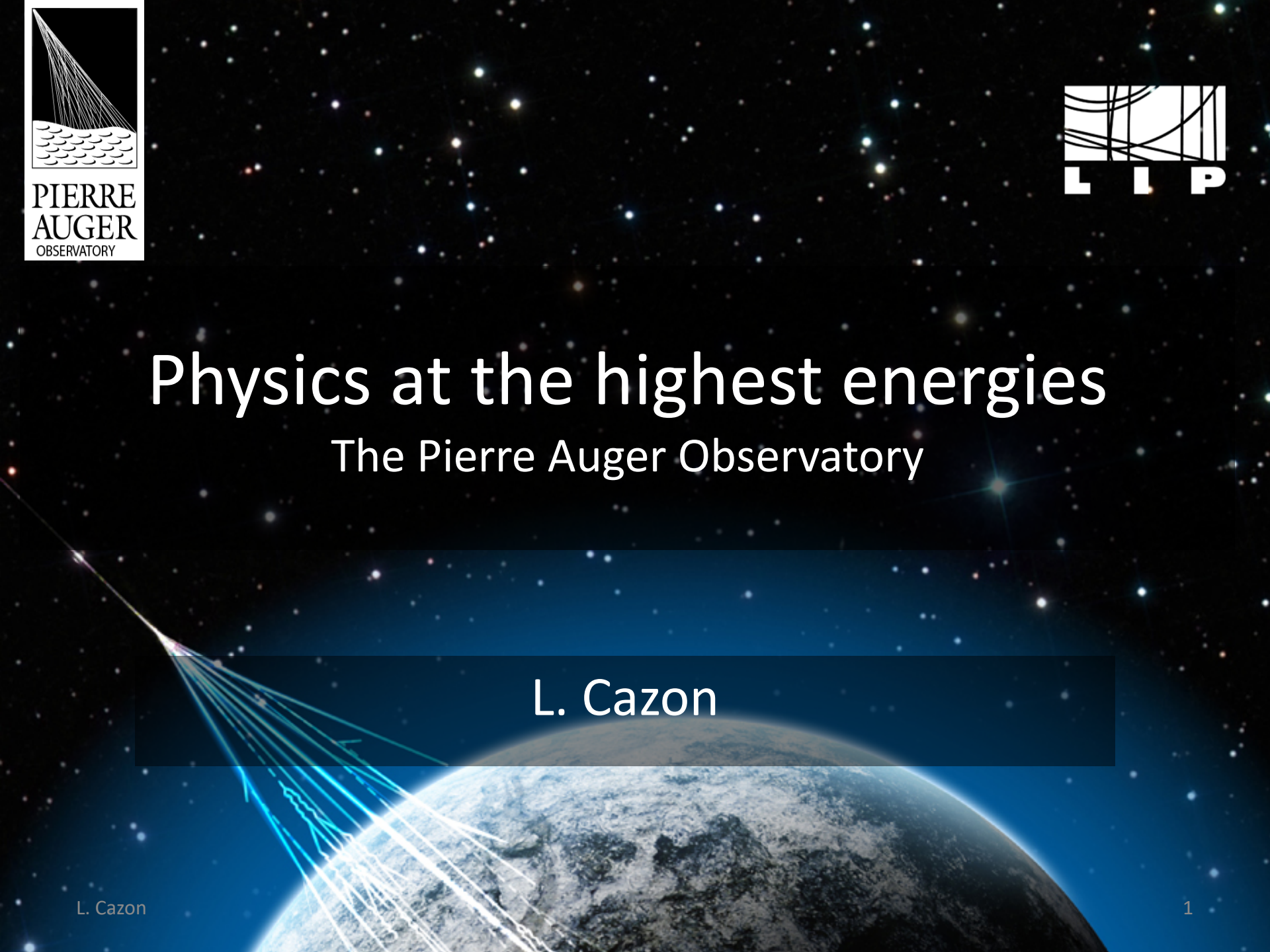


Physics at the highest energies

The Pierre Auger Observatory

L. Cazon

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

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 Bremshtrahlung)
  - UV-light (Air Fluorescence, Cerenkov)
- Plasma formation
  - Radar detection, Molecular Bremstrahlung)

Earth Sciences

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

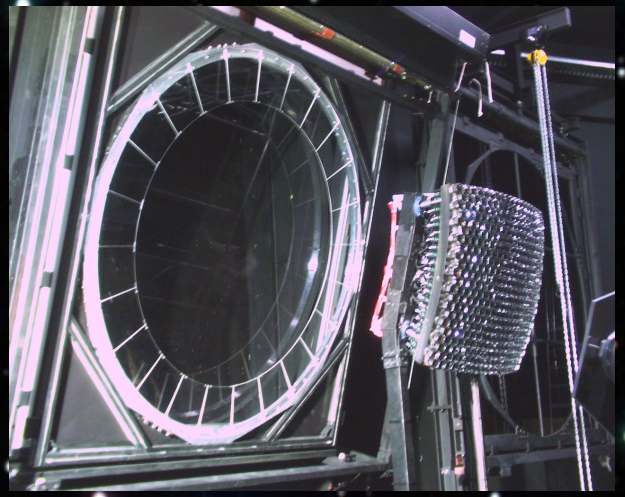
A multidisciplinary field

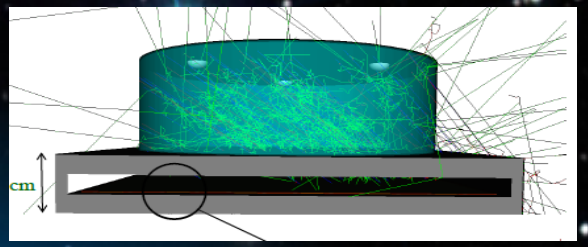
Data Science

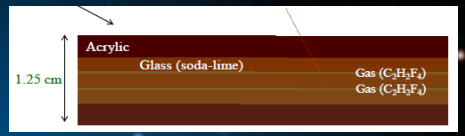
- Data mining
- Monte Carlo
- Machine learning
- Synthesis & Display
- Communication

Technology R&D

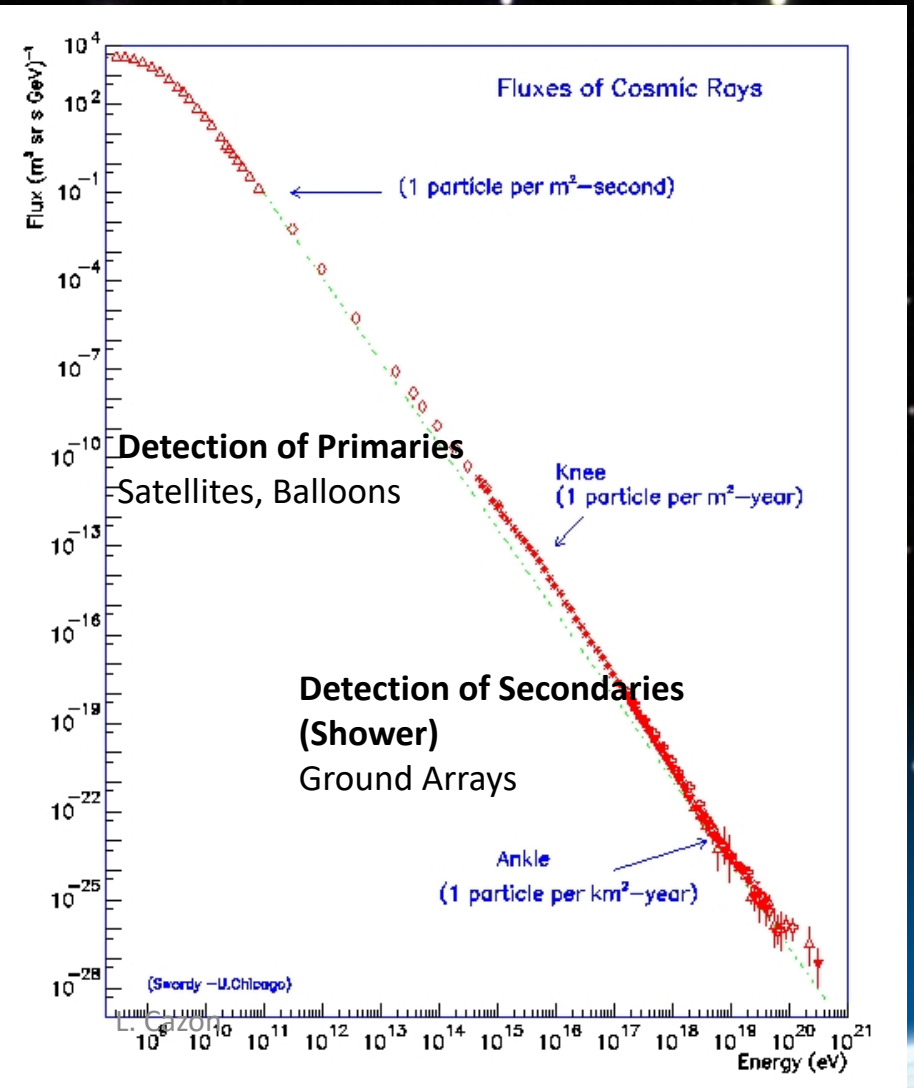
- Particle Detectors
  - Cerenkov tanks
  - RPC's
  - Scintillators
- Electronics,DAQ
- Communications
- LASERs , LIDARs
- RADAR
- Antenna Design
  - MHz Microwaves
- Optics:
  - Telescopes
- Solar Pannels

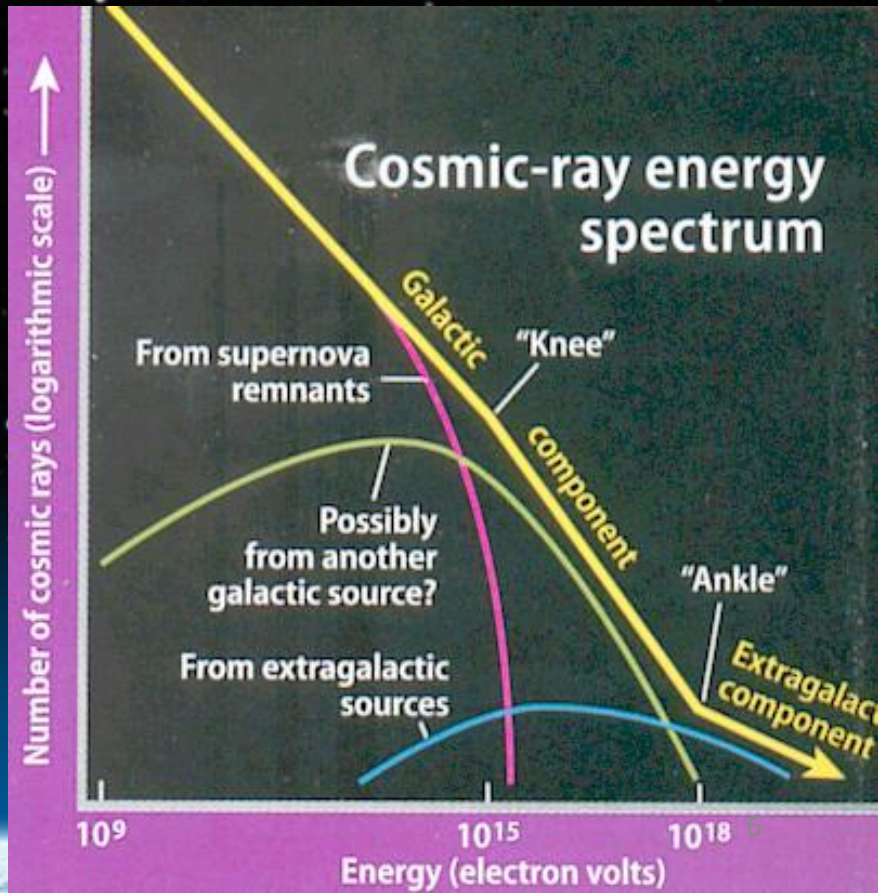






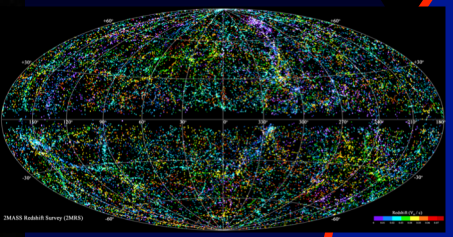
Cosmic Ray Spectrum

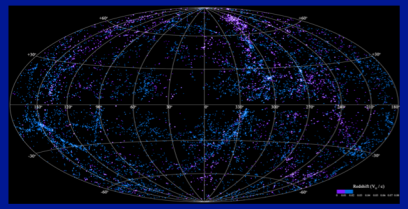




$$\gamma_{\mathrm{CMB}} + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0},$$
$$\rightarrow \gamma + \gamma$$
$$\gamma_{\mathrm{CMB}} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}.$$
$$\rightarrow \mu^{+} + \nu_{\mu}$$

10^{19} eV ~ 1 Gpc



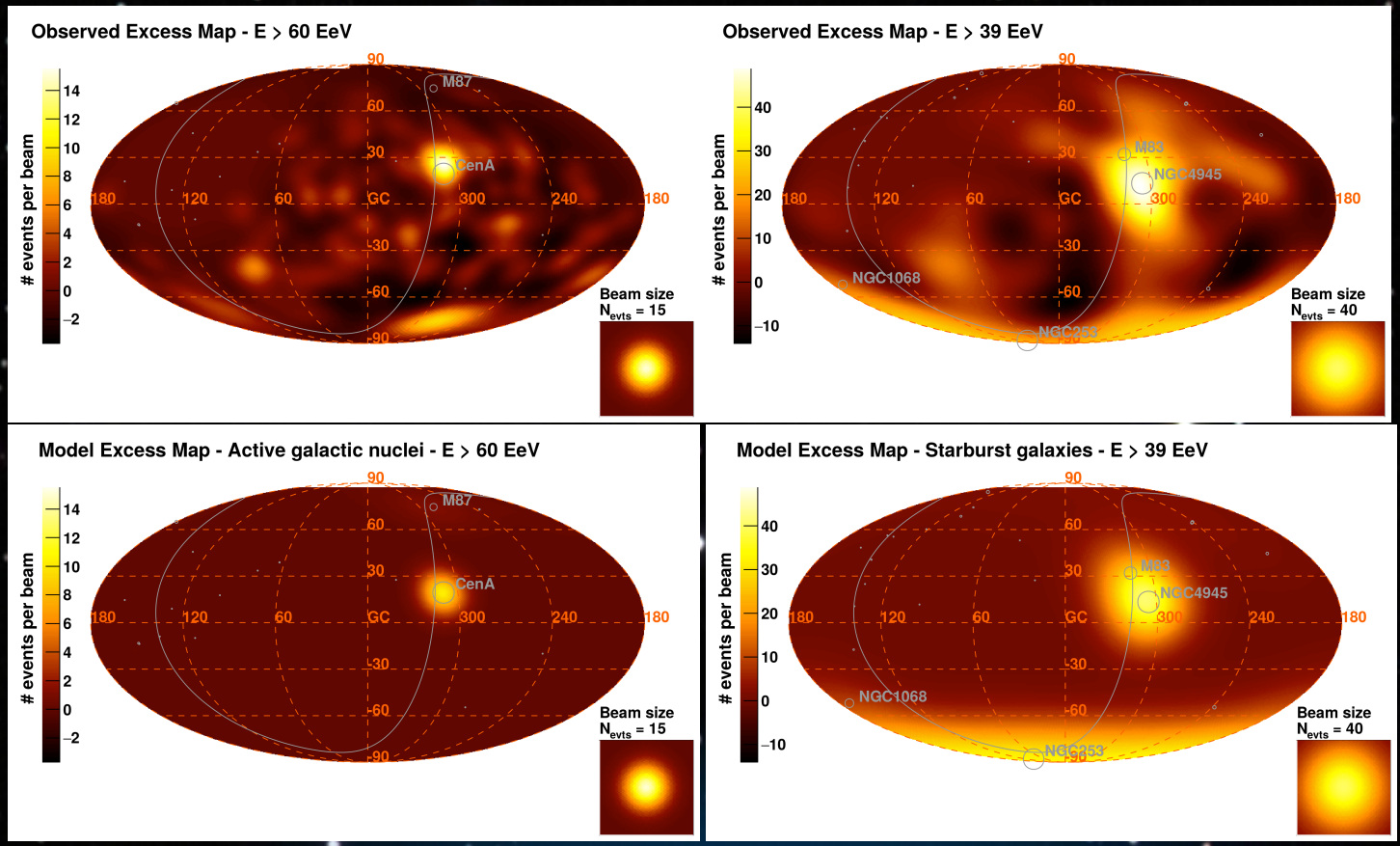


Gpc

100 Mpc

10^{20} eV < 100 Mpc

Hints at the highest energies

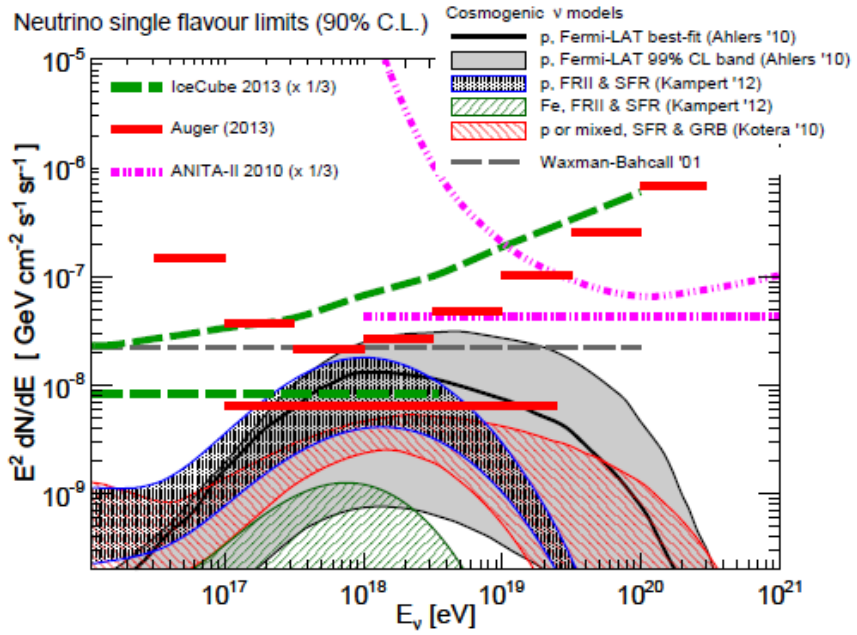


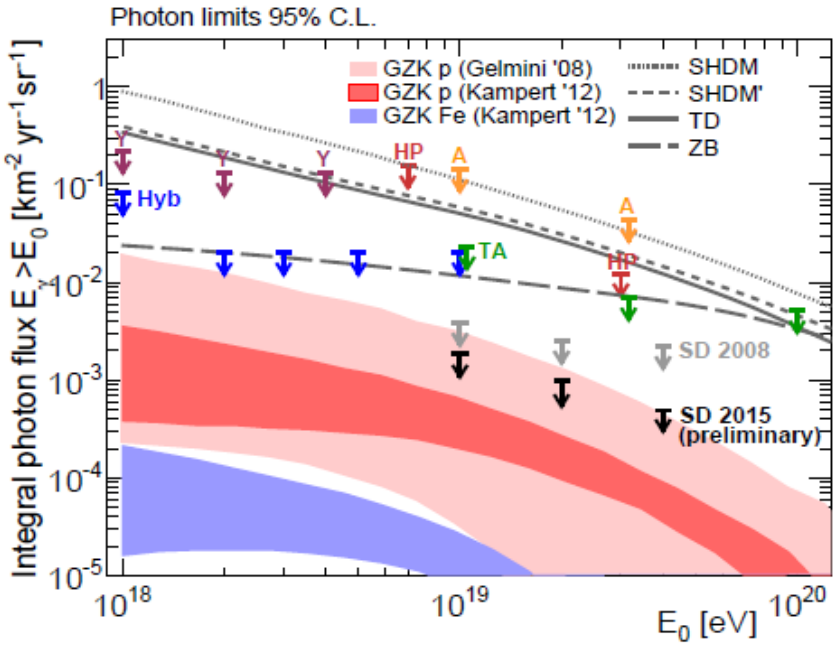
AGN:

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
Starbust Galaxies	E>39 EeV, 13 deg,	4σ

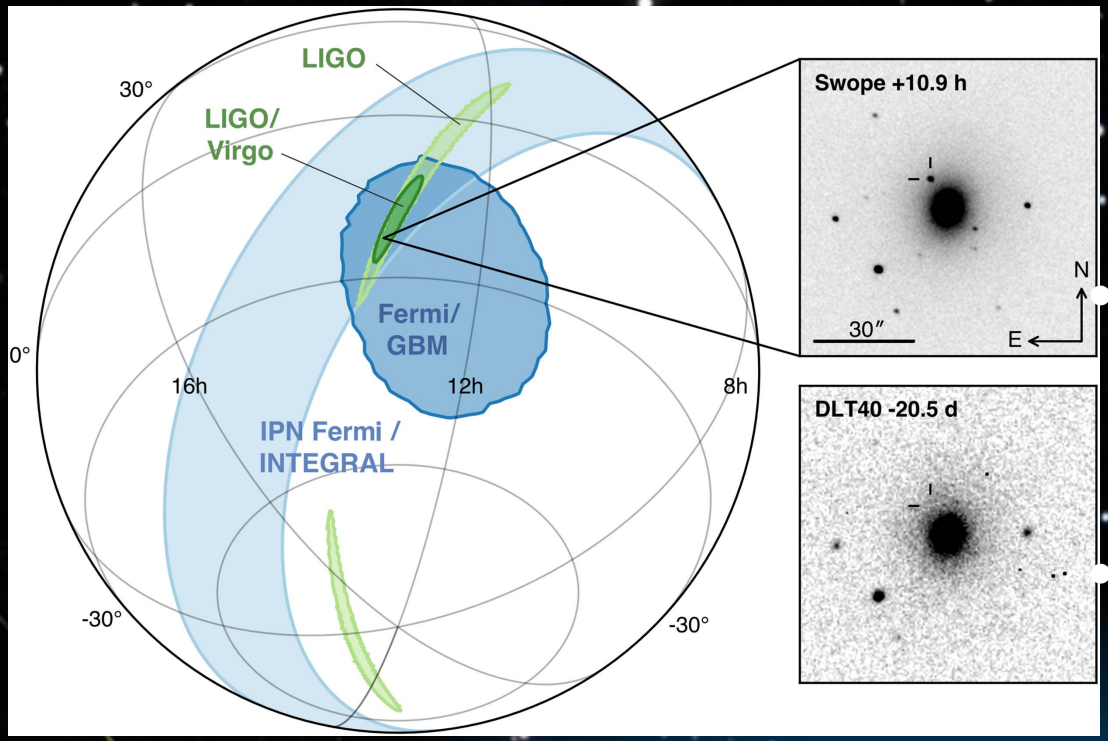




Photon & neutrino fluxes

- 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

Air Showers: the engine

Primary: Hadron

Hadronic shower (mainly pions)

Muonic component

Electromagnetic shower (electrons and photons)

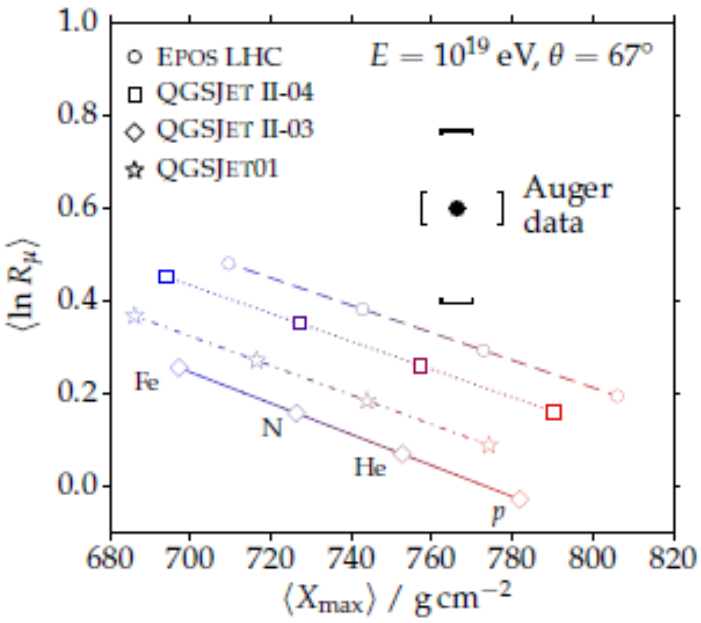
The bulk of radiated and visible energy comes from the EM cascade

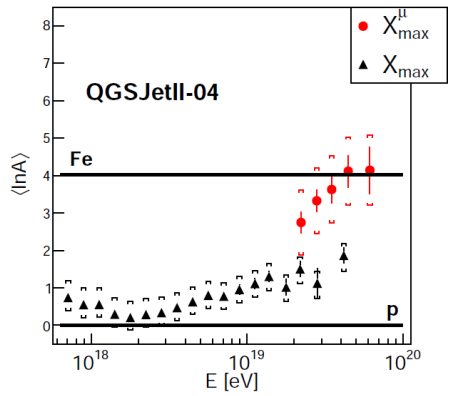
Primary: Photon

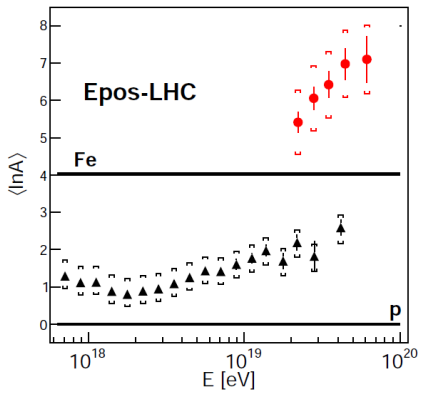
Muons are the smoking gun of the hadronic shower which is the real backbone of the whole shower.

Λ^0 decays are smoking canyons

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 though muons
  - Study the connections of muon distributions with the developement of the hadronic cascade
  - Develope 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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[2]Instituto Superior Técnico (IST), Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal

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 missmatch 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*, $E_{\rm had}$, 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-

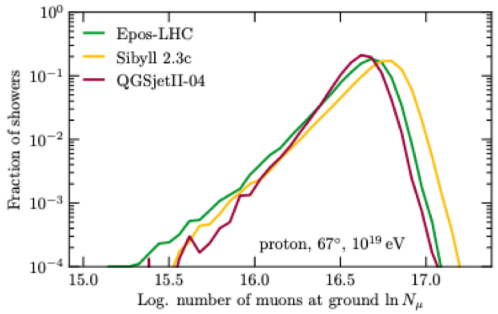


Figure 1. Distribution of the number of muons at ground in extensive air showers induced by protons with an energy of 10^{19} eV.

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 anysotropies & mass/sky anisotropies and correlation with astrophysical objects

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

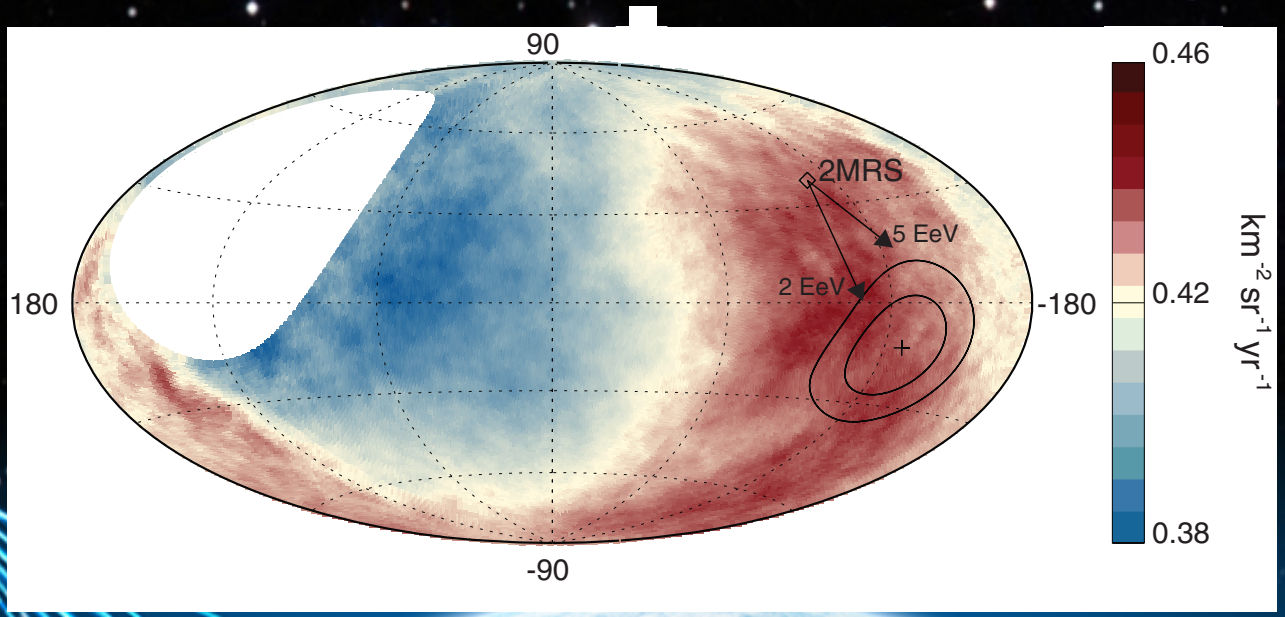
Do not hesitate to ask us.

cazon@lip.pt

Thanks!!!

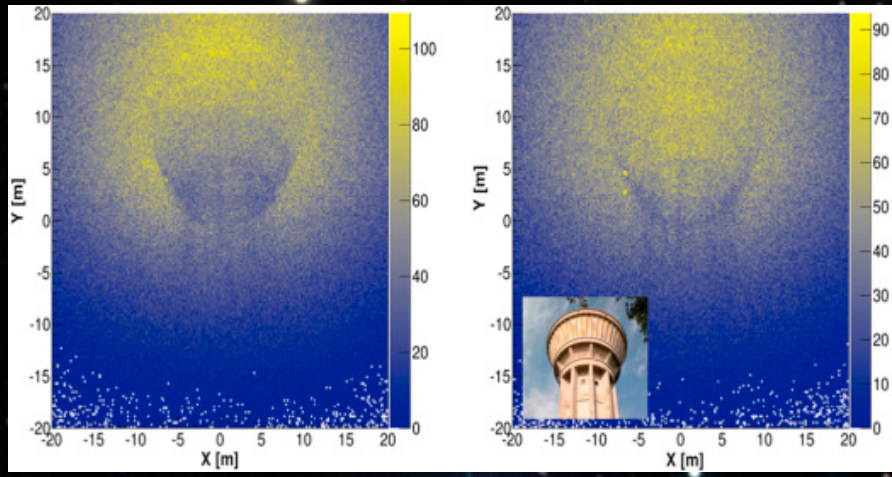
Extragalactic matter

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

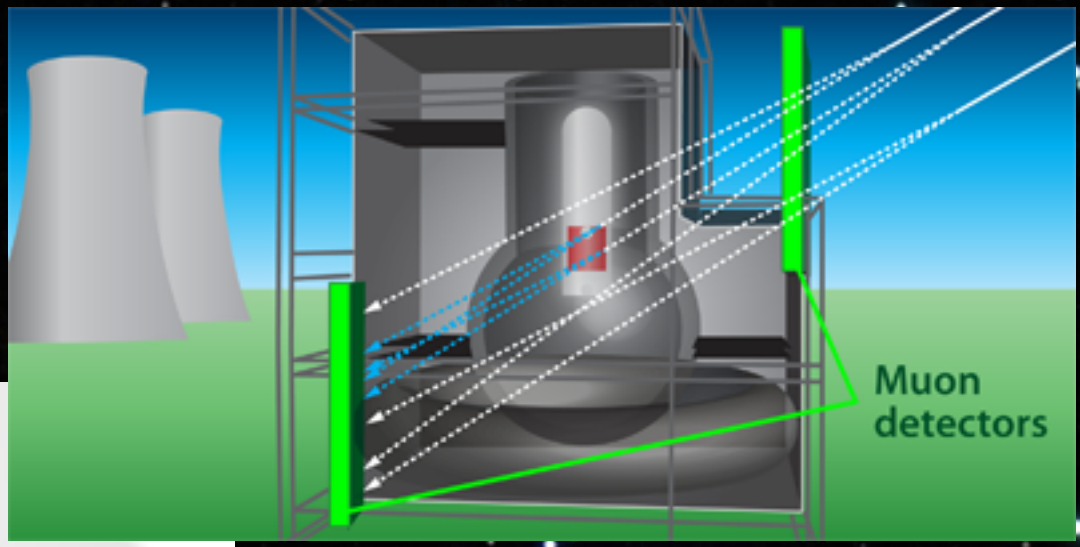


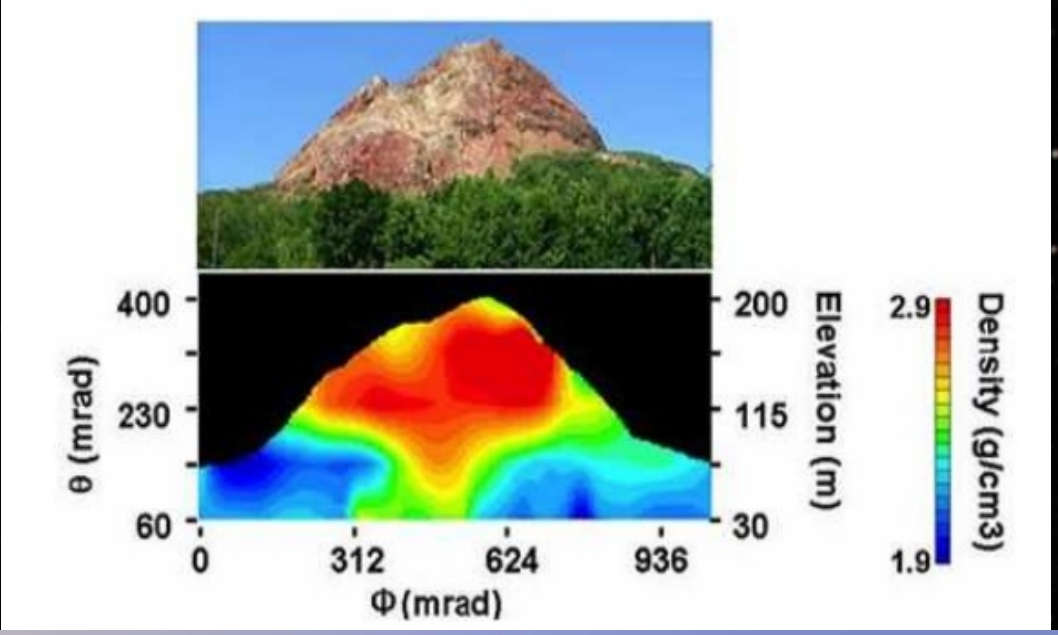
A new related field: Tomography with cosmic ray muons

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



Fukushima-Daichi




400
230
60
θ (mrad)
0
312
624
936
Φ (mrad)
200
115
30
Elevation (m)
2.9
1.9
Density (g/cm3)


Muon
Gaz à base d'argon
Espace d'ionisation
Électron primaire
Micro-grille de cuivre
Espace d'amplification
Électrode de lecture
4 détecteurs
Bouteille de gaz à base d'argon
25 à 30°
100 à 150m
Pluie de muons