Pierre Auger Observatory

studying the universe's highest energy particles

Very high energy cosmic-rays

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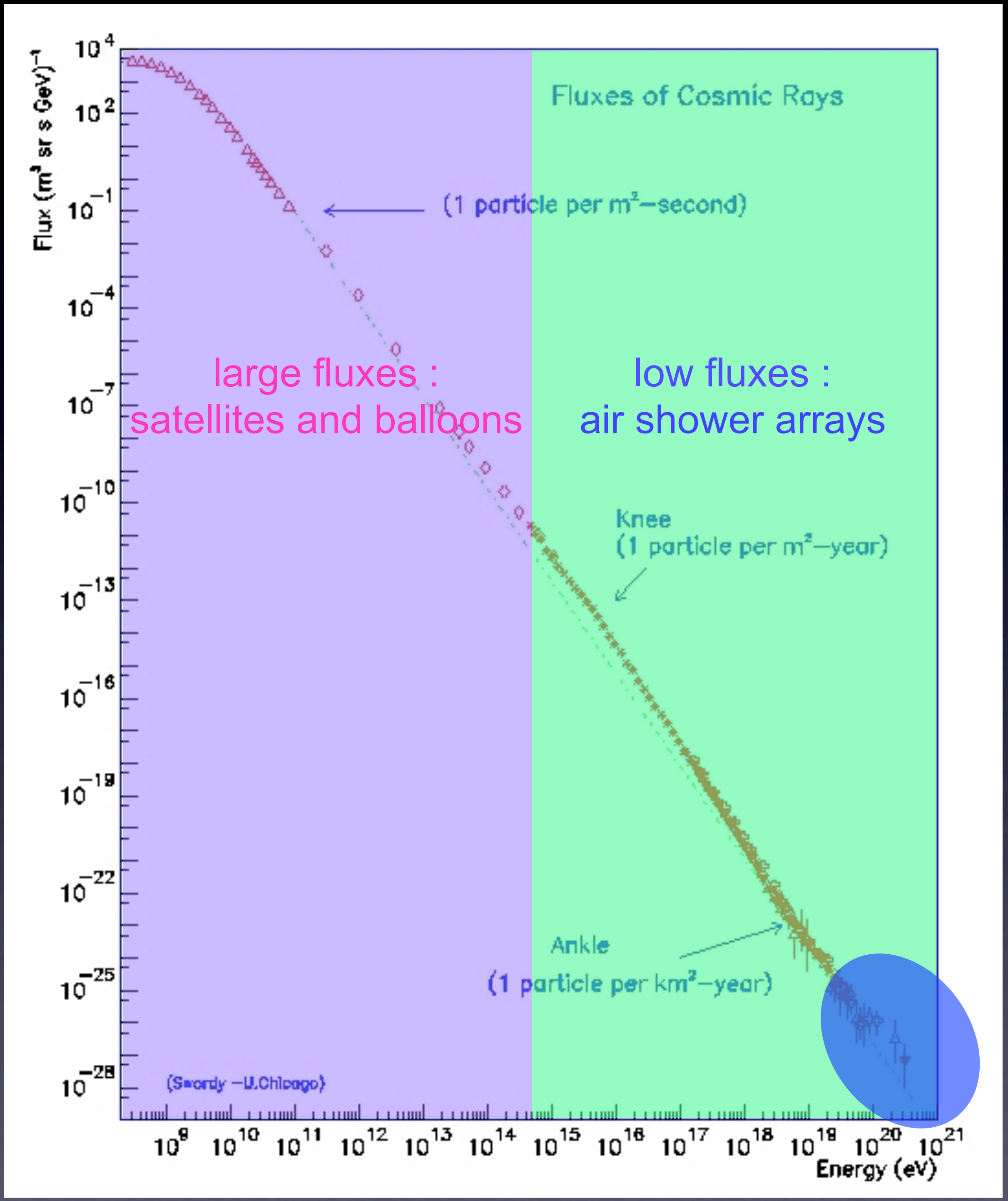
The cosmic spectrum : a 50 years old mystery



Spectrum measured on 12 orders of magnitude in energy and 32 in flux

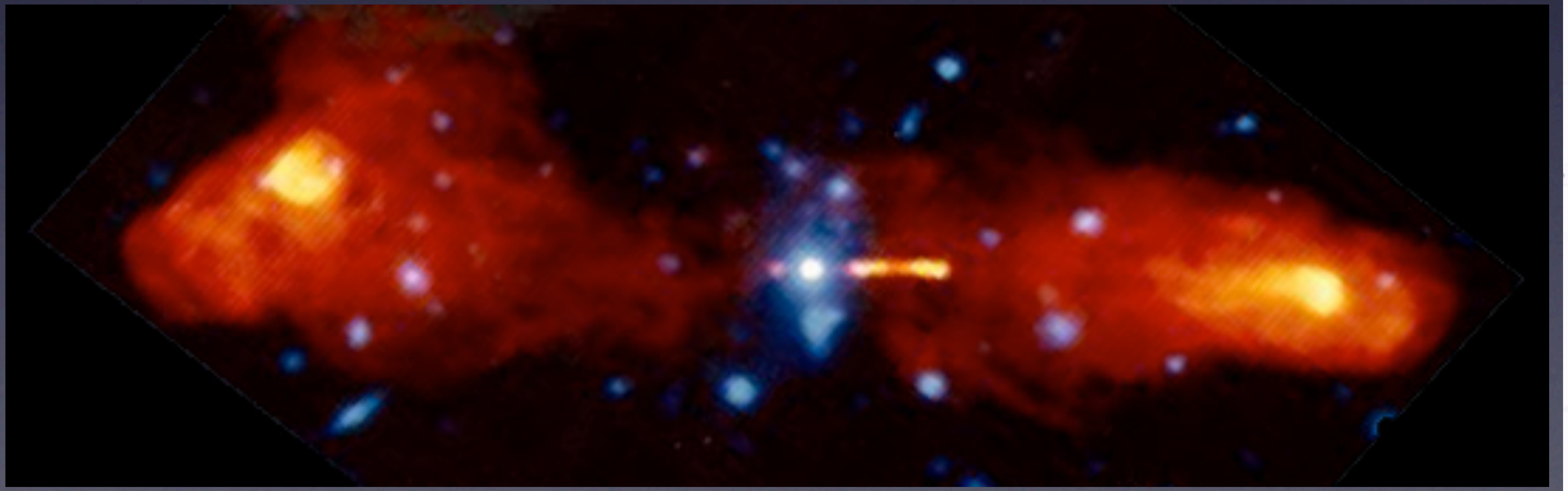
- At low energy (<$10^{14\text{-}15}$ eV) the fluxes are large
-> domain of satellite and atmospheric balloons

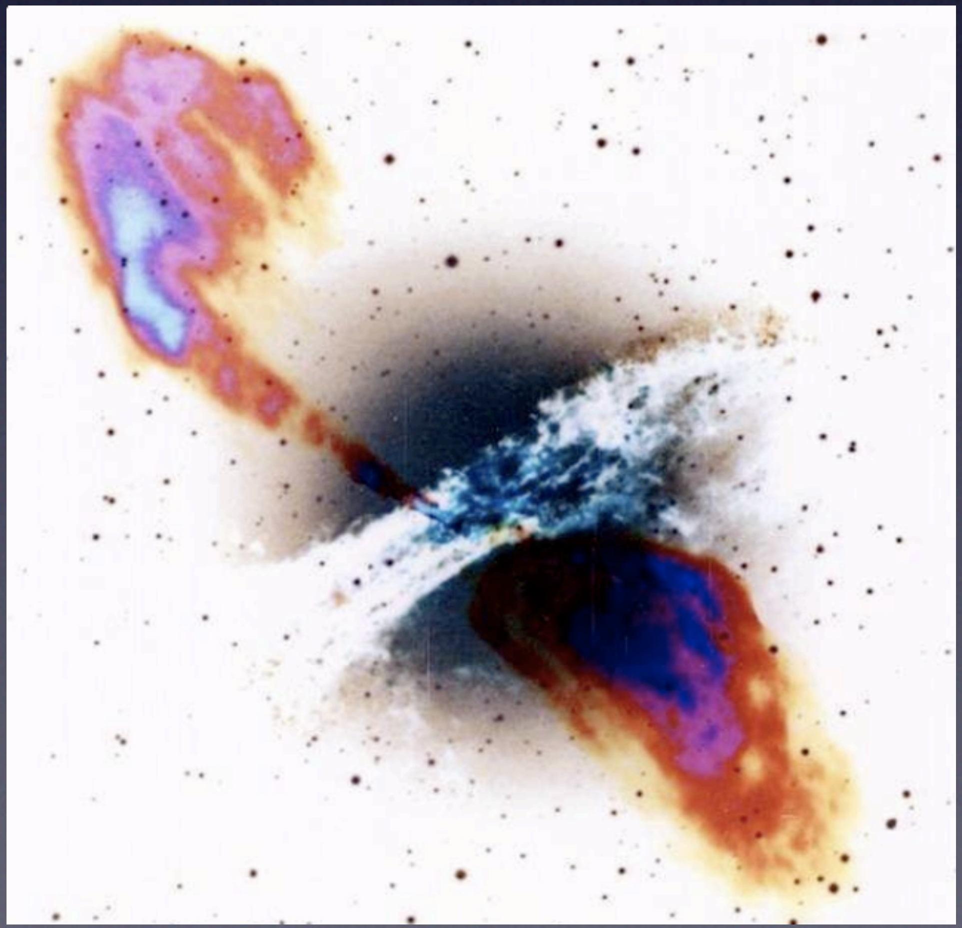
- At high energies (low fluxes) one uses air shower properties to detect cosmic-ray
-> domain of air shower arrays and fluorescence detector

- At the highest energies (~10^{20} eV), extremely low fluxes (<1 CR.km^{-2}.century^{-1})
-> domain of giant air shower detectors

Possible sources of UHE cosmic-rays

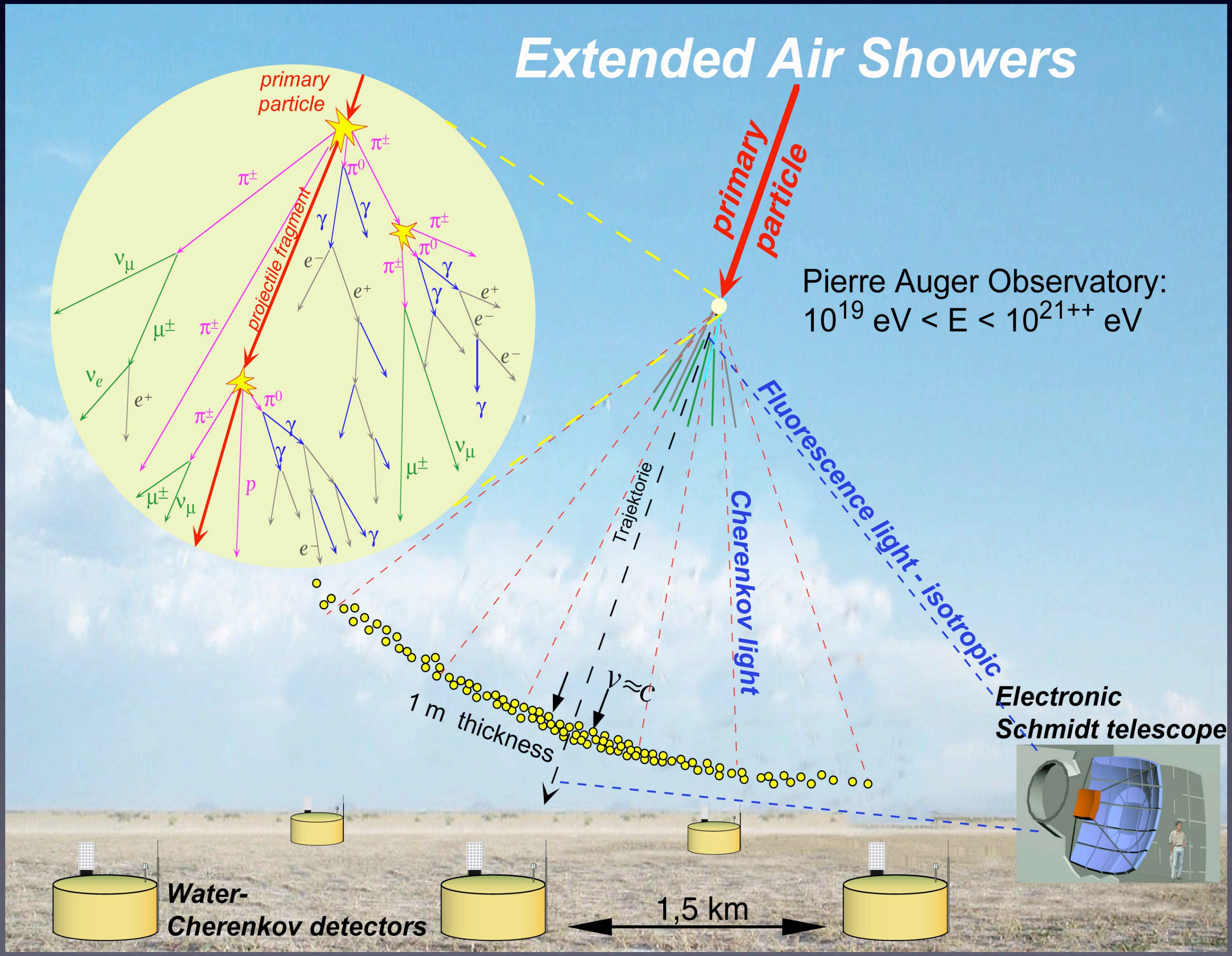
- Astrophysical sources : bottom-up scenarios
  - Acceraleration takes place in astrophysical sites due to electromagnetic processes (Fermi acceleration)
  - Maximum energy reachable constrained by : ambiant magnetic fields, size of the acceleration site, ambiant radiation density
  - Potential sources :
    - Galactic : SNRs, superbubles, Gamma ray bursts, neutron stars
    - Extragalactic : AGN, relativistic jets, hot spots, Gamma Ray bursts





Detection of VHE and UHE cosmic-rays

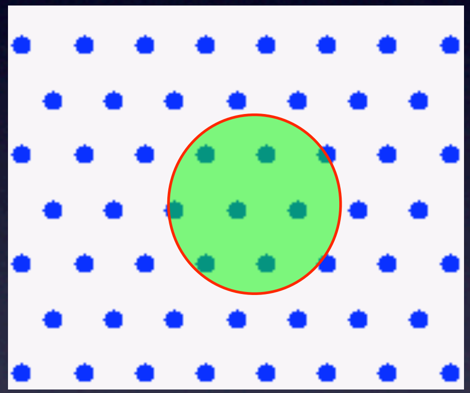
- Above ~10^{14} eV, fluxes are too low for satellites and balloons detection
- Ground based observatory detect atmospheric air showers
- Principle : detect secondary particles in order to reconstruct the properties of the primary cosmic-ray
- Mainly two detection methods :
  - Ground arrays
  - Fluorescence telescope



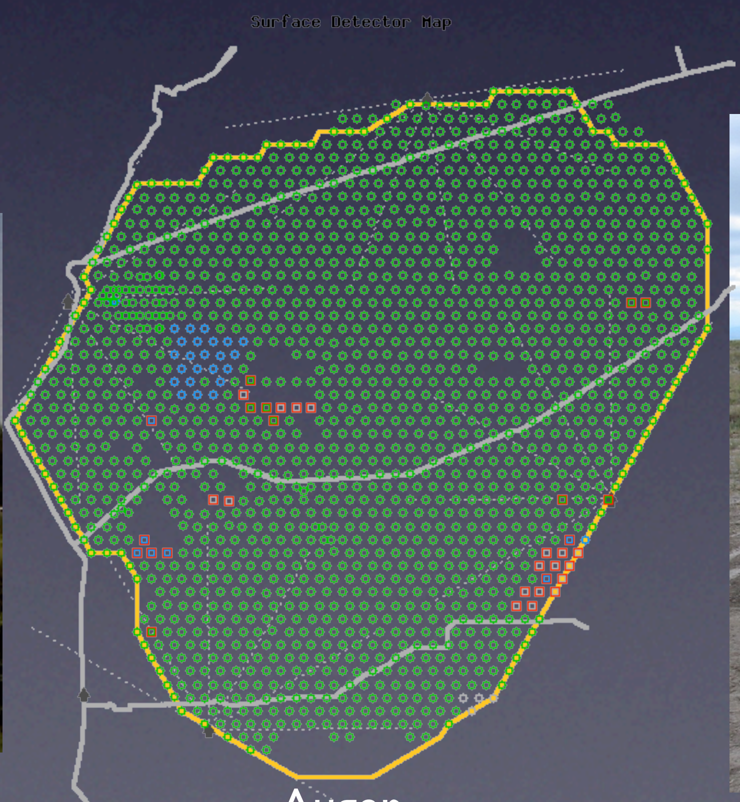
Ground array detectors

- Sampling air shower particles at ground level
- Surface covered and detector spacing depends on the targeted energy range :
  - Kascade (10^{15}-10^{17} eV) : surface 40000 m^2, 252 detectors, spacing 13m
  - Auger (10^{18}- >10^{20} eV) : surface 3000 km^2, 1600 detectors, spacing 1500 m

- Different type of detectors :
  - Scintillators (Kascade, AGASA)
  - Shielded scintillators (AGASA, Yakutzk)
  - Water Cerenkov Tanks (Haverah Park, Auger)



Kascade



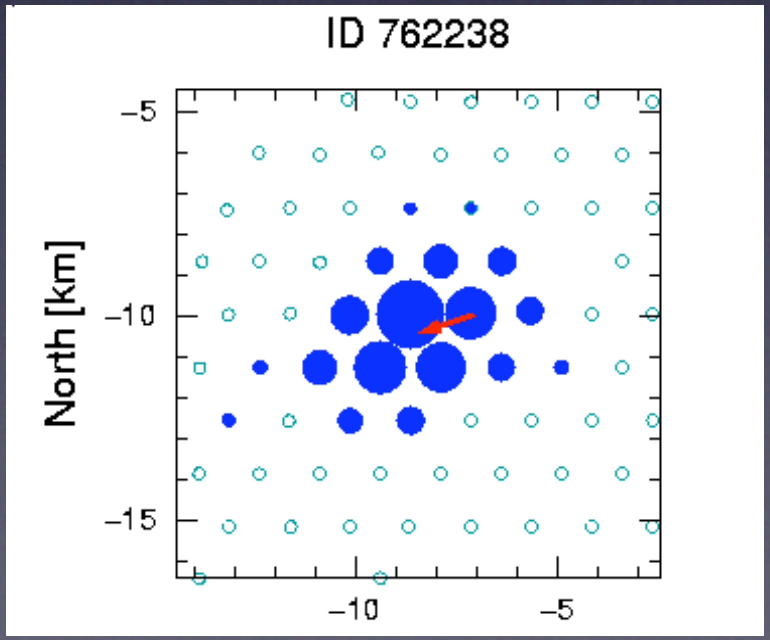
Auger

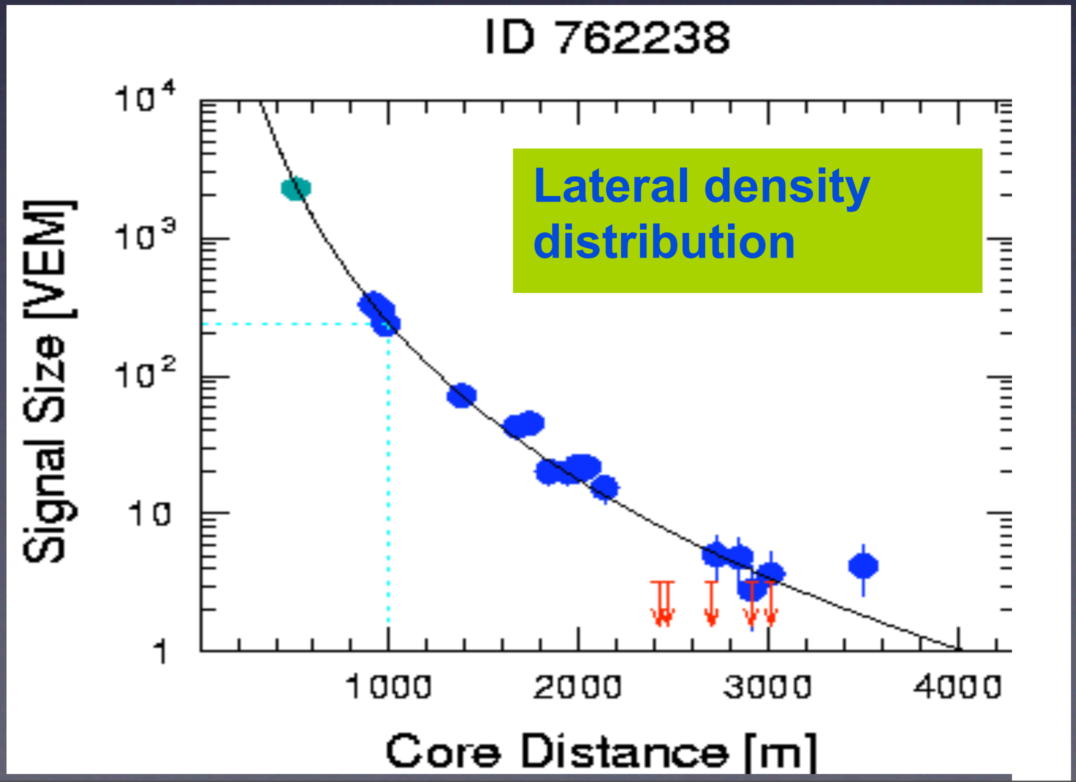
Ground array detectors

- Reconstruction methods :
  - Direction estimated using the time structure of the shower front
  - Energy reconstructed using the evolution signal size as a function of core distance
  - nature estimated mainly using the number of muons (not on a shower to shower base)

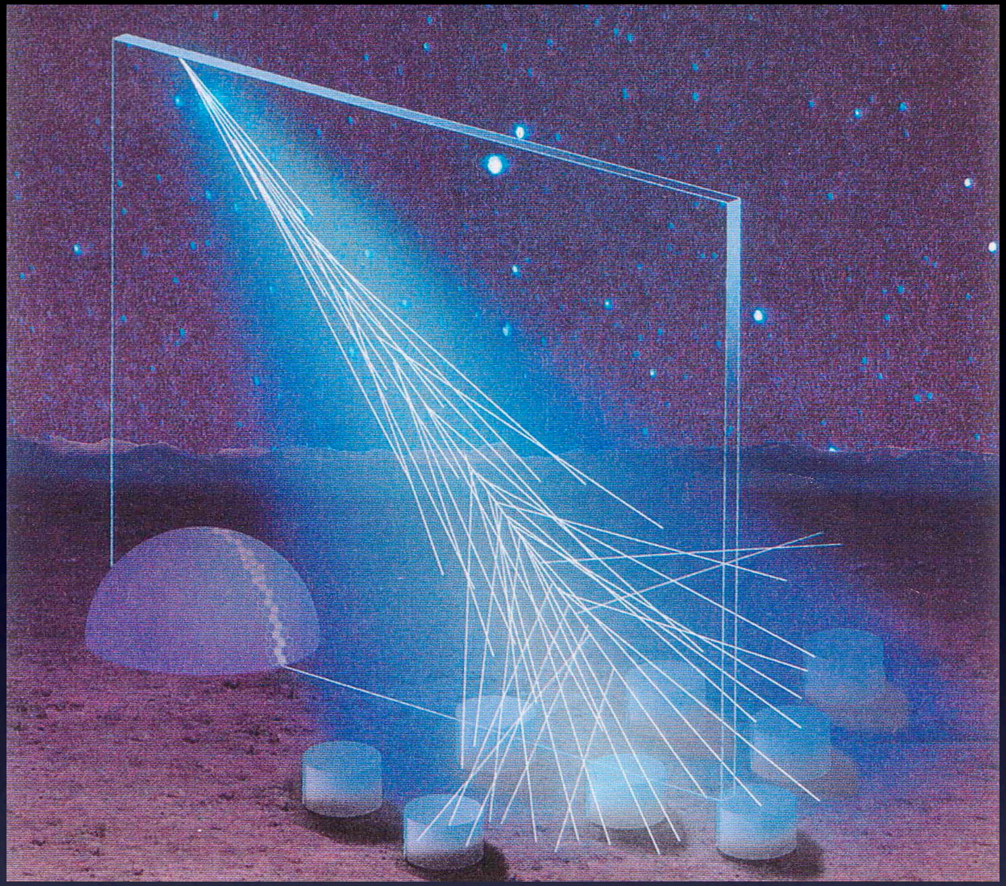
The relation Signal/Energy is extracted from air shower simulations
-> Hadronic model and composition dependent

Acceptance purely geometric above the saturation -> trivial to estimate





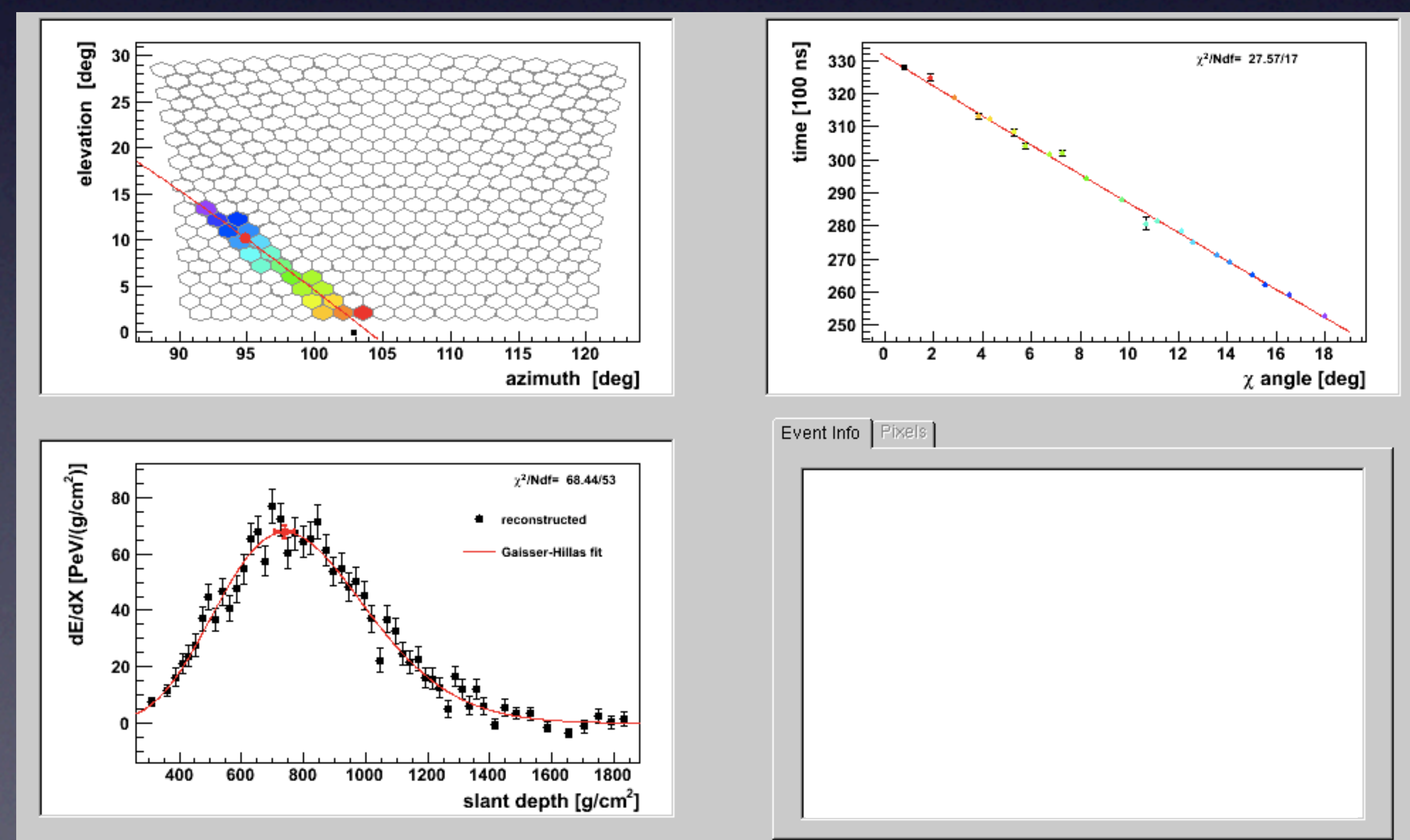
Fluorescence detectors



- The fluorescence (UV) emitted by N_2 molecules exited the air shower e^+e^- is detected
- Fluorescence light proportional to the number of electromagnetic particles in the shower -> proportional to the energy of the cosmic-ray
- UV light can only be detected by moonless nights -> ~15% duty cycle
- Calorimetric measurement -> widely independent of the modeling of hadronic interaction
- Technique pioneered by the Fly's eye experiment in the 80's
- Systematic uncertainty mainly due to the fluorescence yield
- Energy dependent aperture

Fluorescence detectors

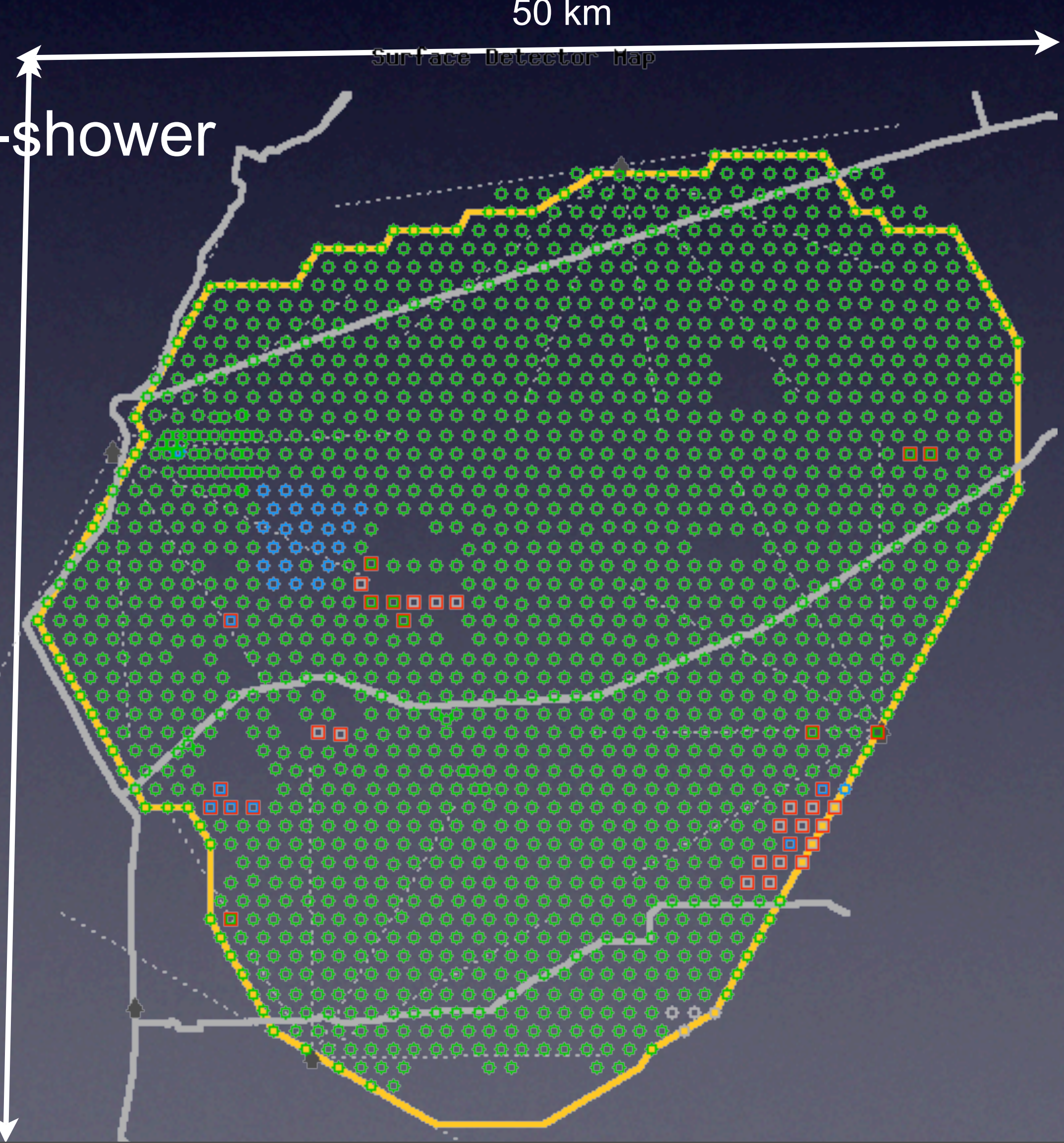
- Reconstruction methods :
  - The UV picture of the shower development is captured by the PMTs
  - The timing of the different channels constrains the shower geometry
  - The energy is estimated by integrating the shower profile
  - The position of the maximum of longitudinal development (X_{max}) constrains the composition (statistical discrimination)

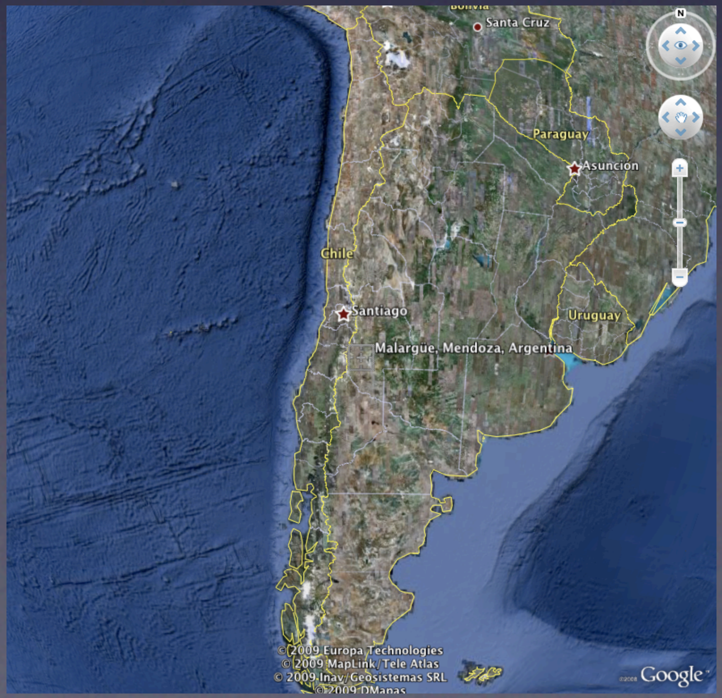


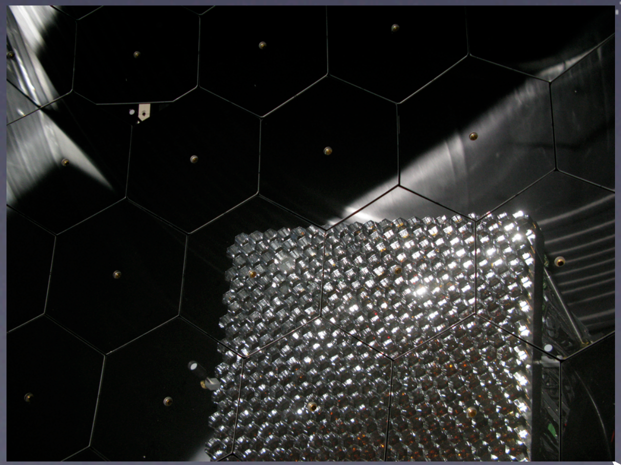
Pierre Auger Observatory : the hybrid detection revolution

• Located in Malargue (Mendoza, Argentina, 1400m a.s.l
• 1600 Water Cerenkov Tanks, spacing 1500 m
-> ground array surface 3000 km^2
• 4 Fluorescence detectors overlook the array

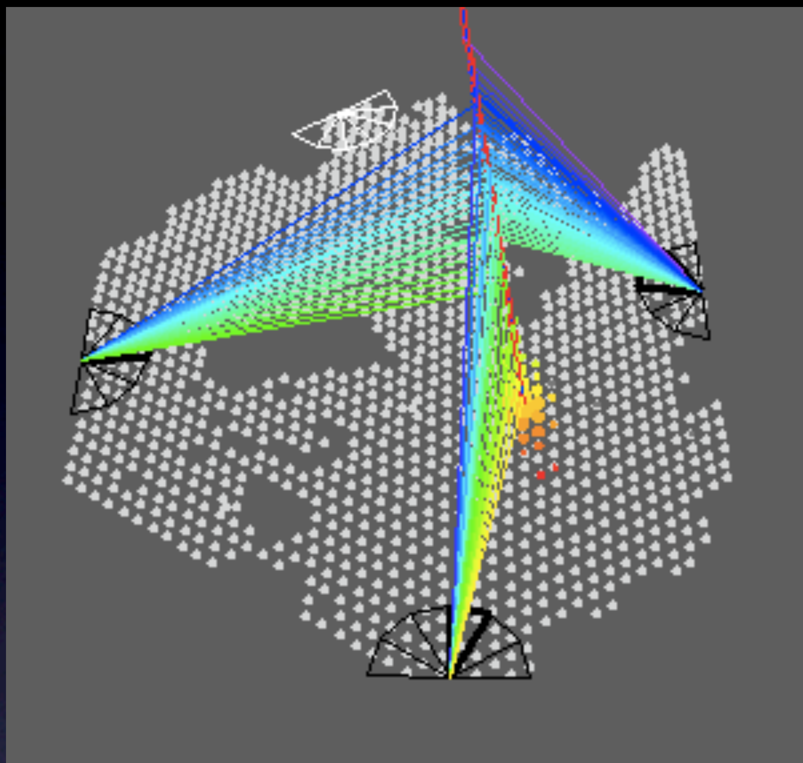
Huge surface for an unprecedented statistics above 10^{19} eV
Hybrid detection for a good understanding of air-shower physics

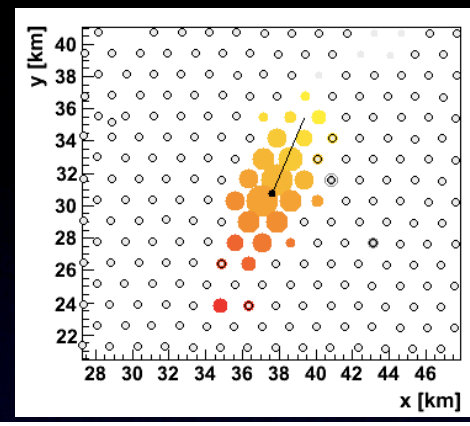


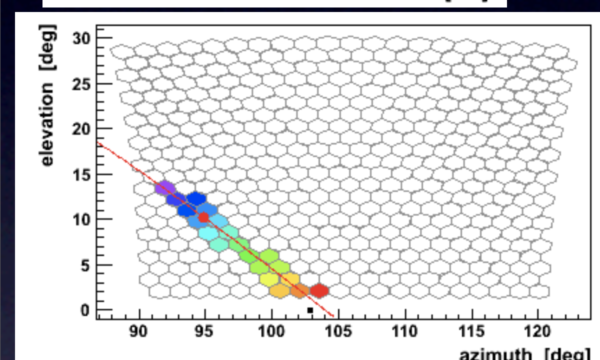


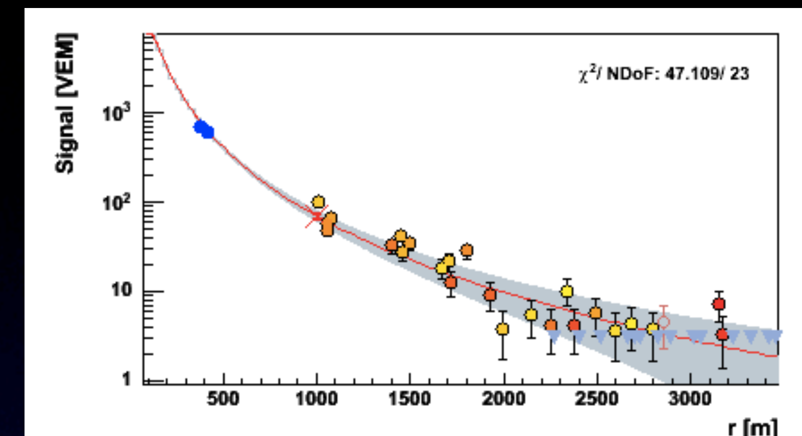


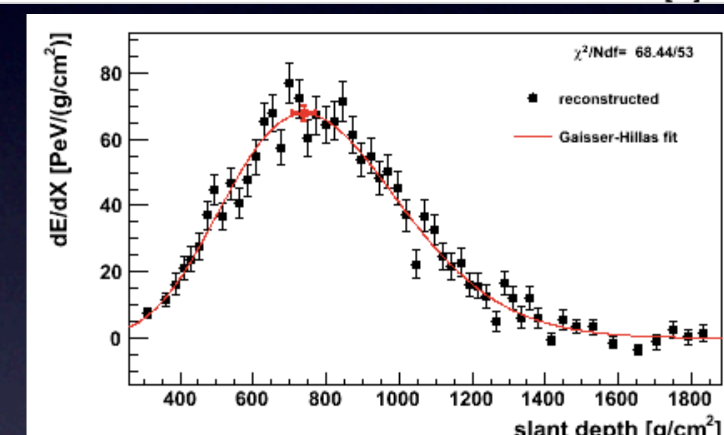
Pierre Auger Observatory : the hybrid detection revolution



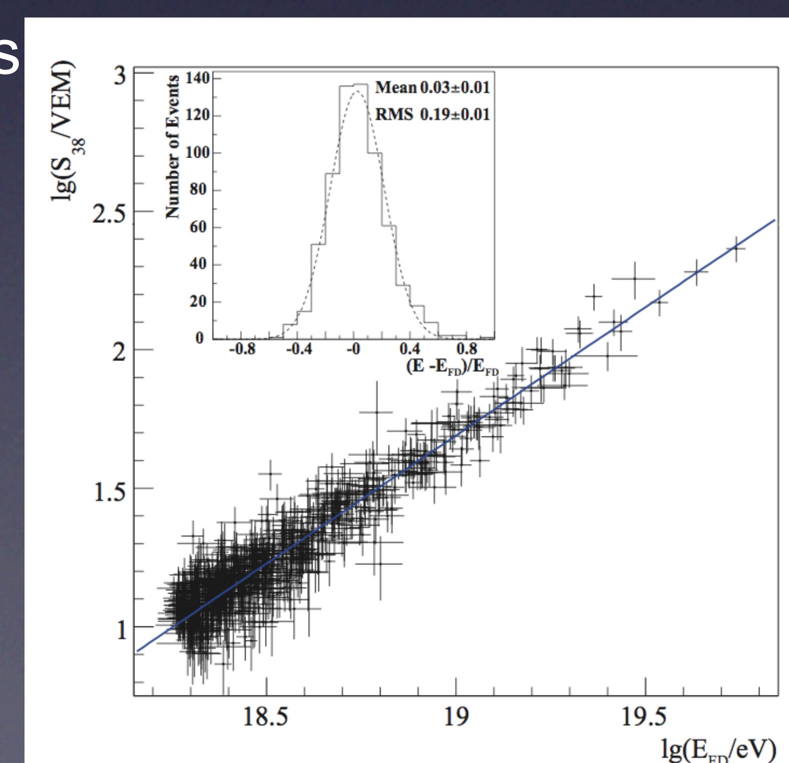






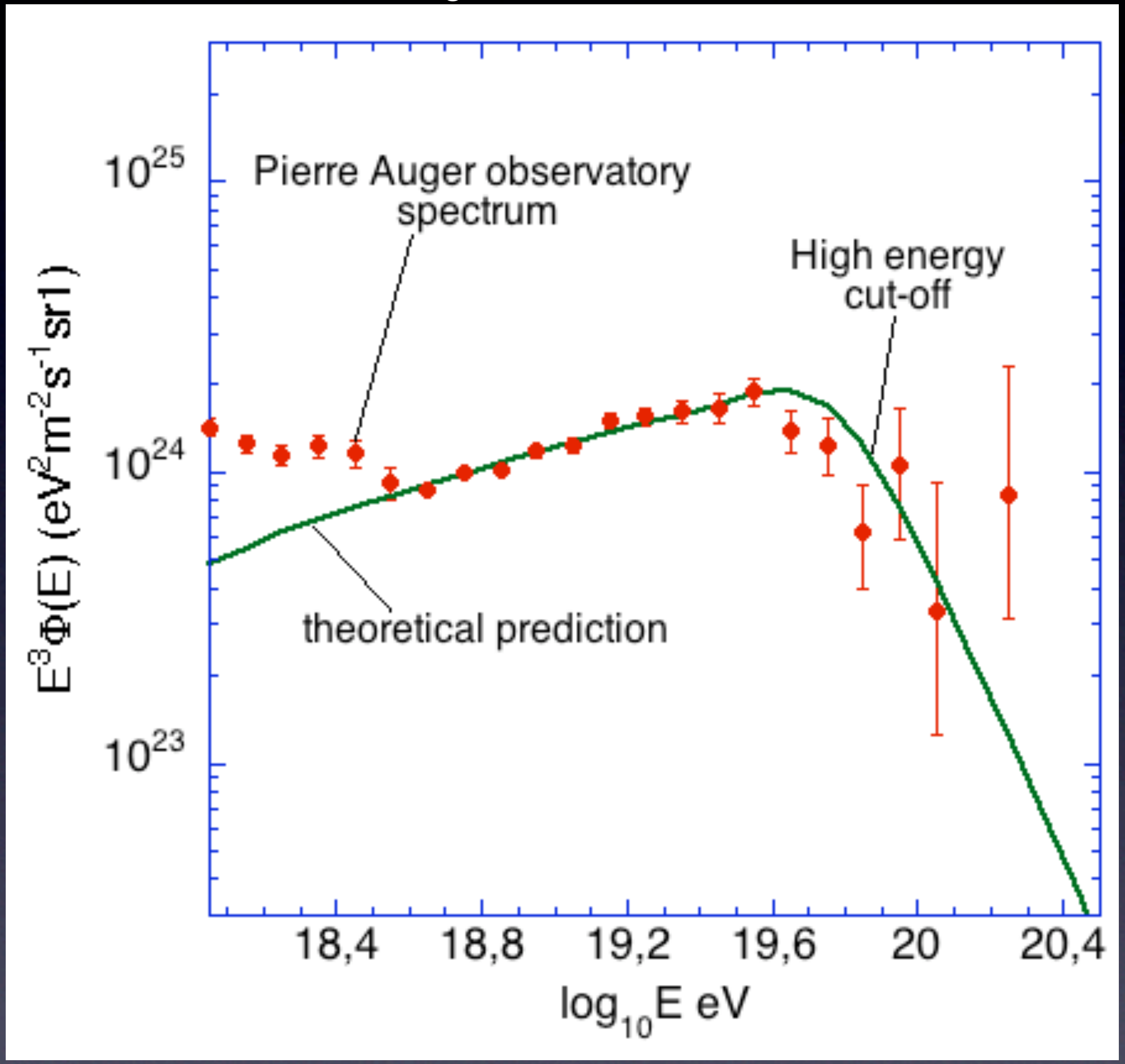


- One can calibrate the relation E/Signal using hybrid events
  - SD gives S1000
  - FD gives a calorimetric measurement of the energy
- Energy evolution measured without using simulations
  - No hadronic model dependence
  - Composition changes handled naturally
  - Spread measured



UHECR spectrum

Auger Collaboration ICRC 2007



Ankle observed around 3-4 10^{18} eV

Very significant suppression of the flux above ~4.10^{19} eV

-> observation of the GZK cut-off

Expected cut-off at the highest energies

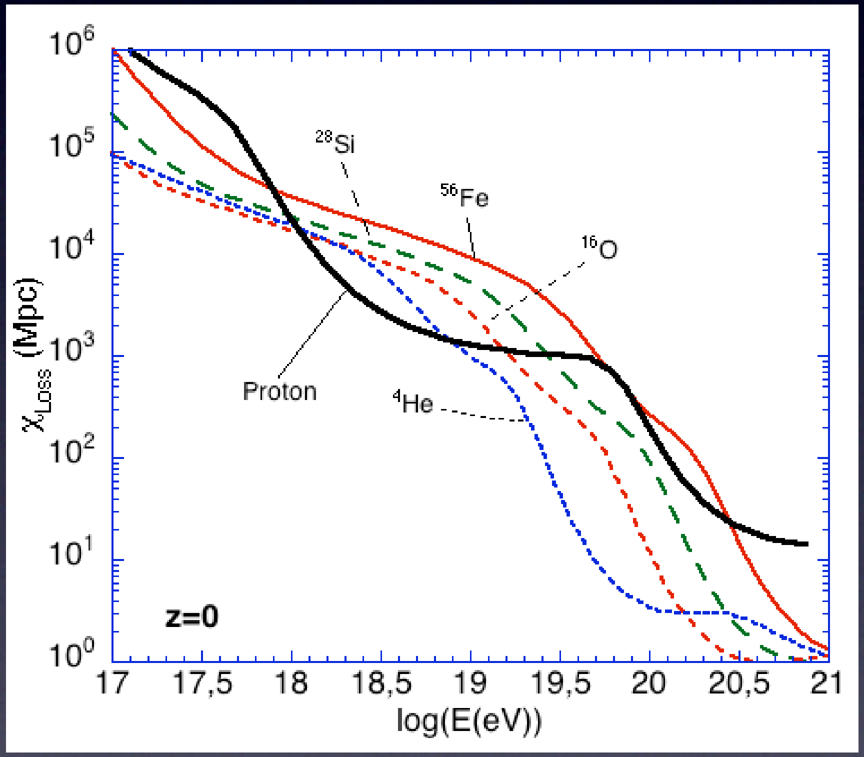
Above a few 10^{19} eV, protons and nuclei are expected to interact strongly with photon backgrounds (IR-CMB)

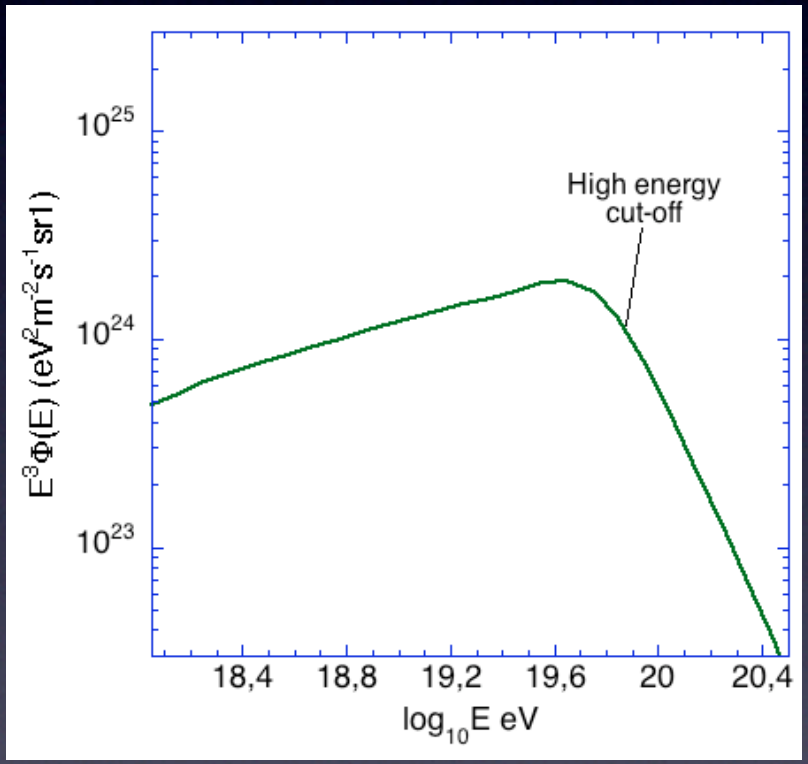
- protons lose energy through the pion production process
- nuclei are photo-disintegrated through the giant dipole resonance process

➡ above the interaction threshold, the particles horizon is reduced

➡ only nearby sources can contribute at the highest energies

➡ a cut-off is expected in the spectrum (whatever the composition at the sources)





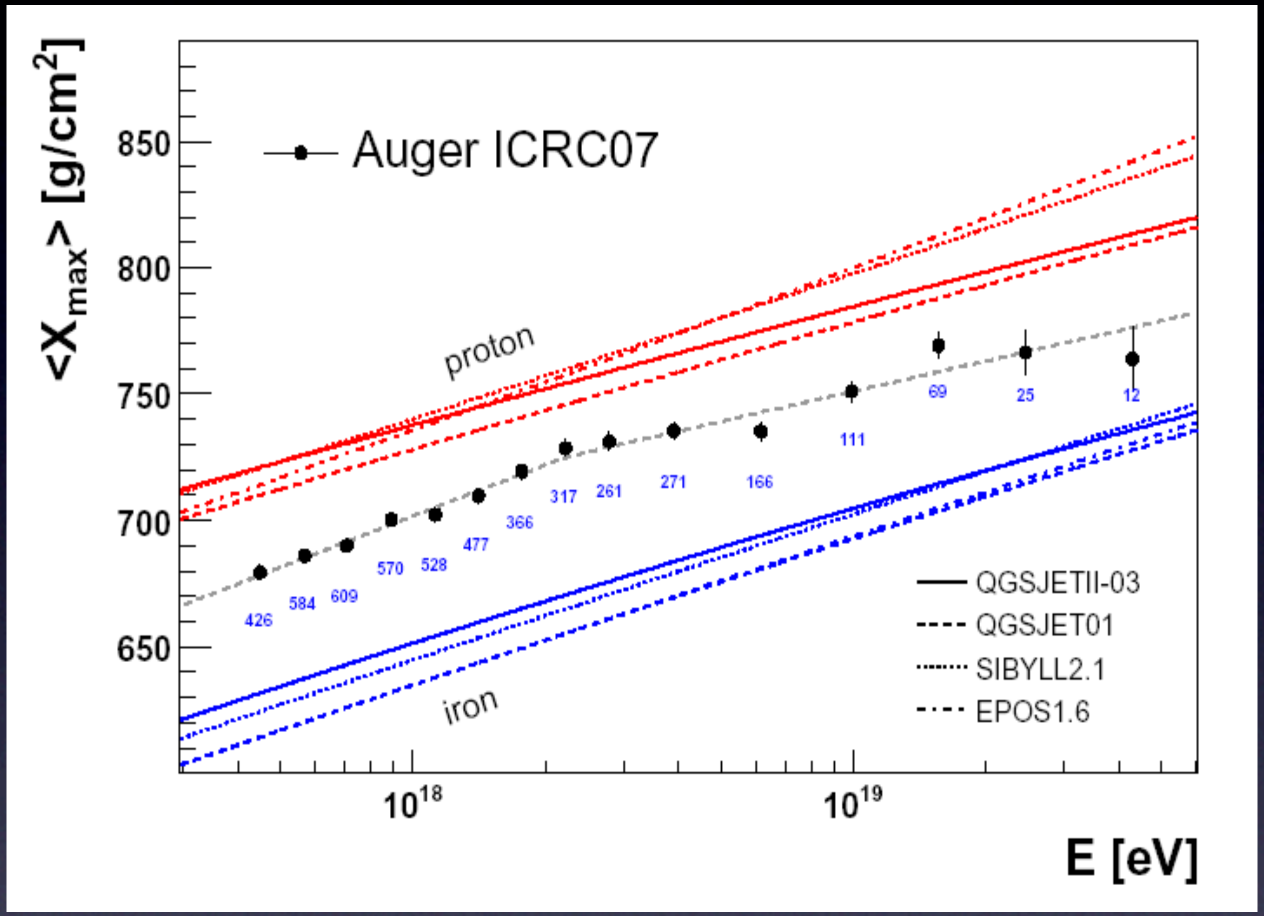
- Energy loss processes isolate the nearby Universe at the highest energies, the sky is supposed to be anisotropic if the sources are somehow correlated with the local matter
- Magnetic deflections are expected to be small at such high energies

➡ if protons are present they should point back to their sources

Drawback : the fluxes are extremely low

➡ Huge aperture experiments are needed to accumulate statistics

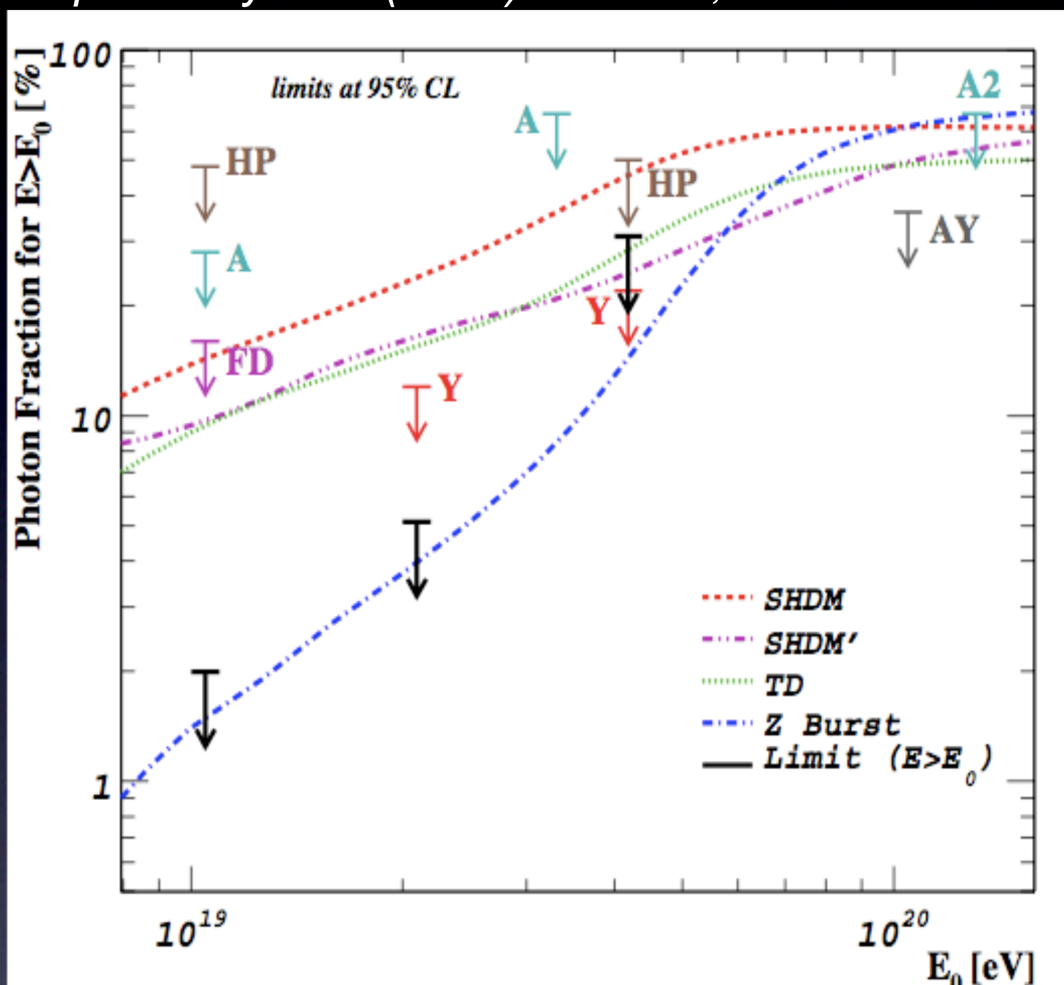
UHECR compostion



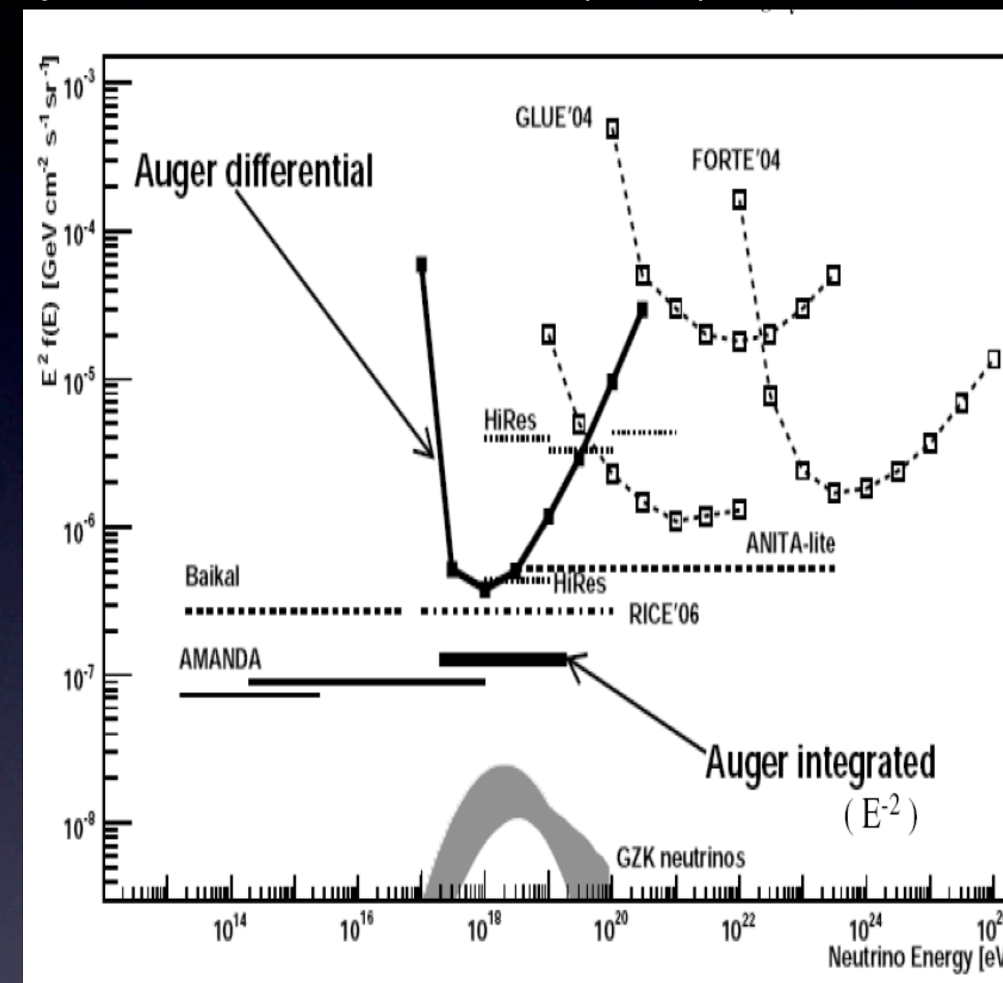
- X_{max} based composition analysis favor a mixed composition at all energies
- Steeper elongation rate at low energies breaking ~ at the ankle -> constrains on the GCR to EGCR transition
- Composition possibly getting heavier above ~2.10^{19} eV (more statistics needed to confirm)

UHECR photons and neutrinos

[*Astropart. Phys. 29 (2008) 243-256, arXiv:0712.1147*]



[*Phys.Rev.Lett. 100, 211101 (2008),arXiv:0712.1909*]



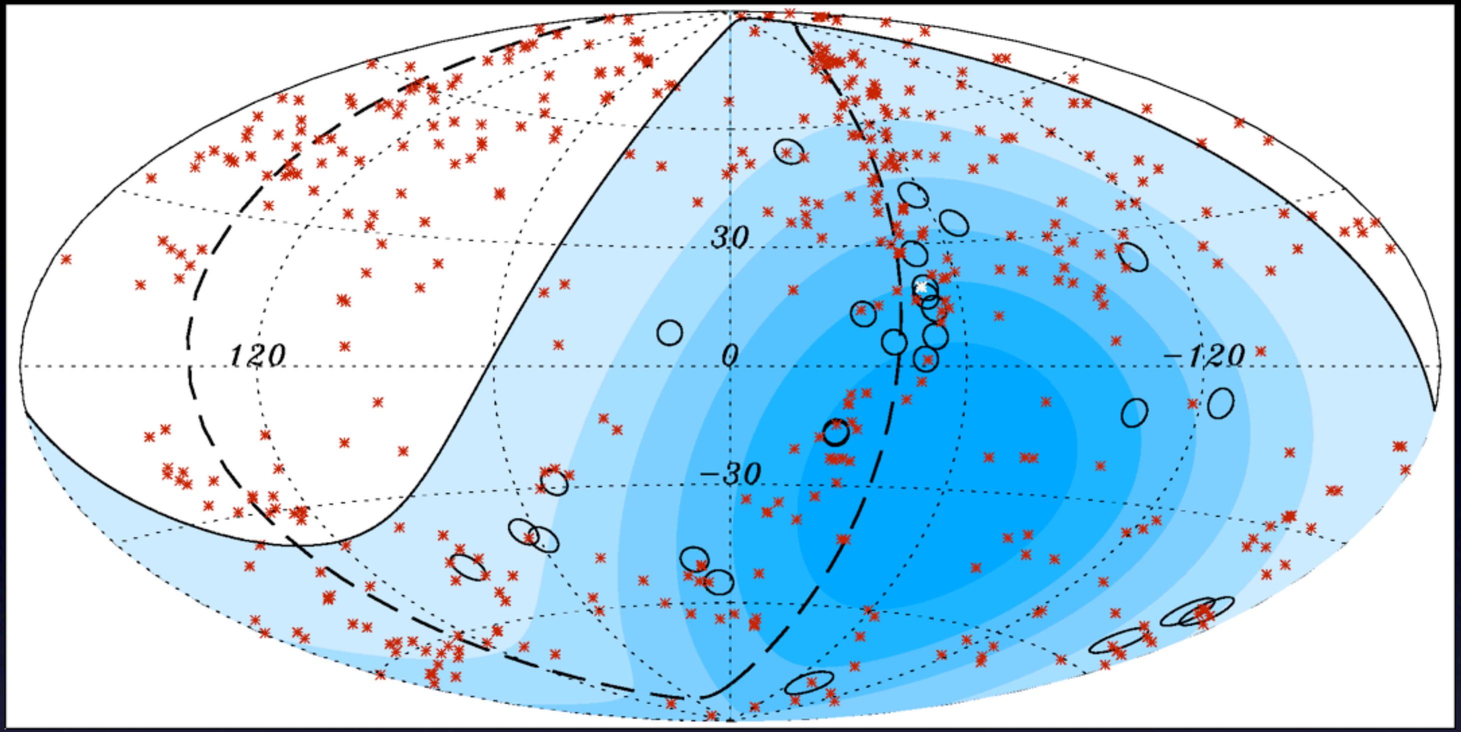
Auger is potentially able to detect and identify photons and neutrinos -> upper limits can be placed on their flux

• Neutrinos : good energy range for Cosmogenic Neutrinos

• Auger will soon give the best limit, constrains on the most optimistic model expected in a few years

• Photons : limits already put strong constrains on particle physics scenarios -> astrophysical origin of UHECRs

Anisotropies



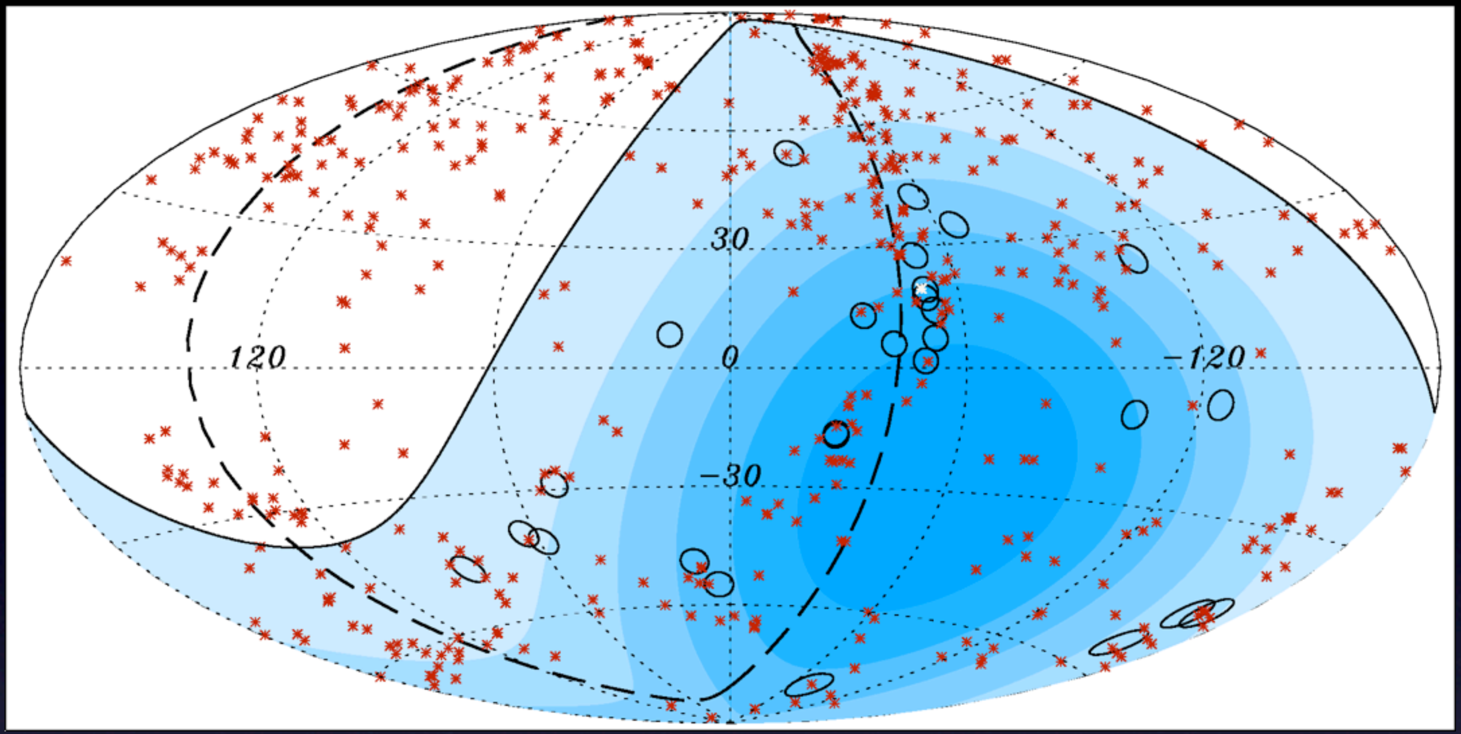
Auger Collaboration science 2007

Nov 2007 : the Auger collaboration published results showing the correlation between the arrival direction of the 27th highest energy events and the direction of nearby AGN

Result obtained after a prescription placed on the Energy of the events, the maximum distance of the correlating objects and the angular scale of the correlation

Parameter of the correlation : E_{min}=57 EeV, D_{max}=75 Mpc, θ=3.1 deg
21/27 correlating events (19/21 outside galactic plane)

Anisotropies



Auger Collaboration science 2007

What is it telling us?

The sky is anisotropic with 99 C.L (promise of cosmic-ray astrophysics)
-> very probably extragalactic origin

But it does not tell us :

What the sources are
whether or not the correlation parameters are physically meaningfull

Protons coming from AGNs?

The AGN that correlate could be the sources and the correlation parameters could be physically relevant
-> small deflexions
-> most likely protons

Parameter of the correlation : E_{min}=57 EeV, D_{max}=75 Mpc, θ=3.1 deg
21/27 correlating events (19/21 outside galactic plane)
Assuming sources distributed like AGN
From propagation studies one would expect D_{max} between 160 and 200 Mpc
-> either an energy or a horizon crisis (one would have to increase Auger energy scale by ~40% to reconcile E_{min} and D_{max})
-> one can actually show "simulating" the scan and prescription procedure that the correlation parameters are not trivially related to the physical parameters (N.G Busca et al., 2008)

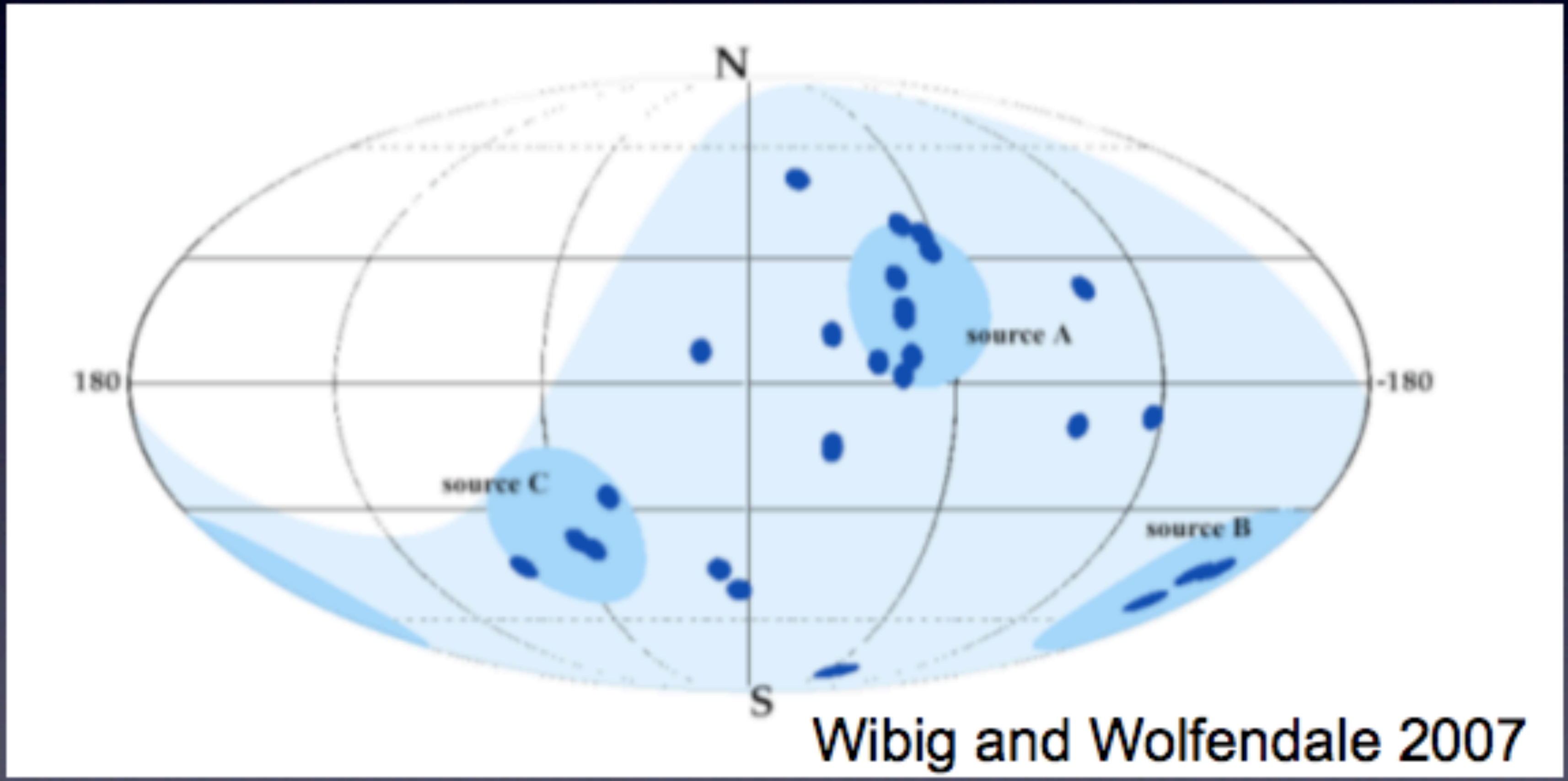
We have a correlation with an imcomplete and inhomogenous catalogue
Most of the AGN that correlate are not especially strong objects for non thermal radiations

Arrival directions might just point toward the last (magnetic) scattering center and not the source (hypothesis quantitatively studied by Kotera and Lemoine (2007))

Does a composition getting heavy contradict Auger anisotropy result?

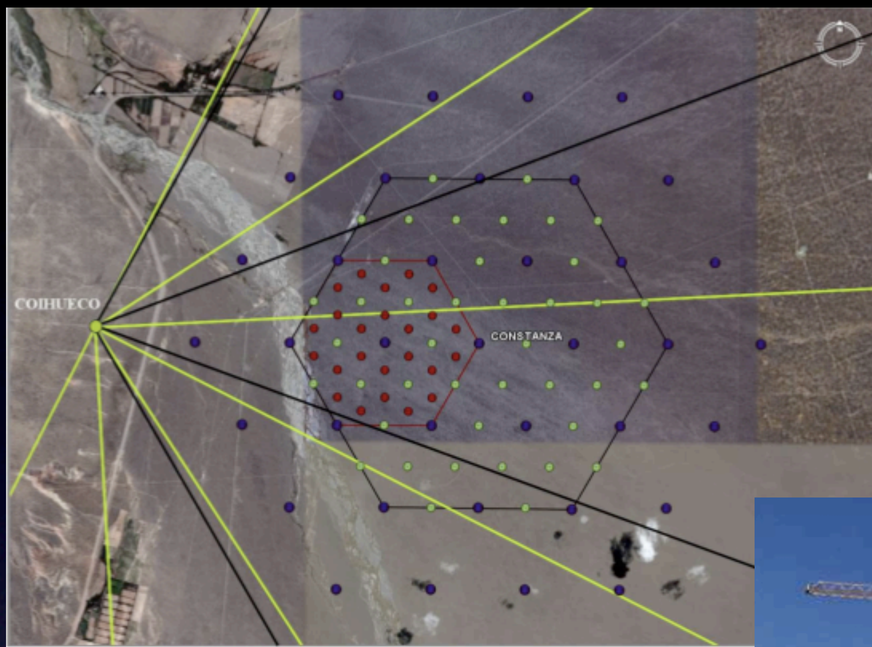
Not at the current level of statistics : Anisotropy depends on the source density, the magnetic fields and the composition. An anisotropic sky does not imply protons (neither do protons imply anisotropy).

Significant small scale clustering would be difficult to handle but is not seen so far



Wibig and Wolfendale 2007 : a few dominant sources of heavy nuclei reproduce most of the correlation

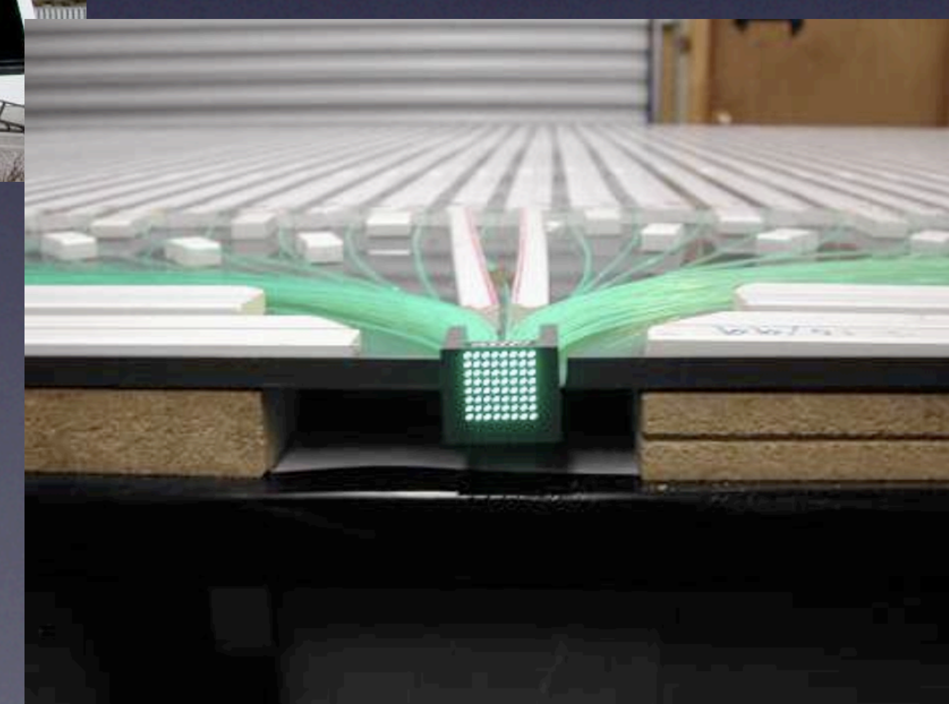
The future : Auger South low energy extension



Increasing the dynamic range of the Pierre Auger Observatory down to 10^{17} eV
A better “lever arm” on the transition from GCR to EGCR

Four components :

- infilled water cerenkov tanks array
- high elevation fluorescence telescopes
- burried muon detectors
- Radio detection

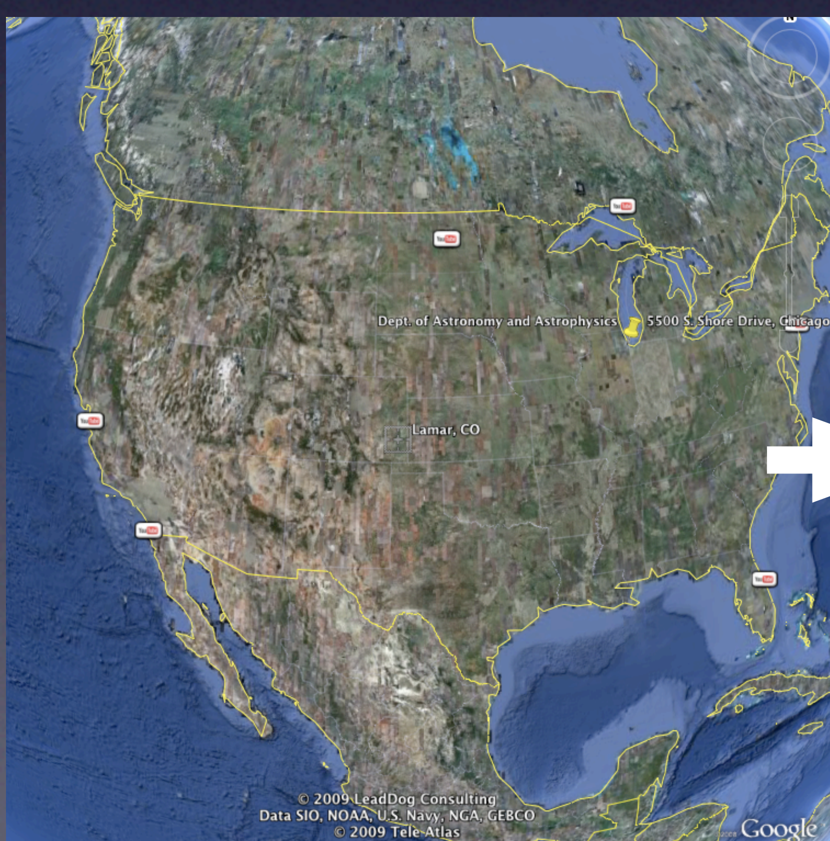


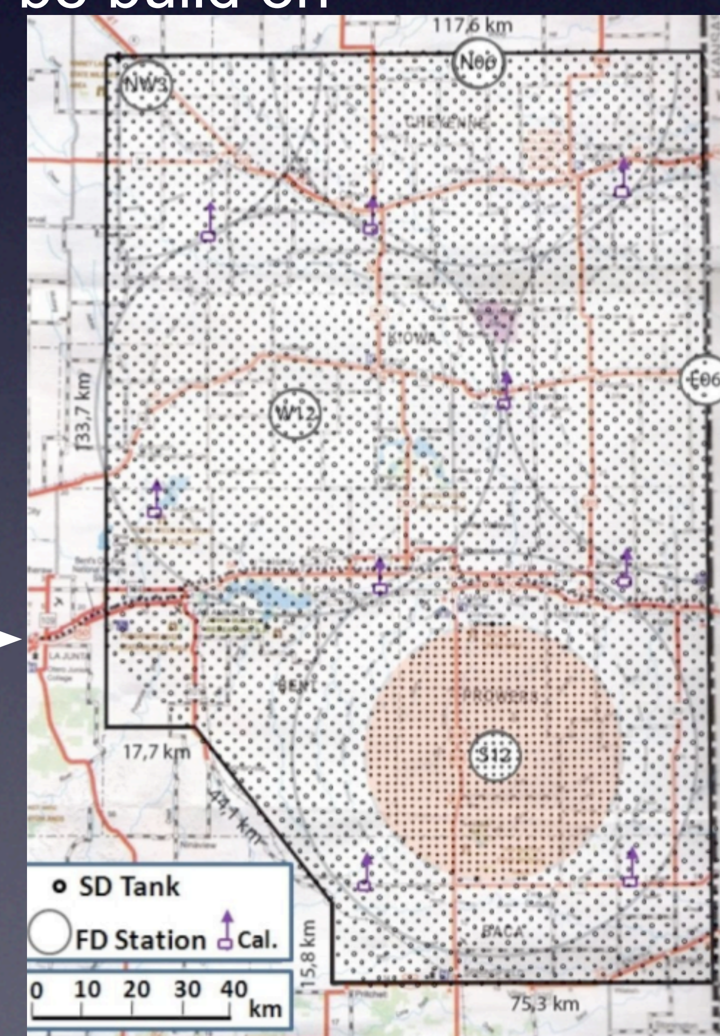
Very good sampling of air showers
Multi-detector analysis
Promising for composition analysis and hadronic physics studies

Auger North the ultimate ground-based observatory

- At the highest energies detailled CR astronomy require a large statistics
- Auger South is not big enough for this purpose
- Idea : building bigger while keeping the same (very successful) design
- Auger North in the US, Lamar CO -> access to the north sky
- ~20000 km^2, 4000 tanks, spacing ~2.3 km + infilled
- 7 fluorescence sites overlooking the array
- R&D Array construction starting end 2009

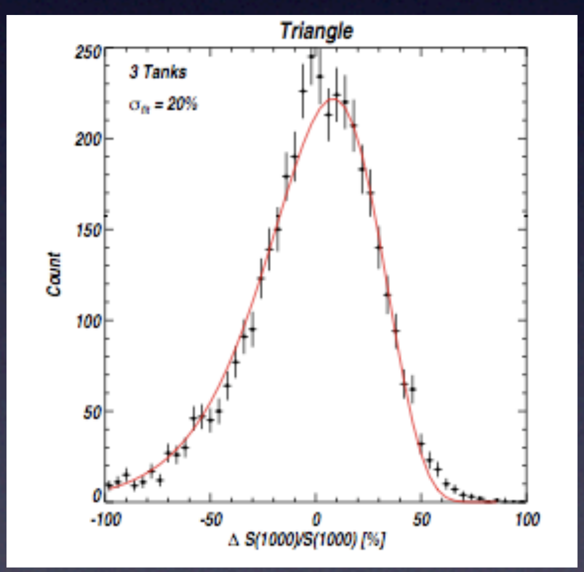
Using on a larger scale an already successful technique
Certainly the biggest and best UHECR observatory that can be build on earth

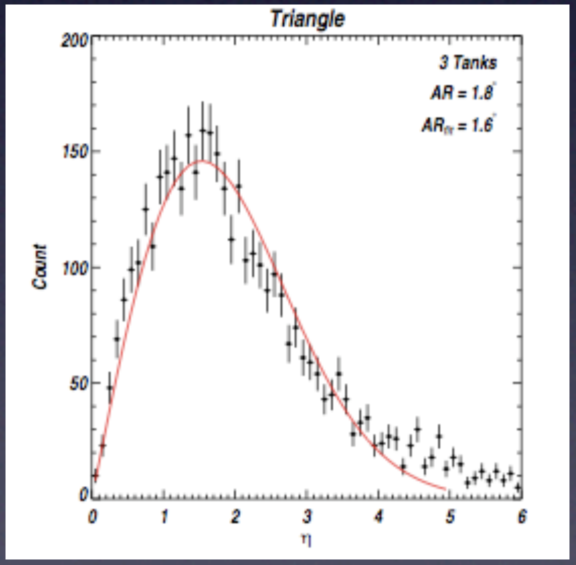


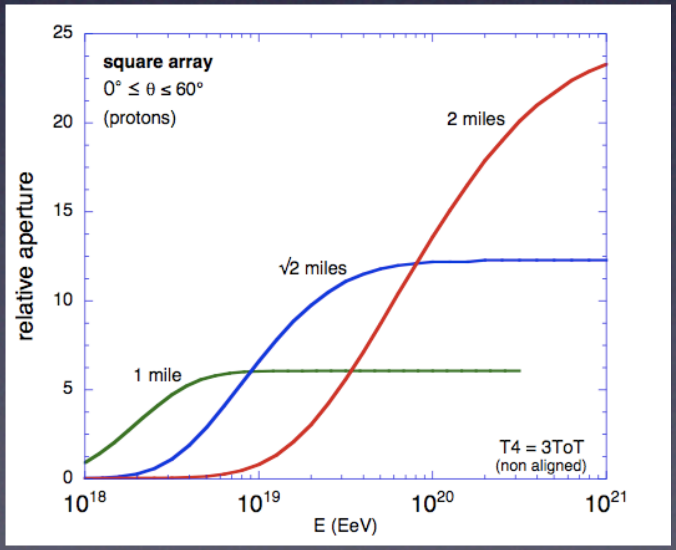


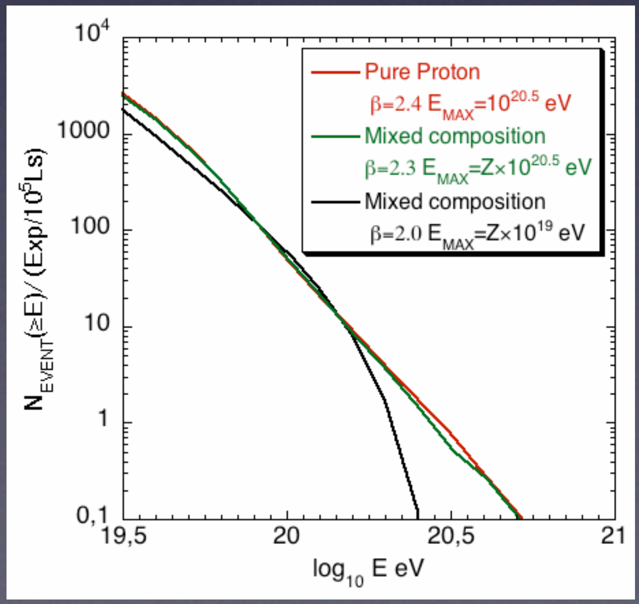
Auger North : performance

- The resolution can be estimated using Auger south data (no bad surprises to expect we know it is gonna work)
- S1000 reconstruction and angular resolution already good for three tank events
- √2 miles array optimal choice
- extrapolation of Auger South statistics : 50 events above 10^{20} eV expected for two years of Auger North
- Auger North among the 7 major projects in the European roadmap



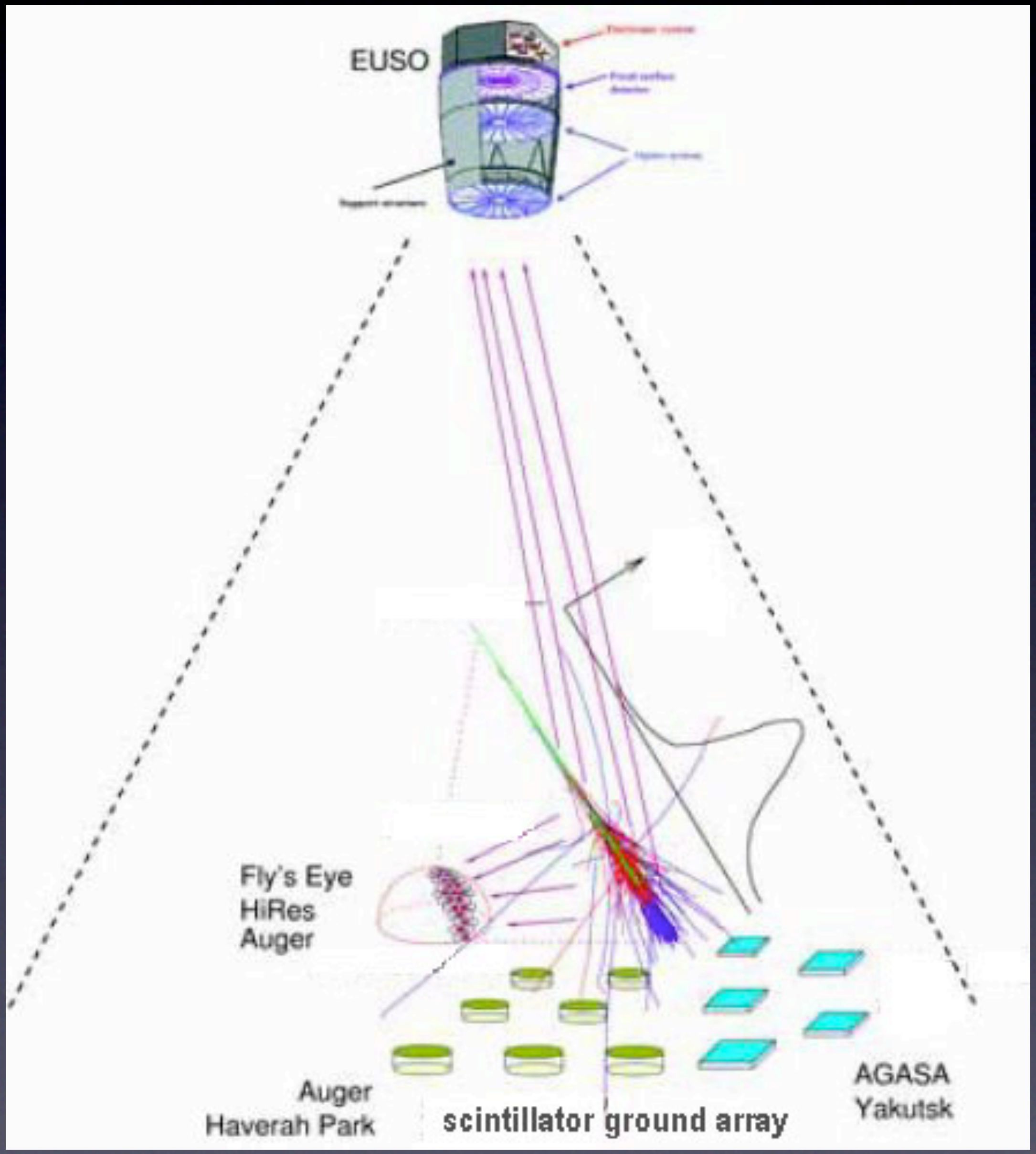


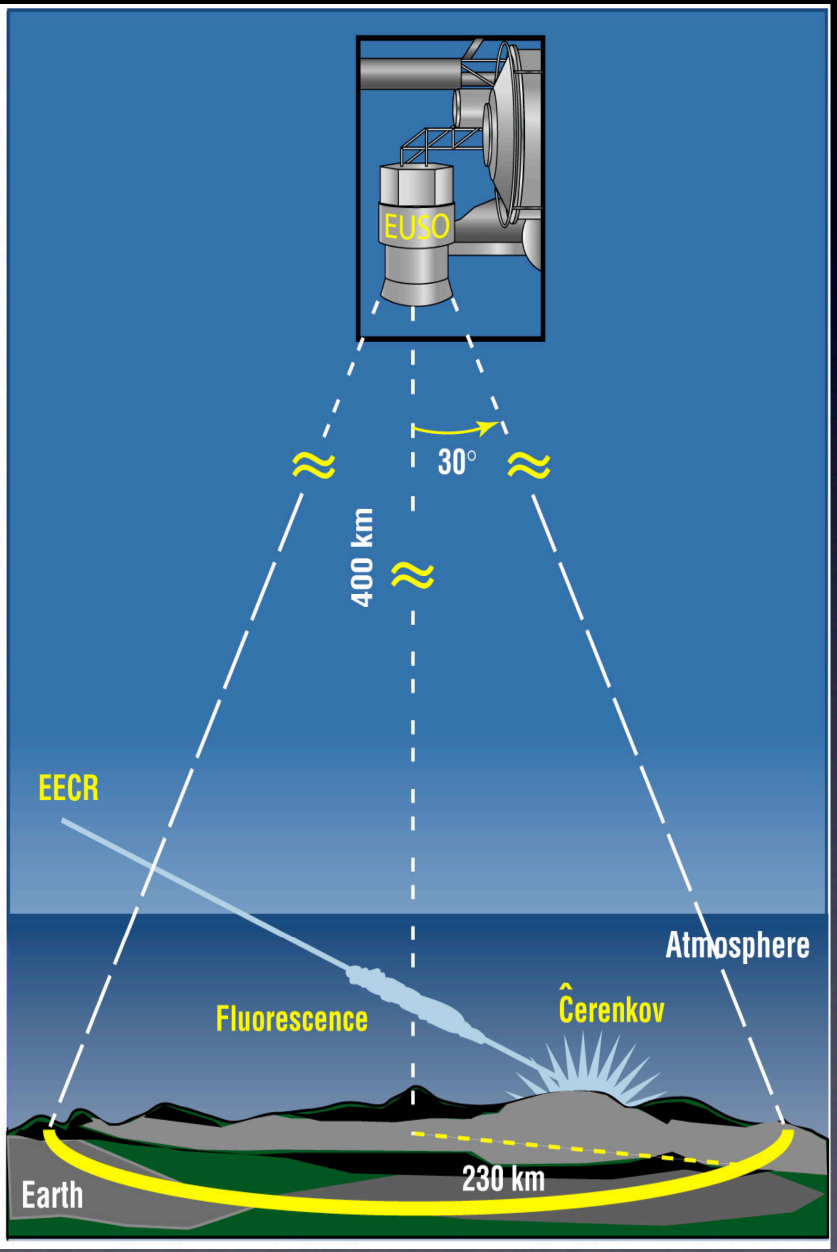




JEM-EUSO : back to space

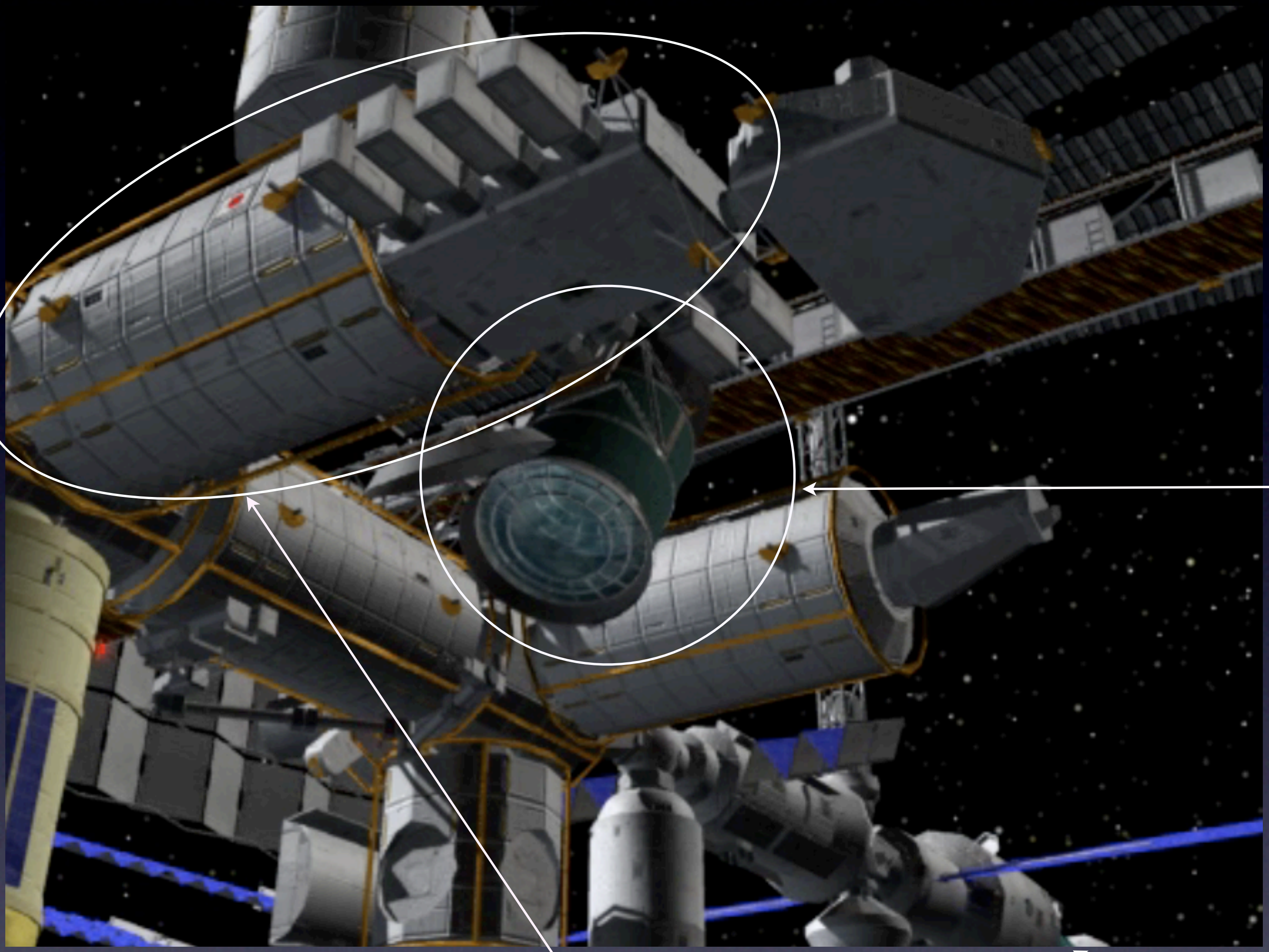
Principle : observing the fluorescence light, emitted during the longitudinal development, from space





Keep the advantage of the fluorescence detection : calorimetric measurement of the energy
Huge field of view

JEM-EUSO : back to space



Launch expected in 2013-2014

EUSO

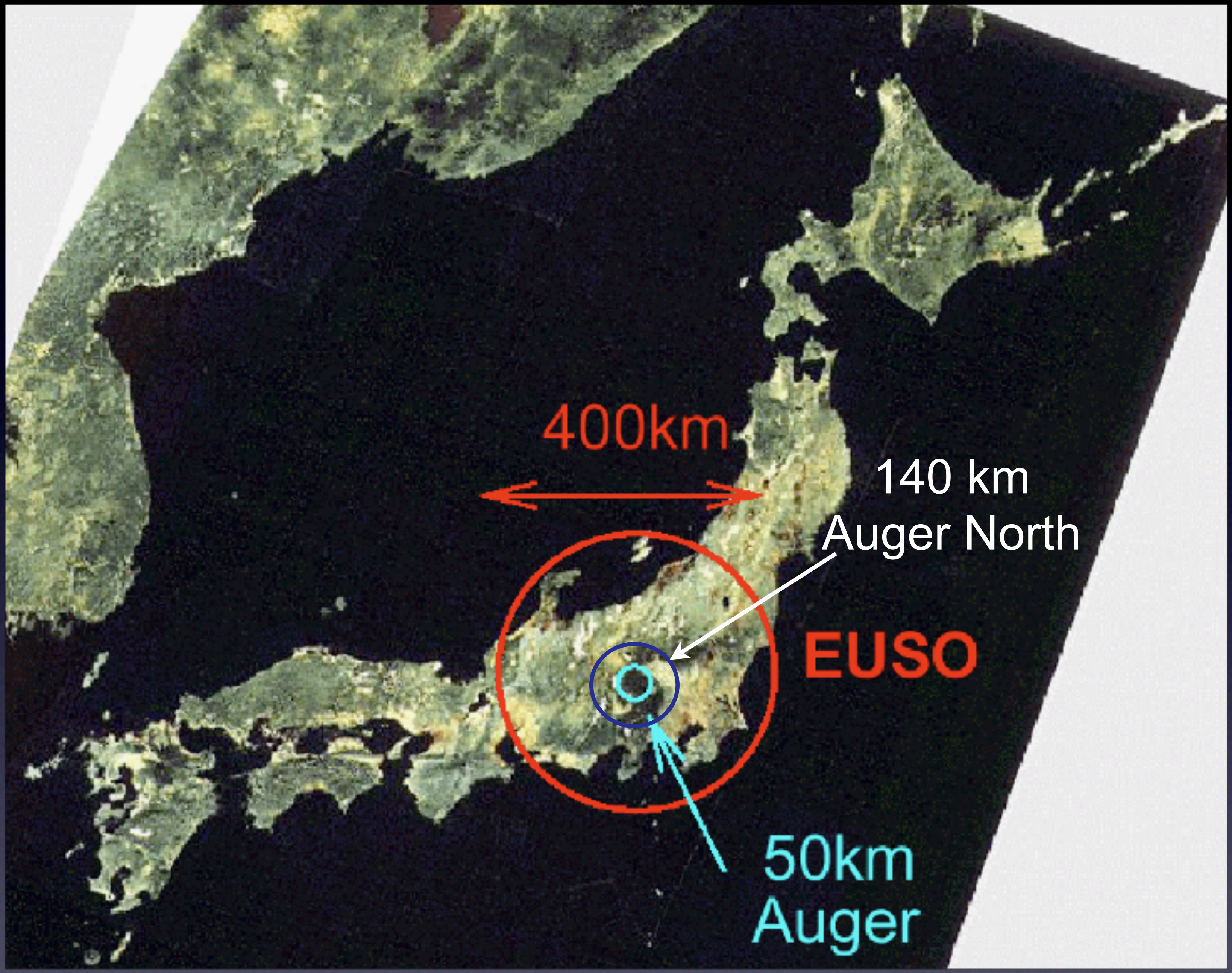
Extreme
Universe
Space
Observatory

accommodated on **JEM** of **ISS**

Japanese
Experiment
Module

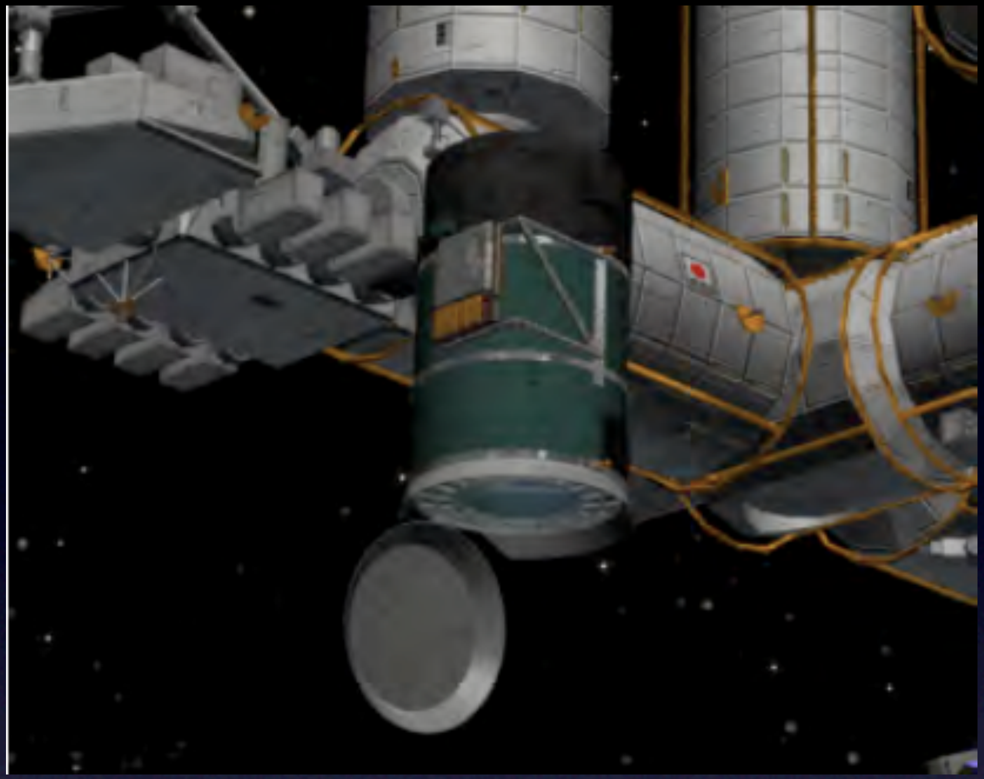
International
Space
Station

A huge collection area



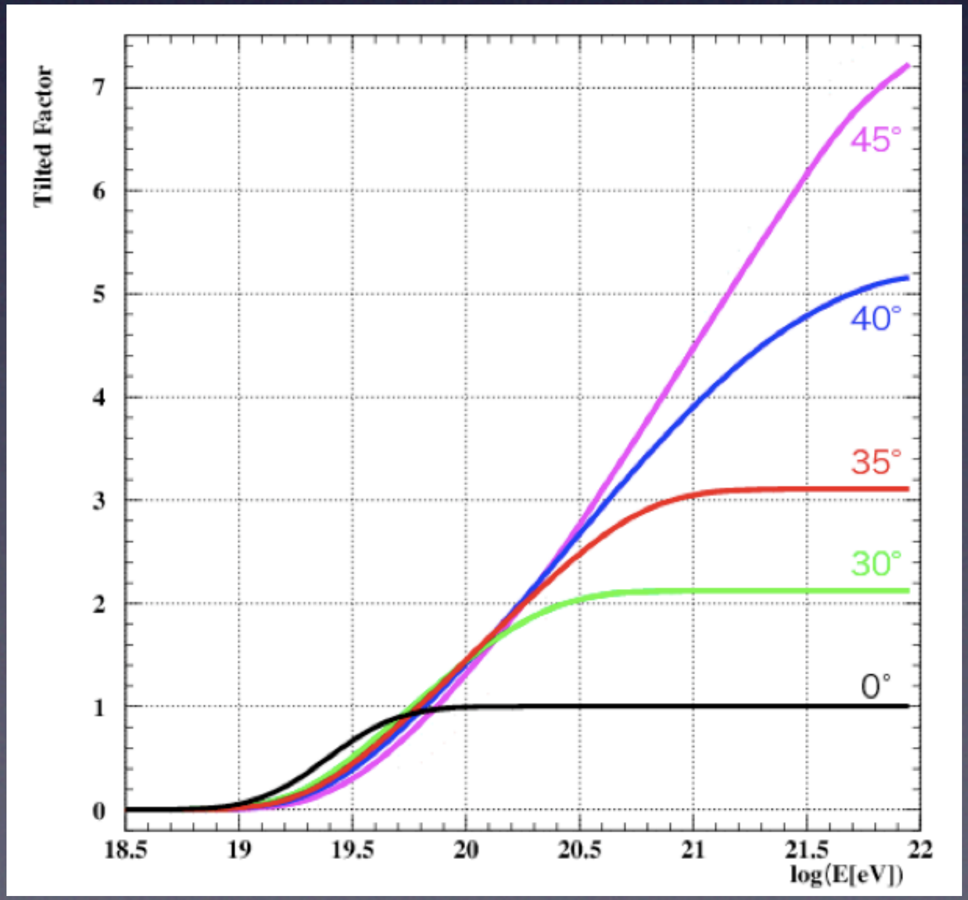
~10 times bigger than Auger South+North
~20% of duty cycle
fully efficient above 10^{20} eV
➡ twice more event per year

A tilted mode to increase the statistics



nadir mode

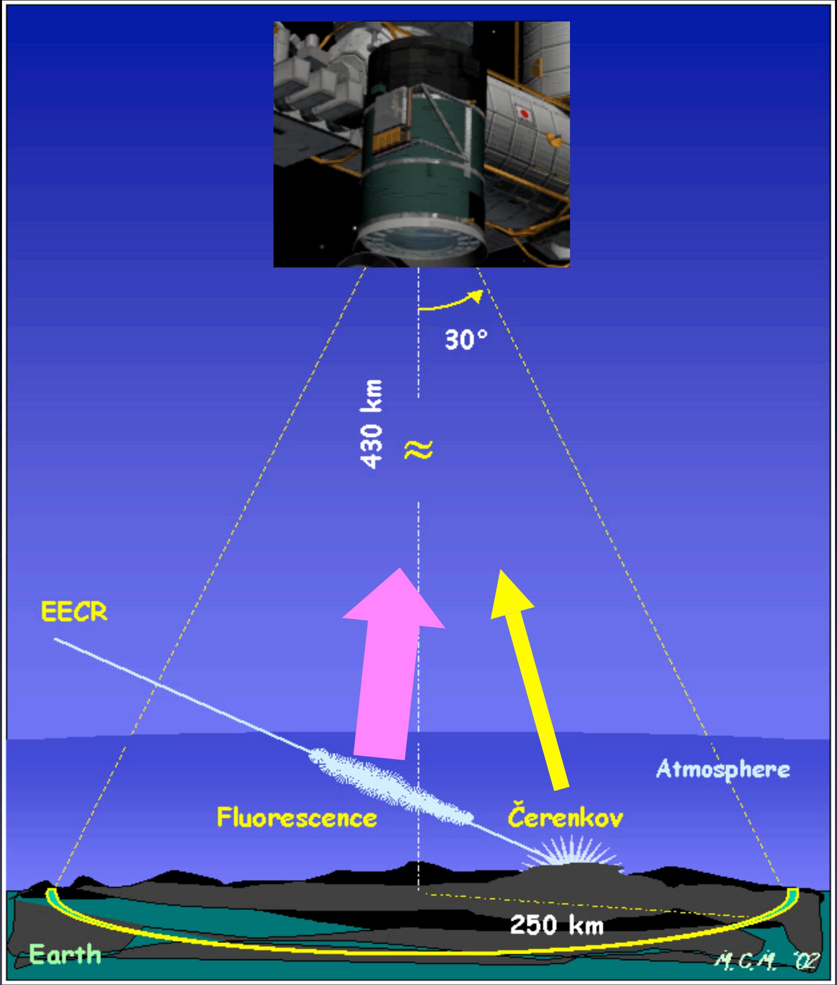
tilted mode

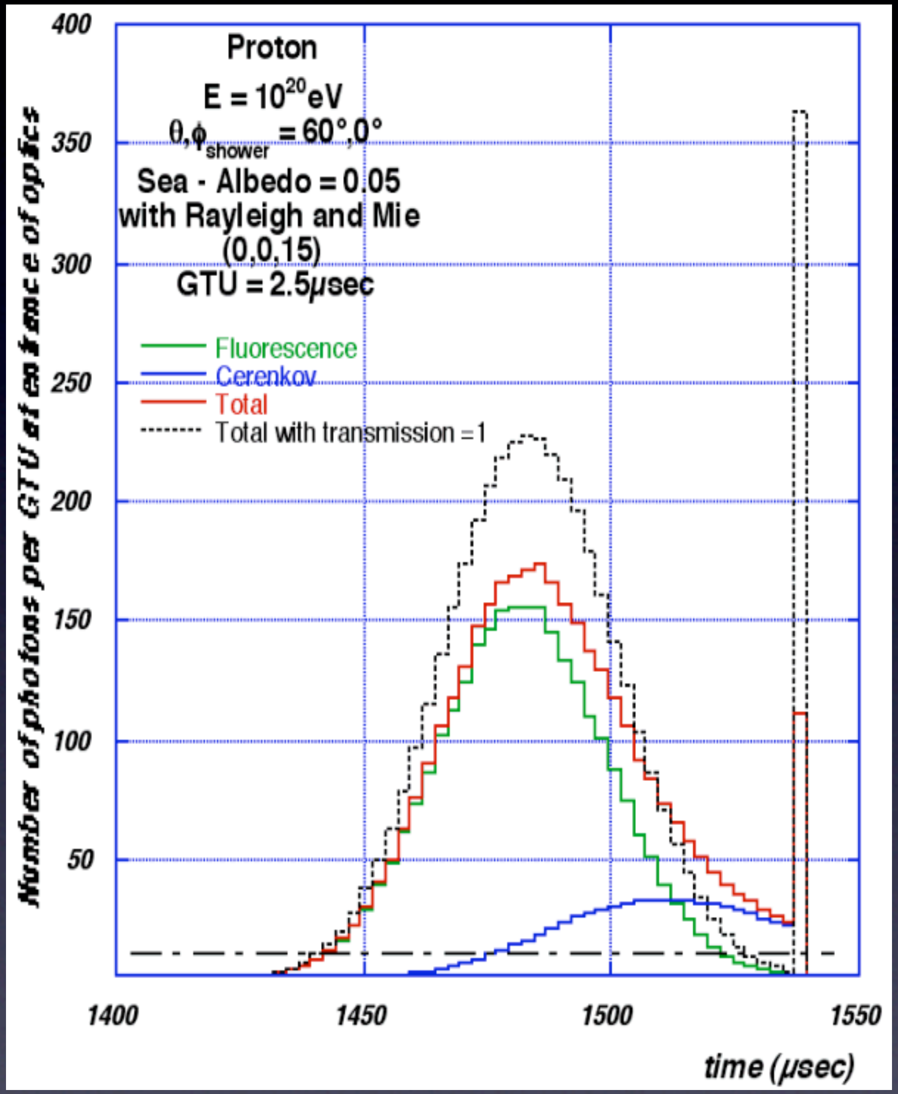


Significant increase of the statistics above 10^{20} eV could be crucial to accumulate statistics at the highest energies

Expected performances

A typical event :





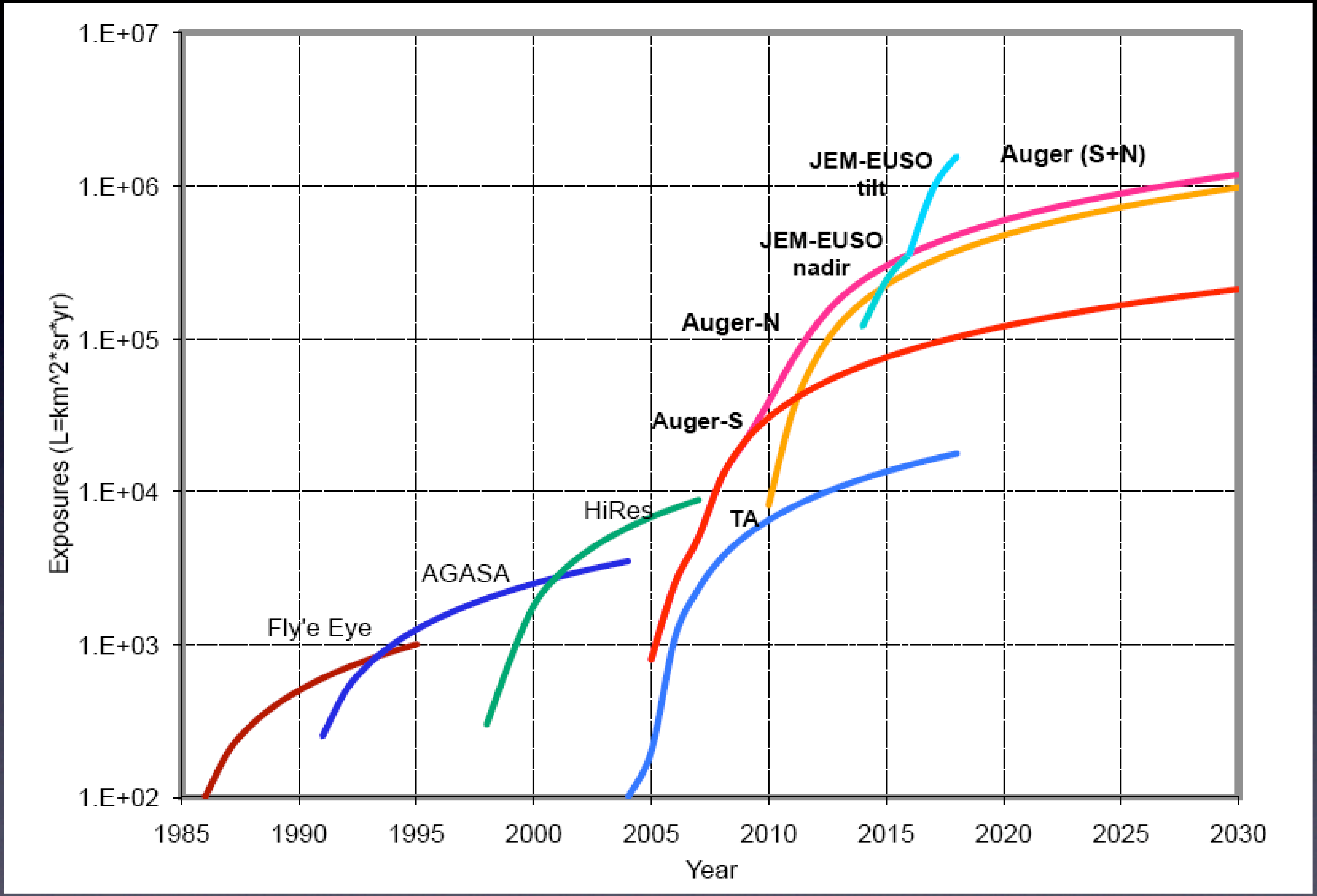
Resolution :

E ≤ 30%

$\Delta\theta$ ~ 2 deg

ΔX_{MAX}~100-140 g.cm^2

Exposure evolution with time



1 million km^2.sr.yr should be reached

Conclusion and outlook

- The origin of the highest energy particles in the universe is one of the hotest question of high energy astrophysics
- The Pierre Auger observatory starts to accumulate statistics :
  - The existence of the GZK suppression is confirmed
  - Constrains on the composition
  - Anisotropic sky at the highest energies
- More statistics expected at high energy in the next few years
- Low energy extension should allow to understand the GCR to EGCR transition and constrain air shower physics
- Auger North should allow to build detailled and high statistics sky maps -> road toward individual sources spectra -> cosmic-ray astronomy
- A very large statistics is also expected for JEM-EUSO, pathfinder for a new promising technique