

Physics at the highest energies

The Pierre Auger Observatory

L. Cazon

Ultra High Energy Cosmic Rays

A multidisciplinary field

Cosmology & Astrophysics

- Acceleration Scenarios
 - AGN, GRB,...
- Decay Scenarios
 - Super Heavy Dark Matter
 - Cosmic Strings
 - Relic Particles
- Propagation:
 - Galactic & Extragalactic magnetic fields
 - Source evolution
- Astrophysical Gamma Ray Sources
- GZK neutrinos
- Lorentz Violation

Particle Physics

- High Energy Hadronic Interaction Models
- LHC-complementarity measurements
- New phenomena
 - high density QCD
- Exotic particles
 - Magnetic Monopoles
 - Mini-Black Holes
 - R-Hadrons

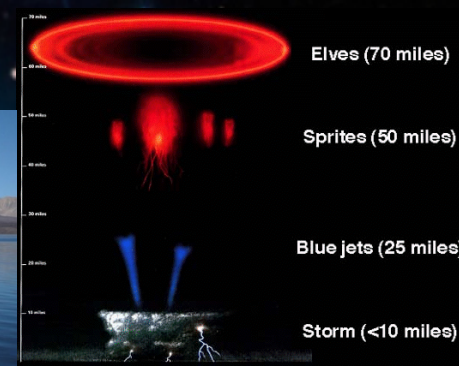
A multidisciplinary field

Shower Phenomenology

- Balance and evolution of the cascades
- EM radiation:
 - MHz (Geosyncrotron, Cerenkov)
 - GHz (Molecular Bremsstrahlung)
 - UV-light (Air Fluorescence, Cerenkov)
- Plasma formation
 - Radar detection, Molecular Bremstrahlung)

Earth Sciences

- Atmosphere
- Lightning
- Space weather
- Seismology
 - 1600 GPS stations tracking a large active area!



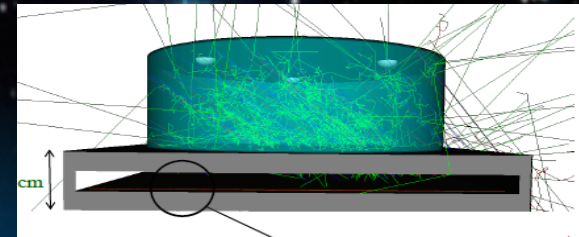
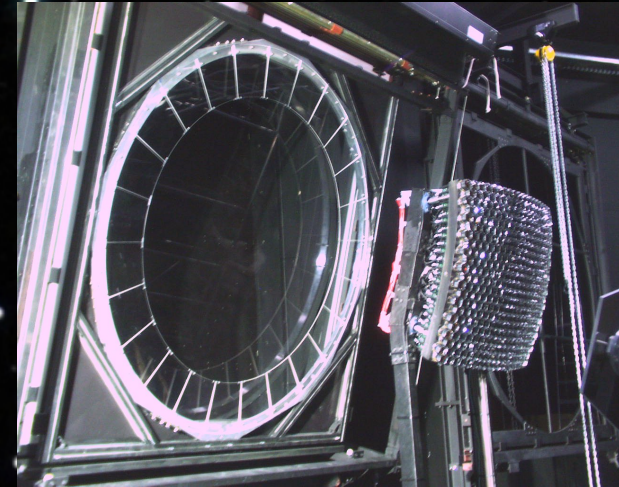
A multidisciplinary field

Data Science

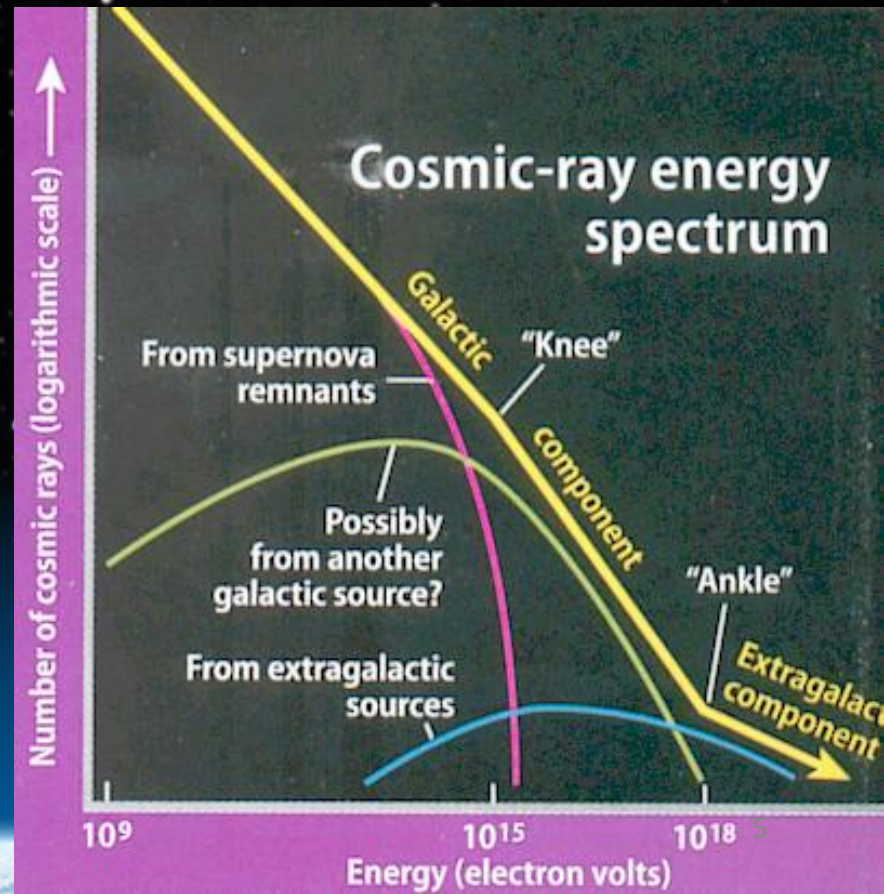
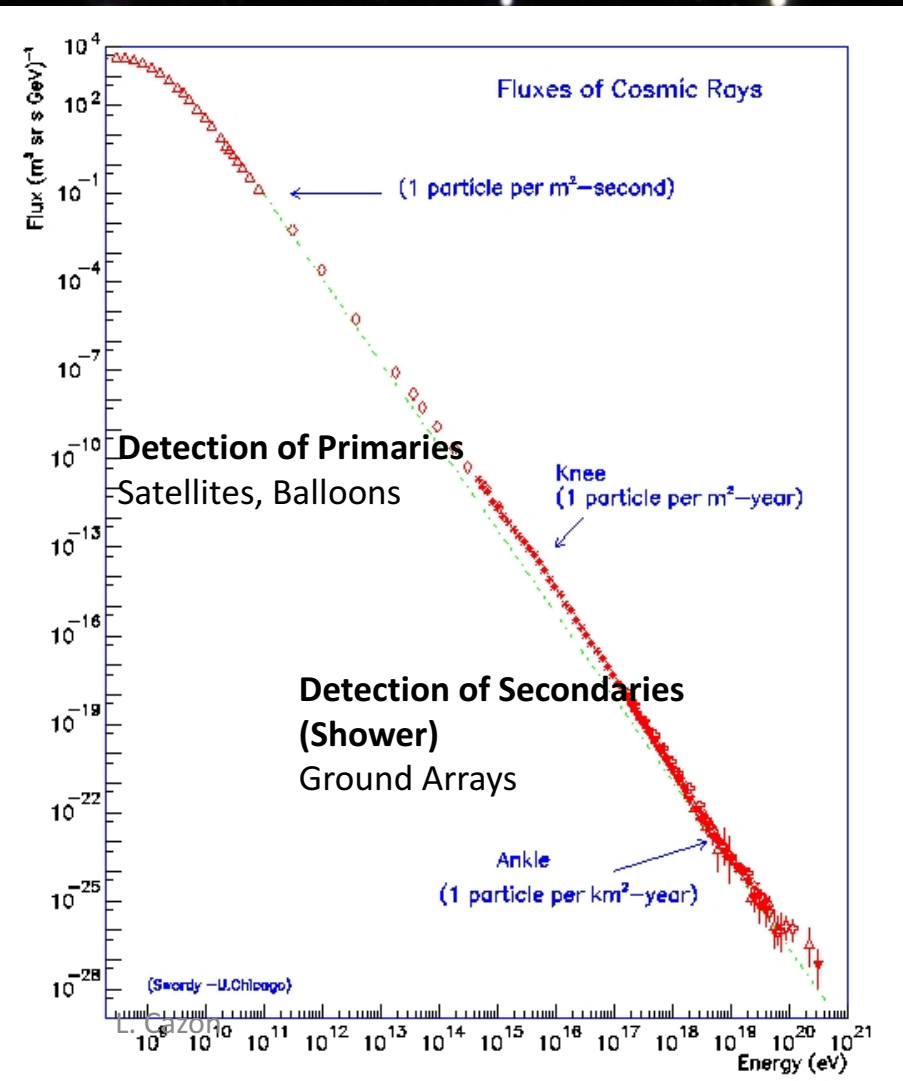
- Data mining
- Monte Carlo
- Machine learning
- Synthesis & Display
- Communication

Technology R&D

- Particle Detectors
 - Cerenkov tanks
 - RPC's
 - Scintillators
- Electronics, DAQ
- Communications
- LASERs , LIDARs
- RADAR
- Antenna Design
 - MHz Microwaves
- Optics:
 - Telescopes
- Solar Pannels



Cosmic Ray Spectrum



A comparison

1.5 eV



10 000.0 eV



6 500 000 000 000.0 eV



300 000 000 000 000 000 000.0 eV



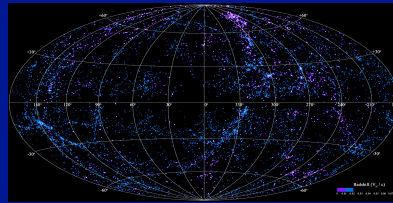
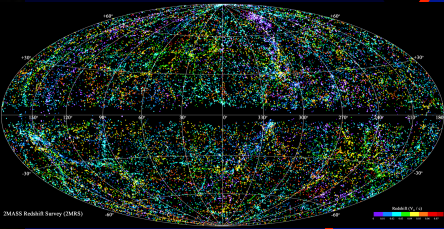
$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow p + \pi^0,$$

$$\rightarrow \gamma + \gamma$$

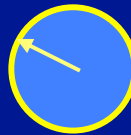
$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+.$$

$$\rightarrow \mu^+ + \nu_{\mu}$$

10^{19} eV \sim 1 Gpc



100 Mpc

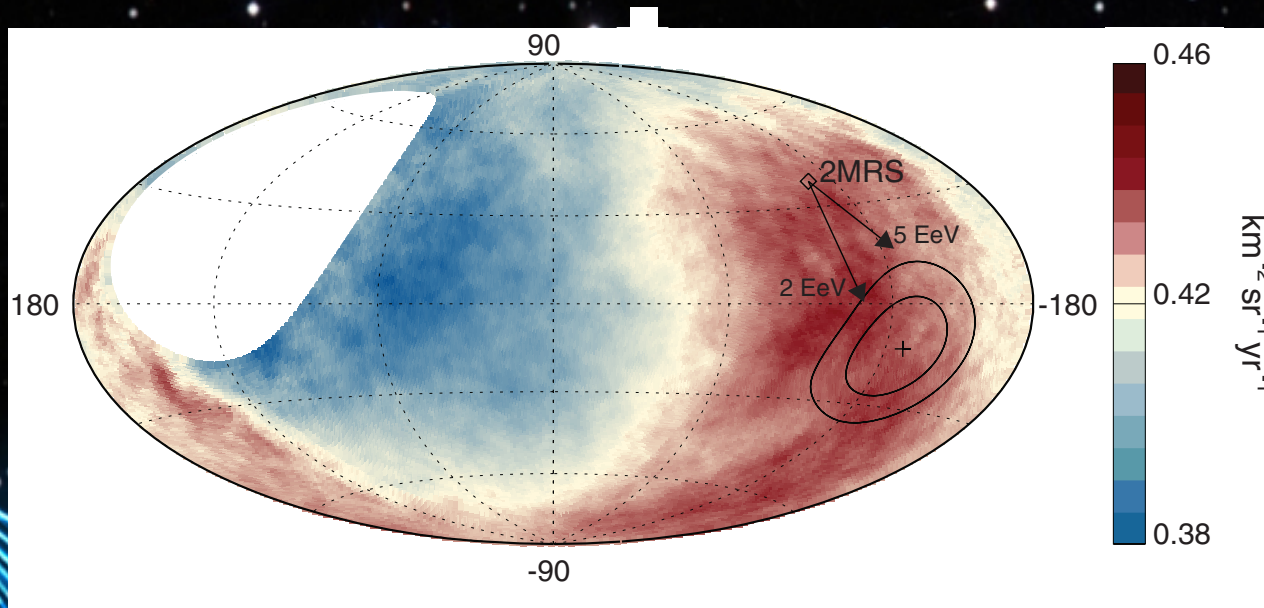


Gpc

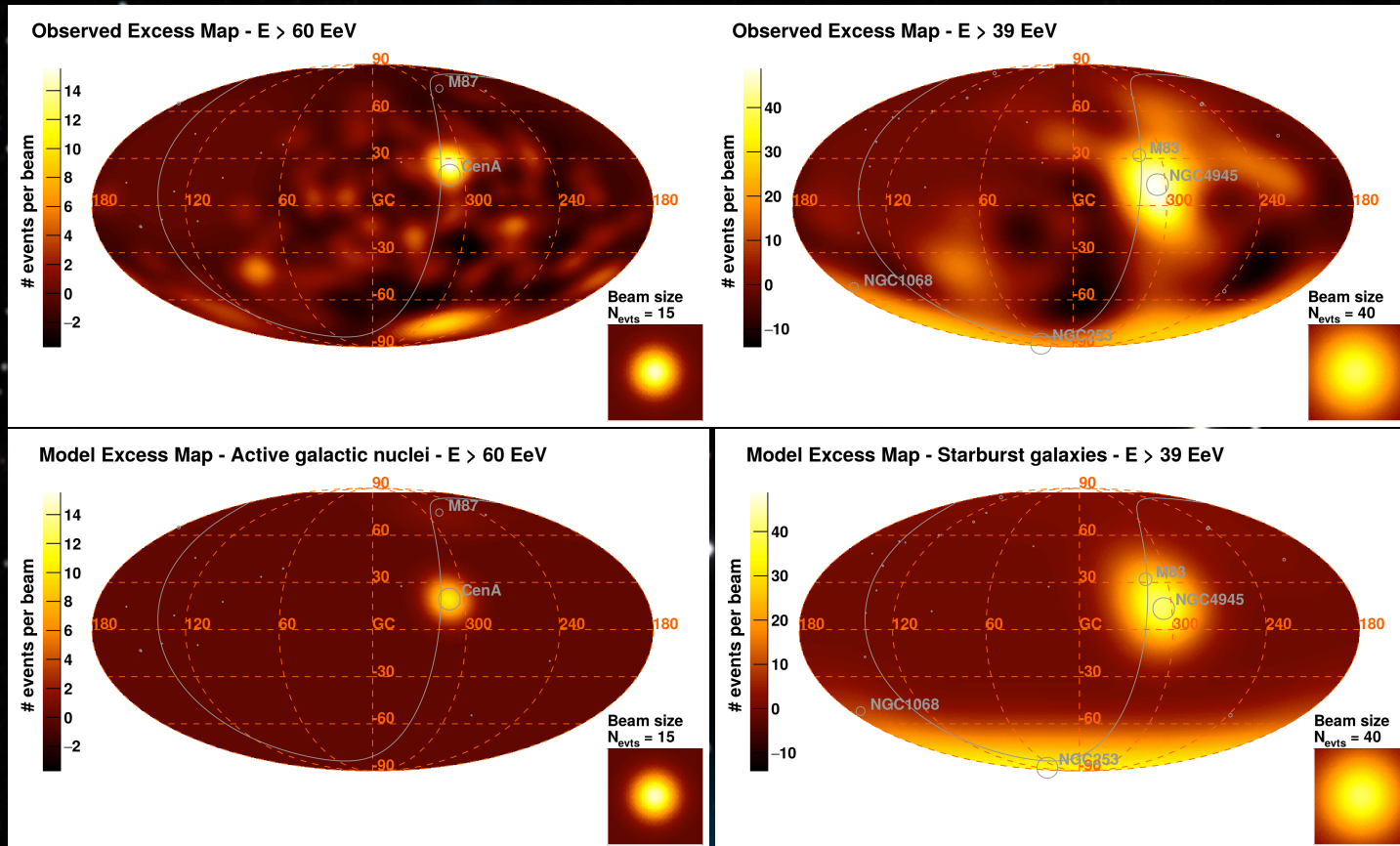
10^{20} eV $<$ 100 Mpc

Extragalactic matter

- ~ 55 deg away from the 2MRS dipole
- If including effects of Galactic Magnetic Field for $E/Z=2$ EeV and $E/Z=5$ EeV agreement improves

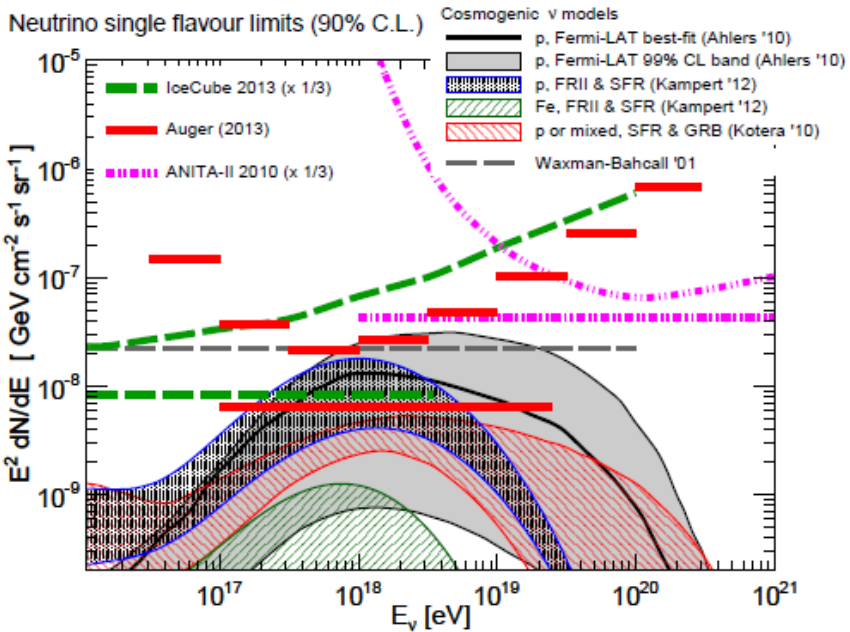


Hints at the highest energies



AGN:
 Cen A: $E > 58$ EeV, 15 deg. 3σ
 Swift-BAT: $E > 62$ EeV, 16 deg. 3σ

Fermi-LAT gamma ray sources:
 AGN: $E > 60$ EeV, 7 deg. 2.6σ
 Starburst Galaxies $E > 39$ EeV, 13 deg. 4σ



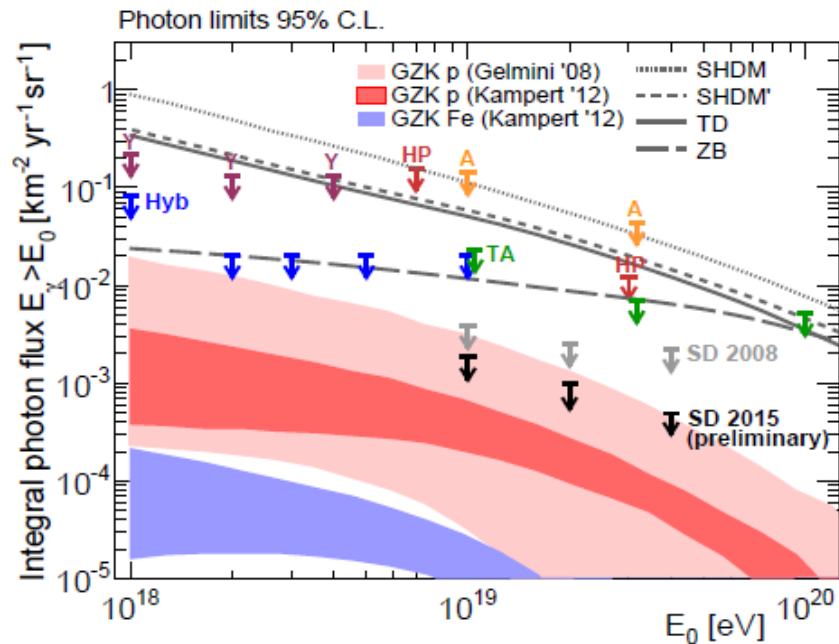
Photon & neutrino fluxes

Observations disfavour most of the exotic decay scenarios to produce UHECR and favour acceleration in astrophysical scenarios

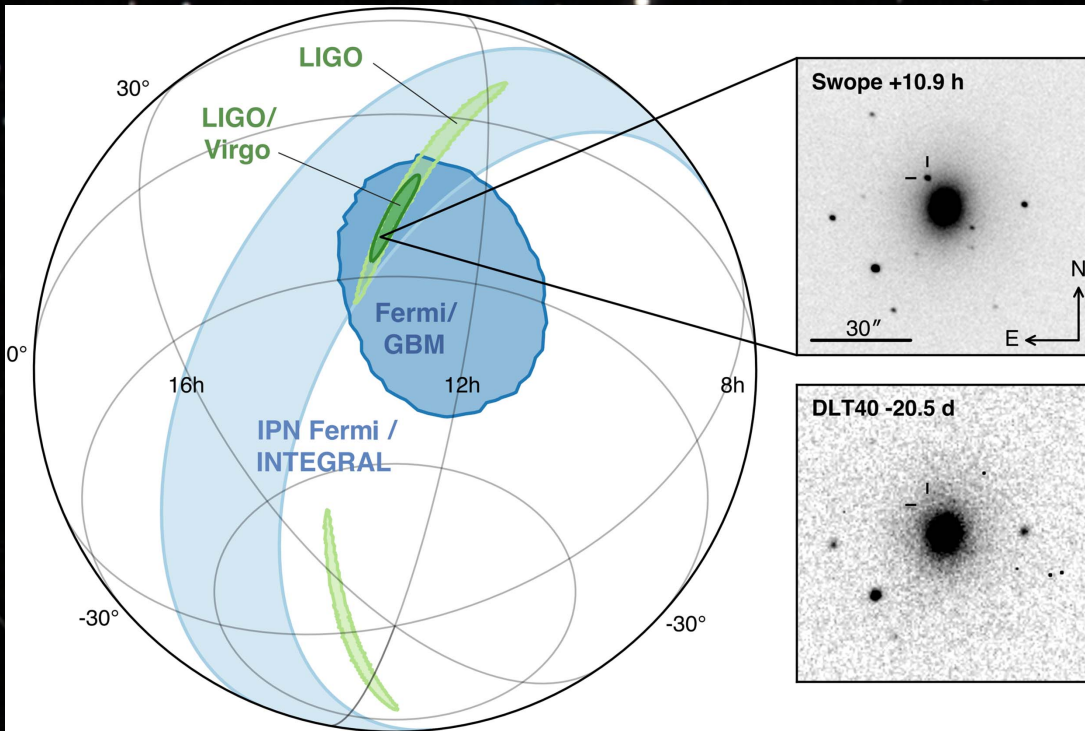
They are reaching the guaranteed cosmogenic fluxes

No point sources

No events associated with interesting objects



Multimessenger Physics



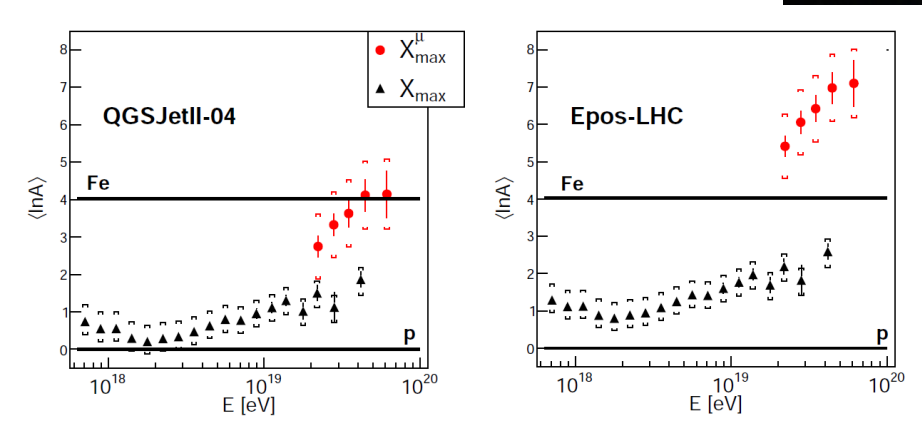
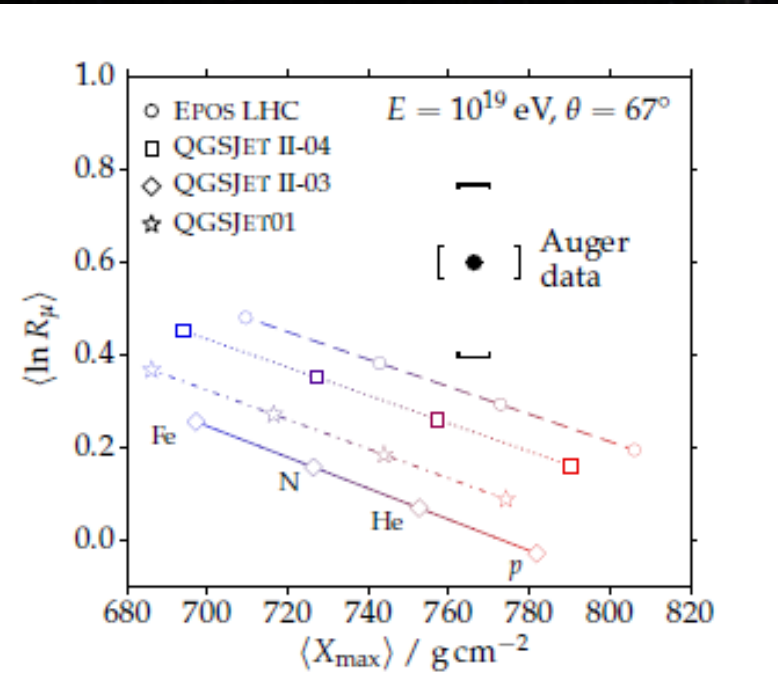
- Observations of a Binary Neutron Star Merger (GW170817)
- Event was in the Auger field of view
- No neutrinos detected

Hadronic Physics

Our interpretation of air shower rely on unexplored physics: energies above LHC and forward regions

We know that something is missing in the current high energy hadronic models.

New physics?



Thesis project in phenomenology

- Peering into the hadronic cascades through muons
 - Study the connections of muon distributions with the development of the hadronic cascade
 - Develop analytical models that can explain the hadronic cascades
 - Investigate the sensitivity of muon distribution to hadronic parameters

Thesis project data analysis

- Measurement of the number of muons in inclined showers at the Pierre Auger Observatory

- Data mining:

- Cleaning, finding of unexpected correlations, proper statistical treatment, assesement of significance to findings

- Understading of the detector and the physics of the detector

- Calculation of systematics uncertainties

- Physics interpretation of the results

An example

Probing the π^0 spectrum at high- x in proton-Air interactions at ultra-high energies

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Abstract. The average number of muons in air showers and its connection with shower development has been studied extensively in the past. With the upcoming detector upgrades, UHECR observatories will be able to probe higher moments of the distribution of the number of muons. Here a study of the physics of the fluctuations of the muon content is presented. In addition to proving that the fluctuations must be dominated by the first interactions, we show that low- N_μ tail of the shower-to-shower distribution of the number of muons is determined by the high- x_L region of the production cross-section of neutral pions in the first interaction.

1 Introduction

Due to the mismatch between the predicted and observed number of muons at ground [1–5], much of the efforts to understand muon production in extensive air showers has been focused on the study of the average muon content [6–8]. The experimental situation is summarized in the report of the working group on hadronic interactions [9]. These studies suggest that the average muon number very much depends on low-energy interactions in the shower. In a recent paper [10], it was shown that, in contrast to the average, the relative fluctuations of the number of muons, $\sigma(N_\mu)/\langle N_\mu \rangle$, to a large degree are determined by the first interaction. In fact, it was shown that the very shape of the shower-to-shower distribution of the number of muons is determined mostly by the fluctuations of the *hadronic energy*, E_{had} , i.e. the energy carried by the particles that are likely to undergo another hadronic interaction. In the following we show that these fluctuations of hadronic en-

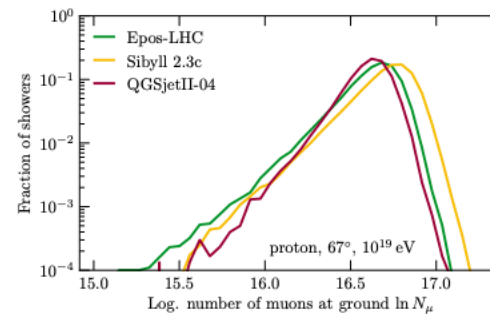


Figure 1. Distribution of the number of muons at ground in extensive air showers induced by protons with an energy of 10^{19} eV.

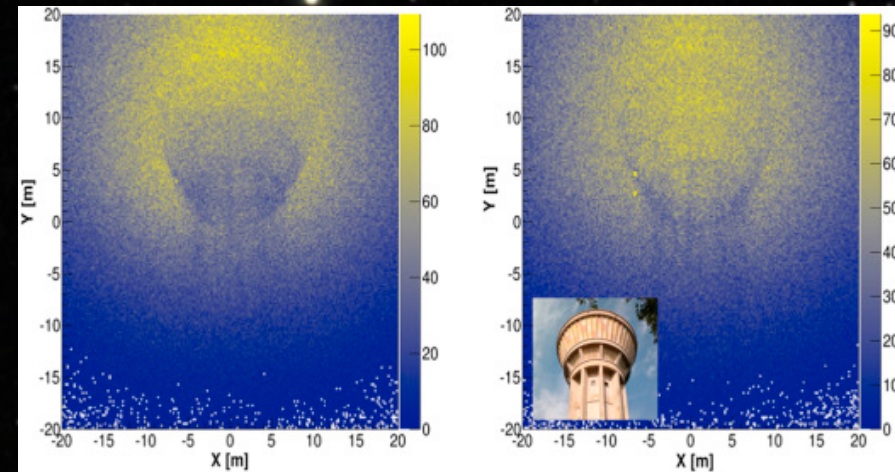
1812.09121v1 [astro-ph.HE] 21 Dec 2018

Other possible topics

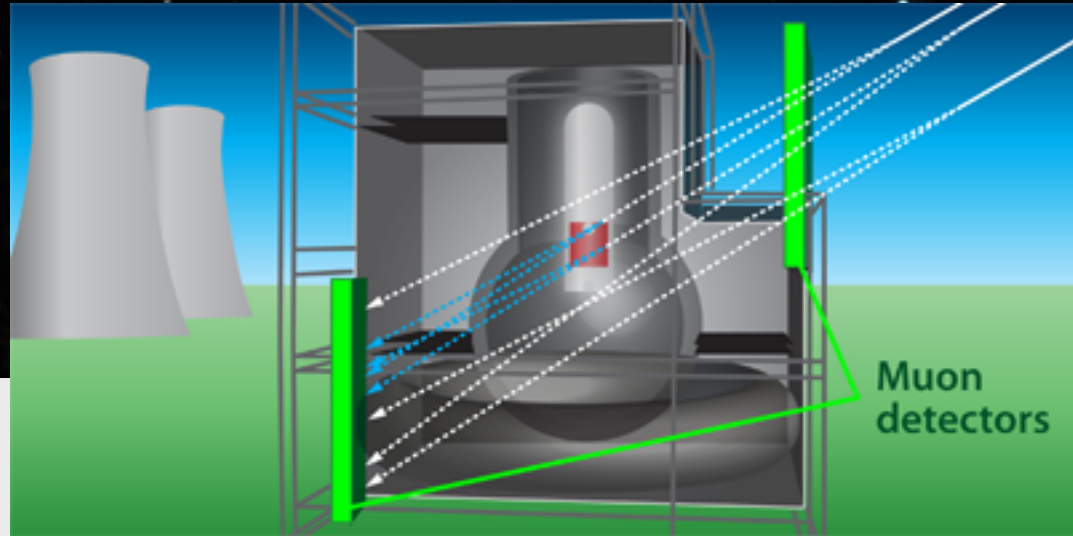
- Study of the information encoded in the **EM longitudinal shape**
- High resolution analysis and modelling of **Cerenkov emission** by the EM component
- Study of the **energy spectrum of muons**
- **Universality** of EAS across models and primaries
- Global fit techniques: study of performance and limitations
- Search of **exotic** events
- Search for sky **anisotropies** & mass/sky anisotropies and correlation with astrophysical objects

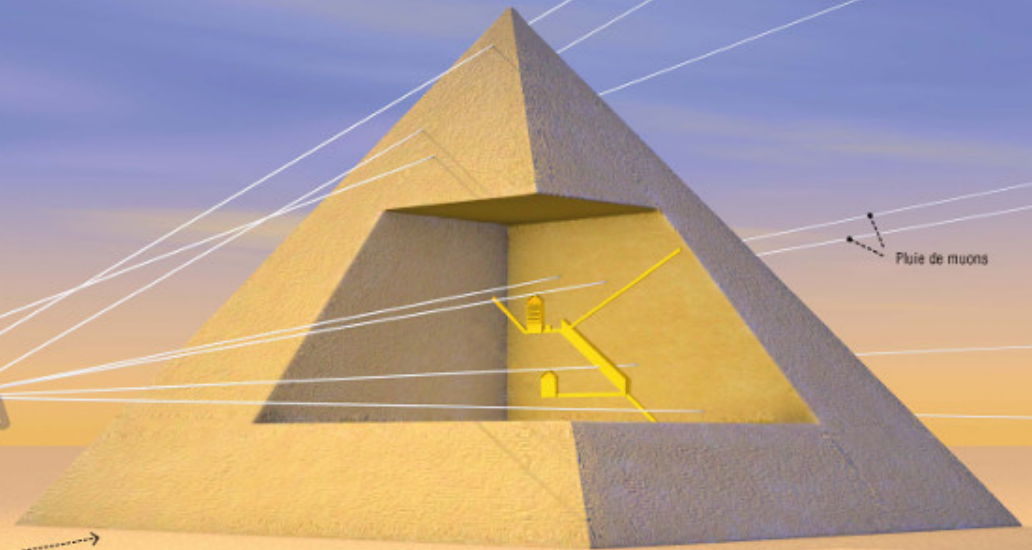
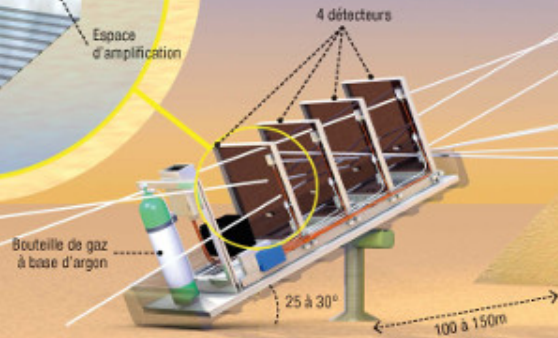
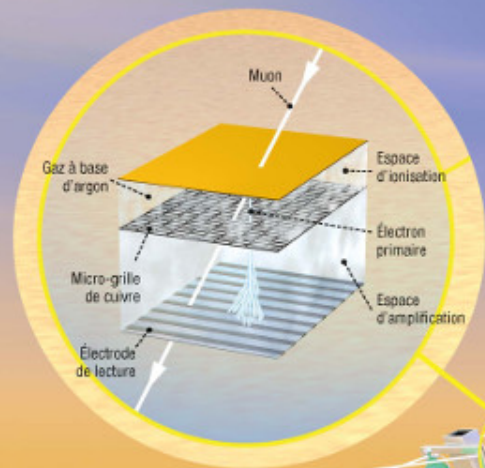
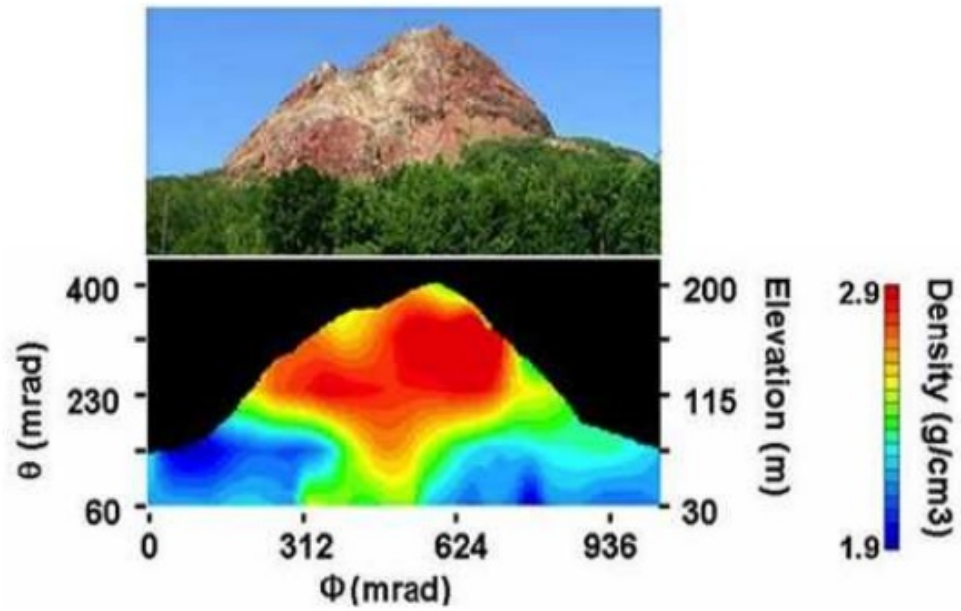
A new related field: Tomography with cosmic ray muons

- Emerging technique, thanks to R&D tech. improvements
- Many applications:
 - Geological survey, geotechnics, civil engineering monitoring, archaeology, homeland security, nuclear security....
- A proof of concept project using tRPCs was recently started. Master and PhD opportunities



Fukushima-Daichi





Thesis topics are also shaped by the particular
interest and abilities of students.
This is a large field.

Do not hesitate to ask us.

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Thanks!!!