(Selected) Results from the Pierre Auger Observatory

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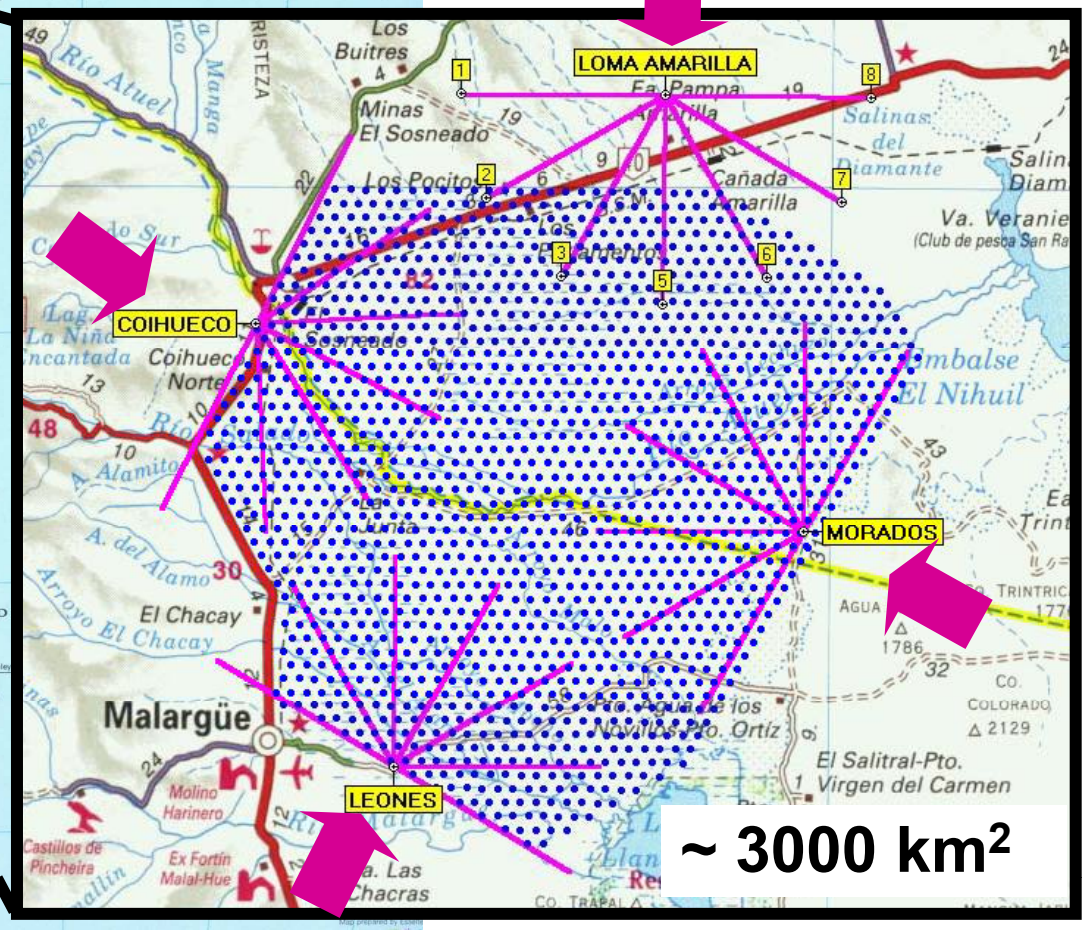
DISCRETE´08: Symposium on Prospects in the Physics of Discrete Symmetries

Valencia, December 15, 2008

The Pierre Auger Observatory

The Pierre Auger Southern Observatory: Malargüe, Mendoza (Argentina)

- 1600 water Cherenkov tanks
- 4 Fluorescence Buildings



35.5º S, 69.3º W
1400 m a.s.l. (880 g cm^{-2})

Hybrid detector

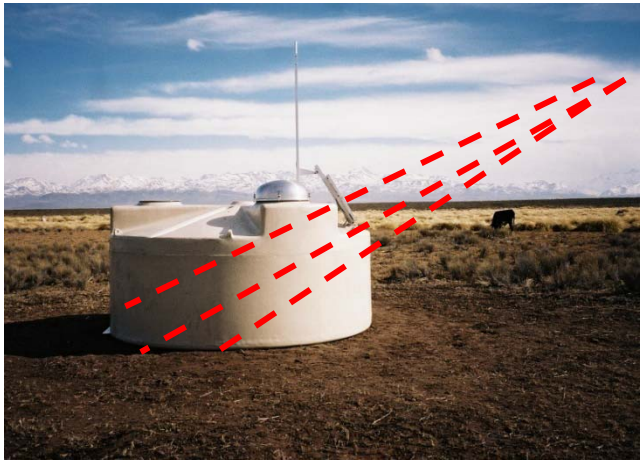
Combines 2 different techniques:

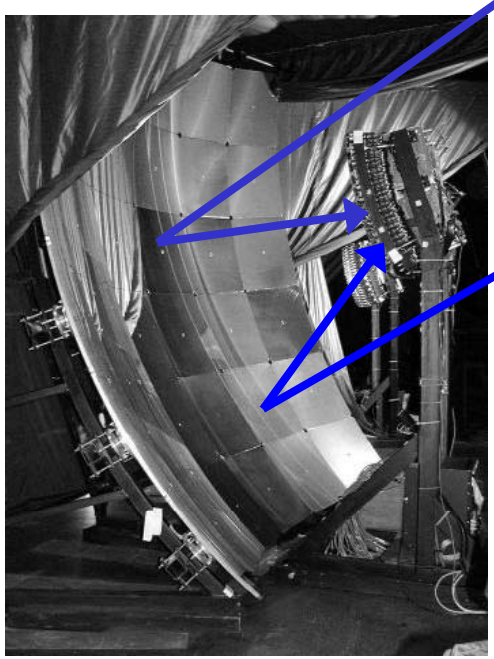
Fluorescence telescopes

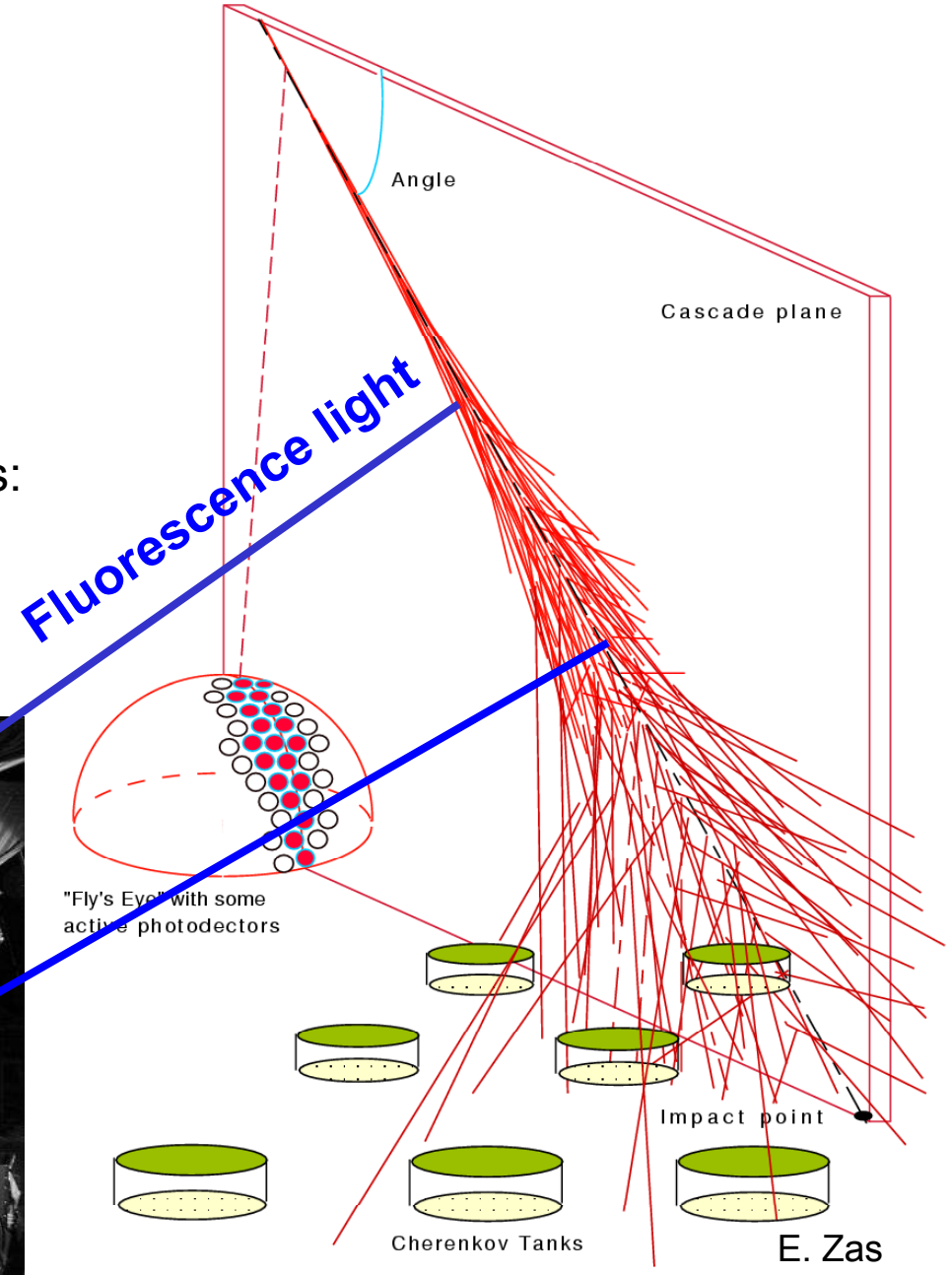
Water Cherenkov stations

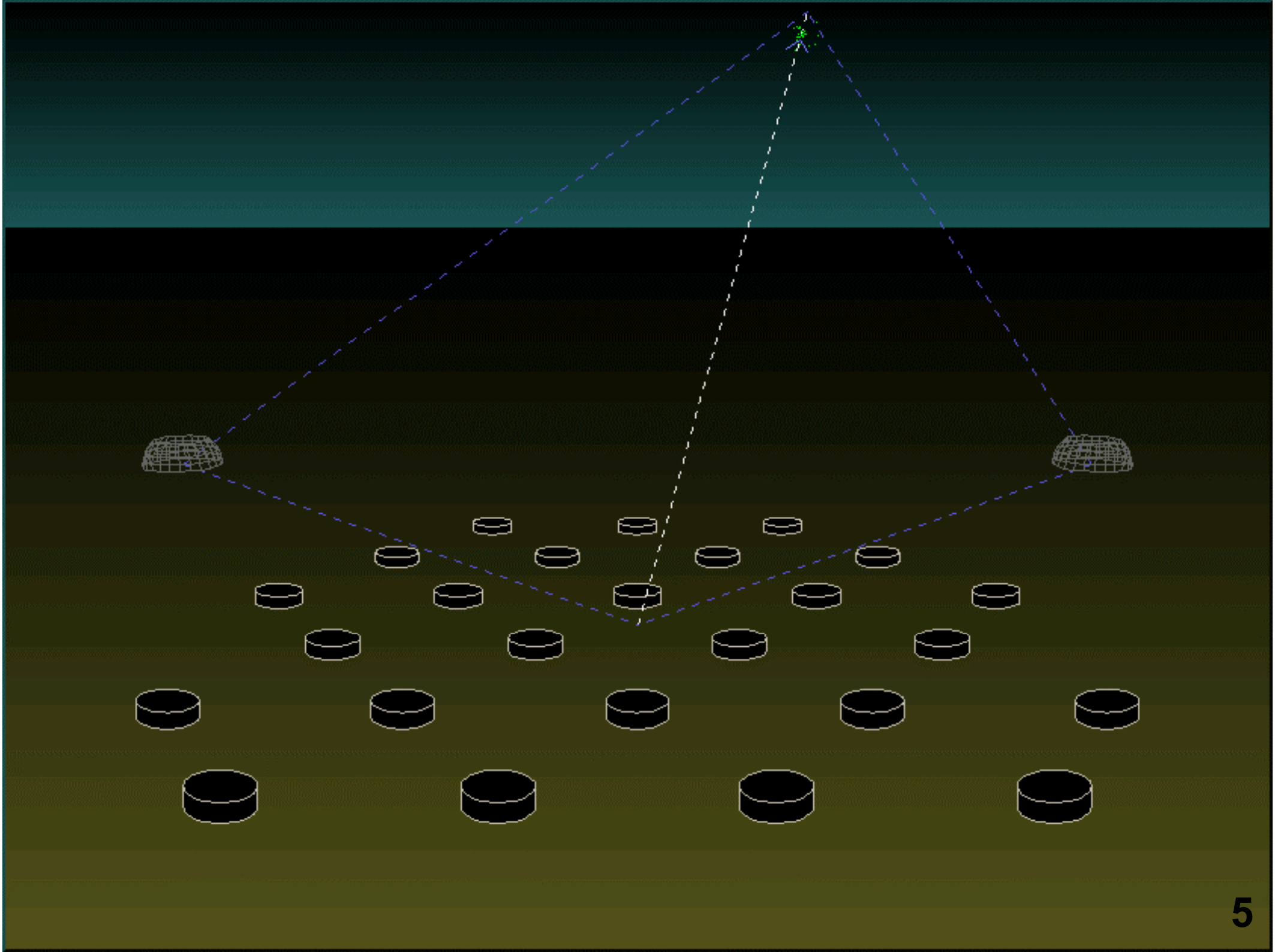
~ 10% of events are observed with both techniques: wealth of information about shower development.

Surface detectors









The importance of being hybrid

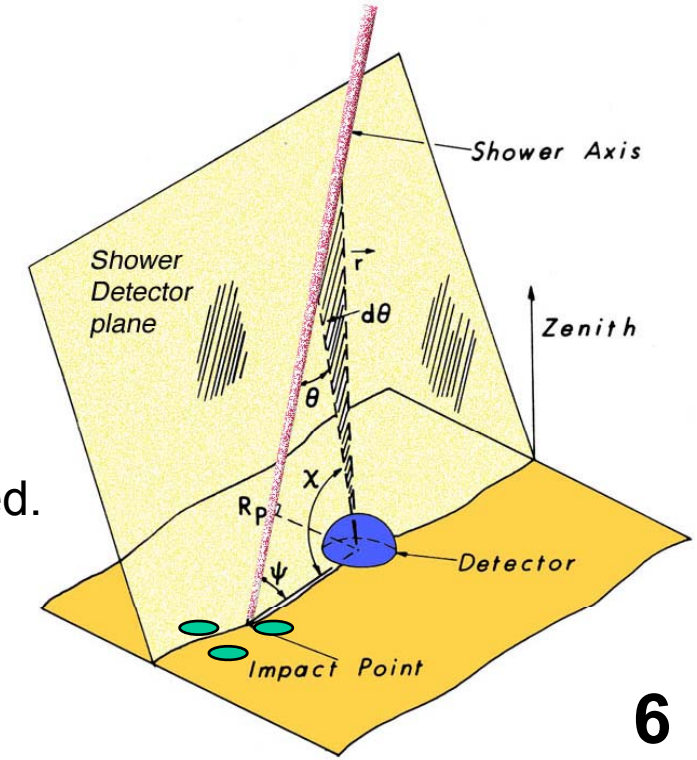
	hybrid	SD only	FD only
angular resolution	0.2°	1-2°	3-5°
aperture	independent of E, mass, models	independent of E, mass, models	dependent of E, mass, models and spectral slope
energy	~ independent of mass, models	dependent of mass, models	independent of mass, models

Most events are detected only with the SD (~ 100% duty cycle).

~ 10% of hybrid events (detected with both the SD and the FD).

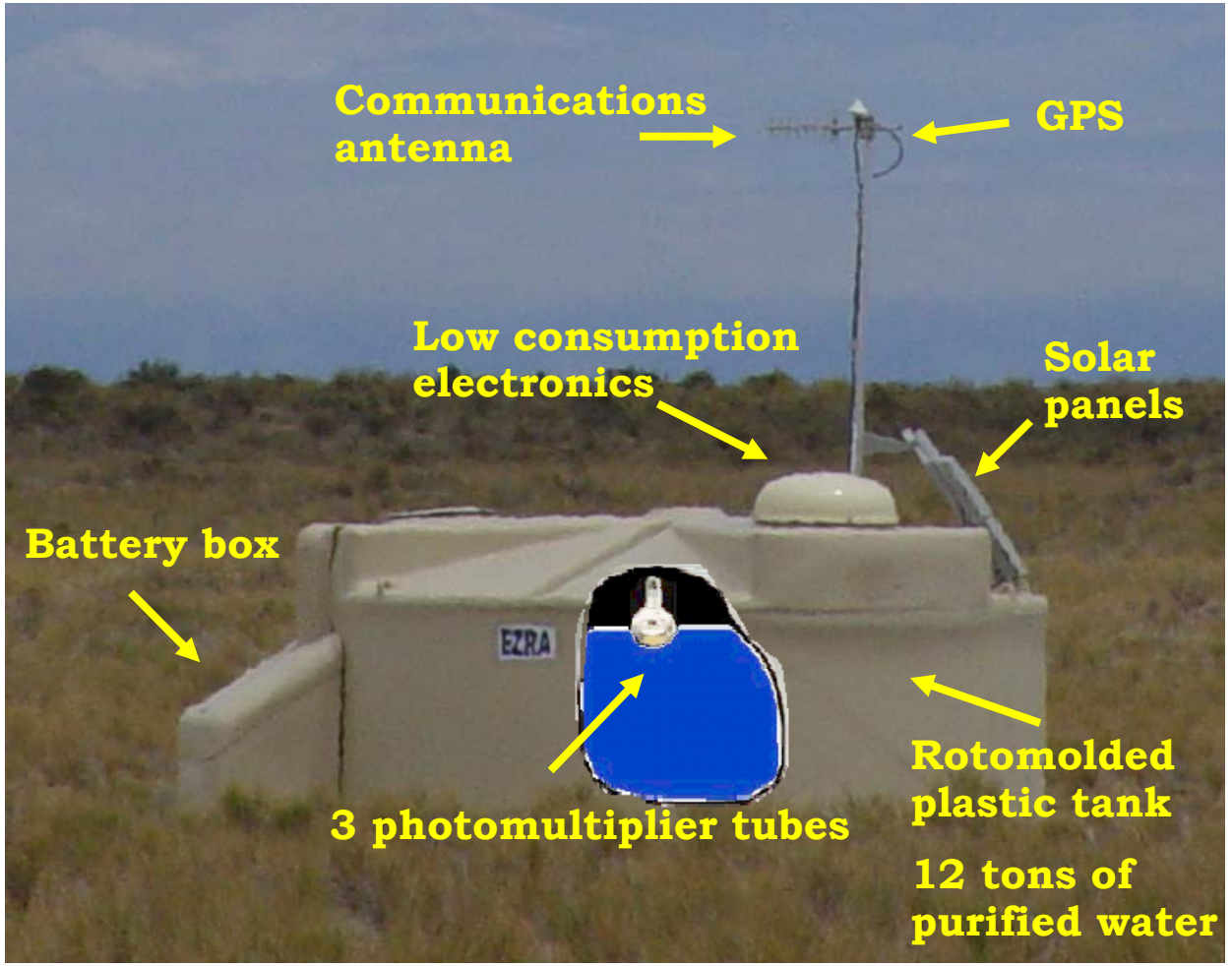
Using hybrid events:

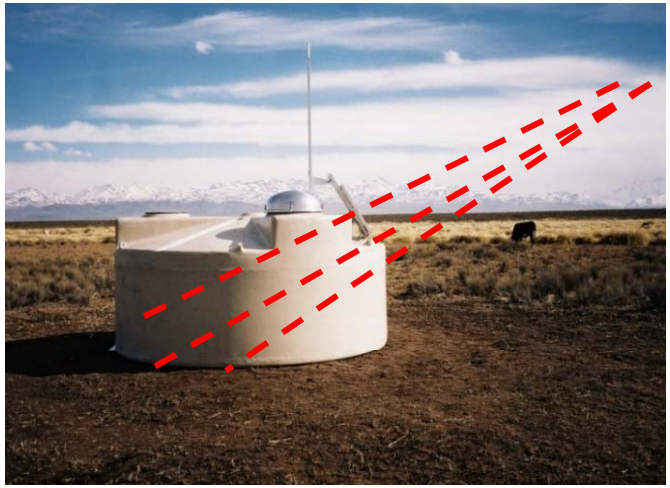
- ✓ **Angular reconstruction** of SD-only events can be fine-tuned.
- ✓ **Energy** of SD-only can be calibrated with hybrid events.
- ✓ X_{max} of shower can be related to surface-only observables



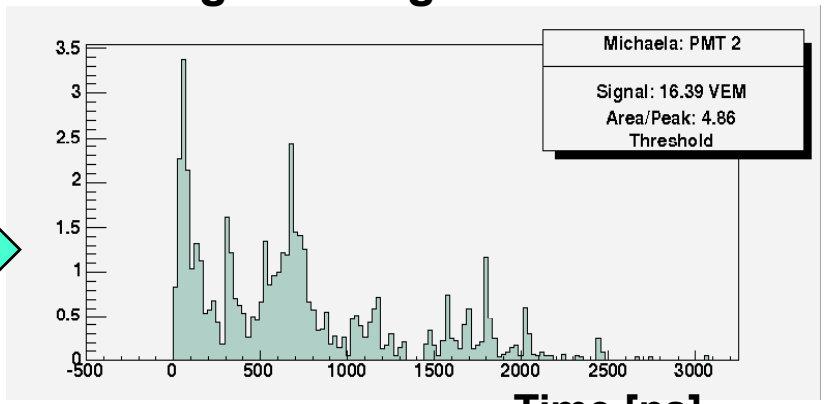
Surface detector unit

Calibrated online every few seconds using signals induced by atmospheric muons



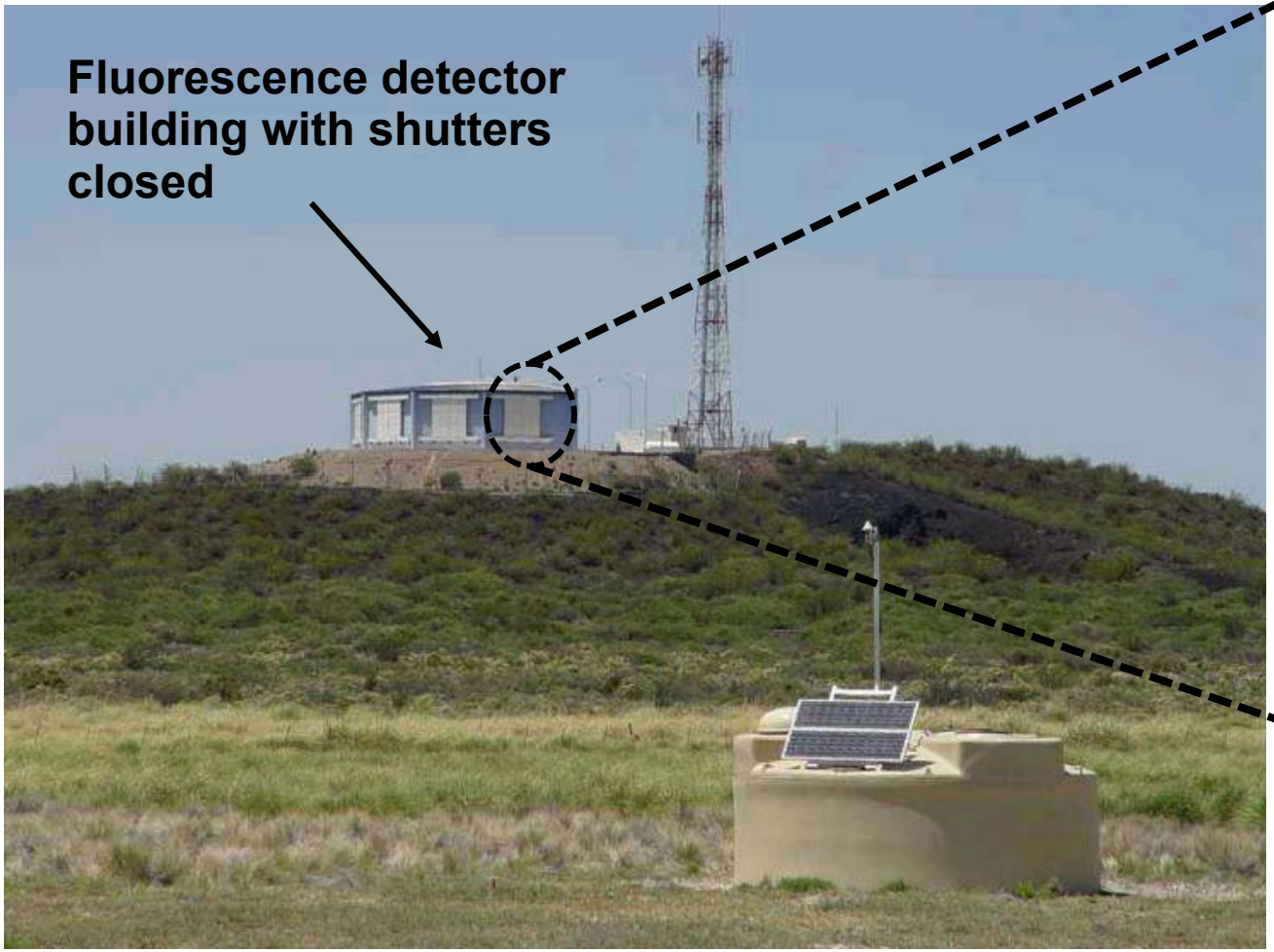


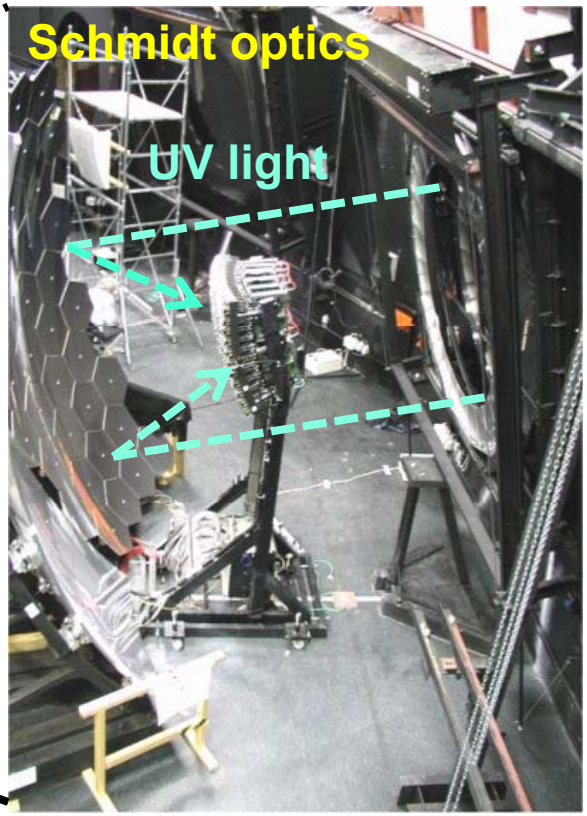
Digitised signals: FADC

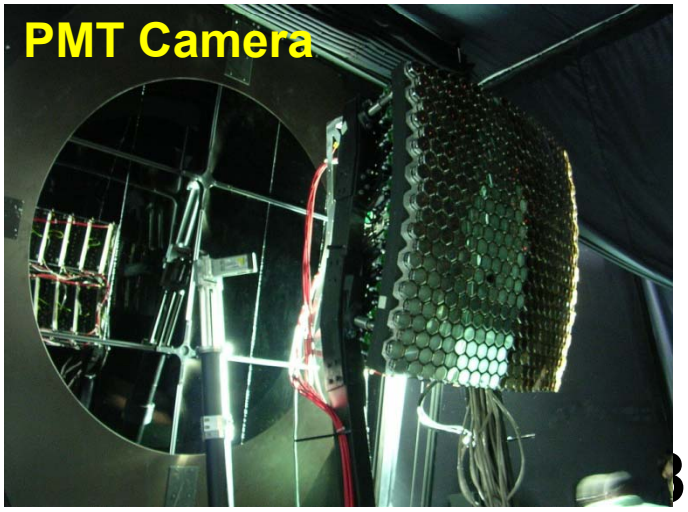


25 ns time resolution

Fluorescence telescope



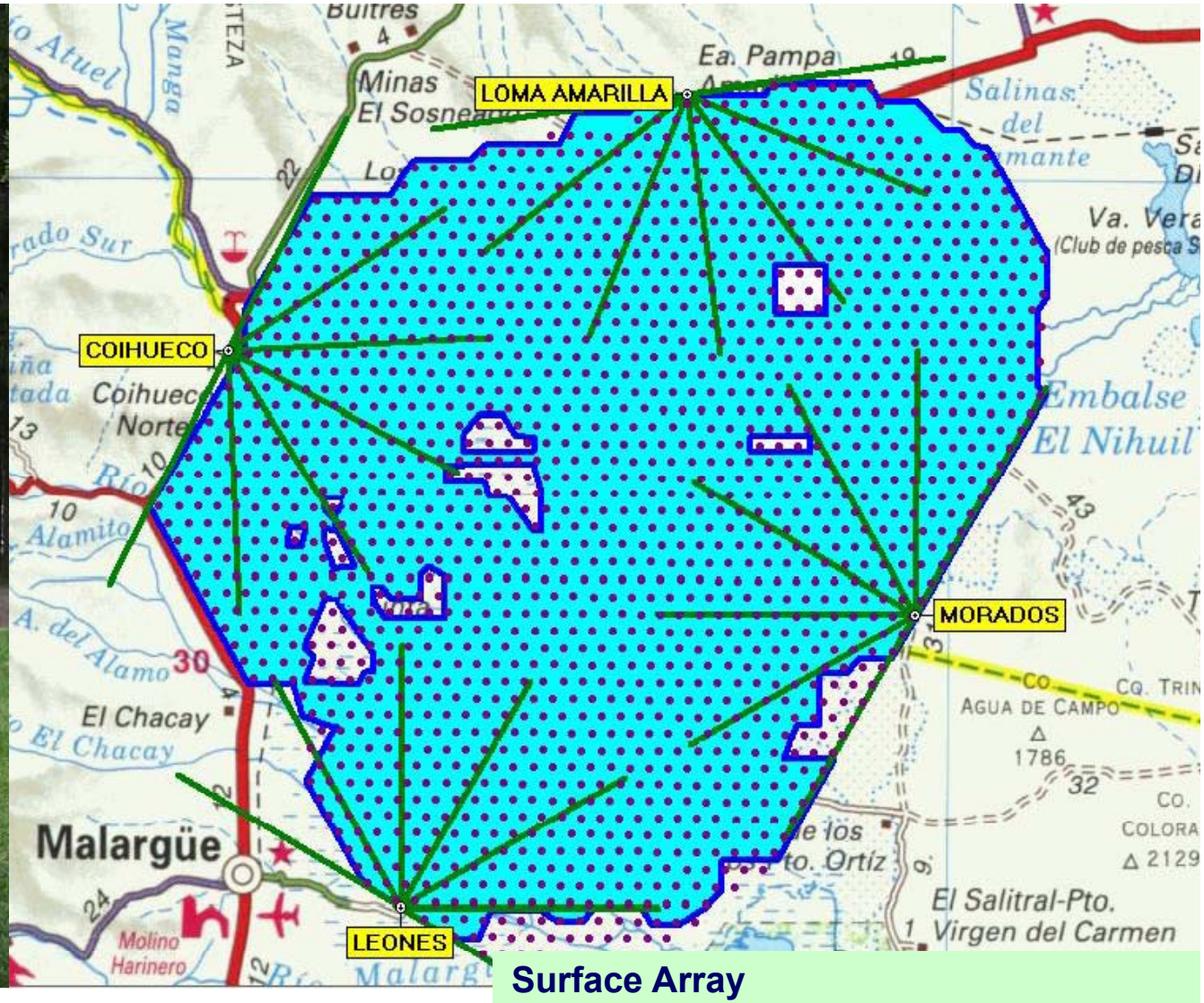




Each telescope observes a 30º x 30º patch of the sky

Pierre Auger Observatory: Status

June 11 2008



Watson/Cronin/Mantsch

Auger South Inauguration Celebration:
14-15 November 2008

Surface Array

1660 surface tanks deployed

1637 with water, 1603 totally equipped

Fluorescence Detector

24 FD telescopes working and taking data

The Pierre Auger Collaboration

~ 400 Scientists from

~ 70 Institutions and 17 countries

Objectives, aims, questions,…

Measure properties of UHECRs ($E > 10^{18}$ eV) with unprecedented statistics & accuracy

Energy spectrum:

Cutoff at the highest energies?

Nature of the UHECRs:

Is the UHECR flux proton-dominated ?, iron?, mixed composition ?

Are there any photons in the UHECR flux ?

Are there any neutrinos in the UHECR flux ?

Establish arrival directions of UHECR:

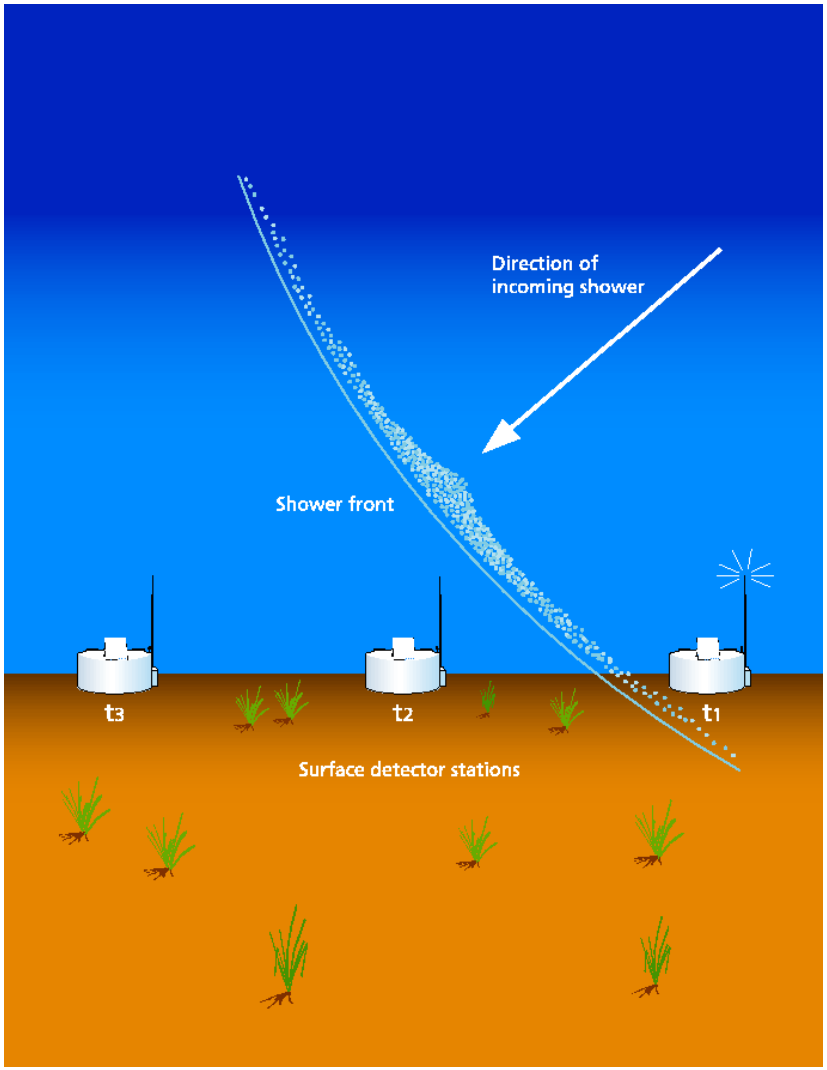
Is the UHECR flux isotropic ?

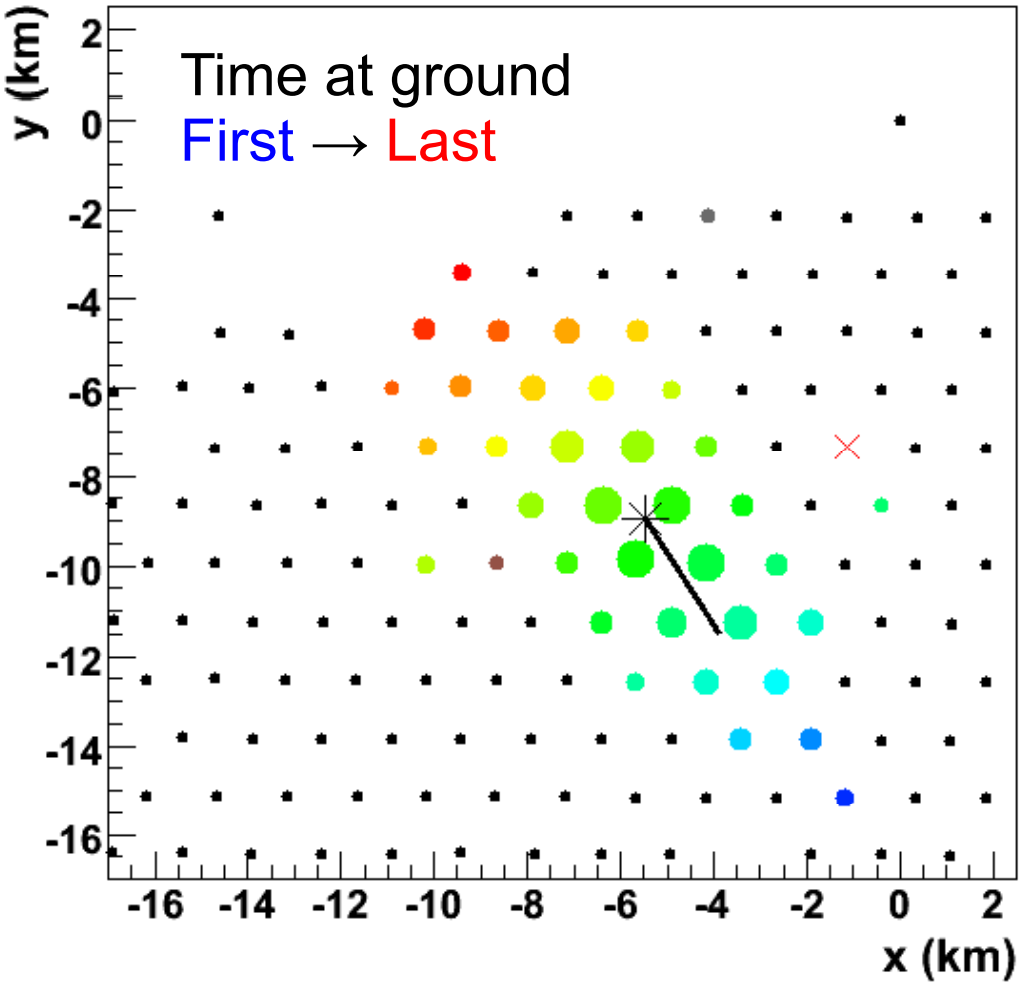
What are the sources of the UHECRs ?

Energy spectrum of UHECRs

Reconstruction of events: Arrival direction

Fit arrival times of shower particles at tanks to a curved front propagating at the speed of light.

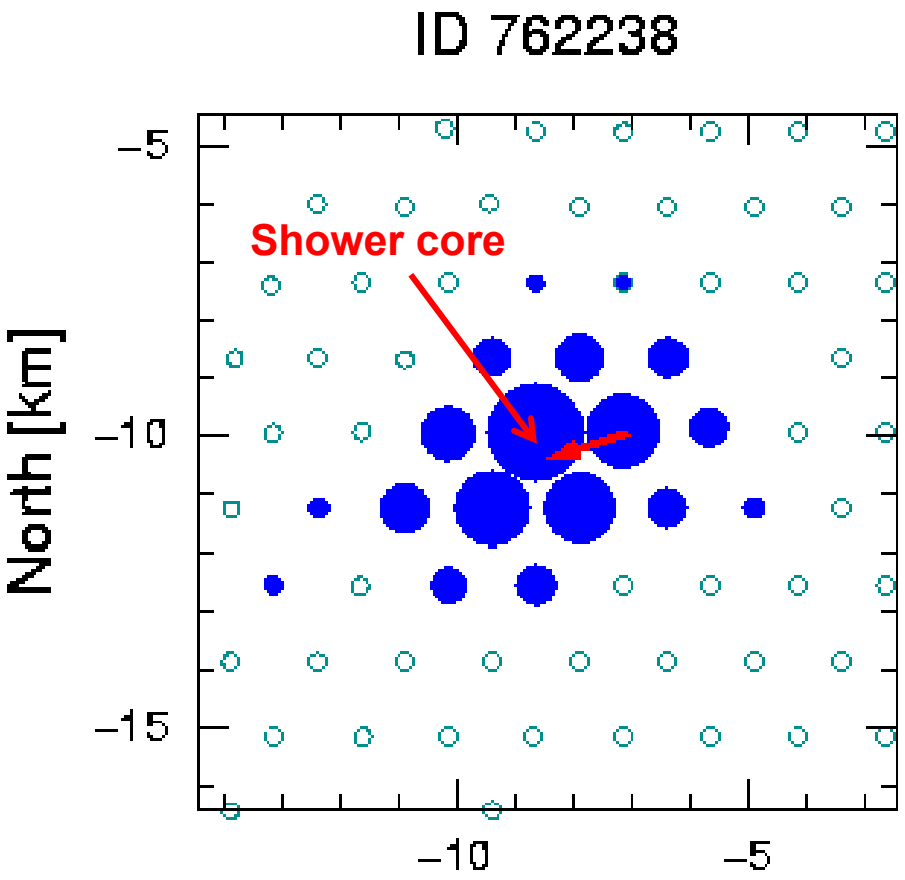




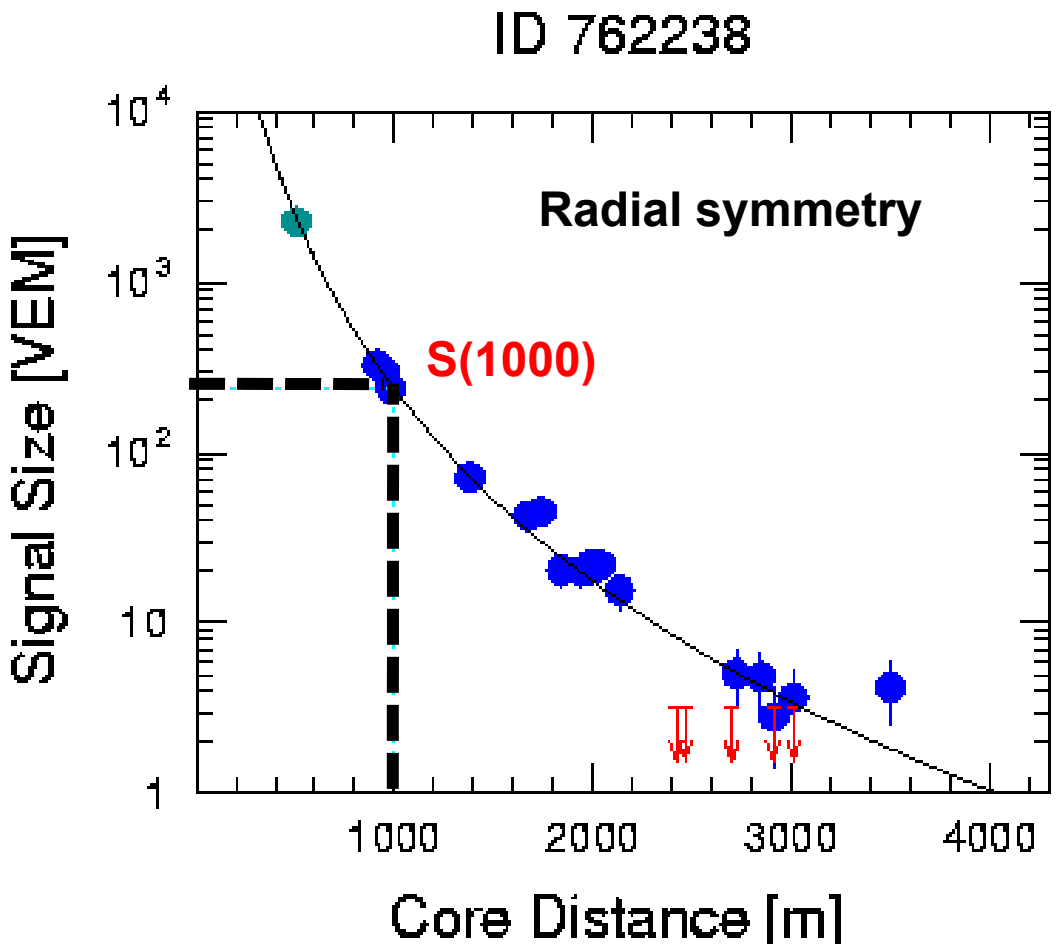
Angular reconstruction accuracy < 1º above 10^{19} eV

Reconstruction of “vertical” SD events θ < 60º

Footprint on the ground



Lateral signal distribution



Energy estimator:

S(1000) = signal at 1000 m from the core of the shower.

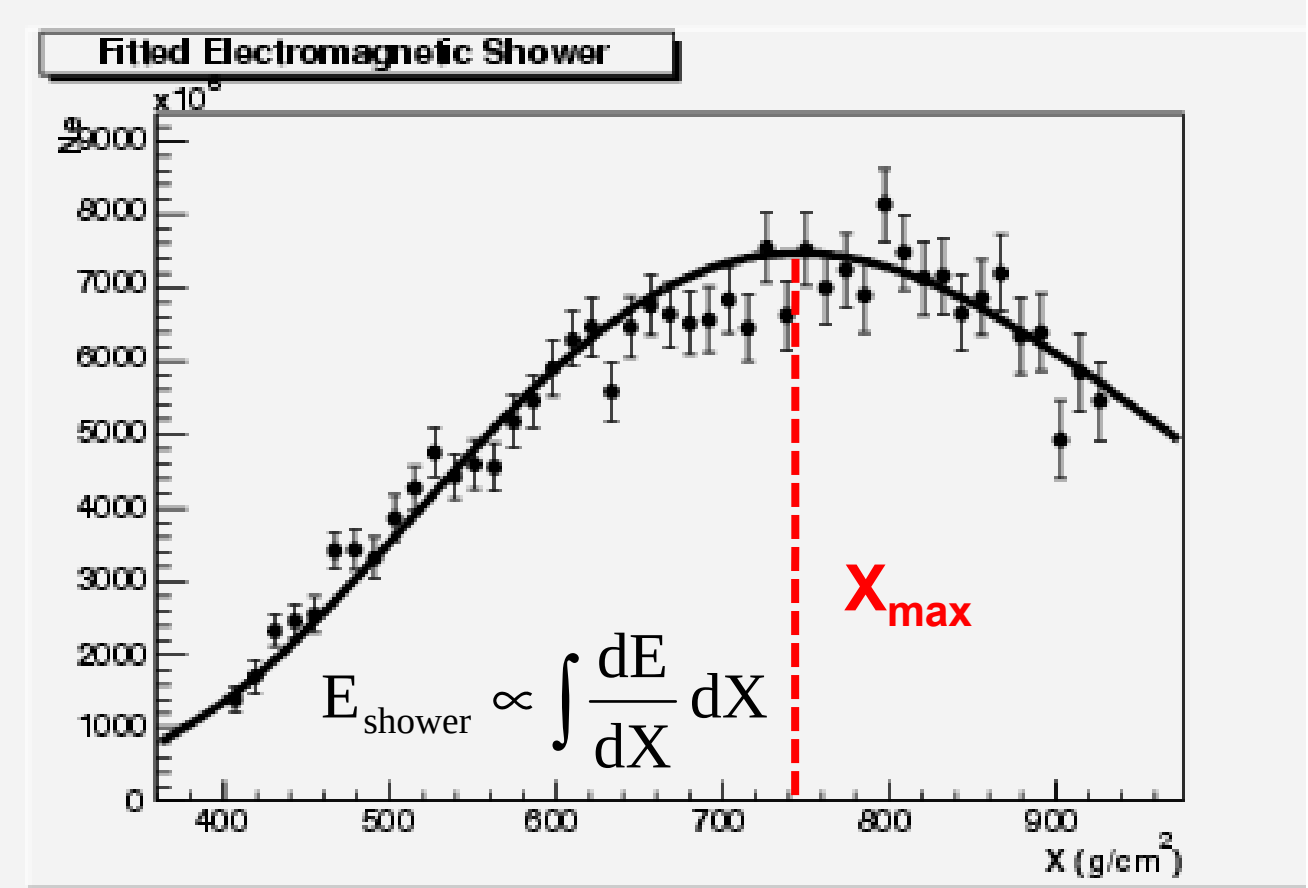
Event with θ ~ 48º & E ~ 70 EeV

Energy calibration of S(1000): hybrid events

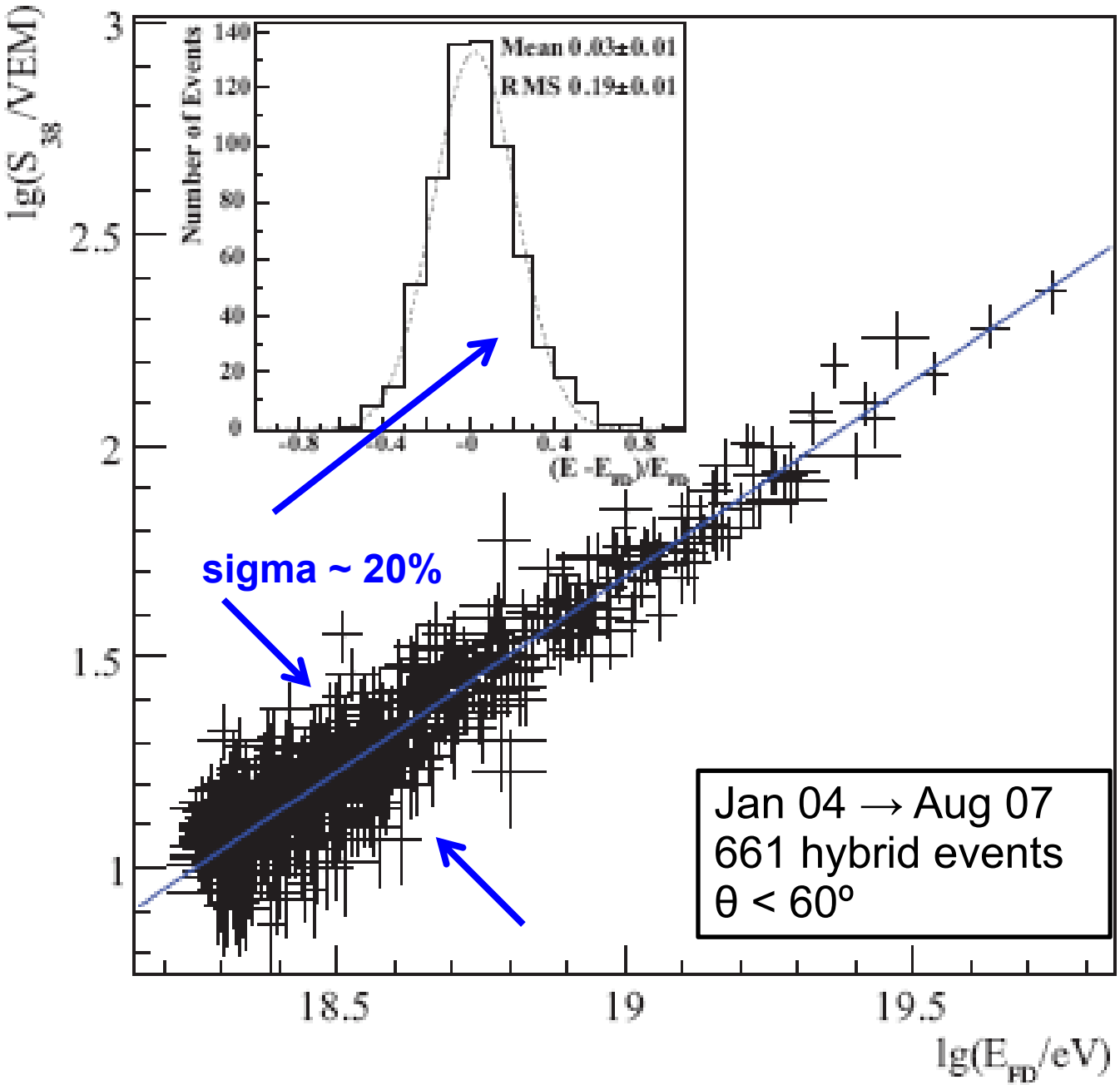
Energy reconstruction with the fluorescence detector

- Measured dE/dX vs X (shower longitudinal profile proportional to fluorescence light collected) fitted to a “Gaisser-Hillas” function.
- Shower E ~ $\int$dX (dE/dX): near-**calorimetric** measurement

  weakly dependent on hadronic model & composition (~ 5%).



Energy calibration of S(1000)



Linear correlation between E_{FD} and S(1000)

Energy scale determined with hybrid events:

~ 20% E resolution.

Extrapolate calibration to events observed with the Surface Detector only

Minimises Monte Carlo and mass composition dependence

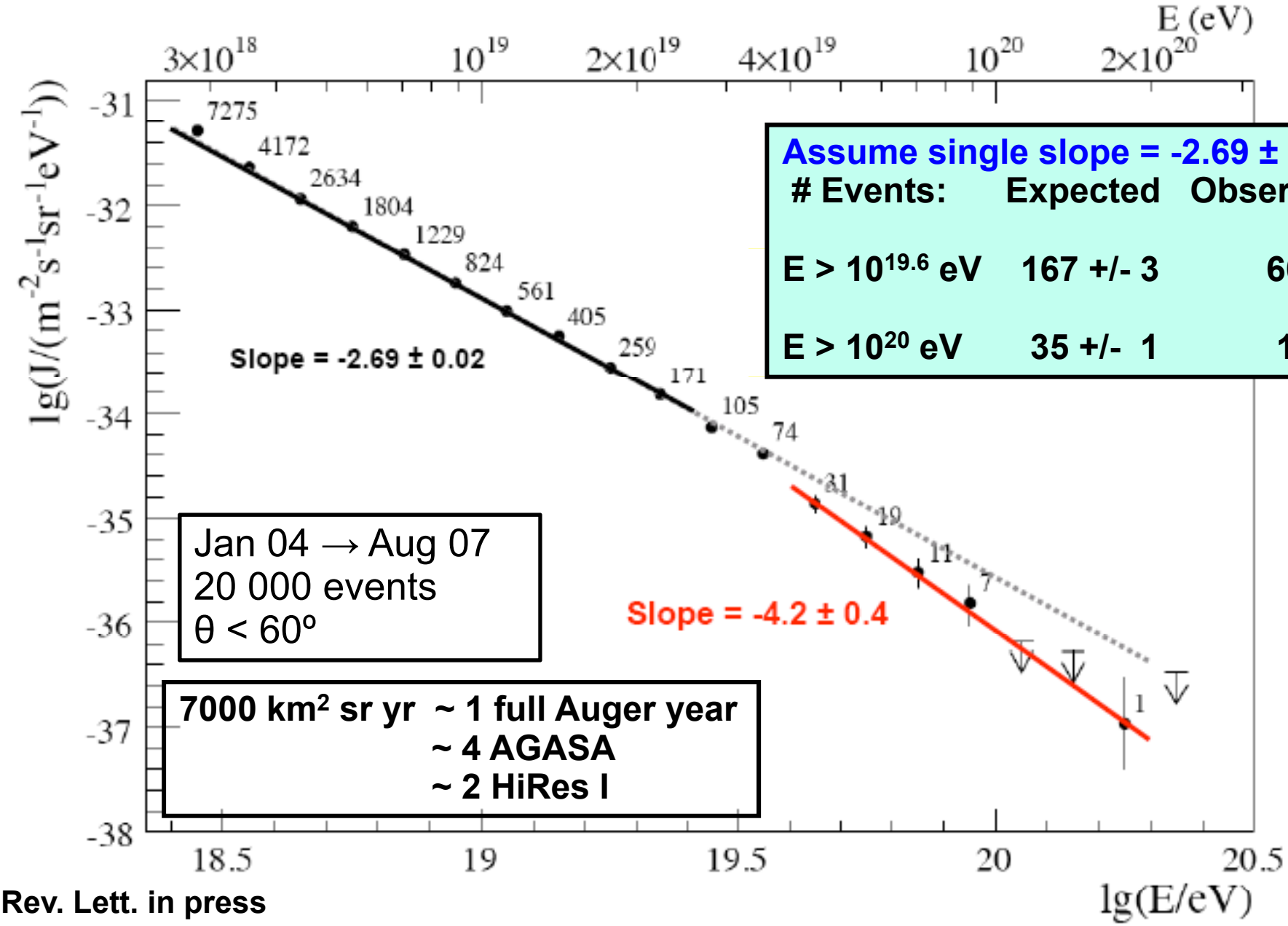
Systematic Uncertainties

Fluorescence Detector Uncertainties Dominate

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

Activity on several fronts (yield, calibration, …) to reduce uncertainties

Energy spectrum SD events (θ < 60°)



Assume single slope = -2.69 ± 0.02

# Events:	Expected	Observed
E > $10^{19.6}$ eV	167 +/- 3	66
E > 10^{20} eV	35 +/- 1	1

Jan 04 → Aug 07
20 000 events
θ < 60°

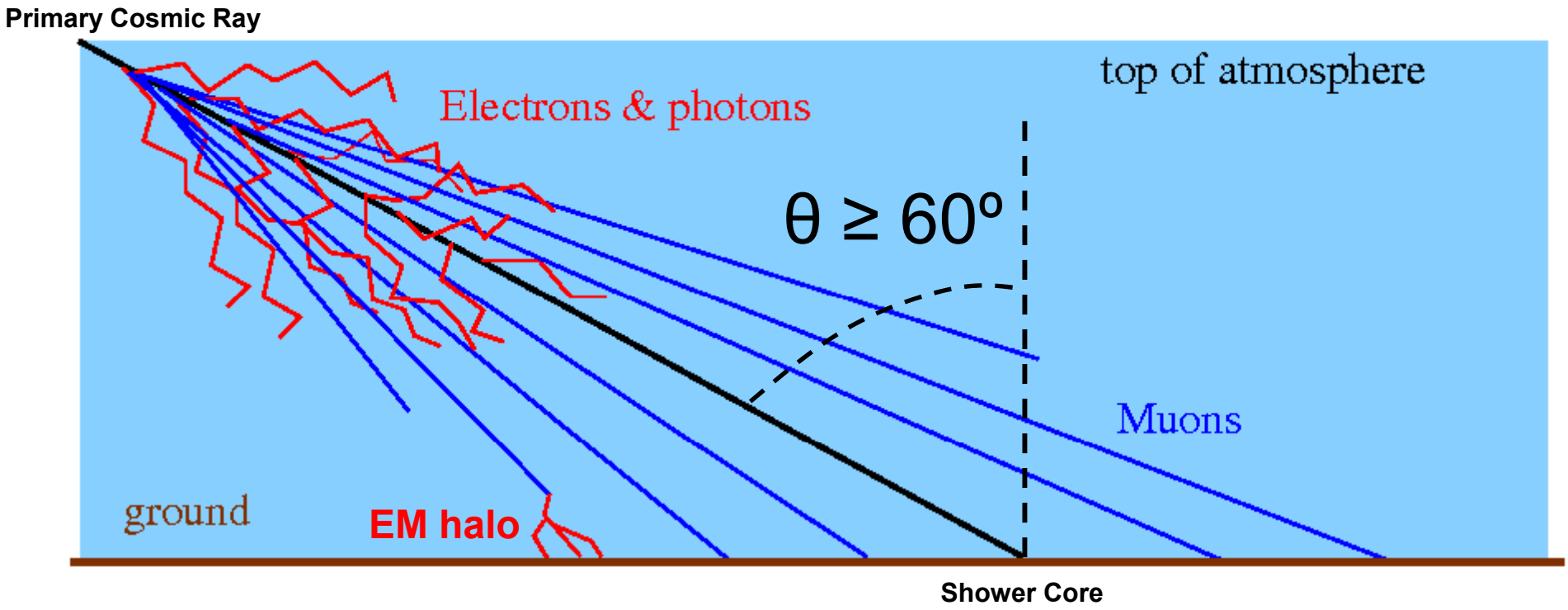
7000 km² sr yr ~ 1 full Auger year
~ 4 AGASA
~ 2 HiRes I

Phys. Rev. Lett. in press

Suppression of the spectrum above ~ 4 x 10^{19} eV @ 6 σ: GZK?

Spectrum with Inclined Air Showers

Inclined Air Showers



- Electromagnetic (EM) component absorbed in the atmosphere: only muons survive. Small EM halo (~ 15 %) mainly due to muon decay close to the ground.
- Muons travel large distances and are deflected by the magnetic field of the Earth.

WHY STUDYING INCLINED SHOWERS?

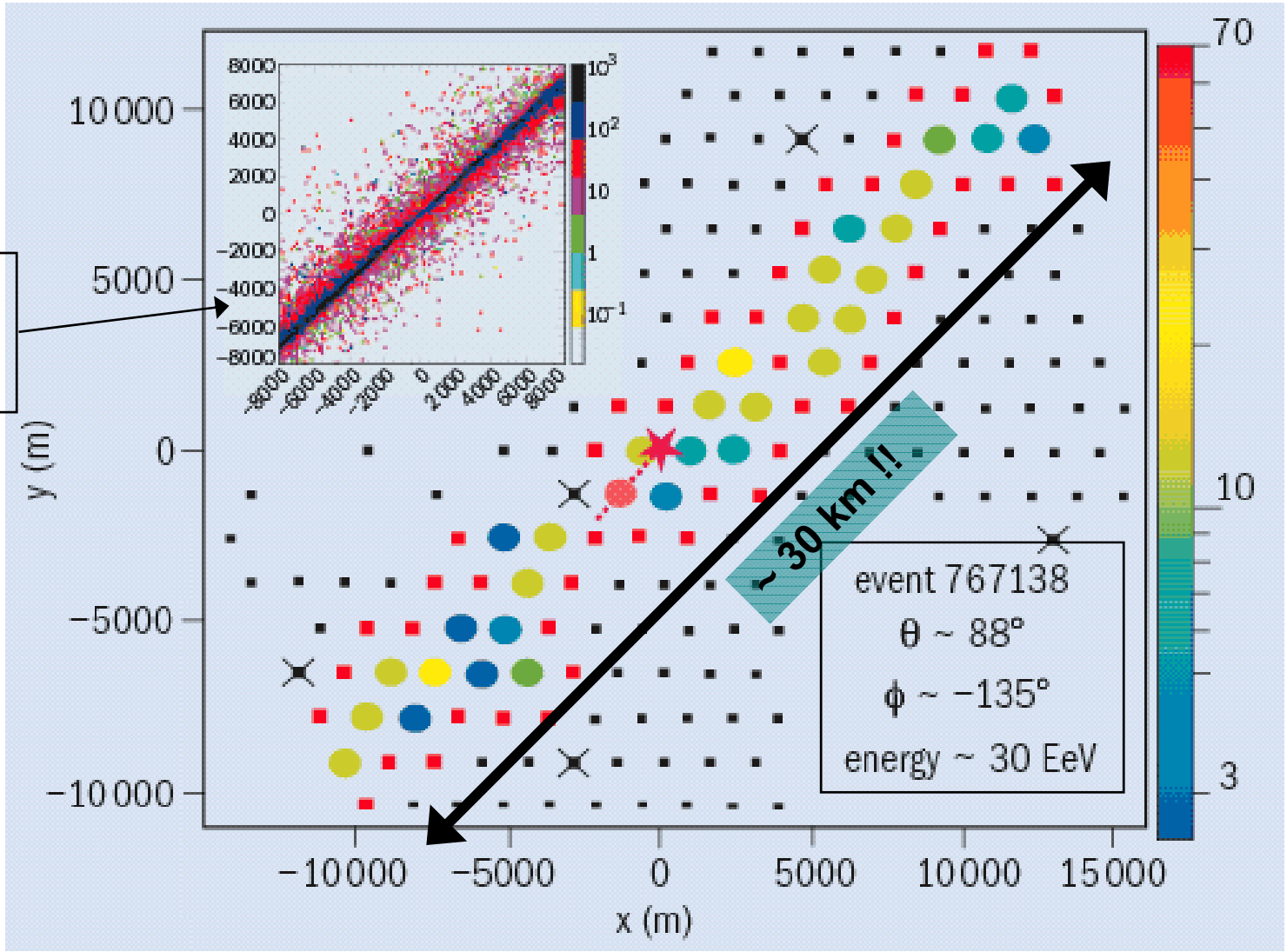
(1) Extend exposure (by ~ 30%) and sky coverage of the Pierre Auger Observatory.

(2) Enhanced sensitivity to UHE neutrinos.

A (beautiful) example

CERN Courier
July 25 2006

MC simulation of event with the same angle and energy.



Ricardo A. Vázquez

2-lobed footprint on the ground due to muon deflection by the geomagnetic field

Reconstruction of inclined air showers: why a dedicated analysis?

Footprint on the ground

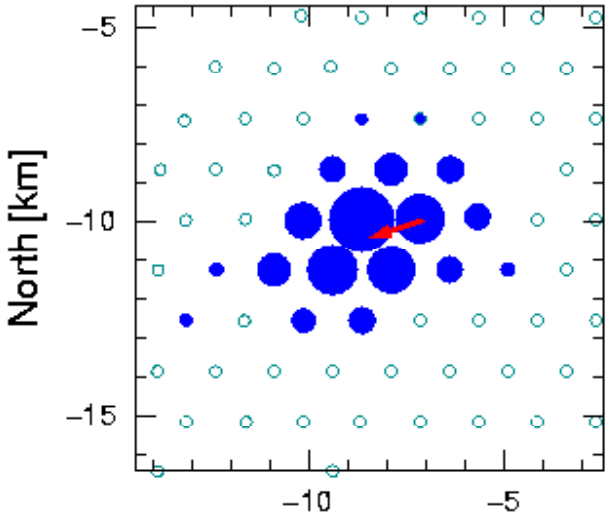
Radial symmetry

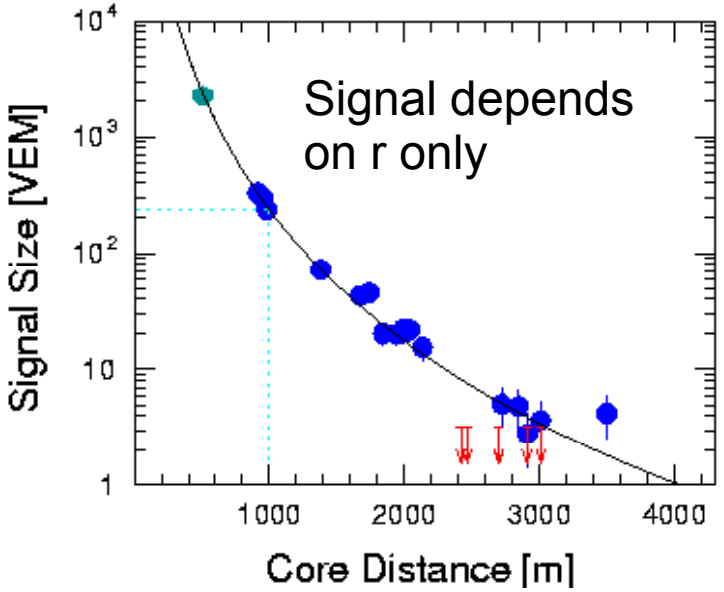
Lateral density distribution

Vertical event

ID 762238

θ ~ 48°





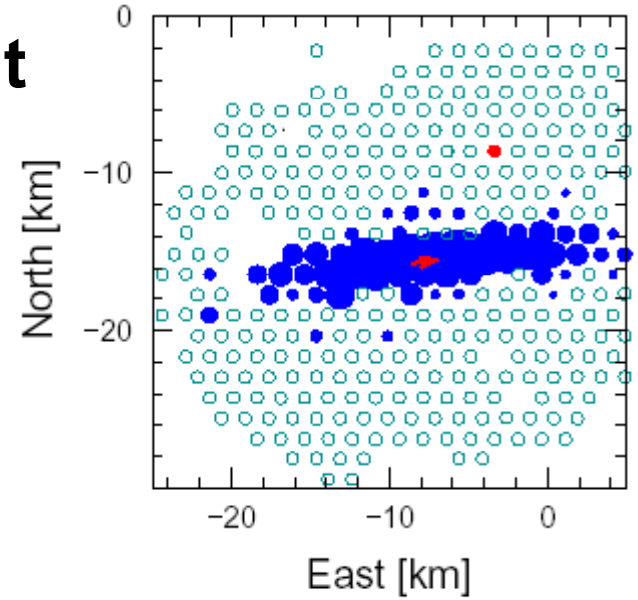
Broken radial symmetry due to muon deflection

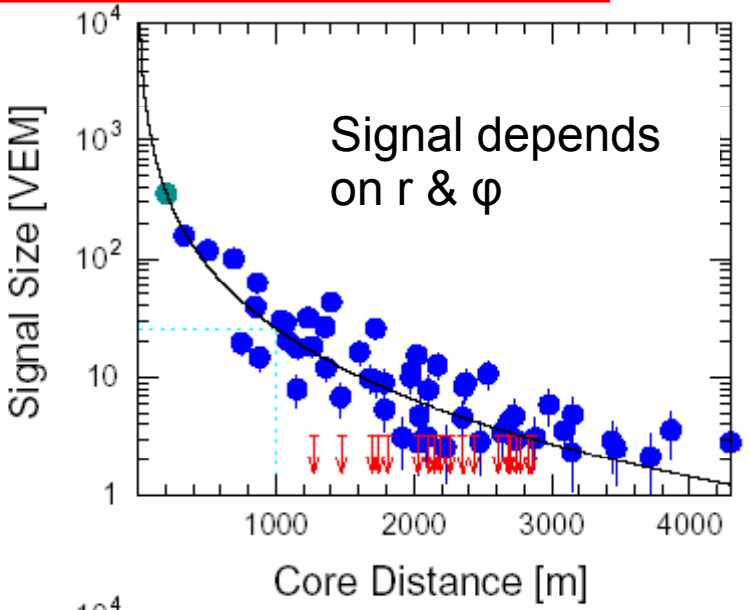
Inclined event

ID 856369

θ ~ 79°

55 tanks triggered



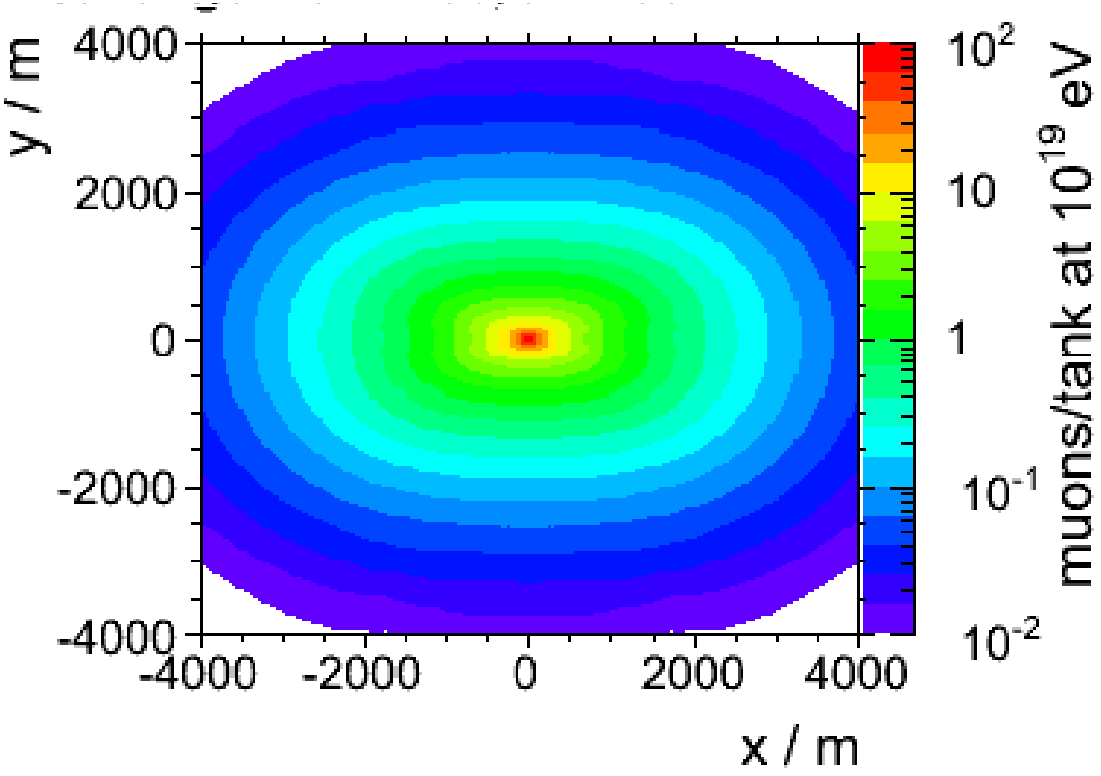


Energy reconstruction of inclined showers

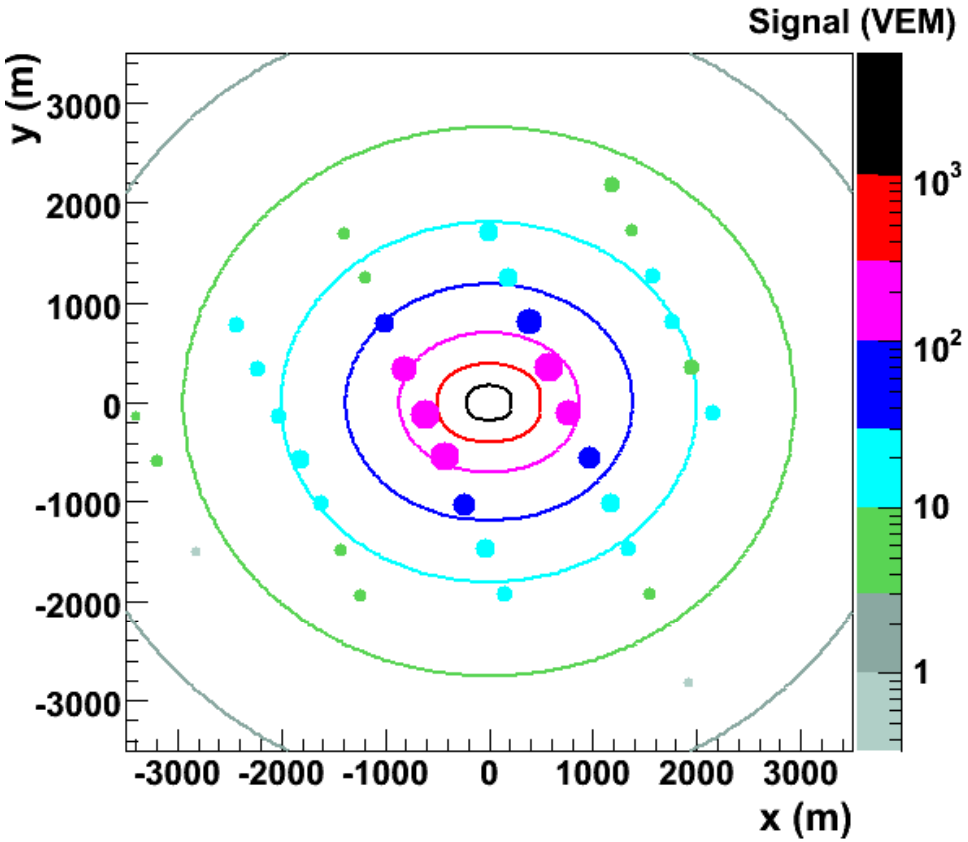
Broken radial symmetry → 2-Dimensional (r, φ) "lateral" distribution.

Simulated μ map

Shape of μ map weakly dependent on Energy, Mass & Hadronic model

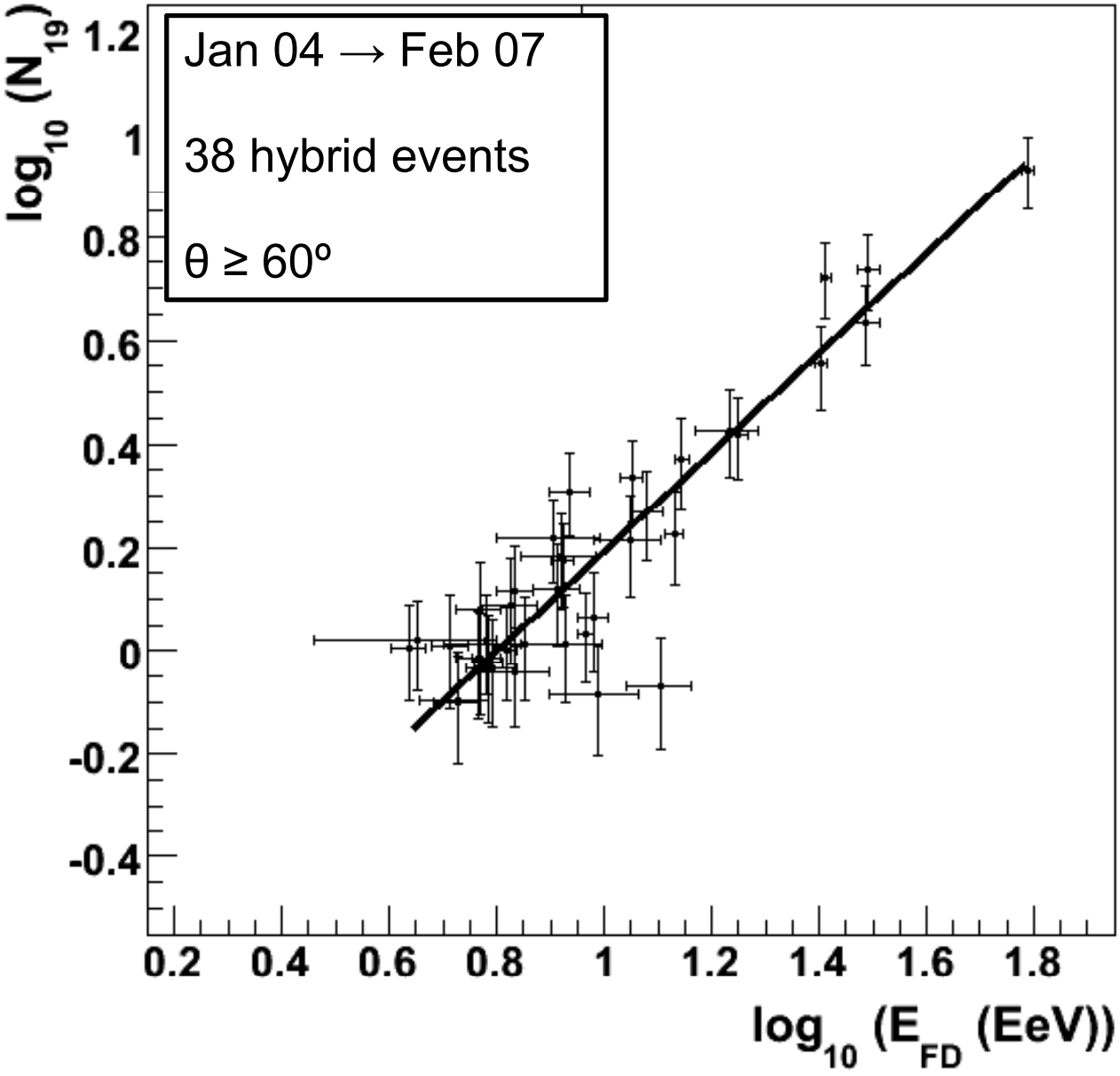


Observed signals



→ **Simulated μ map fitted to observed signals, 1 parameter the muon map normalization (N_{19}) energy estimator**

Energy calibration of N_{19}: use hybrid events (again)



Linear correlation between E_{FD} and N_{19}

Energy scale determined with hybrid events:

~ 20% energy resolution.

Extrapolate calibration to events observed with the Surface Detector only

Minimises model and mass composition dependence

Energy spectrum SD events (θ ≥ 60°)

Pierre Auger Collaboration

ICRC 2007

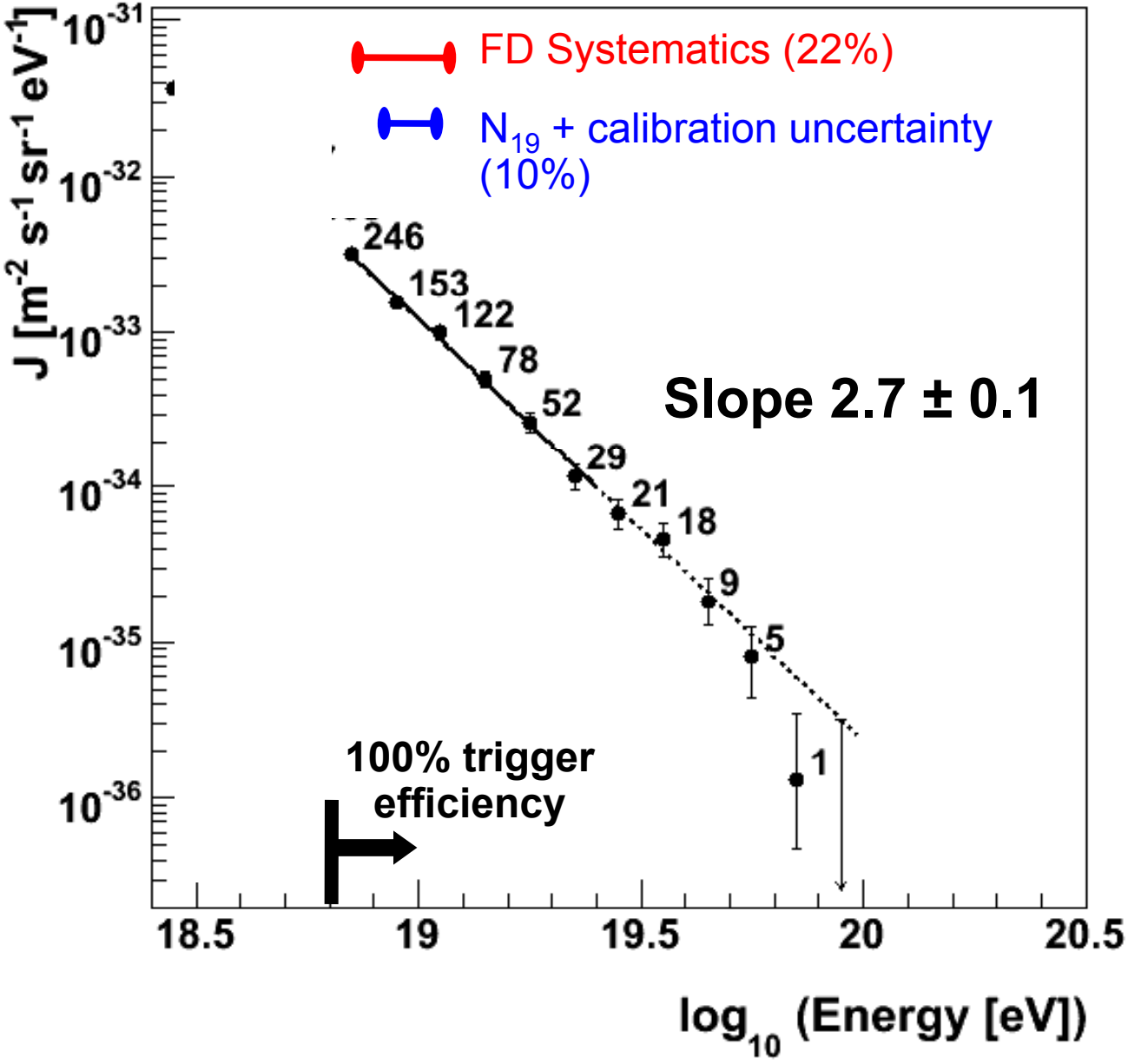
Jan 04 → Feb 07

734 events

θ ϵ [60º, 80º]

Integrated exposure

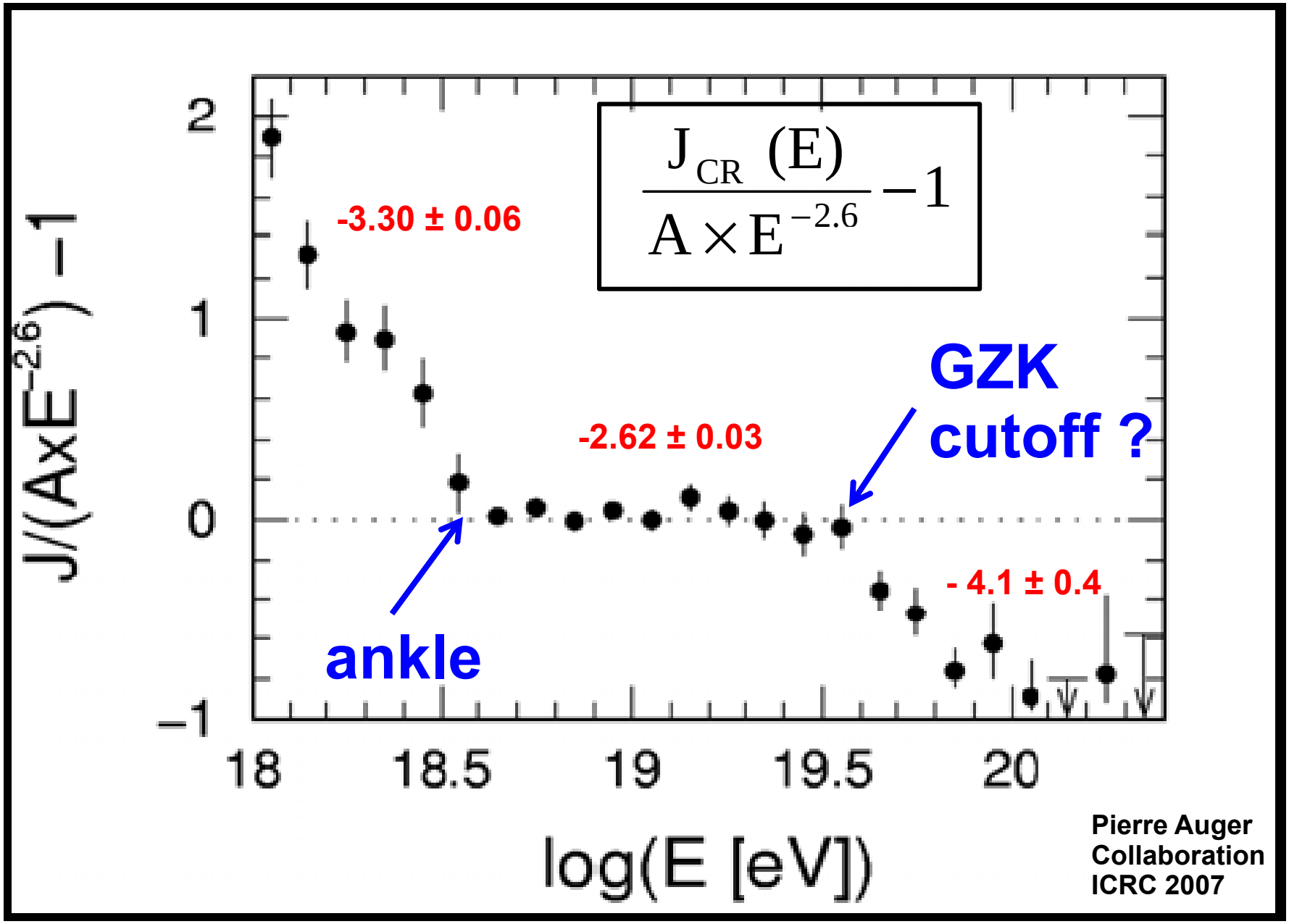
1510 km² sr yr



1st UHECR spectrum ever measured with inclined showers

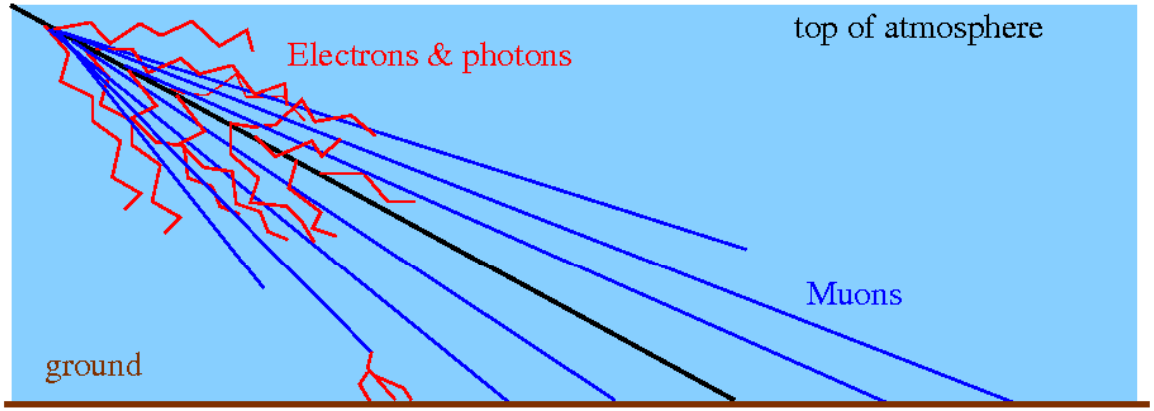
Consistent with spectra from vertical showers < 60º

Residuals w.r.t. a “standard” spectrum

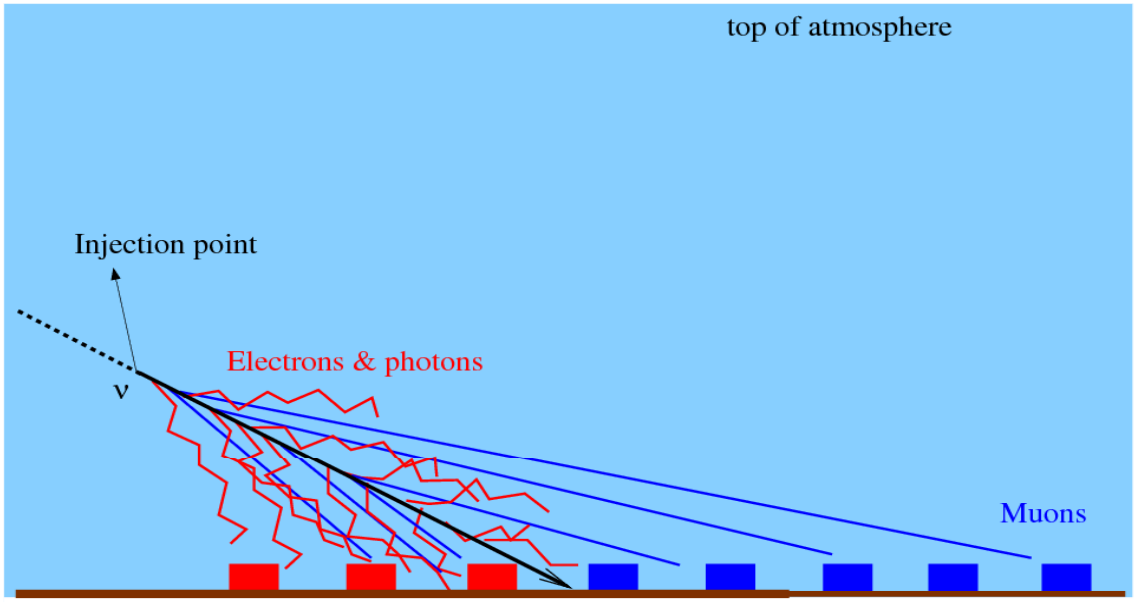


Neutrinos

Inclined showers & Neutrino search



Inclined showers induced by protons or nuclei high in the atmosphere are composed (mainly) of muons at ground.



Deeply penetrating particles such as neutrinos, induce inclined showers exhibiting a significant electromagnetic component at ground.

Search for inclined showers with a significant electromag. component at ground

Earth-skimming ν_τ

↓ ν_τ production in astrophysical sources disfavoured…

↑ …however, after travelling over cosmological distances:

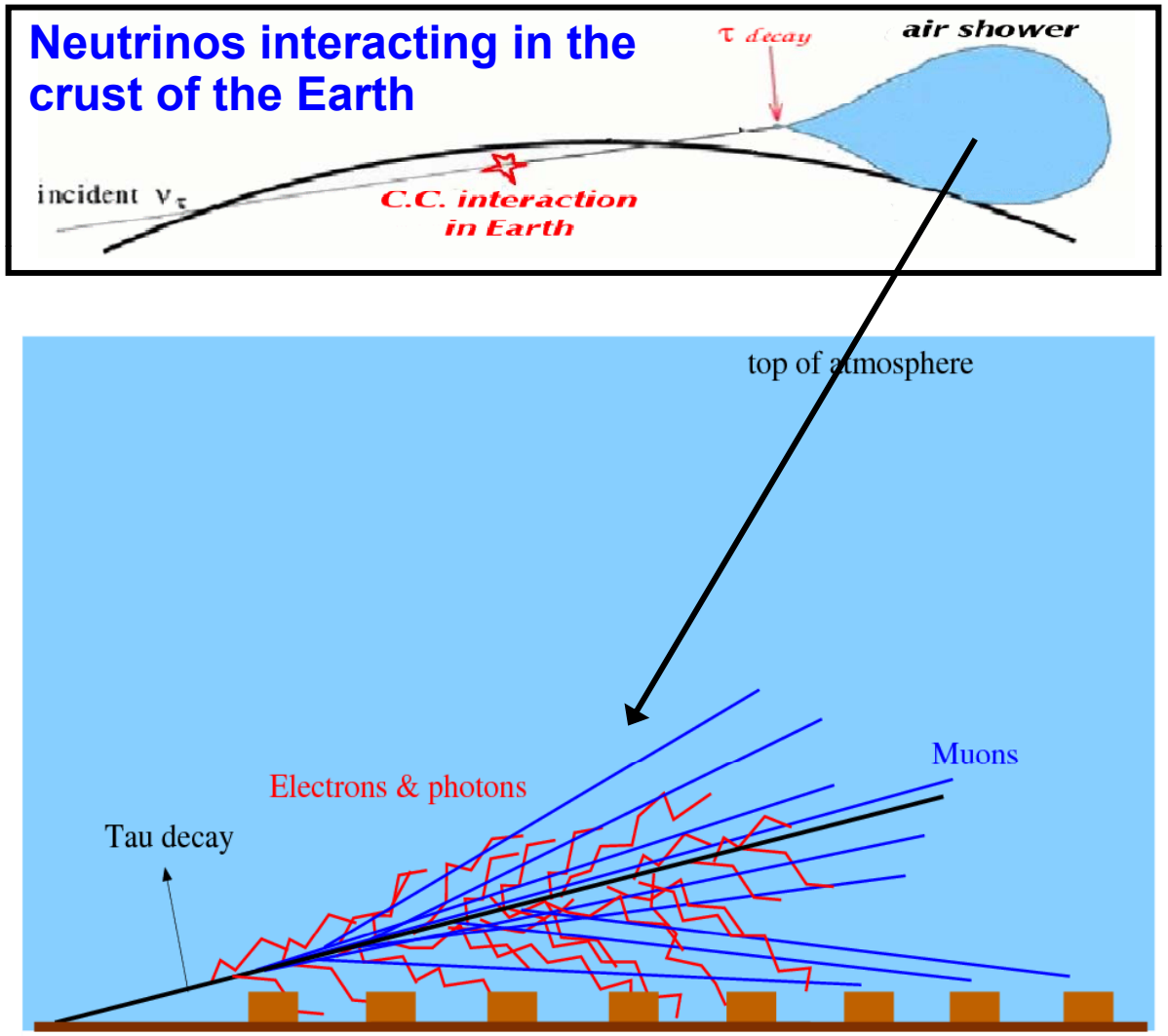
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

↑ τ_s travel large distances in the Earth without losing too much energy before decaying close to the detector.

↑ ↓ Sensitivity to ν_τ CC channel

↓ Small solid angle (few deg.)

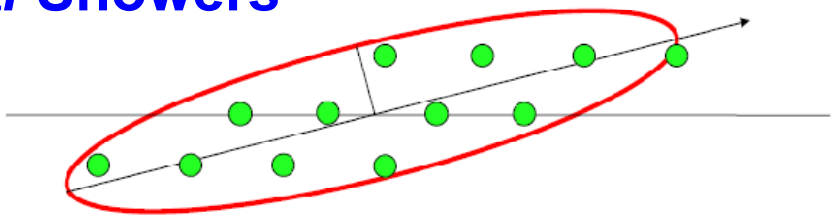
↑ Dense mass target (Earth crust)



Signature: almost horizontal shower with a significant EM content

Finding Earth-skimming ν_τ in data

~ *Horizontal* Showers



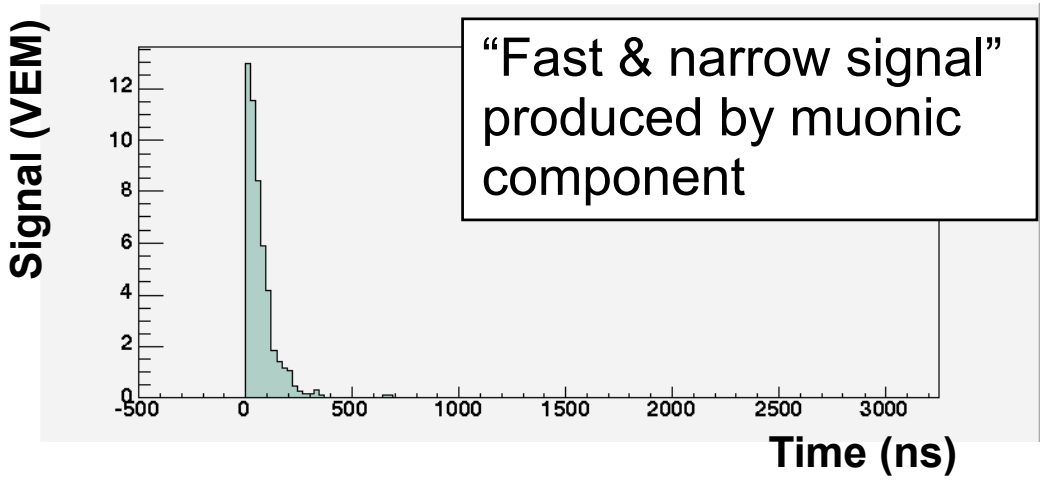
Phys. Rev. Lett. 100, 211101 (2008)

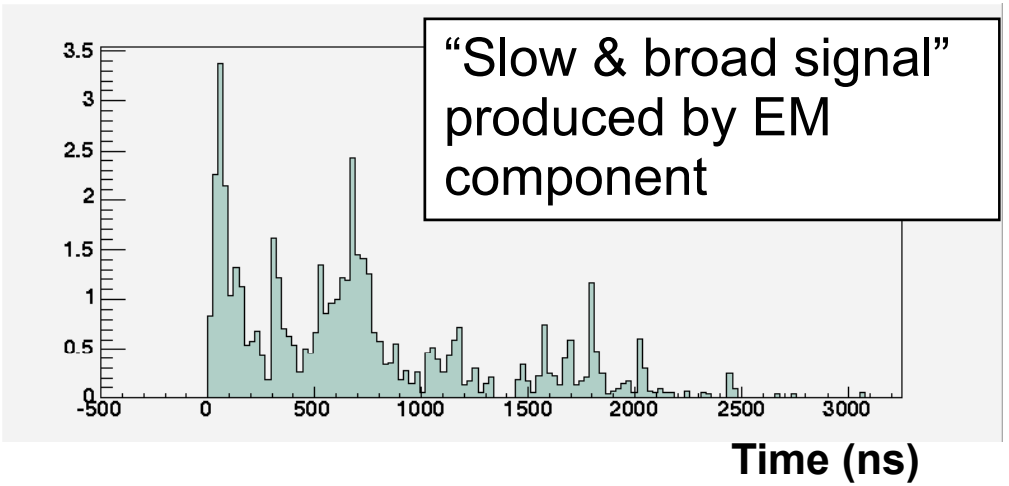
Footprint of the shower on ground compatible with a very inclined shower:

- **Shape (elongated pattern).**
- **"Speed of propagation of signal" along the footprint very close to speed of light.**

Showers with significant EM component

Most tanks have signals characteristic of electromagnetic showers

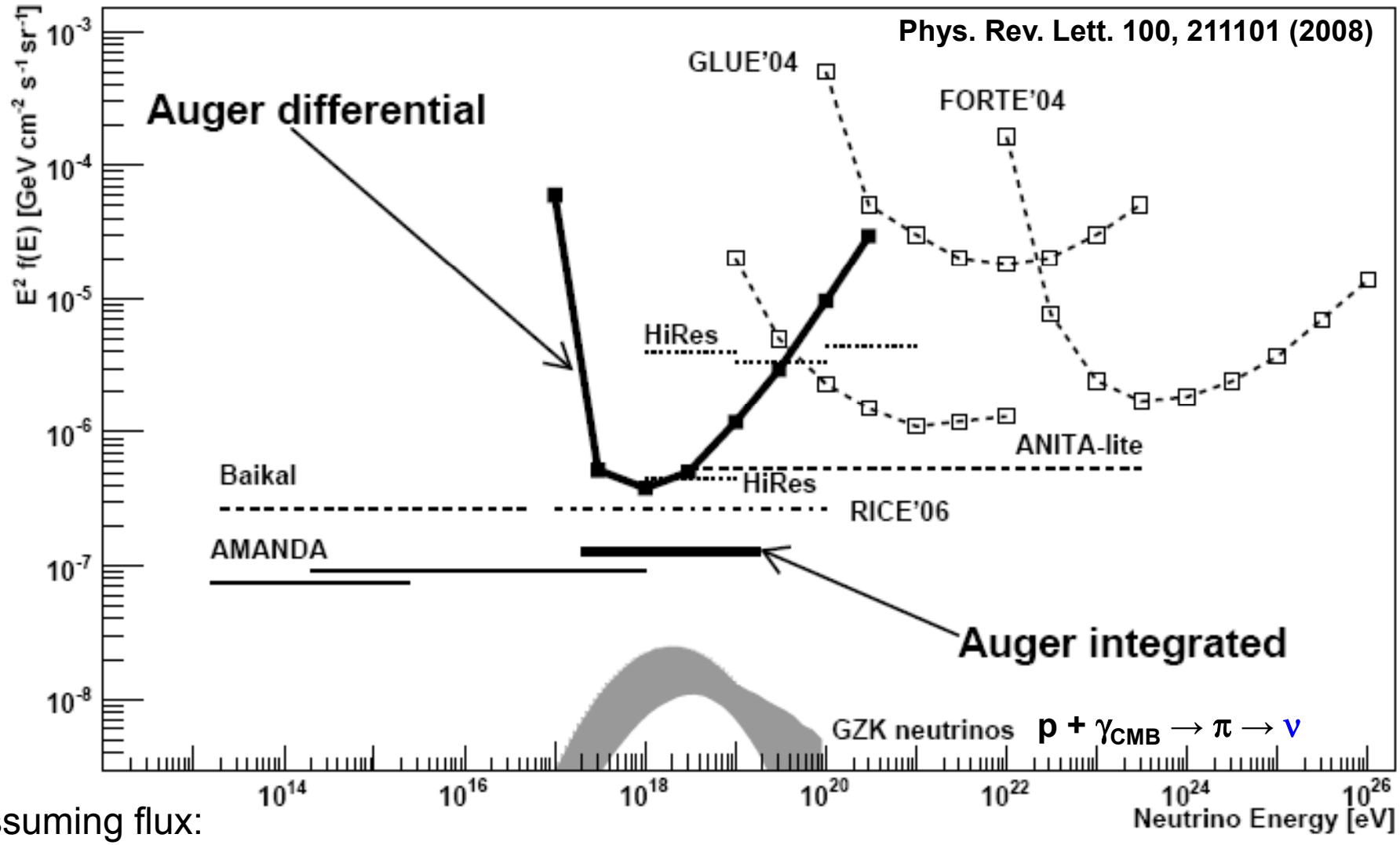




Jan 04 – Aug 07 → Zero candidates

(~ 80% identification efficiency)

Upper limit to the diffuse flux of UHE ν_τ



Assuming flux:

$$\frac{dN_{\nu_\tau}}{dE} = KE^{-2}$$

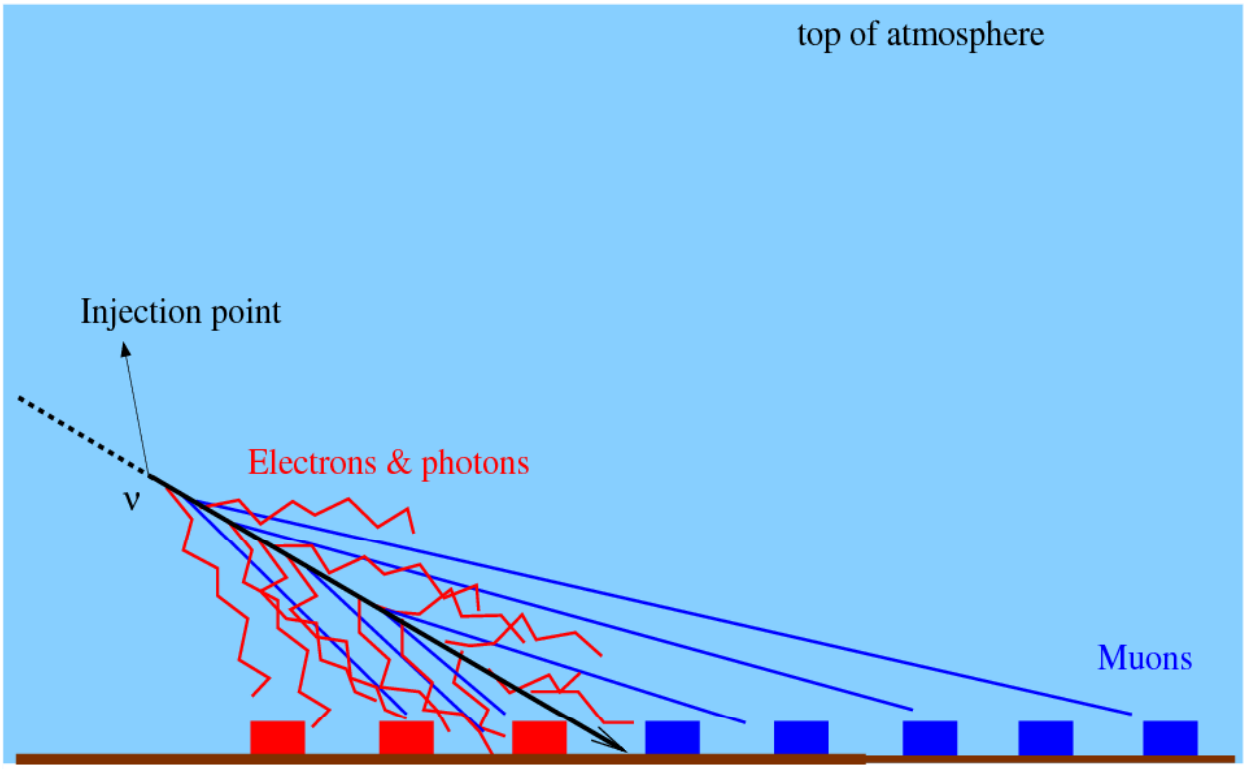
K = 1.3 x 10^{-7} GeV cm^{-2} s^{-1} sr^{-1} (90% C.L.) Jan 04 – Aug 07

Conservative: worst-case for systematic uncertainties in the acceptance.

“Down-going” ν

Neutrinos interacting deep in the atmosphere

- ↑ **Sensitivity to ALL ν flavours**
- ↑ **Sensitivity to ALL weak interaction channels CC & NC**
- ↑ **Large solid angle: 60º → ~ 90º**
- ↓ **Dilute mass target (air)**



“Early” region **“Late” region**

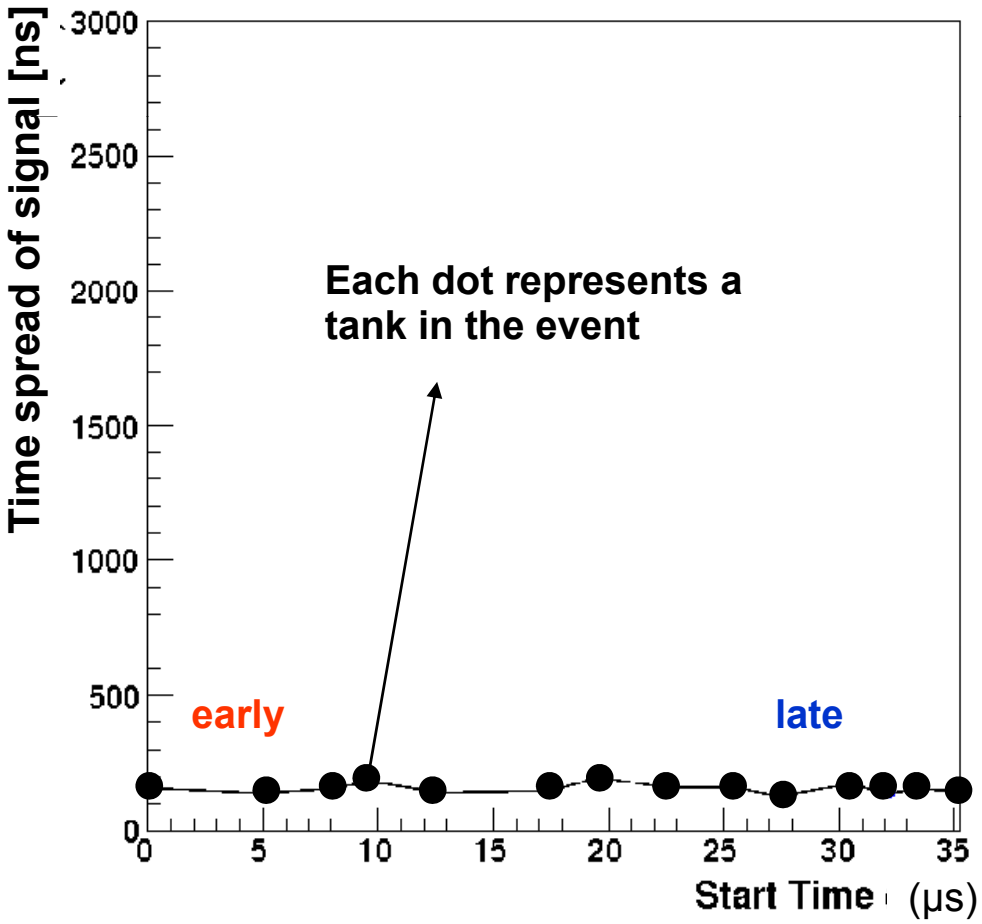
Signature: inclined showers with significant EM content, mainly in the “early” part of the shower.

(work in progress)

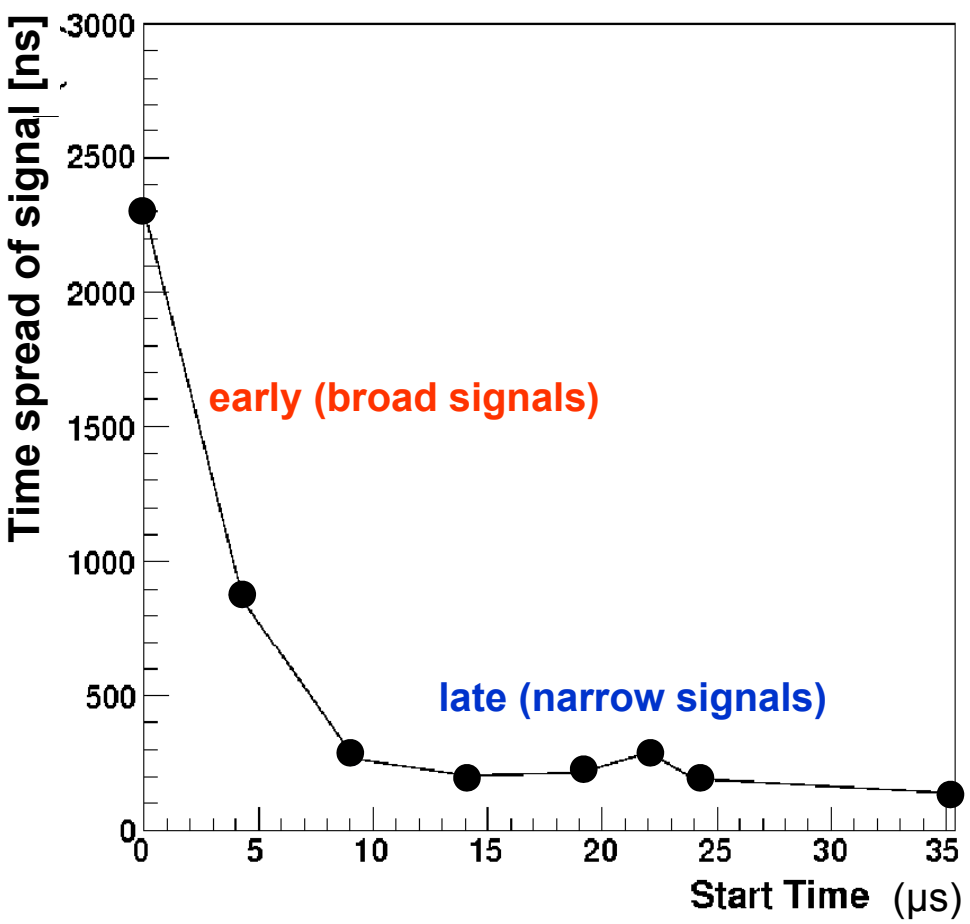
Inclined real event vs. simulation of ν deep shower

Time spread of the signal vs. start time of each station in event

Example of a real inclined event



Example of a neutrino simulation



Attenuation of the EM component of the shower from the earliest to the latest station

CONCLUSIONS

Hybrid character & large size of the Auger Obs. allows measuring UHECR properties with unprecedented statistics & accuracy

Energy spectrum:

Cutoff at the highest energies ? → **clear evidence $E > 4 \times 10^{19}$ eV**

Ankle ? → **clear evidence $E \sim 4 \times 10^{18}$ eV**

Mass composition (nature of the UHECRs):

Protons ?, iron ? → **not proton-dominated at the highest energies**

Are there any photons in the UHECR flux ? → **< 2% above 10^{19} eV**

Are there any neutrinos ? → **no candidates: strong constraints**

Establish arrival directions of UHECR:

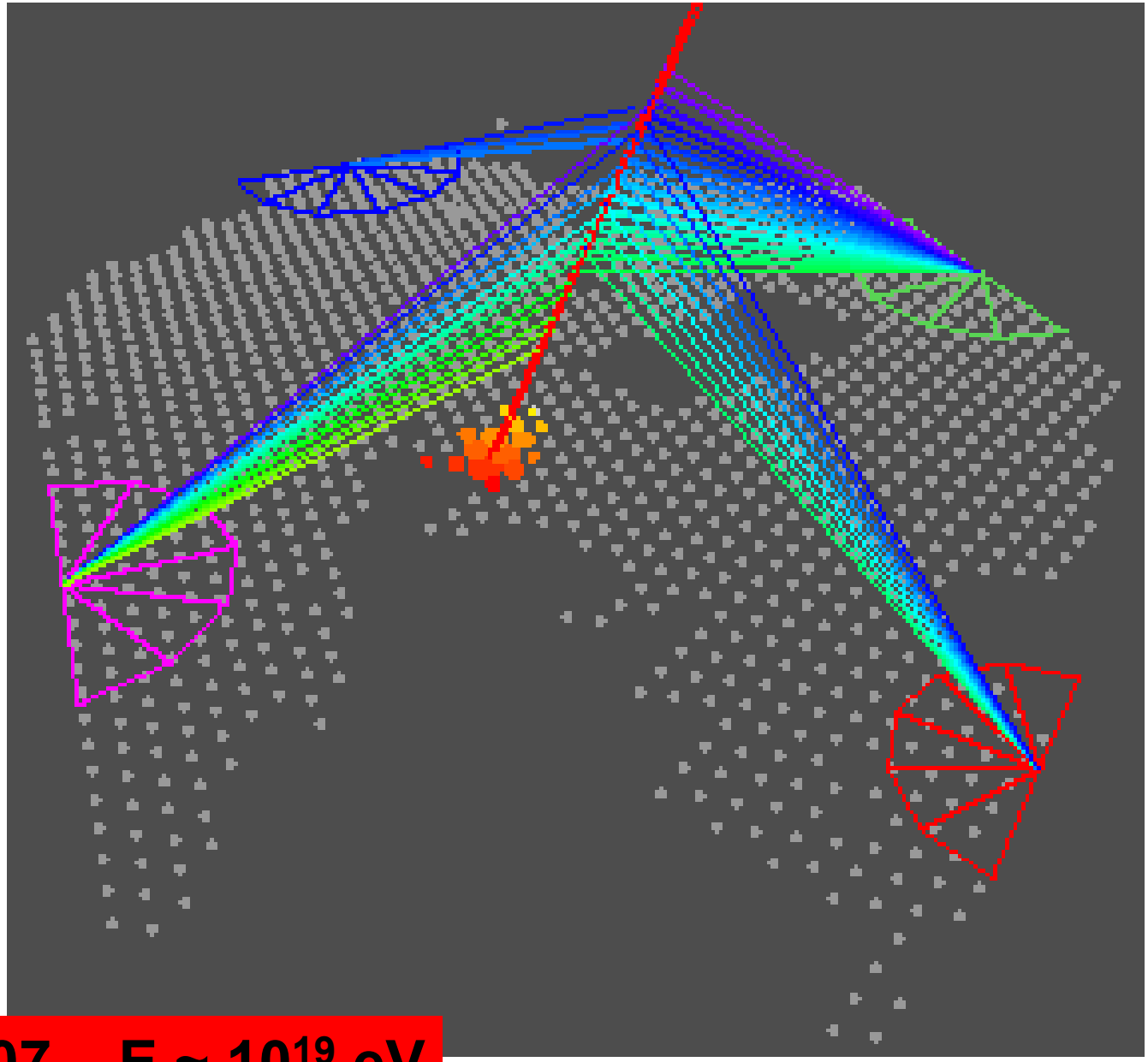
Is the UHECR flux isotropic ? → **clear evidence against (E > 60 EeV)**

True nature of the sources of UHECRs ? → **still more data needed…**

More slides

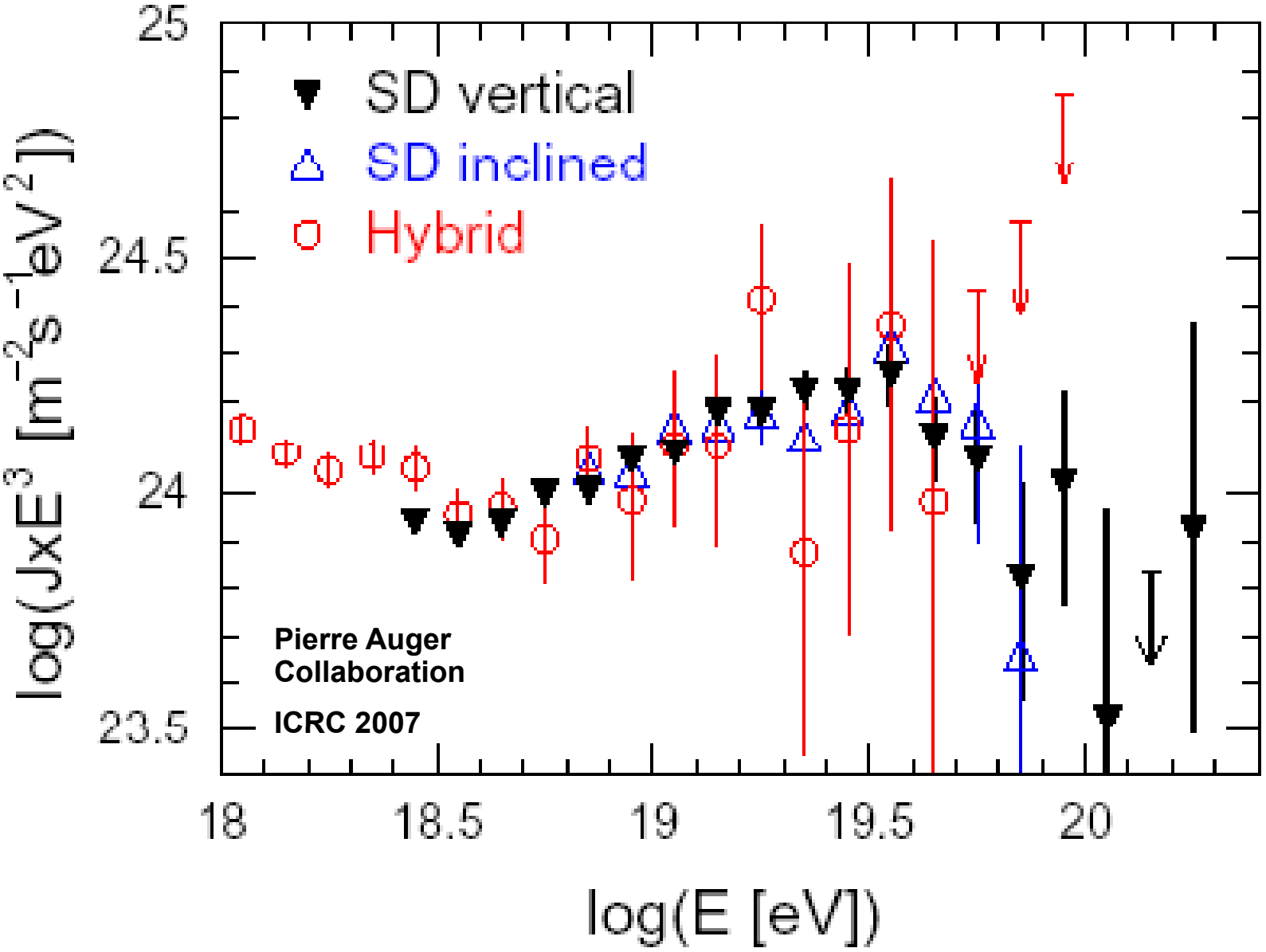
Hybrid event detected with 4 FD eyes & surface detector

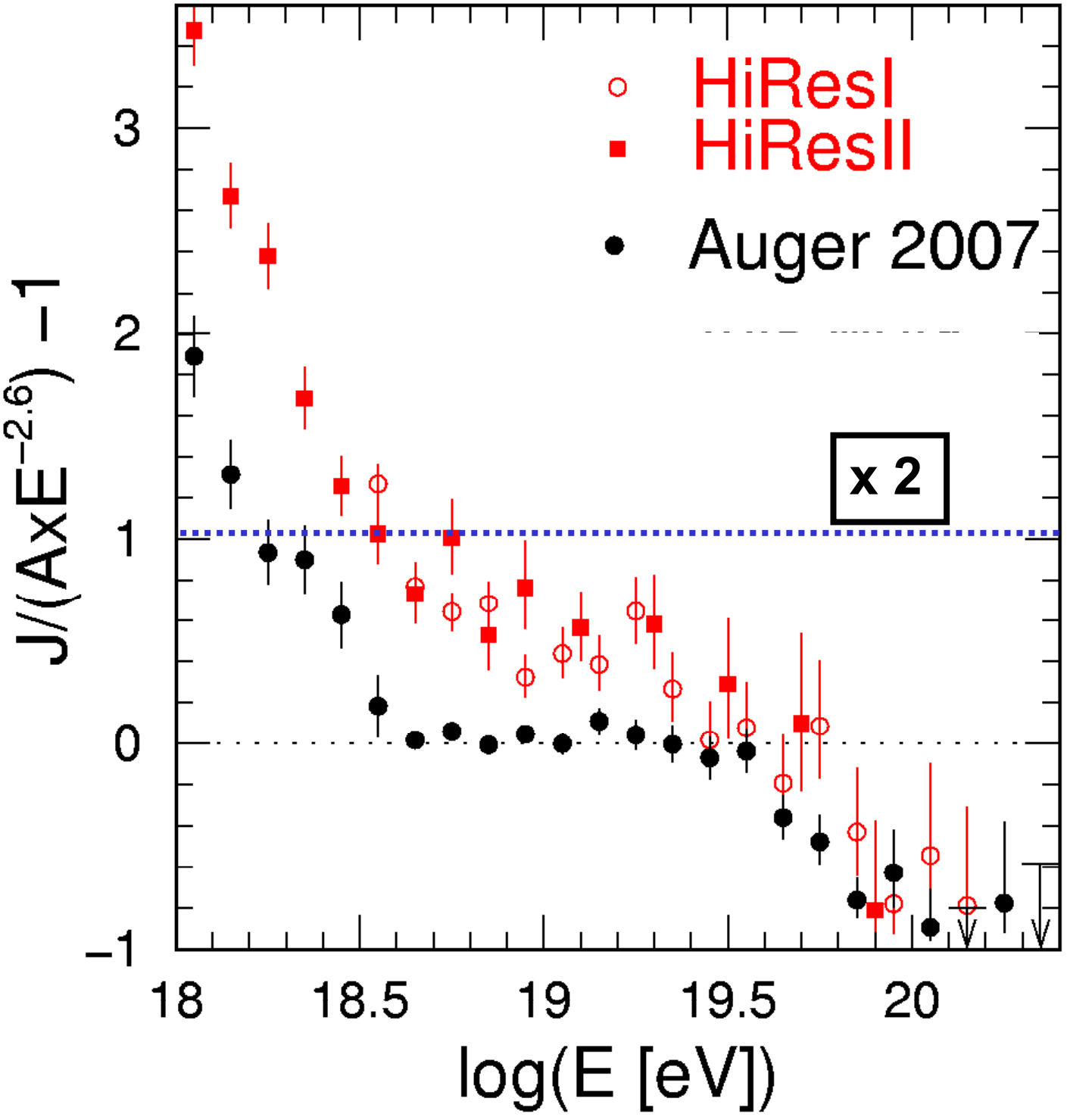
Miguel Mostafá



20 May 2007 E ~ 10^{19} eV

Consistency between E spectra: vertical, inclined & hybrid events




HiResI
HiResII
Auger 2007
x 2
J/(AxE^-2.6) -1
log(E [eV])
3
2
1
0
−1
18
18.5
19
19.5
20

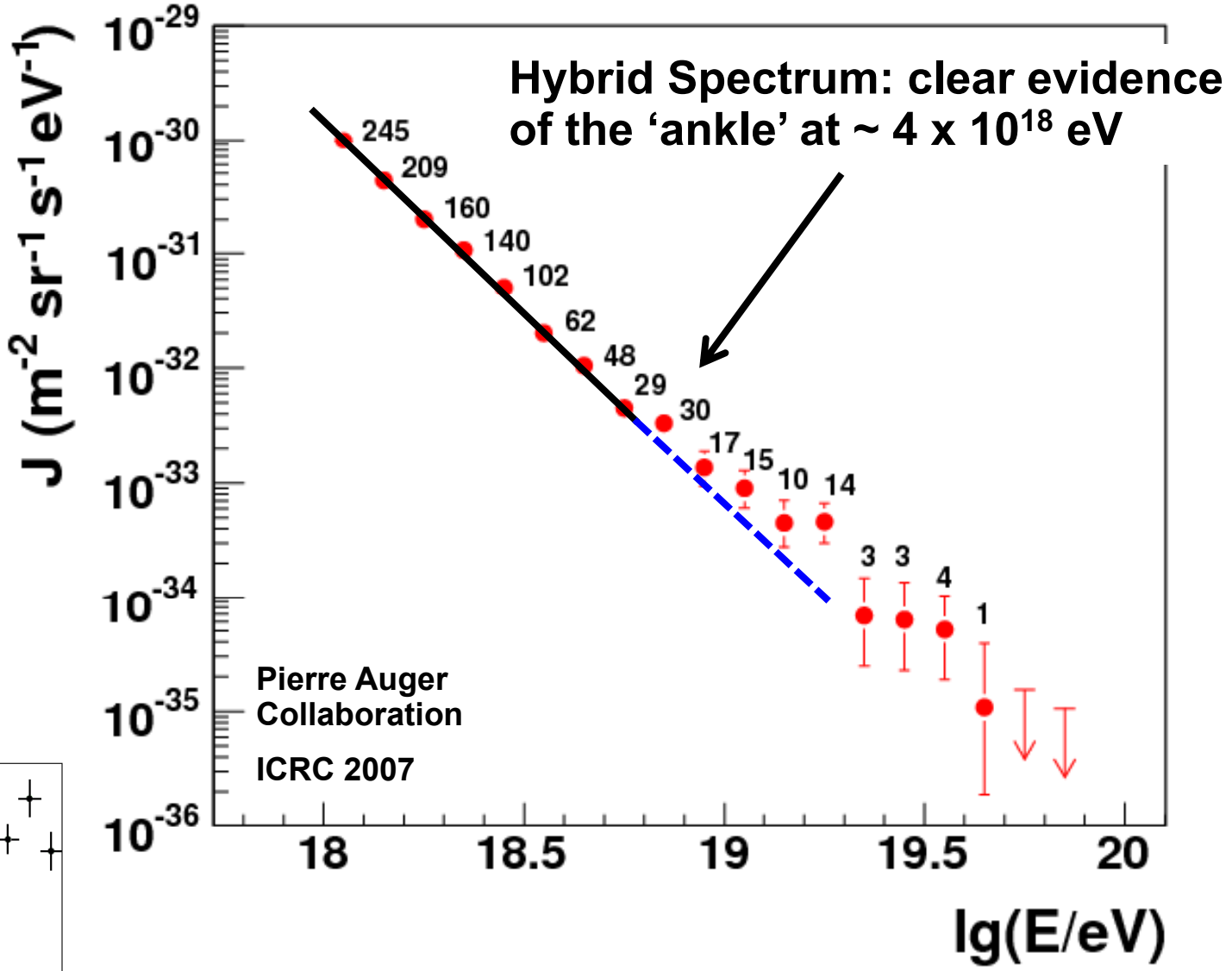
Spectrum with hybrid events

Energy spectrum hybrid events (θ < 60°)

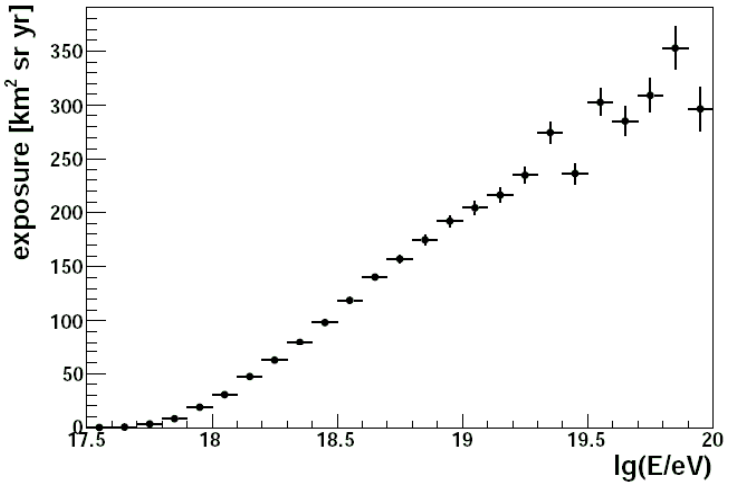
Jan 04 → Feb 07

1092 events

θ < 60°



Hybrid exposure vs E

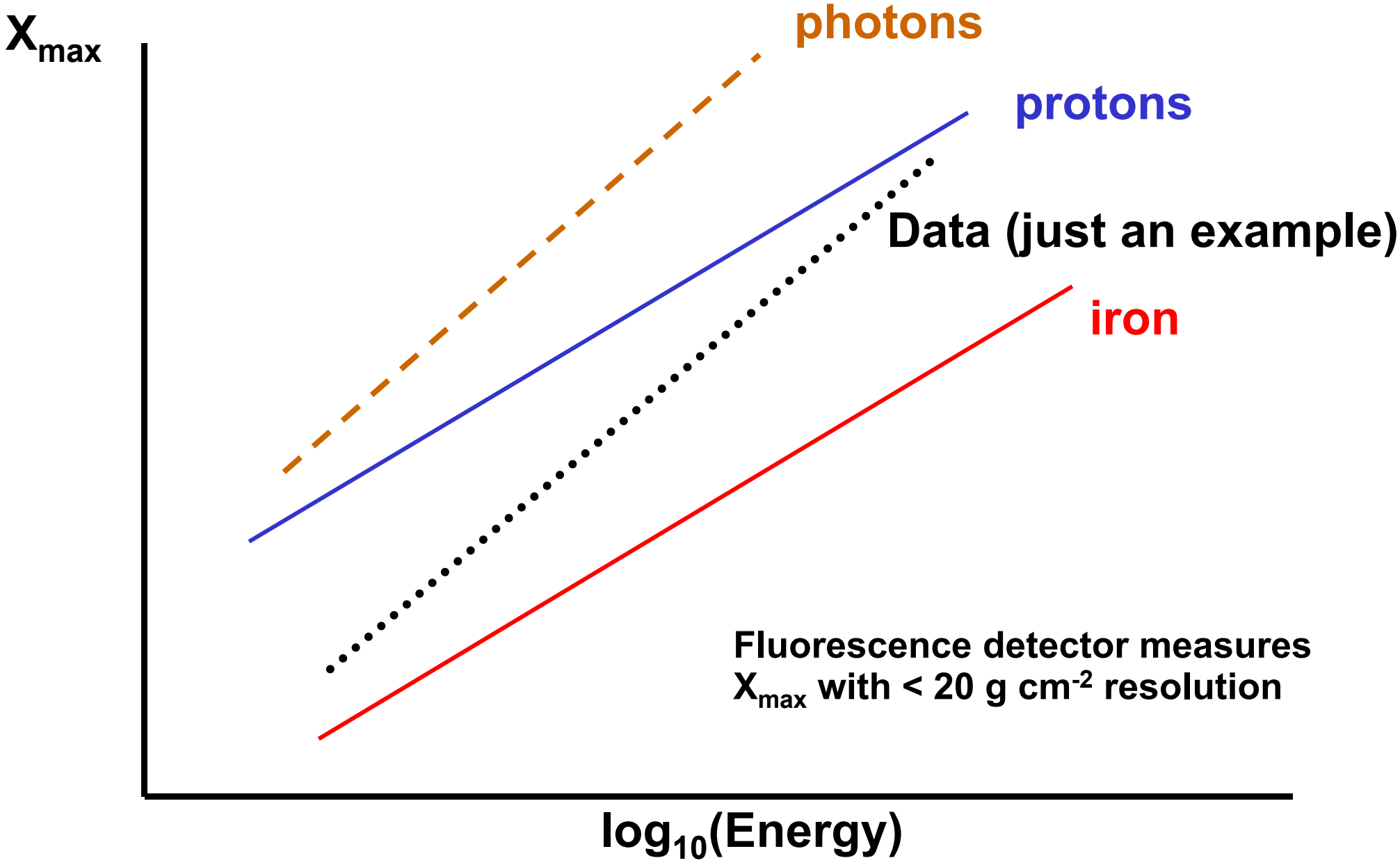


1st UHECR hybrid spectrum ever measured

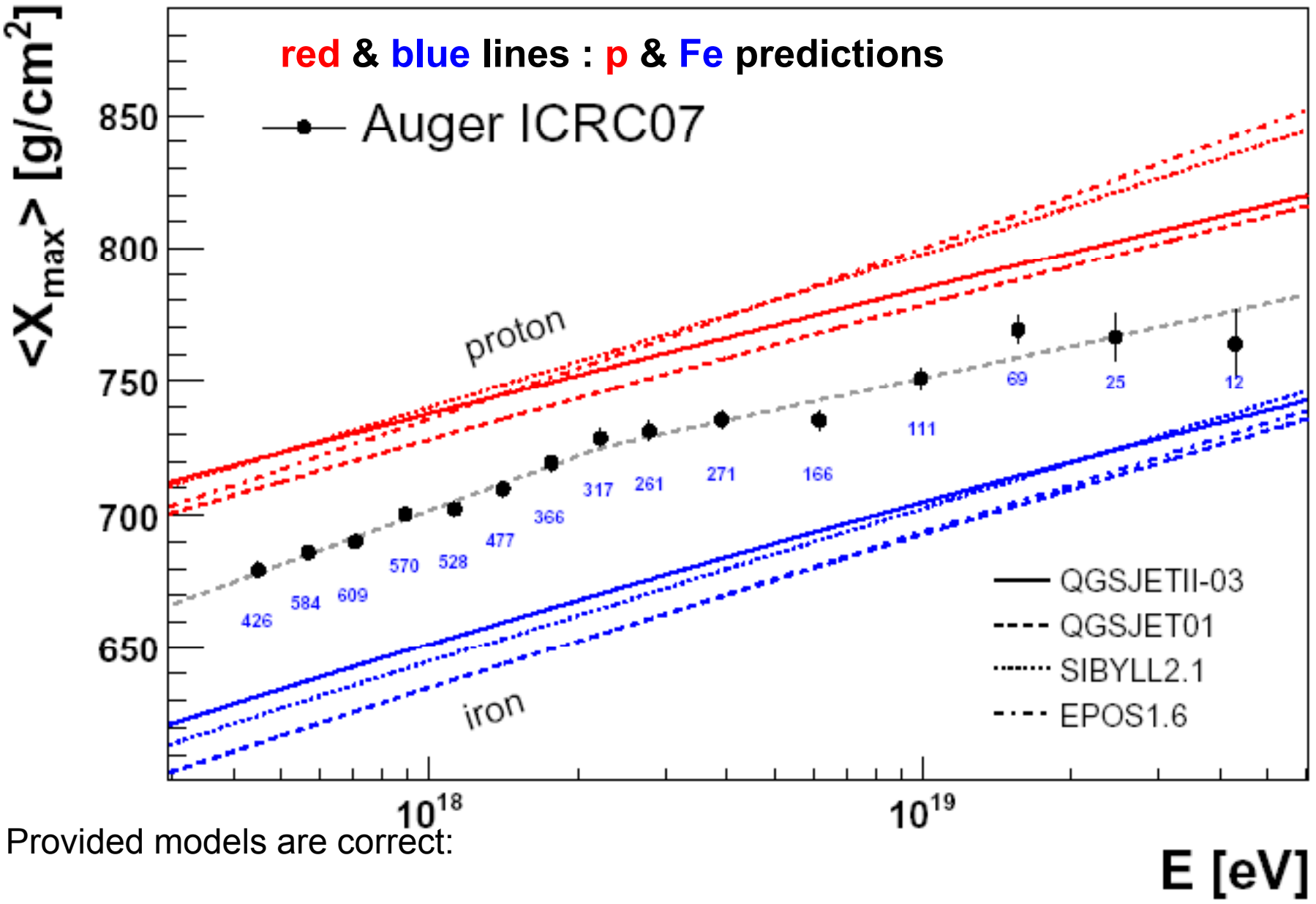
Consistent with vertical & inclined spectra

Mass composition

How we try to infer the variation of mass with E



Elongation Rate: X_{max} vs E

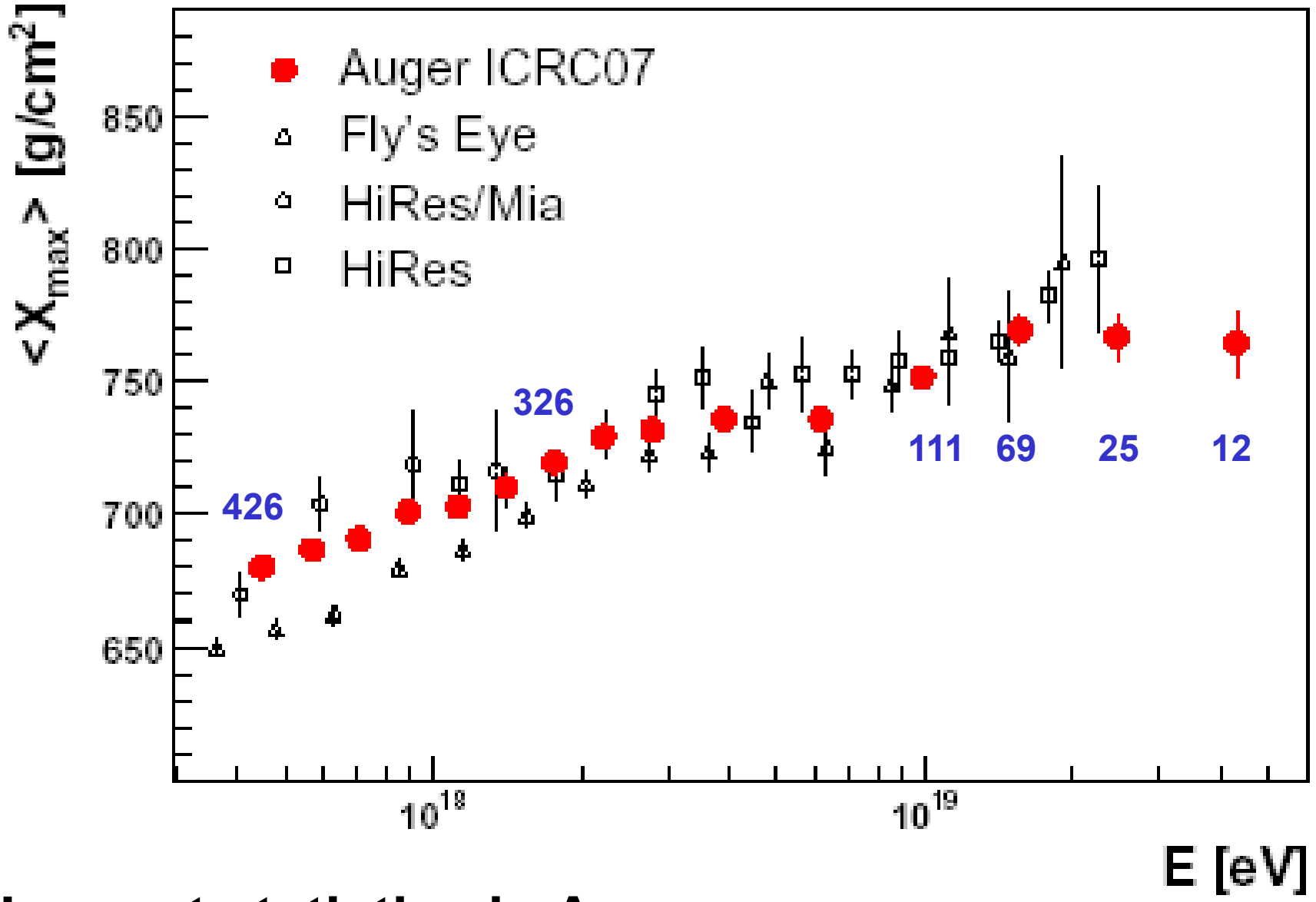


Provided models are correct:

UHECR mass is NOT proton-dominated

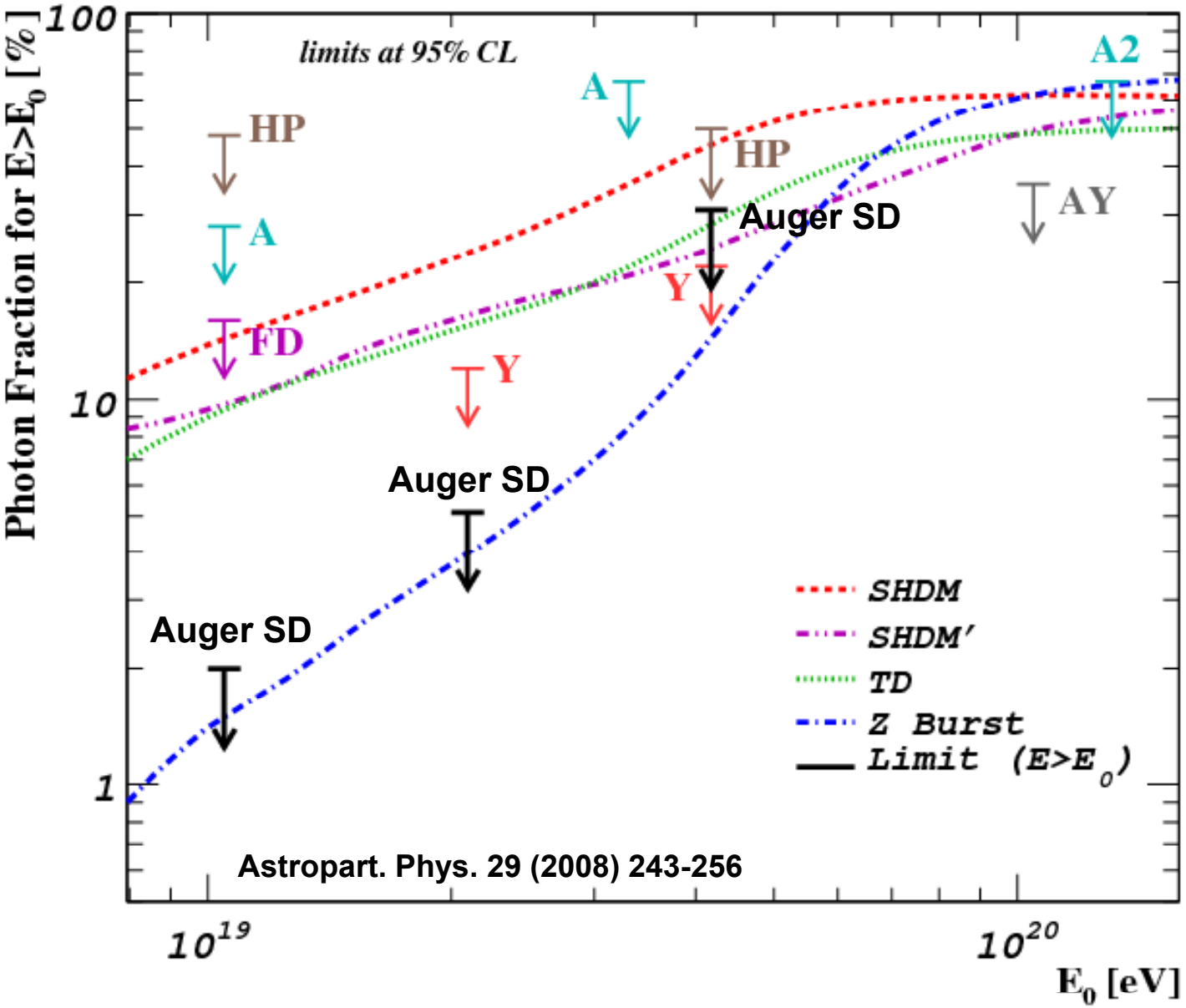
(Fluctuations in X_{max} yet to be exploited)

Comparison of X_{max} vs E



Largest statistics in Auger

Are UHECRs photons?



A, A2 = AGASA

HP = Haverah Park

Y = Yakutsk

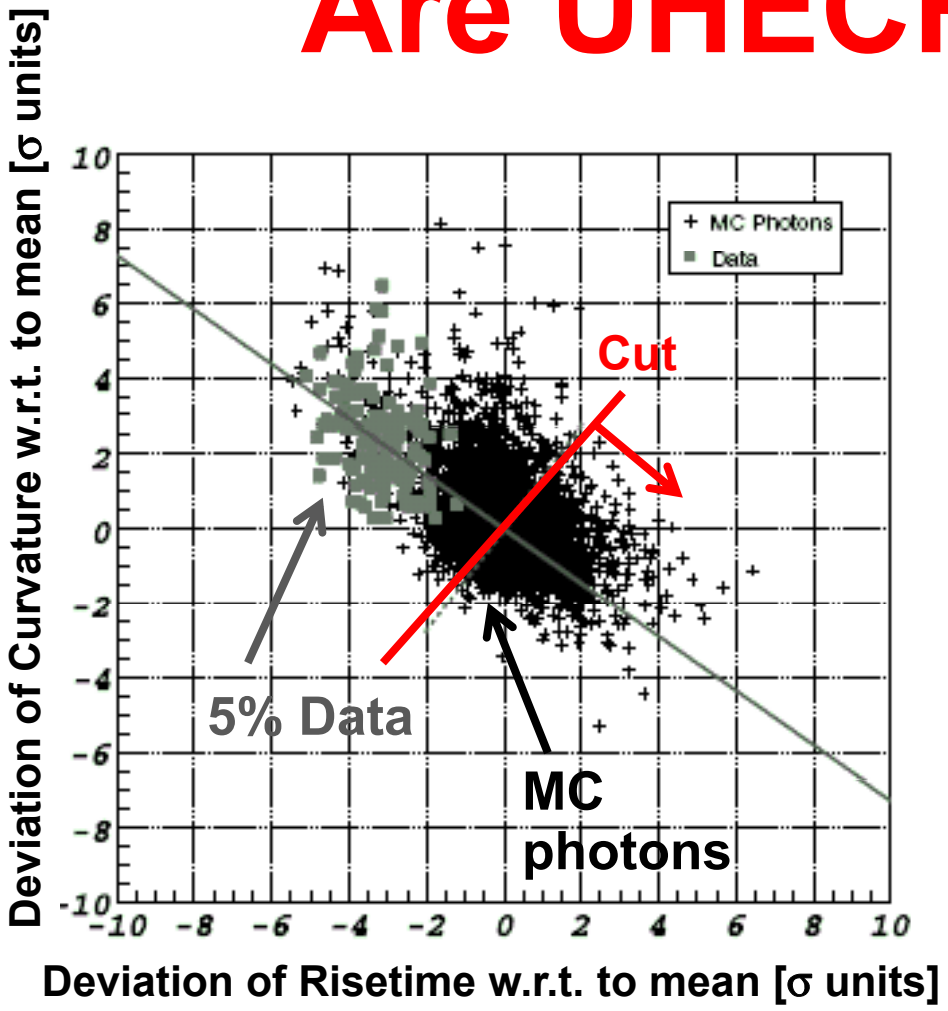
FD = Auger FD

Zero γ candidates

Strong constraints on Super-Heavy DM & Topological Defect models

Less than 2% of CRs of E > 10^{19} eV are photons

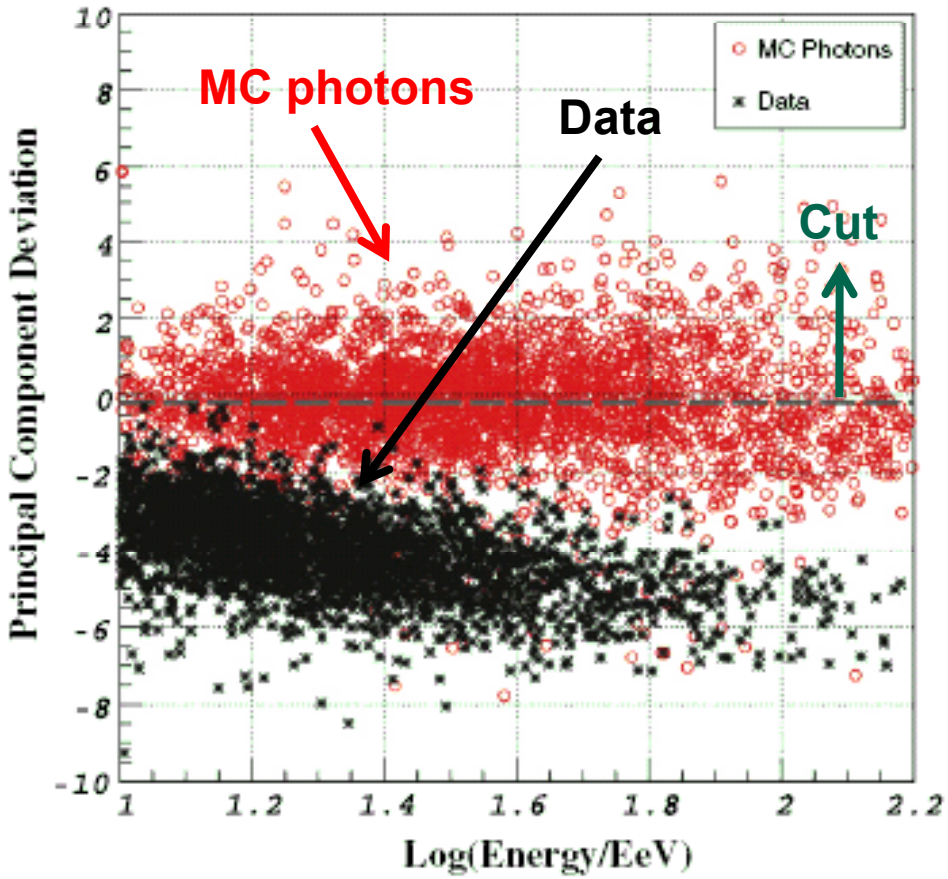
Are UHECRs photons?



Discrimination between γs & hadrons

- Radius of curvature of shower front
- Time structure of shower front (Risetime)

(both correlated to X_{max})



Principal component analysis

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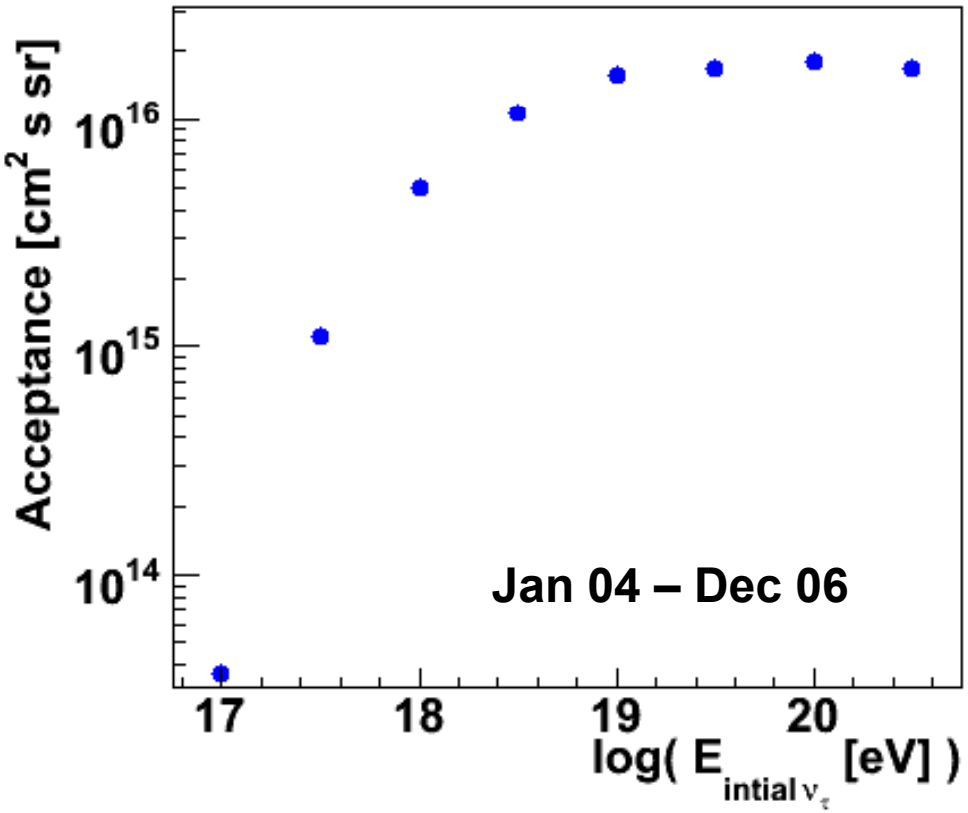
Auger acceptance to ν_τ

(1) MC simulation of the conversion ν_τ → τ in the Earth :

- Dedicated simulation code.
- ν cross section: Charged and Neutral Currents.
- τ energy losses: bremms., pair production & nuclear interactions.
- τ decay and τ weak interactions.



(2) MC simulation of τ decay in the atmosphere:

- Account for all the branching ratios & polarisation.

(TAUOLA Monte Carlo Code)

(3) MC simulation of shower produced by τ decay products in the atmosphere:

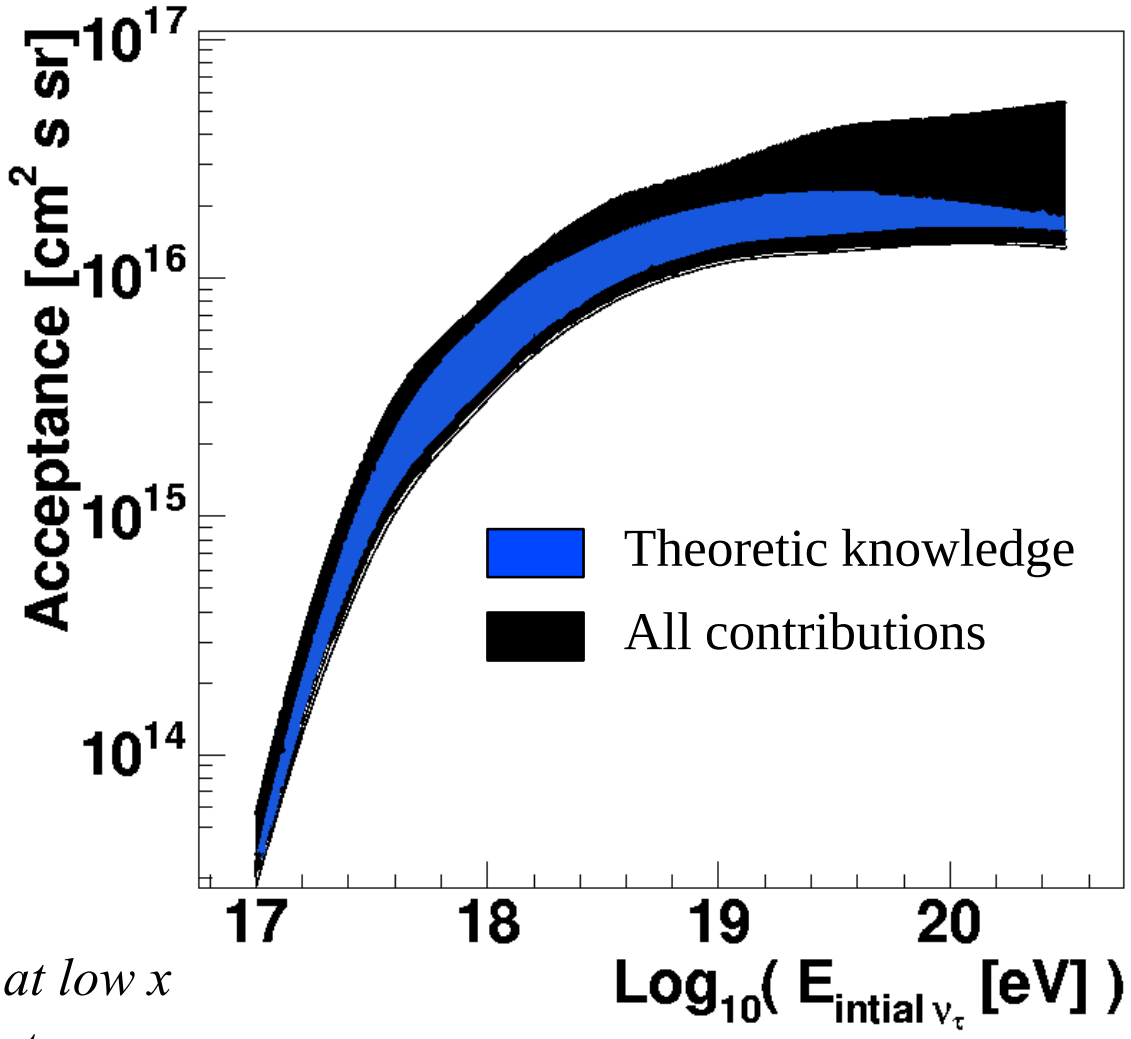
- Air shower simulator: AIRES + QGSJET01 or SIBYLL2.1

(4) Surface Detector simulation:

- GEANT4-based simulation.
- Account for a growing array whose configuration changes with time.

Systematic Uncertainties

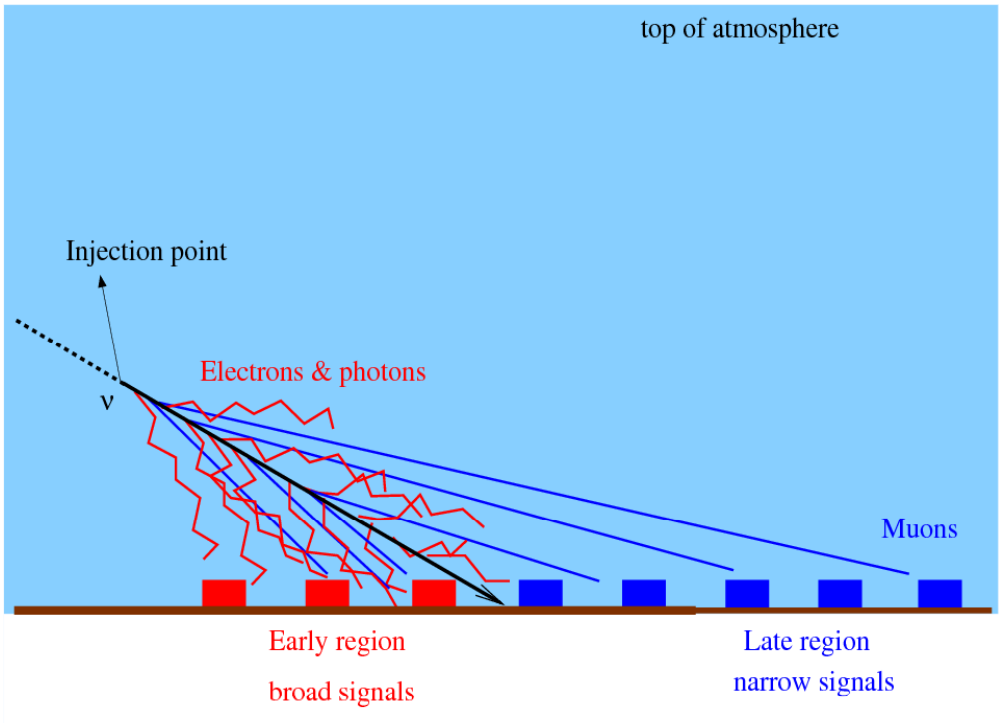
Source	Uncertainty
MC Simulations	
Interactions in Earth	± 5%
Extensive Air Shower	+20%, -5%
Pierre Auger Observatory	
Acceptance	± 2%
Topography	+18%
Theoretic knowledge	
Tau Polarisation	+17%, -10%
Cross Section	+5, -9%
Energy Losses	+25%, -10%



Parton Distribution Function uncertainties at low x and high Q^2 are not taken into account

Worst/Best combination of scenarios leads to a factor ~3 difference for the flux limit

Search for down-going neutrinos

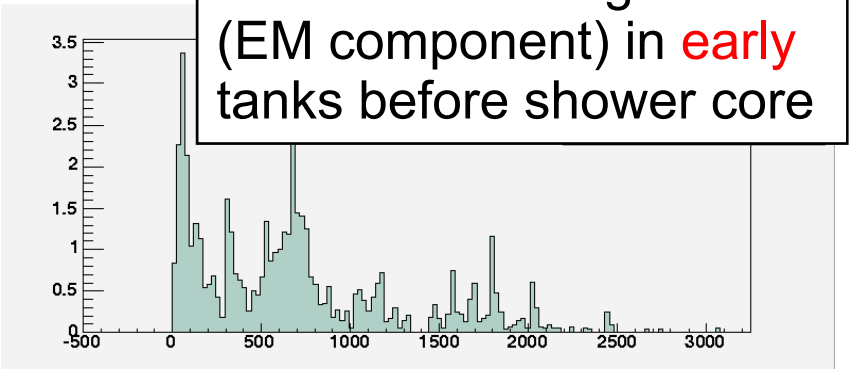


Very Inclined Showers

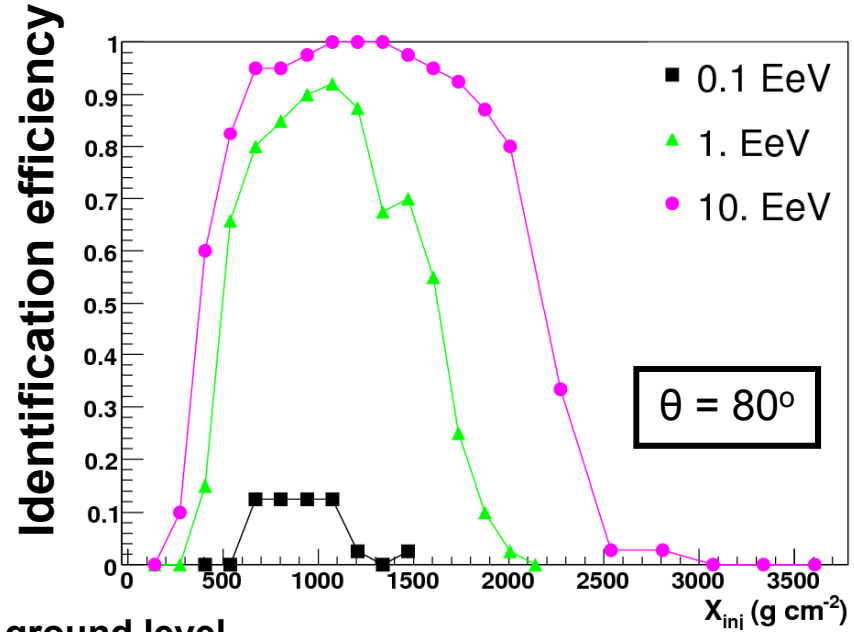
Perform angular reconstruction and select events with $\theta > \theta_{cut}$

"Young" showers

"Slow & broad signal" (EM component) in early tanks before shower core



Time (ns)

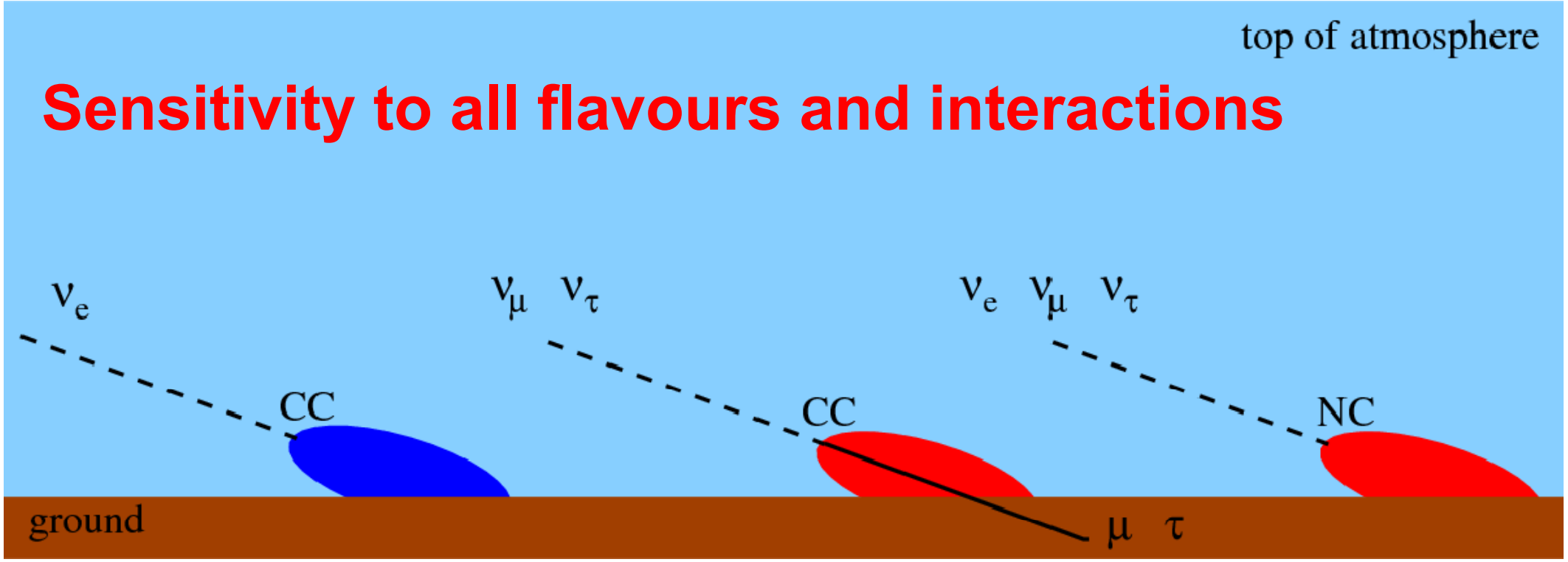


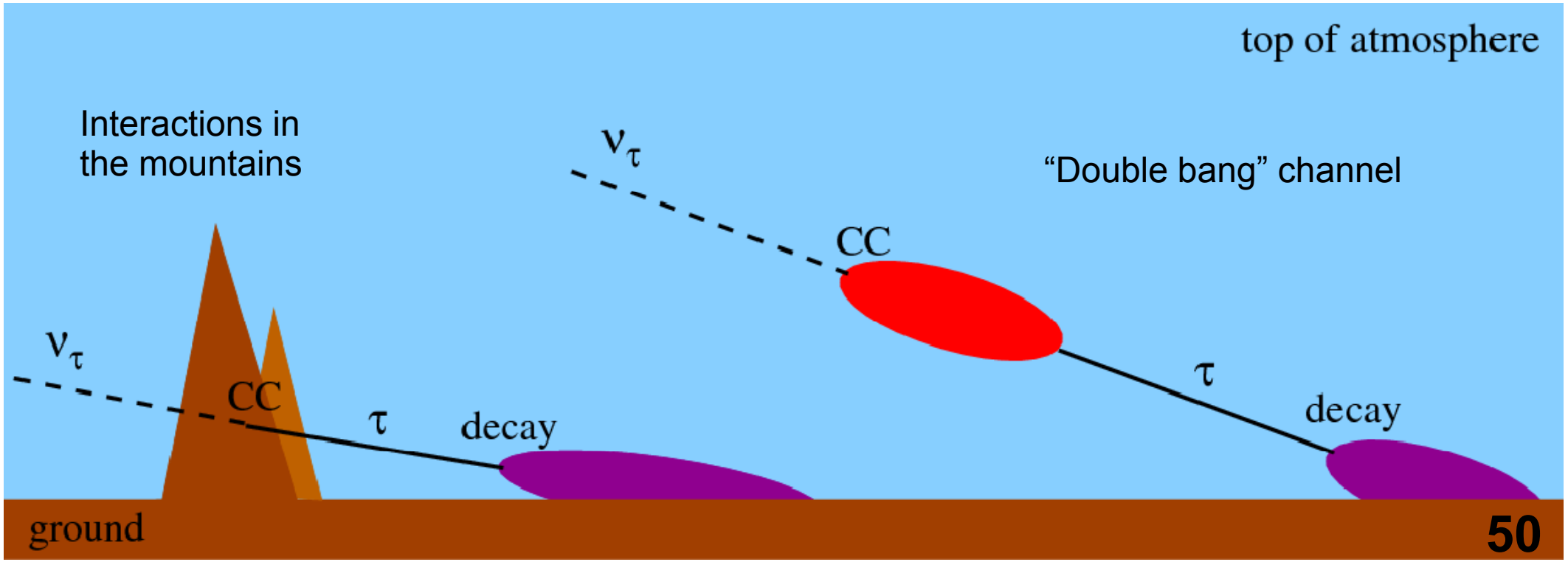
ground level

Identification efficiencies depend on: neutrino energy, injection point in the atmosphere and zenith angle

… work in progress…

Sensitivity to all flavours and interactions





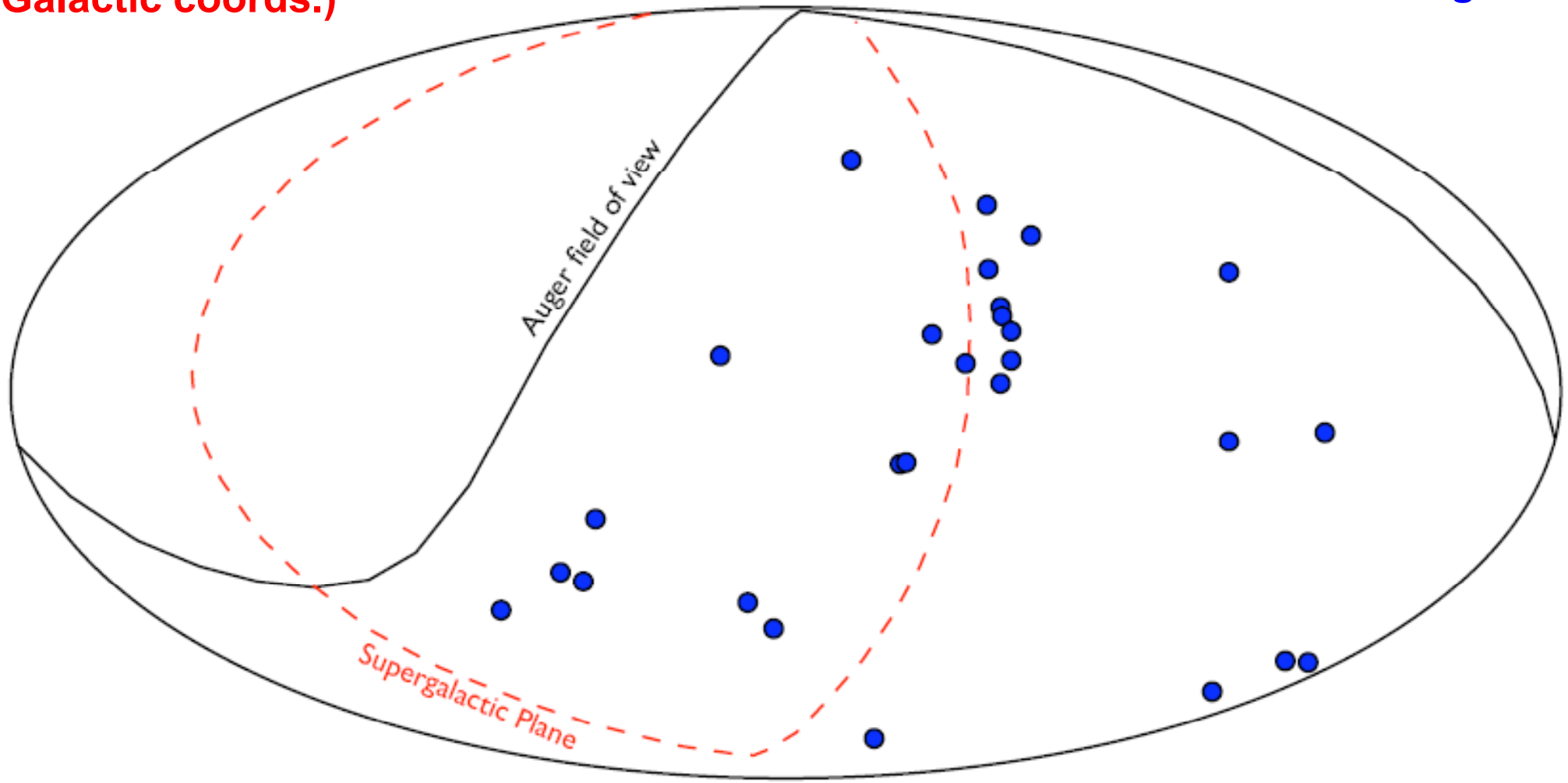
Arrival directions of UHECRs

Auger UHECR sky

27 events with E > 56 EeV

1 Jan 2004 → 31 Aug 2007

(Galactic coords.)

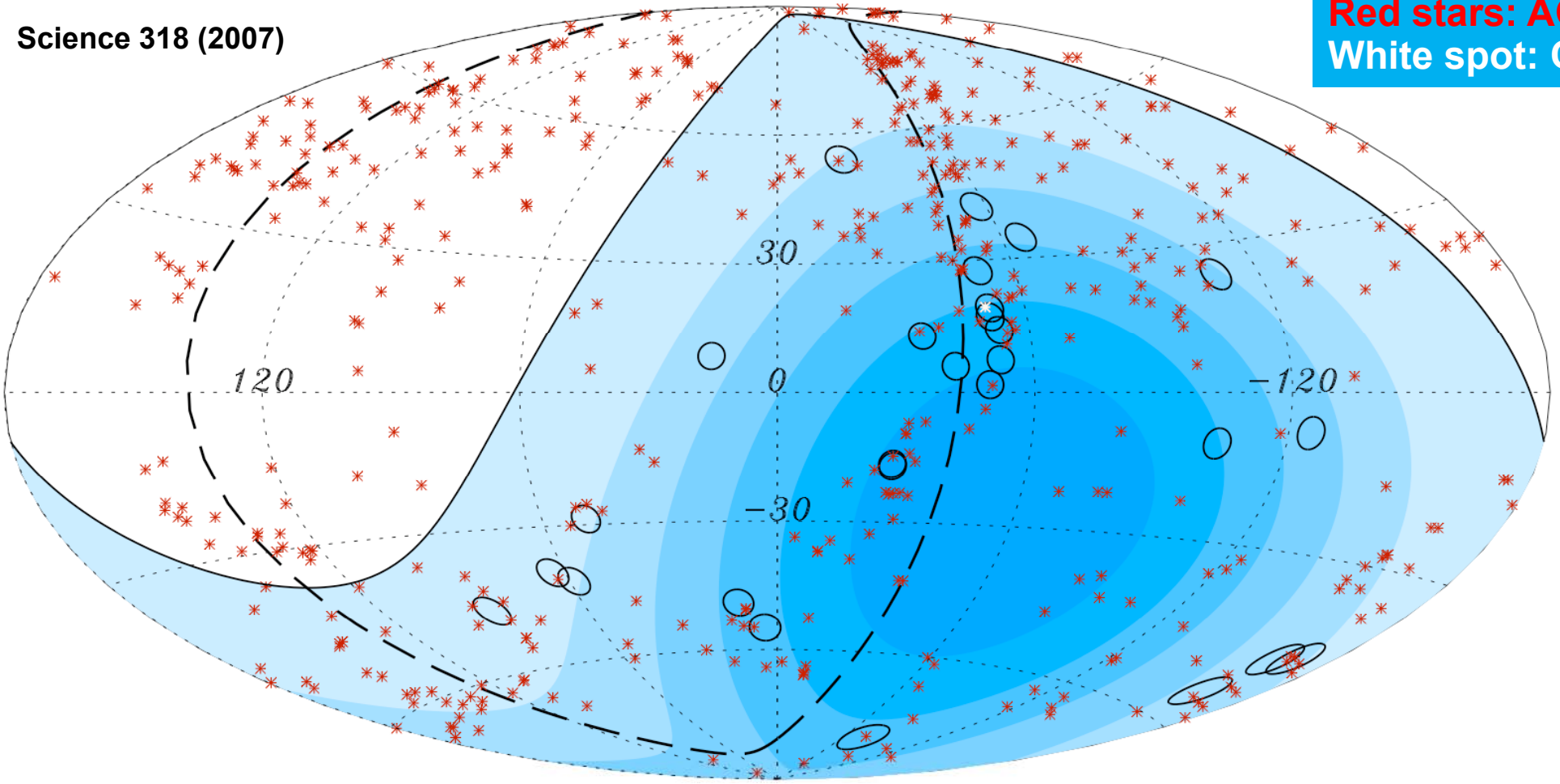


Is the UHECR sky isotropic?, how to quantify?

Correlation with potential source population?

Black circles: data
Red stars: AGNs
White spot: CenA

Science 318 (2007)



Demonstrate/refute isotropy hypothesis based on correlation w source catalog:

12th ed. Veron-Cetty catalog (694 AGNs, D < 100 Mpc)

Vary: Max. Angular distance to sources (ψ)
Max. distance to AGNs (D_{max})
Min. CR Energy (E_{min})

Find params. minimising the probability that an isotropic distr. of CR directions produces the same degree of correlation

Procedure

Science 318 (2007) & Astropart. Phys. 29 (2008) 188

1 **Exploratory scan: 12/15 correlate with AGN (3.5 expected from isotropy)**

1Jan 04 → 26 May 06 ($\psi = 3.2^{o}$ $D_{max} \sim 75$ Mpc $E_{min} = 56$ EeV)

↓

2 Fix ψ, D_{max}, E_{min} & **test on an independent data set**

(Require 1% probability of wrongly rejecting the isotropy hypothesis)

↓

3 **Confirmation: 8/13 correlate with AGN (2.7 expected from isotropy)**

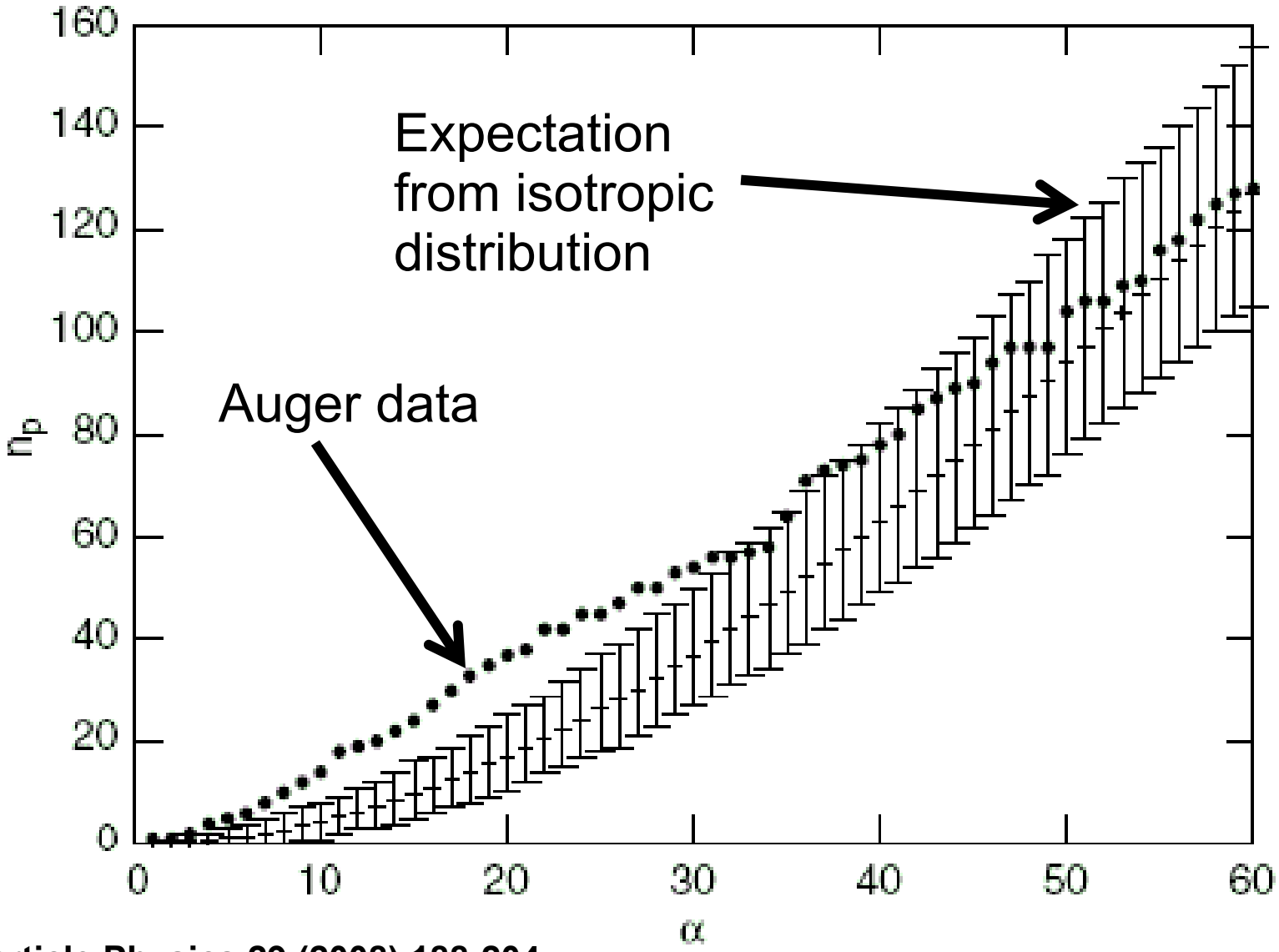
27 May 06 → 31 Aug 07

20/27 correlations (Chance probability = 10^{-5})

The UHECR sky is NOT isotropic at 99% C.L.

Auto-correlation

Number of pairs vs angular separation between them



Error bars:
90% C.L.
dispersion

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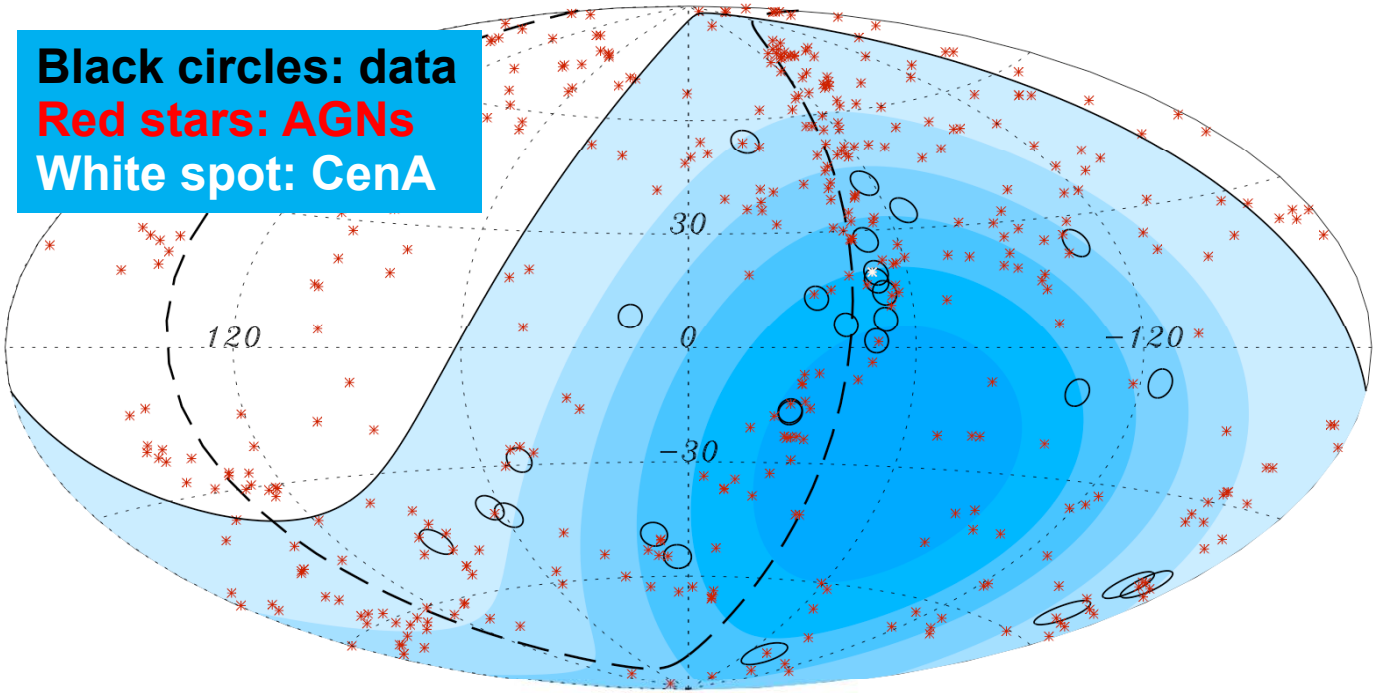
What is the correlation telling us?



Arrival directions of UHECRs are NOT distributed isotropically
Extragalactic origin.

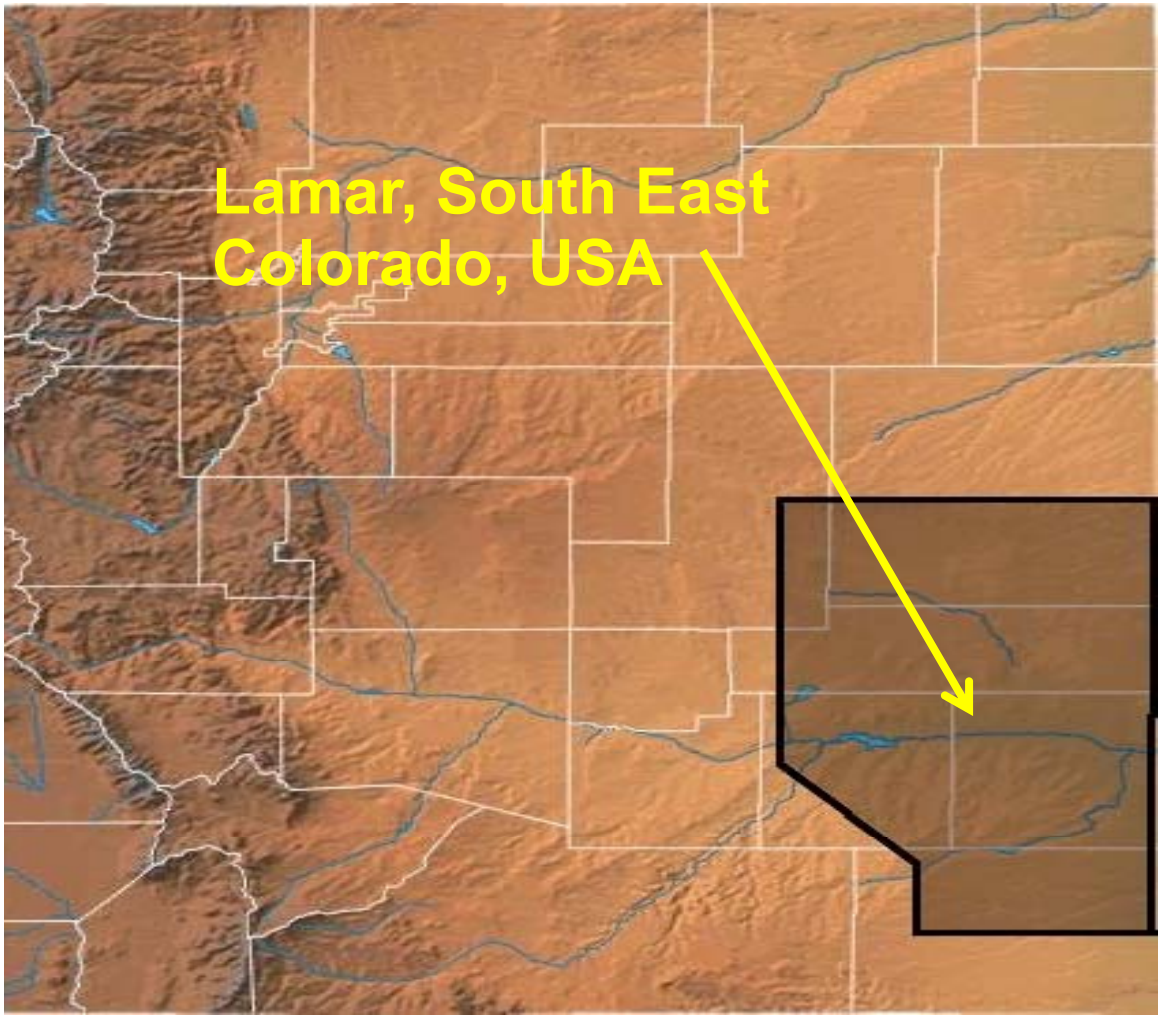
E_{min} = 57 EeV & D_{max} ~ 75 Mpc consistent with GZK
ψ = 3.2º scale consistent with light primaries (or small B-fields)

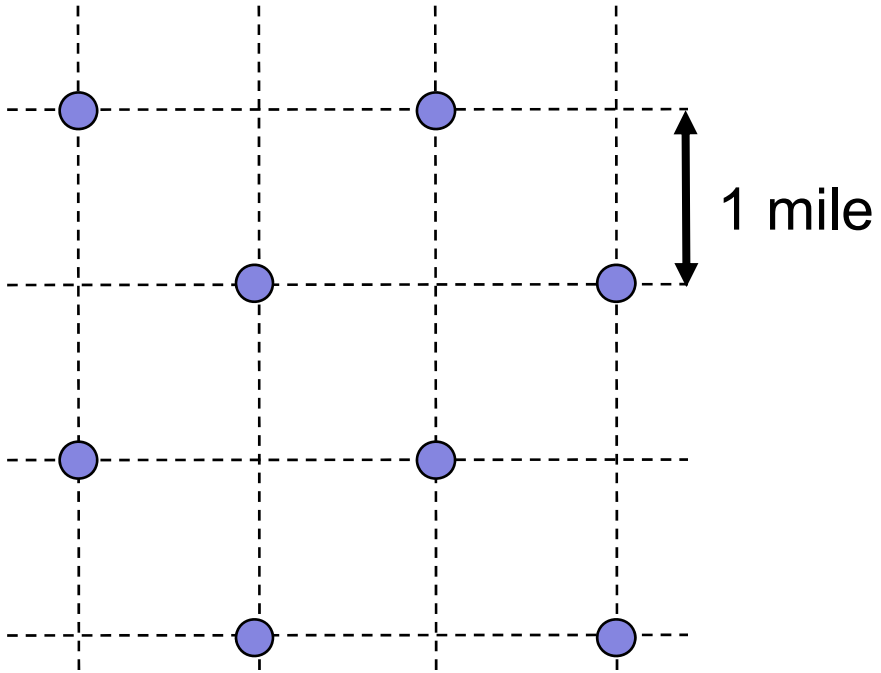
Are AGNs the sources?, or something else with a similar sky distribution?, acceleration mechanisms? (more data needed).

Other interesting features:
Correlation with Supergalactic Plane, cluster at CenA position

The future: Auger North

	AUGER SOUTH	AUGER NORTH
SD units:	1,600	**4,400**
SD area:	3,000 km^2	**20,000 km^2**
# PMT/tank:	3	1
Type of tank:	Non-insulated	Insulated





+ several Fluorescence Telescopes

ARRIVAL DIRECTION DISTRIBUTION

Typical accuracy of angular reconstruction < 1°

NO significant emission from Galactic Centre

NO broadband signals – e.g. Dipole – at any E (above 1 EeV)

NO clustering of the type claimed by AGASA

NO signal from BL Lacs as possibly seen by HiRes

Summary: Previous reports have not been confirmed despite ~ 6 times more statistics E > 10 EeV