Astroparticle physics at extreme energies and the muon puzzle

Ruben Conceição

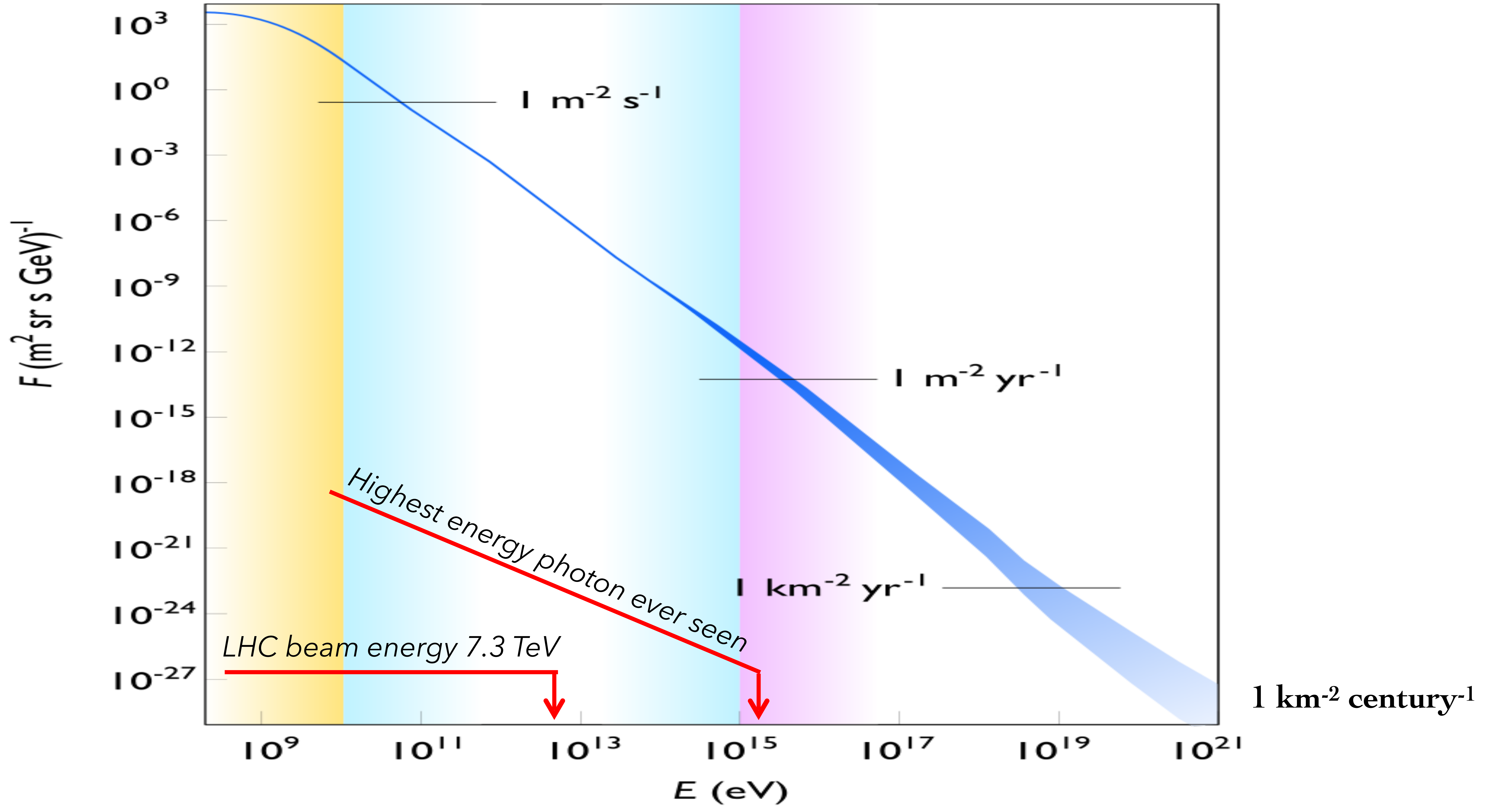
LIP

TÉCNICO LISBOA

Café com Física, Coimbra, June 15th 2022

Cosmic ray energy spectrum

(Charged particles continuously bombarding Earth)



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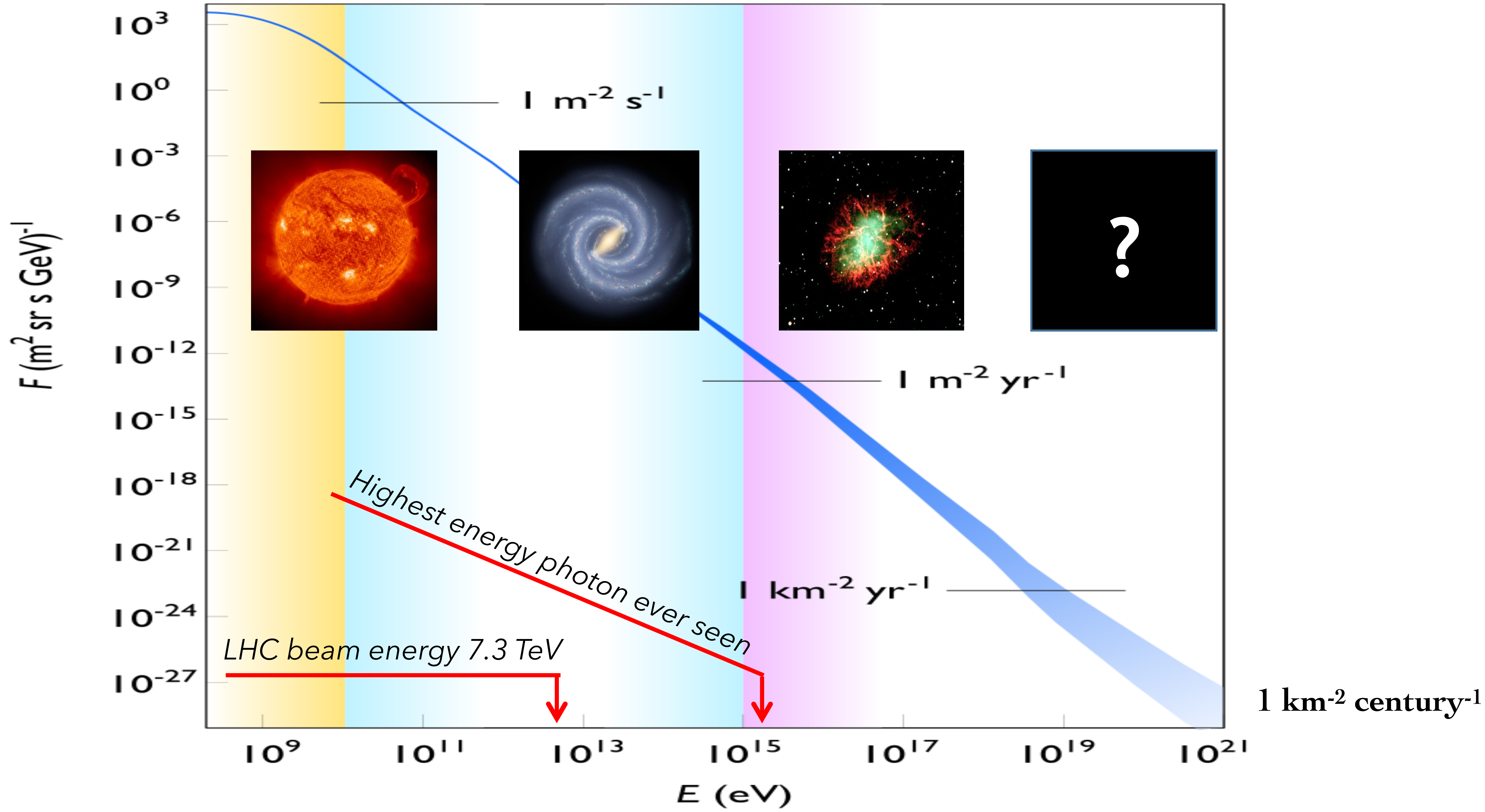
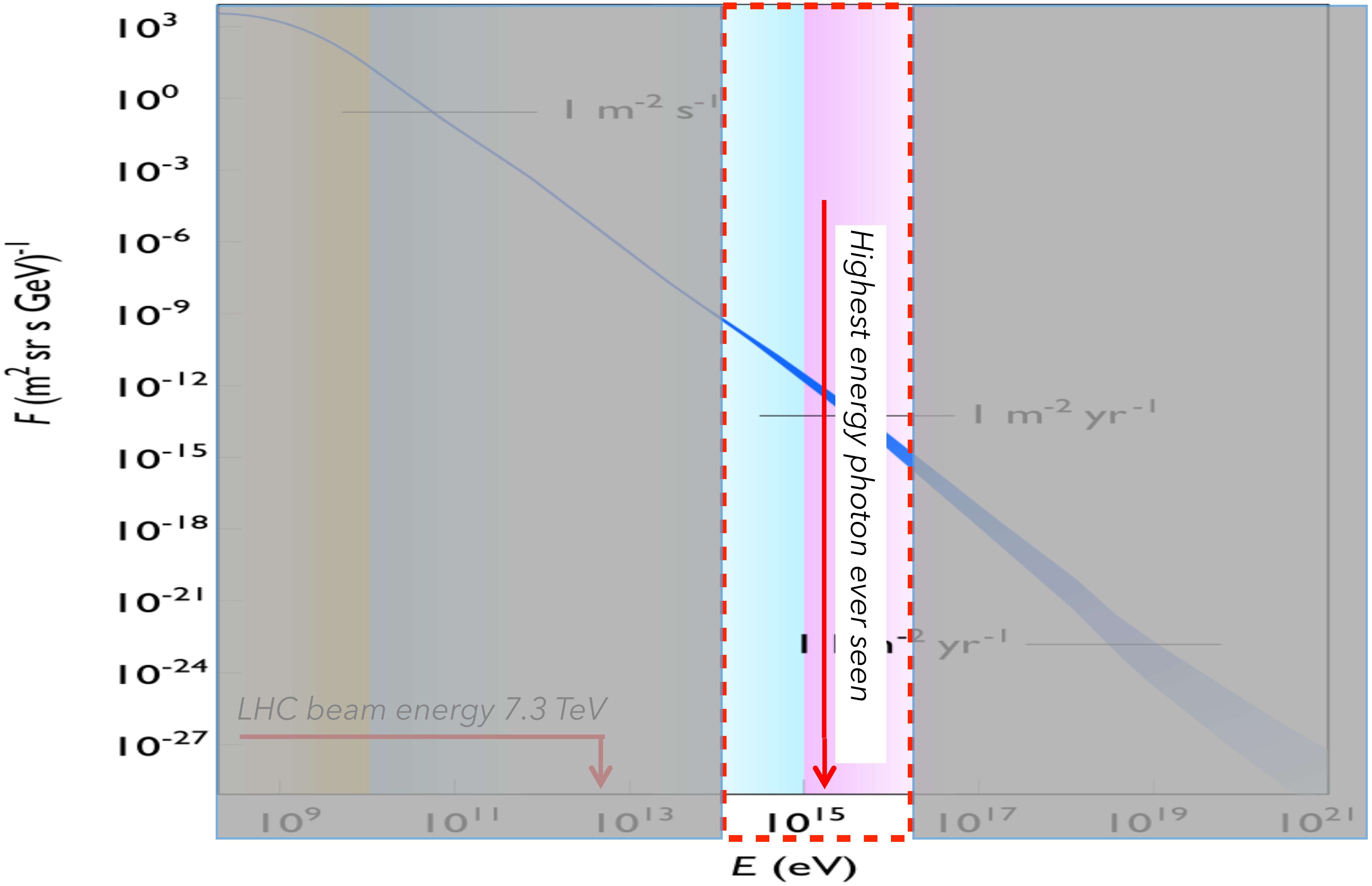
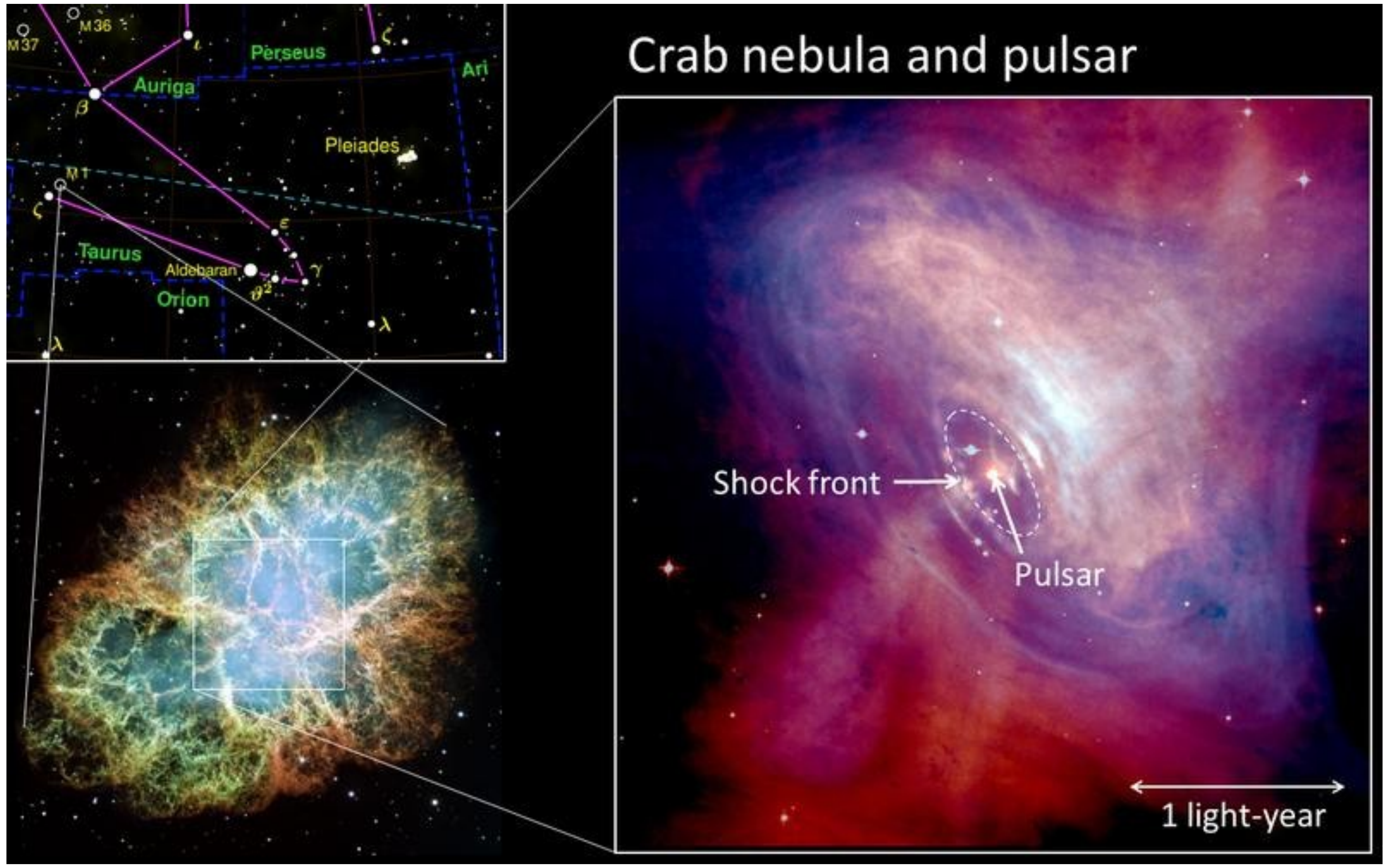
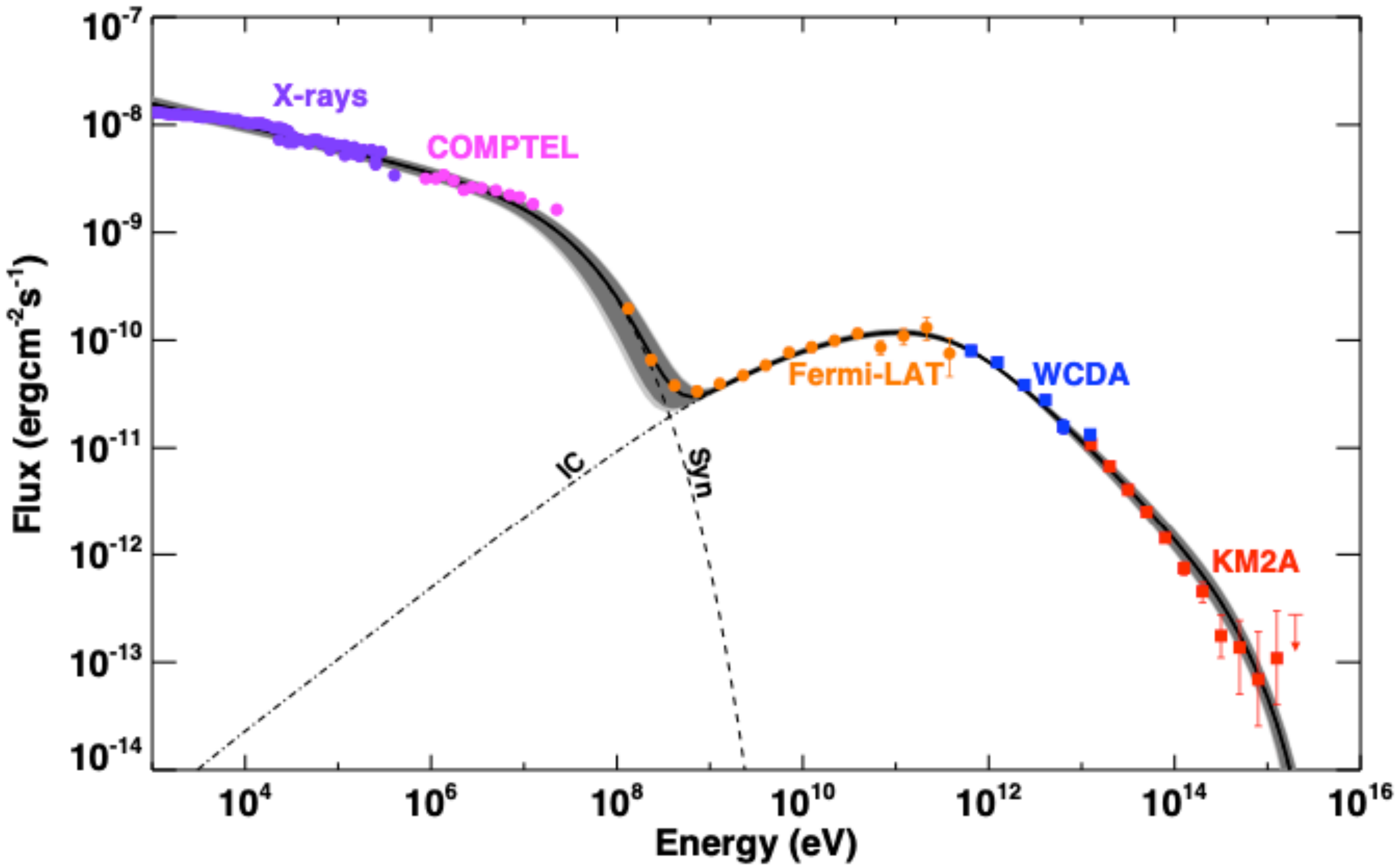


Why do we care?

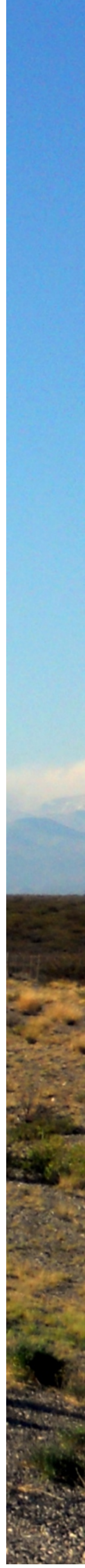


Ultra-high-energy gamma-rays

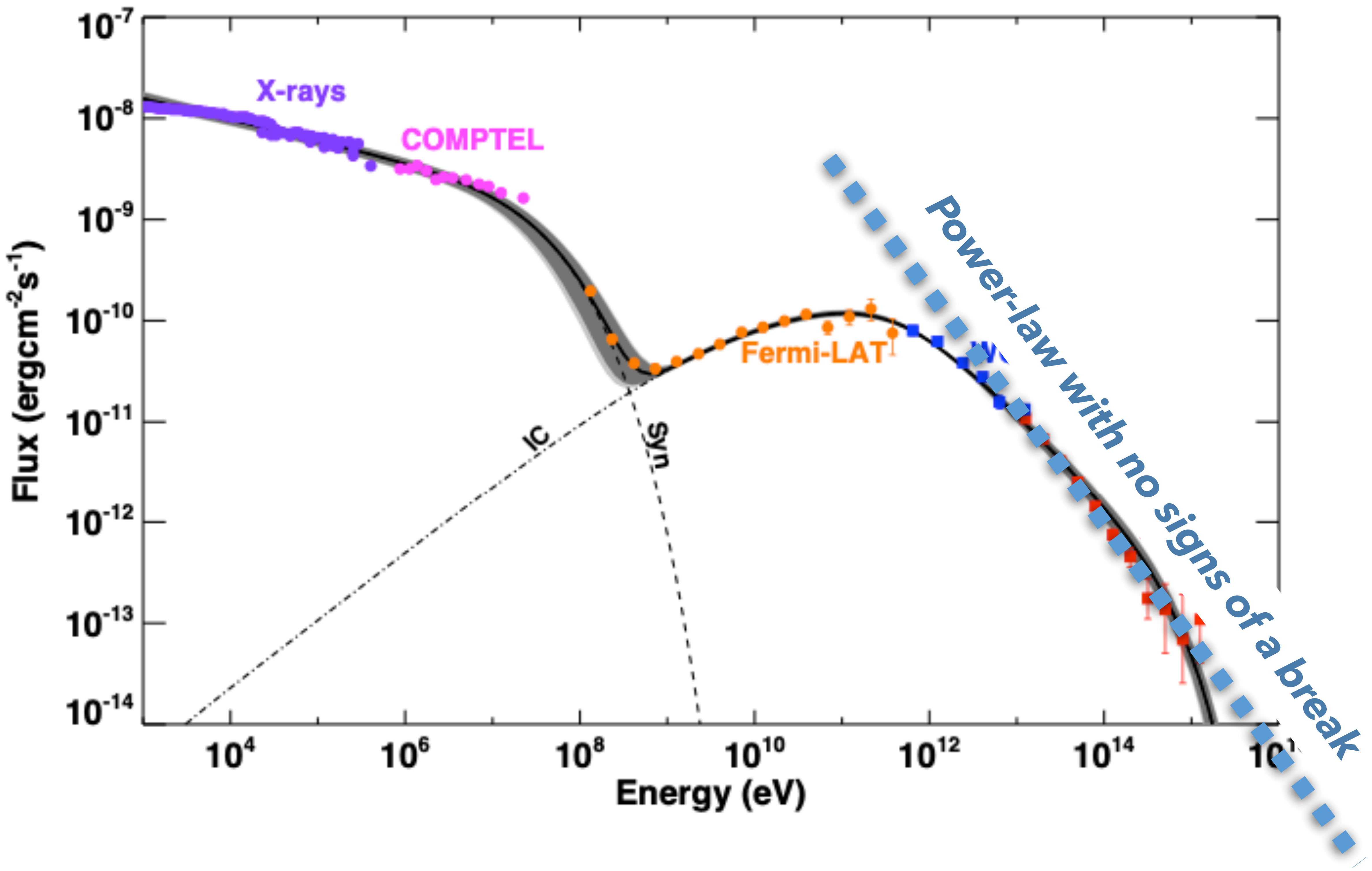




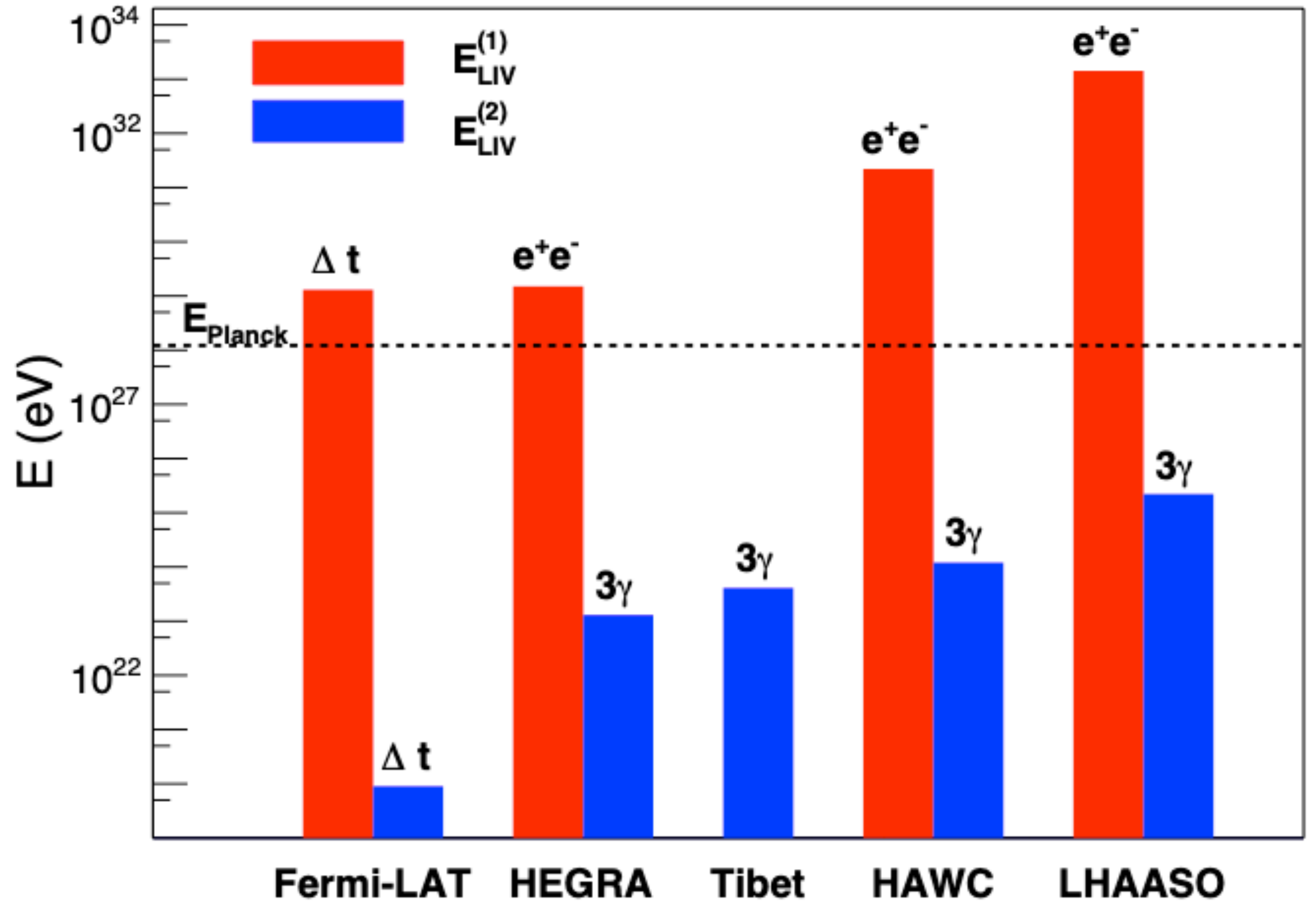
The LHAASO experiment detected photons from the Crab Nebula with energies surpassing 1 PeV (10^{15} eV)



Lorentz Invariance Violation



$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^{n+2}}$$



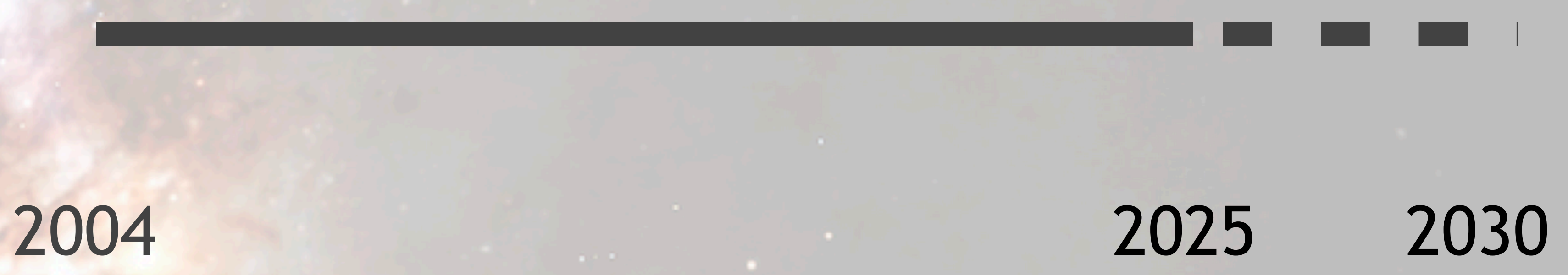
The analysis of the energy spectrum can be used to evaluate LIV at energies above the Planck scale!

Exploring the extreme Universe

✧ Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

UHE
Cosmic Rays



✧ Southern Wide-field Gamma-ray Observatory

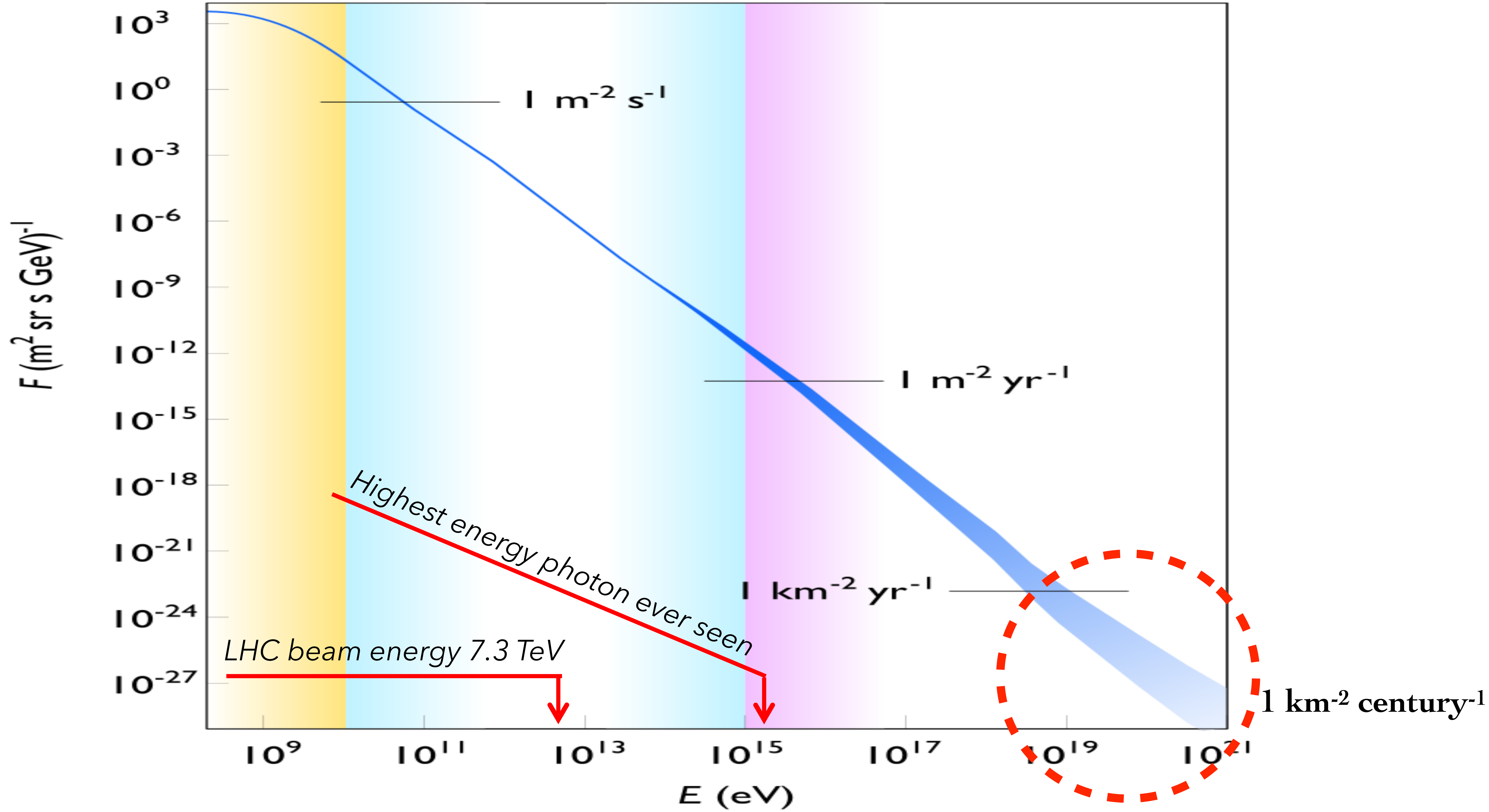
SWGO
The Southern Wide-field Gamma-ray Observatory

VHE
Gamma Rays

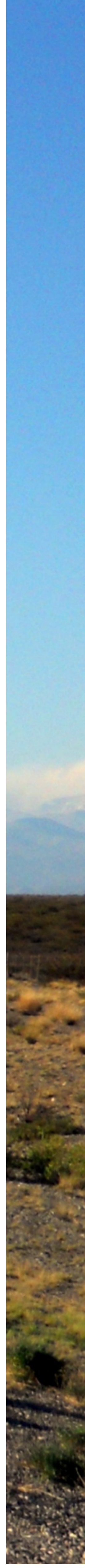
Ultra high energy cosmic rays

Pierre Auger Observatory

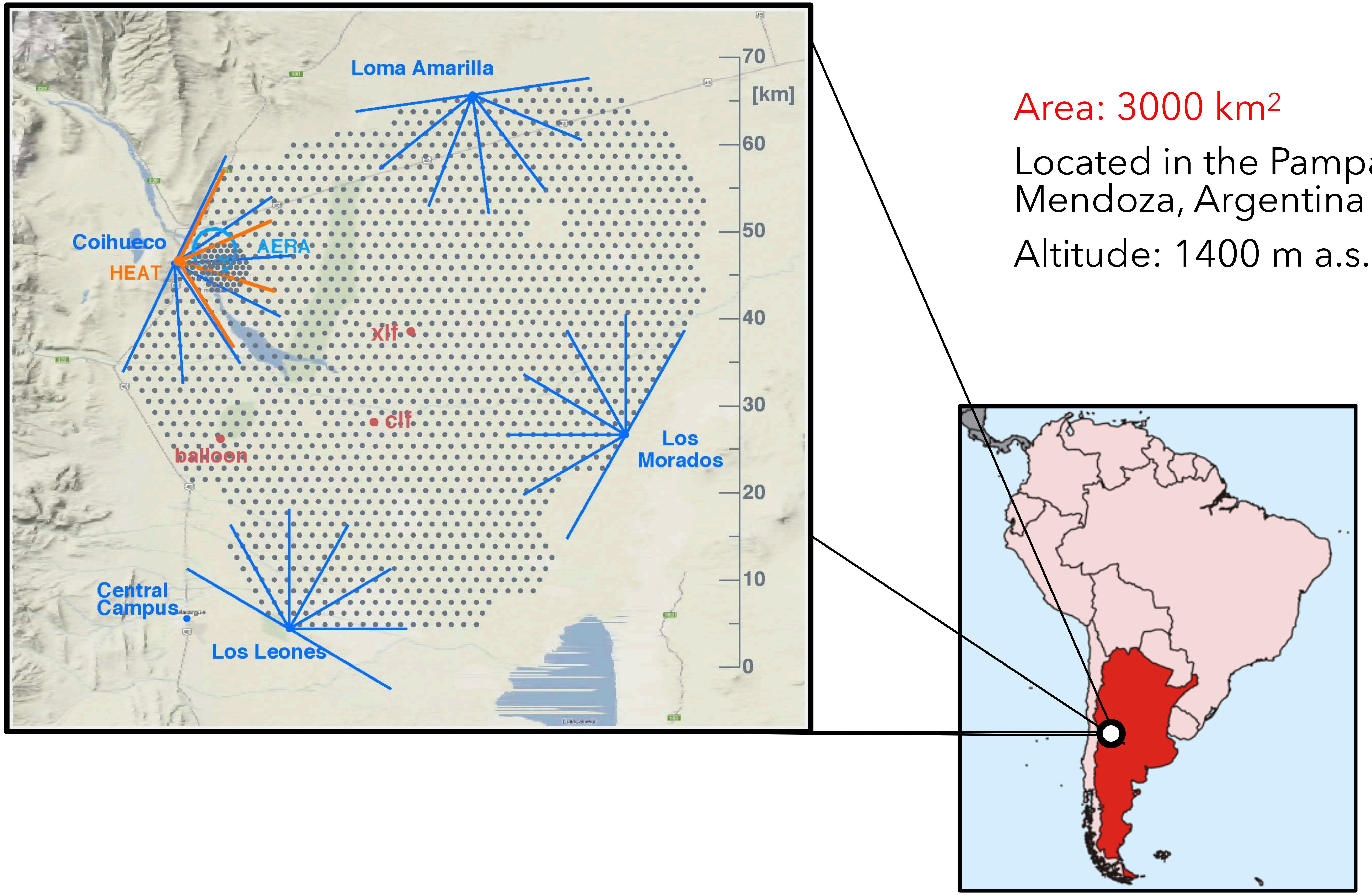
UHECRs



10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
10^{-27}
F (m^{2} sr s GeV)$^{-1}$
1 m^{-2} s^{-1}
1 m^{-2} yr^{-1}
1 km^{-2} yr^{-1}
1 km^{-2} century^{-1}
Highest energy photon ever seen
LHC beam energy 7.3 TeV
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
E (eV)



Pierre Auger Observatory

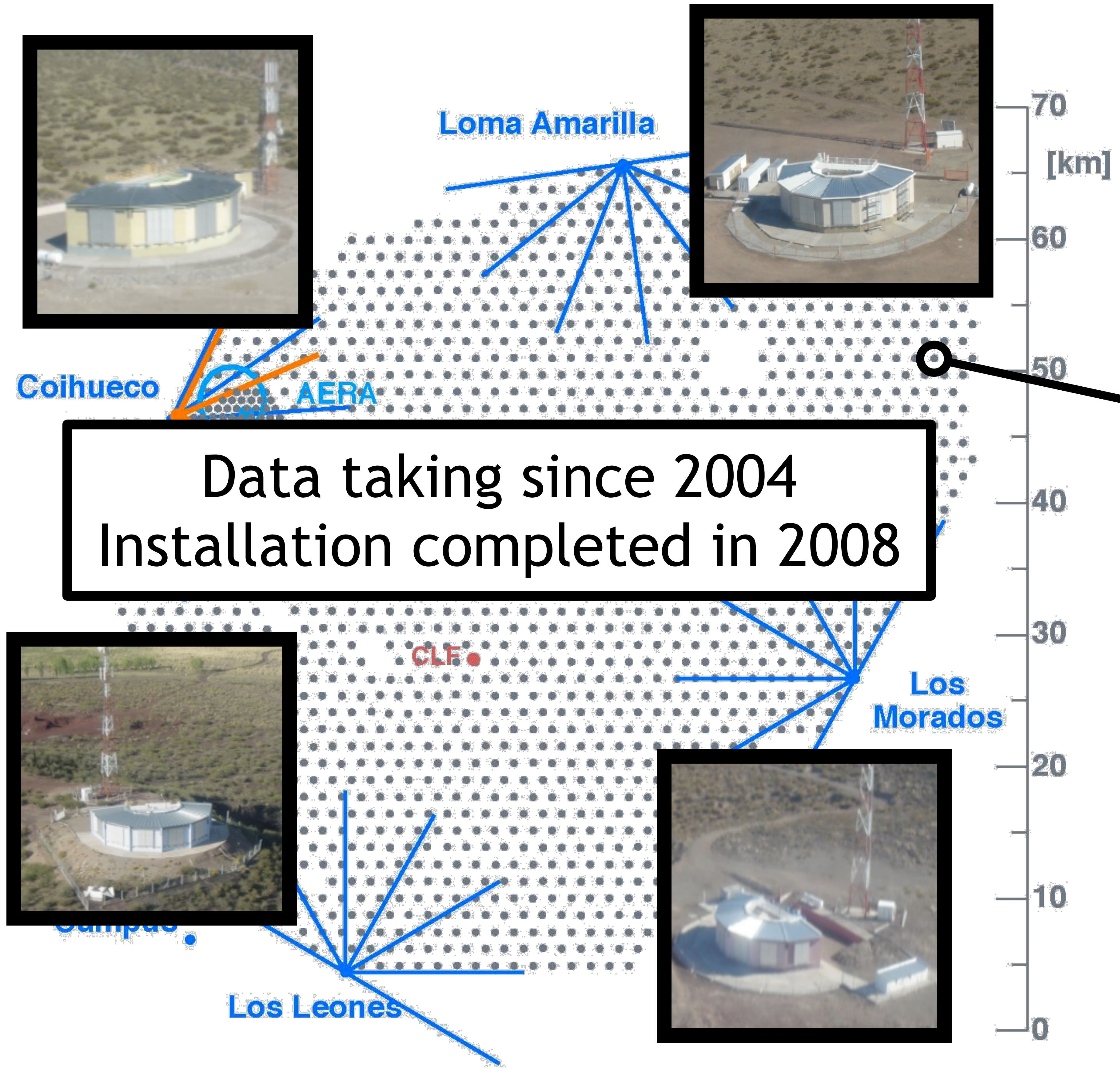


Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

Pierre Auger Observatory

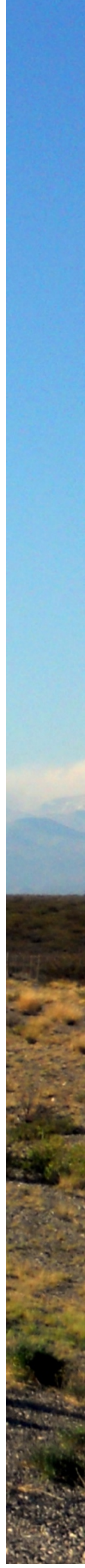


Data taking since 2004
Installation completed in 2008

~ 60 km

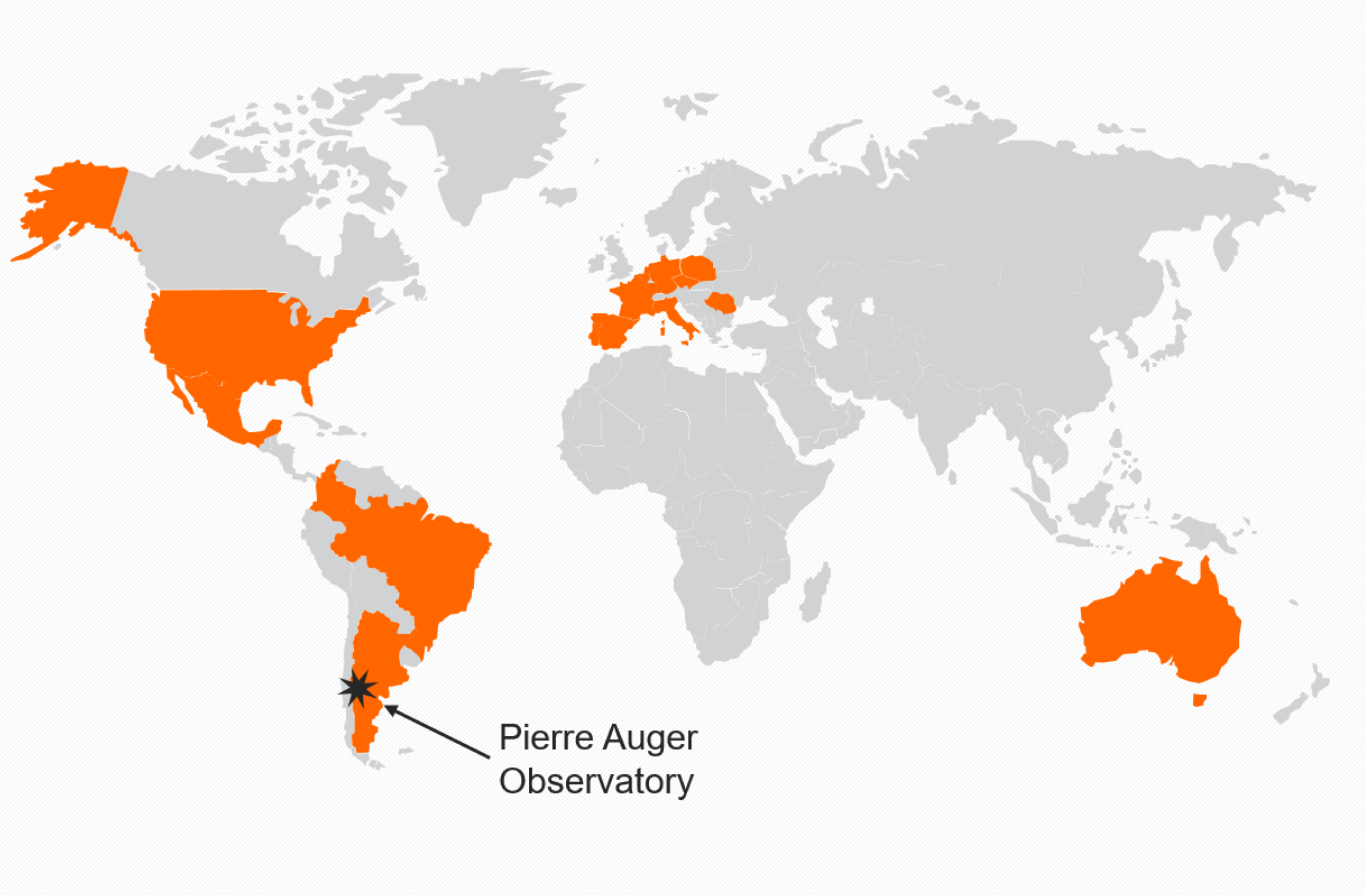
- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes

- ~ 1600 Surface Detectors (SD) Stations
- SD stations spaced by 1.5 km
- Covering an area of 3000 km^2



Pierre Auger Collaboration

Argentina
Australia
Belgium
Brazil
Colombia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA



International collaboration of 17 Countries and ~ 400 scientists

Surface detector

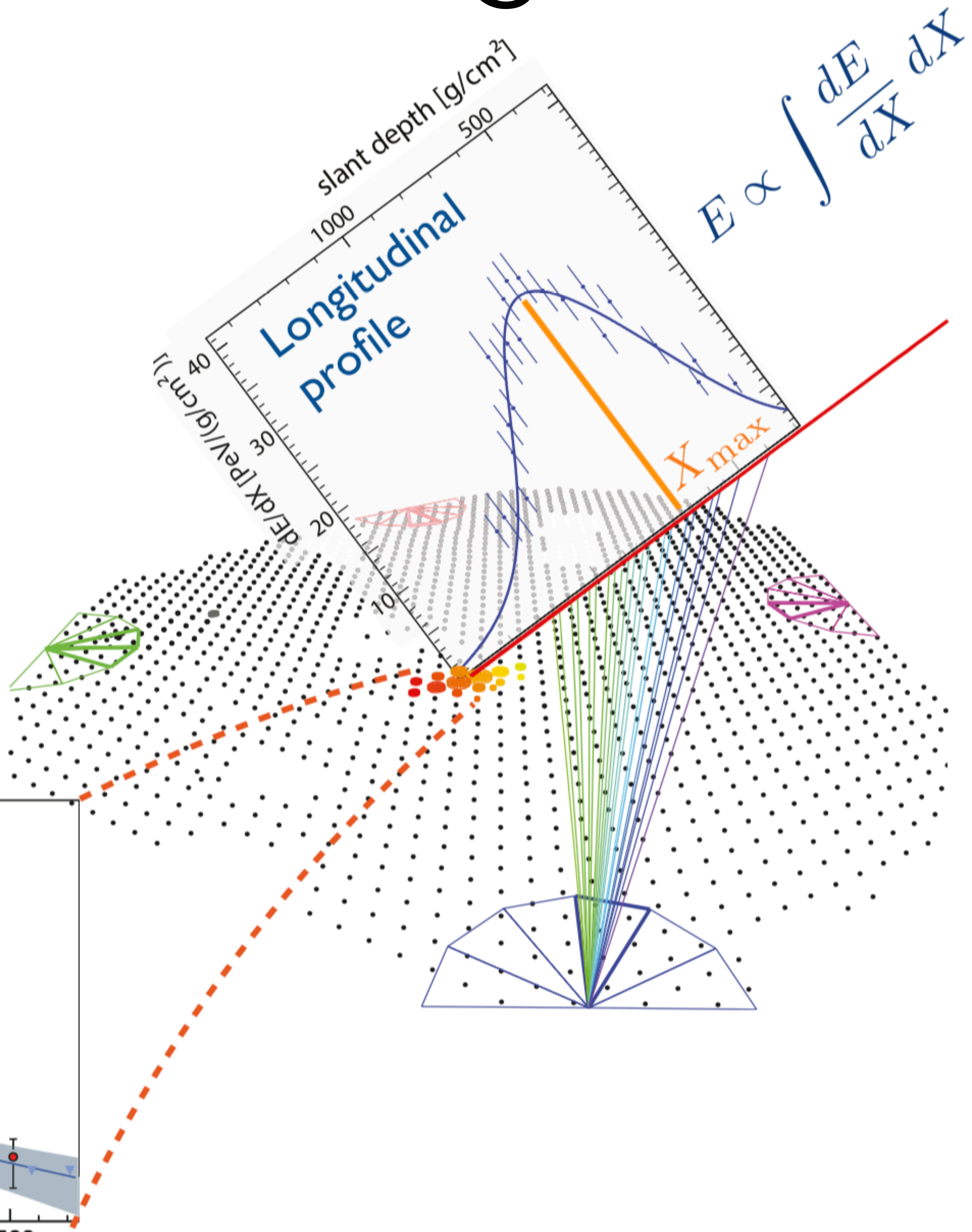
WCD + Fluorescence Detector

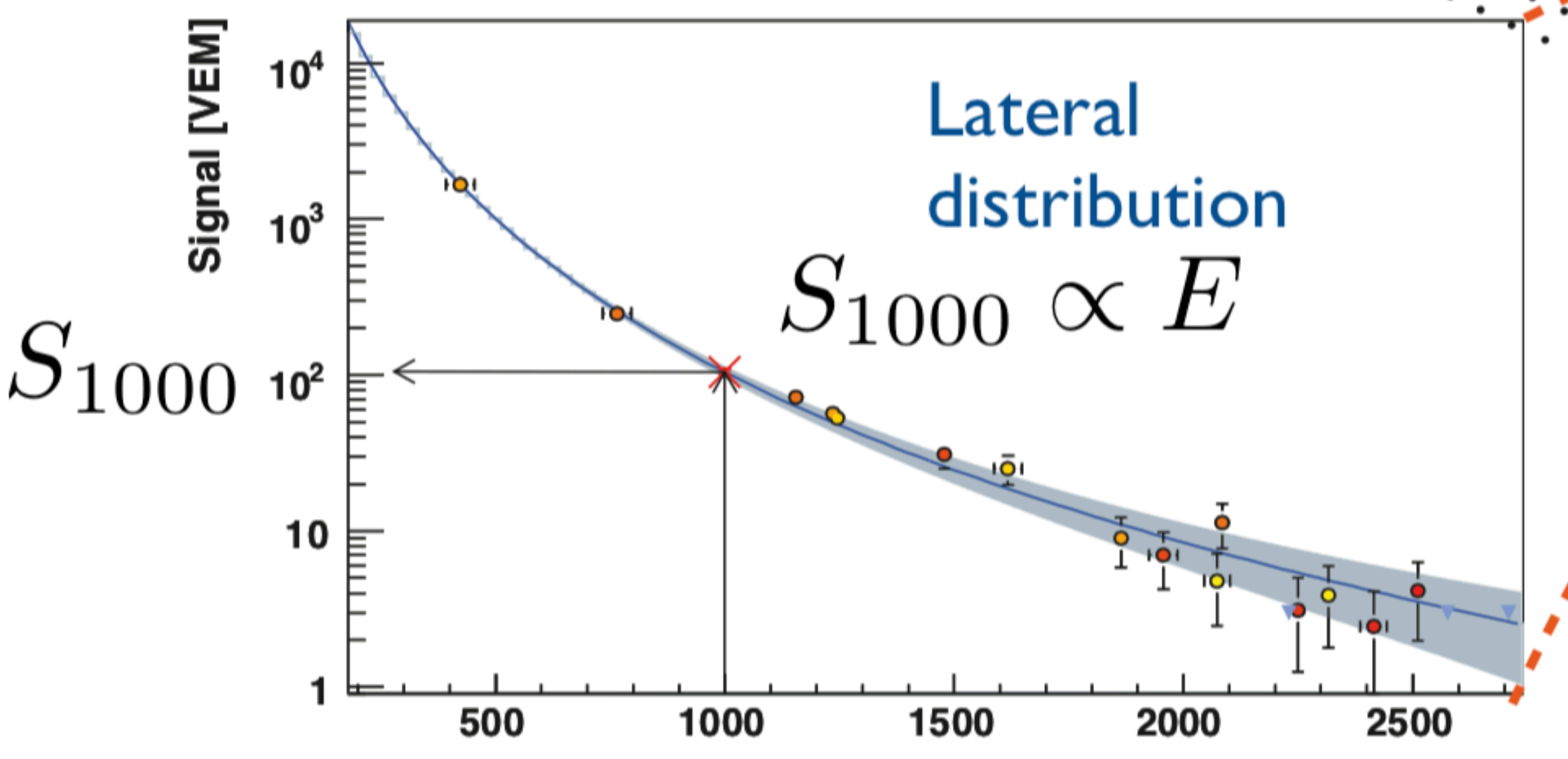
Pierre Auger Observatory

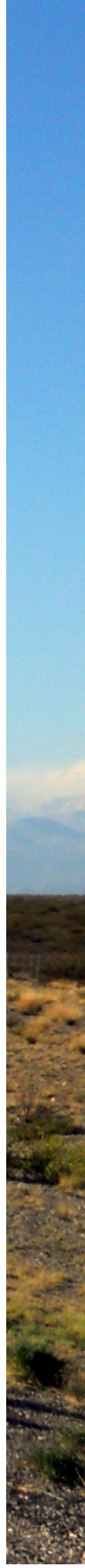
ruben@lip.pt

Measurement of EAS at Auger

- **Fluorescence Detector**
  - Quasi-calorimetric energy measurement
  - ~ 15% duty cycle
- **Surface Detector**
  - Sensitive to both e.m. and muonic shower components

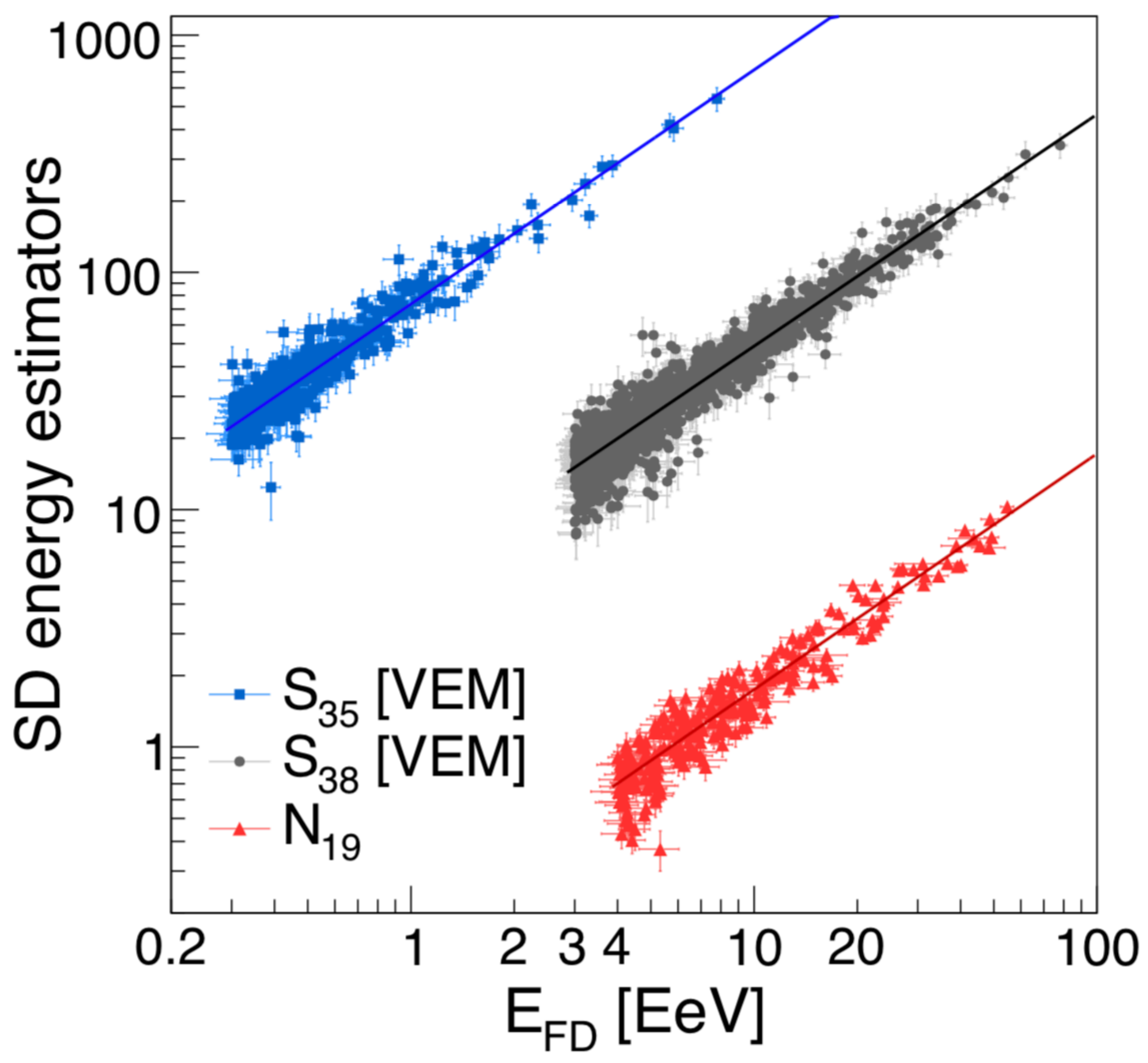


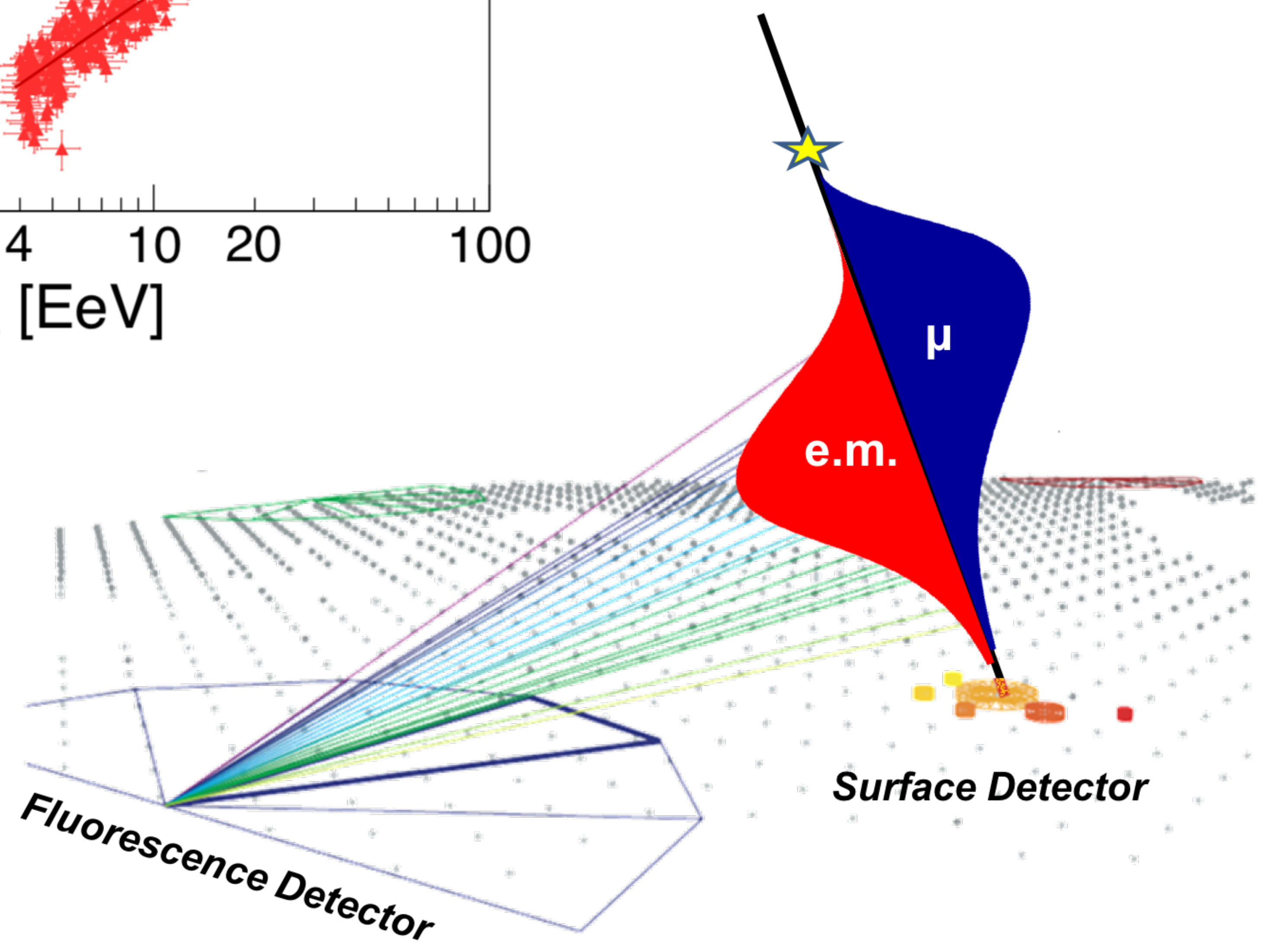




Hybrid technique

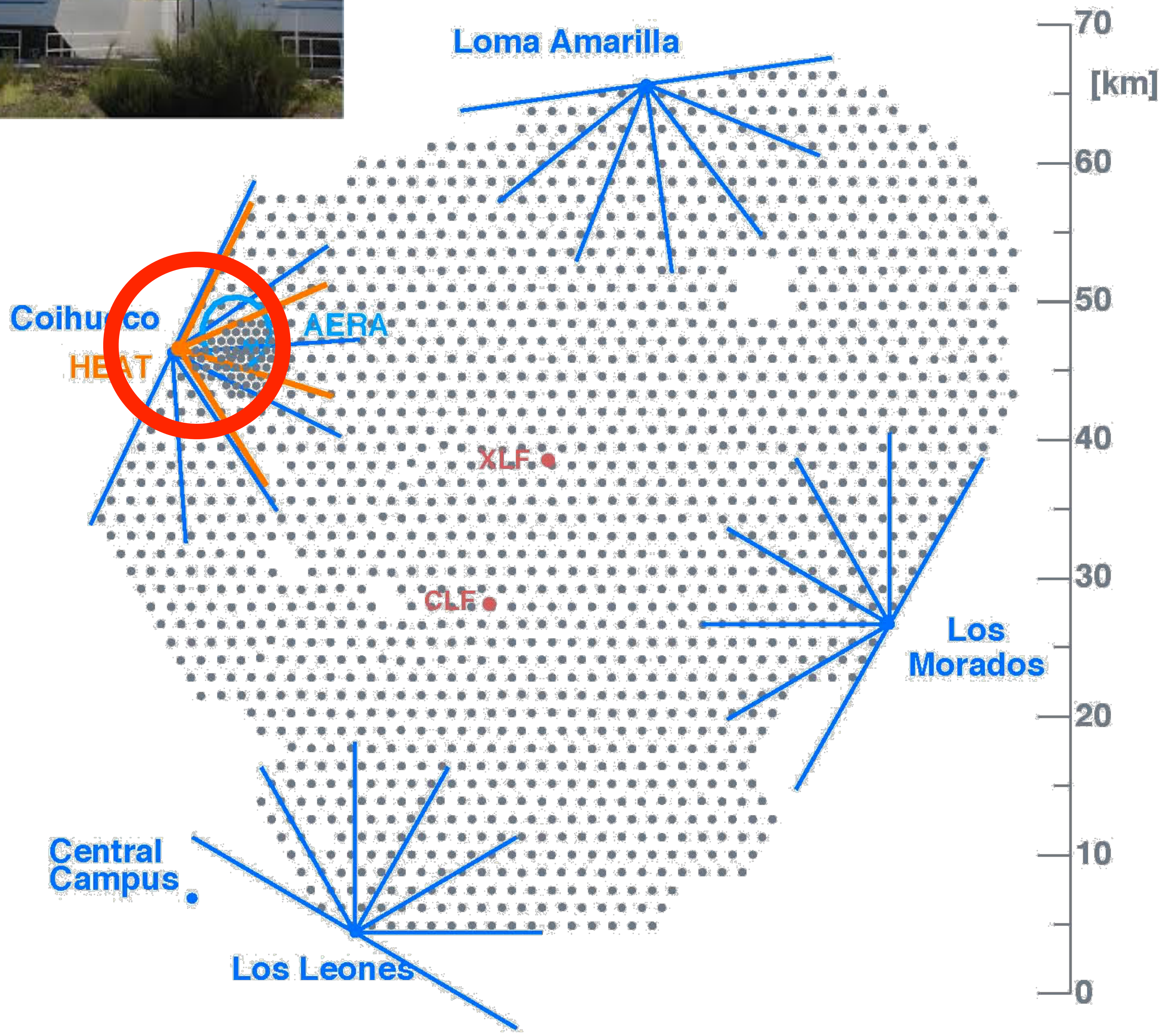
- Calibration of SD with FD
  - FD provides a quasi-calorimetric energy measurement
- Improve geometry reconstruction
  - For hybrid events
- Better assess/control systematic uncertainties
- Different insights of the shower
  - Access different shower components
  - Test shower consistency



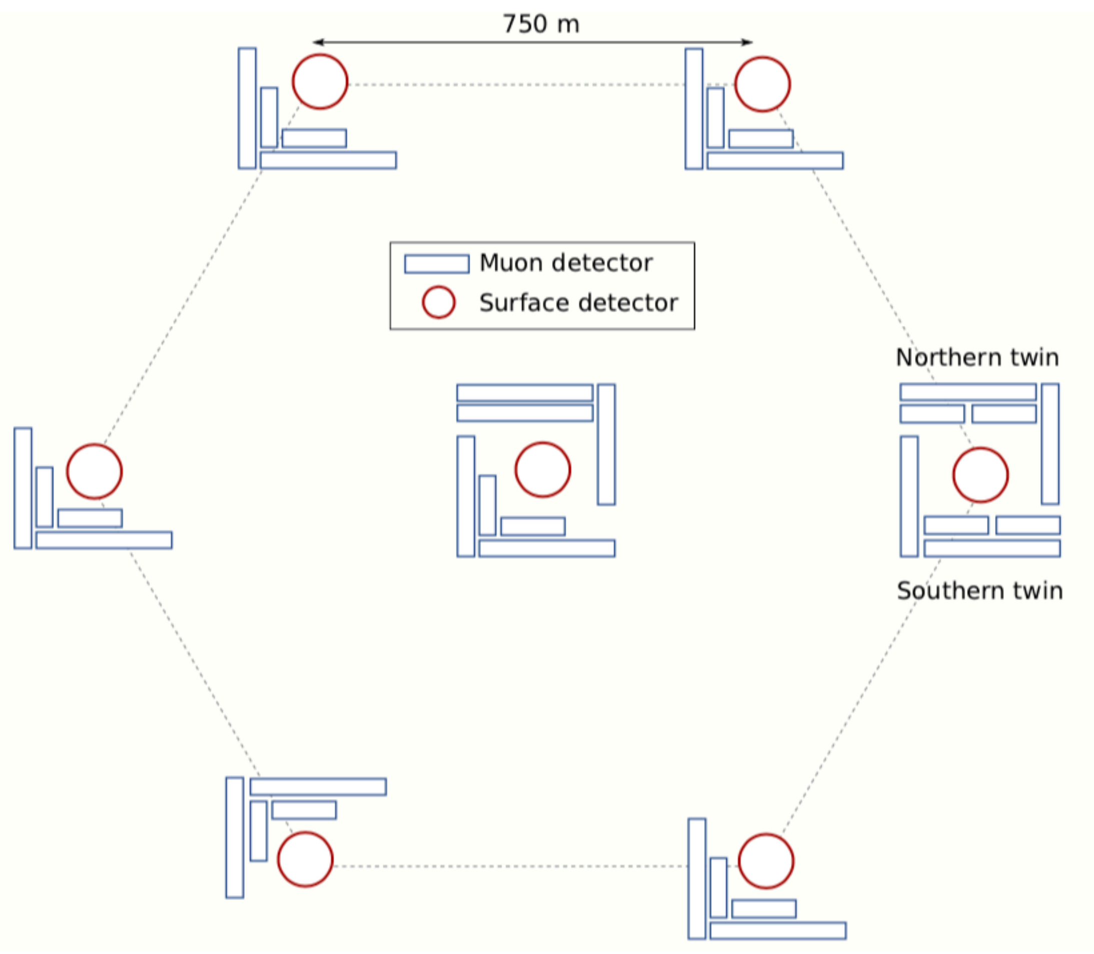


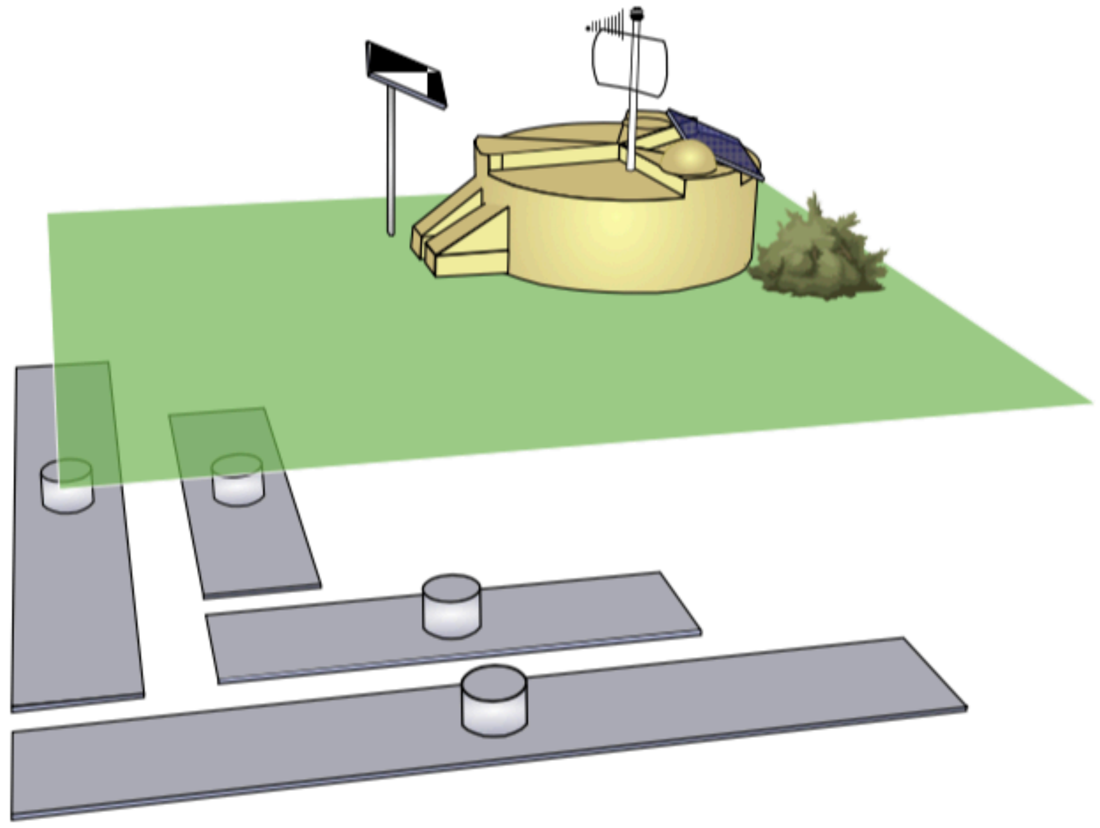
Pierre Auger Observatory

(Low energy extensions)

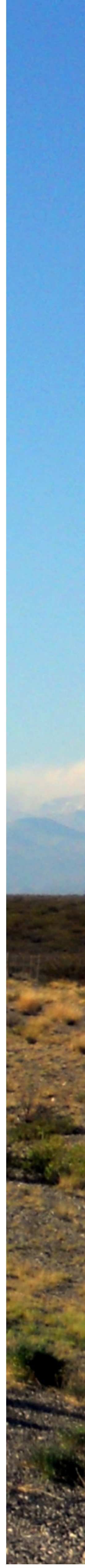


- **Infill**
  - Denser array (433 m and 750 m grid)
- **AMIGA**
  - Buried scintillators (muon detectors)
    - 7 stations
    - 30 (60) m^2 scintillator modules
    - 2.3 m below ground

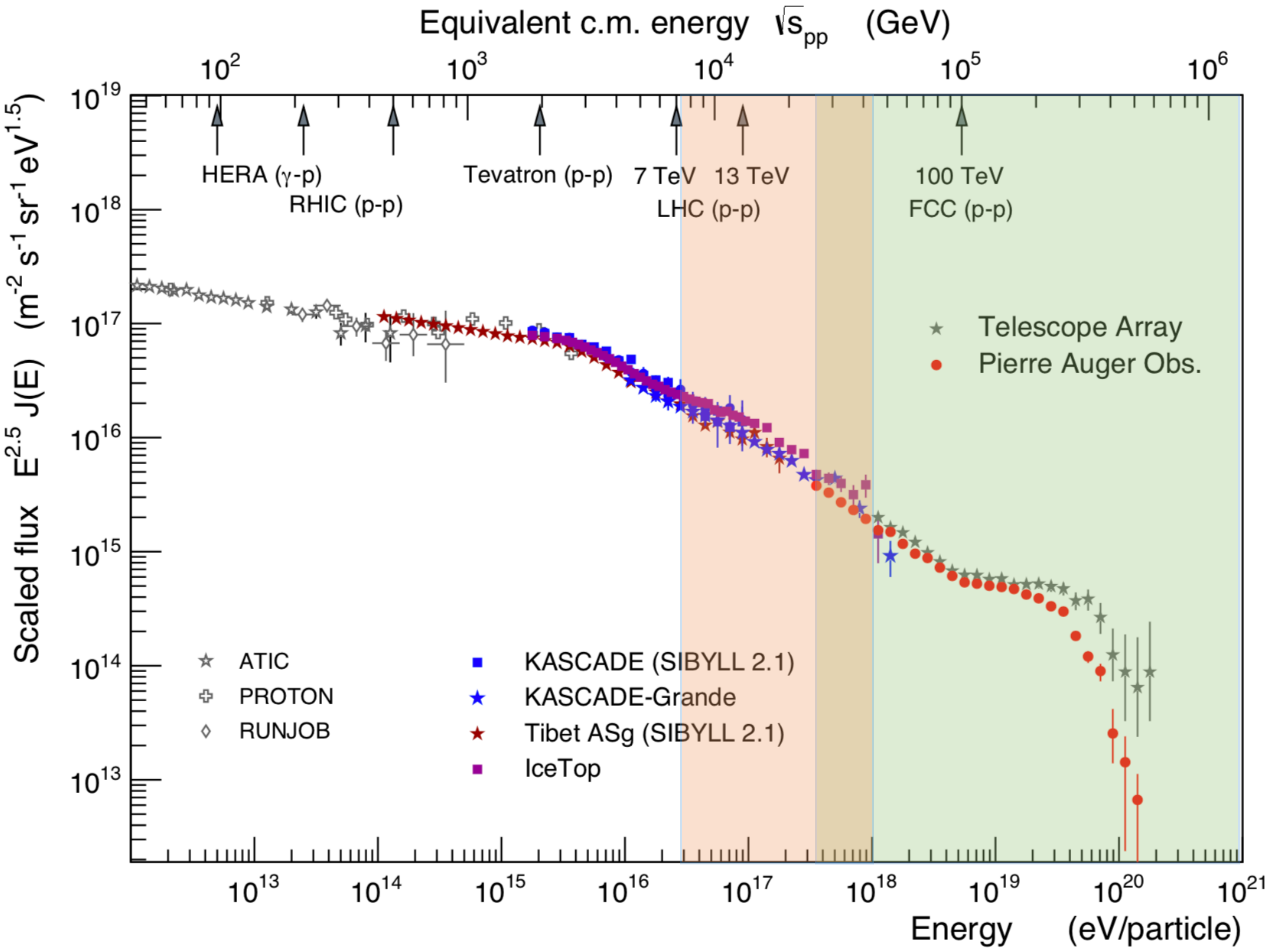




- **HEAT**
  - 3 additional FD telescopes with a high elevation FoV



Ultra High Energy Cosmic Rays



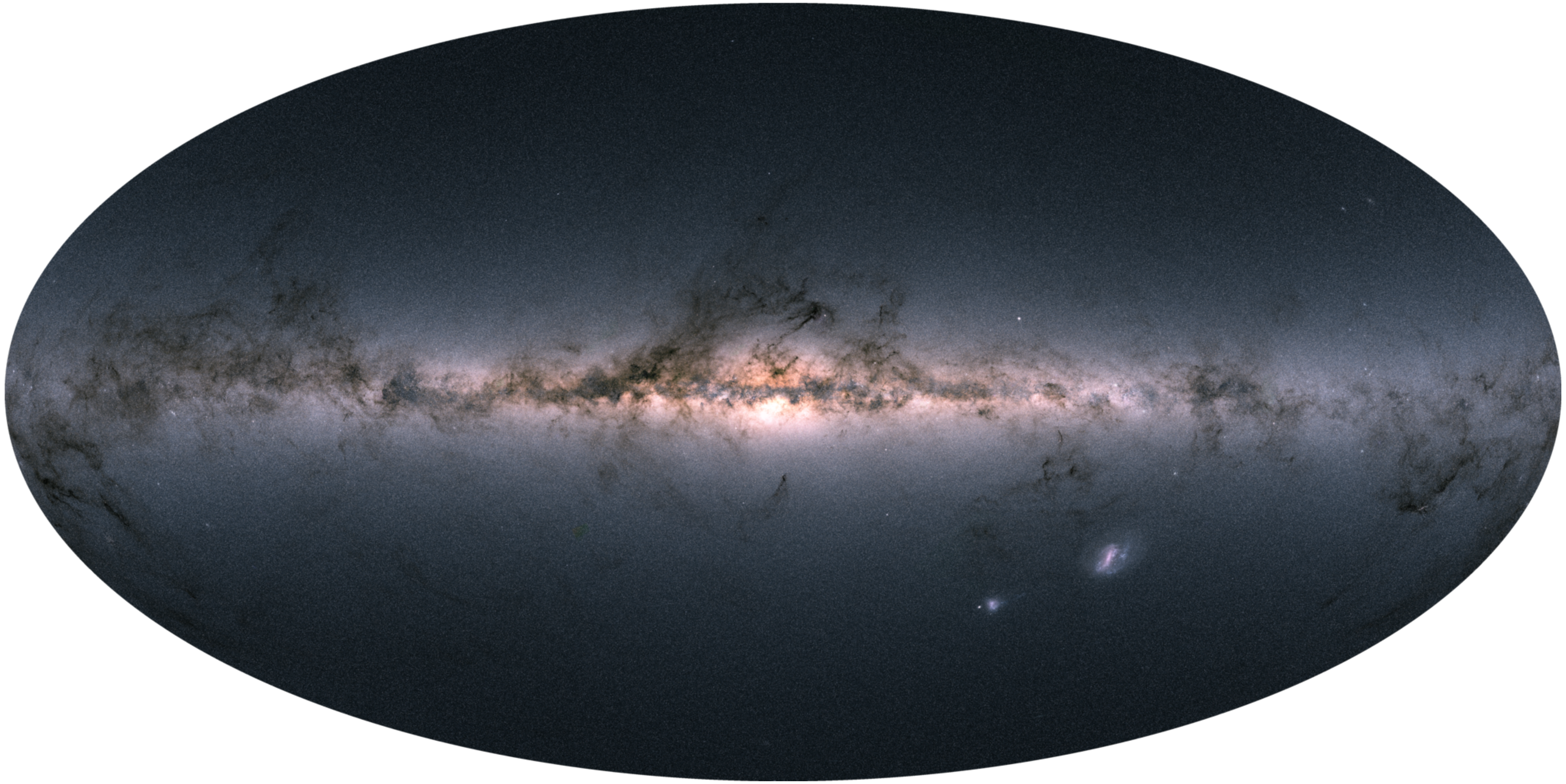
Pierre Auger Observatory

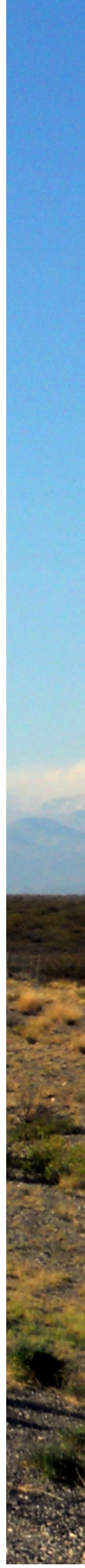
Low energy Extension

Ultra High Energy Cosmic Rays

What have we learned so far?

Are UHECRs produced in our galaxy?





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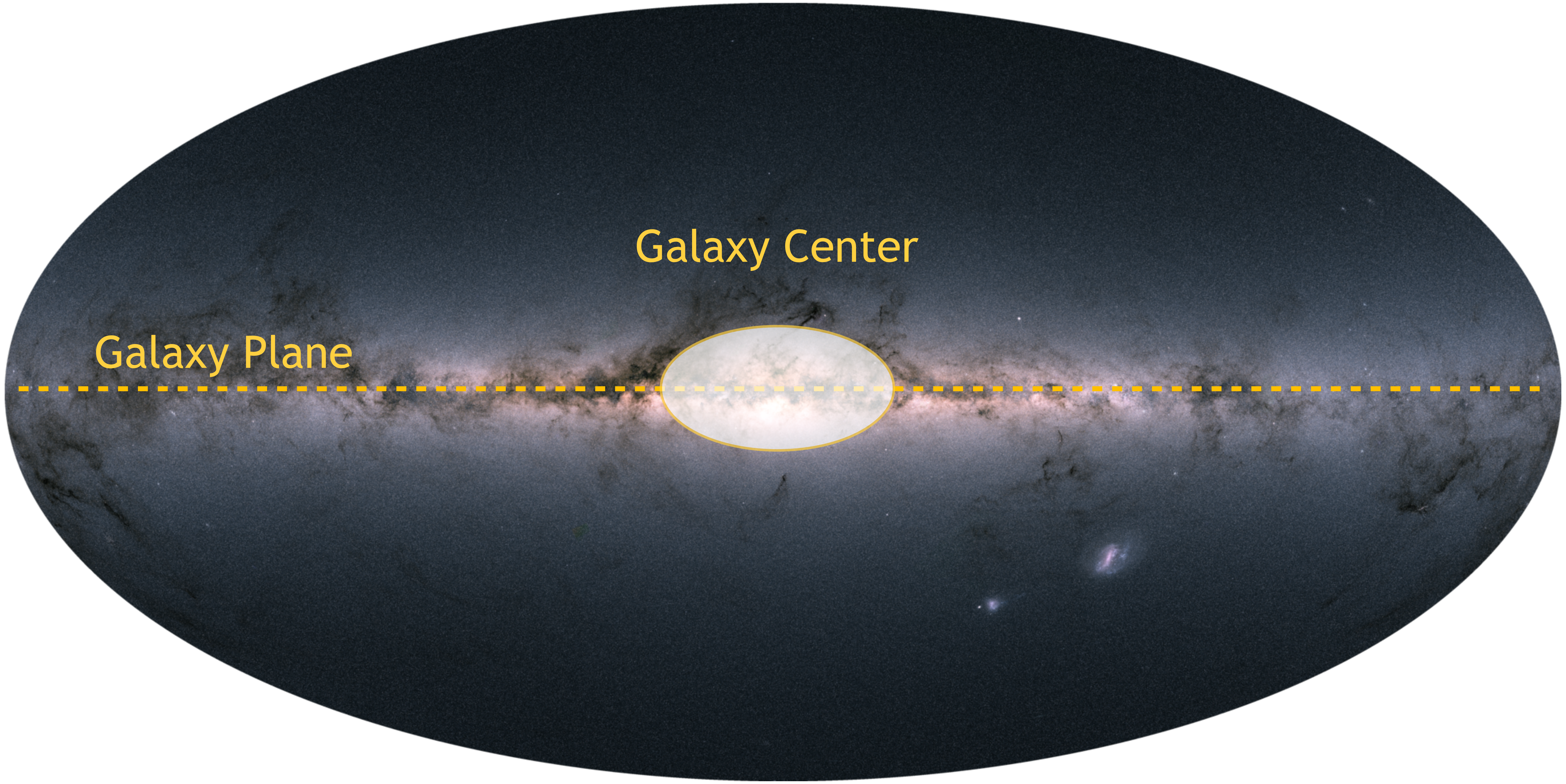
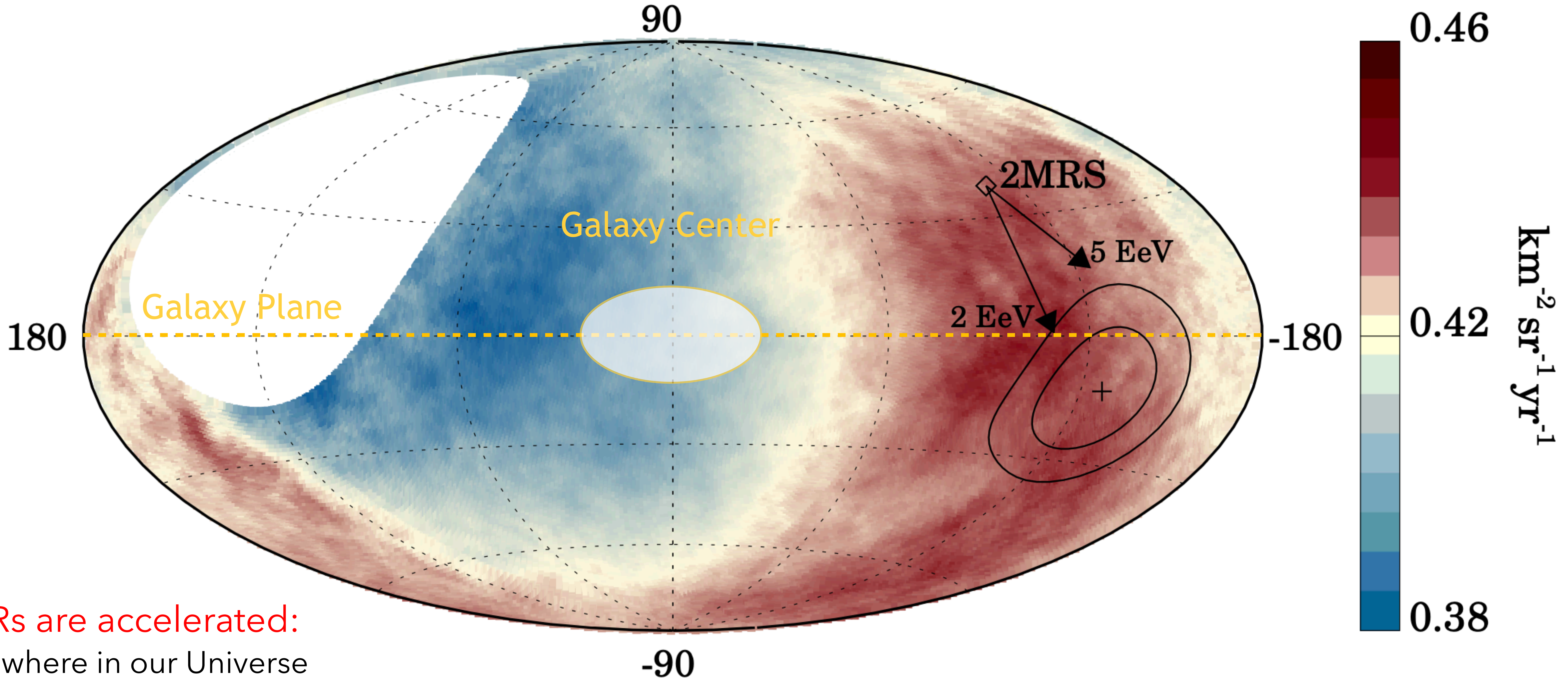


UHECR have an extra-galactic origin

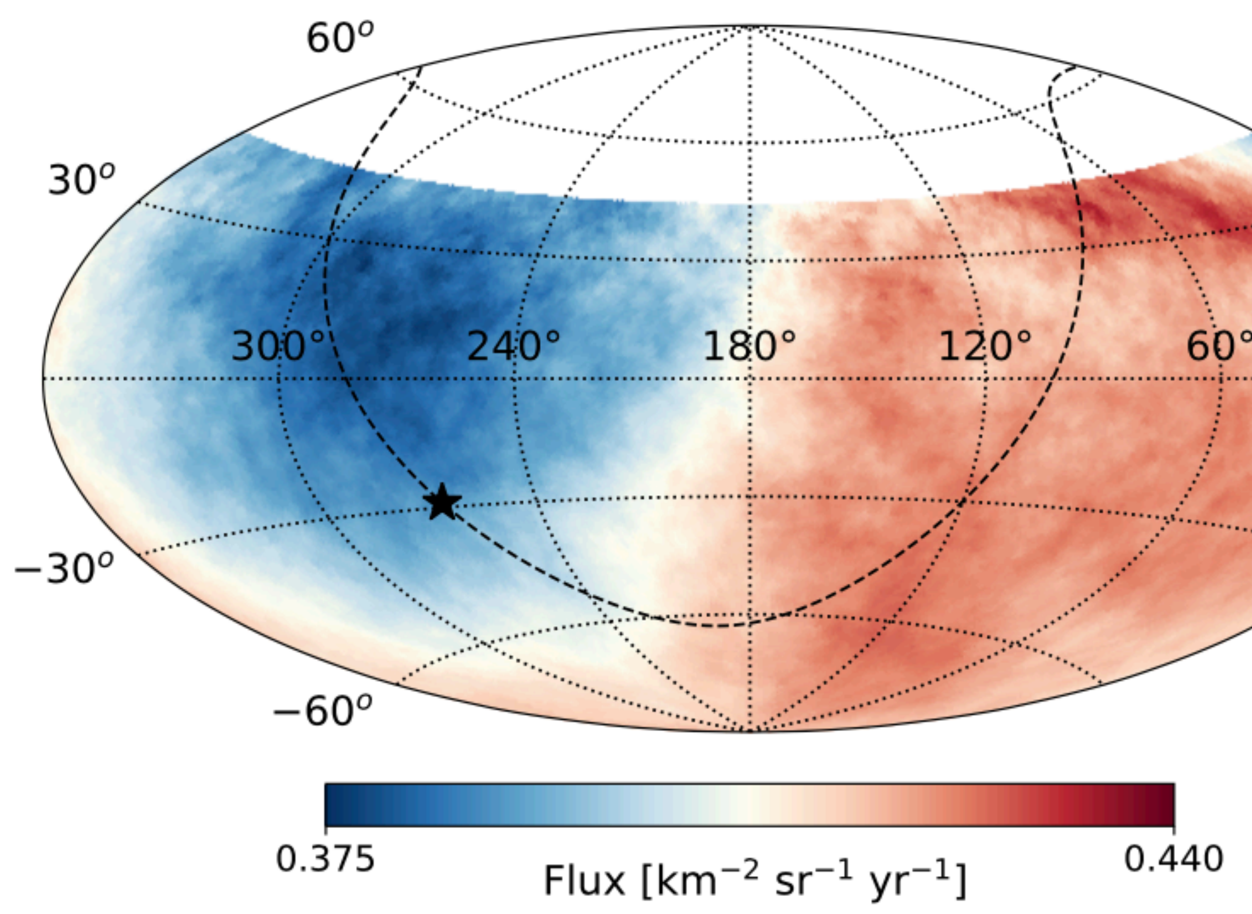
Science 357 (2017) no.6537, 1266-1270

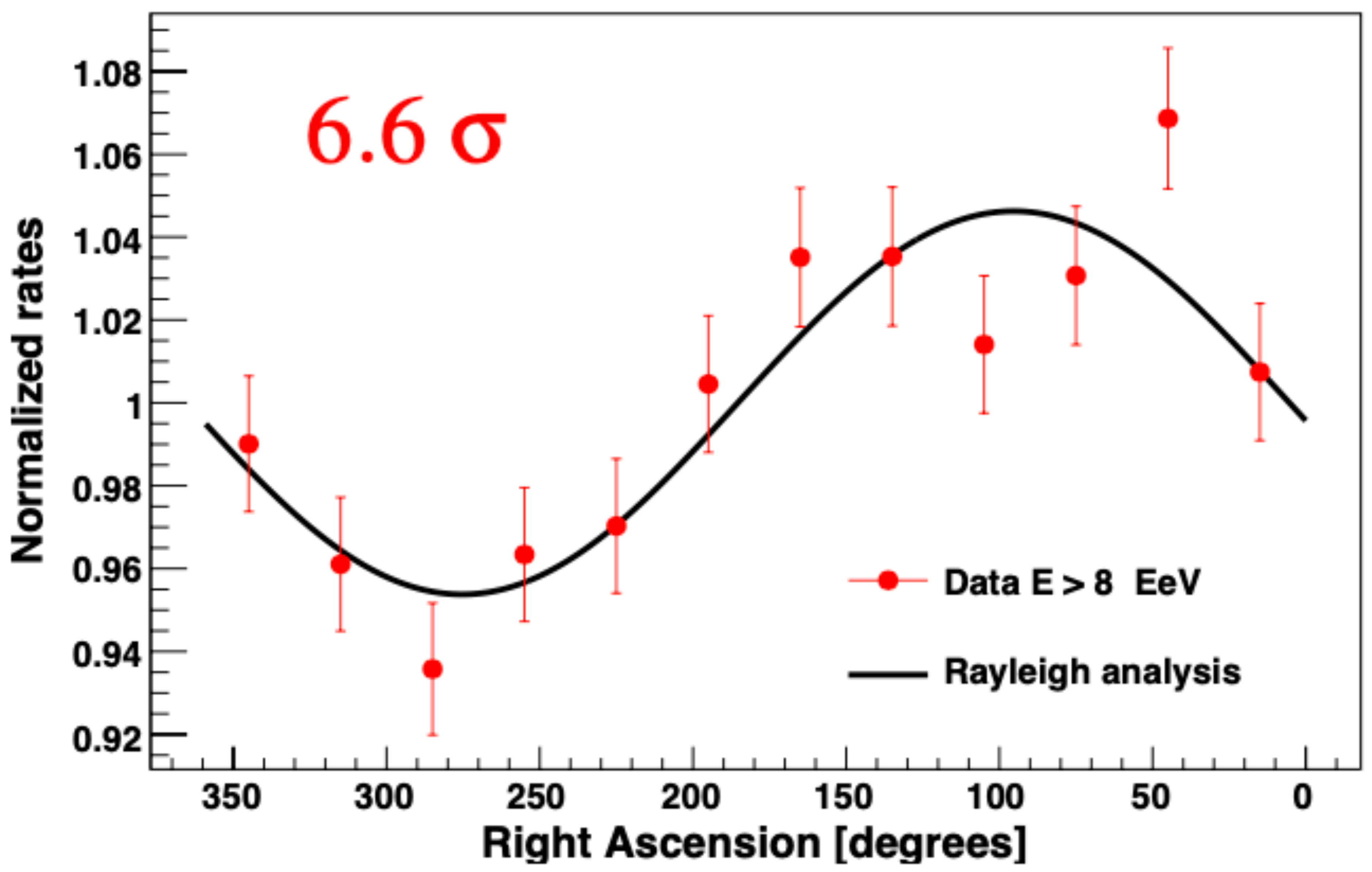


- UHECRs are accelerated:
  - somewhere in our Universe
    - from the photon and neutrino limits (next class)
  - Outside the galaxy

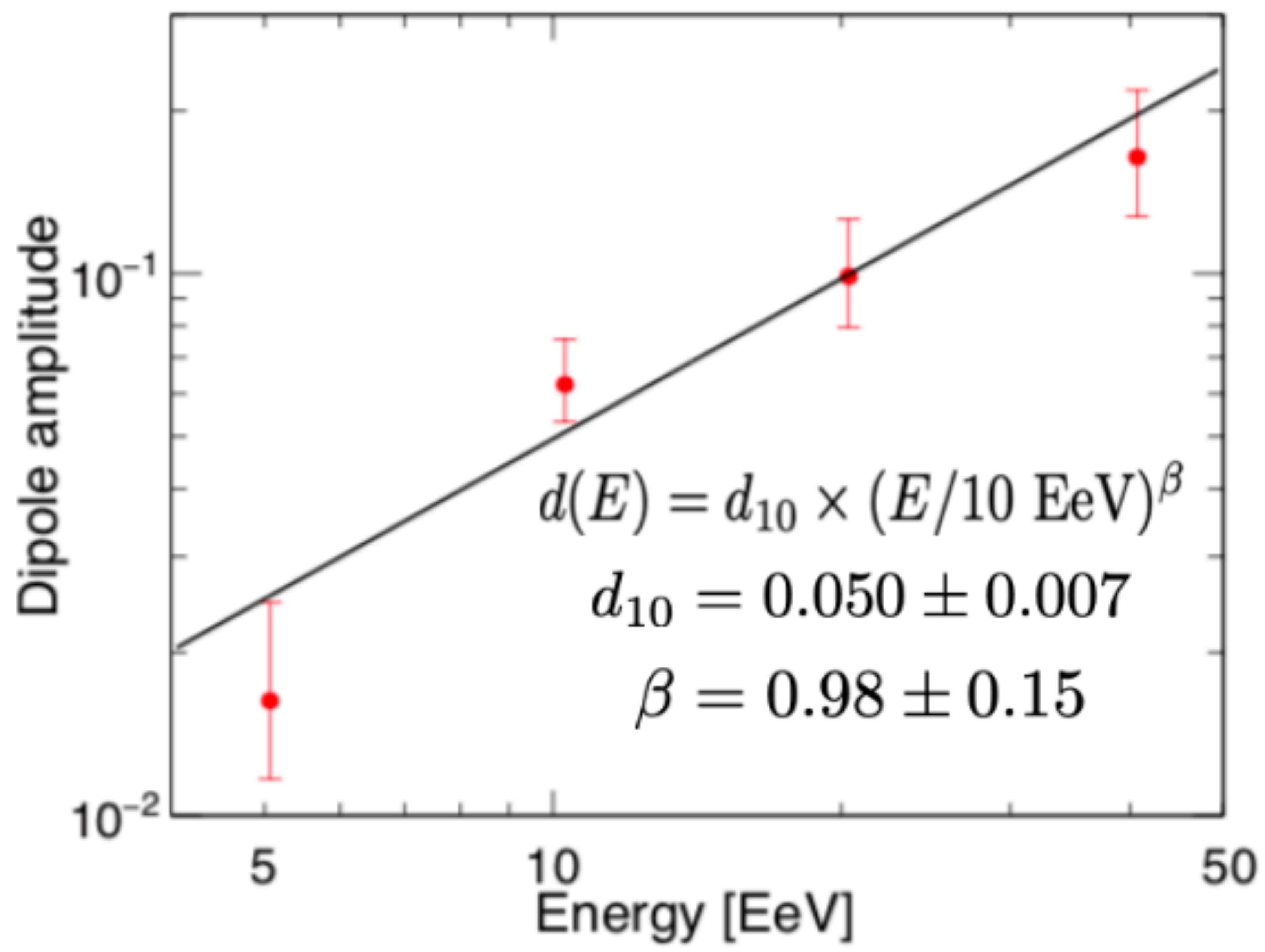
The UHECR dipole

Pierre Auger Collaboration, ICRC21

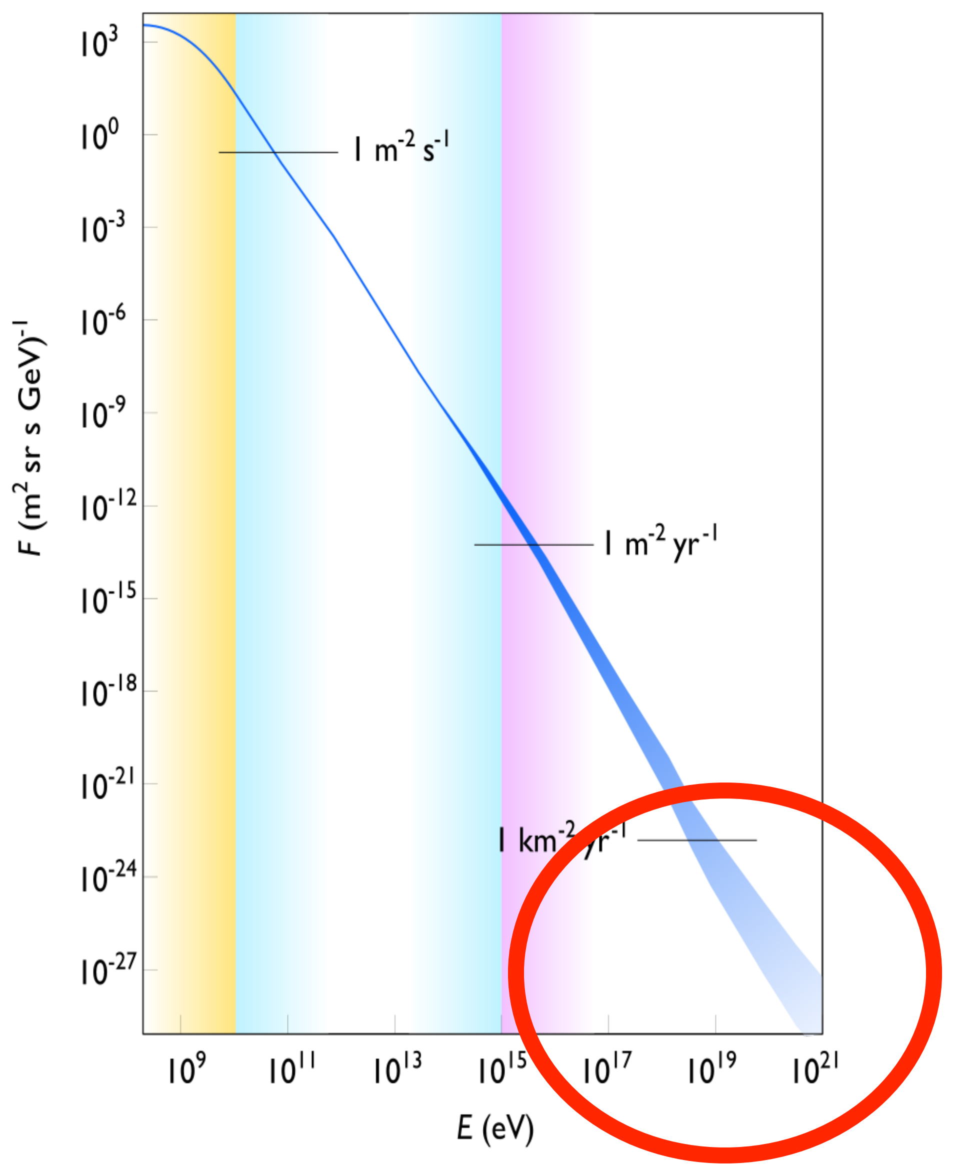




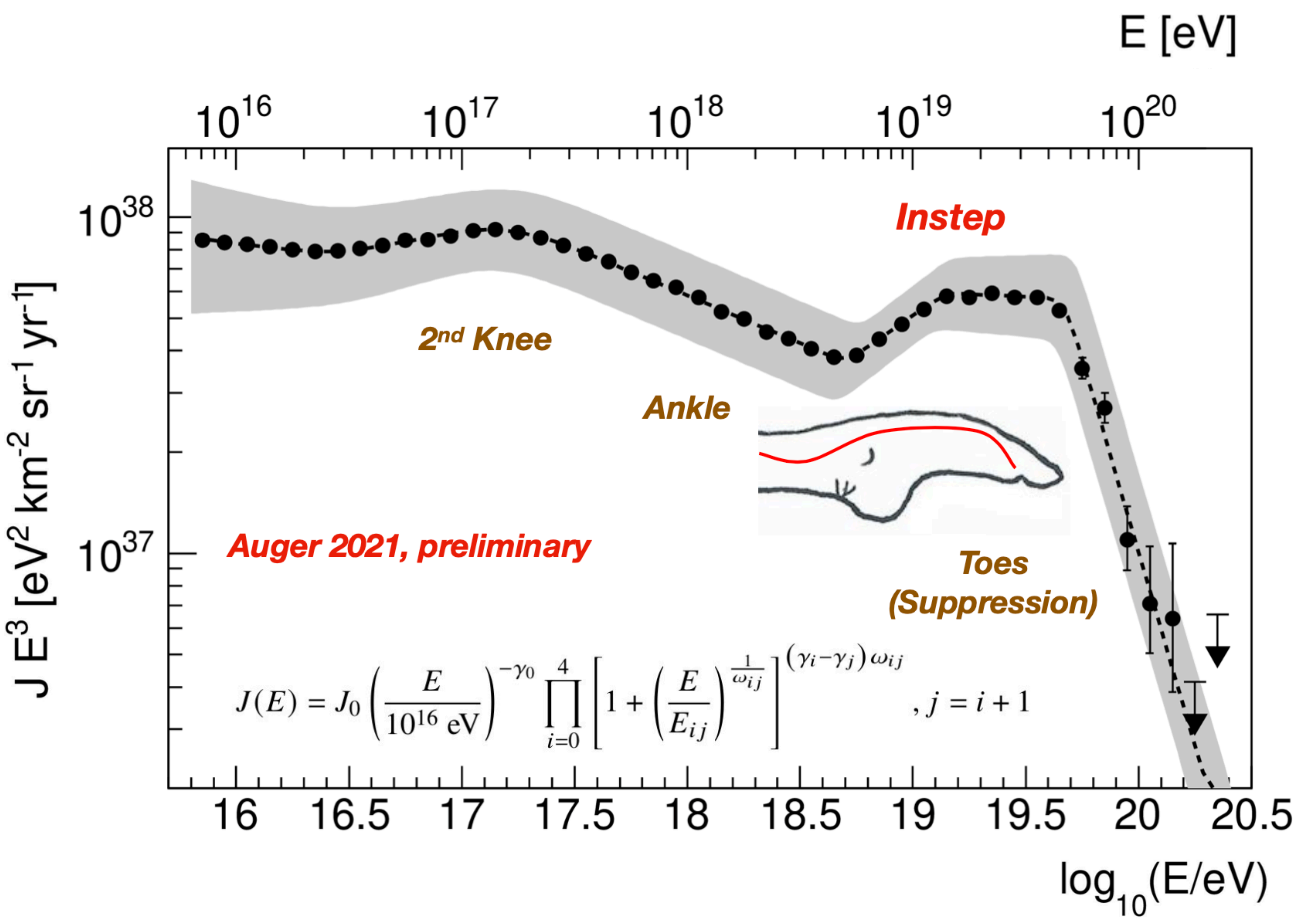
Exposure
until end of 2020
(θ < 80°)
110 000 km² sr yr
p ~ 5 x 10^{-11}



UHECR energy spectrum

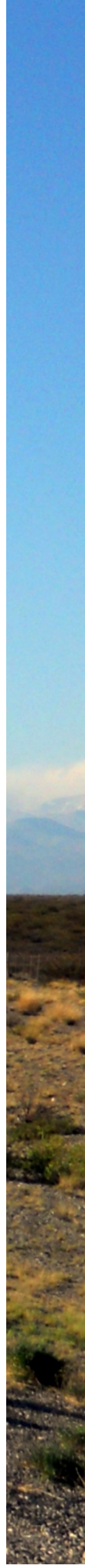


Phys. Rev. Lett. 125 (2020) 121106

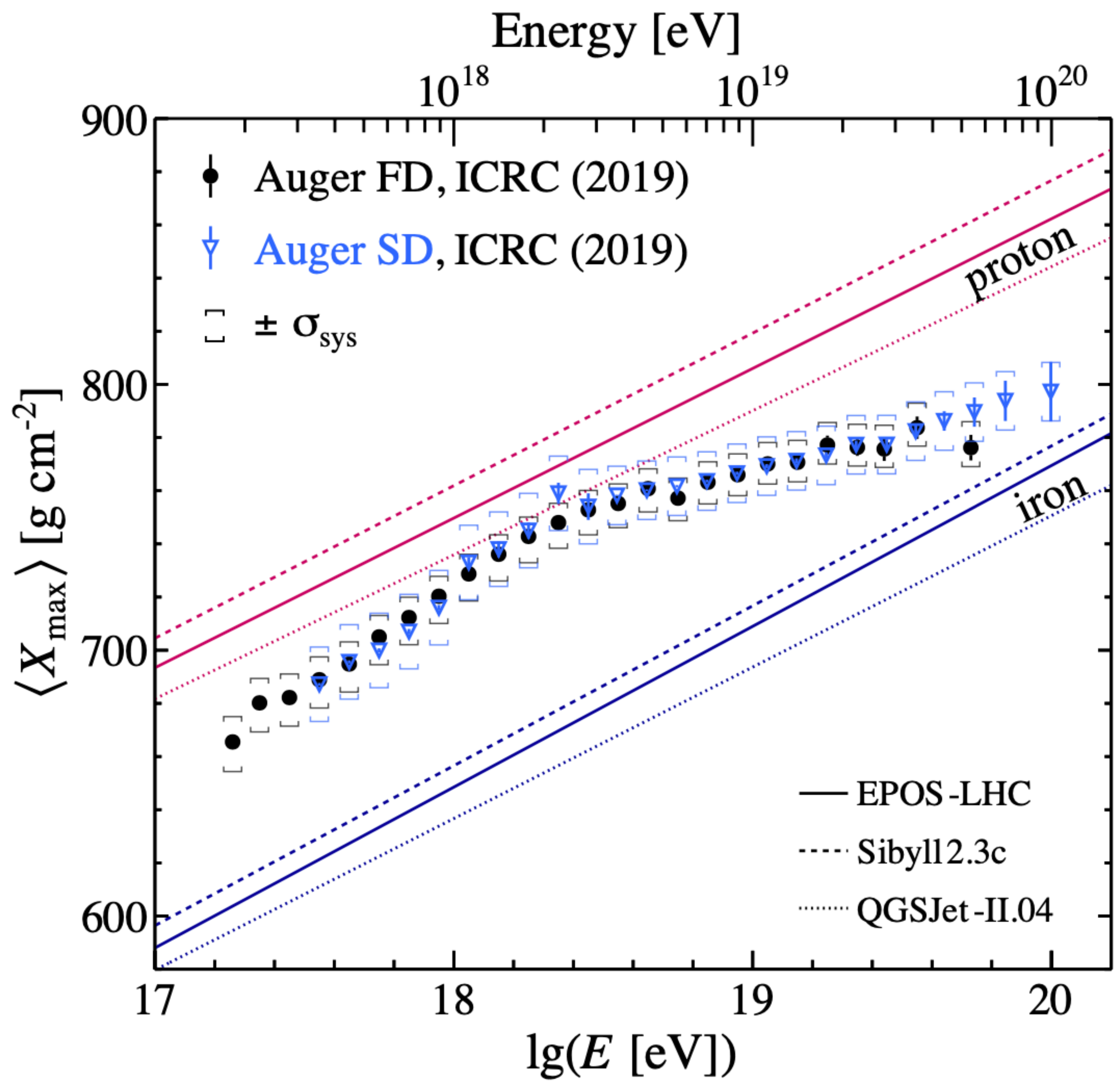


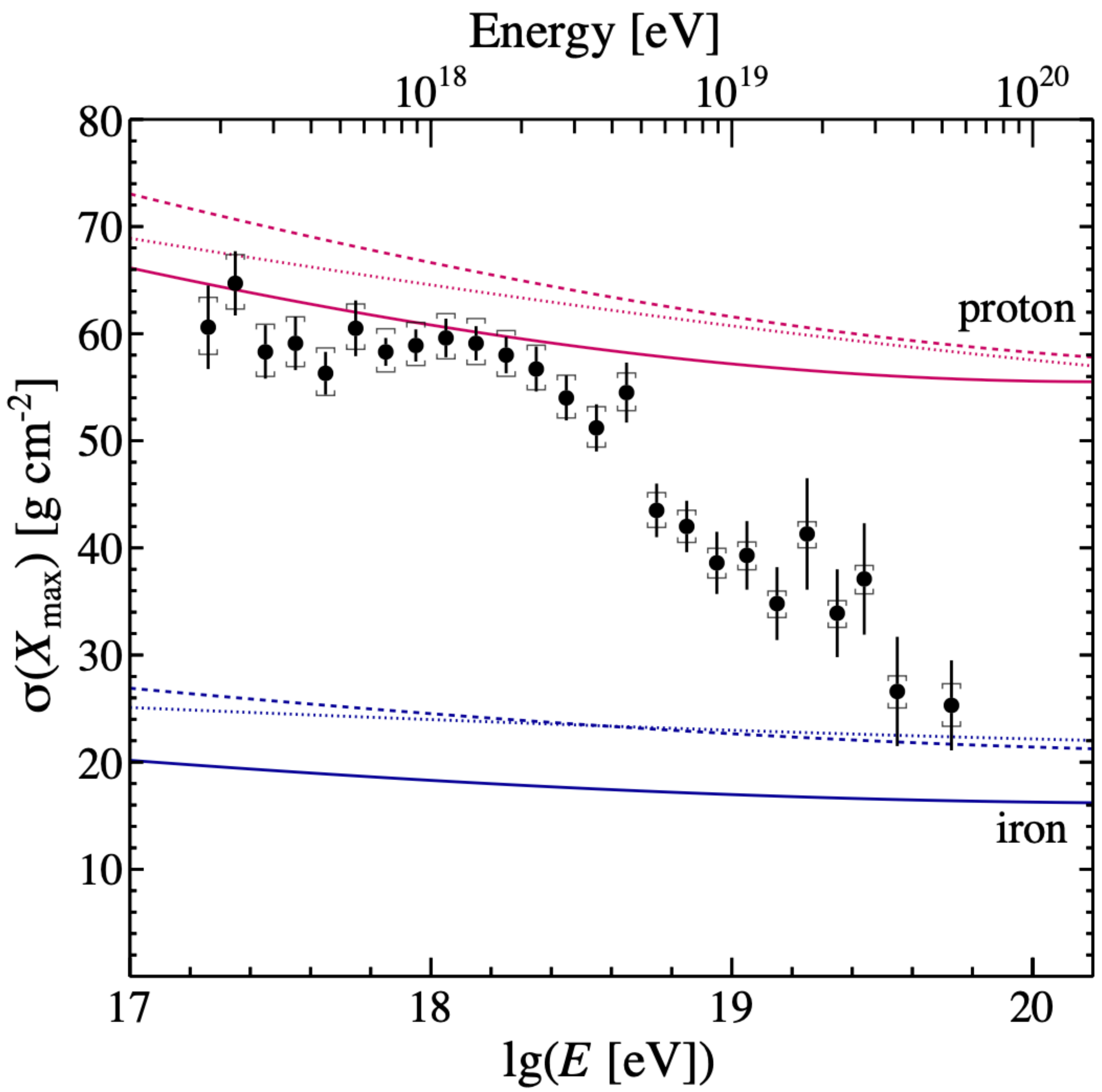
Put strong constraints on UHECR production and propagation

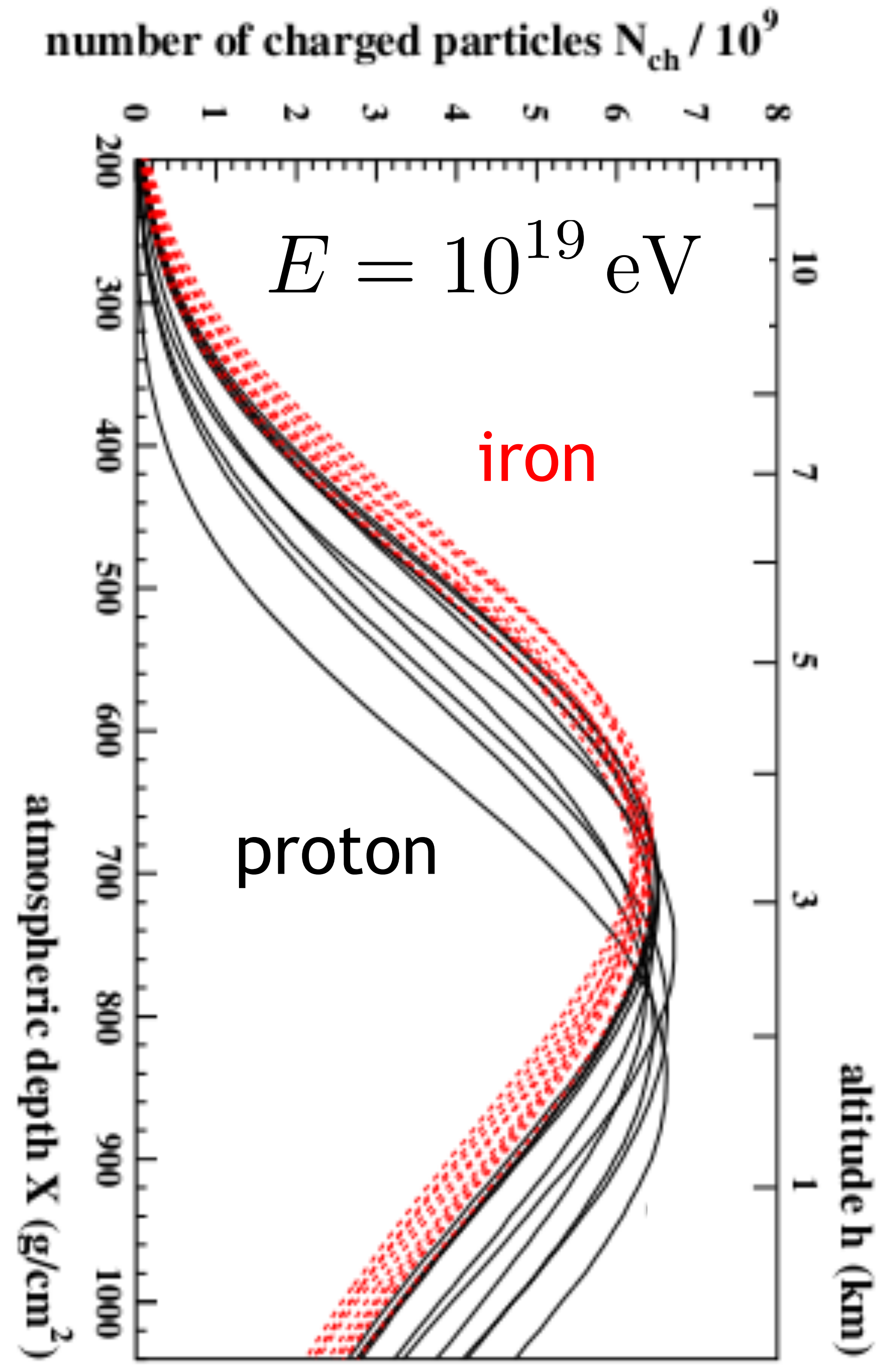
But the nature of the suppression is still unclear!!



X_{max} distribution momenta



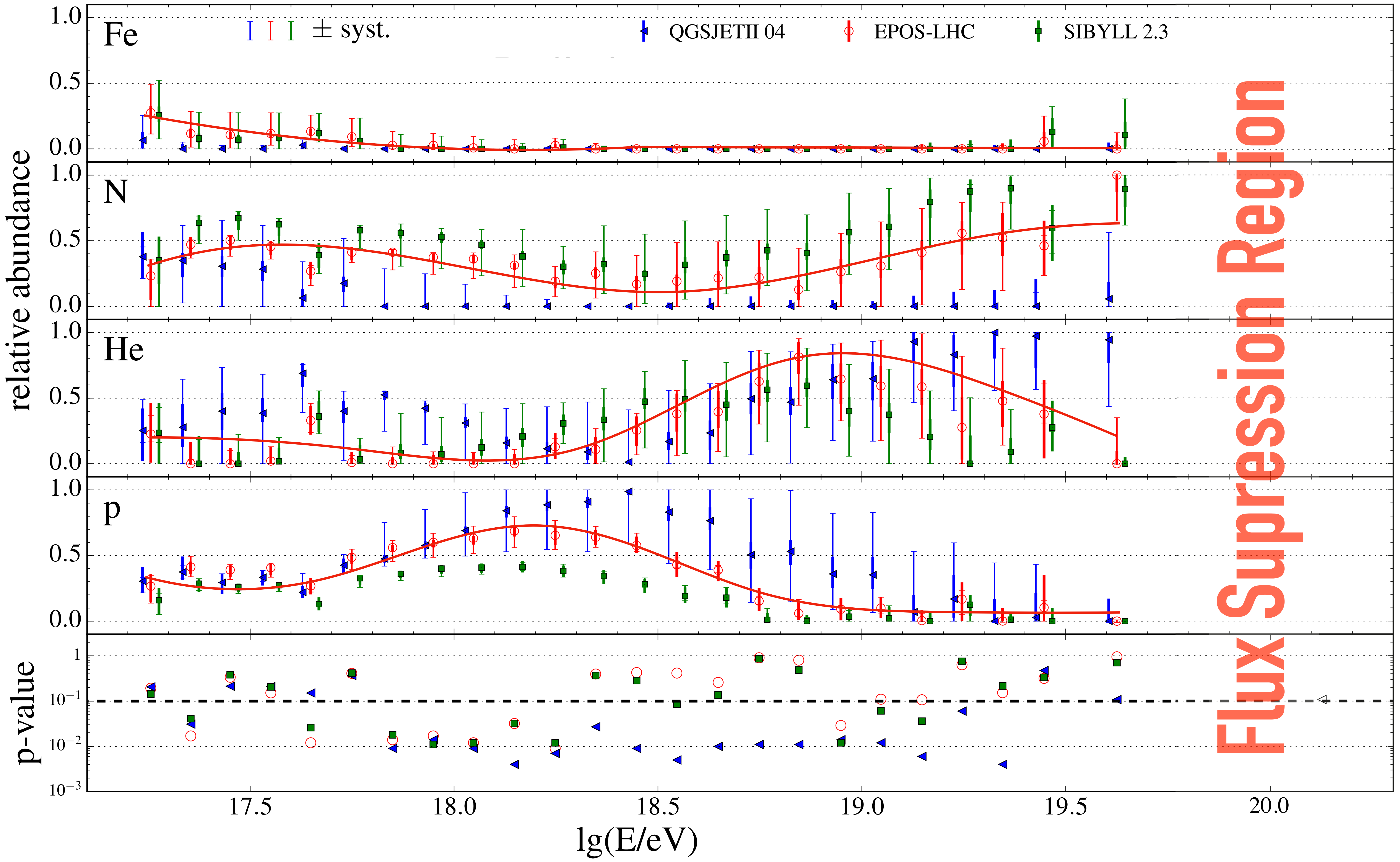


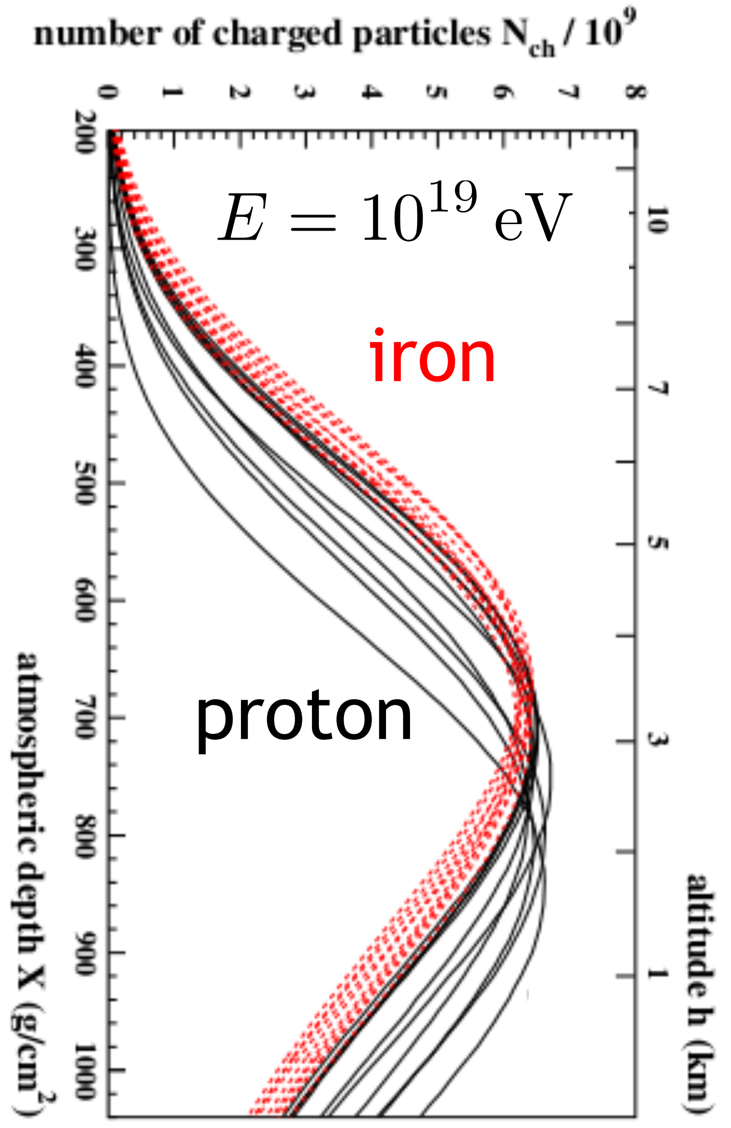


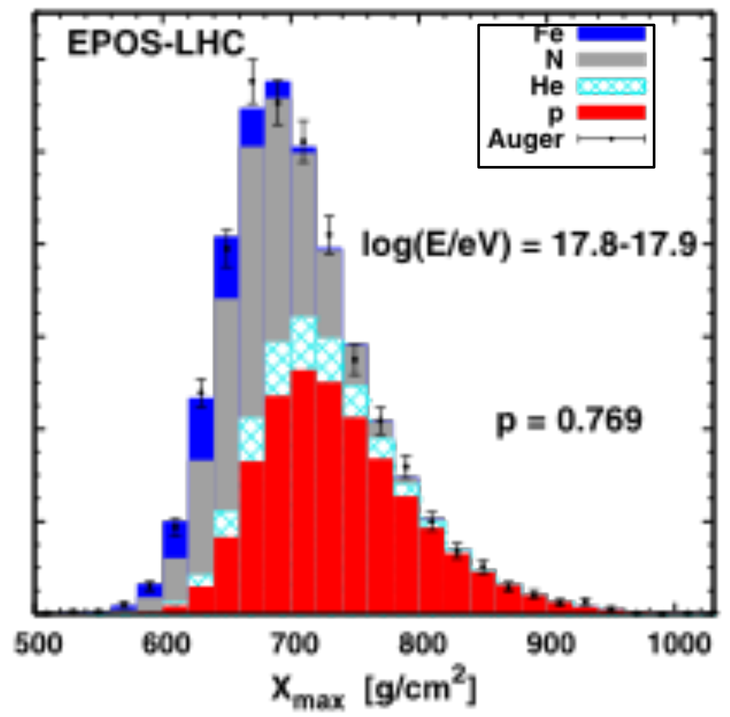
Proton showers have a deeper X_{max} and with more fluctuation event-by-event than iron showers

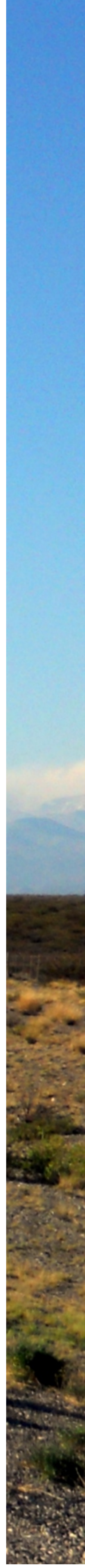
Composition fits to X_{max}

35th ICRC, PoS (2017) 506









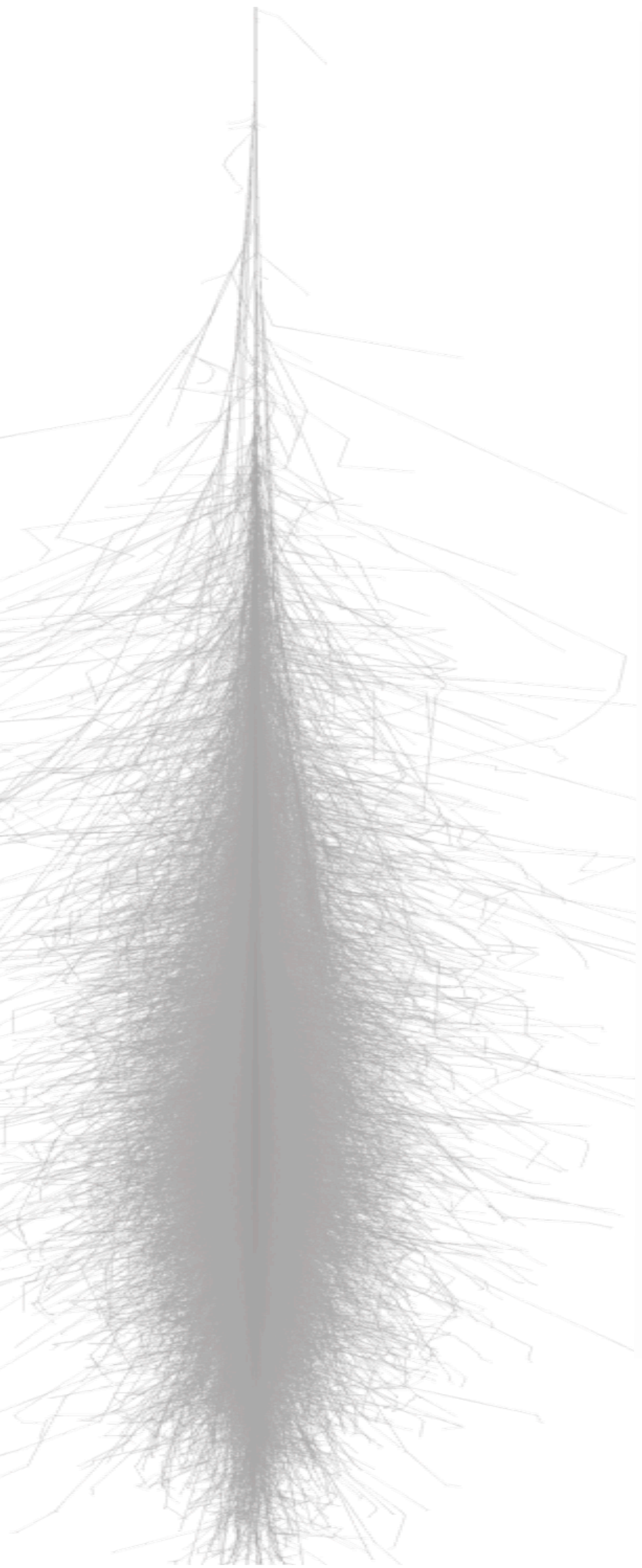
*The primary **composition** goes from **light to heavier** as its energy increases*

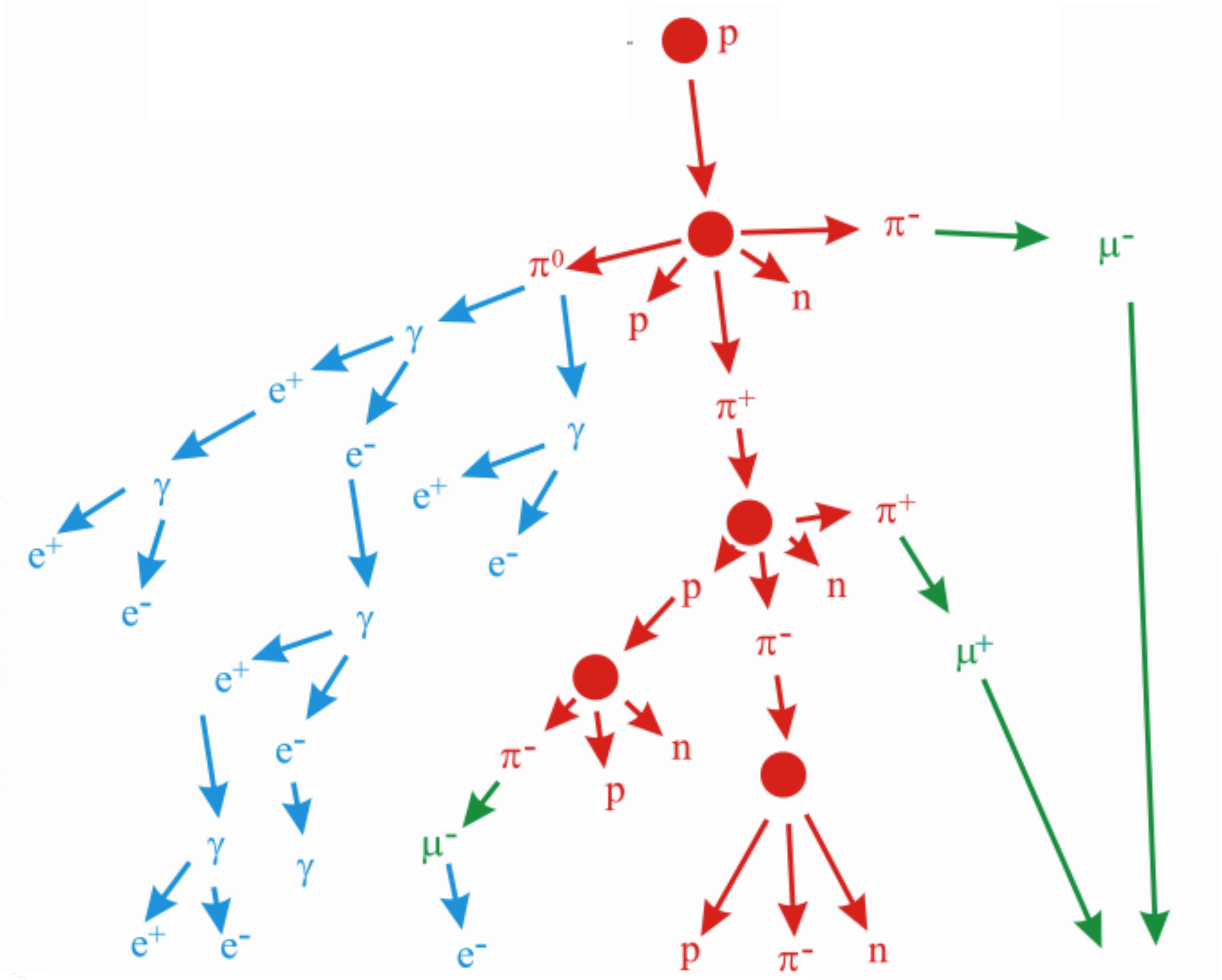
Shower physics

Peeking into high-energy hadronic interactions

EAS engine

Monte Carlo EAS simulation [CORSIKA]

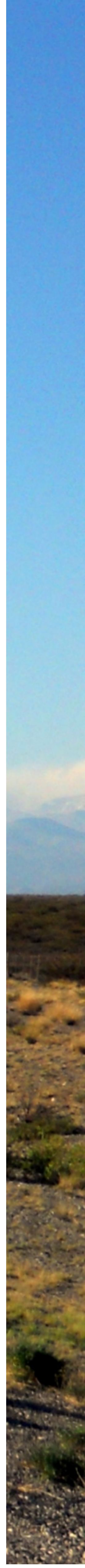




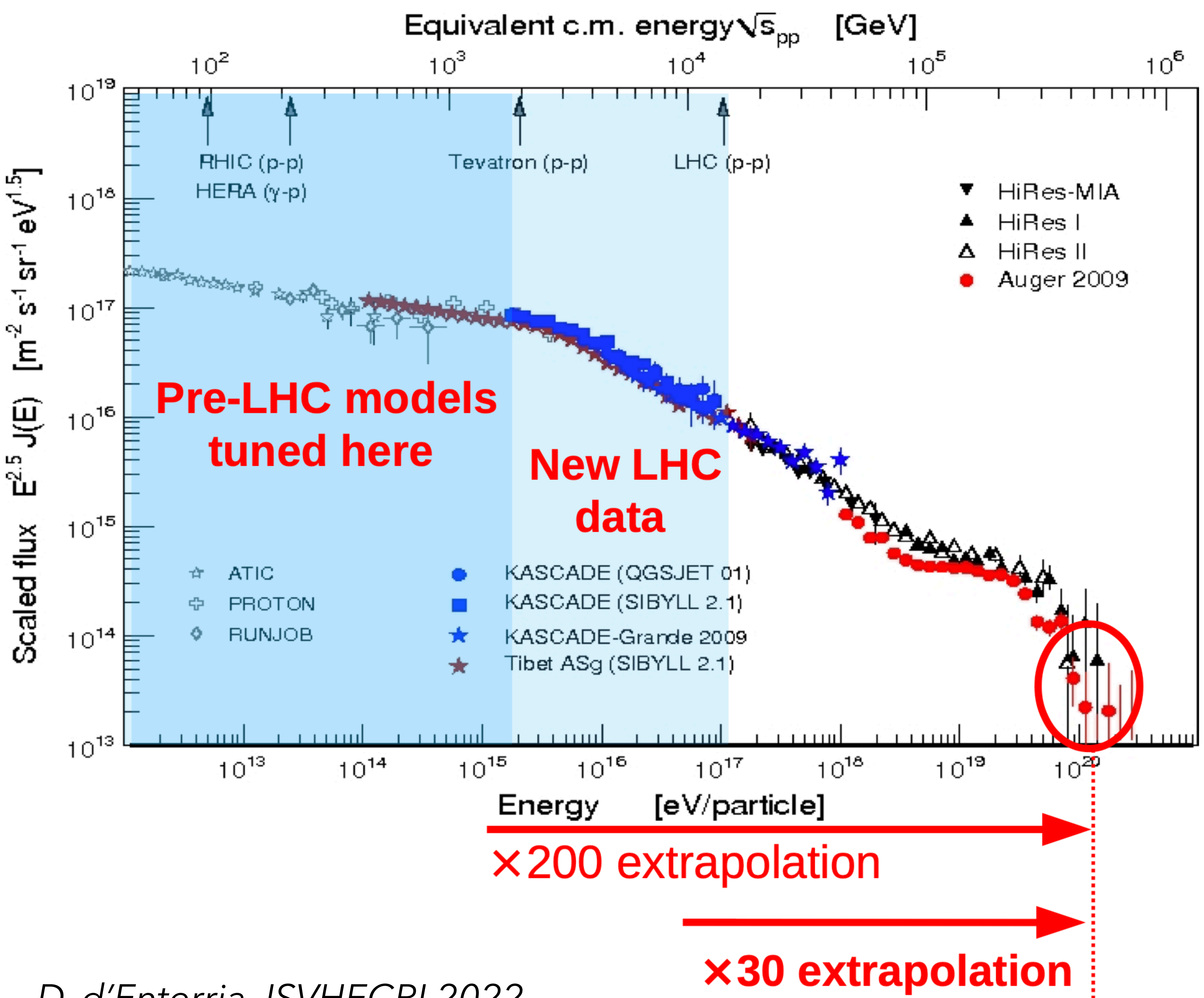
Electromagnetic component

Hadronic component

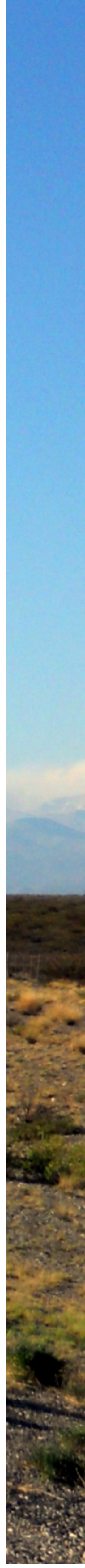
Muonic component



The challenge



D. d'Enterria, ISVHECRI 2022



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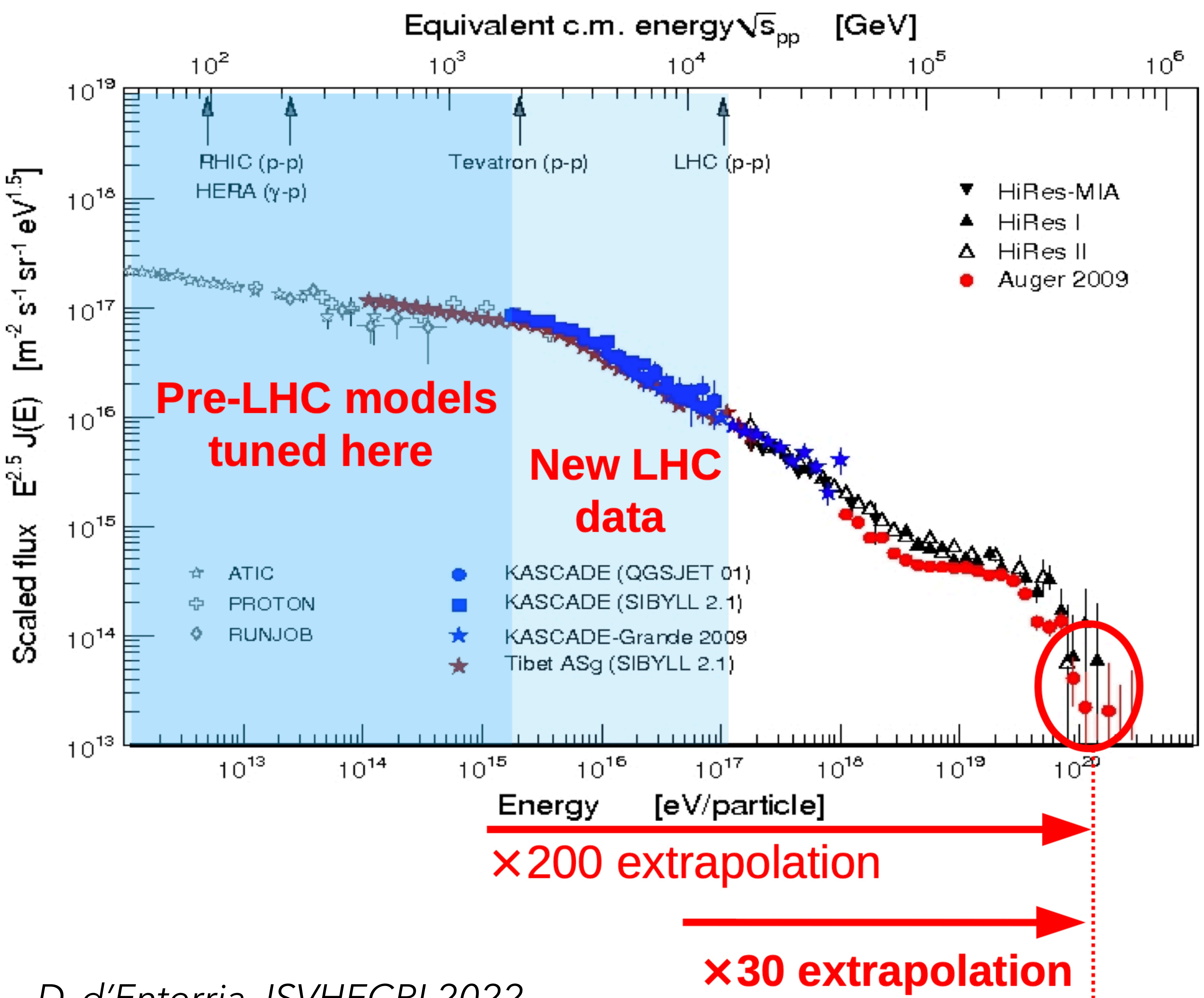
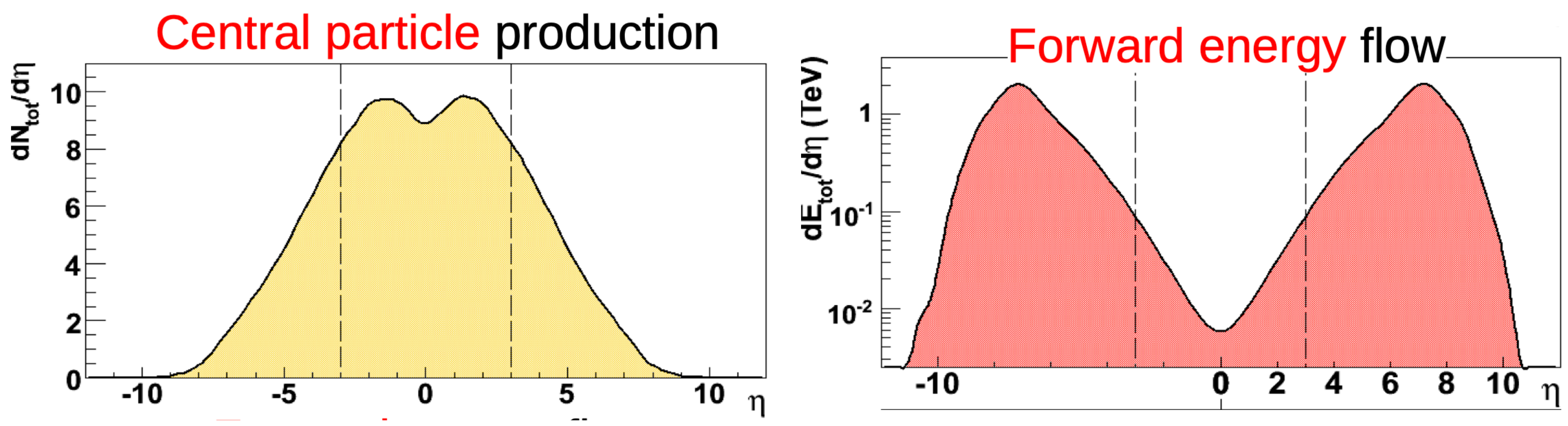
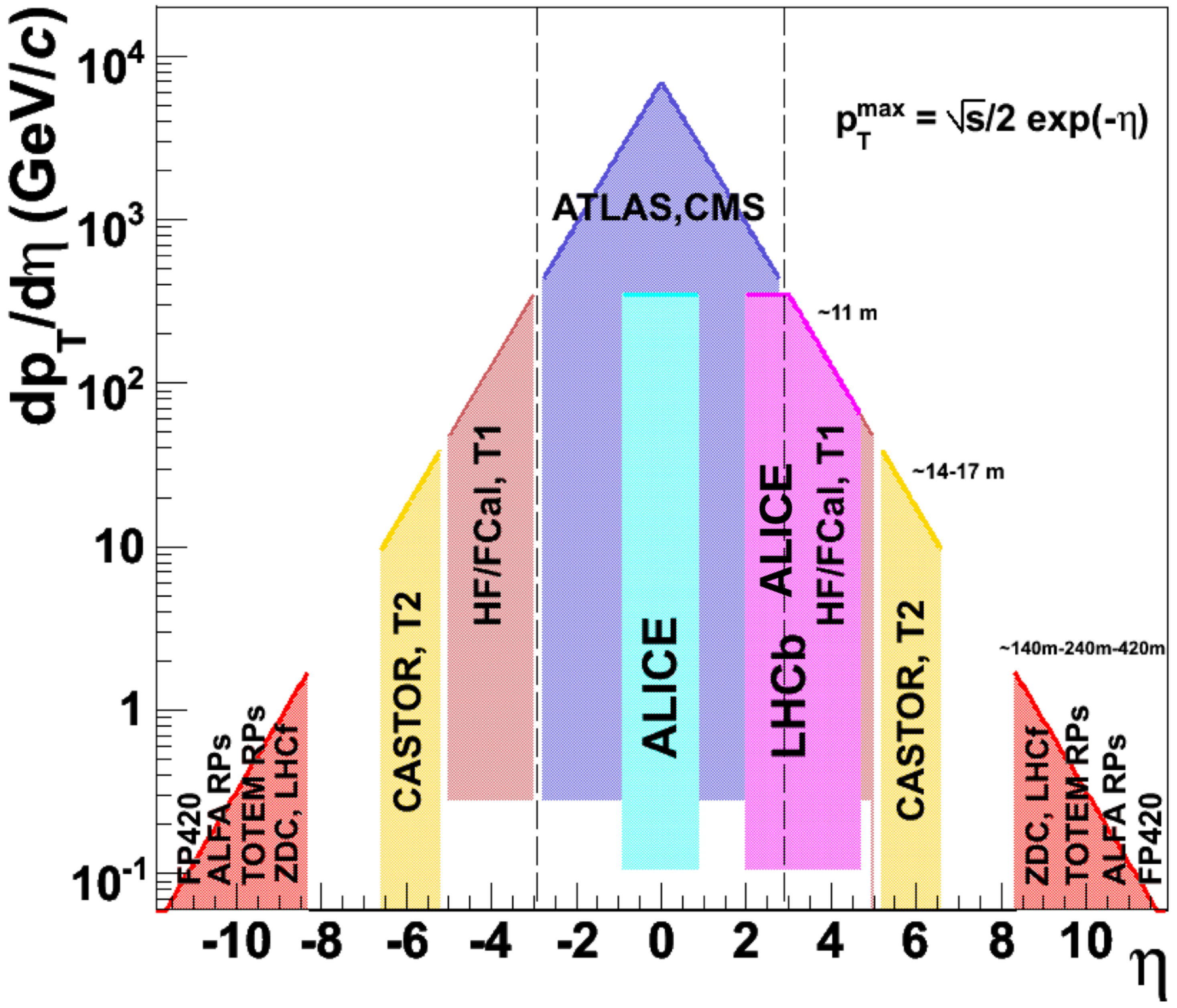
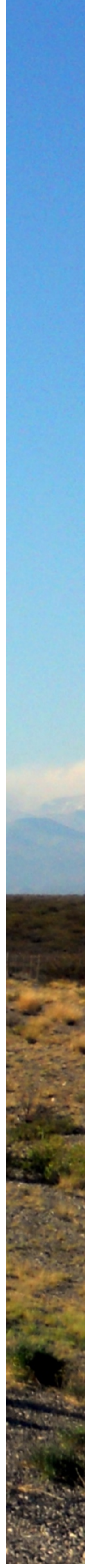


D. d'Enterria, ISVHECRI 2022

p-p @ 14 TeV

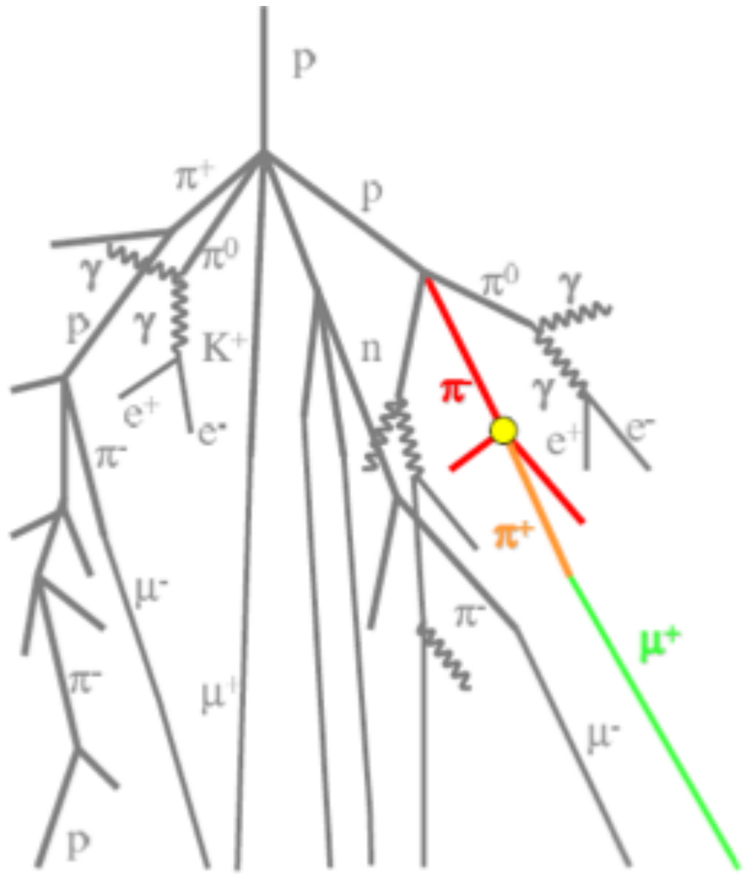






Exploration of inclined showers

- Muons → Assess Hadronic interaction models
- Data selection
  - Zenith angles [62° ; 80°]
  - $E > 4 \times 10^{18}$ eV



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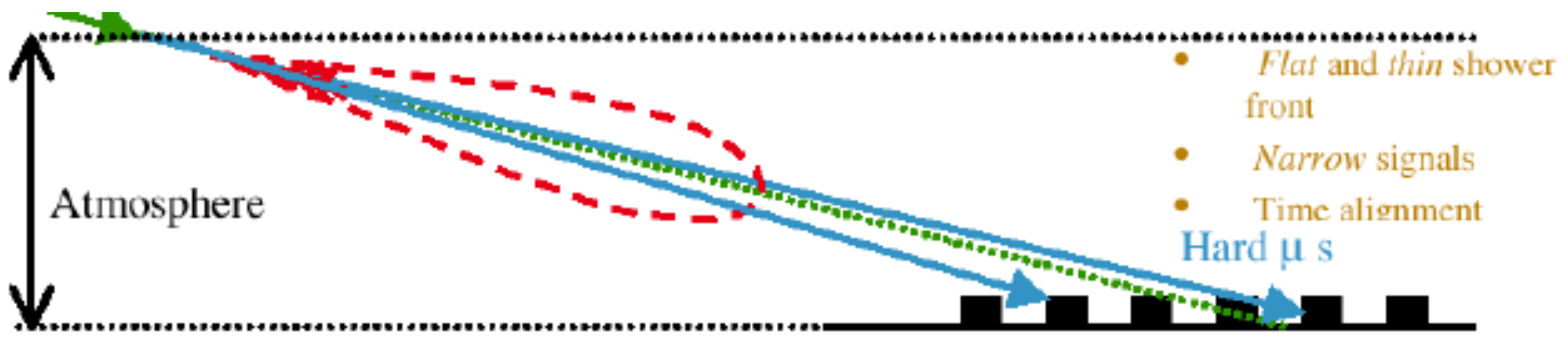

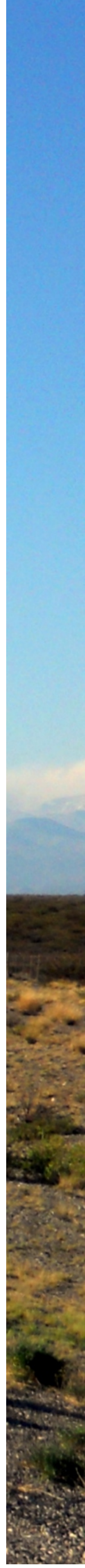

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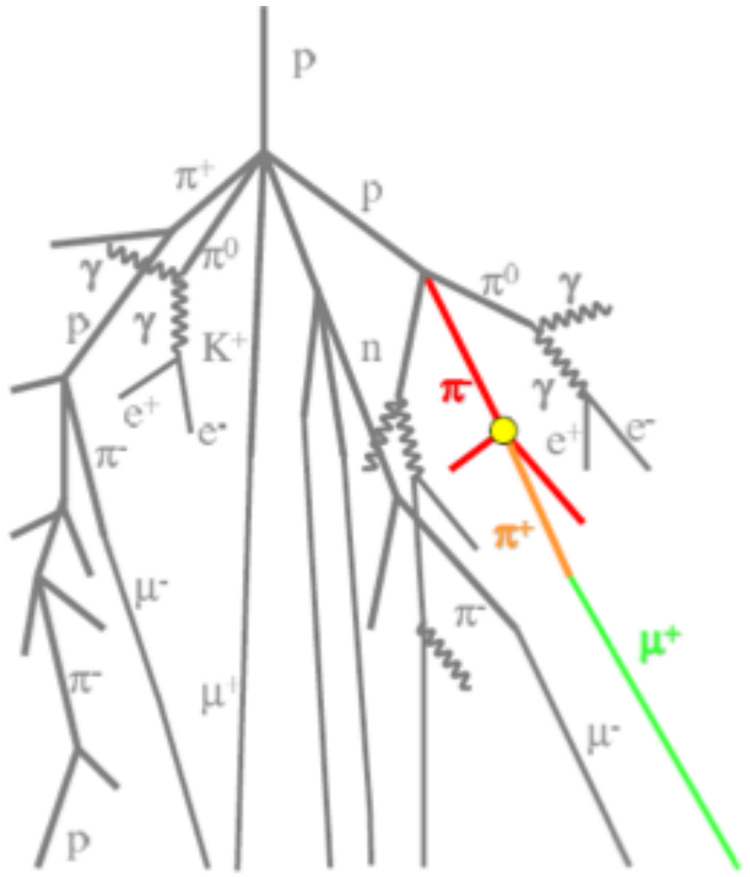

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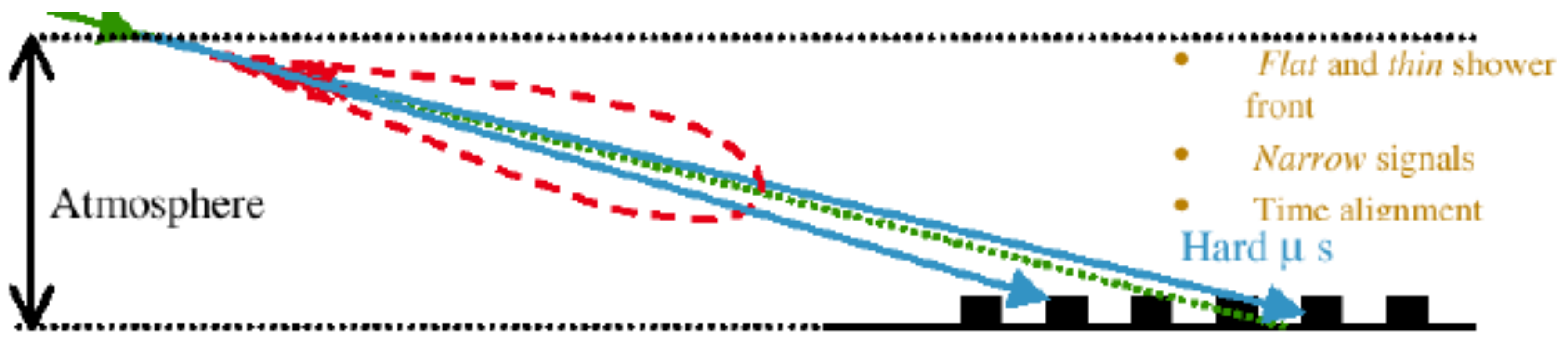
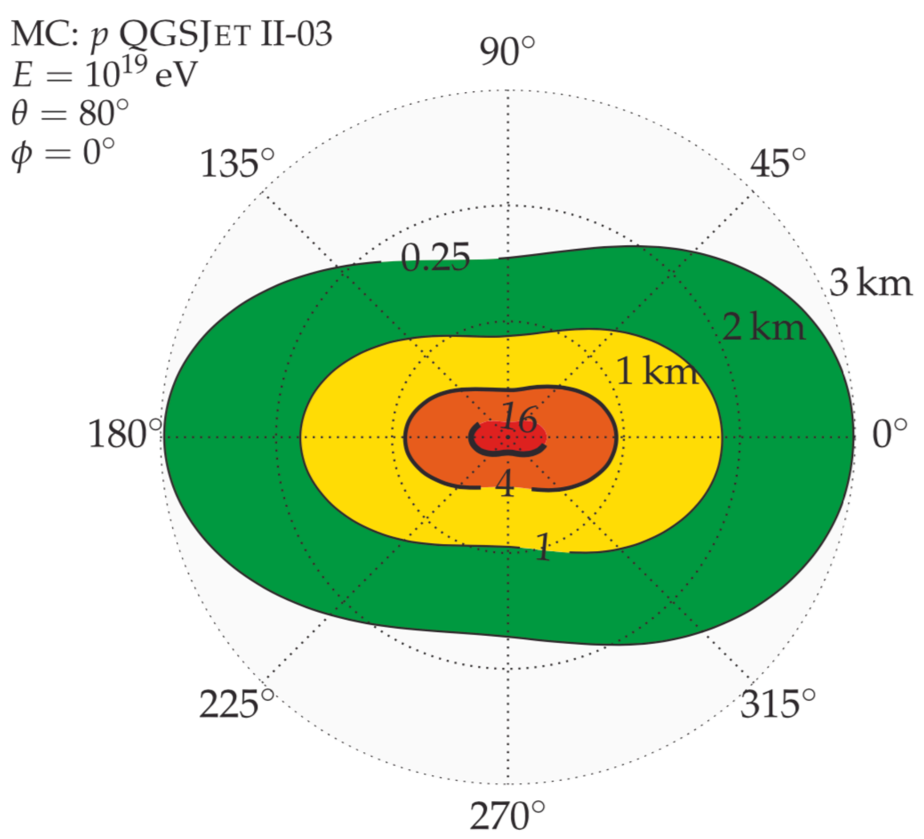
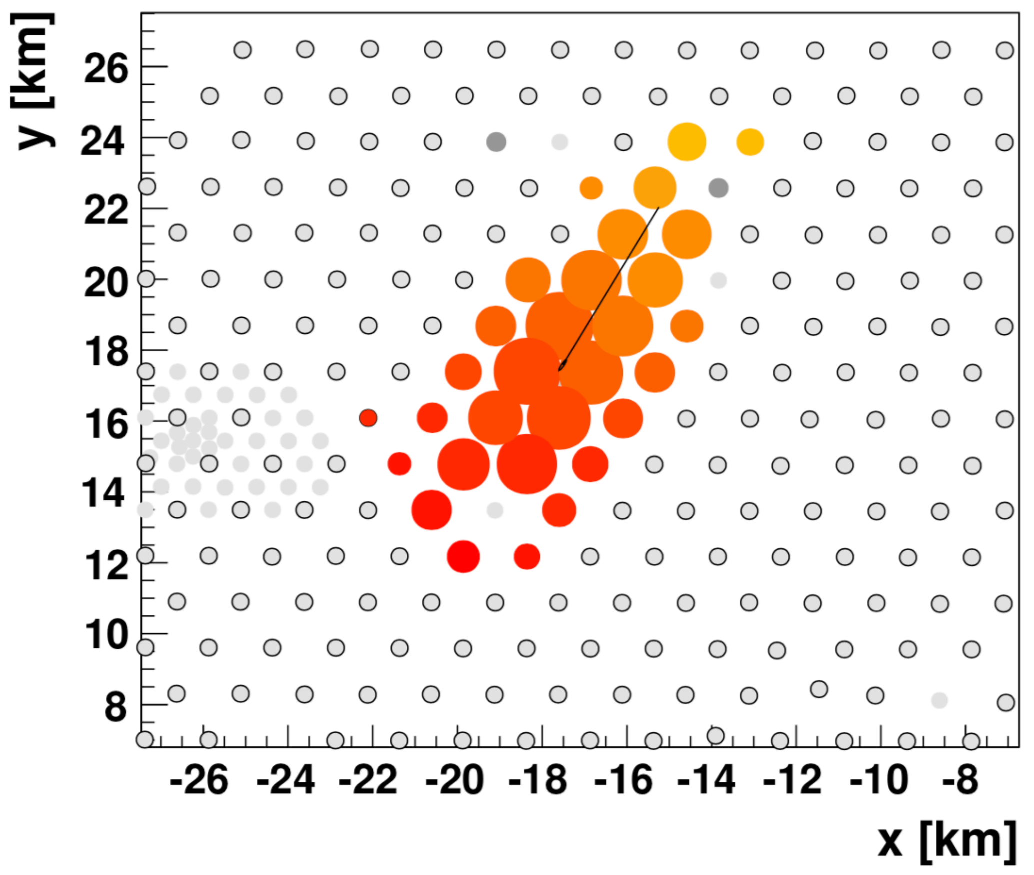


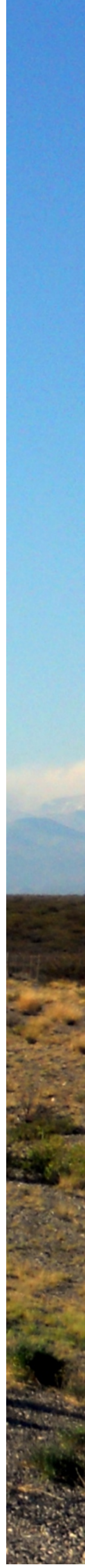
- Energy given by the Fluorescence Detector
- 281 hybrid events



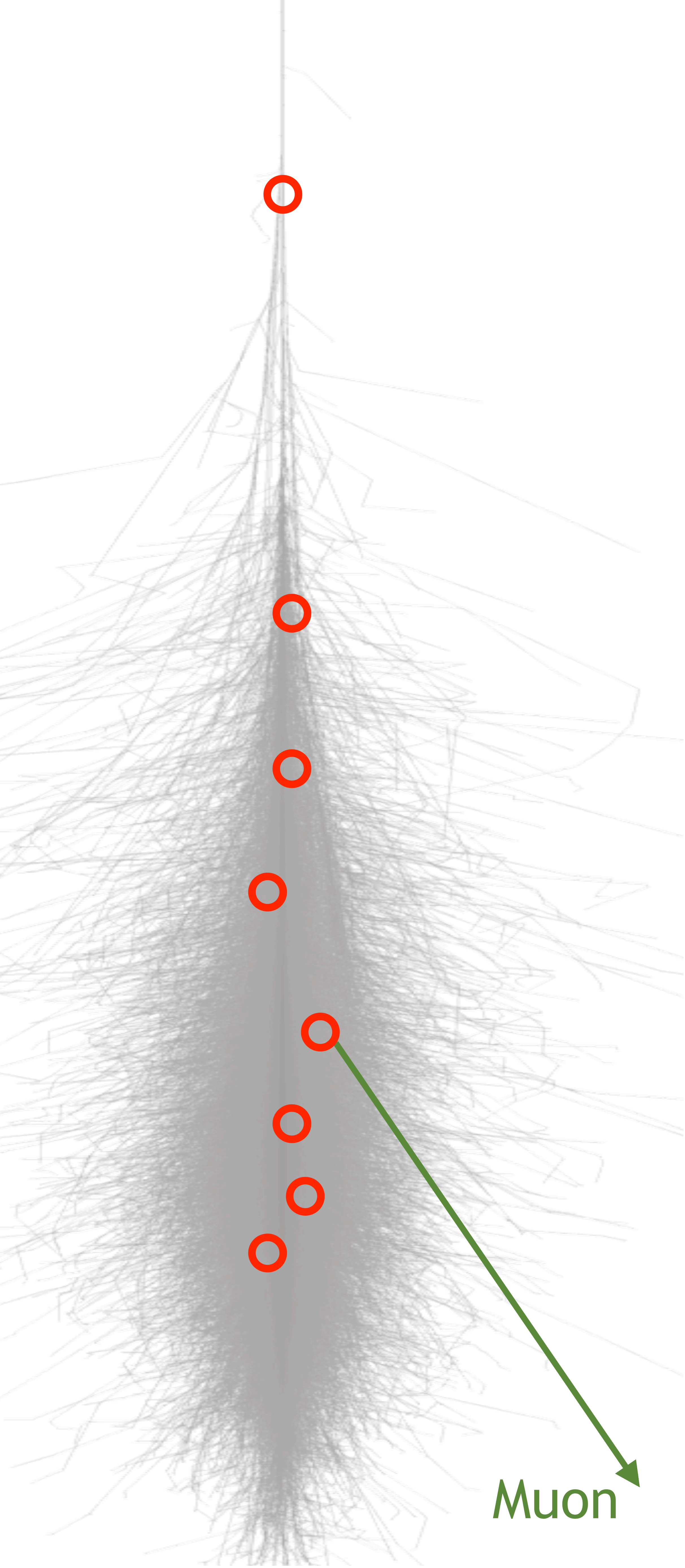


$$\rho_\mu(\mathrm{data}) = N_{19} \cdot \rho_\mu(\mathrm{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

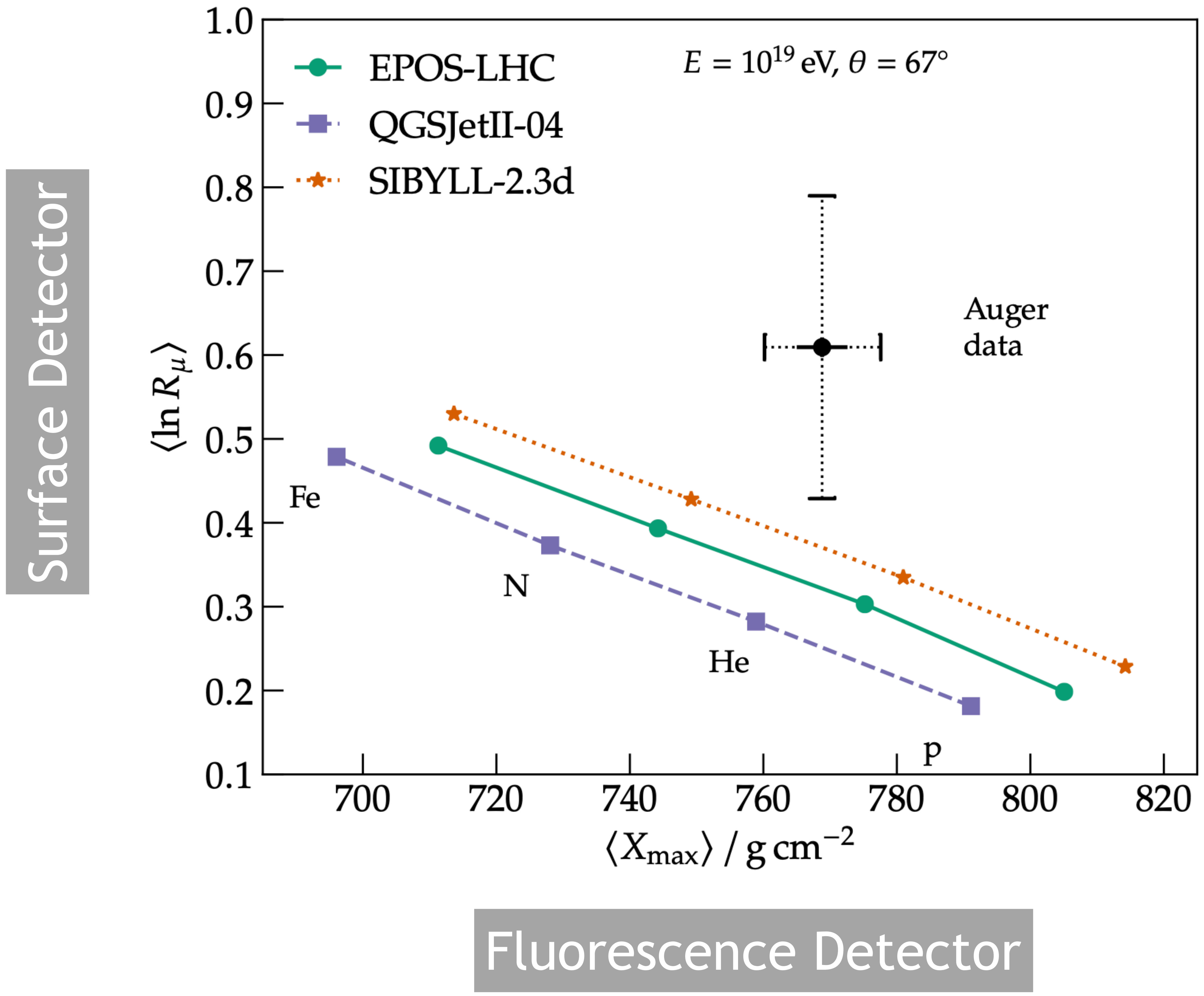
$$\boxed{R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}}$$



Shower description



Phys.Rev.Lett. 126 (2021) 15, 152002

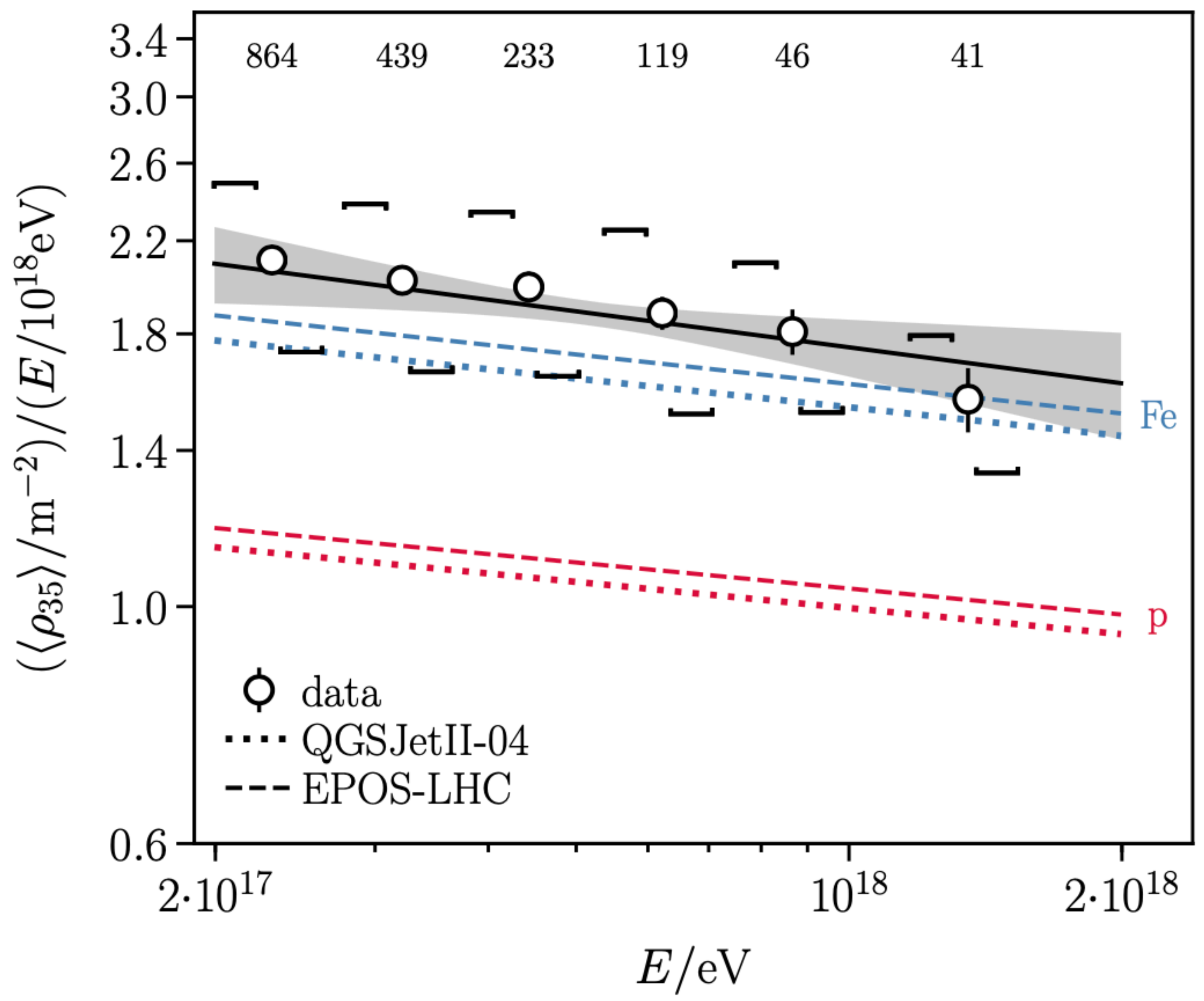


Combination of different measurements **reveals tension between data and all hadronic interaction models**

EAS muon content over an extended energy range

Eur.Phys.J.C 80 (2020) 8, 751

Phys.Rev.Lett. 126 (2021) 15, 152002

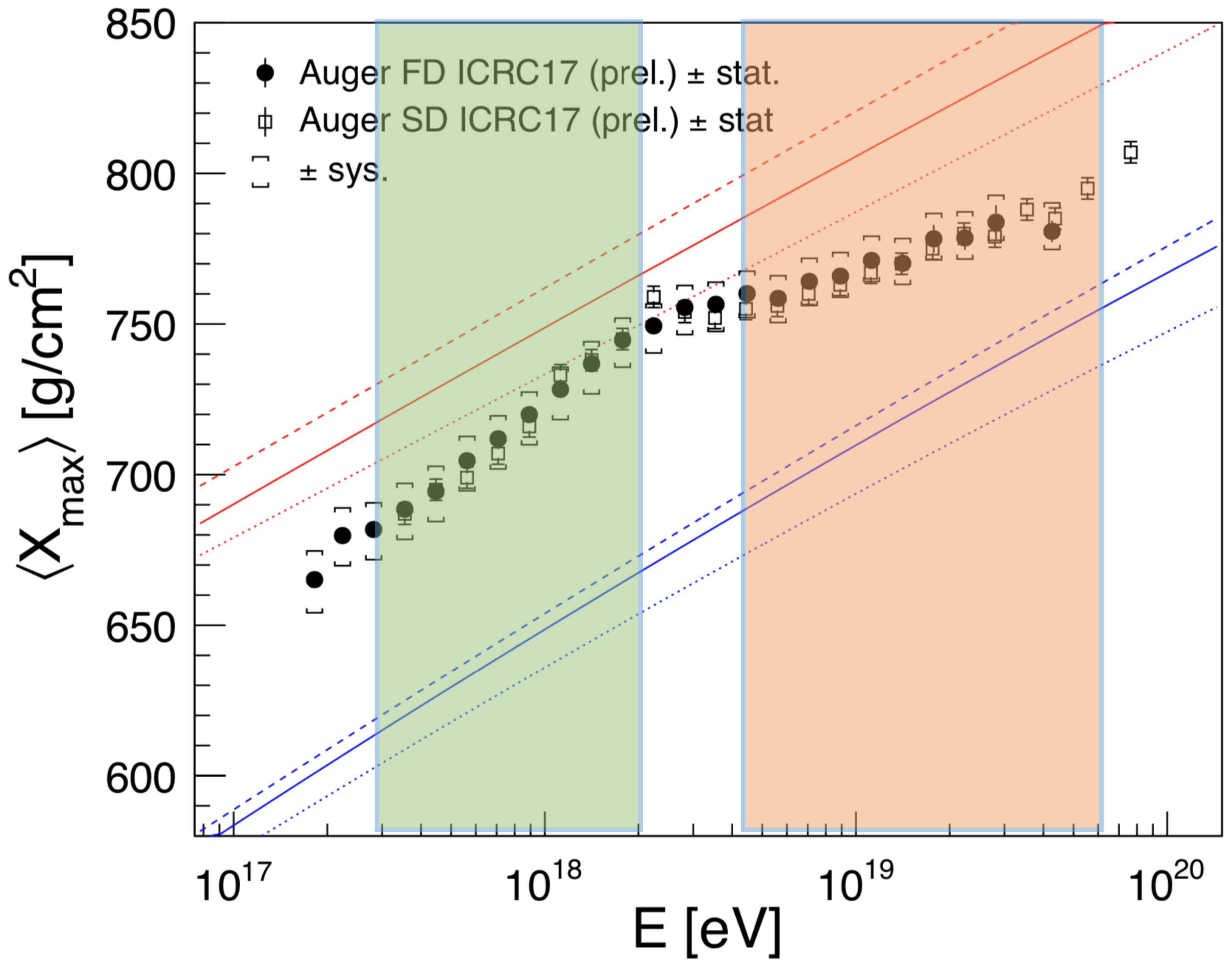


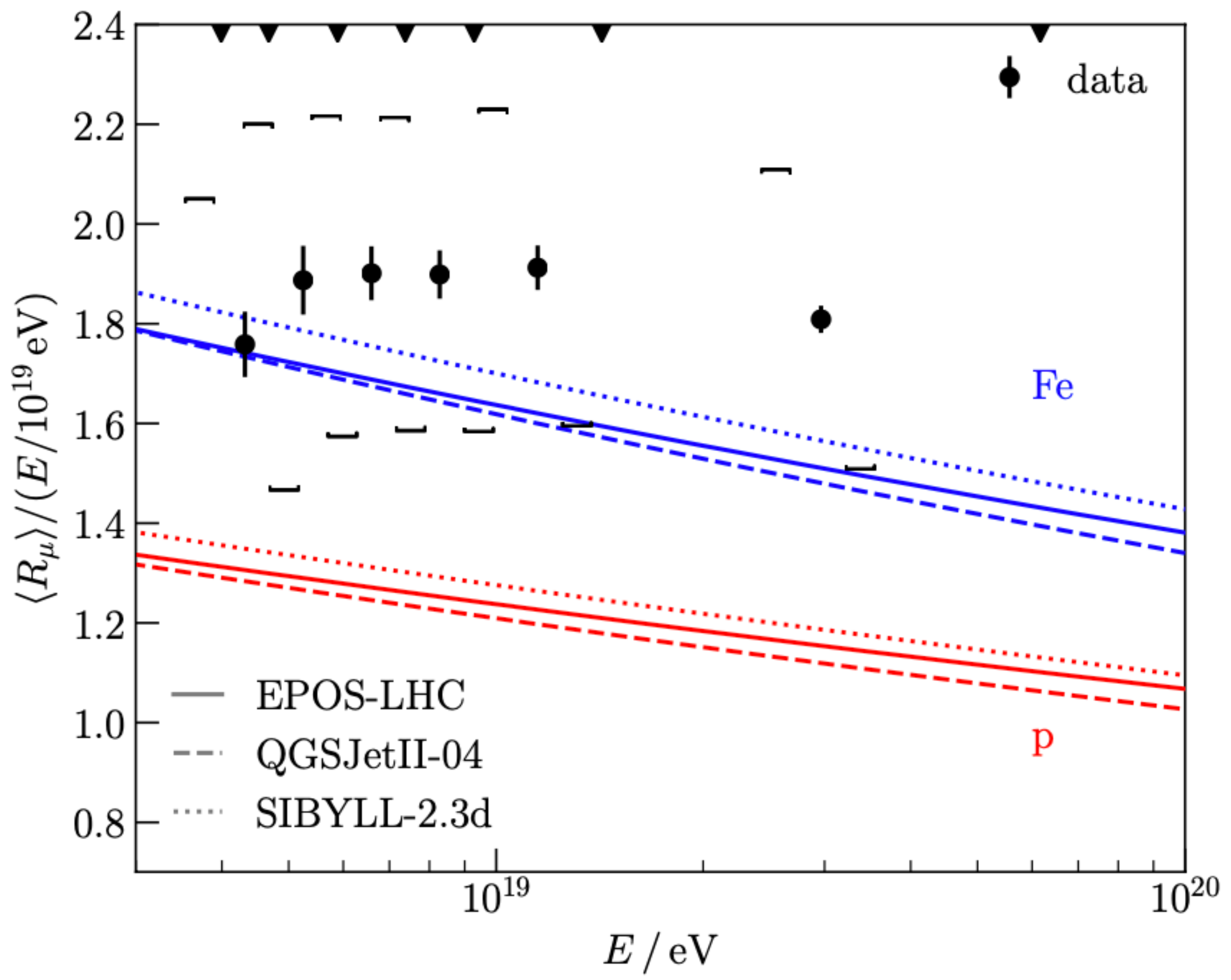
AMIGA

Data slightly above iron model predictions

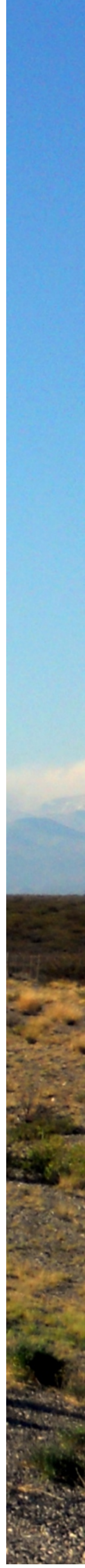
Large errors due to energy scale uncertainty

FD data





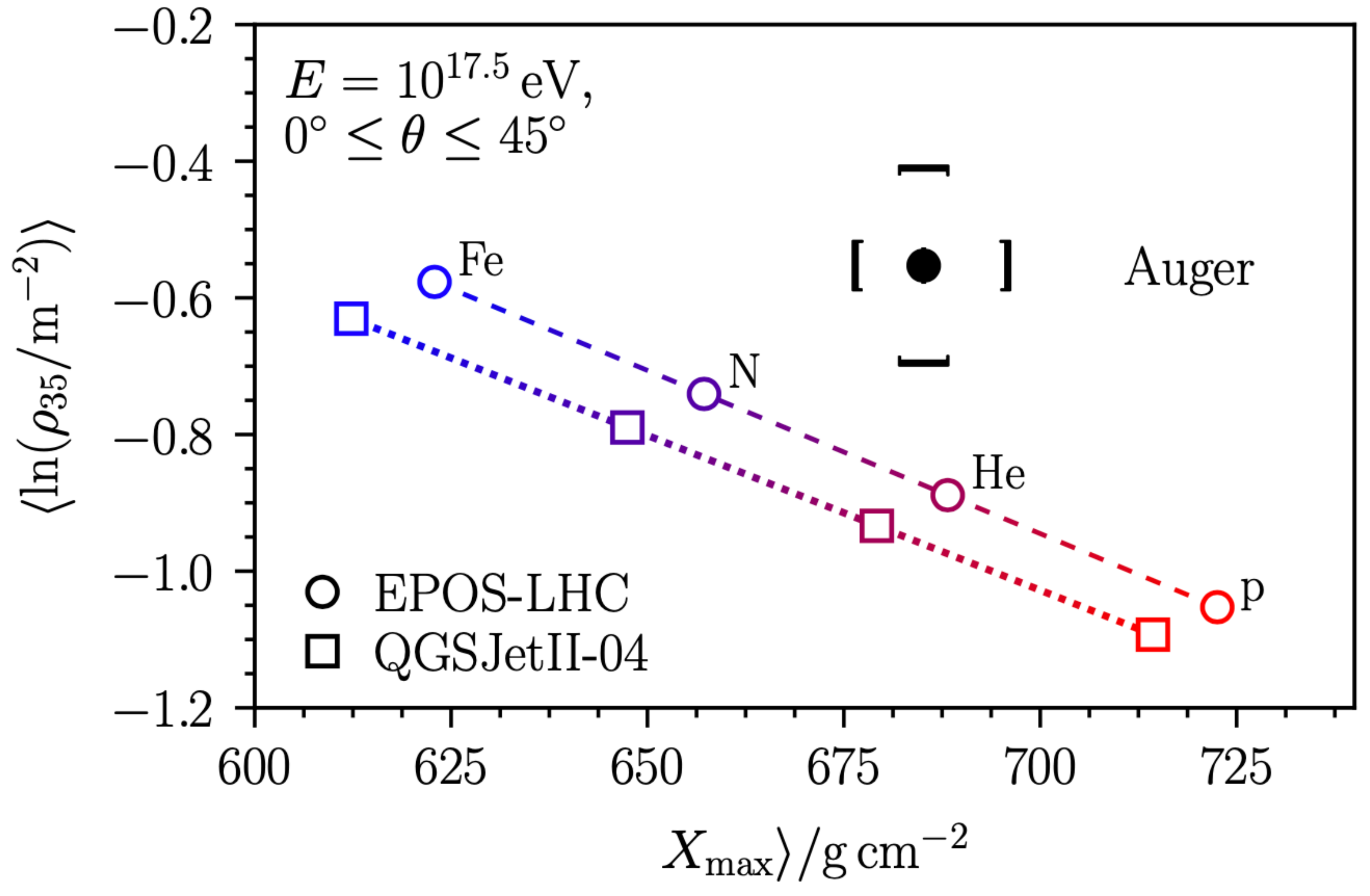
SD inclined



The EAS muon puzzle @ Auger

Eur.Phys.J.C 80 (2020) 8, 751

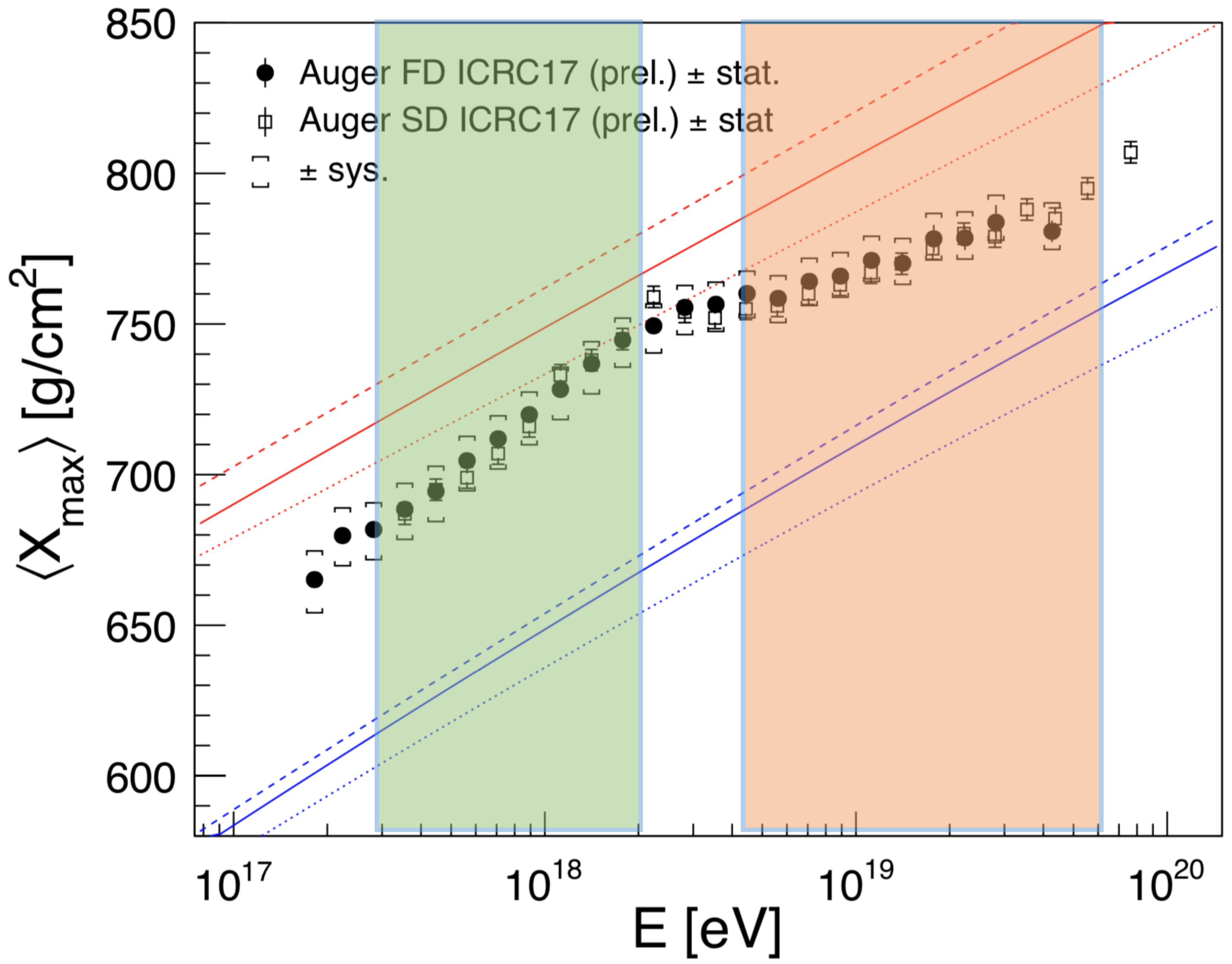
Phys.Rev.Lett. 126 (2021) 15, 152002

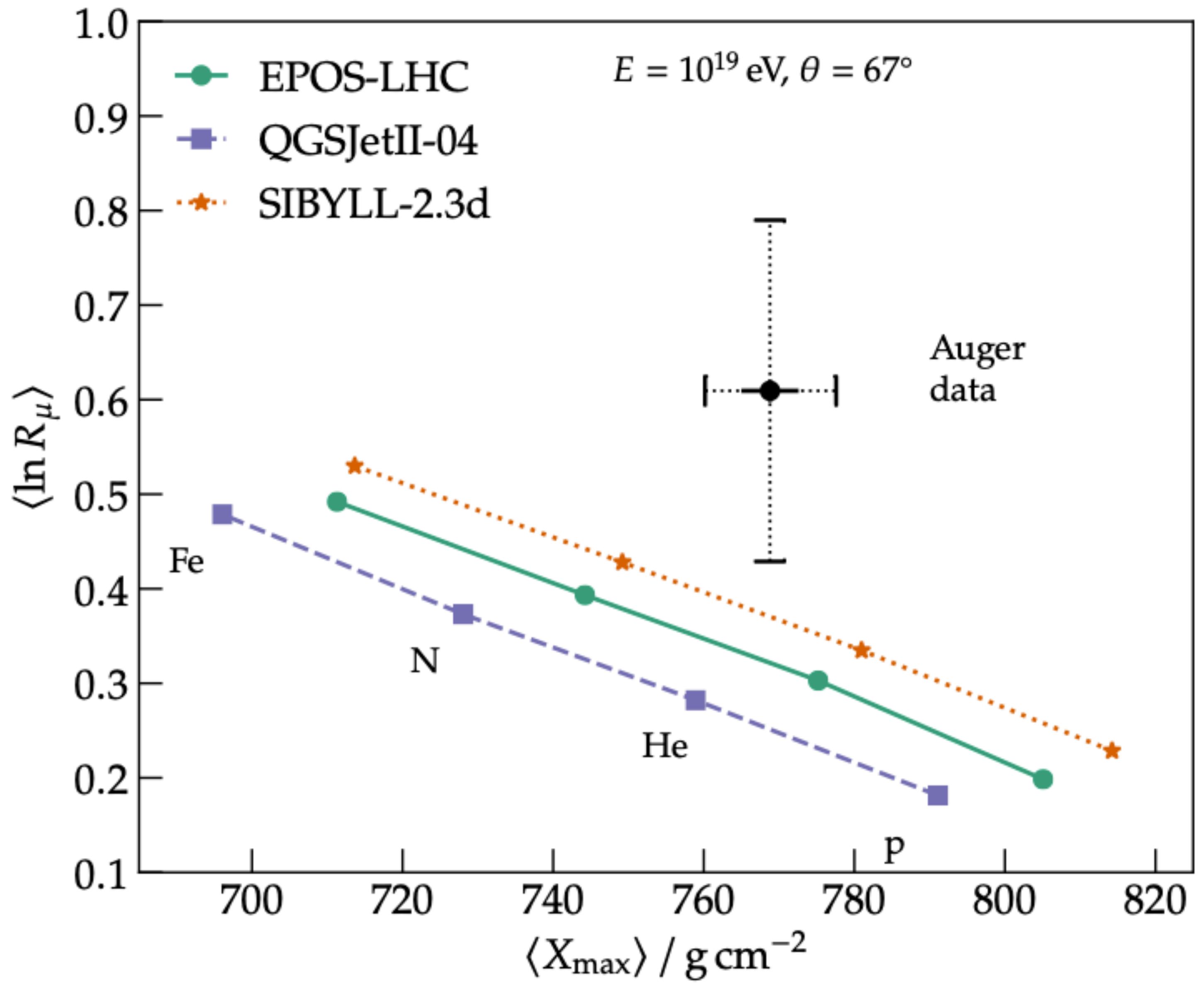


AMIGA

Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition

FD data

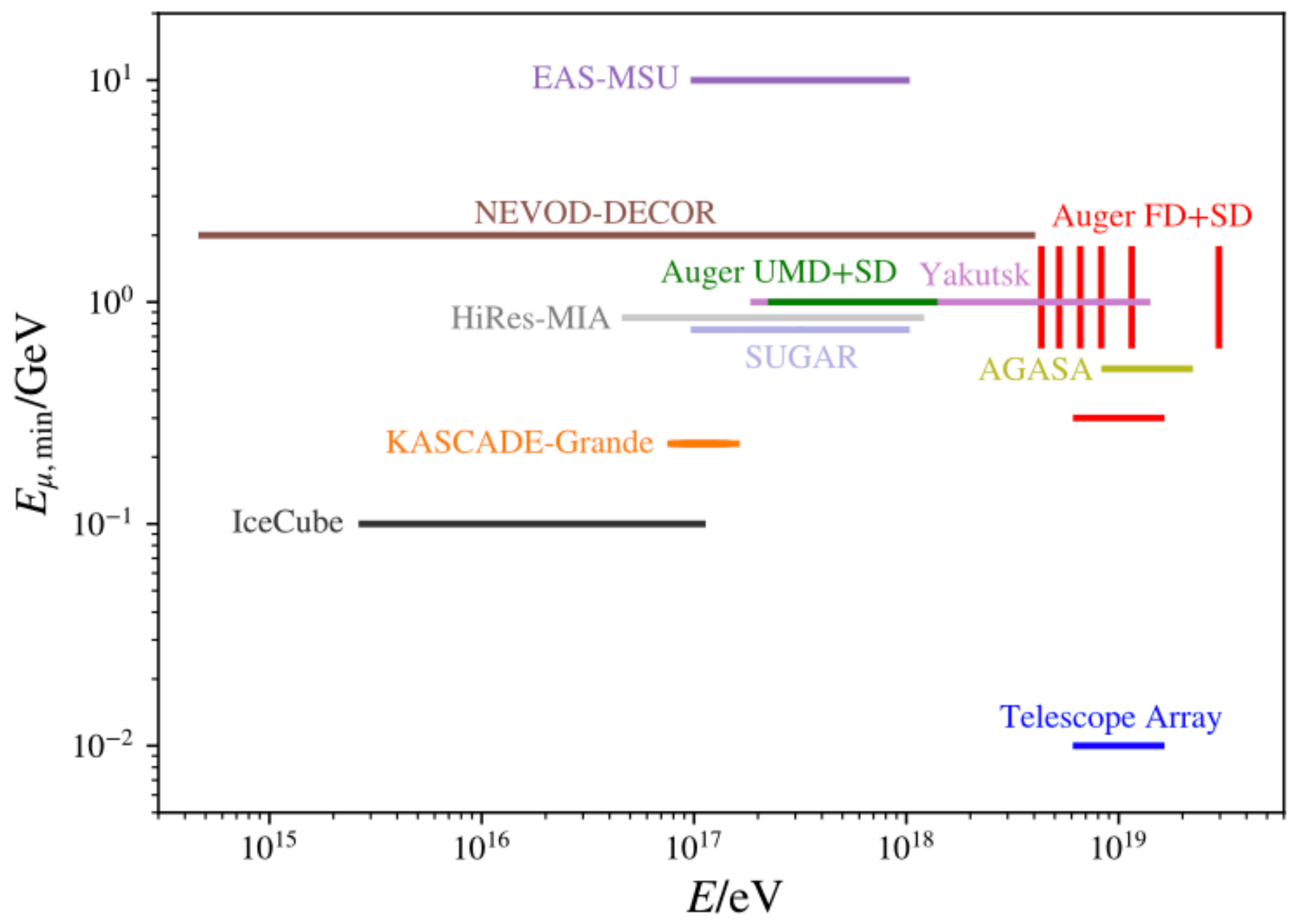


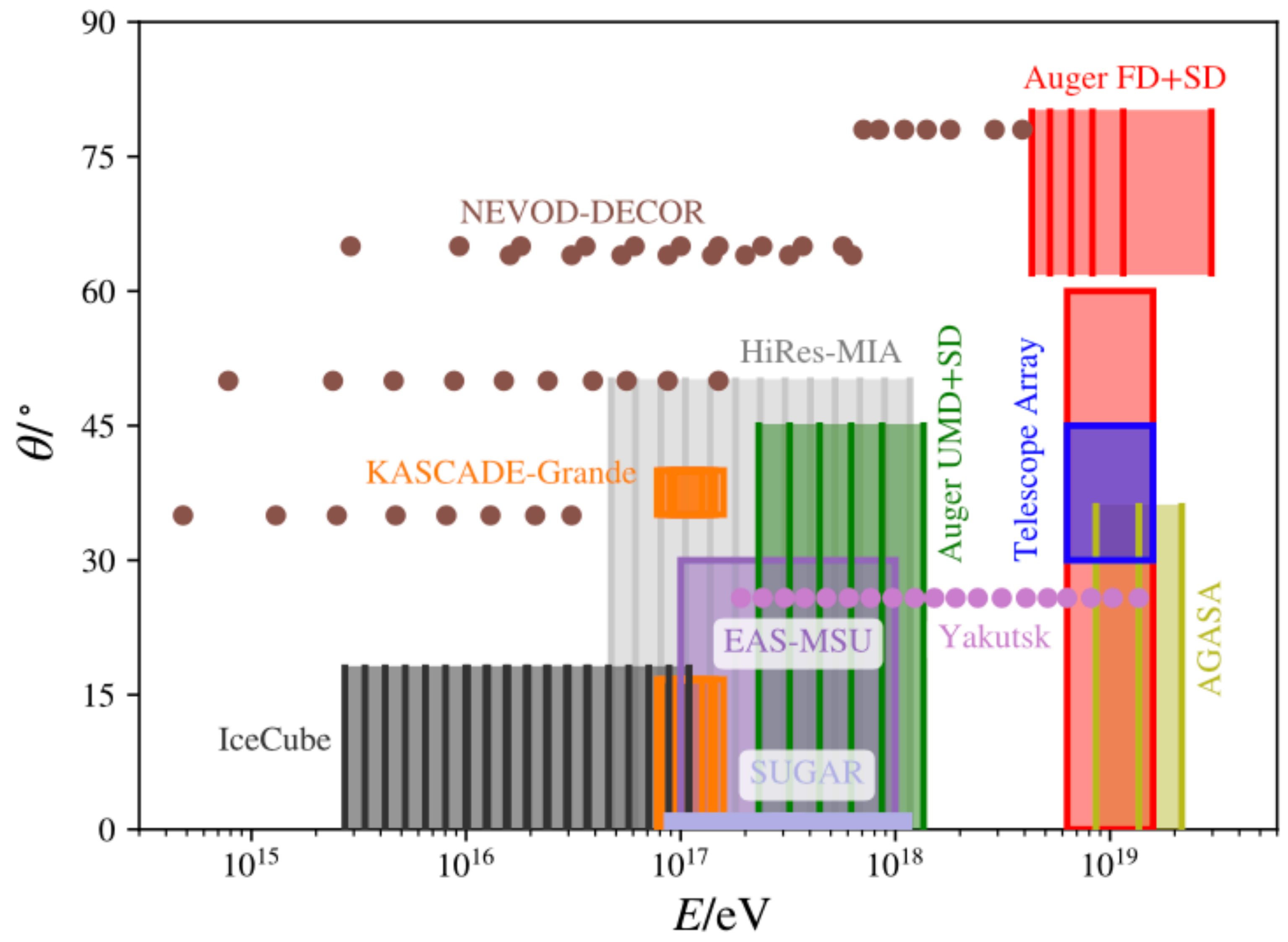


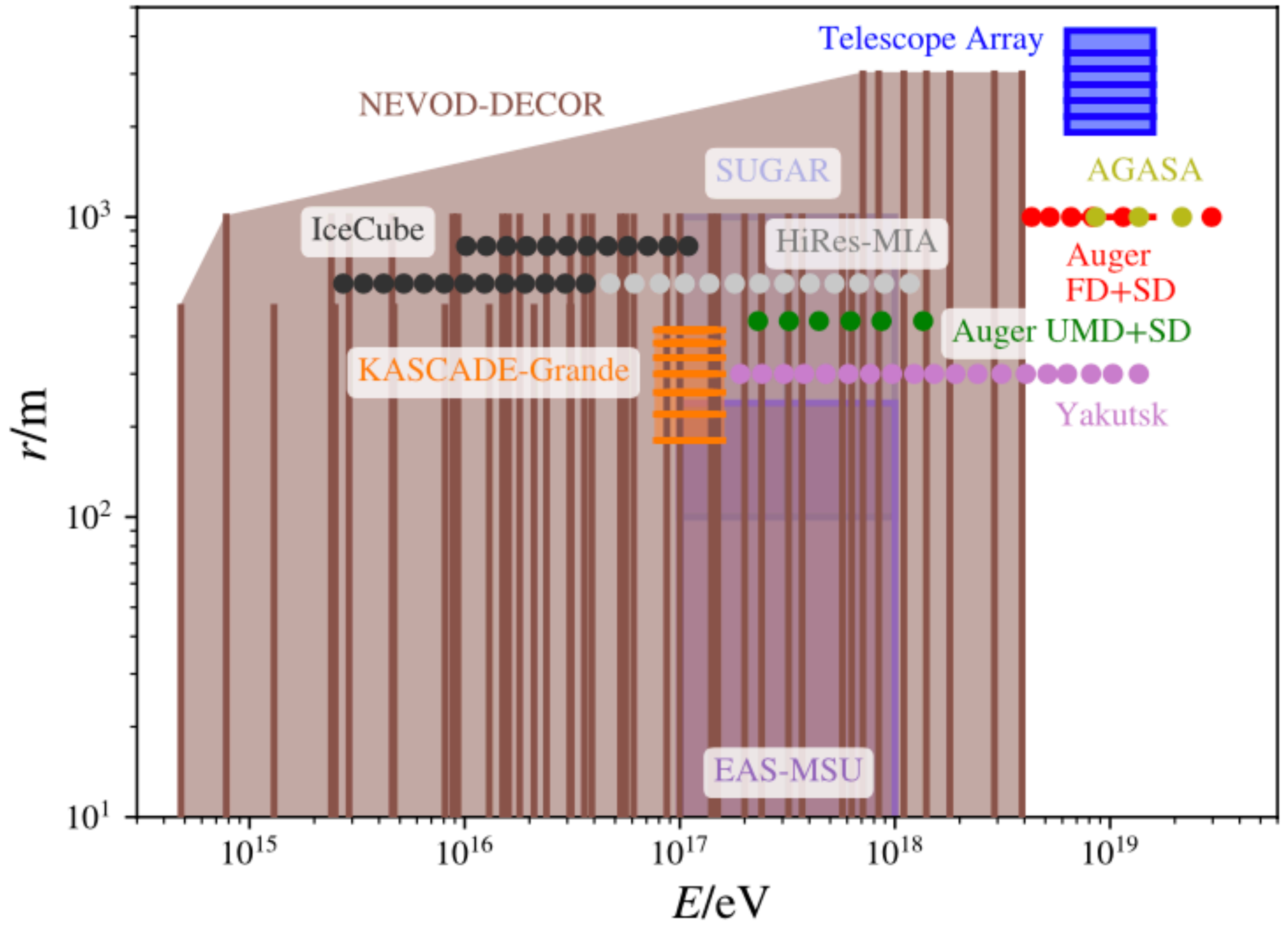
SD inclined

WHISP

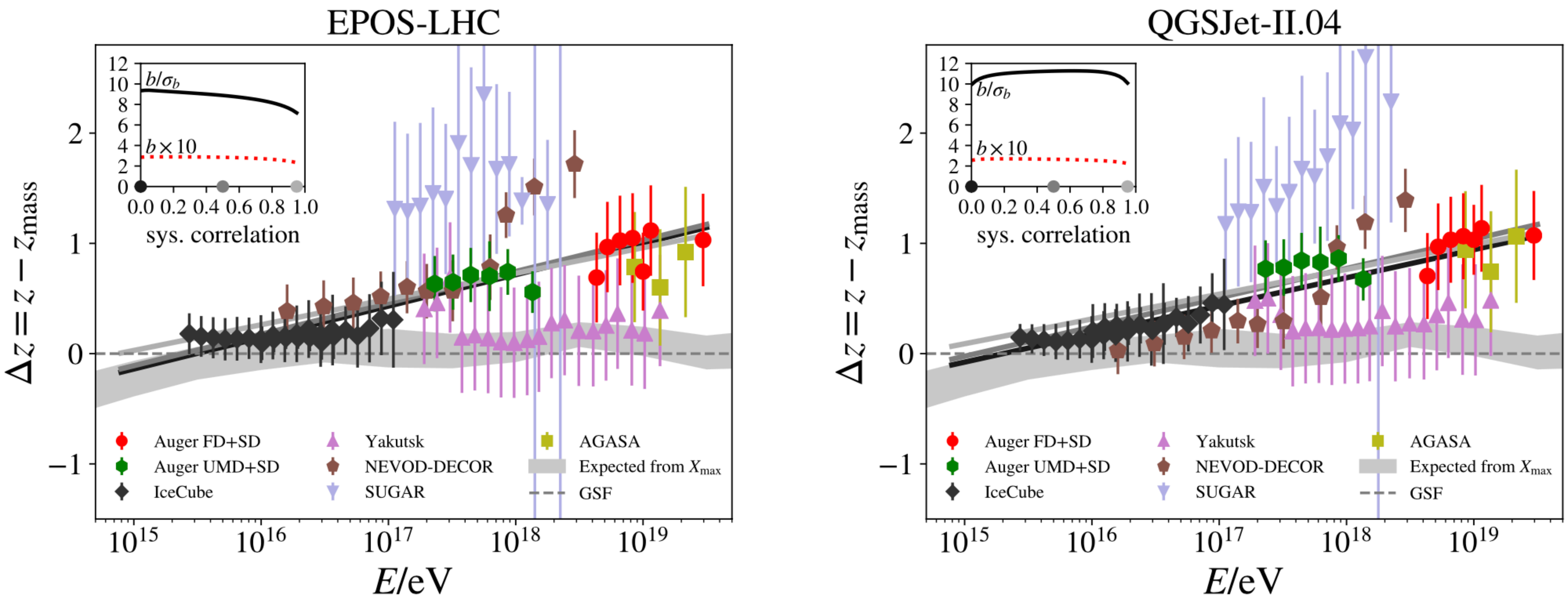
- Working Group for Hadronic Models and Shower Physics (WHISP)
- **Meta-data analysis of 9 cosmic ray experiments**: AGASA, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger Observatory (SD+FD, UMD+FD), SUGAR, Telescope Array, Yakutsk







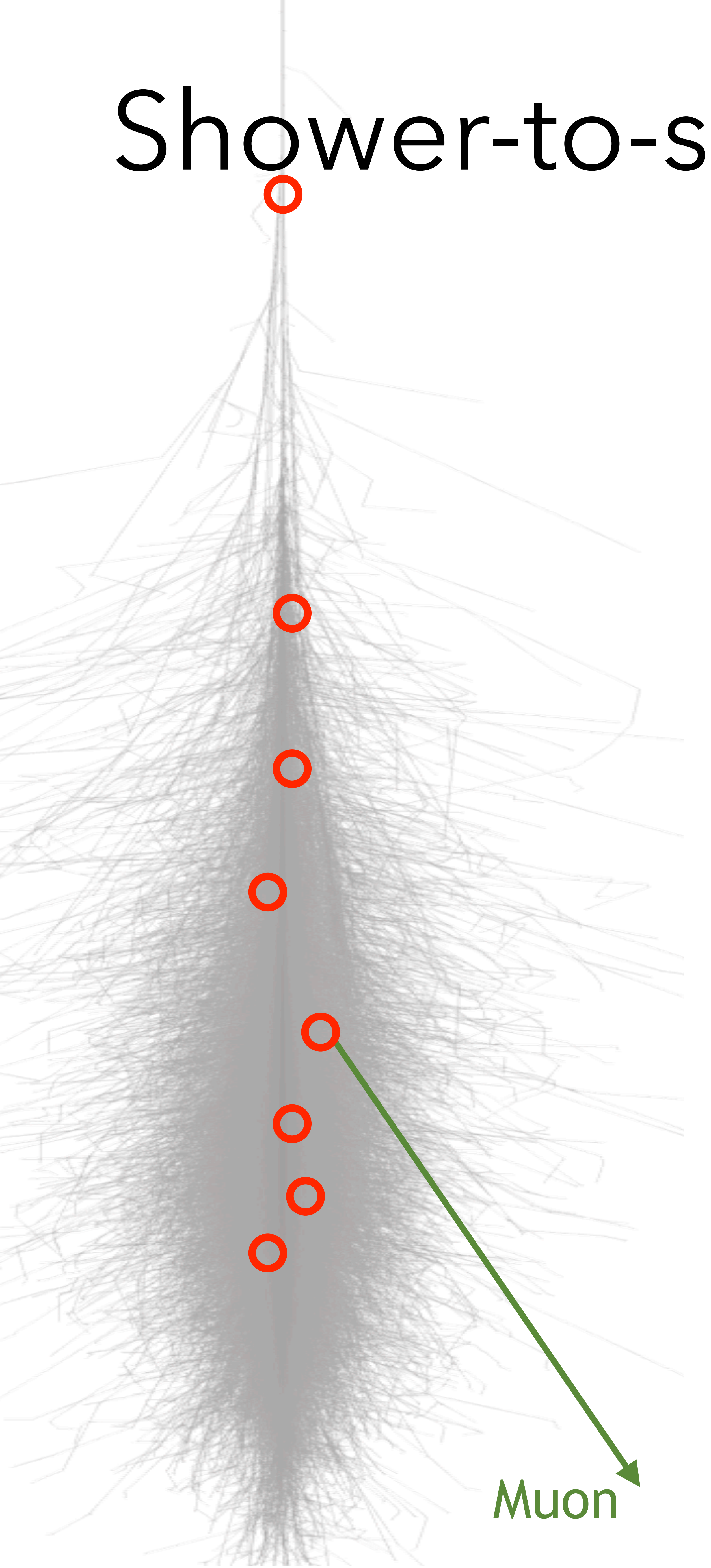
WHISP: EAS muon puzzle

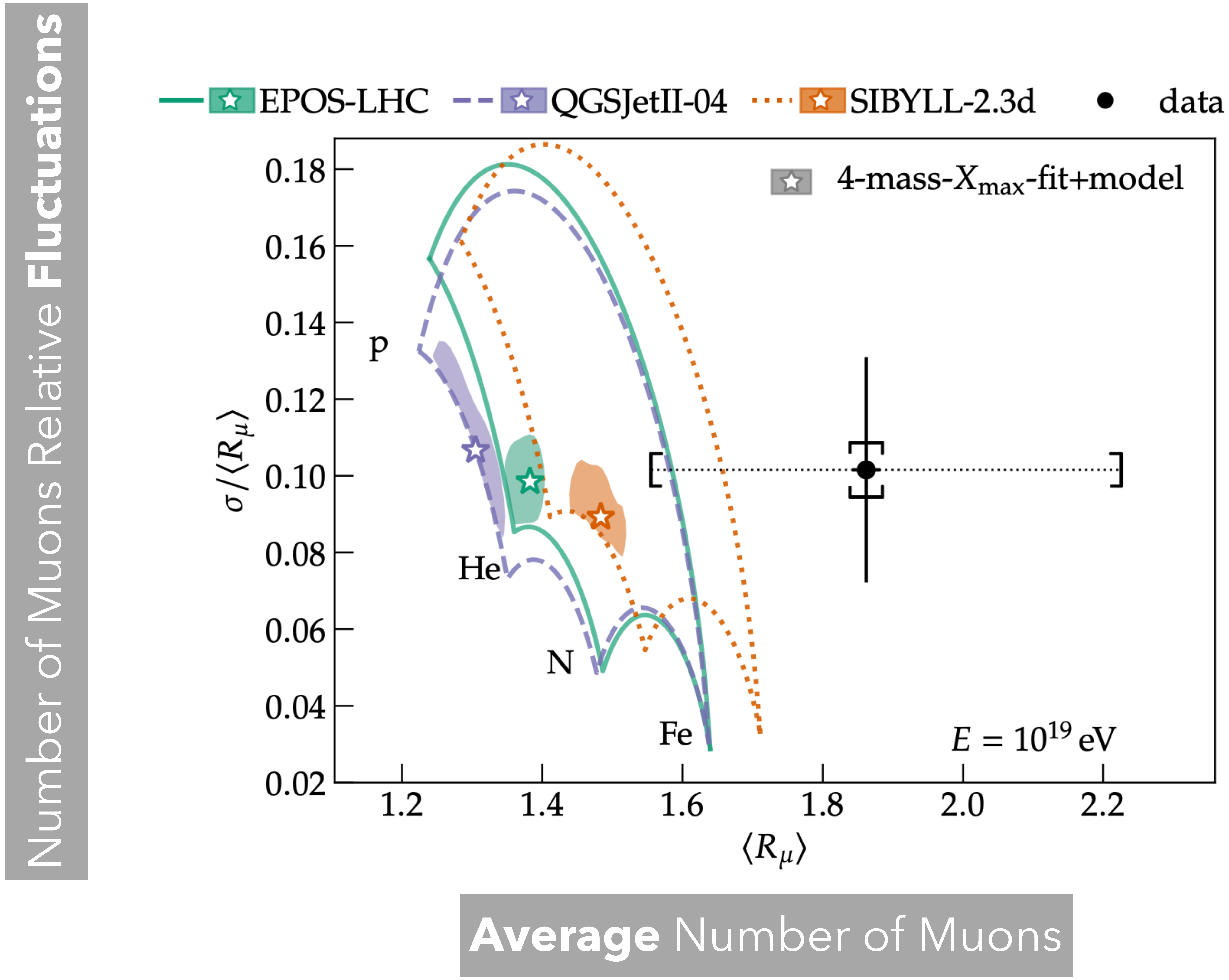


- ✧ Energy-rescaling and mass subtraction required for comparison
- ✧ Linear fit finds significant slope of muon excess in data at 8-10 sigma level

Shower-to-shower muon number relative fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002



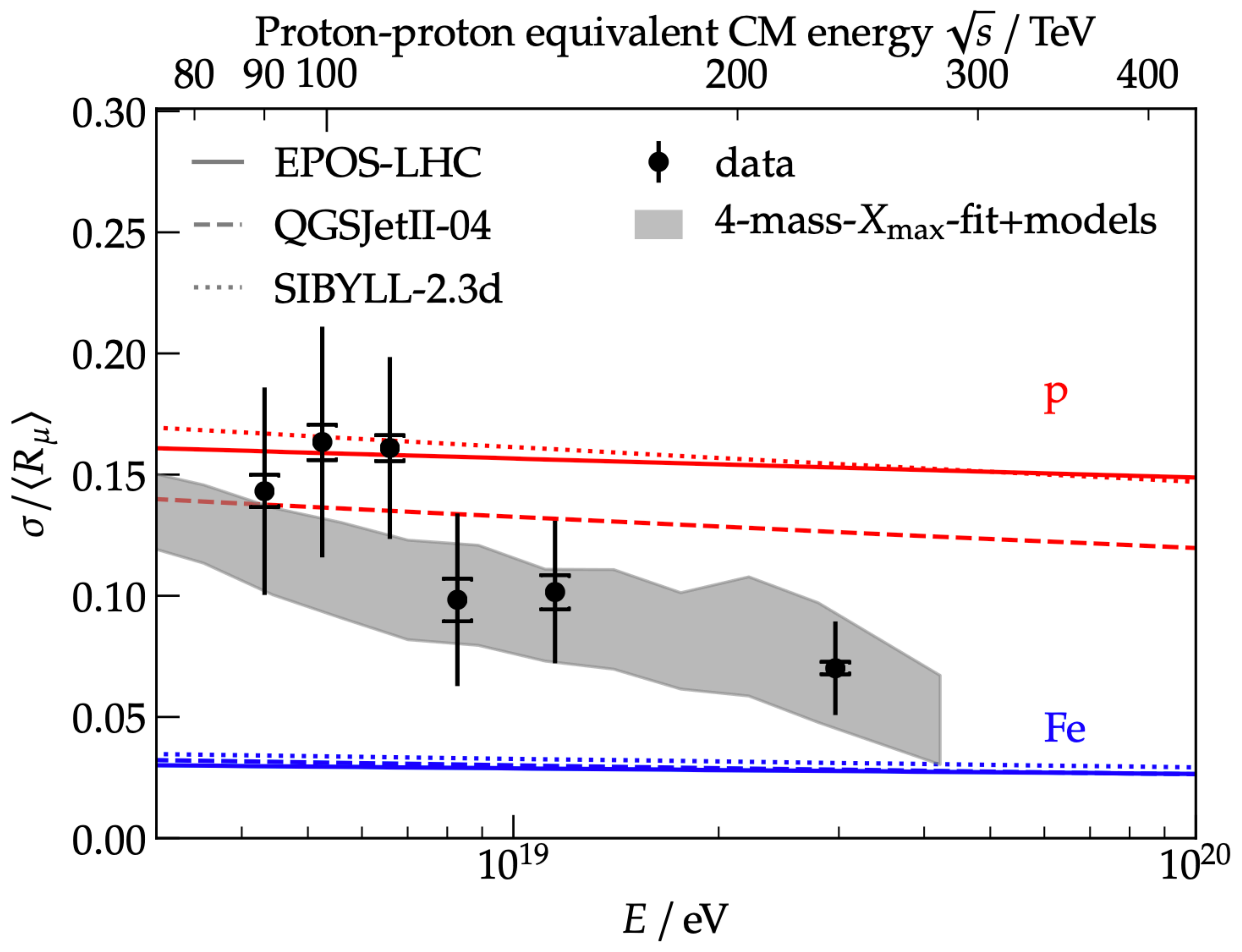


Implies a strong control over the detector response (RPC hodoscopes - Coimbra!)

Need of an independent energy scale (FD)

EAS muon fluctuations

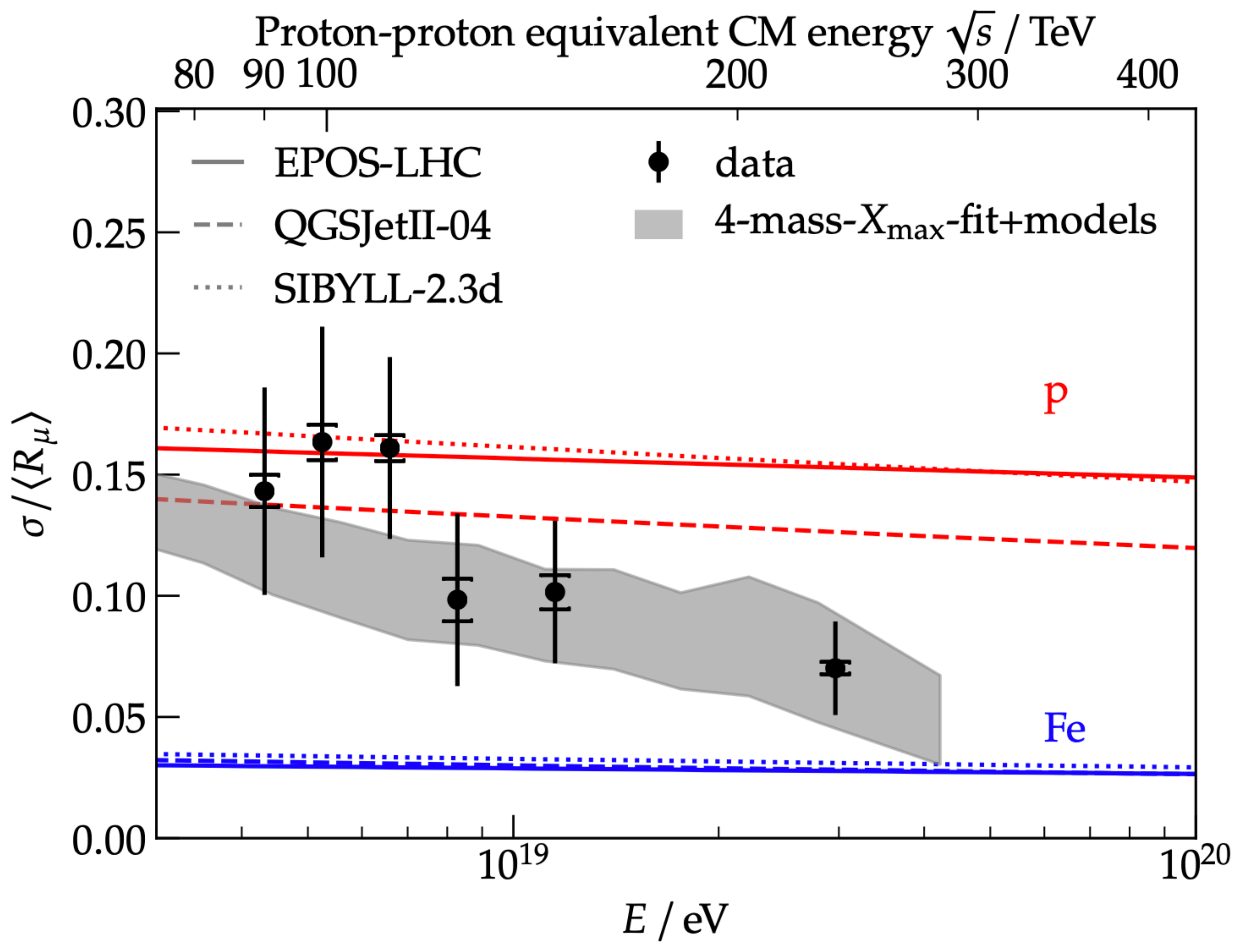
Phys.Rev.Lett. 126 (2021) 15, 152002



The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data

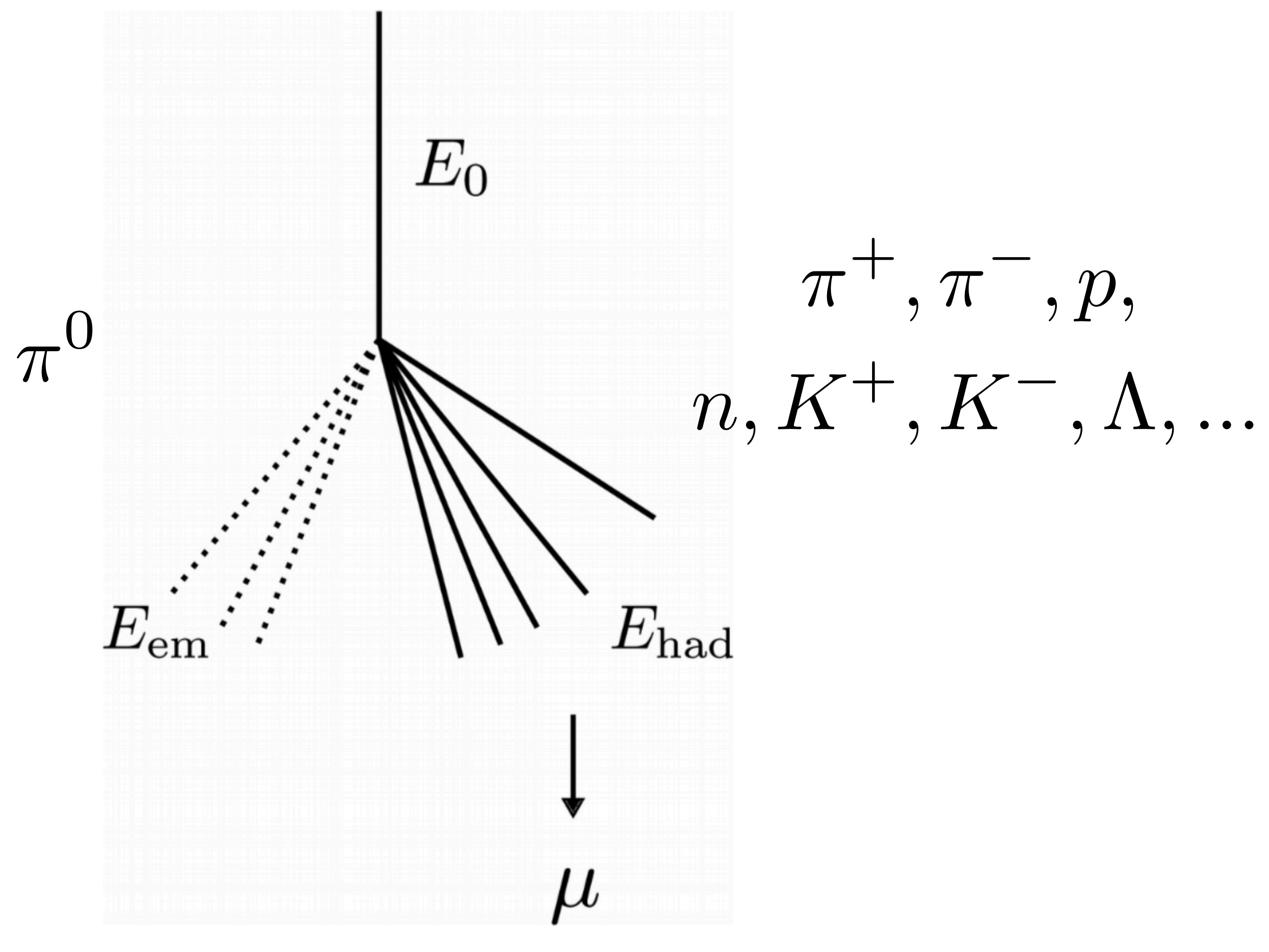
EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002



The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data

L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76

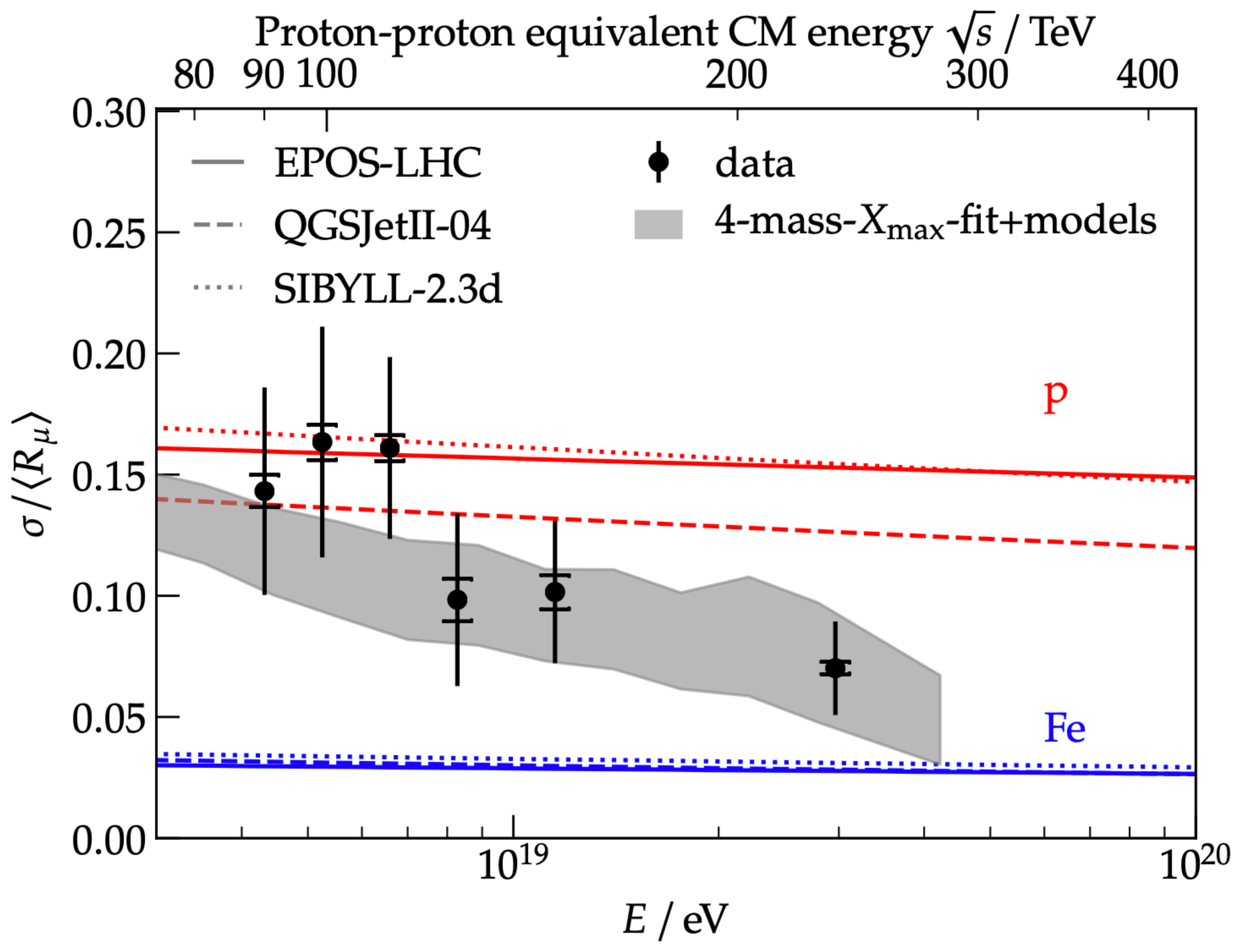


$$N_\mu \sim E_{had}$$

α_1 is the fraction of energy going into the hadronic sector in the first interaction

EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002



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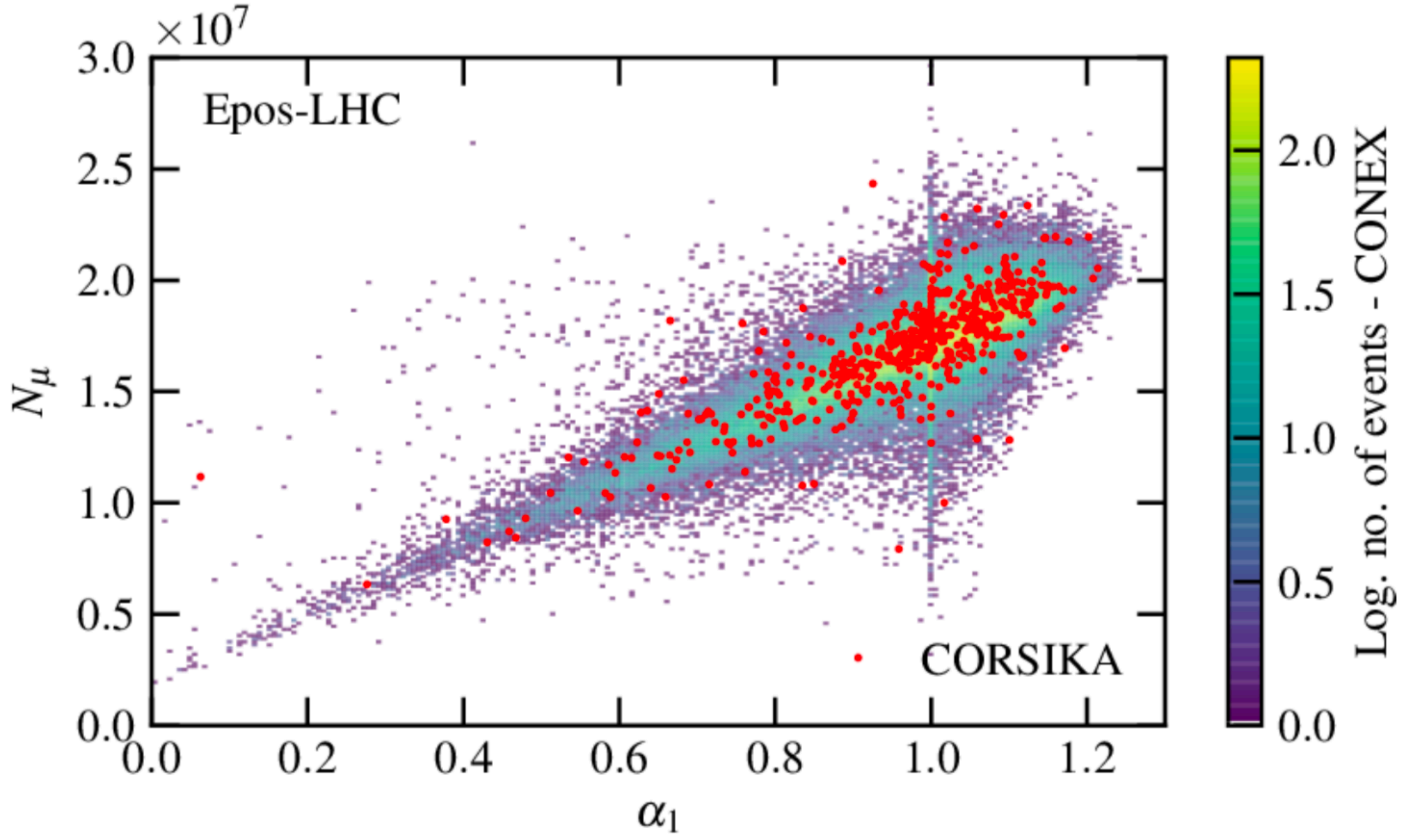


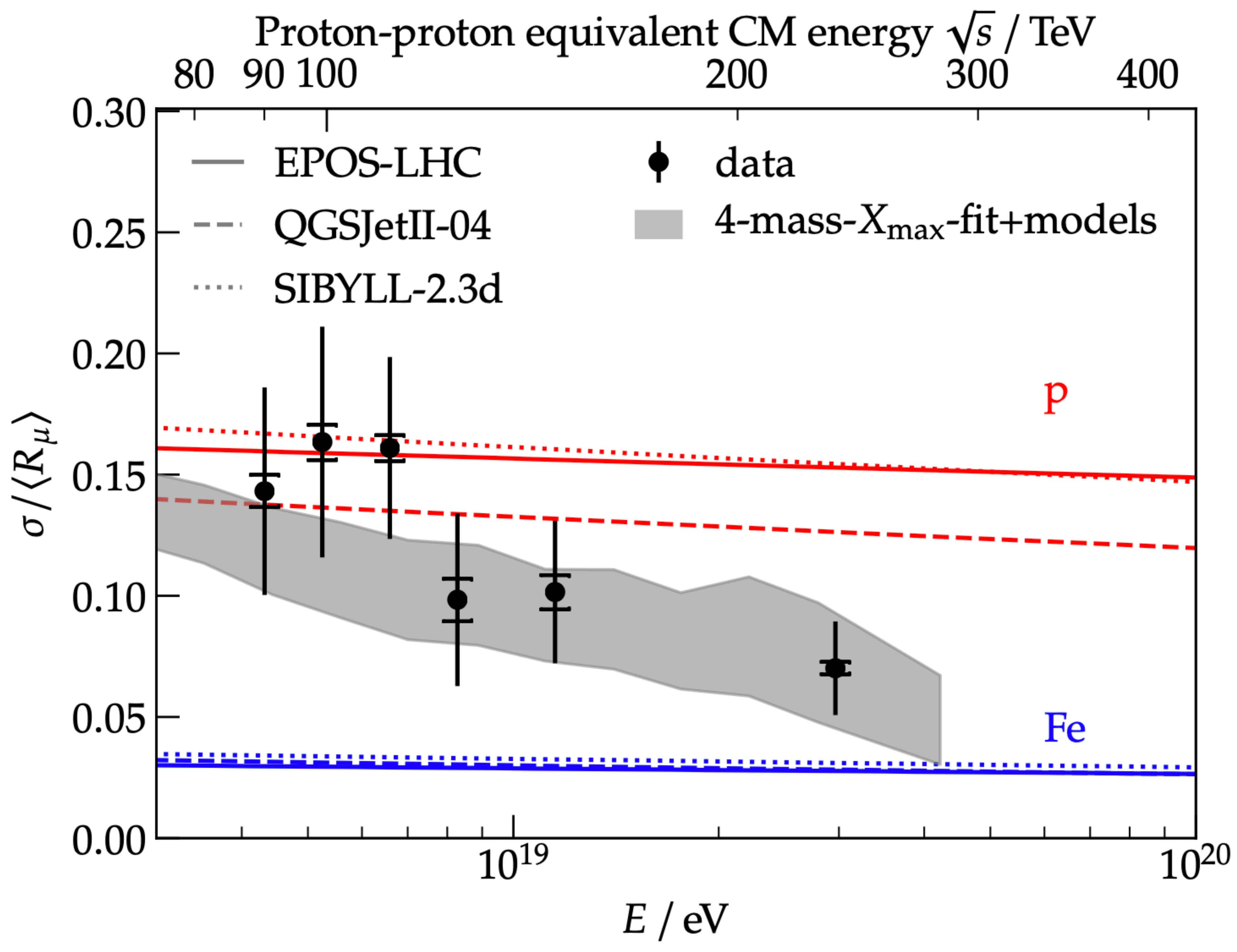
α_1 is the fraction of energy going into the hadronic sector in the first interaction

$$\sigma(\alpha) \rightarrow 70\% \, \sigma(N_\mu)$$

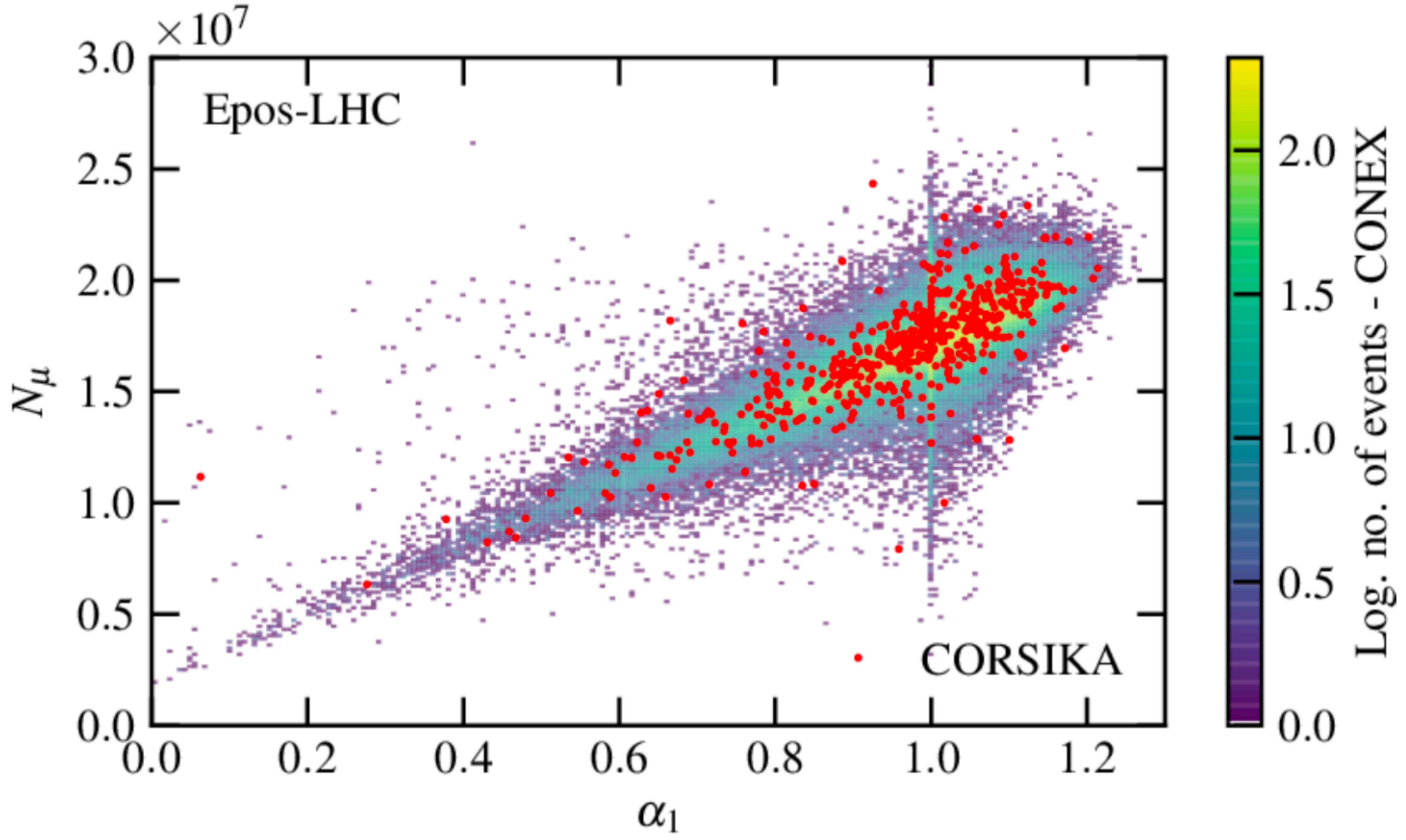
EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002

L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76



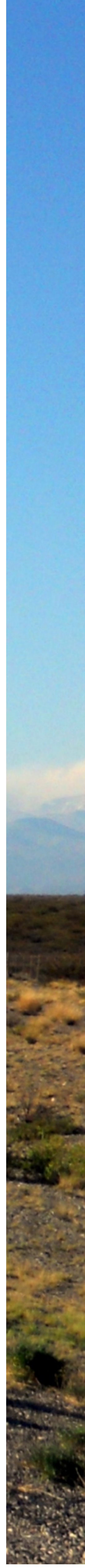
The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data



α_1 is the fraction of energy going into the hadronic sector in the first interaction

$$\sigma(\alpha) \rightarrow 70\% \, \sigma(N_\mu)$$

Suggestion that muon deficit might be related with description of low energy interactions

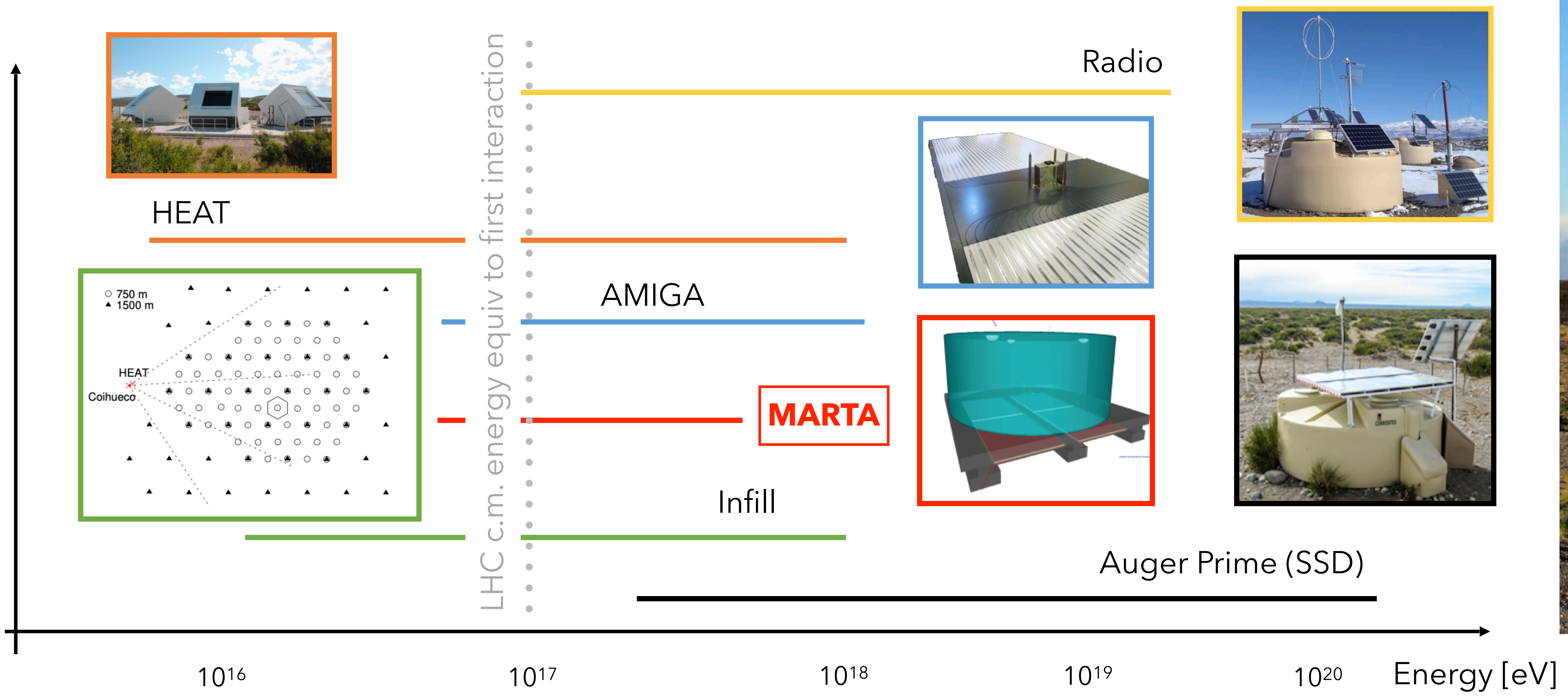


Pierre Auger Observatory

Future Plans

Multi-hybrid shower events

(A plethora of measurements to fully understand the shower)



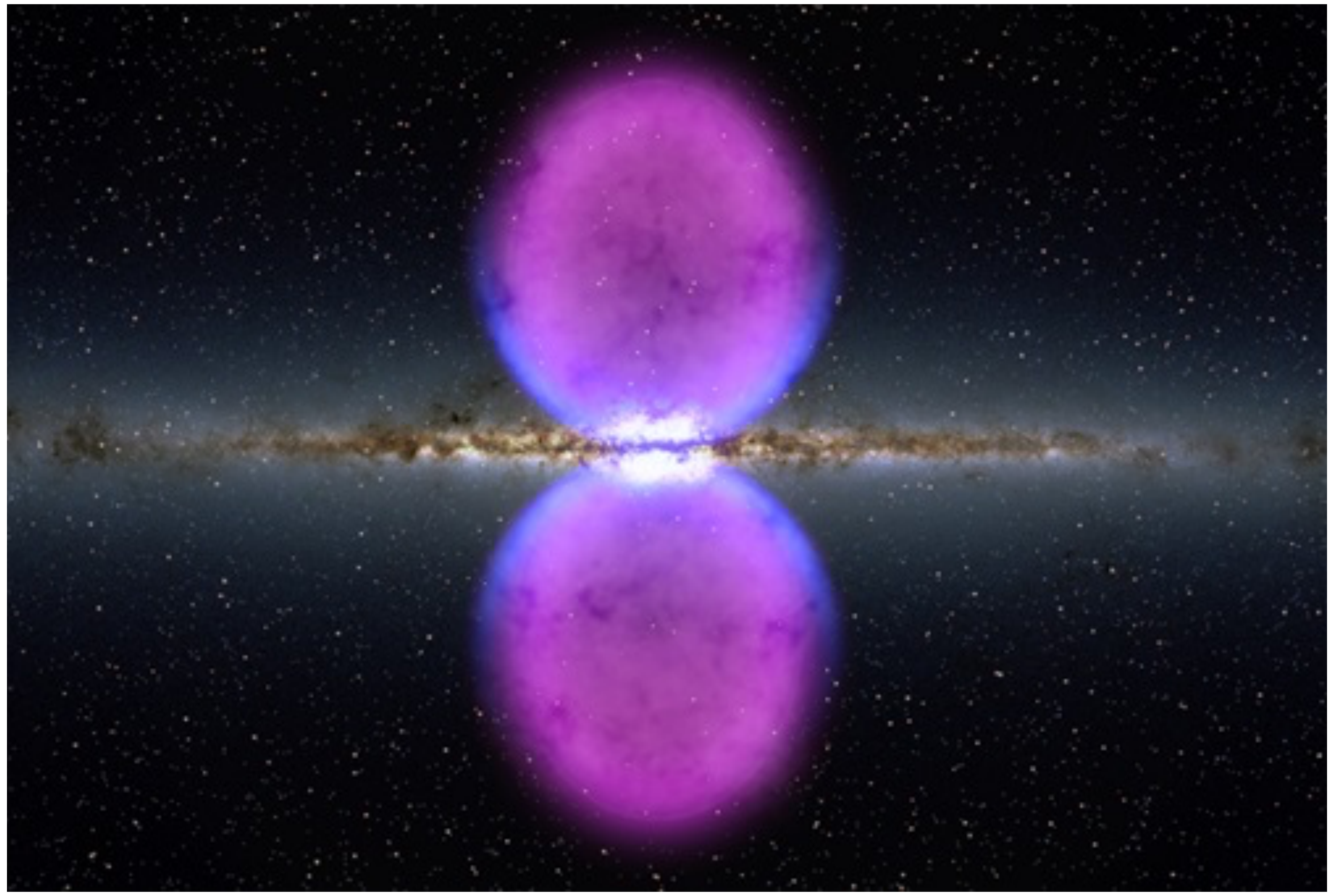
Southern Wide-field Gamma-ray Observatory

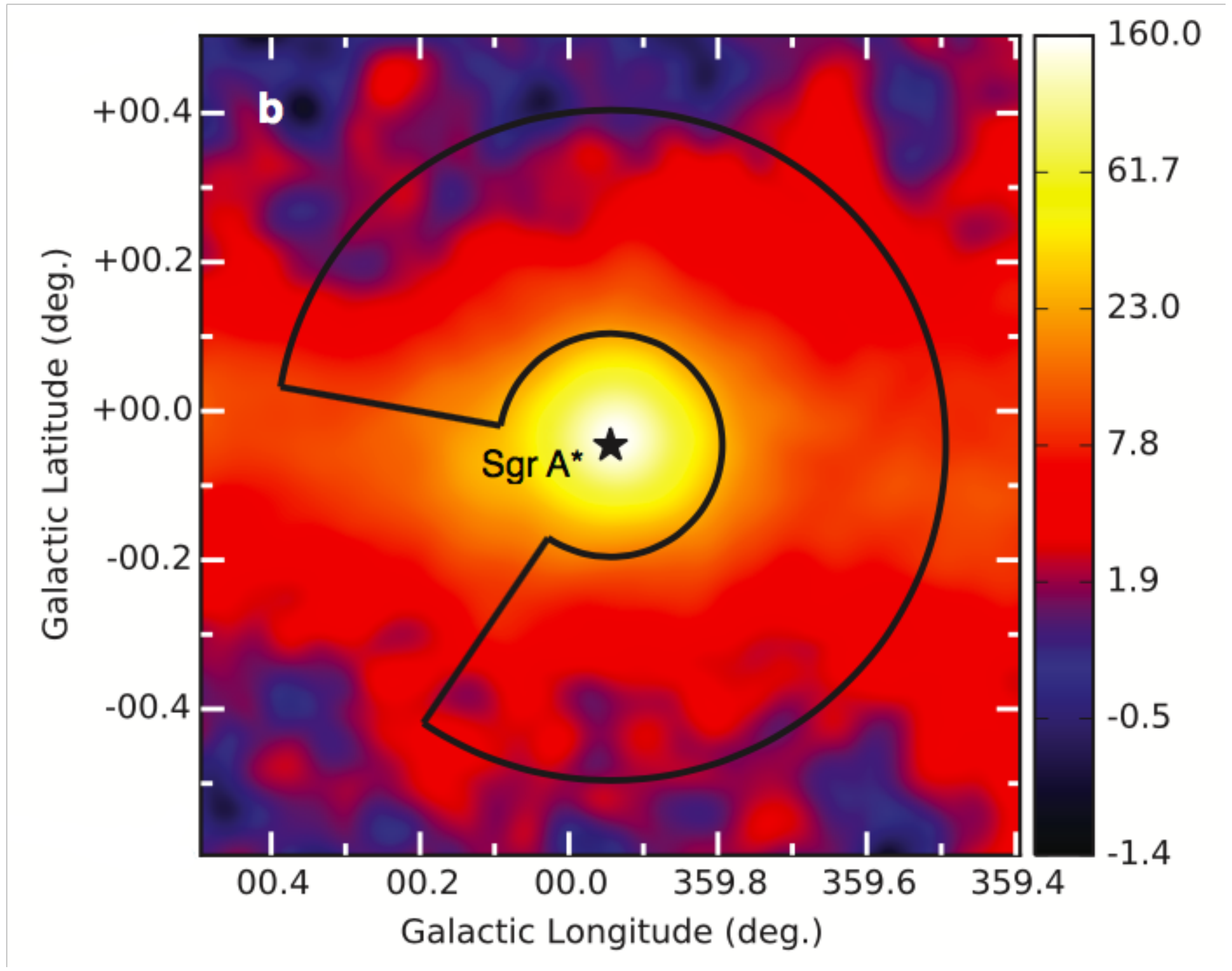
Very High Energy Gamma Rays

HAWC
LHASSO
EAS Array

Complementary to the powerful Cherenkov Telescope Array project
cta
cherenkov telescope array
Galactic Center
CTA
SWGO
Scorpius
Sagittarius

Some interesting highlights…





Fermi bubbles - gamma-ray emission (up to ~100 GeV) in outbursts from our galaxy

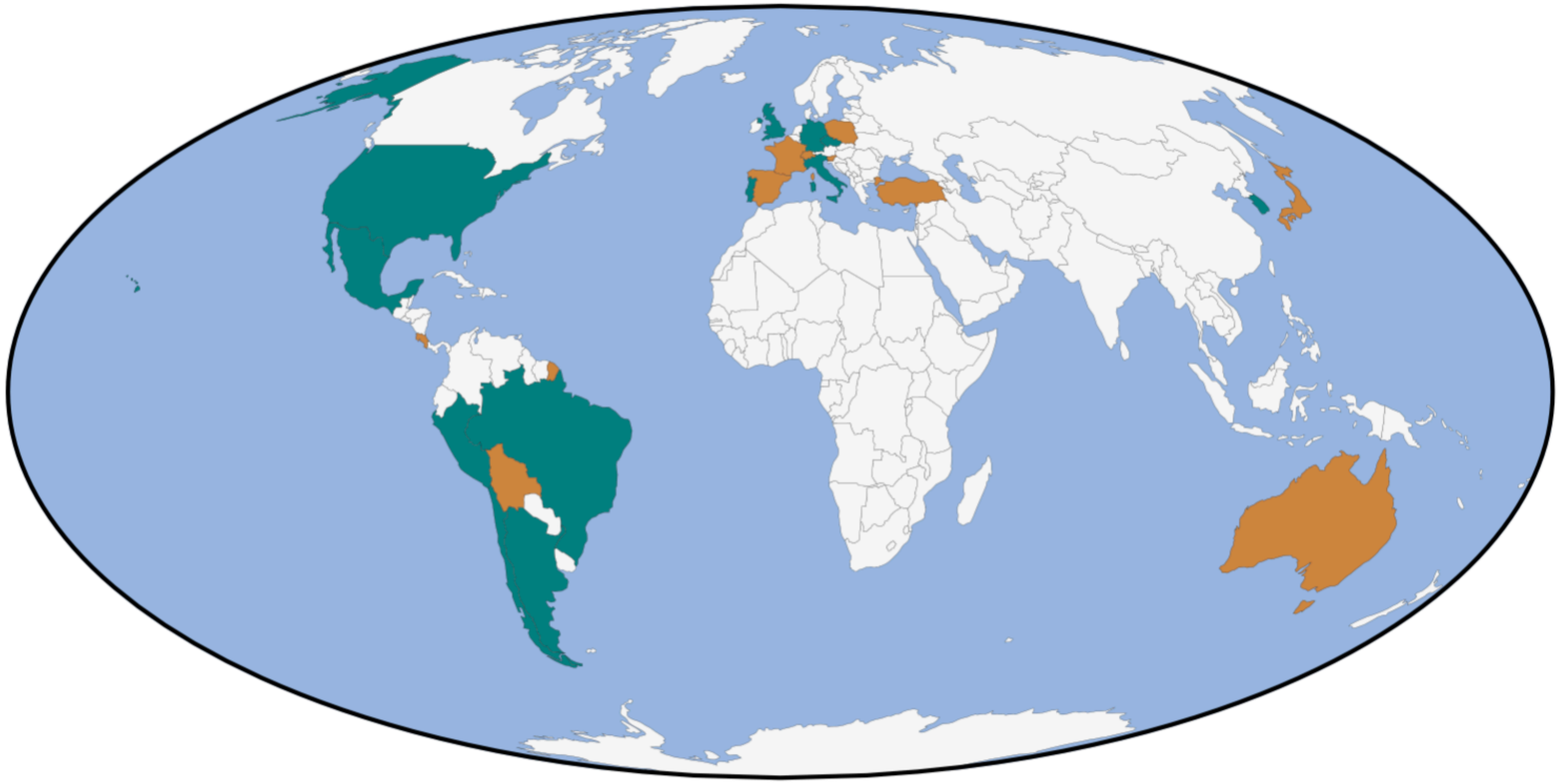
Search PeVatron sources (10^{15} eV) which should be the birth place of cosmic rays up to 10^{17} eV

SWGO

(Southern Wide-field Gamma-ray Observatory)

3 year R&D project to design the next gamma-ray wide field of view experiment

- ✧ 53 institutes
- ✧ > 100 scientists
- ✧ 13 countries
- ✧ 32 supporting scientists



Countries in SWGO

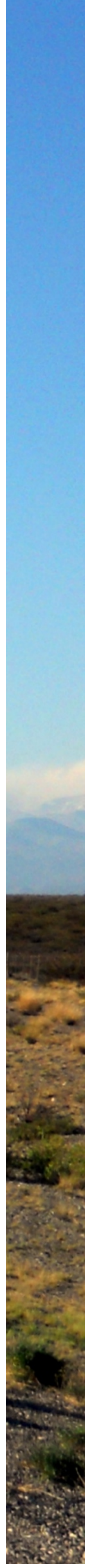
Institutes

Argentina*, Brazil, Chile, Czech Republic, Germany*, Italy, Mexico, Peru, Portugal, South Korea, United Kingdom, United States*

Supporting scientists

Australia, Bolivia, Costa Rica, France, Japan, Poland, Slovenia, Spain, Switzerland, Turkey

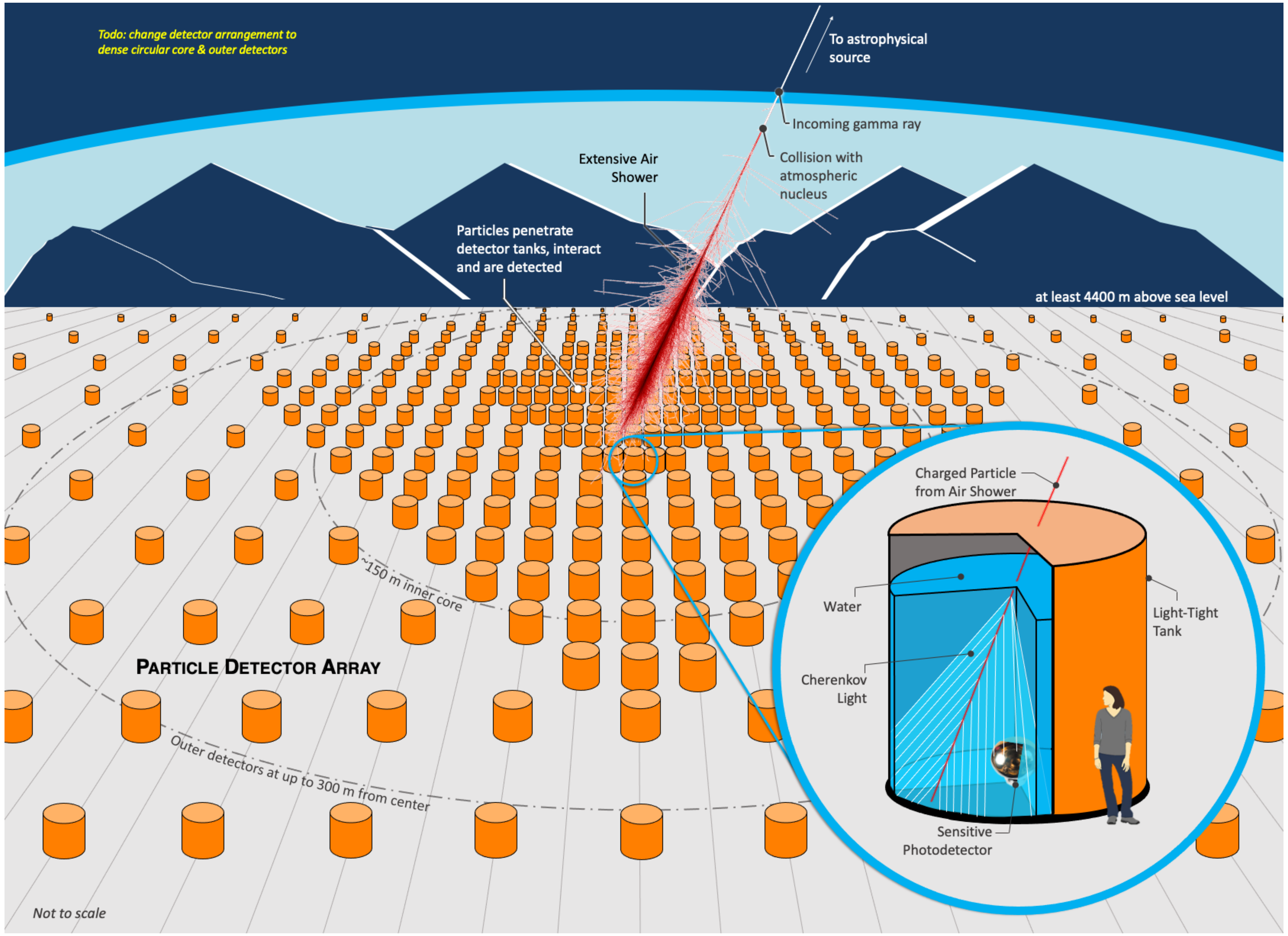
**also supporting scientists*

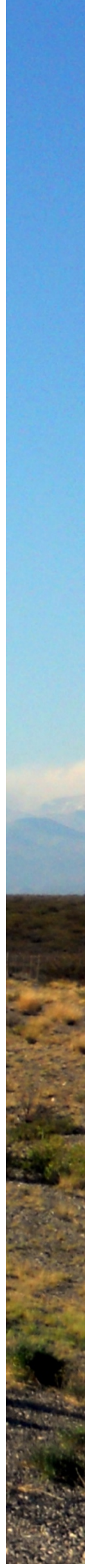


Goal: to cover the high energy Southern gamma-ray sky from ~100 GeV to ~10 PeV

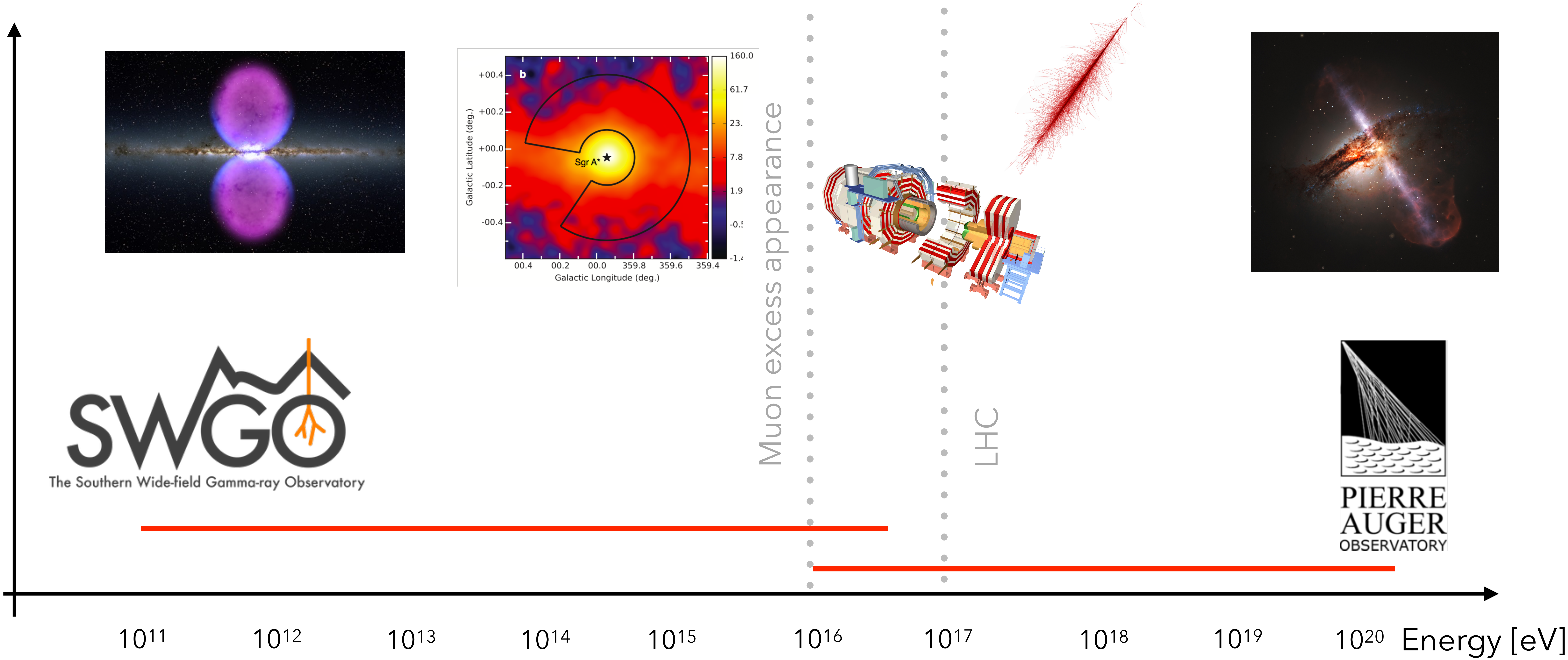
The challenge…

- To design an experiment able to fulfil the following requirements:
  - **Muon tagging**/counting capability
  - Lower energies
    - to be placed at **high altitude** (~5000 m a.s.l.)
    - **Compact array**
  - Higher energies
    - **Large area** (~ few km^2)



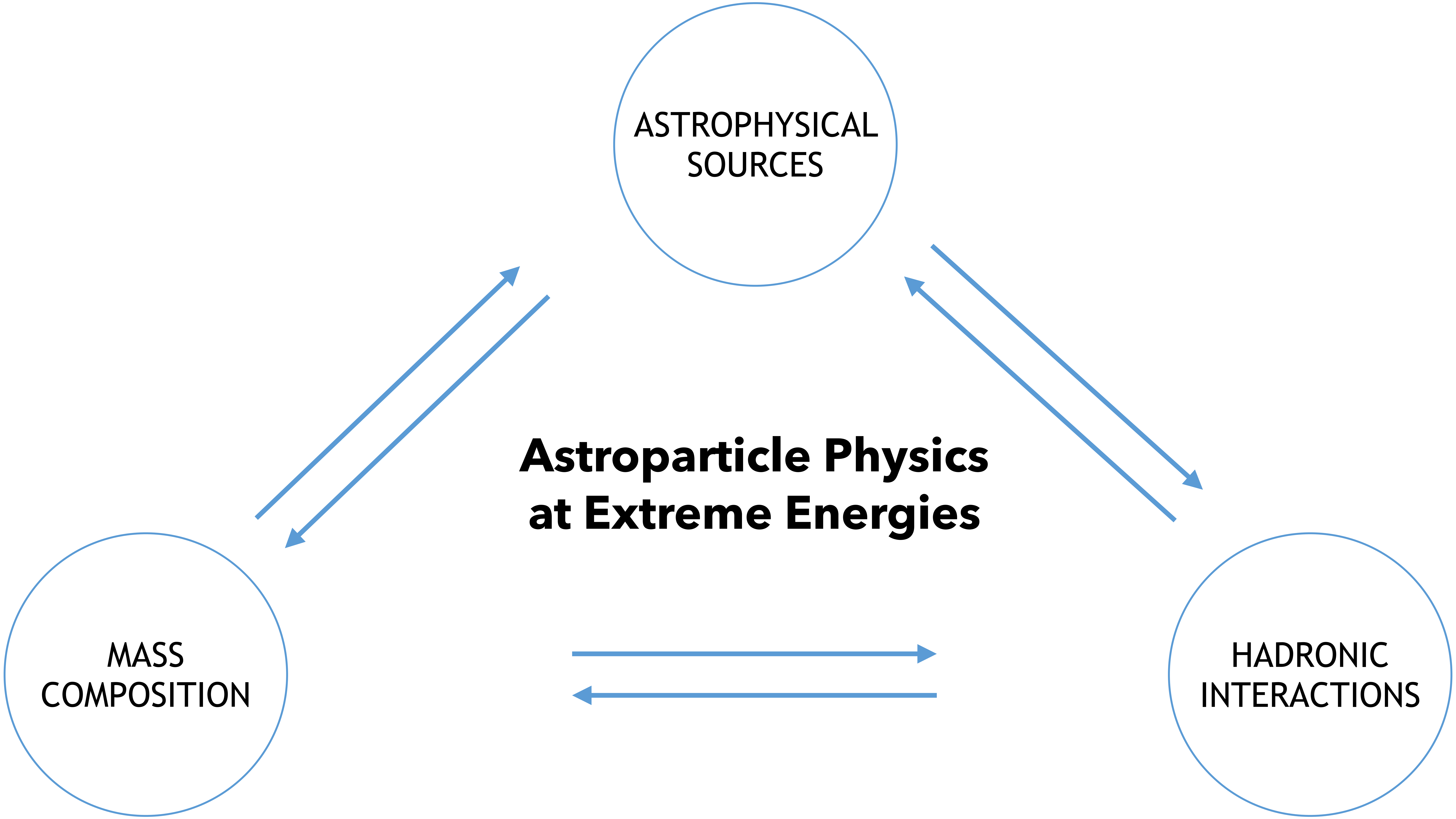


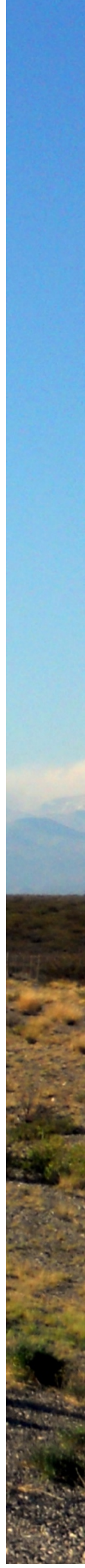
Summary (I)



Sgr A*
Galactic Latitude (deg.)
Galactic Longitude (deg.)
Muon excess appearance
LHC
The Southern Wide-field Gamma-ray Observatory
PIERRE AUGER OBSERVATORY
10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} Energy [eV]

Summary (II)


ASTROPHYSICAL SOURCES
Astroparticle Physics at Extreme Energies
MASS COMPOSITION
HADRONIC INTERACTIONS



Acknowledgements

FCT
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REPÚBLICA
PORTUGUESA

LIP

TÉCNICO
LISBOA