IceTop Observables for the Tuning of Hadronic Interaction Models

Workshop on the Tuning of Hadronic Interaction Models

Wuppertal, Germany

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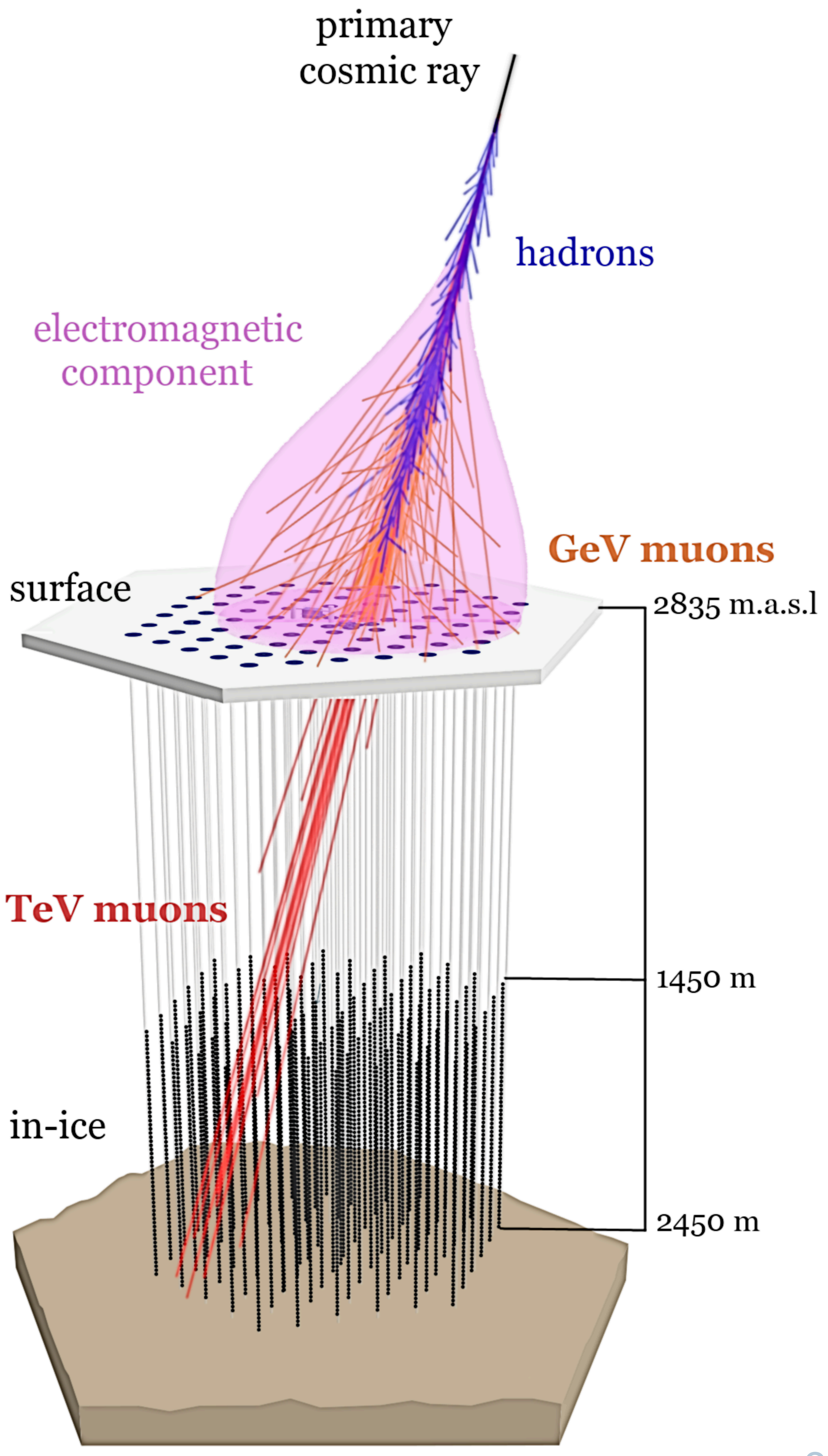
Dennis Soldin
for the IceCube Collaboration

University of Utah

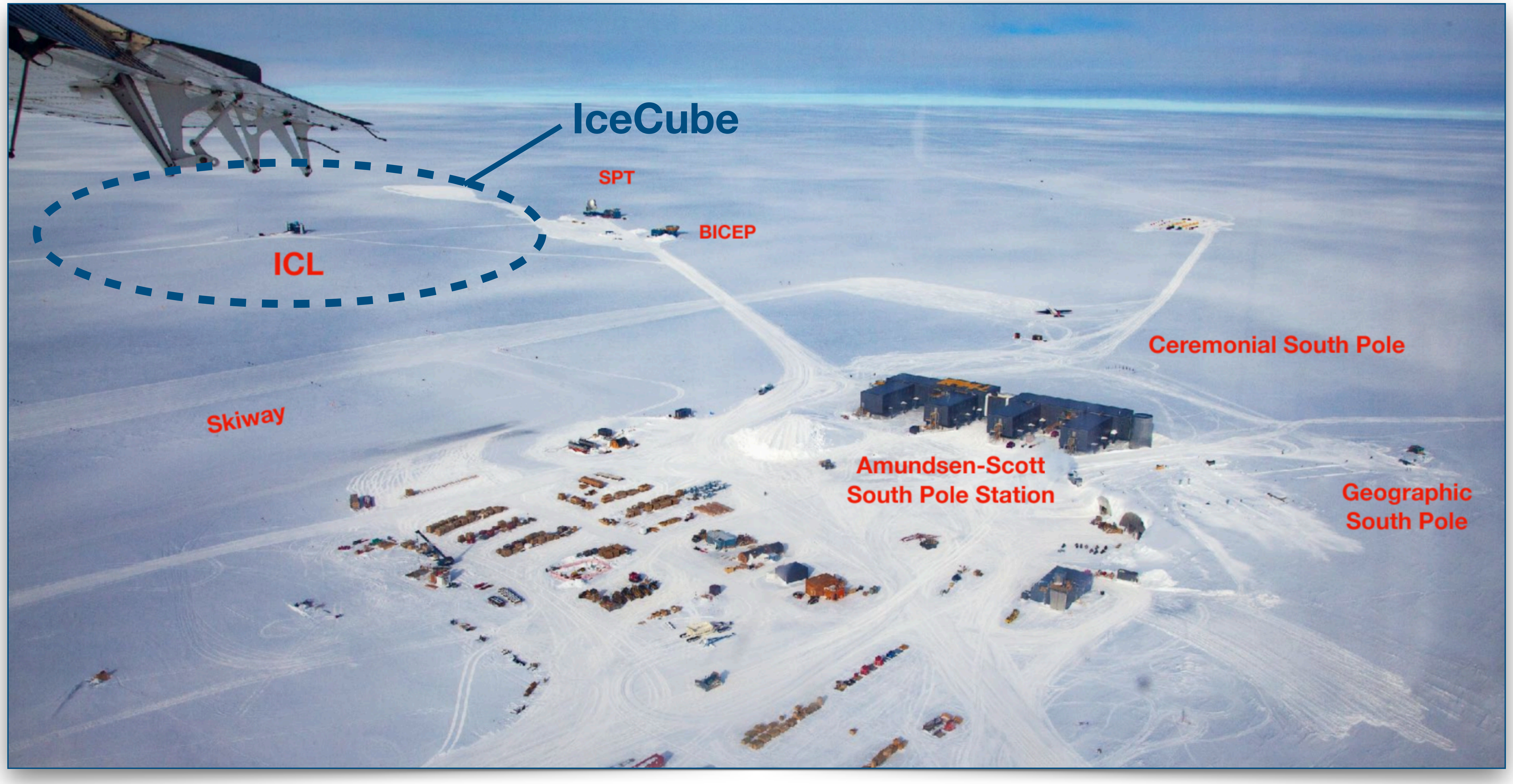
Outline

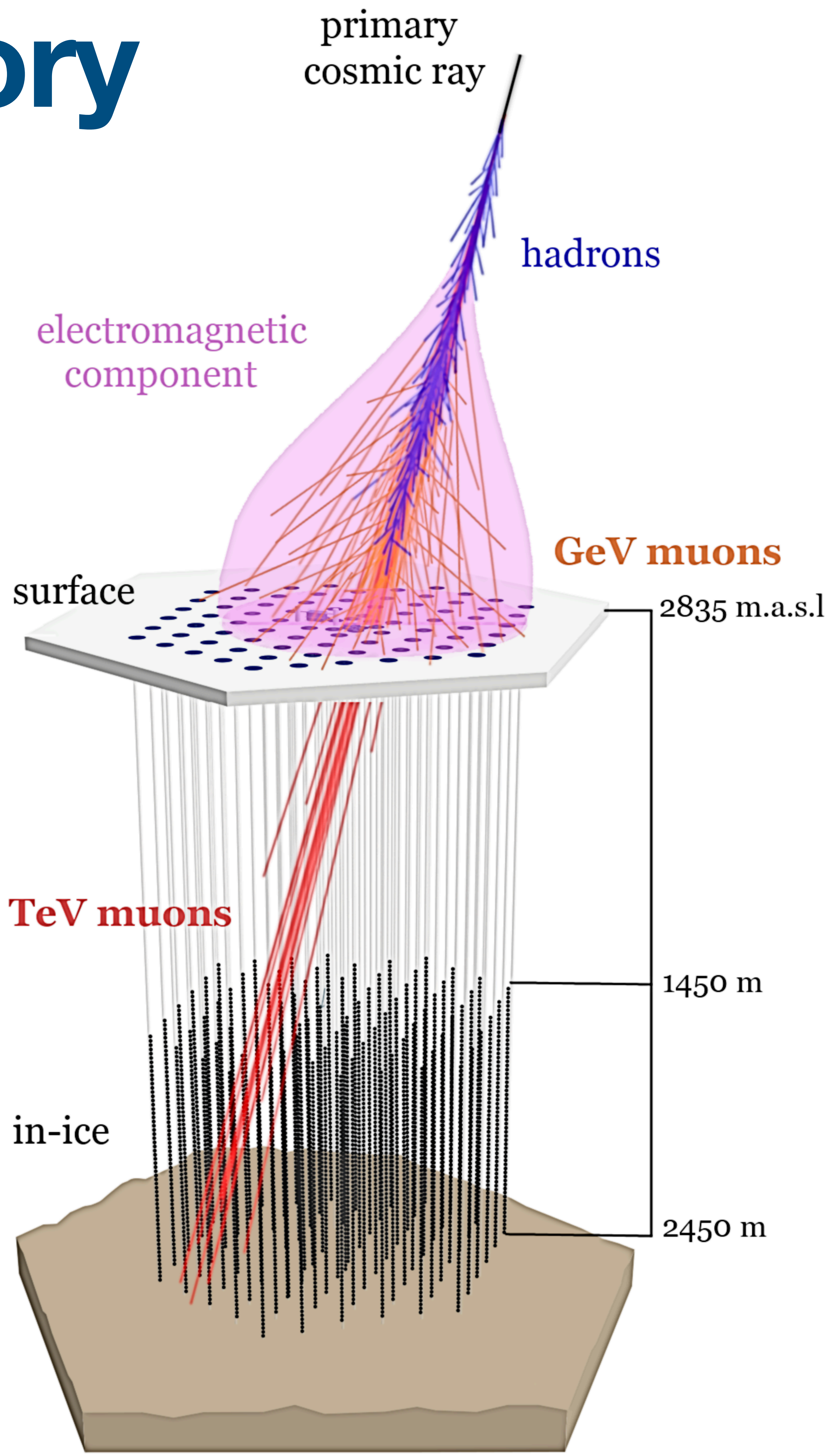
- IceCube & IceTop
- Measurement of GeV muons with IceTop
- Coincident muon measurements with IceTop and IceCube (in-ice)
- Future perspectives
- Conclusions



The IceCube Neutrino Observatory

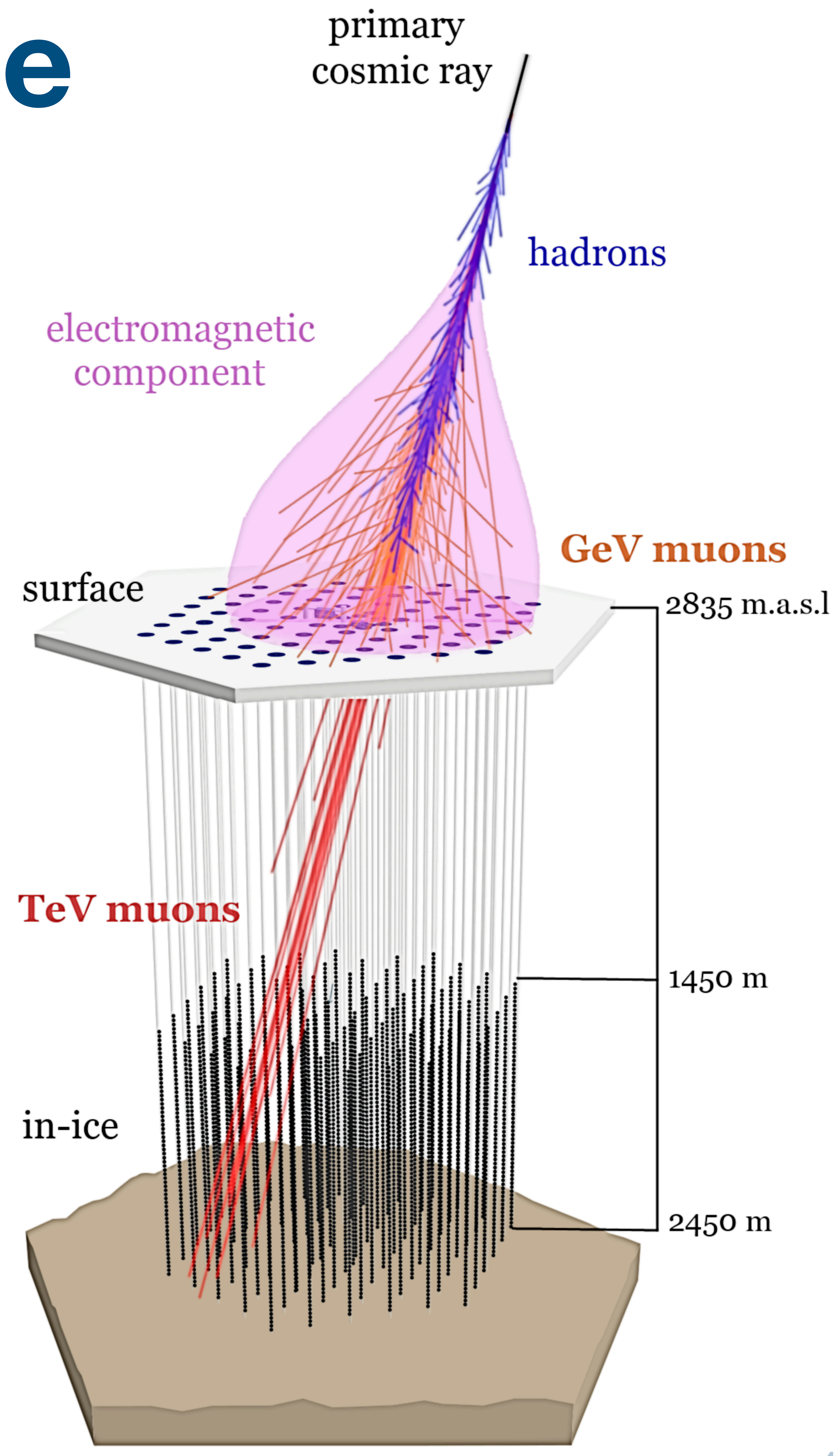
- Hybrid cubic-kilometer particle detector at the South Pole
  - Surface detector at 2835 m.a.s.l
  - In-ice detector at depths between 1450 m and 2450 m





EAS Measurements with IceCube

- <u>In-ice detector:</u>
  - $\sim 1\,\text{km}^3$ instrumented detector volume at depths between 1450 m and 2450 m
  - 86 strings with 5160 digital optical modules (DOMs)
  - Measures mainly TeV (up to >PeV) muons from EAS
- <u>Surface detector, IceTop:</u>
  - $\sim 1\,\text{km}^2$ air shower array with 162 ice-Cherenkov tanks in 81 stations (2 DOMs per tank)
  - Electromagnetic EAS component (EAS energy)
  - Cosmic ray energies of $\sim 1\,\text{PeV}^*$ to $\sim 1\,\text{EeV}$
  - GeV muon content in EAS
- <u>Ideal facility to study muon (hadron) production in EAS!</u>



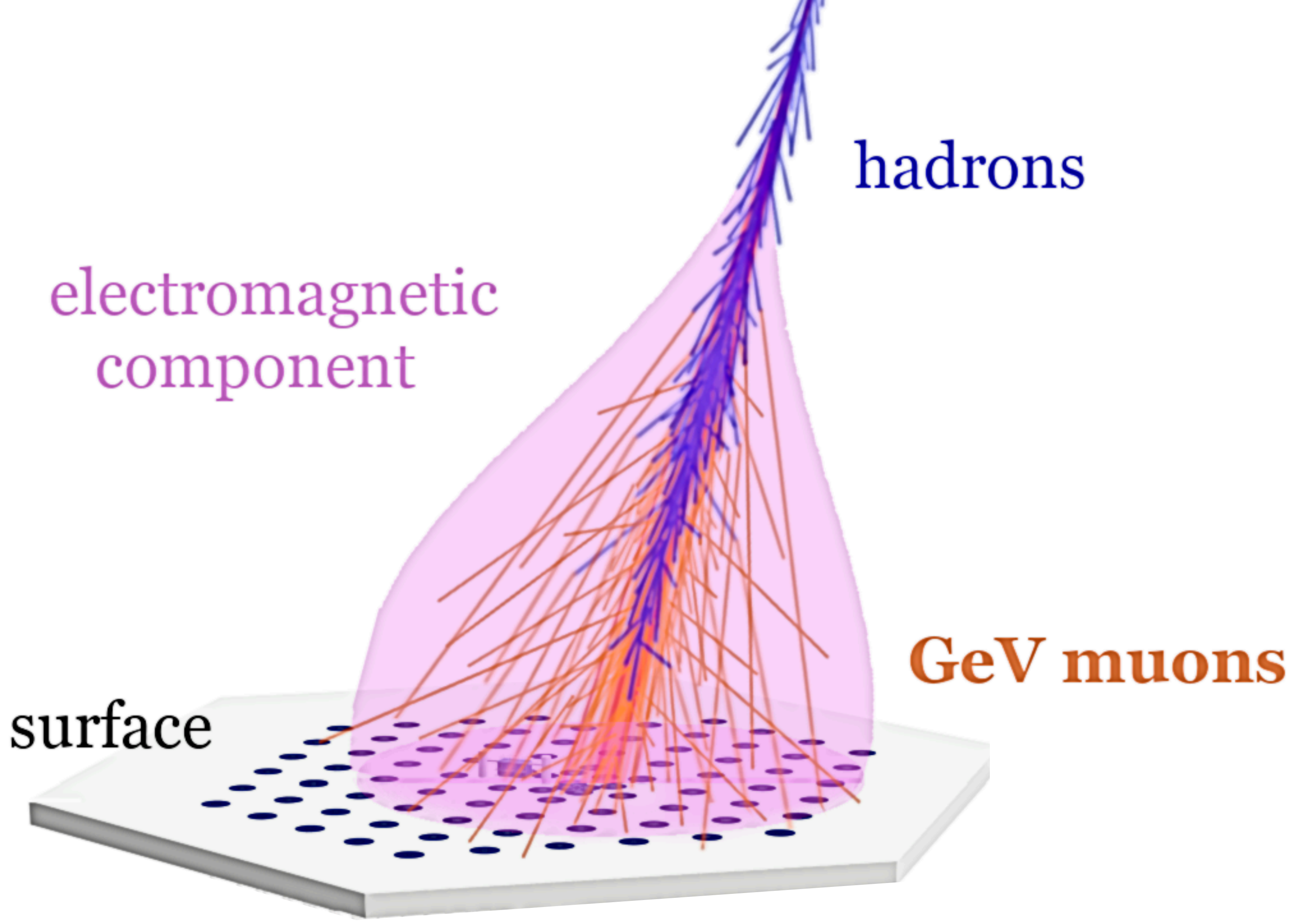
* the all particle spectrum can be measured down to ~250 TeV

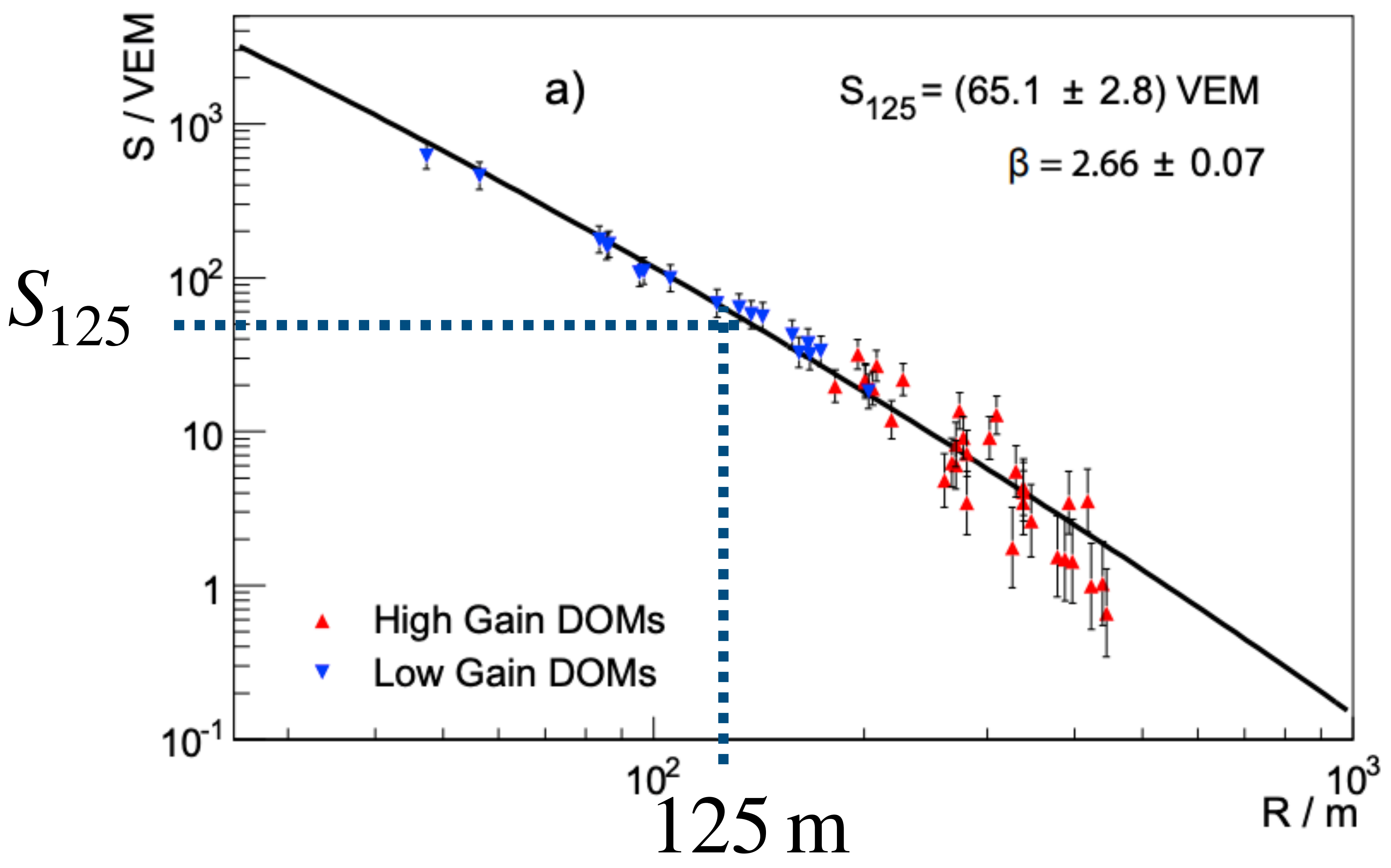
EAS Energy in IceTop

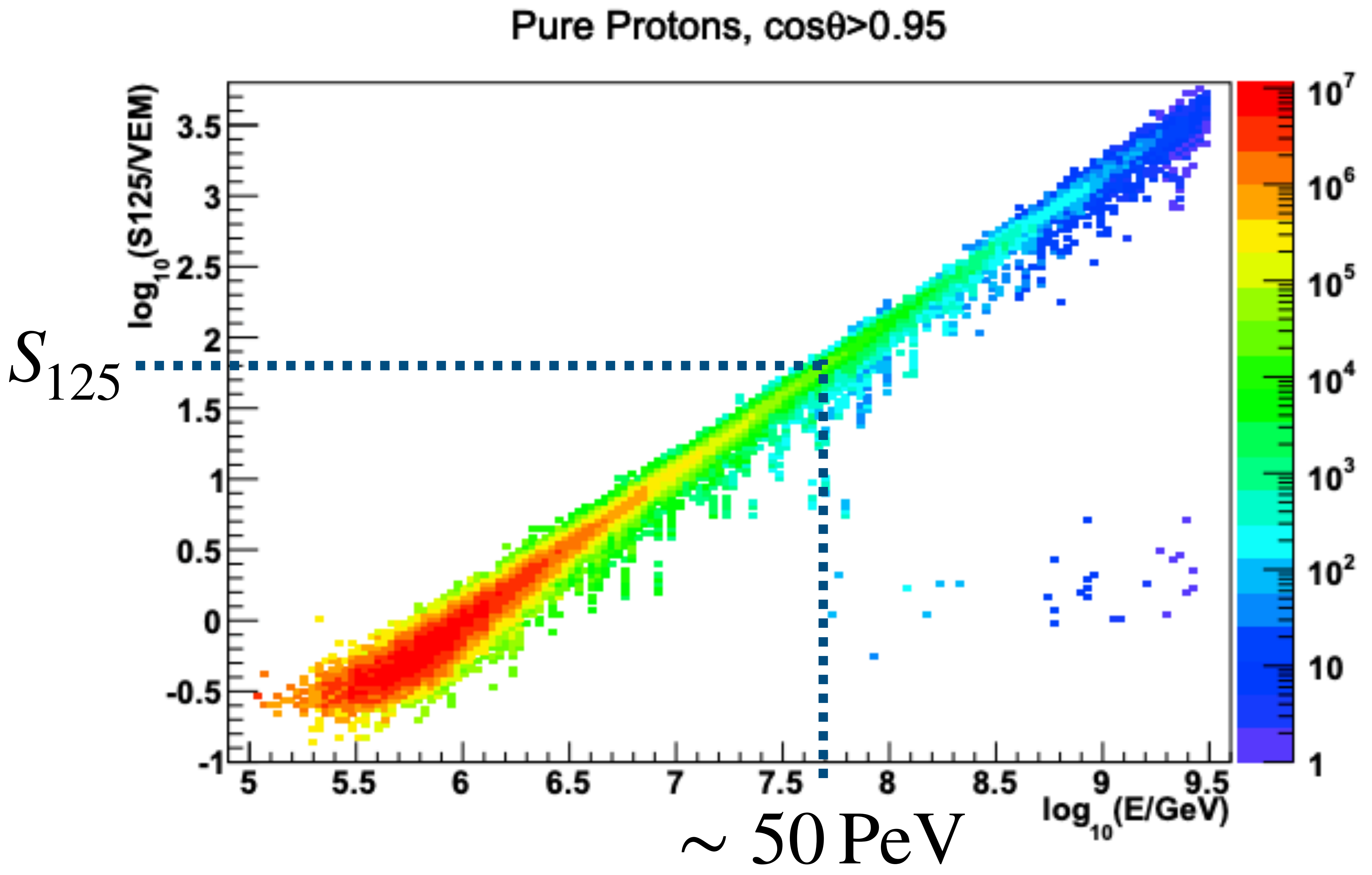
- EAS energy determined from surface signals
- Lateral Distribution Function (LDF)

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

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

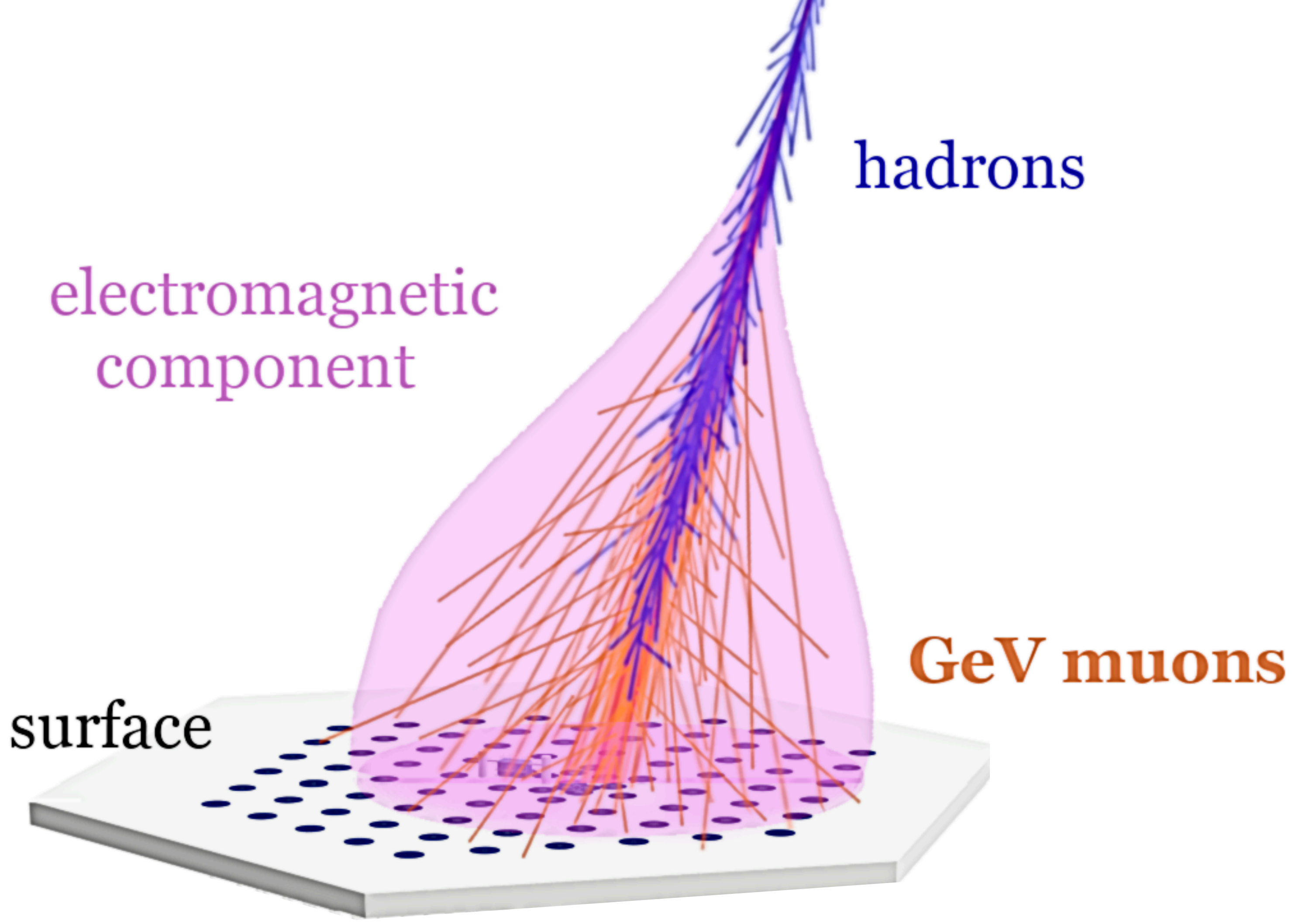


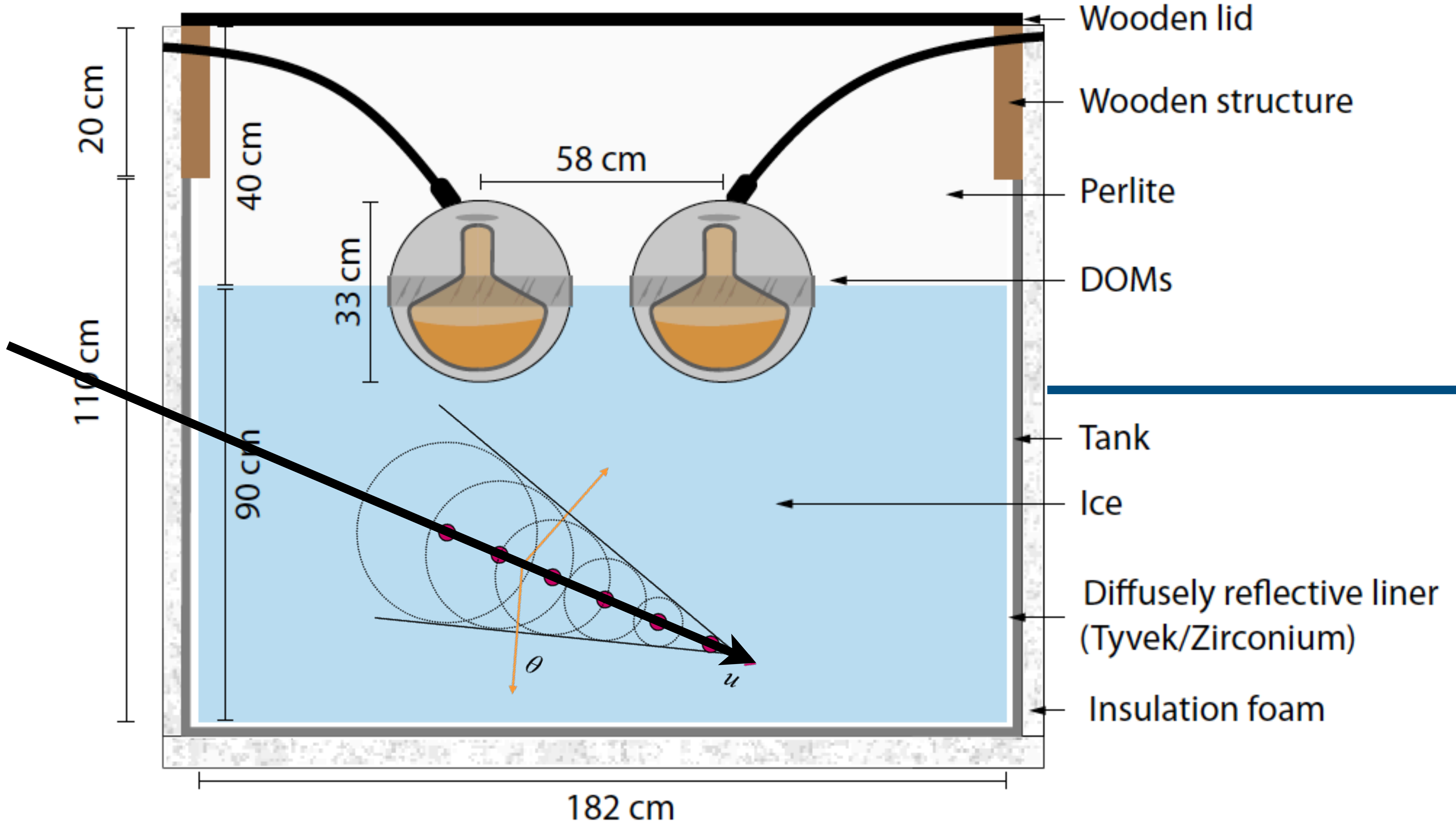


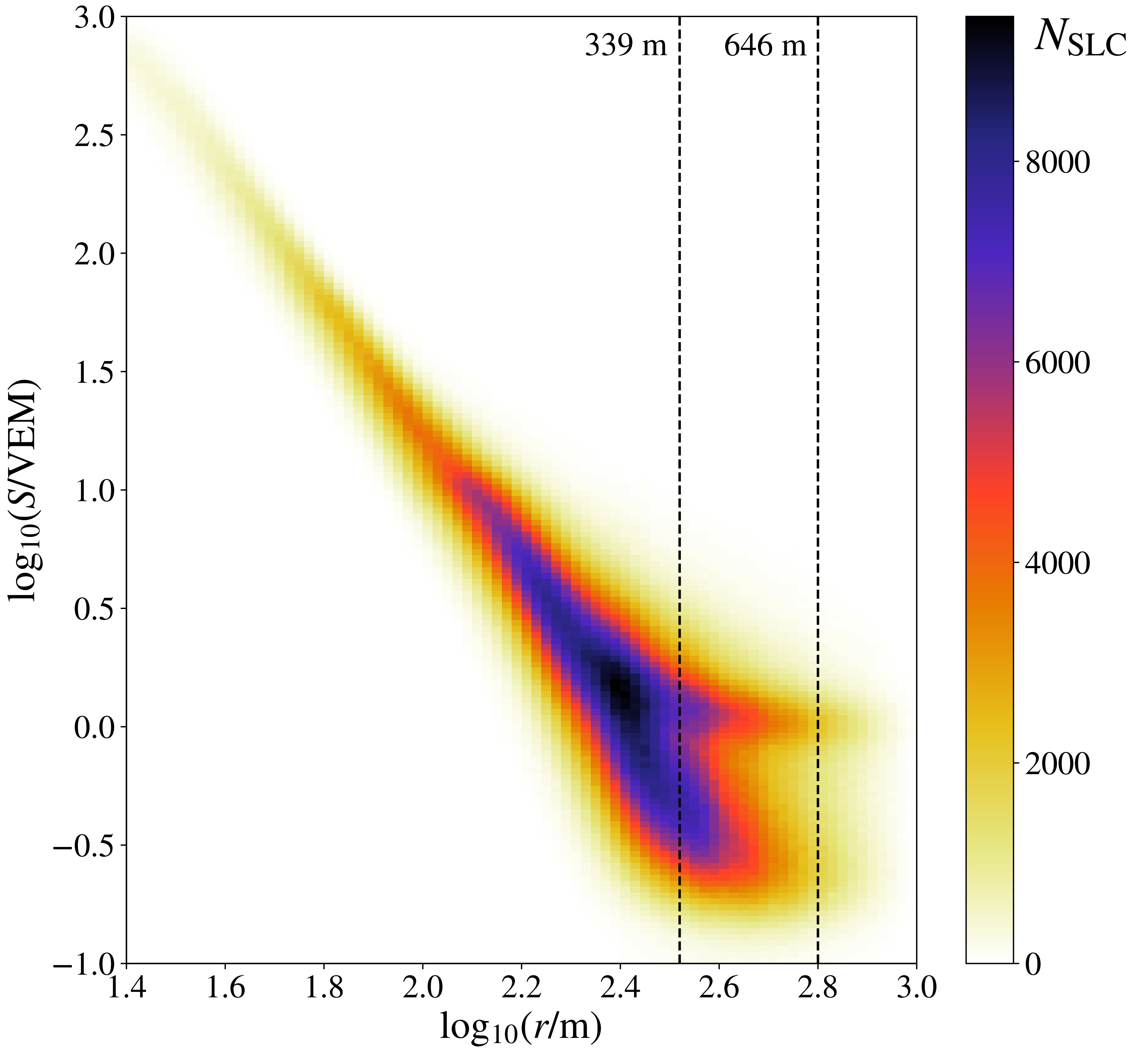


GeV Muons in IceTop

- Individual tank signals (vertical-equivalent-muon, VEM)
- Characteristic signal distributions for em part and muons
- Separation of GeV muons from other particles in EAS







[IceCube Collaboration, Phys. Rev. D 106 (2022)]

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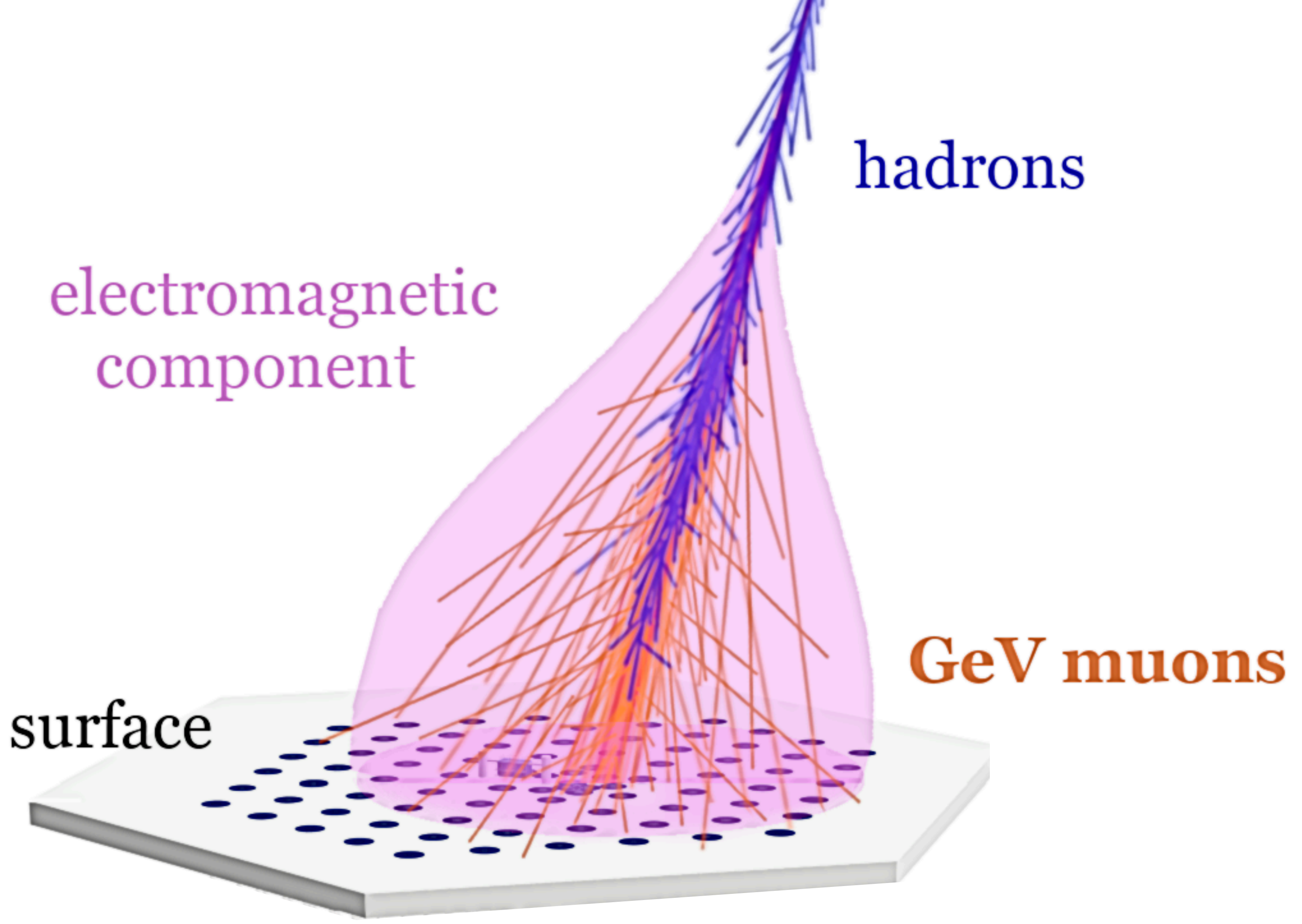

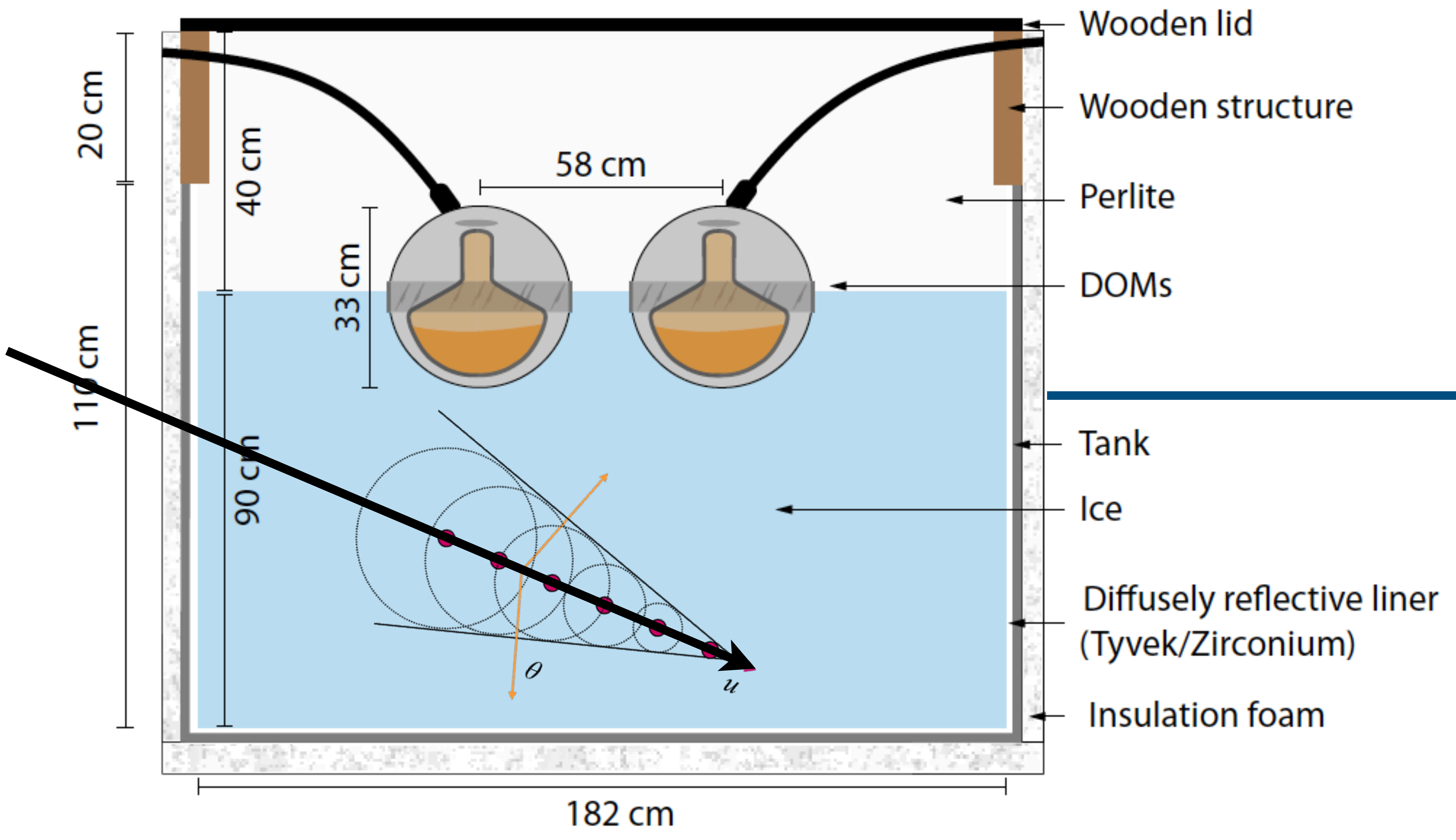

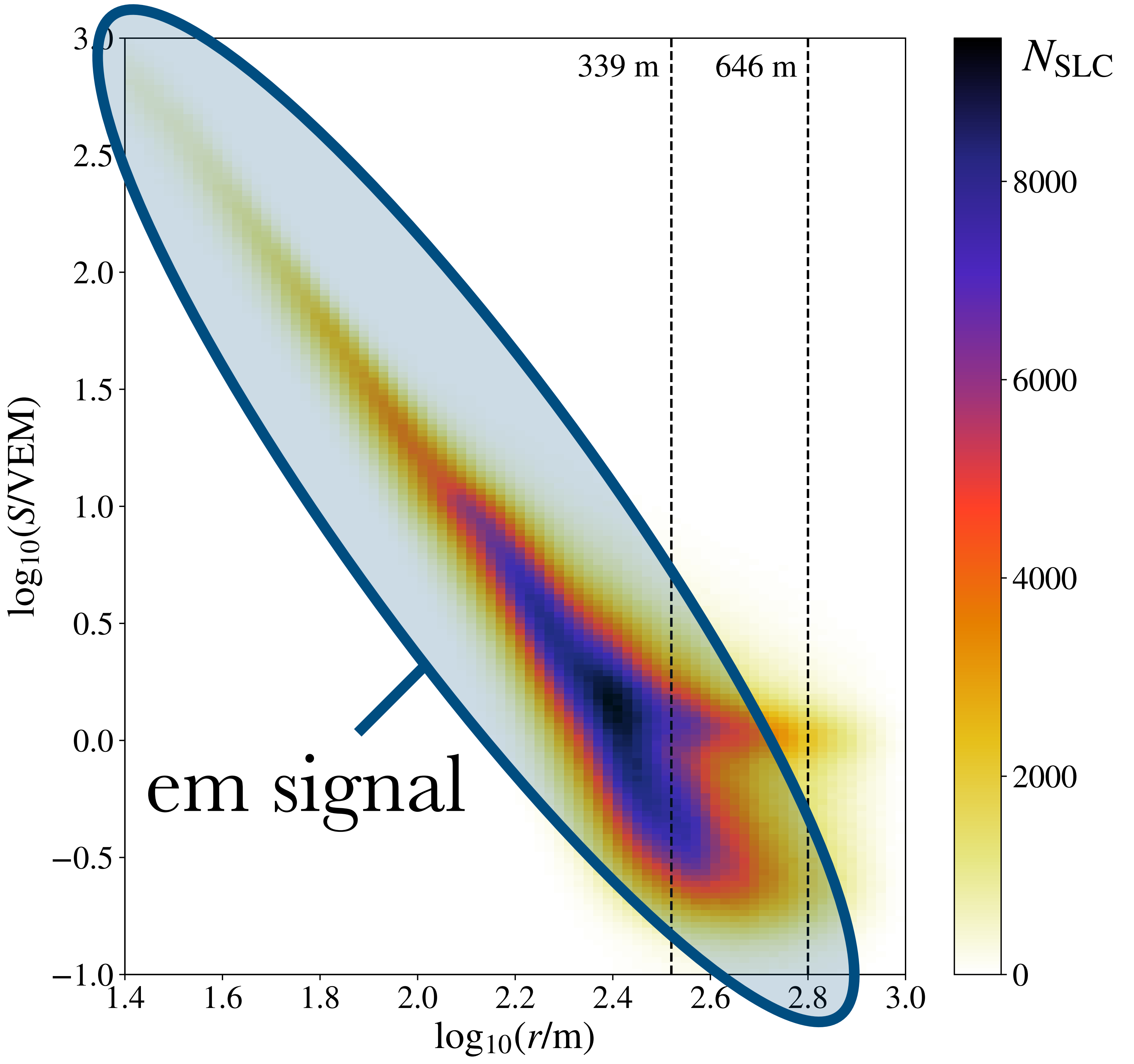

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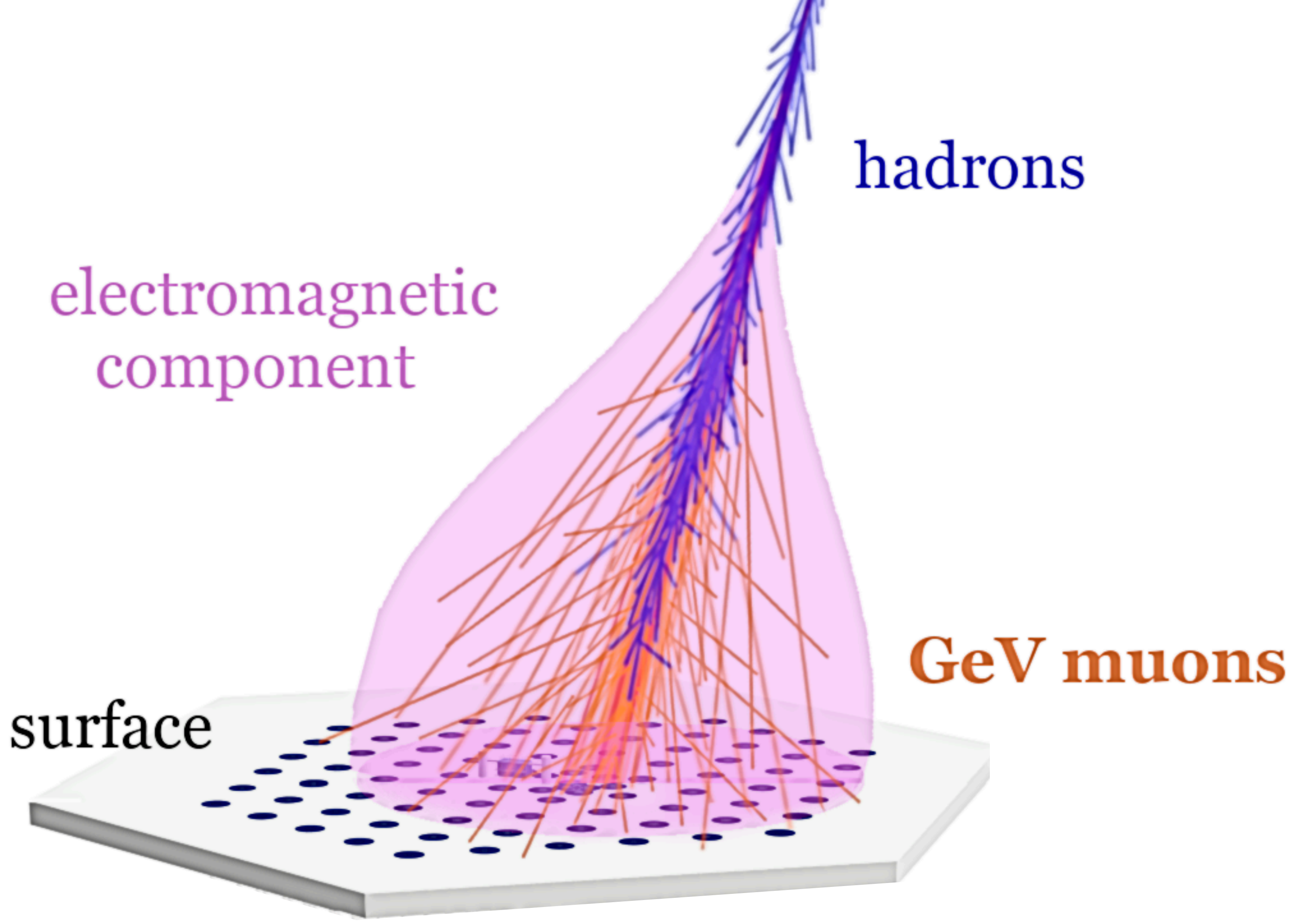
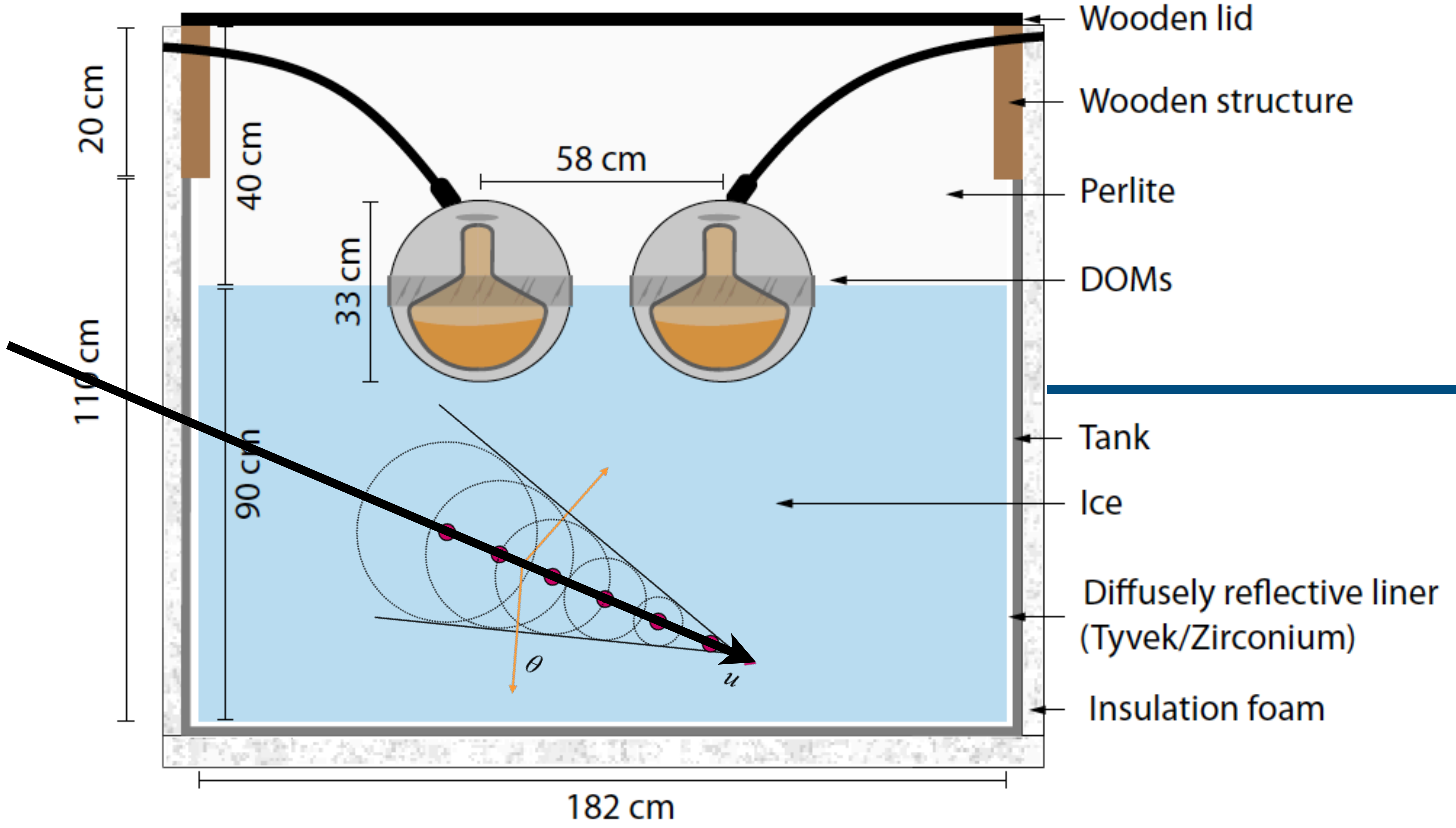
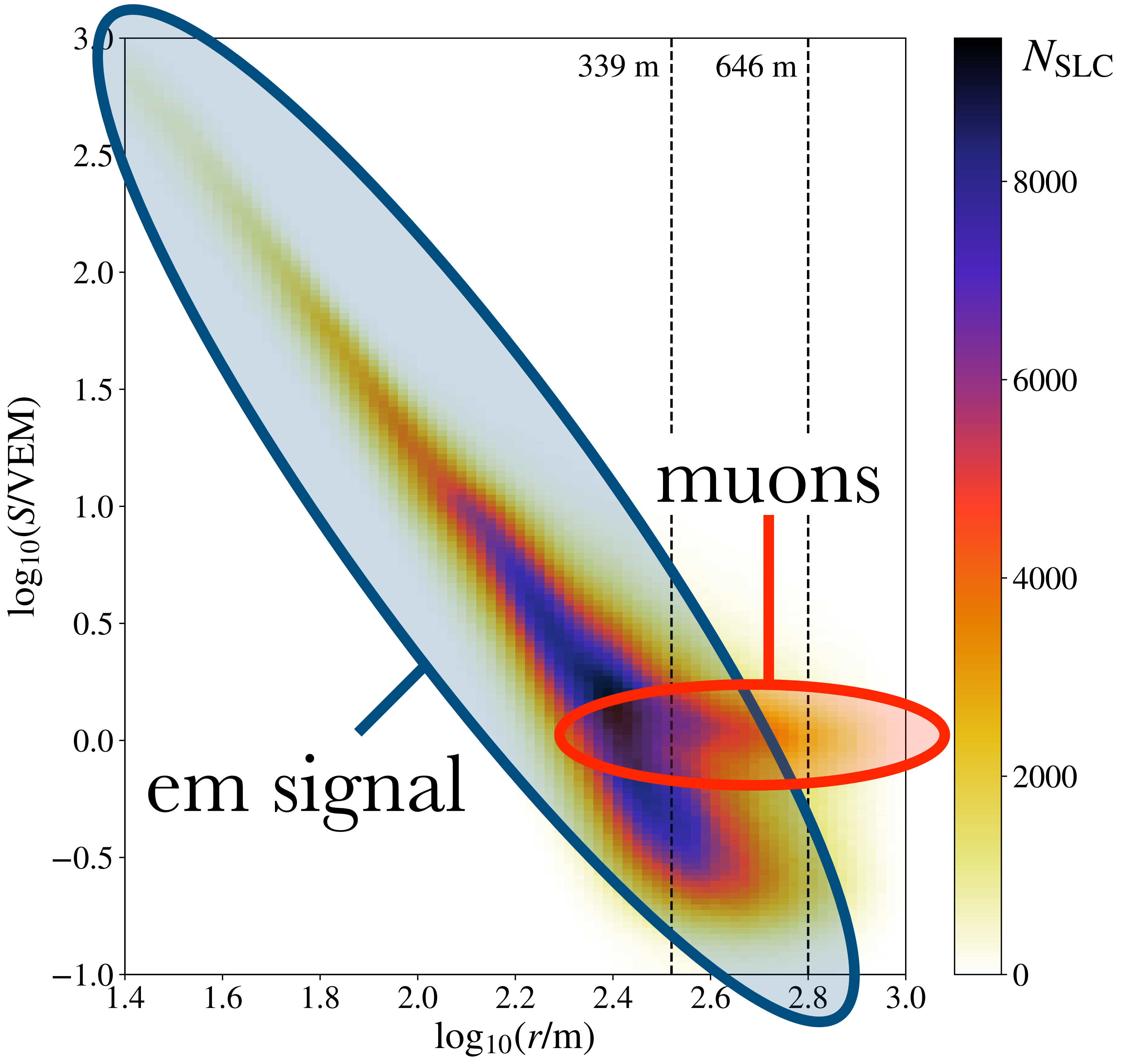


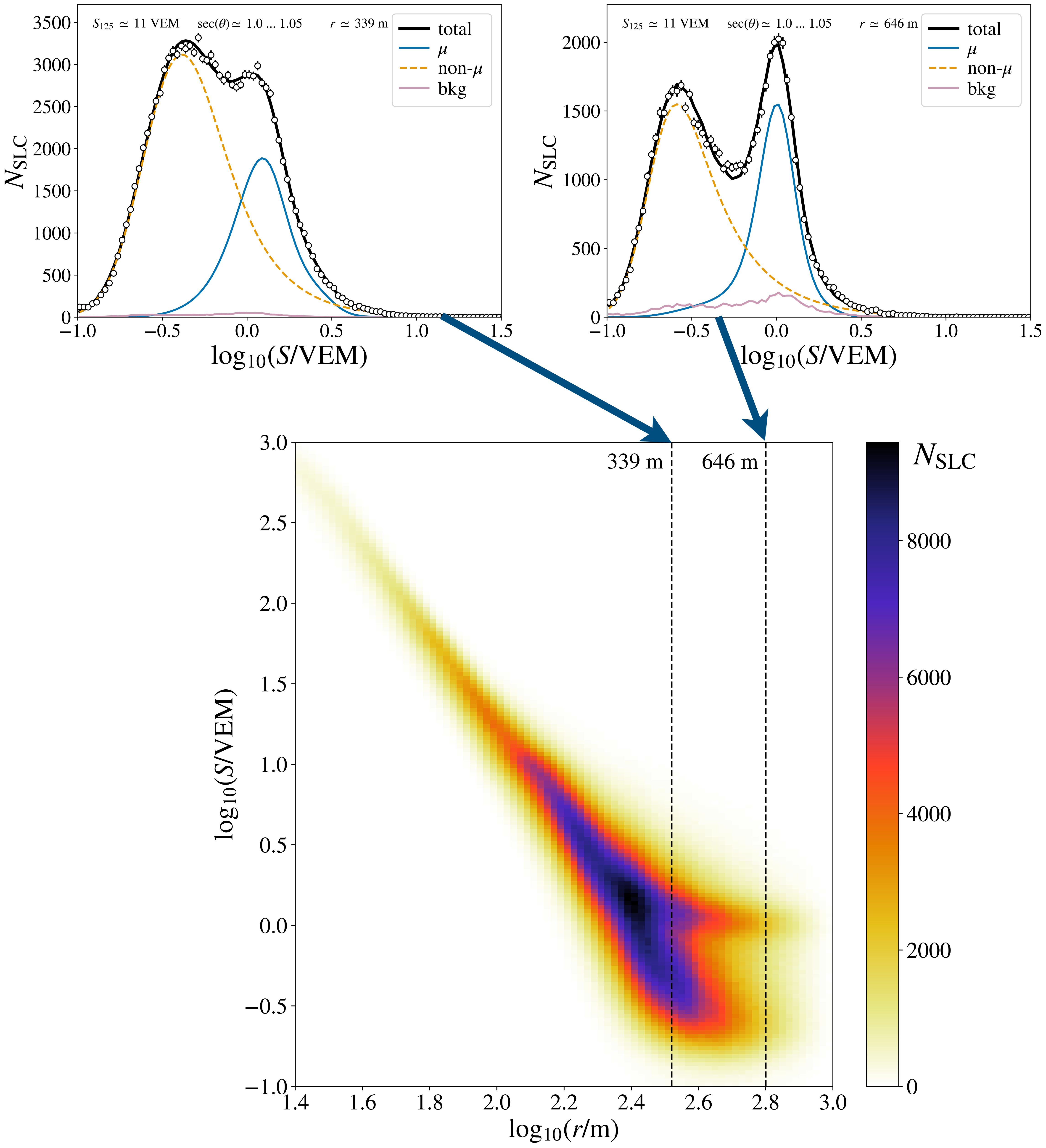




[IceCube Collaboration, Phys. Rev. D 106 (2022)]

GeV Muons in IceTop

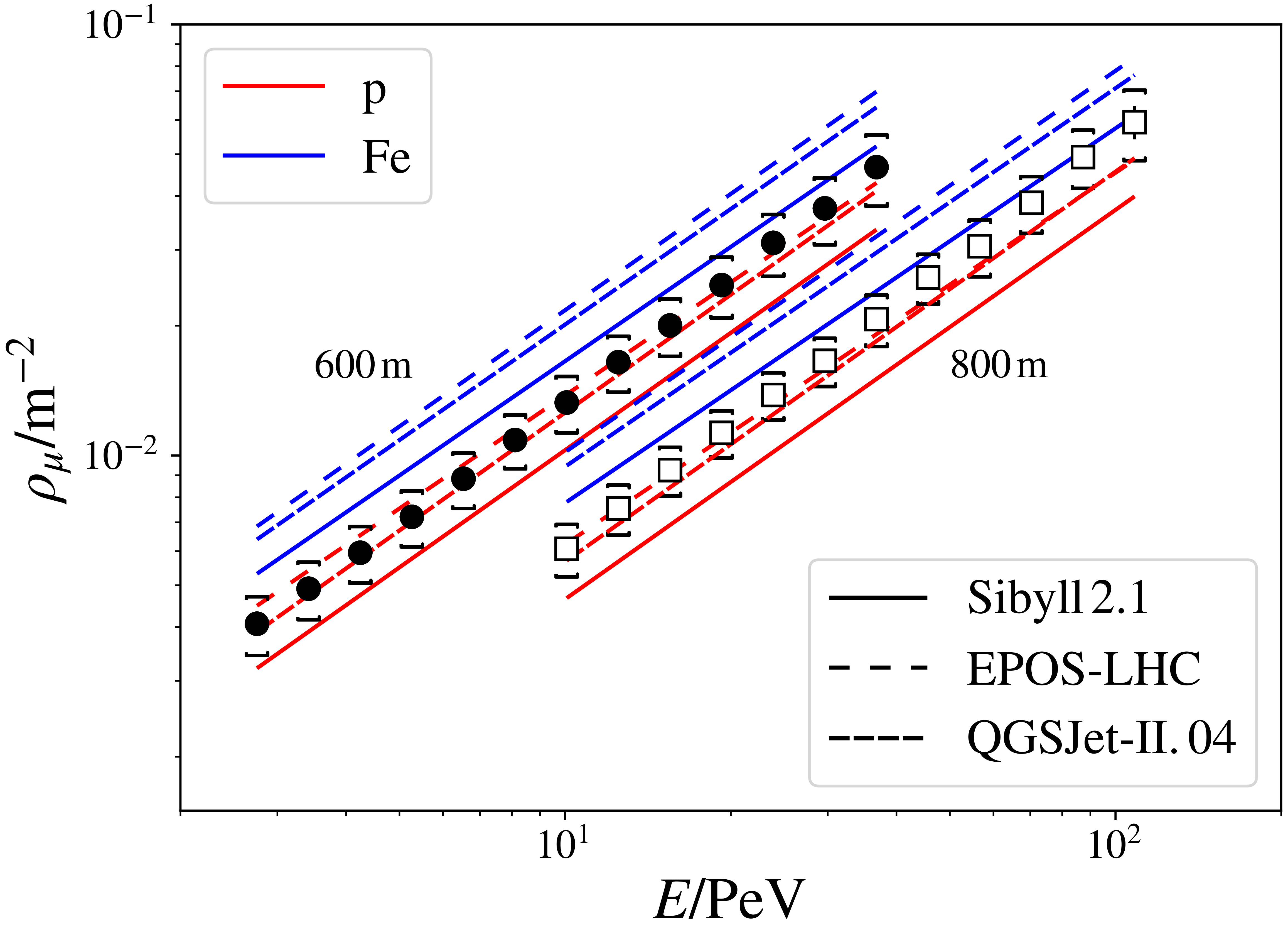
- Complex signal model, includes:
  - electromagnetic response model
  - muon response model
  - uncorrelated background
- Larger muon fraction at large distances from the shower central region
- Likelihood fits at 600 m and 800 m from the core in bins of the EAS energy
- <u>Muon density as a function of CR energy!</u>
- Notice: No event-by-event information
  - Improved analyses currently in progress…

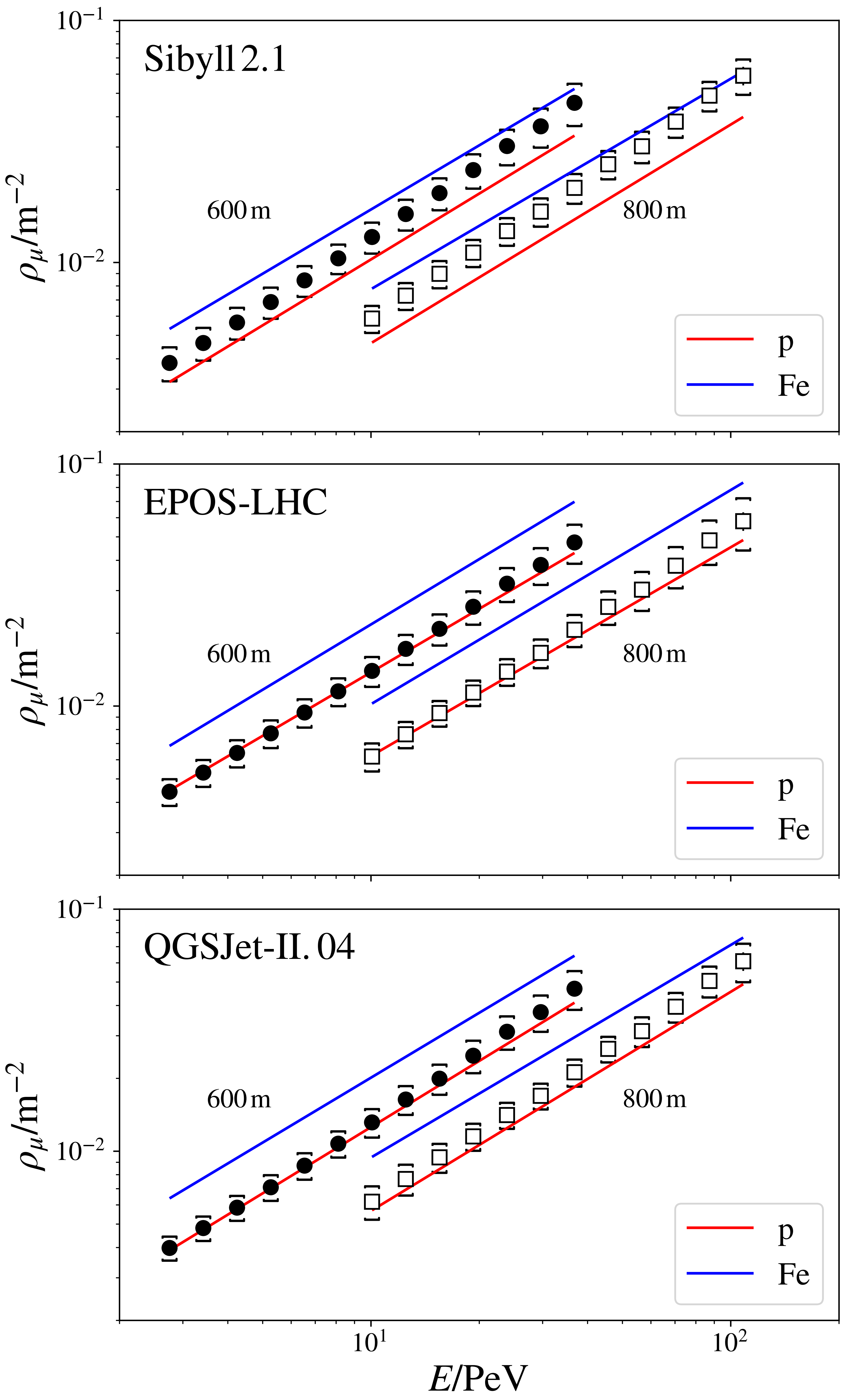


[IceCube Collaboration, Phys. Rev. D 106 (2022)]

GeV Muons in IceTop

- Muon densities compared to hadronic model predictions





- How does the data compare to the actual CR flux?

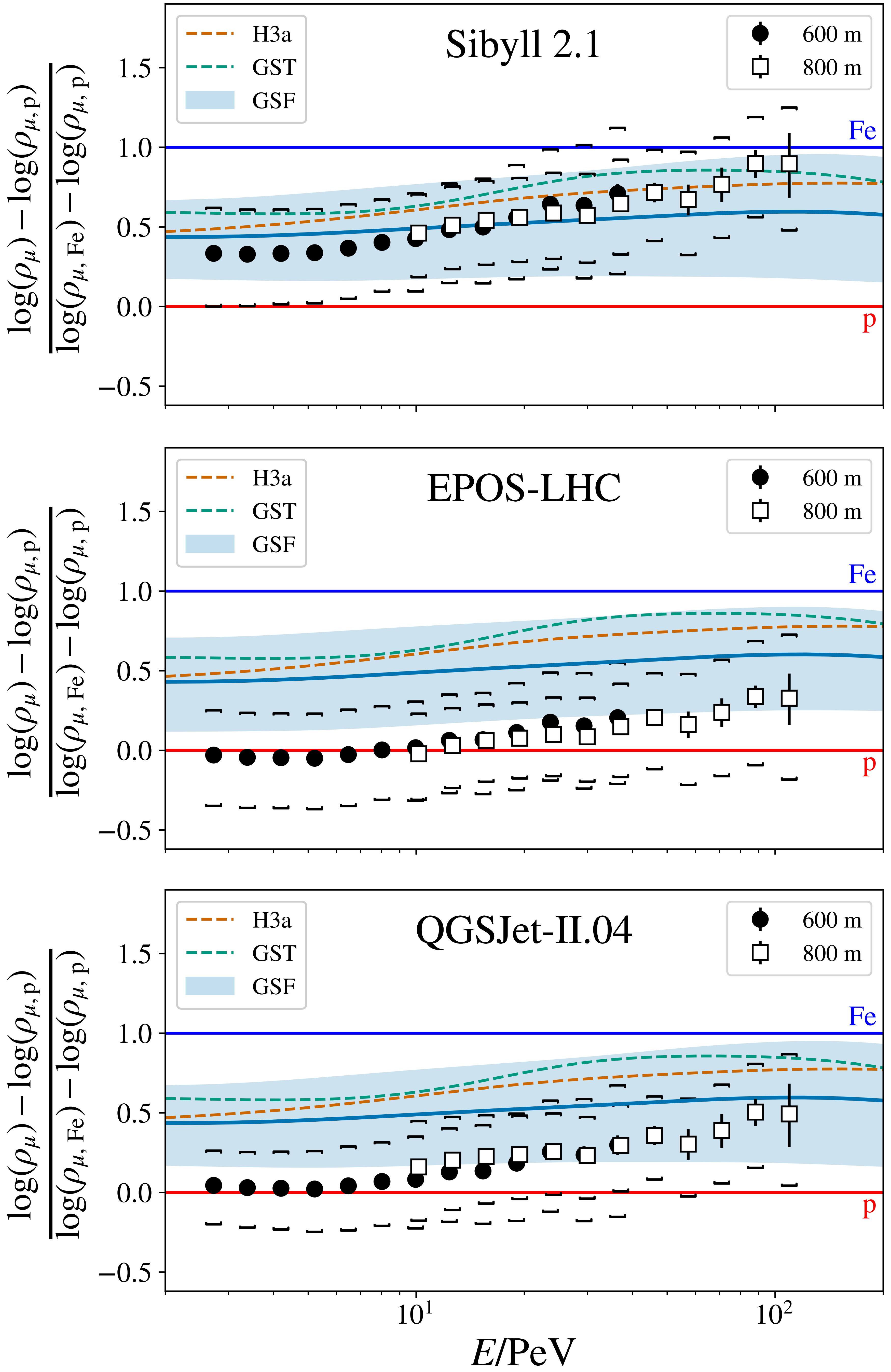
[IceCube Collaboration, Phys. Rev. D 106 (2022)]

GeV Muons in IceTop

- The z-scale:

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

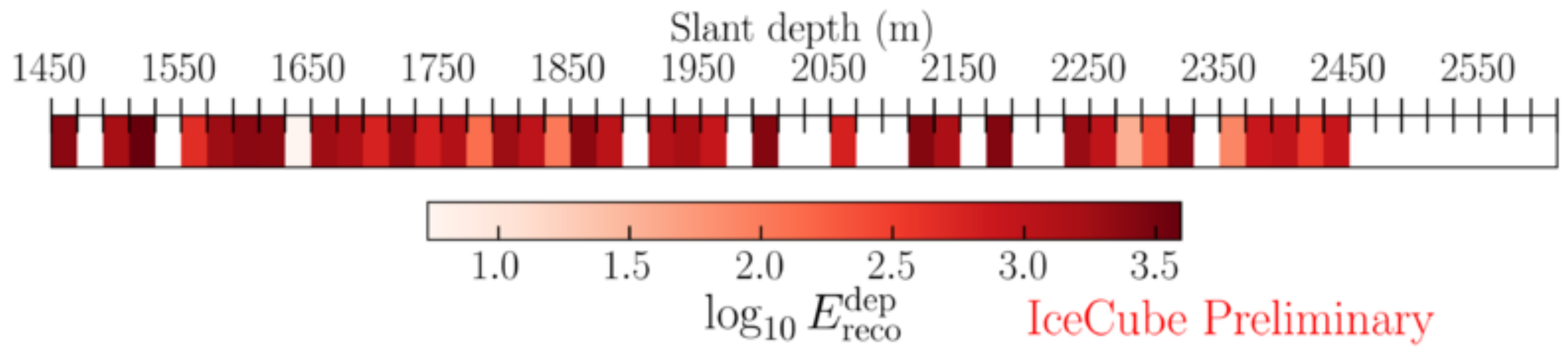
  - Proton: $z = 0$, iron: $z = 1$
- Comparison for different flux model predictions
- Best data/MC agreement for Sibyll 2.1
- EPOS-LHC and QGSJet-II.04 yield very light masses (they predict more muons)
- Comparison with other experiments?
  - See talk by Lorenzo Cazon!

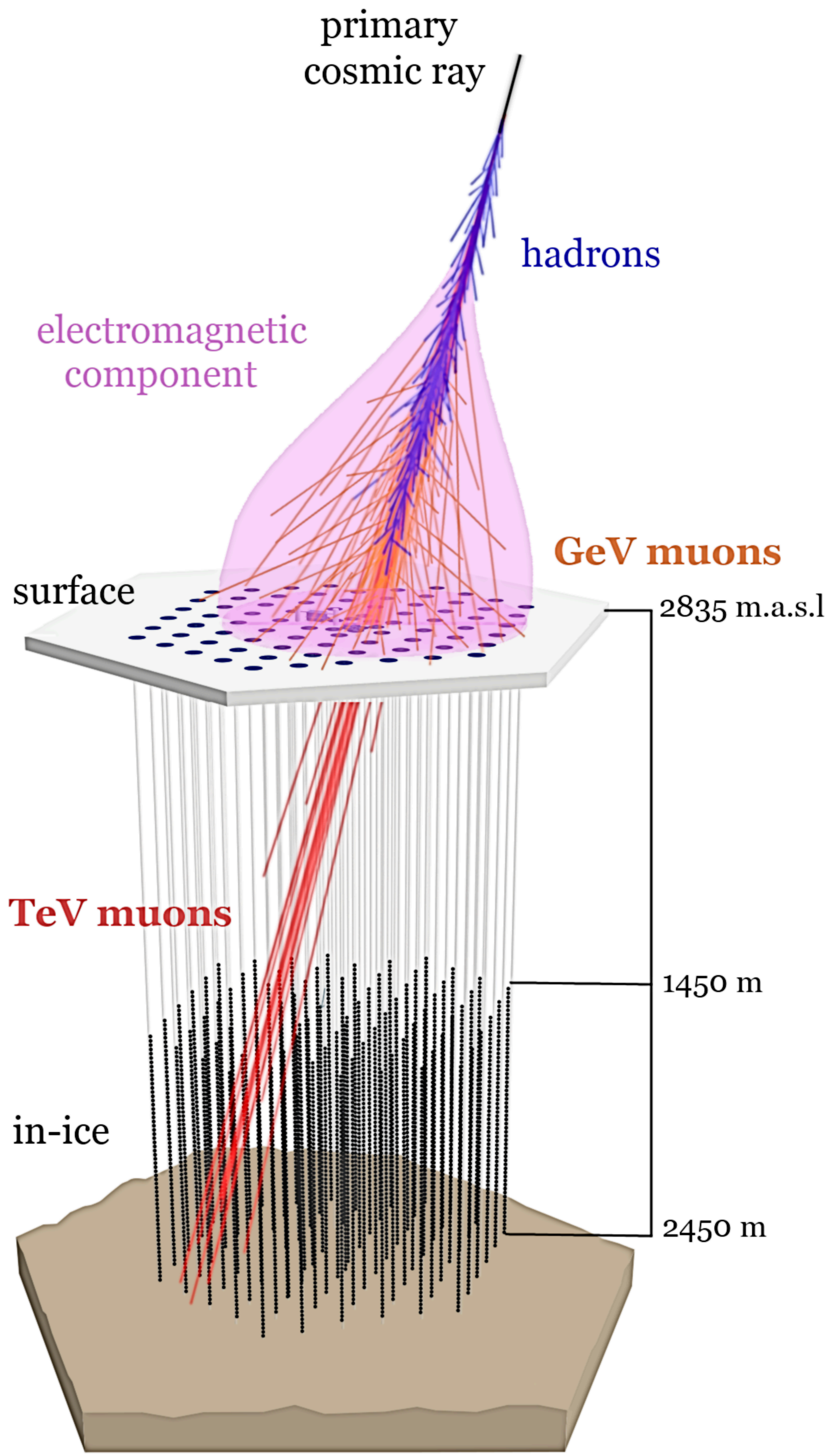


[IceCube Collaboration, Phys. Rev. D 106 (2022)]

TeV Muons in IceCube

- Coincident machine learning analysis using IceTop and in-ice detector (event-by-event basis)
- Neural network inputs:
  - IceTop: zenith angle, energy proxy S125
  - In-ice: energy loss profile vector
- Neural network outputs:
  - Primary CR energy
  - Multiplicity of in-ice muons above 500 GeV

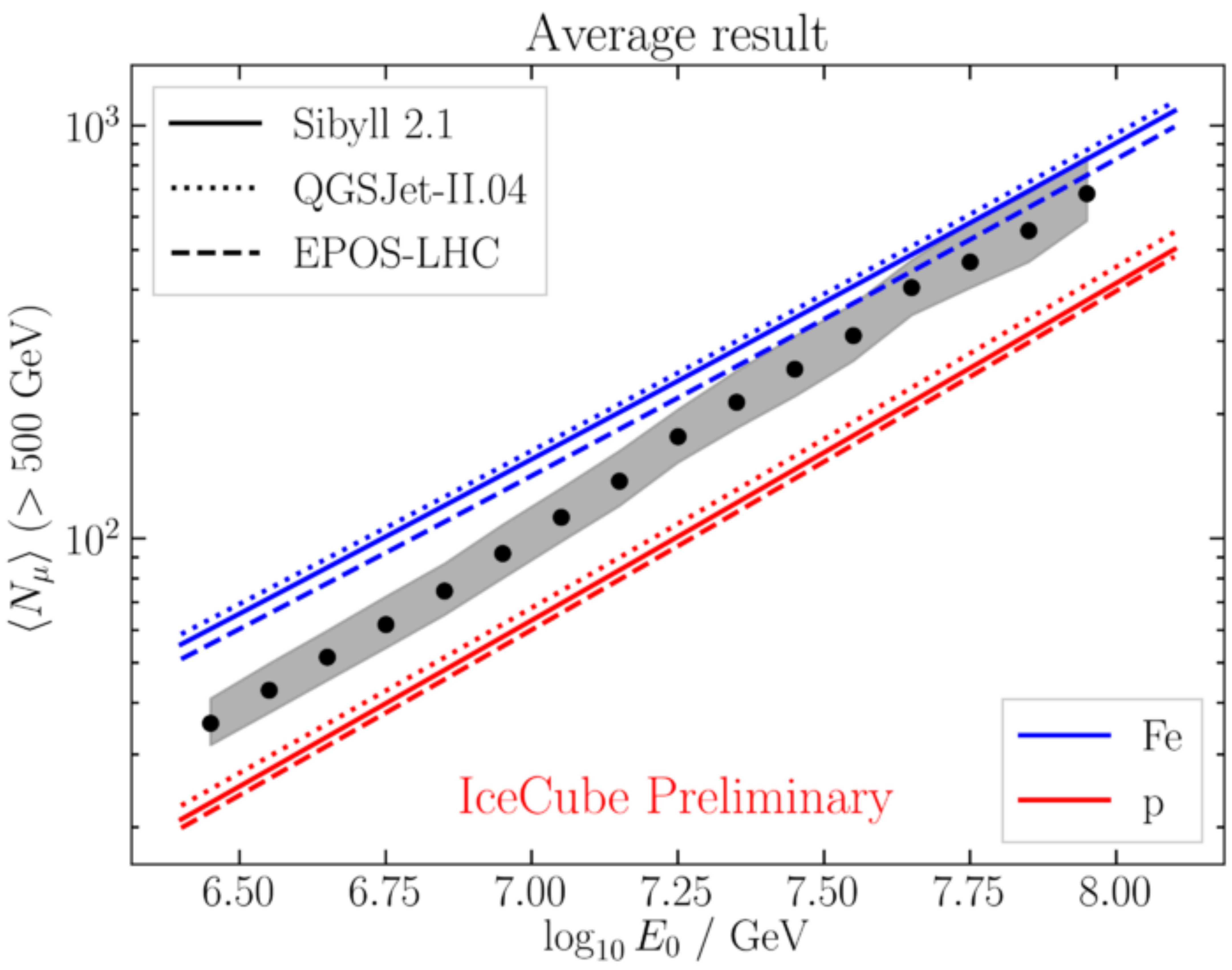




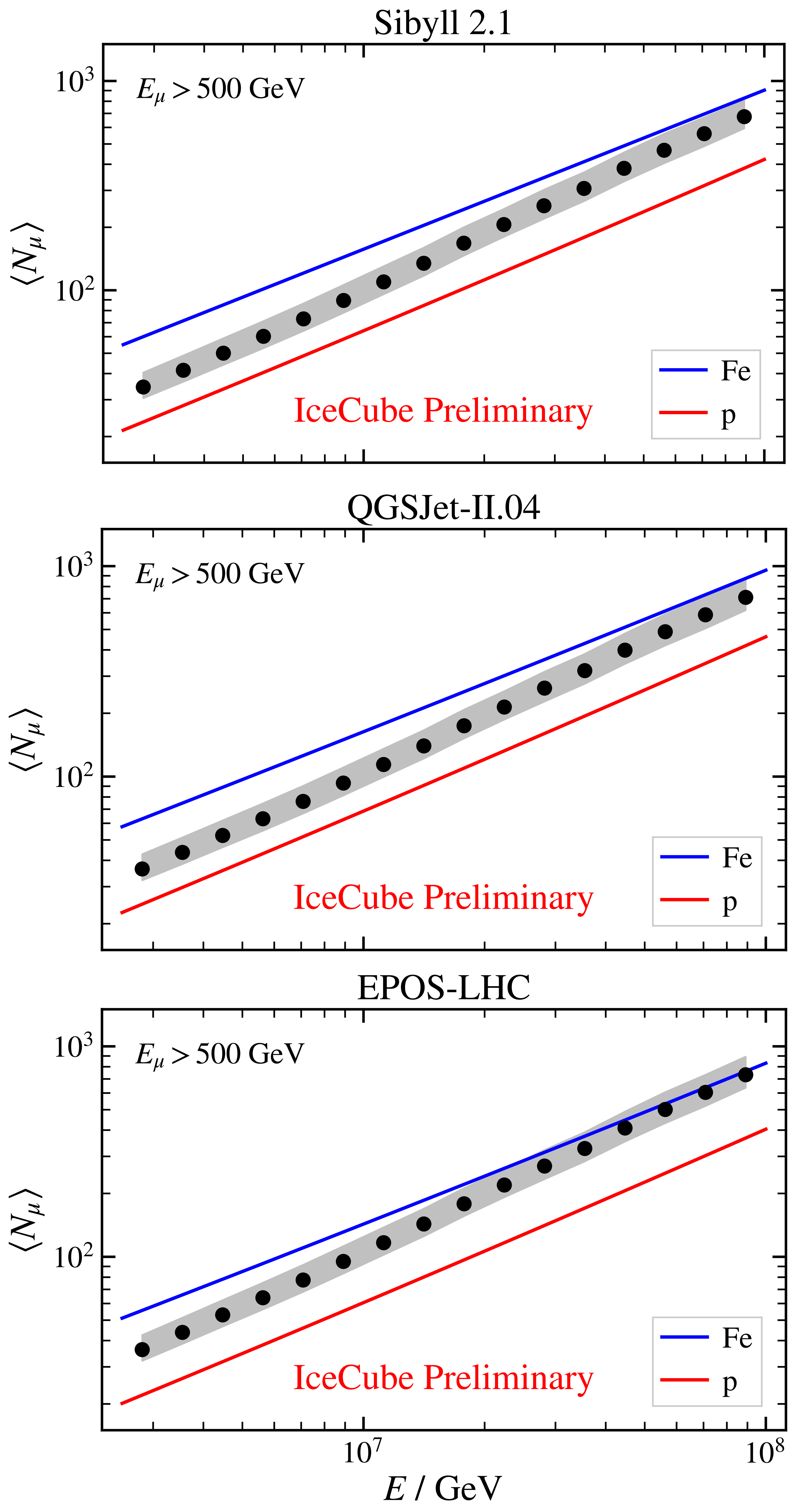
[S. Verpoest (for the IceCube Collaboration), PoS ICRC2023 (2023) 207]

TeV Muons in IceCube

- Muon bundle multiplicity compared to model predictions



- How does the data compare to CR flux models?



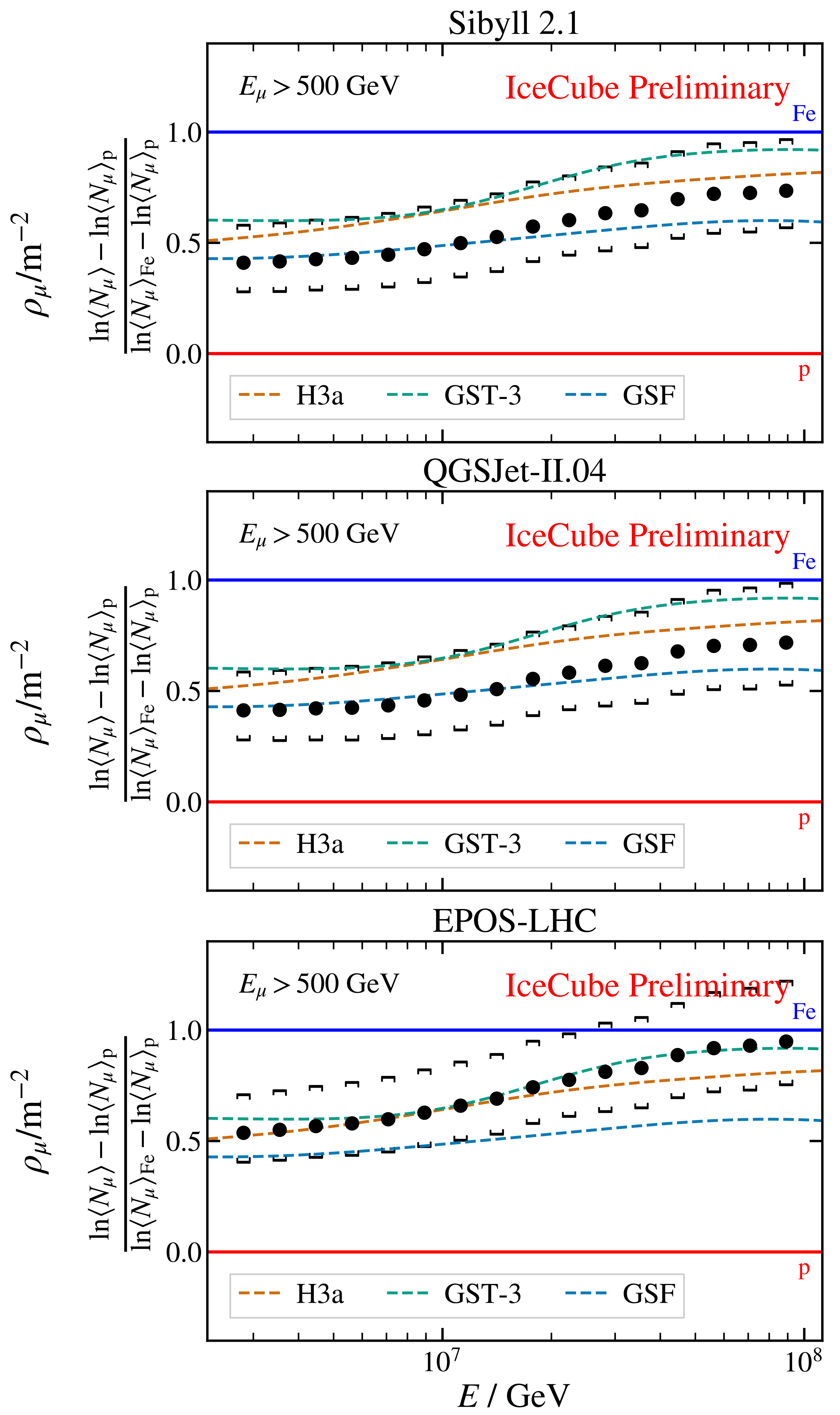
[S. Verpoest (for the IceCube Collaboration), PoS ICRC2023 (2023) 207]

TeV Muons in IceCube

- Reminder z-scale:

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

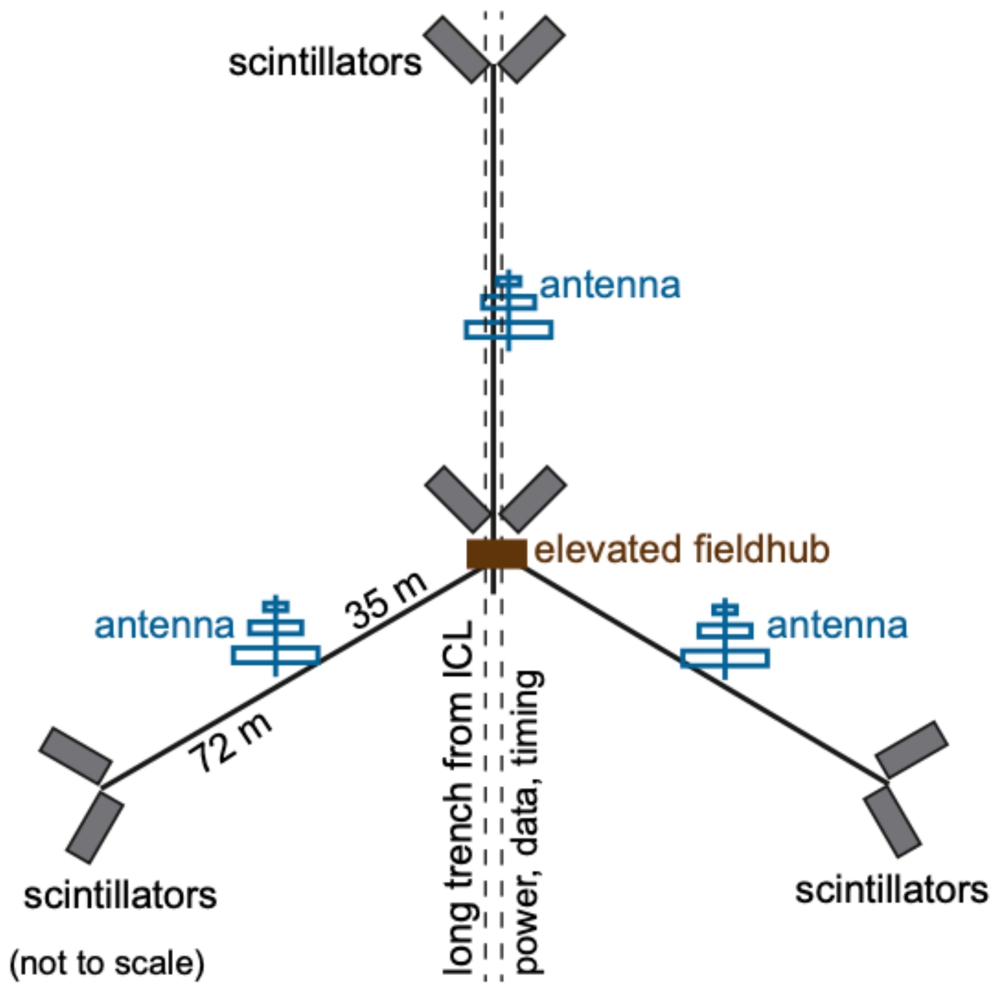
  - Proton: $z = 0$, iron: $z = 1$
- Comparison for different flux model predictions
- Good agreement in TeV muons for all models!
- Inconsistencies between GeV and TeV muons in post-LHC models, i.e. EPOS-LHC and QGSJet-II.04!

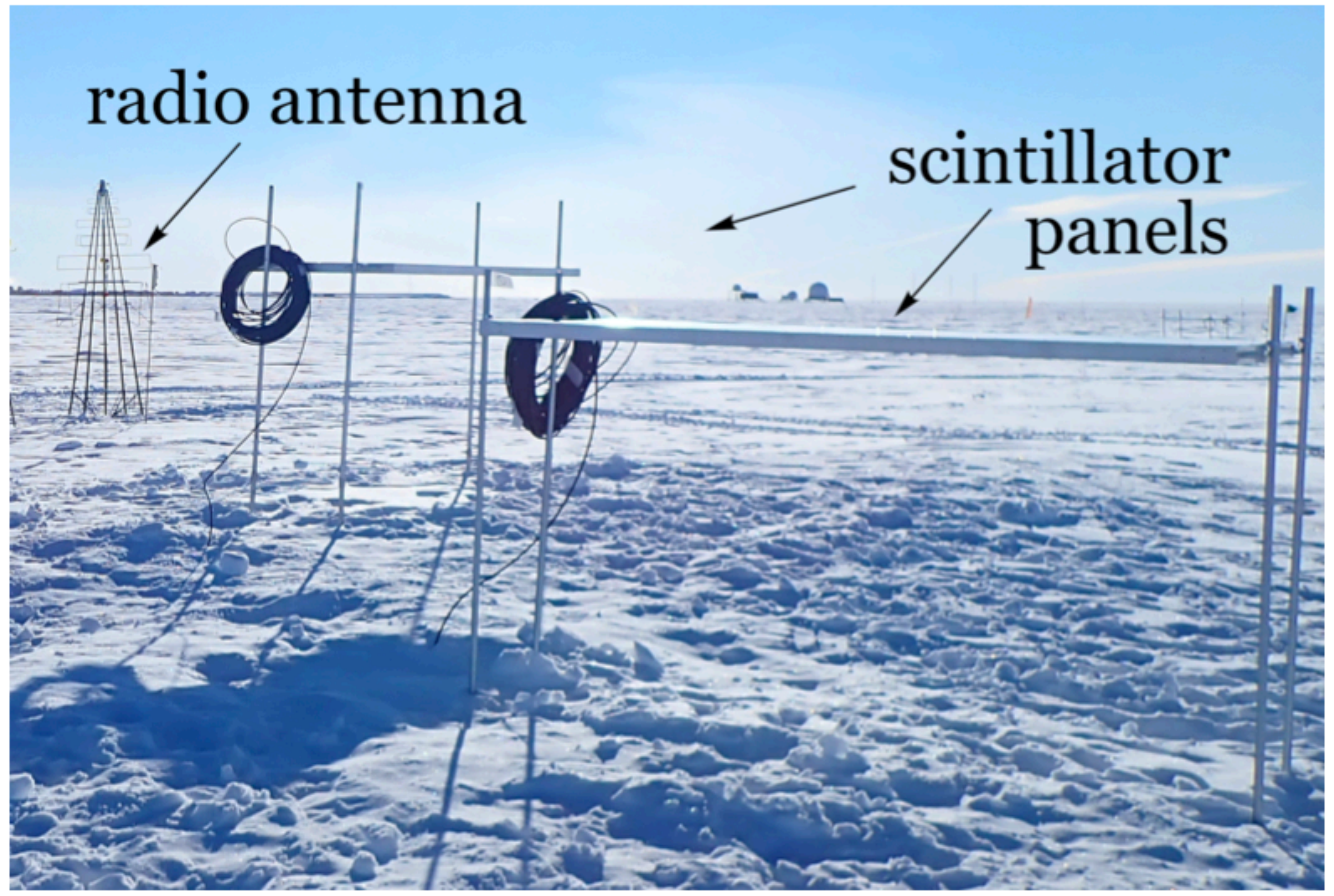


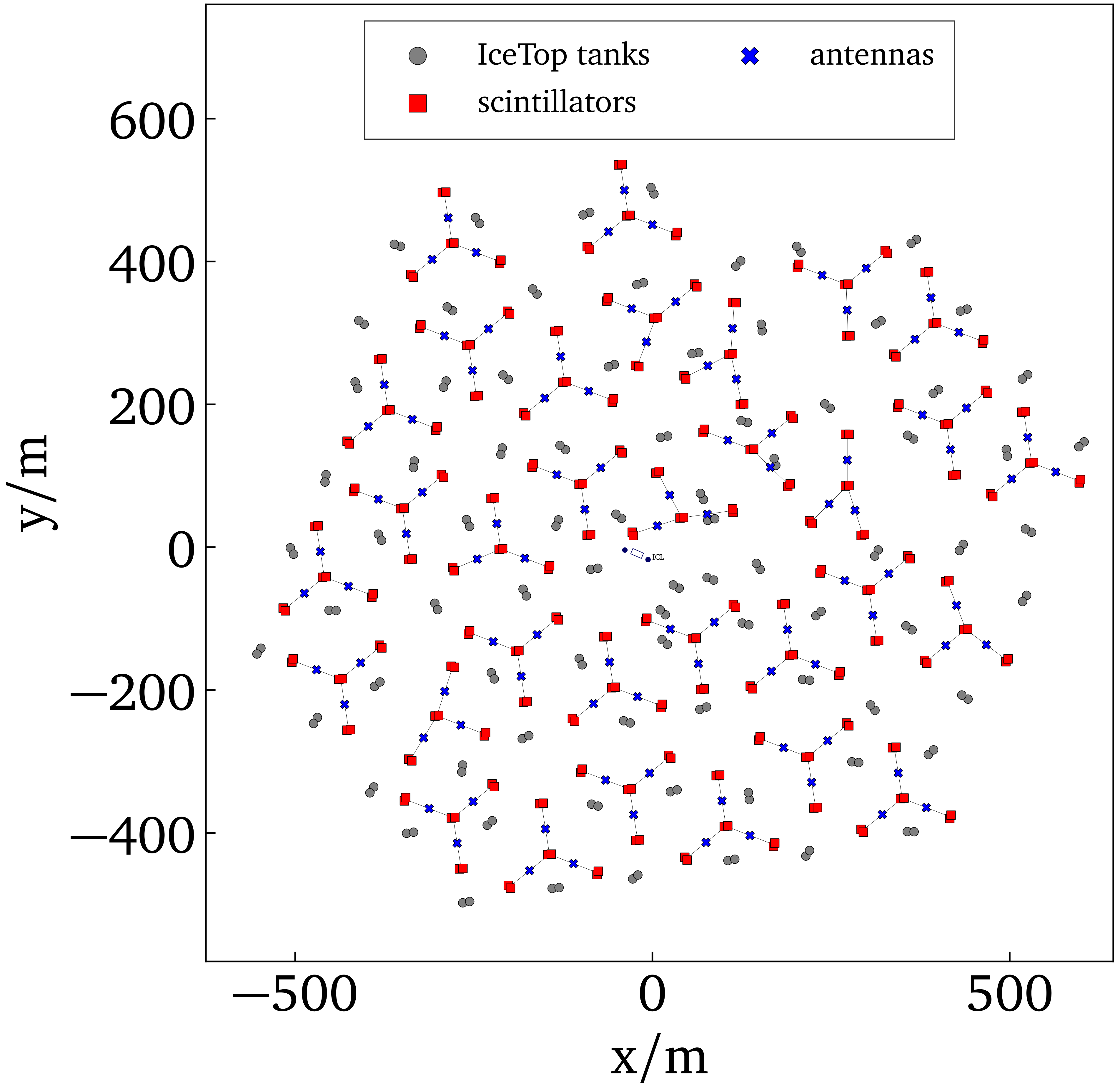
[S. Verpoest (for the IceCube Collaboration), PoS ICRC2023 (2023) 207]

Future Detector Improvements

- Surface enhancement in progress:
  - New scintillator array
    - Better GeV muon separation in EAS
  - New radio antenna array
    - Improved EAS energy reconstruction
    - Increased angular acceptance



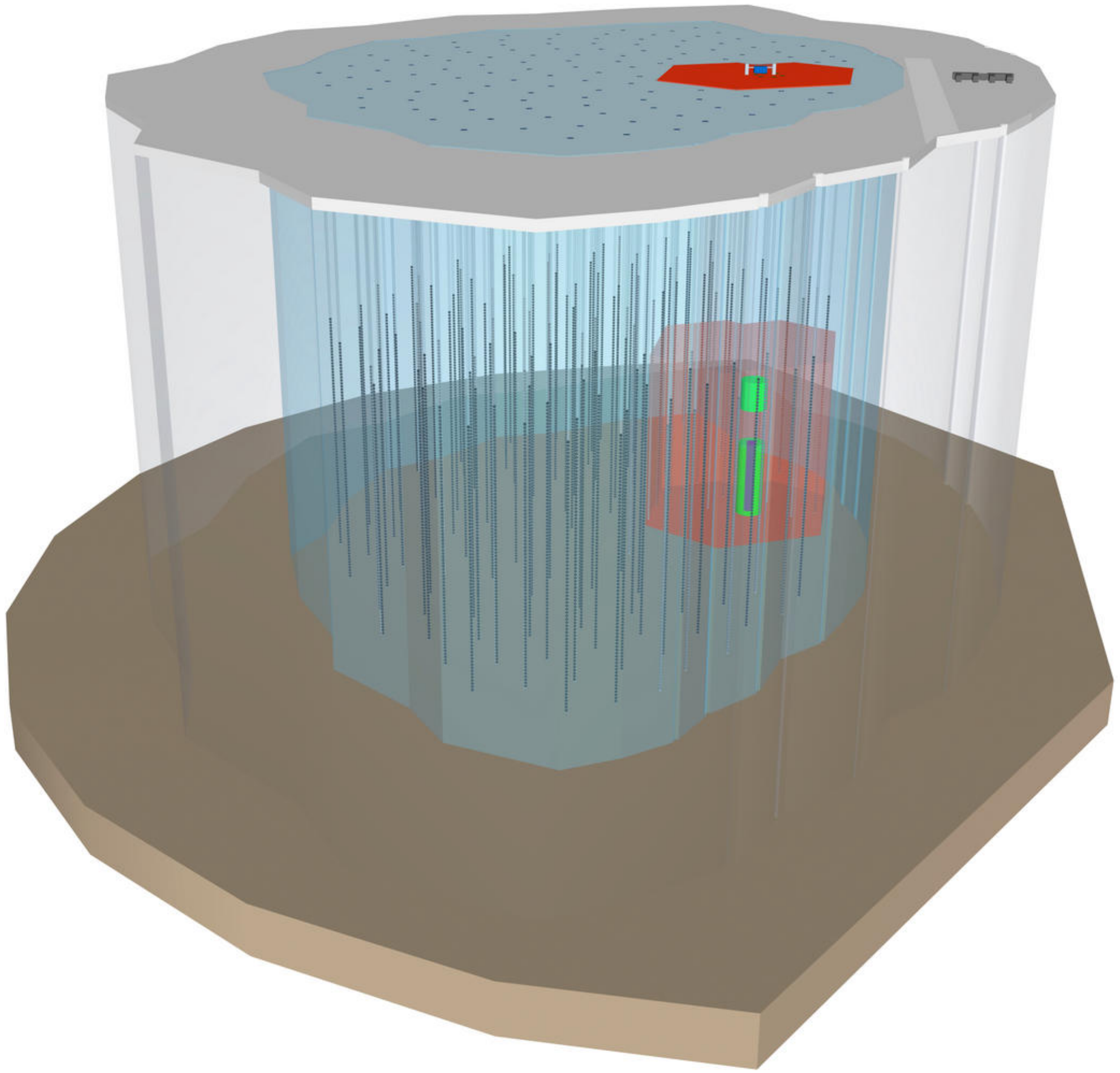




[A. Haungs et al., EPJ Web Conf. 210 (2019)]

Future Detector Improvements

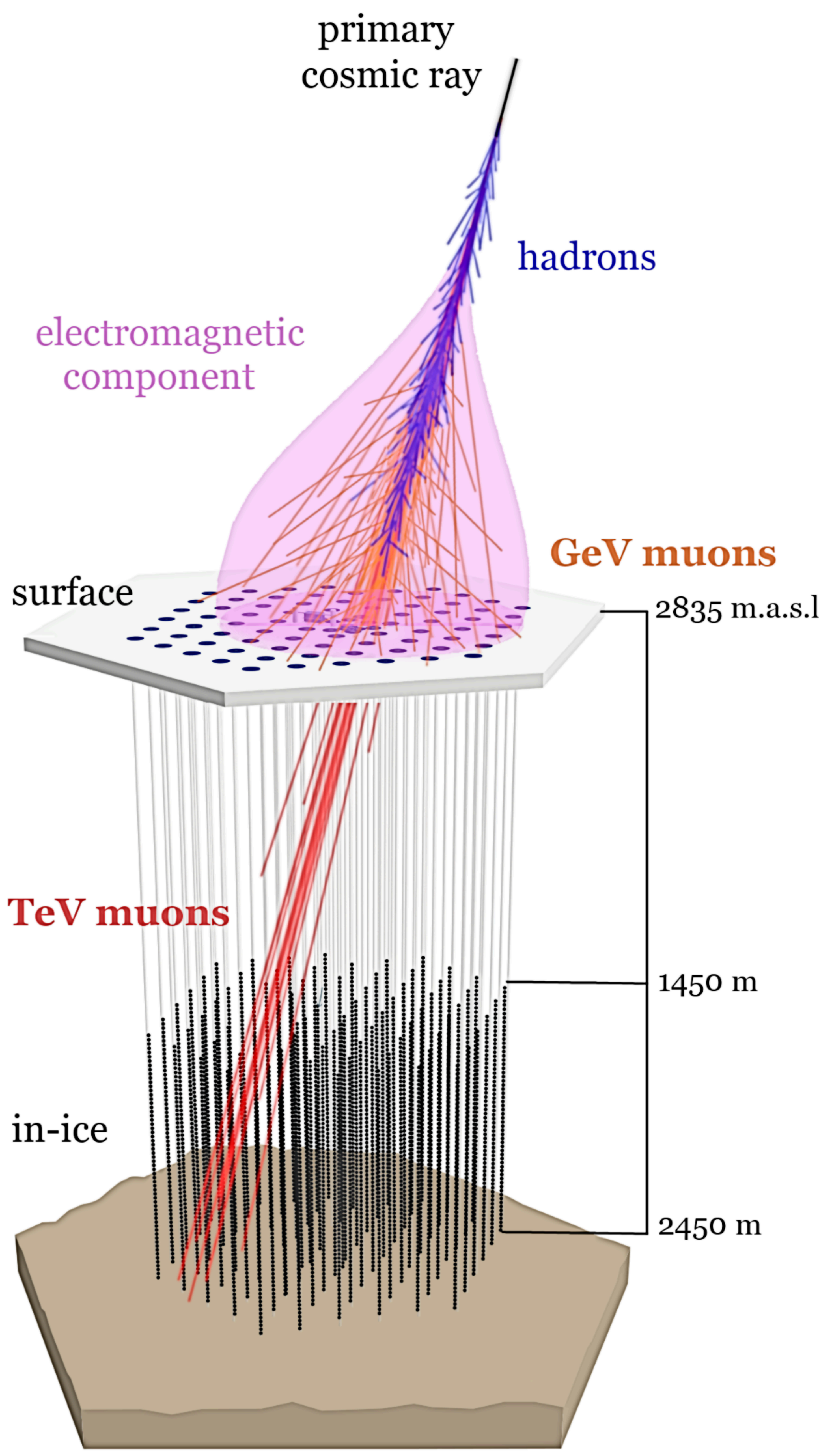
- IceCube-Gen2:
  - Significant larger in-ice and surface detectors
  - Increased solid angle, larger inclinations
  - Increased statistics at the highest energies
    - Measurement of prompt muons!
    - Close the gap to Auger in muon measurements!
  - Better understanding of the absolute energy scale
  - Reduced in-ice systematics
  - See also talk by Mirco Huennefeld



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

Conclusions

- IceTop + IceCube in-ice represents an ideal facility to study muon production in EAS!
- IceTop:
  - Measurement of GeV muons shows best agreement with Sibyll 2.1
  - EPOS-LHC and QGSJet-II.04 yield very light masses
- IceCube (in-ice):
  - Measurement of TeV muons shows agreement with all models, i.e. Sibyll 2.1, EPOS-LHC, and QGSJet-II.04
- IceTop's surface enhancement and IceCube-Gen2 will further improve studies of muon production in EAS!




Thank You!

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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