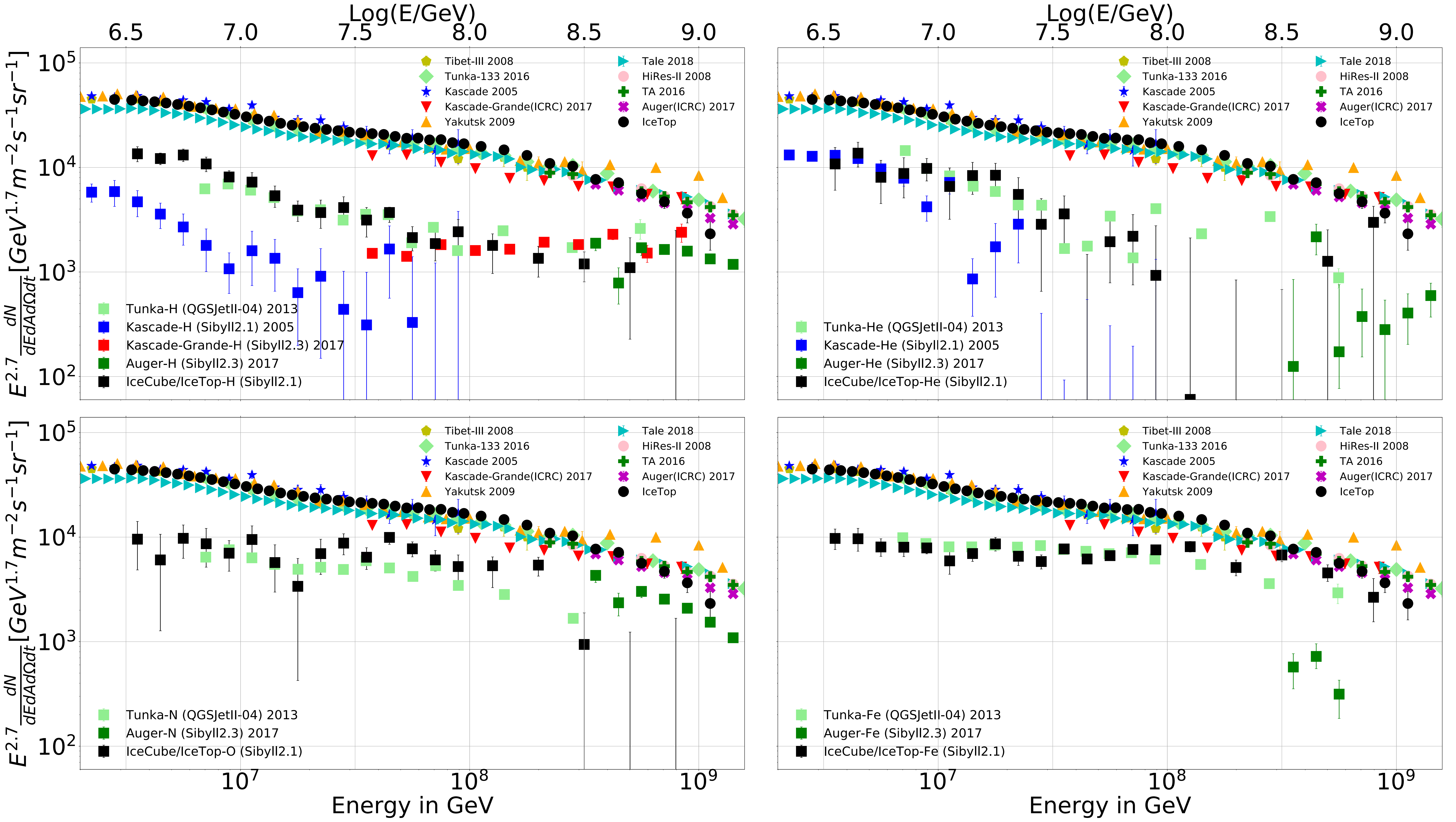
- Hadr. model dependence of ⟨ln A⟩:



- In-ice light yield and hadronic interaction models are dominating systematics

[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]

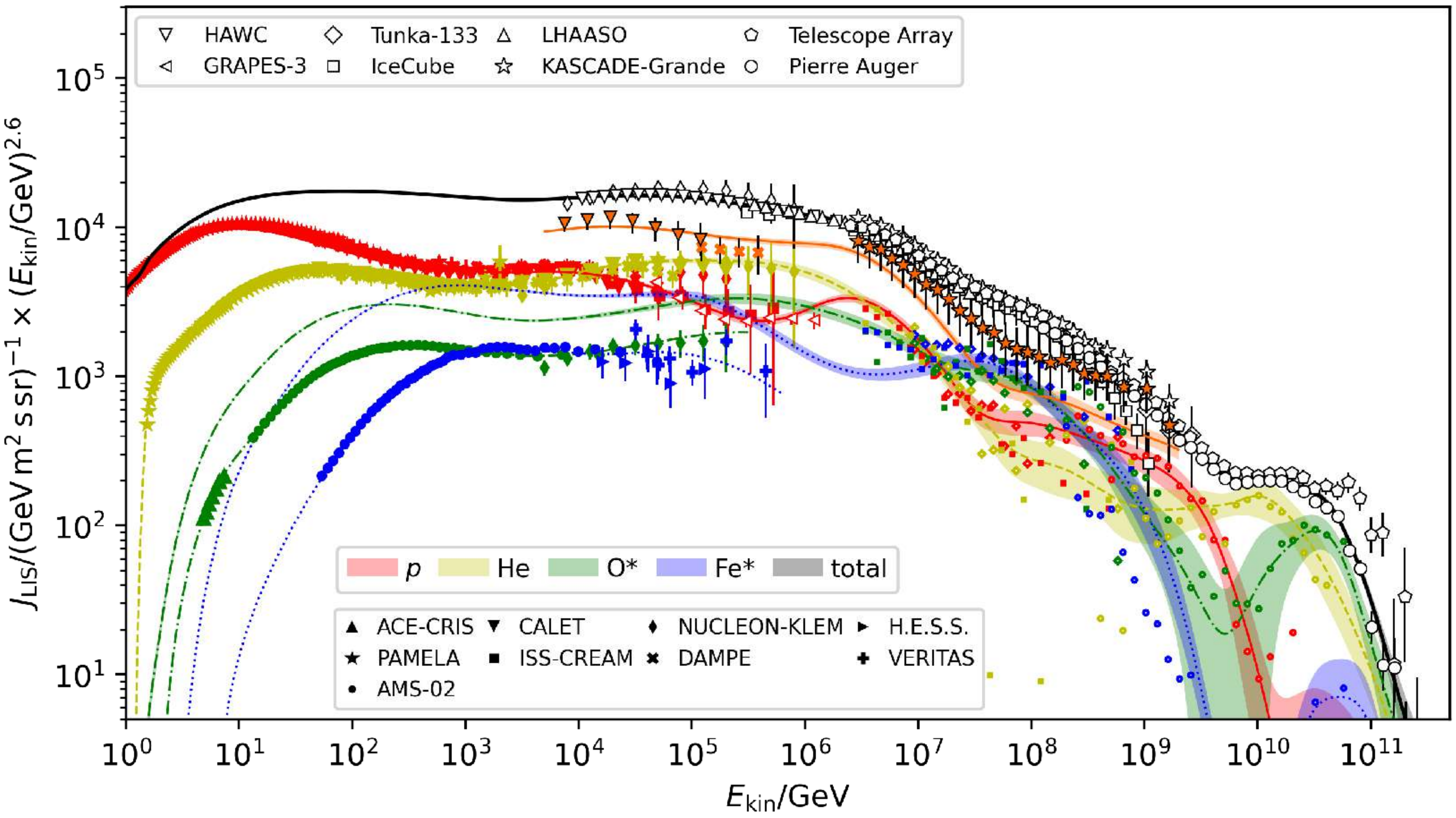
Cosmic Ray Mass Composition

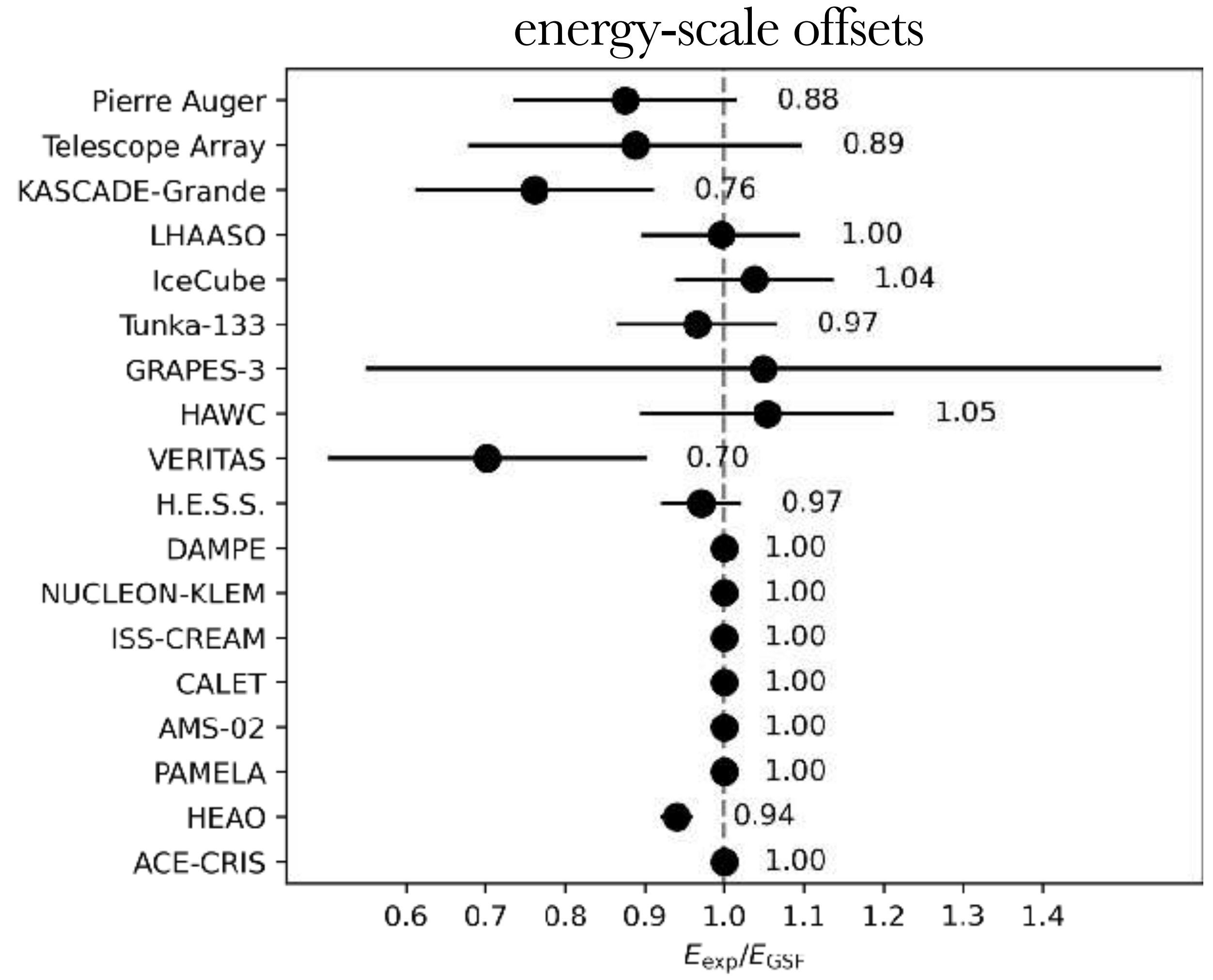


[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]

Cosmic Ray Mass Composition

- Comparison with other measurements (GSF 2024)





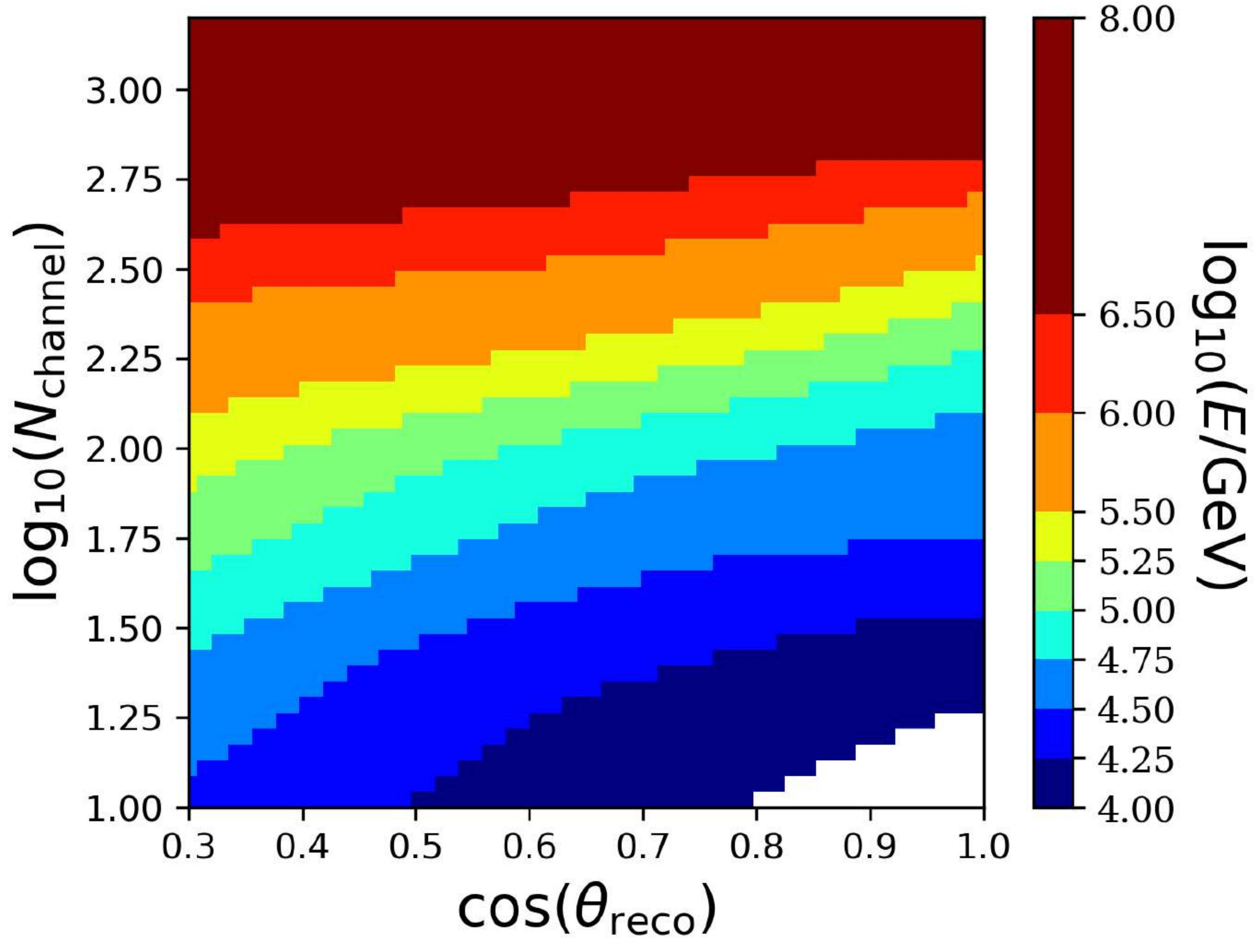
modified from [H. Dembinski et al., PoS(ICRC2017)533], as shown at UHECR2024

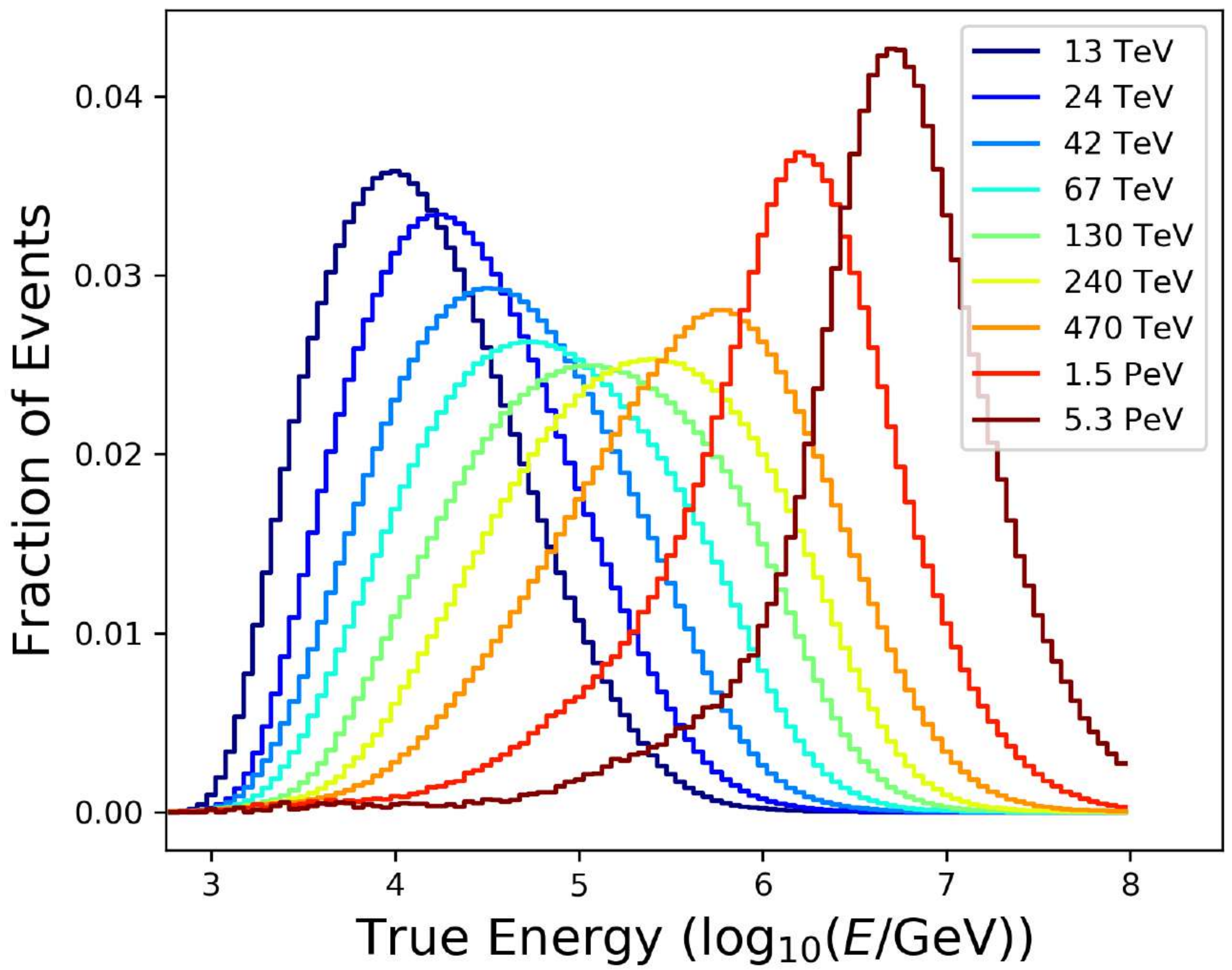
Cosmic Ray Anisotropy

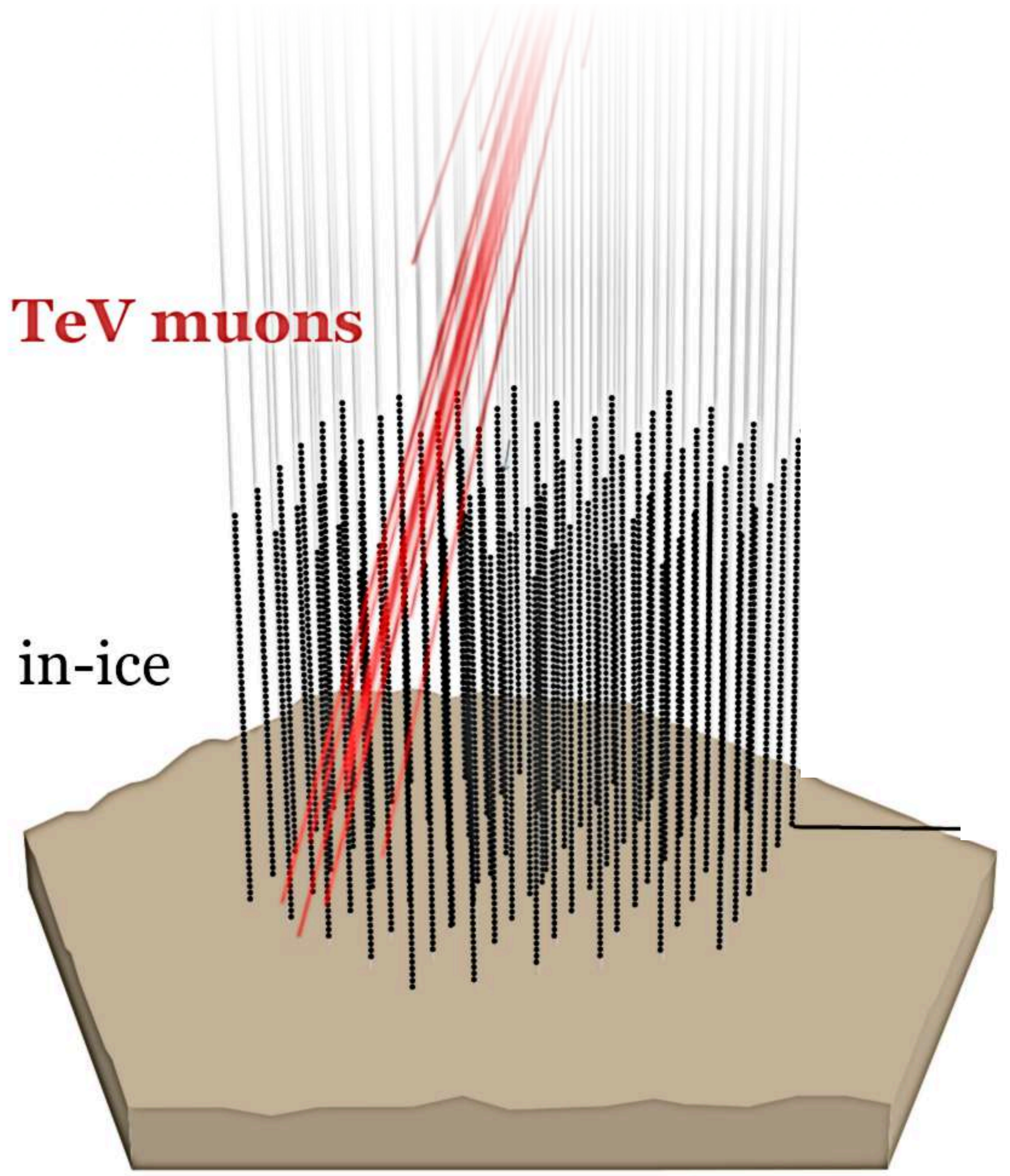
credit: IceCube/NSF

Cosmic Ray Anisotropy

- Arrival direction of cosmic rays measured with muons in the in-ice detector
- 12 years of data (792 billion events!), covers more than full solar cycle
- Simple energy estimator based on number of in-ice signals (>10 TeV)
- Paper submitted to ApJ (last week)!



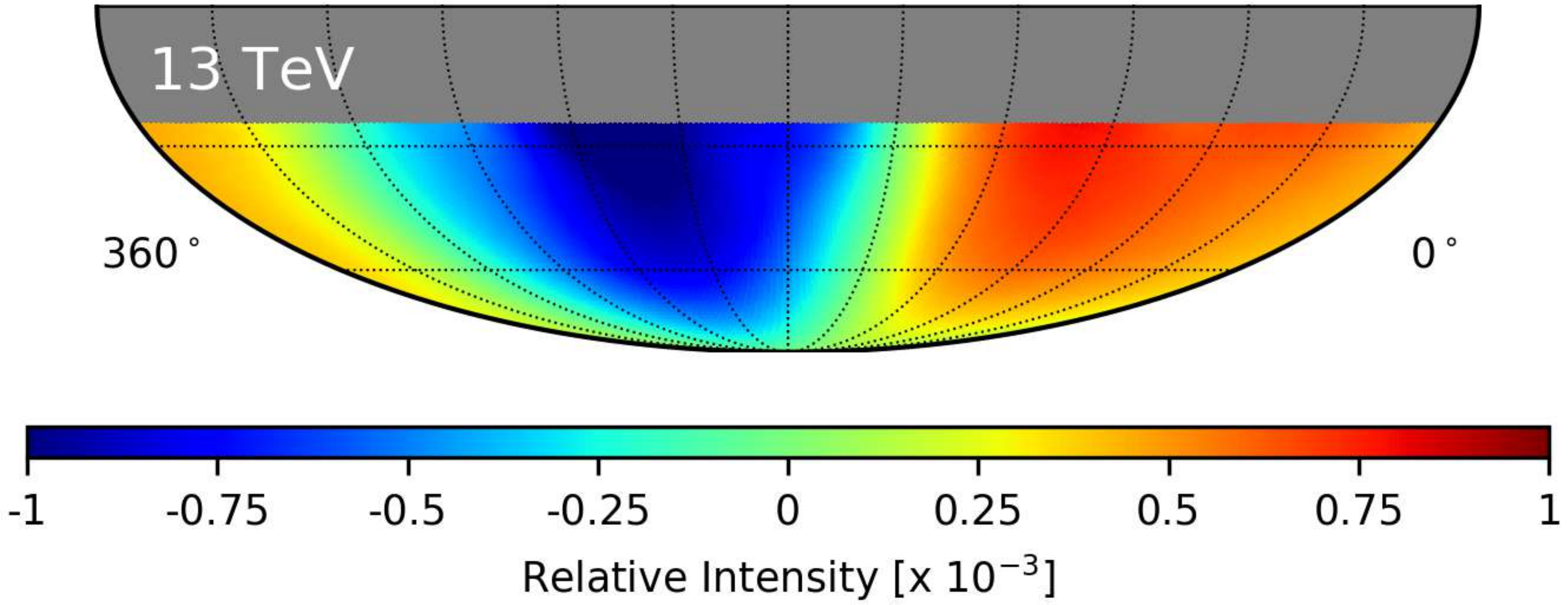


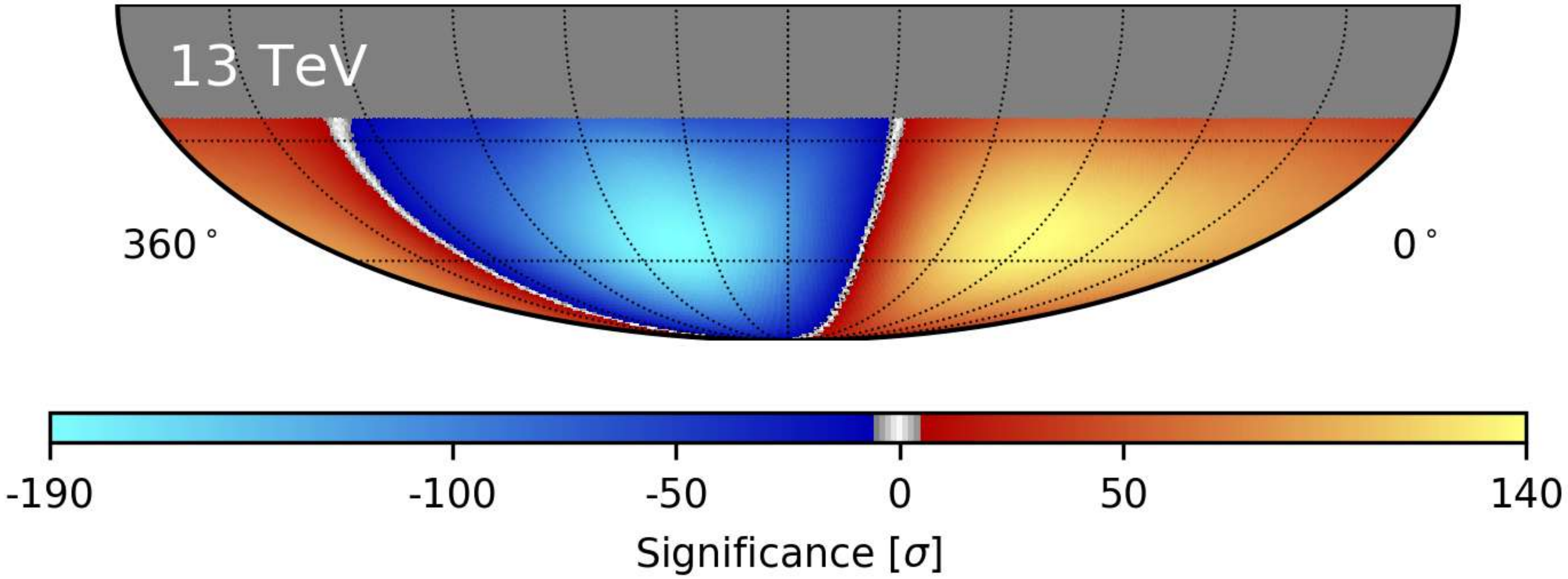


paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

- Median energy: 13 TeV

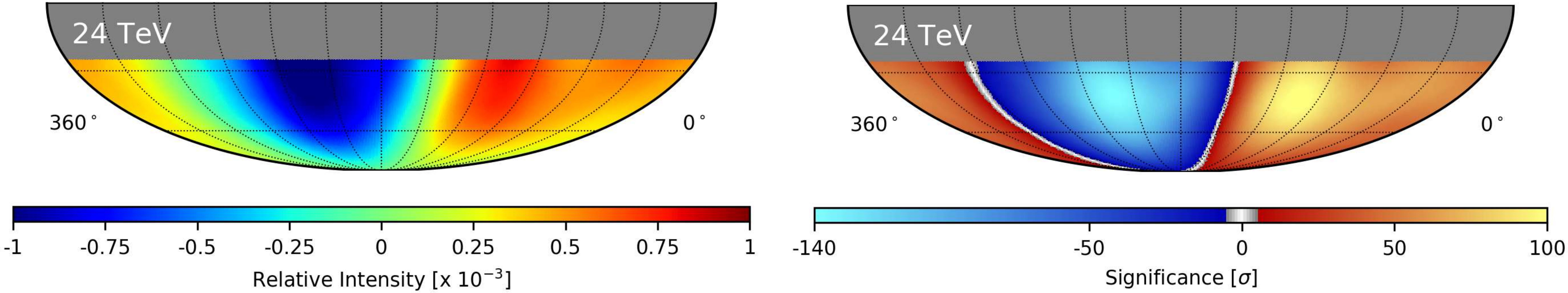




paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

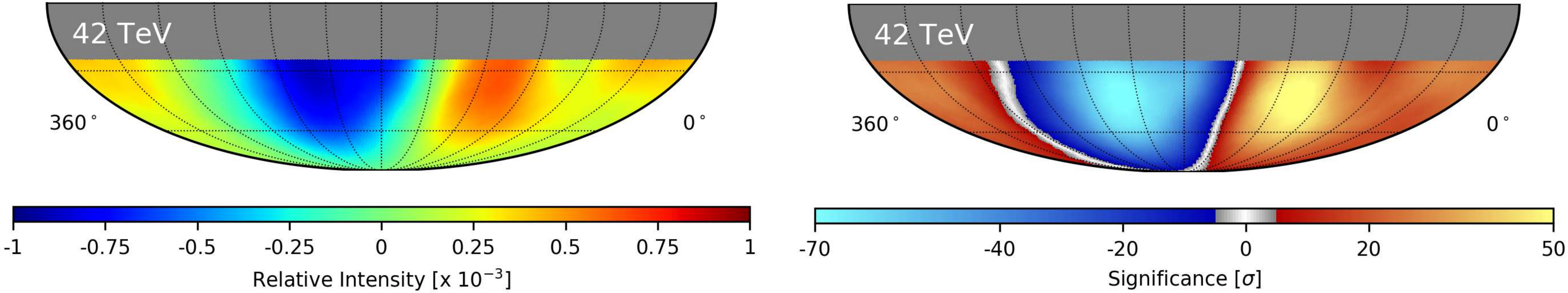
- Median energy: 24 TeV



paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

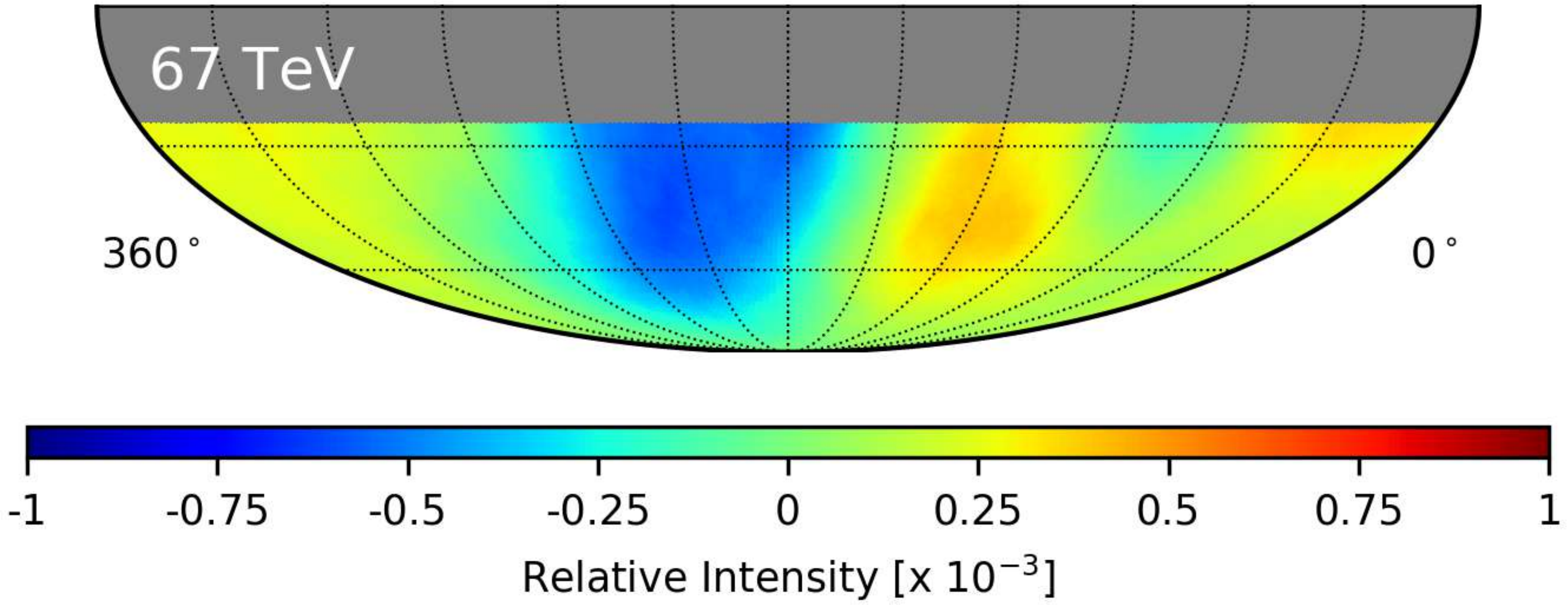
- Median energy: 42 TeV

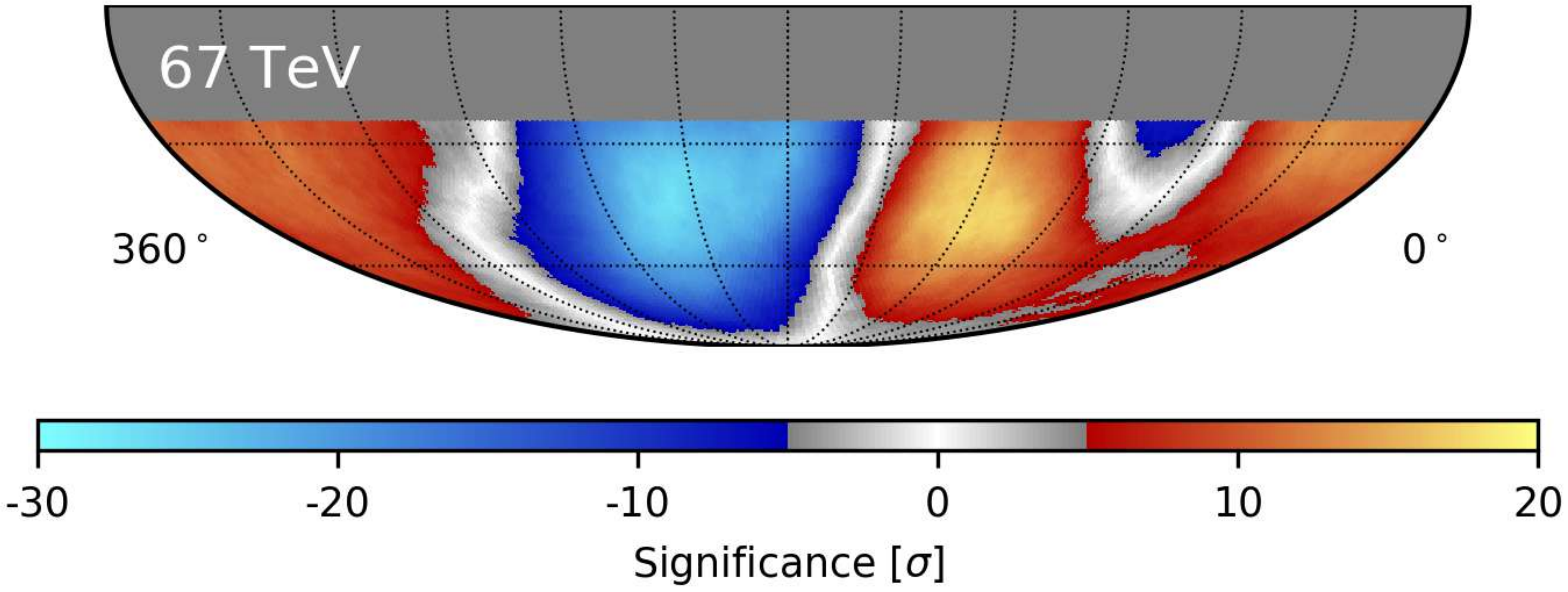


paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

- Median energy: 67 TeV

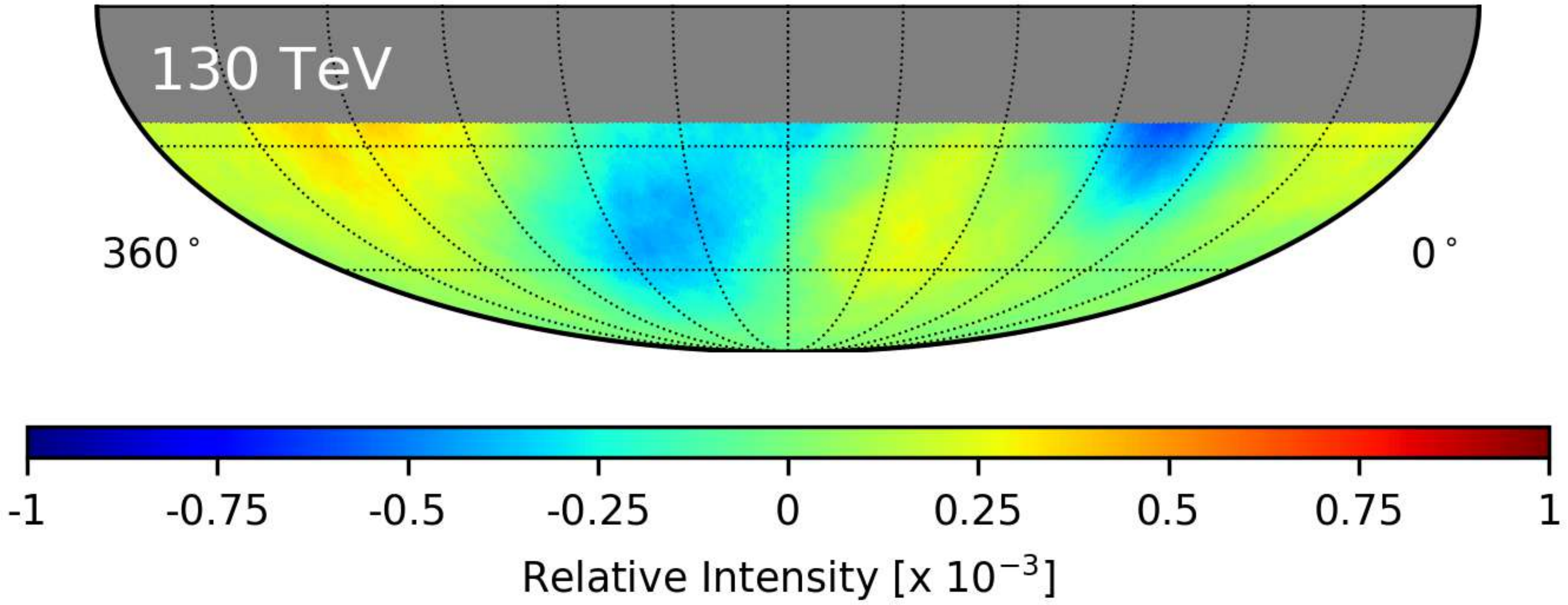


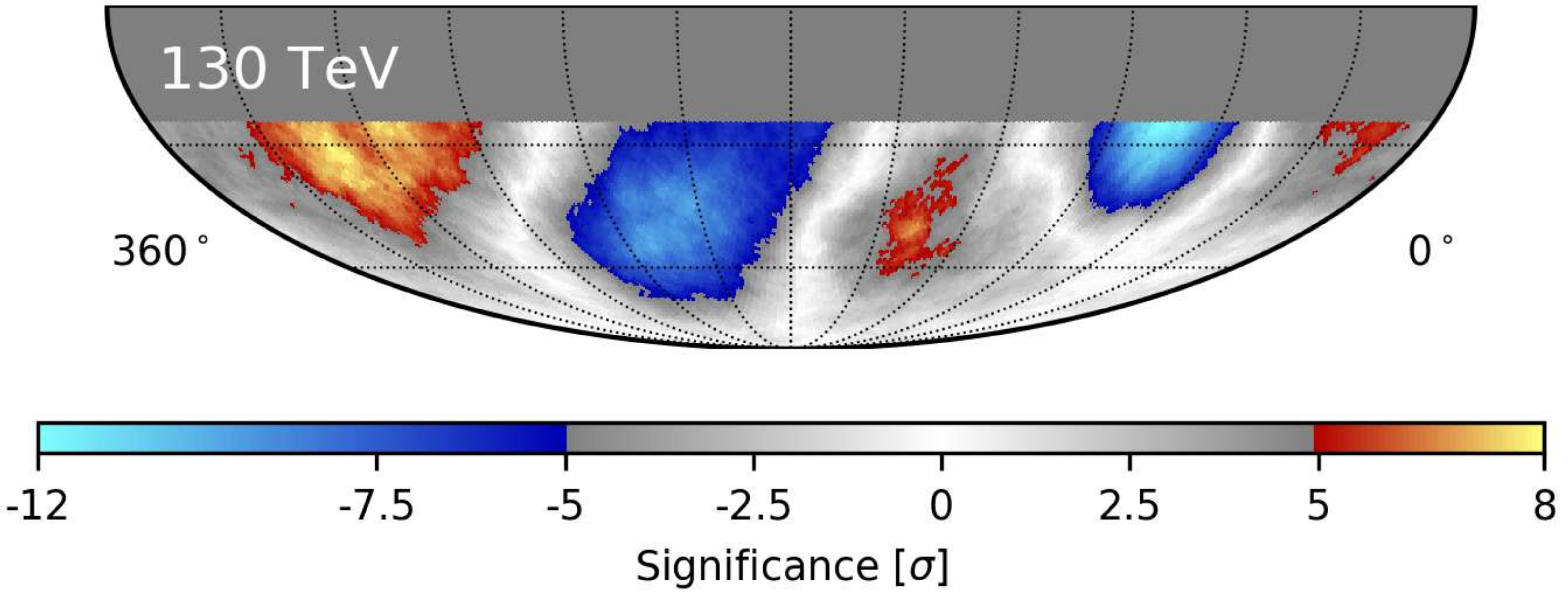


paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

- Median energy: 130 TeV

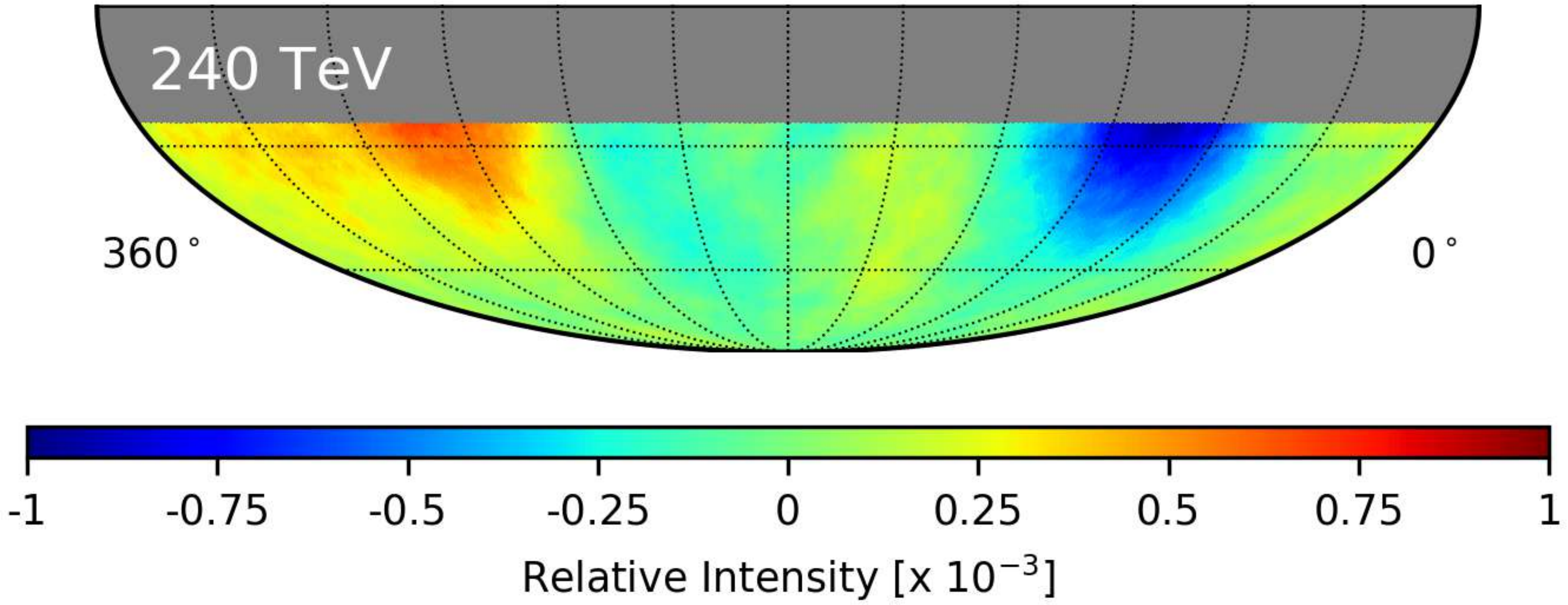


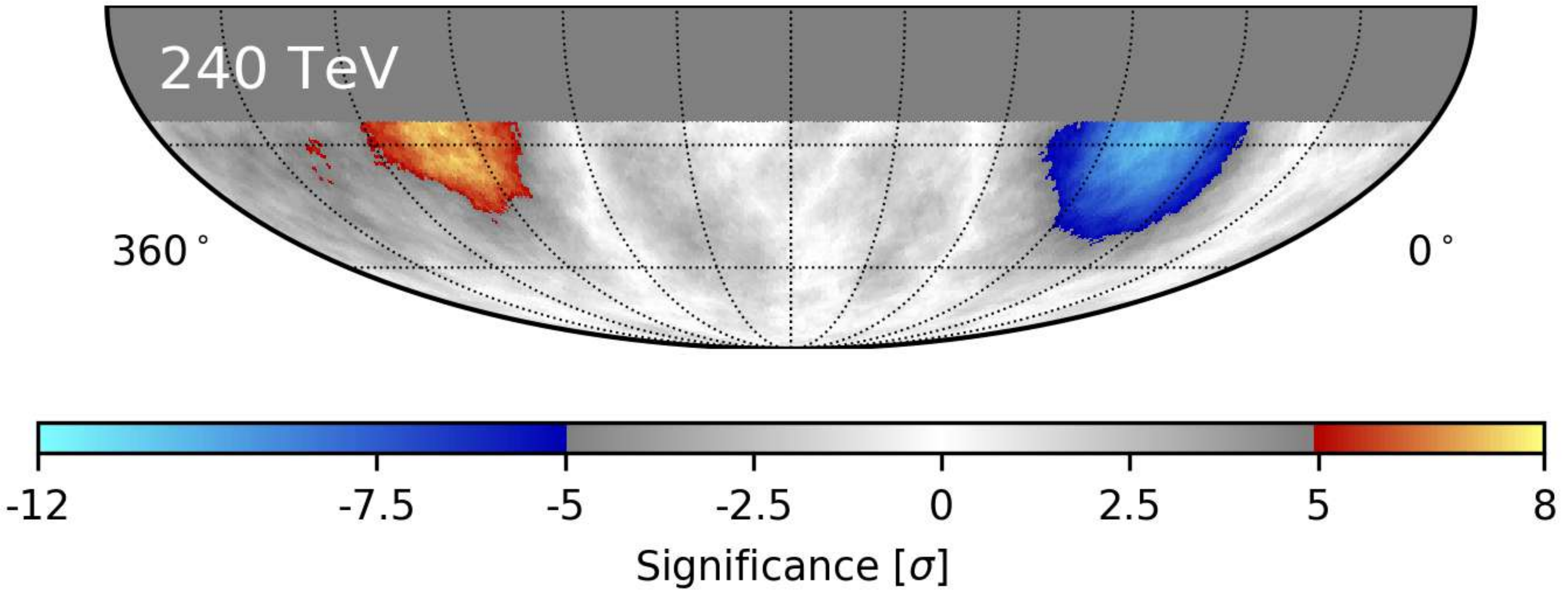


paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

- Median energy: 240 TeV

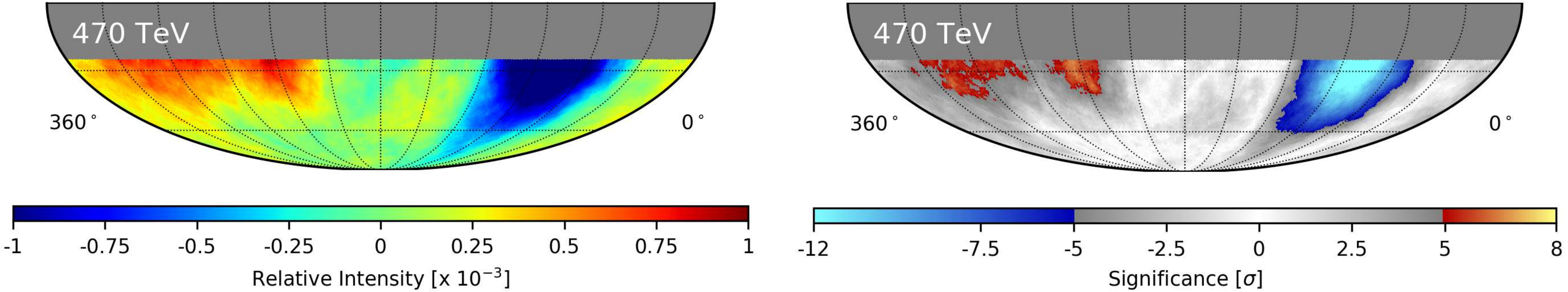




paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

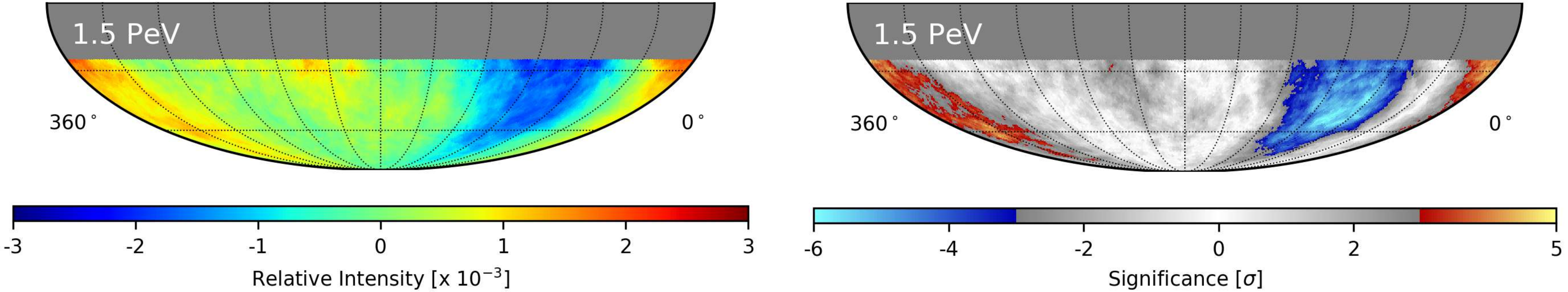
- Median energy: 470 TeV



paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

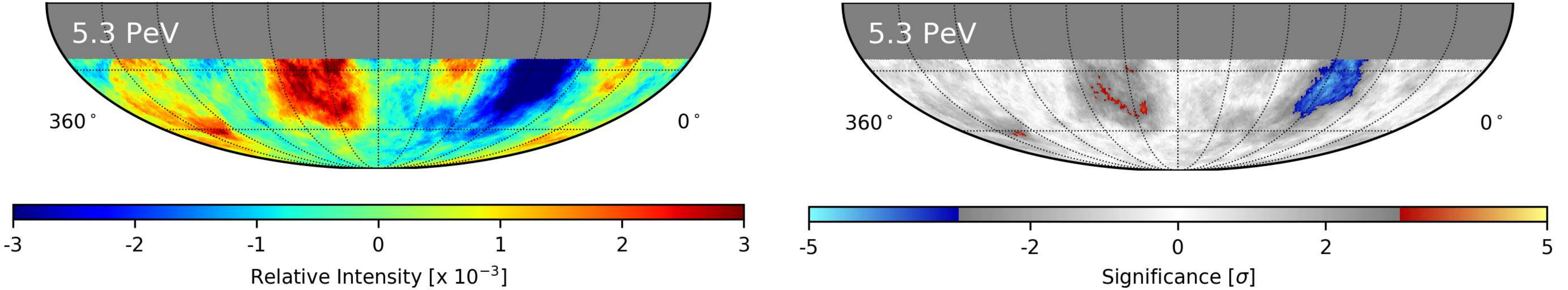
- Median energy: 1.5 PeV



paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

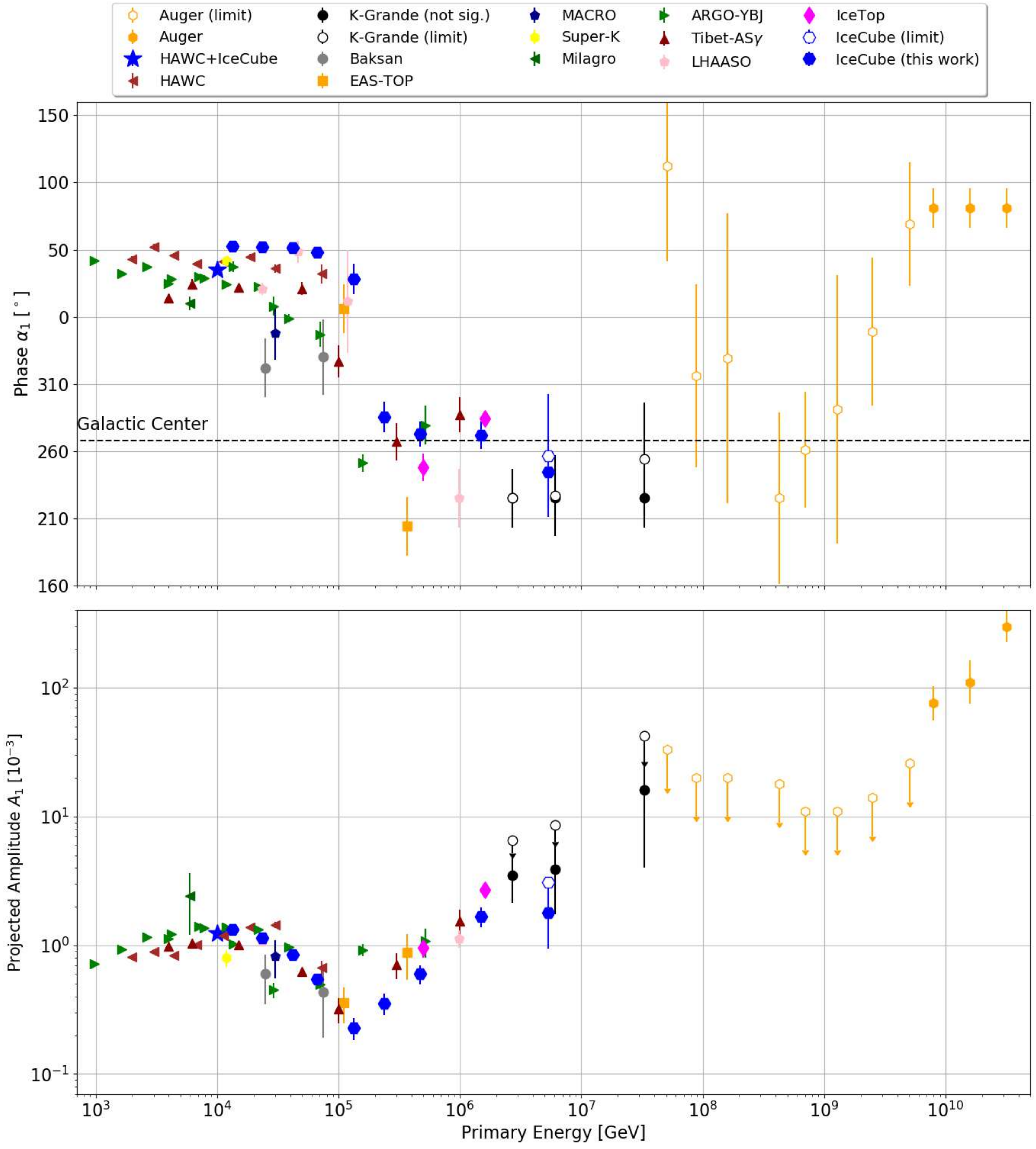
- Median energy: 5.3 PeV



paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

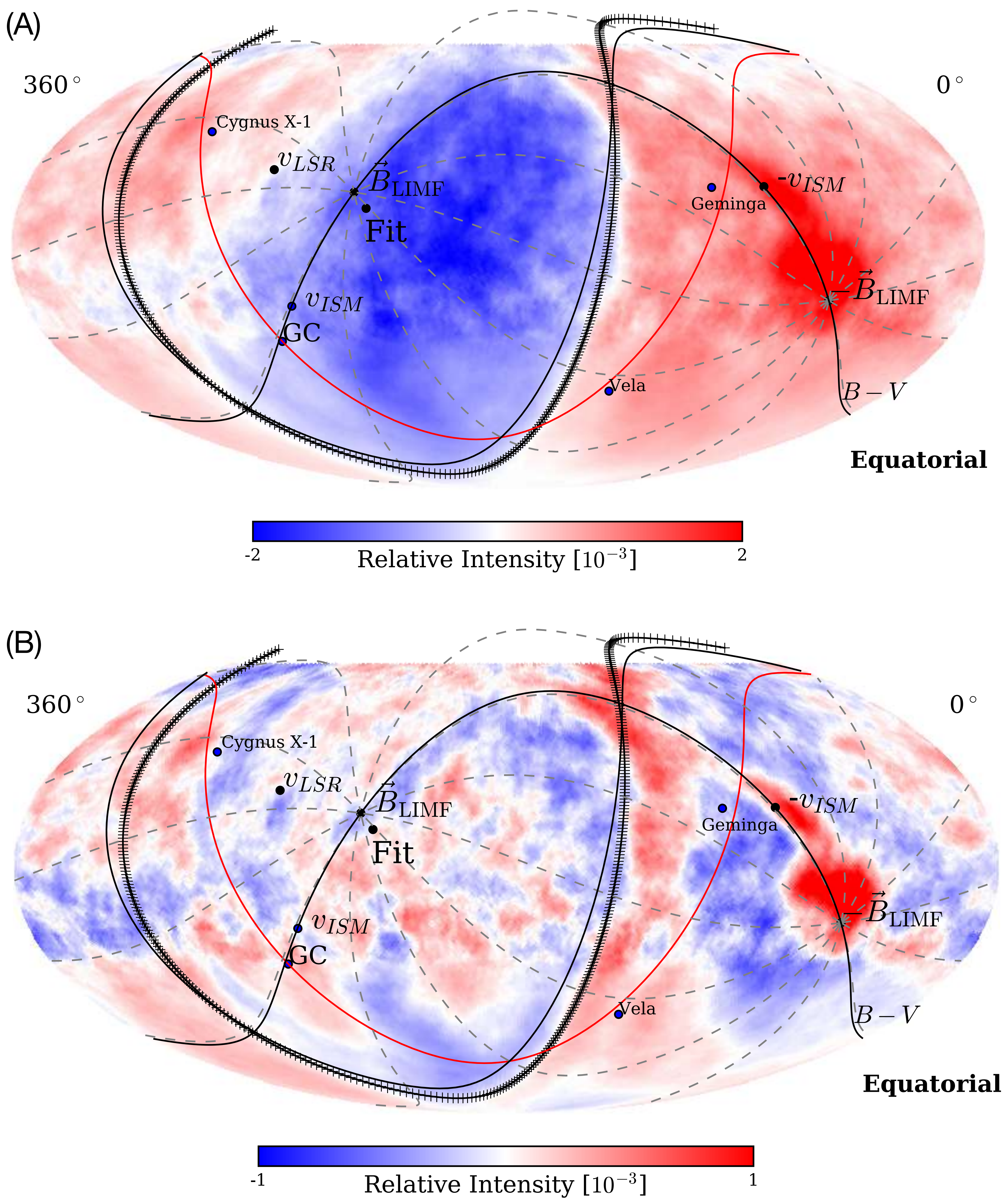
- Dipol phase and amplitude:
  - Comparison with other experiments
  - Change in the angular structure of anisotropy at around 100-130 TeV
  - Consistent picture between experiments!
- For studies of small-scale features and power spectrum, see arXiv:2412.05046
- However, full sky coverage important…



paper submitted to ApJ, [arXiv:2412.05046]

Cosmic Ray Anisotropy

- <u>Combined IceCube + HAWC analysis (full sky)</u>
  - IceCube data: May 2011 - May 2016
  - HAWC data: May 2015 - May 2017
  - Small-scale structures:
    - Subtraction of the fitted multipole components with $l \leq 3$
    - Small-scale structures align with features in the local interstellar magnetic field (LIMF)
      [E. J. Zirnstein et al., ApJL 818 (2016)]



[IceCube & HAWC Collaborations, Astrophys. J. 871 (2019).]

Future Cosmic Ray Measurements at the South Pole

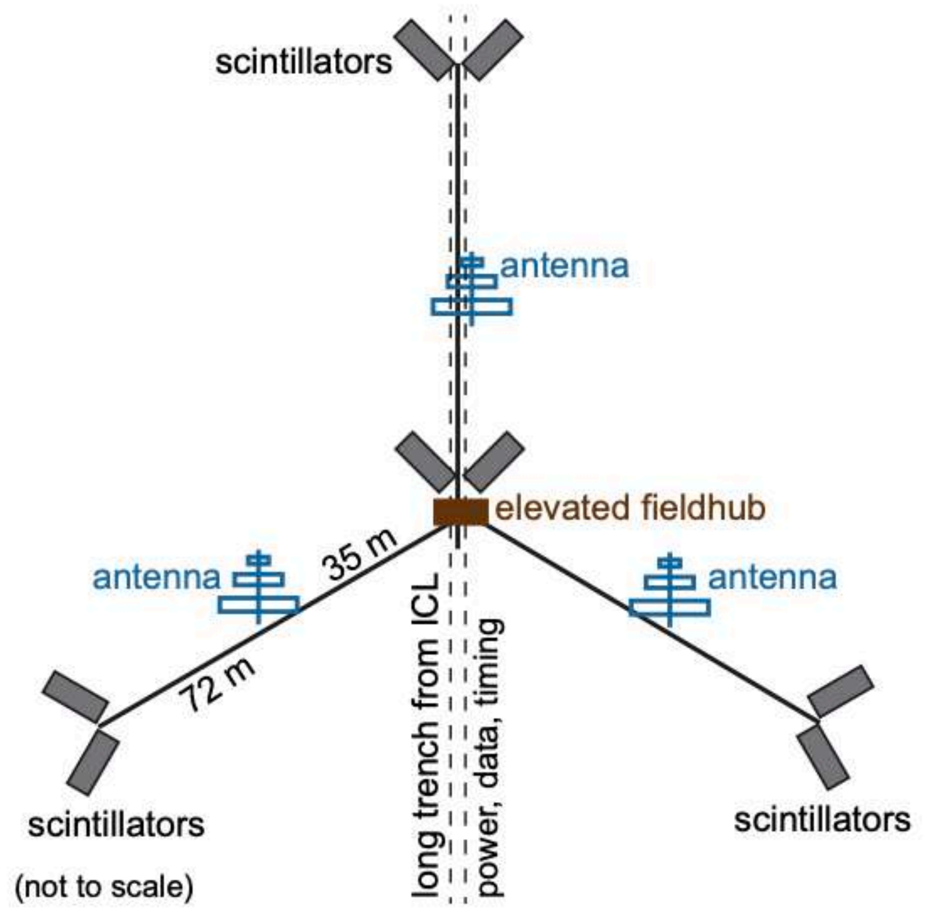
credit: IceCube/NSF

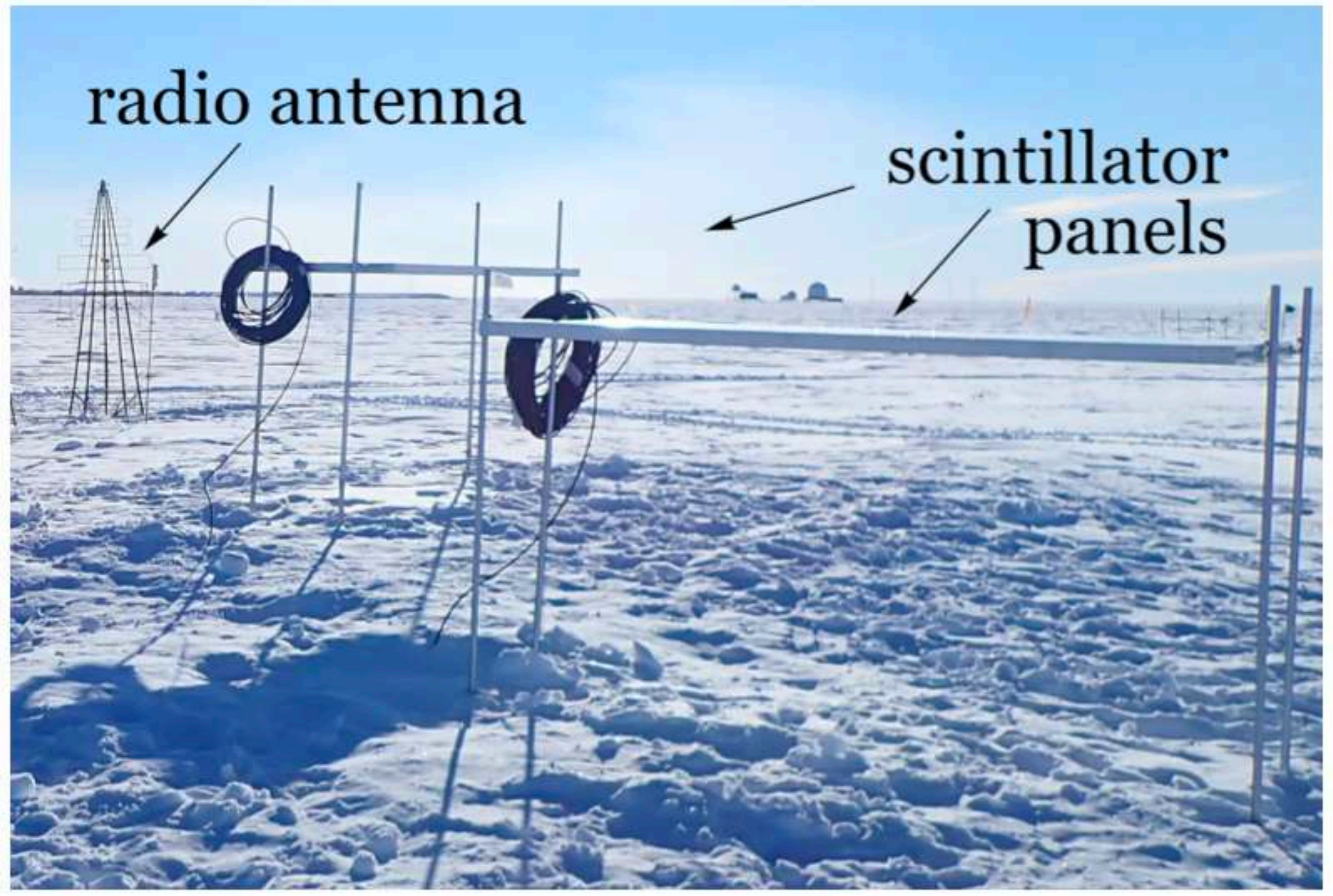
Upcoming IceCube Analyses

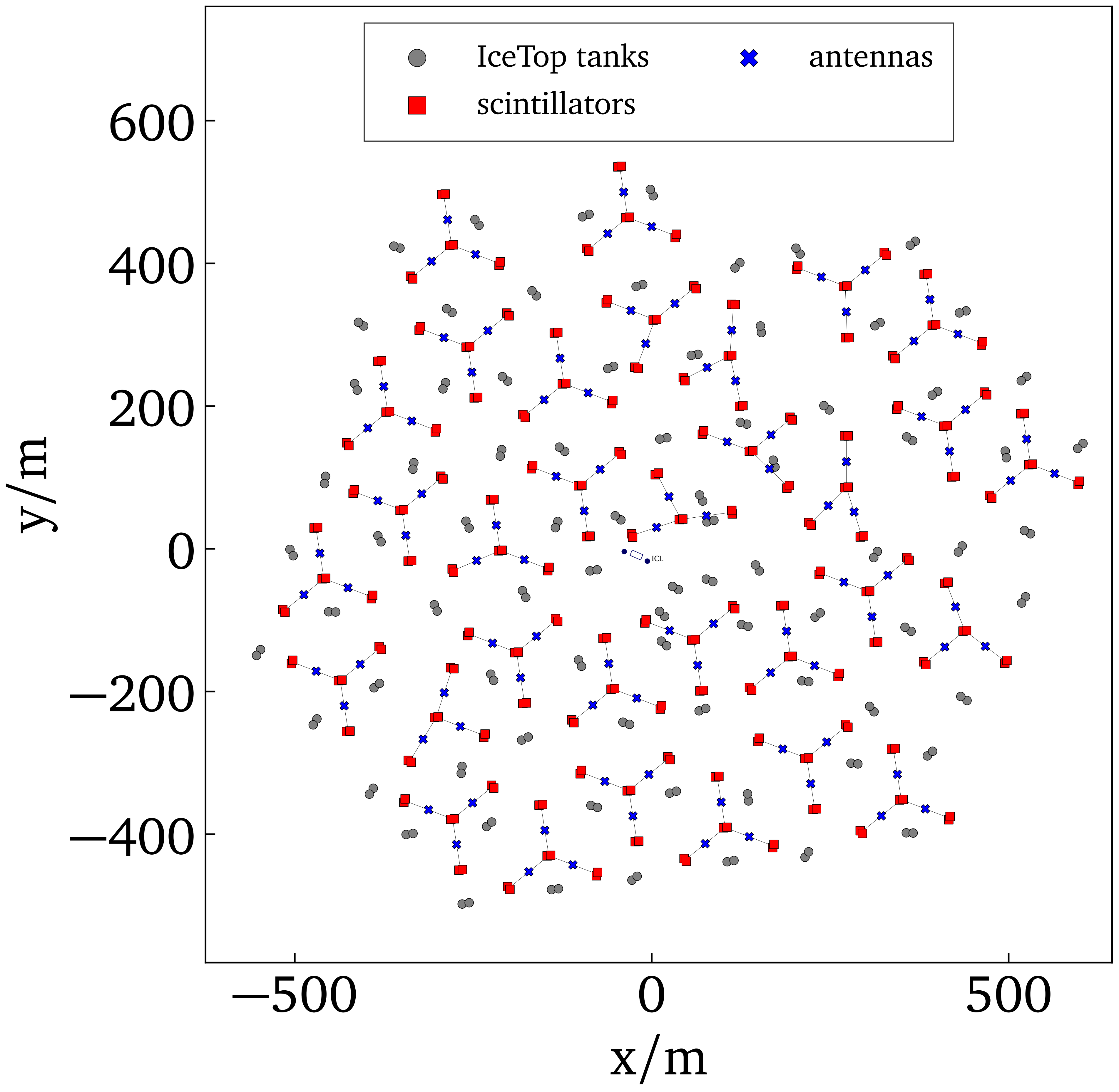
- Spectrum
  - High-energy spectrum (>100 PeV), closing the gap to Auger/TA
  - Include IceTop uncontained events (higher statistics / higher energy)
  - Work in progress…
- Composition
  - Low-energy (>250 TeV) composition measurement (proton spectrum)
  - Closing the gap to direct measurements
  - Work in progress…
- Anisotropy
  - Full-sky observation in combination with other experiments
  - IceTop data between 1 PeV and 10 PeV
  - Work in progress…

Future Detector Improvements

- <u>Surface enhancement in progress:</u>
  - New elevated scintillator panels
    - Improved air shower energy reconstruction
    - Lower cosmic ray energy threshold
  - New radio antennas
    - Improved air shower energy reconstruction
    - Increased angular acceptance



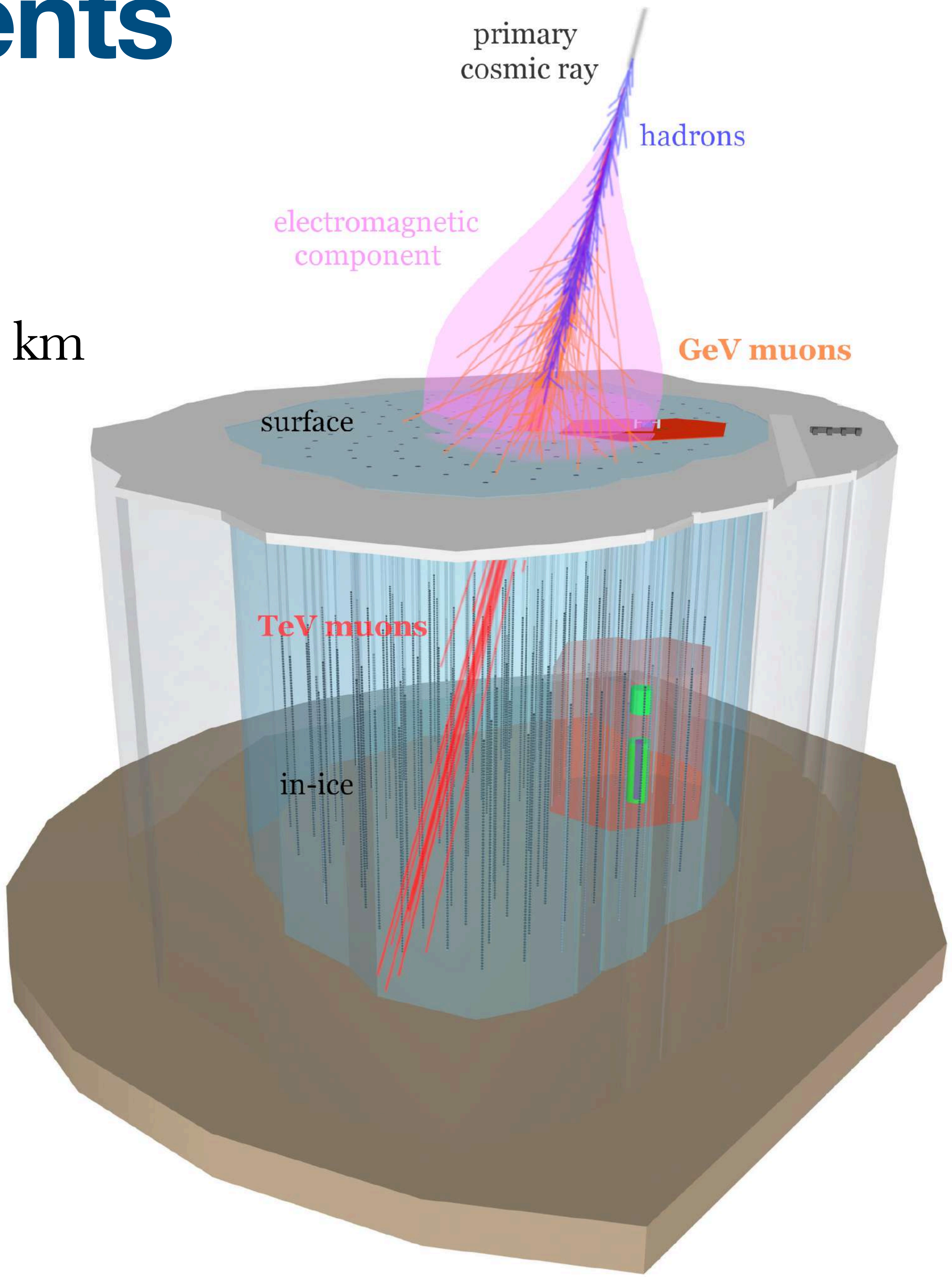




[IceCube Collaboration, EPJ Web Conf. 210 (2019)]

Future Detector Improvements

- <u>IceCube-Gen2:</u>
  - <u>8 km^3 in-ice instrumented volume:</u>
    - ~10,000 optical sensors at depths of ~1.3 km to ~2.6 km
    - New strings with a spacing of 240 m
  - <u>8 km^2 surface array:</u>
    - Elevated scintillator panels
    - Radio antennas
  - Increased solid angle, larger inclinations
  - Increased statistics at the highest energies
  - Better understanding of the energy scale
  - Reduced in-ice systematics
  - Much more …



[IceCube-Gen2 Collaboration, J. Phys. G 48 (2021)]

Many more interesting results!

THE ICECUBE COLLABORATION

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Vrije Universiteit Brussel

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ECAP, Universität Erlangen-Nürnberg
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The Swedish Research Council (VR)
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US National Science Foundation (NSF)

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Thank you!

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Muon Measurements IceTop and IceCube

- GeV muon density (IceTop) and TeV muon multiplicity (IceCube)
- The z-scale:

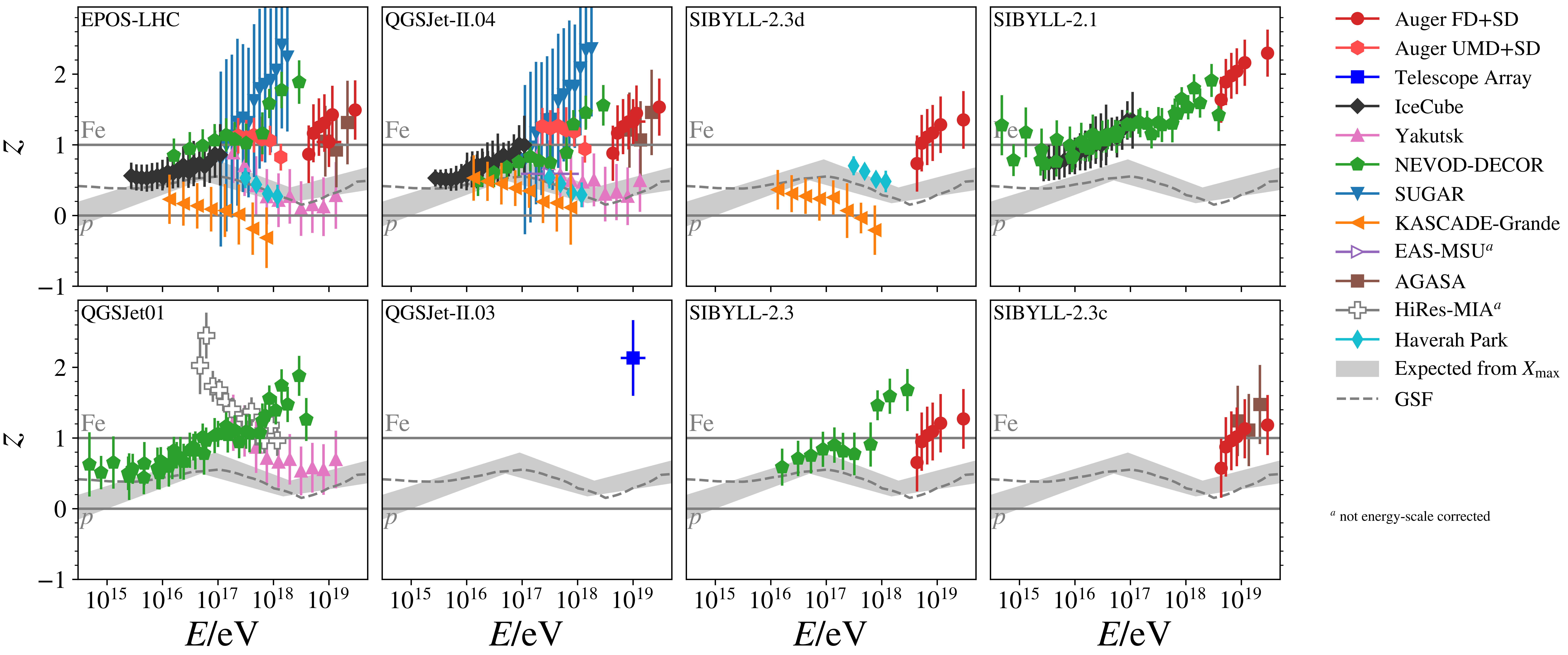
$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

  - Proton: $z = 0$, iron: $z = 1$

[S. Verpoest (IceCube Collaboration), PoS(ICRC2023)207 (2023)]

Muon Measurements IceTop and IceCube

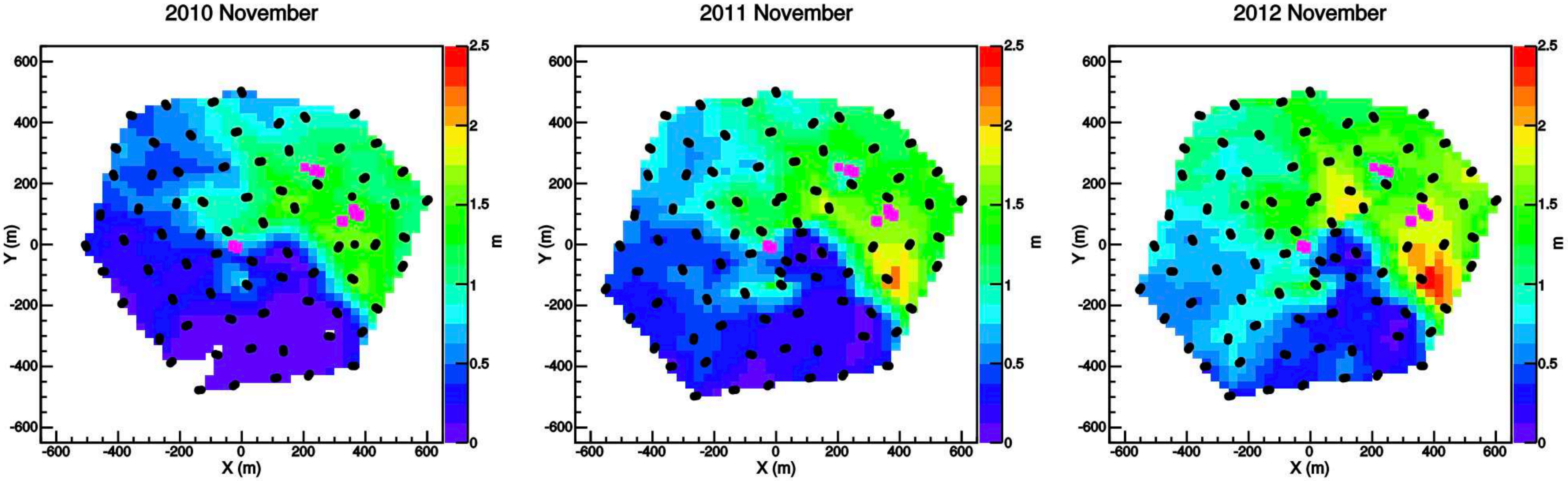
- Comparison with other experiments



[J. C. Arteaga-Velázquez (WHISP), PoS ICRC2023 (2023) 466]

Snow Accumulation

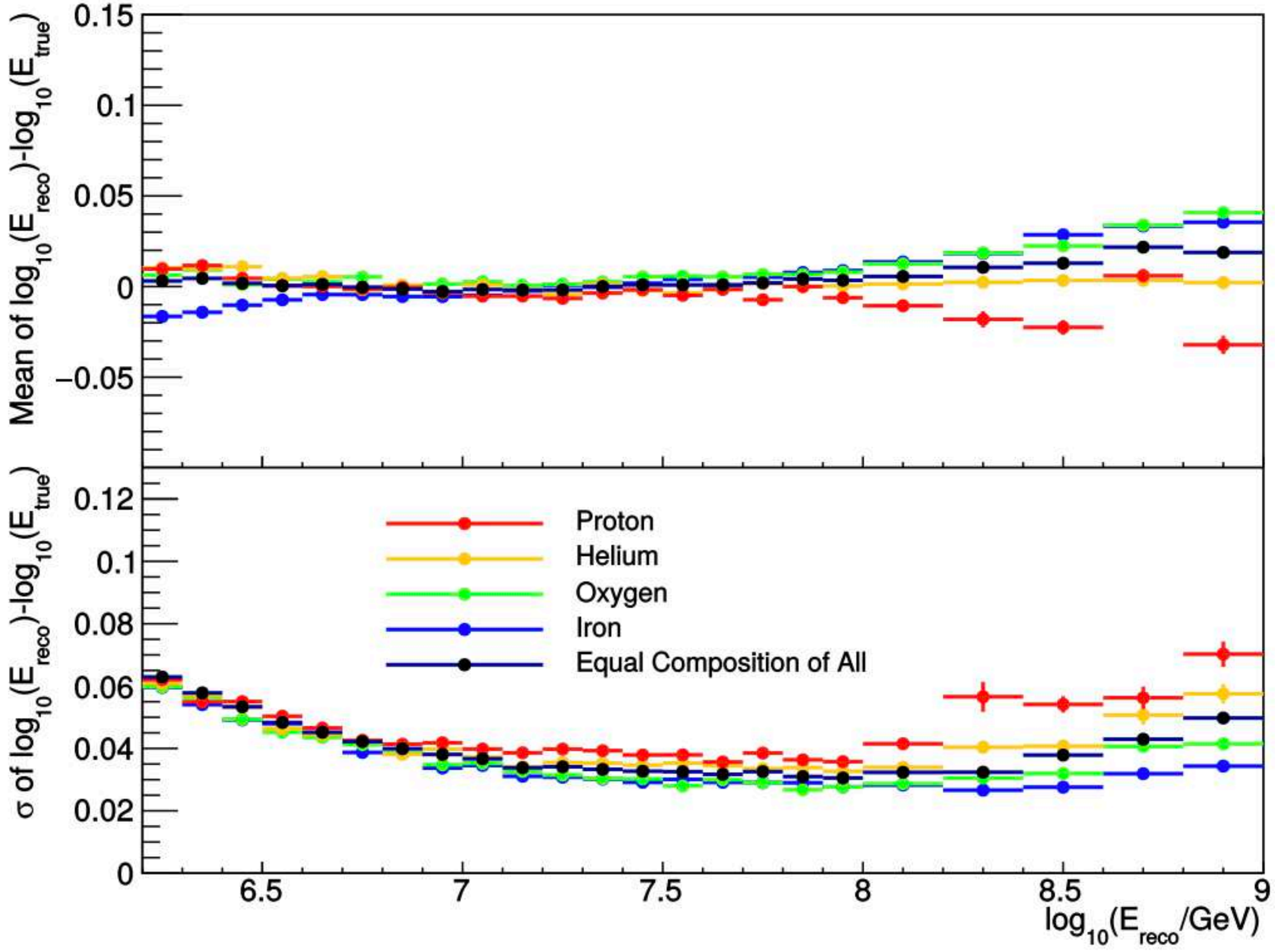
- Snow accumulation in IceTop 2010 - 2012



[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]

Energy Resolution

- Energy resolution and bias in IceTop



[IceCube Collaboration, Phys. Rev. D 100, 082002 (2019)]