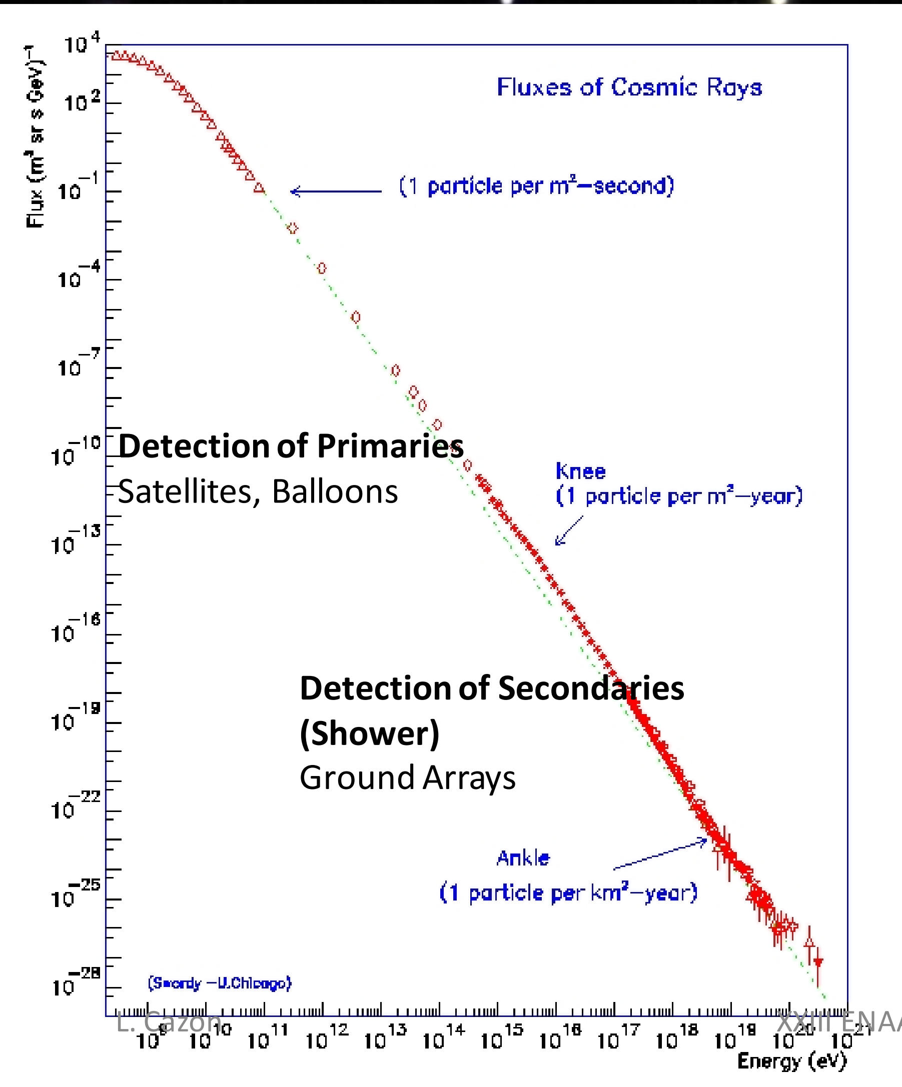
Ultra-high energy cosmic rays with the Pierre Auger Observatory

The quest for the highest energy frontier

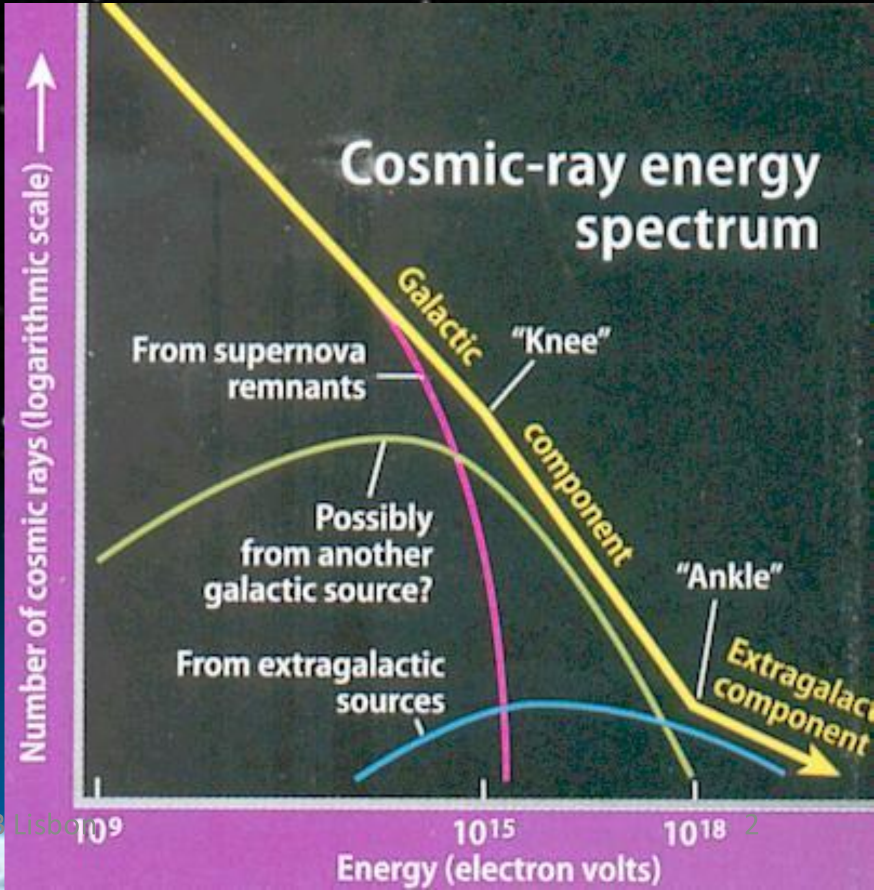
L. Cazon

Cosmic Ray Spectrum

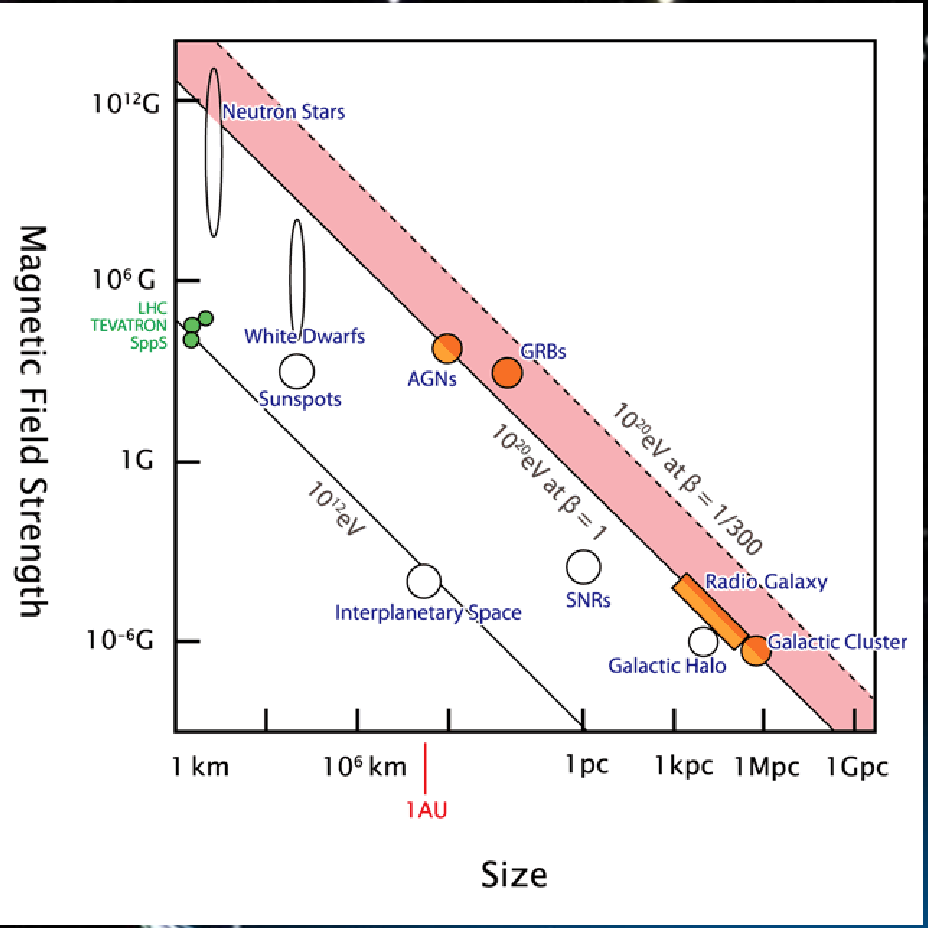


Detection of Primaries
Satellites, Balloons

Detection of Secondaries (Shower)
Ground Arrays

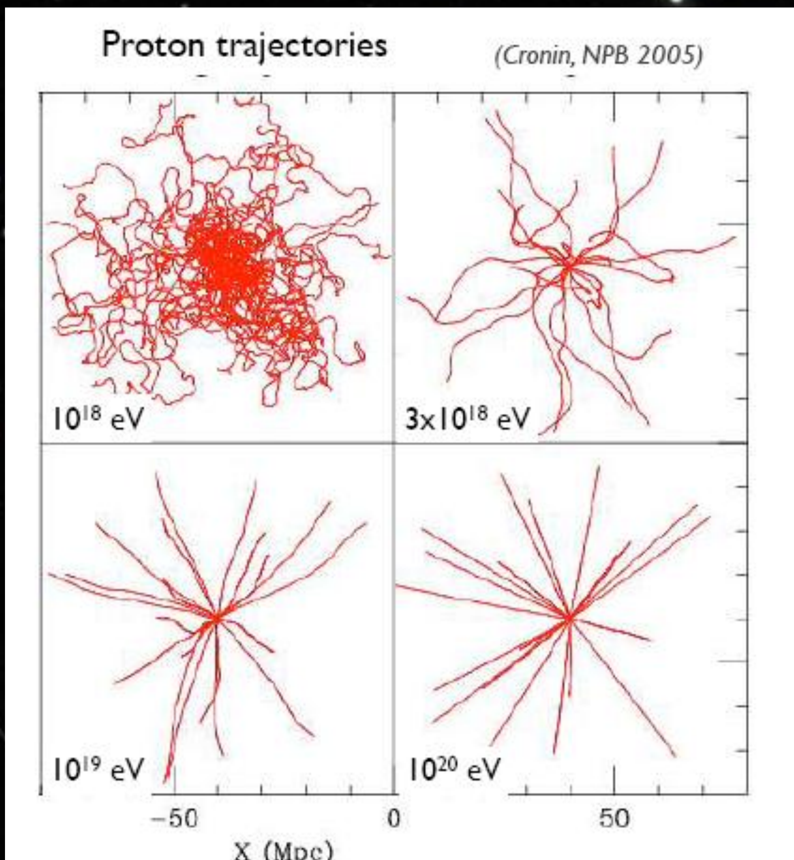


Super-Powerful Accelerators in Nature

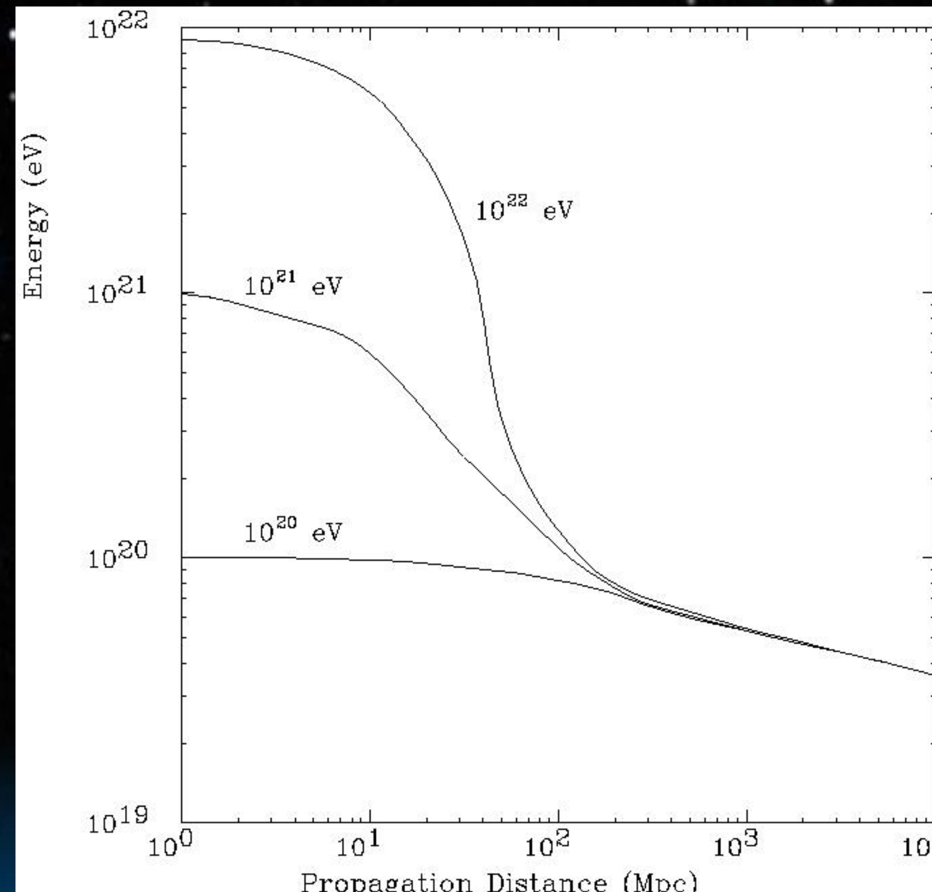


Few astrophysical objects comply with the size and B field required for containment of the CR trajectories at those energies

Intergalactic B field and GZK cutoff



Simple model for extragalactic B. B=1 nG, Lcoh=1 MPc



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

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

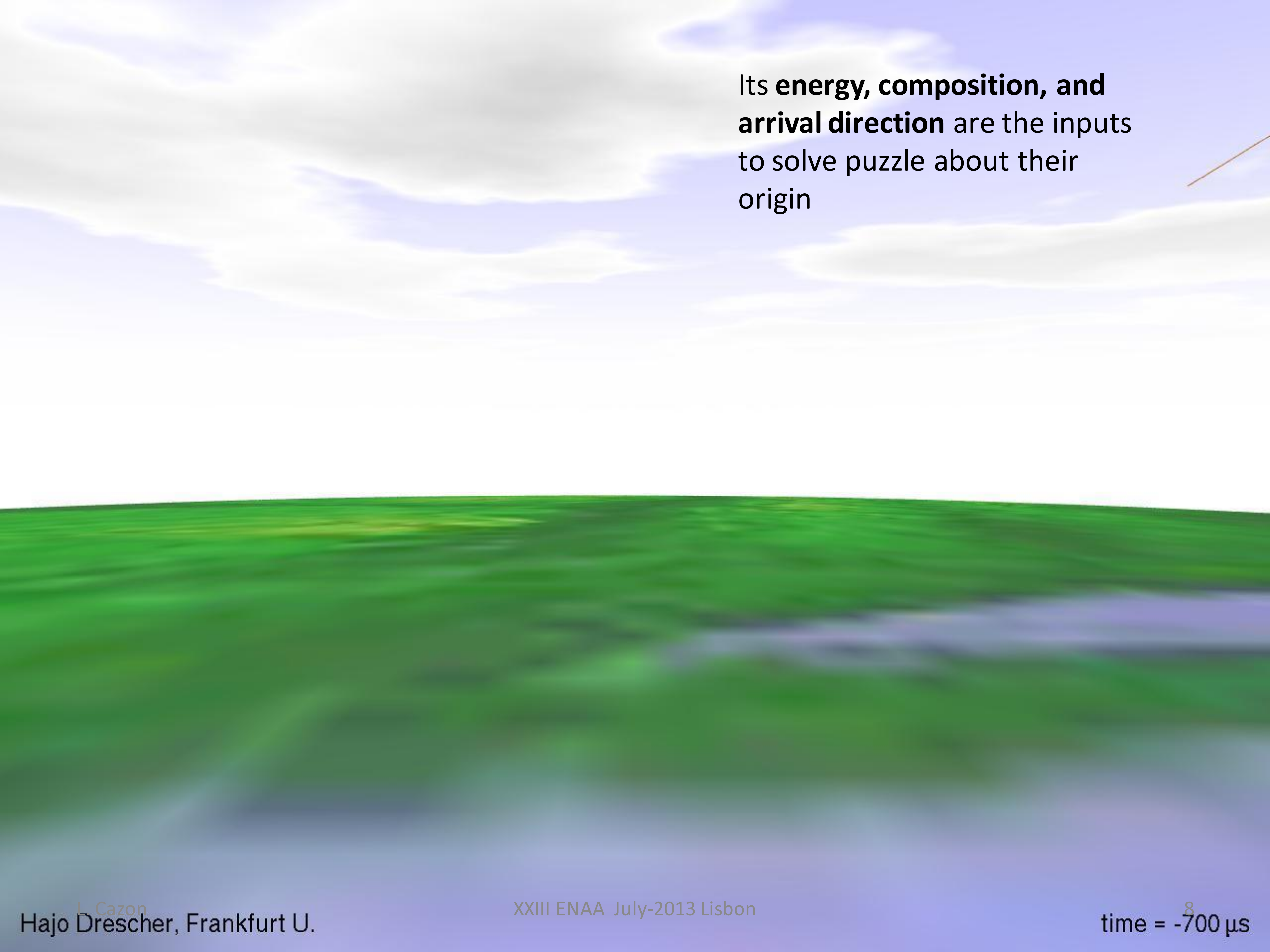
An Air Shower

An Air Shower

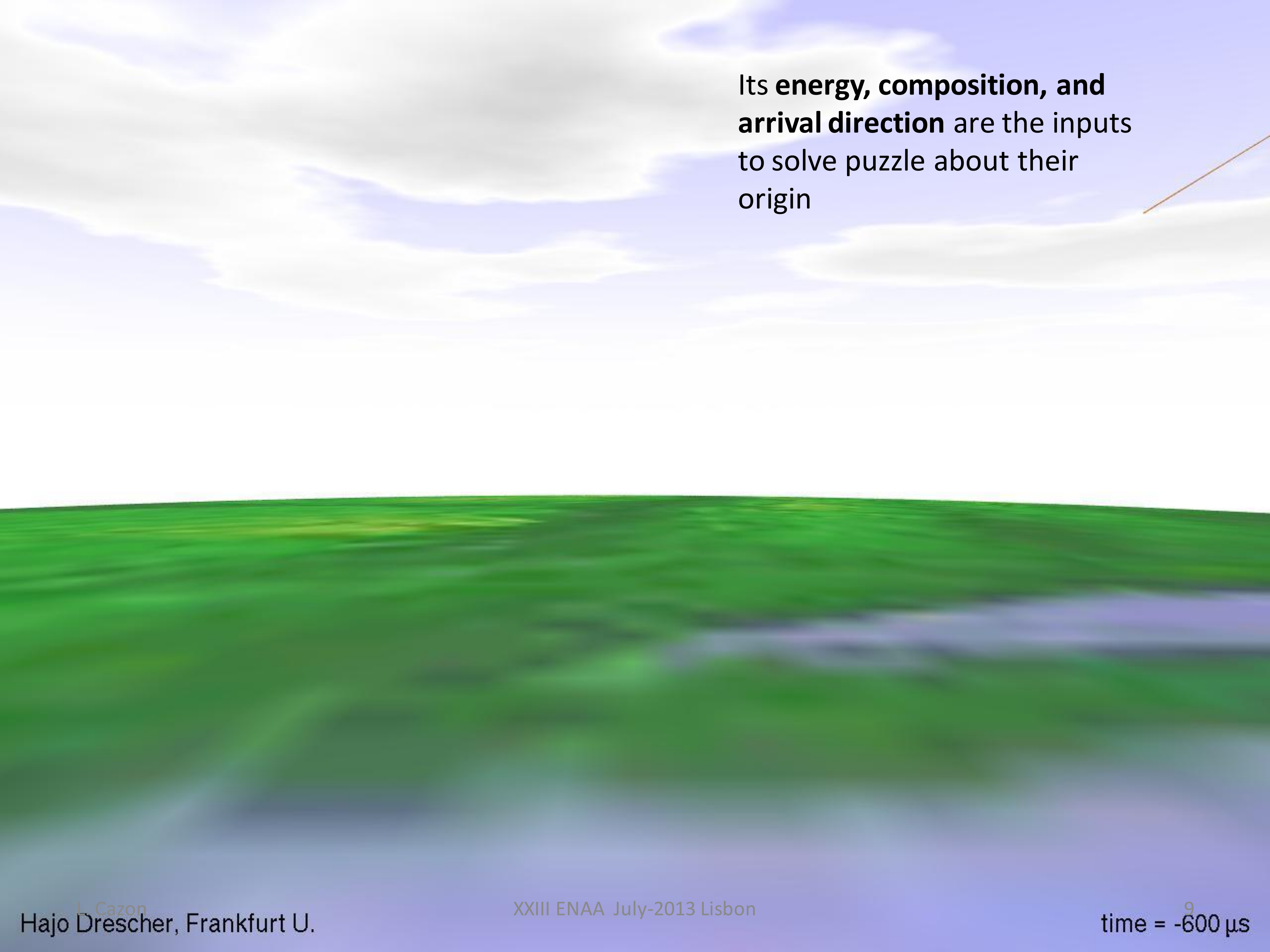
A cosmic ray enters the atmosphere

An Air Shower

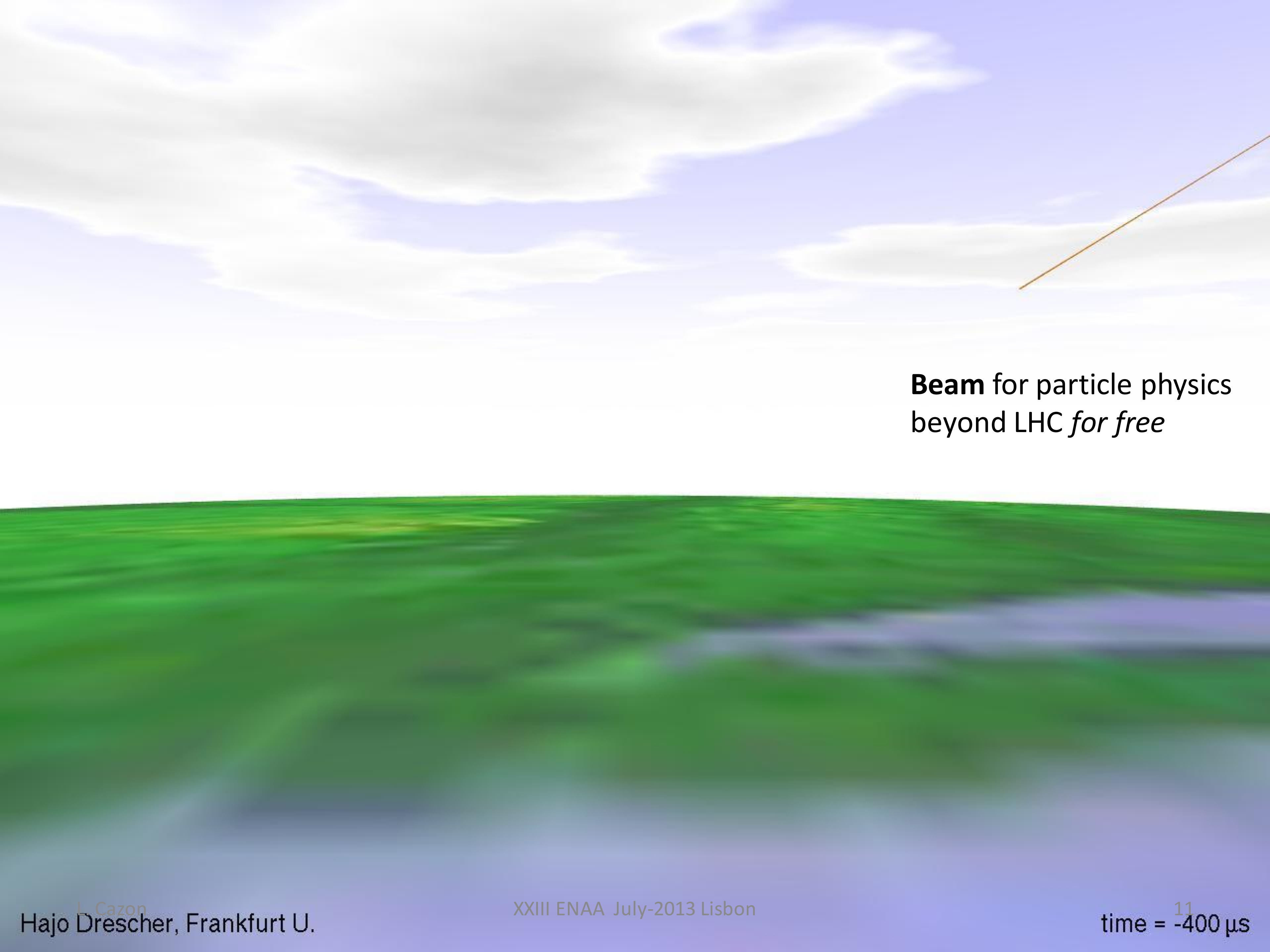
Its **energy, composition, and arrival direction** are the inputs to solve puzzle about their origin



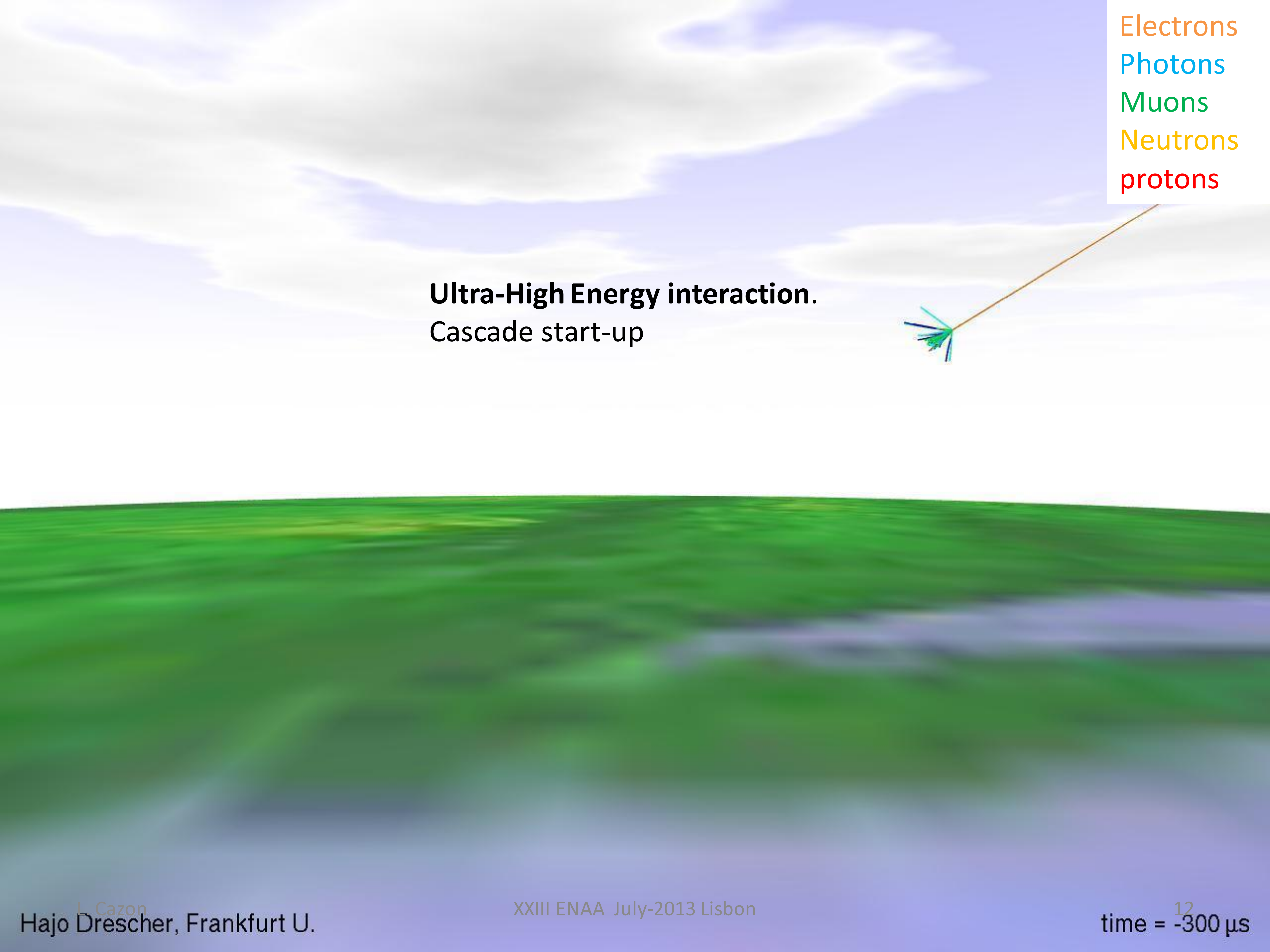
Its **energy, composition, and arrival direction** are the inputs to solve puzzle about their origin



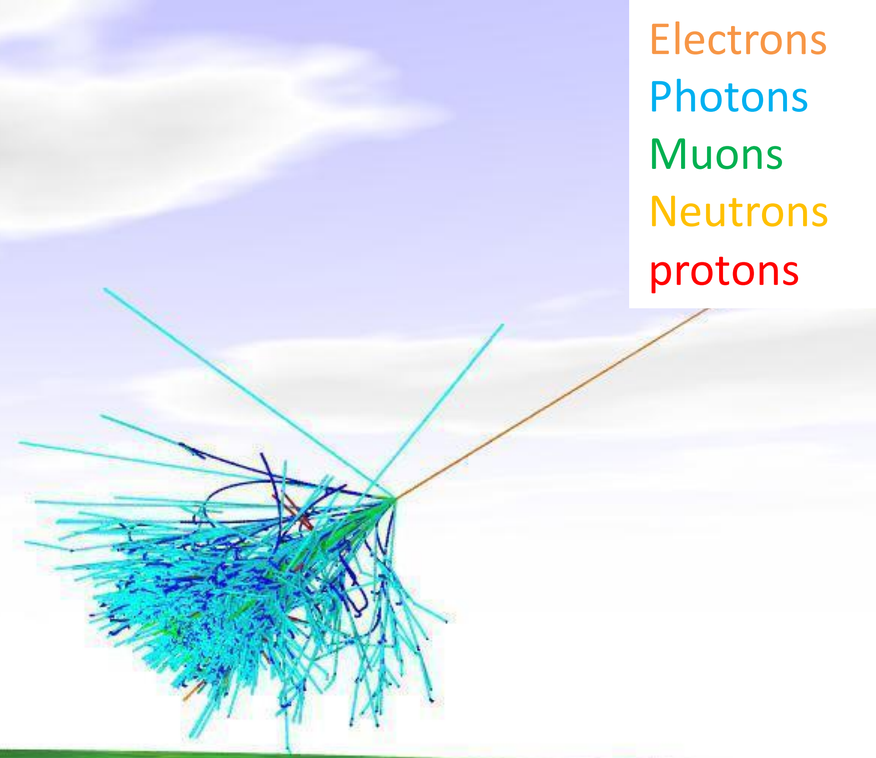
Beam for particle physics beyond LHC *for free*



Beam for particle physics beyond LHC *for free*



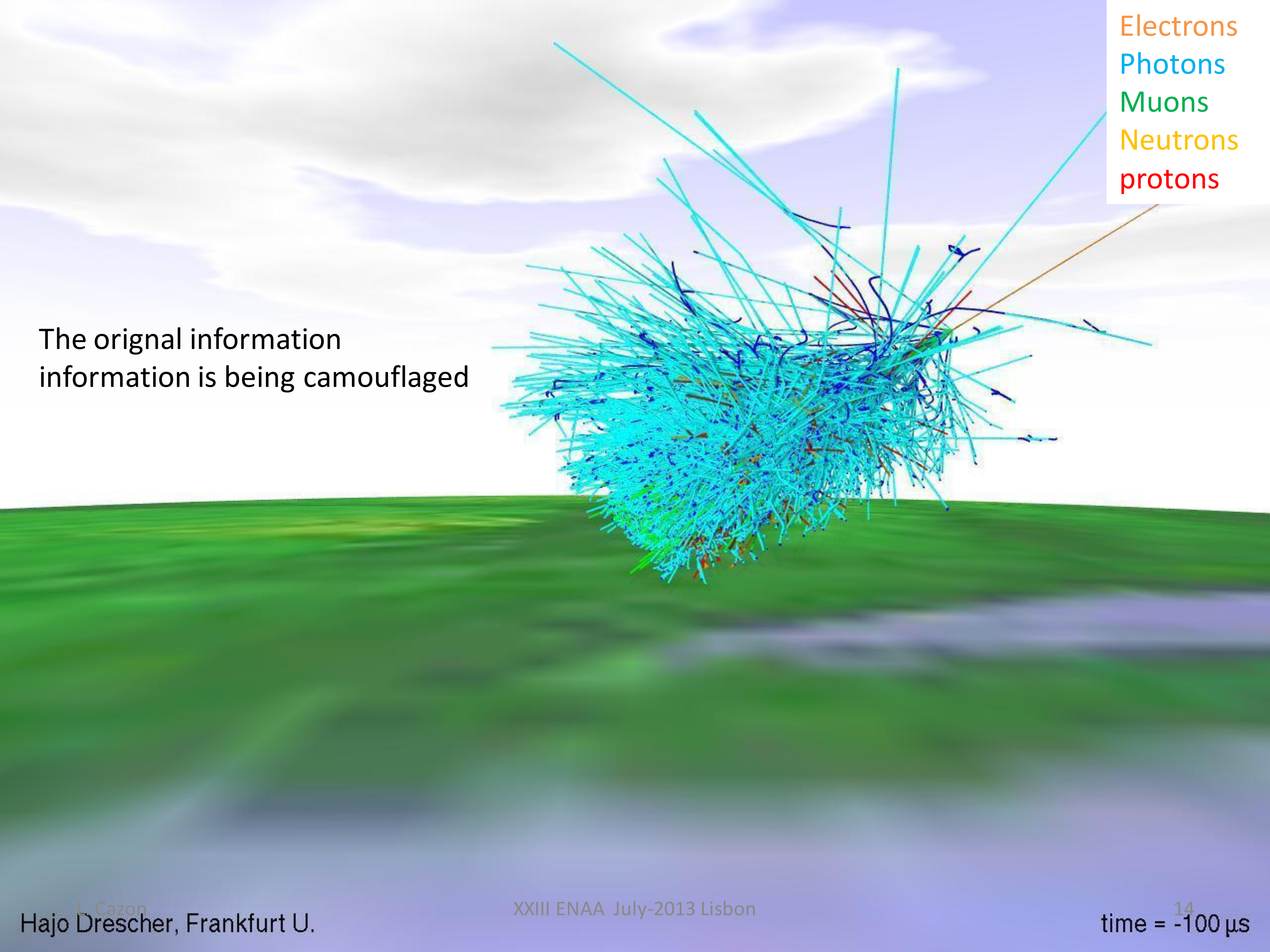
Ultra-High Energy interaction.
Cascade start-up



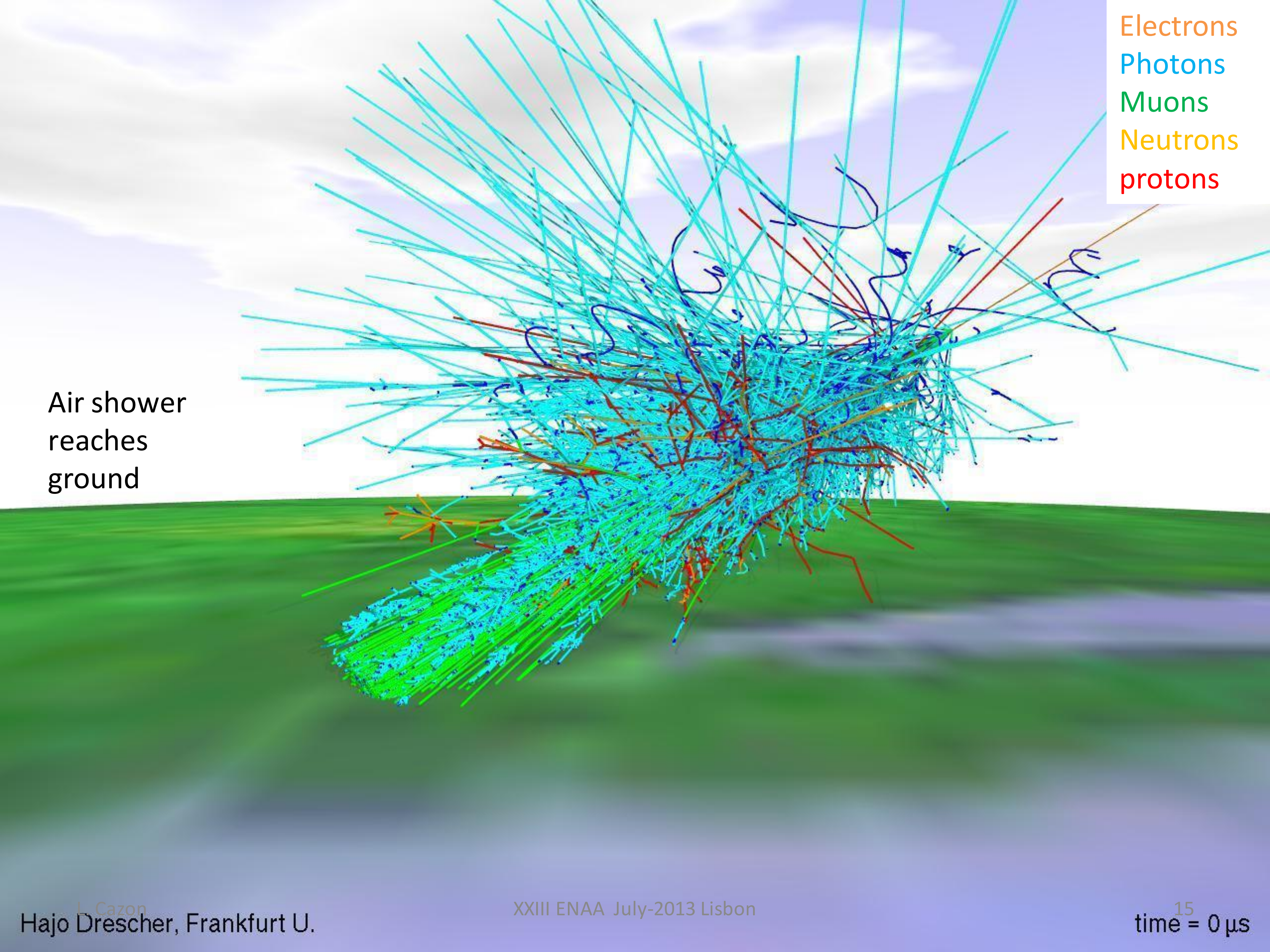
2nd and 3rd generation.
Leading baryons still carrying very high energy.

Hajo Drescher, Frankfurt U.

time = -200 µs



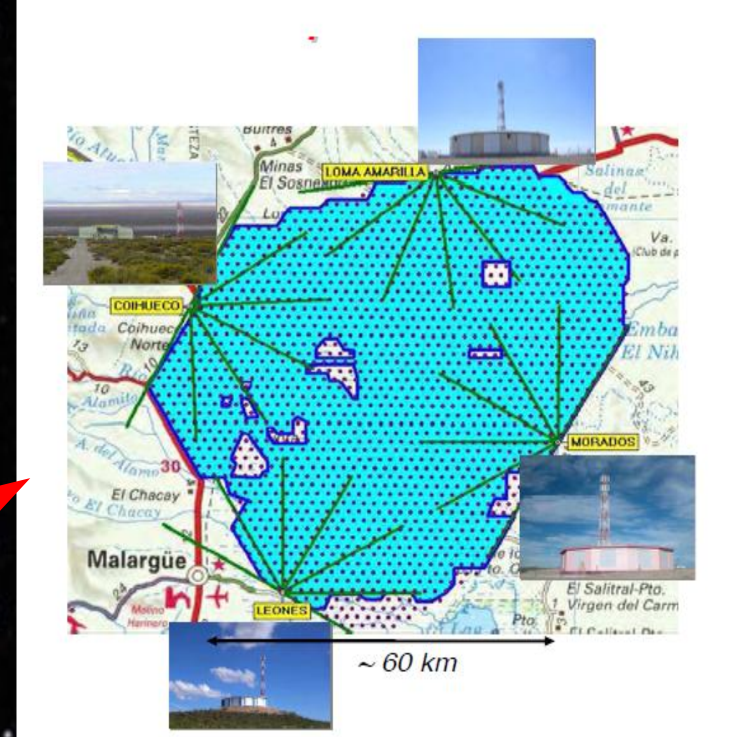
The orignal information
information is being camouflaged


Electrons
Photons
Muons
Neutrons
protons
Air shower
reaches
ground
Hajo Drescher, Frankfurt U.
time = 0 µs

PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory

- Malargüe. Mendoza
- Latitude 35 *S* – Longitude 69 W
- 1400m a.s.l. X=870 g cm^2
- Data taking since 2004
- Installation completed in 2008



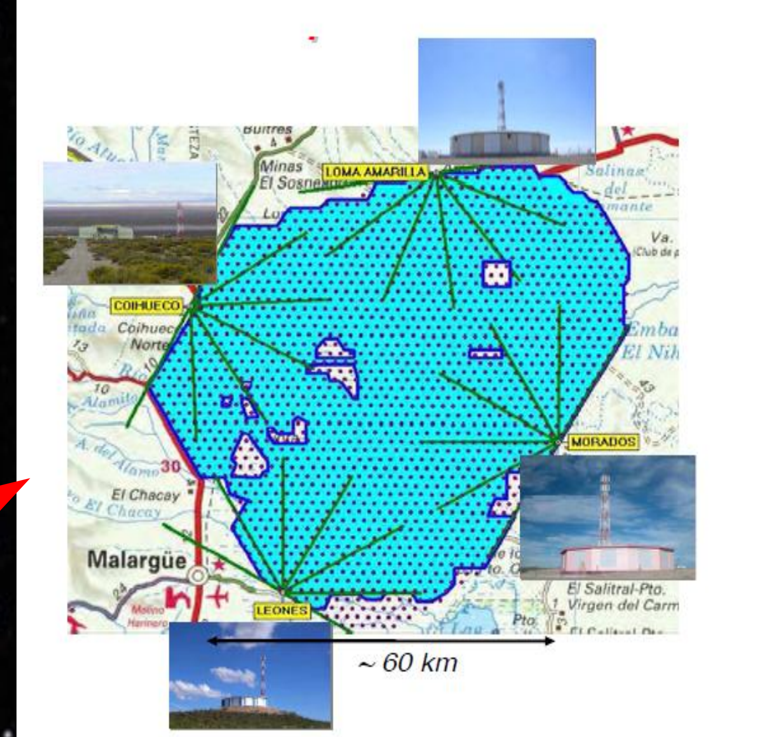
Surface Detector (SD)
1600 Cherenkov stations spaced 1.5 km
Area of 3000 km^2
100% duty cycle
Provides Large Statistics

Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
~10% duty cycle
Provides High Accuracy

+ Enhancements: AMIGA, HEAT, Radio, etc
+Atmospheric monitoring: LIDAR, LDF, cloud monitors

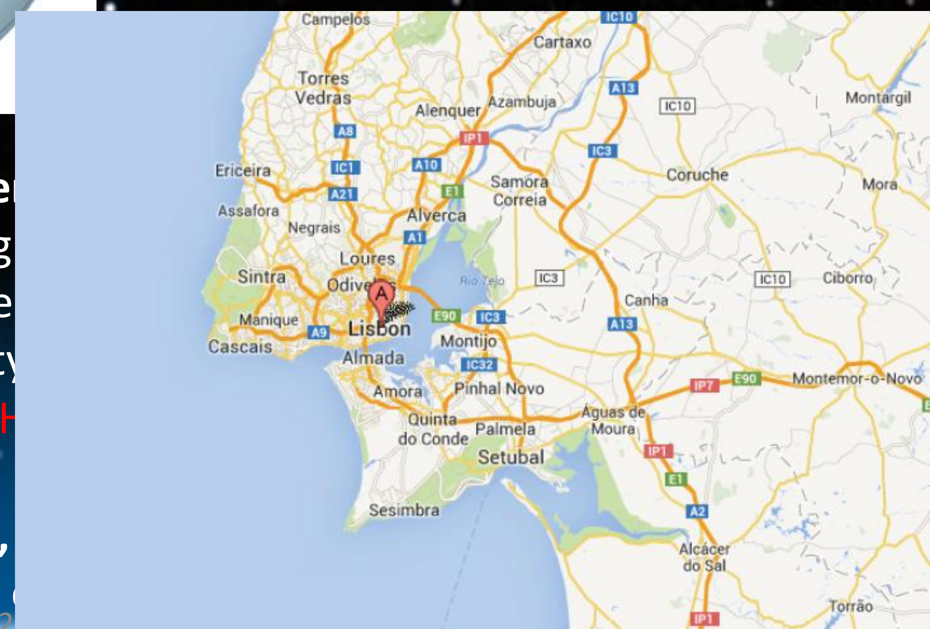
The Pierre Auger Observatory

- Malargüe. Mendoza
- Latitude 35 *S* – Longitude 69 W
- 1400m a.s.l. X=870 g cm^2
- Data taking since 2004
- Installation completed in 2008



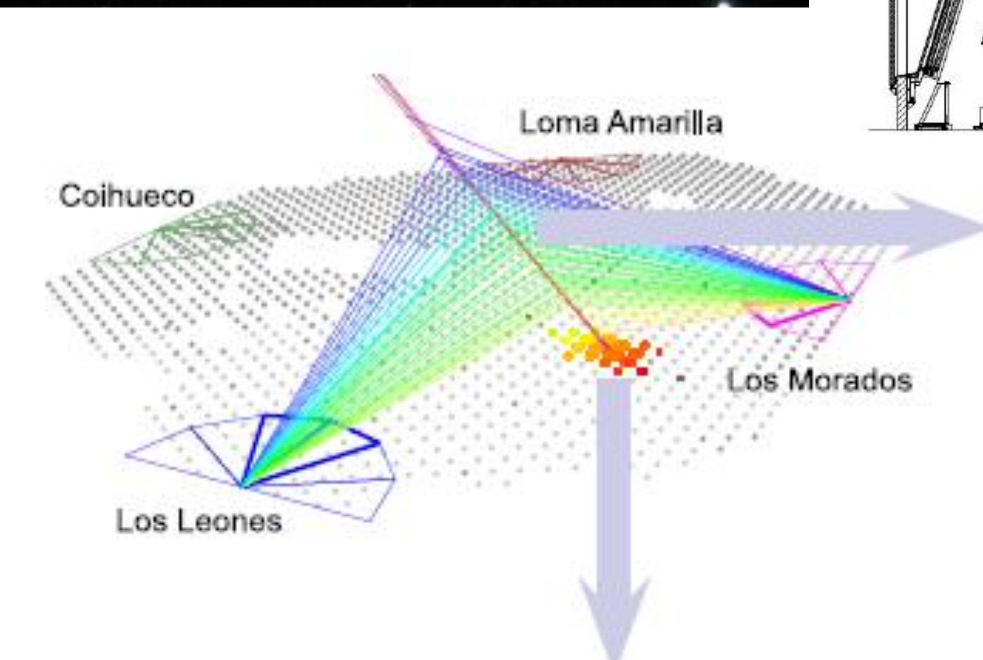
Surface Detector (SD)
1600 Cherenkov stations spaced 1.5 km
Area of 3000 km^2
100% duty cycle
Provides Large Statistics

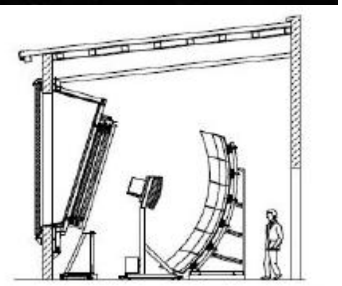
Fluoresce
4 building
Telescope
~10% duty
Provides H

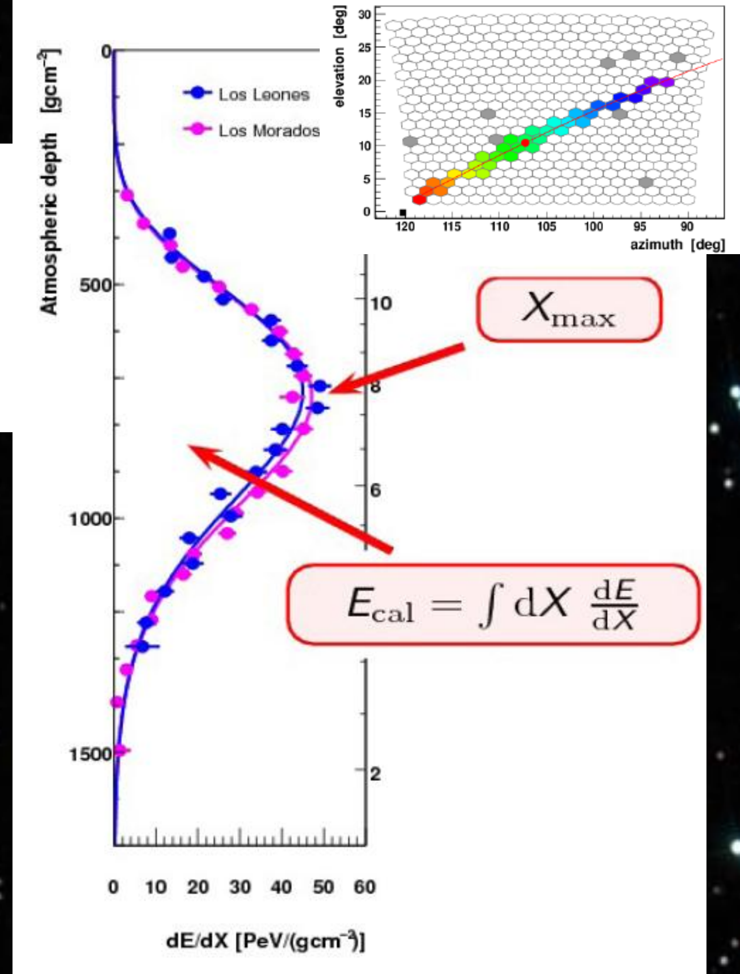


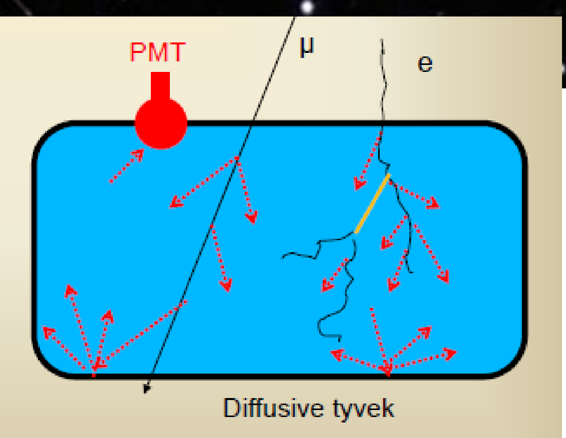
+ Enhancements: AMIGA, HEAT, Radio,
+Atmospheric monitoring: LIDAR, LDF,

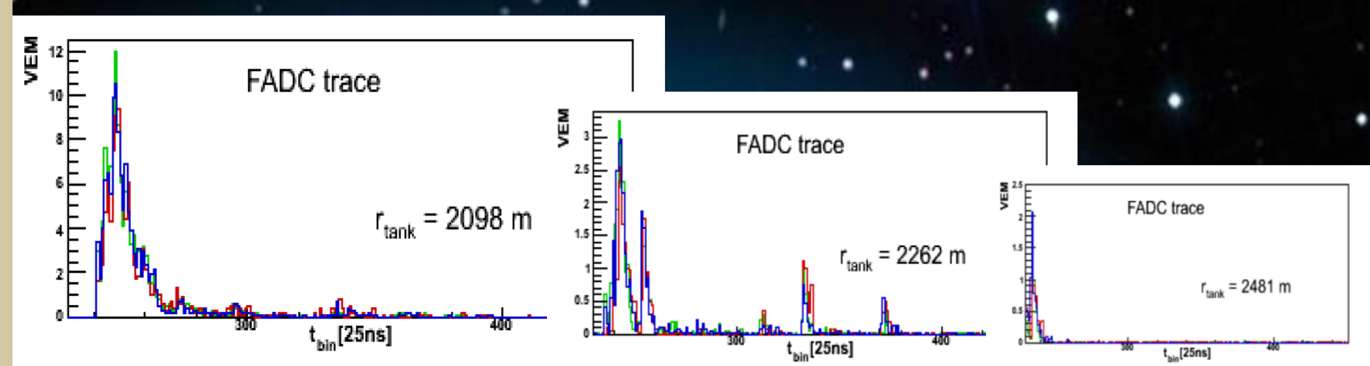
Hybrid detector







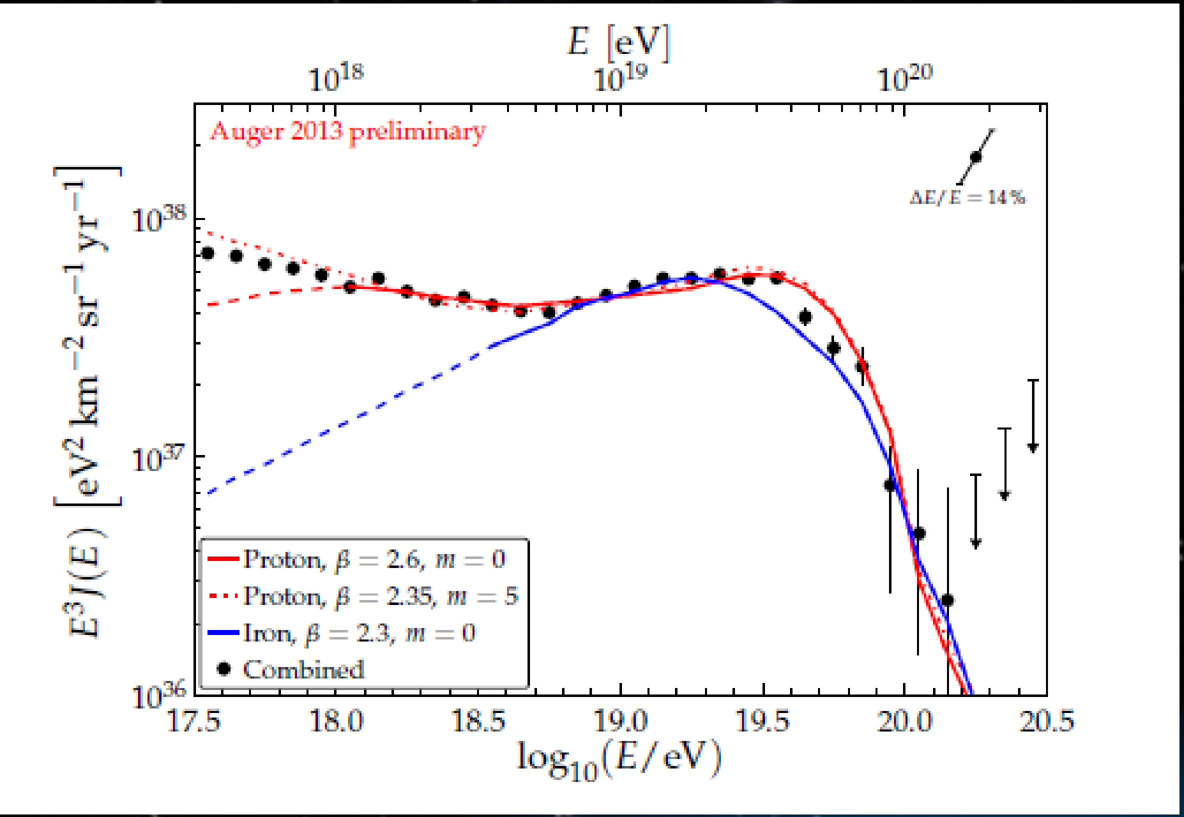




Selected

RESULTS

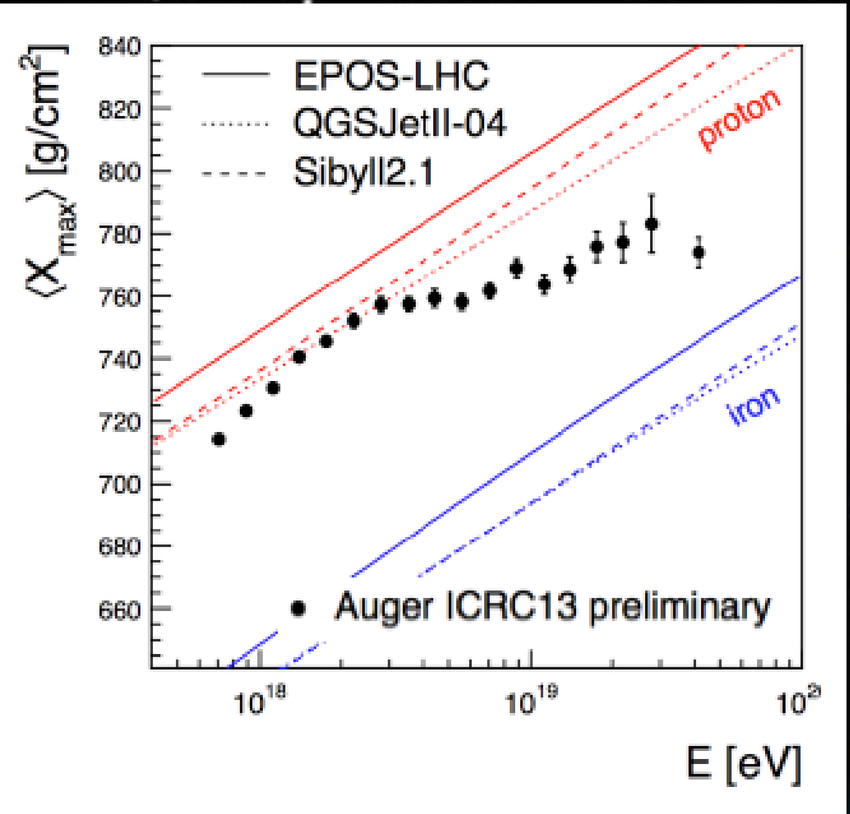
Spectrum

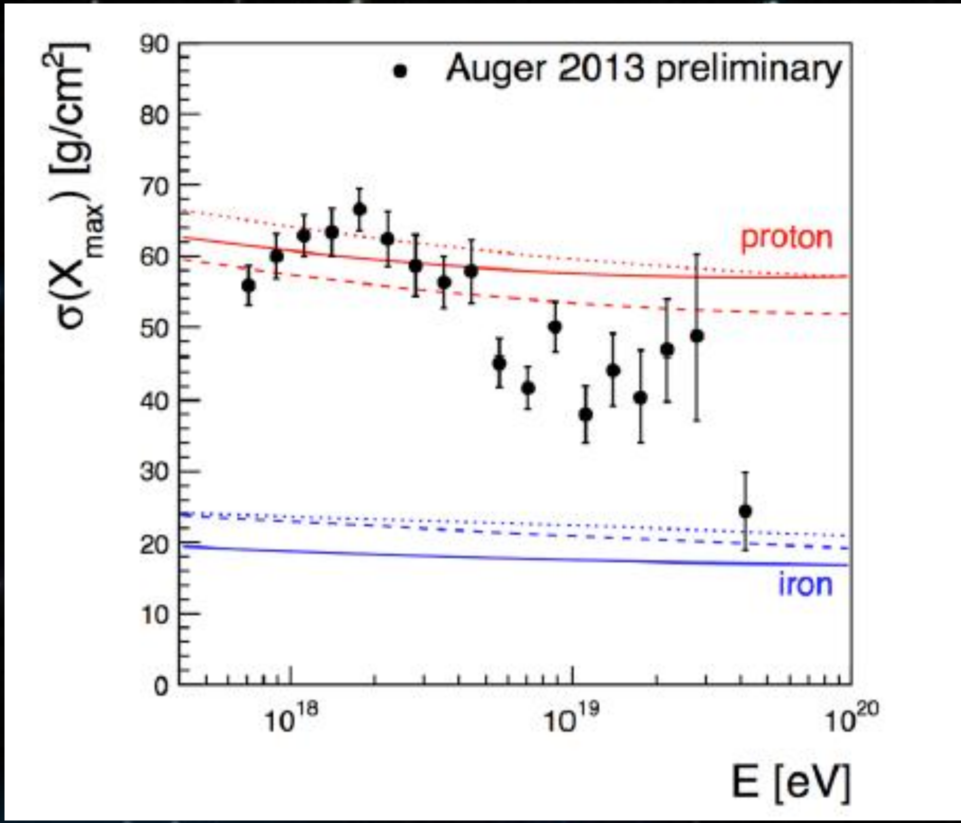


Cutoff at $E_{1/2} = 10^{19.6}$ eV confirmed

Spectrum alone is not enough to discriminate between scenarios

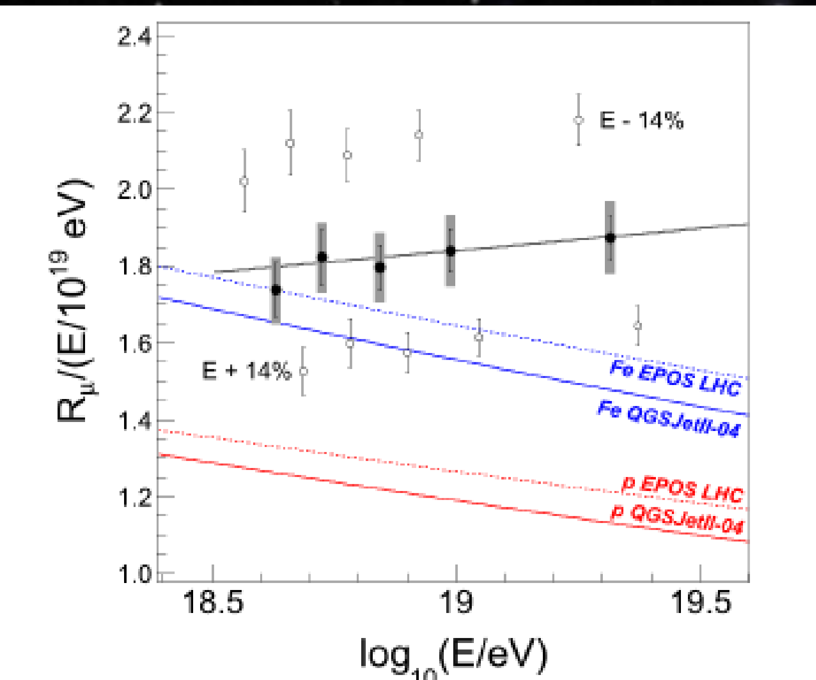
Composition



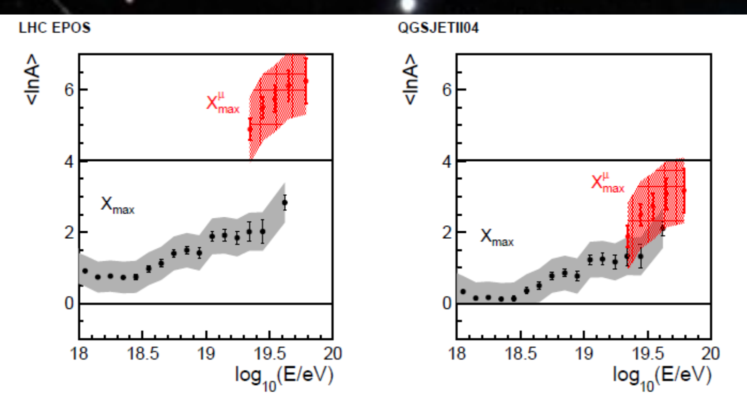


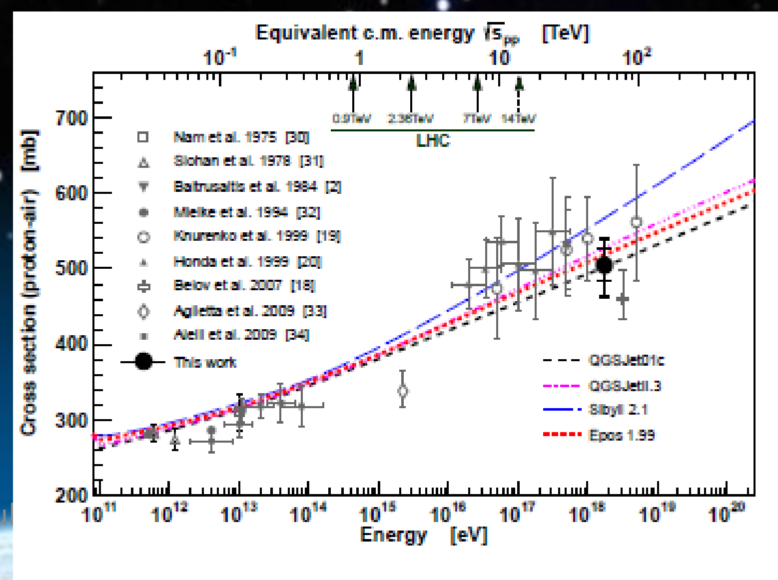
High metallicity (provided the high energy interaction models are right)
Can we trust the model extrapolations beyond the LHC energies that far?

Particle Physics & Hadronic Models



- Evidence that model predictions need to be improved
  - Muons are sensitive to the hadronic backbone of the air shower
- UHECR + air showers data constrain high energy models

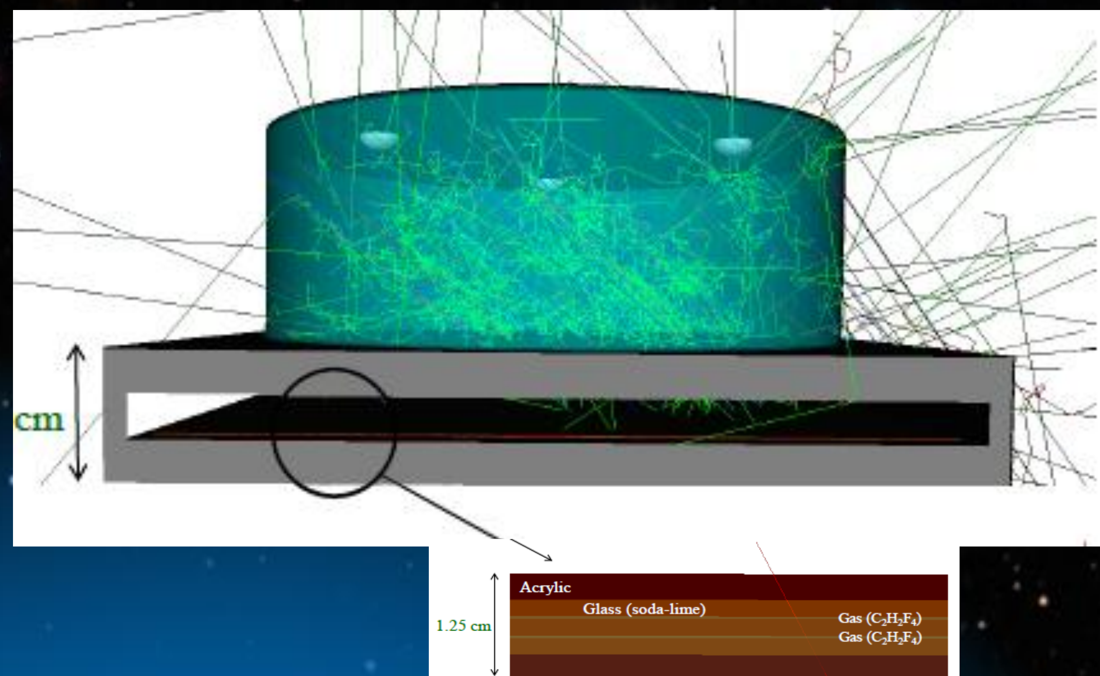




MARTA
Muon Auger RPC Tank Array

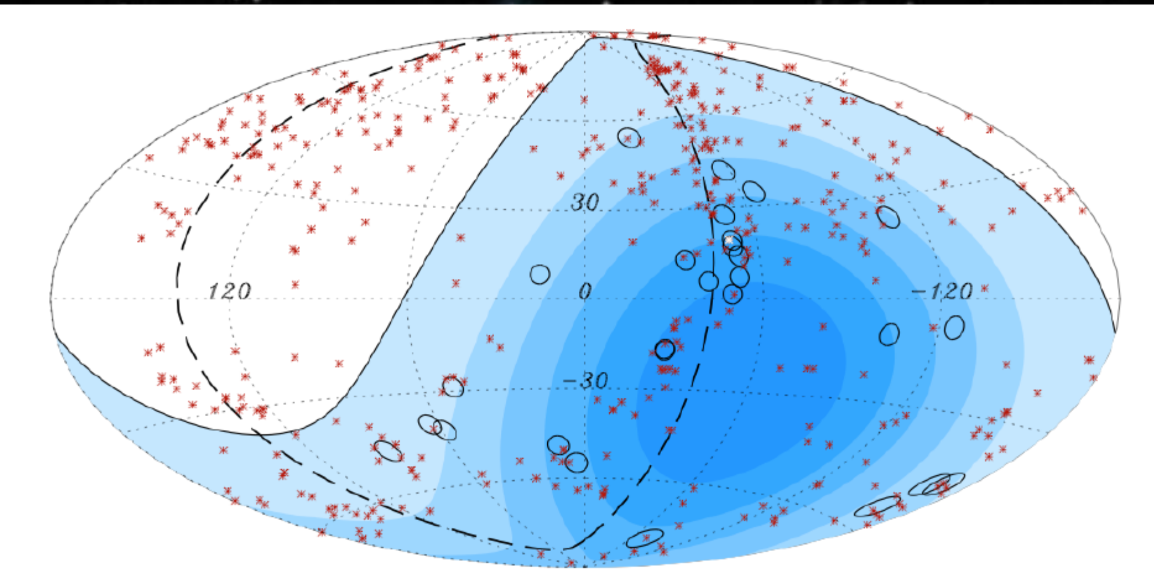
- LIP is leading a proposal for an Auger upgrade to enhance the muon sensitivity and improve the capabilities to do:

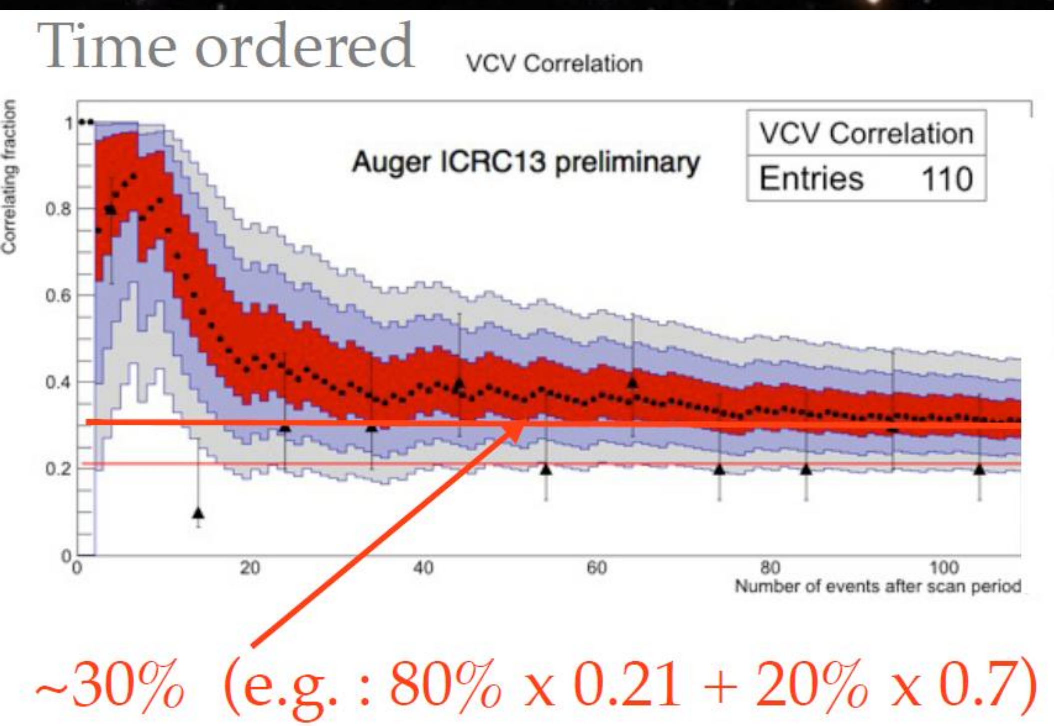
- Hadronic physics beyond the LHC
- Mass separation of light and heavy primaries
  - Charged particle astronomy!!



~ns time resolution

L. Cazon XXIII ENAA July-2013 Lisbon 23

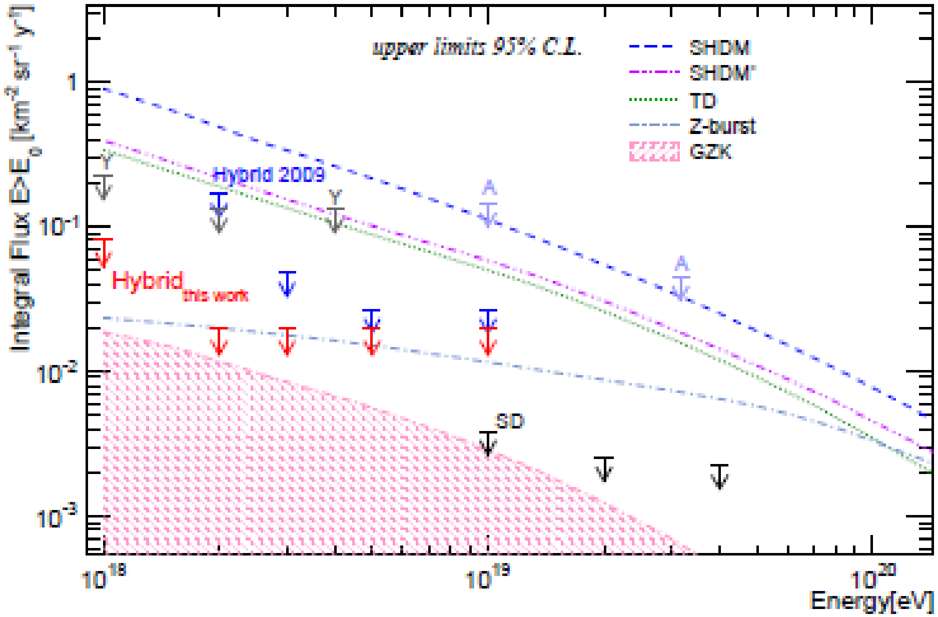


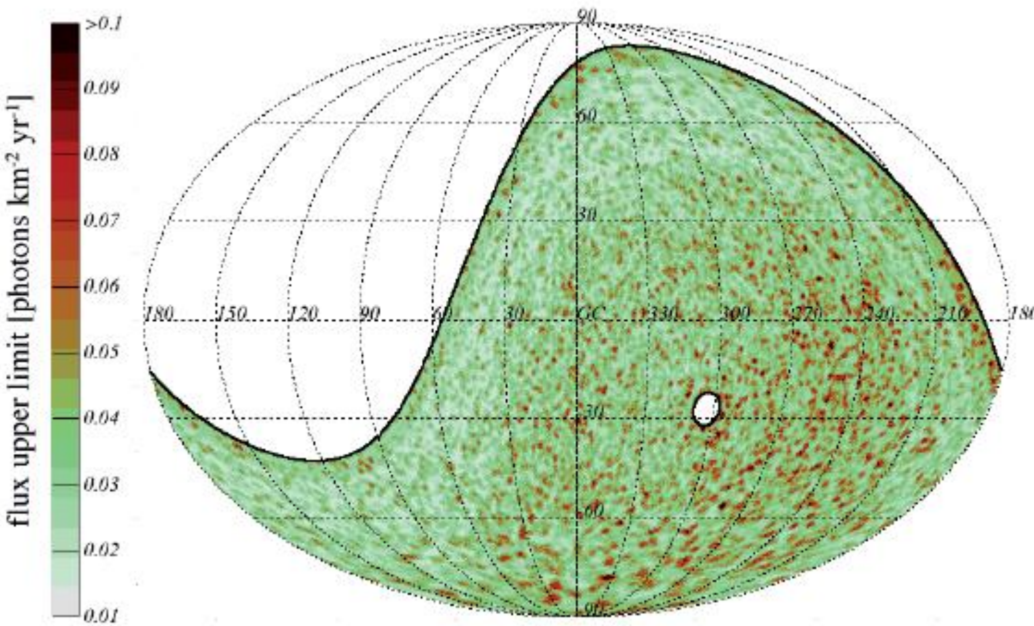


Sky Anisotropy

- In 2008 a correlation of the arrival direction of the highest energy CR with AGN was published
- The degree of correlation has dropped to 30%

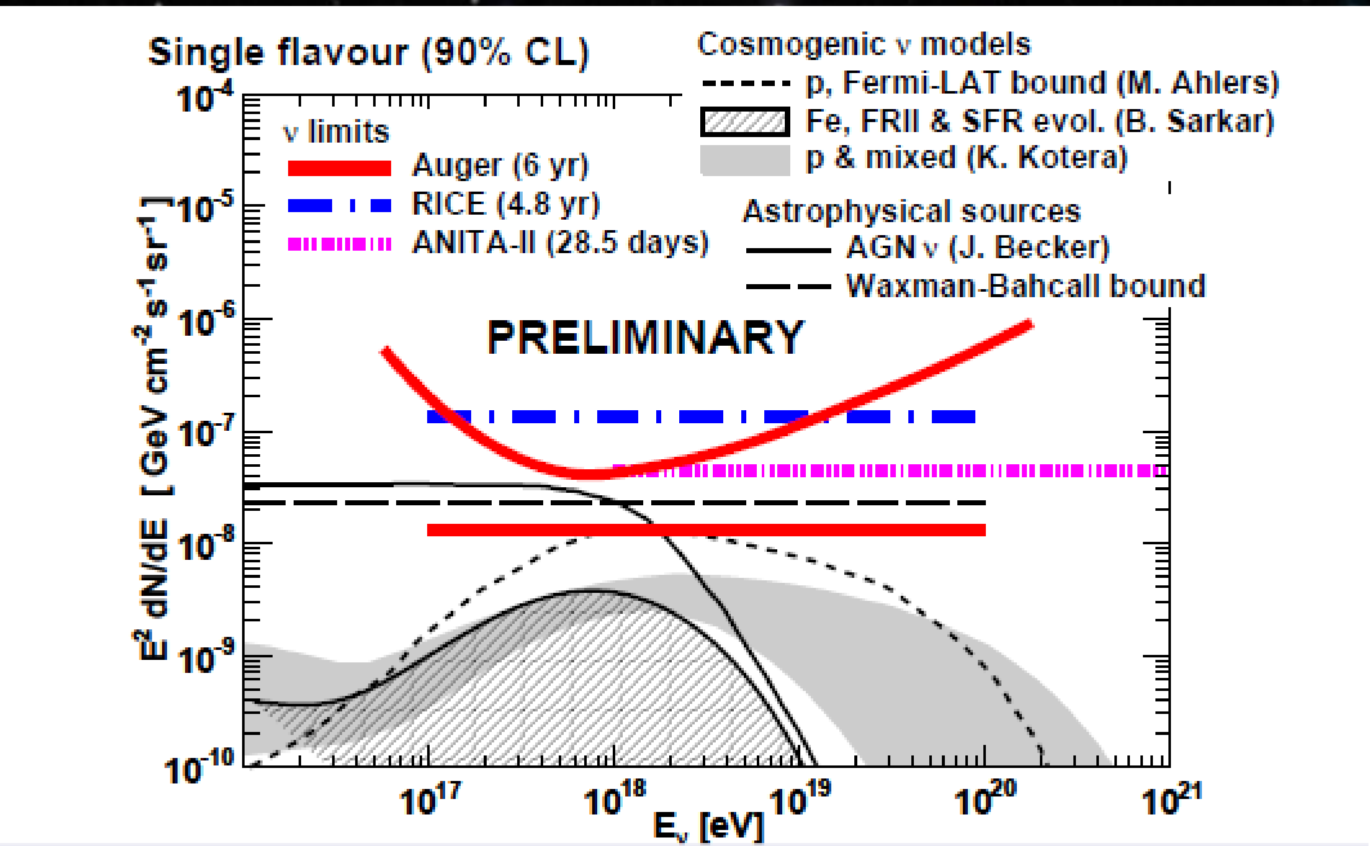
Photons

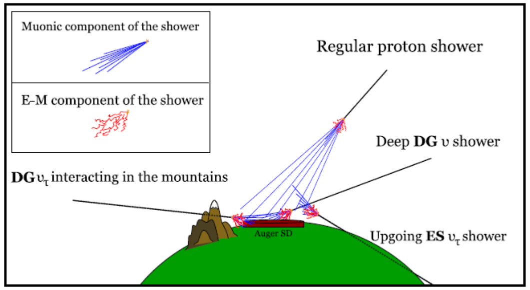




- Top-down models excluded
- Astrophysical acceleration favoured

Neutrinos


Single flavour (90% CL)
ν limits
Auger (6 yr)
RICE (4.8 yr)
ANITA-II (28.5 days)
Cosmogenic ν models
p, Fermi-LAT bound (M. Ahlers)
Fe, FRII & SFR evol. (B. Sarkar)
p & mixed (K. Kotera)
Astrophysical sources
AGN ν (J. Becker)
Waxman-Bahcall bound
PRELIMINARY
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E_ν [eV]


Muonic component of the shower
E-M component of the shower
Regular proton shower
Deep DG υ shower
DG $υ_\tau$ interacting in the mountains
Upgoing ES $υ_\tau$ shower

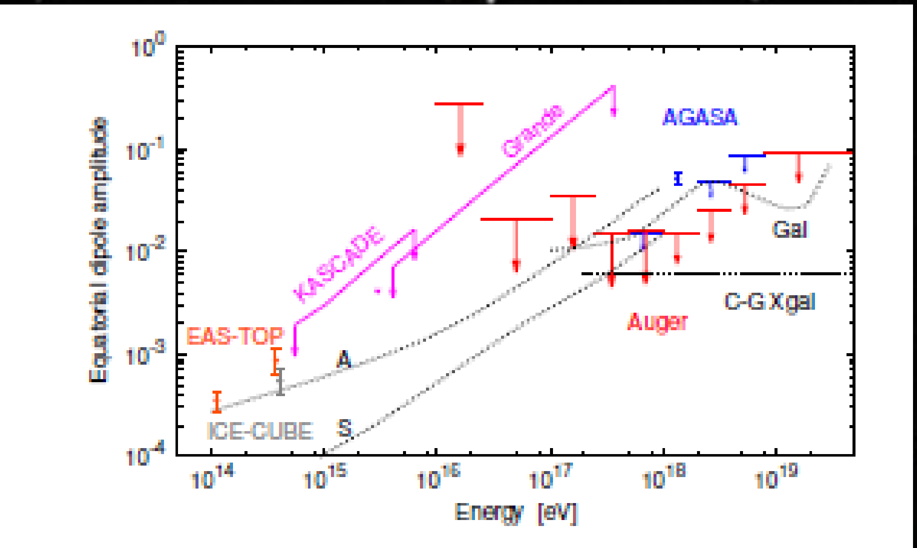
Conclusions

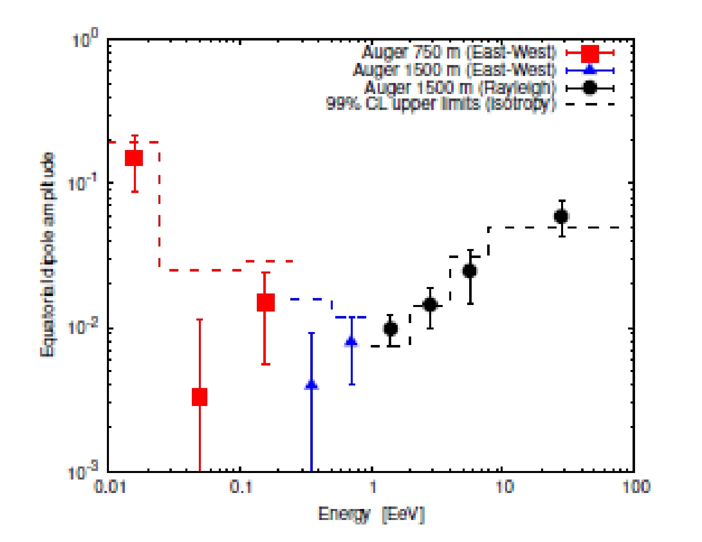
- Spectrum termination observed:
  - GZK cutoff (CMB) or Emax of the sources?
- Astrophysical acceleration prefered (vs Top-Down)
- Super GZK (weak) anisotropy
  - Sources within ~100 Mpc sphere (light composition)
- High energy interaction models (above LHC) under stress. (New physics?)
- Mass composition *apparently* heavy (extremely high metallicity)

Puzzle on the UHECR origin still waits for the missing piece

Back up

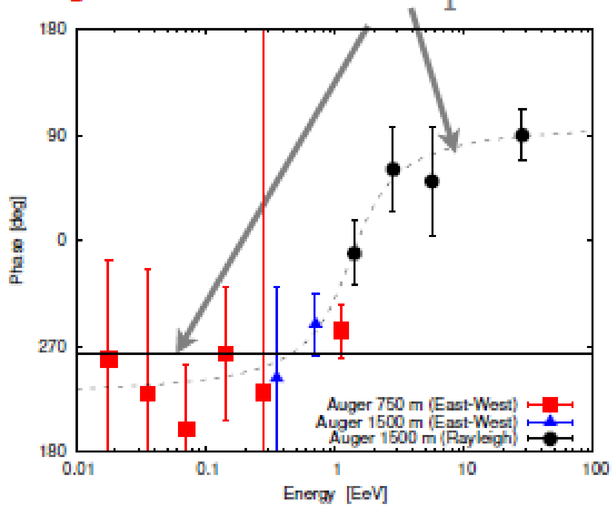
CR Dipole



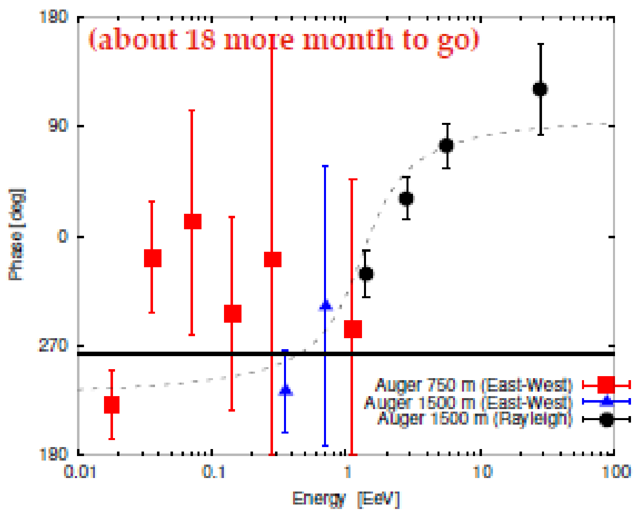


Data up to December 2010

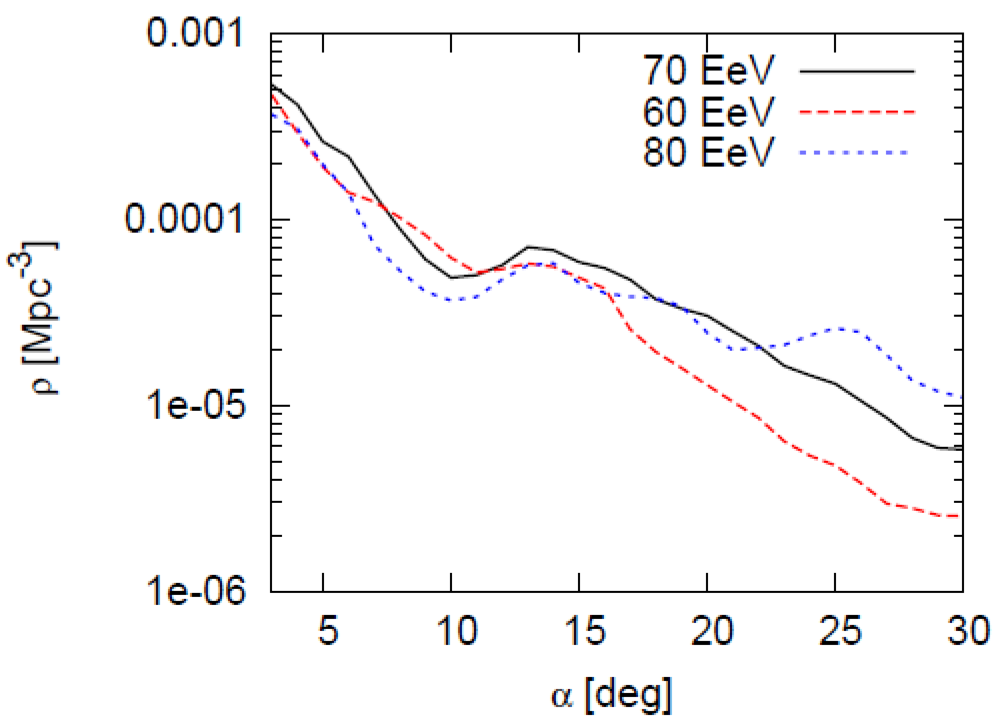
(April 2011) Prescription set

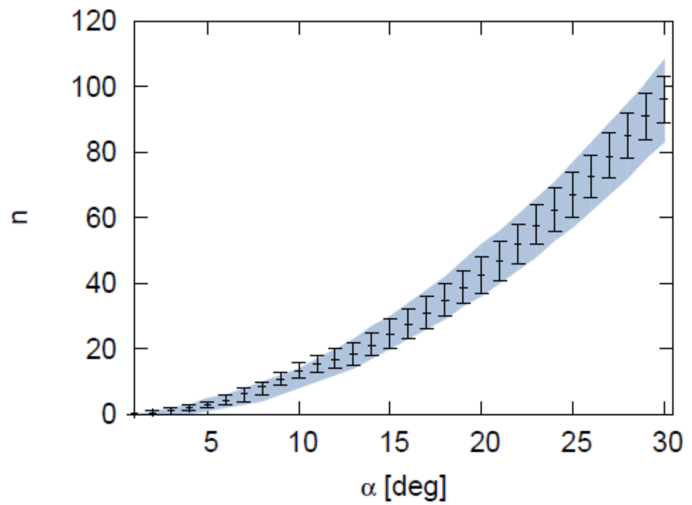


New data Prescription status



Density of sources





Autocorrelation function

Absence of clustering means high density of sources -> Limits can be imposed

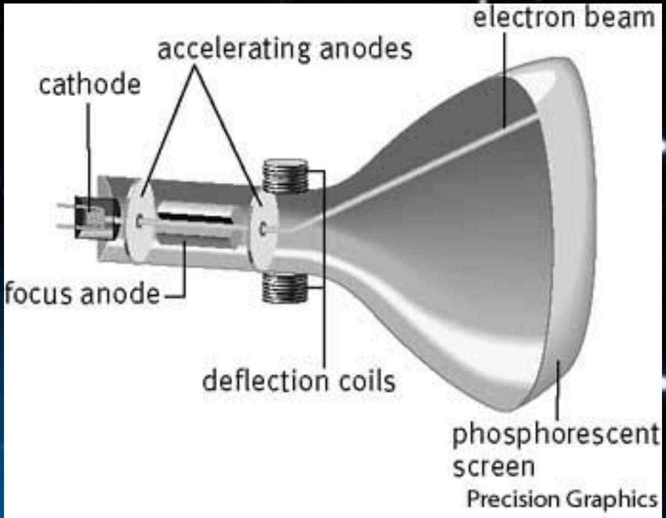
The energy of an Ultra High Energy Cosmic Ray

- $E = 3 \times 10^{20}$ eV = 50 Joules (detected by Fly's Eye)
  - Equivalent to the energy of a full speed tennis ball
  - But this energy is carried by a single atomic nucleus!

IF YOU ARE NOT IMPRESSED, think about this:

- A electron on an old TV (Catodic Ray Tube) is accelerated in 10,000 V

  $E = 10^4$ eV
- We need to multiply by factor 10^{16} to get close to a UHECR



- If we multiply the energy released by a match by the same factor, we would obtain the energy released by the “Tsar Bomb”, the largest on the soviet arsenal.

10,000 times Hiroshima

If the atoms of a human cell were accelerated to the energy of an UHECR, it would also reach this energy

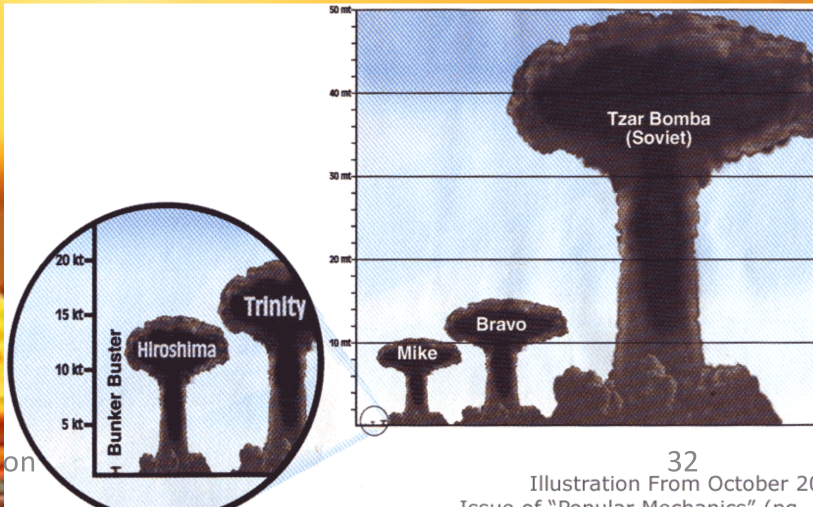
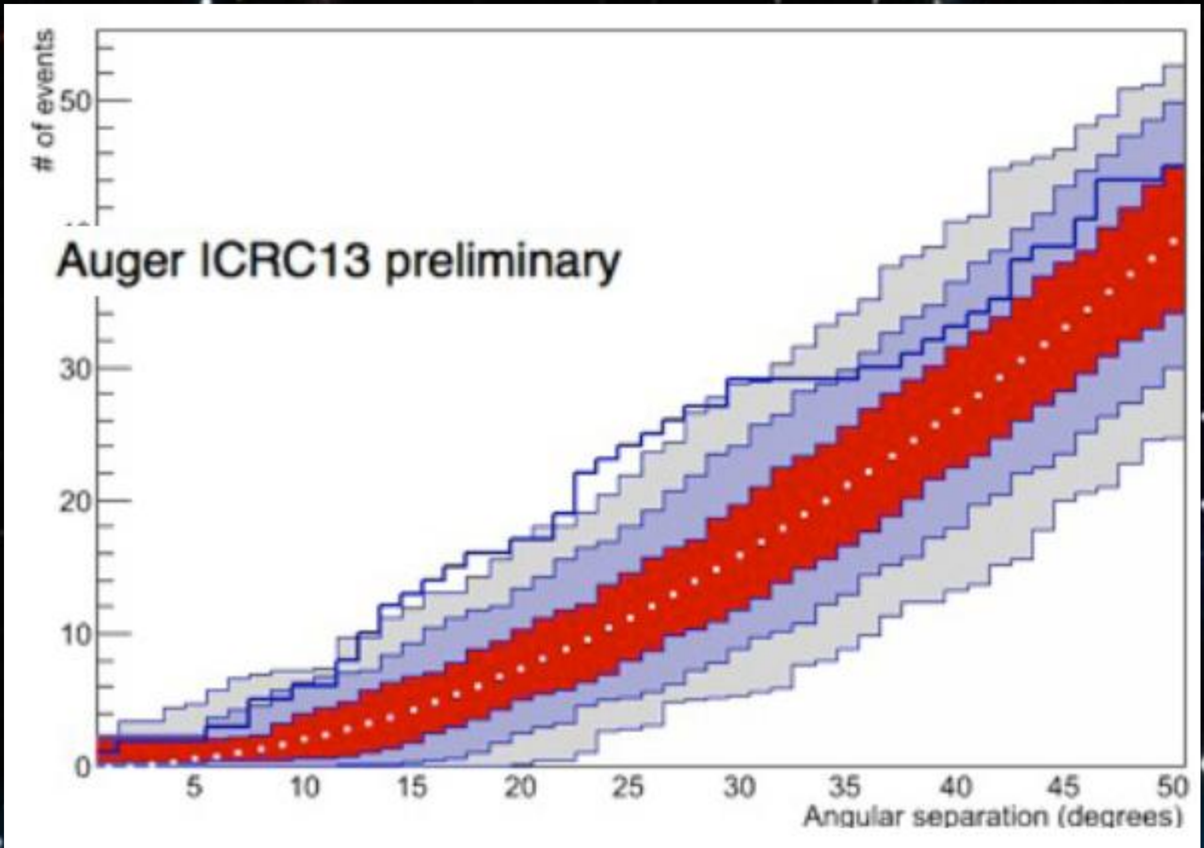


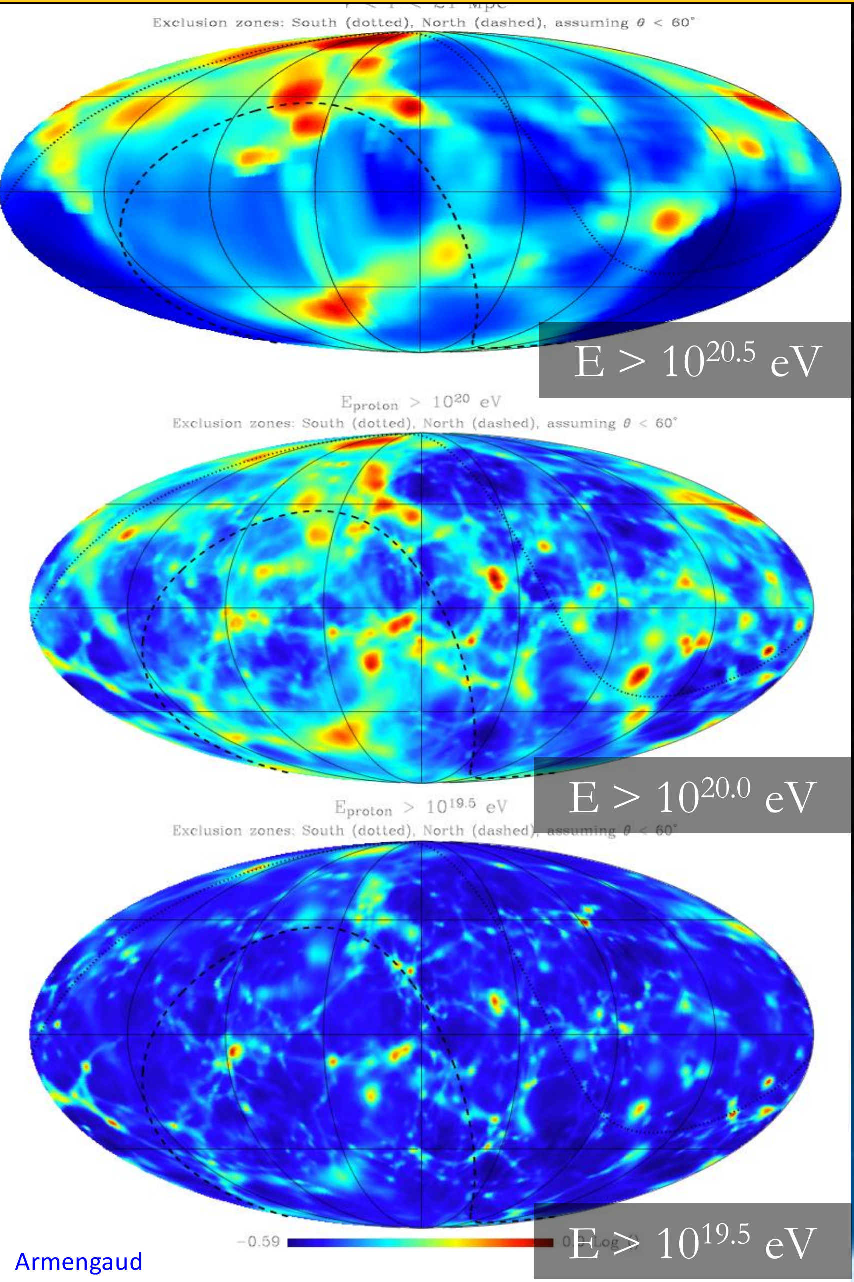
Illustration From October 20
Issue of “Popular Mechanics” (pg.

Cen-A correlation

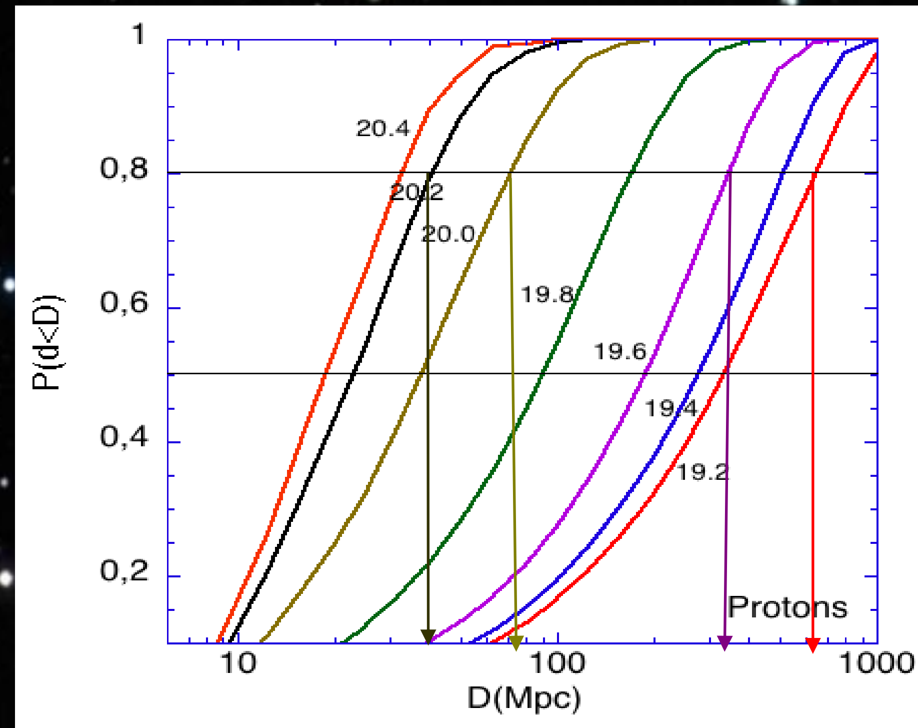


Why this window of opportunity?

Below: Constraint DM Simulations showing column density up to the event horizon corresponding to each energy. The closer, the more anisotropic.



Armengaud

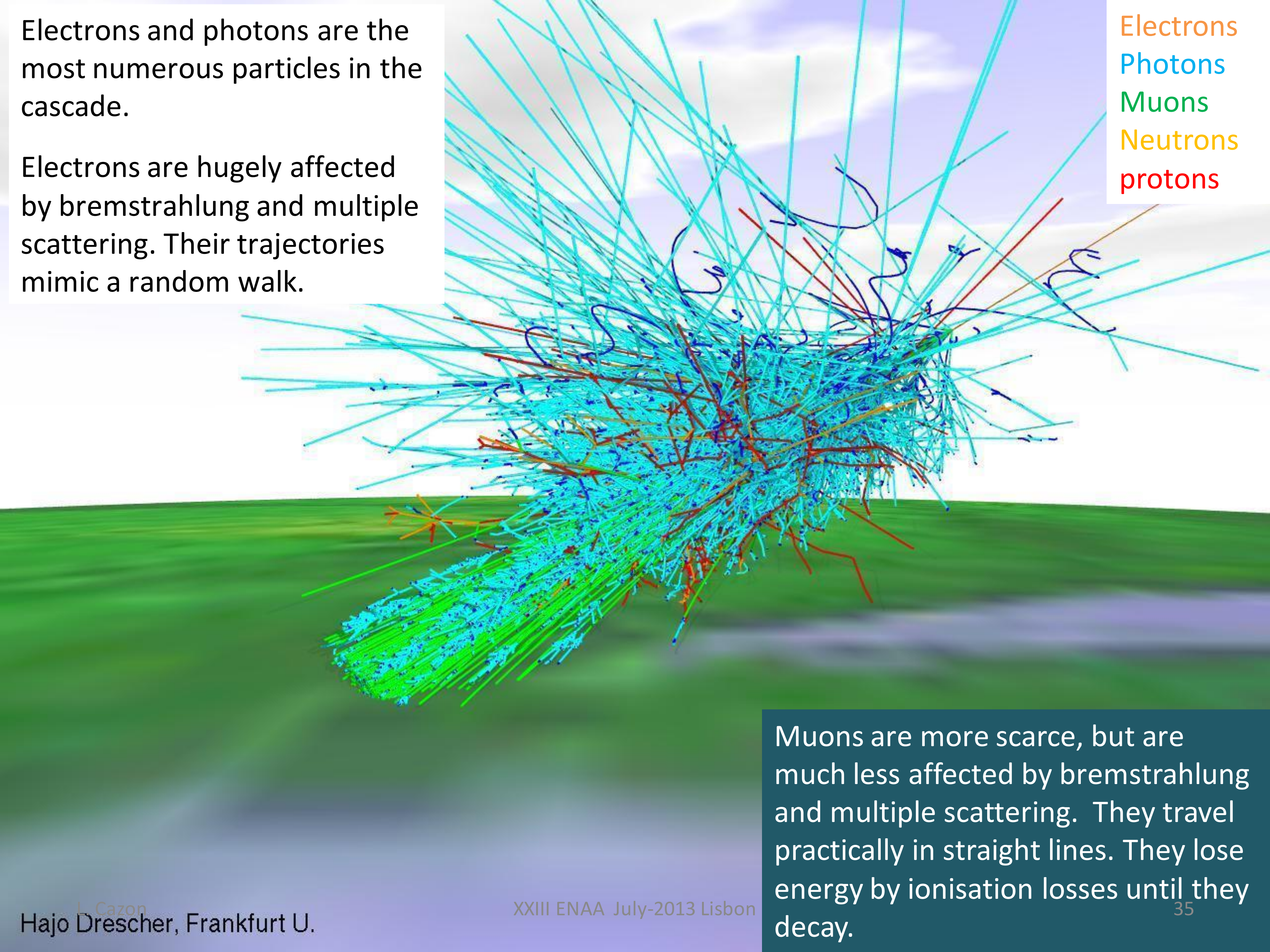


Above: fraction of UHECR protons produced within a sphere of radius D and reaching Earth at different energies. (Interactions CMB)

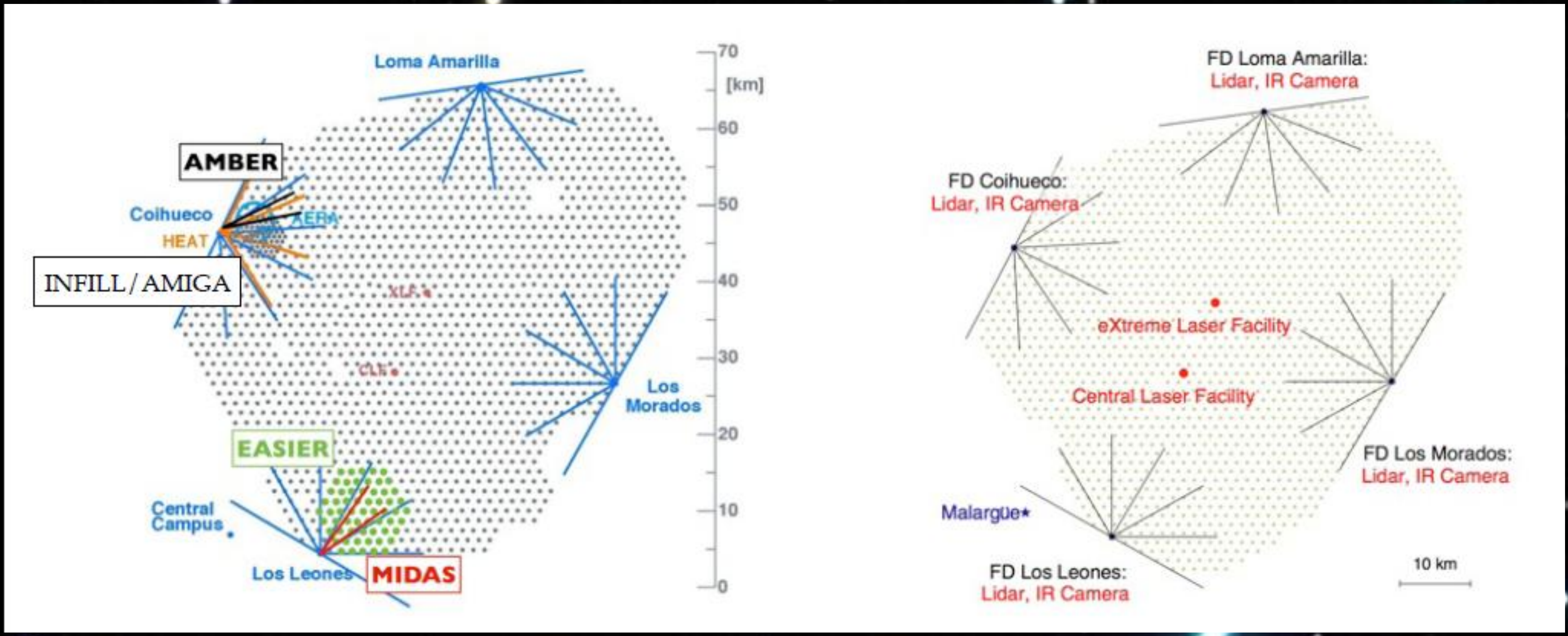
The higher the energy, the smaller the **event horizon**

Electrons and photons are the most numerous particles in the cascade.

Electrons are hugely affected by bremstrahlung and multiple scattering. Their trajectories mimic a random walk.



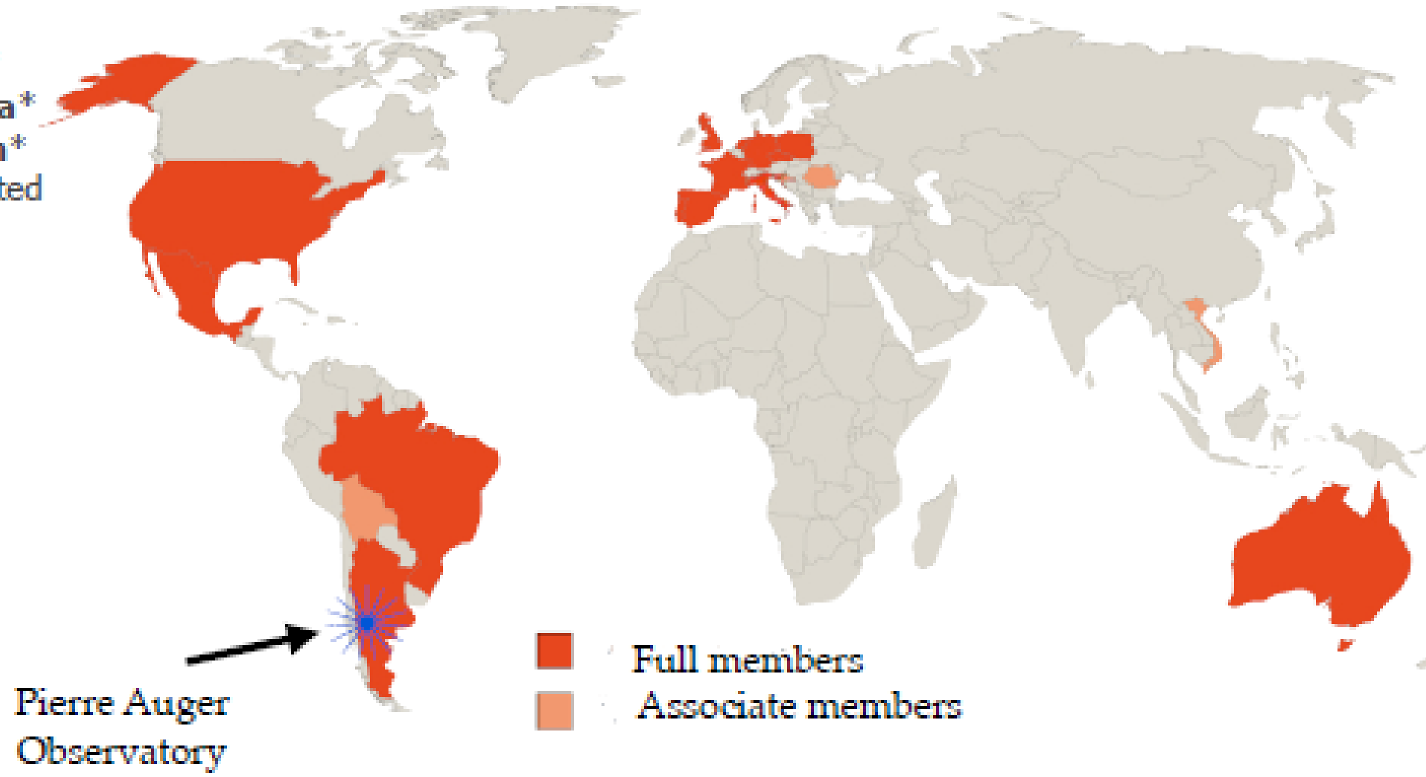
Muons are more scarce, but are much less affected by bremstrahlung and multiple scattering. They travel practically in straight lines. They lose energy by ionisation losses until they decay.


Loma Amarilla
AMBER
Coihueco
HEAT
AERA
INFILL / AMIGA
XLF
CLF
Los
Morados
EASIER
Central
Campus
Los Leones
MIDAS
70
[km]
60
50
40
30
20
10
0
FD Loma Amarilla:
Lidar, IR Camera
FD Coihueco:
Lidar, IR Camera
eXtreme Laser Facility
Central Laser Facility
FD Los Morados:
Lidar, IR Camera
Malargüe
FD Los Leones:
Lidar, IR Camera
10 km

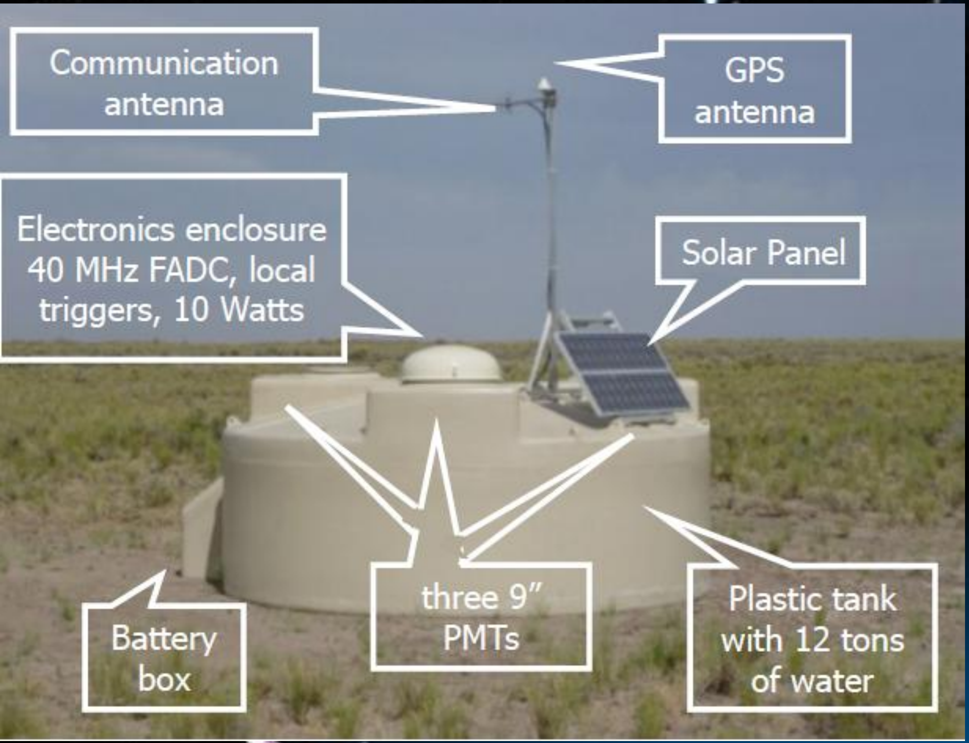
Collaboration : ~ 500 members & 19 countries

Argentina
Australia
Brazil
Croatia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom
USA

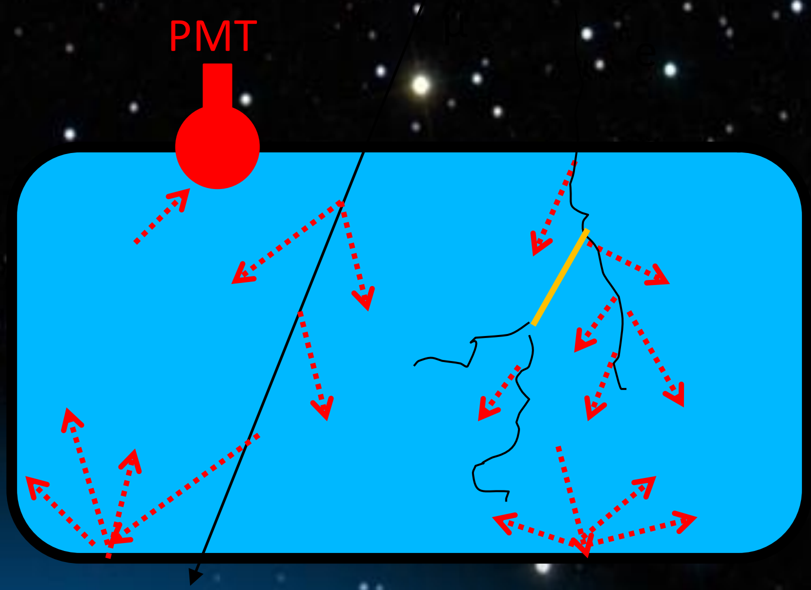
Bolivia*
Romania*
Vietnam*
*Associated



SD detectors

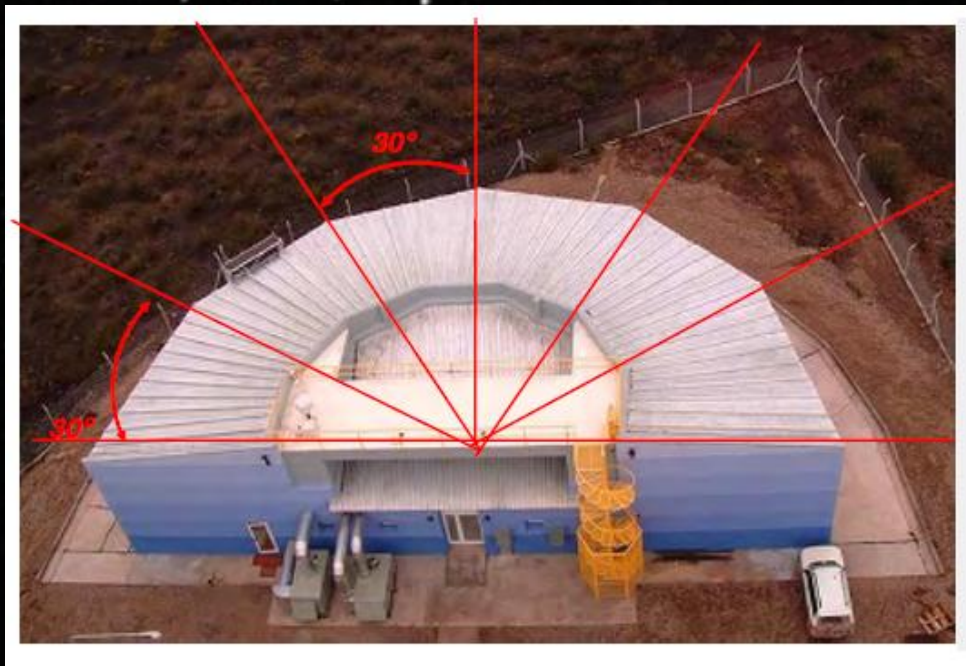


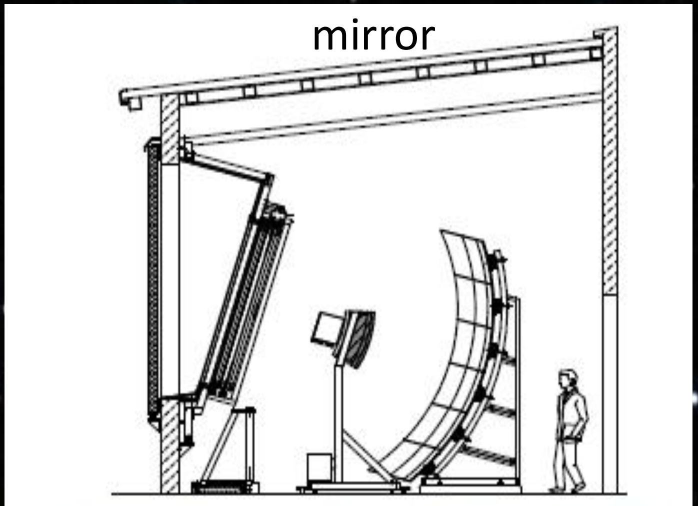
Water Cerenkov Detectors give signal proportional to their track lengh in water
Difficult to separate different particle types.
Some indirect methods

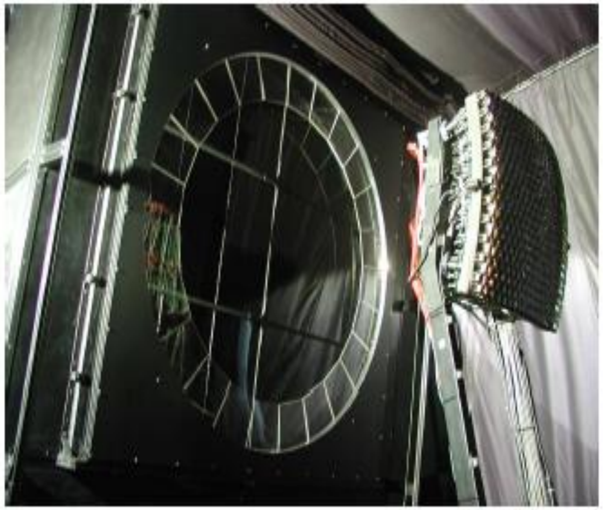


Diffusive tyvek

FD detectors

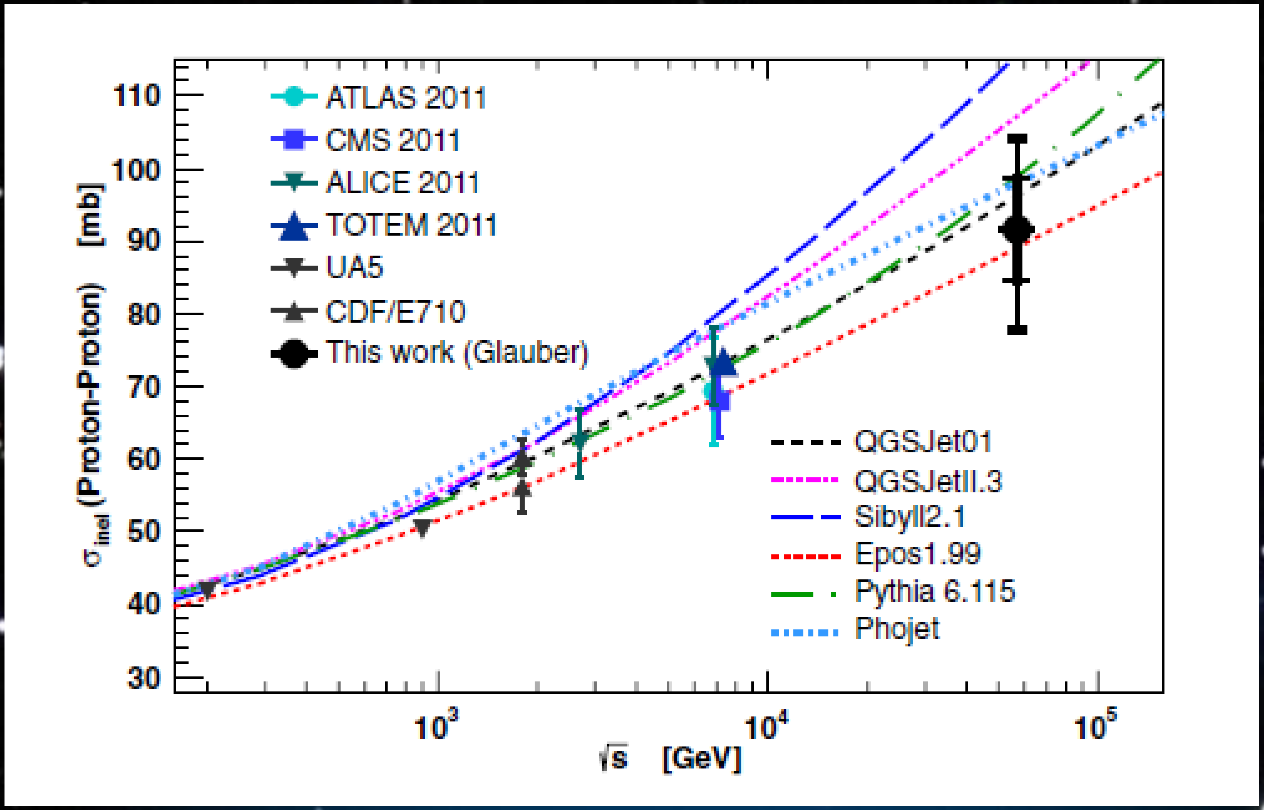






- pixels
- 440 Photonis XP3062
- Pixel f.o.v. = 1.5 x 1.5 deg
- Collect Fluorescence light emited by the shower. Mainly the central region of the EM cascade.

p-Air -> p-p cross section



Photons and neutrinos

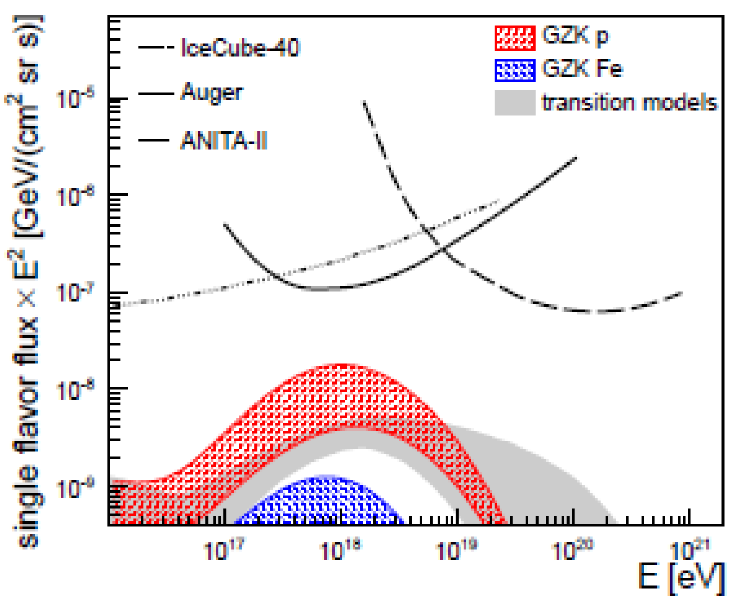


Figure 17: Compilation of 90 %CL single-flavor upper limits for diffuse neutrino fluxes assuming a proportion of flavors of 1:1:1 due to neutrino oscillations. Data are from IceCube [175], Auger [176] and ANITA [177]. The shaded area corresponds to expected GZK neutrino fluxes computed under different assumptions of source evolution scenarios [166] with power-law energy spectra of $\gamma = -2.0$ and $E^{Z}_{\max} = Z \cdot 10^{20}$ eV. The grey band depicts different transition models and source evolutions adapted from Ref. [178] (see text for details).

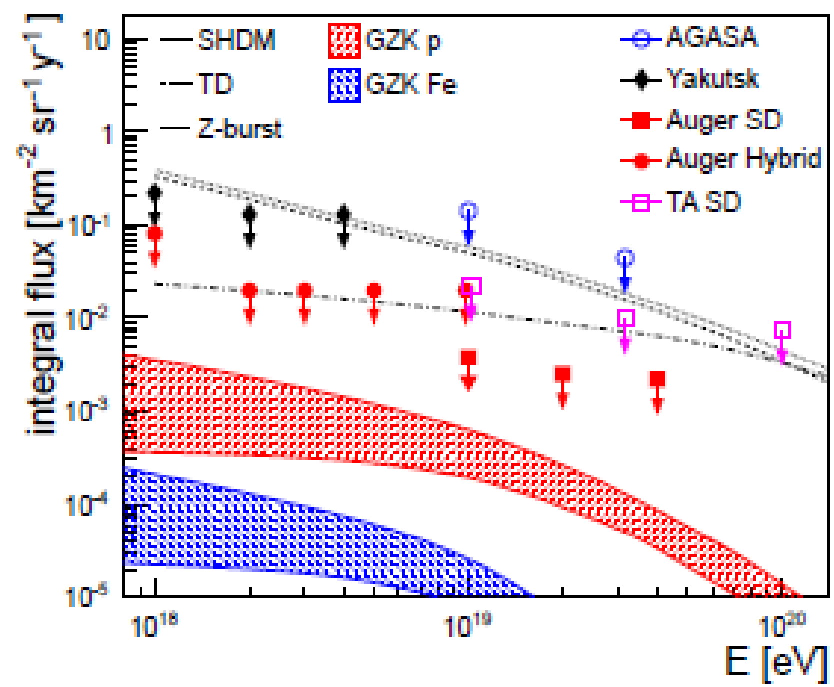


Figure 16: Integral photon flux limits at 95% C.L. from AGASA [161], Yakutsk [162], Auger [163, 164] and TA [165] compared to flux predicitons for GZK-photons [166], top-down scenarios of super-heavy dark matter (SHDM) [167] and topological defect (TD) models, and Z-bursts [168].