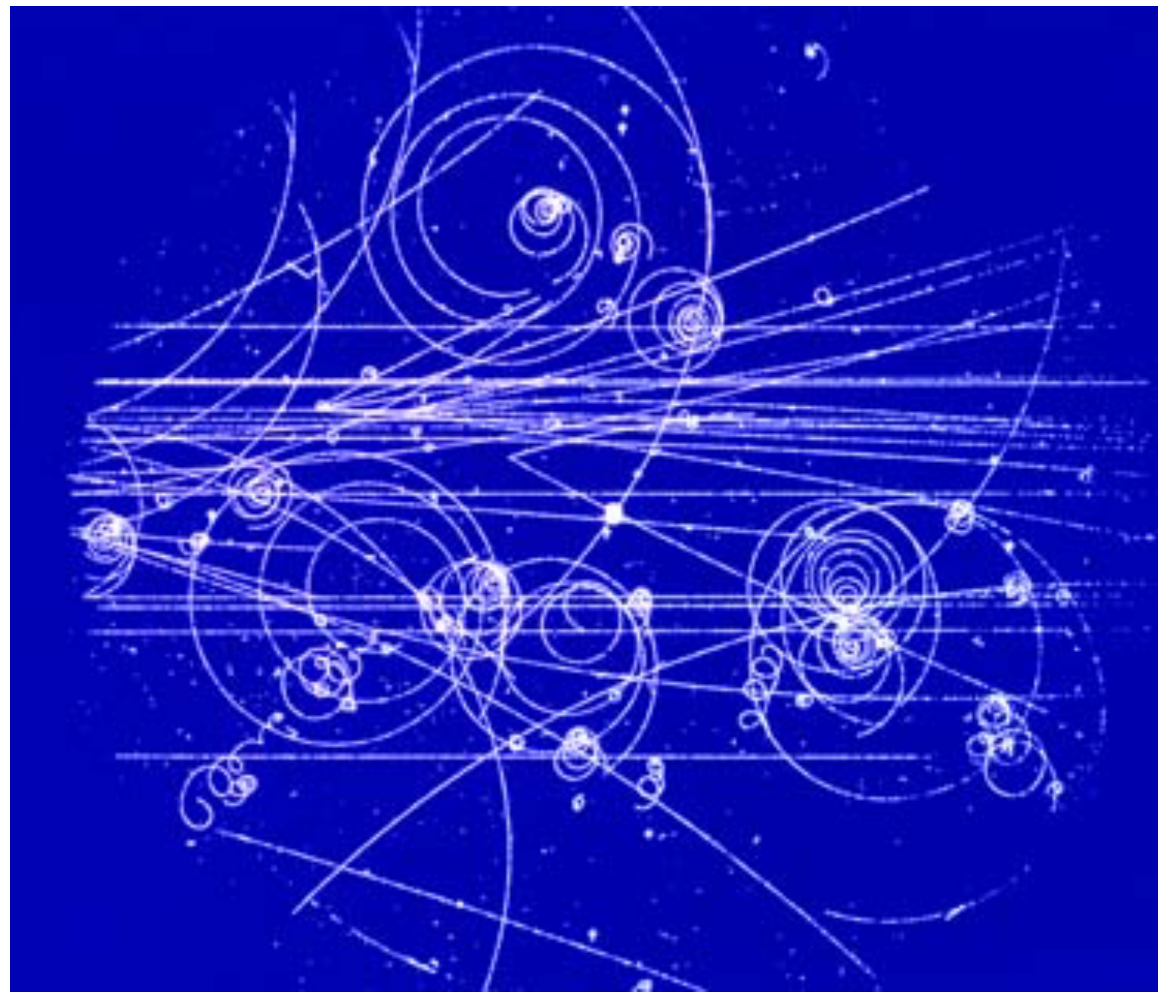
Astroparticle Physics

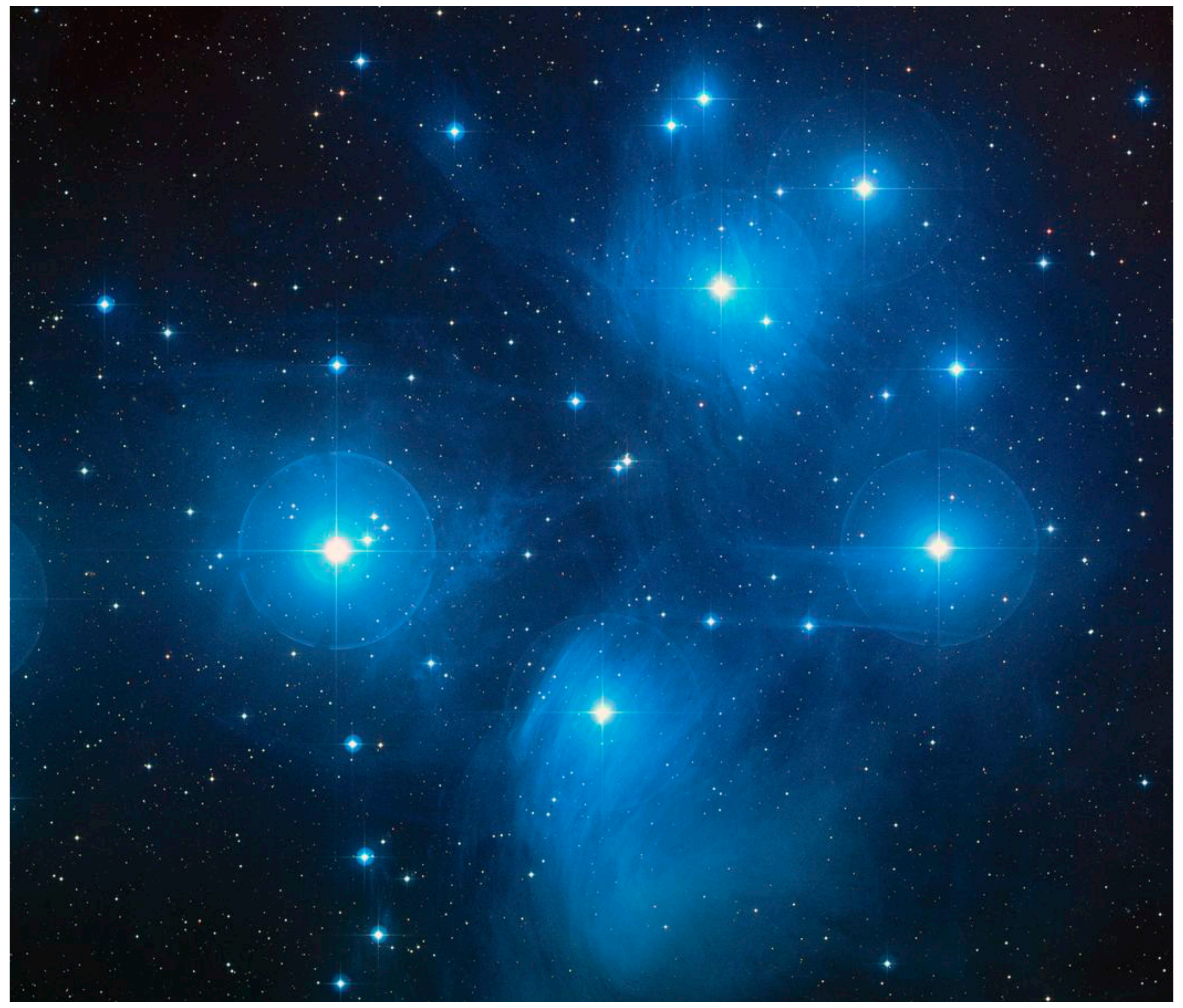
Cosmic Rays

Ruben Conceição

10th IDPASC school, Nazaré, September 15th 2021

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

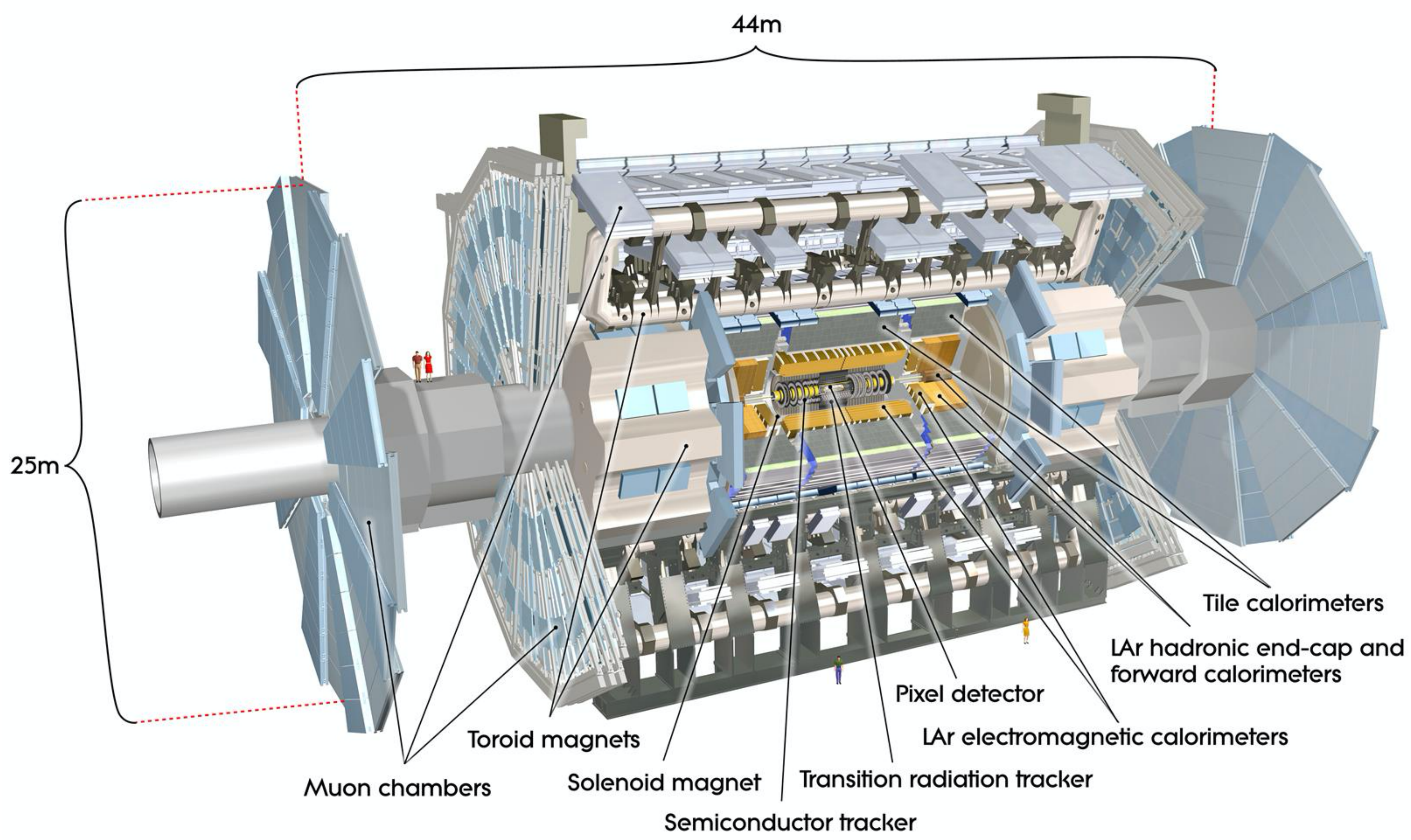
Cosmology

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


Photons
Neutrinos
Messengers from the Universe
Charged cosmic rays
Gravitational waves

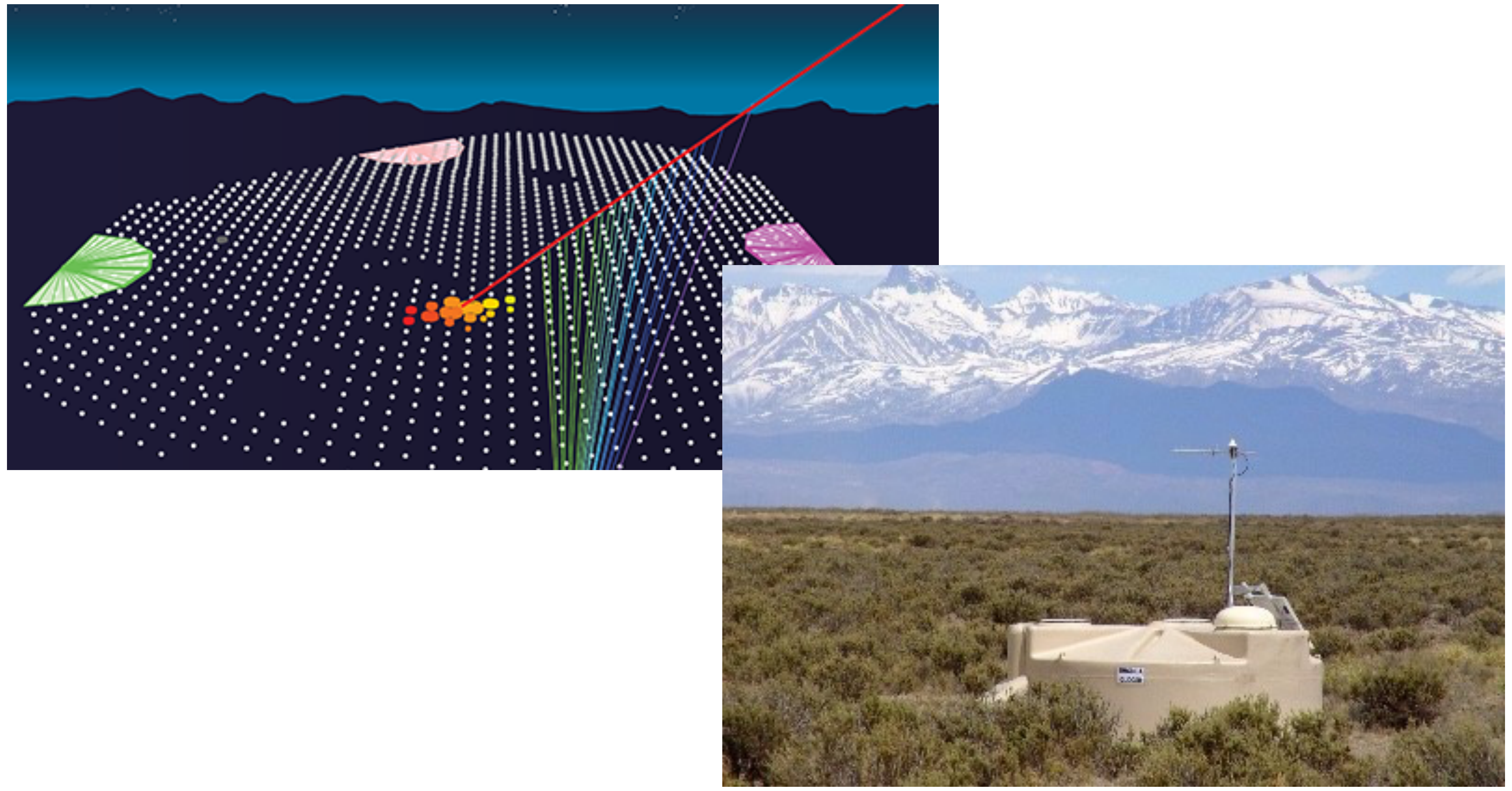
Fundamental Particle Physics

Accelerator Experiment



- Controlled environment:
  - Beam, background…

Astroparticle Experiment



- Access **energy**, **space** and **time** scales unattainable in Earth

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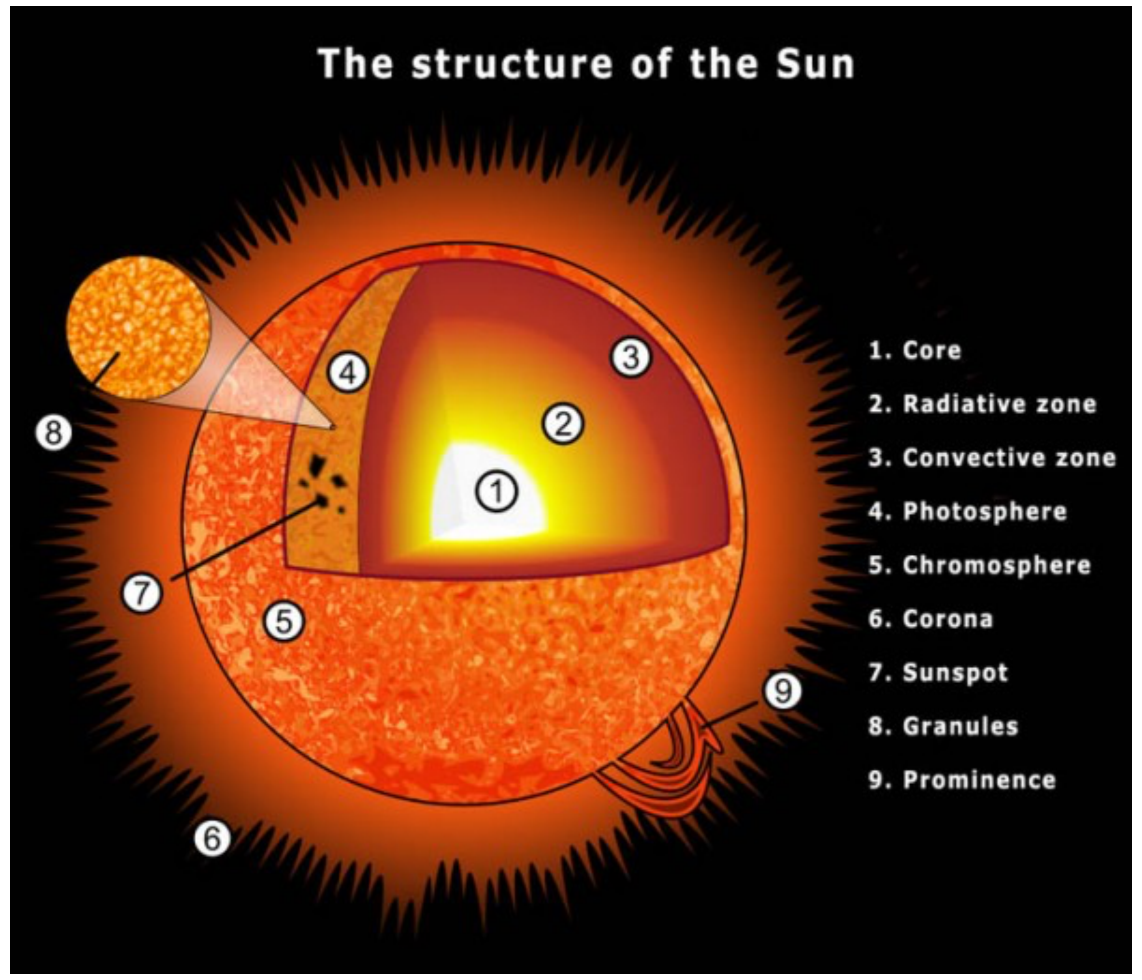
Neutrino oscillations

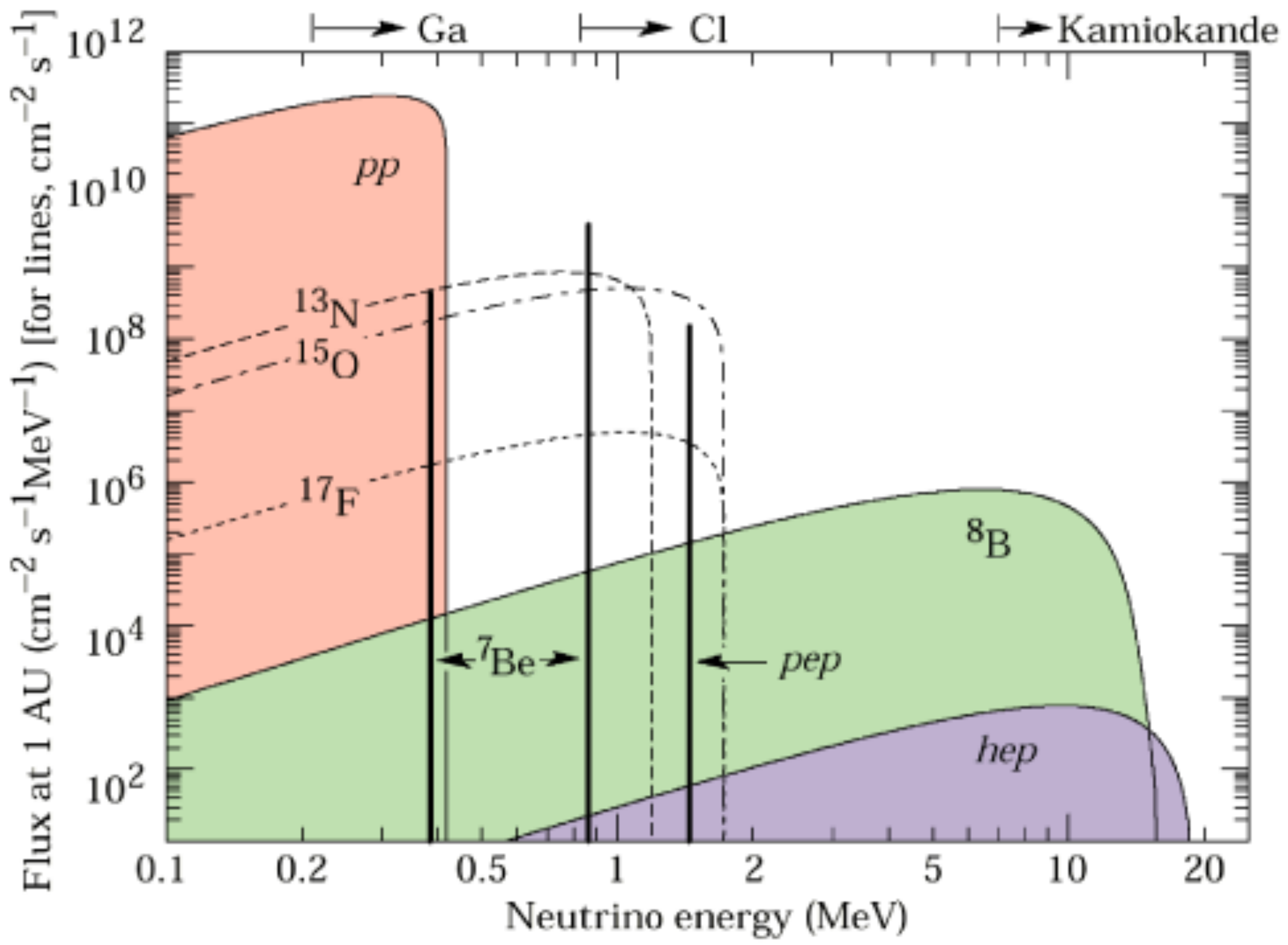
A pratical example

Solar Neutrinos

- Standard Solar Model
  - Built upon our knowledge over:
    - Solar dynamics
    - Interaction cross-sections



- It was noted since the 60's that the prediction of the flux of solar neutrino exceeded the observations



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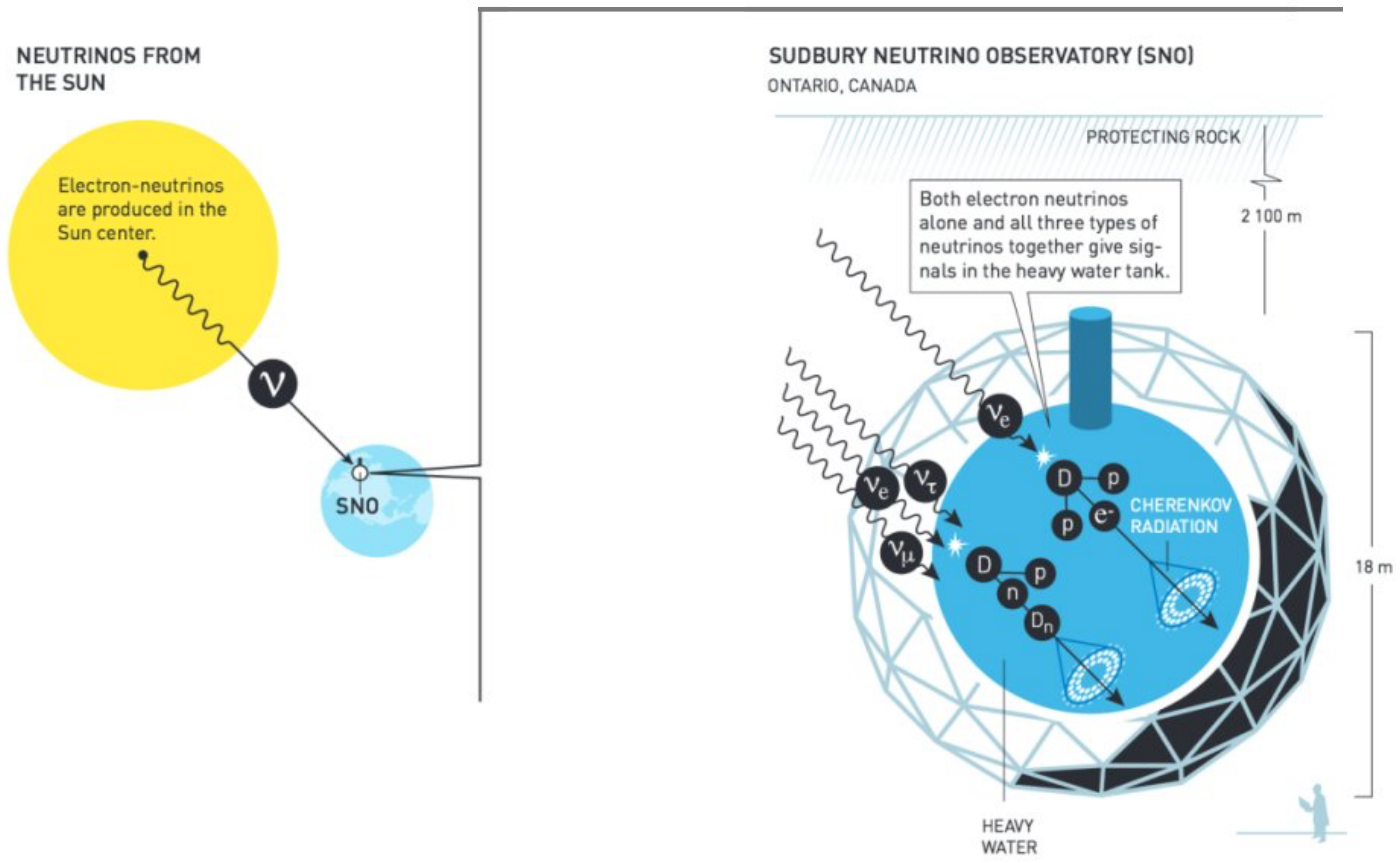
Neutrino oscillation



- Neutrino oscillation was found while trying to solve the Solar neutrino problem
- Nobel prize 2015 (A. MacDonald [SNO] ; T. Kajita [Super-Kamiokande])

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Course Outline

- First Class
  - Cosmic Rays
- Second Class
  - Gamma-rays and Neutrinos
  - The multi-messenger approach
  - Future Projects
- Exercises Class
  - Understand/compute some of the phenomena discussed in the theoretical classes

Through this course…

Astrophysical Sources

Fundamental Particle Physics

Experimental Challenges

Disclaimer: biased view towards the highest energies
Member of the Pierre Auger and SWGO collaborations

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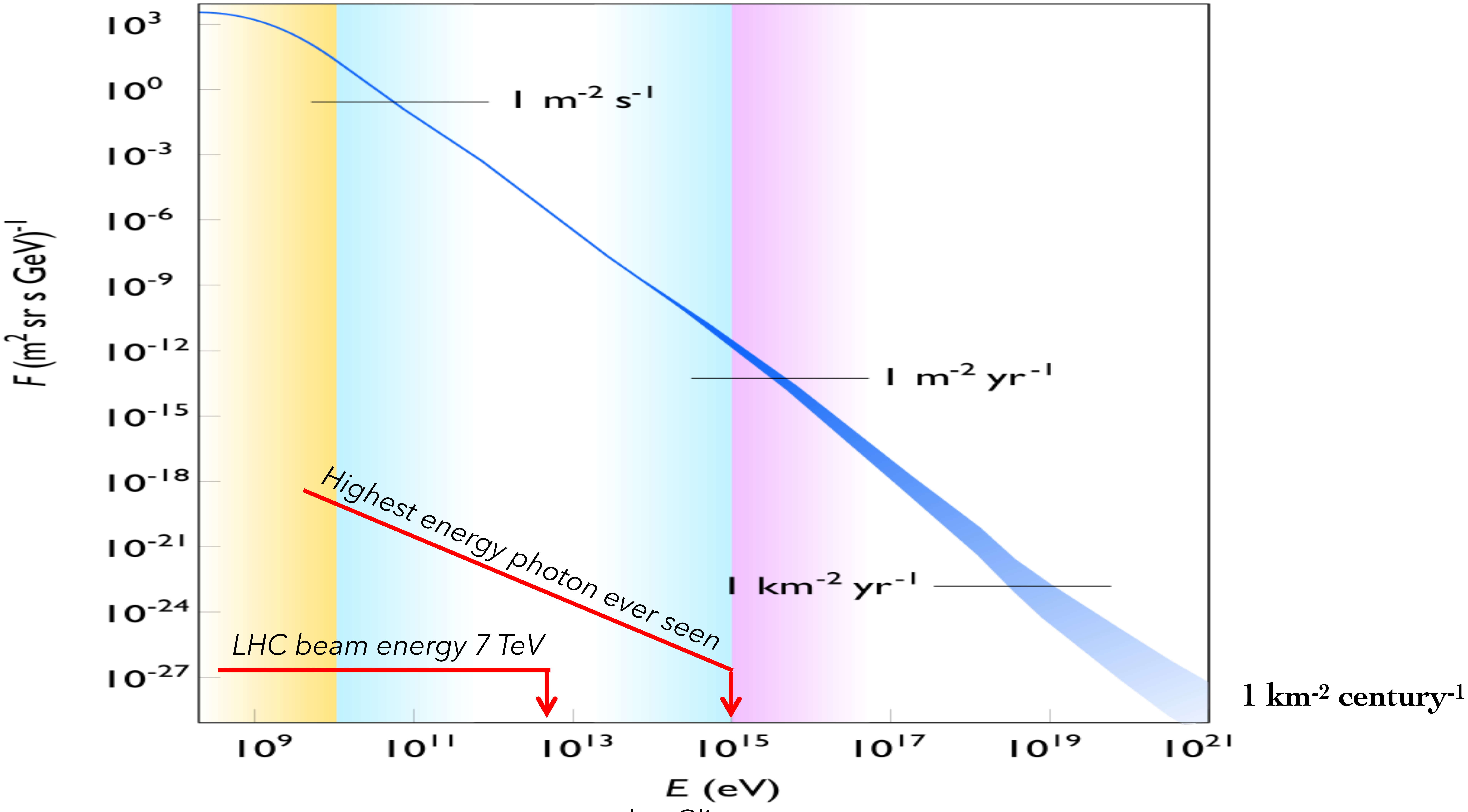
Cosmic Rays

Cosmic ray energy spectrum

(Charged particles continuously bombarding Earth)



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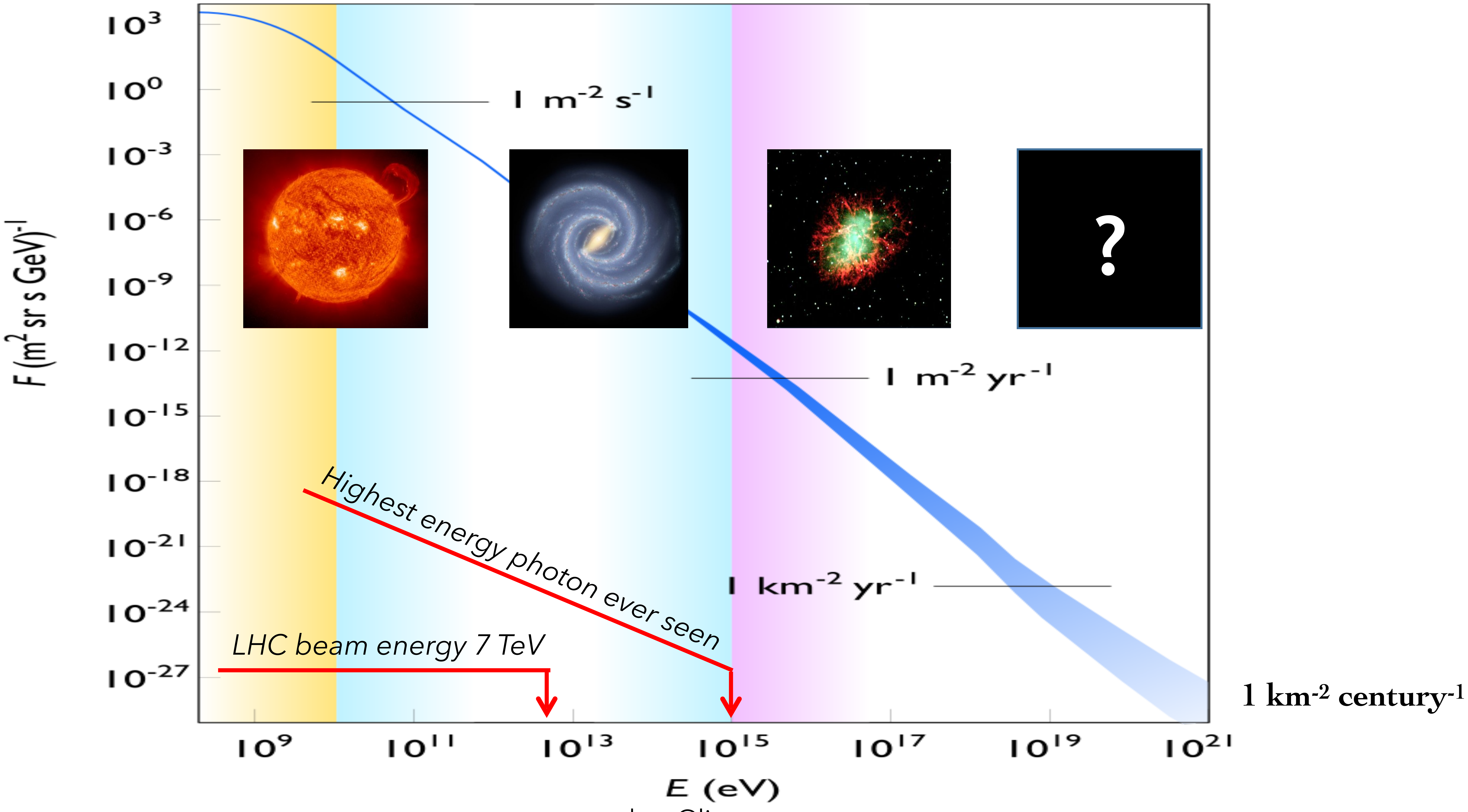
Cosmic ray energy spectrum



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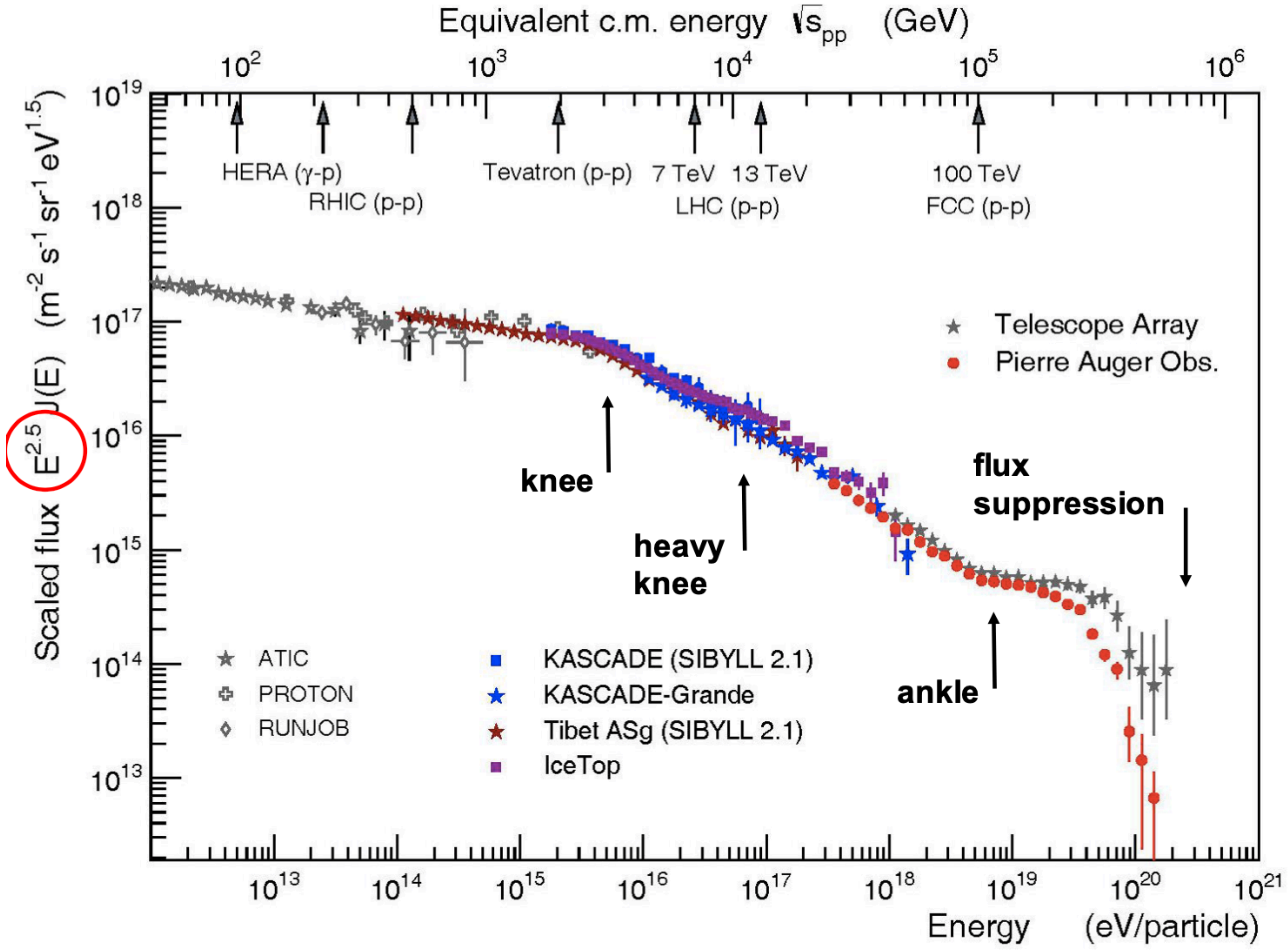
Cosmic ray energy spectrum



- ✧ Spectral features (kinks) are related to the production and propagation of cosmic rays

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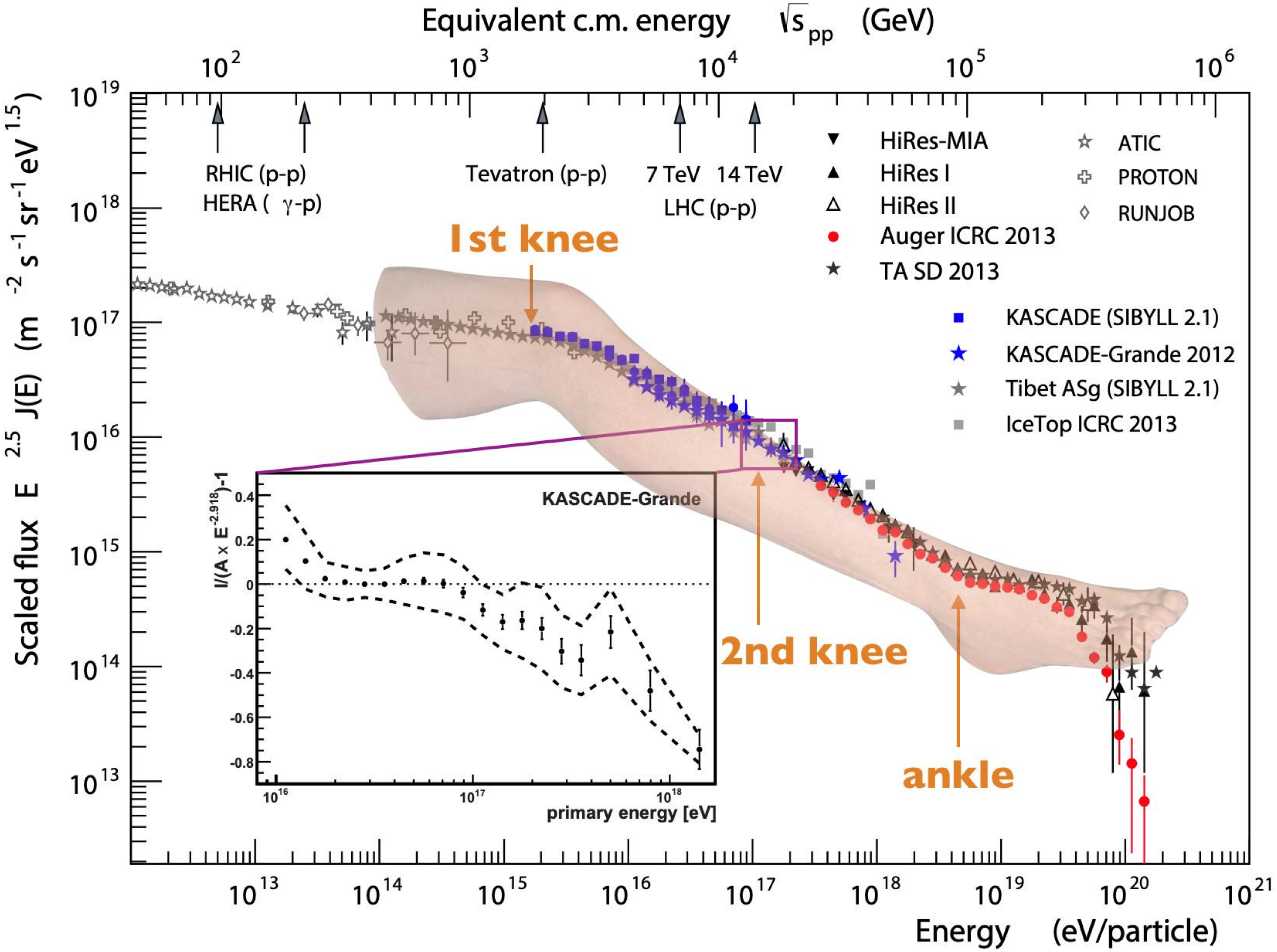
Cosmic ray energy spectrum



✧ An anthropomorphic interpretation of the spectrum

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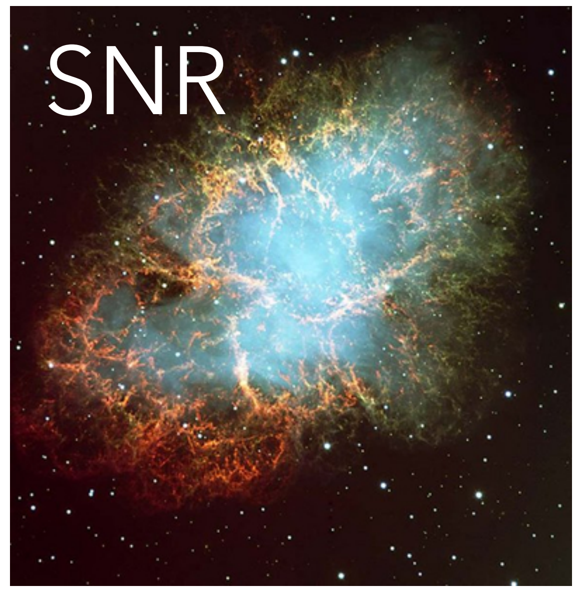
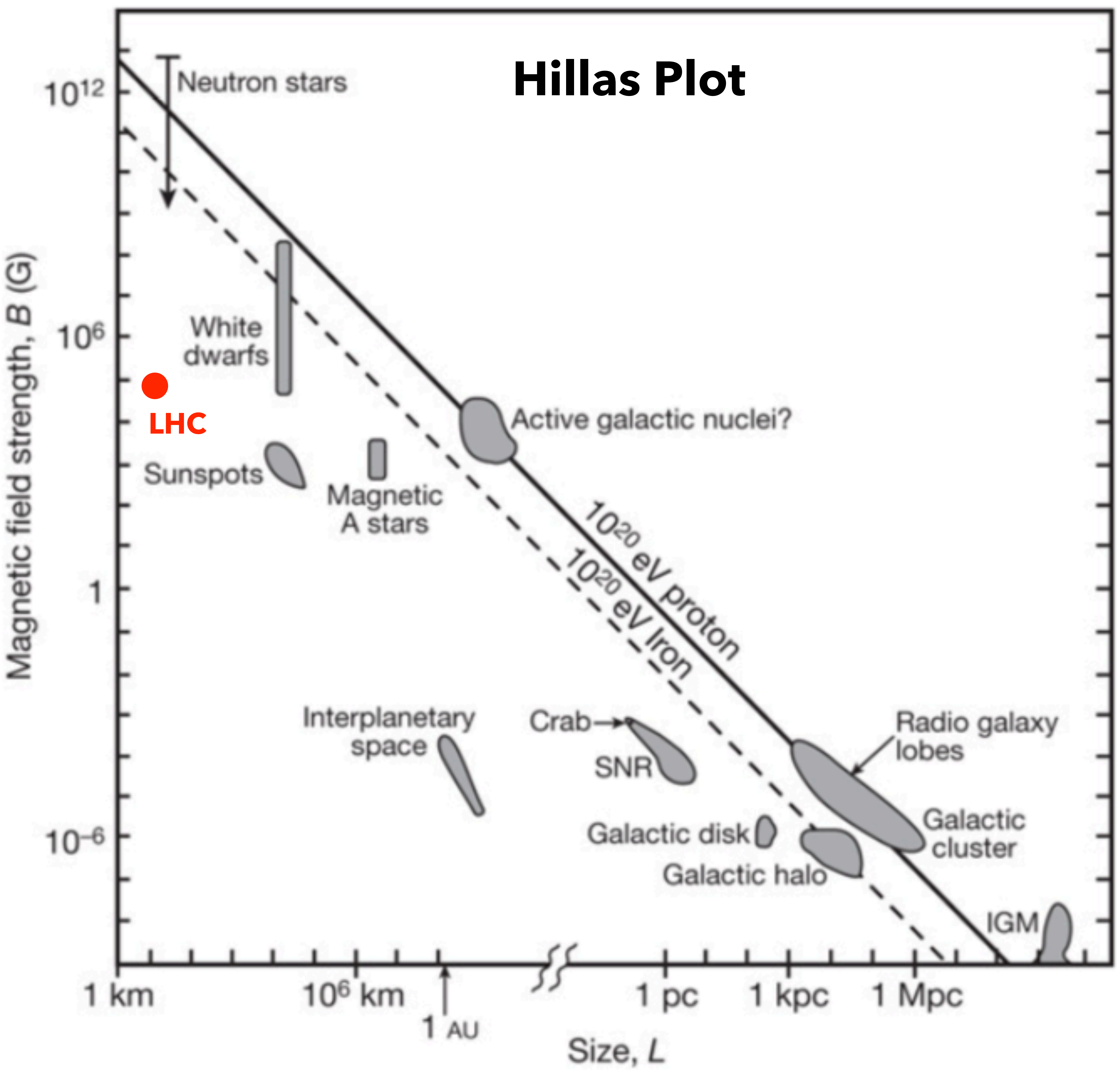
Acceleration

Cosmic ray accelerators

- Charge particles can be accelerated by:
  - Violent phenomena like supernovas or pulsars
  - Strong magnetic fields like supernova remnants (SNR) or active galactic nuclei (AGN)
- Interplay between strength of the magnetic field and the size of the "accelerator"

$$E_{max} \sim \beta_s \, z \, B \, L$$





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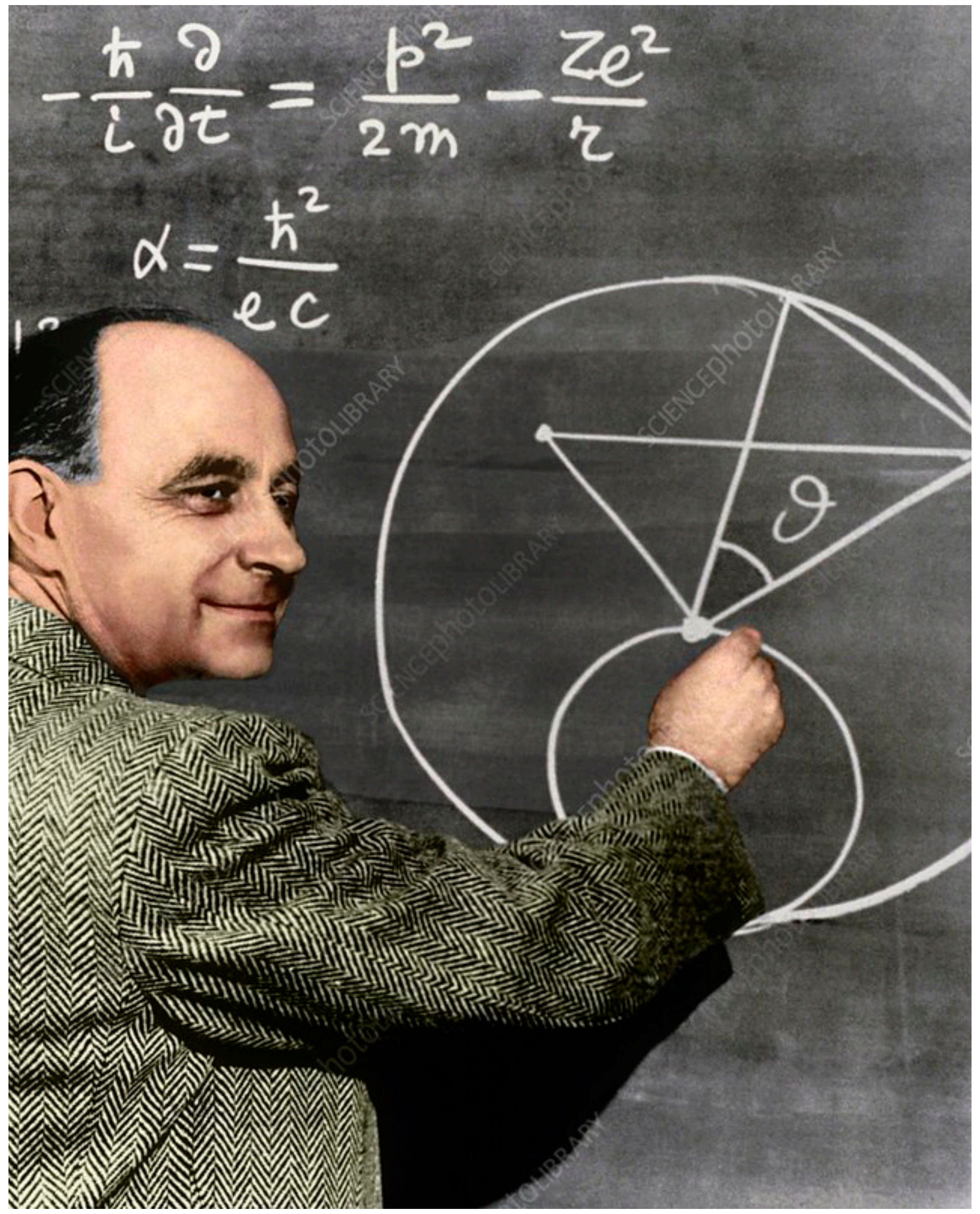
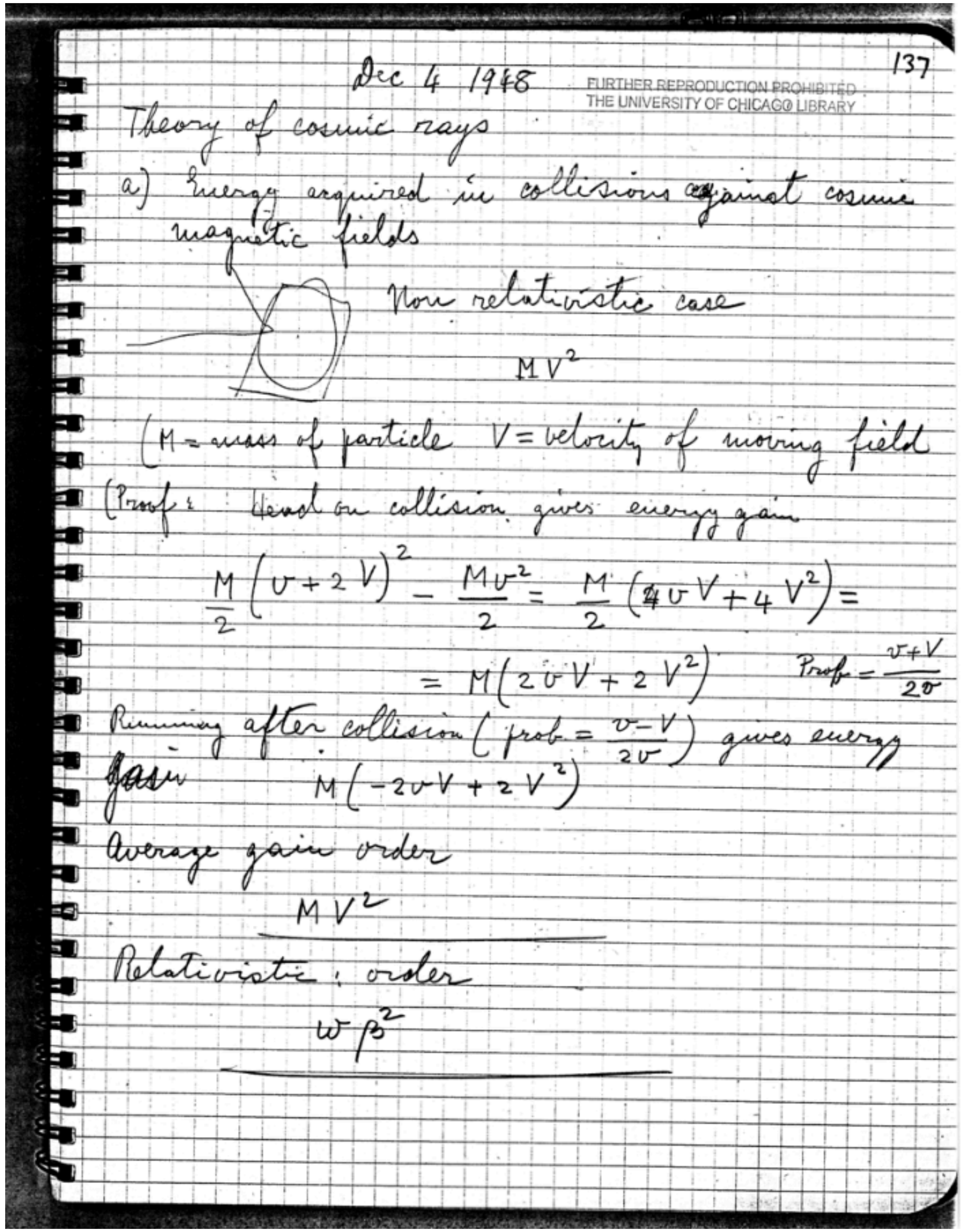
How to accelerate particles above thermal energies?



Bottom-up acceleration mechanism initially proposed by Enrico Fermi (1949)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Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Prob: Head on collision gives energy gain

$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$

$= M(2vV + 2V^2)$ Prob $= \frac{v+V}{2v}$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain

$M(-2vV+2V^2)$

Average gain order

MV^2

Relativistic: order

$w\beta^2$

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Fermi 2nd order acceleration mechanism

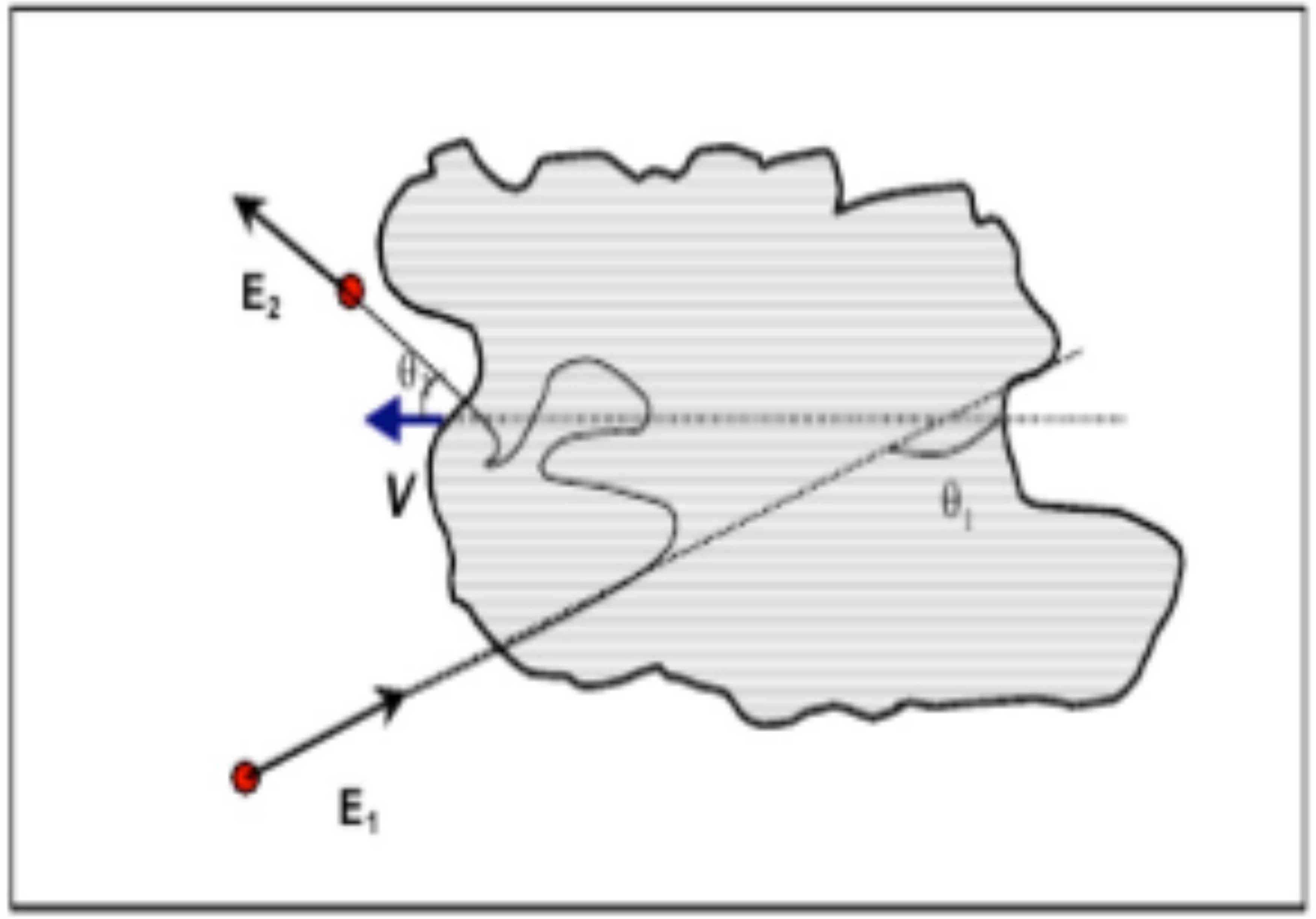
- Particles accelerated in stochastic collisions with massive interstellar cloud
- In the cloud reference frame

$$E_1^* = \gamma E_1 (1 - \beta \cos\theta_1)$$

$$E_2^* = E_1^*$$

- Returning to the LAB reference frame

$$E_2 = \gamma E_2^* (1 + \beta \cos\theta_2^*)$$



- Therefore the relative energy gain is:

$$\frac{\Delta E}{E} \equiv \frac{E_2 - E_1}{E_1} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2\cos\theta_1\cos\theta_2^*}{1-\beta^2} - 1$$

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Fermi 2^{nd} order acceleration mechanism

- Particles are randomly scattered on the magnetic field in the cloud (diffusion process)

$$\langle \cos\theta_2^* \rangle = 0$$

- Due to the cloud movement, head on collisions are slightly more probable

$$\langle \cos\theta_1 \rangle = \frac{\int_{-1}^{1} \cos\theta_1 (1-\beta\cos\theta_1) \mathrm{d}\cos\theta_1}{\int_{-1}^{1} (1-\beta\cos\theta_1) \mathrm{d}\cos\theta_1} = -\frac{\beta}{3}$$

- Fermi 2^{nd} order gain:

$$\boxed{\left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{4}{3}\beta^2}$$

(Clouds typically move at $\beta \sim 10^{-4}$)

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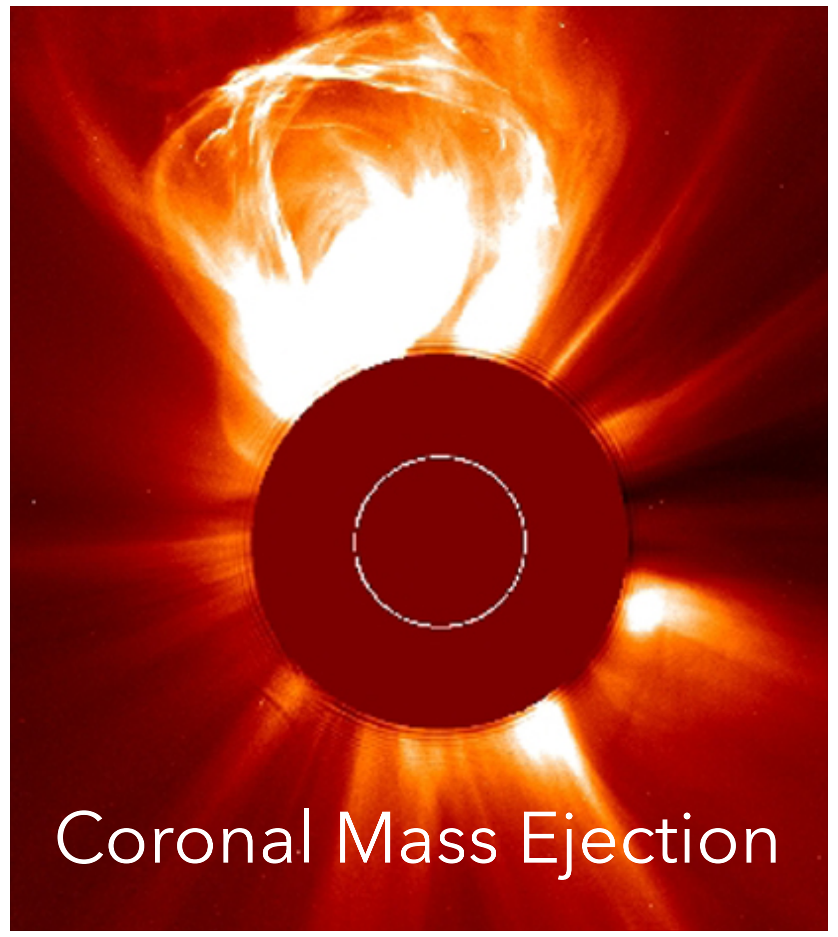
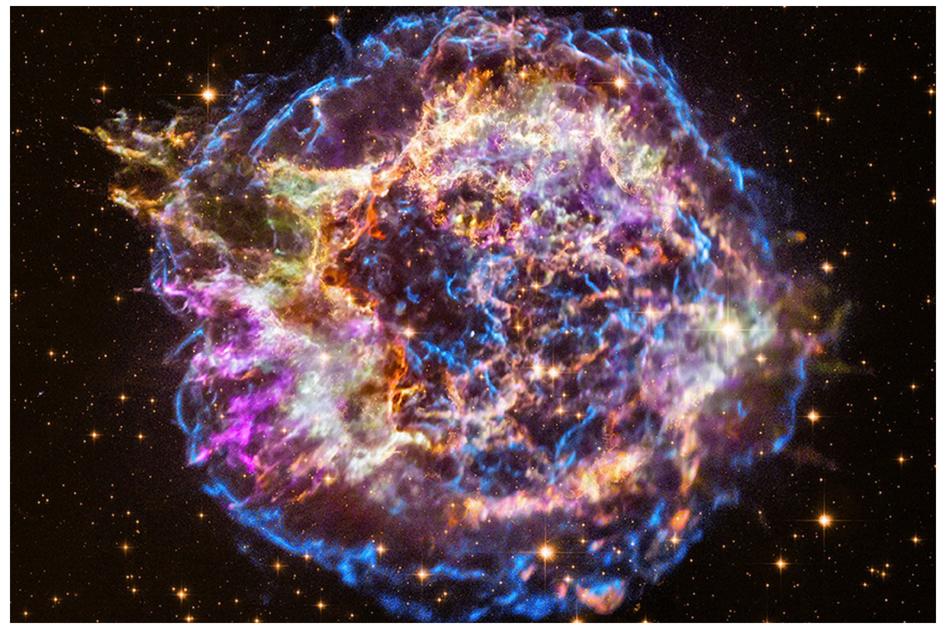
Fermi 1st order acceleration mechanism

- Shock formation:
  - Sudden release of energy (CMEs, SNRs, GRBs, …)
  - Supersonic flow hits an obstacle (AGNs jets, pulsar winds, …)



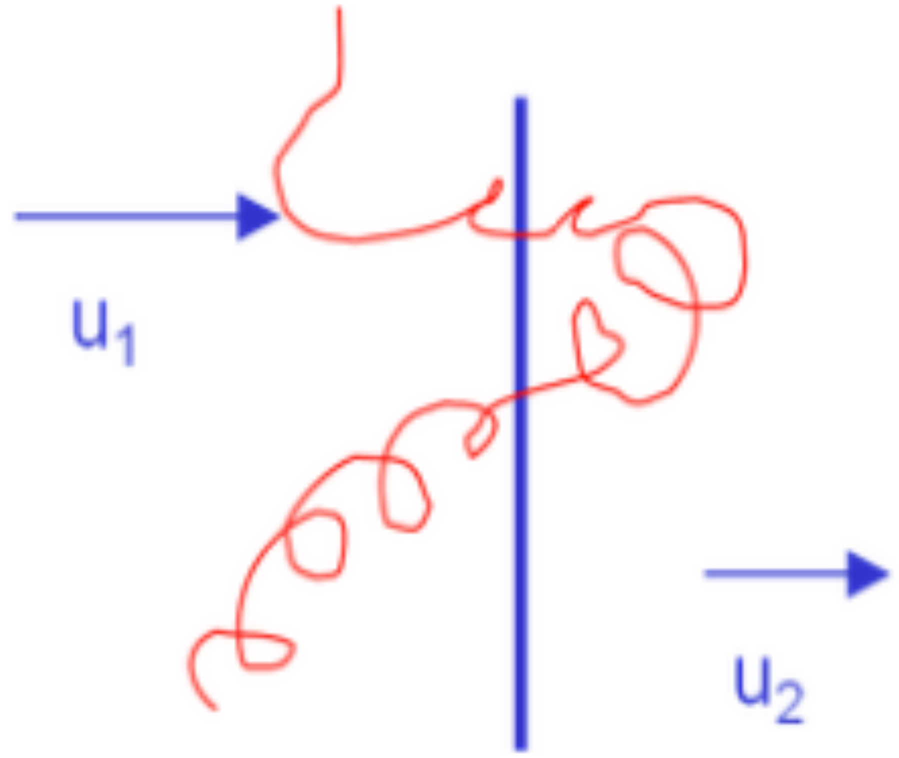
Coronal Mass Ejection

Supernova Remnant



- Same idea as before:

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2\cos\theta_1\cos\theta_2^*}{1-\beta^2} - 1$$



- But now the crossing probability is proportional to:

$$\propto \cos\theta$$

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Fermi 1st order acceleration mechanism

✧ Crossing the plane shock front downstream

$$\langle \cos\theta_1 \rangle = \frac{\int_{-1}^{0} \cos^2\theta_1 \,\mathrm{d}\cos\theta_1}{\int_{-1}^{0} \cos\theta_1 \,\mathrm{d}\cos\theta_1} = -\frac{2}{3}$$

✧ Crossing the plane shock front upstream

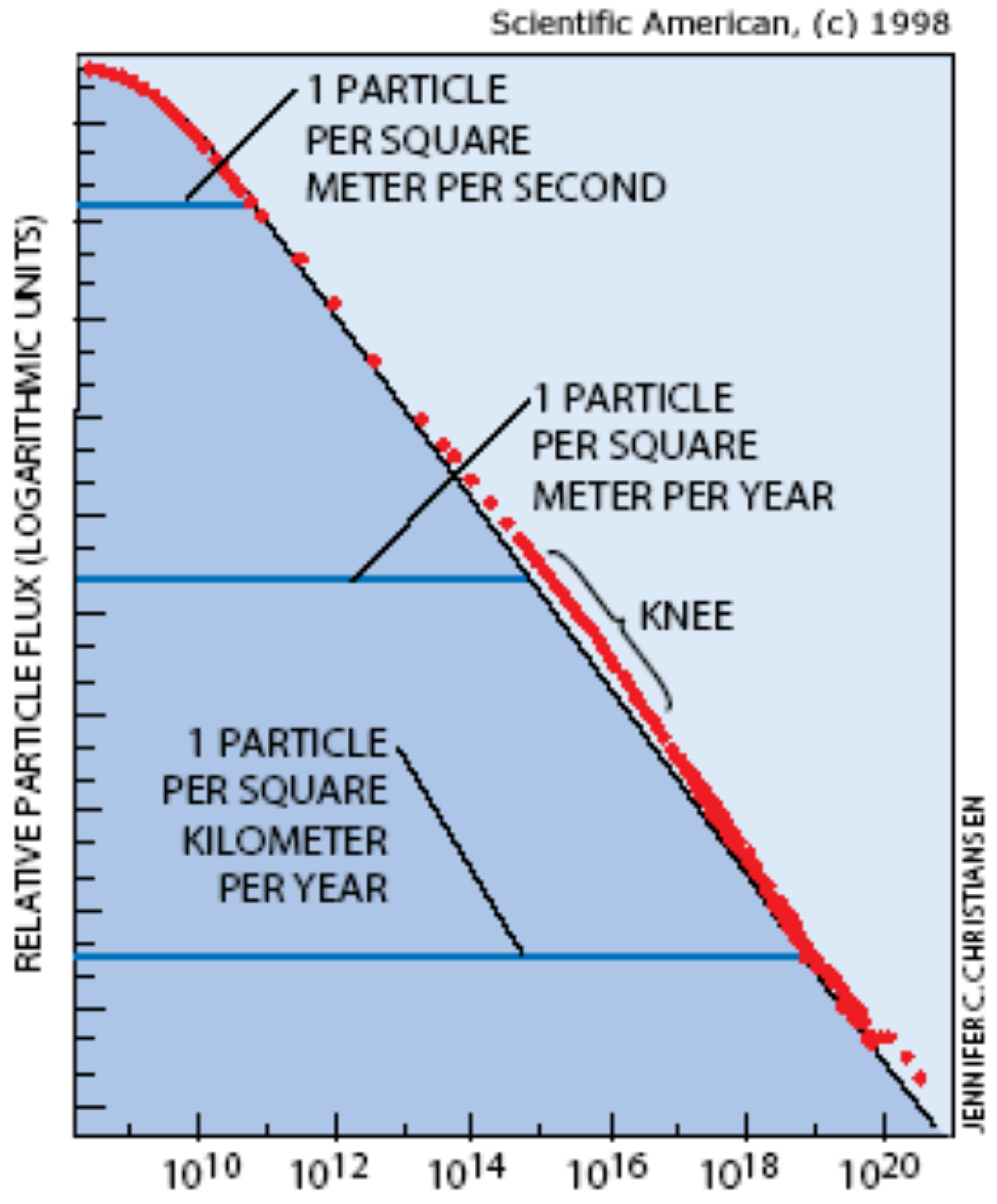
$$\langle \cos\theta_2^* \rangle = \frac{\int_{0}^{1} \cos^2\theta_2^* \mathrm{d}\cos\theta_2^*}{\int_{0}^{1} \cos\theta_2^* \mathrm{d}\cos\theta_2^*} = \frac{2}{3}$$

✧ Fermi 1st order gain:

$$\left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{4}{3}\beta$$

(Shock fronts typically move at $\beta \sim 10^{-2}$)

The power law



Differential energy flux

$$\frac{dN}{dE} \propto E^{-\gamma}$$

Integral energy flux

$$N(E > E_0) \propto E^{-\gamma+1}$$

✧ In each cycle the particle gains a small fraction of energy ε. After n cycles it gets an energy:

$$E_n = E_0(1+\varepsilon)^n$$

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The power law

- If the particle escapes from the shock region with some probability P_e then the probability to escape with $E > E_n$ is:

$$P_{E_n} = P_e \sum_{j=n}^{\infty} (1 - P_e)^j = (1 - P_e)^n$$

$$P_{E_n} = (1 - P_e)^{\ln\left(\frac{E}{E_0}\right)/\ln(1+\varepsilon)}$$

$$\frac{N}{N_0} = P_{E_n} = \left(\frac{E}{E_0}\right)^{-\alpha} \quad \text{with} \quad \alpha = -\frac{\ln(1 - P_e)}{\ln(1 + \varepsilon)} \simeq \frac{P_e}{\varepsilon}$$

$$\ln P_{E_n} = \frac{\ln\left(\frac{E}{E_0}\right)}{\ln(1 + \varepsilon)} \ln(1 - P_e) = \frac{\ln(1 - P_e)}{\ln(1 + \varepsilon)} \ln\left(\frac{E}{E_0}\right)$$

- The index of the power-law carries information about production and propagation

$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{\gamma} \quad \text{with} \quad \gamma = \alpha + 1$$

$$\left(\frac{dN}{dE}\right)_{\text{source}} \propto E^{-2}$$

$$\left(\frac{dN}{dE}\right)_{\text{Earth}} \propto \left(\frac{dN}{dE}\right)_{\text{source}} \times \tau_{\text{escape}}(E) \propto E^{-2.7}$$

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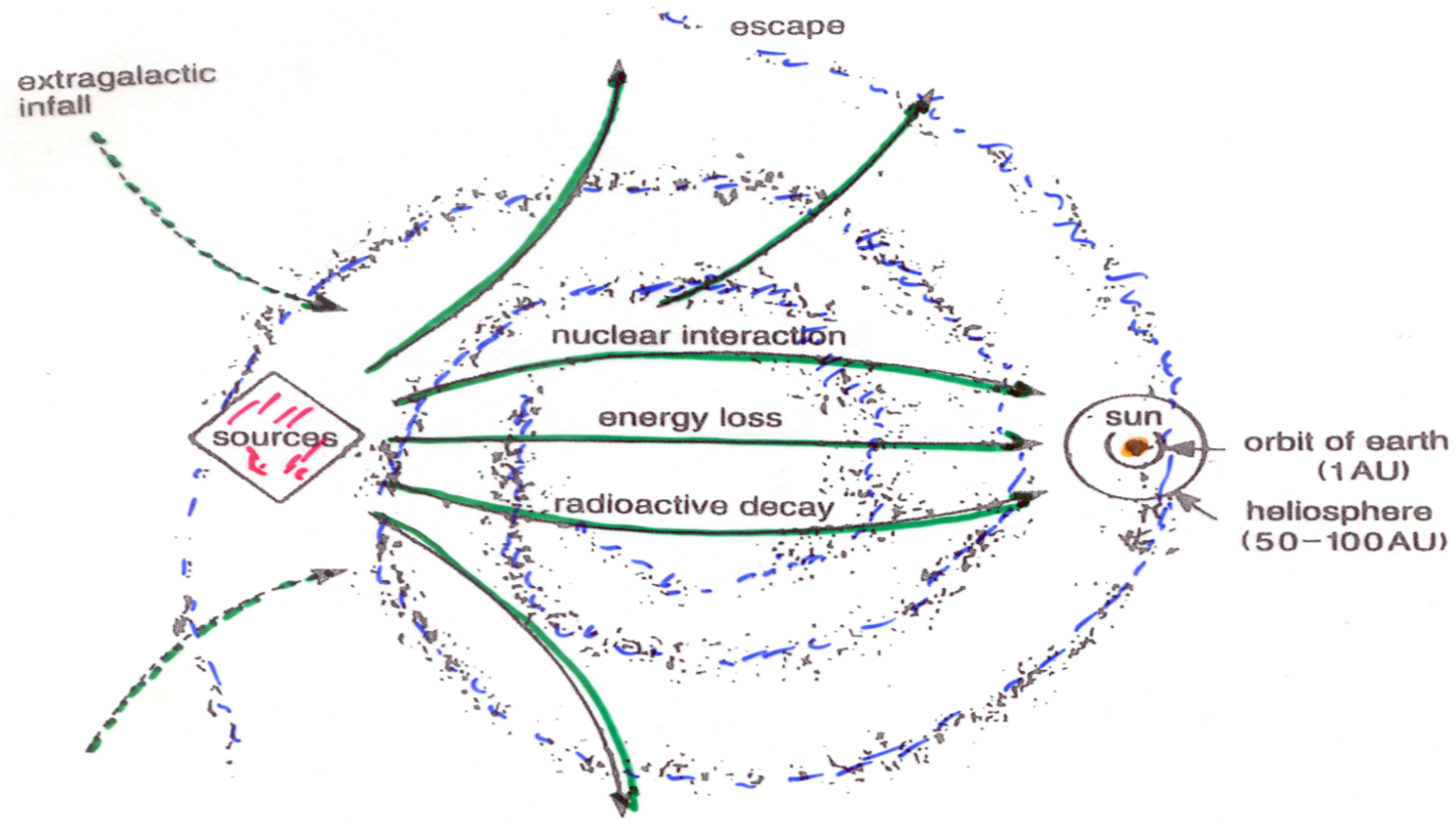
Propagation

Propagation in the galaxy



$$\frac{\partial N_i}{\partial t} = Q_i + \vec{\nabla} \cdot \left(D\vec{\nabla} N_i - \vec{V} N_i \right) + \frac{\partial}{\partial E}(b(E)N_i) - \frac{N_i}{\tau_i} + \sum_{j>i} \frac{P_{ji} N_j}{\tau_j} - \ldots$$

Sources | Diffusion | Convection | Energy gains and losses | Escape | Spallation gains | Spallation and decay losses

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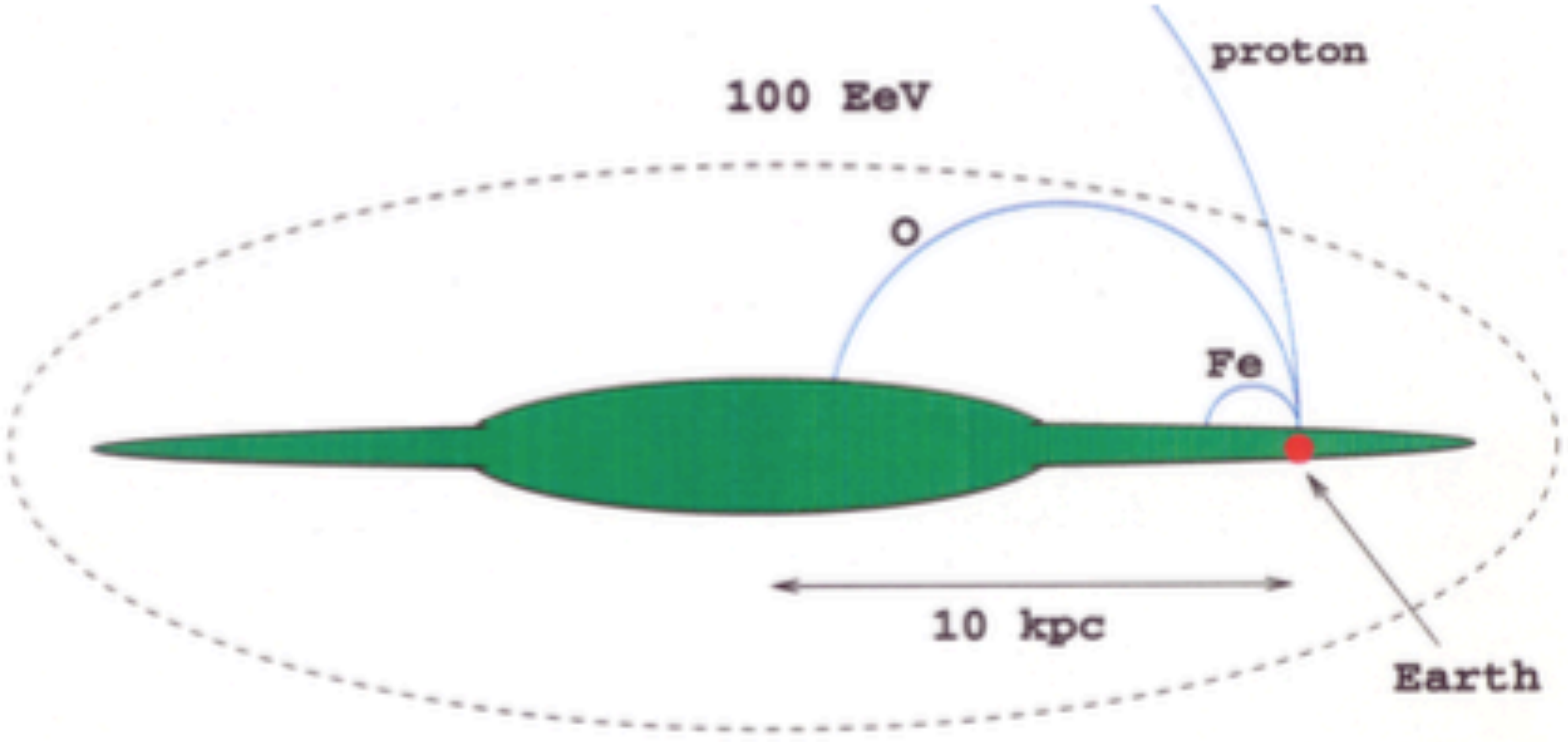
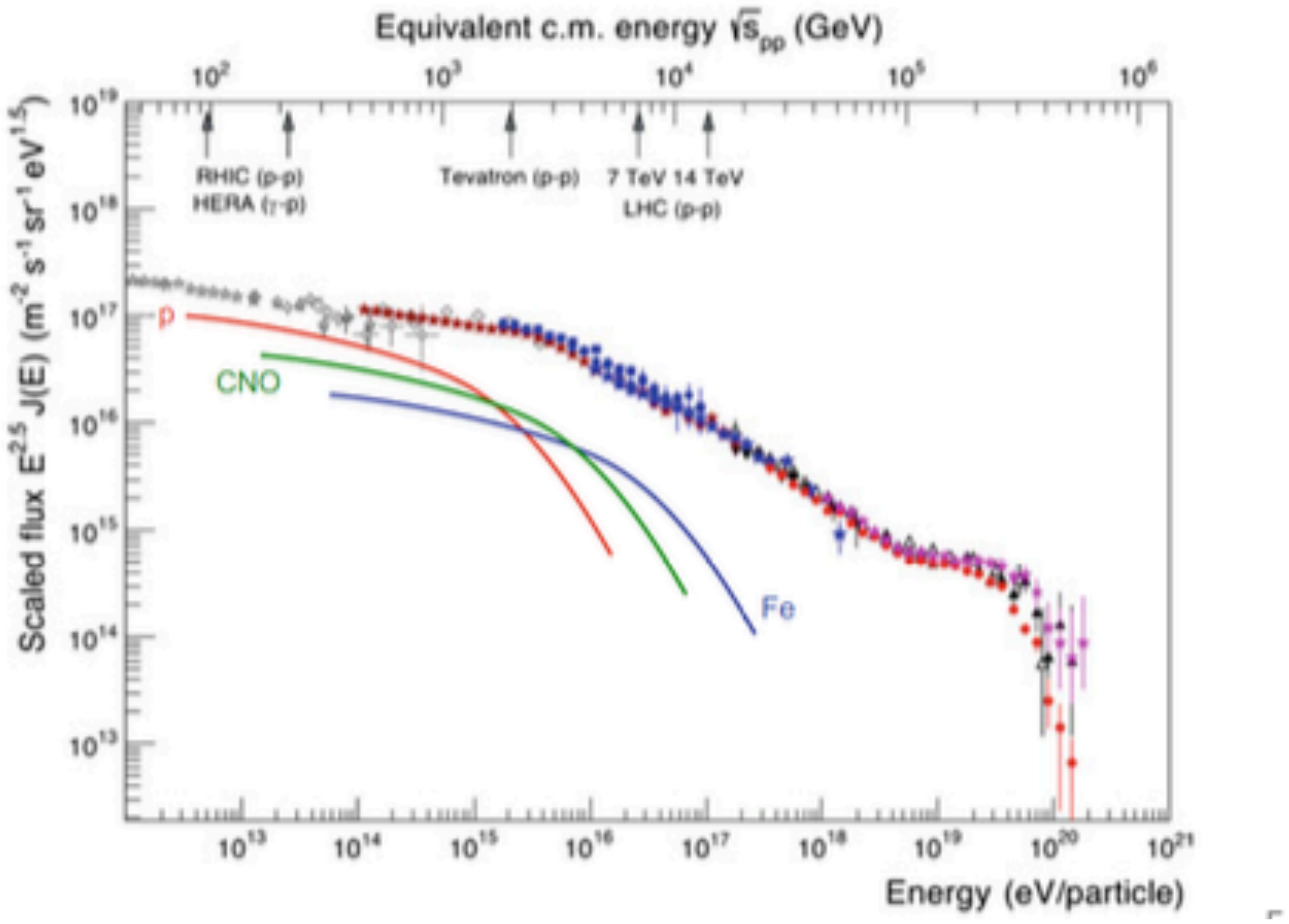
The knee(s)

- Charged cosmic rays diffuse and interact in the Galactic randomly magnetised ISM
  - Confinement times ~10^7 years
  - CR are basically isotropic
- Use secondary/primary composition ratios to constrain the propagation models
  - e.g. B/C ratio

$$\begin{aligned}\frac{\partial N_i}{\partial t} =& Q_i + \vec{\nabla}\cdot\left(D\vec{\nabla}N_i - \vec{V}N_i\right) + \frac{\partial}{\partial E}(b(E)N_i) \\ & - \left(n\beta_i c\sigma_i^{spall} + \frac{1}{\gamma_i\tau_i^{\mathrm{decay}}} + \frac{1}{\gamma_i\hat{\tau}_i^{\mathrm{esc}}}\right)N_i \\ & + \sum_{j>i}\left(n\beta_j c\sigma_{ji}^{spall} + \frac{1}{\gamma_i\tau_{ji}^{\mathrm{decay}}}\right)\end{aligned}$$





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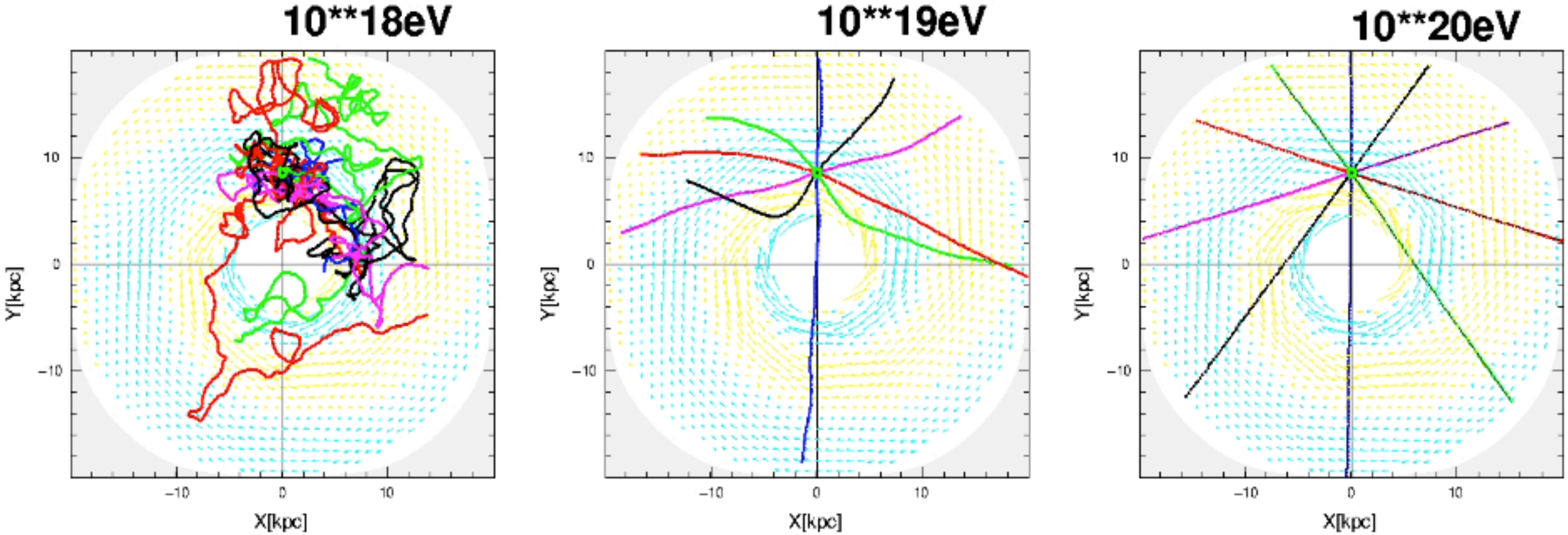
Towards the highest energies

Proton deflection in the galactic magnetic field



Magnetic (extra-)galactic field : (nG) μG

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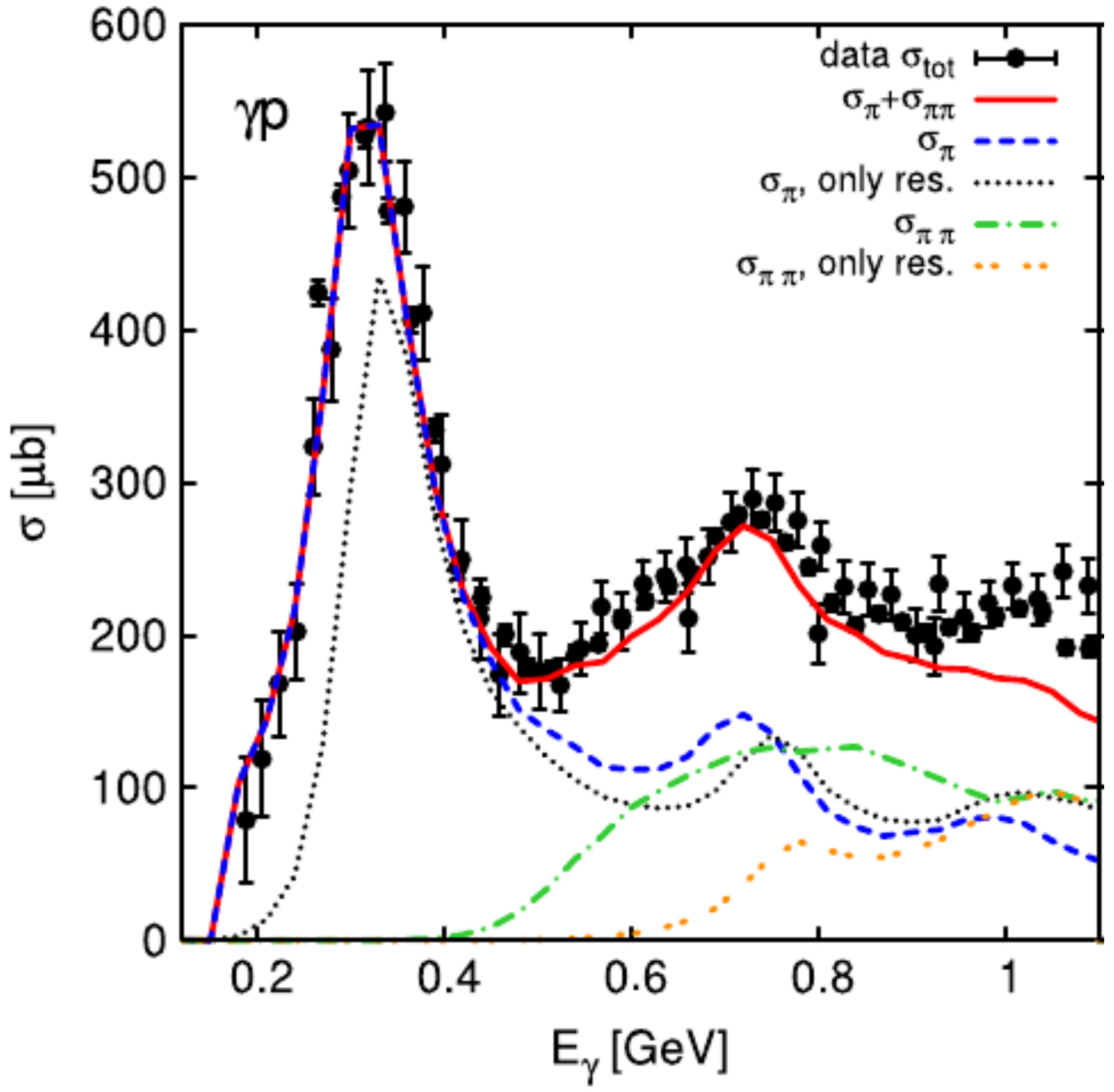
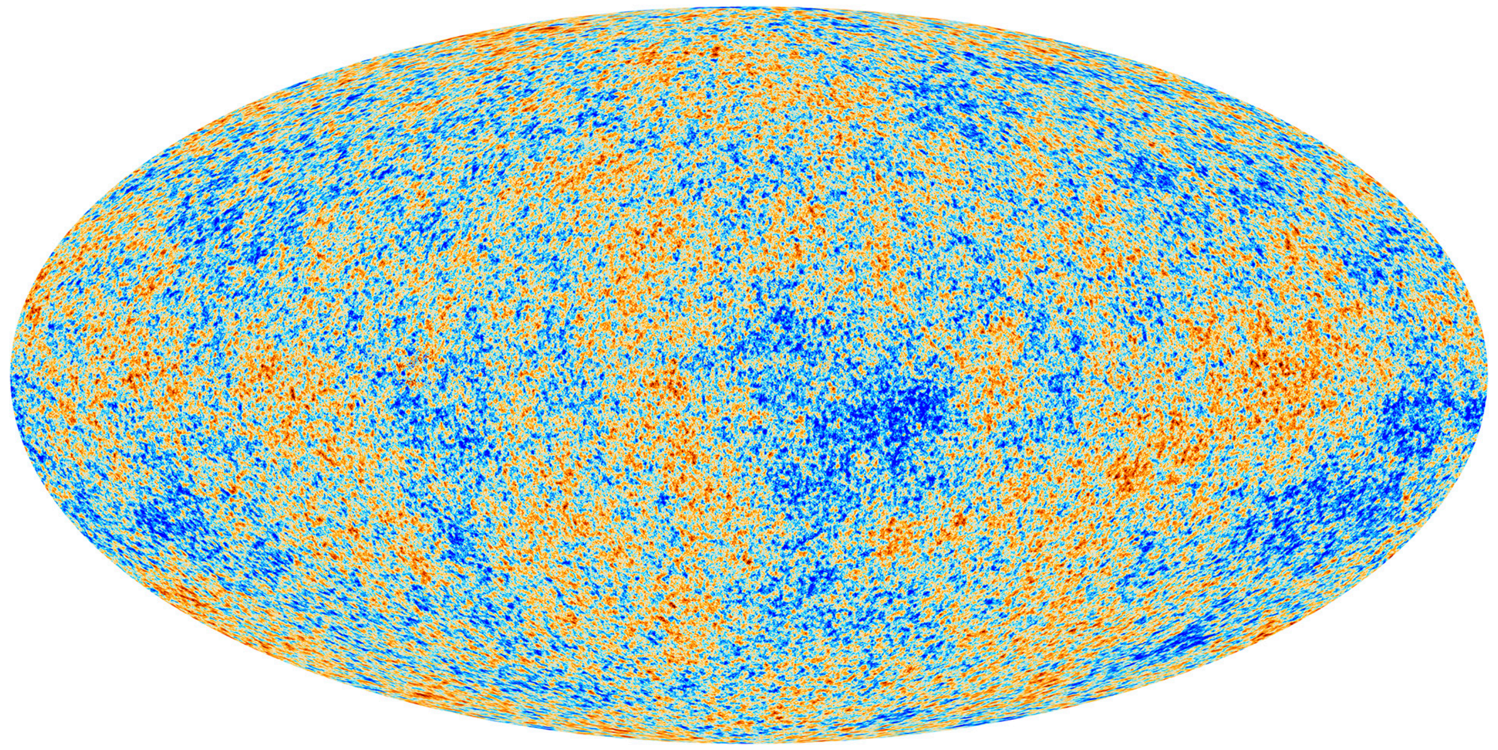
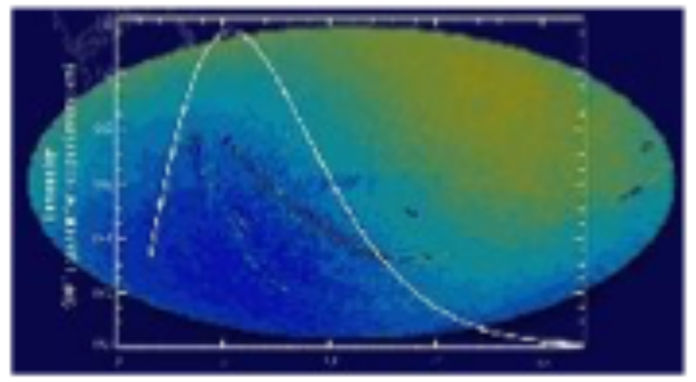
GZK effect





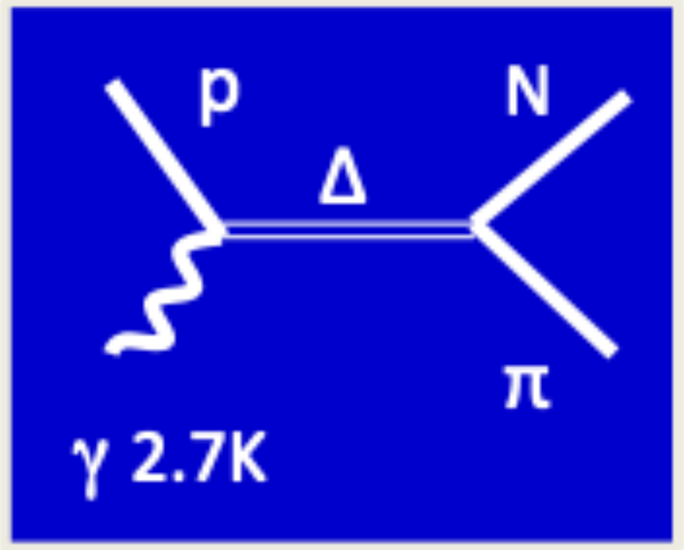
- ✧ Discovery of the Δ baryon in accelerator measurements
- ✧ Discovery of the cosmic microwave background

GZK effect

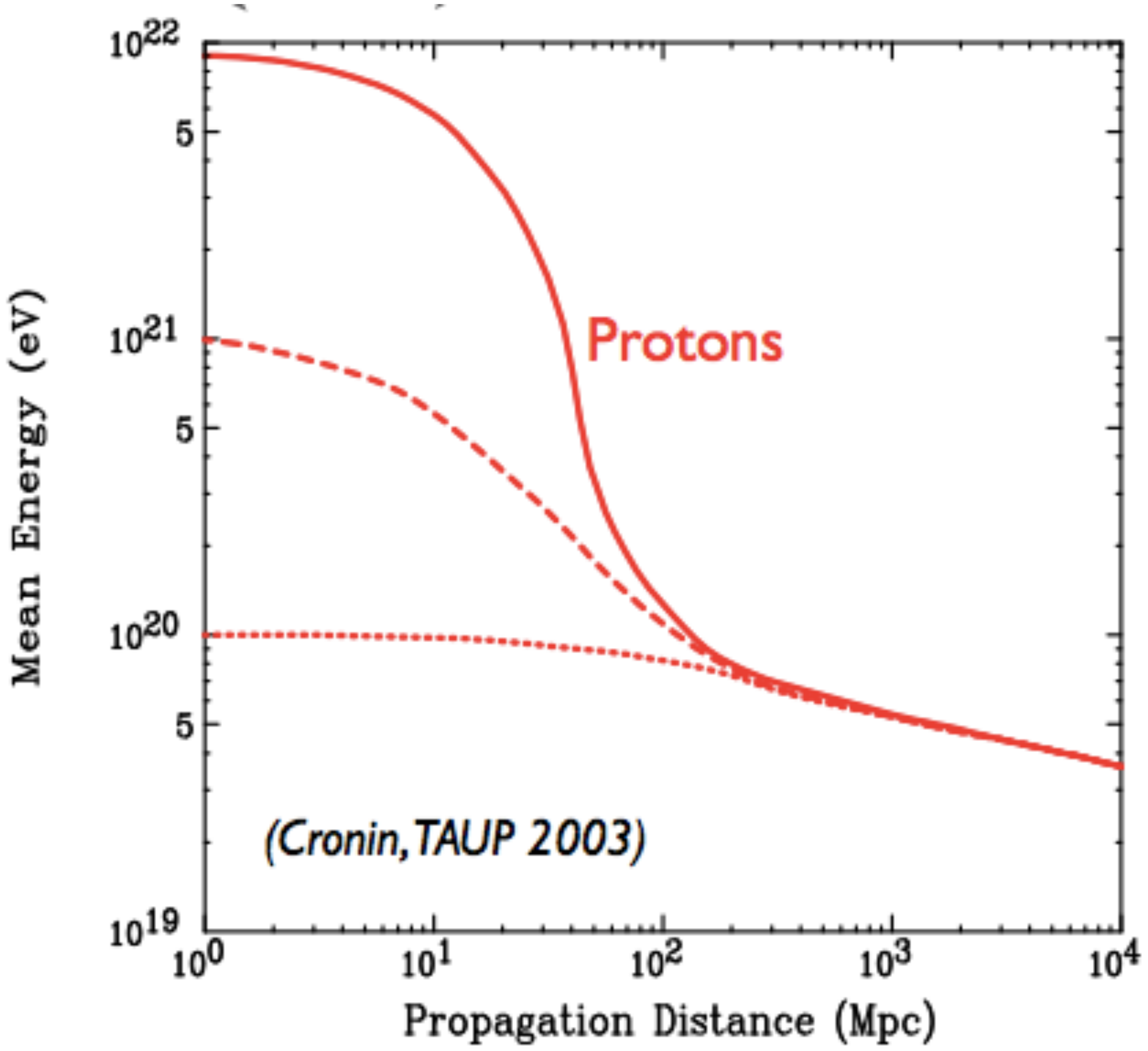


- GZK cuttoff
  - Greisen, Zatsepin, Kuz'min (1966)
  - Cosmic ray interaction with CMB
  - Energy loss process

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

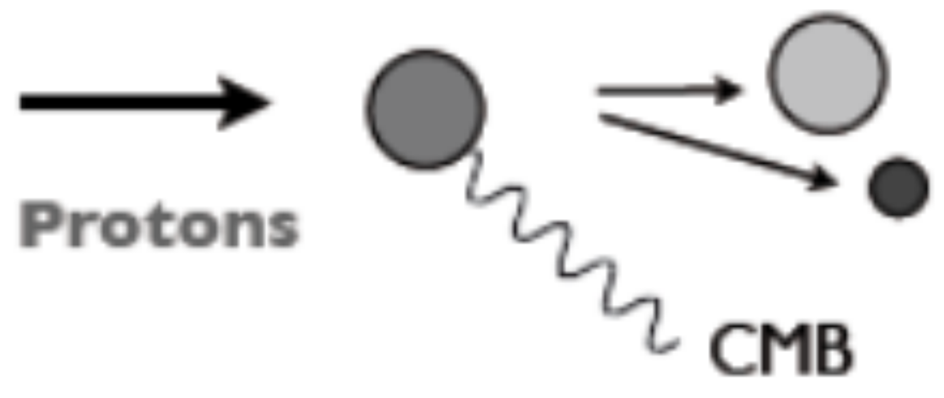


- Prediction: CR energy spectrum should have a cutoff around E ~ 10^{20} eV

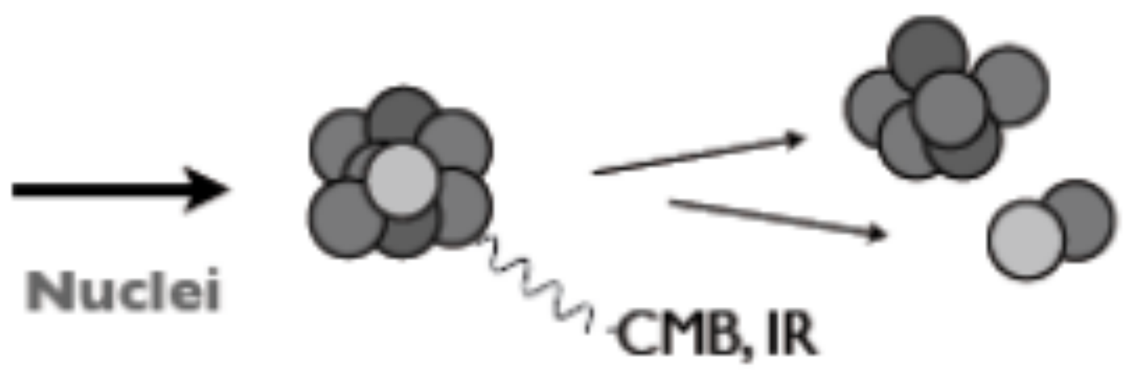


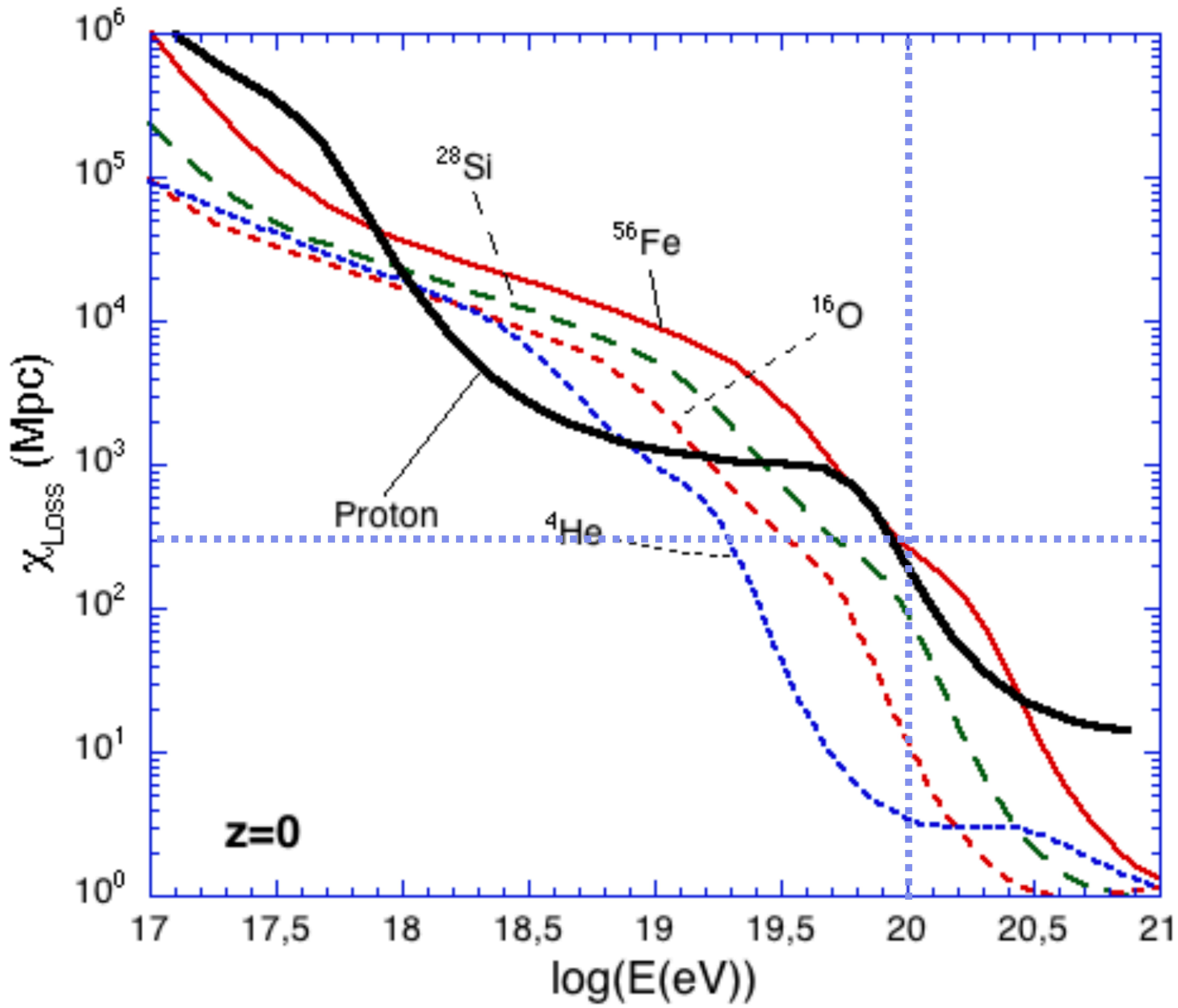
GZK vs nuclei photo-desintegration

GZK effect



Giant Dipole Resonance





At 10^{20} eV proton and iron have similar attenuation lengths

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Direct Measurements

Direct detection of cosmic rays

Balloon experiments
e.g.: CREAM-III

Satellite experiments
e.g.: AMS-II

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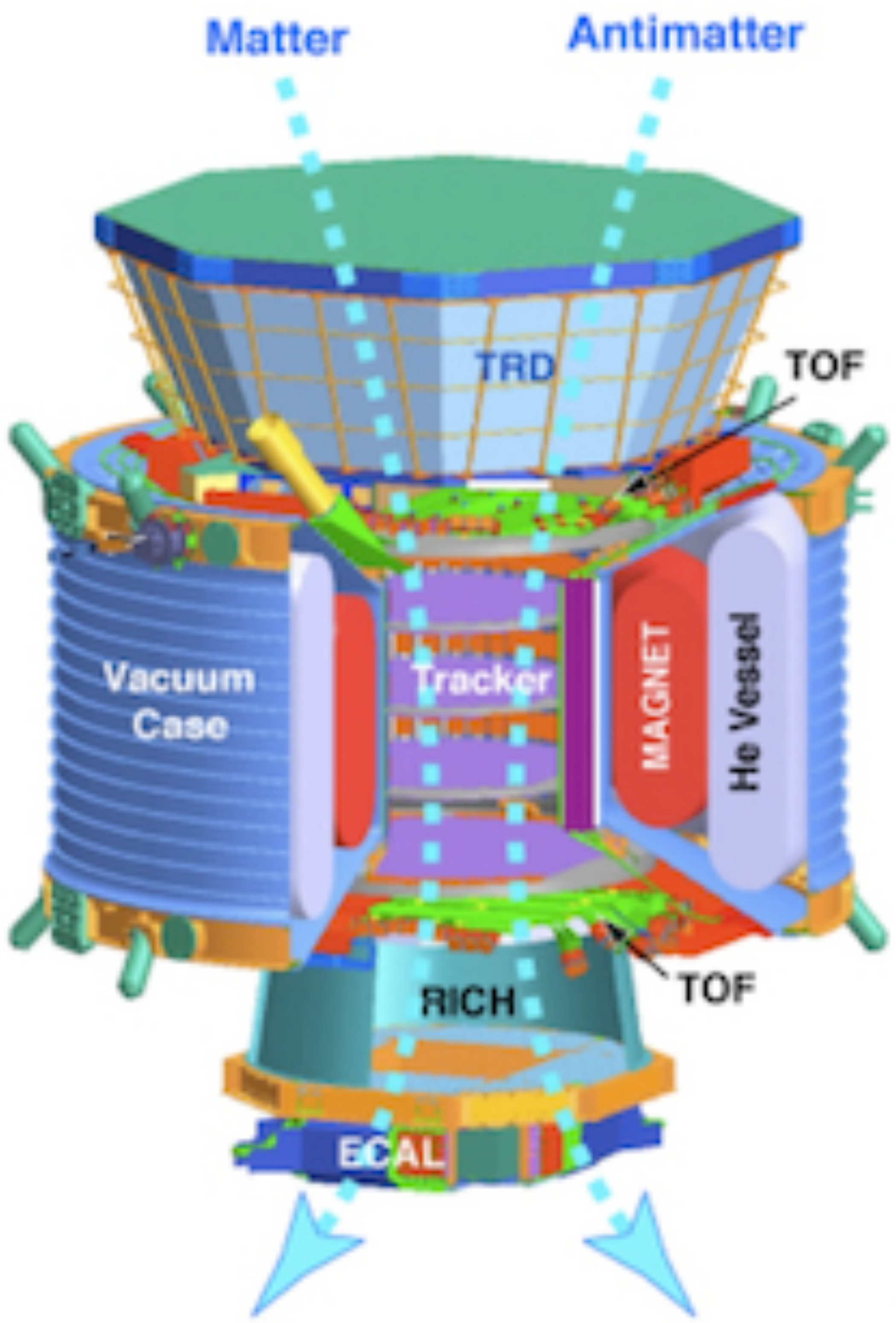
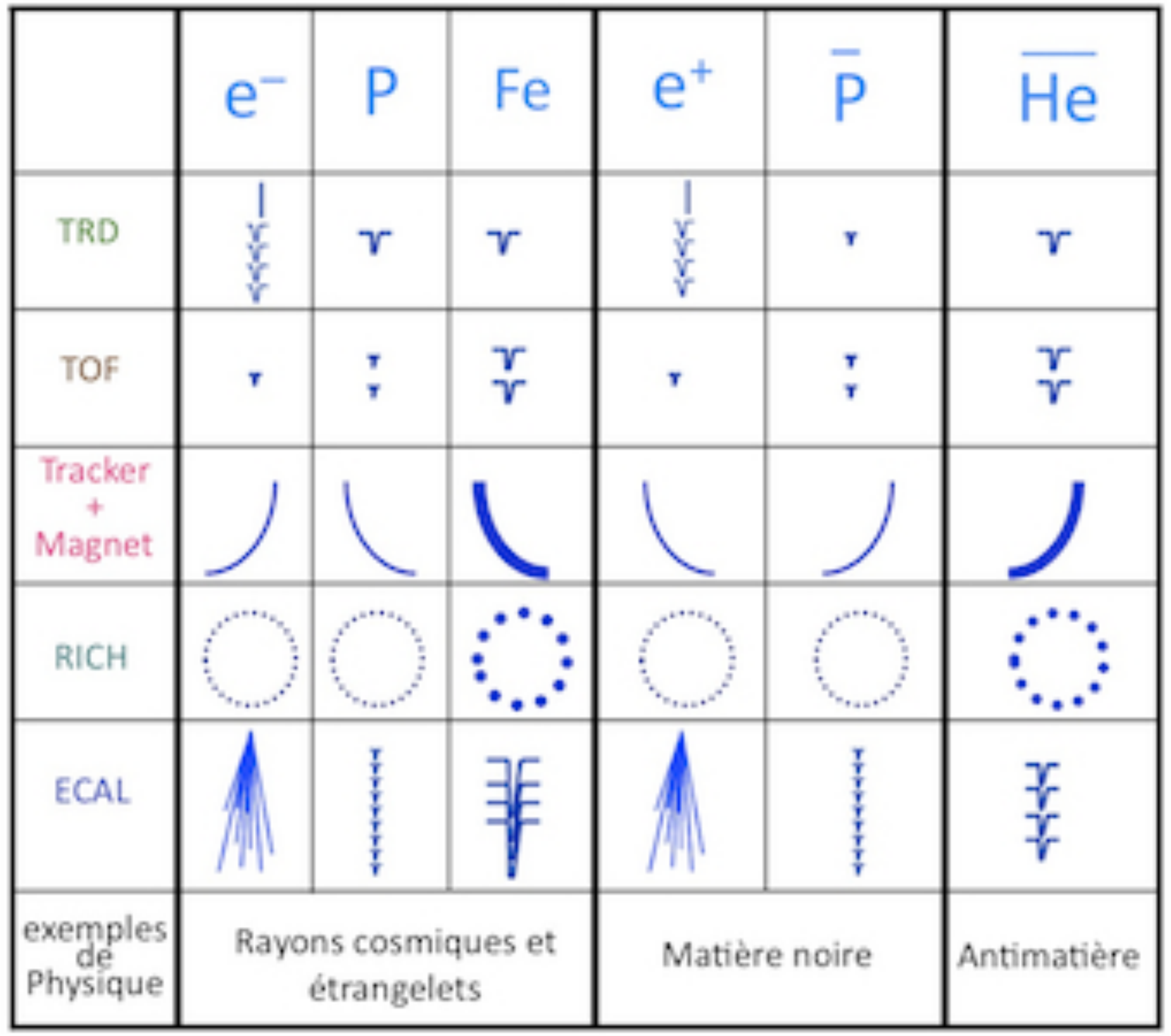
Operation principle

✧ Use particle spectrometers to identify particle nature and energy

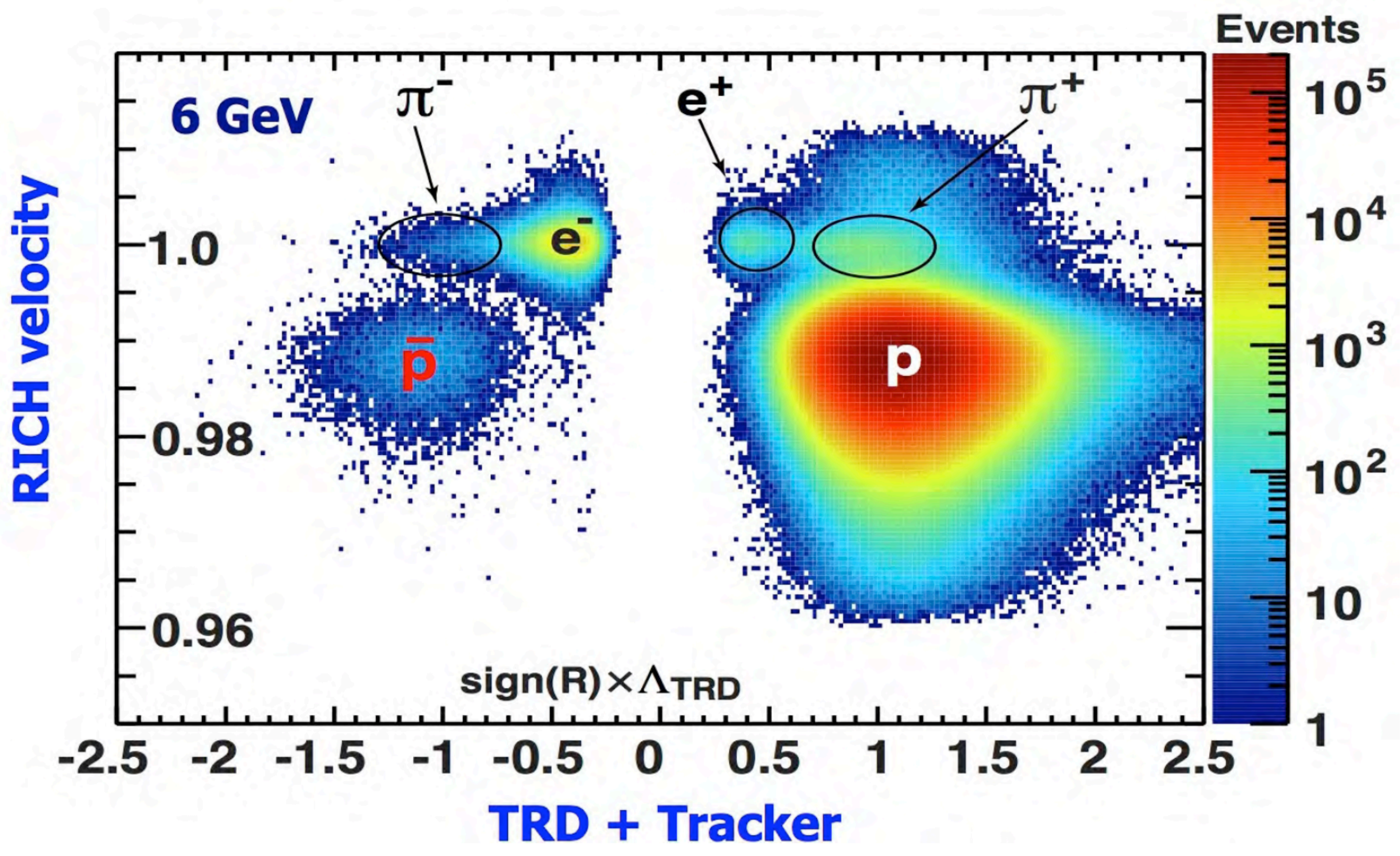


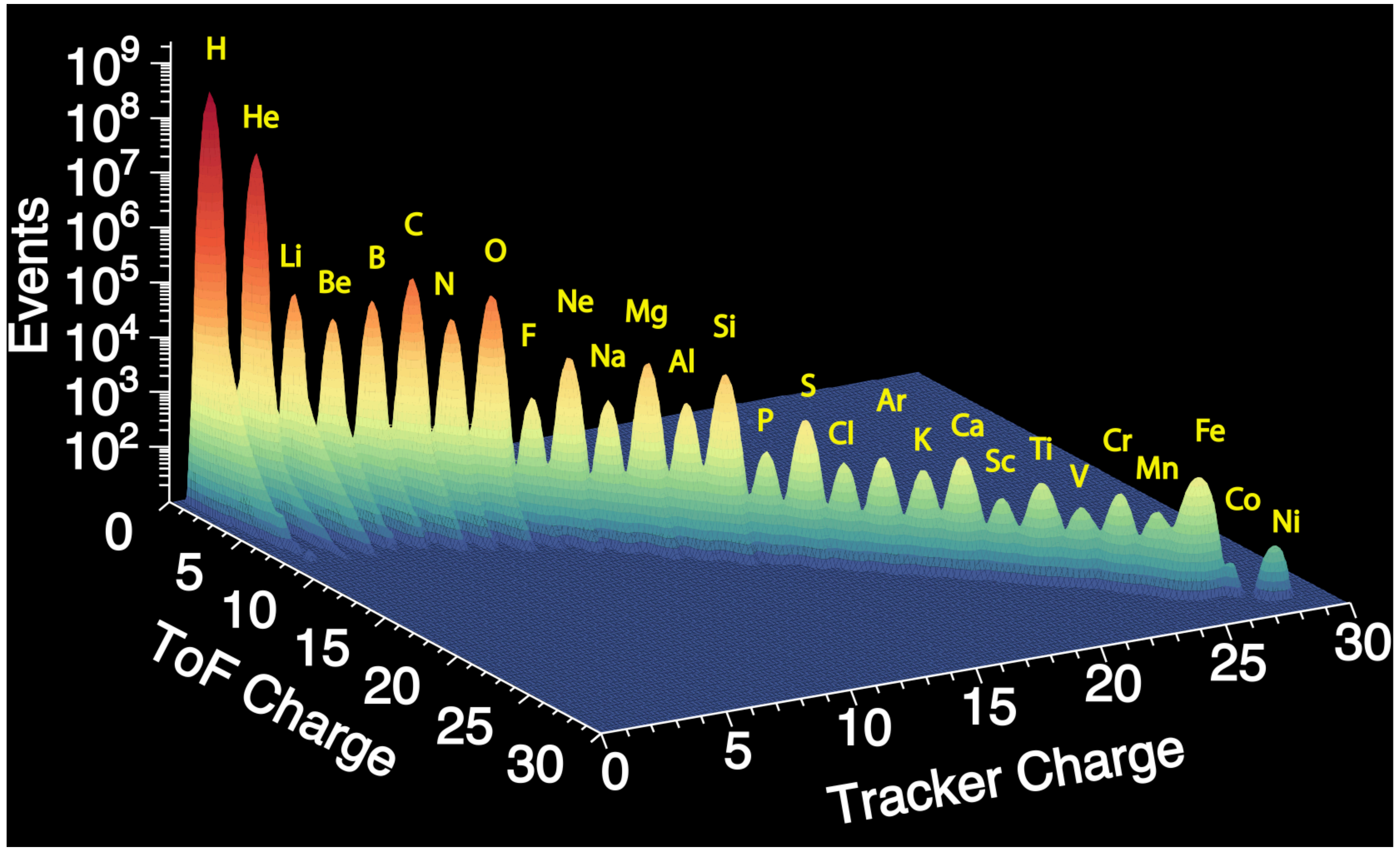


✧ Similar to what is done in an HEP accelerator experiment

Operation principle

- Use particle spectrometers to identify particle nature and energy



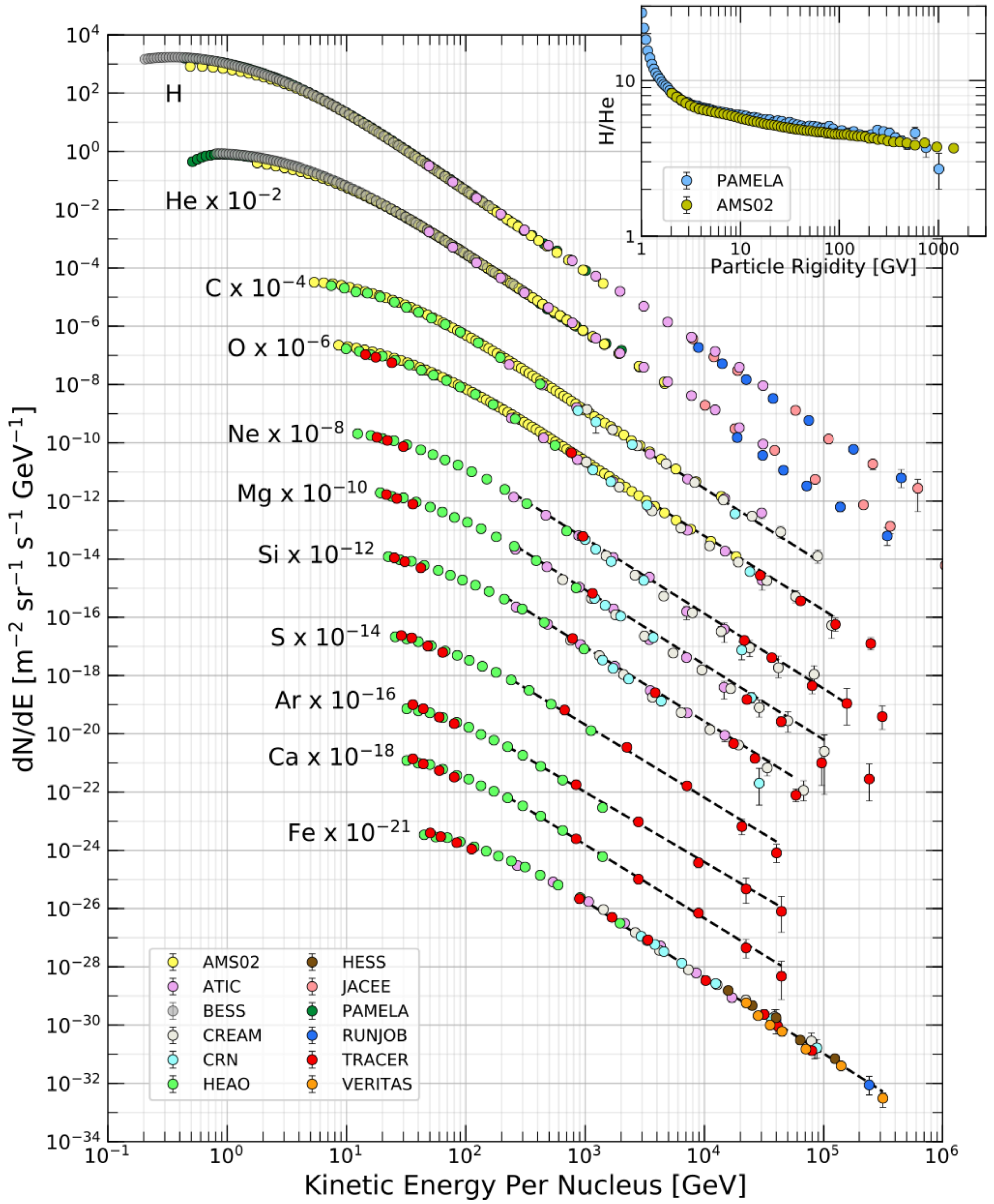


- Similar to what is done in an HEP accelerator experiment

Energy spectrum

- ✧ Cosmic ray composition can be directly measured up to PeV

- ✧ Relation between elements can be used to constrain acceleration properties



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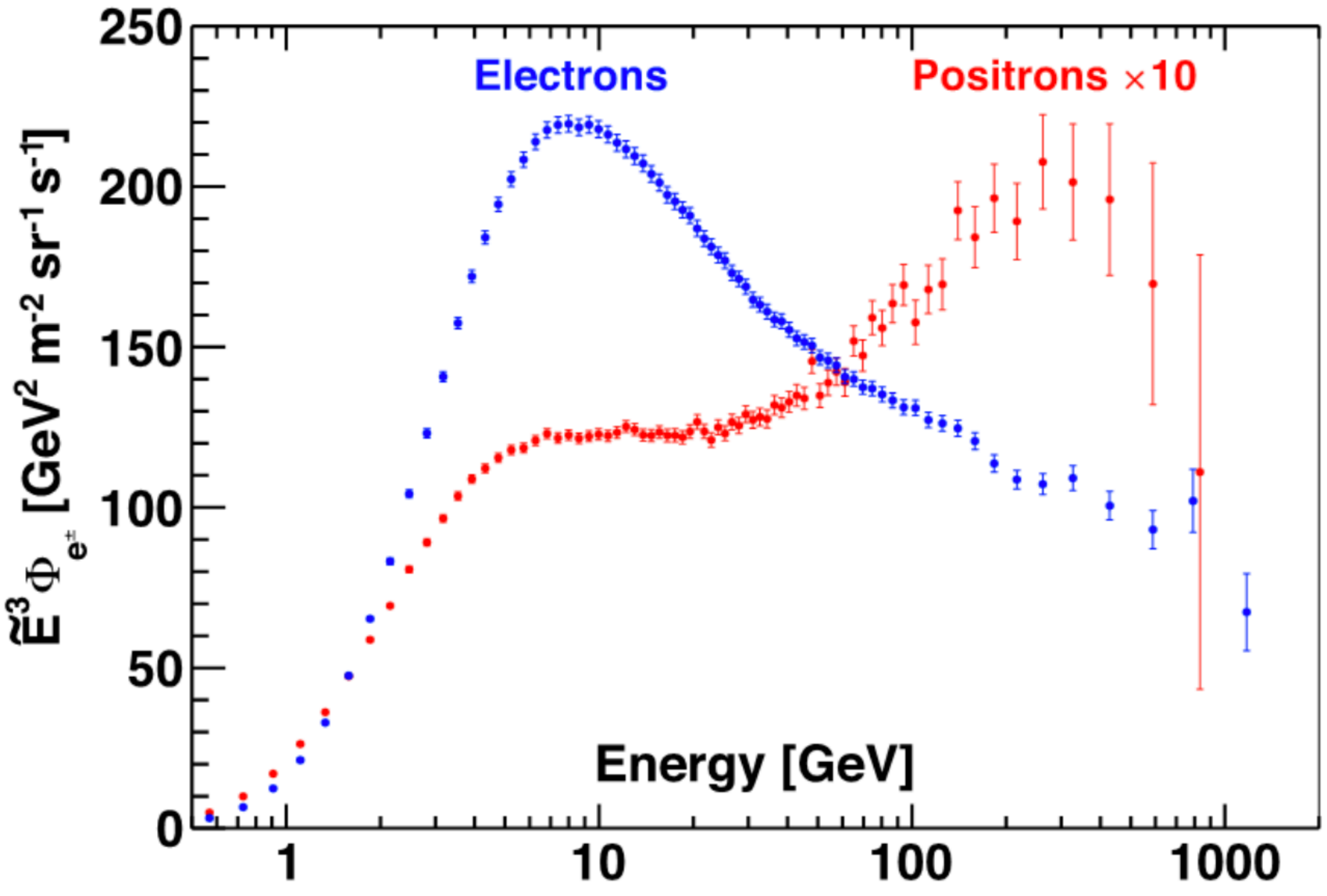
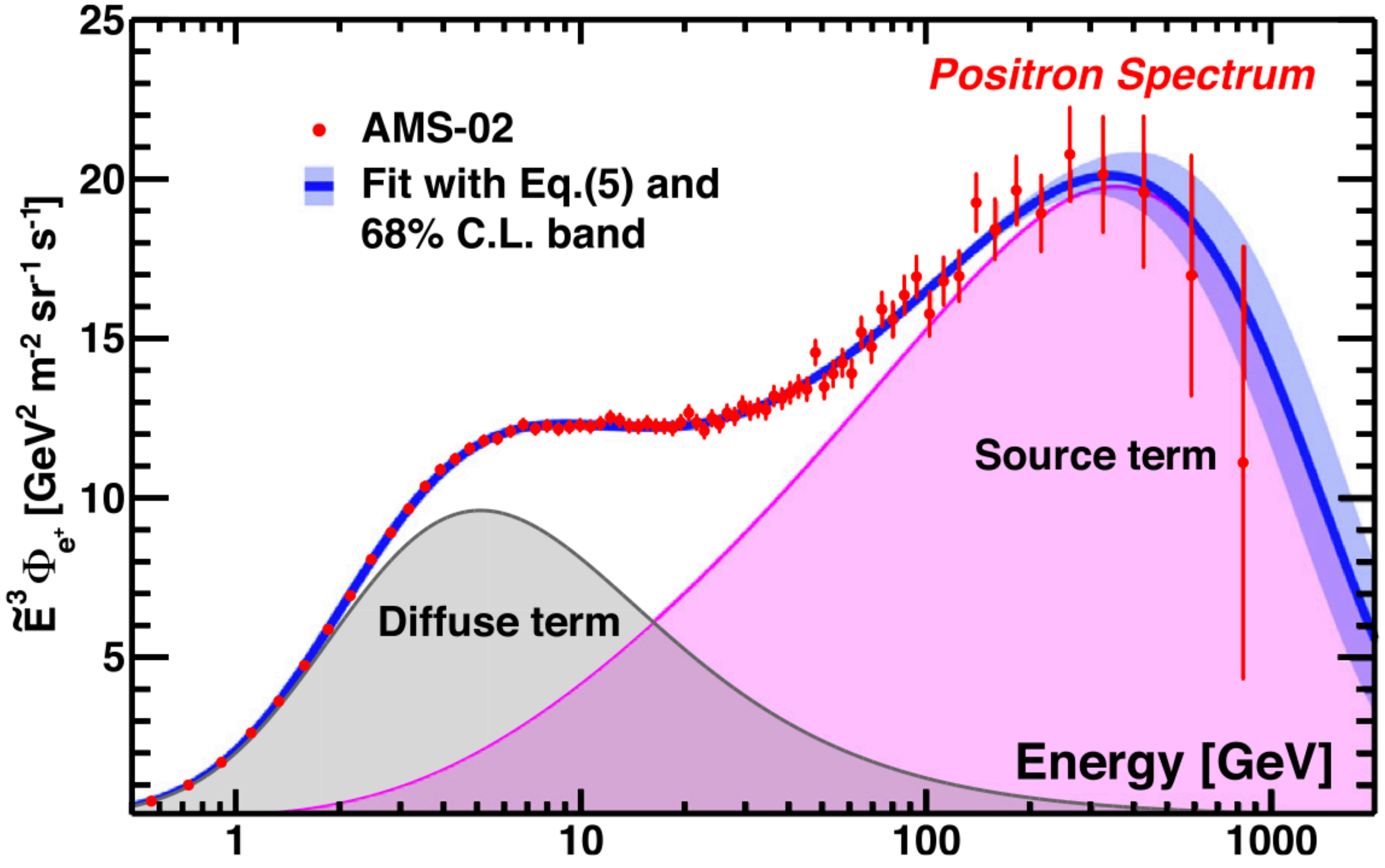
Positron flux



Positron excess origin

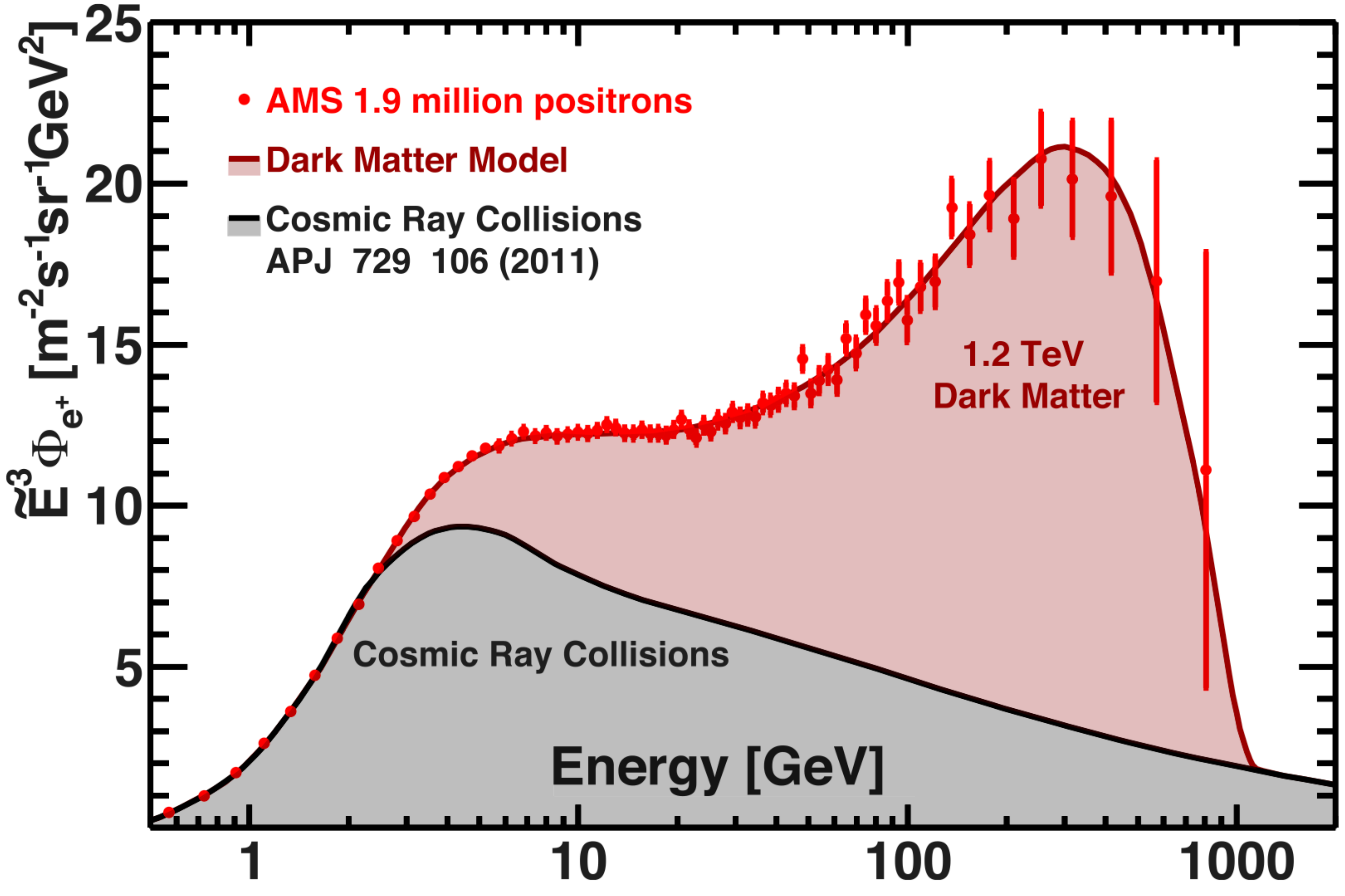
Astrophysical origin

Pulsar winds



Fundamental particle physics

Dark matter decay/annihilation



AMS continues to gather statistics and by 2024 should be able to distinguish between the two scenarios

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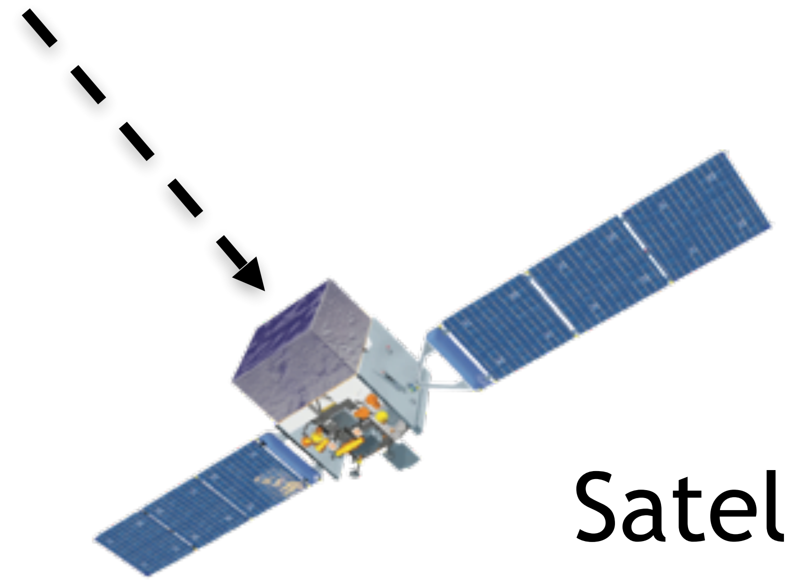
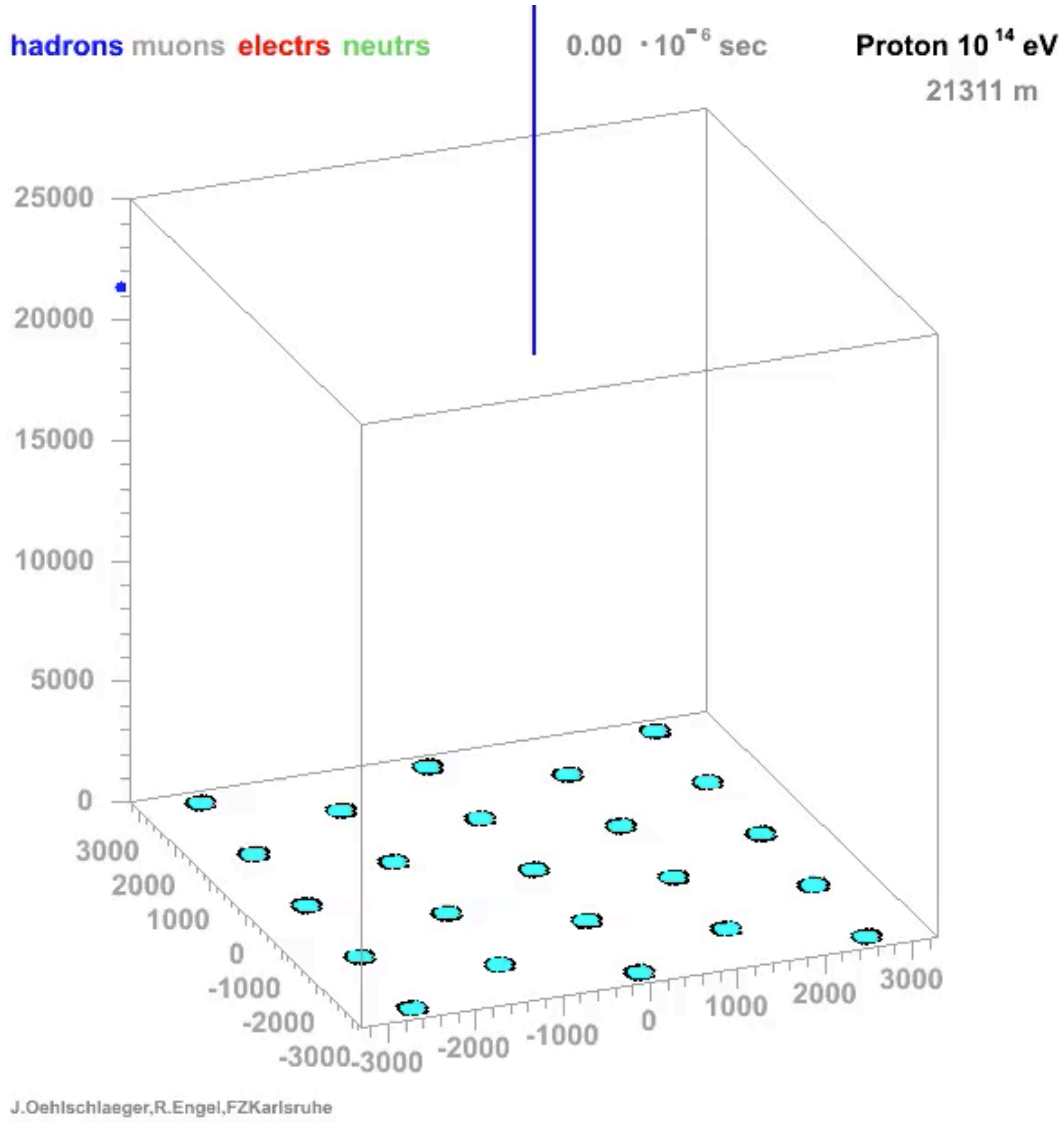
Indirect Measurements

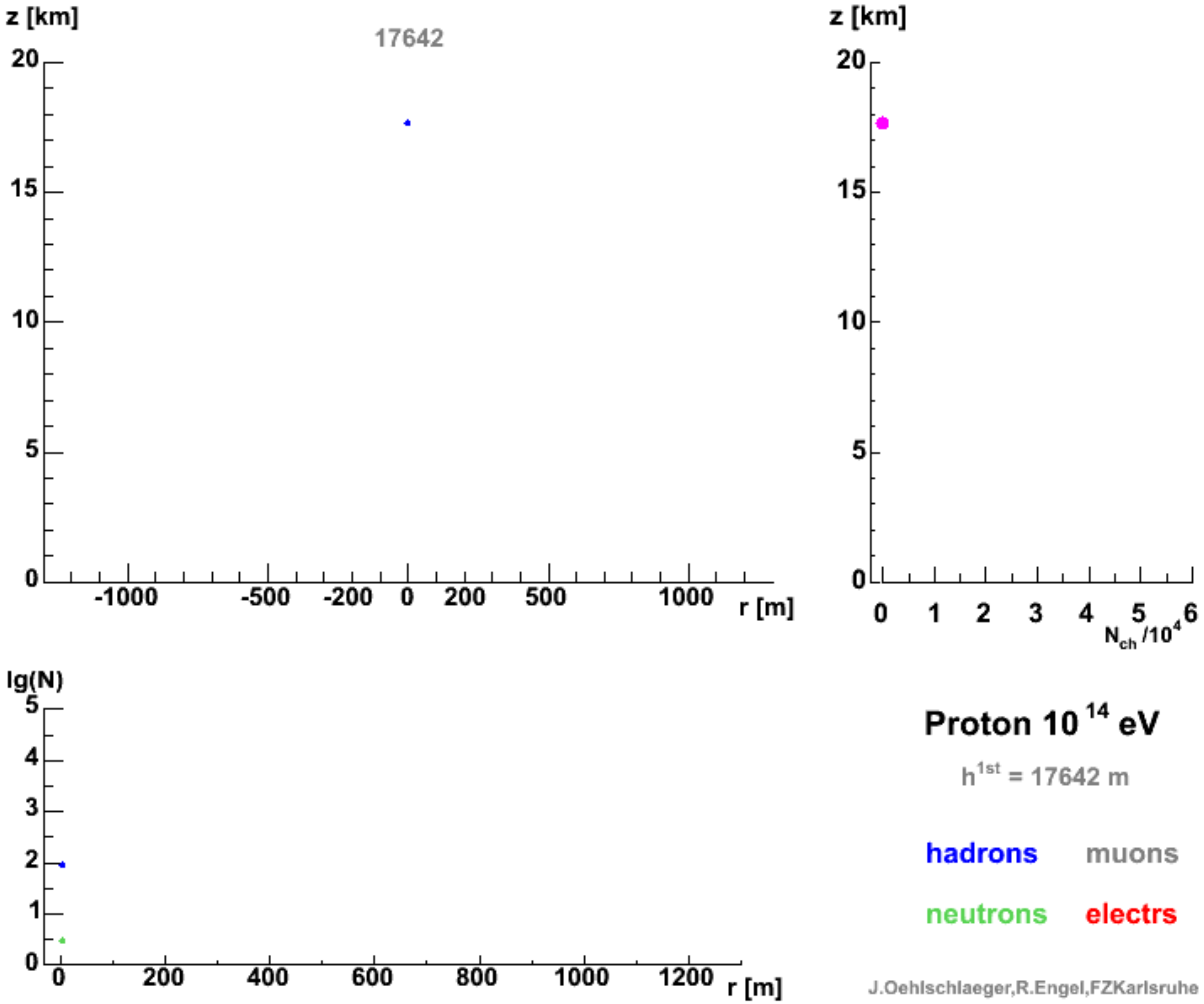
Extensive Air Showers





- Satellites are not a viable option given the scarce fluxes and extreme high energies
- The interaction of high energy radiation/particles with Earth atmosphere produce **huge particle cascades**

Shower observables



Longitudinal Profile

Lateral Profile (LDF)

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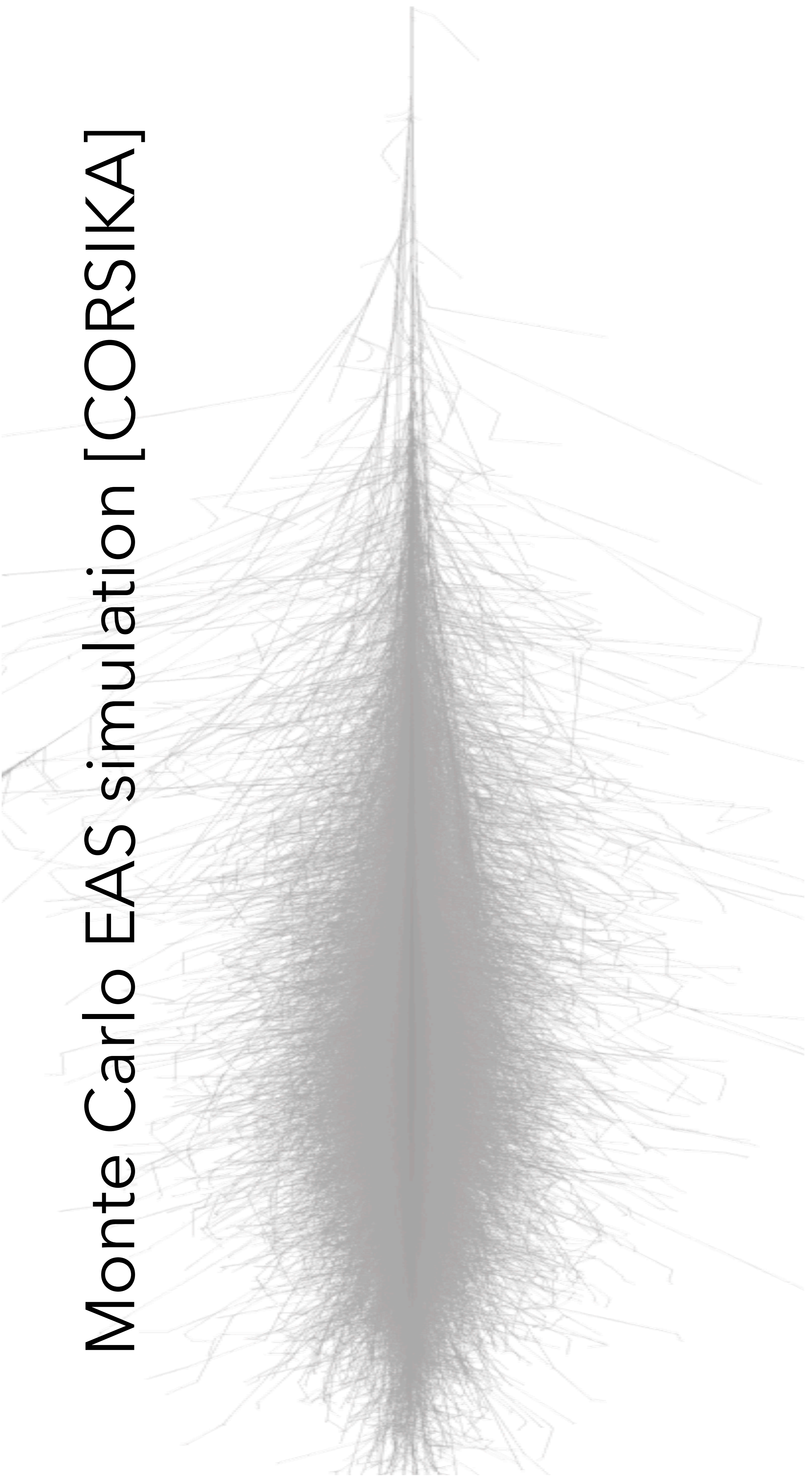
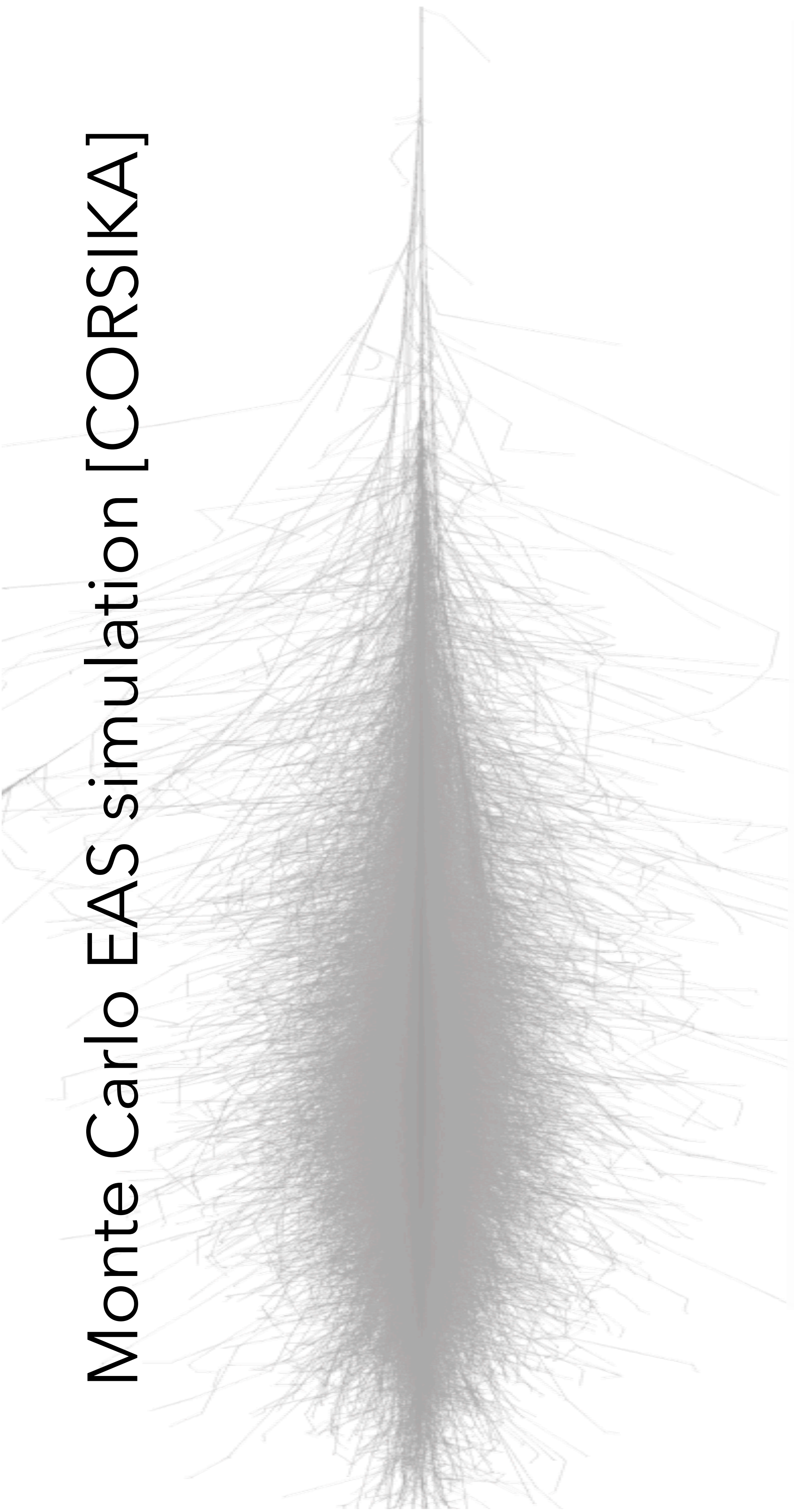
EAS engine

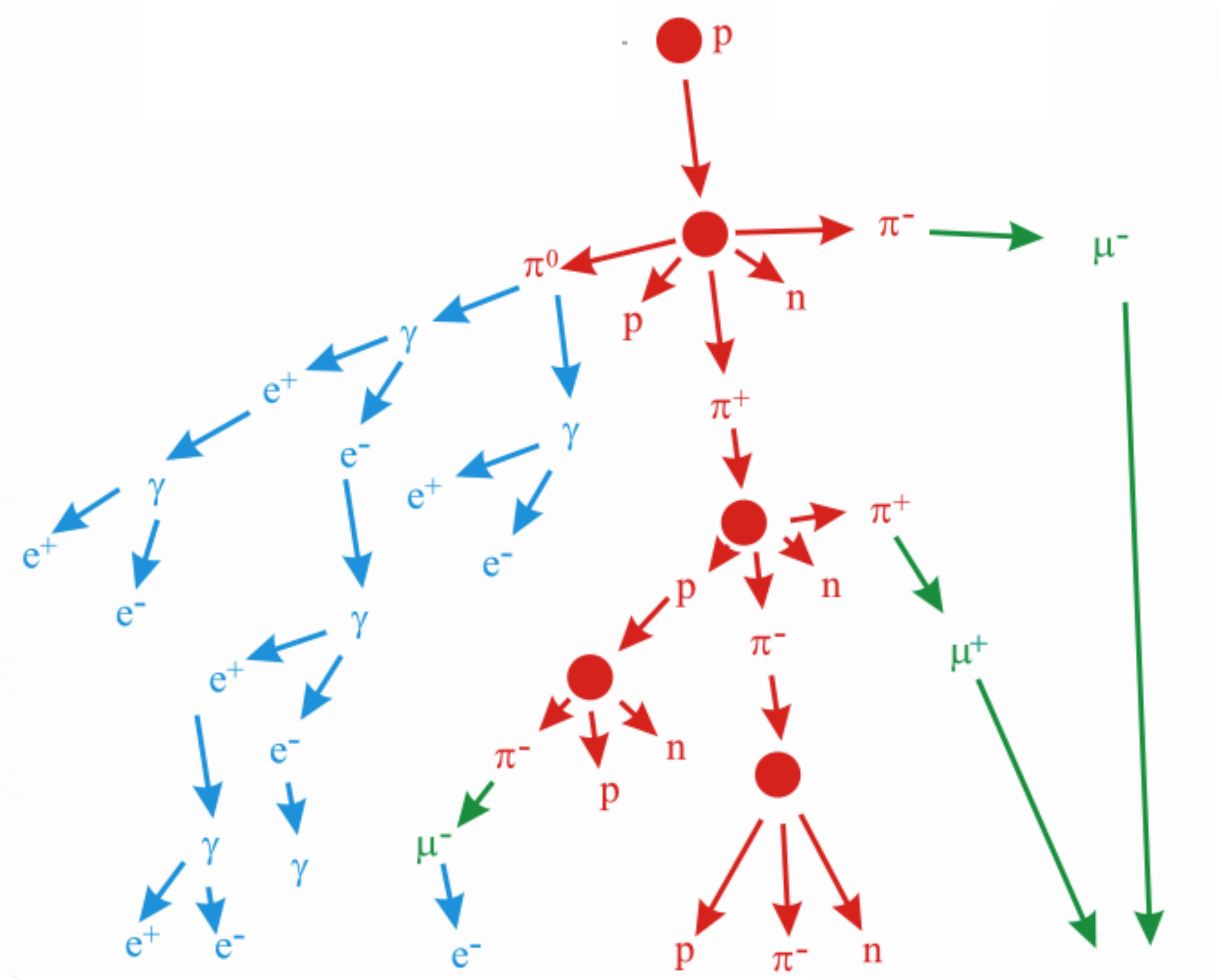


Monte Carlo EAS simulation [CORSIKA]

EAS engine

Monte Carlo EAS simulation [CORSIKA]





Electromagnetic component

Hadronic component

Muonic component

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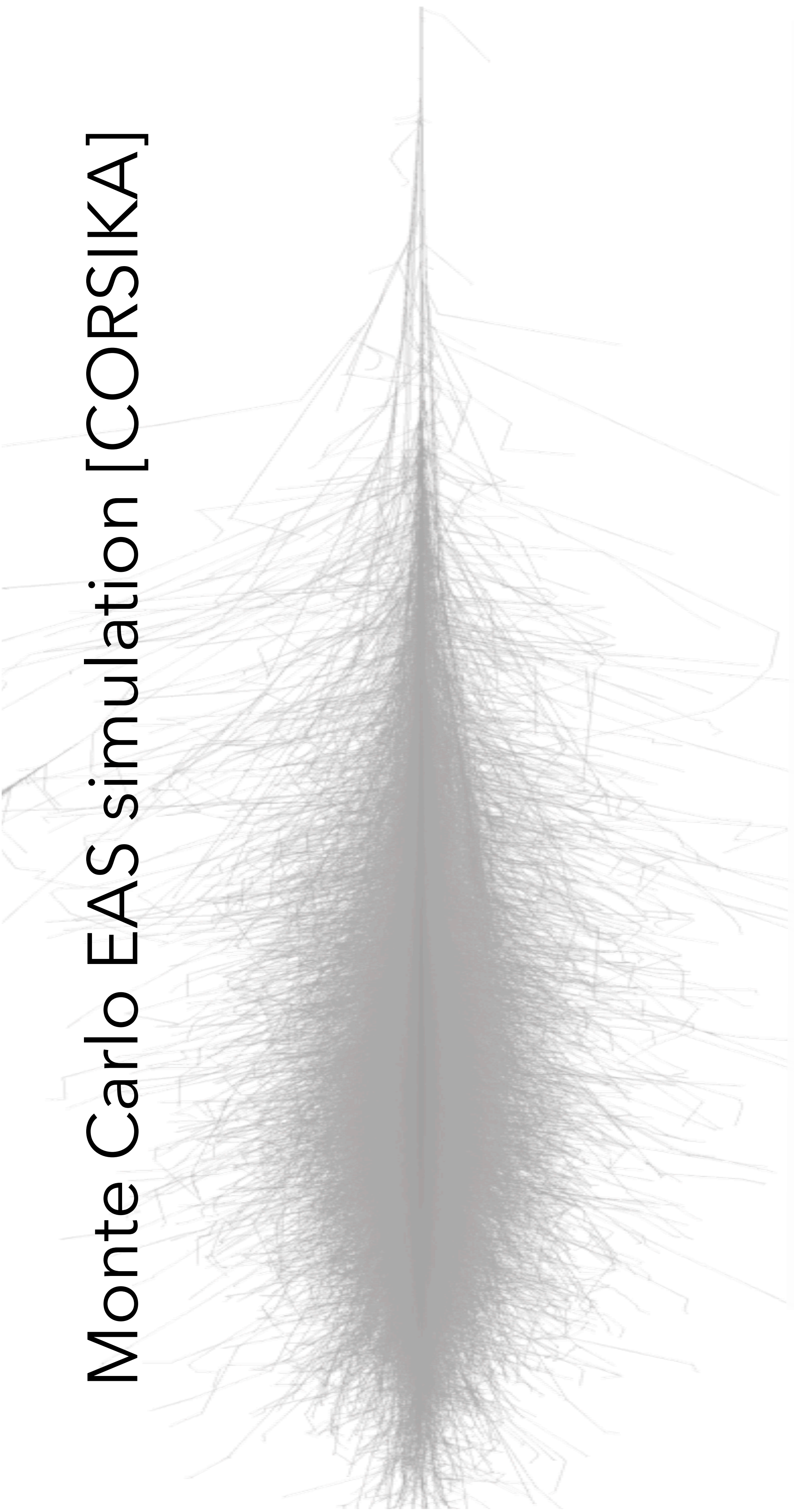
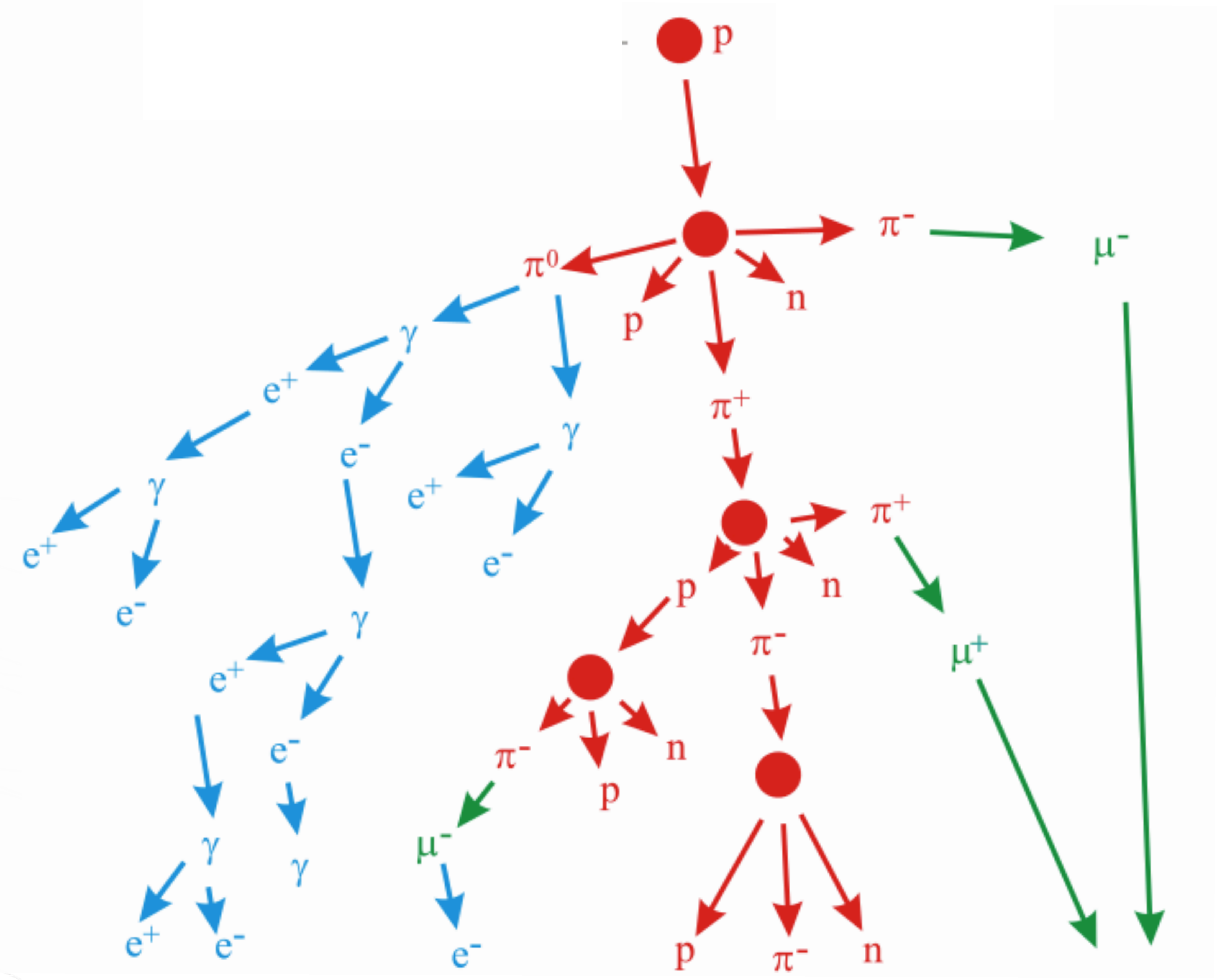
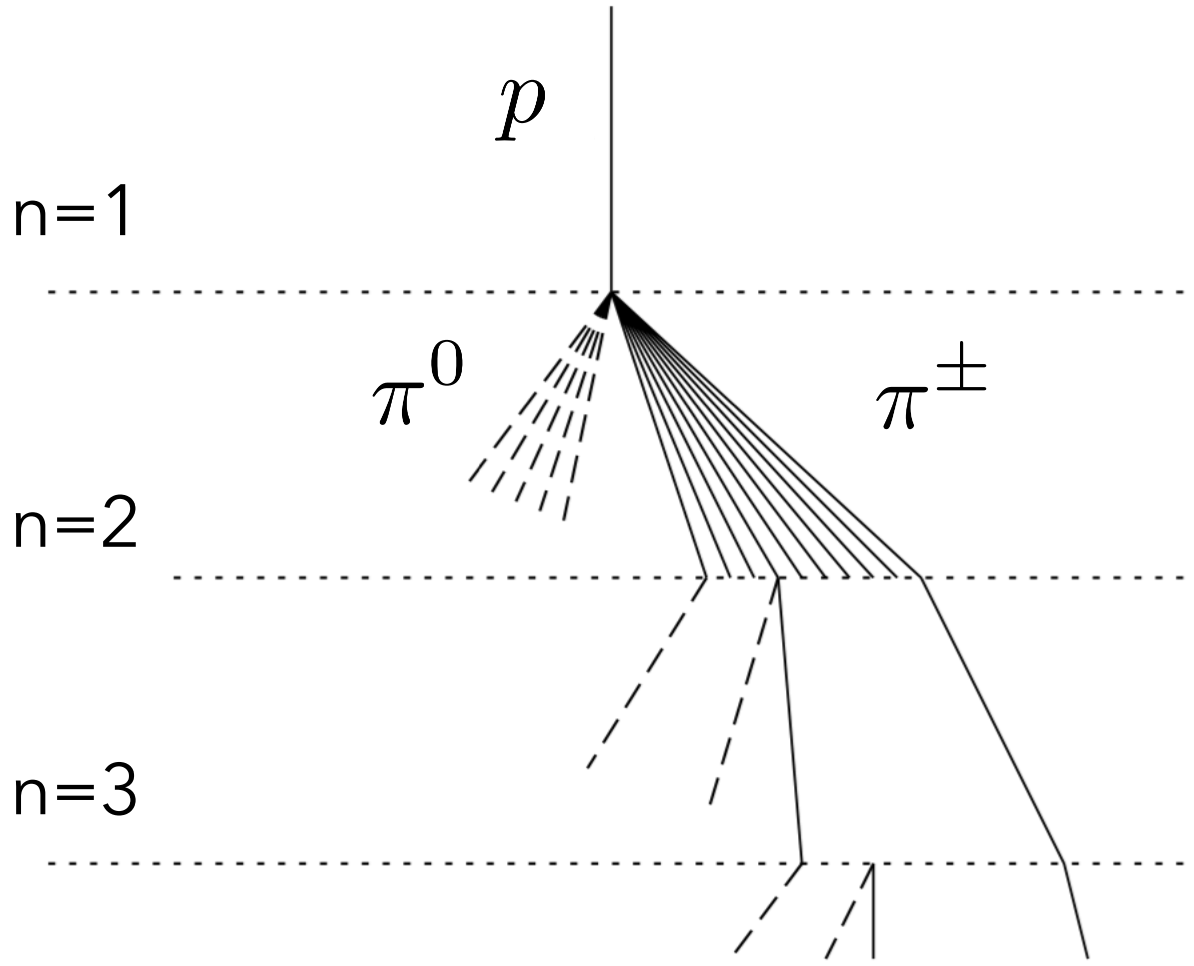
EAS engine

Monte Carlo EAS simulation [CORSIKA]





Heitler-Matthews model



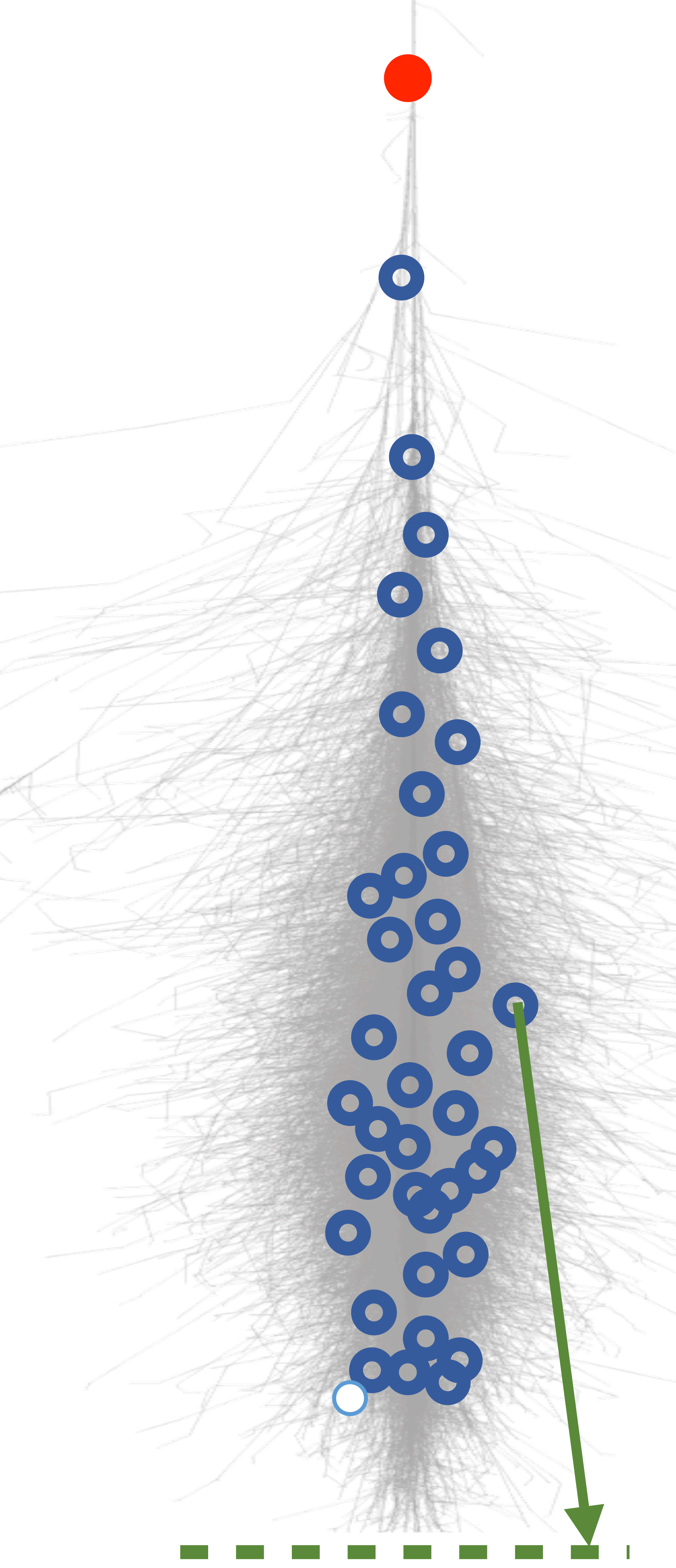
$$\langle X_{\max} \rangle \propto \ln\left(\frac{E_0}{A}\right)$$

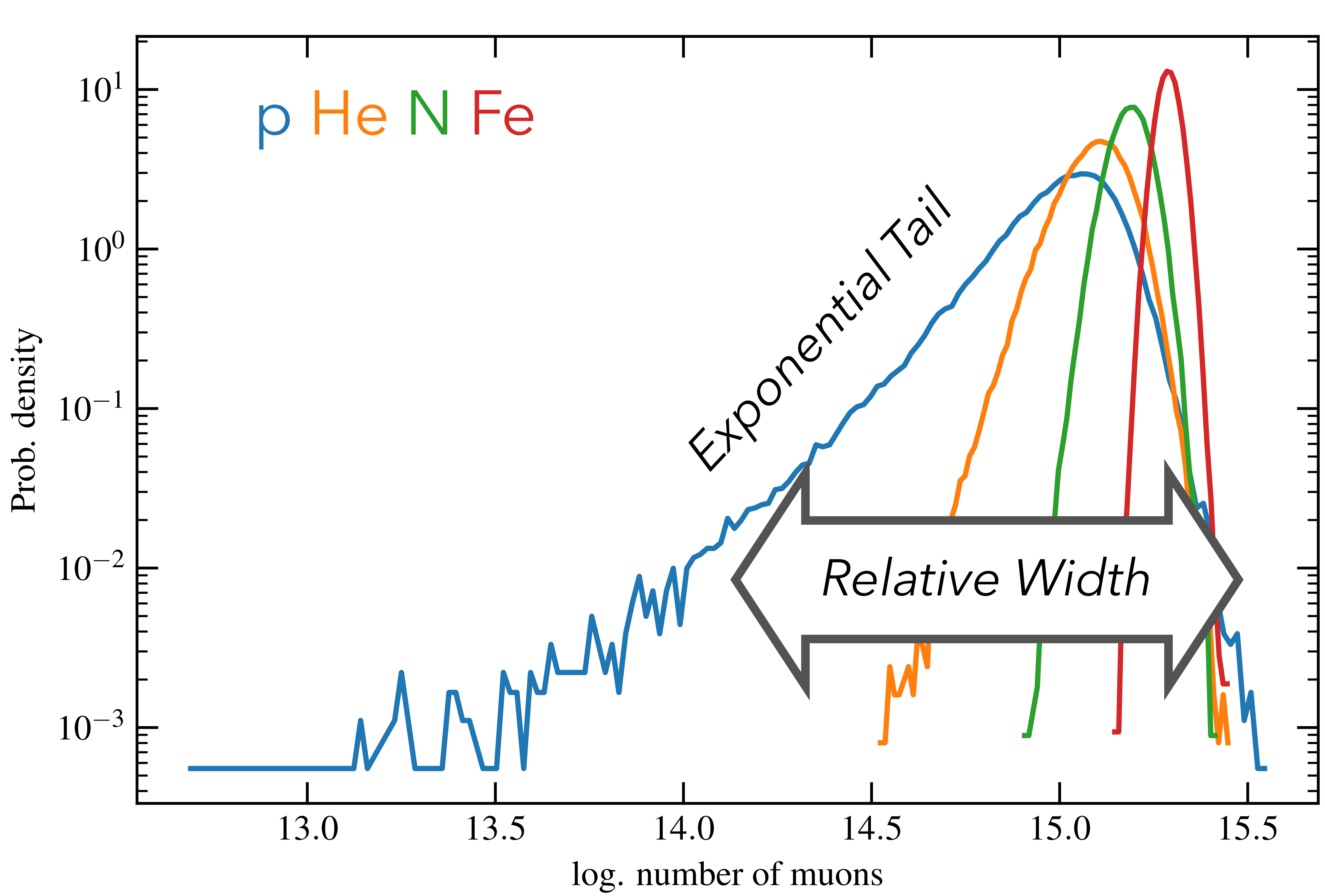
$$\langle N_\mu \rangle \propto A^{1-\beta} E_0^\beta$$

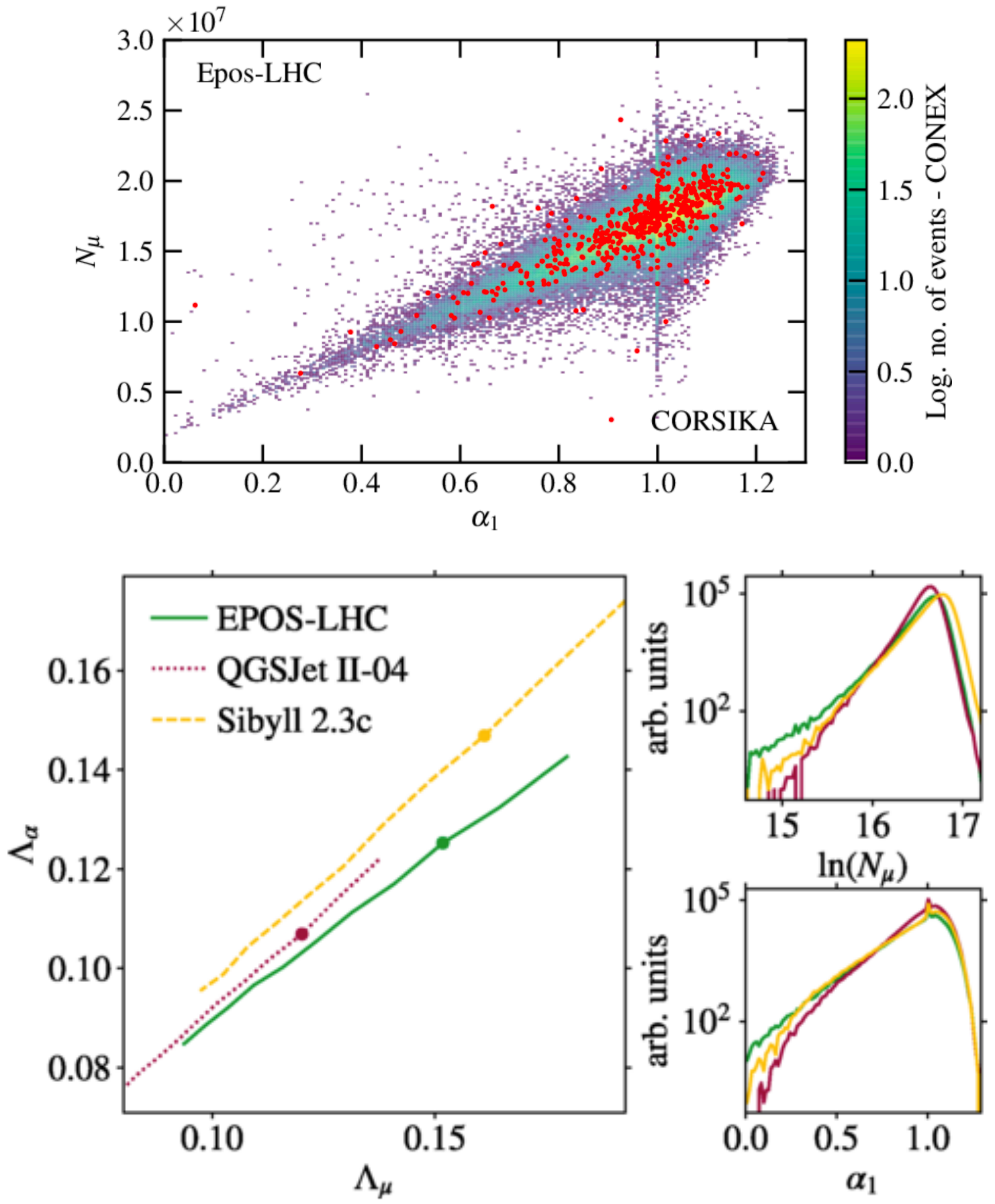
Accessing the first interaction

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

L. Cazon, RC, M. Martins, F. Riehn,Phys.Rev.D 103 (2021) 2, 022001







The shape and relative fluctuations of the muon number distribution gives access to the properties of the **FIRST hadronic interaction** (fraction of energy carried by neutral pions)

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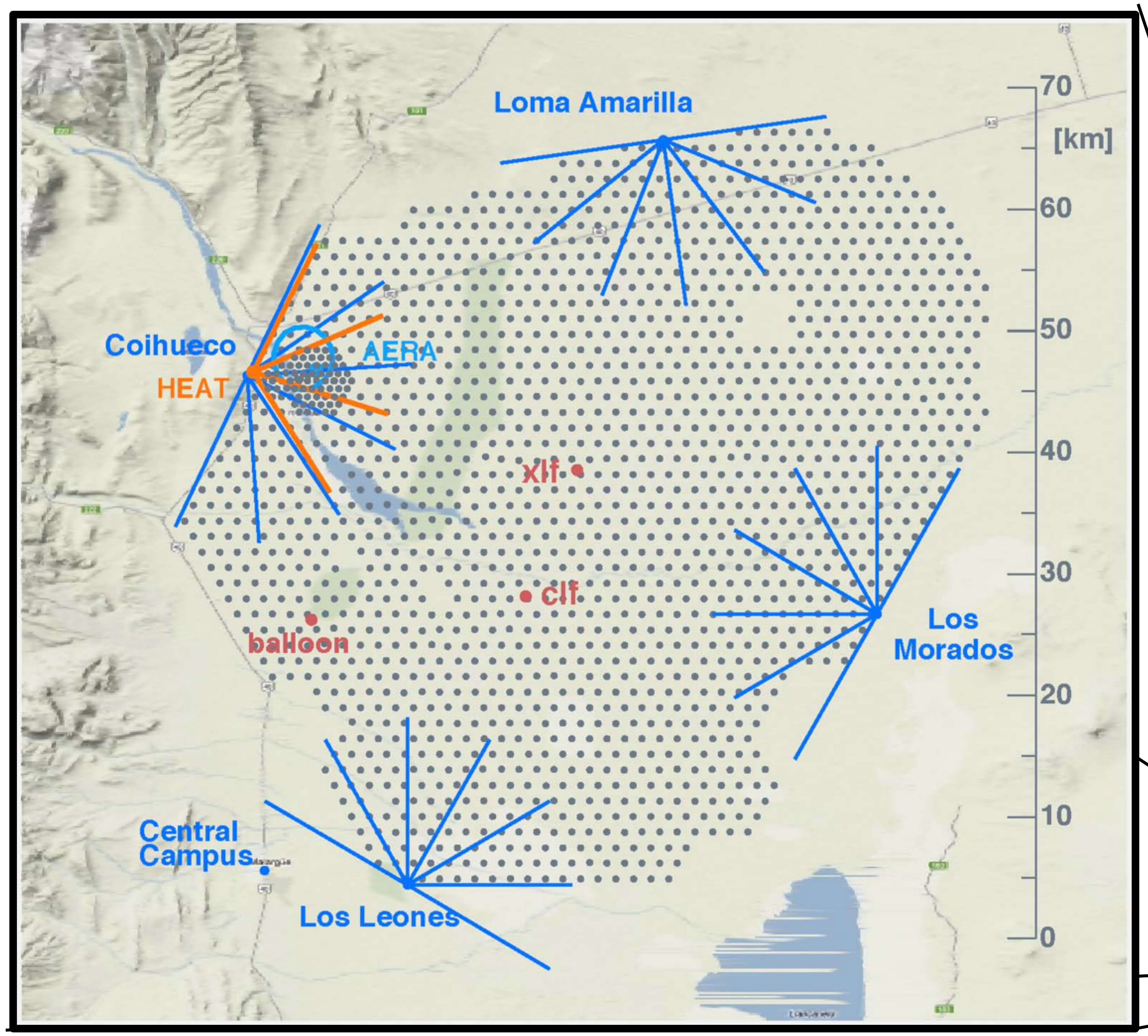
Detection Techniques

The Pierre Auger Observatory as a case study for the Cosmic Ray indirect detection field

Pierre Auger Observatory



Area: 3000 km^2

Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

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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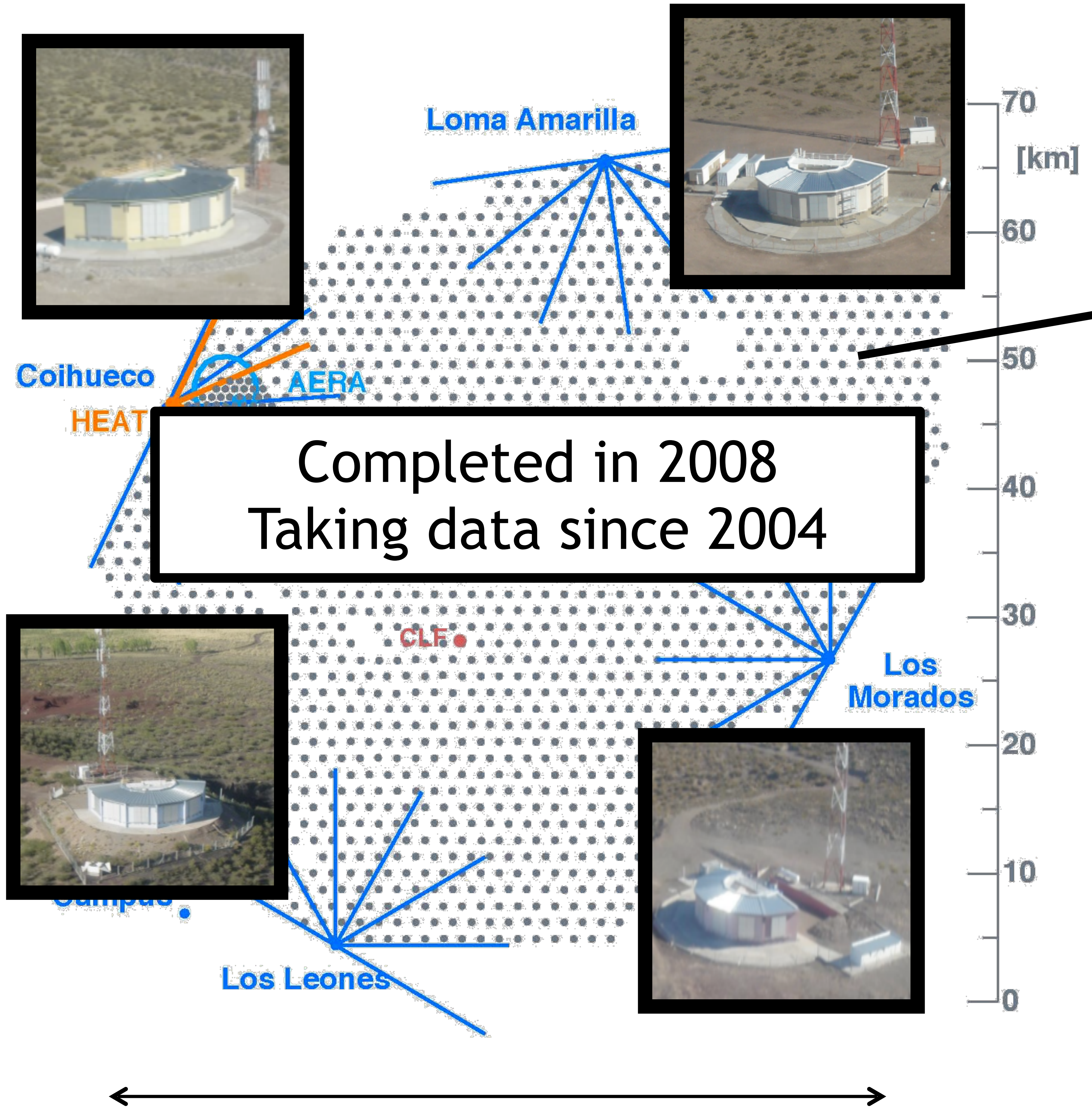
Pierre Auger Observatory

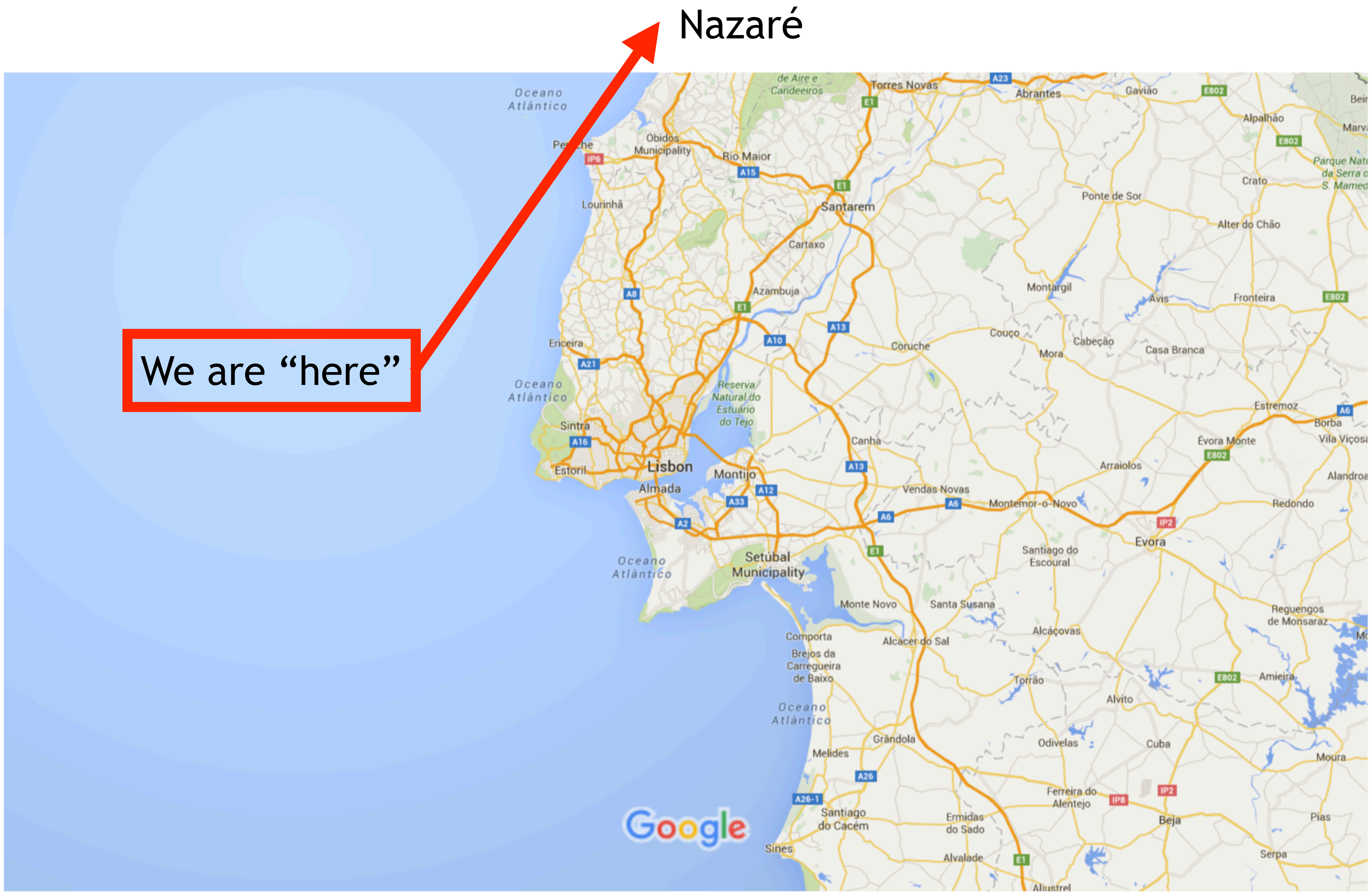


- ~ 1600 Surface detectors (SD)
- In a 1.5 km hexagonal grid
- 3000 km^2

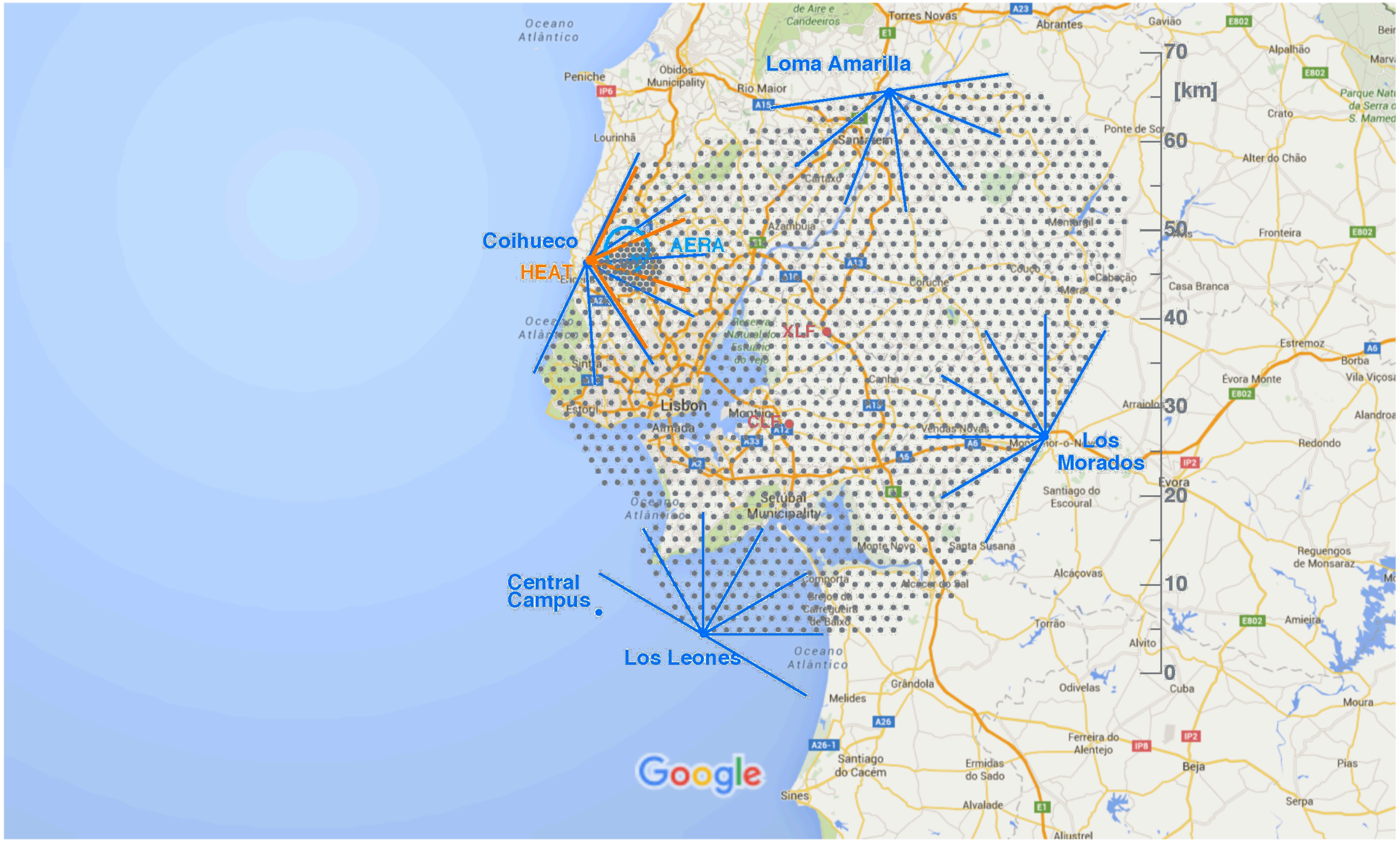
- 4 Fluorescence Detectors (FD)
- 6 x 4 + 3 Fluorescence Telescopes

Built to detect and study the extremely rare UHECR

What’s the size of the Observatory?



Really big!!



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

Pierre Auger Observatory

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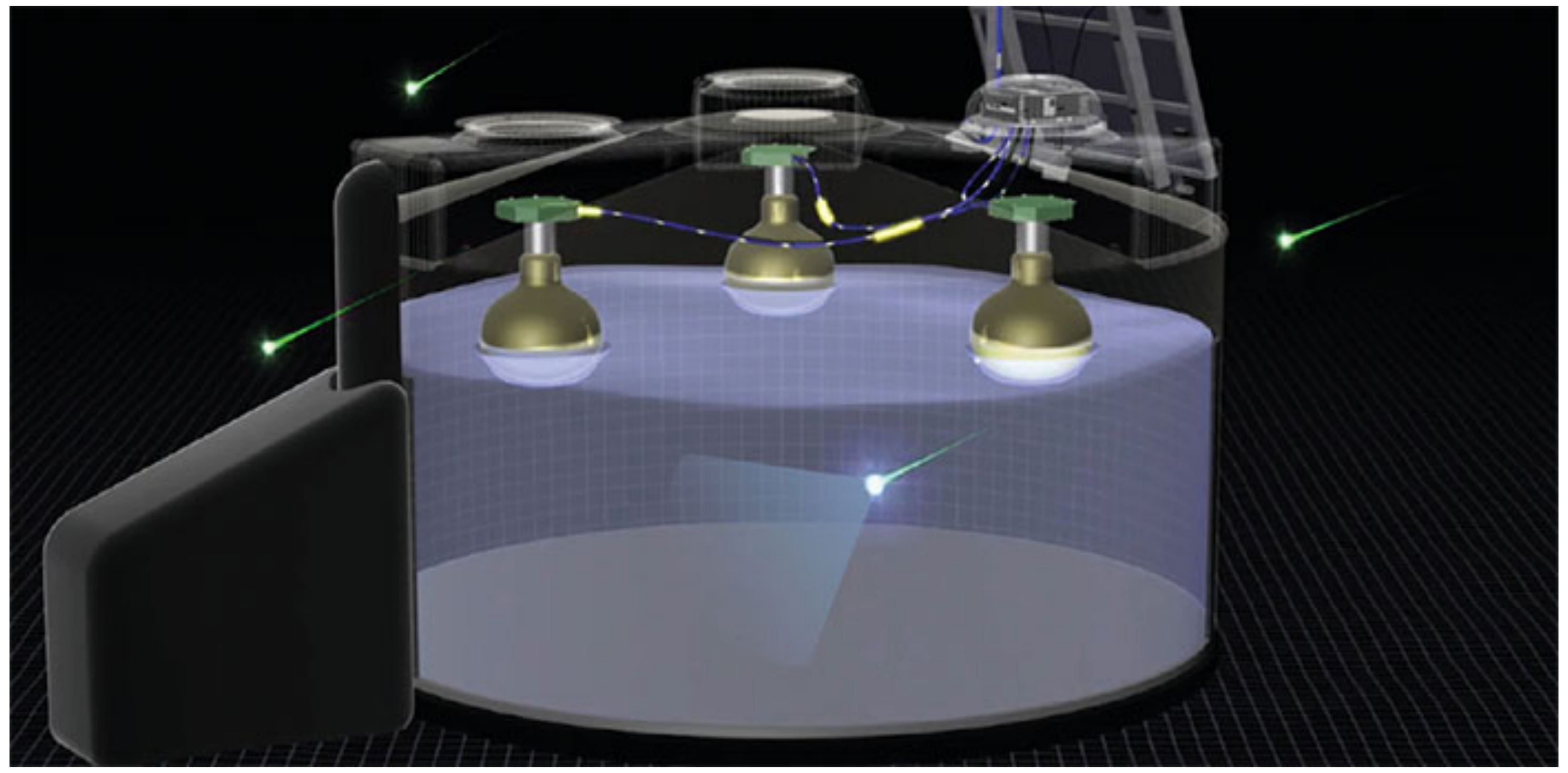
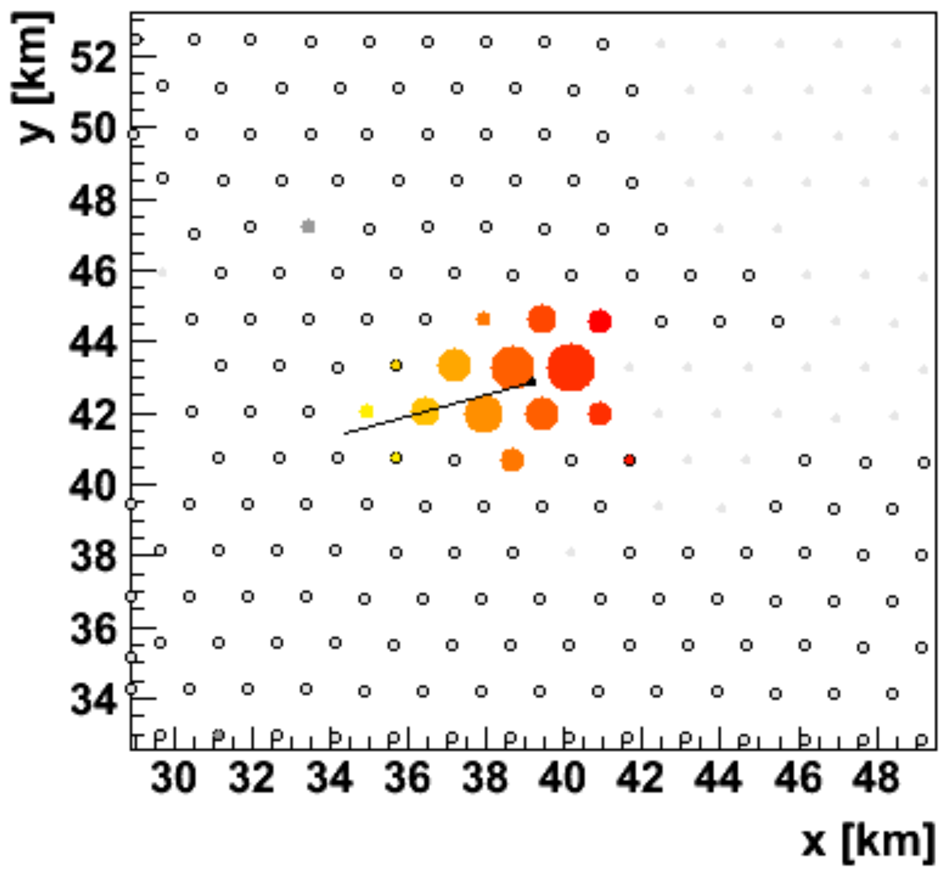
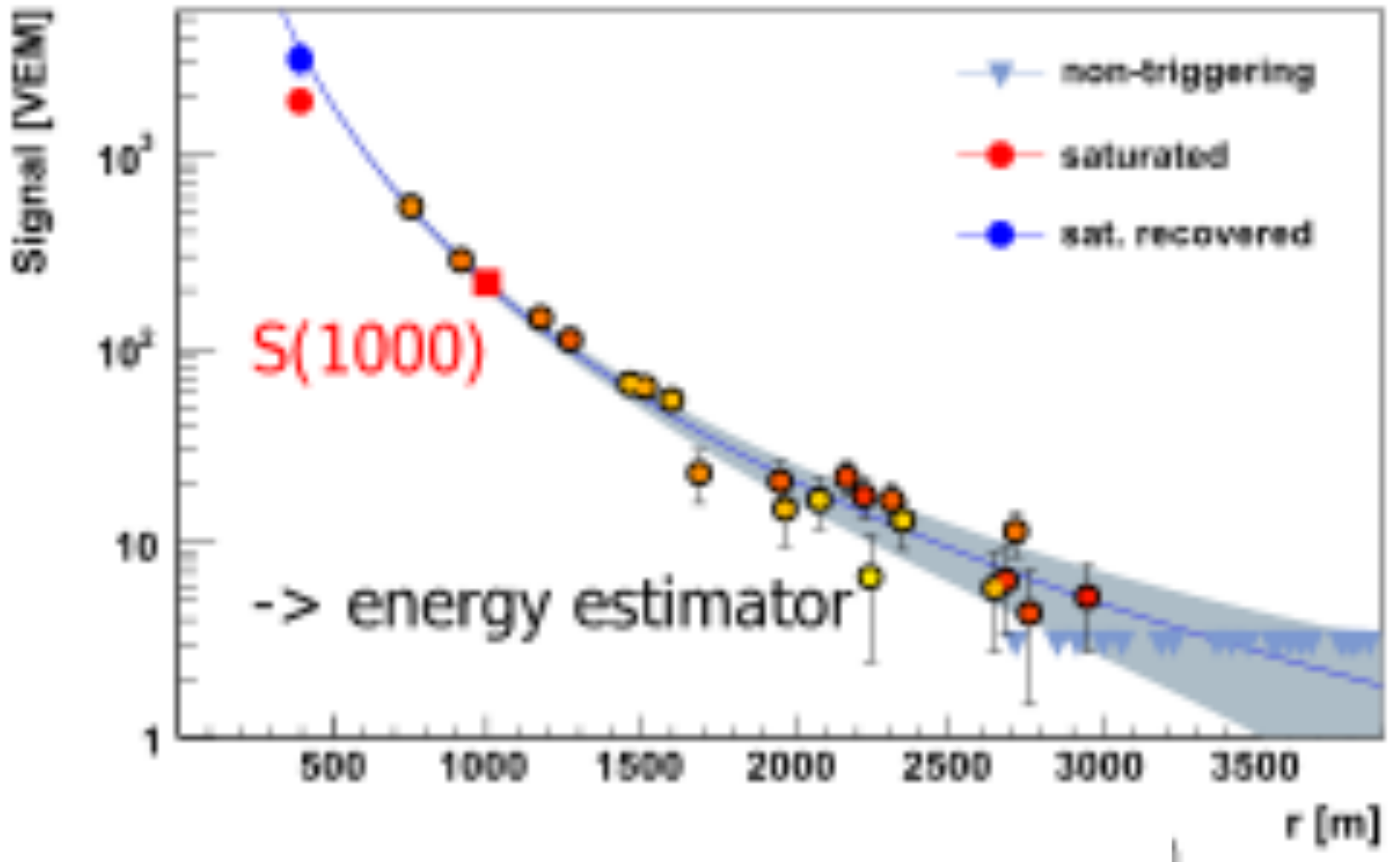
Surface Detectors (SD)

Surface Detectors

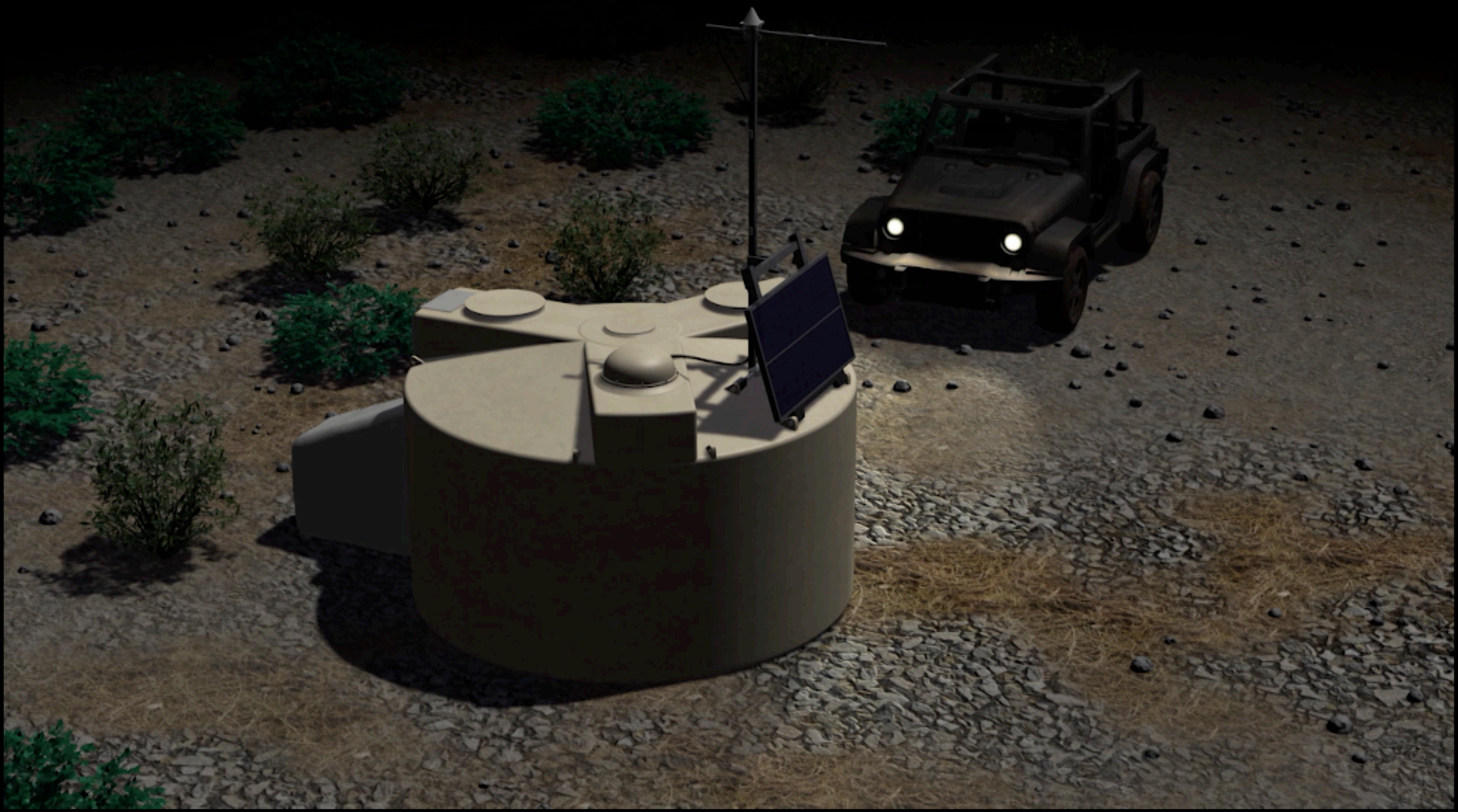
- Sample shower secondary particles reaching the ground
  - 100% duty cycle
  - Arrival time → primary cosmic ray direction
  - Energy estimation: signal at 1000 meters from the shower core





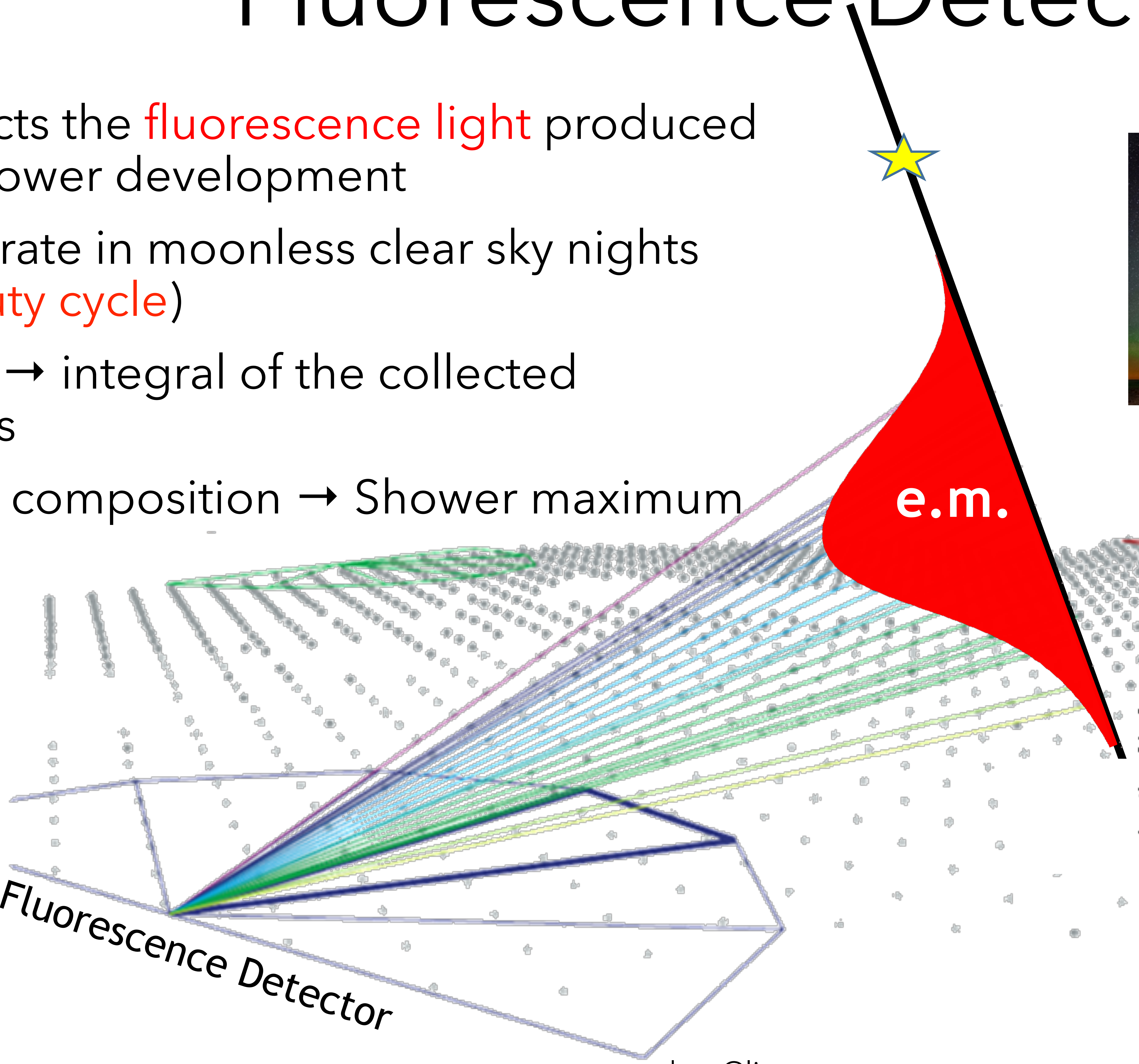


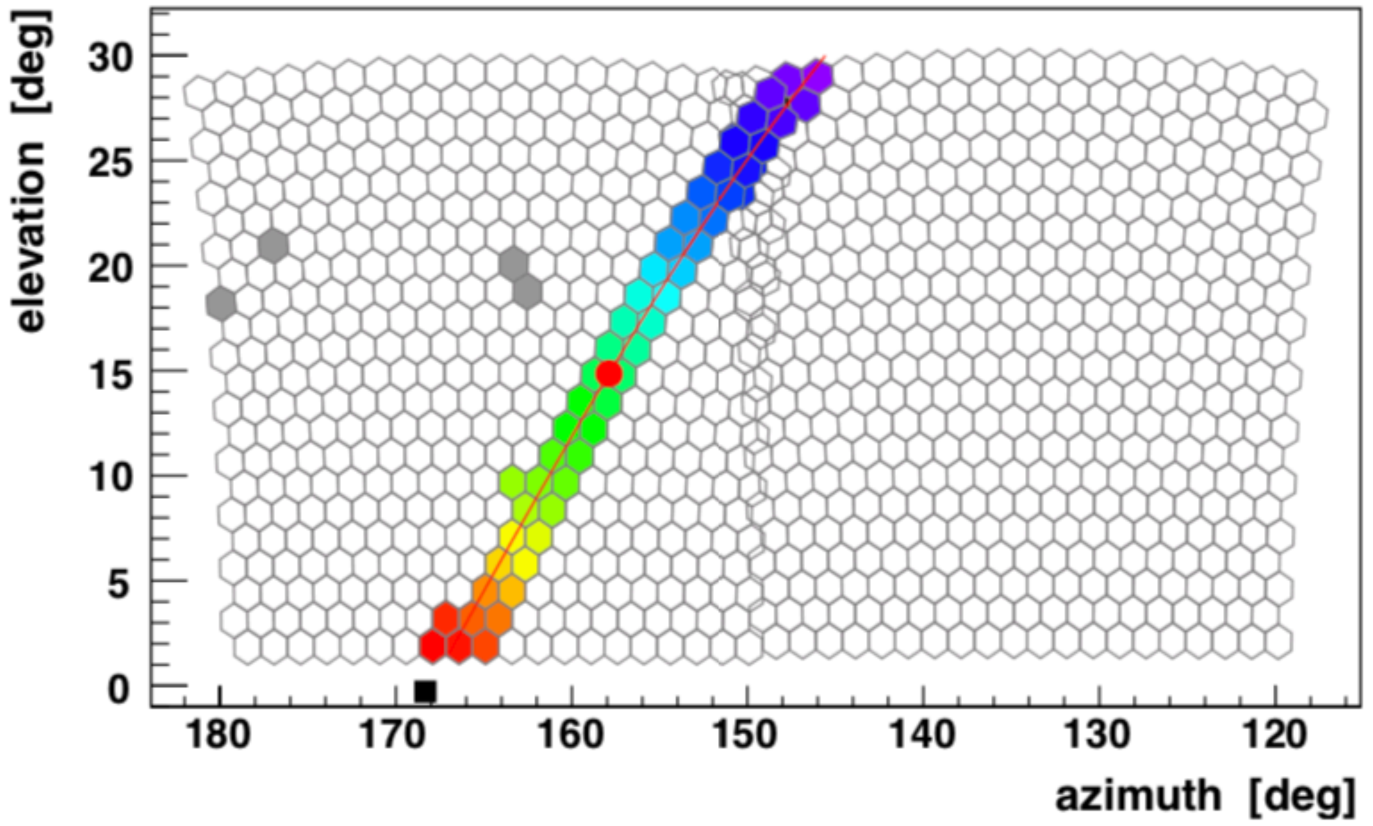
Water Cherenkov Detector (WCD)



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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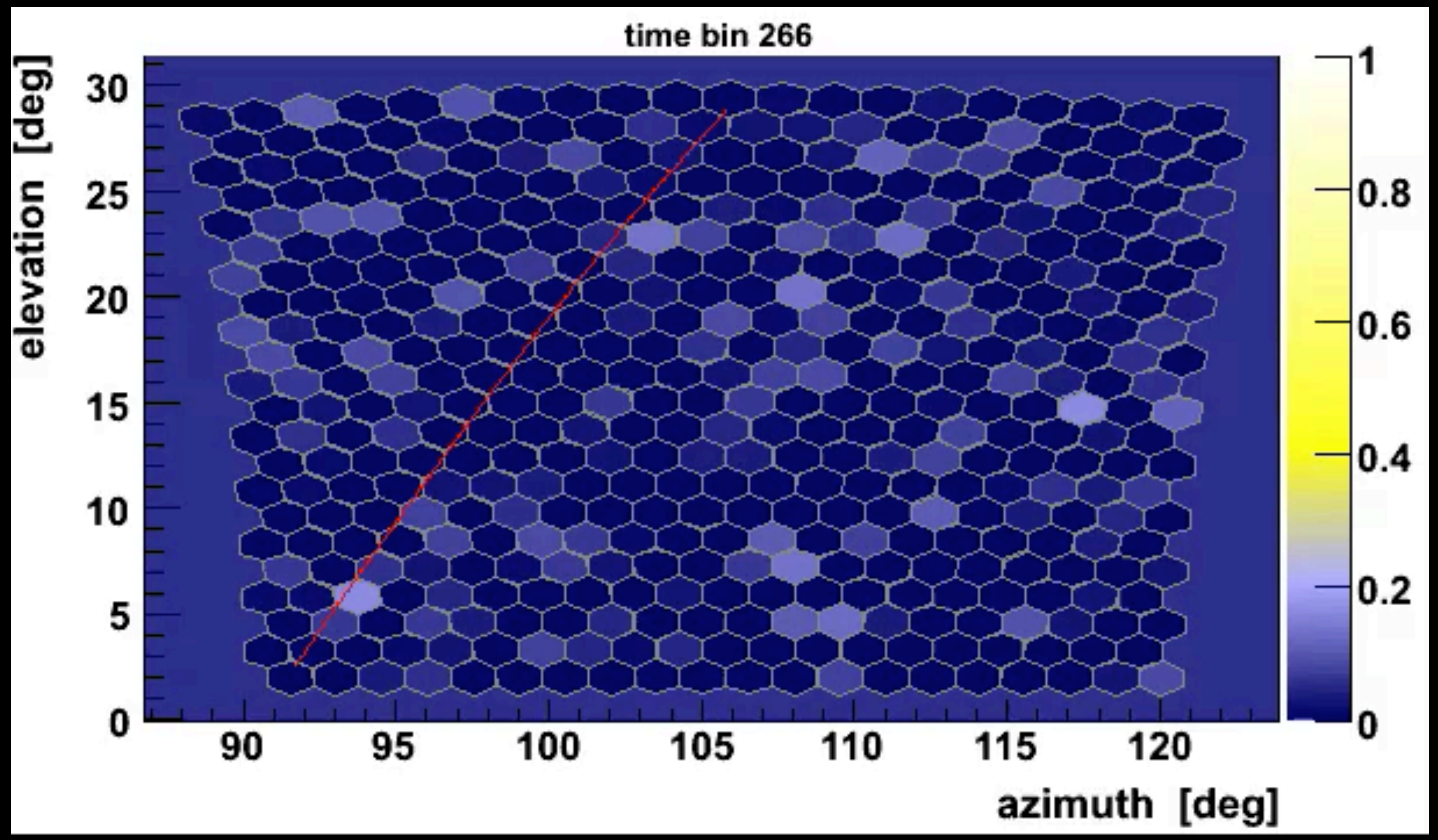
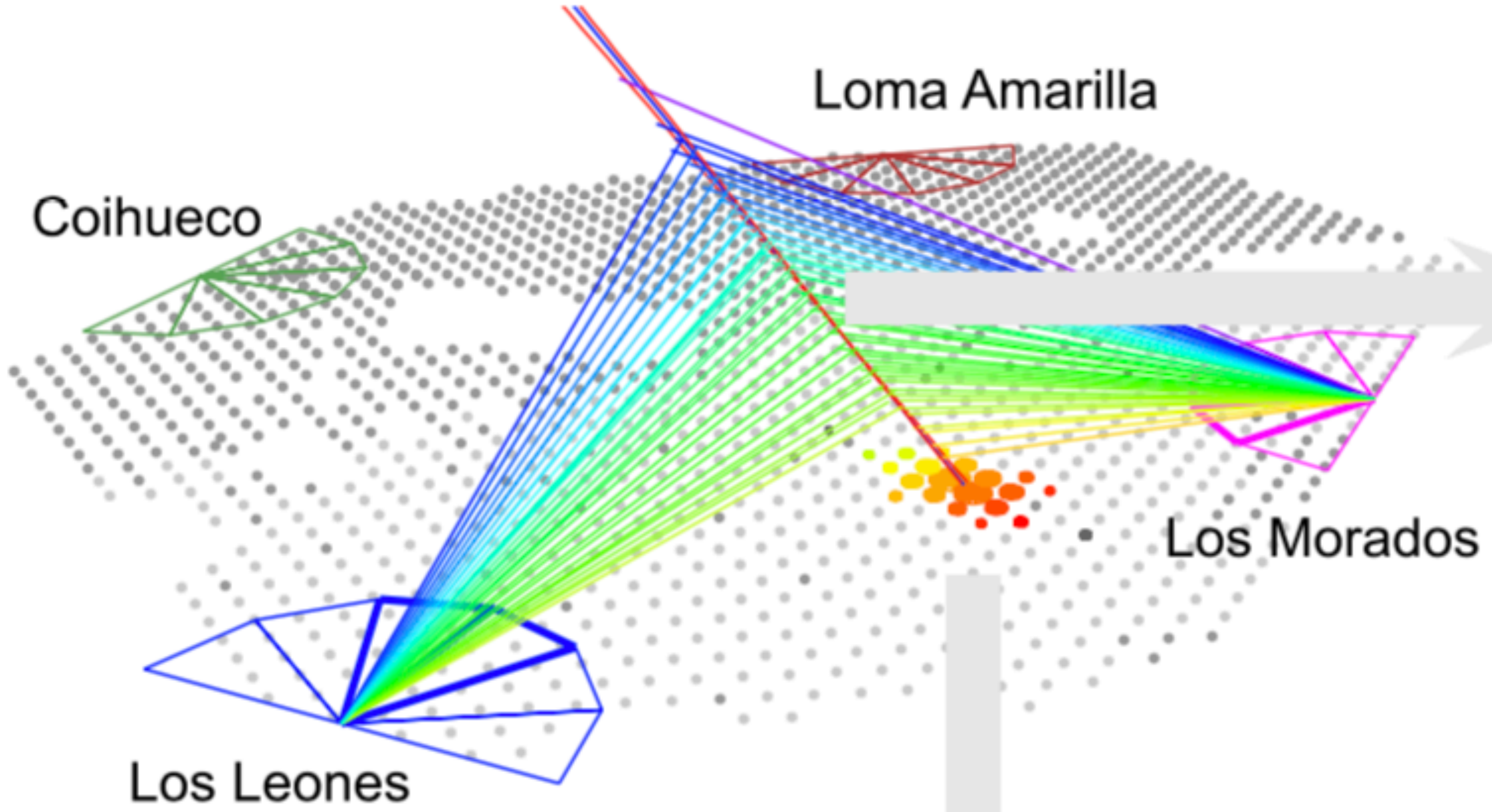
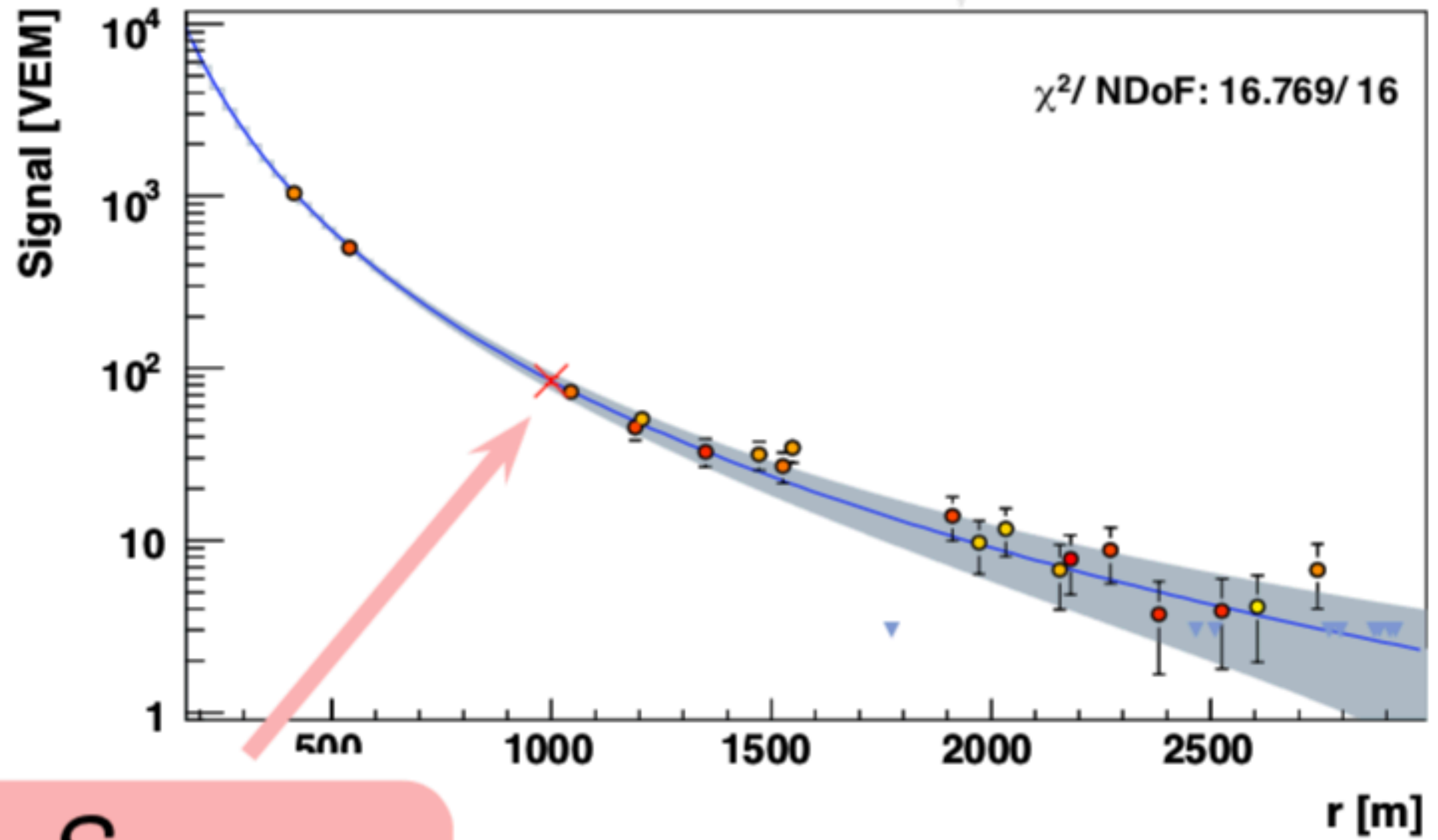
Fluorescence Detector



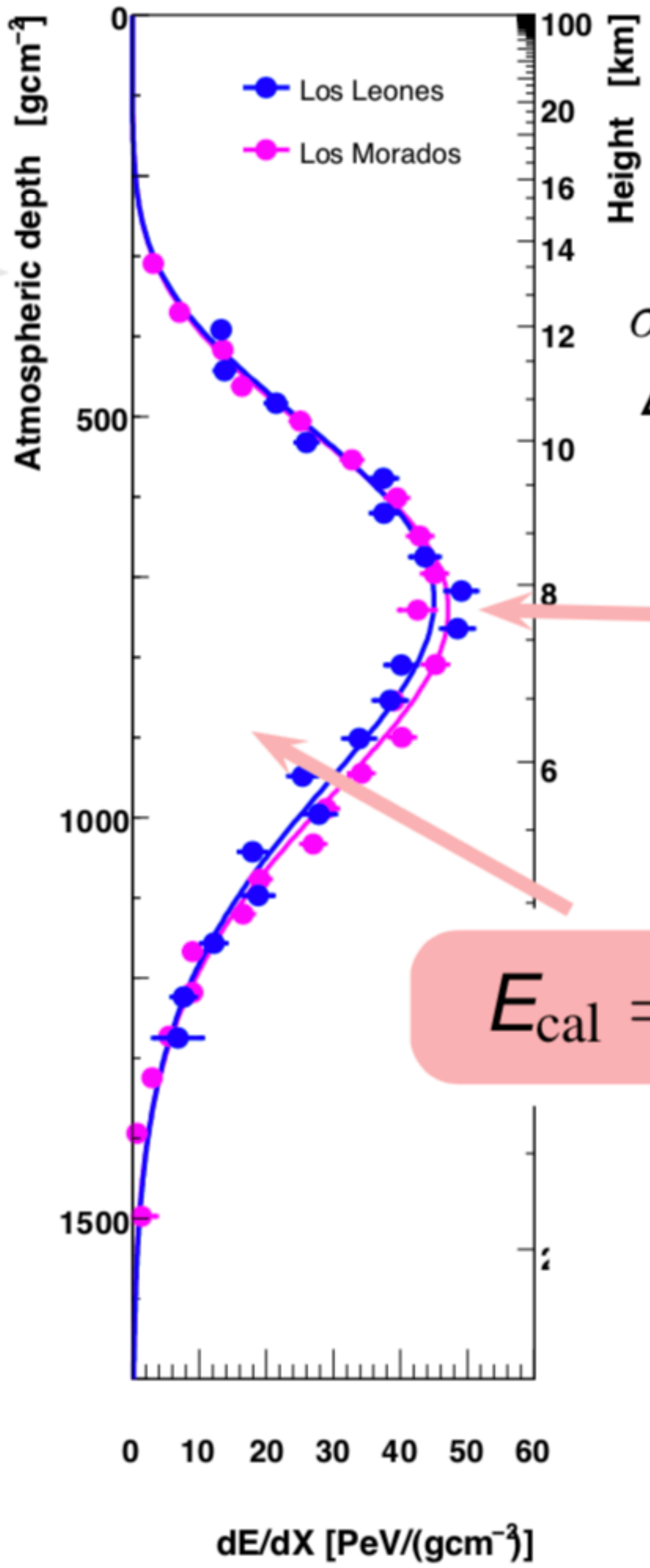
Hybrid Technique (FD + SD)





S_{1000}

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



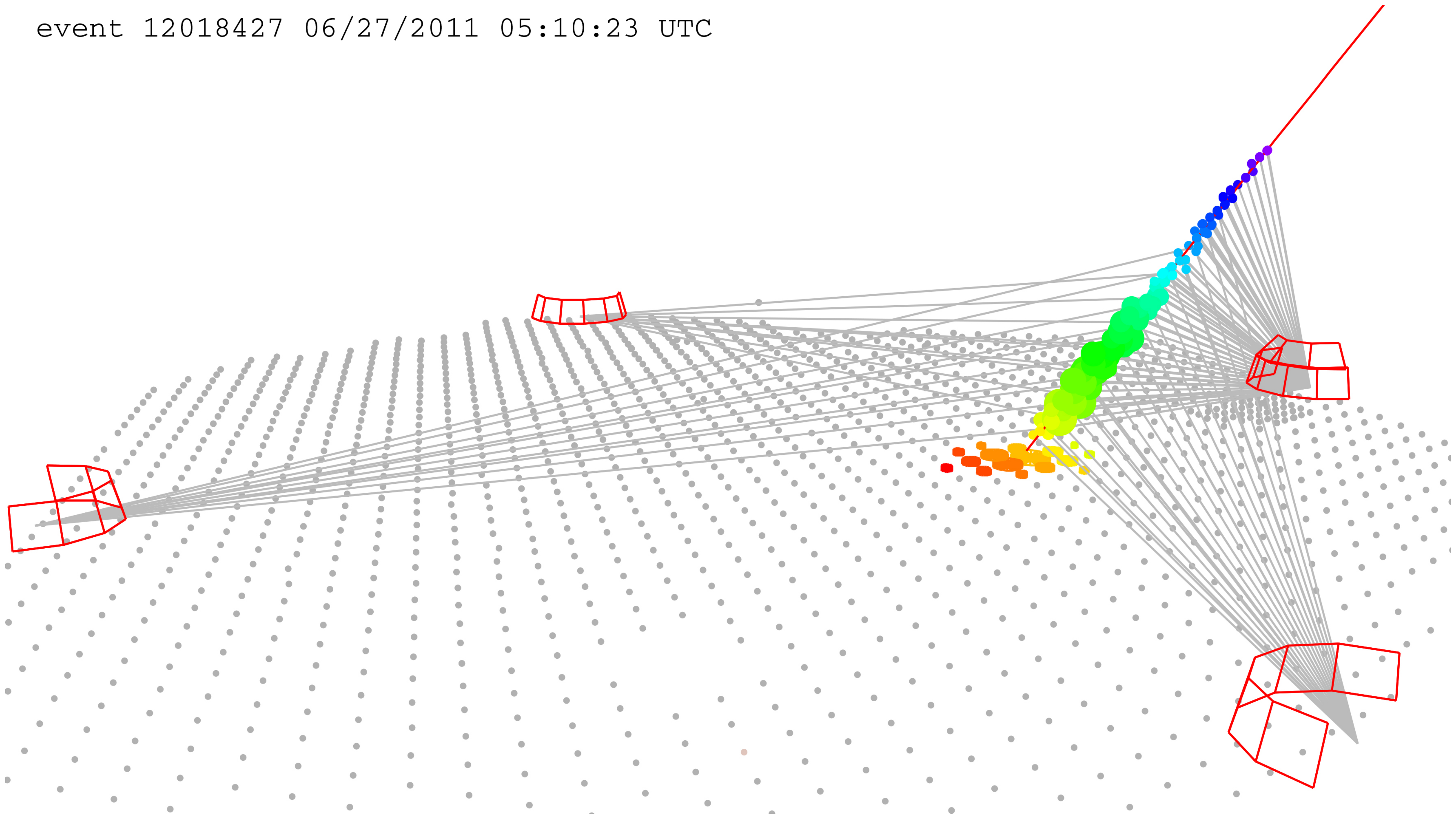
$\sigma X_{\mathrm{max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

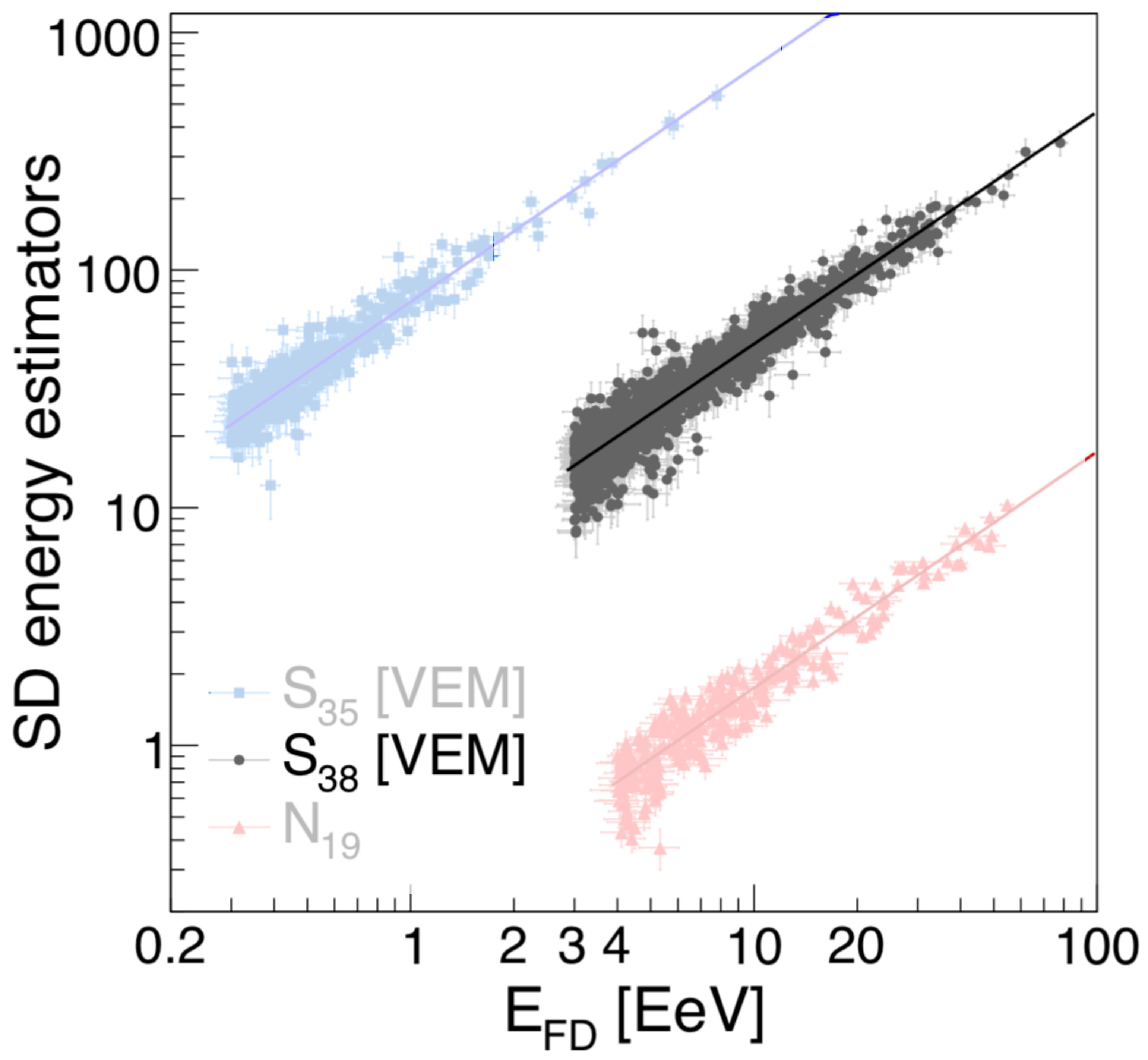
X_{max}

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

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

Hybrid technique (FD + SD)





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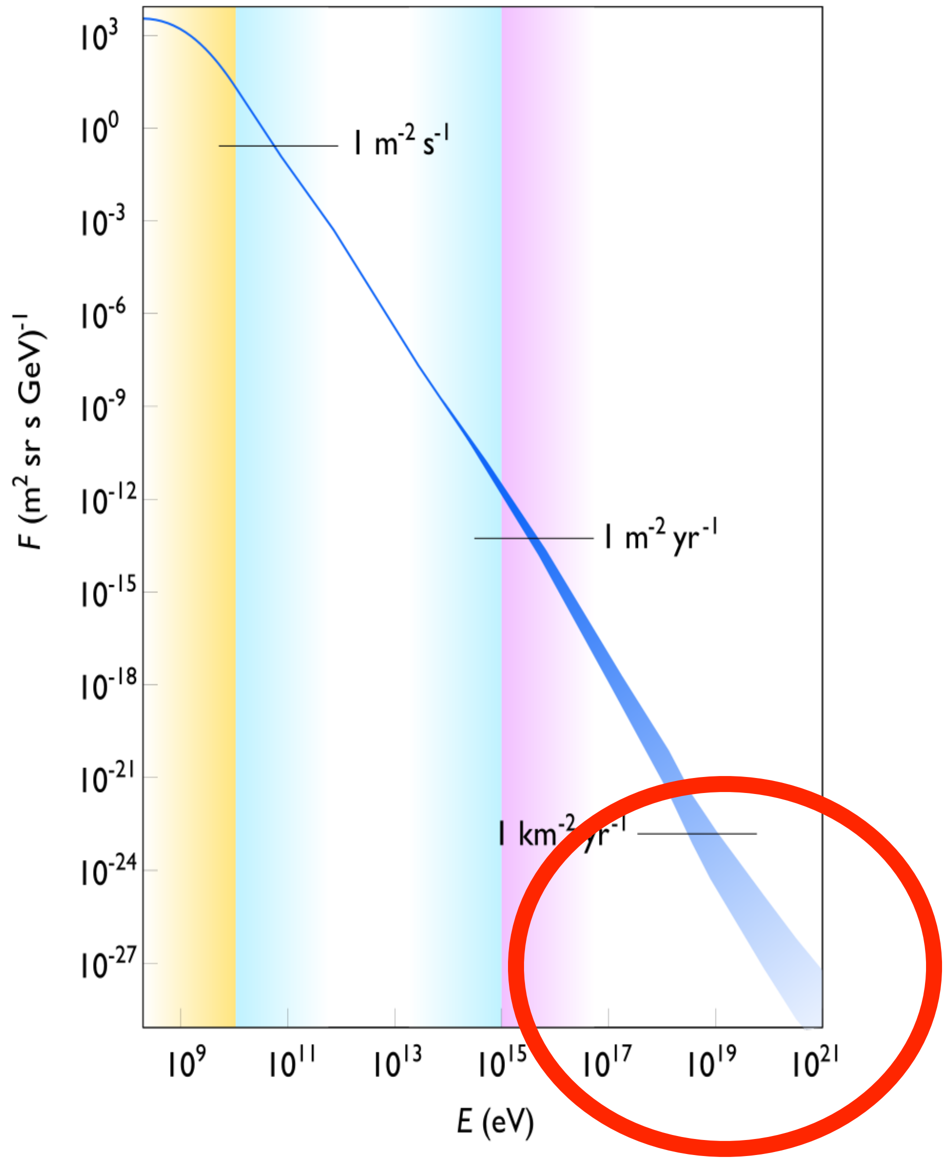
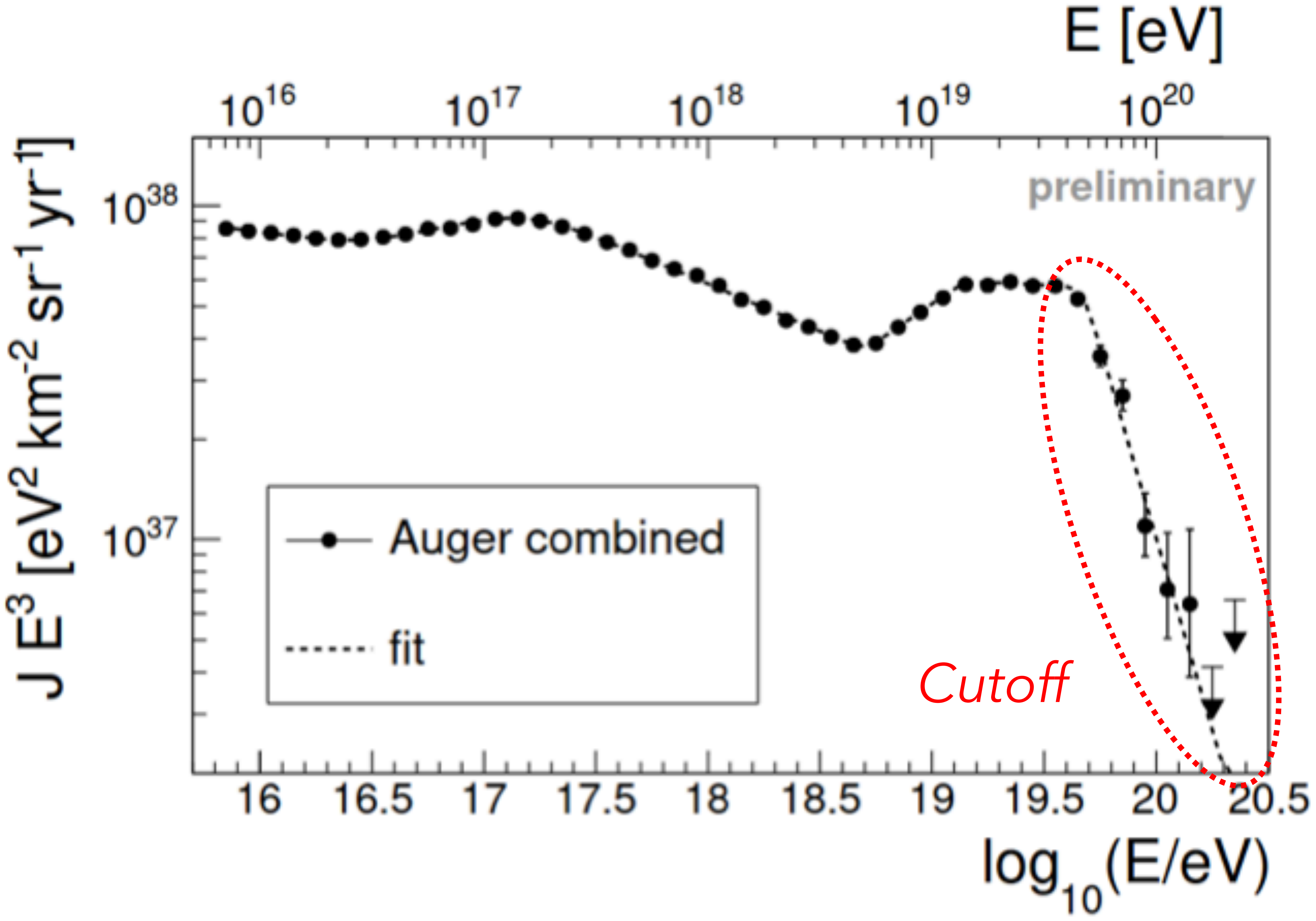
Ultra High Energy Cosmic Rays

What have we learned so far?

UHECR energy spectrum



Pierre Auger Collaboration, ICRC this year



Put strong constraints on UHECR production and propagation

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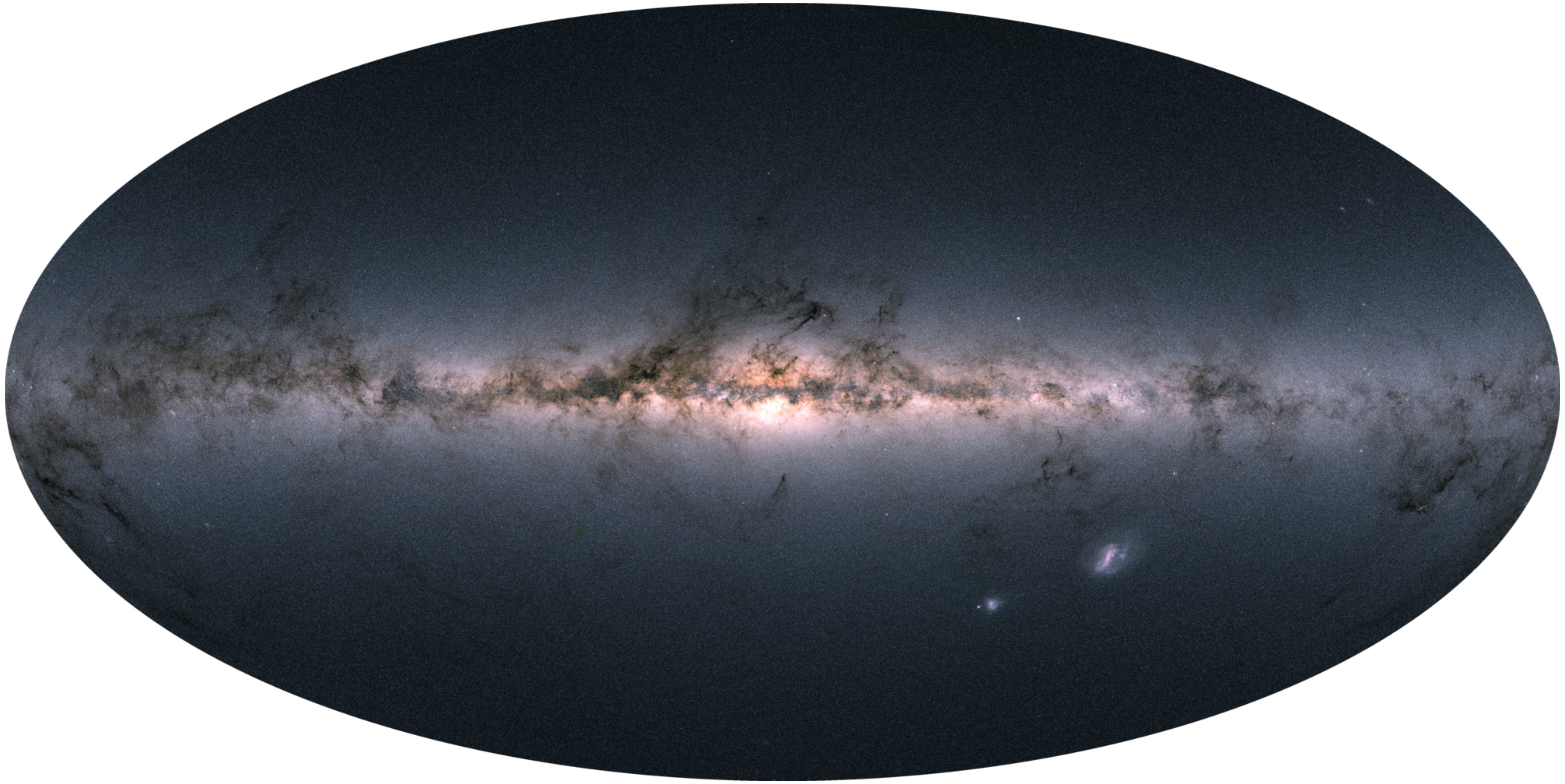
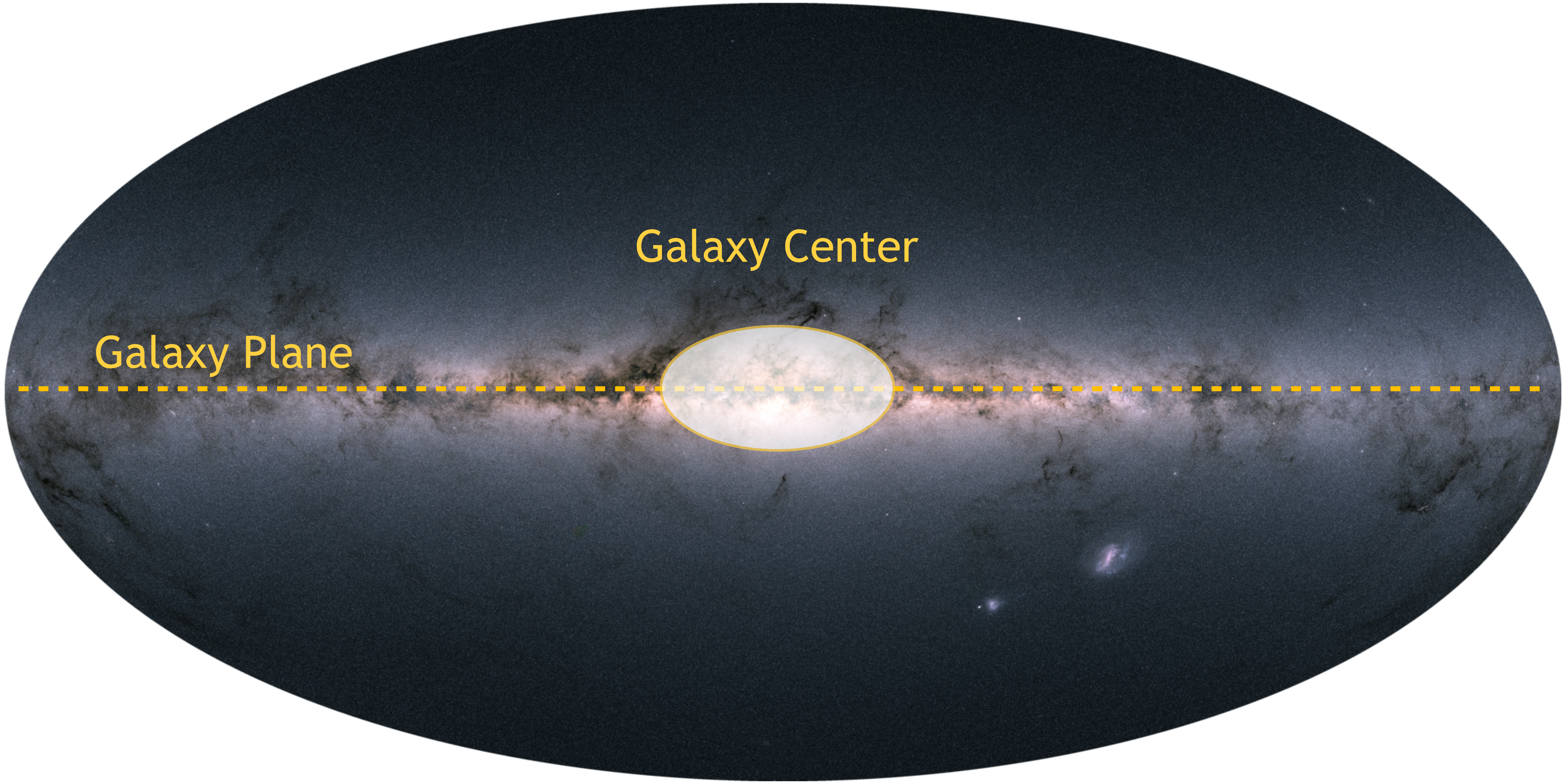
Are UHECRs produced in our galaxy?



Are UHECRs produced in our galaxy?



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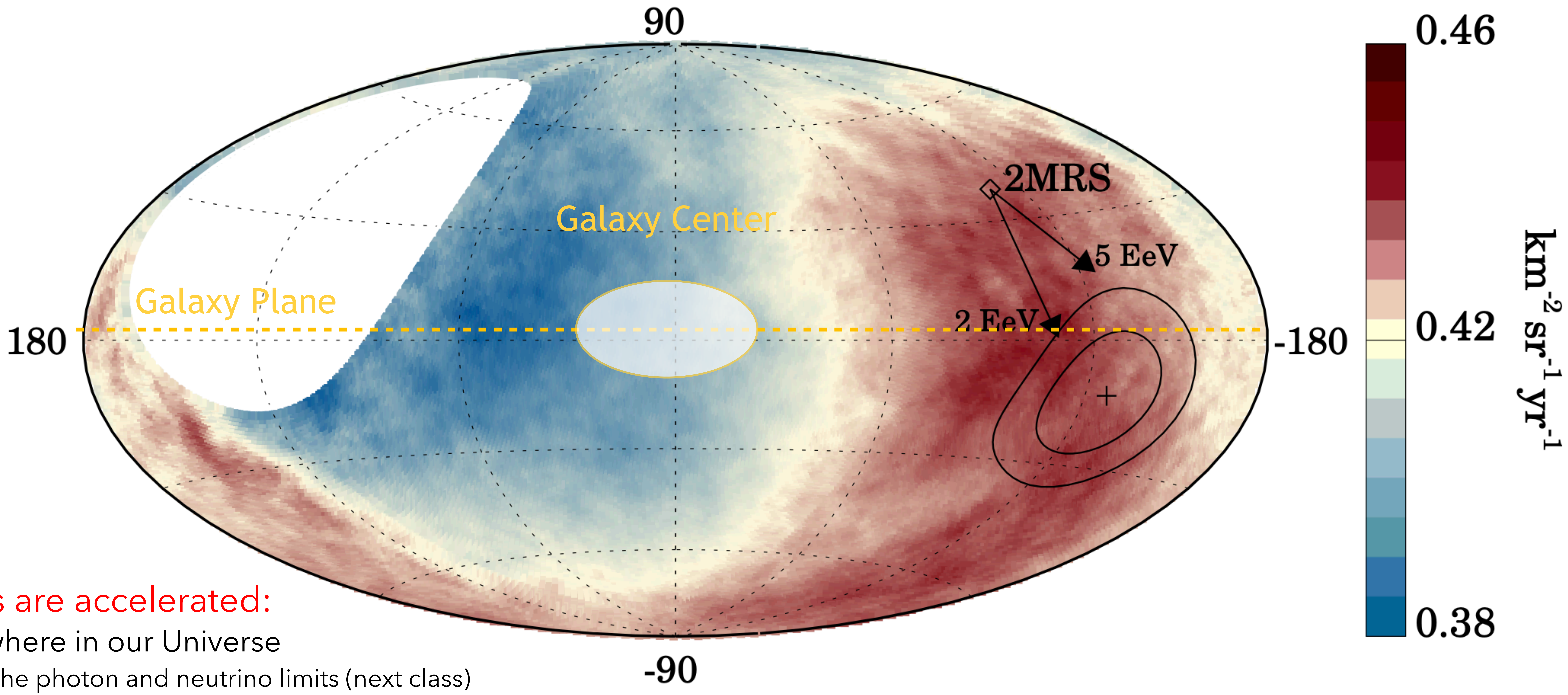
UHECR have an extra-galactic origin

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

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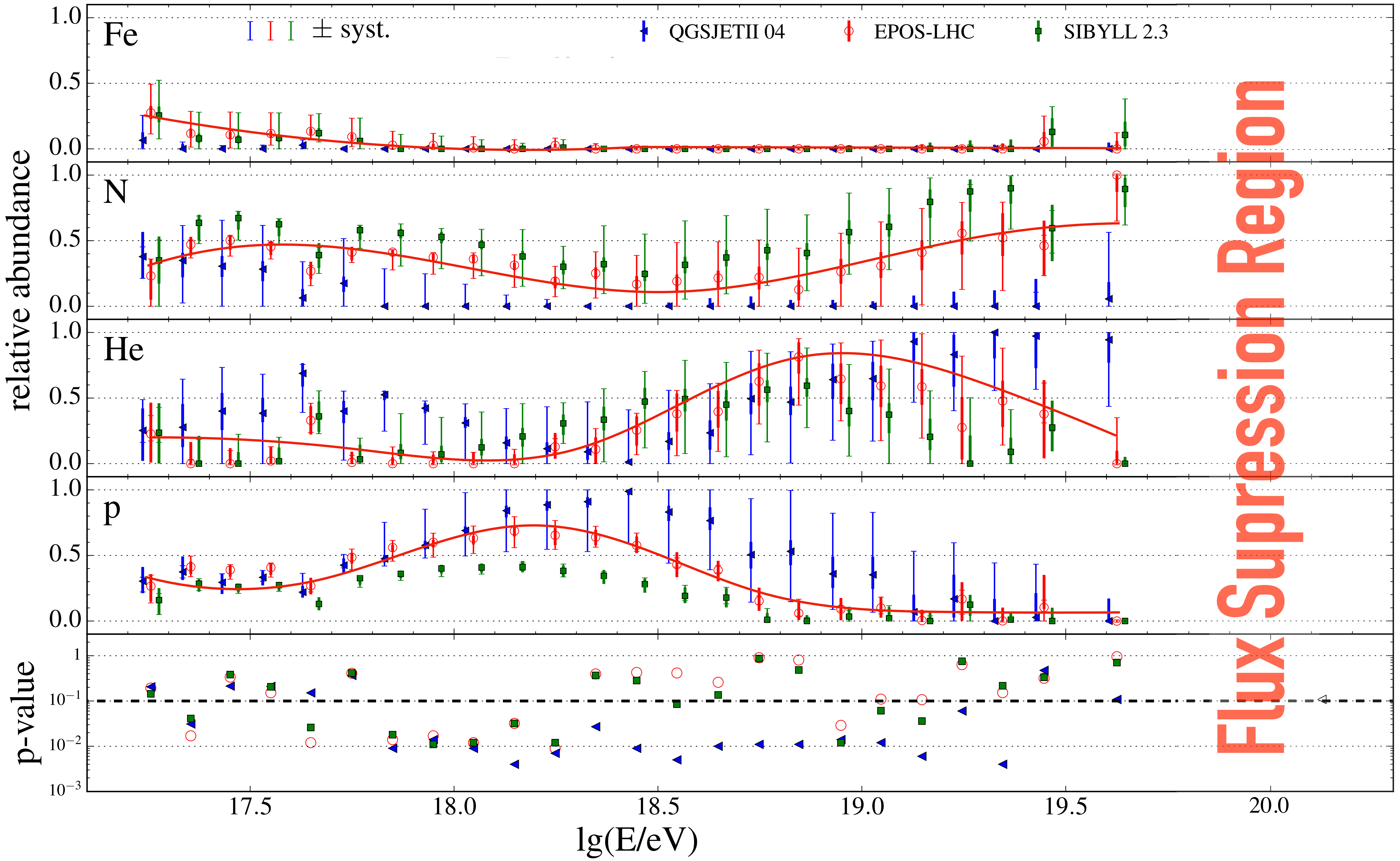
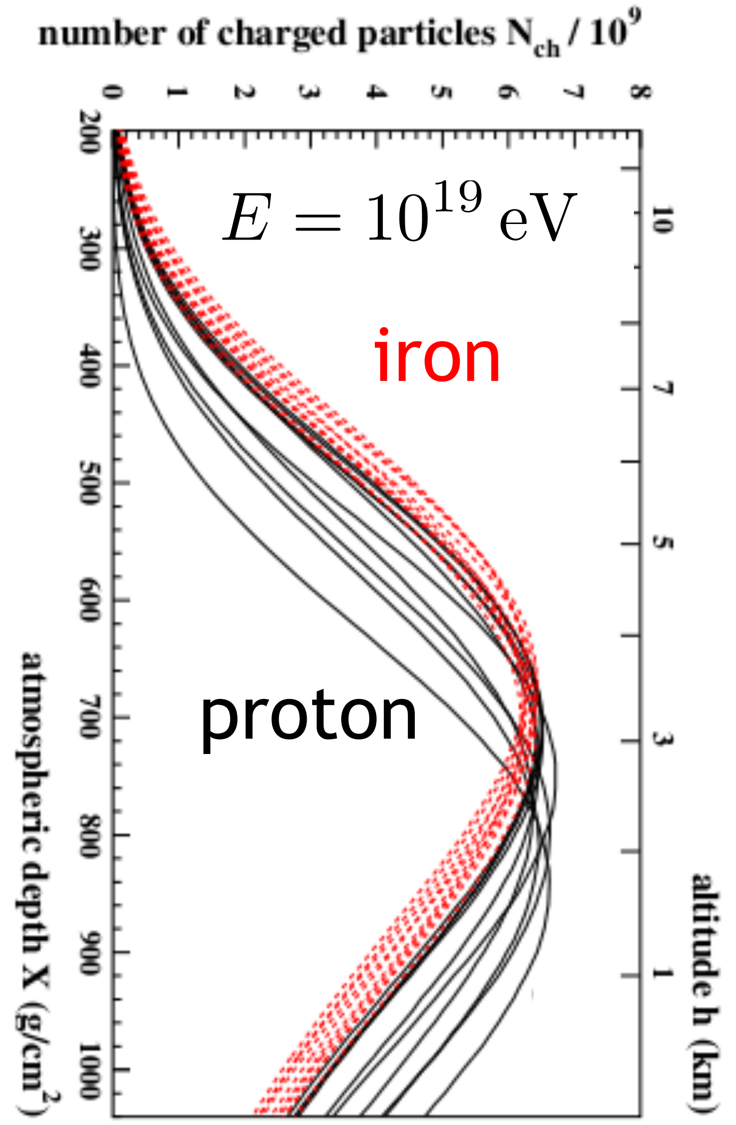
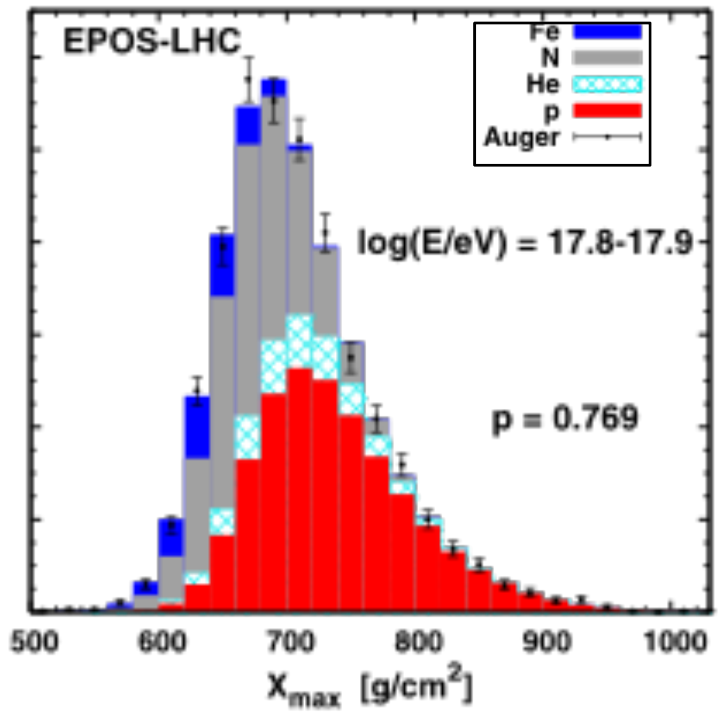
Composition fits to X_{max}

35th ICRC, PoS (2017) 506







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

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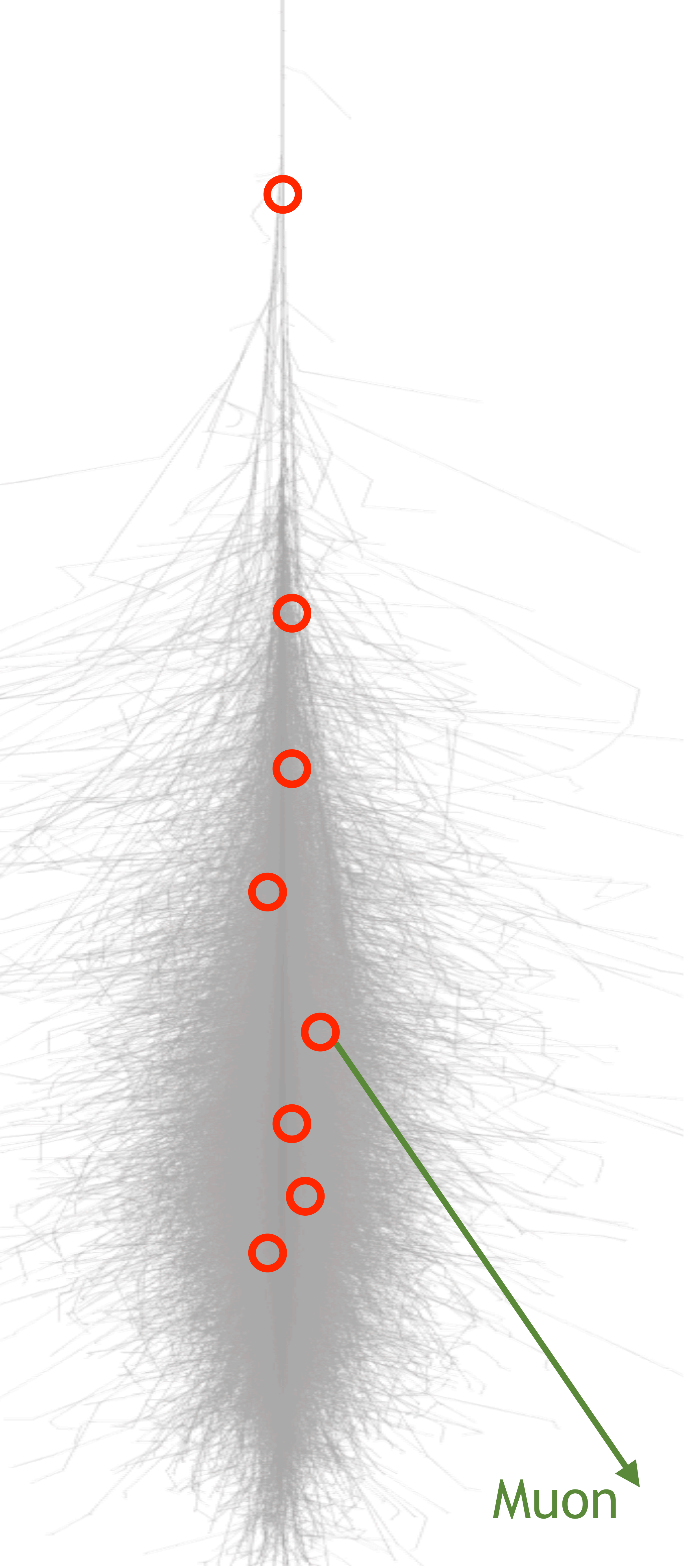
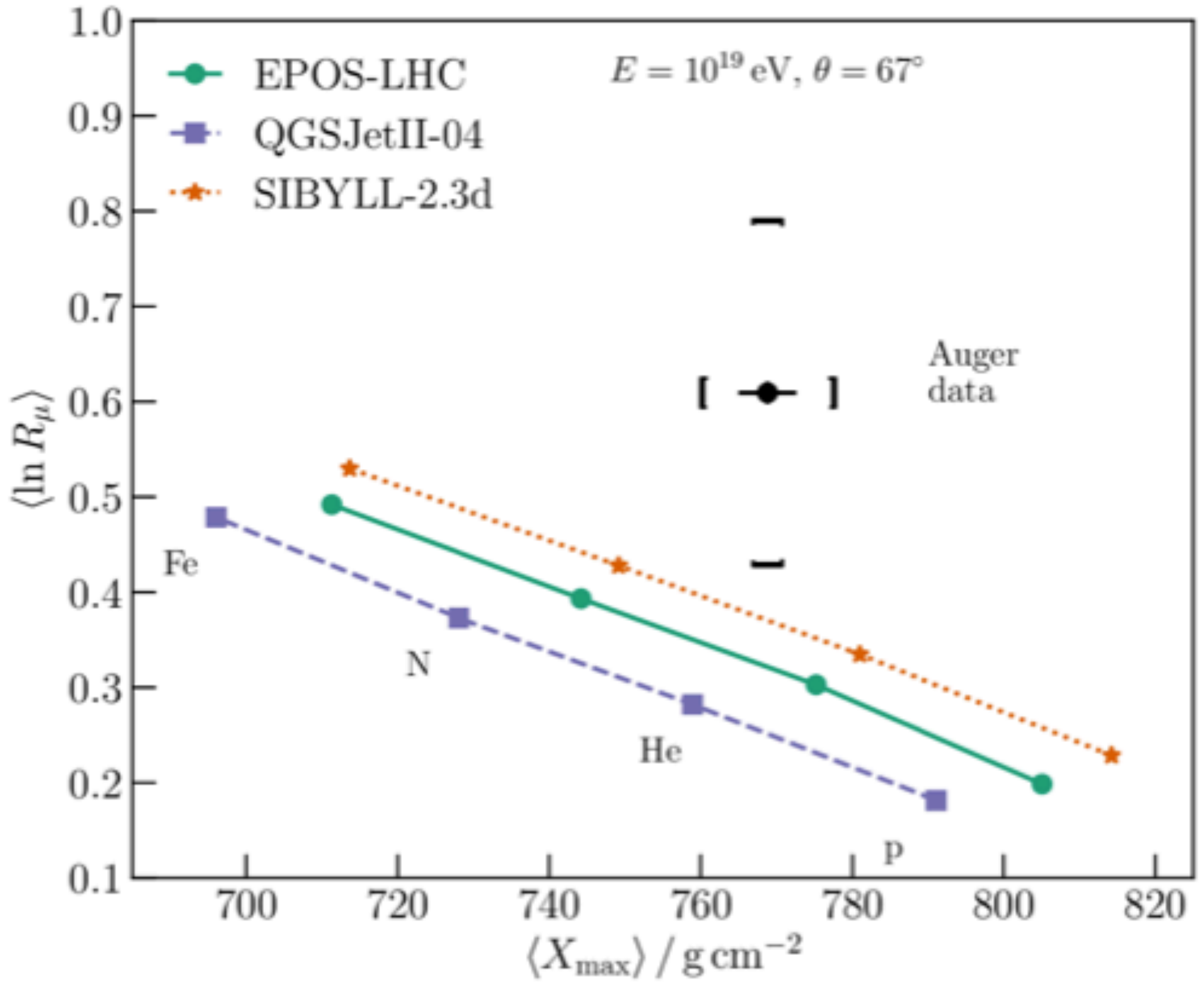
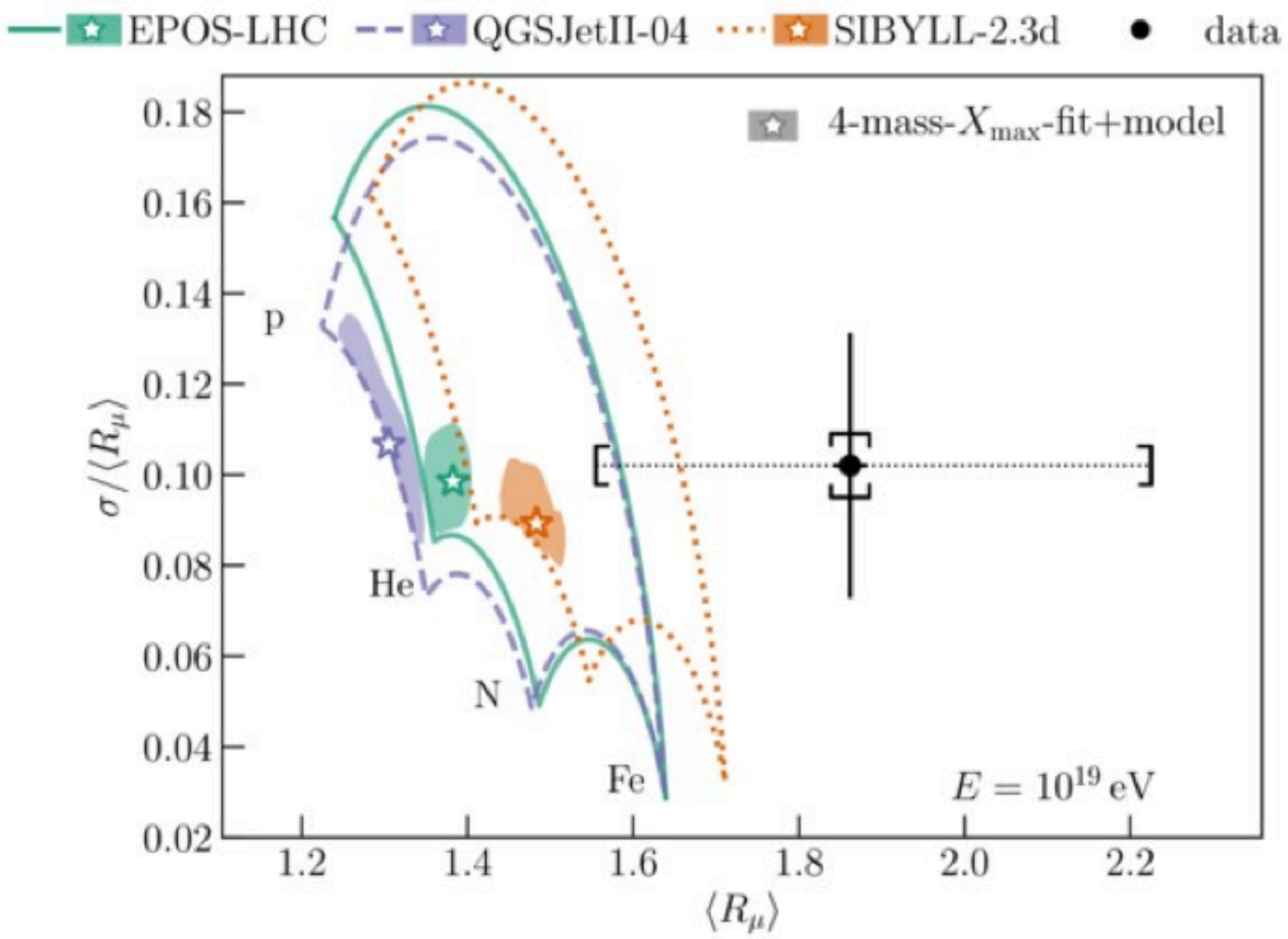
Shower description



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





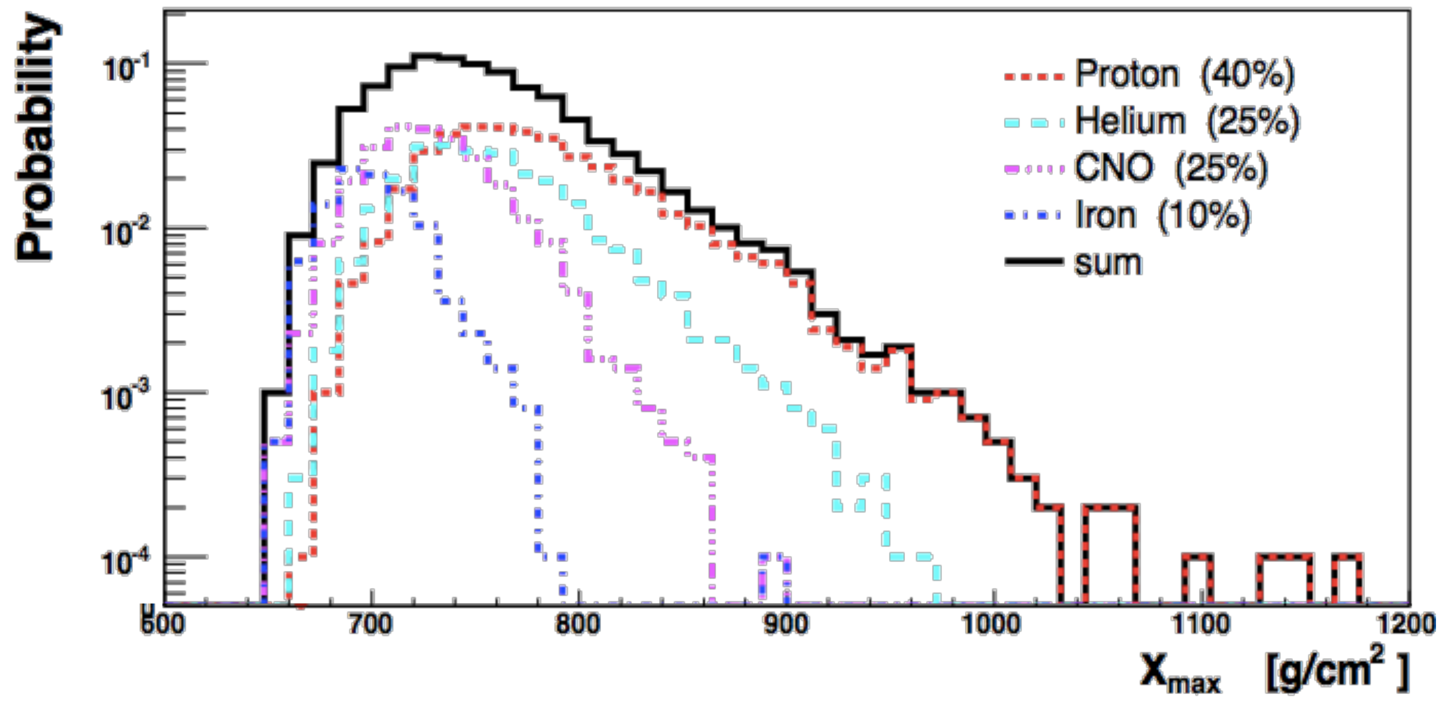
Combination of different measurements **reveals tension between data and all hadronic interaction models**

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

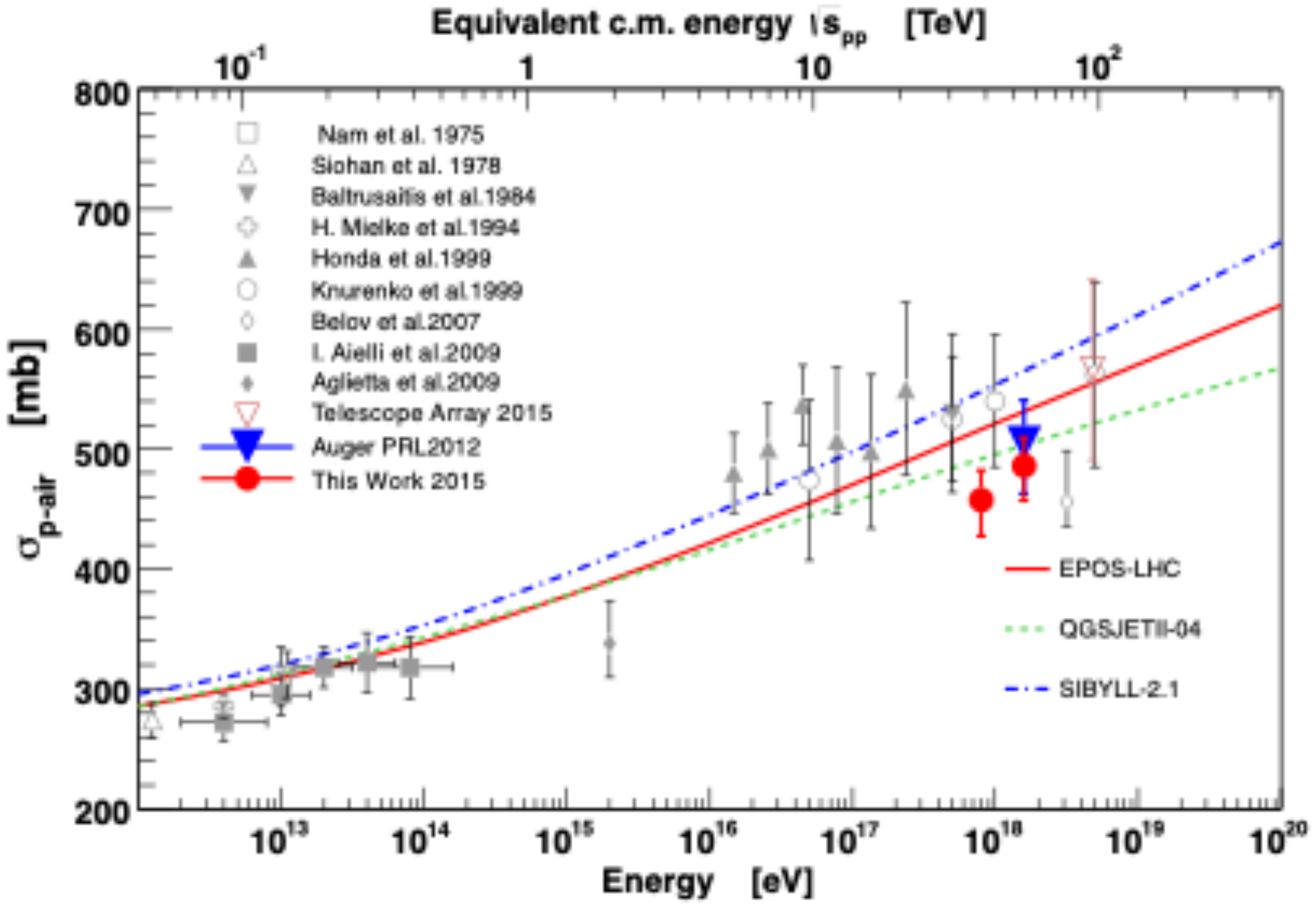
Proton-air cross-section

34th ICRC, PoS (2015) 401

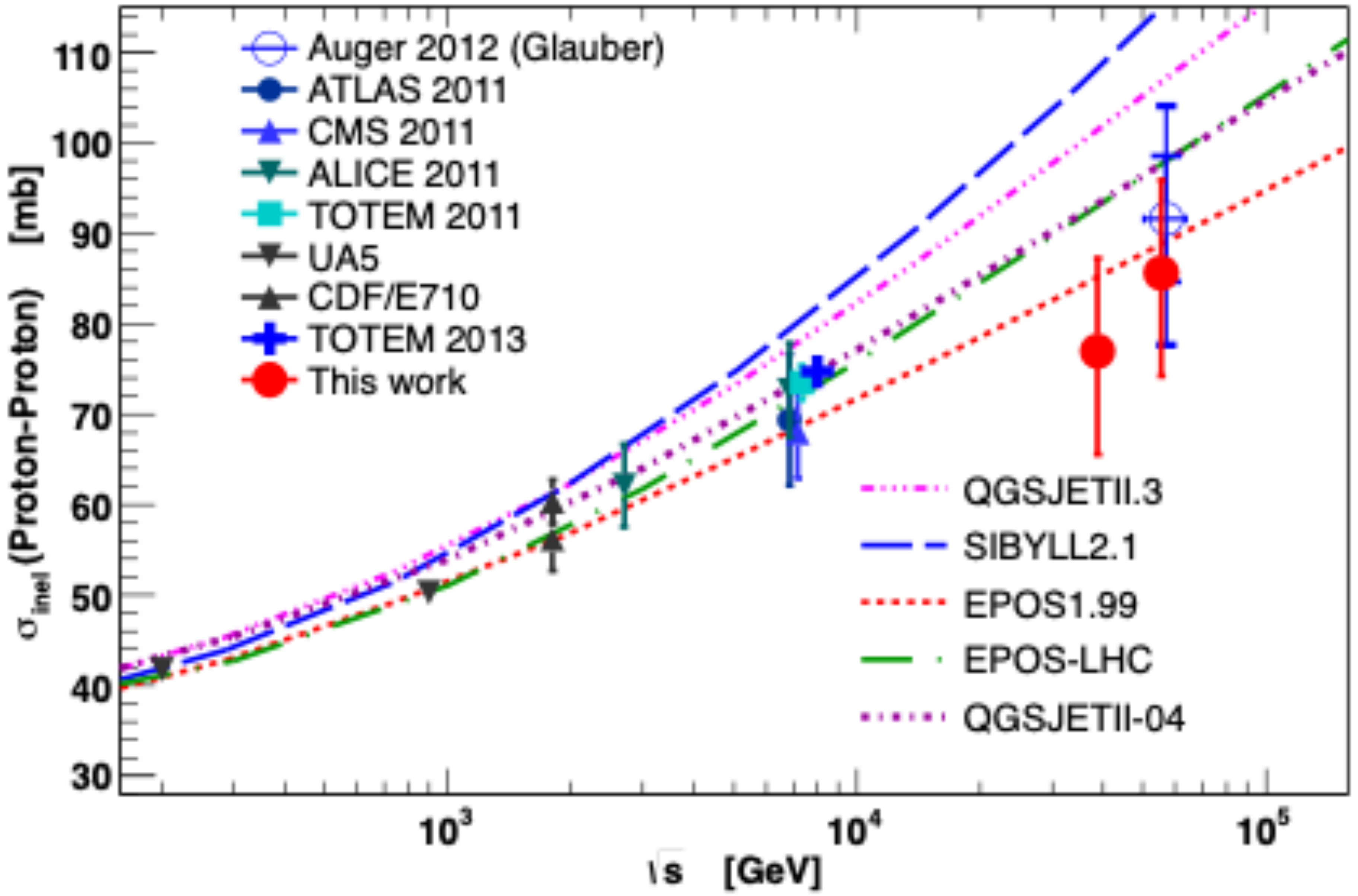
- p-Air cross-section can be extracted from the X_{max} distribution tail
  - If there is a large fraction of protons



Proton-Air Cross-section



Proton-proton Cross-section



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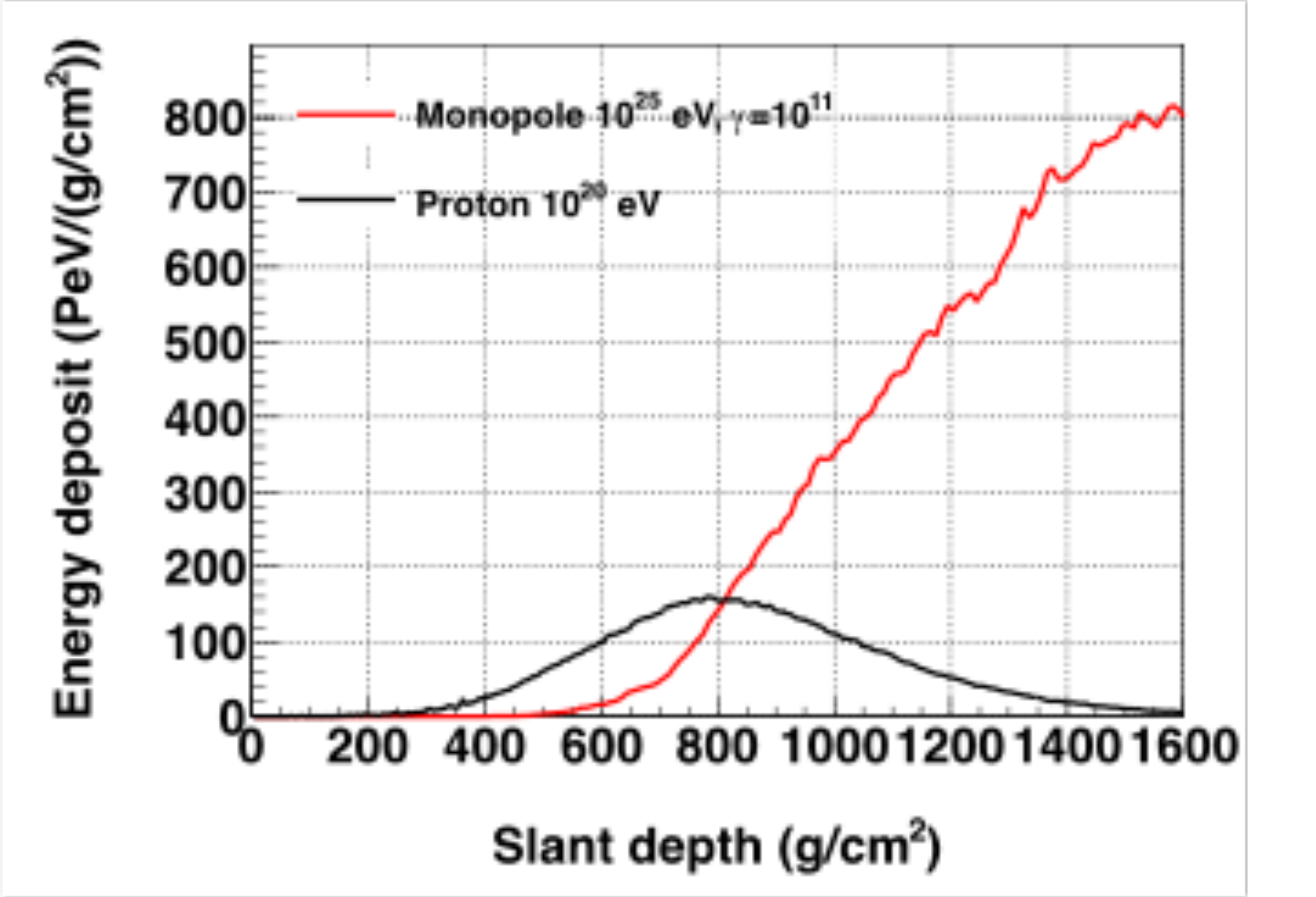
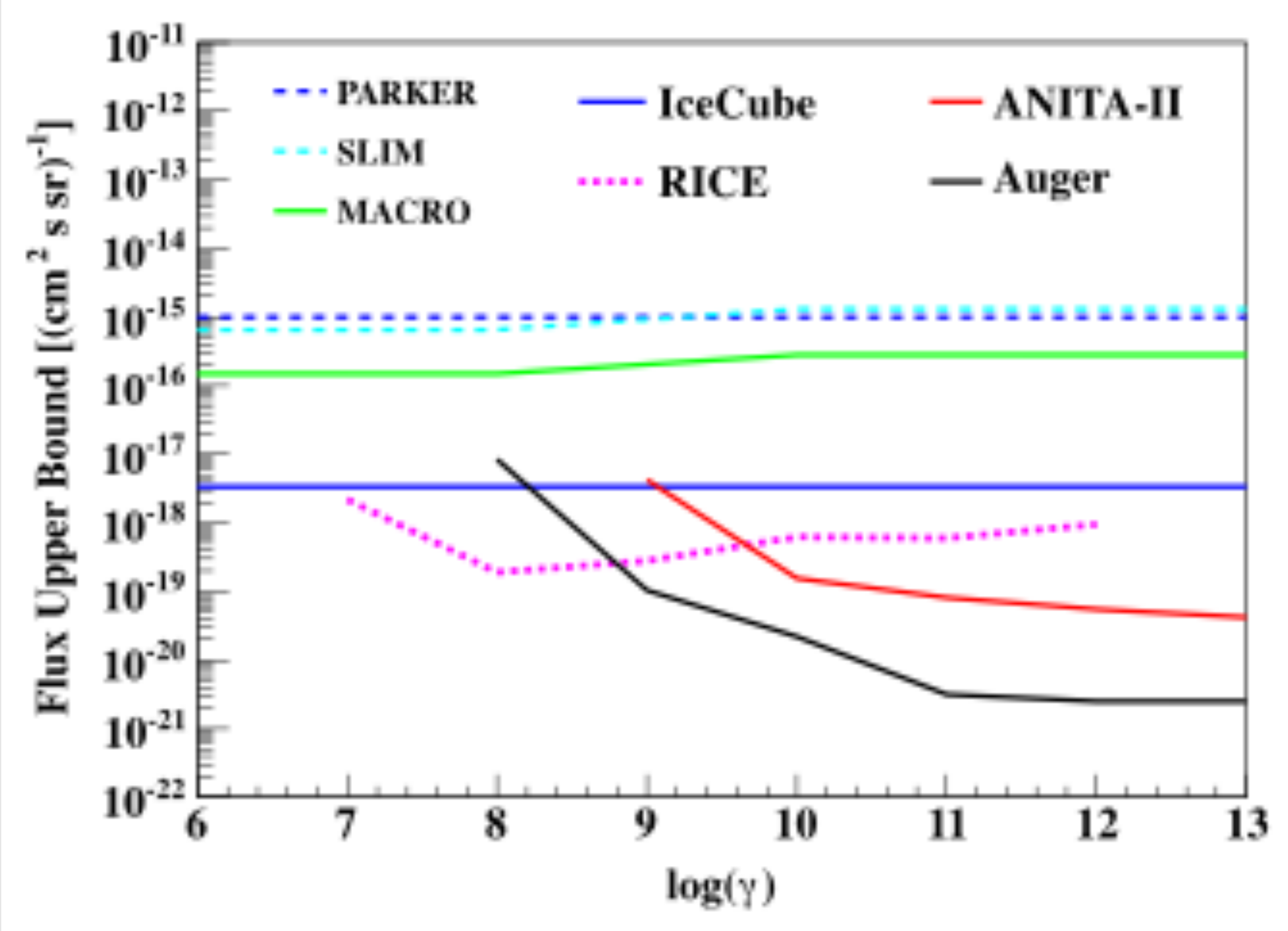
Testing exotic scenarios

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
  - $E_{mon} \approx 10^{25}\,\mathrm{eV}$
  - $M_{mon} \in [10^{11}; 10^{16}]\,\mathrm{eV/c^2}$

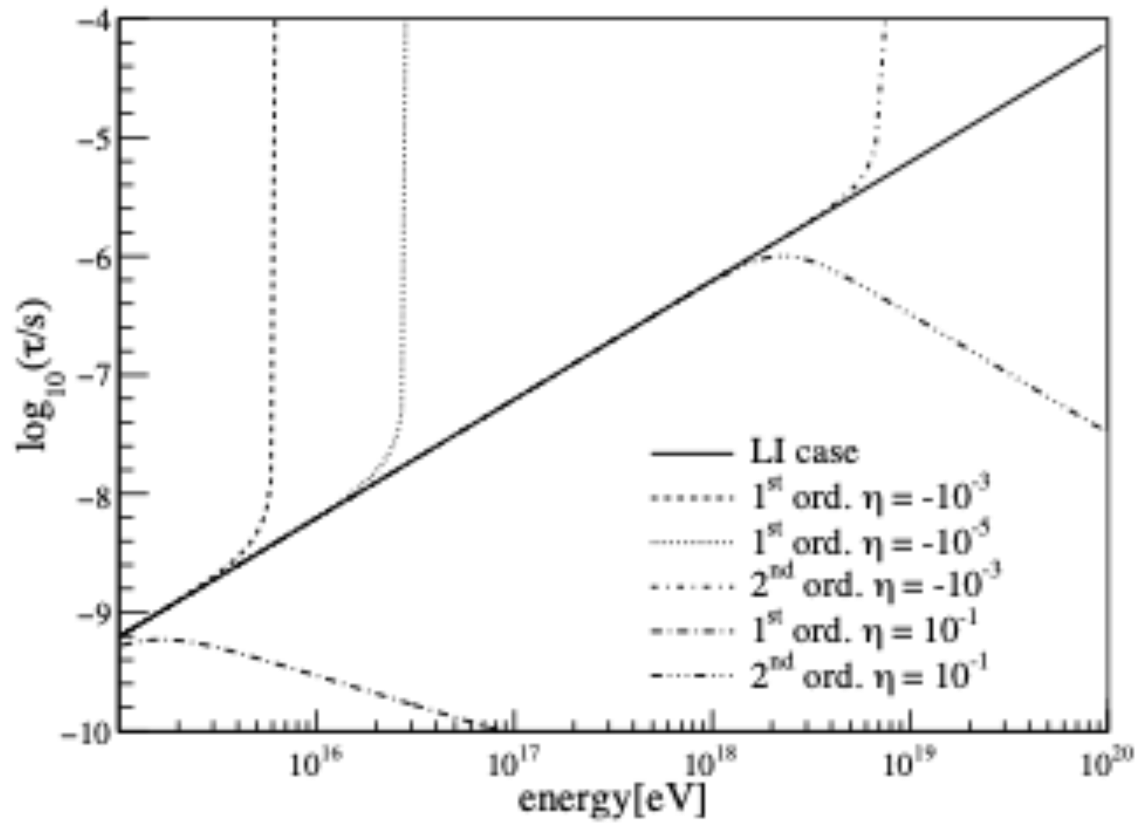


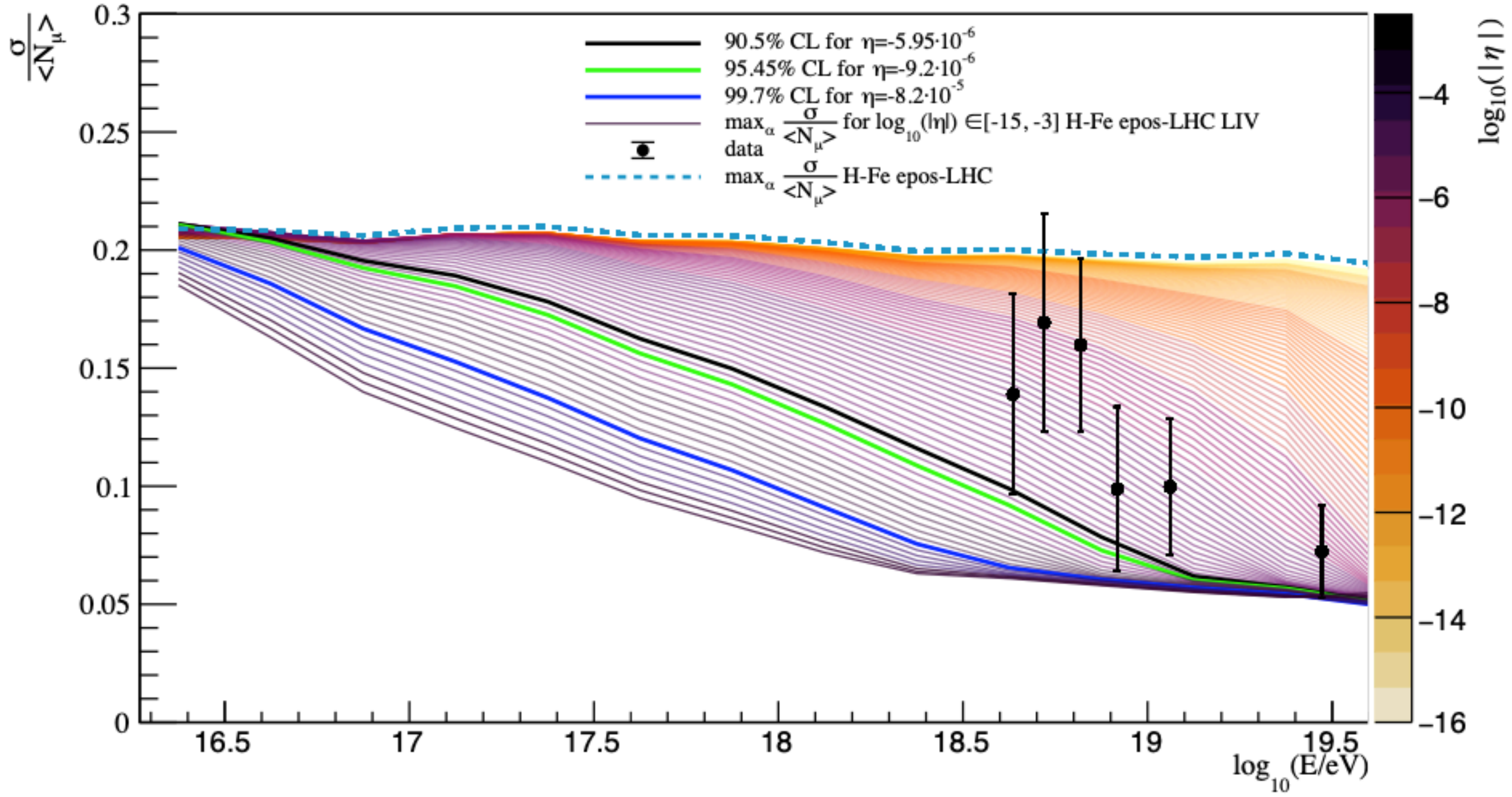
Lorentz Invariance Violation

- LIV is predicted by many Quantum Gravity theories
- Change the dispersion relation in a phenomenological way and see impact in shower observables

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

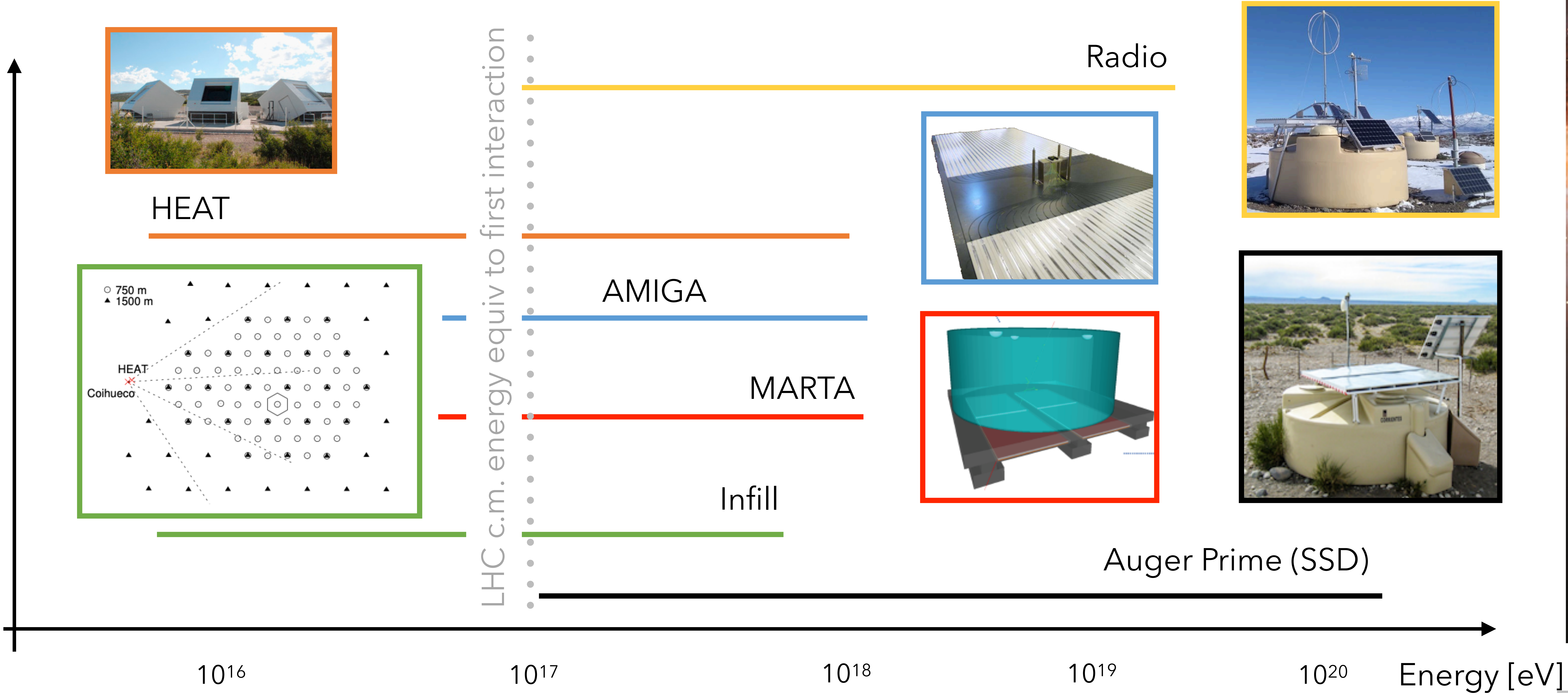
  - LIV doesn’t allow the pi0 to decay immediately
- The fluctuations of the number of muons at the ground shows a high sensitivity to LIV
- Stringent cut for high energy interactions





Next years of the Pierre Auger Observatory

(A plethora of measurements to fully understand the shower)



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Next Class

Next class

- Neutral messengers
  - Photons (Gamma-rays)
  - Neutrinos

- Astroparticle Multi-messenger Era

- Future Projects

Acknowledgements

FCT Fundação para a Ciência e a Tecnologia

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COMPETE 2020
PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO

PORTUGAL 2020

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

LIP

TÉCNICO LISBOA

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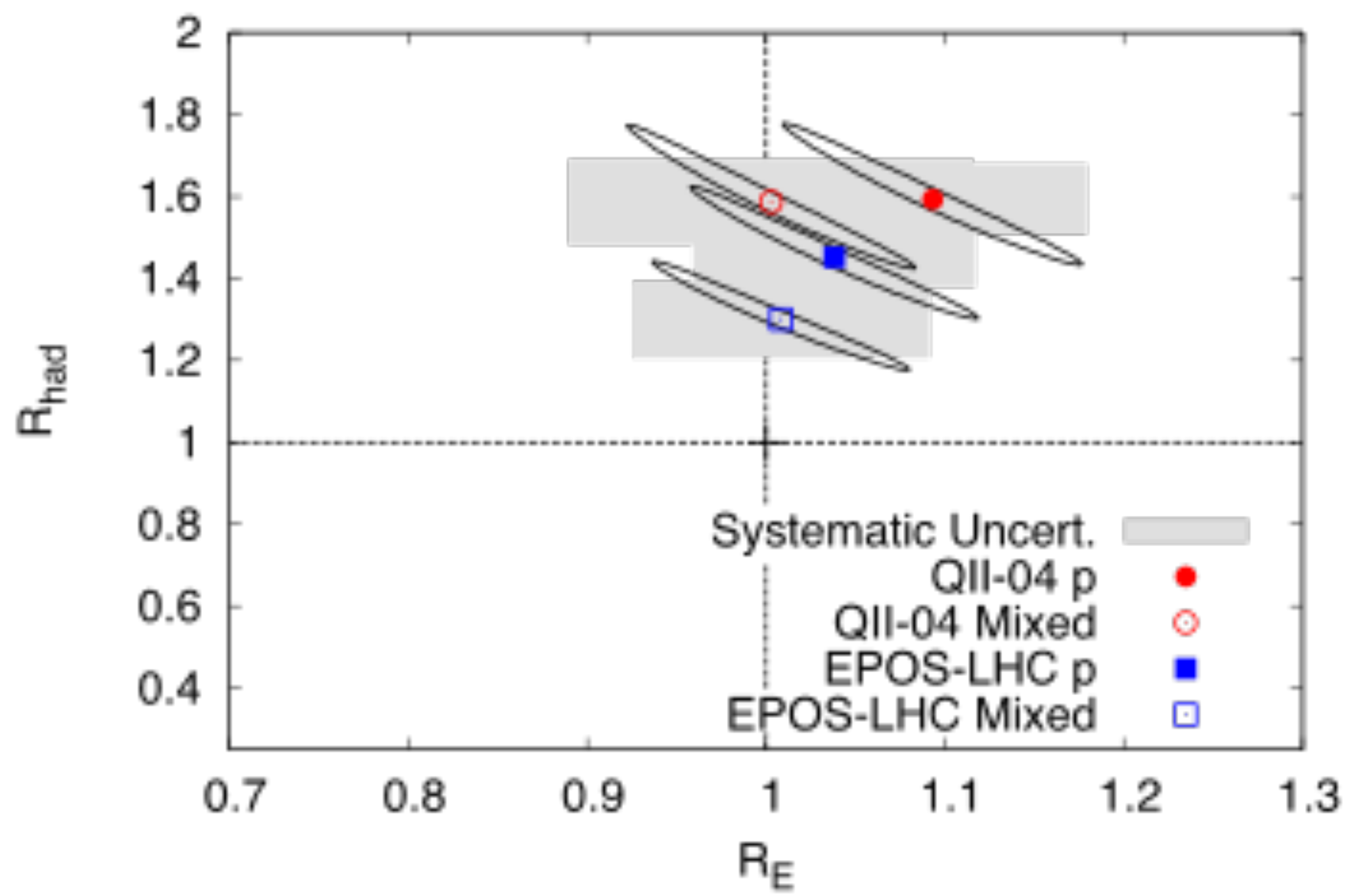
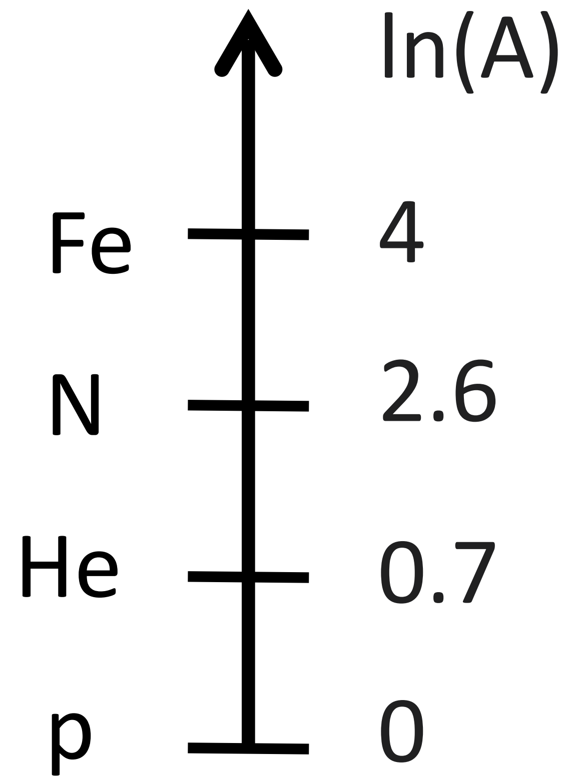
Backup slides

More trouble for Hadronic Interaction Models…

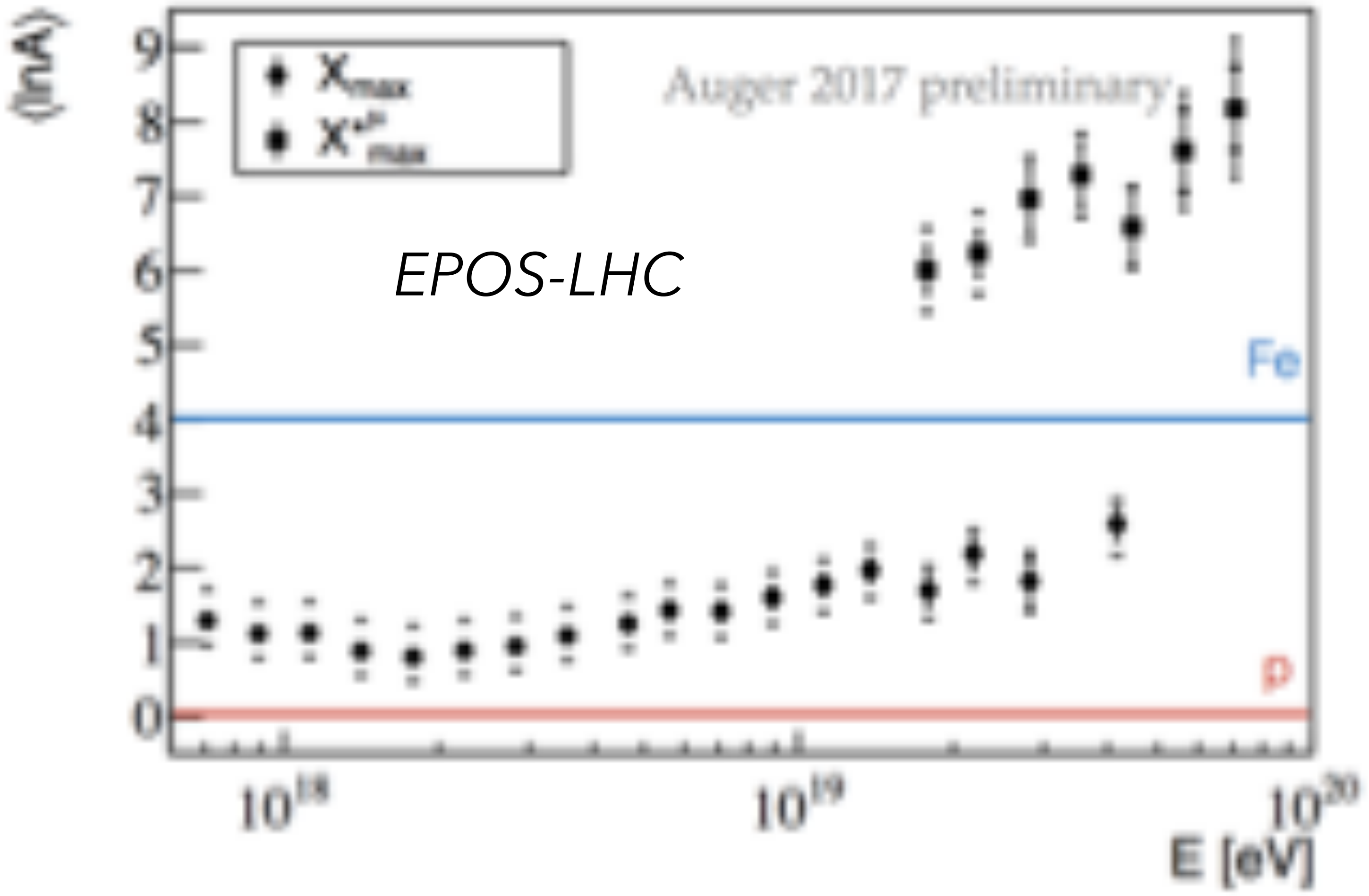
- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had}) [Hybrid: SD + FD]
- Depth of maximum of muon production depth ($X^{*\mu}_{max}$)

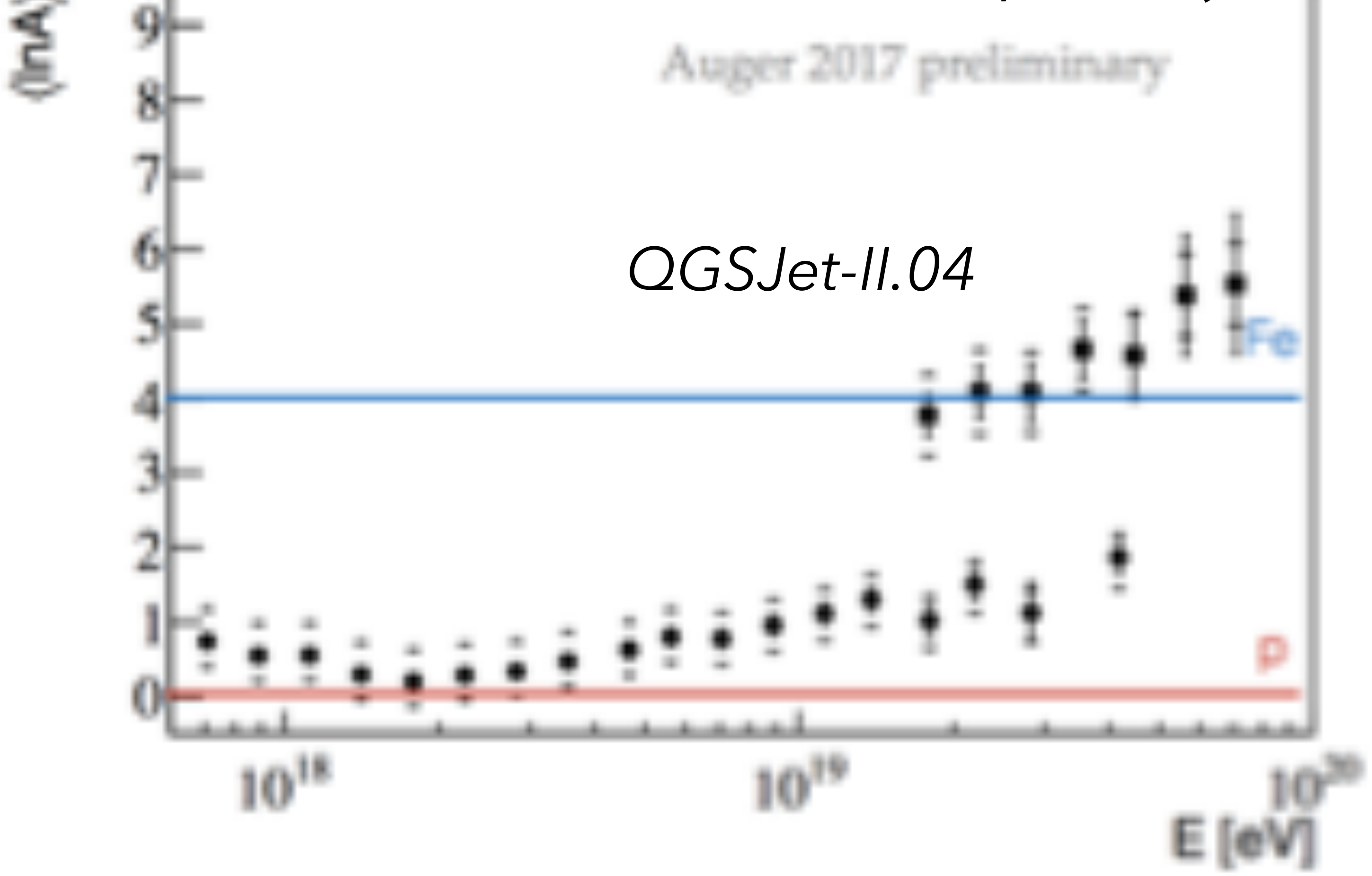
Phys.Rev.Lett. 117 (2016) no.19, 192001



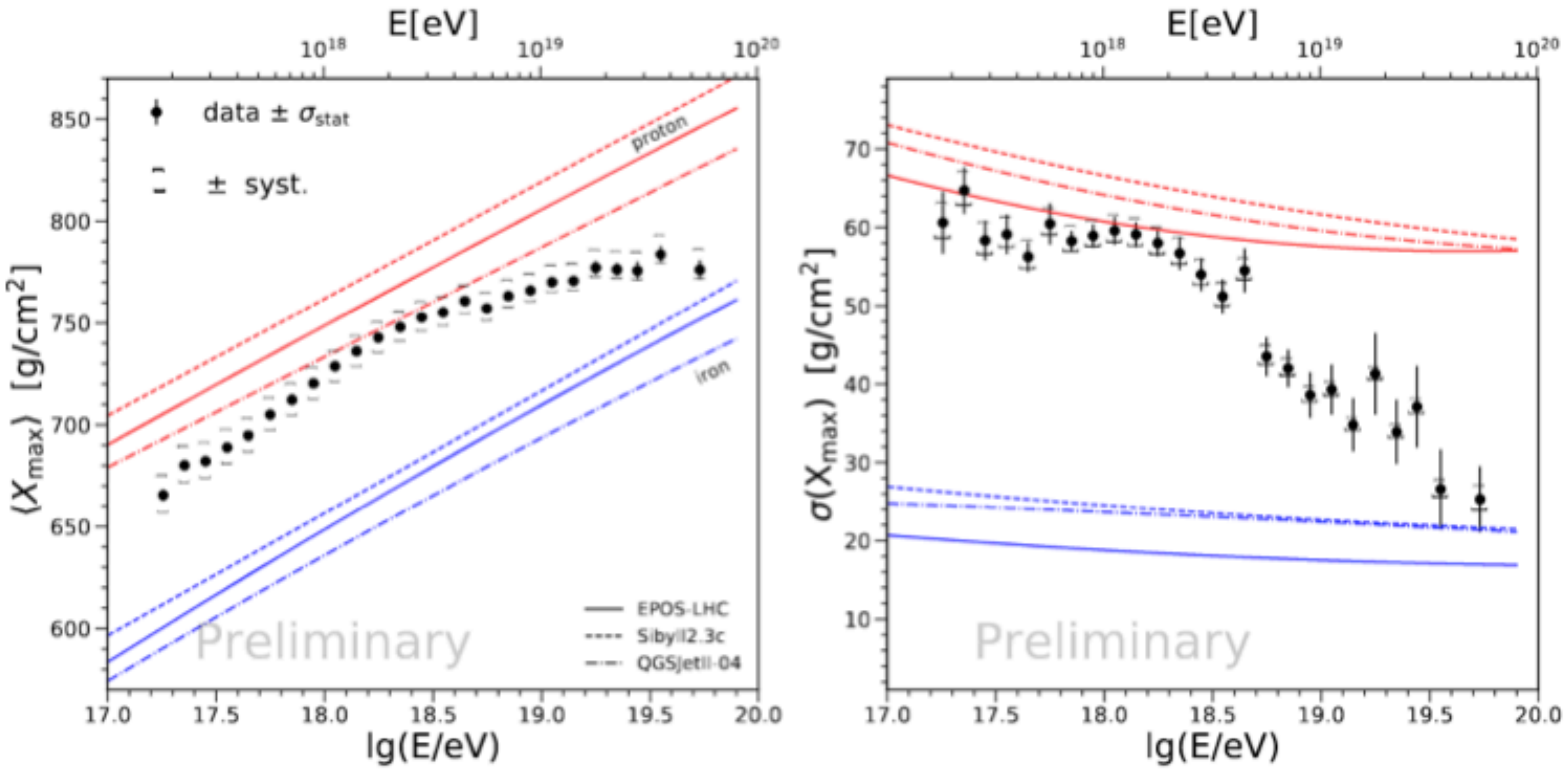


35th ICRC, PoS (2017) 398





X_{max} distribution momenta



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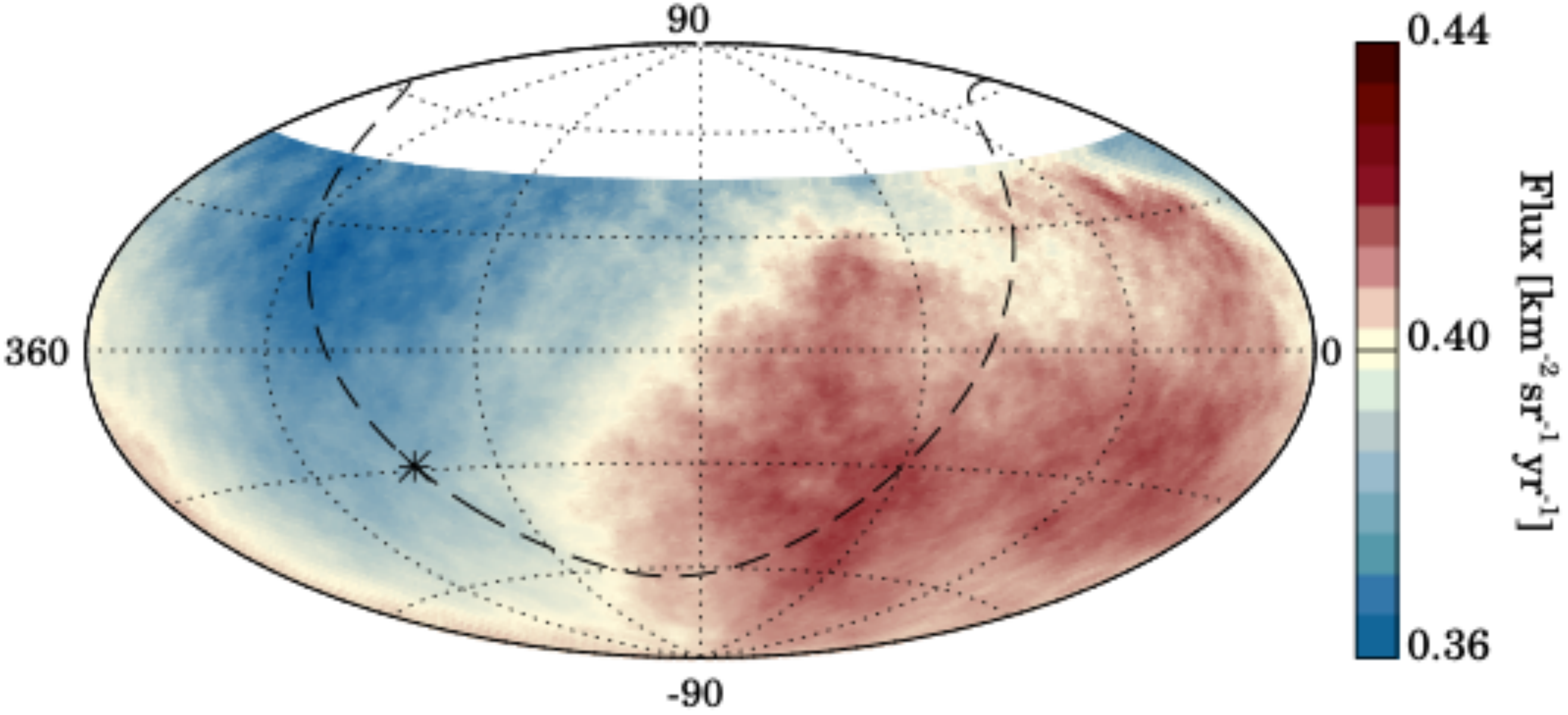
UHECR



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