Probing Hadronic Interactions in Extensive Air Showers with the IceCube Neutrino Observatory

Teilchenkolloquium

TU Dortmund

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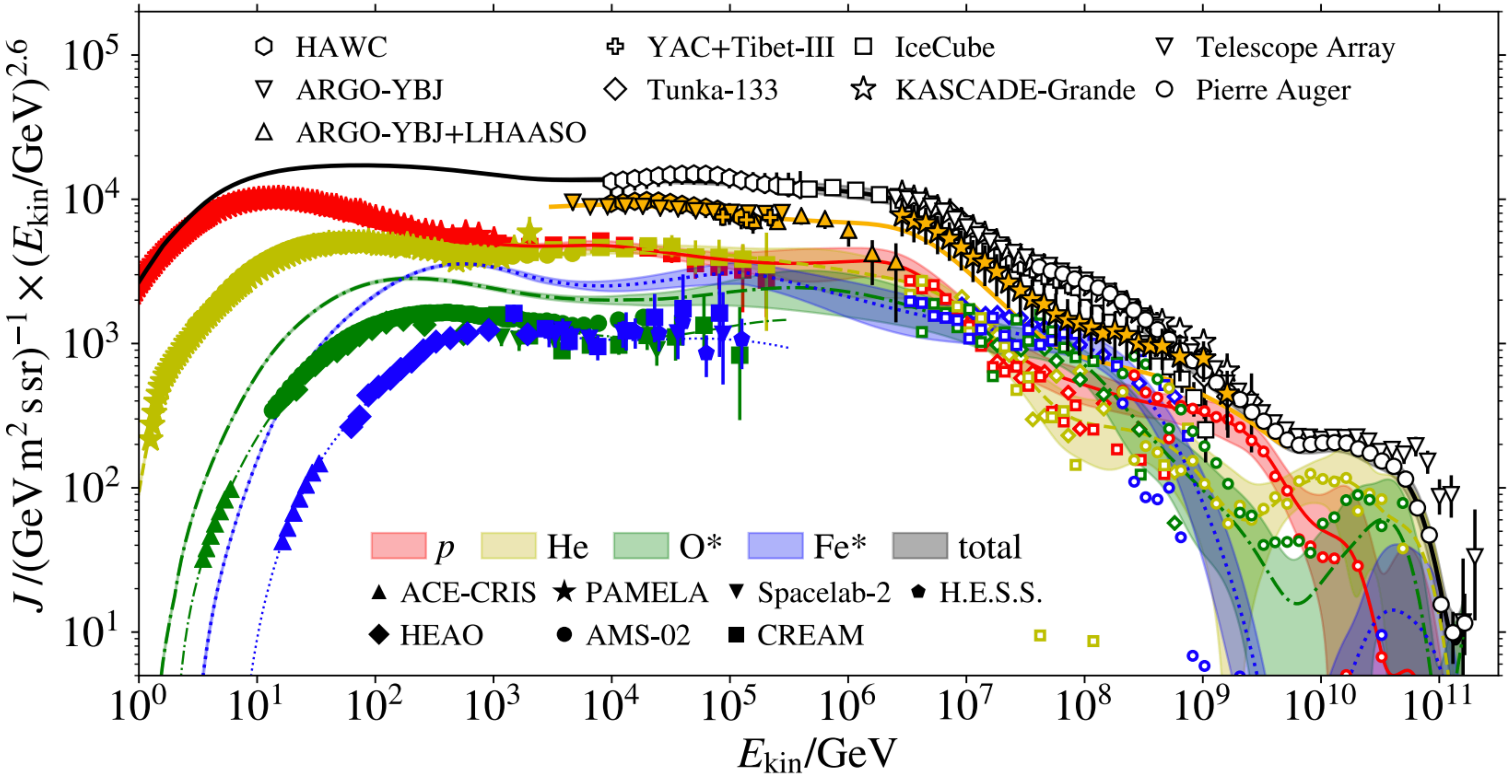
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

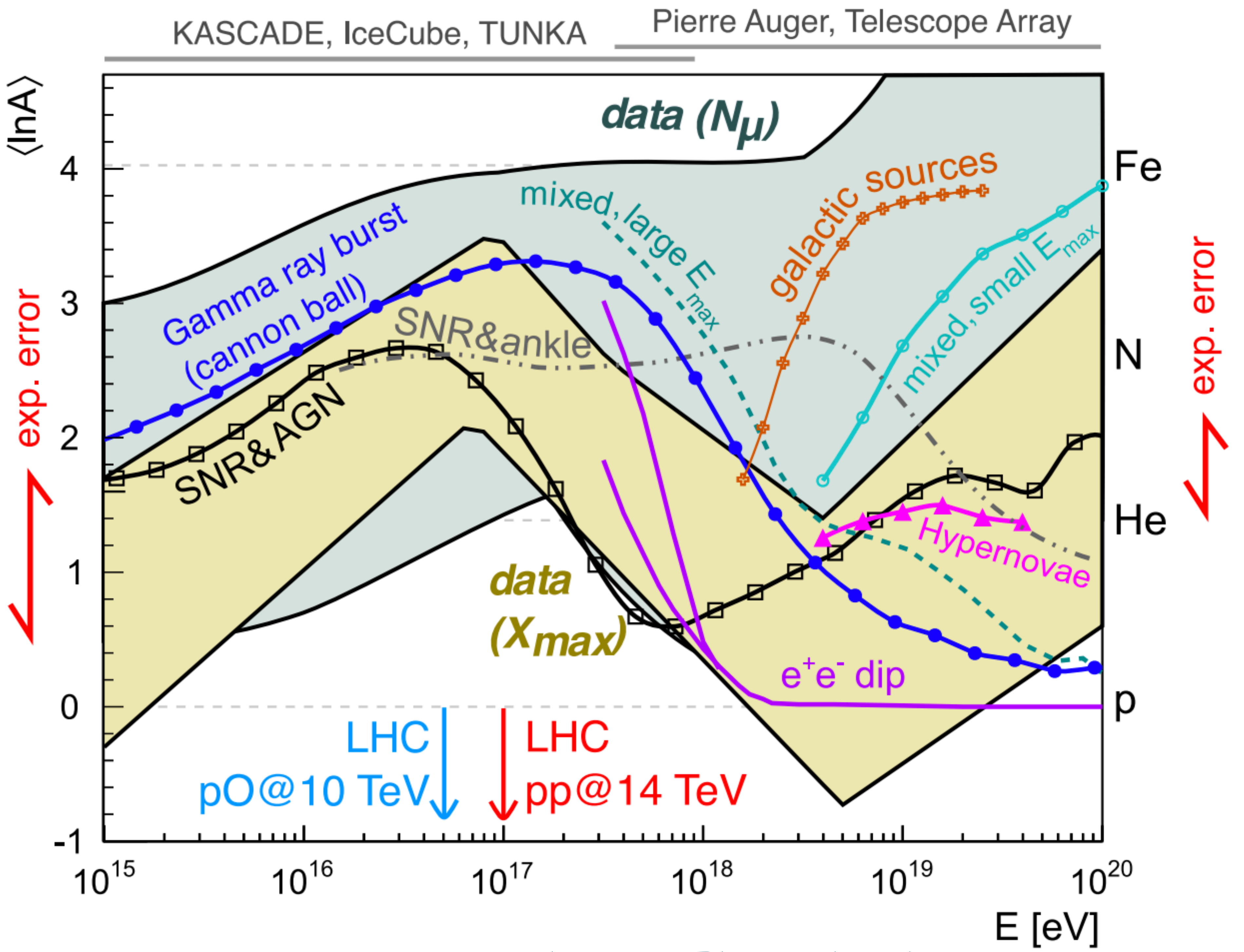
KIT
Karlsruhe Institute of Technology

Cosmic Rays

- Cosmic rays (CRs) are charged particles that reach Earth from space
- Very steep energy spectrum, well-known up to above $\sim 100\,\mathrm{EeV}$ ($10^{20}\,\mathrm{eV}$)
- However, large uncertainties in CR mass composition measurements remain!
- <u>CR properties are inferred indirectly from measurements of Extensive Air Showers (EAS)!</u>

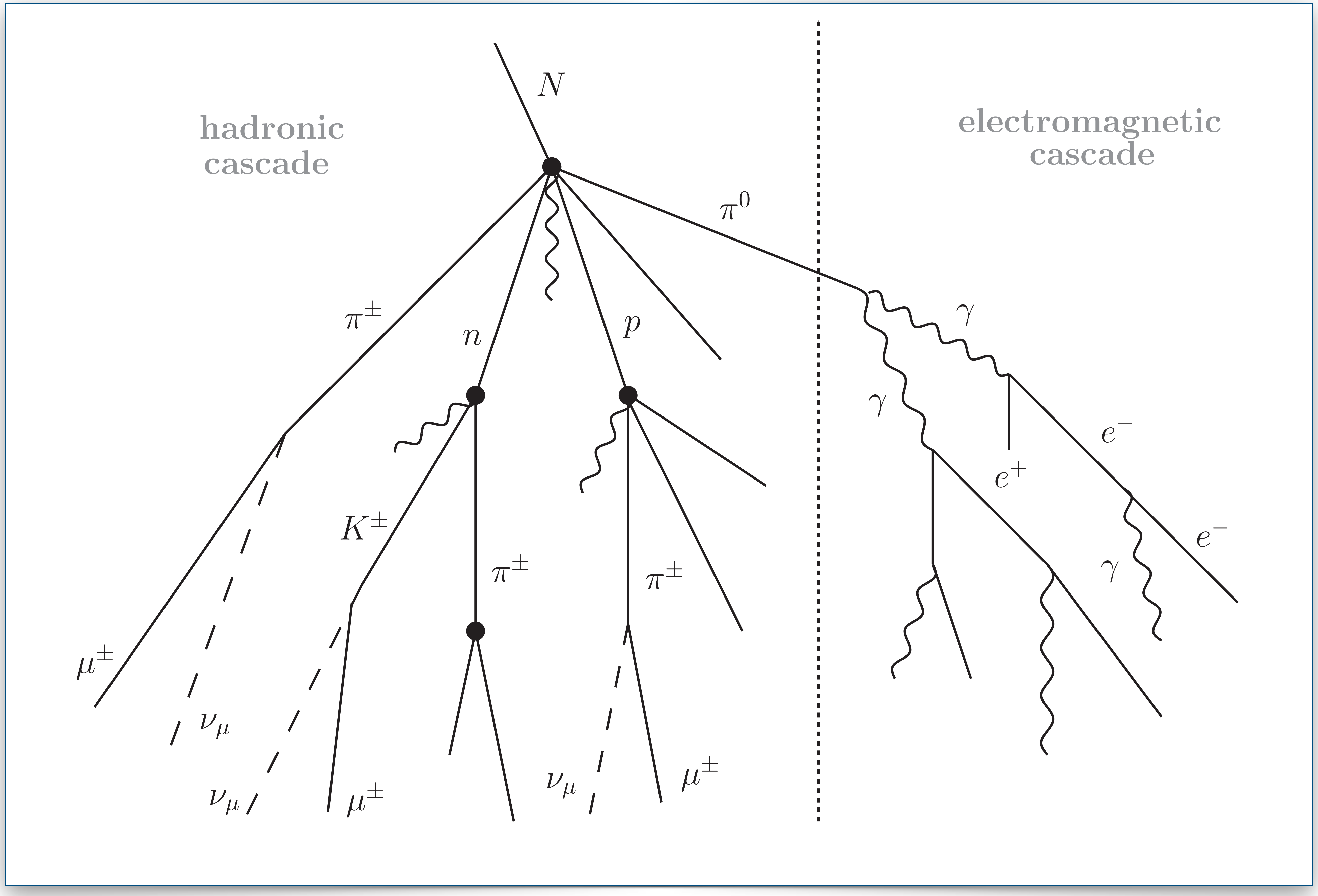


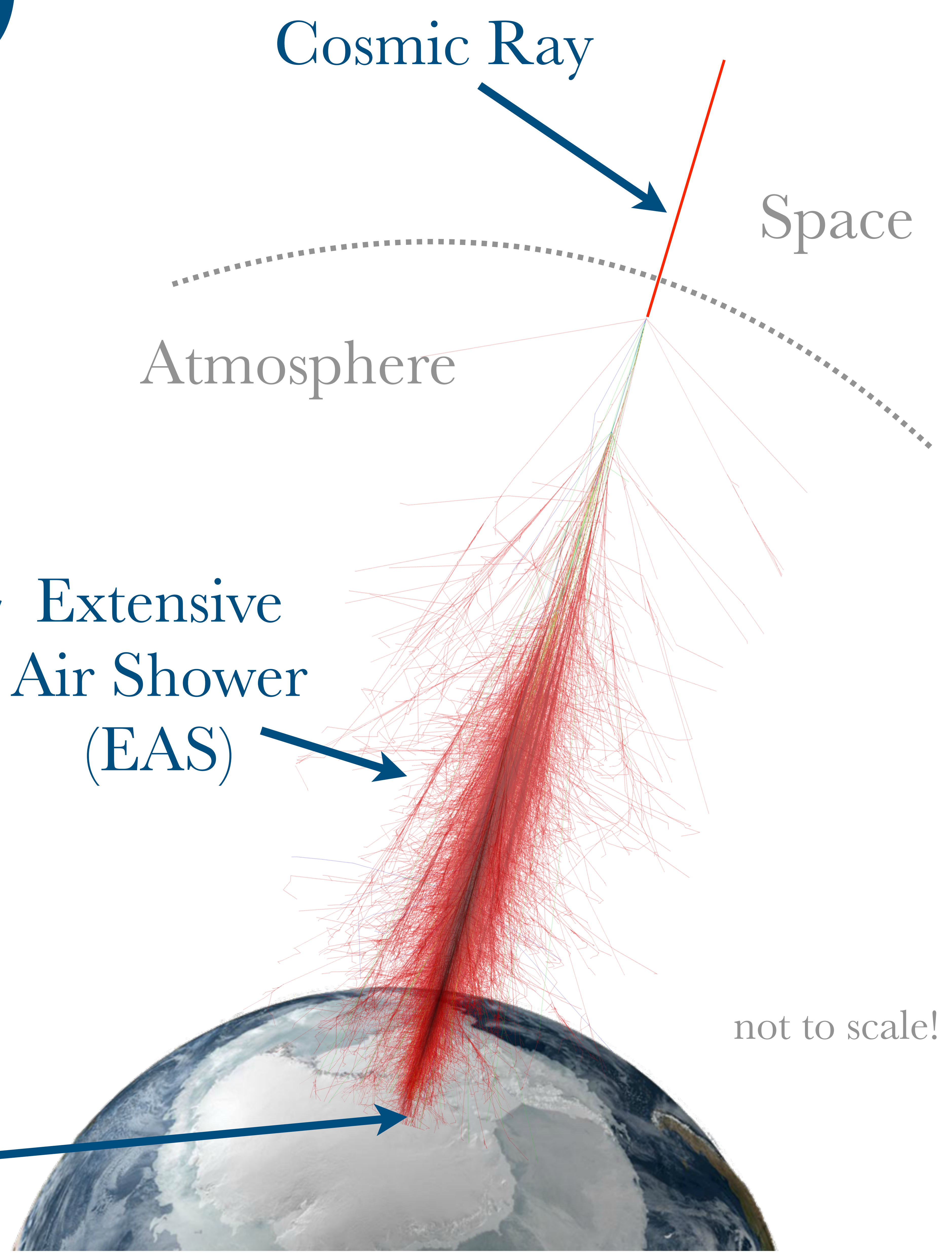
[H.P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser, F. Riehn, T. Stanev, PoS ICRC2017 (2017) 533]



[K.-H. Kampert, M. Unger, Astropart. Phys. 35 (2012) 660–678]

Extensive Air Showers (EAS)





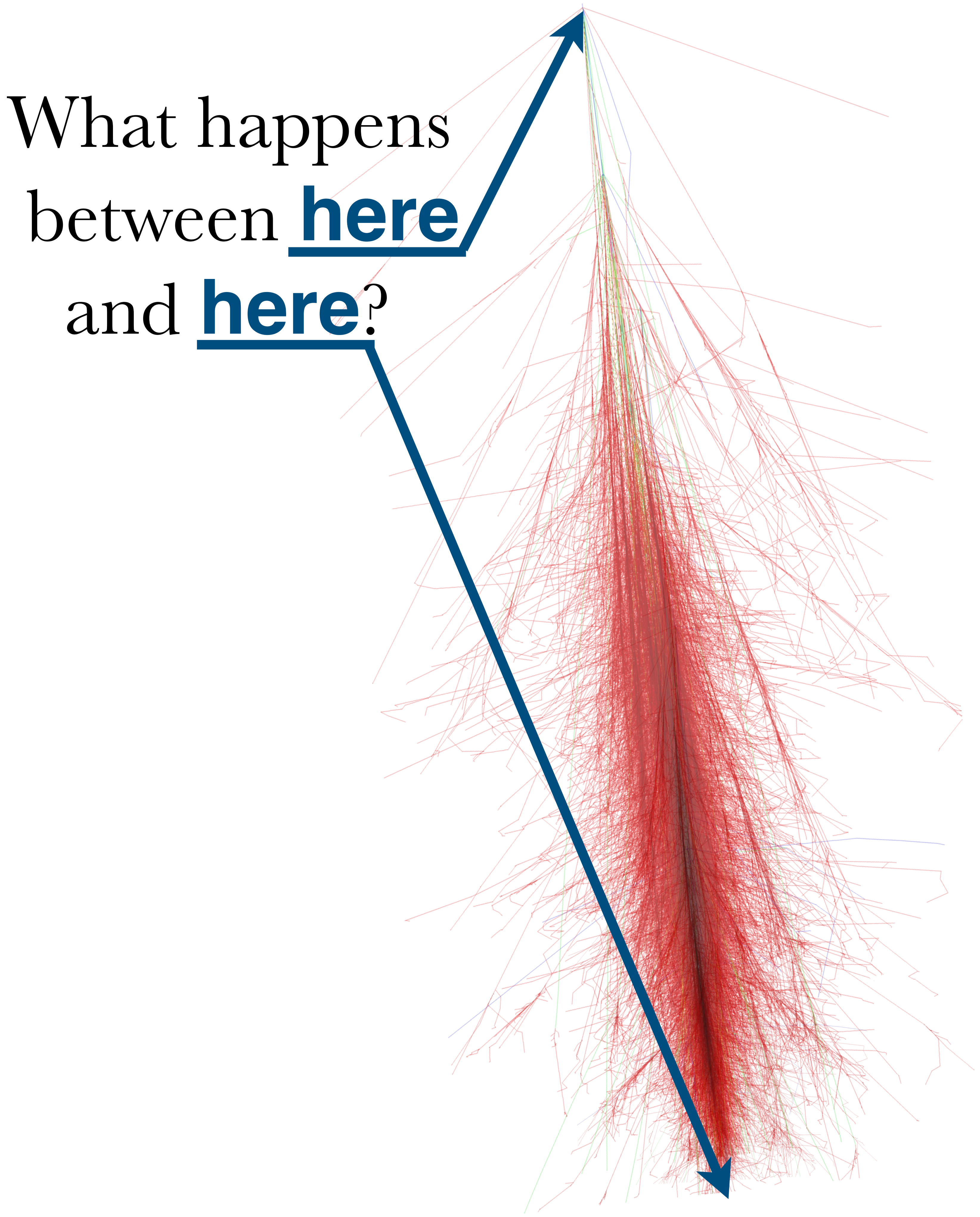
Extensive Air Shower (EAS)

Ground-Based Particle Detector

- EAS are a connection between cosmic ray and particle physics!

Extensive Air Showers (EAS)

- CR properties are inferred from the (secondary) particles measured at the ground



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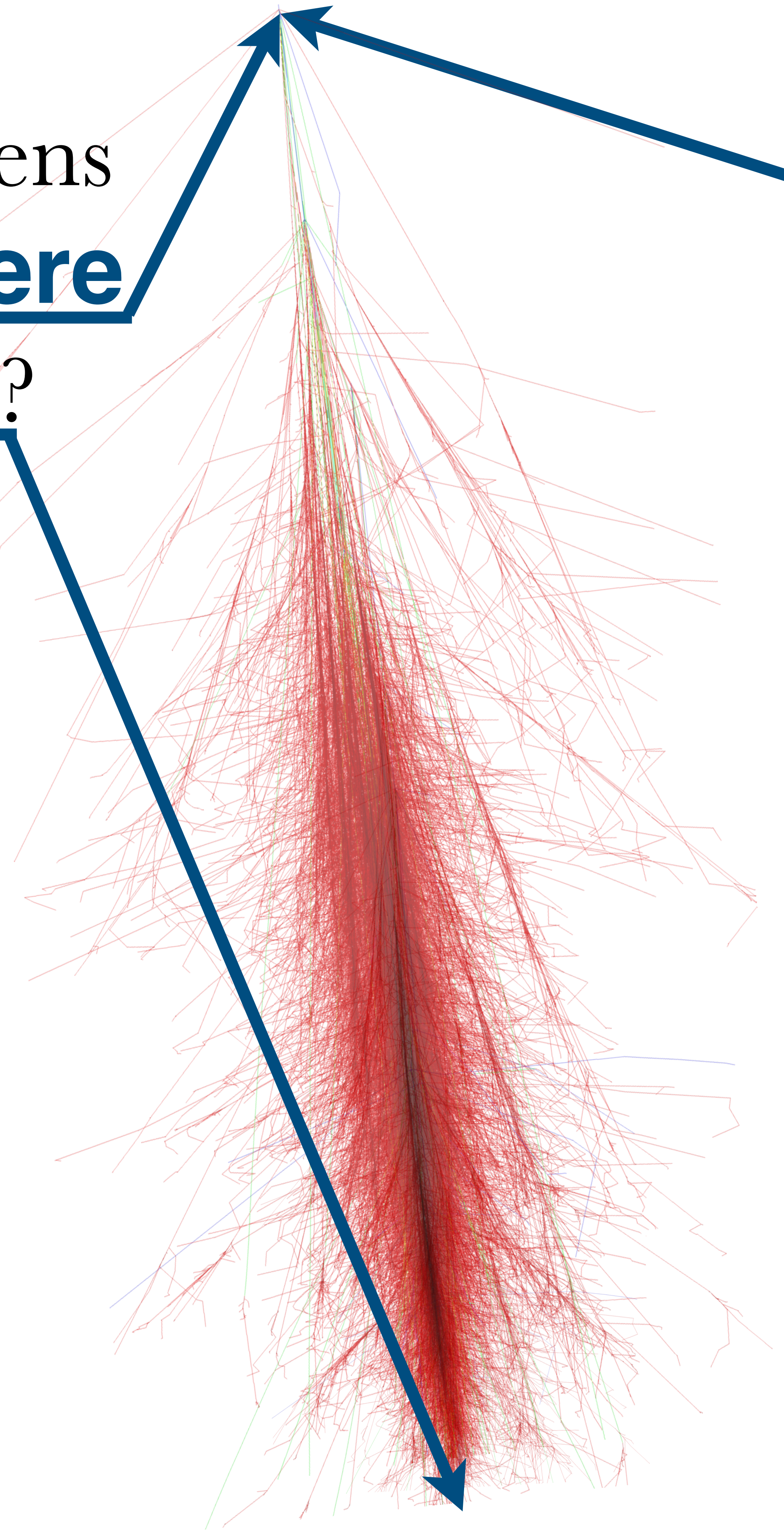

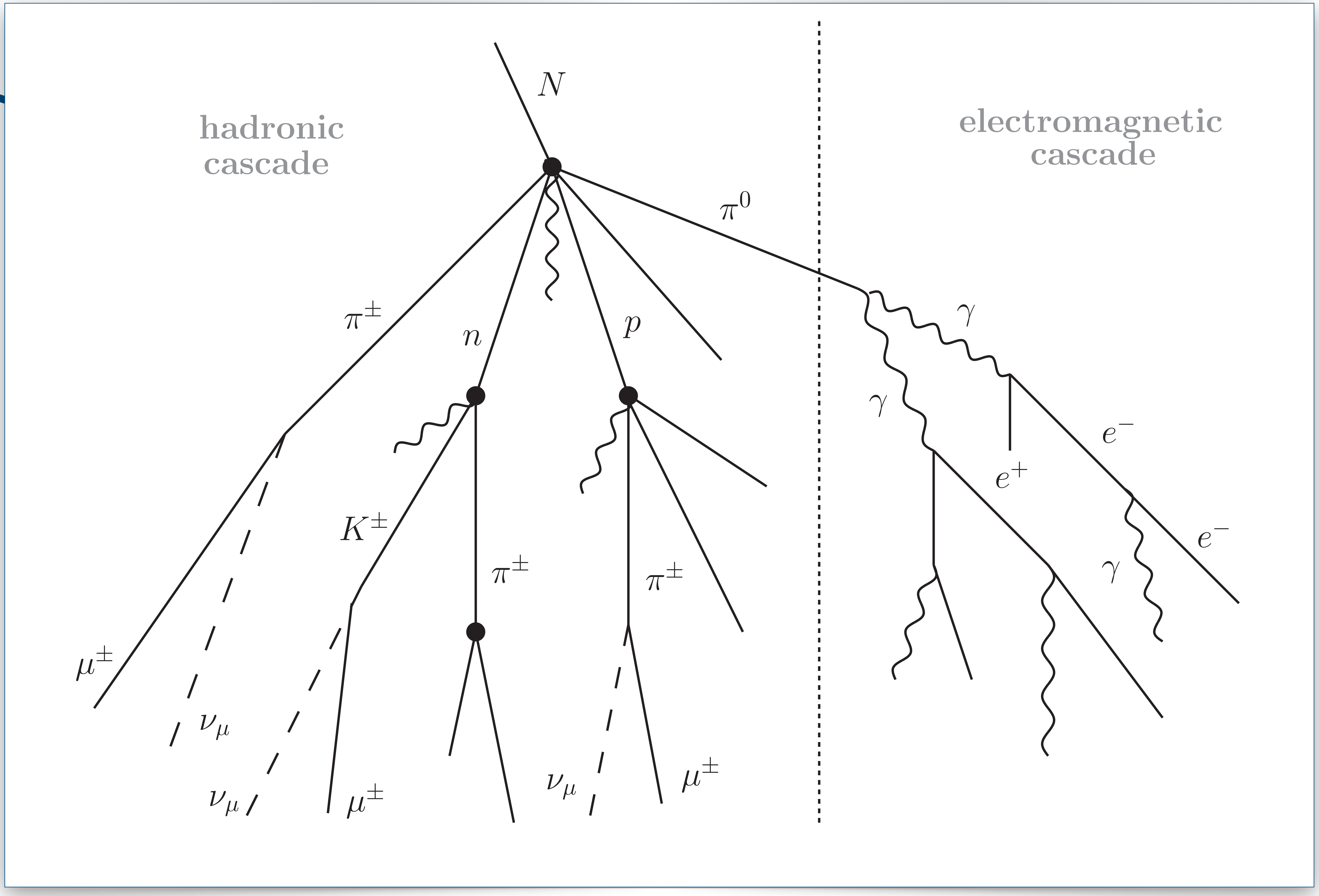

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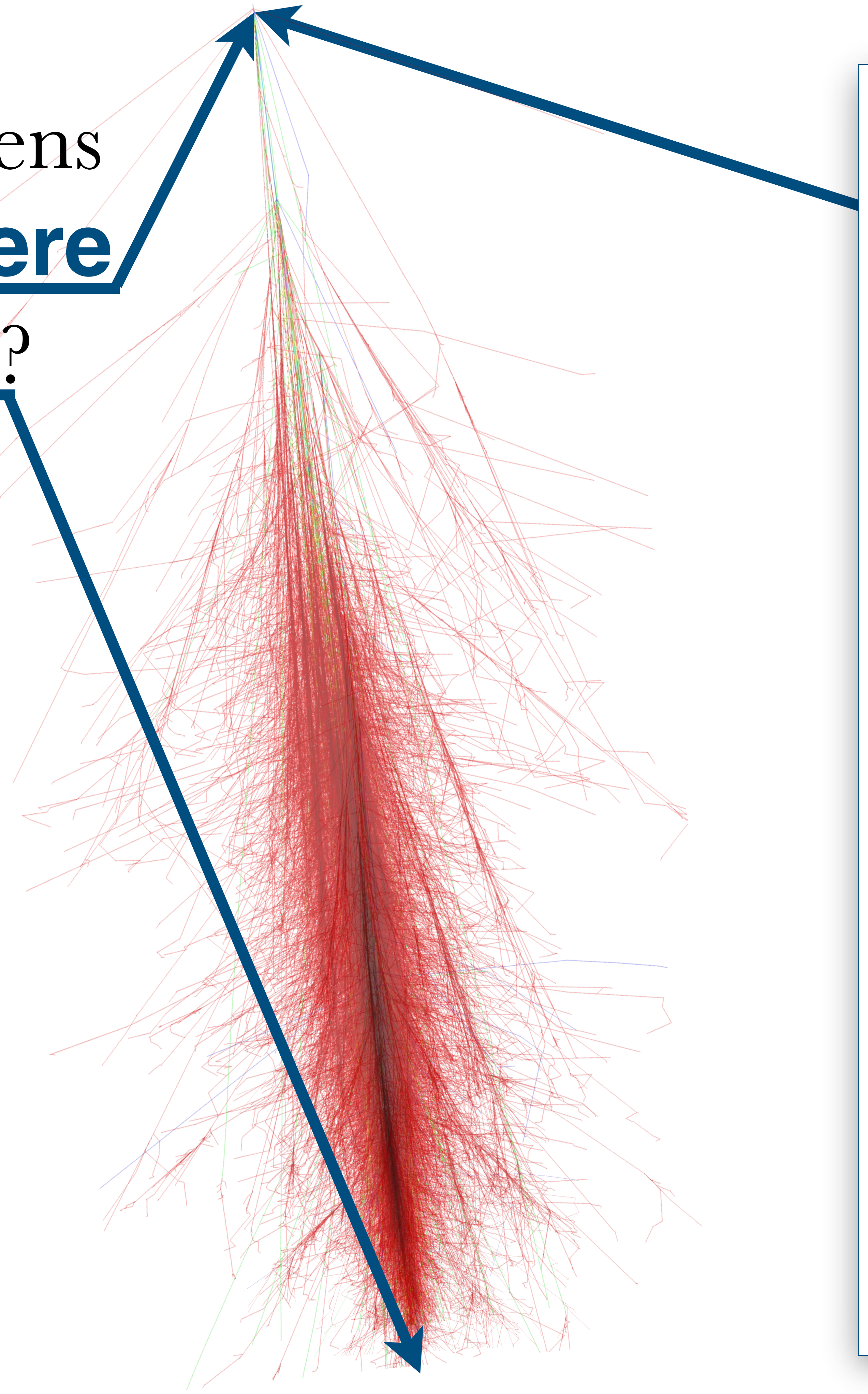

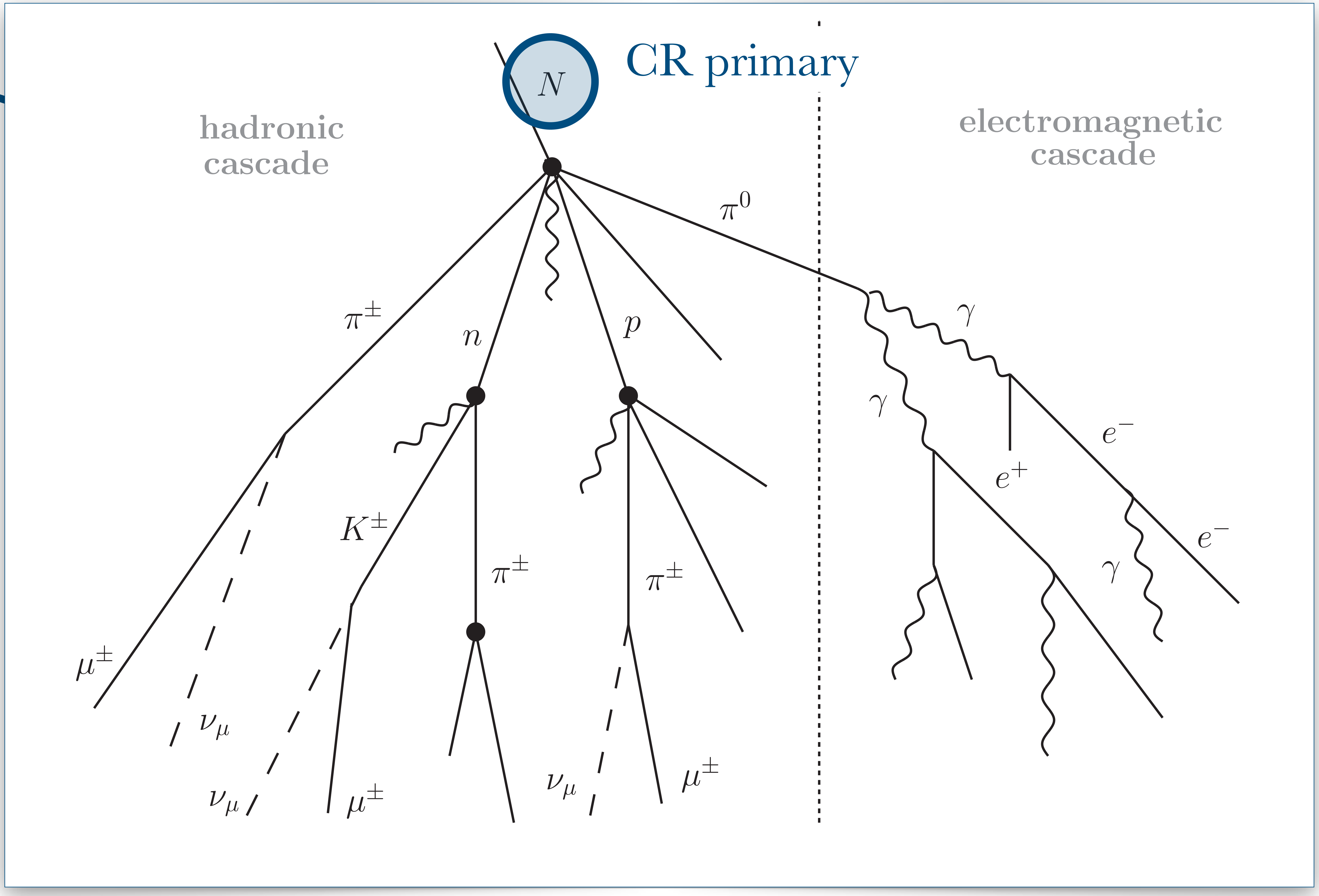

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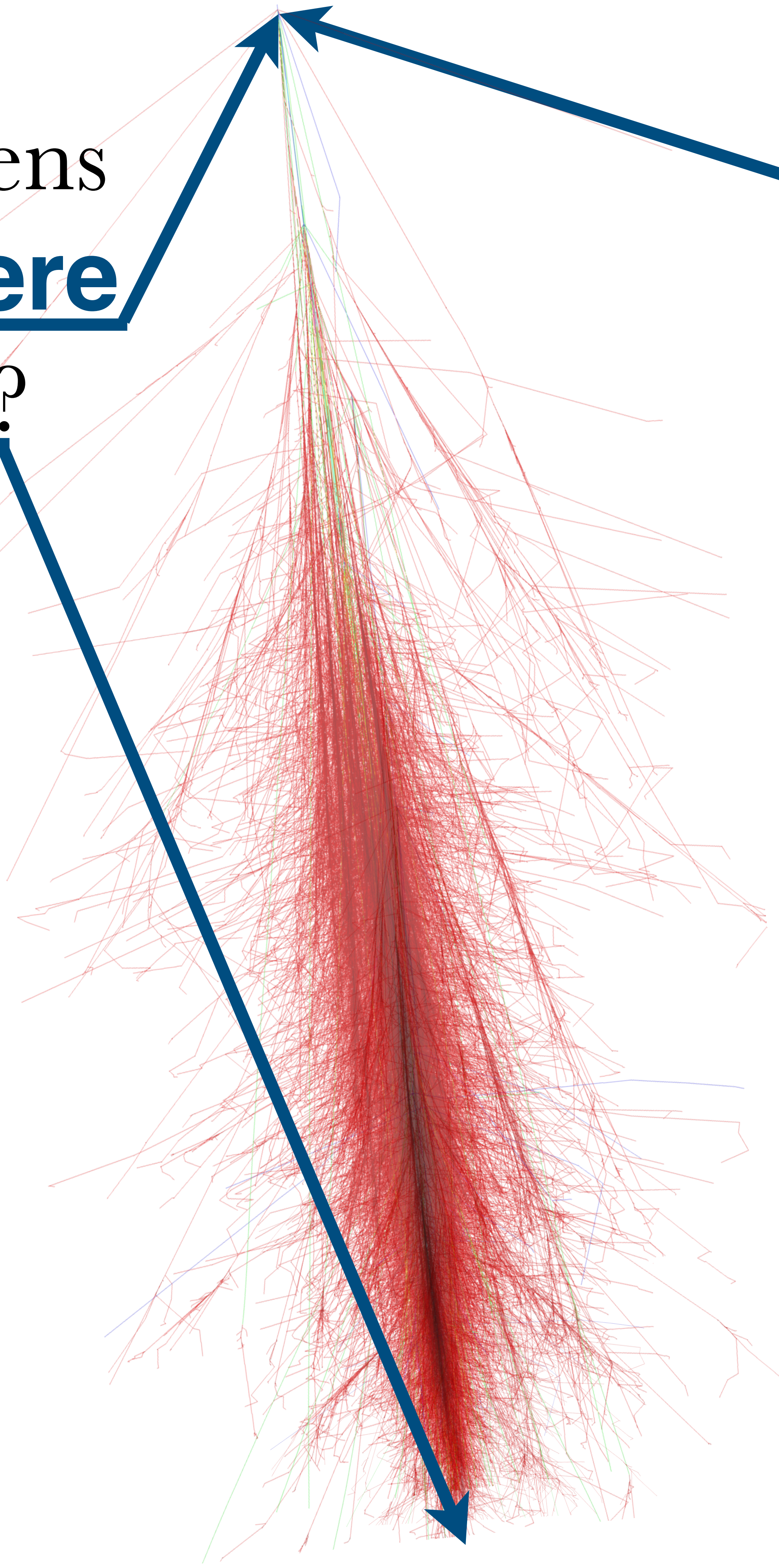

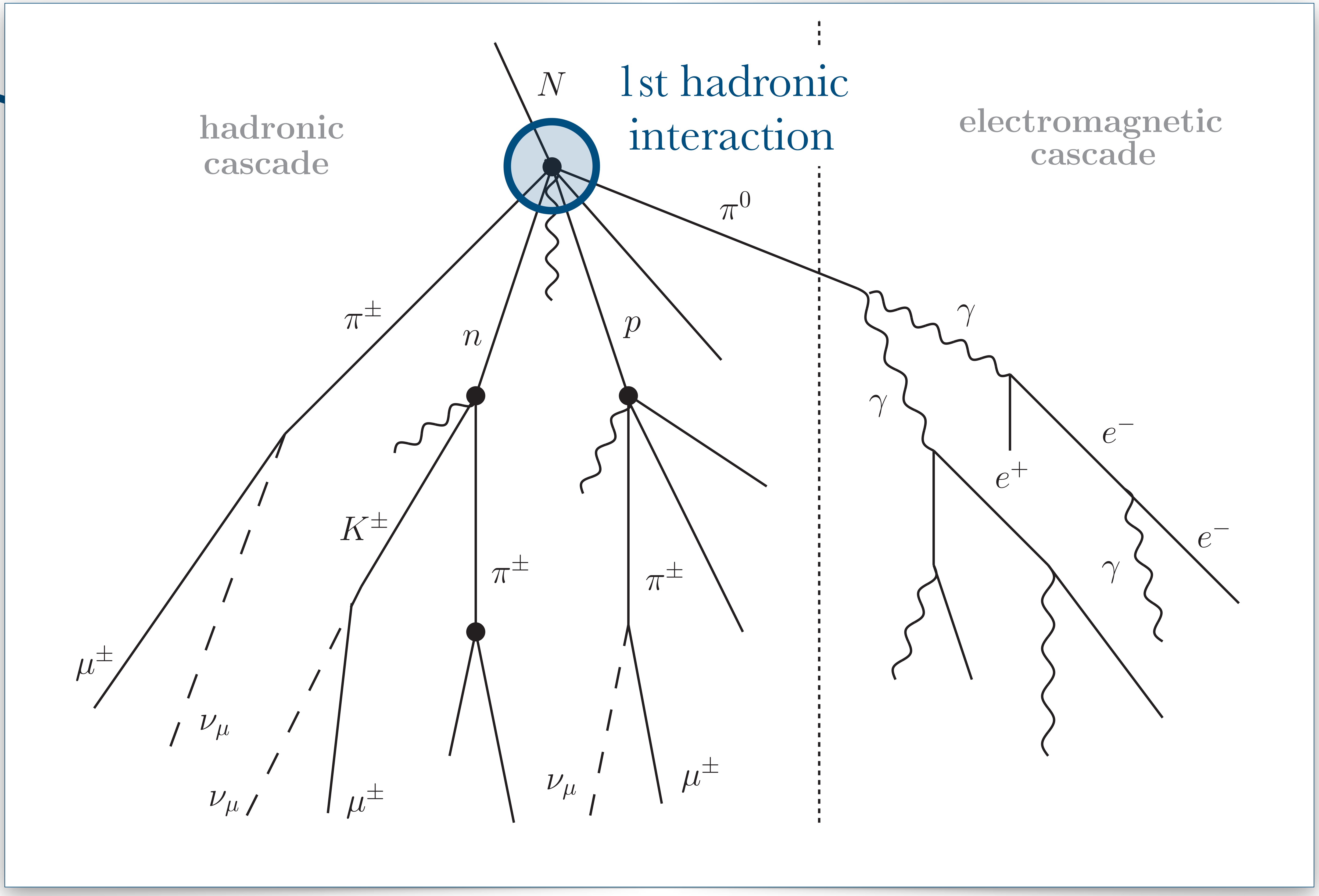

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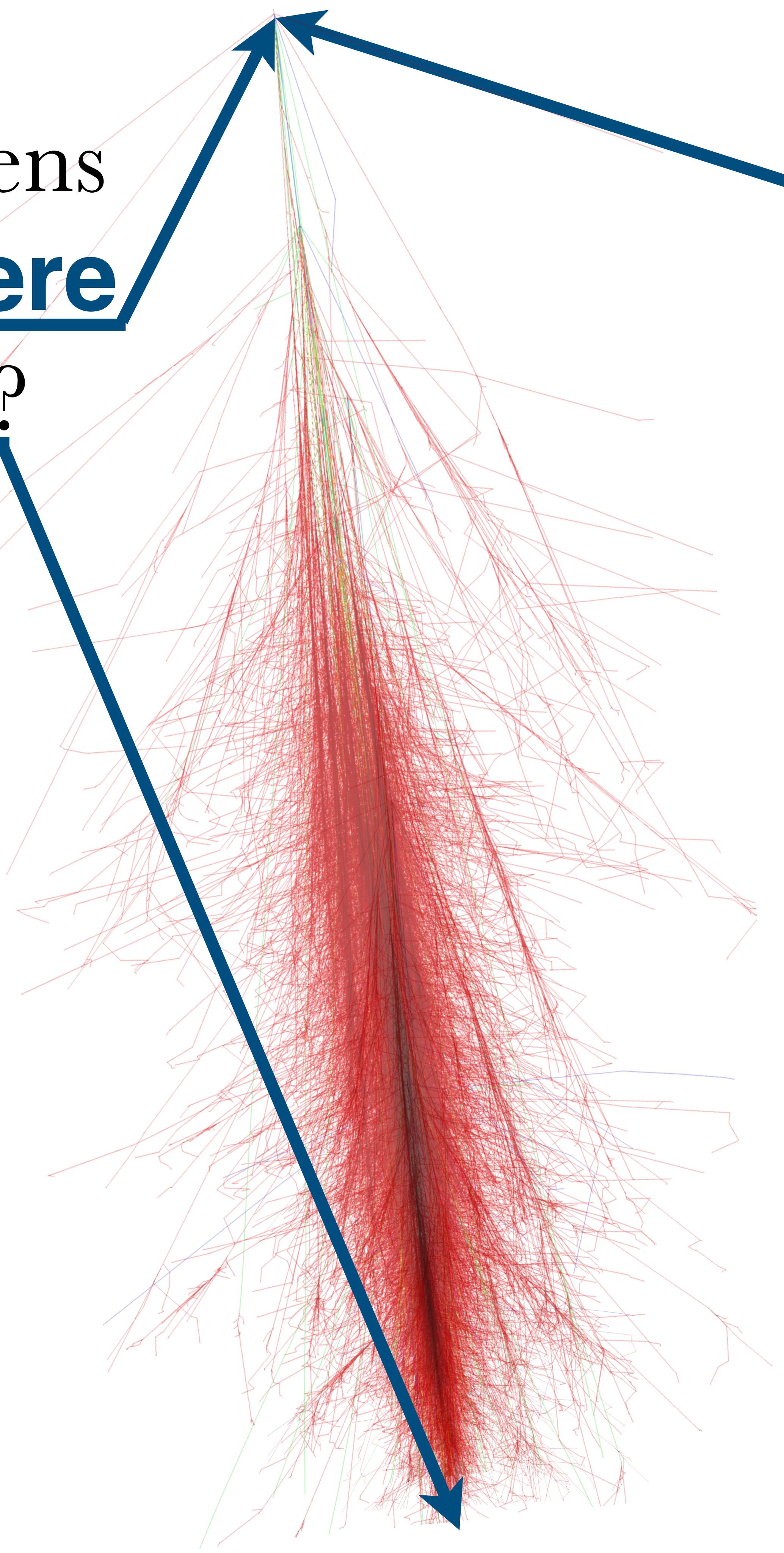

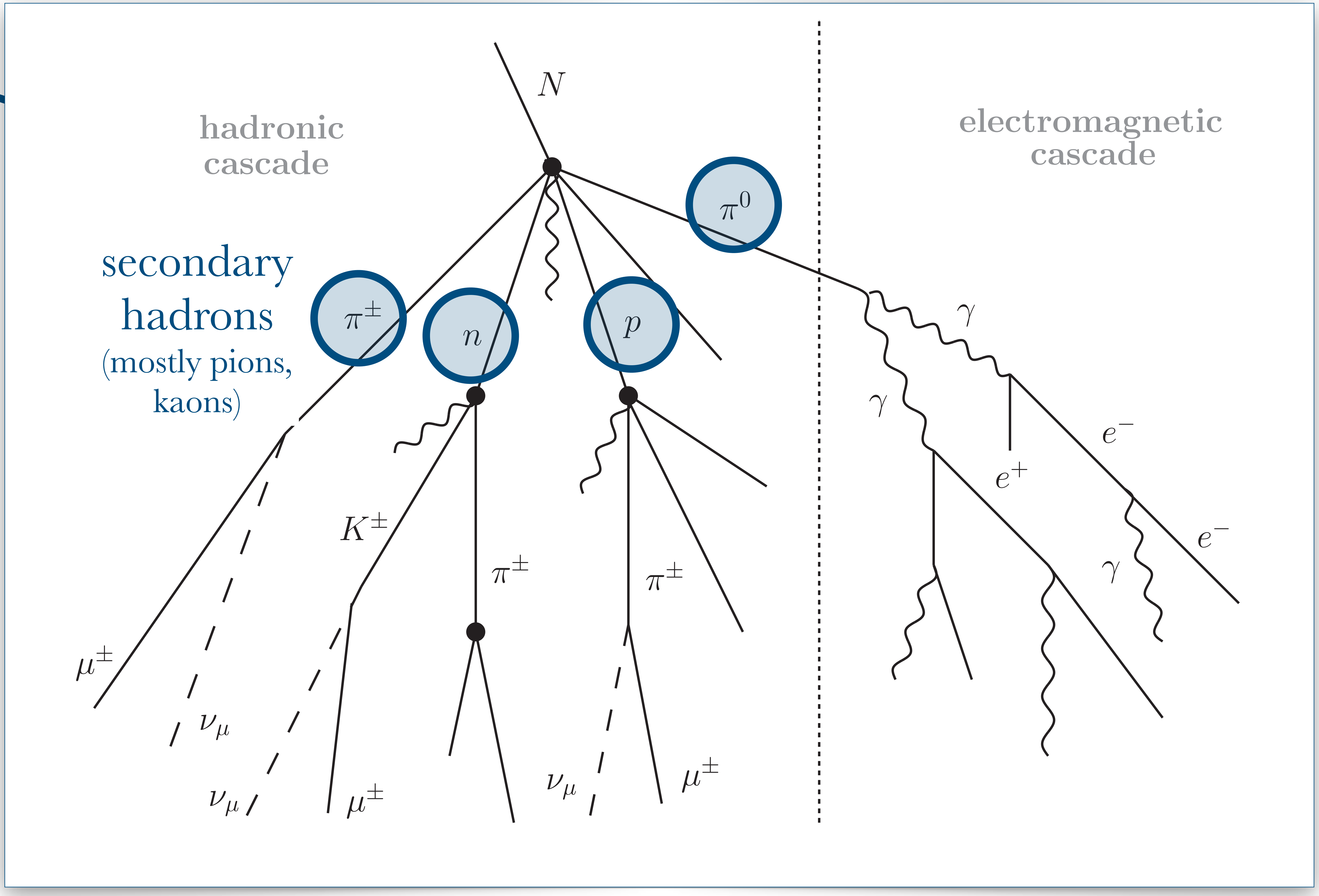

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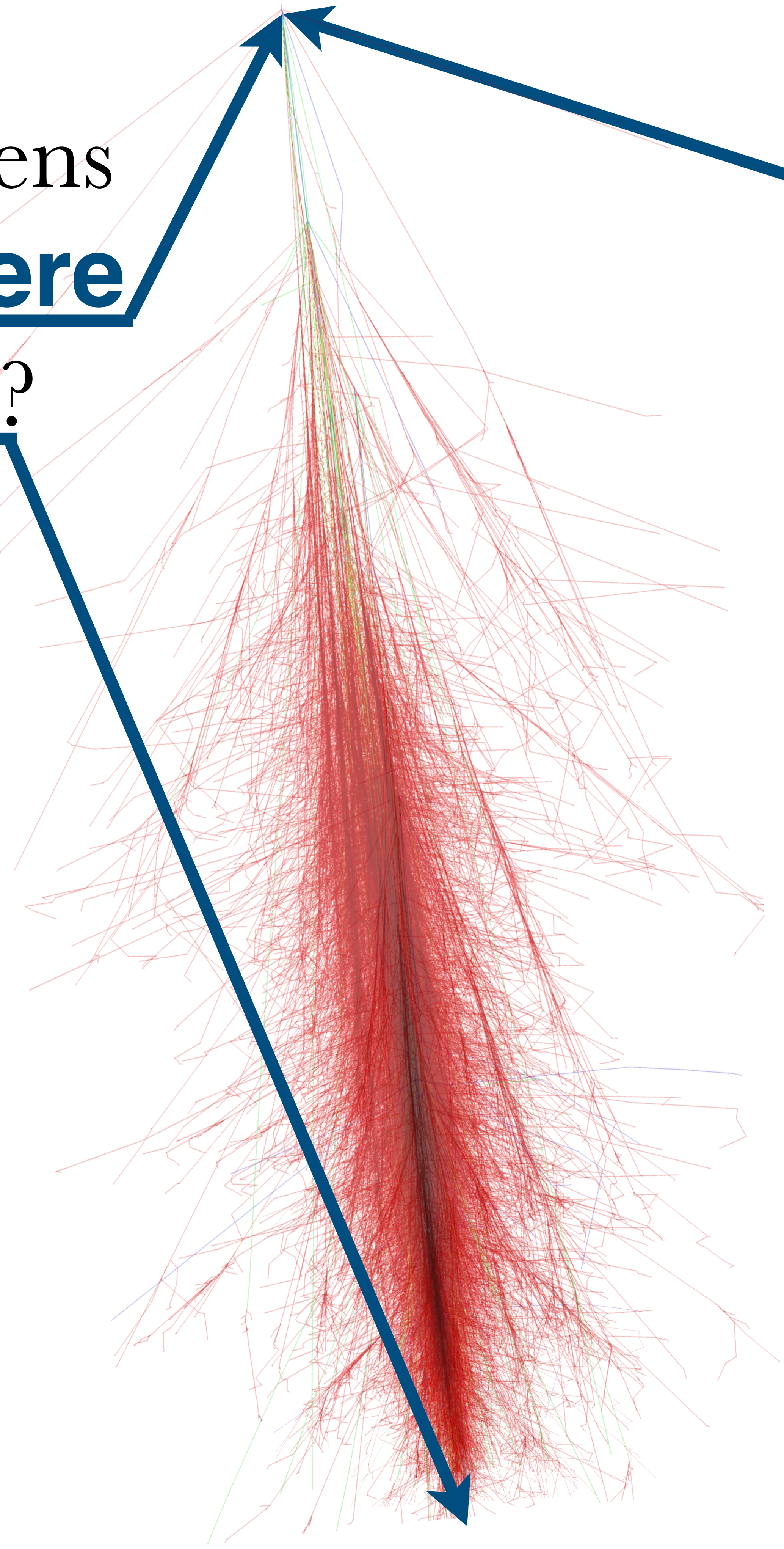

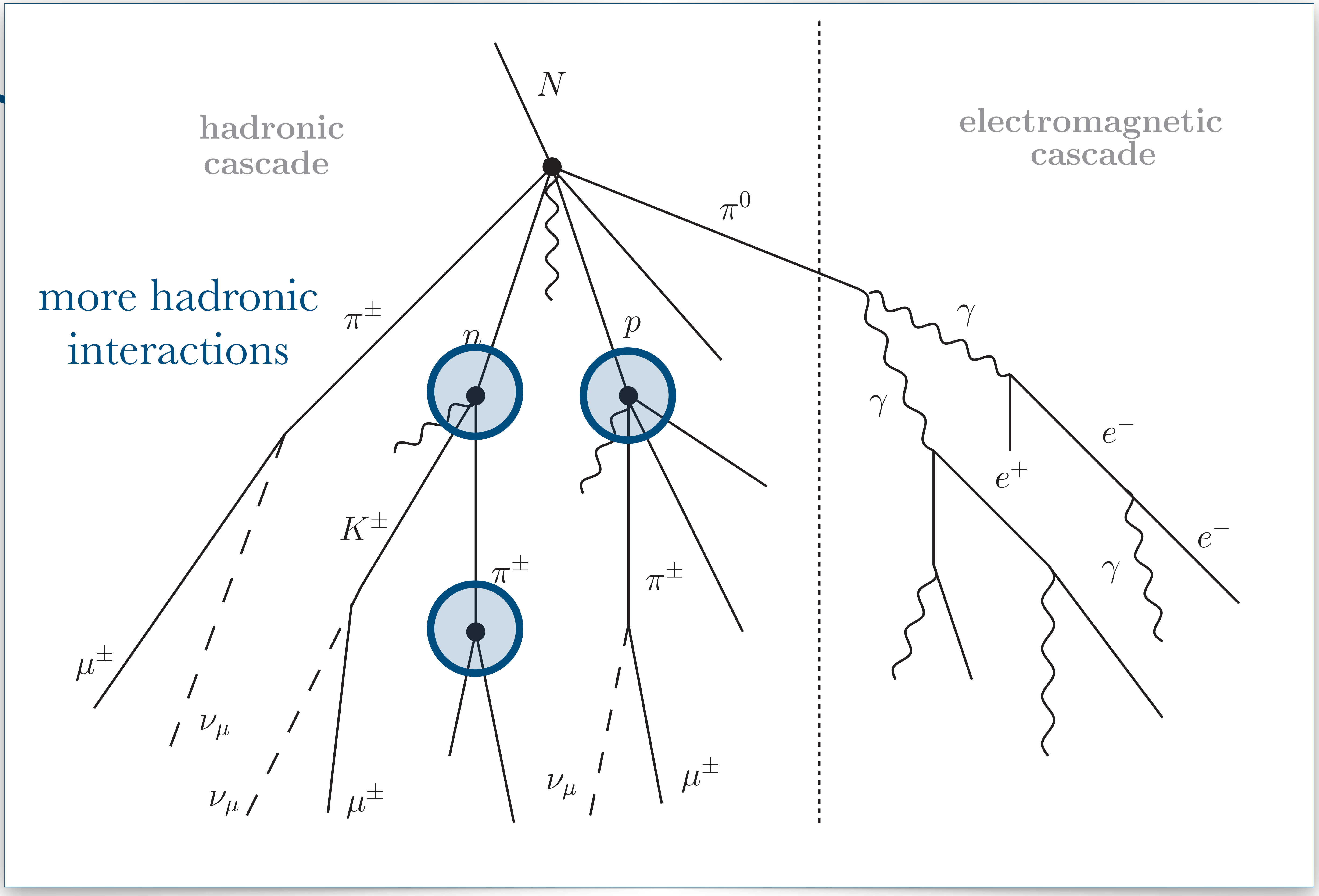

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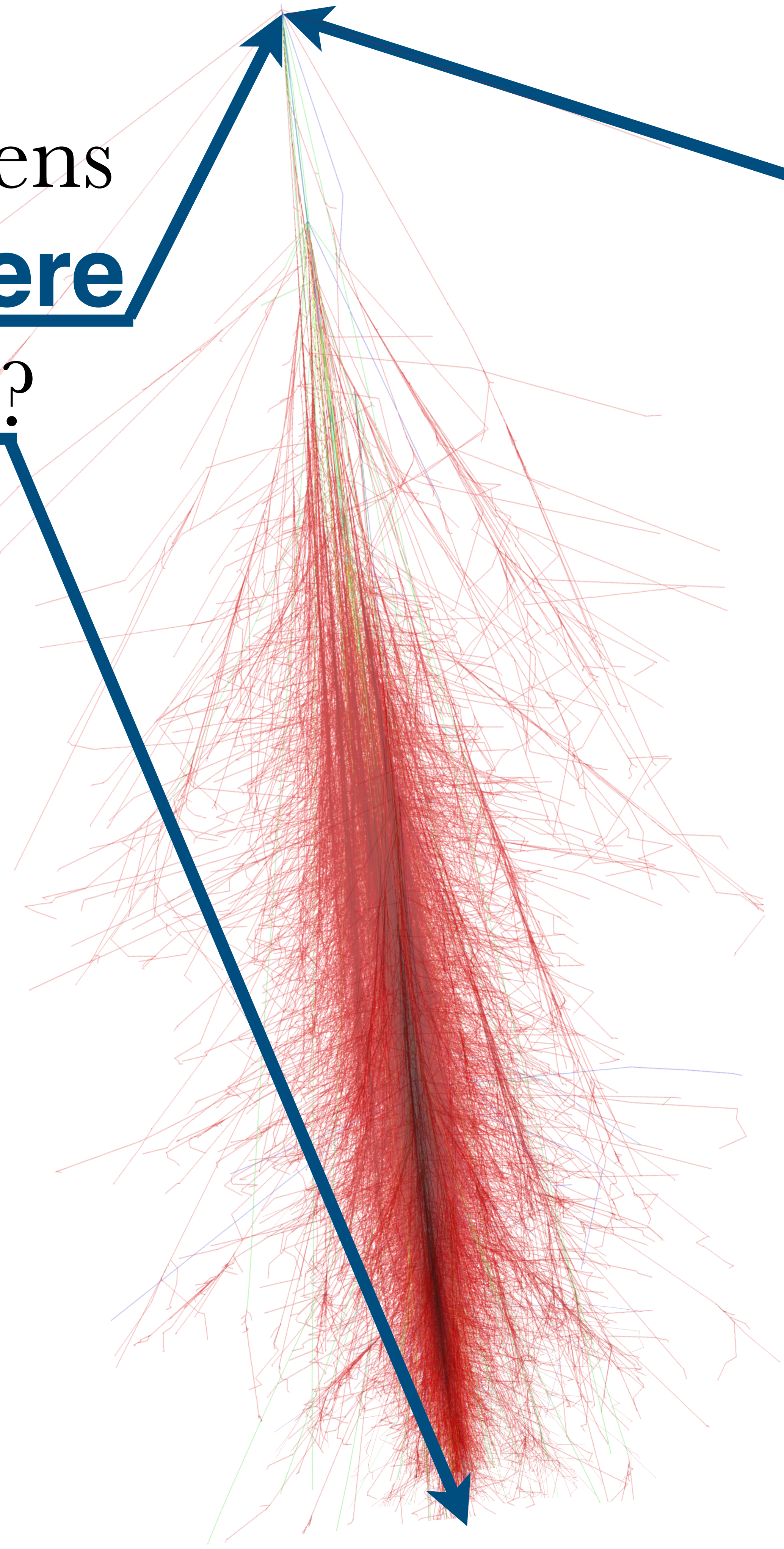

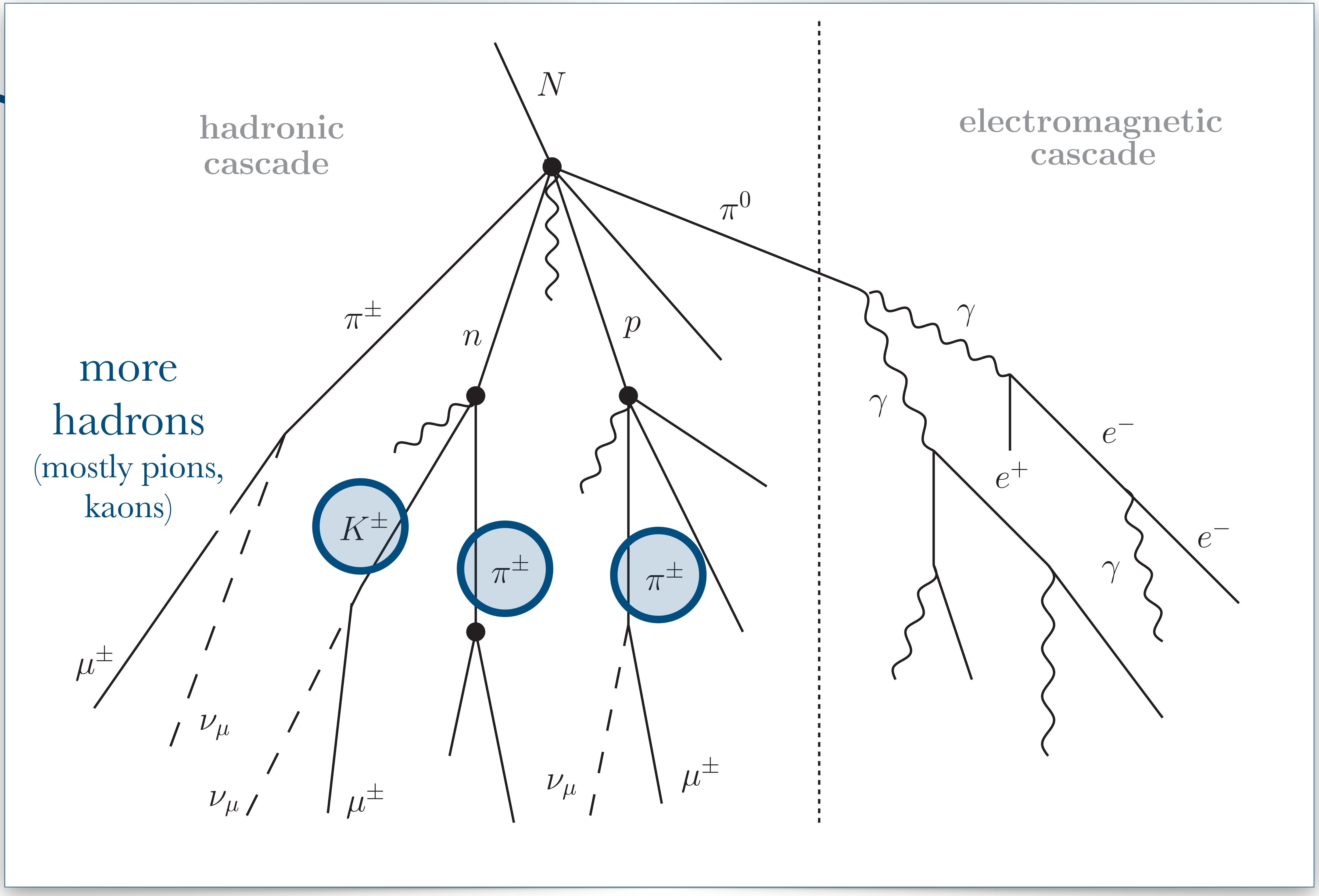

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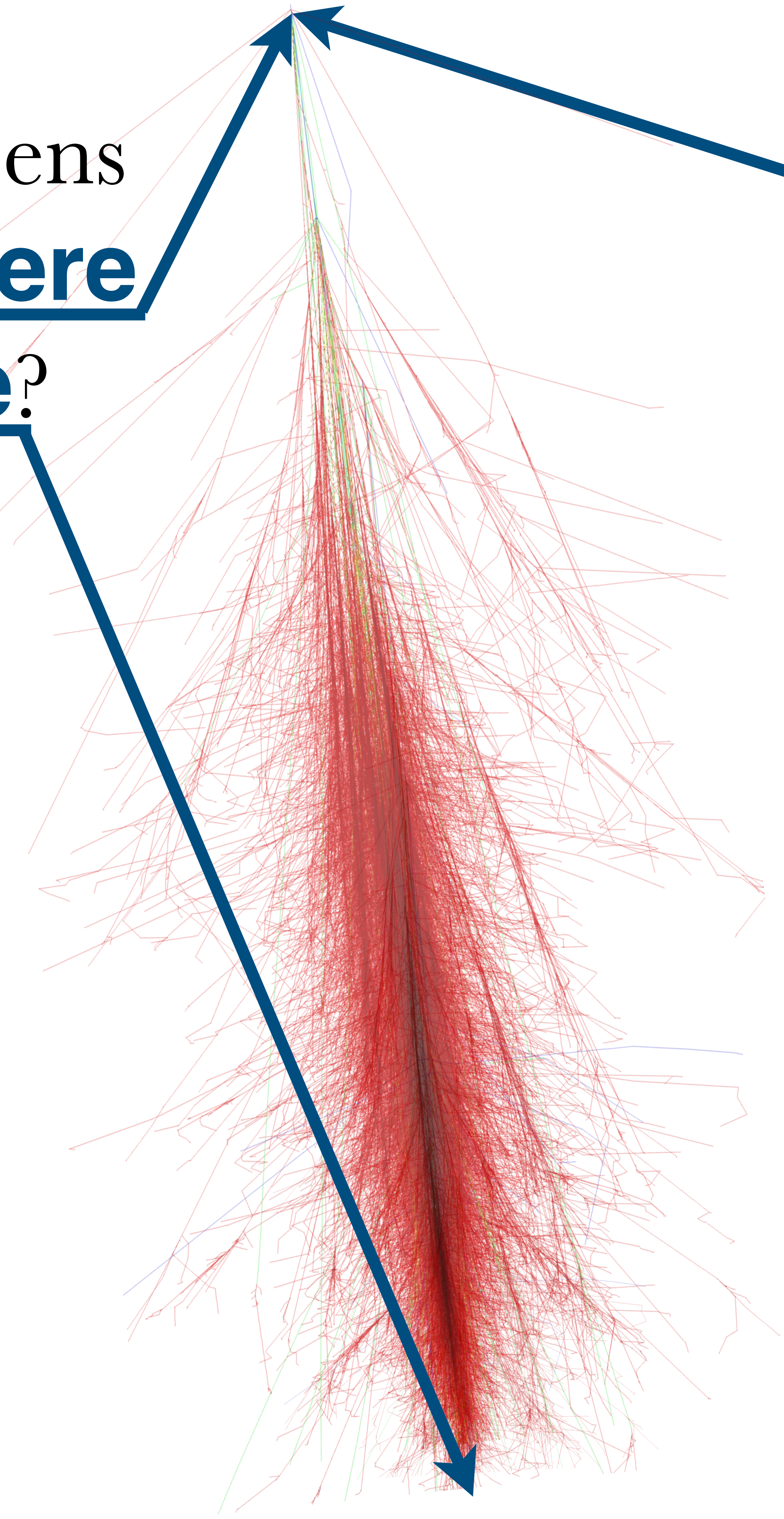

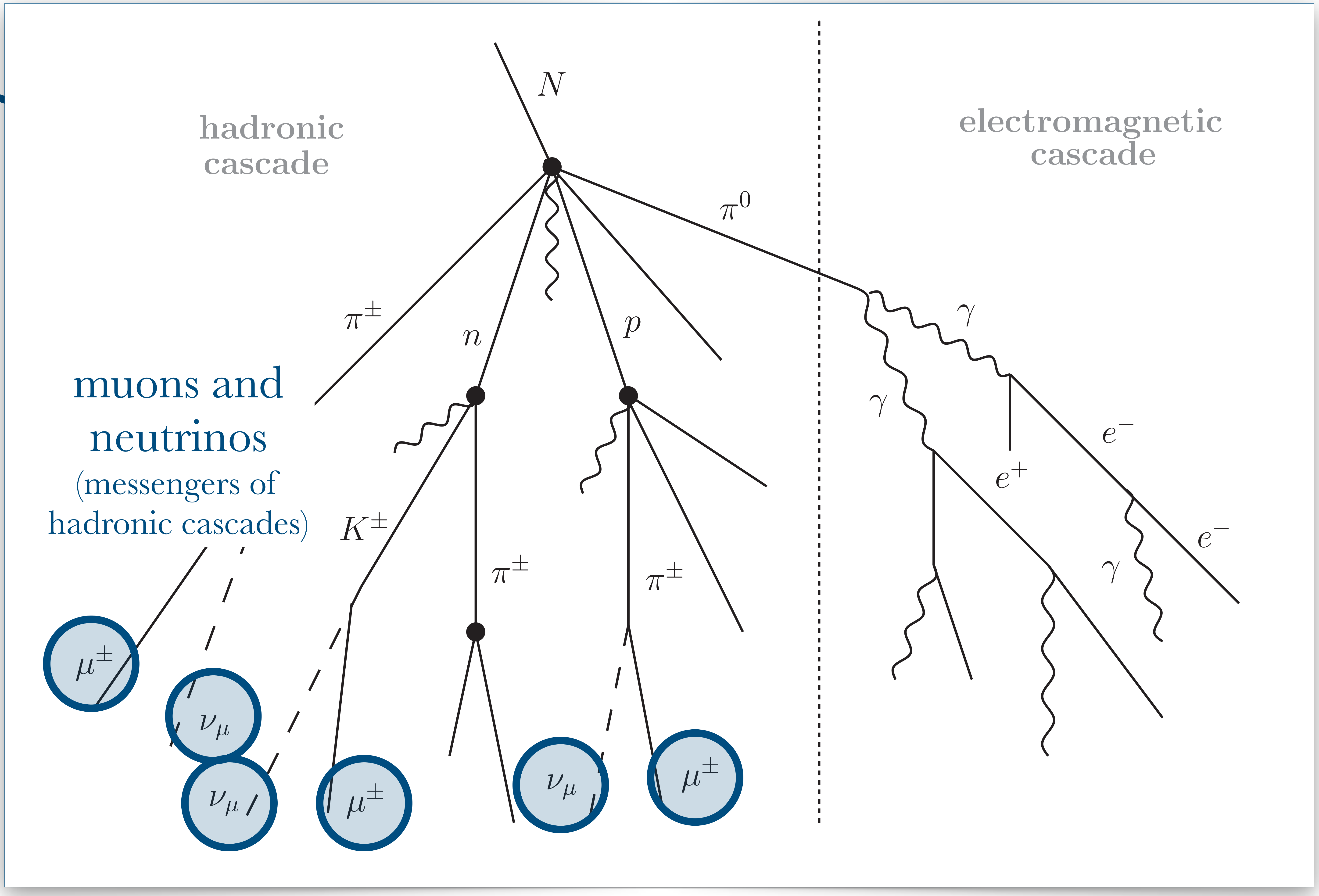

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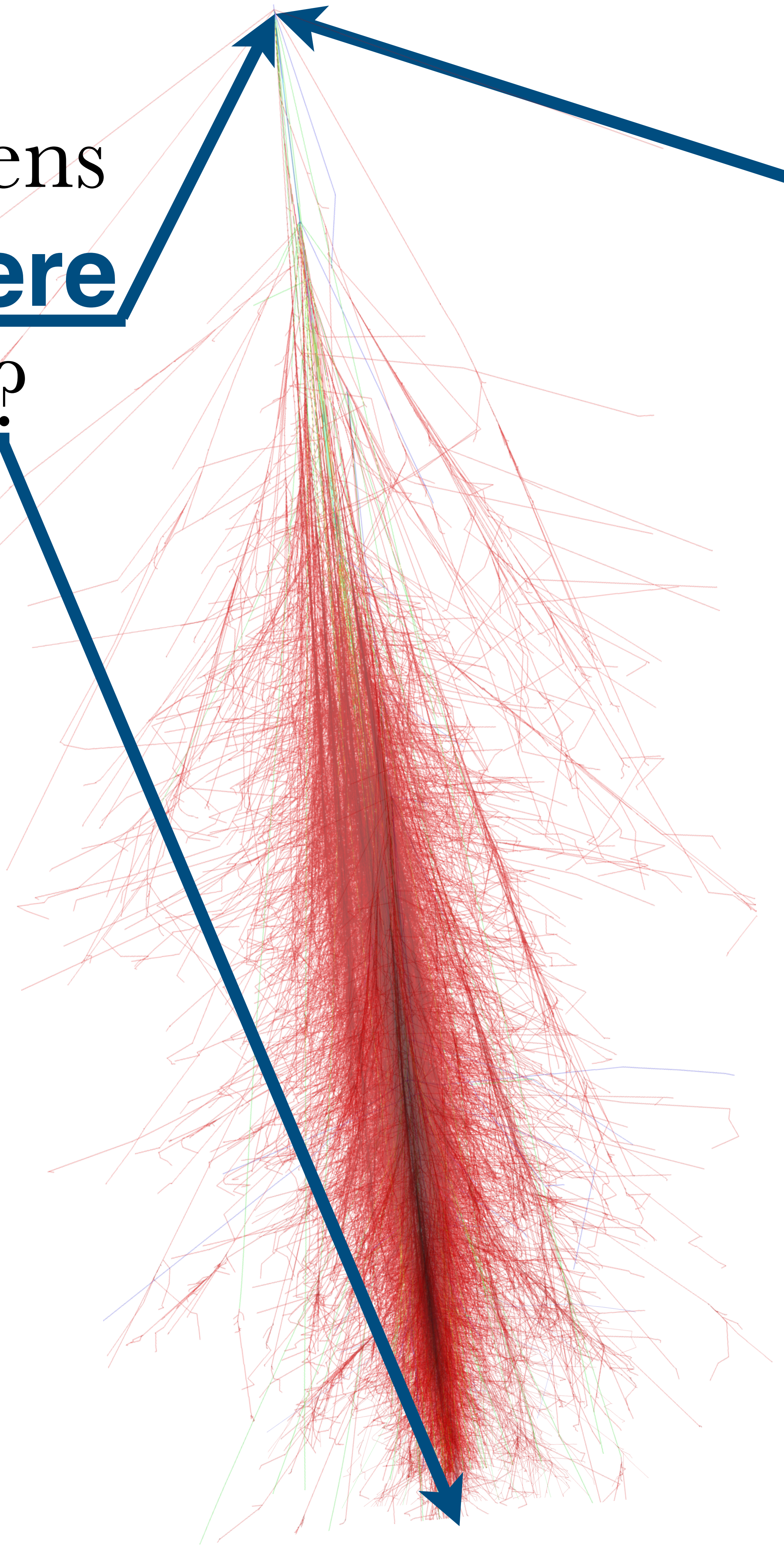

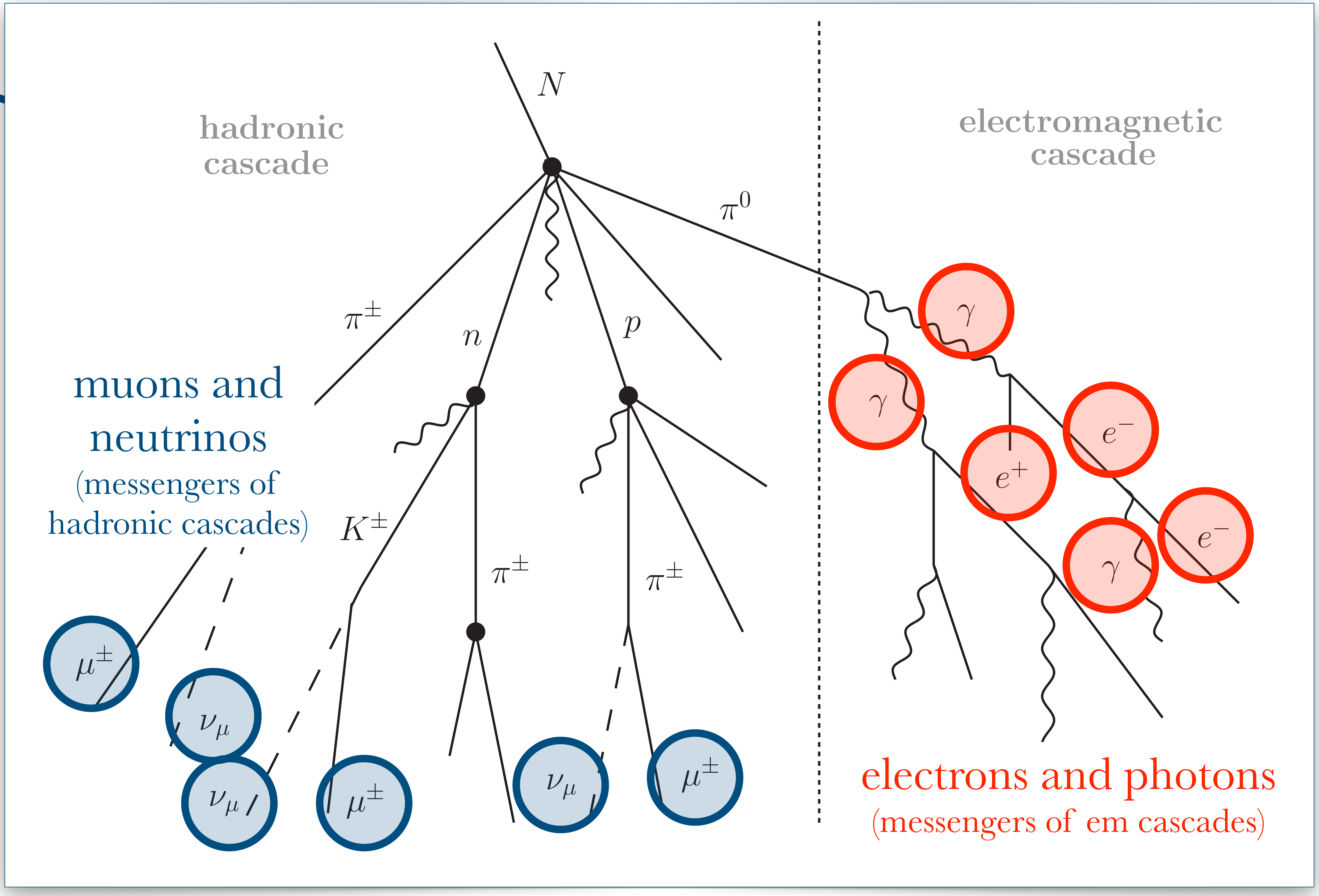

Extensive Air Showers (EAS)

Plays an important role, transferring energy from the hadronic to the electromagnetic cascade!

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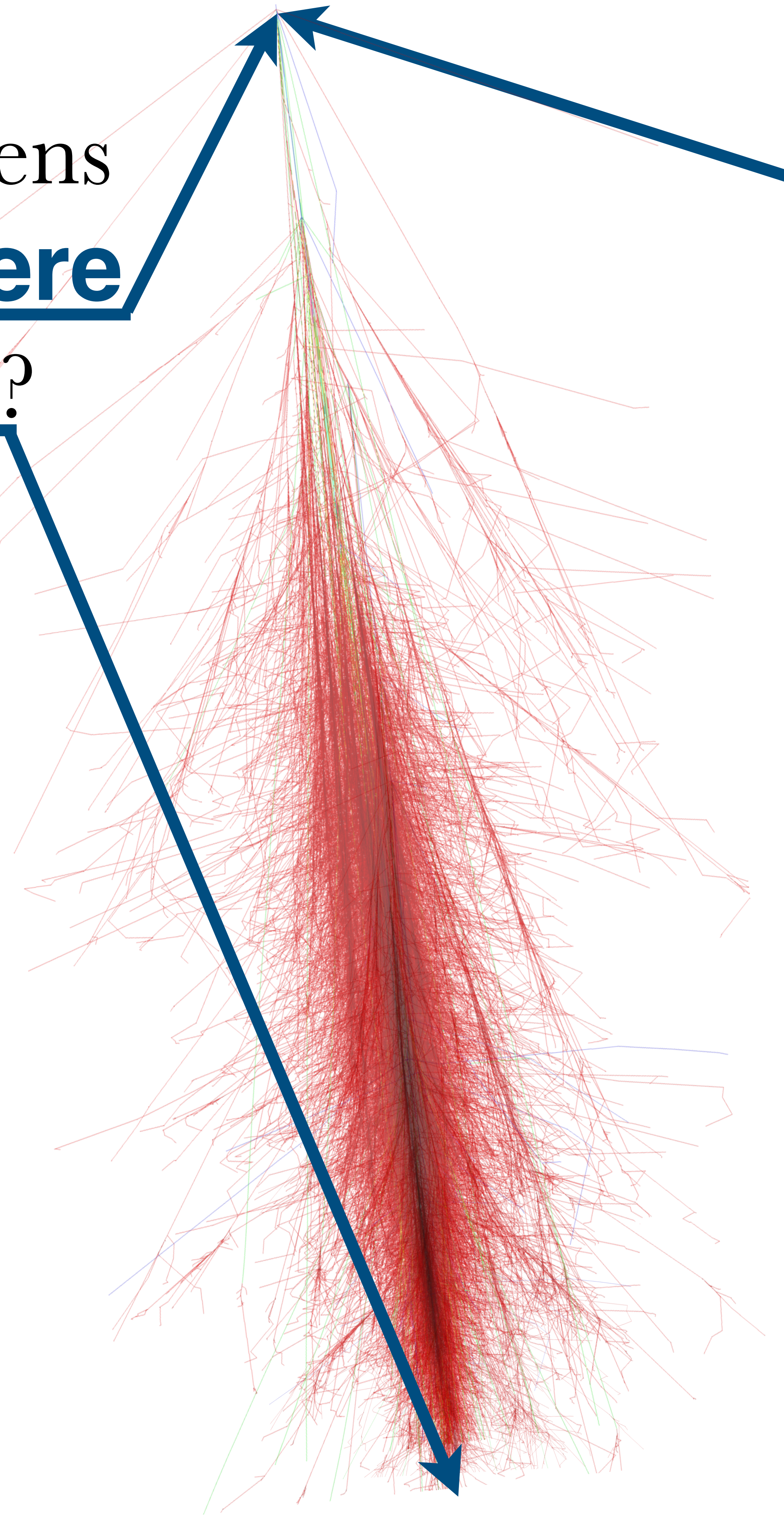
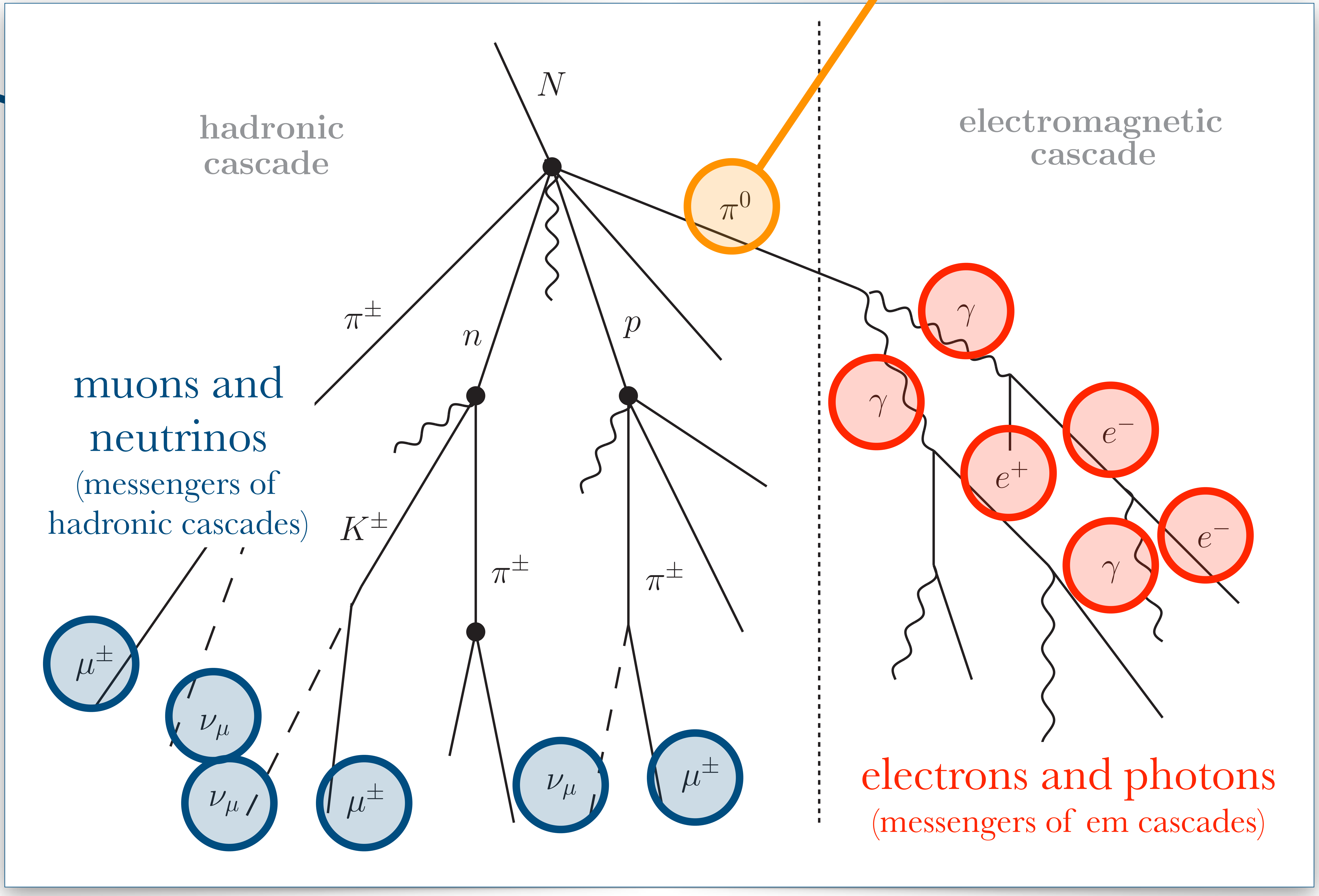
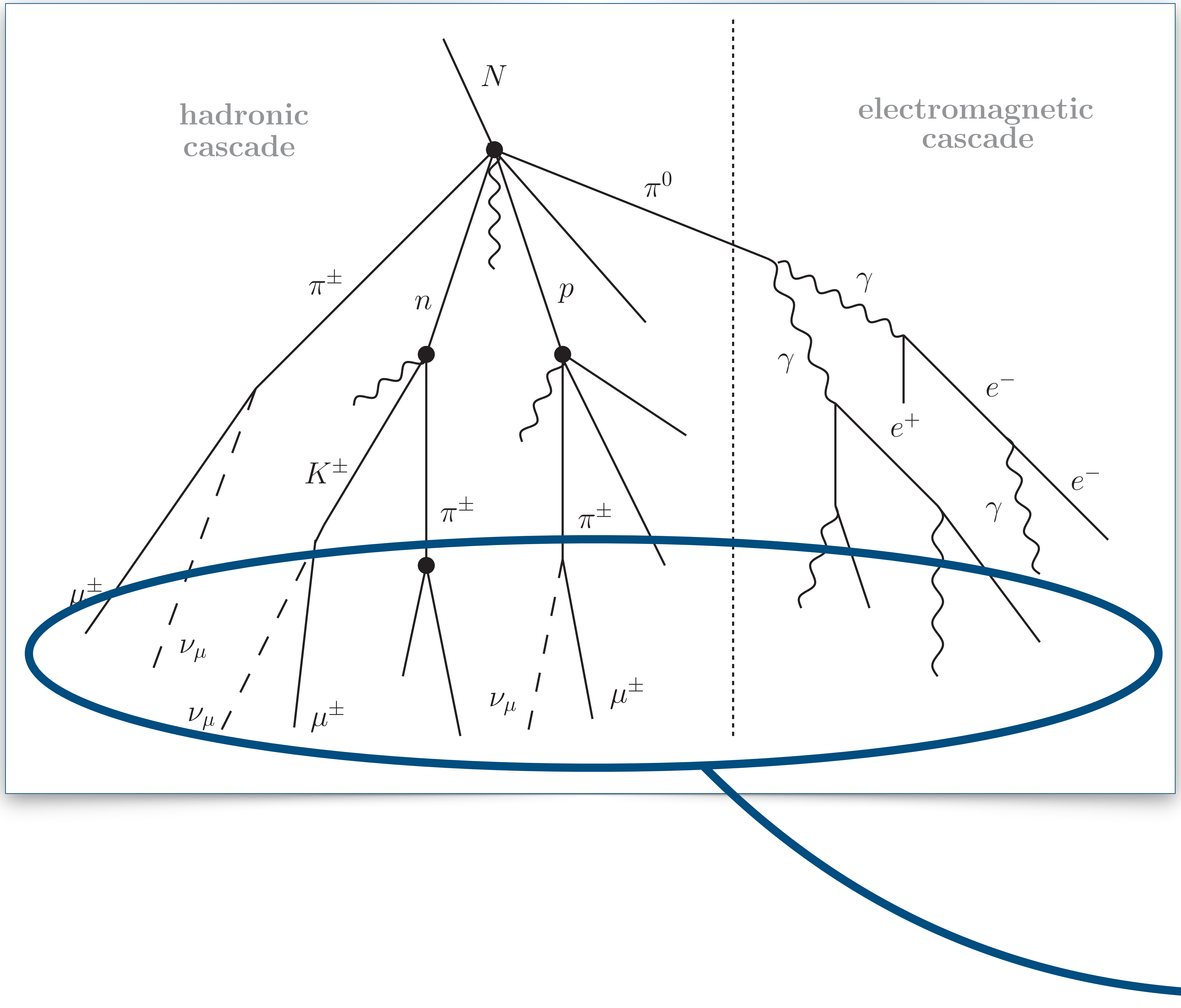


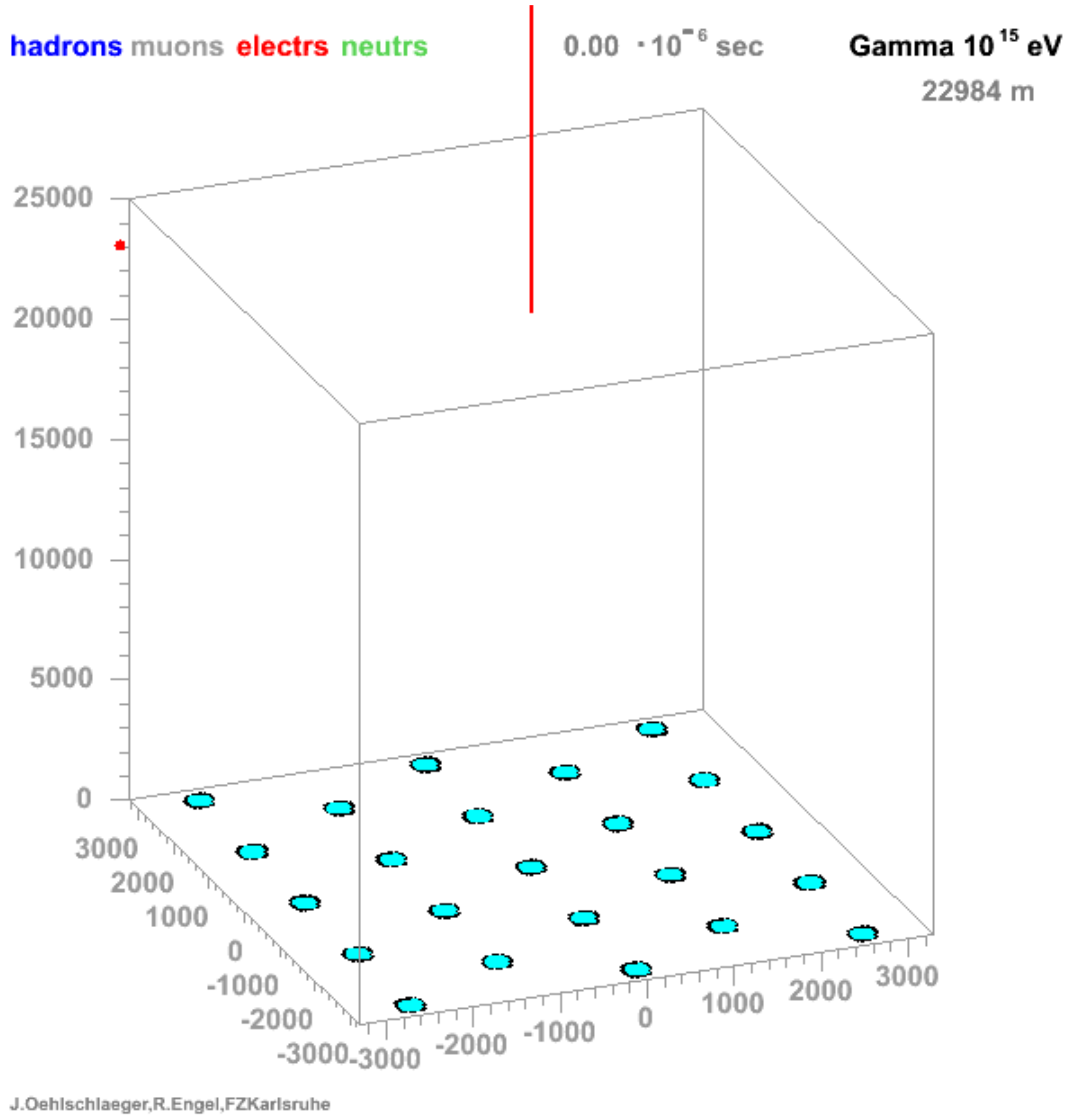


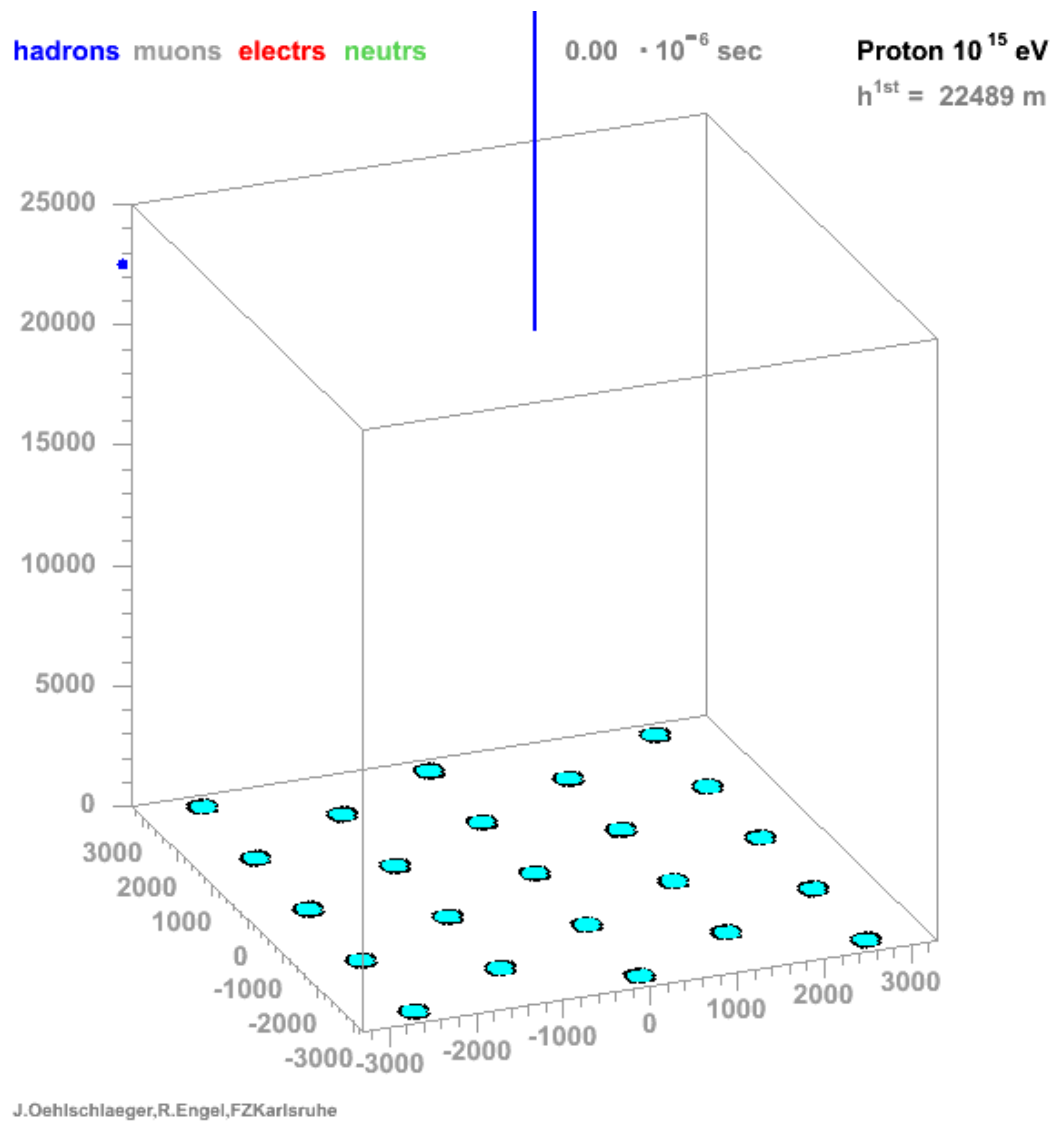
The Challenge

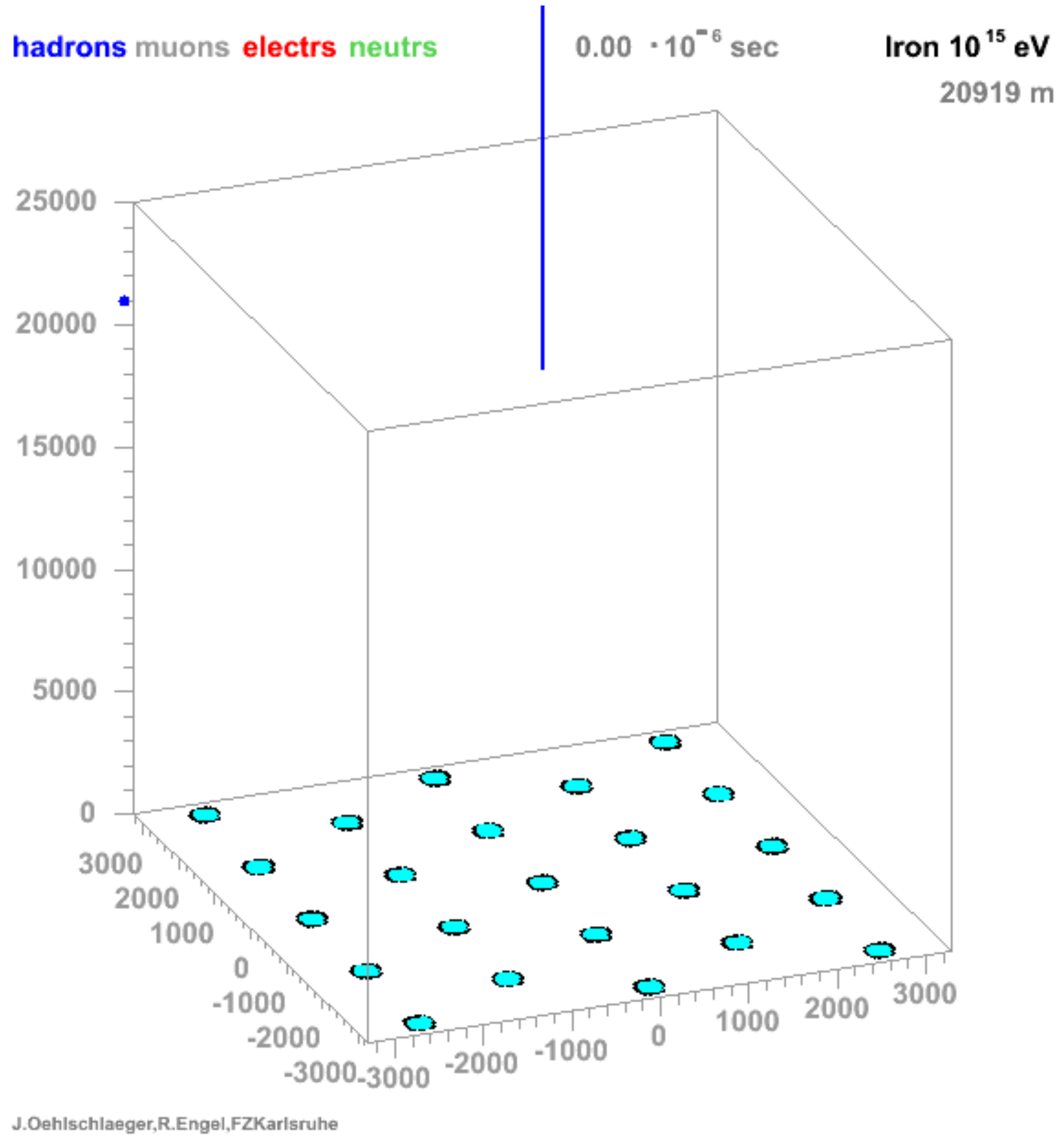


- Observation: We see the complex "mess" after multiple collisions
- Goal: Find out what initiated the collision
- Not trivial… based on simulations…

EAS Simulations





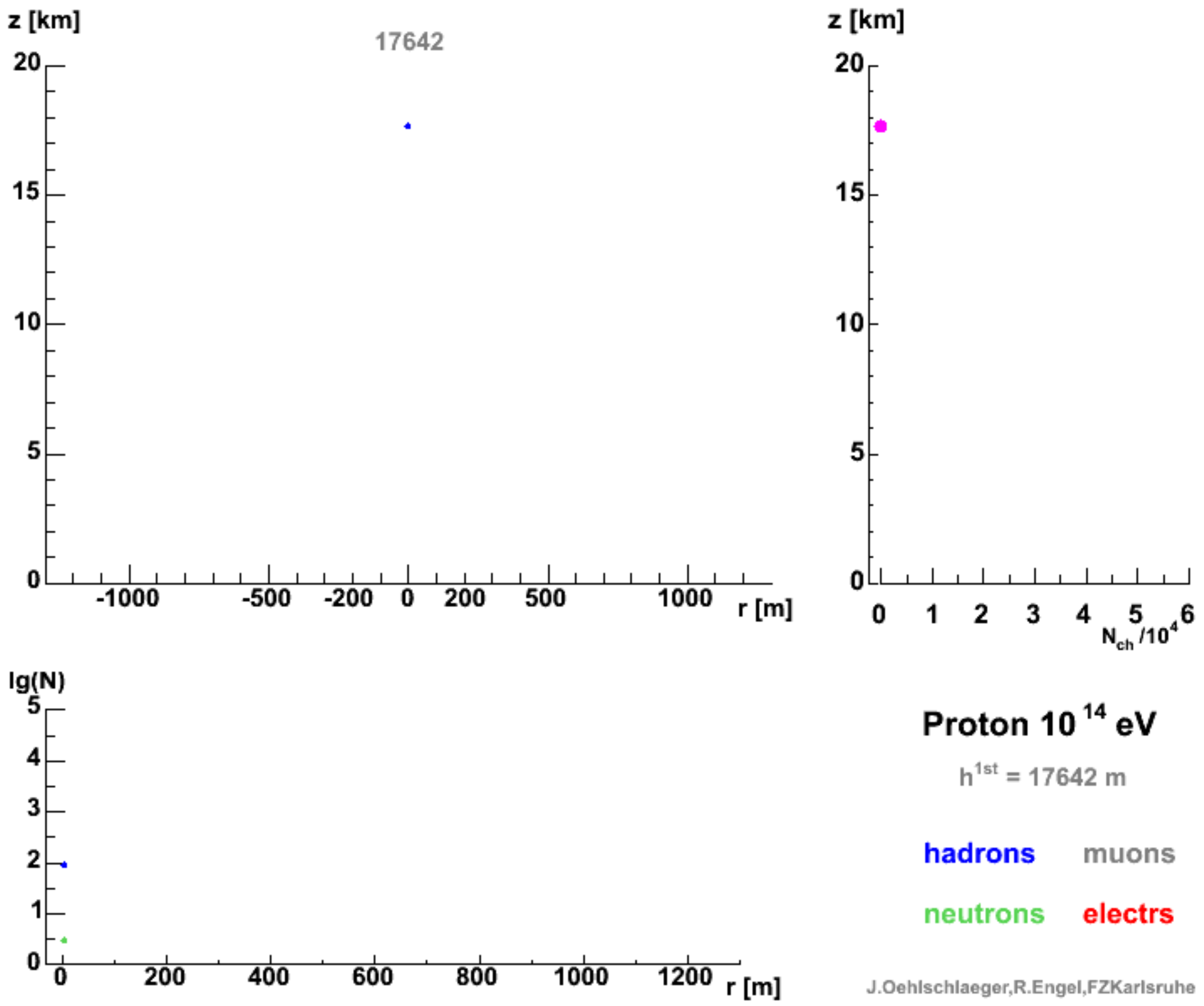


- Simulated gamma, proton, and iron showers at $E_0 = 10^{15}\,\text{eV}$ [https://www.iap.kit.edu/corsika/]
- <u>Challenge:</u> description of particle interactions / particle production in the atmosphere

EAS Simulations

[https://www.iap.kit.edu/corsika/]

- EAS simulation (proton, 10^{15} eV)
  - Shower front
  - Longitudinal profile
  - Lateral profile
- <u>Notice:</u>
  - Largest particle abundance at ground: electrons
  - X_{max} is the depth in the atmosphere where longitudinal profile becomes maximal
  - Different lateral profiles for all particle types



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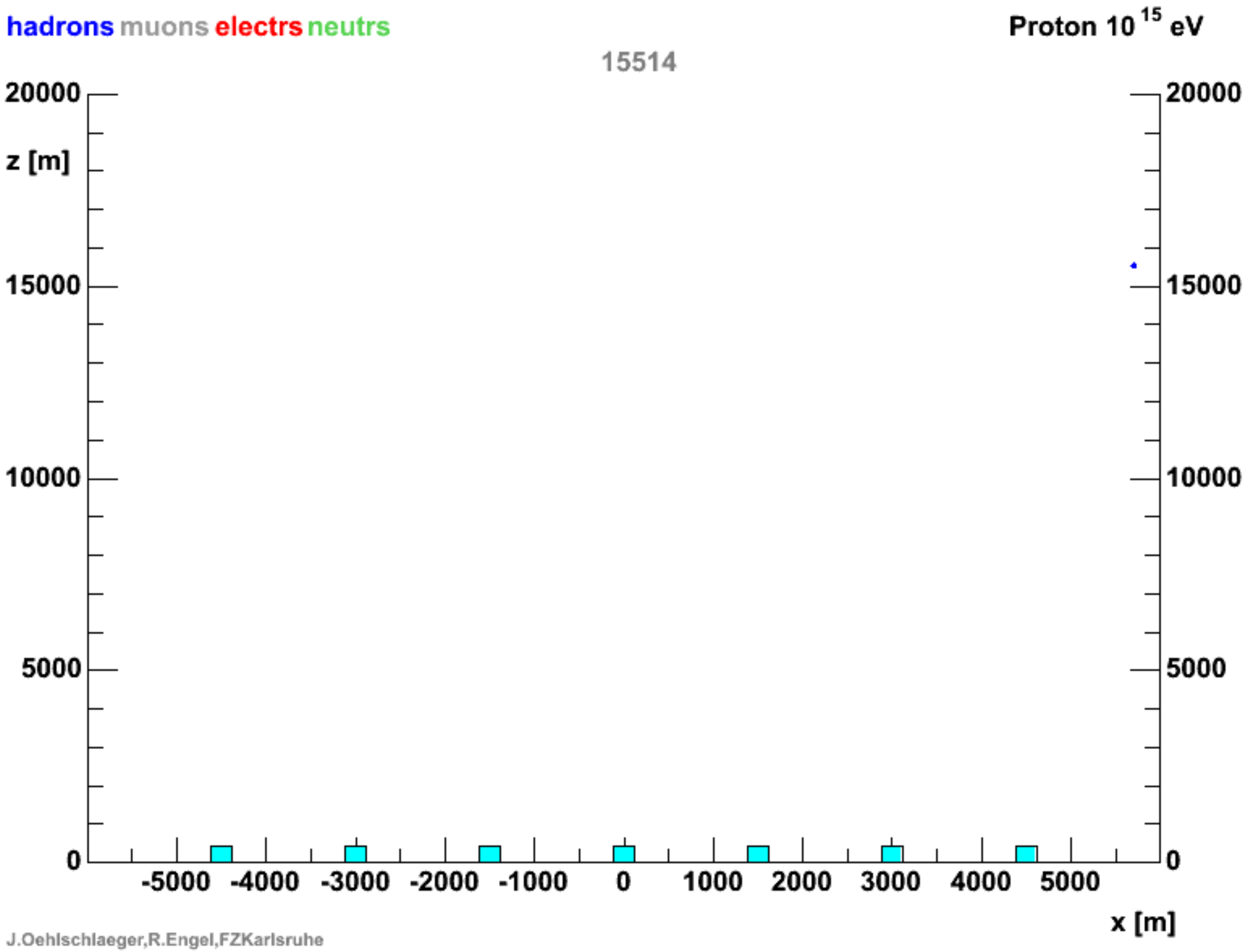

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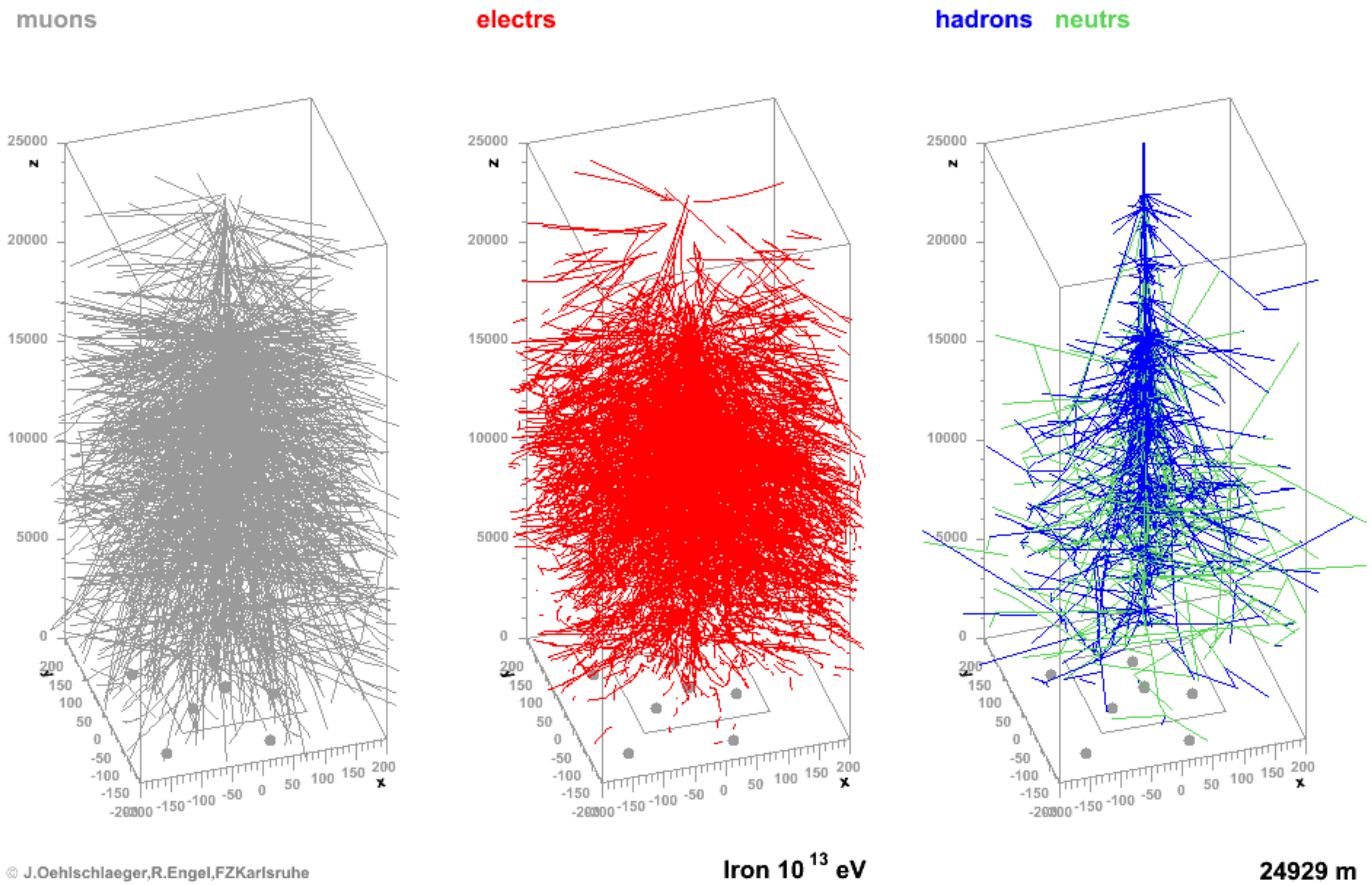
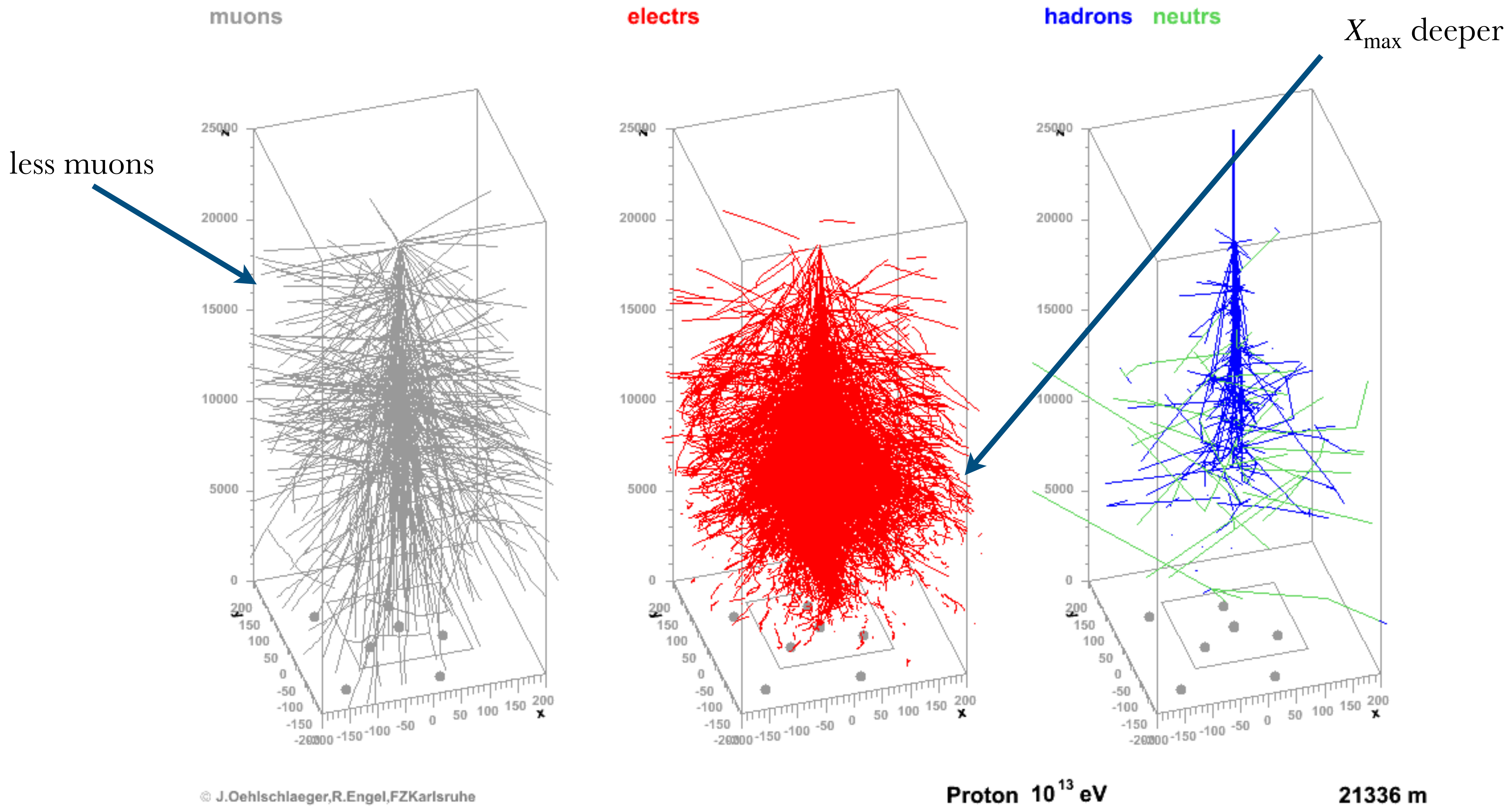
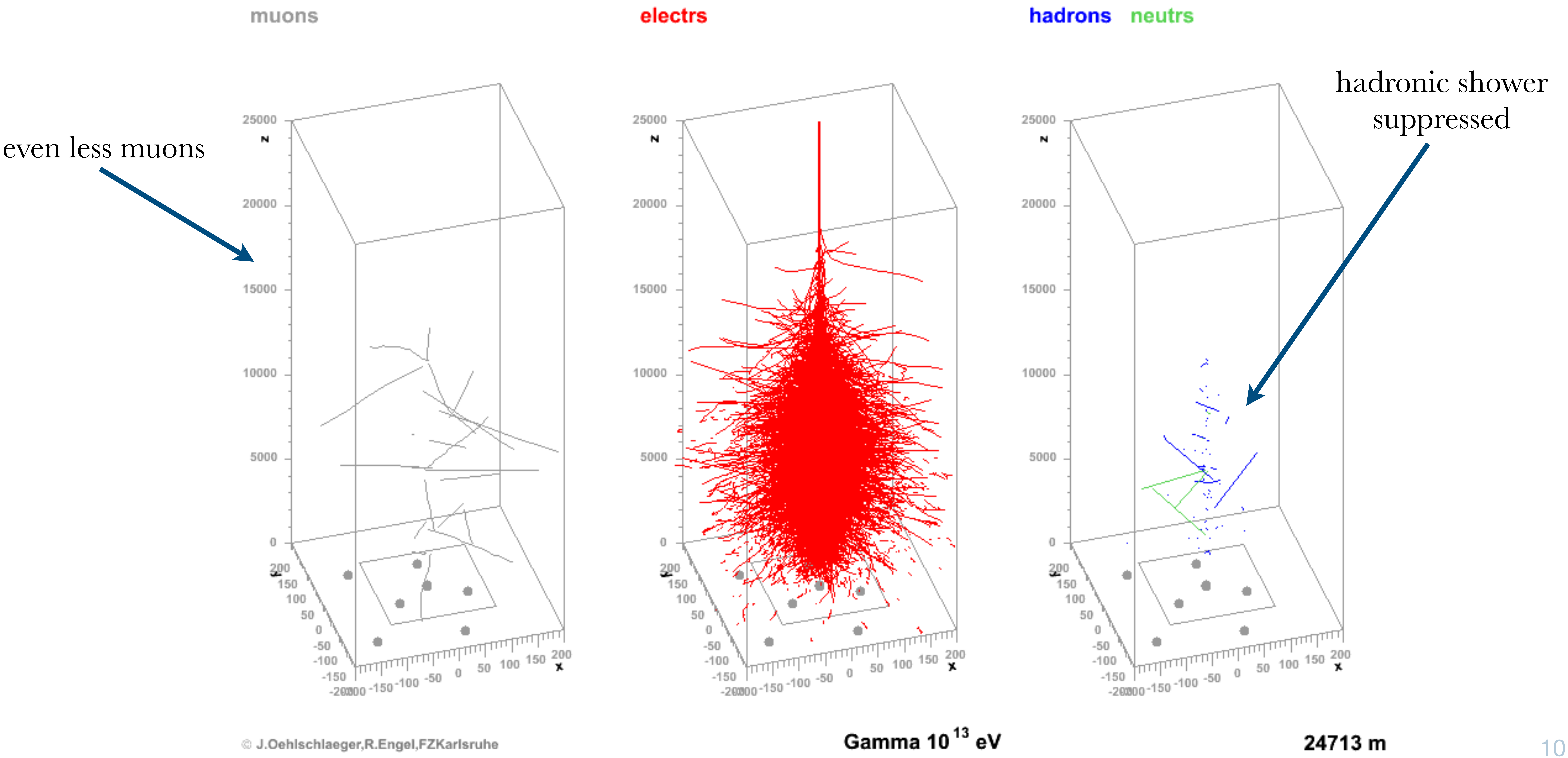
EAS Particles (Iron Shower)



EAS Particles (Proton Shower)

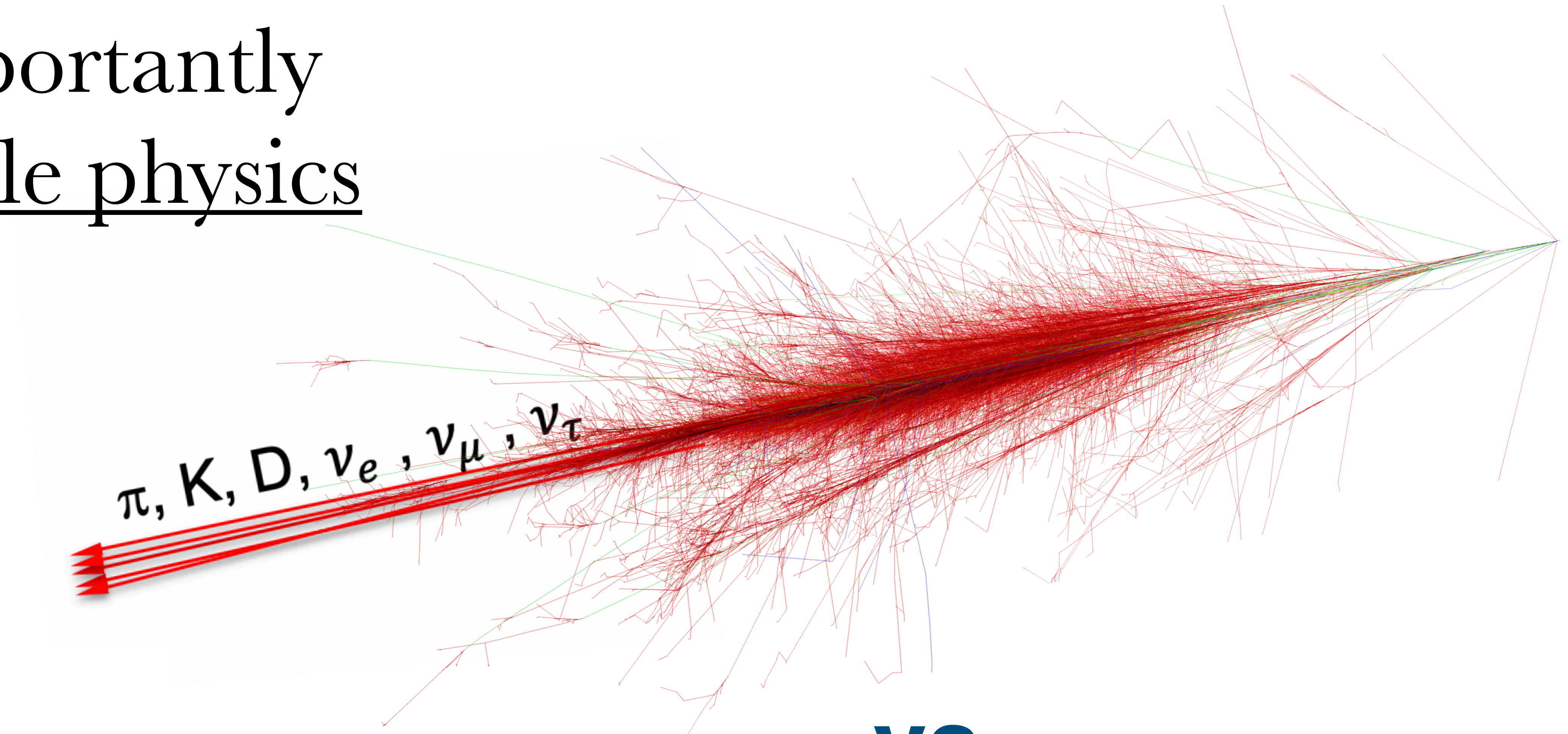


EAS Particles (Gamma Shower)



EAS Simulations

- To infer the properties of the initial cosmic ray, experimental data is interpreted based on Monte-Carlo simulations (e.g. CORSIKA, CONEX)
- Simulations depend on theoretical models, most importantly hadronic interaction models, based on known particle physics
- Interactions in EAS at LHC energies and beyond
- Various types of hadron interactions in EAS
- Particle production in EAS in the forward region
  - Not accessible by current accelerator experiments
  - Not calculable within perturbative QCD
  - Extrapolations into unknown phase space!



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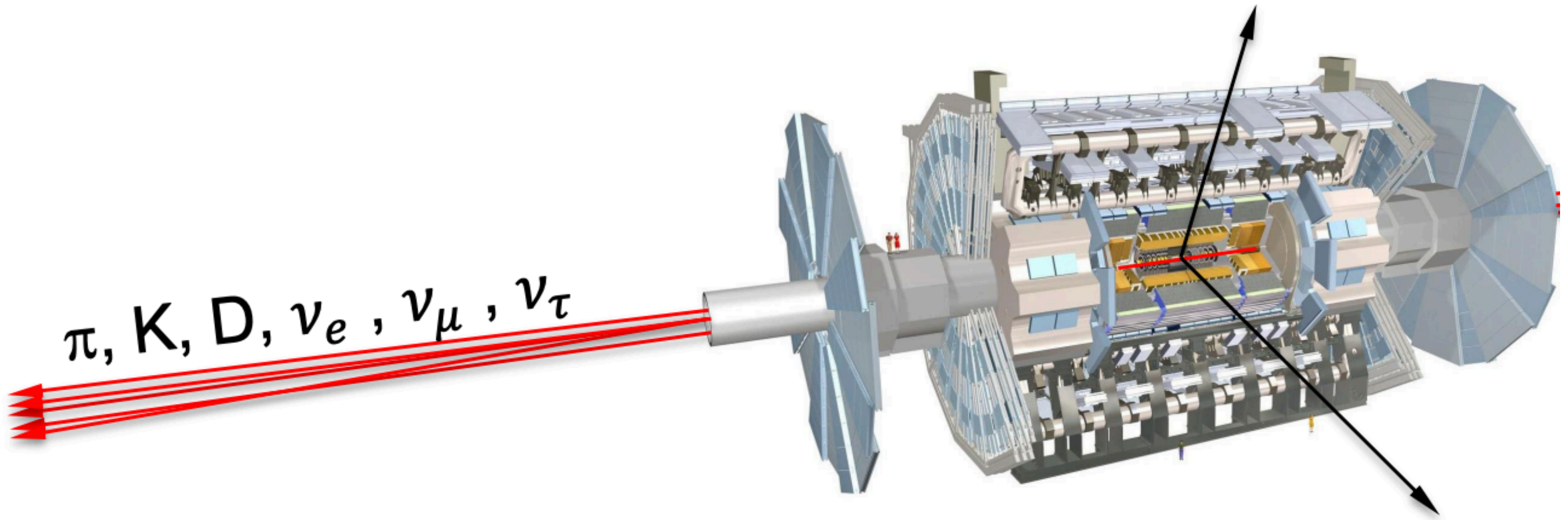

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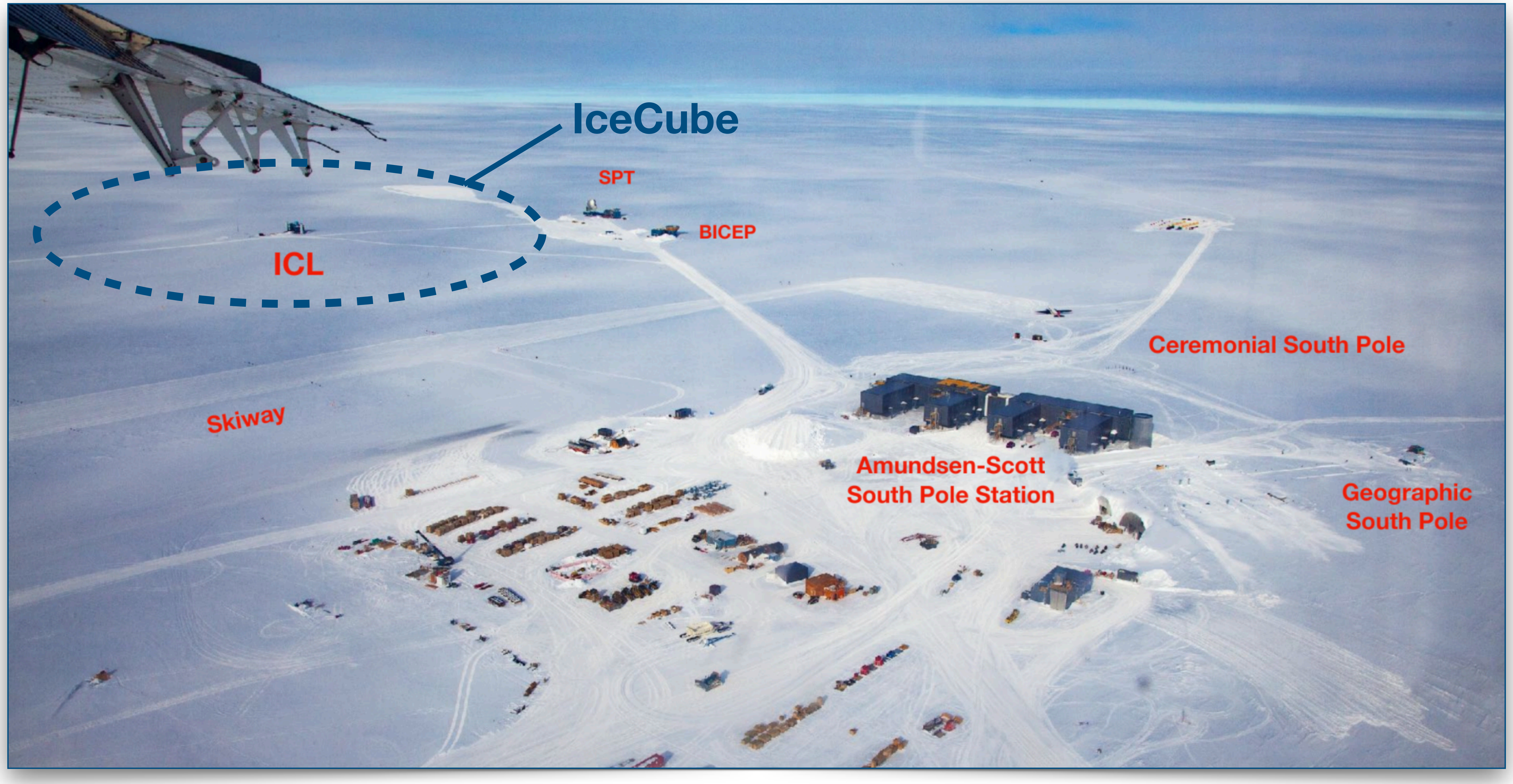
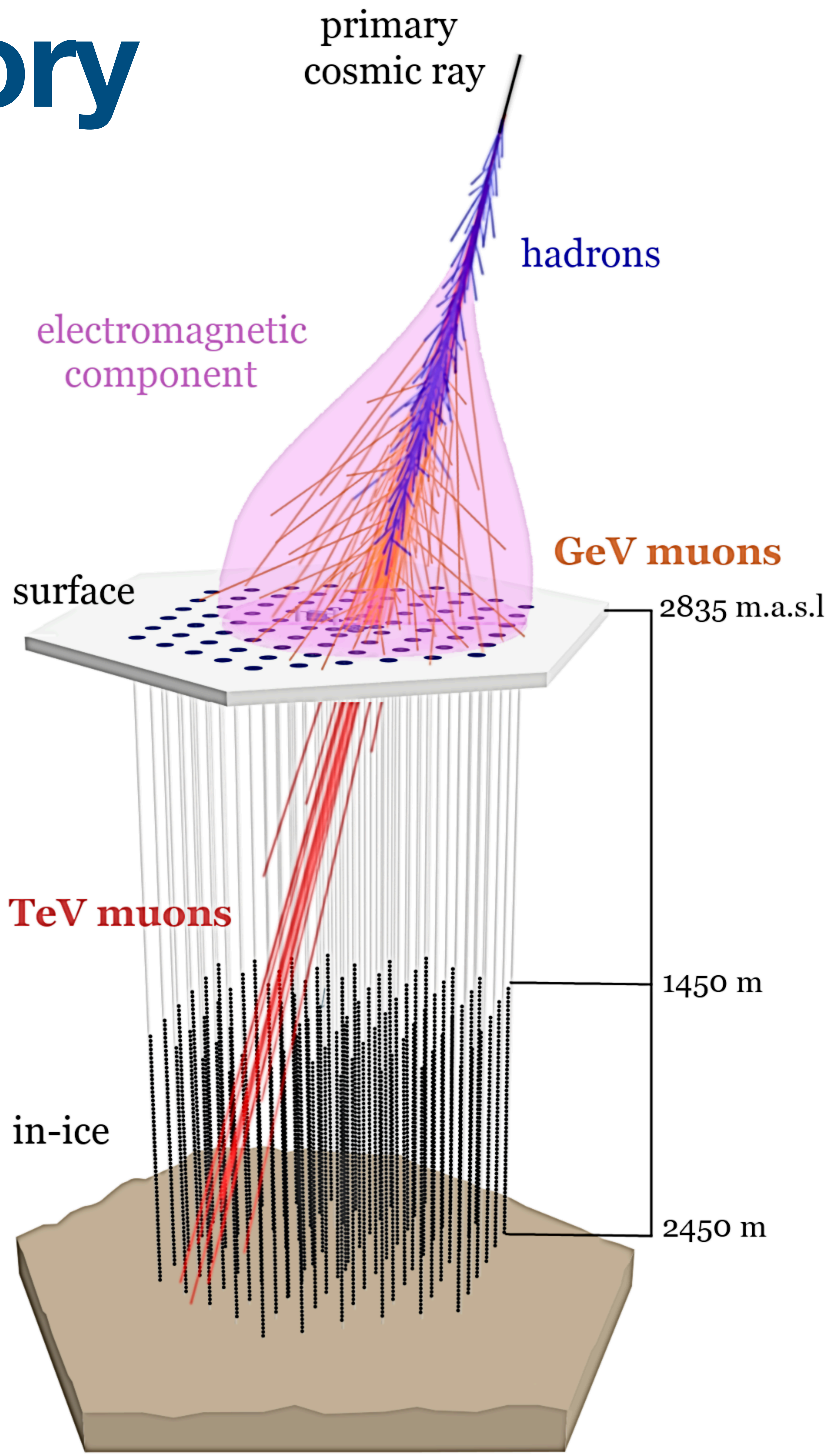
Dedicated measurements of multi-particle production with EAS observatories and collider experiments needed!

The IceCube Neutrino Observatory

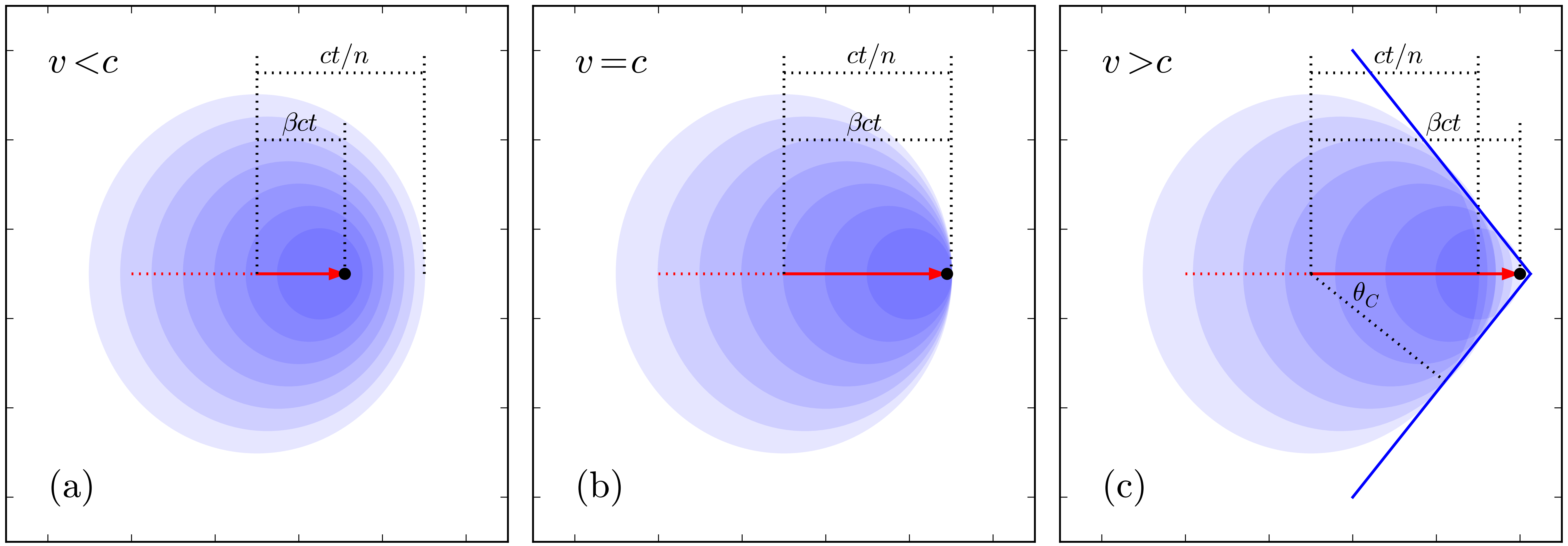
- Hybrid cubic-kilometer particle detector at the South Pole
  - Surface detector at 2835 m.a.s.l
  - In-ice detector at depths between 1450 m and 2450 m

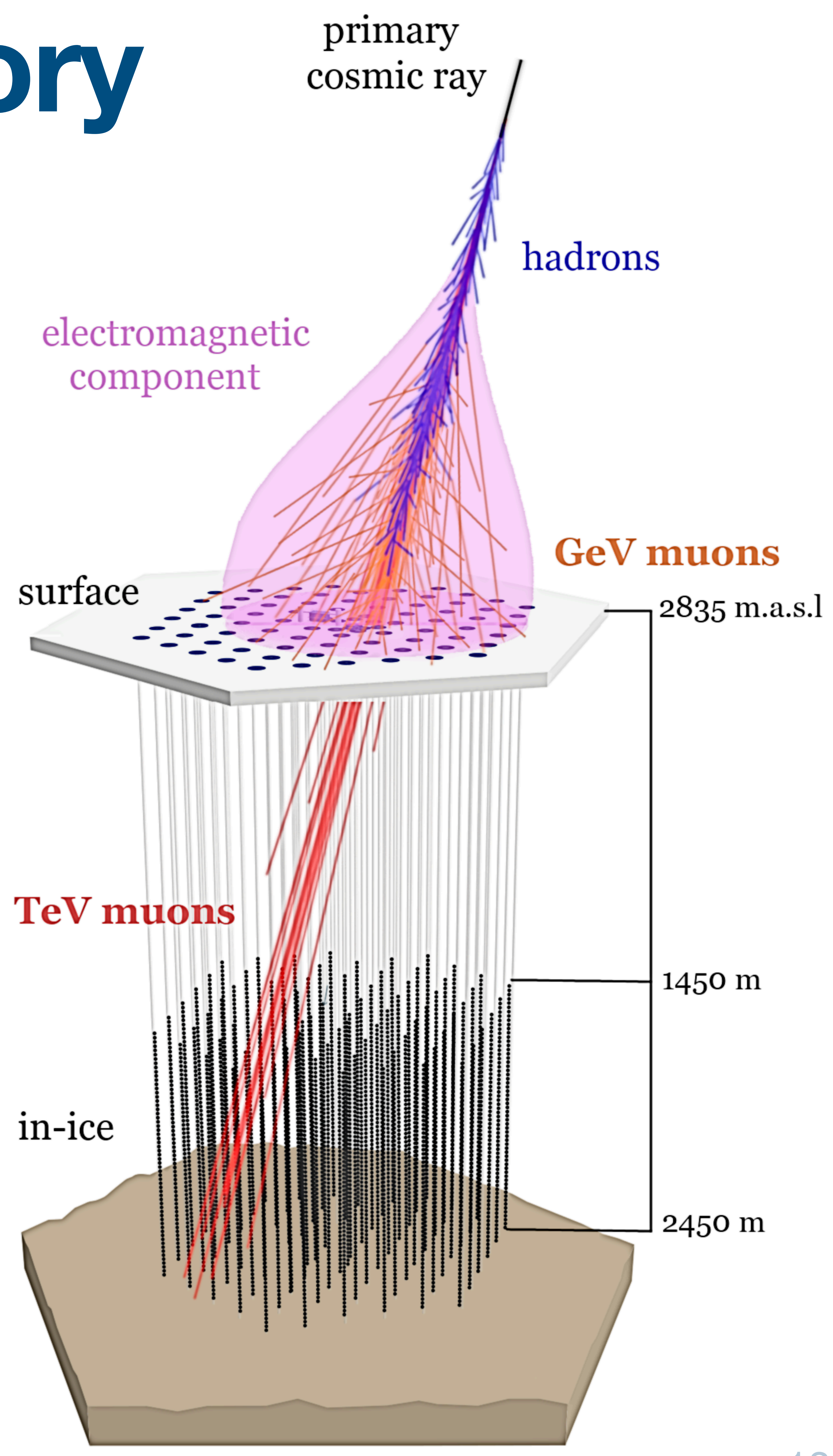




The IceCube Neutrino Observatory

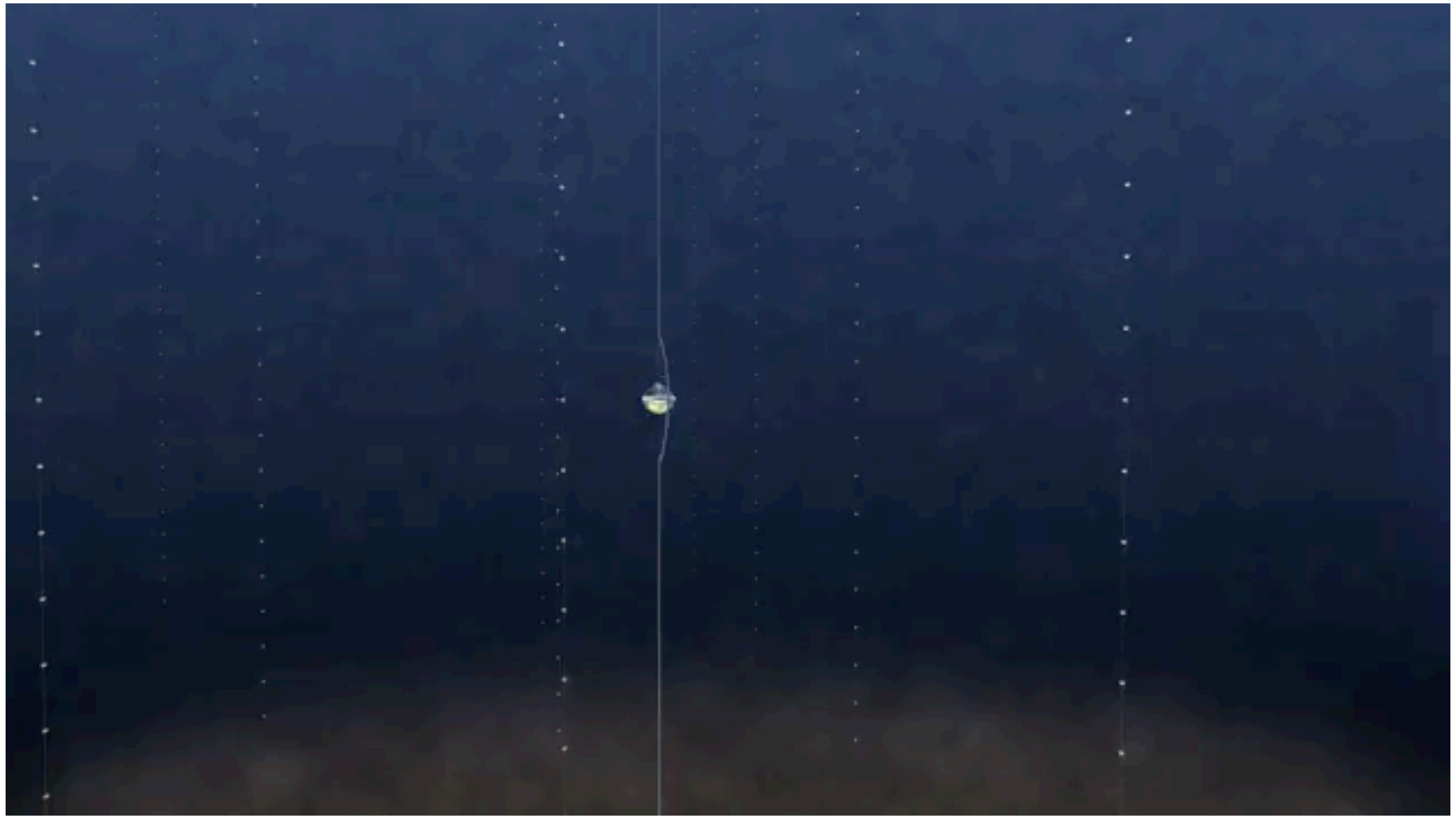
- Cherenkov detectors:
  - Speed of light in a dense medium: $c < c_{vacuum}$
  - Relativistic charged particles with $v > c$ produce Cherenkov light in a dense medium
  - E.g. IceCube / KM3NeT / Auger: ice /water / water
  - Light can be measured with optical sensors

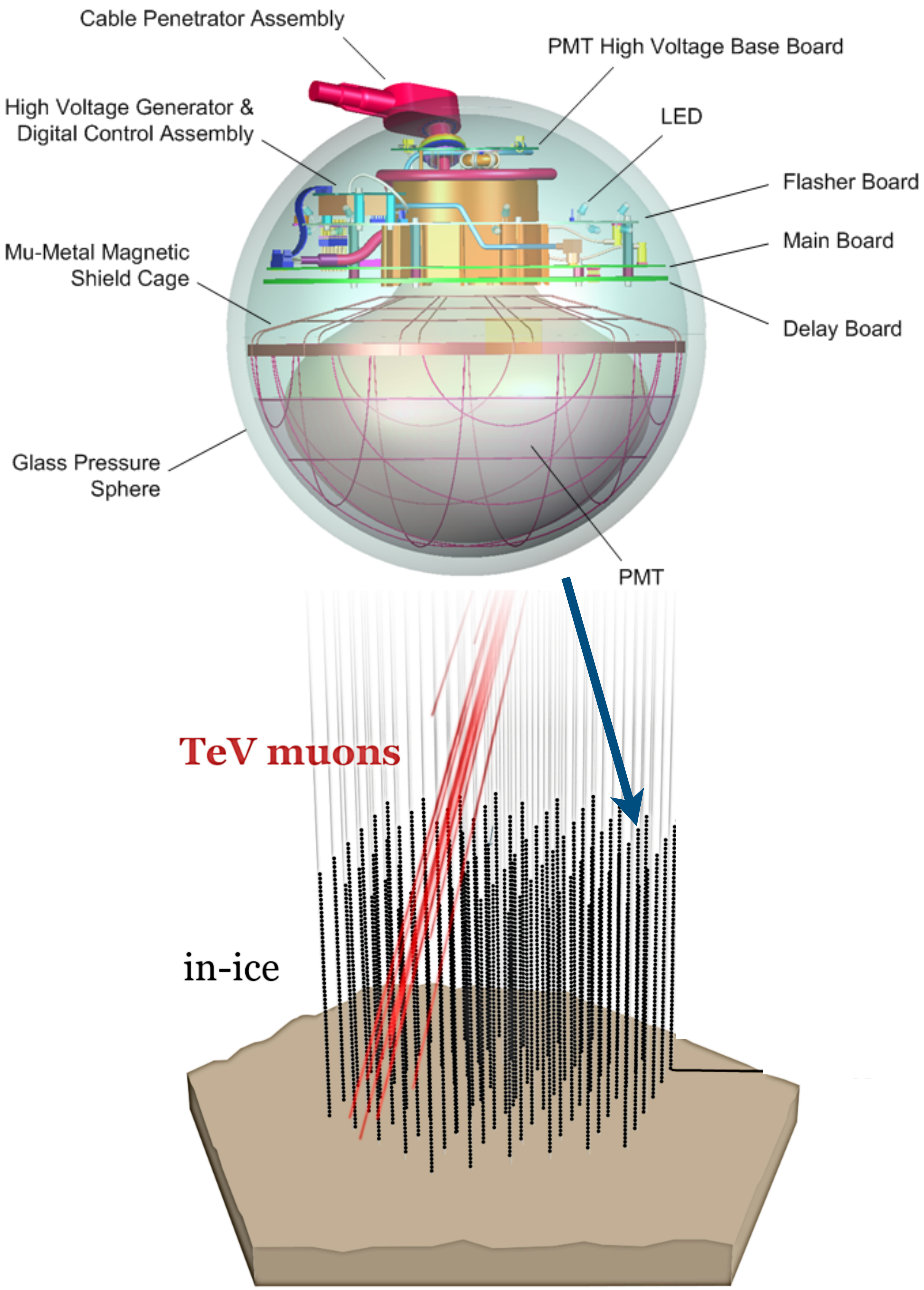




The IceCube Neutrino Observatory

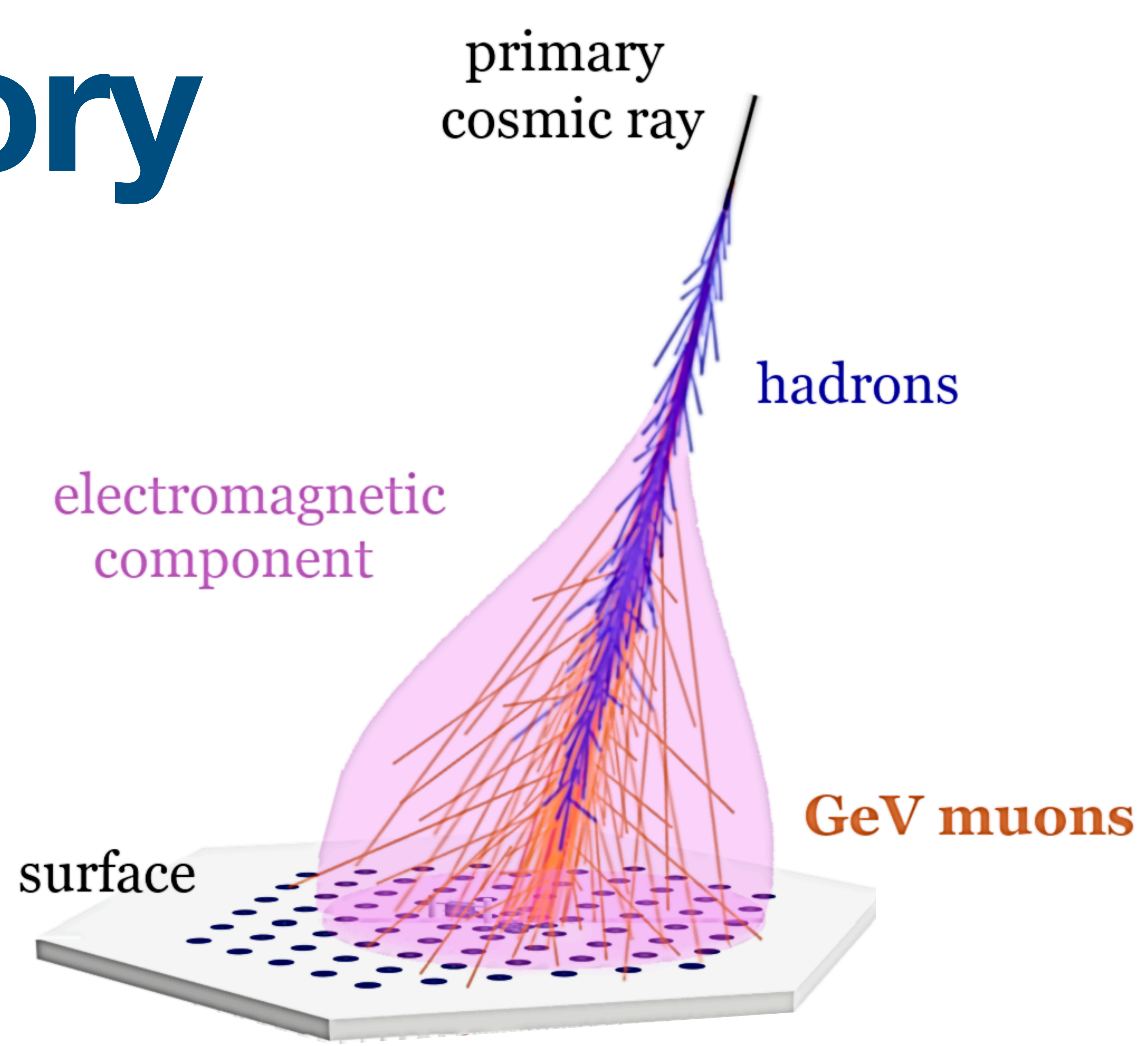
- <u>In-ice detector:</u>
  - 86 strings with grid spacing of ~125 m
  - 5600+ Digital Optical Modules (DOMs)
  - Few 100 GeV (up to several PeV) muons

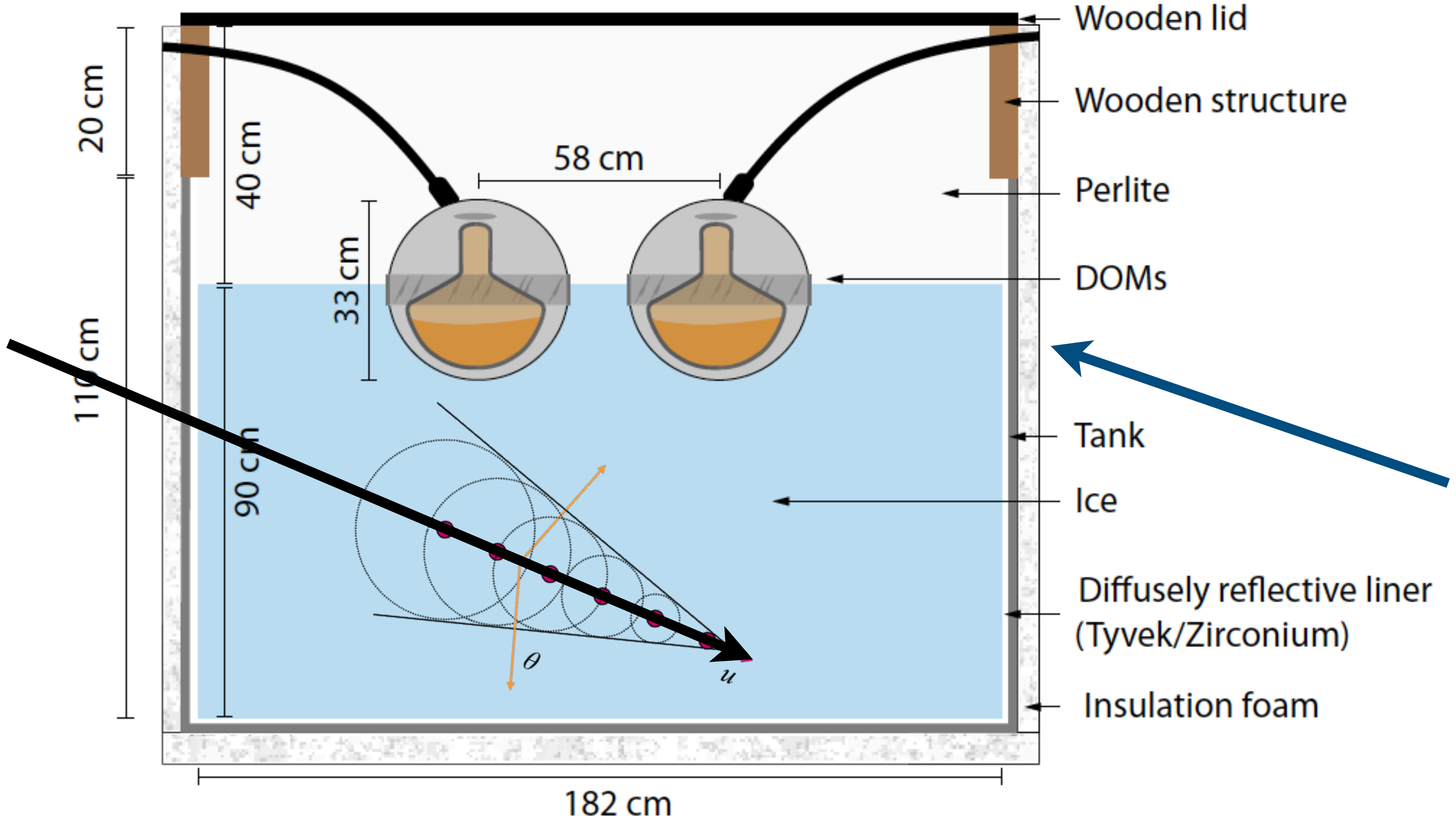


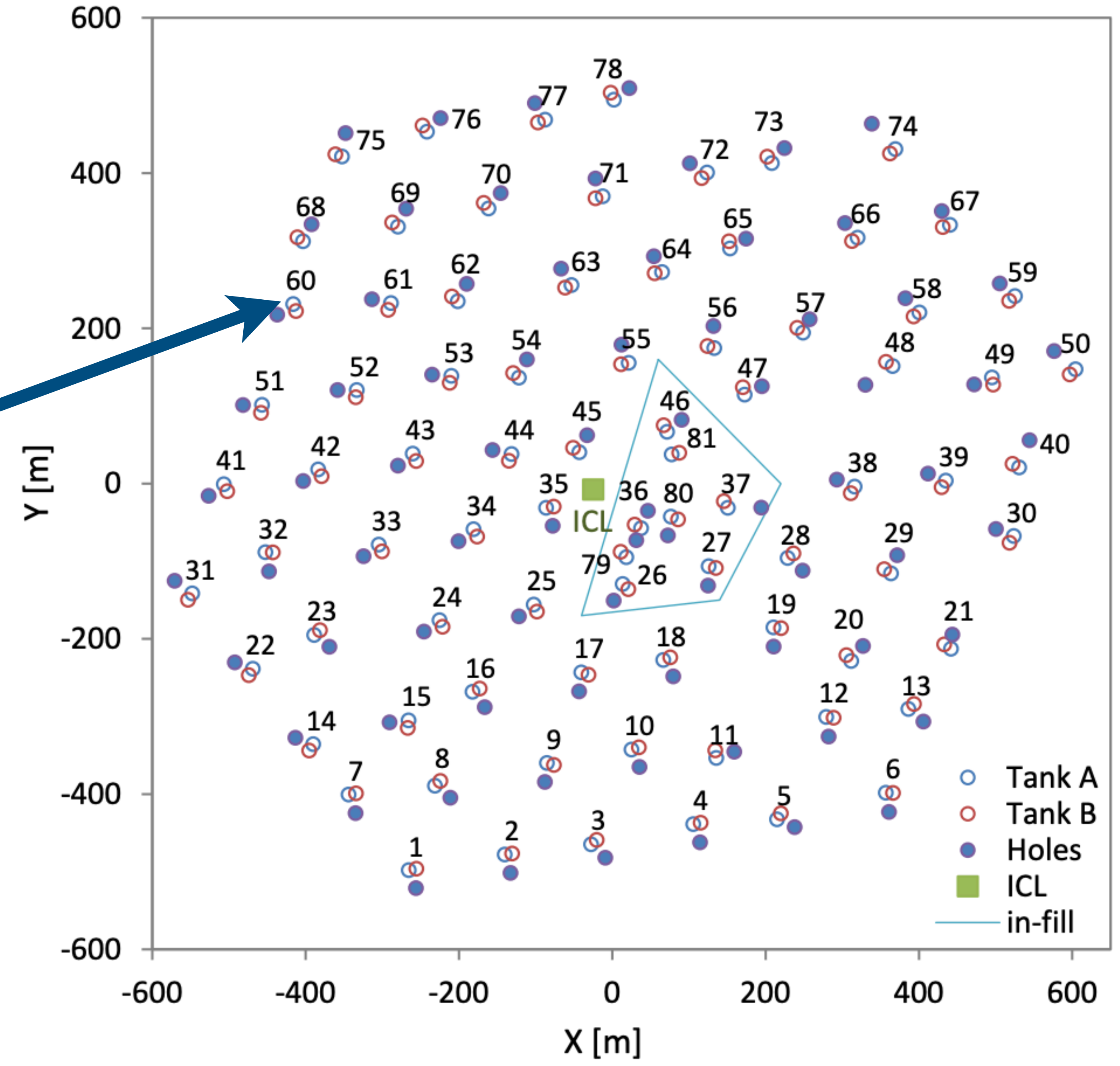


The IceCube Neutrino Observatory

- <u>Surface detector, IceTop:</u>
  - 81 stations with grid spacing of ~125 m
  - Each station: 2 tanks (each tank: 2 DOMs)
  - Electromagnetic EAS component (EAS energy)
  - GeV muon content in EAS



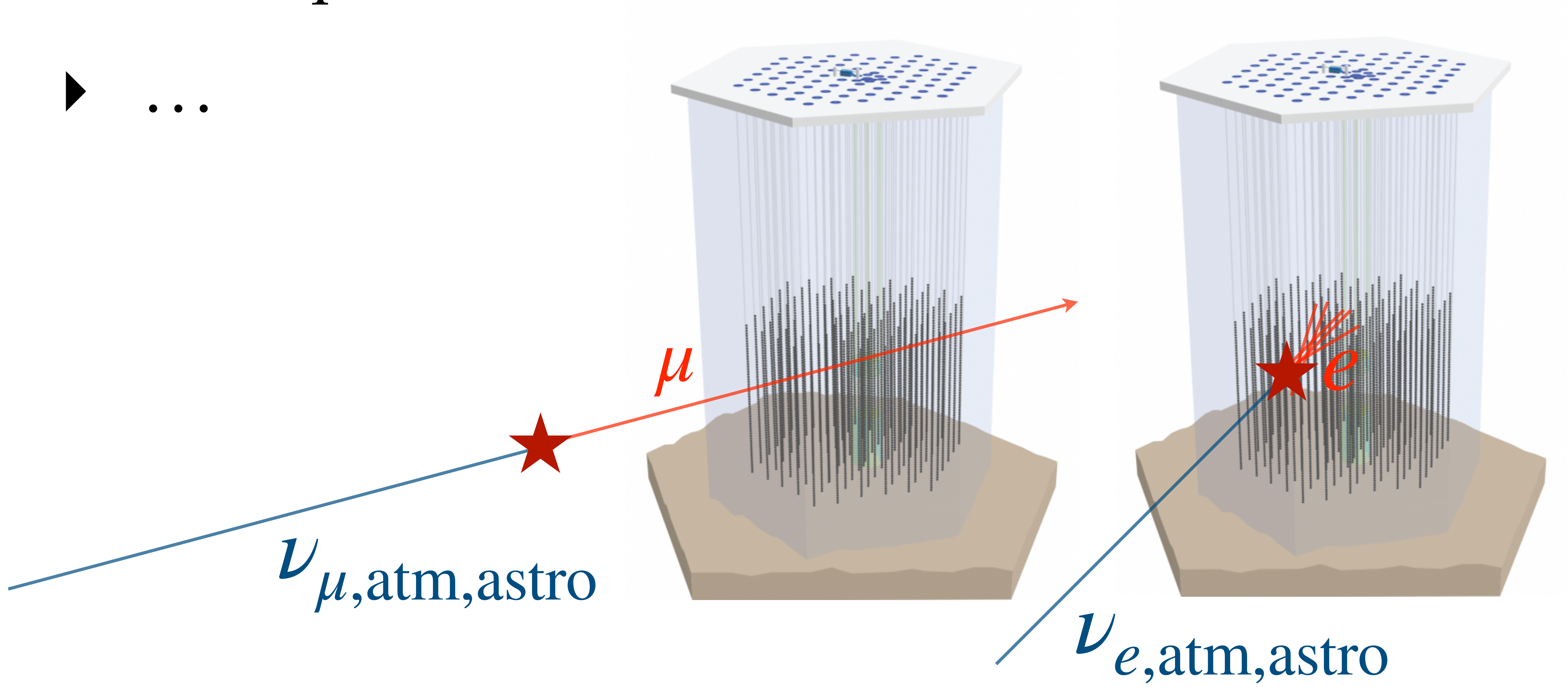


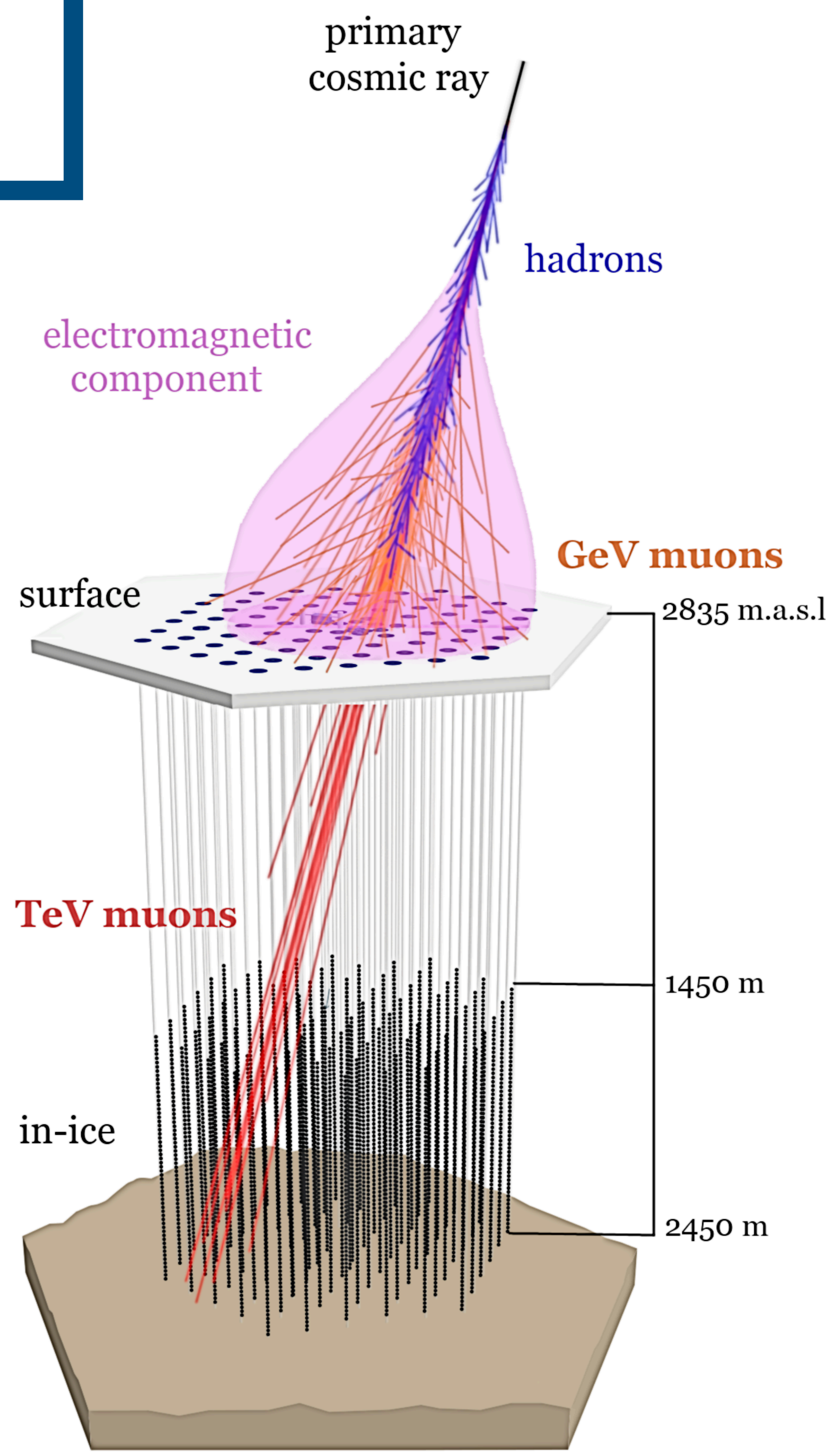


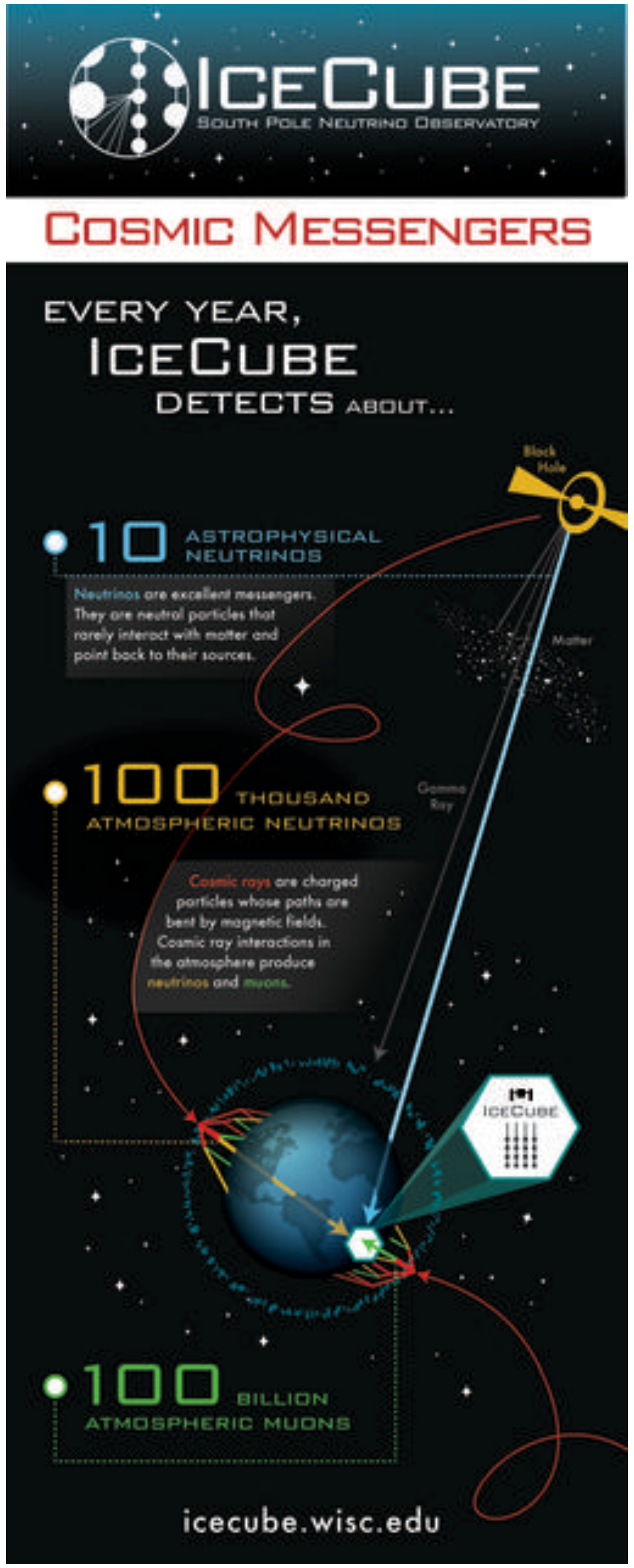
The IceCube Neutrino Observatory

- <u>Measurements of various particles:</u>
  - EAS particles
    - Atmospheric muons / neutrinos
    - Electromagnetic EAS component (IceTop only)
  - Astrophysical neutrinos
  - BSM particles
  - …

This talk

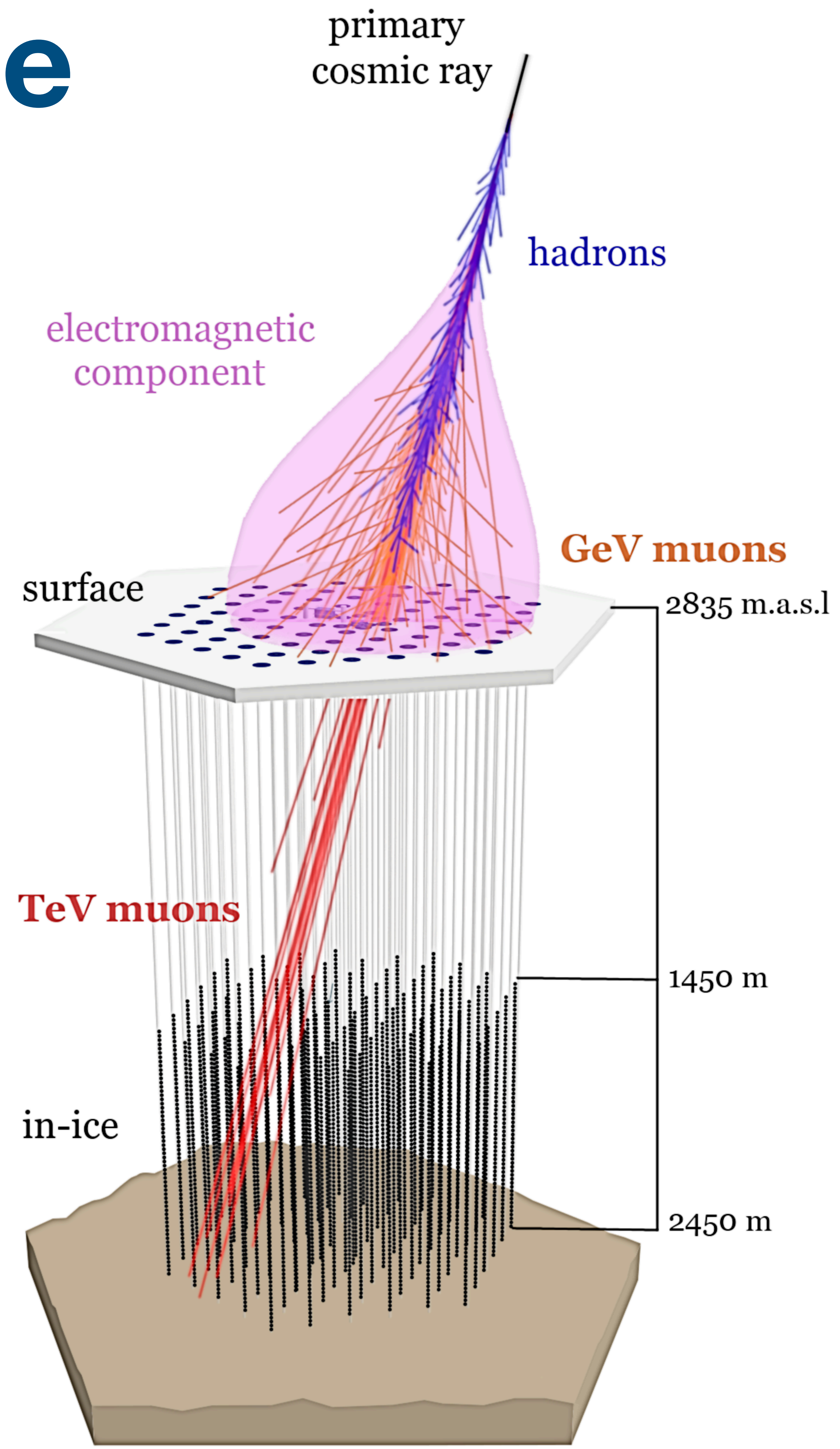






EAS Measurements with IceCube

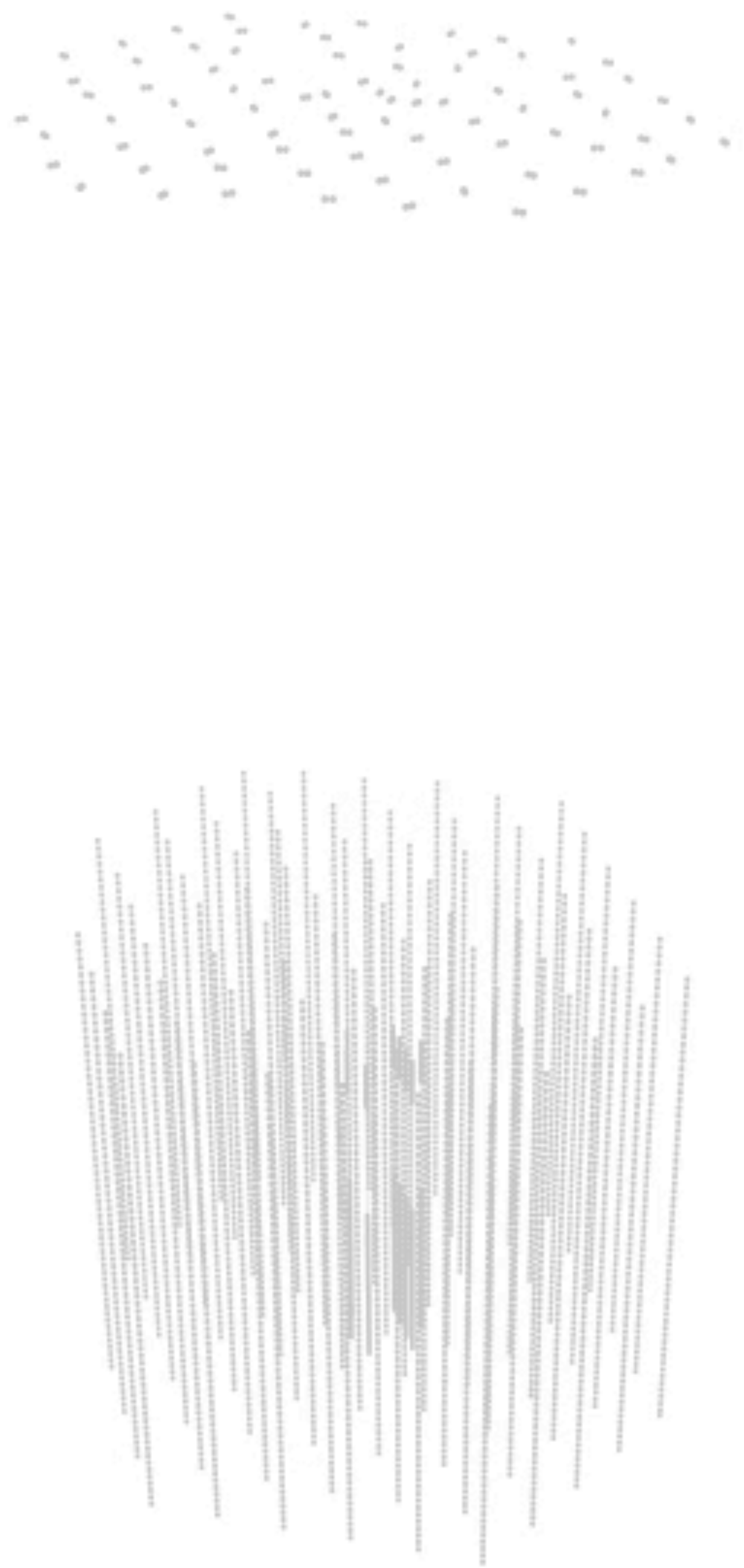
- Surface detector, IceTop, measures:
  - Electromagnetic EAS component (EAS energy)
  - ~GeV muon content in EAS
- In-ice detector measures:
  - TeV muon content in EAS (up to several PeV)
- CR energies of $\sim 1\,\mathrm{PeV}\ (10^{15}\,\mathrm{eV})$* to $\sim 1\,\mathrm{EeV}\ (10^{18}\,\mathrm{eV})$
- Coincident measurements possible!
- Ideal facility to study muon (hadron) production in the forward region in EAS!



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

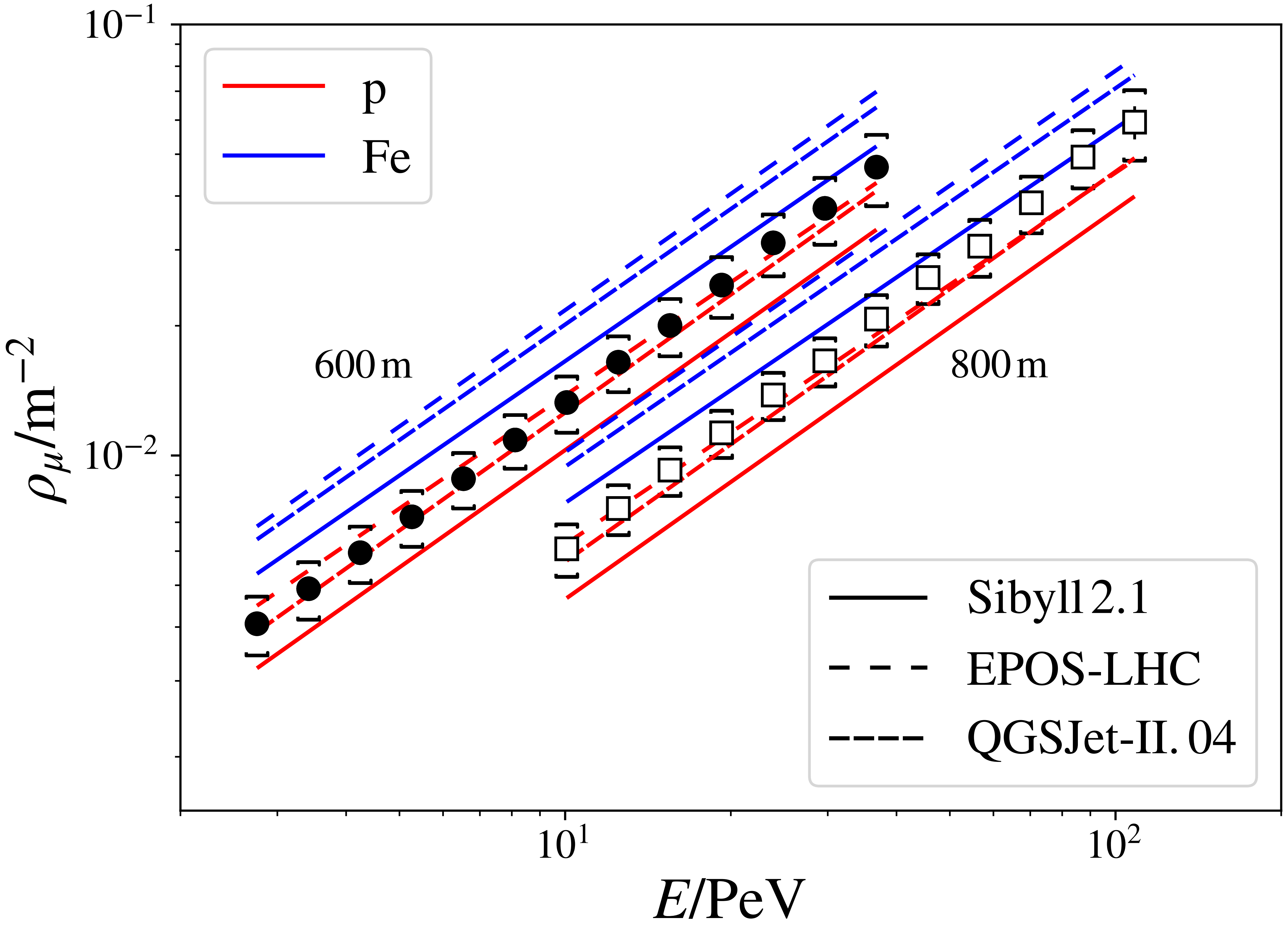
EAS Measurements with IceCube

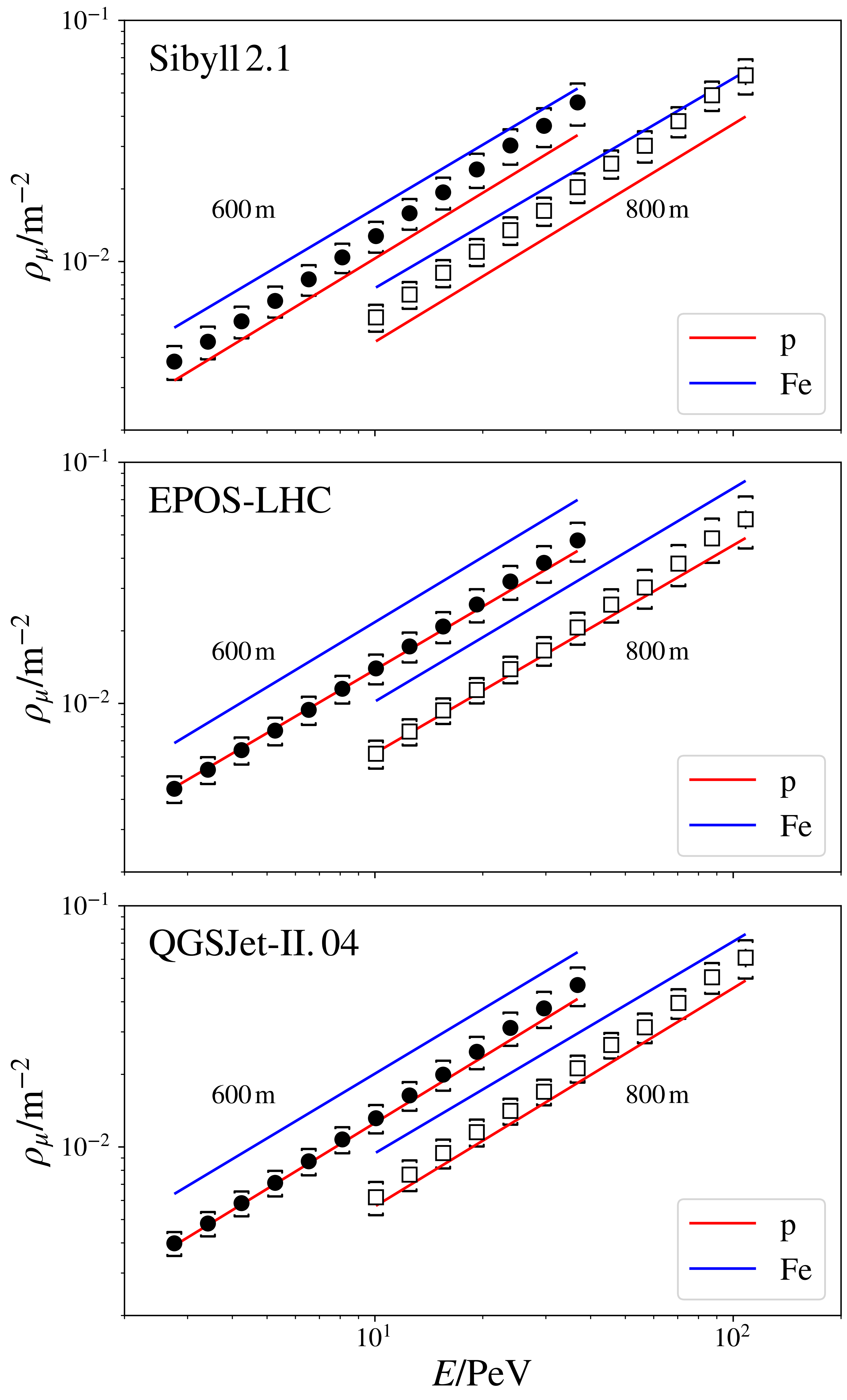
- <u>Example:</u> experimental data event (2012)
- <u>Color-coding of time:</u>
  - From red (early) to blue (late)
- <u>Sizes of "blobs":</u>
  - Amount of detected light by each DOM
- The red line indicates the reconstructed event trajectory



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:

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

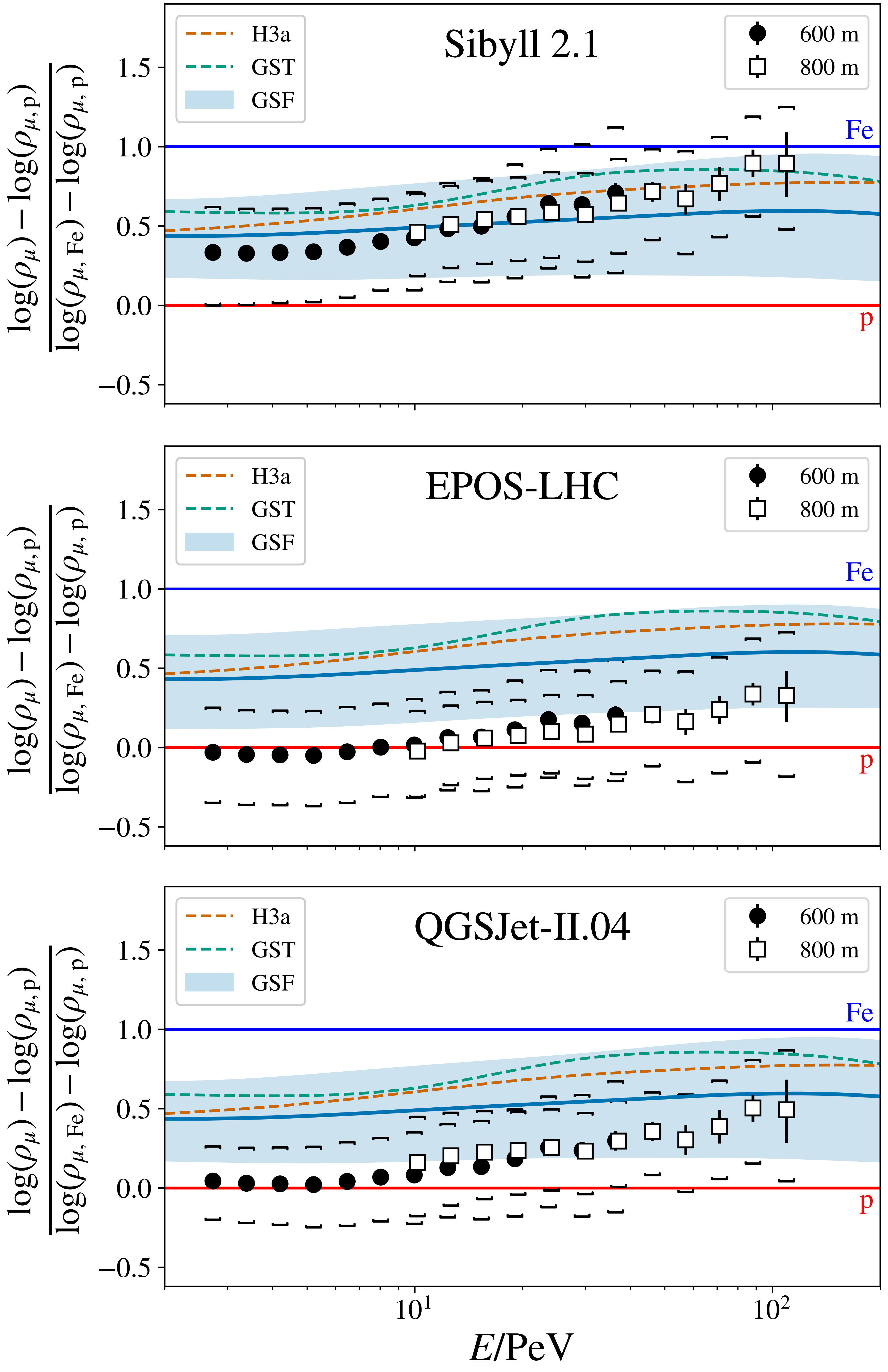
  - Proton: $z = 0$, iron: $z = 1$

- Comparison for different flux model predictions which are in agreement with measurements within uncertainties

- Best data/MC agreement for Sibyll 2.1

- EPOS and QGSJet yield very light masses (they predict more muons)

- Comparison with other experiments?



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GeV Muons in IceTop

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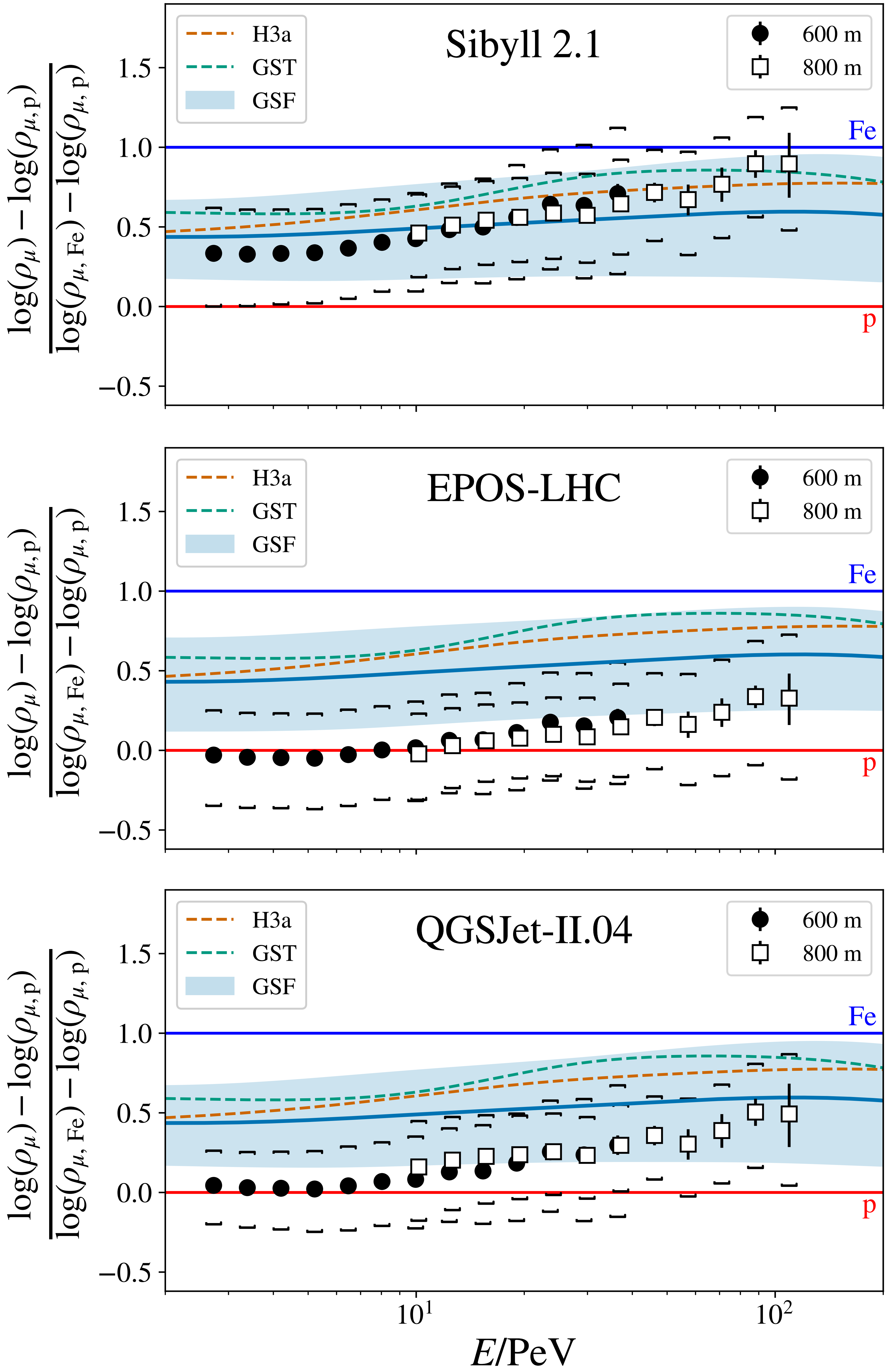

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GeV Muons in IceTop

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simulations

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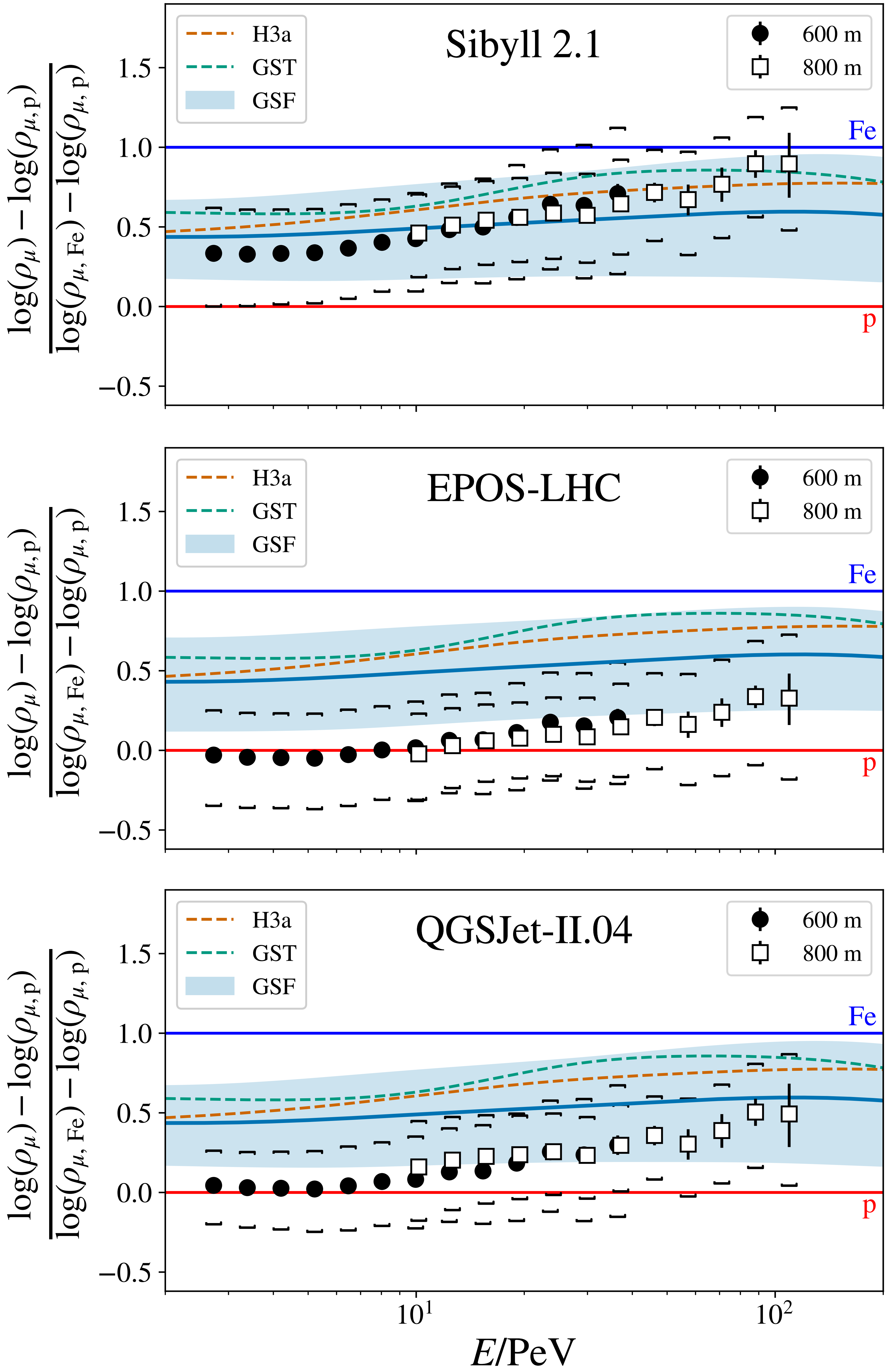

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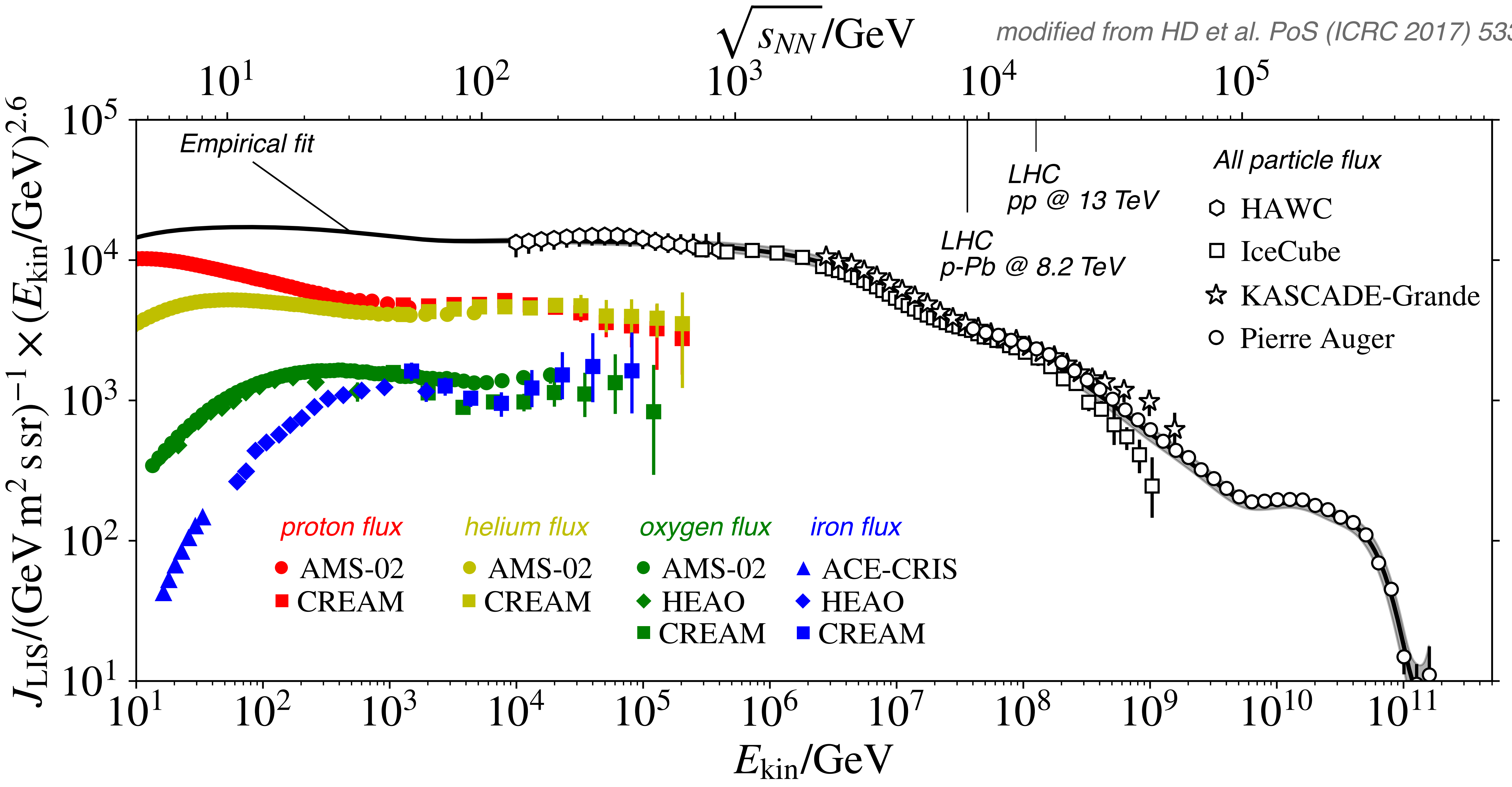
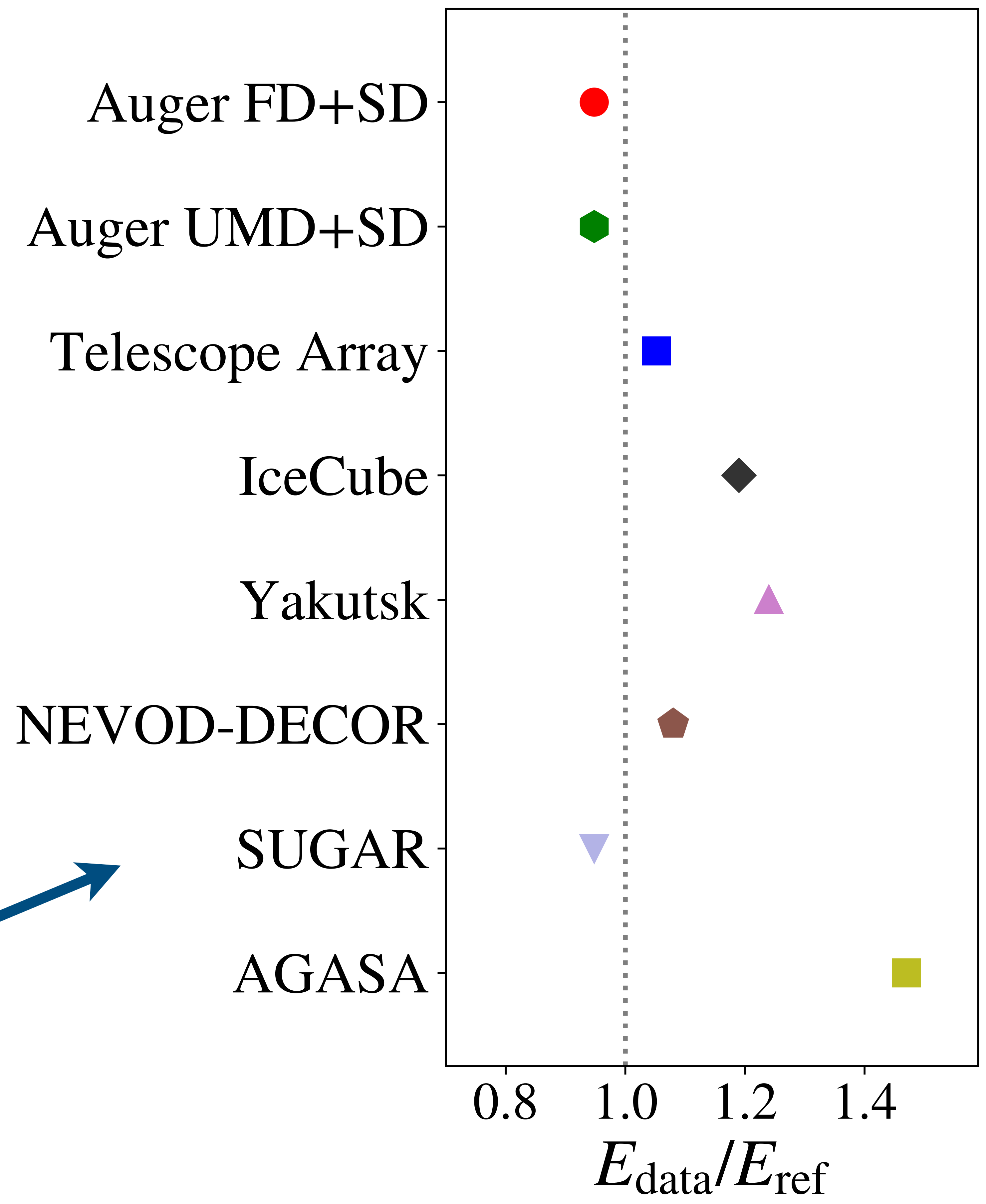
Energy-Scale Cross-Calibration

- Known energy-scale offsets between EAS experiments!
- 20% offset in energy causes 18% shift in muons!
  - Energy rescaling required! ("line up all features")
- Reference model: Global-Spline Fit Model (GSF)

modified from HD et al. PoS (ICRC 2017) 533



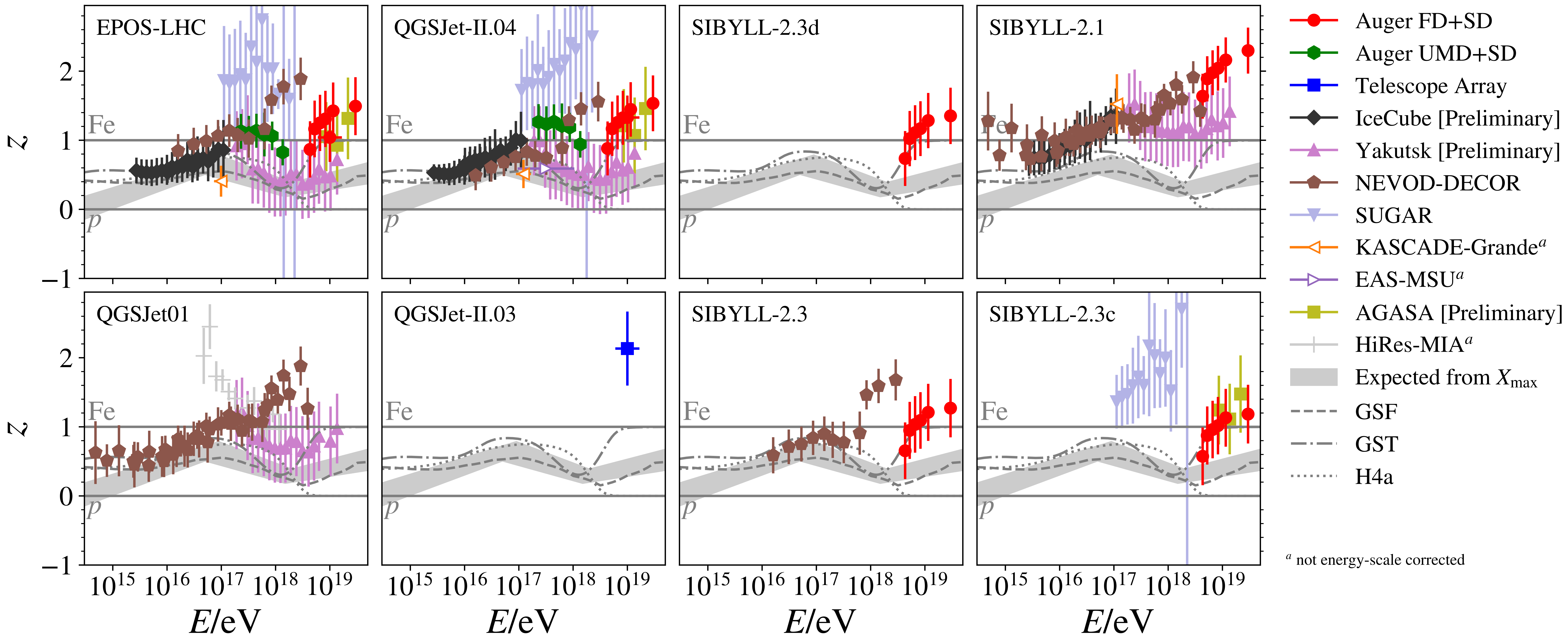


[H. P. Dembinski et al., PoS ICRC2017 (2017) 533]

The Muon Puzzle

- Muon numbers in EAS after energy-scale cross-calibration

[D. Soldin et al., PoS ICRC2021 (2021) 349]

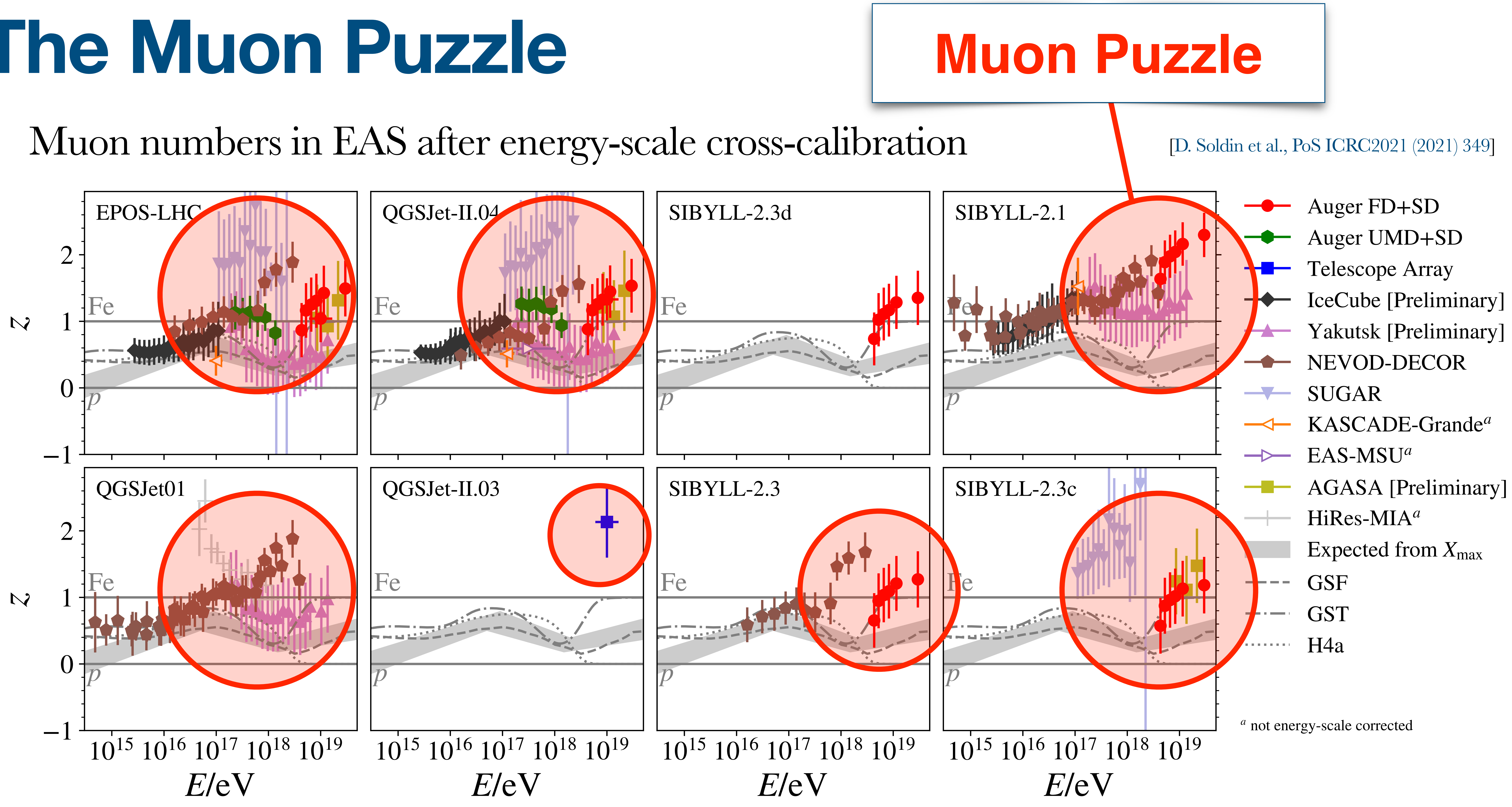


- (Most) muon measurements indicate mass composition heavier than iron at high E_0!

The Muon Puzzle

- Muon numbers in EAS after energy-scale cross-calibration

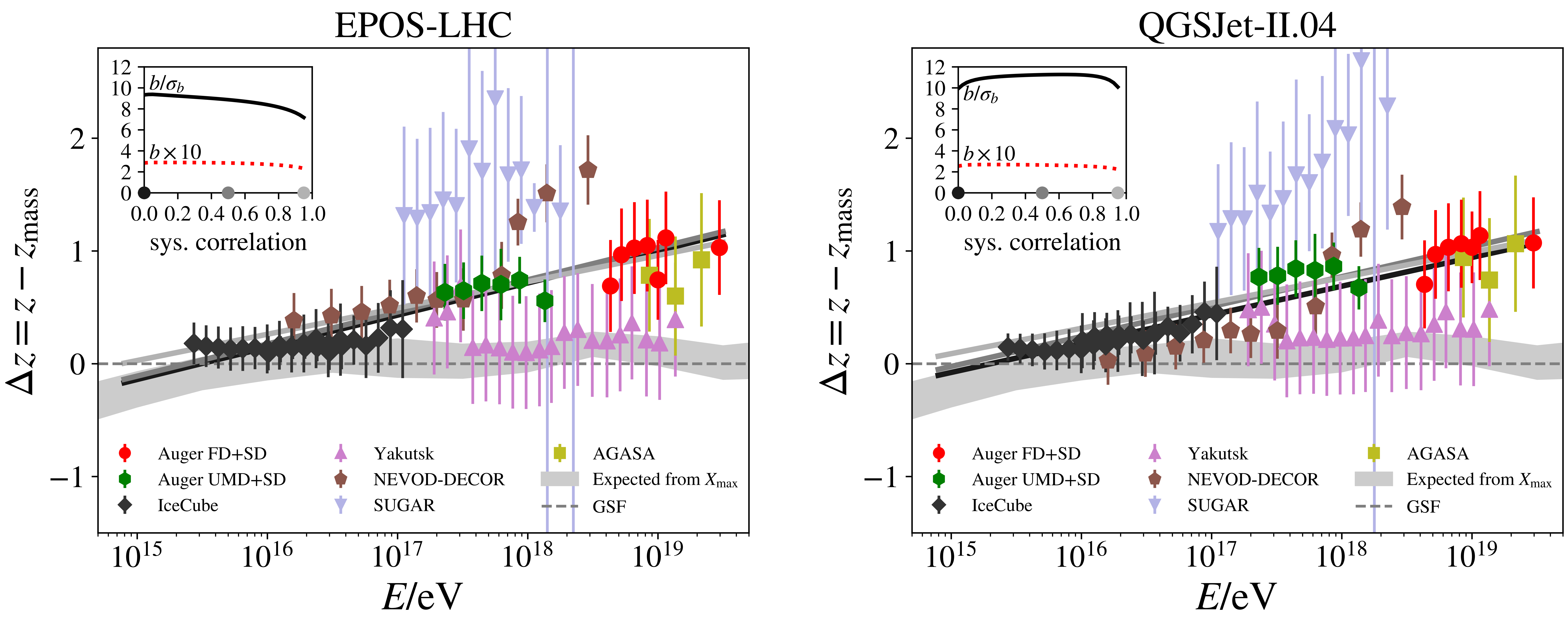
[D. Soldin et al., PoS ICRC2021 (2021) 349]



- (Most) muon measurements indicate mass composition heavier than iron at high E_0!

The Muon Puzzle

- Subtracting expected values z_{mass} obtained from GSF flux model (consistent with X_{max})

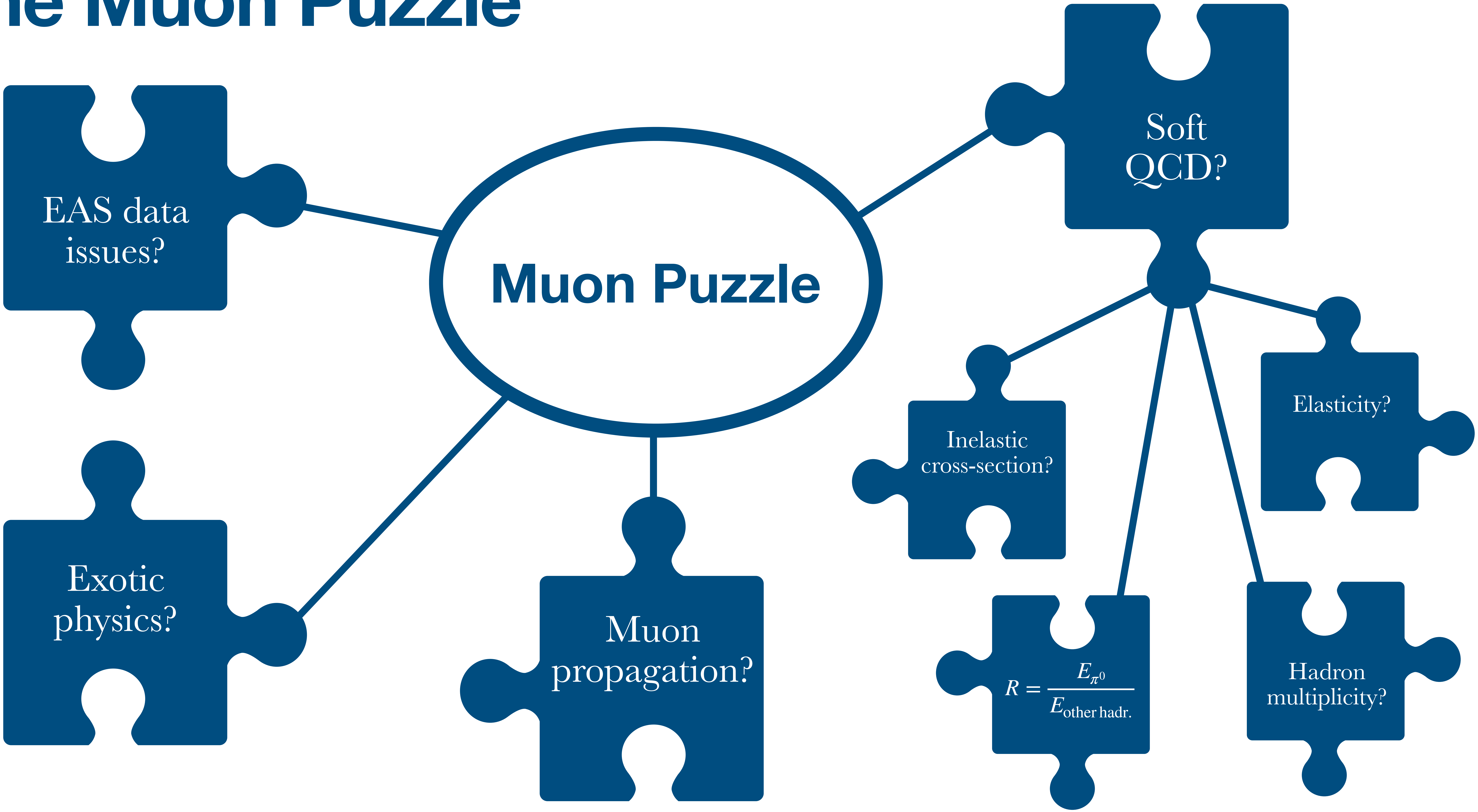


[D. Soldin et al., PoS ICRC2021 (2021) 349]

- Slope of the excess is significant with more than 8σ!
- Indicates severe shortcomings in the understanding of hadronic interactions

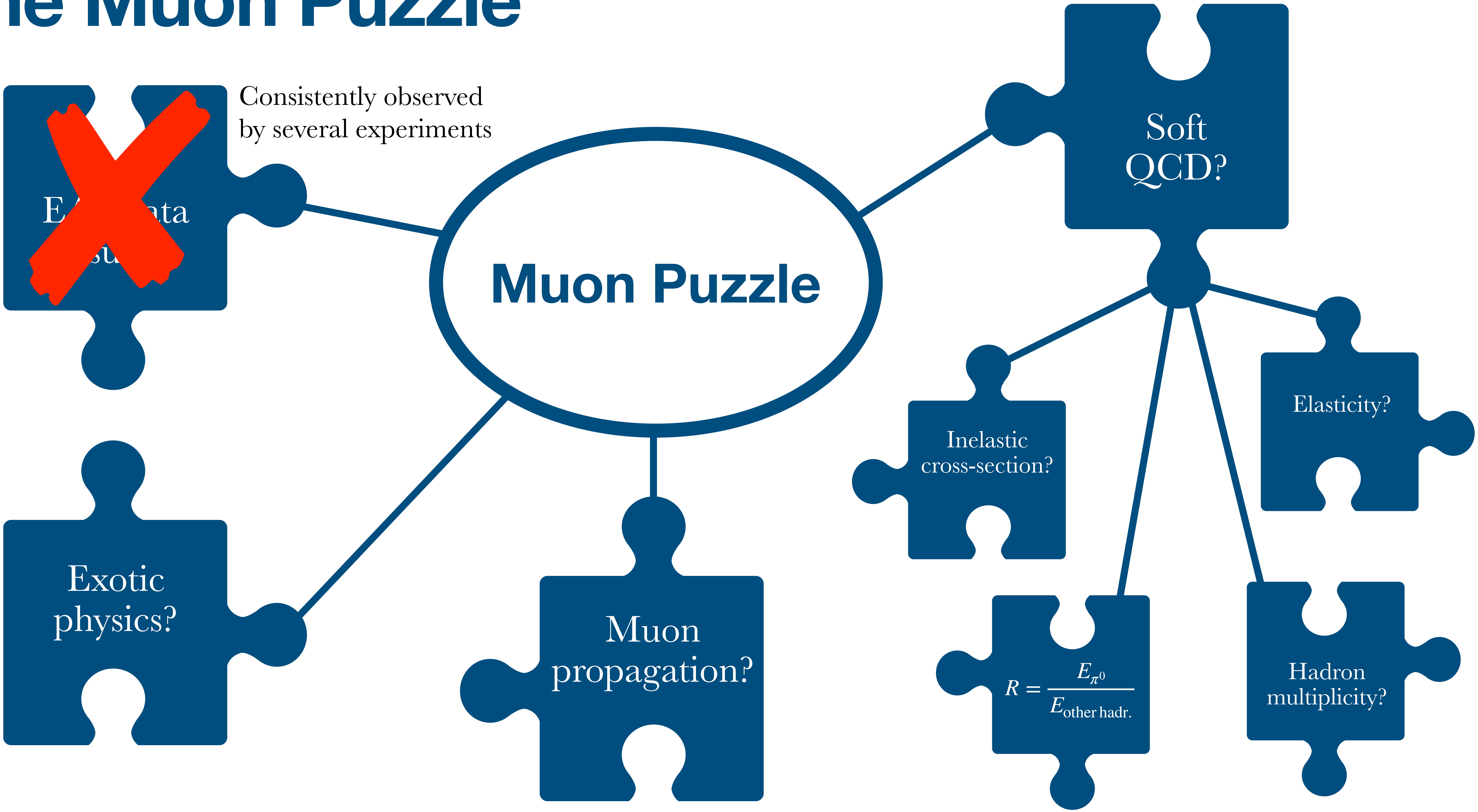
For details, please see [J. Albrecht, H. Dembinski, D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

The Muon Puzzle



For details, please see [J. Albrecht, H. Dembinski, D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

The Muon Puzzle



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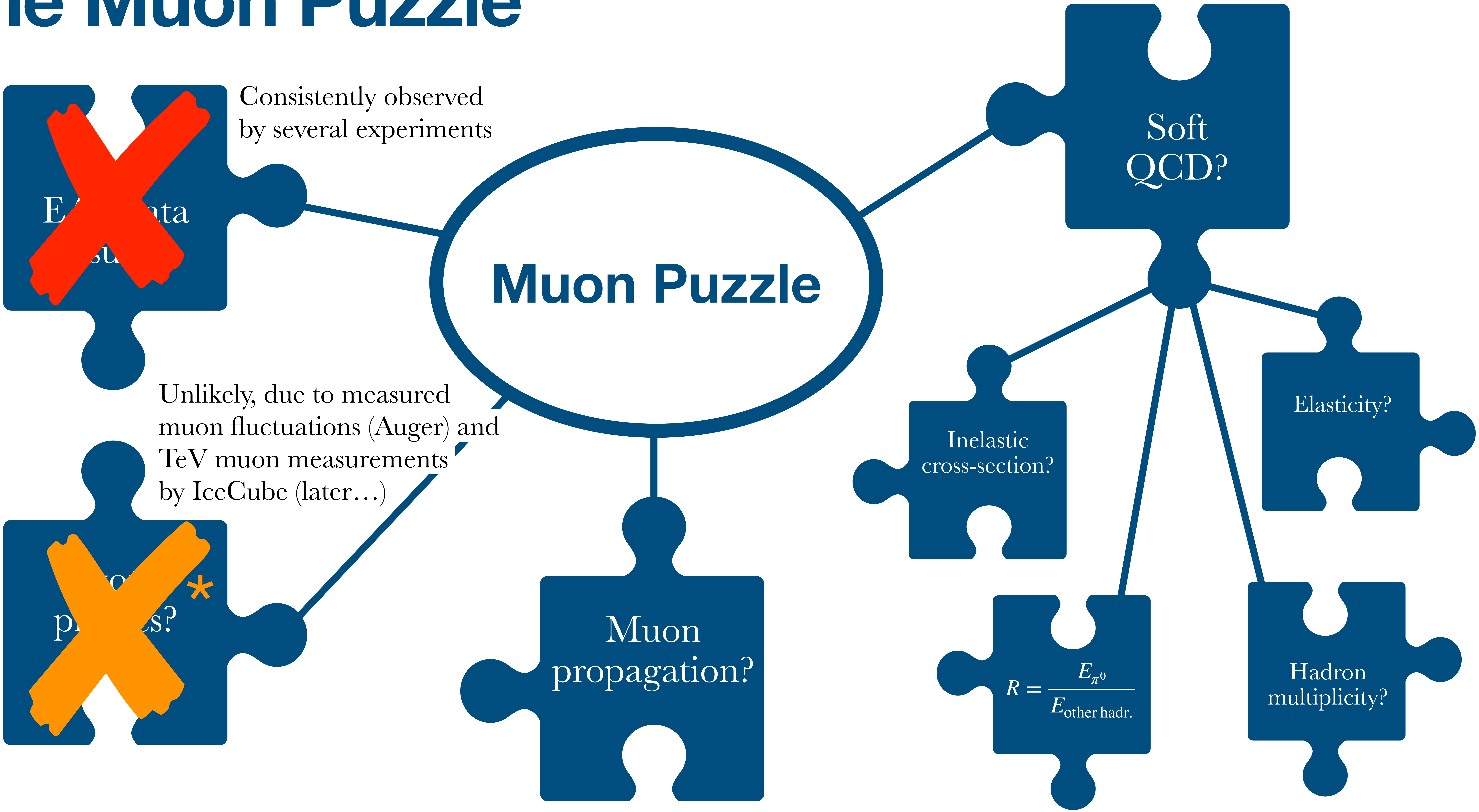
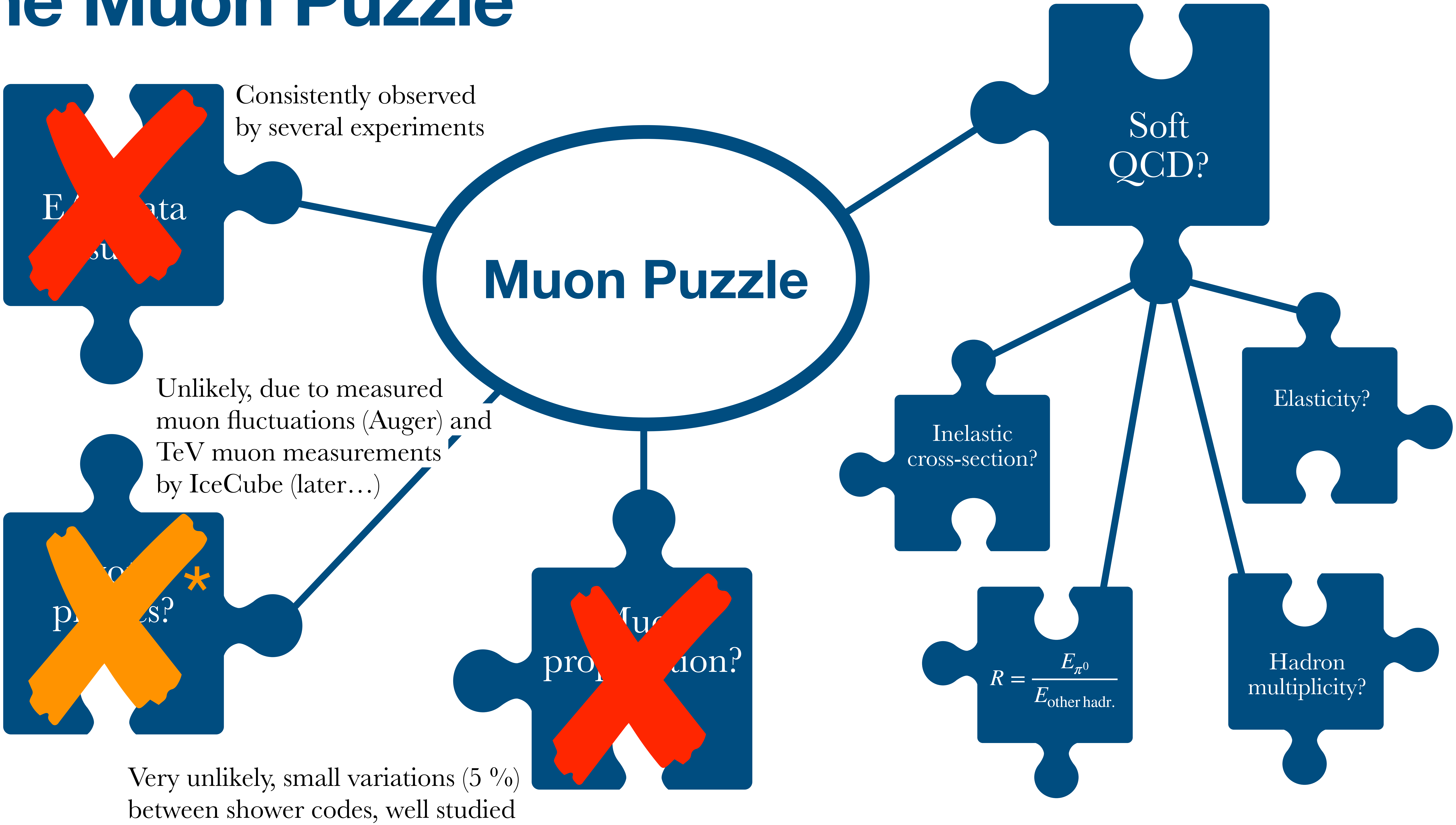
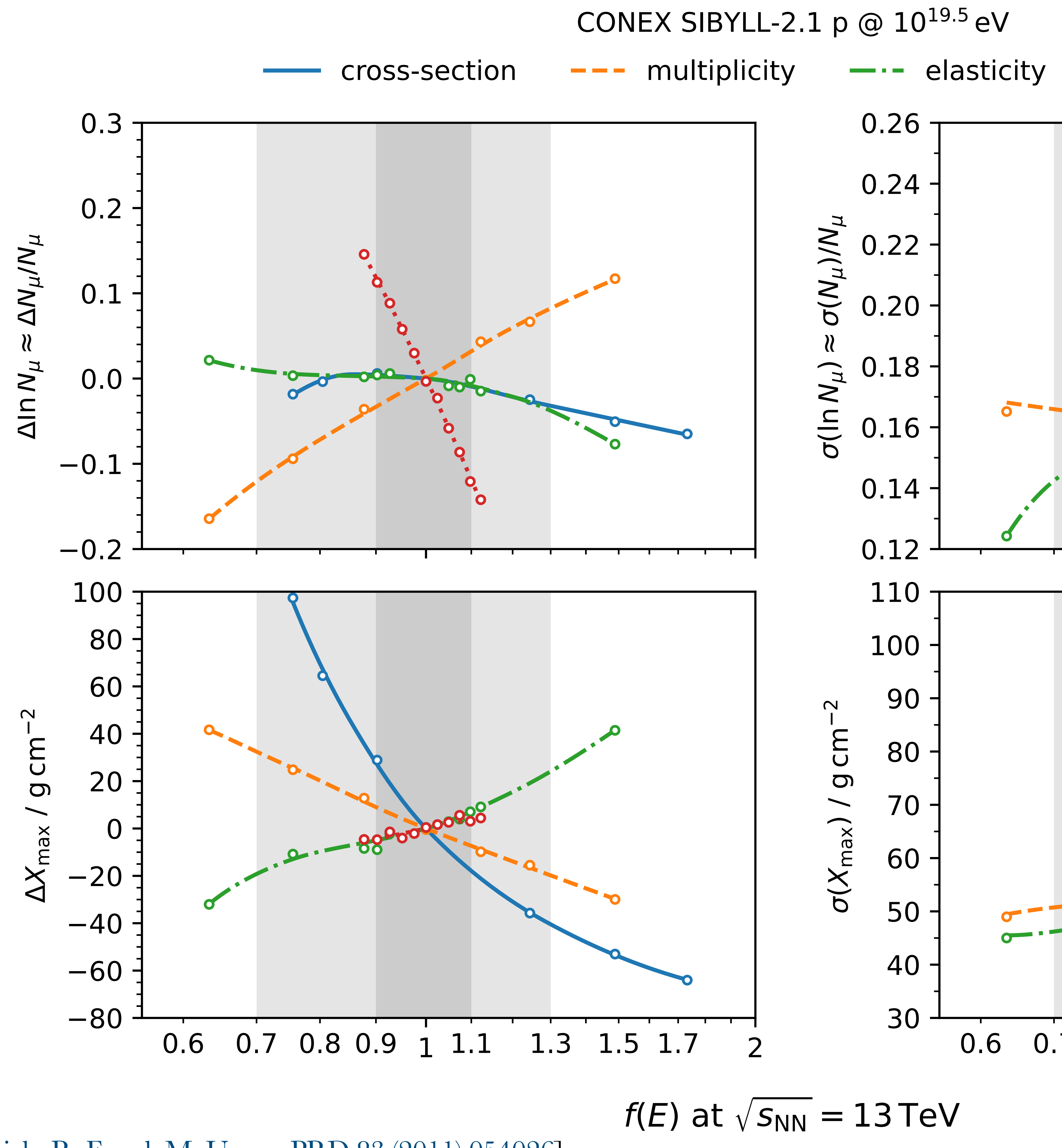


For details, please see [J. Albrecht, H. Dembinski, D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

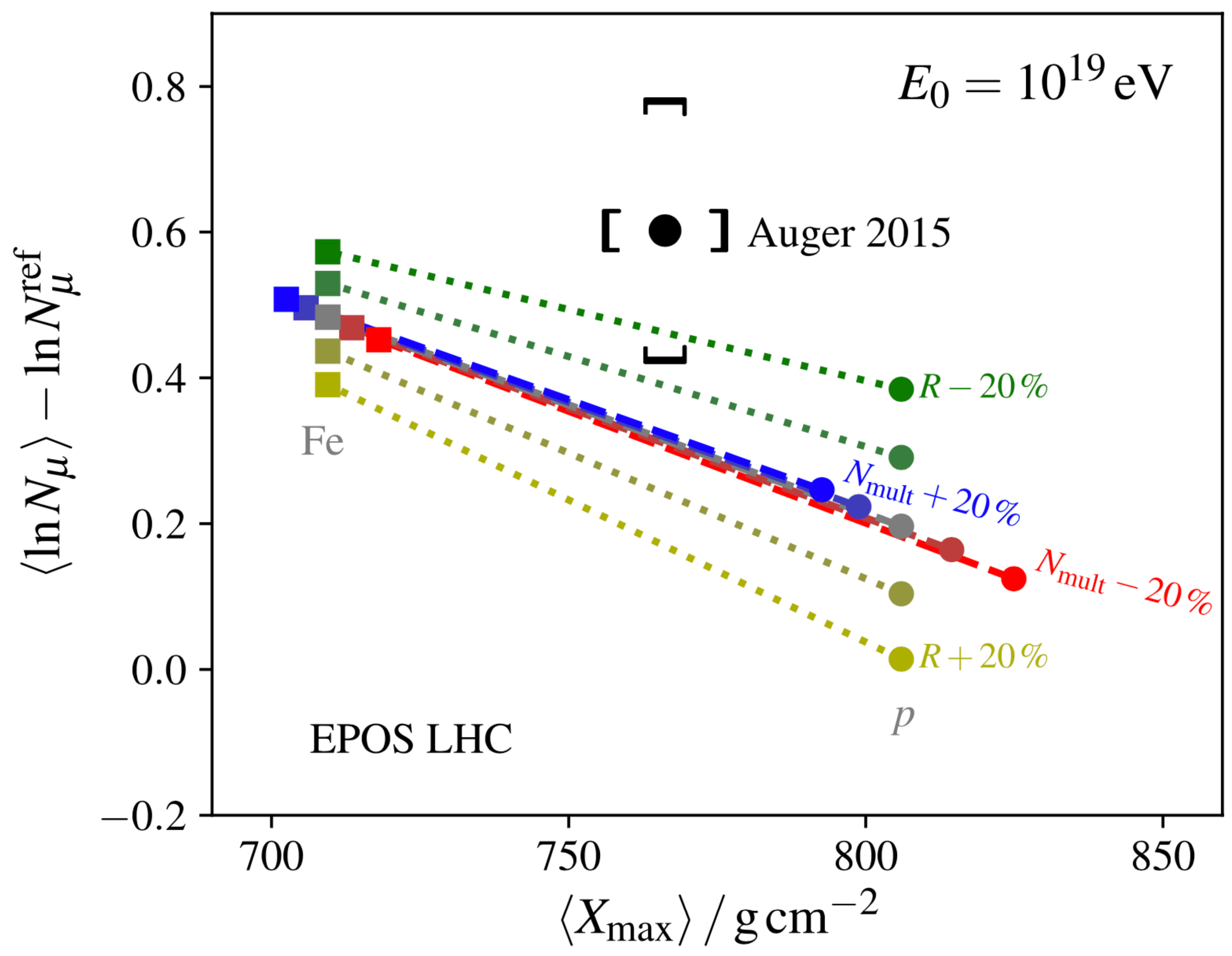
The Muon Puzzle



Study of Shower Impact Parameters



[S. Baur et al., arXiv:1902.09265 (2019)]



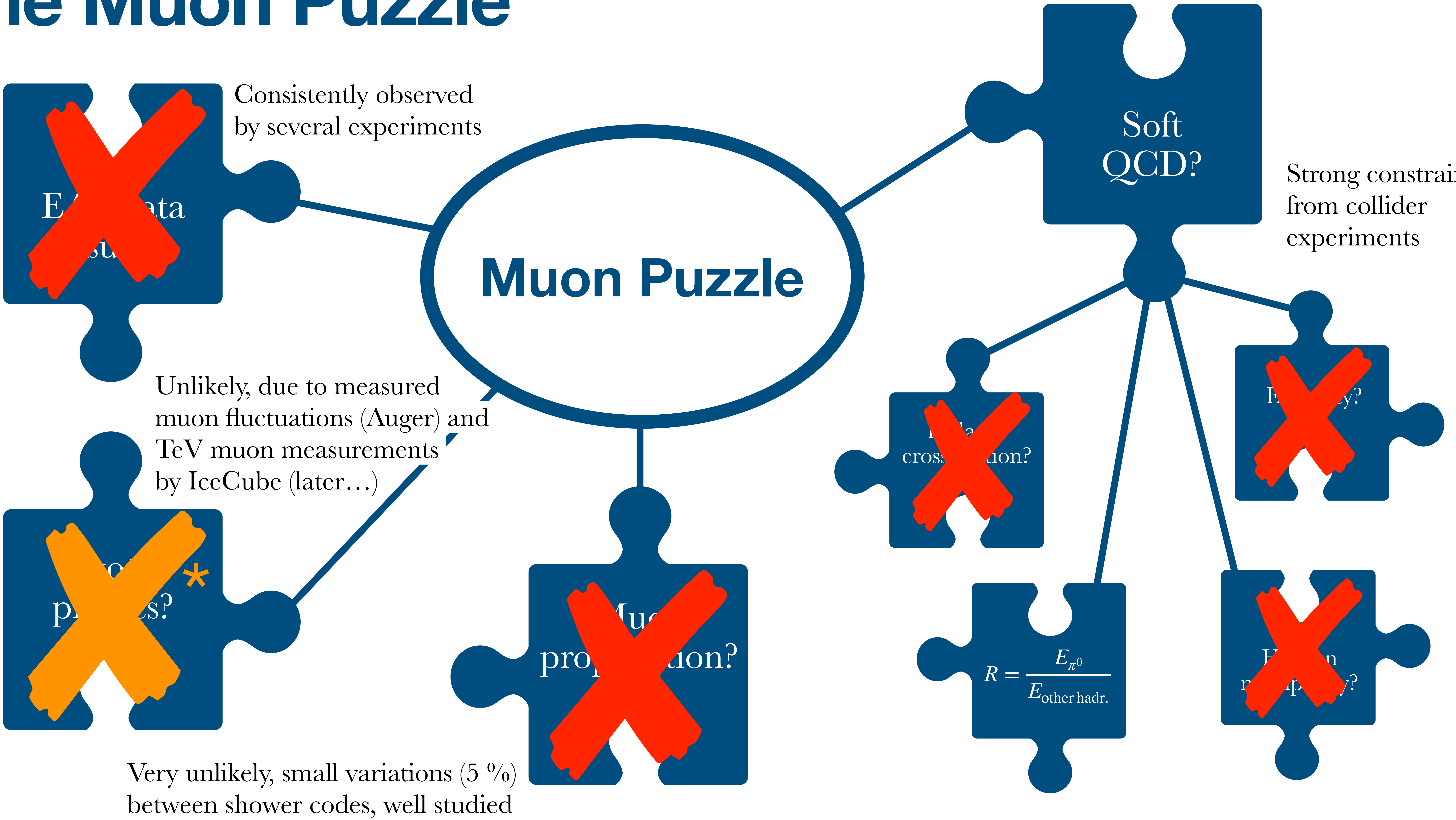
$\pm 10\,\%$ and $\pm 30\,\%$ modification

[R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026]

see also [J. Albrecht, H. Dembinski, D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

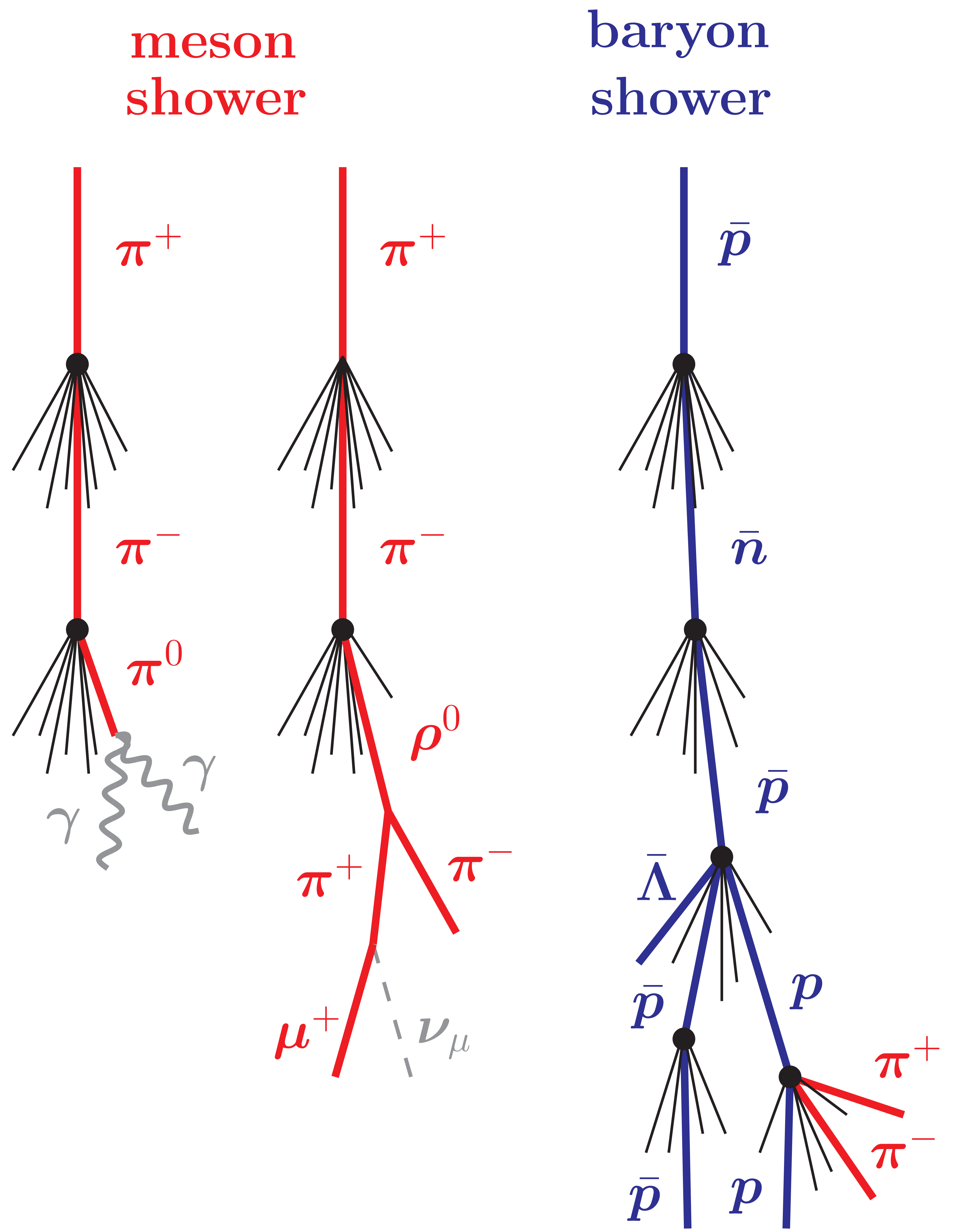
For details, please see [J. Albrecht, H. Dembinski, D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

The Muon Puzzle



The Muon Puzzle

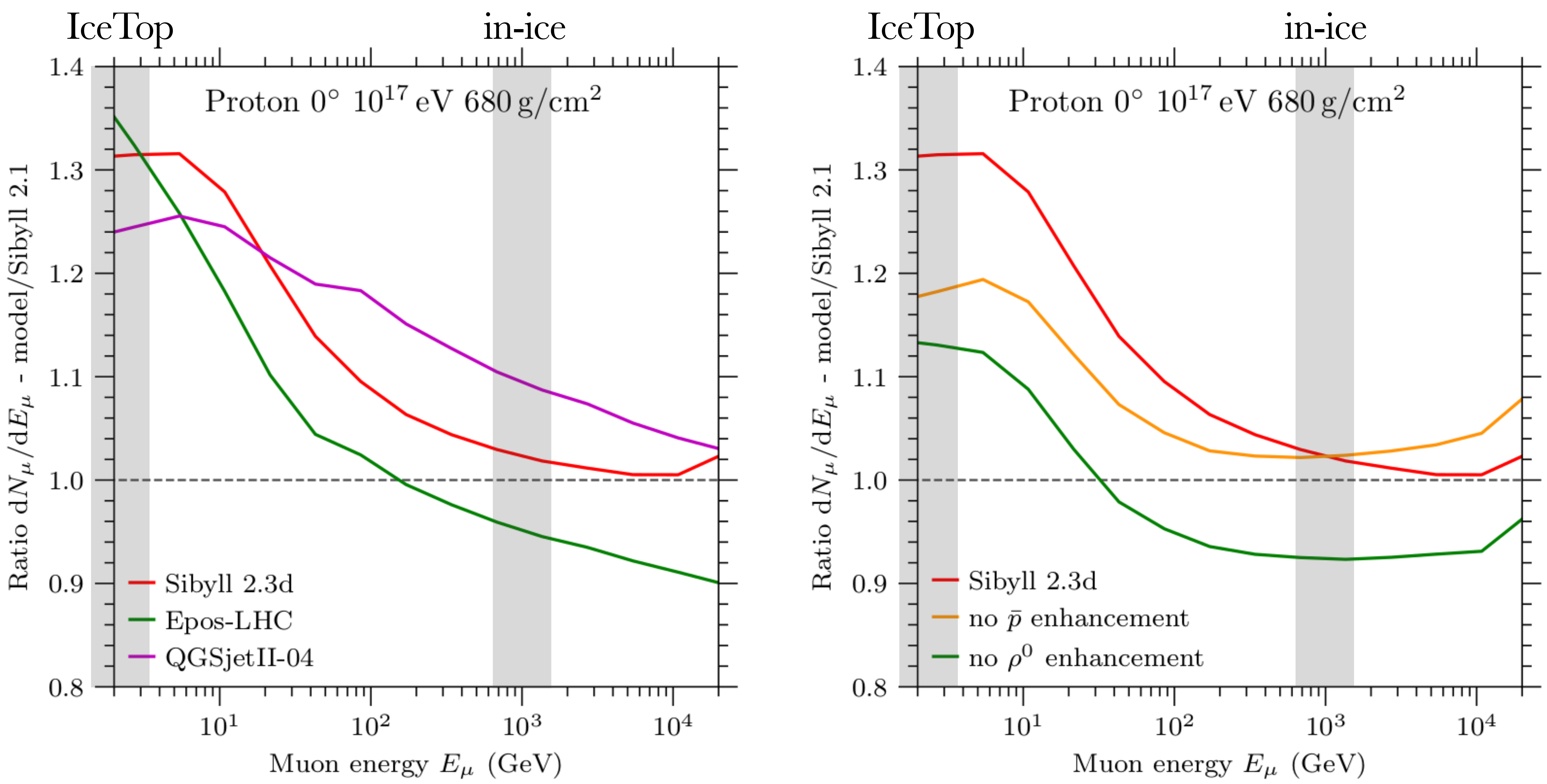
- Difficult to change R within standard QCD
- Possible explanations for the Muon Puzzle:
  - Neutral rho meson enhancement, e.g. [1]
    - Decay of ρ_0 via charged pions into muons
    - Muon production at all energies
  - Baryon enhancement, e.g. [2]
    - Many re-interactions, low-energy particles
    - Mainly low-energy muons
  - Stangeness enhancement, e.g. [3]
    - Evidence from ALICE at LHC
- Different predicted muon spectra!

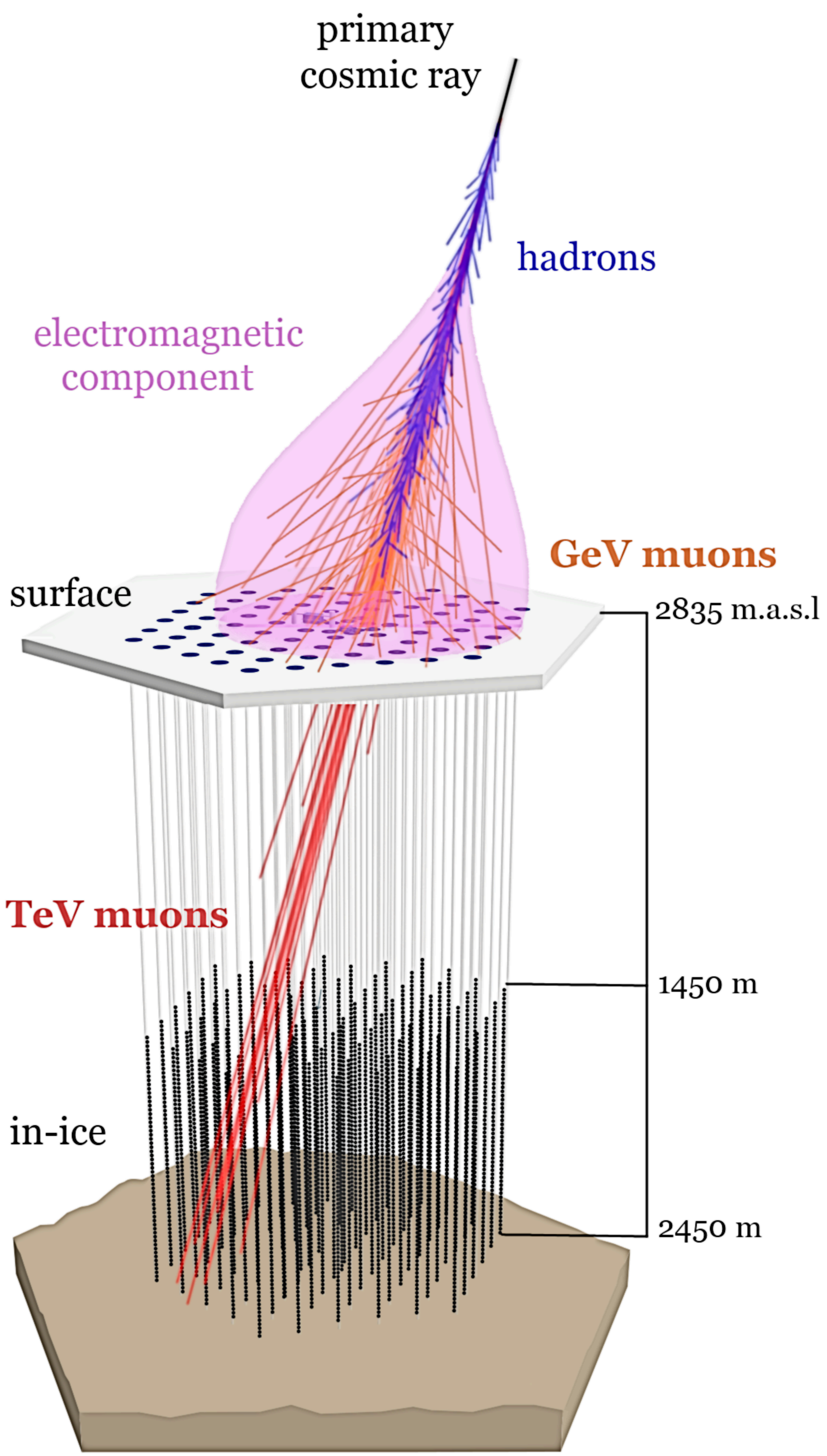


[1]: See e.g. [F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]
[2]: See e.g. [T. Pierog, K. Werner, Phys. Rev. Lett., 101 (2008)]
[3]: See e.g. [ALICE Collaboration, Nature Phys. 13 (2017) 535]

The Muon Puzzle and IceCube

- Coincident measurements provide spectral muon information
- Unique tests of multi-particle production (forward region)!
- Will strongly constrain / exclude muon production models
- Crucial contribution to solve the Muon Puzzle

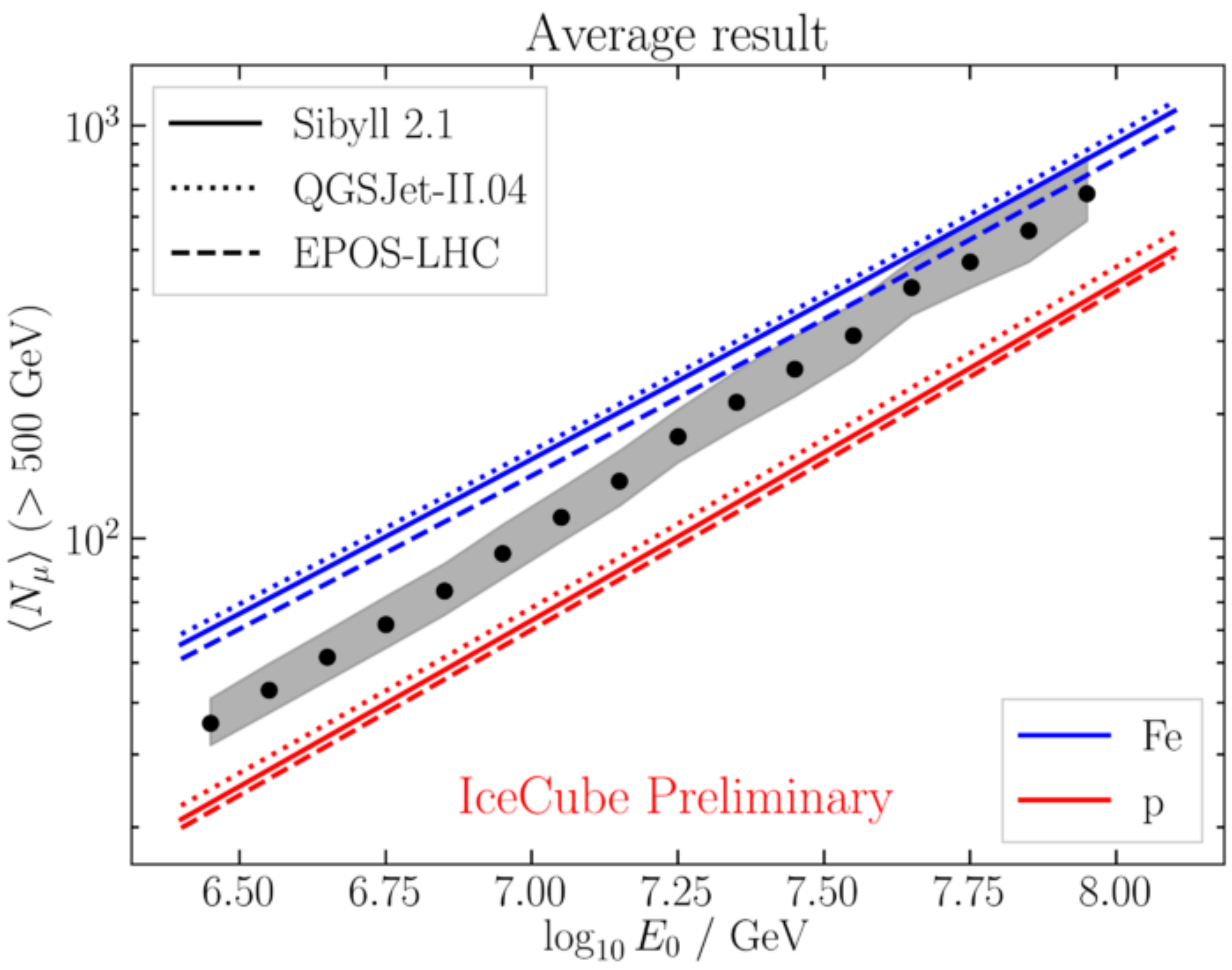


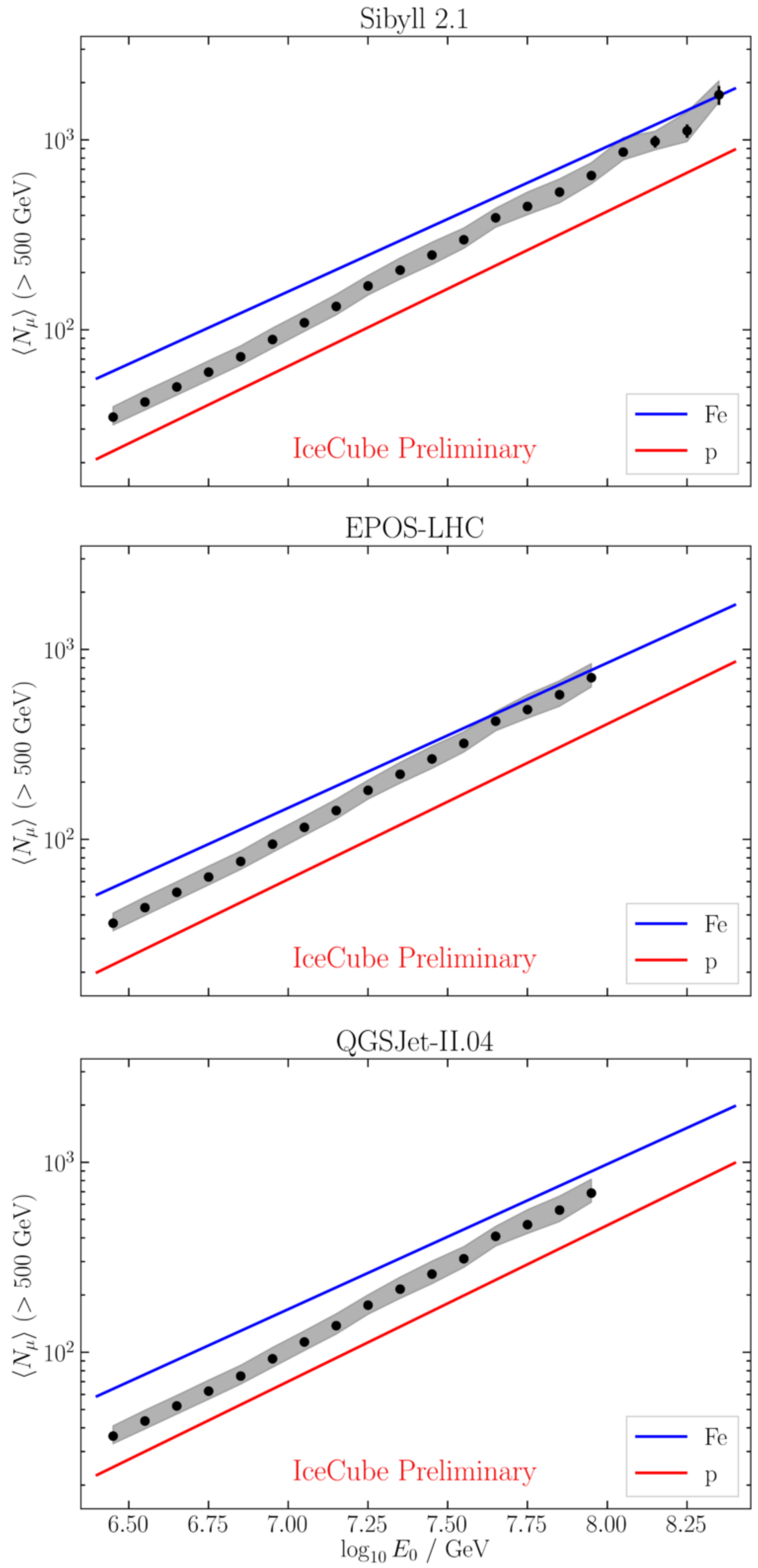


[F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]

TeV Muons in IceCube

- Muon bundle multiplicity compared to model predictions





- How does the data compare to CR flux models?

[S. Verpoest (IceCube Collaboration), PoS ECRS (2022) 074]
see also [S. Verpoest, D. Soldin, S. De Ridder et al., PoS ICRC2021 (2021) 357]

TeV Muons in IceCube

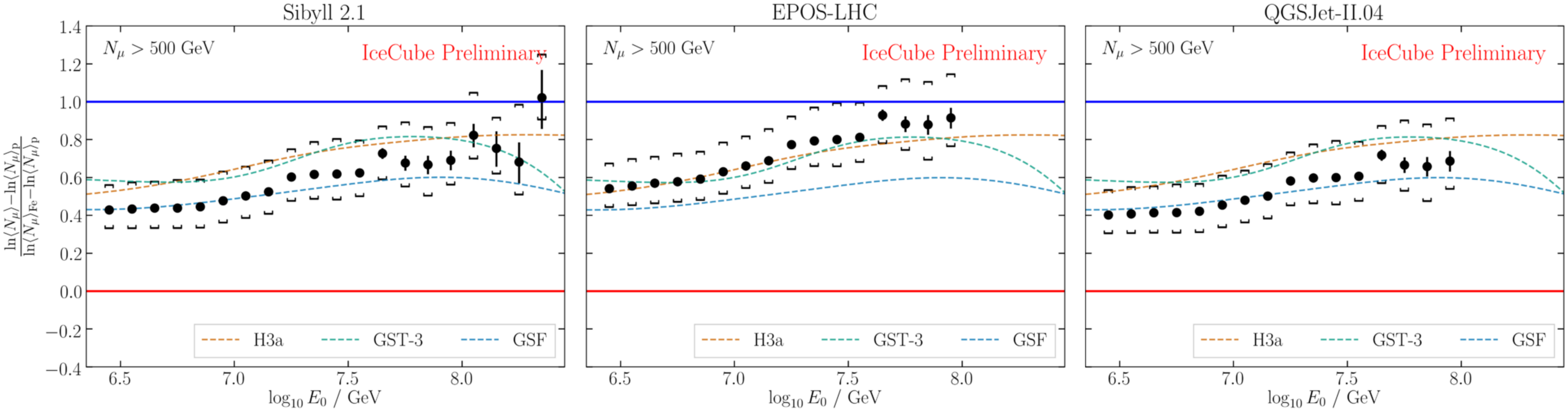
- Reminder z-scale:

$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})} \quad , \quad \text{proton: } z = 0, \text{ iron: } z = 1$$

- No significant discrepancies between MC and data for TeV muons!

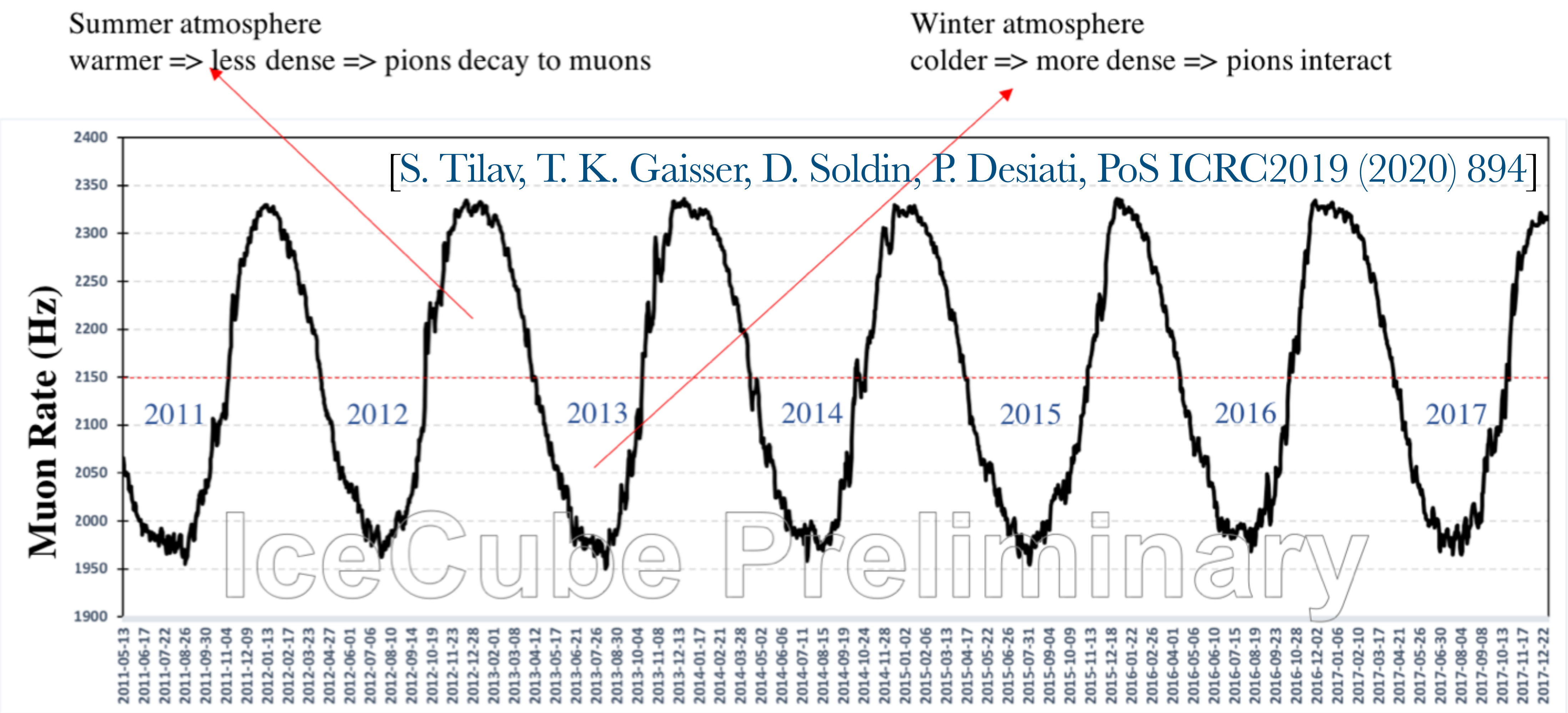
- Coincident (event-by-event) analysis in preparation which will put strong constraints on hadronic interaction models

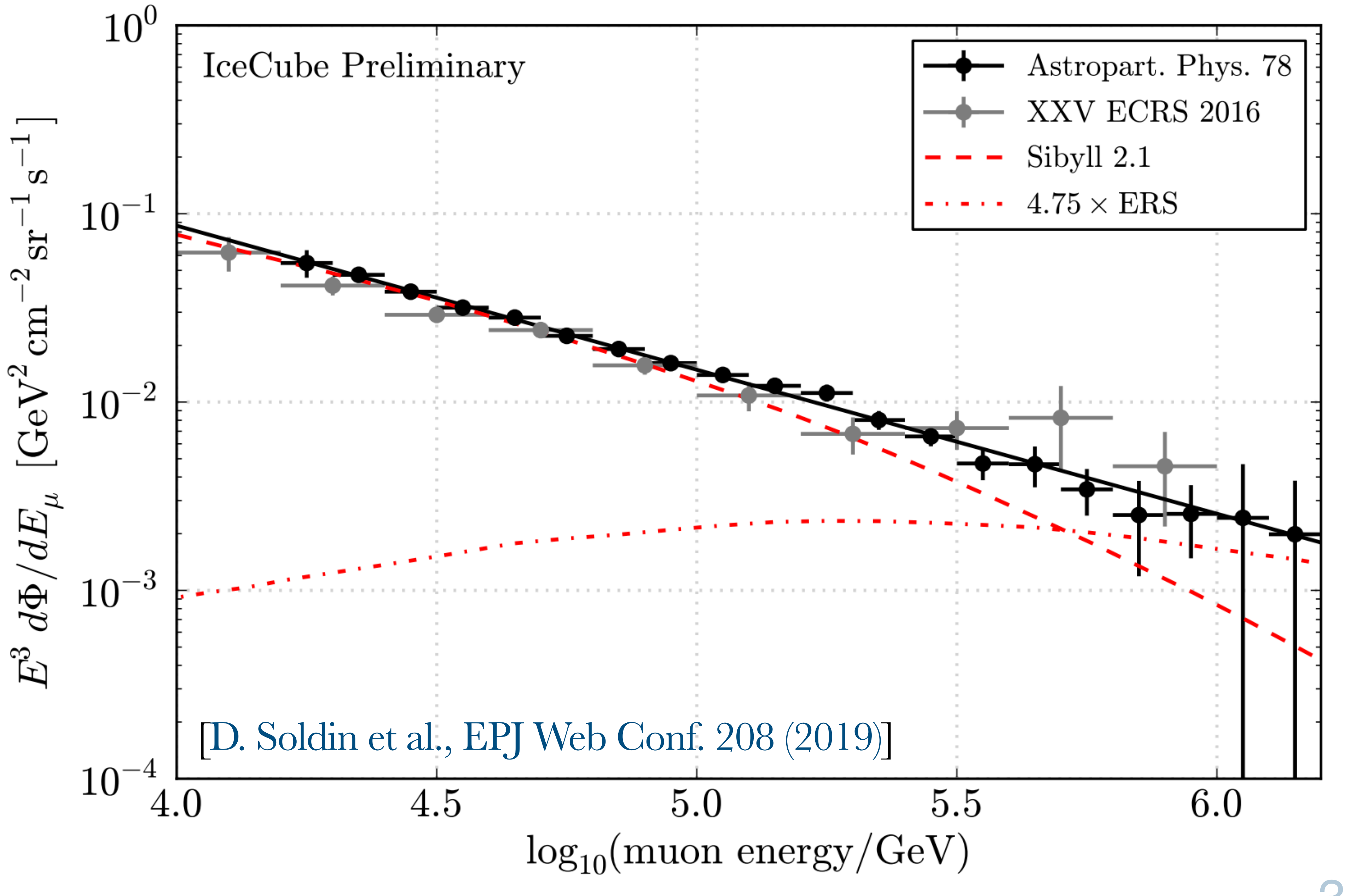
[S. Verpoest (IceCube Collaboration), PoS ECRS (2022) 074]
see also [S. Verpoest, D. Soldin, S. De Ridder et al., PoS ICRC2021 (2021) 357]



Further Muon Measurements in IceCube

- Seasonal variations of atmospheric muons
  - Muon flux depends on atmospheric density / temperature
  - High statistics measurement of TeV muons in IceCube (in-ice)
  - Probe of kaon/pion (charm?) ratio!
- PeV muons in IceCube
  - Prompt decays (e.g. D-mesons) dominate the muon flux at high energy
  - Probe of charm production in hadronic interactions for the first time

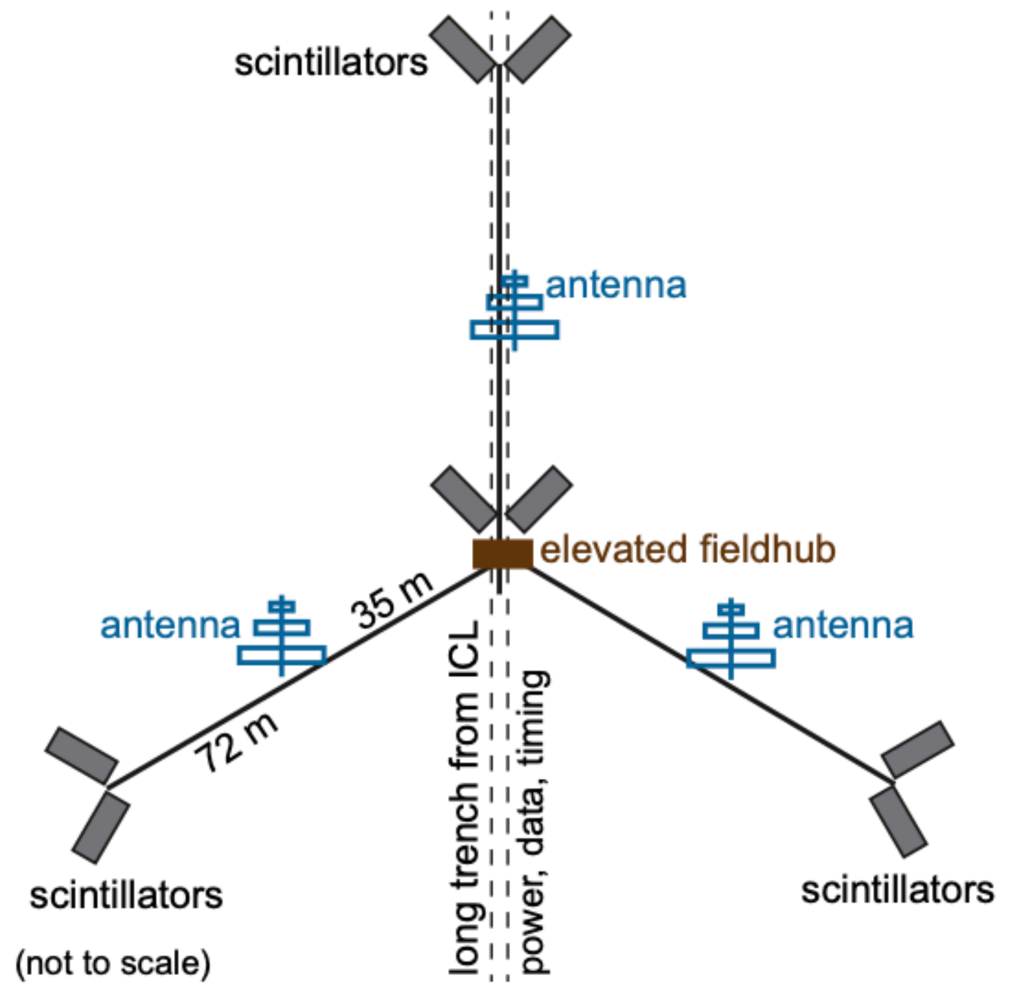


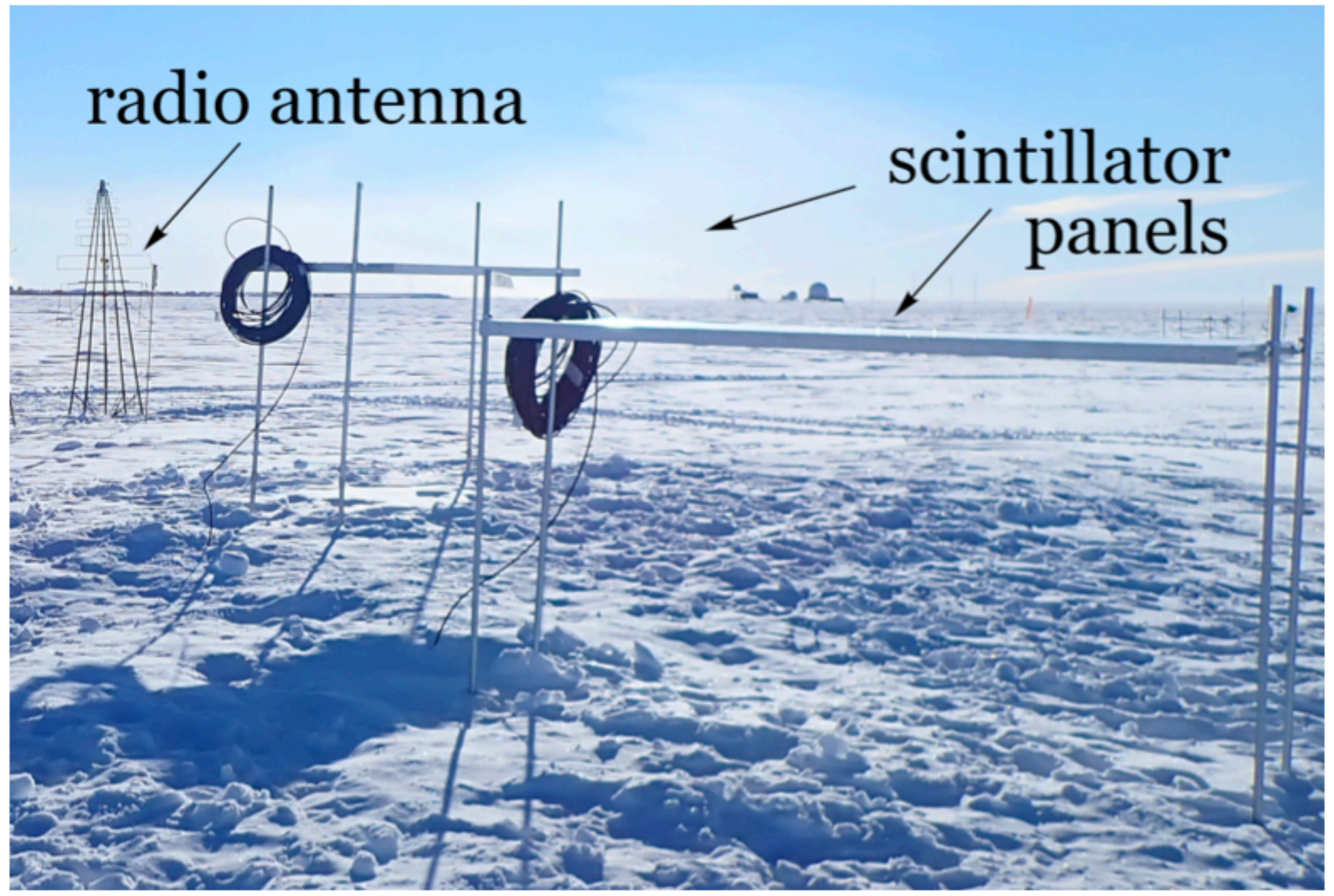


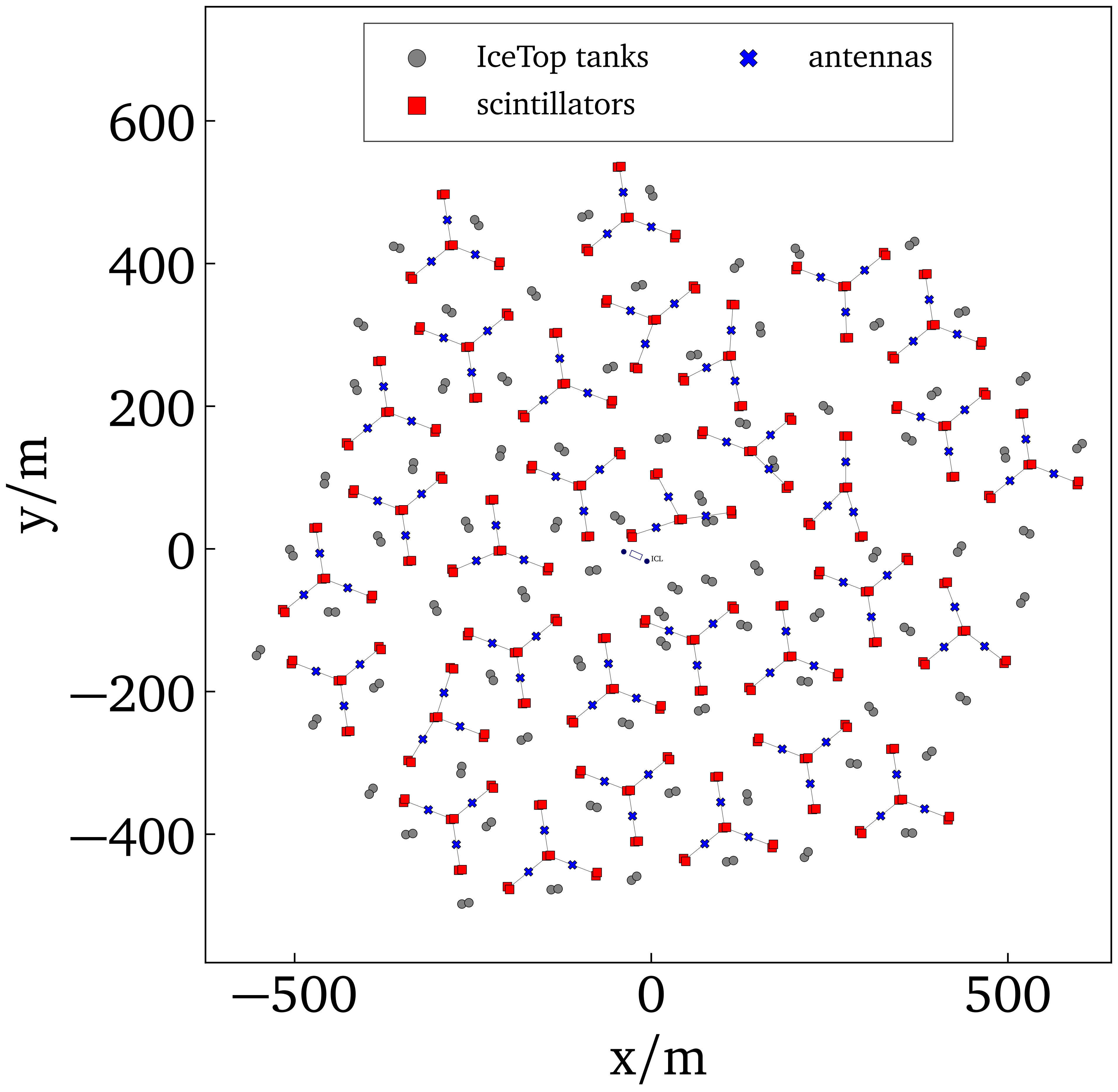
Future IceCube Detector Improvements

- <u>Surface enhancement in progress:</u>
  - 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)]



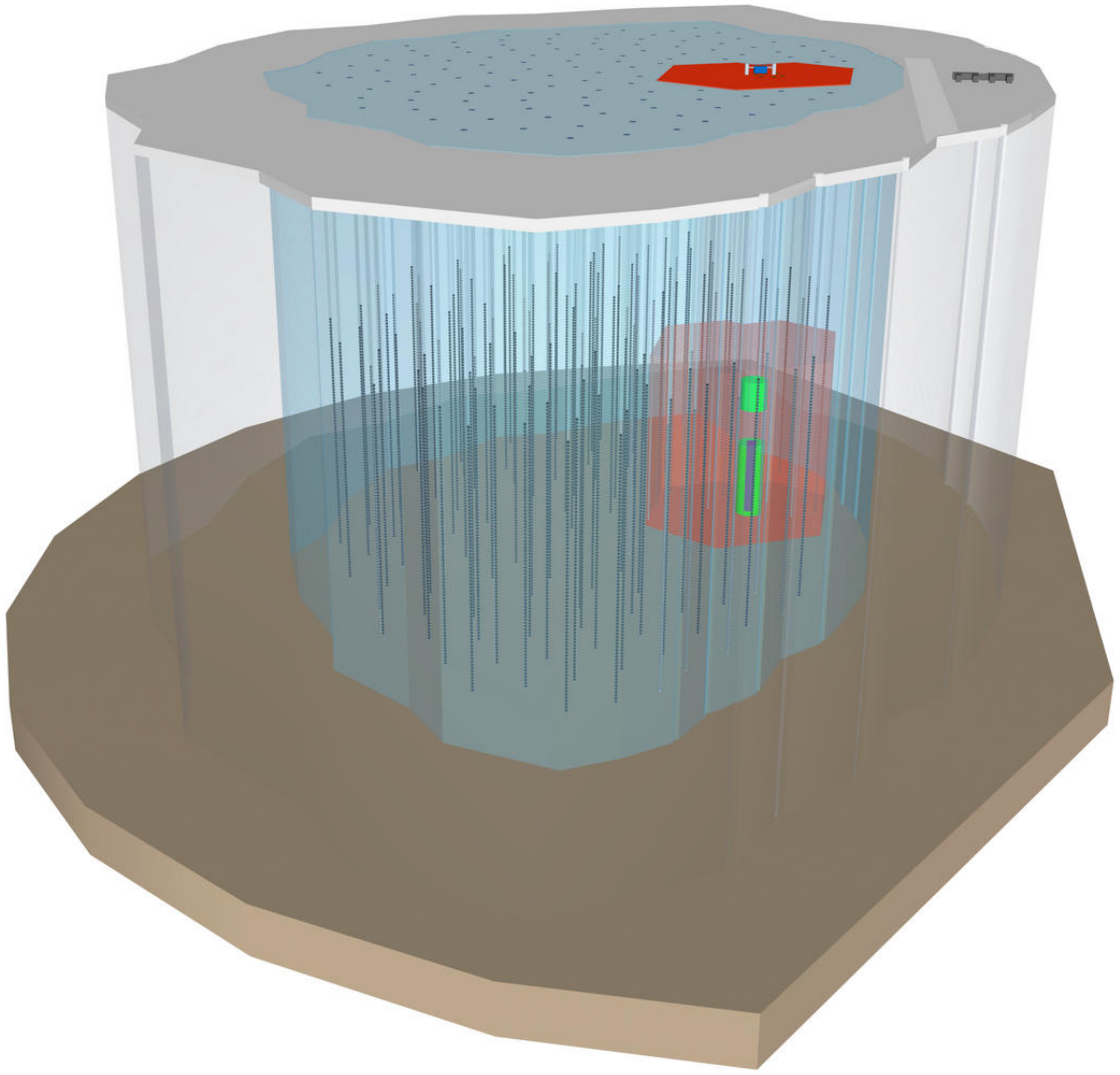




see also [A. Coleman, D. Soldin et al., Astropart. Phys. 147 (2023)]

Future Detector Improvements

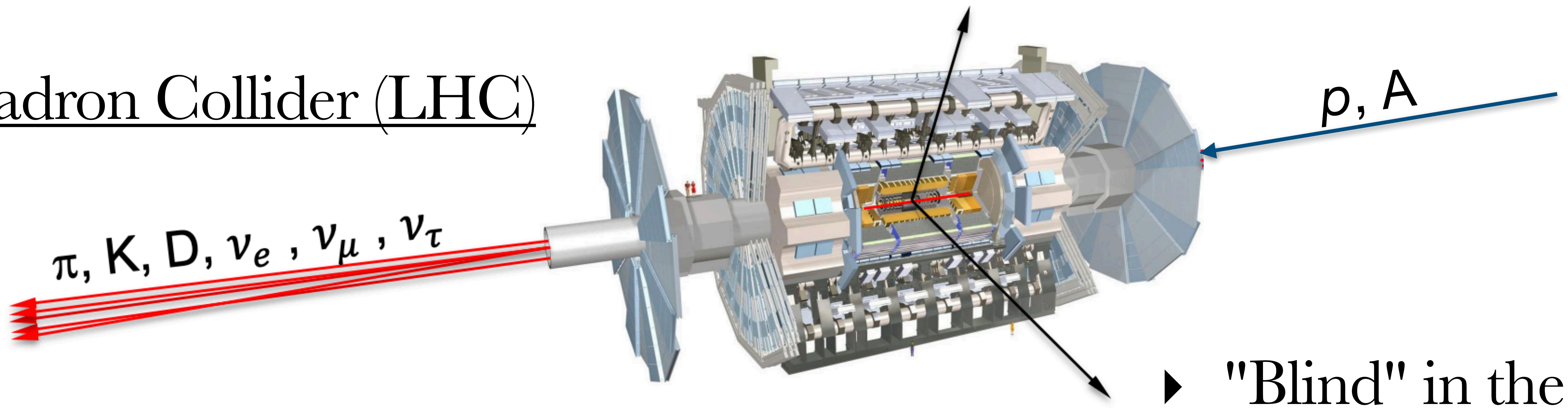
- IceCube-Gen2:
  - Significant larger in-ice and surface detectors
  - Increased solid angle, larger inclinations
  - Increased statistics at the highest energies
    - Measurement of prompt muons!
    - Close the gap to Auger in muon measurements!
  - Better understanding of the absolute energy scale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



[IceCube-Gen2 Collaboration, J. Phys. G 48 (2021)]
see also [A. Coleman, D. Soldin et al., Astropart. Phys. 147 (2023)]

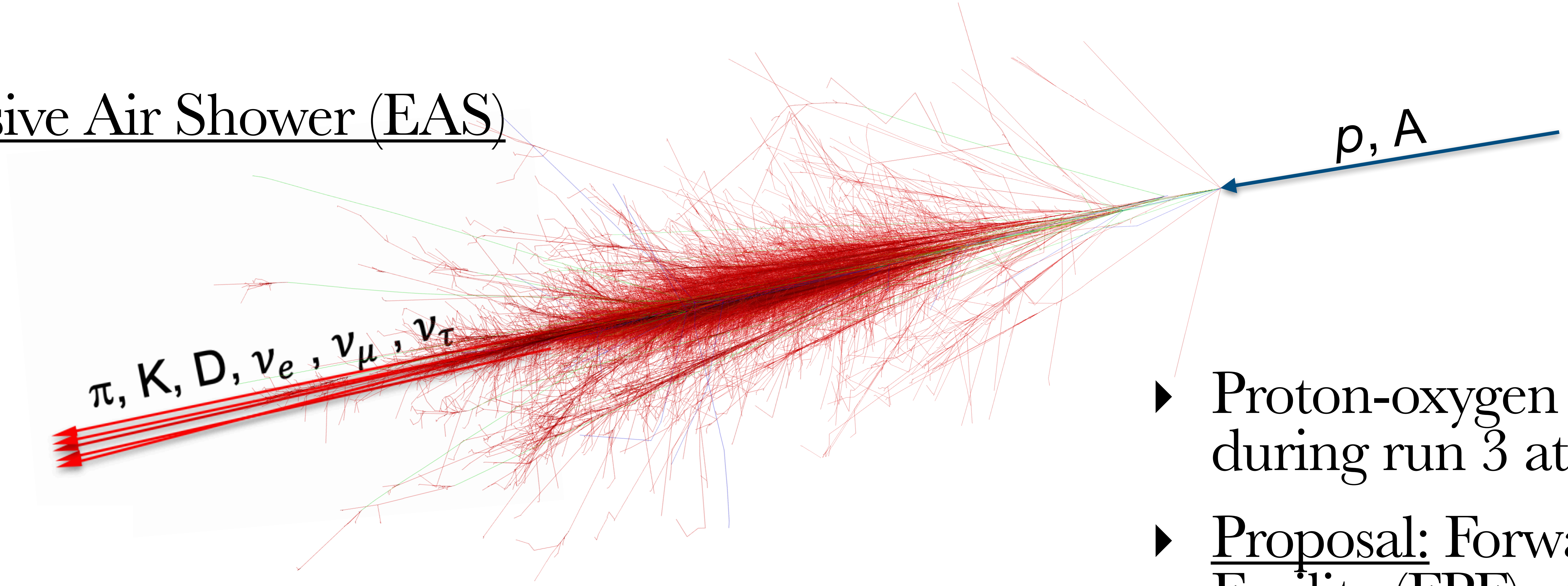
Collider vs. EAS

- Large Hadron Collider (LHC)



- "Blind" in the forward region

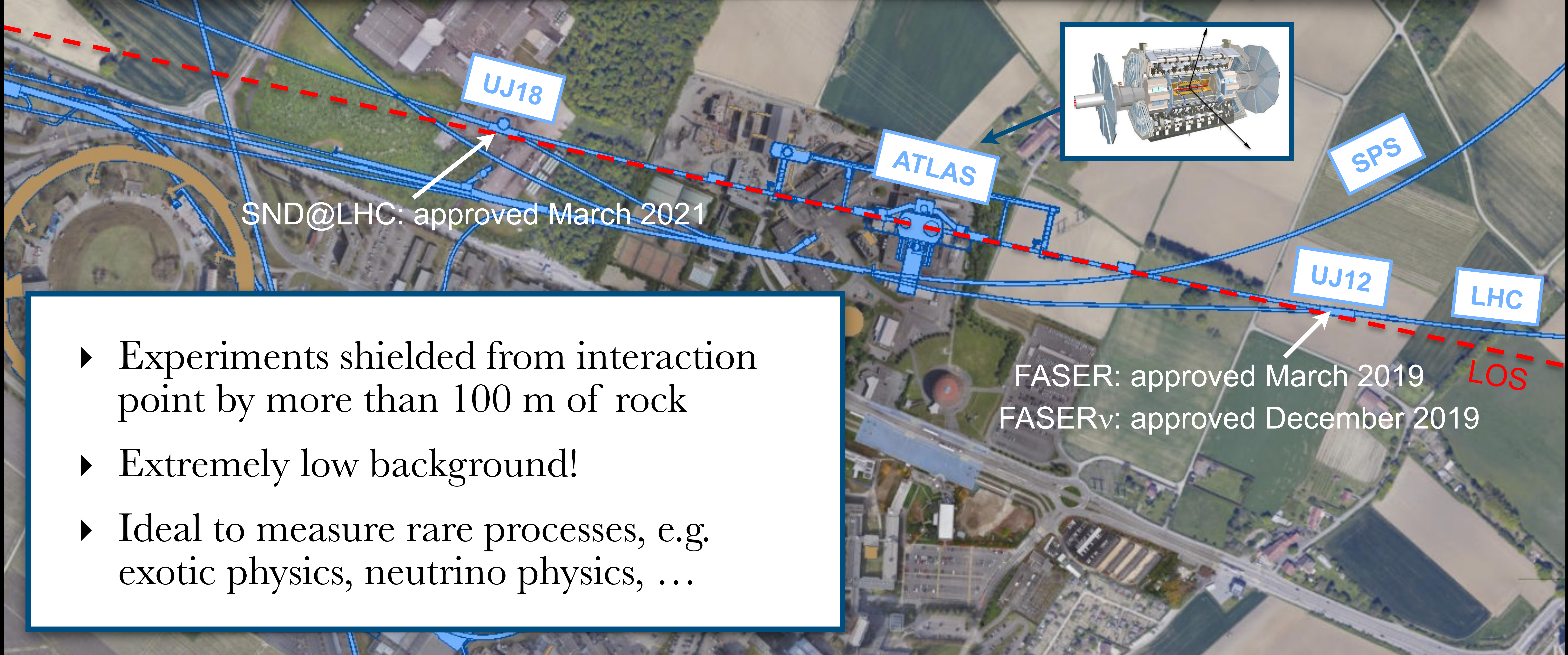
- Extensive Air Shower (EAS)



- Proton-oxygen collisions during run 3 at LHC
- Proposal: Forward Physics Facility (FPF) at LHC

FAR FORWARD EXPERIMENTS AT LHC RUN 3

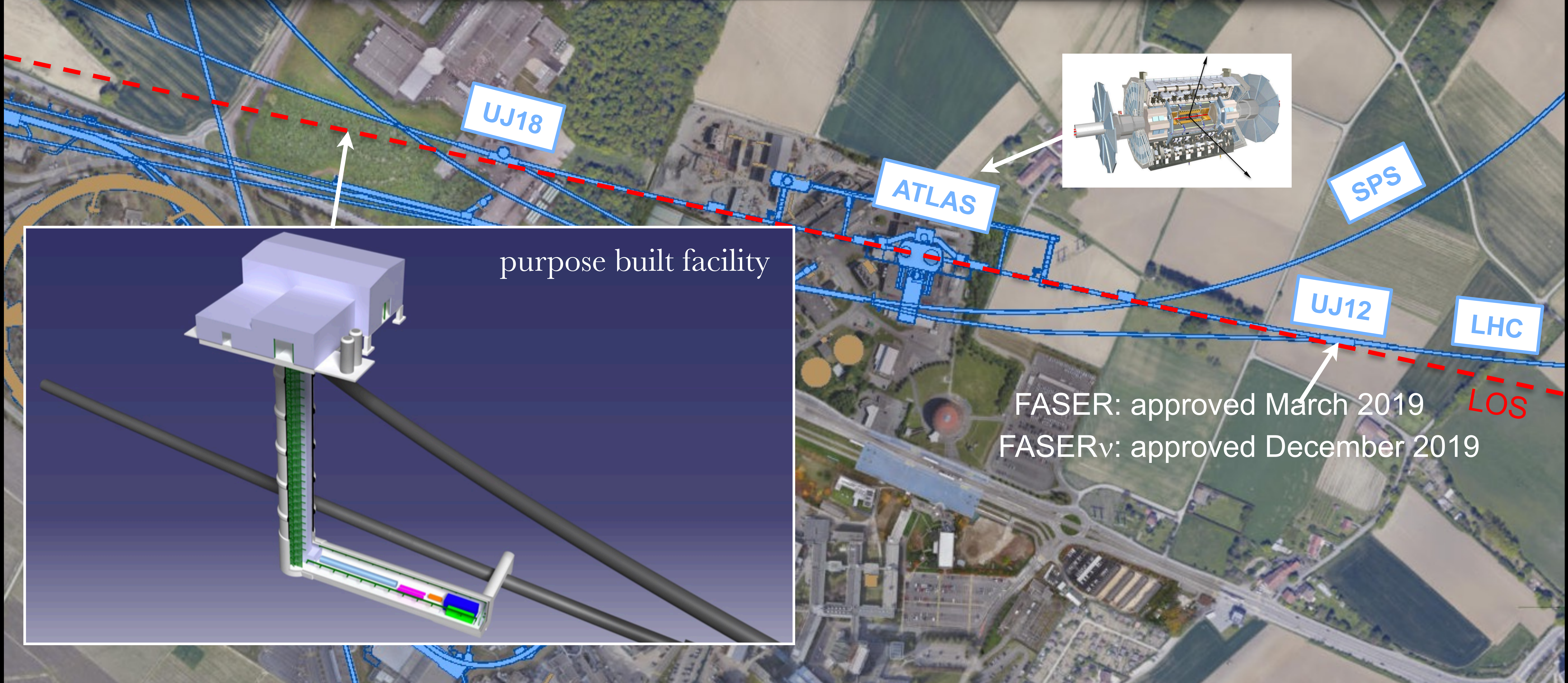
There are currently 3 detectors running to exploit forward physics potential in run 3 at the LHC



- Experiments shielded from interaction point by more than 100 m of rock
- Extremely low background!
- Ideal to measure rare processes, e.g. exotic physics, neutrino physics, …

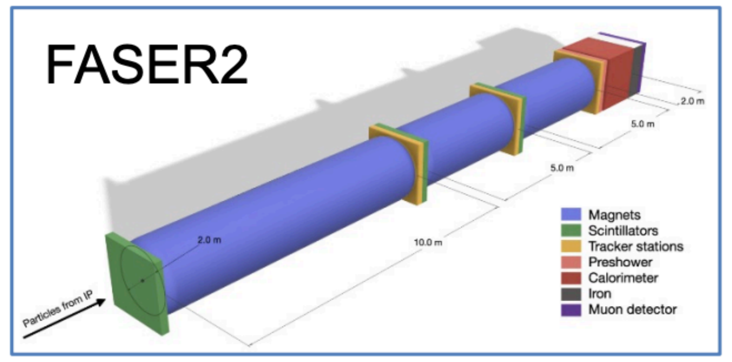
FAR FORWARD EXPERIMENTS AT LHC RUN 3

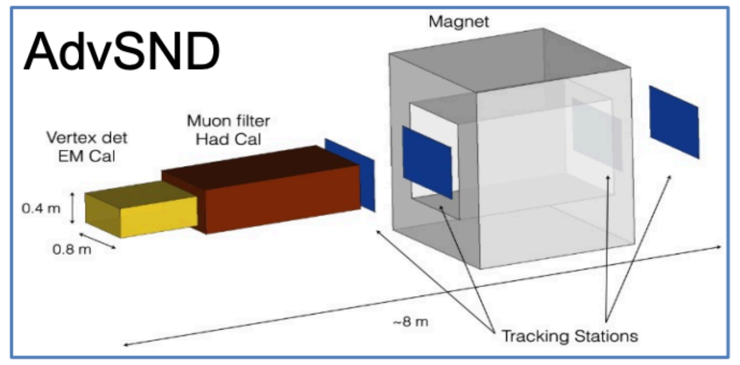
The FPF is proposed to extend this program into the HL-LHC era!

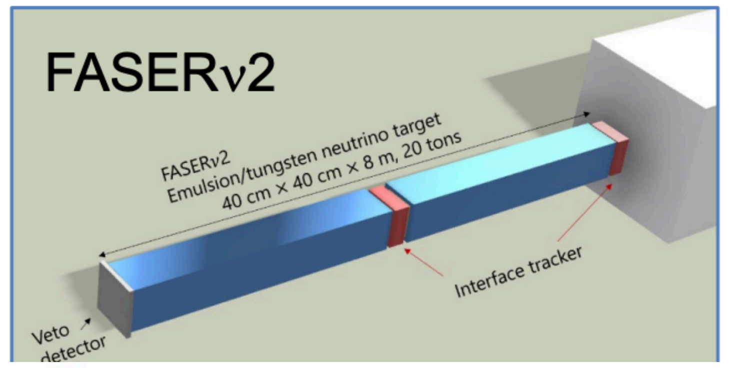


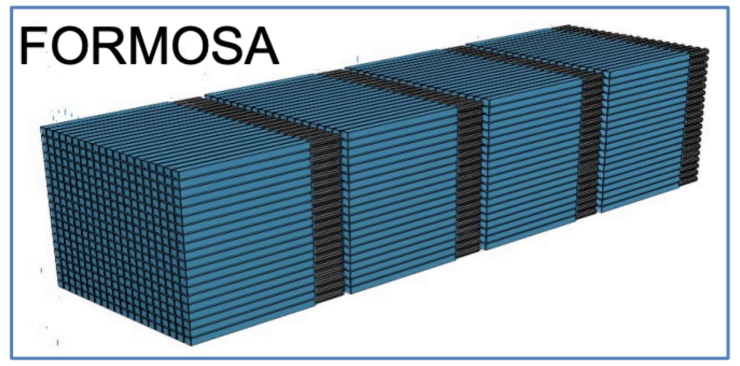
Forward Physics Facility

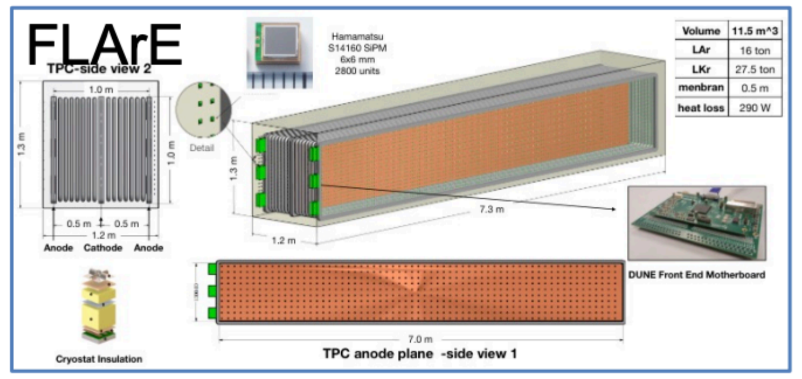
- <u>Proposal:</u> Forward Physics Facility at the LHC
- FPF will house various particle experiments
- Neutrino (muon) measurements will give insights in hadron production in the forward region
- <u>First LHC measurements in the phase space relevant for EAS development</u>
- Overview of the FPF and its physics potential in recent "Short Paper" [1]
- Comprehensive white Paper for Snowmass 2021 [2]

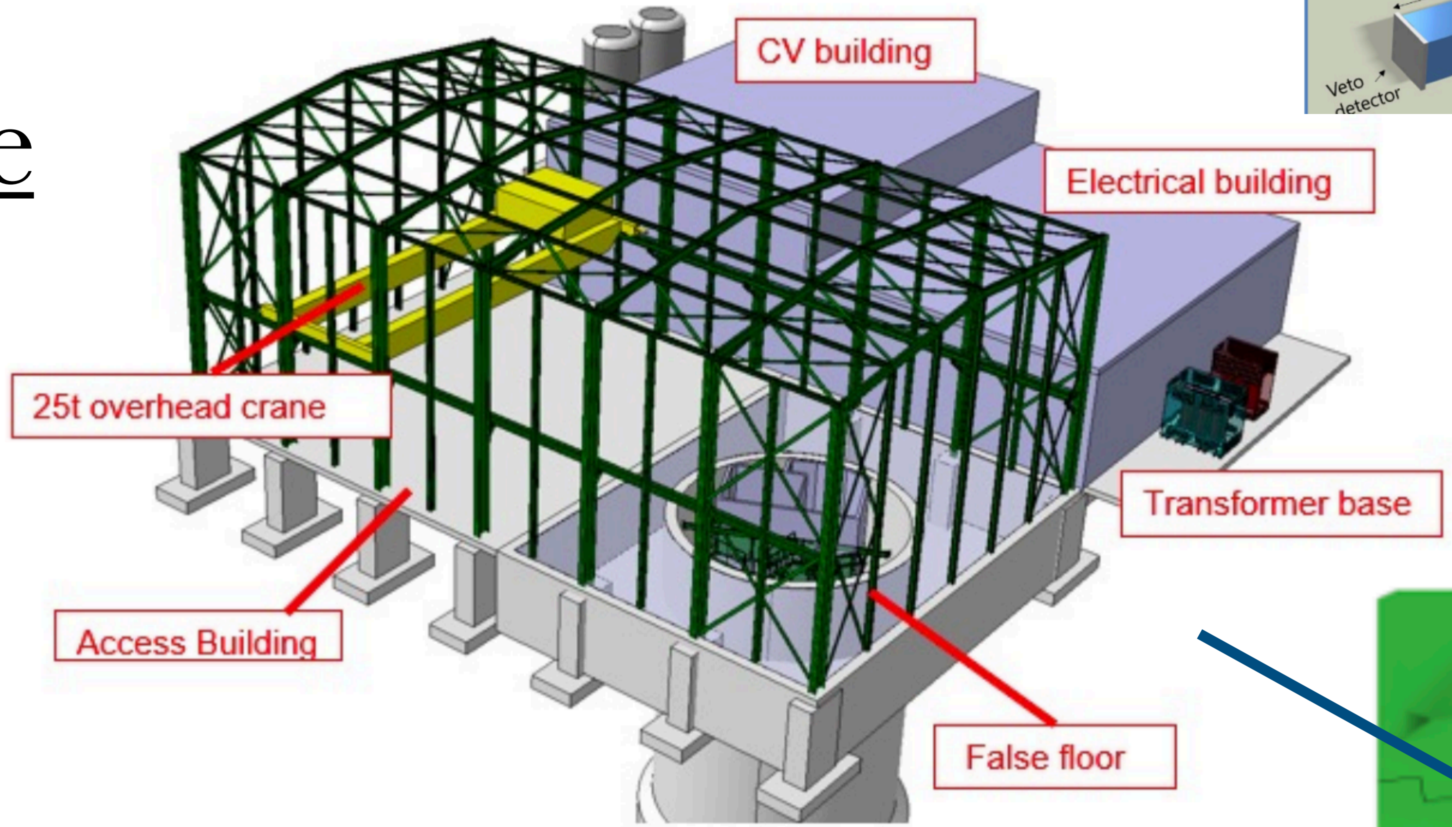


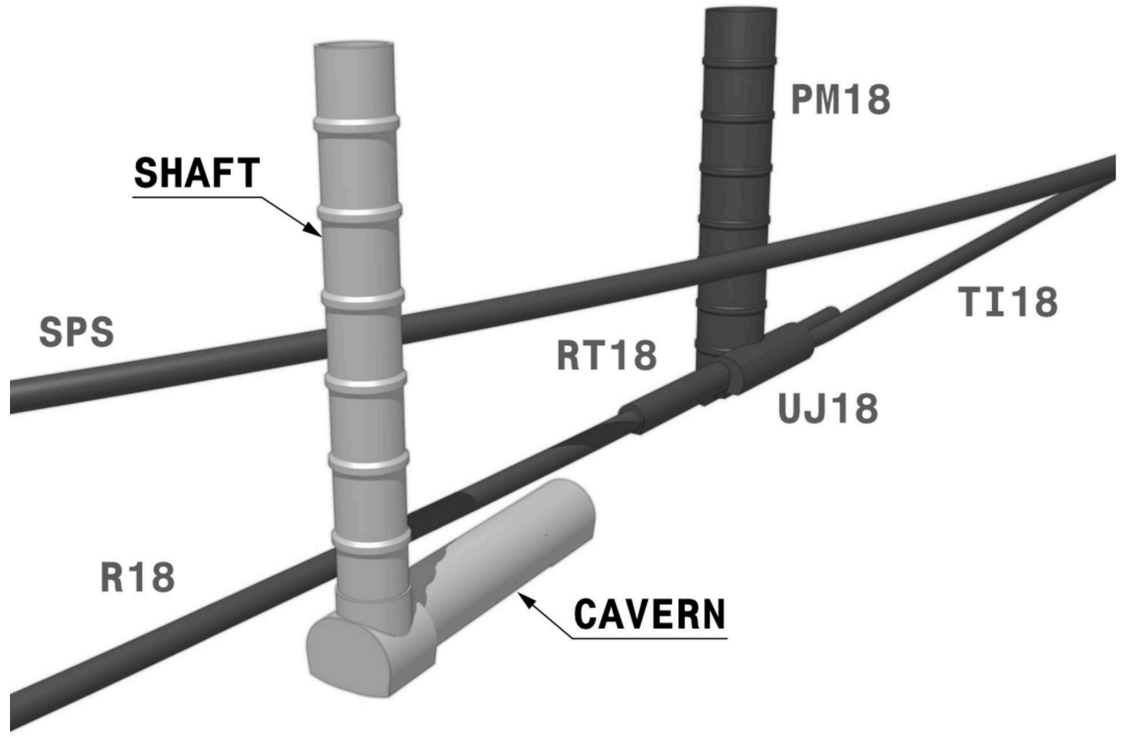


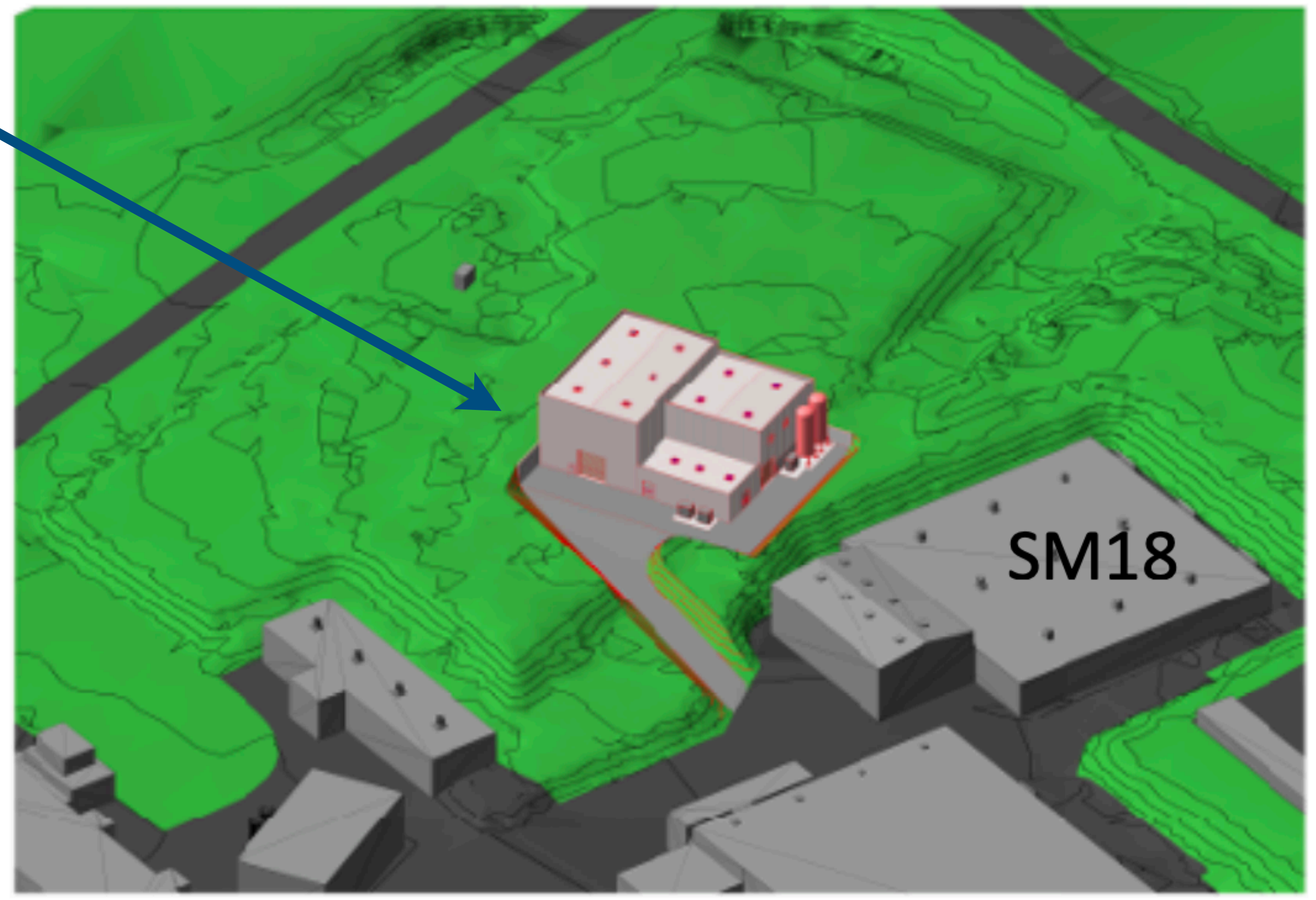








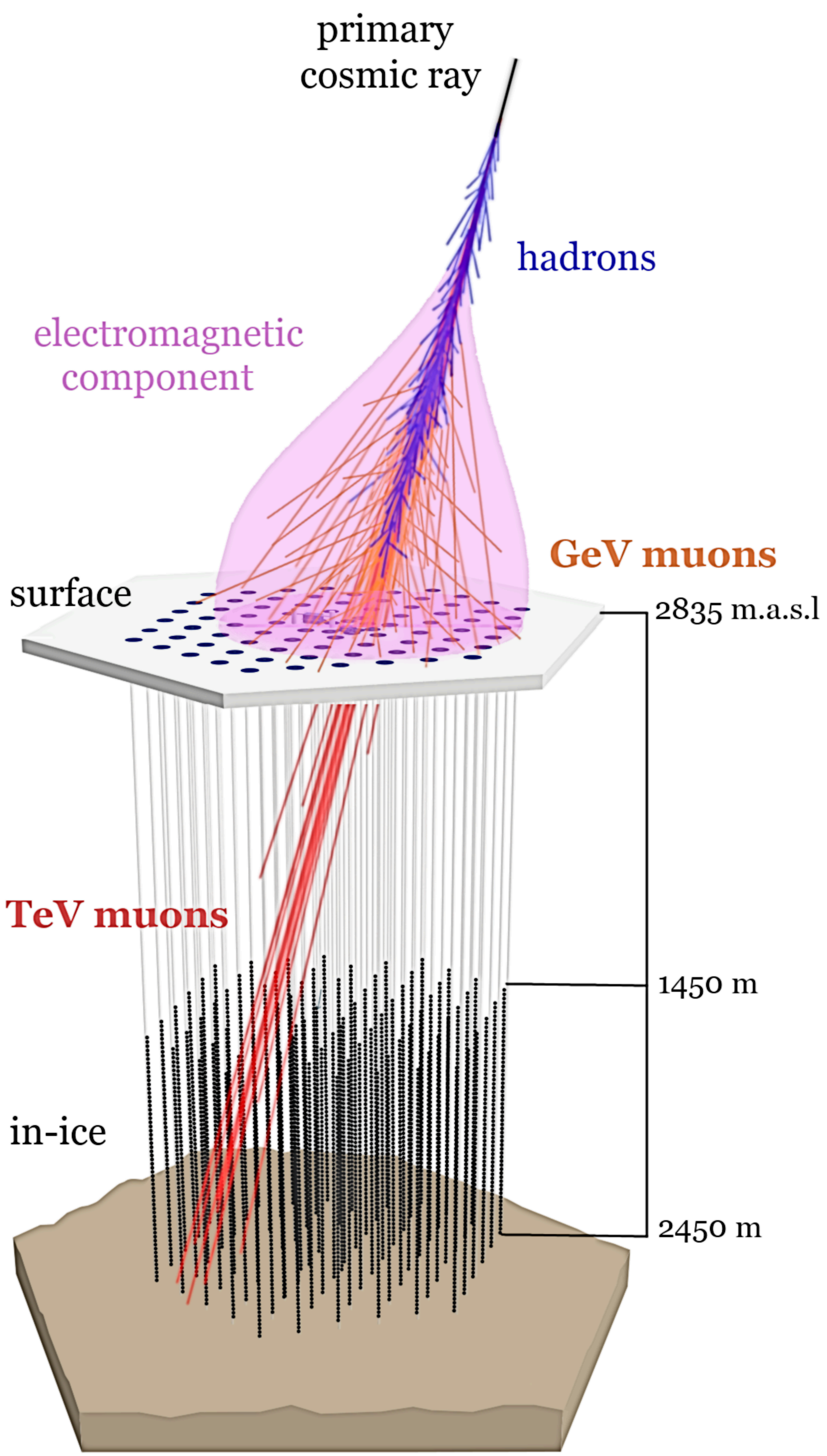




[1]: See [L. A. Anchordoqui, D. Soldin et al., Phys. Rept. 968 (2022)]
[2]: See [J. Feng, D. Soldin et al., J. Phys. G 50 (2023)]

Summary & Conclusions

- IceCube measures muons produced in EAS
- Significant data/MC discrepancies in the number of muons observed by various experiments at the highest (EeV) energies
- No discrepancies observed in muon measurements, i.e. GeV and TeV muons, by IceCube
- Combined analysis of global muon data shows consistent picture of increasing data/MC discrepancies
- Further measurements needed
  - EAS measurements of muons, i.e. N_μ, $X_{\mu,\max}$, σ_μ, …
  - Accelerator measurements in the forward region
- Solution or precise characterization within the next decade (?)



Thank You!

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
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Yale University

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Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
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Swedish Polar Research Secretariat
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University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

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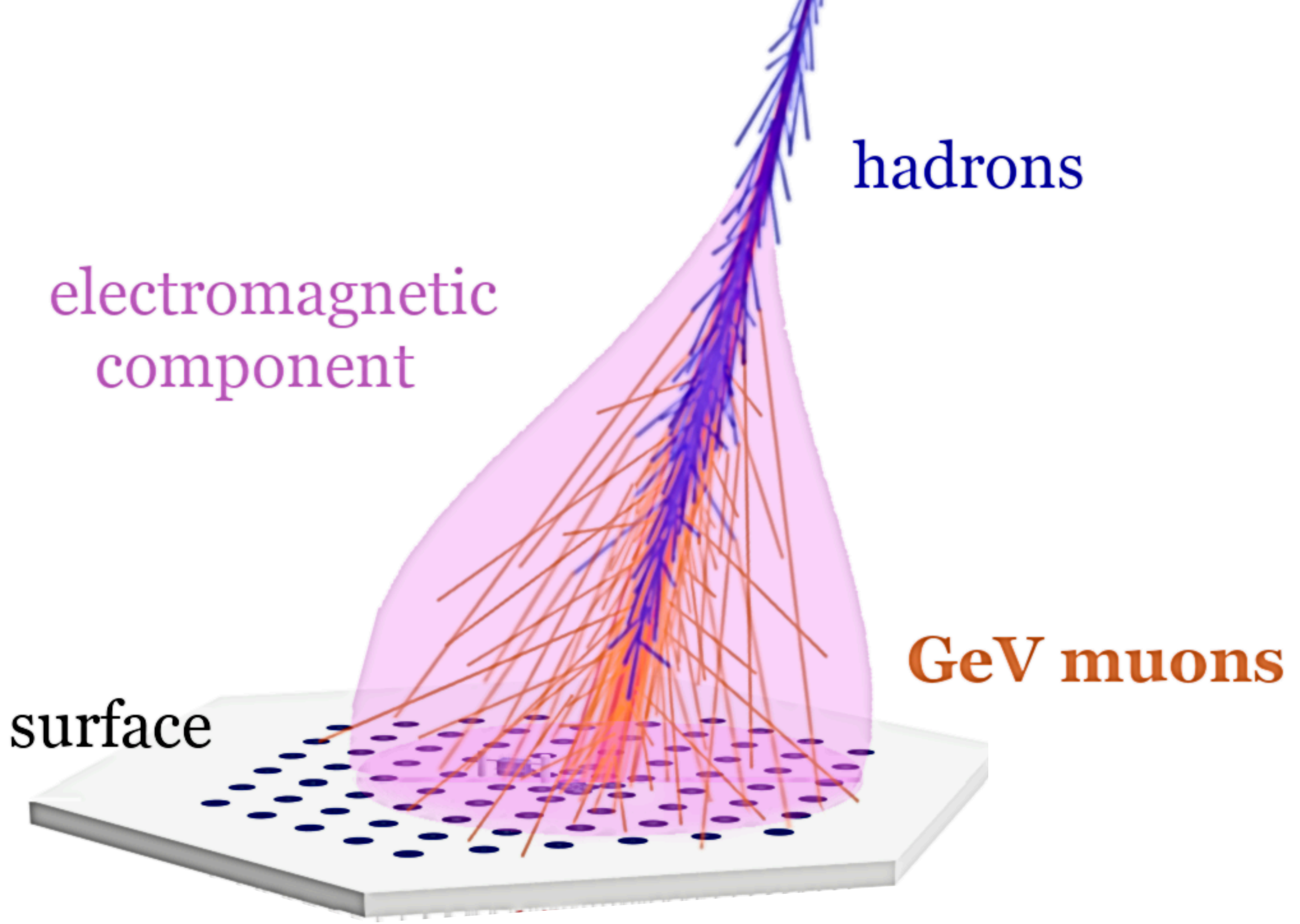
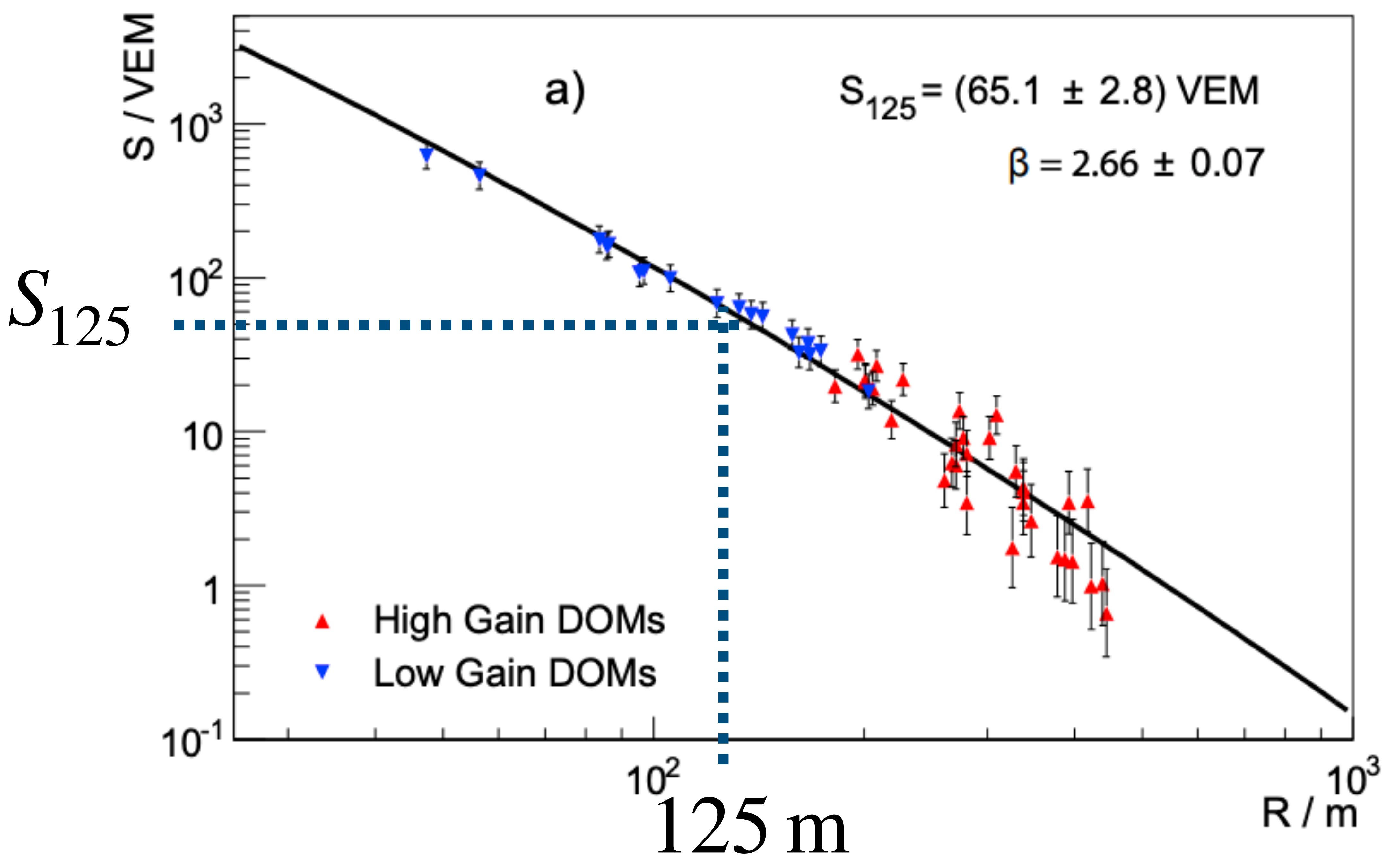
EAS Energy in IceTop

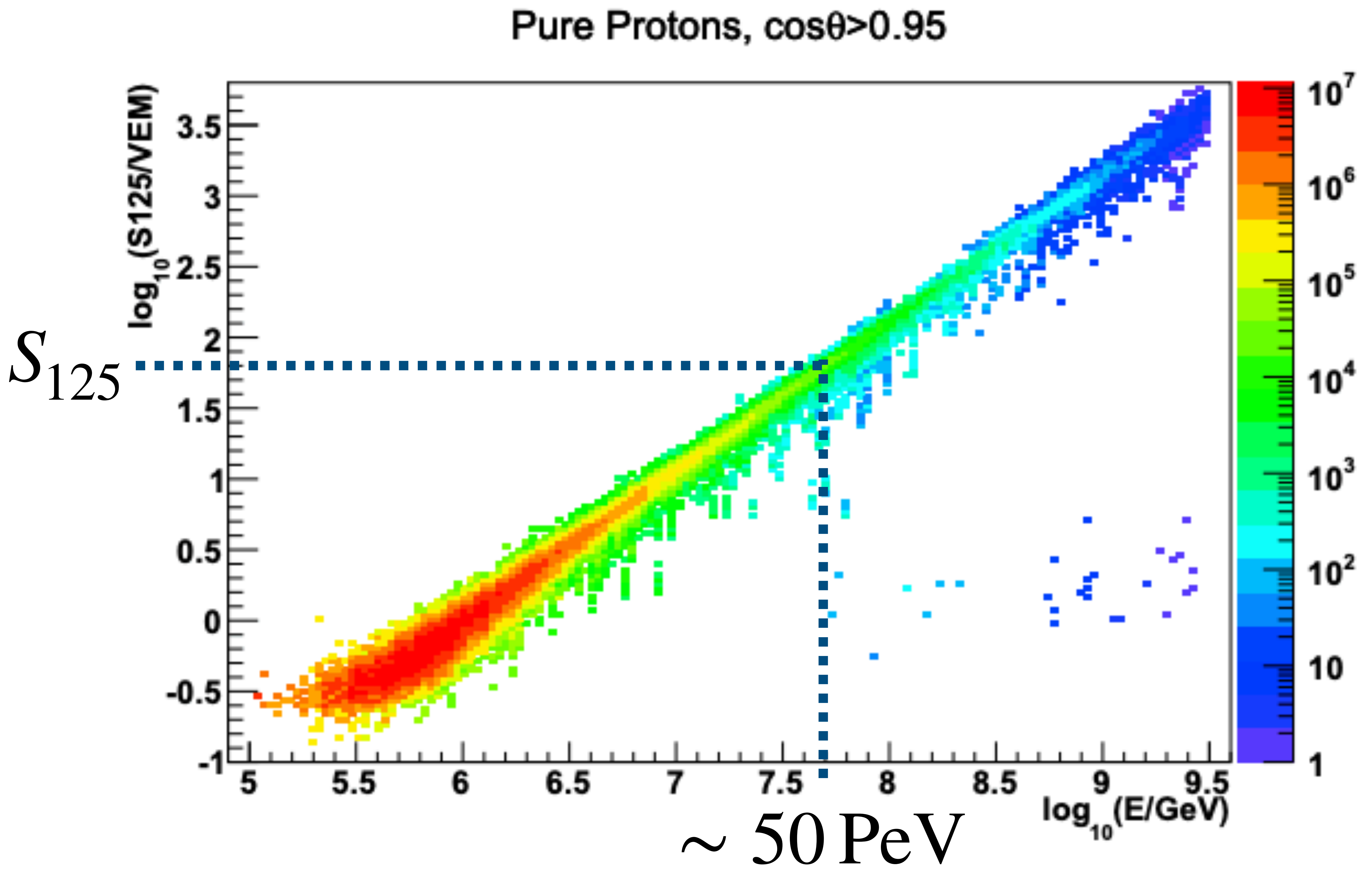
- EAS energy determined from surface signals
- Lateral Distribution Function (LDF)

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

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

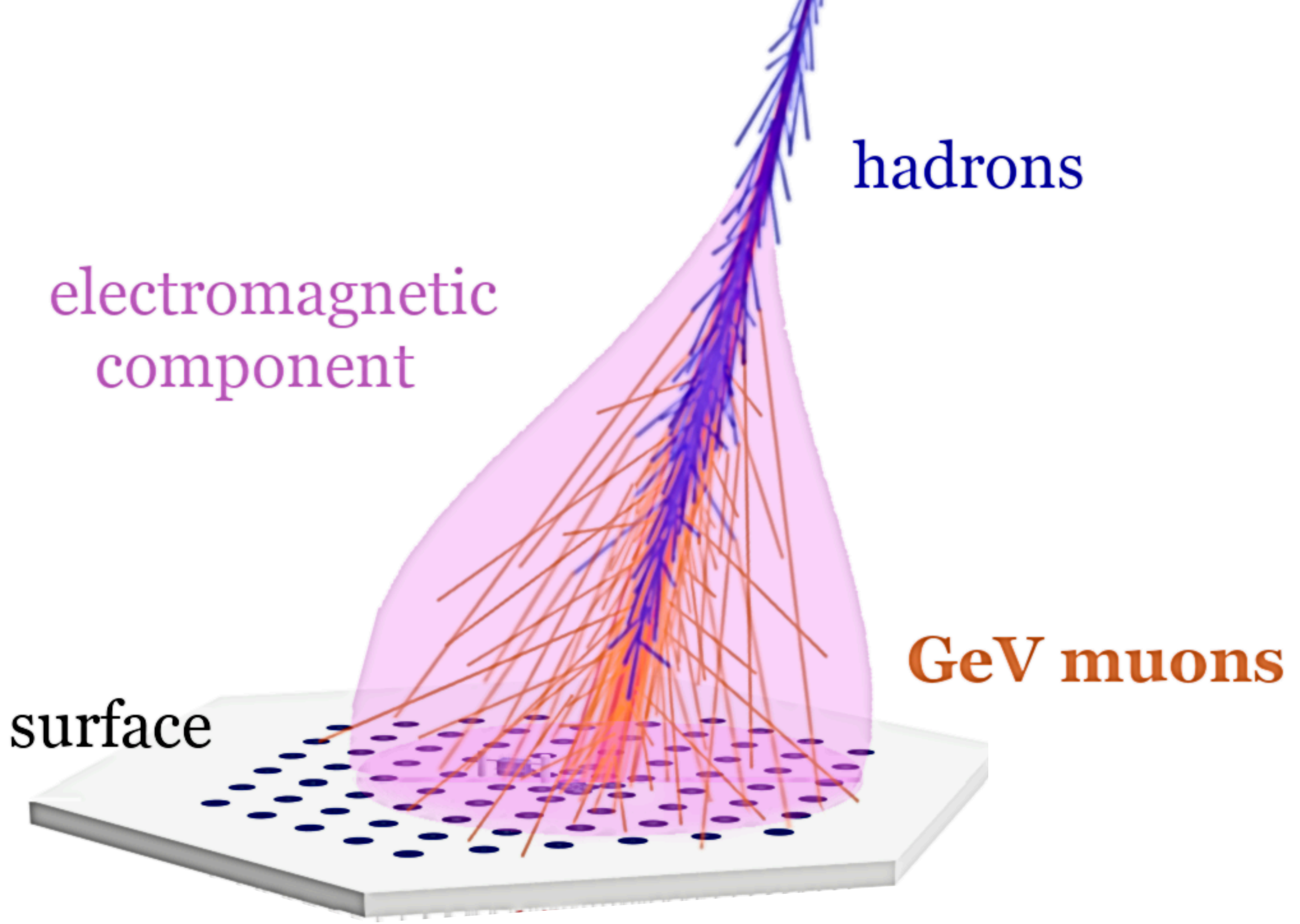


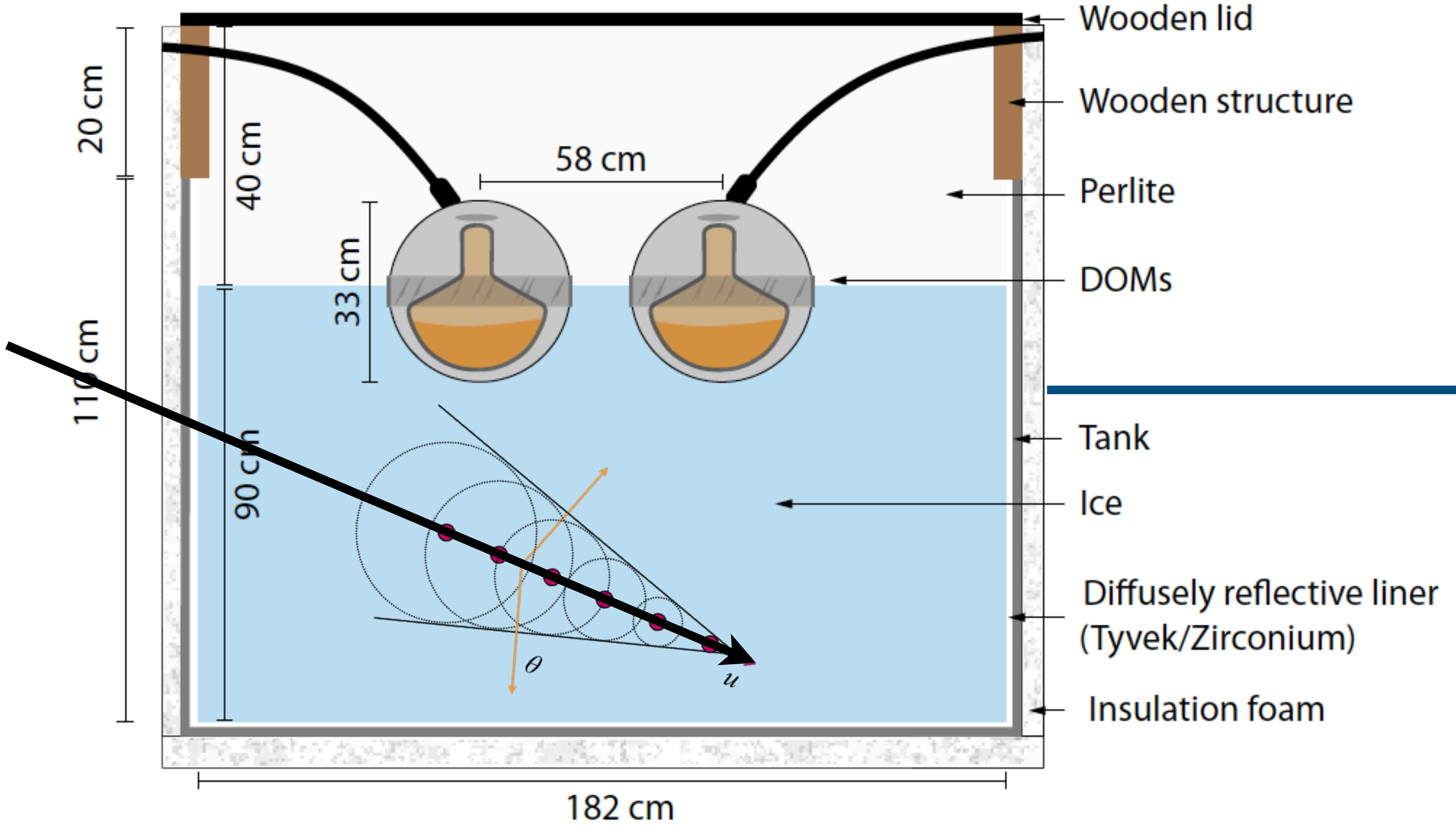


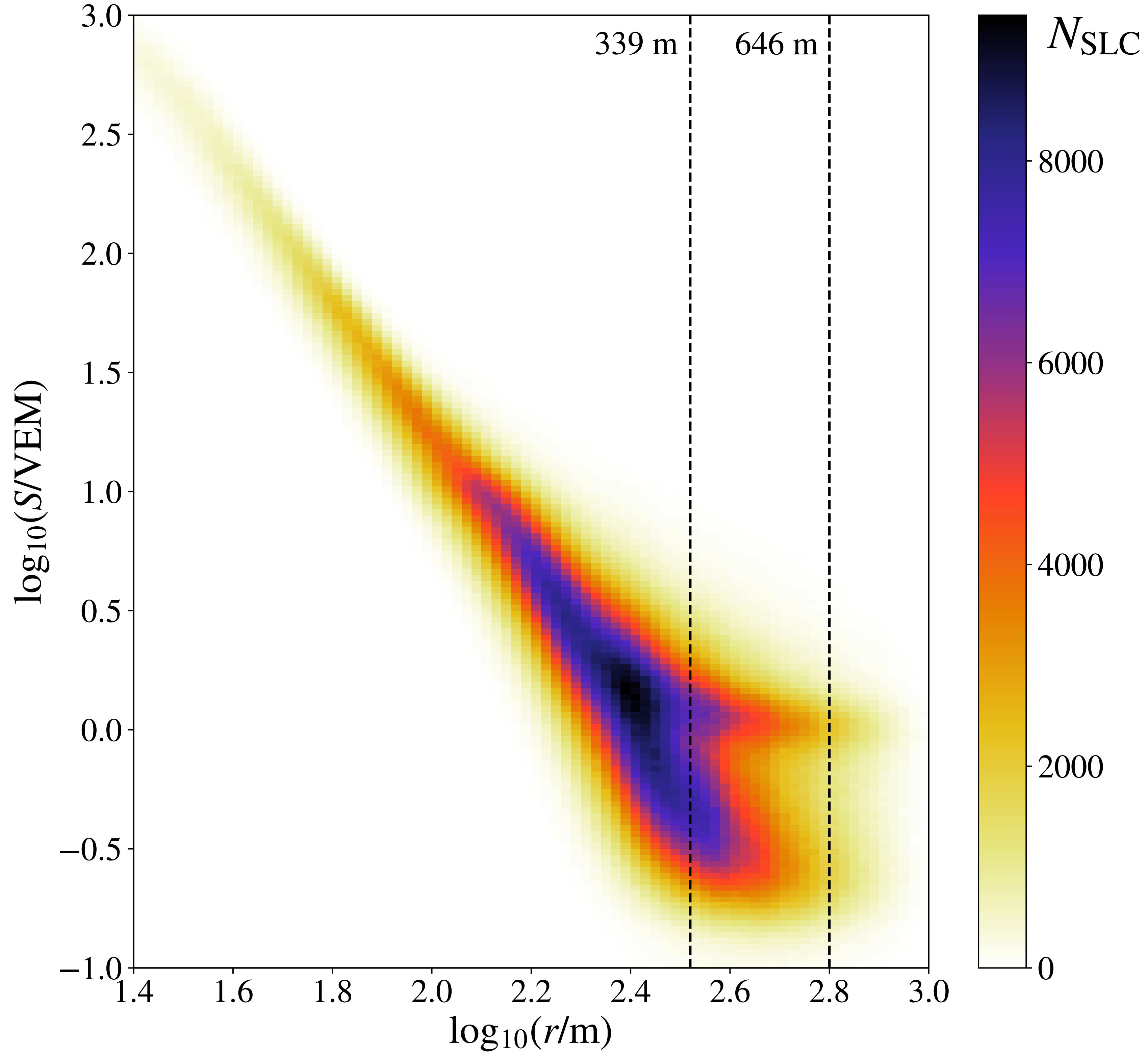


GeV Muons in IceTop

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







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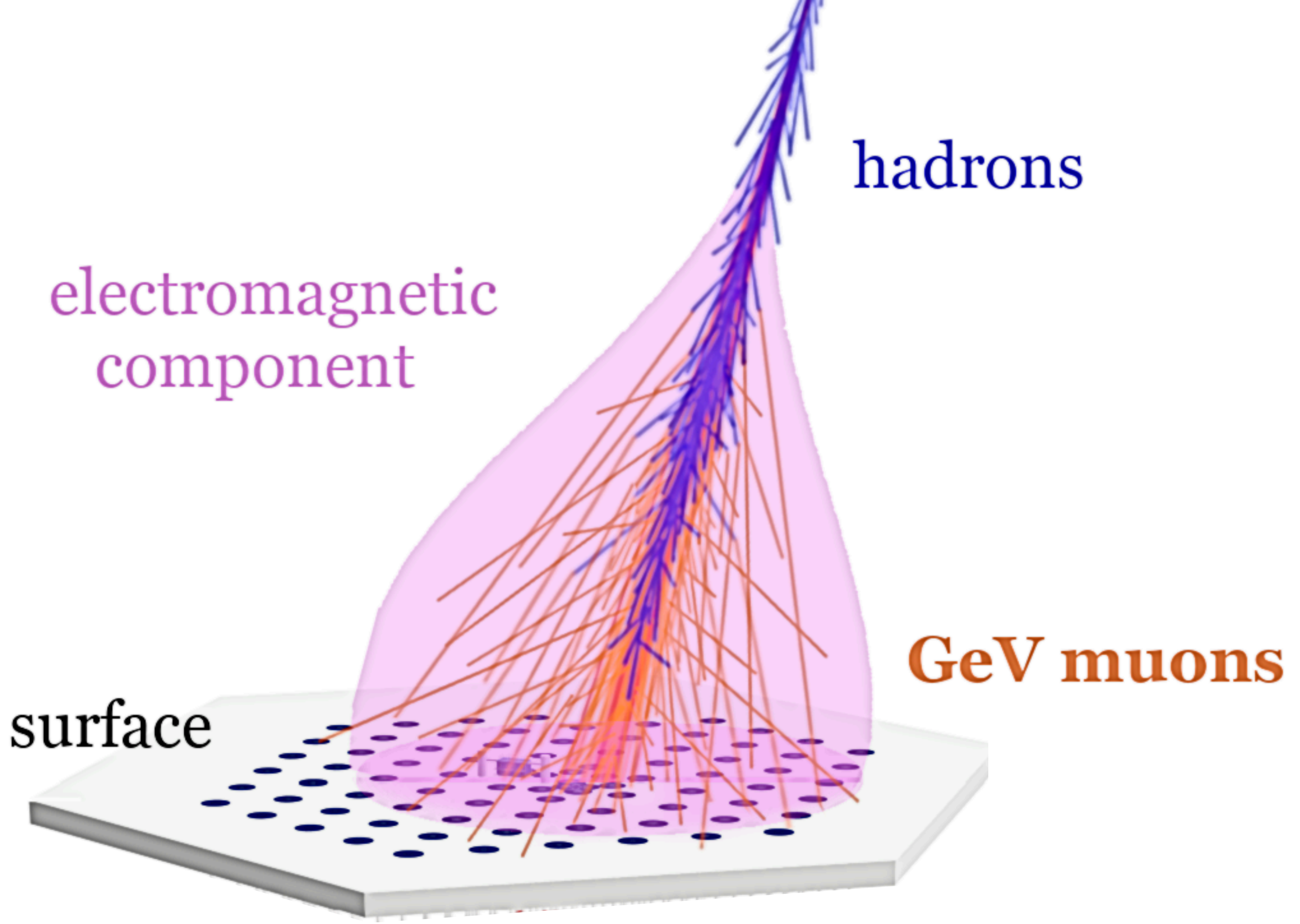
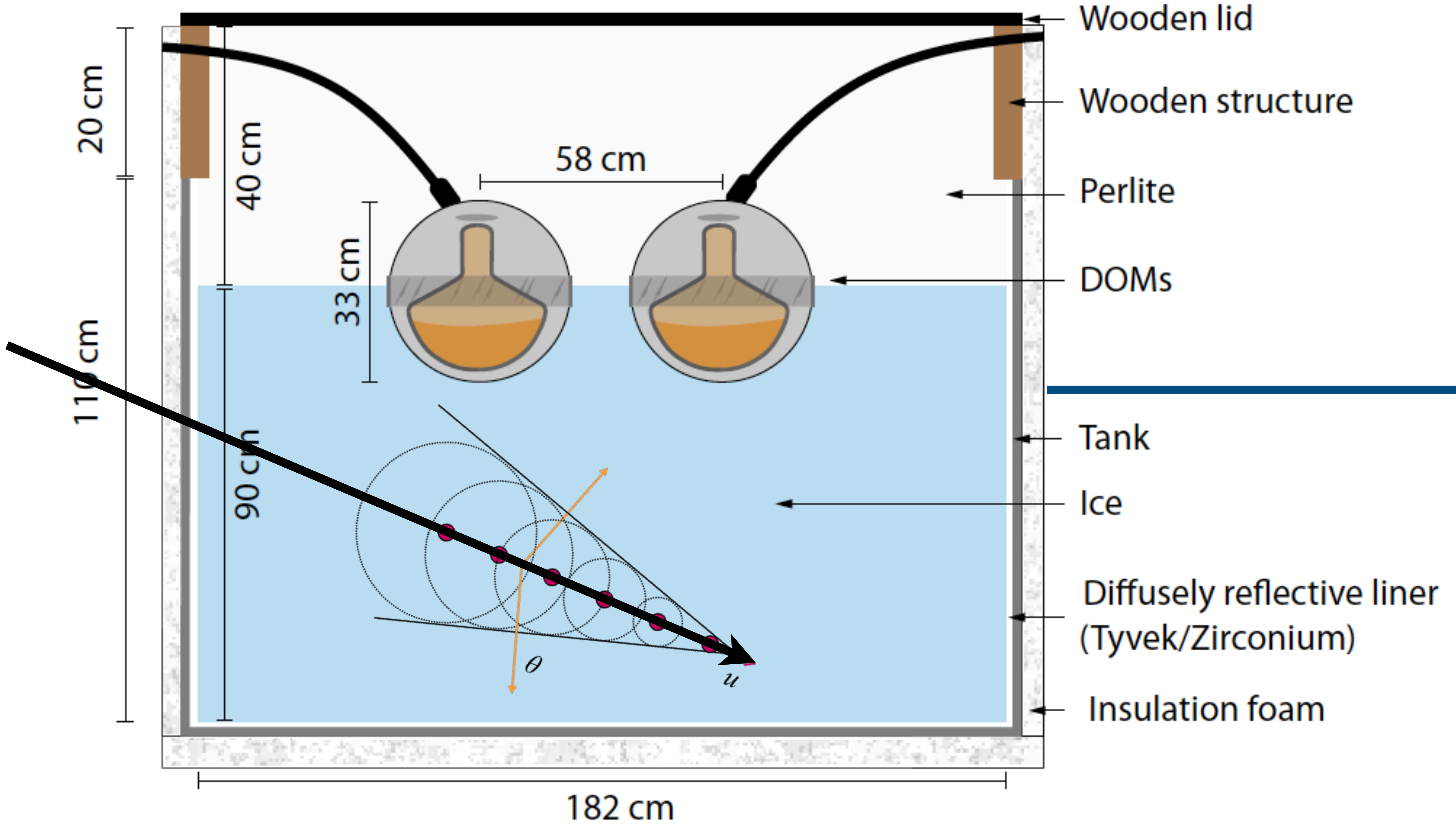
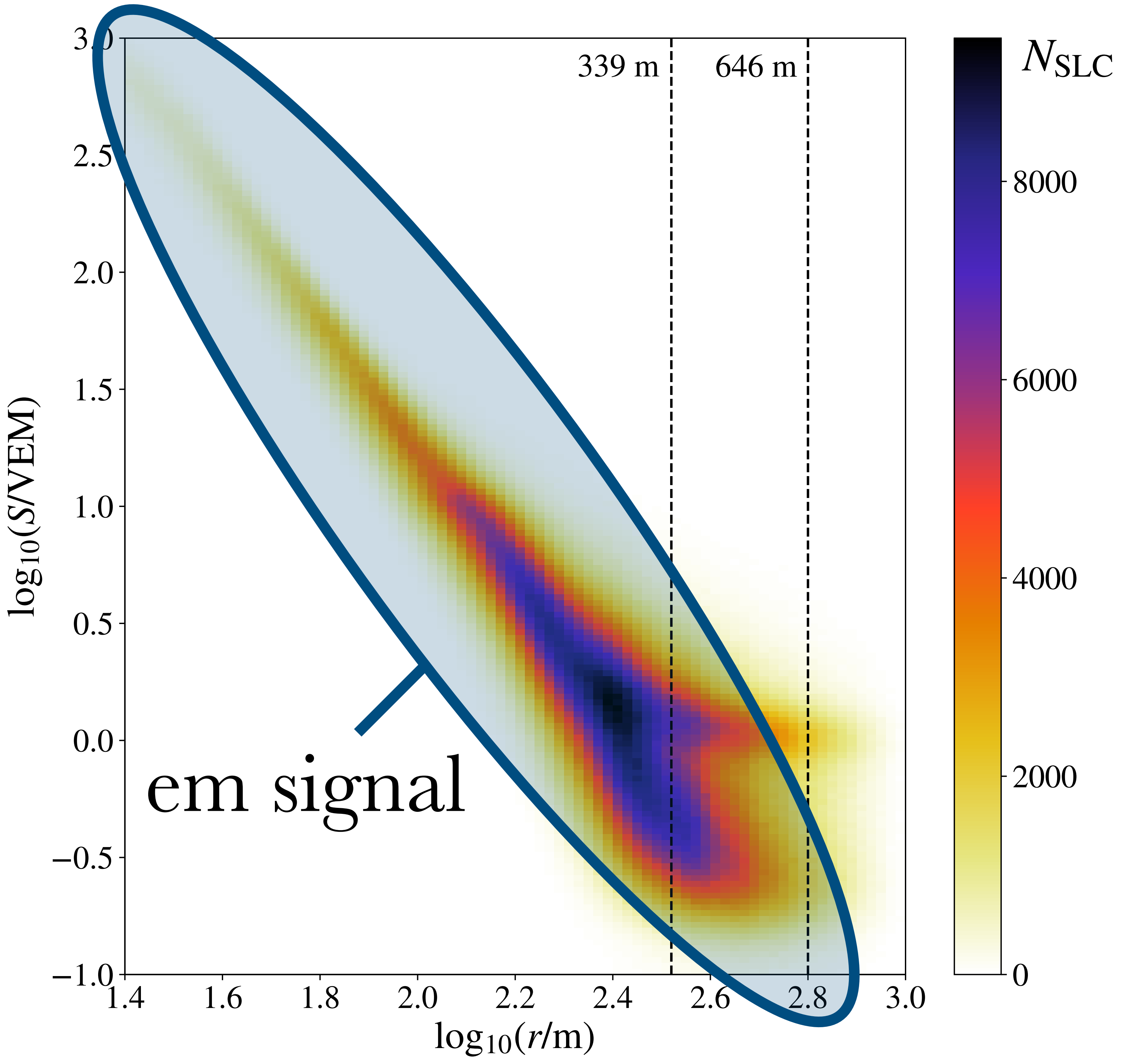


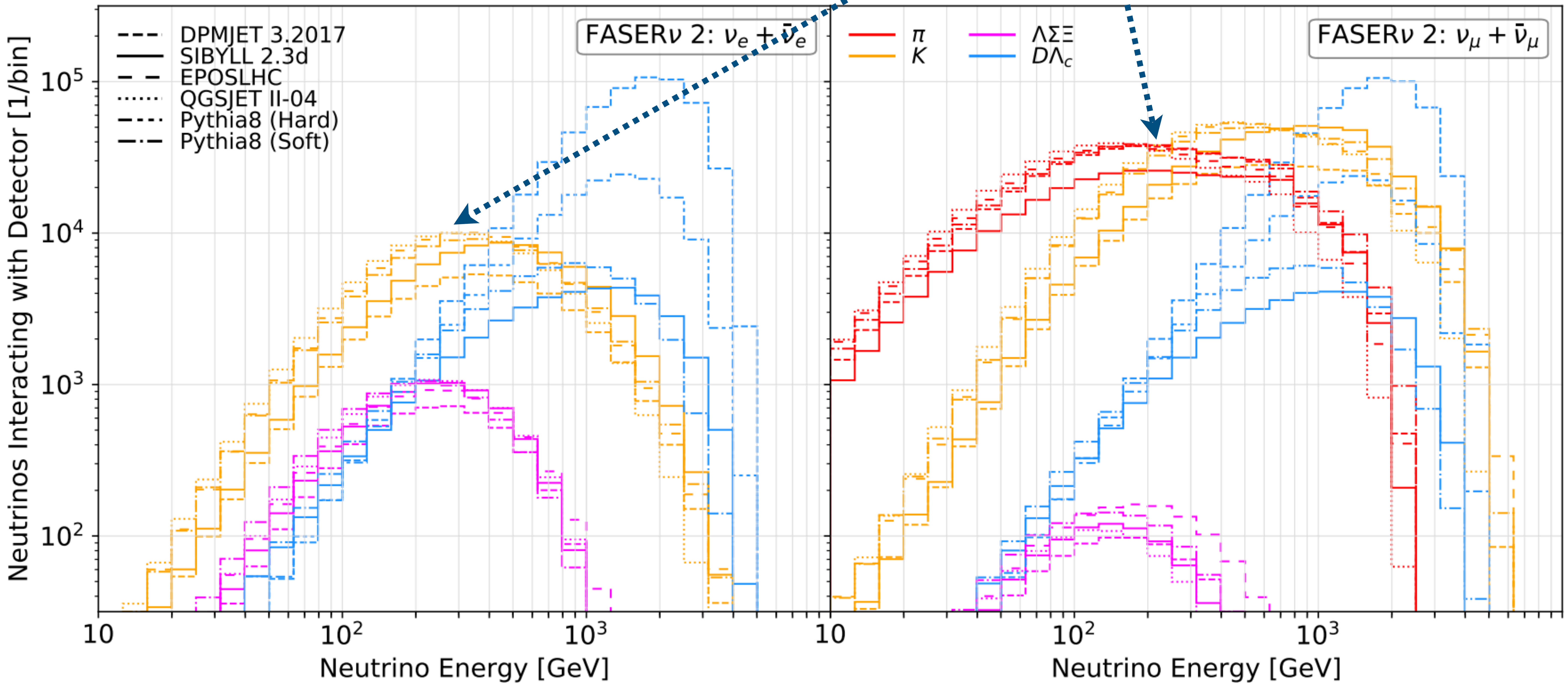




Light Hadron Production

- Neutrino fluxes at FASERν2:

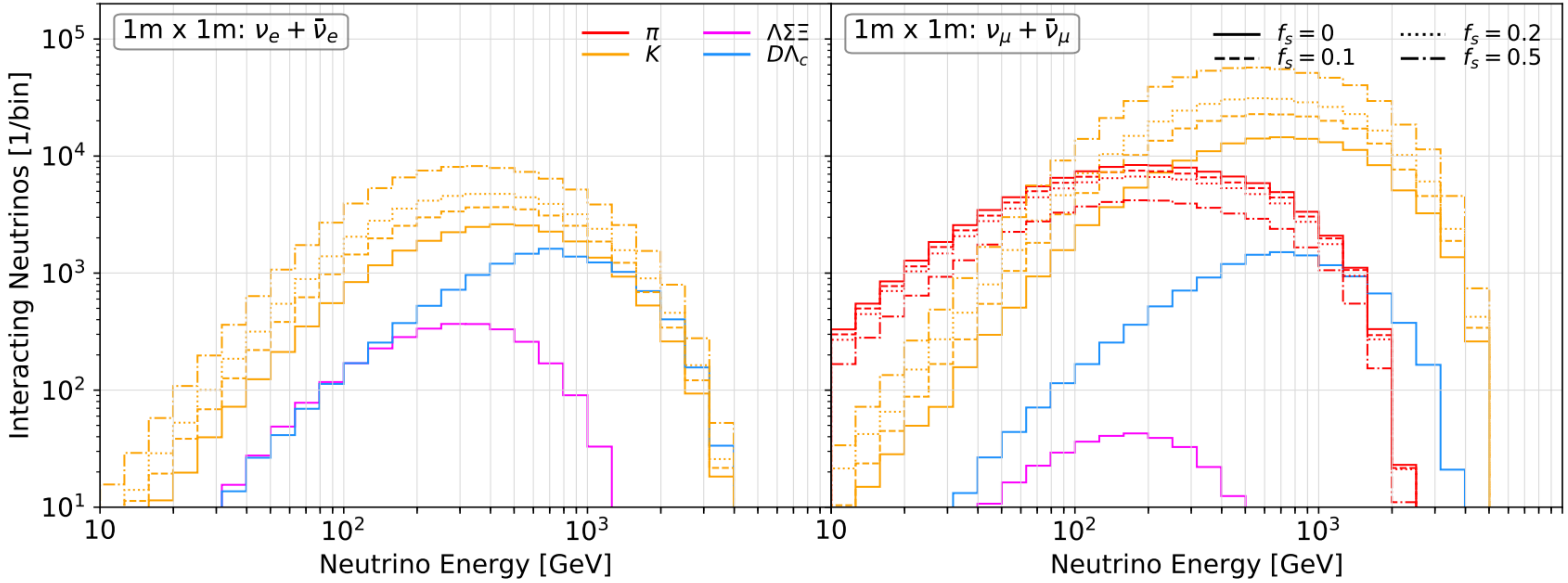
low energy region relevant!



- Predictions differ by a factor of up to 2, much bigger than the anticipated FPF uncertainties

Light Hadron Production

- Neutrino fluxes at FLArE:



- Example: strangeness enhancement toy model [L. Anchordoqui et al., JHEAp 34 (2022)]

GeV Muons in IceTop

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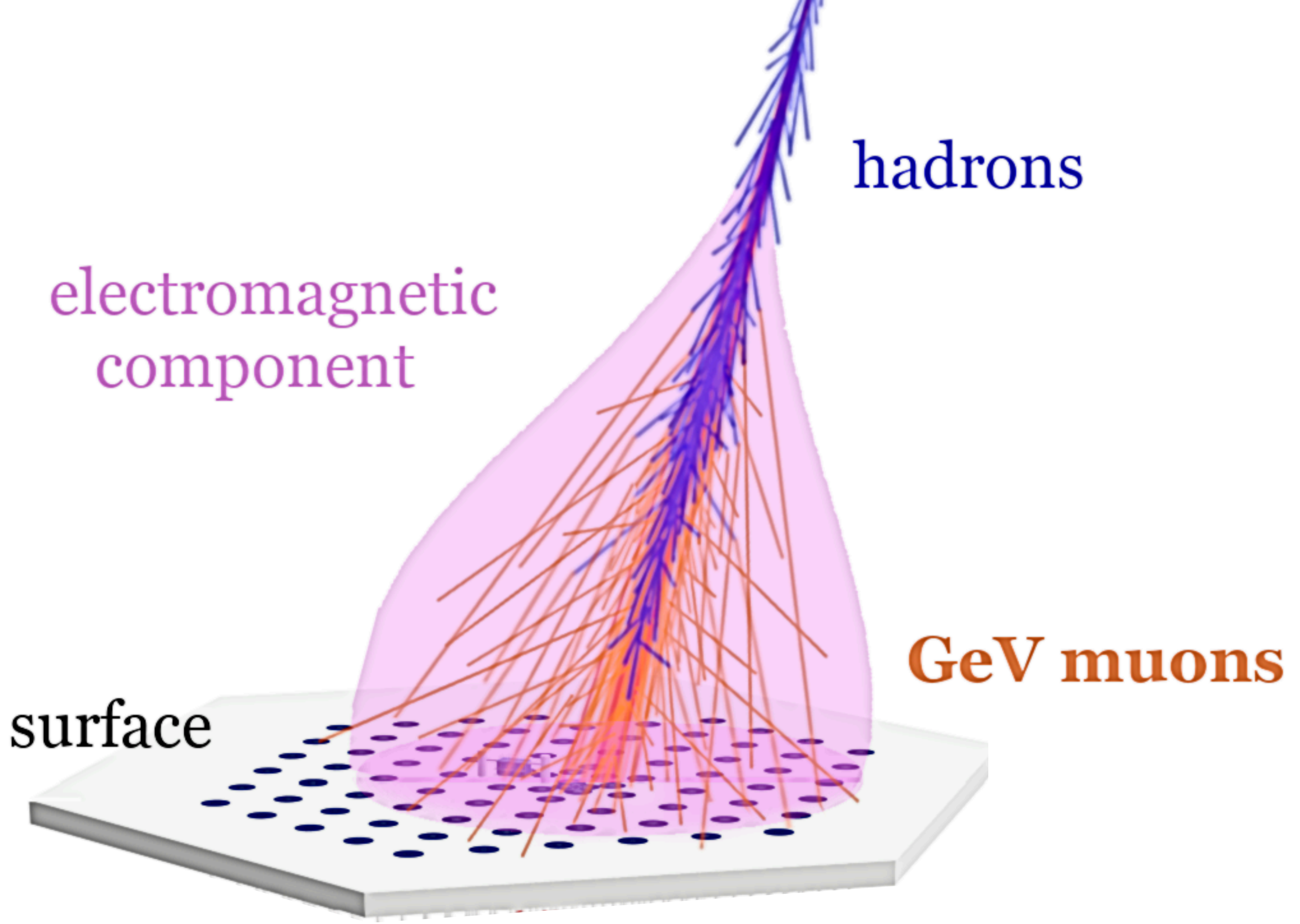
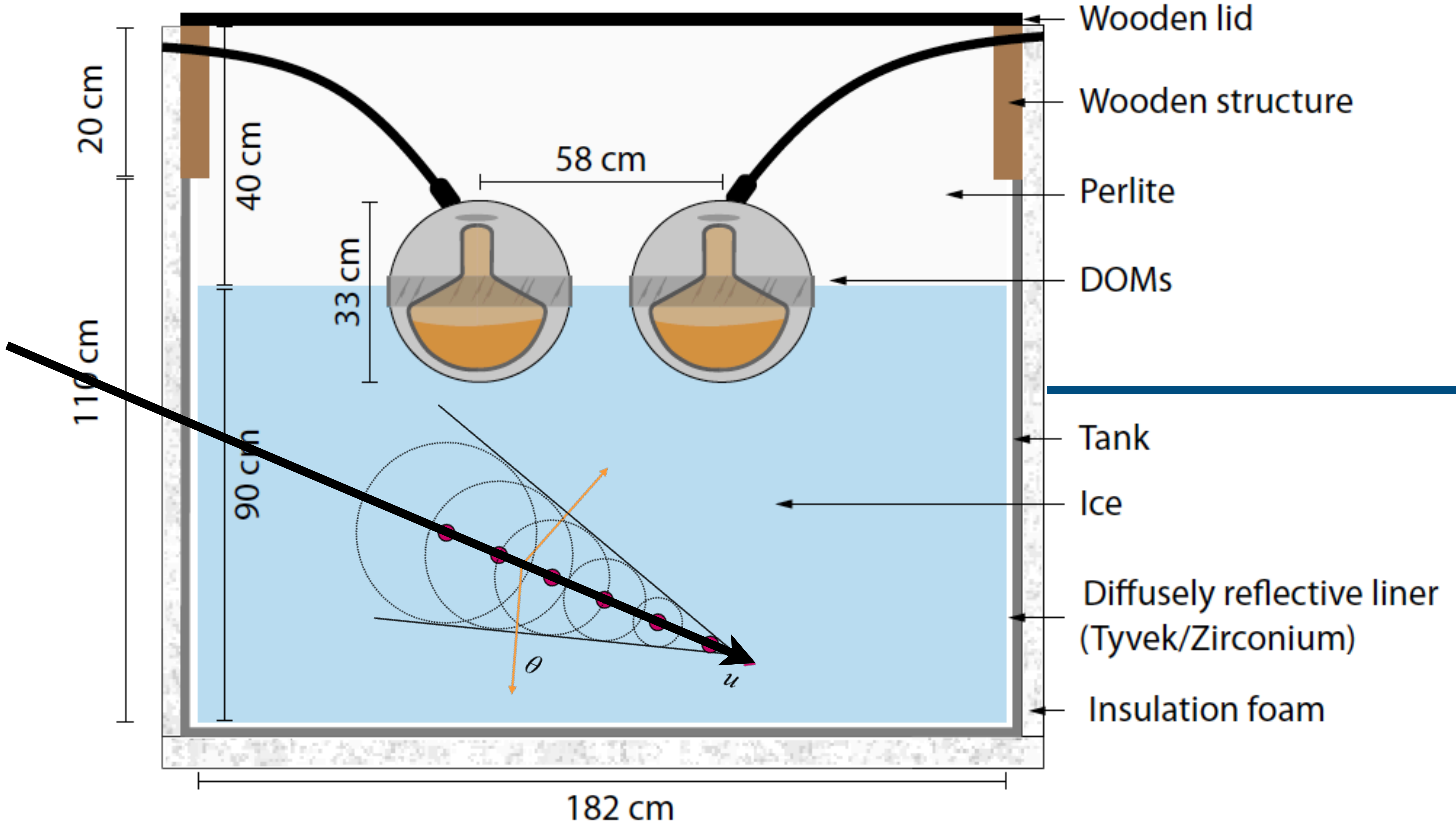
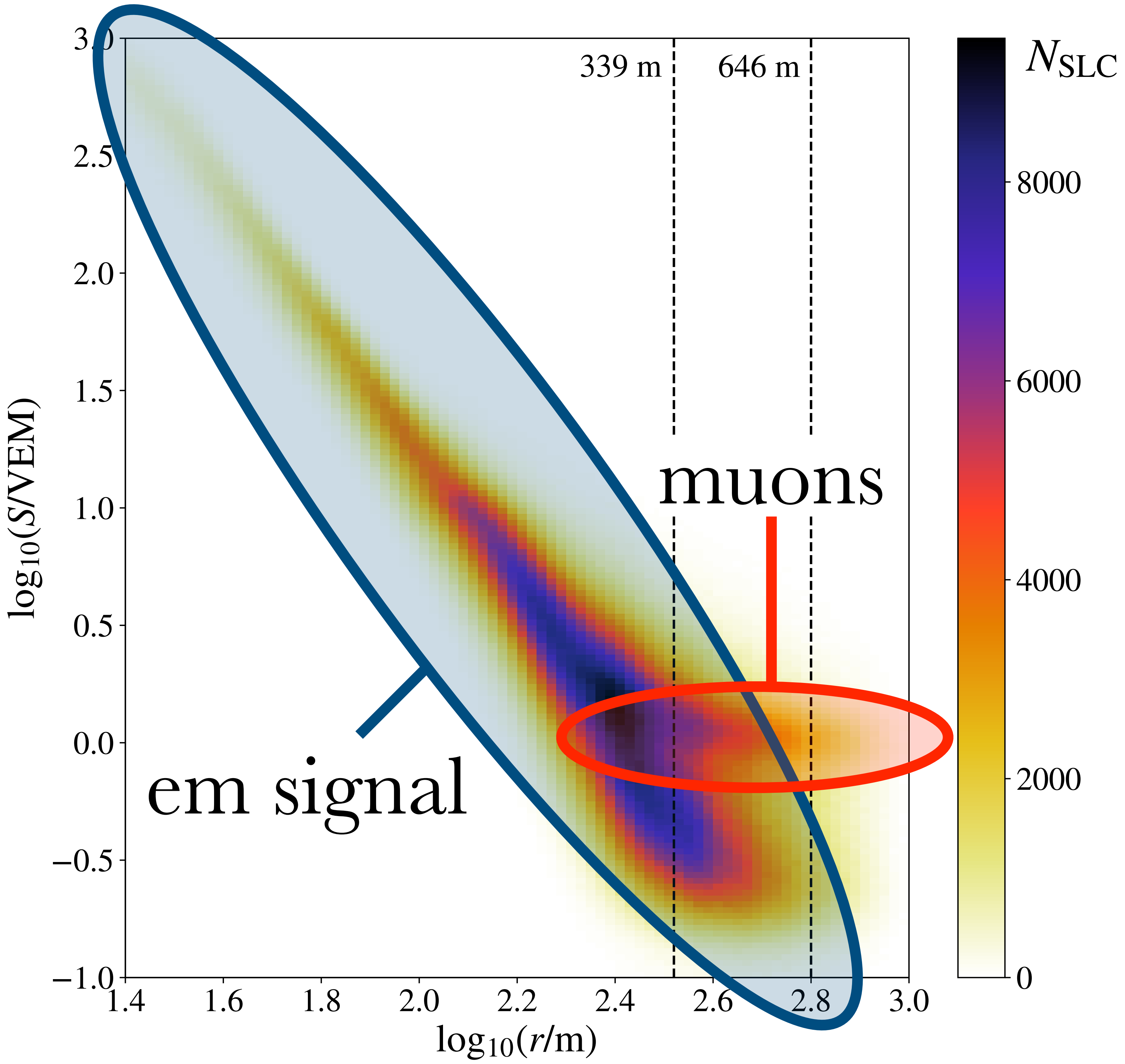
- Characteristic signal distributions for em part and muons
- Separation of GeV muons from other particles in EAS



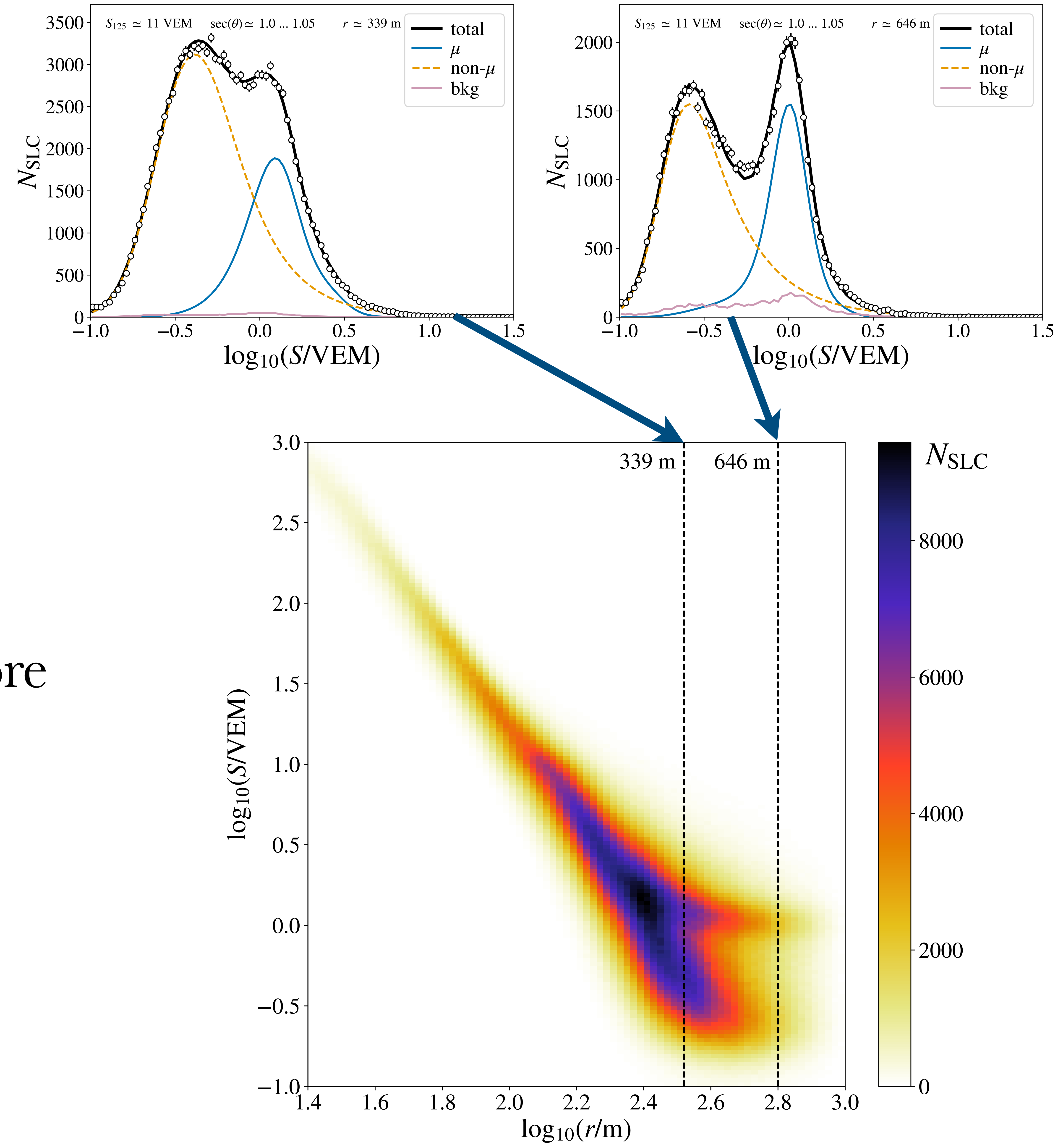




GeV Muons in IceTop

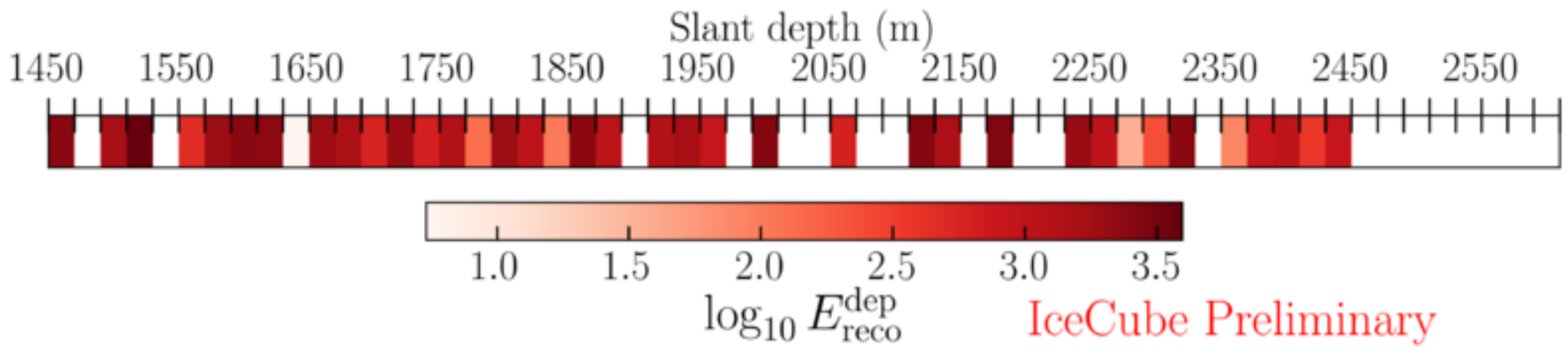
- Complex signal model, includes:
  - electromagnetic response model
  - muon response model
  - uncorrelated background
- Larger muon fraction at large distances from the shower central region
- Likelihood fits at 600 m and 800 m from the core in bins of the energy of inclined EAS ($\theta < 18°$)
- Muon density as a function of CR energy!
- Reminder: muons are messengers of the hadronic interactions in EAS!

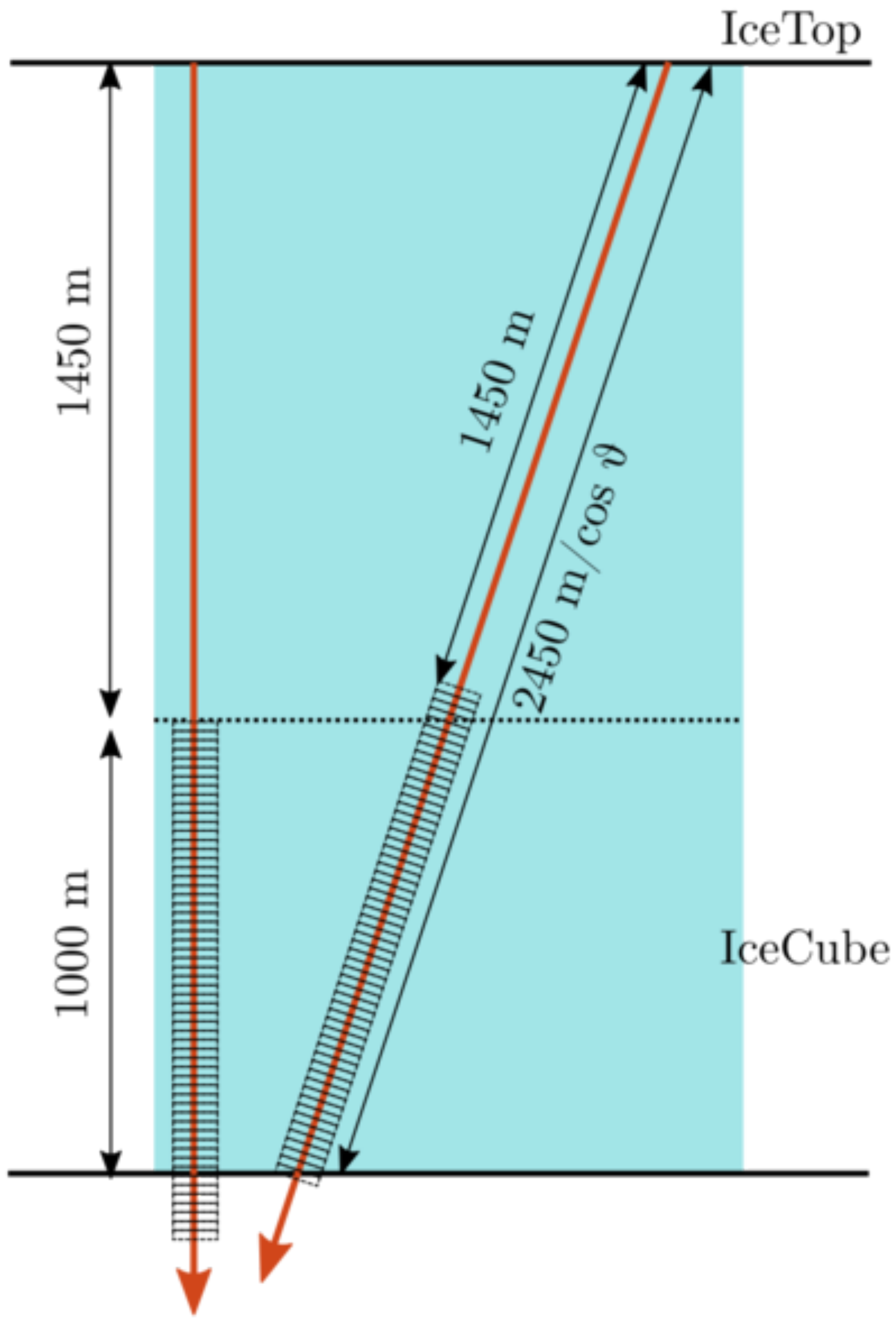
[IceCube Collaboration, Phys. Rev. D 106 (2022)]



TeV Muon Multiplicity

- Coincident machine learning analysis using IceTop and in-ice
- <u>Neural network inputs:</u>
  - IceTop: zenith angle, energy proxy S125 (laputop)
  - In-ice: energy loss profile vector (millipede)
- <u>Neural network outputs:</u>
  - Primary CR energy
  - Multiplicity of in-ice muons above 500 GeV

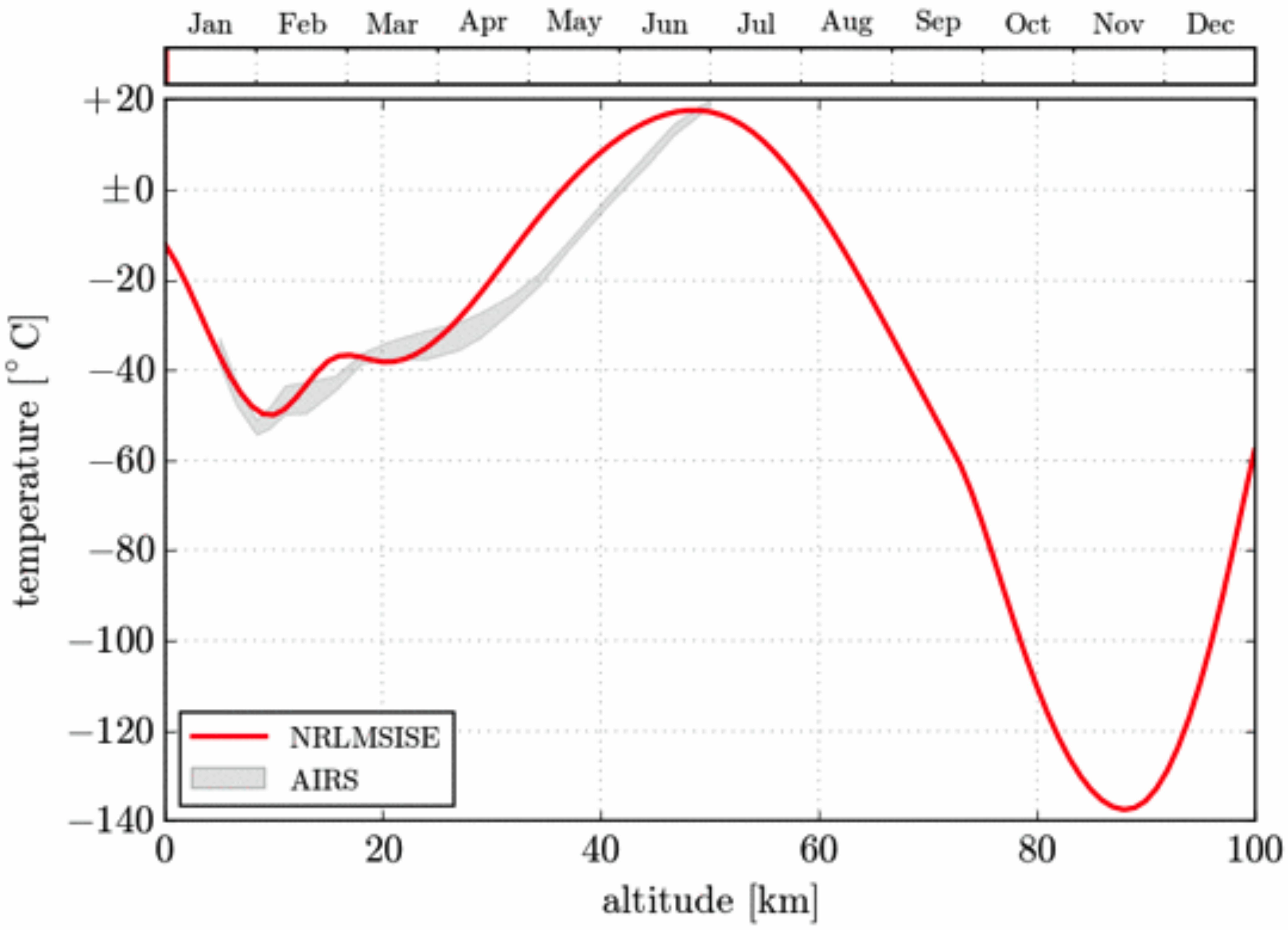




[S. Verpoest (IceCube Collaboration), ECRS2022 (proceedings in preparation)]
see also [S. Verpoest, D. Soldin, S. De Ridder et al., PoS ICRC2021 (2021) 357]

Physics Beyond the Muon Puzzle…

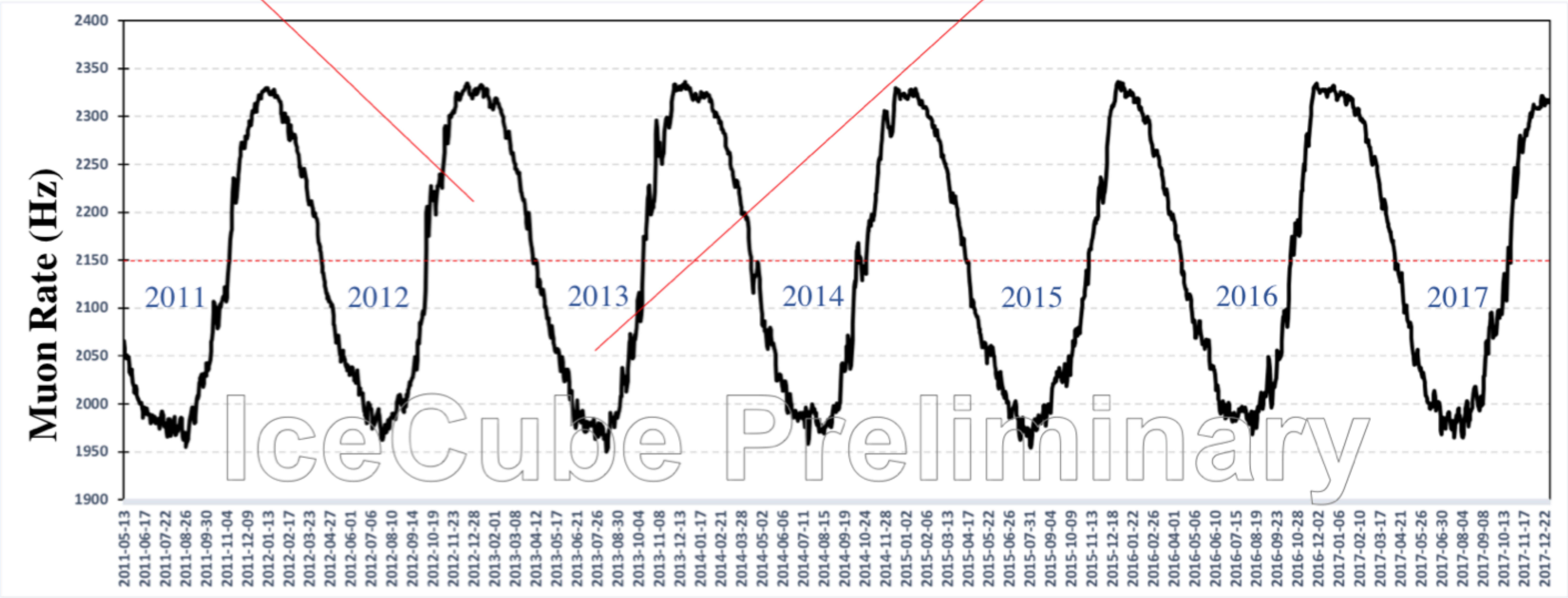
- Atmospheric muon flux depends on atmospheric density (temperature, pressure)!



Seasonal Variations of TeV Muons

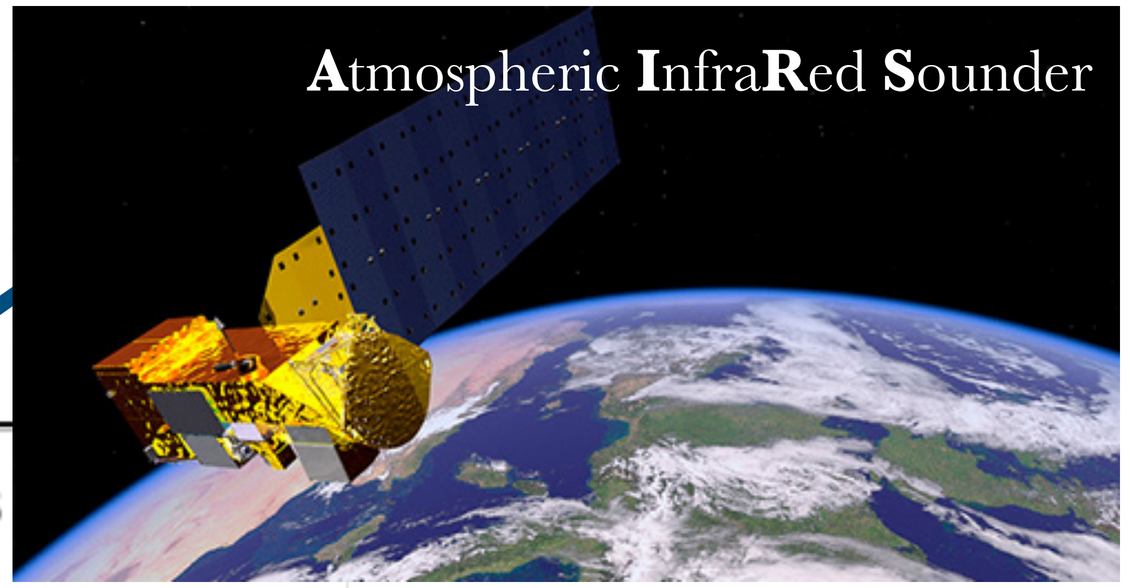
Summer atmosphere
warmer => less dense => pions decay to muons

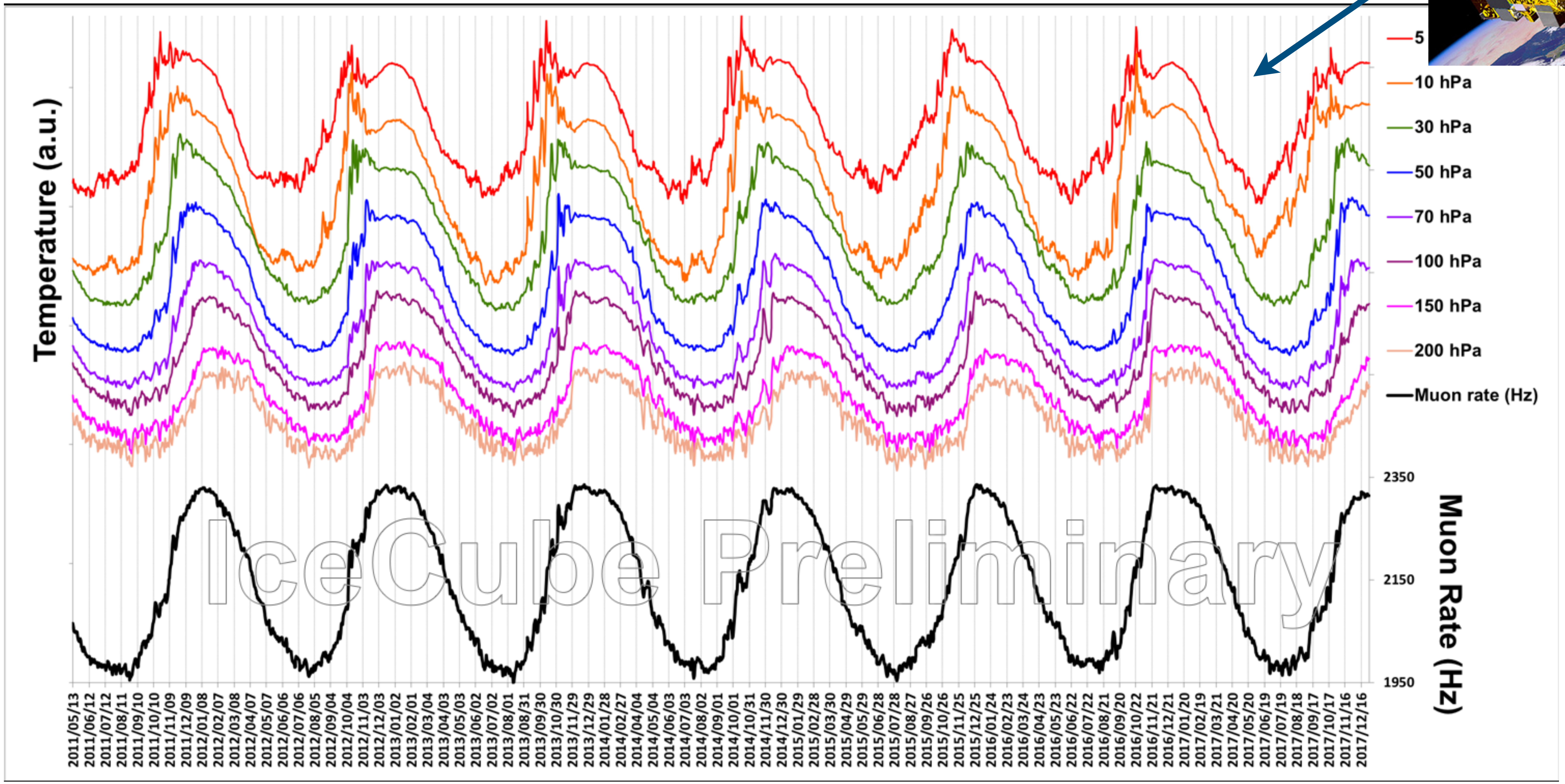
Winter atmosphere
colder => more dense => pions interact



[S. Tilav, T. K. Gaisser, D. Soldin, P. Desiati, PoS ICRC2019 (2020) 894]

Seasonal Variations of TeV Muons

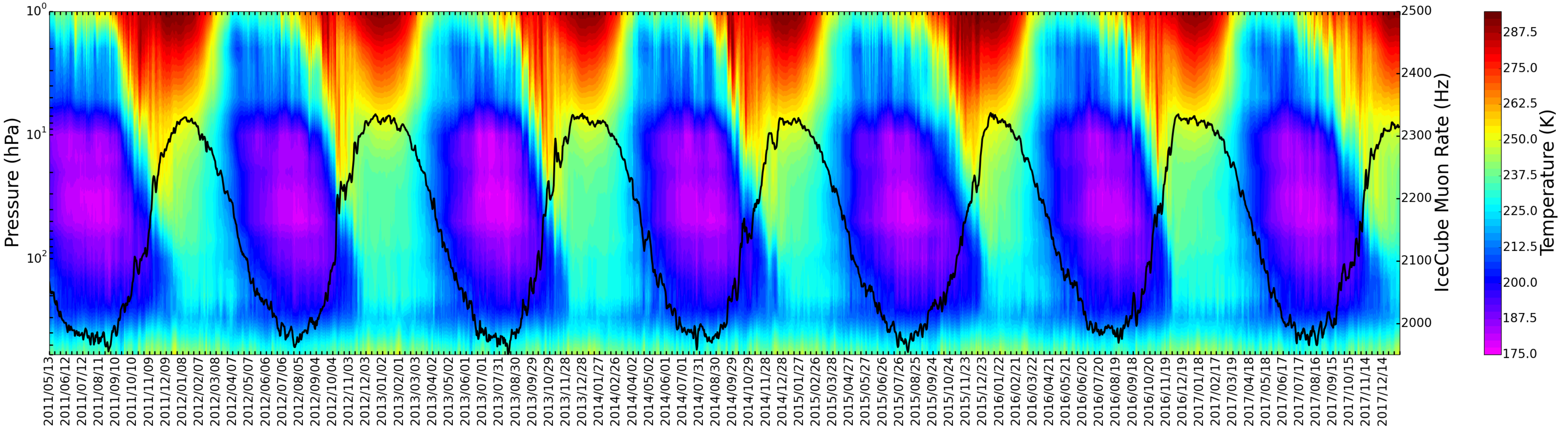


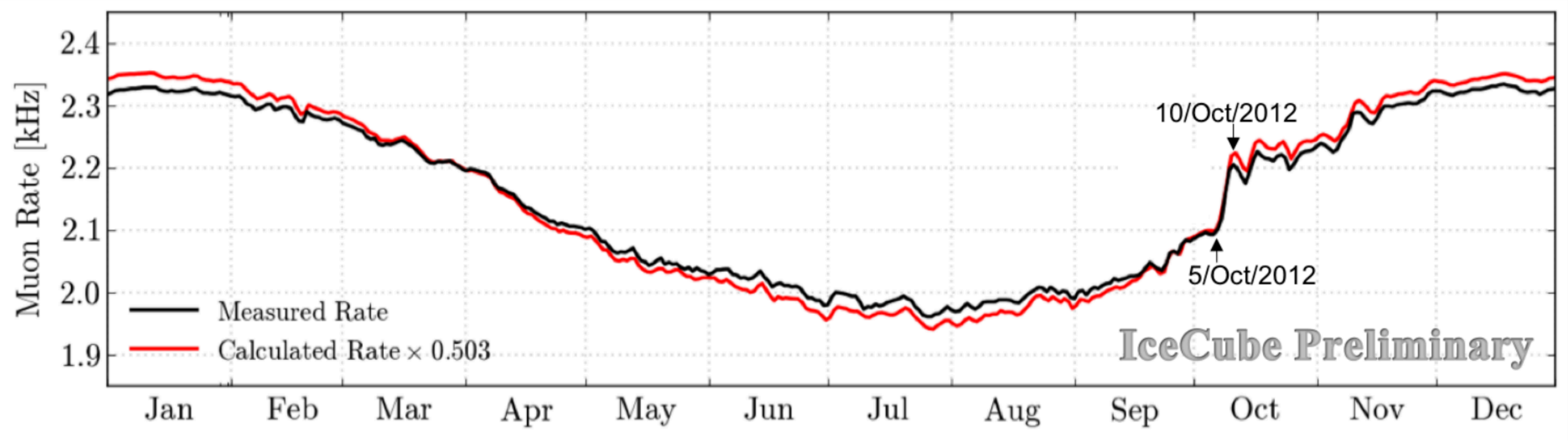


[S. Tilav, T. K. Gaisser, D. Soldin, P. Desiati, PoS ICRC2019 (2020) 894]

Seasonal Variations of TeV Muons

[S. Tilav, T. K. Gaisser, D. Soldin, P. Desiati, PoS ICRC2019 (2020) 894]

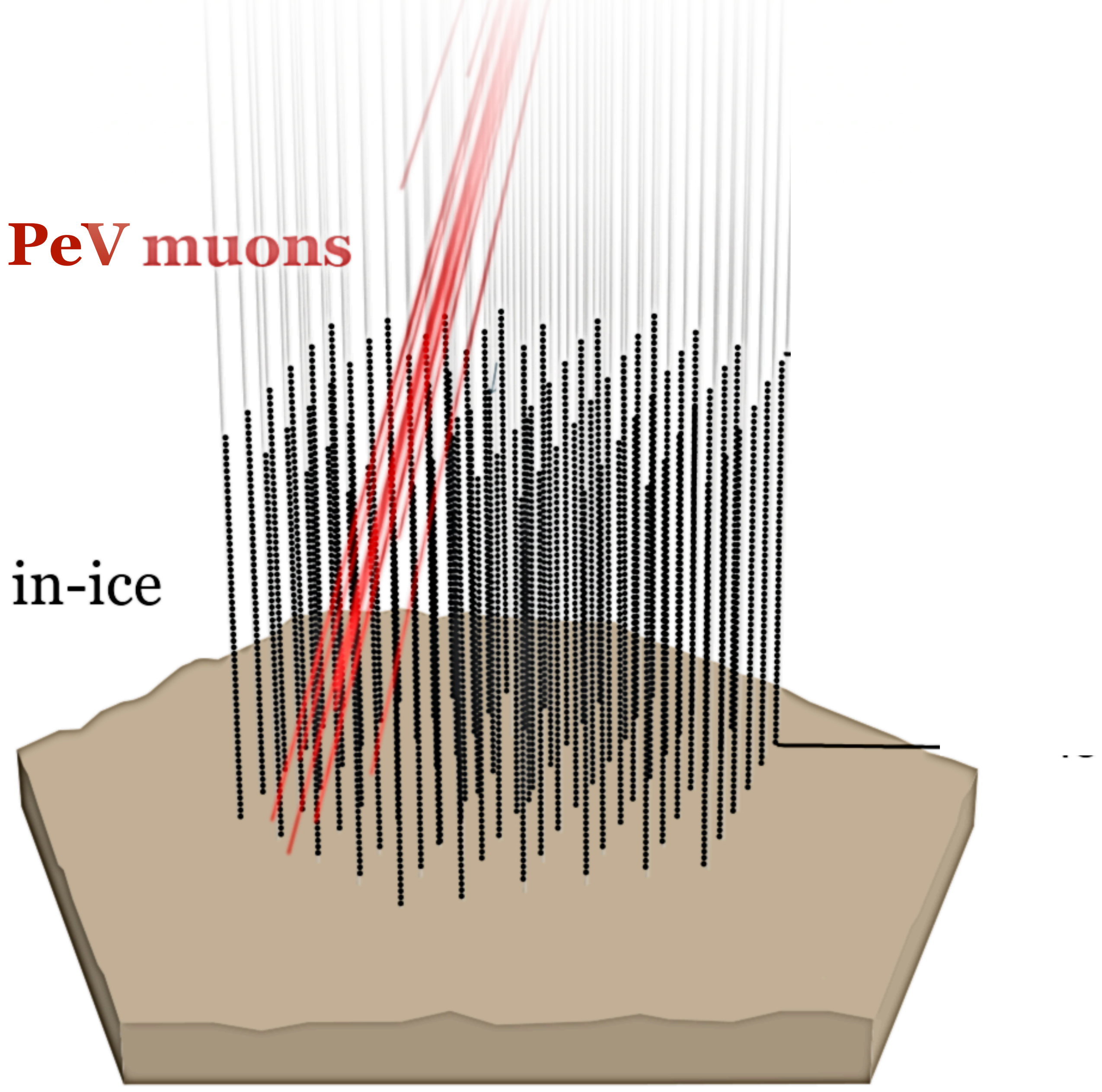


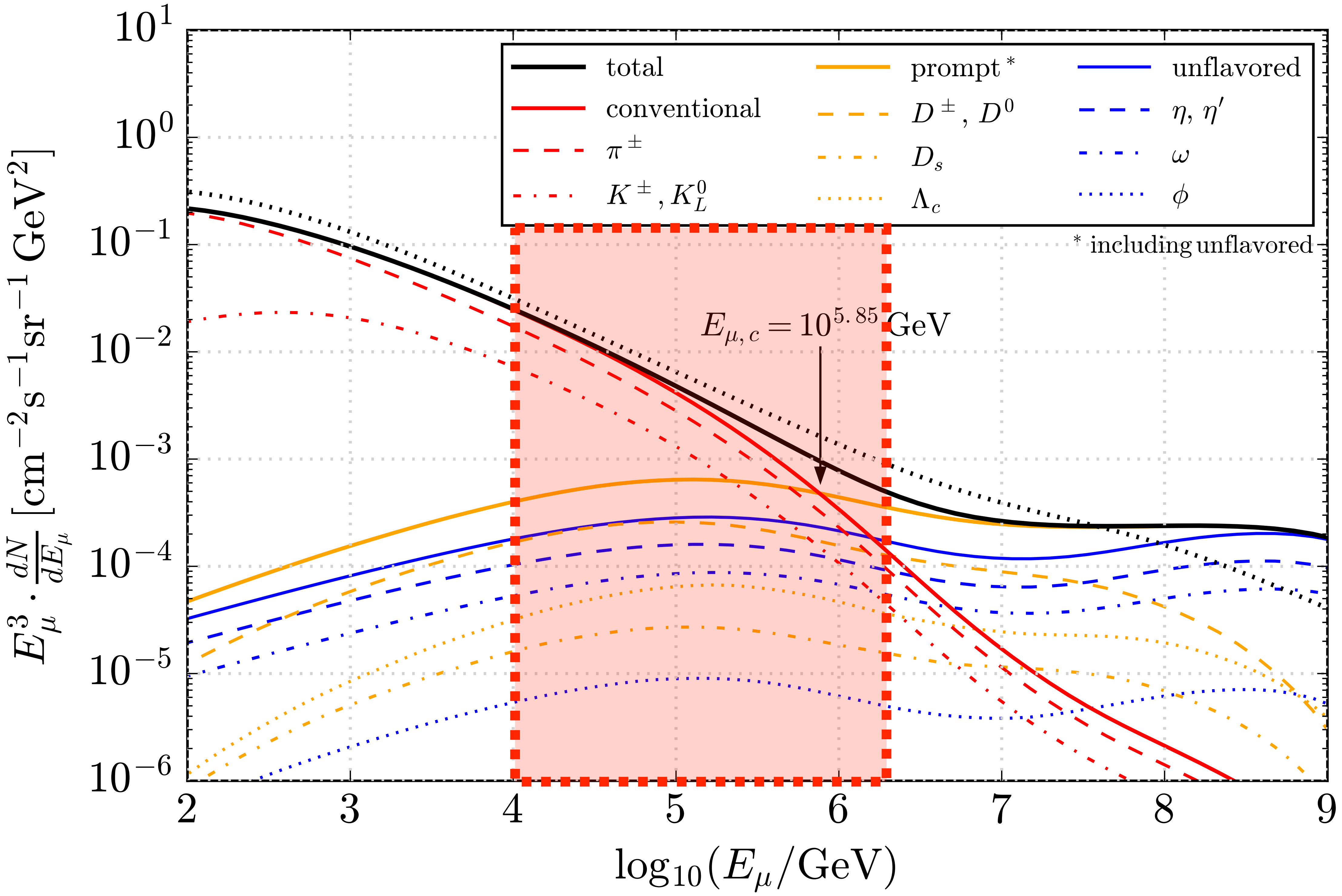


- Probe of atmospheric conditions (stratosphere)
- <u>Sensitive to the kaon/pion ratio in EAS!</u>
- Analysis in progress…

PeV Muons in IceCube

- For muon energies from GeV to TeV, the muon production is dominated by pion and kaon decays ("conventional flux")
- "Prompt muons" from decay of heavy hadrons (e.g. $D^{\pm}$, D^0, Λ_c) are expected to dominate at PeV energies!
- Prompt flux has yet to be experimentally confirmed…
- Also, yields information about prompt atmospheric neutrino production
- Expected to be relevant background for astrophysical neutrino searches in the PeV region
- <u>Understanding of prompt fluxes important for neutrino astrophysics!</u>

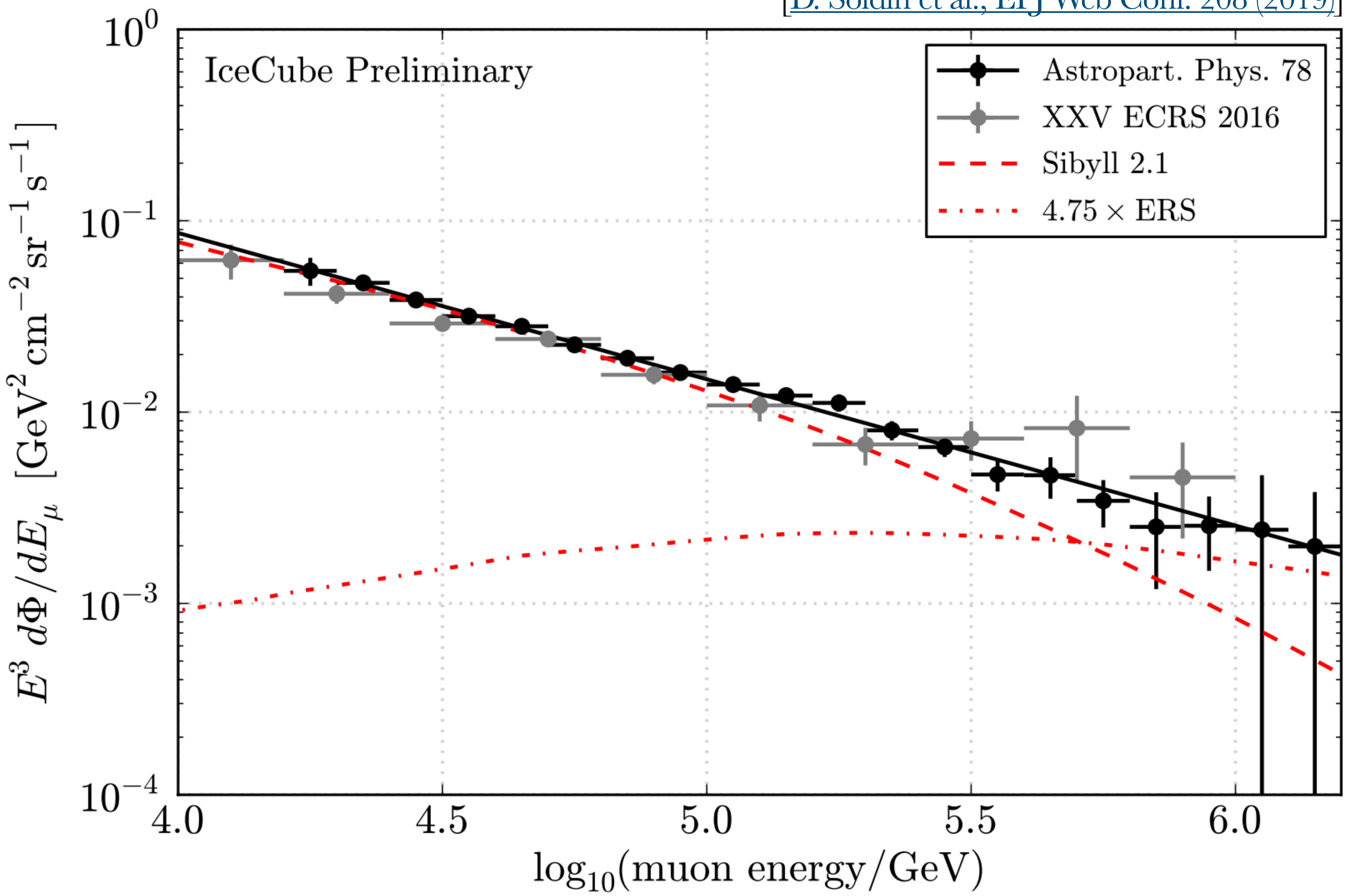




PeV Muons in IceCube

- Atmospheric muon spectrum above $E_\mu \simeq 10\,\mathrm{TeV}$
- Reaching the transition region where the prompt muon flux becomes dominant
- Large uncertainties due to CR flux model assumption!
- Low statistics at high energies
  - Larger in-ice detector needed!
- Here: no EAS energy
  - New reconstruction methods needed (more tomorrow…)
  - Larger surface detector needed!

[D. Soldin et al., EPJ Web Conf. 208 (2019)]

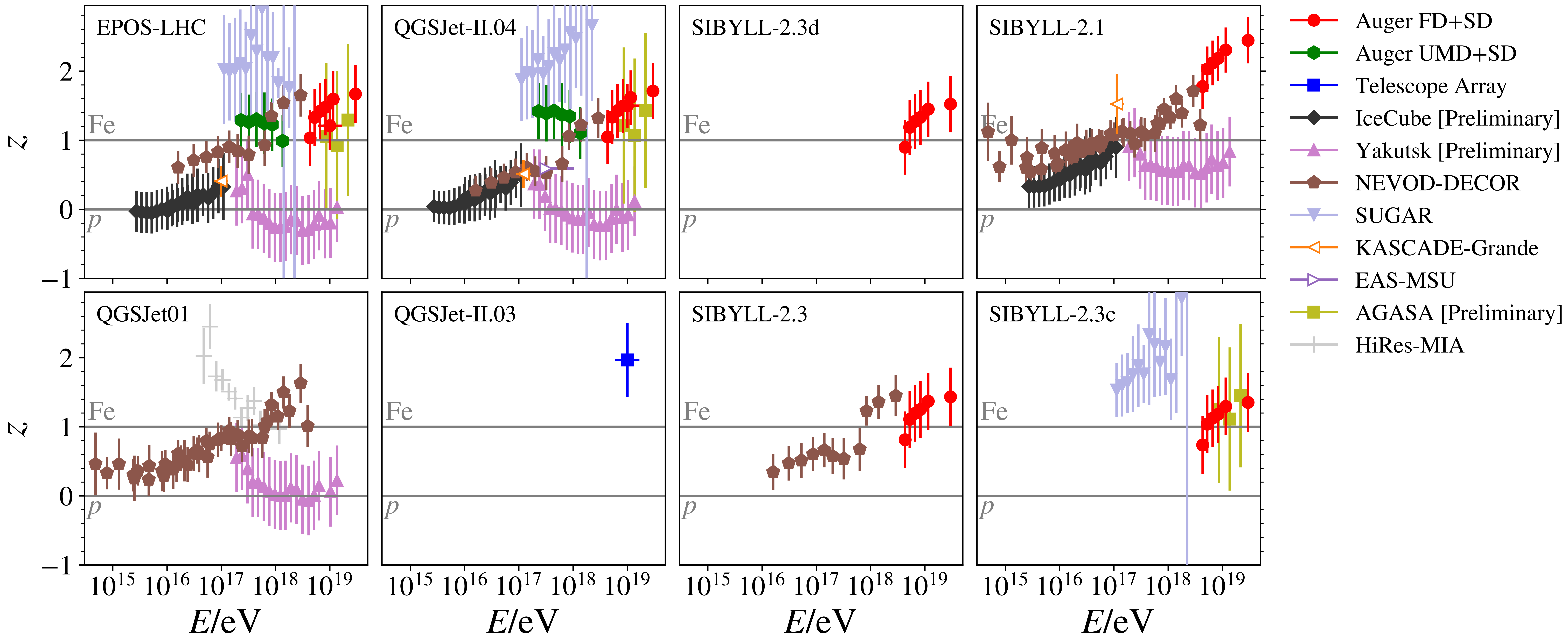


CR Model	Best Fit (ERS)	χ^2/dof	1σ Interval	Pull ($\Delta\gamma$)	$\sigma(\Phi_{Prompt} > 0)$
GST-Global Fit [13]	2.14	7.96/9	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [13]	4.75	9.09/9	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97
Zats.-Sok. [35]	6.23	13.98/9	4.55 - 8.70 (3.59 - 10.68)	-0.23	5.24
PG Constant $\Delta\gamma$ [33]	0.94	9.07/9	0.36 - 1.63 (< 2.15)	0.03	1.52
PG Rigidity [33]	6.97	5.86/9	4.73 - 10.61 (3.53 - 13.83)	-0.06	4.35

[IceCube Collaboration, Astropart.Phys. 78 (2016)]

Data Comparison

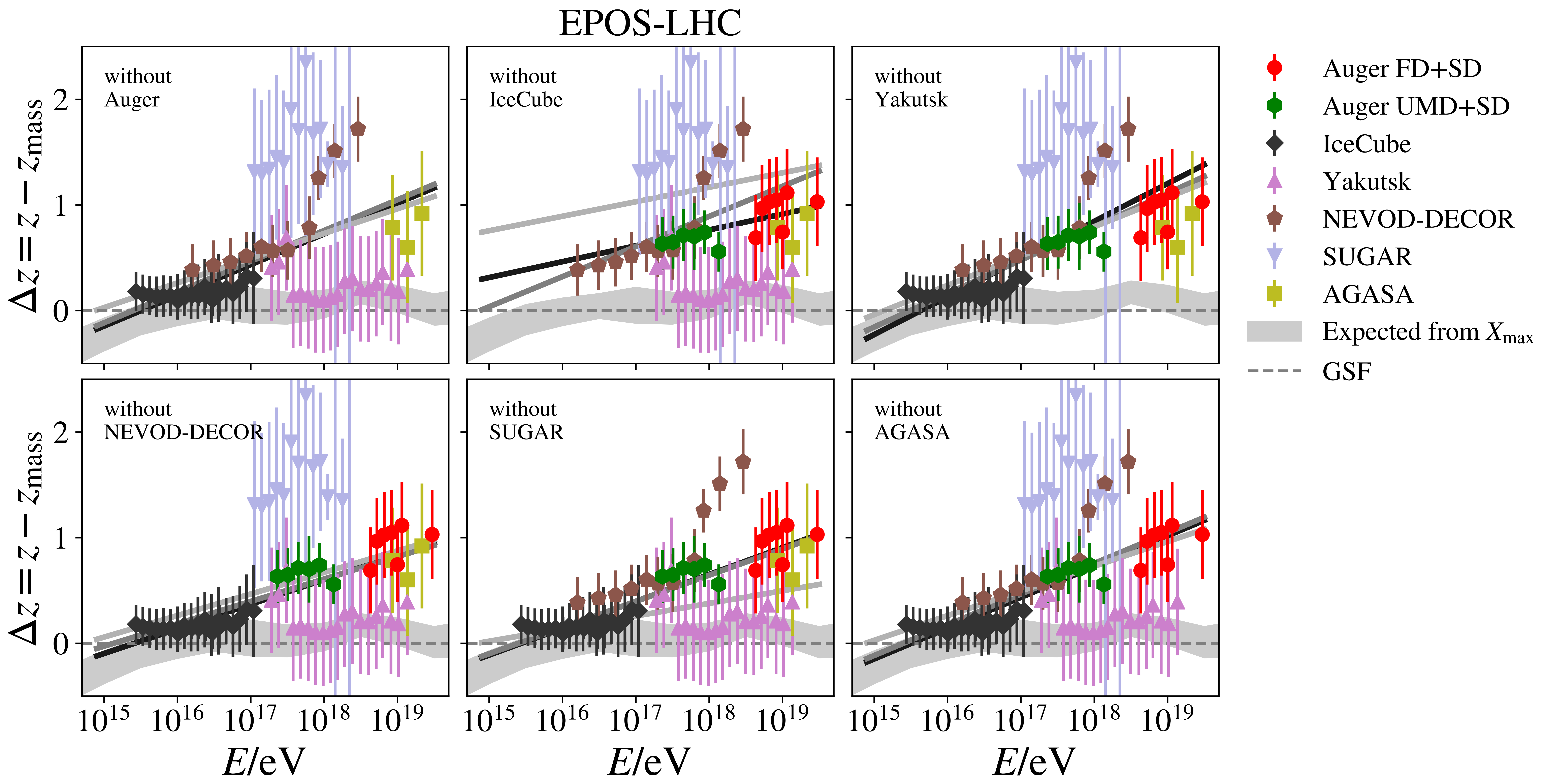
- Muon numbers measured by 9 EAS experiments [D. Soldin et al., PoS ICRC2021 (2021) 349]



- Working Group for Hadronic Interactions and Shower Physics (WHISP)

IceTop's Crucial Role

- How do the fits change when we remove one experiment at a time?



[D. Soldin et al., PoS ICRC2021 (2021) 349]

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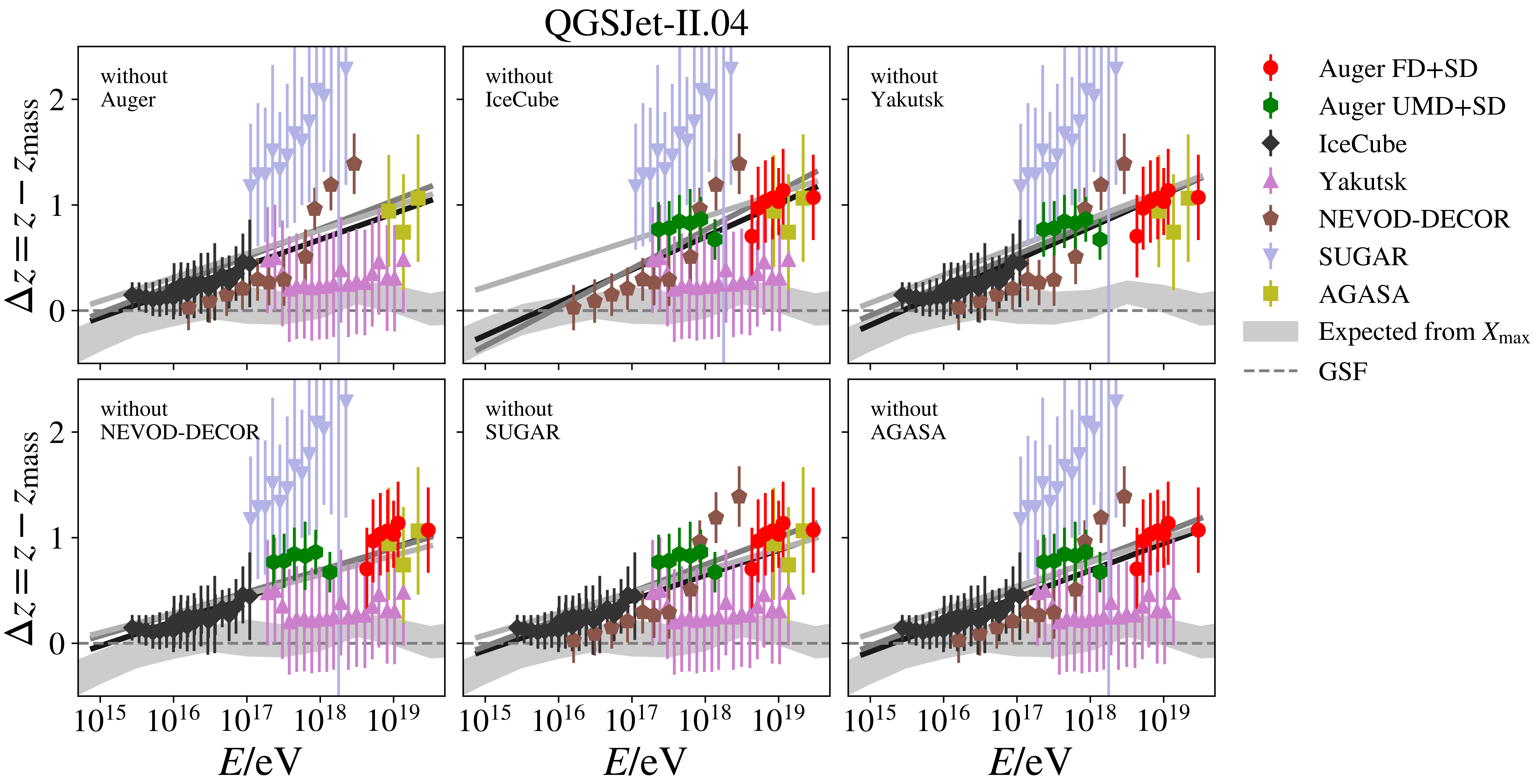
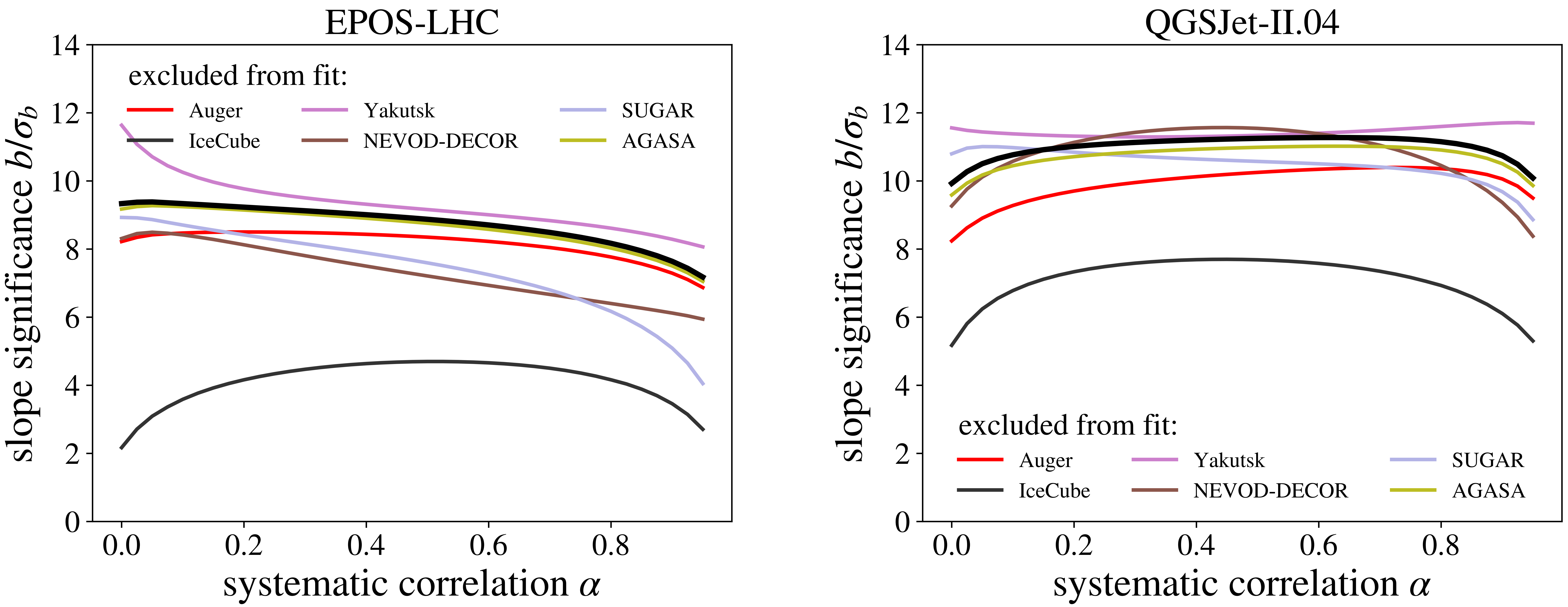


[D. Soldin et al., PoS ICRC2021 (2021) 349]

IceTop's Crucial Role

- Significance of the slope when removing one experiment

[D. Soldin et al., PoS ICRC2021 (2021) 349]



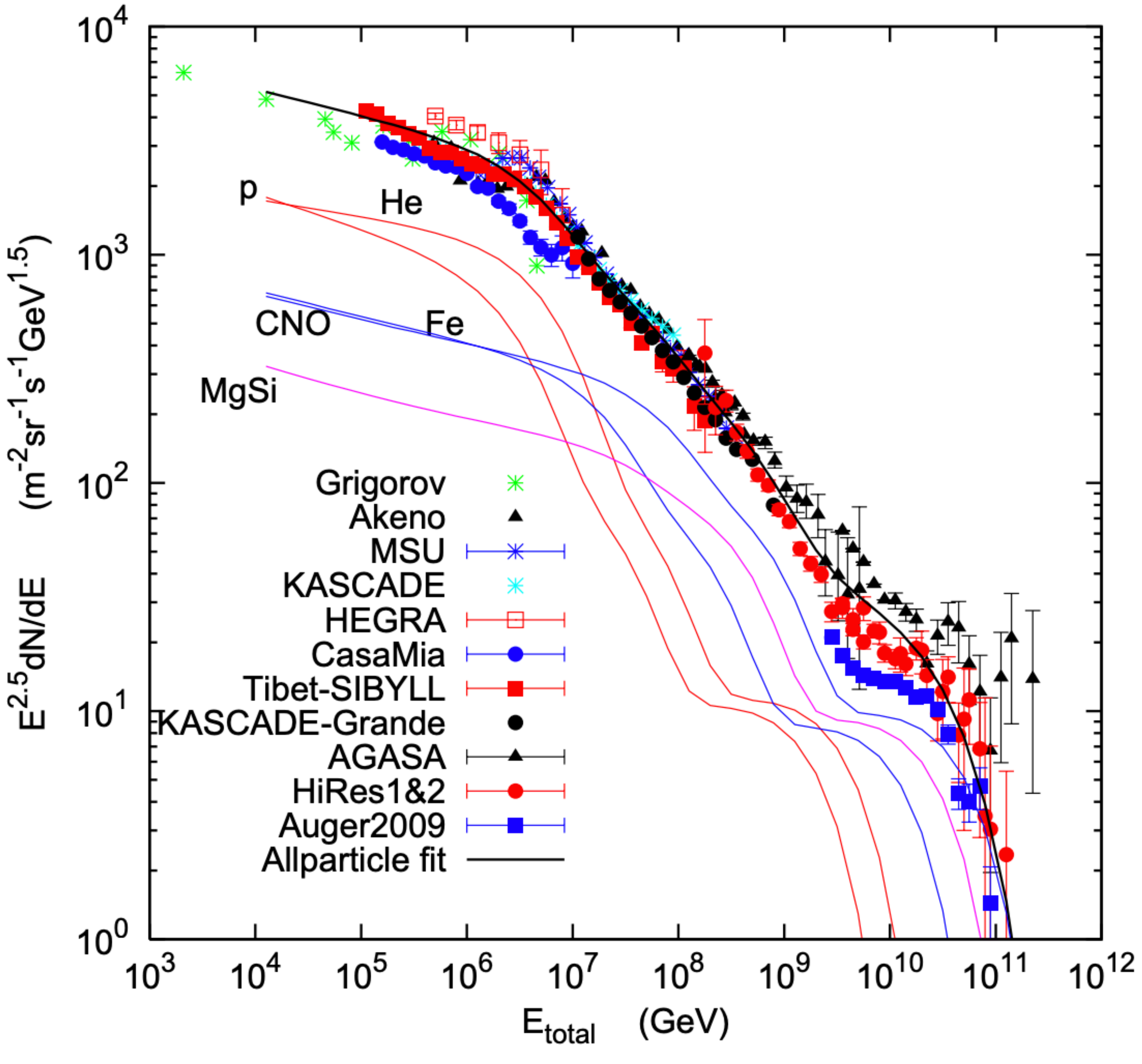
- Substantial decrease of significance without IceCube/IceTop!
- Yakutsk data becomes more important but is in tension with other measurements

CR Flux Models

- Physics-motivated flux models assuming different source populations

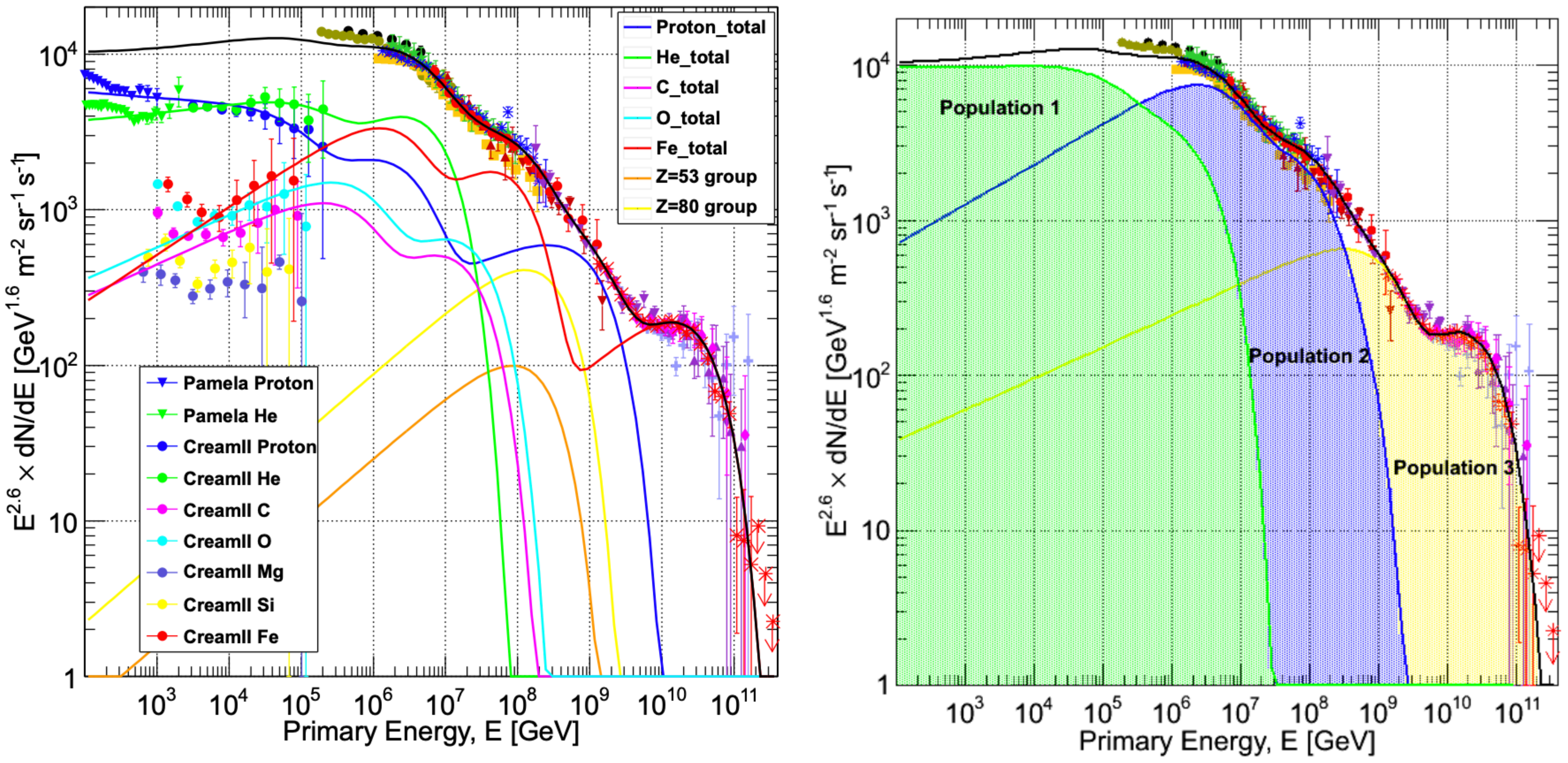
Gaisser H3a:

[T. K. Gaisser, Astropart. Phys. 35 (2012)]



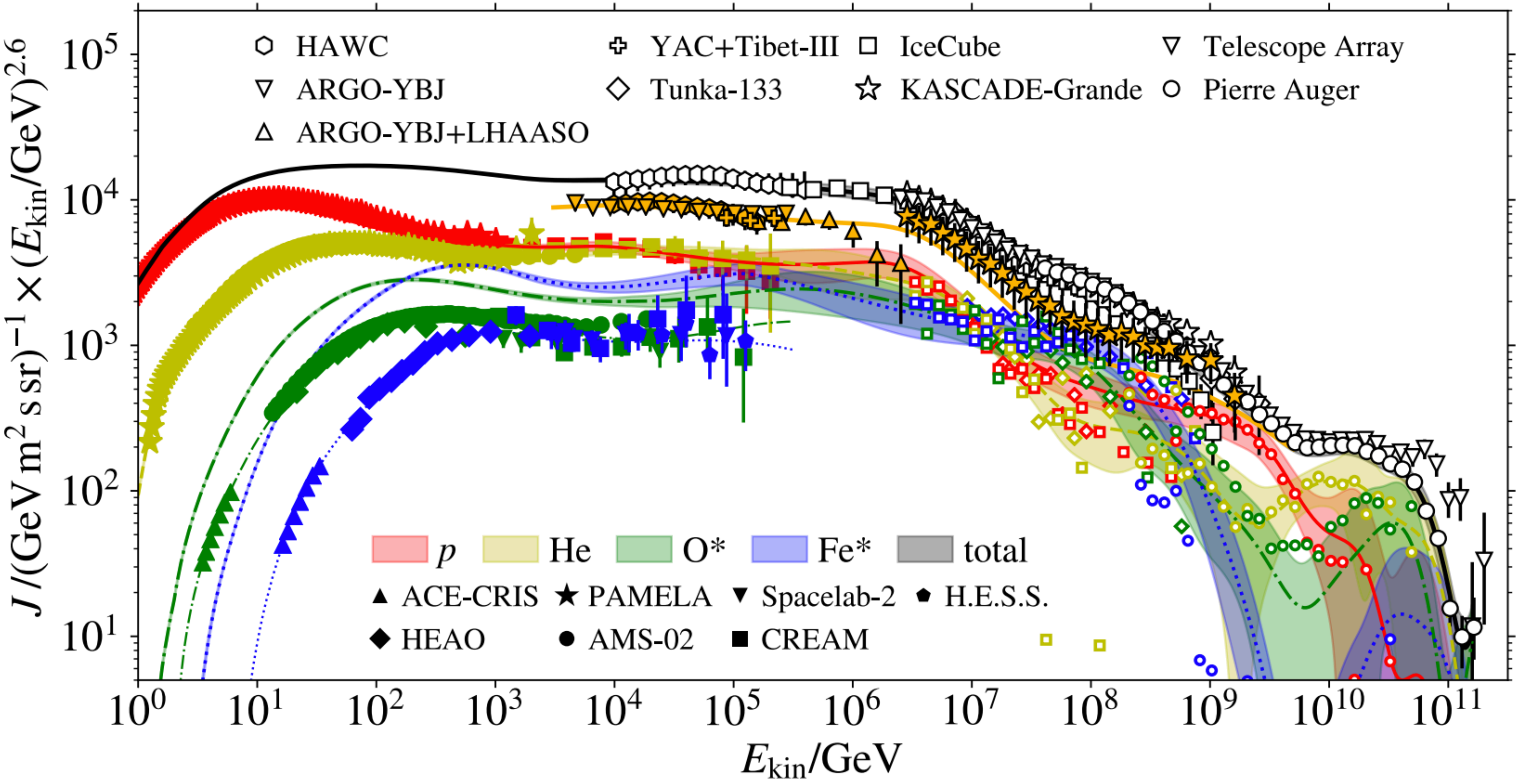
GST:

[T. K. Gaisser, T. Stanev, S. Tilav, Front. Phys. China 8 (2013)]



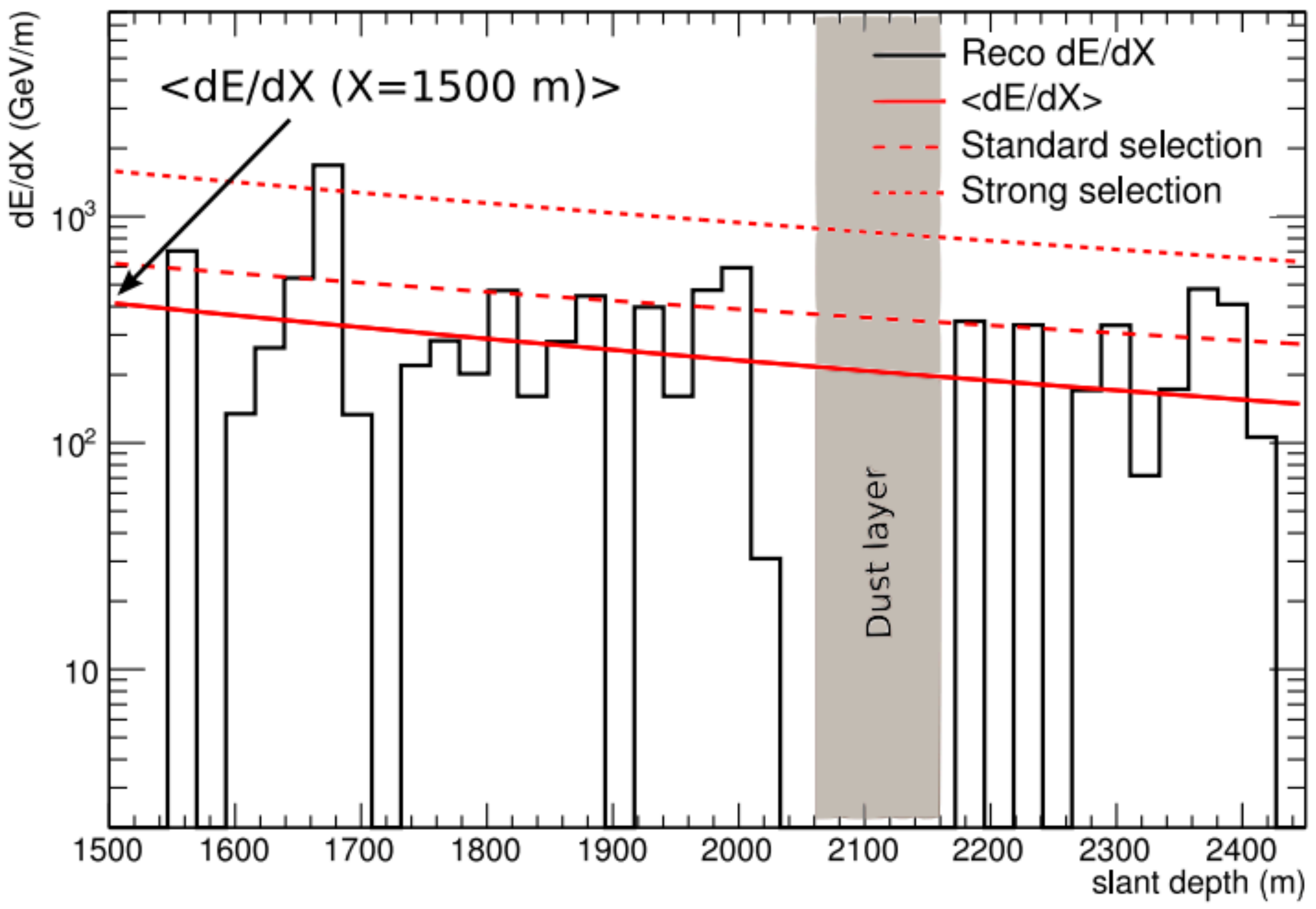
CR Mass Composition

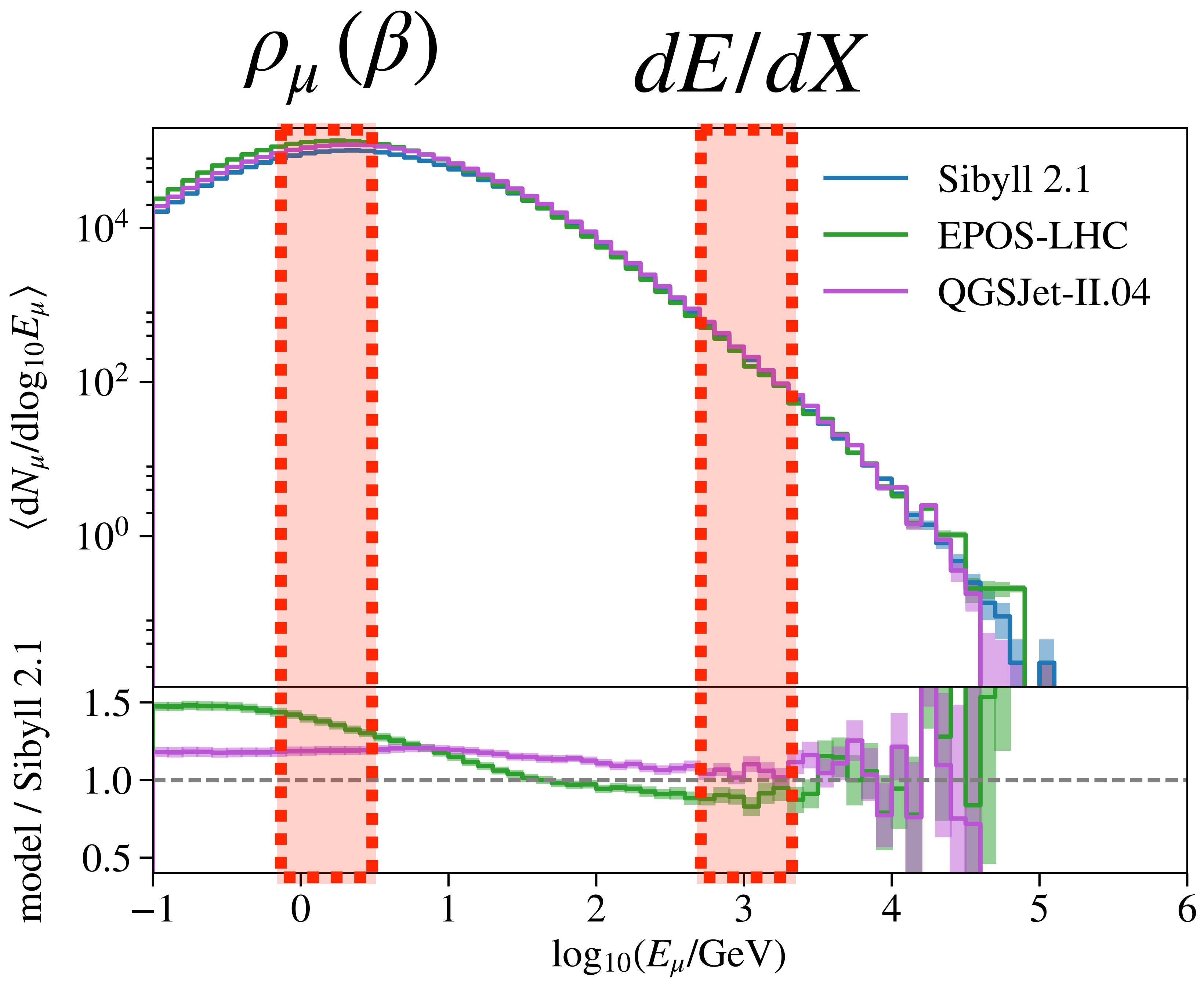
- Empirical Global Spline Fit (GSF) flux model
  [H.P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser, F. Riehn, T. Stanev, PoS ICRC2017 (2017) 533]

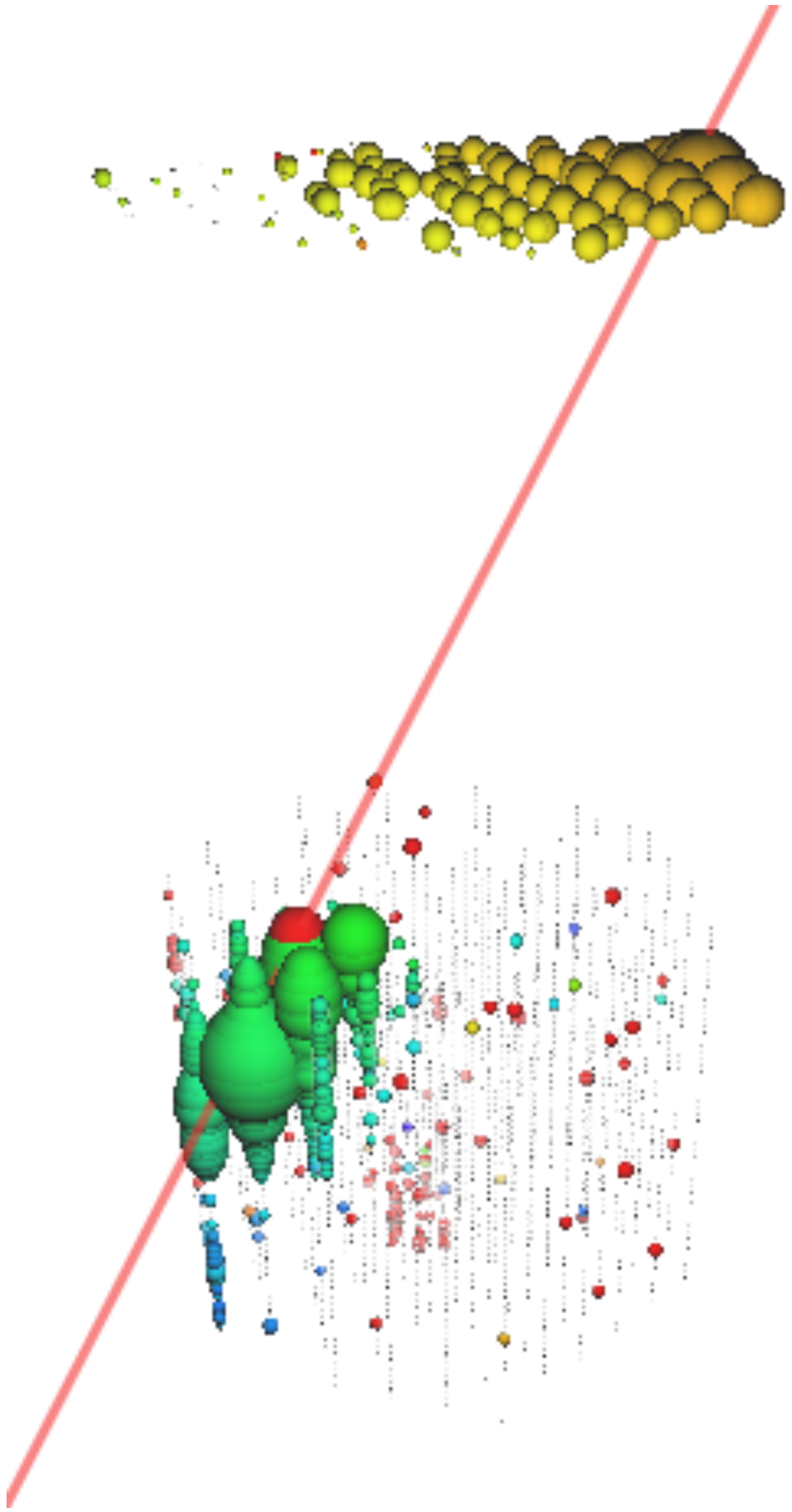


Hybrid Muon Measurements

- Preliminary studies of three muon estimators:
  - Muon density, ρ_μ (GeV muons)
  - Deposited in-ice energy, dE/dX (TeV muons)
  - LDF slope parameter, β (GeV muons + em)
- Analysis ongoing…

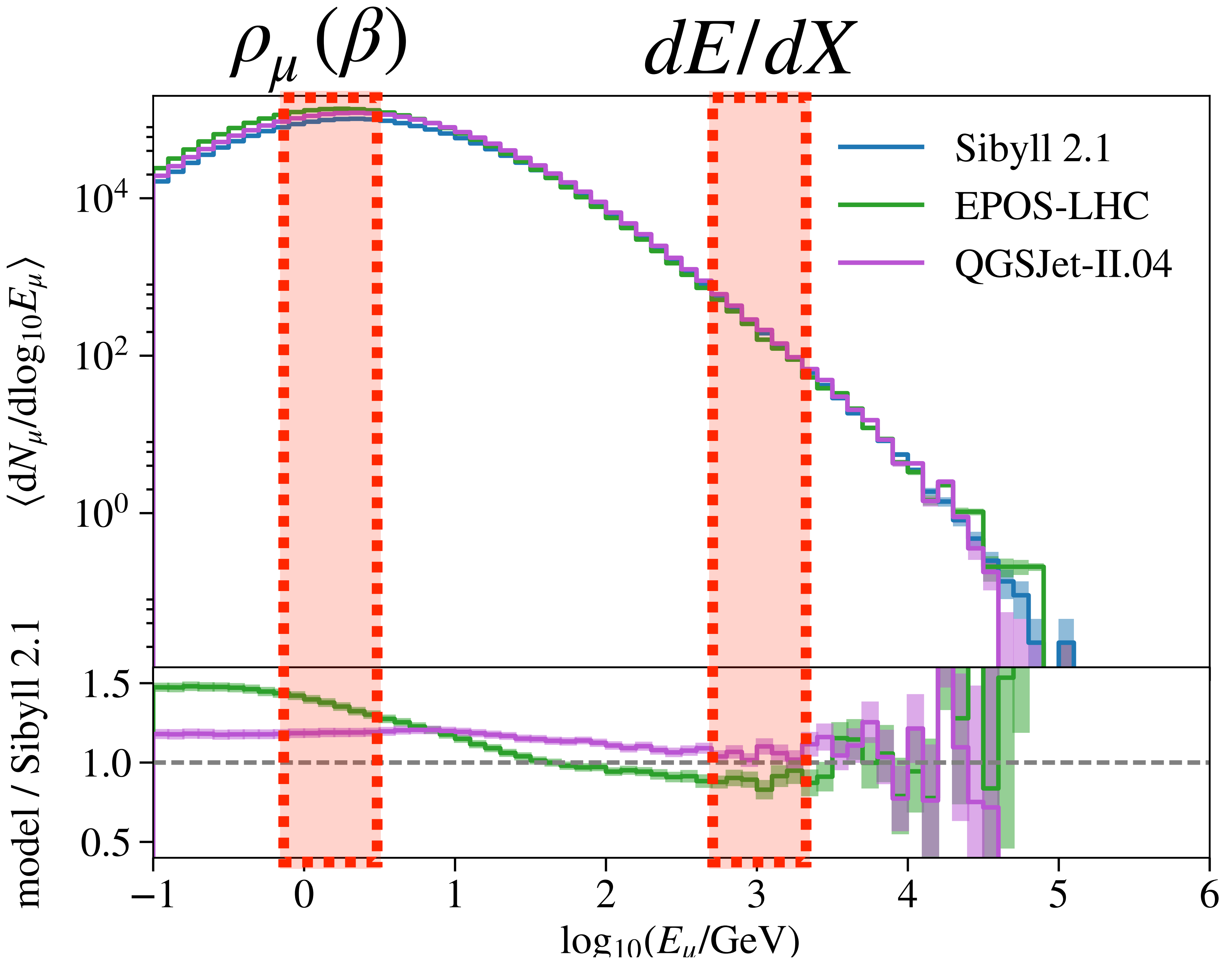


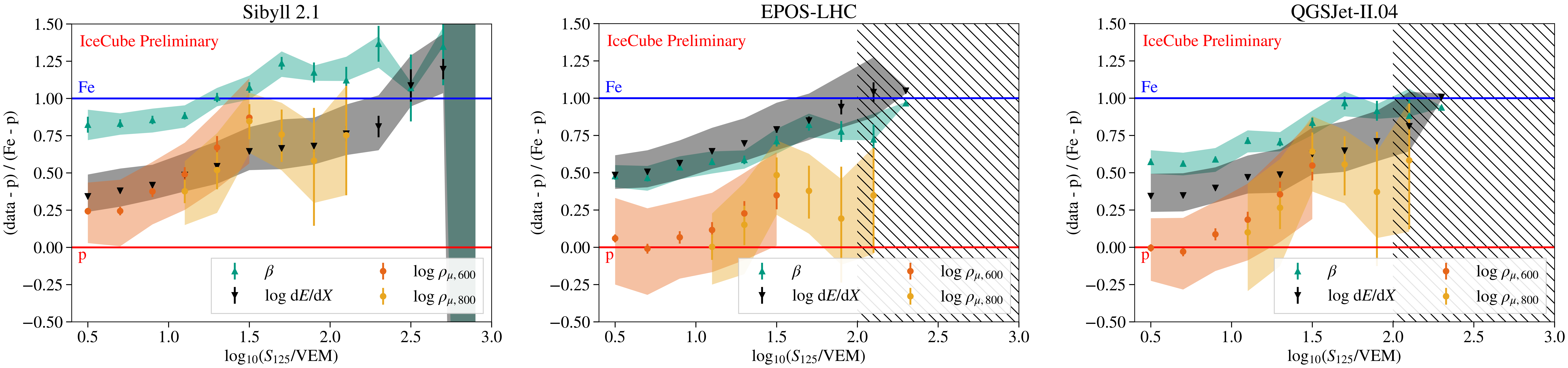




Hybrid Muon Measurements

- Very preliminary results!
- Inconsistencies within each model observed!
- However, no obvious discrepancies of TeV muons observed and exotic models (e.g. BSM) are thus disfavored
- Improved analysis ongoing… (more tomorrow)



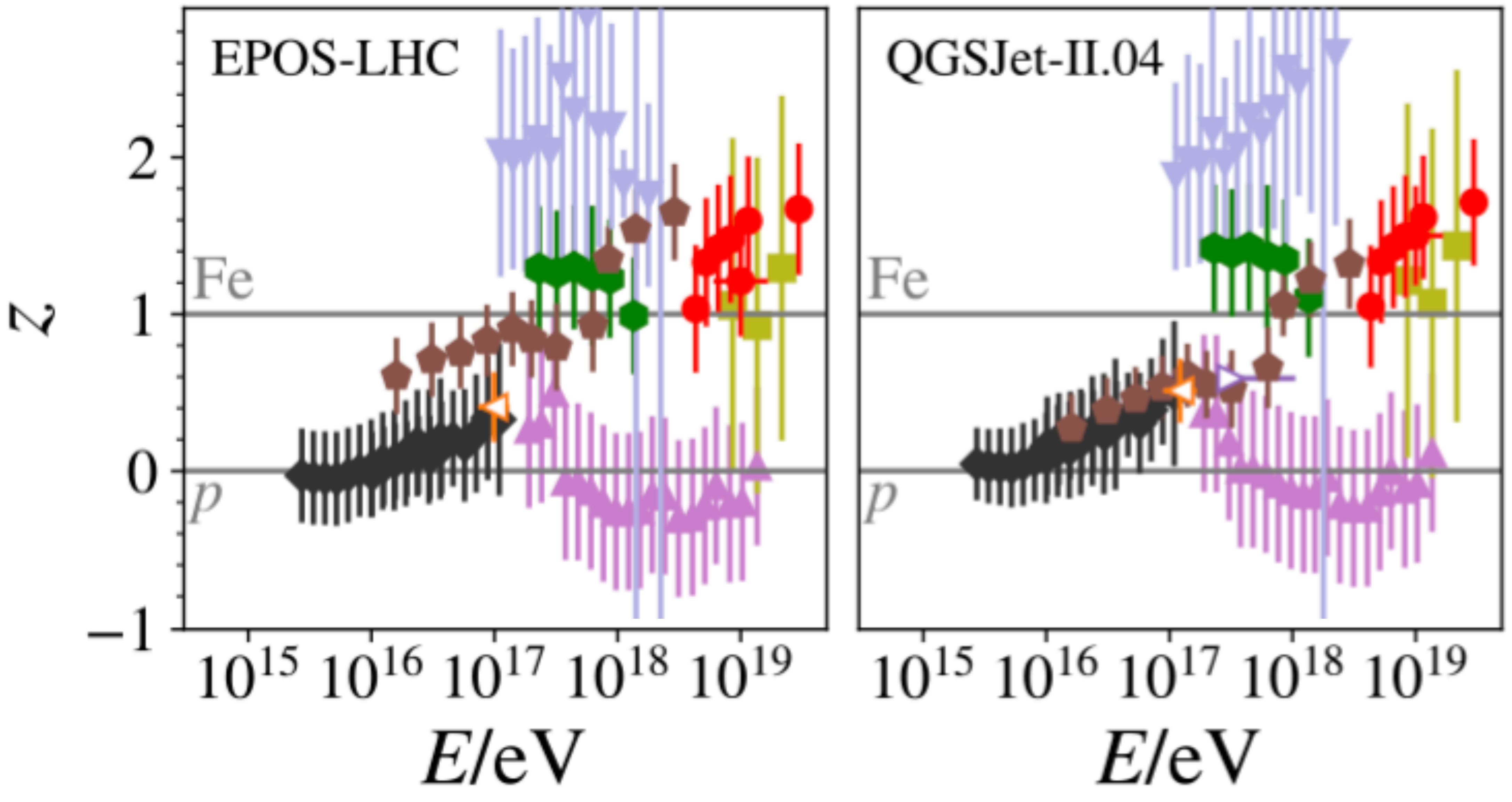


[S. Verpoest, D. Soldin, S. De Ridder et al., PoS ICRC2021 (2021) 357]

Current Analysis Limitations

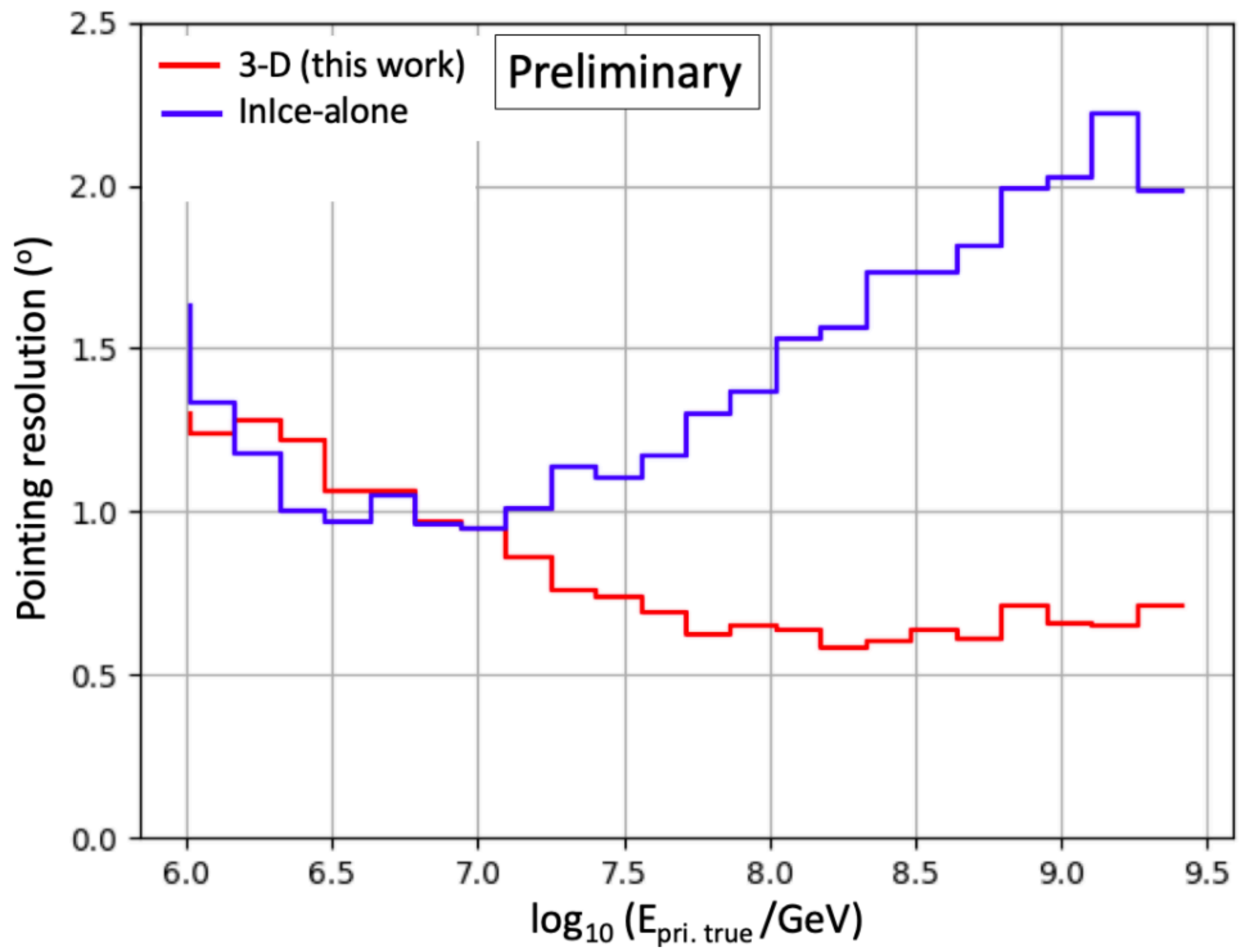
- Hybrid GeV/TeV muon measurements:
  - Maximum CR energies of ~120 PeV
  - Shower contained in IceTop array
  - Near-vertical showers, i.e. $\theta < 18°$
  - GeV muons at 600 m and 800 m
  - TeV muon multiplicity estimated from reconstructed energy loss at 1500 m
  - Statistical analysis only, i.e. no event-by-event GeV muon information
  - Large in-ice uncertainties, mainly due to light propagation
- Improvements?

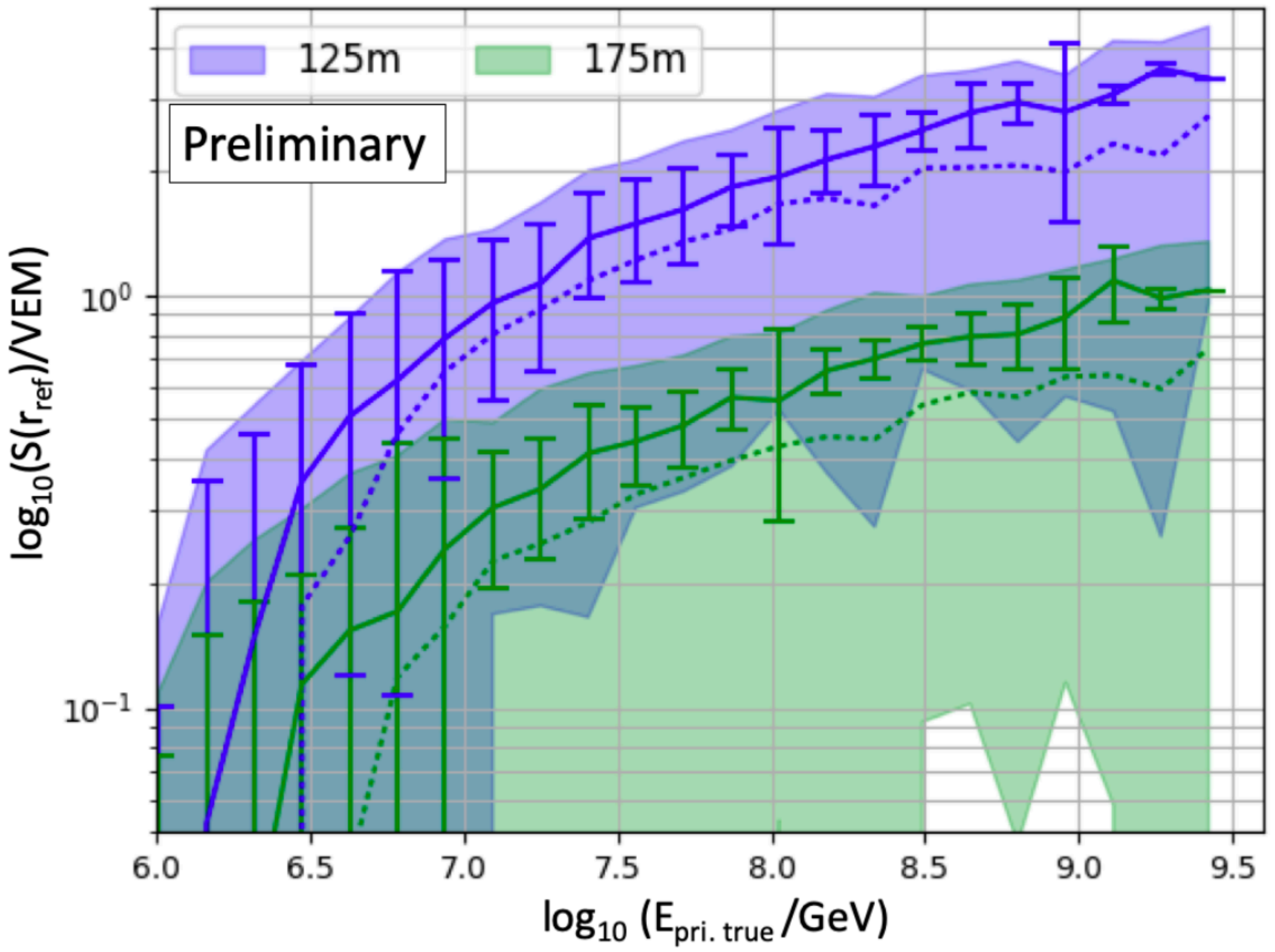
[D. Soldin et al., PoS ICRC2021 (2021) 349]



Improved EAS Reconstruction

- <u>Combined EAS likelihood reconstruction:</u>
  - Uses information from both detector components
  - Simultaneous fit of event trajectory, surface LDF, and shower front curvature
  - Allows reconstruction of un-contained events
  - <u>Extension towards higher inclinations!</u>
  - Extension towards higher energies?
  - Energy estimation in progress
    - $\log_{10}(S_{ref})$ vs. $\log_{10}(E_0)$ becomes non-linear
    - Further studies needed!
    - Machine learning approach?

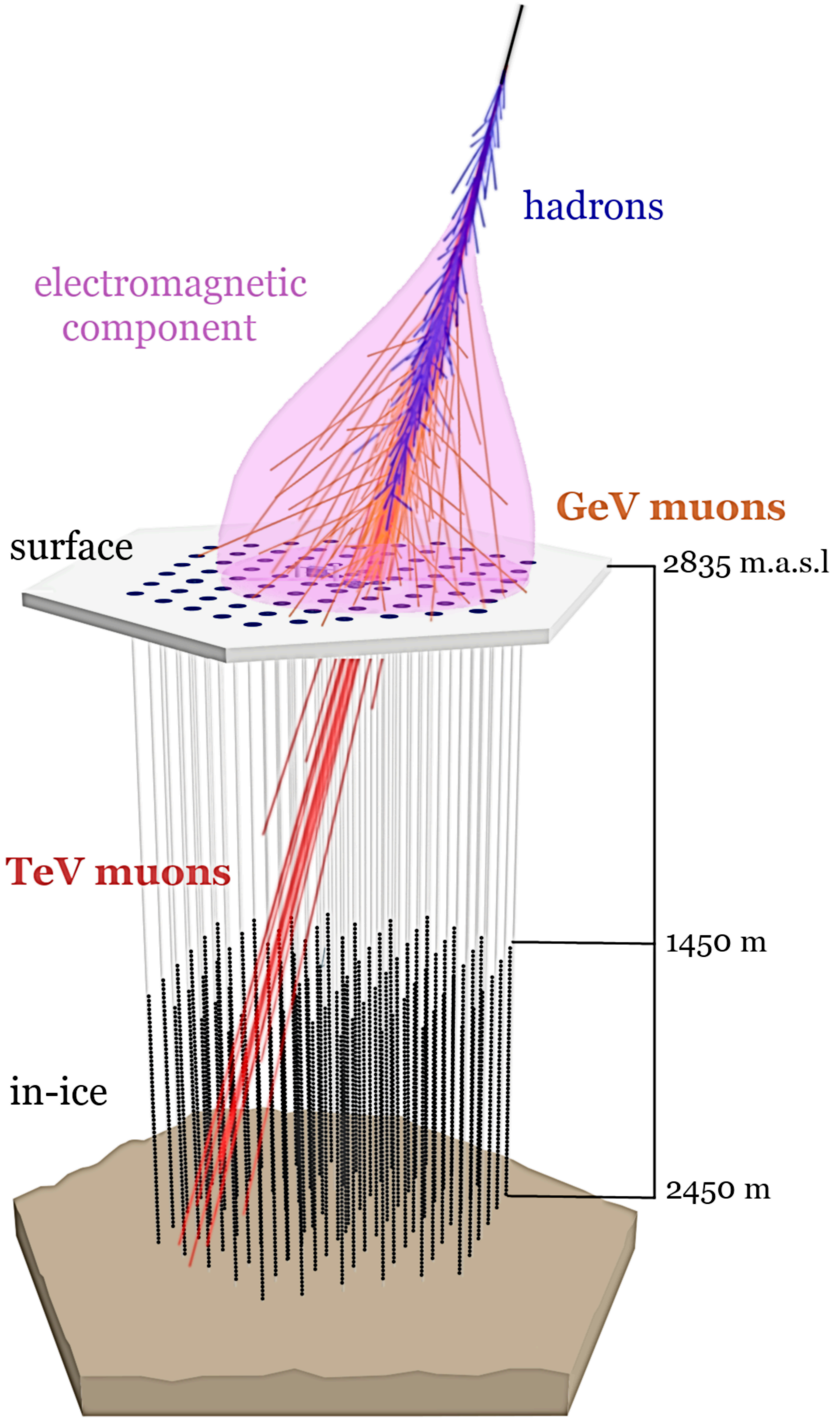




[X. Bai, E. Dvorak, J. Gonzale, D. Soldin et al., PoS ICRC2021 (2019) 244]

Improved Muon Estimators

- <u>GeV muon density estimator:</u>
  - Event-by-event reconstruction
    - Muon LDF reconstruction under development
    - Machine learning approaches to be investigated
- <u>TeV muon density estimator:</u>
  - Machine learning methods using energy losses along the track currently under investigation
  - Very promising first results!
  - Further investigations and optimization ongoing
  - Needs more work…



FPF Physics Potential

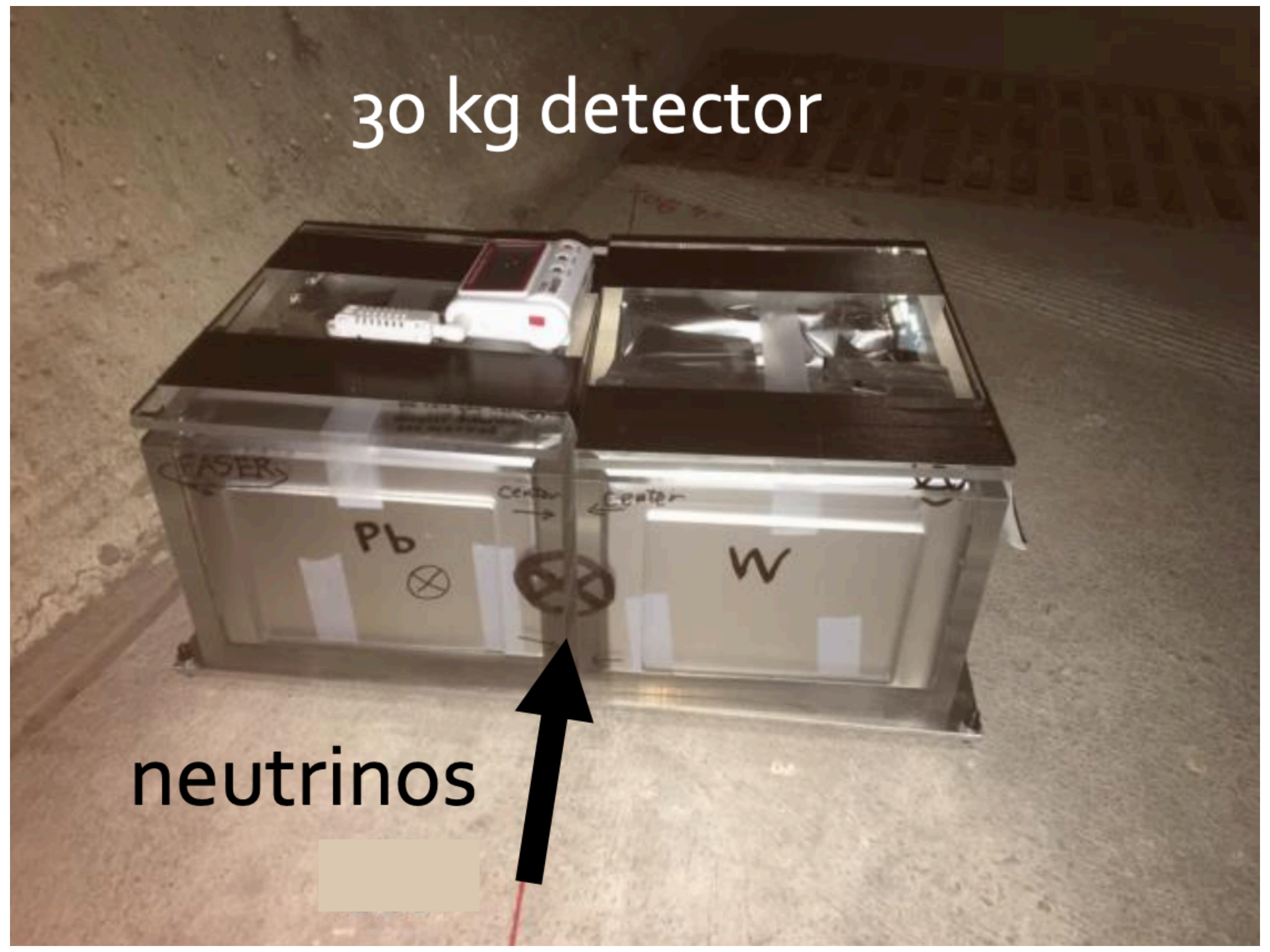
- Example:

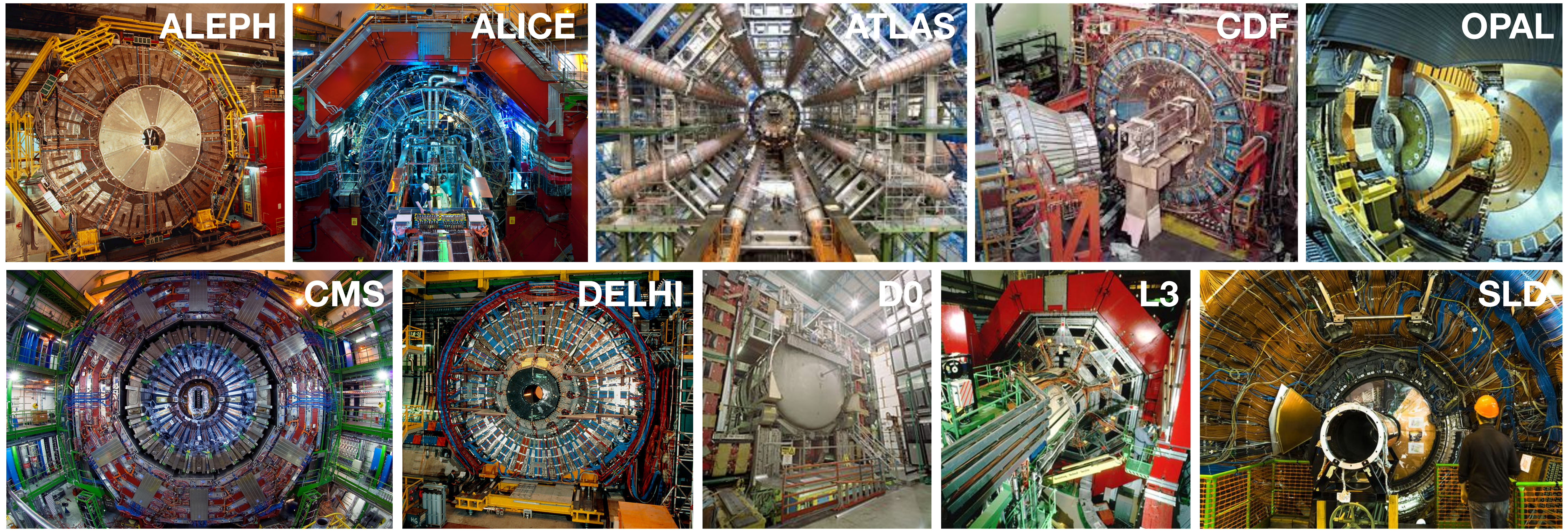
FASERν pilot detector vs. All previous collider experiments

- Suitcase size, 4 weeks of data
- Costs: $0 (recycled parts)
- 6 neutrino candidates

[FASER Collaboration, Phys. Rev. D 104 (2021)]

- Building size, decades of data
- Costs: ~ $\$10^9$
- 0 neutrino candidates





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  - Suitcase size, 4 weeks of data
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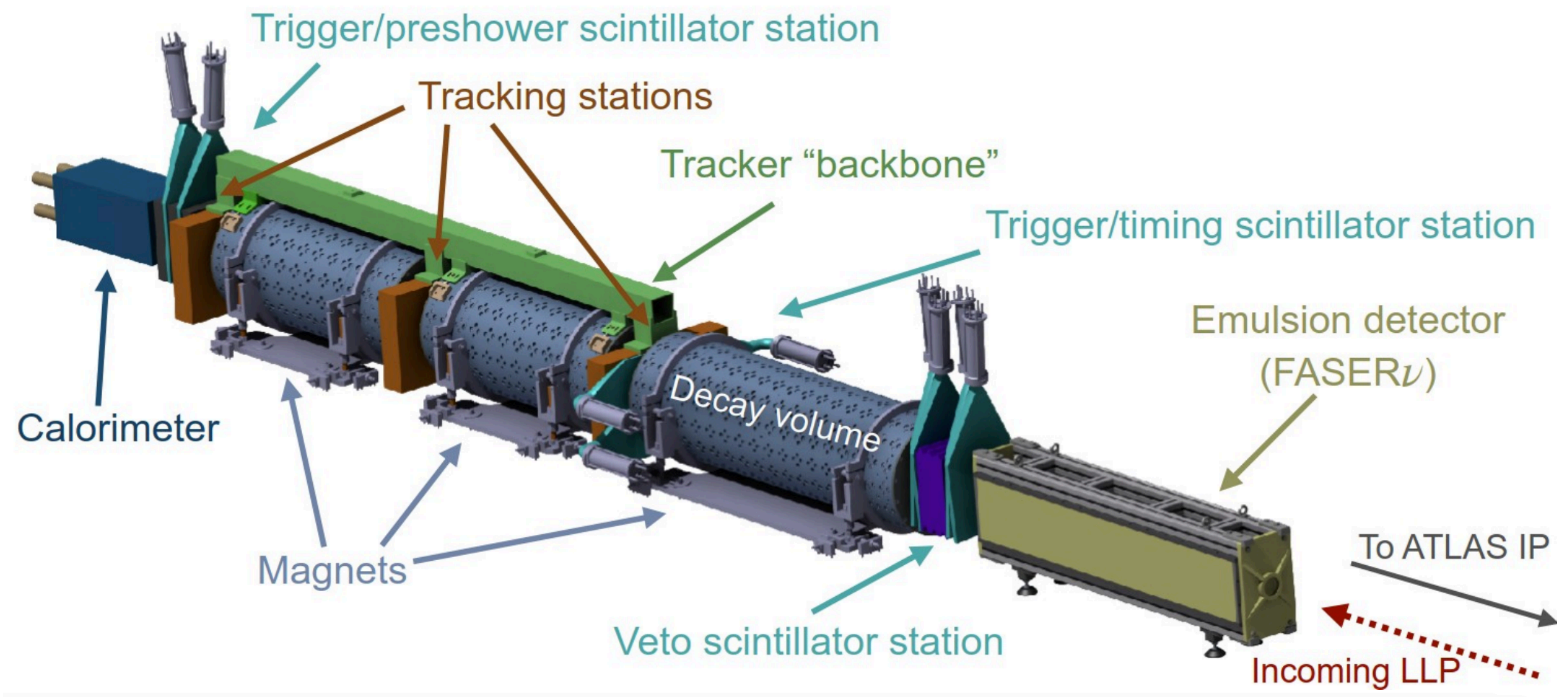
  - 6 neutrino candidates
    [FASER Collaboration, Phys. Rev. D 104 (2021)]

All previous collider experiments:
  - Building size, decades of data
  - Costs: ~ $\$10^9$
  - 0 neutrino candidates

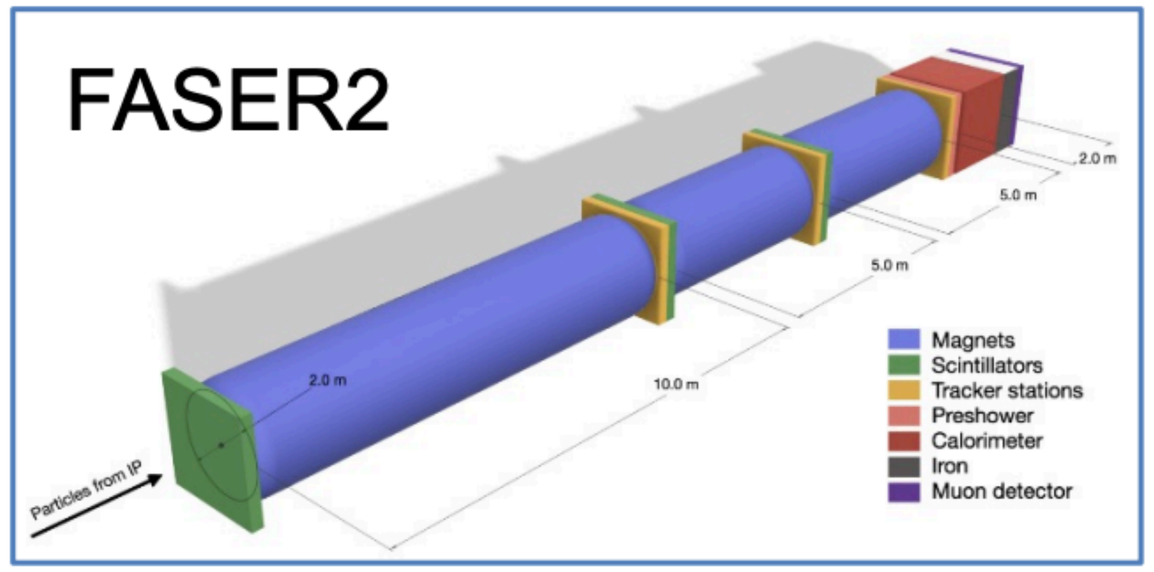
- FASERν years 2022-2024:
  - ~ 10000 ν candidates expected (~ 10^9 muons*)
- Forward Physics Facility:
  - ~ 10^6 ν candidates expected! (~ 10^{12} muons*)

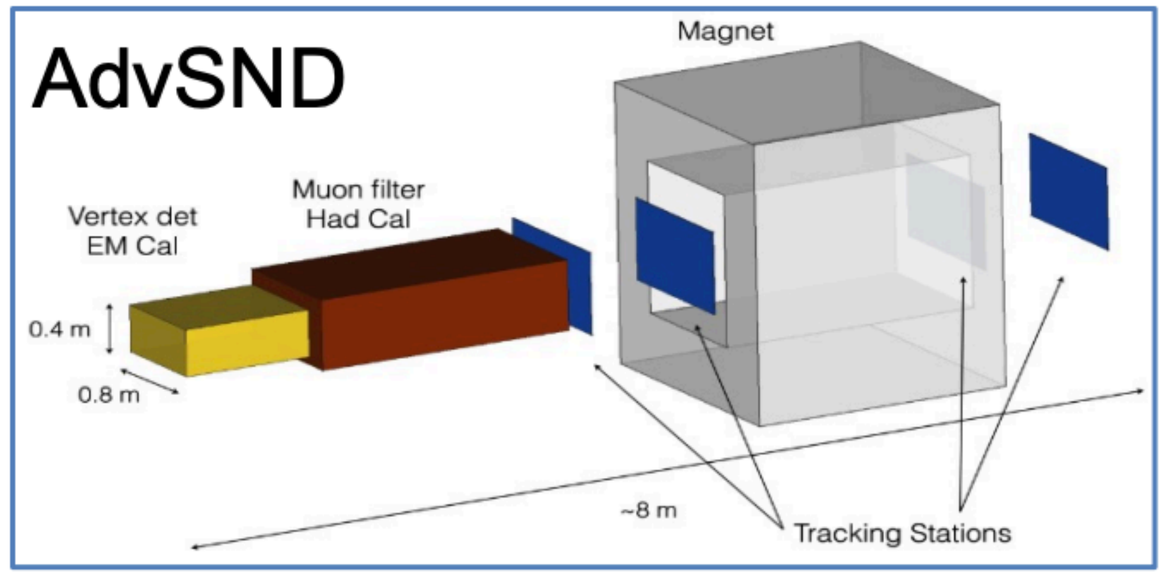


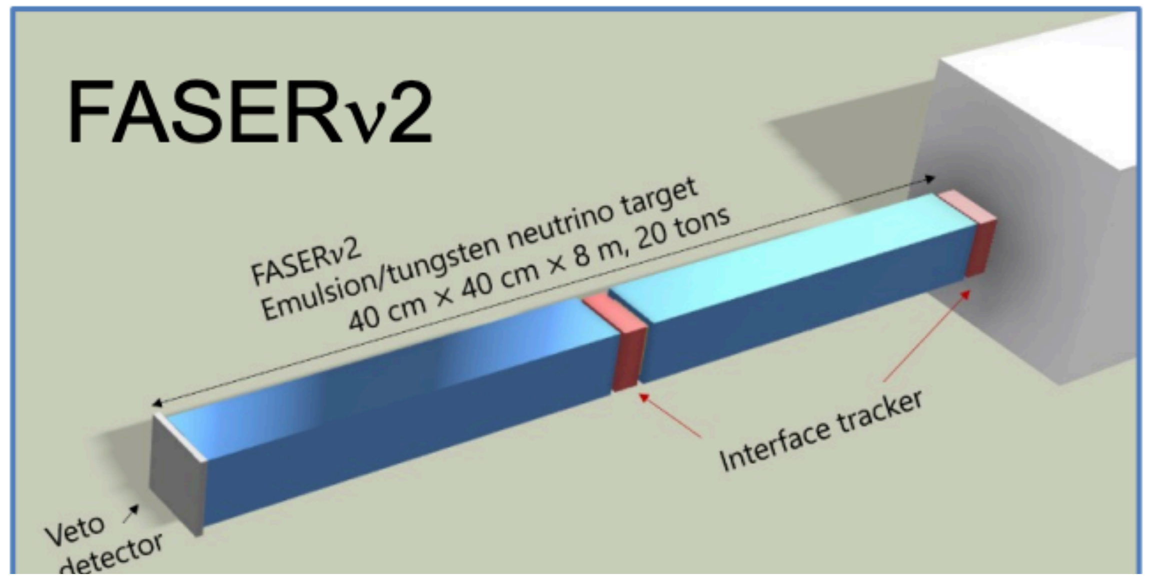
*origin not well understood, further studies needed

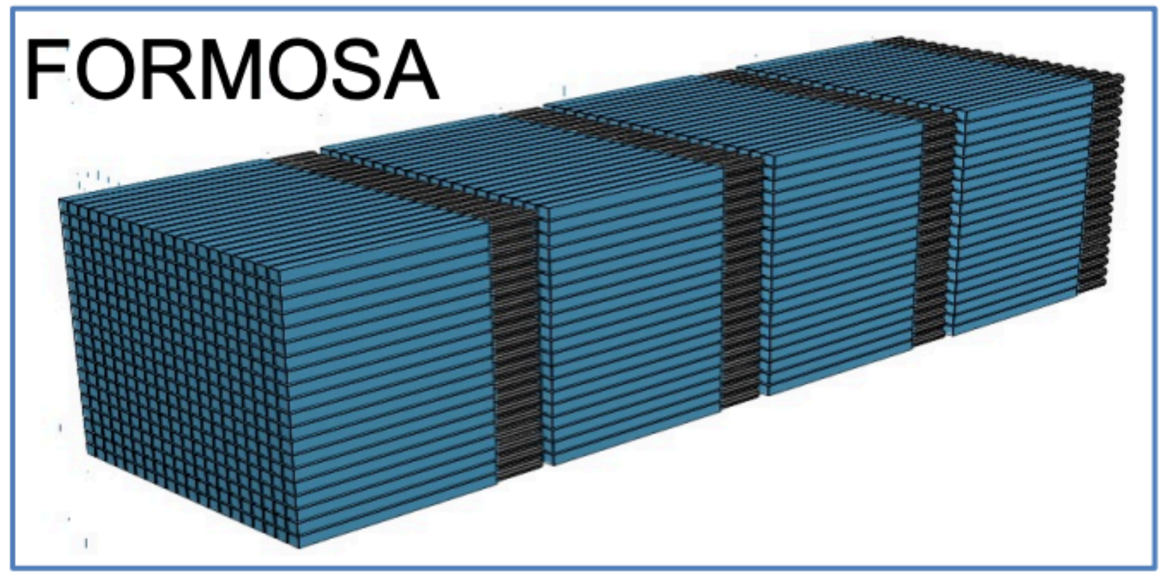
Proposed FPF Experiments

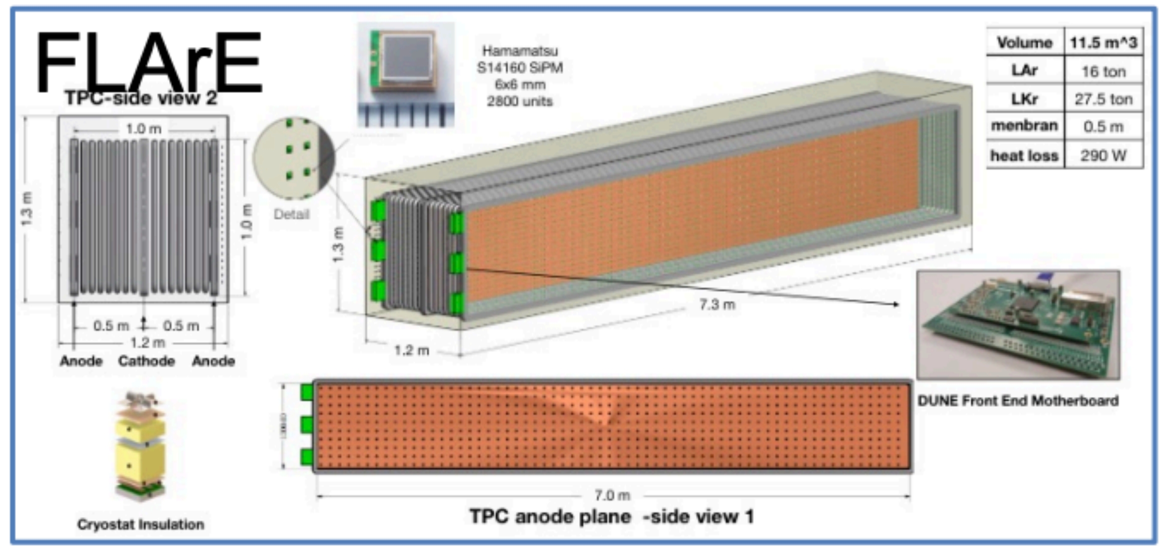
- Five proposed experiments* with different (main) physics goals:
  - FASER2
    - Long-lived particles
  - FASERν2
    - TeV neutrinos
  - AdvSND
    - TeV neutrinos
  - FORMOSA
    - BSM physics: millicharged particles
  - FLArE
    - TeV neutrinos & light dark matter
- Details of detector designs under investigation…









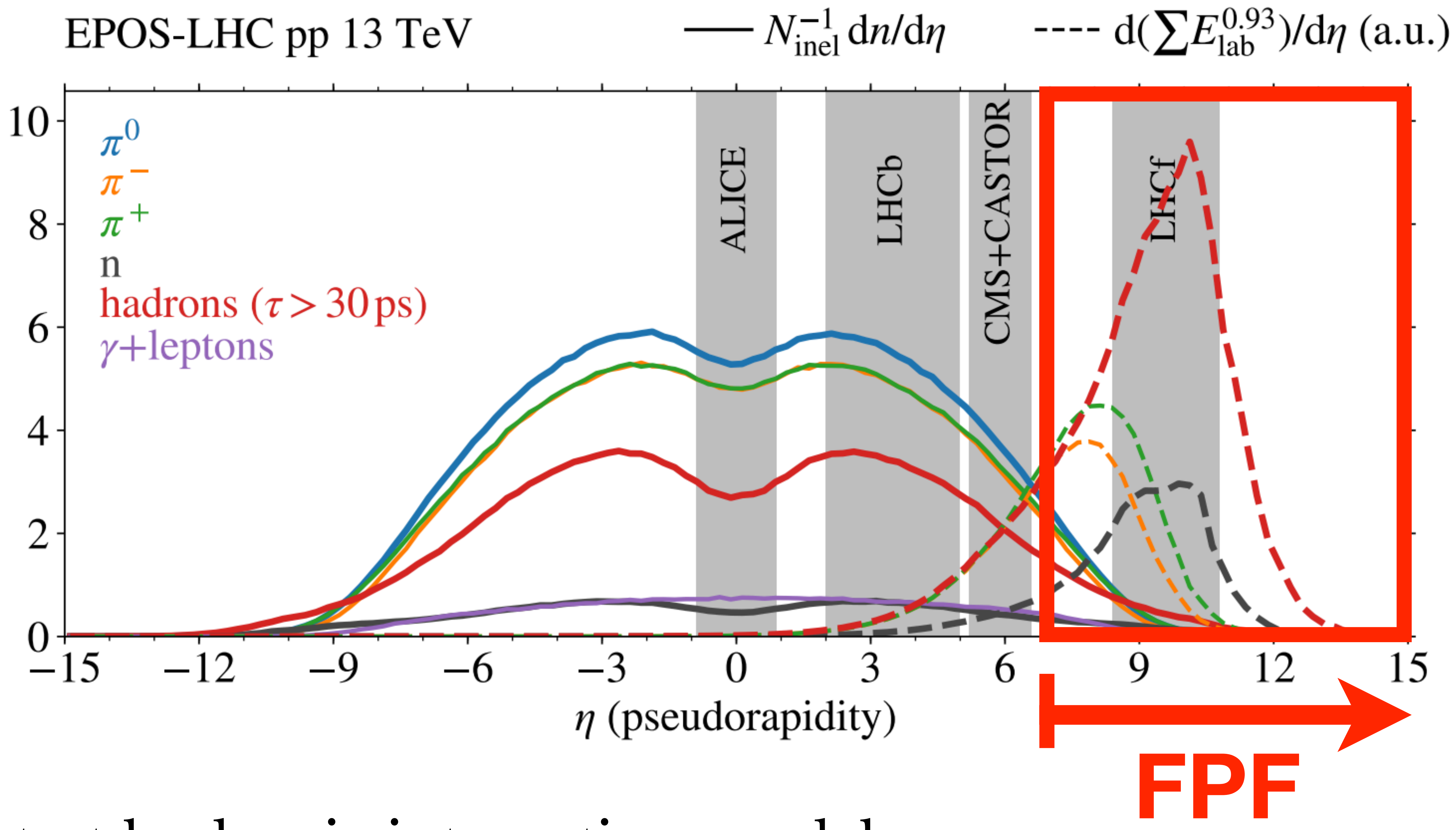


* for a complete description of the experiments, please see the FPF white paper

Motivation I (Snowmass)

- Extensive air showers:
  - Particle production in the far-forward region
  - Low momentum transfer
  - Non-perturbative regime
  - Complex particle composition
  - Energies range over many orders of magnitude
- Modeling of particle interactions based on phenomenological models developed for EAS simulations

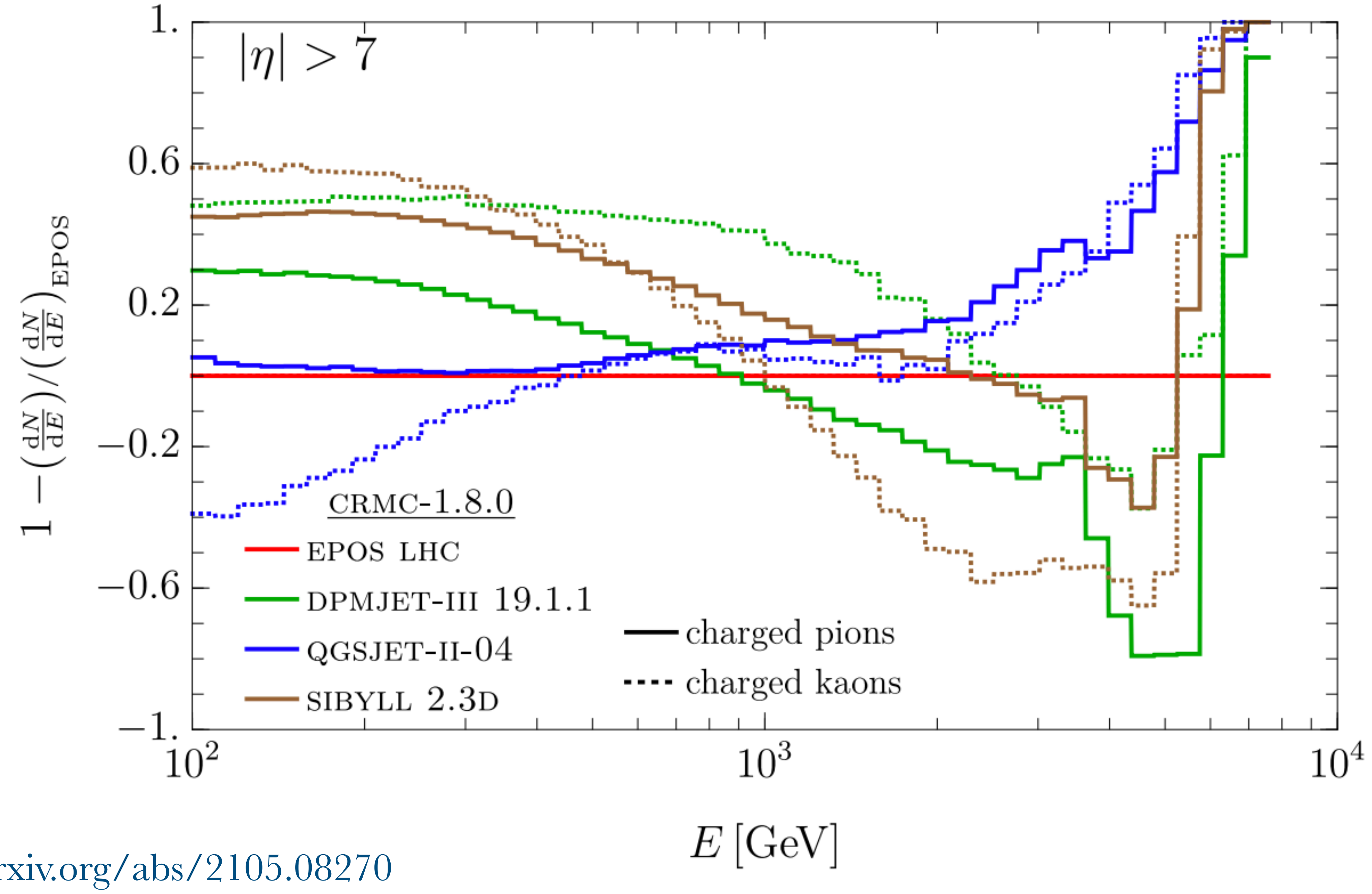
[J. Albrecht et al., Astrophys. Space Sci. 367 (2022)]



- FPF will provide unique opportunities to test hadronic interaction models

WG3 Science Topics

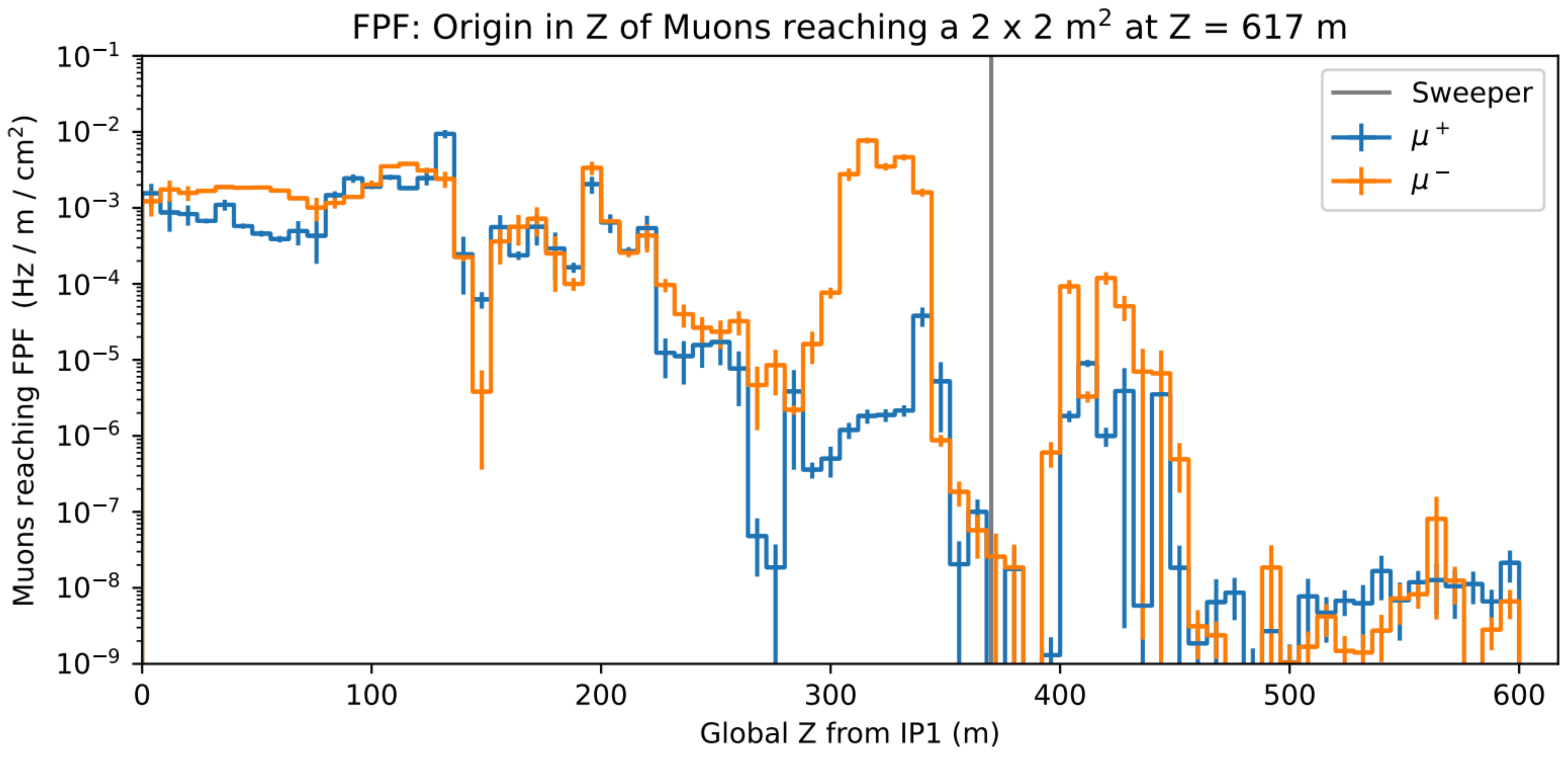
- Neutrino fluxes at the FPF:
  - Ratio of electron and muon neutrinos is a proxy for the ratio of charged pions and kaons
  - Electron and muon neutrino fluxes populate different energy regions which will help to disentangle them
  - Neutrinos from pion and kaon decays have different rapidity distributions which will help to disentangle them
  - Fast simulation package* available! (F. Kling)
  - Further studies needed:
    - MC based on different generators
    - Neutrino fluxes in different detectors
    - Tests of dedicated strangeness (muon) enhancement models



* Simulation code available at: https://github.com/KlingFelix/FastNeutrinoFluxSimulation, see also https://arxiv.org/abs/2105.08270

WG3 Science Topics

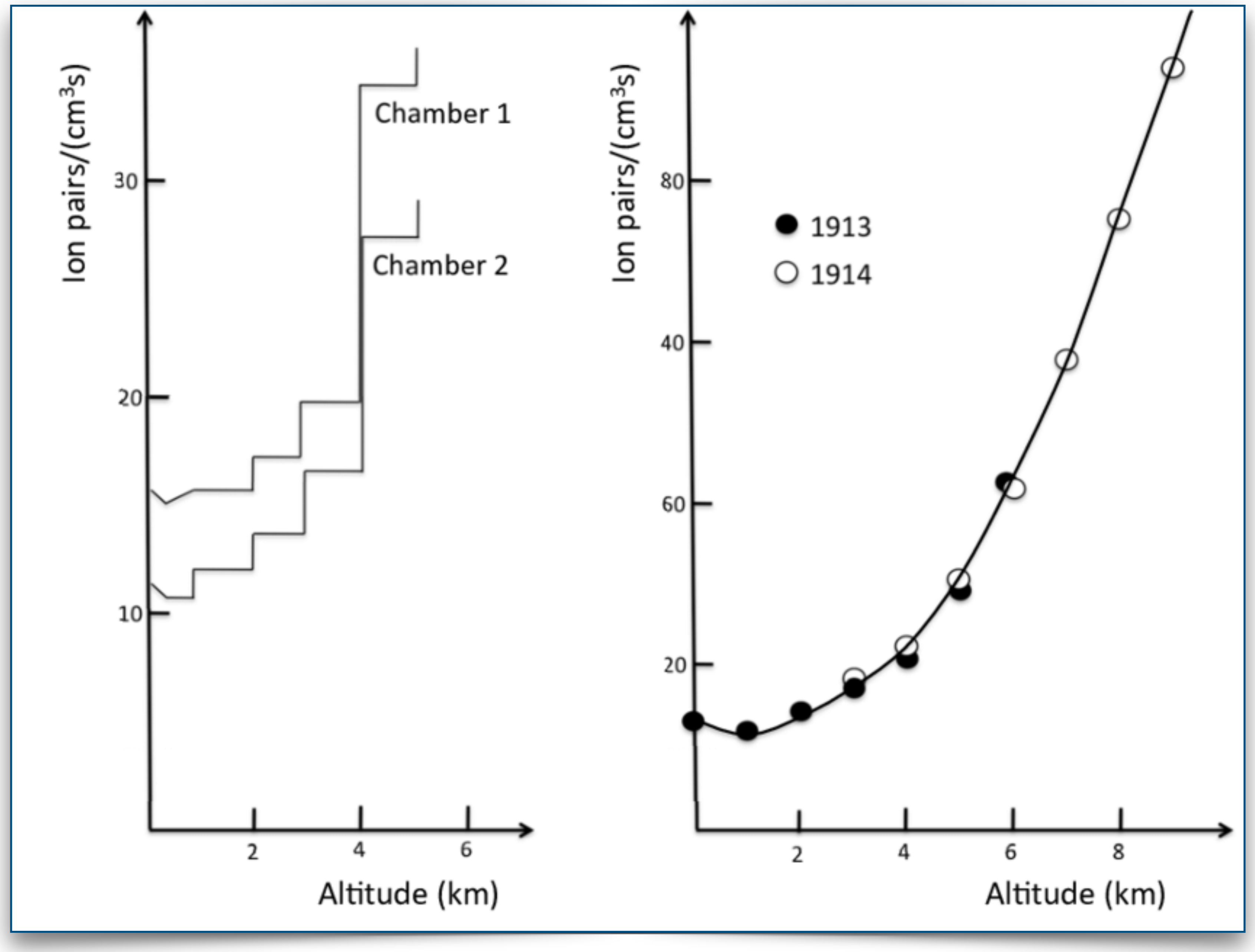
- Muon fluxes at the FPF:
  - Large muon flux at the FPF, e.g. ~1 Hz per cm^2 in FASER
  - Challenging to study as the origin of production is uncertain…
  - BDSIM/Geant4 simulations available, including full muon history (L. Nevay)
  - Open questions:
    - Can we use muons to study light hadron production?
    - Can we measure the muon charge ratio?
    - Do sweeper magnets help our physics case?
    - What can we learn from muon fluxes measured at FASER and SND@LHC?
  - Dedicated studies of the muon yield at the FPF (incl. full muon history) needed!



Cosmic Rays

[picture credit: www.wikipedia.org]

- D. Pacini (1910):
  - Ionization in the atmosphere is due to extra-terrestrial radiation
- V. Hess (1911/12, Nobel prize 1936):
  - First prove that radiation is of extra-terrestrial origin
- Confirmation by W. Kolhörster, 1913
- Many experiments followed over the last 100 years…
  - Comic rays (CRs) are charged particles, mostly protons, which reach Earth from Space
  - CRs can have extremely high energies…



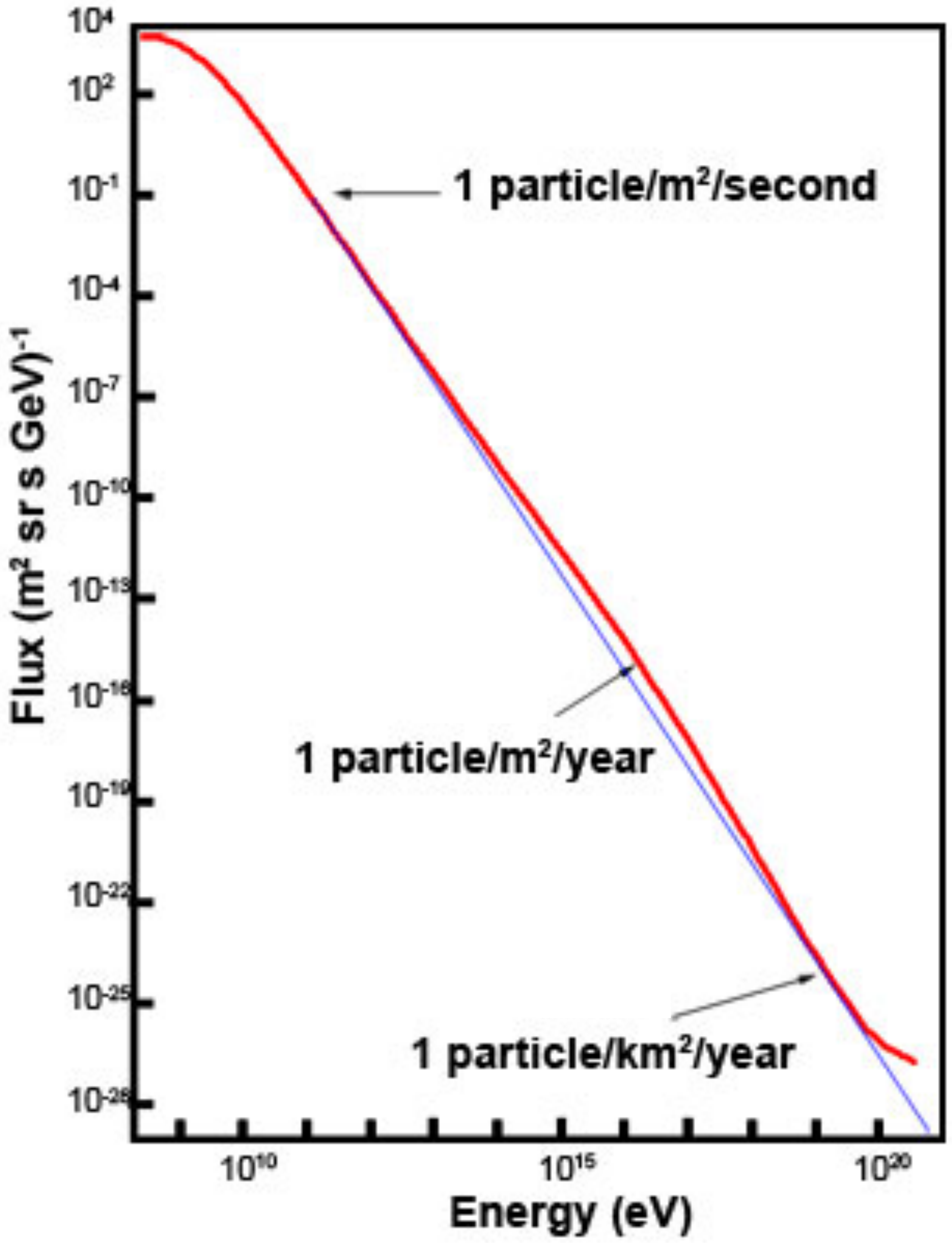
Cosmic Rays

- Today, cosmic rays with energies, E_0, up to a few ~100 EeV have been observed
- Very steep CR spectrum, measured over more than 10 orders of magnitude in energy
- Simple first-order power-law approximation:

$$\frac{d\Phi}{dE_0} \simeq 1.8 \cdot E_0^{-\gamma} \frac{\text{nucleons}}{\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV/A}}$$

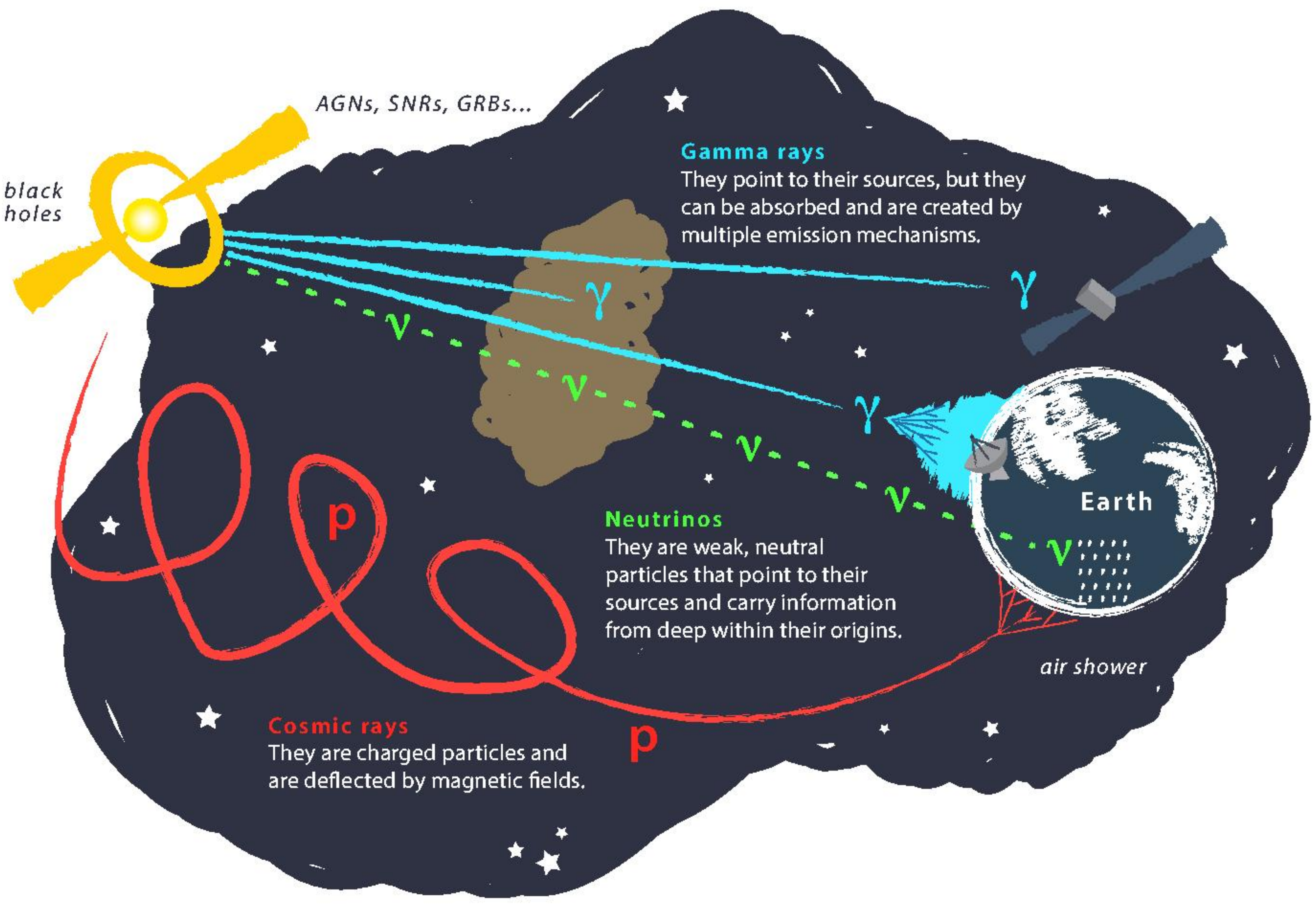
with $\gamma \simeq 2.7$

- Many open questions about the origin and nature of cosmic rays remain open until today!



Open Questions

- What are the sources of high-energy CRs?
- What are the acceleration mechanisms of CRs?
- What is their mass composition? (later more…)
- What is the origin of features observed in the CR spectrum? (later more…)
- …



Can only be answered with precise multimessenger observations!

Open Questions

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- What are the acceleration mechanisms of CRs?
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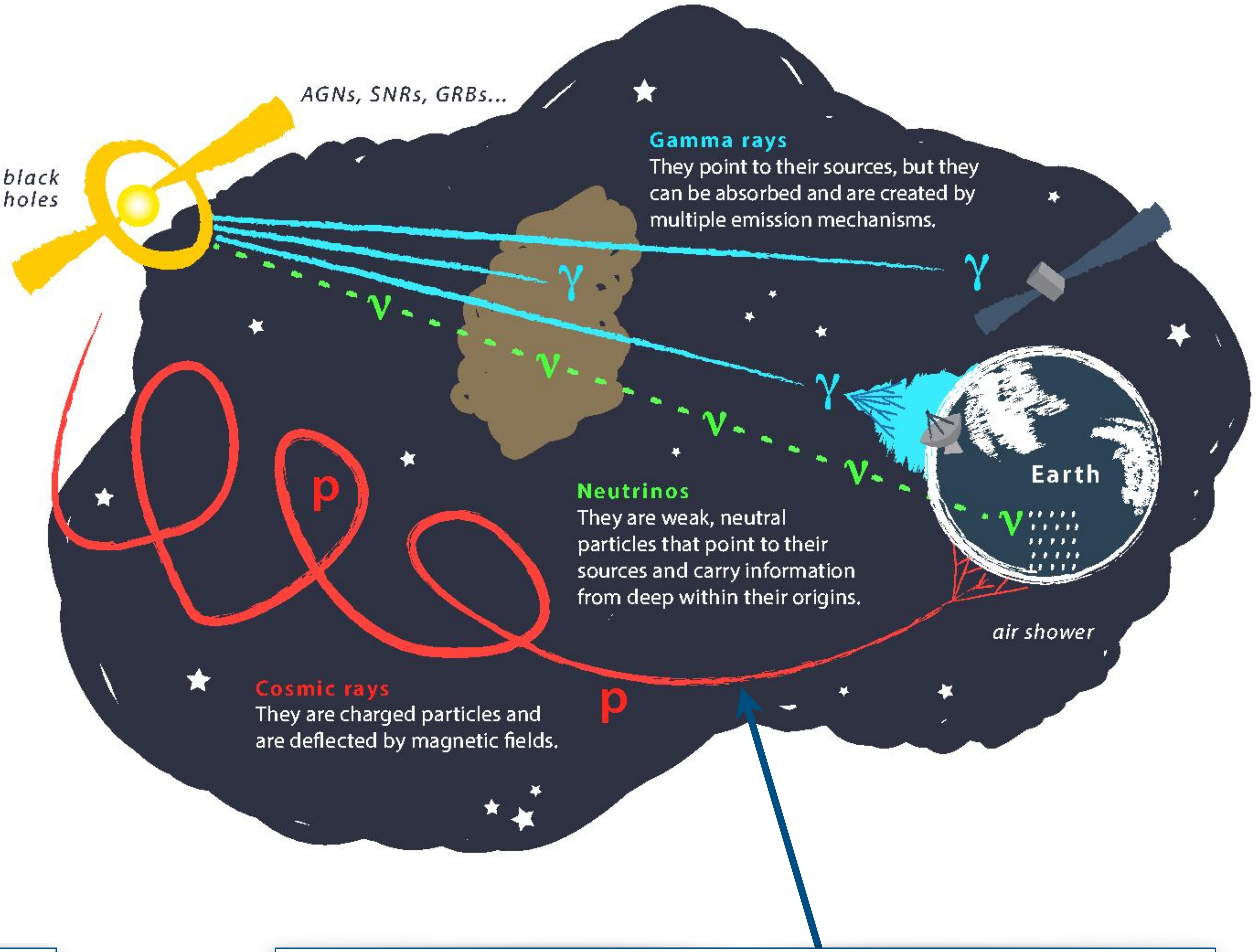
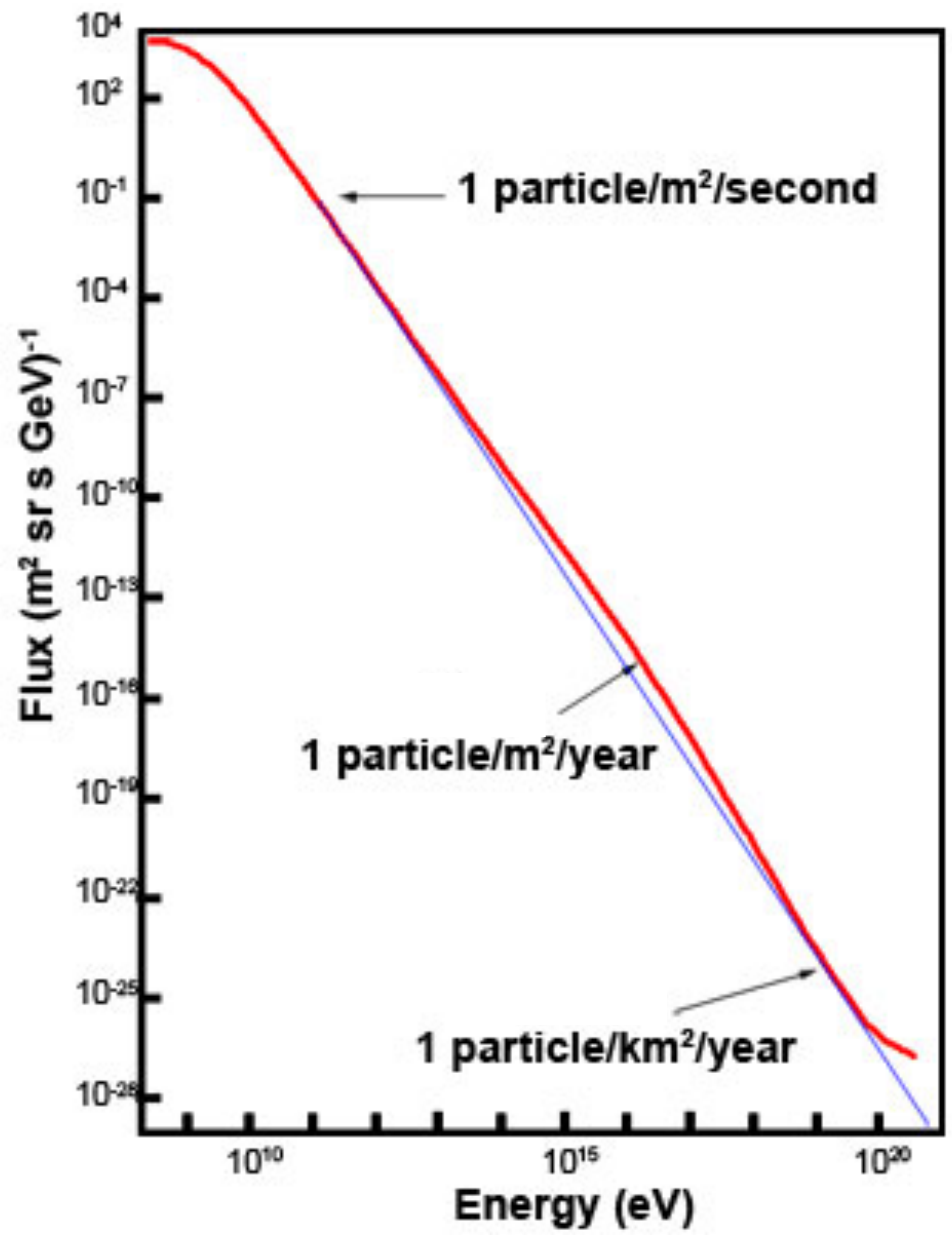
- What is the origin of features observed in the CR spectrum? (later more…)
- …



Can only be answered with precise multimessenger observations!

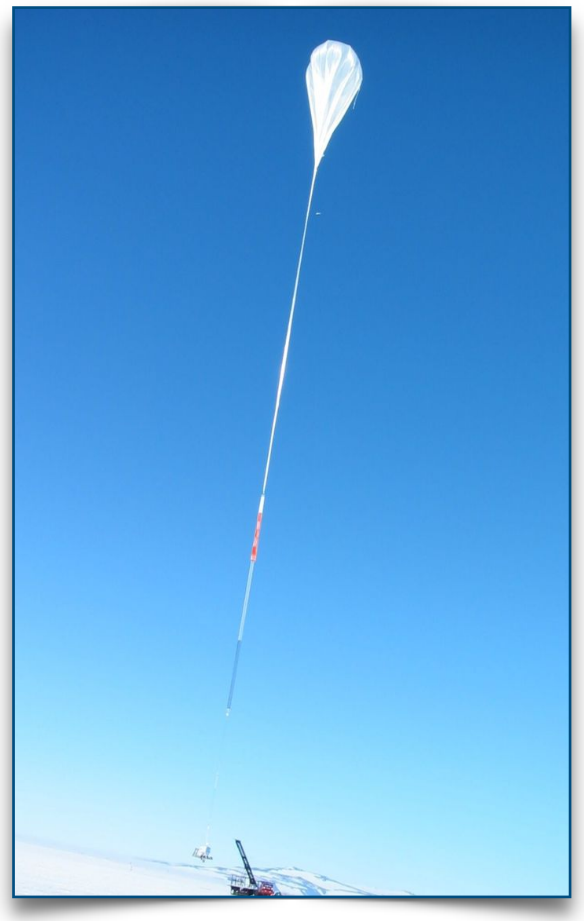
This talk:
Cosmic Rays

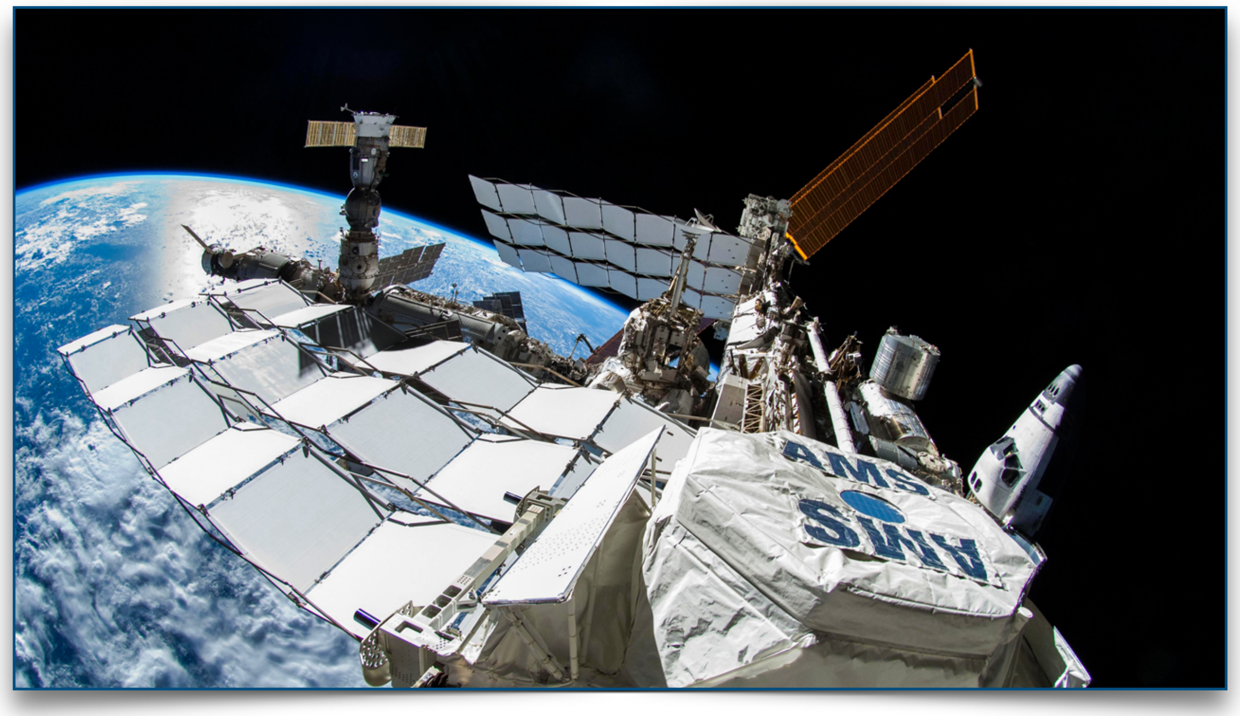
How to Detect Cosmic Rays?

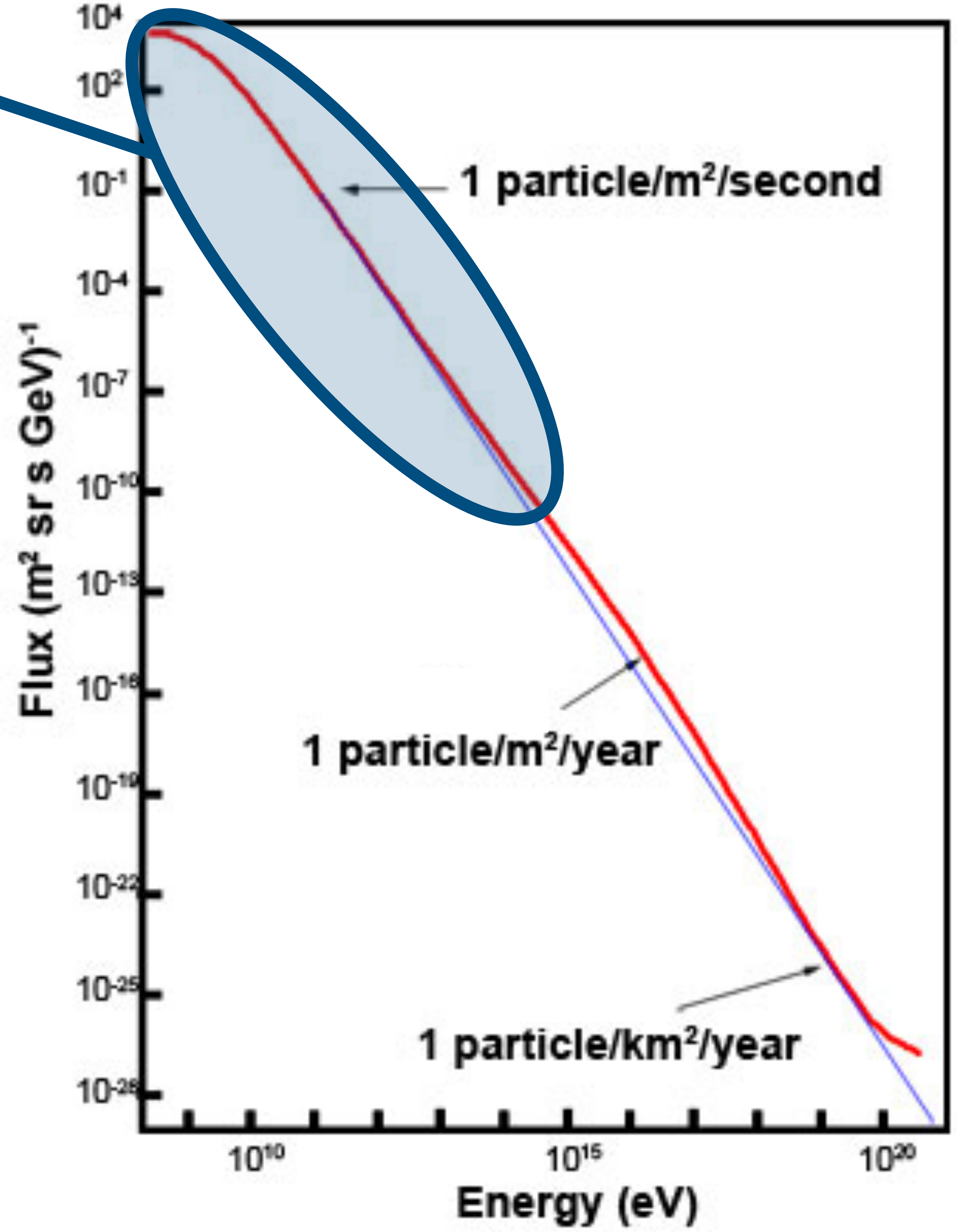


How to Detect Cosmic Rays?

Direct measurements (balloon / space)







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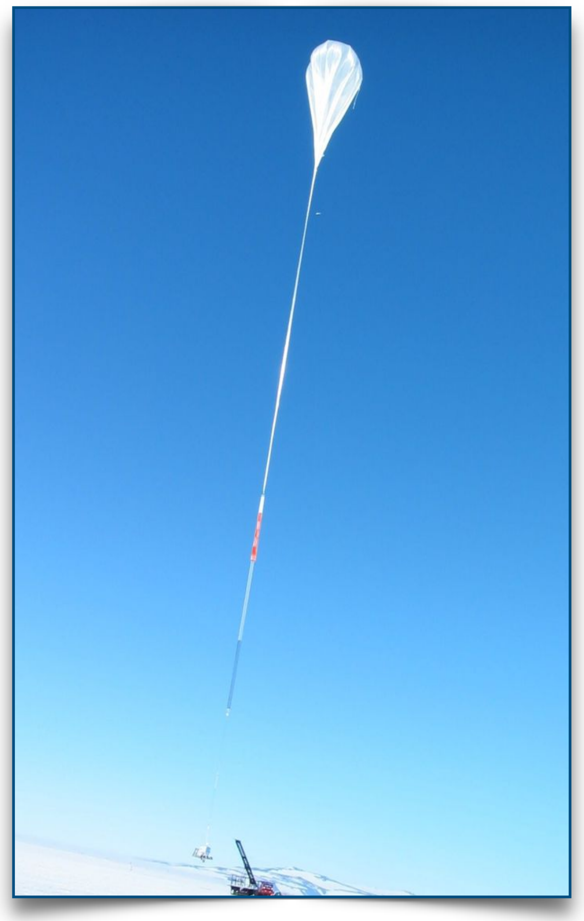
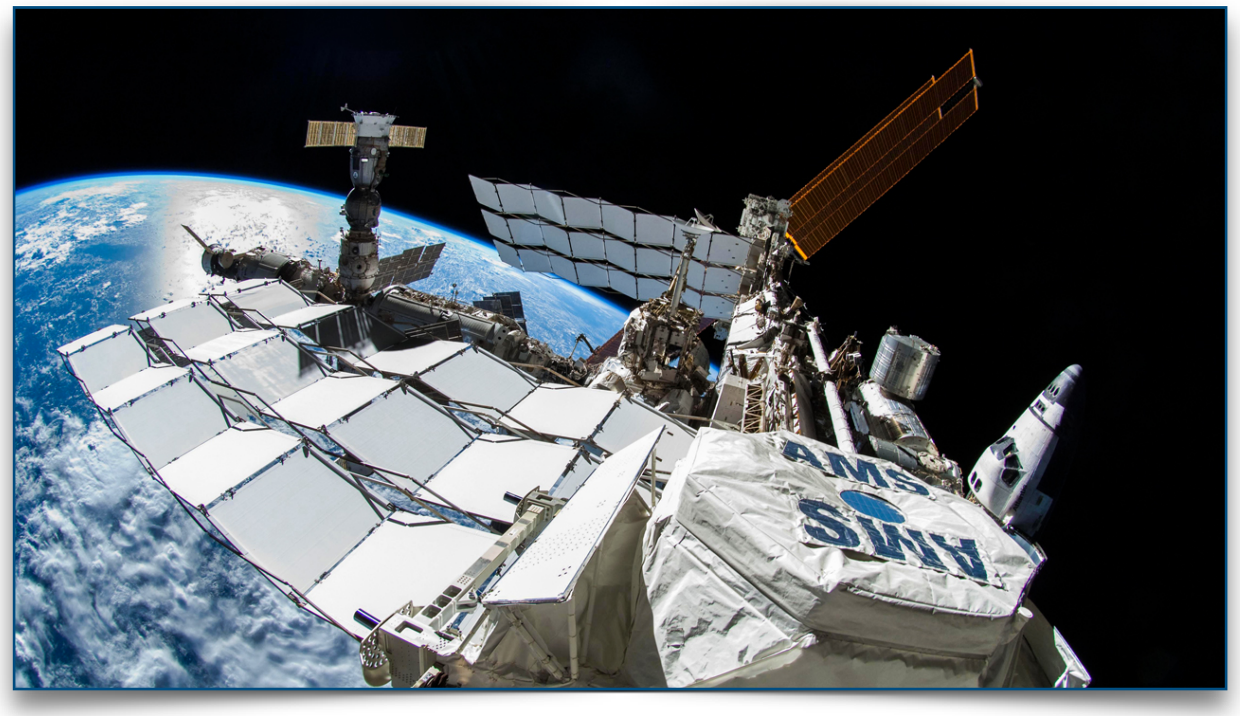
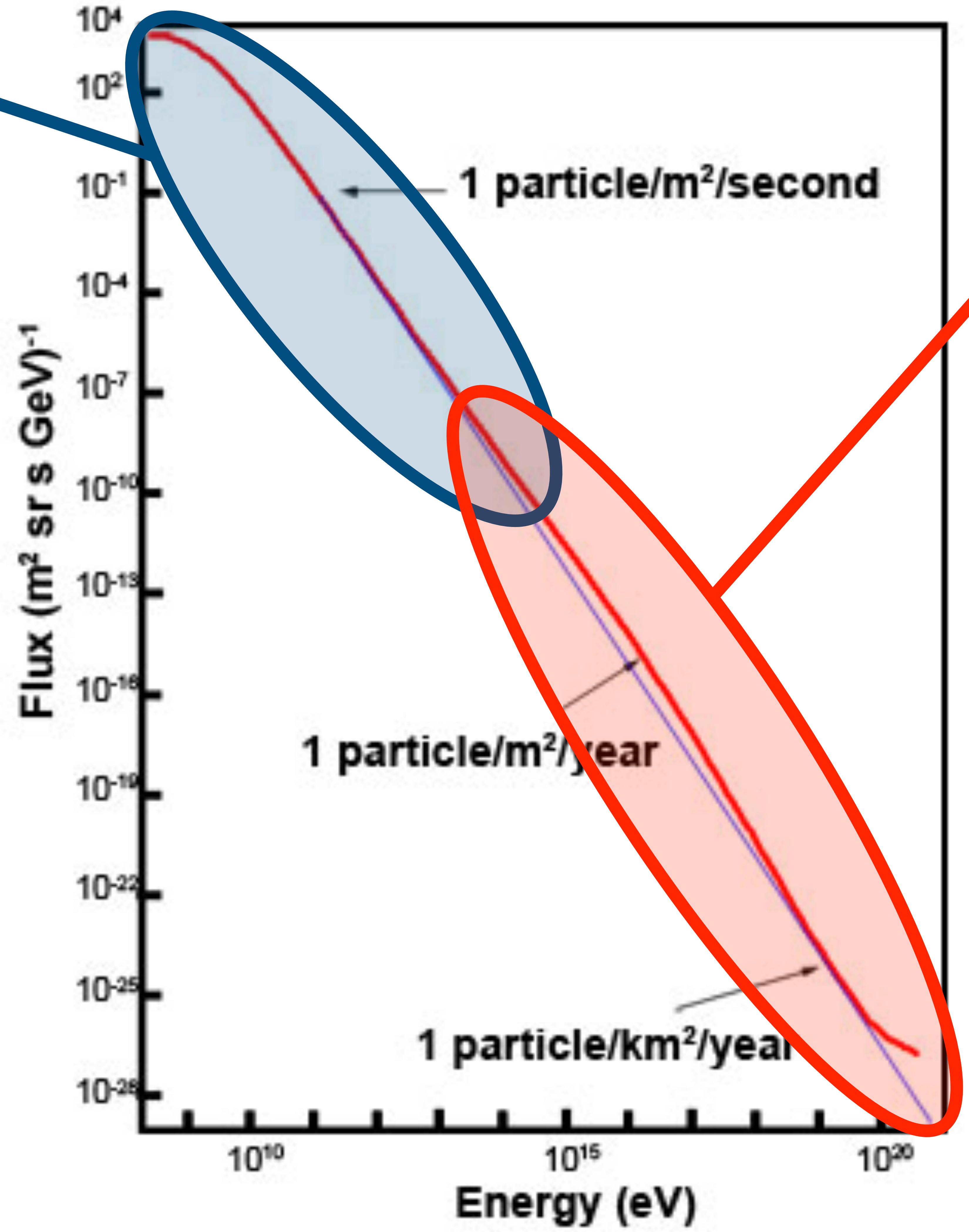





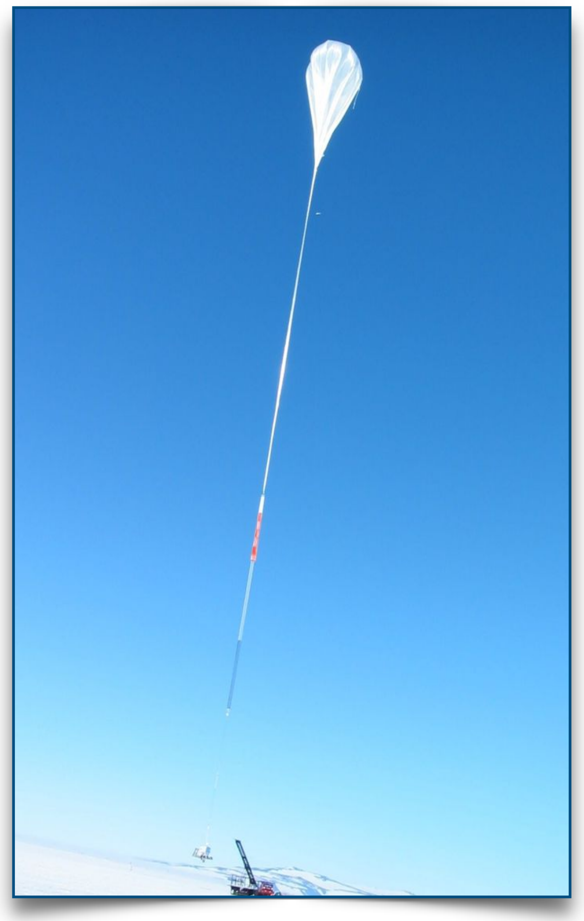
Indirect measurements (ground-based)

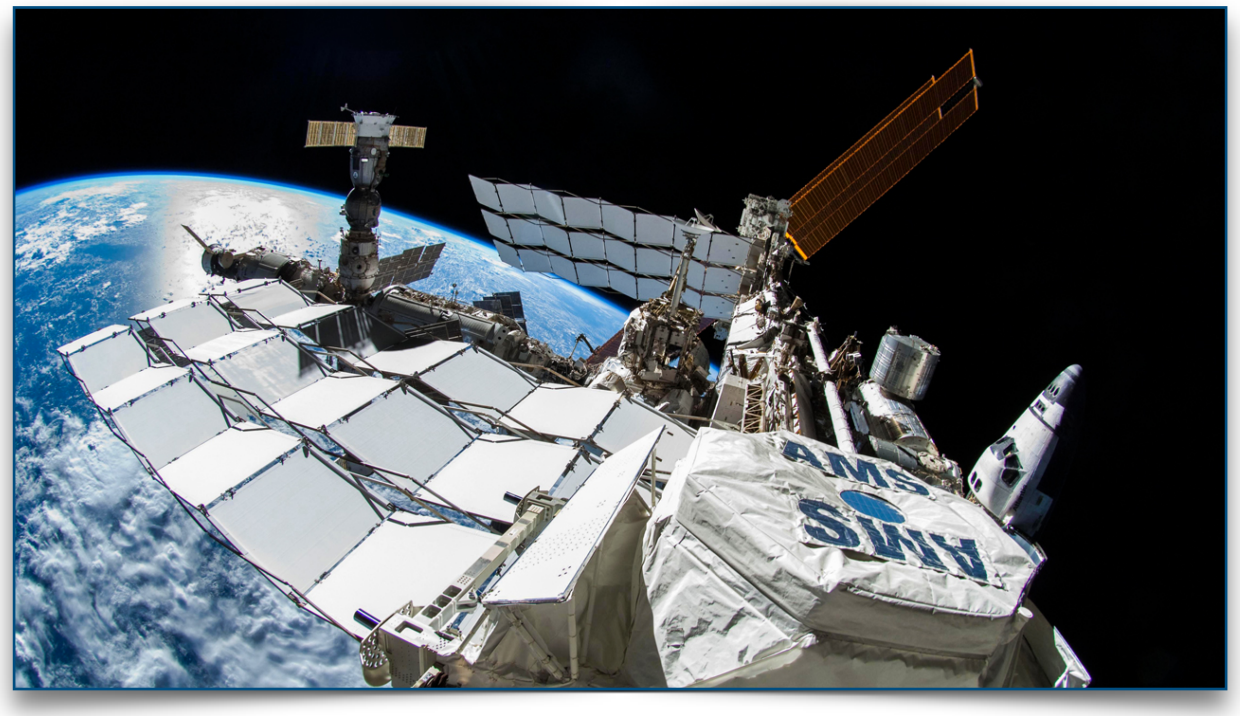


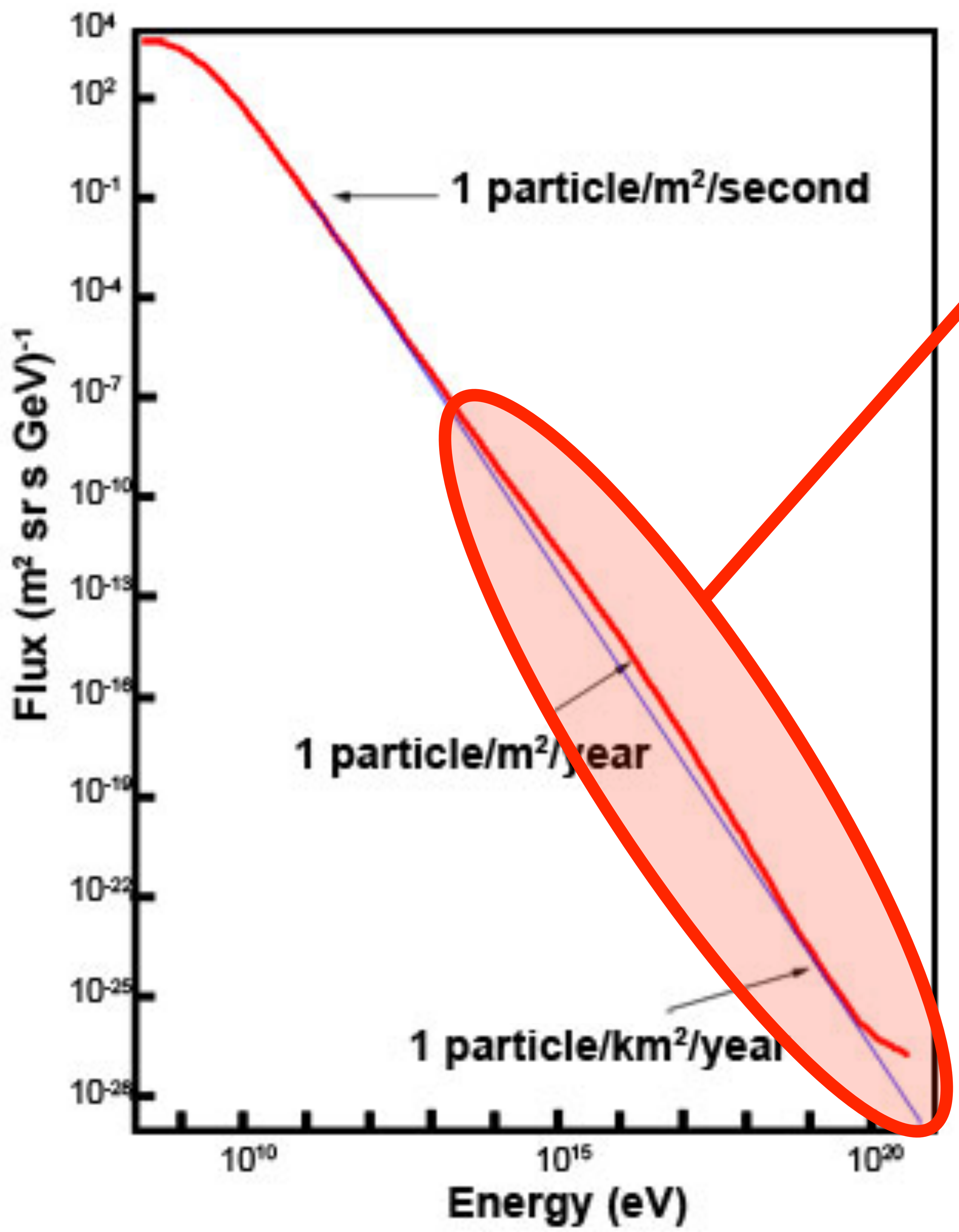

How to Detect Cosmic Rays?

This talk

Direct measurements (balloon / space)



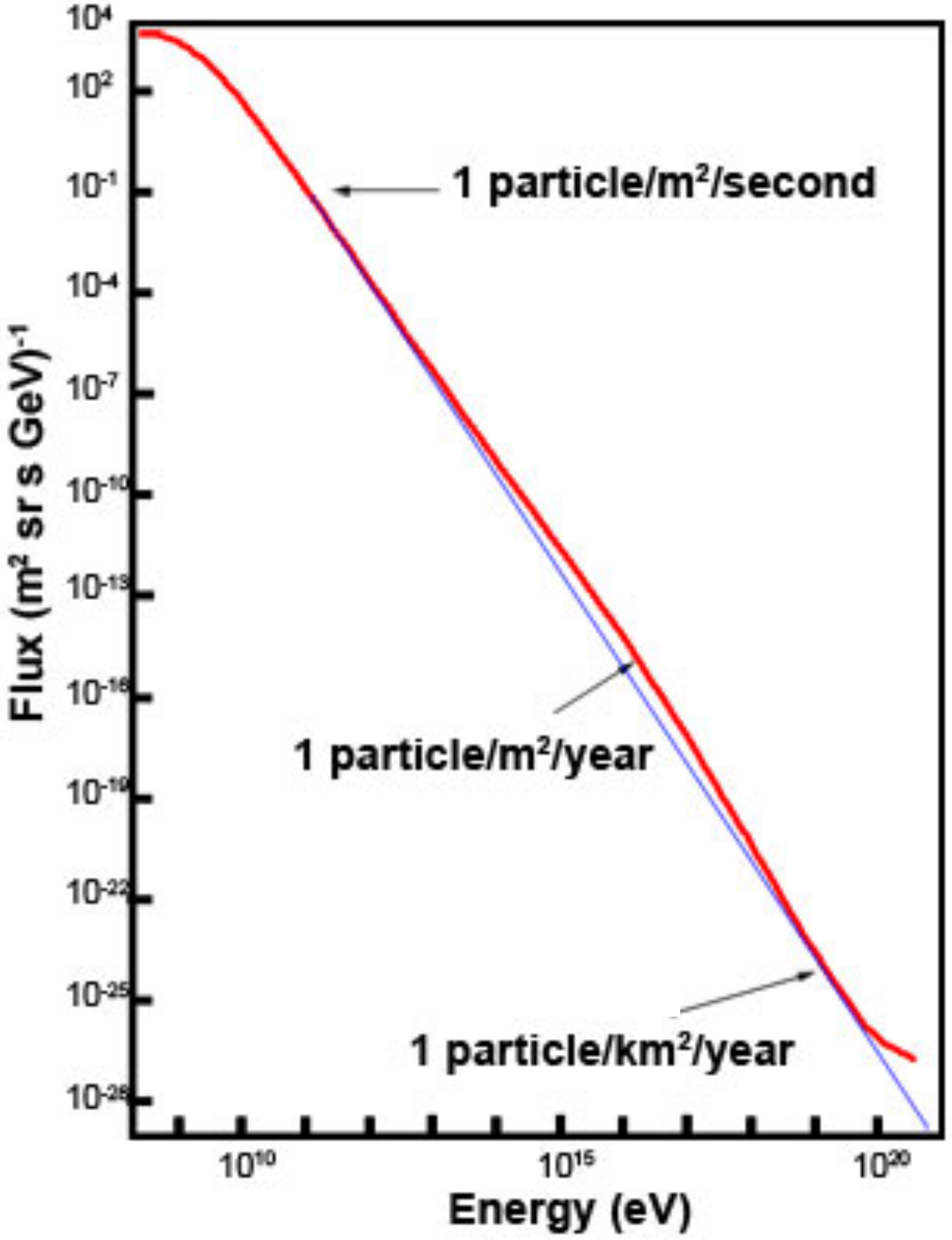


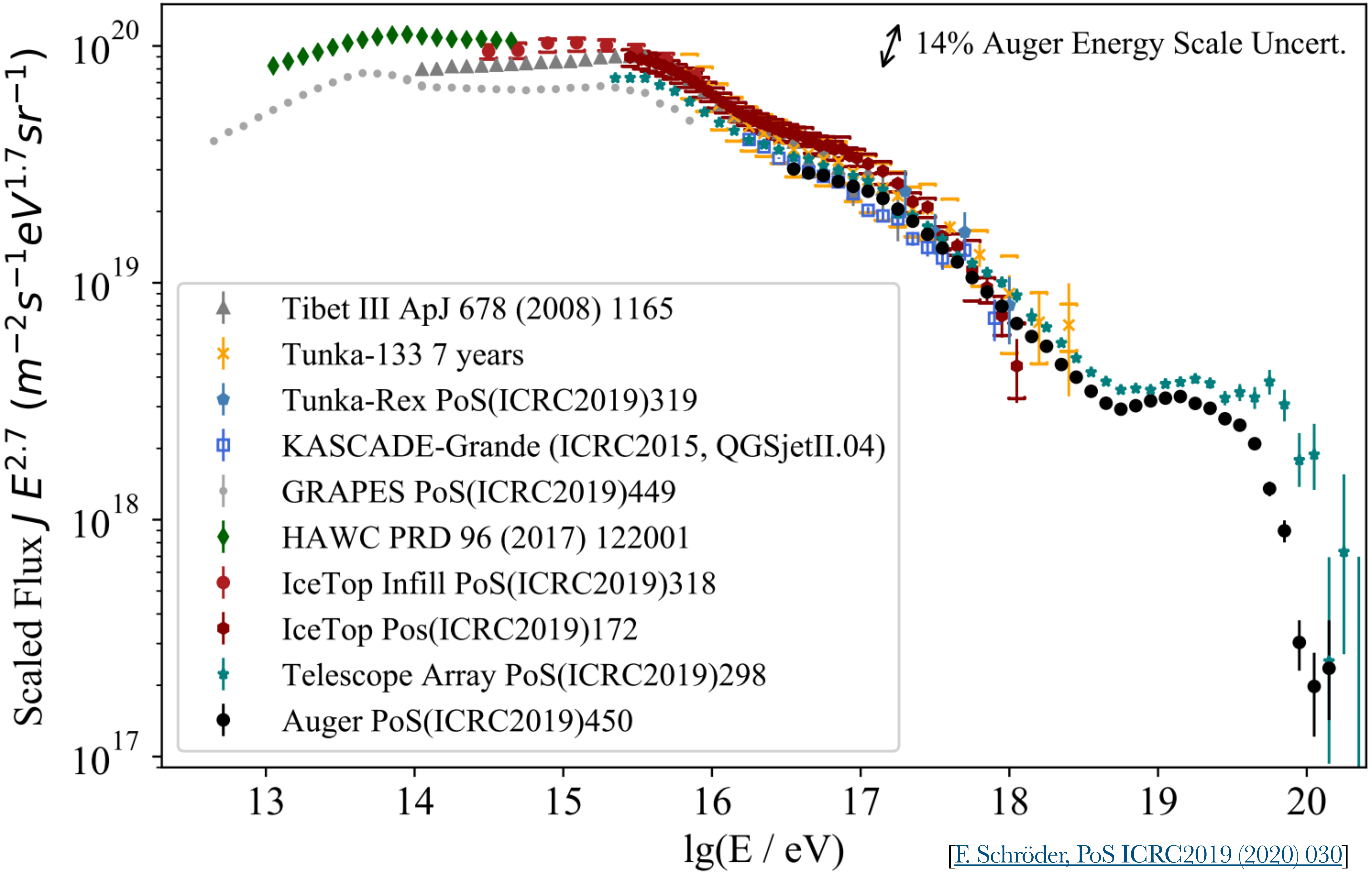


Indirect measurements (ground-based)

Cosmic Ray Spectrum

- Various prominent features have been observed





[F. Schröder, PoS ICRC2019 (2020) 030]

Cosmic Ray Spectrum

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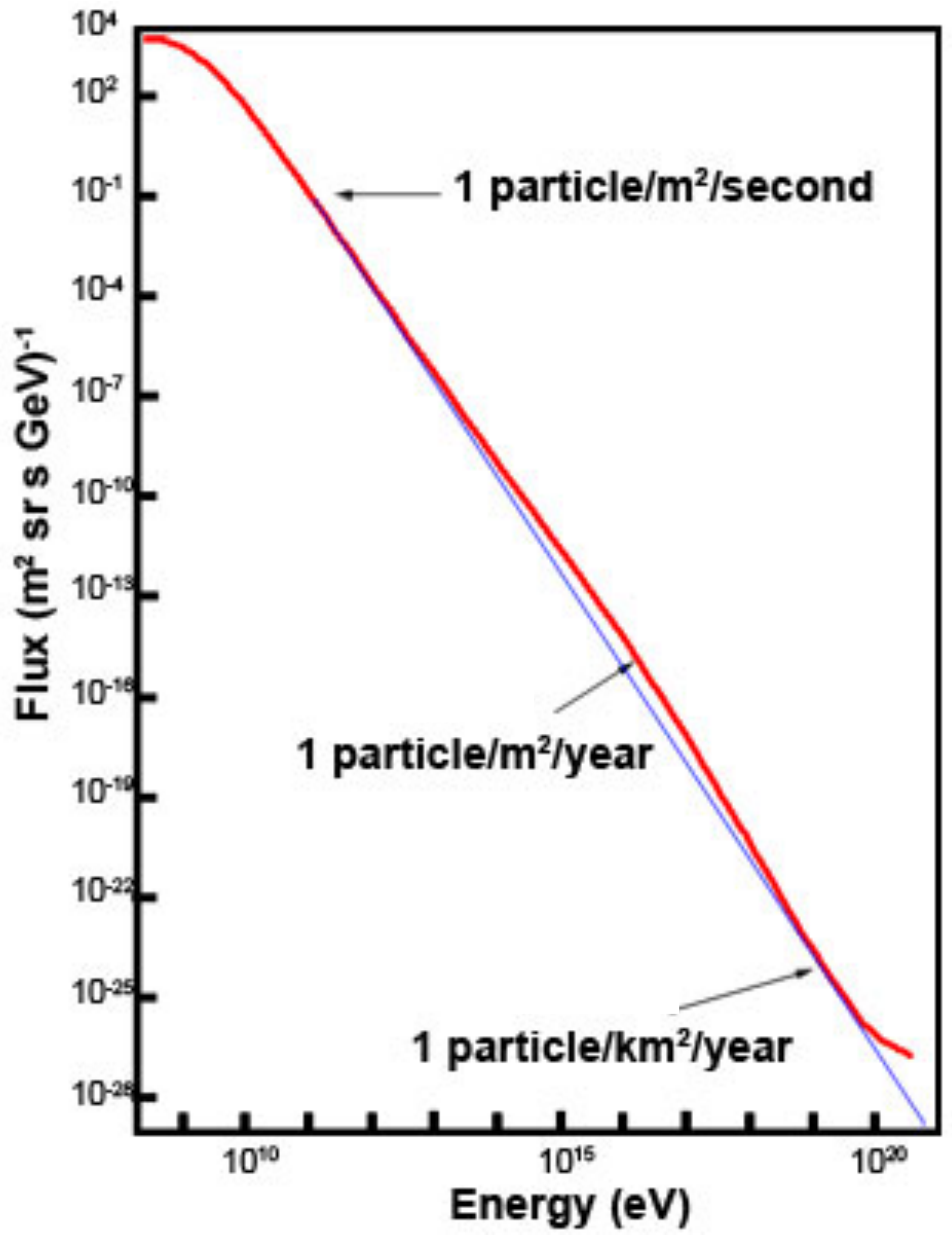

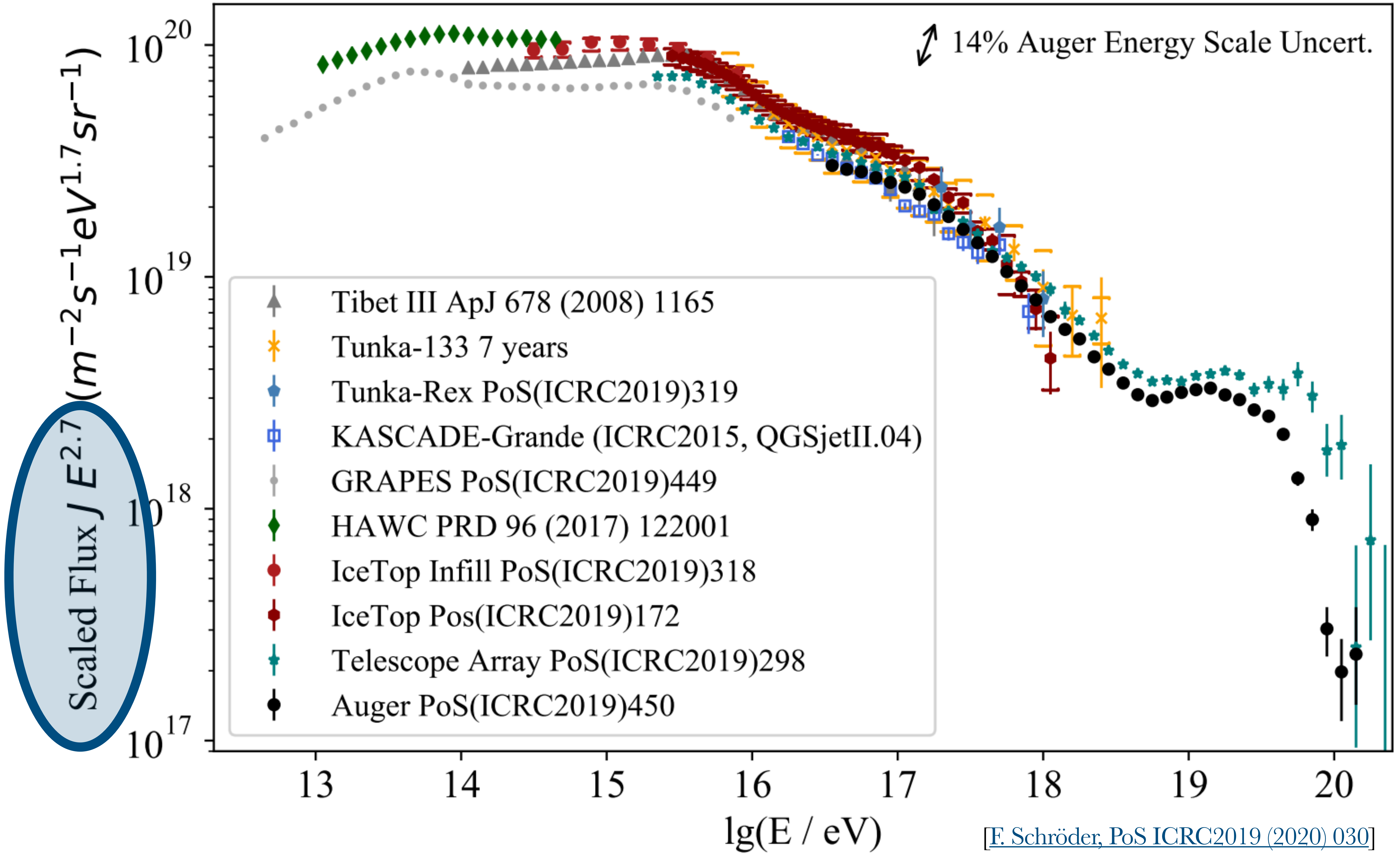

[F. Schröder, PoS ICRC2019 (2020) 030]

Cosmic Ray Spectrum

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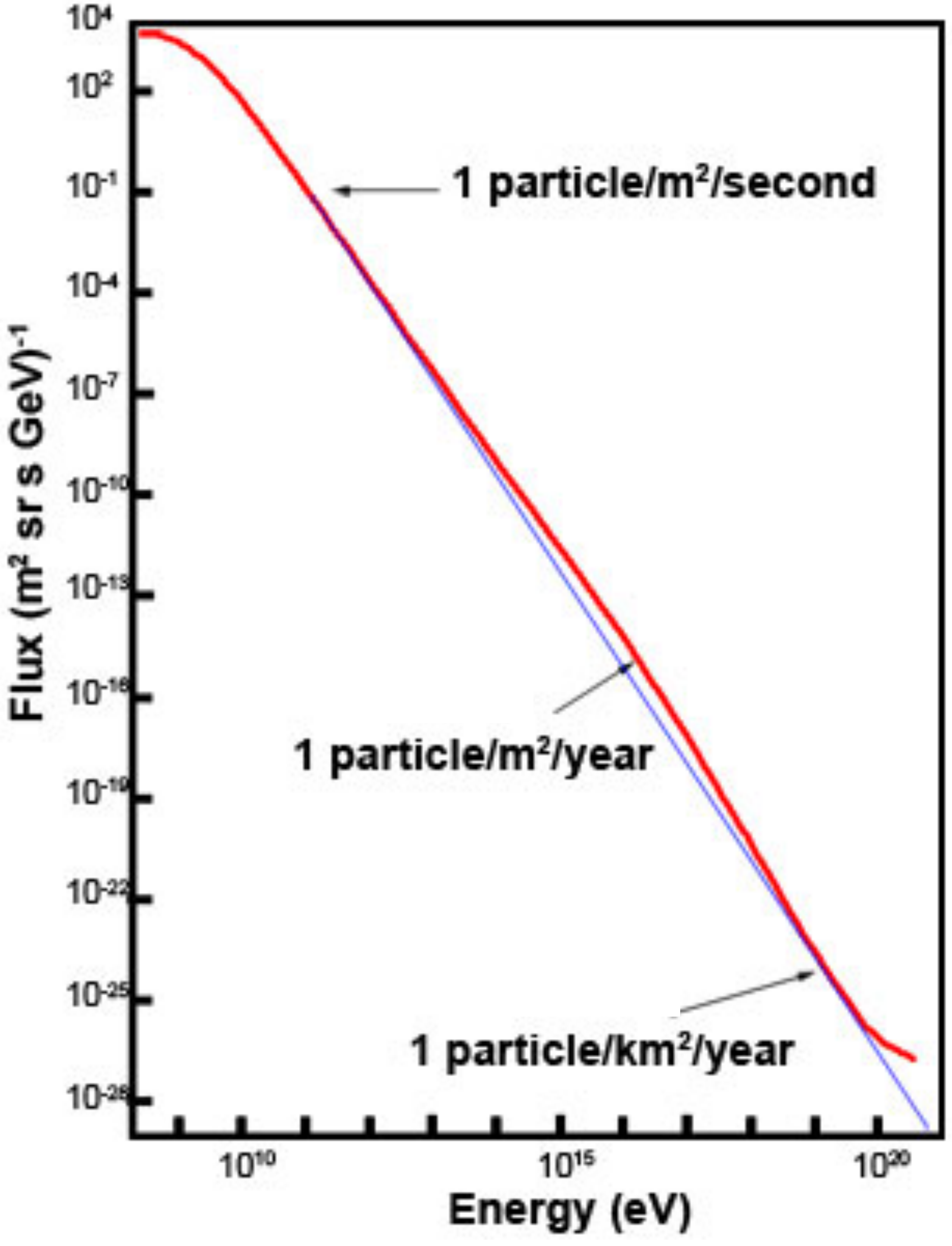

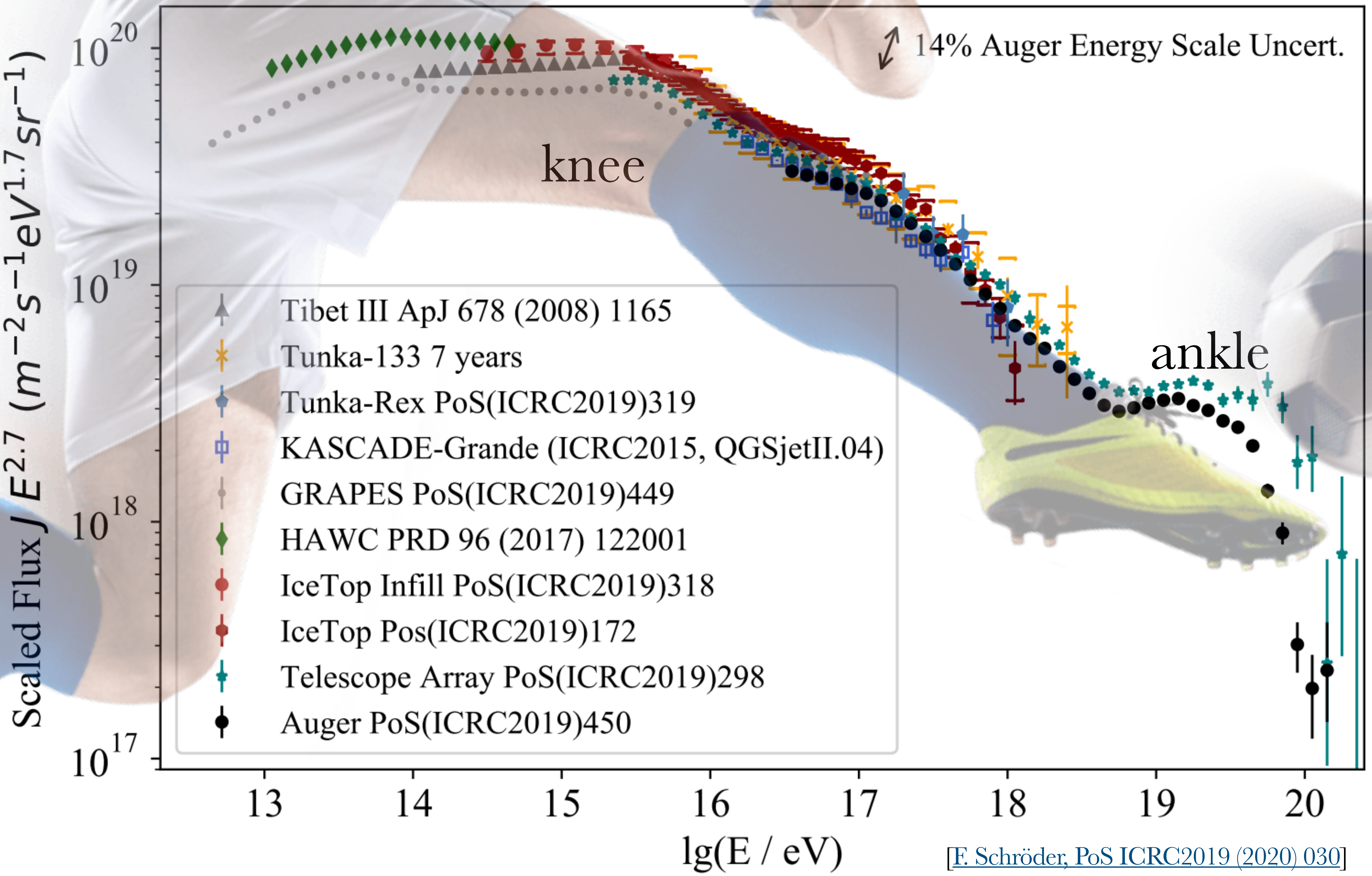

[F. Schröder, PoS ICRC2019 (2020) 030]

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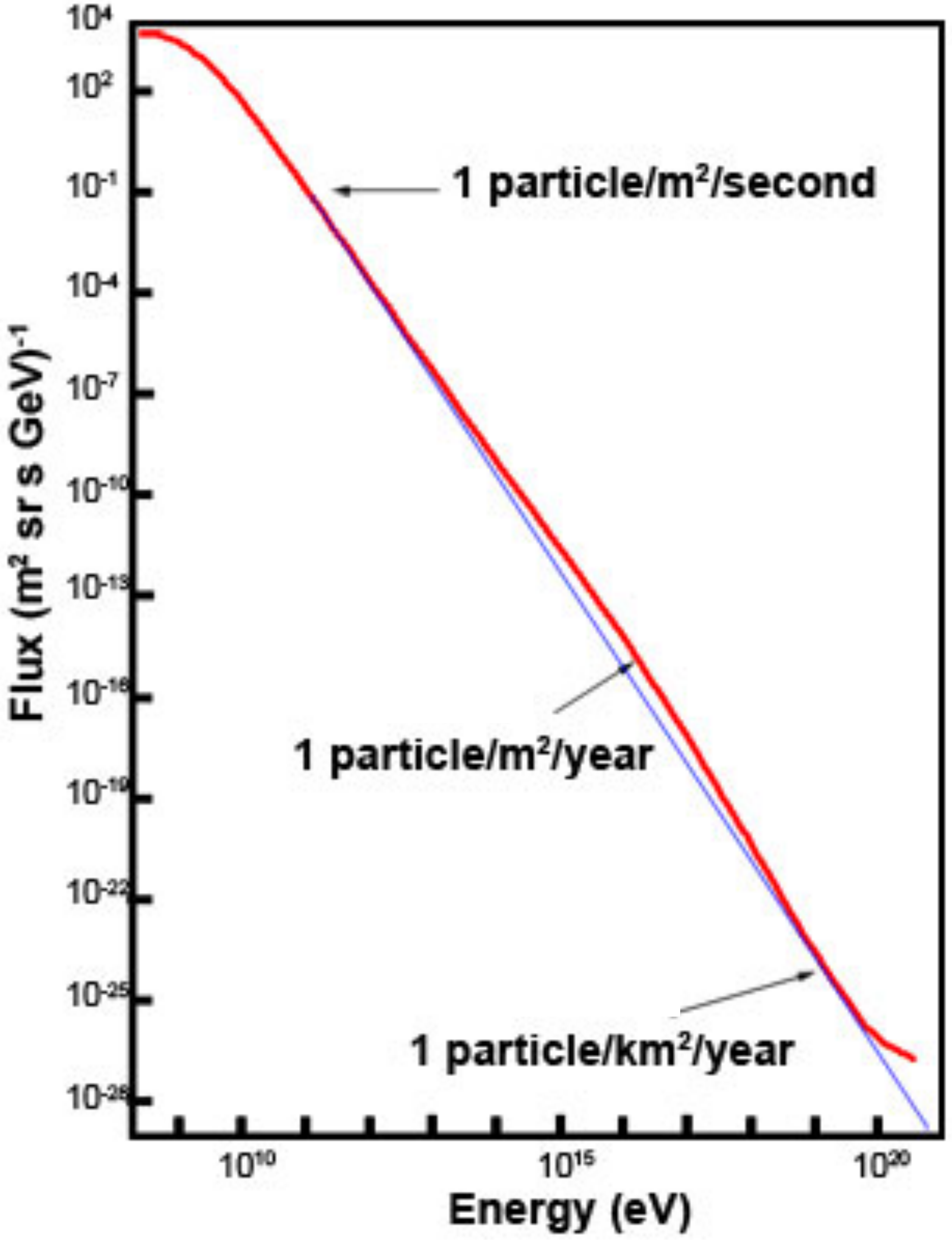

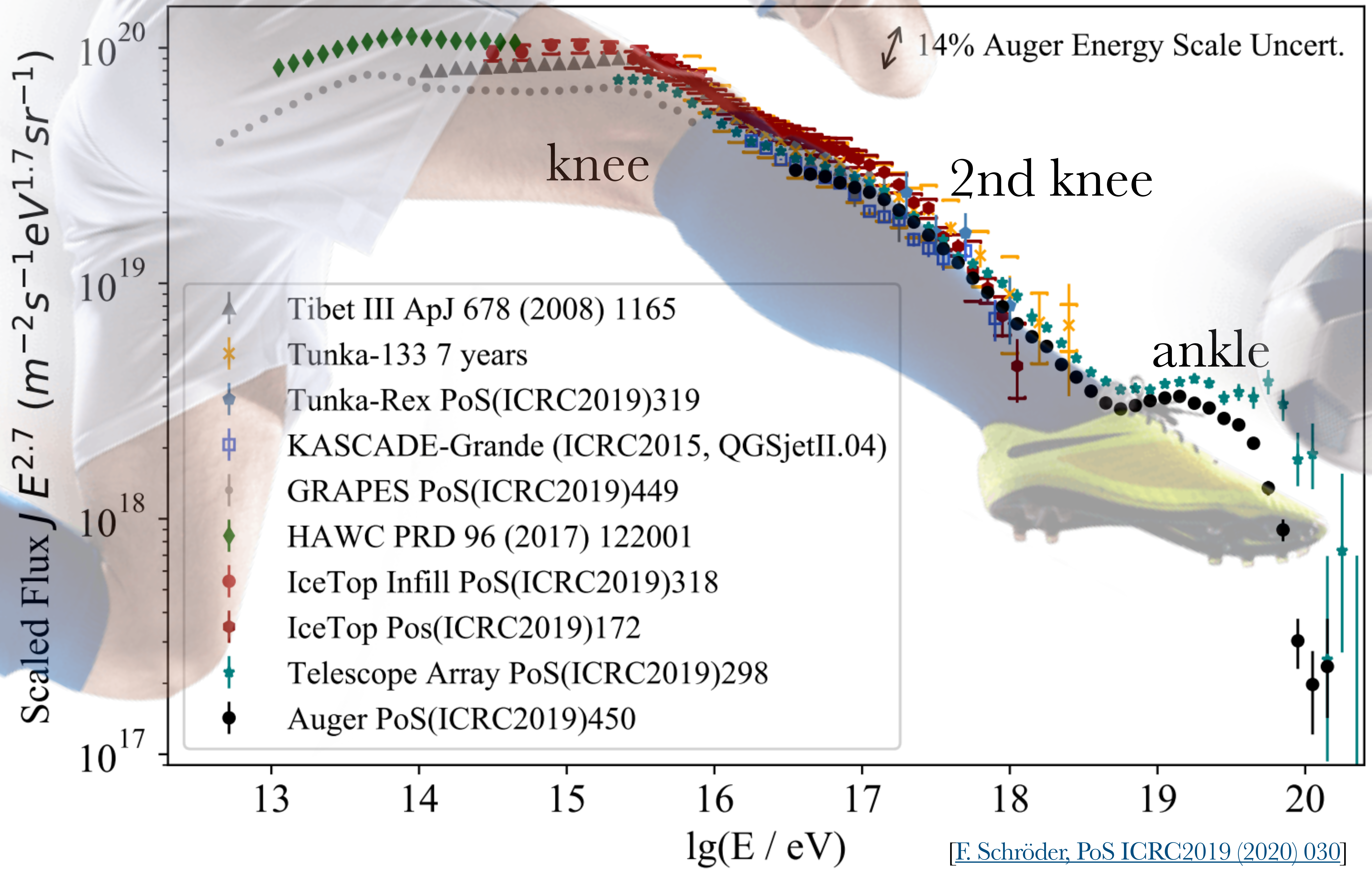

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