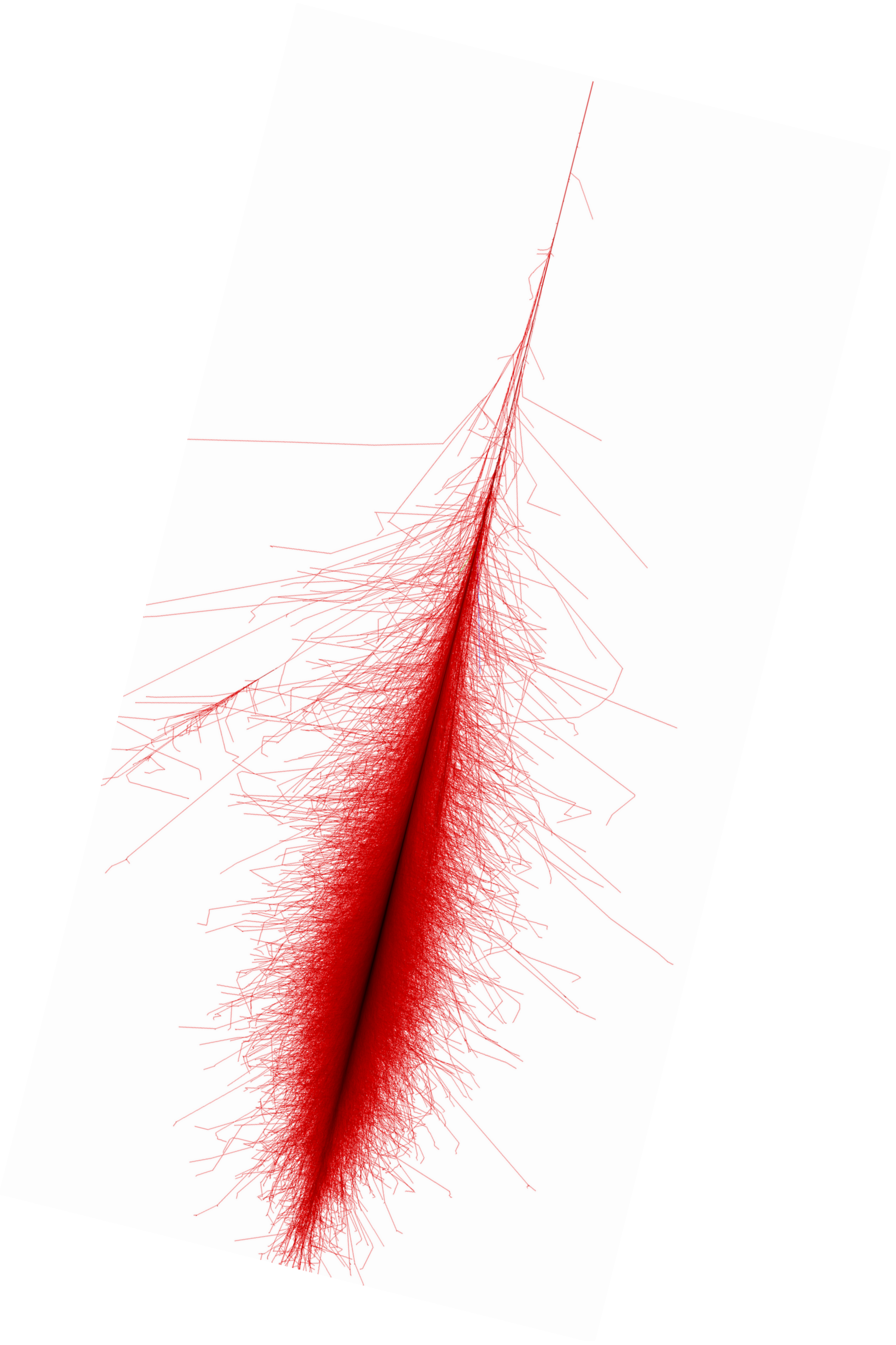
EAS Simulations / Calculations

EAS Simulations

- Accurate predictions of EAS observables at the ground requires solving the cascade equations numerically or via Monte-Carlo methods
- Common simulation codes:
  - CORSIKA (**CO**smic **R**ay **SI**mulations for **KA**scade) https://www.iap.kit.edu/corsika/
  - CONEX https://www.iap.kit.edu/corsika/
  - CoReas (**C**orsika-based **R**adio **E**mission from **A**ir **S**howers) https://www.huege.org/coreas/
- Handle propagation of particles in the atmosphere
- Hadronic interactions simulated by "hadronic interaction models"
- Configuration of input parameters and output format
- Some inputs already configured during compilation, e.g. hadronic models



CORSIKA

- Example input/output parameters:
  - Input "steering file":
    - Primary energy (range) / mass
    - Zenith / azimuth (range)
    - Atmospheric model / depth
    - Earth magnetic field
    - …
  - Output "DAT file":
    - Meta information
    - Particle content at observation level
      - Energy / momentum
      - Position
      - Particle type

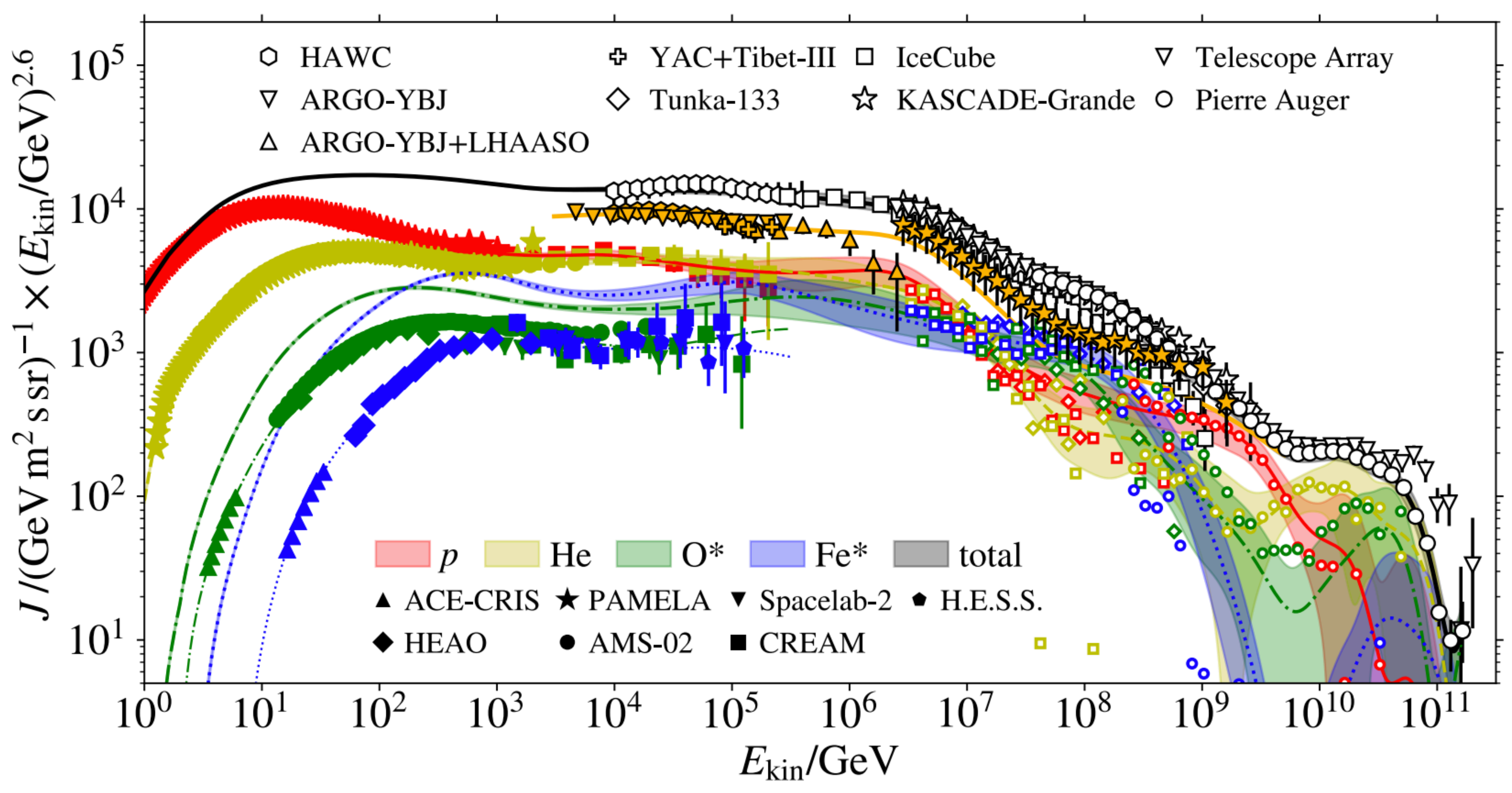
```
RUNNR    1
EVTNR    1
NSHOW    1
PRMPAR   14
ESLOPE   -1.0
ERANGE   1e5   1e6
THETAP   0.0   65.0
PHIP     0.0   359.99
SEED     111    0    0
SEED     222    0    0
SEED     333    0    0
OBSLEV   2840.E2
ELMFLG   T  T
RADNKG   2.E5
ARRANG   -120.7
MAGNET   16.75   -51.96
HADFLG   0  1  0  1  0  2
SIBYLL   T  0
SIBSIG   T
ECUTS    0.05000 0.05000 0.01000 0.00200
MUADDI   T
MUMULT   T
LONGI    T  20.  T  F
MAXPRT   0
ECTMAP   100
STEPFC   1.0
DEBUG    F  6  F  1000000
DIRECT   ./
ATMOD    33
EXIT
```

Hadronic Interaction Models

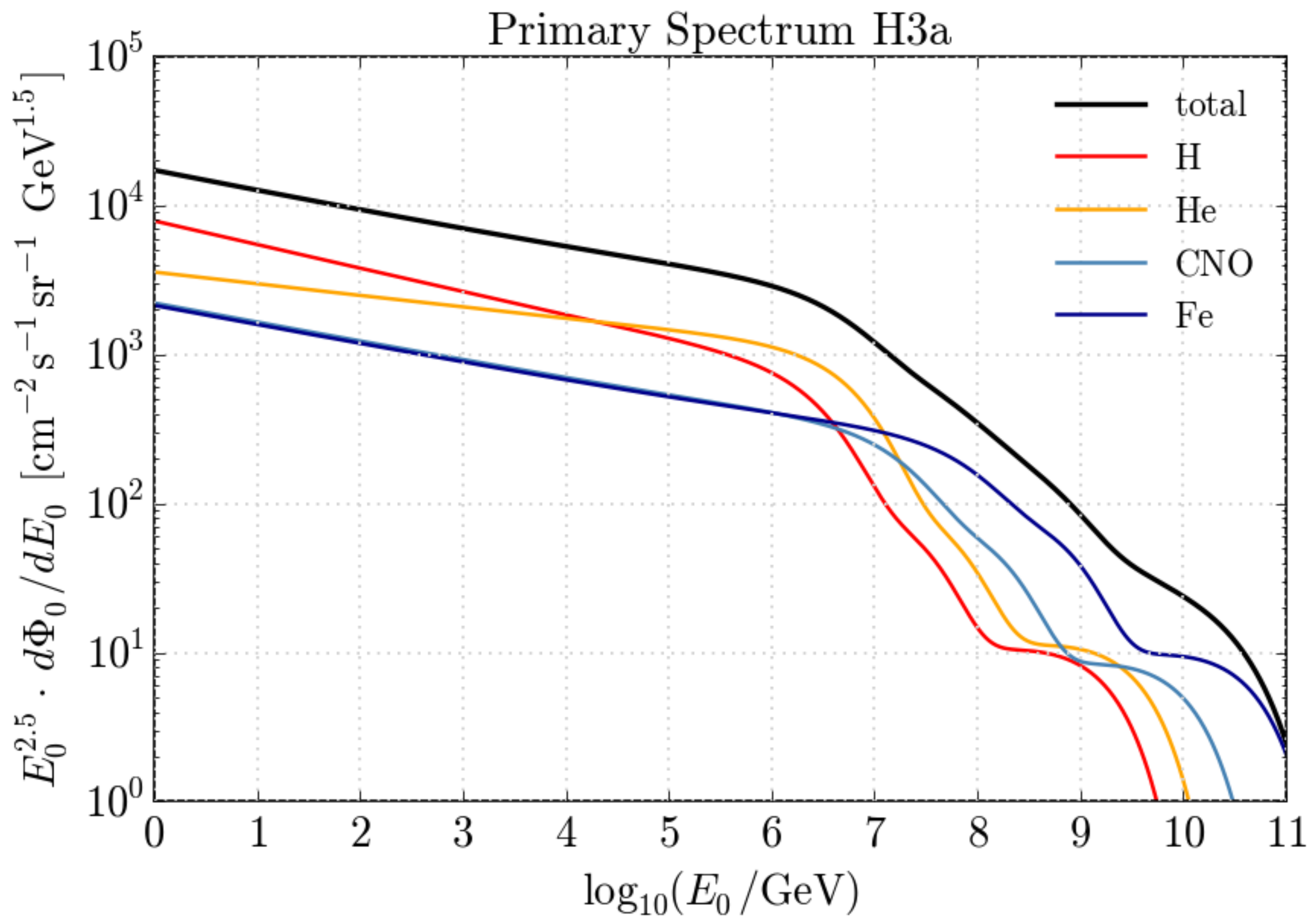
- Crucial part of EAS simulations is the treatment of hadronic interactions
- Multi-particle production in the forward region with low momentum transfer
  - Can not be computed using perturbative quantum chromodynamics (pQCD)!
- Forward region difficult to measure with current accelerators (too close to the beam)
- Phenomenological hadronic interaction models are needed!
- These models are tuned to data from collider/fixed-target experiments and extrapolated to the ranges of phase space relevant for EAS
- High-energy models ($E > 80\,\mathrm{GeV}$):
  - Sibyll
  - EPOS
  - QGSJet
- Low-energy models ($E \leq 80\,\mathrm{GeV}$):
  - Gheisha
  - Fluka
  - UrQMD

CR Flux Models

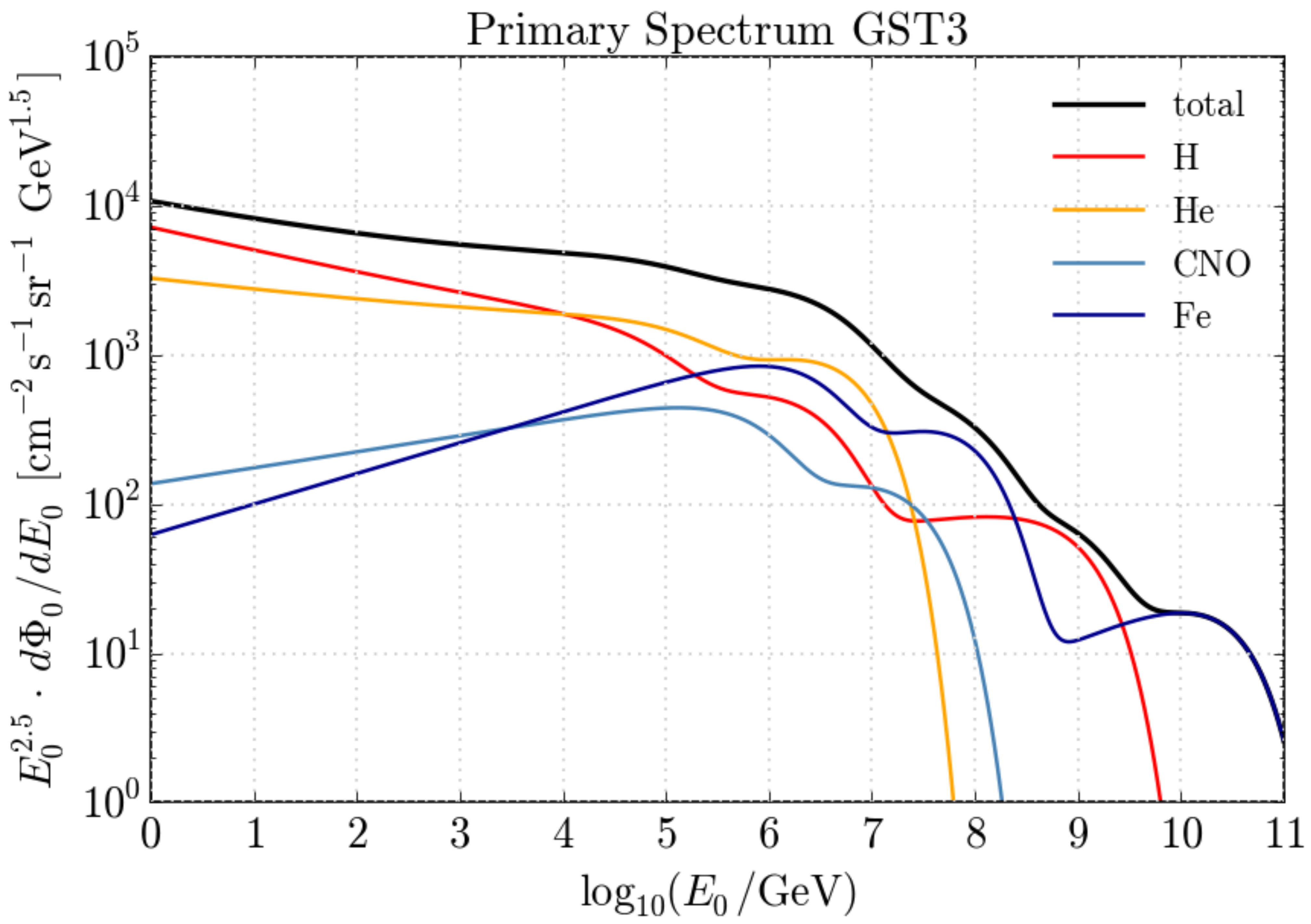
[H.P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser, F. Riehn, T. Stanev, PoS ICRC2017 (2017) 533]



- CR flux is important input
- Models based on fits to data are used
- Examples: H3a/4a, GST3/4, GSF



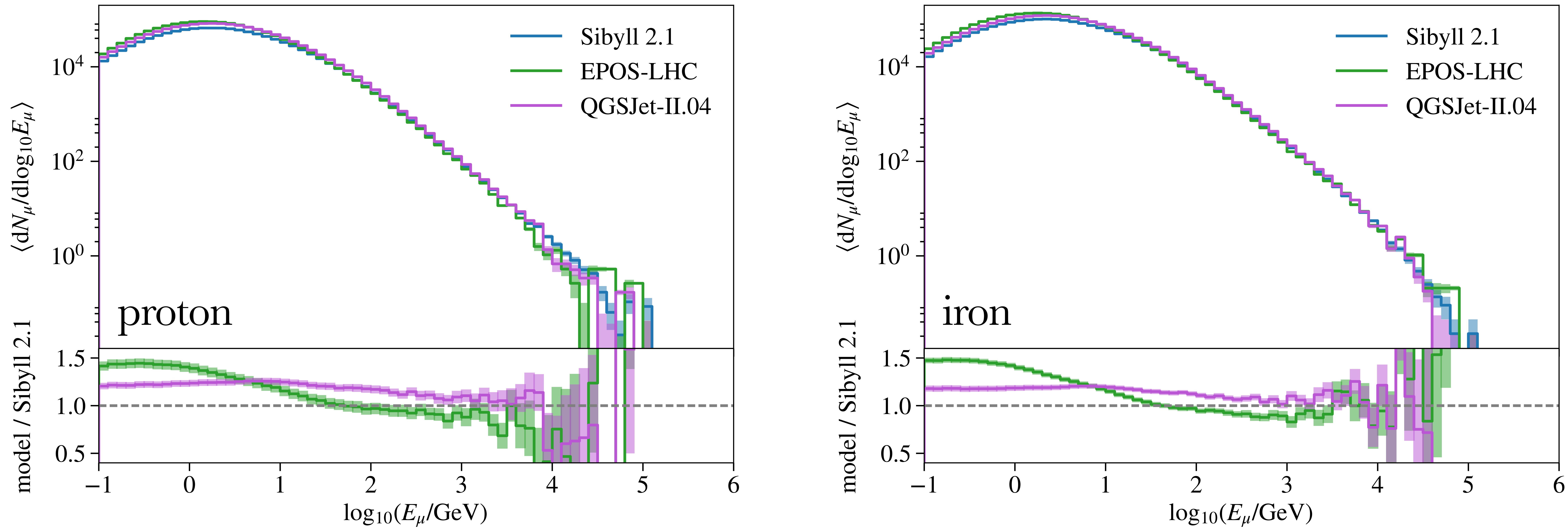
[T. K. Gaisser, Astropart. Phys. 35 (2012)]



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

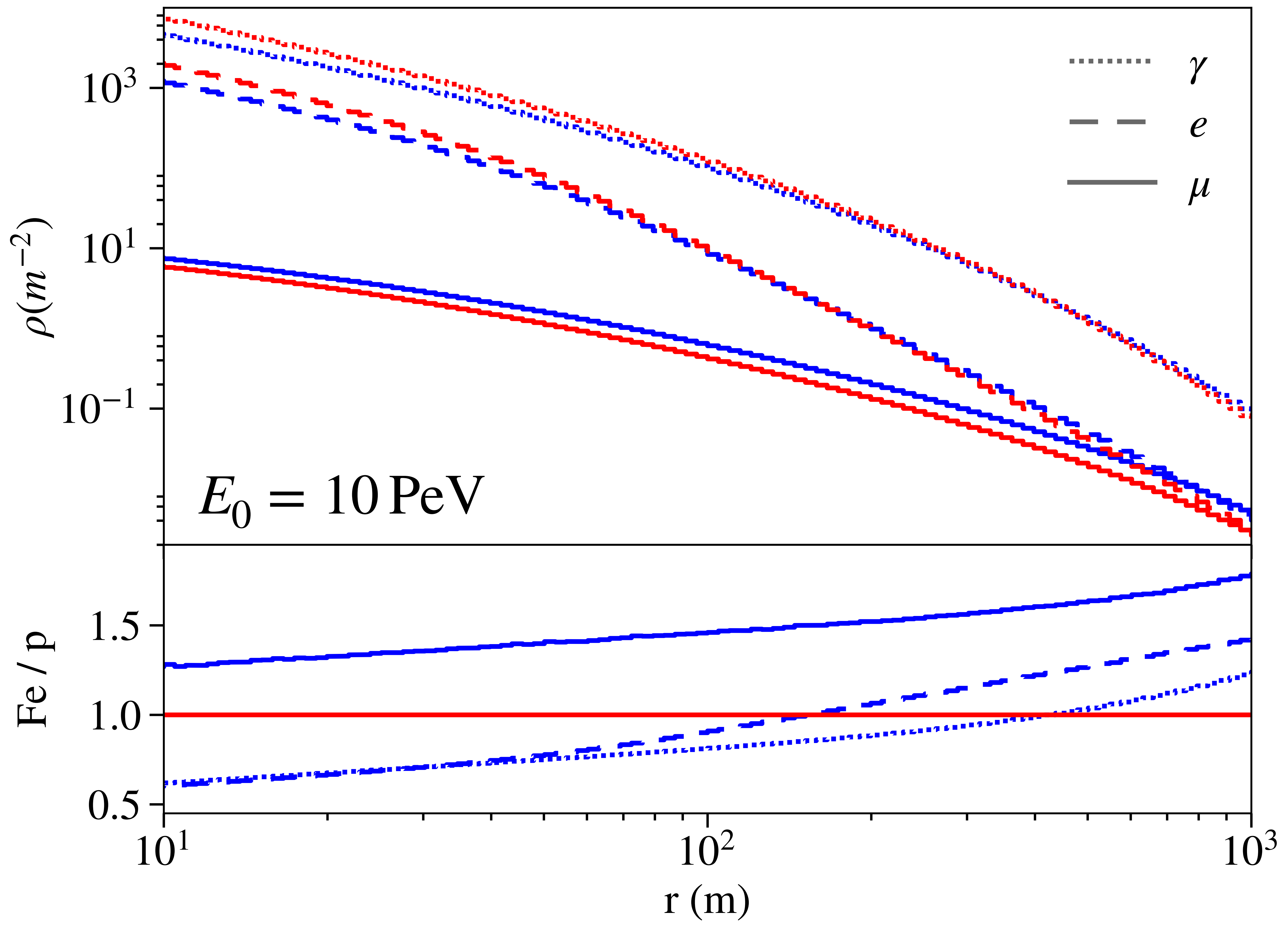
CORSIKA Simulations

- Muon energy spectra obtained from 3 hadronic interaction models (H3a flux)



CORSIKA Simulations

- Lateral distribution of
  - photons, γ
  - electrons, $e^{\pm}$
  - muons, $\mu^{\pm}$
- Muon distribution flatter than EM!
- Muons dominate at large distances from the shower!
  - Can be used to select muons
- Iron showers produce more muons than proton showers!
  - Can be used to measure CR mass composition



Analytical Approximations

- Cascade equations can be solved with **A**nalytical **A**pproximations (AA)

$$\frac{d\Phi_h(E_h, X)}{dX} = -\left(\frac{1}{\lambda_{\text{int},h}} - \frac{1}{\lambda_{\text{dec},h}}\right) \cdot \Phi_h(E_h, X) + \sum_j \int \frac{E_j \cdot dN_j(E_h, E_j)}{E_h \cdot dE_j} \cdot \frac{\Phi_j(E_j)}{\lambda_{\text{int},j}} dE_j$$

- Calculation uses spectrum weighted moments ("Z-factors")
- Z-factors need to be obtained from hadronic interaction models (later more)
- First-order approximation:

$$\frac{d\Phi_\mu(E_\mu, \theta)}{dE_\mu} = \frac{0.14 \cdot E_\mu^{-2.7}}{\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV}^{-3.7}} \cdot \left[\left(\frac{1}{1 + 1.1 \cdot E_\mu \cdot \cos(\theta)/\xi_\pi}\right) + \left(\frac{0.054}{1 + 1.1 \cdot E_\mu \cdot \cos(\theta)/\xi_K}\right) + \left(\frac{9.1 \cdot 10^{-6}}{1 + E_\mu \cdot \cos(\theta)/\xi_{\text{prompt}}}\right)\right]$$

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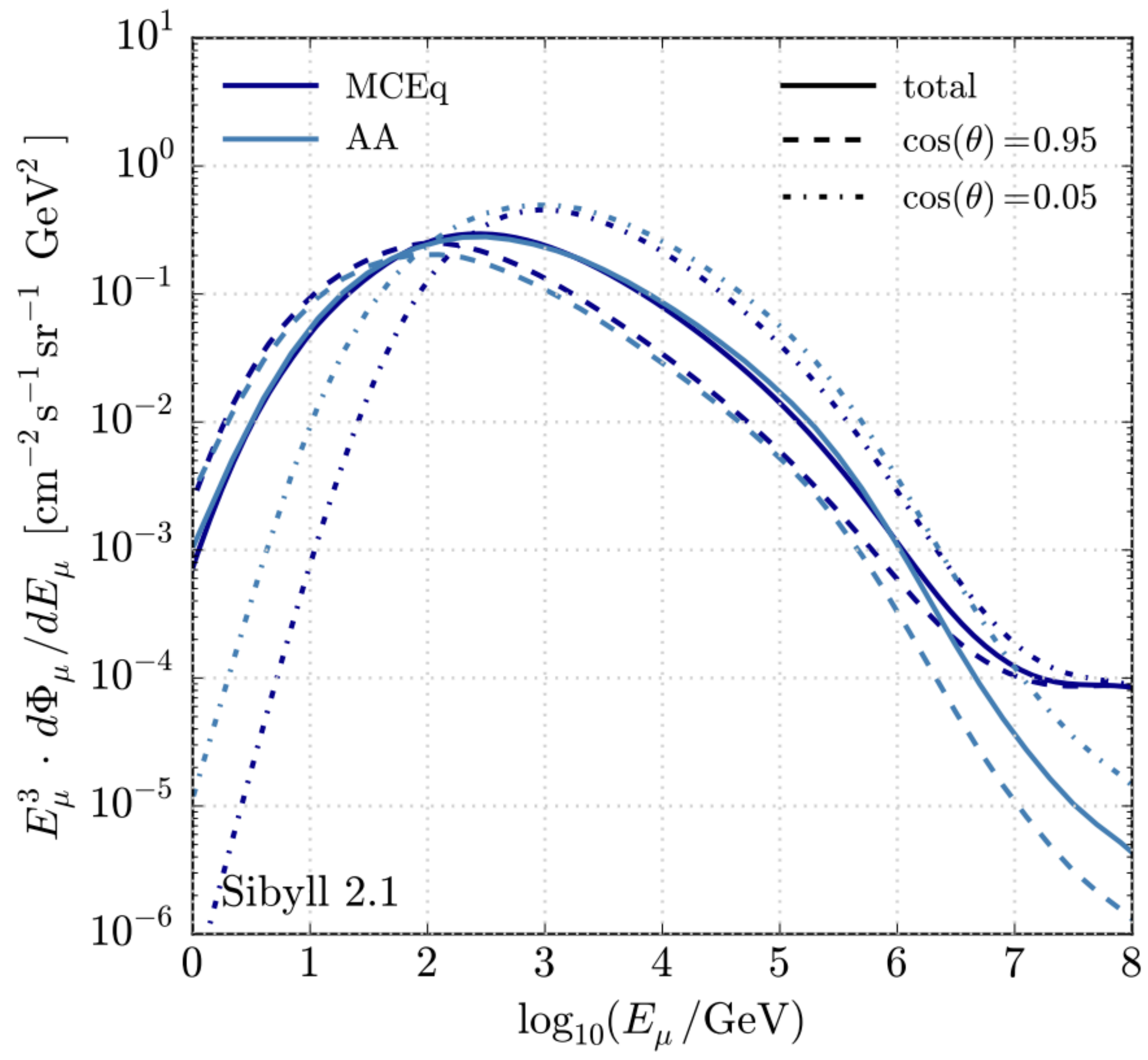
power law!

pions | kaons | prompt

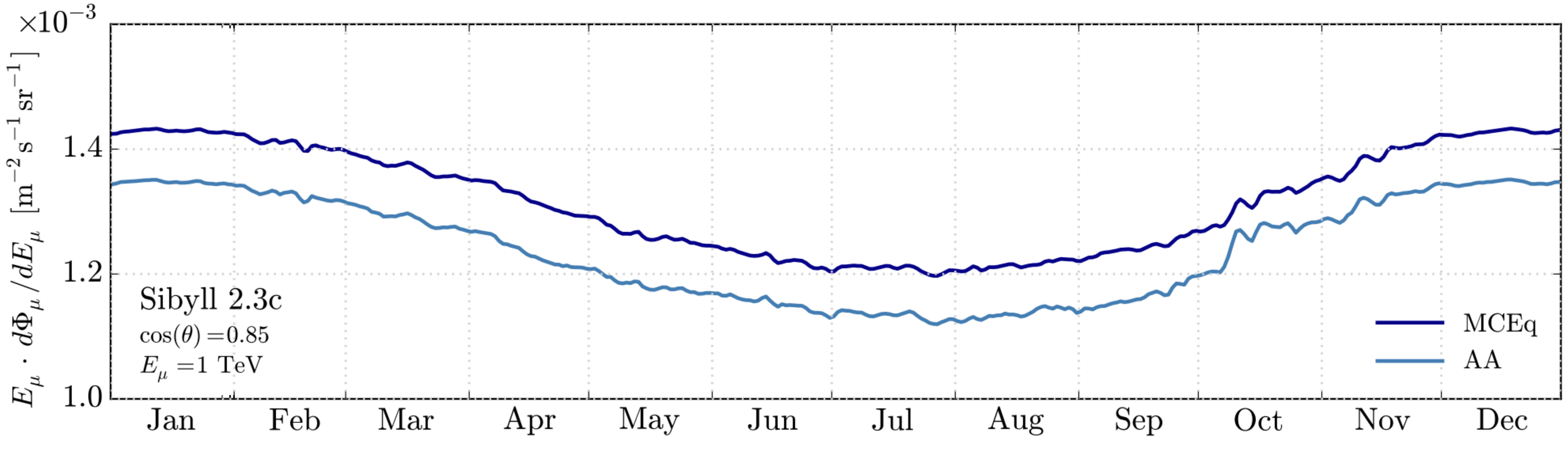
conventional (pions + kaons)

MCEq

- **M**atrix **C**ascade **Eq**uation code (MCEq)
- Analytical solution of cascade equations
- Also relies on hadronic model predictions
- Provides parent particle information
    - Conventional muons: pion / kaon decays
    - Prompt muons: short-lived hadron decays
- "Fairly good" agreement between AA and MCEq



[T.K Gaisser, D. Soldin, A. Crossman, A. Fedynitch, PoS ICRC2019 (2020) 893]



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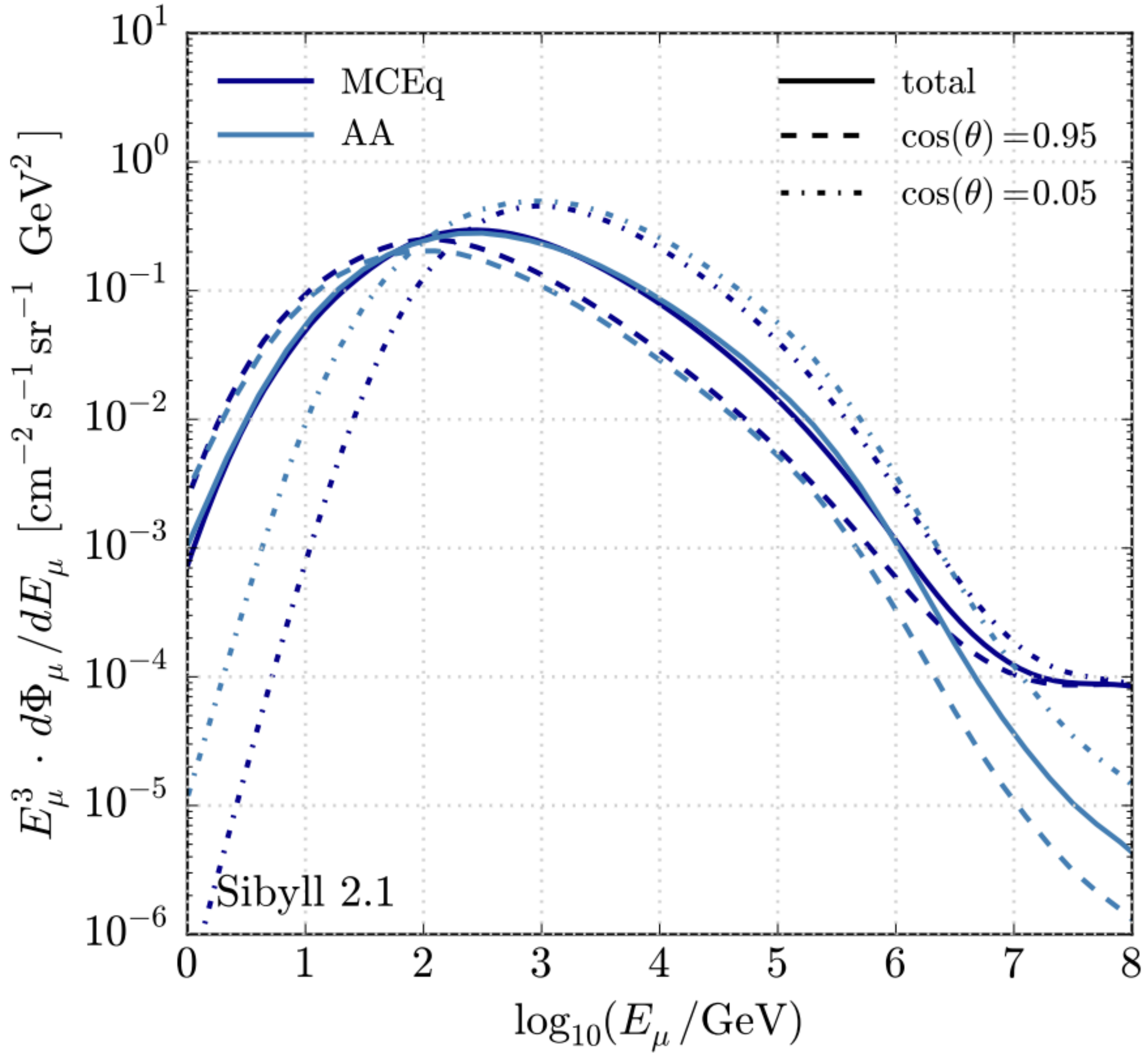
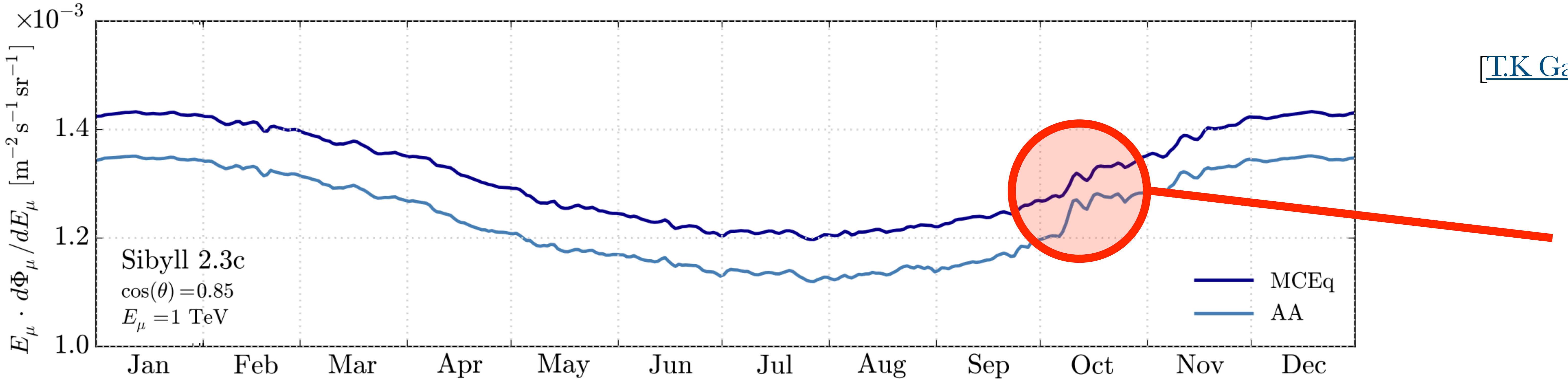


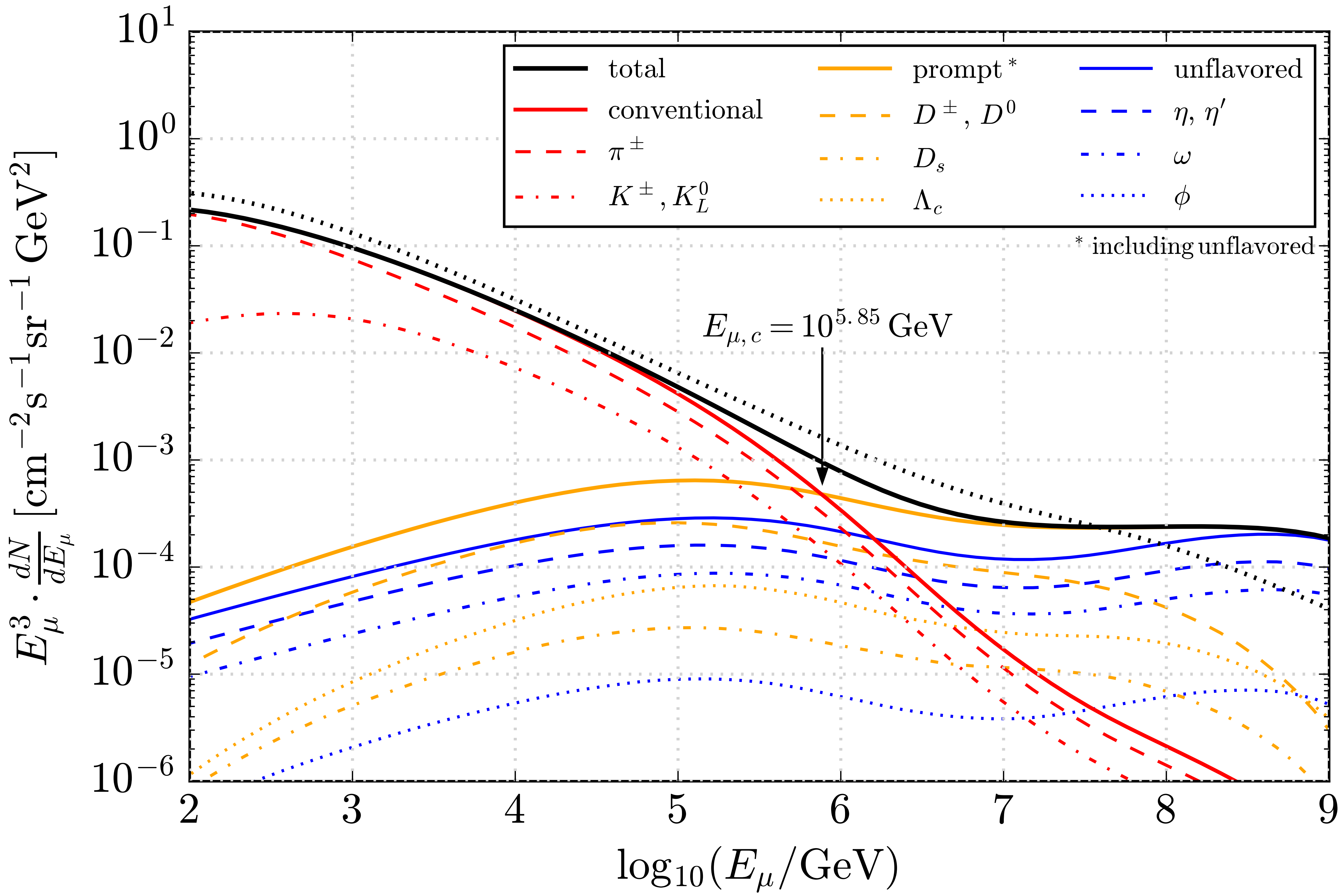
[T.K Gaisser, D. Soldin, A. Crossman, A. Fedynitch, PoS ICRC2019 (2020) 893]

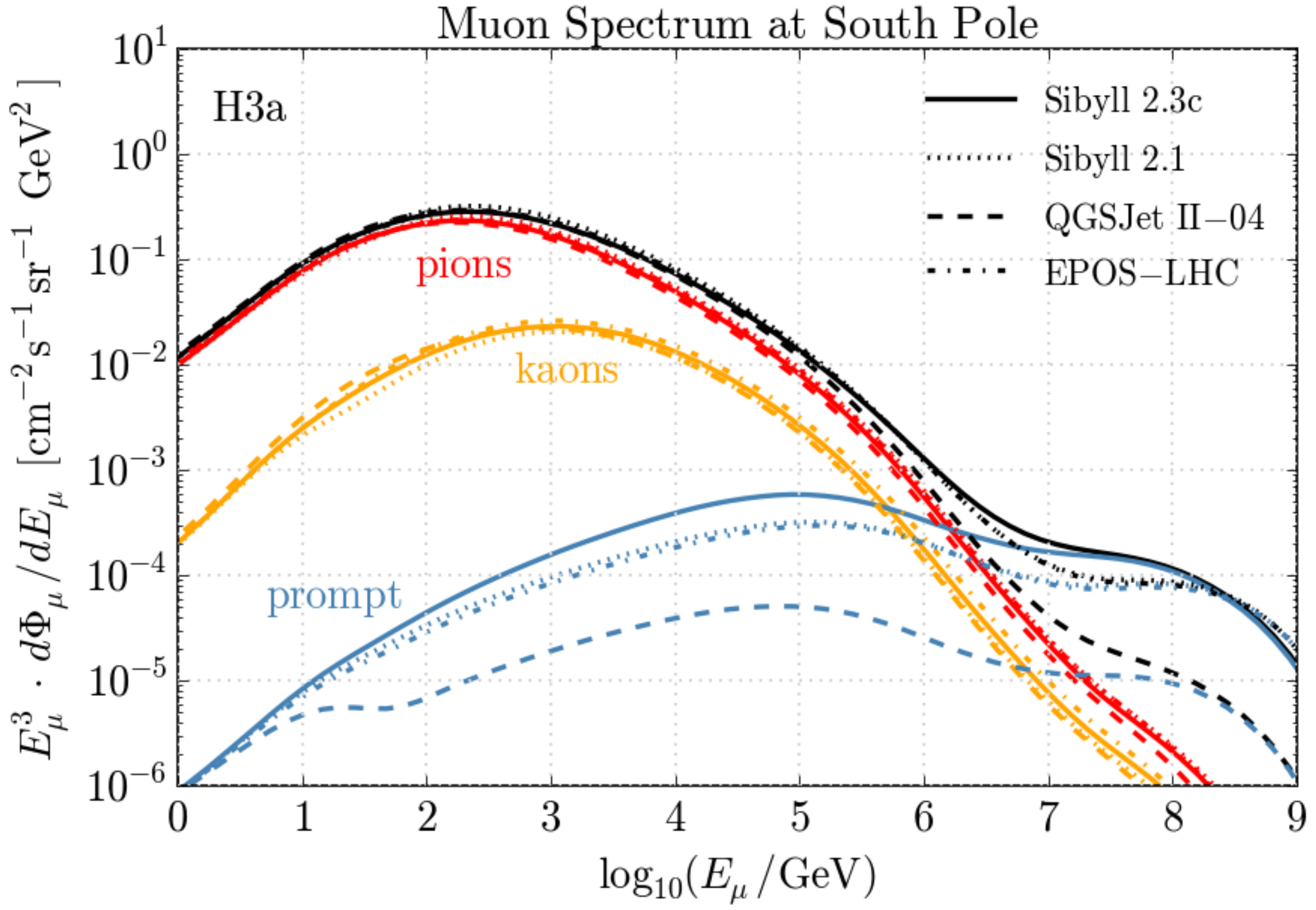


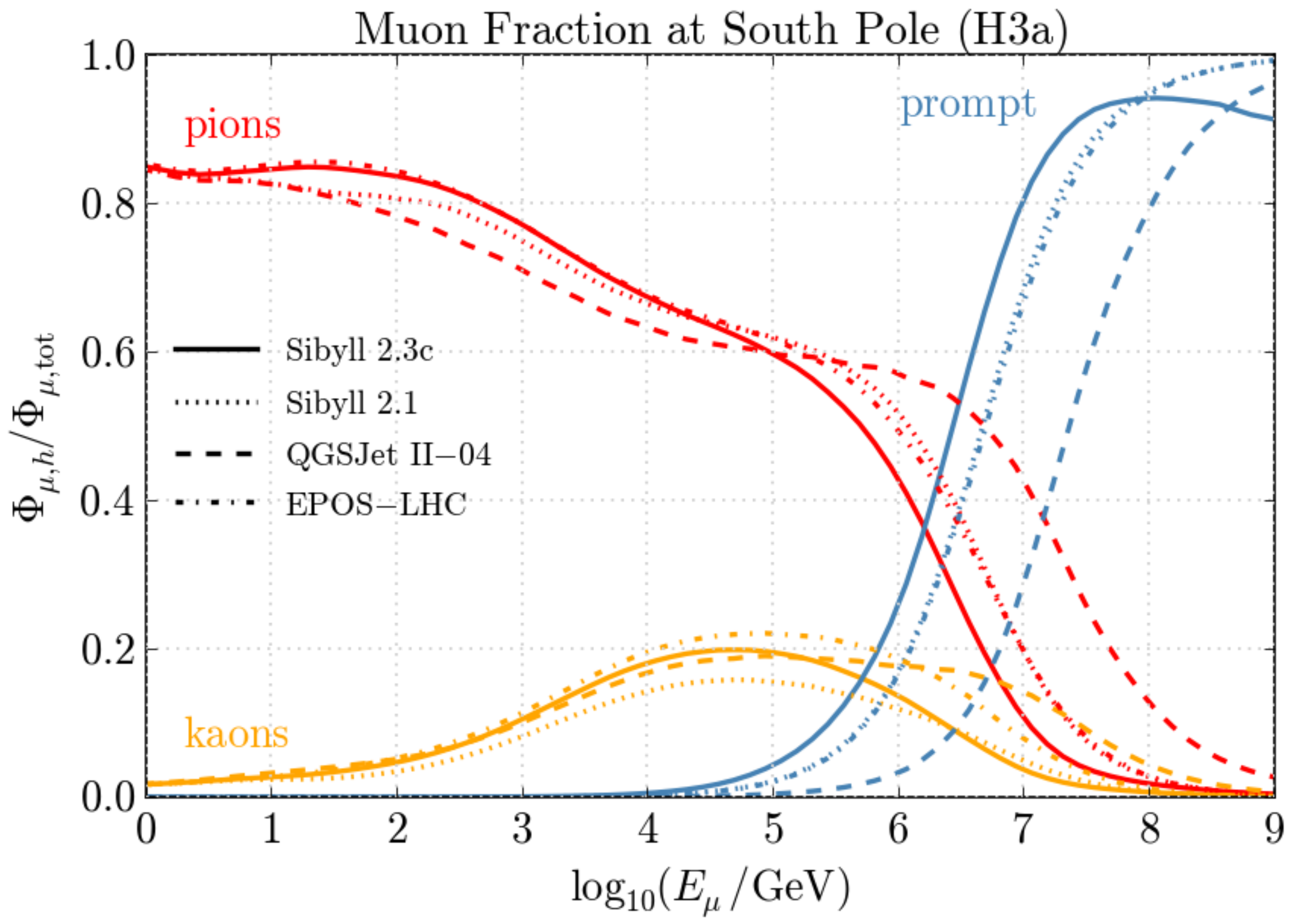
effects due to atmosphere!
(later more…)

MCEq

- Conventional muons dominating up to $\sim 1\,\text{PeV}$
- Prompt muons dominating above $\sim 1\,\text{PeV}$
- Contribution from unflavored (vector-)mesons

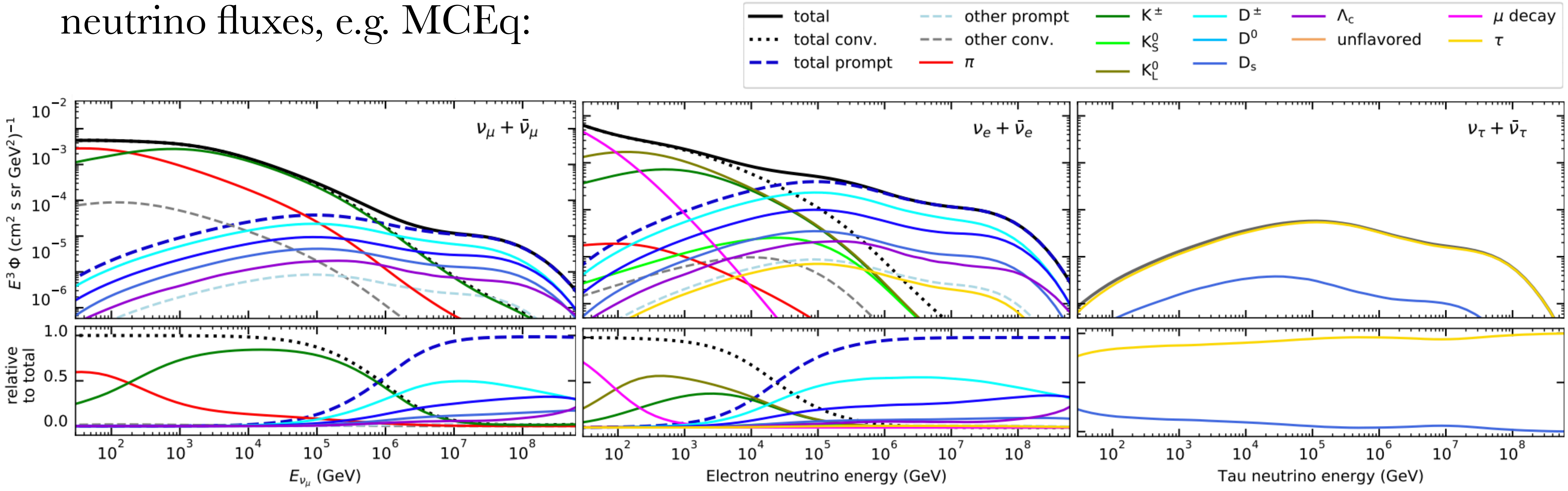






A Note on Neutrinos in EAS

- Decays into muons also produce neutrinos
- However, electron and tau neutrinos are also produced and reach the ground
- Same calculations as for muons (no decay/energy losses)!
- Same tools yield atmospheric neutrino fluxes, e.g. MCEq:

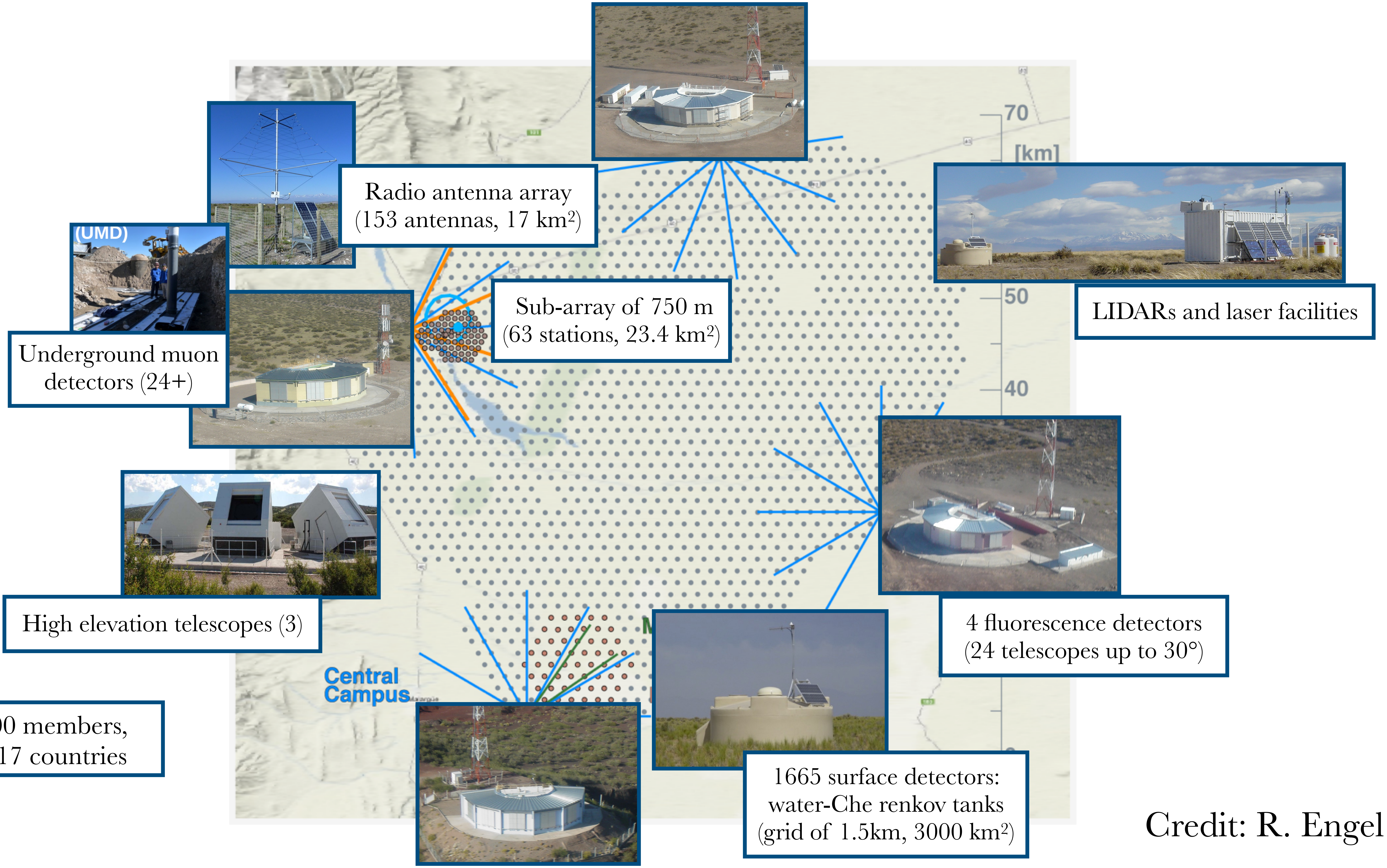


[A. Fedynitch, F. Riehn, R. Engel, T. K. Gaisser, T. Stanev, Phys. Rev. D 100, 103018 (2019)]

Indirect CR Detection
(Selected Examples)

The Pierre Auger Observatory

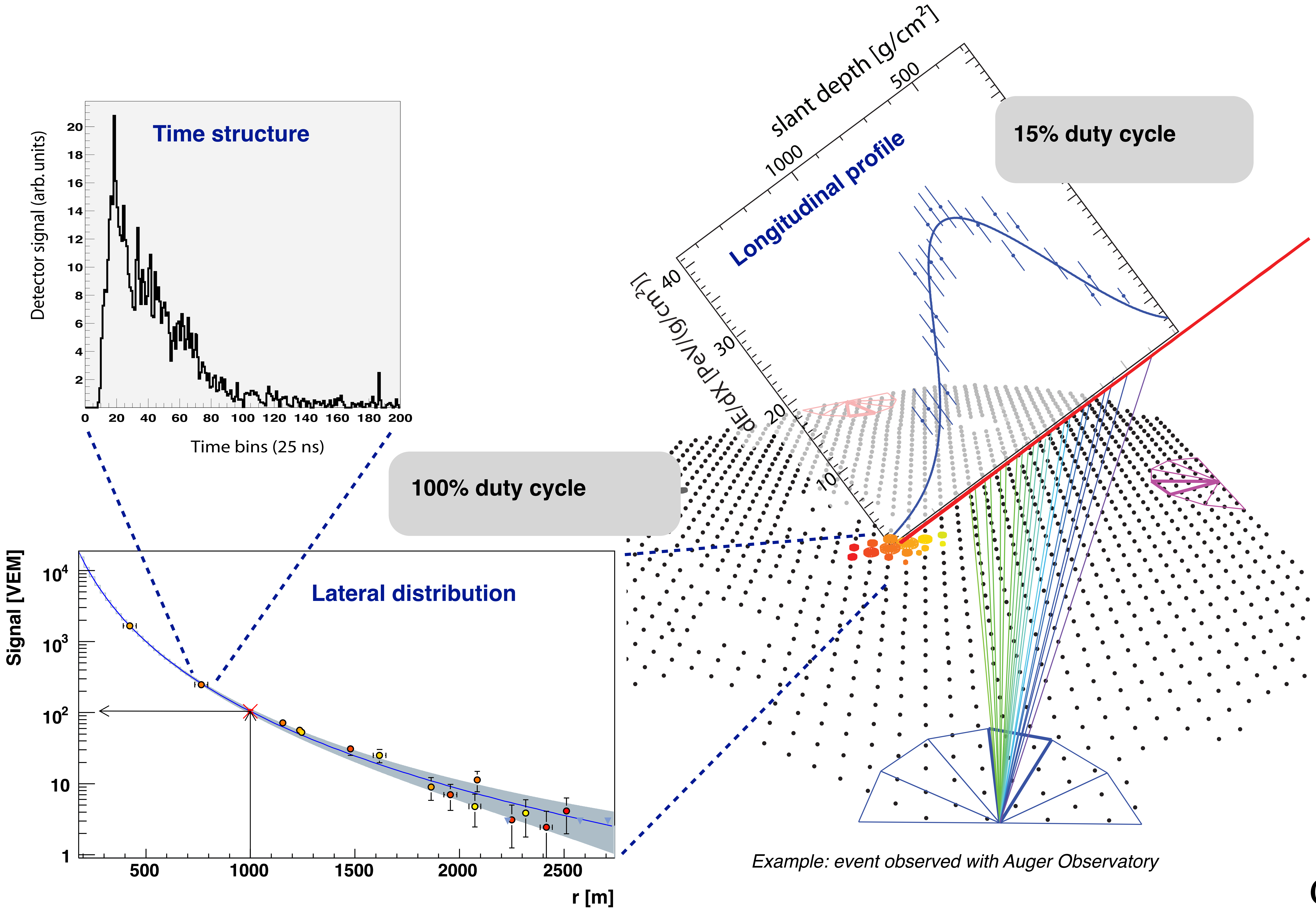
Pierre Auger Observatory
Province Mendoza, Argentina



More than 400 members,
98 institutes, 17 countries

Credit: R. Engel

The Pierre Auger Observatory



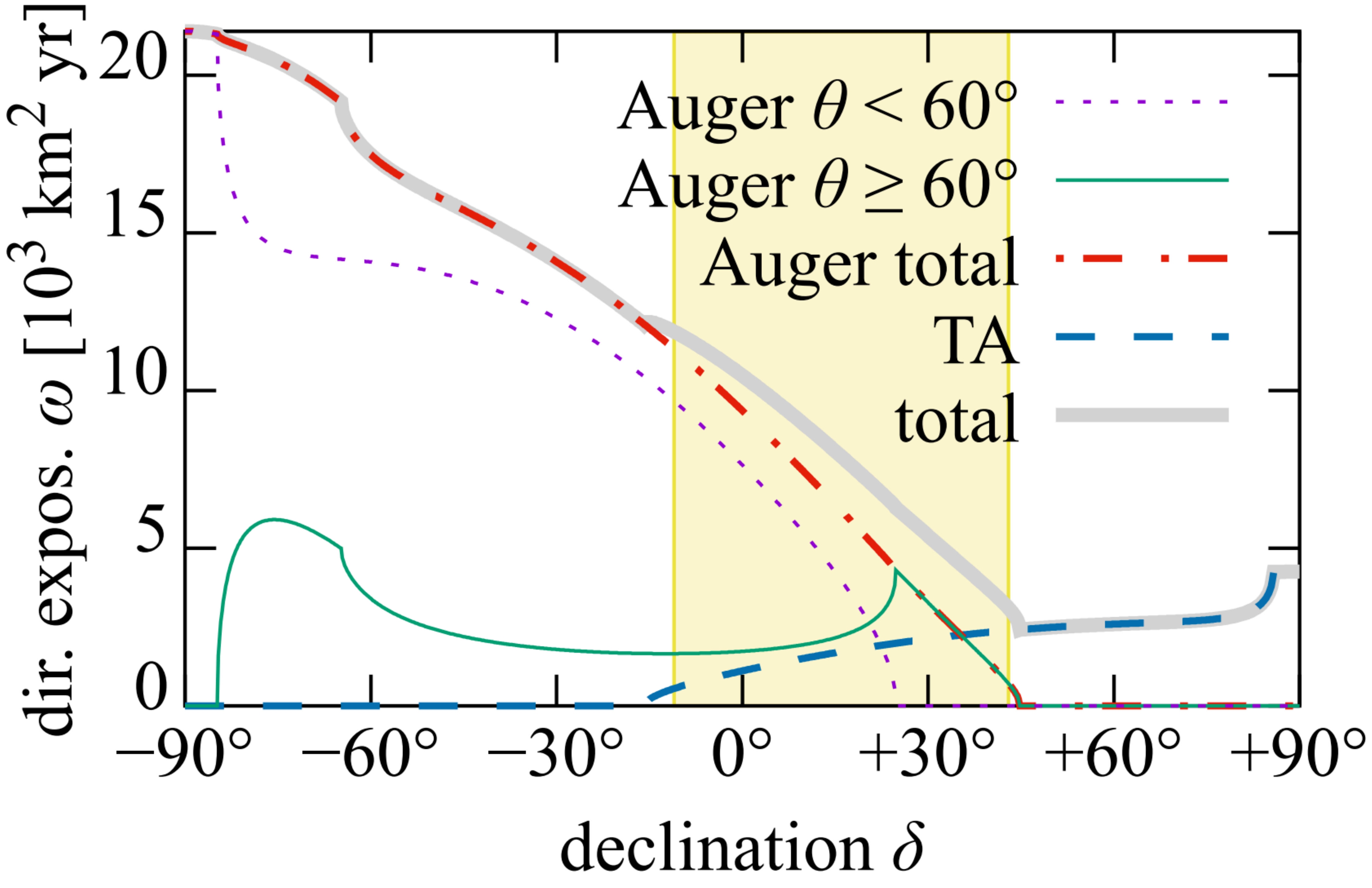
Example: event observed with Auger Observatory

Credit: R. Engel

Highest Energies: Two Observatories

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

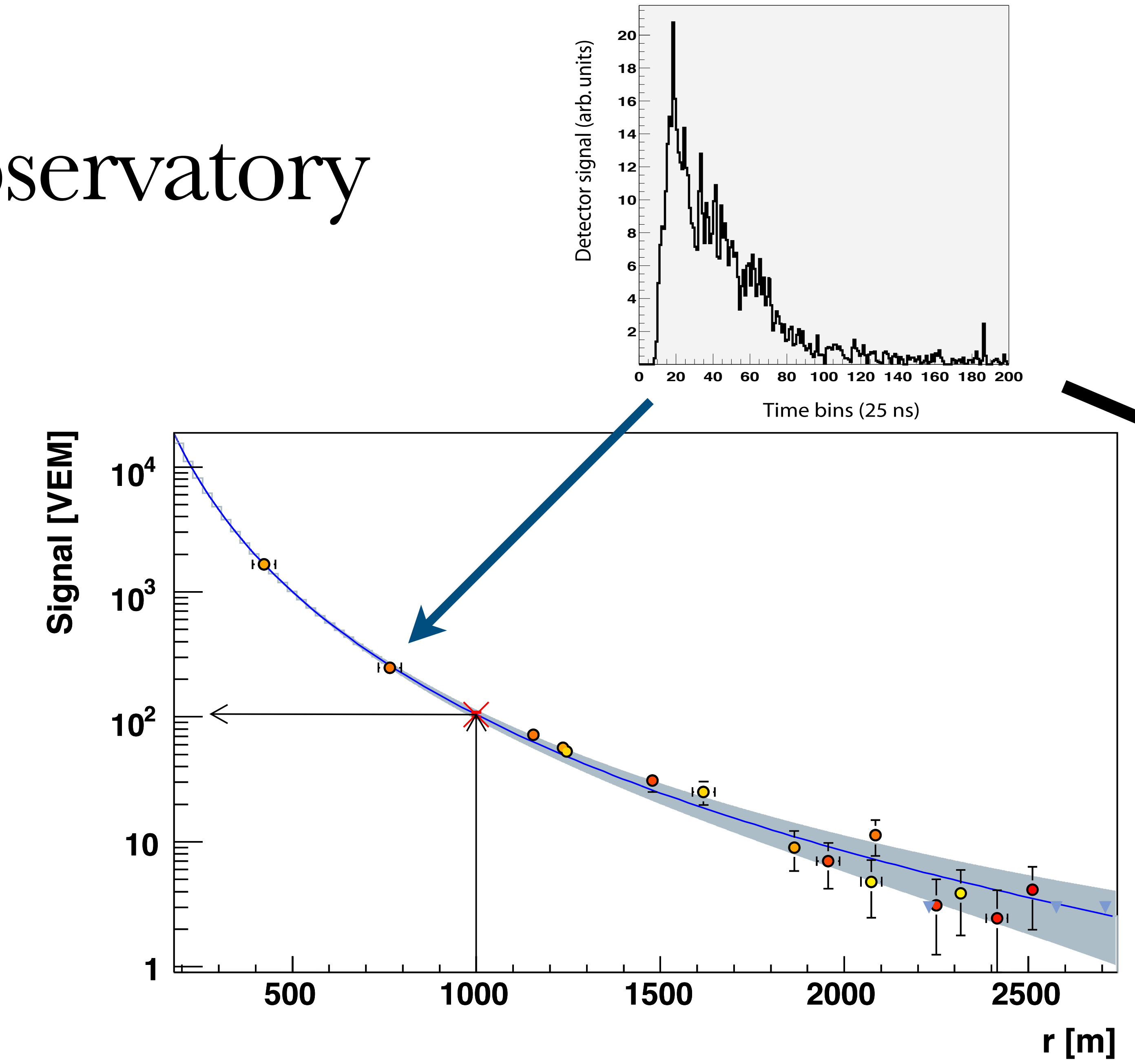
Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

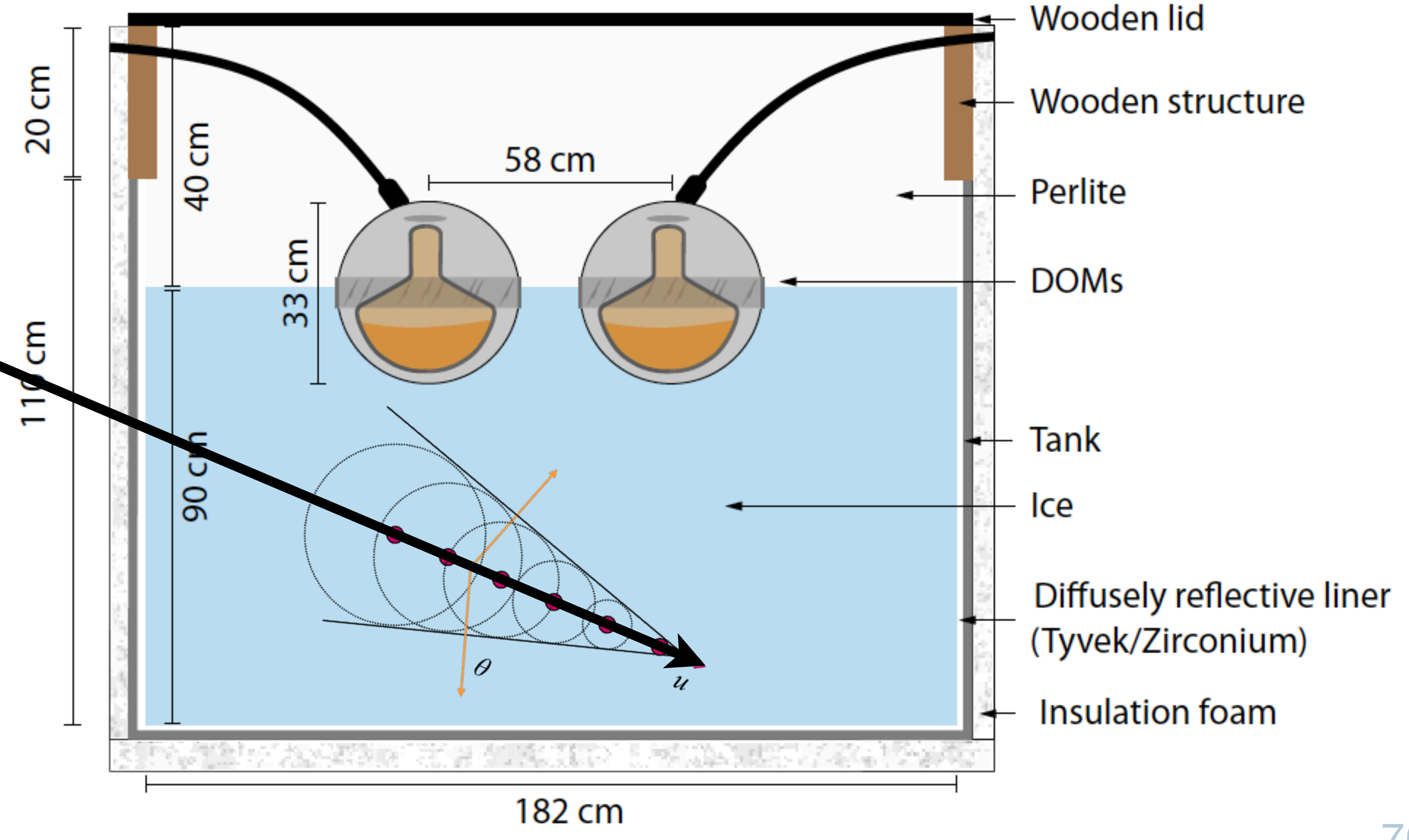


Credit: R. Engel

Water (Ice) Cherenkov Detectors

- Typically large particle detectors arrays equipped with water (ice) Cherenkov tanks
- Light sensors detect Cherenkov light from relativistic charged particles (next slide)
- Measures the lateral EAS profile
- Deposited energy, particle identification
- Examples:
  - Pierre Auger Observatory
  - IceTop





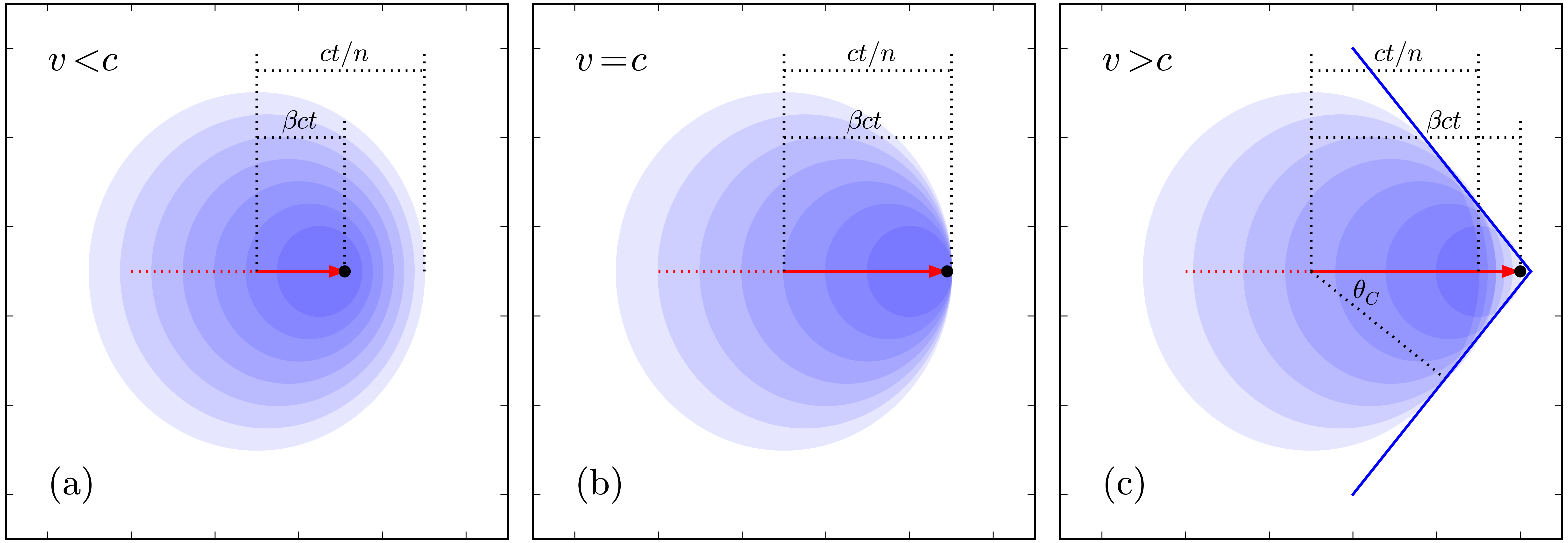
~100% duty cycle

Basics: Cherenkov Light

- Particle travels in dielectric medium (e.g. water) with refractive index n
- Speed of charged particle: $v_p = \beta c$
- Speed of electromagnetic wave (light) in medium: $v_{\text{em}} = c/n \equiv c_{\text{water}}$
- If $v_p > c_{\text{water}}$ (or $\beta n > 0$) constructive interference leads to an observed cone-like light signal at a characteristic angle
- Cherenkov angle:

$$\cos(\theta_C) = \frac{v_{\text{em}}}{v_p} = \frac{1}{\beta n}$$

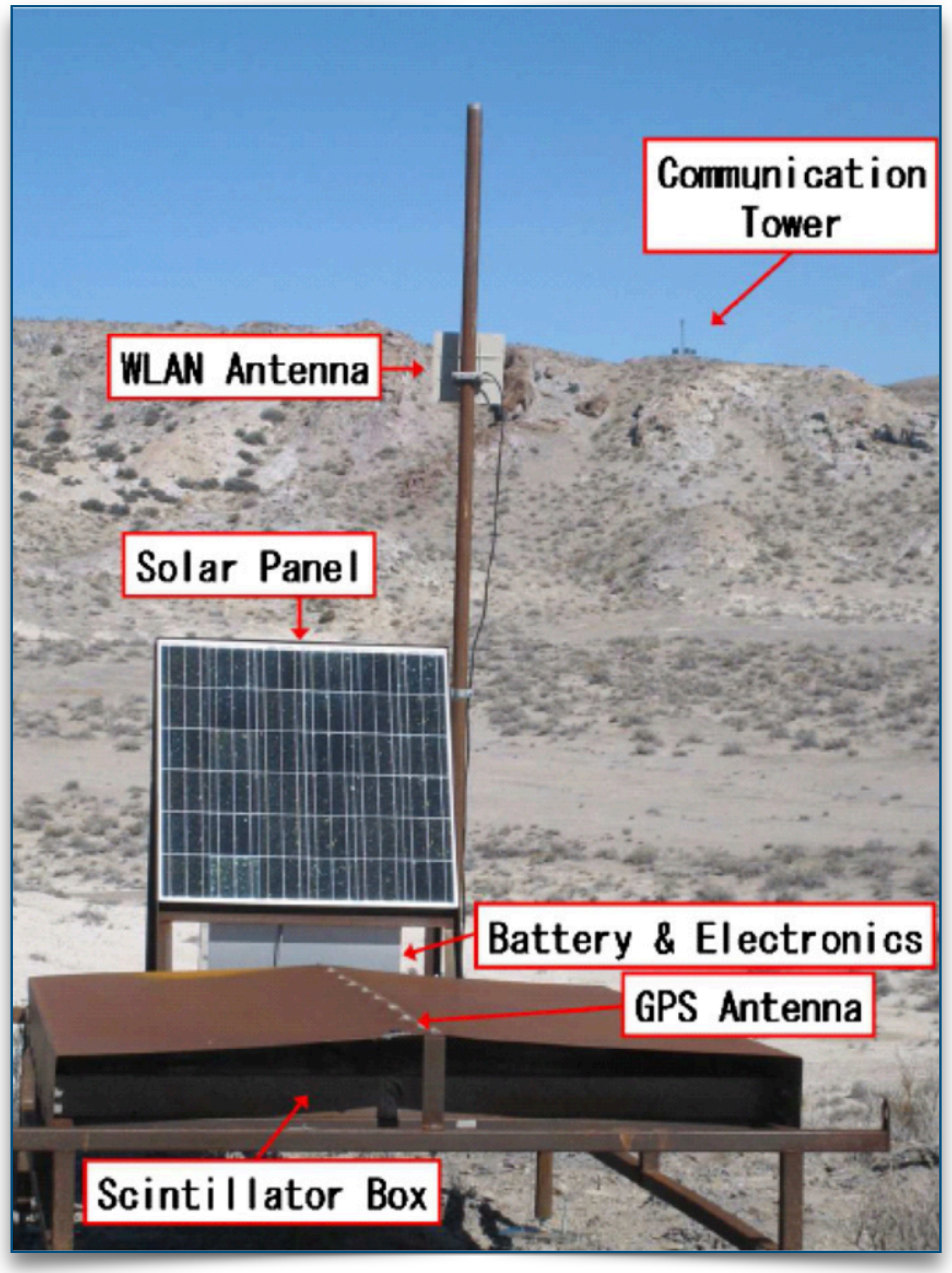
- More in the exercise!

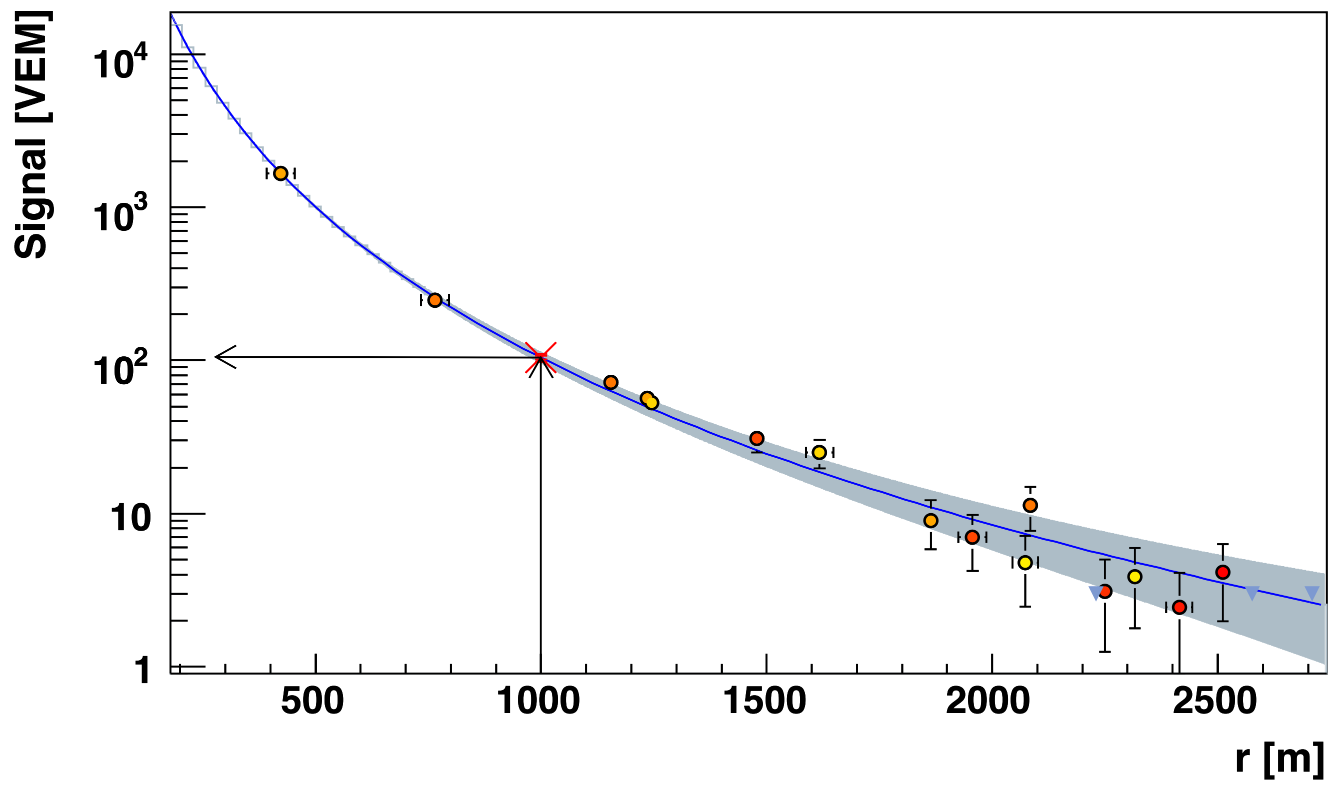


Scintillator Detectors

- Typically large particle detectors arrays equipped with scintillator panels
- Particles produce light in scintillator which is measured with light sensors (PMT, SiPM)
- Measures the <u>lateral EAS profile</u>
- Deposited energy, particle identification
- <u>Examples:</u>
  - Kascade-Grande
  - Telescope Array
  - IceTop Enhancement
  - AugerPrime

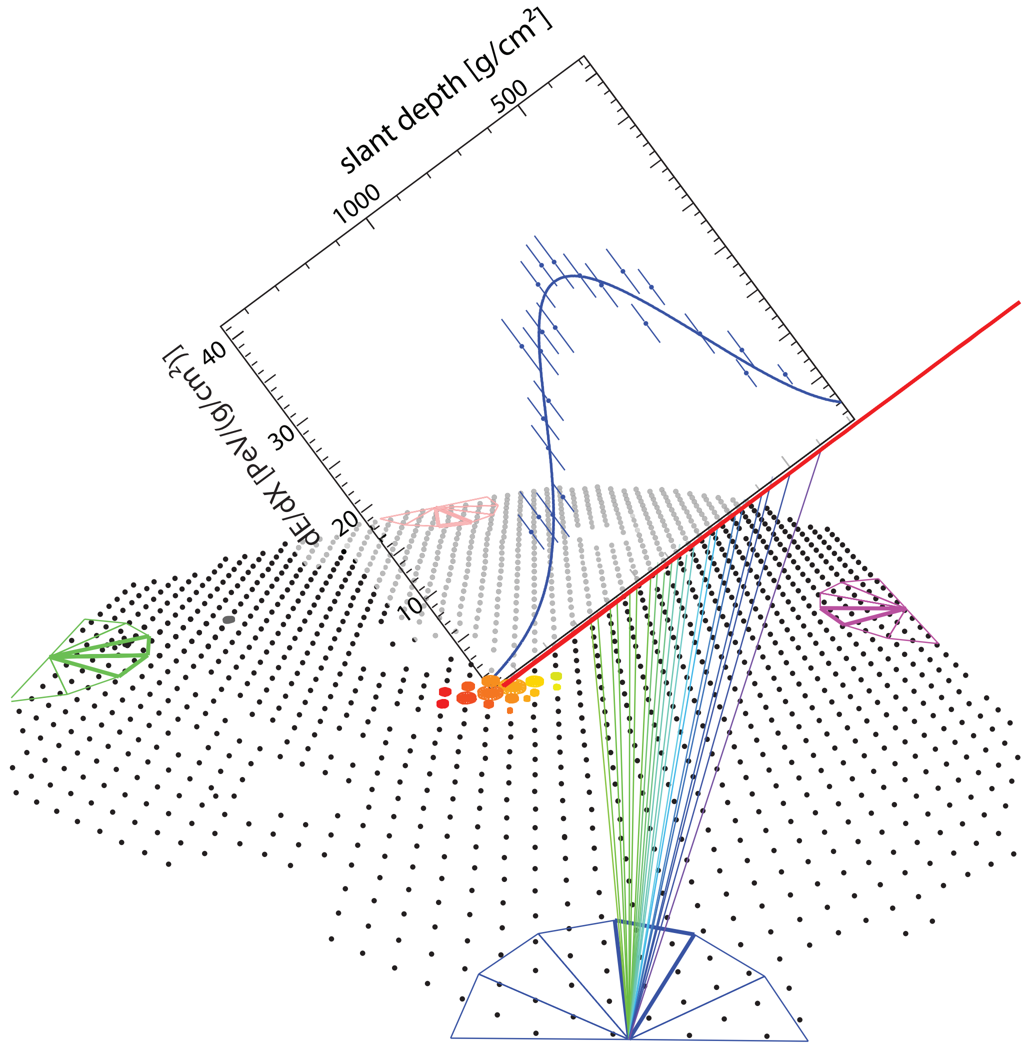
~100% duty cycle

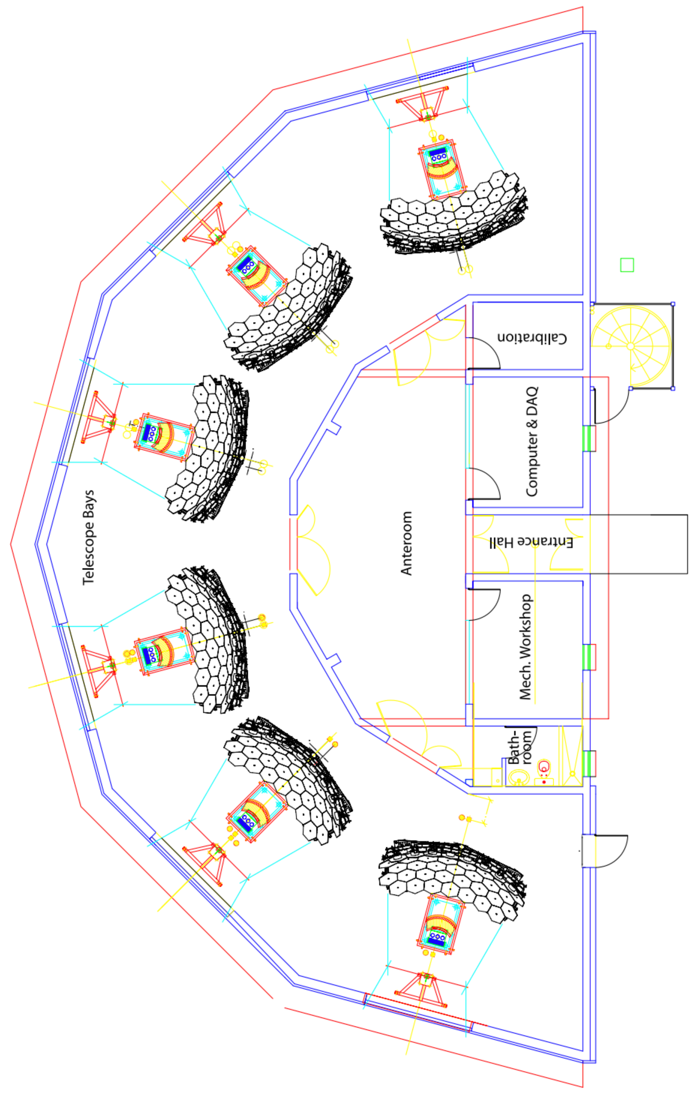


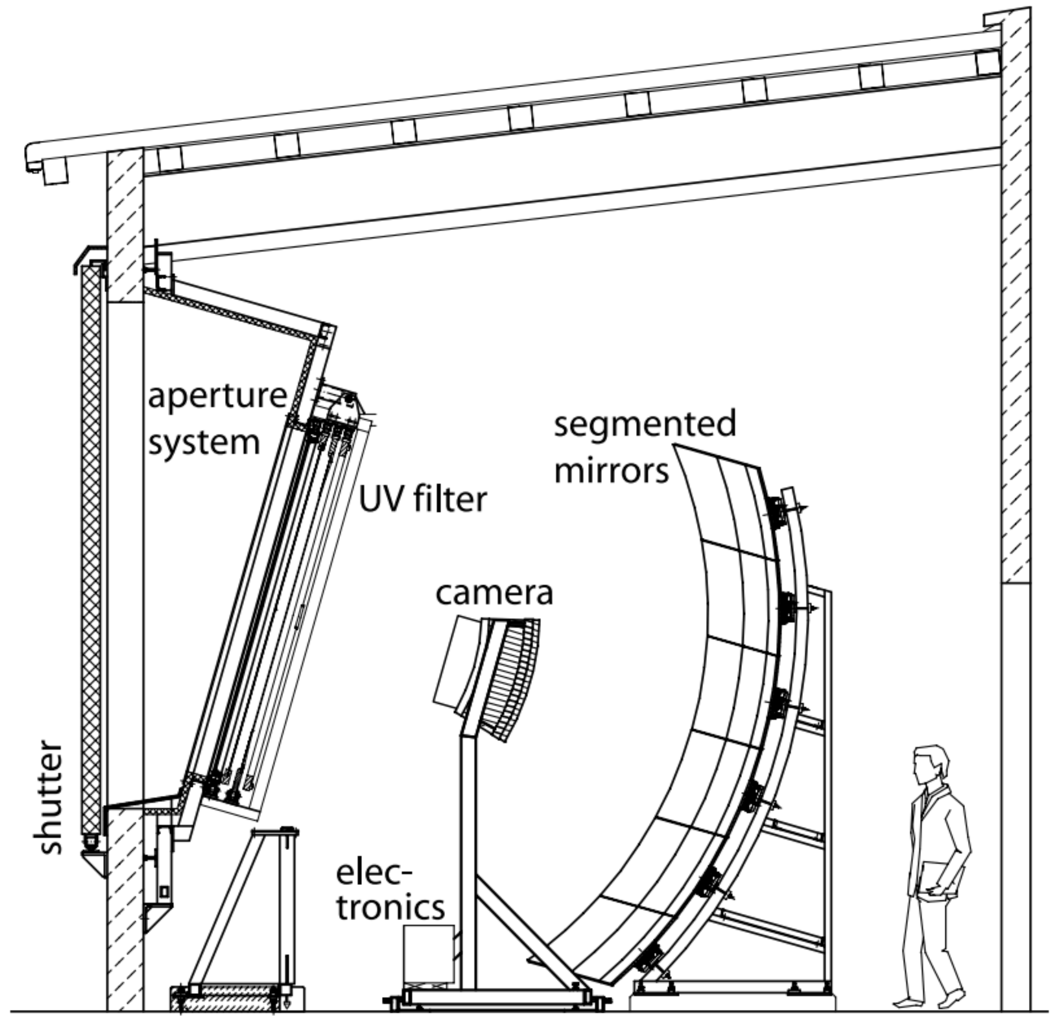


Fluorescence Telescopes

- Charged particles excite atmospheric nitrogen molecules in the air
- These molecules then emit fluorescence light in the ~ 300 − 430 nm range
- Number of emitted fluorescence photons is proportional to the energy deposited in the atmosphere due to electromagnetic energy losses
- Measures the longitudinal EAS profile $dE(X)/dX$
- Examples:
  - Pierre Auger Observatory
  - Telescope Array





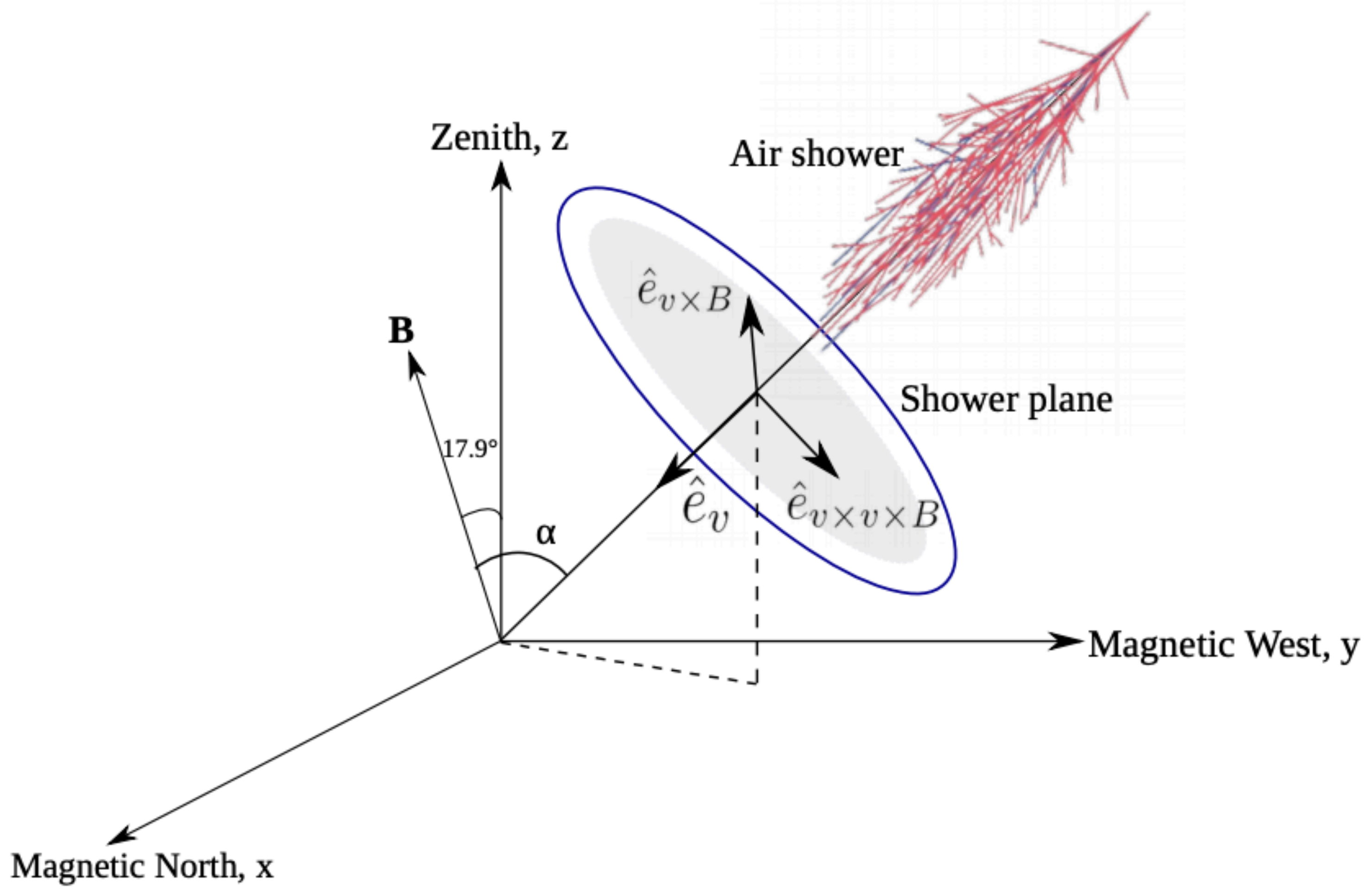


~15% duty cycle

Radio Detection of EAS

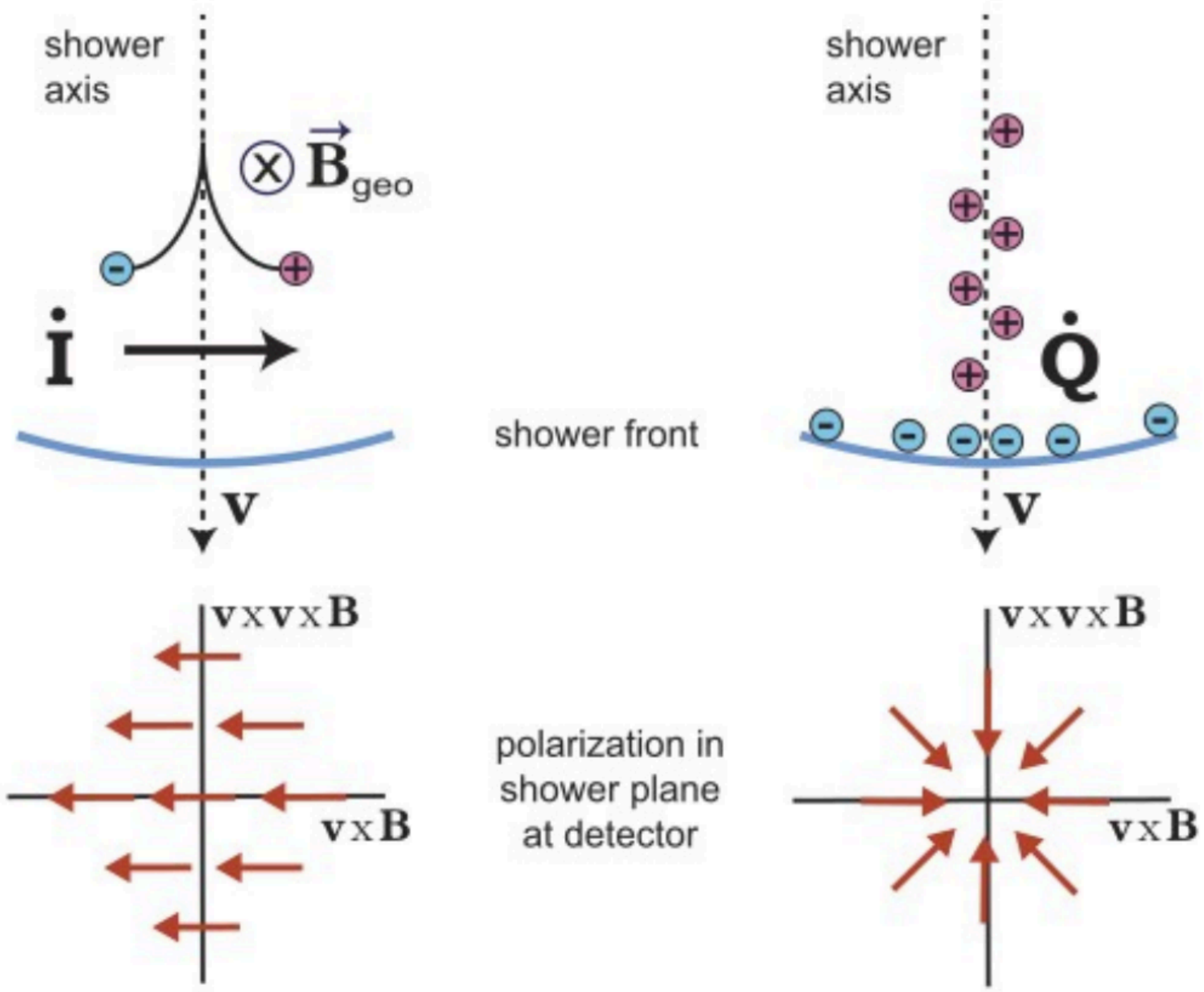
- Two main mechanisms in EAS to produce radio emission:

shower coordinates



Geomagnetic emission

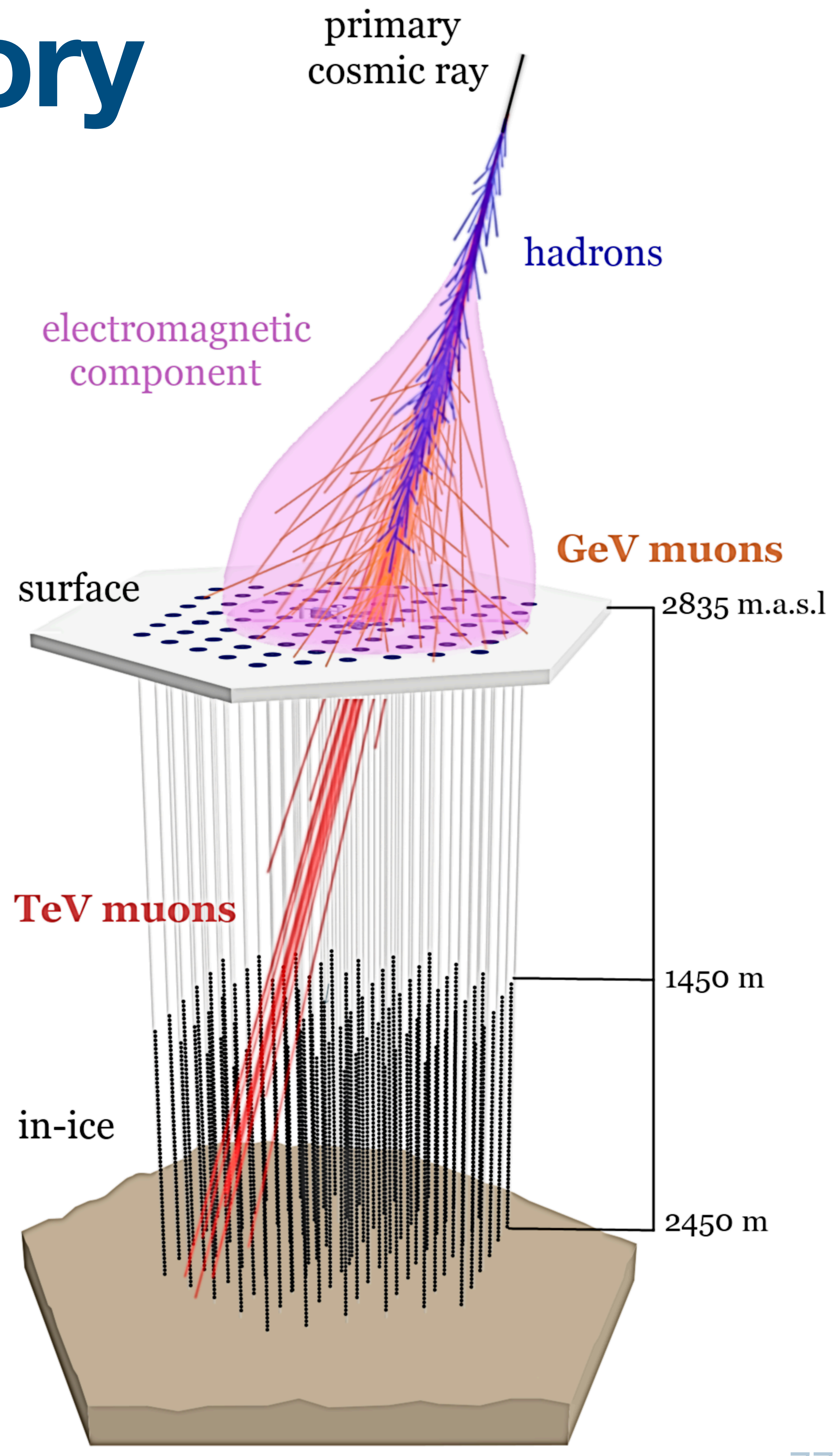
Askaryan emission



~100% duty cycle

The IceCube Neutrino Observatory

- Hybrid cubic-kilometer particle detector at South Pole
- Surface detector, IceTop, measures:
  - Electromagnetic EAS component (EAS energy)
  - GeV muon content
- In-ice detector measures:
  - TeV (up to several PeV) muon content
- Coincident measurements possible!
- Ideal facility to study lepton production in EAS!
- New surface detectors under construction
  - Scintillator panels
  - Radio antennas
  - Imaging Cherenkov telescopes



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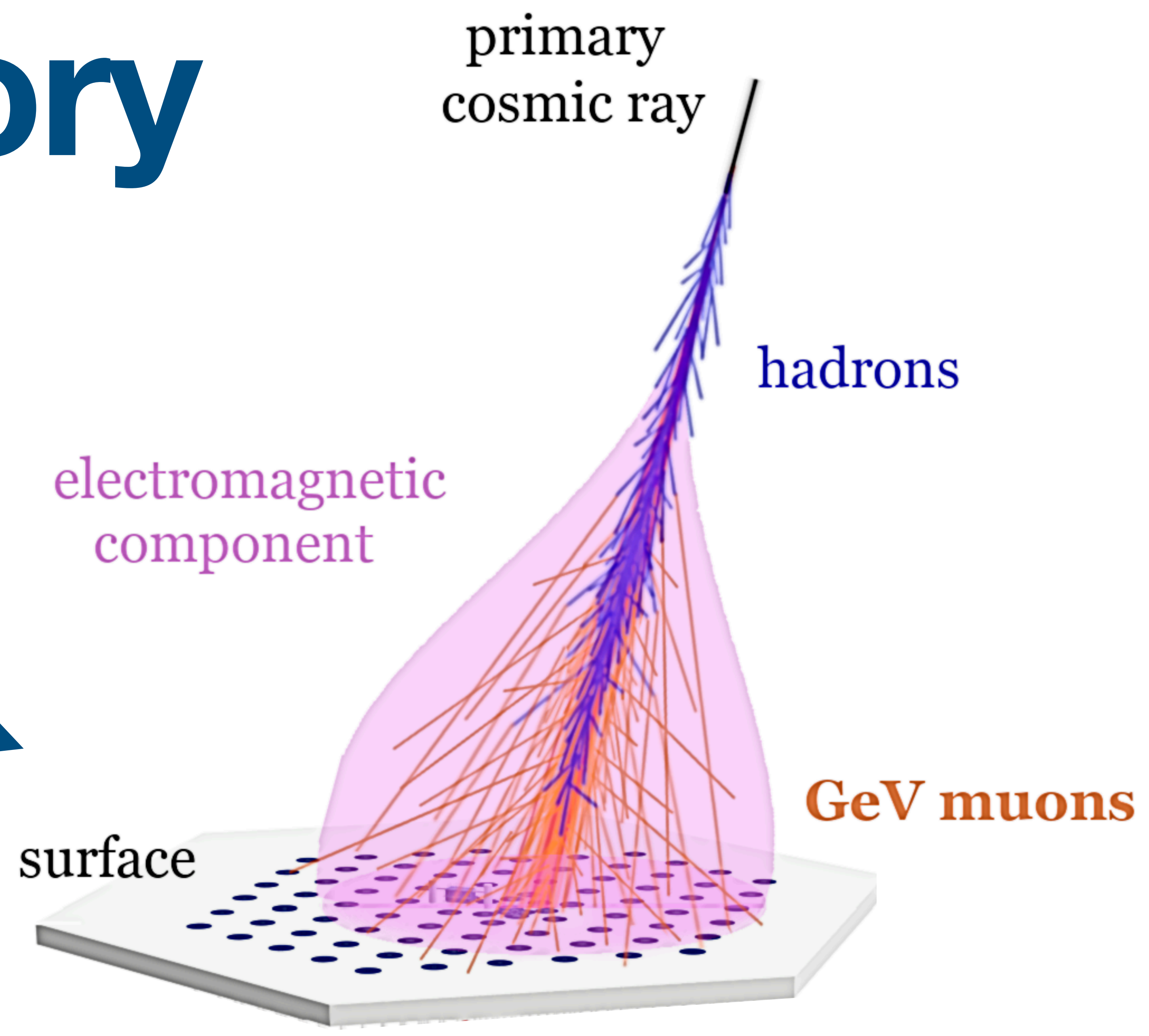

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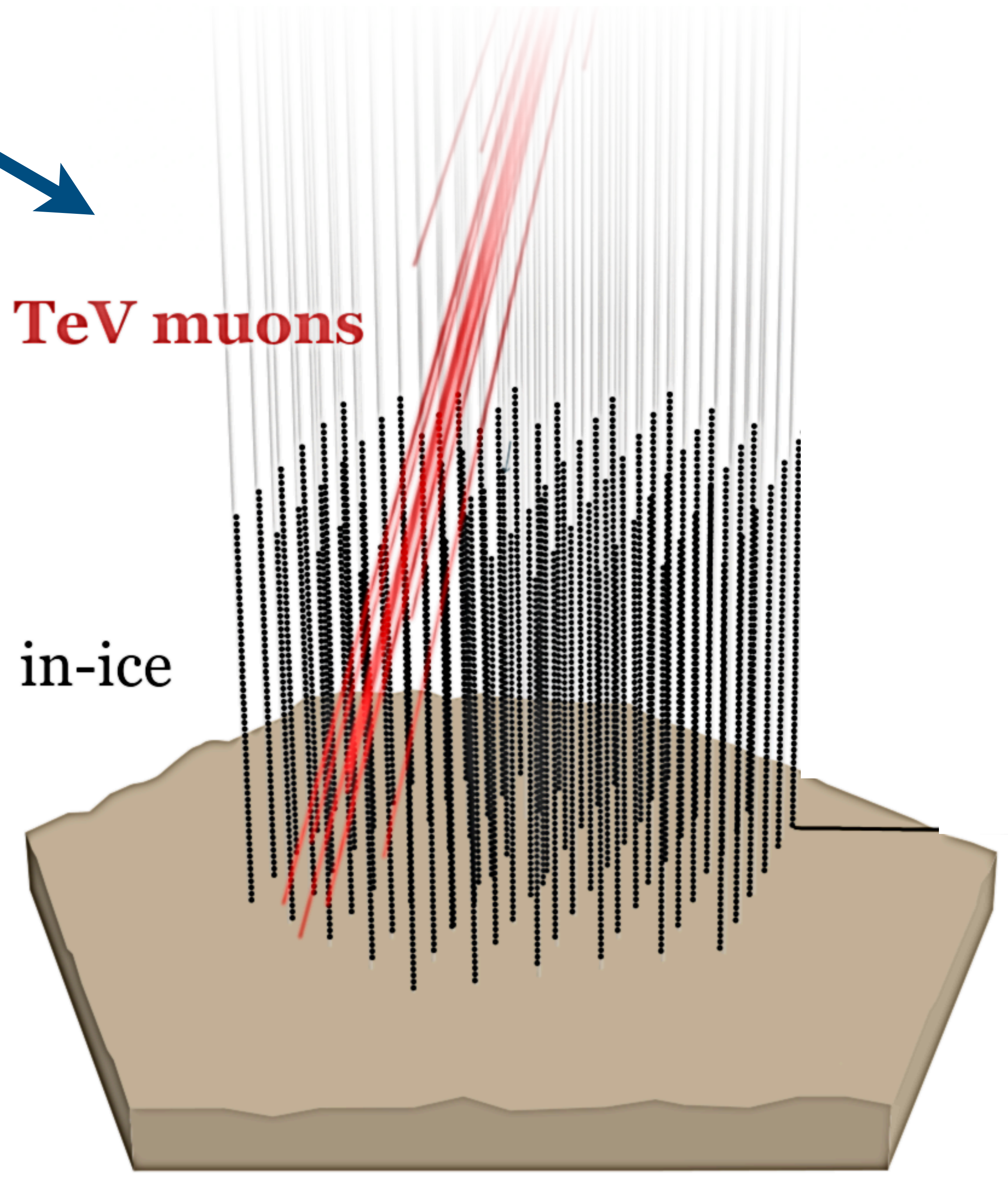

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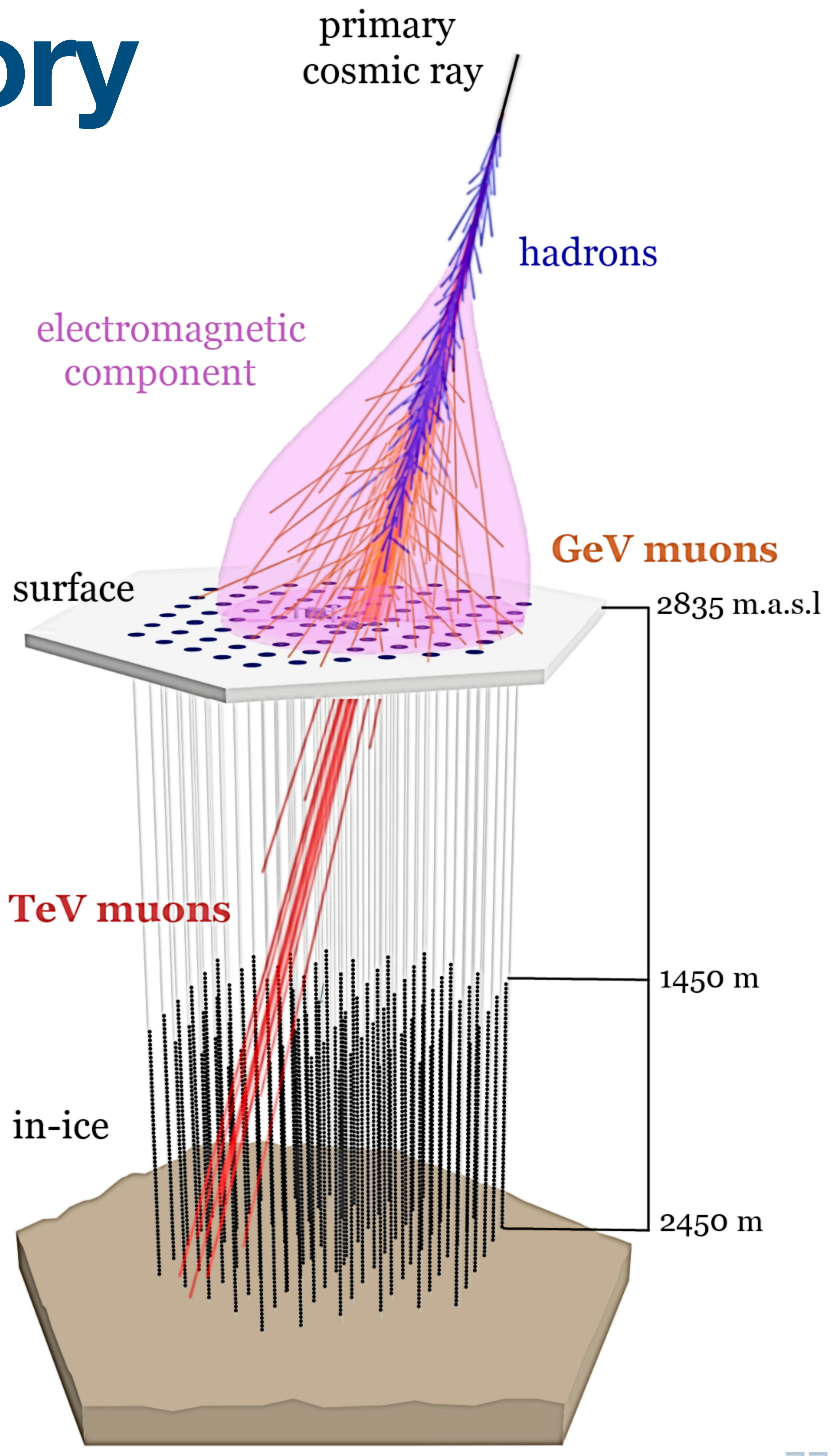

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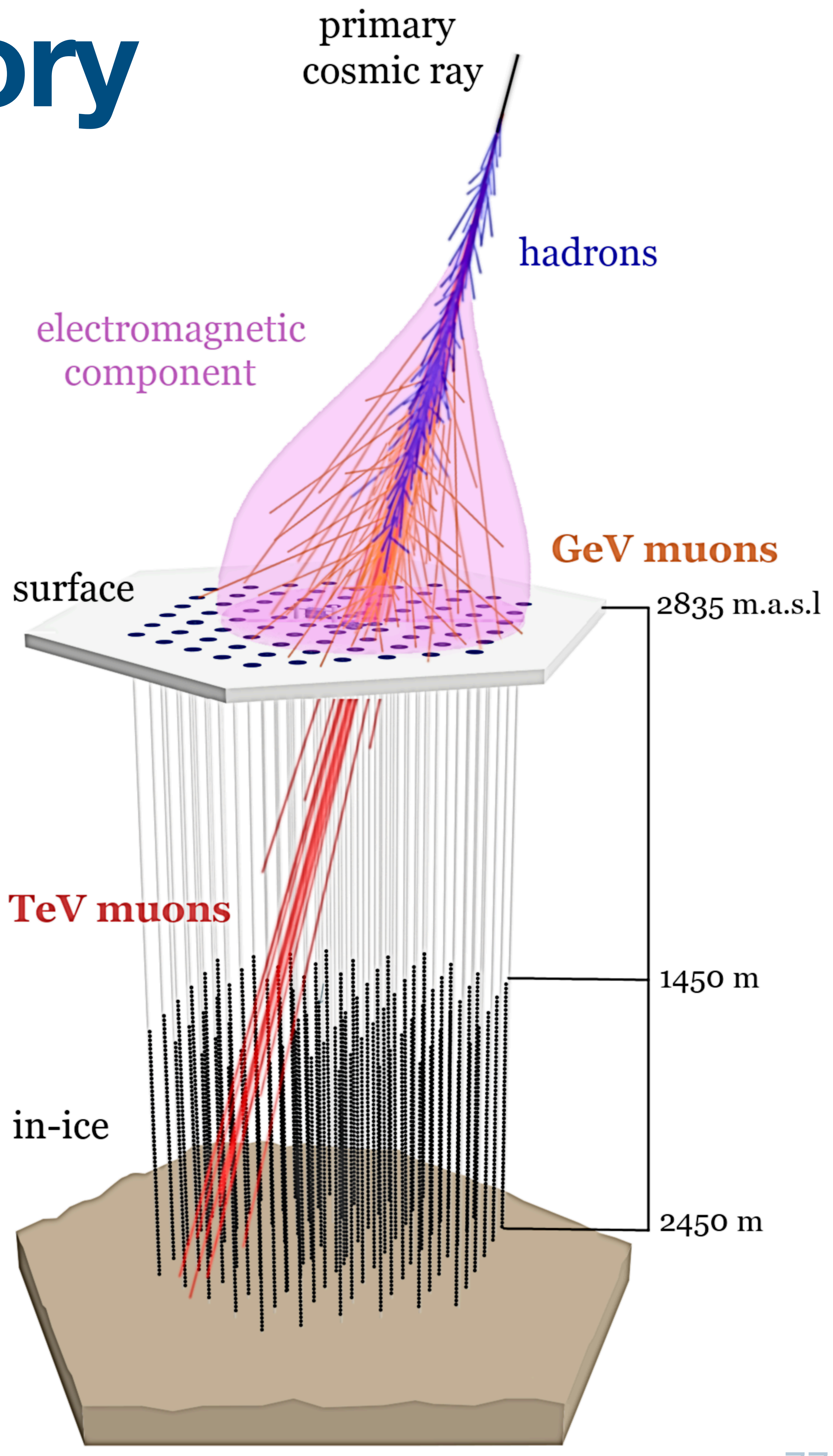

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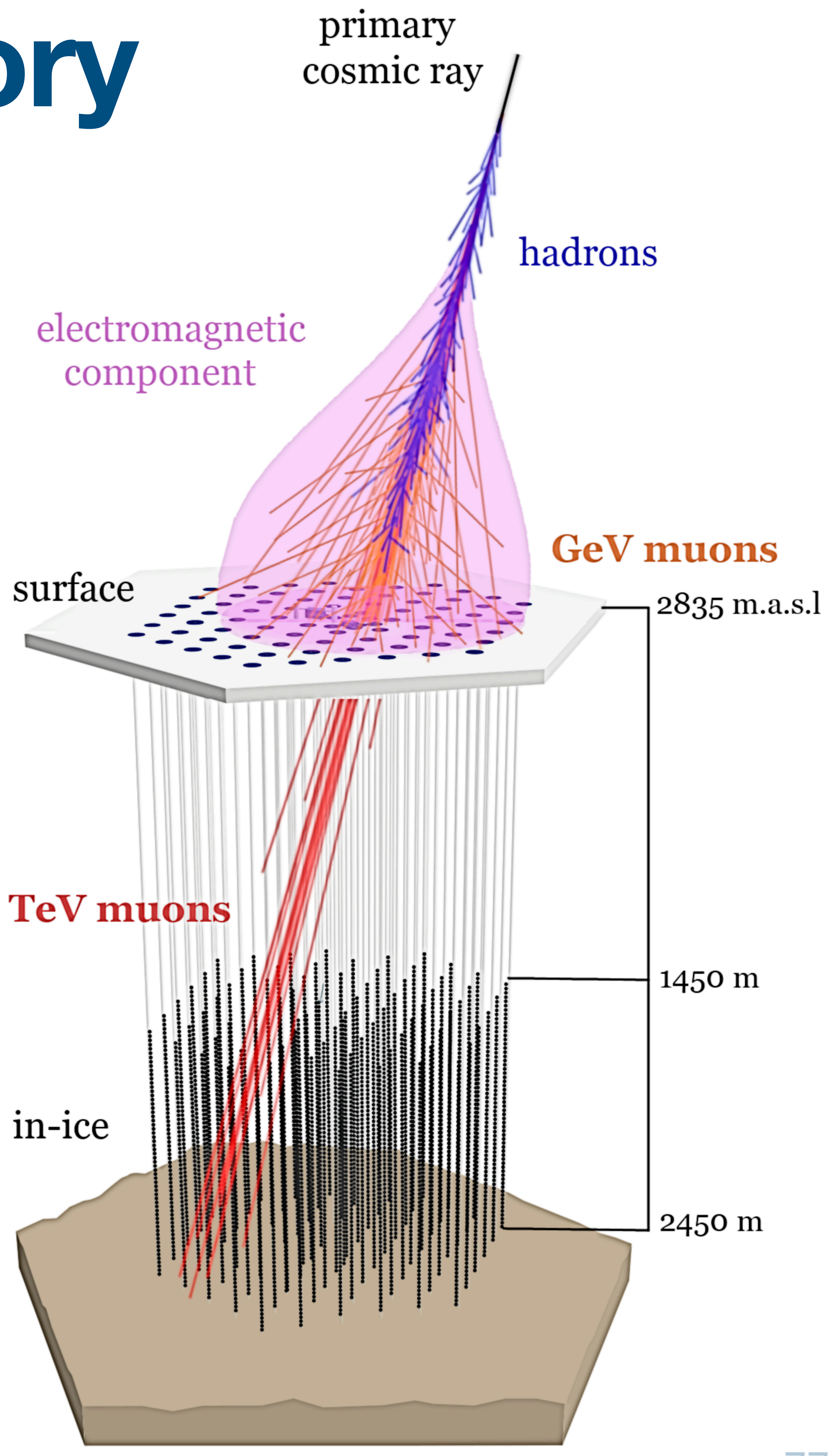
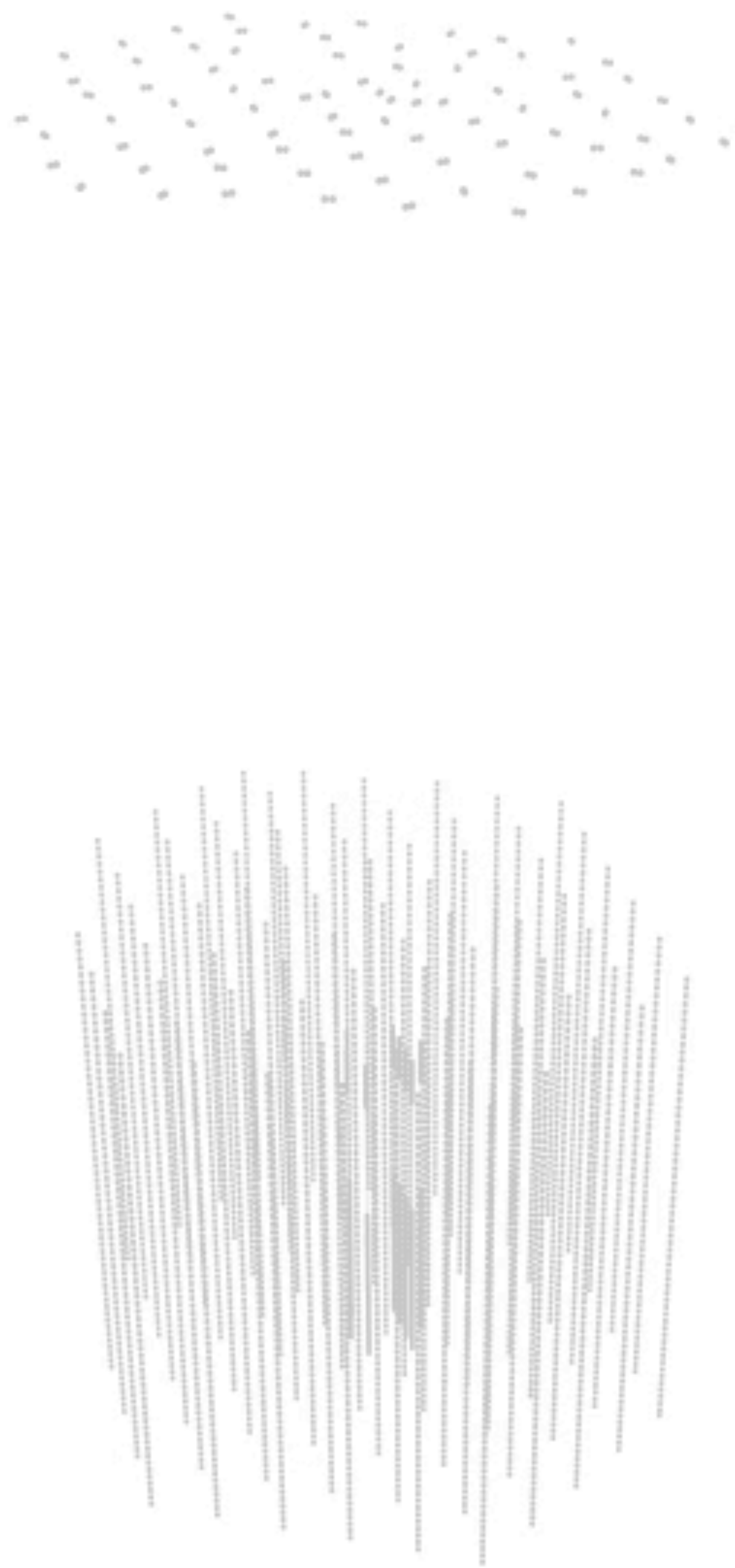


EAS Measurements with IceCube

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

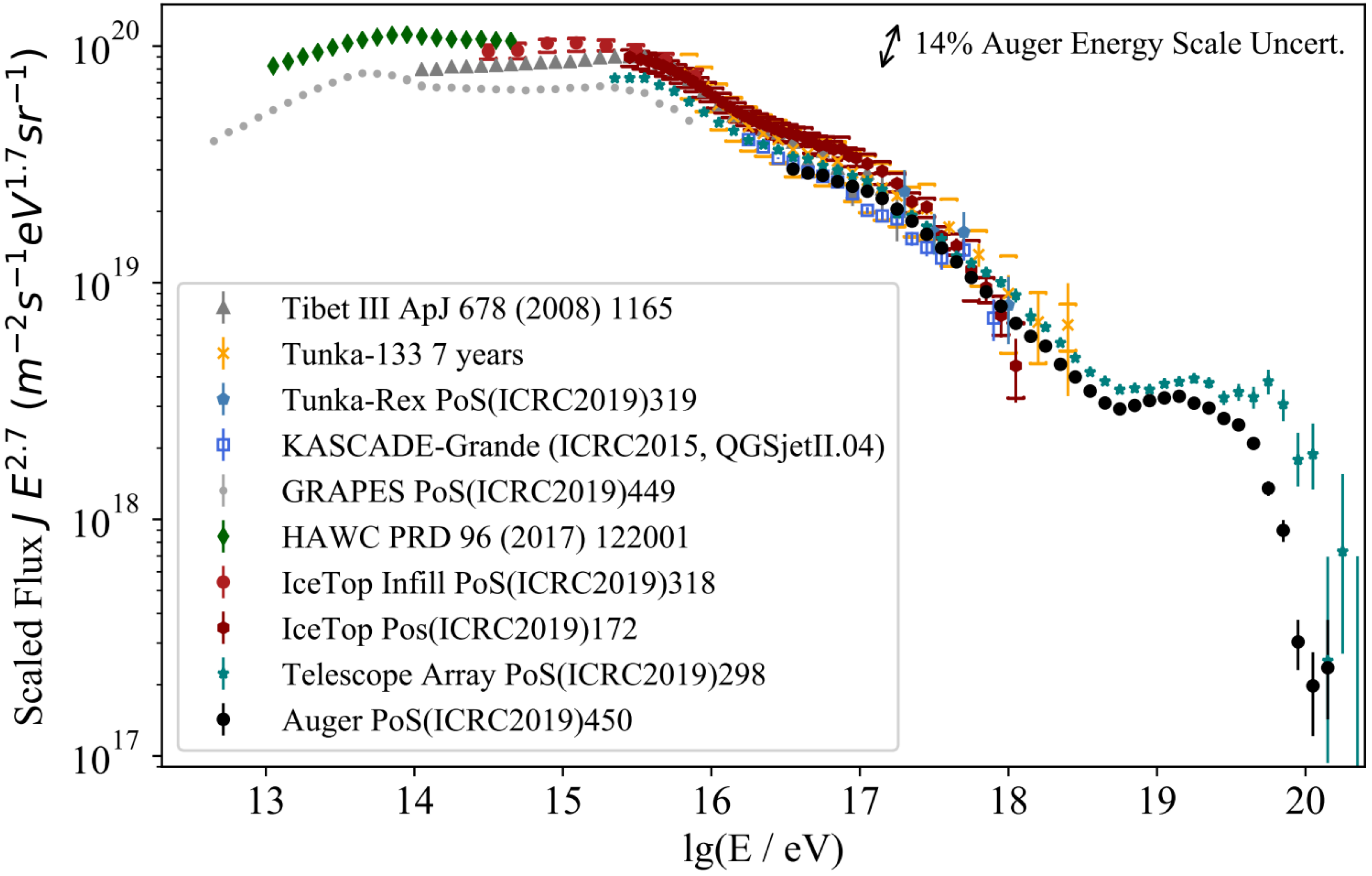


Recent Selected Results

Cosmic Ray Spectrum and Mass Composition

Cosmic Ray Spectrum

- Qualitative agreement between experiments
- Several features observed by all experiments
  - Sources?
  - Propagation?
- Energy offsets between experiments visible
- Tension between Auger and TA at the highest energies



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

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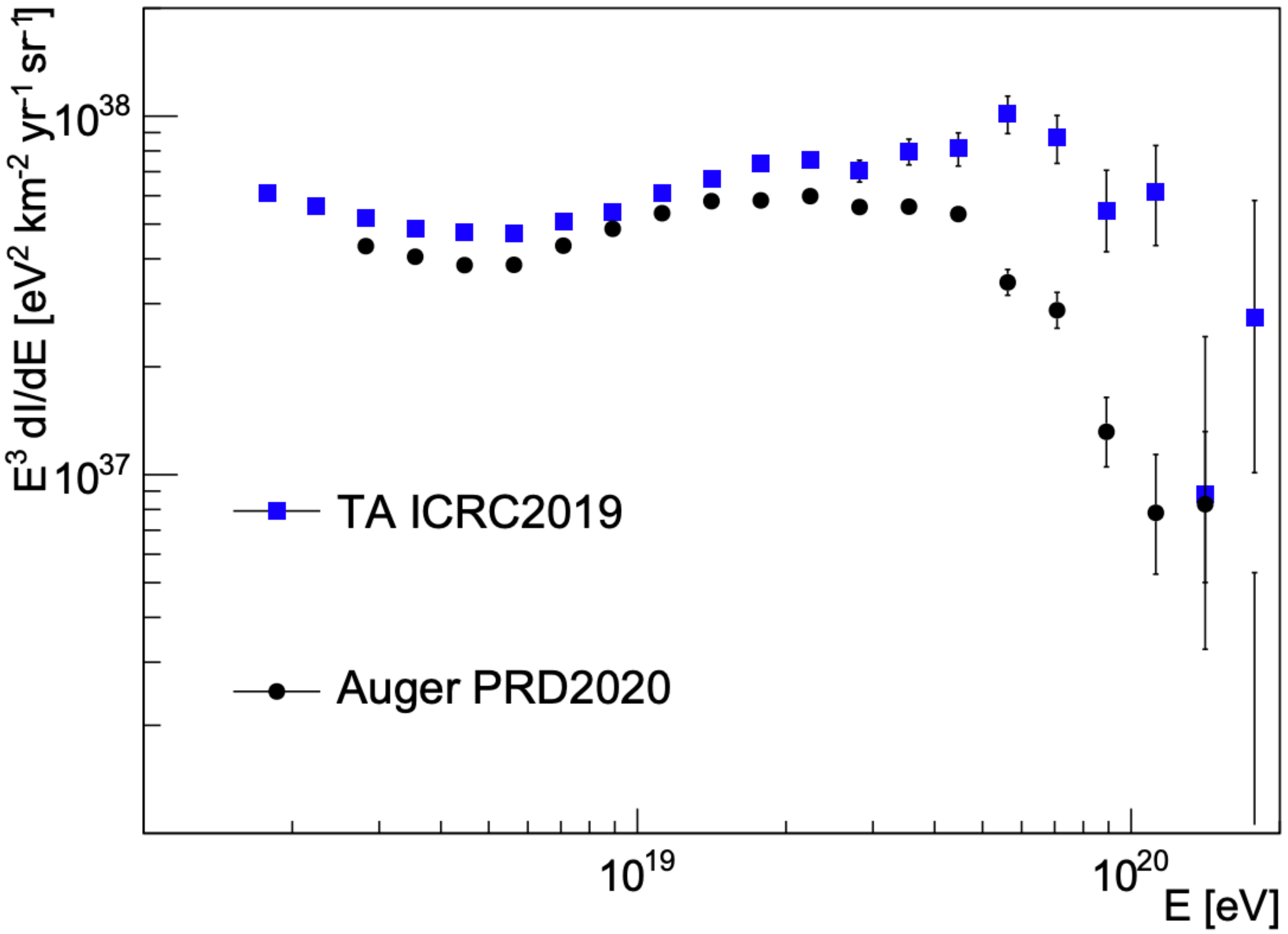
[A. Coleman et al., Astropart. Phys. 147 (2023)]



Cosmic Ray Spectrum

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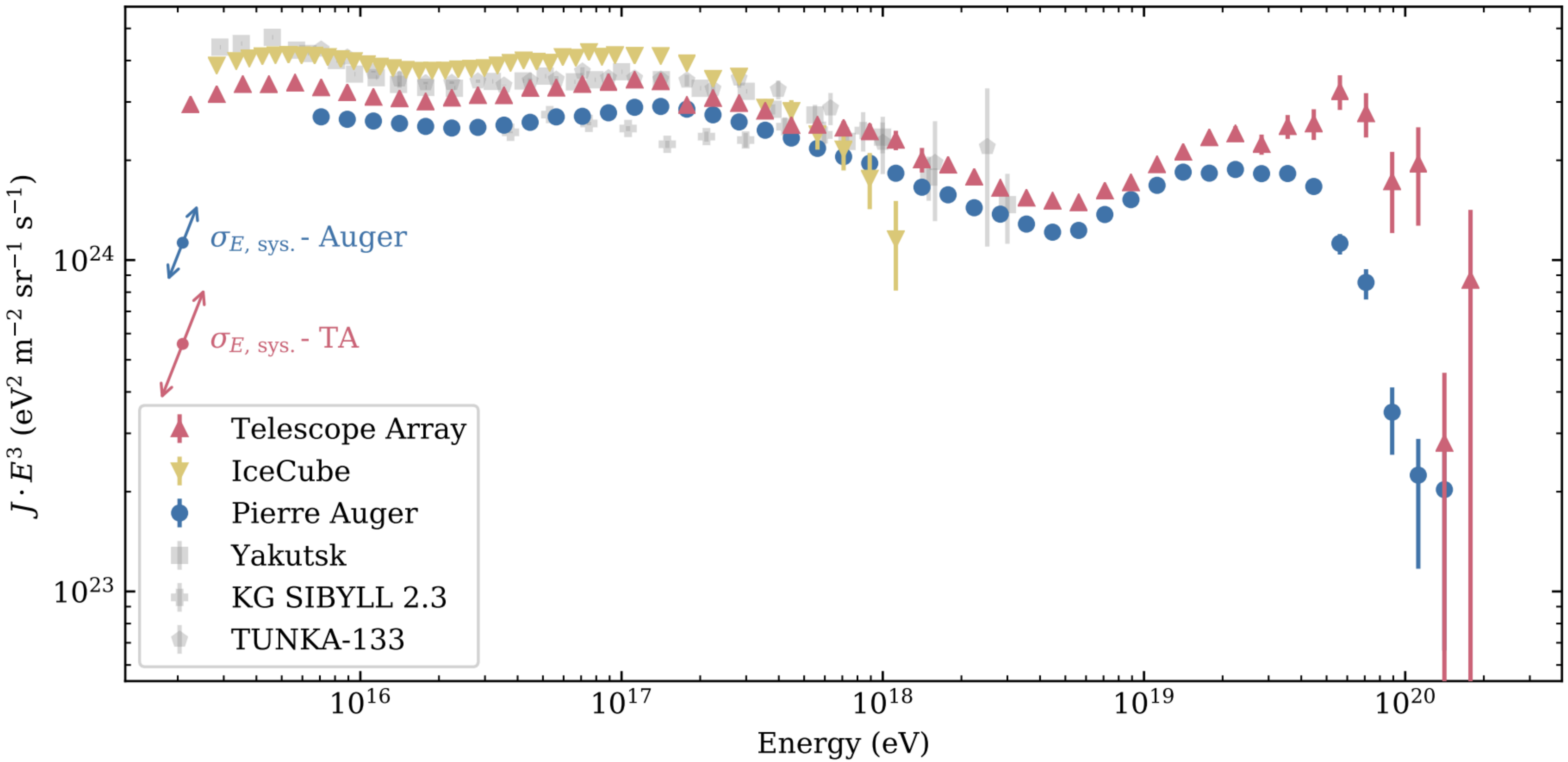
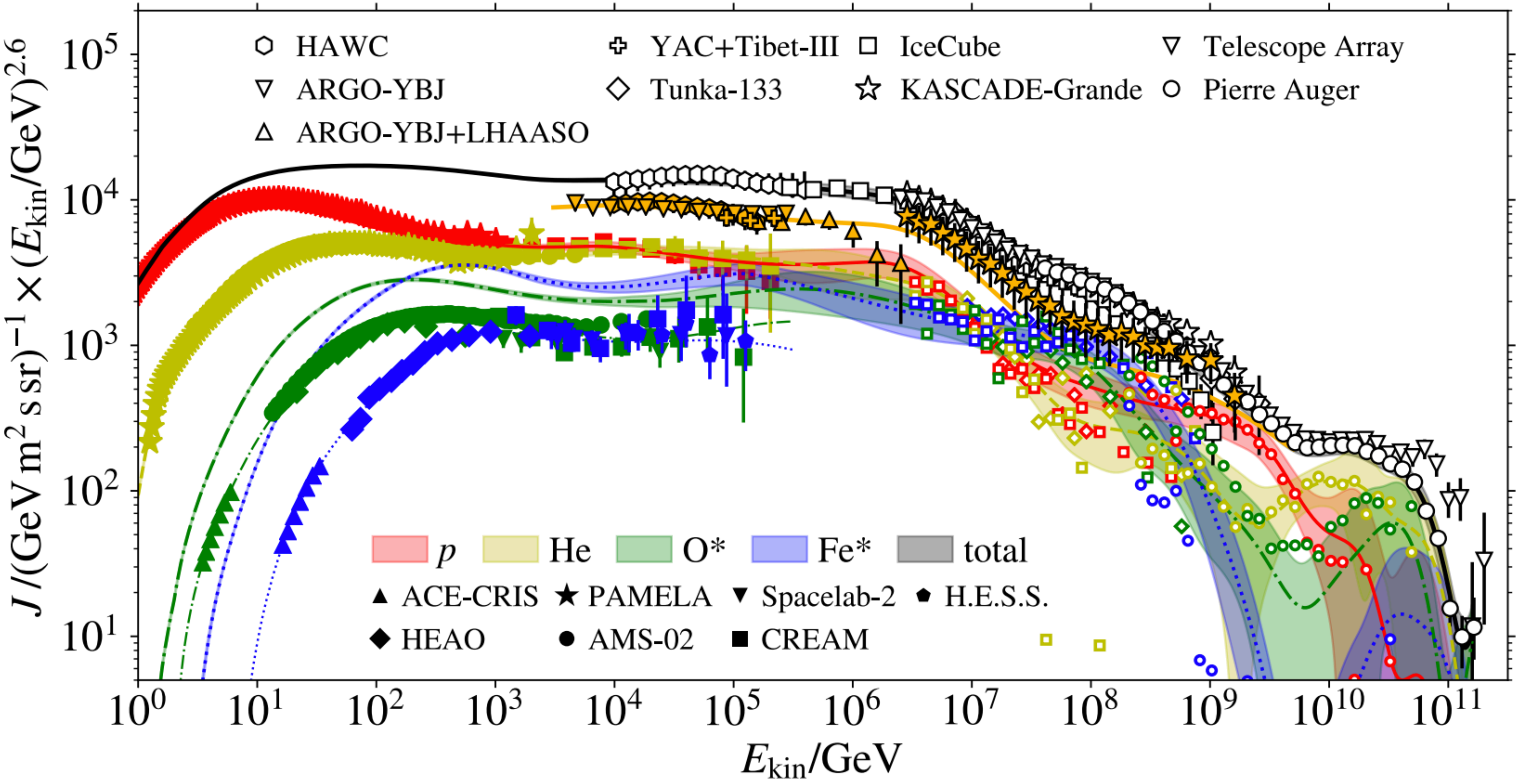


Cosmic Ray Mass Composition

- **G**lobal **S**pline **F**it (GSF) flux model

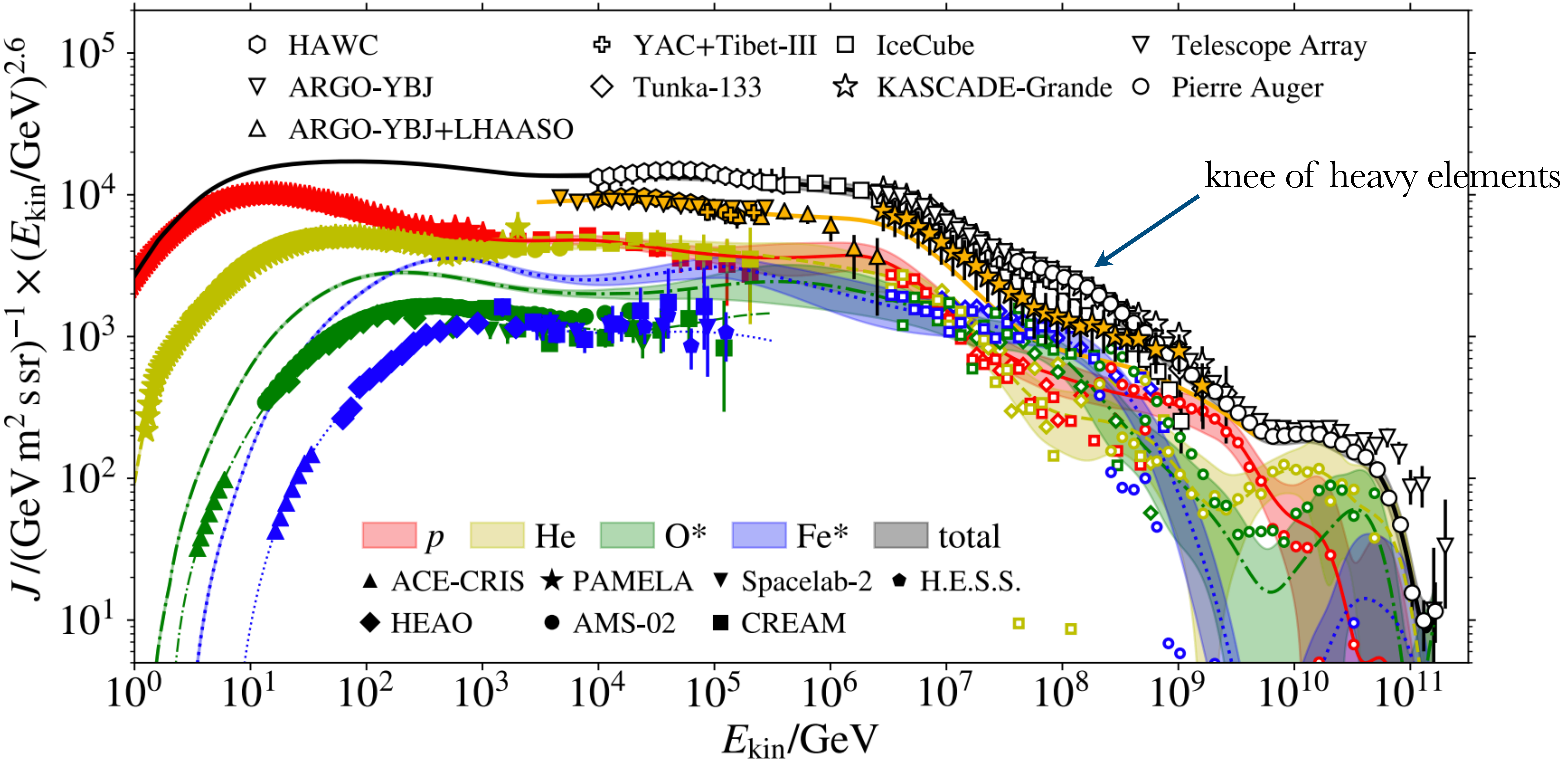
[H.P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser, F. Riehn, T. Stanev, PoS ICRC2017 (2017) 533]



Cosmic Ray Mass Composition

- **G**lobal **S**pline **F**it (GSF) flux model

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



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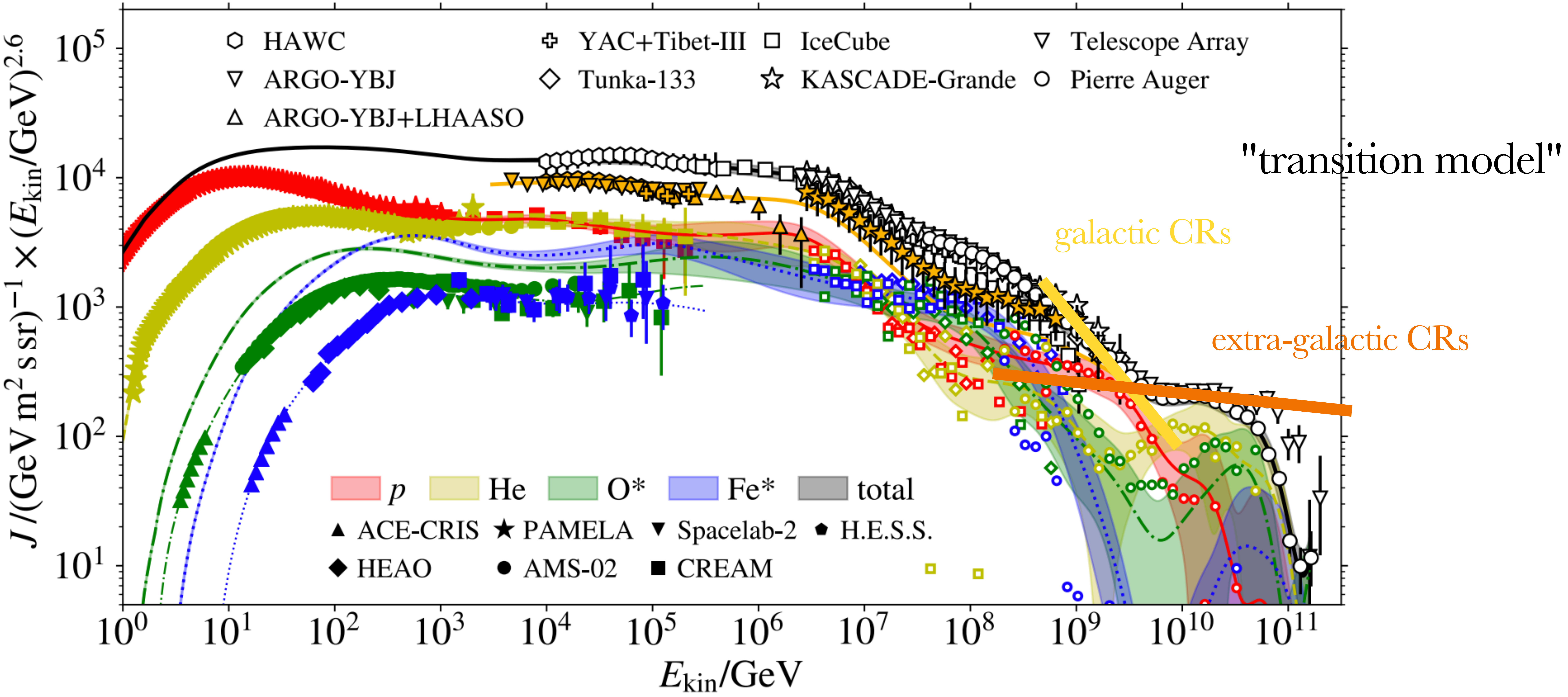

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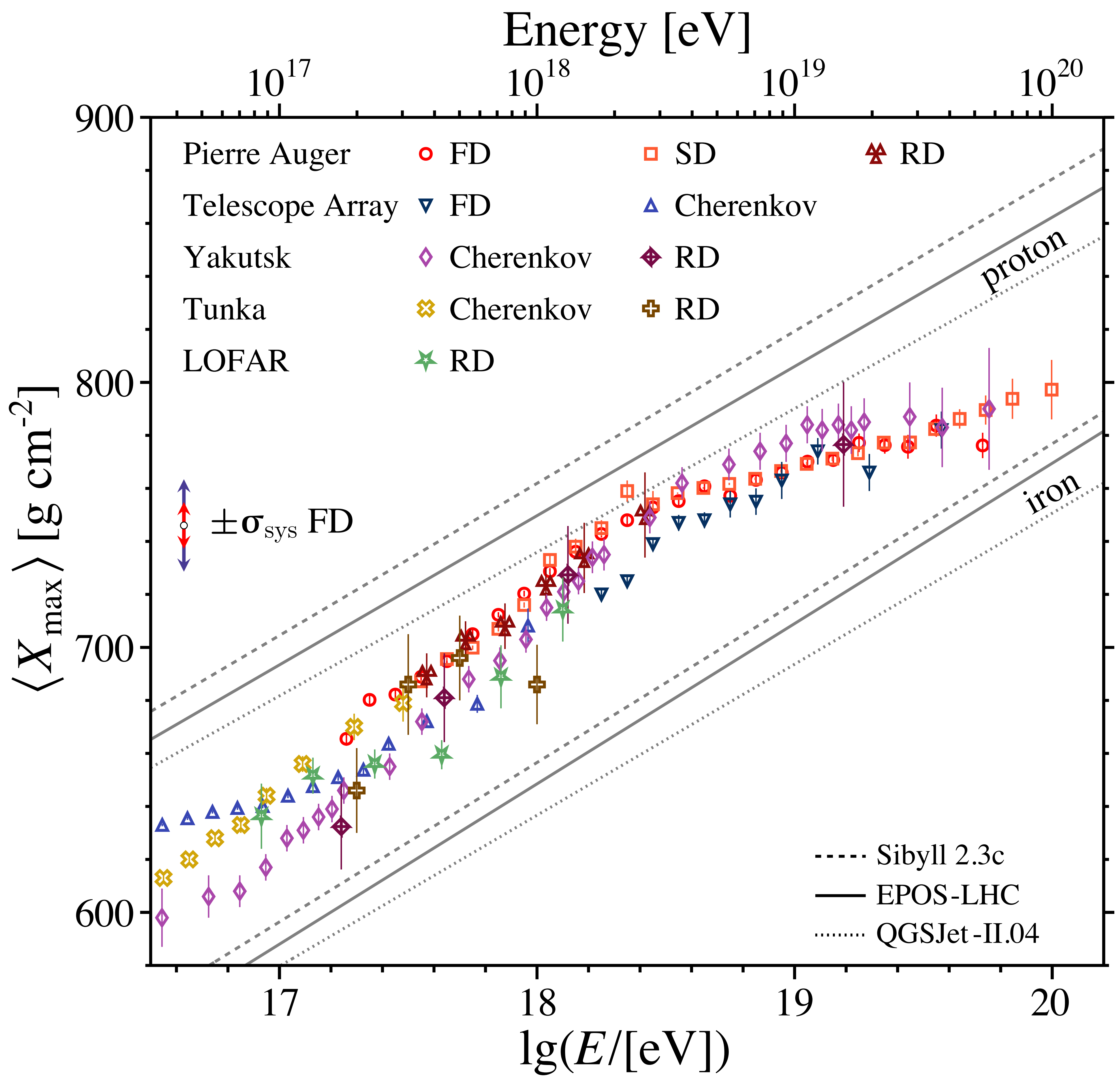
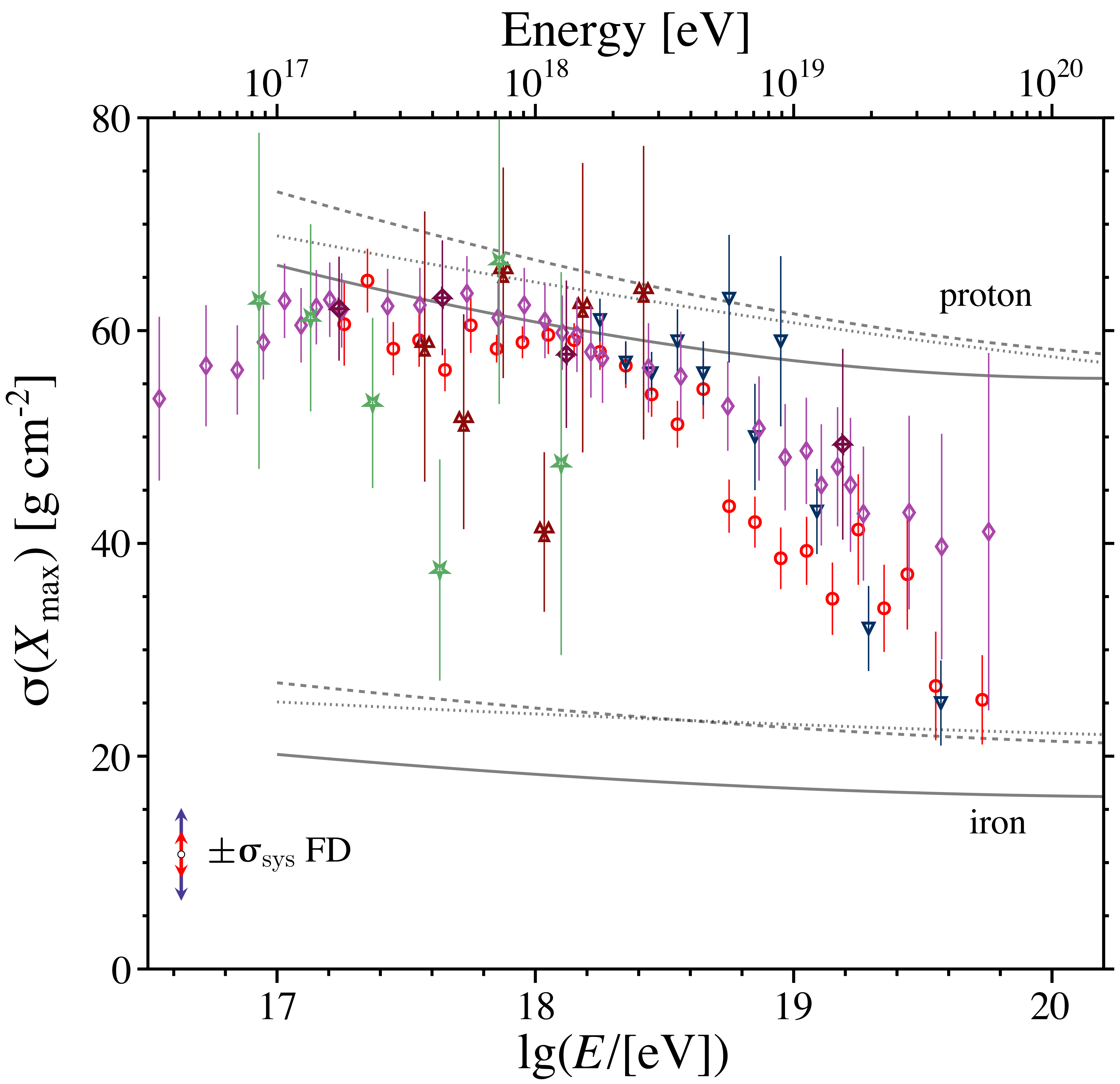




[A. Coleman et al., Astropart. Phys. 147 (2023)]

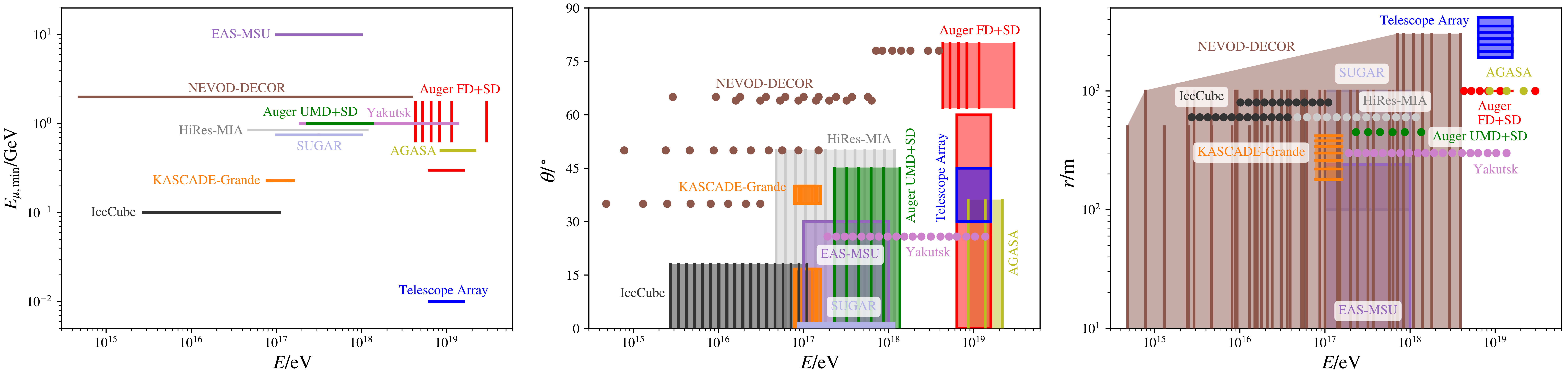
Muon Measurements

Global Muon Measurements

- Data taken over large parameter space under very different experimental conditions!
- Muon content is expressed in terms of z-scale:

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

  - N_μ^{det}: muon content measured in the detector
  - $N_{\mu,\mathrm{p}}^{\mathrm{det}}$, $N_{\mu,\mathrm{Fe}}^{\mathrm{det}}$: muon content in simulated EAS (proton/iron) at the detector



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Depends on hadronic interaction models!

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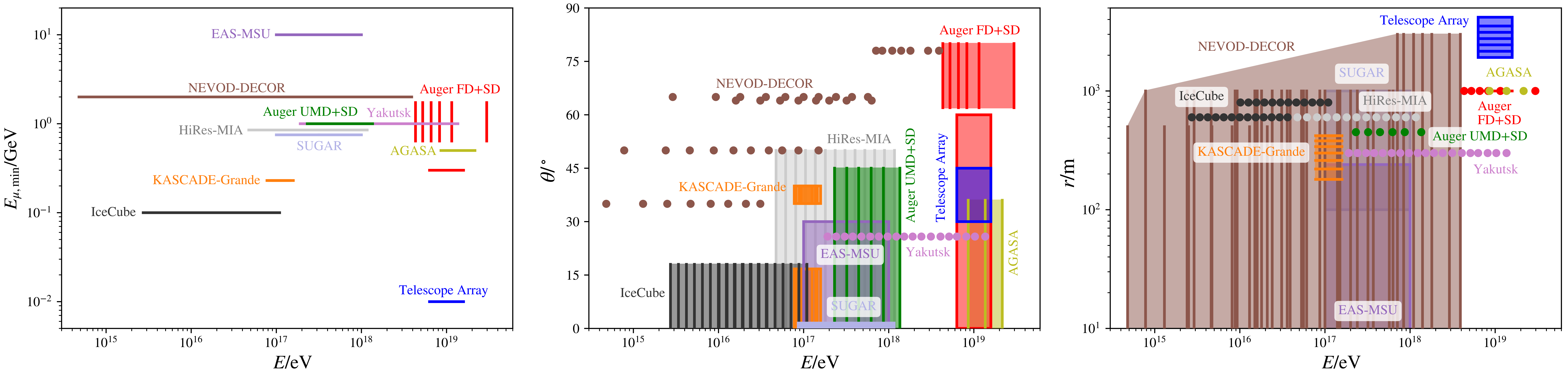

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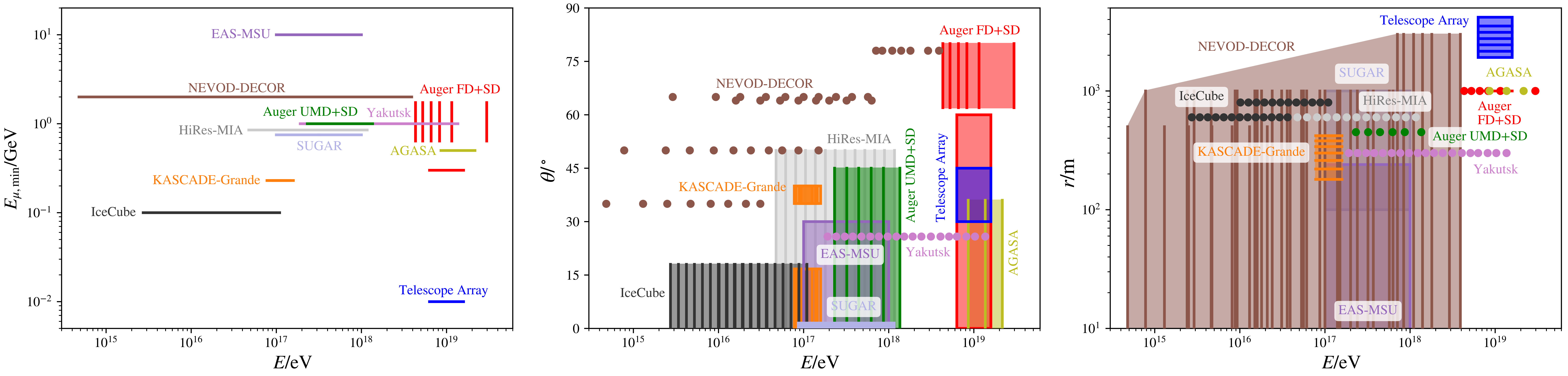
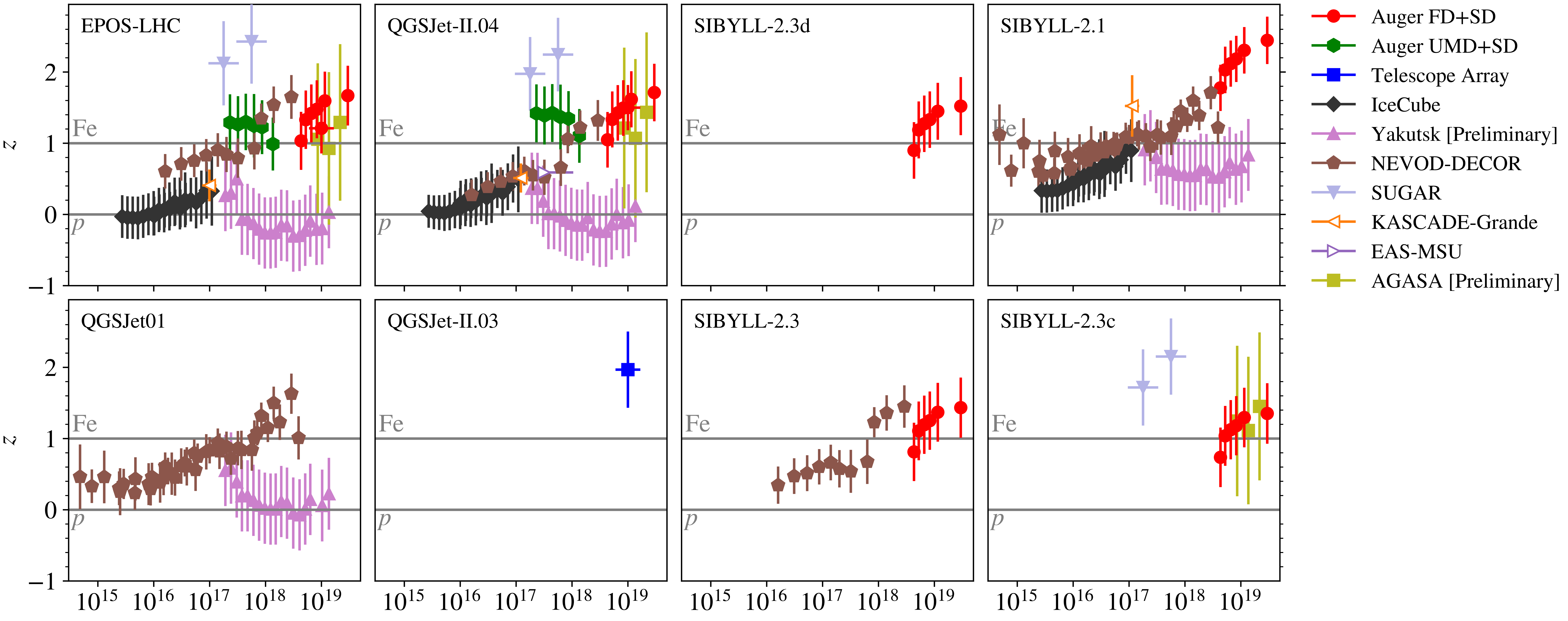


Global Muon Measurements

- Muon measurements by 9 EAS experiments

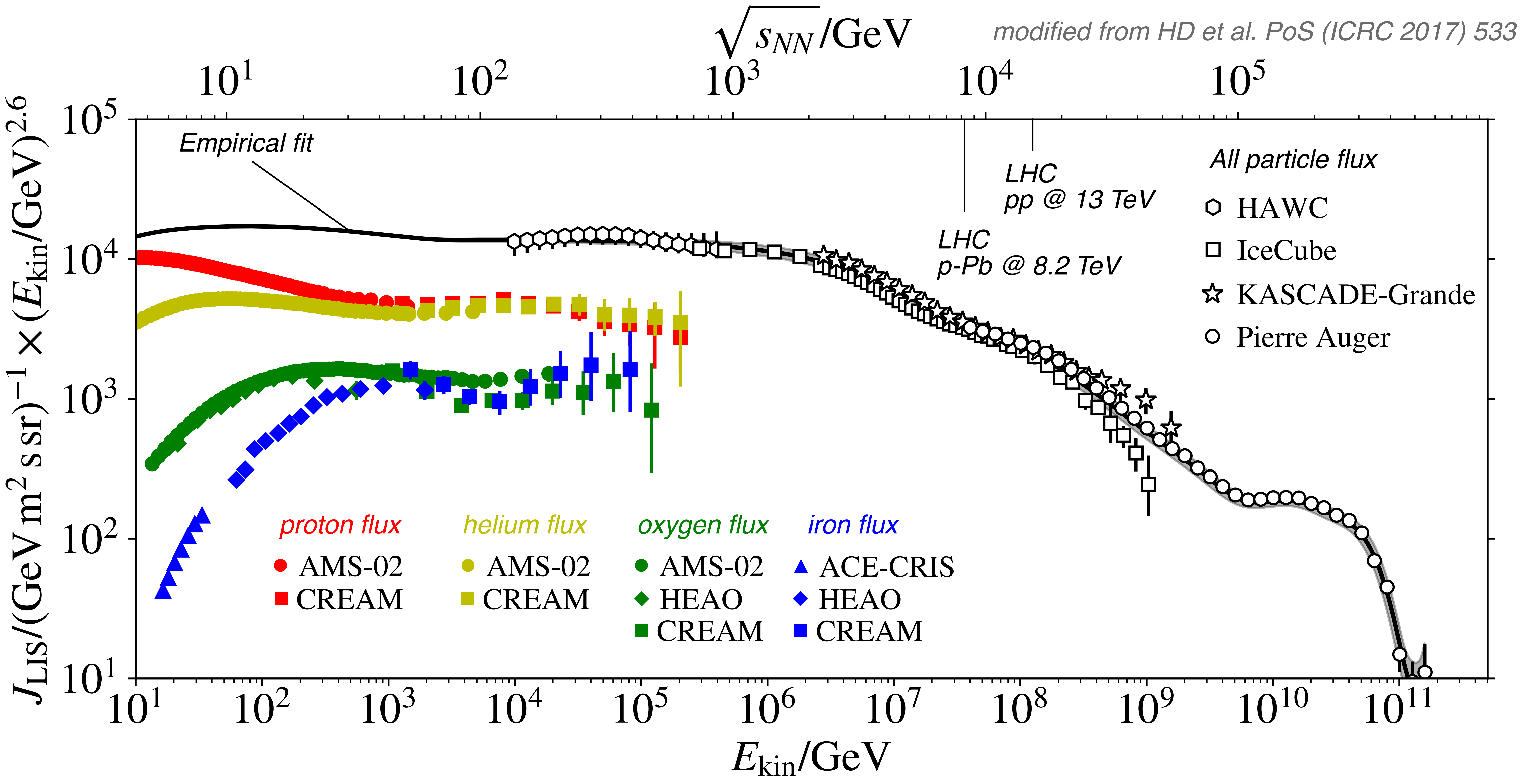
[D. Soldin et al., PoS ICRC2021 (2021) 349]

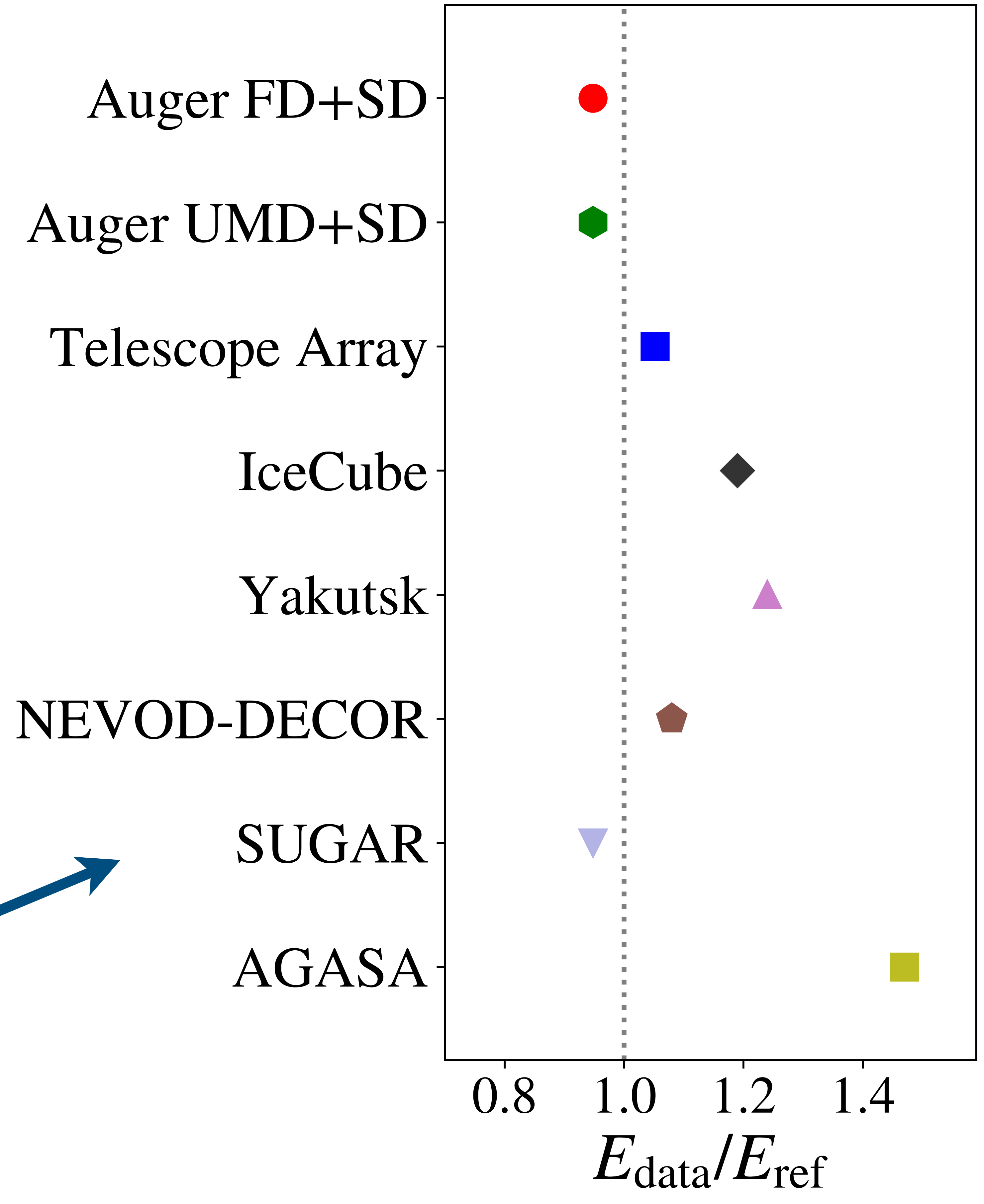


Energy-Rescaling

$$N_\mu = A \cdot \left(\frac{E_0}{A \cdot \xi_C} \right)^\beta$$

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

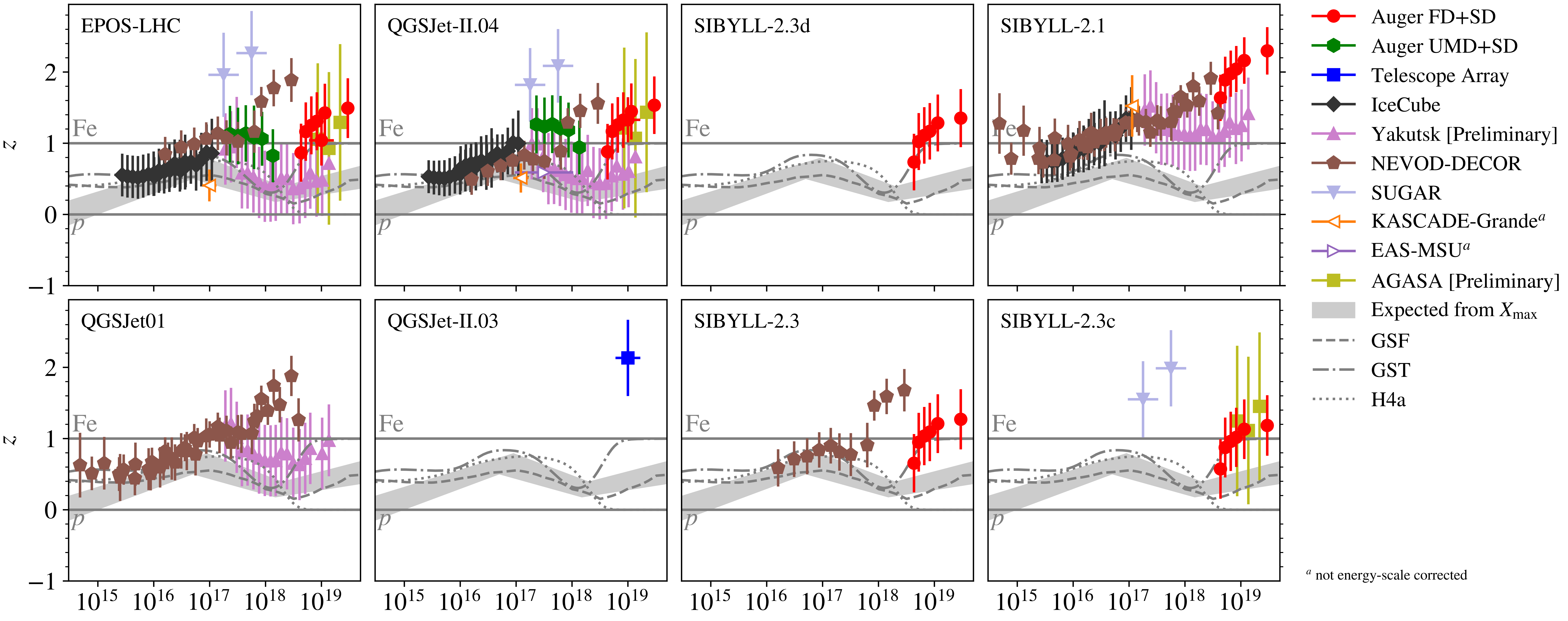




[H.P. Dembinski et al., PoS(ICRC2017)533]

The Muon Puzzle

- Muon lateral density after cross-calibration of the energy-scales [D. Soldin et al., PoS ICRC2021 (2021) 349]



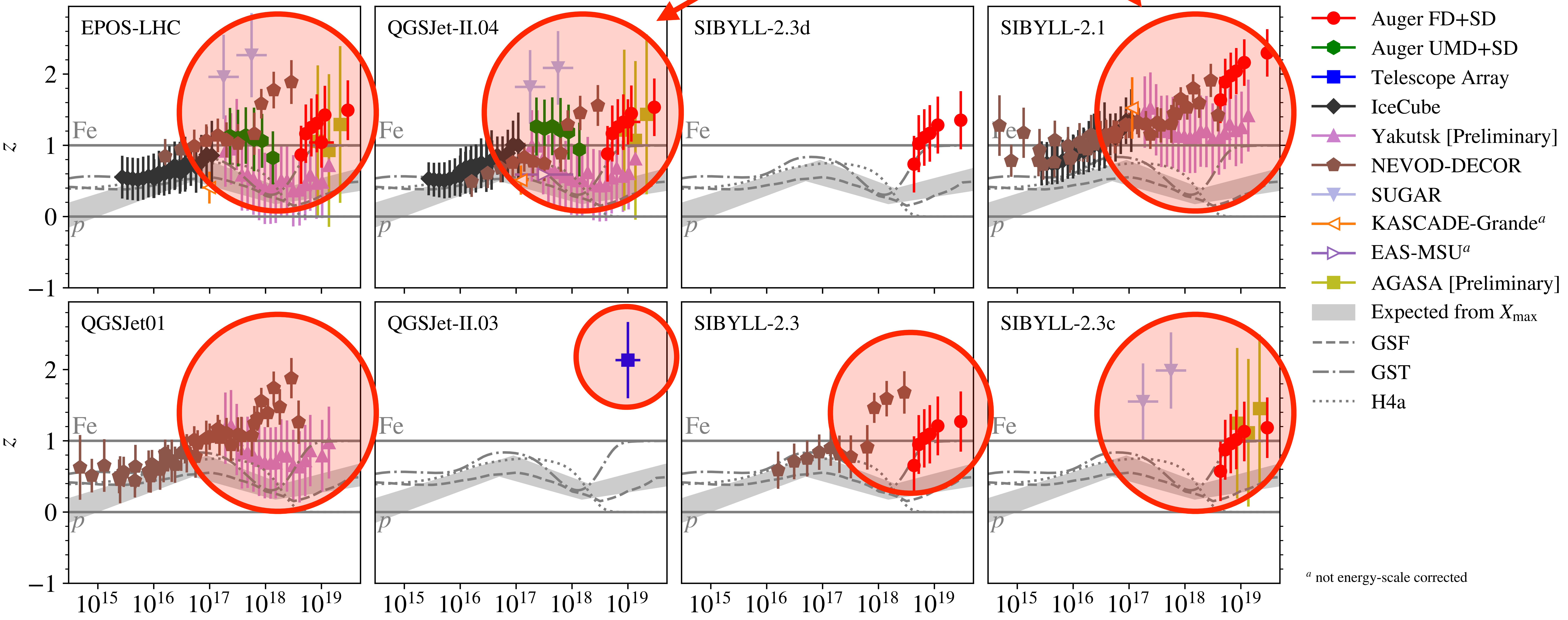
- Muon measurements indicate mass composition heavier than iron at high E_0!

The Muon Puzzle

Muon Puzzle in EAS

- Muon lateral density after cross-calibration of the energy-scales

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



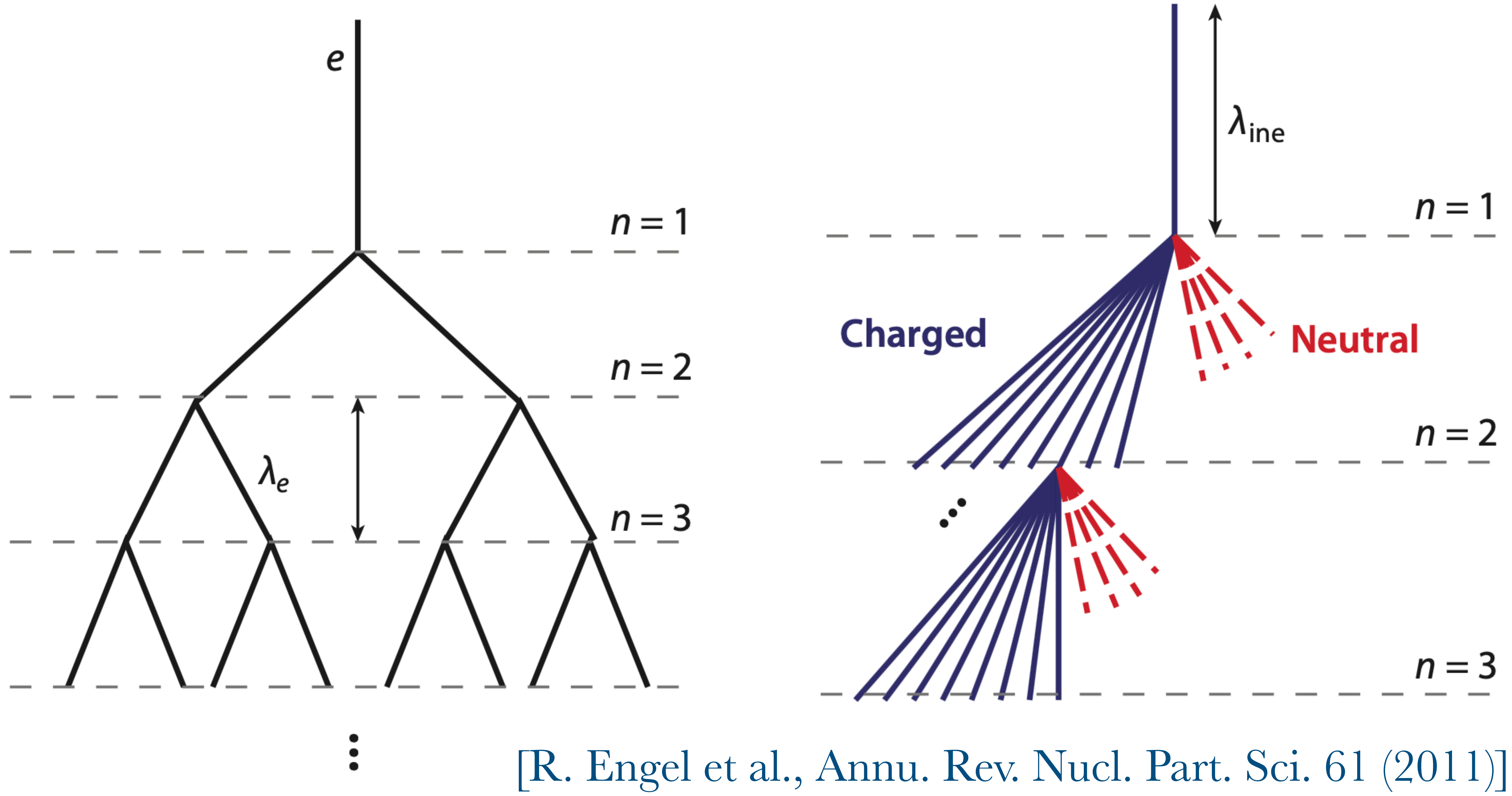
- Muon measurements indicate mass composition heavier than iron at high E_0!

Mass Dependence

- Number of muons is described by the <u>Heitler-Matthews model:</u>

$$N_\mu = A^{1-\beta} \cdot \left(\frac{E}{\xi_C}\right)^{\beta} \quad , \quad \beta \simeq 0.9$$

  - E: primary cosmic ray energy
  - A: primary mass number
  - ξ_C: energy constant

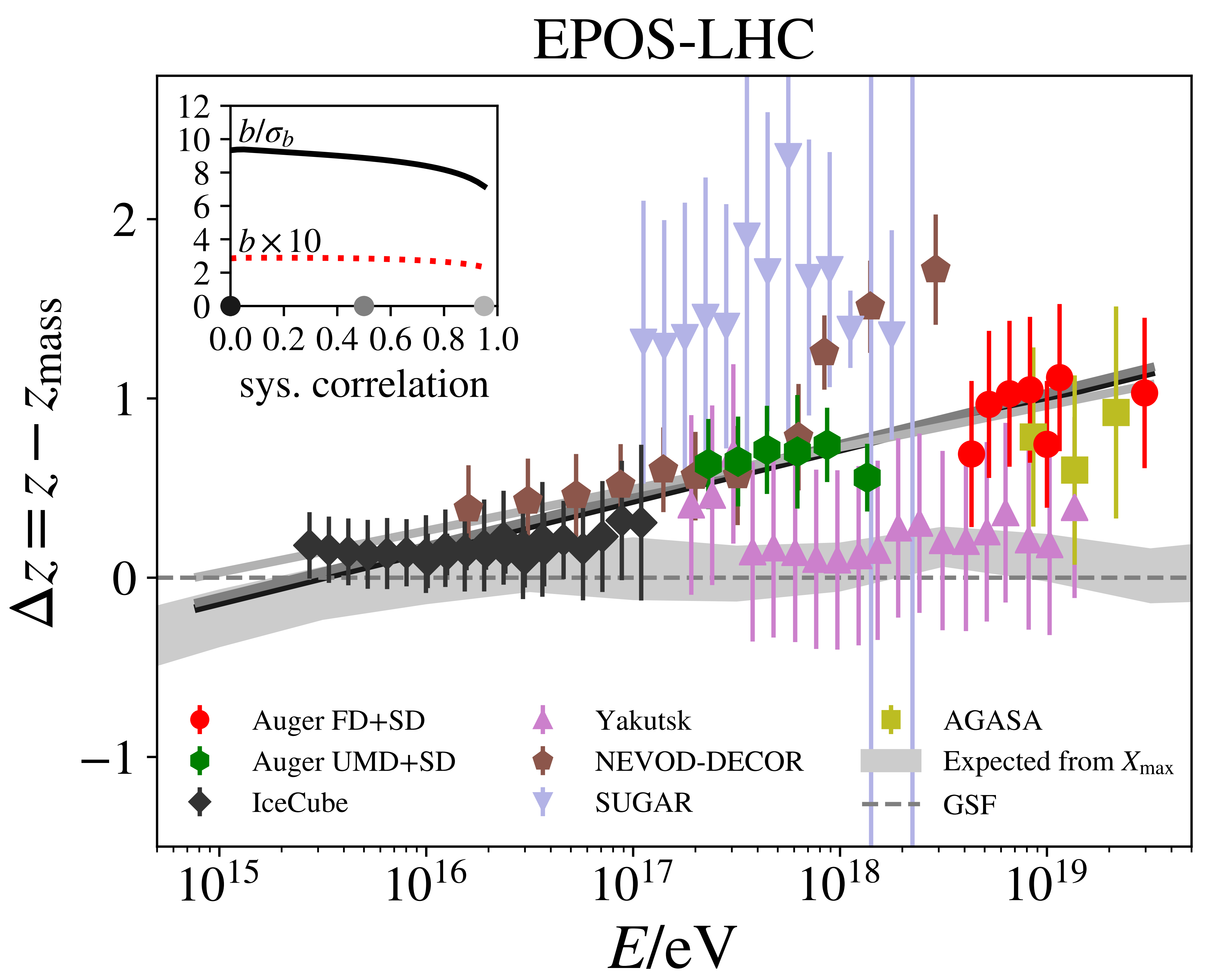


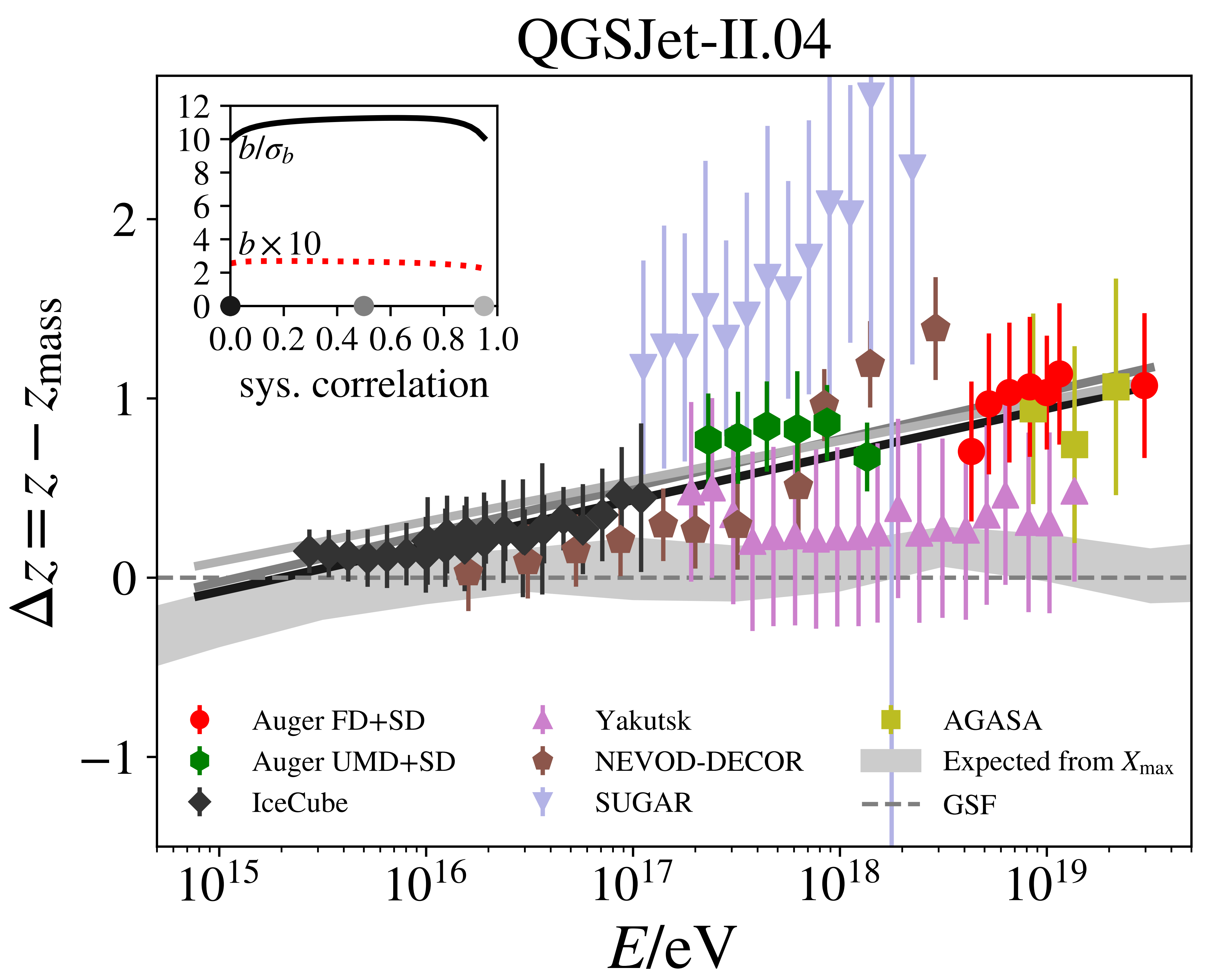
[R. Engel et al., Annu. Rev. Nucl. Part. Sci. 61 (2011)]

- When studying the energy-dependent trend in the muon measurements, the <u>cosmic ray mass need to be taken into account!</u>

- Mass dependence can be removed by subtracting z_{mass} based on the GSF model, i.e. in the plot on the previous slide "subtract the GSF line from the data points"

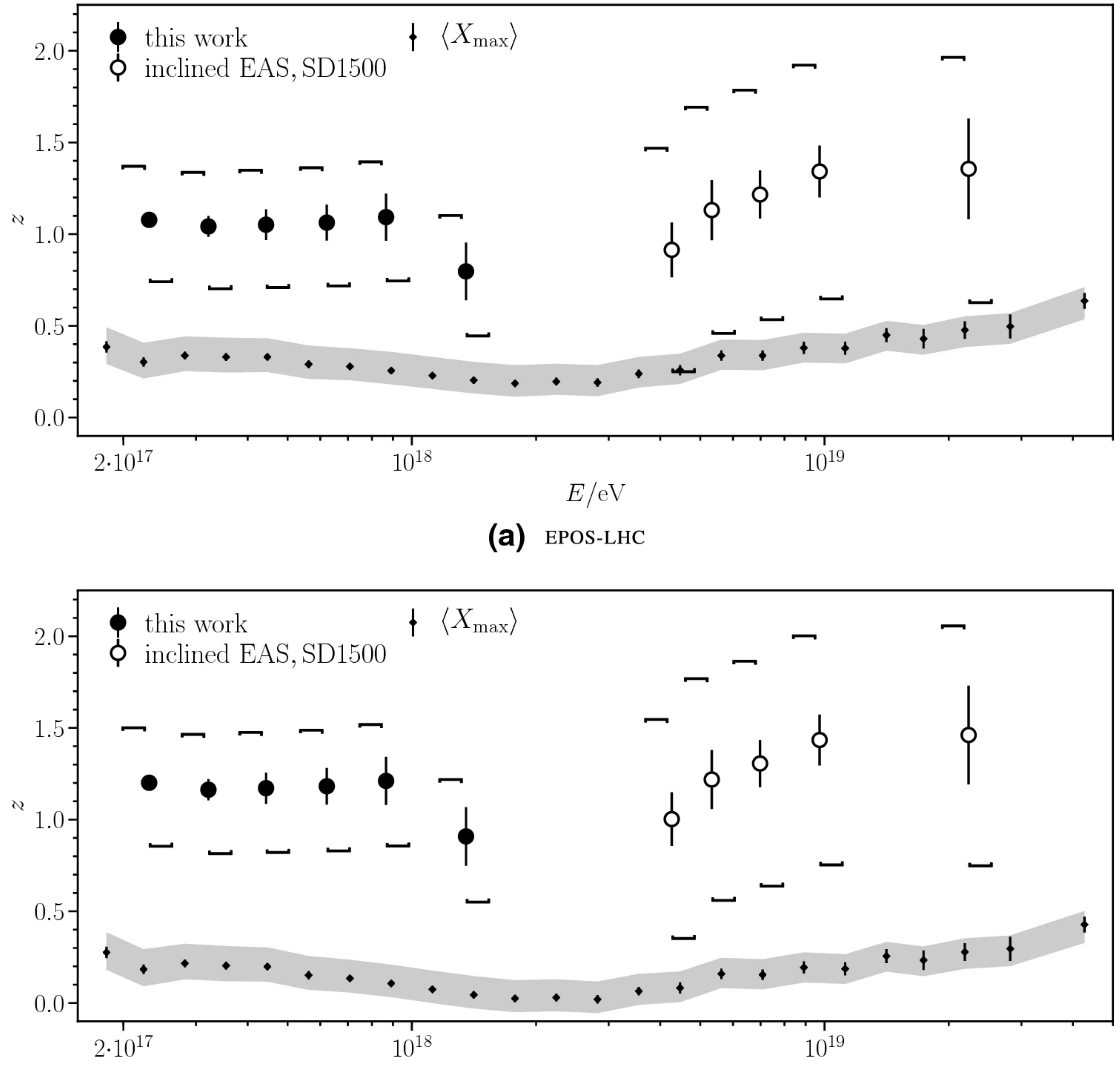
Mass-Corrected z-Scale





- Fit depends on assumption of correlation, α, between systematic uncertainties
- Slope of the fit: $b = 0.23 - 0.29$ (EPOS-LHC), $b = 0.22 - 0.25$ (QGSJet-II.04)
- Significance of the slope: $\sim 7\sigma - 9\sigma$ (EPOS-LHC), $\sim 10\sigma - 11\sigma$ (QGSJet-II.04)

Muon Measurements at High Energies



(a) EPOS-LHC

(b) QGSJetII-04

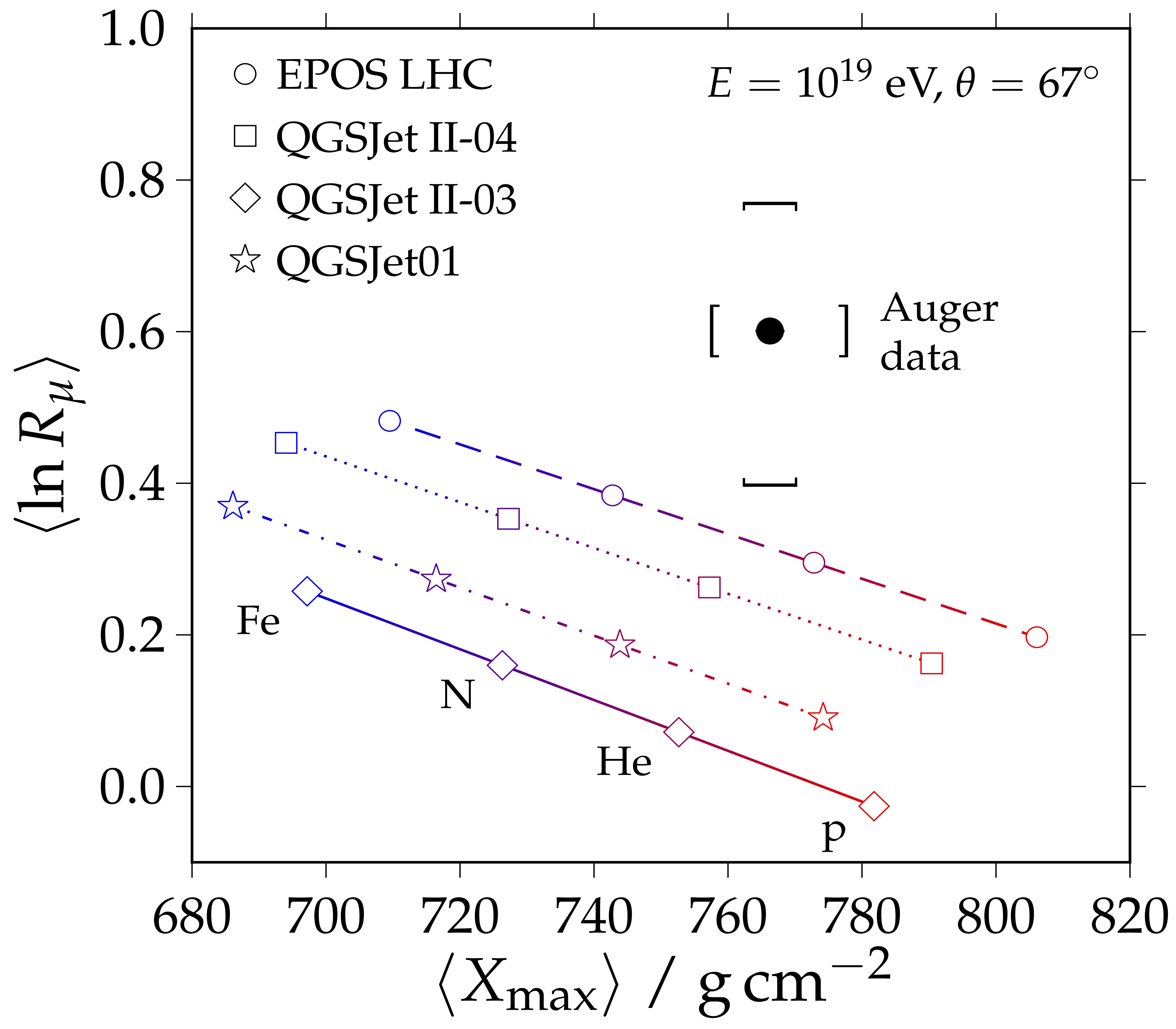
In range $2 \cdot 10^{17}$ eV to $2 \cdot 10^{19}$ eVsimulations don't reproduce muon densities!

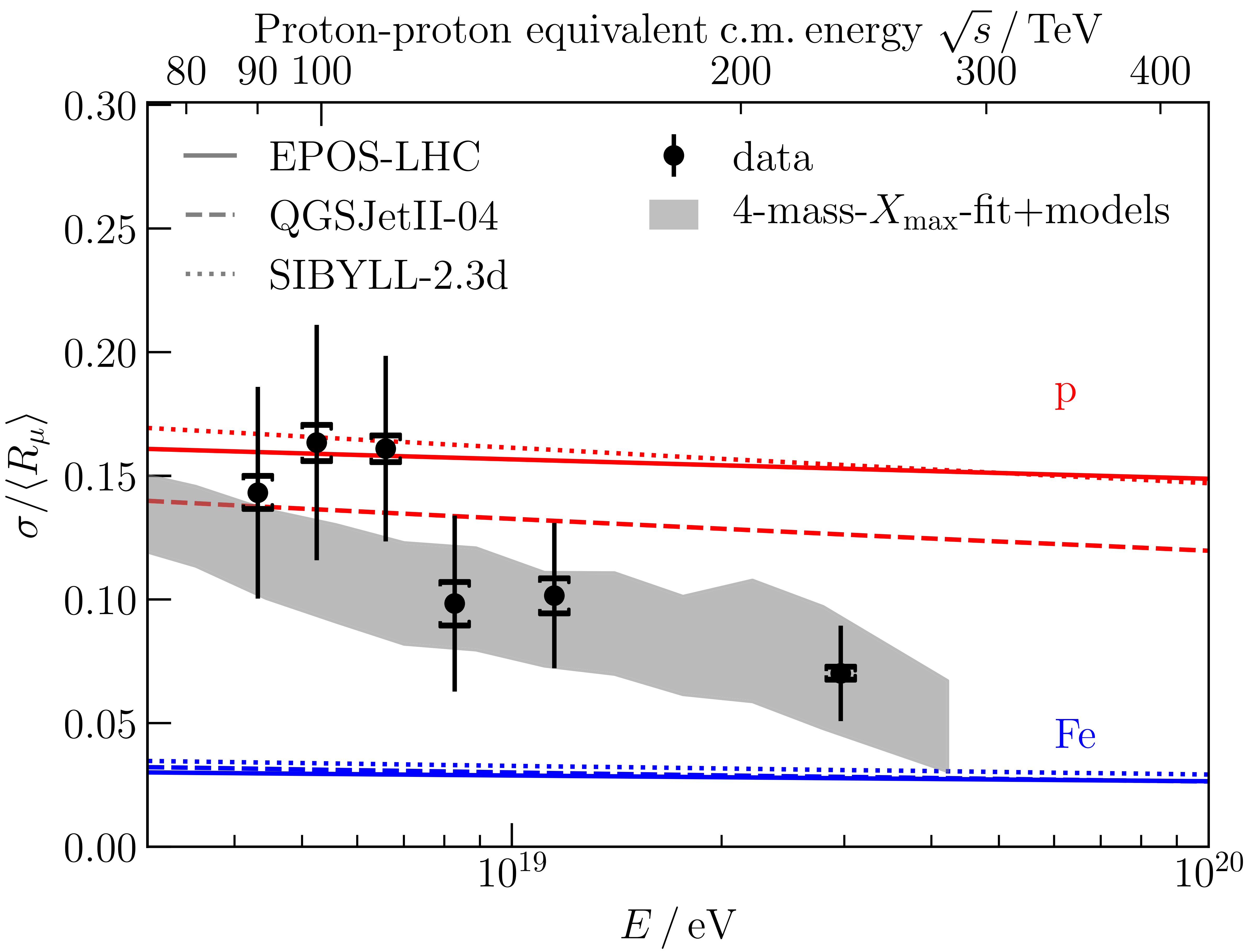
40% (50%) increase in $\langle N_\mu \rangle$ at 10^{18} eV needed for EPOS-LHC (QGSJet-II.04)

[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. D91 (2015)]
[A. Aab et al. (Pierre Auger Collaboration), Eur. Phys. J. C 80 (2020)]

Muon Measurements at High Energies

- Discrepancy in number of muons but relative fluctuations as expected!

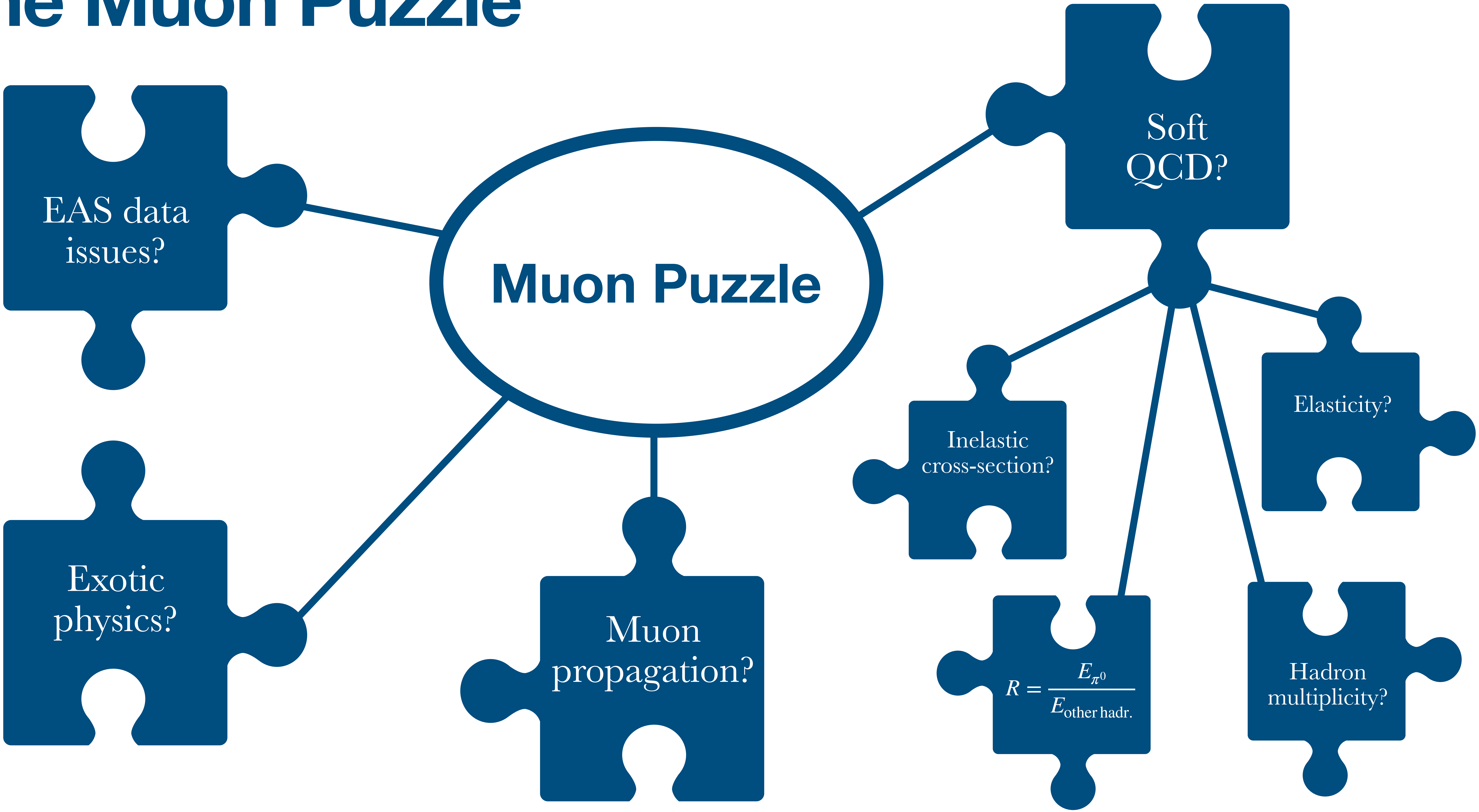




[A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. Lett. 126 (2021)]

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

The Muon Puzzle



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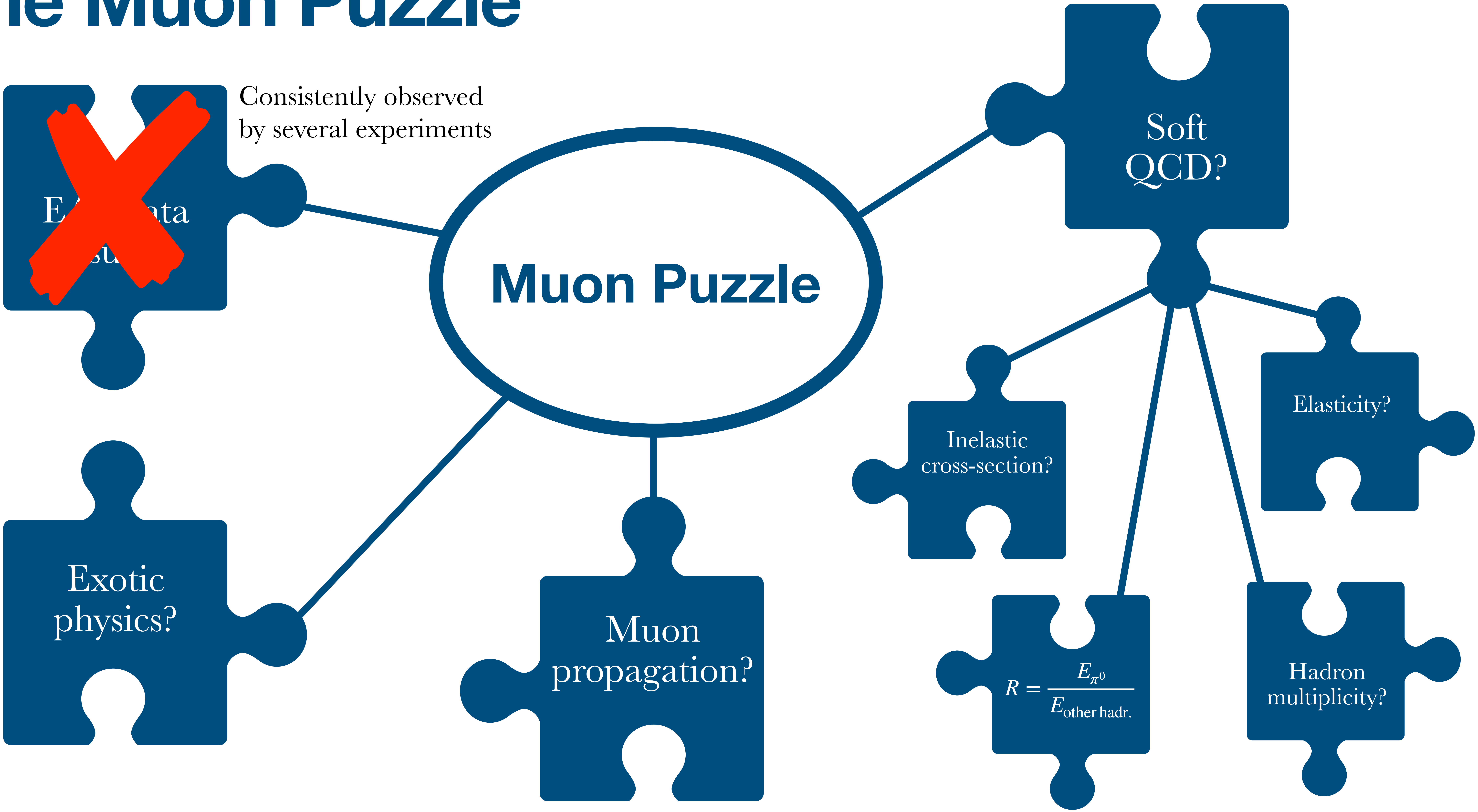

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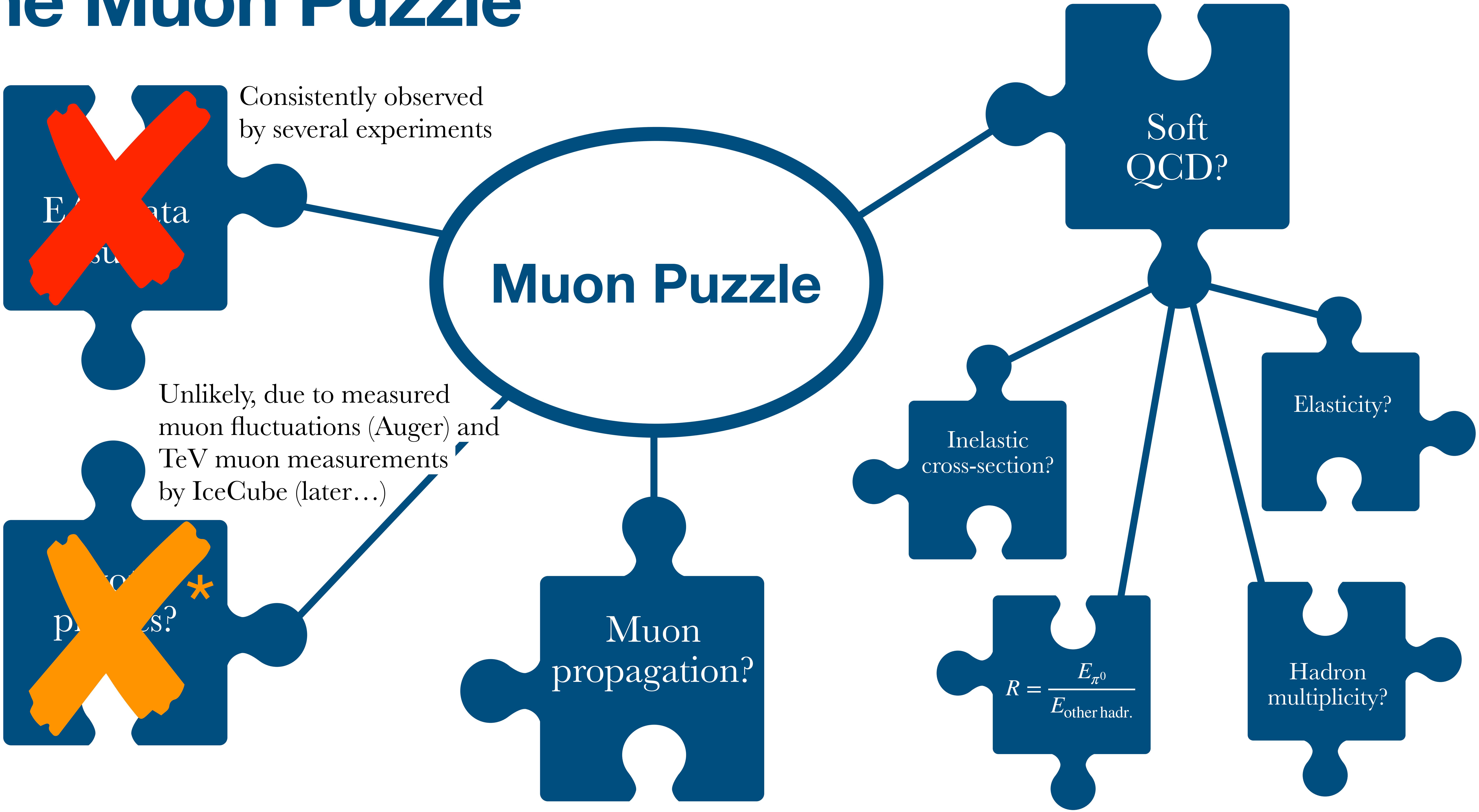

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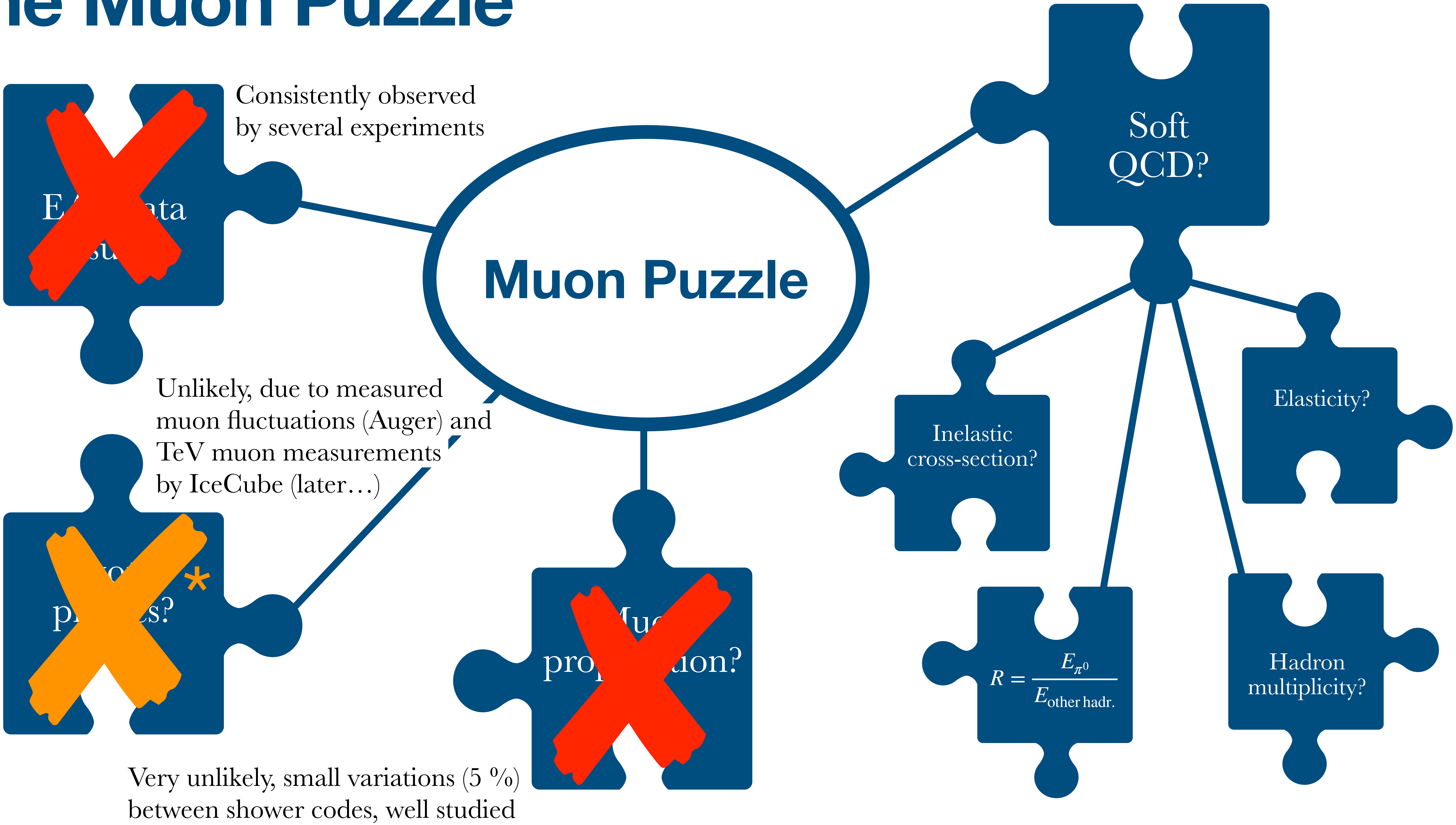
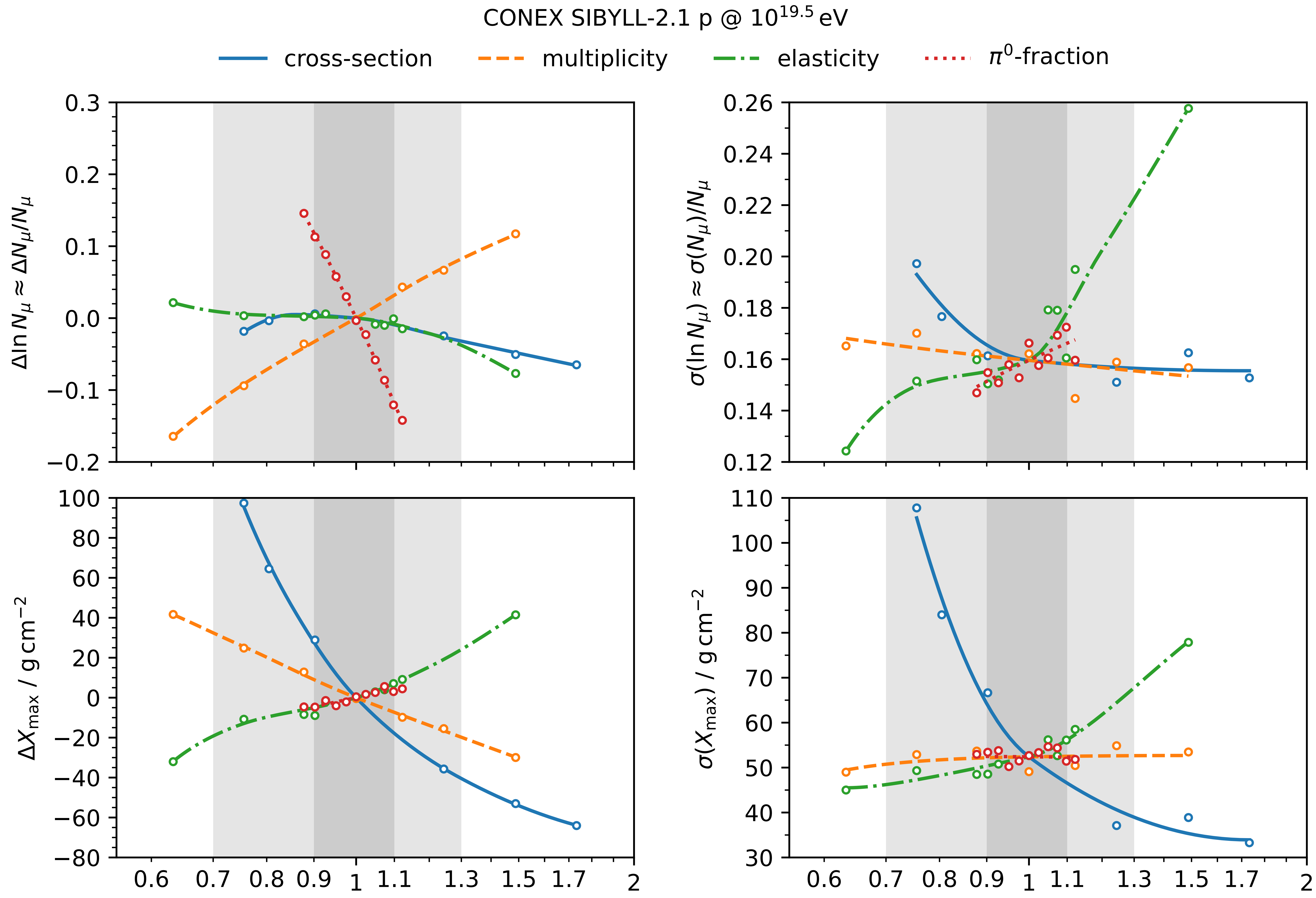
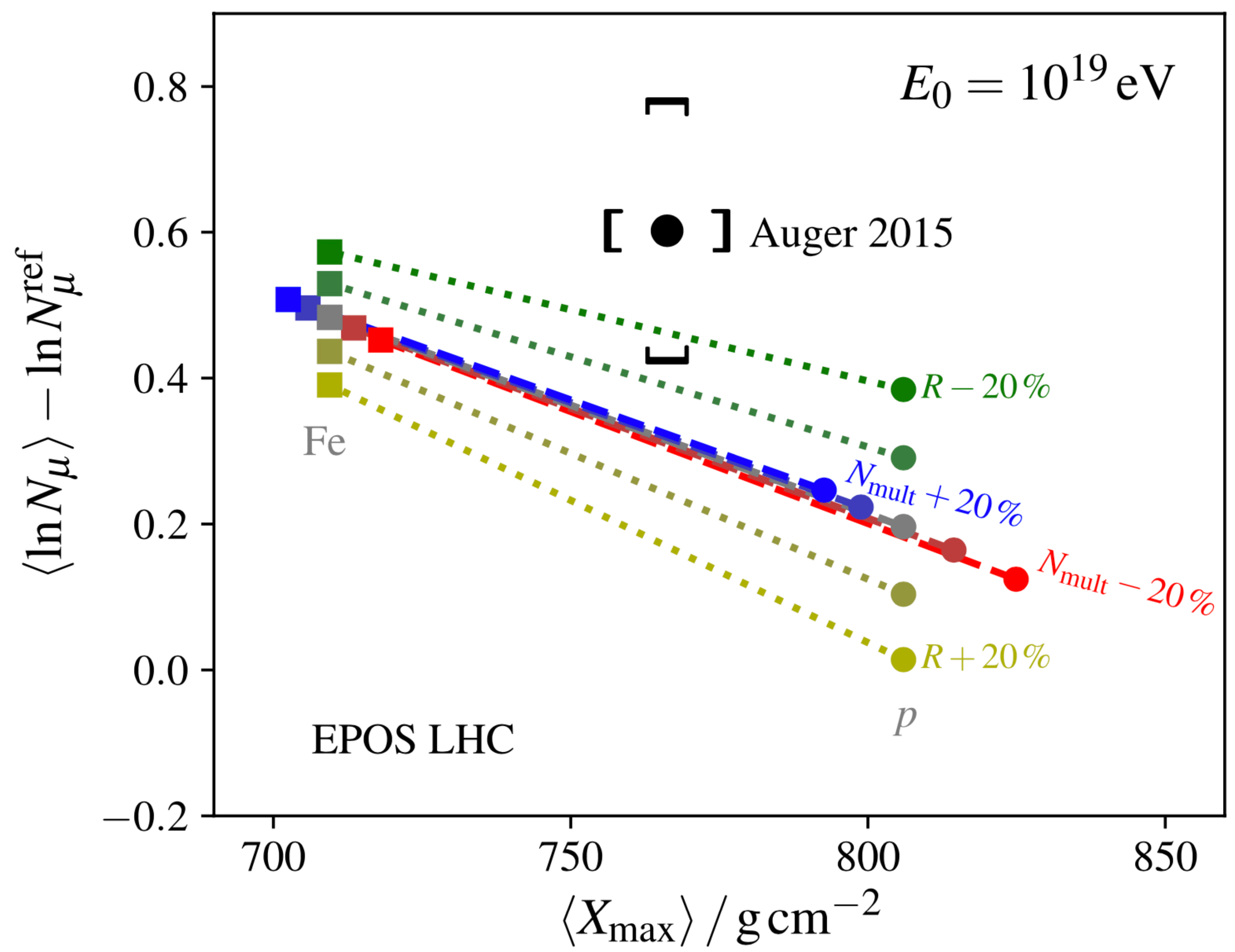


Study of Shower Impact Parameters



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

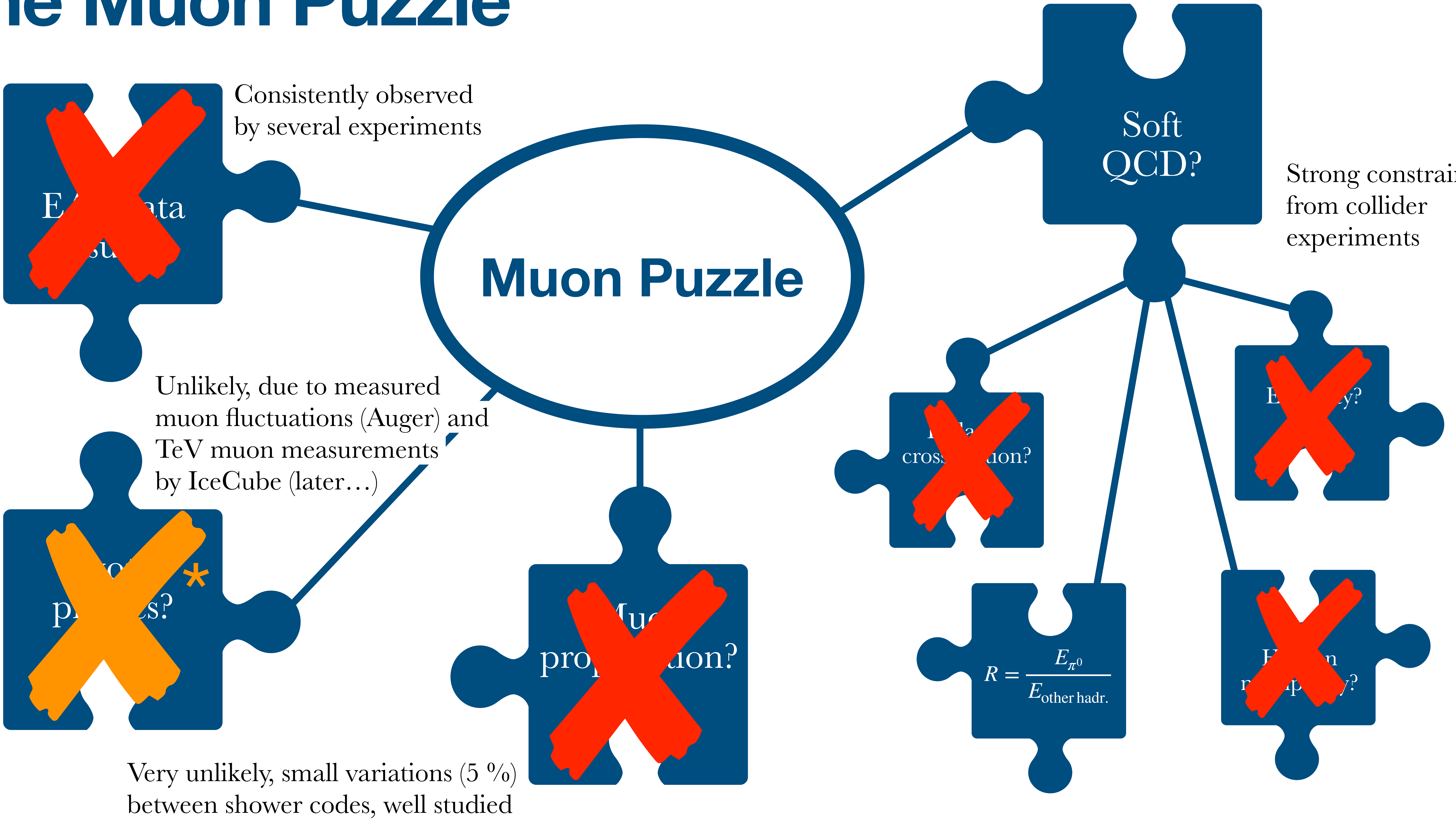
[S. Baur et al., arXiv:1902.09265 (2019)]



Strong constraints from collider experiments!

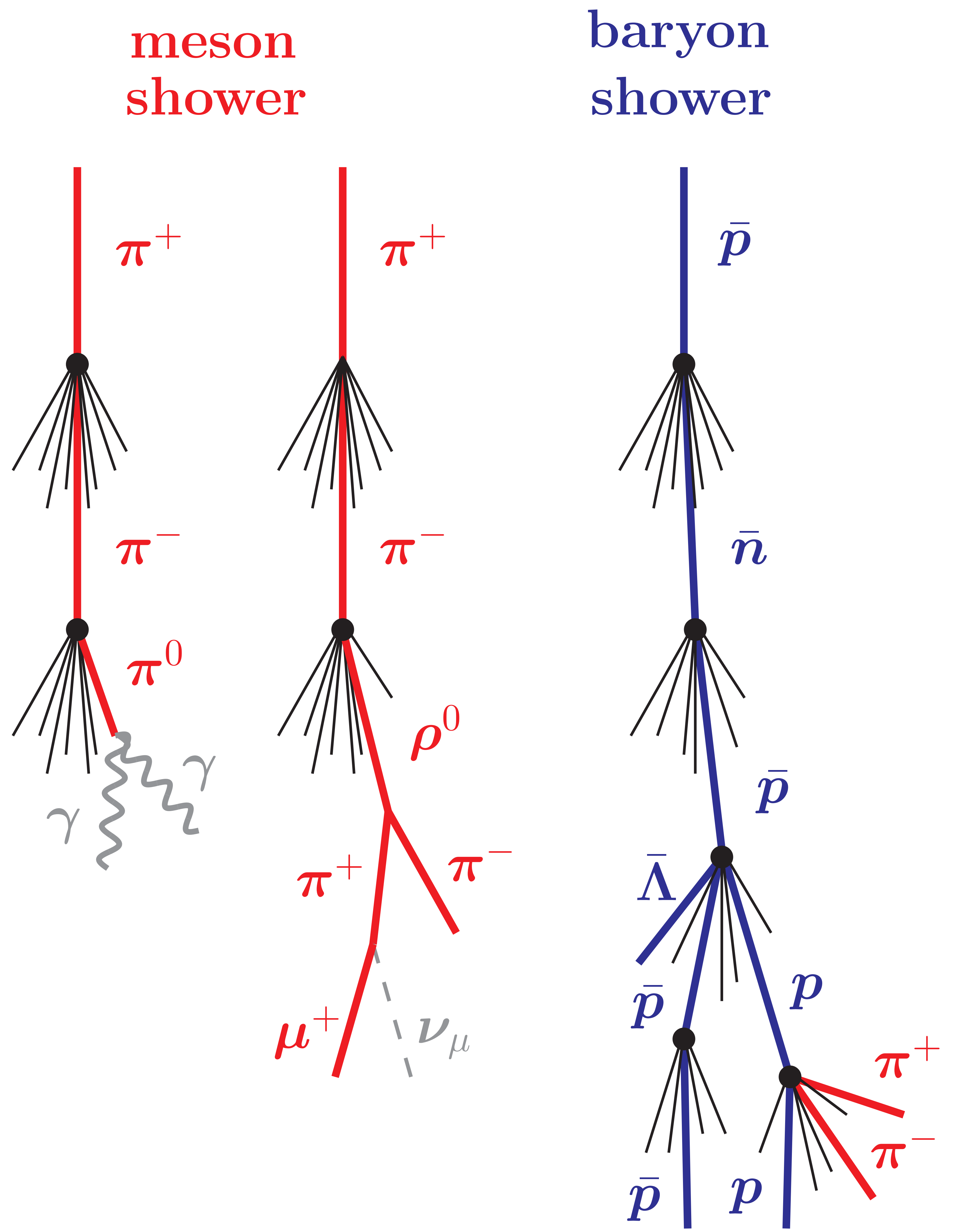
For details, please see [J. Albrecht, H. Dembinski, D. Soldin et al., Astrophys. Space Sci. 367 (2022)]

The Muon Puzzle



The Muon Puzzle

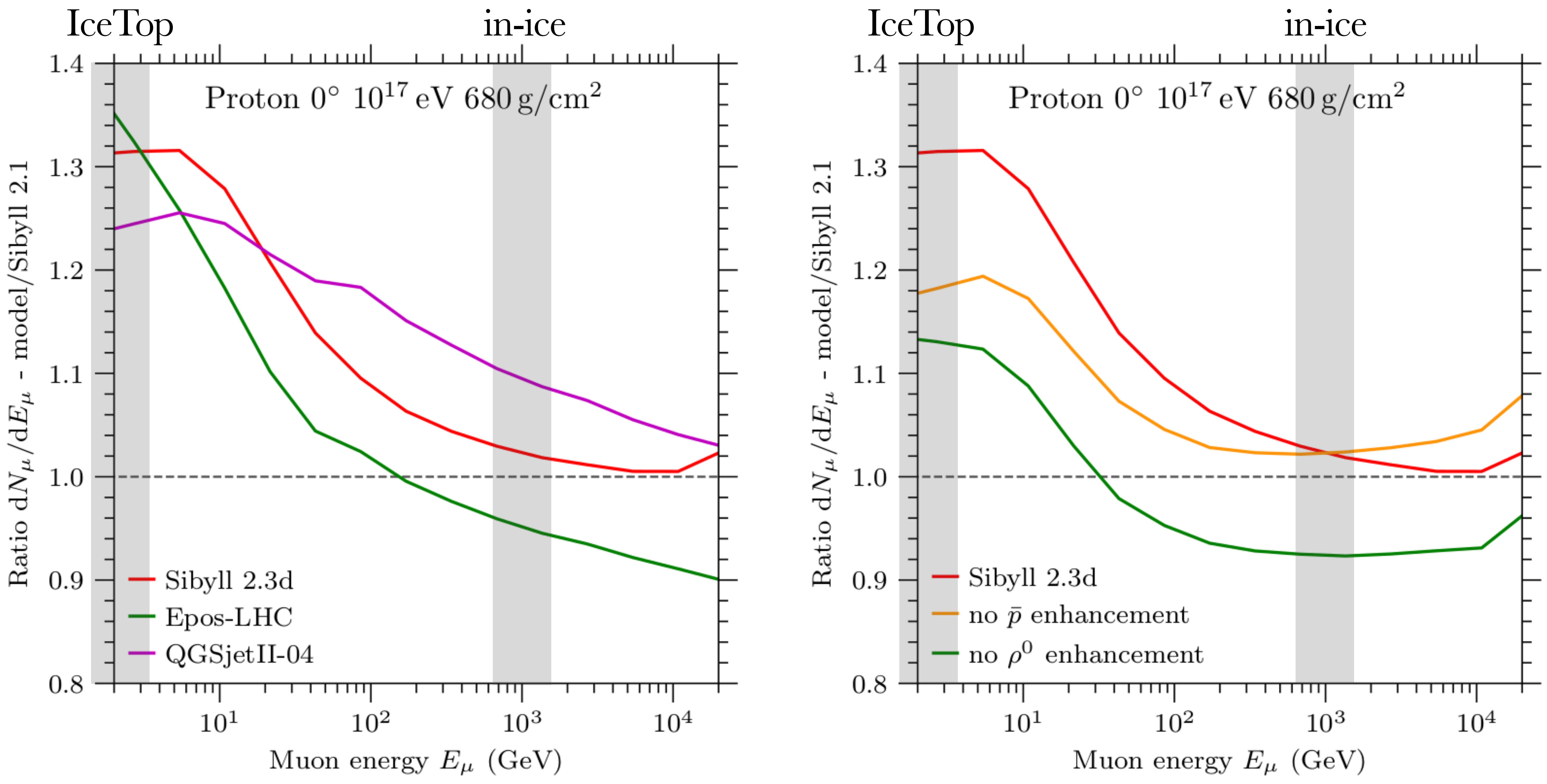
- Possible explanations for the Muon Puzzle:
  - Neutral rho meson enhancement, e.g. [1]
    - Leading particle in meson shower could be ρ_0
    - Decay of ρ_0 via charged pions into muons
    - Muon production at all energies
  - Baryon enhancement, e.g. [2]
    - Baryon anti-baryon production
    - Many re-interactions, low-energy particles
    - Mainly low-energy muons
  - New physics, e.g. [3]
    - Hadronic physics at high energies
- Different predicted muon spectra!

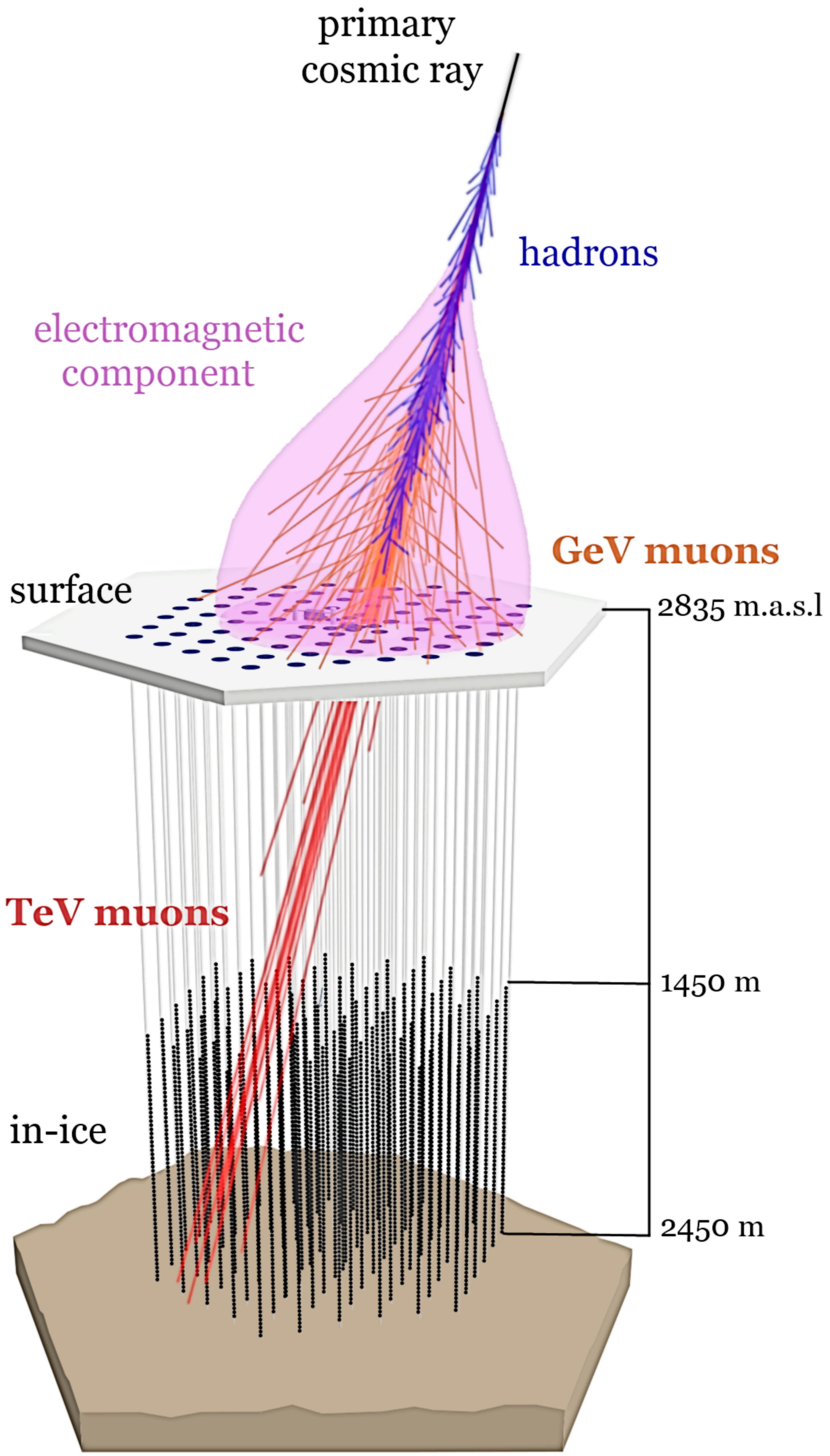


[1]: See e.g. [F. Riehn et al., Phys. Rev. D102 (2020)]
[2]: See e.g. [T. Pierog, K. Werner, Phys. Rev. Lett., 101 (2008)]
[3]: See e.g. [G. R. Farrar, J. D. Allen, EPJ Web Conf., 53 (2013)]

The Muon Puzzle and IceCube

- Multiple (two+) muon energy regimes in IceCube!
- Coincident measurements provide spectral muon information
- Unique tests of multi-particle production (forward region)
- EAS energy from EM component

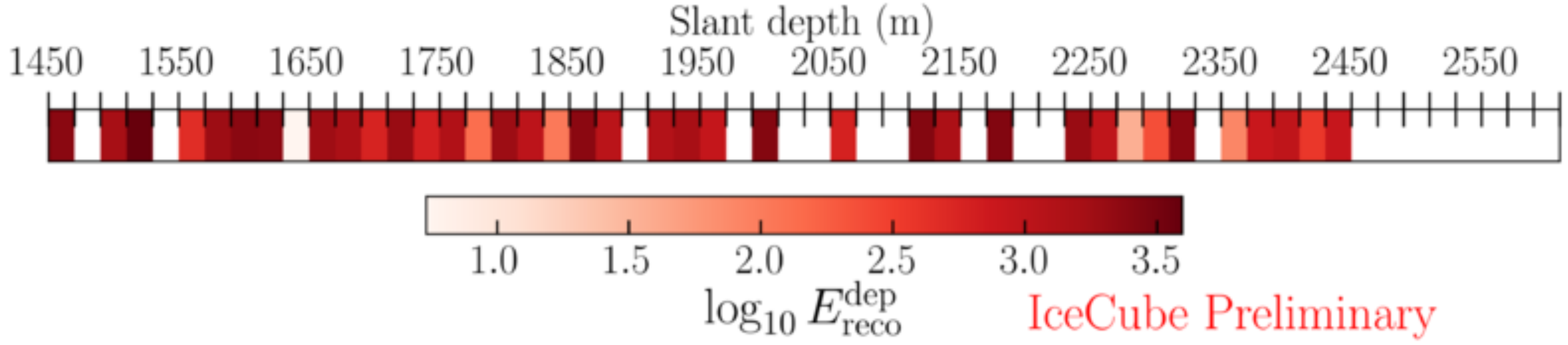


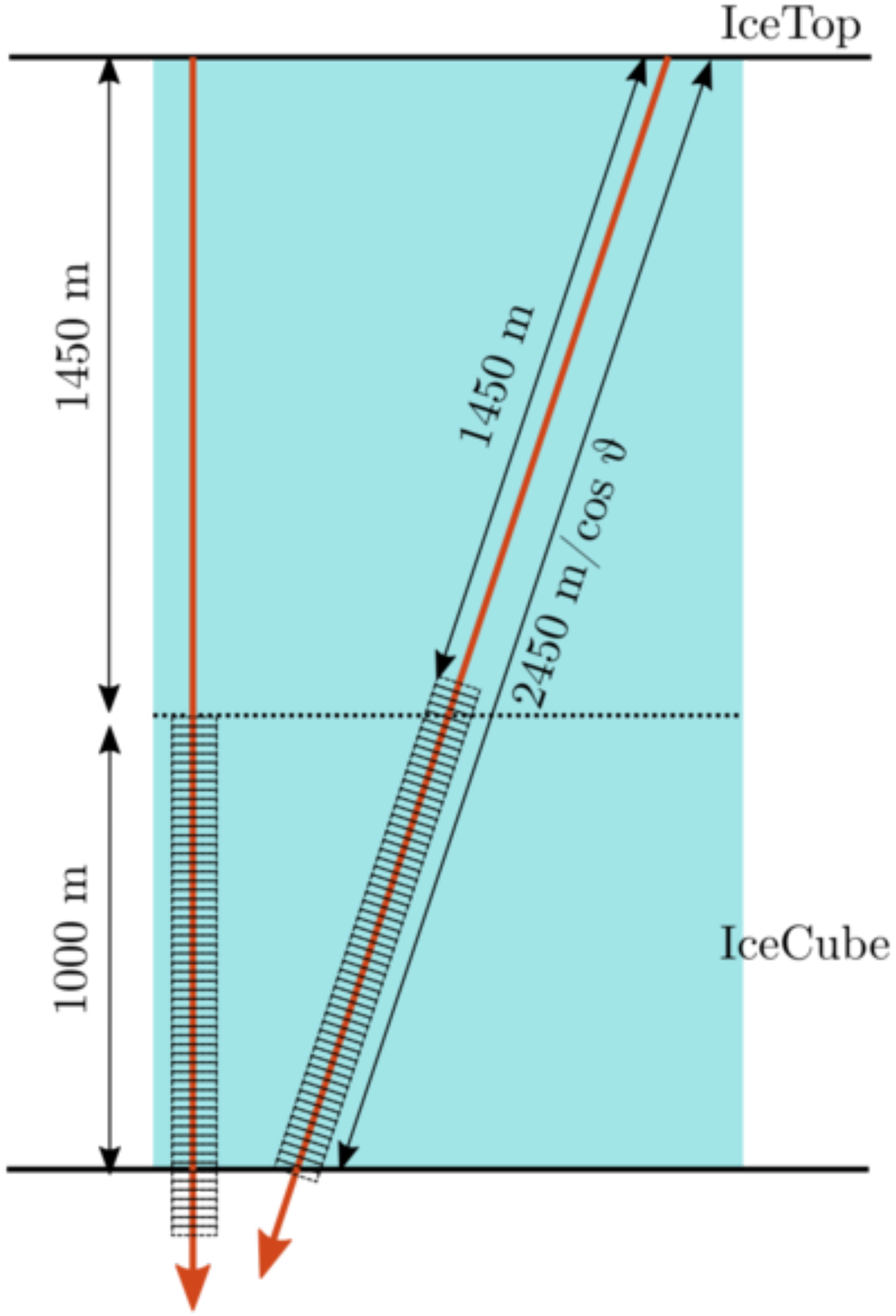


[F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]

TeV Muon Multiplicity

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

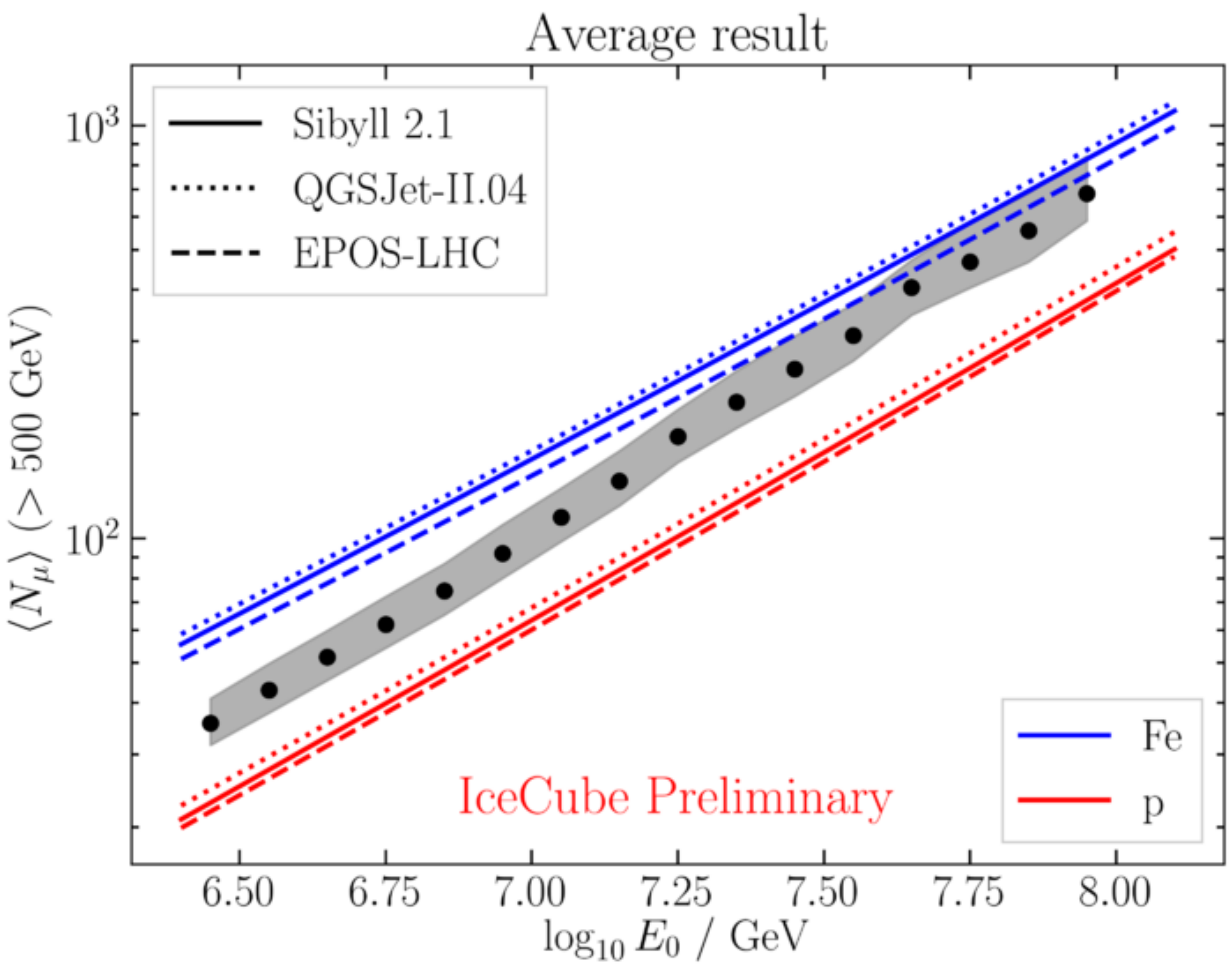




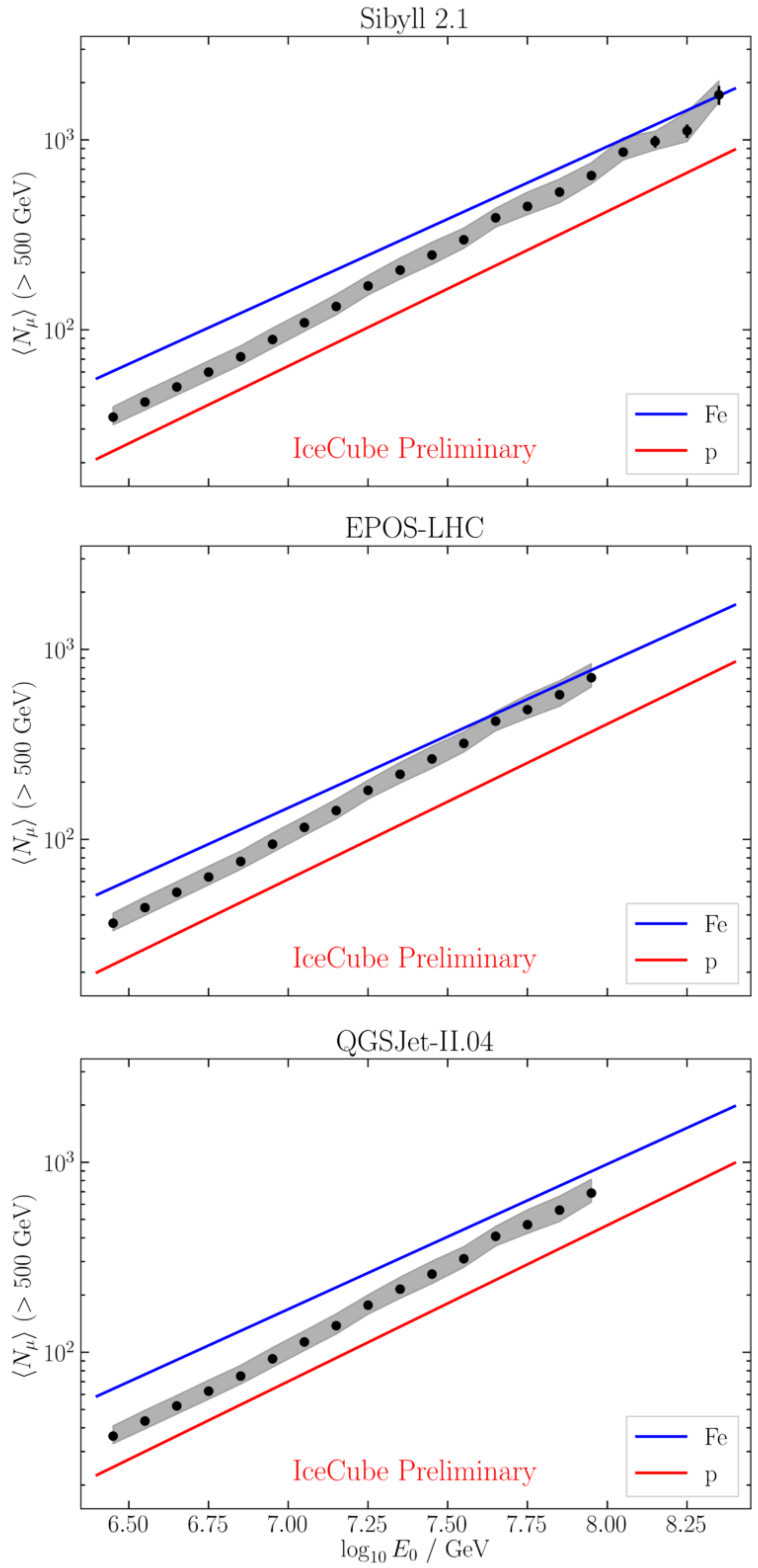
[S. Verpoest (IceCube Collaboration), ECRS2022 (proceedings in preparation)]

TeV Muons in IceCube

- Muon bundle multiplicity compared to model predictions



- How does the data compare to CR flux models?



[S. Verpoest (IceCube Collaboration), ECRS2022 (proceedings in preparation)]

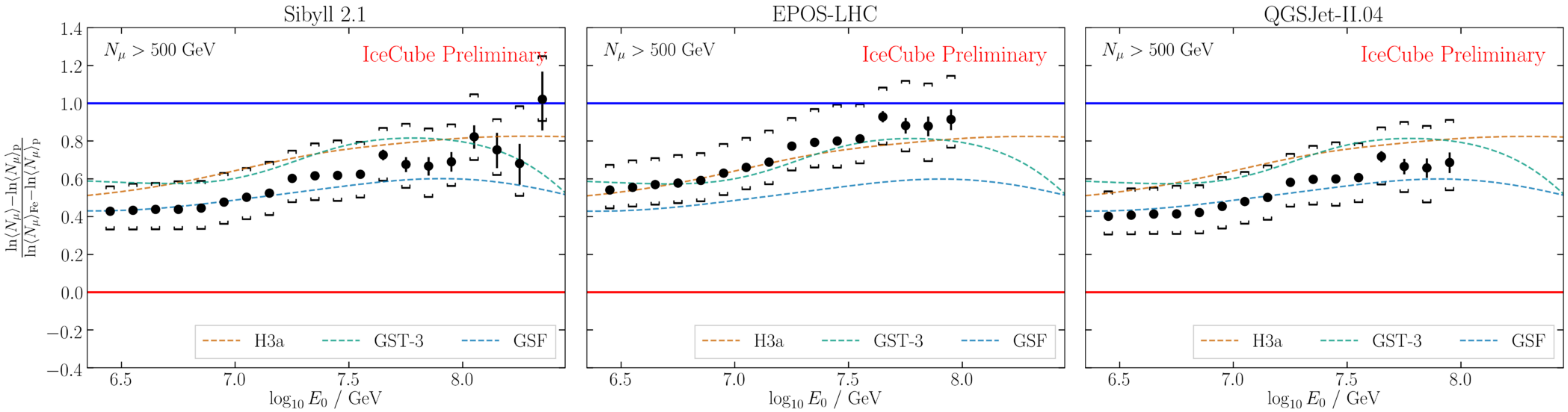
TeV Muons in IceCube

- Reminder z-scale:

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

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

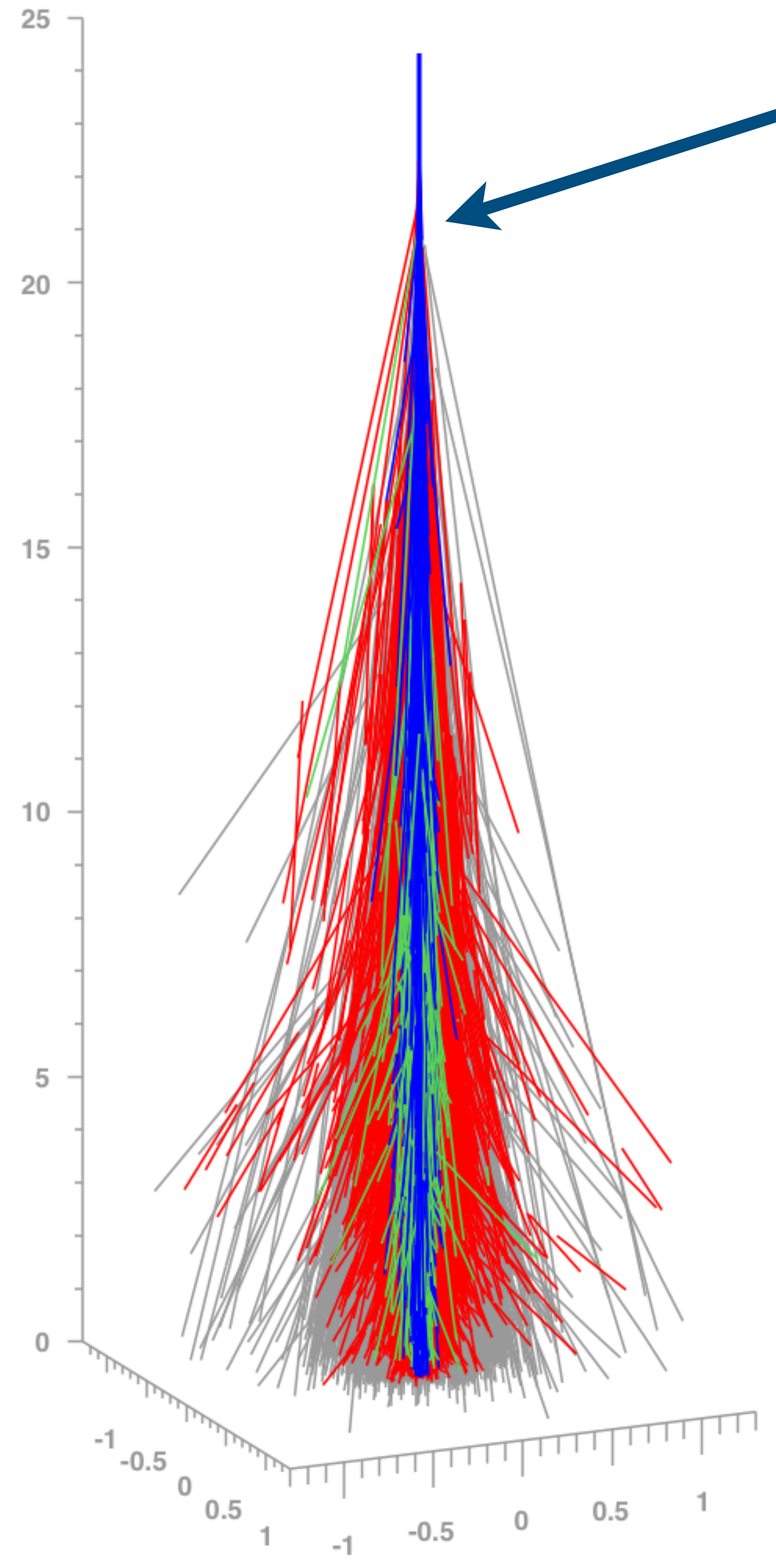
[S. Verpoest (IceCube Collaboration), ECRS2022 (proceedings in preparation)]

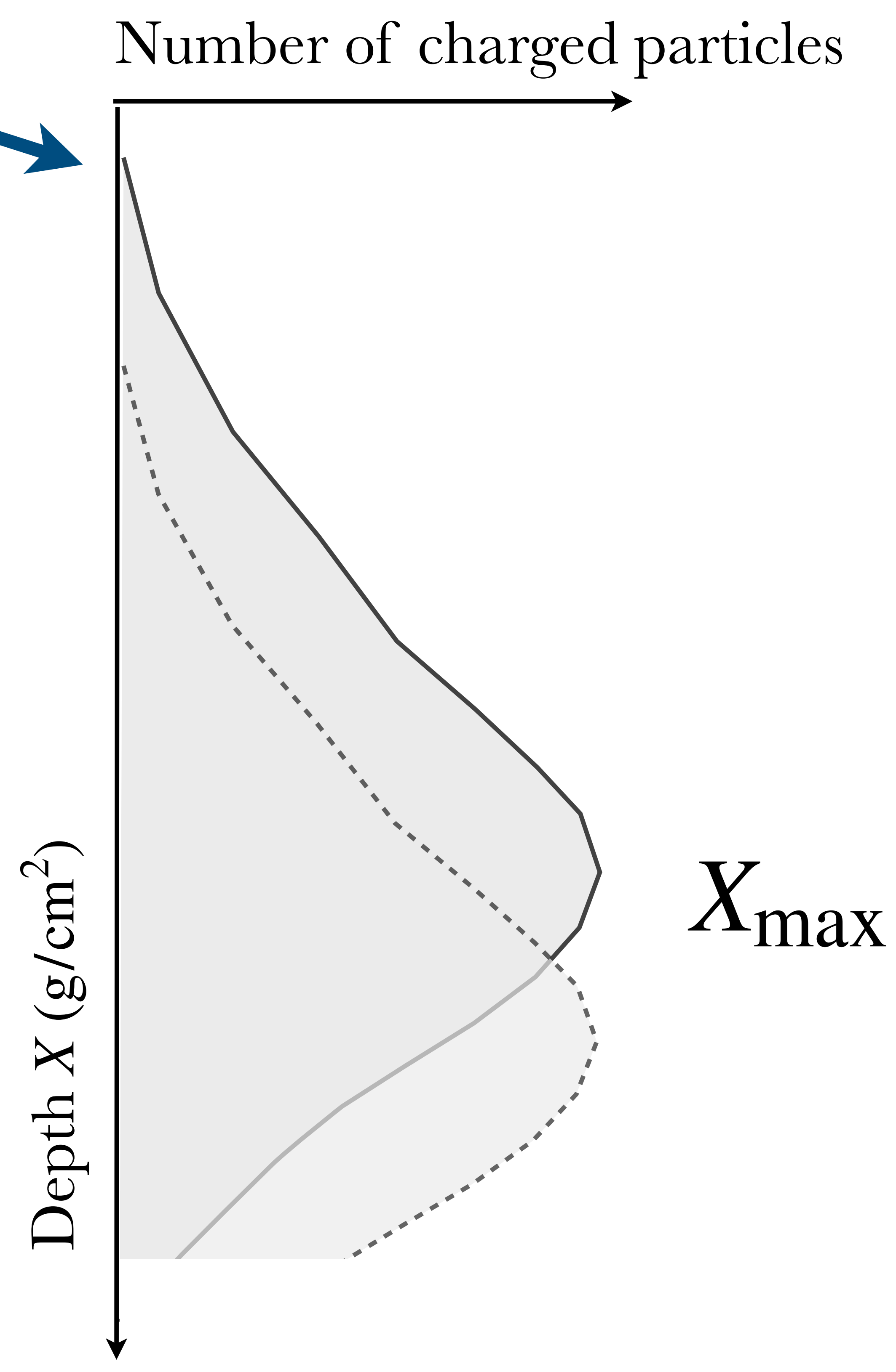


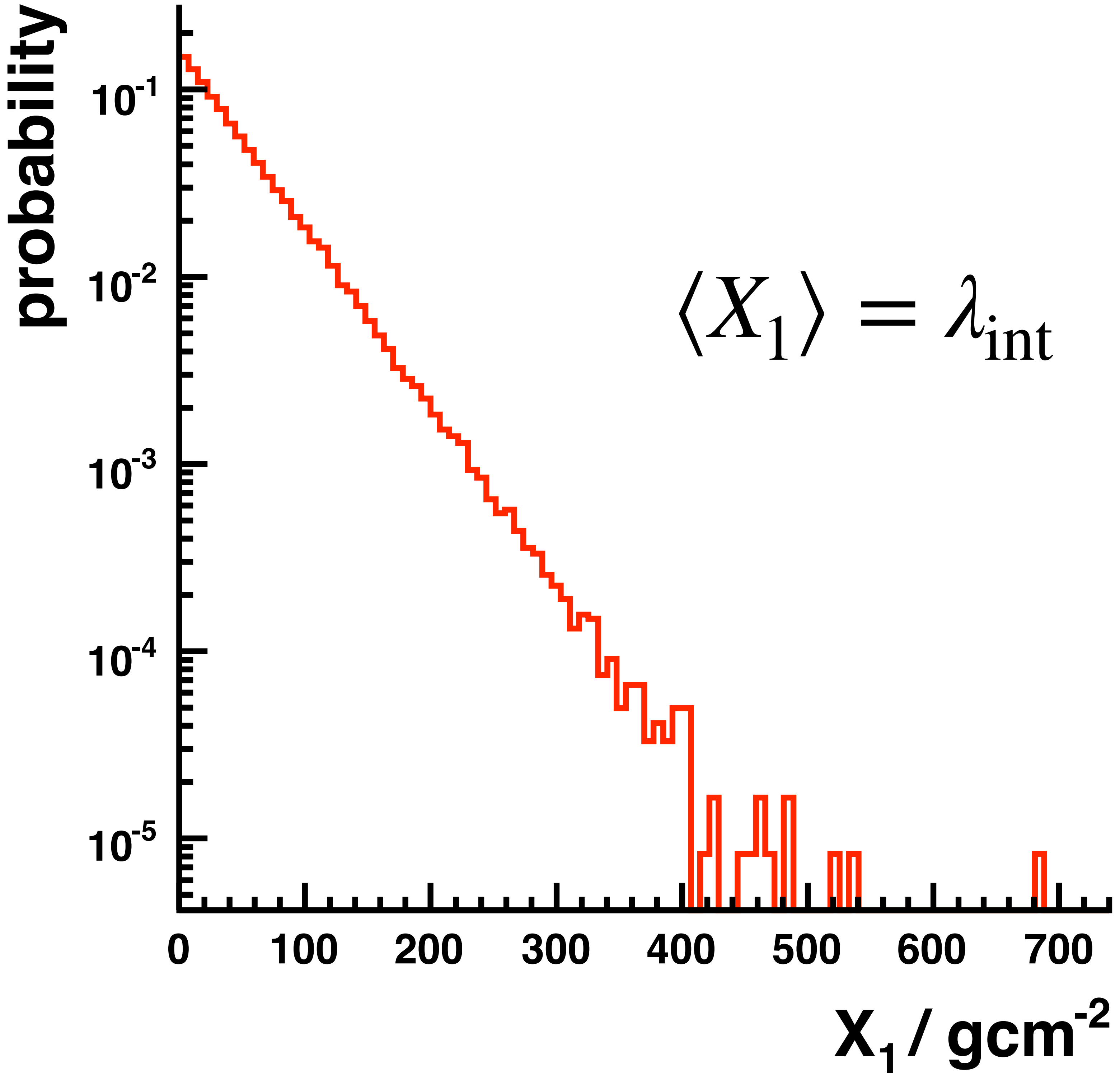
Cross Section Measurements

Distribution of Point of First Interaction

- X_1 is the point of first interaction



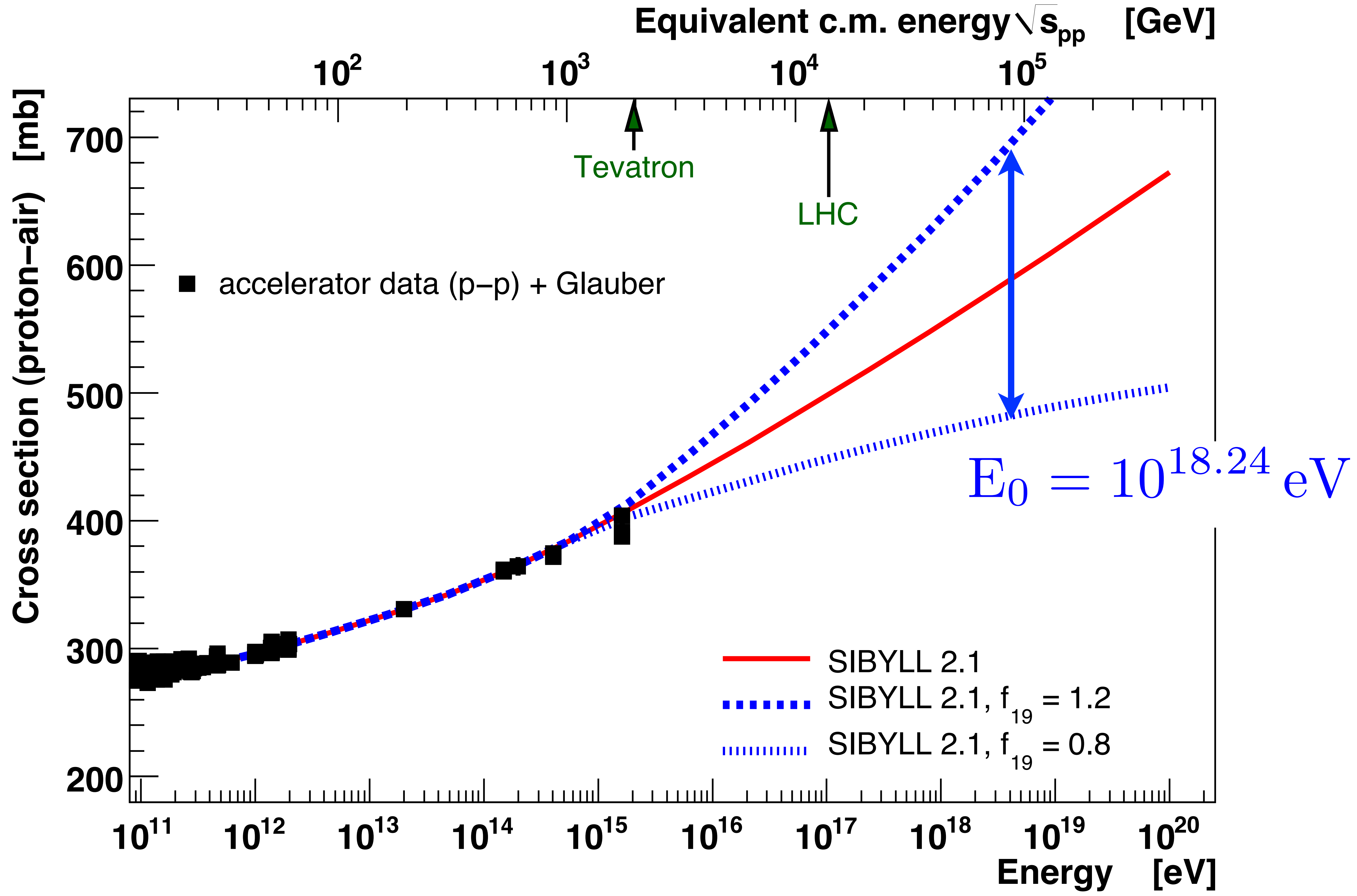


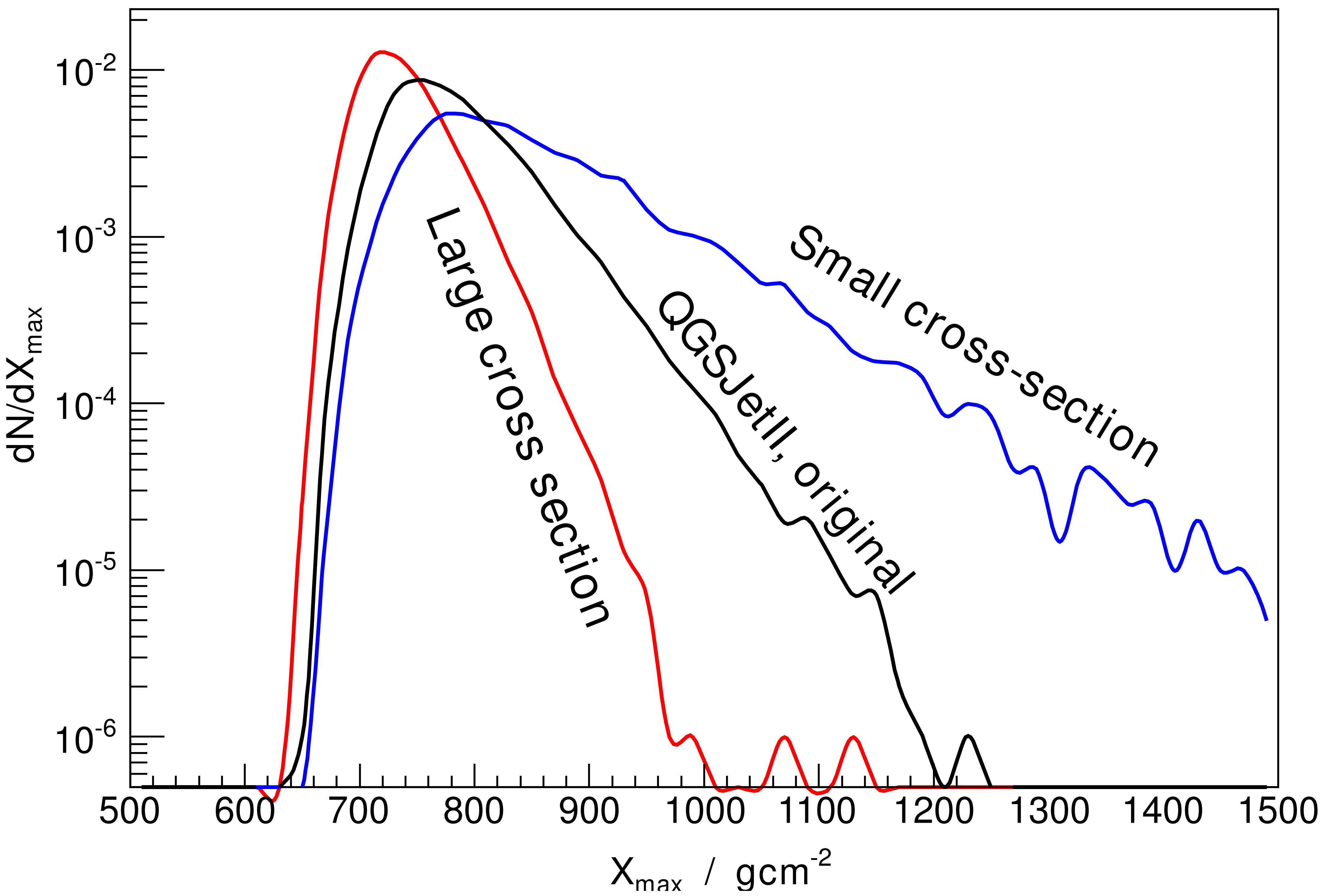


[R. Ulrich et al, NJP 11, 2009]

Cross Section Measurement

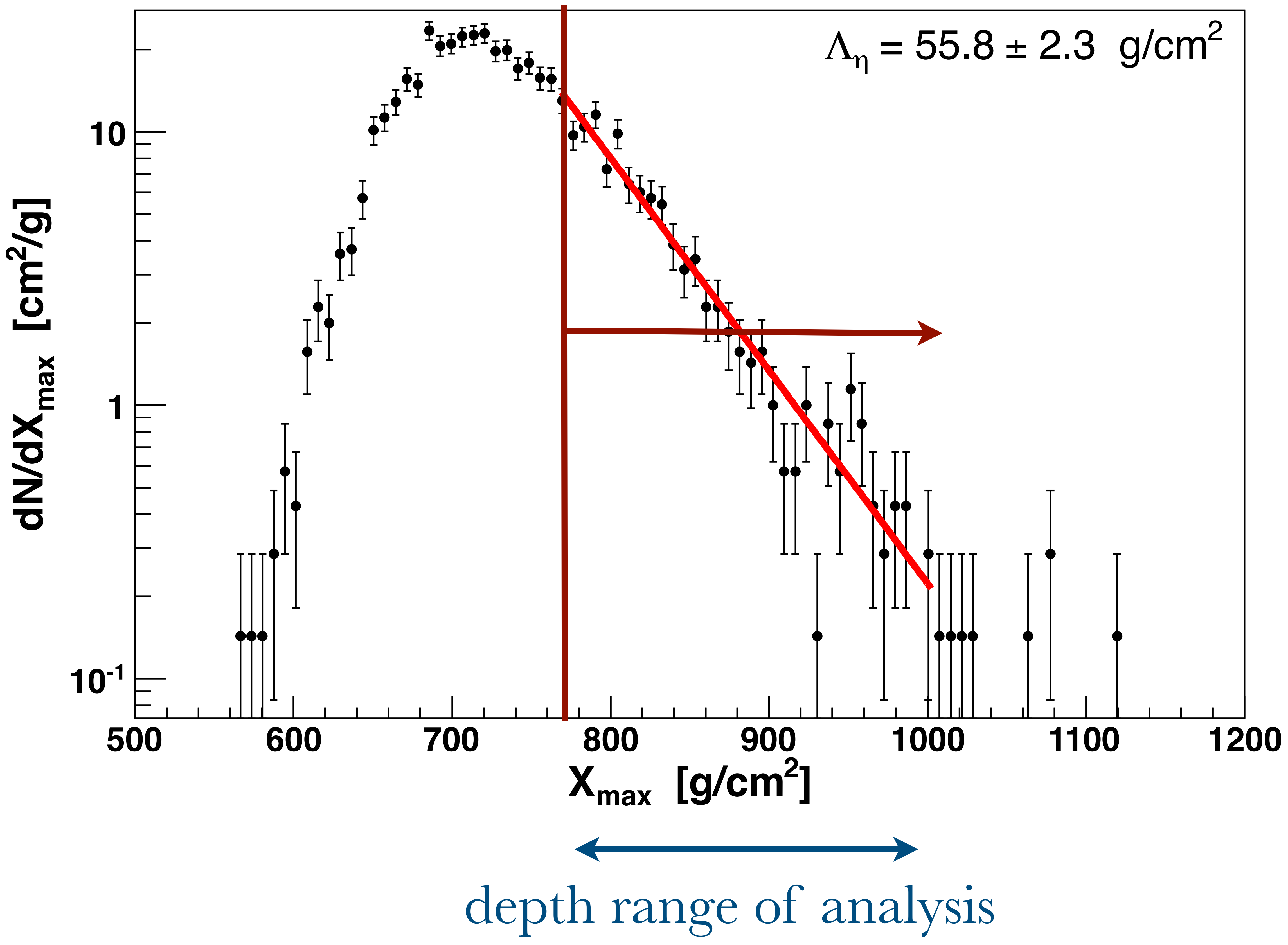
- Simulation of proton showers with different cross sections
- Very good sensitivity of tail of distribution!
- Cross section accepted if simulated slope fits measured slope of X_{max} distribution





Cross Section Measurement

- Only deep showers are used in analysis to enhance proton fraction in data sample
- Effective slope of X_{max} measured after event selection



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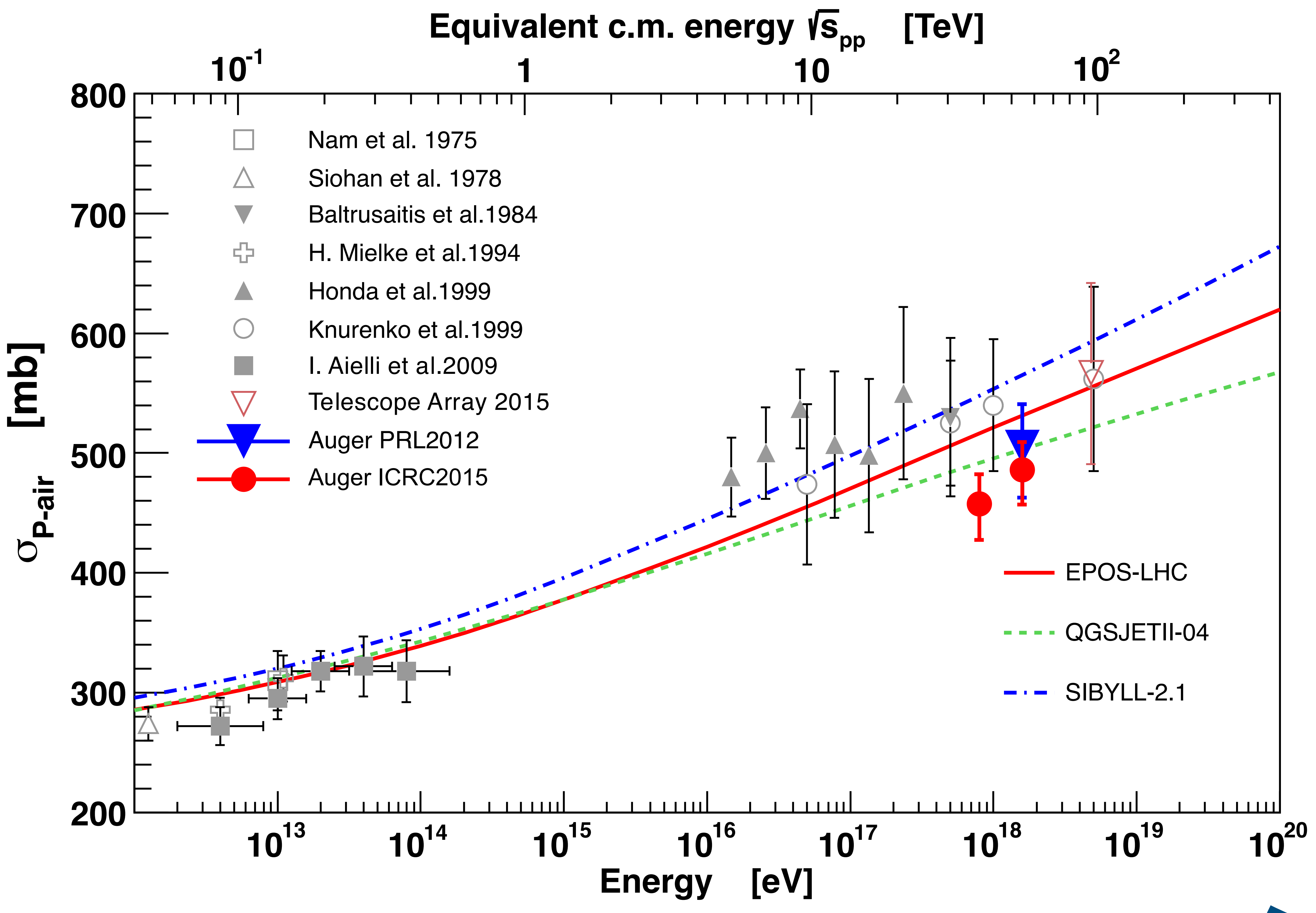
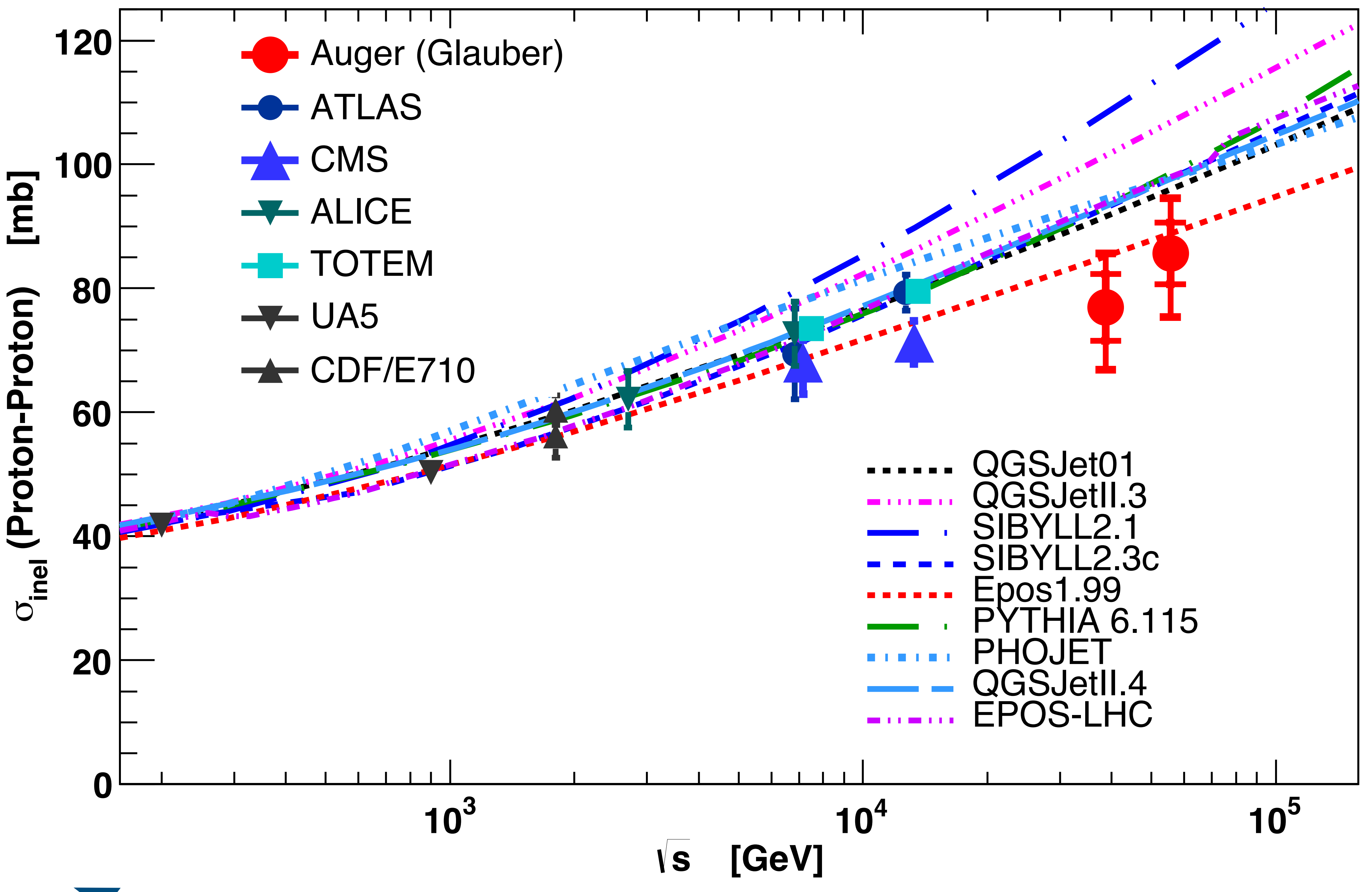




Glauber model

[R. Ulrich (Pierre Auger Collaboration), PoS(ICRC2015)401 (2016)]

Seasonal Variations of TeV Muons

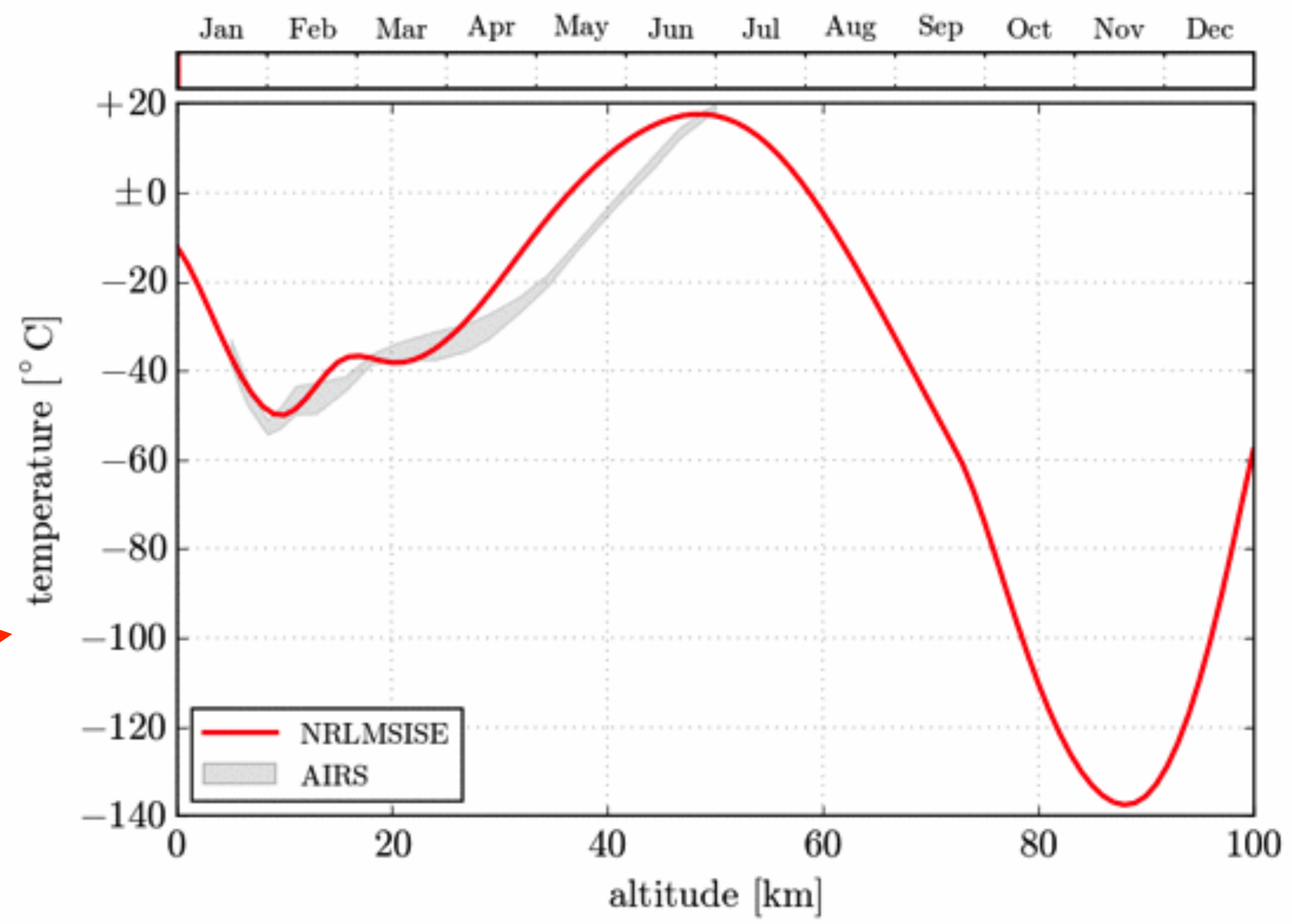
Seasonal Variations of TeV Muons

- If a particle h decays or re-interacts in the atmosphere depends on its
  - decay length:

$$\lambda_{\mathrm{dec},h}(E_h, X) = c \cdot \tau_h \cdot \beta \cdot \gamma \; \rho(X)$$

  - interaction length:

$$\lambda_{\mathrm{int},h}(E_h, X) = \frac{\rho(X)}{\sum_A \sigma_{hA}(E_h) \cdot n_A(X)}$$



- Propagation described by coupled cascade equations:

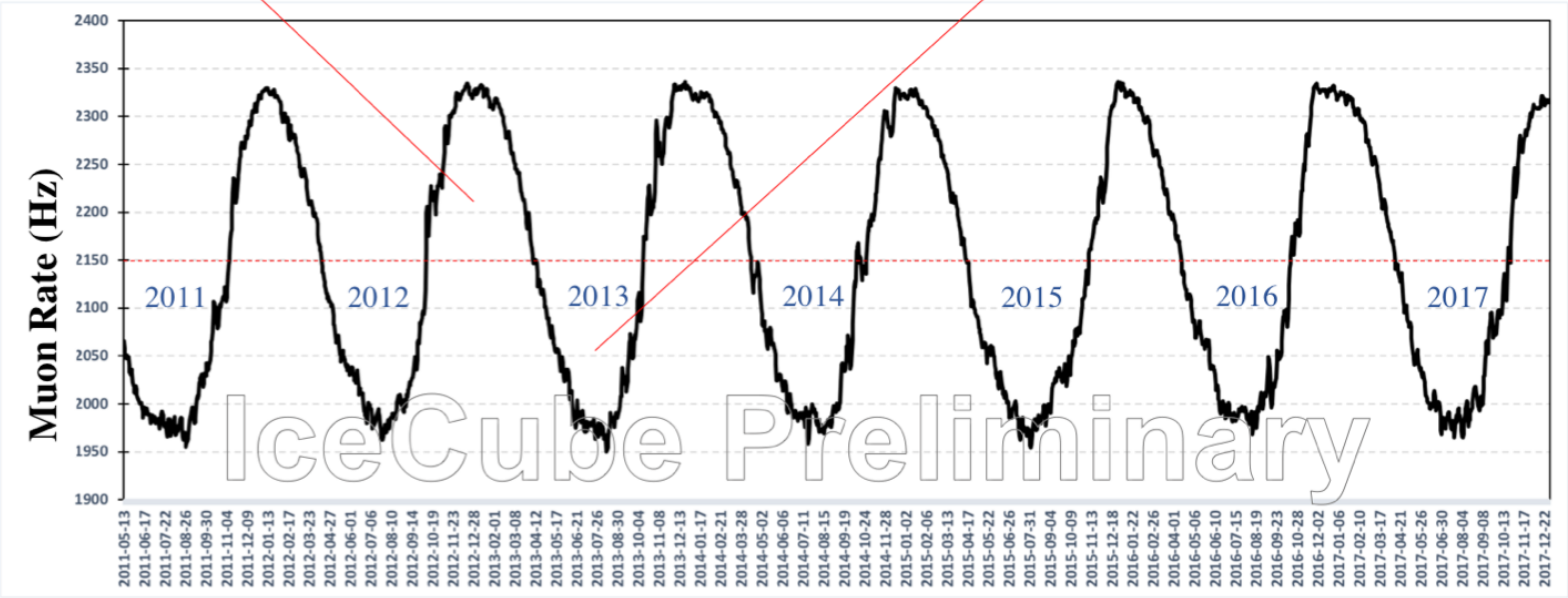
$$\frac{d\Phi_h(E,X)}{dX} = -\left(\frac{1}{\lambda_{\mathrm{int},h}} - \frac{1}{\lambda_{\mathrm{dec},h}}\right) \cdot \Phi(E,X) + \sum_h \int \frac{F_{hj}(E_h, E_j)}{E_h} \cdot \frac{\Phi_j(E_j)}{\lambda_{\mathrm{int},j}} dE_j$$

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

Seasonal Variations of TeV Muons

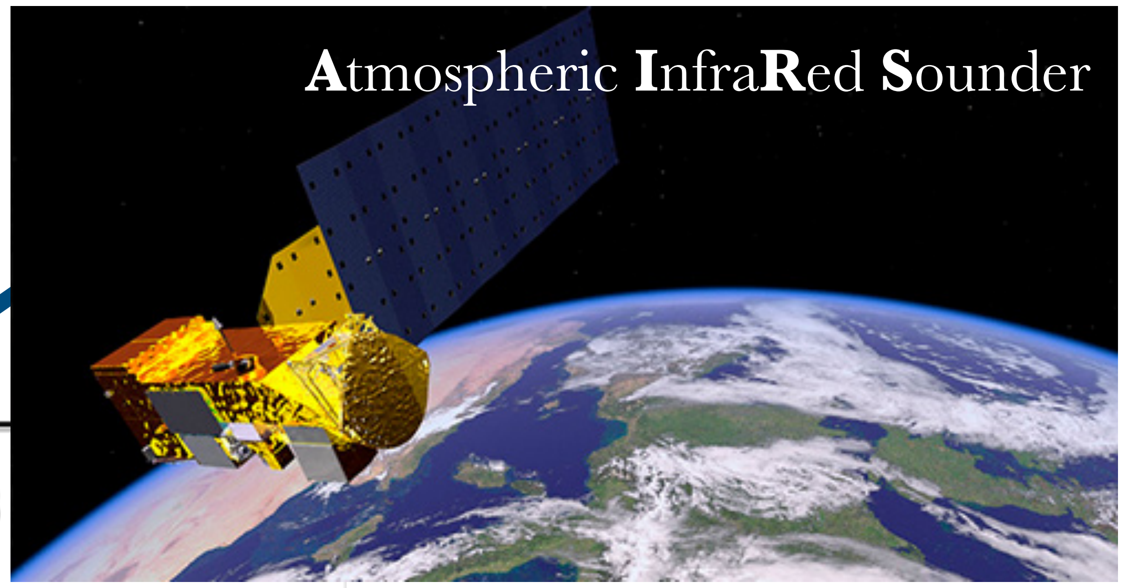
Summer atmosphere
warmer => less dense => pions decay to muons

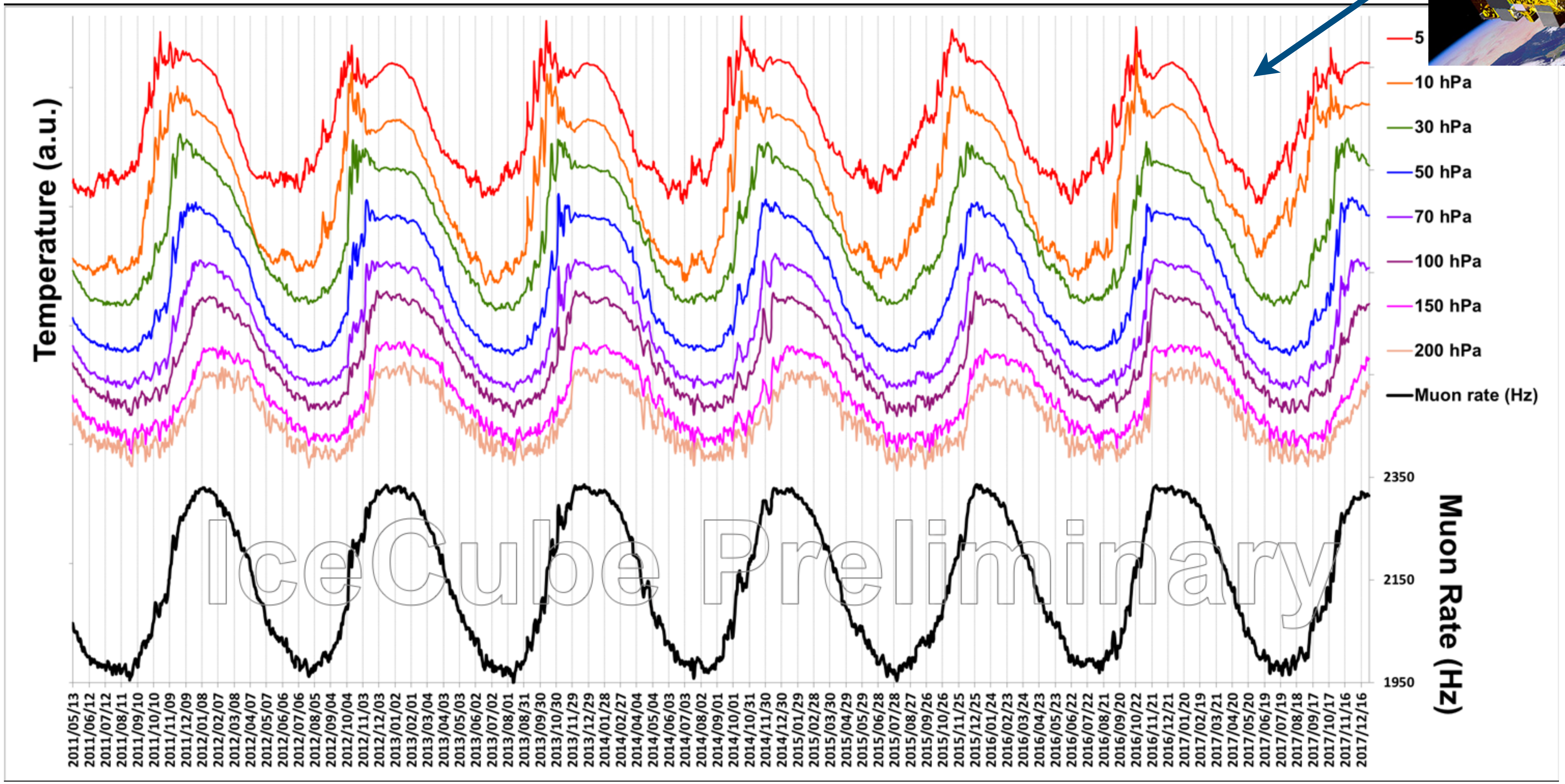
Winter atmosphere
colder => more dense => pions interact



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

Seasonal Variations of TeV Muons

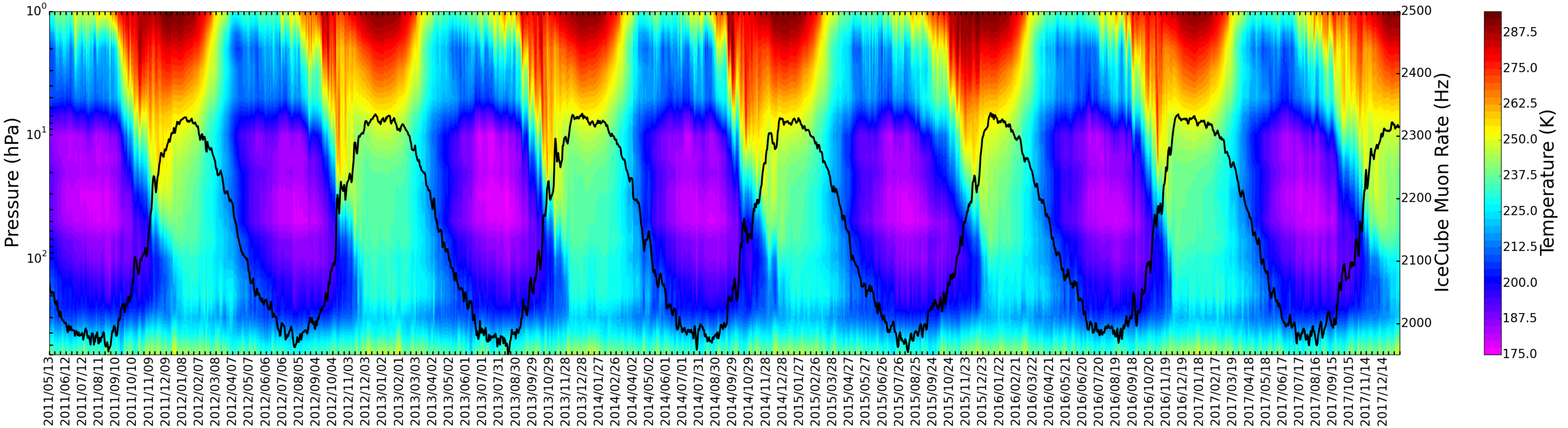


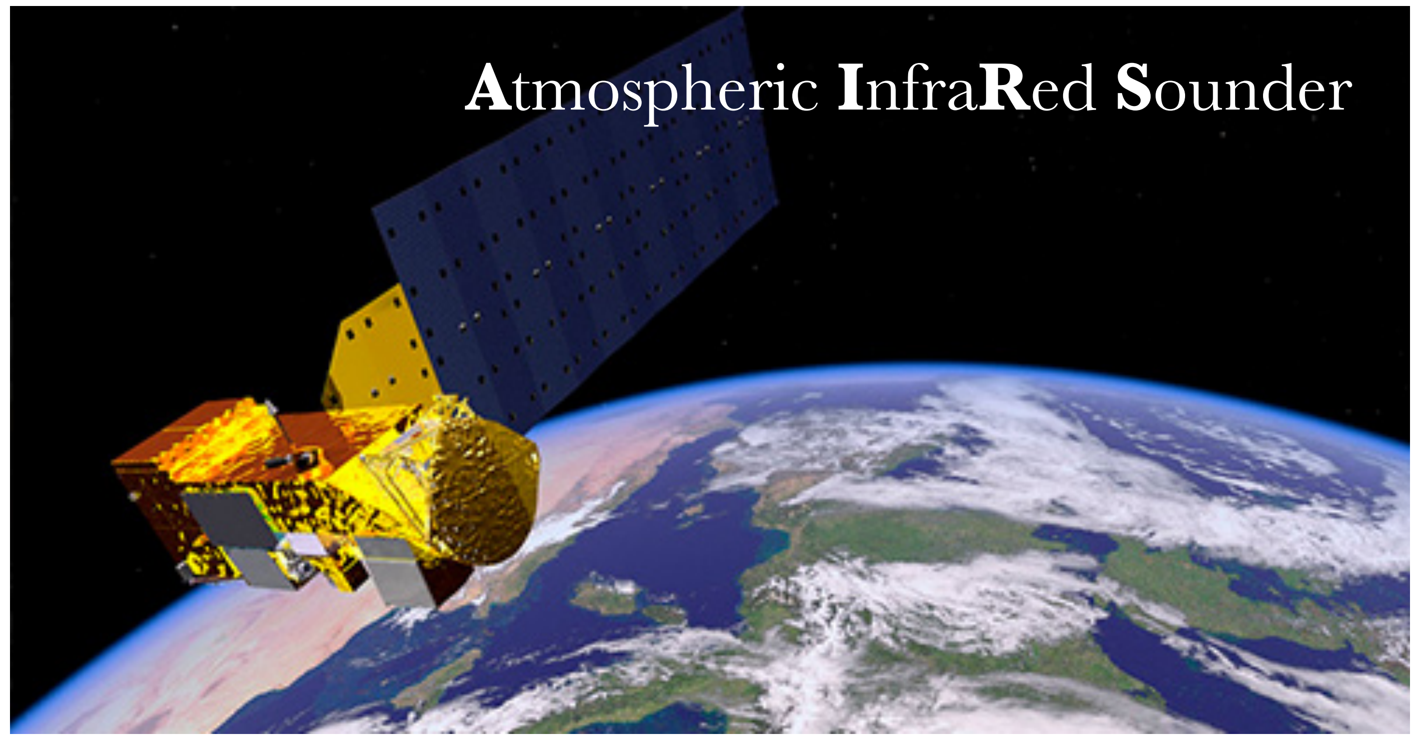


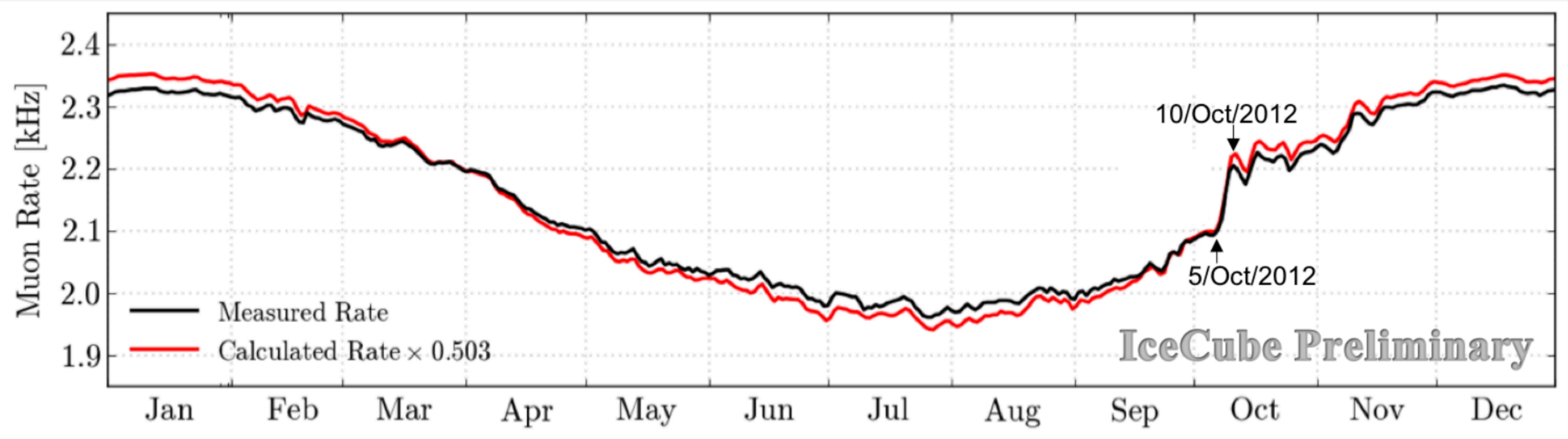
[S. Tilav, T.K Gaisser, D. Soldin, P.Desiati, PoS ICRC2019 (2020) 894]

Seasonal Variations of TeV Muons

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





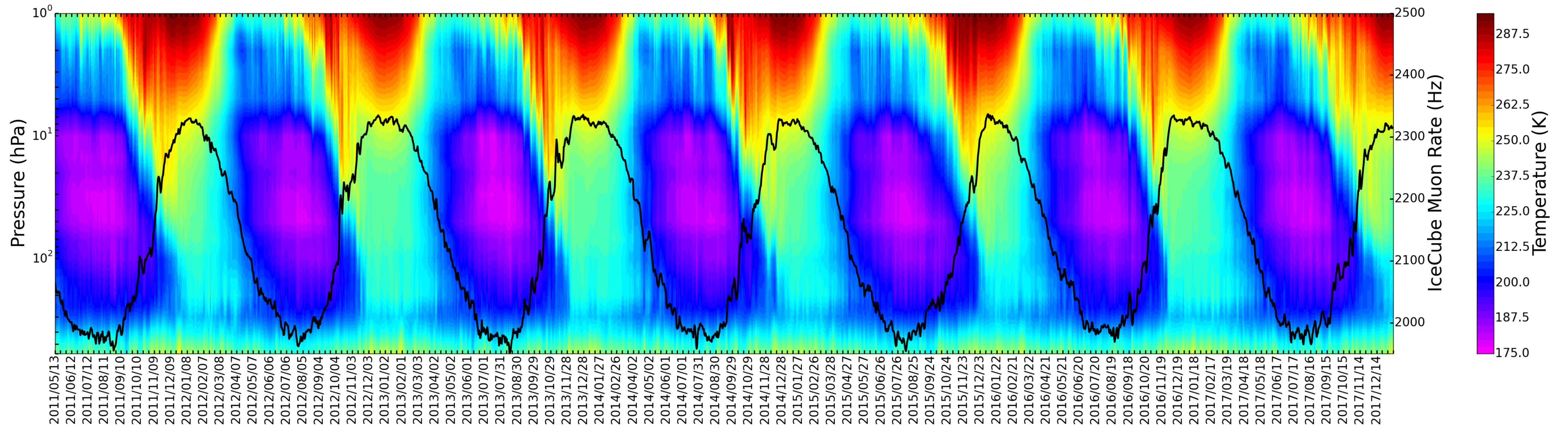


Seasonal Variations of TeV Muons

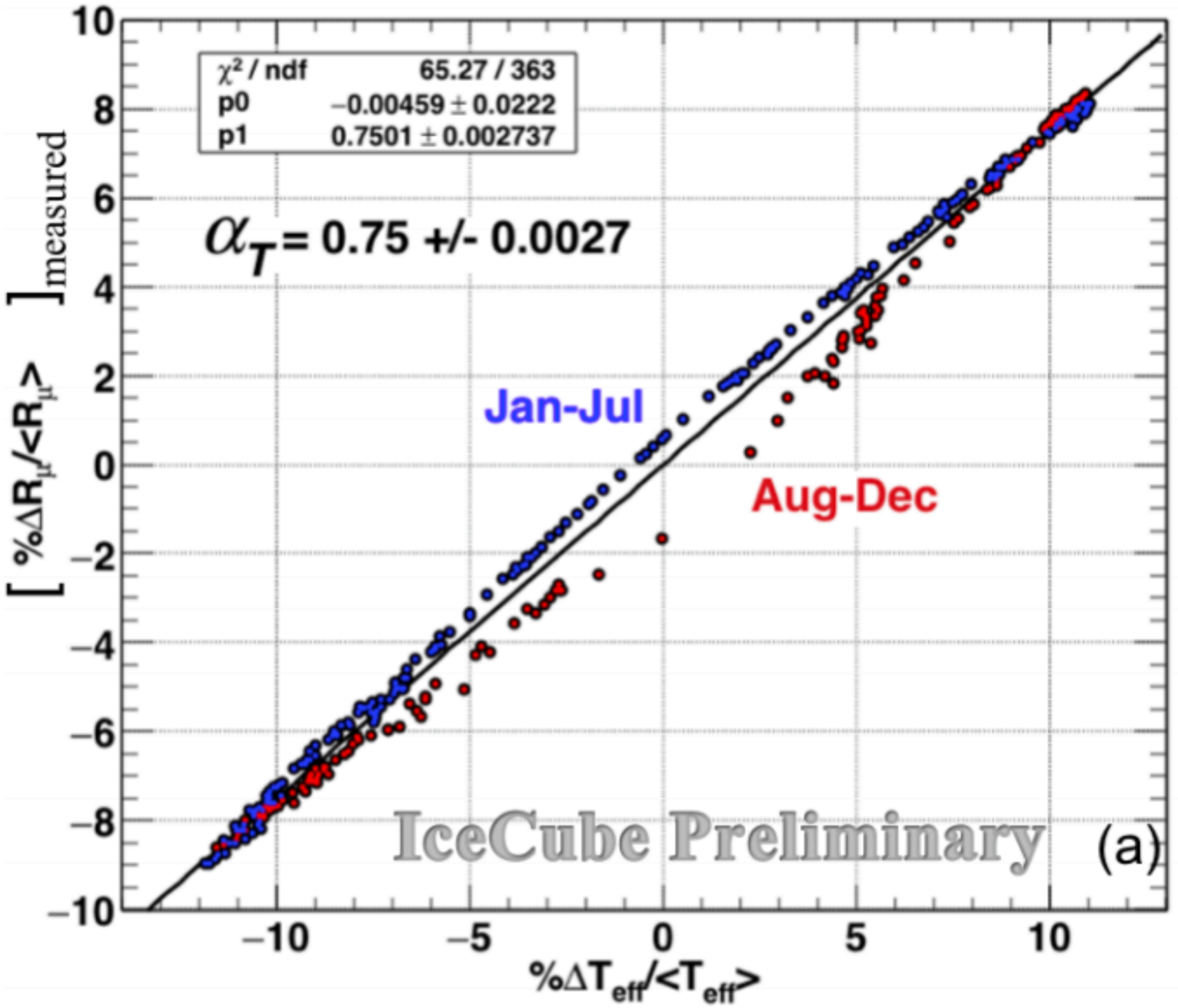
- Temperature coefficient, α:

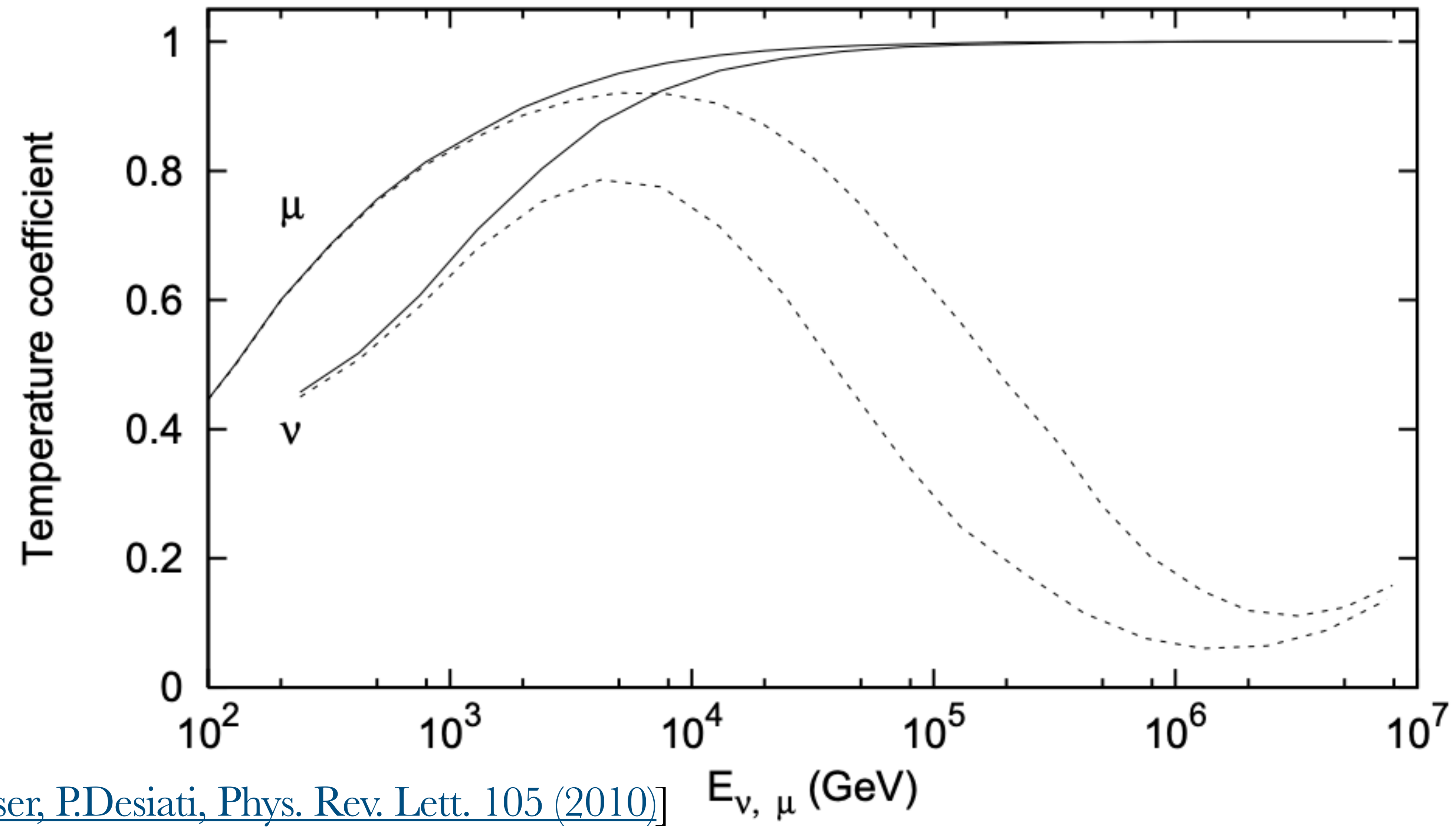
$$\frac{R}{\langle R \rangle} = \alpha \cdot \frac{T_{\text{eff}}}{\langle T_{\text{eff}} \rangle}$$

- "Effective temperature", T_{eff}
  - Temperature of average layer where muons are produced
- Estimate of the K/π-ratio (+prompt)



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





[T.K Gaisser, P.Desiati, Phys. Rev. Lett. 105 (2010)]


(Almost) The End

A Few Final Remarks

- I will upload my slides to the indico tonight
- I'll leave on Wednesday around noon, until then, please feel free to ask any questions!
- If you have any questions at a later point, please contact me at soldin@kit.edu
- However, we will also have a discussion session tomorrow!
- If you have any questions, this will be the opportunity to have an informal discussion
- Also, if you already have questions, please don't hesitate to catch me during breaks / dinner and I will try to address them
- We will also solve some problems related to the topics discussed during lectures!
- This will be done "old" school, i.e. please bring pen and paper!


The End