Cosmic Ray Experiments

(below the atmosphere)

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Talk Outline

- Overview and definitions
- Techniques used to measure CR properties
- Main updated results in different energy regions

Physical Motivation(s)

To study and understand:

- CR origin (production sites, acceleration mechanisms,…)
- High Energy Astrophysics and Cosmology
- Particle physics at c.m. energies up to 1000 TeV
- …….

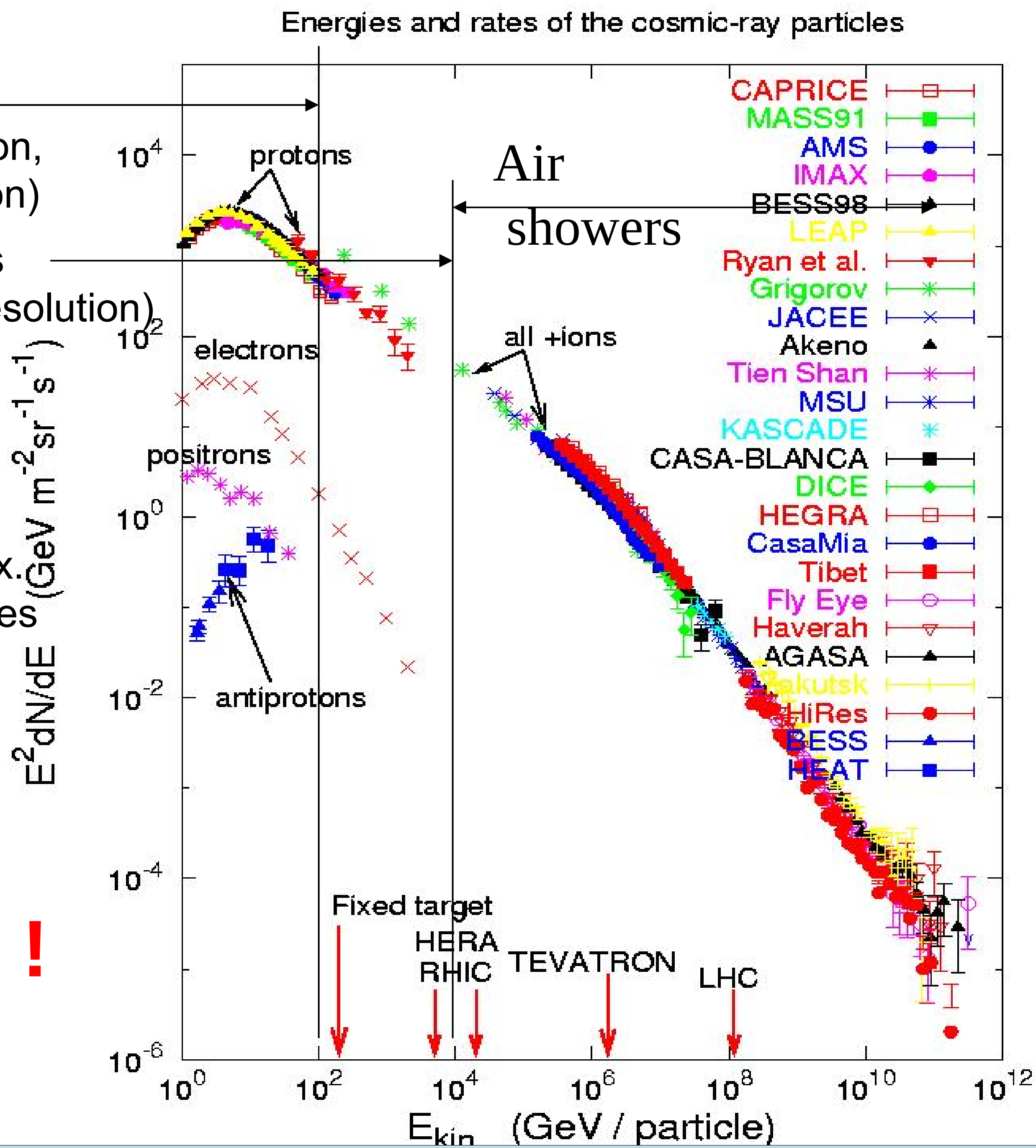
Through the measurement of:

- Energy spectra
- Chemical composition
- Arrival directions
- …..

Spectrometers
($\Delta A = 1$ resolution,
good E resolution)

Calorimeters
(less good resolution)

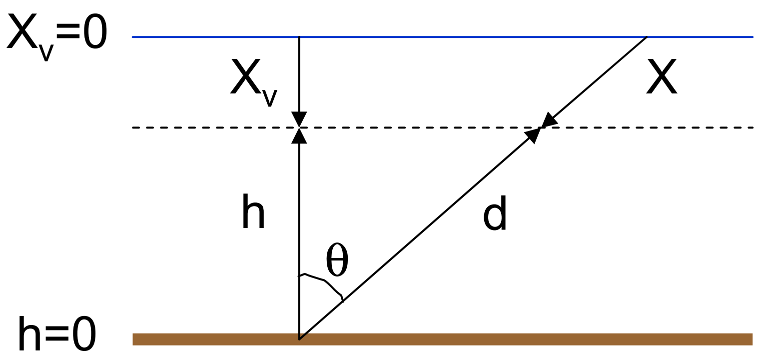
EAS arrays
on the ground to
overcome low flux.
Don't see primaries
directly.



The beam !

The (high energy physicist) atmosphere

The target !



"*Standard*" atmosphere :

$X_v = X_0 \exp(-h/h_0)$

$X_0 \approx 1030$ g/cm^2

$h_0 \approx 6.4 - 8.4$ km

$\sigma_{p\text{-}Air} \sim 300$ mb @ $E \sim 1\text{-}100$ TeV

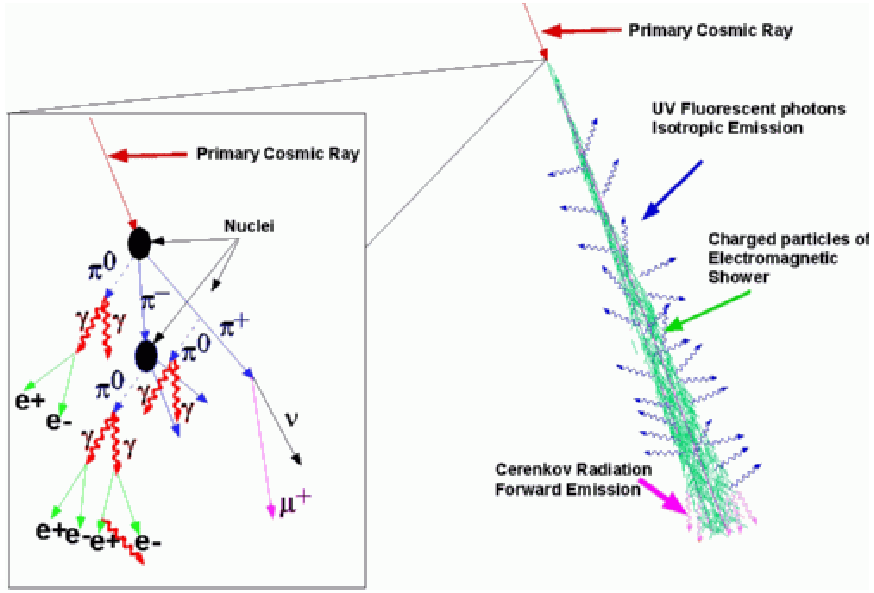
$\Lambda_p \sim 80$ g/cm^2 $\Lambda_{Fe} \sim 2\text{-}3$ g/cm^2 $\Lambda_{rad} \sim 37$ g/cm^2

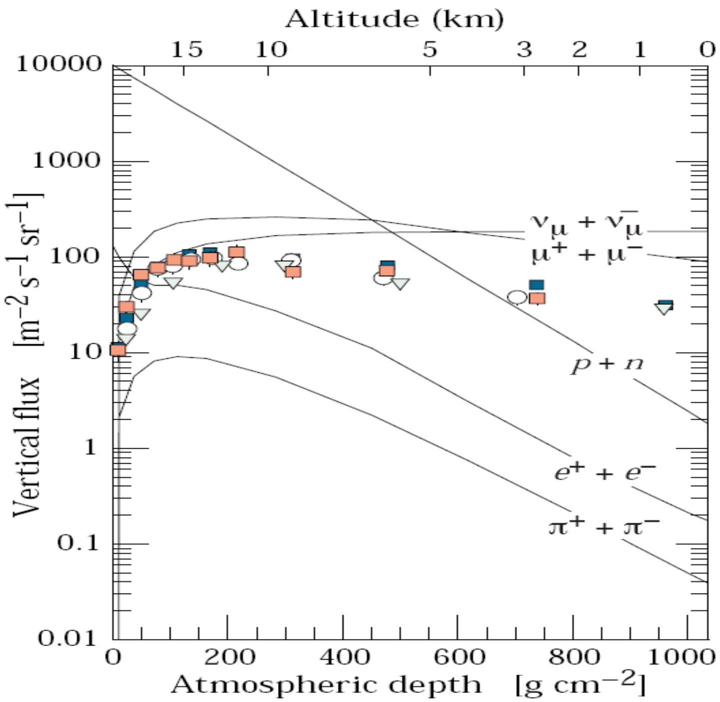
$X_0 \sim 13\Lambda_p \sim 28\ \Lambda_{rad}$

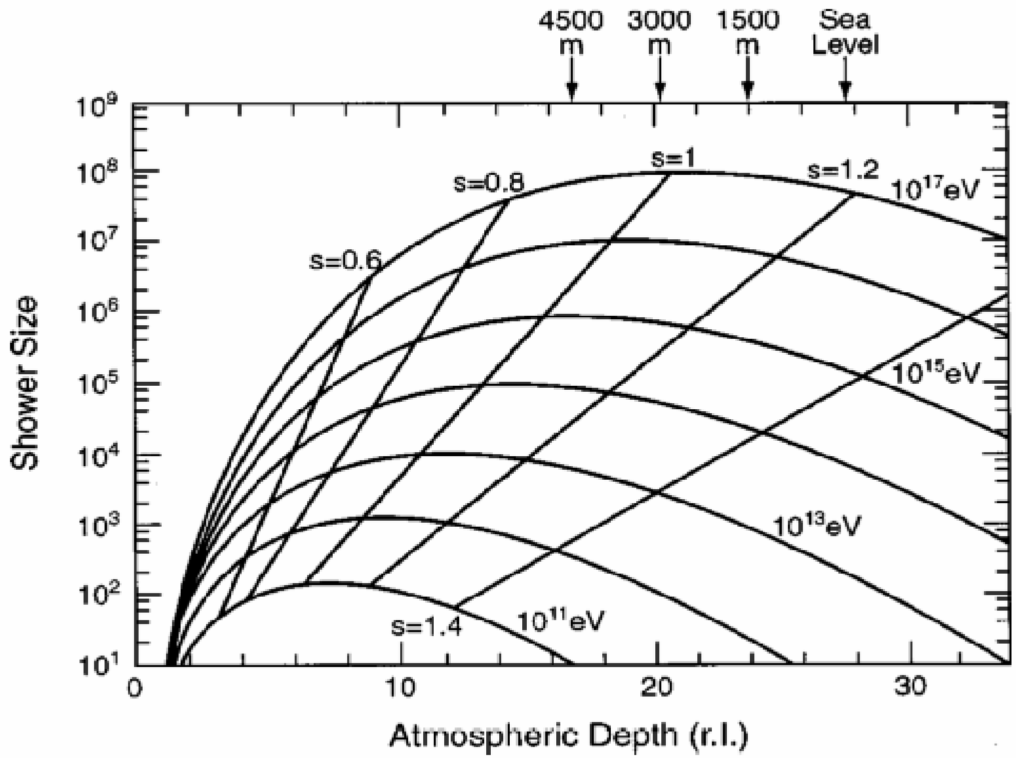
$X_v \sim \Lambda_p \Leftrightarrow h \sim 18$km

EAS Components

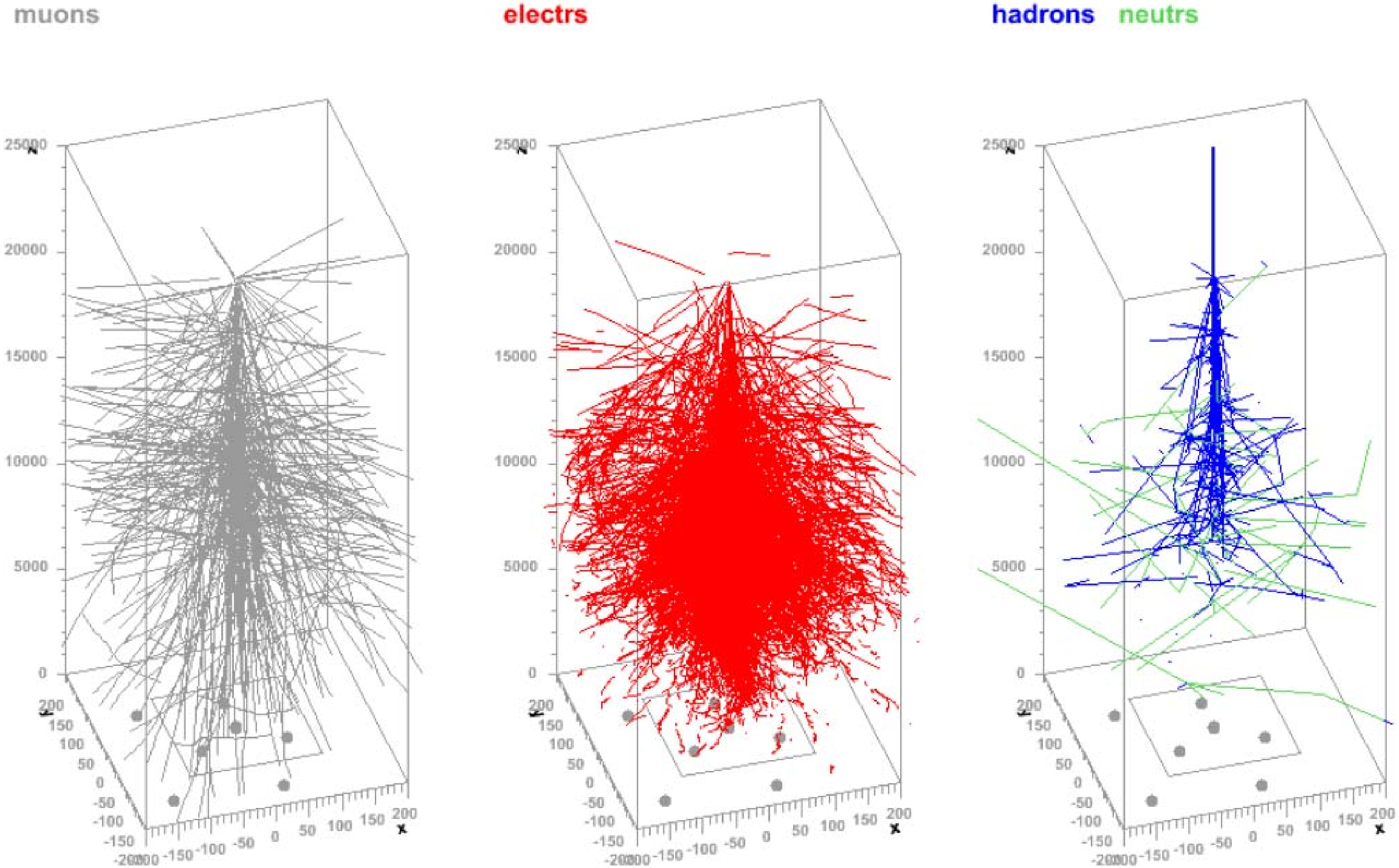
- Soft: p, n, π, e, γ,..
- Hard: μ, ν
- Čerenkov light (mainly produced by electrons)
- Fluorescence light







Shower particle tracks: proton



Proton 10^{13} eV

21336 m

Data Analysis flowchart in a "typical" EAS experiments

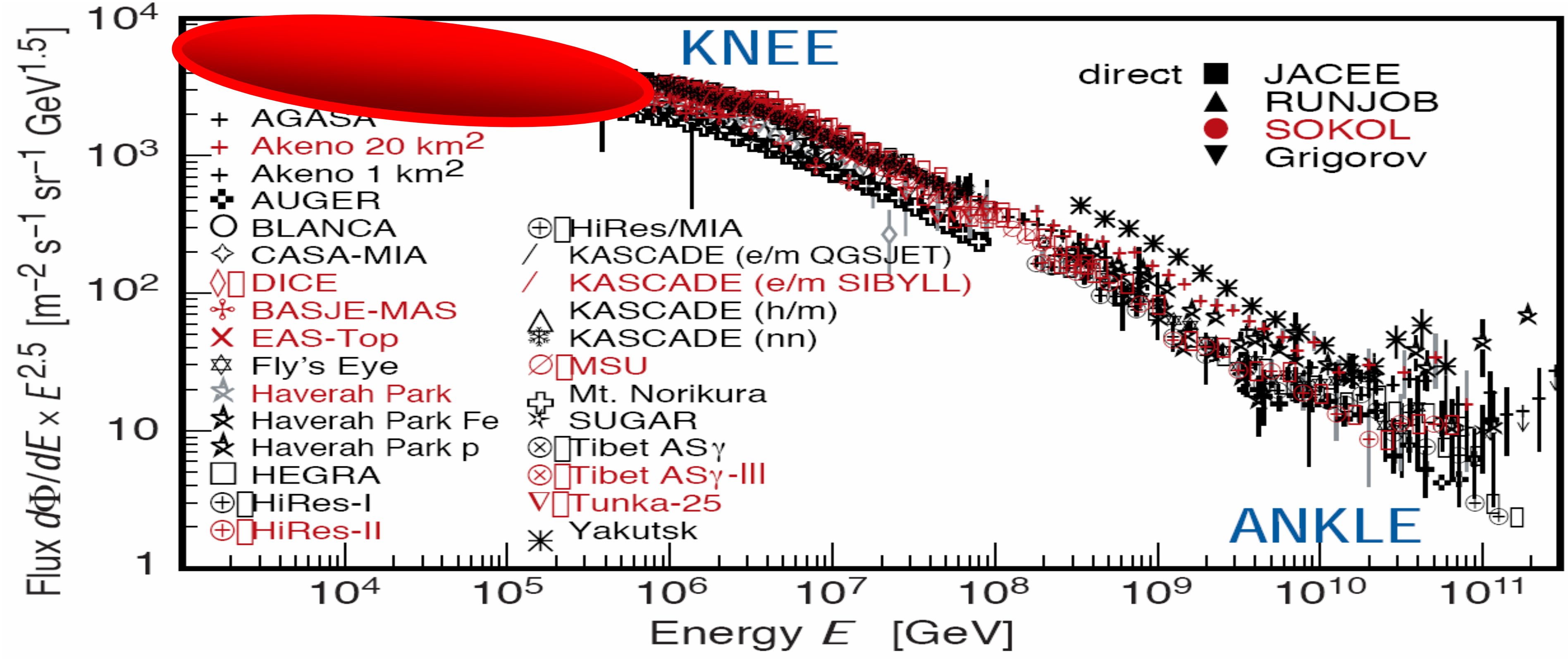
- Shower axis
- Shape of the lateral distribution
- Measurement of the muon component
- Cerenkov light image and lateral distribution
- Shower development information provided by the fluorescence light

→

- Measurement of energy spectra and arrival directions
- Information on the chemical composition vs energy
- Information on the interaction model

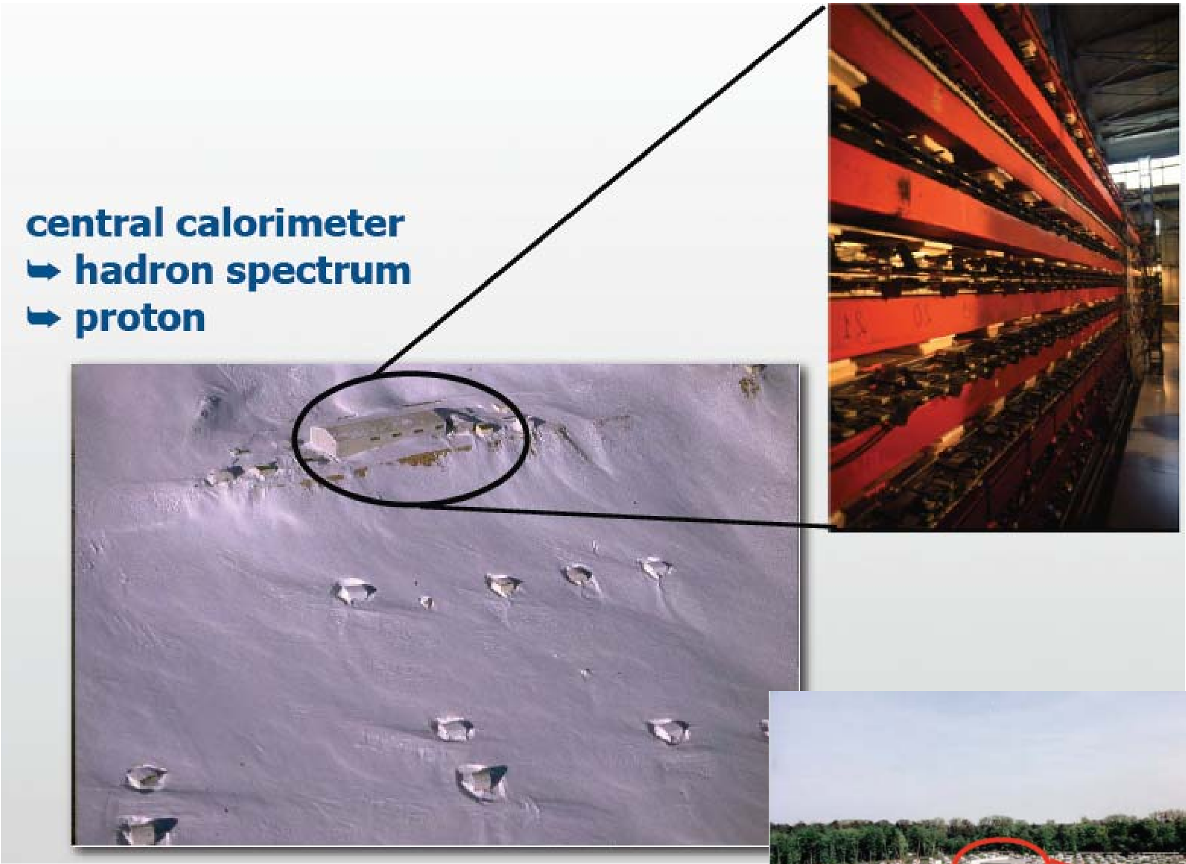
MC simulations of the shower development and of the detector response

- Detector features and performances
- Characteristics of the experimental site
- Reconstruction algorithms
- Analysis procedures



Below the knee

- Measure the unaccompanied hadrons flux with hadrons calorimeters
- Go to high altitude to lower the energy threshold



EAS-TOP

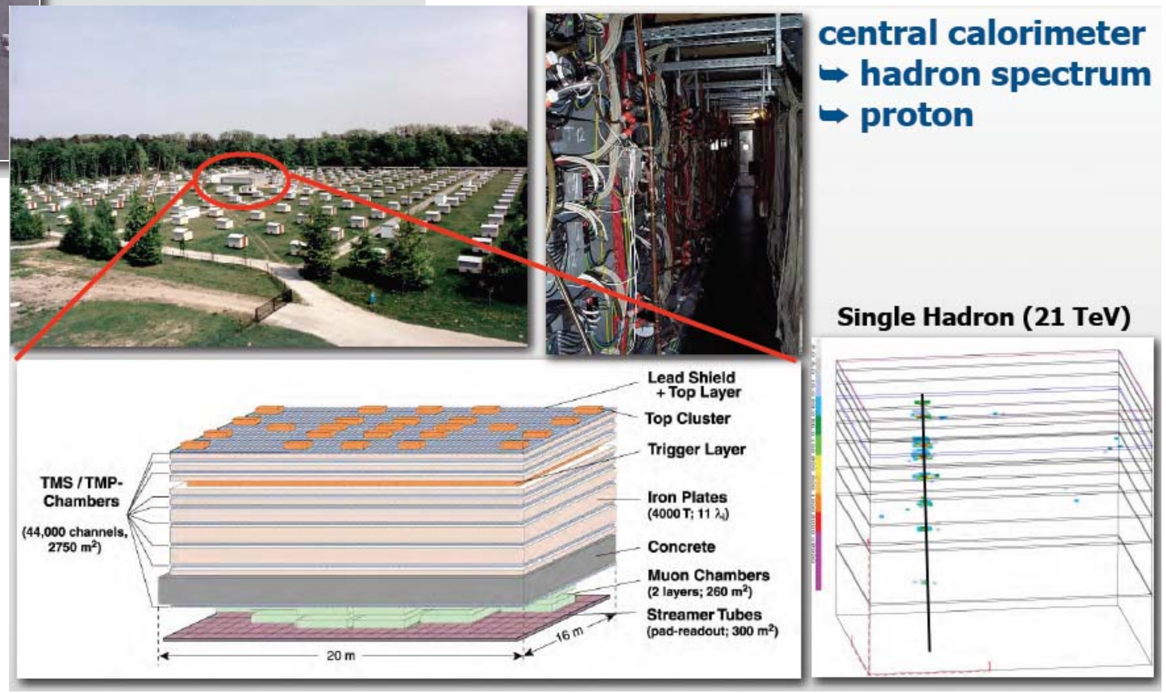
Campo Imperatore

2000 m a.s.l. (~ 820 g/cm^2)

KASKADE

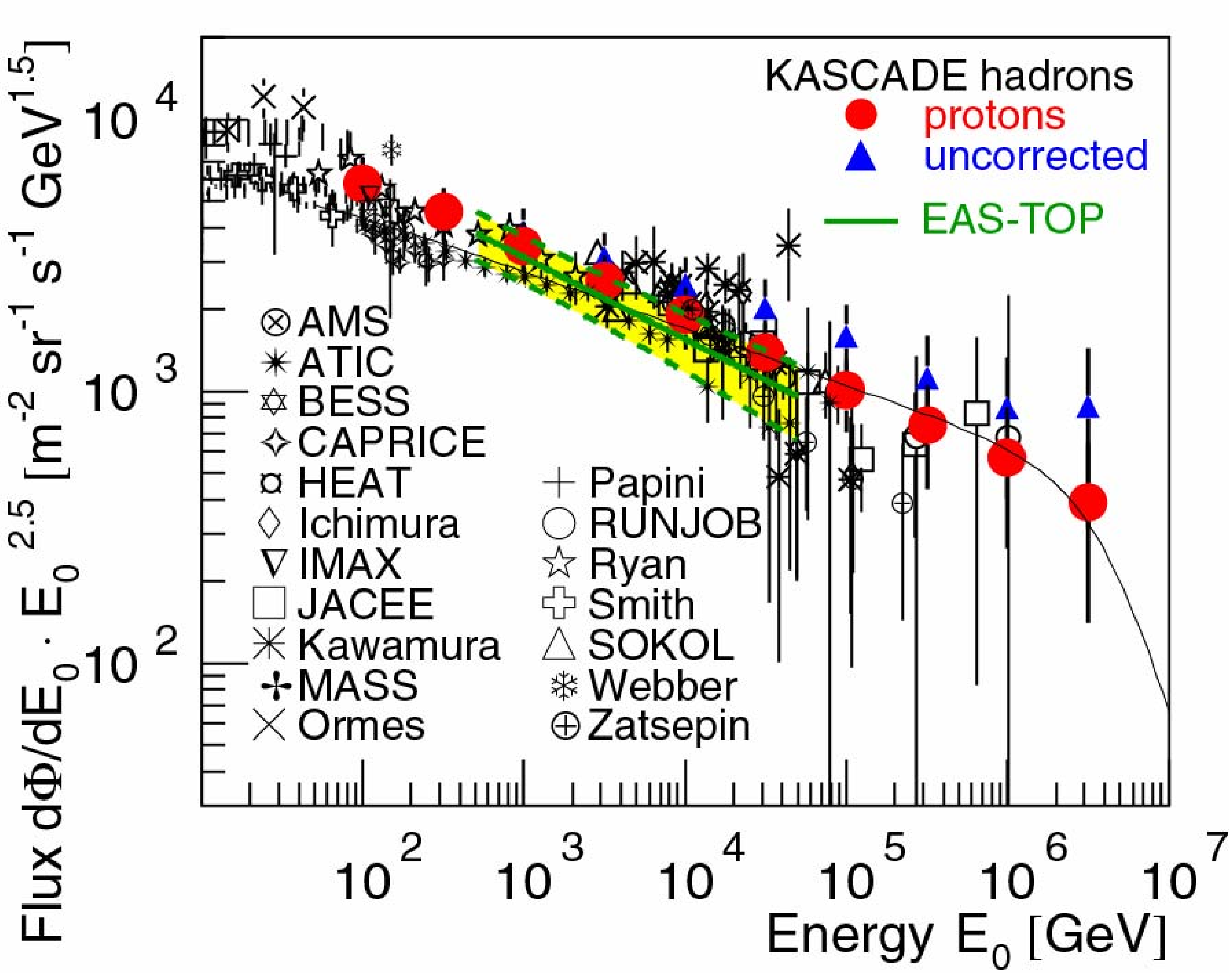
FZK - Karlsruhe

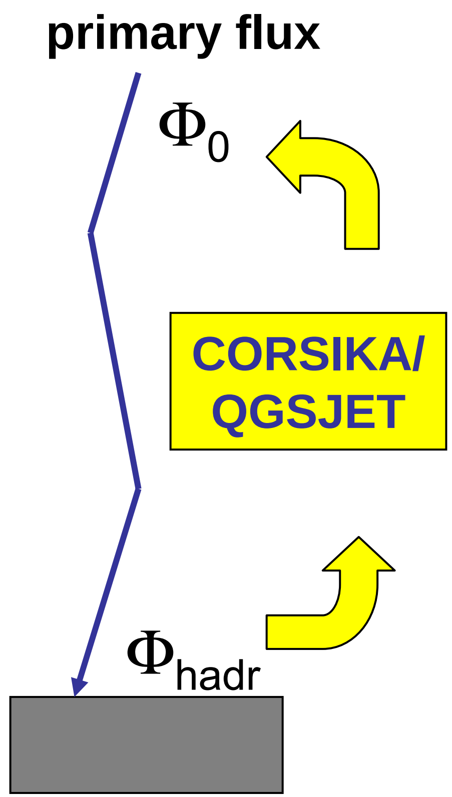
110 m a.s.l. (~1000 g/cm^2)

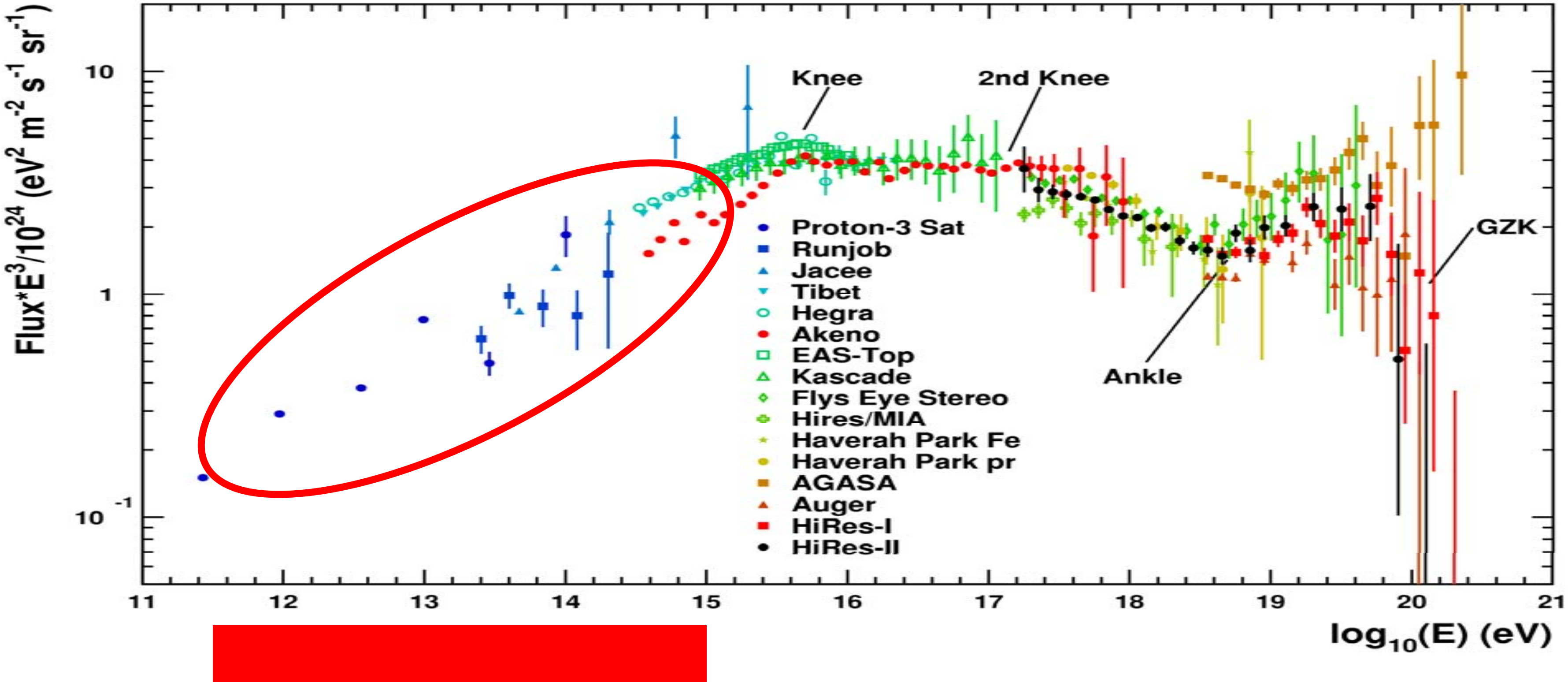


Primary proton spectrum

reconstructed from unaccompanied hadrons







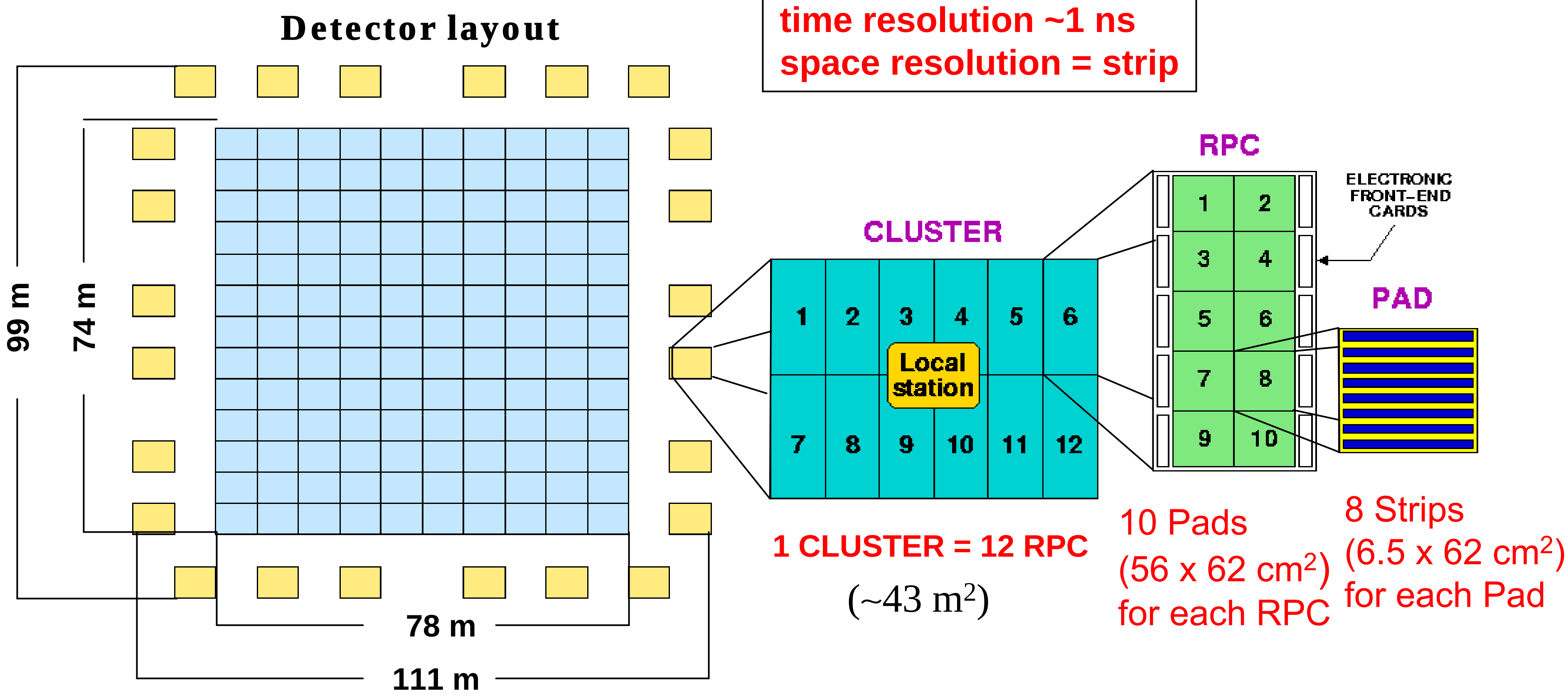
High Altitude Cosmic Ray Laboratory @ YangBaJing

Site Altitude: 4300 m a.s.l. , ~ 600 g/cm^2

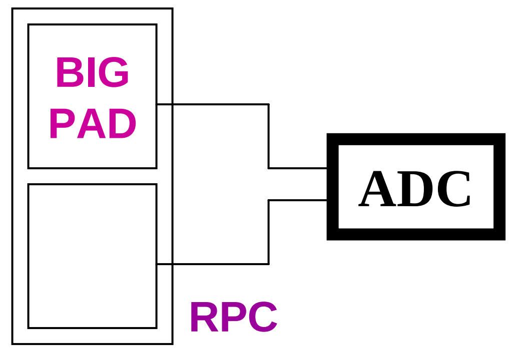
Site Coordinates: longitude 90° 31’ 50” E, latitude 30° 06’ 38” N

ARGO-YBJ layout

time resolution ~1 ns
space resolution = strip



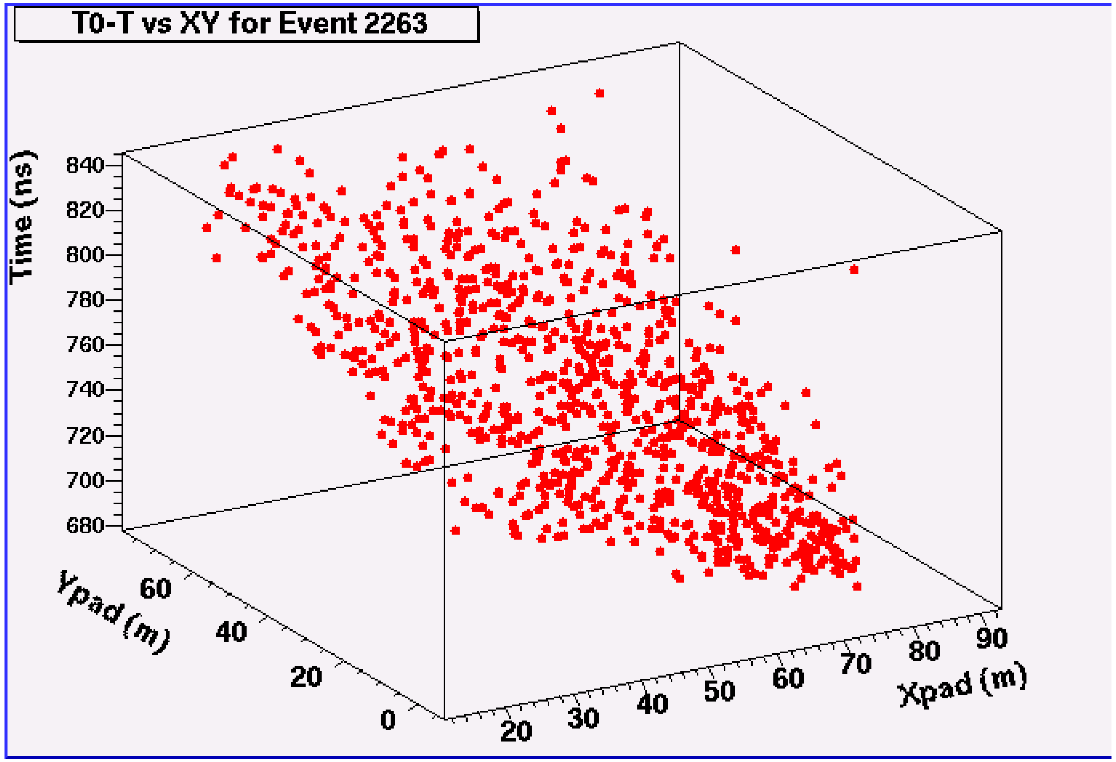
Layer (~92% active surface) of Resistive Plate Chambers (RPC), covering a large area (5600 m²)
+ sampling guard ring
+ 0.5 cm lead converter

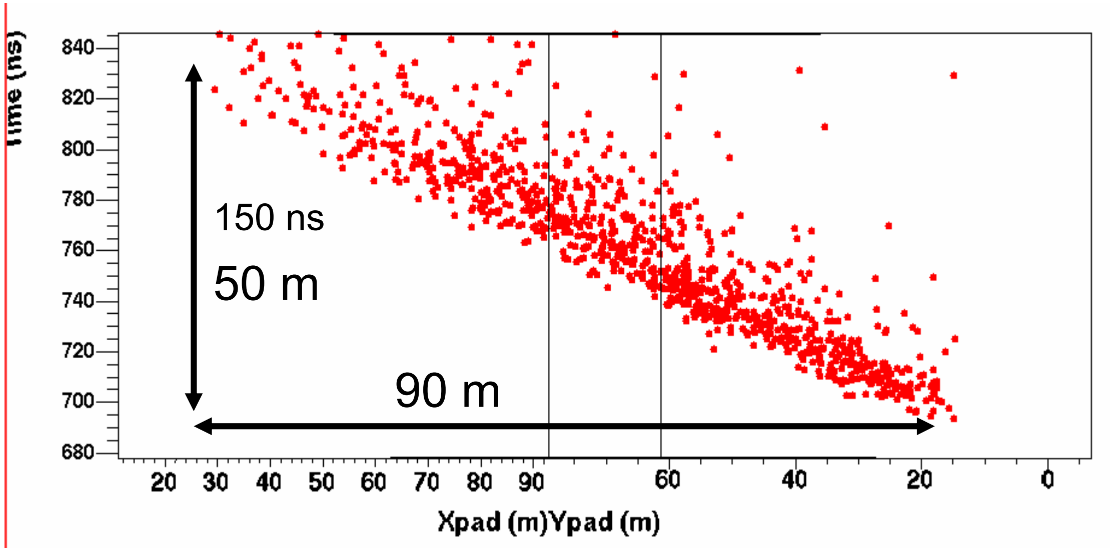


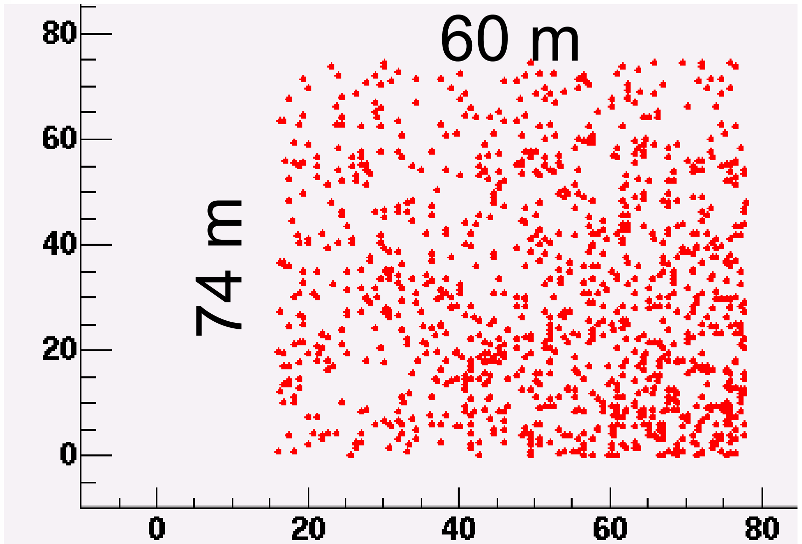
Read-out of the charge induced on "Big Pads"

A unique way to study EAS

- Full space-time reconstruction
- Shower topology
- Structure of the shower front
- ……..



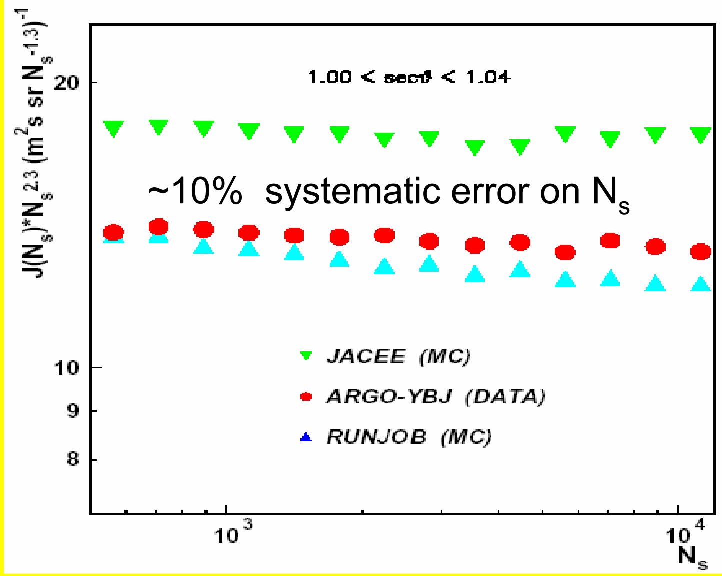


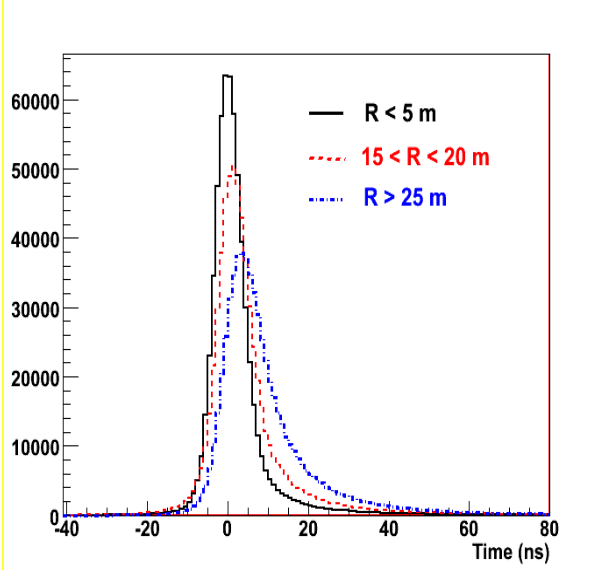


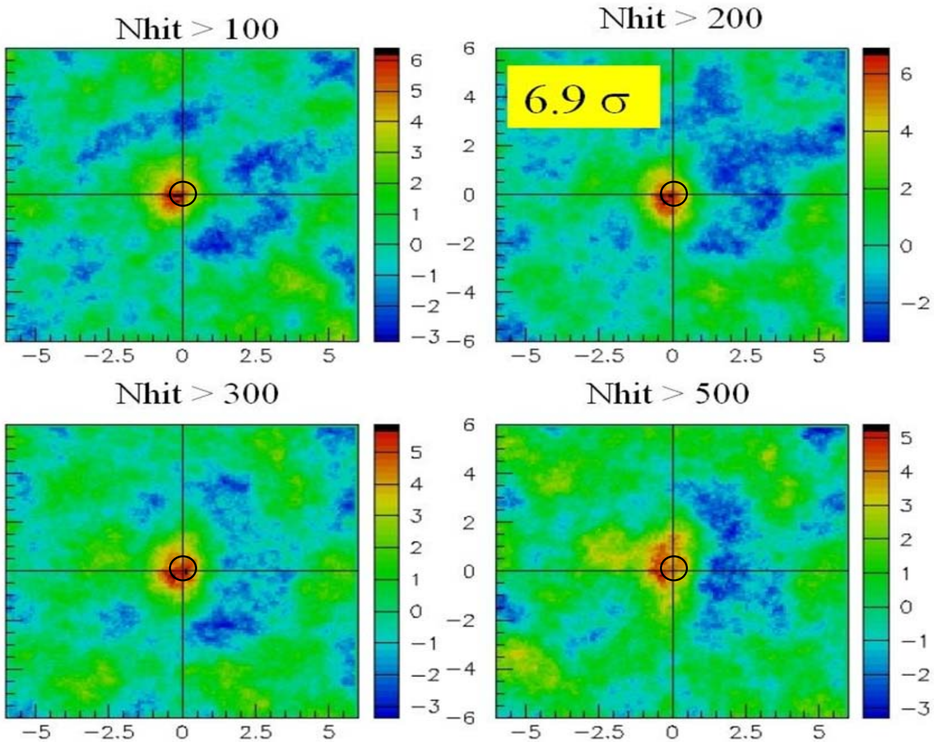
First preliminary

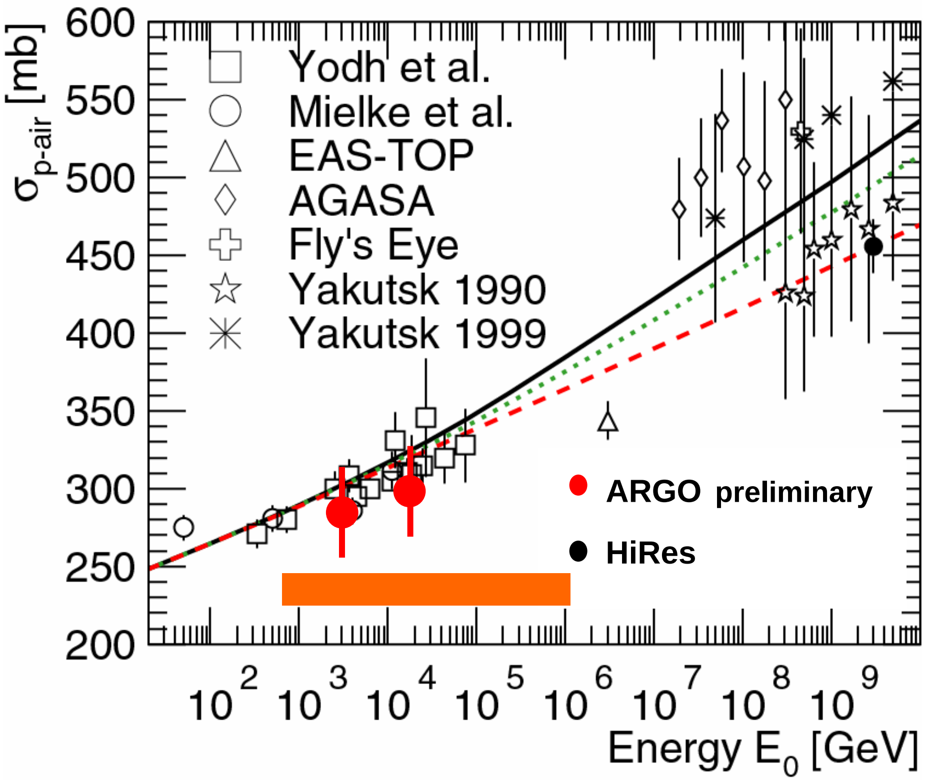
results on:

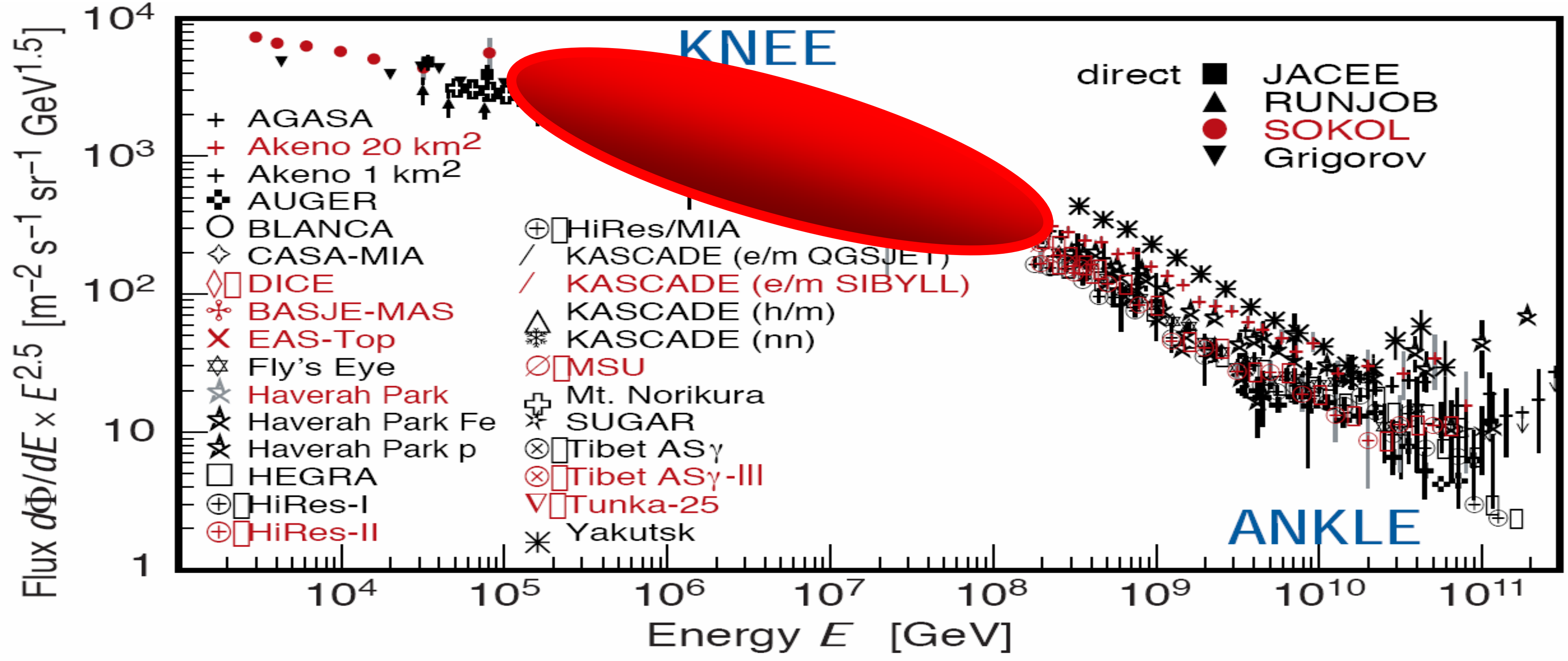
- EAS phenomenology
- CR spectrum
- primary interaction
- Moon shadow , …..











The knee region

- Measure the particle distributions at ground

- Use the air Cherenkov signal produced in along the shower development

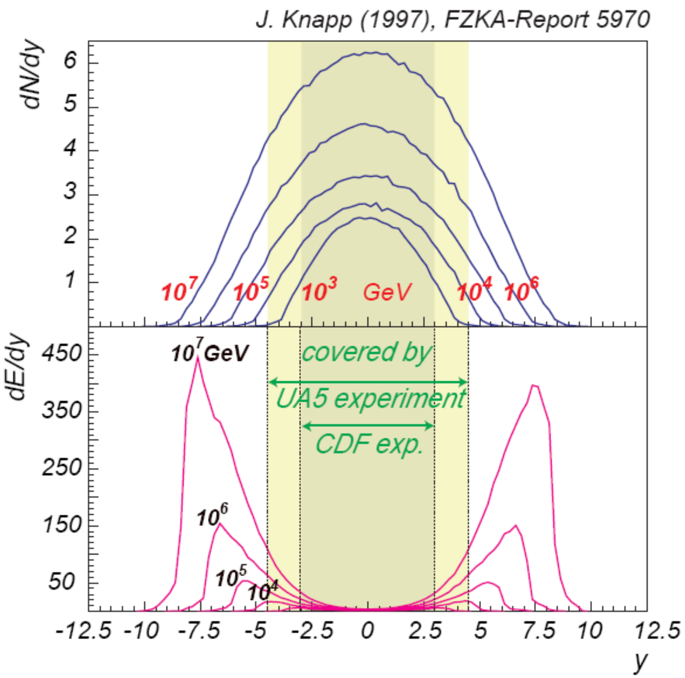
Many possible explanations for the knee

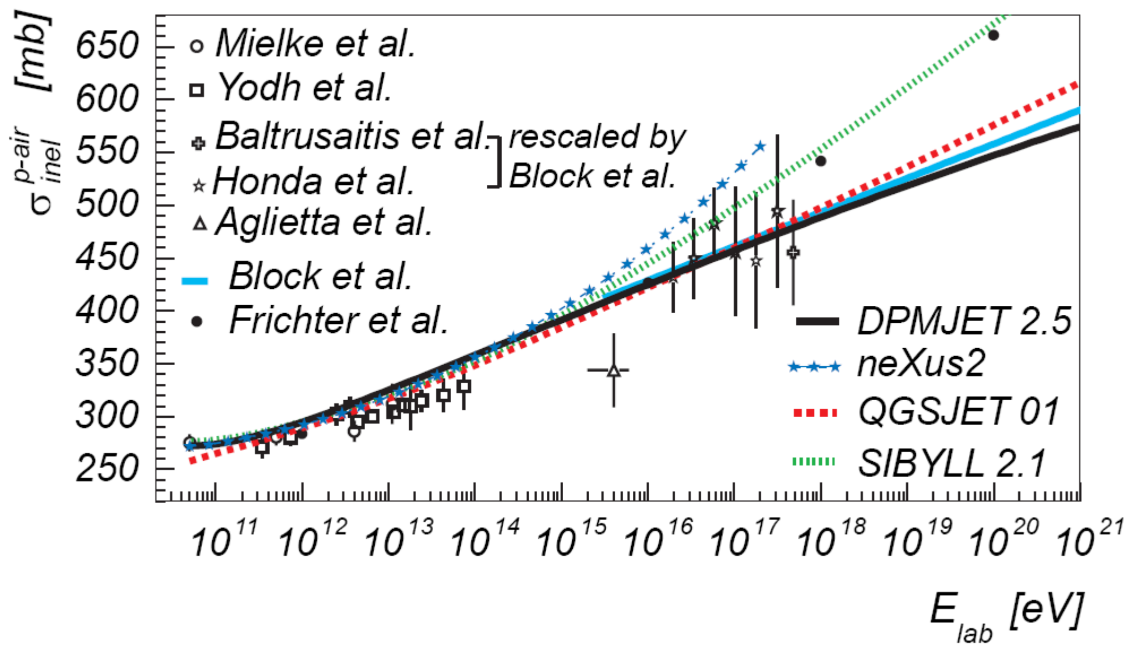
- Change of acceleration mechanism
- Energy dependent diffusion coefficient
- Escape from the Galaxy
- New interactions during shower development

Composition analyses and energy spectra needed

Uncertainties due to particle interaction models

- Accelerator data needed in order to cover the very forward direction
- Use of phenomenological interaction models
- Different predictions do not get completely smeared during the shower development



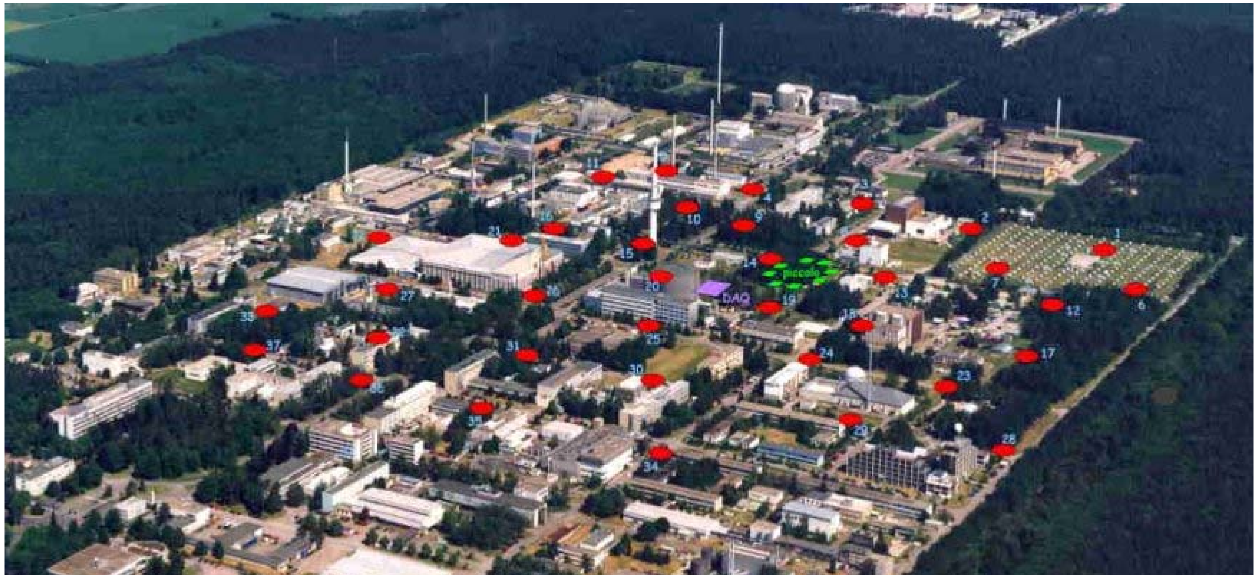


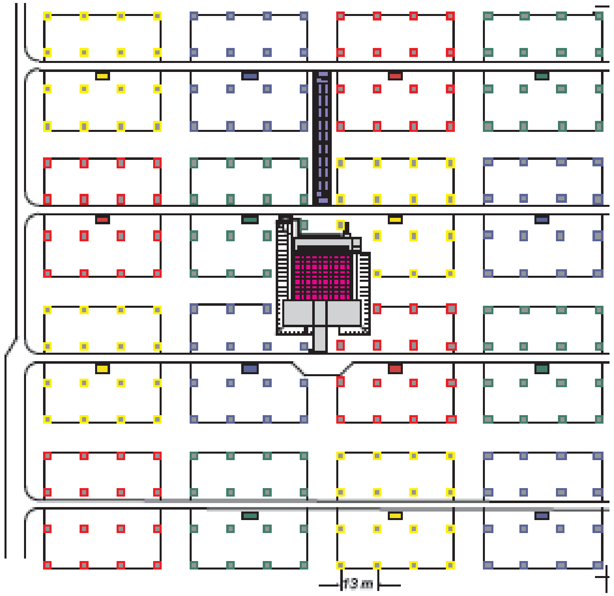
KASKADE +

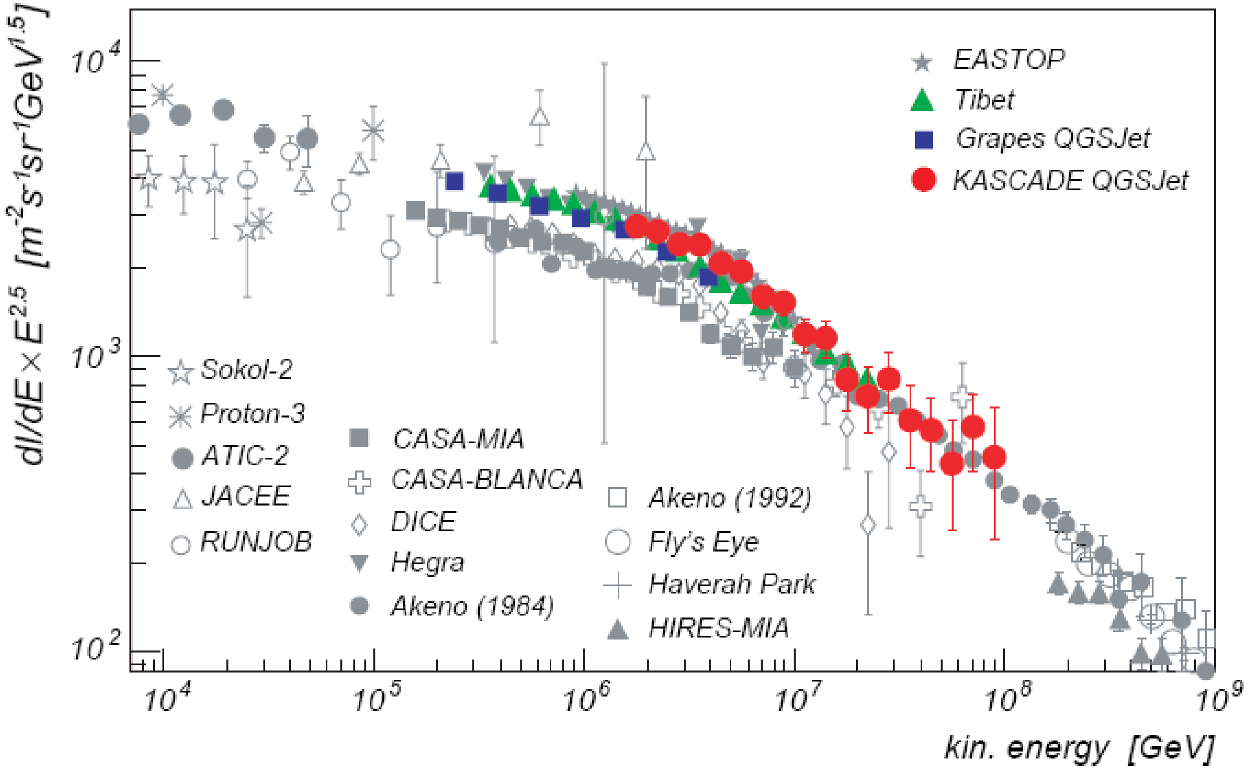
KASKADE-Grande

It measures :

- n. of electrons
- n. of muons
- core position
- arrival direction



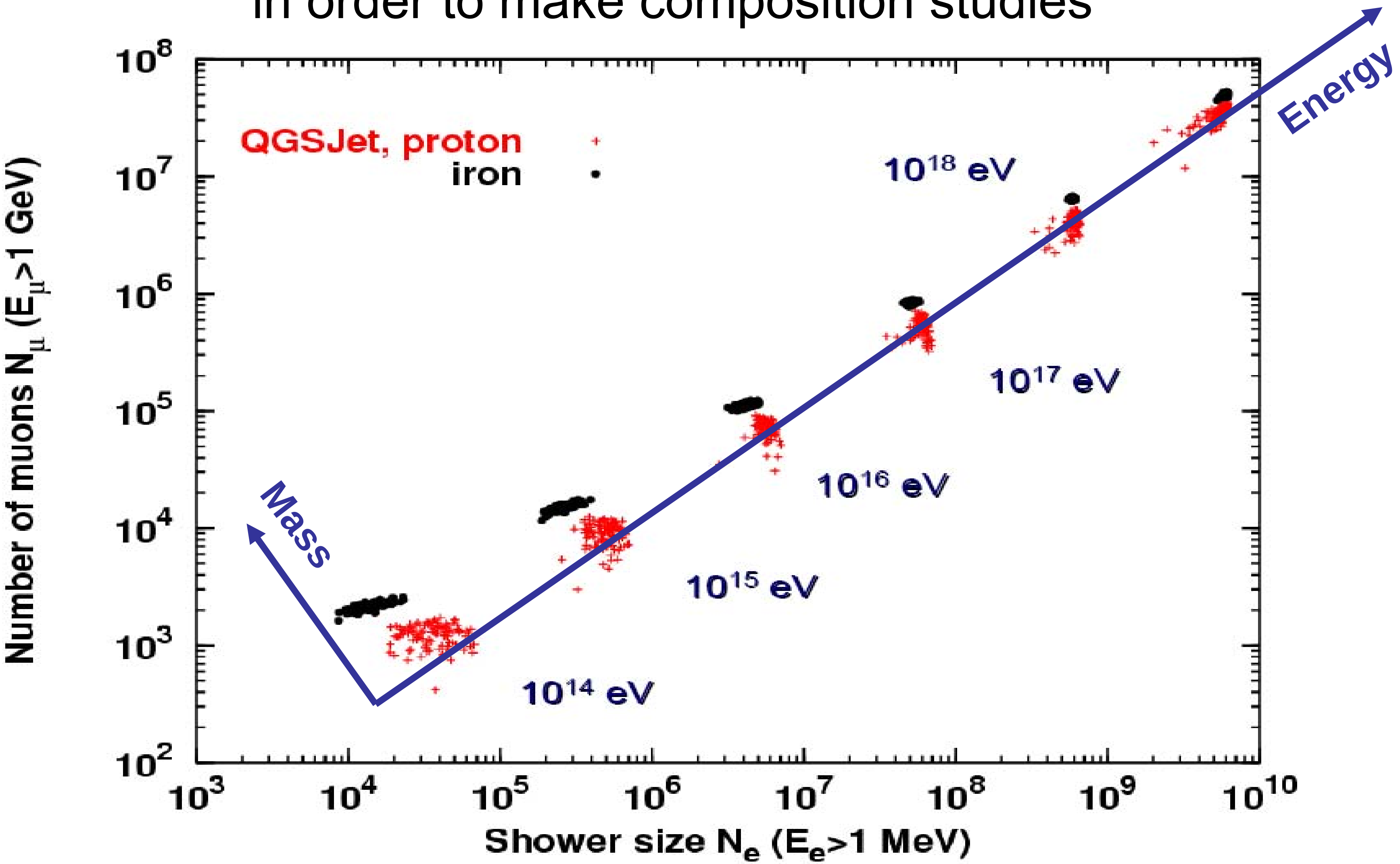


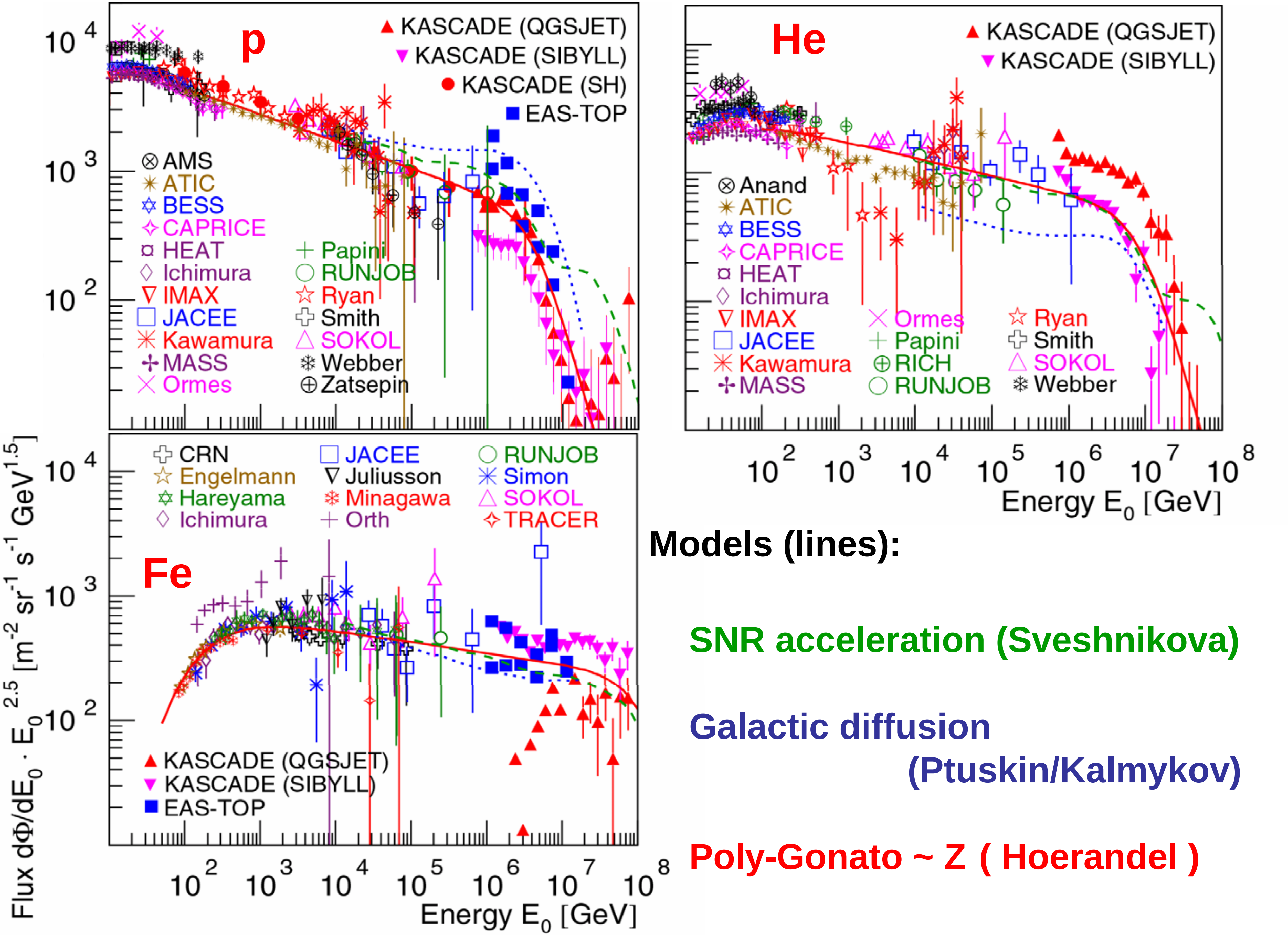


Use differences in muon yeld for different primaries

+ unfolding methods

in order to make composition studies





Models (lines):

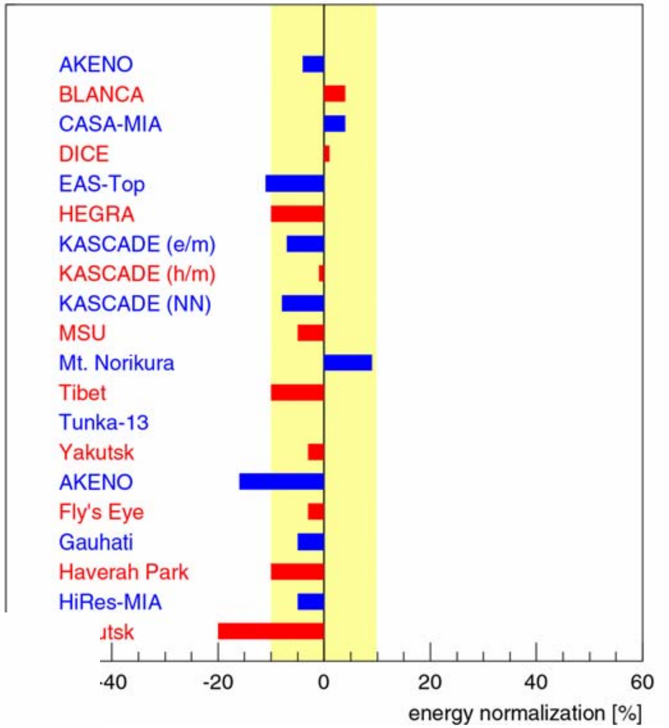
SNR acceleration (Sveshnikova)

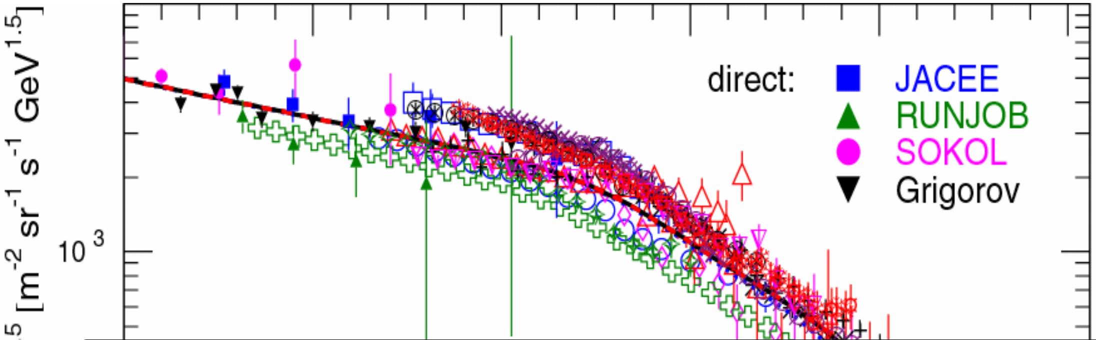
Galactic diffusion (Ptuskin/Kalmykov)

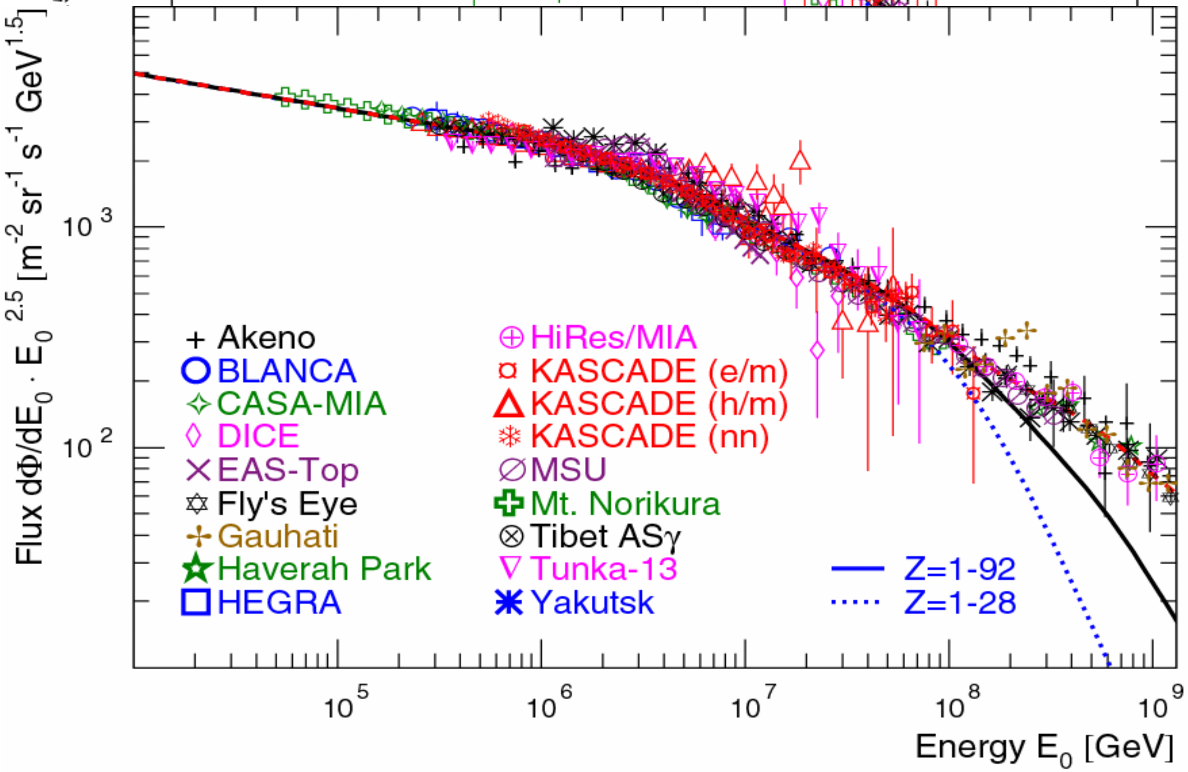
Poly-Gonato ~ Z (Hoerandel)

A test:

Renormalize the energy scales

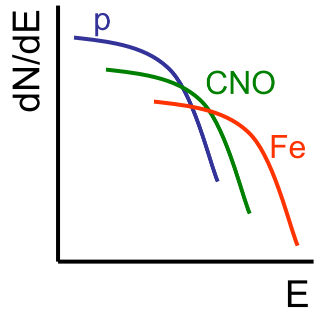


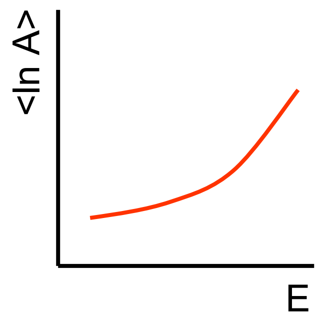




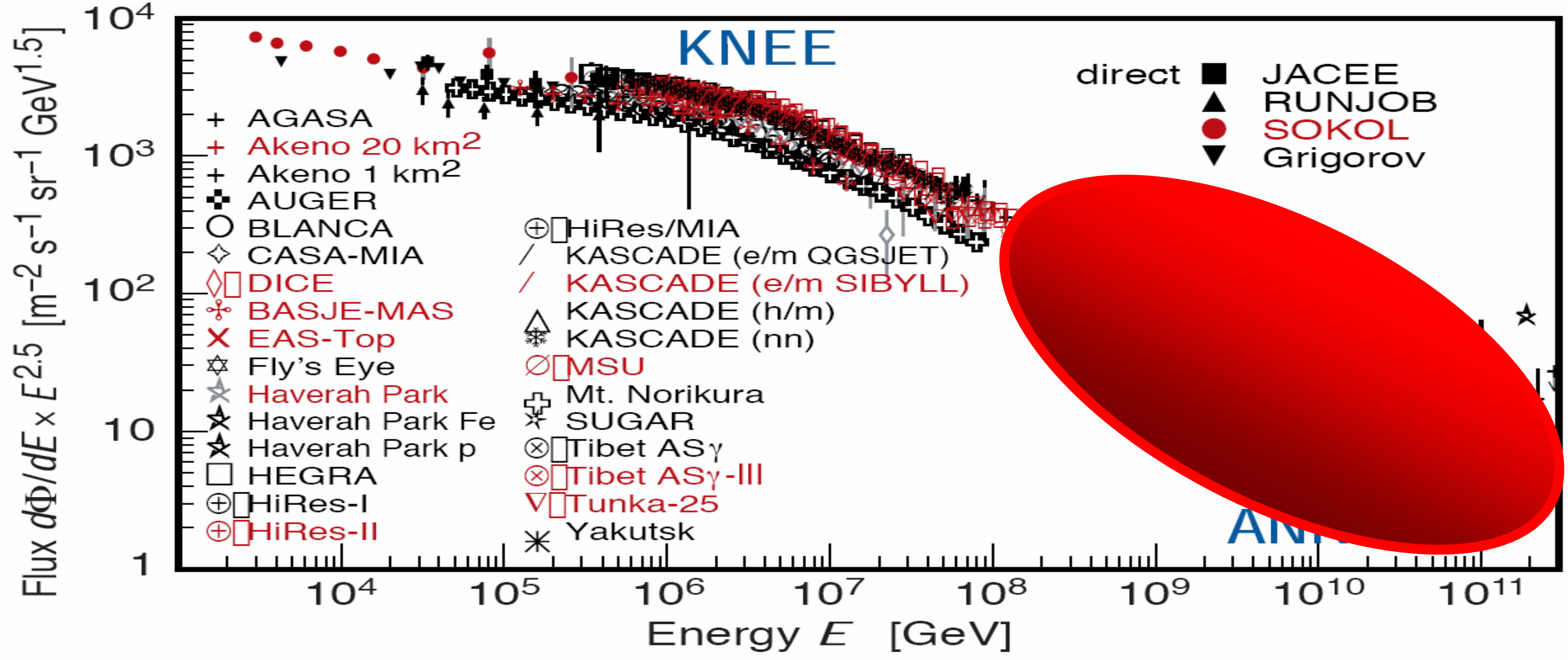
The “knee” summary (at first order)

- “All-particle” energy spectra are reasonably under control
- Individual energy spectra are sensitive to the interaction models
- New inputs needed by running and future CR experiments and by accelerator data (low p_t particles, …)





- SNR maximun acceleration energy and/or galactic diffusion provide a good possible explanation of the knee
- Transition from light to heavy elements (Z dependent cutoff) …
- …till the onset of the extragalactic component (ankle)



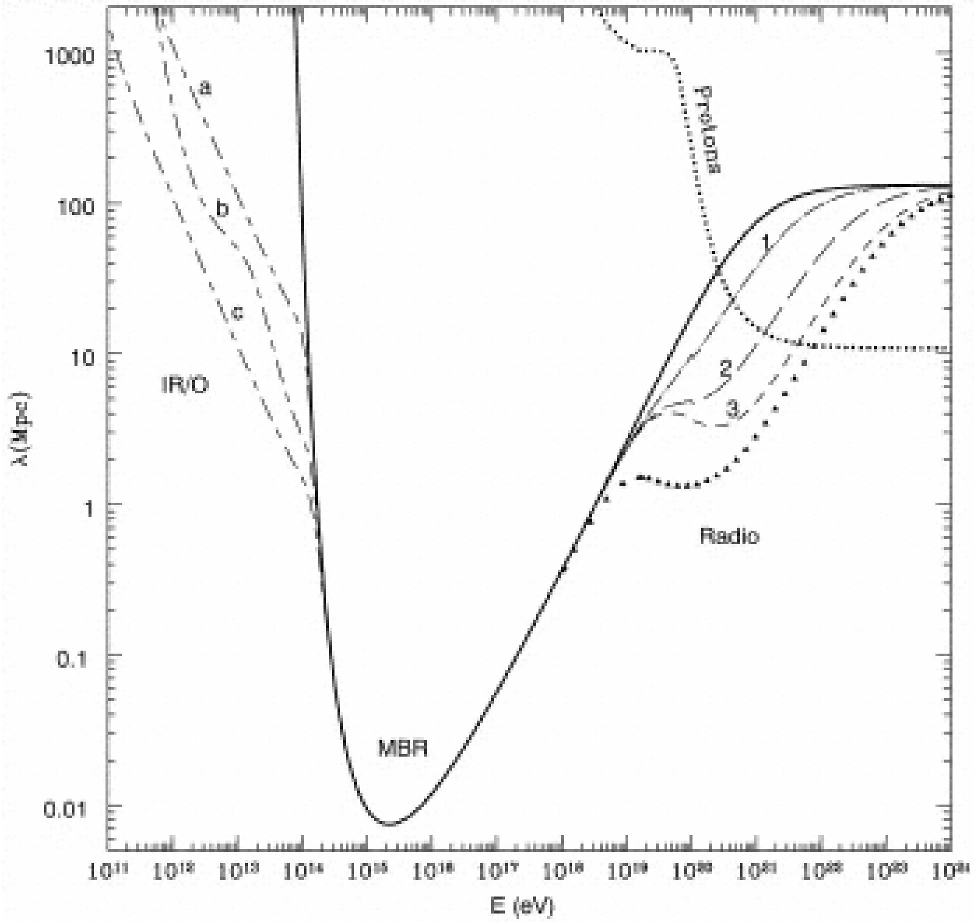
The ankle region

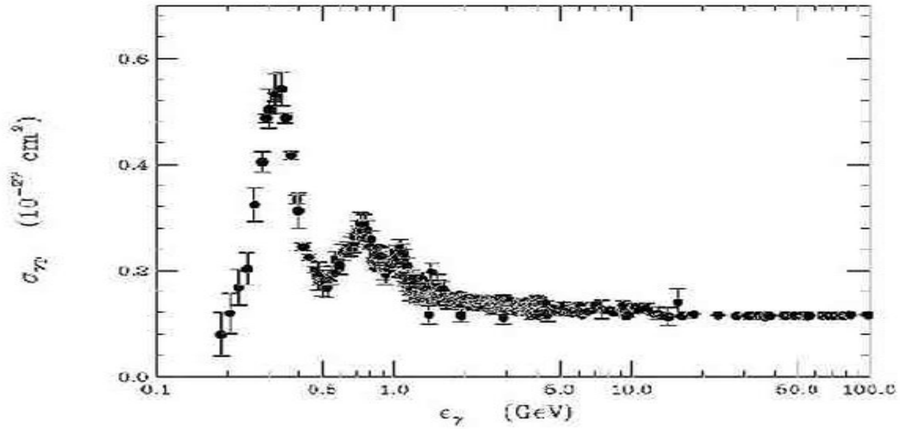
- Measure the particle distributions at ground with huge arrays
- Use the atmosphere as a scintillator by detecting the fluorescence light

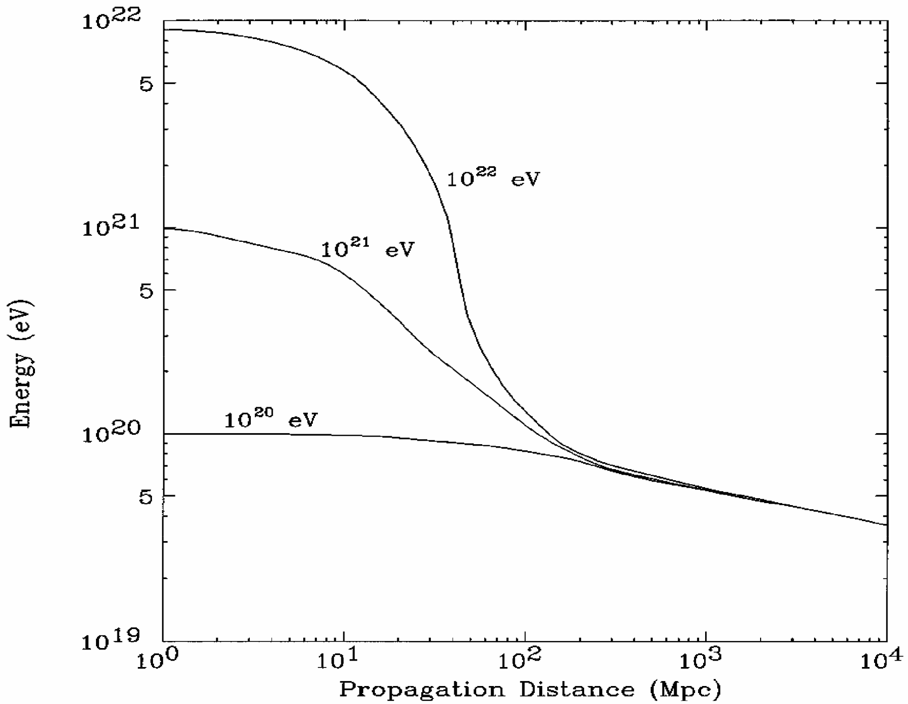
GZK Cutoff at E > 5 ·10^{19}eV

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

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







Cutoff of photon flux at E > 10^{14}eV

$\gamma\ \gamma_{CMB} \rightarrow e^+\ e^-$

Eo >10^{20} eV:

1 part. / (km^2 century sr)

→ 10^2 - 10^3 km^2 areas

Time

Volcano Ranch (SD)

Haverah Park (SD)

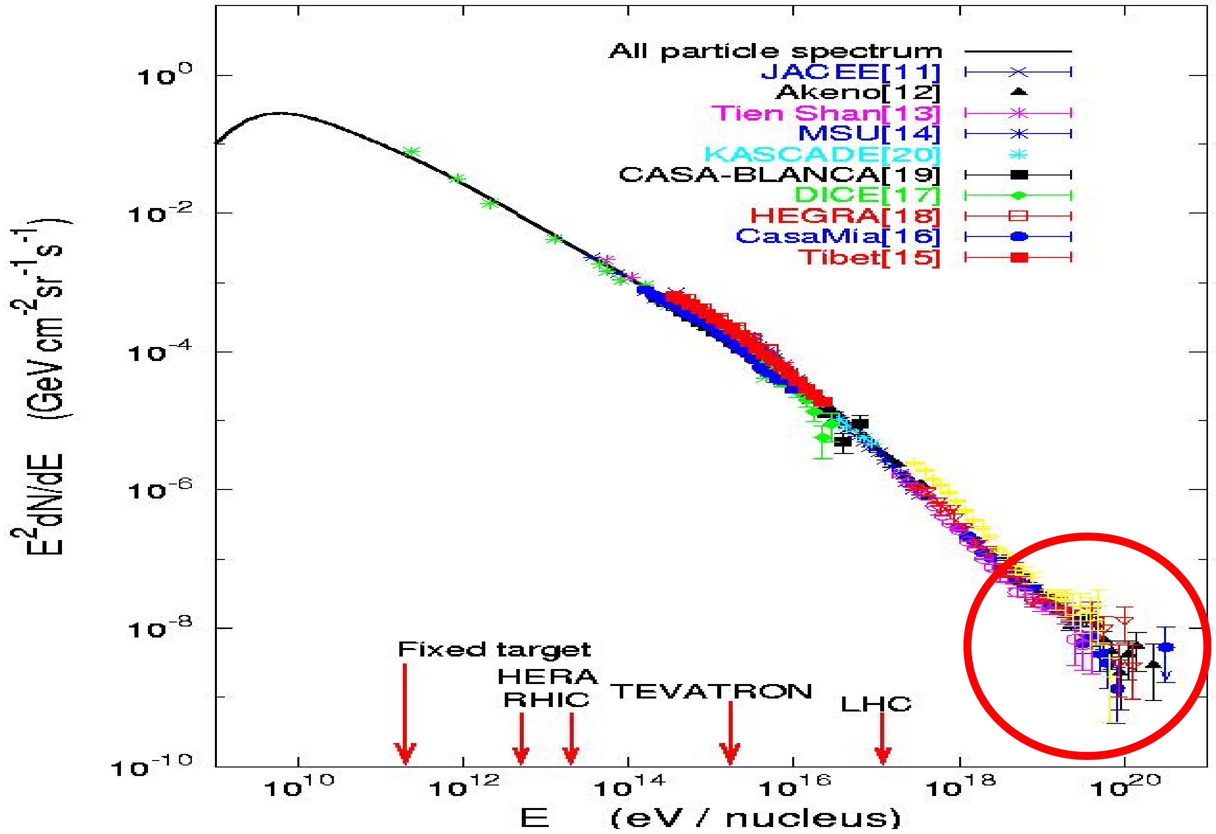
Yakutsk (SD)

Fly'Eye (FD)

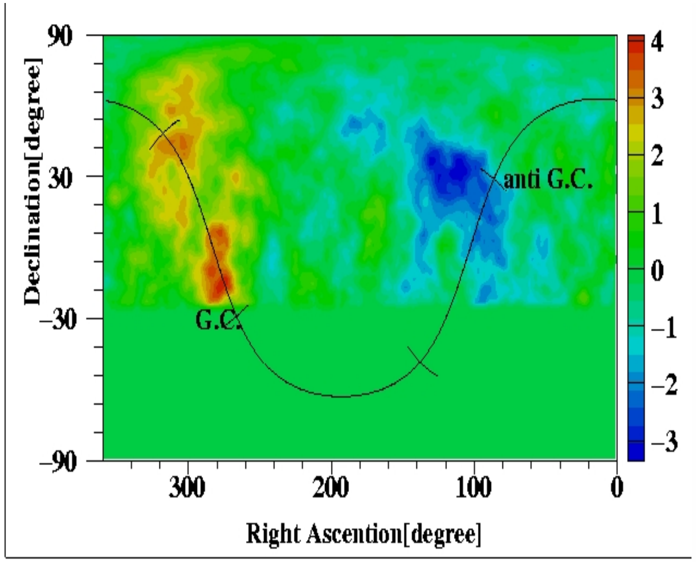
AGASA (SD)

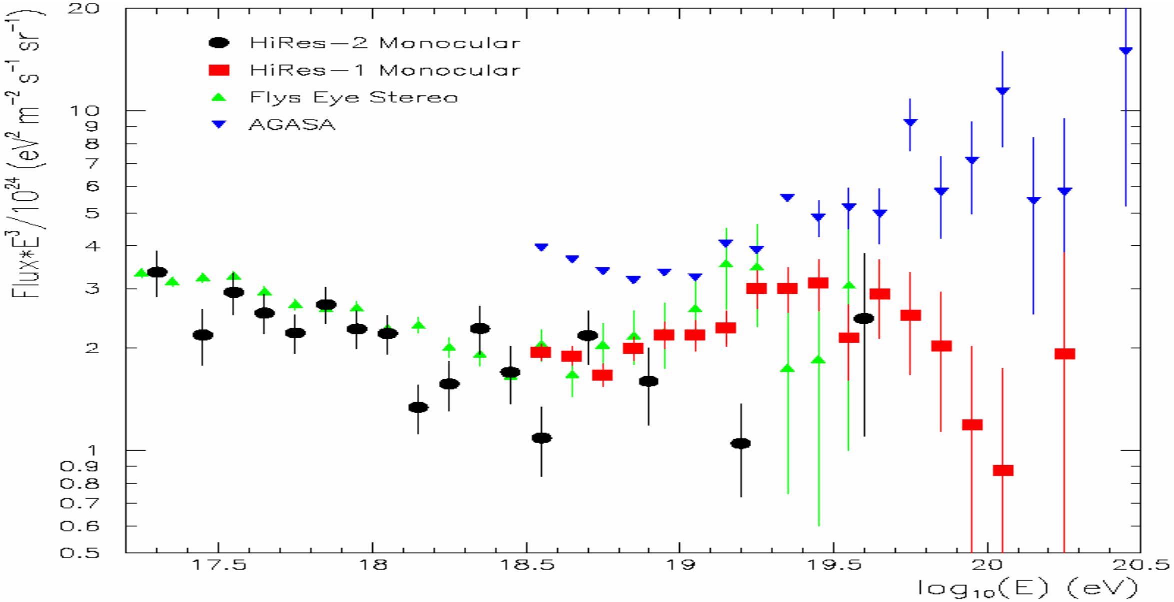
HiRes (FD)

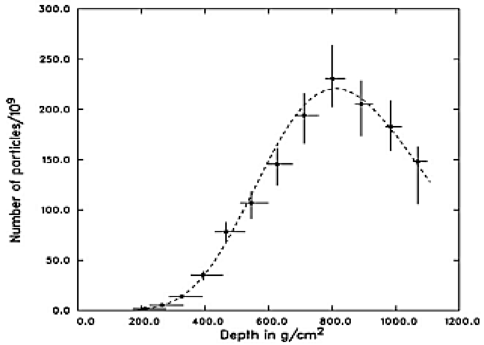
AUGER (SD + FD)



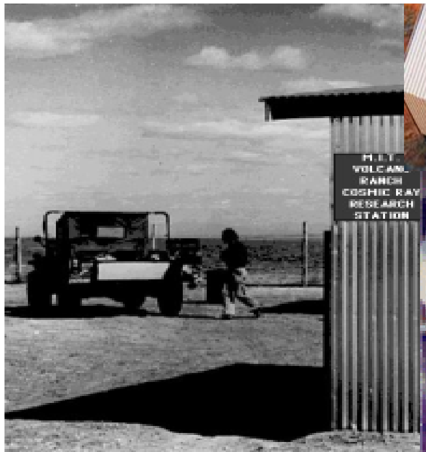
- Understand the ankle and GZK features (galactic/extragalactic, matter distribution,..)
- Study particle physics at c.m. energy 1000 TeV (x-sections, Lorentz invariance, …)
- Map extragalactic sources (Active Galactic Nuclei, …)
- Study acceleration processes (electromagnetic, hadronic, …)
- Test Top-down models (topological defects, ..) and other exotic mechanisms
- ……………

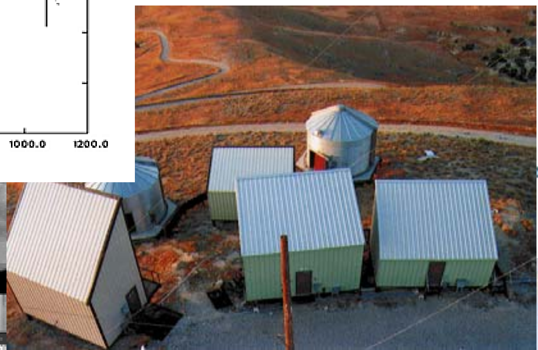






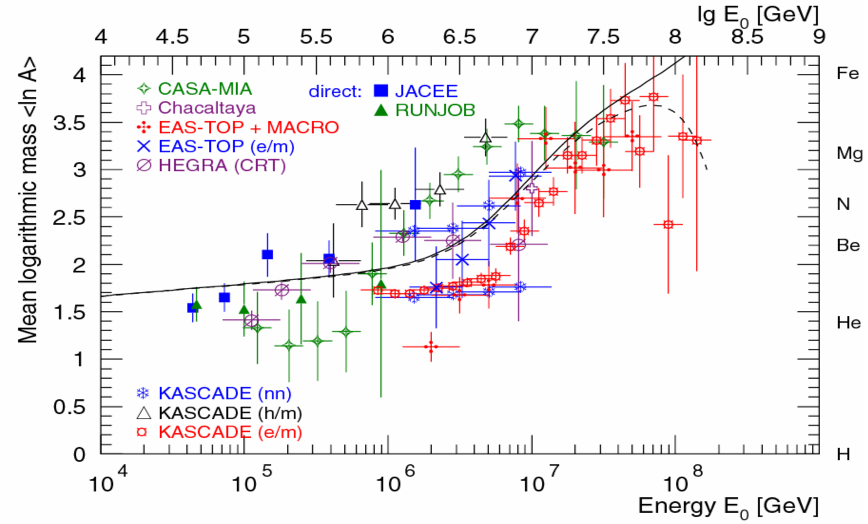
The pre-Auger Era

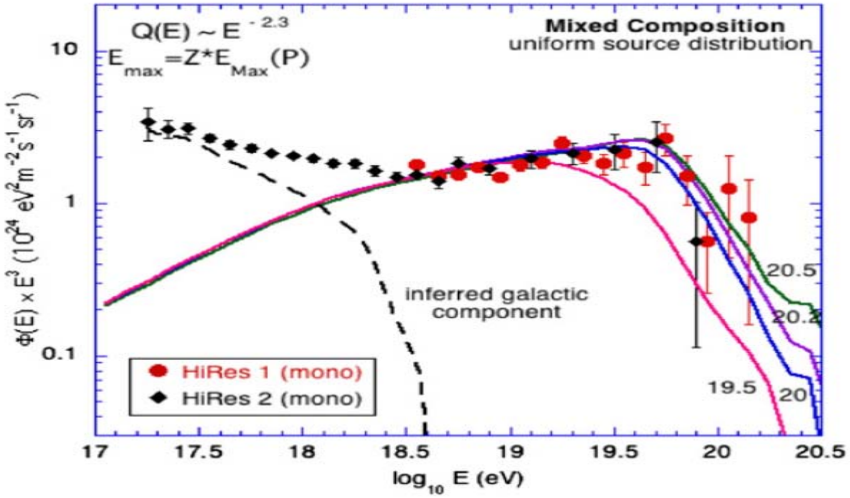


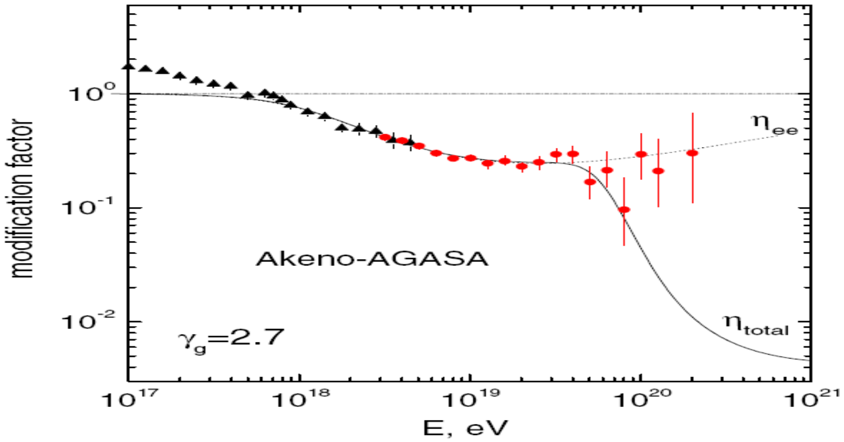


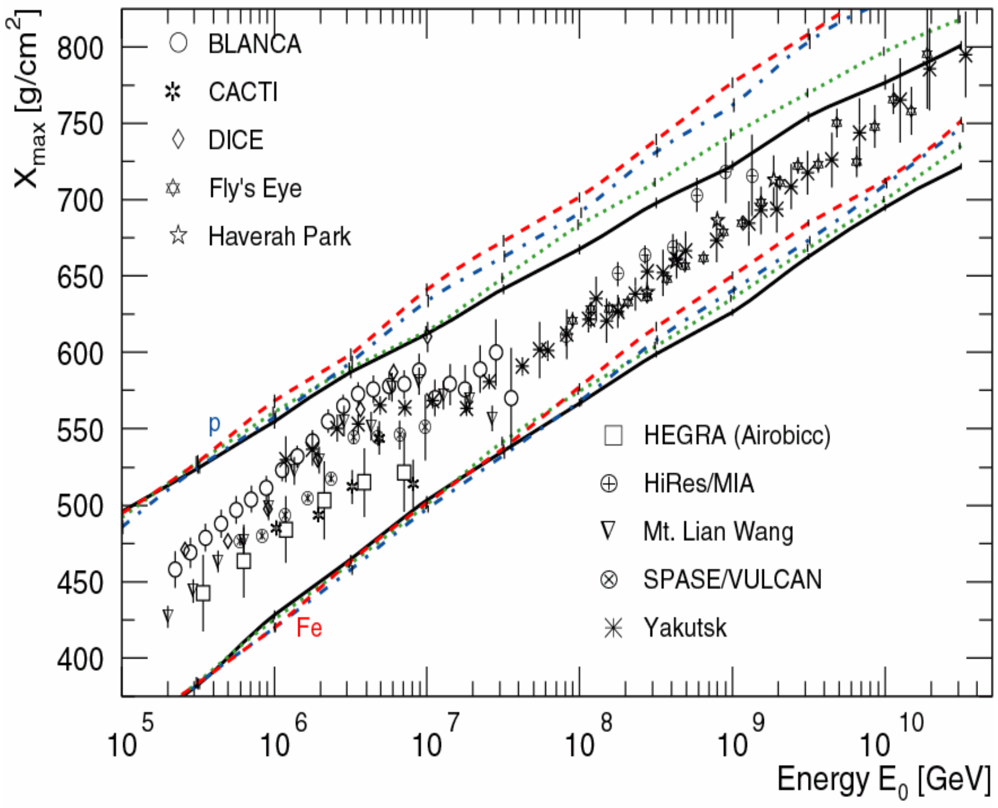
CR Composition:

- Increasing average mass from the knee to the ankle
- Decreasing after the ankle (onset of extragalactic components) ?









AUGER

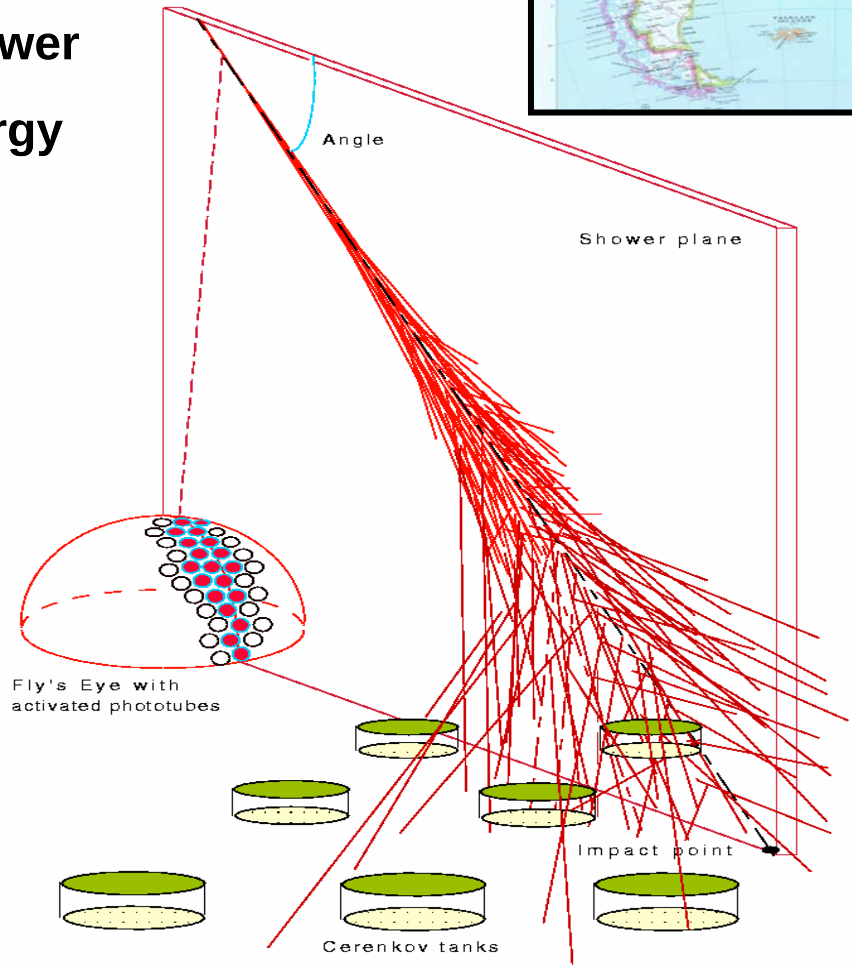
Fluorescence Detector (FD)

- Longitudinal development of the shower
- Calorimetric measurement of the energy

  Calibration of the energy scale

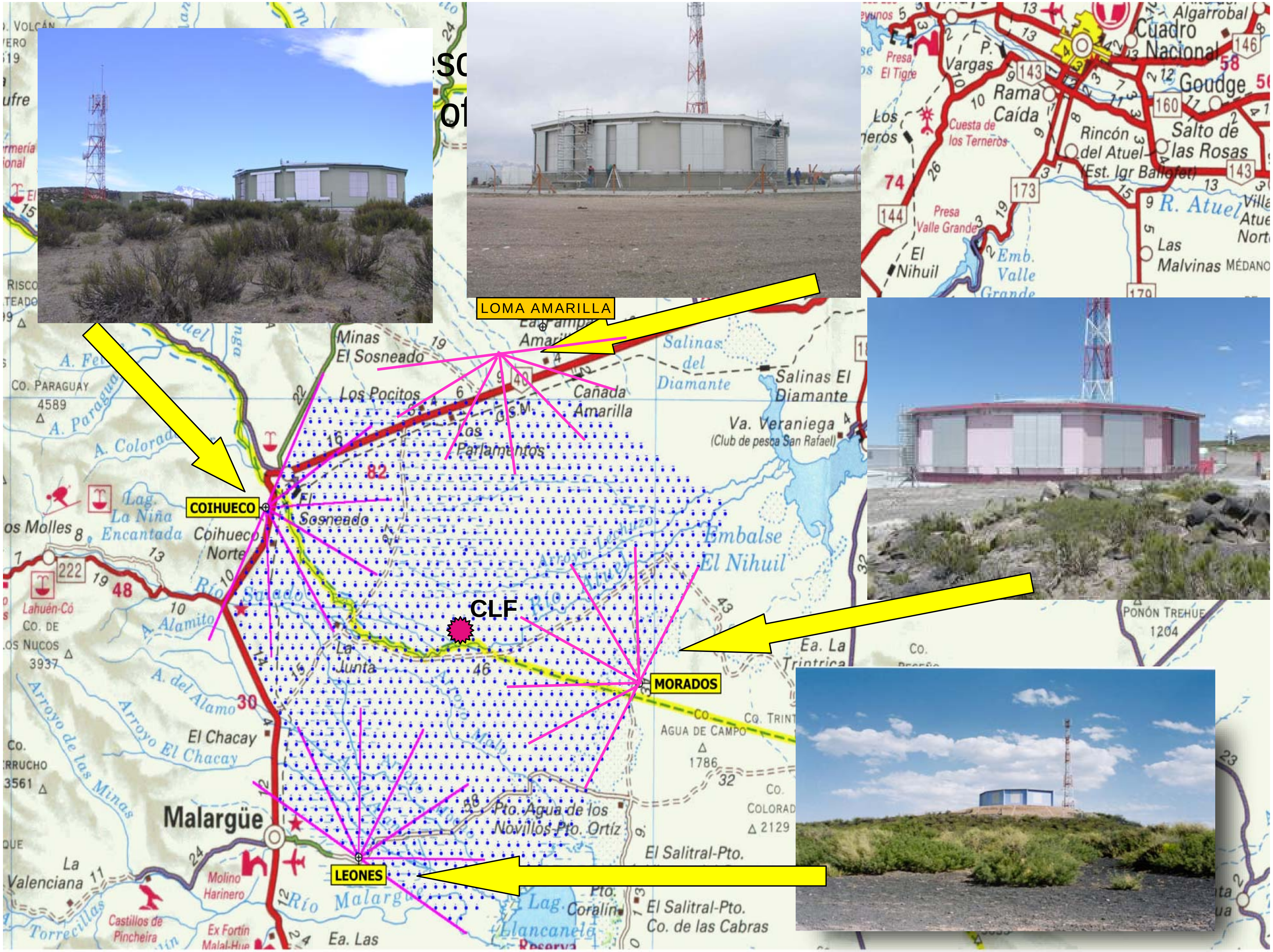
- Direction of the shower

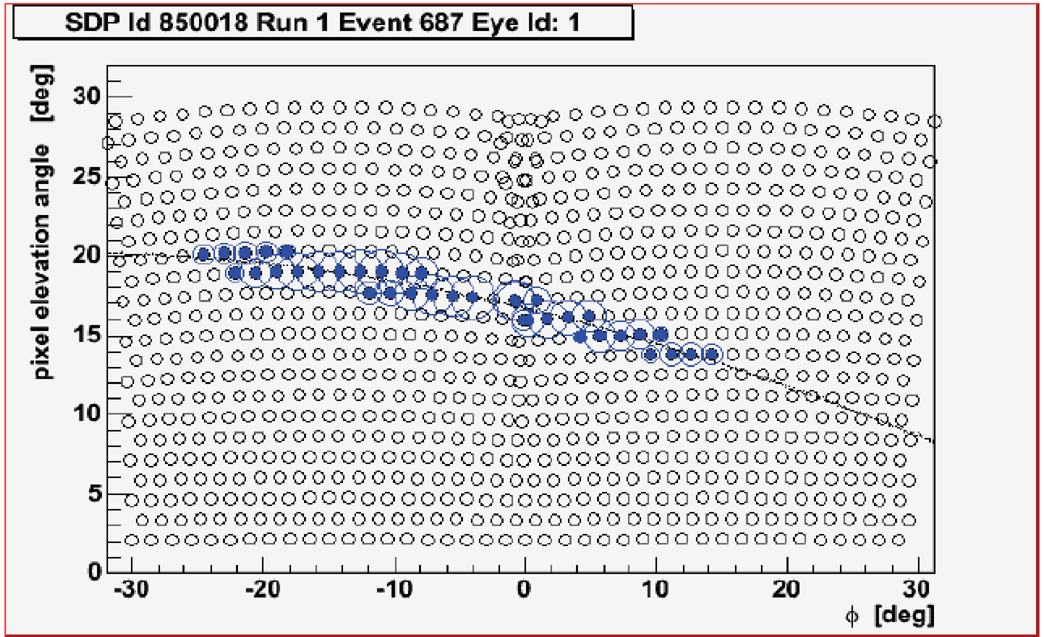
  12% duty cycle !

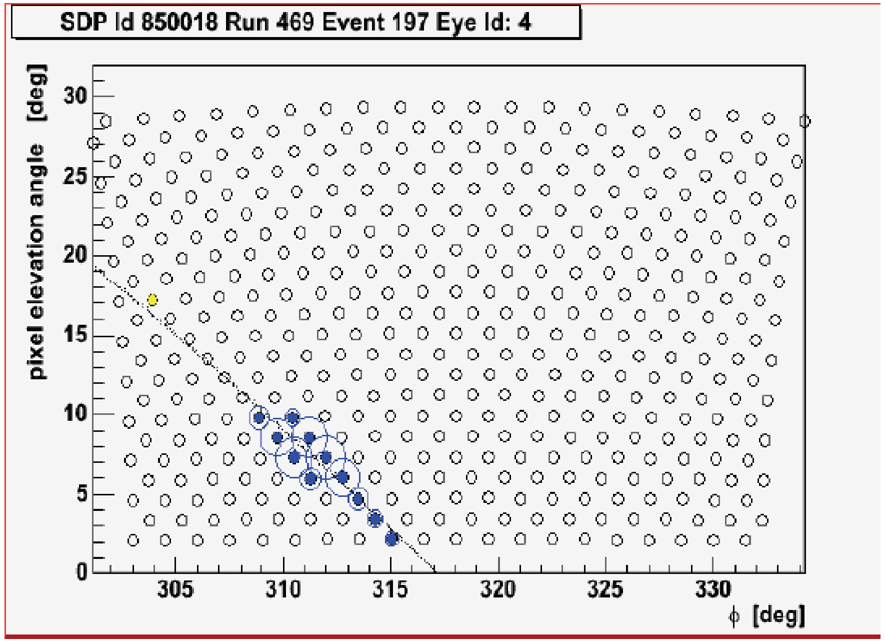


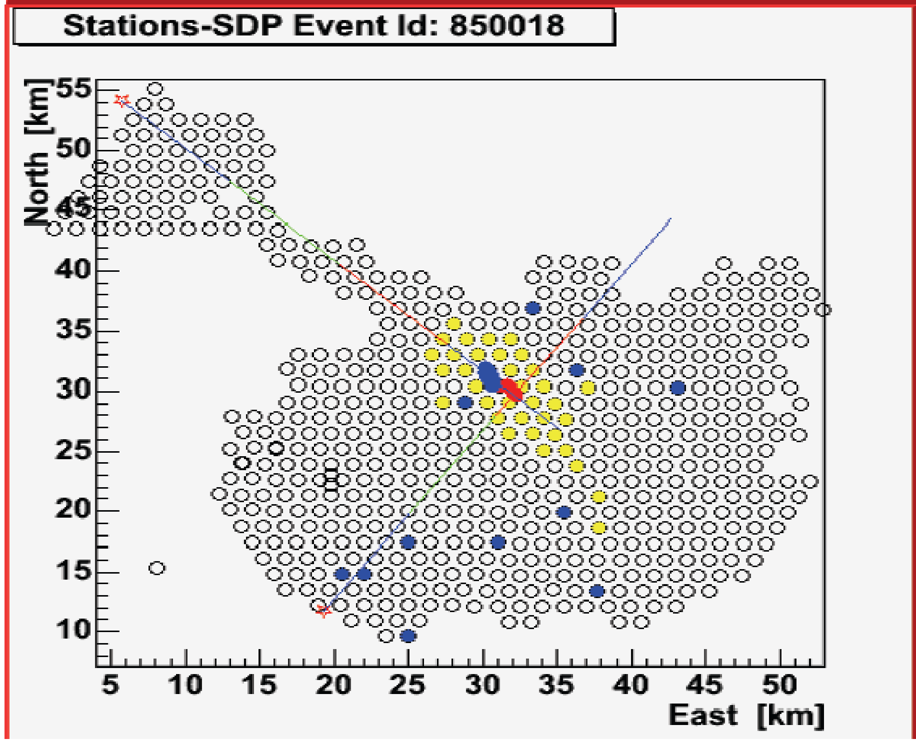
Surface Detector (SD)

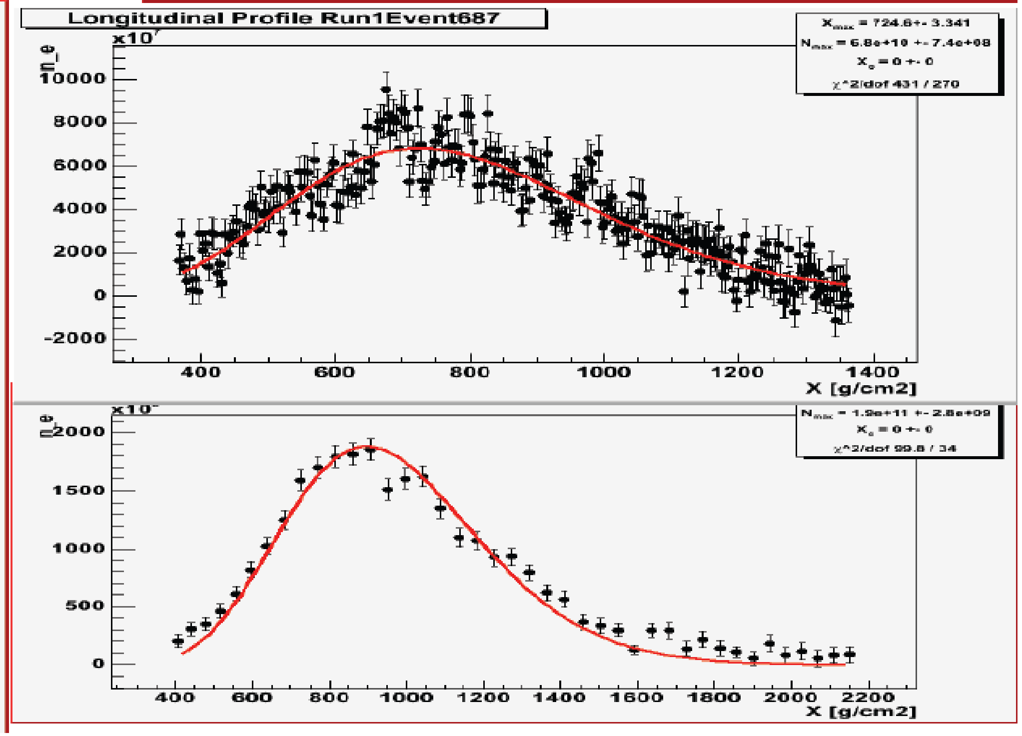
- Front of shower at ground
- Direction of the shower
- “High” statistics


LOMA AMARILLA
COIHUECO
MORADOS
LEONES
CLF
Malargüe
Embalse El Nihuil
Salinas del Diamante
Cuadro Nacional
Goudge
Rama Caída
Rincón del Atuel
Salto de las Rosas
El Nihuil
Los Parlamentos
El Sosneado
La Junta
El Chacay
Lag. Llancanelo

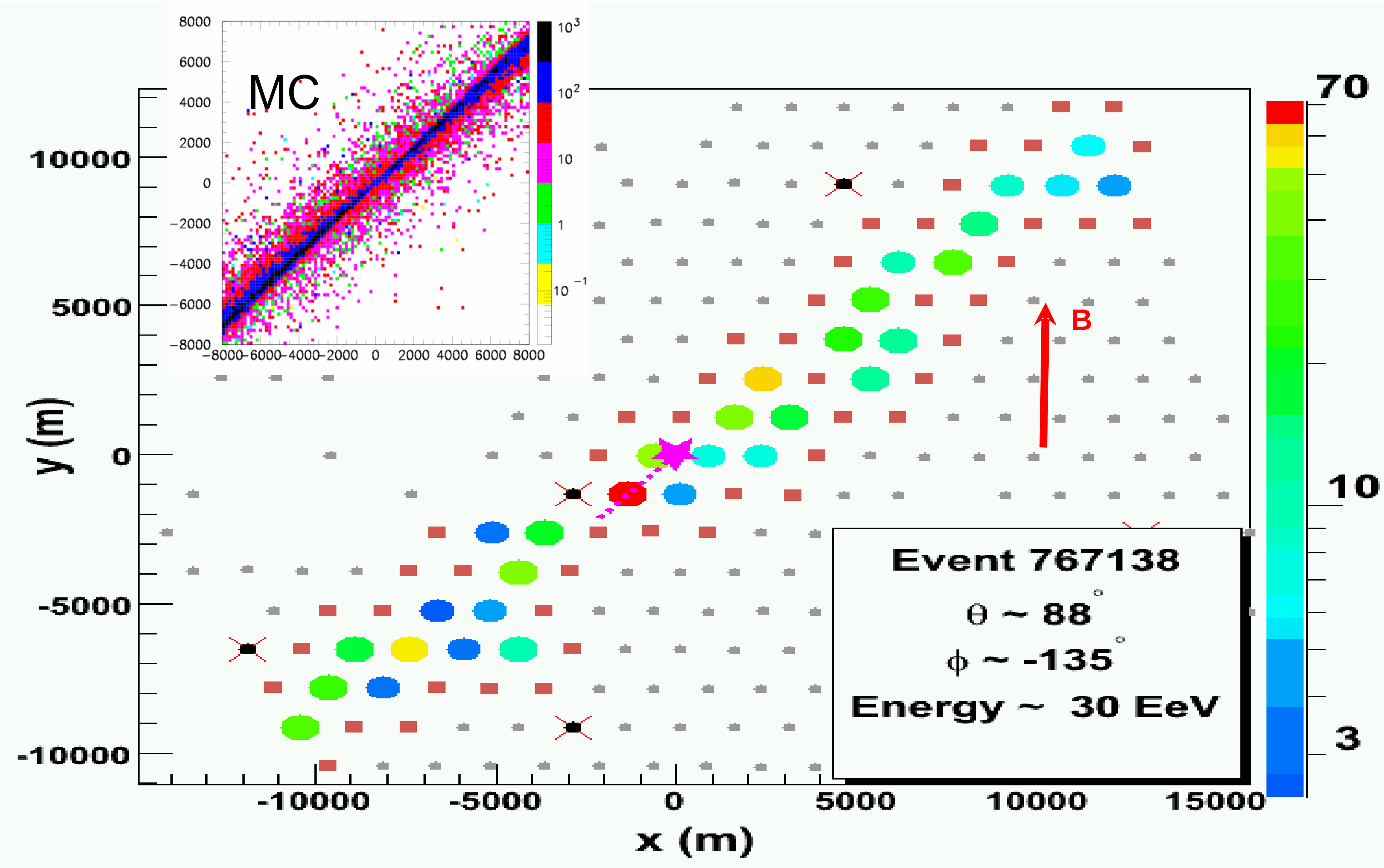

SDP Id 850018 Run 1 Event 687 Eye Id: 1
pixel elevation angle [deg]
ϕ [deg]


SDP Id 850018 Run 469 Event 197 Eye Id: 4
pixel elevation angle [deg]
ϕ [deg]


Stations-SDP Event Id: 850018
North [km]
East [km]


Longitudinal Profile Run1Event687
X_max = 724.6+- 3.341
N_max = 6.8e+10 +- 7.4e+08
X_0 = 0 +- 0
χ^2/dof 431 / 270
n_e
X [g/cm2]
N_max = 1.9e+11 +- 2.8e+09
X_0 = 0 +- 0
χ^2/dof 99.8 / 34
n_e
X [g/cm2]

Events . . . . a bit bigger one

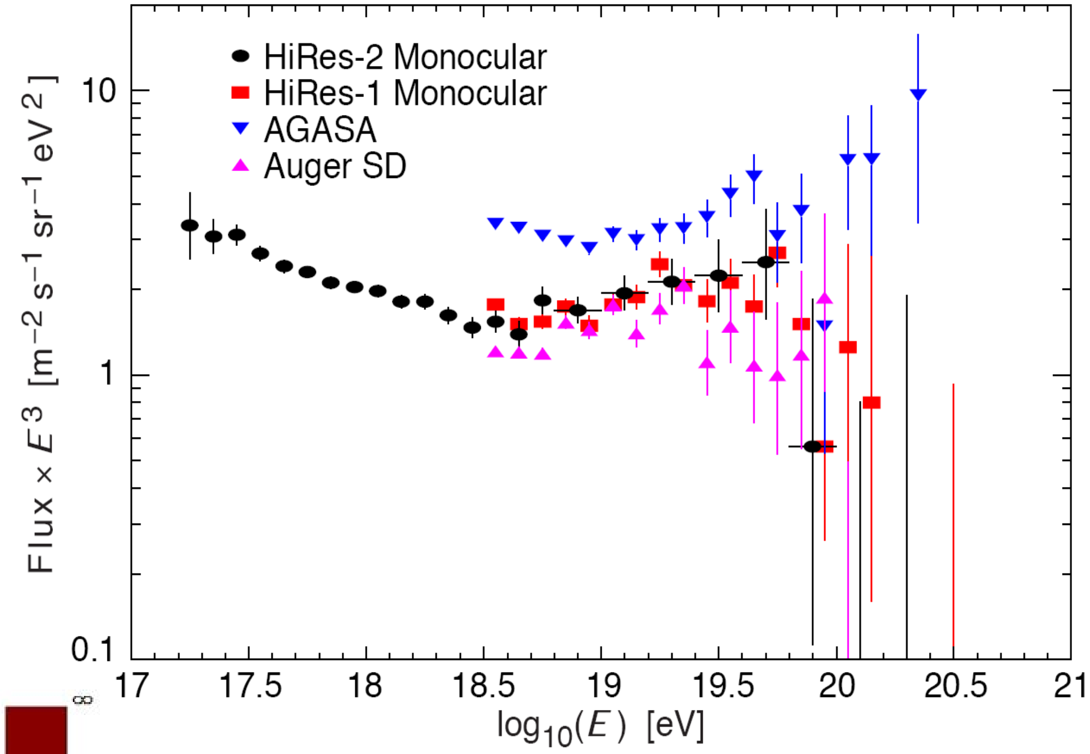


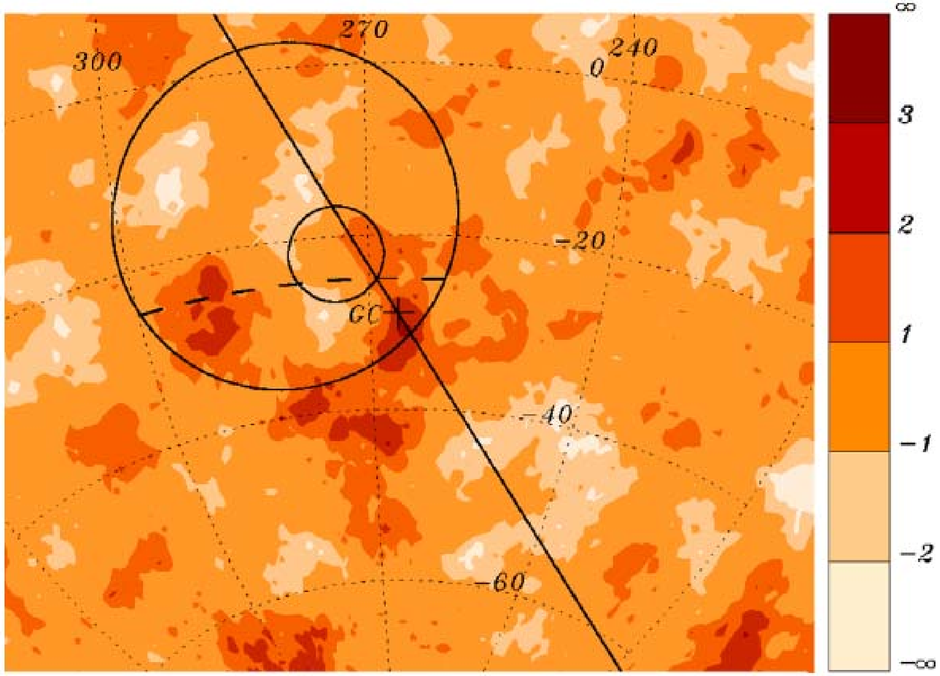
First AUGER science results

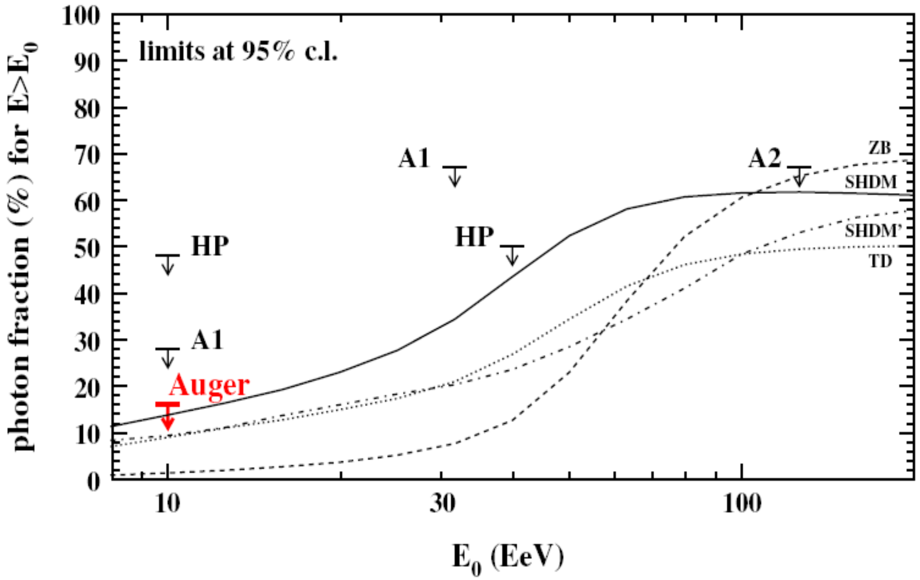
Updated energy spectrum coming soon

AGASA and Sugar excess from the galactic center was not confirmed (with much larger stats)

Strong limit on the primary γ flux

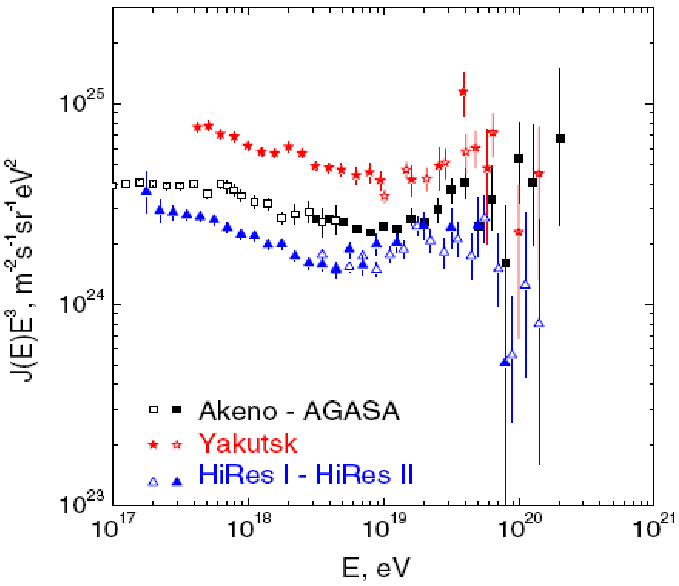


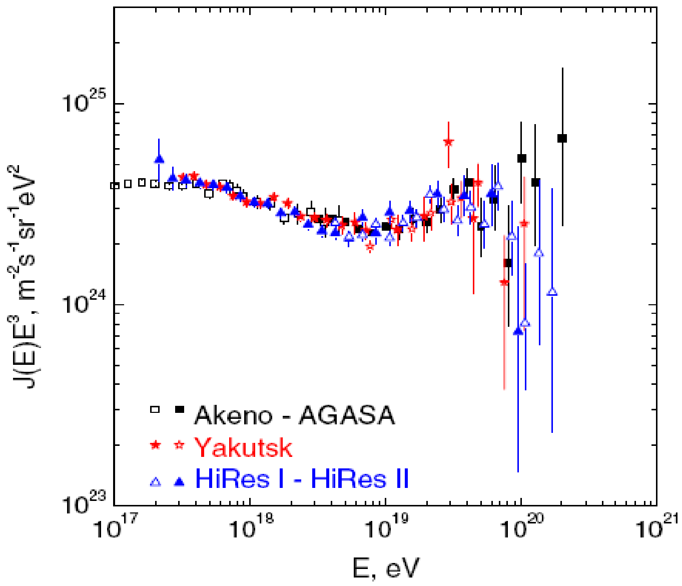




The "ankle" summary (at first order)

- GZK feature not yet understood
- Systematics in energy scales for different techniques (SD vs FD)
- Use the "dip" to calibrate different detectors ?



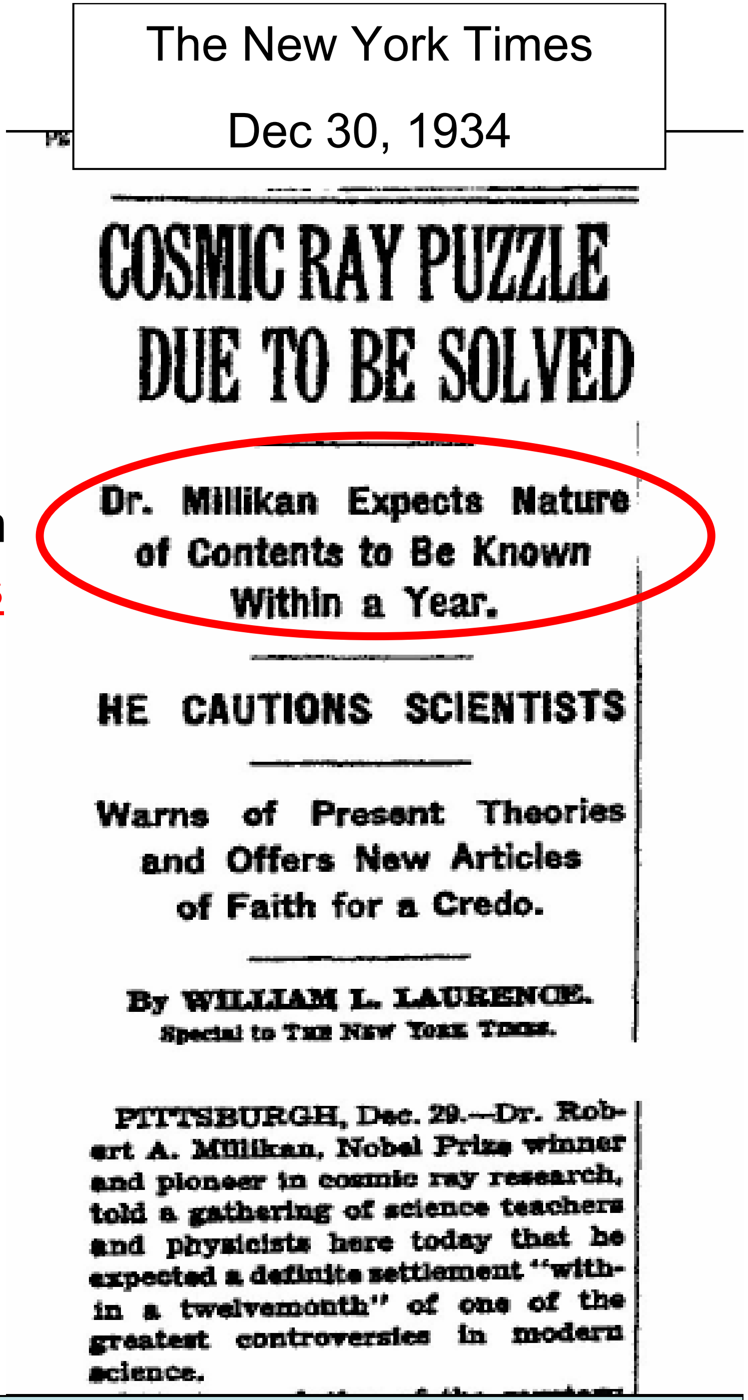


- The observed spectra (and compositions) are consistent with a transition from galactic to extra-galactic components
- Need more exposure and reduced systematics (AUGER)

Conclusions

- The “cosmic ray beam” is reasonably understood but far from well known
- Underlying physical processes, involving both particle physics and high energy astrophysics need to be better investigated (fragmentation region, Active Galactic Nuclei,…)
- Unique possibility for discoveries and/or for testing standard physics in “extreme conditions”
- Many experiments all around the Earth trying solve the puzzle(s). Sorry for not reporting on all of them.
- A more than exiciting future ahead

(Difficult predictions !)


The New York Times

Dec 30, 1934

COSMIC RAY PUZZLE DUE TO BE SOLVED

Dr. Millikan Expects Nature of Contents to Be Known Within a Year.

HE CAUTIONS SCIENTISTS

Warns of Present Theories and Offers New Articles of Faith for a Credo.

By WILLIAM L. LAURENCE.
Special to THE NEW YORK TIMES.

PITTSBURGH, Dec. 29.—Dr. Robert A. Millikan, Nobel Prize winner and pioneer in cosmic ray research, told a gathering of science teachers and physicists here today that he expected a definite settlement “within a twelvemonth” of one of the greatest controversies in modern science.


Thank You !
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16 Dec/06
MACRO