

# **Status of extensive air shower studies at the Pierre Auger Observatory**

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The Pierre Auger Collaboration

VIA, 25 April 2008

– UHECR studies with Auger –

E. Parizot (APC / Univ. Paris 7)

# Overview

- Cosmic ray phenomenology and observations
  - ◆ Ultra-high-energy cosmic rays
  - ◆ The three main observables: angular distribution, energy spectrum, mass composition
- The Pierre Auger Observatory (or “Auger”)
  - ◆ Design and implementation
  - ◆ Current status and future developments
- The first results of Auger
  - ◆ Spectrum, composition, anisotropy
  - ◆ Photon limit, neutrino limit
- Perspective: astronomy, astrophysics, astroparticles and high-energy physics...

## Cosmic rays and particle physics

- Long, rich and successful story
- Major discoveries
  - ◆ Antimatter, muons, pions, strange particles...

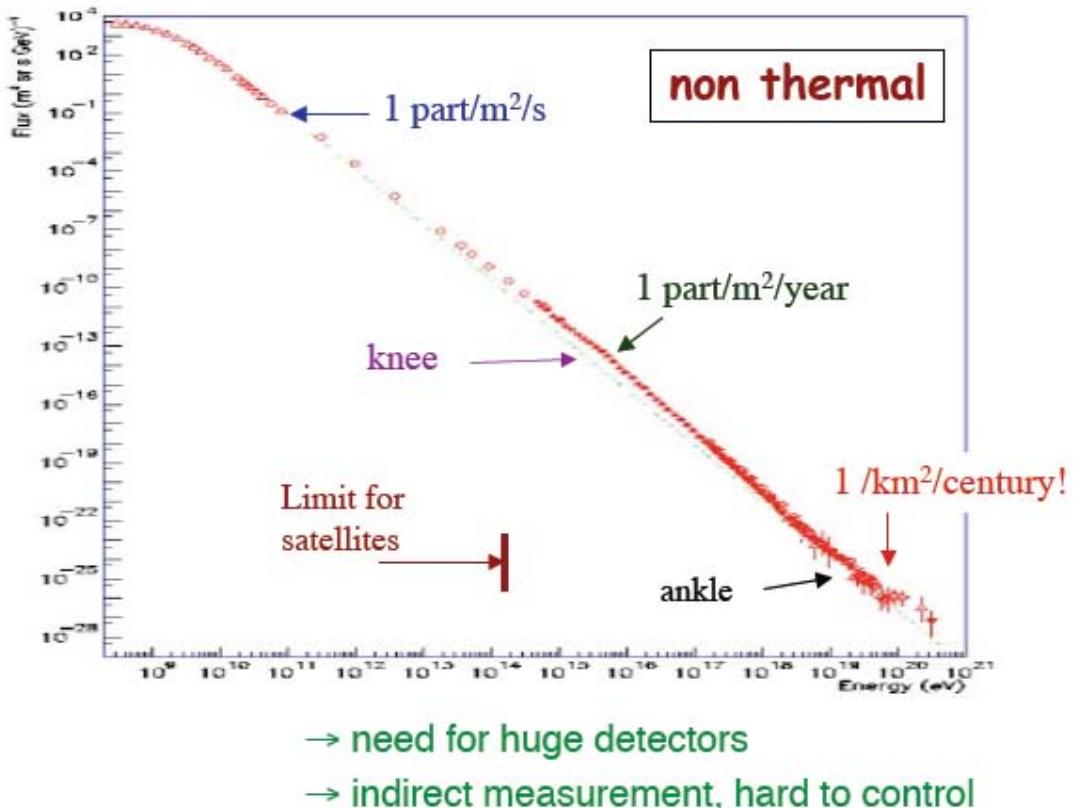
## Cosmic rays and astrophysics

- Long, rich and successful story
  - Major discoveries
    - ◆ Non-thermal astronomy
    - ◆ Central role of CRs in Galactic ecology
    - ◆ Existence of CRs up to  $10^{20}$  eV!
    - ◆ CR astronomy is possible!
- Overcome isotropization and deflection by magnetic field
- (ionisation, heating, magnetic fields, astrochemistry, LiBeB nucleosynthesis, star formation...)
- challenge for particle acceleration!

# Non-thermal astronomy

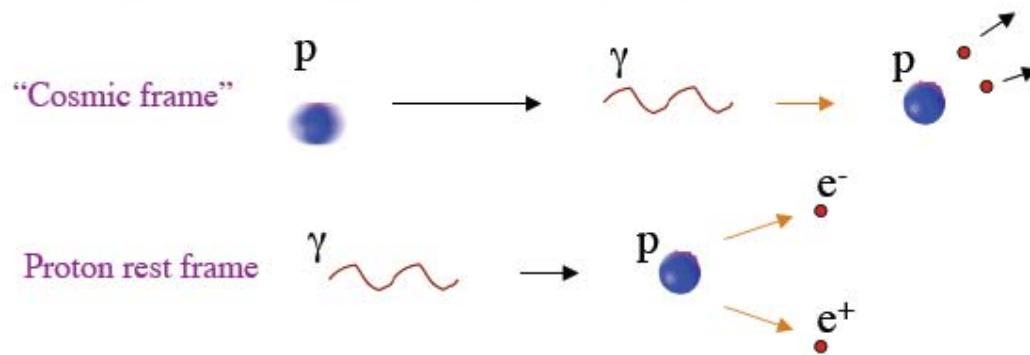
- Energetic particles are ubiquitous in the universe
- Particle acceleration is a central problem
  - ◆ Physics of powerful, high-energy sources
  - ◆ Physics in “extreme conditions”
  - ◆ Multi-scale problem + conditions very different from laboratory exp. (e.g. “collisionless shocks”)
- Multi-wavelength and multi-messenger astronomy: gives access to high-energy processes  
(→ “astroparticle physics”)
- Intermediate goal: identify sources of high-energy cosmic rays!  
Neutrinos: hard to detect them, but then ~easy to find sources  
Charged CRs: ~easy to detect them, but then hard to find sources → UHE...

## Price to pay for CR astronomy: very low flux!



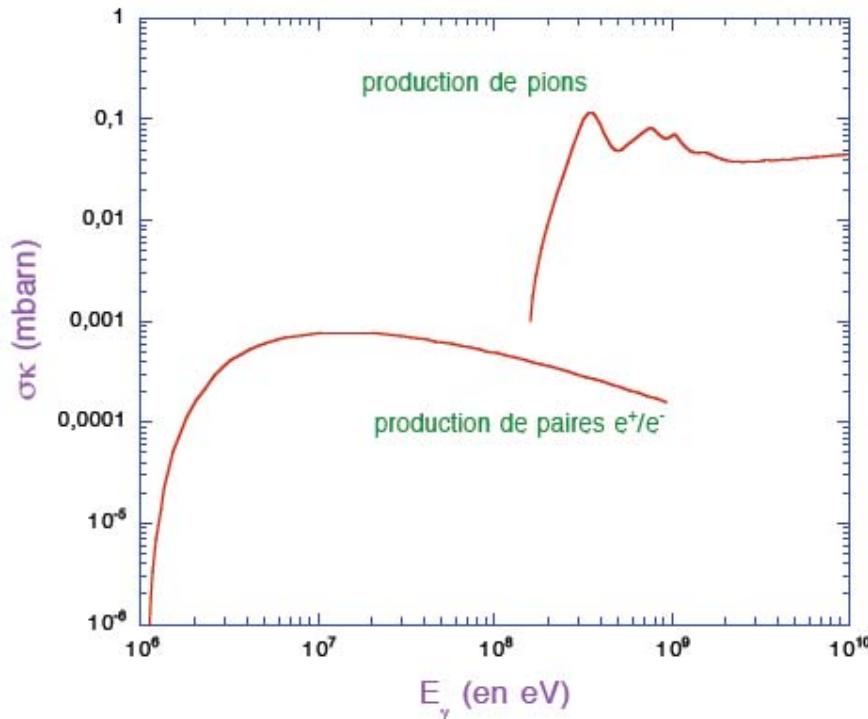
# The GZK effect

- Greisen (1966) + Zatsepin & Kuz'min (1966)
- Energy losses through  $e^+/e^-$  pair and pions production!

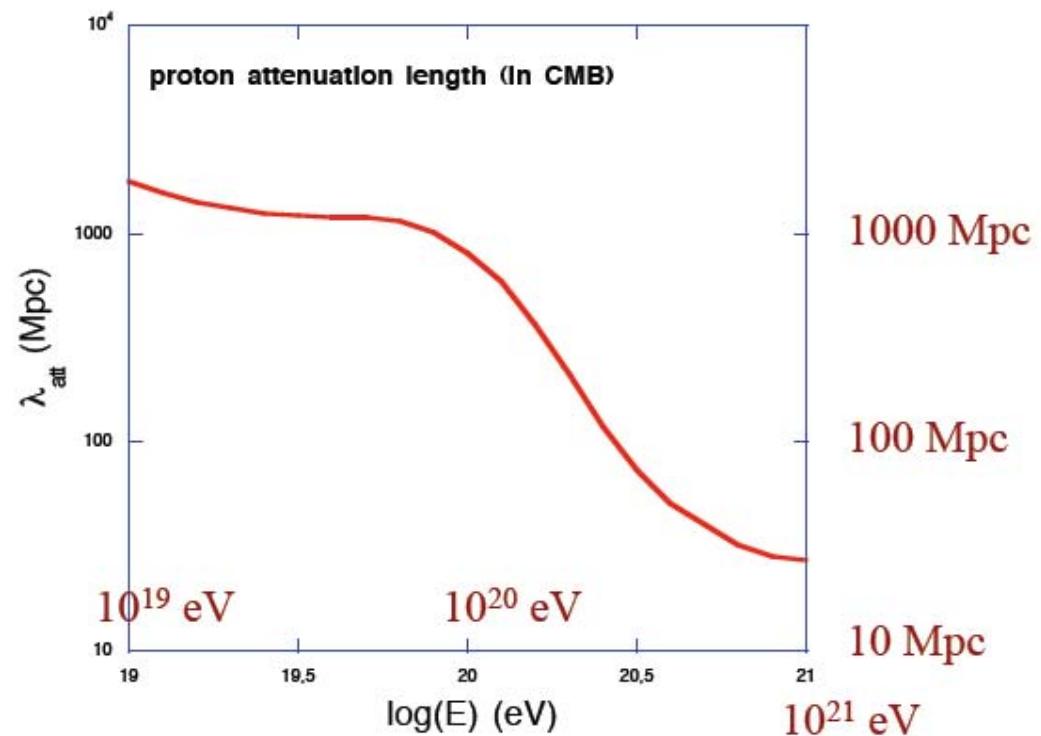


- Threshold :  $E_\gamma \approx 2 m_e c^2$  in the proton rest frame       $E_\gamma > 1 \text{ MeV}$
- Threshold :  $E_\gamma \approx m_\pi c^2$  in the proton rest frame       $E_\gamma > 160 \text{ MeV}$

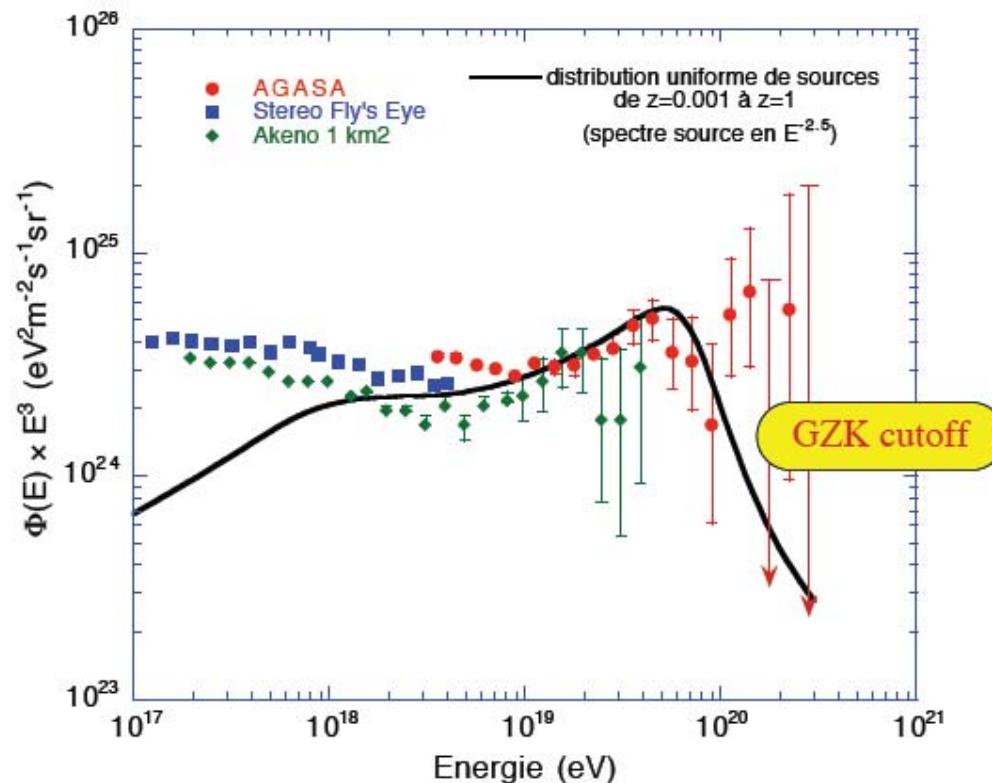
# [cross section] $\times$ [inelasticity]



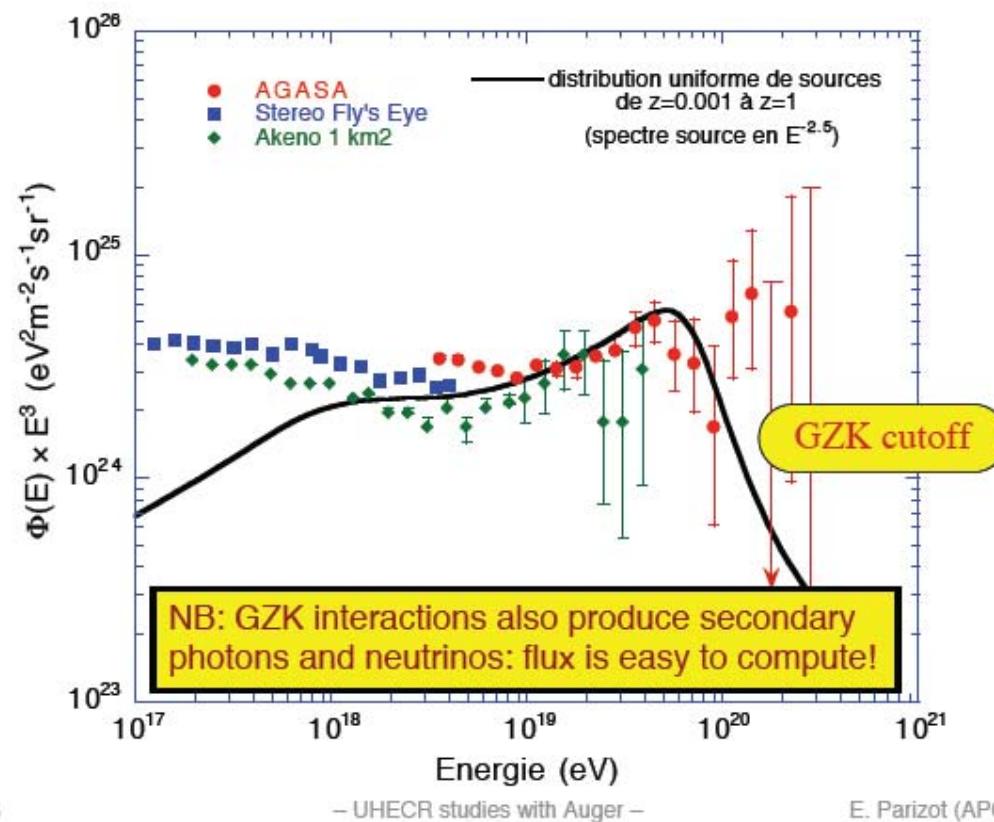
## Attenuation length - horizons



# Uniform source distribution

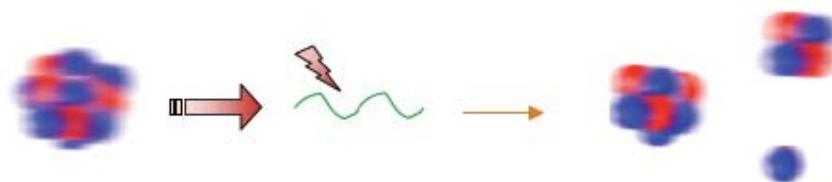


# Uniform source distribution



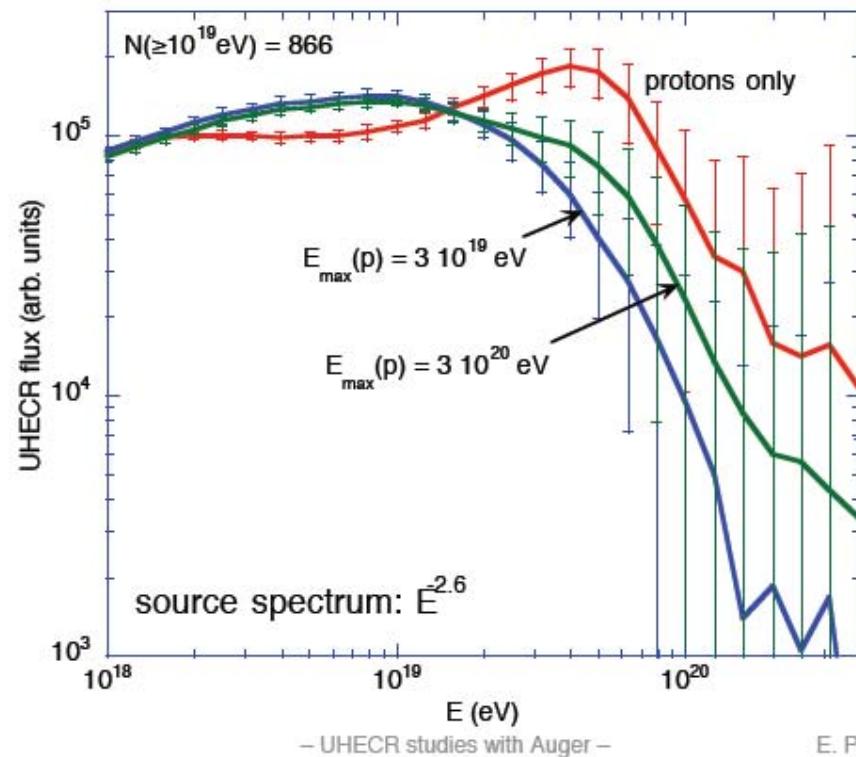
## GZK effect for heavier nuclei

- Ultra-high-energy nuclei can be photo-dissociated by CMB and/or IR photons → lose nucleons, and thus energy



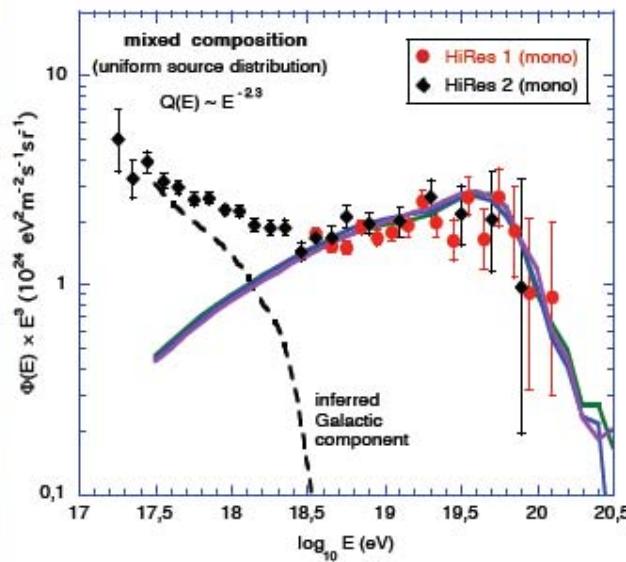
- NB: even if no UHE nuclei reach the Earth, the phenomenology of extragalactic CRs depends on the presence of nuclei at the source!

## Examples of "propagated" spectra



# Are there nuclei among EGCRs?

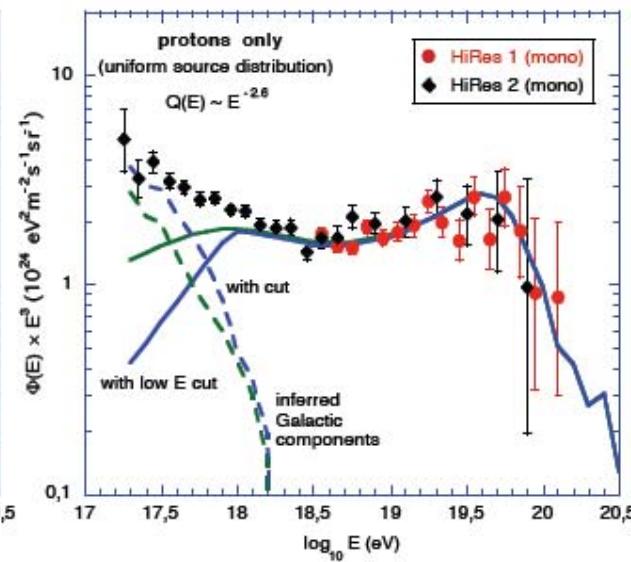
Mixed composition (Allard et al.)



Source spectrum in  $E^{-2.3}$

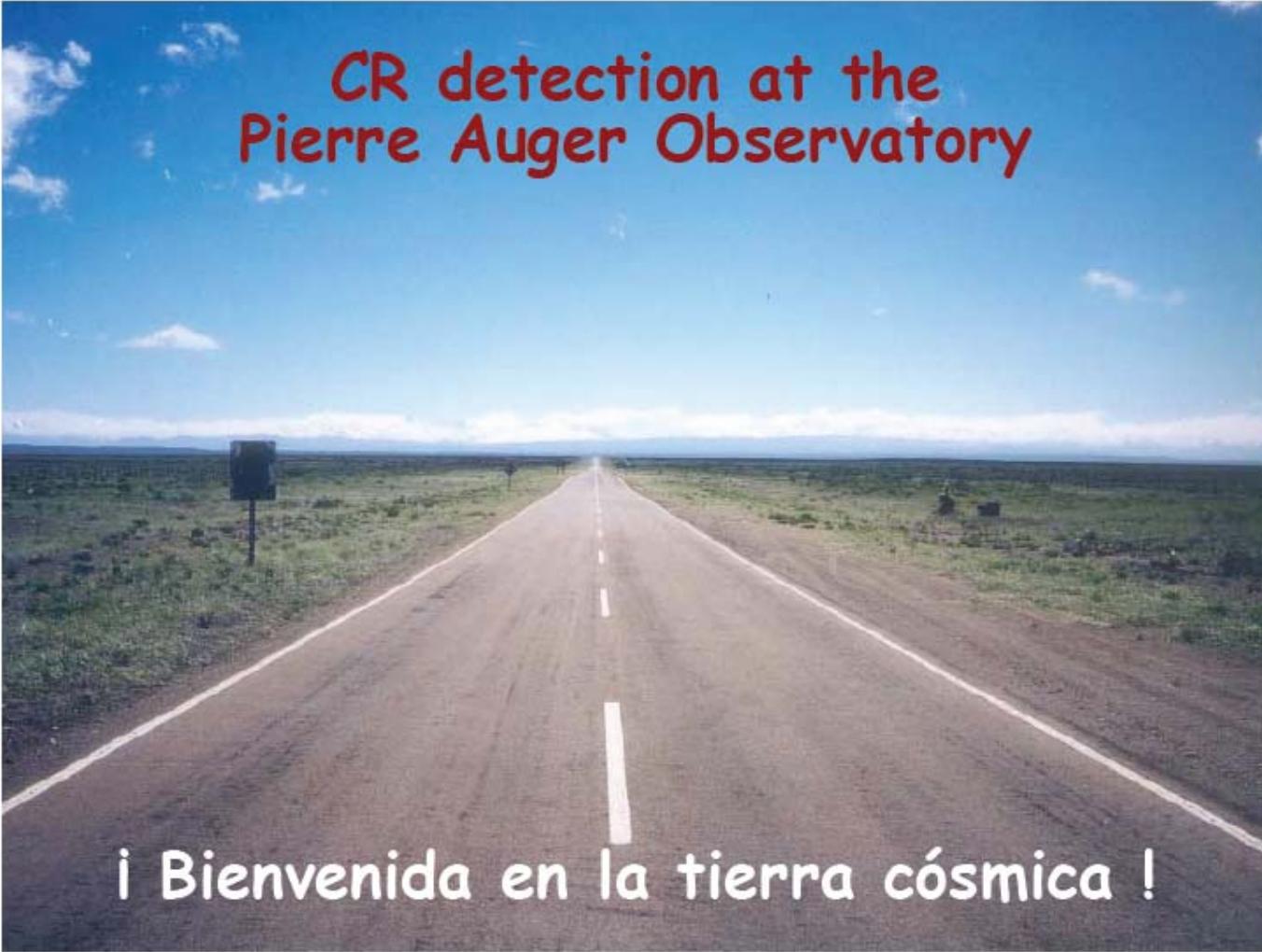
Ankle = gal./extragal. transition

Pure protons (cf. Berezinsky et al.)



Source spectrum in  $E^{-2.6}$

Ankle = "pair production dip"

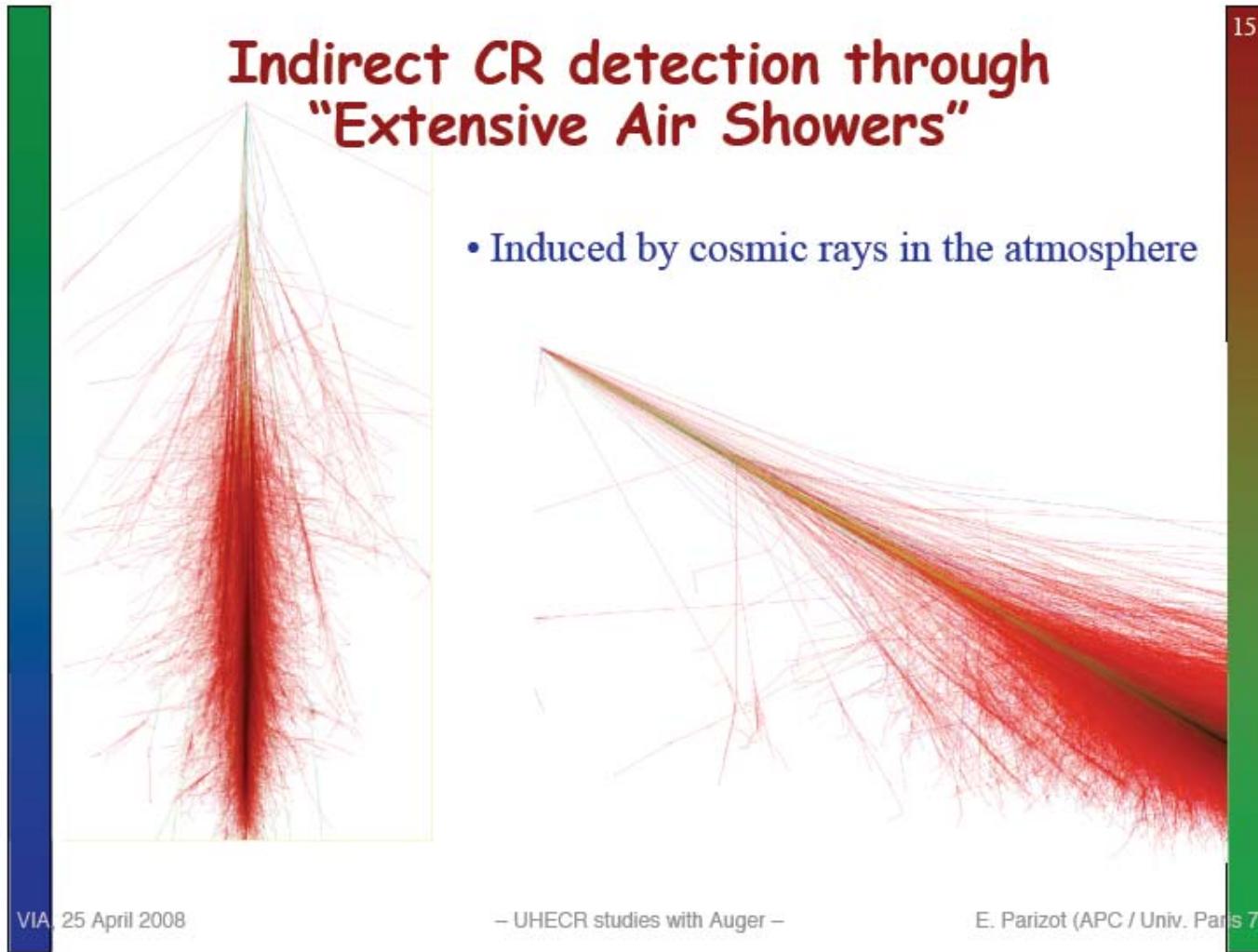


CR detection at the  
Pierre Auger Observatory

¡ Bienvenida en la tierra cósmica !

## Indirect CR detection through “Extensive Air Showers”

- Induced by cosmic rays in the atmosphere



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– UHECR studies with Auger –

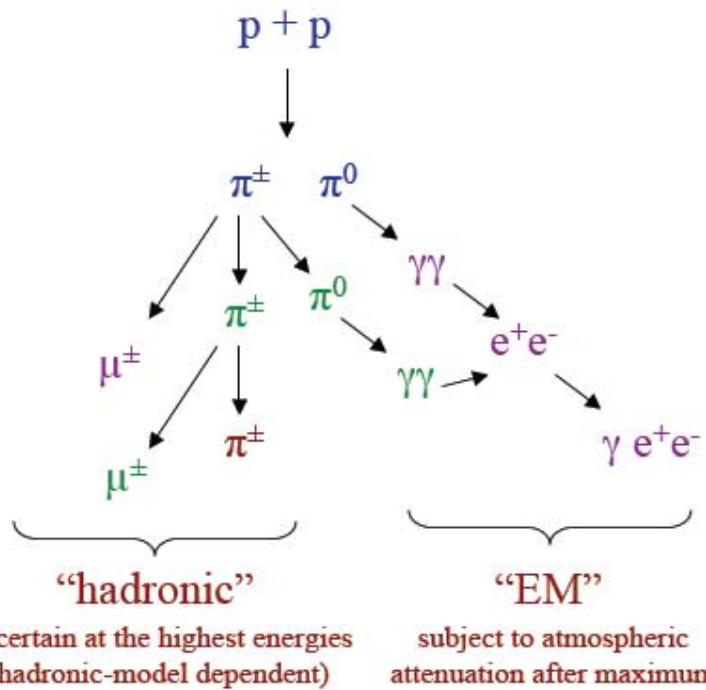
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## EM & hadronic “sub-showers”

- electromagnetic and hadronic subshowers



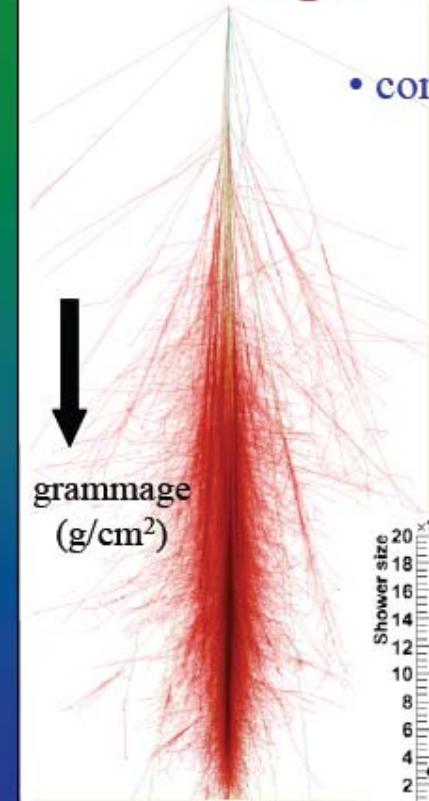
– UHECR studies with Auger –

E. Parizot (APC / Univ. Paris 7)



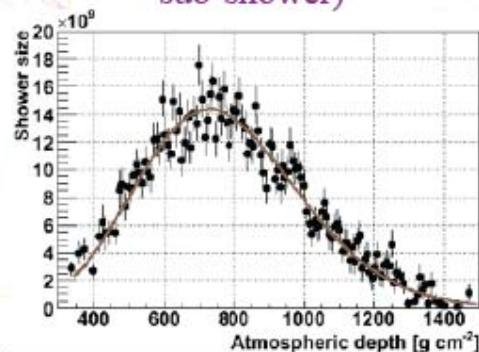
## High-energy CR detection

- comparison of observables with MC simulations



Fluorescence photons  
from atmosphere  
→ longitudinal  
shower development

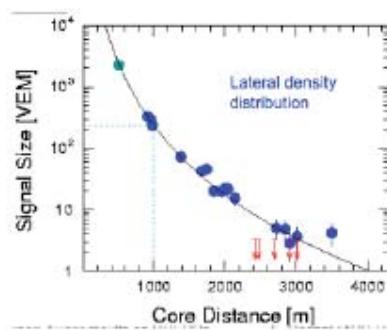
(sensible to EM  
sub-shower)



– UHECR studies with Auger –

Density of shower  
particles on the ground  
→ lateral distribution

(sensible to EM and  
hadronic sub-showers)



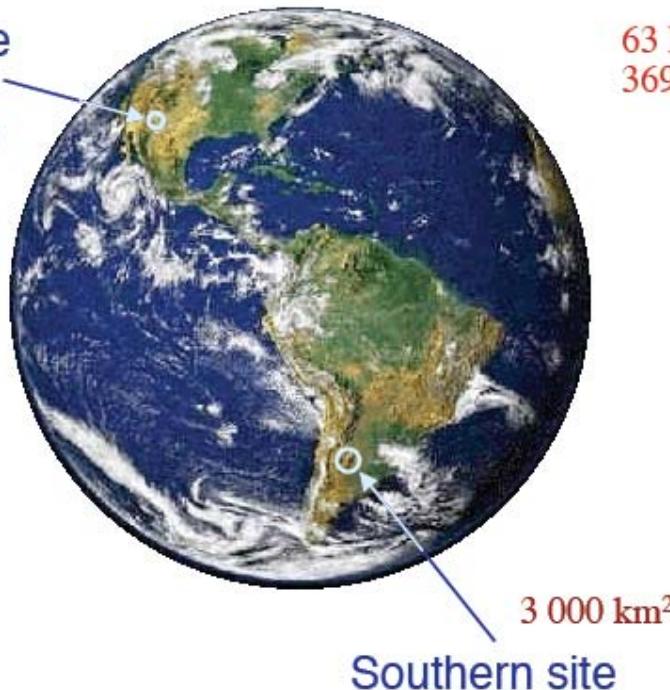
E. Parizot (APC / Univ. Paris 7)

VIA, 25 April 2008

# The Pierre Auger Observatory

Northern site  
20 000 km<sup>2</sup>  
(still to be funded)

- *Participating Countries*
- Argentina
- Australia
- Brazil
- Czech Republic
- France (+ Vietnam)
- Germany
- Italy
- Mexico (+ Bolivia)
- Netherlands
- Poland
- Portugal
- Slovenia
- Spain
- United Kingdom
- USA



63 Institutions  
369 Scientists

# One of the Auger stations

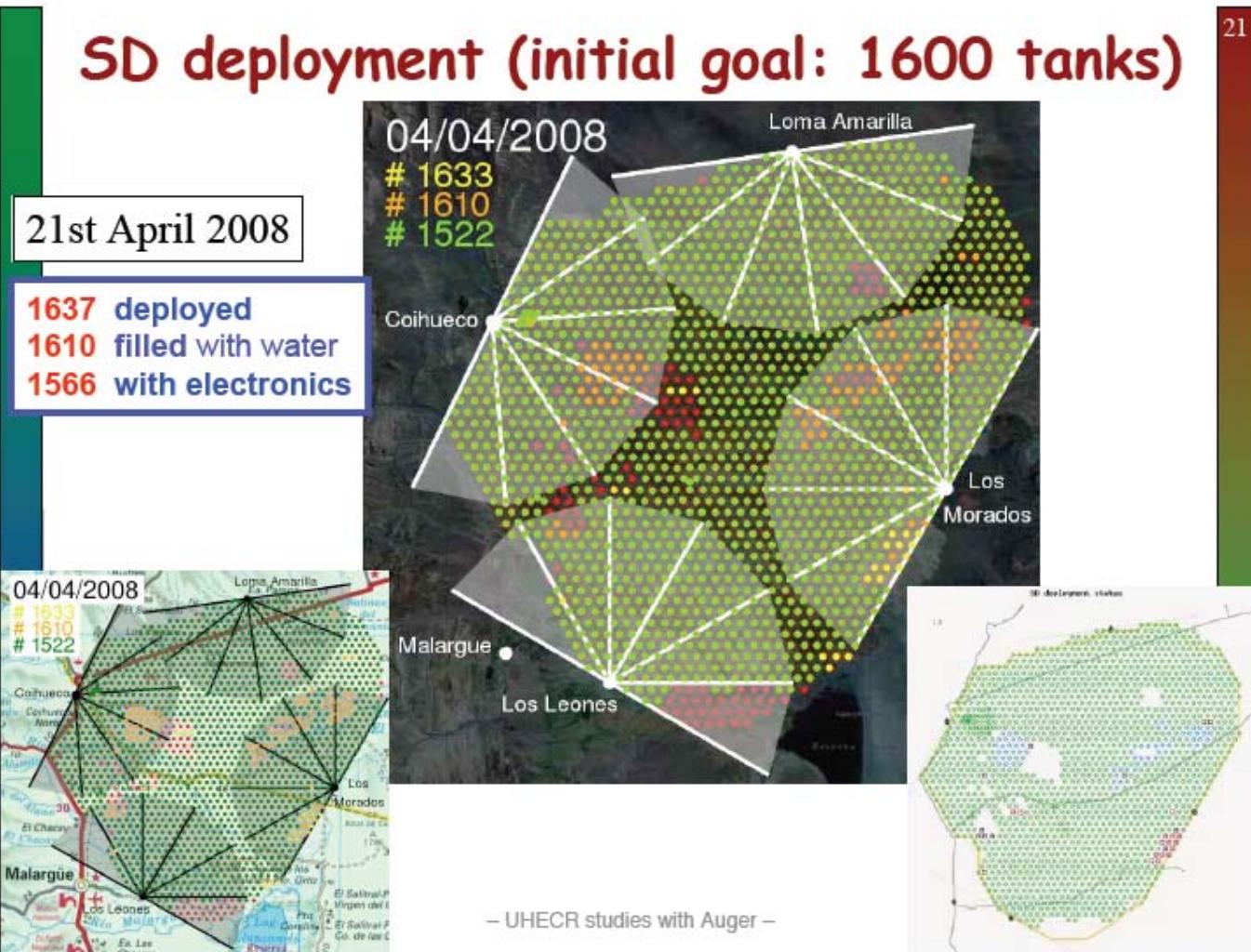
(Cherenkov water tank)



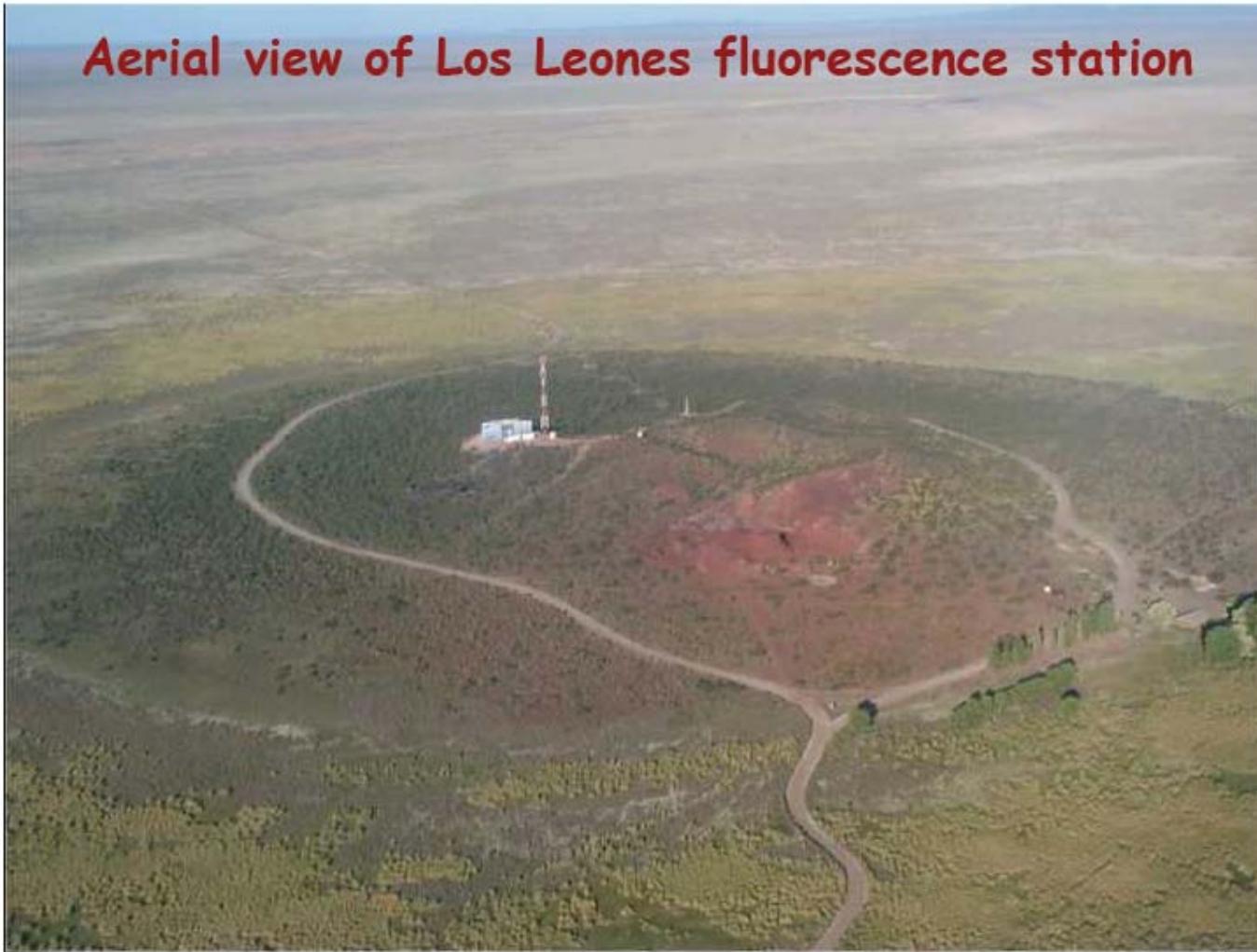
**Hexagonal array (1.5 km spacing, 3000 km<sup>2</sup>)**



## SD deployment (initial goal: 1600 tanks)



Aerial view of Los Leones fluorescence station

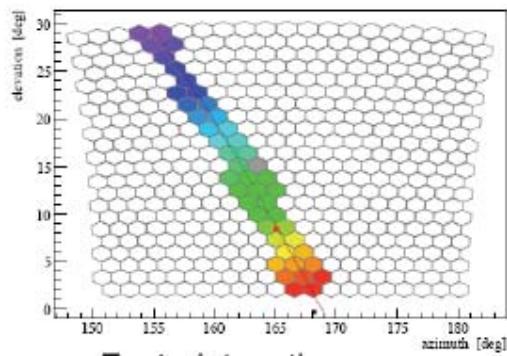
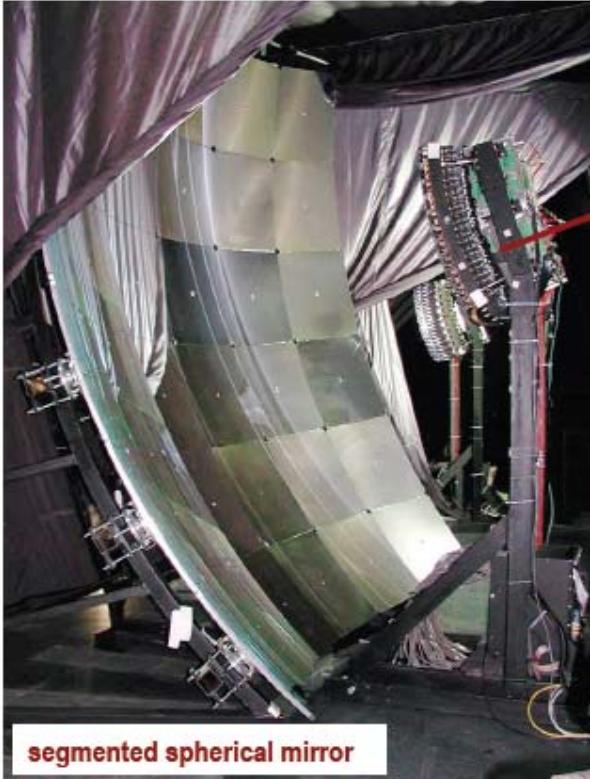


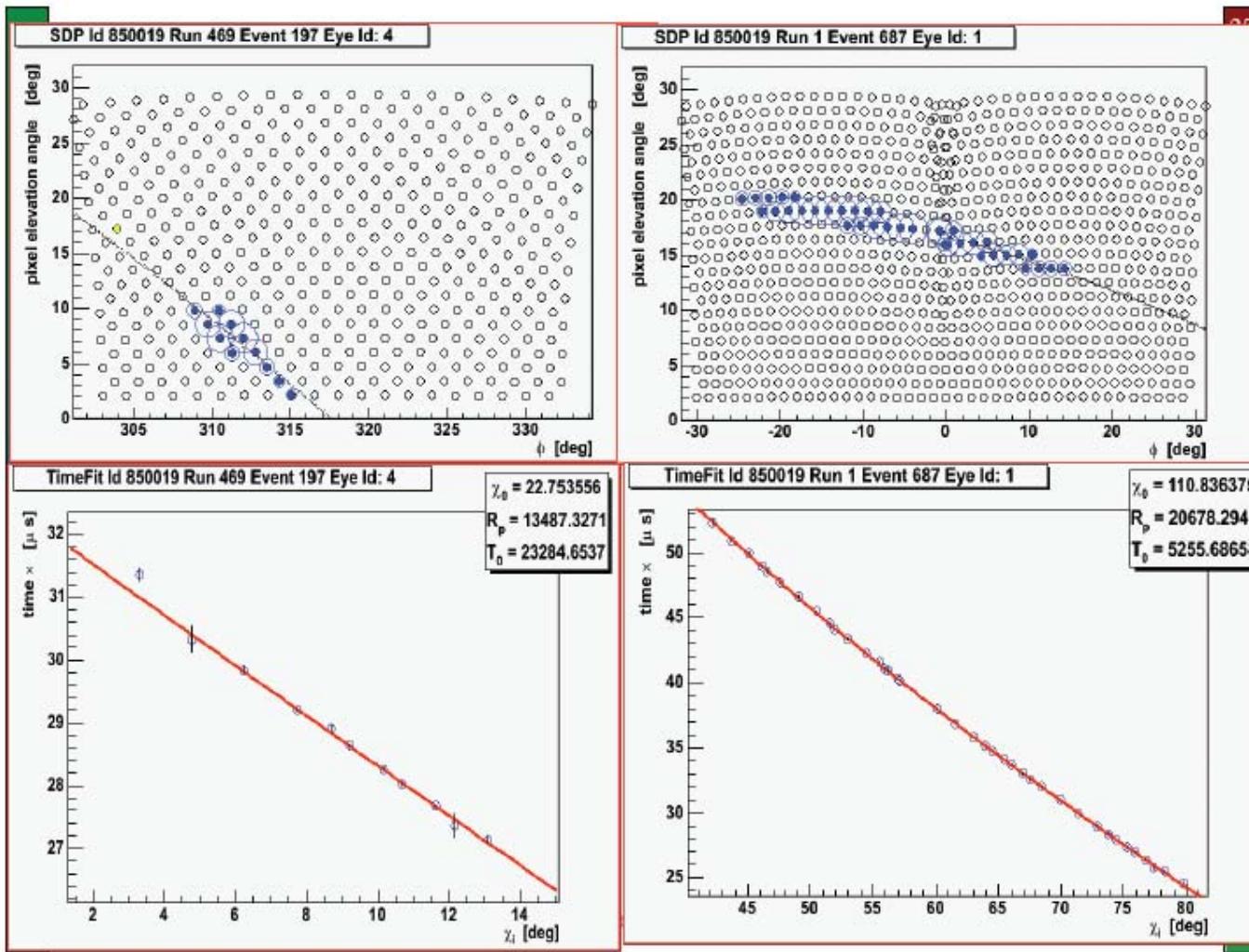
**4 times 6 telescopes overlooking the site**



**Completed!**

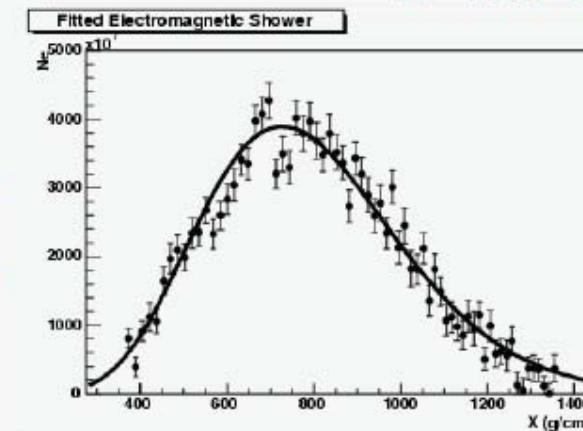
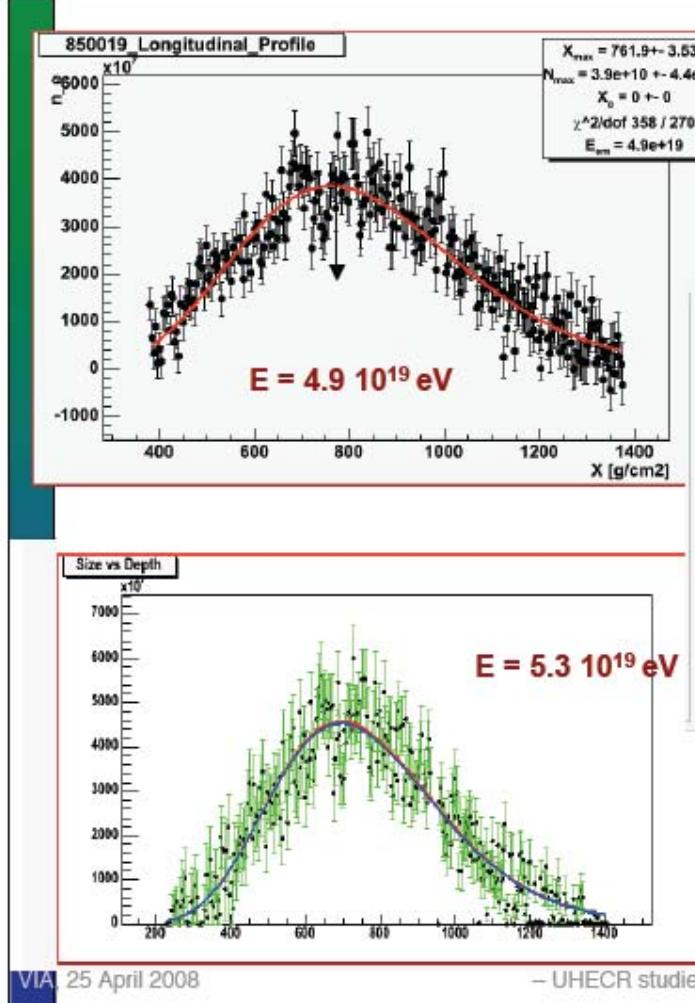
# One of the fluorescence eyes





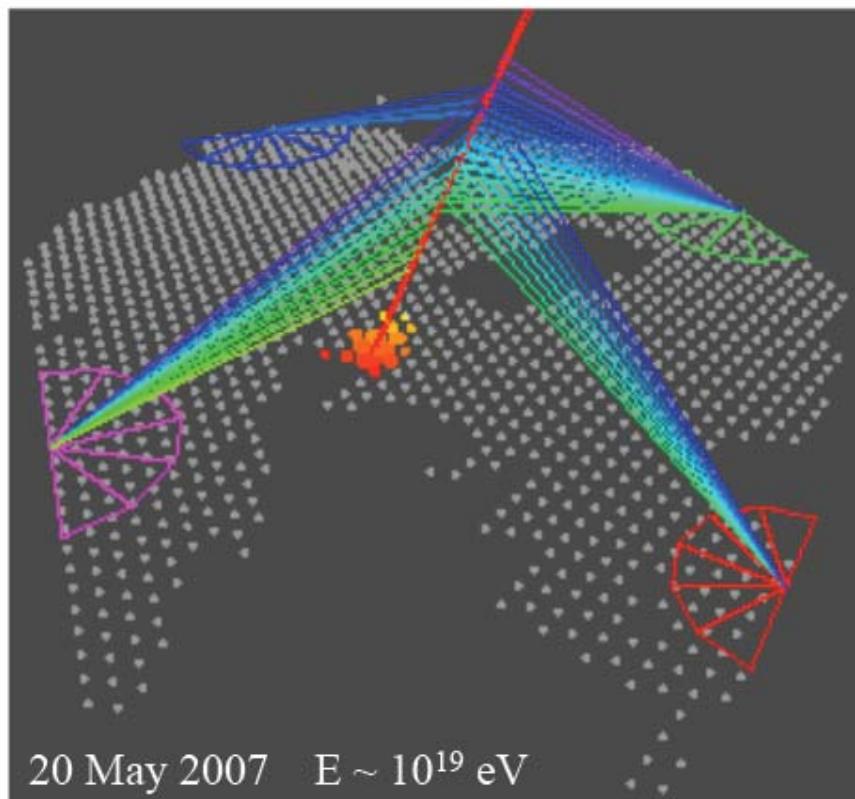
## Independent analyses of stereo events

$E = 4.8 \cdot 10^{19} \text{ eV}$



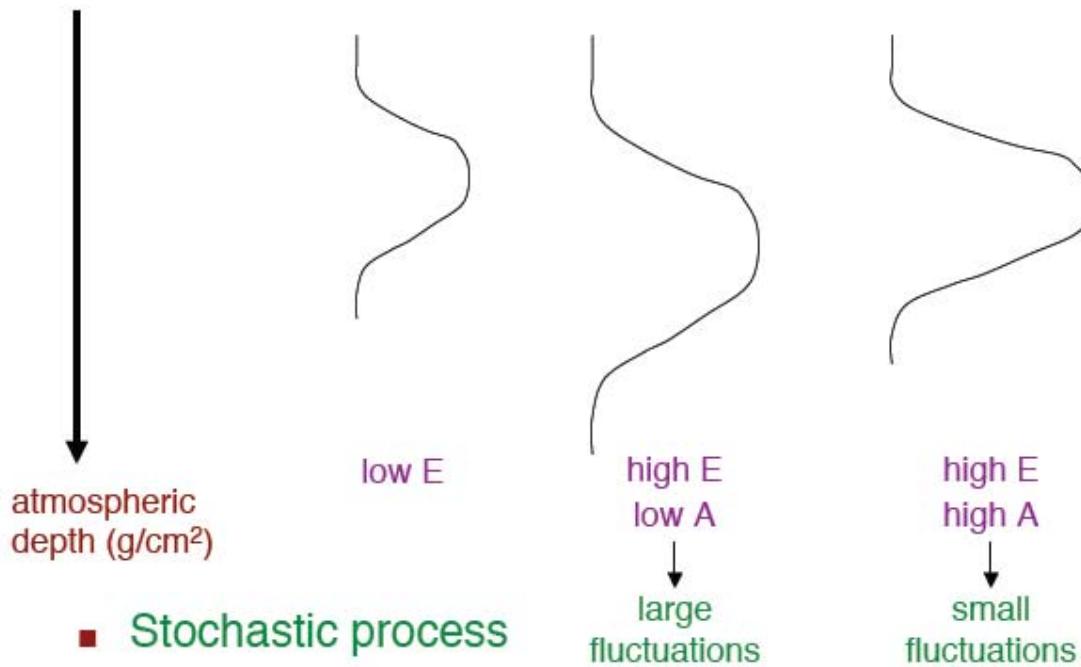
$E_{\text{em}}$  calculated by fitting a GH profile and integrating

## First 4-fold hybrid event!



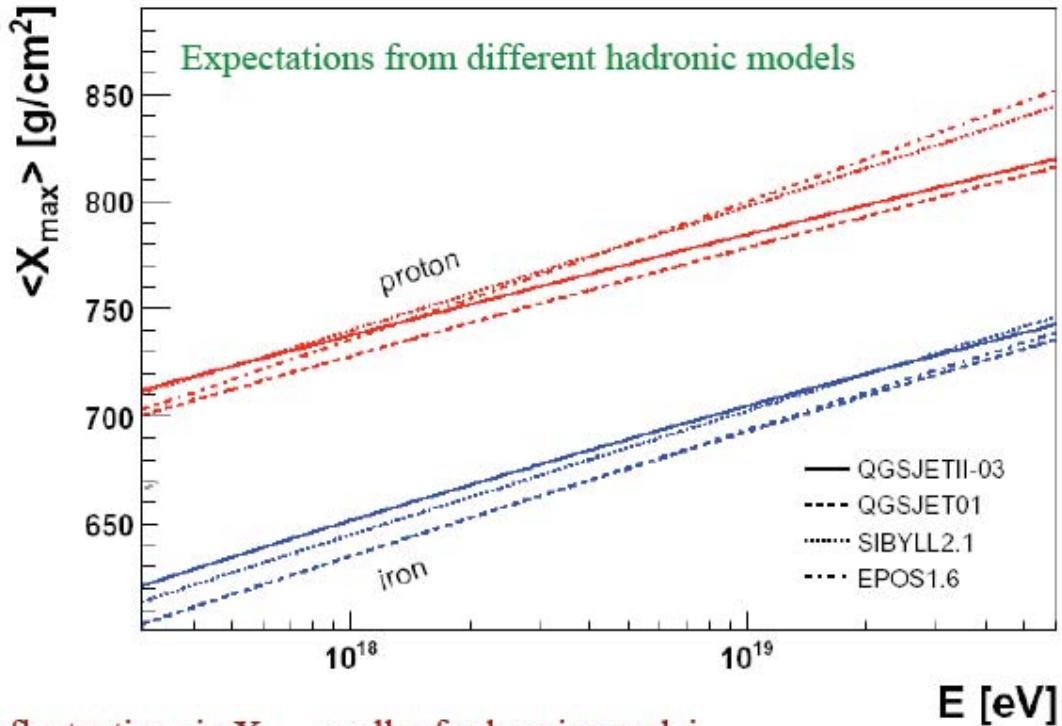
## Composition-sensitive observable

- Depth of shower maximum development:  $X_{\max}$



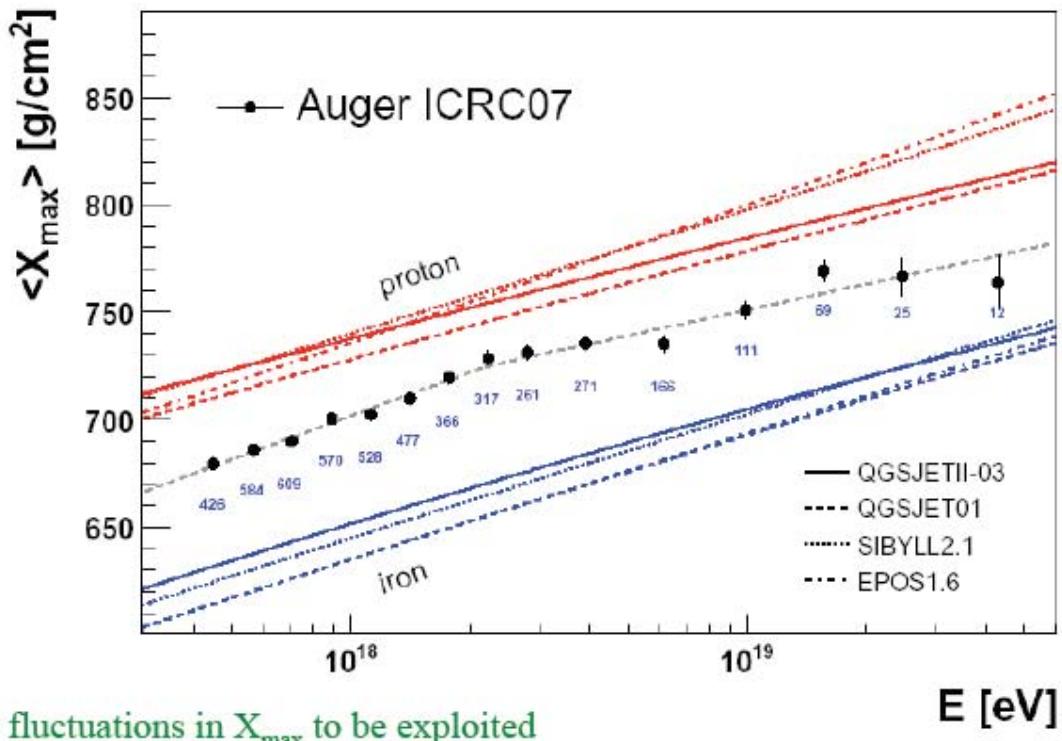
- Stochastic process

## Atmospheric depth of shower maximum



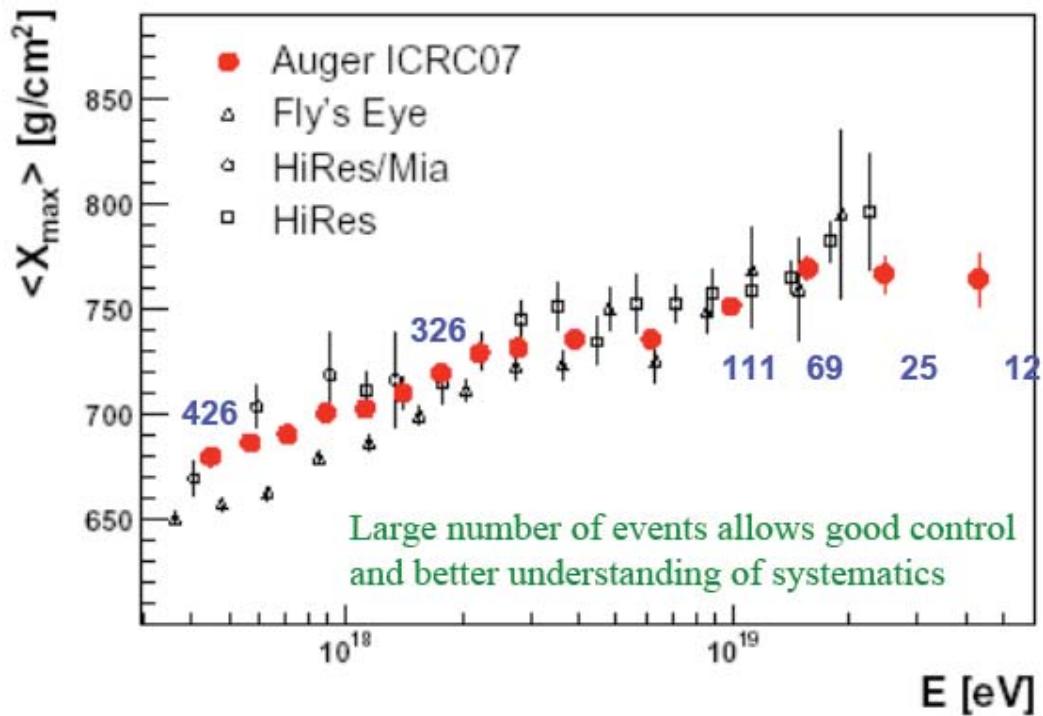
+ fluctuations in  $X_{\max}$  smaller for heavier nuclei

## Shower maximum measured over 2 decades in E



+ fluctuations in  $X_{\max}$  to be exploited

## Comparison with previous studies



## Composition-sensitive observables

- Parameters of the shower front
  - ◆ Radius of curvature → “time delays” in particle arrival times
  - ◆ Thickness of the front → “rise time” of the measured signals
- Relative weight of hadronic subshower
  - ◆ “number of muons” →  $F_\mu(\text{Fe})/F_\mu(\text{p})$  ~ 1.27 (Sibill 2.1)  
~ 1.39 (QGSJet 2)
- NB: unexplored physics at > 300 TeV in CM frame
- NB: dependence on CR arrival direction
  - ◆ Zenith angle of the shower → atmospheric depth  
→ attenuation of EM subshower only

# Photon limit

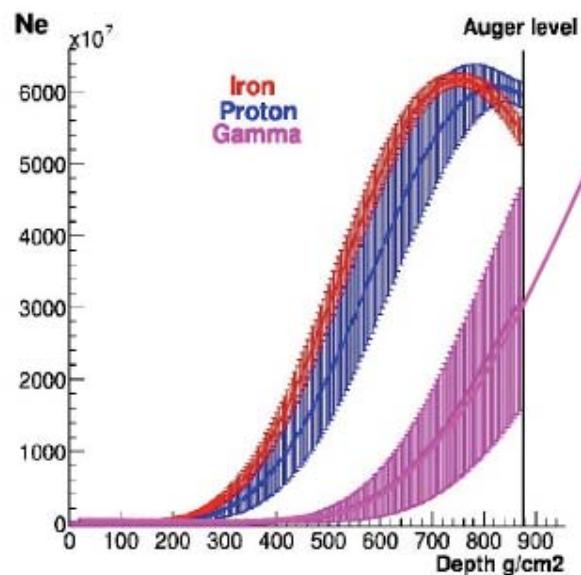
- Top-down models predict abundant fluxes of UHE photons

SHDM models: decay of super-heavy dark matter accumulated in Galactic halo

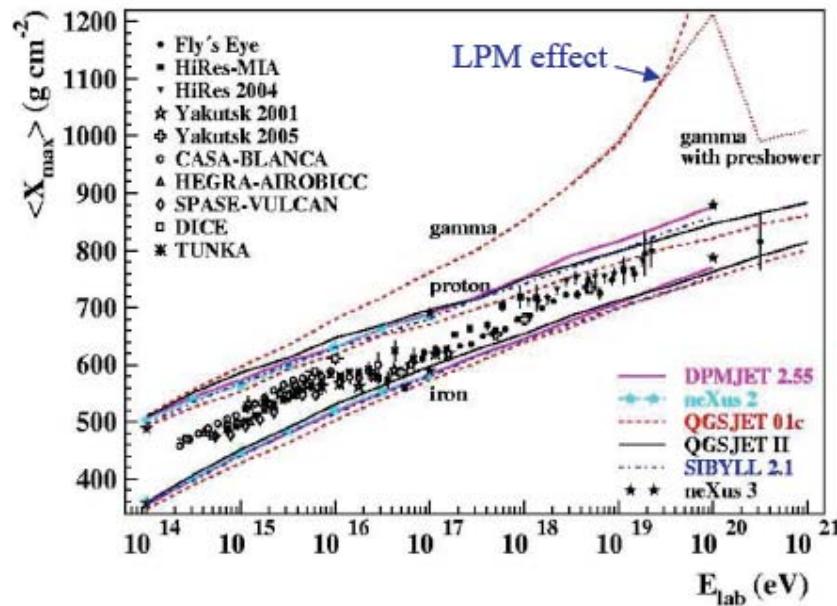
TD models: supermassive particle decay from topological defect interaction or annihilation

- Photon-induced showers look very different

Showers at  $E = 10^{19}$  eV,  $\theta = 0^\circ$  :



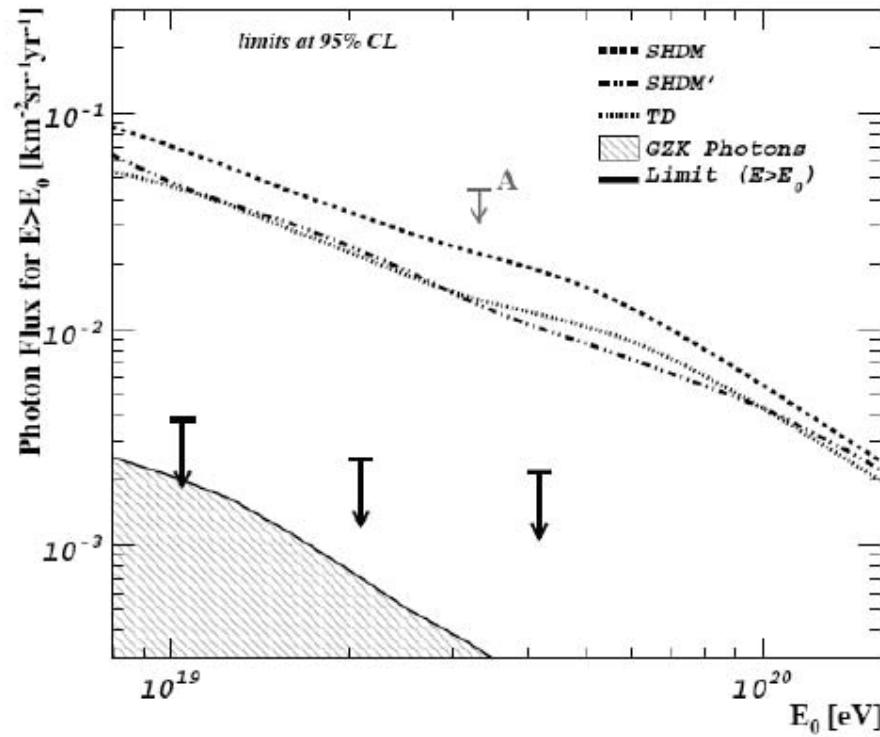
## Photon limit



- Larger  $X_{\max}$ : photon showers delayed by  $> 200 \text{ g/cm}^2$  at  $10^{19} \text{ eV}$
- ➡ ≠ SD observables: { smaller rise time of the signals  
smaller radius of curvature of the shower front }

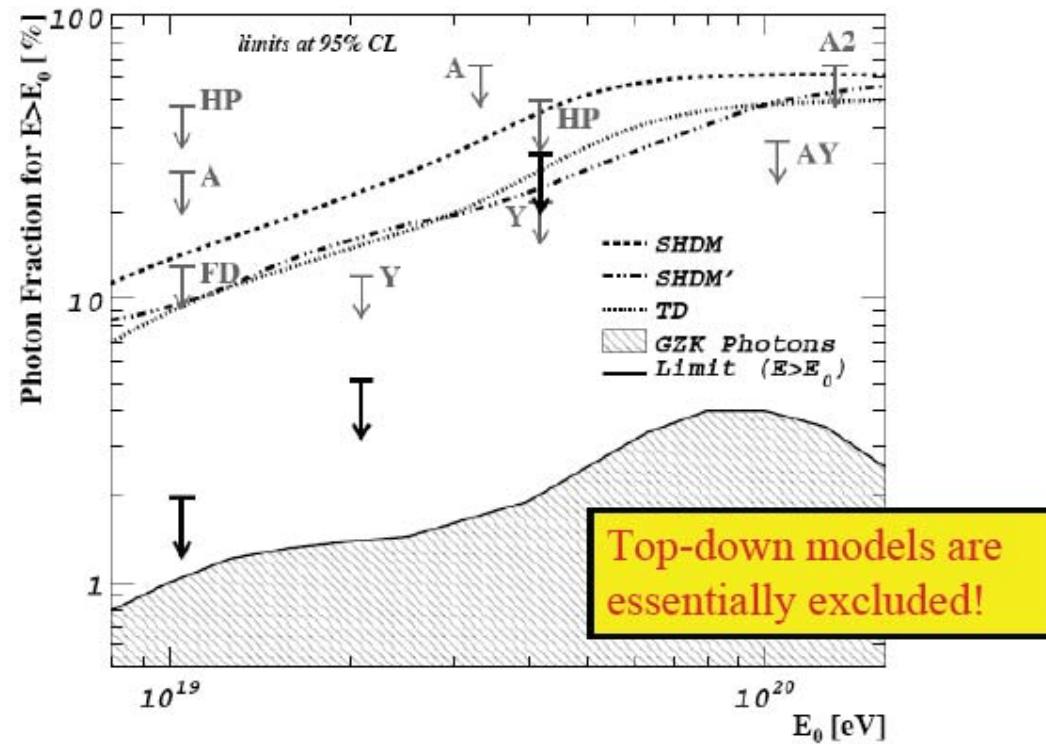
# Photon flux limit

astro-ph/0712.1147



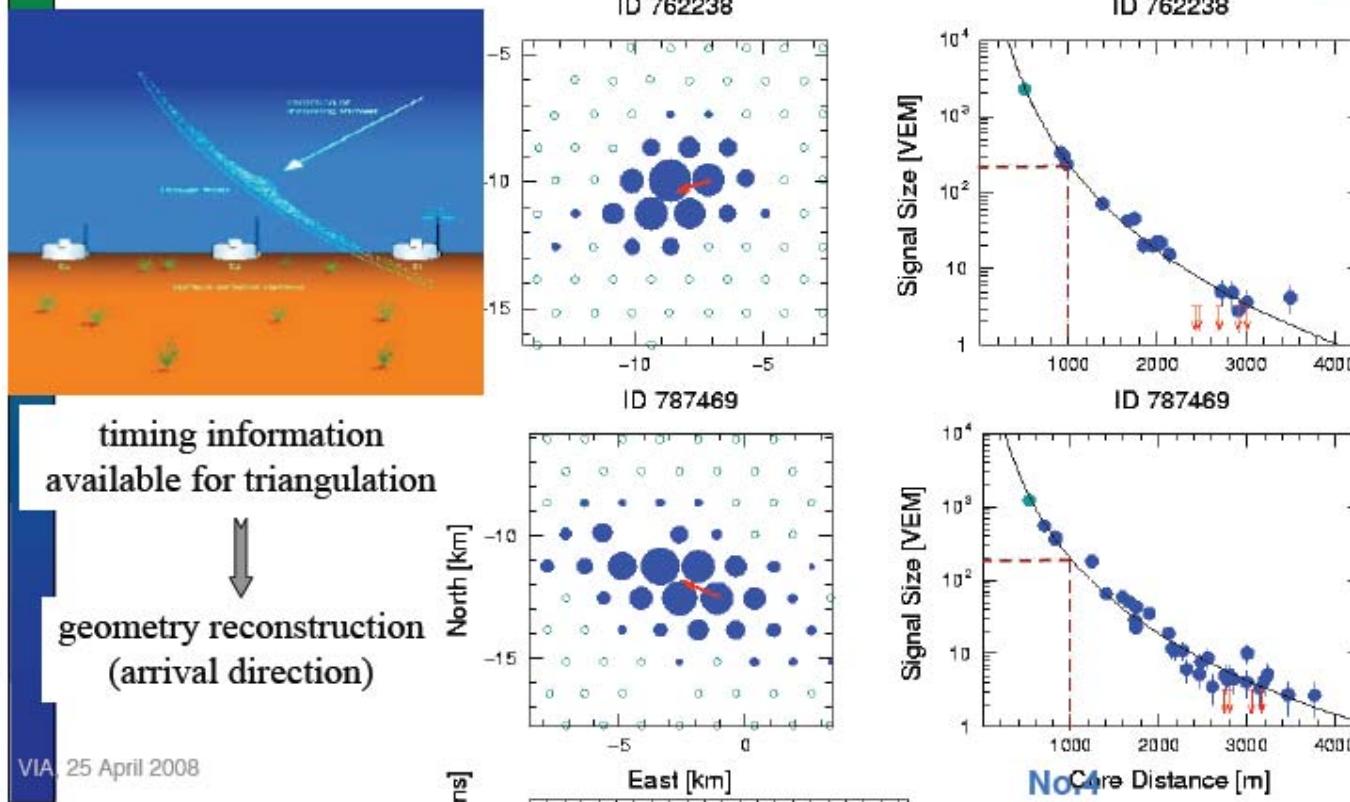
# Photon flux limit

astro-ph/0712.1147

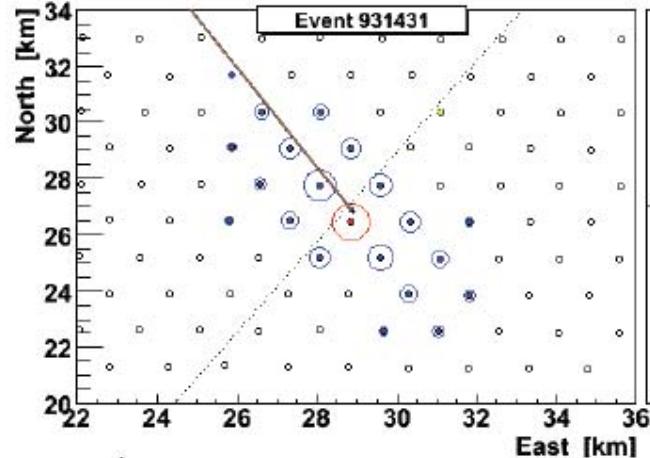


## Energy reconstruction with surface detector

- SD energy estimator: interpolated signal in a tank at 1000 meters and 38°

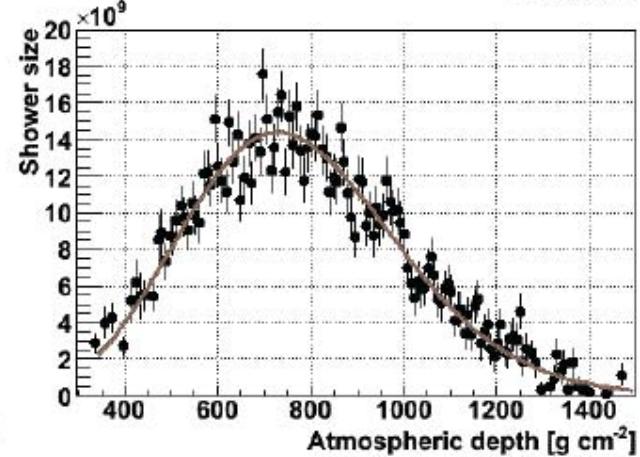


## Example of a Hybrid Event



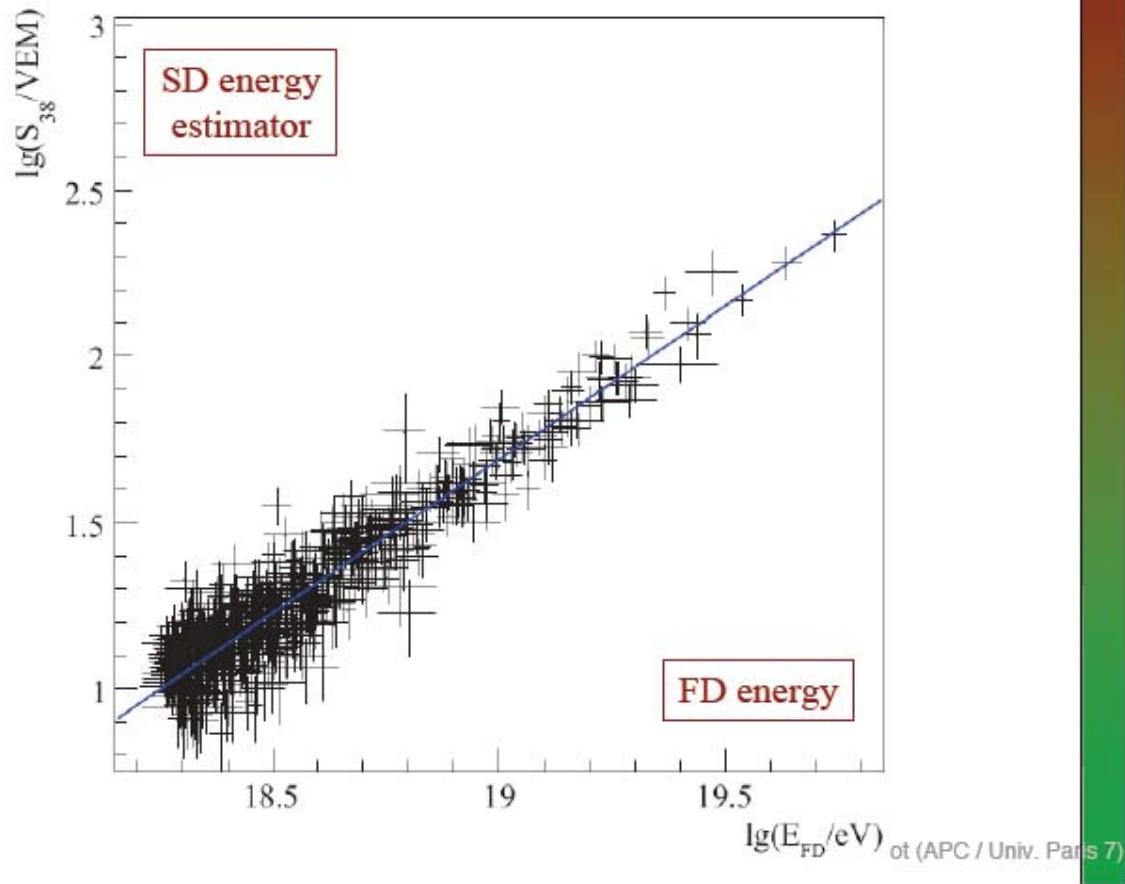
Core location  
Easting  $468693 \pm 59$   
Northing  $6087022 \pm 80$   
Altitude = 1390 m a.s.l.

Shower Axis  
 $\theta = (62.3 \pm 0.2)^\circ$   
 $\phi = (119.7 \pm 0.1)^\circ$



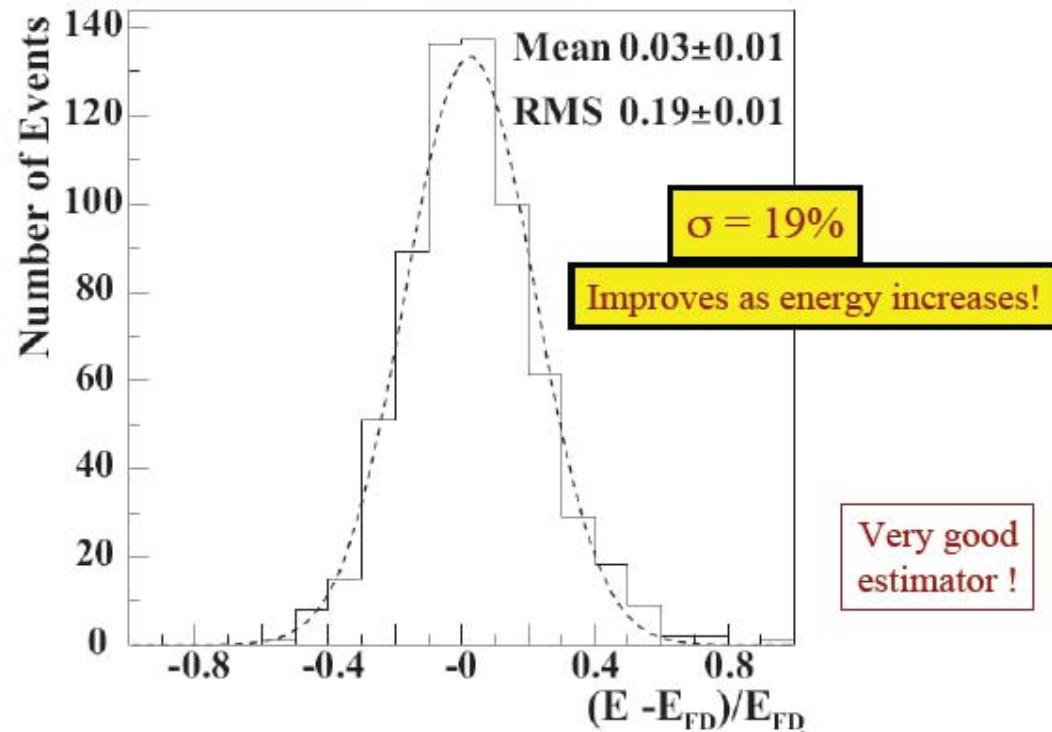
Energy Estimate:  
 $X_{\max} = (728 \pm 20) \text{ g cm}^{-2}$   
 $\chi^2/\text{dof} = 258 / 134$   
  
 $E_{\text{em}} = (21 \pm 5) \text{ EeV}$   
 $E_{\text{tot}} = (23 \pm 6) \text{ EeV}$

## Cross-calibration of the detectors

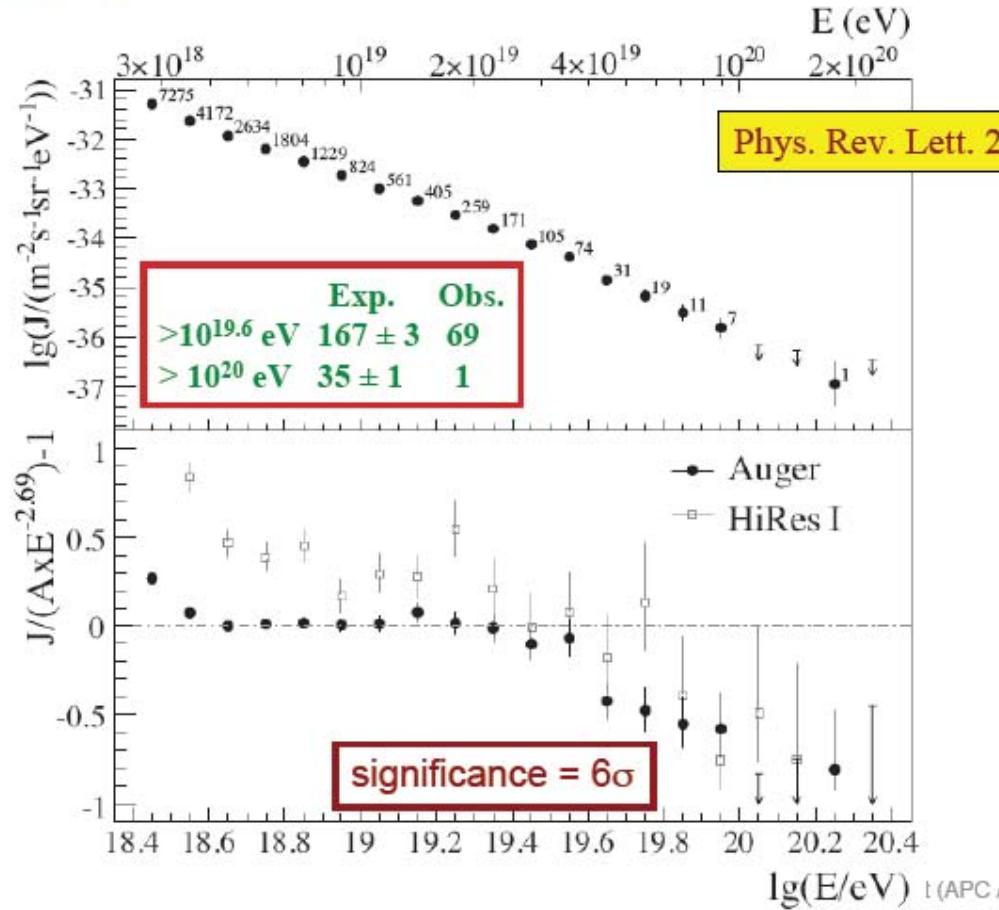


# Cross-calibration of the detectors

Fractional dispersion of FD/SD energy estimates

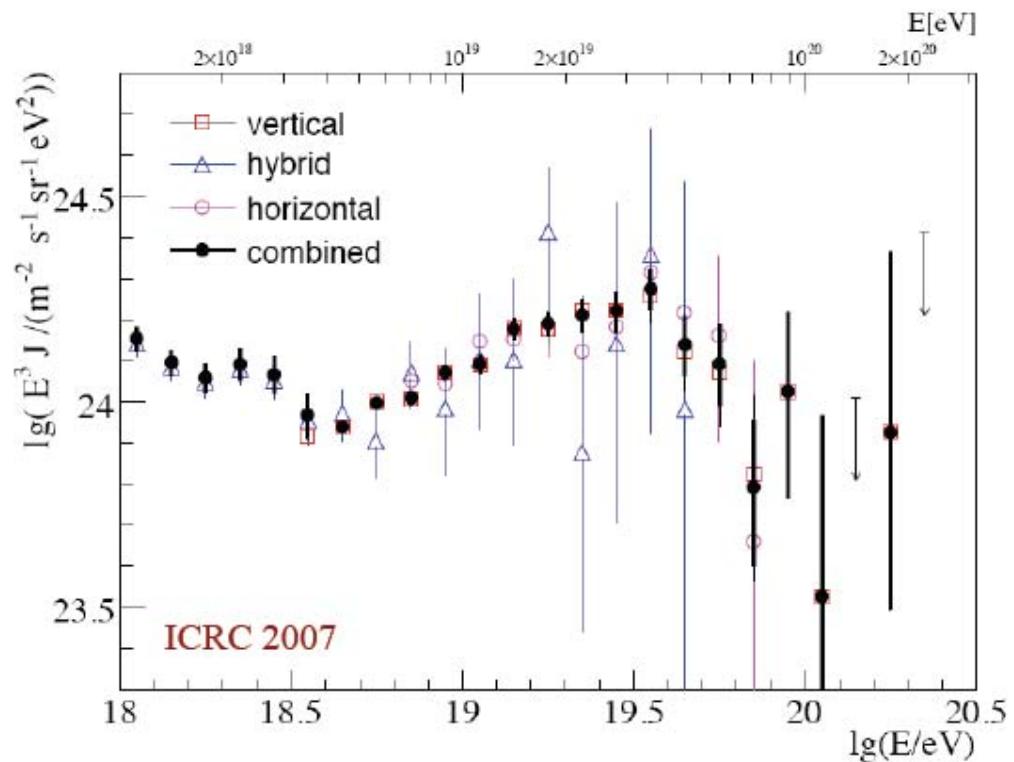


## Energy spectrum from SD showers with $\theta \leq 60^\circ$

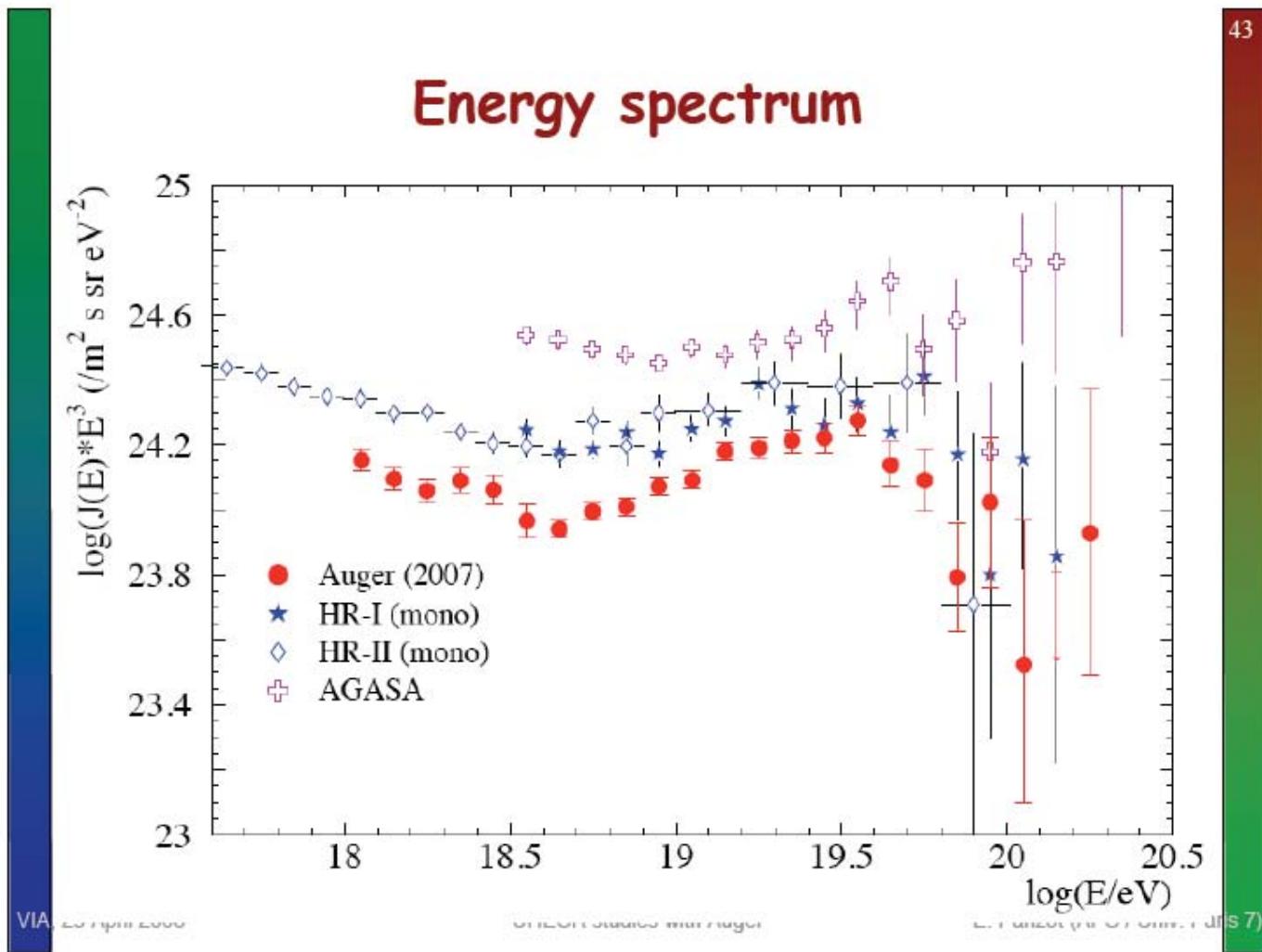


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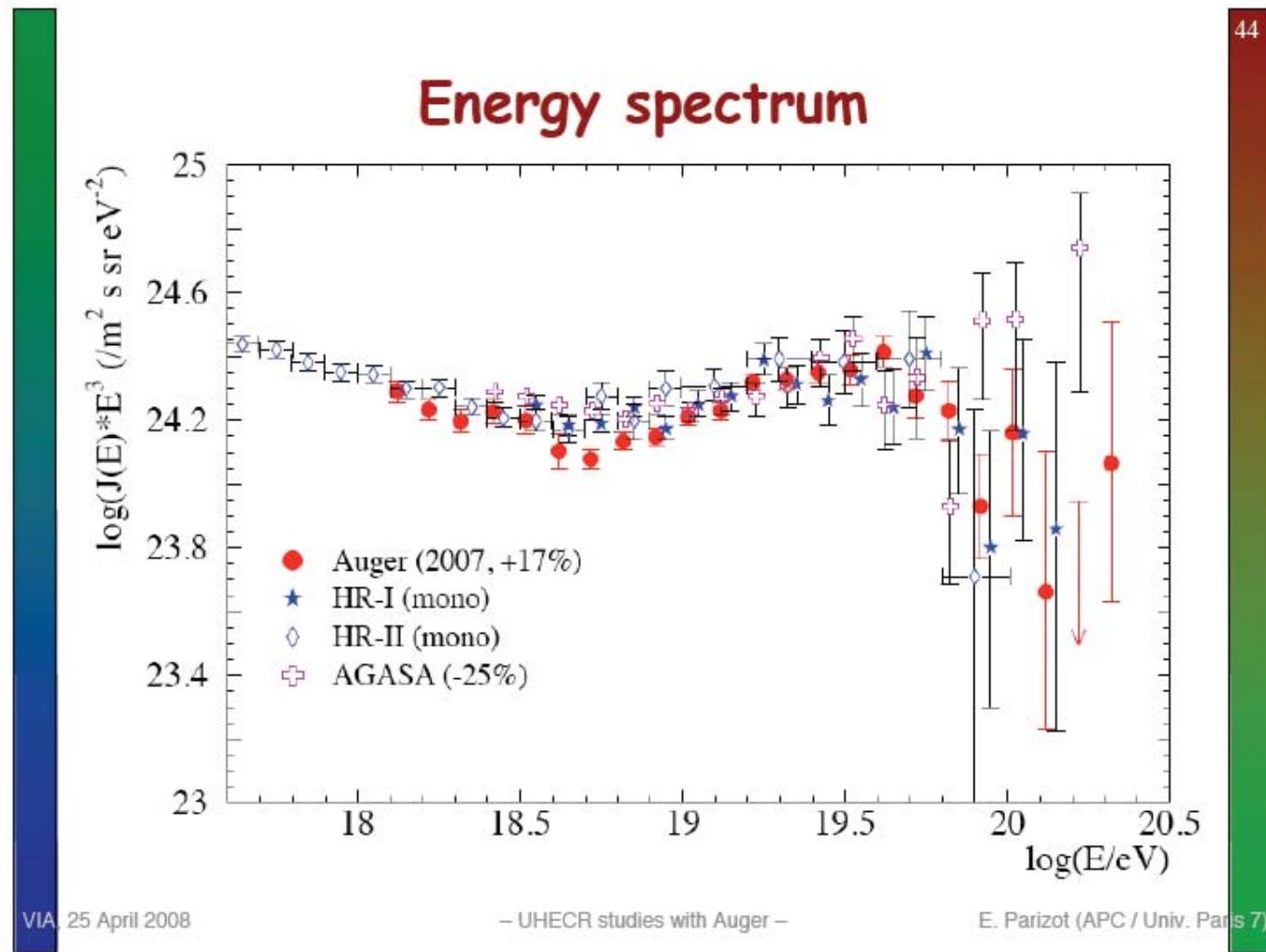
## Auger energy spectrum



## Energy spectrum



## Energy spectrum



## Auger anisotropy results

- Angular resolution of  $\sim 1^\circ$ : good enough!
  - No large-scale signal (dipole) at any energy above 1 EeV
    - e.g.  $\alpha < 0.7\%$  for  $1 \text{ EeV} \leq E \leq 3 \text{ EeV}$
  - No significant excess emission from Galactic center
  - No signal from BL-Lacs as possibly seen by HiRes
- ➡ none of the previous reports have been confirmed...

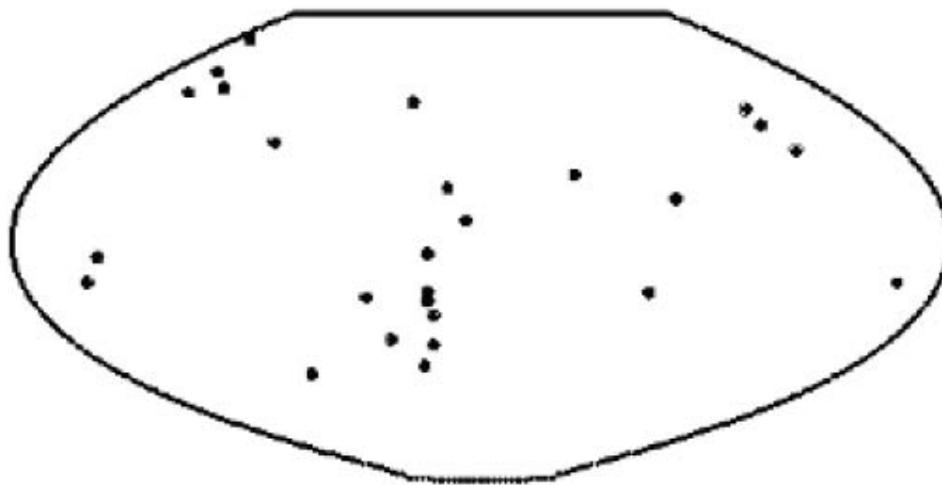
## Auger main anisotropy result

- Highest energy cosmic rays have an anisotropic distribution!
- First evidence that cosmic-ray astronomy is indeed possible!
- Correlation with the most nearby AGNs in the 12<sup>th</sup> Véron-Cetty/Véron catalogue
- Opening of a new era:
  - ◆ Study of particle acceleration in high-energy astrophysical sources
  - ◆ Multi-messenger study of sources
  - ◆ High-energy physics!



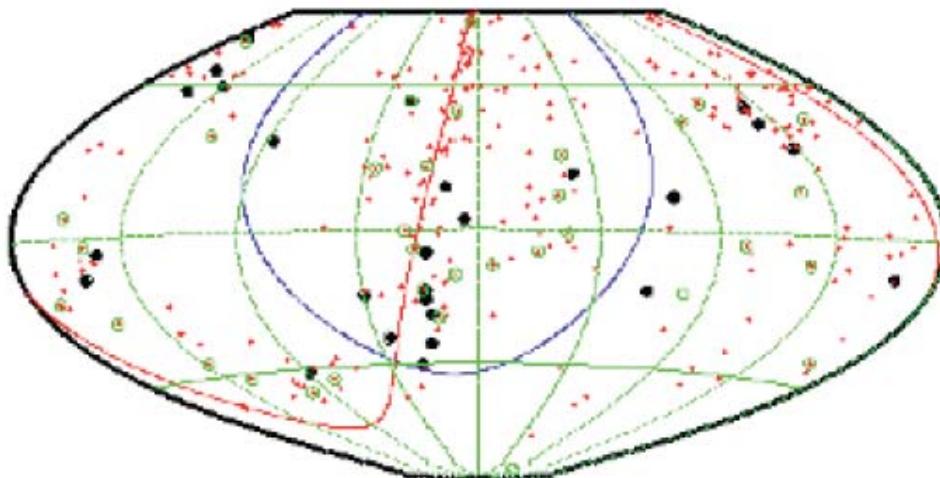
## Auger main anisotropy result

Position of the 27 highest energy events on an equal exposure map



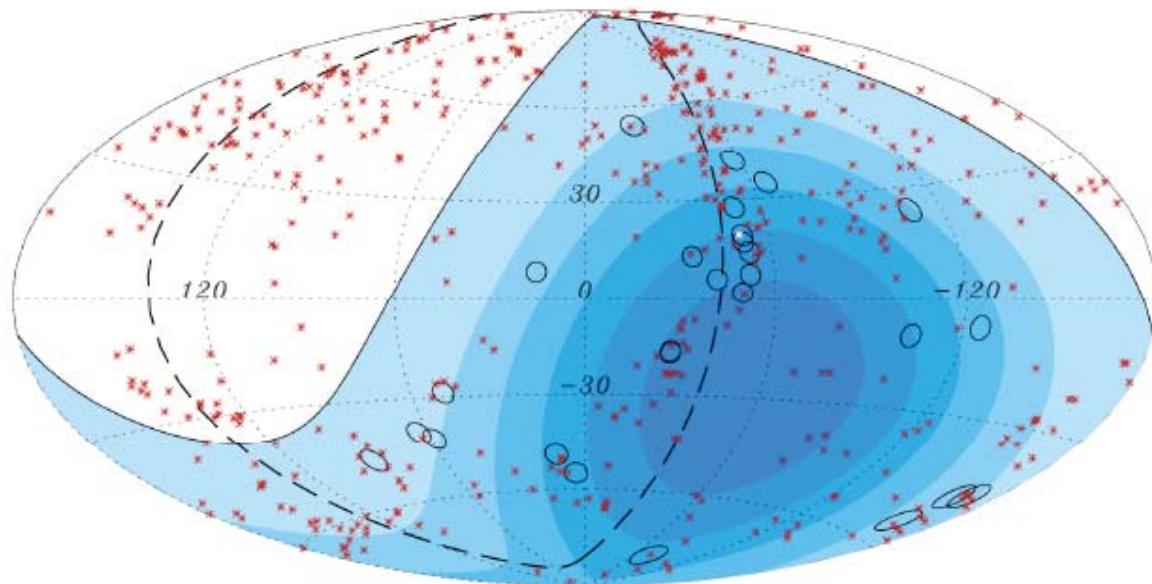
## Auger main anisotropy result

Position of the 27 highest energy events on an equal exposure map



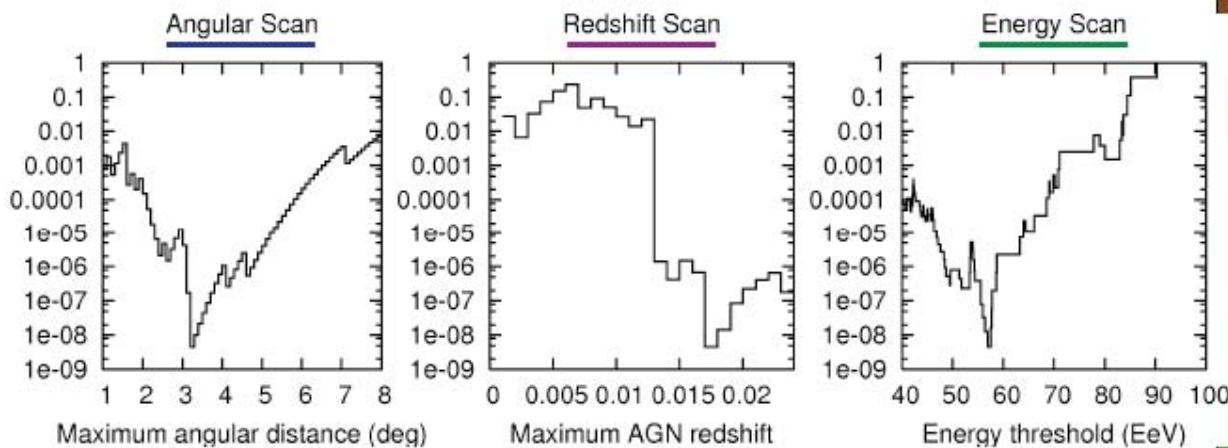
Galactic and supergalactic planes  
AGNs in VCV catalogue and Swift X-ray AGN catalogue

## Auger main anisotropy result



# Auger main anisotropy result

3 free parameters in the definition of the correlation



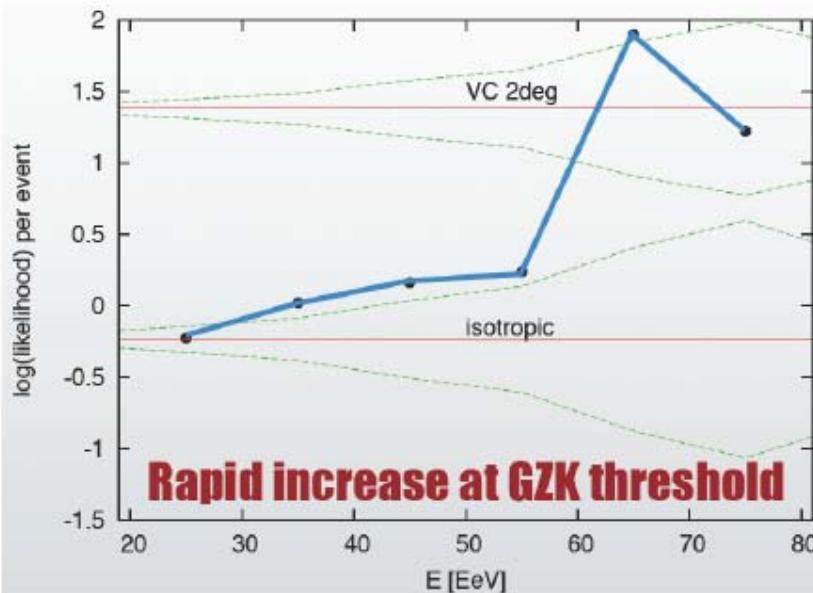
$$\Delta\theta \leq 3.1^\circ$$

$$z \leq 0.018$$

$$(D \leq 75 \text{ Mpc})$$

$$E \geq 56 \text{ EeV}$$

## Auger main anisotropy result



The energy above which the correlation is most significant corresponds to an energy where the CR flux drops... (supporting the GZK interpretation)

## Significance of the anisotropy result

Not an “AGN correlation” result!

- Véron-Cetty / Véron, 12th Edition, 2006

“This catalogue should not be used for any statistical analysis as it is not complete in any sense, except that it is, we hope, a complete survey of the literature.”

## Significance of the anisotropy result

Not an “AGN correlation” result!

- **1st step:** search between HECR arrival directions and various source catalogues (hard to estimate how many, how intensively, etc.) (data from 2004/01/01 to 2006/05/26)
- A very large “raw significance” was found with the 12<sup>th</sup> VCV catalogue of AGNs
  - ◆ Even after taking into account generous penalty factors for a posteriori searches and scanning of parameter space
  - Did not seem to be fluctuation
  - Auger collaboration set up a prescription for future data
- Most significant *a posteriori* “correlation signal”:

3.2 expected  
from isotropic  
distribution

12 out of 15 events above “56 EeV” are closer than  $3.1^\circ$   
from an AGN in 12<sup>th</sup> VCV with  $z \leq 0.018$  ( $D \leq 75$  Mpc)

## Significance of the anisotropy result

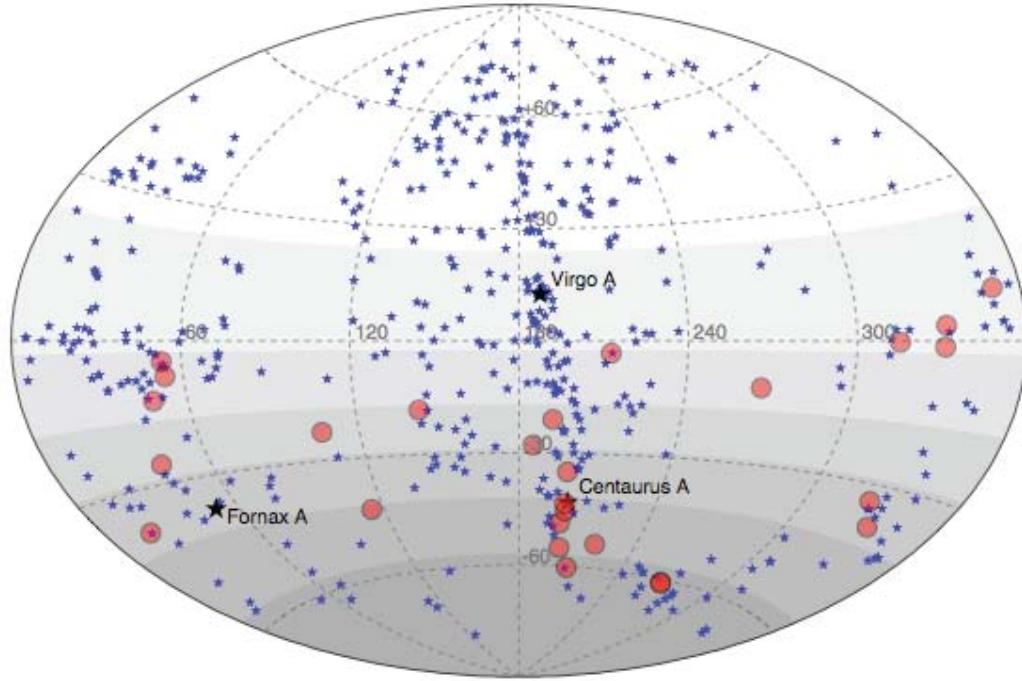
Not an “AGN correlation” result!

- **2nd step:** predefine a region in the sky where there seems to be an excess of CR flux, and see if the next highest energy cosmic rays come from this region
    - ➡ ■ Independent data set
    - prescribed parameters
    - unambiguous significance (Confidence Level)
  - **Result:** 99% CL that the excess we had seen in the original data set was not a random fluctuation from an otherwise isotropic cosmic ray distribution
    - ➡ **“CR distribution is anisotropic at the highest energies!”**
- 21% chance  
from isotropic  
distribution
- 8 “correlating  
events” out of 13  
(2.7 expected)
- corroborated by other analyses, independent of any source catalogue

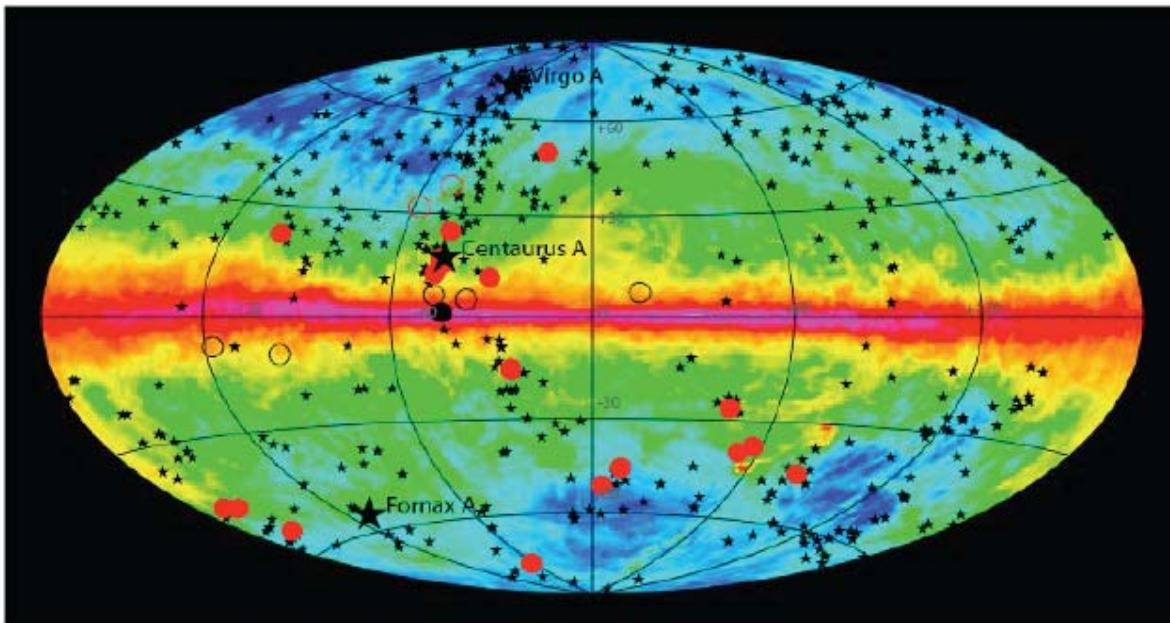
## Astrophysical implications?

- Not clear yet! (very low statistics to check against any model, whether naive or sophisticated)
- Can UHECRs come from AGNs? → YES  
But we knew that before!
- Do UHECRs have to come from AGNs? → NO!
- NB: no claim from Auger!

## Centaurus A, Virgo, Fornax, etc.



## Centaurus A, Virgo, Fornax, etc.?

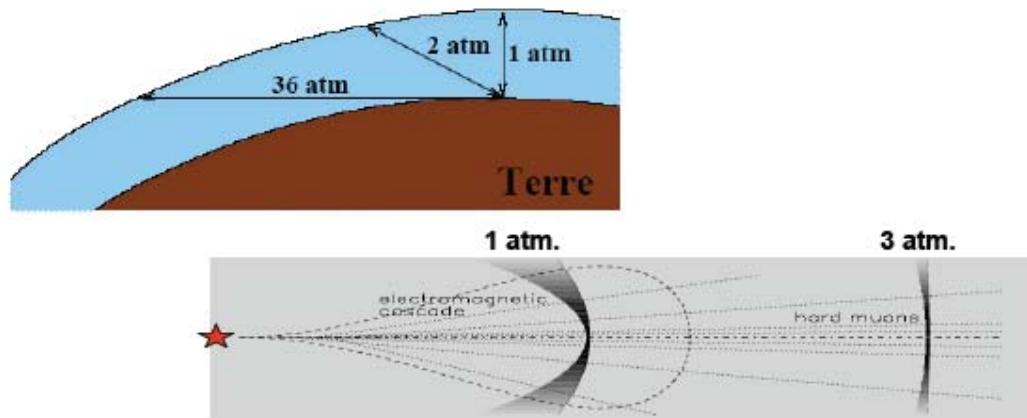


Galactic plane: catalogue even more incomplete + larger deflections expected

# Neutrino detection with Auger

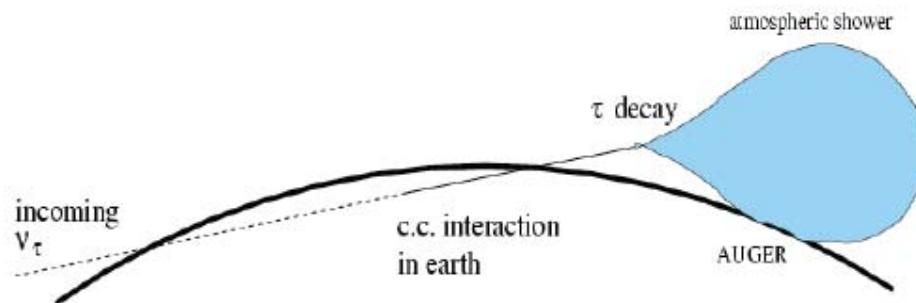
"GZK neutrinos" or from astrophysical sources

- Neutrinos can interact by chance anywhere in the atmosphere, including much deeper than would do protons, nuclei and photons
  - easy to recognize and discriminate:
  - “young” horizontal showers



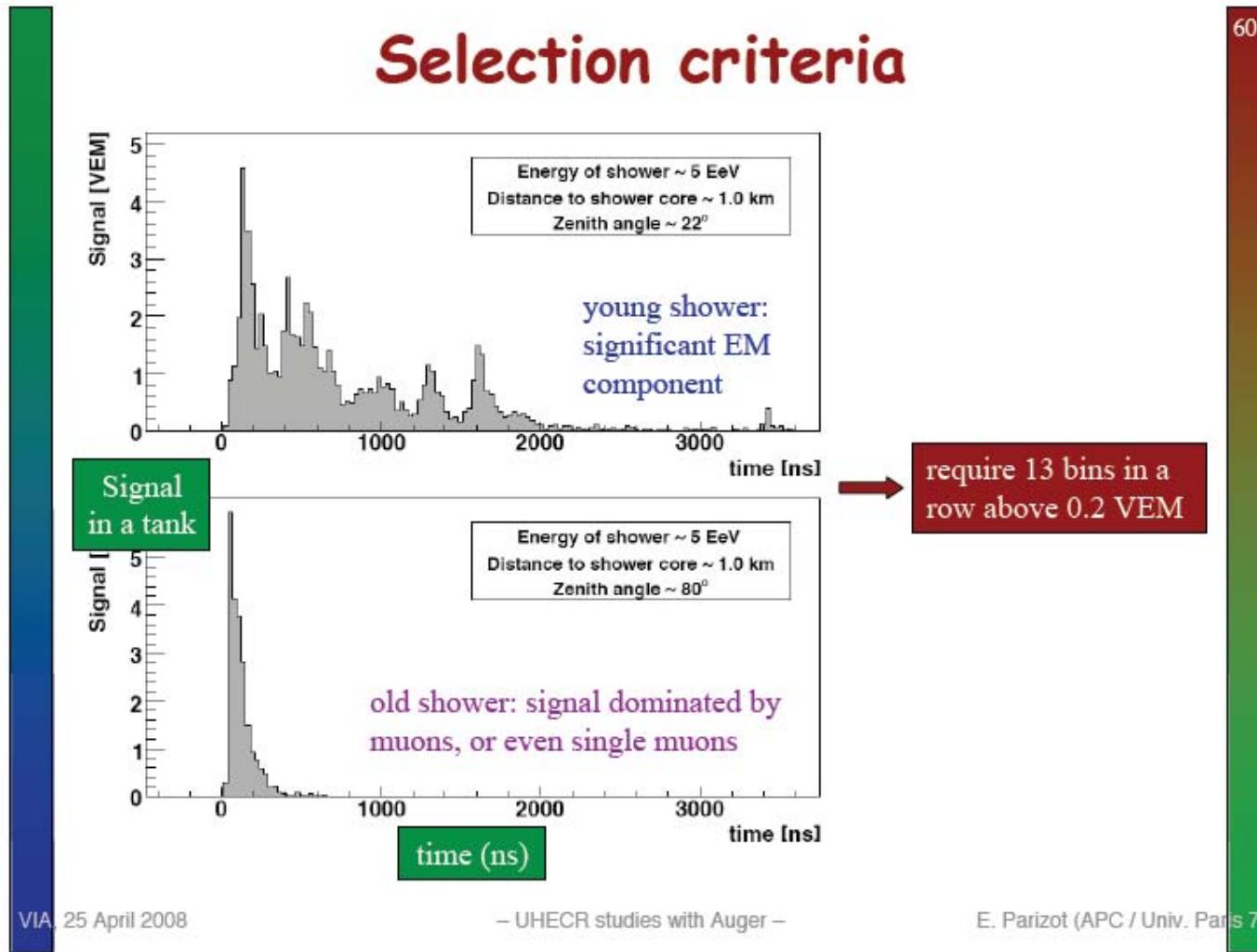
## Neutrino detection with Auger

- Additional detection technique, with excellent (perfect?) discrimination:  
“Earth-skimming tau neutrinos”

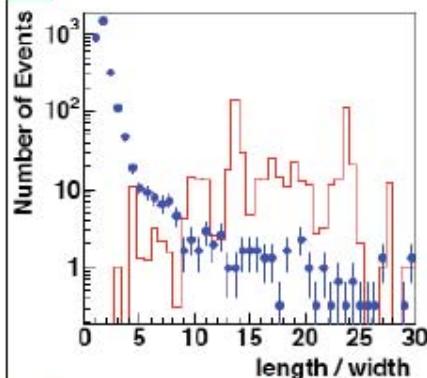
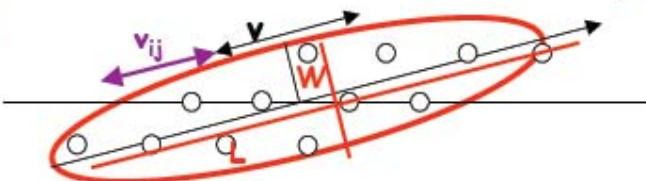


- even more powerful (higher sensitivity)!
- most stringent upper limits in the GZK energy range  
Probably a detection within a few years...

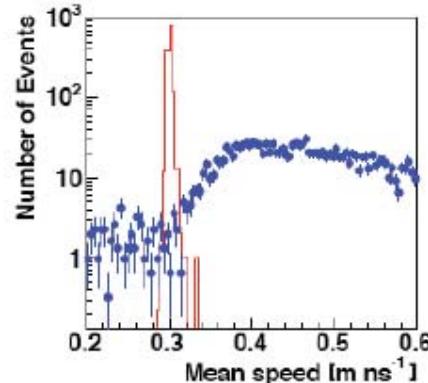
## Selection criteria



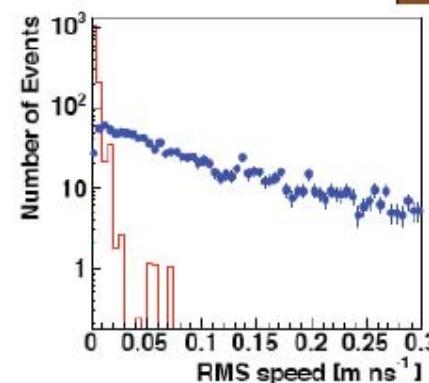
## Selection criteria



require elongated pattern on the ground  
(length/width > 5)



require apparent velocity on the ground in the range  
0.29–0.31 m/ns

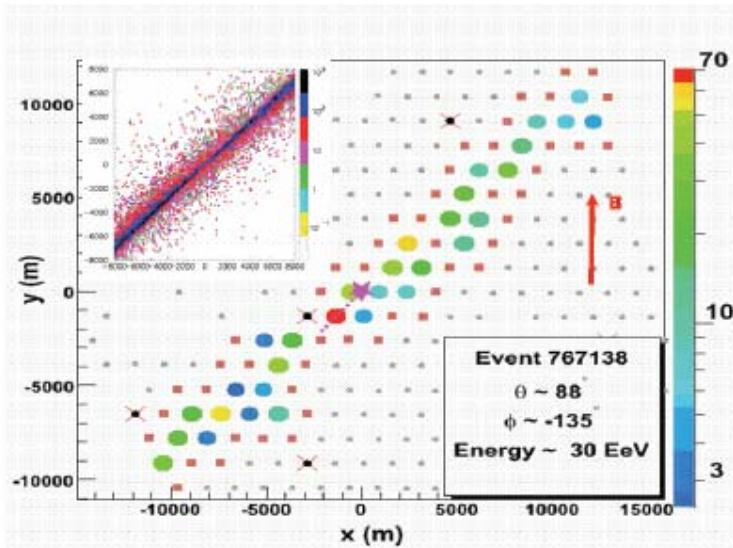


require rms velocity scatter < 0.08 m/ns

→ Selection efficiency: 80%

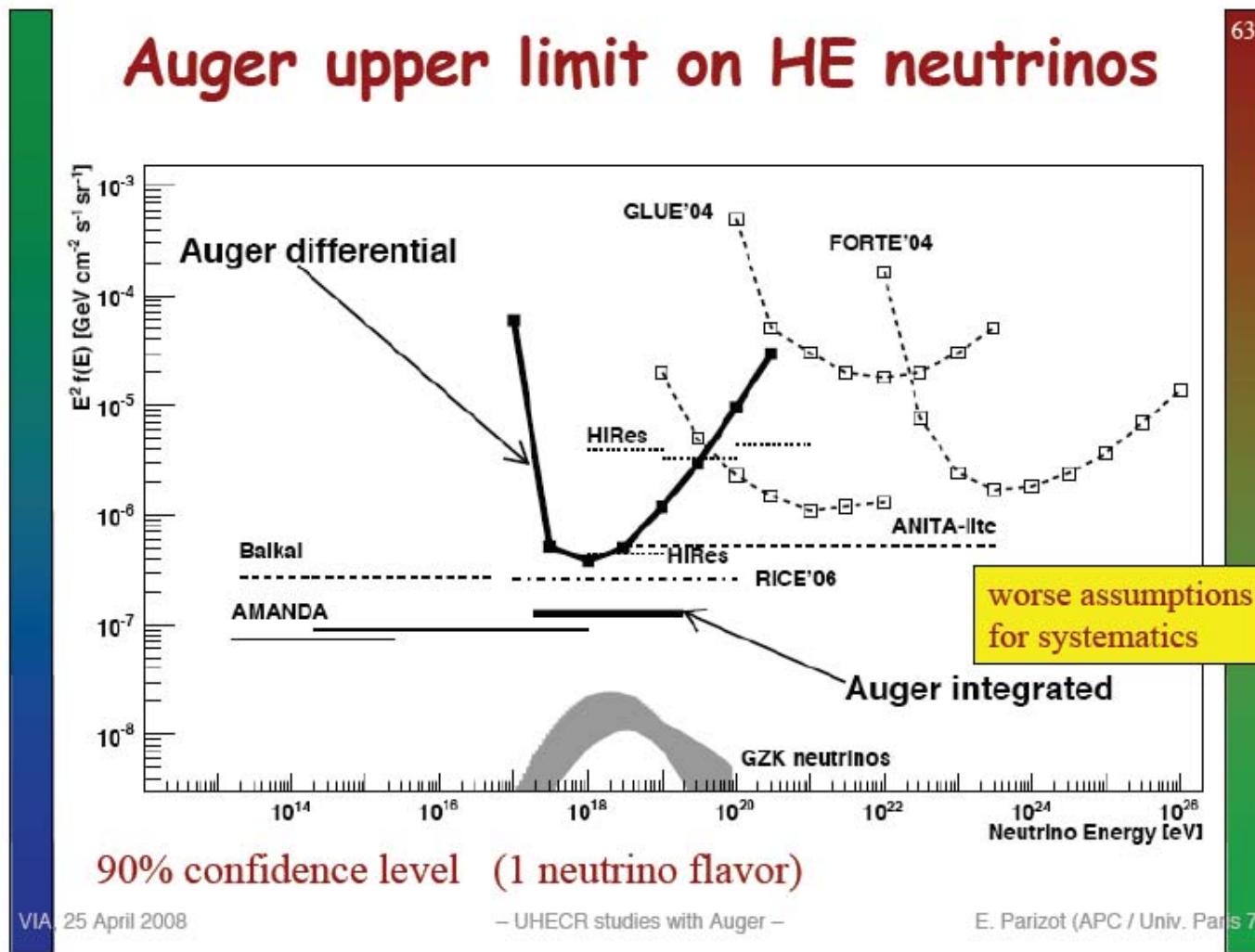
## Horizontal showers

Example of a horizontal event (31 tanks)



But ZERO neutrino candidate

# Auger upper limit on HE neutrinos



# Summary of Auger results

## composition

some nuclei,  
no photons, no  
neutrinos yet

**matches** astrophysical  
expectations

Implications for  
gal./extragal. **transition?**

**Unity** with the CR  
science and sources at  
low E?

Makes HECR studies  
even **richer!**

## E spectrum

ankle +  
GZK cutoff

**Excellent news!**  
40 years-old prediction!

⇒ nearby sources  
⇒ « proton astronomy »!  
+ isolated sources!

+ high-energy physics  
study of showers (muons,  
hadronic models, energy scale)

cf. knee + **LHC** !

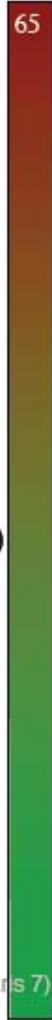
## directions

anisotropic sky

**Most important result**  
**since 100 years!**

⇒ “cosmic-ray  
astronomy” is possible  
(it just began!)

⇒ cosmic rays integrated  
into the scientific *corpus*  
of astrophysics



# Cosmic rays, year zero!

- Historical opening of a non-photonic astronomy!
  - ◆ Eventually: identification and study of individual sources
  - ◆ Necessary to increase collecting power at the highest energies
    - ➡ Auger Nord (Lamar, Colorado)  
(sources are there: let's go and get them!)
    - ➡ Shower detection from space (JEM-EUSO, S-EUSO...)
- Many questions
  - ◆ sources, CR origin, acceleration mechanisms, behaviour of energetic sources in the universe, link with low-energy CRs and galactic ecology
  - ◆ study of high-energy physics (LHC results are awaited!)
- All this starts today!



Merci !



Pierre Auger Observatory  
studying the universe's highest energy particles



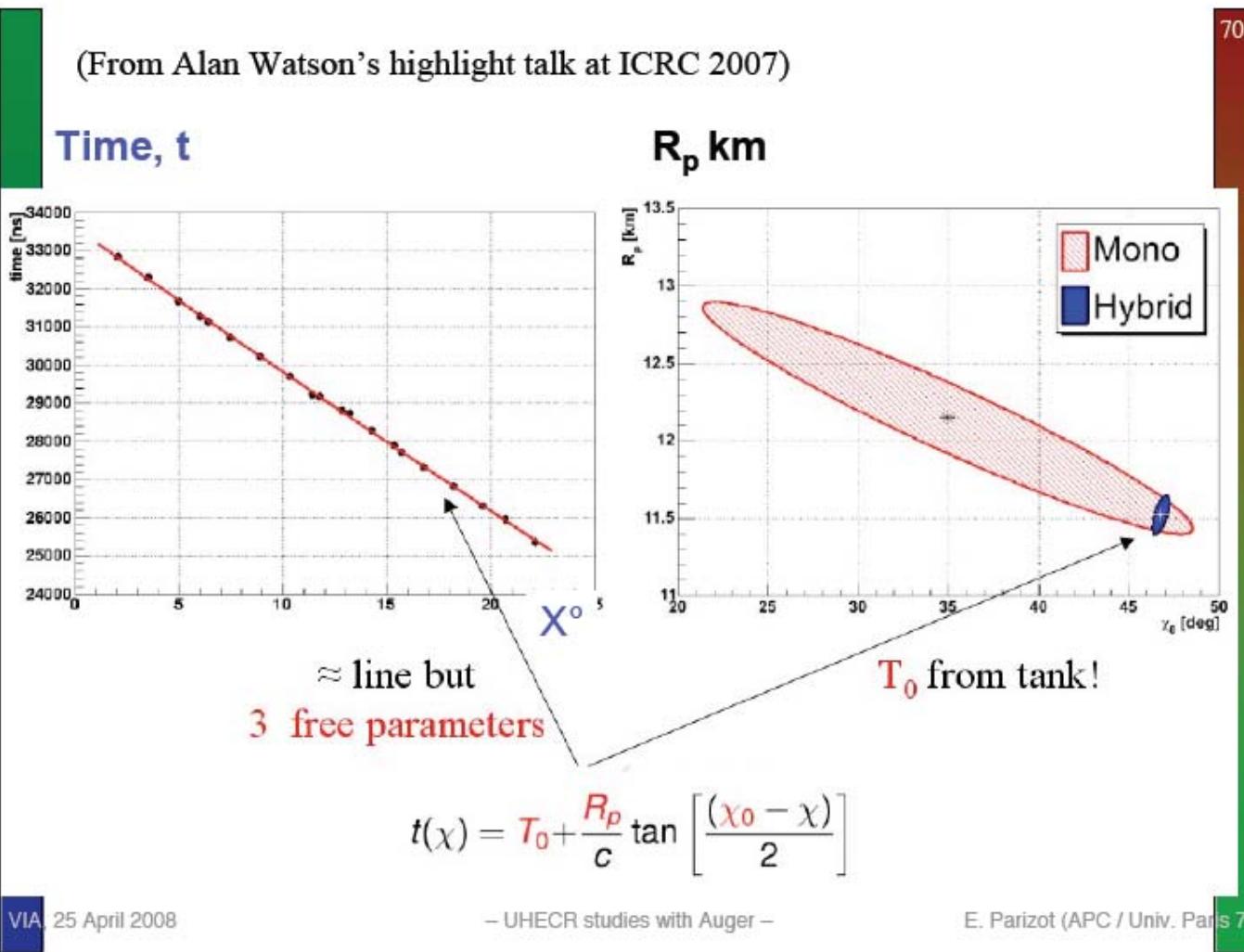


Extra slides

# Uncertainty on the energy scale

<u>source</u>	<u>systematic uncertainty</u>
Fluorescence yield	14%
P, T and humidity effects	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
Total:	<b>22%</b>
(improvements expected soon...)	

(From Alan Watson's highlight talk at ICRC 2007)



## Shower development

- yet unexplored physics
  - $\geq 300$  TeV in p-p center-of-mass frame

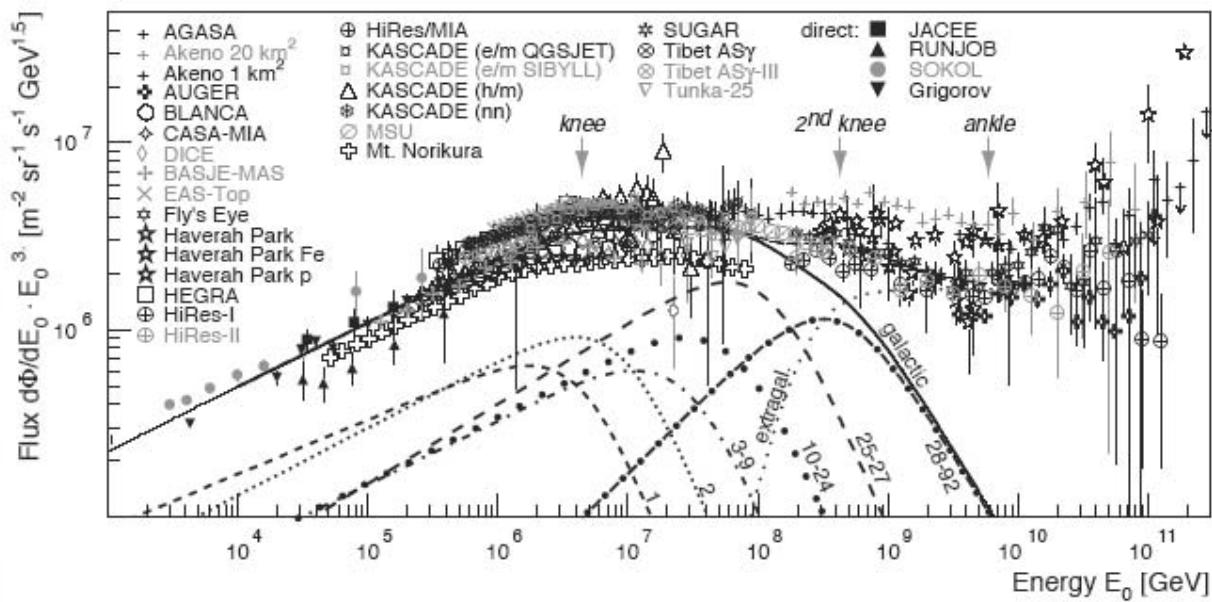
grammage  
(g/cm<sup>2</sup>)

- High-energy hadronic interactions
    - extrapolation of hadronic models
    - important source of uncertainty!
  - “Forward cross sections” important!
- • Implications for high-energy physics

# [CR flux] $\times E^3$

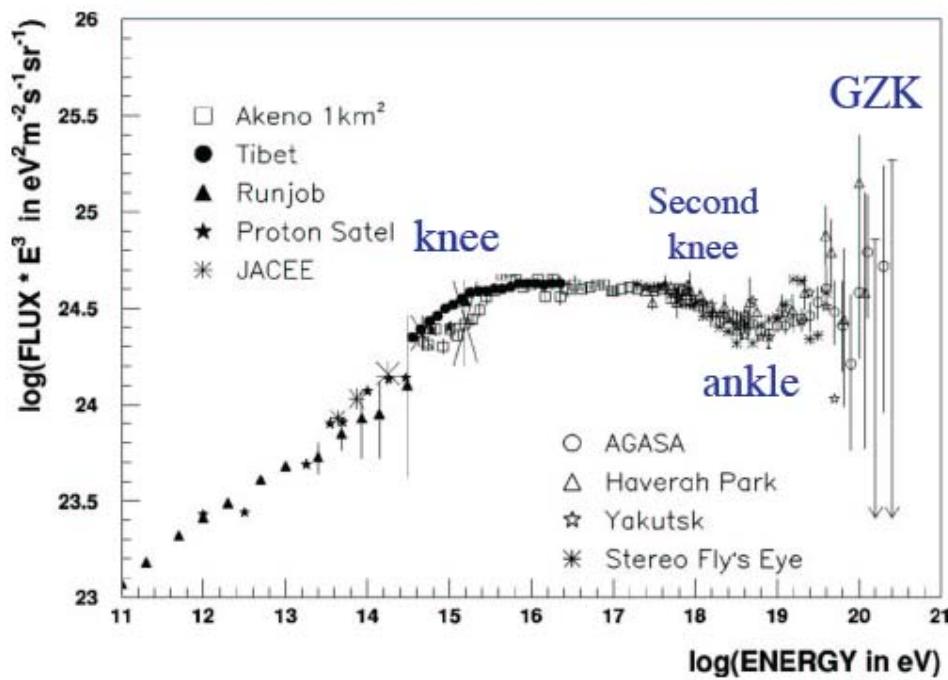
72

- Some confusion at high E...



# [CR flux] $\times E^3$

- Essentially due to uncertainties in the energy scale or the detector's acceptance



# Fluorescence detector (FD)



Drum for uniform illumination of each fluorescence camera – part of end to end calibration .



Central Laser Facility (laser optically linked to adjacent surface detector tank)



– UHECR studies with Auger –



Lidar at each Fluorescence building



Year around balloon borne atmospheric measurements.