Risultati recenti dall'Osservatorio Pierre Auger

Sergio Petrera, L'Aquila

Roma, 14 Dicembre 07

- La fisica di Auger
- L'Osservatorio
- Rivelazione e analisi degli sciami
- Risultati recenti:
  - → *Spettro*
  - → *Composizione*
  - → *Astronomia*
- Conclusioni

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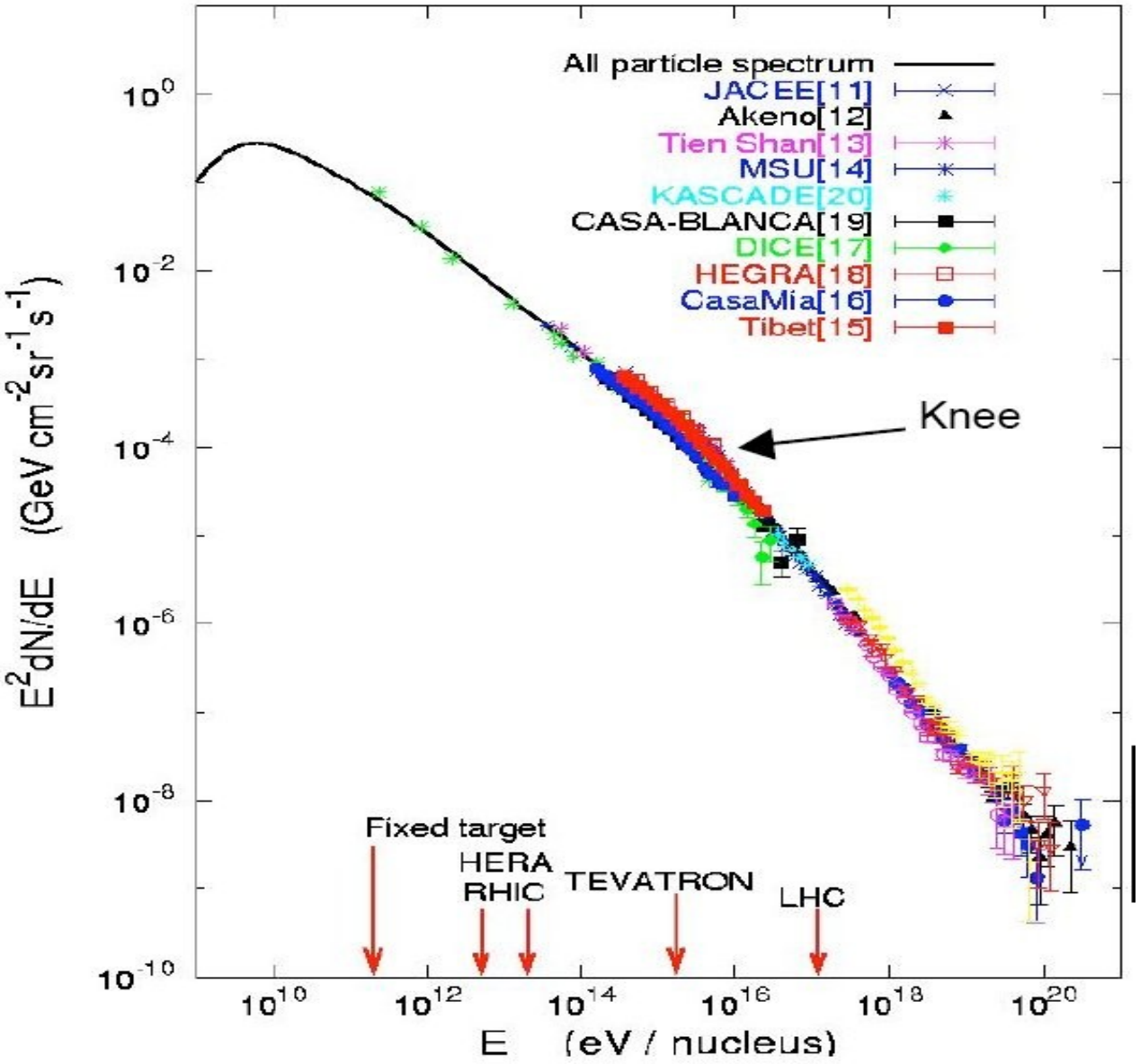
Nuclear (p, He.... Fe) component



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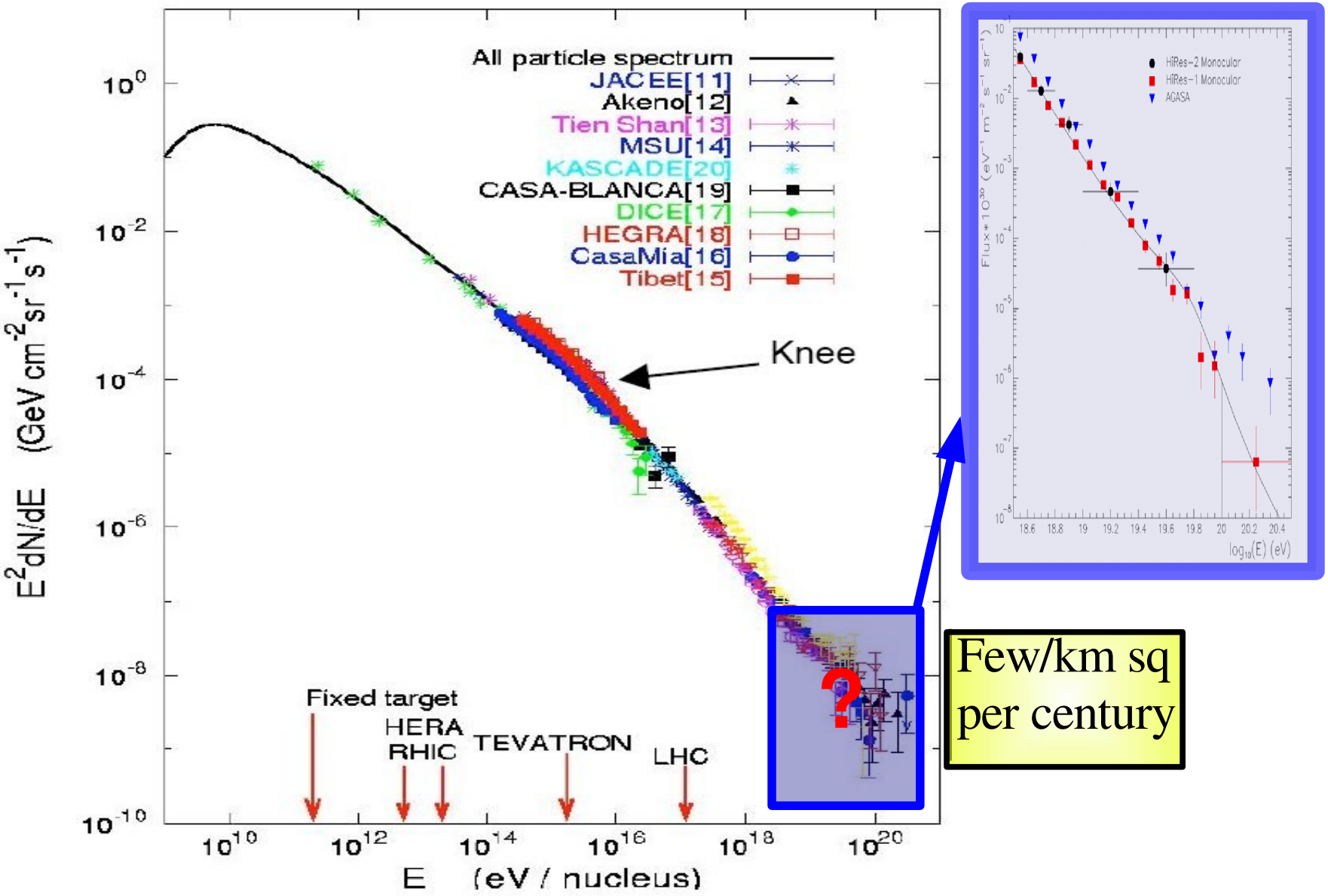
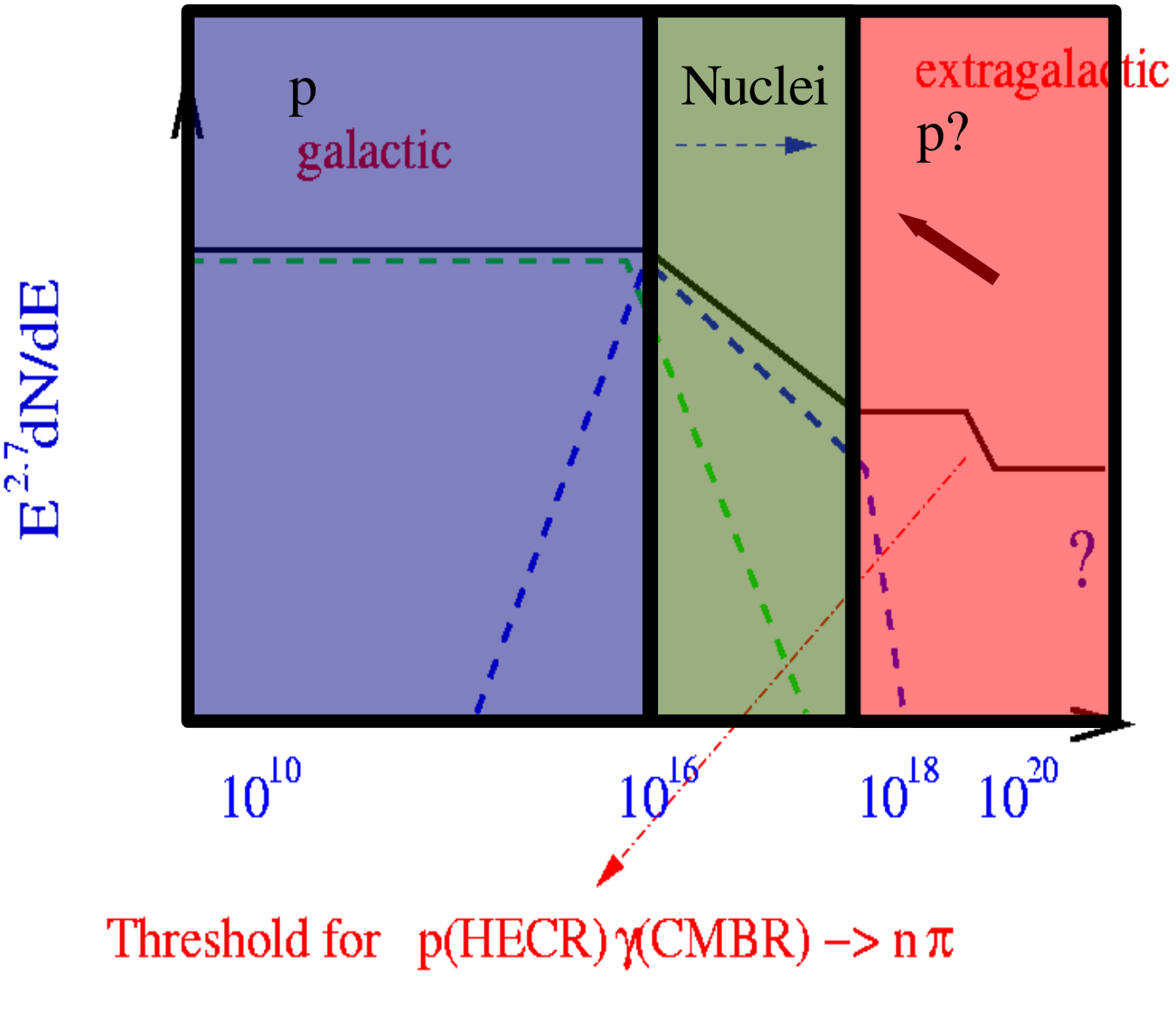


Few/km sq per century


p
galactic
Nuclei
extragalactic
p?
?
$E^{2.7}dN/dE$
10^{10}
10^{16}
10^{18}
10^{20}
Threshold for p(HECR) γ(CMBR) –> n π

GZK cut-off

At UHE, protons interact with CMB photons by photo production, and nuclei with CMB and IR photons through photo dissociation

UHECR should lose energy quickly on short distances (<100 Mpc)

The Greisen -Zatsepin-Kuzmin "cutoff"

$$p + \gamma \rightarrow p + \pi^{\circ}$$

$$p + \gamma \rightarrow n + \pi^{+}$$

Photoproduction Threshold

$$s = m_p^2 + 2\,E_p\,\epsilon\,(1 - \beta\cos\theta_{\gamma p}) > (m_p + m_\pi)^2$$

$$E \geq \frac{(m_p + m_\pi)^2 - m_p^2}{2\,\varepsilon\,(1 - \cos\theta_{\gamma e})} \geq \frac{(m_p + m_\pi)^2 - m_p^2}{4\,\varepsilon}$$

$$E > 6 \times 10^{19} \left(\frac{10^{-3}\ \mathrm{eV}}{\varepsilon}\right)\ \mathrm{eV}$$

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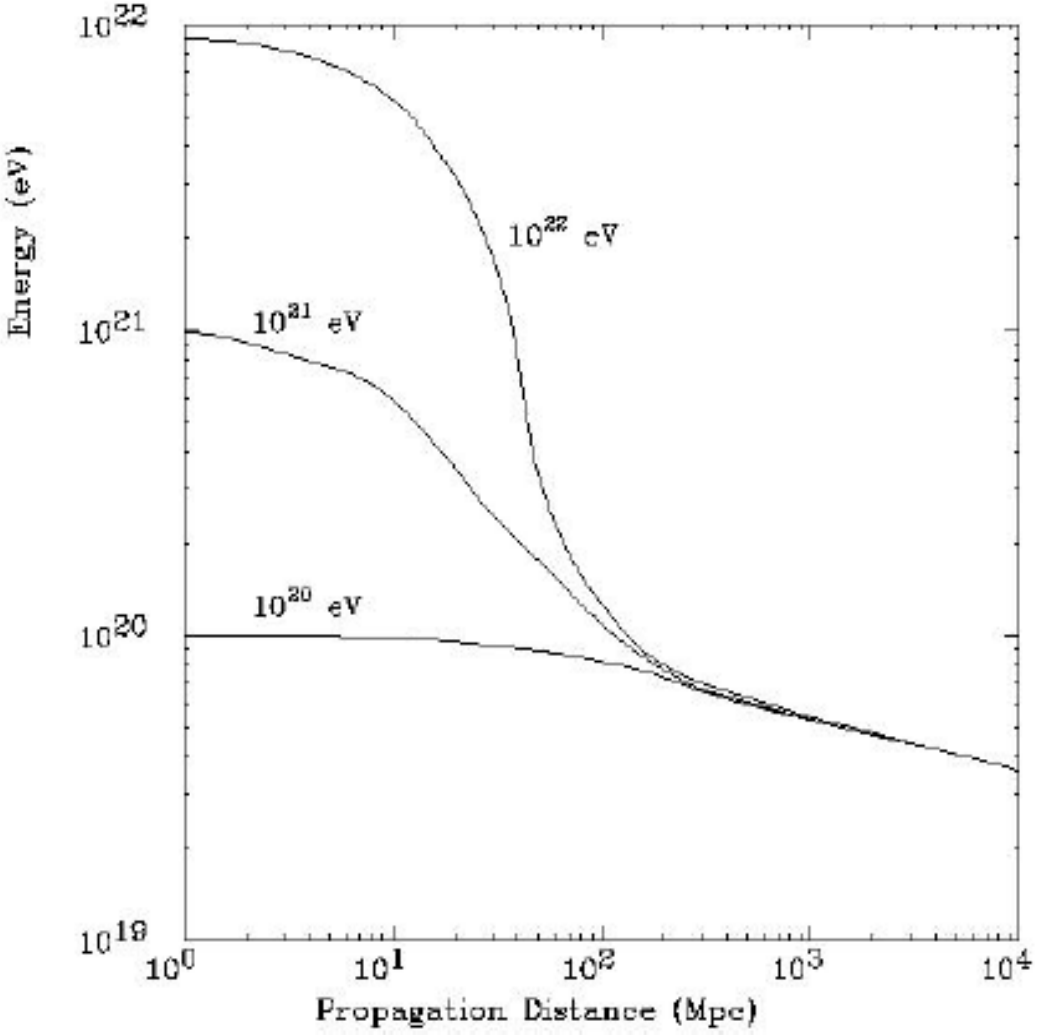
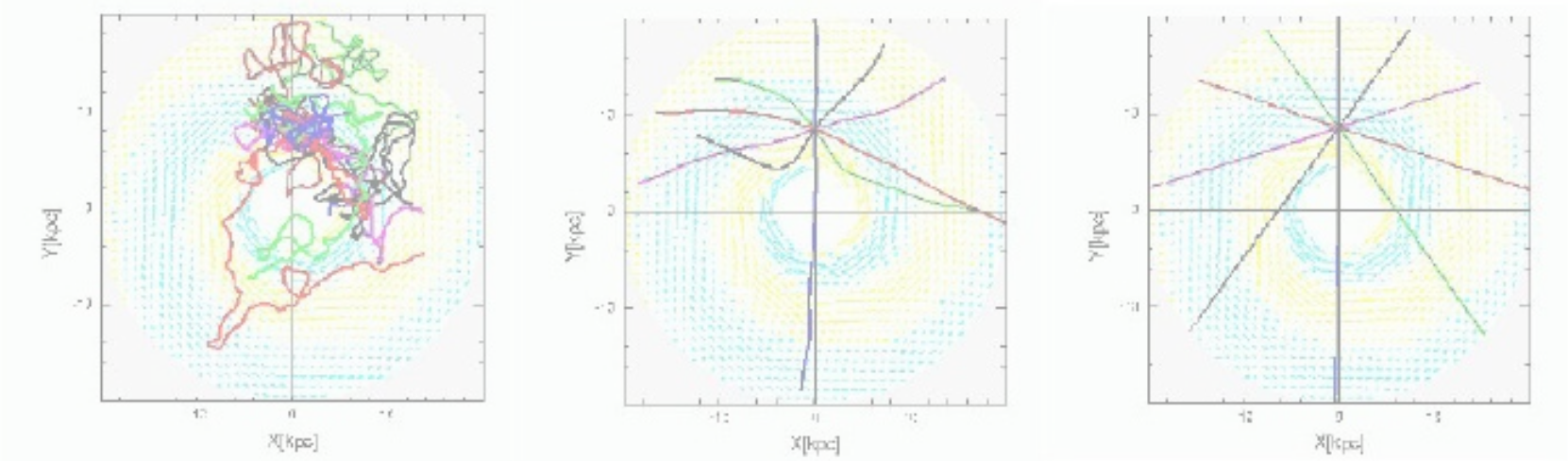


UHECR Astronomy

Magnetic fields

At low energies, CR are deflected by galactic and extra-galactic magnetic fields.
UHECR should point to the source



10^{18} eV | 10^{19} eV | 10^{20} eV

UHECR Astronomy

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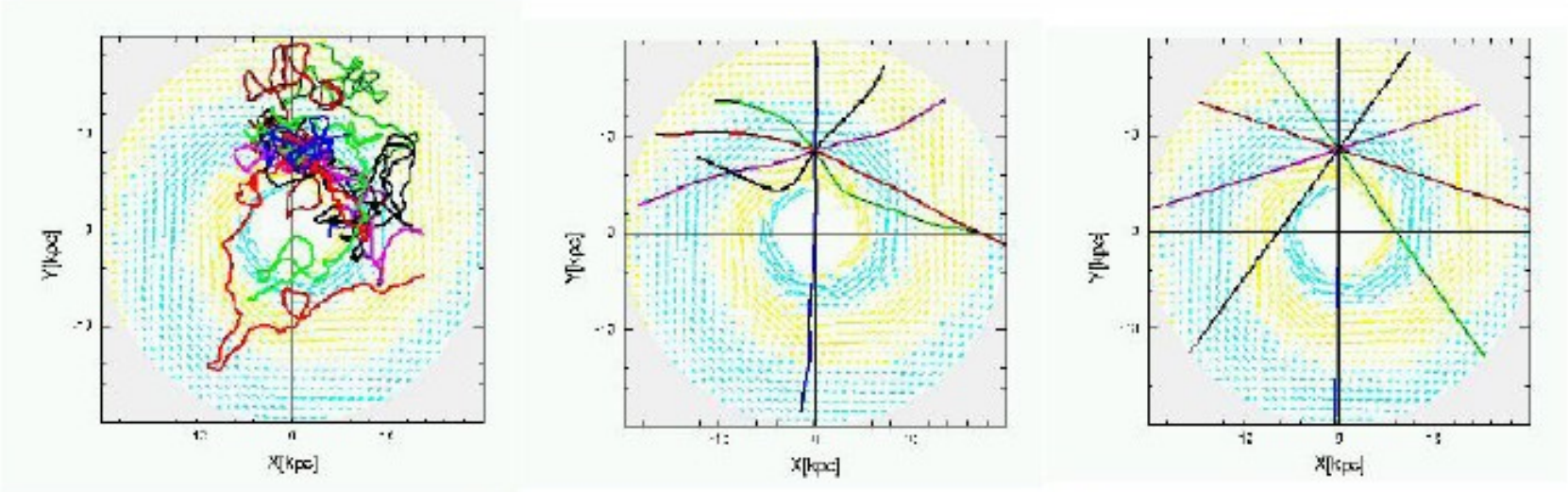

10^{18} eV | 10^{19} eV | 10^{20} eV

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The Pierre Auger Observatory

Colorado, USA
(in planning)

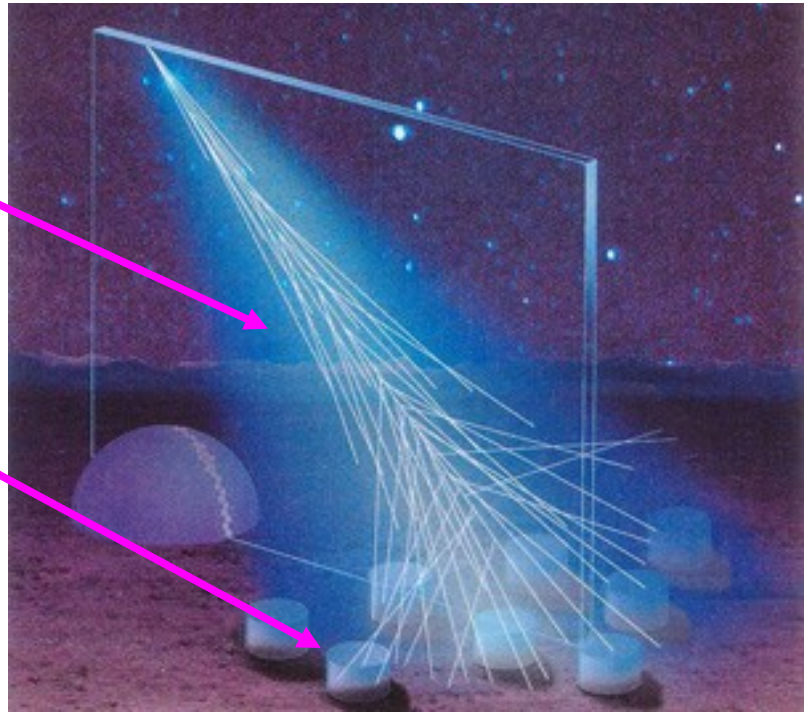
Mendoza, Argentina
(construction underway)

A Giant Hybrid Observatory

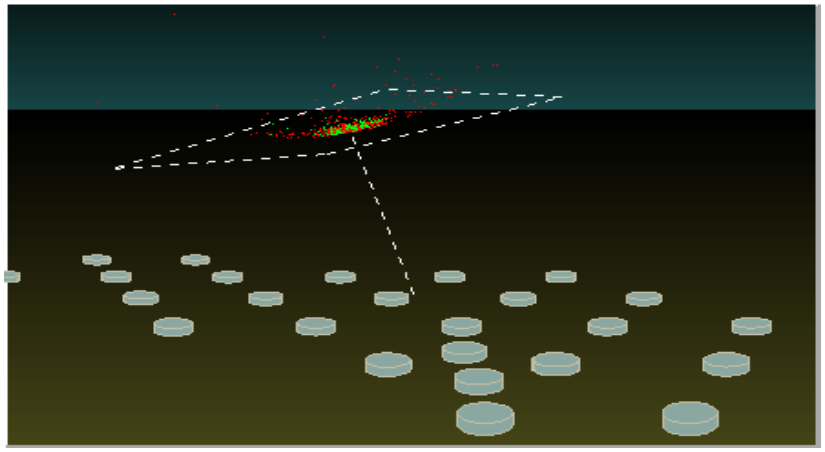
Detection Techniques

Nitrogen fluorescence detected as shower develops

Particles detected as they reach ground

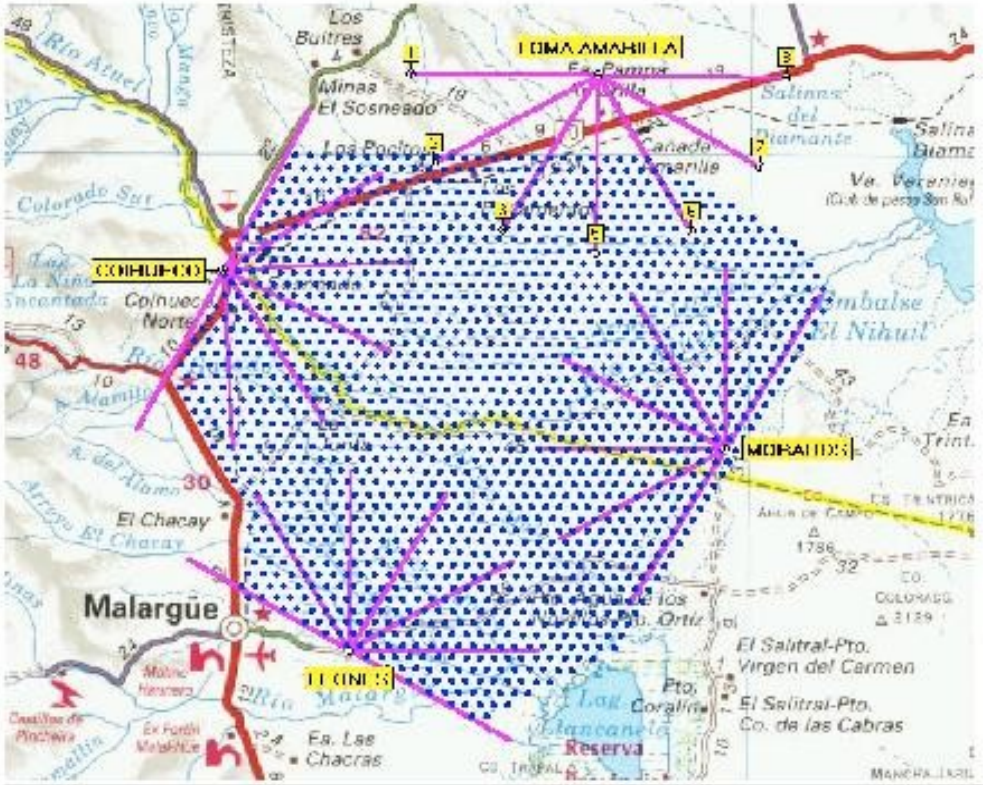


- Fluorescence (50 W light bulb @ c)
  - nearly calorimetric
  - direct view of shower evolution
  - 10% duty cycle
  - Acceptance depends on energy + atmosphere
- Surface (10^{12} particles over 20 km^2)
  - 100% duty cycle
  - Flat acceptance above threshold
  - Indirect measurements of primary energy and mass (relies on simulation)



Hybrid = surface + fluorescence

The Observatory Plan



Surface Array

1600 detector stations

1.5 km spacing

3000 km²

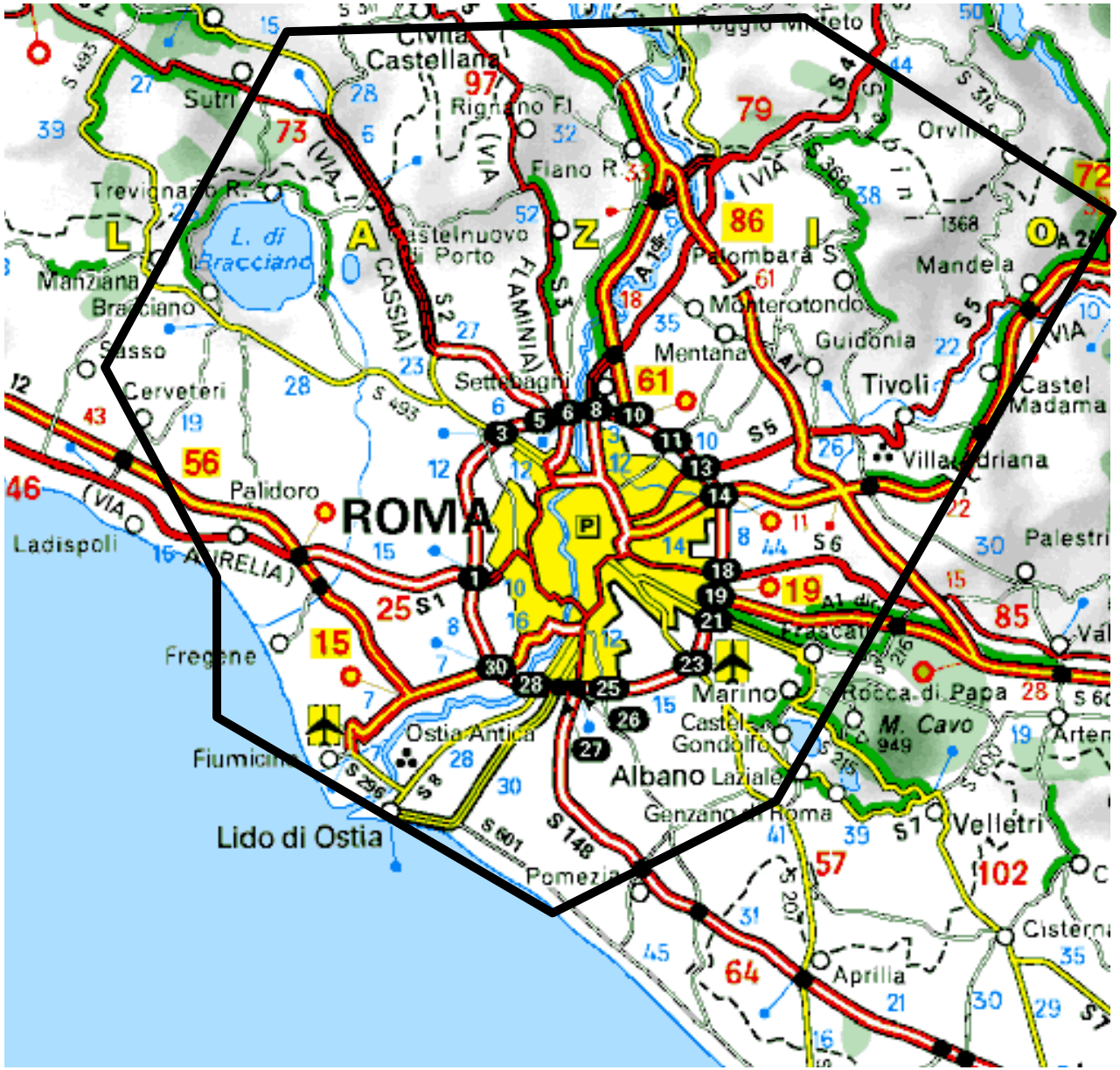
Fluorescence Detectors

4 Telescope enclosures

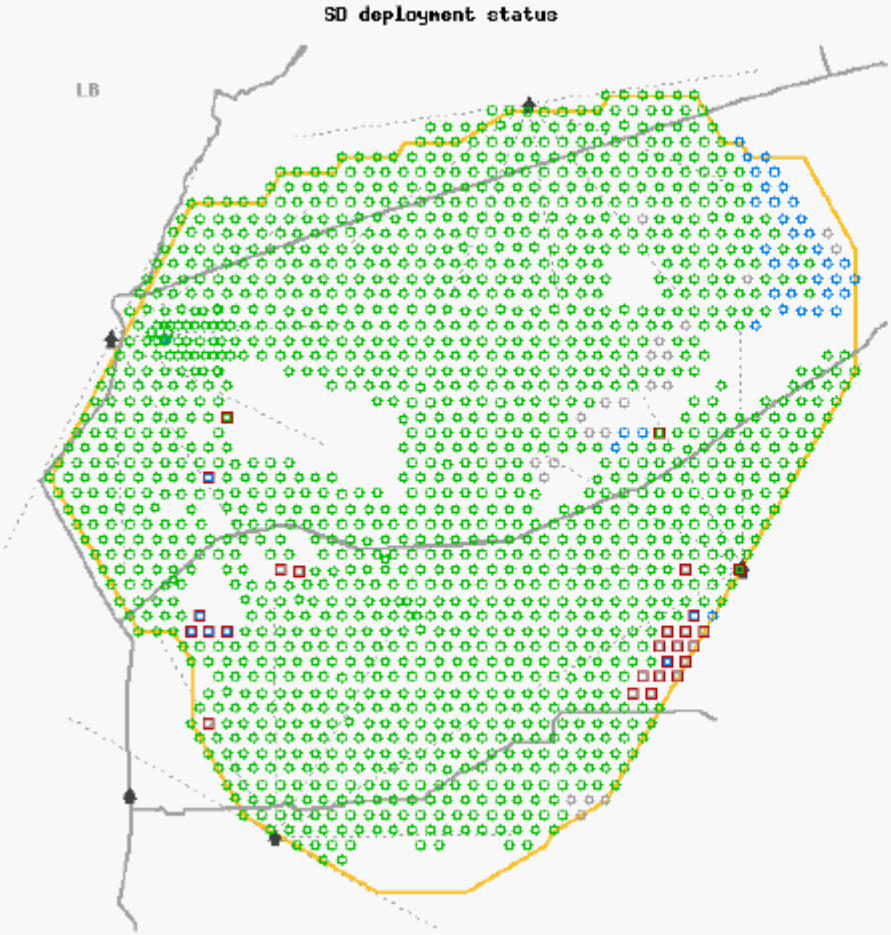
6 Telescopes per enclosure

24 Telescopes total

3000 km^2 area



Almost completely operating, now ~ 1 year full observatory !



Today

- 1539 tanks deployed
- 1501 with water
- 1456 with electronics

SD Data

- 972652 events <60°
- 720044 for analysis
- 4.8× AGASA

The Surface Detector

Water Cherenkov tank

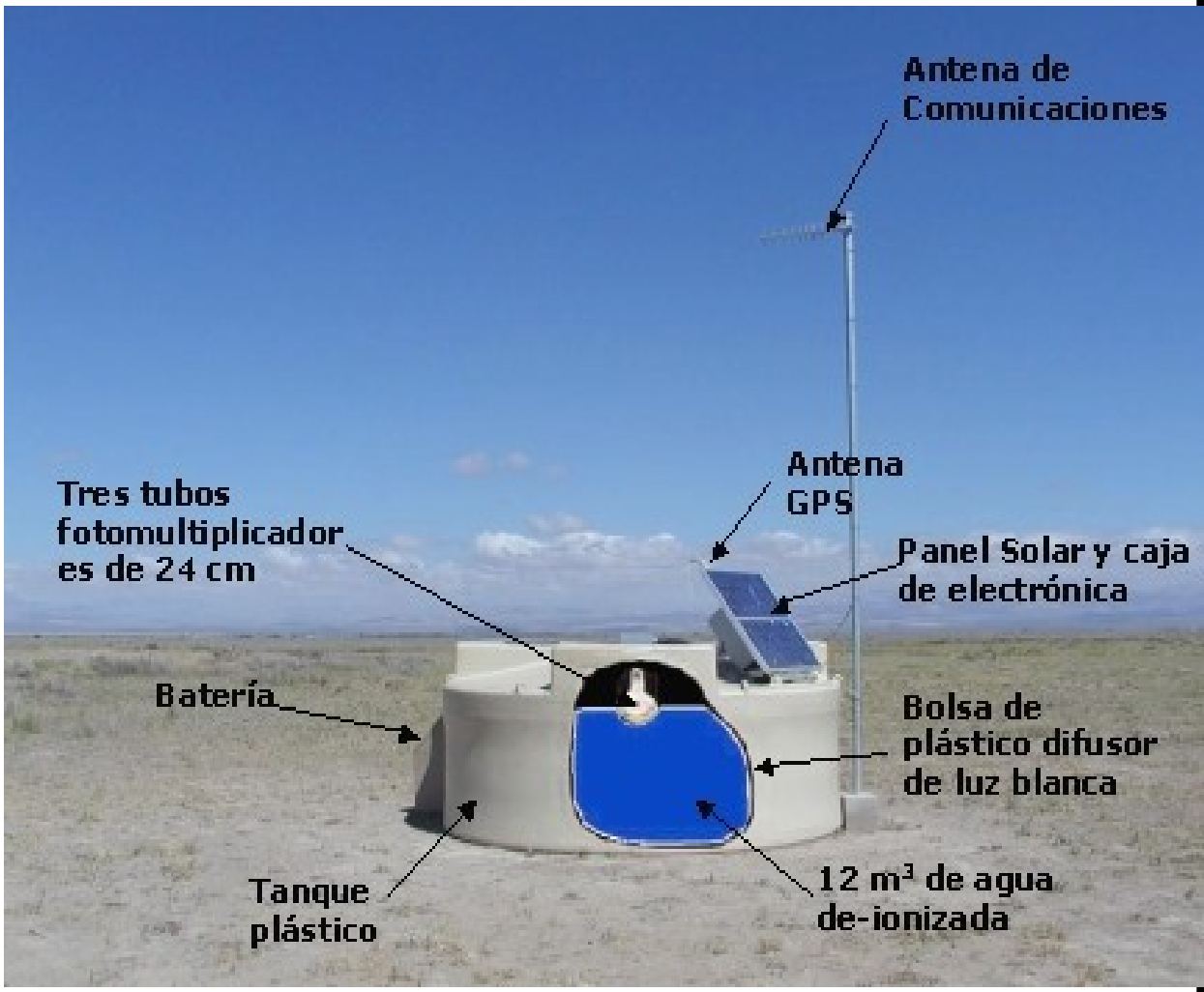
Rotomolded polyethylene tank

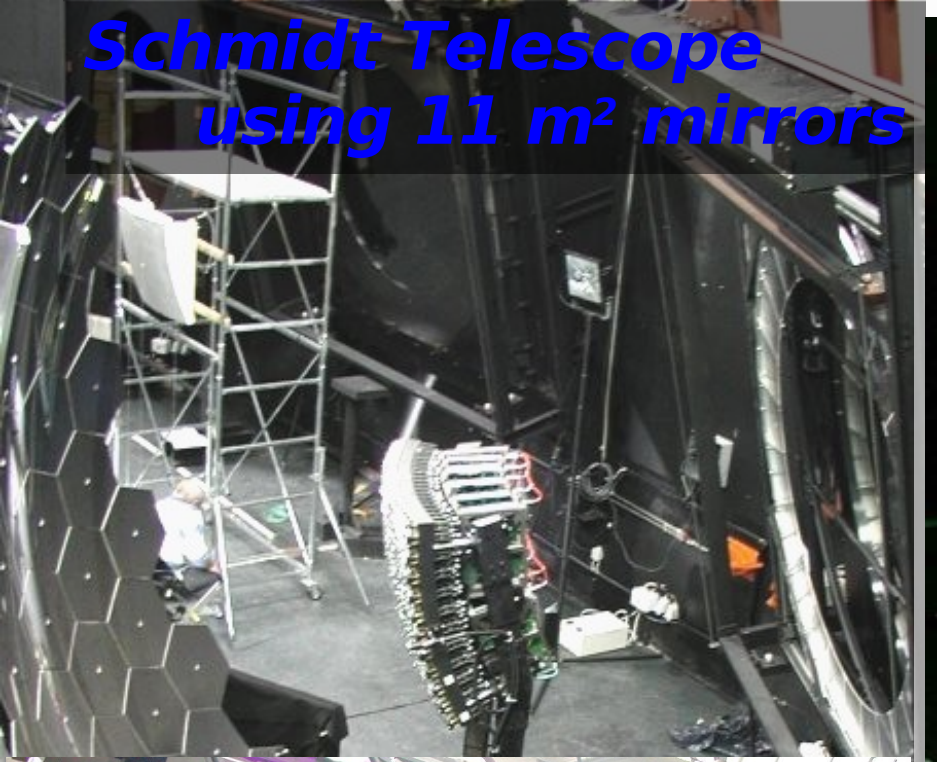
10 m^2 x 1.2 m of ultrapure water in a light diffusing Tyvek liner,

3 PMTs Photonis (9'' diameter);

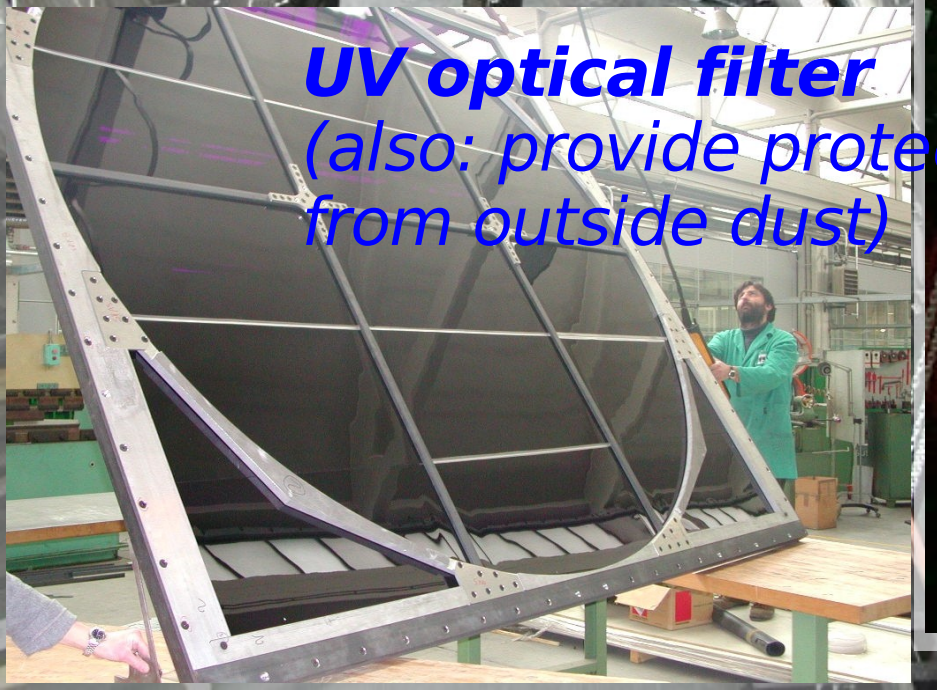
Autonomous unit: solar panel+battery, GPS timing, communication antenna, electronics

Max 10 W power consumption





Schmidt Telescope using 11 m² mirrors

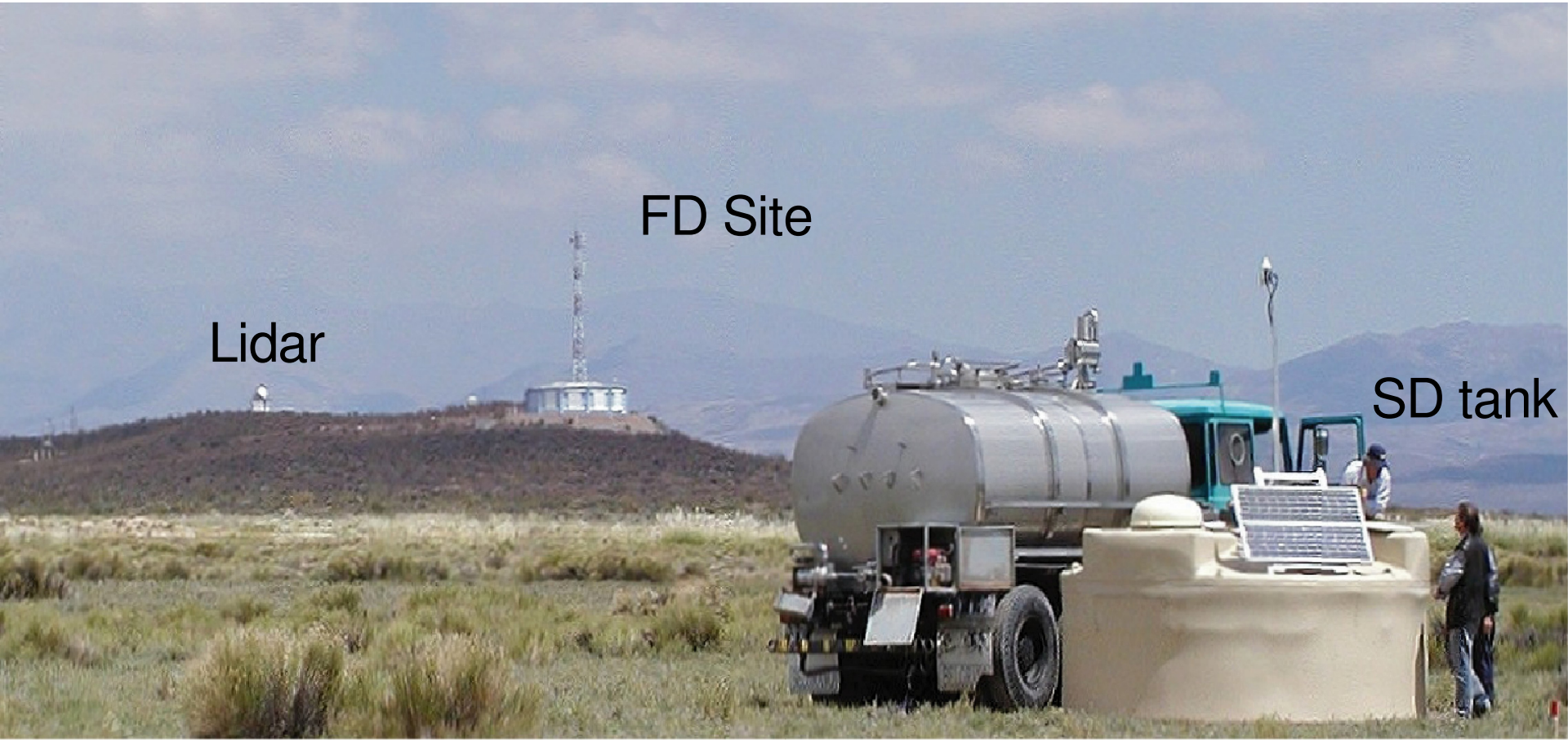


UV optical filter
(also: provide protection from outside dust)

The Fluorescence Detector

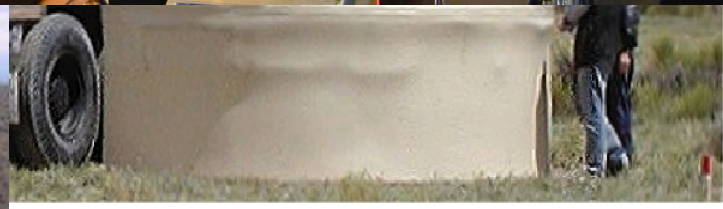
Camera with 440 PMTs
(Photonis XP 3062)


Schmidt Telescope
using 11 m² mirrors
Los Leones
(Photonis XP 3062)


FD Site
Lidar
SD tank

F

Men at work



Lidar

F

Men at work

Men in trouble...

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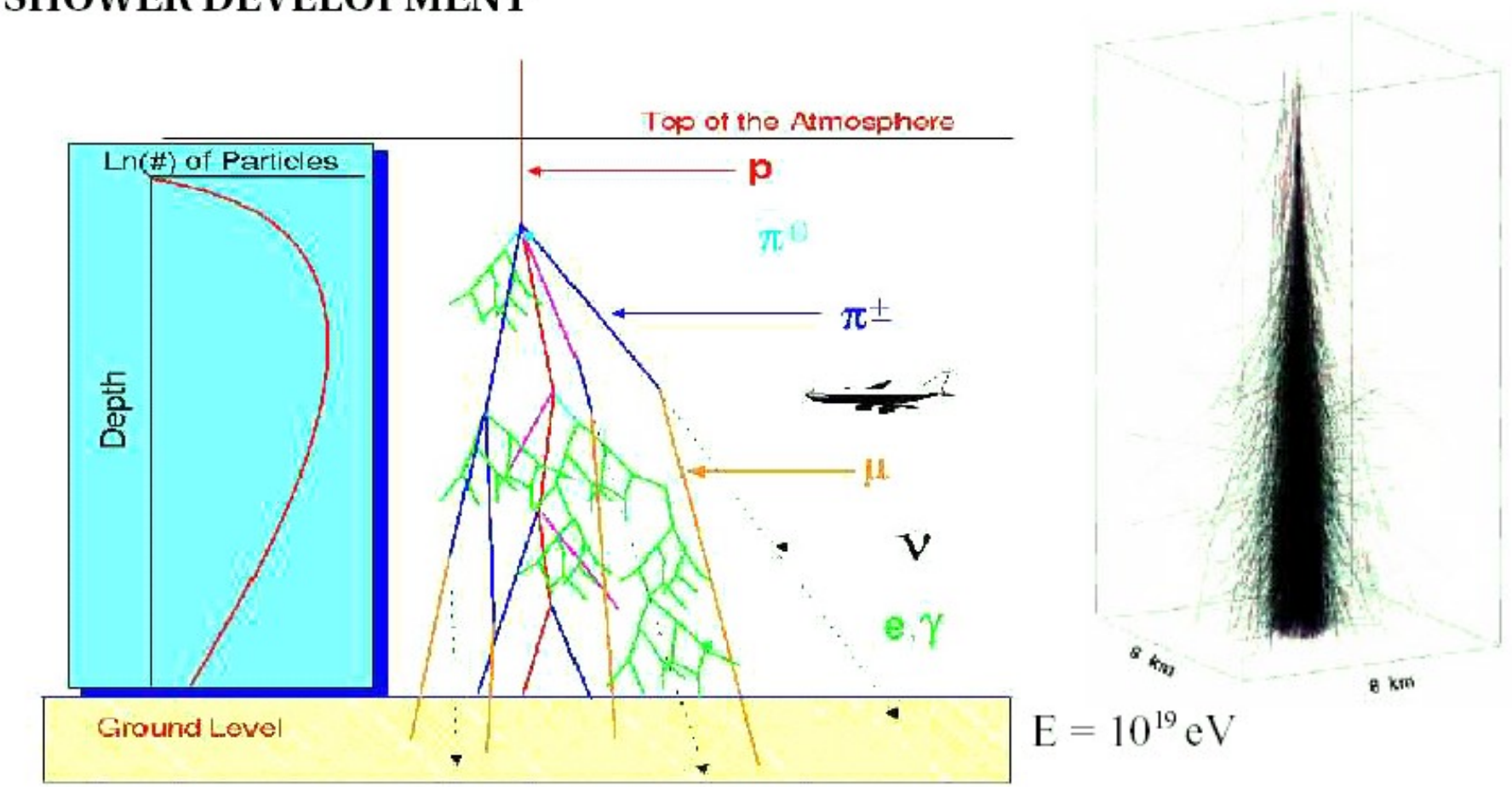
An UHECR shower: as it is...



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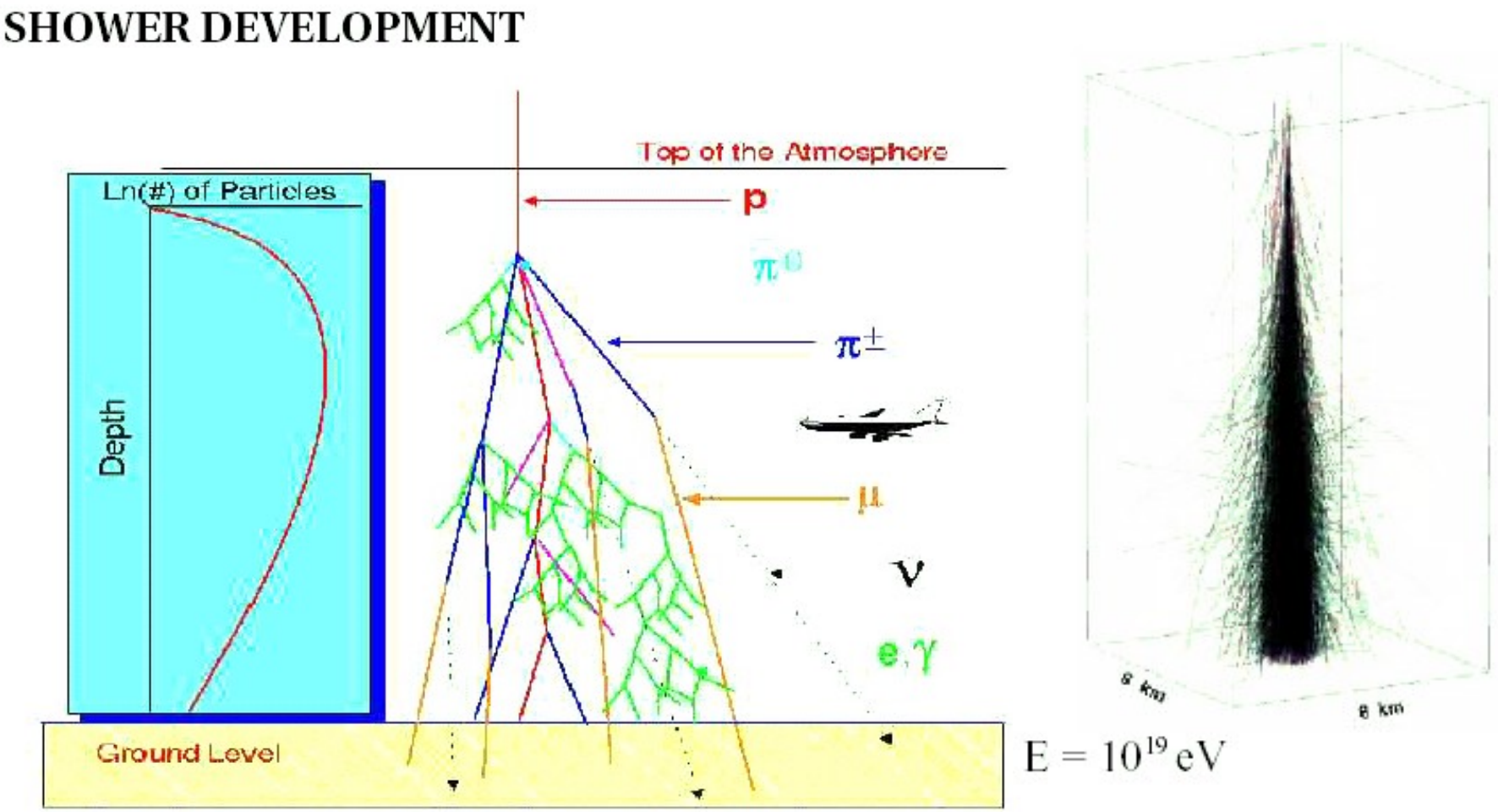


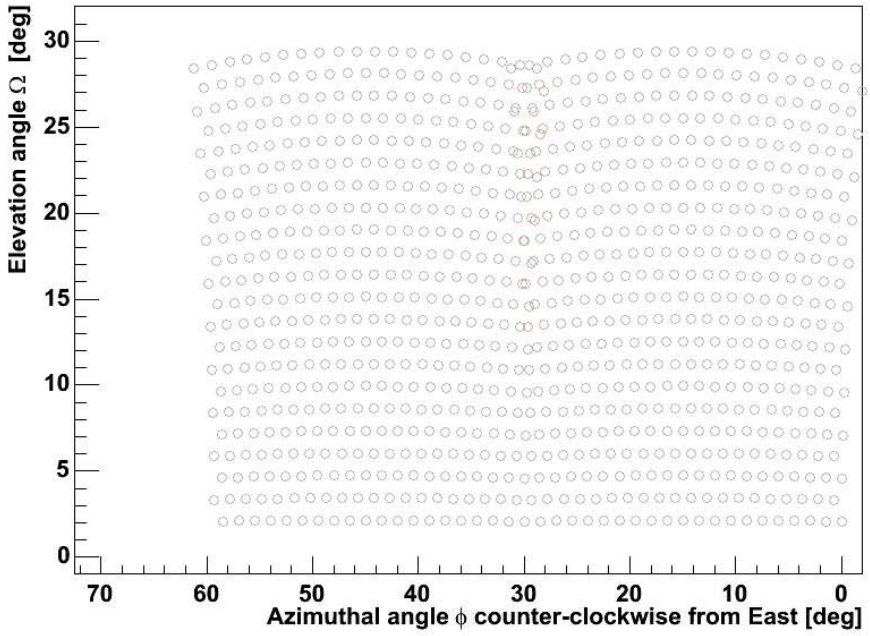
... as it appears

What's a "Hybrid" Event? (slide 7)

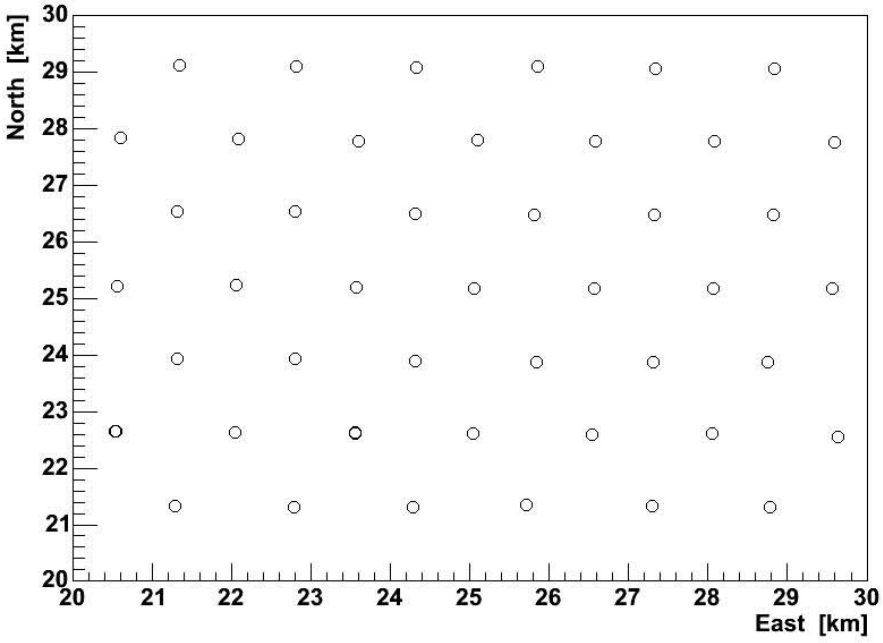
DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers



`FD`: Track in the sky



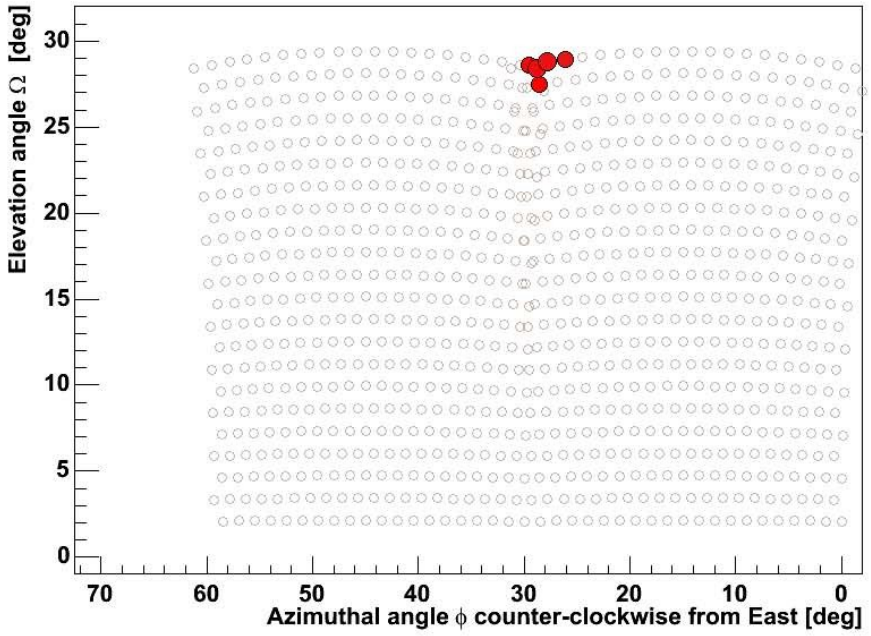
`SD`: Ground view

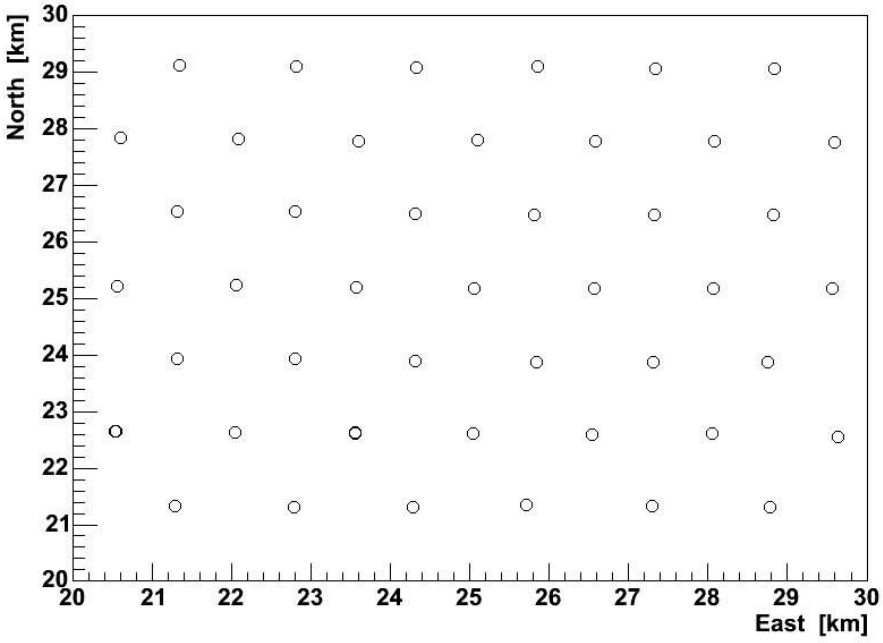
WHAT'S A "HYBRID" EVENT? (SLIDE 8)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

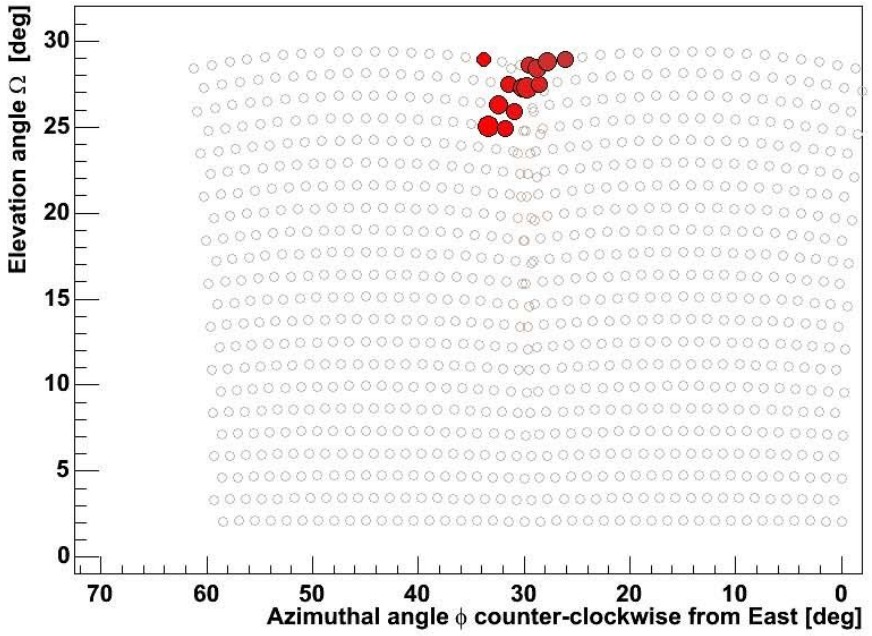
`SD`: Ground view

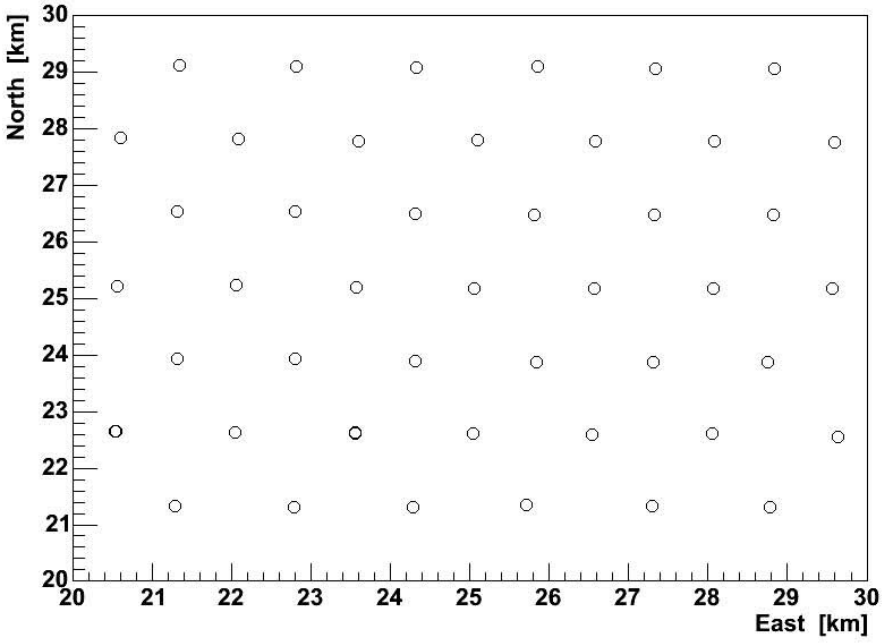
WHAT'S A "HYBRID" EVENT? (SLIDE 9)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

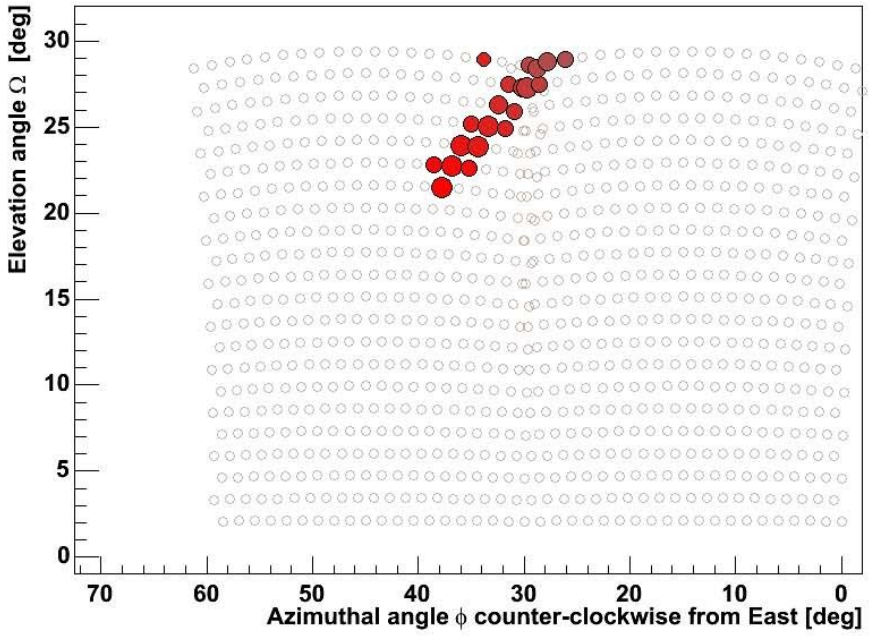
`SD`: Ground view

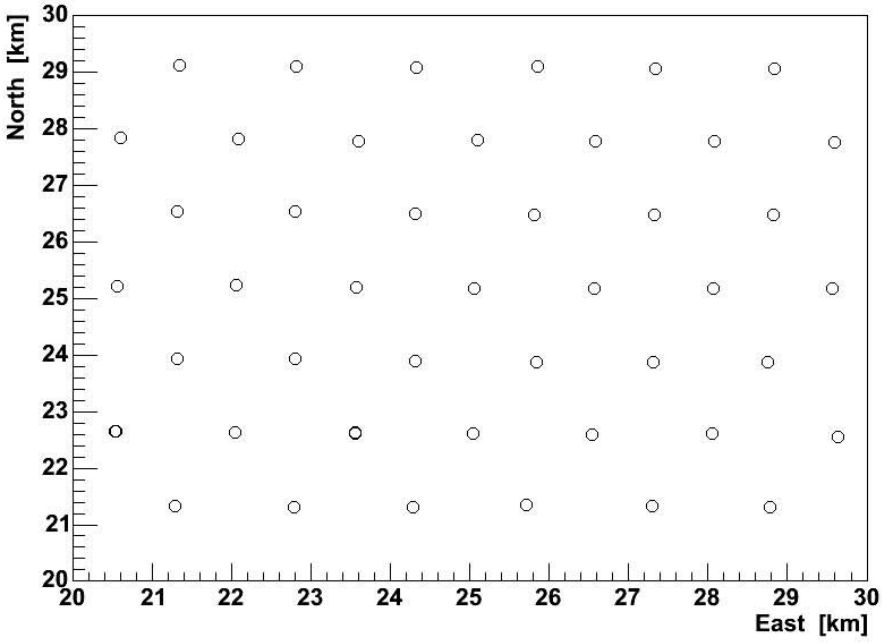
WHAT'S A "HYBRID" EVENT? (SLIDE 10)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

`SD`: Ground view

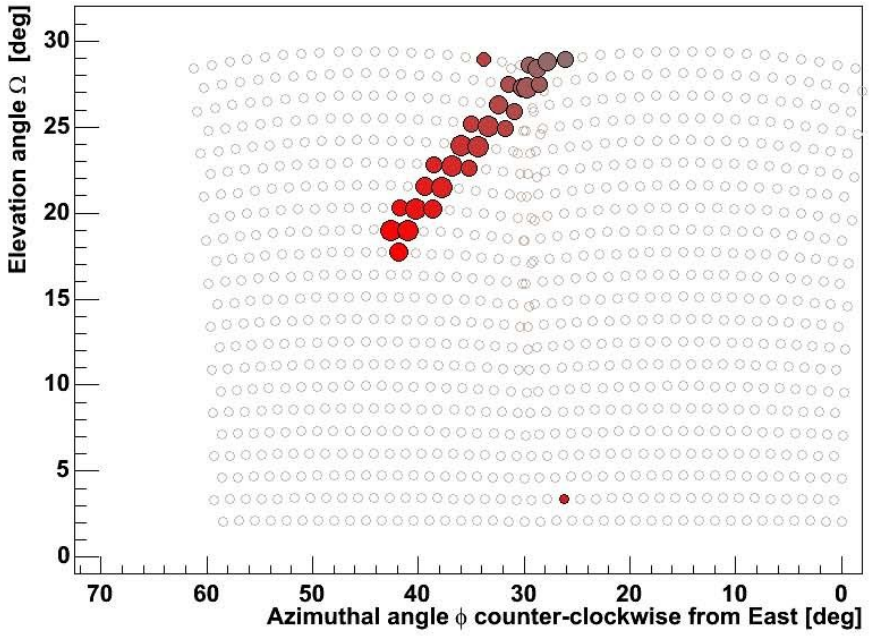
The University of New Mexico

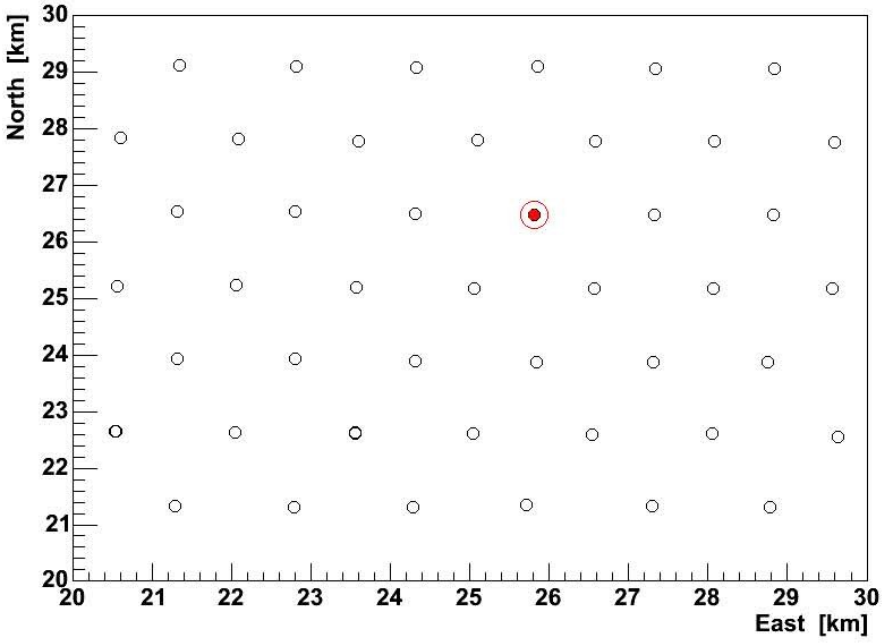
WHAT'S A "HYBRID" EVENT? (SLIDE 11)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

`SD`: Ground view

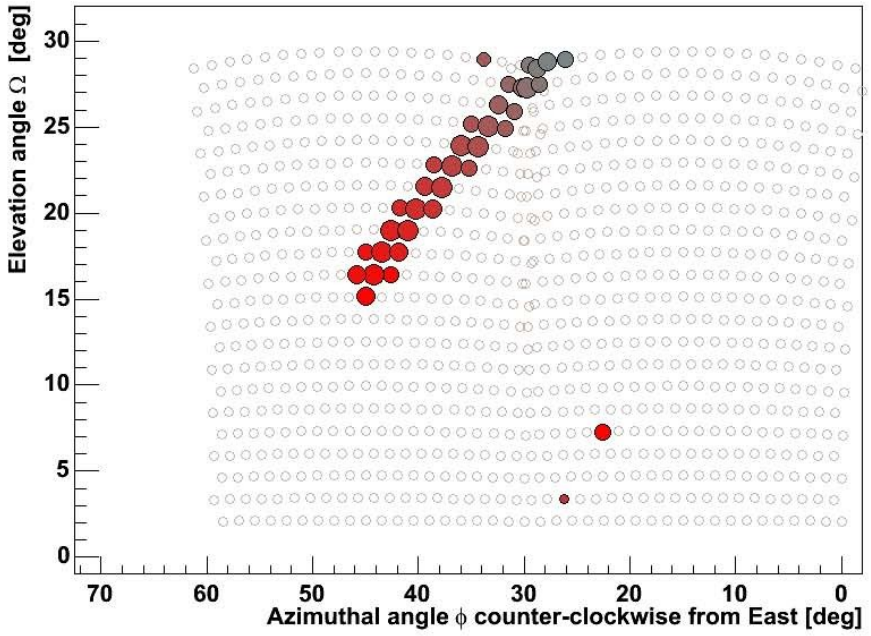
The University of New Mexico

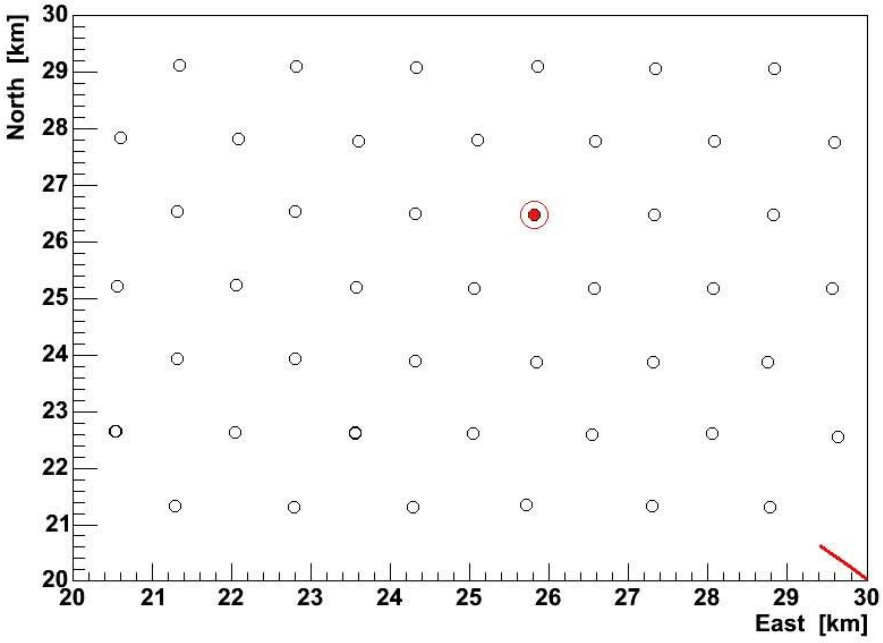
WHAT'S A "HYBRID" EVENT? (SLIDE 12)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

`SD`: Ground view

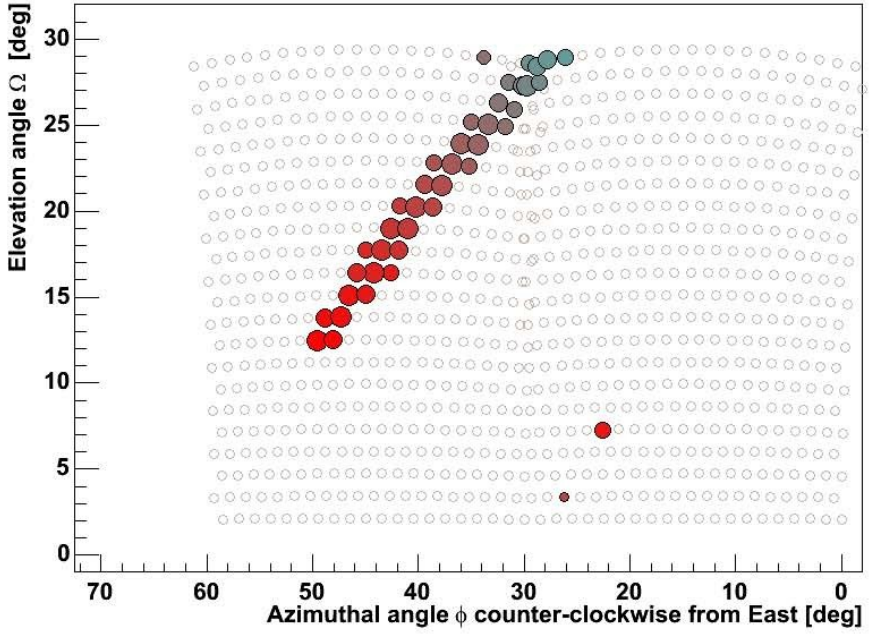
The University of New Mexico

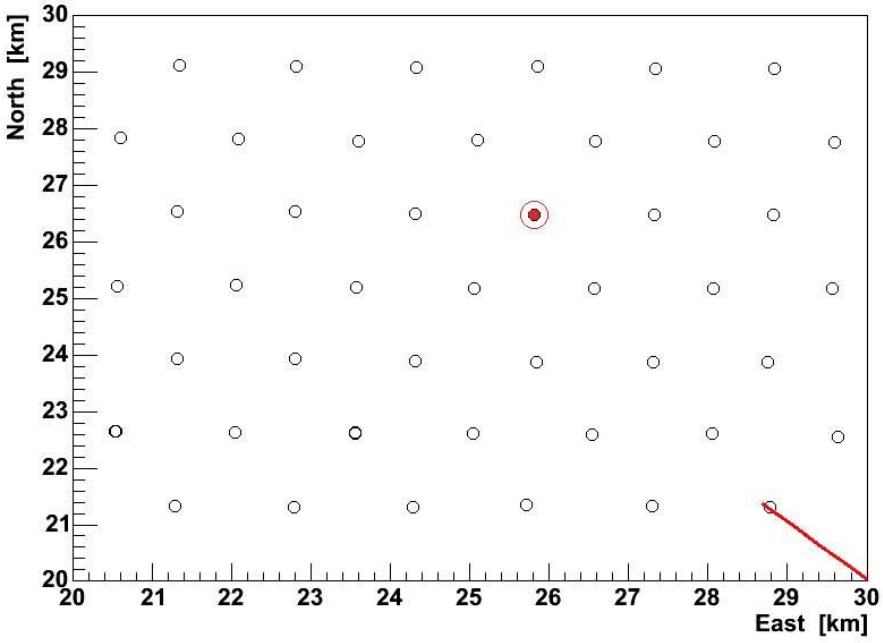
WHAT'S A "HYBRID" EVENT? (SLIDE 13)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

`SD`: Ground view

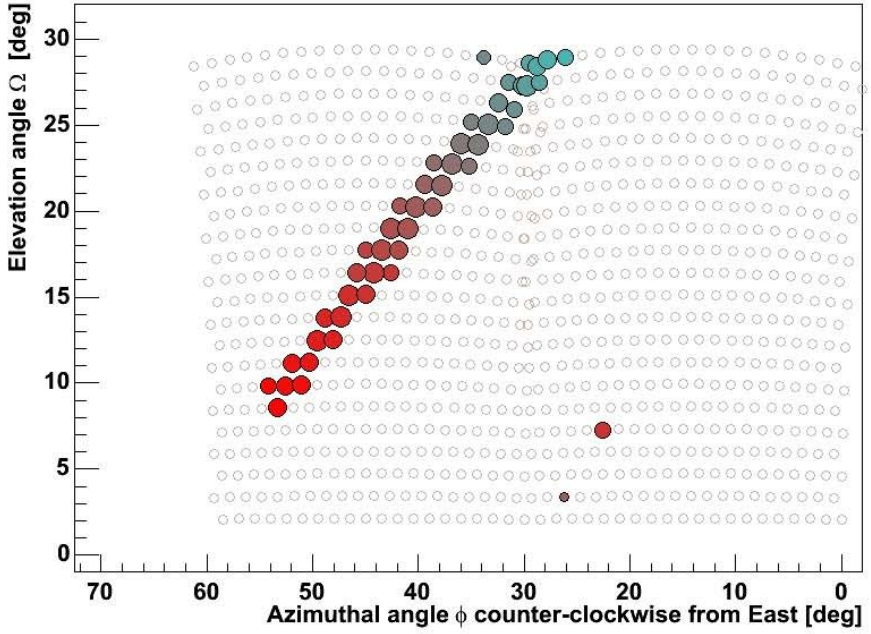
The University of New Mexico

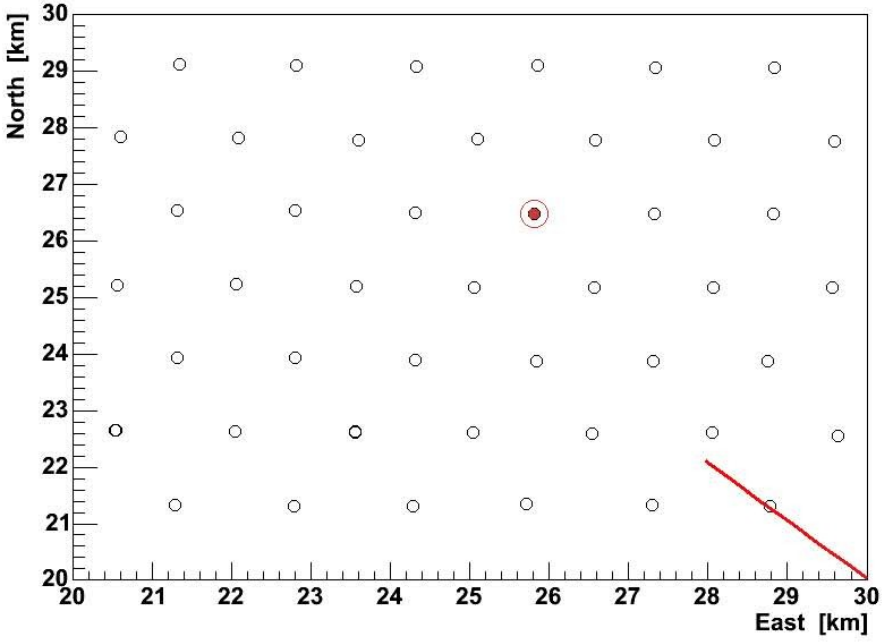
WHAT'S A "HYBRID" EVENT? (SLIDE 14)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

`SD`: Ground view

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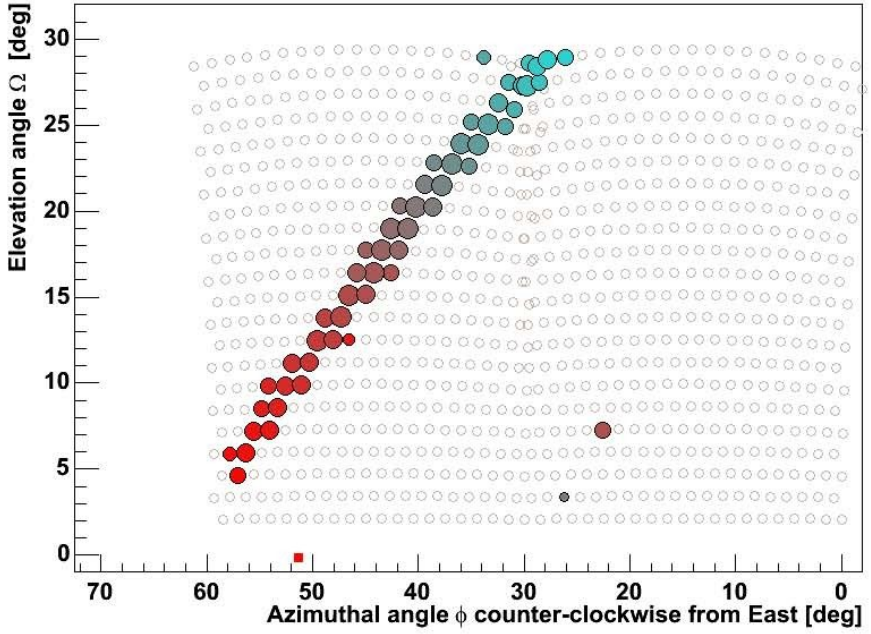
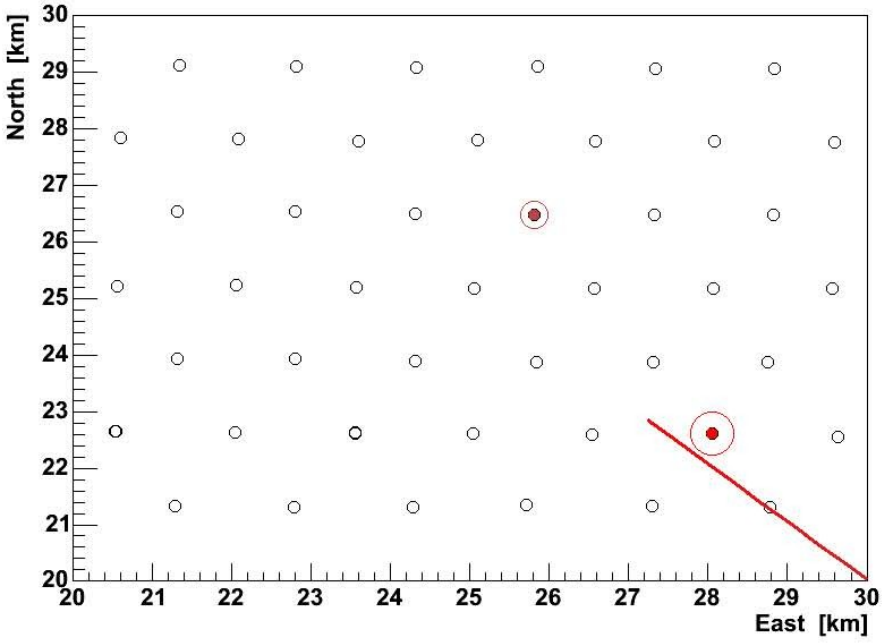
WHAT'S A "HYBRID" EVENT? (SLIDE 15)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

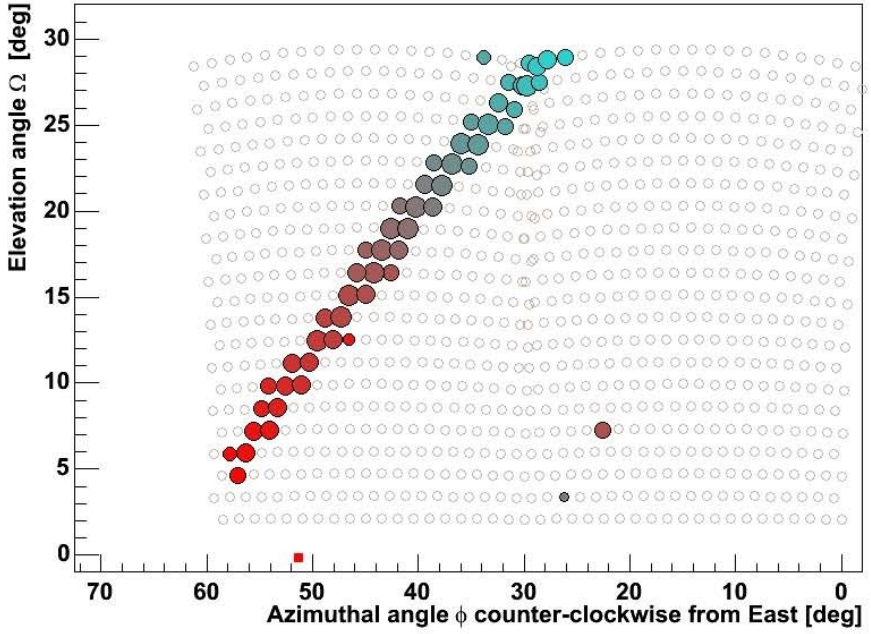
`SD`: Ground view

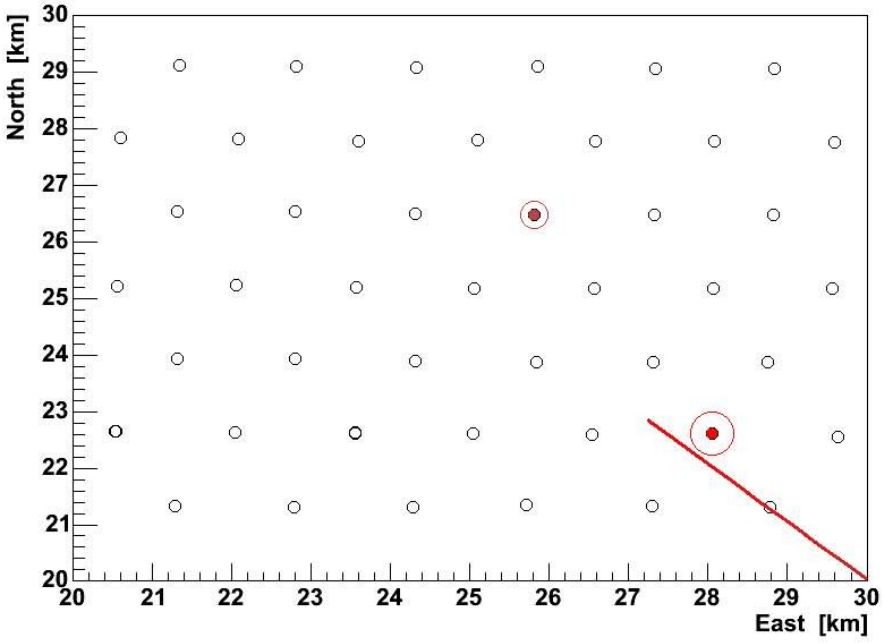
WHAT'S A "HYBRID" EVENT? (SLIDE 15)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

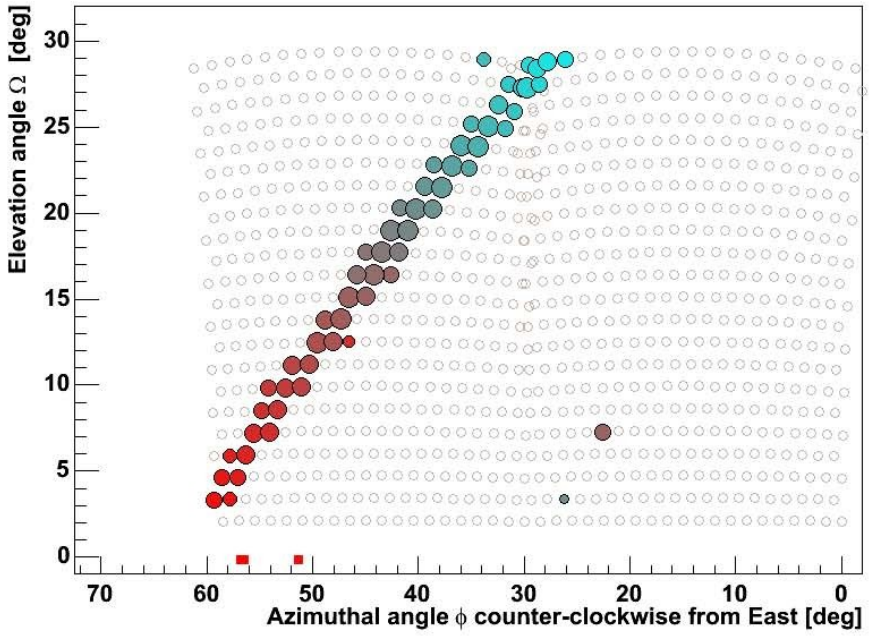
`SD`: Ground view

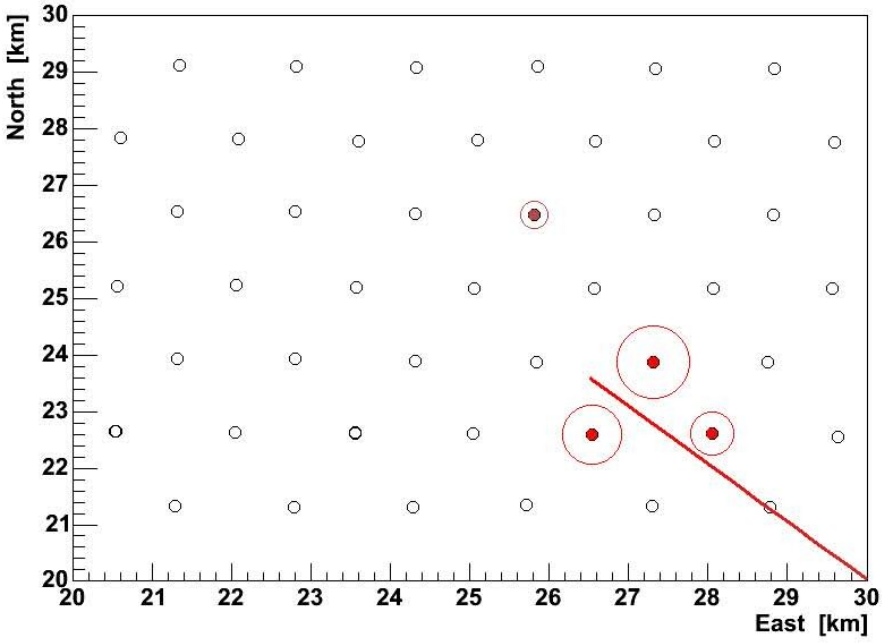
WHAT'S A "HYBRID" EVENT? (SLIDE 16)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

`SD`: Ground view

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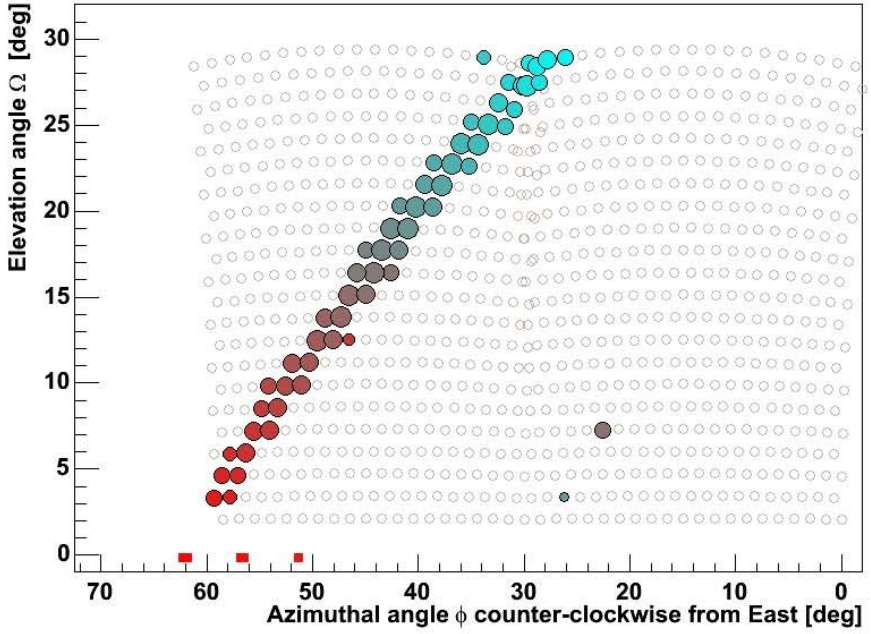
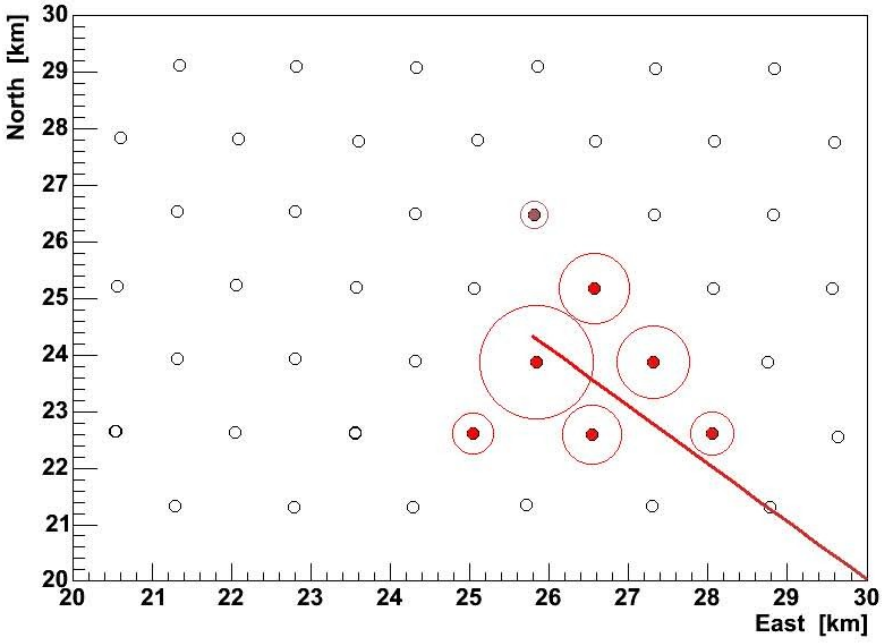
WHAT'S A "HYBRID" EVENT? (SLIDE 17)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

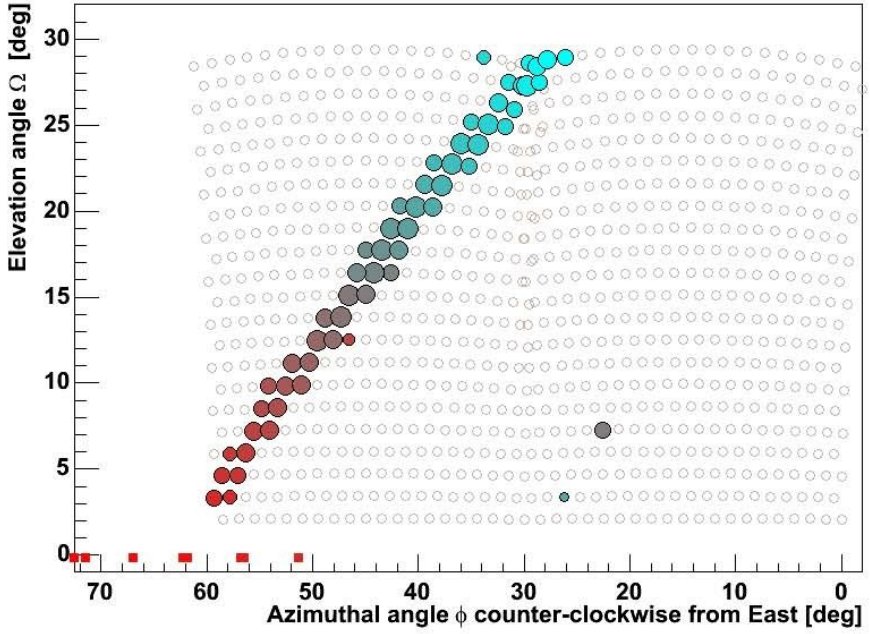
`SD`: Ground view

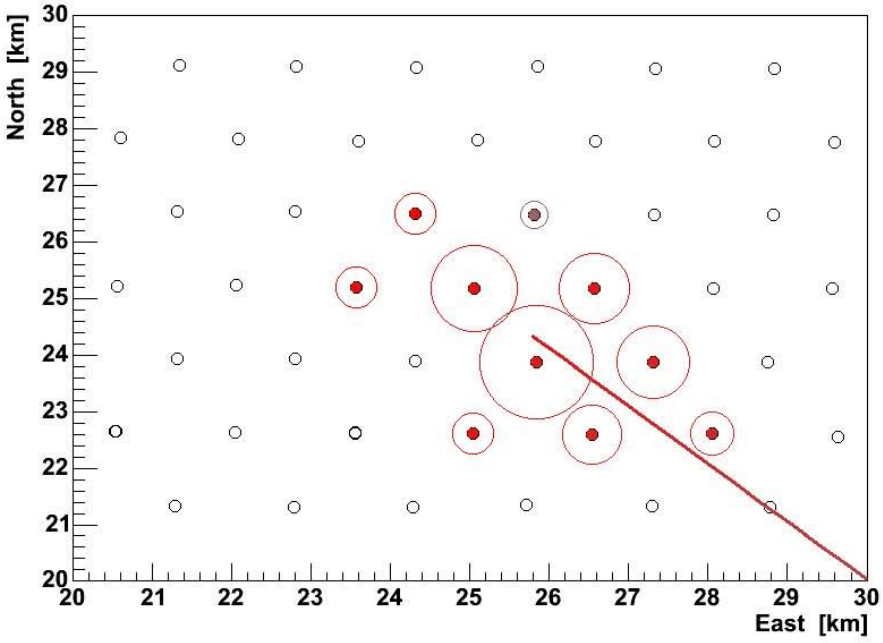
WHAT'S A "HYBRID" EVENT? (SLIDE 18)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers





`FD`: Track in the sky

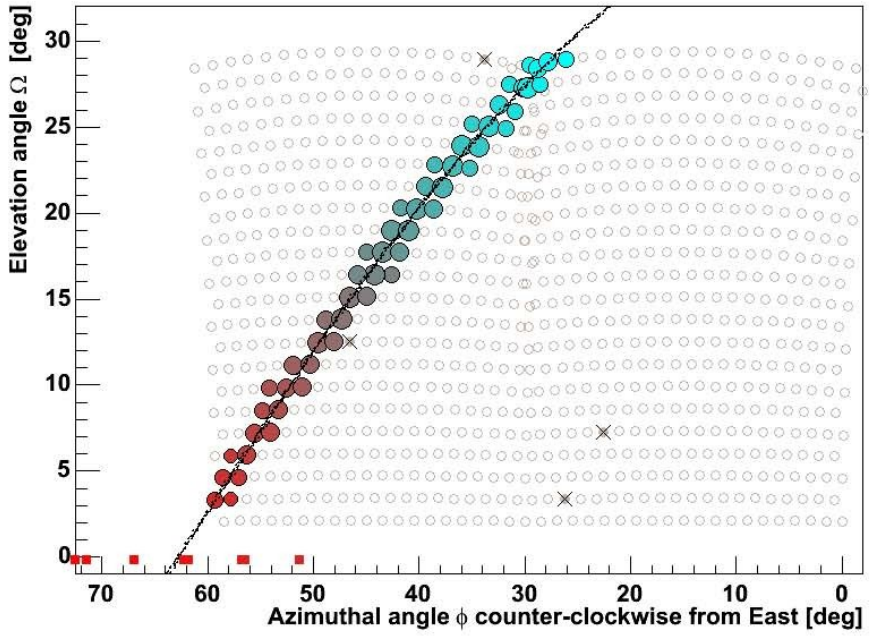
`SD`: Ground view

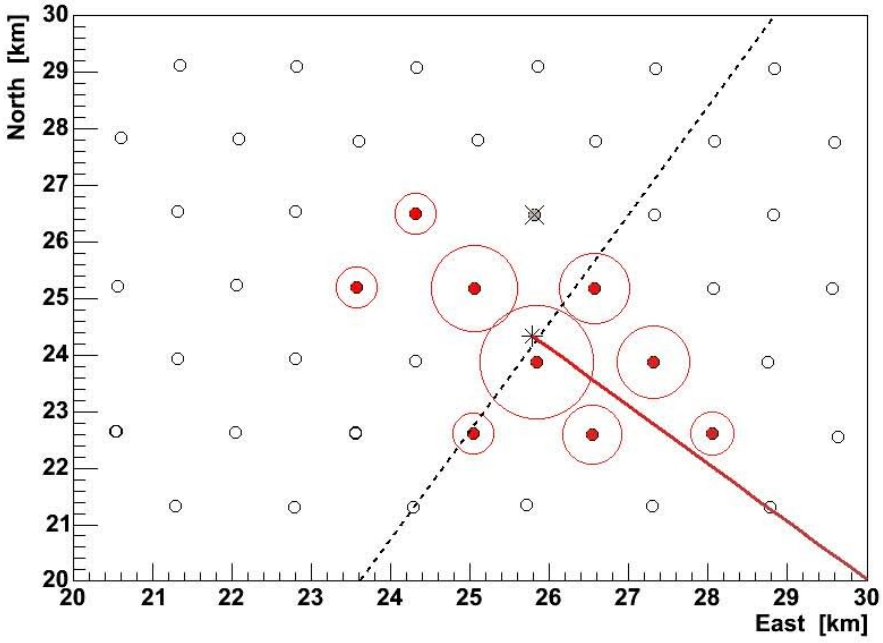
WHAT'S A "HYBRID" EVENT? (SLIDE 19)

DEFINITION

`Simultaneous` detection in the sky **and** at ground

- Golden Events: independent triggers



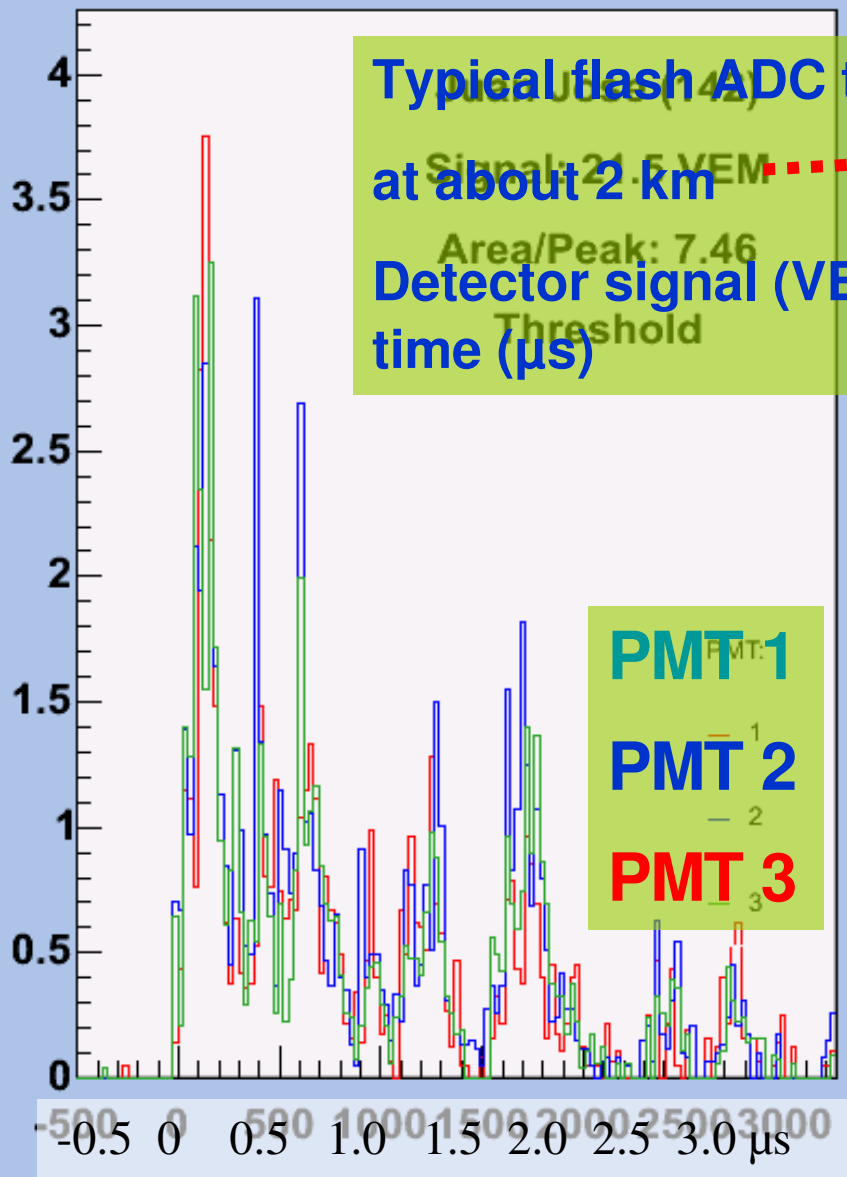


`FD`: Track in the sky

`SD`: Ground view

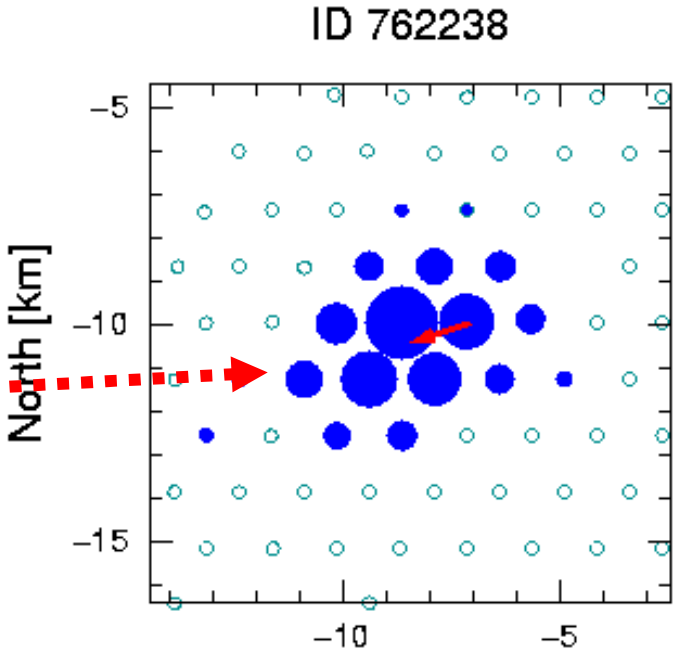
θ~ 48°, E ~ 70 EeV

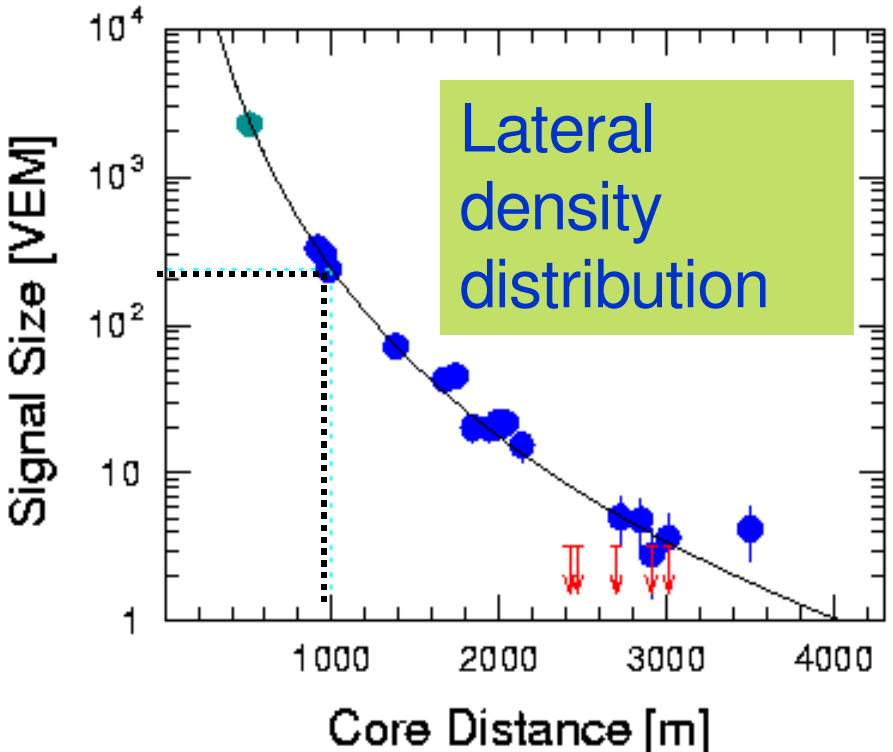
18 detectors triggered

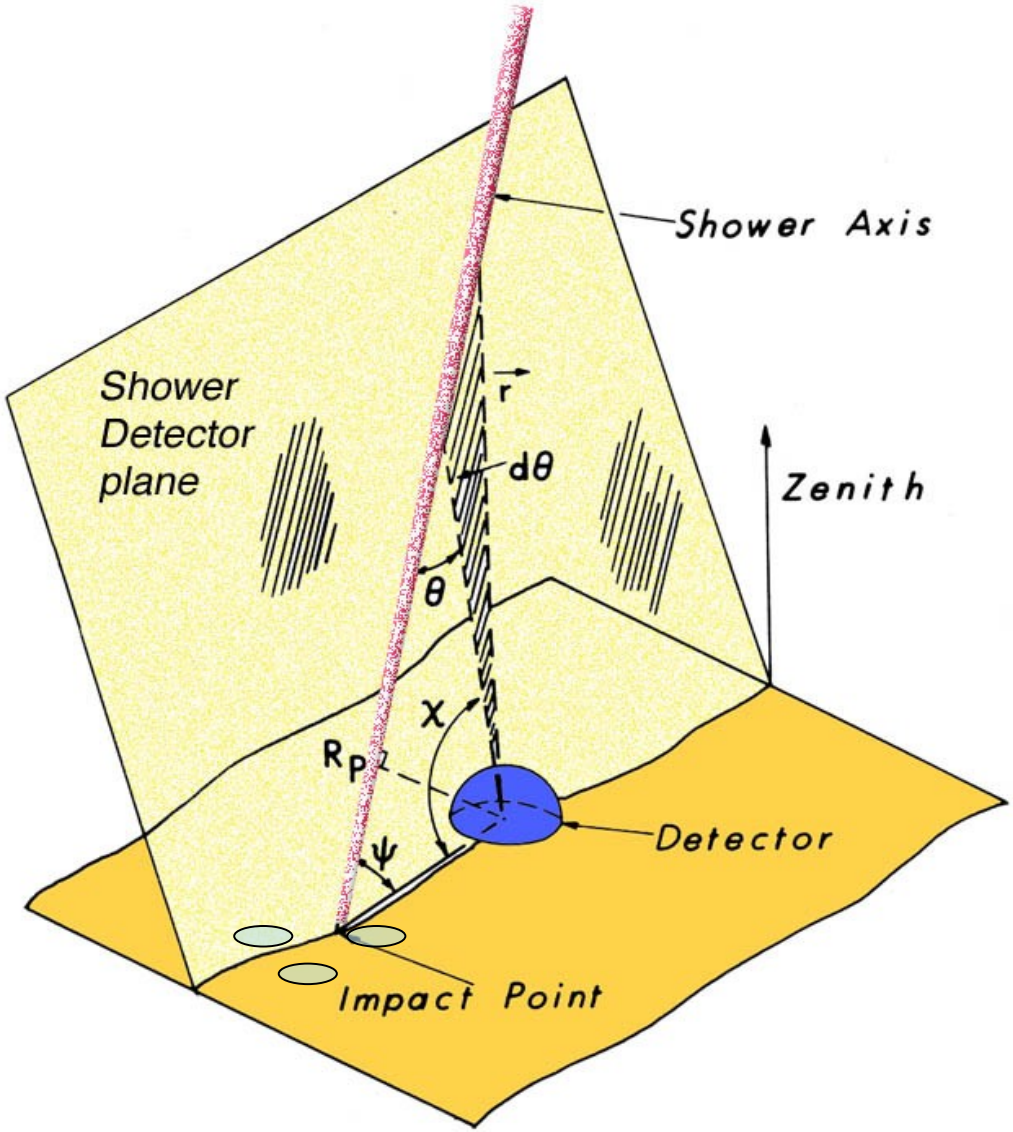


Typical flash ADC trace at about 2 km

Detector signal (VEM) vs time (µs)







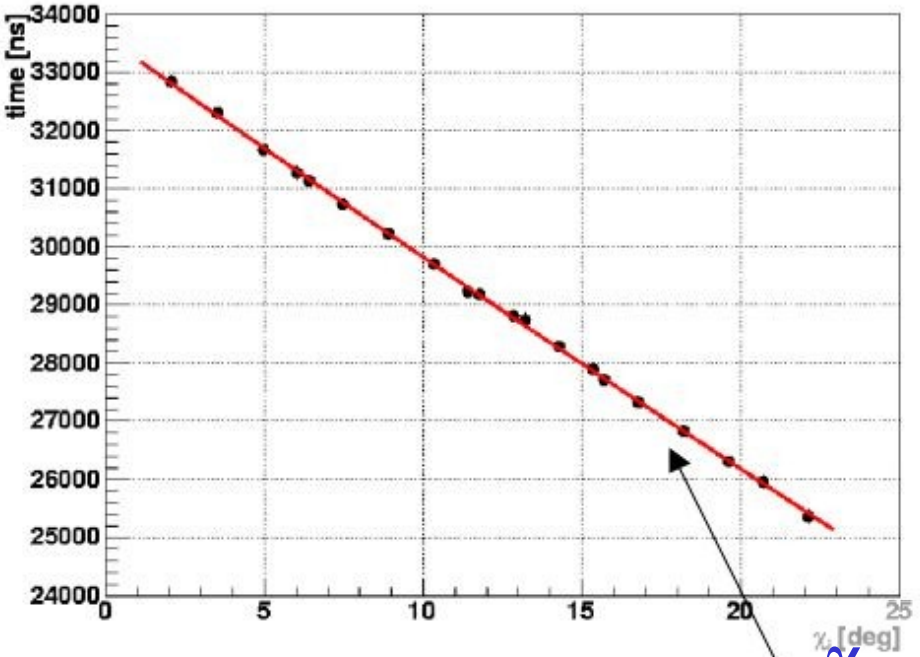
The essence of the hybrid approach

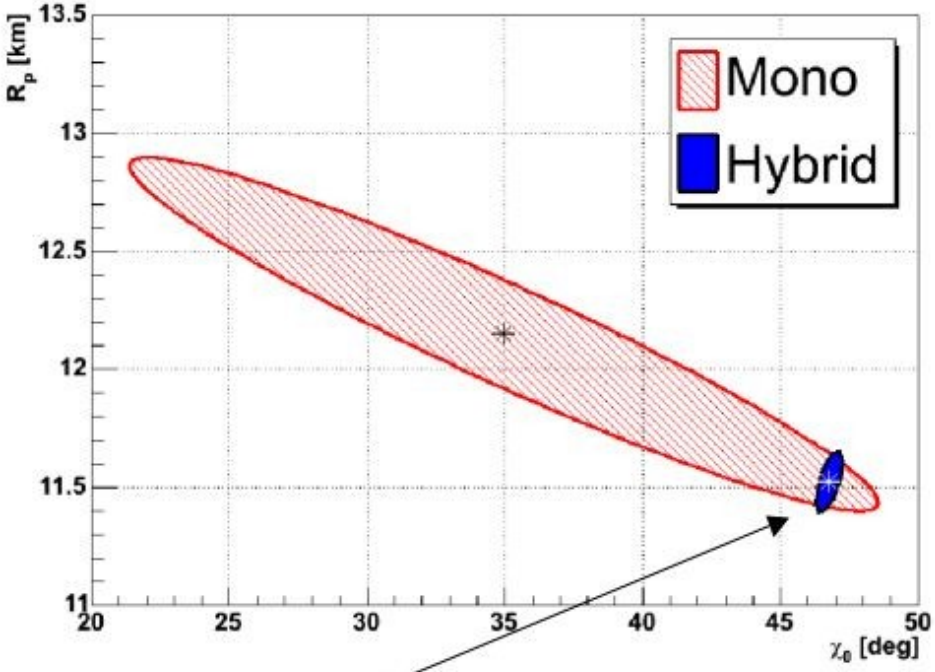
Precise shower geometry removing degeneracy by SD timing

Essential step towards high quality energy and X_{max} resolution

Times at angles, χ, are key to finding R_p

Hybrid Reconstruction





χ

≈ line but

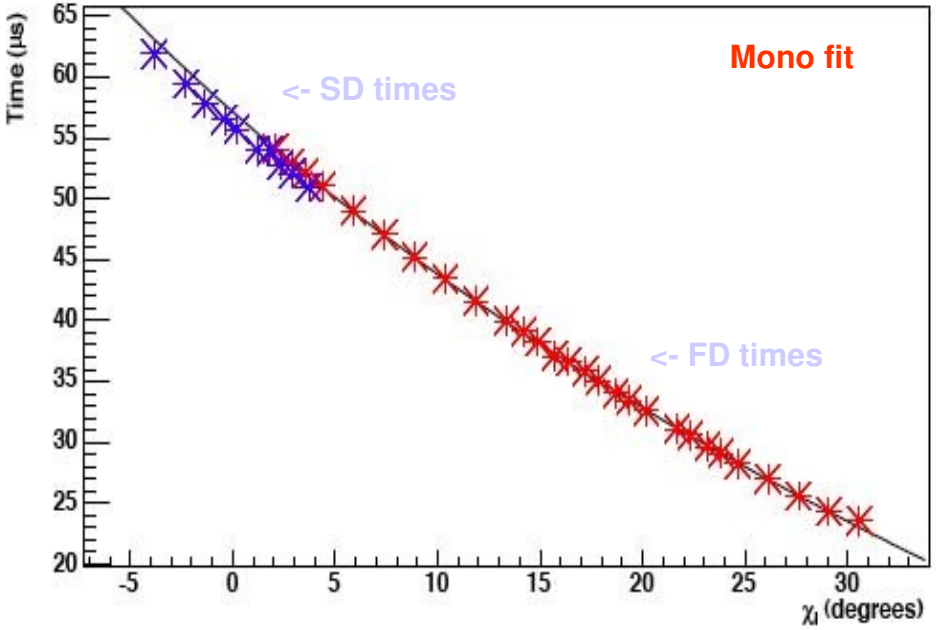
3 free parameters

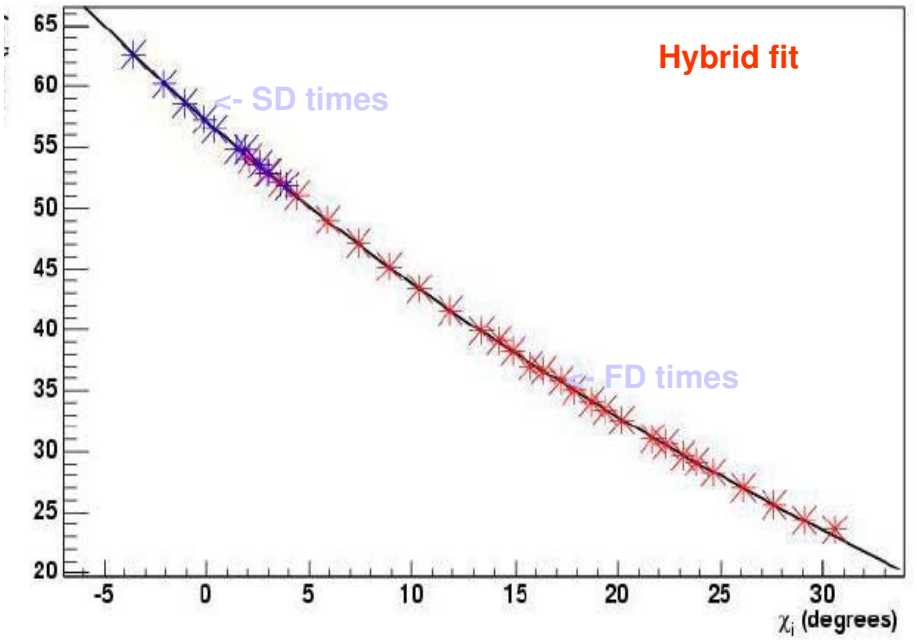
T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

Event 673411

Hybrid Reconstruction



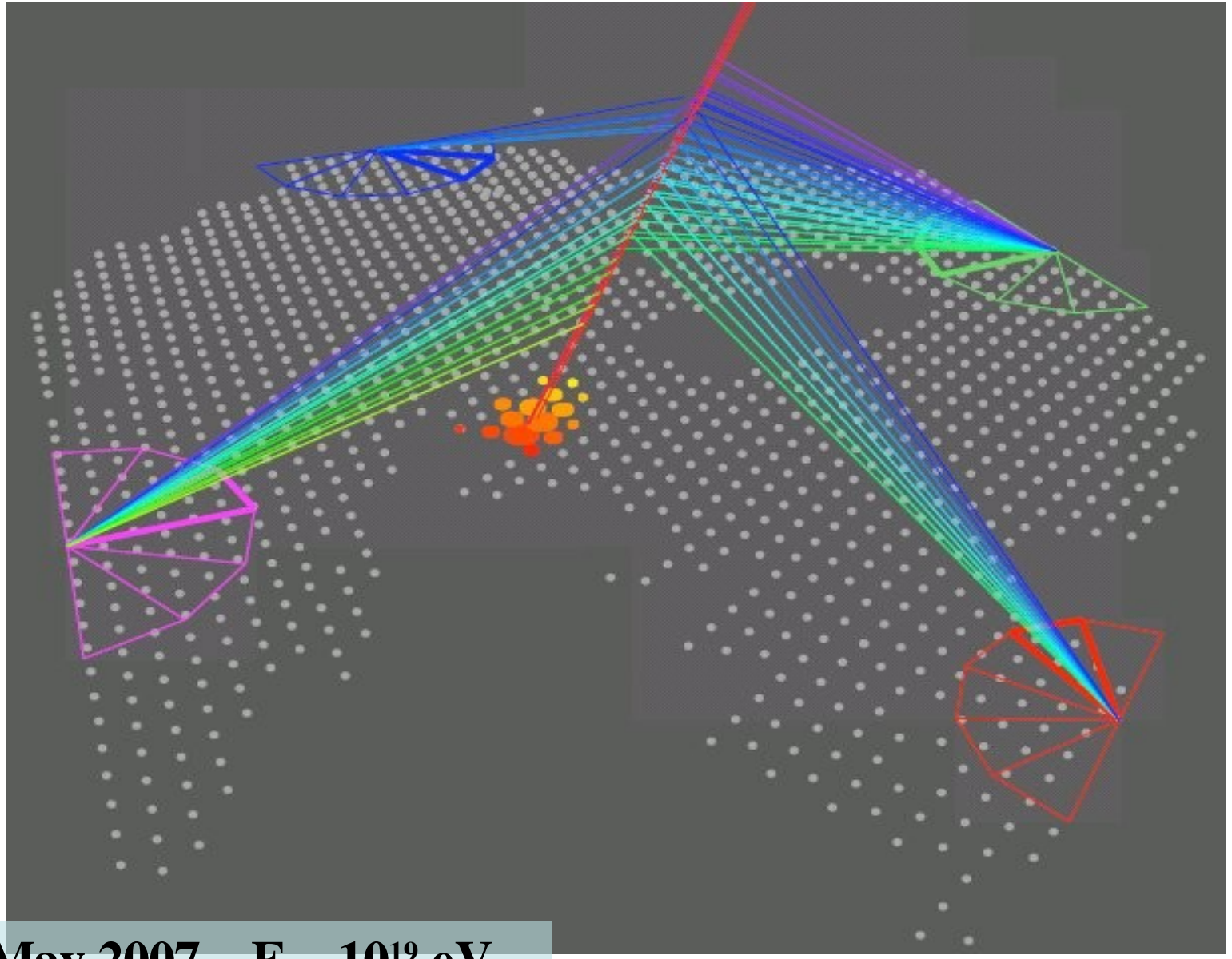


	Hybrid (Los Leones)	Surface	Difference
Easting	465960 ± 80	465830	130 m
Northing	6090234 ± 20	6090308	-74 m
Theta	36.7 deg	35.9 deg	0.8 deg
Phi	185.8 deg	186.7 deg	-0.9 deg

The Hybrid Era

	Hybrid	*SD-only*	*FD-only mono*
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5°
Aperture	*E,A, and M dependence reduced by hybrid geo.*	*Flat with energy mass (A) and model (M) free*	*E, A, and M dependent*
Energy	*A and M free*	*A and M dependent, but adopted hybrid calibration*	*A and M free*

The first 4-fold stereo-hybrid



20 May 2007 E ~ 10^{19} eV

- La fisica di Auger
- L'Osservatorio
- Rivelazione e analisi degli sciami
- Risultati recenti:
  - → *Spettro*
  - → *Composizione*
  - → *Astronomia*
- Conclusioni

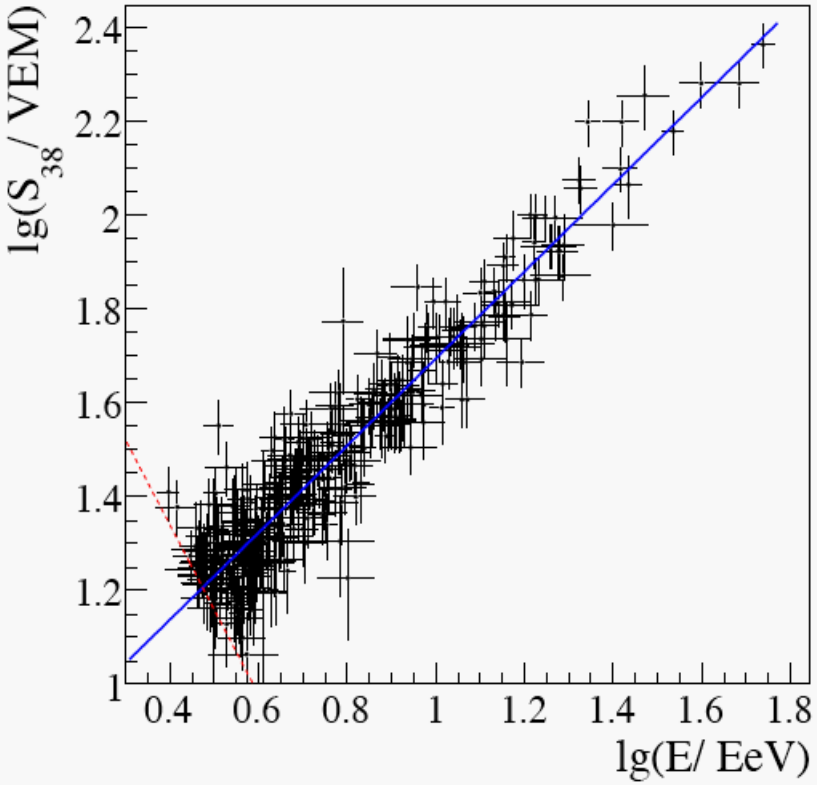
The first physics results

- *35 papers (17 oral + 18 posters) presented at the Merida **ICRC 2007** conference*
- *4 science papers:*
  - *FD Upper Limit on the Cosmic-Ray Photon Flux, **Astropart. Phys.** 27 (2007), 155.*
  - *Anisotropy studies around the galactic centre, **Astropart. Phys.** 27 (2007), 244.*
  - *Correlation of UHECR with nearby extragalactic objects, **Science** 318, 939 (9 November 2007) (arXiv:0711.2256v1).*
  - *SD Upper Limit on the Cosmic-Ray Photon Flux, subm. to **Astropart. Phys.** (arXiv:0712.1147)*
- *New papers coming soon on:*
  - *Energy spectrum*
  - *Search for sources (3 papers)*
  - *Tau-neutrino limit*

The energy spectrum

- *The most statistically significant from SD*
- *calibrated in energy by "golden hybrid" events*
- *energy systematic error ~22 %*

mostly from systematics of the FD detector (fluorescence yield, atmospheric transparency...)

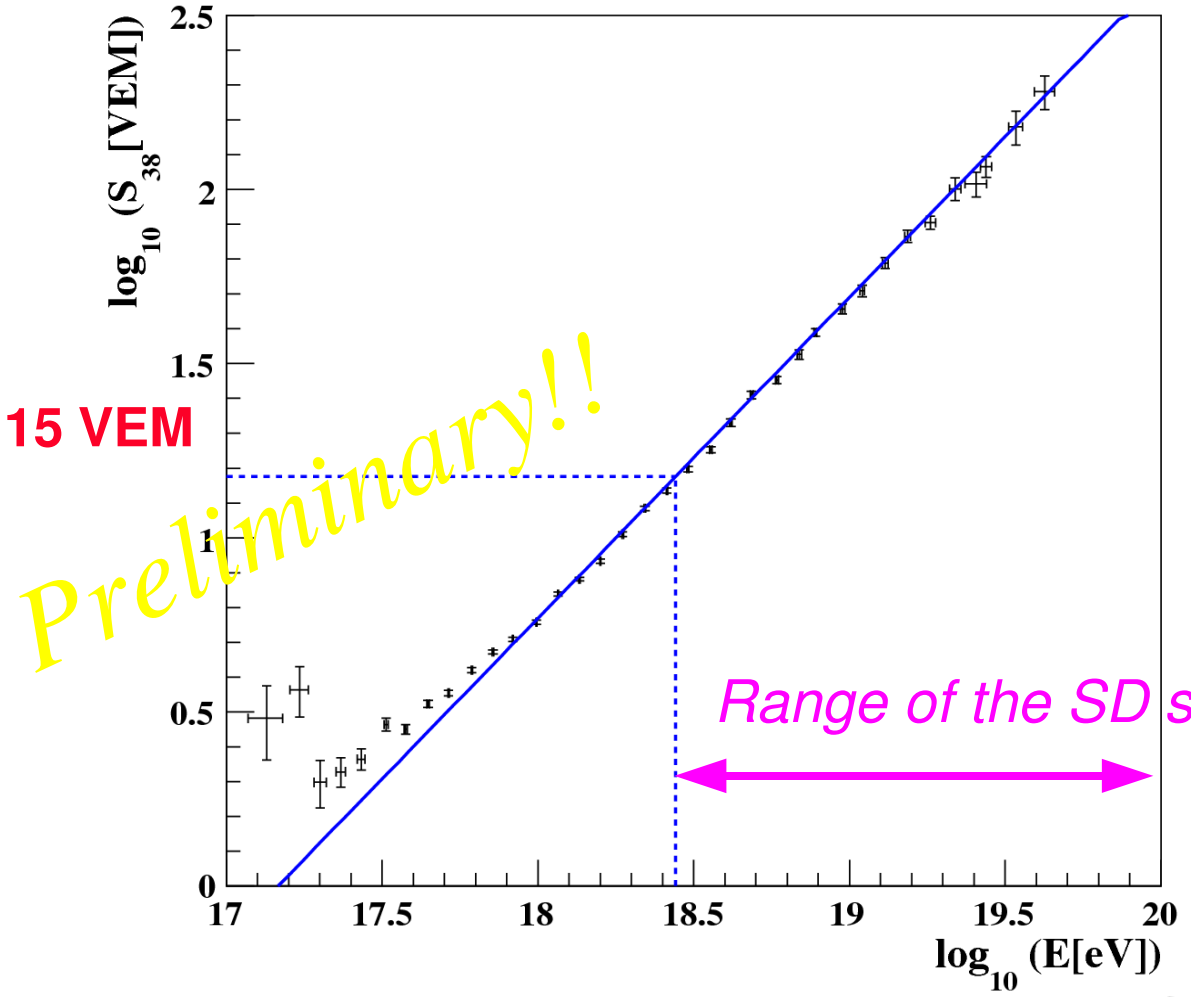


From S(1000) to S_{38}

Need to normalize atmos. absorption
S_{38}: S(1000) of a shower at $\theta = 38^\circ$
Determined by CIC

- $E(EeV) = (0.149 \pm 0.009)\ S_{38}{}^{1.078\pm0.017}$

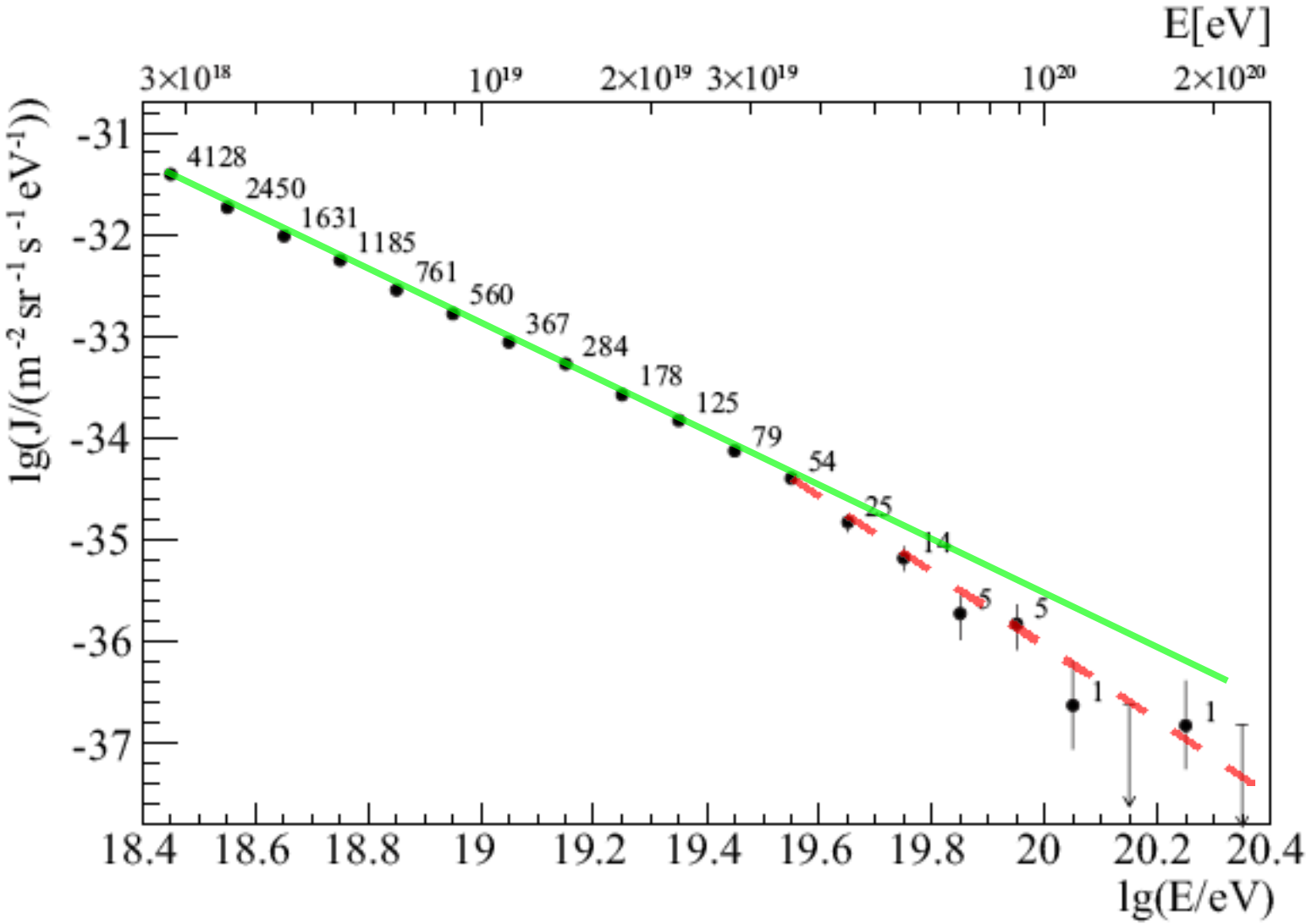
Linearity



estimated. The parameters of the calibration curve $E = 10^A S_{38}^B = R S_{38}^B$ for the hybrid data sample reprocessed with recent AIRFLY measurement are:

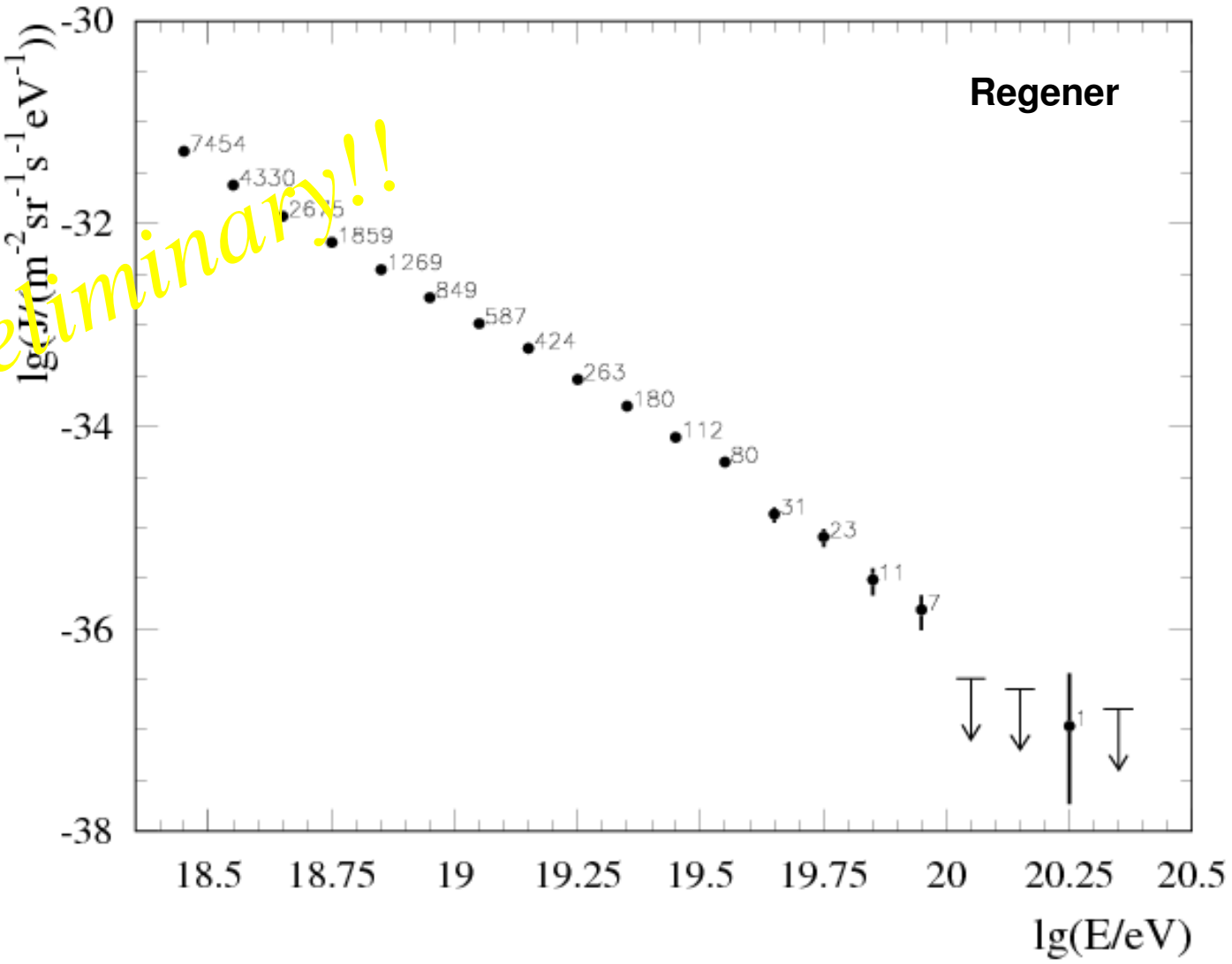
$$A = 17.168 \pm 0.017_{stat} \pm 0.033_{syst}$$
$$R = (1.47 \pm 0.06_{stat} \pm 0.12_{syst}) \cdot 10^{17} \text{ eV}$$
$$B = 1.088 \pm 0.013_{stat} \pm 0.037_{syst}$$

Ultra High Energy CR spectrum ICRC07



latest analysis **7000 km sr yr**

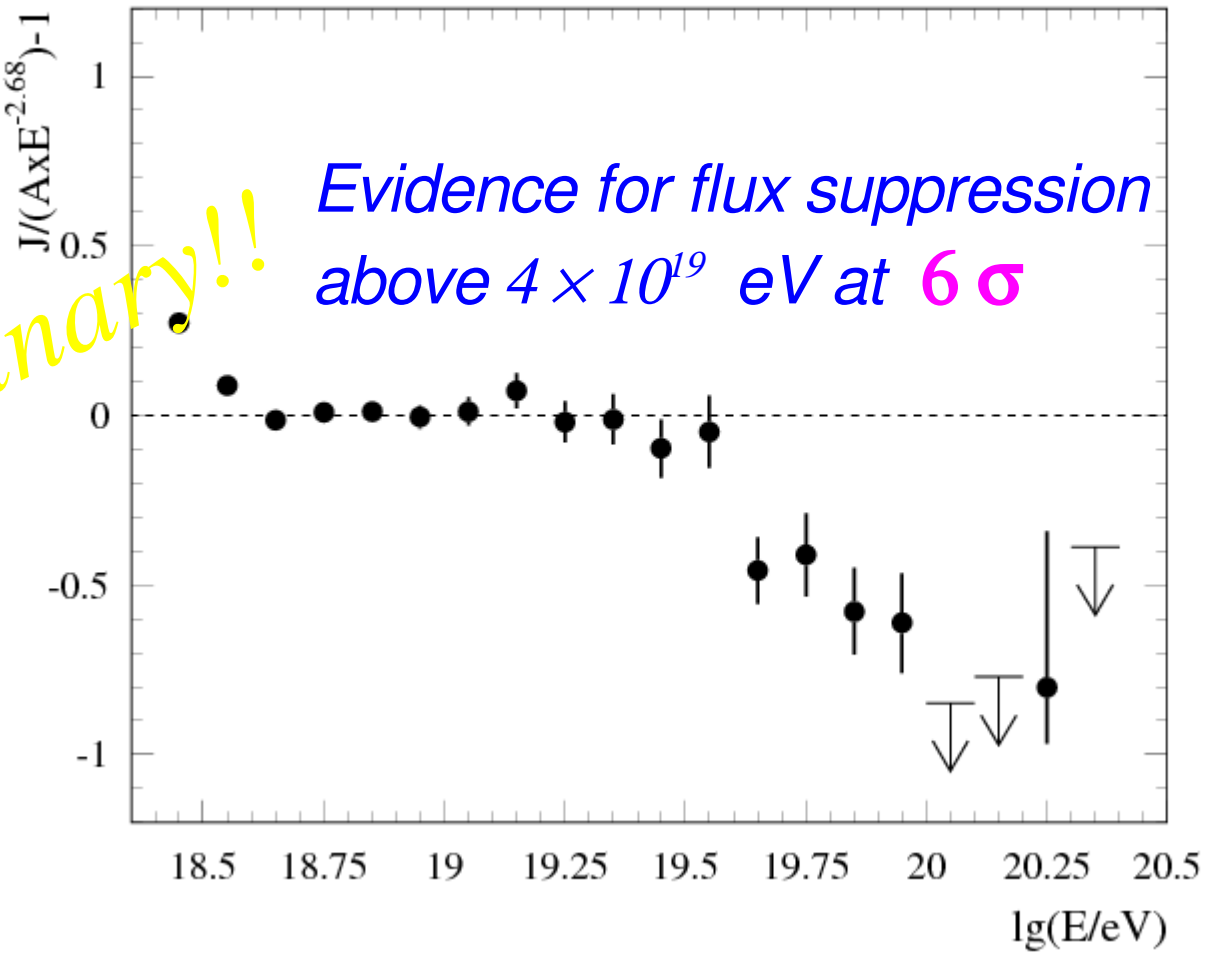
84% CL limits



$E^{2.68} \times$ Spectrum

Regener

84% CL limits



Preliminary!!

Evidence for flux suppression above 4×10^{19} *eV at* $6\,\sigma$

$E^{2.68} \times$ Spectrum

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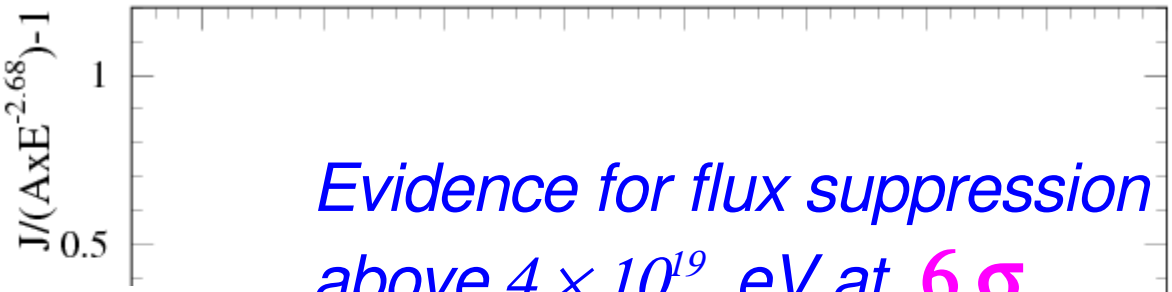
84% CL limits



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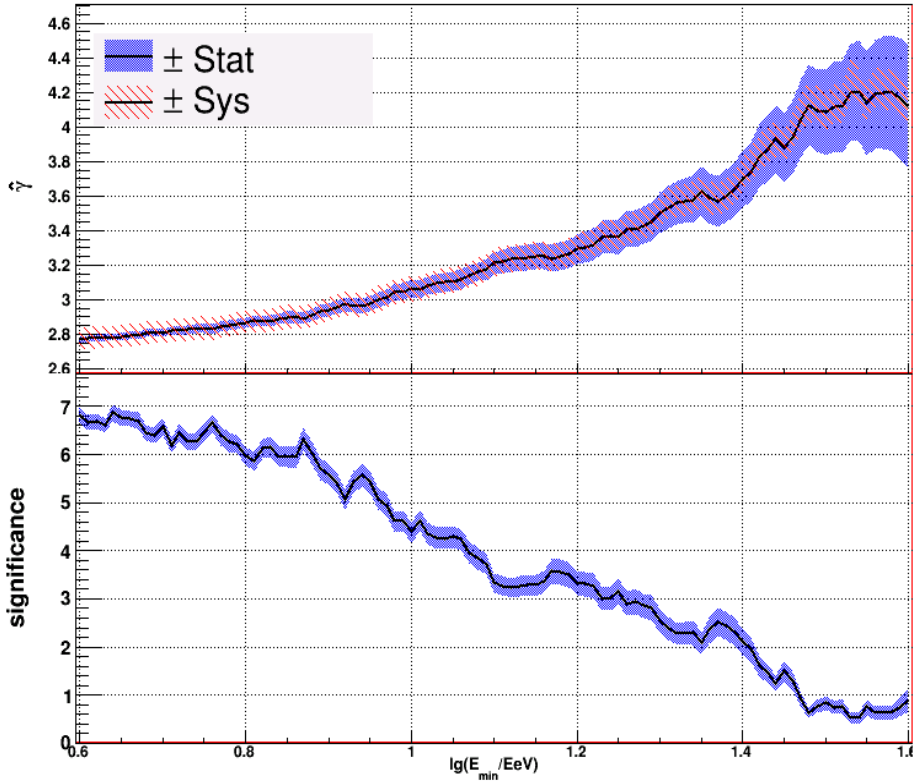
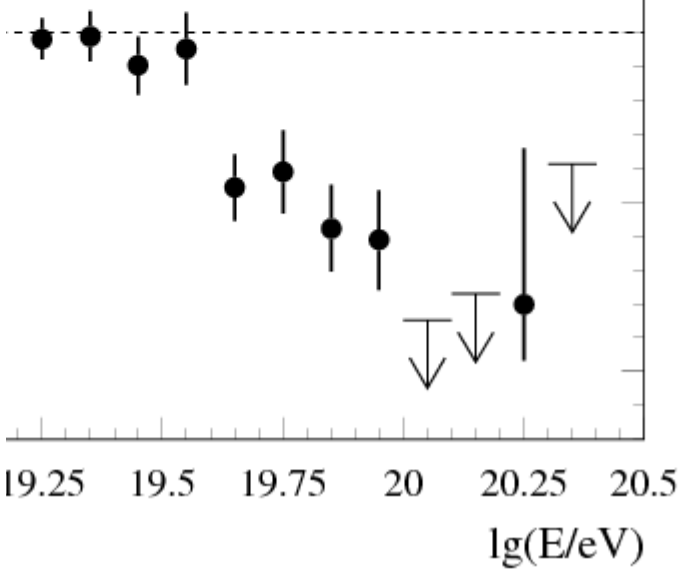
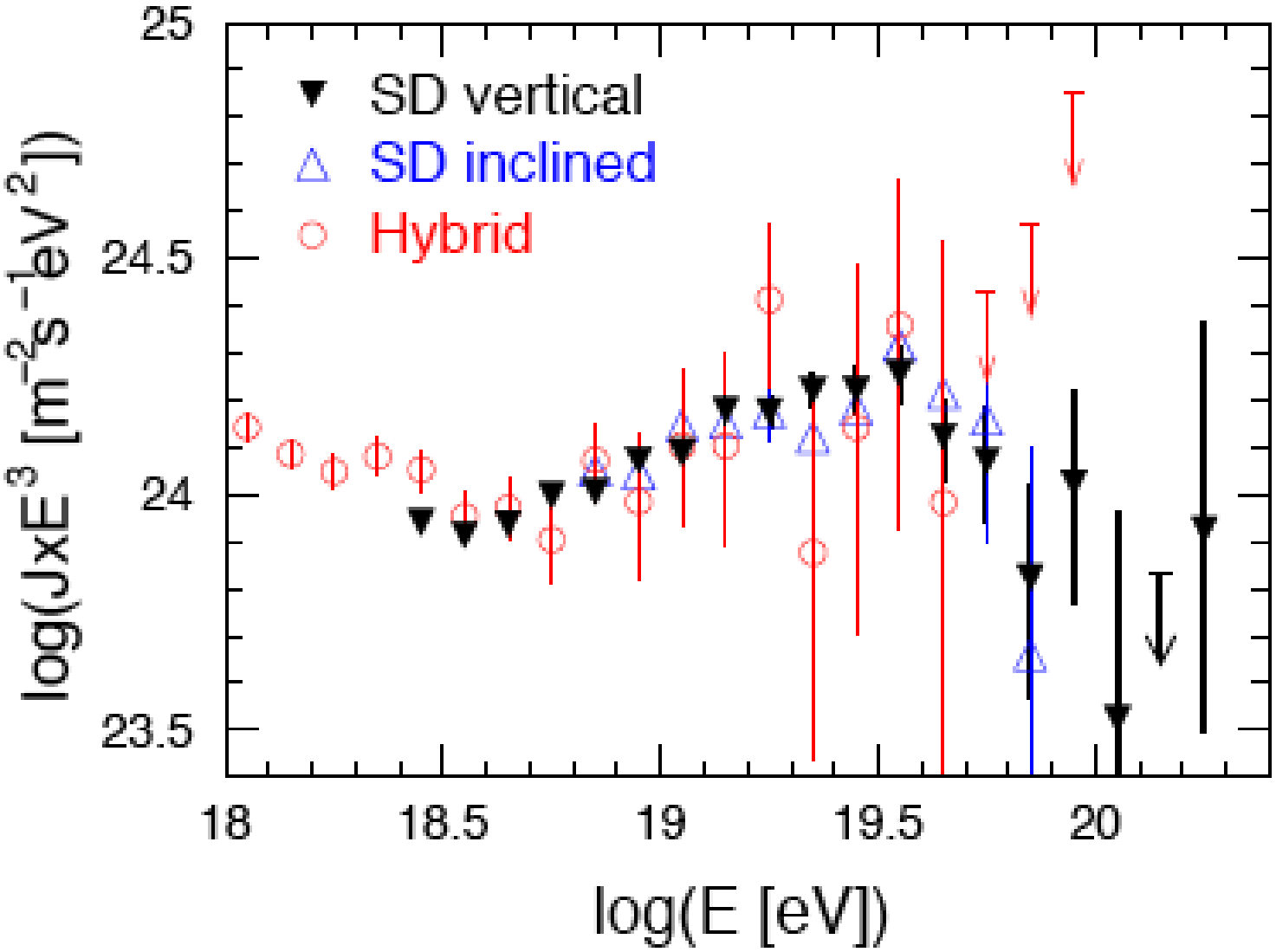
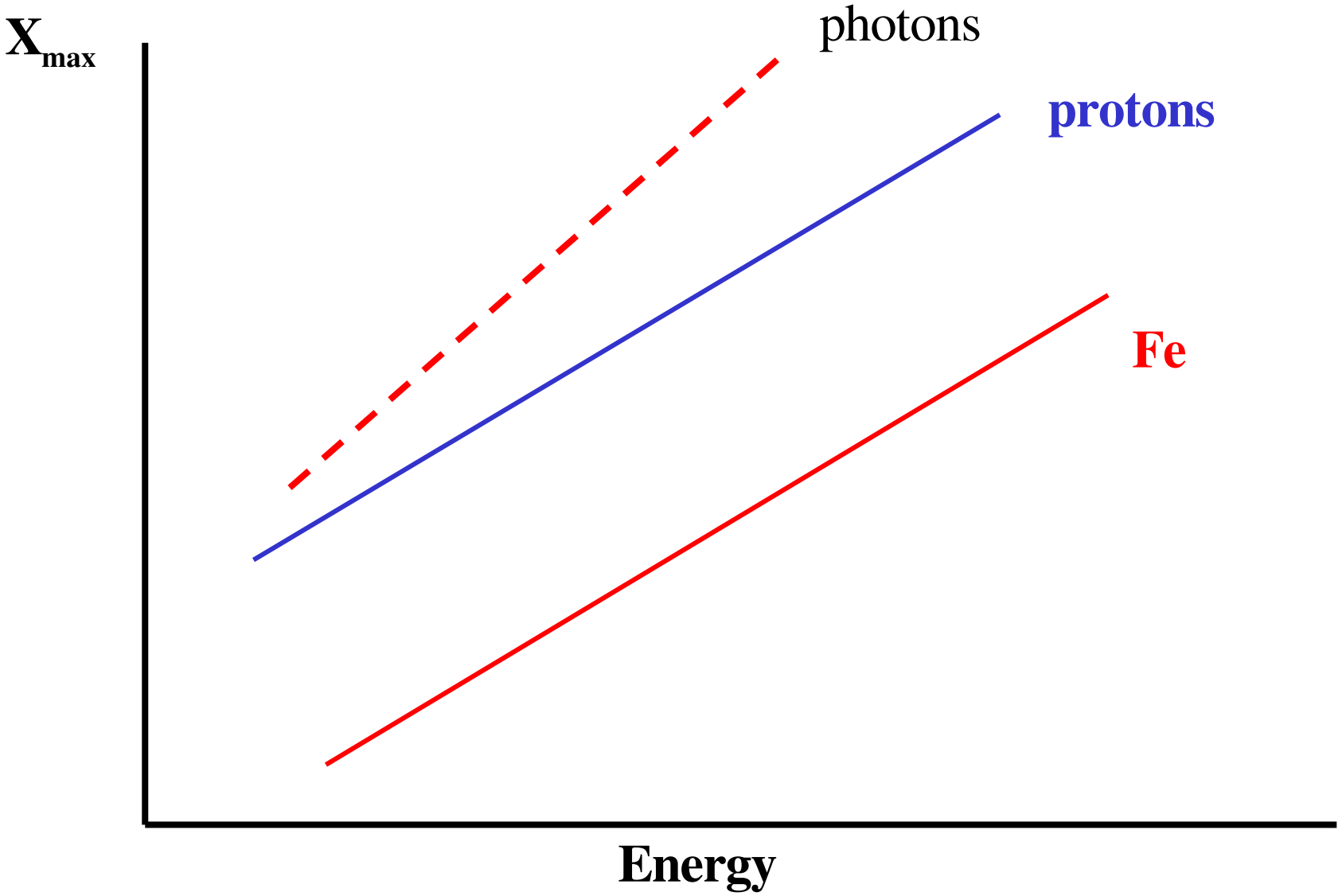




Combining spectra: hybrid + SD + SD inclined (>70º)



Mass Composition: the principle



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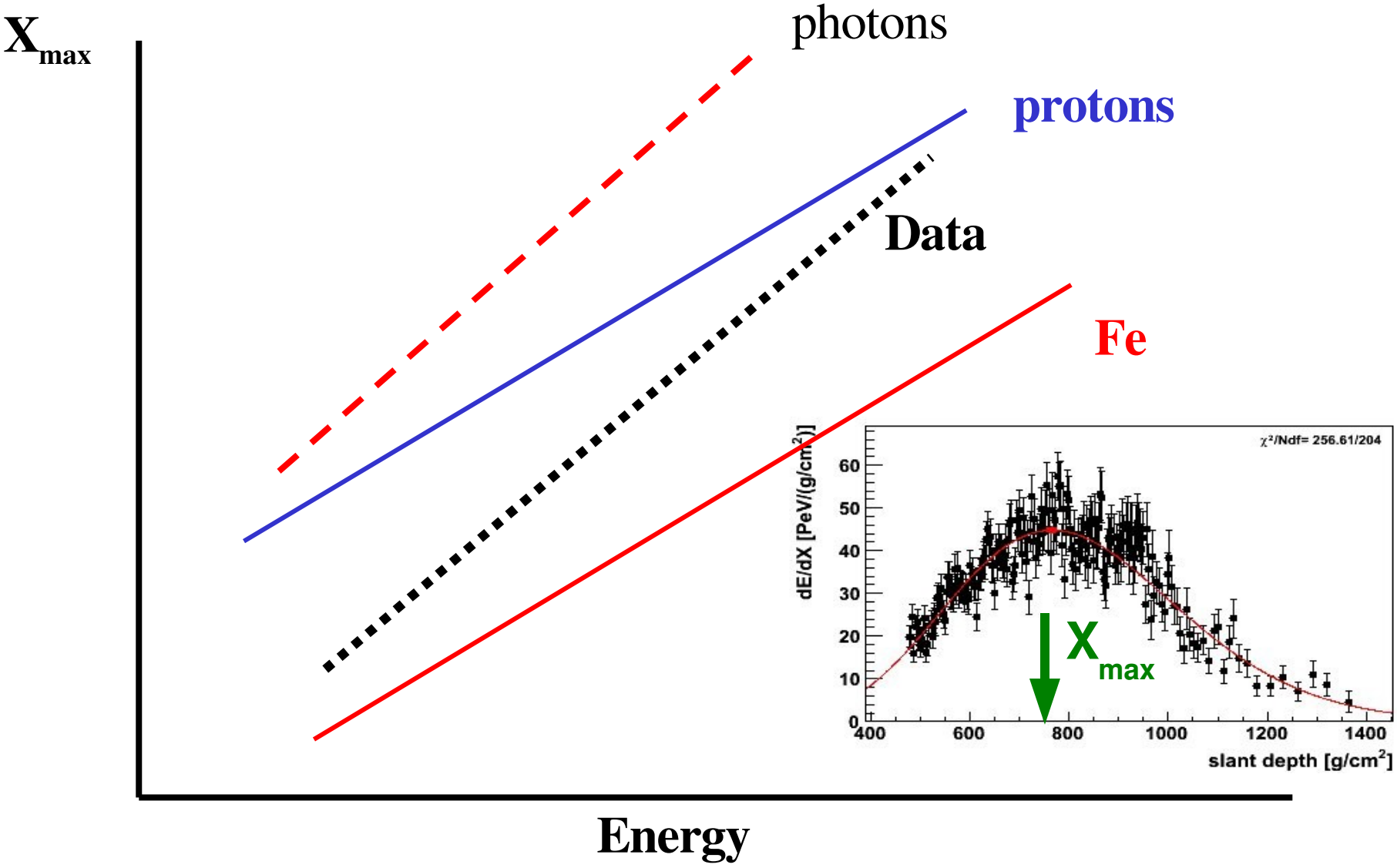
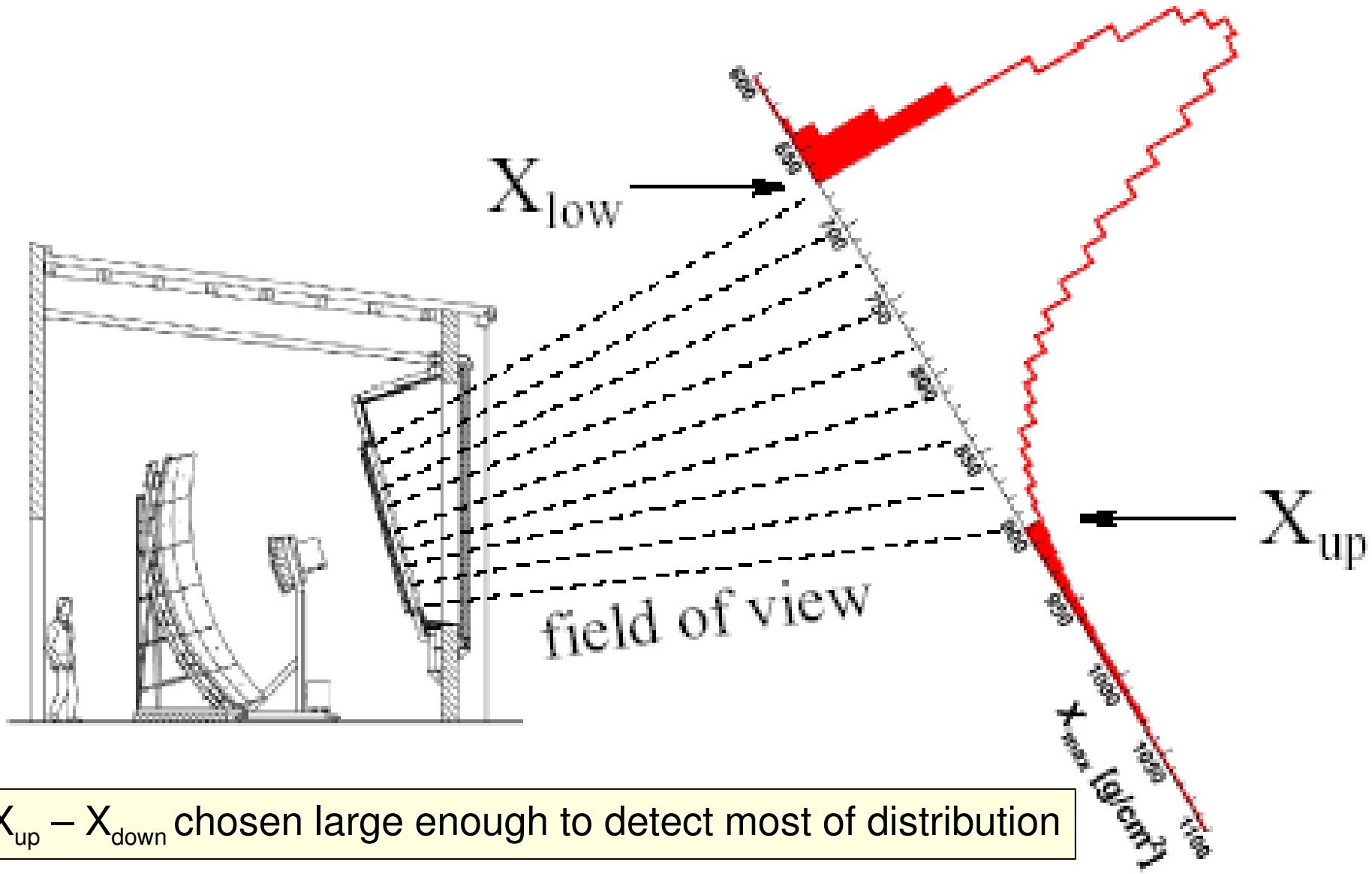
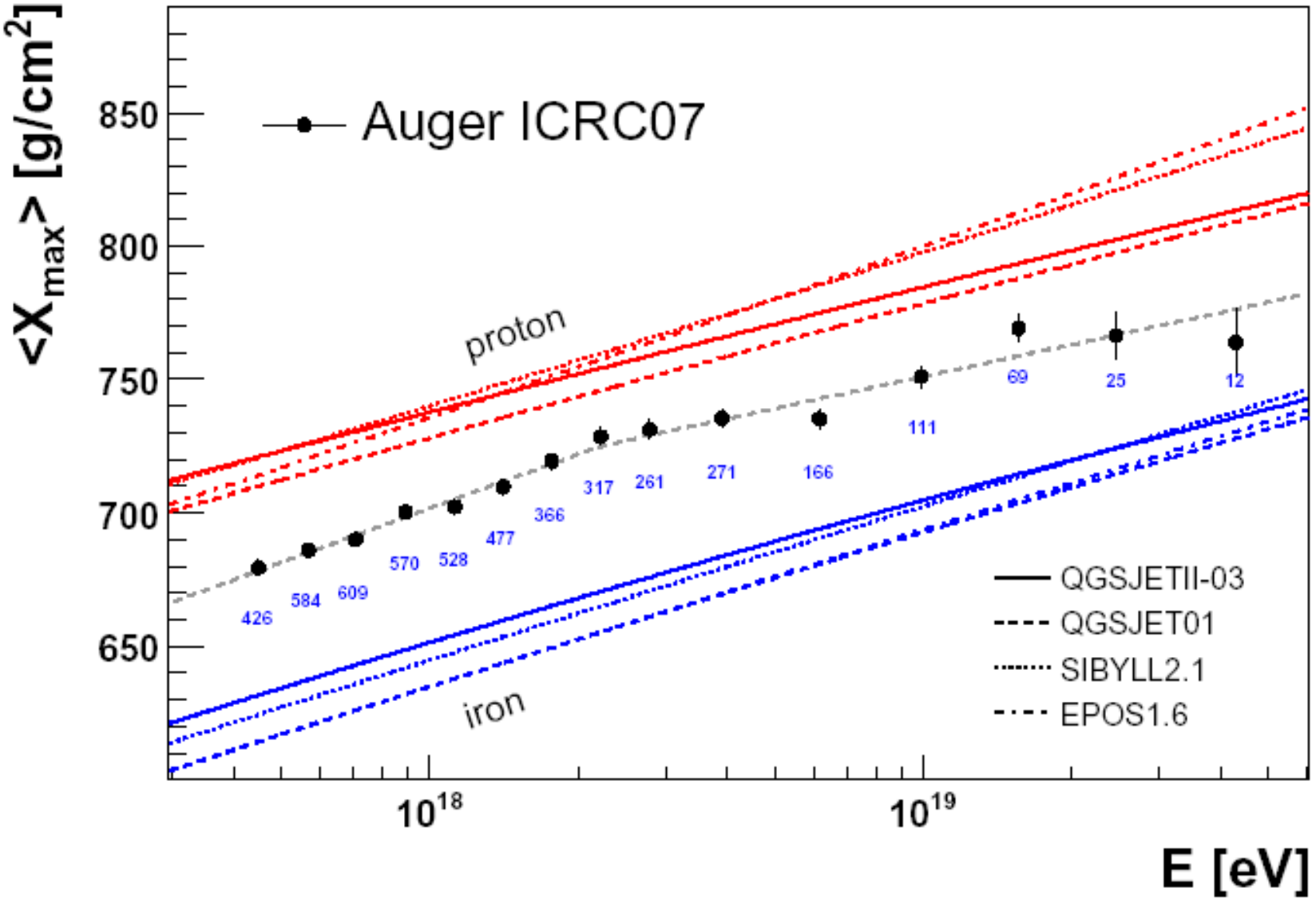




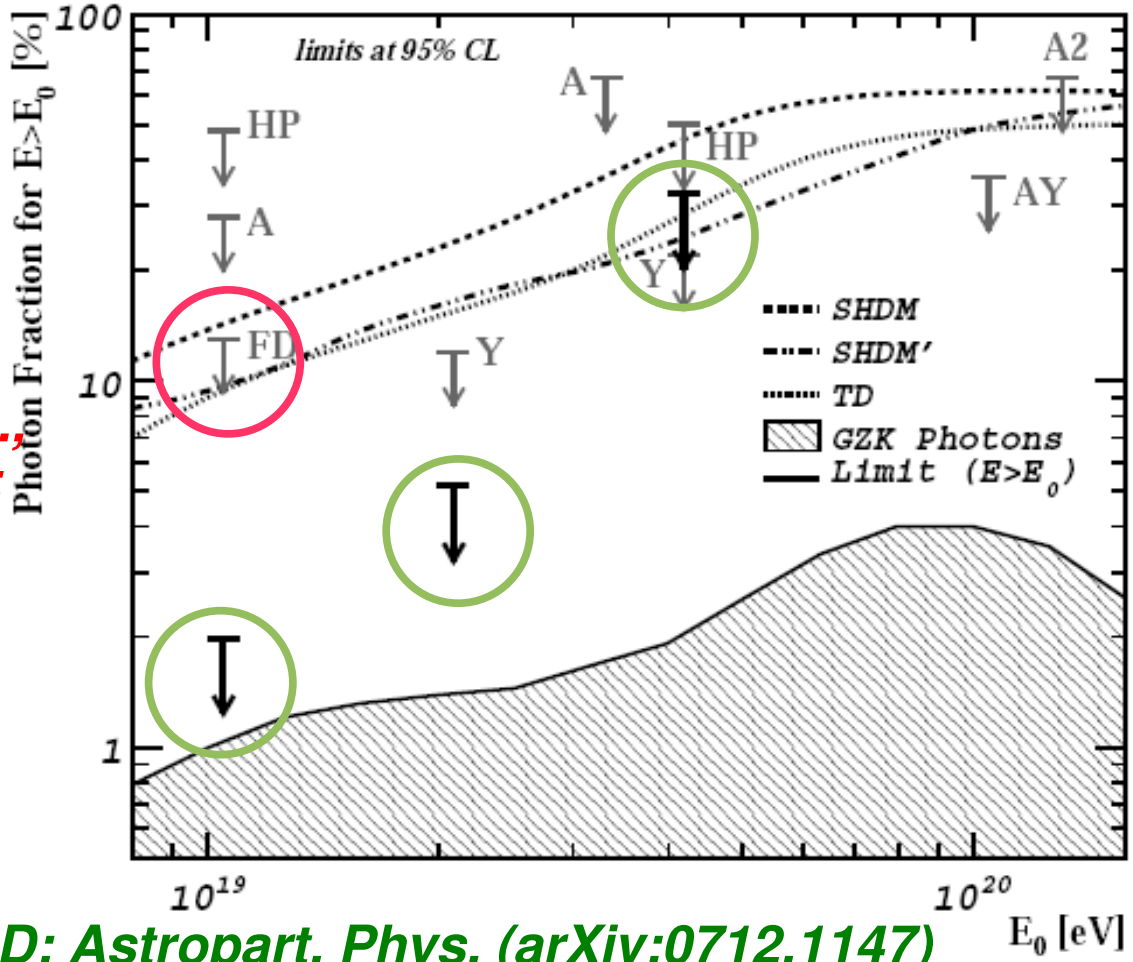
$X_{up} - X_{down}$ chosen large enough to detect most of distribution

Elongation Rate measured over two decades of energy



Photon Fraction Upper Limits

Hybrids:
Astrop. Phys., 27 (2007),155



SD: Astropart. Phys. (arXiv:0712.1147)

Fig. 9. The upper limits on the fraction of photons in the integral cosmic-ray flux derived in this work (black arrows) along with previous experimental limits (HP: Haverah Park [28]; A1, A2: AGASA [29,30]; AY: AGASA-Yakutsk [31]; Y: Yakutsk [32]; FD: Auger hybrid limit [19]). Also shown are predictions from top-down models and predictions of the GZK photon fraction (see text).

Top down models strongly constrained

The promised land....

UHECR astronomy

Why could it be feasible?

The promised land....

UHECR astronomy

Why could it be feasible?

As energy increases, three concurrent effects:

$$\delta \simeq 2.7^{\circ} \frac{60 \text{ EeV}}{E/Z} \left| \int_0^D \left(\frac{\mathrm{dx}}{\mathrm{kpc}} \times \frac{\mathrm{B}}{3\ \mu\mathrm{G}} \right) \right|$$

- *Magnetic deflection* ↘
- *GZK: only close-by sources, R* ↘
- *Close-by Universe* ***is anisotropic***

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conversely

Correlation with sources in the GZK sphere would unambiguously prove the reality of the cutoff (and give hints on the nature of sources)

ARRIVAL DIRECTION DISTRIBUTION

Typical accuracy of reconstruction <1°

ICRC 2007

- No significant emission from Galactic Centre
- No broadband signals – e.g. Dipole – at any energy above 1 EeV
  e.g $1 < E < 3$ EeV, Amplitude < 0.7%
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Summary: Previous reports have not been confirmed

BUT,
two '<u>prescriptions</u>' are currently being tested

The new (Aug. 2007) astronomy analyses

- zenith angle $\theta < 60°$;
- core location within the array boundaries: reconstructed core within a triangle of active stations and station with the highest signal surrounded by at least 5 active tanks;
- reconstructed energy $E > 10$ EeV.

~9000 km^2 sr yr, trigger efficiency 100%

E [EeV]	$N_{events}(> E)$
10	2212
30	203
40	81

Search for point sources: the method

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VC-V catalogue:
85,221 QSO - 1,122 BL Lac - 21,737 AGN.
694 with z < 0.024 (~100 Mpc)
z > 0.024 increasingly incomplete and in-homogeneous.

Search for point sources: the method

Some definitions: probabilities

p: exposure-weighted fraction of the sky accessible to observation, covered by windows of radius ψ centered on the selected sources.

P: probability that k or more out of a total of N events from isotropic flux are correlated by chance with the selected objects at the chosen angular scale

$$P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$$

this probability needs 'penalization' i.e. $\mathbf{P_{fin} = P \times N_t}$ (from MC)

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- Confirmation ***at 99% CL*** that UHECR are anisotropic with an independent data set.
- In sample May 2006-August 2007 ***8/13*** correlating $P= 1.7\ 10^{-3}$

Once **prescription passed**:

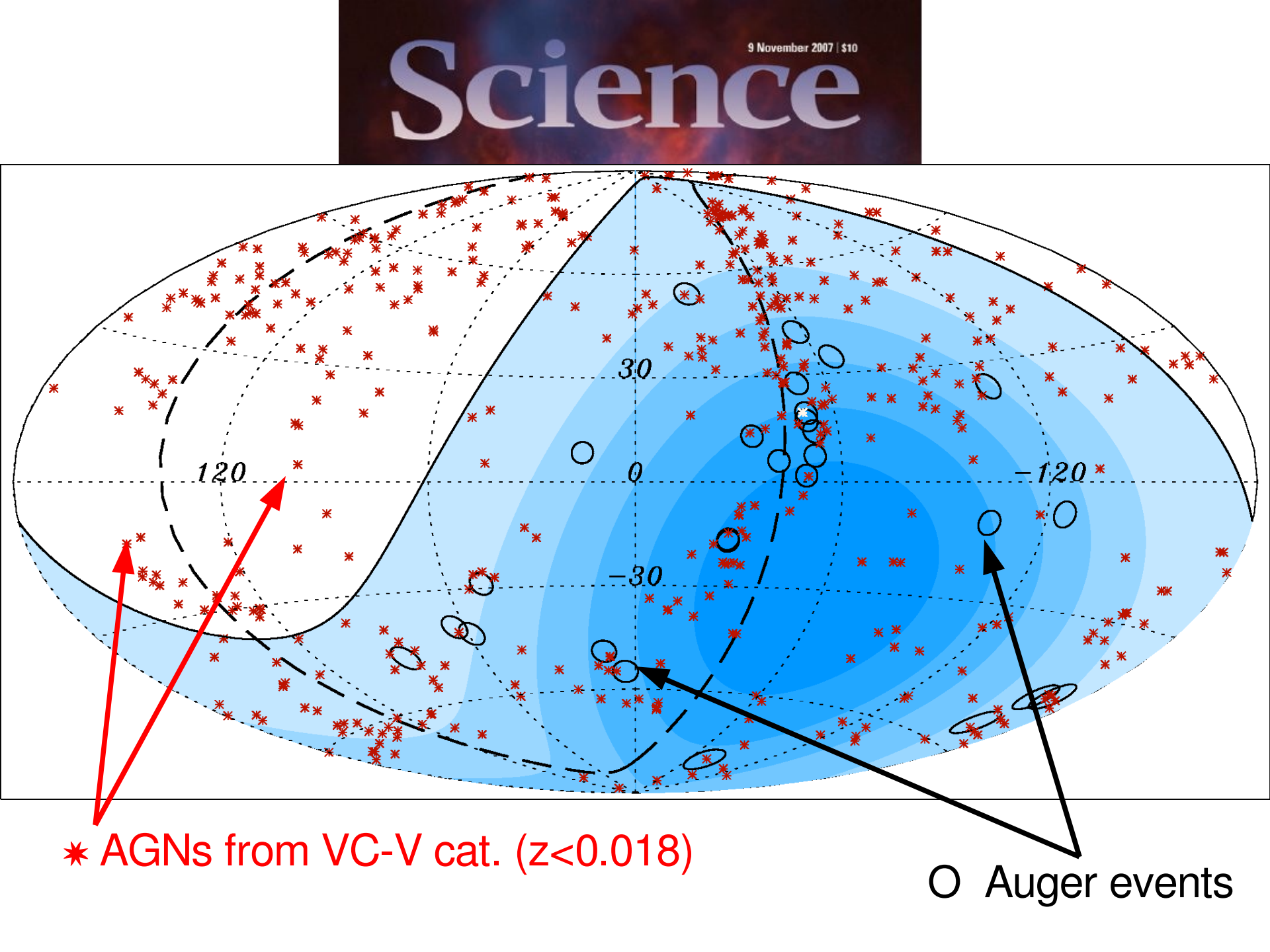
- Scan performed on the whole sample
- Minimum found for ***E > 57 EeV ψ < 3.2° z < 0.017 (D≤ 70 Mpc)***
- **20 out of 27 correlate**; penalized prob. **~10^{-5}**

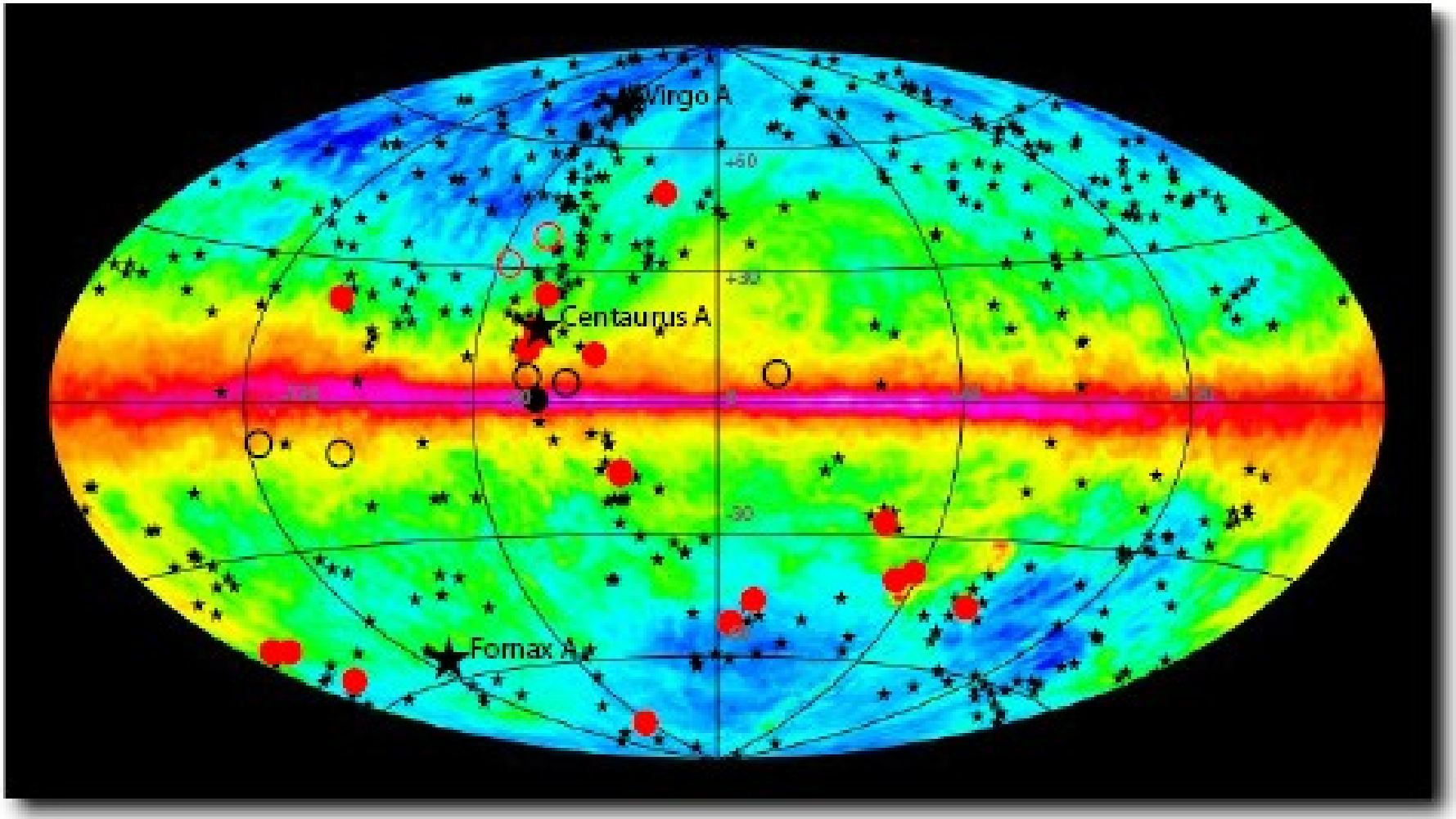
Back-of-envelope estimate:

- All AGNs with z<0.017 with a 3.2° circle area **cover 21% of the whole Sky ⇨ we expect ~5 we get 20 !**

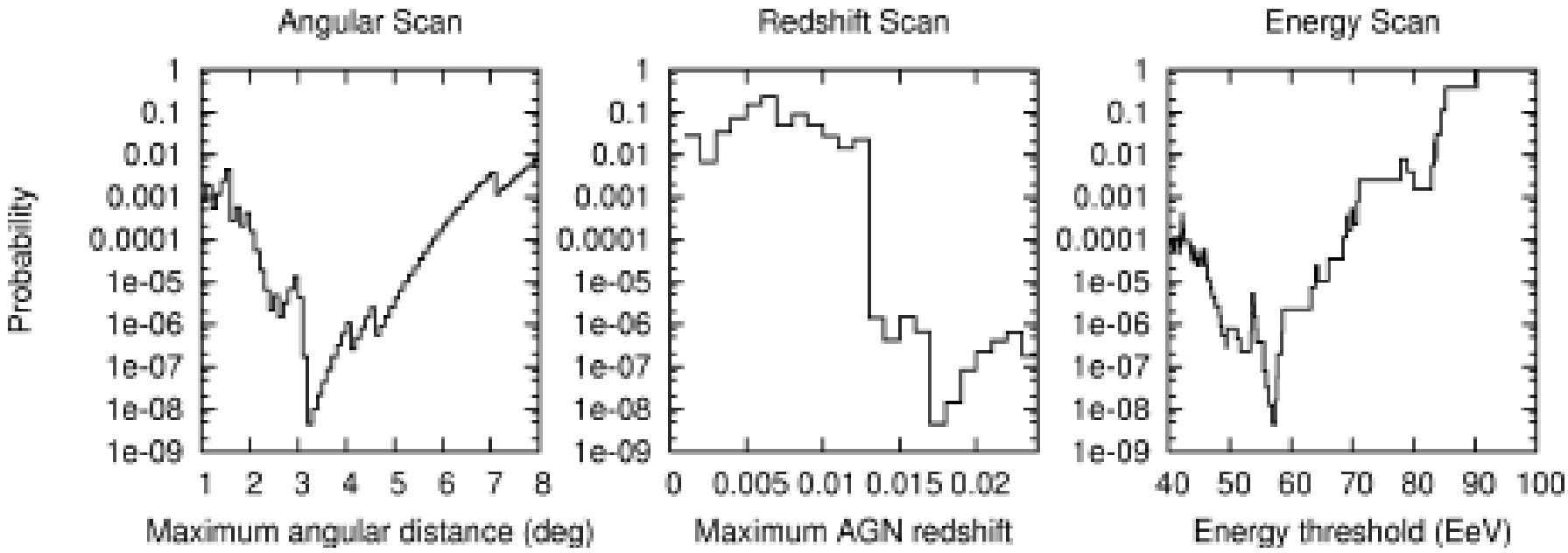
Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

The Pierre Auger Collaboration*


Science
9 November 2007 | $10
30
0
−30
120
−120
✶ AGNs from VC-V cat. (z<0.018)
O Auger events

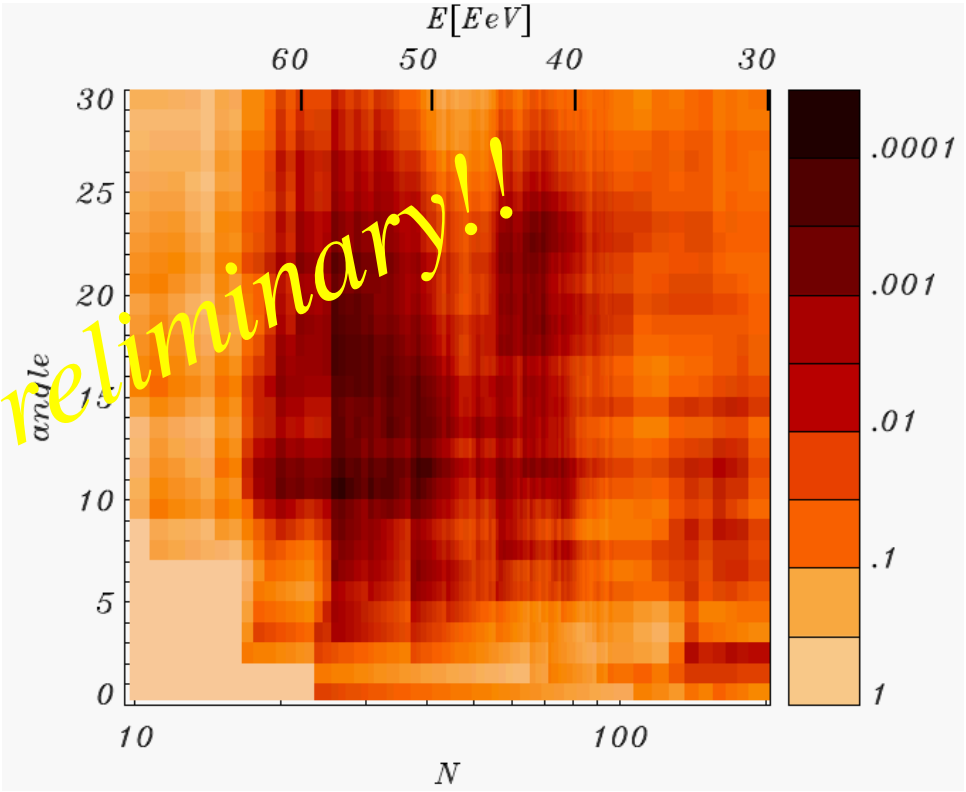

Virgo A
+60
+30
Centaurus A
-30
Fornax A

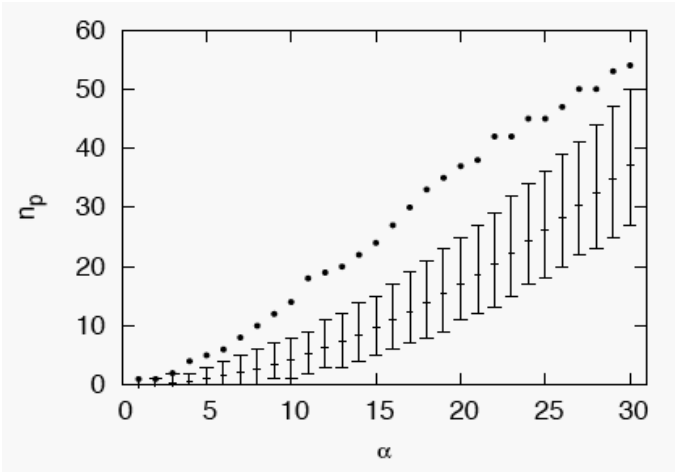
Correlation with close-by AGNs

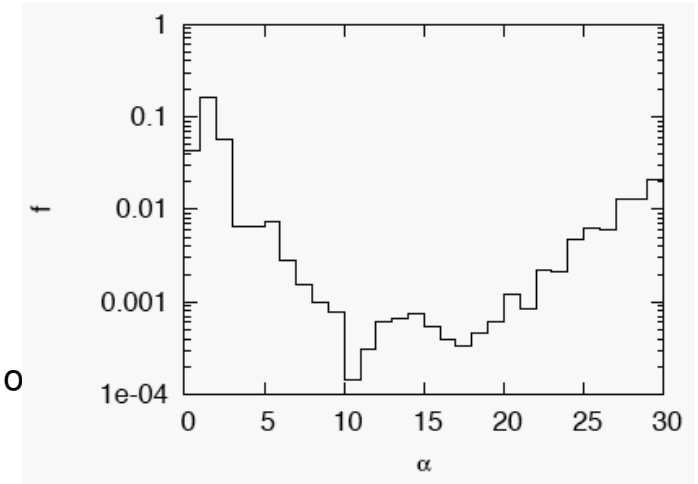


a posteriori $P_{fin}(iso) \sim 10^{-5}$

Autocorrelation: pairs within α



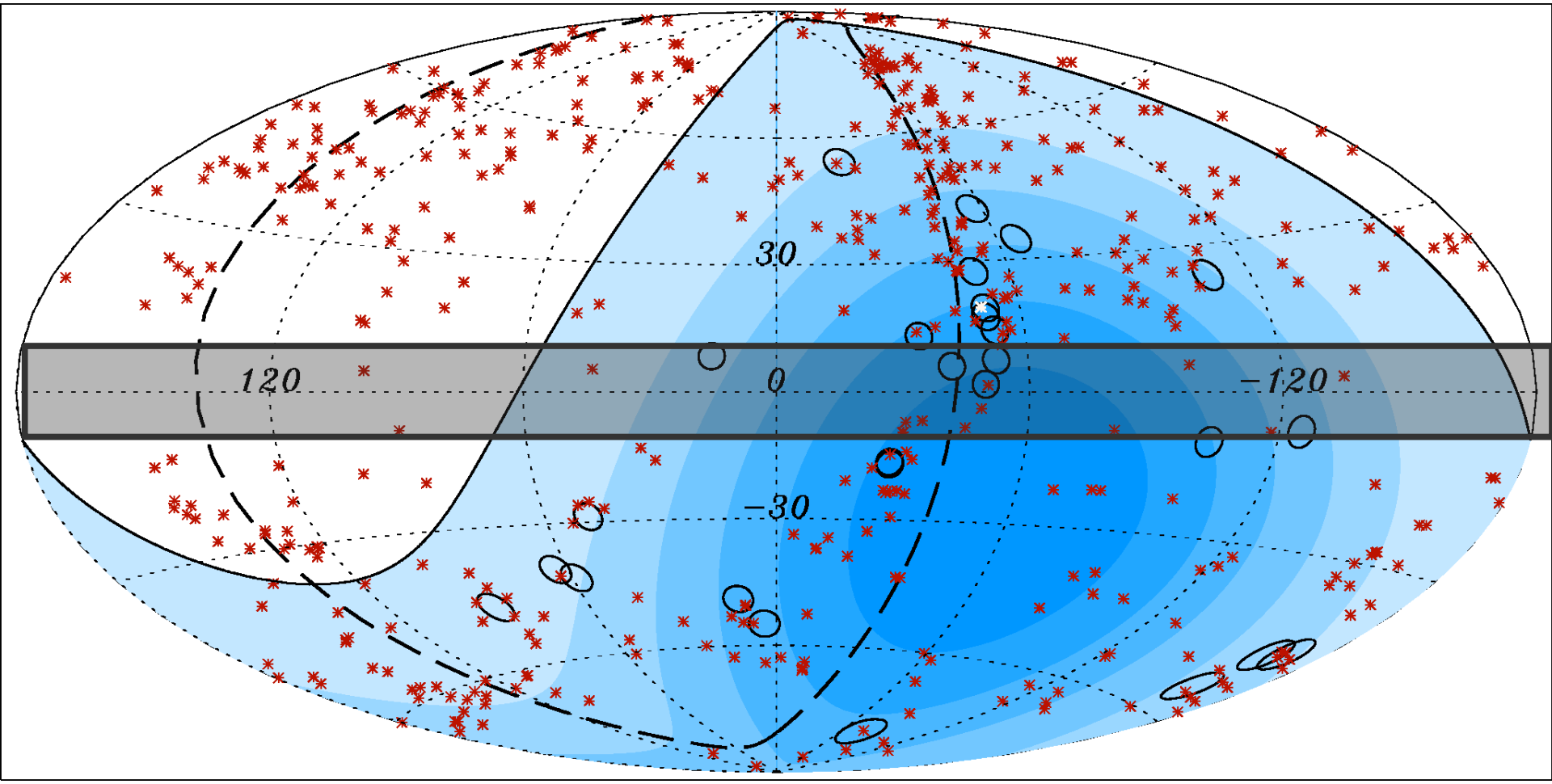




Minimum probability for E>57 EeV α≈11°
(27 events, 5.2 pairs expected 8 found)

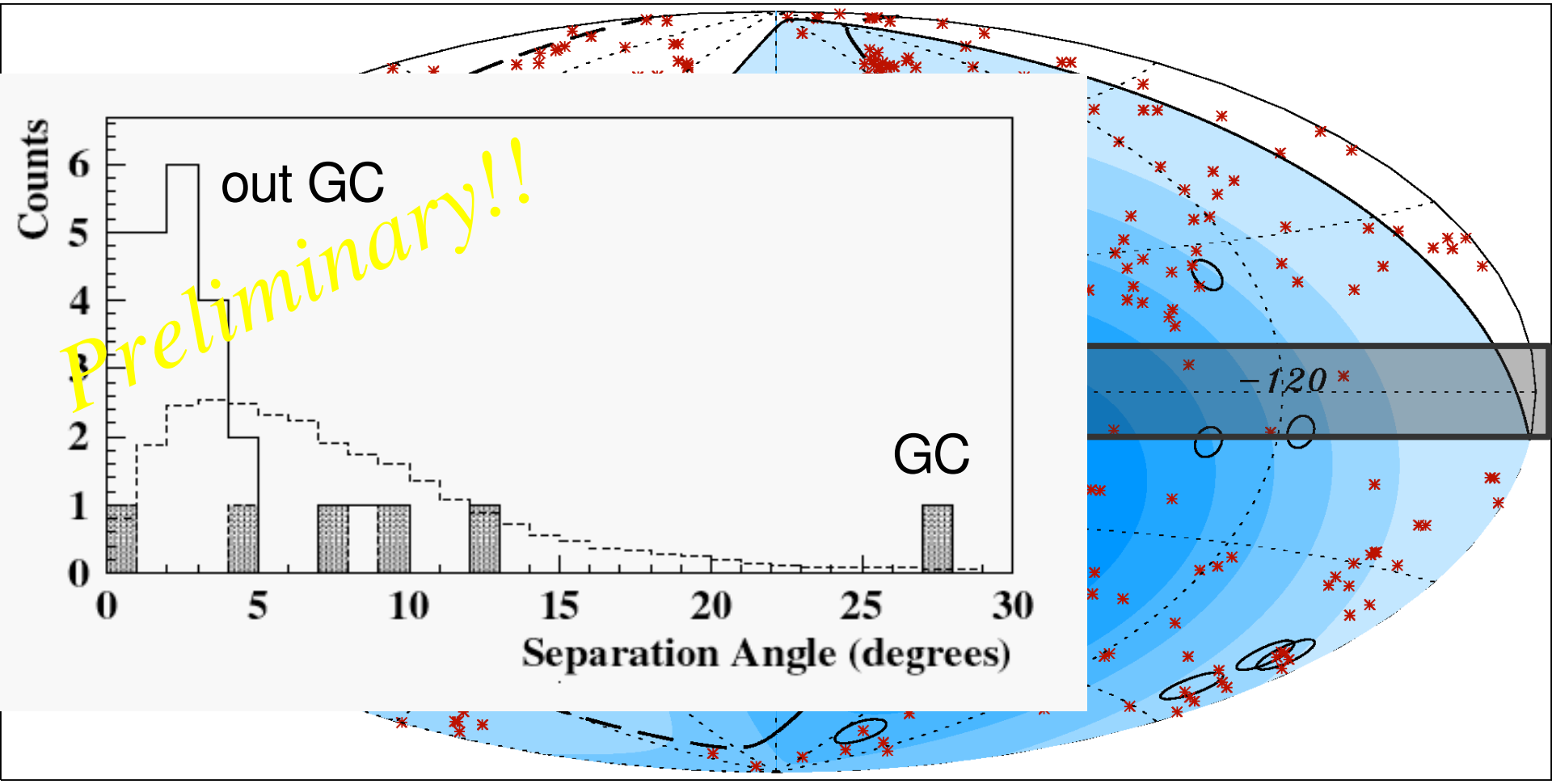
marginal: probability from uniform distribution ~ 1.6%
if real, may reflect source distribution

Galactic plane cut: |b| > 12º



19 out of 21 do correlate

Galactic plane cut: |b| > 12°



19 out of 21 do correlate

Open issues

- AGNs: sources or tracers?

  other catalogues (IRAS, Abell,REFLEX, NORAS)

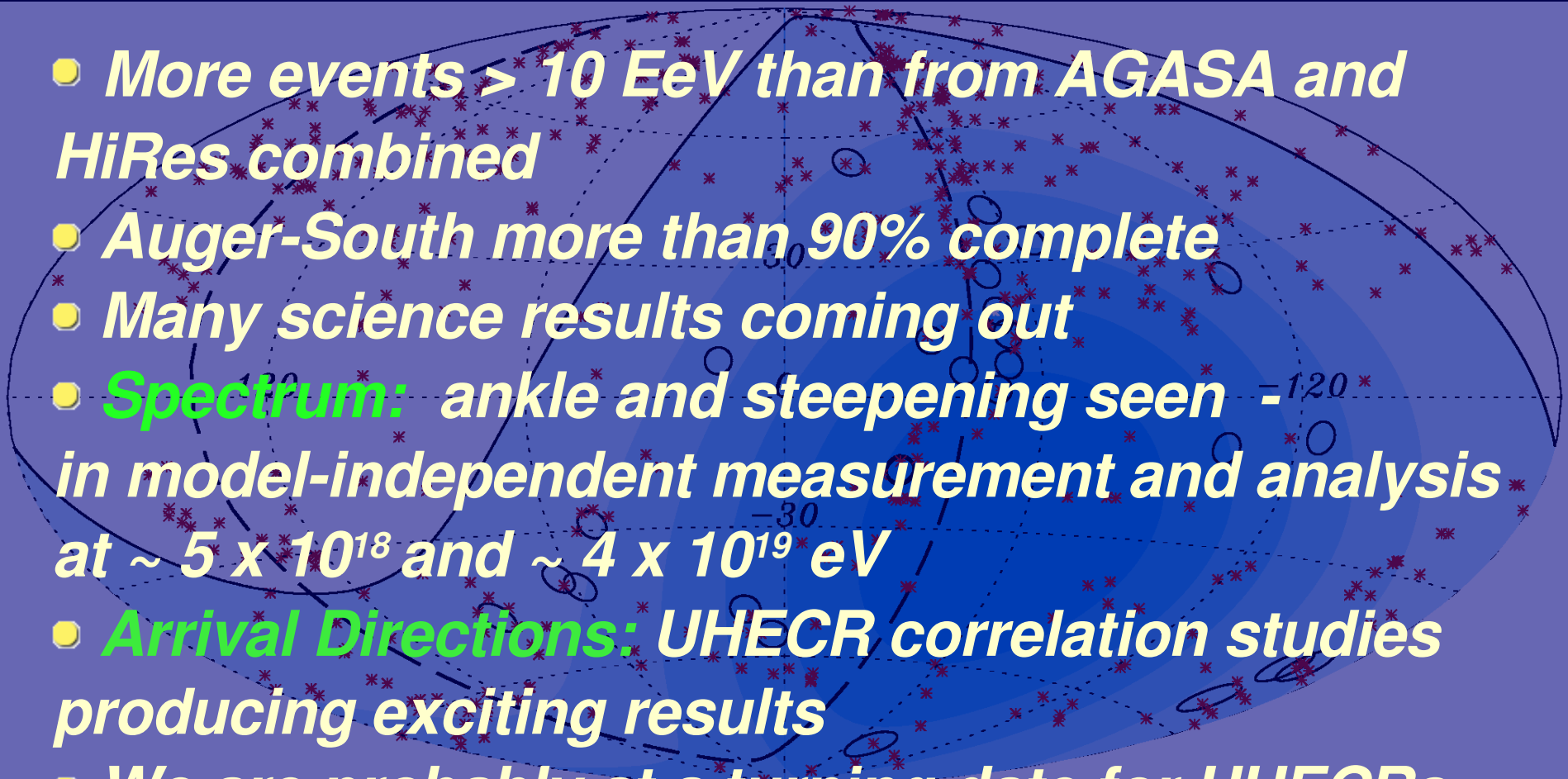
- primary mass vs magnetic deflection

  δ compatible with protons, comp. results not yet a problem

- The GZK “horizon” problem (E^{th} vs z_{max})

  indication of the need of energy shift? Too early...

Conclusions



- *More events > 10 EeV than from AGASA and HiRes combined*
- *Auger-South more than 90% complete*
- *Many science results coming out*
- ***Spectrum:*** *ankle and steepening seen - in model-independent measurement and analysis at ~ 5 x 10^{18} and ~ 4 x 10^{19} eV*
- ***Arrival Directions:*** *UHECR correlation studies producing exciting results*
- *We are probably at a turning date for UHECRs*
- ***Birth of Cosmic Ray Astronomy?***

Many thanks!