Cosmo-03: Ambleside, 24 - 29 August 2003

Ultra High Energy Cosmic Rays: where we are and where we are going

Alan Watson

University of Leeds, UK

Connecting Quarks with the Cosmos
Eleven Science Questions for the New Century

National Research Report 2003
Committee on the Physics of the Universe (M S Turner - chair)

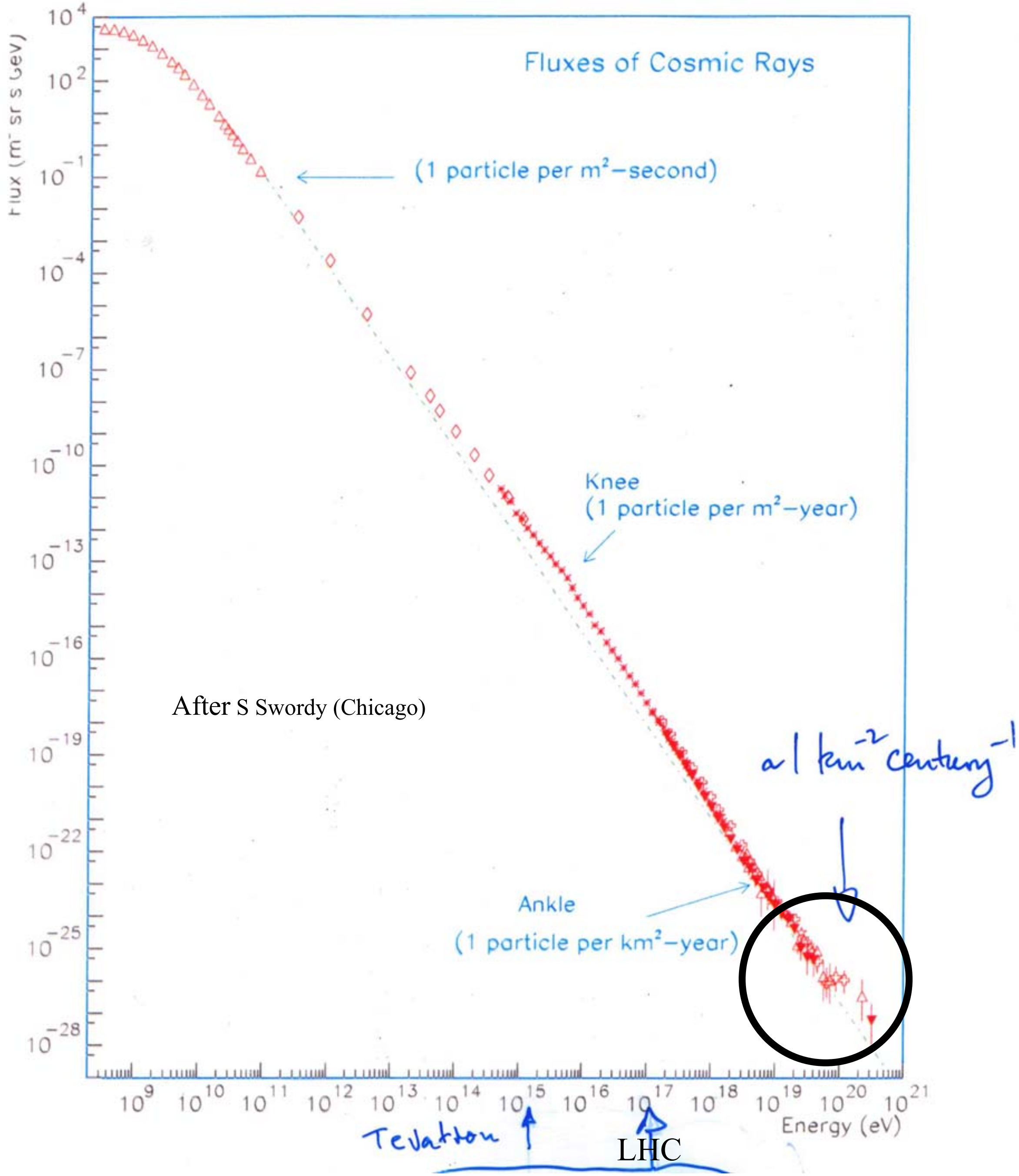
6. What are Nature's most energetic particles?

Gamma Rays, neutrinos and cosmic rays

"A full understanding of how these particles are produced and accelerated could shed light on the unification of nature's forces."

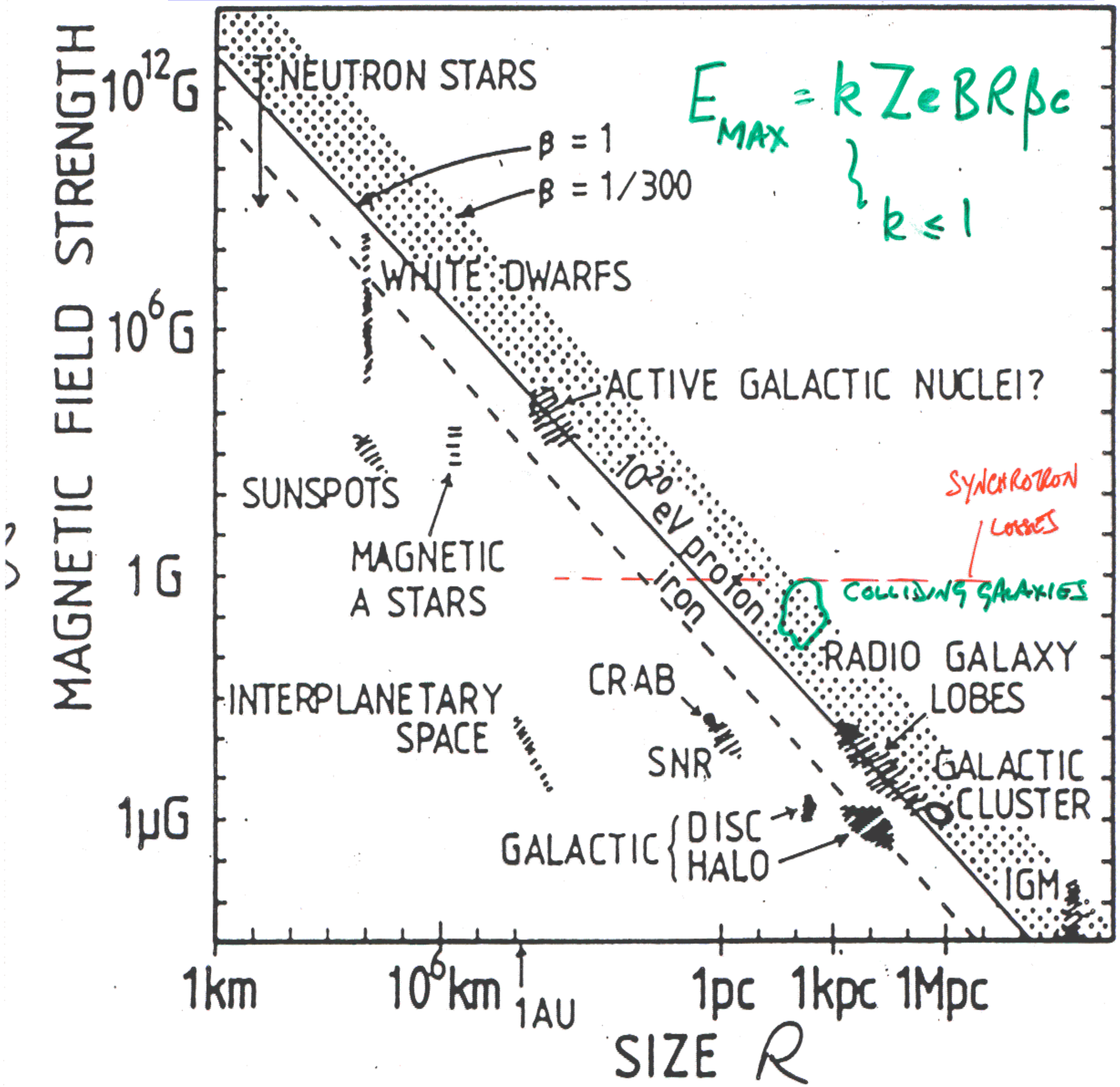
Key Questions about UHECR

- Energy Spectrum above 10^{19} eV?
- Mass Composition?
- Arrival Direction distribution?



Fluxes of Cosmic Rays
Flux (m^2 sr s GeV)$^{-1}$
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
After S Swordy (Chicago)
~1 km^{-2} century^{-1}
Energy (eV)
Tevatron
LHC

The acceleration problem



Hillas 1984
ARA&A
B vs R

Are there UHECR at Earth?

A primary interest is in establishing the existence, or otherwise, of the Greisen-Zatsepin-Kuzmin cut-off

$$\mathbf{p + \gamma_{2.7k} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \quad or}$$

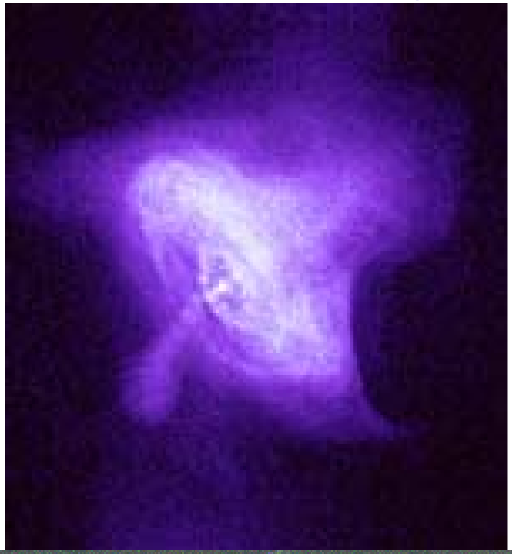
$$\mathbf{n + \pi^{+}}$$

If particles are observed > 5 x 10^{19} eV, then they must be local (GZK cut-off) where Local depends on energy:

>4 x 10^{19} eV	**50% from within 130 Mpc**
>10^{20} eV	**50% from within 20 Mpc**

So ANISOTROPIES expected from nearby sources

IF CR> 10^{20} eV exist, are the sources Astrophysical or do we need New Physics?

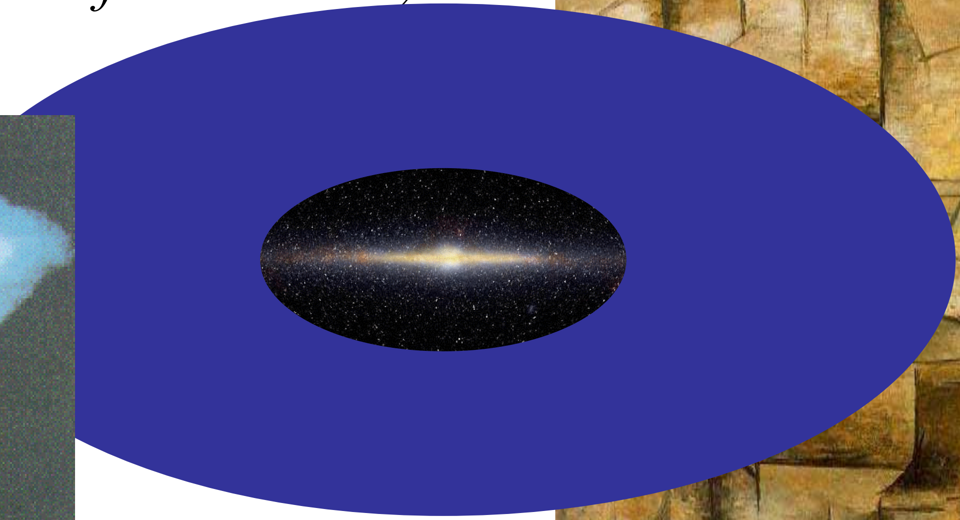


Super Heavy

Dark Matter Relics

in the Dark Halo

of our Galaxy



Cosmic Strings

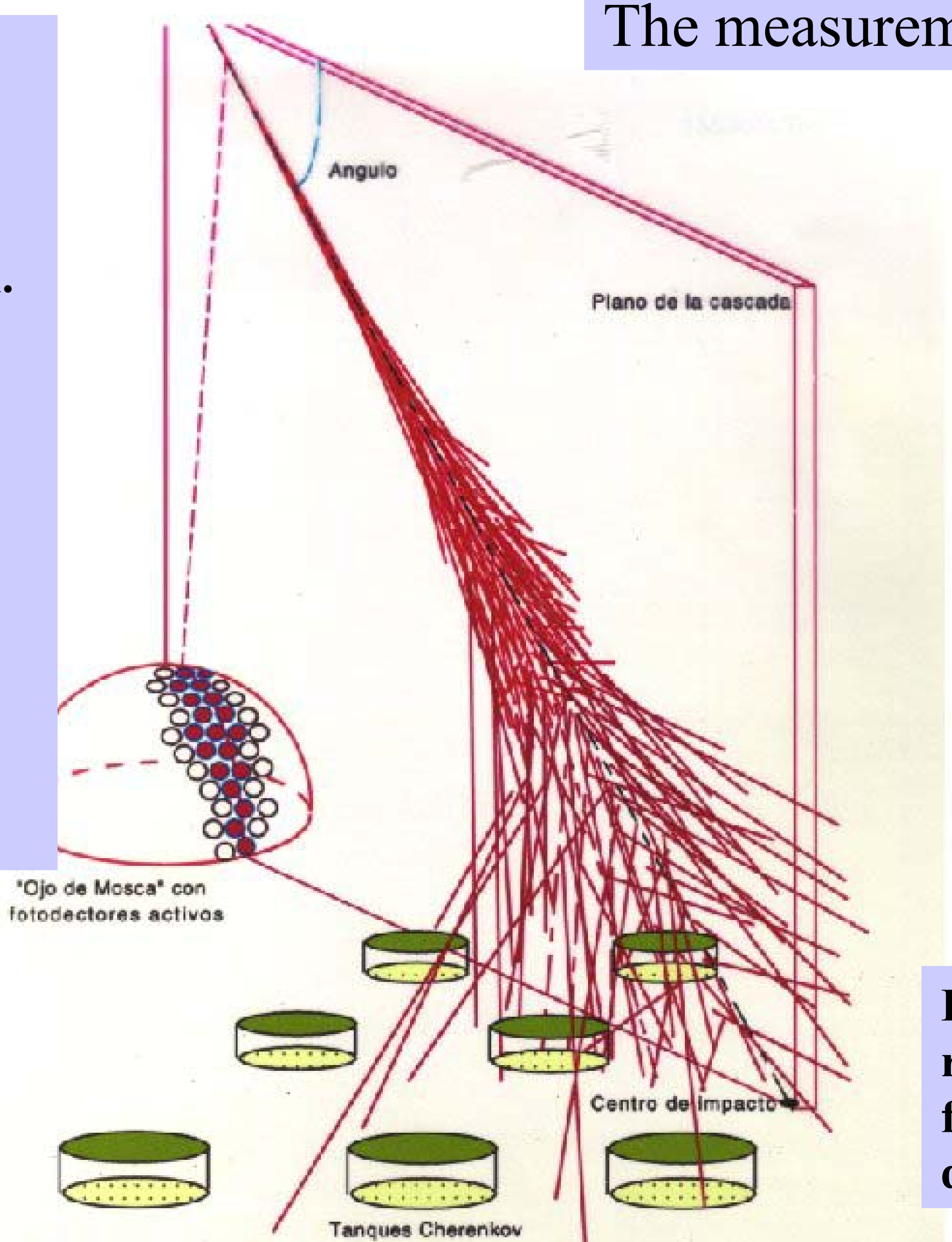
Relics from Early Universe?

thanks to Angela Olinto

The measurement techniques

Fluorescence light emitted isotropically from excited molecular nitrogen.

Detection by pmts allows determination of direction and particle number as function of atmospheric depth ⇒ calorimetric energy estimate.



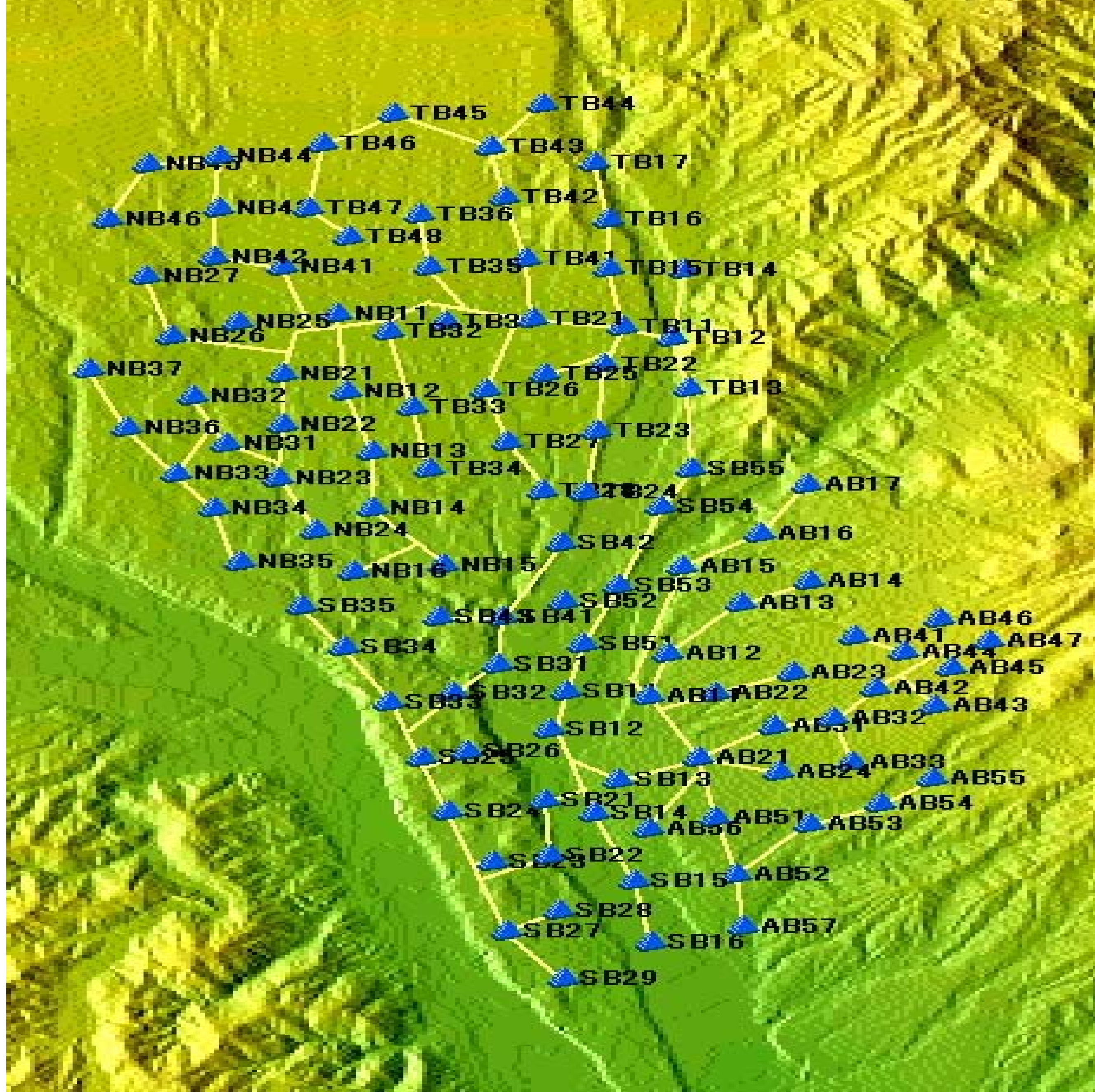
Particle number and relative arrival times found with particle detectors

Diagram by Enrique Zas (Santiago de Compostela)

AGASA

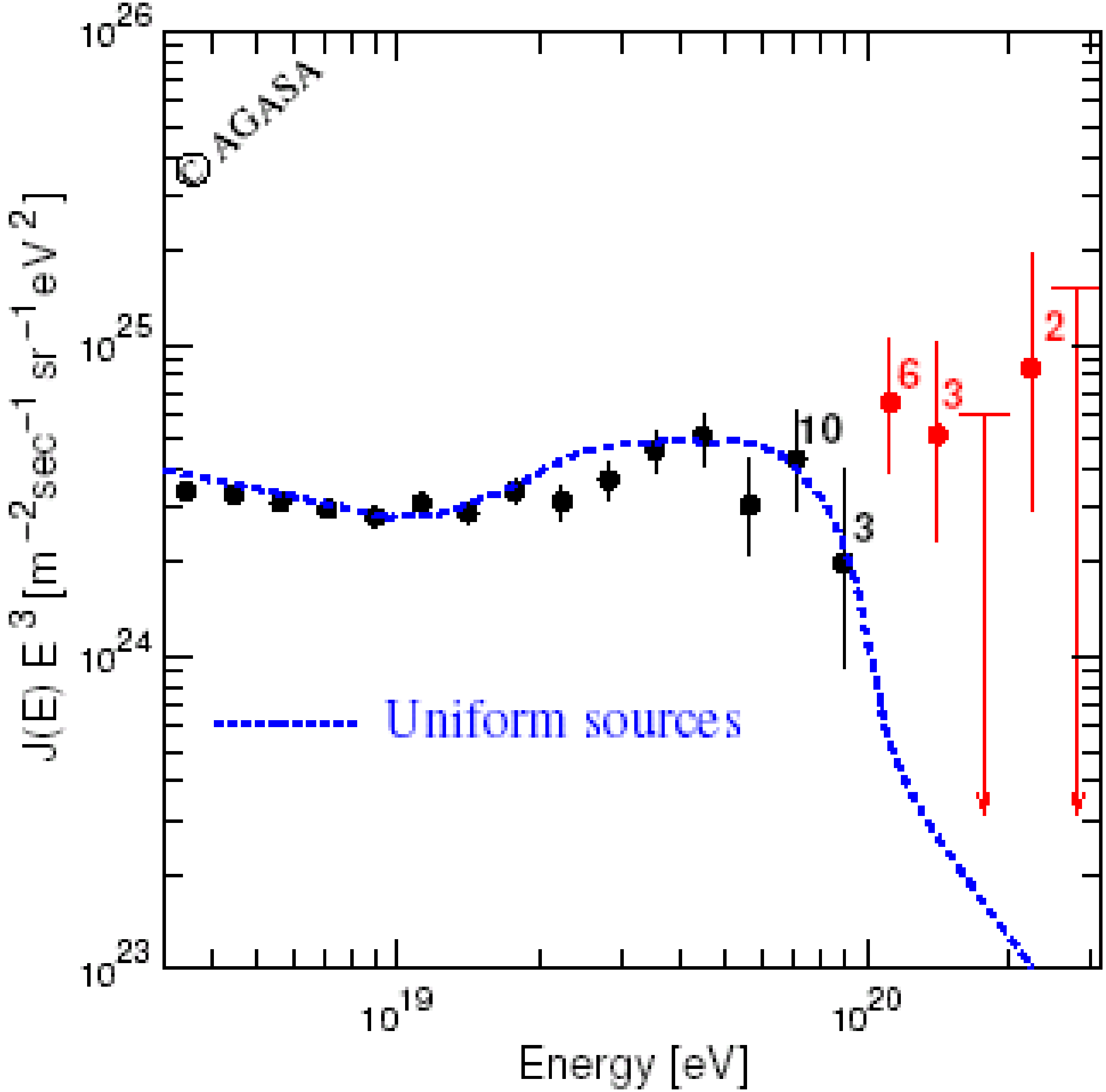
Akeno Giant Air Shower Array

To close in December 2003



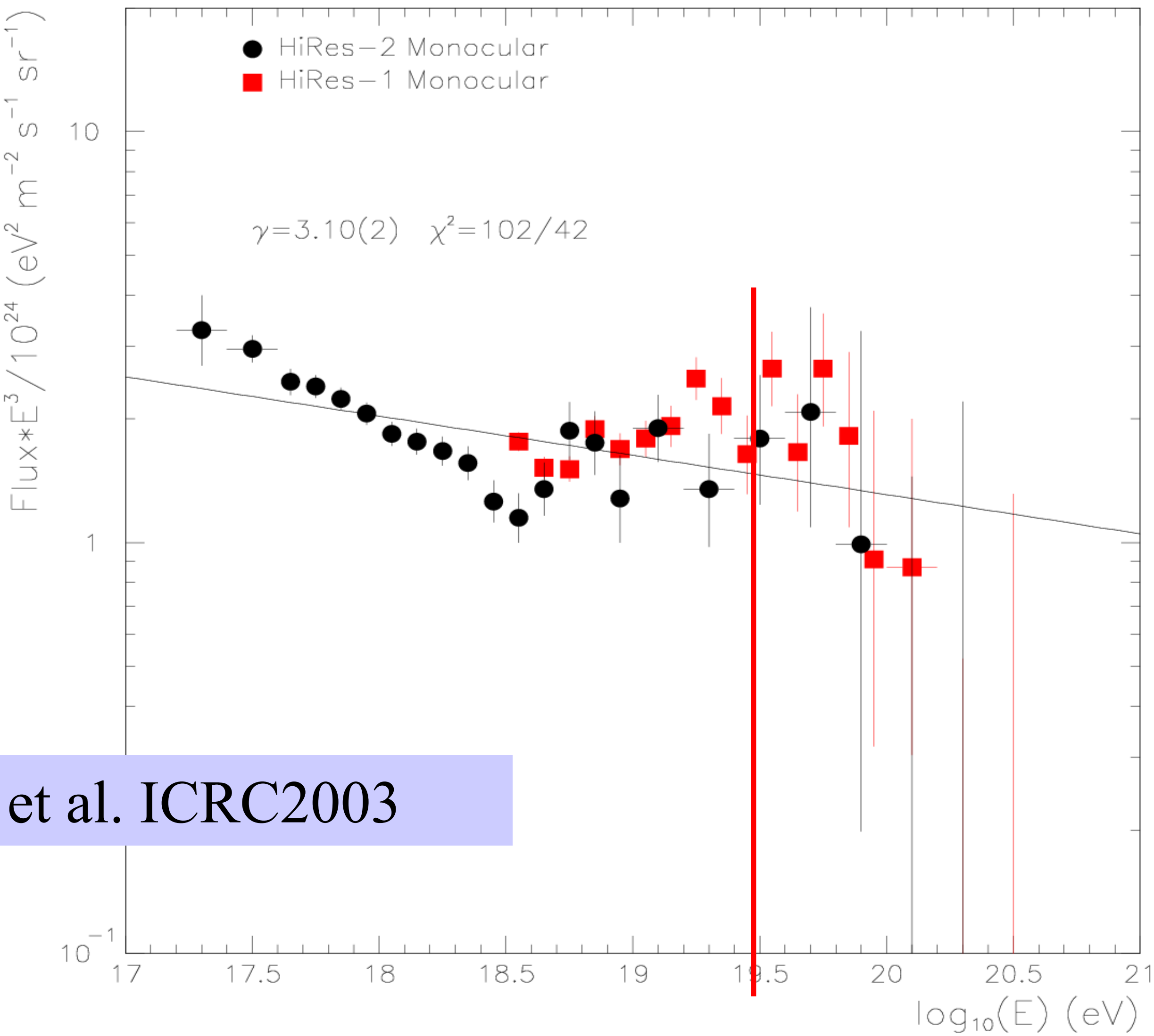
111 scintillators + 27 muon det.

AGASA: Ground array technique



HiRes detector of fluorescence light

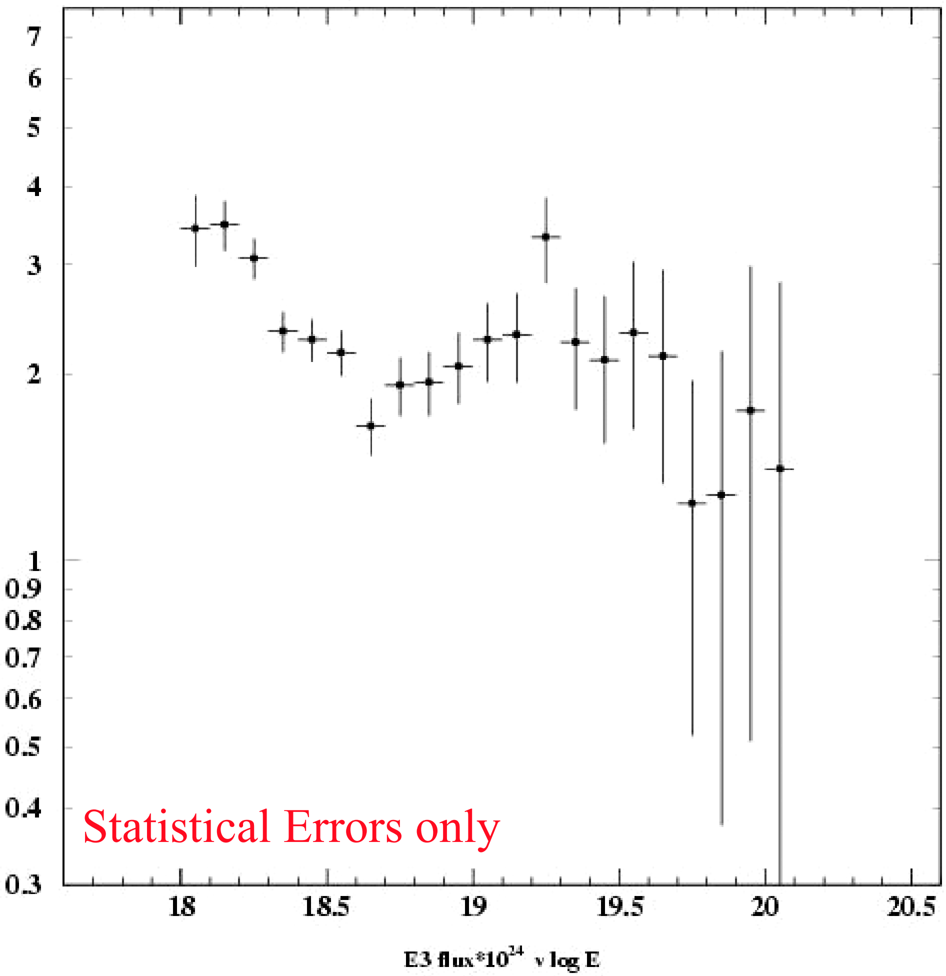
HiRes: Monocular Spectrum from fluorescence



D Bergman et al. ICRC2003

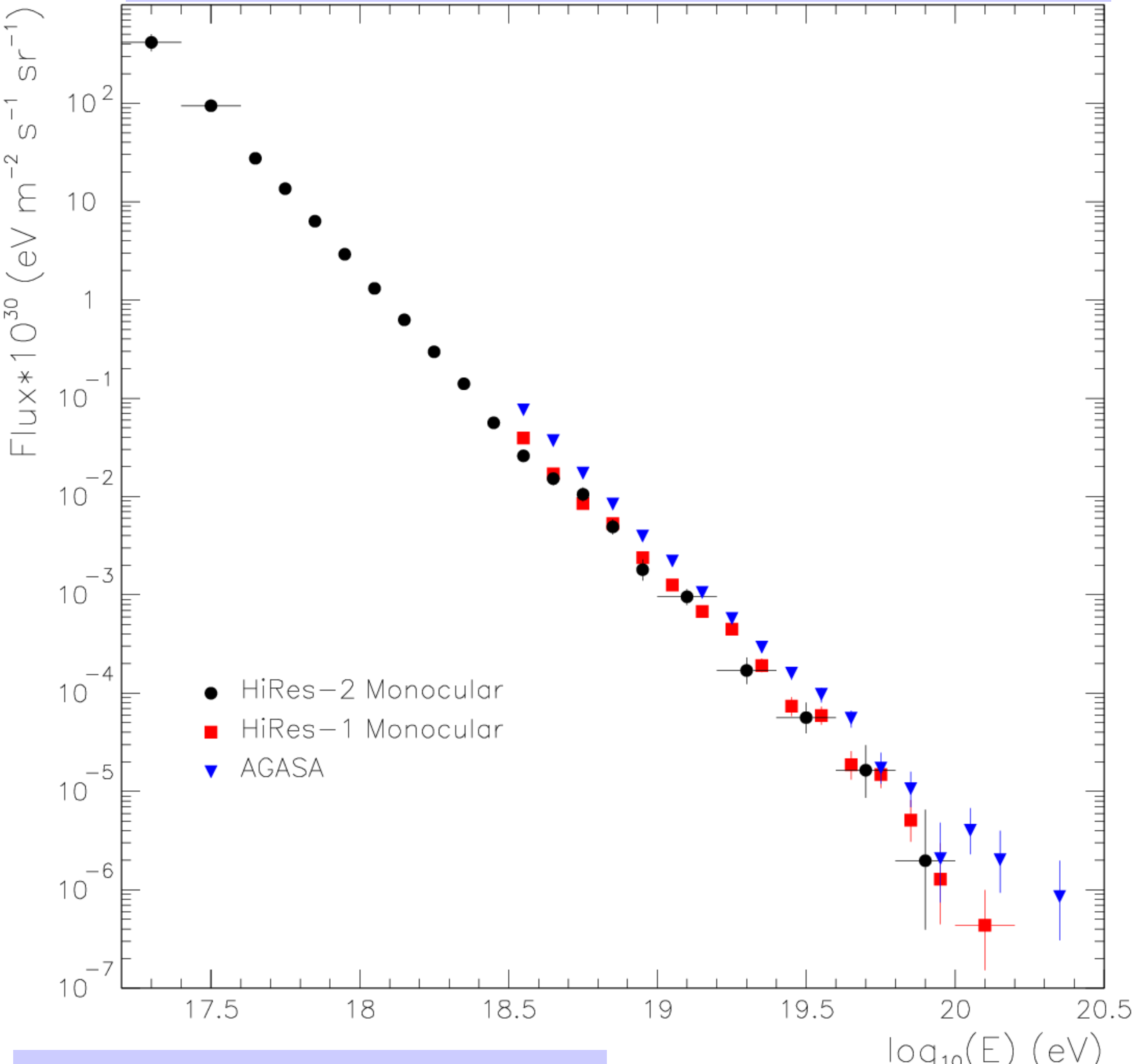
HiRes: Stereo Spectrum

Very Preliminary — **R. W. Springer et al. ICRC**



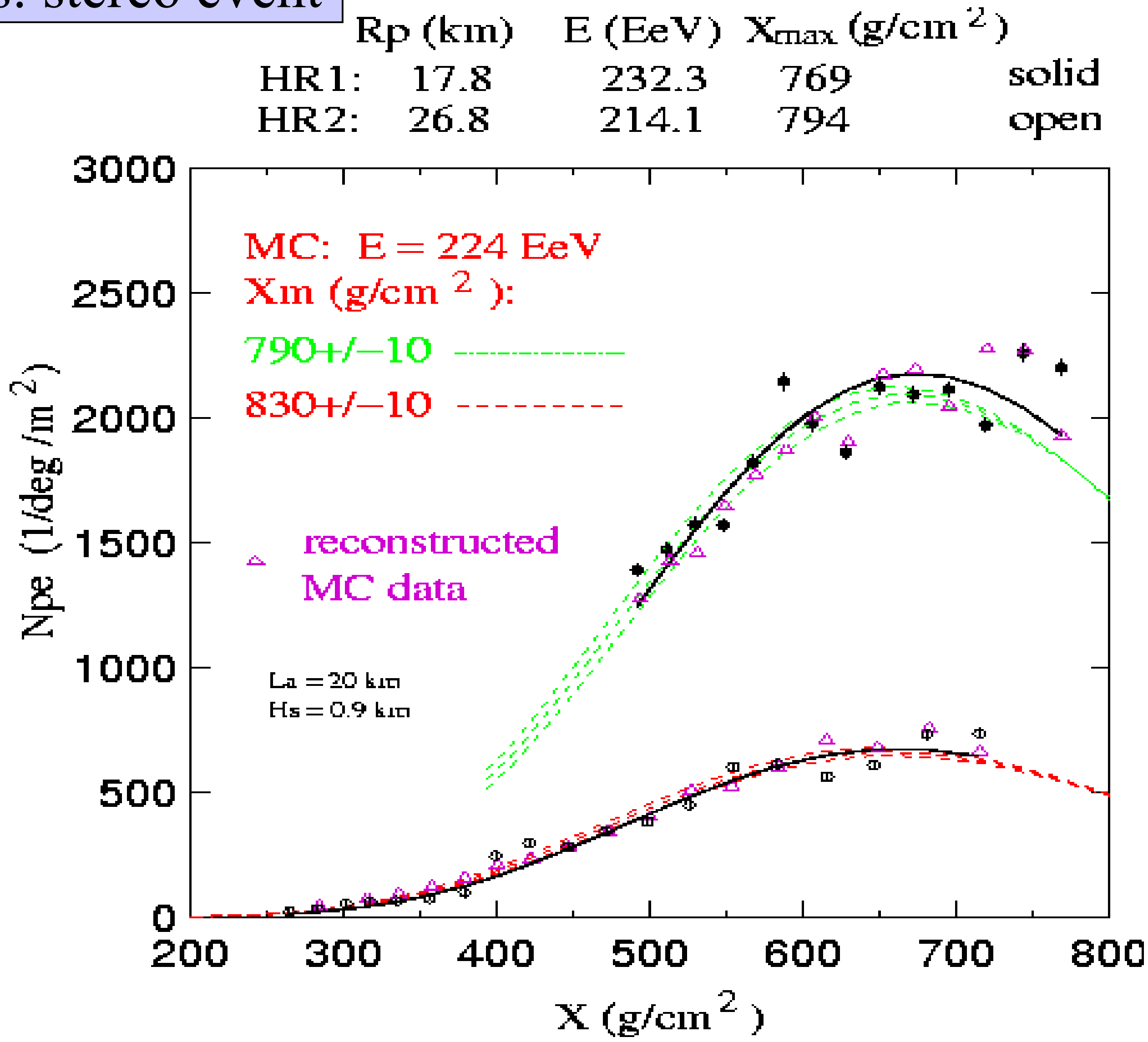
- **Still evaluating sources of systematic uncertainty**
  - Energy scale
  - Fluorescence Yield
  - Atmospheric effects
  - Event by event correction for atmosphere to be implemented

AGASA/HiRes comparison: ICRC2003

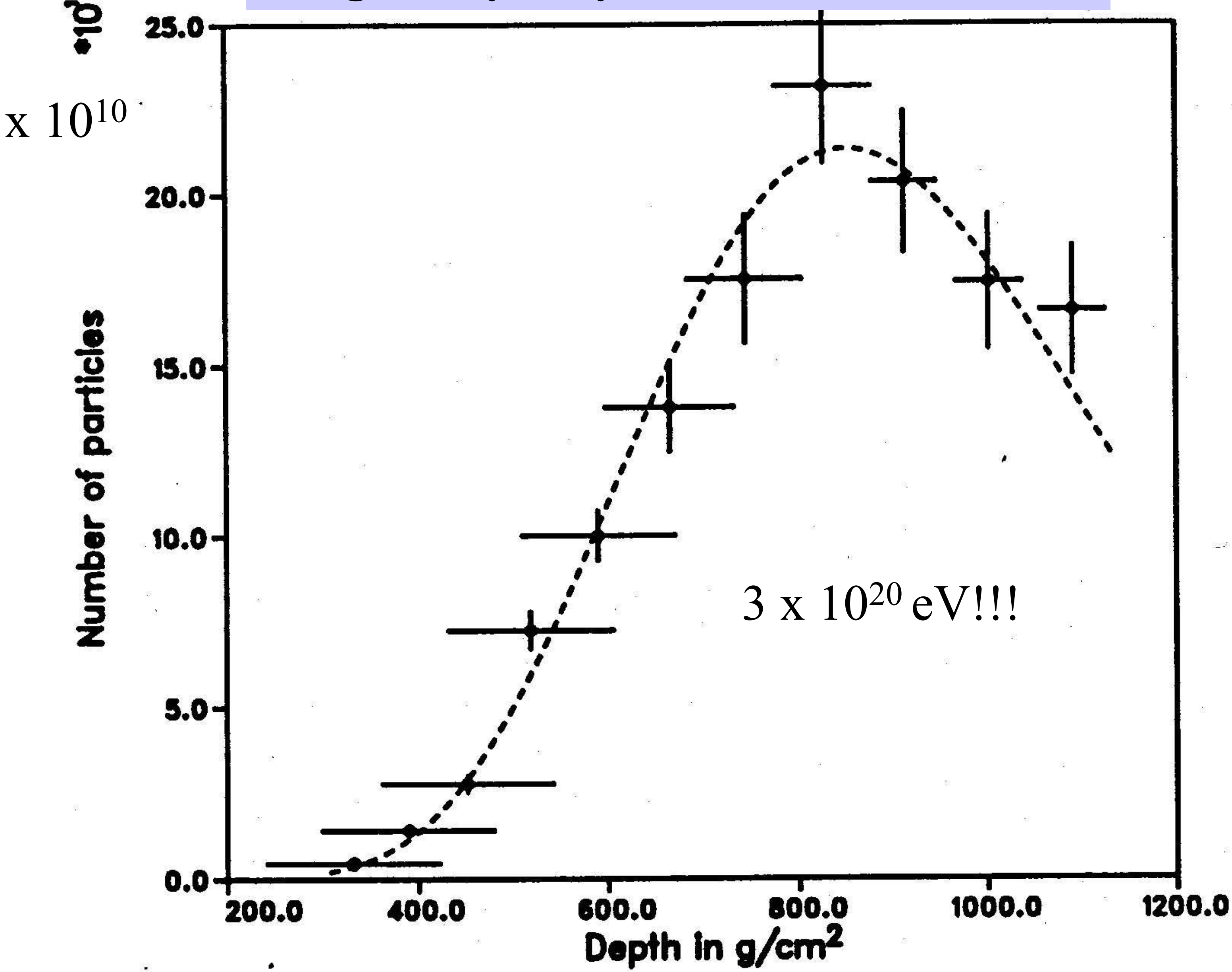


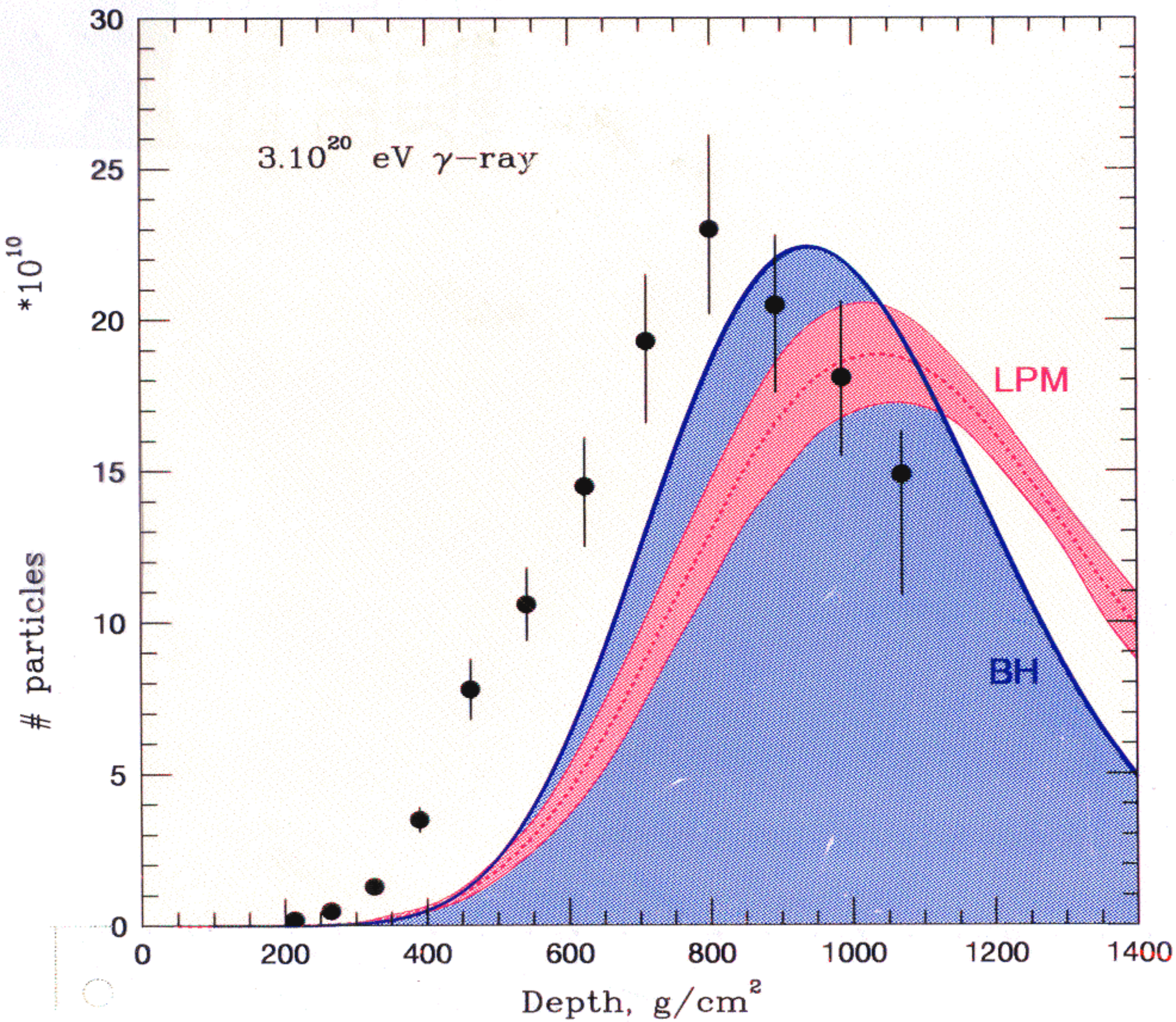
Thanks to D. Bergman: Rutgers

HiRes: stereo event



Largest Fly's Eye event: 3 x 10^{20} eV





Halzen et al. Astroparticle Physics 3 151 1995

Halzen, V
Stanev & V
Astroparti
3, 15

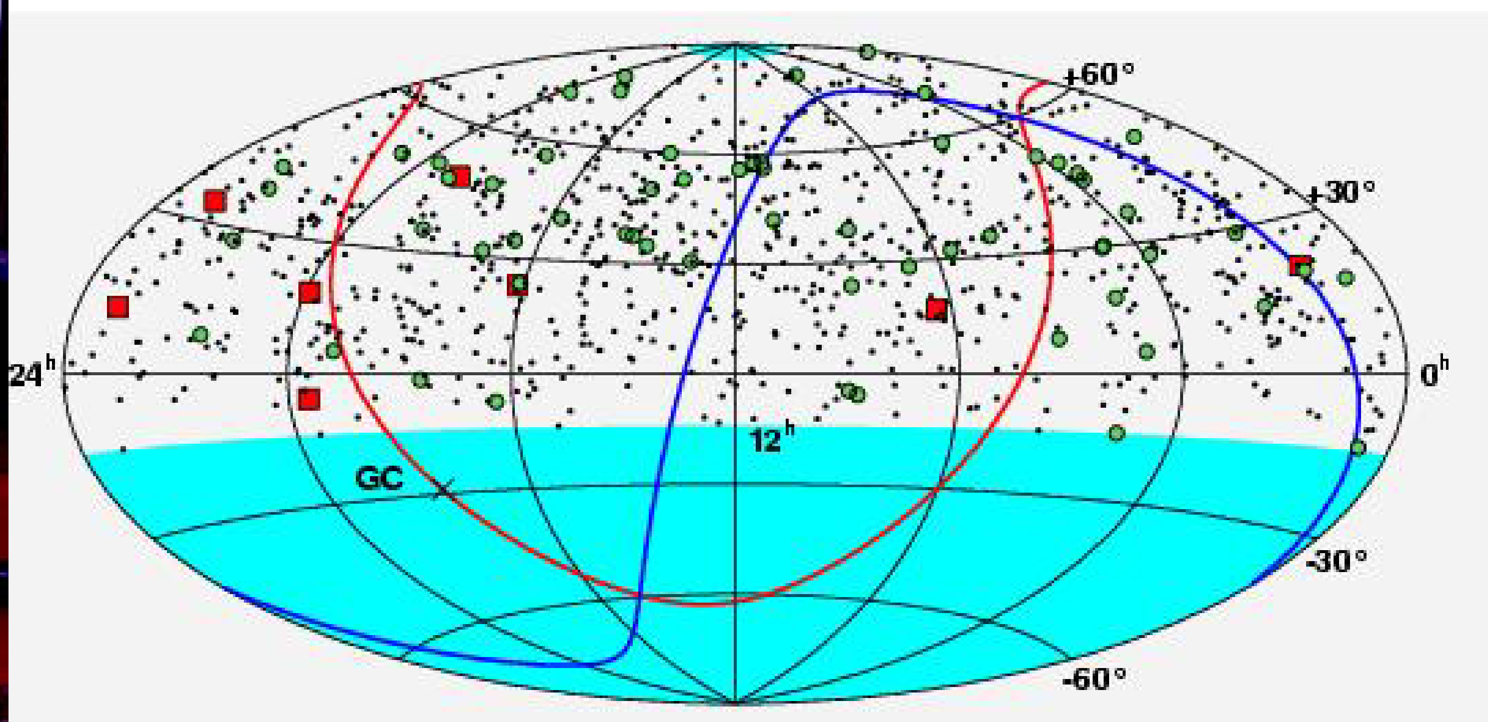
GAMMA-R
NOT FIT

FEW PARTI
BEYOND

AGASA: Small Scale Clustering

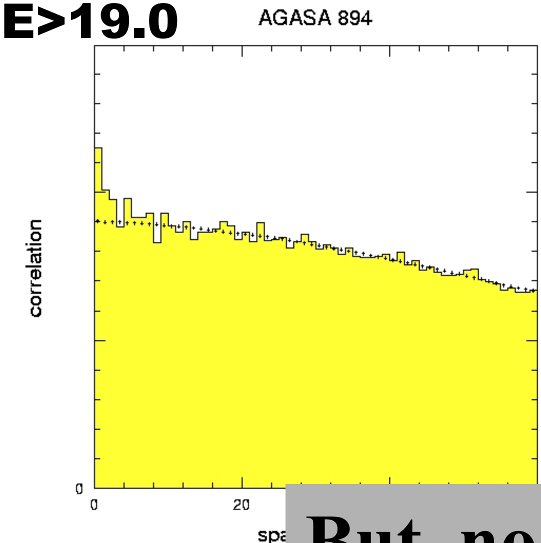
M. Teshima et al. ICRC2003

- 1 triplet + 6 doublets (2 triplets + 6 doublets with looser cut)
- Clustering for E ~10^{19}eV and ~5 x 10^{19}eV,
- Ratio of Cluster/All increases with E up to 5 x 10^{19}eV
- Above GZK energy (5x10^{19}eV) statistics too small

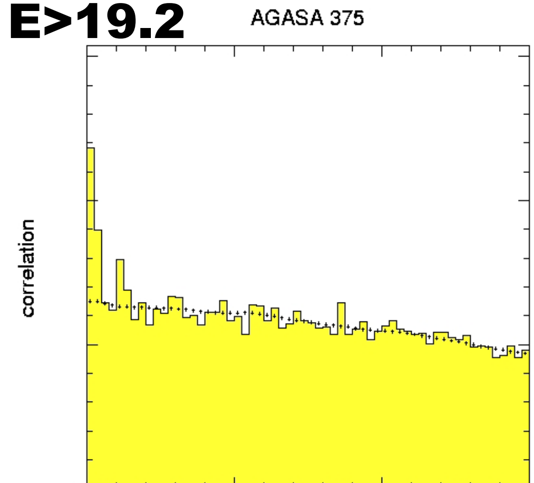


AGASA Angular Correlations

Log E>19.0

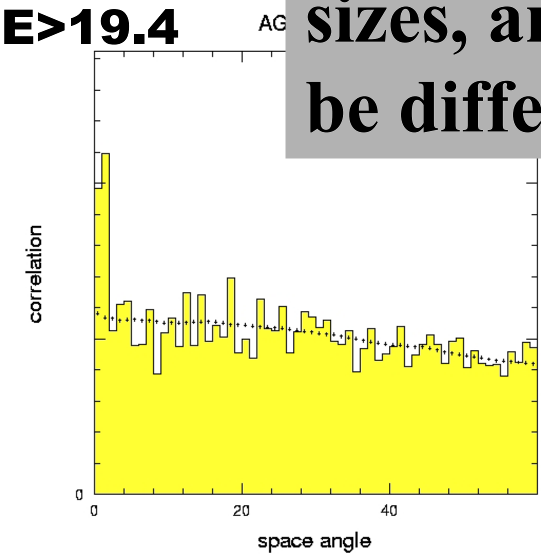


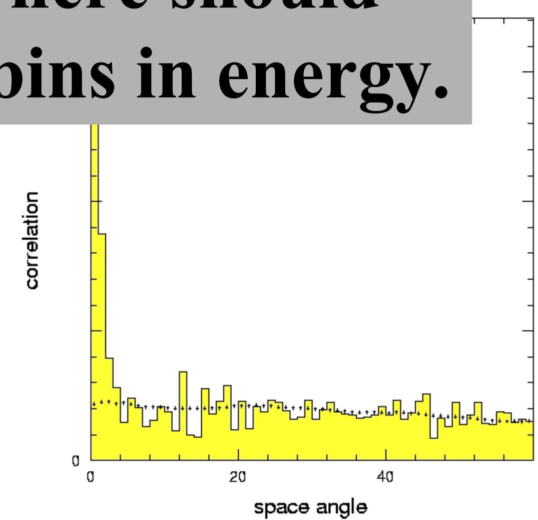
Log E>19.2



But, no *a priori* choice of bin sizes, and plots here should be differential bins in energy.

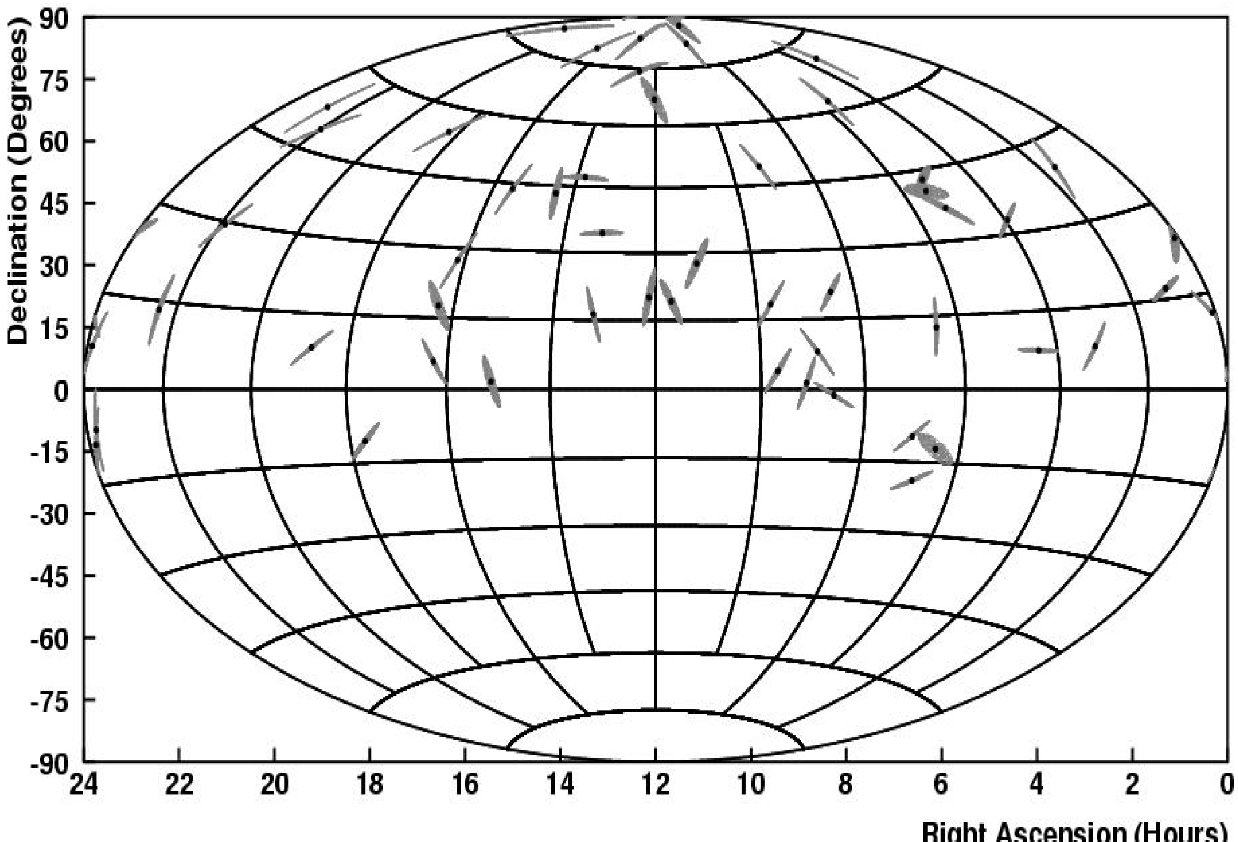
Log E>19.4





HiRes:small scale clustering search (mono)

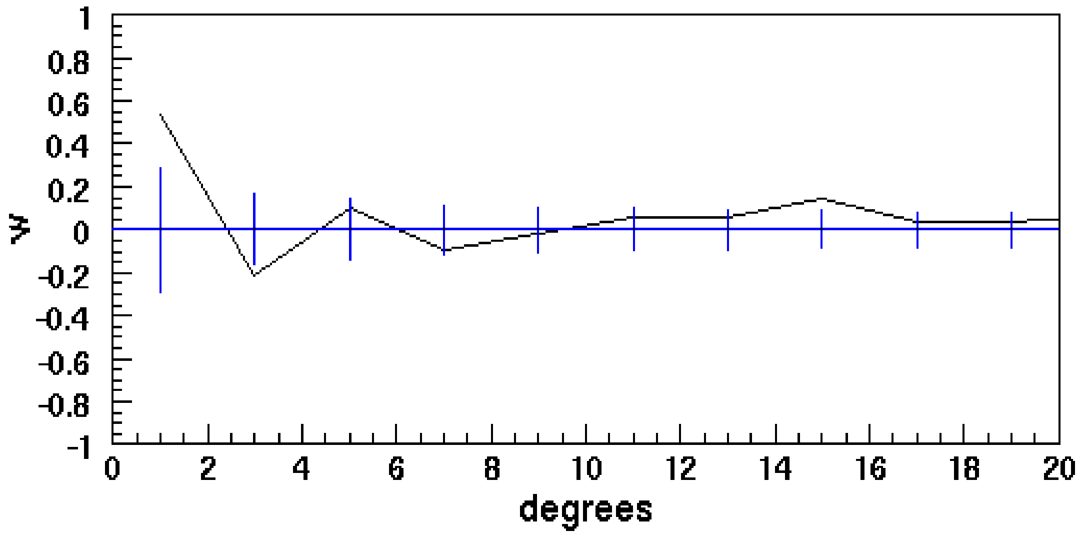
- No significant clustering seen yet.
- “Bananas are harder than circles…”



HiRes-I Monocular Data, E > 3 x 10^{19} eV

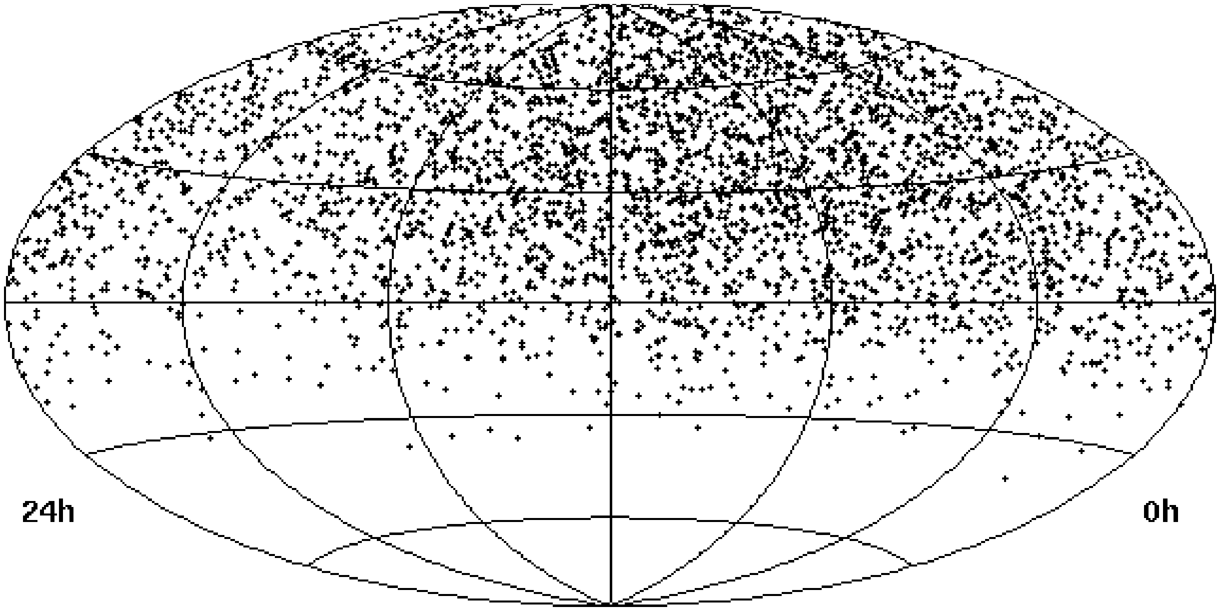
Upper limit of 4 doublets (90% c.l.) in HiRes-I monocular dataset.

HiRes: small scale clustering (stereo)



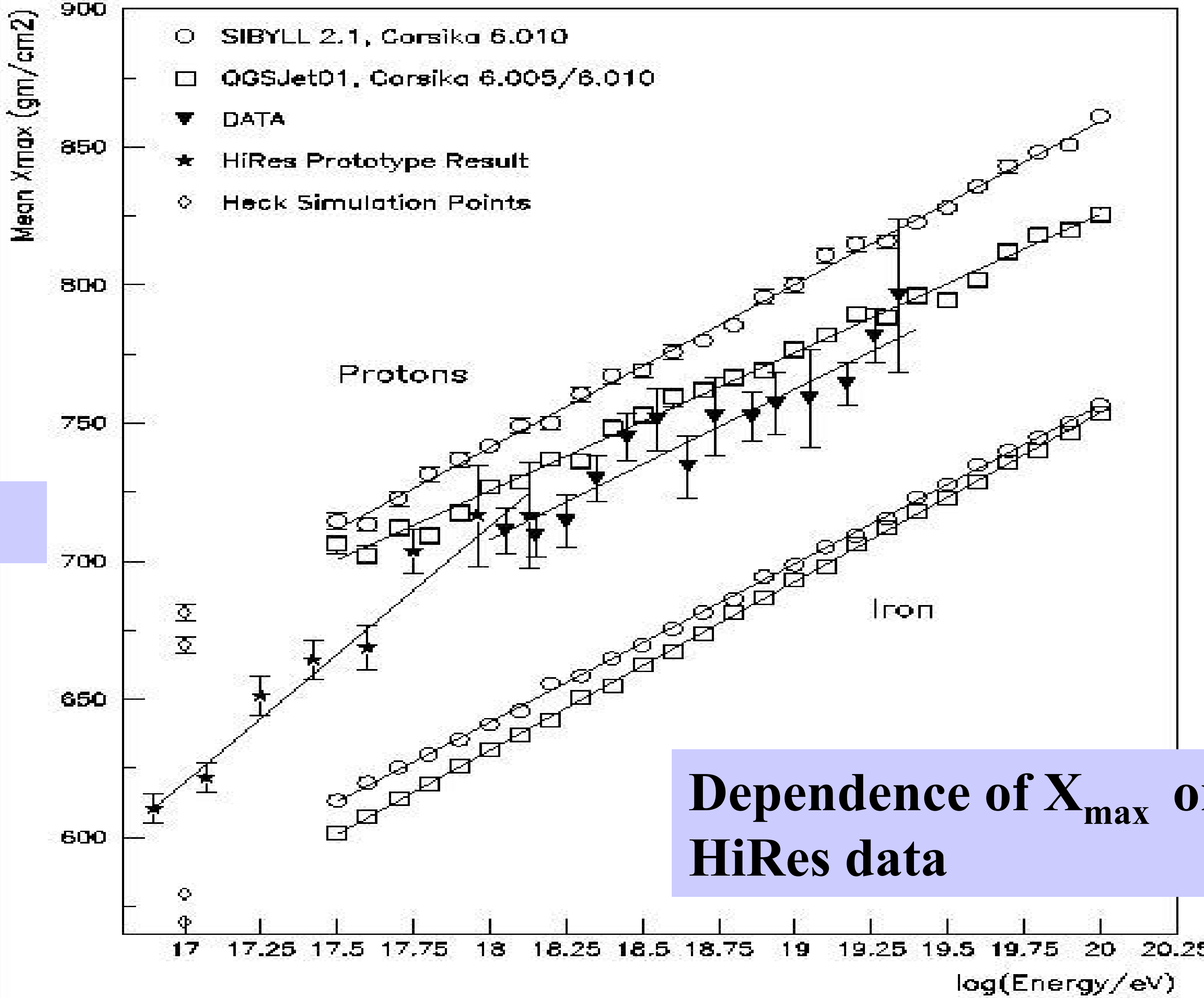
Two-point correlation
for HiRes Stereo Events
> 10^{19} eV

No clustering seen



Mass Composition is a crucial question

X_{max}

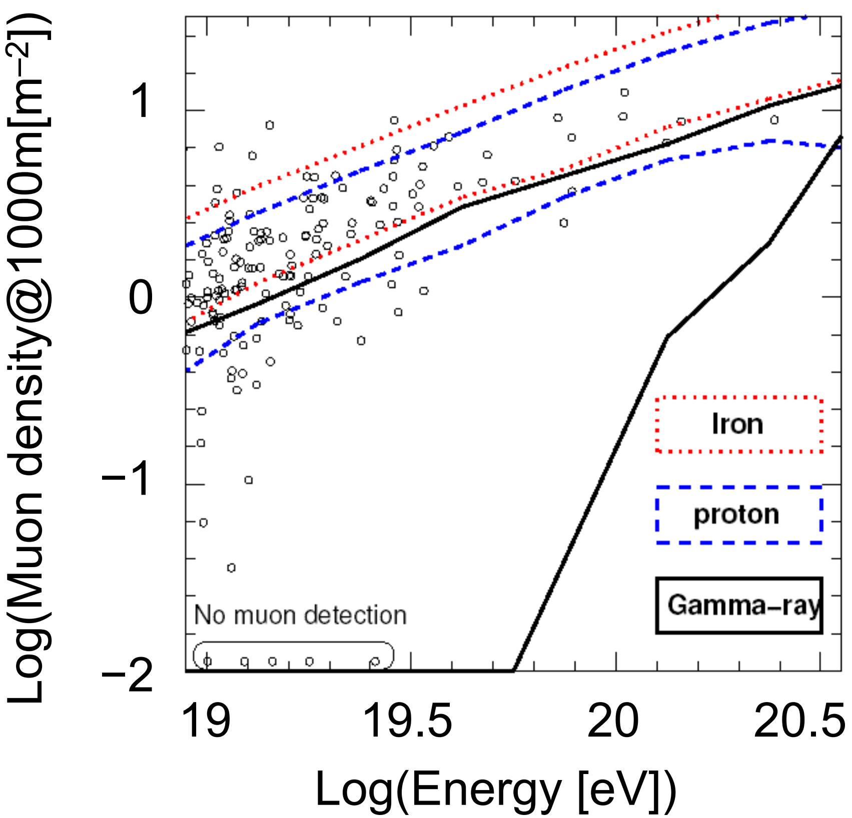


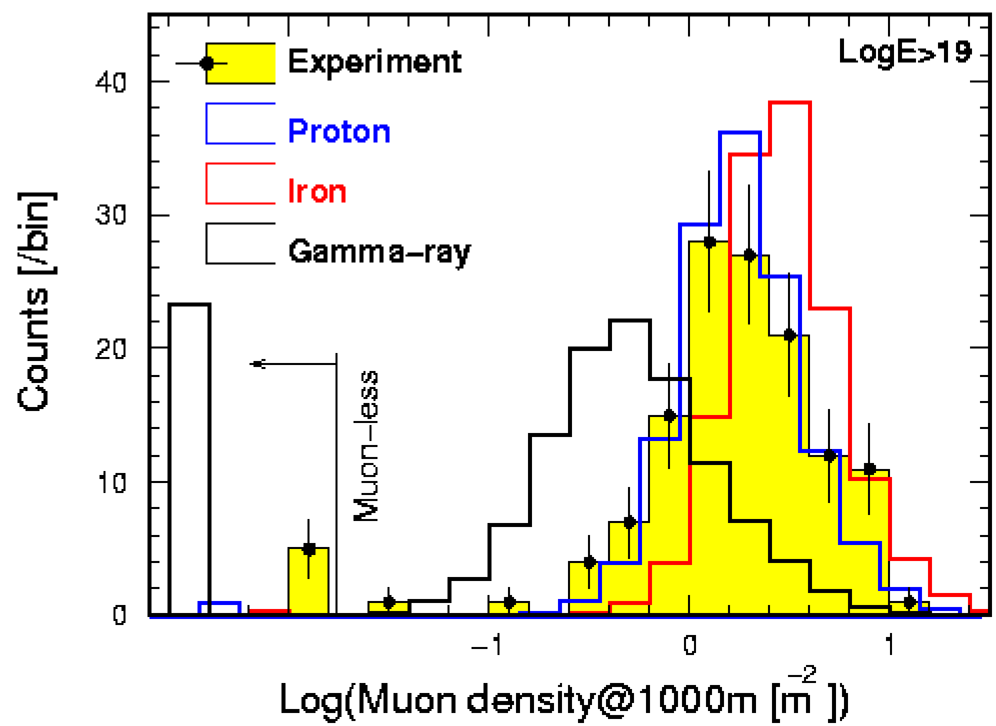
Dependence of X_{max} on energy
HiRes data

Muon Detection with AGASA array

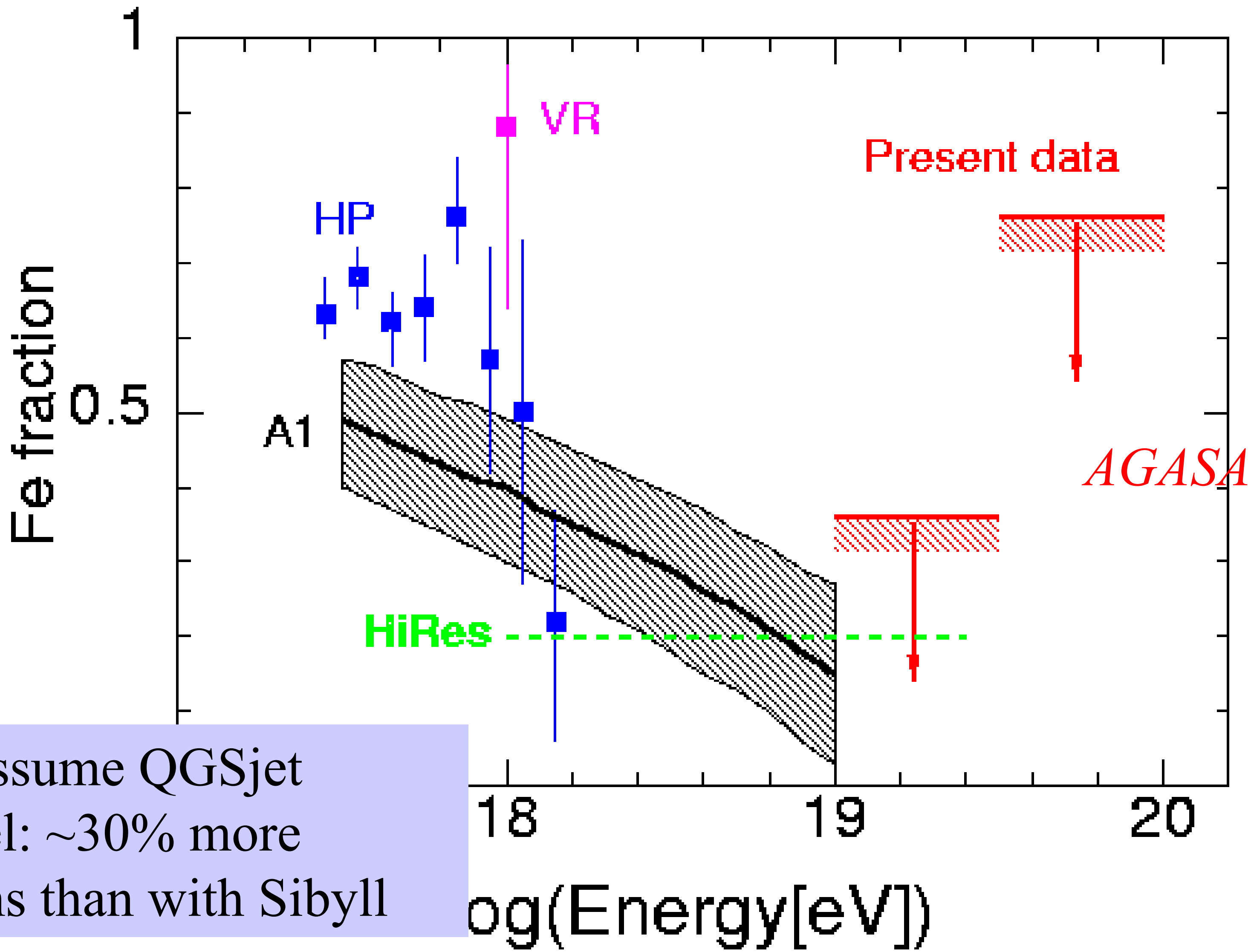
Fe-initiated events will contain more muons.

Claim: Consistent with proton dominant component





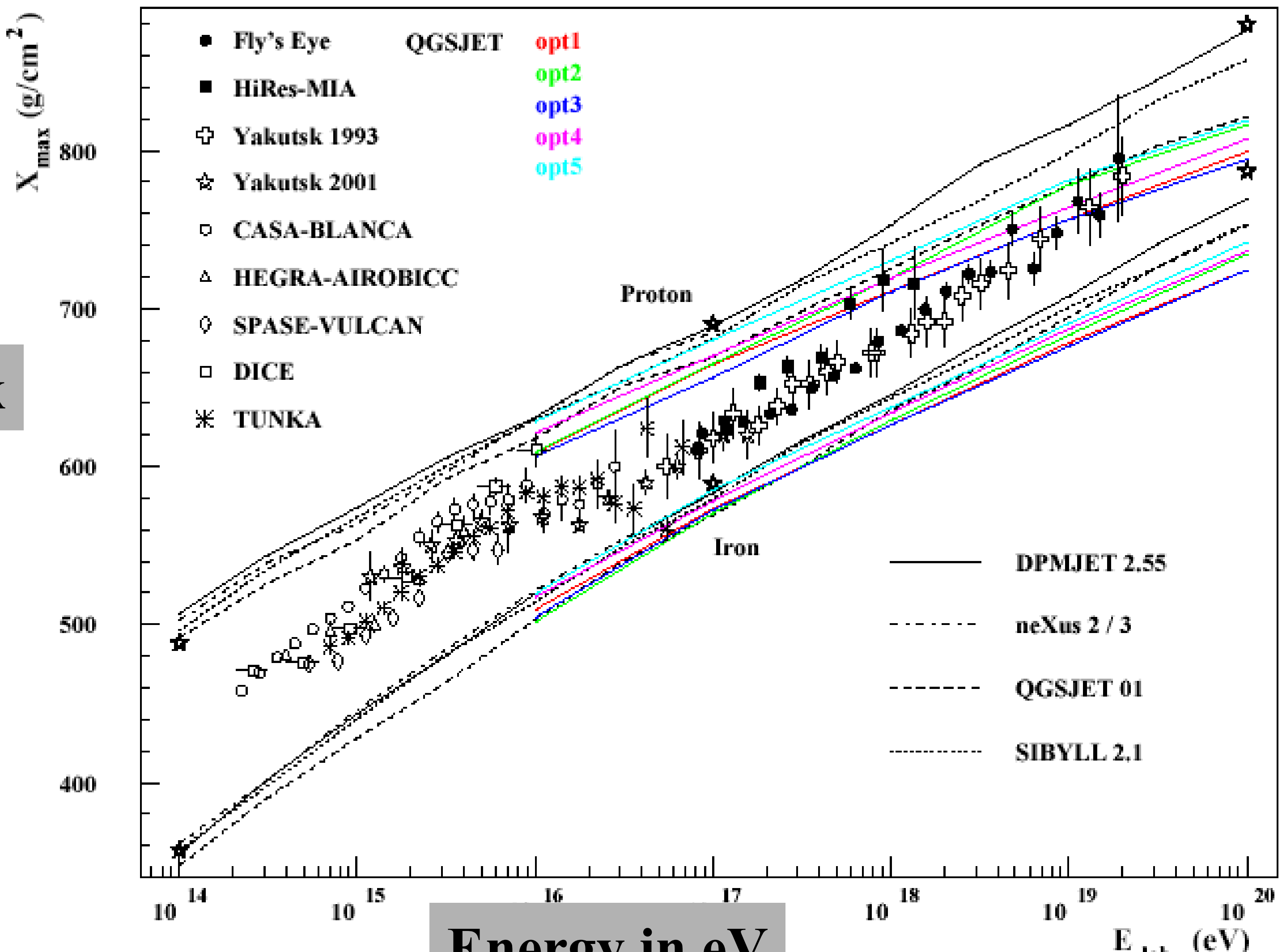
Summary of recent mass composition claims



All assume QGSjet model: ~30% more muons than with Sibyll

Model Uncertainties

An extreme comparison in composition studies with QGSJet:Knapp'03



Xmax

Energy in eV

Results so far suggest:

- Events with energies well beyond the GZK cut-off have been claimed by AGASA, Fly's Eye and HiRes
  - BUT we are not sure of the fluxes
- The arrival directions seem rather isotropic
  - BUT there may be clusters
- The mass composition is still very uncertain
- Major problem is that flux above 10^{20} eV is ~ 1 km^{-2} century^{-1} sr^{-1}

Aims of the Auger Observatory

To measure the properties of the highest energy cosmic rays with unprecedented precision

- **10 years** x **3000 km^2** yields **300 -500** events **>10^{20} eV**

- **SOURCES? Two Observatories Necessary**

- **NATURE OF PRIMARIES**

~250 PhD scientists: 15 countries: \$50M

The Hybrid method

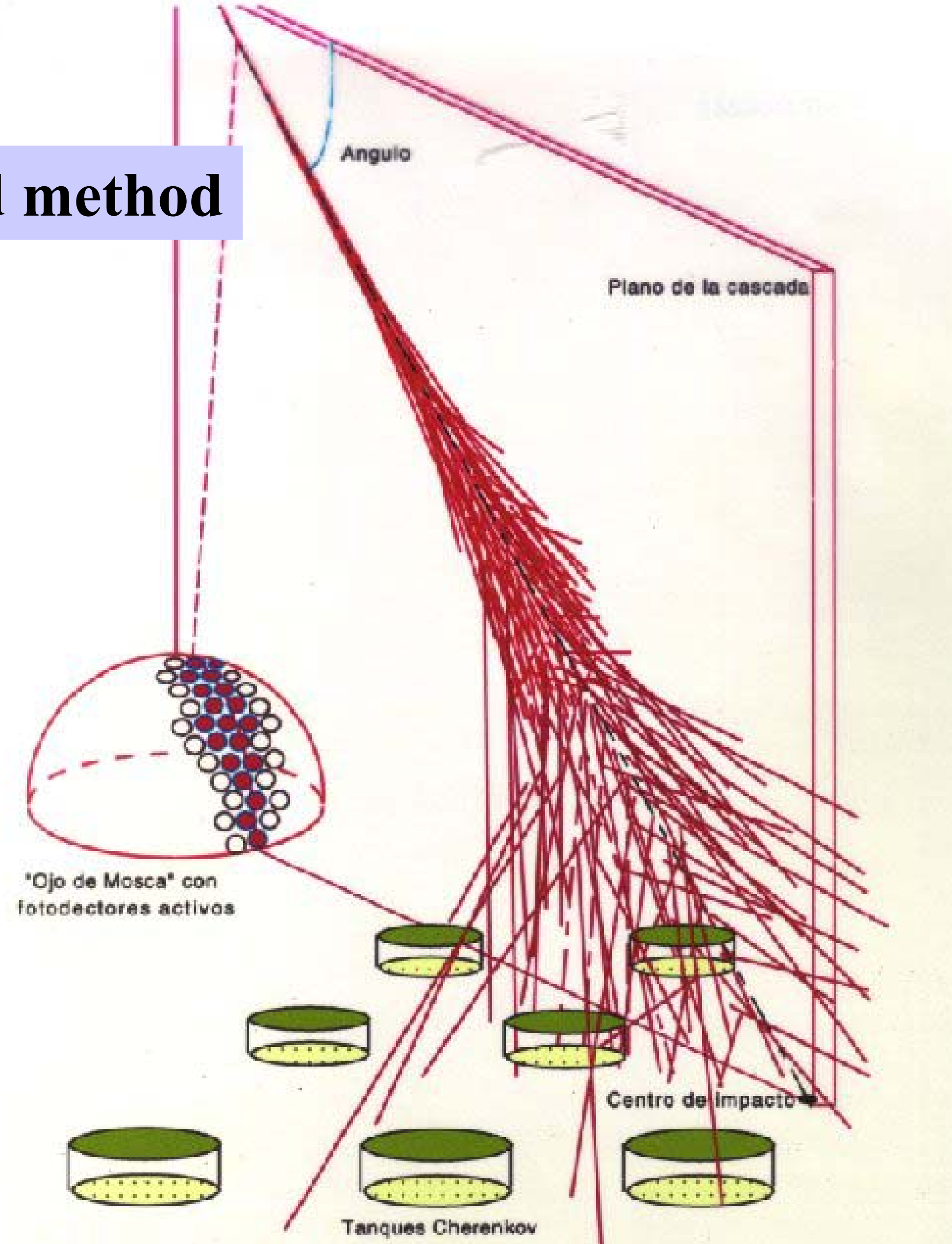
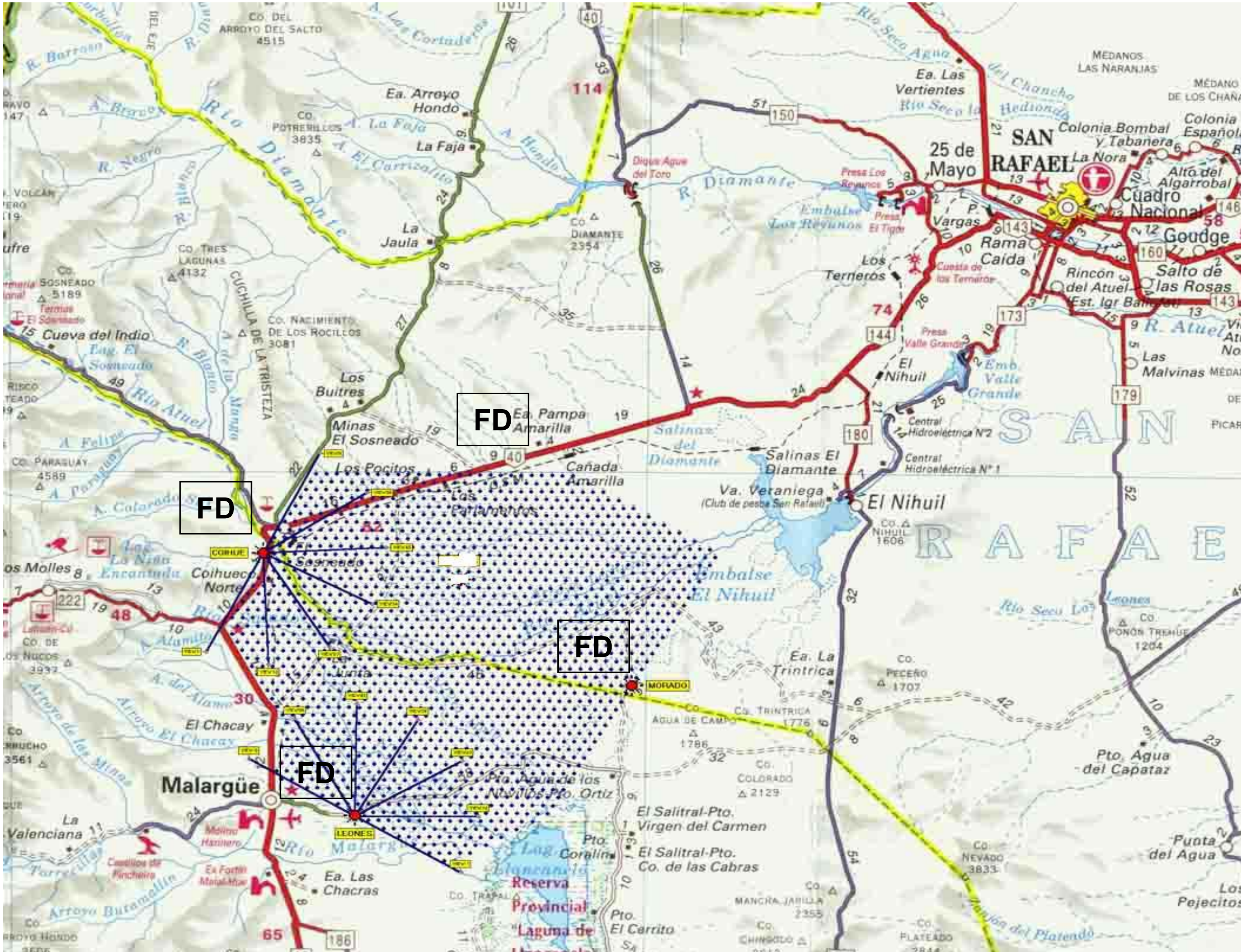


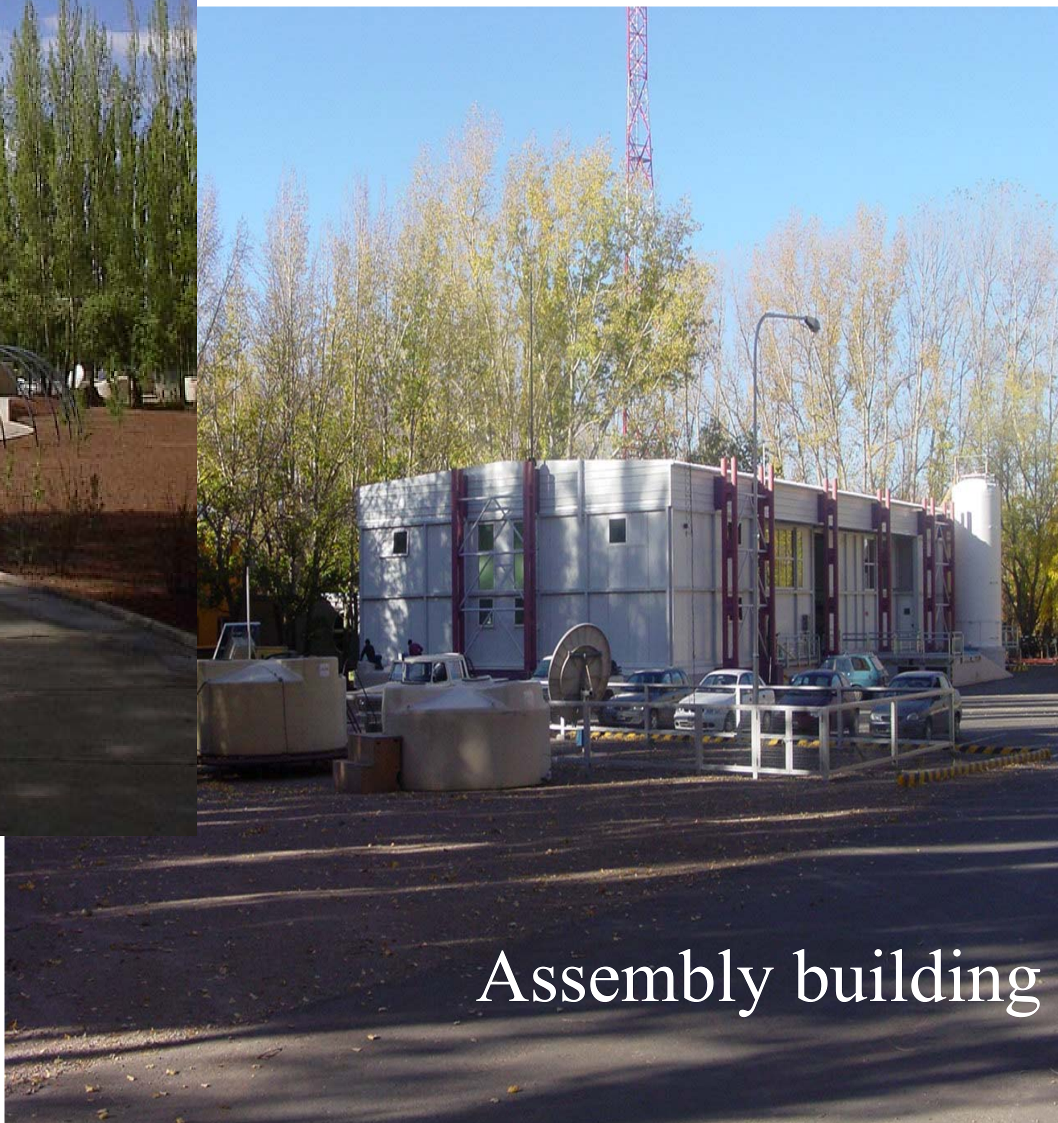
Diagram by Enrique Zas (Santiago de Compostela)

Pampa Amarilla Site



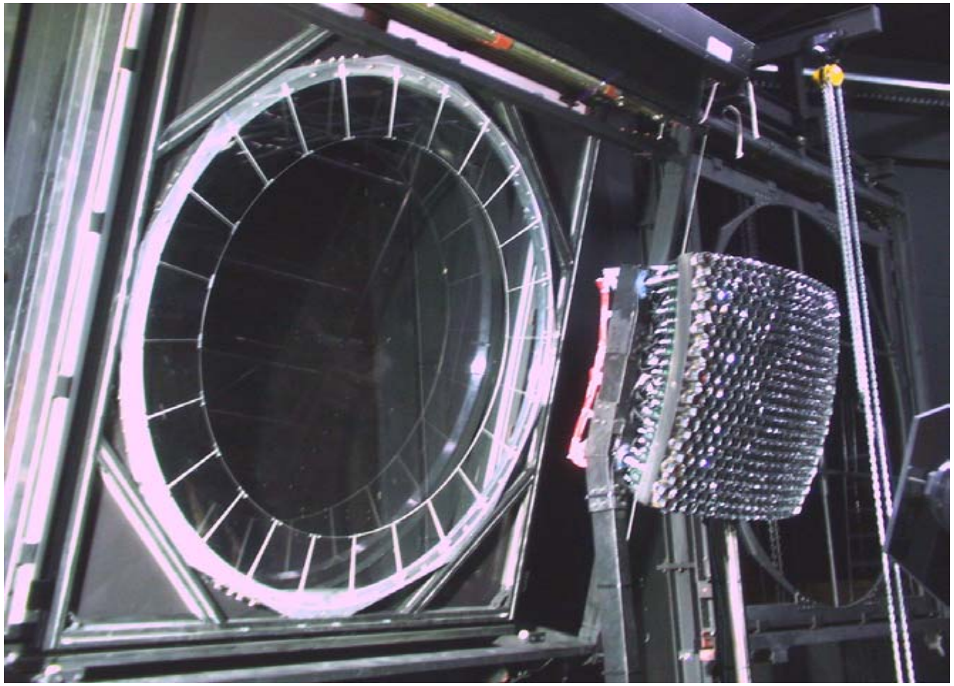
Observatory Infrastructure

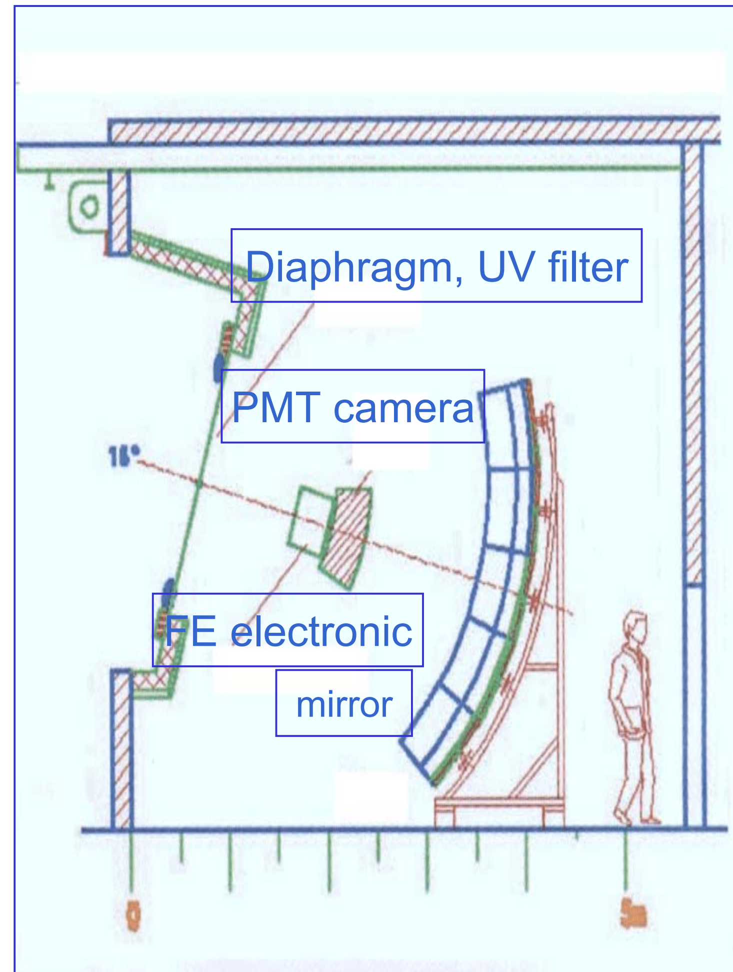
Office and CDAS building

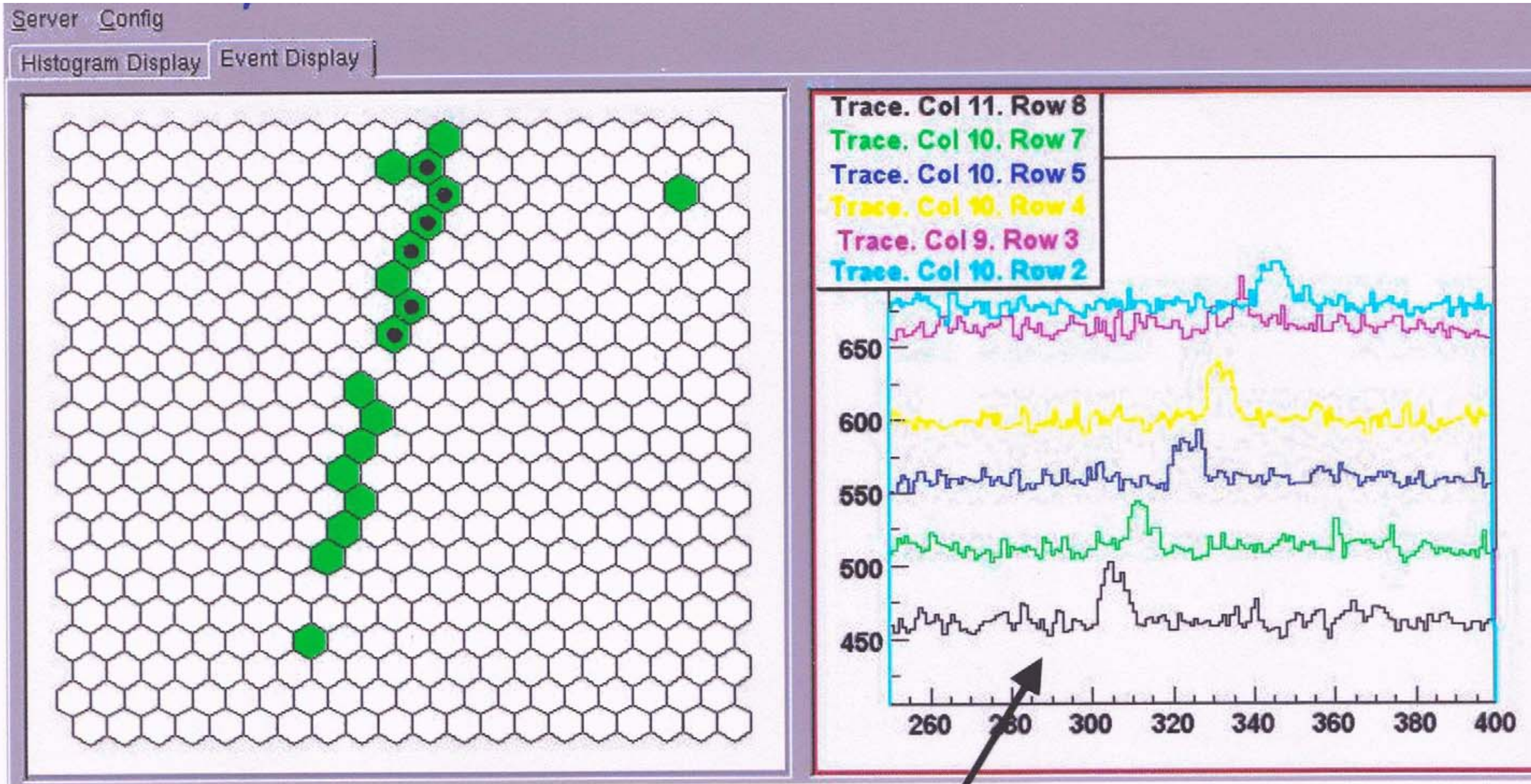


Assembly building

Auger fluorescence detectors







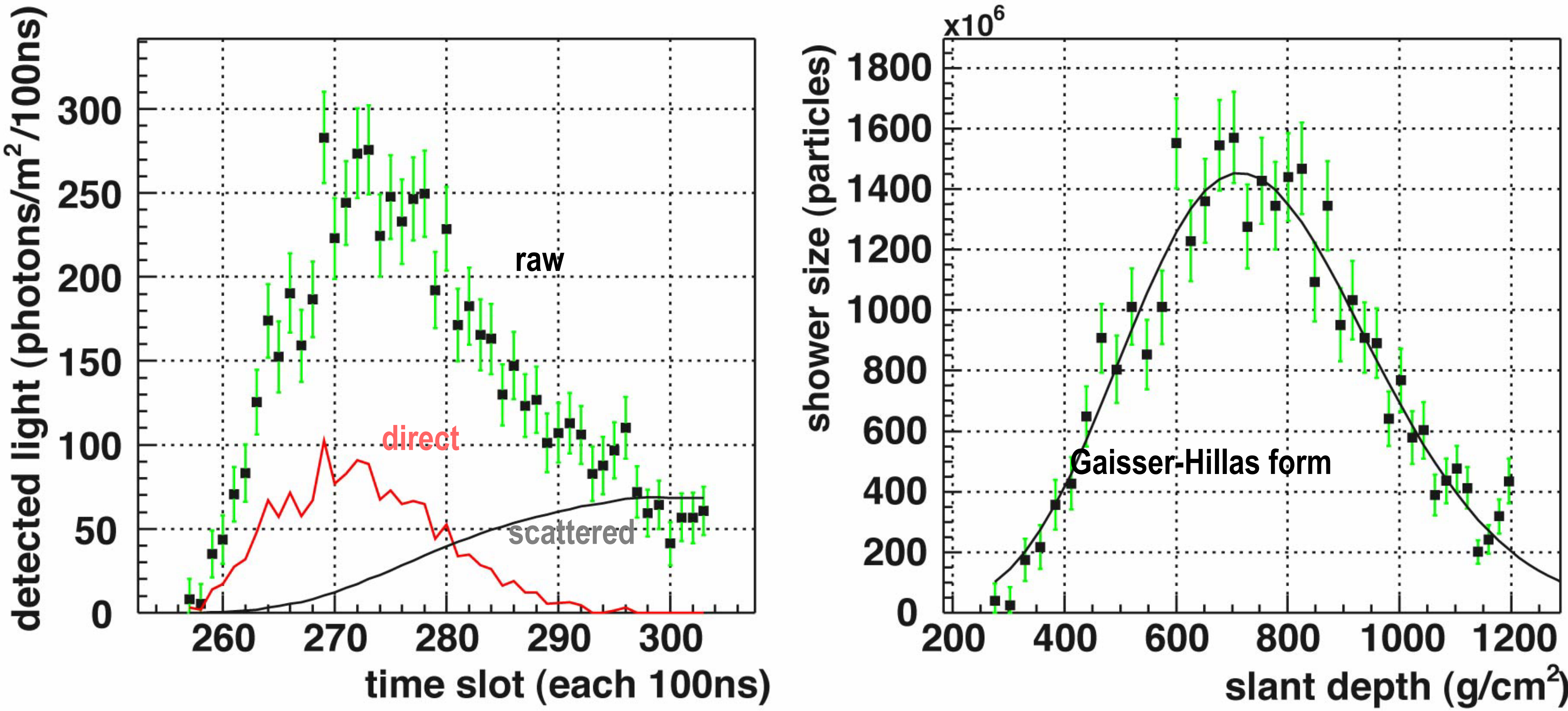
Time (x100 ns

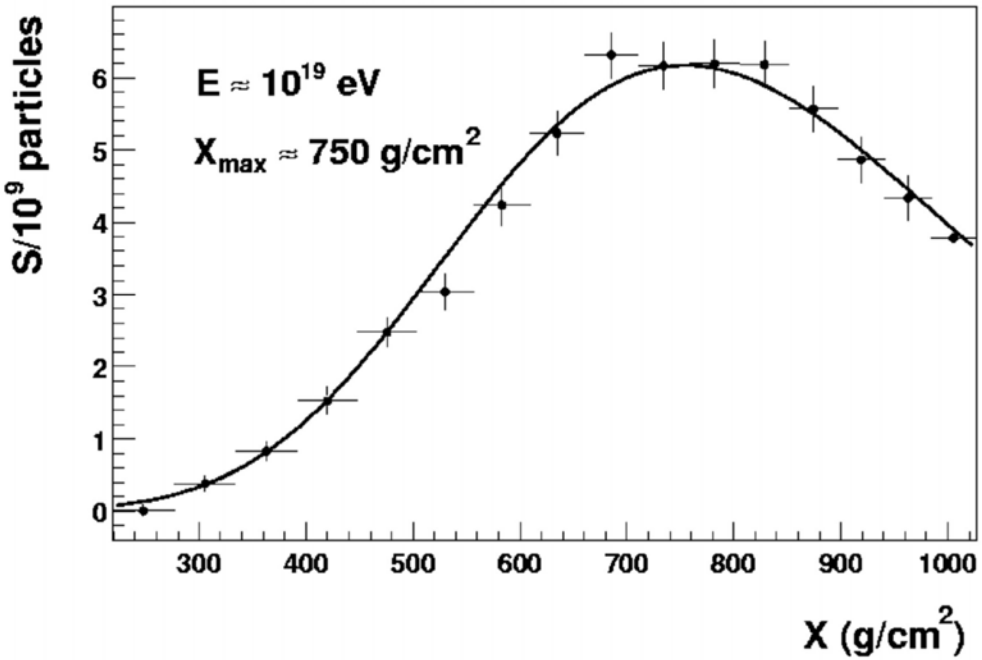
Triggered pixels

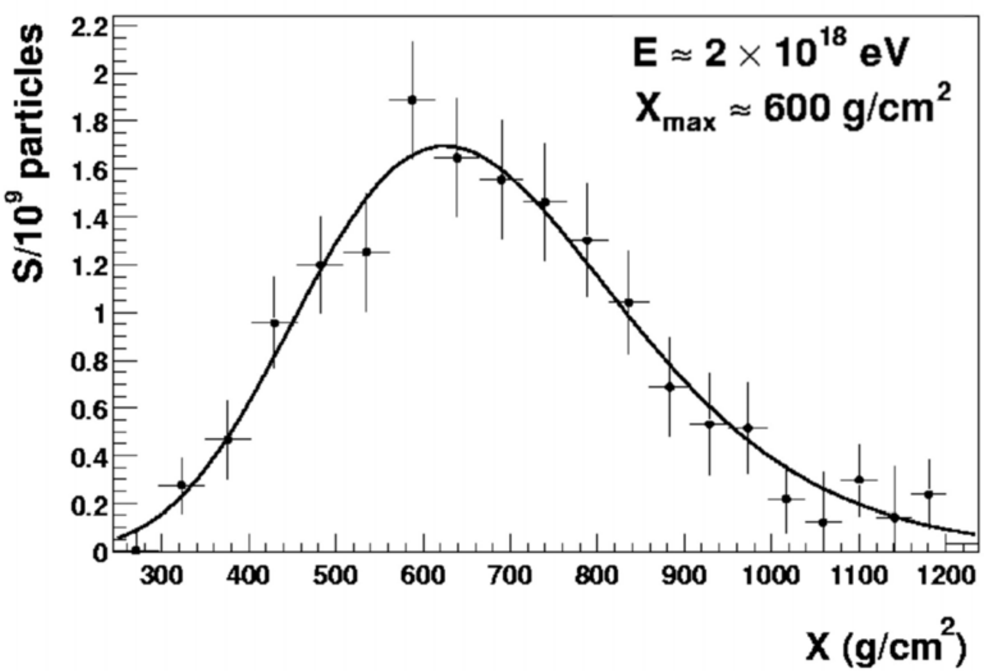
FADC traces

Analysis procedures with the FD

this event: intial viewing angle 15°, i.e. large direct Cherenkov contribution
iterative procedure, converges in <4 steps; suggested energy here 2e18 eV

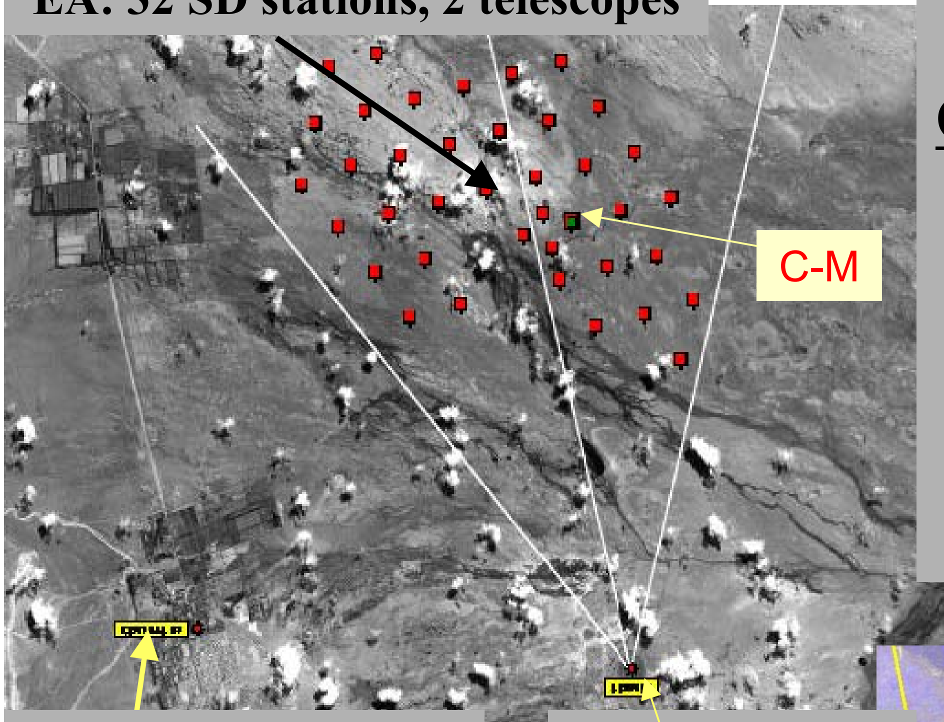






Two more Auger fluorescence events

EA: 32 SD stations, 2 telescopes



Central Campus **Los Leones**

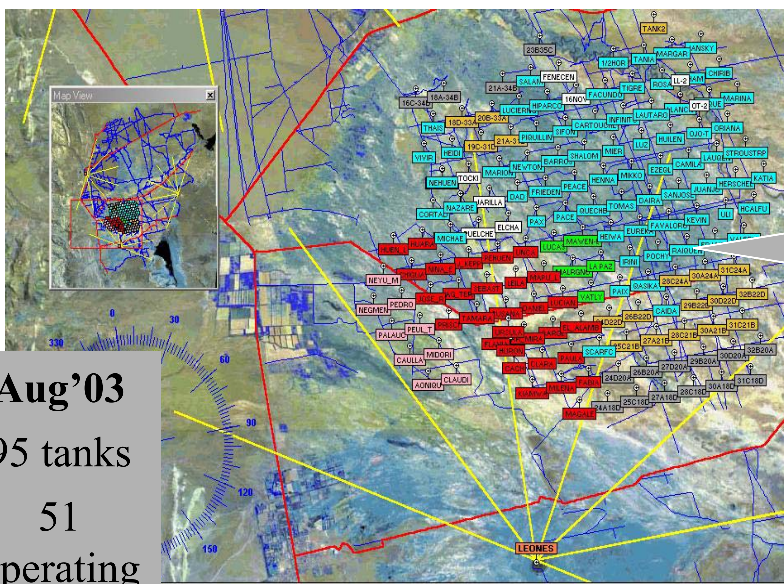
ENGINEERING ARRAY

Objective: Test the performance of every component and system.

Data taking since December ’01.

~80 hybrid triggers (Dec’01-Mar’02)

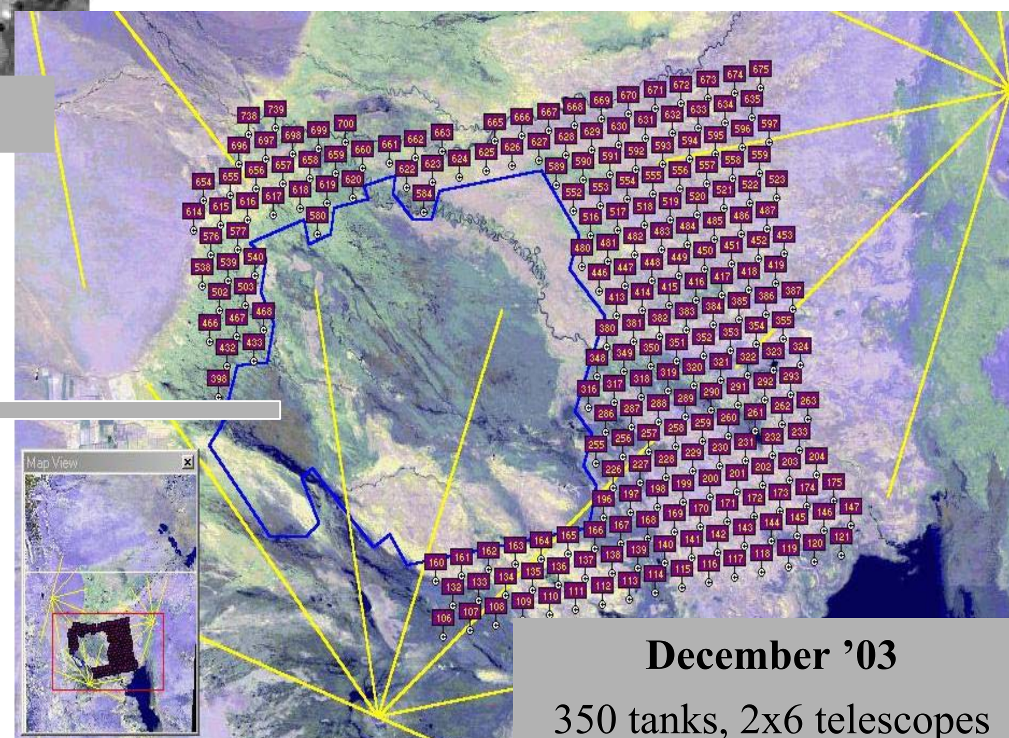
No expectation of science results



Aug’03

95 tanks

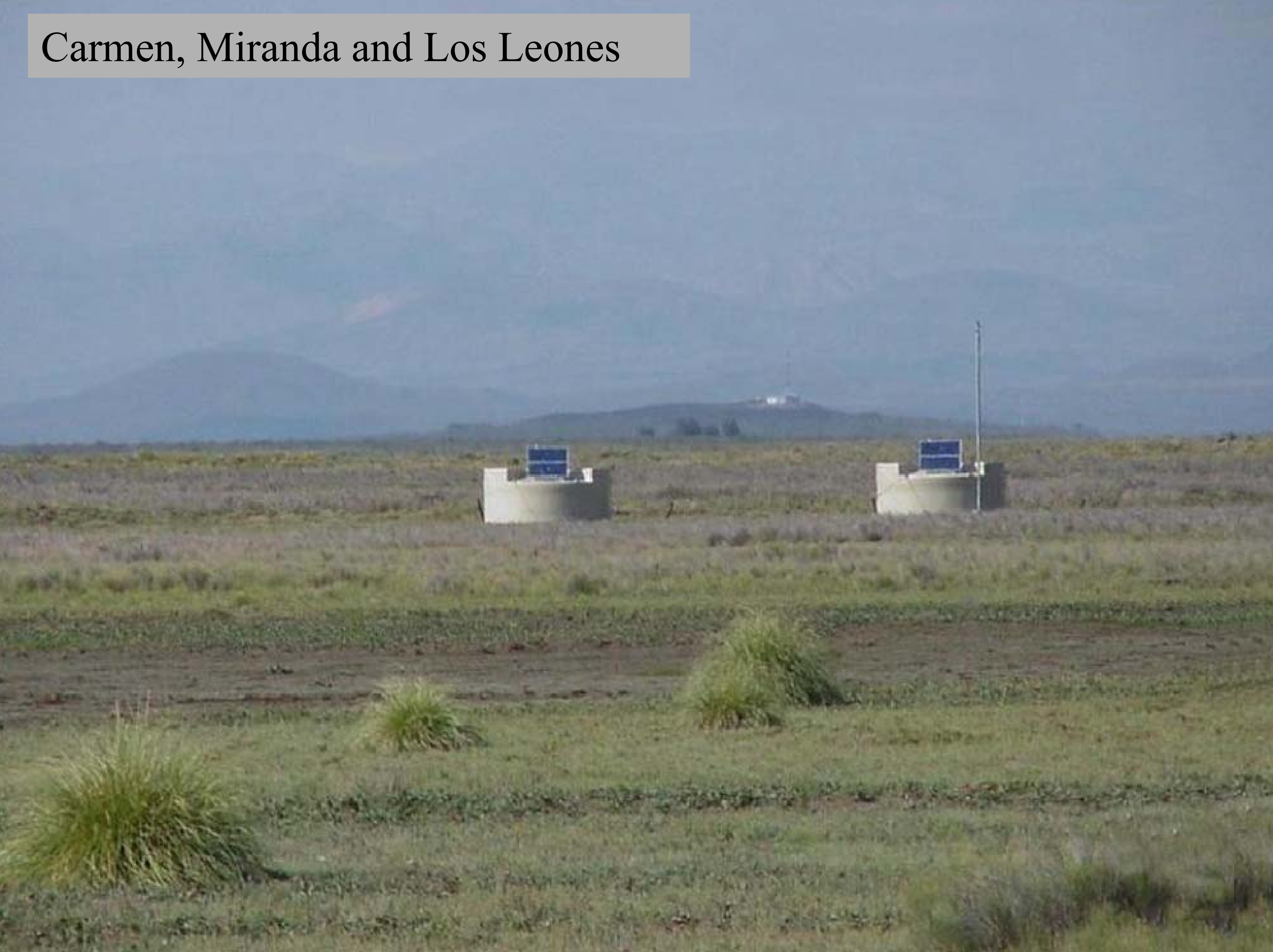
51 operating



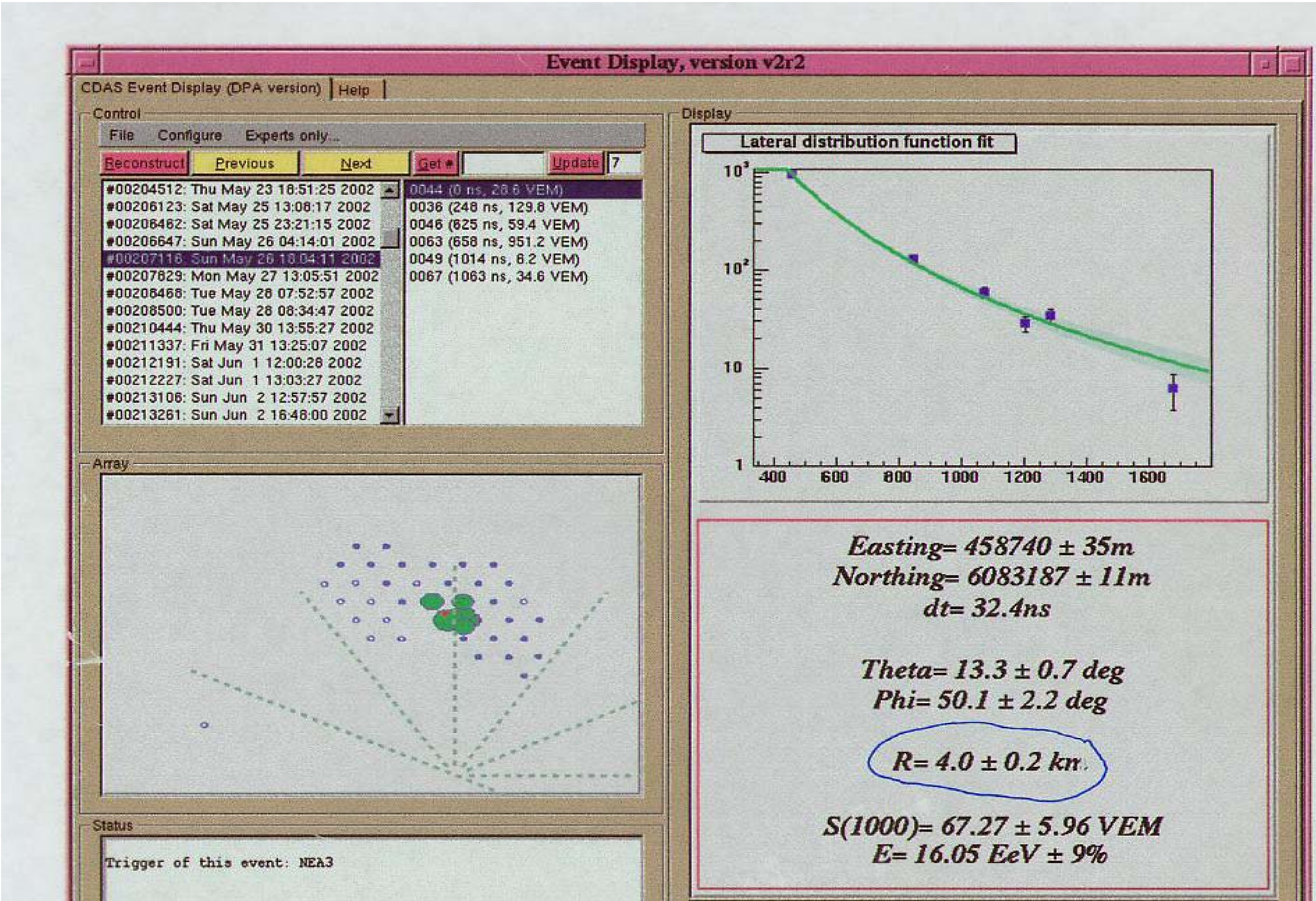
December ’03

350 tanks, 2x6 telescopes

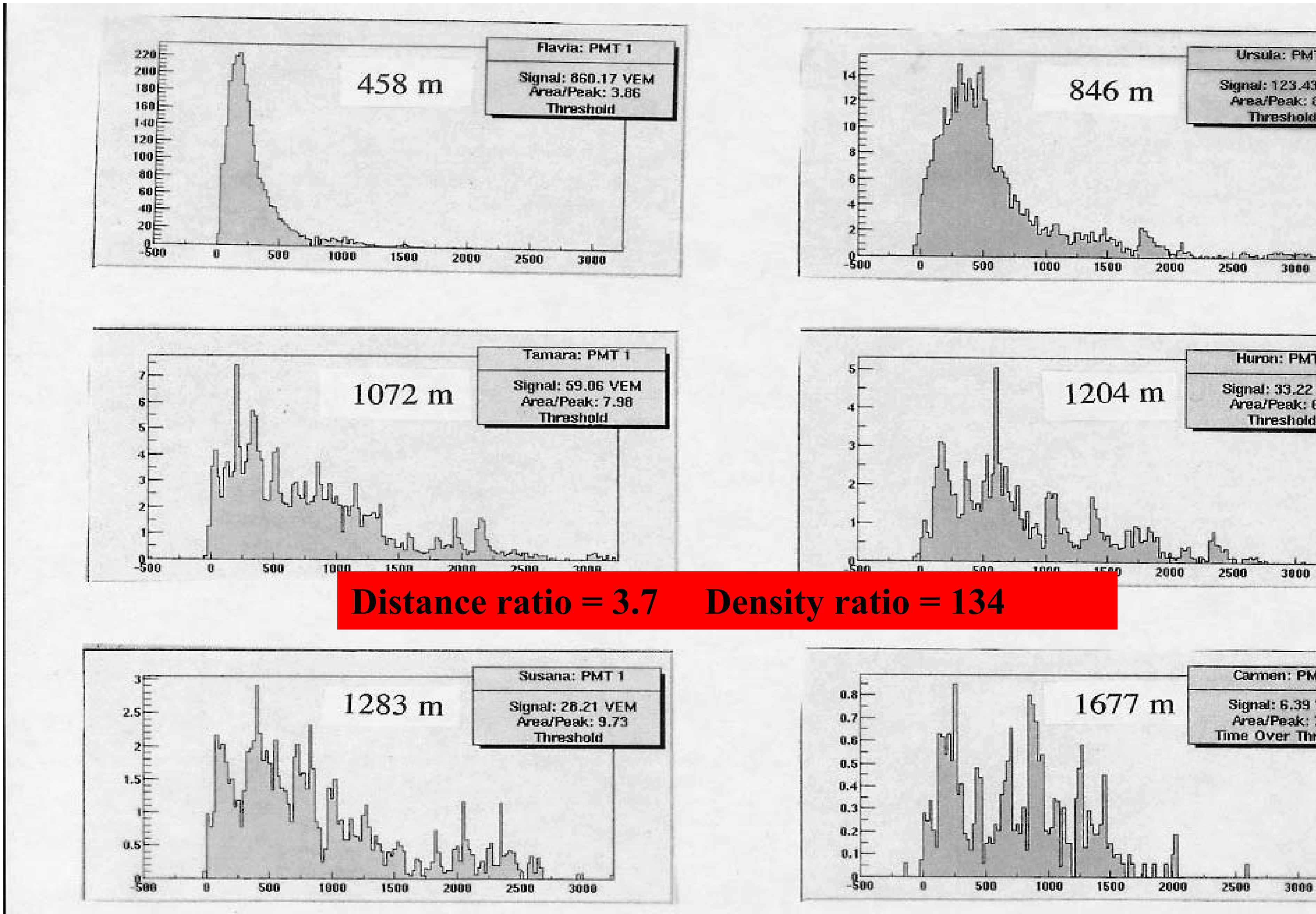
Carmen, Miranda and Los Leones



207116: zenith angle = 13°

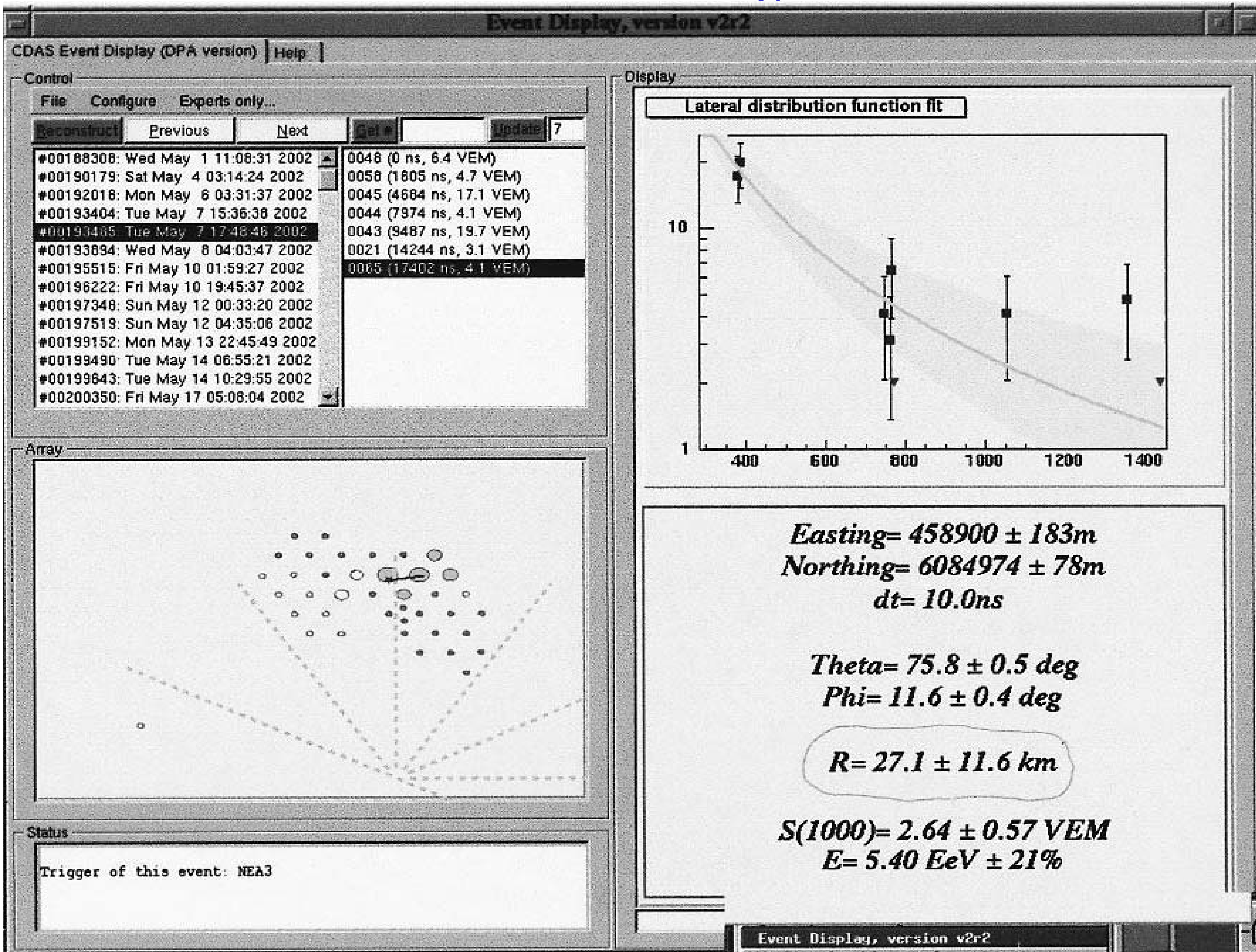


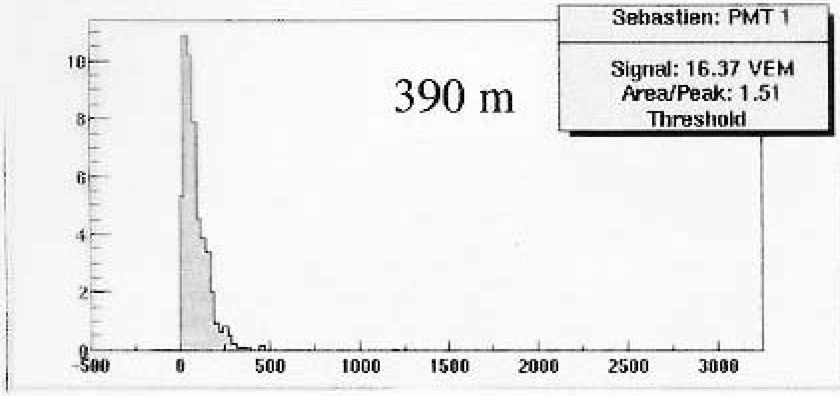
FADC traces for #207116

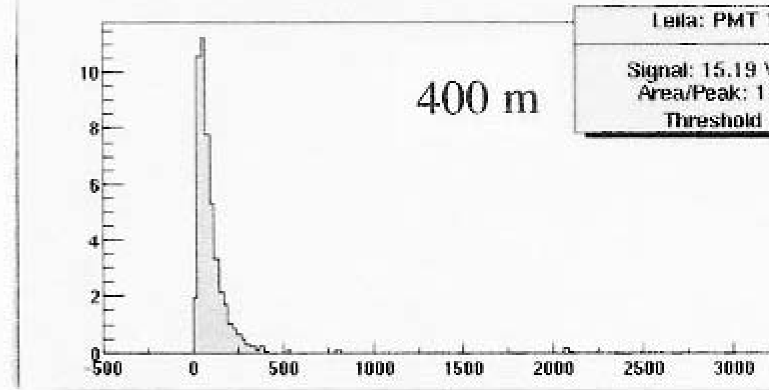


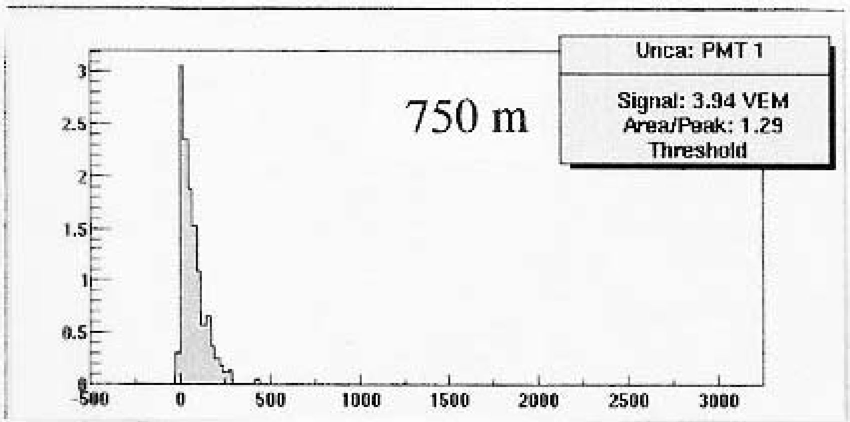
Distance ratio = 3.7   Density ratio = 134

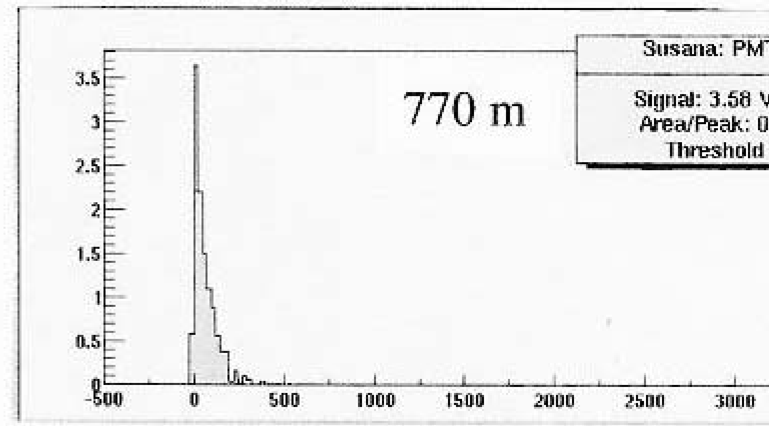
193485: zenith angle = 76°



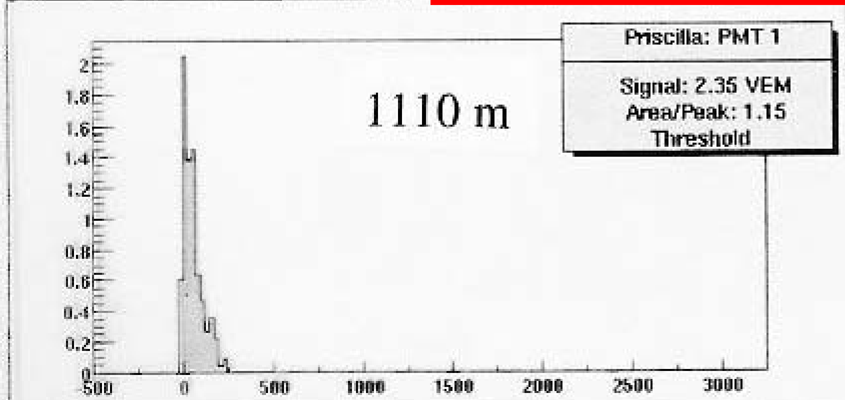


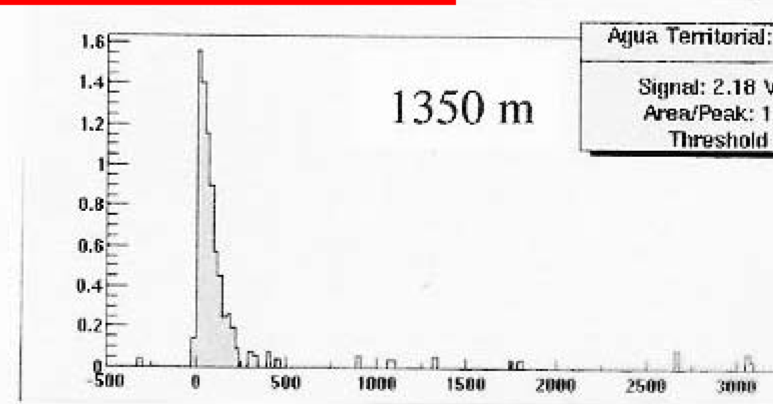






Distance ratio = 3.5 Density ratio = 7.7





Comparison of Exposures

AGASA: ~1750 km^2 sr yr - closing in December 2003

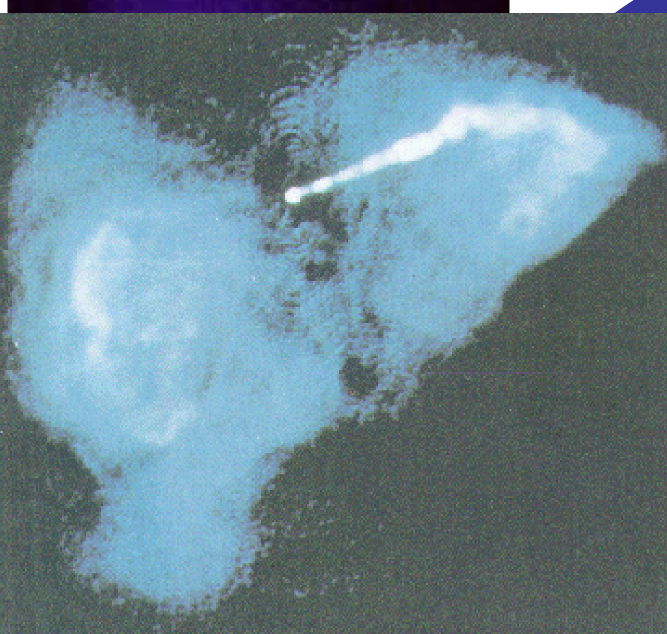
HiRes I and II: each ~1470 km^2 sr yr

Auger, by end of 2004, assuming 70% efficiency and using events with zenith angles up to 60°

~ 1440 km^2 sr yr.

Also there will be fluorescence measurements in 10% of events giving energy calibration.

IF CR> 10^{20} eV exist, are the sources Astrophysical or do we need New Physics?



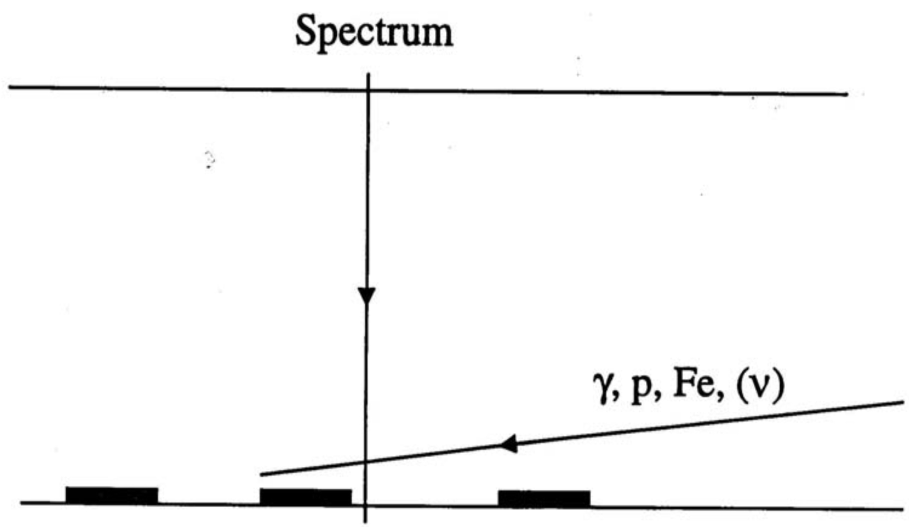
Super Heavy
Dark Matter Relics
in the Dark Halo of our Galaxy

Cosmic Strings

Relics from Early Universe?

thanks to Angela Olinto

Photons and neutrino fluxes from Inclined Showers

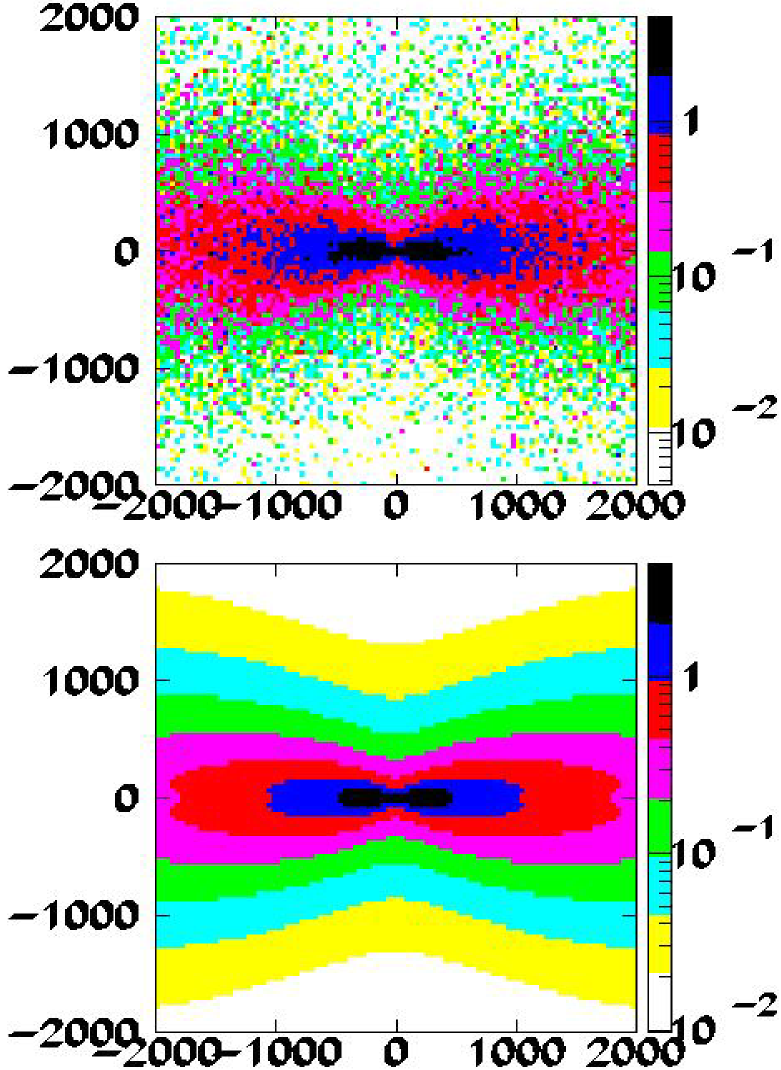


INPUT: Spectrum (mass-independent) e.g. FLUORESCENCE
Assumptions about mass

OUTPUT: Predicted Spectrum

COMPARISON: Measured Rate

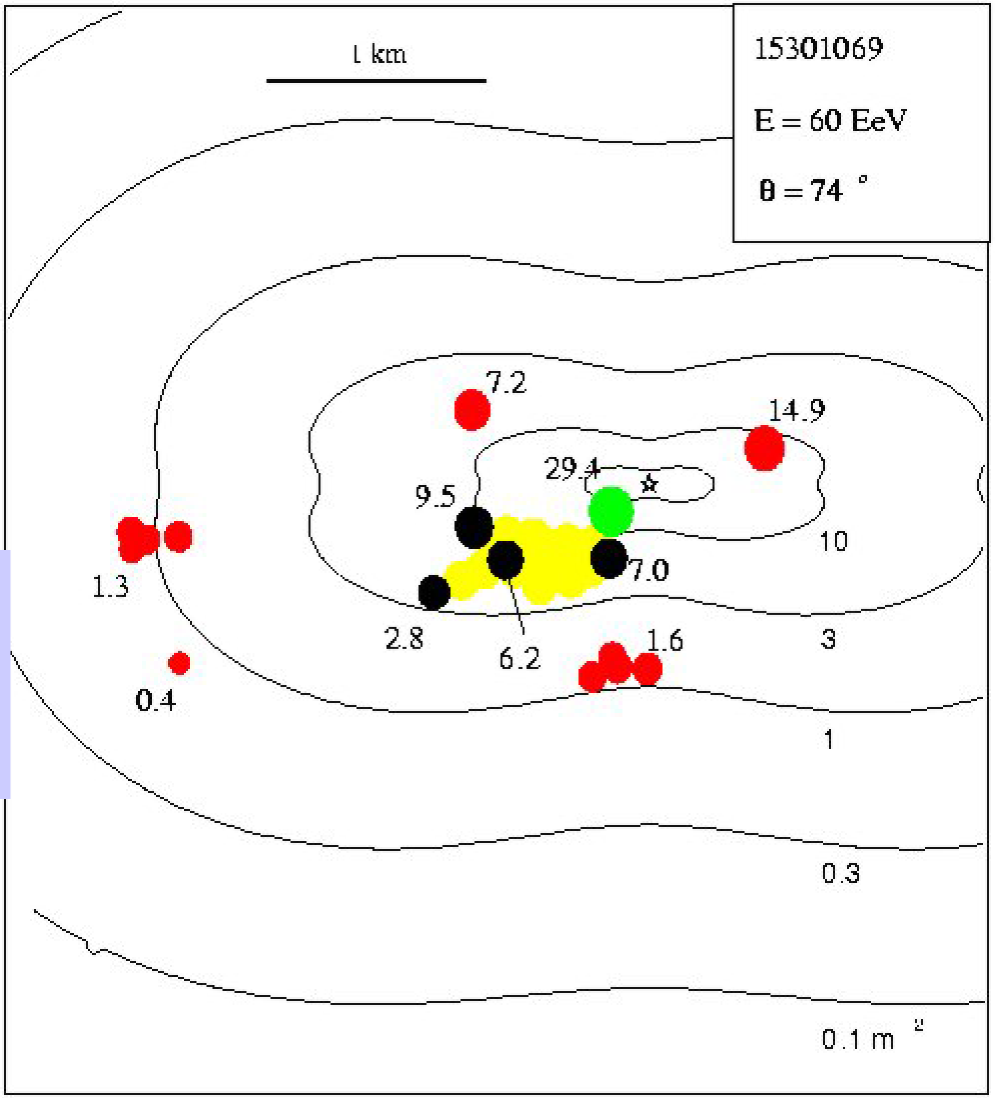
Example: Photon limit at 10^{19} eV
(Ave et al. Phys Rev Lett 2000)



M. Ave: 80°, proton at 10^{19} eV

Details in Ave, Vazquez and Zas, Astroparticle Physics

Test of idea with data from Haverah Park



Ave et al. PRL 85 2244 2000

Haverah Park:
Photon limit at 10^{19} eV
< 40%
(@95% CL)

AGASA: muon poor events

Gamma-ray fraction upper limits (@90%CL)

34% (>10^{19}eV)

56% (>$10^{19.5}$eV)

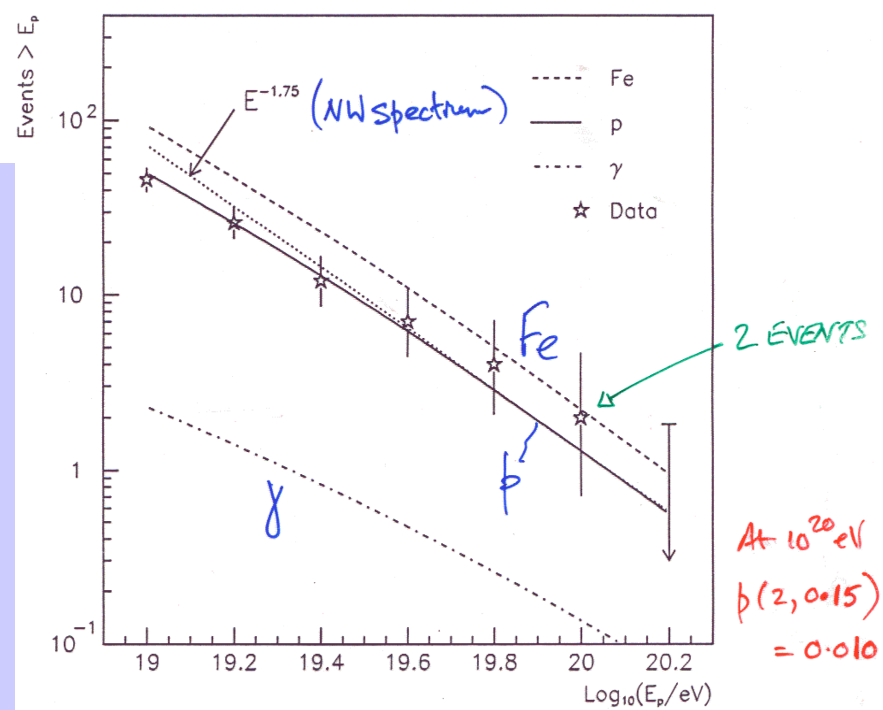
MOST IMPORTANTLY:
We understand how to deal with inclined showers.

$>10^{19}$ eV (49 events)

$\gamma/p \leq 40\%$

$Fe/p \leq 54\%$ at 95% CONFIDENCE LEVEL.

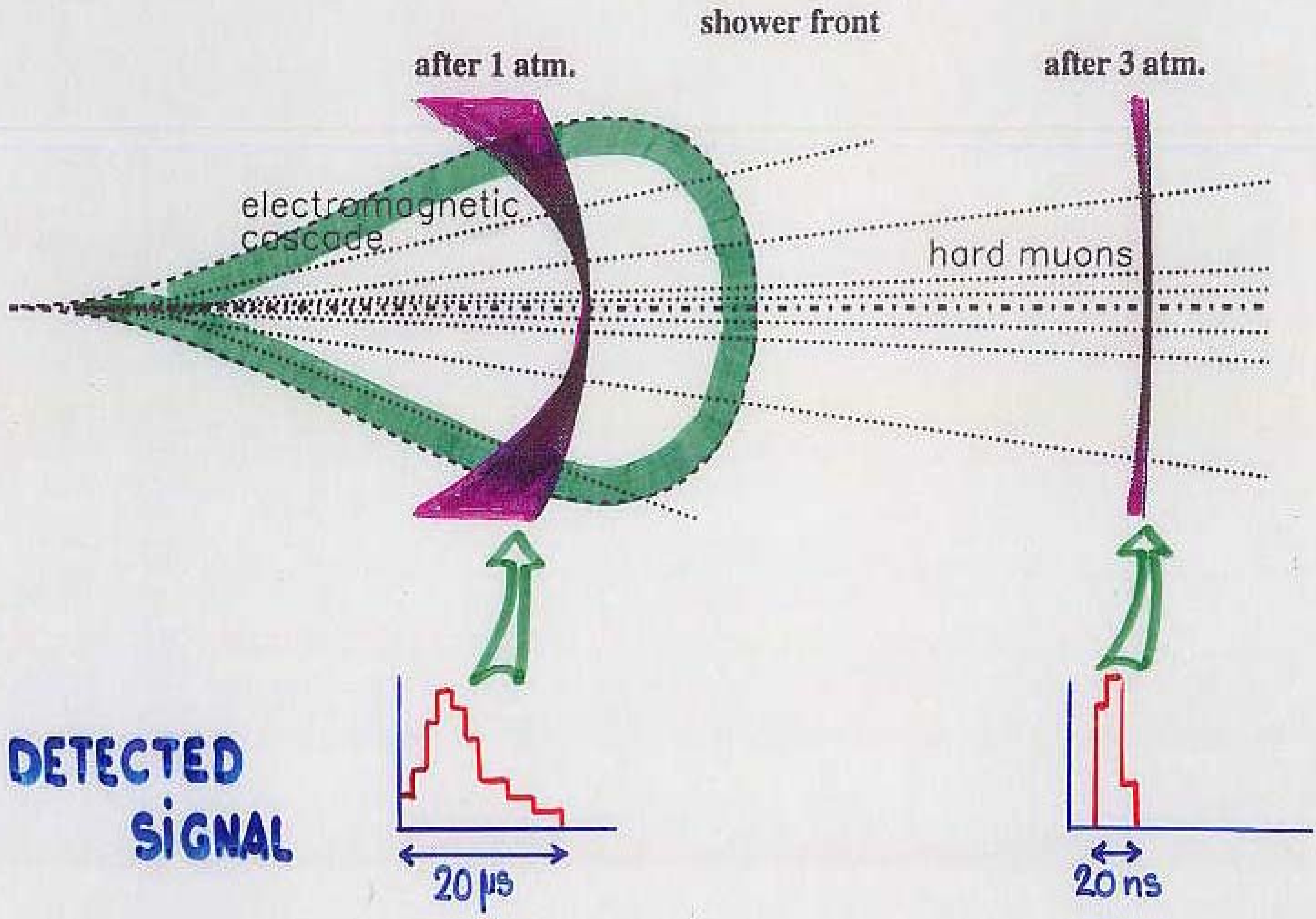
Figure 2



$60° < \theta < 80°$

AVE, HINTON, VAZQUEZ, WATSON & ZAS
PRL 85, 2244, 2000

Concept of neutrino detection with shower array



Tau neutrino detection

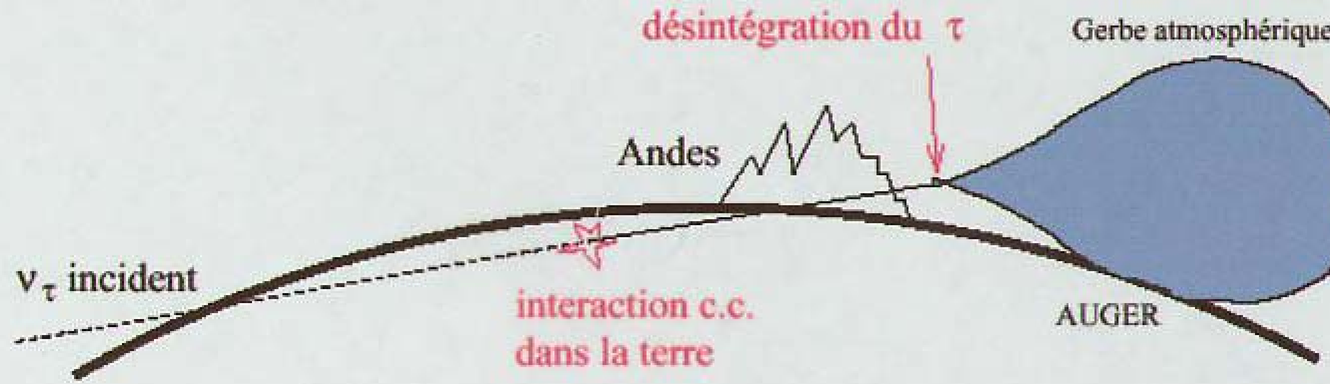
PIERRE AUGER OBSERVATORY

- **Principle:**
  - **Interaction length in the earth ~ 300 km at 10^{18} eV**
  - **Tau time of flight ~ 50 km at 10^{18} eV**
  - **1° below horizon ⇒ 200 km of rock**
  - **Shower maximum ~10 km after decay**

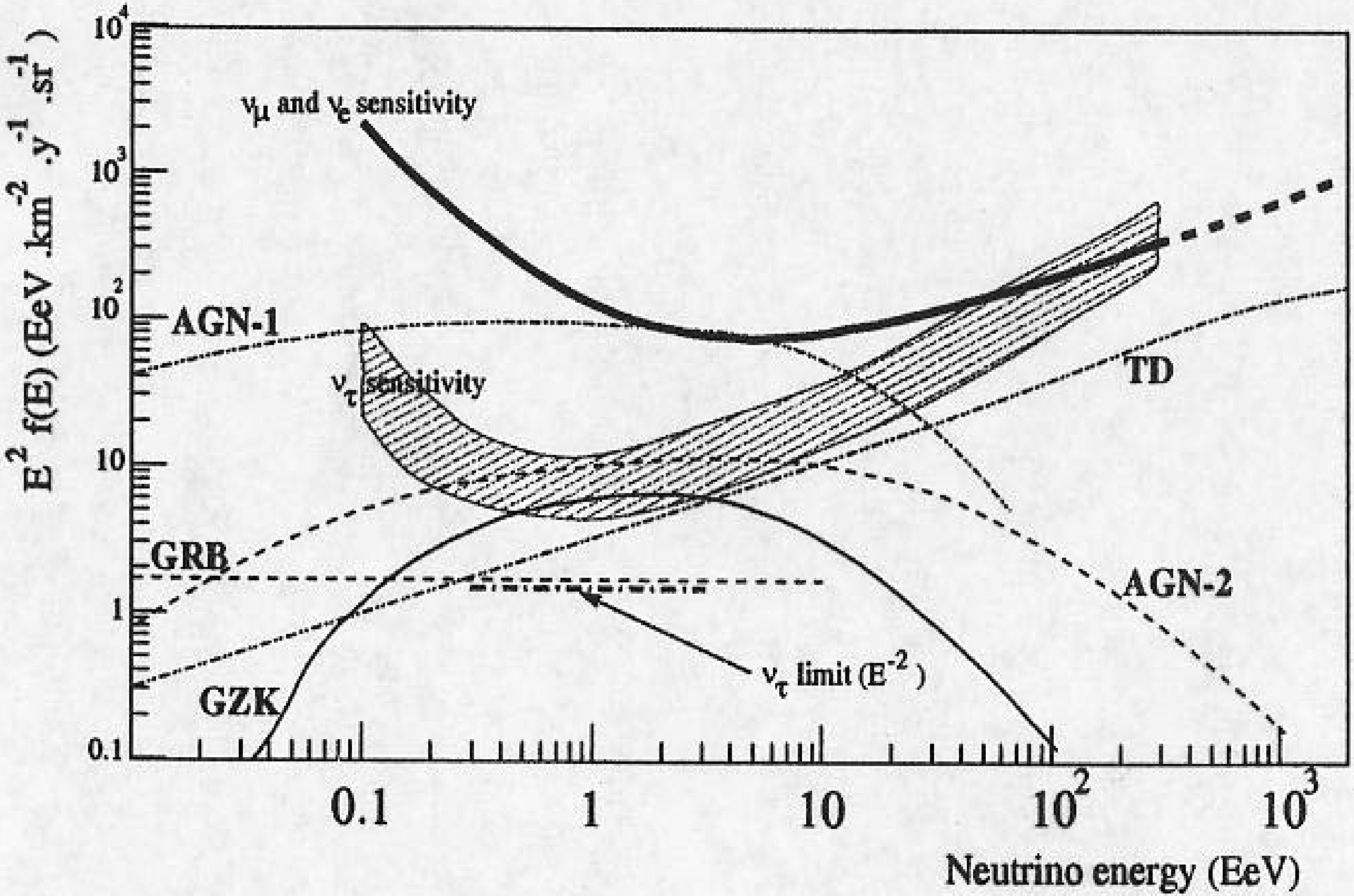
  In practice 85° < θ_z < 95°

  AUGER window: 10^{17} to 10^{20} eV

X.Bertou, P.Billoir, O.Deligny
A.Letessier-Selvon
astro-ph/0104452v4
Accepted in Astropart. Phys.
ApP 17, 183, 2002



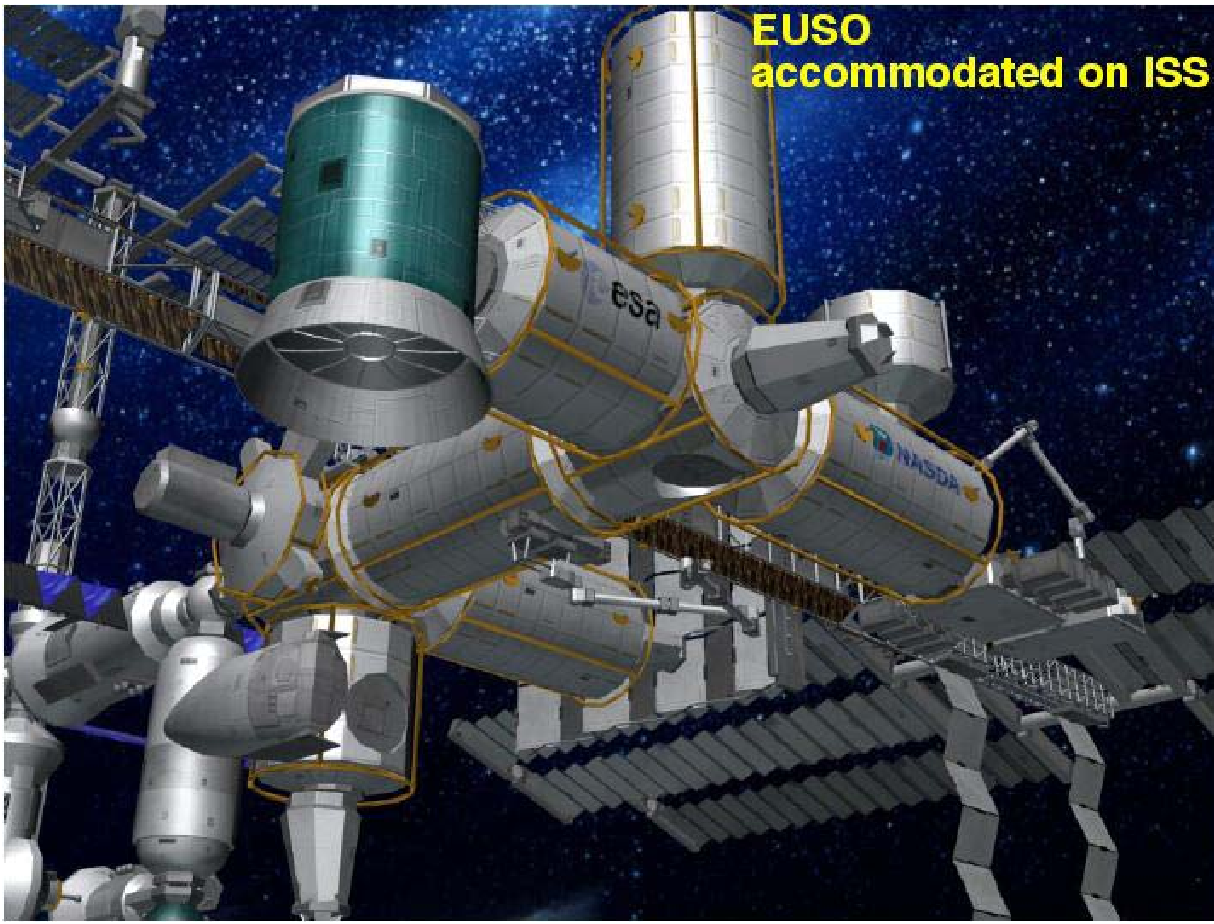
Neutrino Sensitivity of Auger Observatory

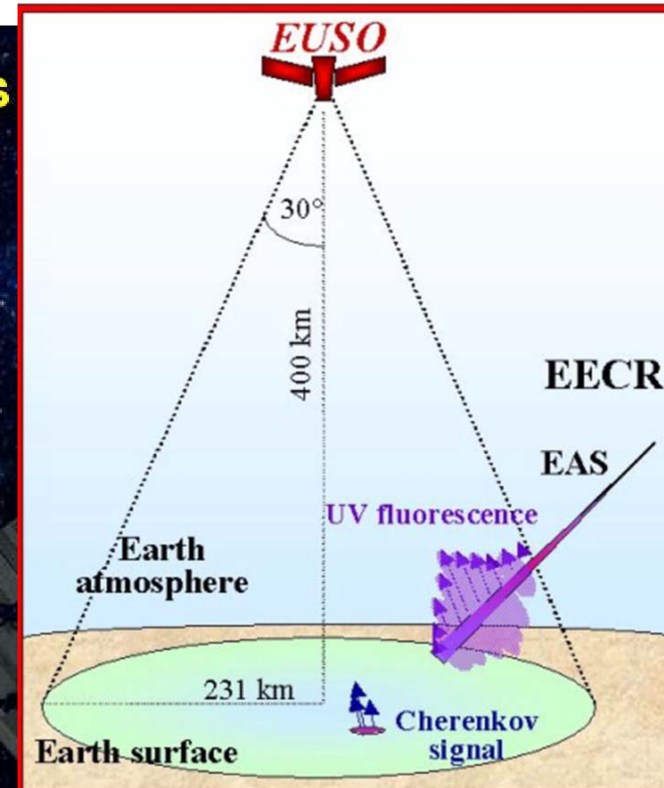


EUSO

Extreme Universe Space Observatory

for Extremely High Energy Cosmic Ray Observation

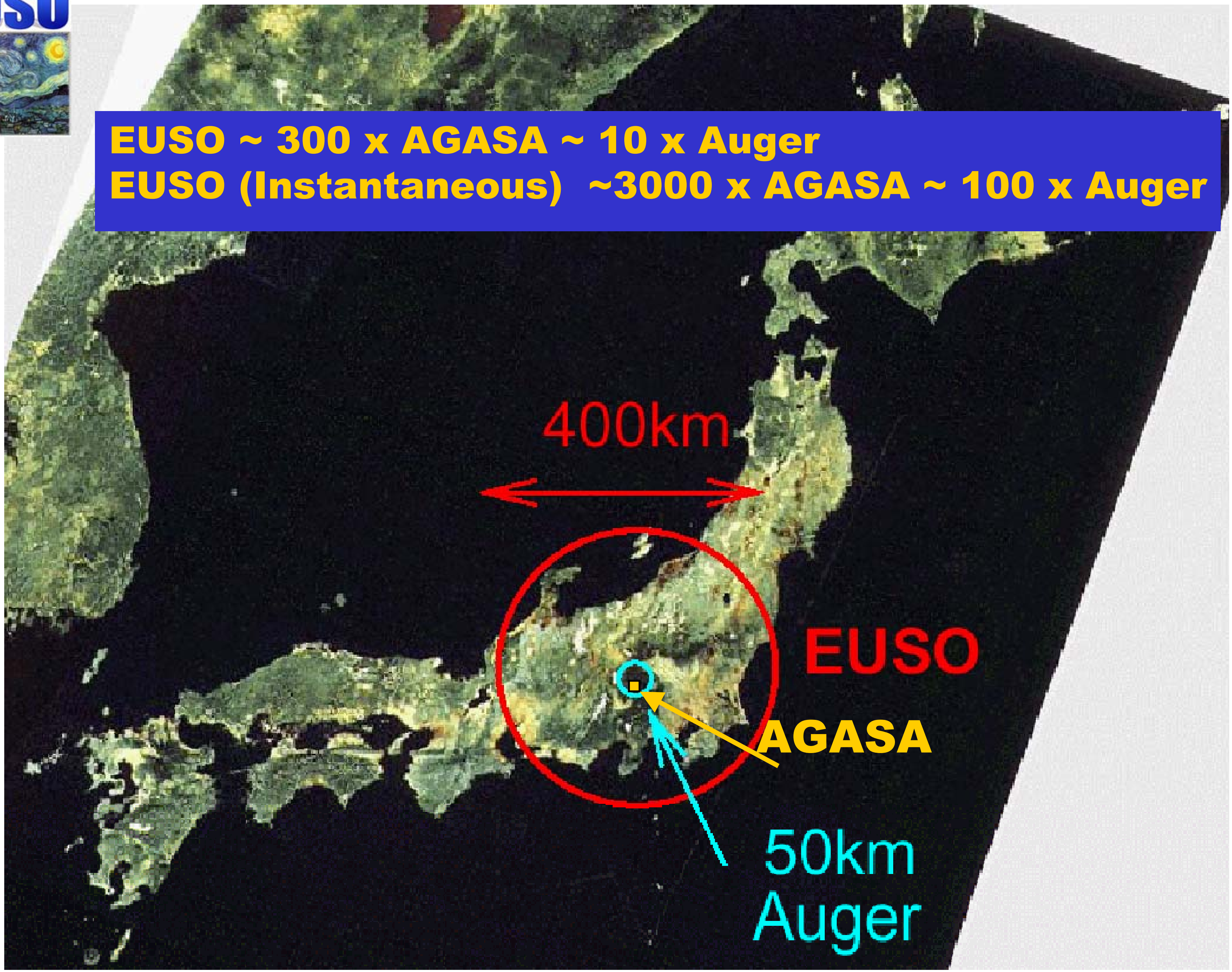




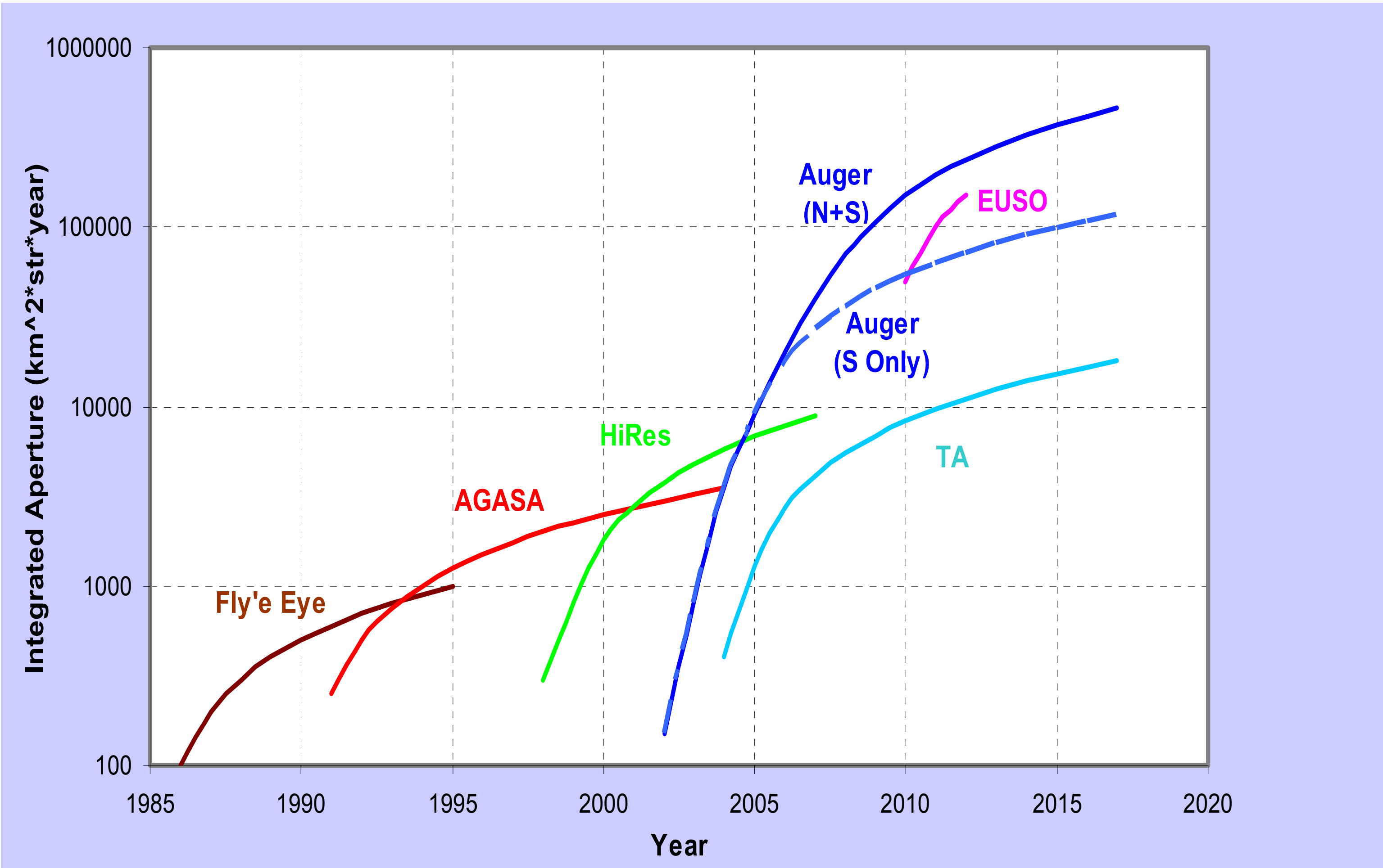
At ICRC2003 10 oral + 18 posters - becoming a reality
Phase A to Phase B within ESA

EUSO

EUSO ~ 300 x AGASA ~ 10 x Auger
EUSO (Instantaneous) ~3000 x AGASA ~ 100 x Auger



Expected Integrated Apertures



K. Arisaka (ICRC03)

Connecting Quarks with the Cosmos
Eleven Science Questions for the New Century

What are Nature's most energetic particles?

Gamma Rays, neutrinos and cosmic rays

"A full understanding of how these particles are produced and accelerated could shed light on the unification of nature's forces."

I anticipate that great progress will have been made in answering this important question within the next 10 years, with first Auger science in 2 years.