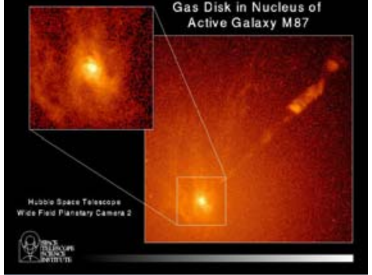

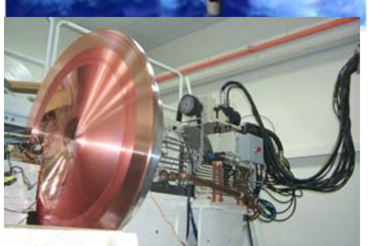

Cosmic rays at highest energies: Scientific objectives, status and plans for the future

Markus Roth
Forschungszentrum Karlsruhe
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- Astrophysical motivation
- Pierre Auger Project and EUSO
  - Experimental concept
  - Status
  - Results
- Summary and outlook

bmb+f
Großgeräte
der physikalischen
Grundlagenforschung

Science Objectives

Fundamental questions

- Primaries of energies $>10^{20}$eV exist
  Standard astrophysical models cannot account for such energies

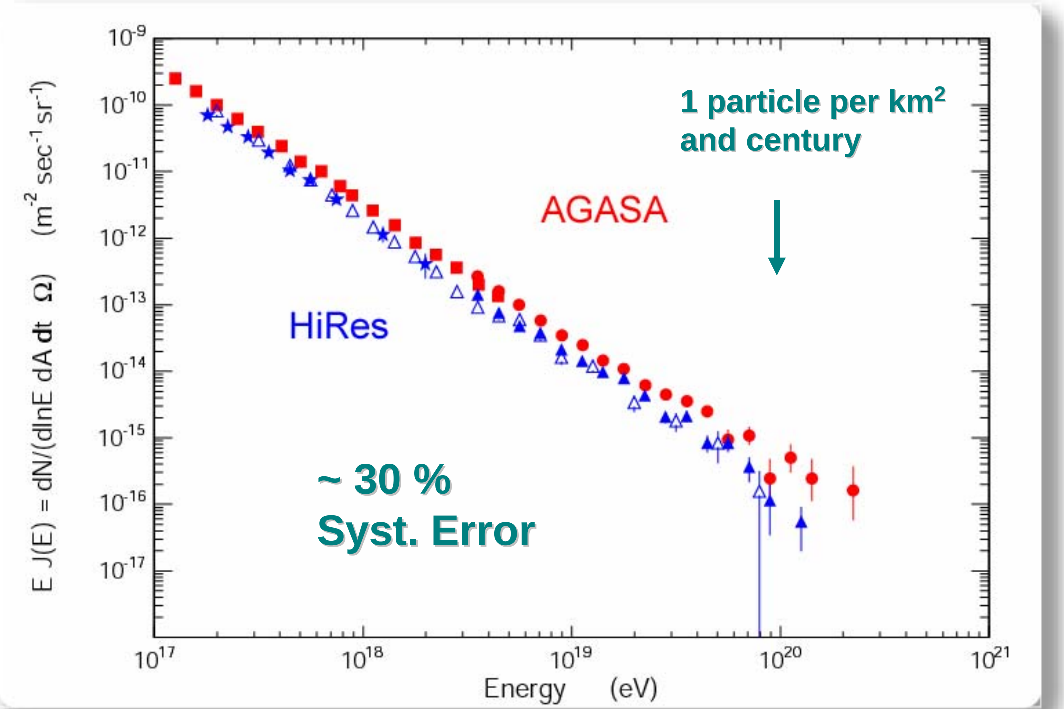
- Complication (d > 20 Mpc):
  GZK cutoff E>5•10^{19}eV

$$p+\gamma_{2.7K} \rightarrow \Delta^{+}(1232) \rightarrow p+\pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n+\pi^{+} \rightarrow pe^{+}\nu$$

- If no GZK:
  - Nearby sources:
    GUT fossils (TD, DM, ...)
  - Propagation effects:
    violation of Lorentz invariance, Z-Bursts, ...

- **Near sources should be identified by point source astronomy**
  High magnetic rigidity of the primaries (charged particle astronomy)

Contradicting measurements



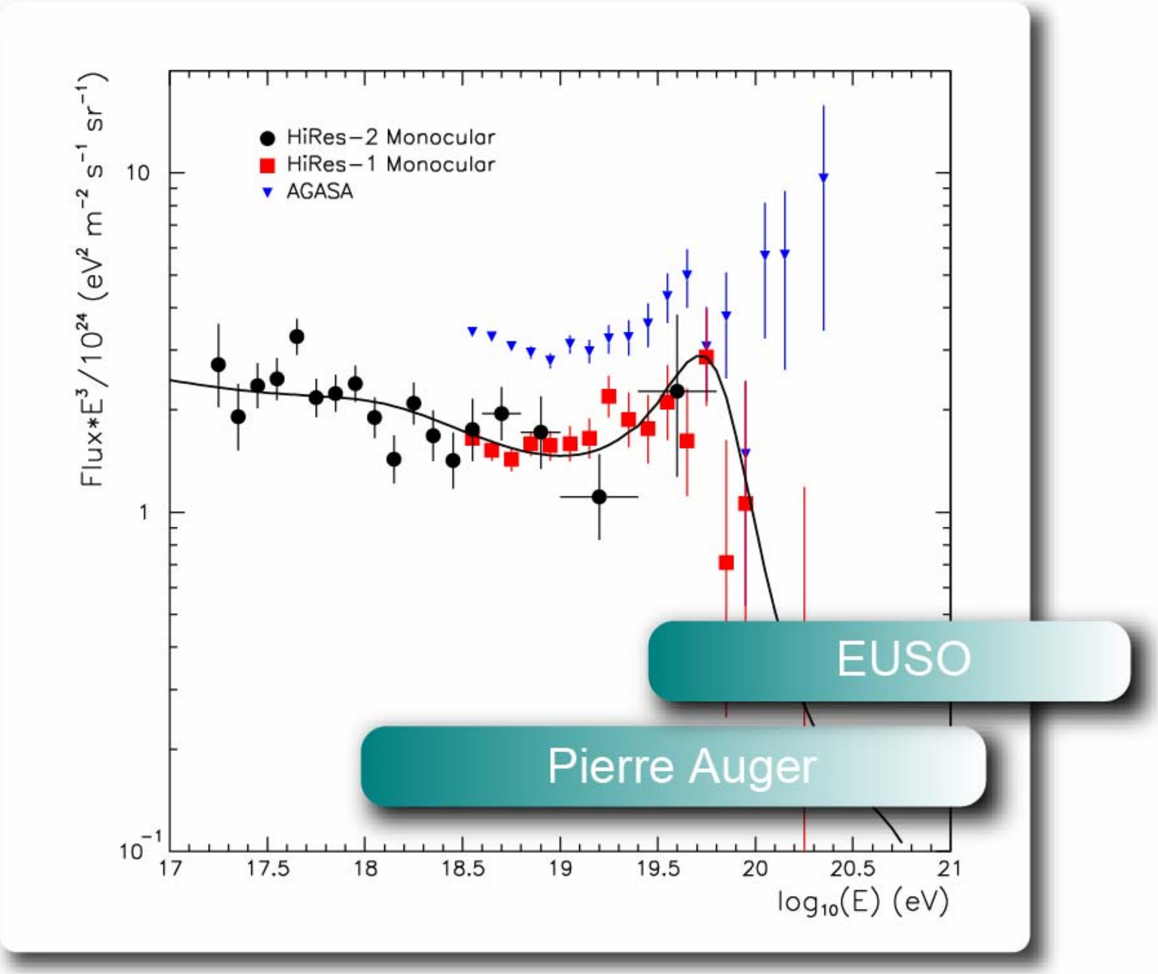
Newest HIRES stereo data give even more contradicting results (W. Springer et al.; ICRC05)

Experimental Approach

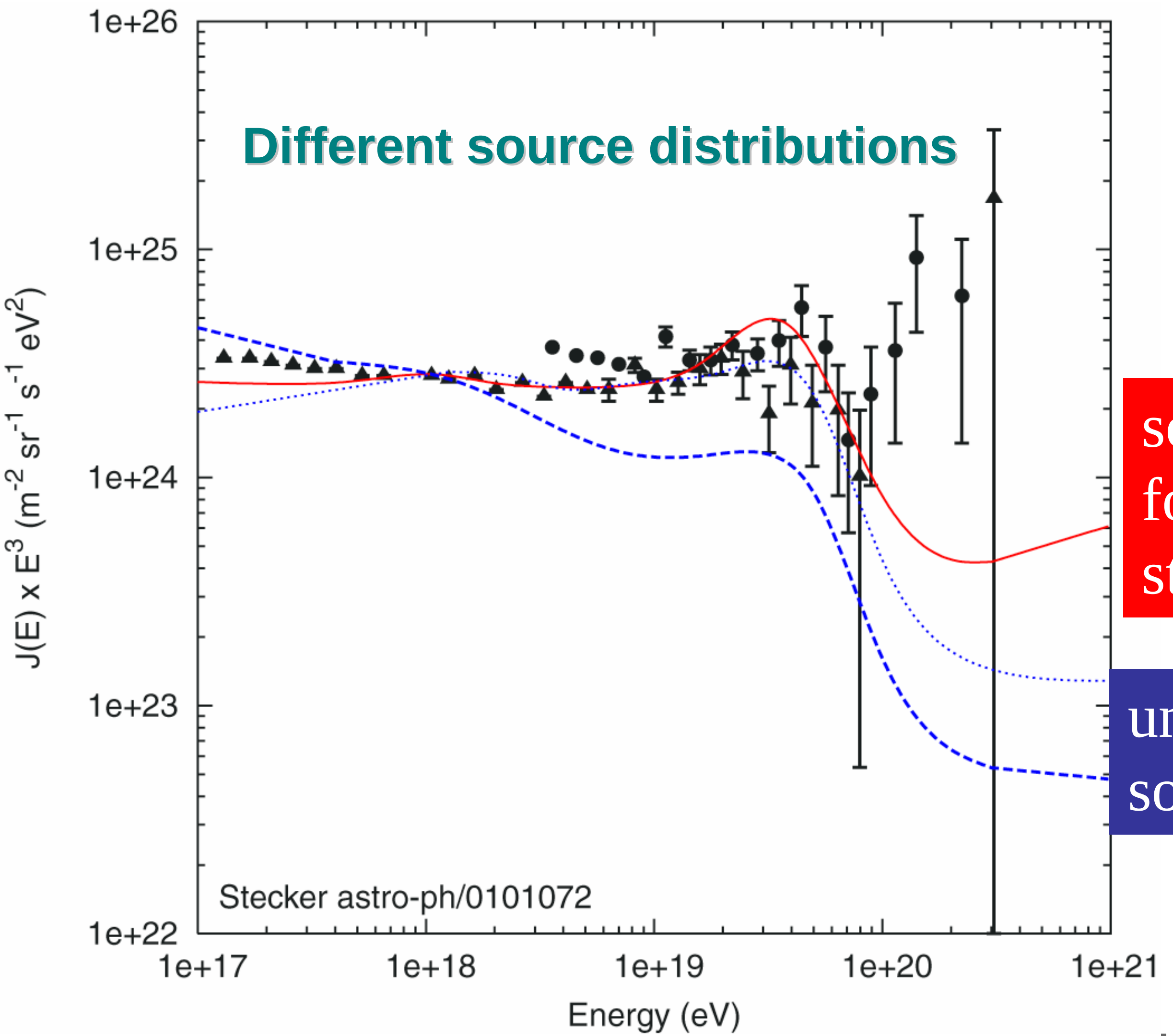
1. Cosmic ray spectrum above 10^{19} eV:
   Shape of the spectrum in the region of the GZK cutoff

2. Arrival direction distribution:
   Search for departure from isotropy, point sources

3. Composition:
   Light or heavy nuclei, photons, neutrinos, exotics(?)



Study of GZK-Cutoff Requires Much Higher Statistics



source distribution following star-formation

uniform $E^{-2.75}$ source distributions

The Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the

The Highest Energy Cosmic Rays

Using

Two Large Air Shower Detectors

Colorado, USA
(in planning)

Mendoza, Argentina
(Auger South)

The Auger Collaboration

Participating Countries

Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
•Aachen
•Bonn
•Karlsruhe
•Siegen
•Wuppertal

Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*
Italy

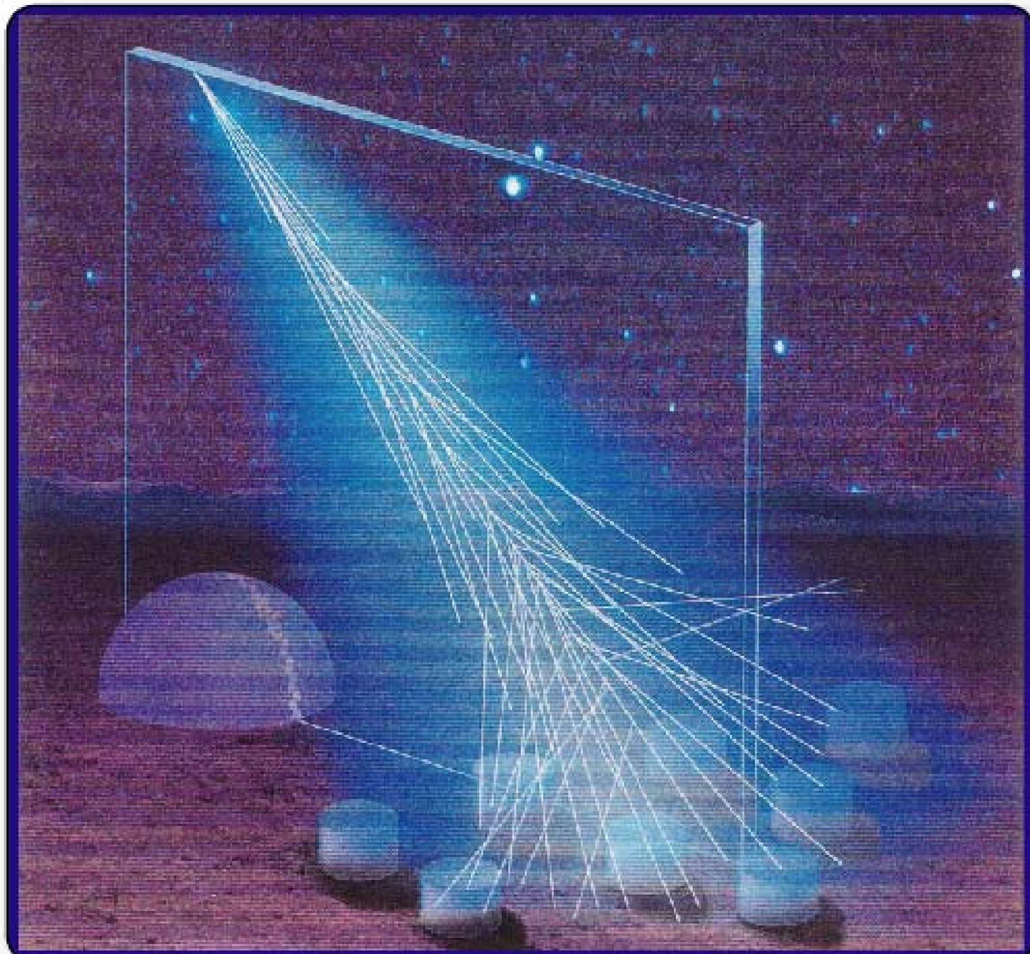
Associate

63 Institutions, 369 Collaborators

The Hybrid Design

Surface detector array + Air fluorescence detectors

A unique and powerful design



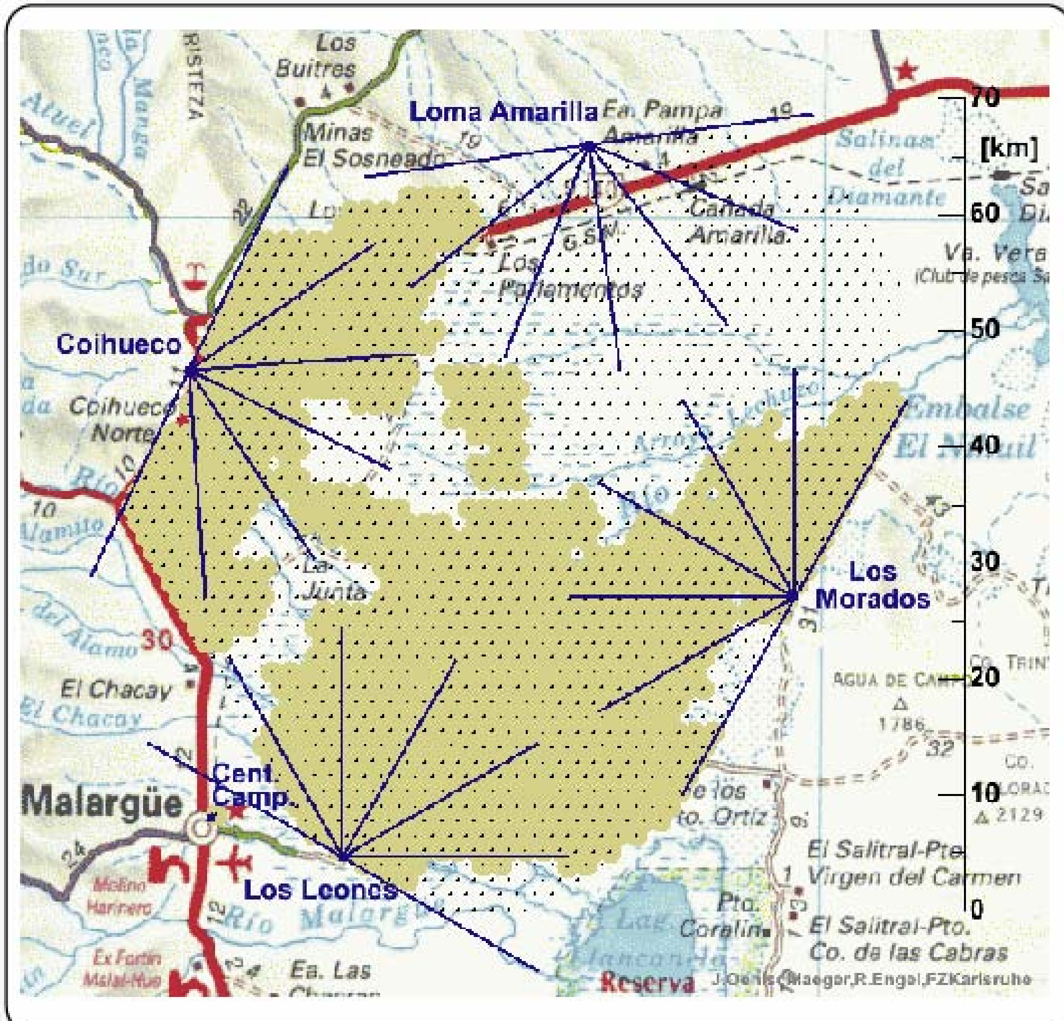
Nearly calorimetric energy calibration of the fluorescence detector transferred to the event gathering power of the surface array.

A complementary set of mass sensitive shower parameters (Xmax, risetime, radius of curvature, …).

Different measurement techniques help understanding of systematic uncertainties

Improve of the angular and core position resolutions

Hybrid Design



Surface Array

- *1600 detector stations (995)*
- *1.5 km spacing*
- *3000 km²*

Fluorescence Detectors

- *4 Telescope enclosures (3)*
- *6 Telescopes per enclosure*
- *24 Telescopes total (18)*

Design Features

Thanks to Kai Daumiller for this movie!

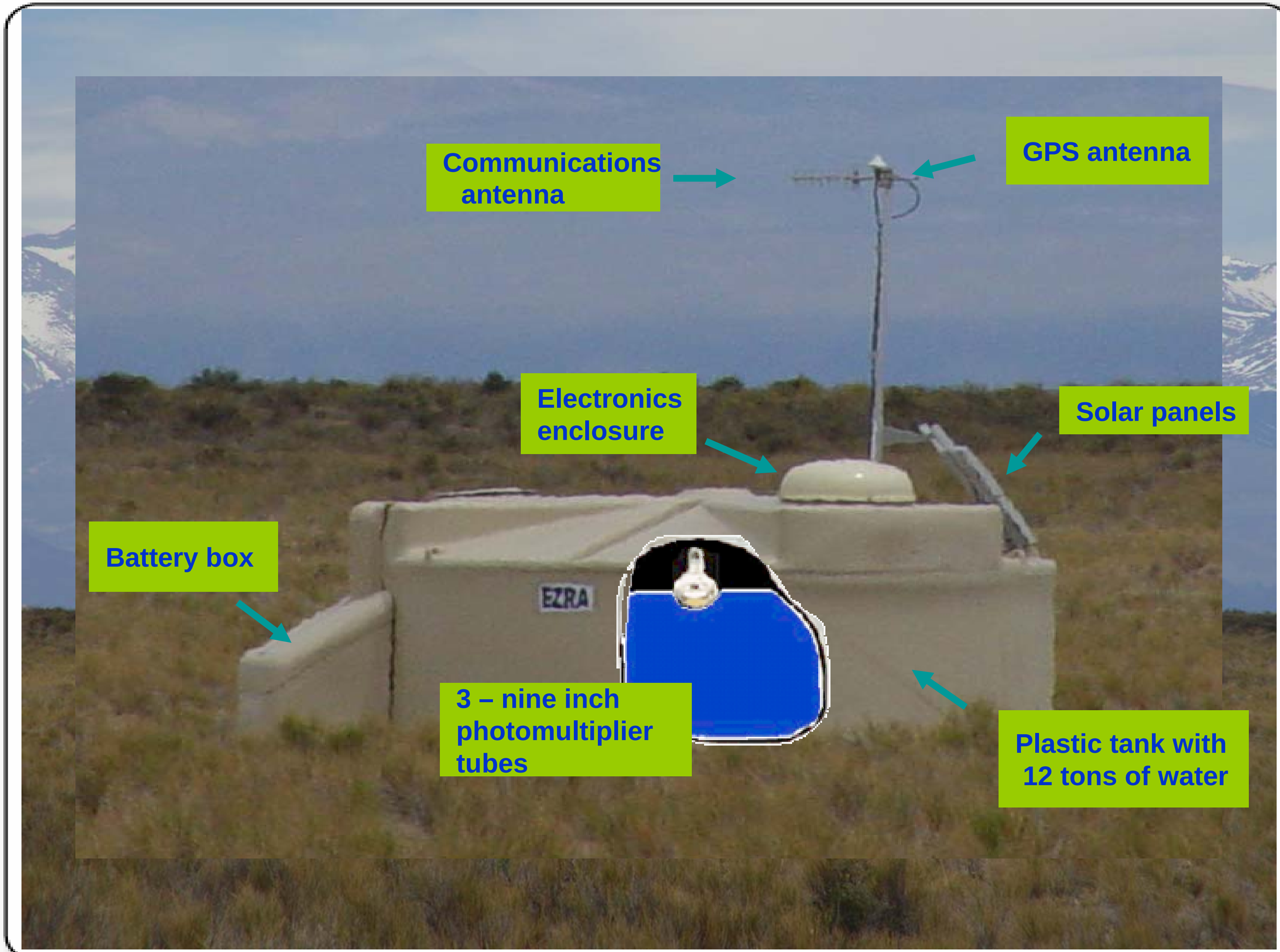
1. High statistics
   (aperture >7000 km^2 sr above 10^{19}eV in each hemisphere)

2. Full sky coverage (S&N)
   with uniform exposure

3. Hybrid configuration
   surface array with fluorescence detector coverage

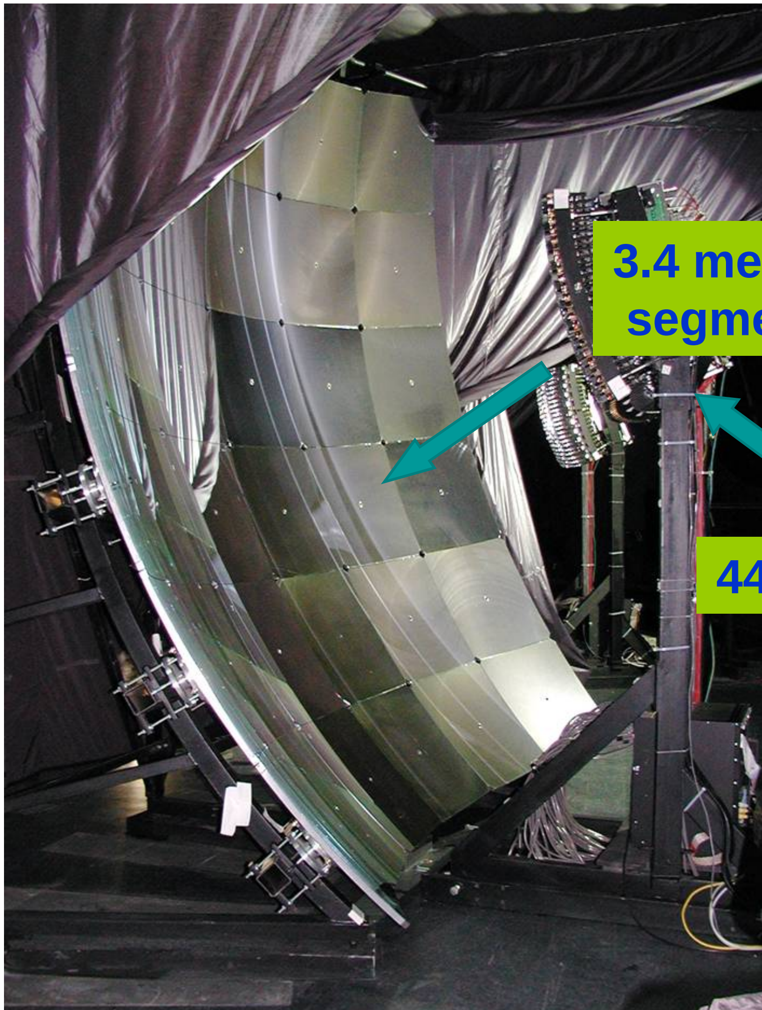
The Surface Array

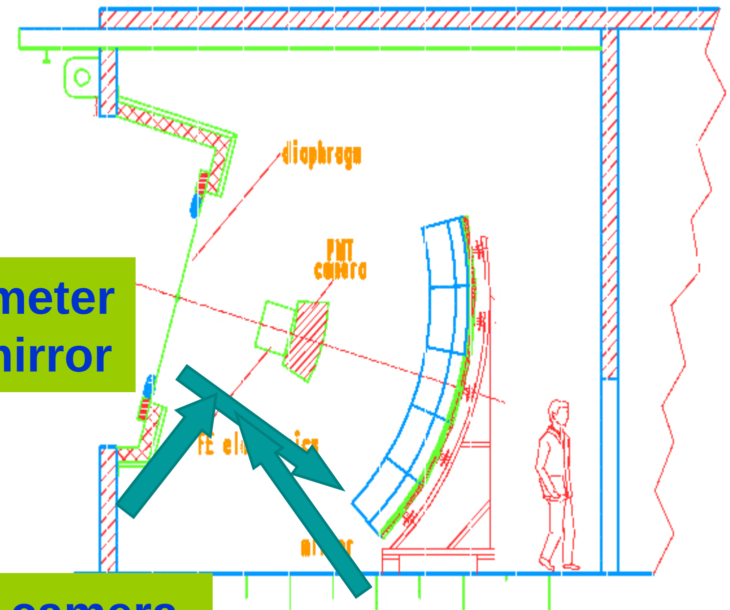
Detector Station

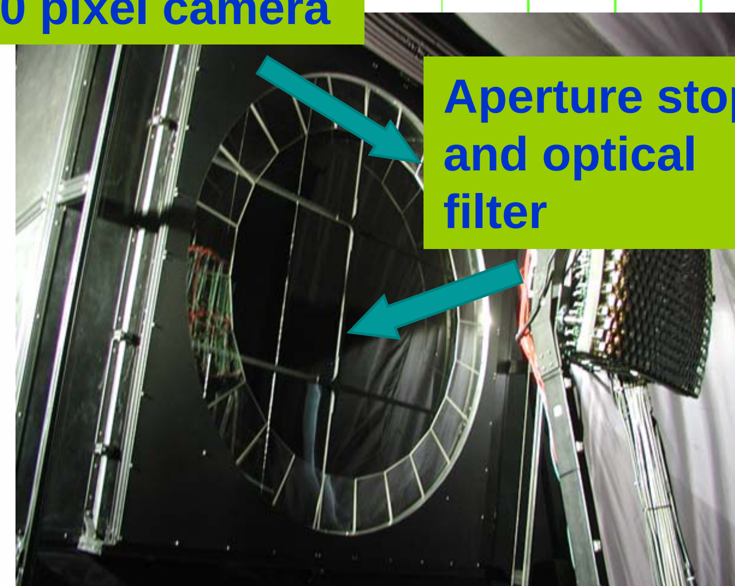


Surface Detector Deployment

The Fluorescence Detector







3.4 meter diameter segmented mirror

440 pixel camera

Aperture stop and optical filter

The Fluorescence Detector Stations

K.-H. Kampert

Atmospheric Monitoring and Calibration

Atmospheric Monitoring

Central Laser Facility

Lidar at each fluorescence eye

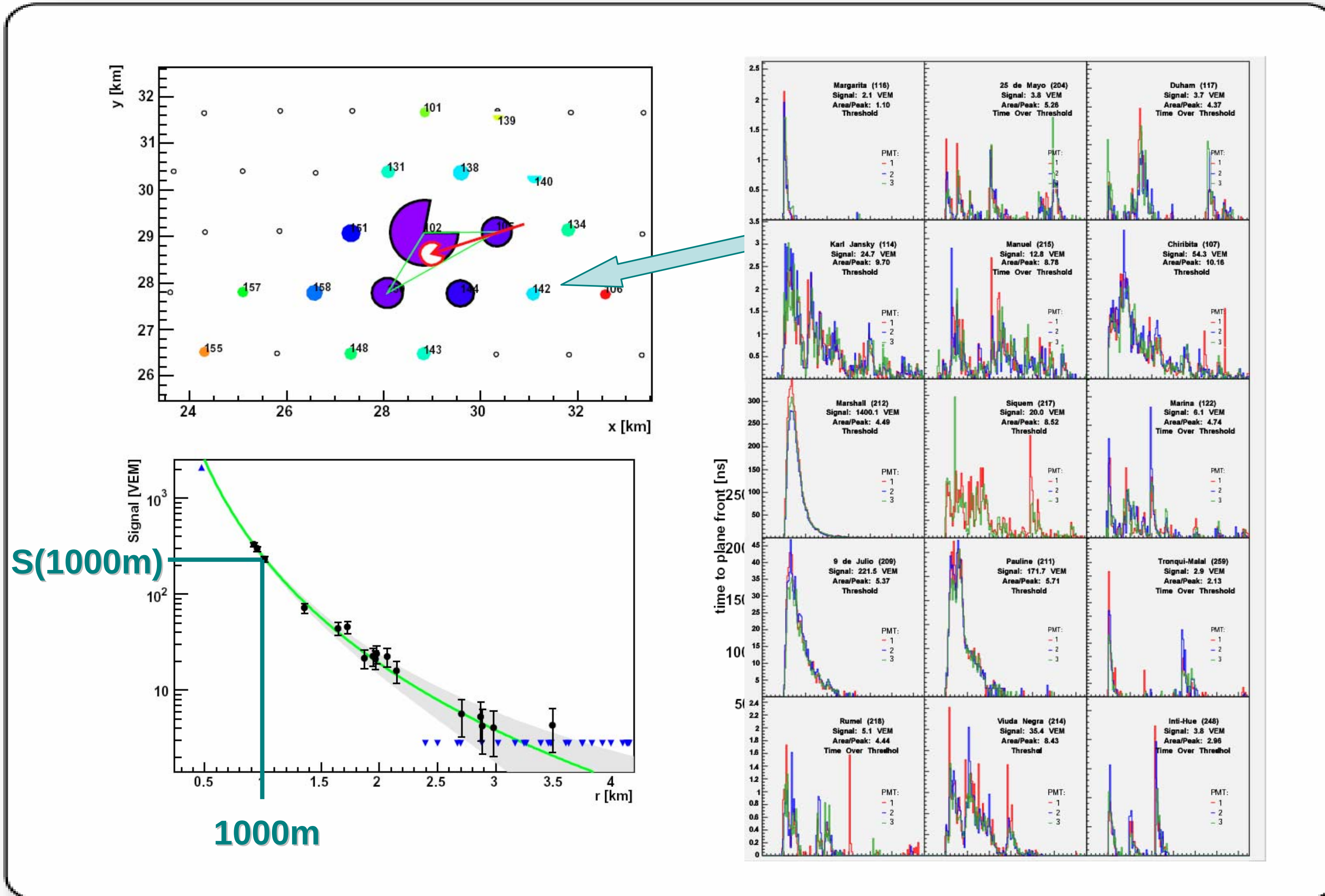
Atmospheric radio sounding measurements

Absolute Calibration

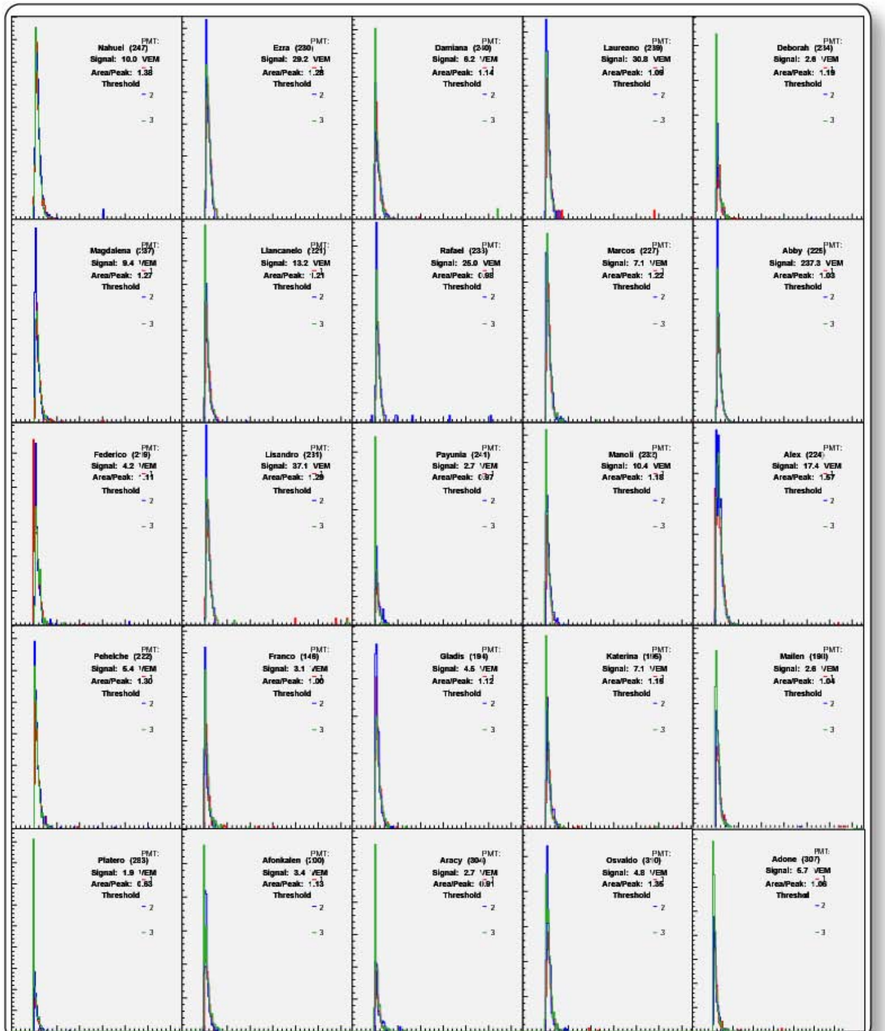
Drum for uniform camera illumination:

end to end calibration

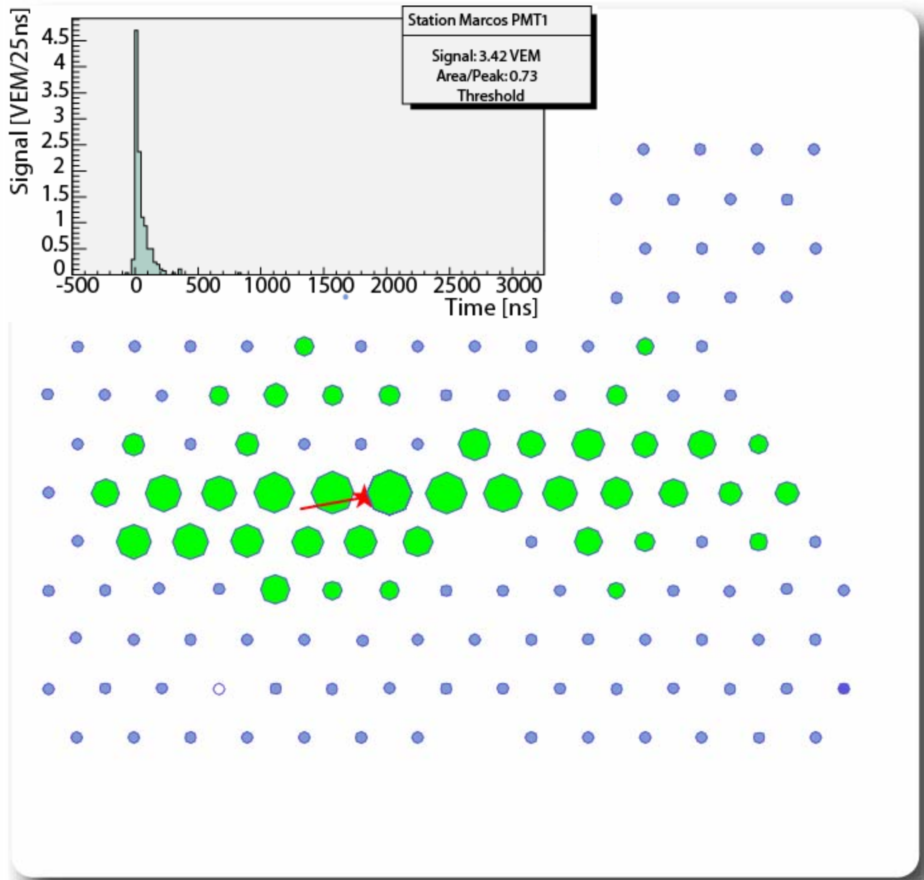
Example Event (48°, E~70 EeV)



Horizontal Showers

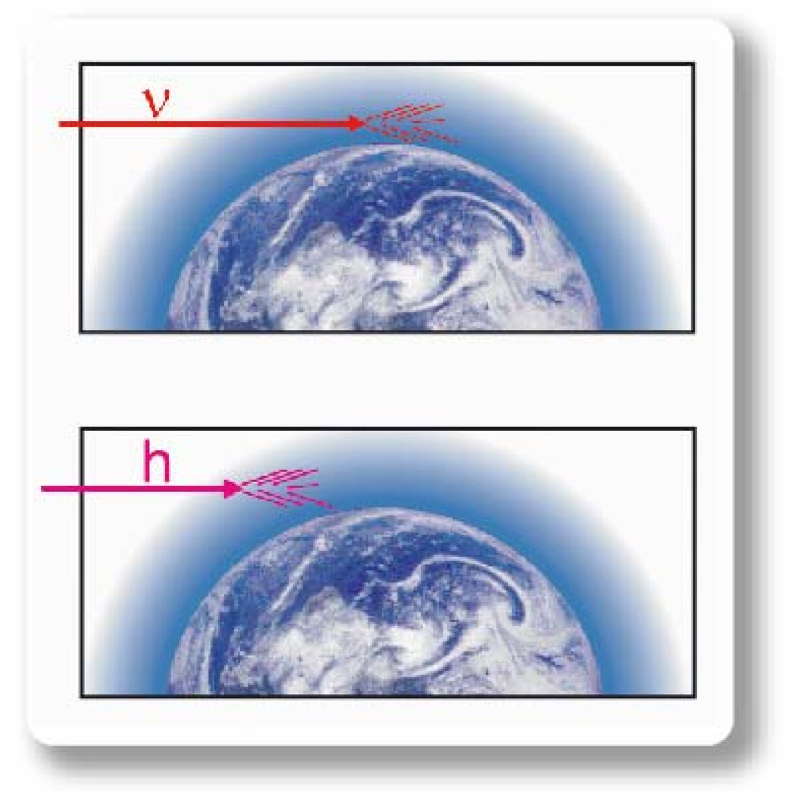


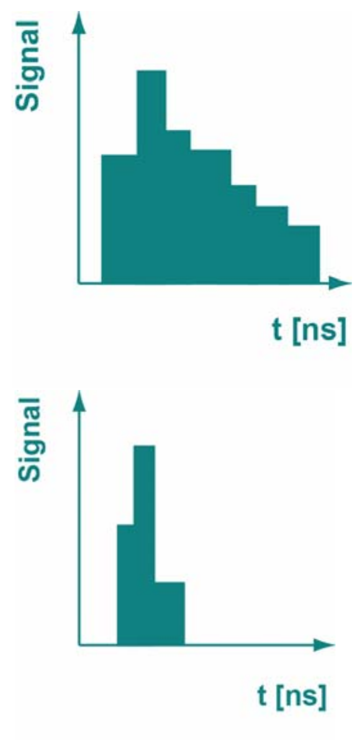
$E\sim5\cdot10^{19}$ eV $\theta=82°$



Horizontal Showers and Neutrinos

E > 10^{18} eV



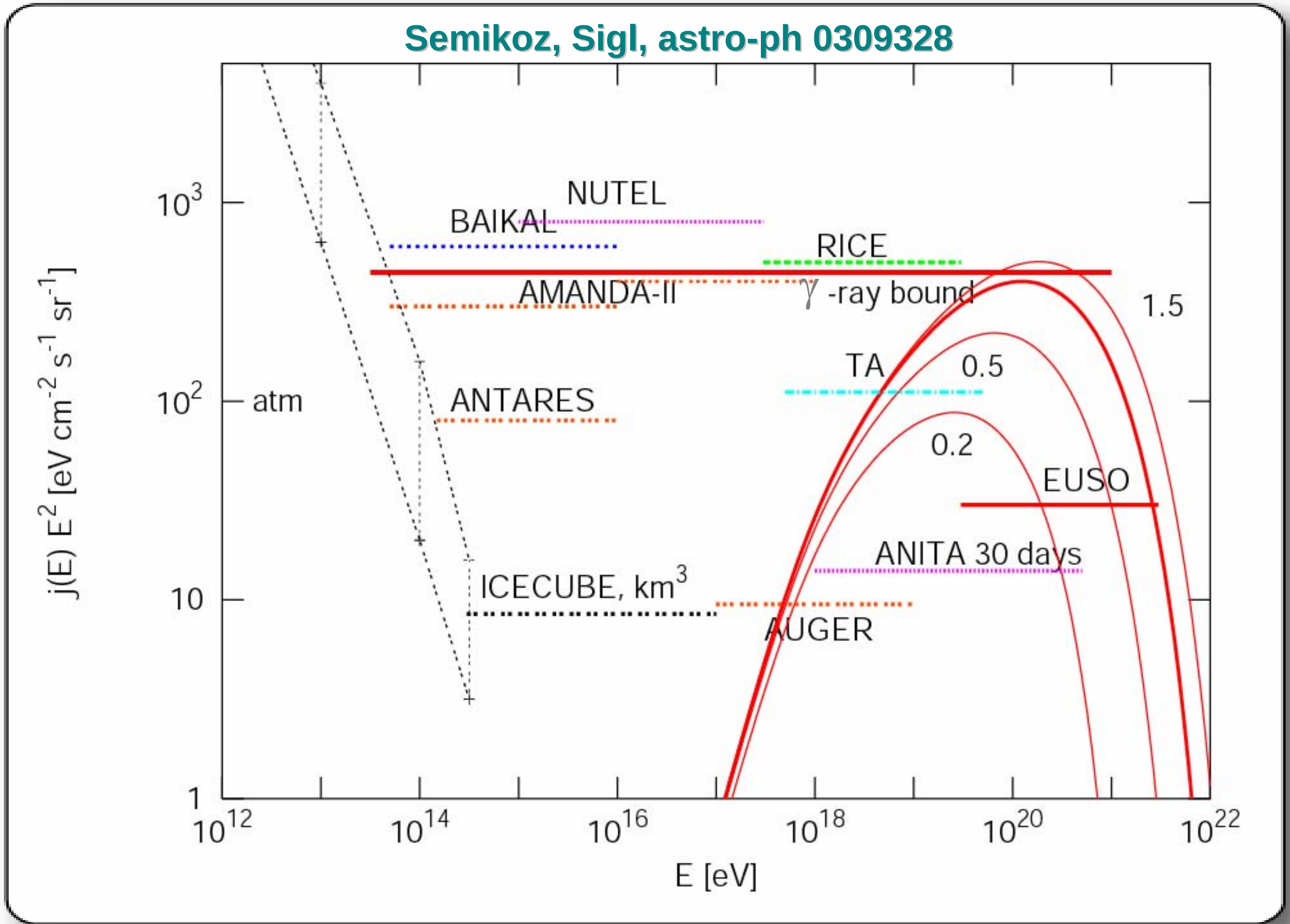


Only neutrinos can produce such signatures

Neutrino rate ~ 0.5 - 1 particle / year

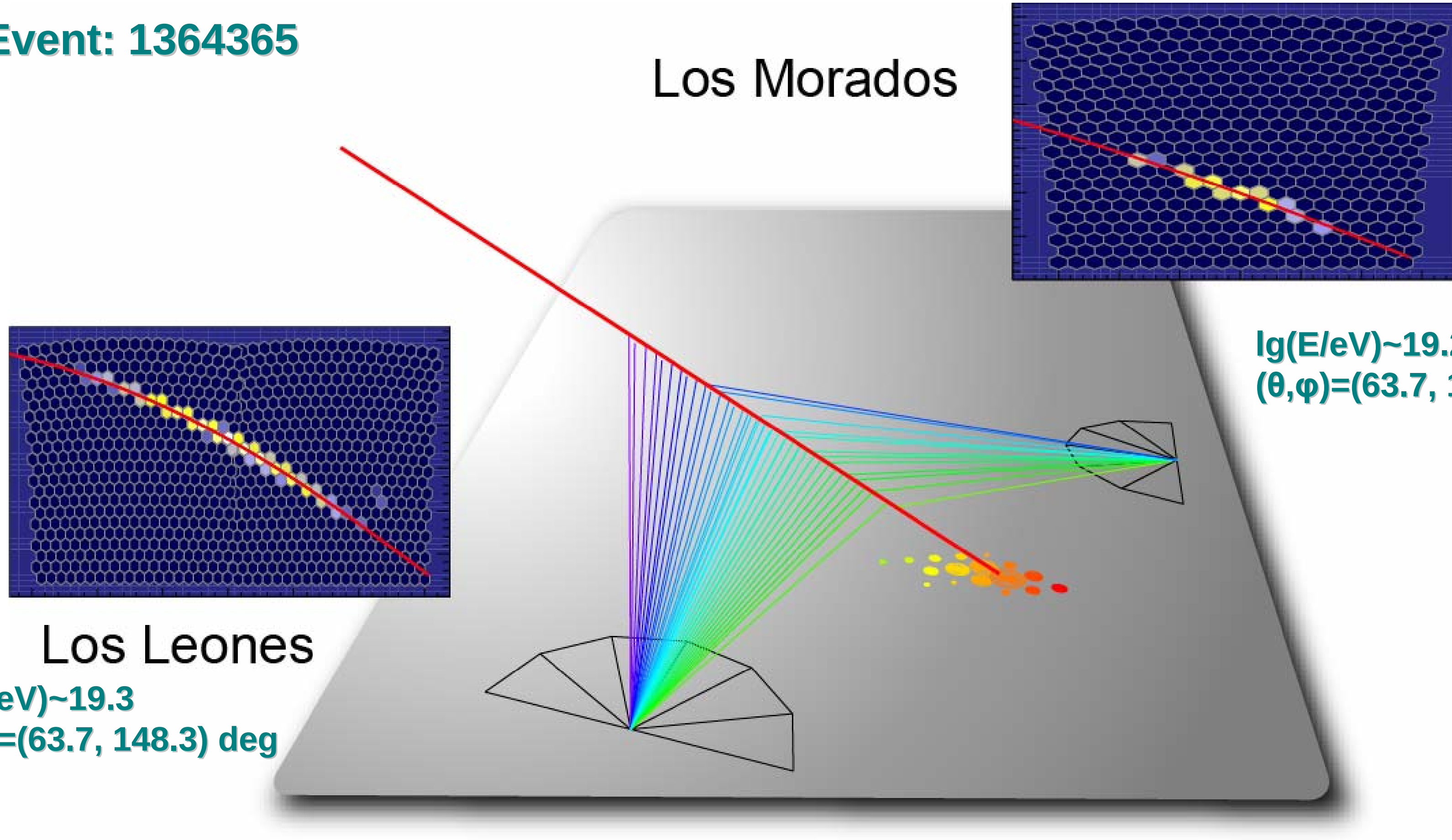
Depends strongly on the theoretical model

Cosmogenic Neutrino-Flux and Experimental Sensitivities



Stereo Hybrid Measurement

Event: 1364365

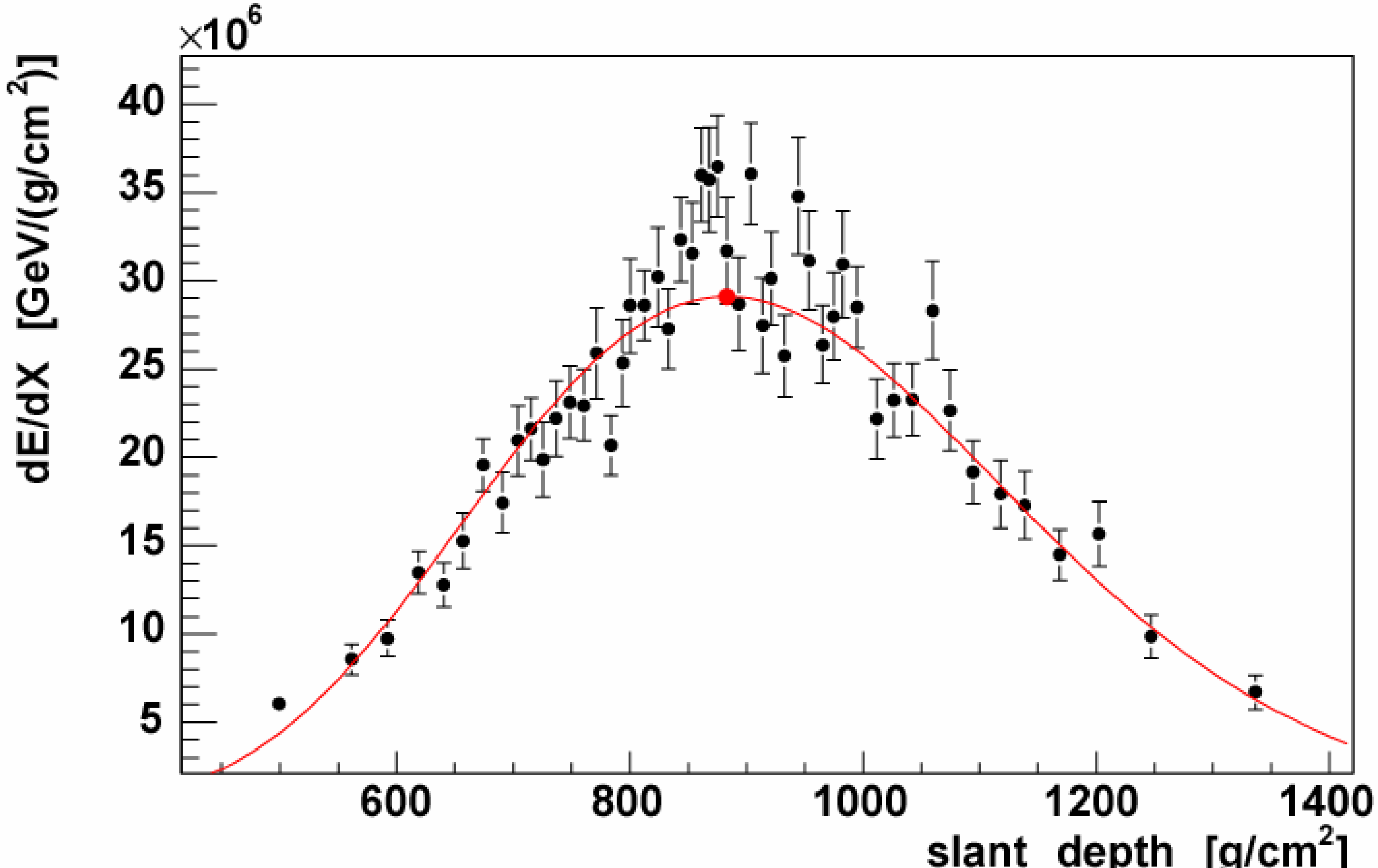


lg(E/eV)~19.2
(θ,φ)=(63.7, 148.4) deg

lg(E/eV)~19.3
(θ,φ)=(63.7, 148.3) deg

lg(E/eV)~19.1
(θ,φ)=(63.3, 148.9) deg

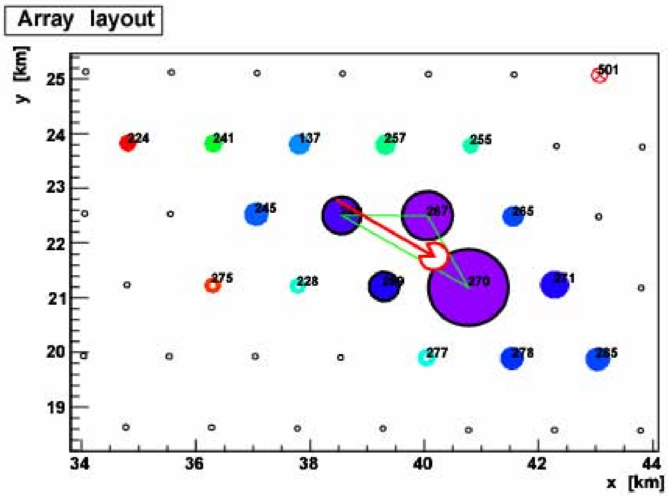
Stereo Hybrid Event: FD-Measurement

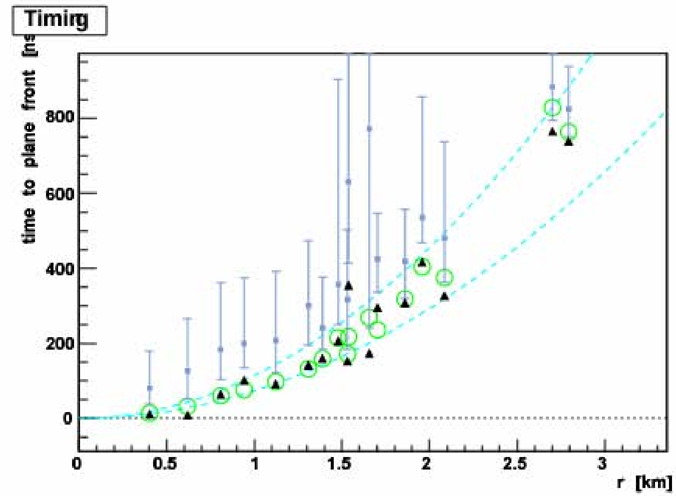


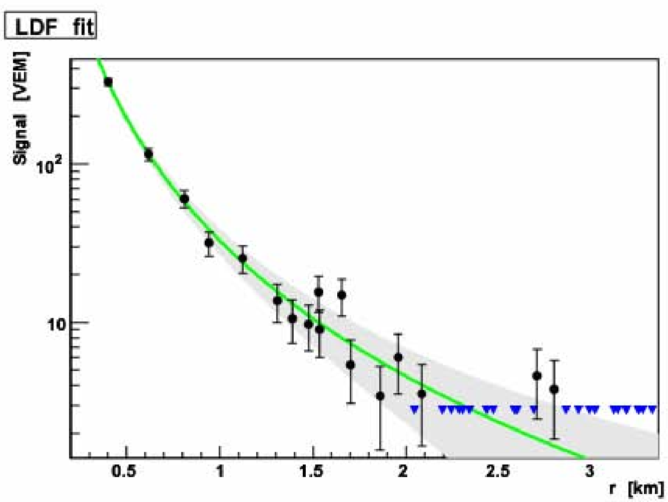
Event: 1364365

Stereo Hybrid Event: SD-Measurement

Event: 1364365

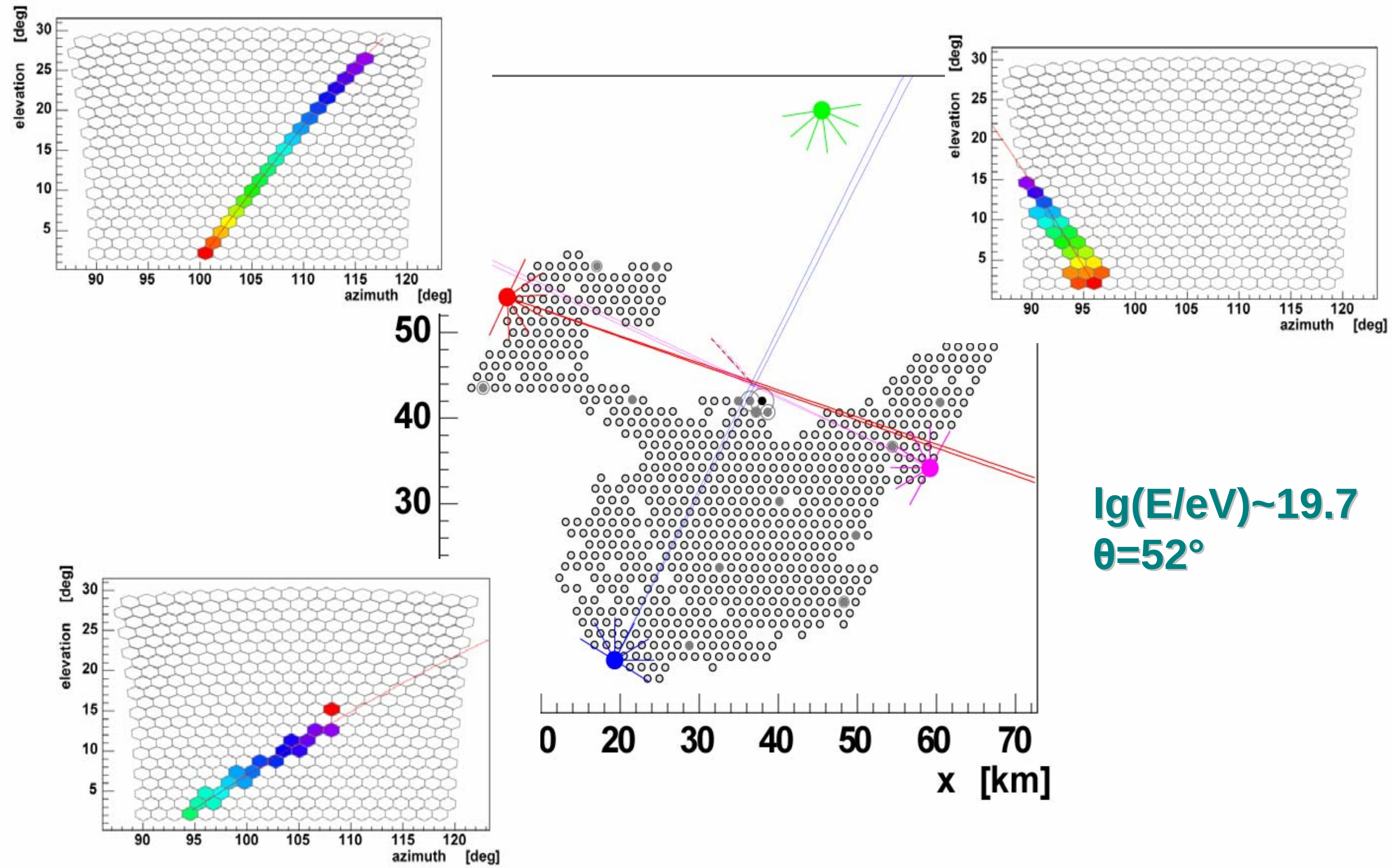






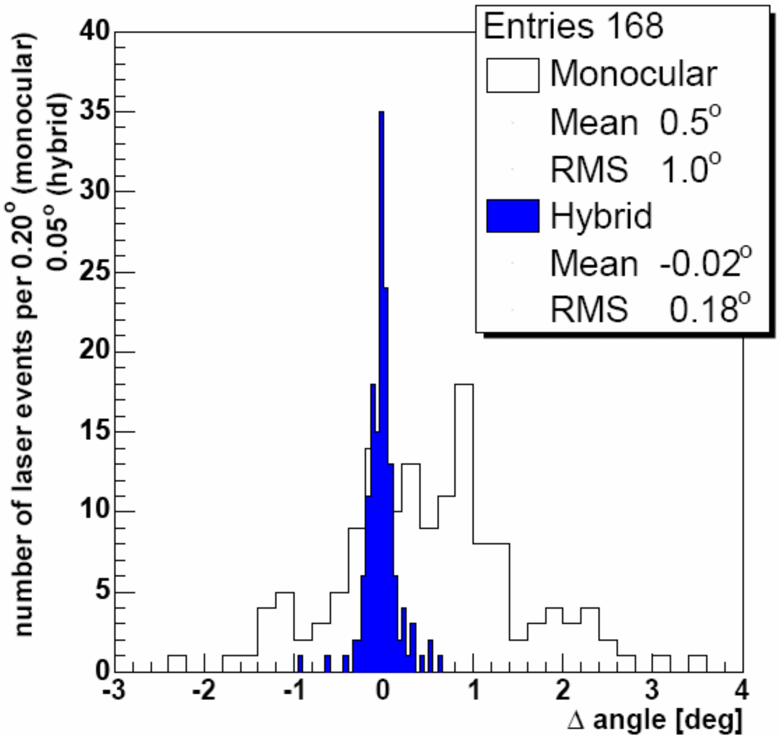
Event: 1364365
Time: 00:33:36 16 MAY 2005
GPS Time: 800238829 s, 347741000 ns
T4: FD+3TOT+4C1 T5: Yes
Reconstruction stage: 4.1
Easting: 479996. ± 35.7 [m]
Northing: 6082011. ± 13.5 [m]
θ: 63.3 ± 0.3 [°]
ϕ: 148.9± 0.3 [°]
R_c: 19.6 ± 0.05 [km]
S_{1000}: 32. ± 1.2 [VEM]
β: -1.71± 0.04

Triocular Event

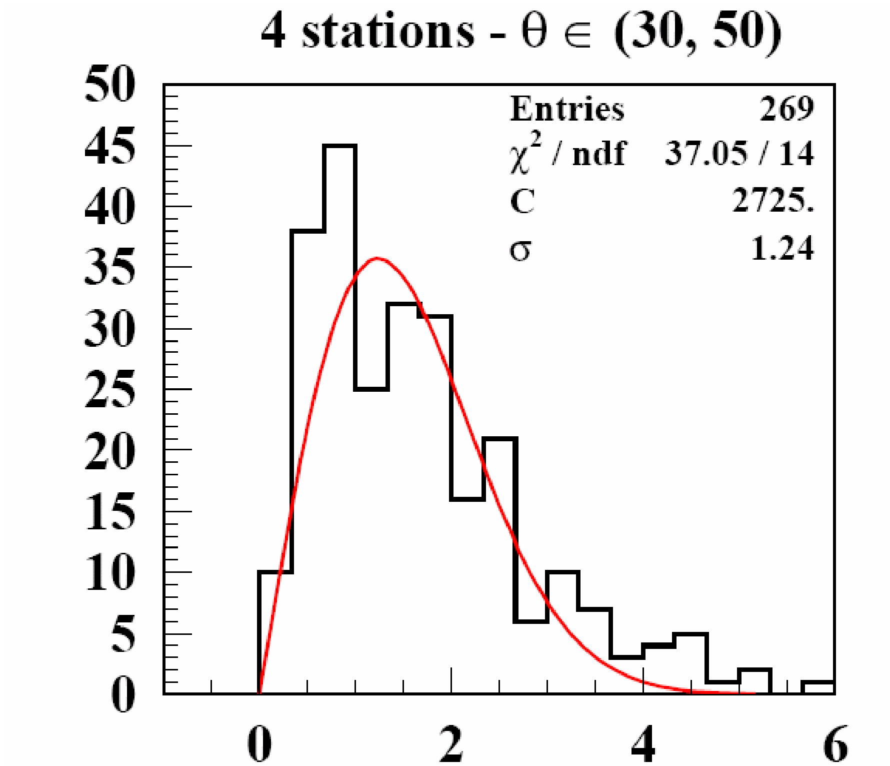


lg(E/eV)~19.7
θ=52°

Performance: Angular Resolution



Angle in laser beam /FD detector plane



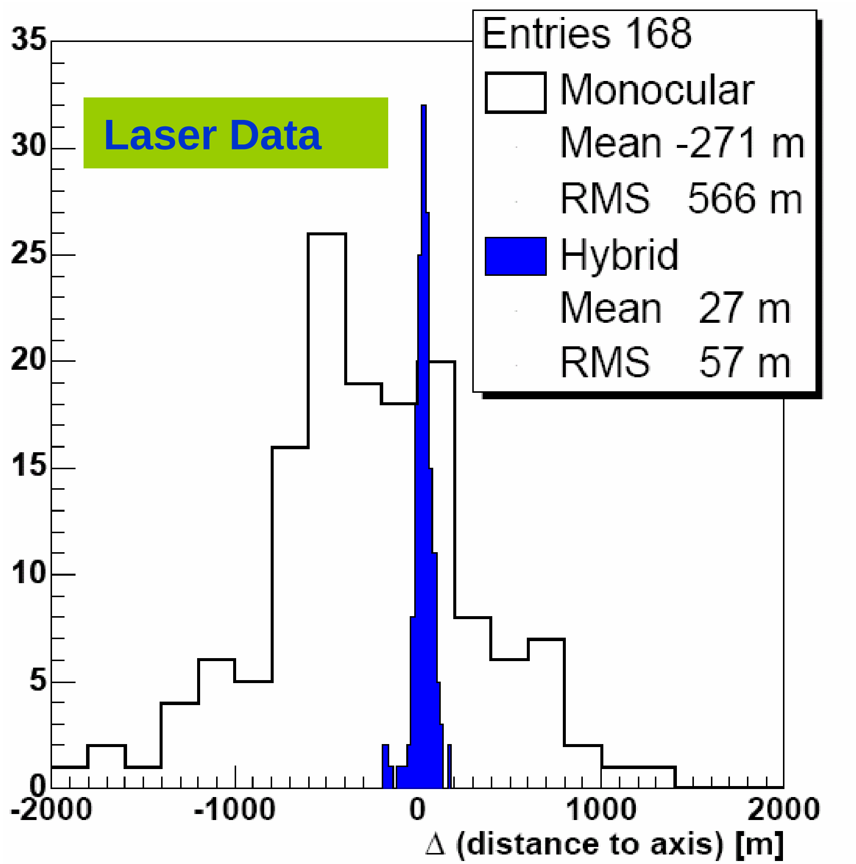
Hybrid-SD only space angle difference

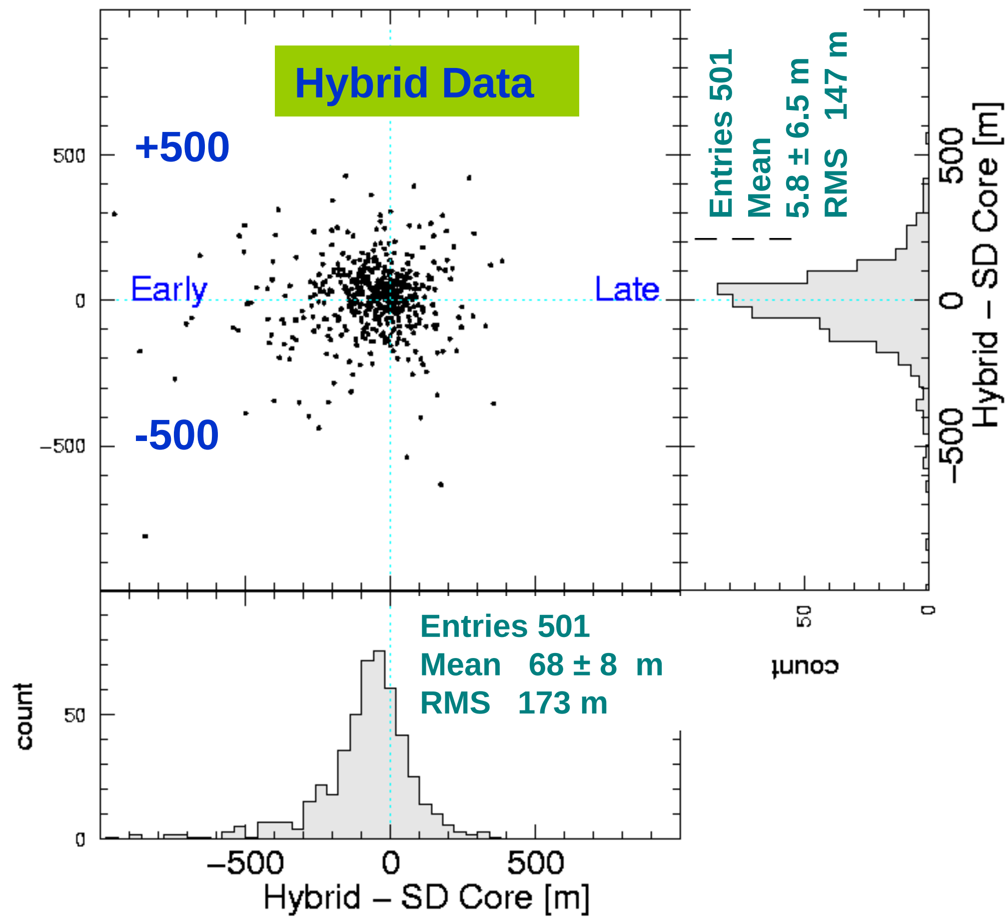
Hybrid Angular resolution
(68% CL)
0.6 degrees (mean)

Surface array Angular resolution (68% CL)

- *< 2.2° for 3 station events (E< 3EeV, θ < 60°)*
- *< 1.7° for 4 station events (3<E<10 EeV)*
- *< 1.4° for 5 or more station events (E>10 EeV)*

Performance: Core Resolution



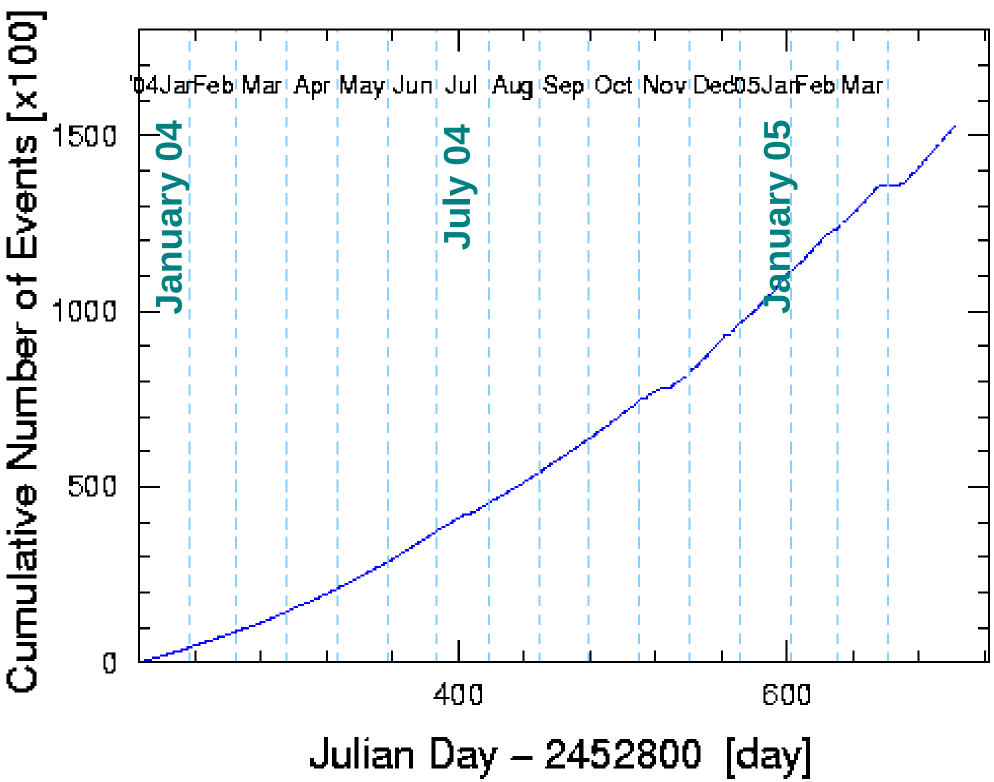


Laser position – Hybrid and FD only (m)

Hybrid – SD only core position

Core position resolution
Hybrid: < *60 m*
Surface array: *~150 m*

The First Data Set



Collection period:

1 January 2004 to 5 June 2005

Zenith angles:

0 - 60º

Total acceptance:

AUGER : ~1750 km² sr yr ~ AGASA

HIRES I : ~5000 km² sr yr (mono)

HIRES II: ~2500 km² sr yr (mono)

Surface array events (after quality cuts):

Current rate: ~18,000 / month

Total: ~180,000

Hybrid events (after quality cuts):

Current rate: ~1,800 / month

Total: ~18,000

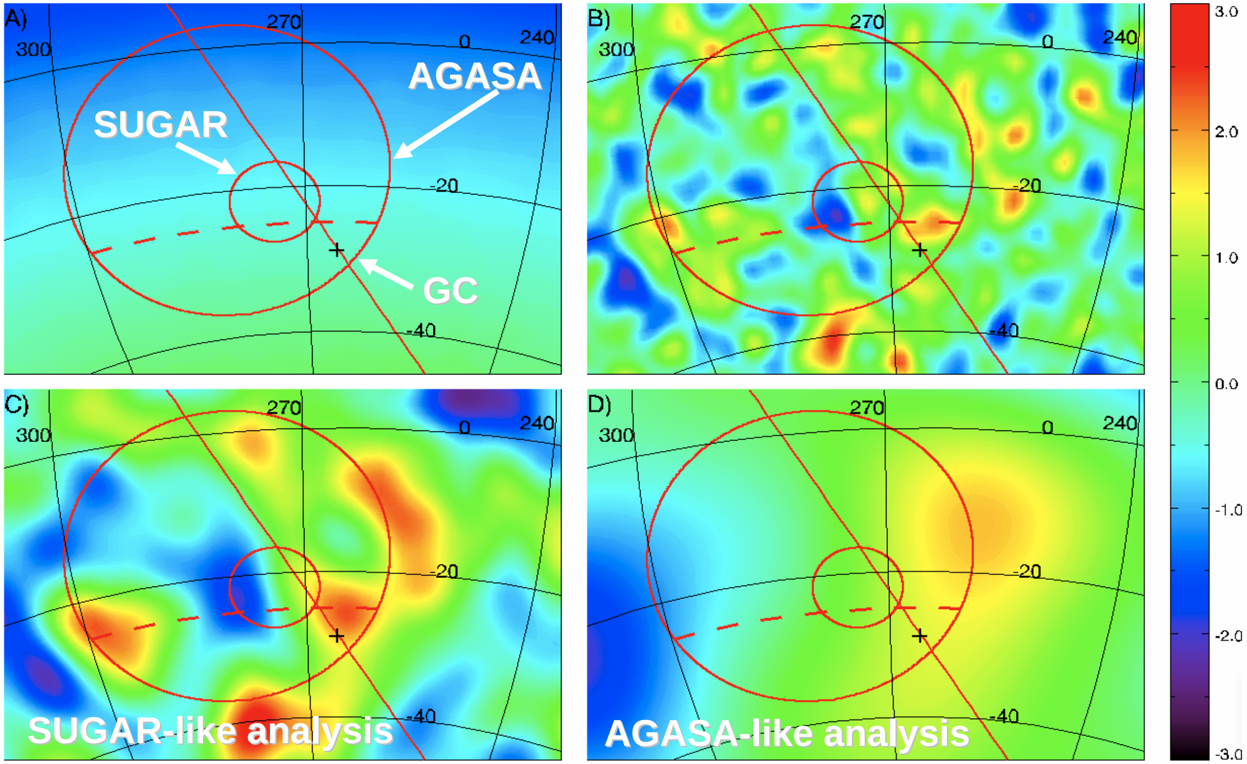
Anisotropy: Galactic Center

excess flux
AGASA: 4.5 σ
Sugar: 2.9 σ

$\Phi_S < 10.6\ 10^{-15}\ m^{-2}\ s^{-1}$

excludes neutron source at the GC

Coverage [0.8-3.2 EeV] Significance (1.5º)



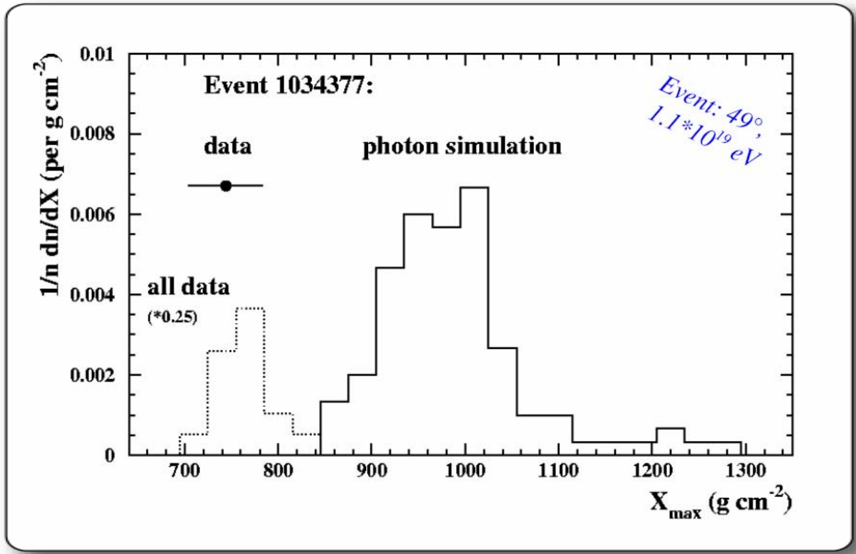
Significance (3.7º) Significance (13.3º) [0.8-2.5 EeV]

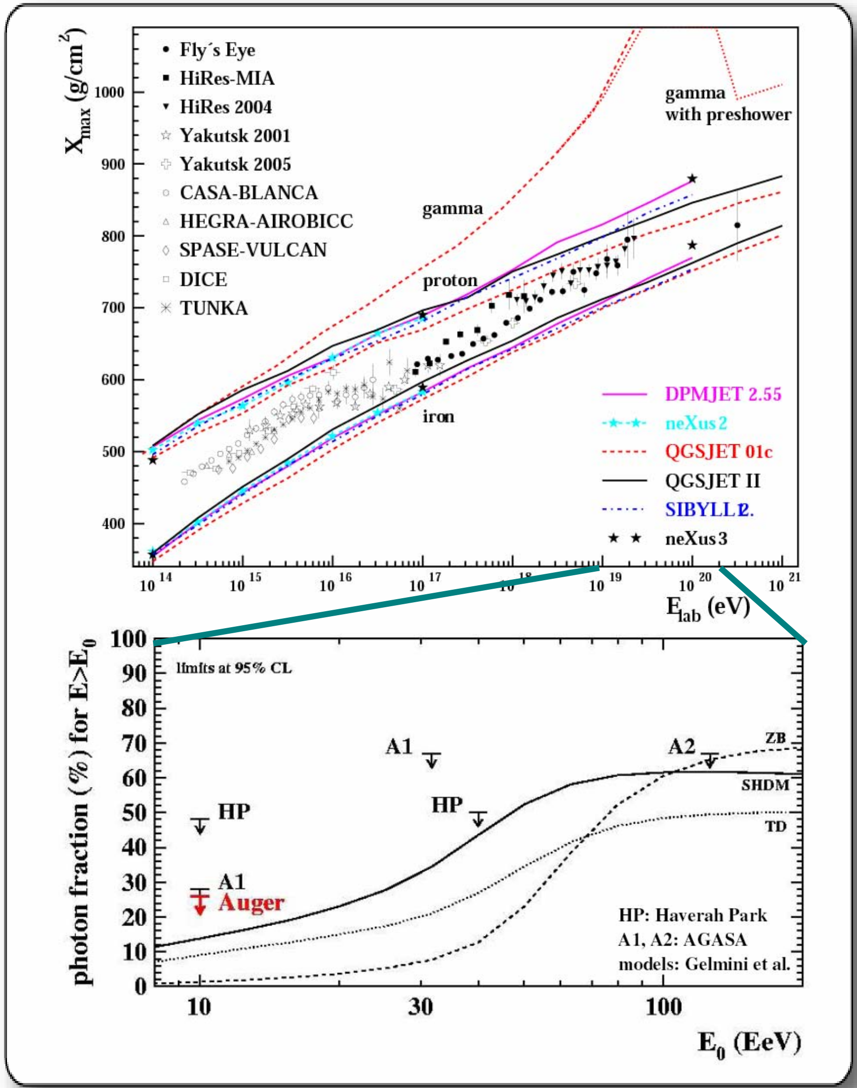
Photon Limit

Hybrid events: **improved geometry fit**

Selection criteria:
- $E > 10^{19}$eV, $\theta > 35°$
- X_{max} observed, track length > 400 g/cm^2
- Energy dependent distance cut

16 Events after cuts





26% upper limit (95% CL) on CR photon fraction

Energy Determination (Conversion)

The energy converter:

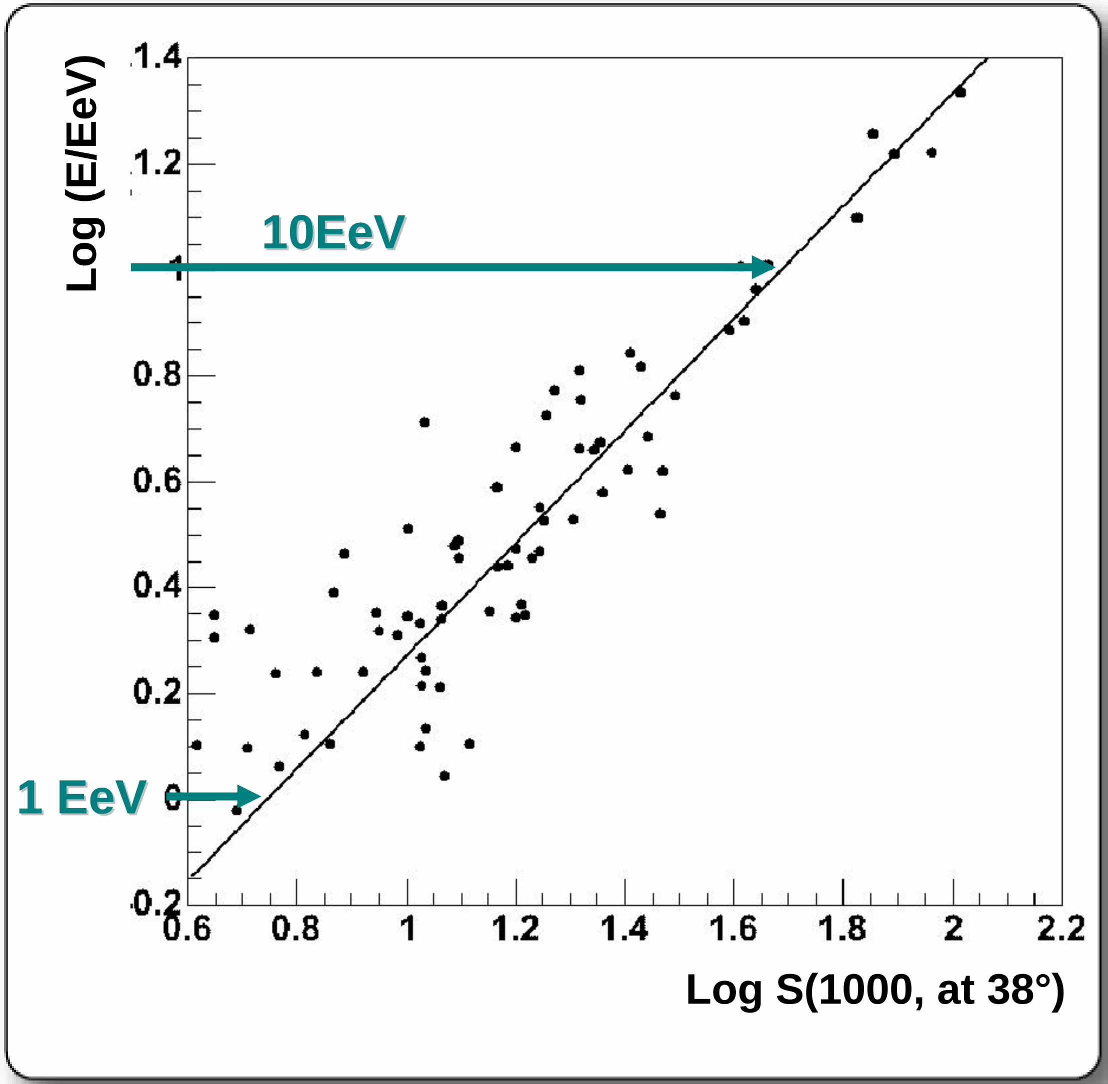
Compare ground parameter S(1000, at 38°) with the fluorescence detector energy (CIC method)

Transfer the energy converter to the surface array only events

$$\mathrm{Log}\,(E) = -0.79 + 1.06\,\mathrm{Log}(S_{38})$$

$$E = 0.16\, S_{38}^{1.06}$$

(E in EeV, S_{38} in VEM)



Auger Energy Spectrum

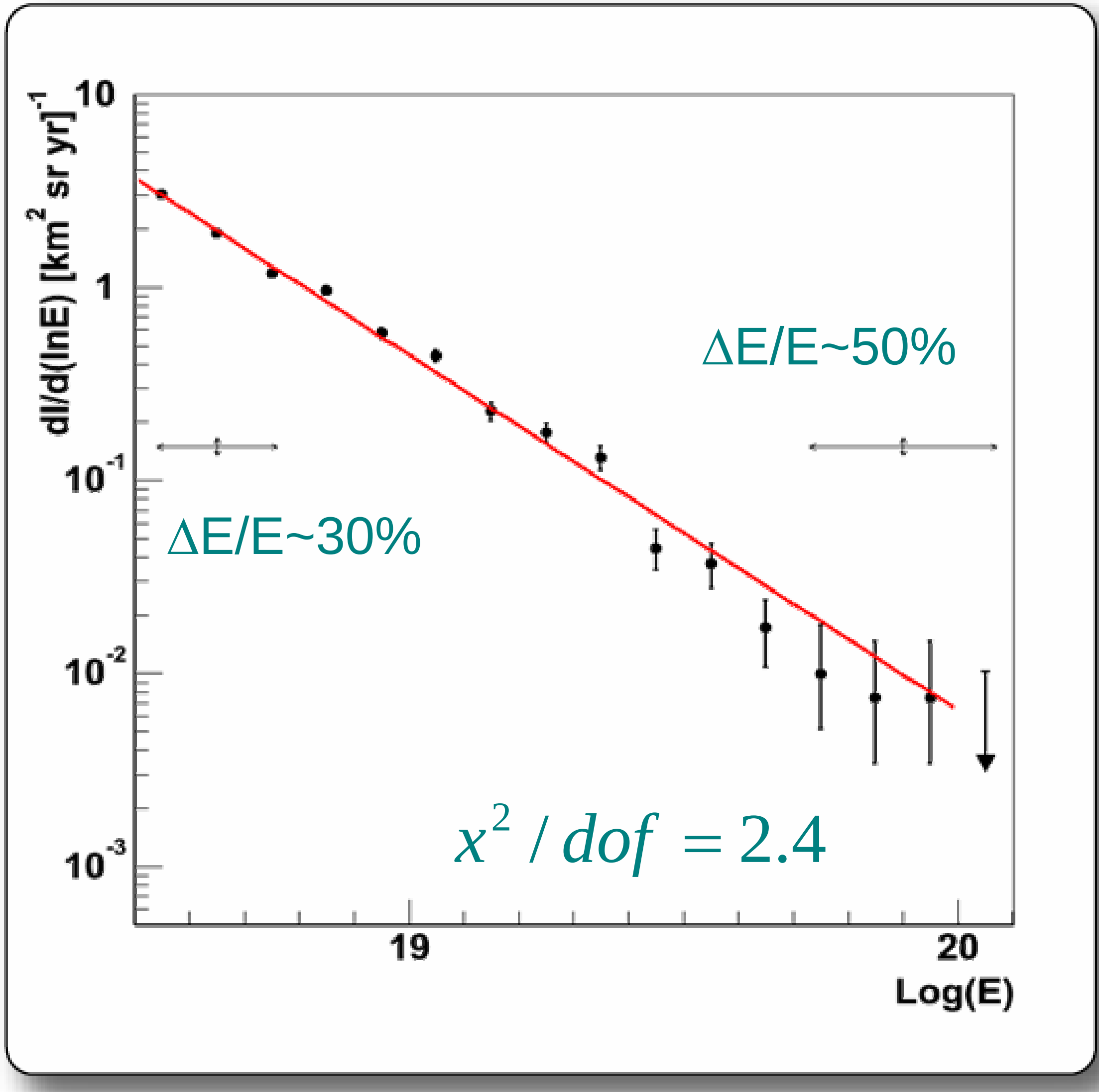
$$\frac{dI}{d\ln(E)} \equiv E\frac{dI}{dE}$$ vs. Lg(E)

Error bars on points indicate Poisson statistical uncertainty (or 95% CL upper limit) based on the number of events.

Systematic uncertainty is indicated by double arrows at two different energies.

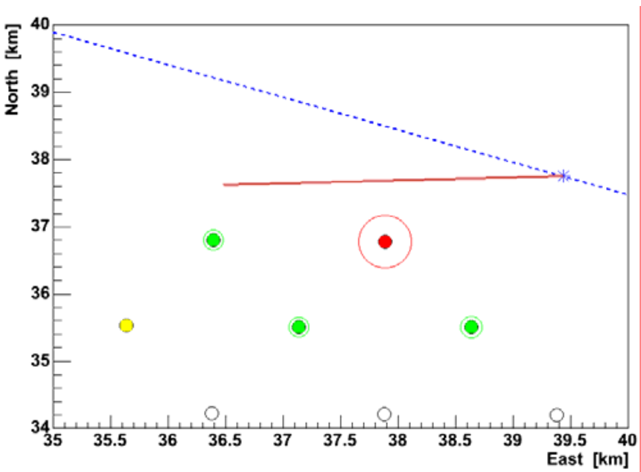
Horizontal: Systematic ΔE.

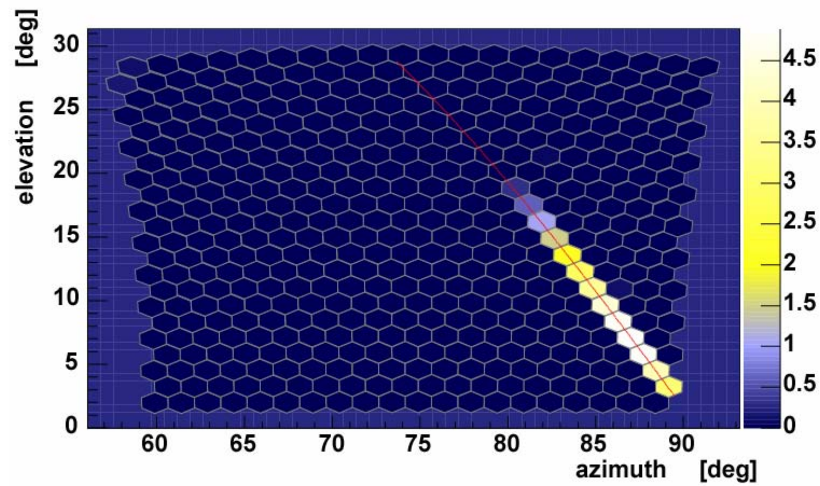
Vertical: Exposure uncertainty.

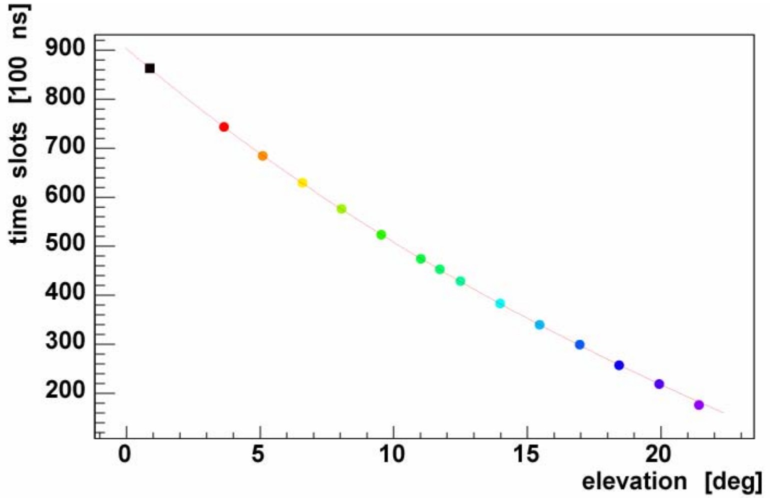


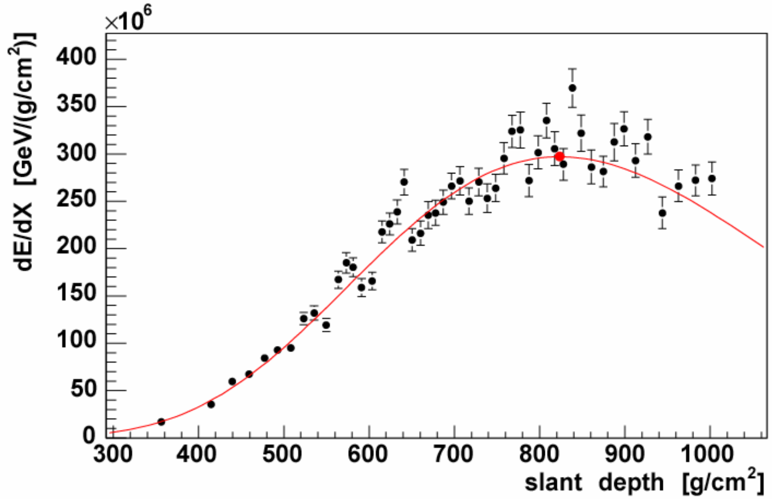
A Big Event - *One that got away!*

Energy estimate >140 EeV

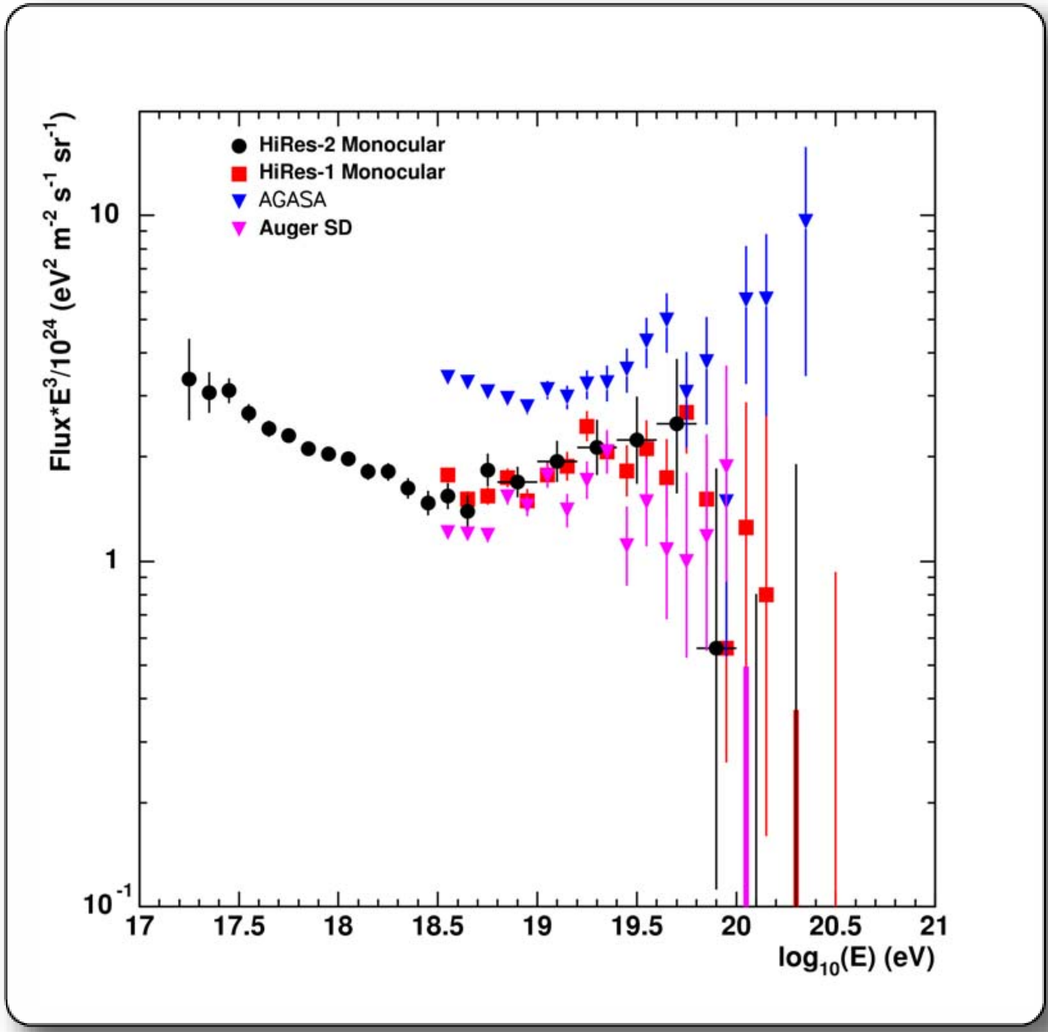








Comparison with HIRES, AGASA

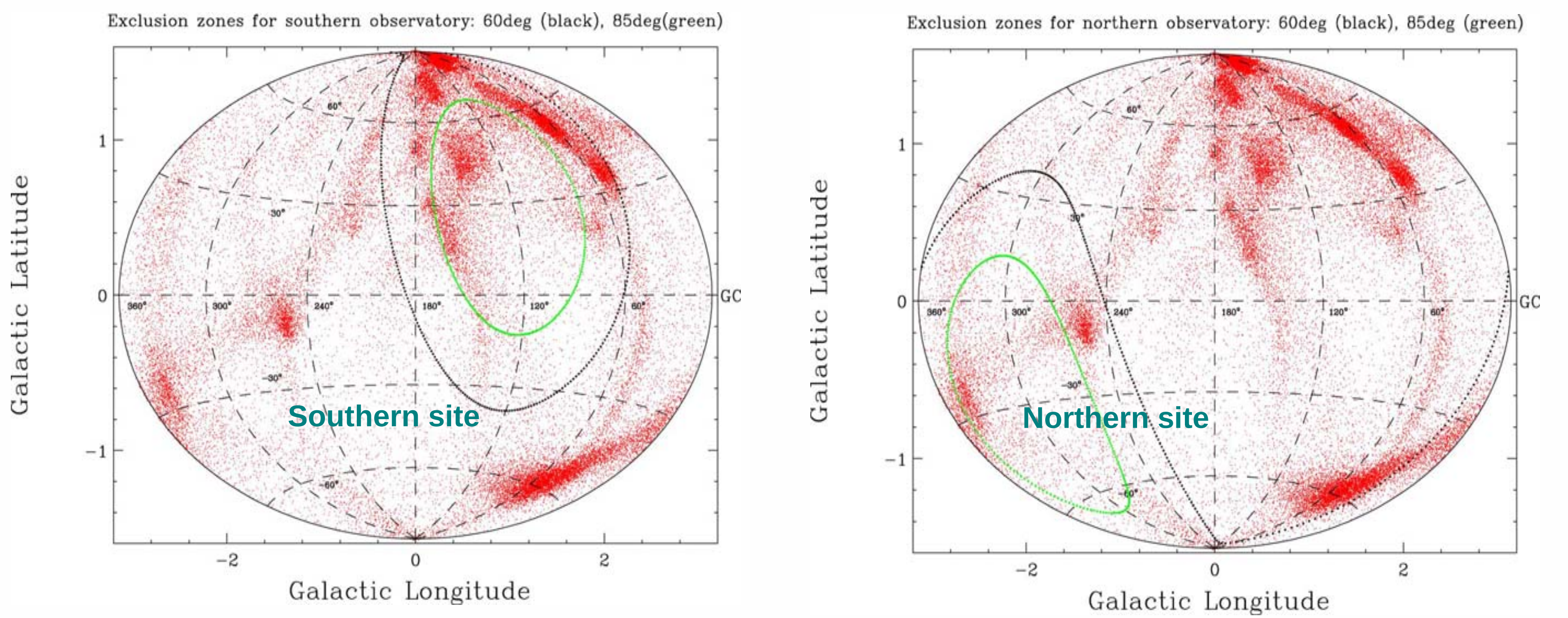


AUGER: Energy scale uncertainty still large

~50 % at 100 EeV

Plans for Auger North

Needed: Full sky coverage



Galaxy Distribution 7-21 Mpc

Colorado, USA has been selected as the northern site

Funding proposals to be prepared over the next two years.

EUSO Science Goals

- **Detection and investigation of the Extreme Energy Component of the Cosmic Radiation: EECRs / UHECRs with E > 5×10^{19} eV**
- **Arrival directions and small-scale clustering will provide information on the origin of the EECRs and inter-galactic magnetic fields.**
- **Open the Channel of High Energy Neutrino Astronomy to probe the boundaries of the Extreme Universe and to investigate the nature and distribution of the EECR sources**
- **…**

Extreme Universe Space Observatory

EUSO Consortium - Institutes

>150 researchers
in 50 institutions in 6 countries in Europe, the USA, Japan and Brazil.

Participant Nations and Institutions

- **Brazil**
  - IAG, Univ Sao Paulo
- **France**
  - APC, Paris
  - CdF, Paris
  - IAP, Paris
  - LPSC, Grenoble
  - LPTHE, Paris
  - OdP, Paris
- **Italy**
  - IASF, Palermo
  - ISAC-CNR, Bologna
  - INFN & Univ. Genova
  - INFN & Univ. Firenze
  - INFN & Univ. Torino
  - INFN & Univ. Trieste
  - INFN Catania & Univ. Palermo
  - Univ. Roma “La Sapienza”
  - Scuola Normale Sup. Pisa
  - Oss. Astrofisico Arcetri
  - Oss. Astrofisico Catania
  - CARSO
  - INOA
- **Germany**
  - MPIfP, Munich
  - MPIHLL, Munich
  - MPIfRA, Bonn
  - Univ. Wuerzburg
  - EKU Tübingen
- **Portugal**
  - LIP, Lisbon
- **Spain**
  - IAA-CSIC, Granada
  - Dpt.FTC & CAFPE, Univ. Granada
- **Switzerland**
  - Obs. Neuchatel
- **USA**
  - MSFC & NSSTC, Huntsville
  - UAH, Huntsville
  - UCB, Berkeley
  - UCLA, Los Angeles
  - Vanderbilt Univ.
- **Japan**
  - RIKEN
  - ICRR
  - Konan Univ.
  - ISAS
  - Rikkyo
  - KEK
  - NAO
  - Tokyo Univ.
  - Saytama
  - Aoyama
  - Kinki
  - Seikei
  - Kanazawa

The Why's of a space-based detector for EECR

- **Geometrical Factor (A · Ω) (FoV=±30° at ISS mean distance h_{ISS}≅430km)**

$$A^{geo} \approx 6 \times 10^5\ km^2 \cdot sr$$

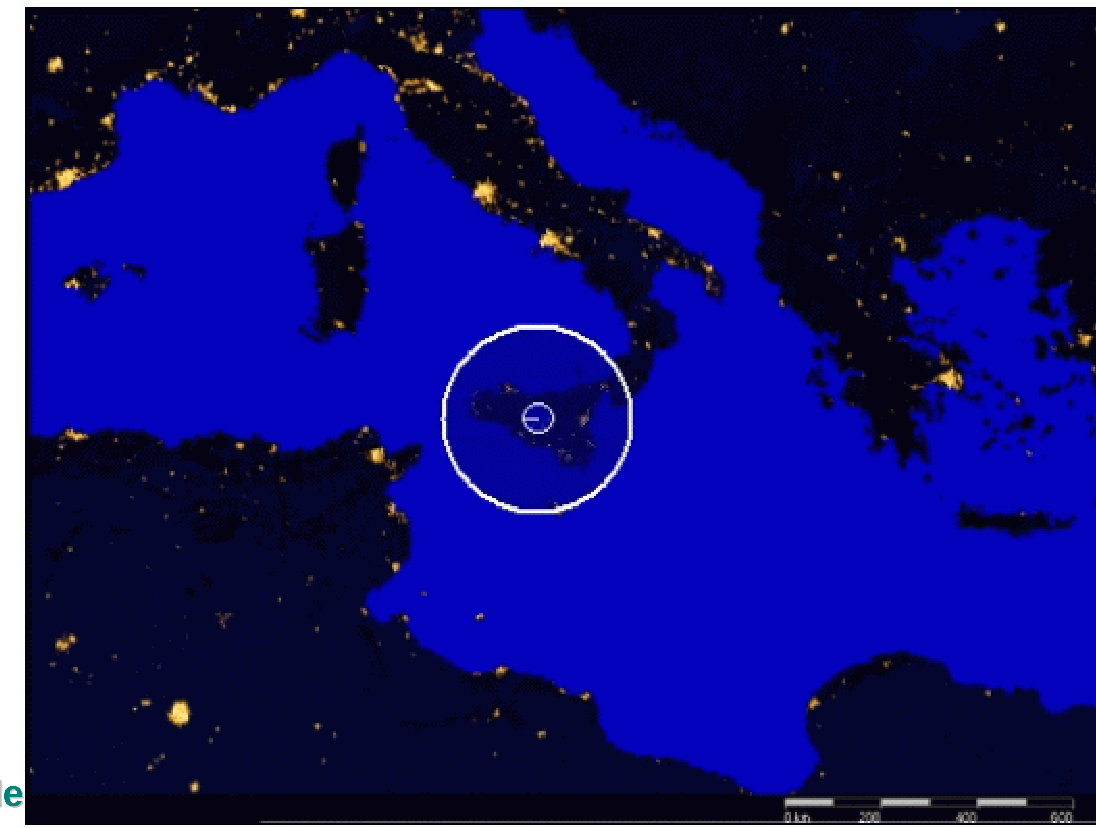
$$\eta_{cycle} \approx 10 \div 25\,\%$$

$$A_{Euso}^{eff} \approx (6 \div 9) \times 10^4\ km^2 \cdot sr$$

- **Full Sky Coverage**
- **Cerenkov "footprint" of shower**

The EUSO observational goal:

~ 1000 events/a in SuperGZK mode
> 70 events/a in GZK-suppressed mode



Comparison of UHECR Experiments.
Large encircled area: EUSO, small encircled area: AUGER. No duty cycle included.
Ratio of effective geometrical factor (EUSO/AUGER):
- including duty cycle (10% for both arrays): ~ 70
- with duty cycle (10%) only for EUSO: ~ 7

Scientific Requirements:

- High statistics ⇒ large aperture
- Energy threshold as low as possible to allow a dynamical range overlap and cross-calibration with ground array (AUGER)
  ⇒ high sensitivity to faint showers, bkg. Rejection
- Pointing capability ⇒ direction resolution

Instrumental Requirements:

- Large aperture ⇒ FoV as large as possible

  (±30° ⇒ ~$6\times10^5 km^2 sr$ from ISS mean orbit height)

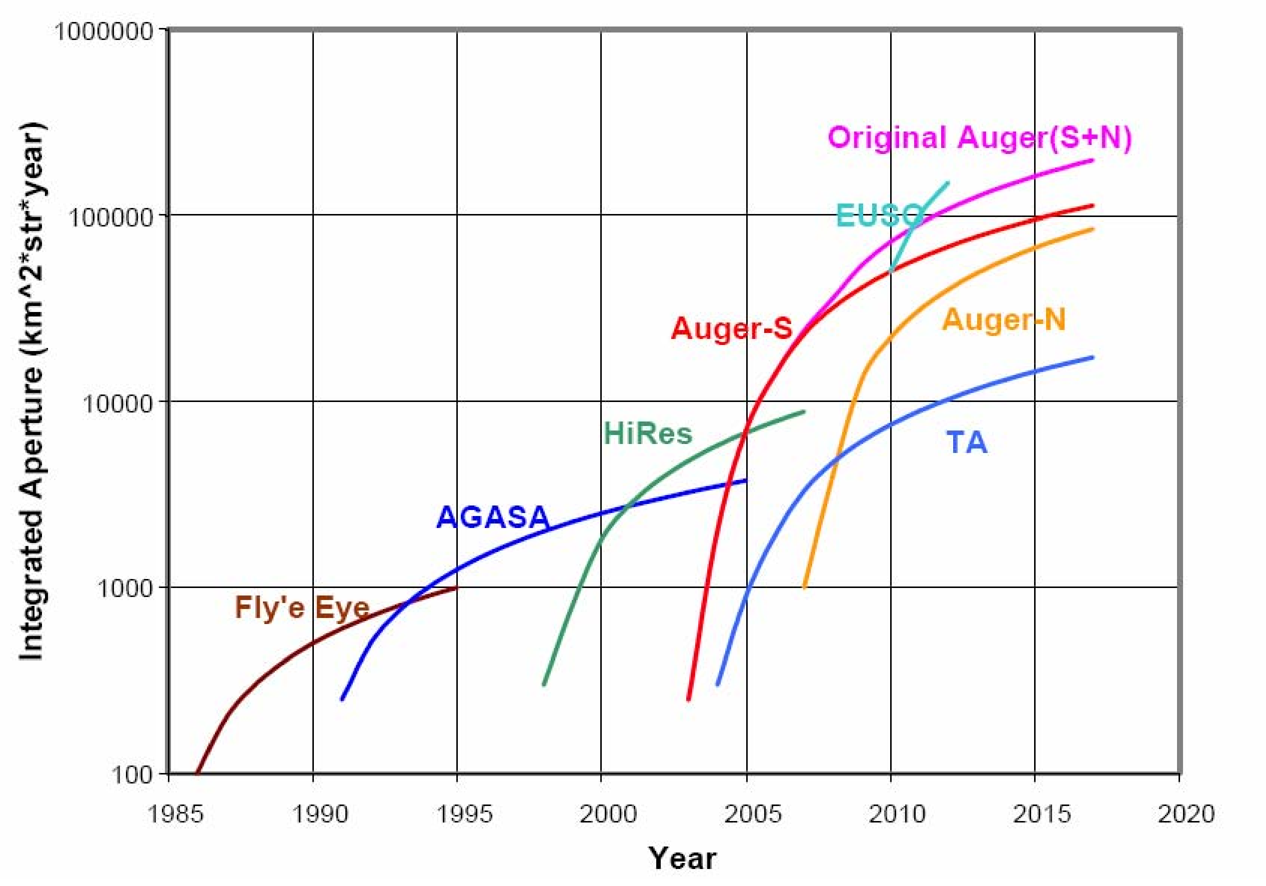
- Sensitivity ⇒ High luminosity

  (2.5m Ø collecting area, 5mm Ø PSF, f#<1.15, Q.E.>0.2
  ⇒~50% efficiency at 5×10^{19}eV, 100% efficiency at 10^{20} eV)

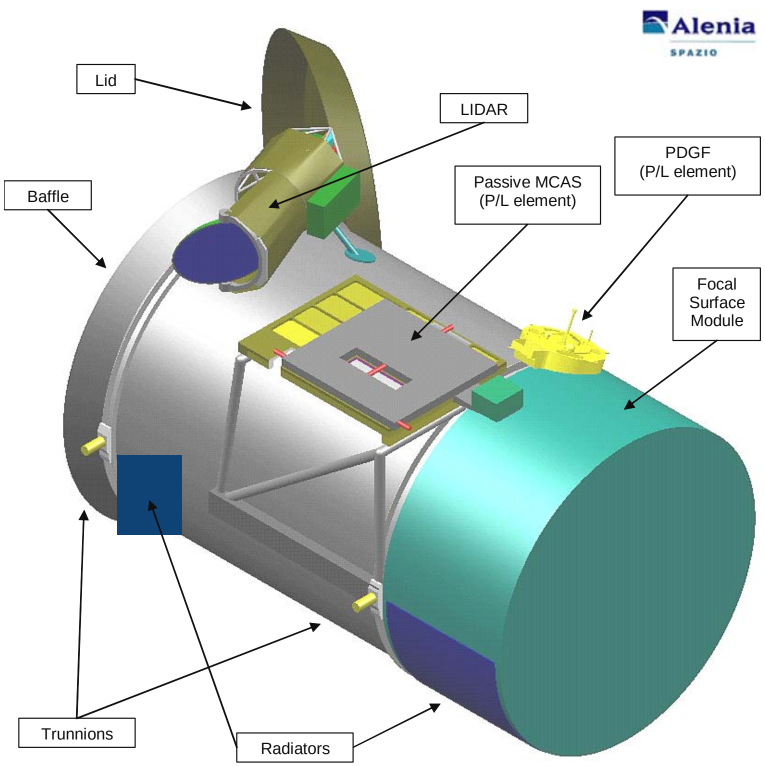
- Primary direction resolution ⇔ space resolution in FoV, time resolution

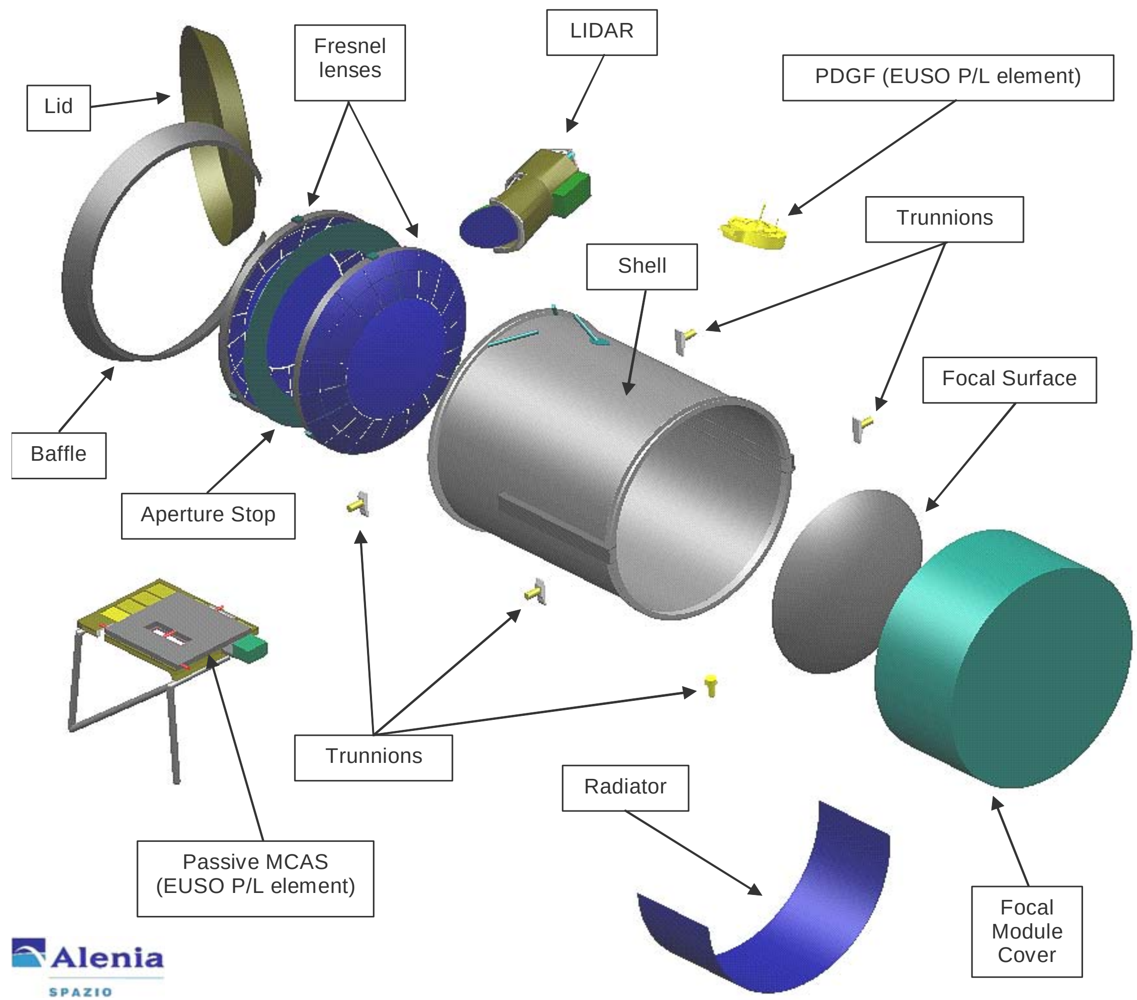
  (0.1° angular resolution, 2.5 μs time resolution
  ⇒ ± 1° on EECR incoming direction)

Integrated Aperture



EUSO – The Instrument





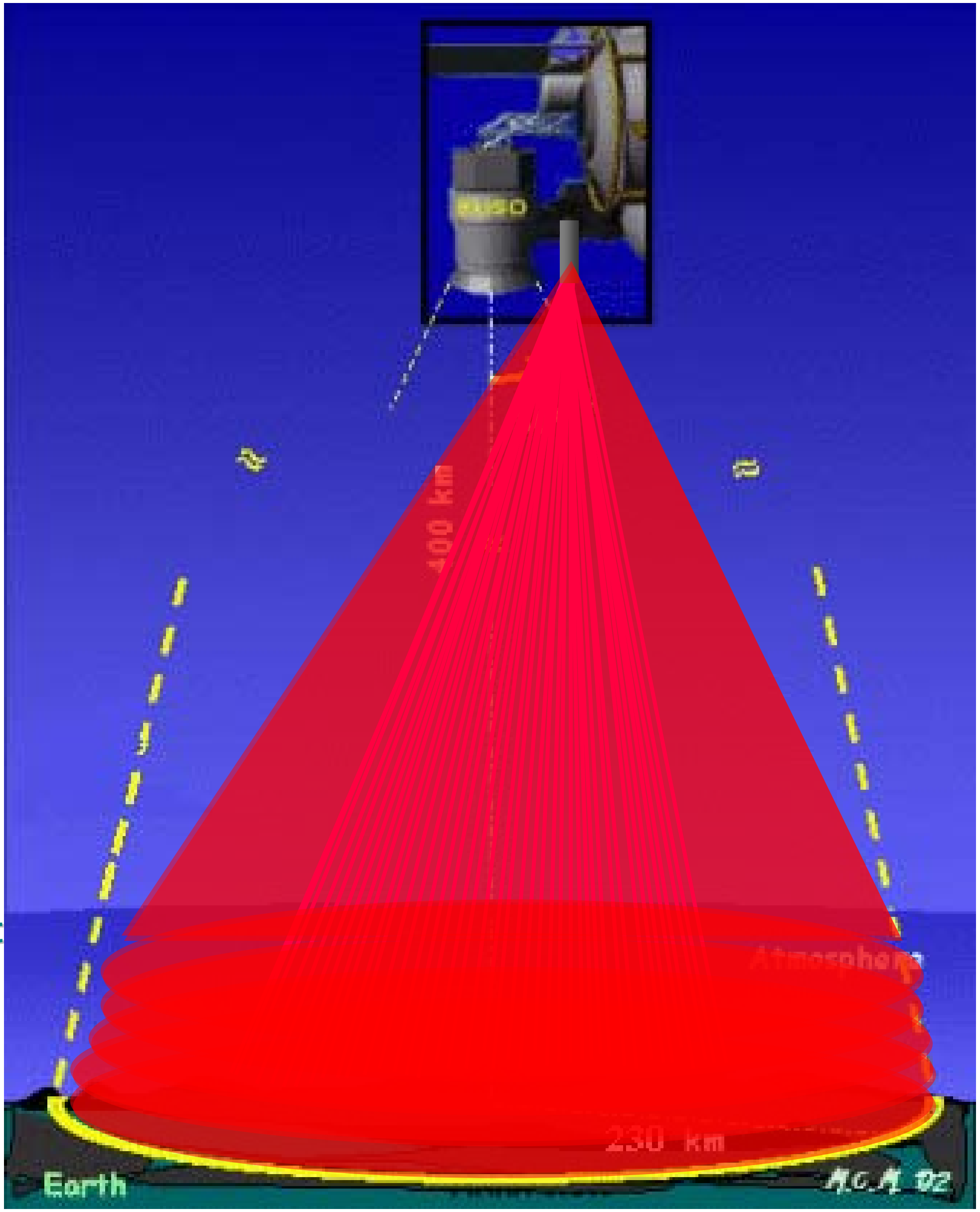
How to detect EECRs from space

STEP 1

Particle penetrating Earth's atmosphere creates an EAS. UV fluorescence light is produced along the particle trajectory and it is imaged by the EUSO telescope

STEP 2

Highly collimated Cherenkov photons are also produced in the forward direction of EAS. At the impact point with the earth surface, reflected/diffused UV light is imaged by the telescope



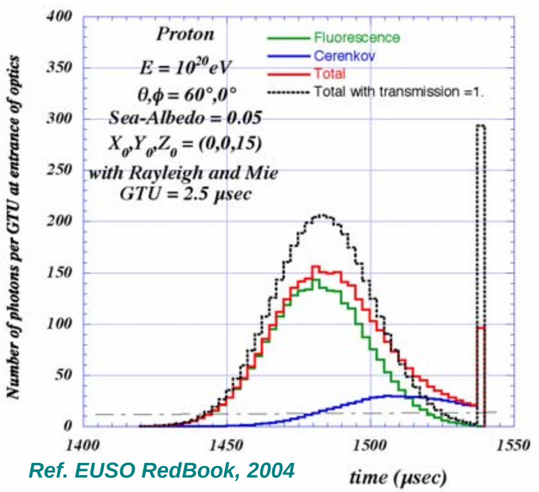
STEP 3

instantaneous IR picture of the FOV is taken at trigger occurrence.

STEP 4

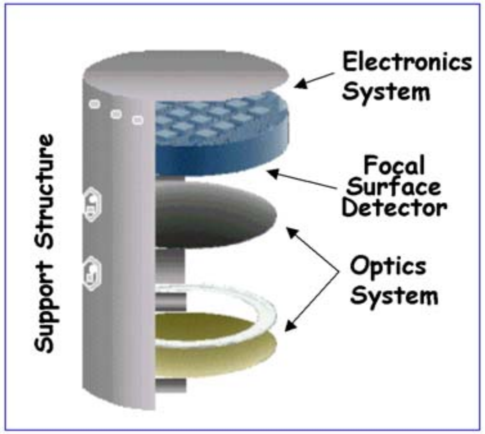
Sounding of the atmosphere, along the EAS direction, is performed by a LIDAR system

The signal arriving on EUSO

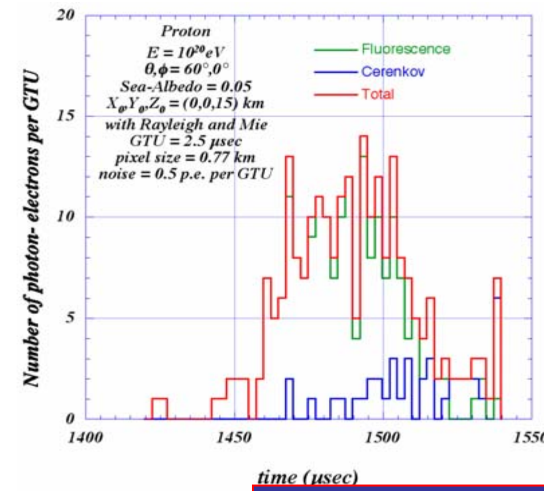


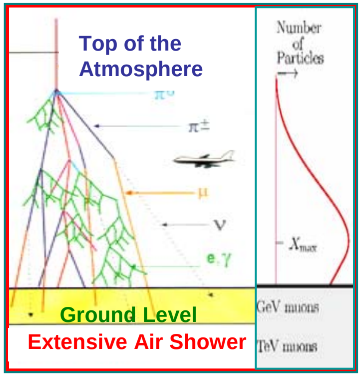
Ref. EUSO RedBook, 2004

The EUSO telescope



The signal registered by EUSO

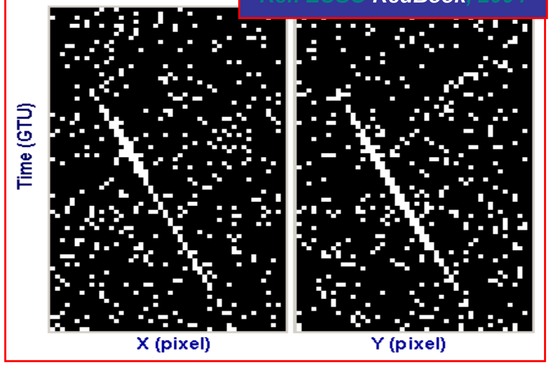




Shower appear as single track event (embedded in the bg)

Duration, X,Y, Intensitiy,
$\Rightarrow$ Θ,φ, E, A of the EECR/ν.

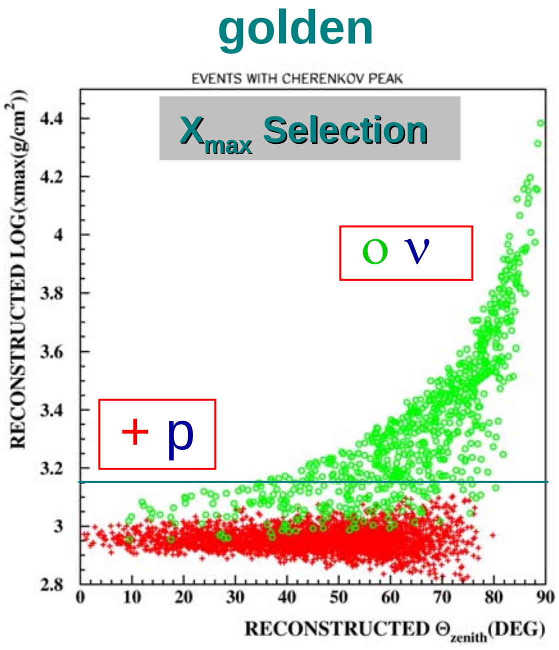
Ref. EUSO RedBook, 2004

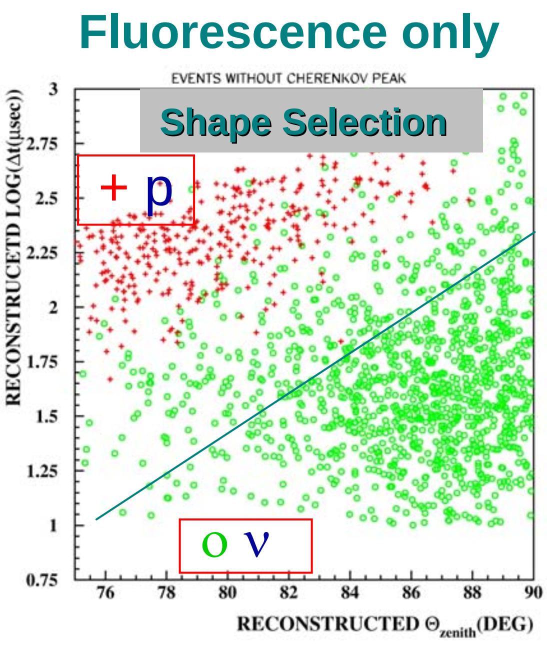


The space-time image is given in terms of X-T and Y-T projections of the collected photoelectrons, X and Y being the coordinates inside the field-of-view; the time coordinate T measures the shower development in depth, providing info about the shower length in the third direction, the height in the atmosphere.

Downward neutrino acceptance for EUSO

S. Bottai



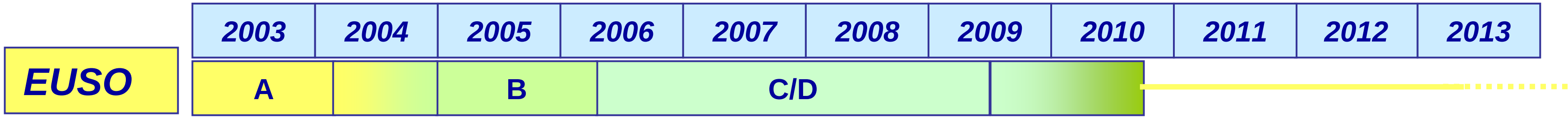


- ✓ $2 * 10^{18}$ g is the total target mass under the FOV
- ✓ reduction due to trigger efficiency calculated by full simulation. Clouds distribution is considered
- ✓ reduction due to selection efficiency needed for 10^{-4} proton rejection calculated from full simulation
- ✓ results show a sensitivity around 10 x AUGER for neutrino in the10^{20}eV energy region

Summary: EUSO

- EUSO is a pioneering experiment studying EAS from space:
  - An instantaneous aperture of $6\times10^5 km^2 sr$ with a duty cycle ~20% is a technically achievable goal with up-to-date technology;
  - The acceptance reduction due to cloud effect has been evaluated to be ~1/3.
- EUSO, with its dynamical range ($E>5\times10^{19}$eV) is a "beyond-GZK experiment". At $E>10^{20}$eV:
  - ~10^3 events/year can be expected according to AGASA findings;
  - ~10^2 events/year can be expected according to GZK-suppressed spectrum due to uniform source distribution.
- EUSO complement the AUGER findings in both cases:
  - Study the source spectra for superGZK model;
  - Analyse the GZK behaviour and the source distribution for GZK-suppressed mode;
- EUSO highly sensitive to neutrino astronomy at $E>5\times10^{19}$ eV

But …



- EUSO on the ESA module Columbus is uncertain due to ISS/Shuttle delays
- Phase A completed, technically ready for phase B (15 July 2004)
- EAS unable to recommend its continuation into phase B in foreseeable future (AWG, FPAG, SSAC)

⇒ Freezer status

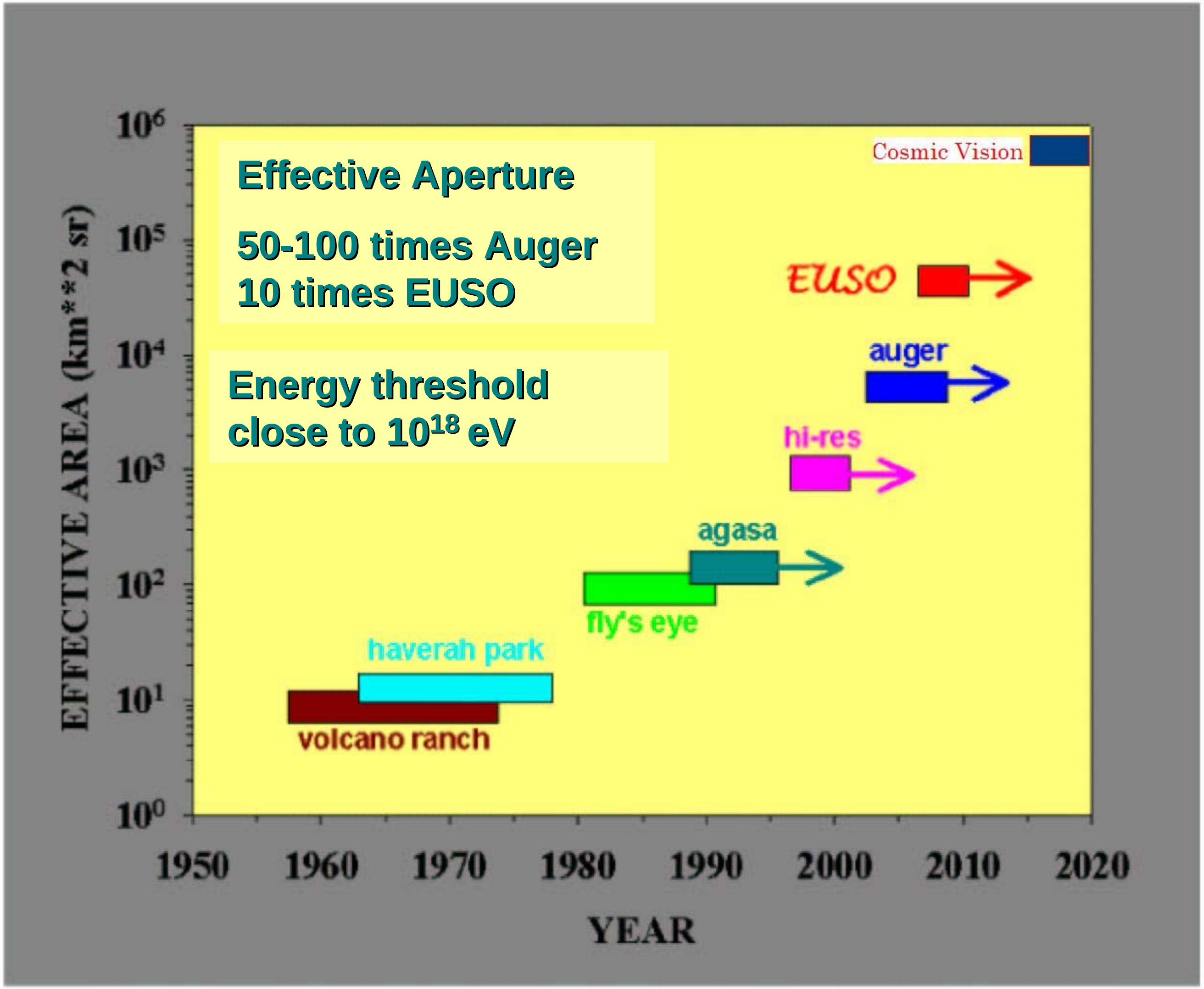
- EUSO will be supported on “exciting” Auger results;

Alternative Solution?

- EUSO mounted on the Japanese Module
- Using a Japanese carrier to launch EUSO
- ? …

3-4 Nov. 2005:
EUSO re-foundation Meeting ESA
ESTEC, Noordwijk, NL

Post Auger Scenario? Cosmic Vision



Cf. Günther Hasinger's talk: Status, Probleme und Perspektiven

Summary and Outlook:
Pierre Auger Observatory

Status:

- Southern Observatory over half finished
- With 25% of a full Auger-year exposure, we have:
    - First estimate of an FD-calibrated spectrum
    - First studies of anisotropies in the sky
    - Limits on photon primaries

Future plans:

- Completion by mid 2006
- Full understanding of our instruments
- Usage of rapidly expanding data set (x7 in two years)
- Measure spectrum around 10^{20}eV with unprecedented precision
- Solve AGASA/HIRES dispute
- Composition studies with SD, FD and HYBRID
- Large/small scale anisotropies
- Search for neutrinos and exotics (horizontal showers)
- Begin working on Auger North
- R&D for radio, …