Astroparticle Physics

Messengers of the Universe

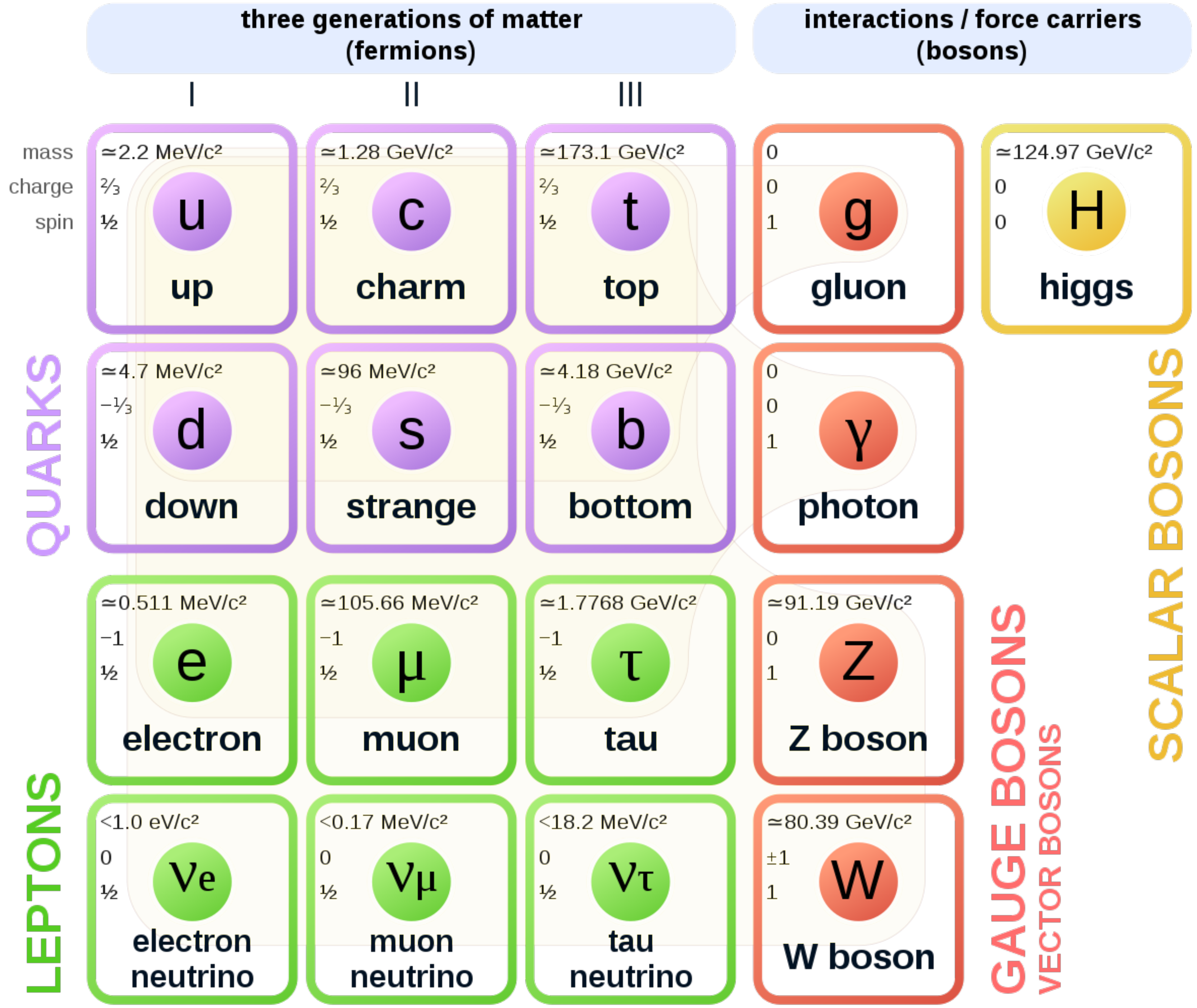
Ruben Conceição

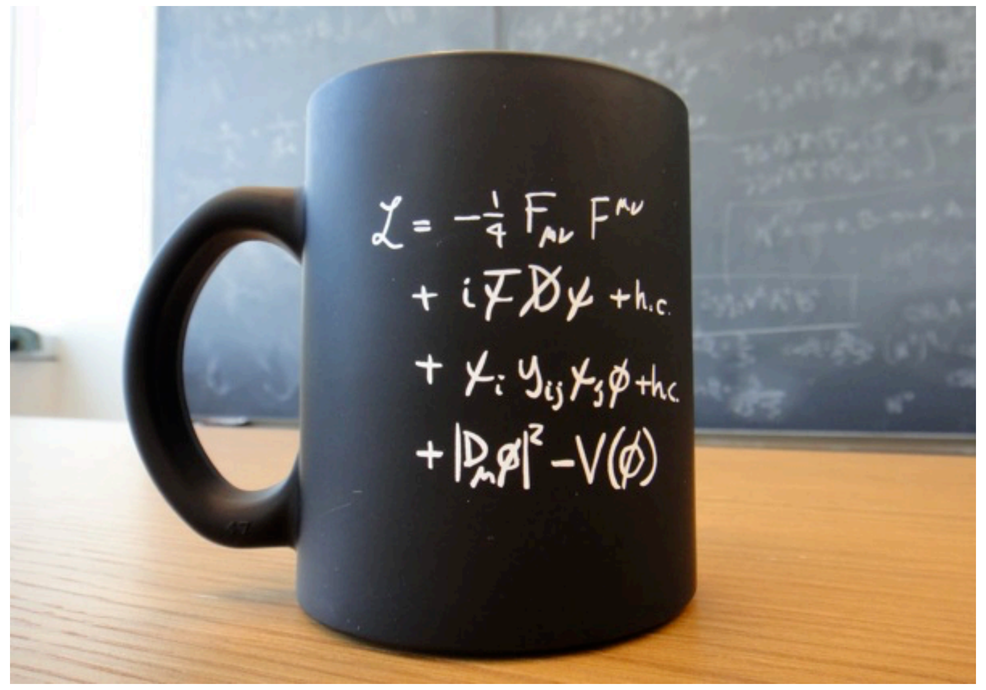
LIP

TÉCNICO LISBOA

LIP/CFTP mini-school, Oeiras, February 5th 2024

The Particle Physics Standard Model





Extremely successful describing the interactions between elementary particles

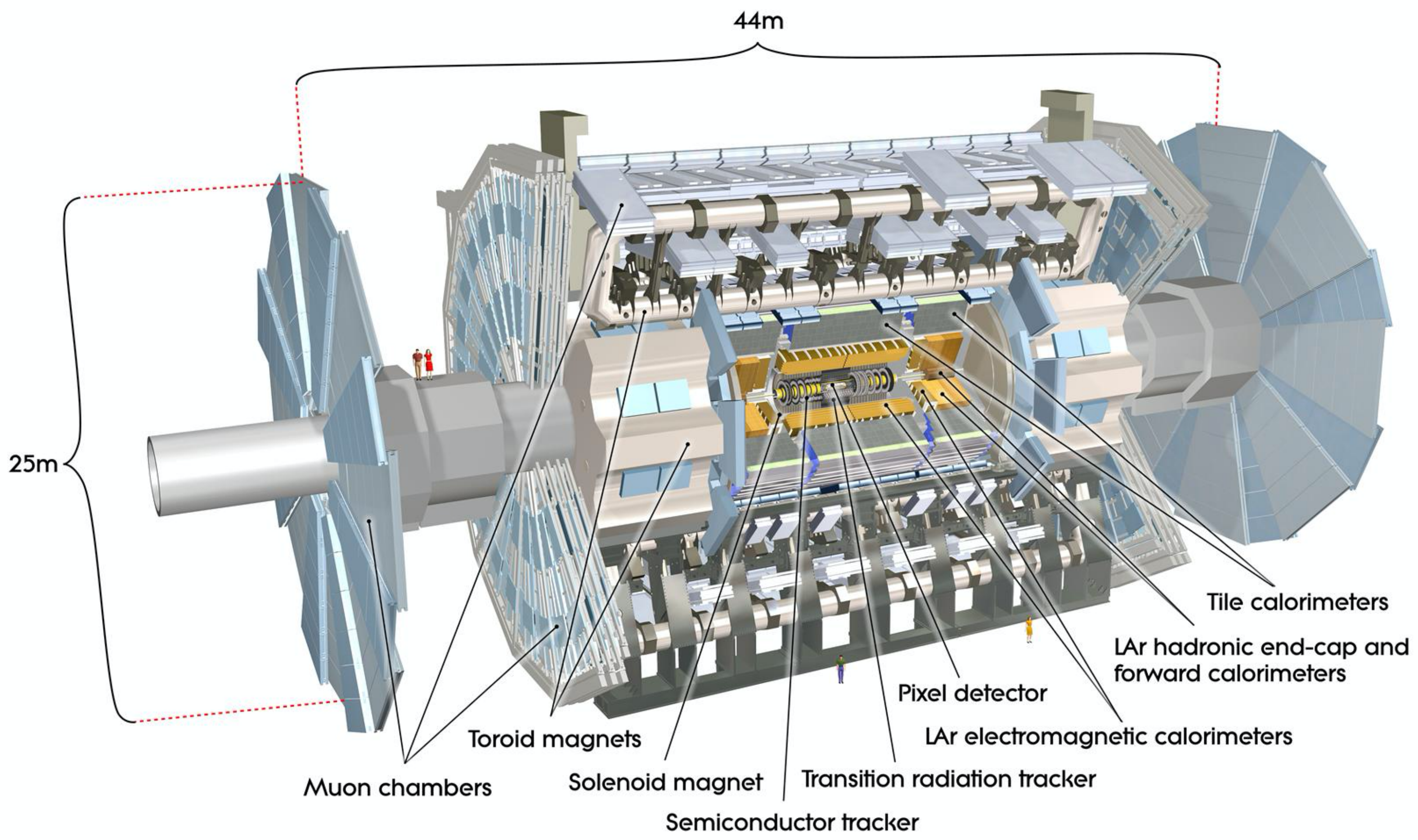
but

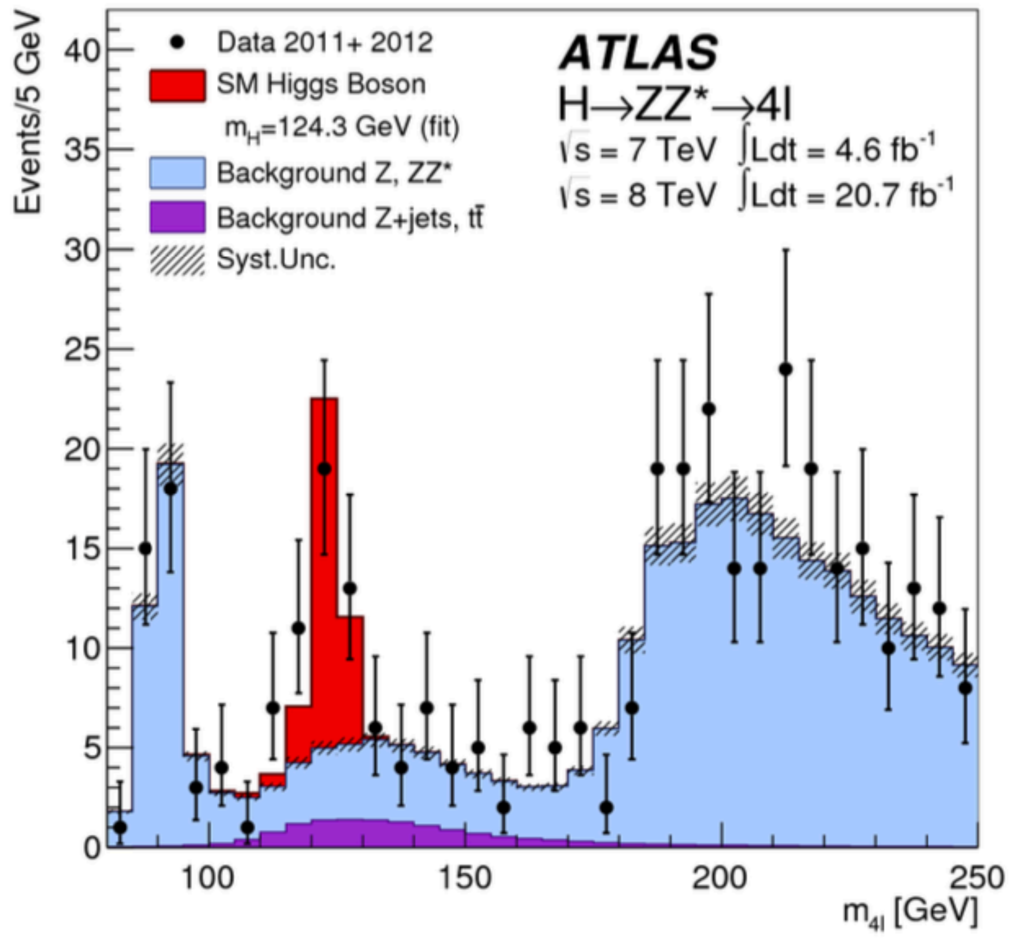
We know it's incomplete!

Dark Matter / Dark Energy

Gravity vs Quantum Mechanics

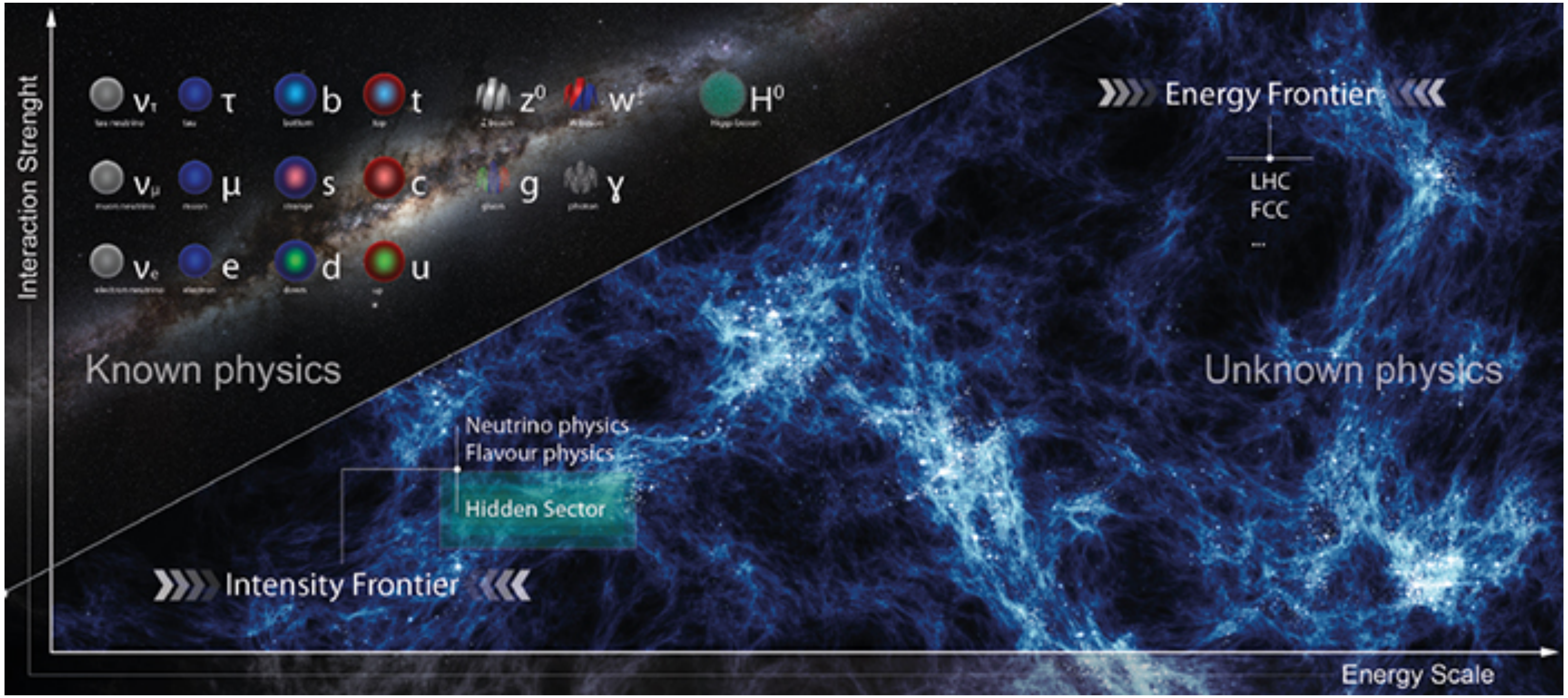
Human-made Accelerators





- How to perform tests to our understanding of fundamental particle physics?
  - Accelerate and collide particles
  - **Measurements in the LAB (controlled conditions)**
  - LHC (Higgs) / HL-LHC / FCC-ee / FCC-hh (up to $\sqrt{s} = 100\,\mathrm{TeV}$; starting 2065)

Energy vs Intensity Frontier

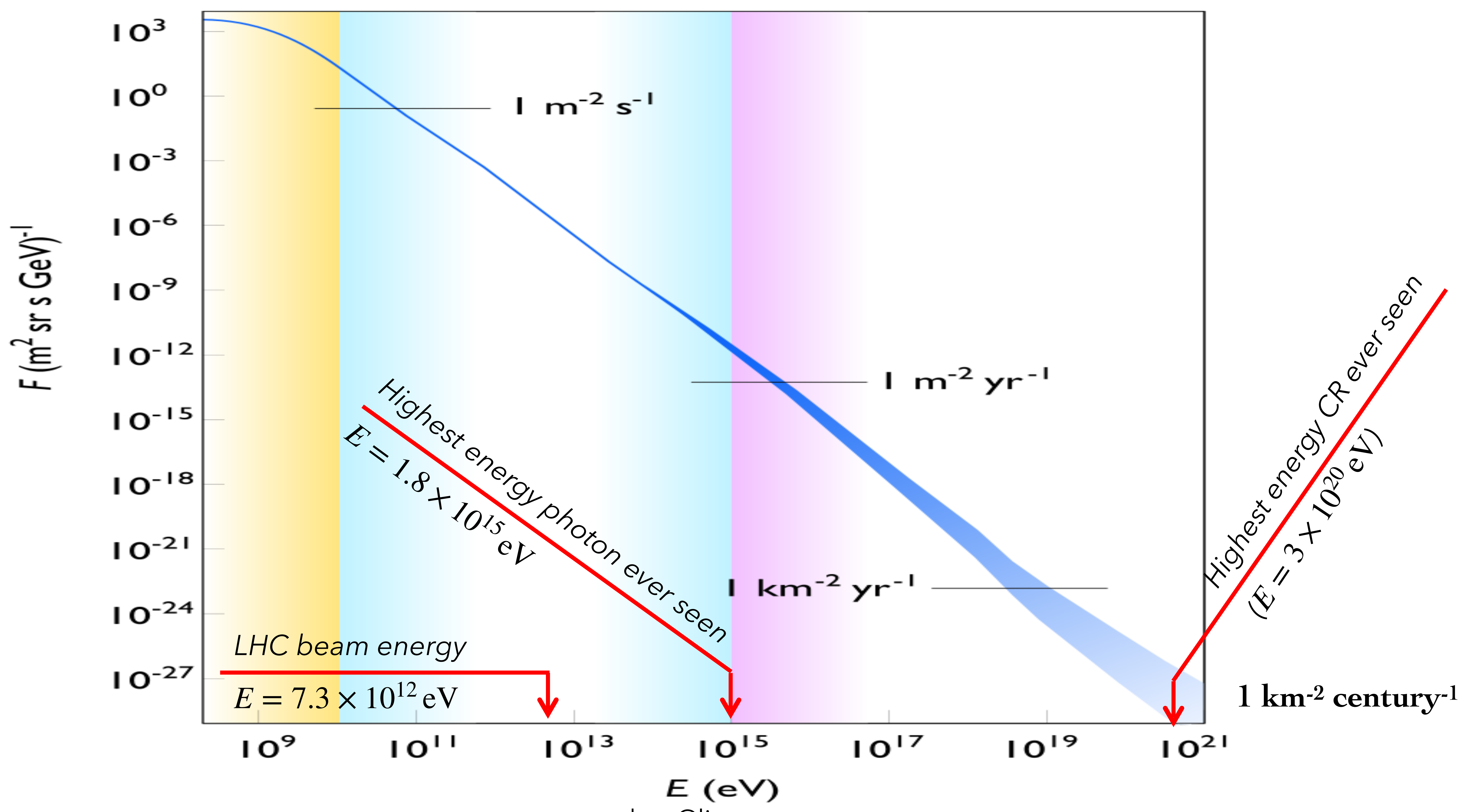


What is our target energy? Are we exploring the optimal energy range?

What is the maximum energy we could aspire to reach?

Ask the Universe

Cosmic ray energy spectrum



How to build an accelerator with $E_b = 10^{20}\,\mathrm{eV}$?

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets

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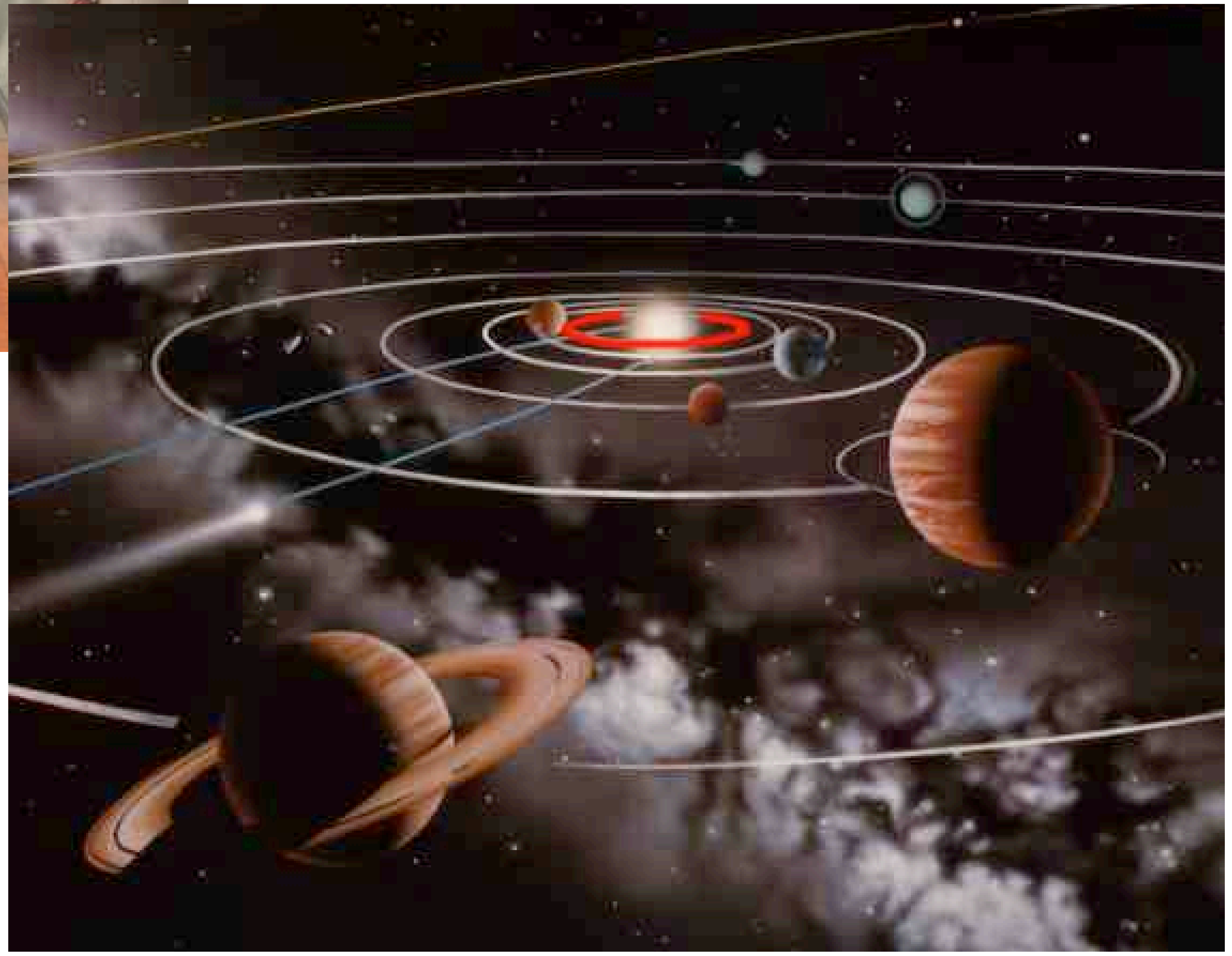

Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology

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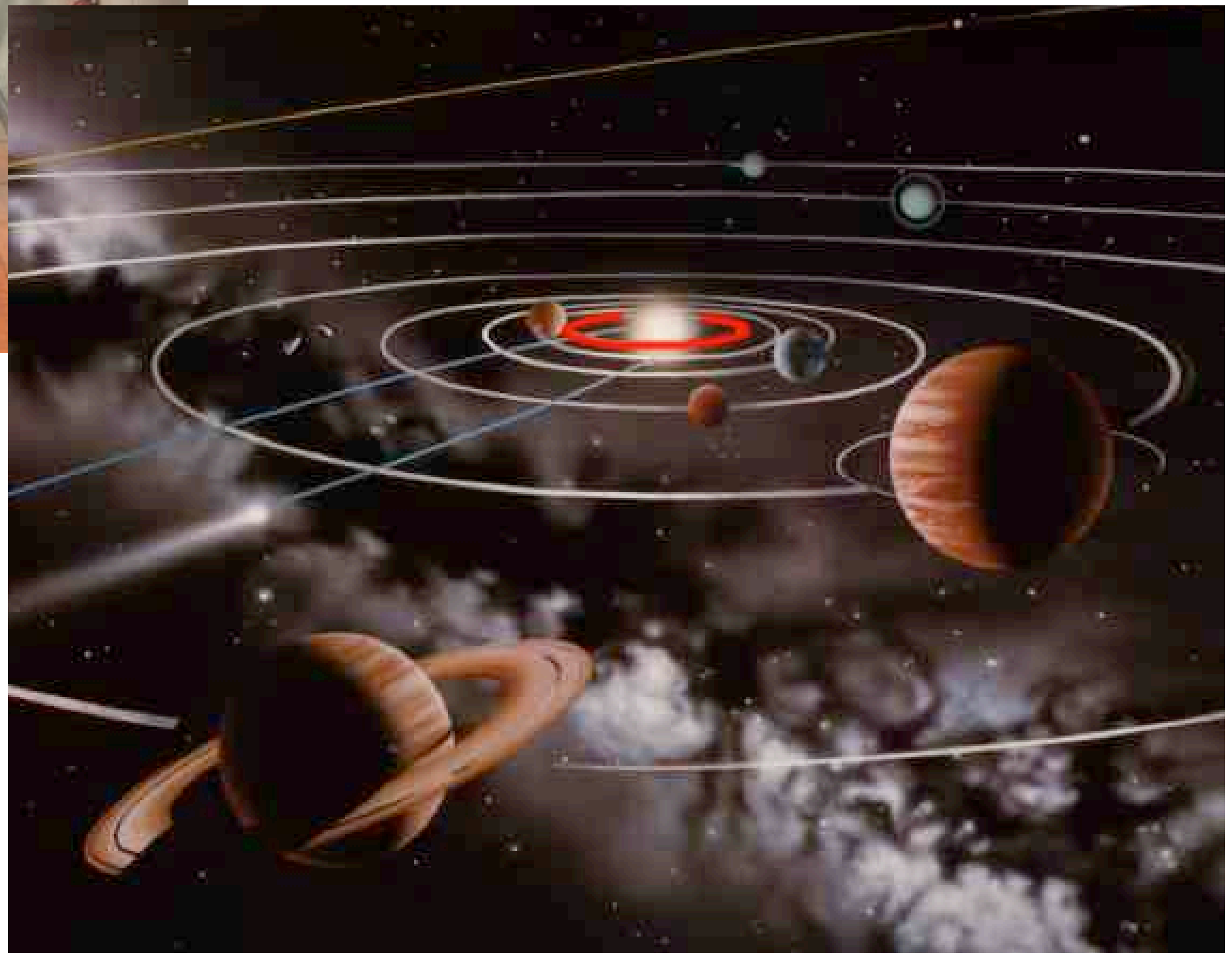
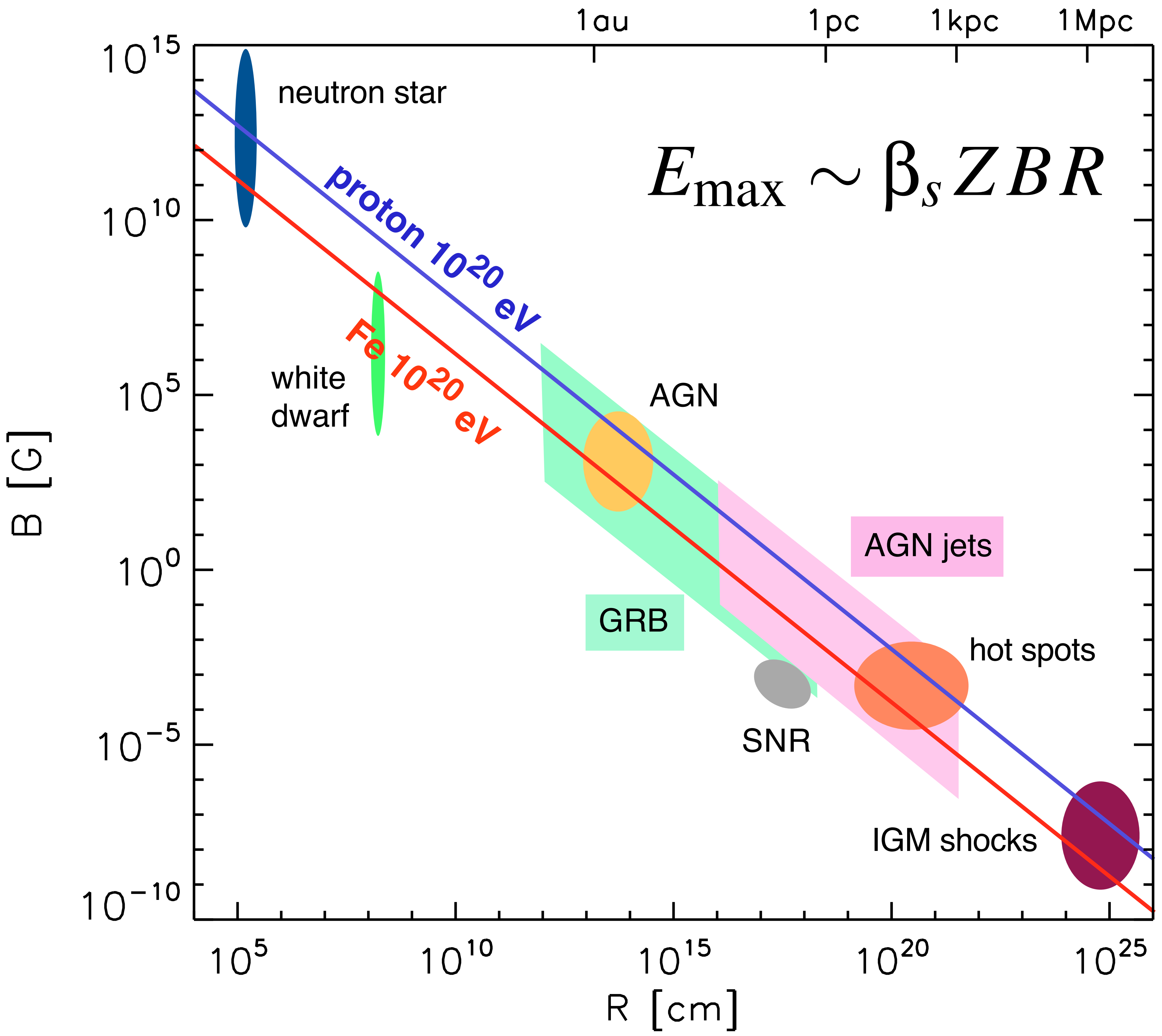
How to build an accelerator with $E_b = 10^{20}\,\mathrm{eV}$?

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets



Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology

Hillas plot (1984)



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Why do we care?

The Planck scale

Gravity meets Quantum Mechanics

Schwarzschild radius ~ Compton wavelength

$$R_S \approx \lambda_C \rightarrow \frac{2G_N m_P}{c^2} \approx \frac{h}{mc}$$

$$m_P \approx \sqrt{\frac{\hbar c}{G_N}}$$

$$l_P \approx \frac{h}{m_P c} \approx \sqrt{\frac{\hbar G_N}{c^3}}$$

$$t_P \approx \frac{l_P}{c} \approx \sqrt{\frac{\hbar G_N}{c^5}}$$

$$m_P \sim 3.86 \times 10^{-8}\,\mathrm{kg}$$

$$\boxed{\sim 2.16 \times 10^{19}\,\mathrm{GeV/c^2}}$$

$$l_P \sim 1.6 \times 10^{-35}\,\mathrm{m}$$

$$t_P \sim 5.4 \times 10^{-44}\,\mathrm{s}$$

m_P can be derived using dimensional analysis

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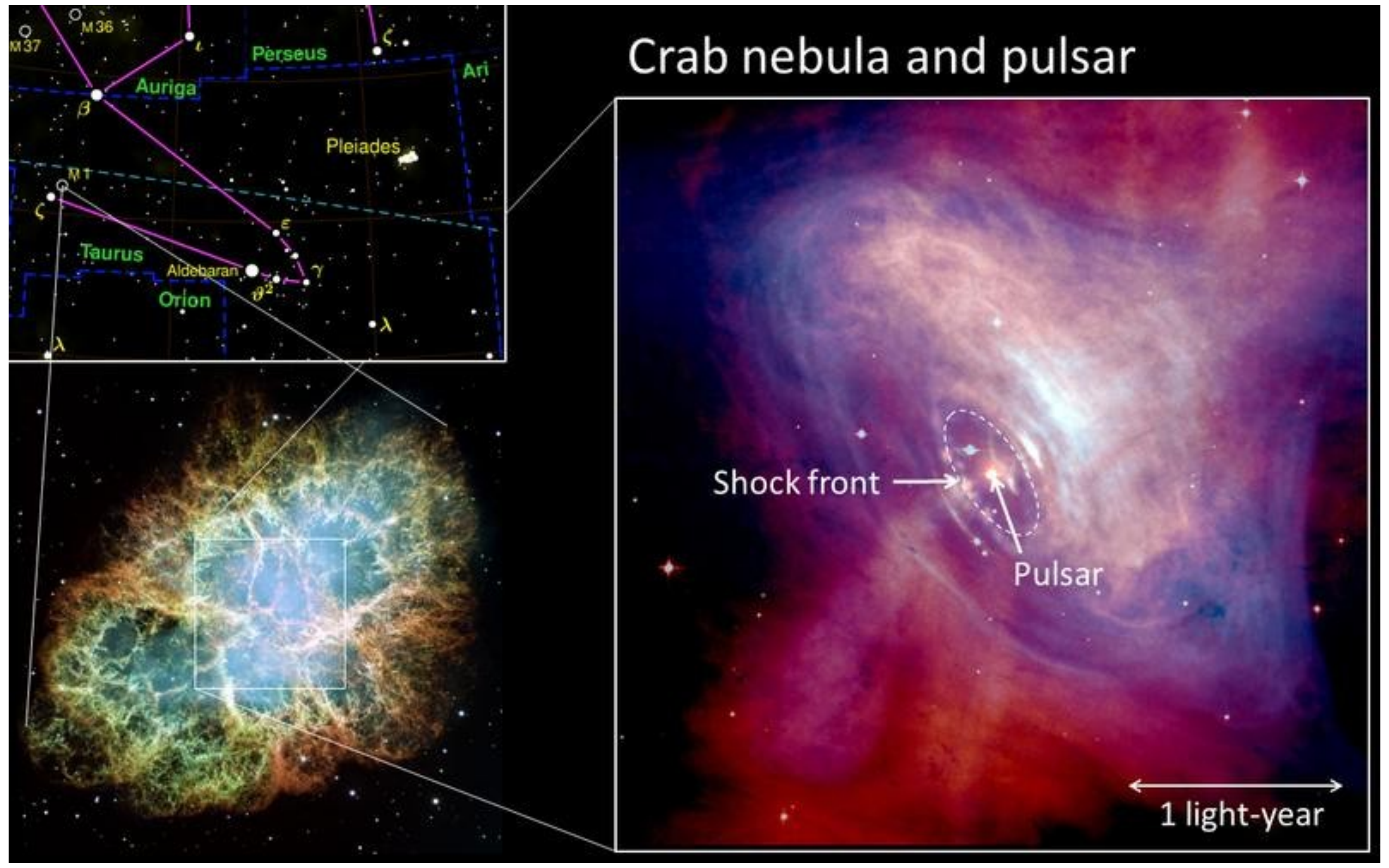
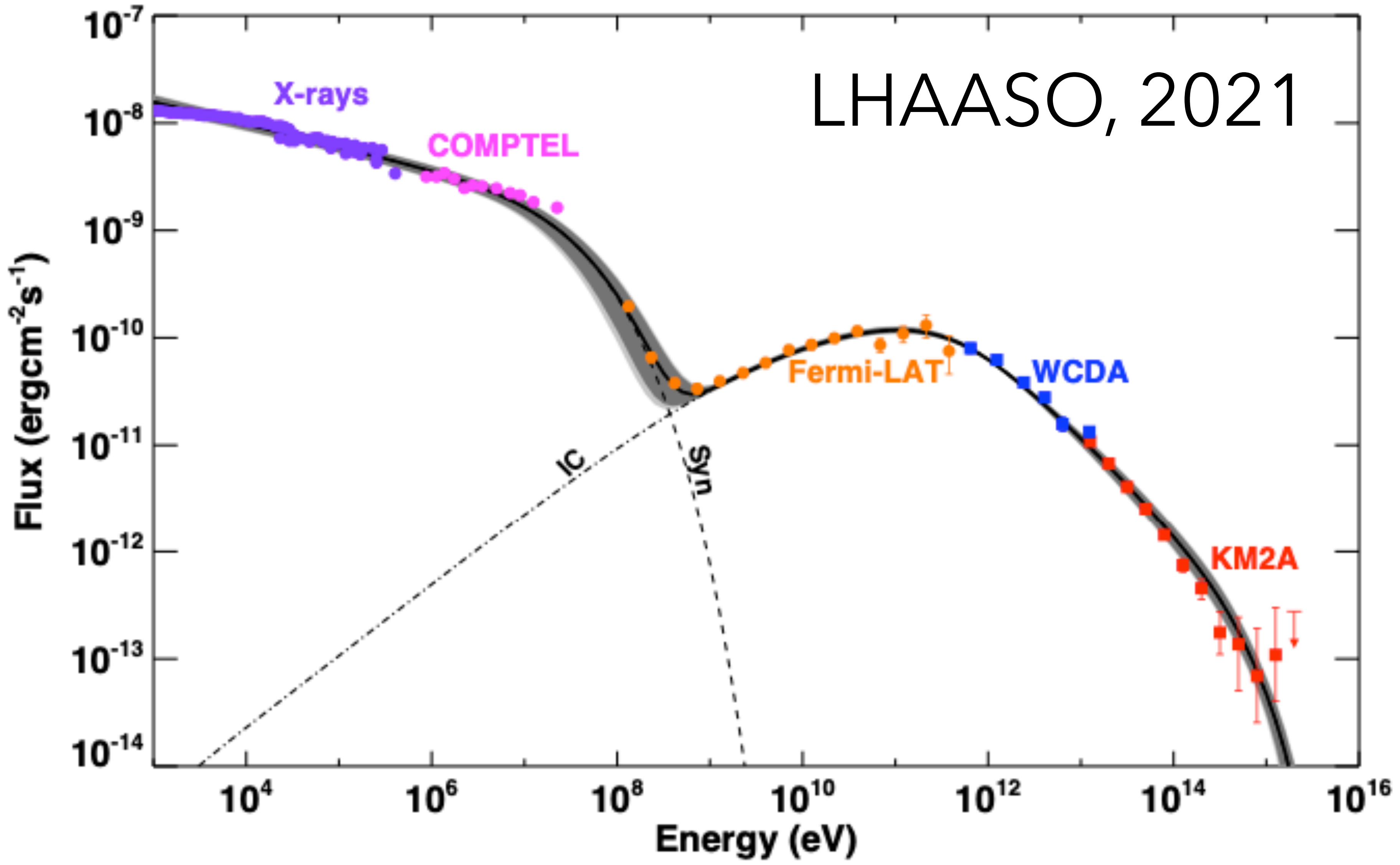
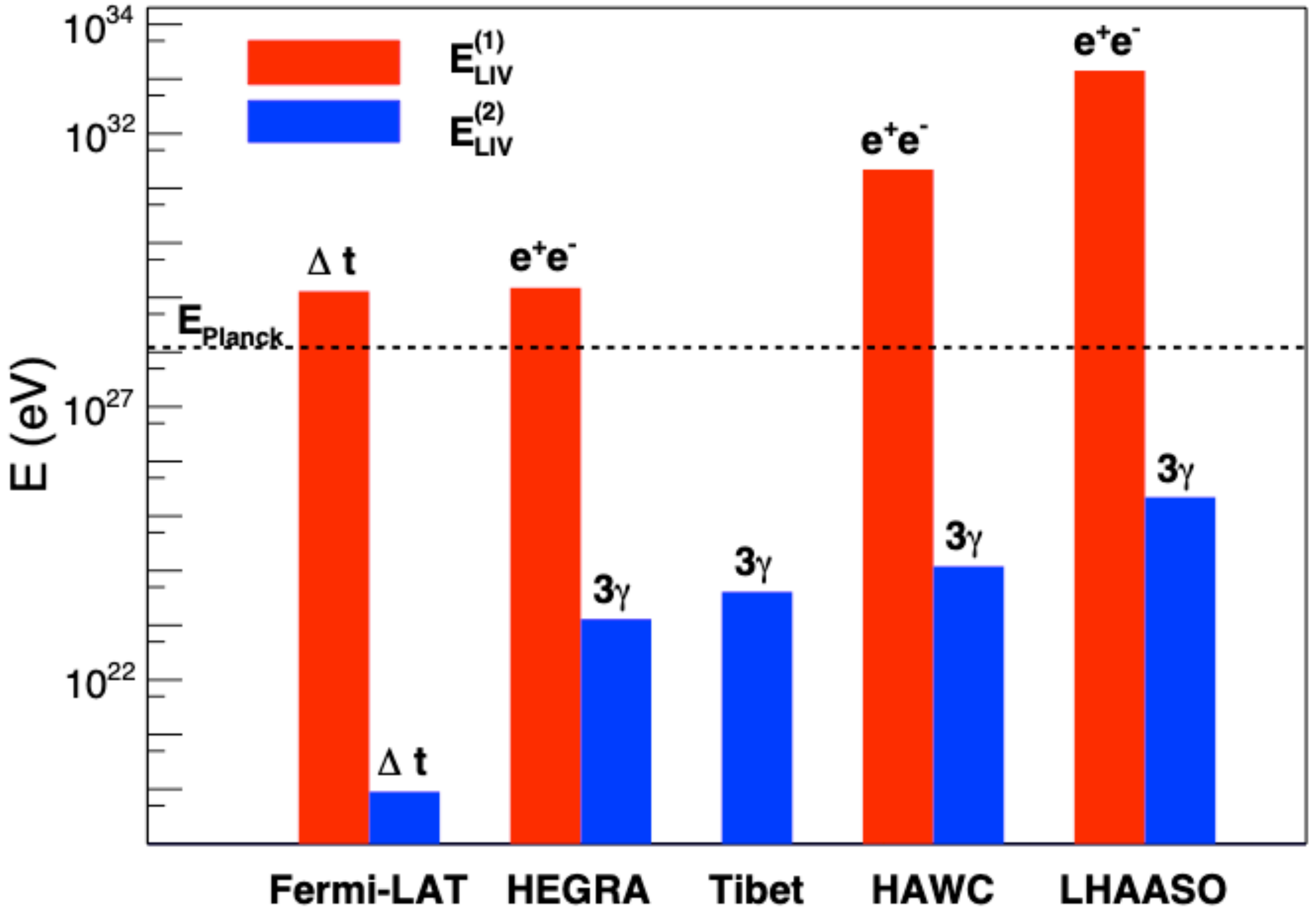
LIV tests with UHE photons





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



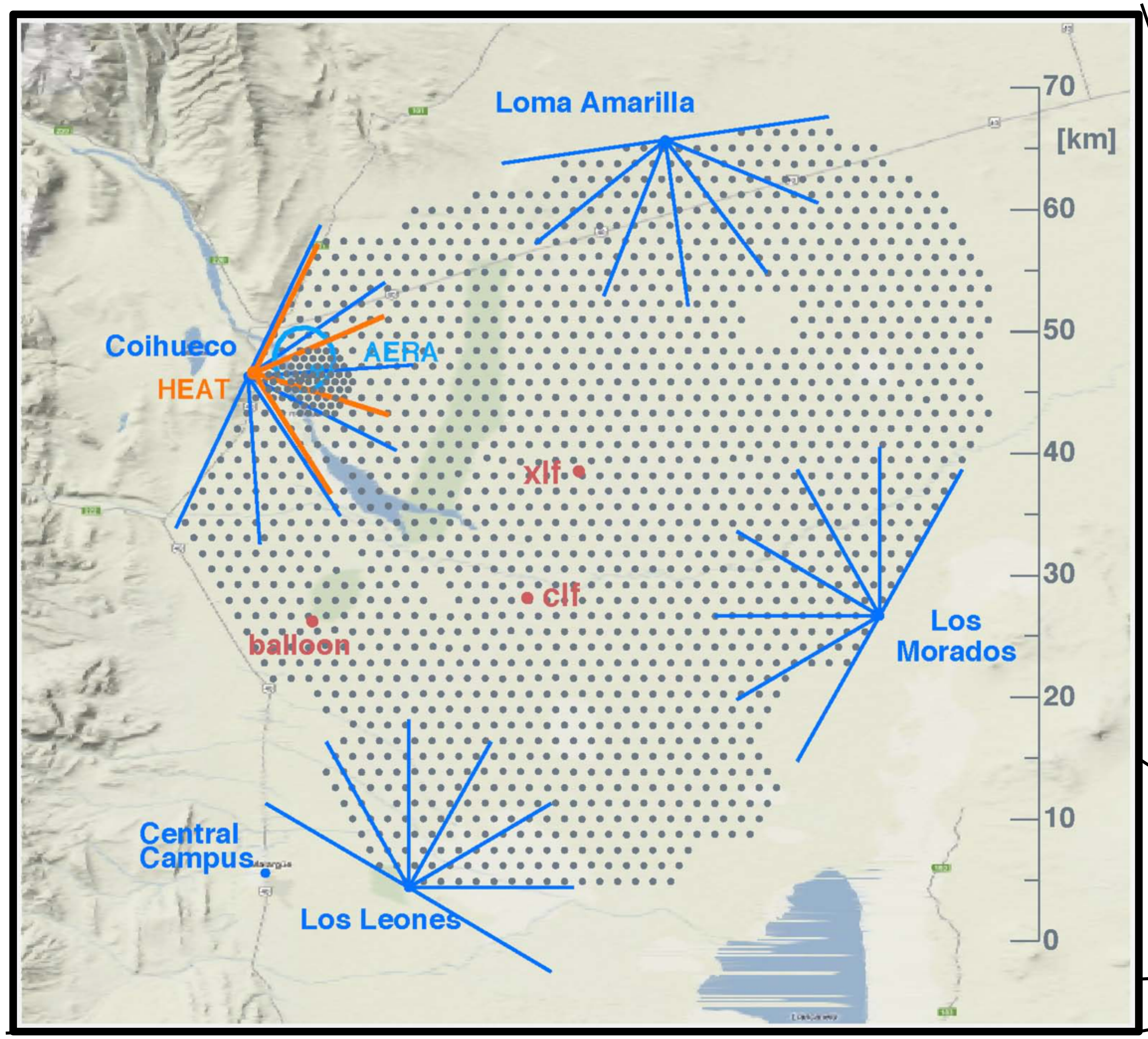
Lorentz invariance Violation (LIV) being probed at energies above the Planck scale

How do we measure Astroparticles?

Pierre Auger Observatory

UHECR: $E > 10^{18}\,\mathrm{eV}$ – $\Phi \sim 1\,\mathrm{km}^{-2}\,\mathrm{sec}^{-1}$

Pierre Auger Observatory



Area: 3000 km²

Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

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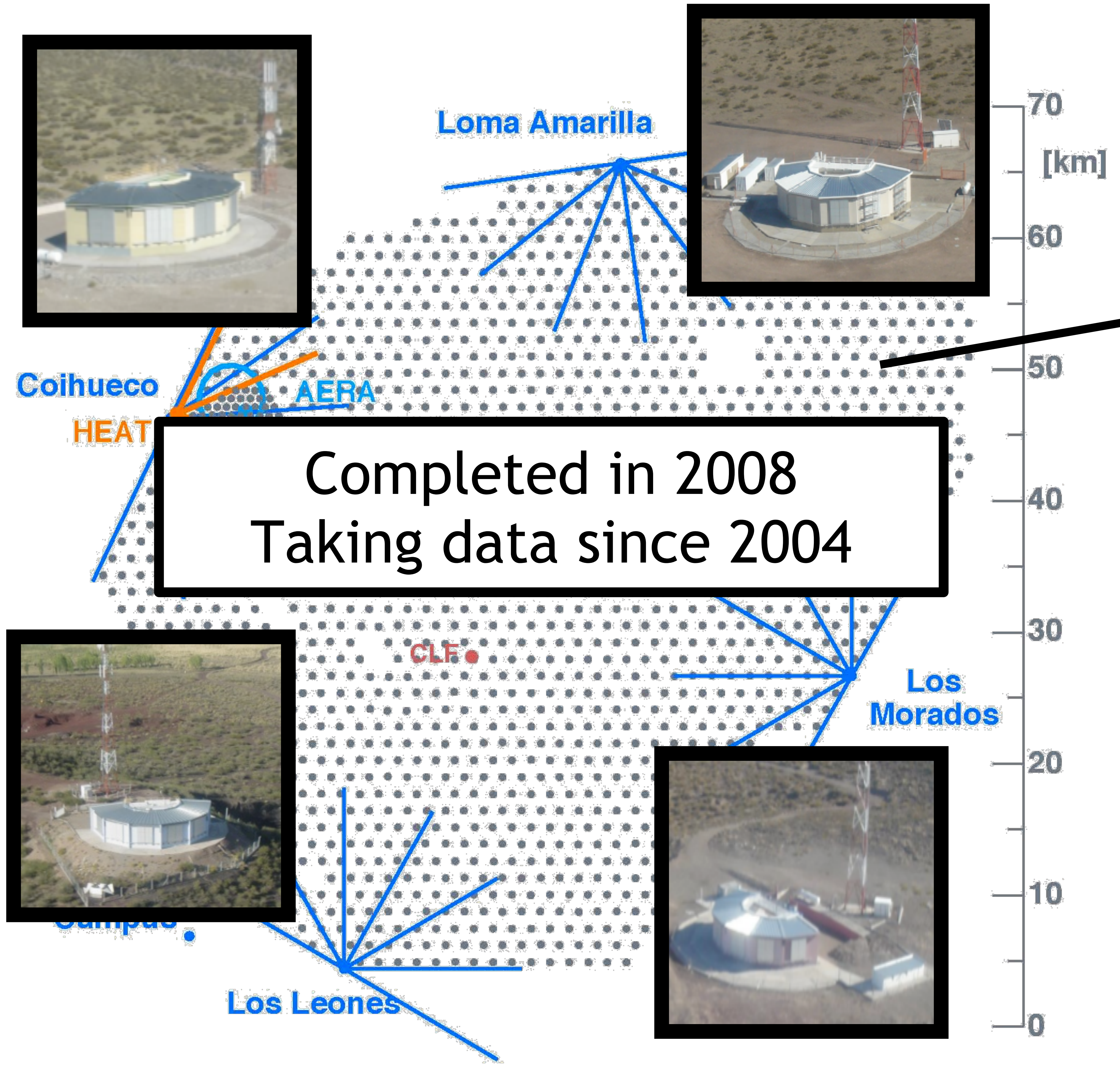
Pierre Auger Observatory



Completed in 2008
Taking data since 2004

~ 60 km

- ~ 1600 Surface detectors (SD)
- In a 1.5 km hexagonal grid
- 3000 km²

- 4 Fluorescence Detectors (FD)
- 6 x 4 + 3 Fluorescence Telescopes

- + low energy extensions

Built to detect and study the extremely rare UHECR

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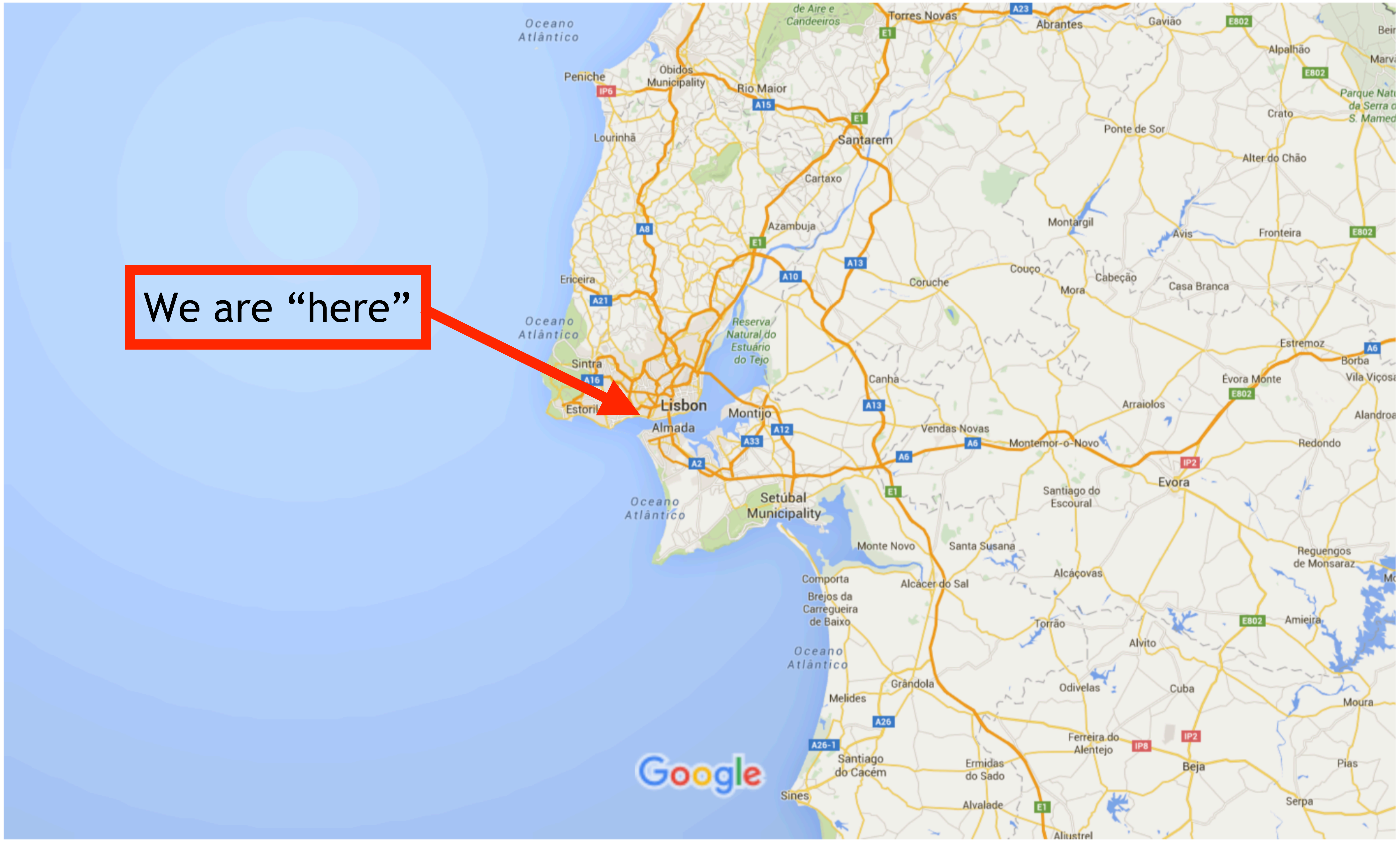
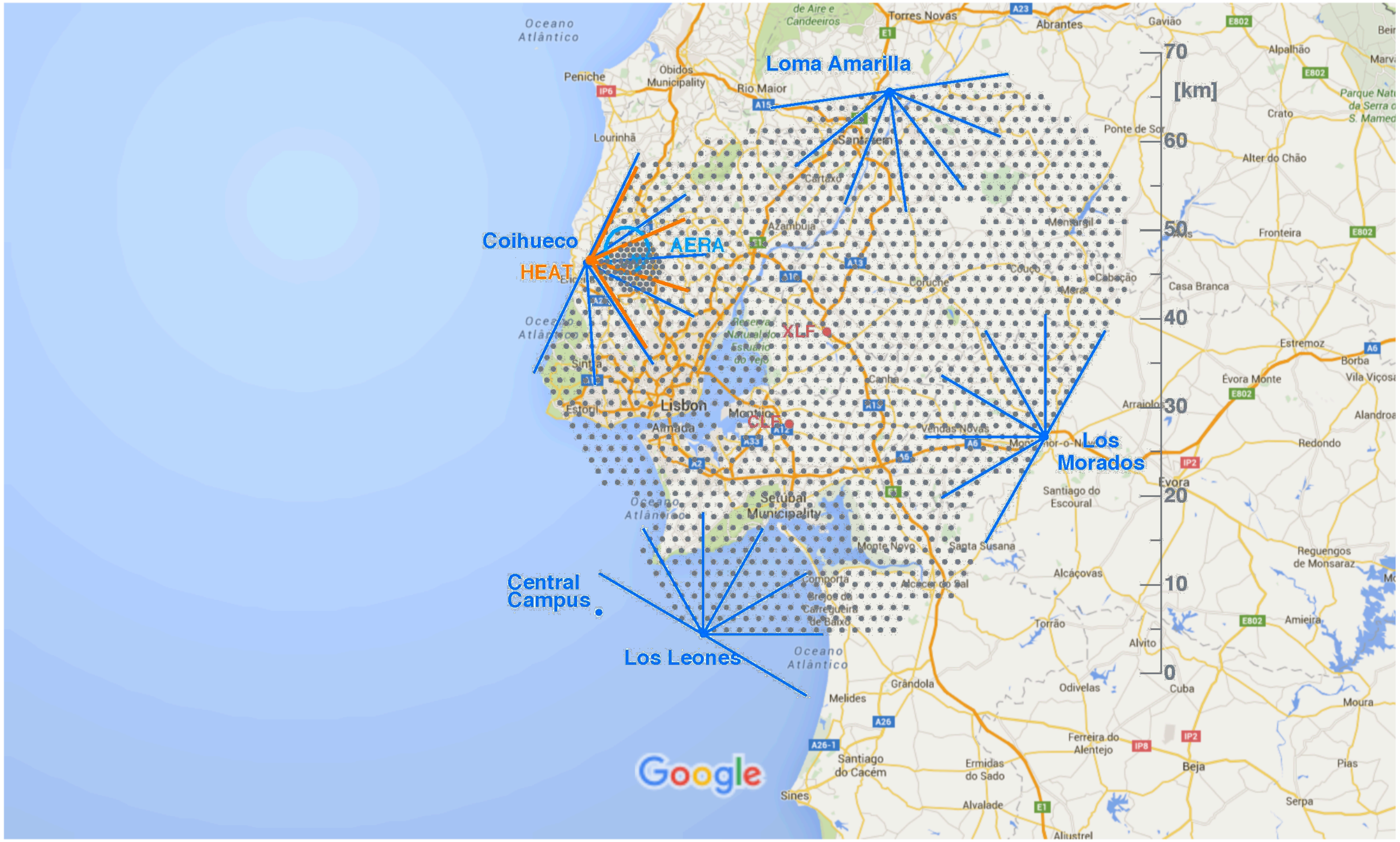
What's the size of the Observatory?

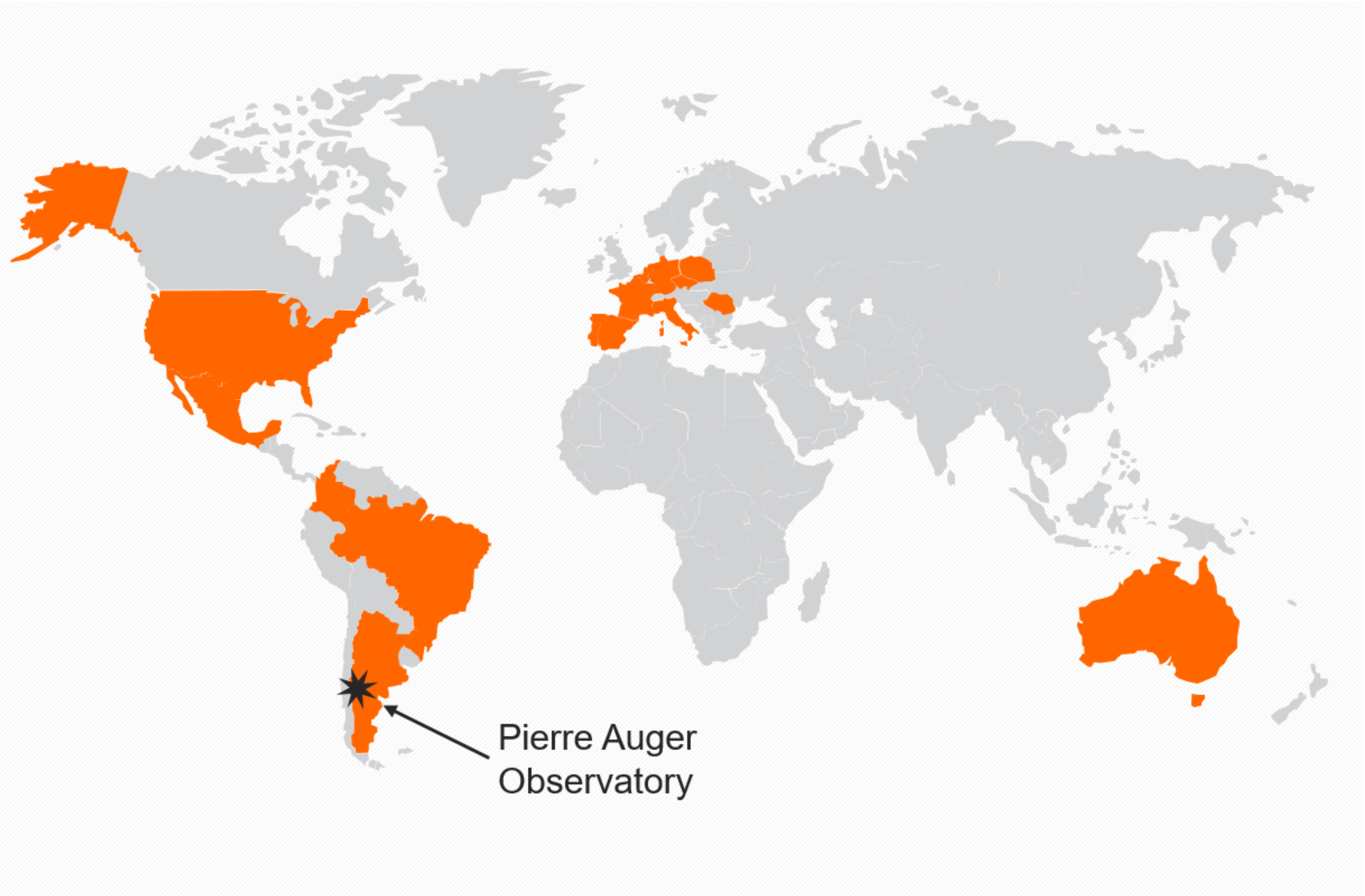


Really big!!


Loma Amarilla
Coihueco
HEAT
AERA
XLF
CLF
Los Morados
Central Campus
Los Leones
[km]
70
60
50
40
30
20
10
0
Lisbon
Google

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

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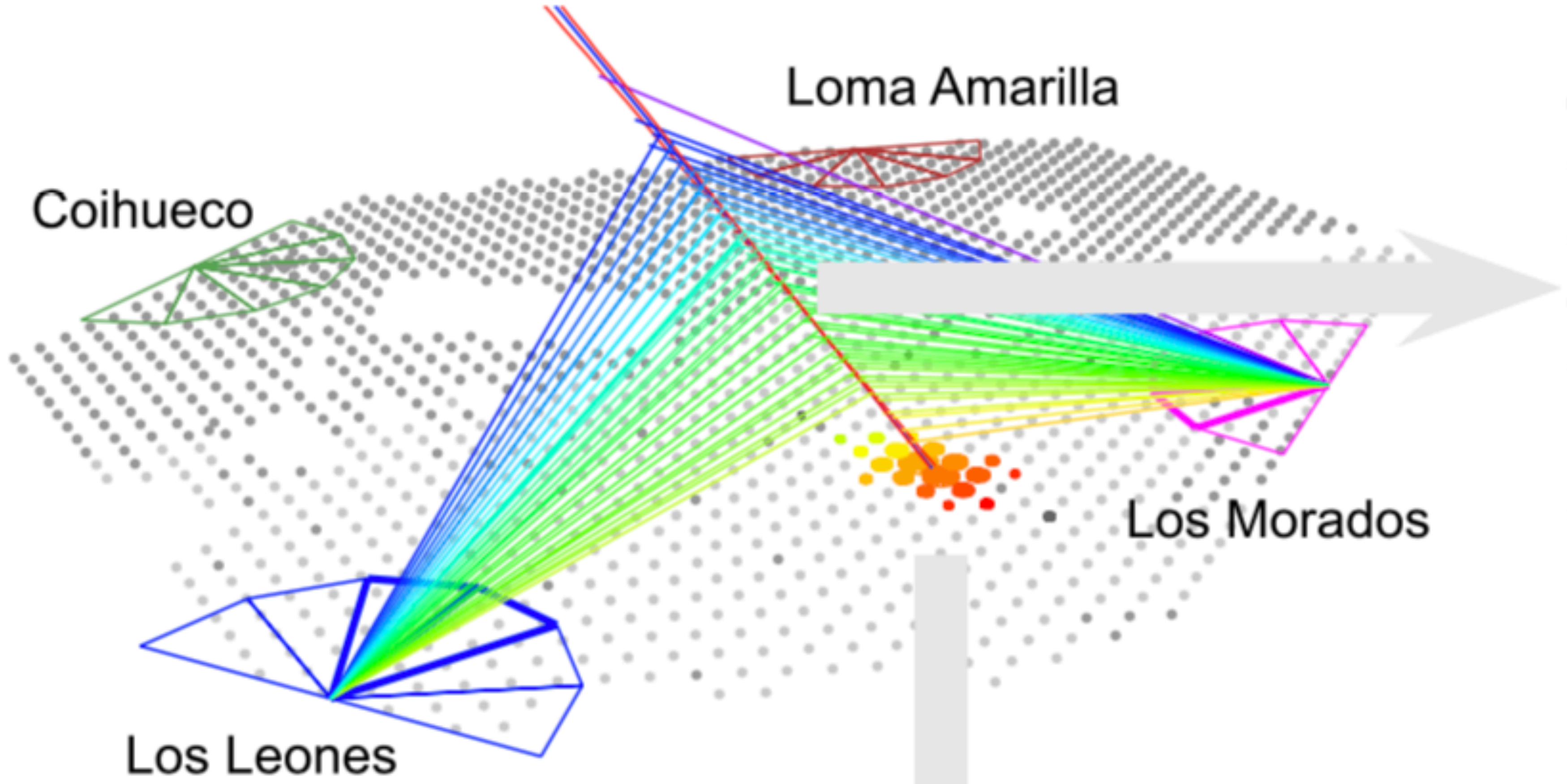
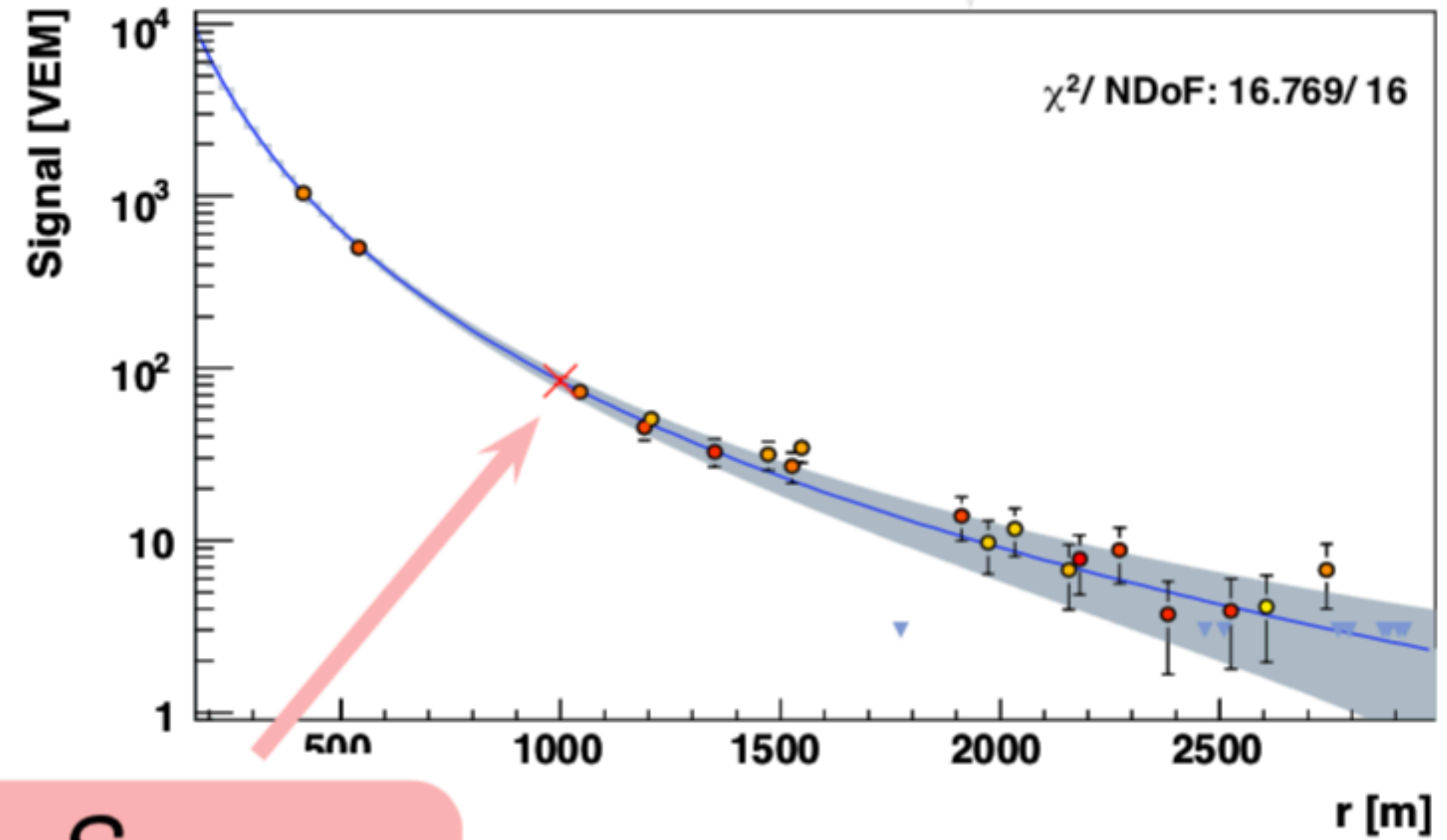
Surface Detectors (SD)

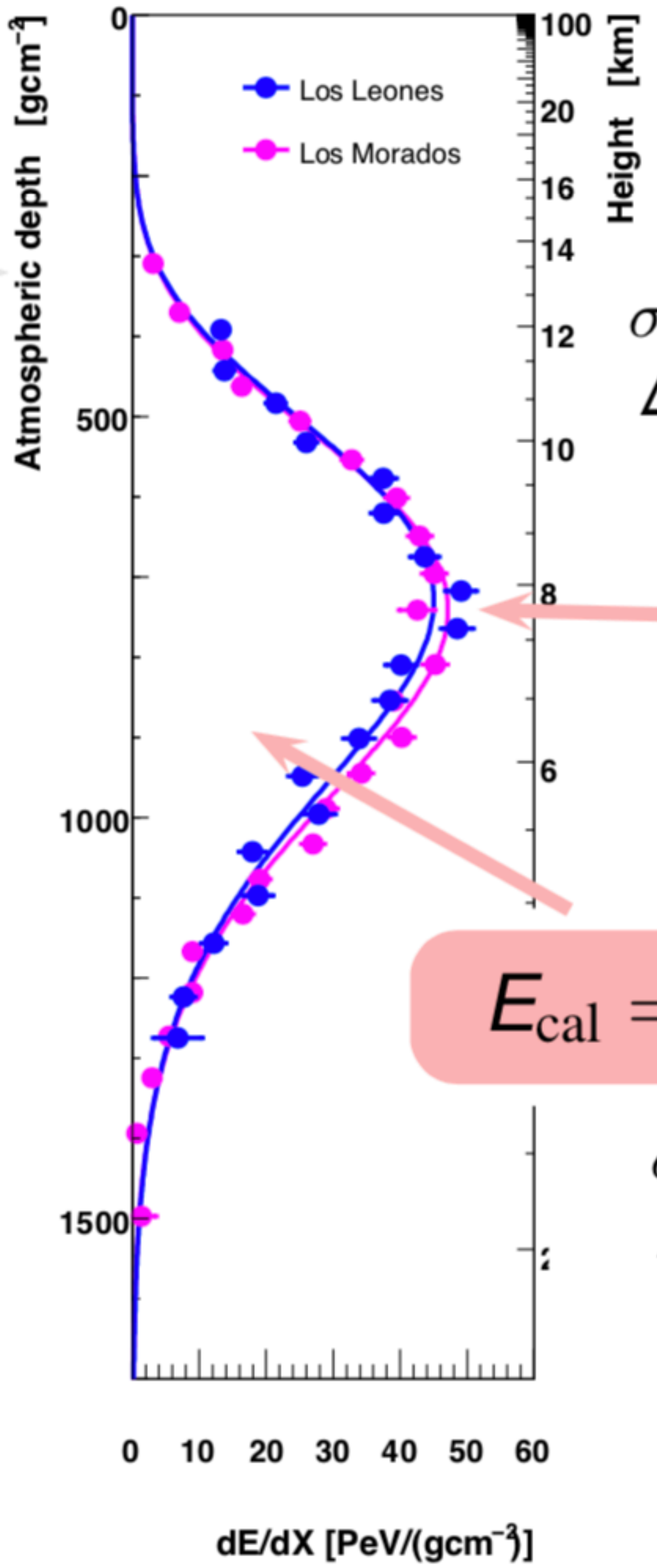
Hybrid Technique (FD + SD)





S_{1000}

$E_{\rm surface} = f(S_{1000},\ \theta)$

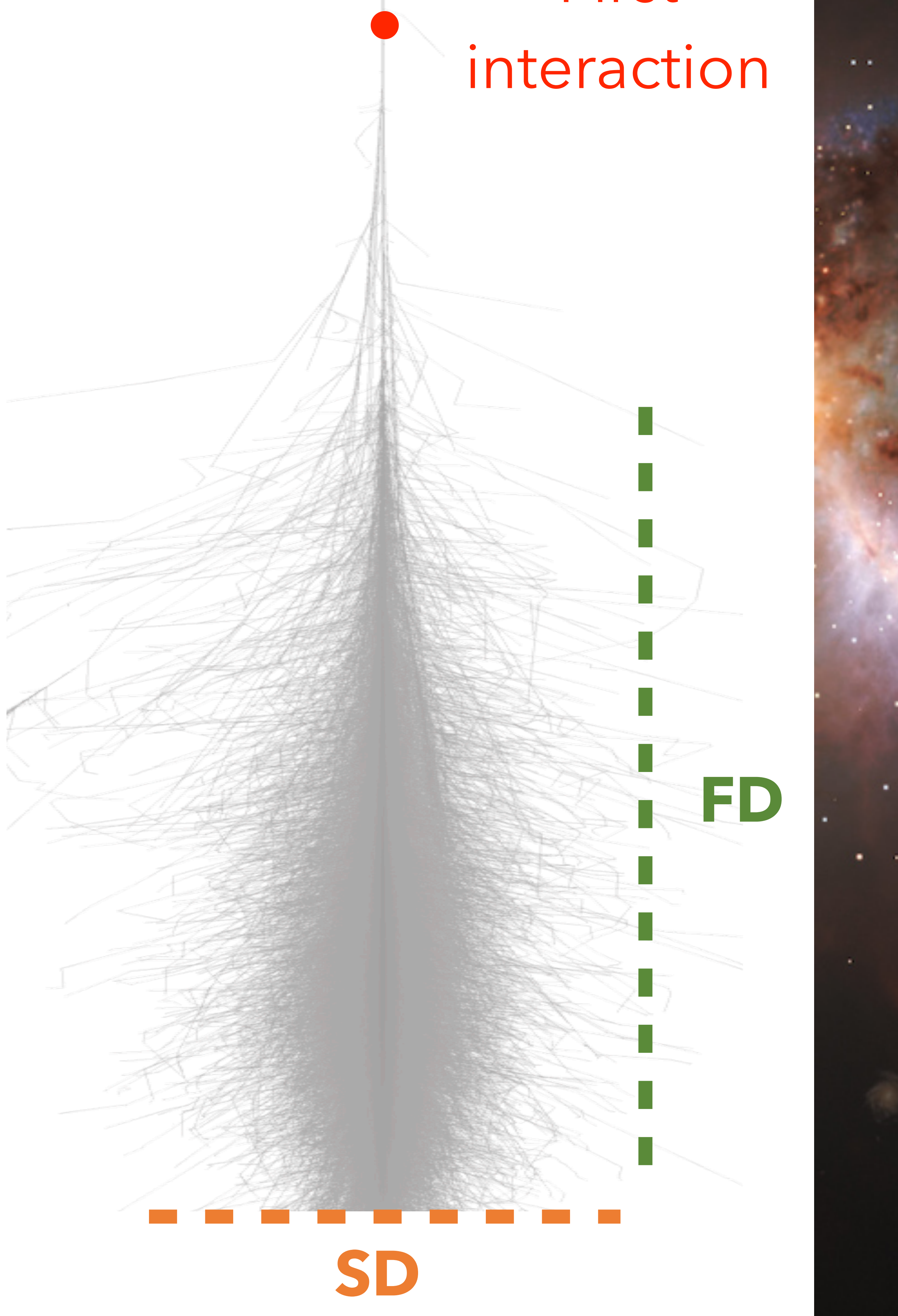


$\sigma X_{\rm max} \leq 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \leq 10\,{\rm g/cm^2}$

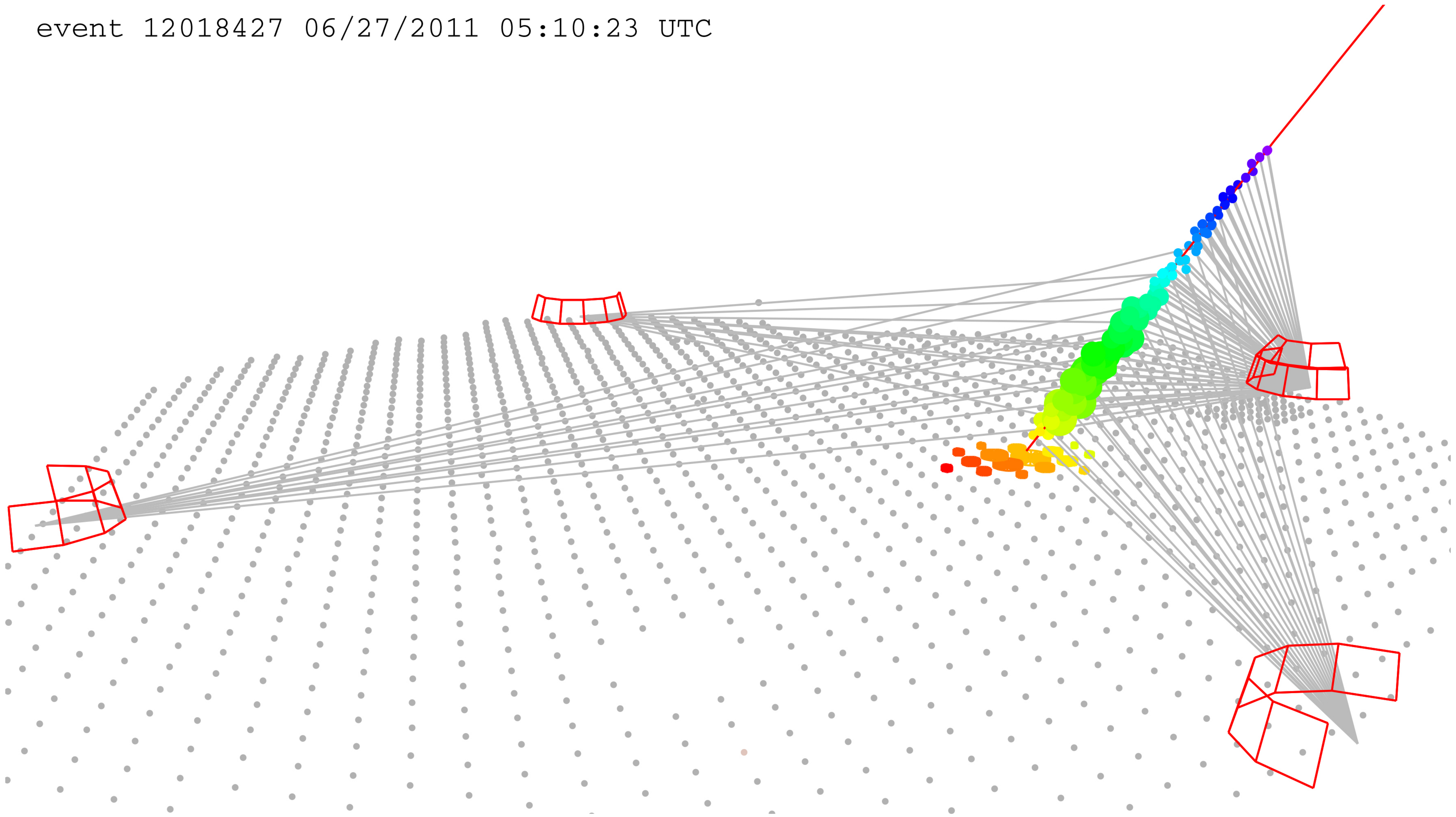
$X_{\rm max}$

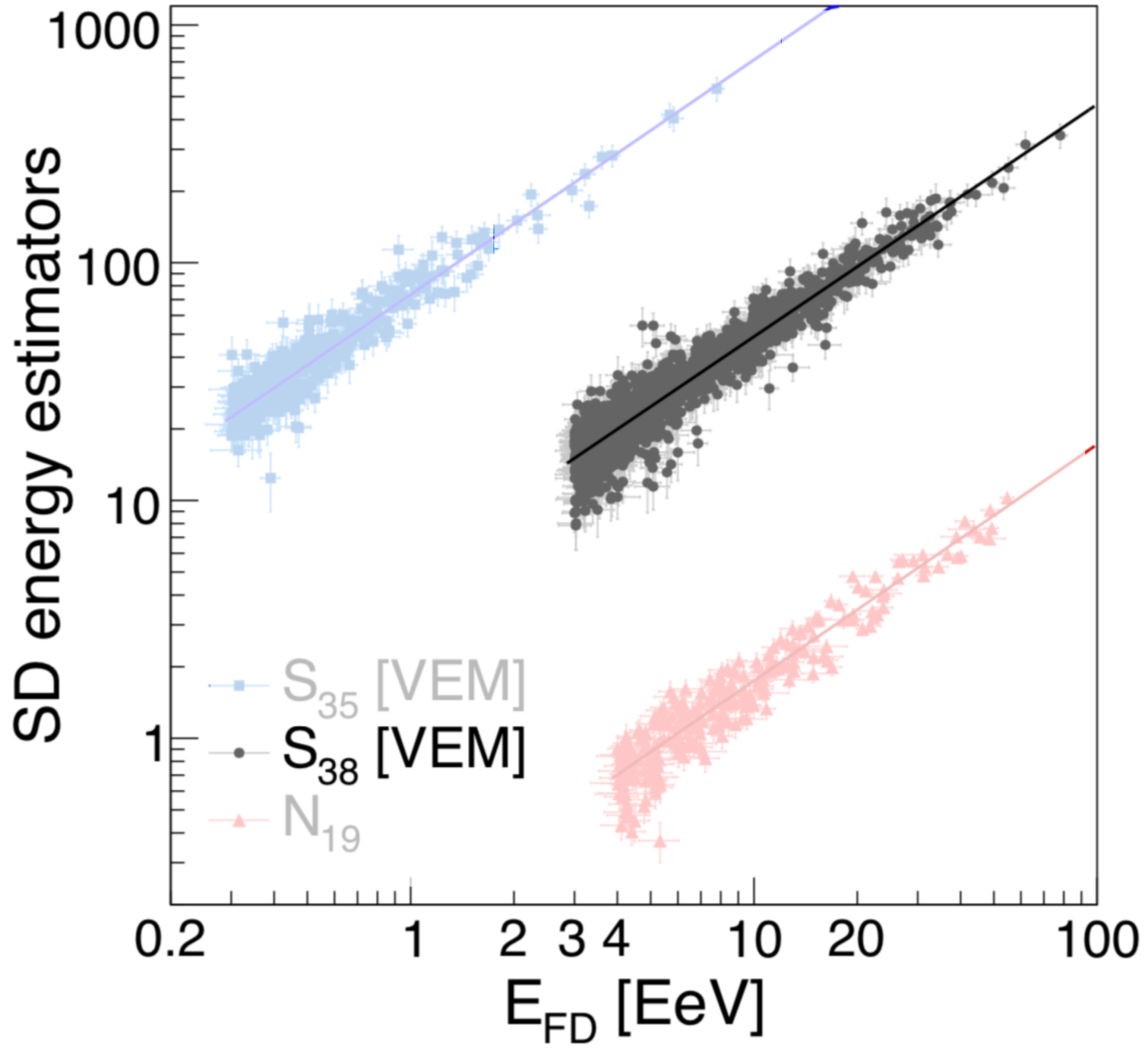
$E_{\rm cal} = \int \frac{{\rm d}E}{{\rm d}X}\,{\rm d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 15\,\%$

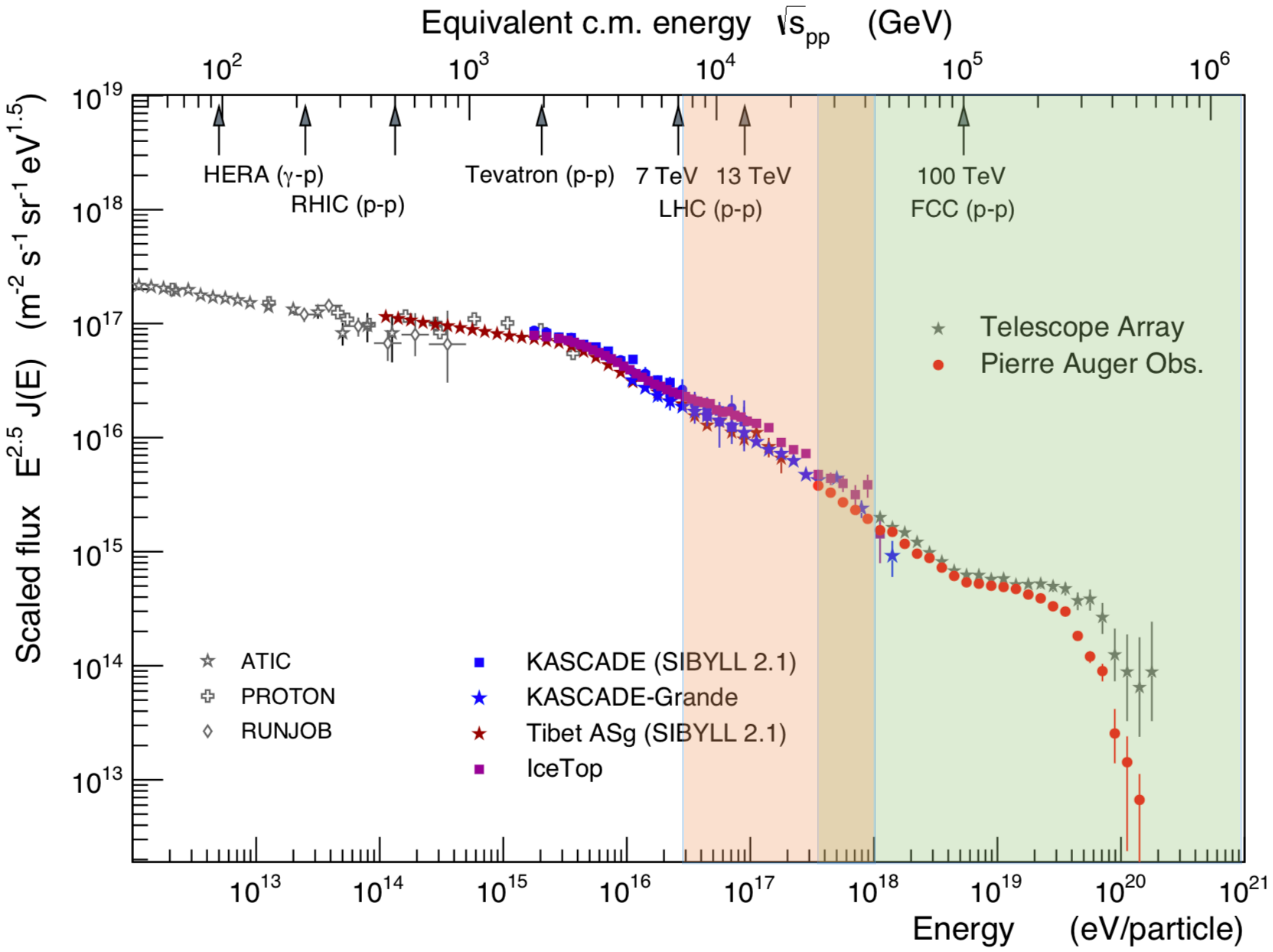


Hybrid technique (FD + SD)





Ultra High Energy Cosmic Rays



Pierre Auger Observatory

Low energy Extension

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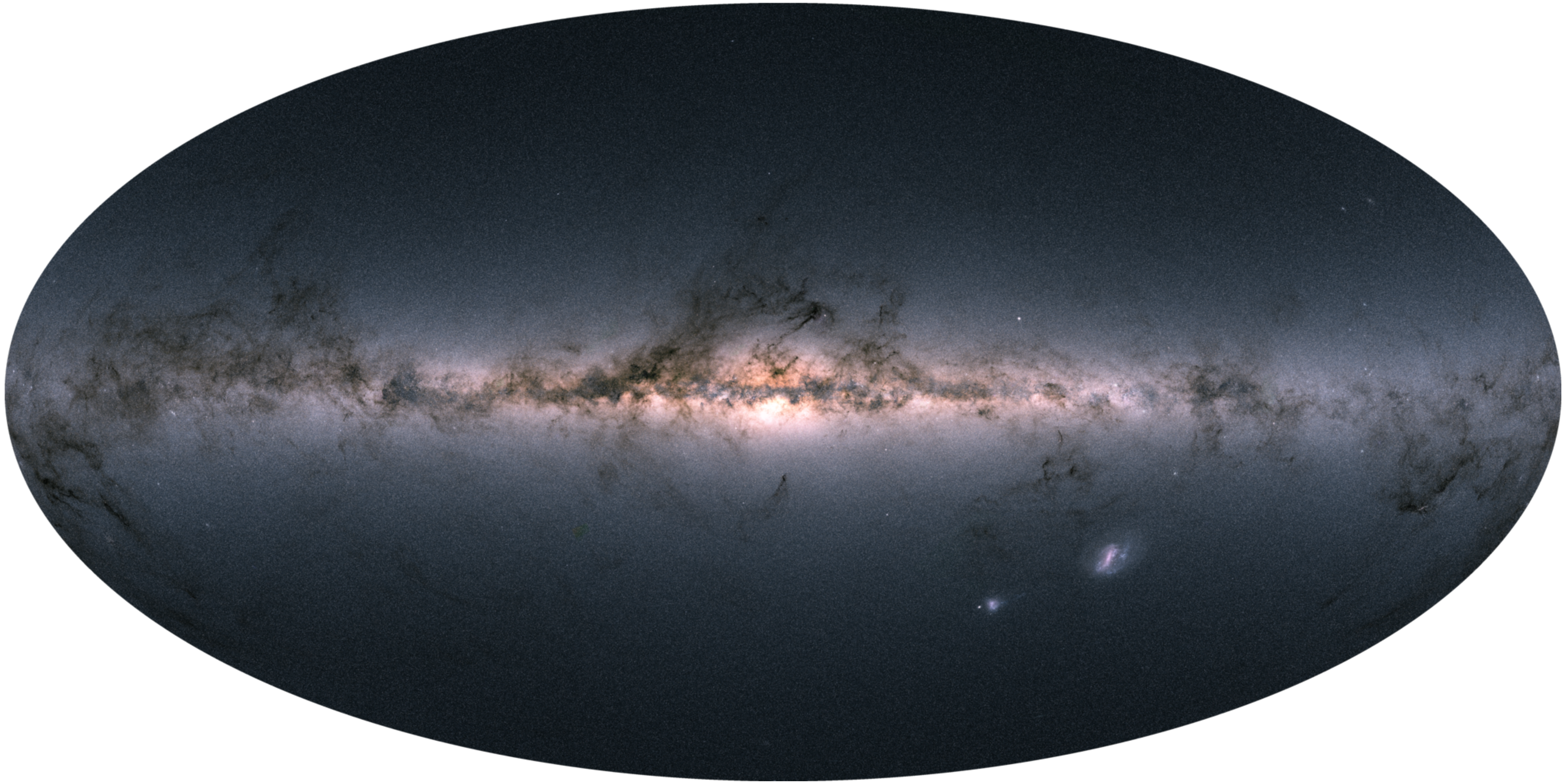
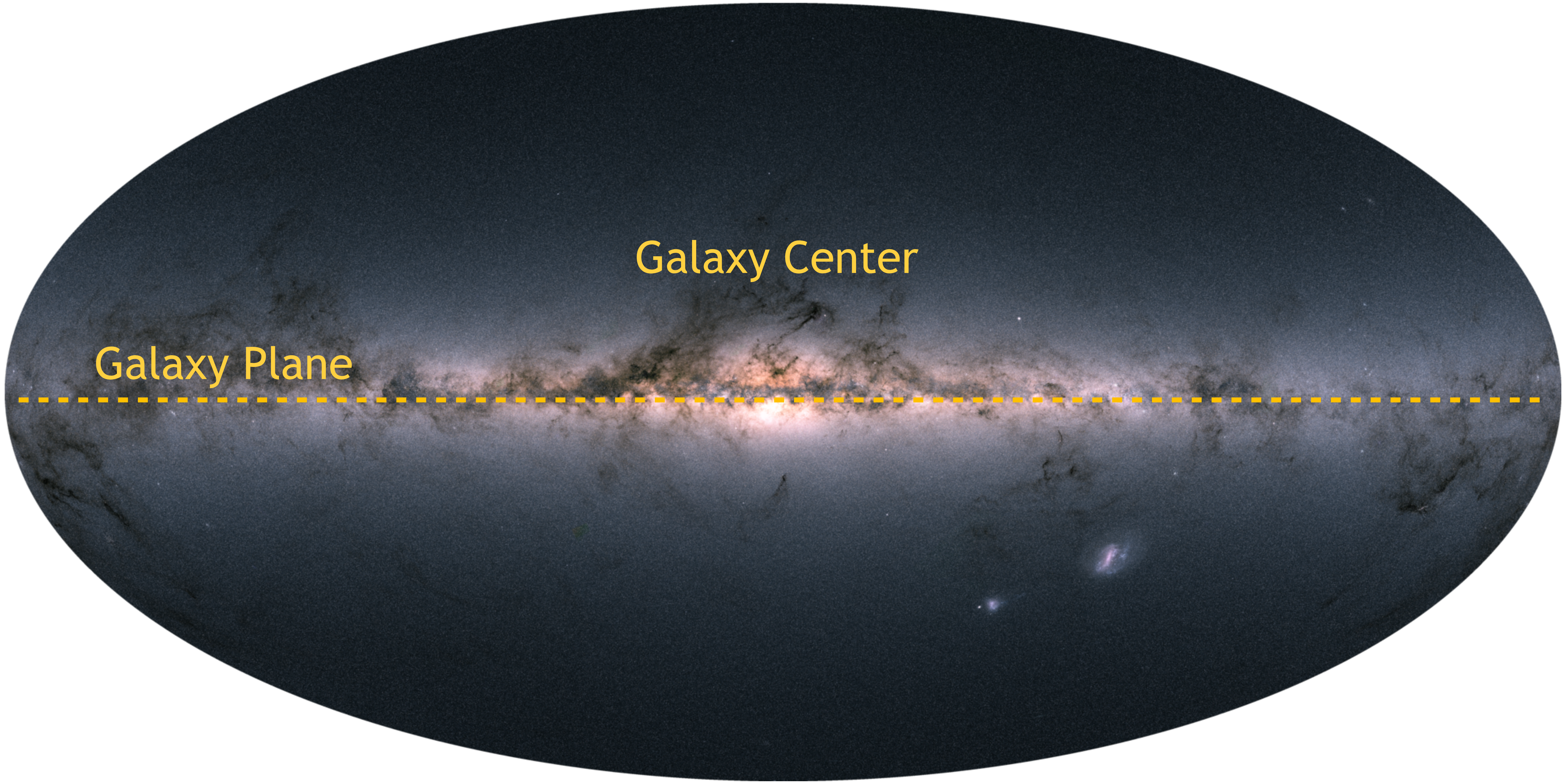
Ultra High Energy Cosmic Rays

What have we learned so far?

Are UHECRs produced in our galaxy?

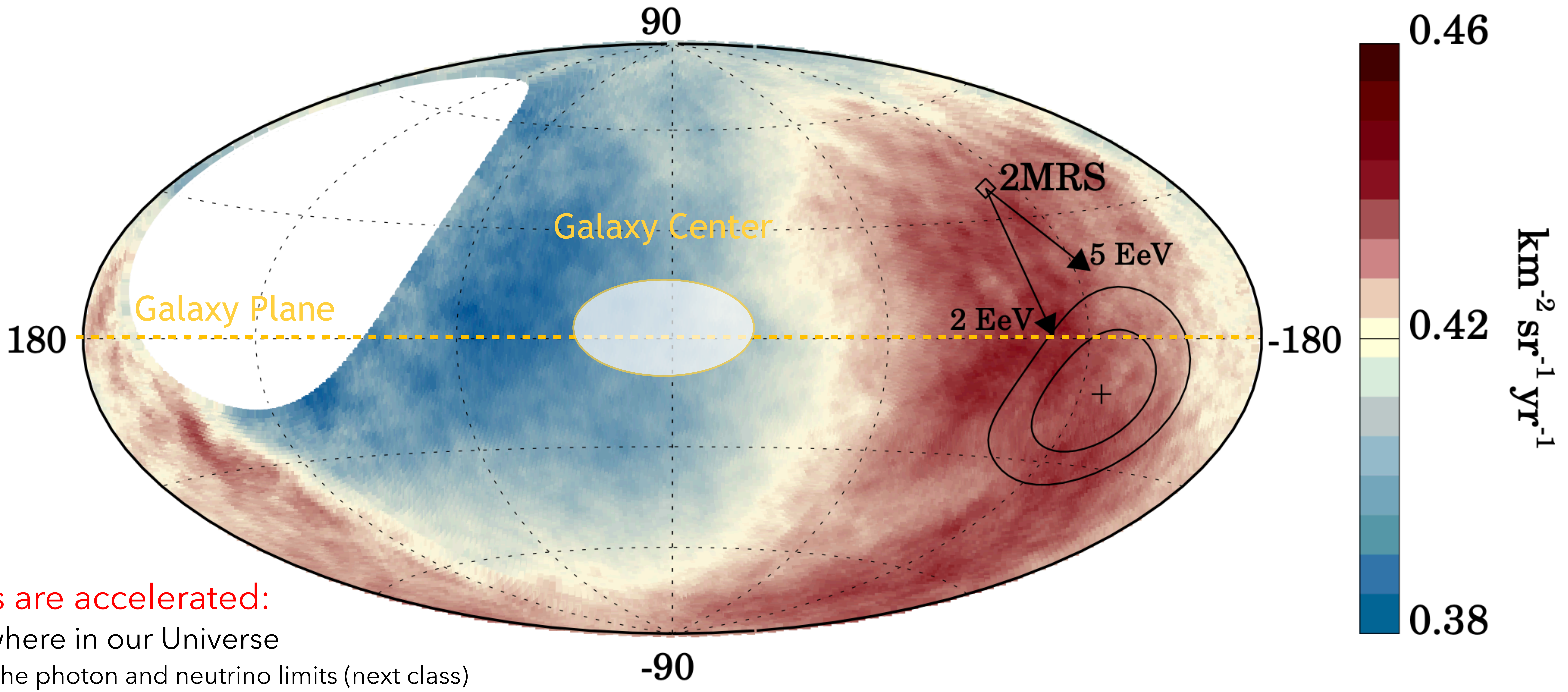


Are UHECRs produced in our galaxy?



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

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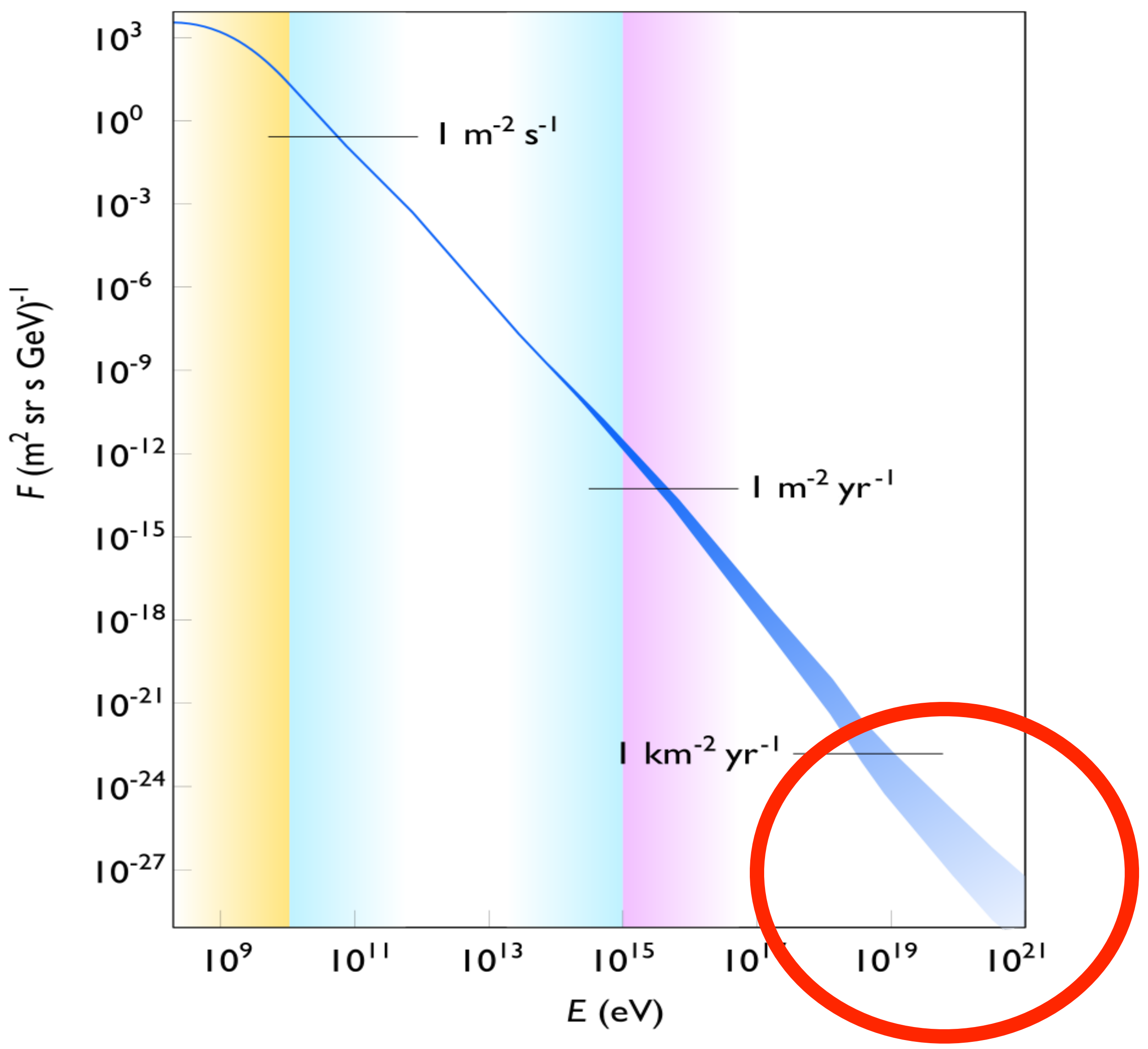
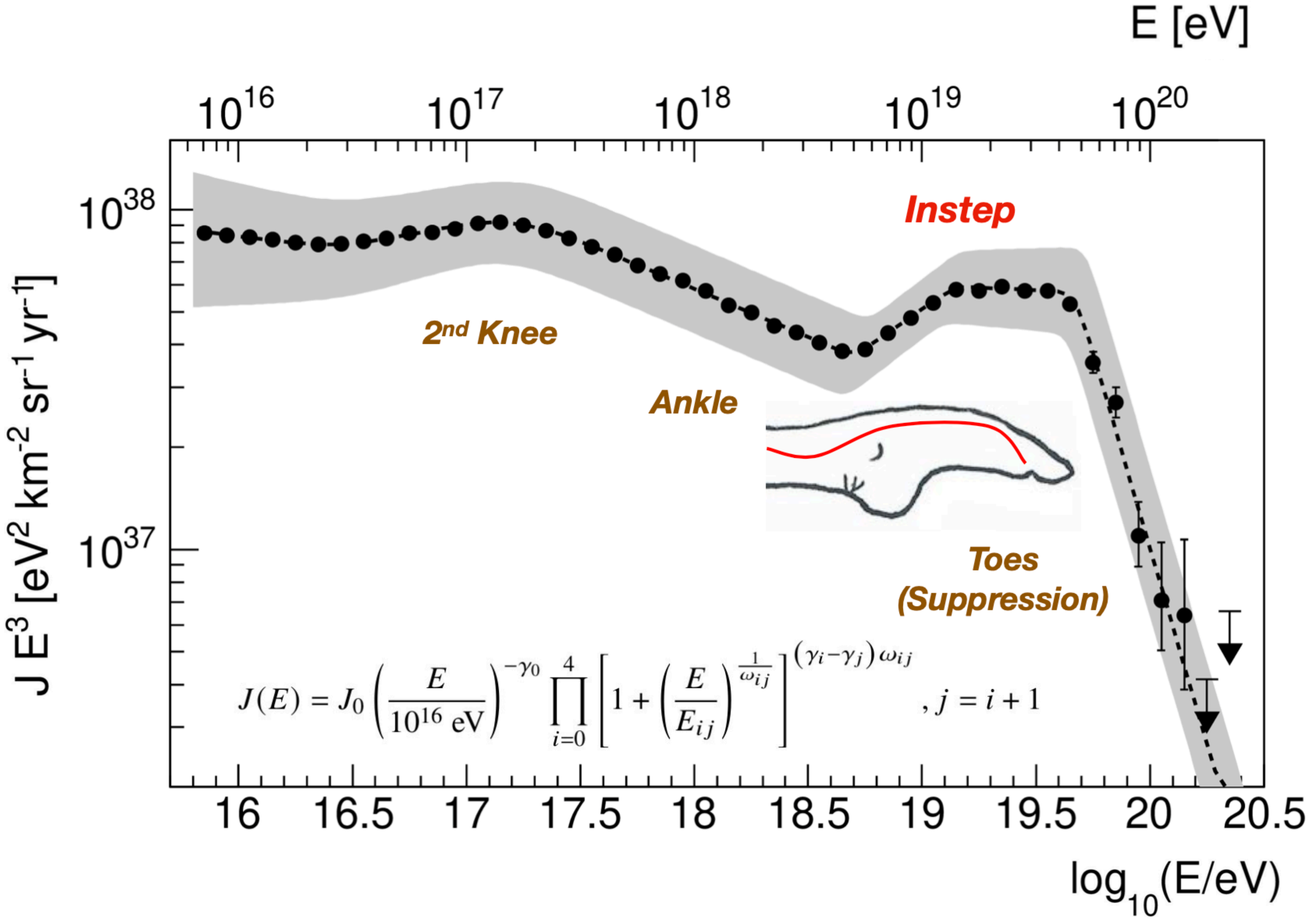
UHECR energy spectrum



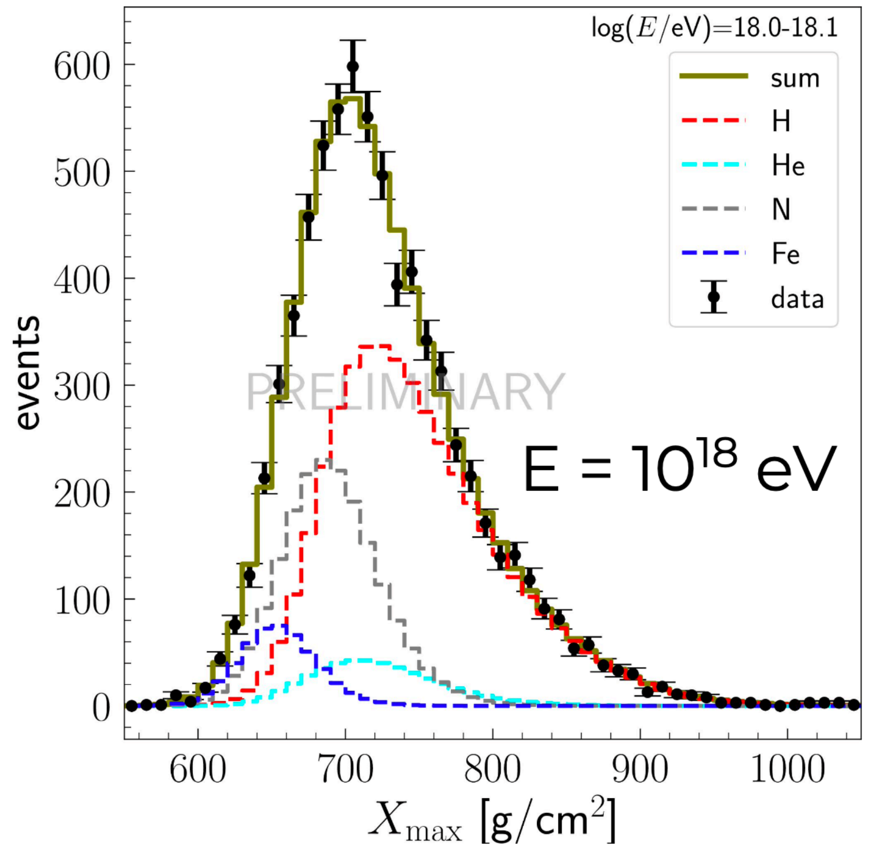
Phys. Rev. Lett. 125 (2020) 121106

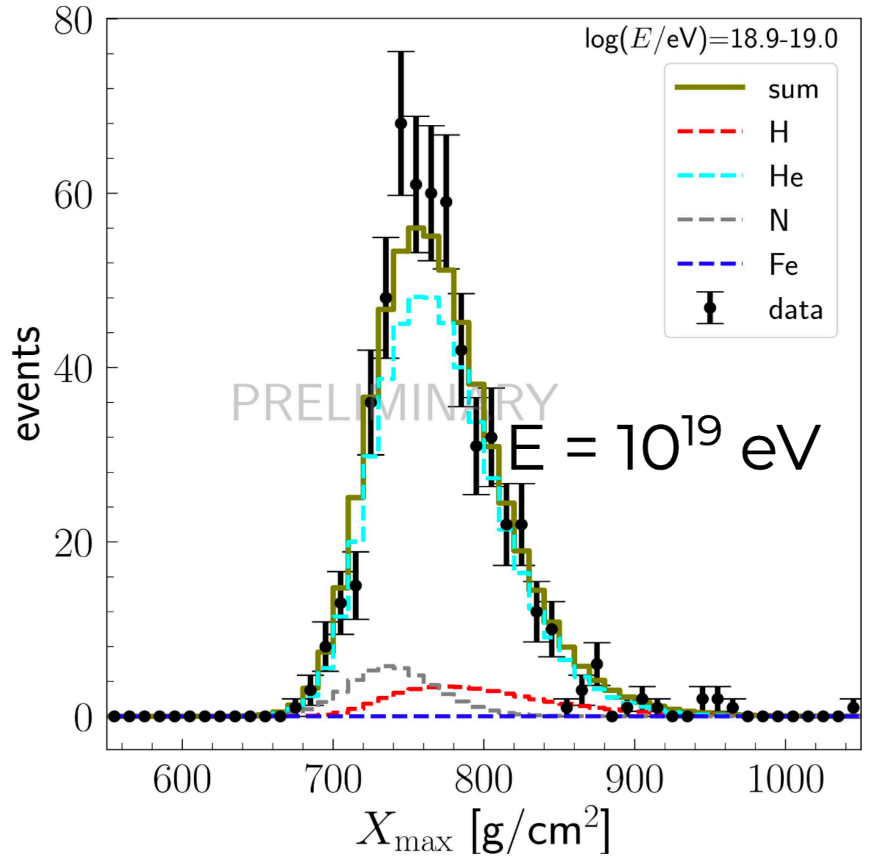


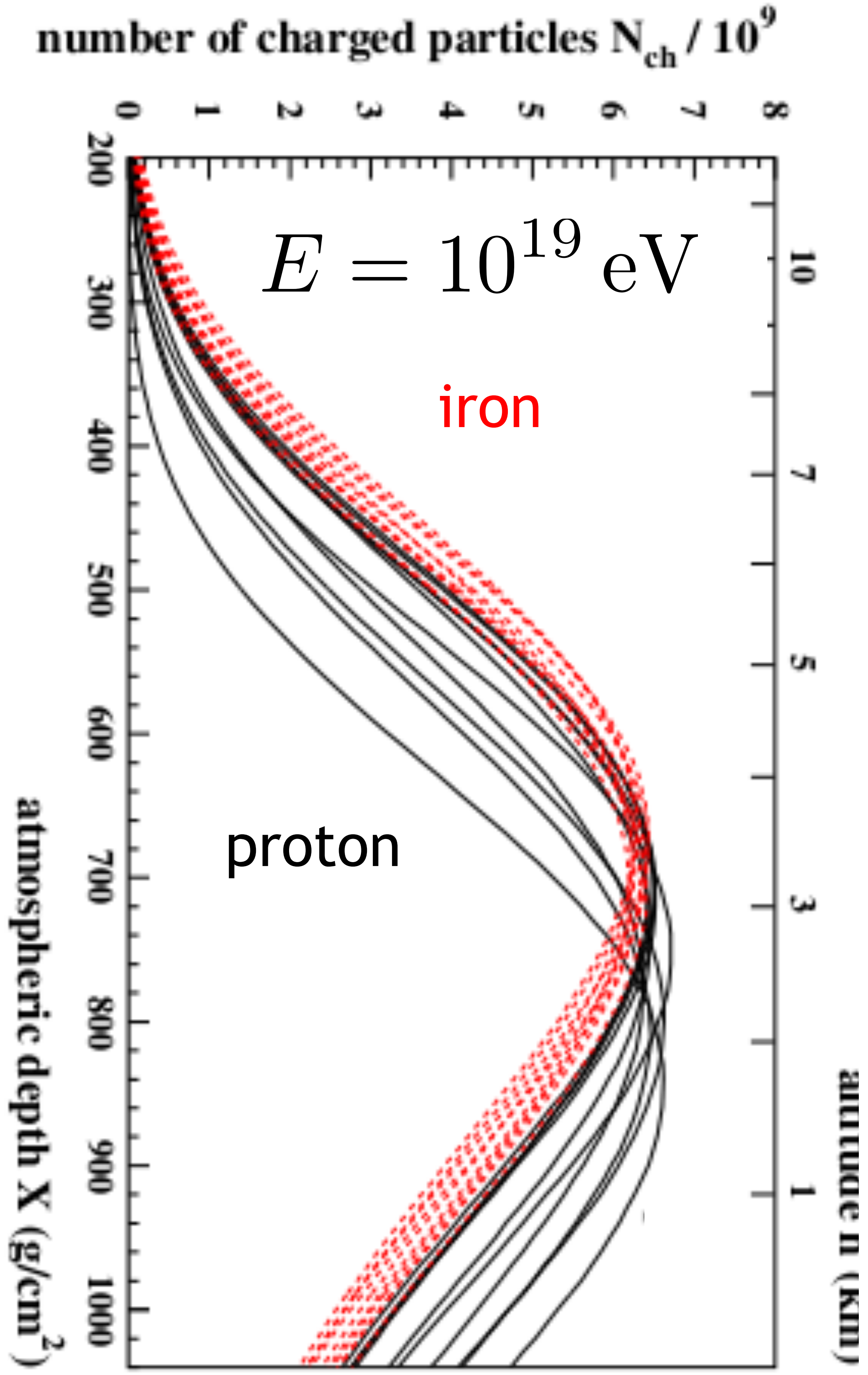
The CR spectrum is full of features!

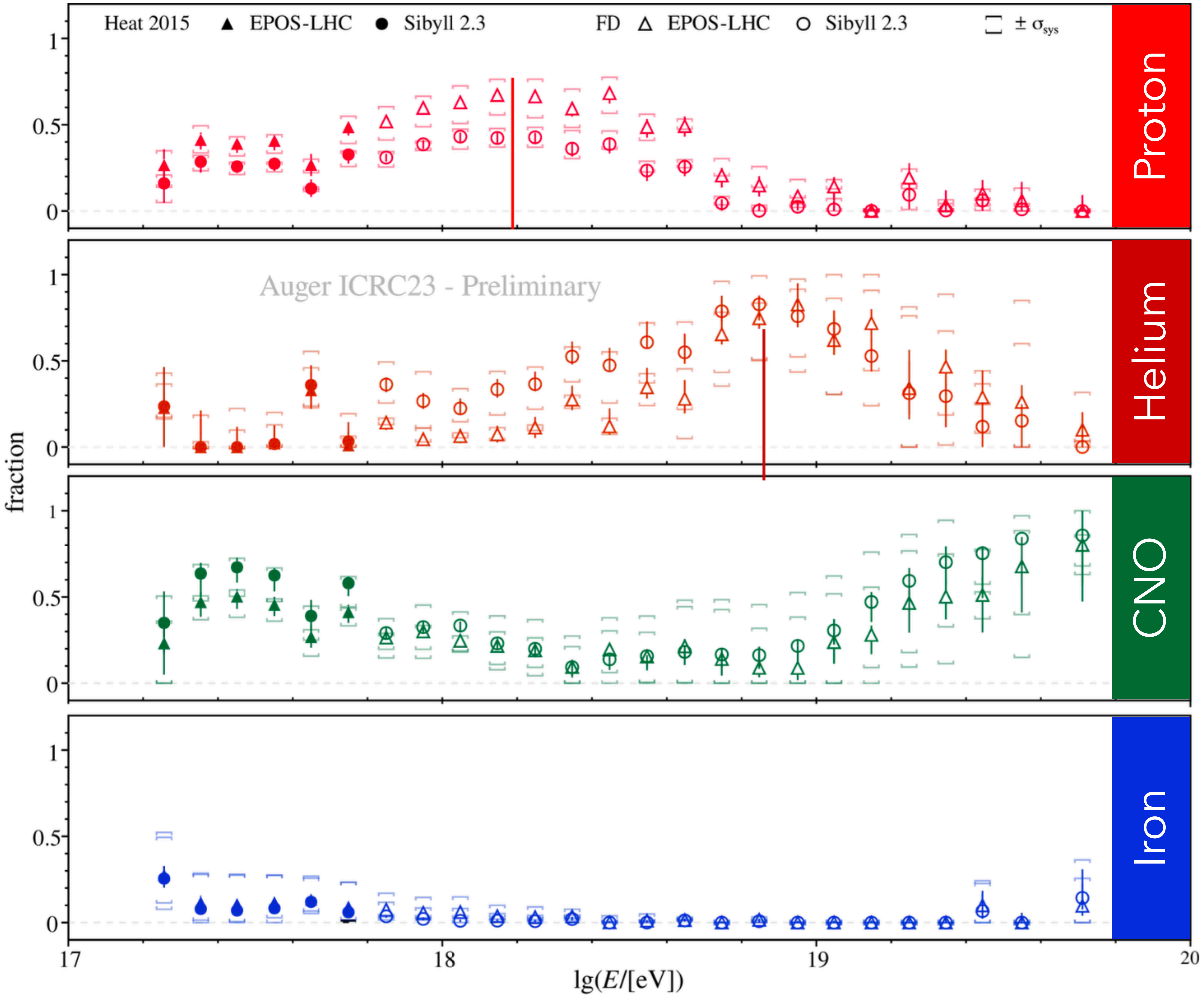
Put strong constraints on UHECR production and propagation

Composition fits to X_{max}









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

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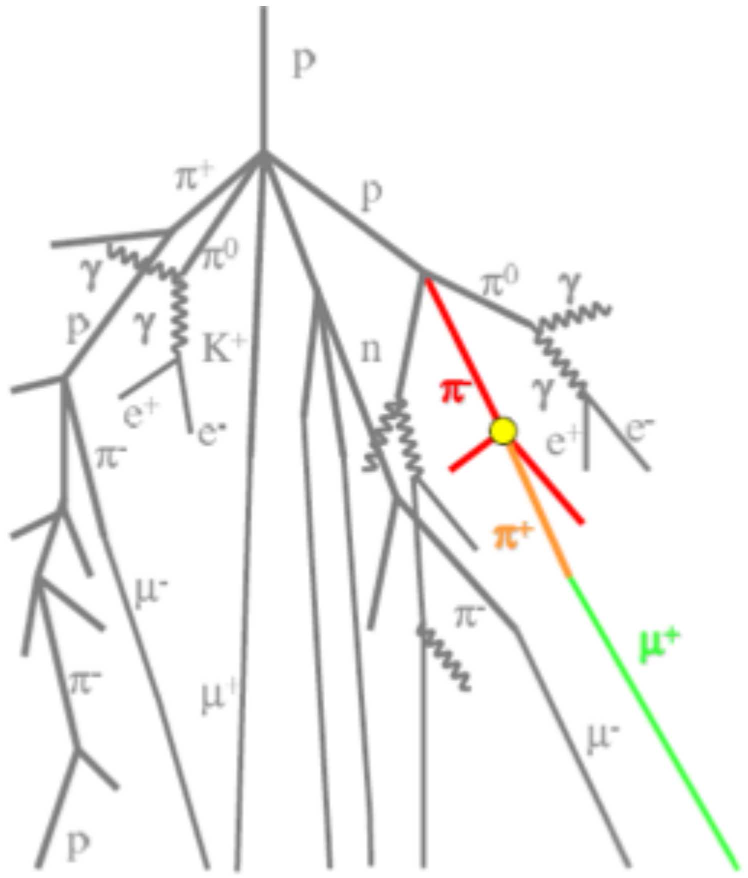
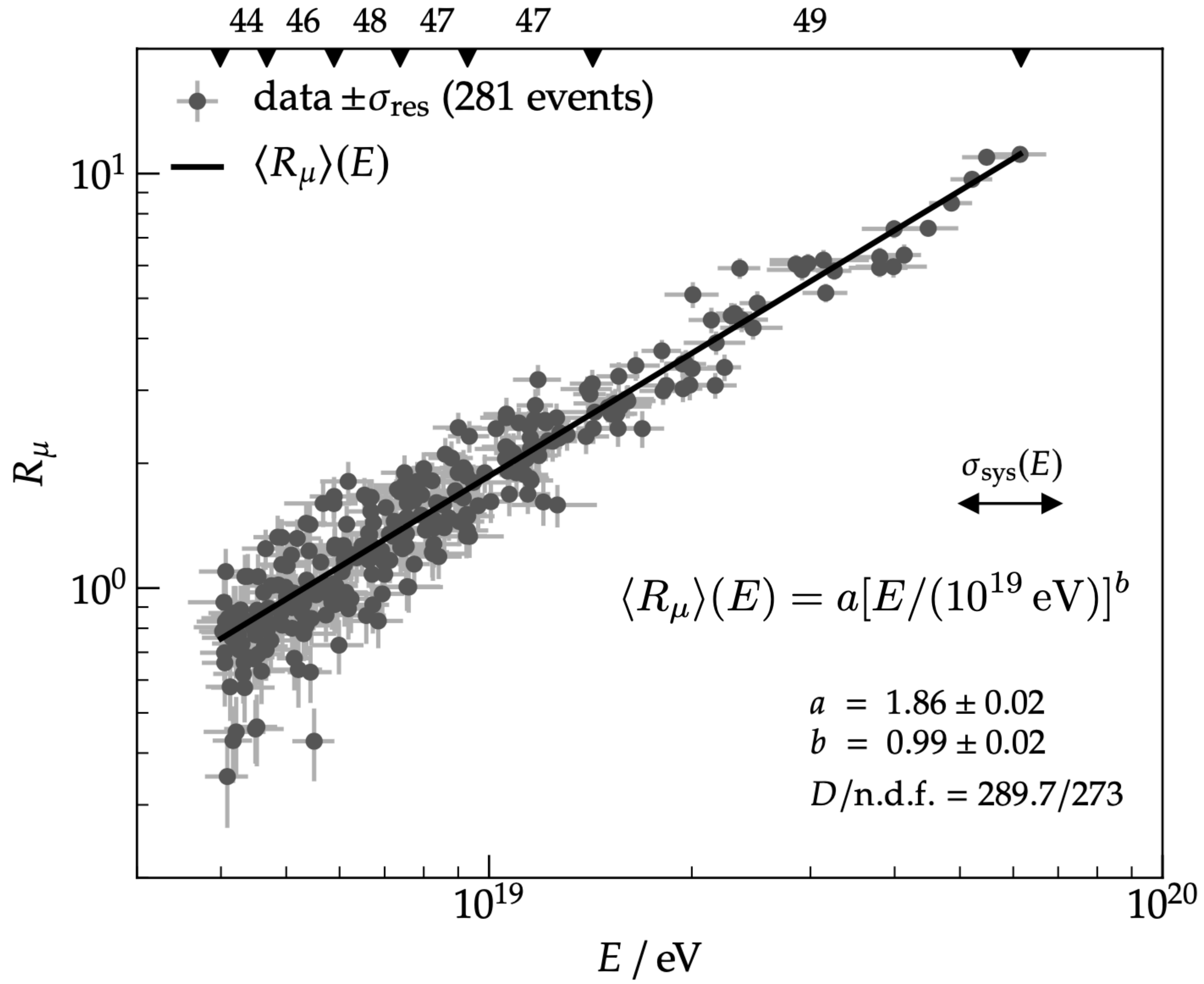
Measurement of the EAS muon content

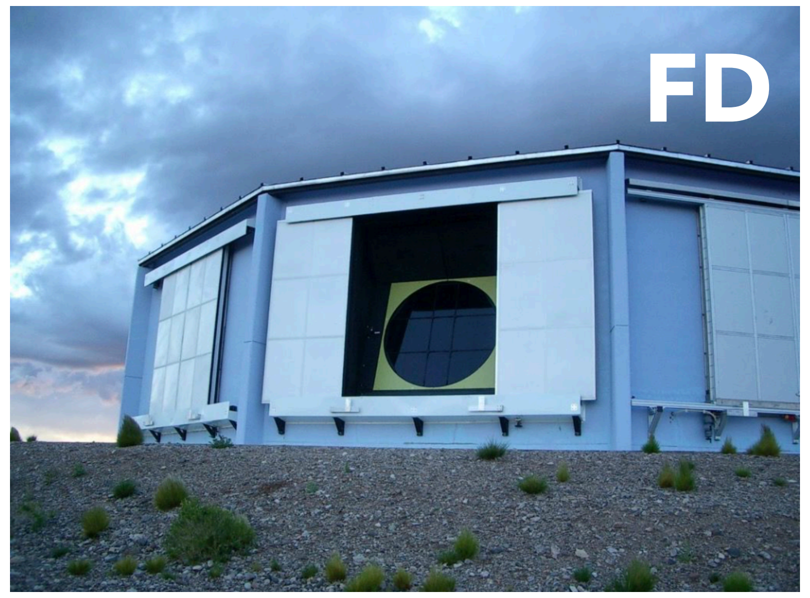
- Muons are sensitive to the details of the hadronic interactions that rules the shower development
- Measurement performed using hybrid (inclined showers



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

Sensitive to the EAS muon number - R_μ





Sensitive to the EAS calorimetric energy - E - and X_{max}

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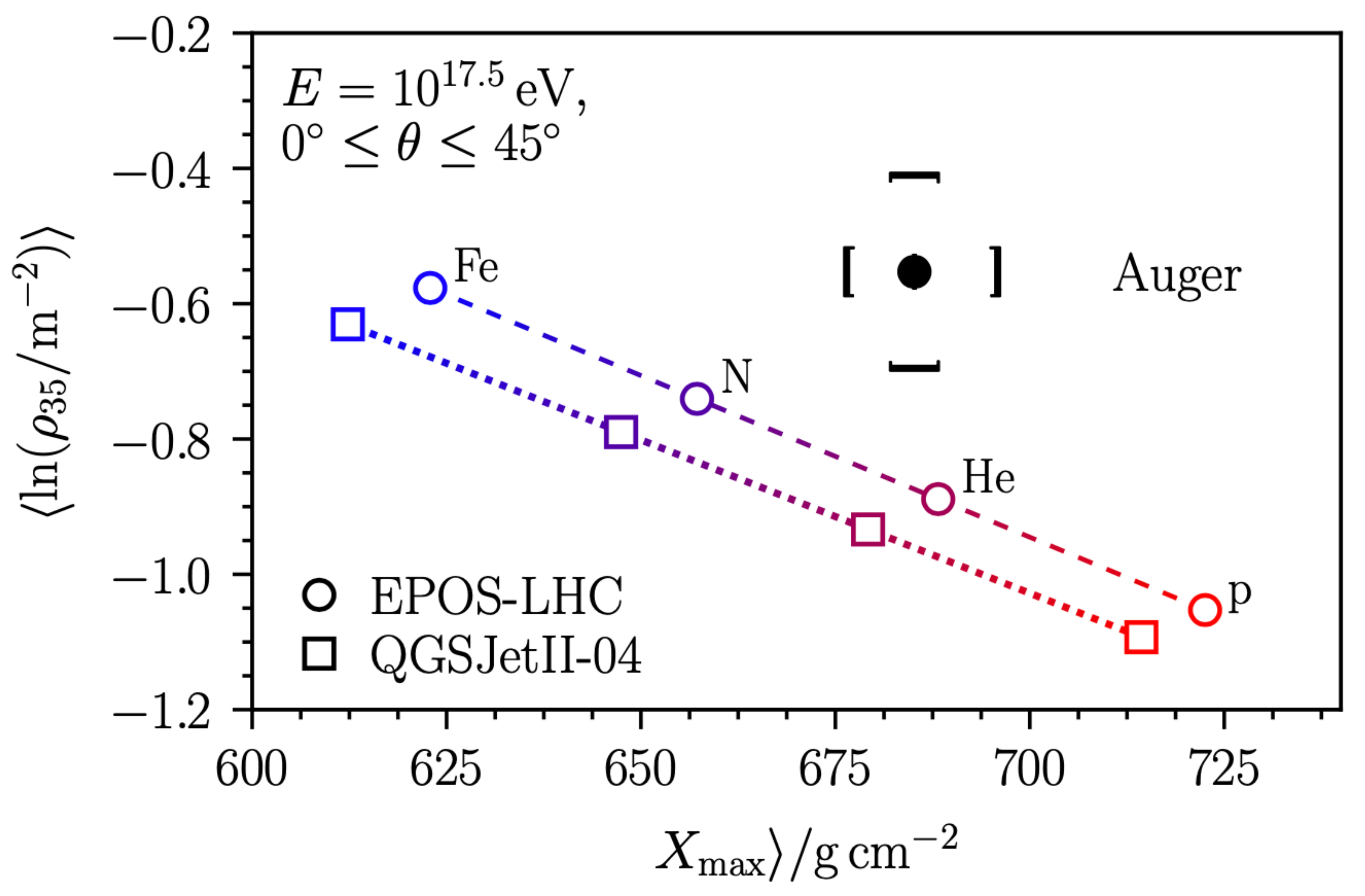
The EAS muon puzzle @ Auger

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

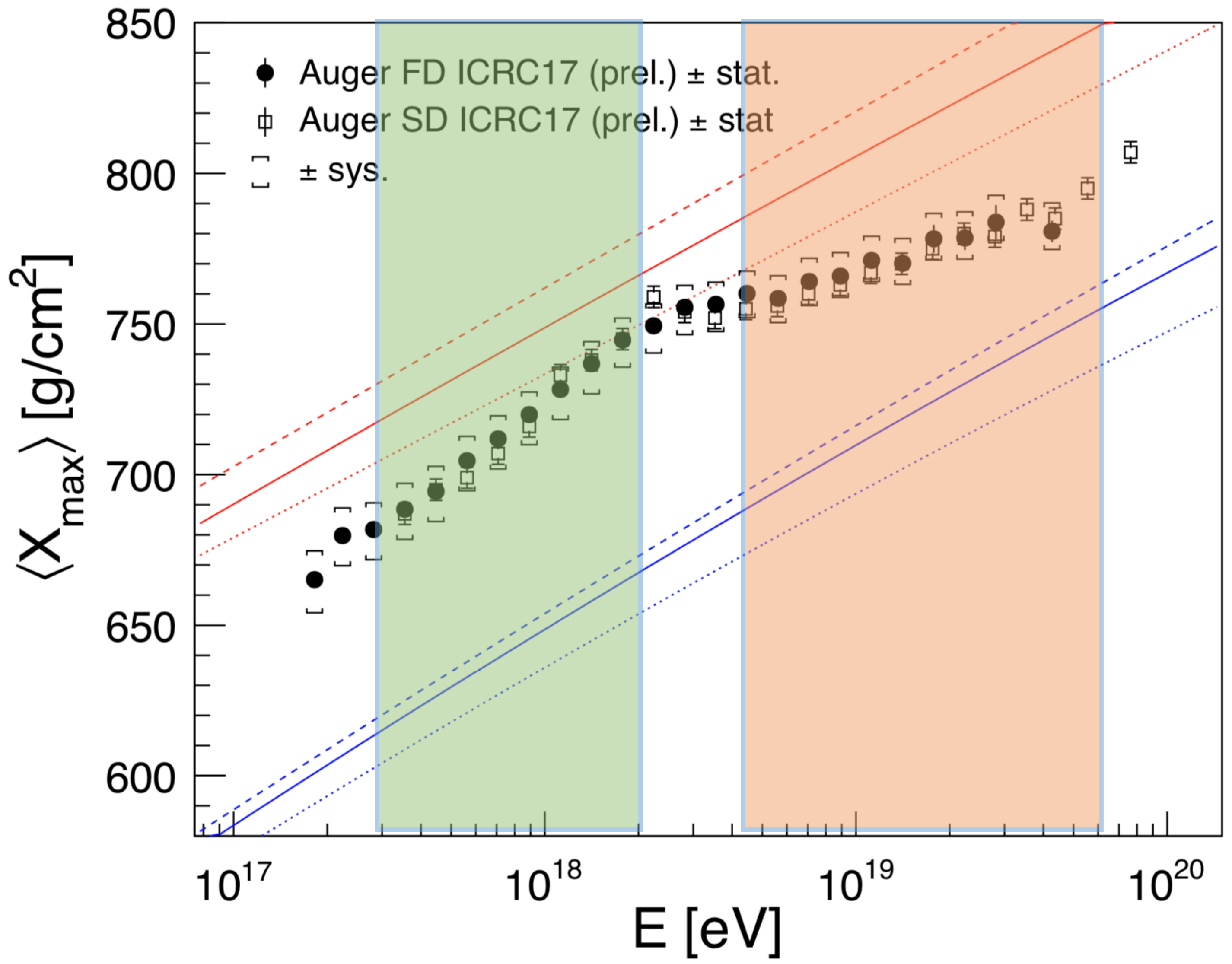
Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition

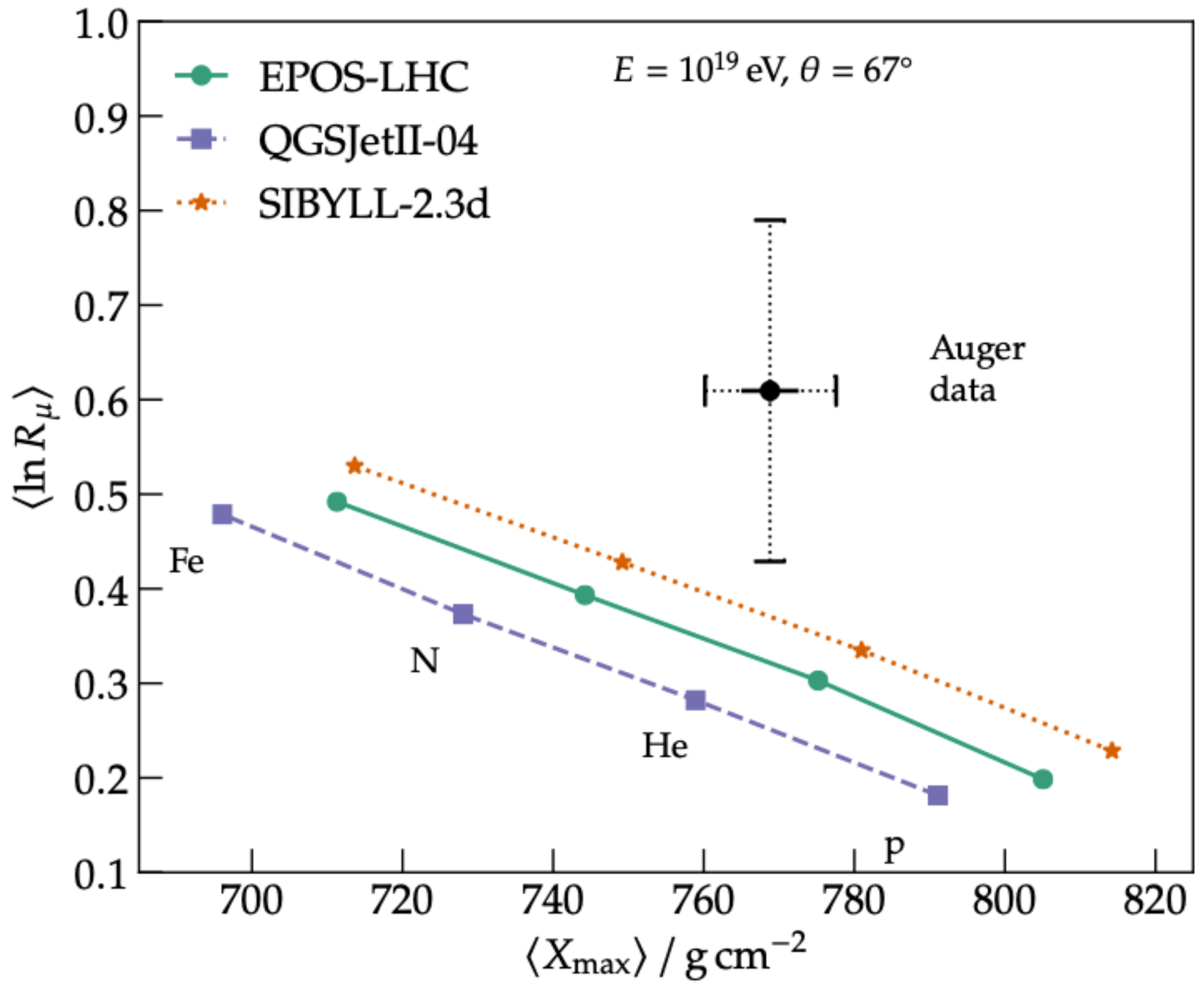
Phys.Rev.Lett. 126 (2021) 15, 152002



AMIGA

FD data

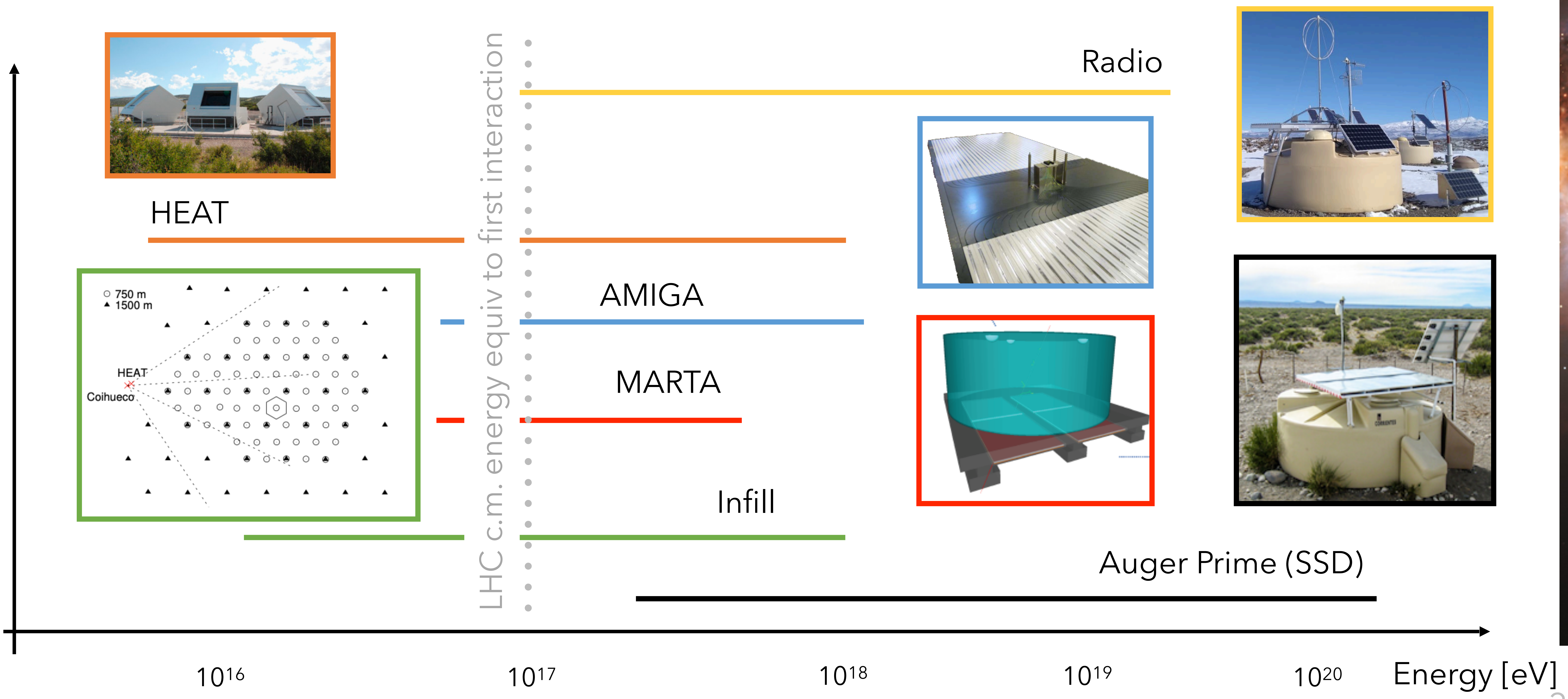




SD inclined

Multi-hybrid shower events

(The future of the Pierre Auger Observatory)



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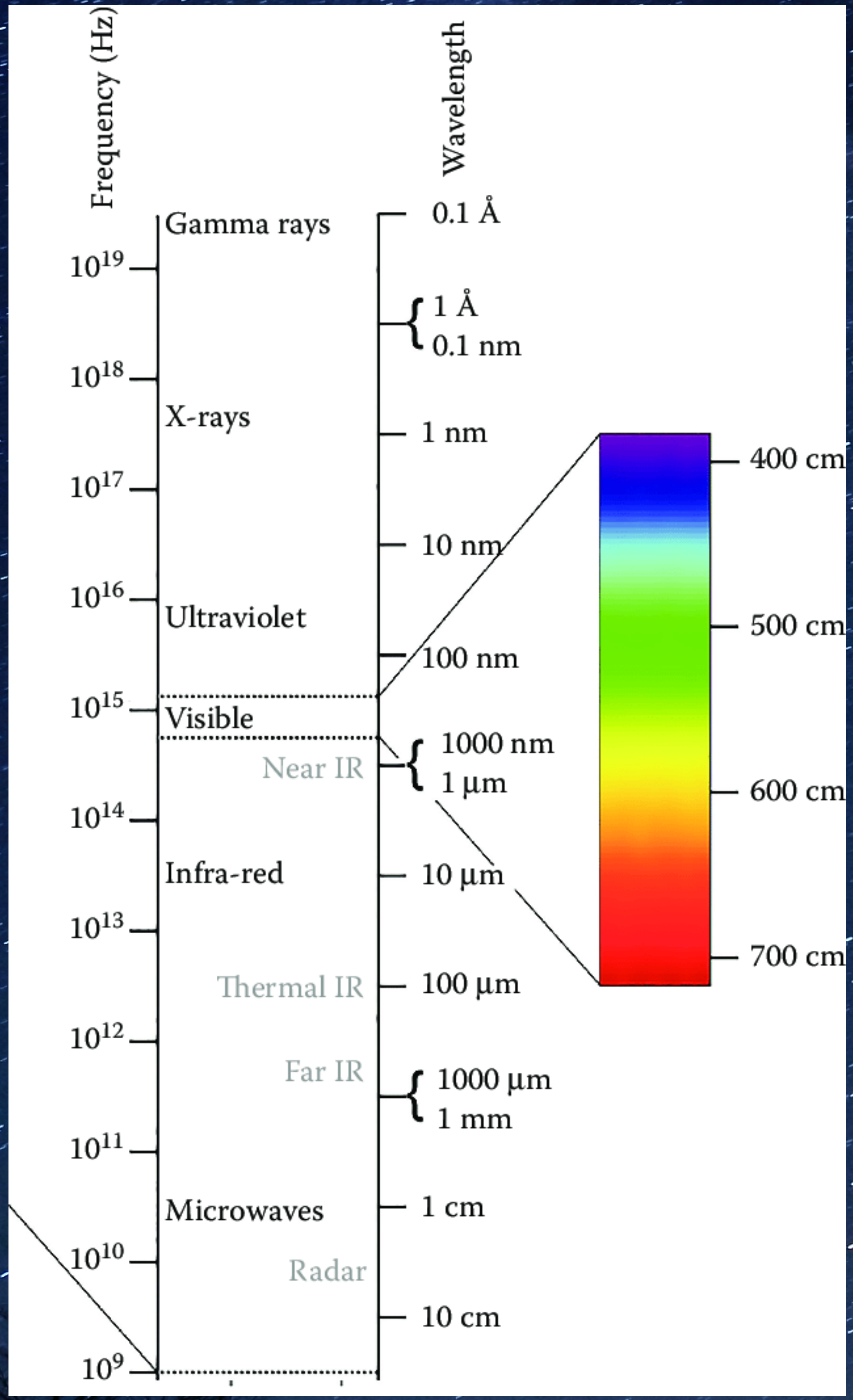
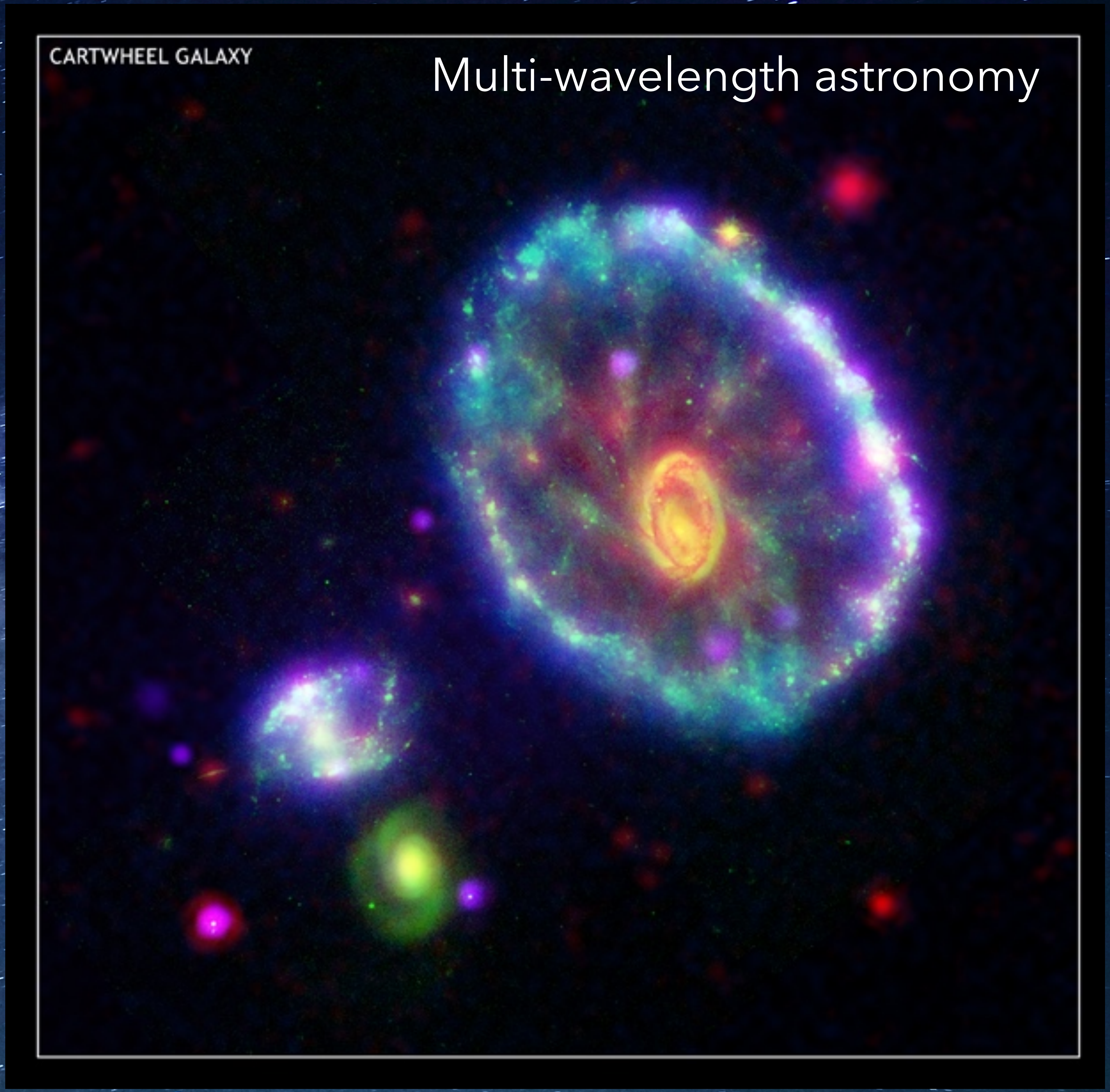
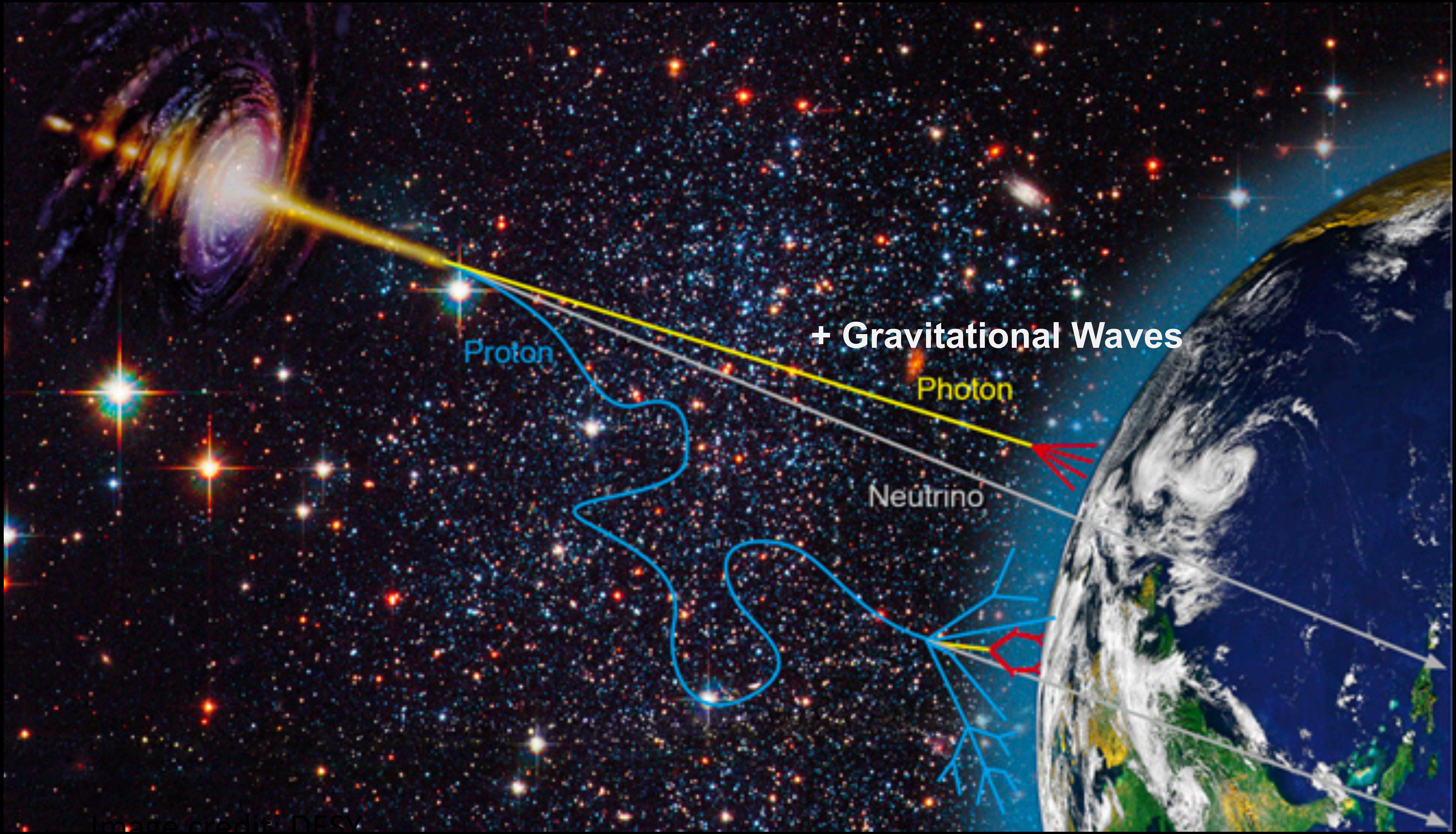
Multi-messenger observations

Multi-wavelength Astronomy





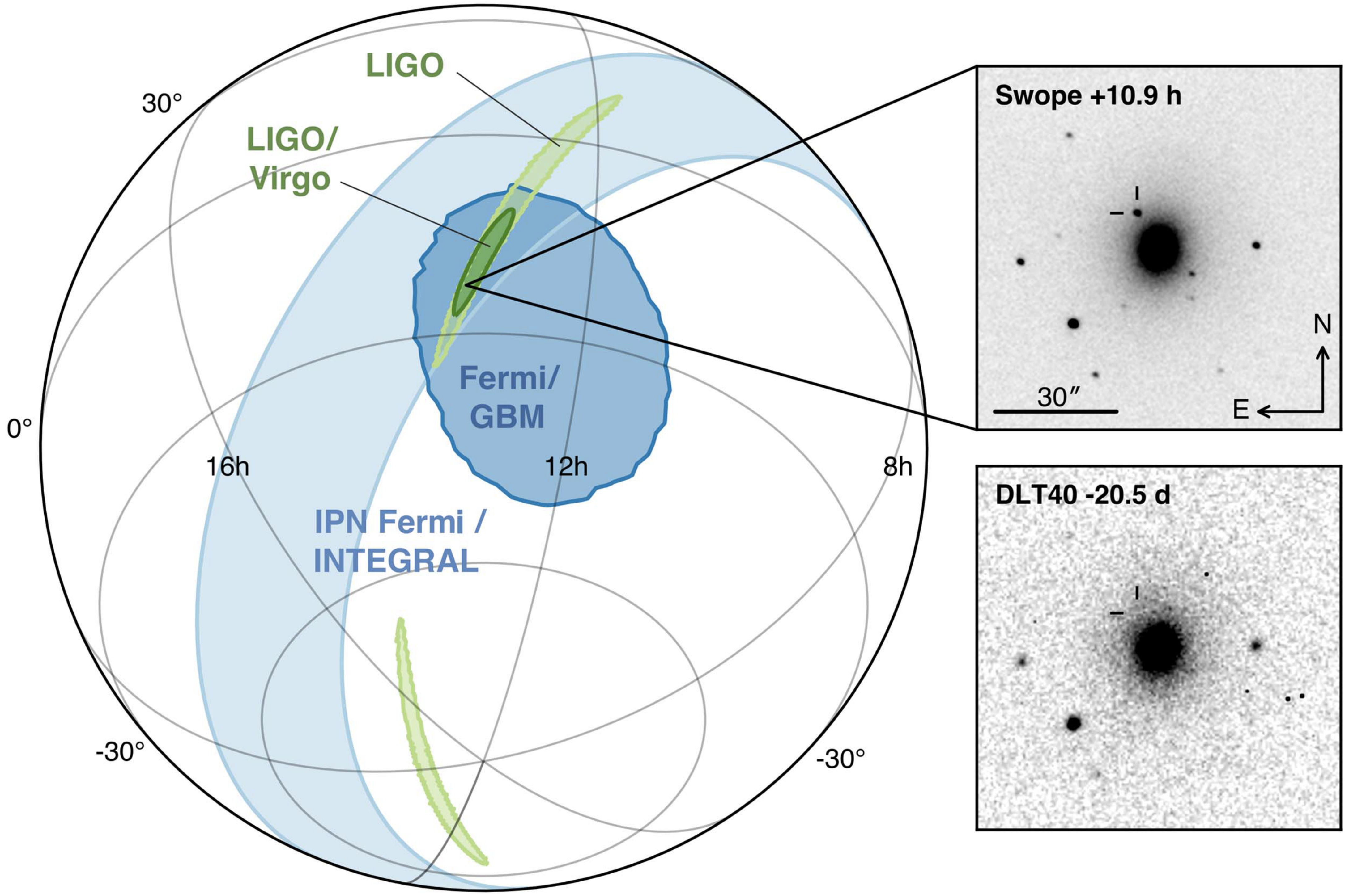
Multi-messenger Astronomy



Multi-messenger observation of a Binary Neutron Star Merger

Joint publication of LIGO, VIRGO, INTEGRAL, Fermi, IceCube, Pierre Auger …

physicsworld
BREAKTHROUGH OF THE YEAR 2017



Simultaneous observation of a Gravitational Wave + electromagnetic counter parts

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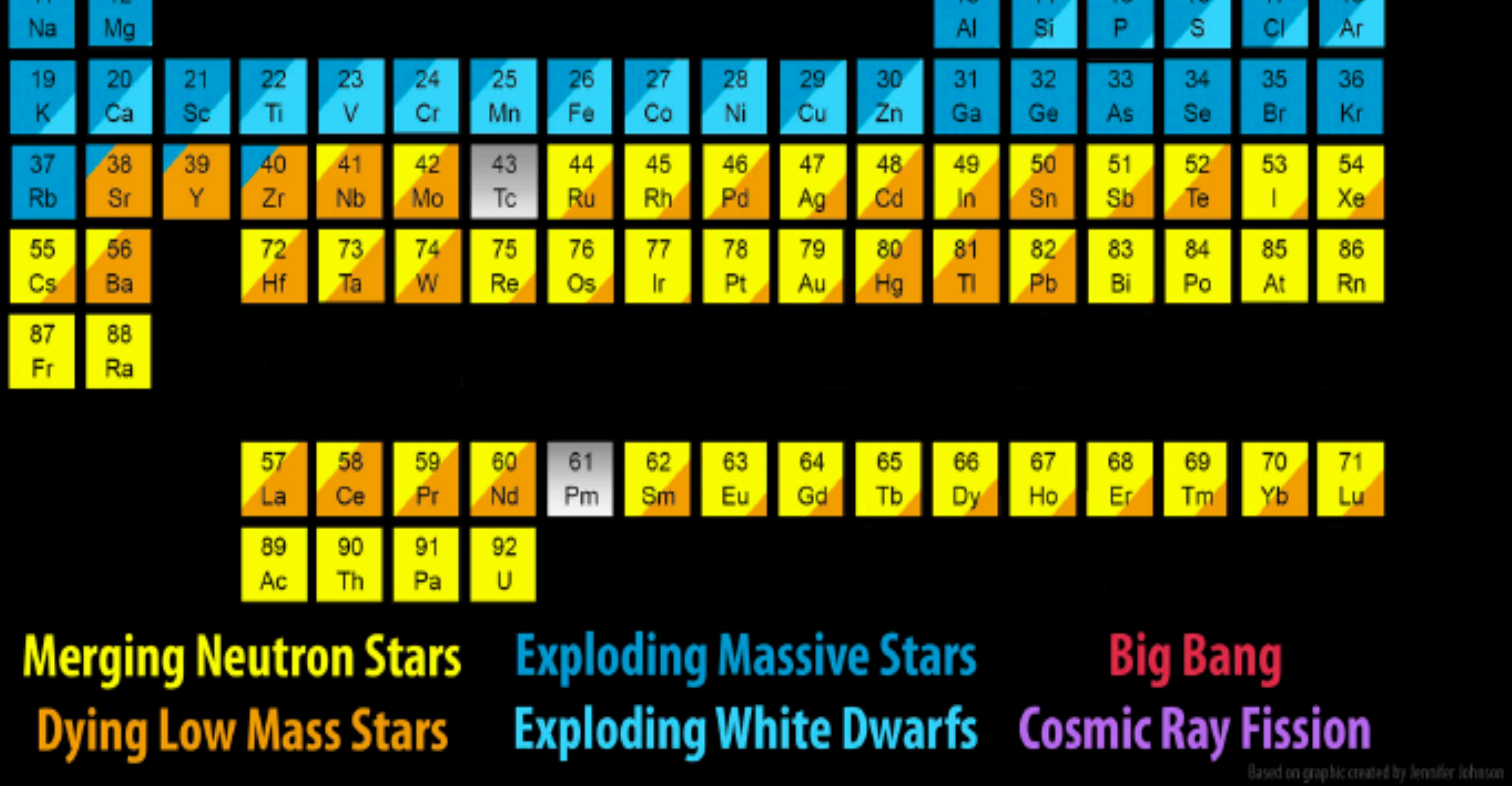
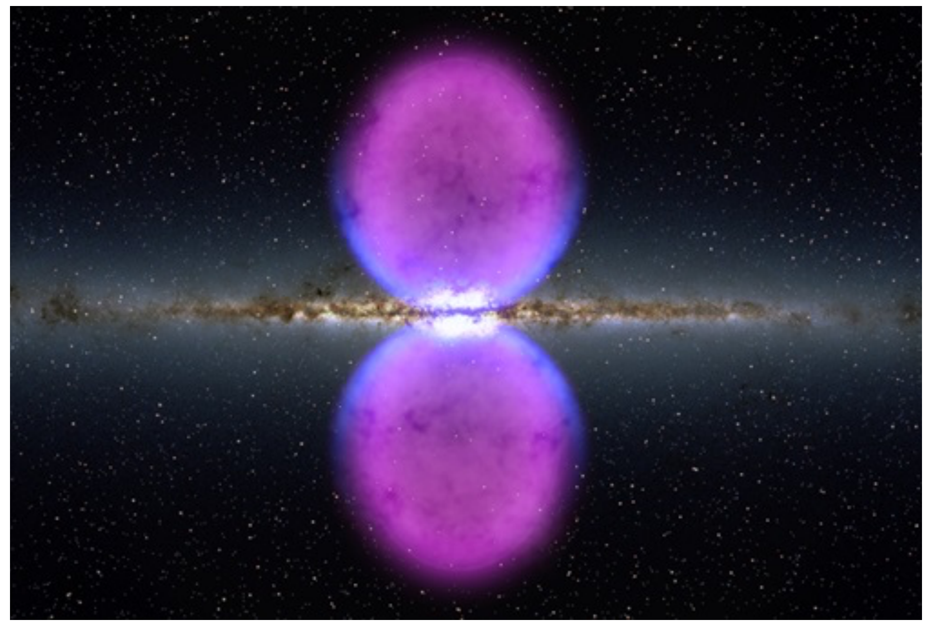
Origin of the elements in the Universe

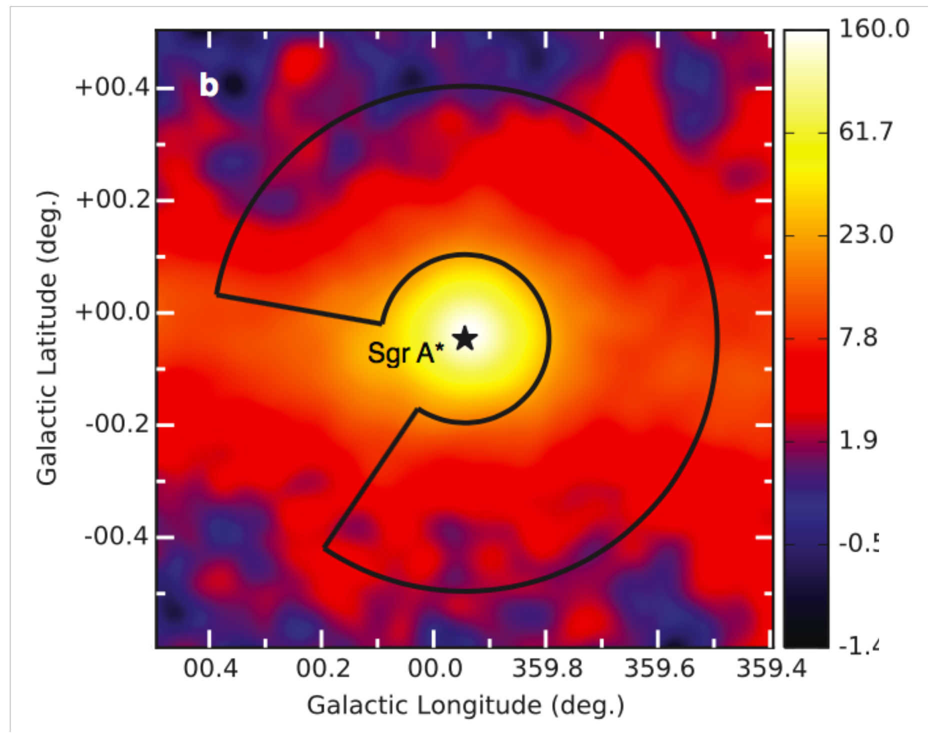


- The merger of neutron stars is known as Kilonovae
- **Kilonovae** are candidates for production of half the chemical elements heavier than iron in the Universe

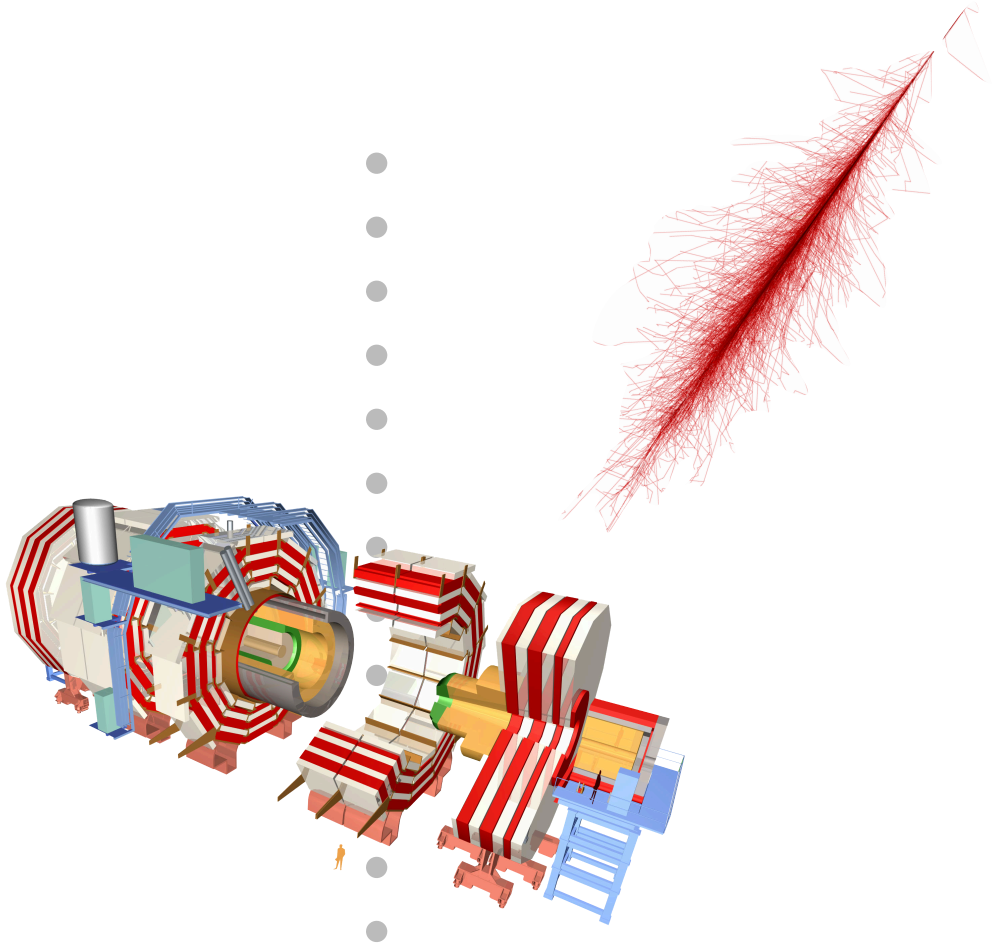
Astroparticle Physics

A unique opportunity to explore the extreme energy Universe





Muon excess appearance



LHC

SWGO
The Southern Wide-field Gamma-ray Observatory

2019 - 2026 - 2040

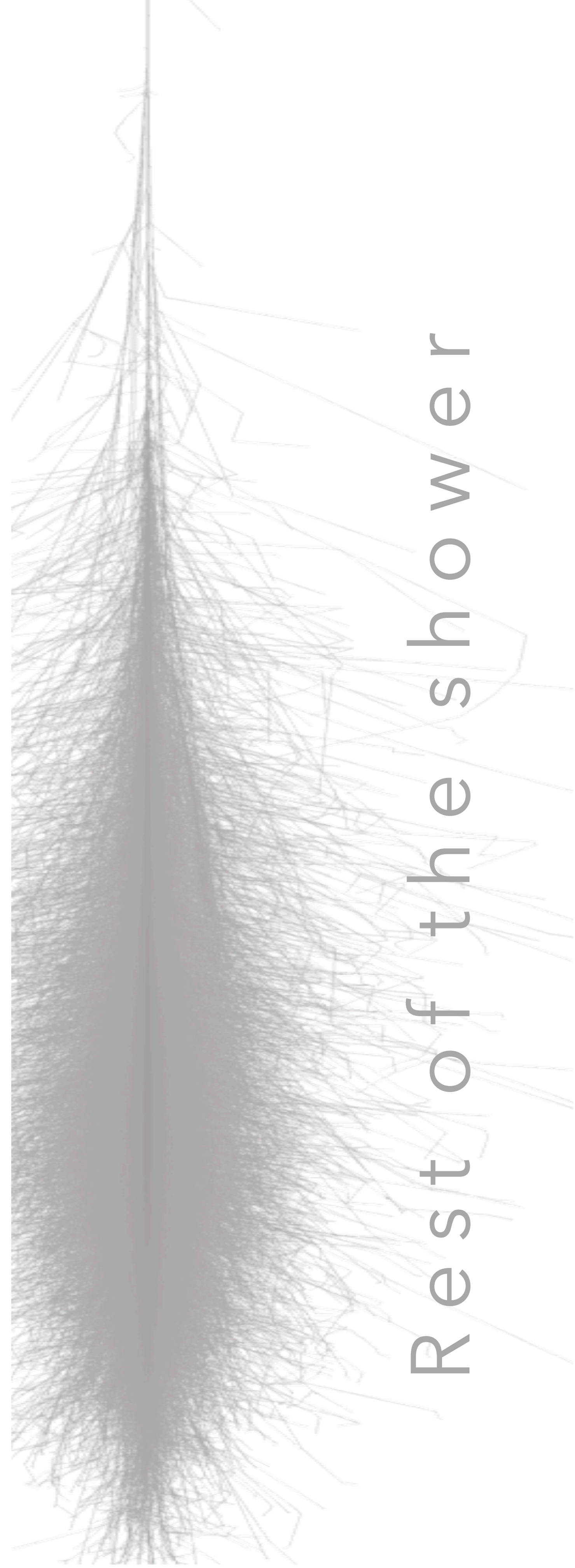
PIERRE AUGER OBSERVATORY

2004 - 2035

10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} Energy [eV]

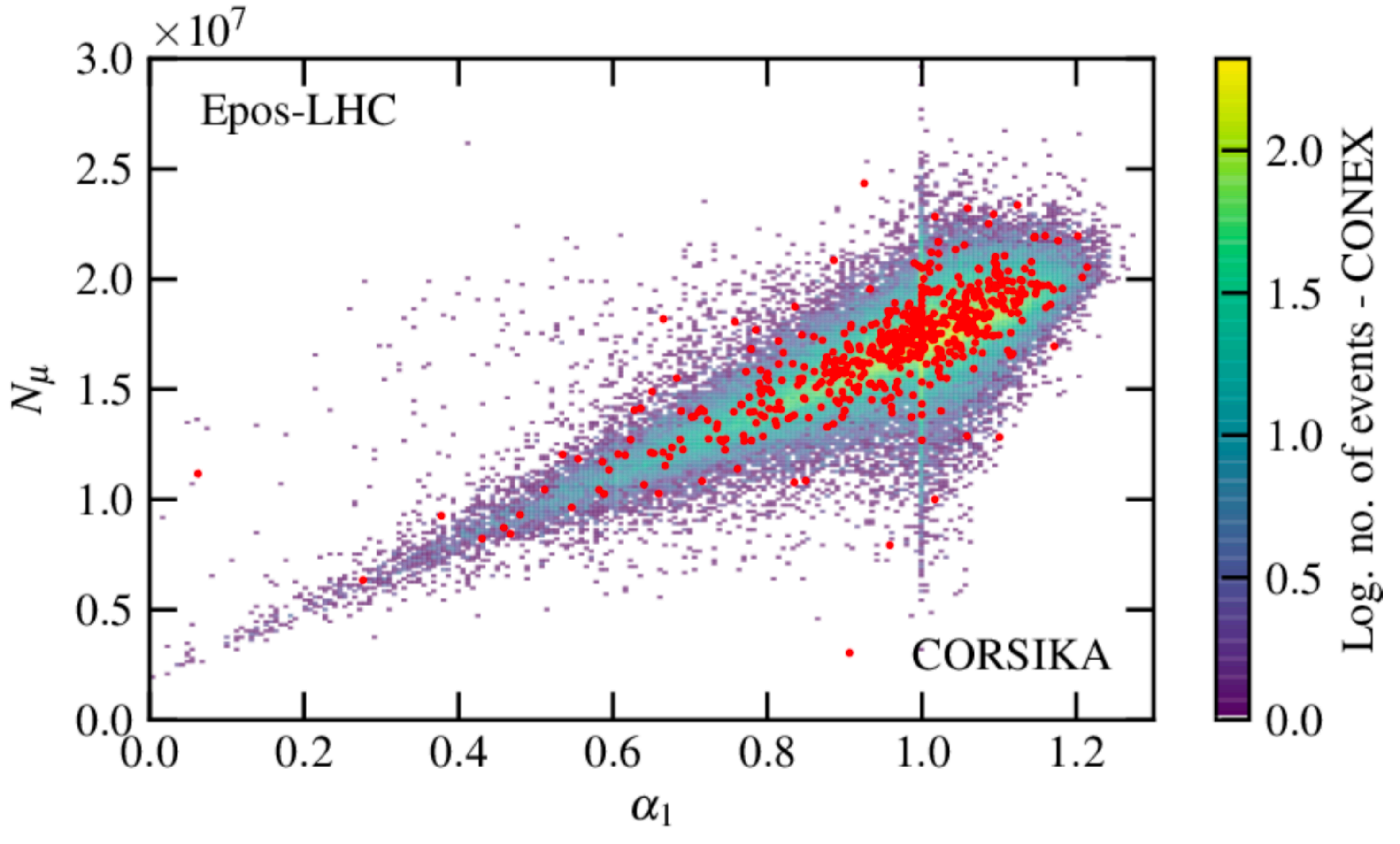
LIP @ Auger

- First interaction



Phenomenology of Air Showers

New observables and measurements

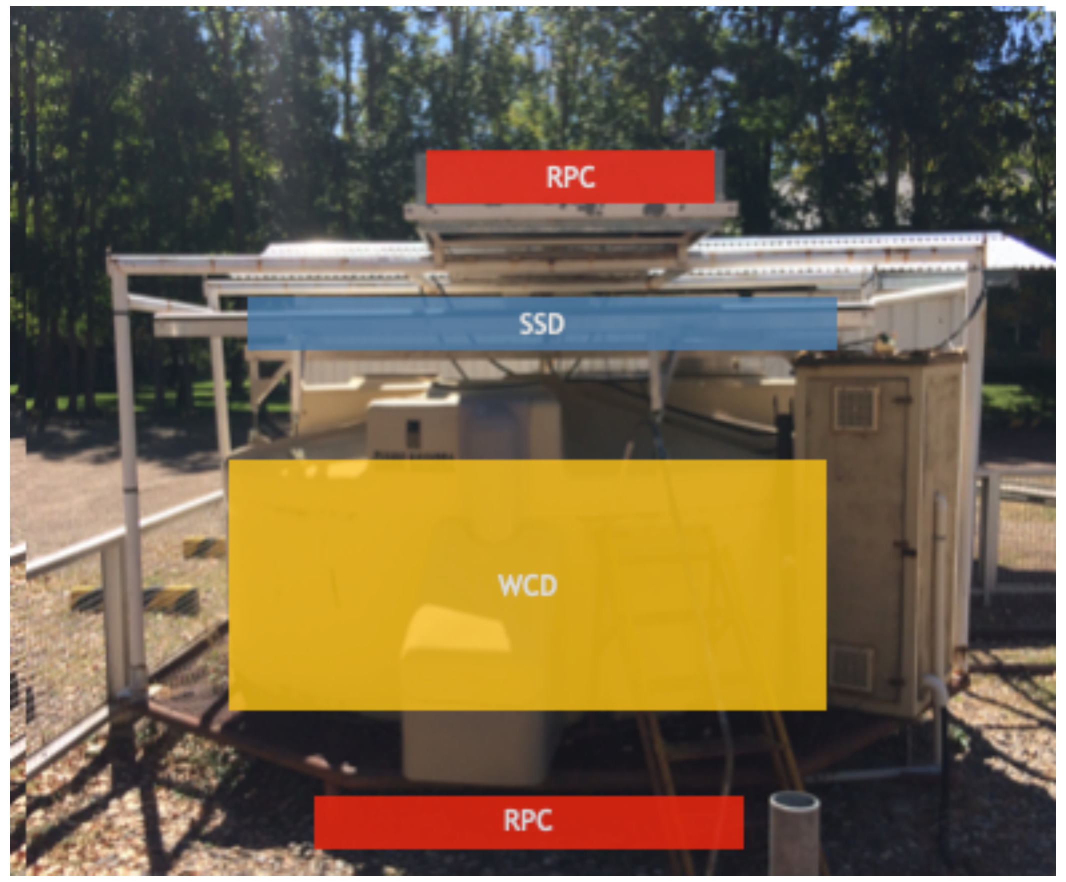


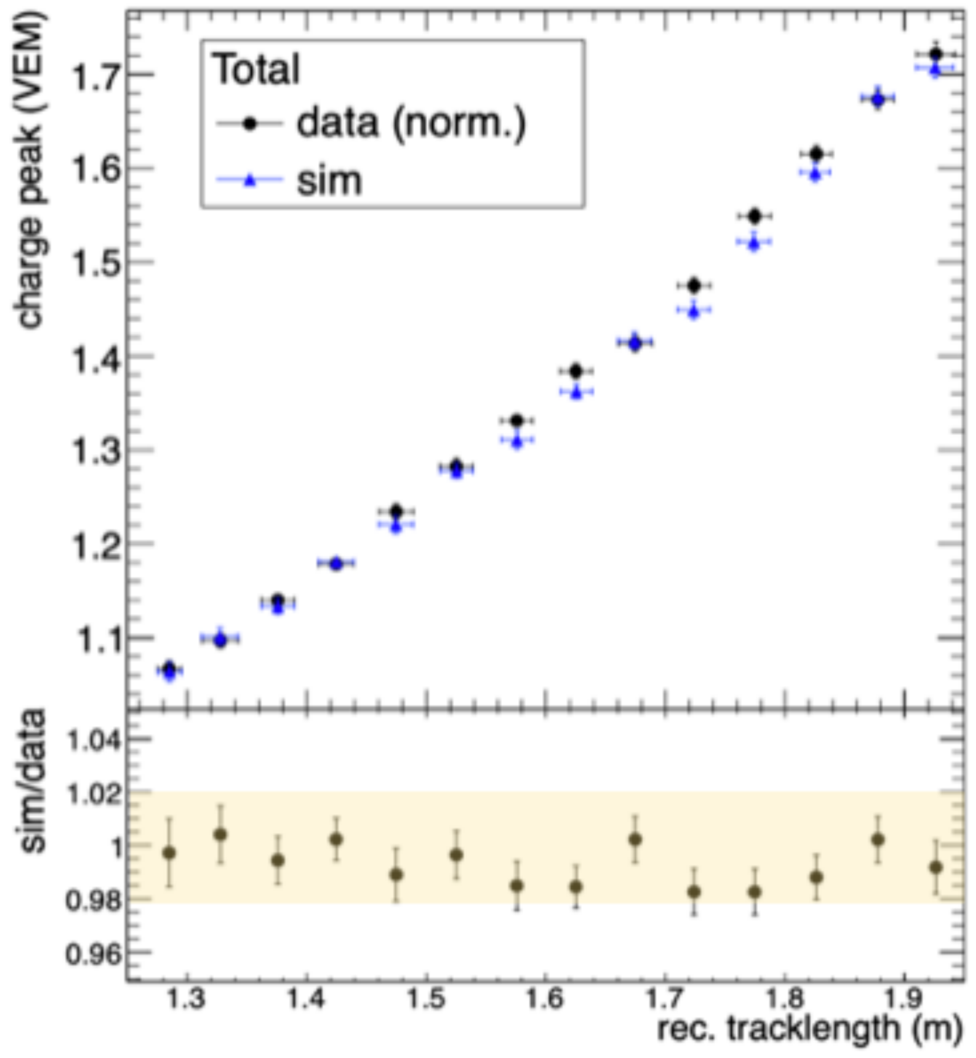
α_1 is the fraction of energy going into the hadronic sector in the first interaction

Particle physics up to $\sqrt{s} \approx 400\,\mathrm{TeV}$

Raising the bar

New detectors and calibration measurements



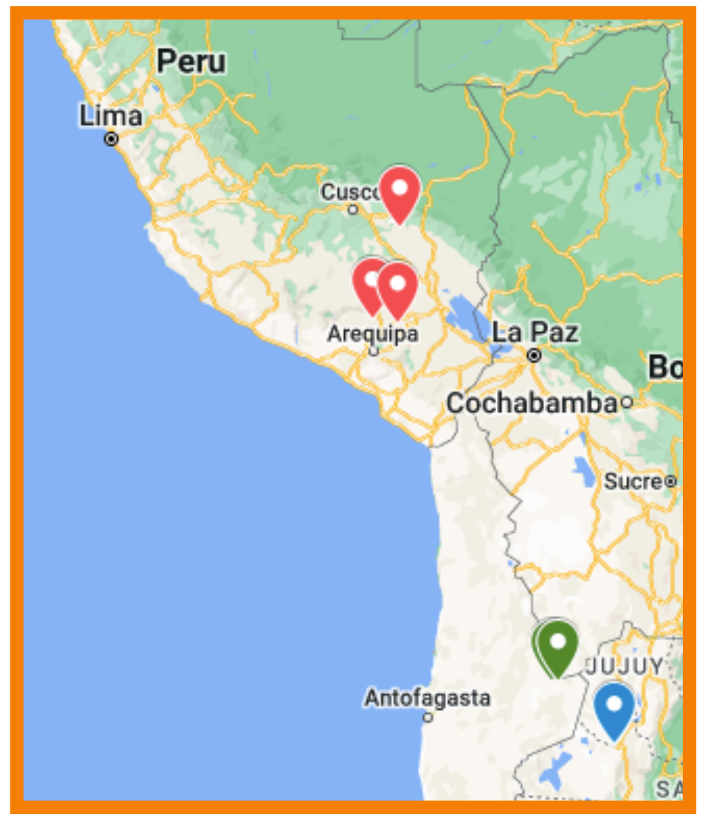


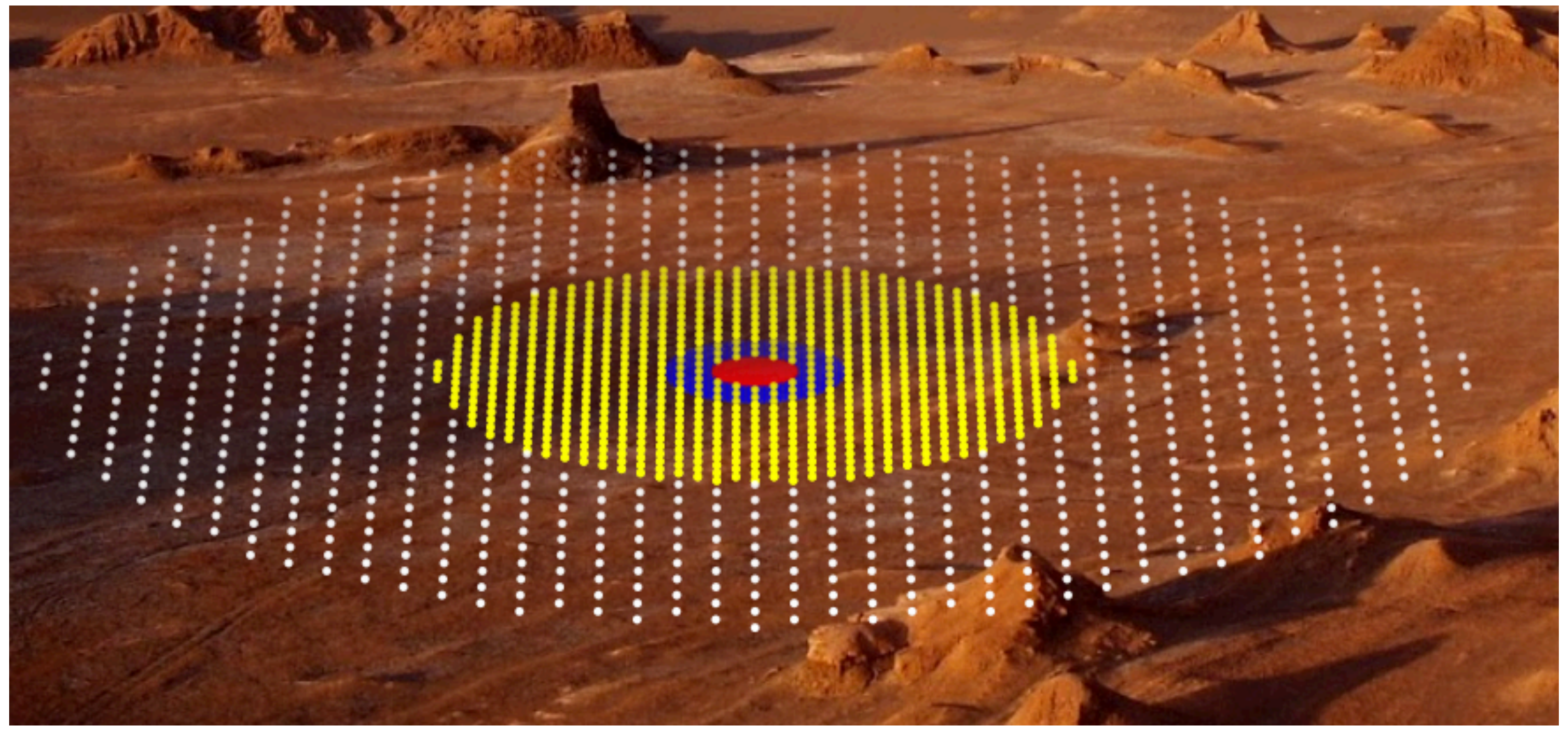
Particularly important

Machine Learning Analysis

LIP @ SWGO

The Southern Wide-field Gamma-ray Observatory

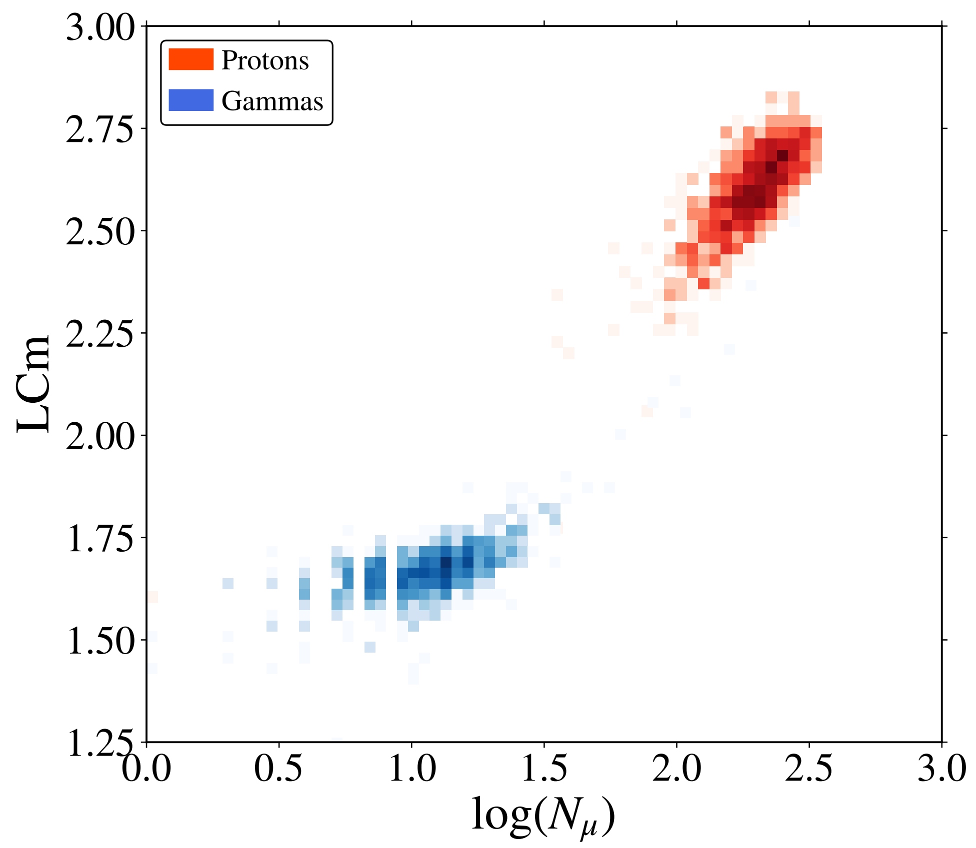


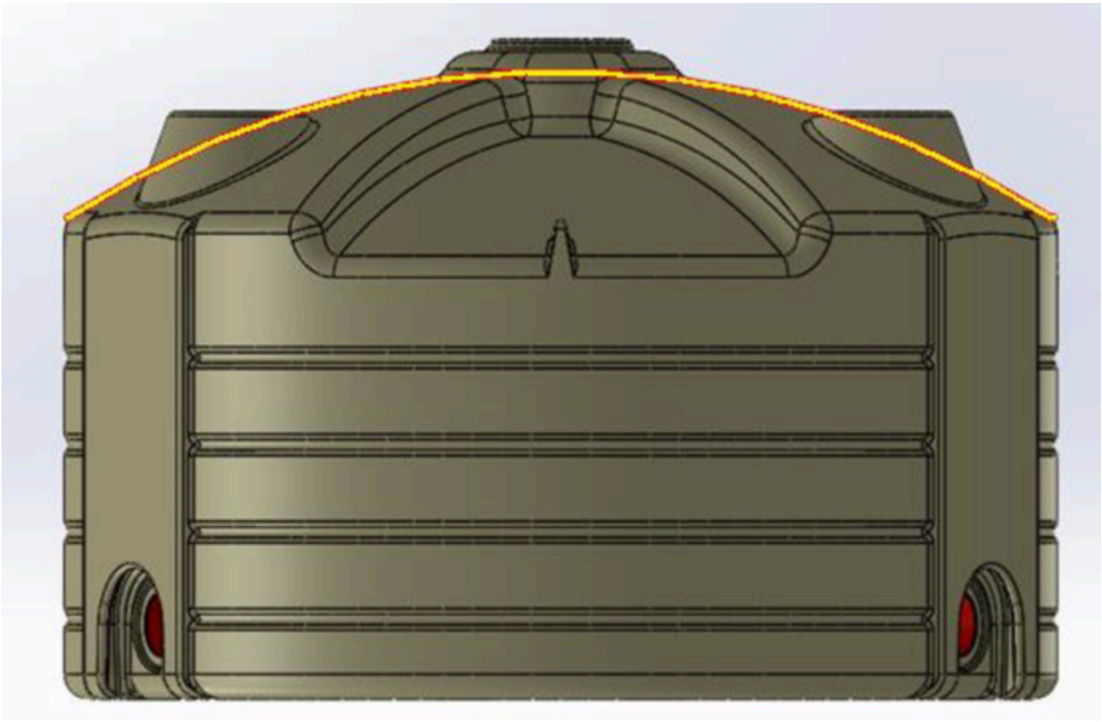


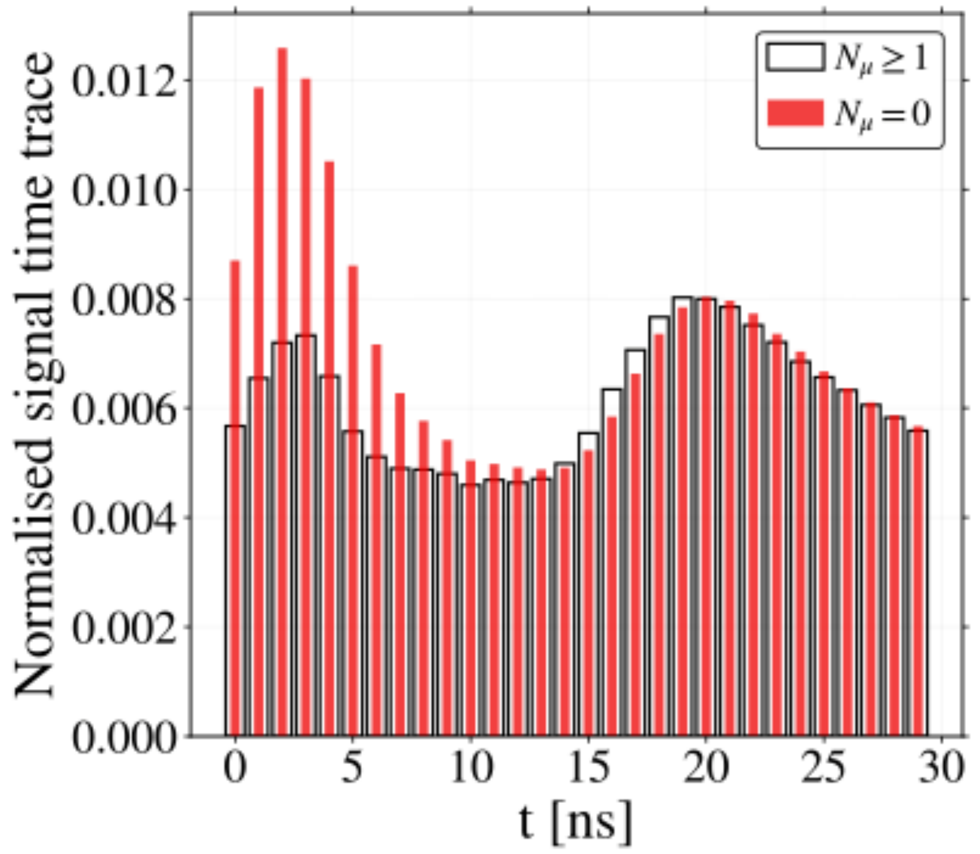
Novel shower observables for gamma/hadron discrimination

New detectors technologies able to cope with harsh environmental conditions

Improved data analysis with integrate machine learning algorithms







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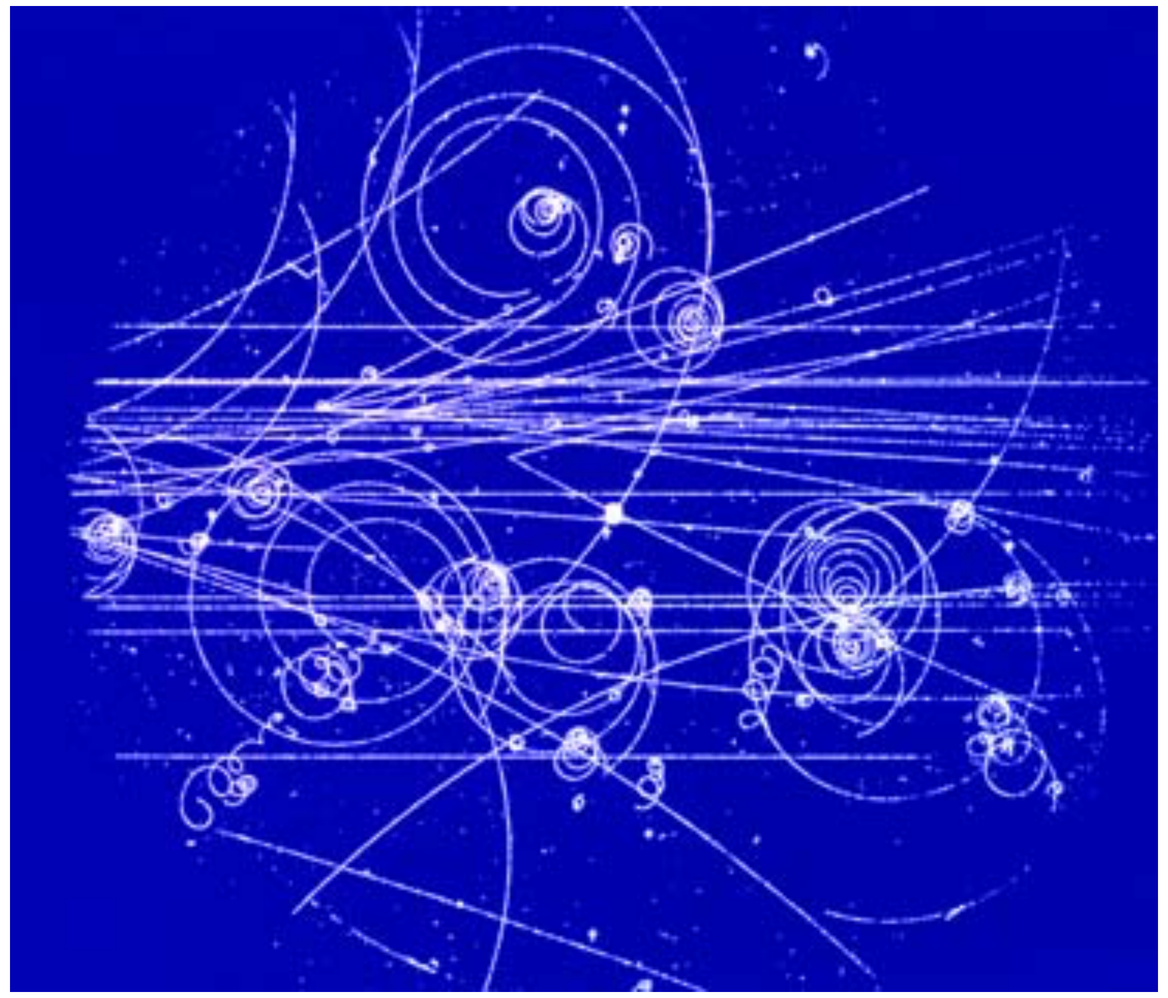
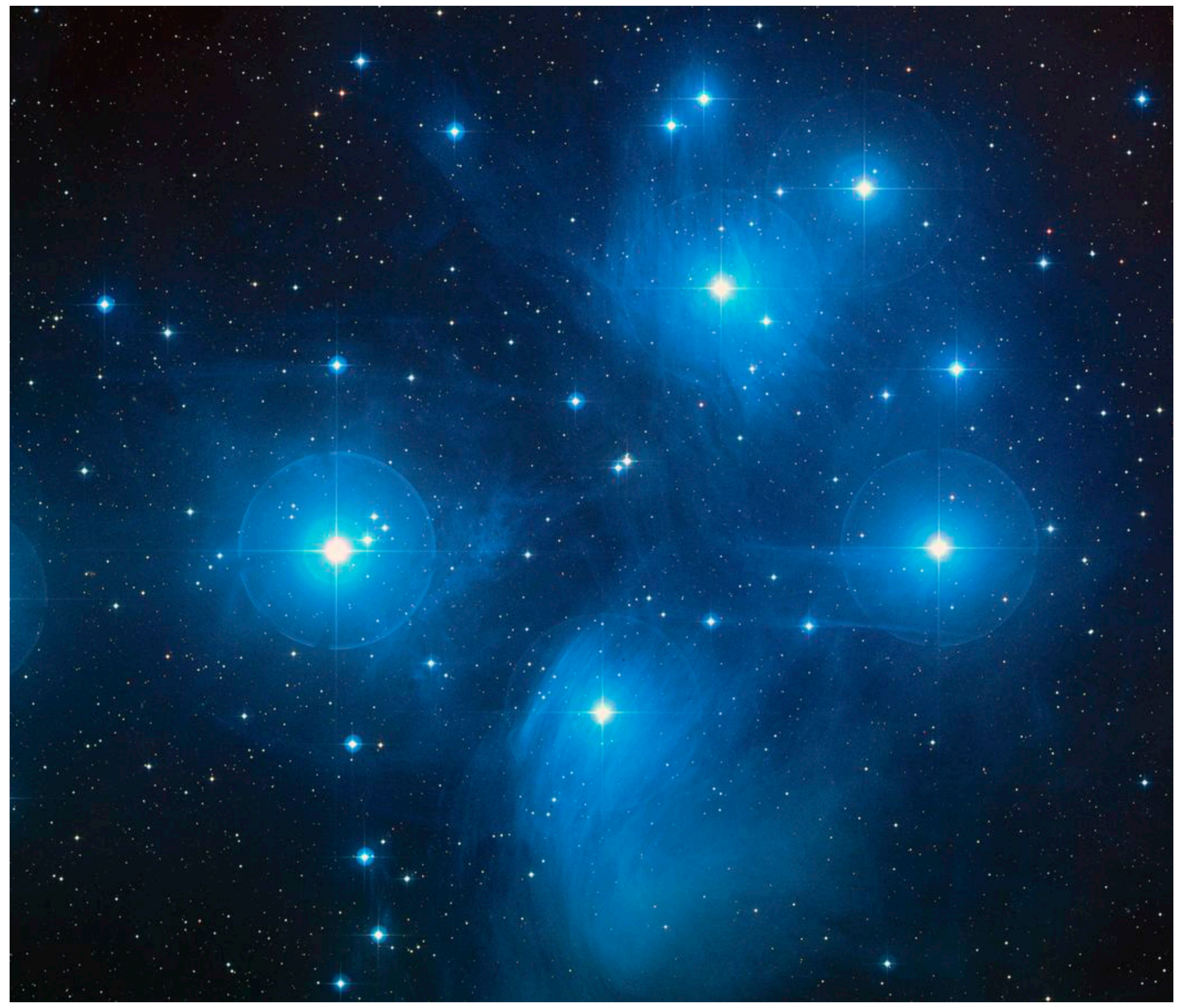
What is Astroparticle Physics?





- **Particle Physics**
  - Study the properties of matter and interactions

- **Astrophysics / Cosmology**
  - Study Universe's evolution and surrounding astrophysical objects

Astroparticle physics

Particle physics

Astrophysics

Cosmology

Understand the dynamics of our Universe through the radiation/particles collected at Earth

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Acknowledgements

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

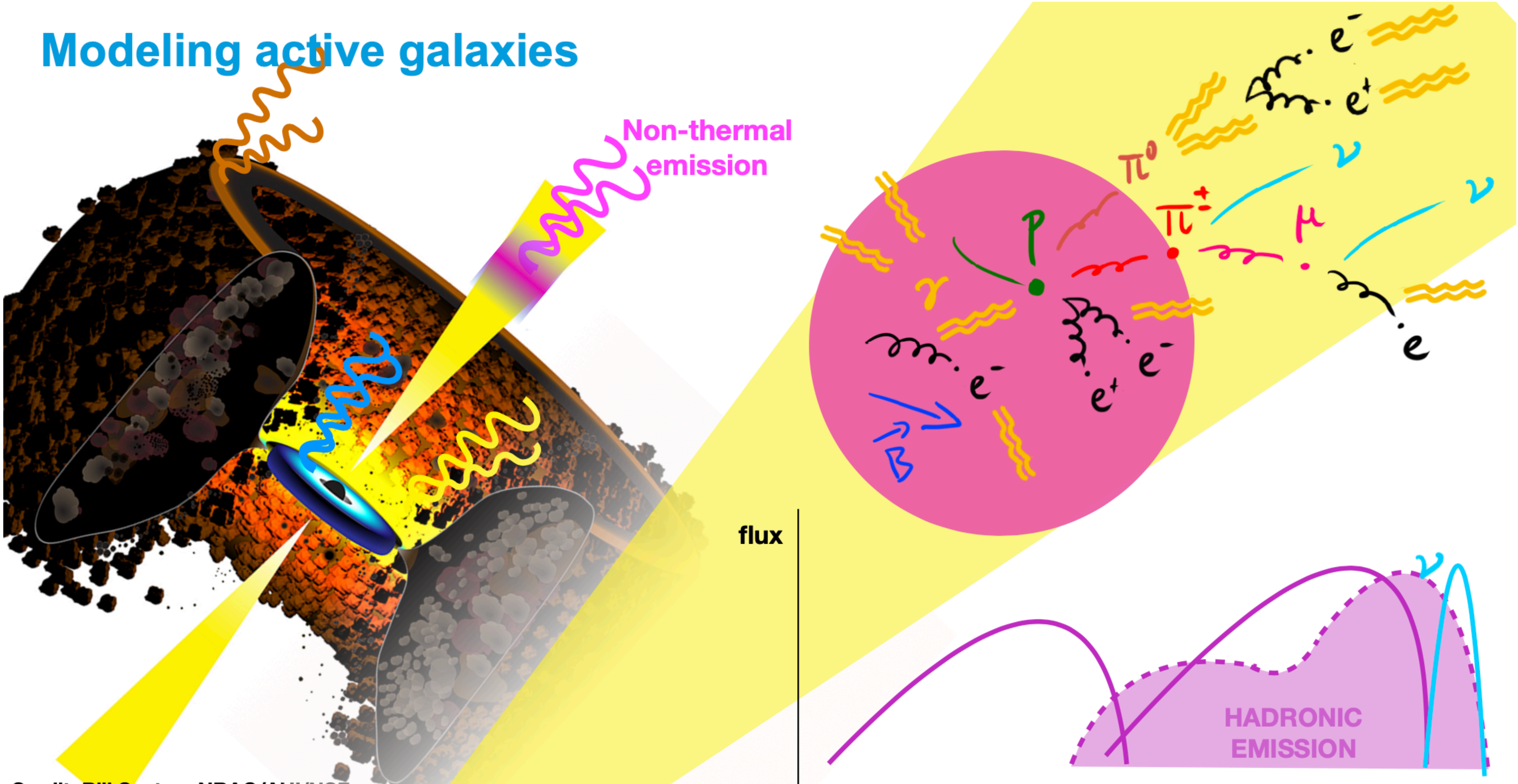
REPÚBLICA PORTUGUESA

LIP

TÉCNICO LISBOA

BACKUP SLIDES

Modeling active galaxies

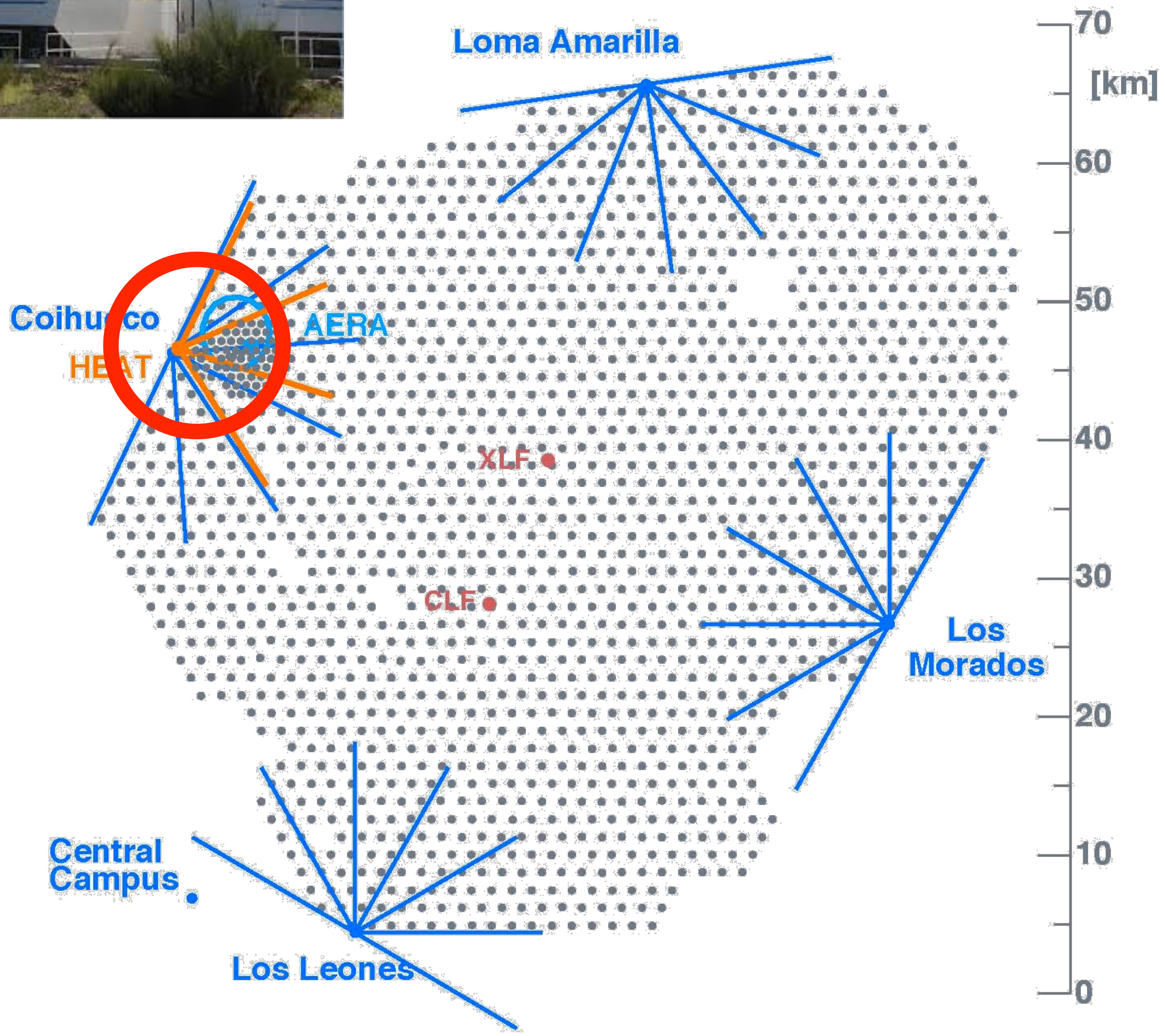


Credit: Bill Saxton, NRAO/AUI/NSF

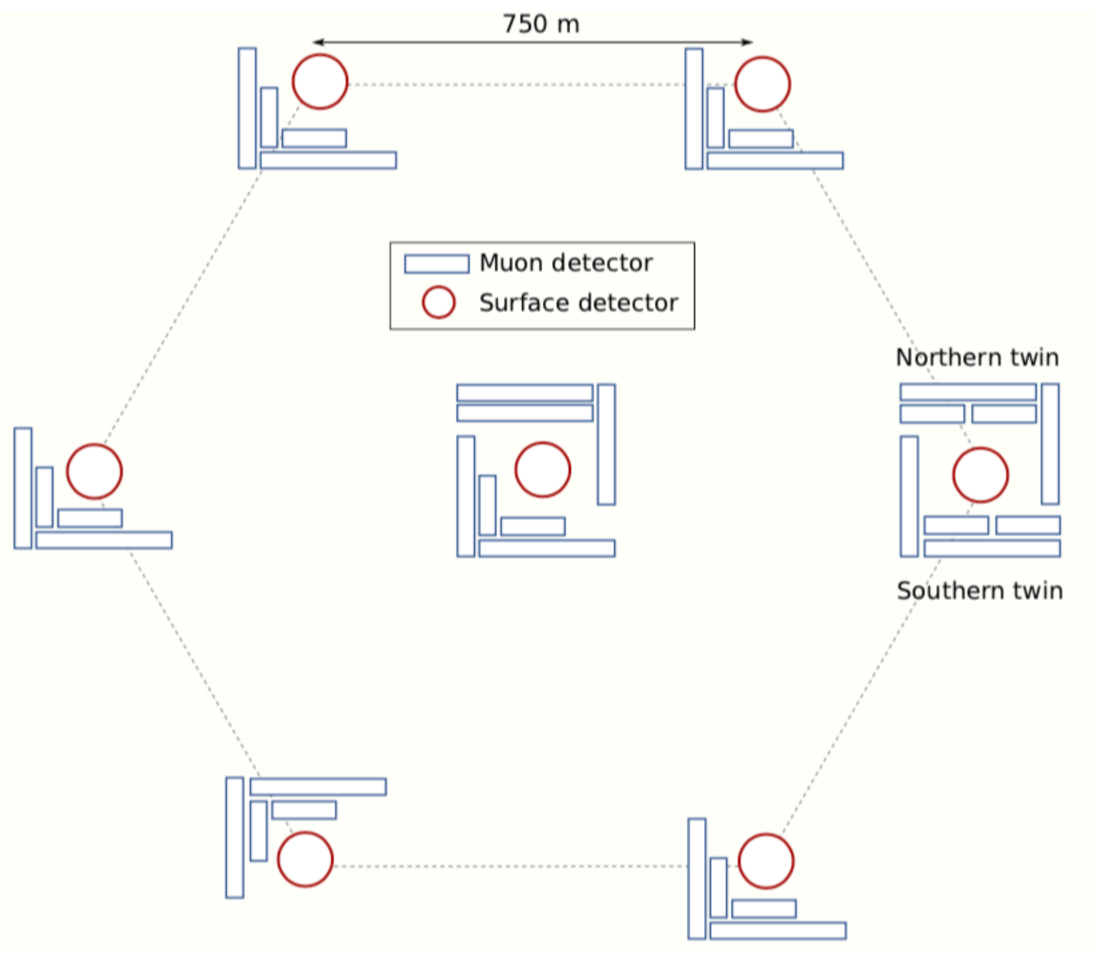
Slide from X. Rodrigues @ LIP seminar

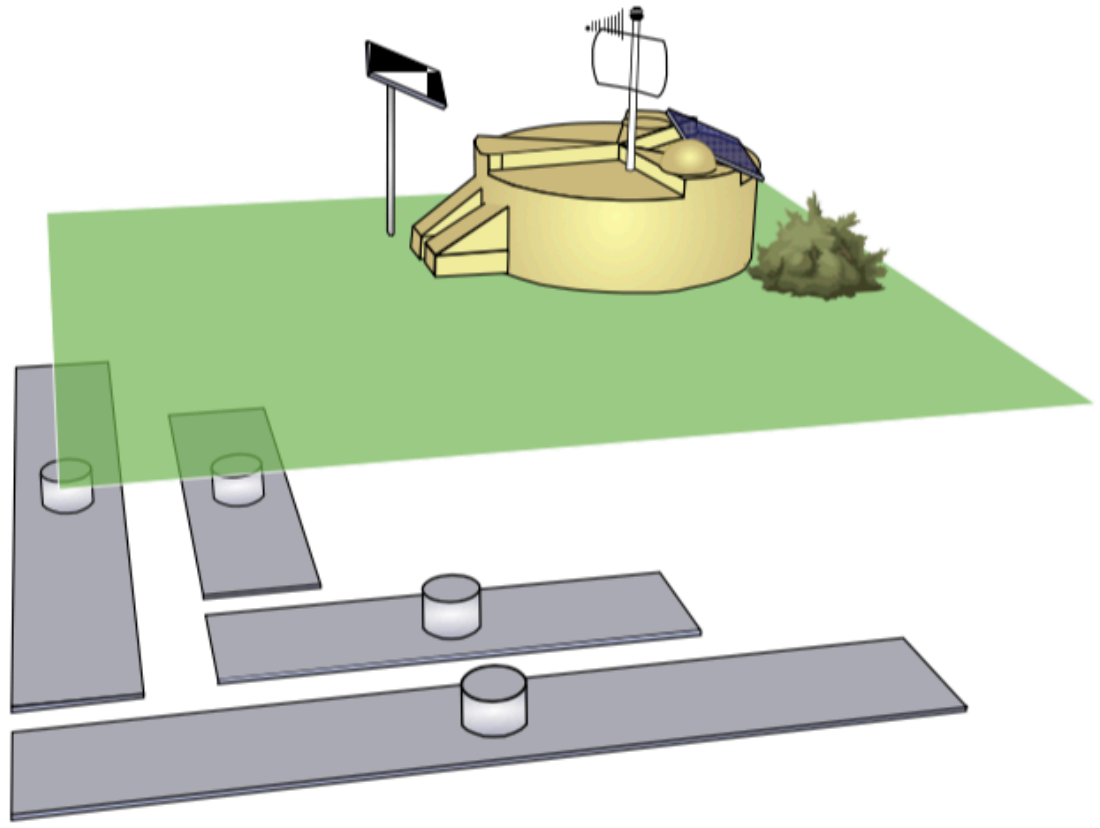
Pierre Auger Observatory

(Low energy extensions)



- **Infill** - Denser array
  - 433 m grid with 19 stations
  - 750 m grid with 61 stations
- **AMIGA** - Buried scintillators (muon detectors)
  - 19 (61) stations in 433 (750) m array, $10^{16.5} < E/\mathrm{eV} < 10^{19}$
  - 30 (60) m^2 scintillator modules
  - 2.3 m below ground
- **Auger Engineering Radio Array (AREA)**
  - 153 antennas in 17 km^2, $E > 4 \times 10^{18}$ eV

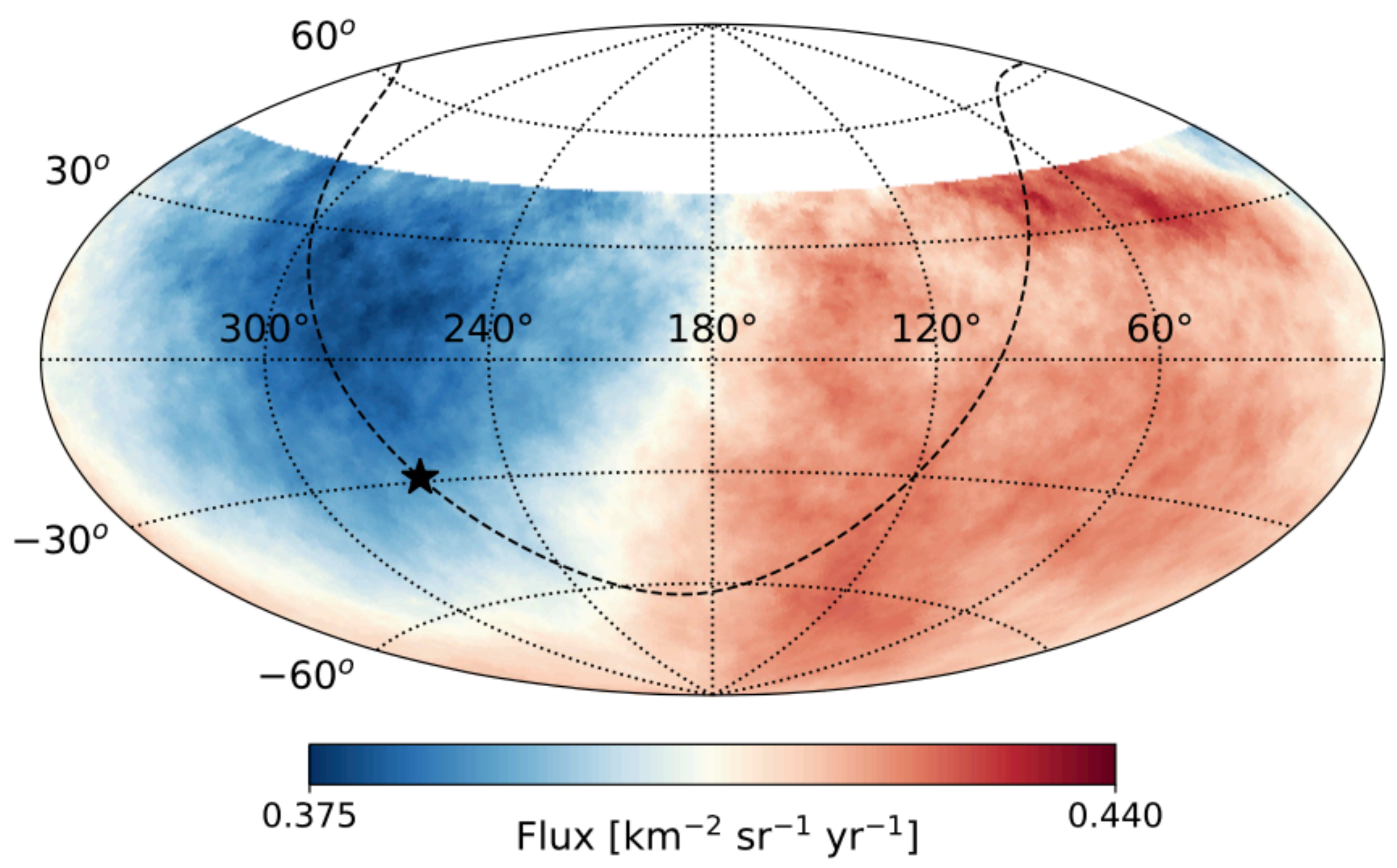


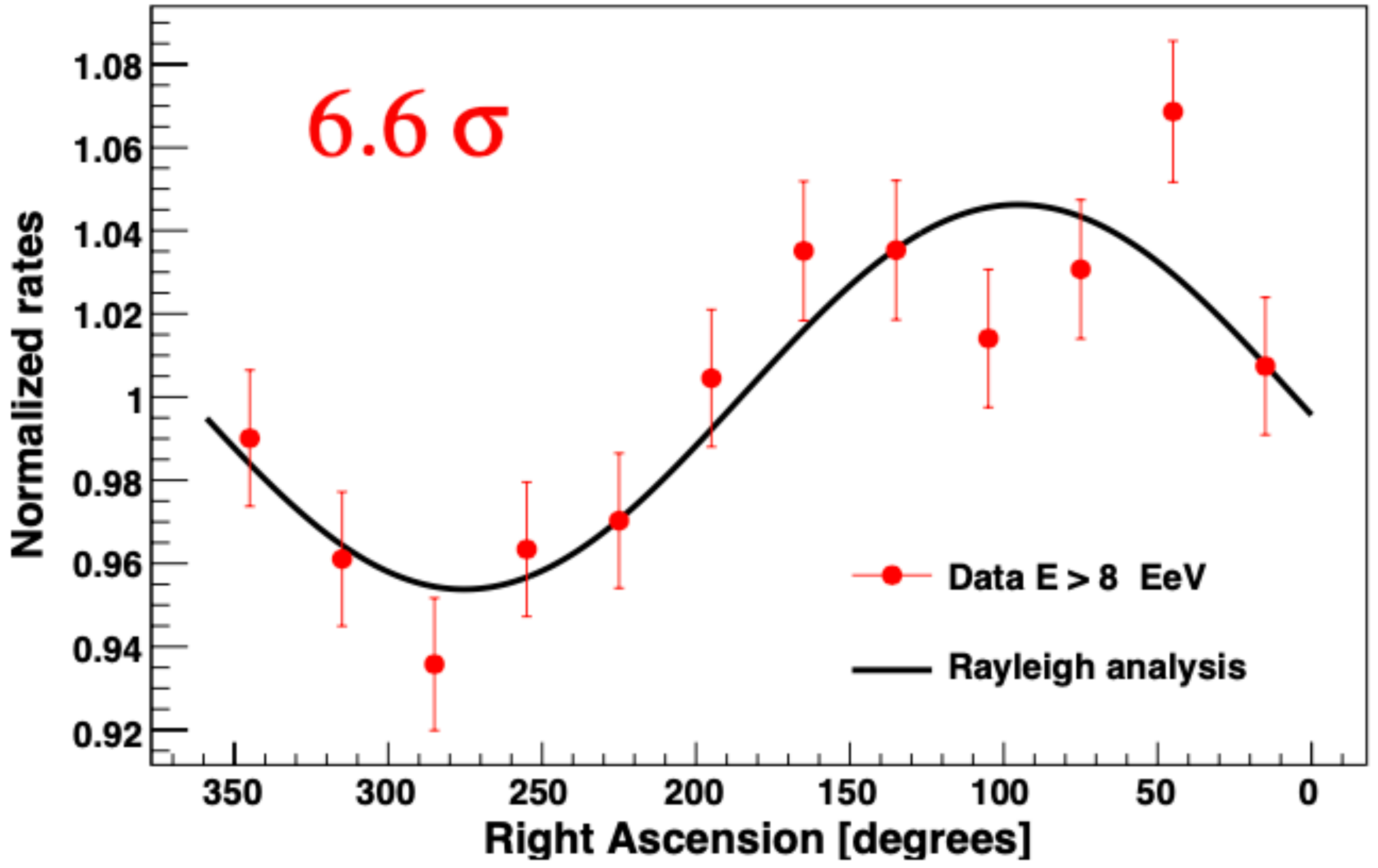


- **HEAT**
  - 3 additional FD telescopes with a high elevation FoV 30° - 60°, $E > 10^{17}$ eV

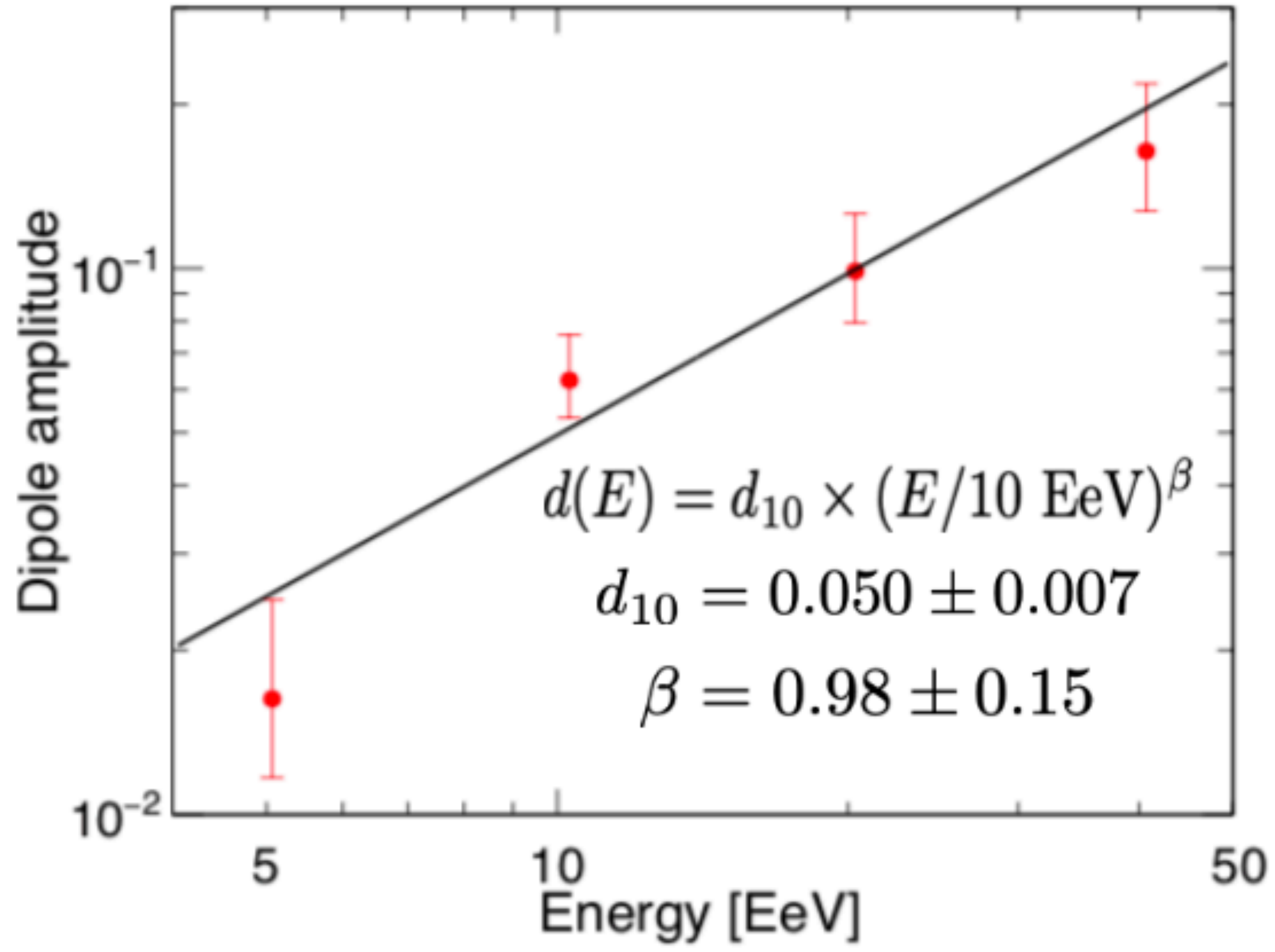
The UHECR dipole

Pierre Auger Collaboration, ICRC21





Exposure
until end of 2020
(θ < 80°)
110 000 km^2 sr yr
p ~ 5 x 10^{-11}



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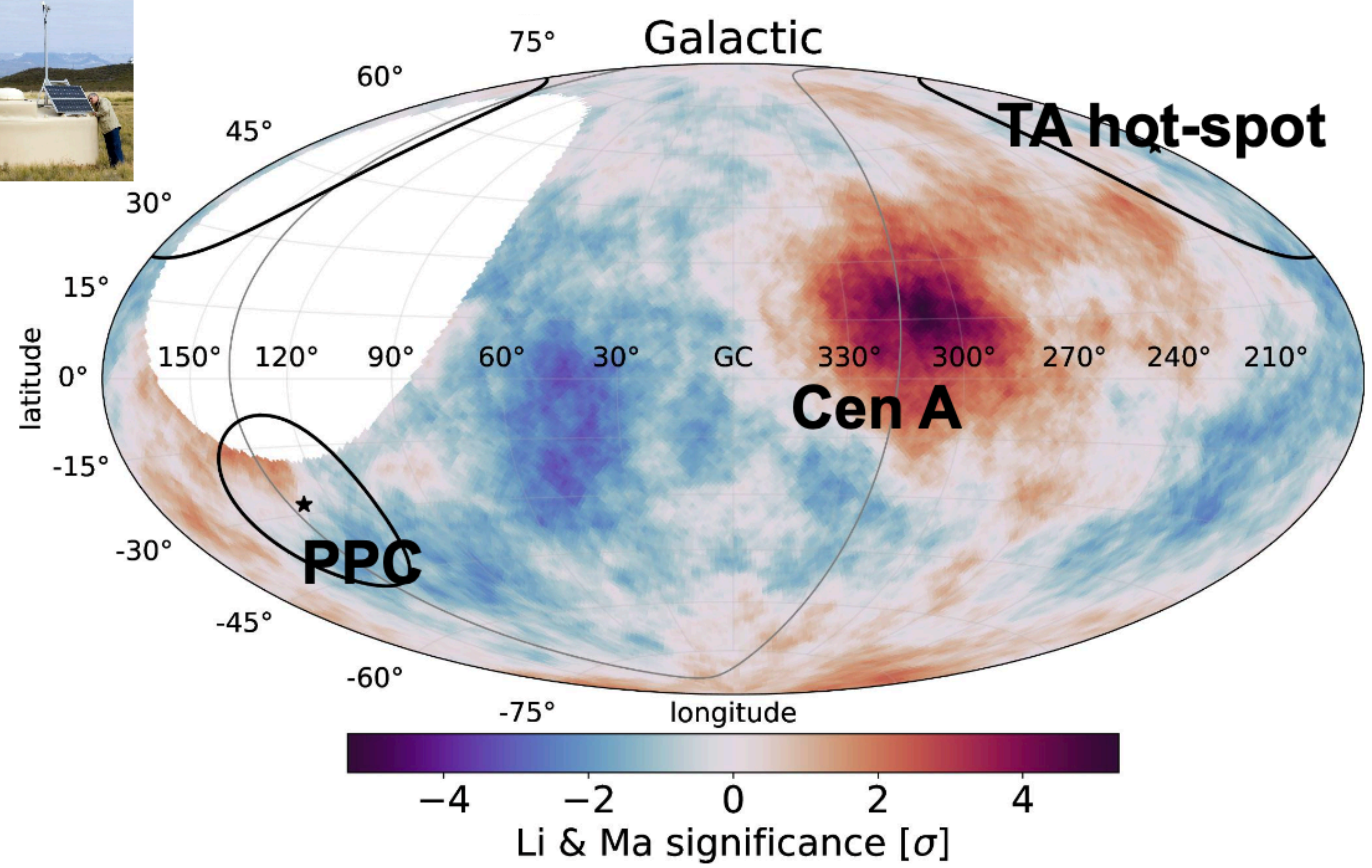
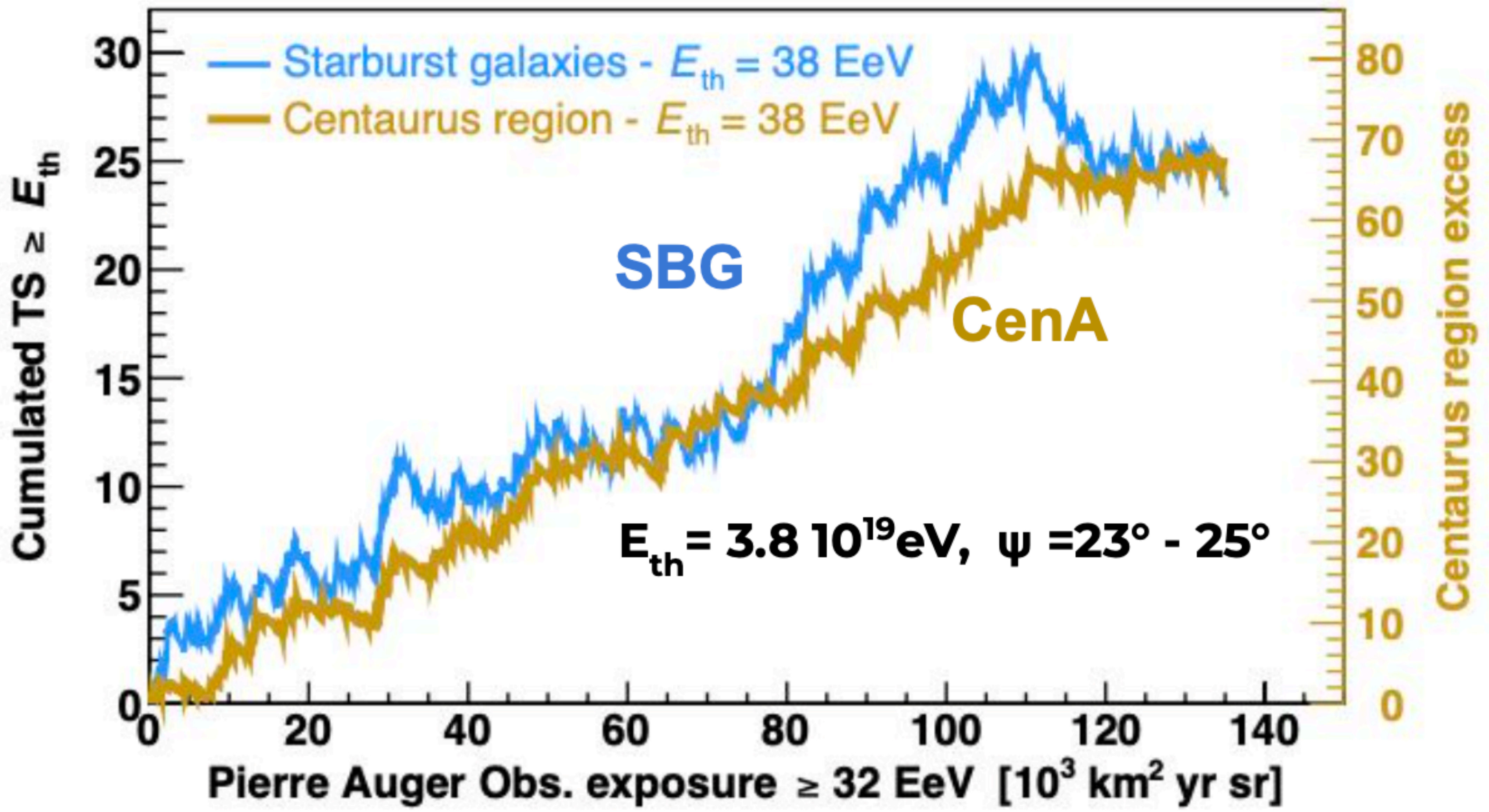
Arrival directions: intermediate scale

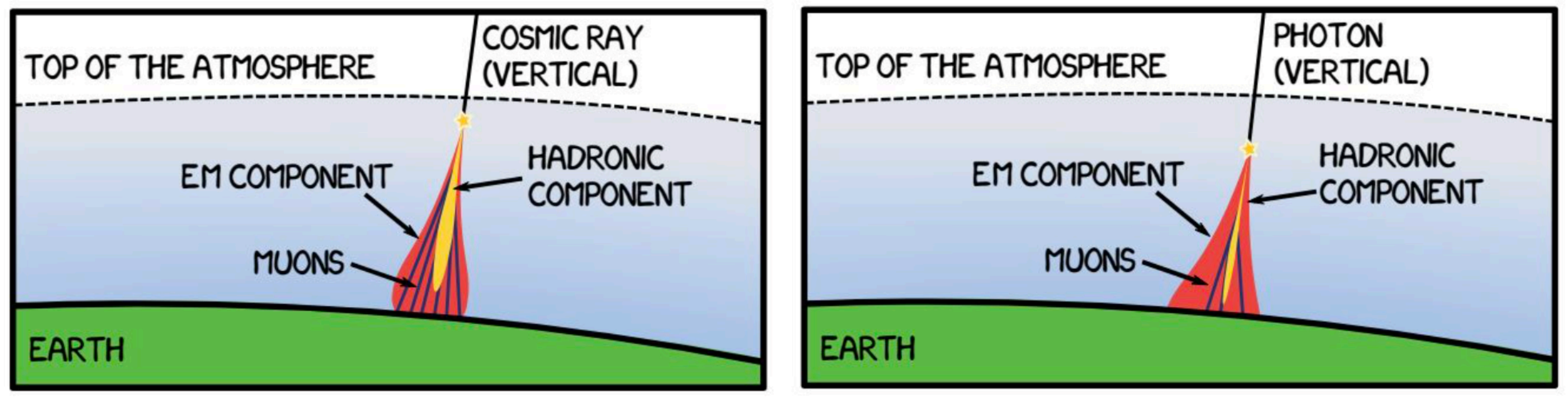


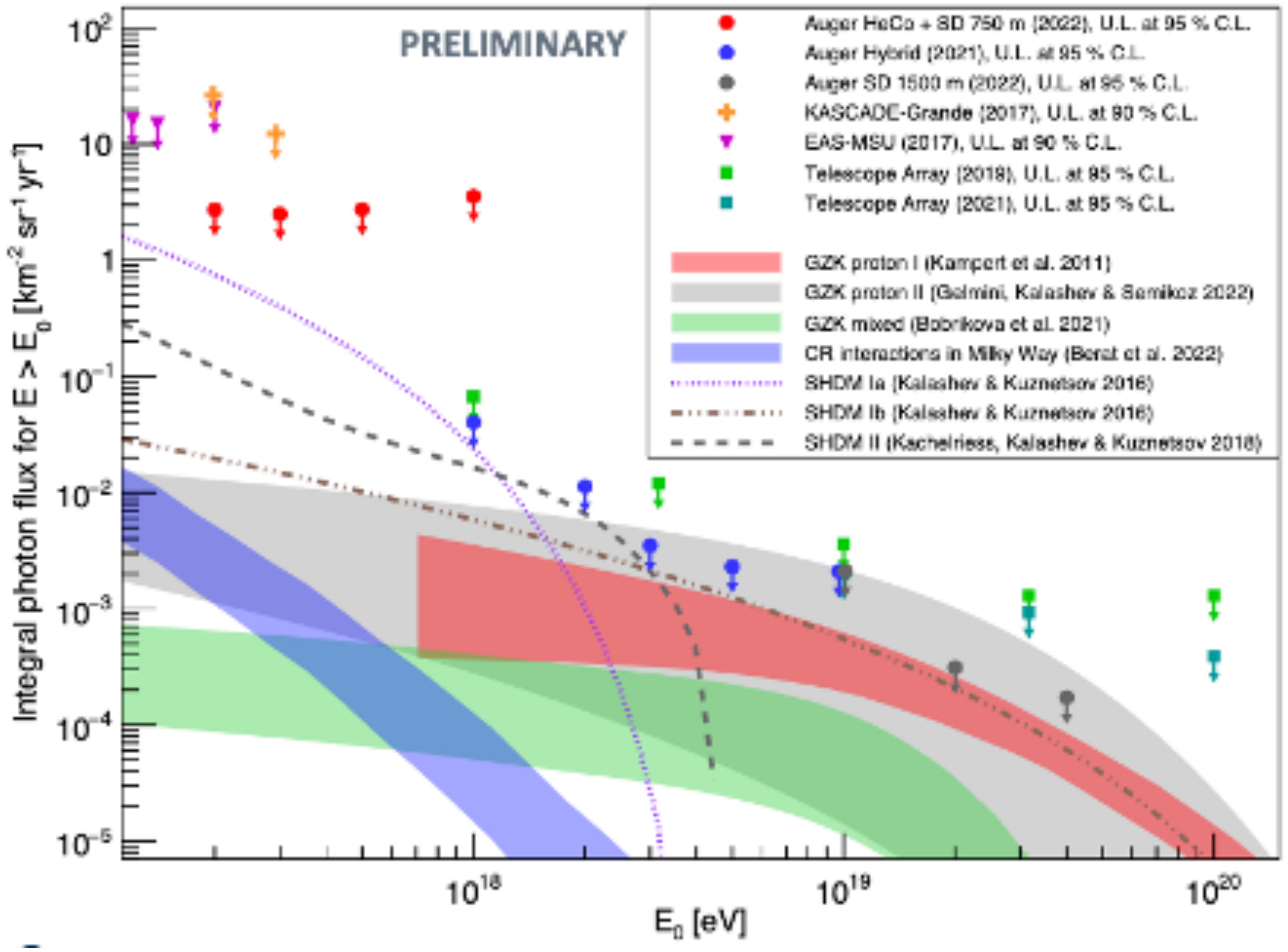


- ✧ The most significant excess at Cen A 4σ
- ✧ Several likelihood tests for correction of arrival direction with astrophysical catalogs
- ✧ Most significant signal at 3.8σ for Star Burst Galaxies catalog

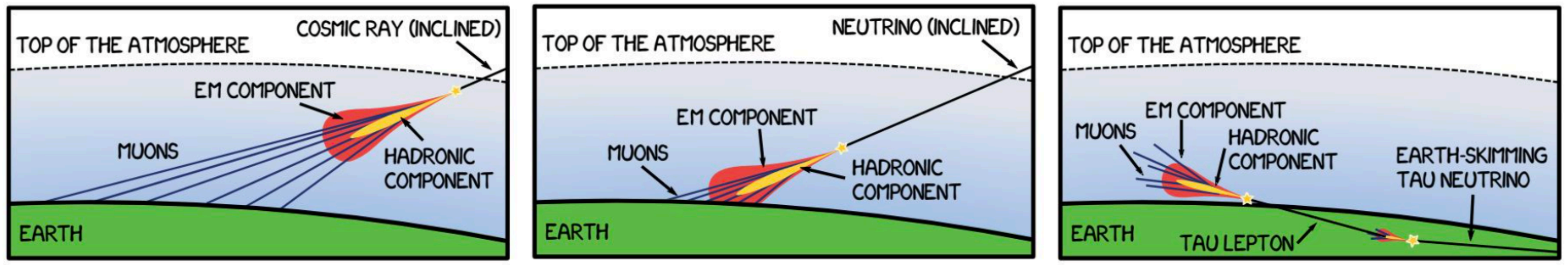
Neutral particles searches

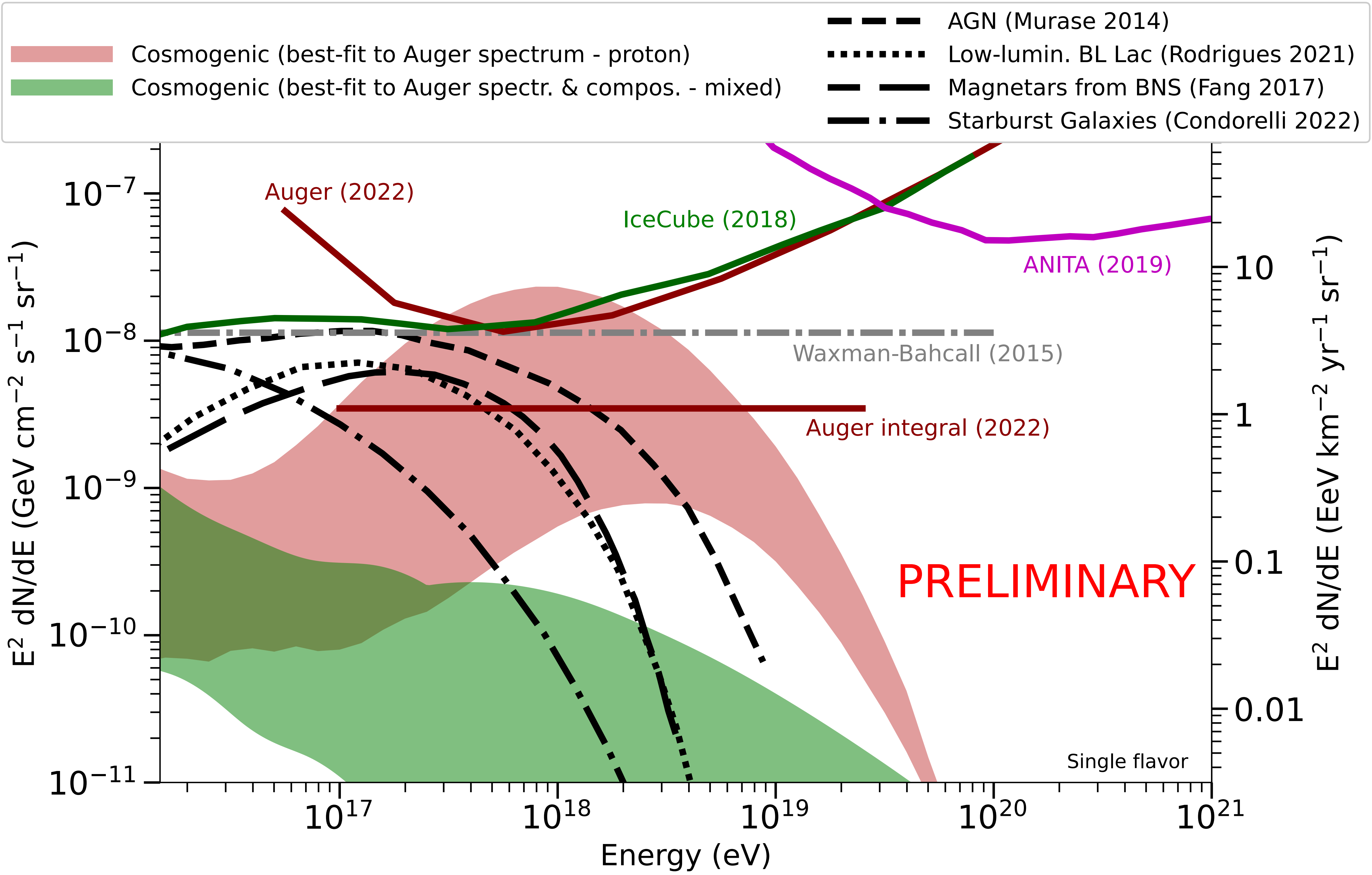
Photons





NeutrInos





No UHE photons or neutrino have been observed yet

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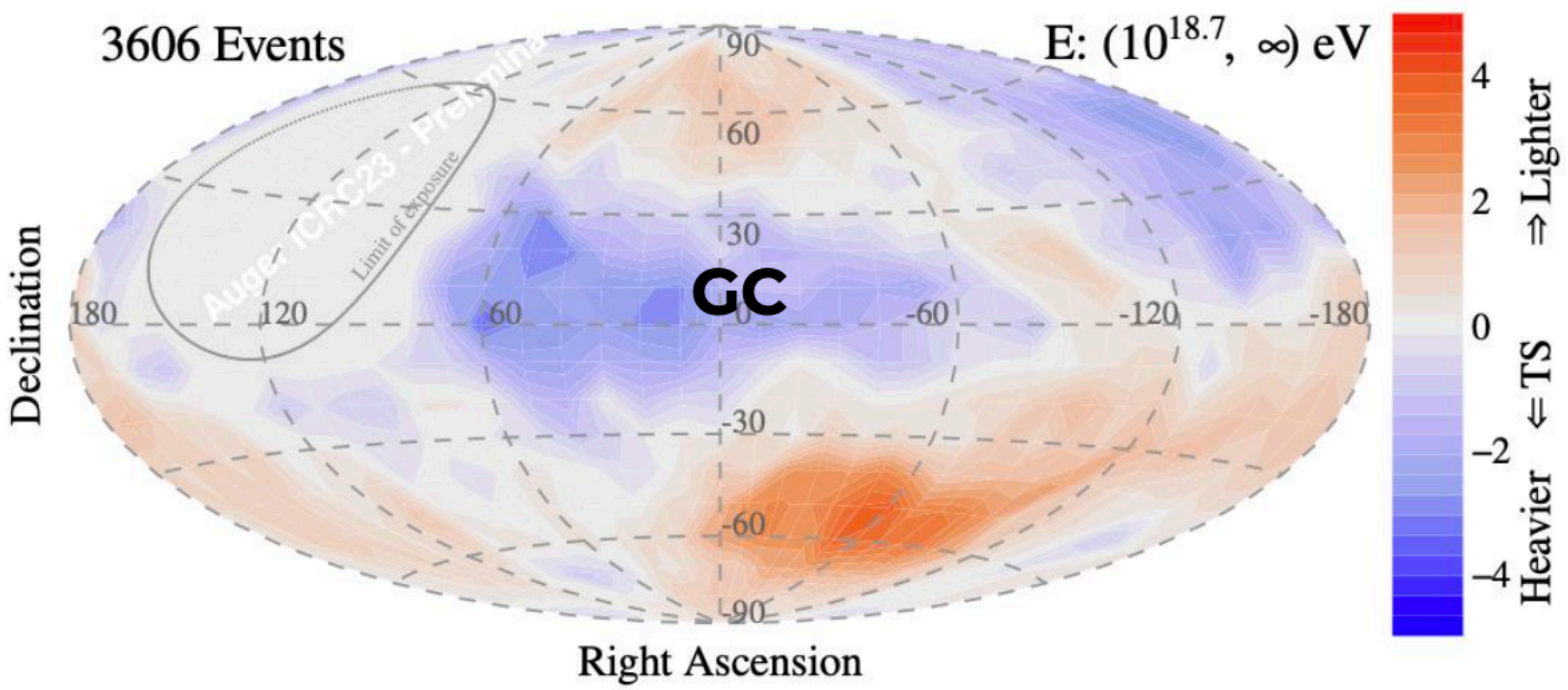
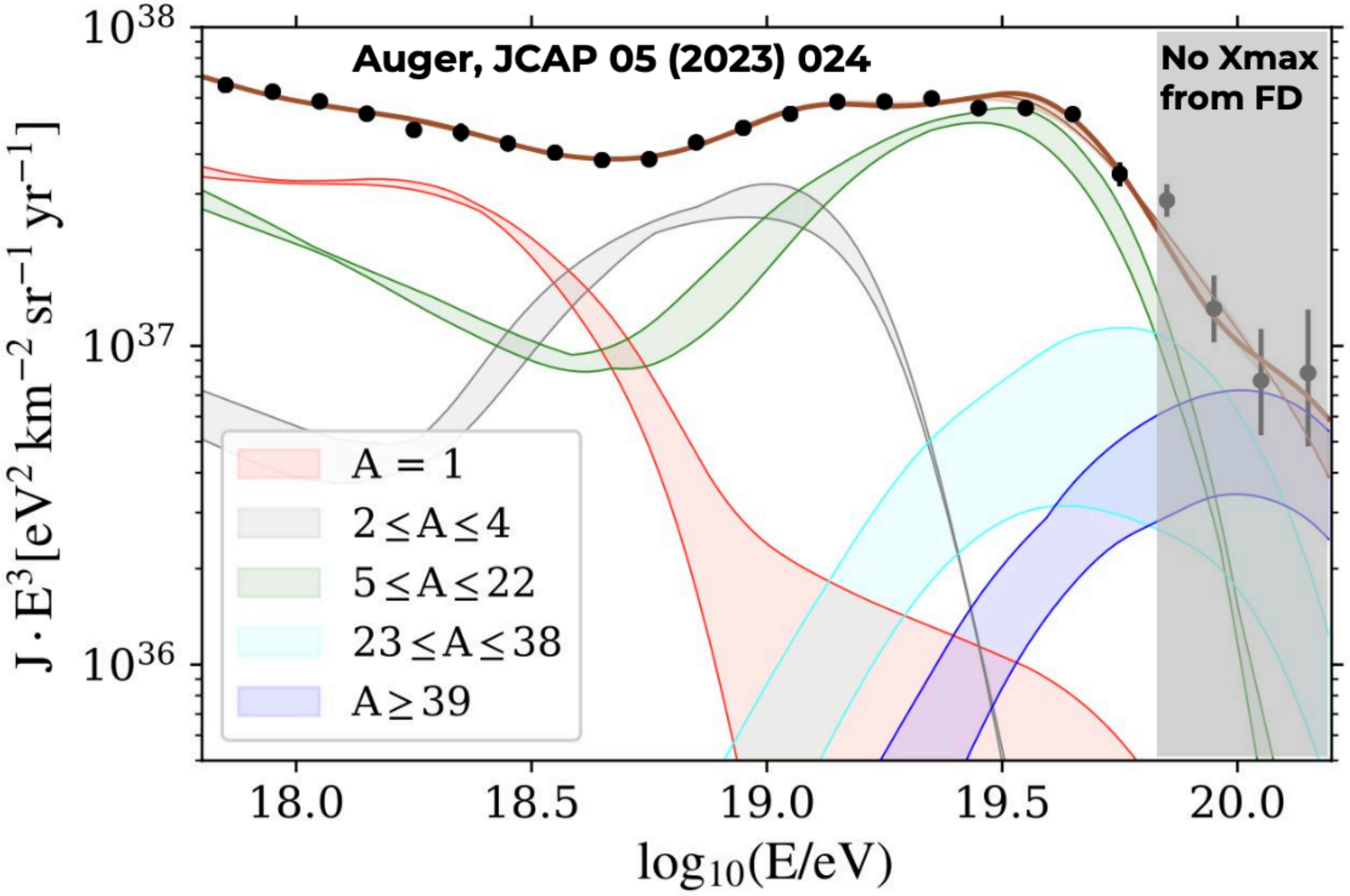
Mass composition enhanced anisotropy





- ✧ Heavier composition from the galactic plane ($< 4\,\sigma$)
- ✧ Combined spectrum + composition fit suggest an acceleration mechanism $\propto A$

But…

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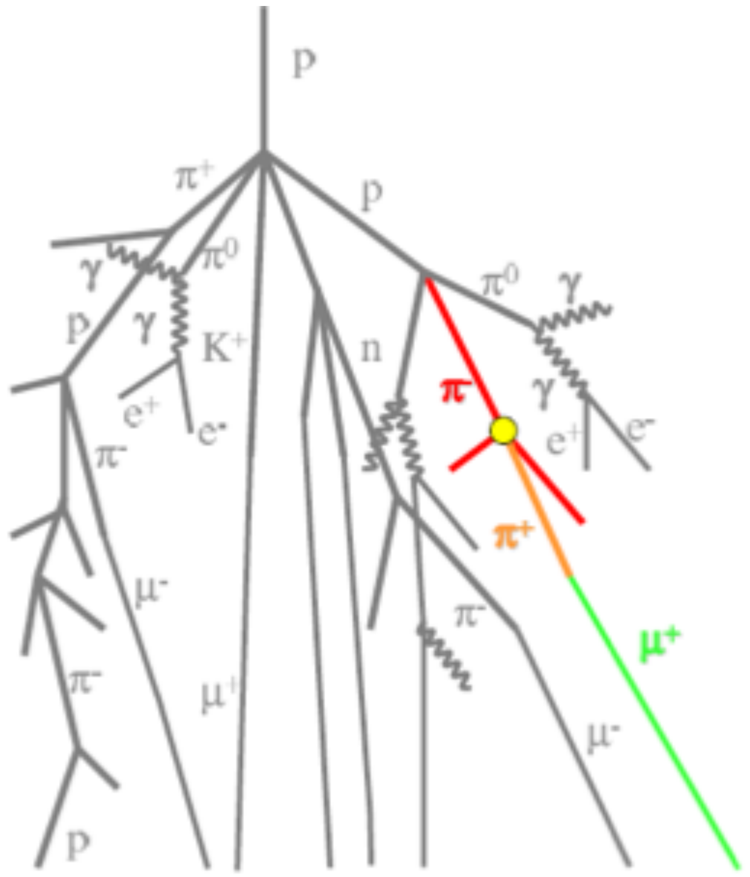
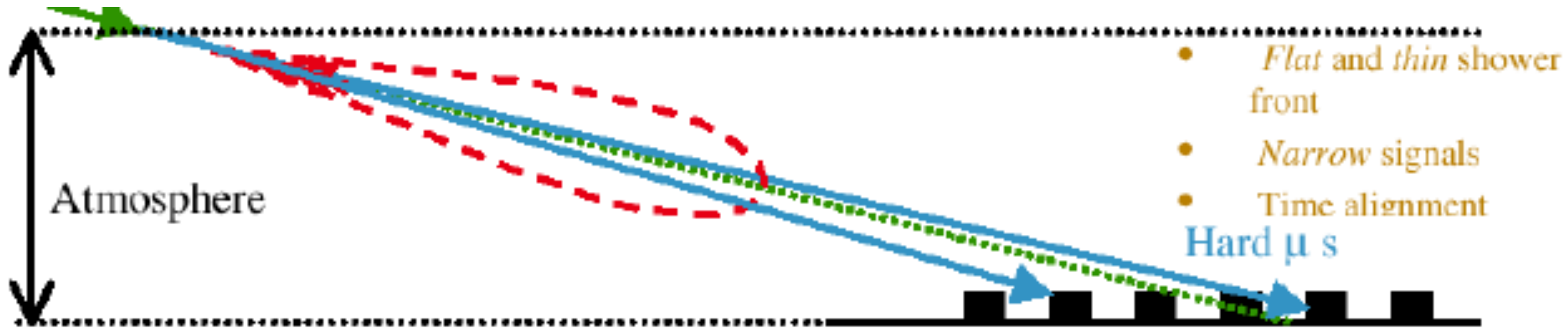
Exploration of inclined showers

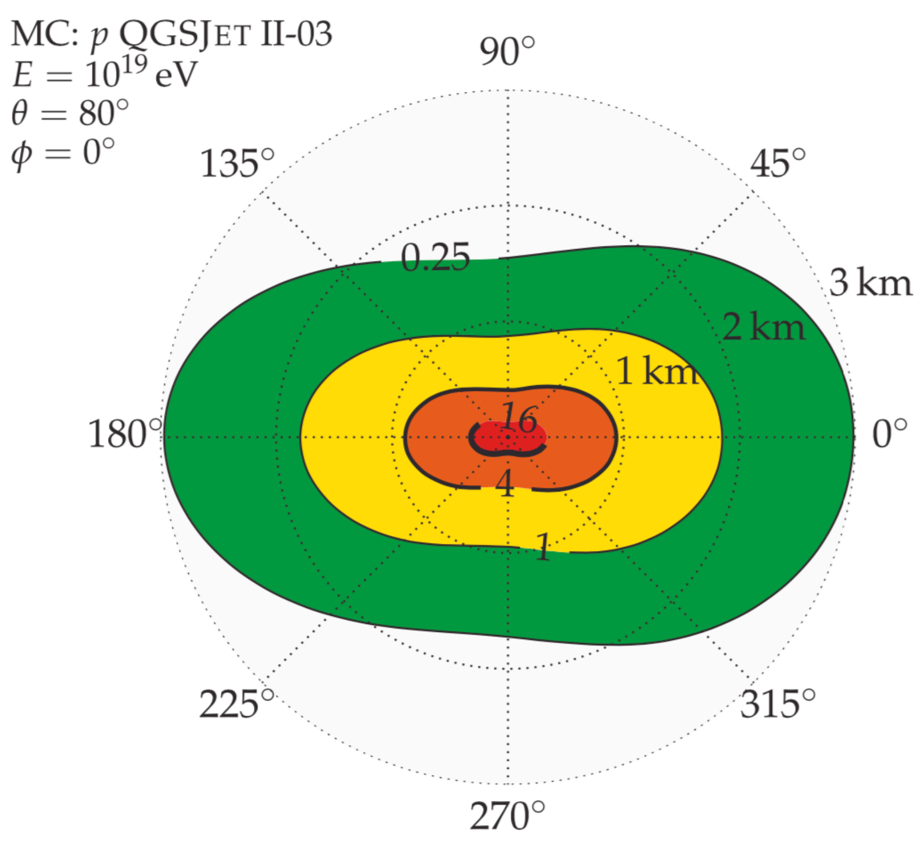
- Muons → Assess Hadronic interaction models
  - Data selection
    - Zenith angles [62° ; 80°]
    - E > 4 x 10^{18} eV

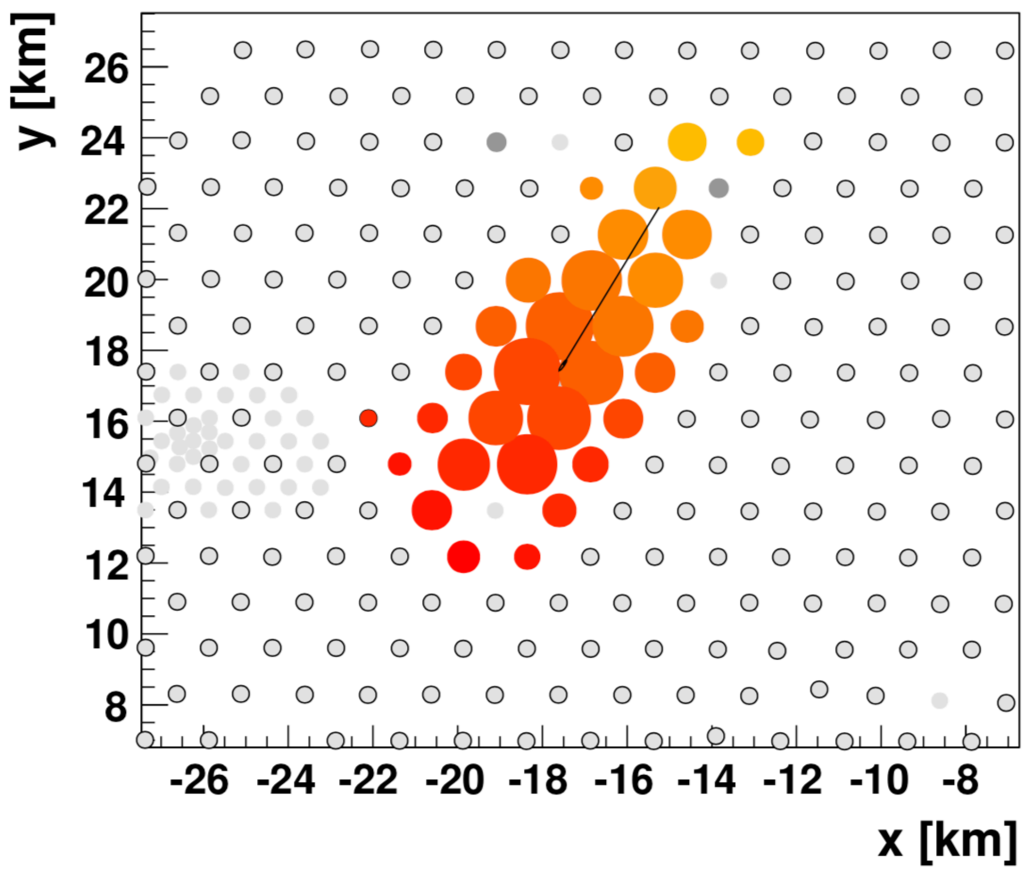


- Inclined shower → Muons



- Energy given by the Fluorescence Detector
- 281 hybrid events





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

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

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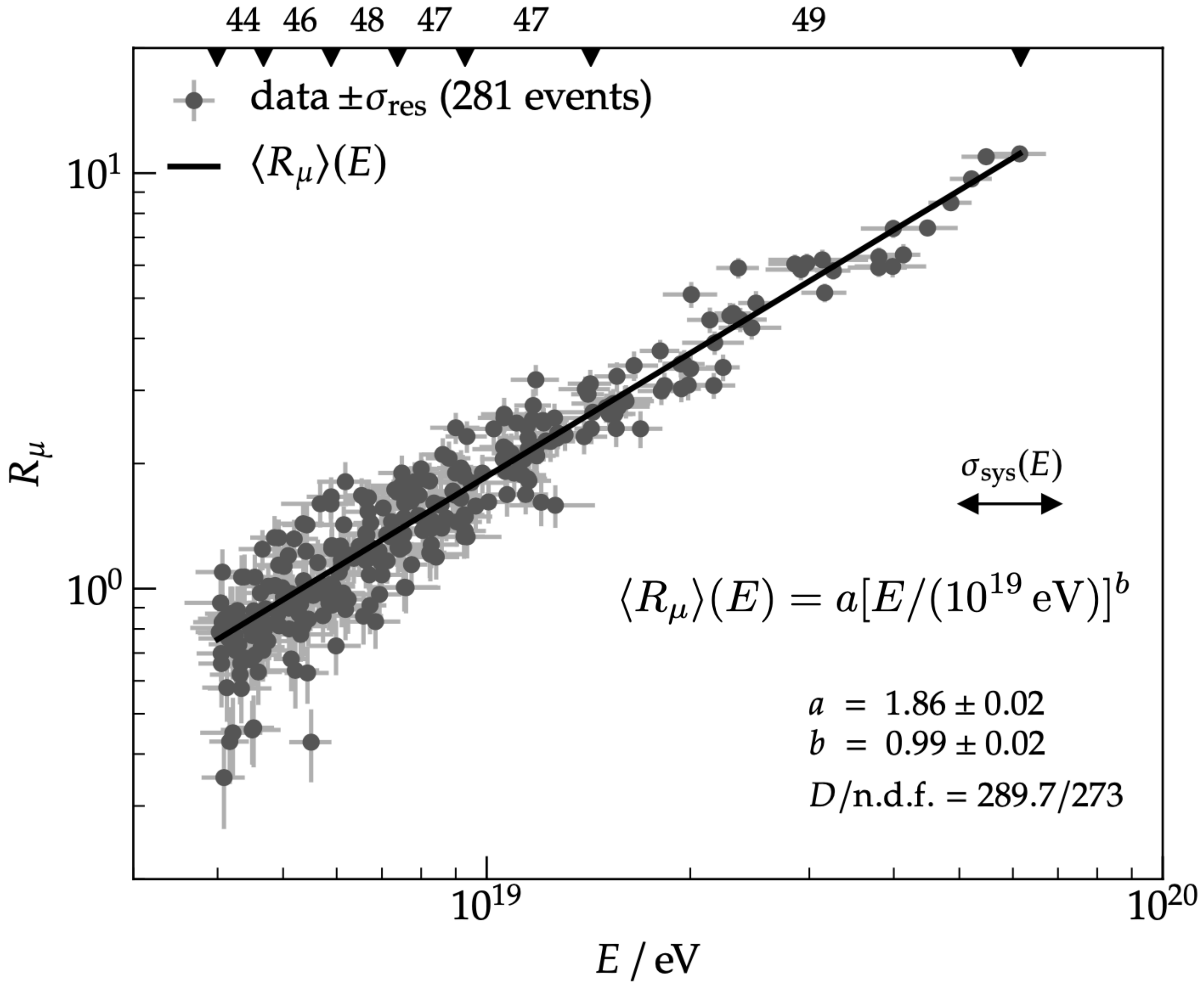
Measurement of the EAS muon content

- Done using hybrid inclined showers
- Perform a **likelihood fit** including all reconstruction uncertainties (detector, energy…)
- Extraction of the **two** first **momenta of the muon distribution** as a function of the primary energy

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

Sensitive to the EAS muon number - R_μ

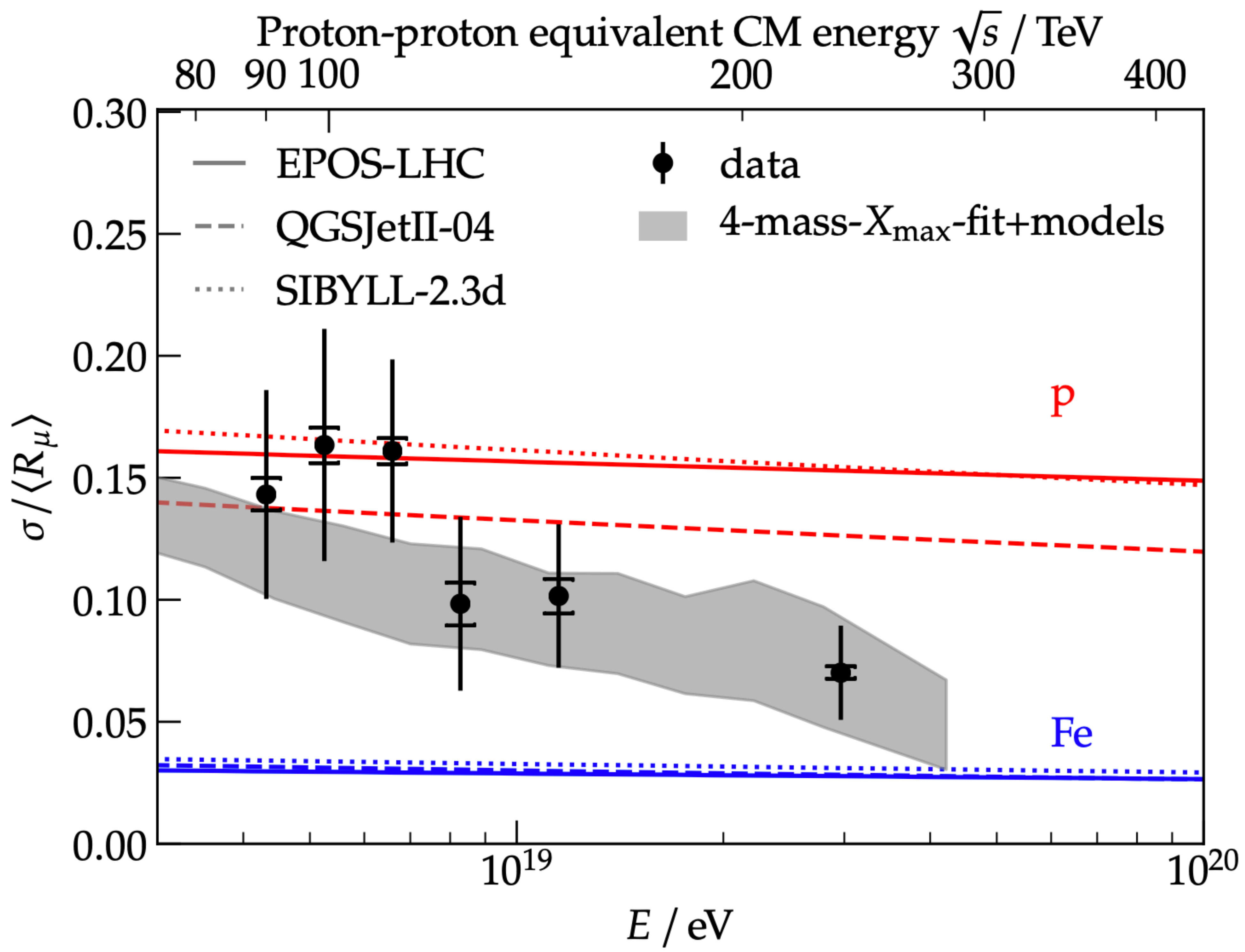


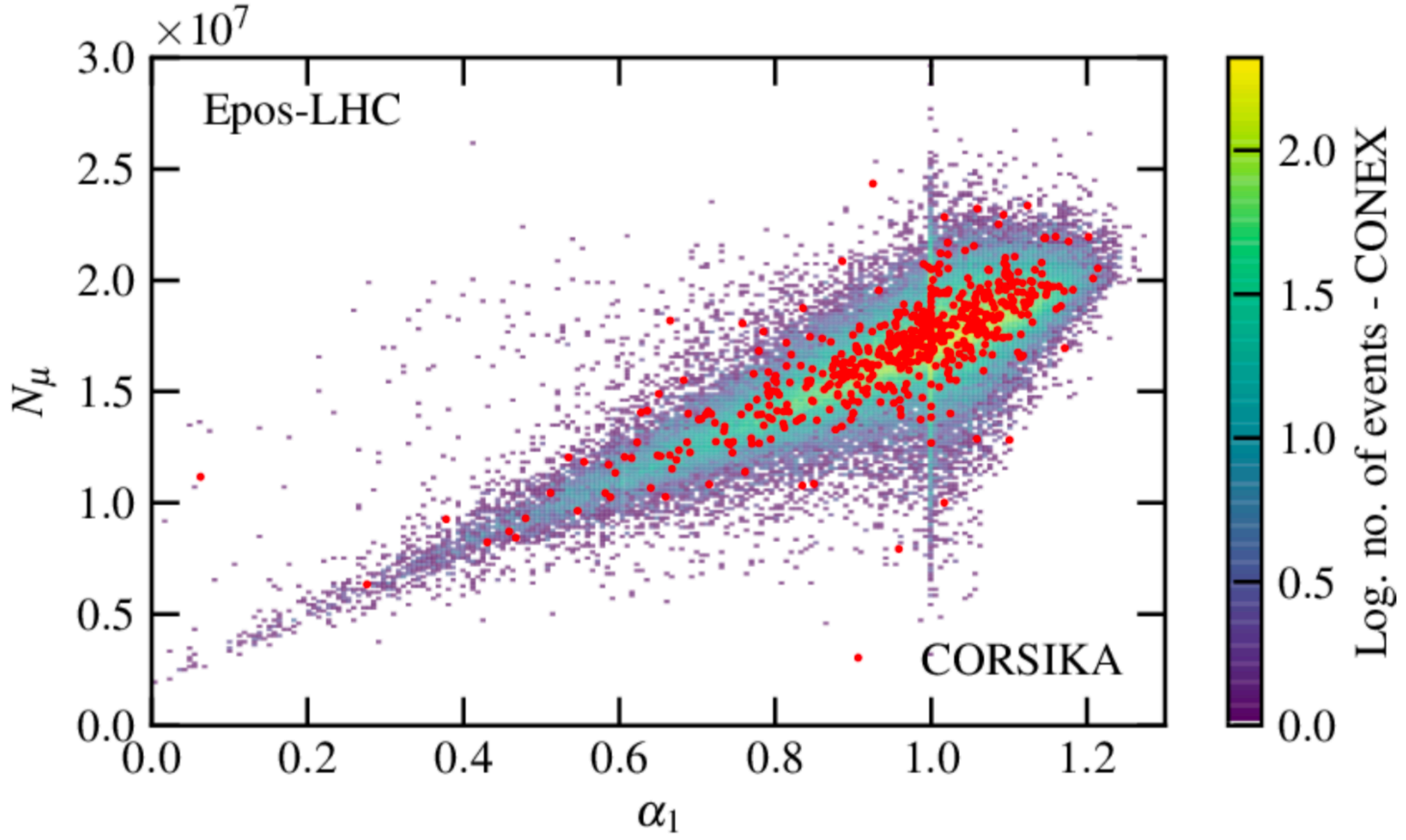
Sensitive to the EAS calorimetric energy - E

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

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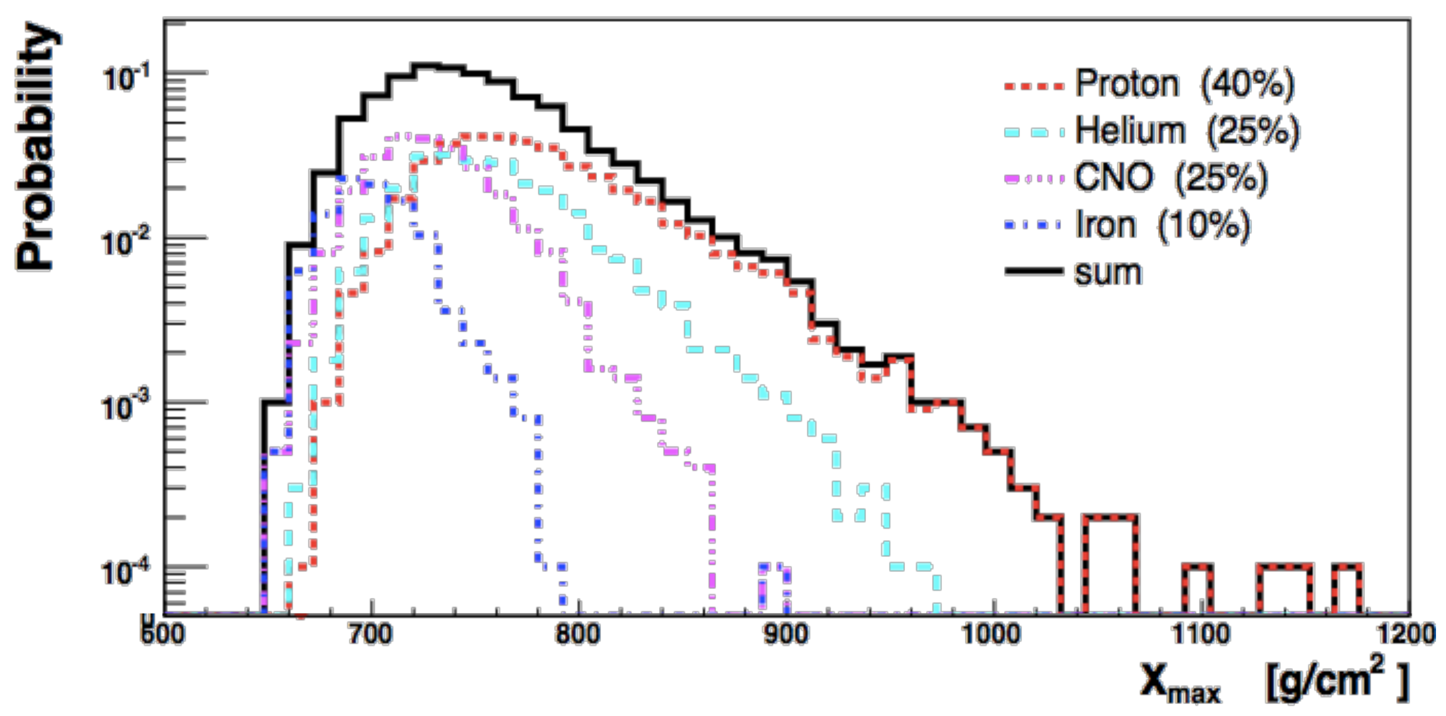
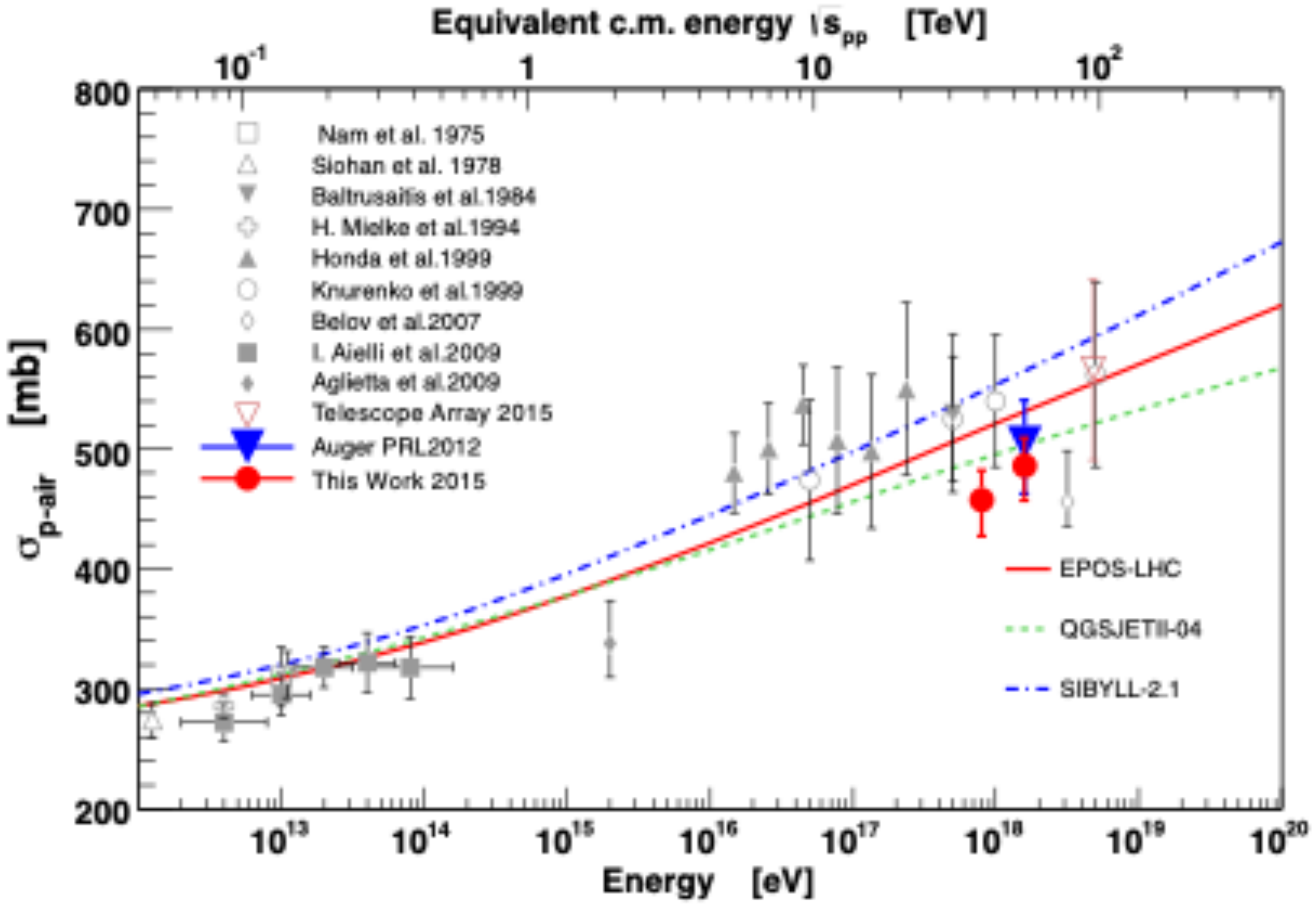
Proton-air cross-section

34th ICRC, PoS (2015) 401

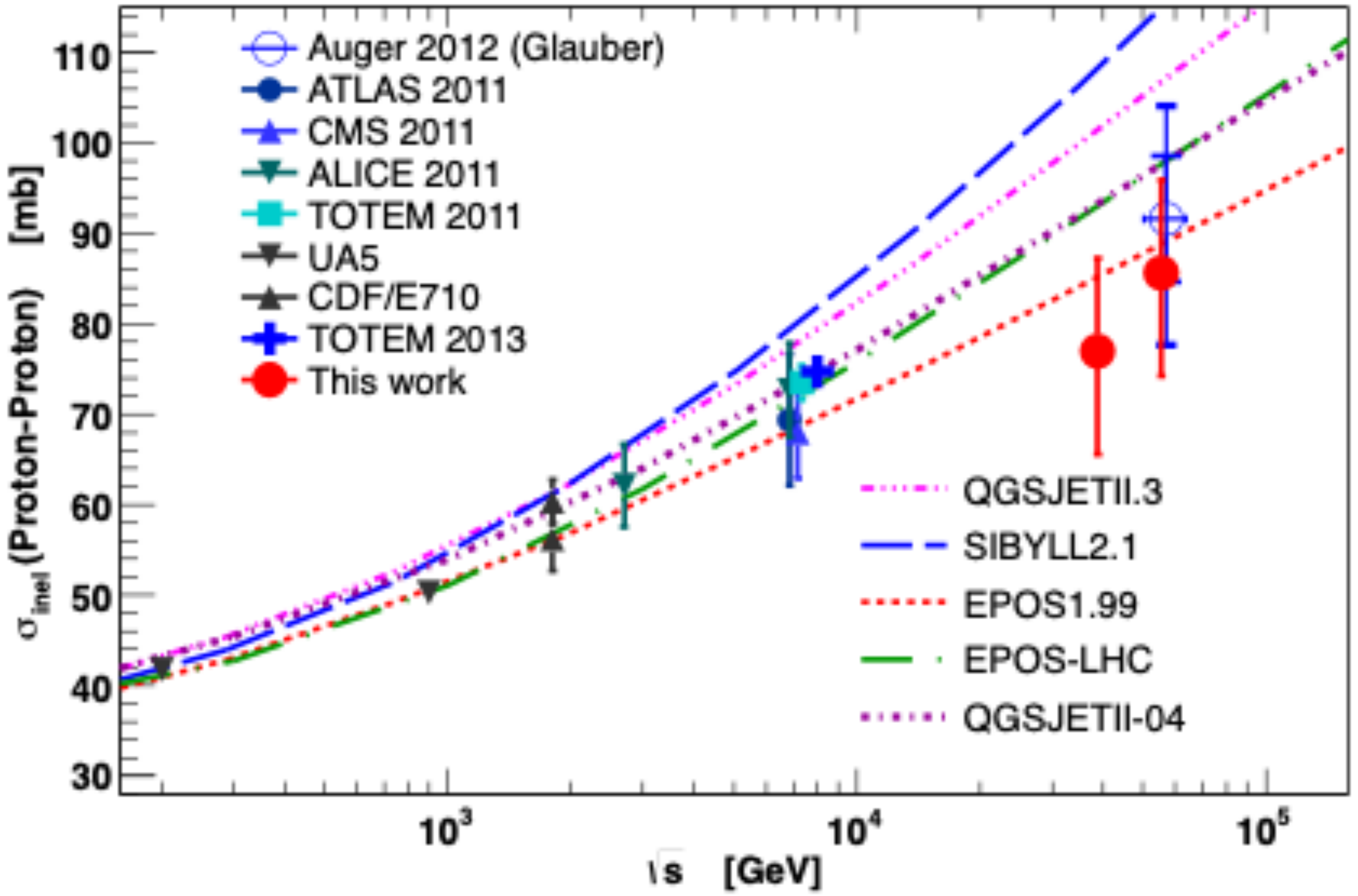
- ✧ p-Air cross-section can be extracted from the X_{max} distribution tail
  - ✧ If there is a large fraction of protons



Proton-Air Cross-section



Proton-proton Cross-section



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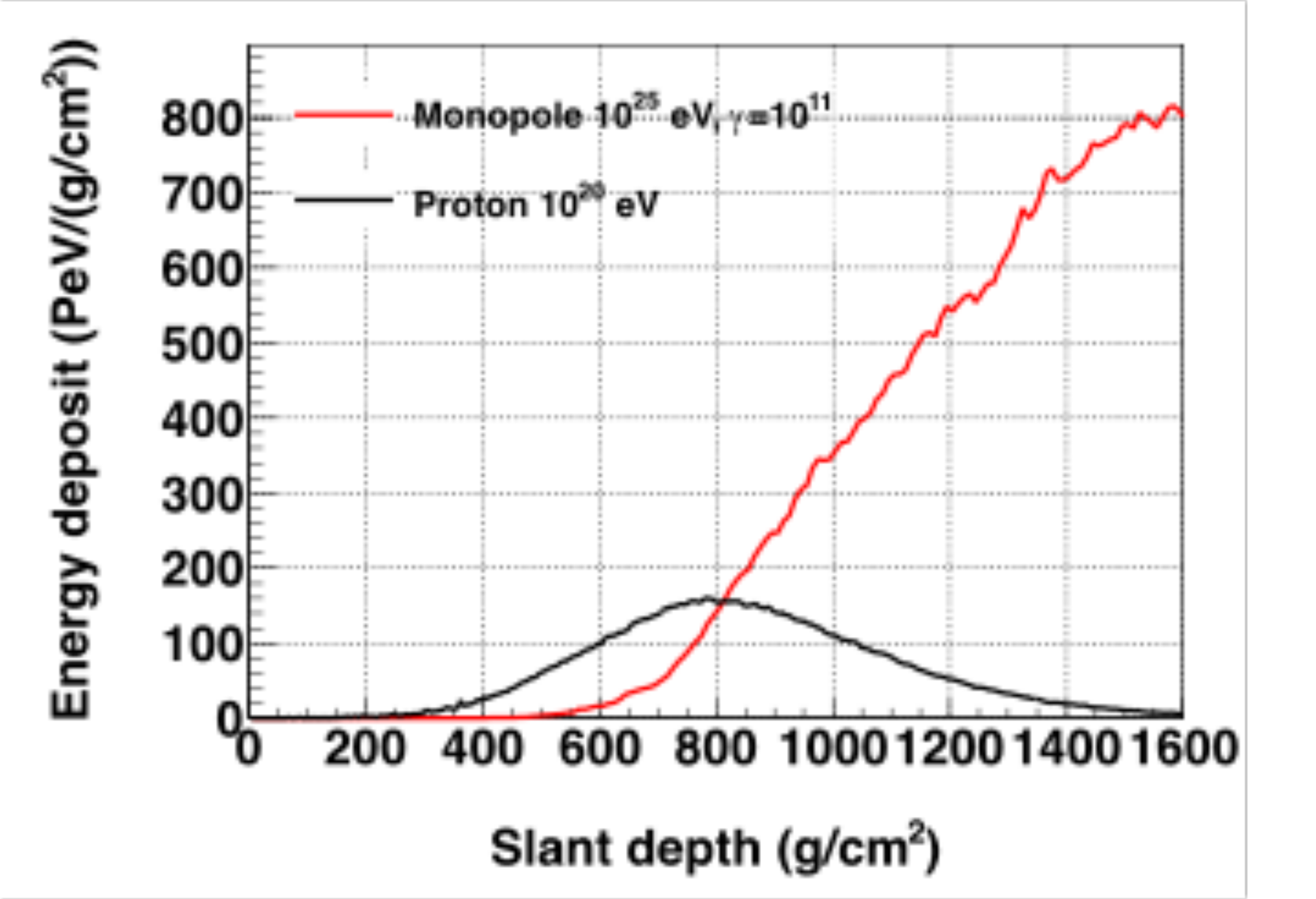
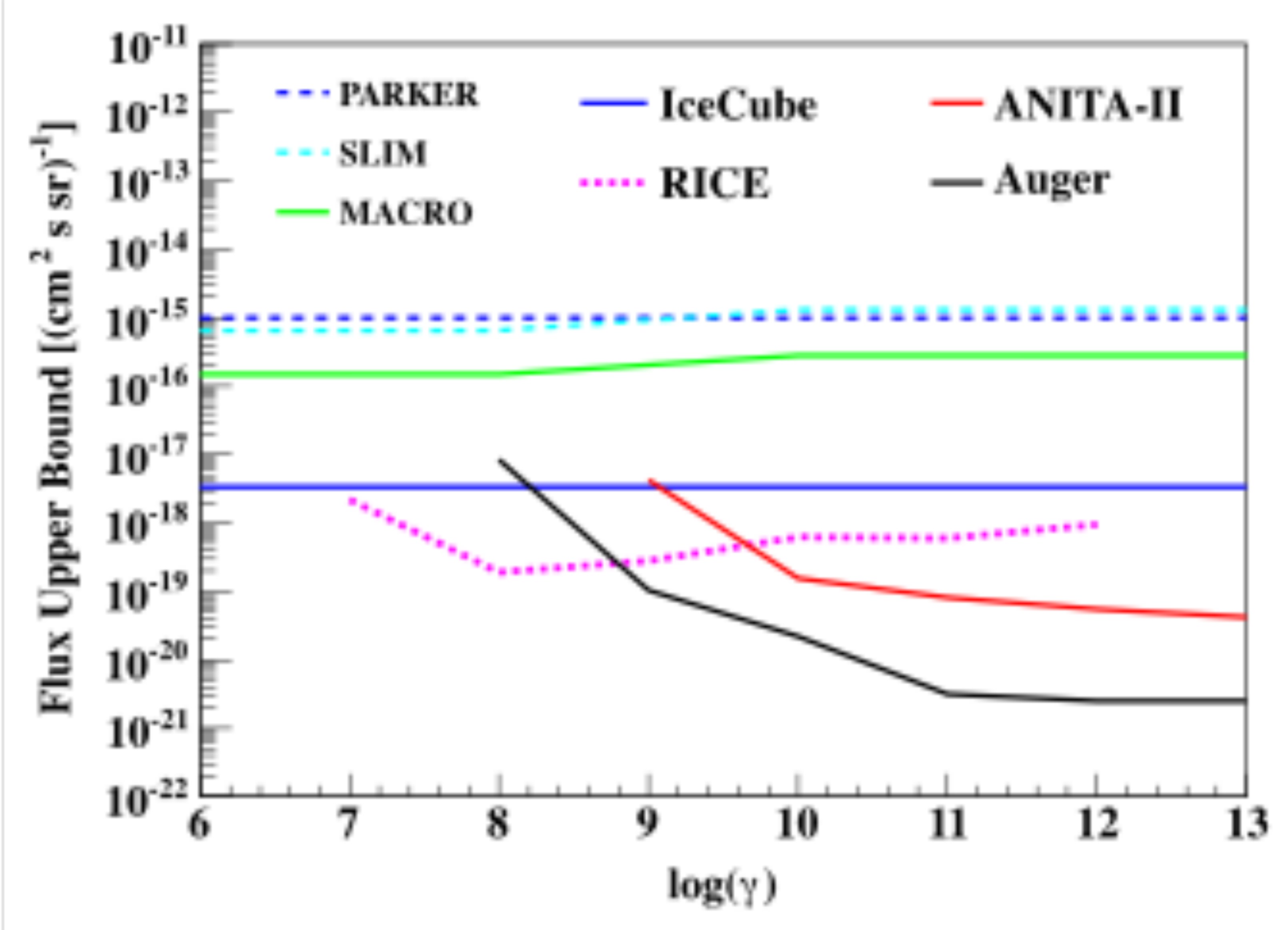
Testing exotic scenarios

Phys.Rev. D94 (2016) no.8, 082002

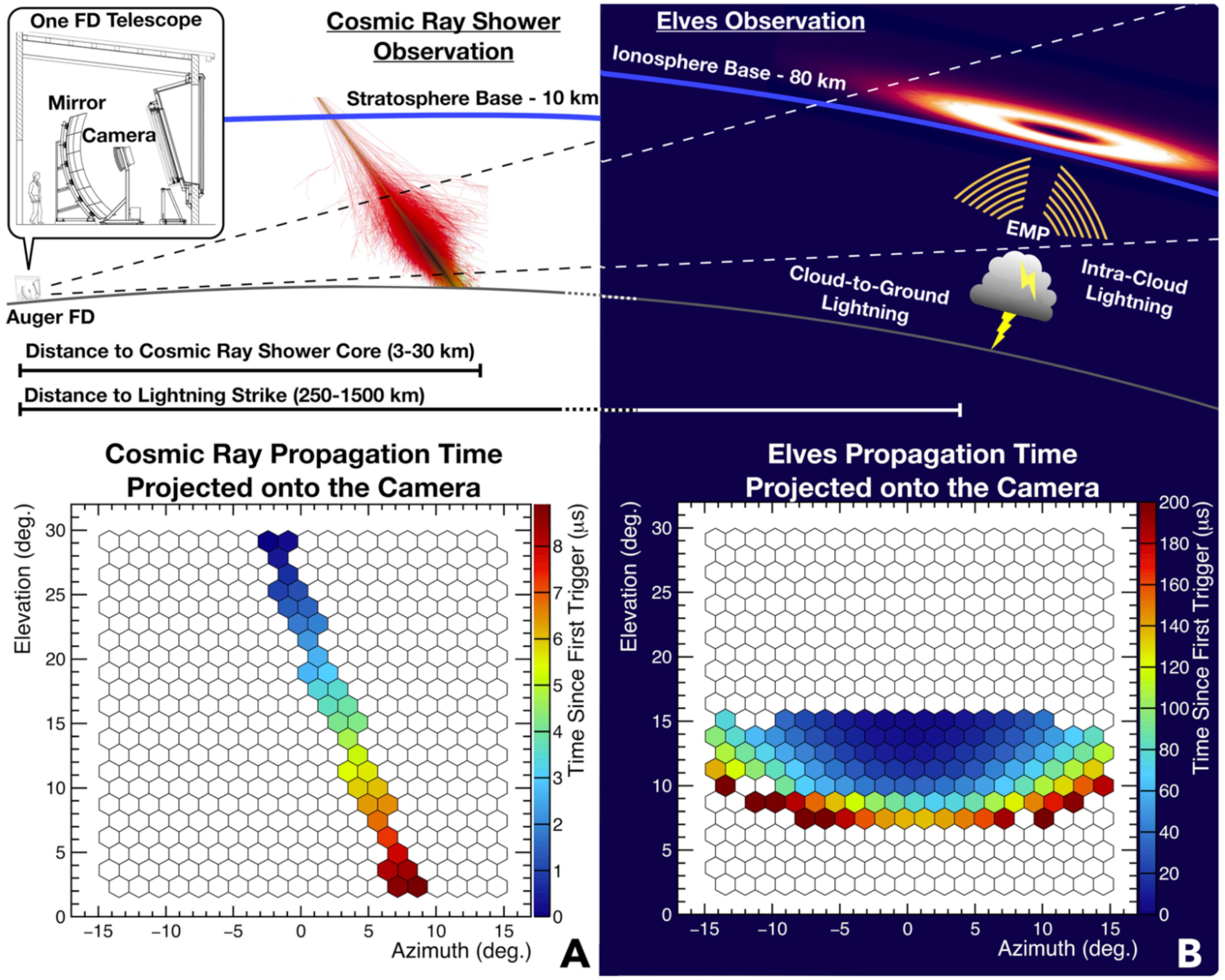
- Put the strongest limit on the existence of ultra-relativistic magnetic monopoles (MM)
  - Test on fundamental particle physics exotic scenarios
    - Relics of phase transitions in the early universe
- MM produce air showers with a distinct signature from standard ones
  - Should be easily observed by the Auger FD
  - $E_{mon} \approx 10^{25}\,\mathrm{eV}$
  - $M_{mon} \in [10^{11}; 10^{16}]\,\mathrm{eV/c^2}$

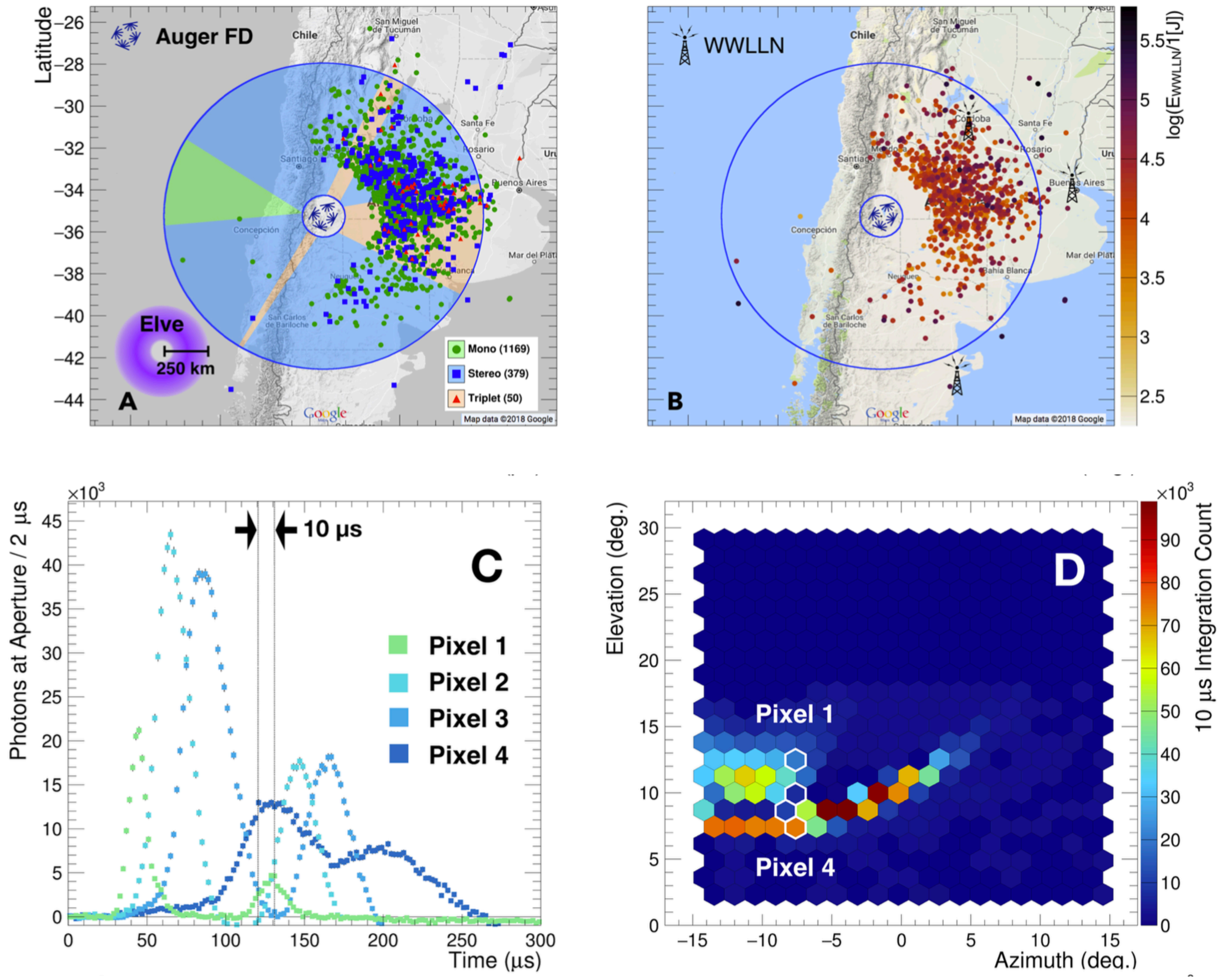




Elves

✧ Use FD to observe rare electromagnetic phenomena in the atmosphere





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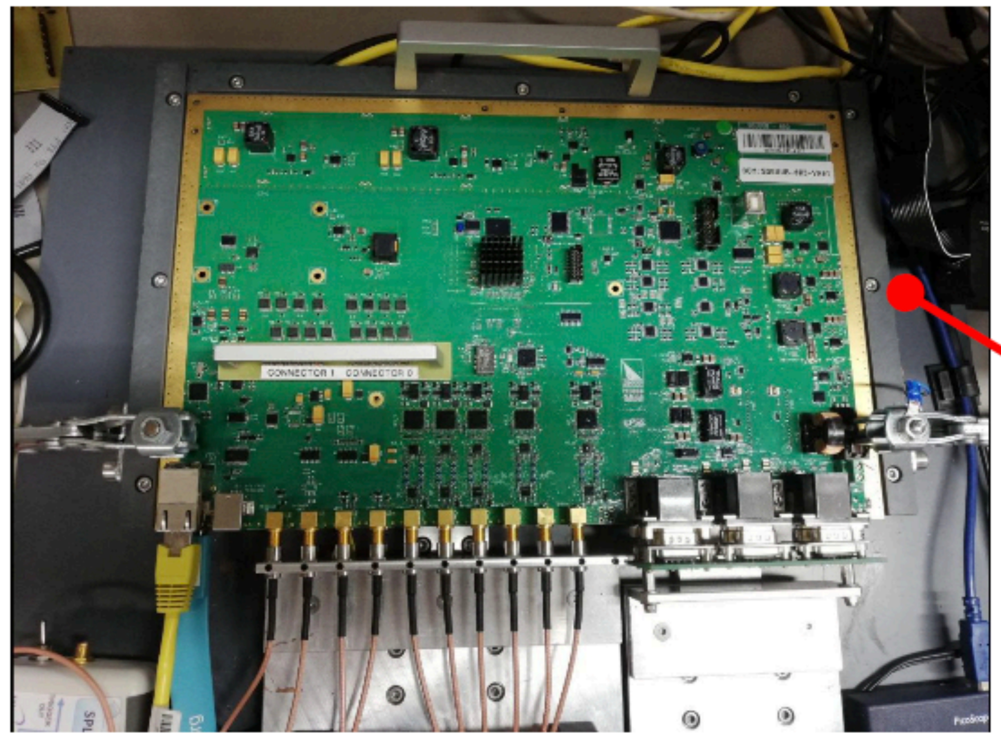
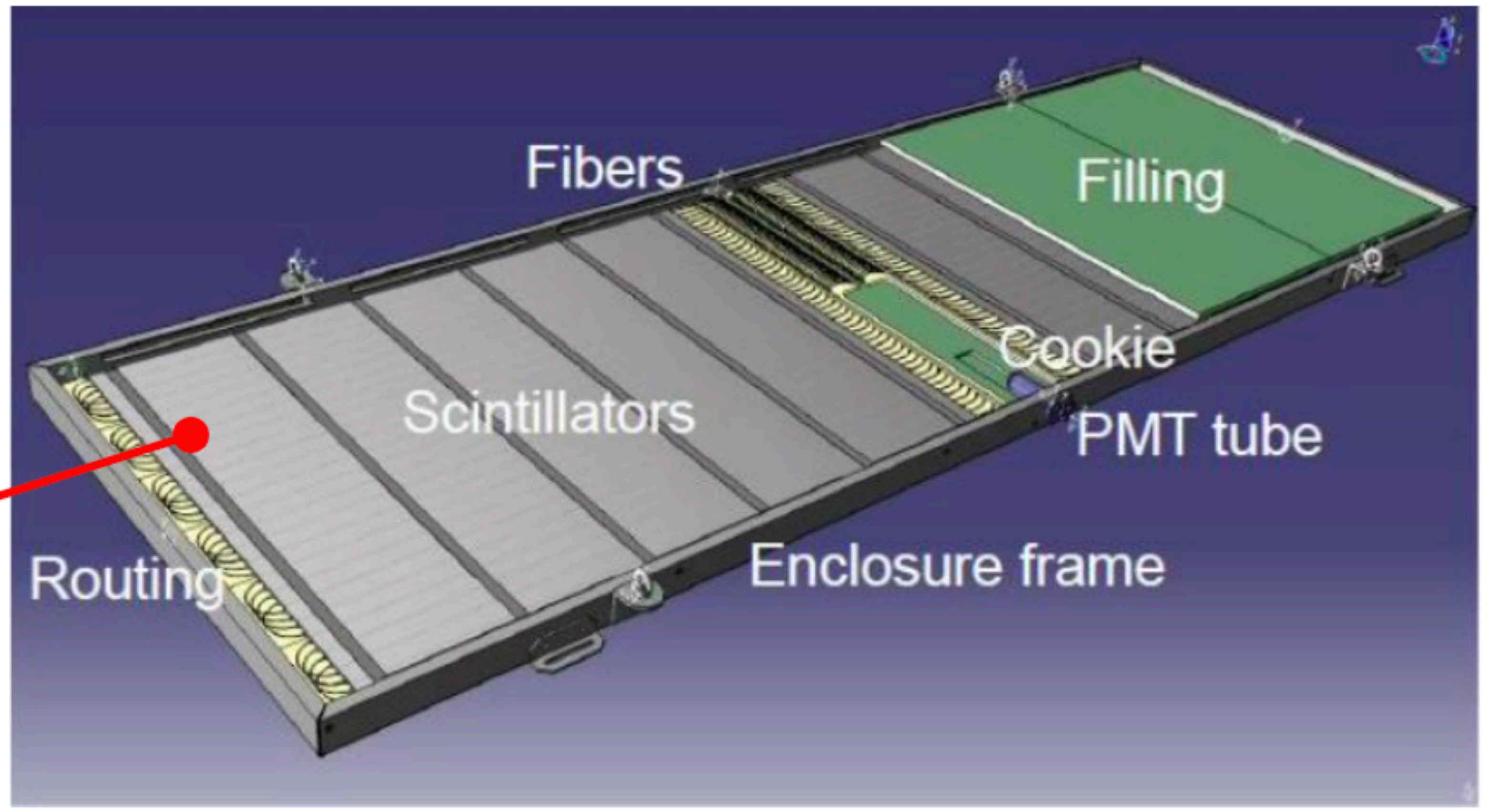
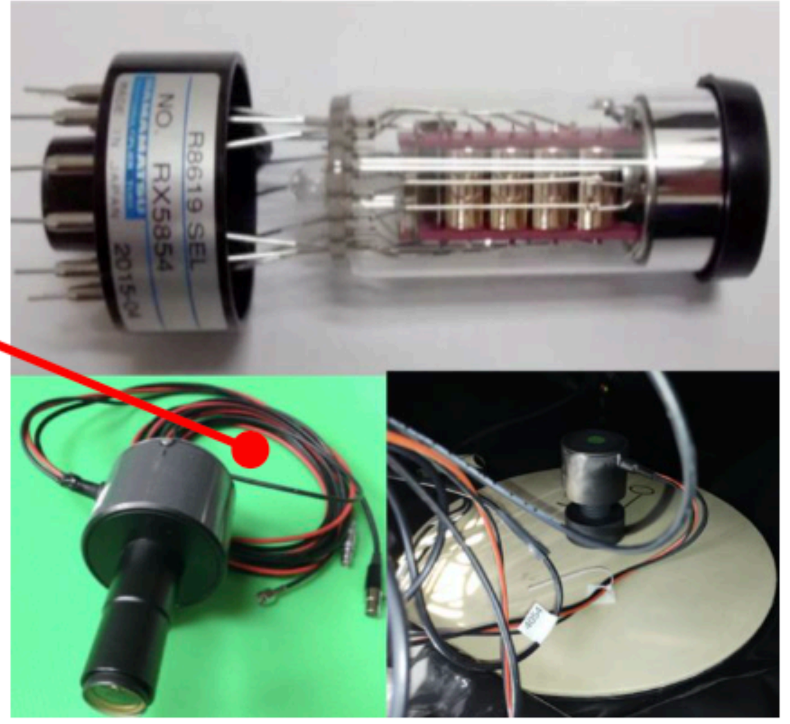
Auger Prime detectors

New electronics (UUB) and Scintillators(SSD)





High dynamic range PMTs



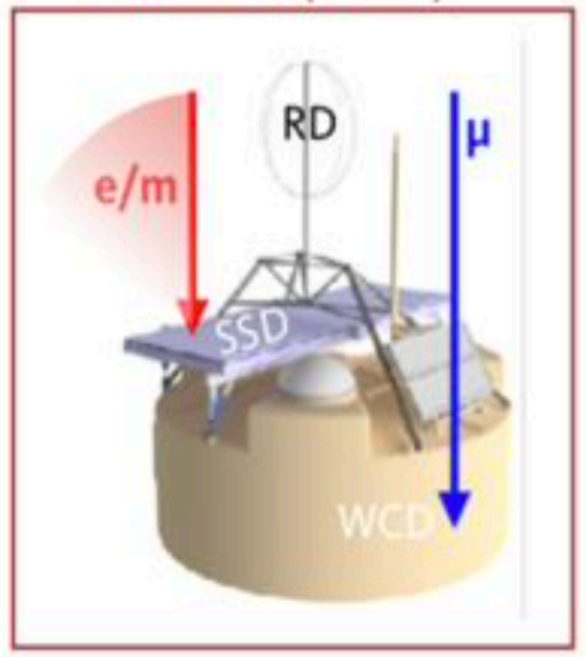
Radio Upgrade

Underground Muon Detector (UMD)

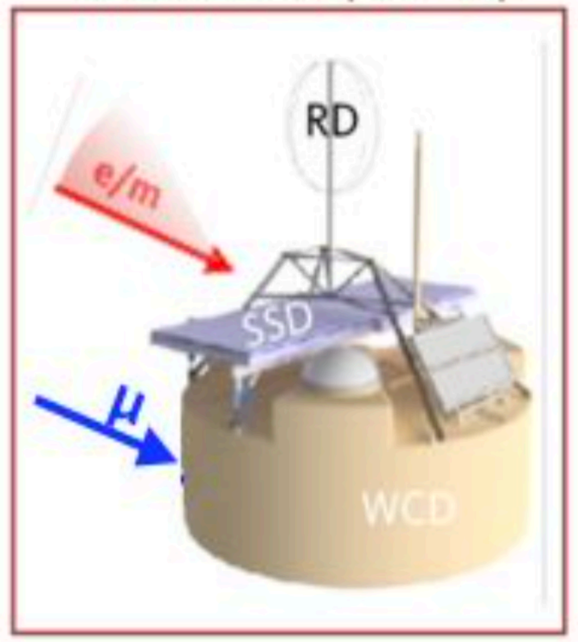
:h t

The strategy

VERTICAL (0-60°)



HORIZONTAL (60-90°)



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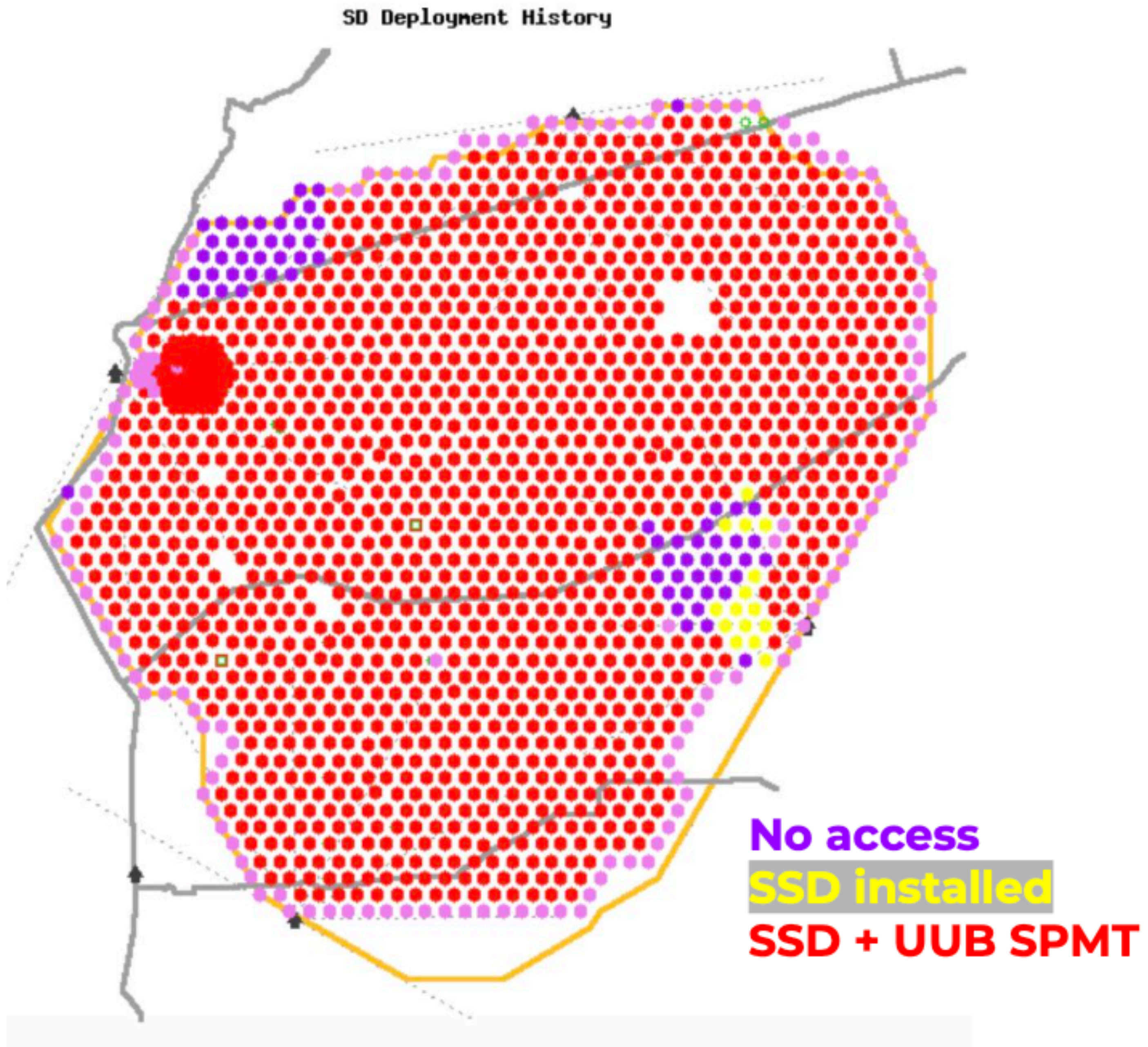
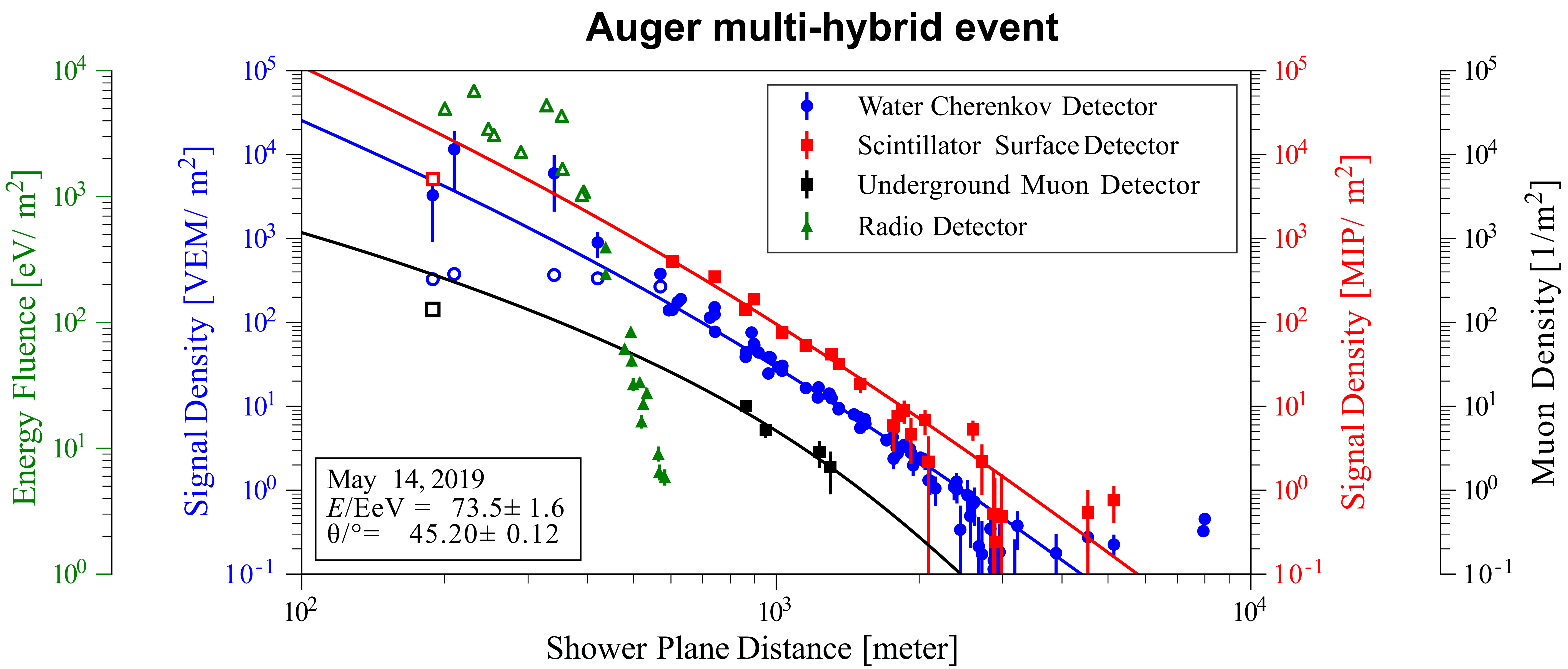
AugerPrime timeline

- 2019 — Start of the Upgrade phase
- 2020 — end of PMTs fabrication
- 2021 — end of SSD shipment on site
- 2022 — end of SSD deployment
- 2023 — end of UUB production and shipment
- 2023 — end of UUB + PMTs deployment
- 2024 — end of Radio+ UMD deployment





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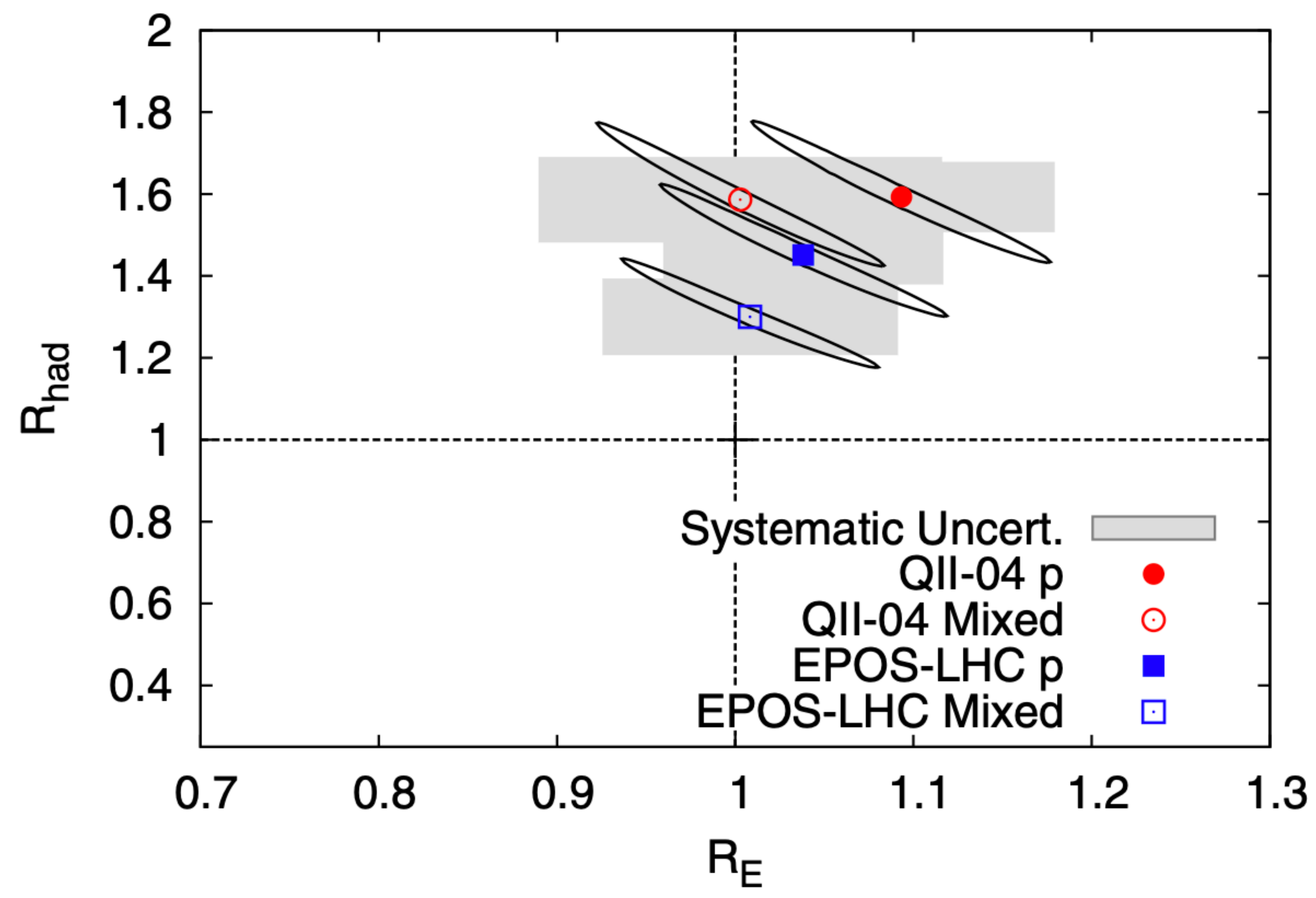
More trouble for Hadronic Interaction Models…

Phys.Rev.Lett. 117 (2016) no.19, 192001

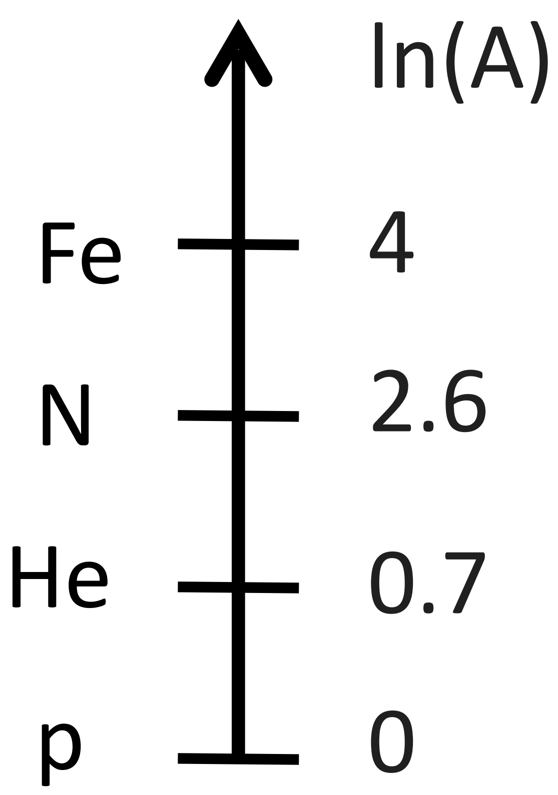


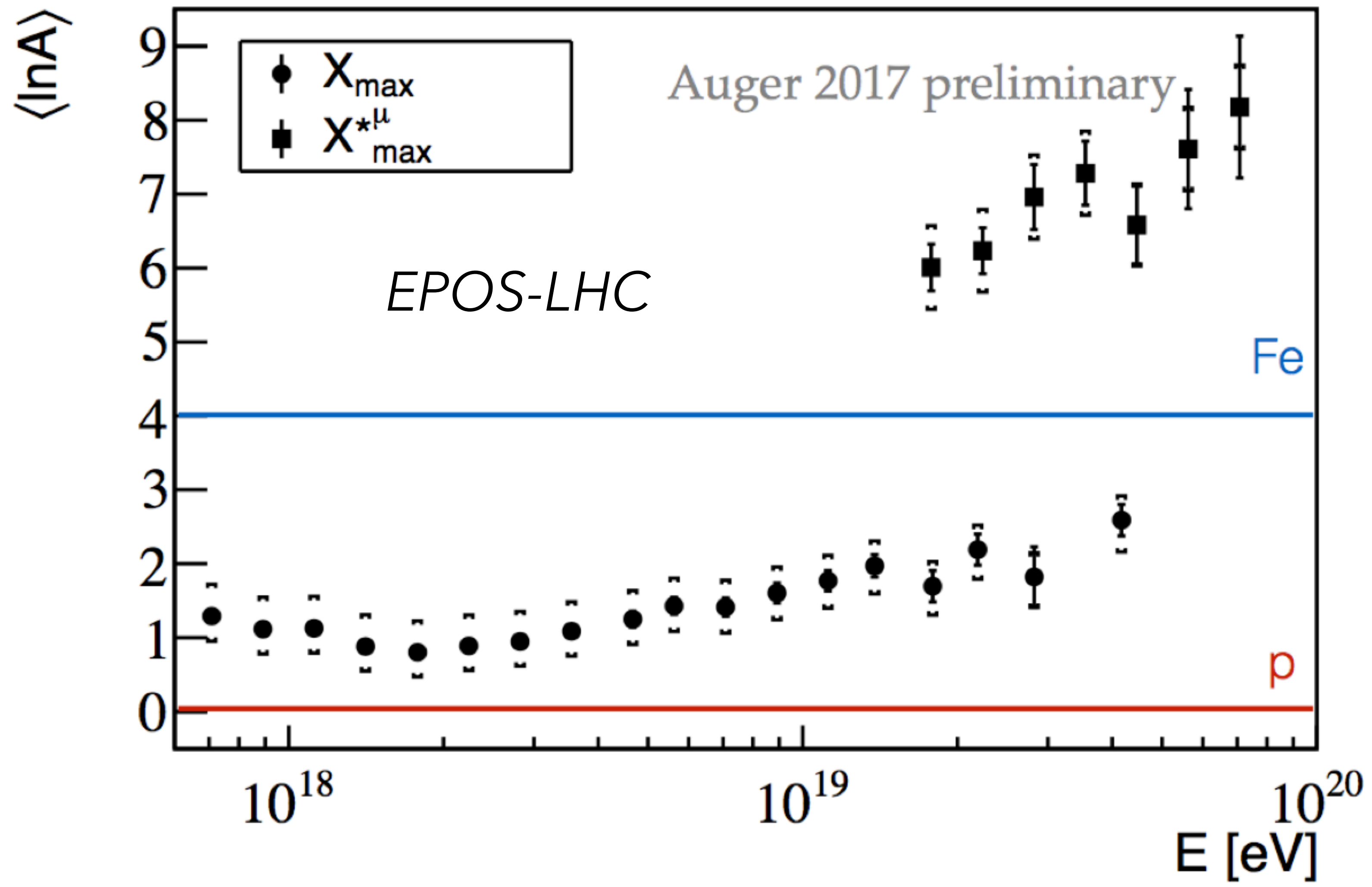
- ✧ Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had}) [Hybrid: SD + FD]

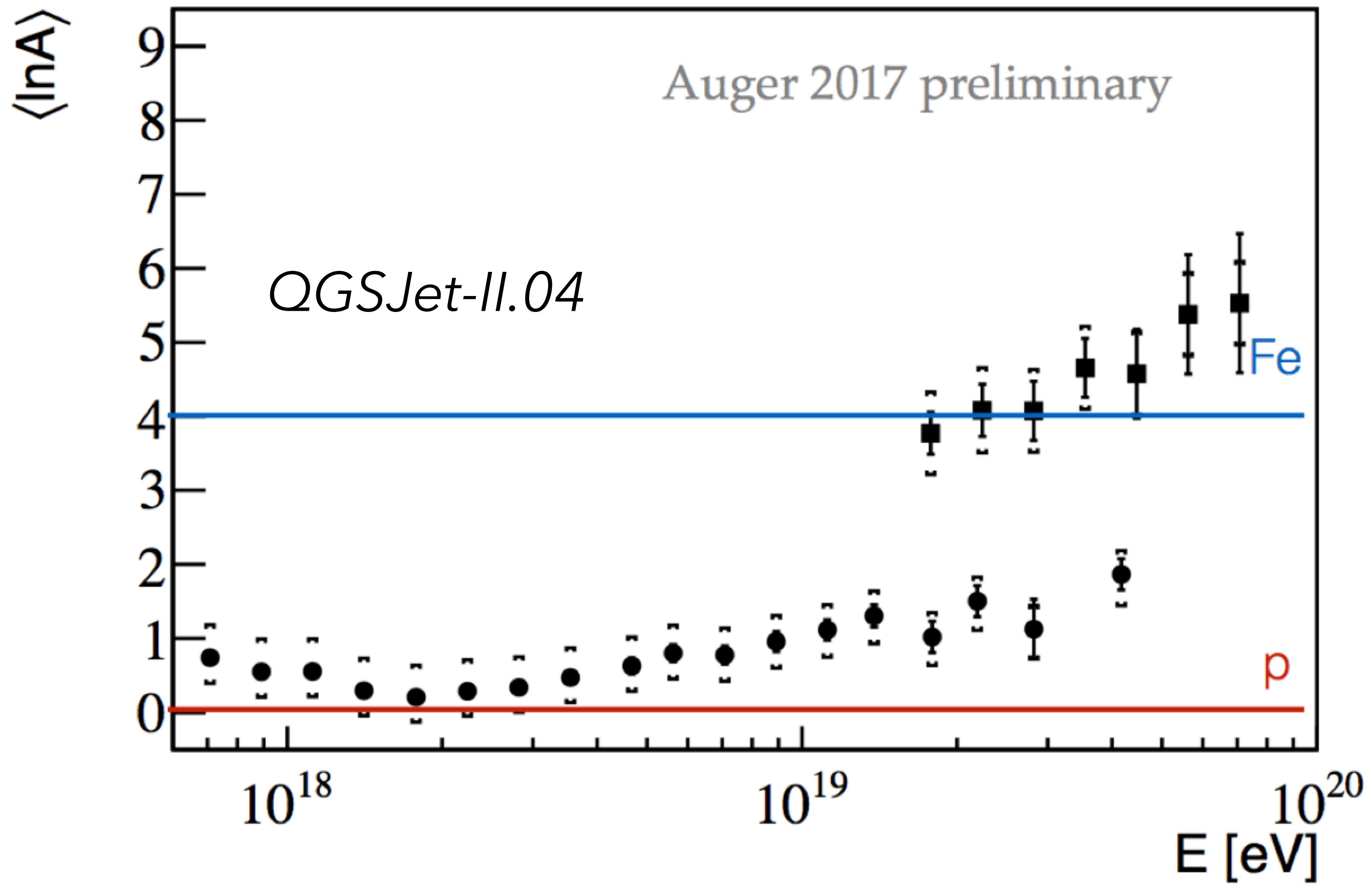
$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E S_{\text{EM},i,j} + R_{\text{had}} R_E^{\alpha} S_{\text{had},i,j}$$

- ✧ Depth of maximum of muon production depth ($X^{*\mu}_{max}$)

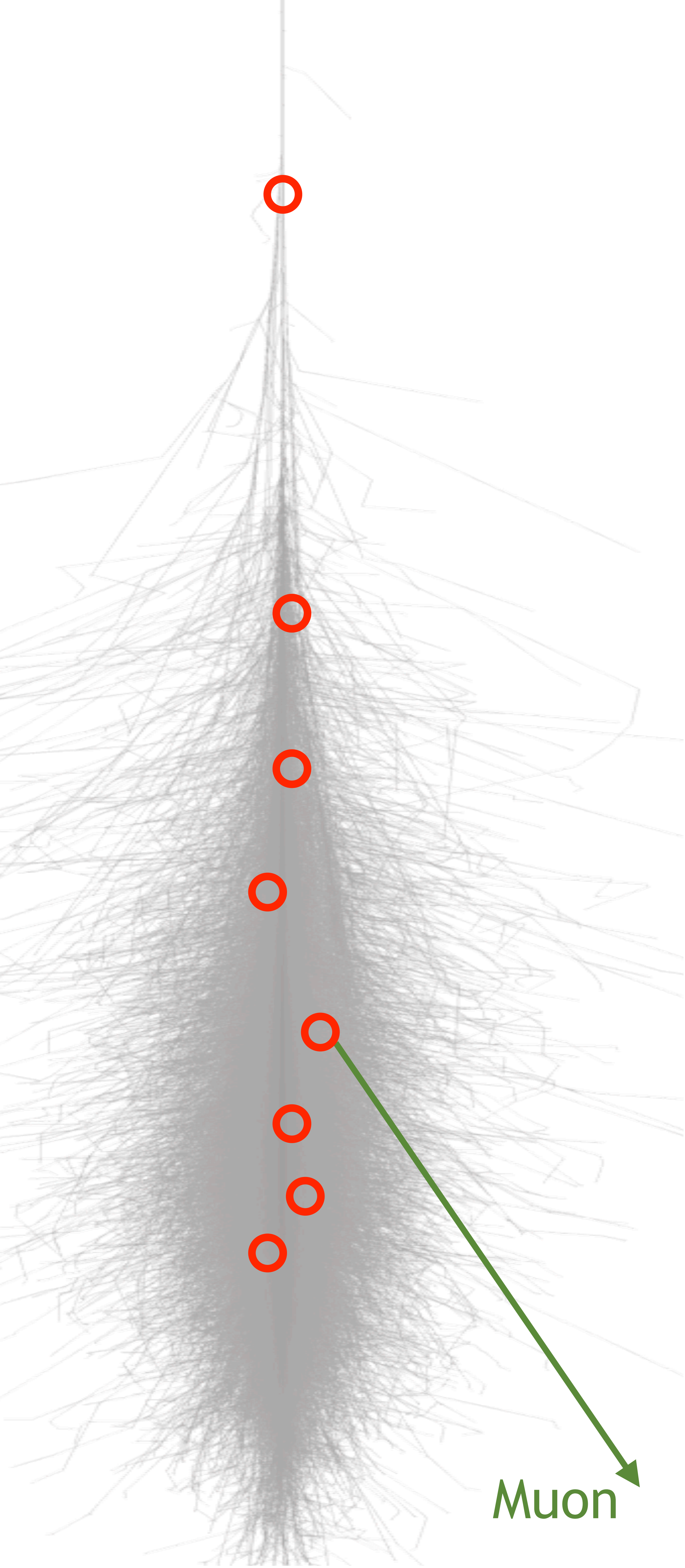
35th ICRC, PoS (2017) 509



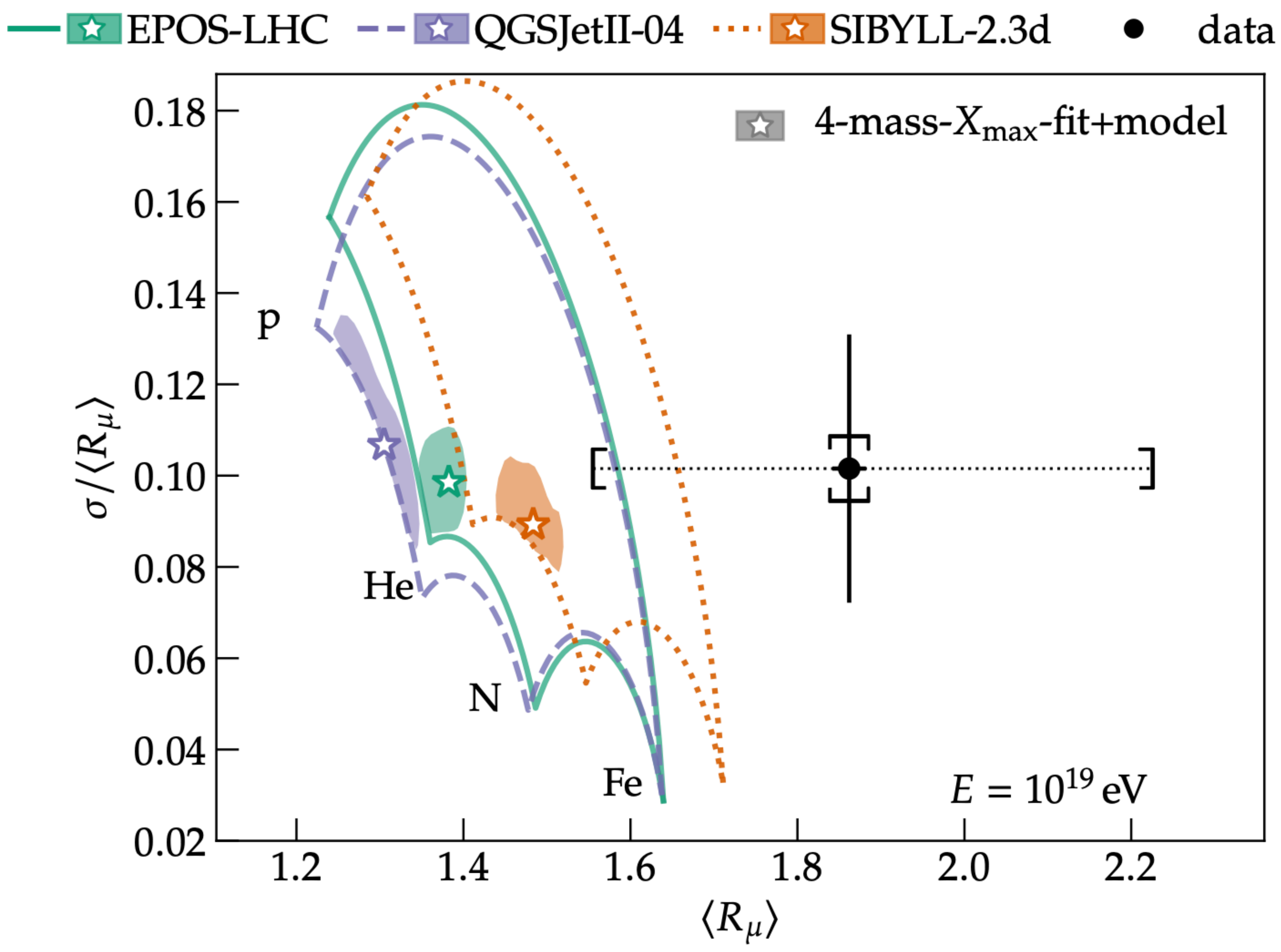




Shower description



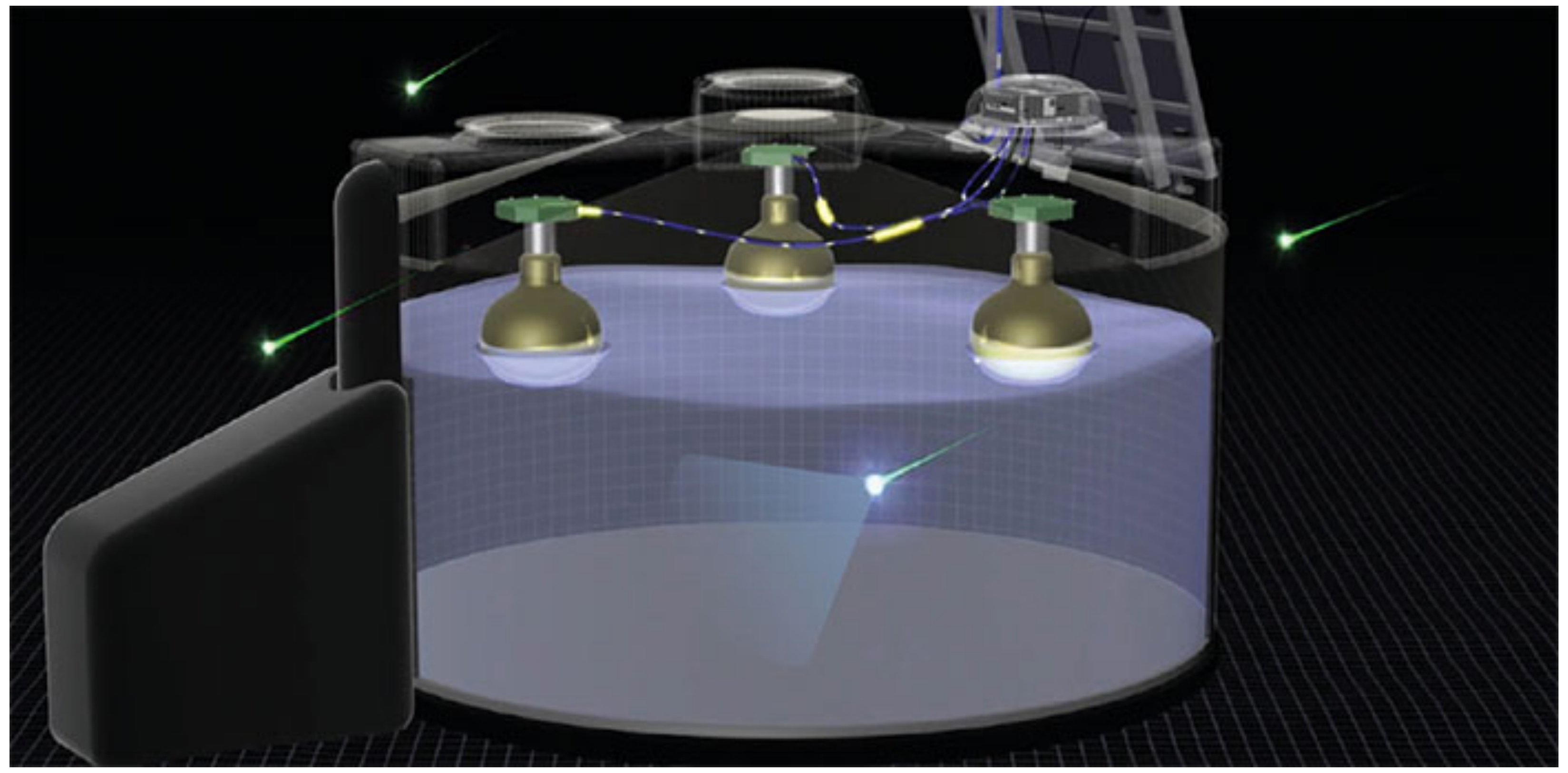
Phys.Rev.Lett. 126 (2021) 15, 152002

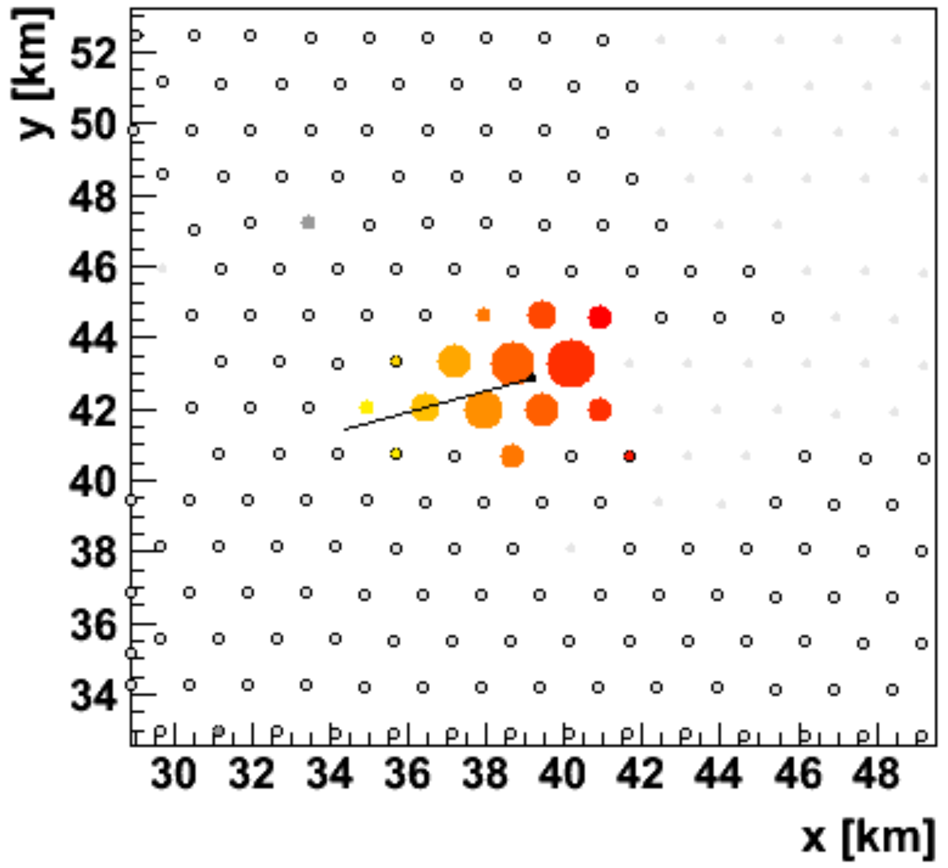


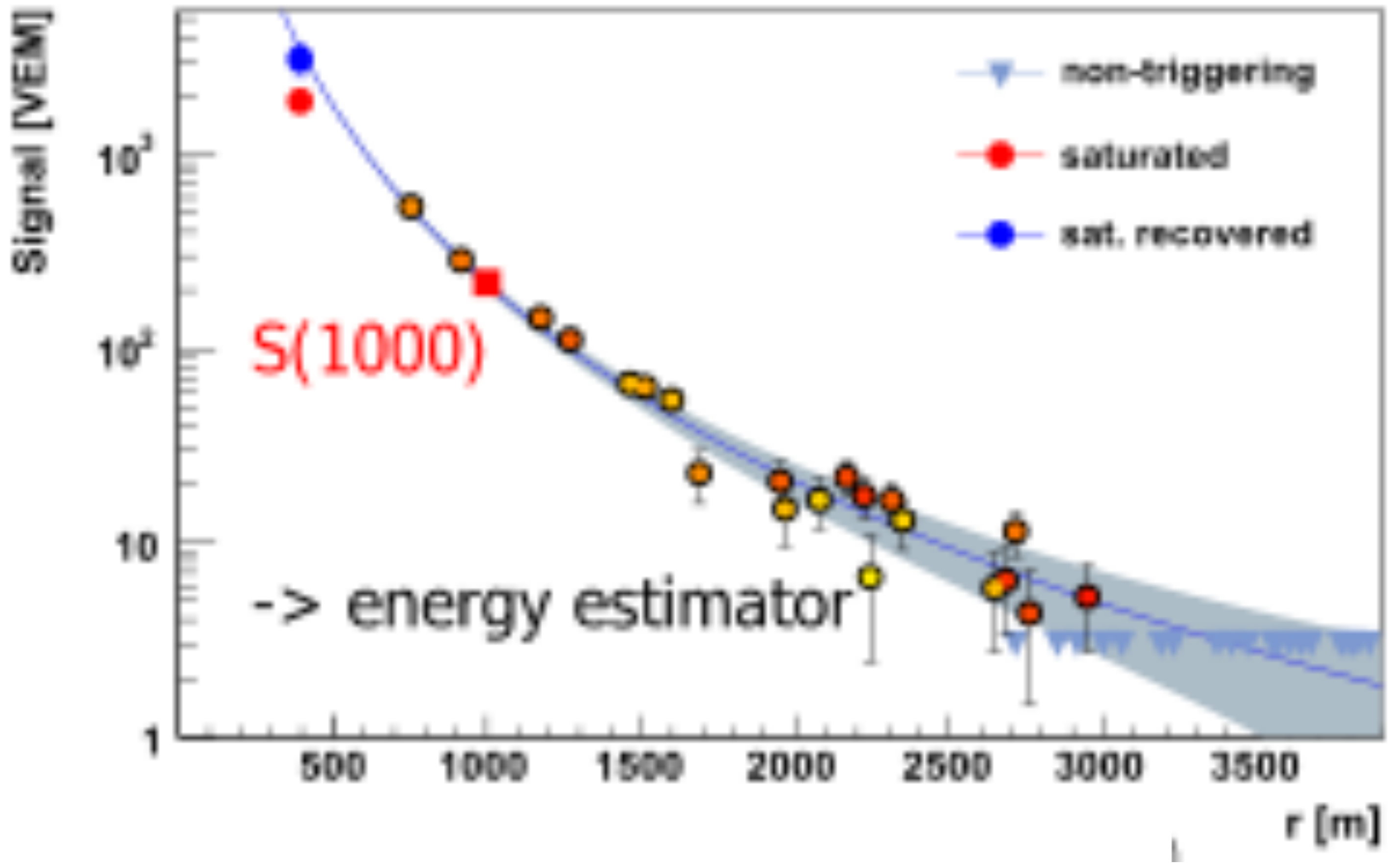
Relative fluctuations suggests that **discrepancy** might be related to hadronic **low energy interactions** in the shower

Surface Detectors

- Sample shower secondary particles reaching the ground
  - 100% duty cycle
  - Arrival time → primary cosmic ray direction
  - Energy estimation: signal at 1000 meters from the shower core

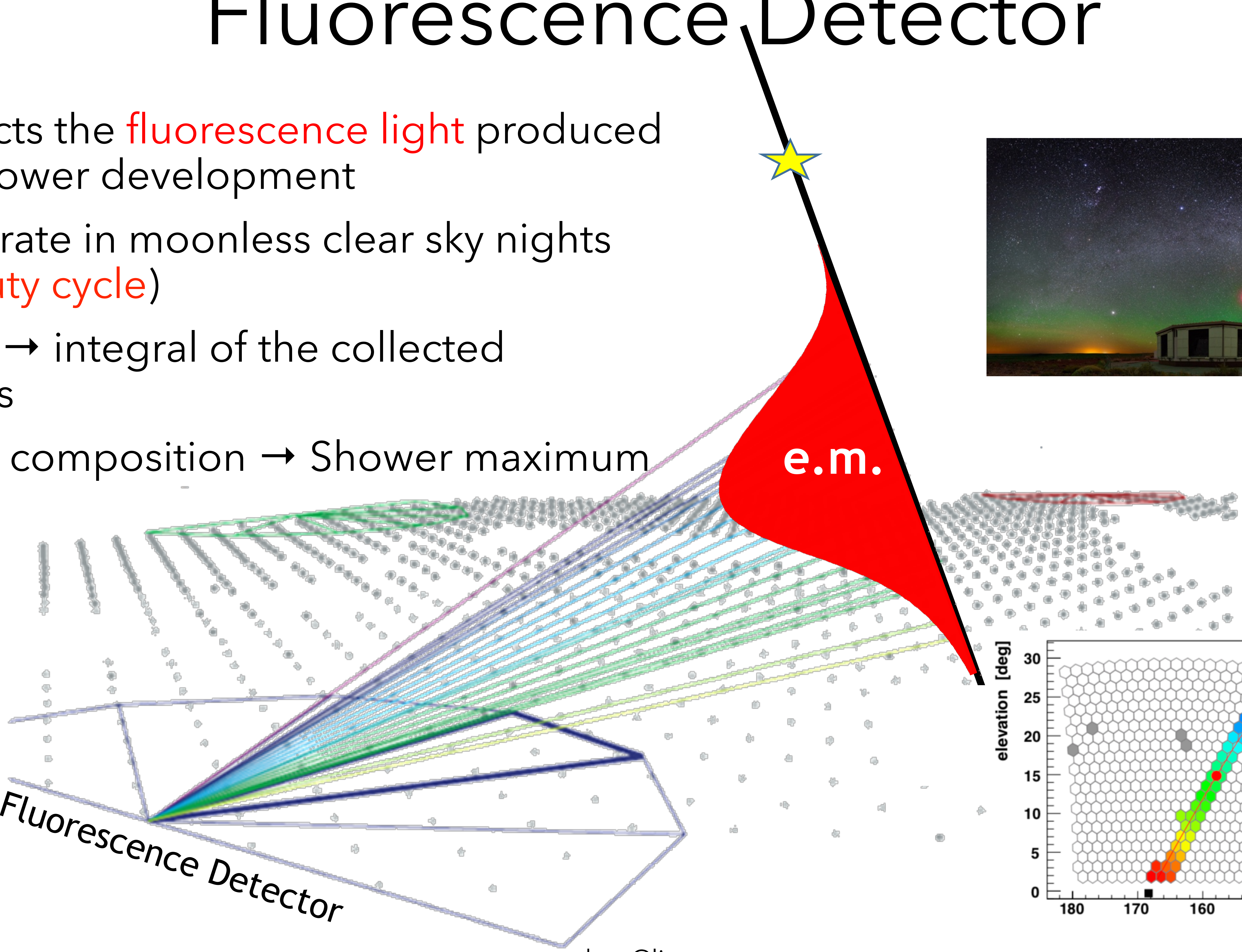


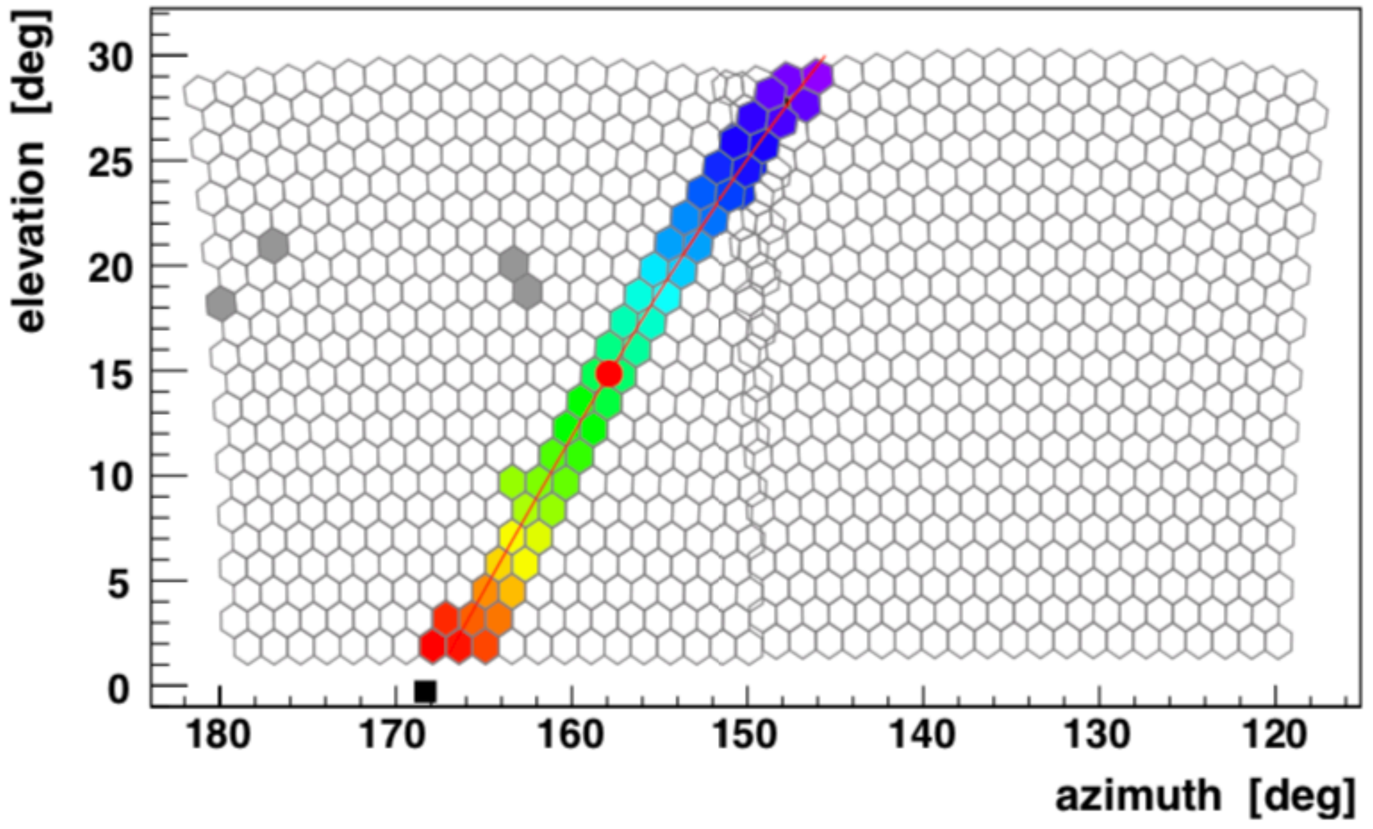




Fluorescence Detector

- FD: collects the fluorescence light produced by the shower development
- Only operate in moonless clear sky nights (~15% duty cycle)
  - Energy → integral of the collected photons
  - Primary composition → Shower maximum depth





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