Messengers from the Universe

Ruben Conceição

2^{nd} Lisbon Mini-School in Particle and Astroparticle Physics, Sesimbra, February 6^{th} 2017

Questions to the Universe

- How can we learn about our surroundings?

Messengers from the Universe

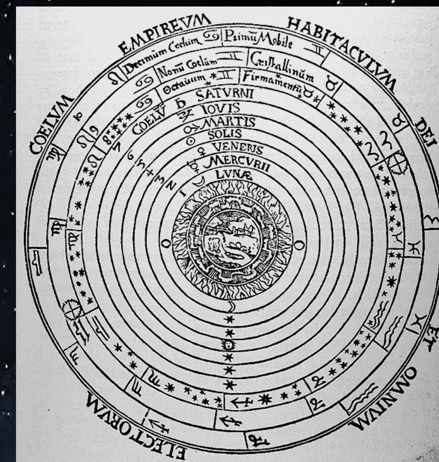
Photons

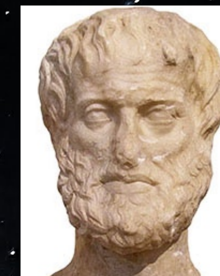
(visible light)

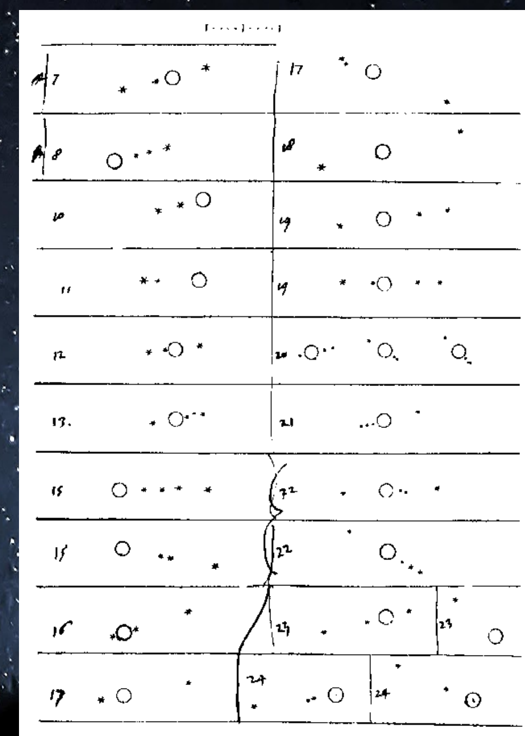
Messengers from the Universe

Photons

(visible light)

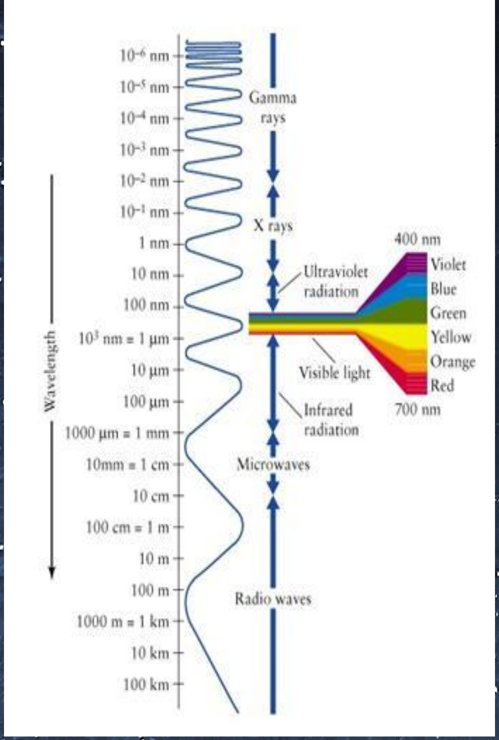


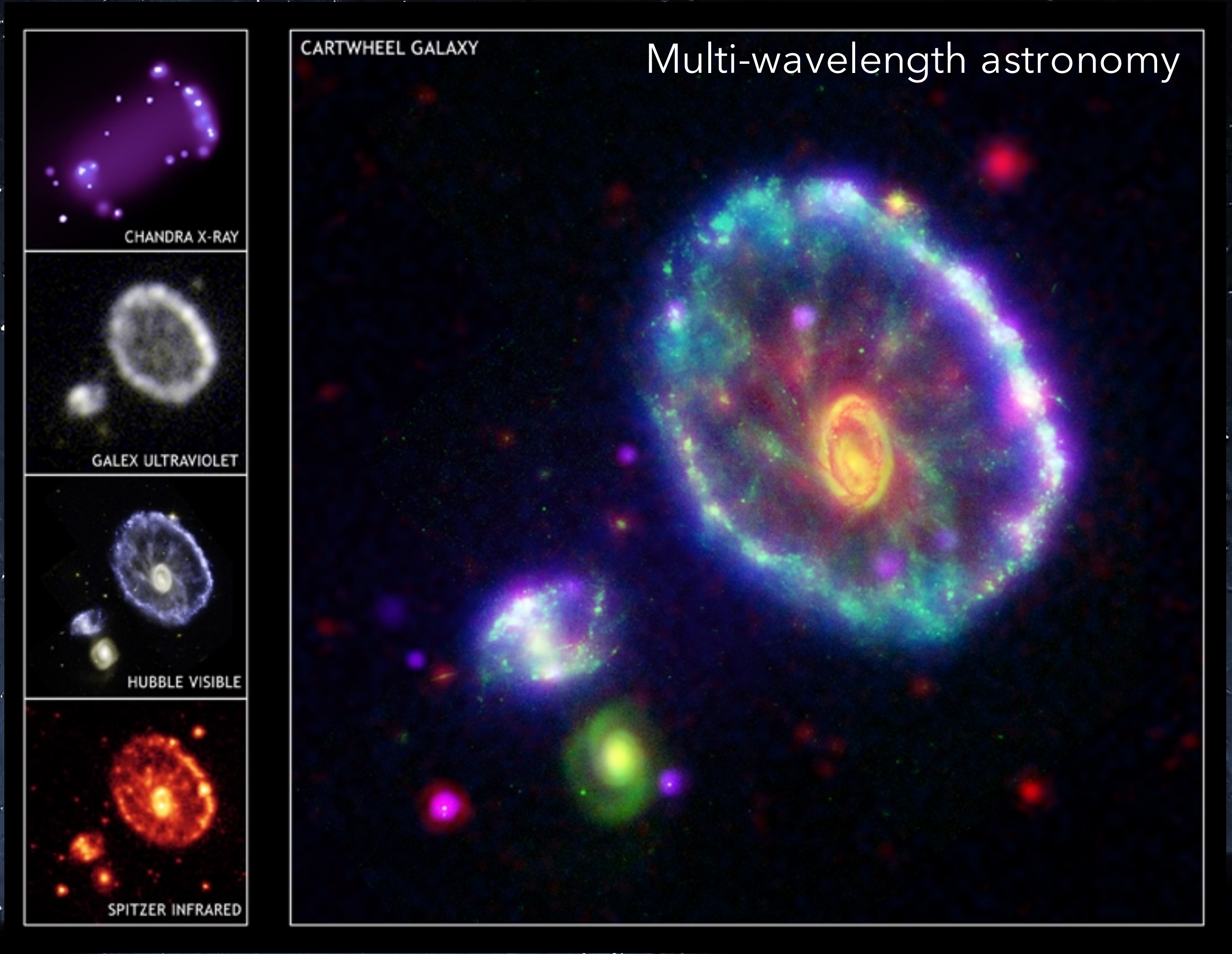




Messengers from the Universe

Photons (other wavelengths)





Photons


Photons
Charged cosmic rays
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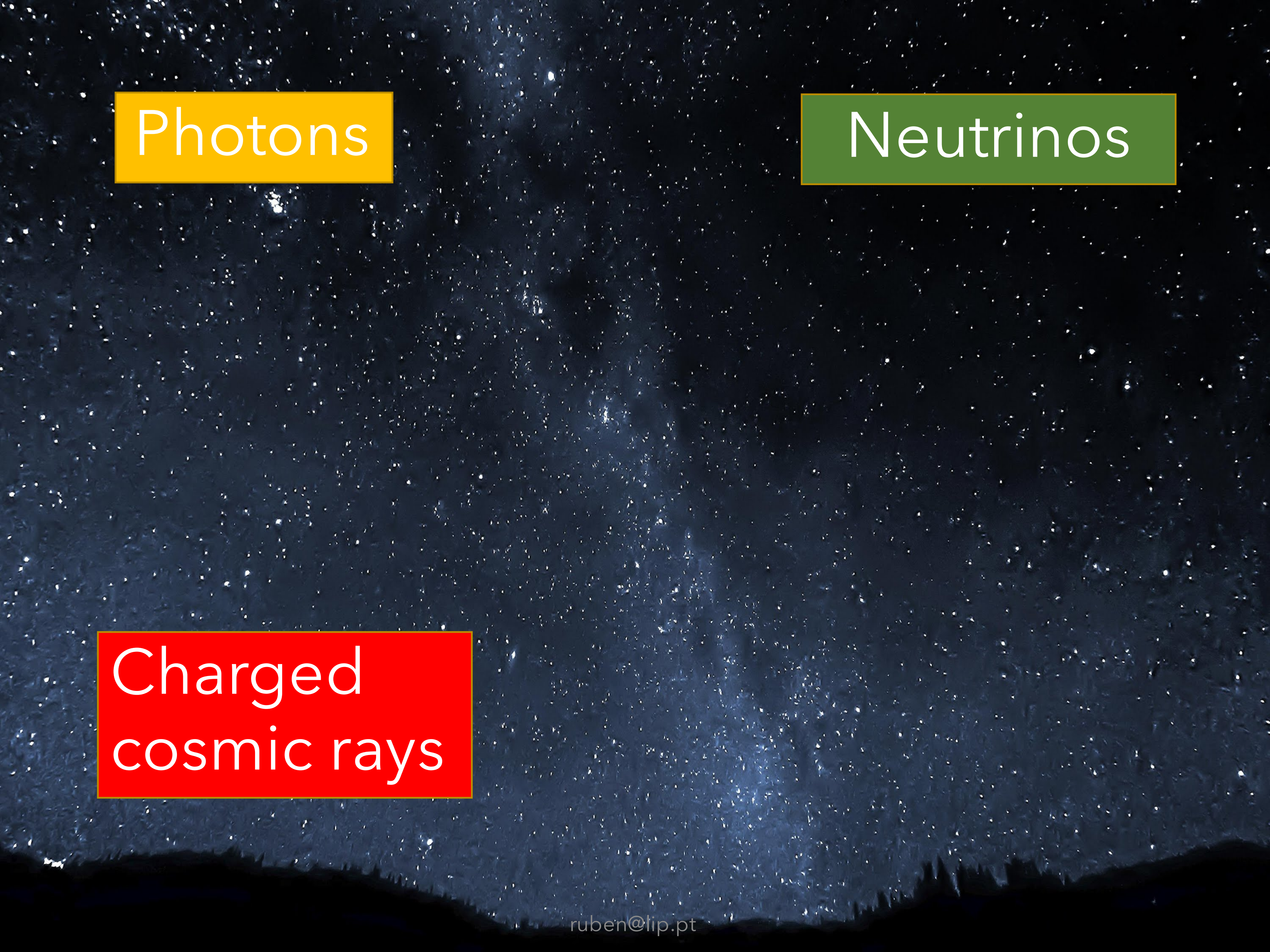
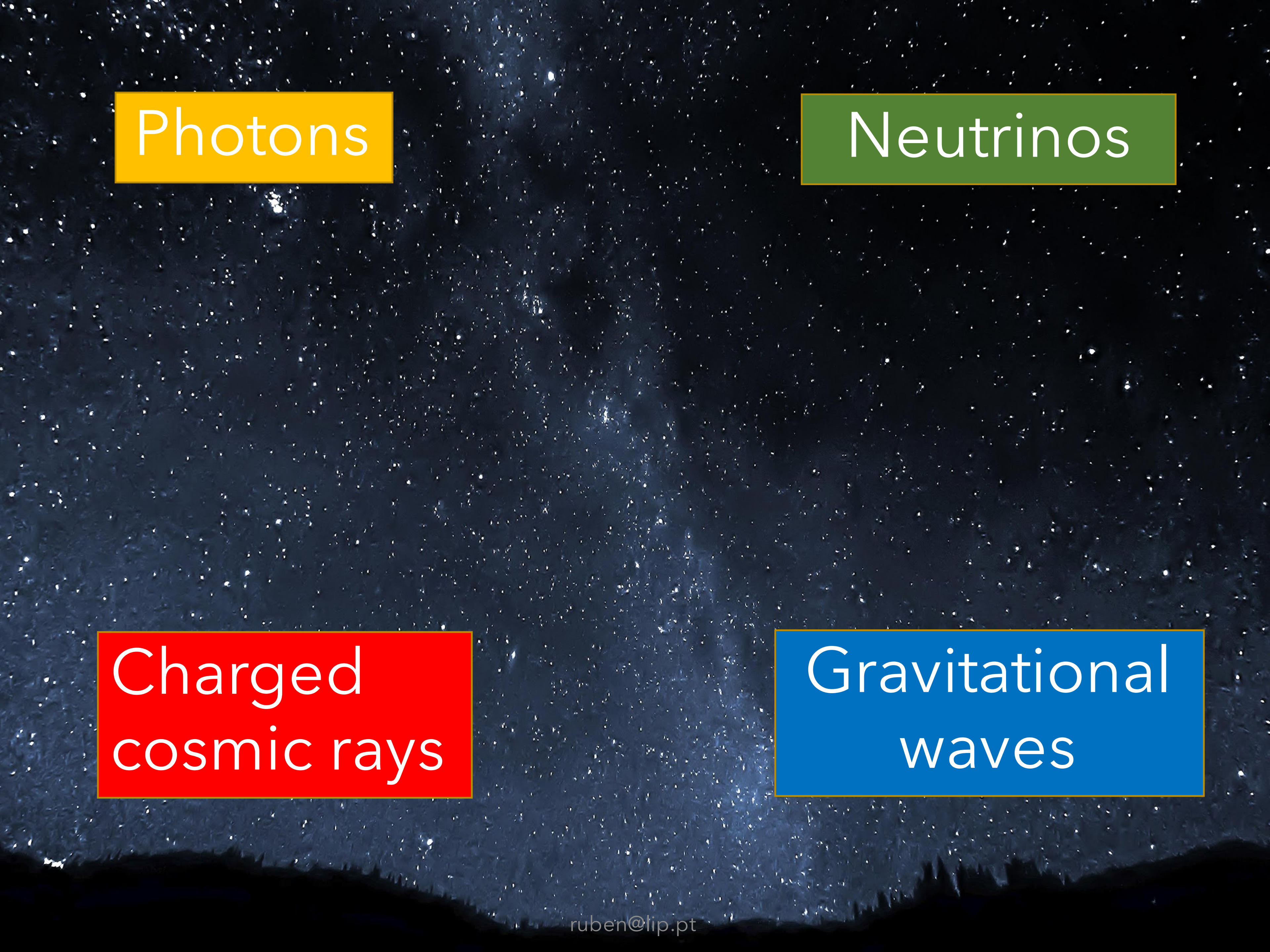

Photons
Neutrinos
Charged cosmic rays


Photons
Neutrinos
Charged cosmic rays
Gravitational waves

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Photons

Neutrinos

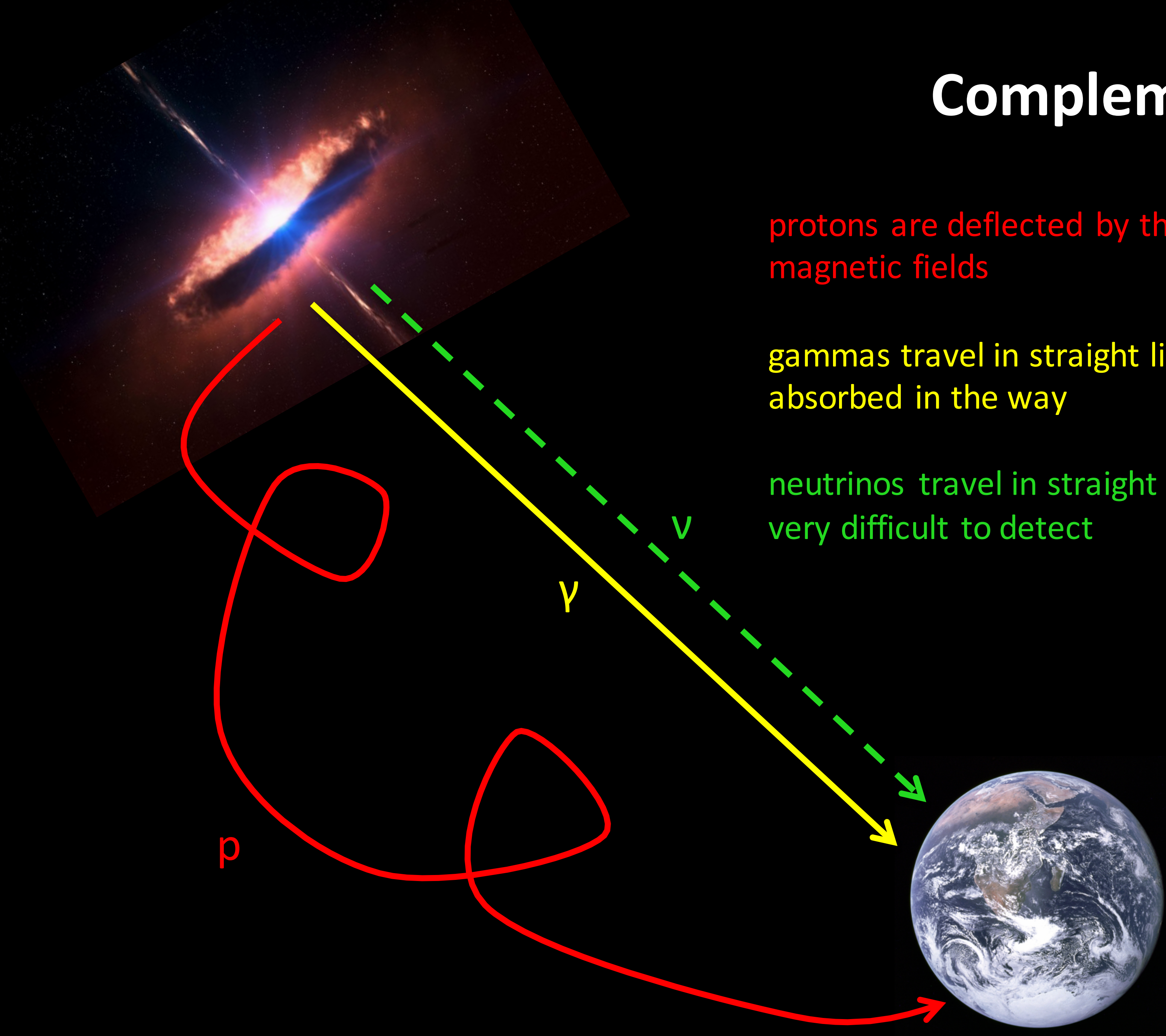
Multi-messenger approach

Test the dynamics of our cosmos

Charged cosmic rays

Gravitational waves

Complementarity



protons are deflected by the galactic magnetic fields

gammas travel in straight lines but can be absorbed in the way

neutrinos travel in straight lines but are very difficult to detect

Photons

Neutrinos

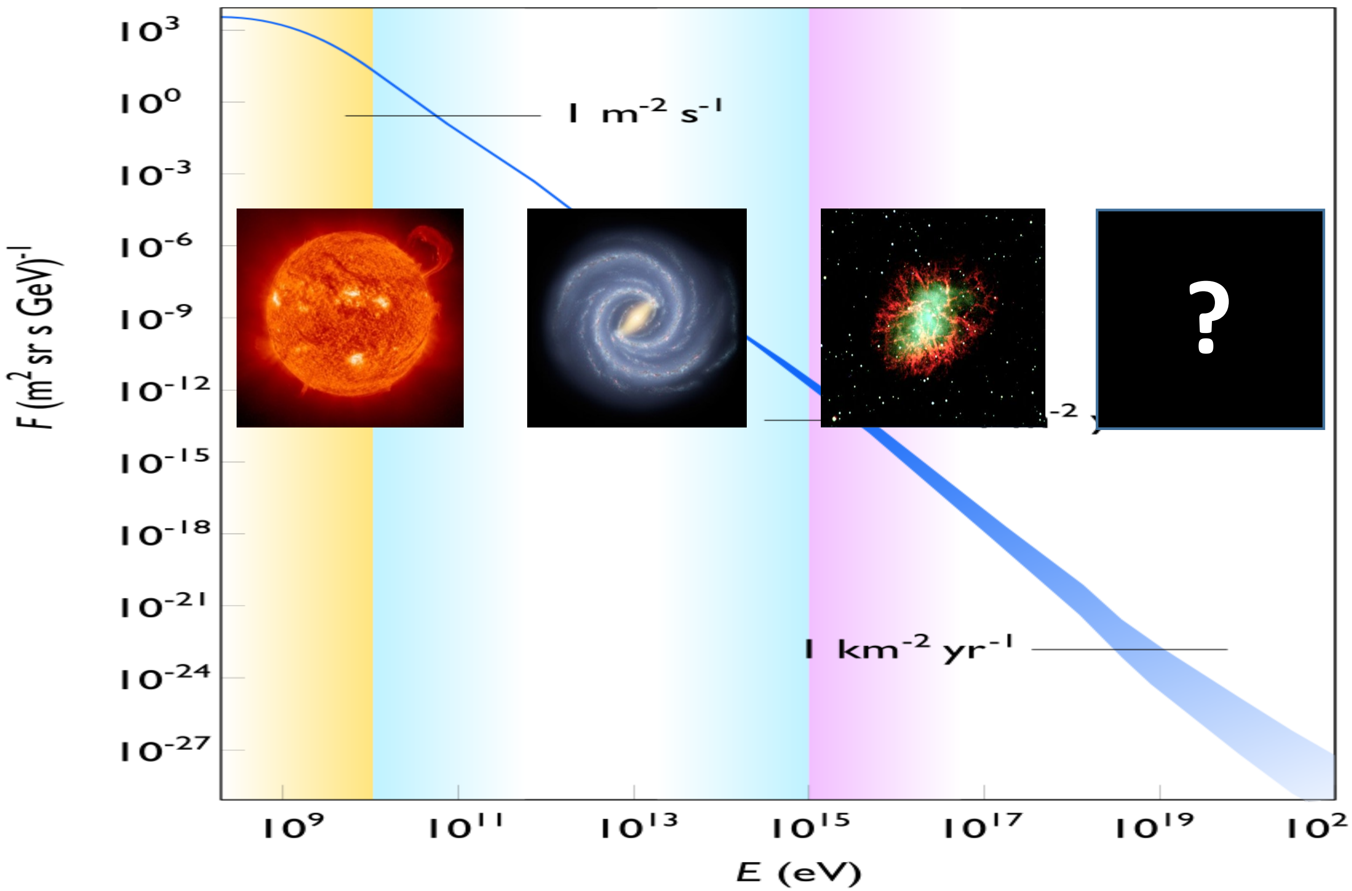
Multi-messenger approach

Test the dynamics of our cosmos

Charged cosmic rays

Gravitational waves

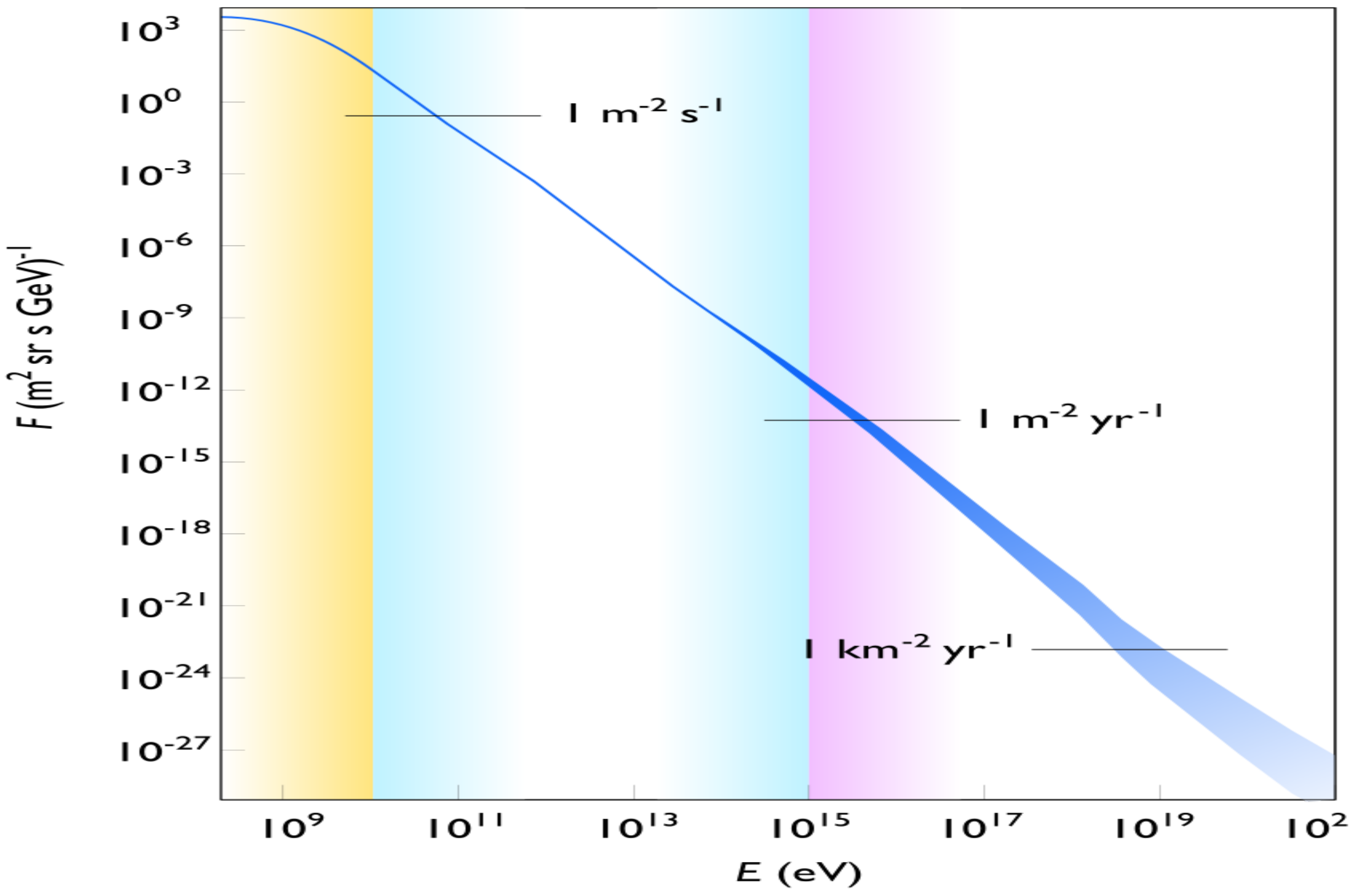
Cosmic ray energy spectrum



Rapidly falling energy spectrum

Different sources according to the energy

Cosmic ray energy spectrum



Rapidly falling energy spectrum

In this talk…

- (Very) high-energy gamma-rays
  - Probe some of the most violent astrophysical phenomena
    - SuperNovae (SN) & SuperNovae Remnants (SNR)
    - Gamma-ray bursts (GRB)
- Ultra high-energy cosmic rays
  - Universe greatest accelerators
    - Nature and origin still a mystery
  - Opportunity to do particle physics above the human-made accelerator energies

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Very High-Energy Gamma-rays

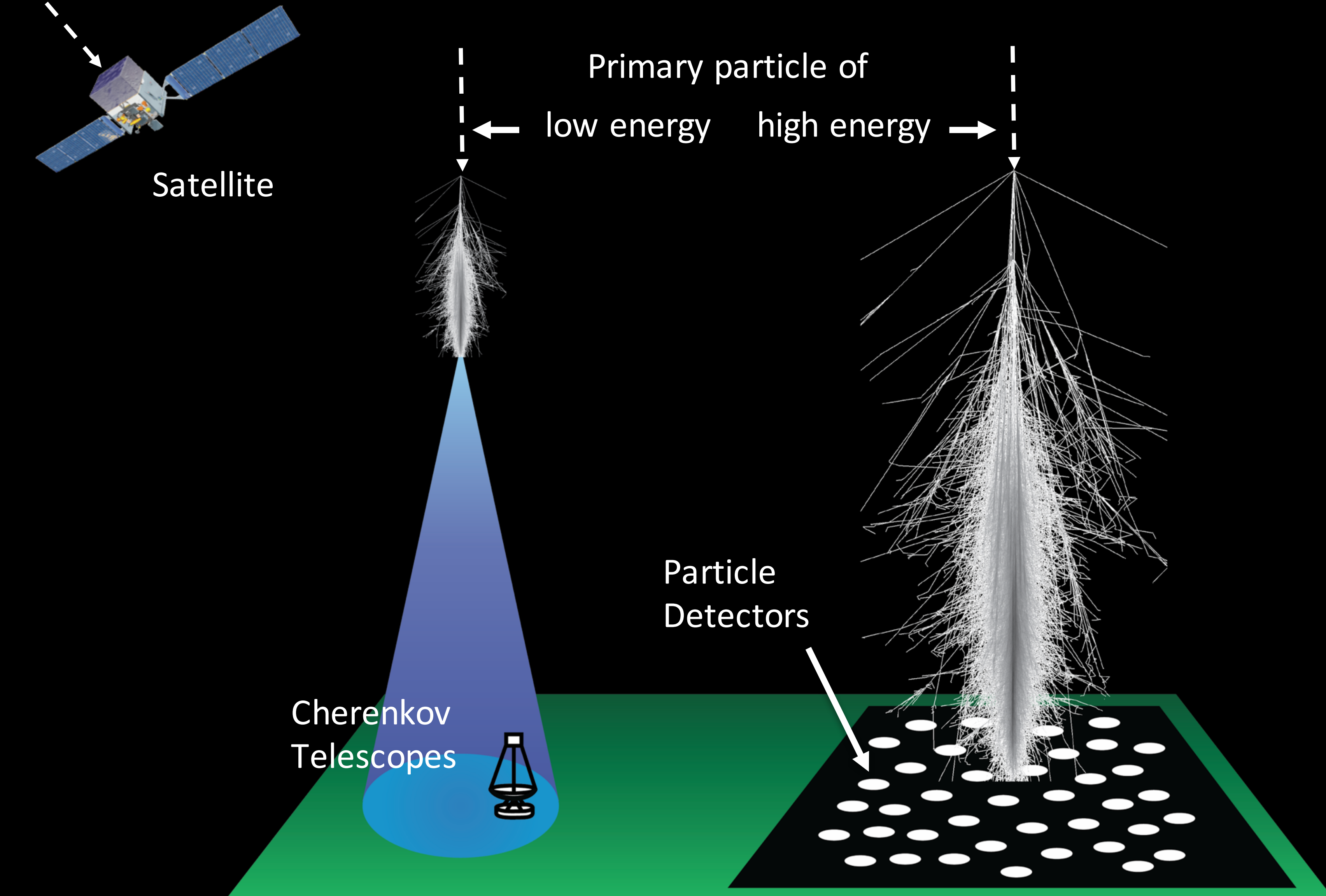
(Very) High-Energy Gamma Rays

- Astrophysical gamma rays
  - Energy region of interest from GeVs to hundreds TeVs

(Very) High-Energy Gamma Rays

- Astrophysical gamma rays
  - Energy region of interest from GeVs to hundreds TeVs
- Scientific interest:
  - Key to understand the **acceleration mechanism** of cosmic rays in our galaxy
  - Violent astrophysical phenomena: pulsars and black holes
  - Galactic magnetic fields
  - Photon radiation fields in the Universe
  - Indirect search of **dark matter** (WIMP interactions)
  - Test fundamental properties of quantum gravity
  - …

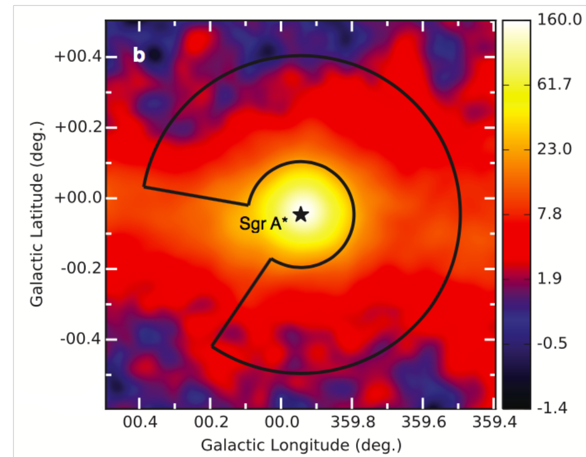
Detection techniques

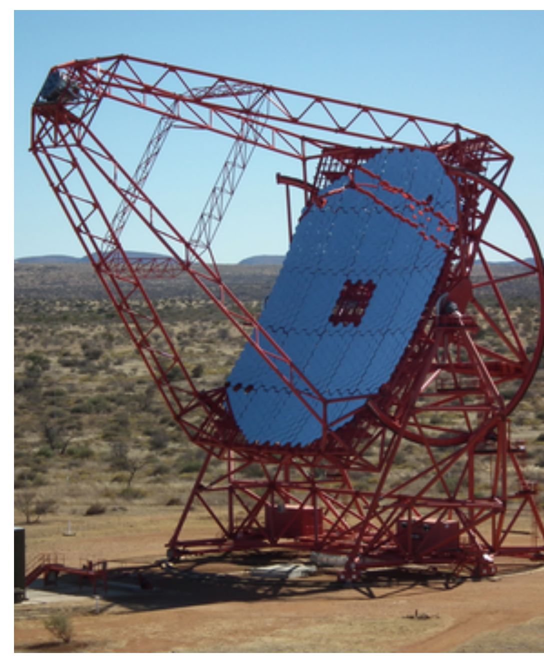


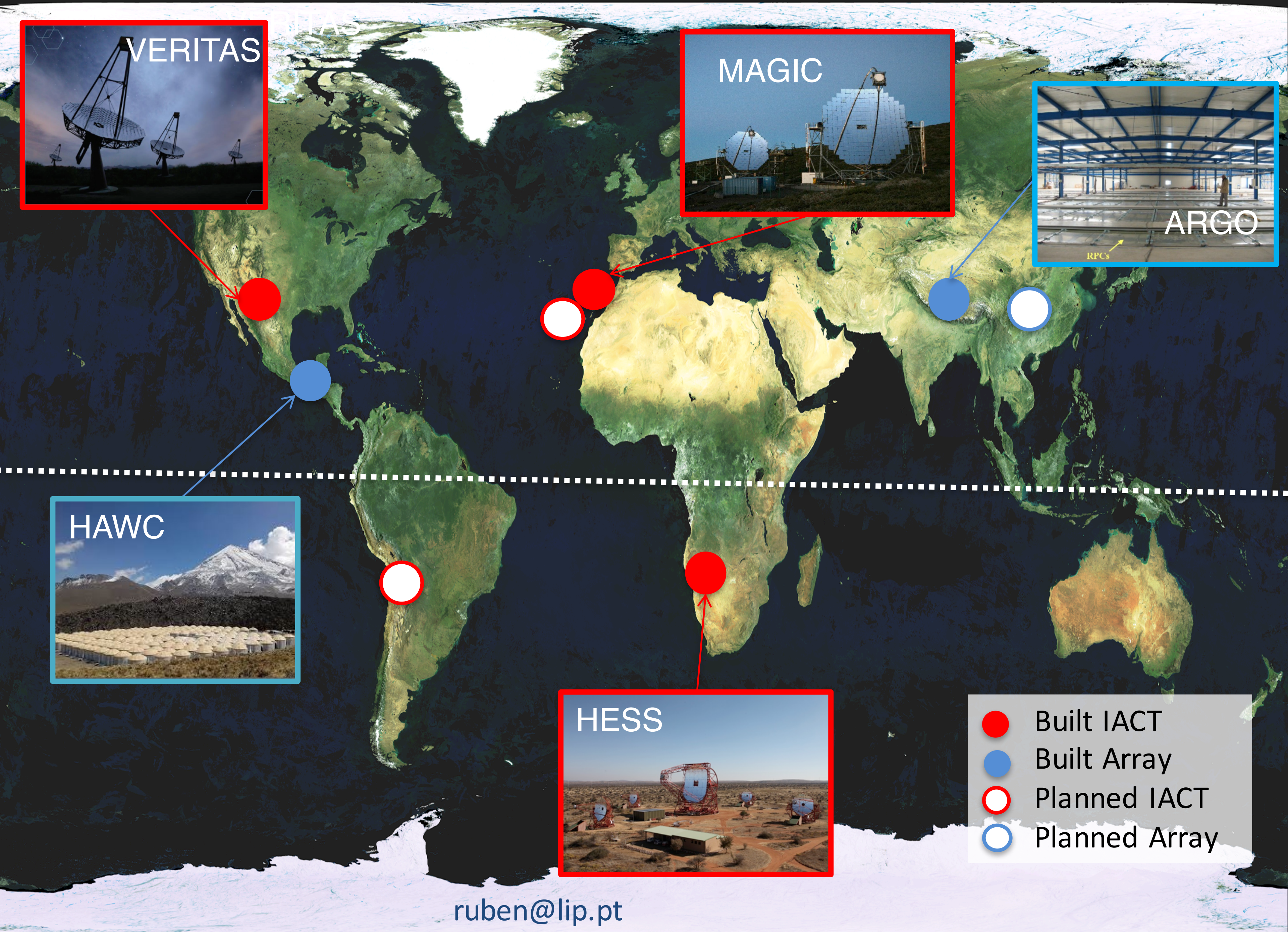
Arrays at high altitude = large field of view + lower energies

What we know so far…

- Protons are known to be accelerated in the galaxy up to PeV energies ($E = 10^{15}$ eV)
- All current acceleration models encounter non-trivial difficulties at these energies
- HESS data suggests that there might be a PeVatron source in the galactic center
- Transient phenomena should help to get a handle dynamics of the acceleration mechanism






VERITAS
MAGIC
ARGO
RPCs
HAWC
HESS
Built IACT
Built Array
Planned IACT
Planned Array
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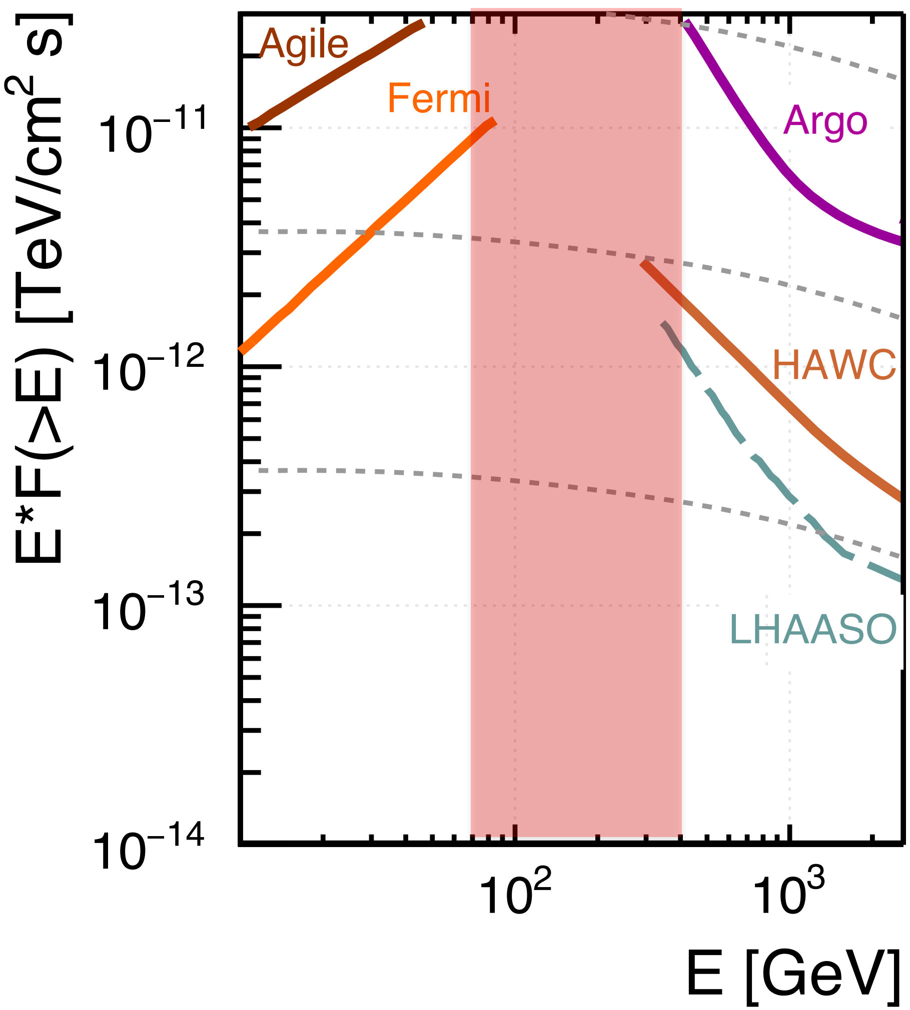
Requirements for the next experiment



- ✧ Should be a wide field-of-view experiment:
  - ✧ EAS array experiment
- ✧ Located in the South Hemisphere
- ✧ Low energy threshold:
  - ✧ High altitude
  - ✧ Next generation detector concept

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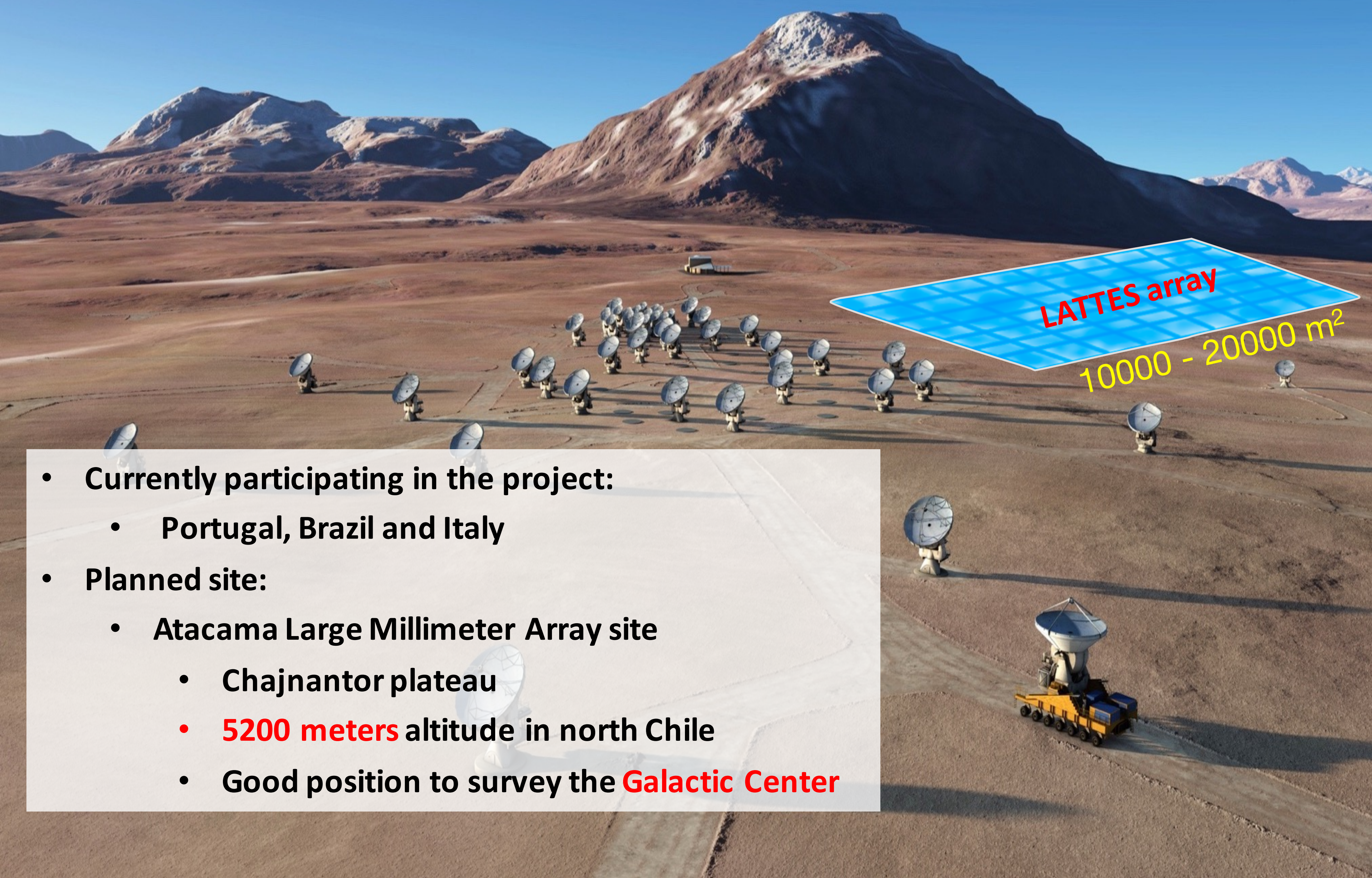
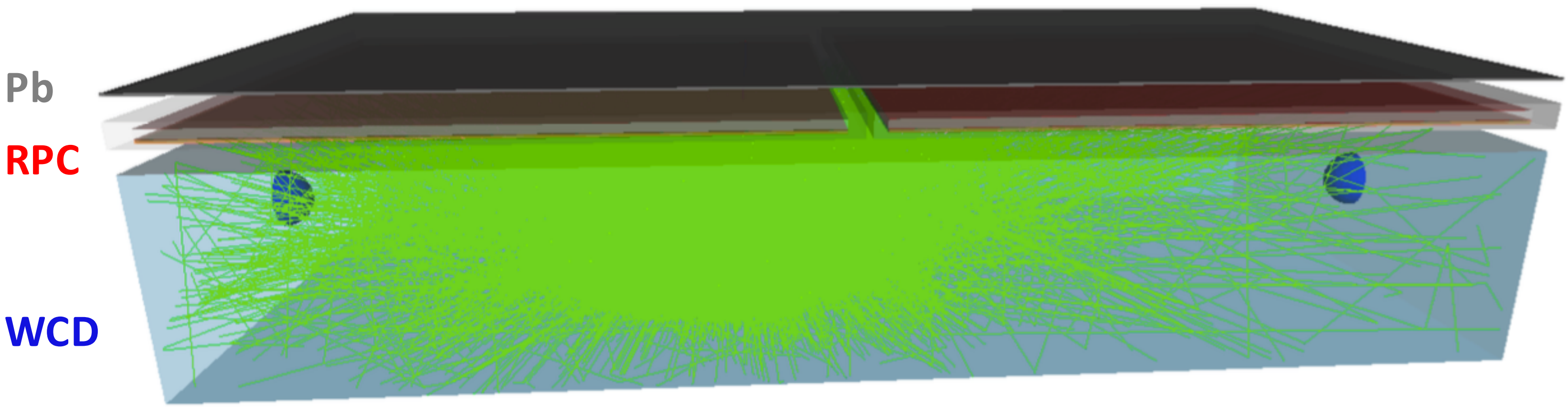
LATTES @ ALMA site

Large Array Telescope for Tracking Energetic Sources



- **Currently participating in the project:**
  - **Portugal, Brazil and Italy**
- **Planned site:**
  - **Atacama Large Millimeter Array site**
    - **Chajnantor plateau**
    - **5200 meters altitude in north Chile**
    - **Good position to survey the Galactic Center**

LATTES station concept



- Next generation detector concept:
  - Lead converter (Pb)
    - Improve shower geometry reconstruction
  - Resistive Plate Chamber (RPC)
    - Measure charged particles with high spatial and time resolution
  - Water Cherenkov Detector
    - Collect photon shower secondary to improve trigger at lower energies

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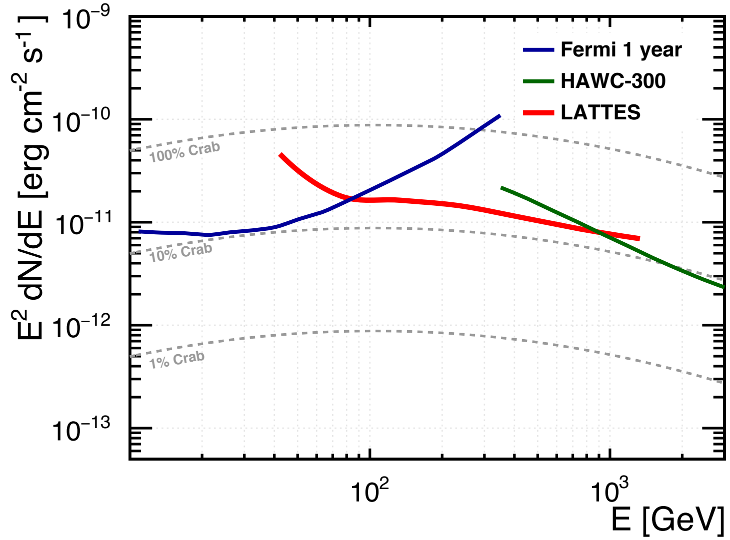
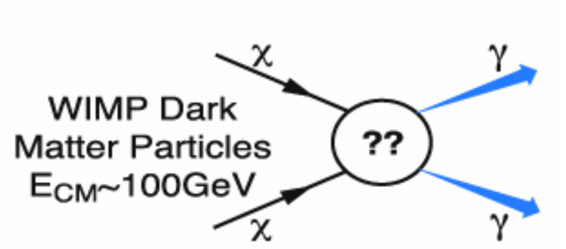
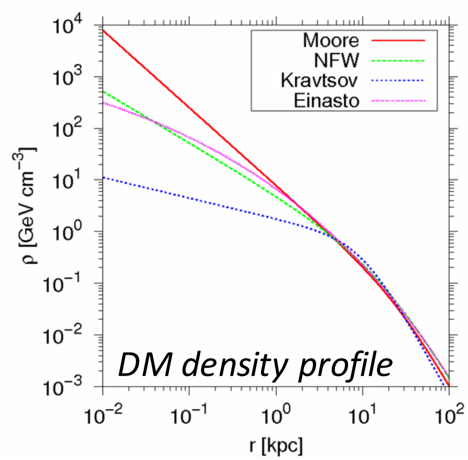
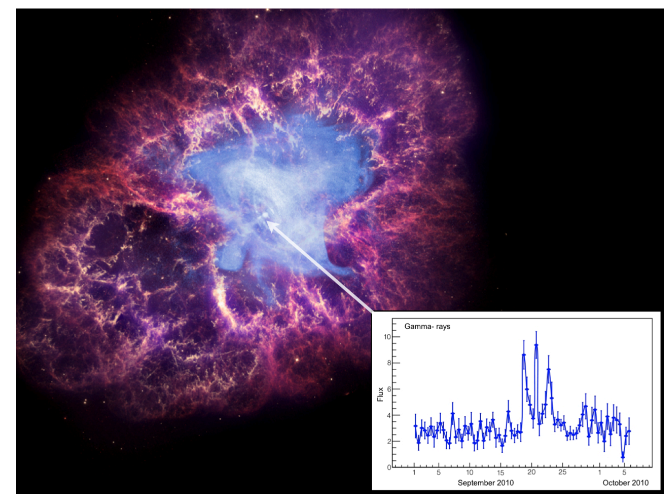
LATTES physics opportunities

- Look for dark matter at the center of the galaxy
- Detect and follow transient phenomena
    - Complementary to the CTA project









Ultra High-Energy Cosmic Rays

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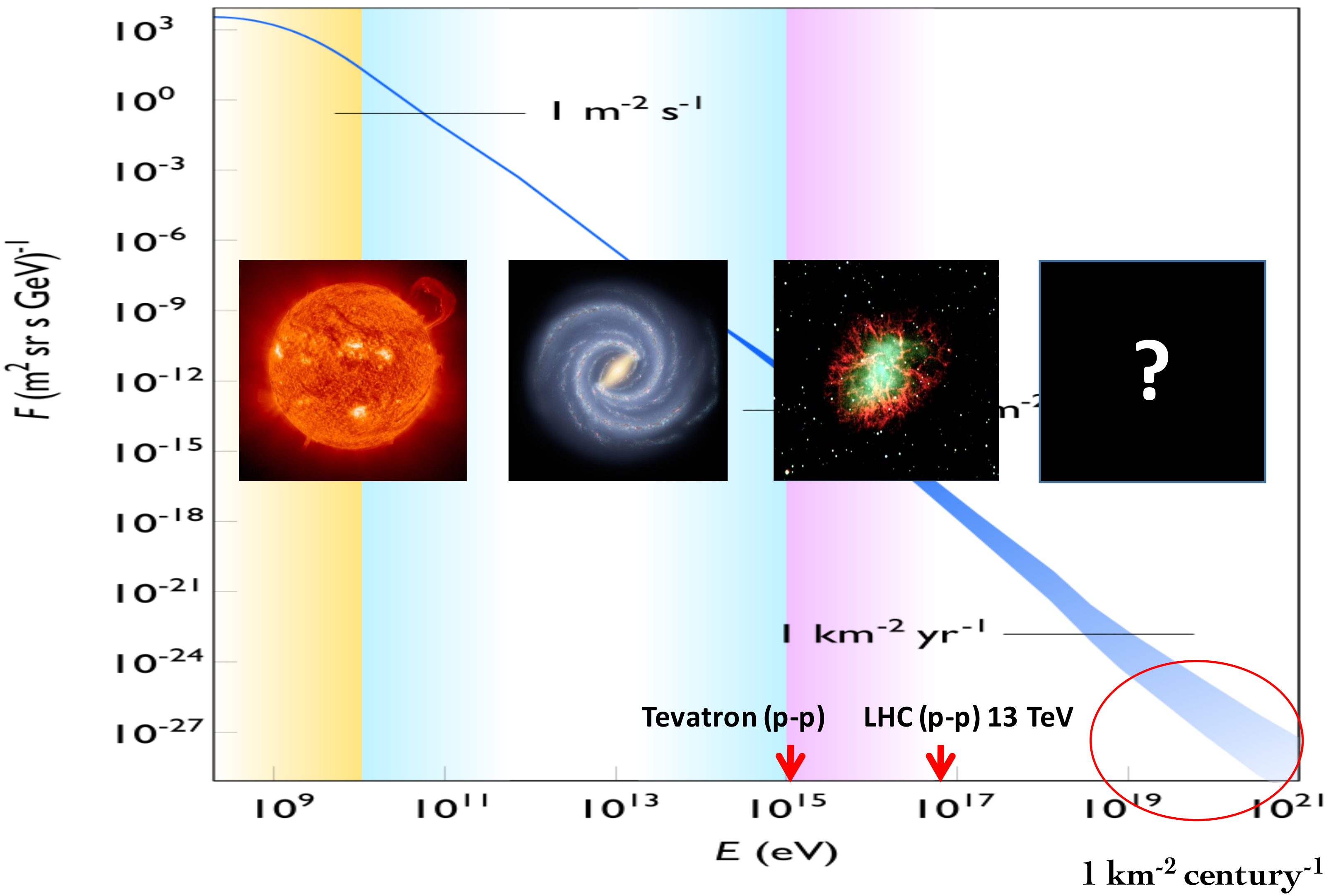
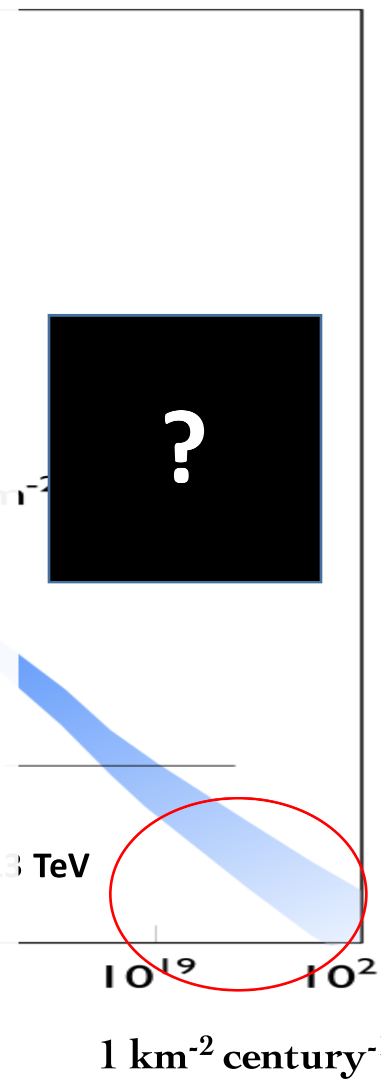
Ultra High Energy Cosmic Rays

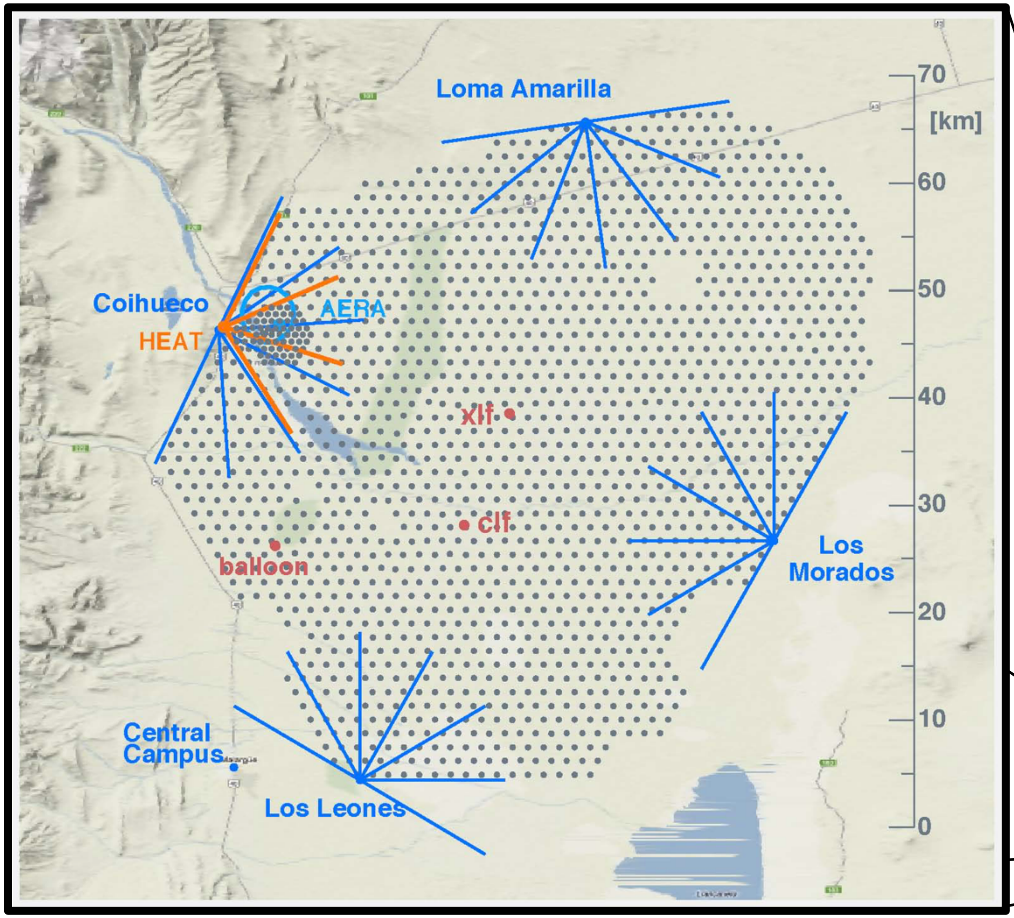


Ultra High Energy Cosmic Rays

- Opportunity to understand high-energy Universe
  - Production (sources; acceleration mechanisms…)
  - Propagation (Magnetic fields…)
- Opportunity to test particle physics at energies above the LHC
  - High-energy interactions
    - $E = 10^{19}$ eV => sqrt(s) ~ 130 TeV
  - Different kinematic regimes
    - E_{beam} up to 10^8 TeV



Pierre Auger Observatory

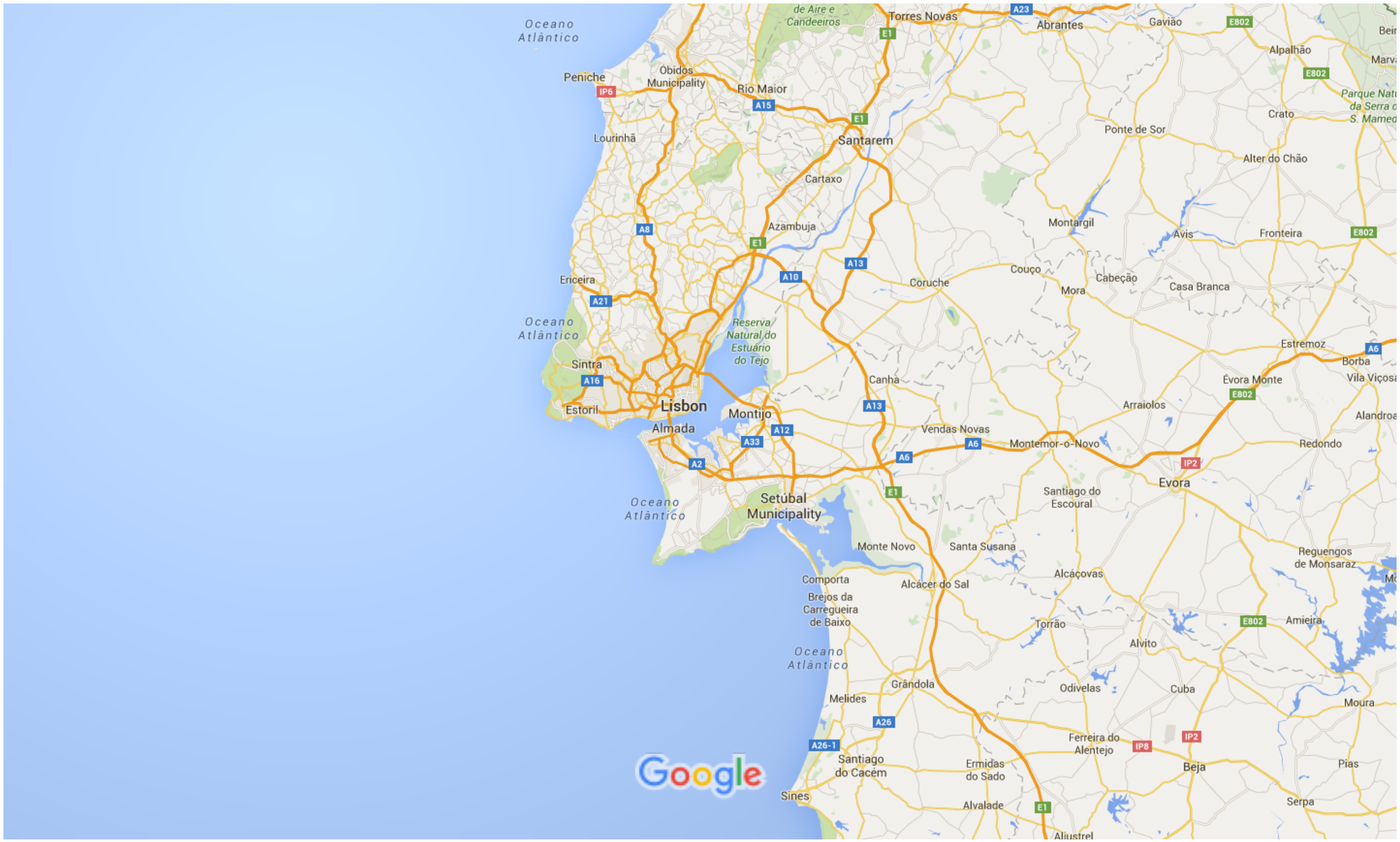


Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

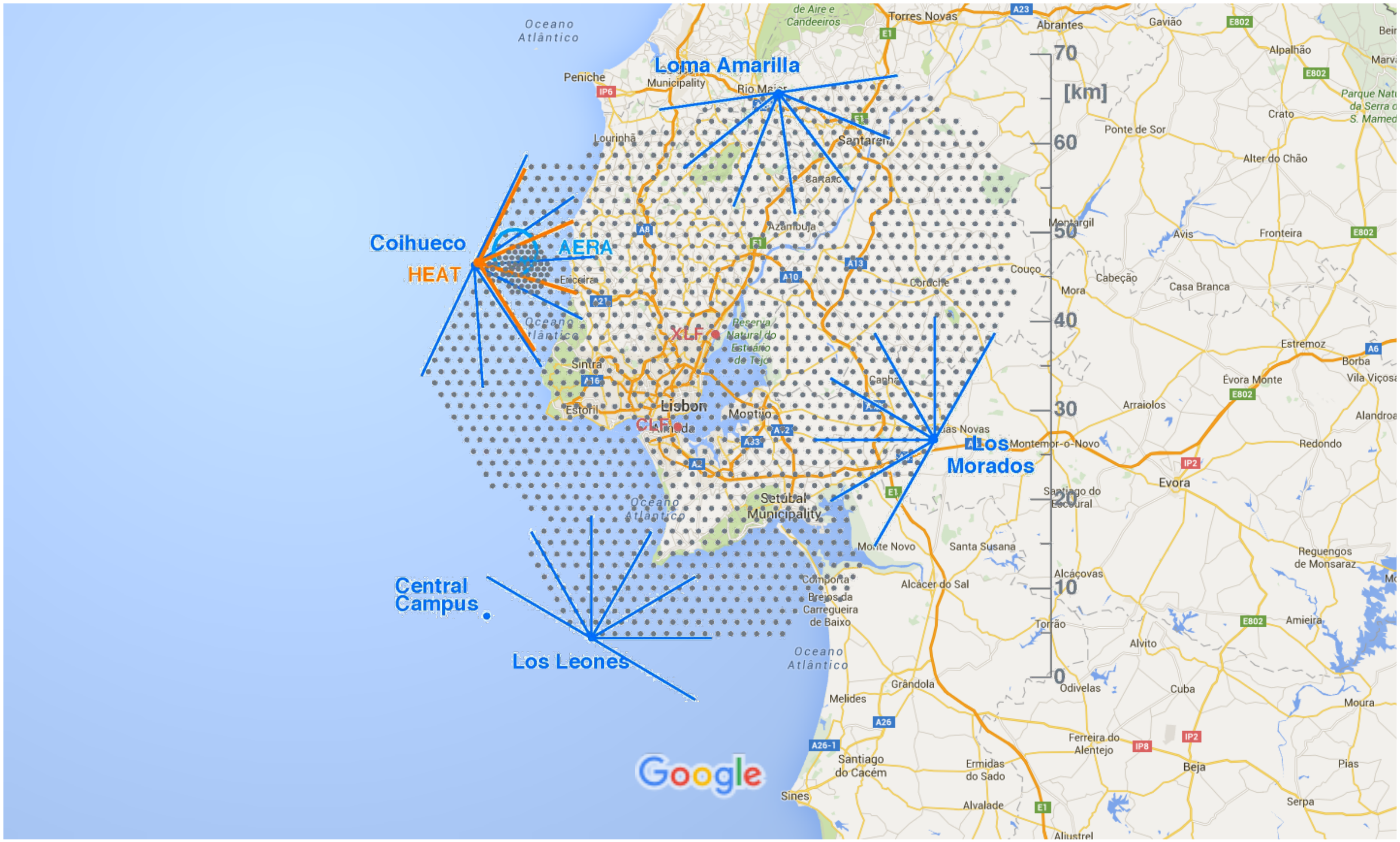
Altitude: 1400 m a.s.l.

How big is it?



Map data ©2016 Google, Inst. Geogr. Nacional 20 km

Really big!!



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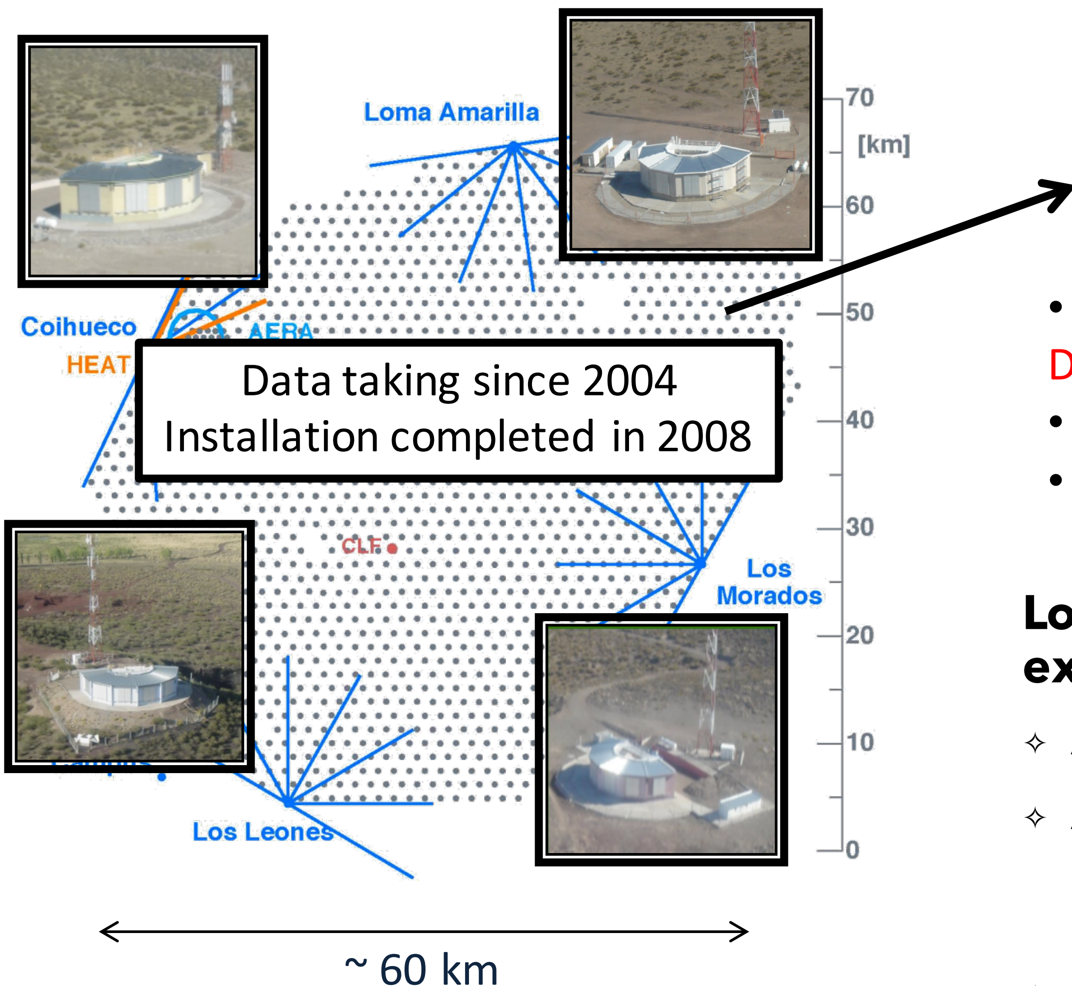
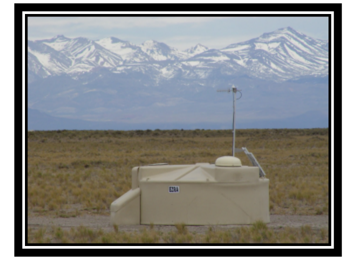




- ~ 1600 Surface Detector (SD) Stations
- 1.5 km spacing
- 3000 km²

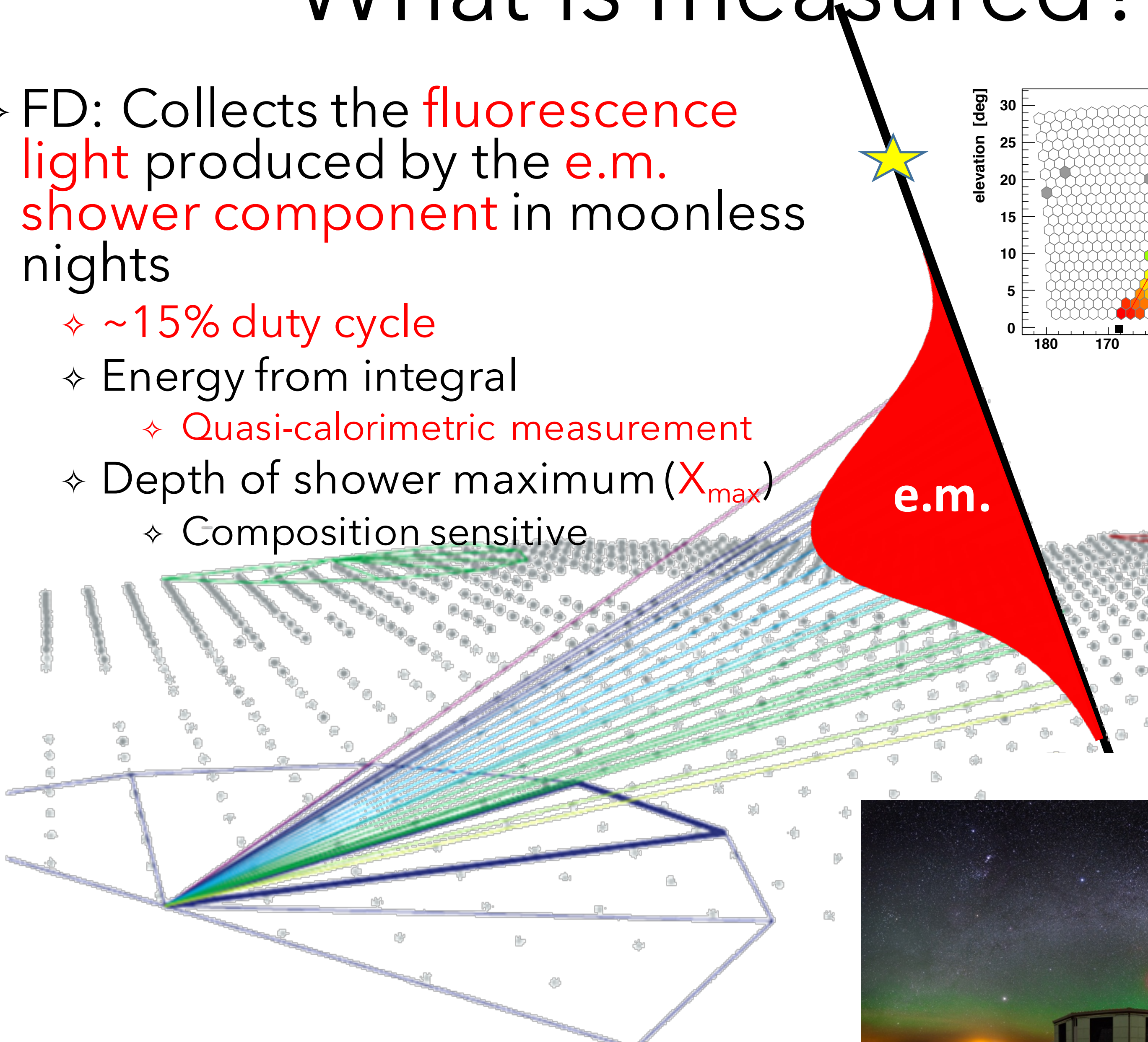
Low energy extension

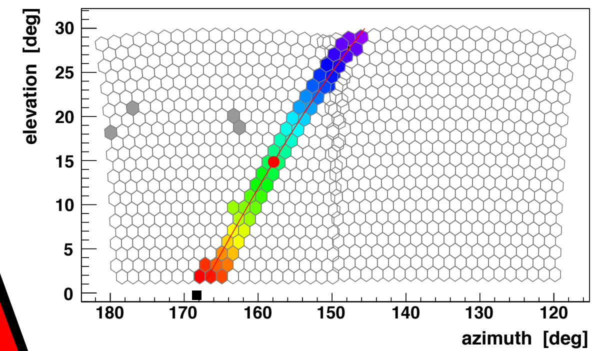
- ✧ Aim to E ≈ 10^{17} eV
- ✧ AMIGA
  - ✧ Denser array plus muon detectors
- ✧ HEAT
  - ✧ 3 additional FD telescopes with a high elevation FoV

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

What is measured?

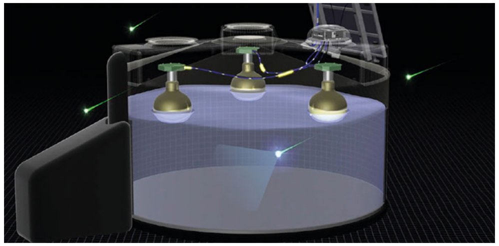
- FD: Collects the fluorescence light produced by the e.m. shower component in moonless nights
  - ~15% duty cycle
  - Energy from integral
    - Quasi-calorimetric measurement
  - Depth of shower maximum (X_{max})
    - Composition sensitive

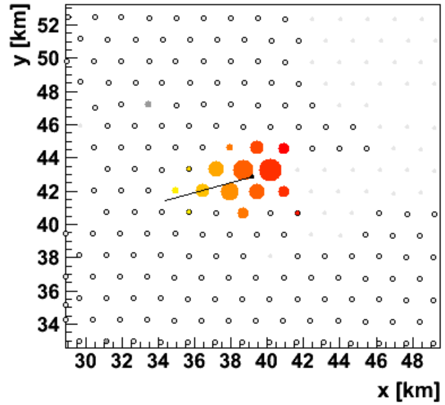


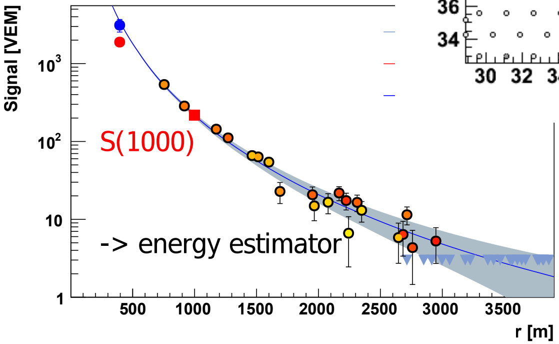


What is measured?

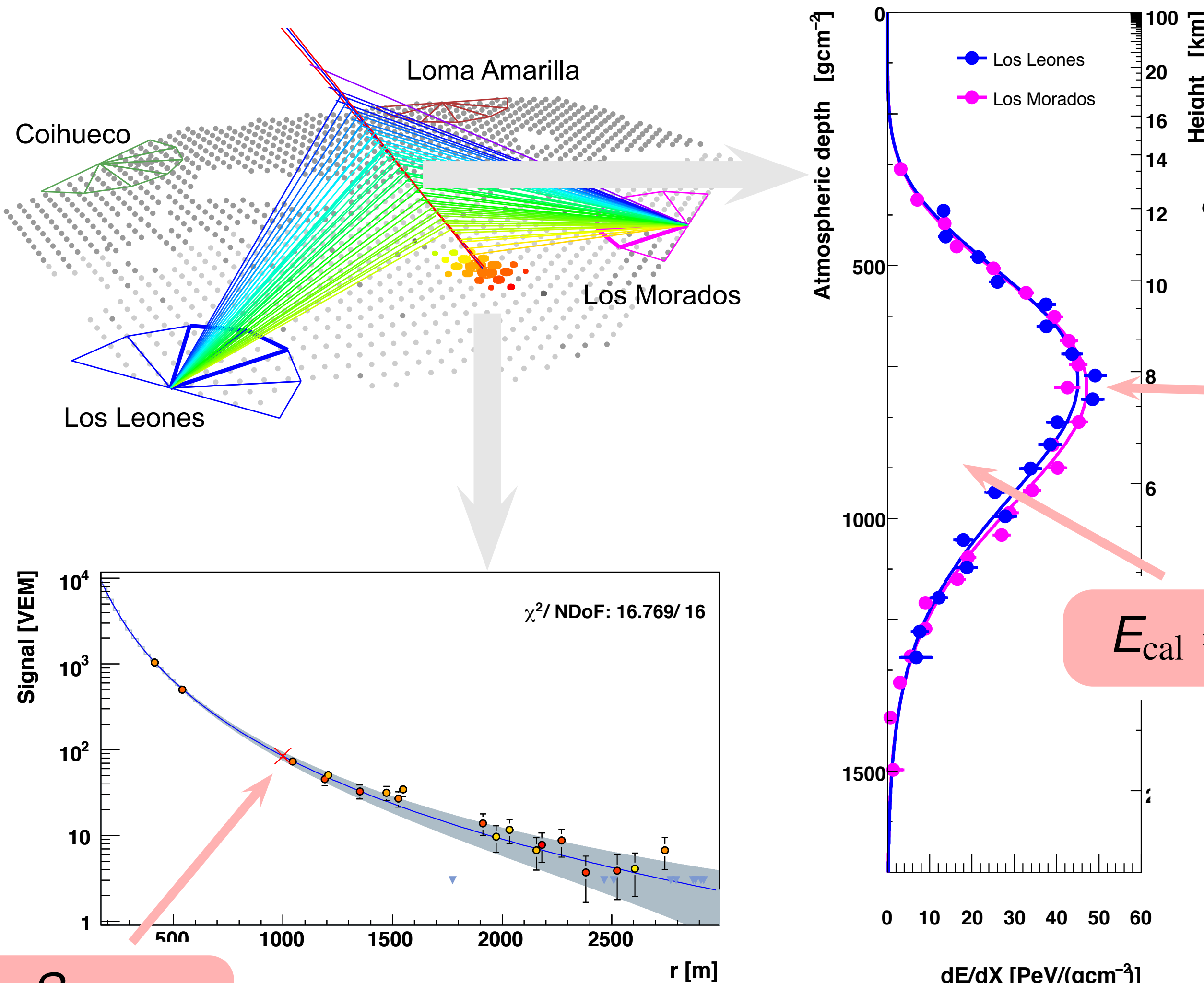
- SD: Sample the charged secondary particles that arrive at ground
  - 100% duty cycle
  - Shower direction: from arrival time
  - Energy estimator: signal at 1000 m from the core







Hybrid Technique



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

$X_{\rm max}$

$E_{\rm cal} = \int \frac{dE}{dX}\, dX$

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

S_{1000}

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

What have we learn so far…

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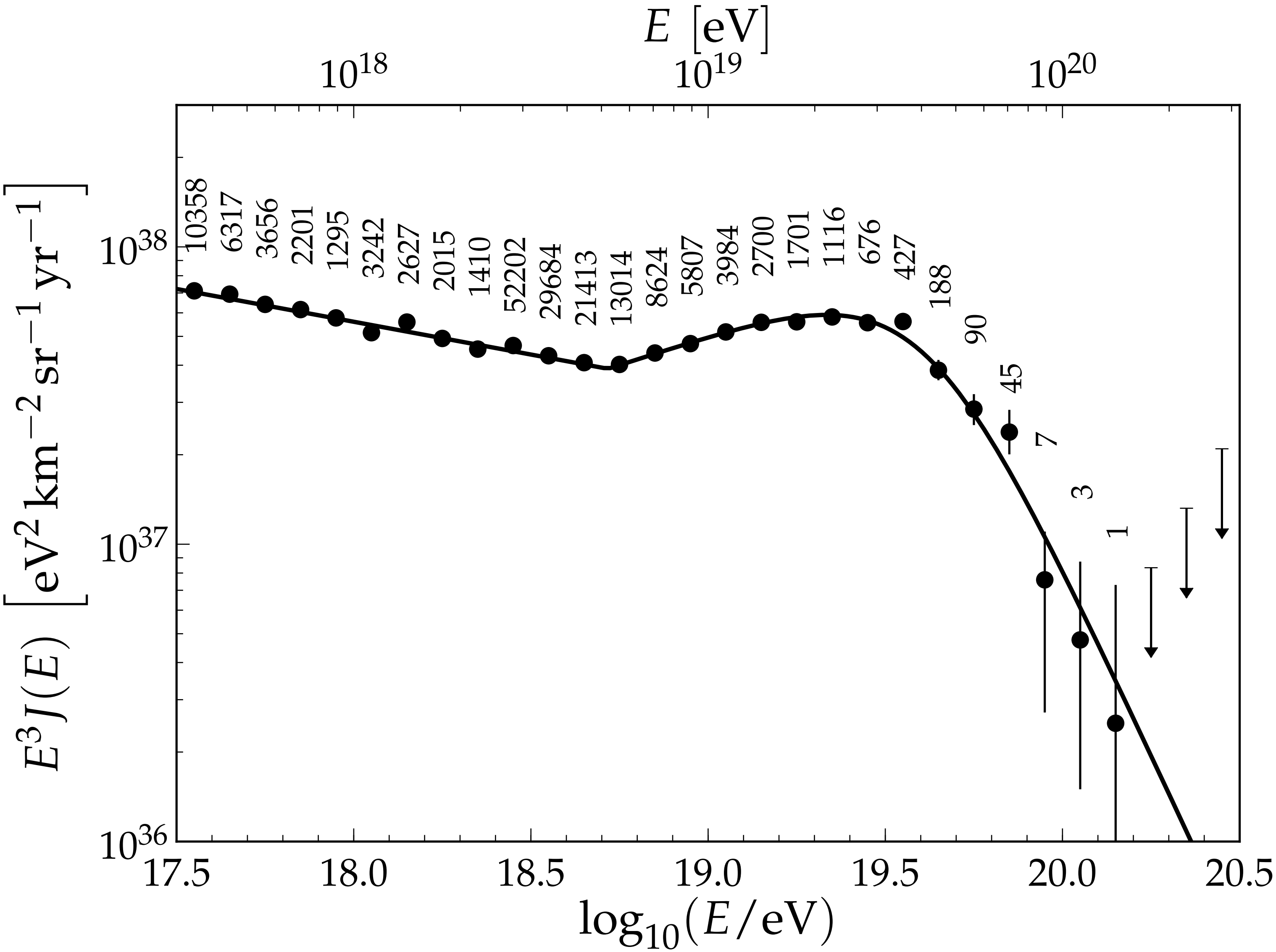
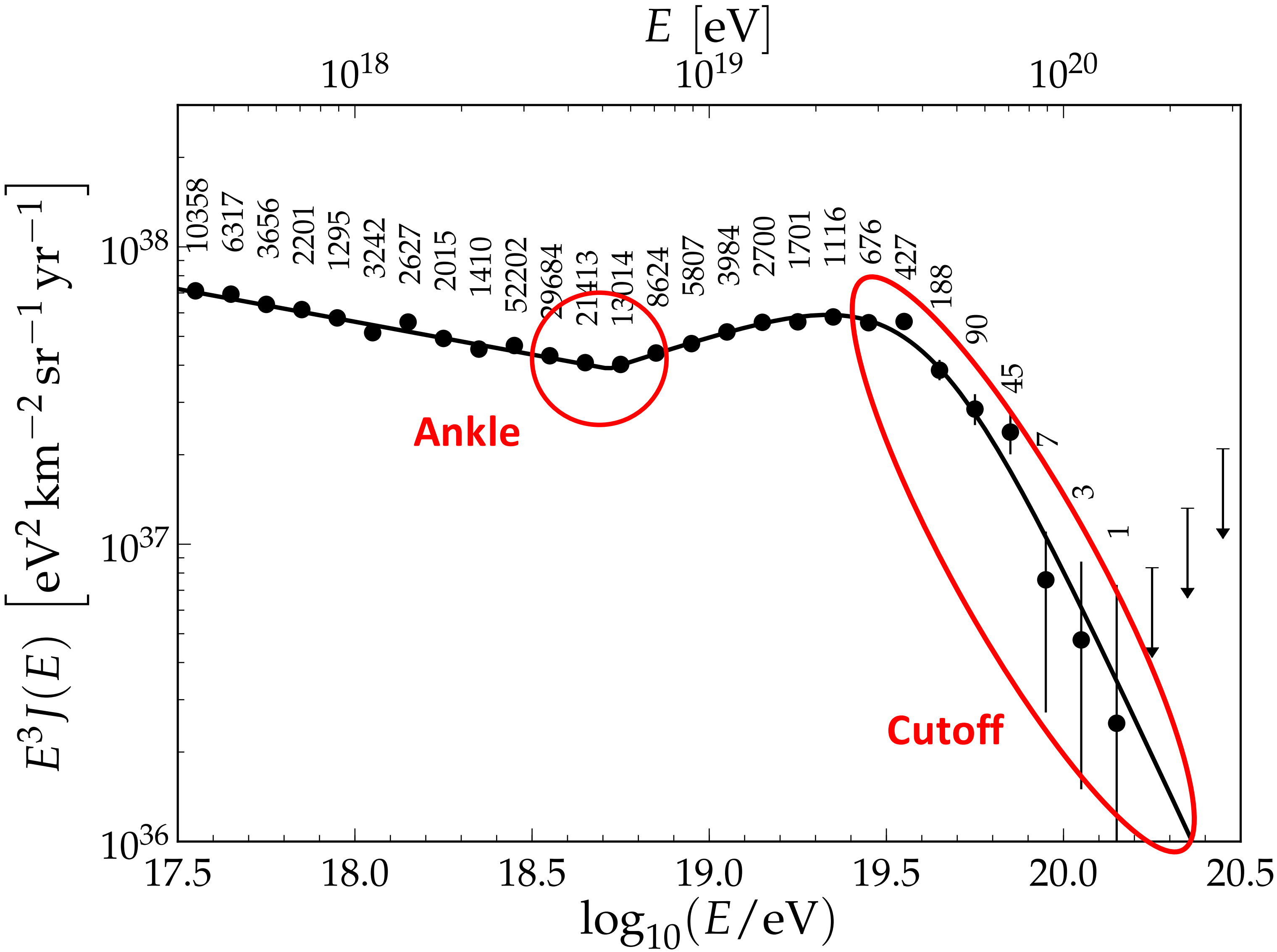
- UHECRs are accelerated somewhere in our Universe
  - From the photon and neutrino limits

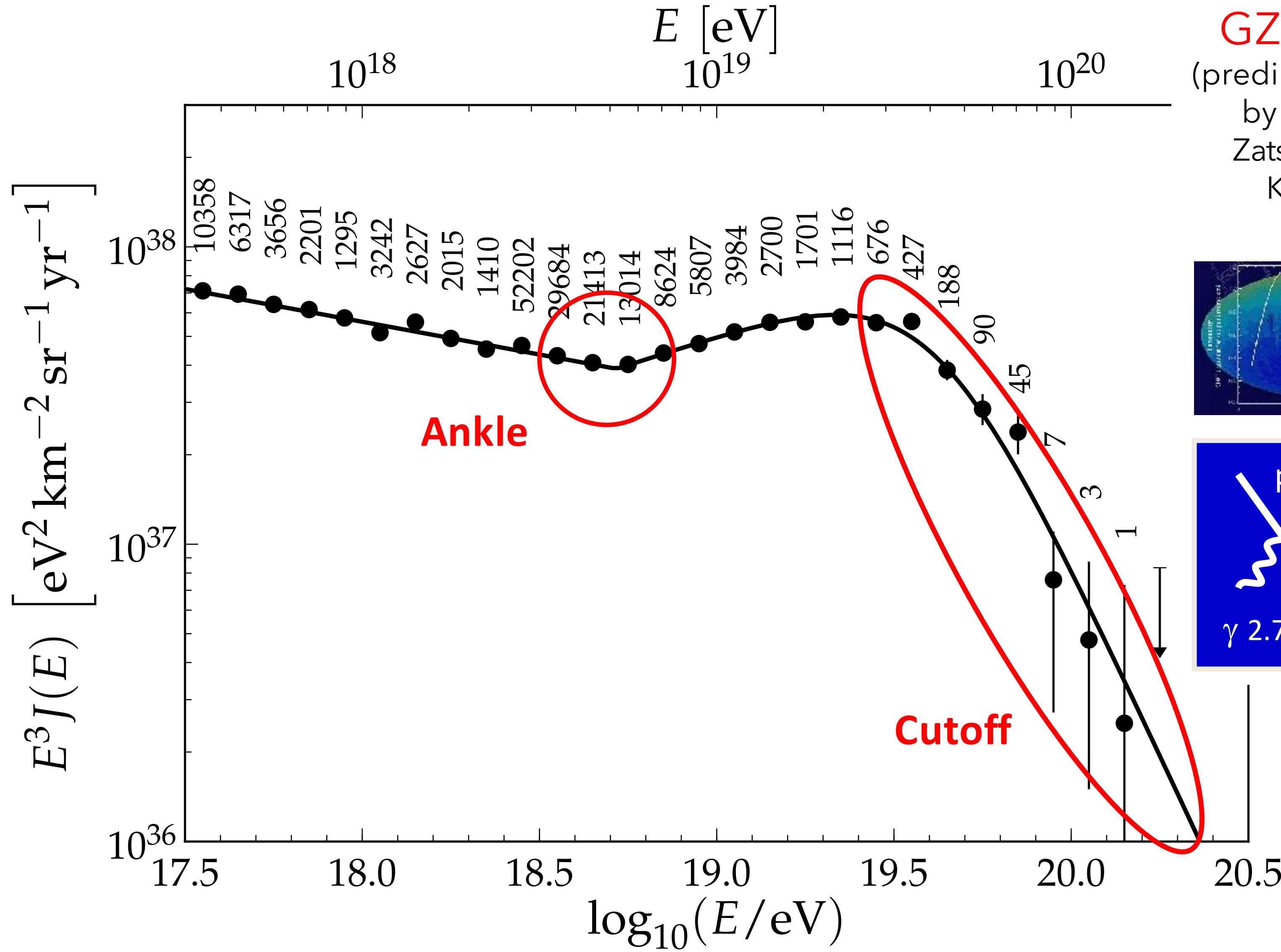
UHECRs energy spectrum



UHECRs energy spectrum

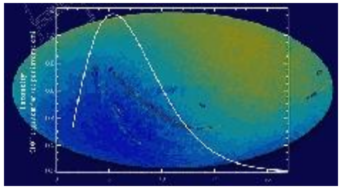


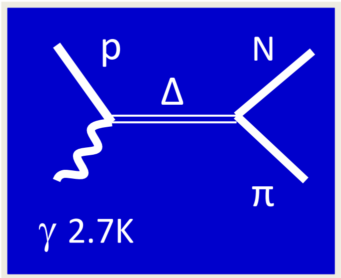
UHECRs energy spectrum



GZK effect

(predicted in 1966 by Greisen, Zatsepin and Kuzmin)





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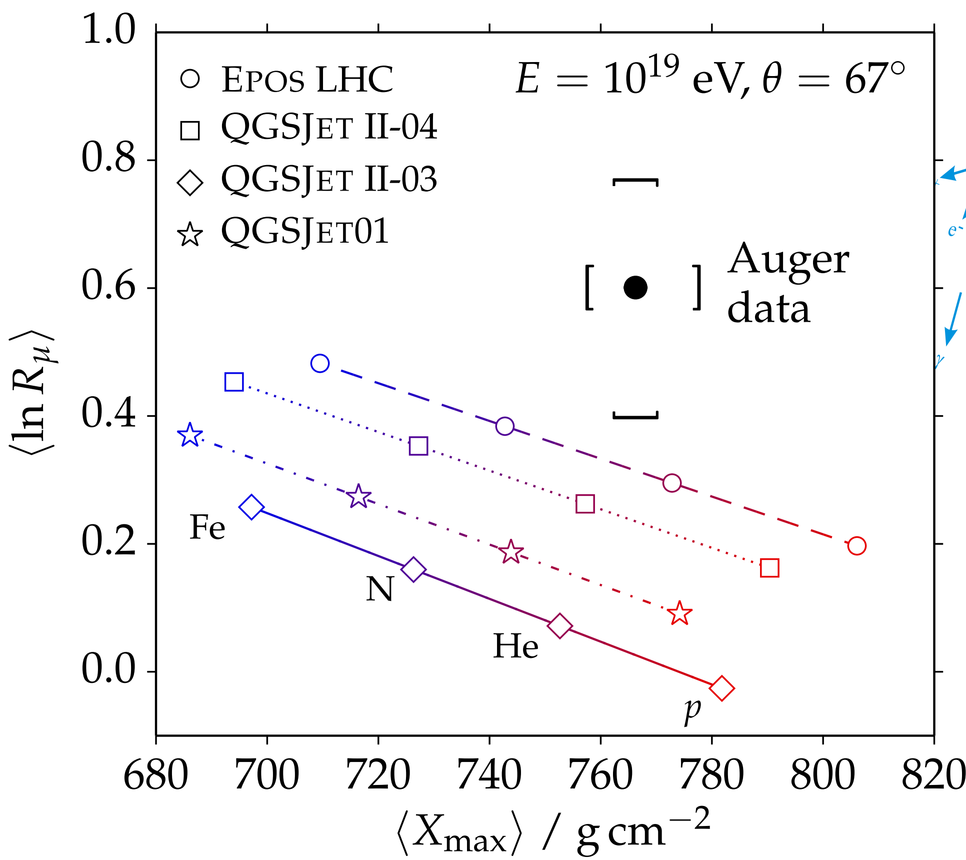
What have we learn so far…

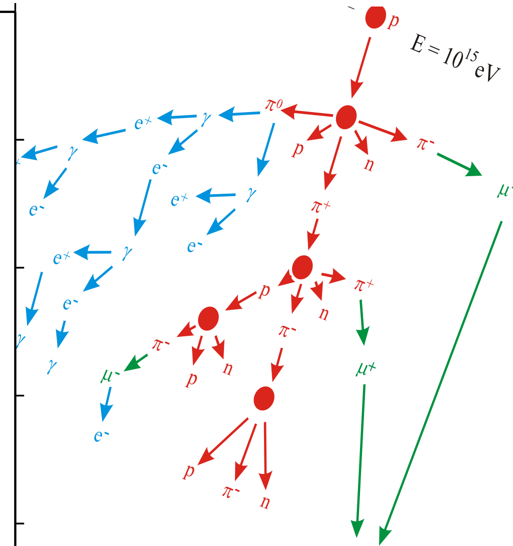
- UHECRs are accelerated somewhere in our Universe
  - From the photon and neutrino limits
- There is a suppression of the cosmic ray energy spectrum at the highest energies
  - Compatible with the predicted GZK cutoff
  - However, could be source energy exhaustion
  - *Nature of UHECRs essential to distinguish*

Testing hadronic interactions

Surface Detector



Fluorescence Detector



Combination of the number of muons R_{μ} with X_{max} reveals tension between data and all hadronic interaction models

What have we learn so far…

- UHECRs are accelerated somewhere in our Universe
  - From the photon and neutrino limits
- There is a suppression of the cosmic ray energy spectrum at the highest energies
  - Compatible with the predicted GZK cutoff
  - However, could be source energy exhaustion
  - Nature of UHECRs essential to distinguish
- Inconsistencies in the shower description
  - New physics at the highest energies?

The future of UHECRs…

- Gain better understanding over the shower physical mechanisms
  - Use LHC data to better tune the hadronic interaction models at low energy

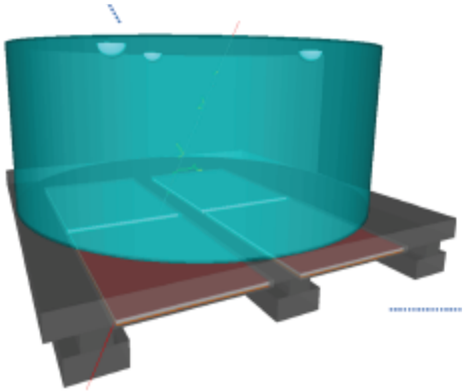
The future of UHECRs…

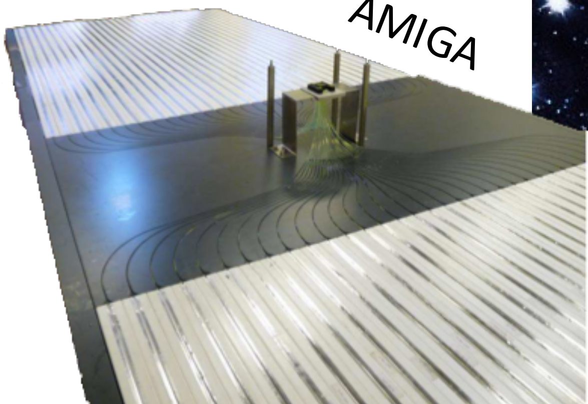
- Gain better understanding over the shower physical mechanisms
  - Use LHC data to better tune the hadronic interaction models at low energy
  - Auger upgrade
    - Auger PRIME (operates until 2025)
    - Put a scintillator on top of the SD
    - Complementary information to separate the muon from the e.m. shower component

Auger PRIME SSD

The future of UHECRs…

- Gain better understanding over the shower physical mechanisms
  - Use LHC data to better tune the hadronic interaction models at low energy
  - Auger upgrade
    - Auger PRIME (operates until 2025)
    - Put a scintillator on top of the SD
    - Complementary information to separate the muon from the e.m. shower component
  - Several R&D projects
    - EAS radio detection
    - MARTA engineering array
      - RPCs below the tank
    - AMIGA
      - Scintillators below the ground





Summary

- Astroparticle physics (Multi-Messengers)
  - Use astrophysical messengers and known particle physics to gain a deeper understanding of the dynamics of our Universe
  - Rapidly evolving field
  - Lots of ambitious projects
  - Will soon provide important tests to our knowledge over fundamental physics

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Acknowledgements

FCT
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COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

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PORTUGAL 2007.2013

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

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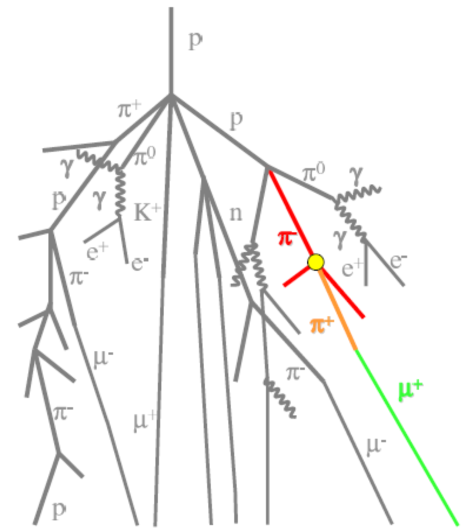
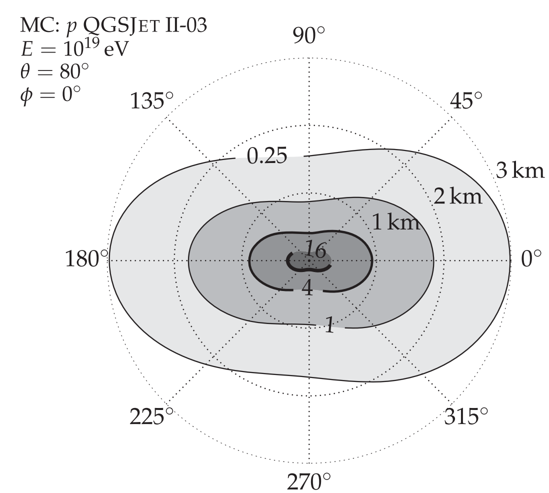
Backup slides

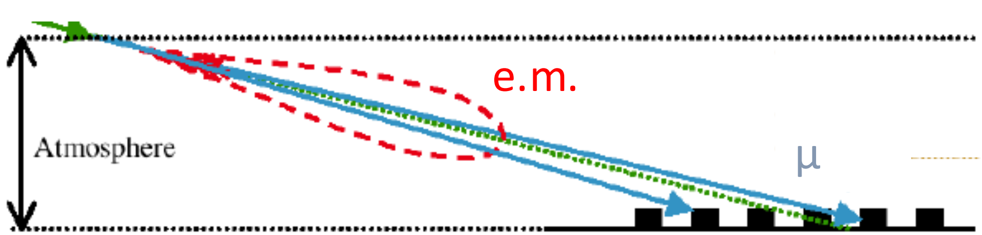
Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component



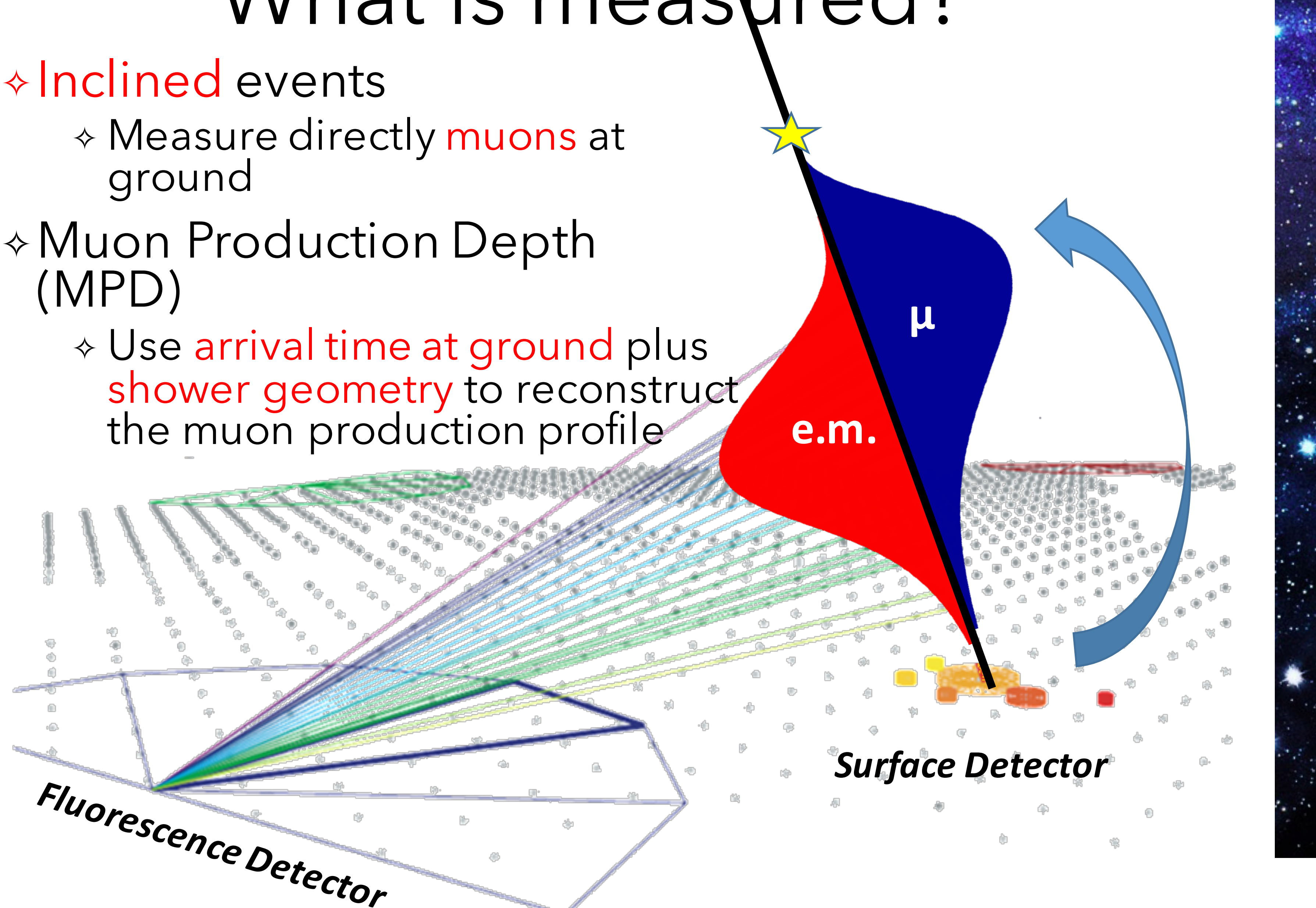
- Through inclined showers is possible to measure directly the muon content (R_μ) in the SD
  - Electromagnetic shower component gets attenuated





What is measured?

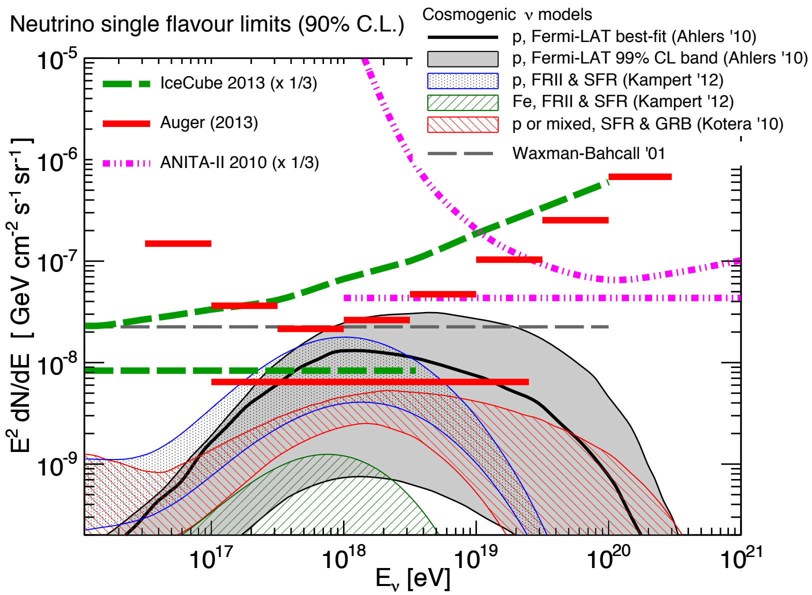
- ✧ Inclined events
  - ✧ Measure directly muons at ground
- ✧ Muon Production Depth (MPD)
  - ✧ Use arrival time at ground plus shower geometry to reconstruct the muon production profile



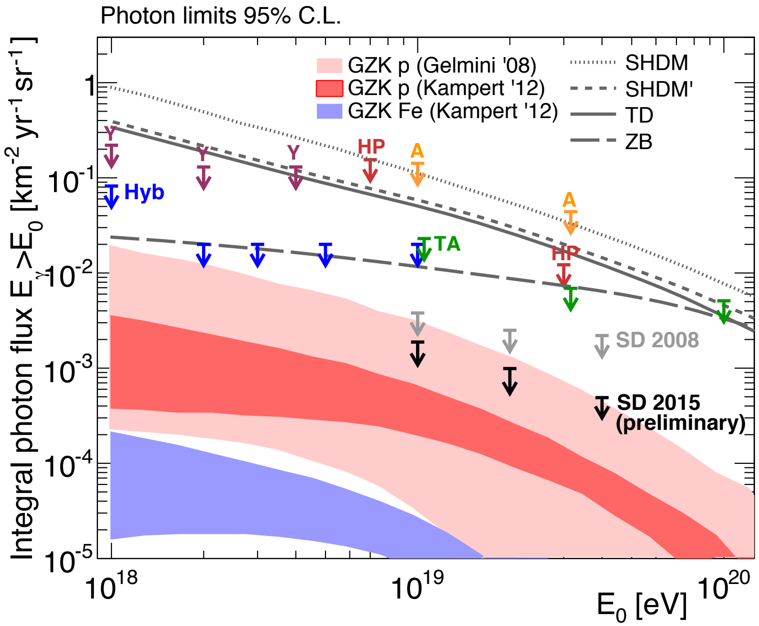
Neutrino and photon limits

C. Bleve for the Pierre Auger Coll., Proc 34th ICRC (2015)

Neutrino limits

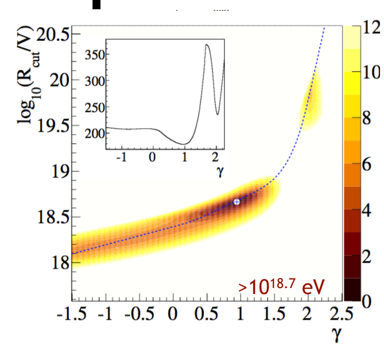


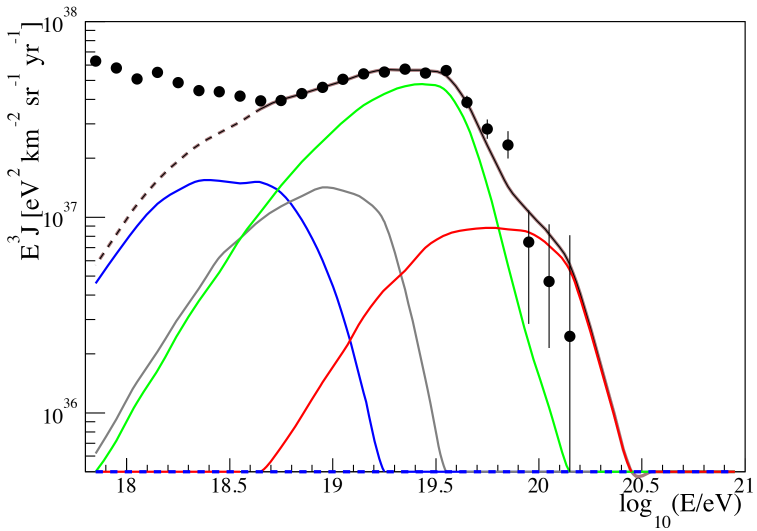
Photon limits

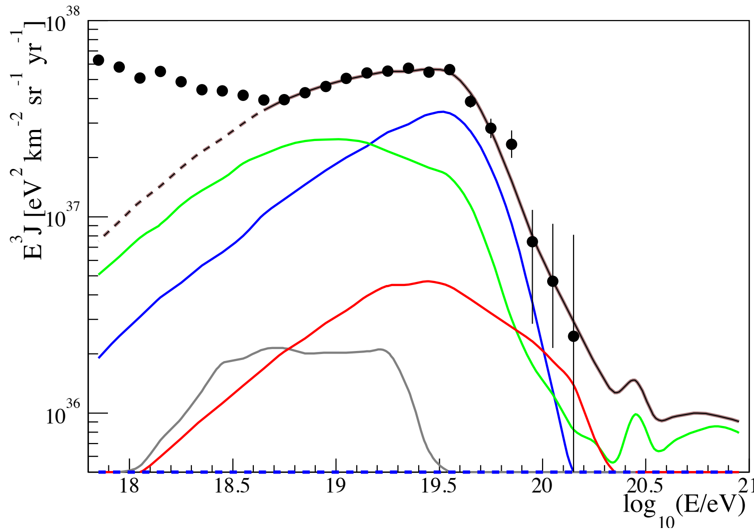


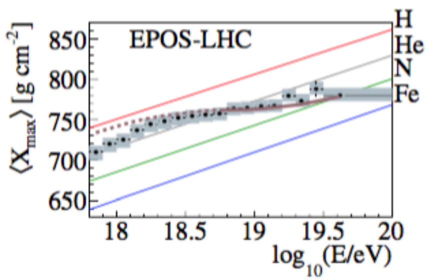
Combined spectrum + comp fits

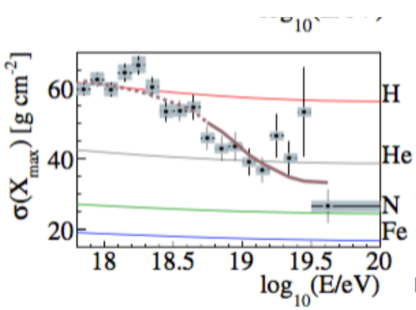
Protons (blue)
Helium (gray)
Nitrogen (green)
Iron (red)

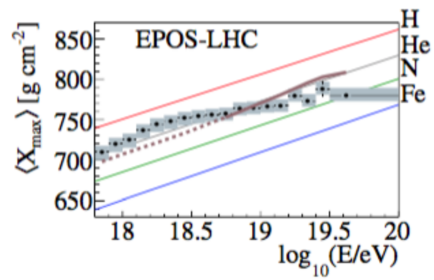


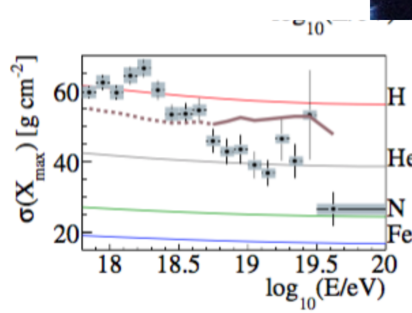












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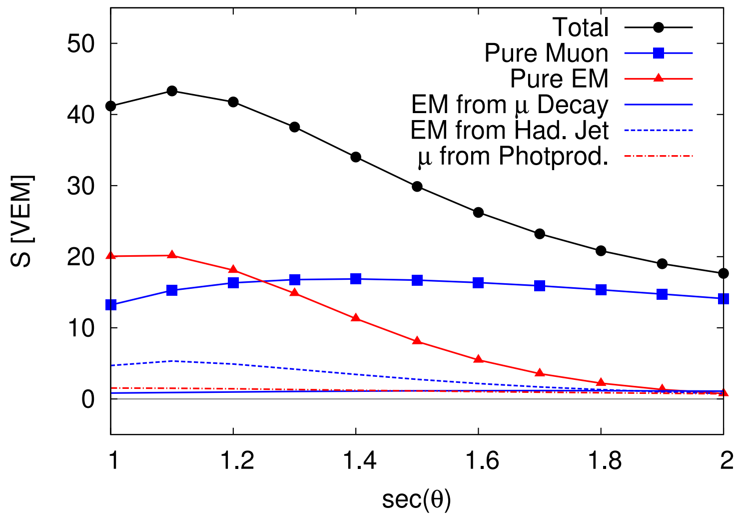
Explore hybrid events

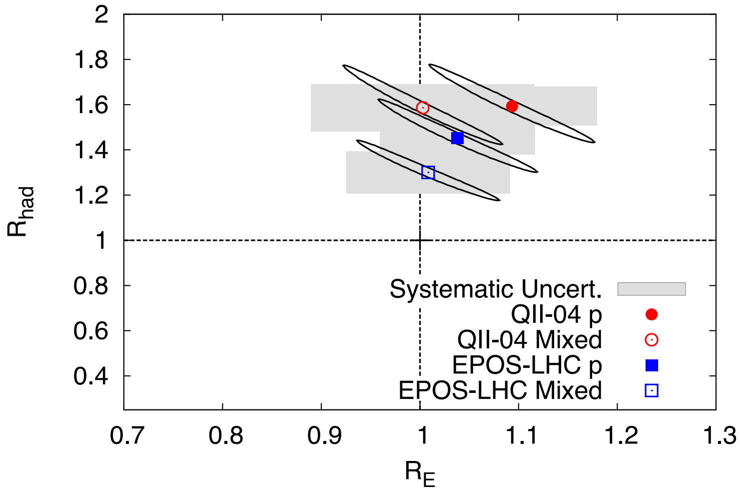
- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had})

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

- Findings:
  - No need for an energy rescaling
  - Hadronic signal in data is significantly larger with respect to simulations

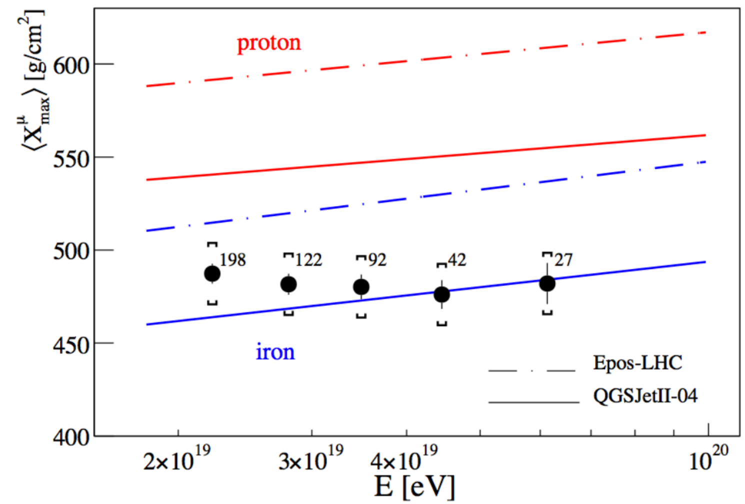
Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

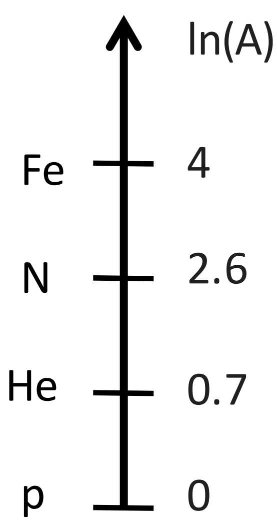


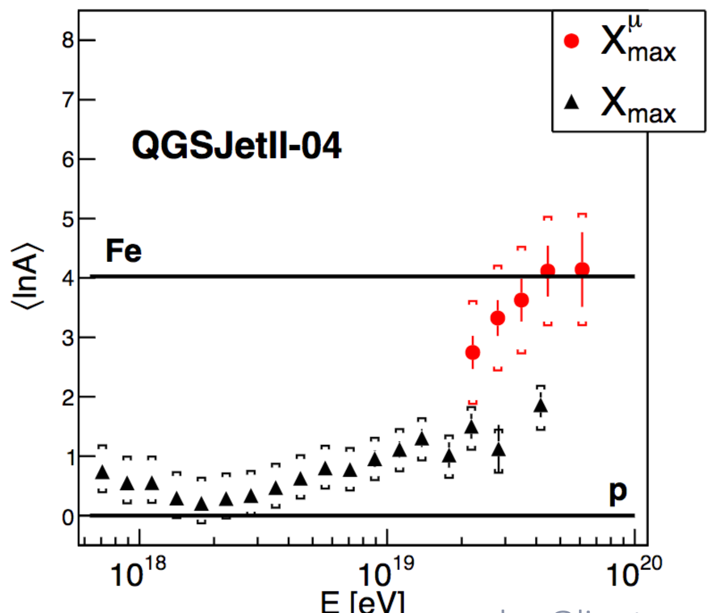


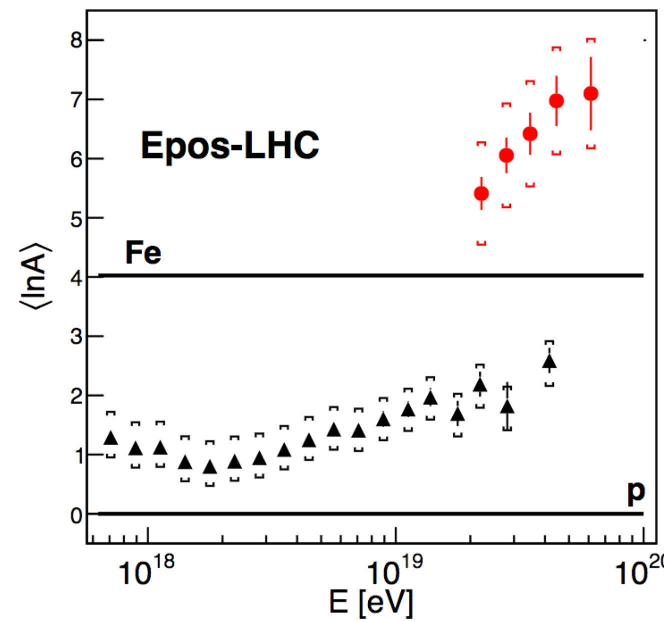
Muon Production Depth

- Muon Production Depth
  - Sensitive to composition
- Mean X_{max} and X^{μ}_{max} should give the same average mass composition
  - EPOS-LHC fails to provide a consistent solution

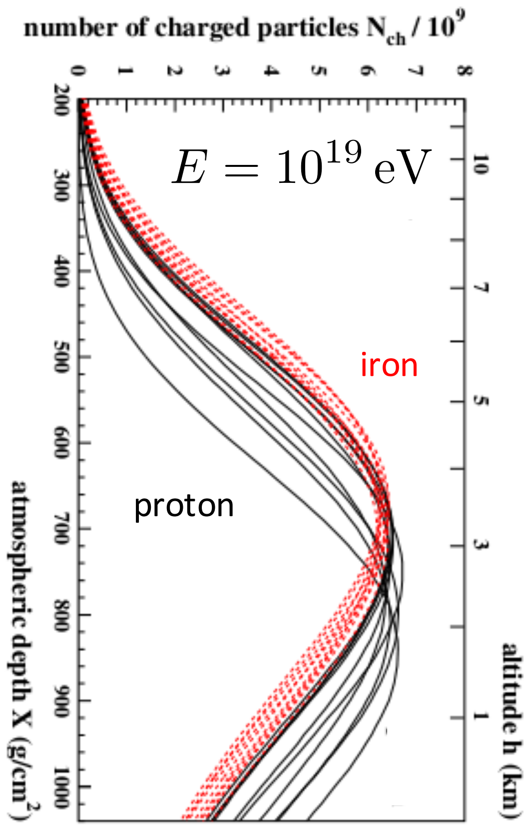


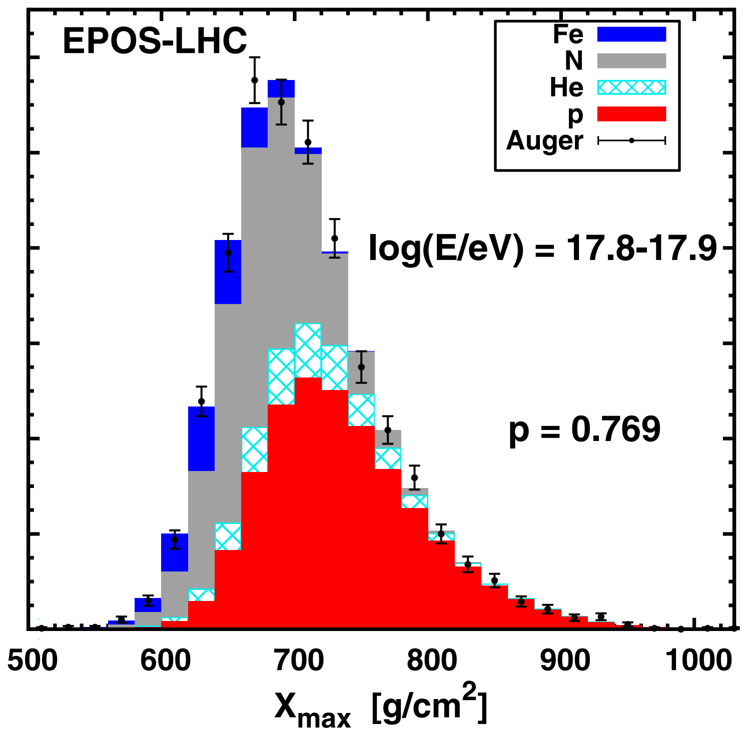






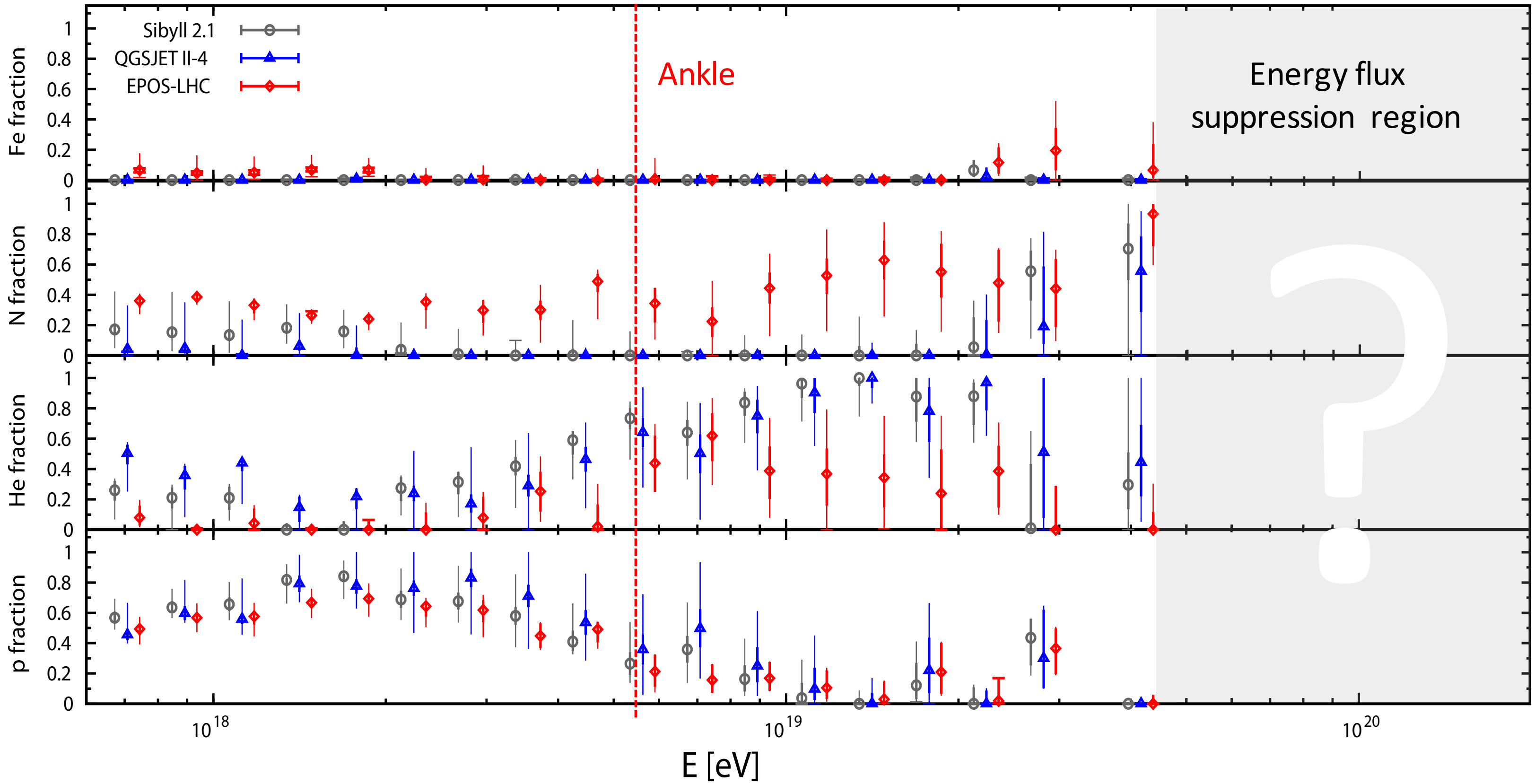
Mass composition interpretation





- Interpretation of the X_{max} distribution in terms of mass composition
  - Proton showers have deeper X_{max} than iron induced showers
  - X_{max} fluctuates more for proton induced showers

Mass composition interpretation



- Interpretation of the X_{max} distribution in terms of mass composition
  - Depends on the performance of hadronic interaction models
    - Mostly proton at low energies
    - Intermediate mass states at the highest available energies
    - Nearly no iron

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