The High-Energy Universe:
Cosmic Rays, Gamma Rays, Neutrinos

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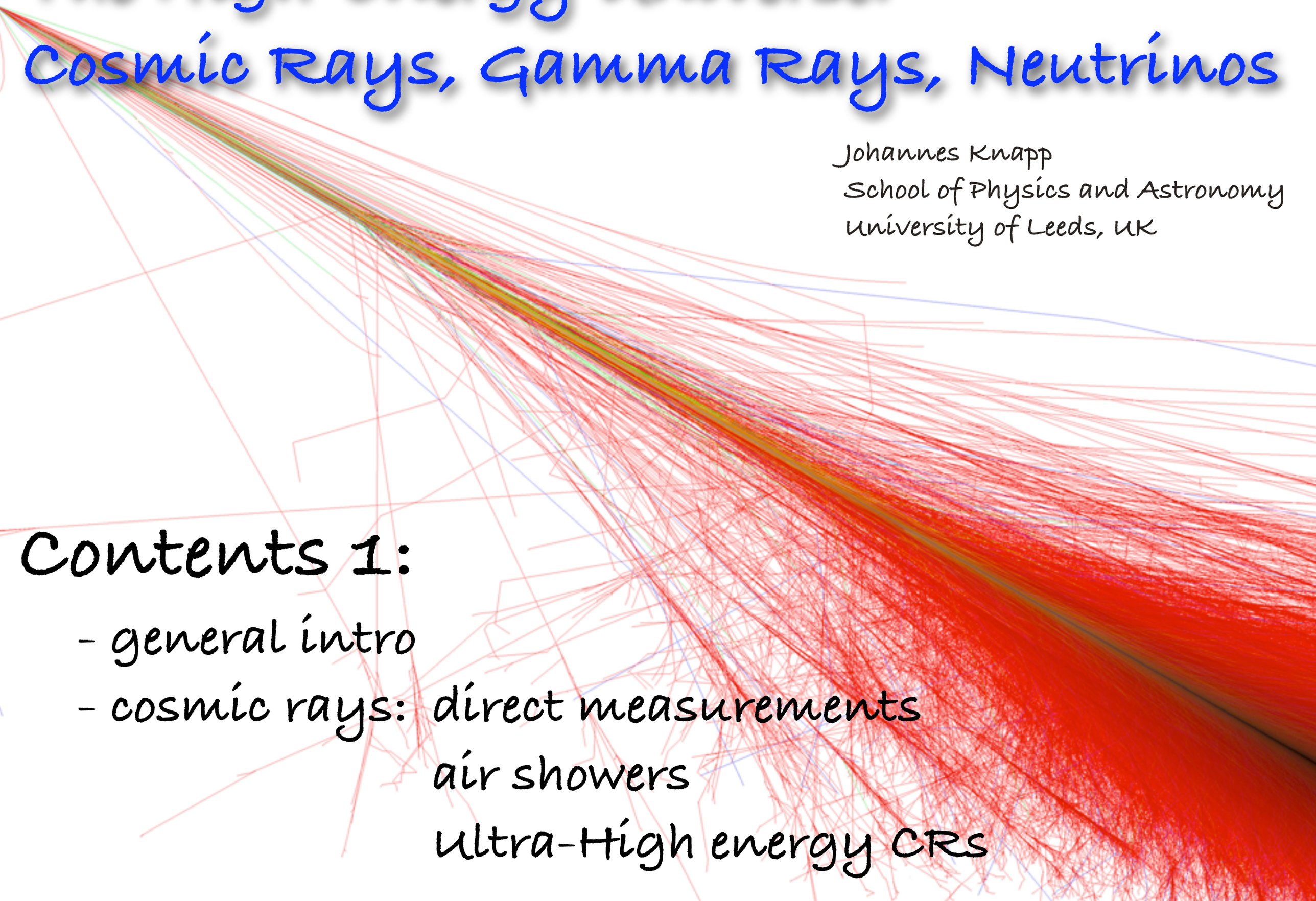


Contents 1:

- general intro
- cosmic rays: direct measurements
  air showers
  Ultra-High energy CRs

Astroparticles: particles from astrophysical sources

... The highest energy particles in the universe !!!!!

Energies keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

10^3 ... 10^6 ... 10^9 ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

Cosmic Rays: p, He, ... Fe, ... fully ionised nuclei,

electrons

Photons: classical astronomy + high-energy gammas

Neutrinos: astrophysical ν (solar, SN, AGN, ...)

Cosmic Rays:

relativistic, charged particles

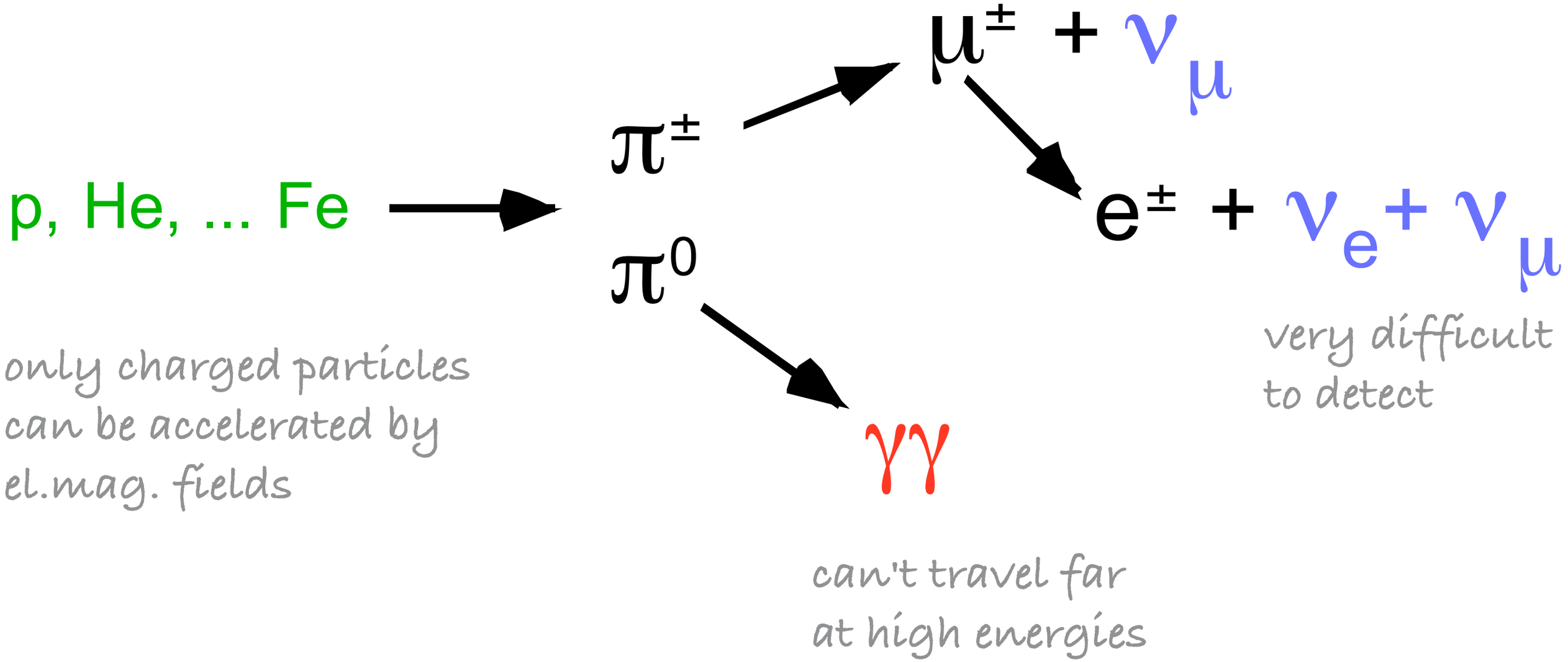
$E_{CR} \approx E_{starlight} \approx E_{CMB} \approx E_{mag} \approx E_{Gas} \approx 1\ eV/cm^3$

total: $\approx 10^{49}$ J in Galaxy

CRs are a major component of our Galaxy

Spectrum ? Composition ?
Identity ? Origin ? Acceleration ?

Cosmic Rays, Gamma Rays and Neutrinos are linked



only charged particles can be accelerated by el.mag. fields

very difficult to detect

can't travel far at high energies

γ and ν travel in straight lines, i.e. point back at source.
CRs are deflected in gal. and intergal. magnetic fields.

If Cosmic Rays exist,

then also ν and γ must exist at similar energies.

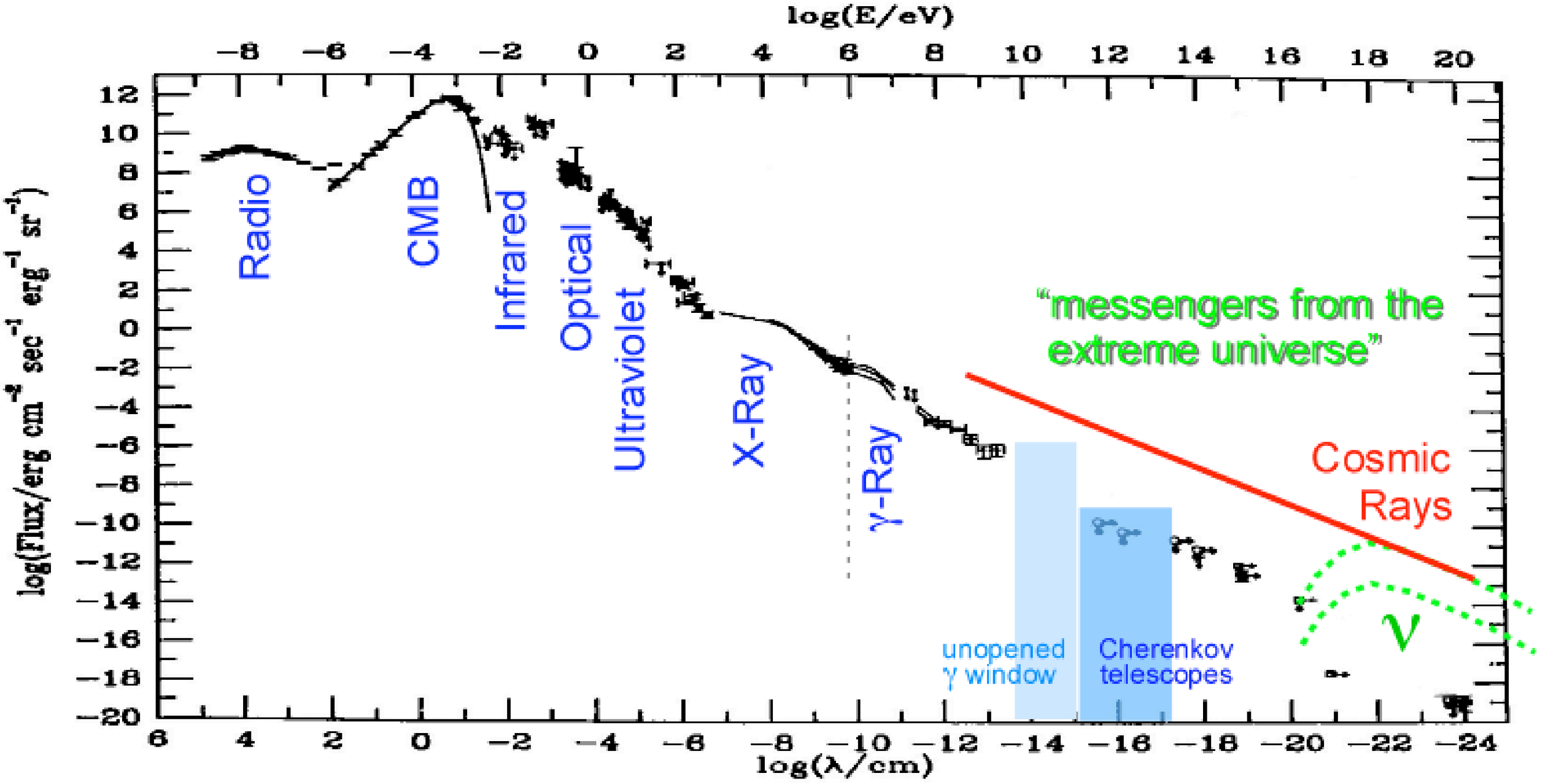
But: can they be detected above backgrounds ???

γ : 100-1000 x more cosmic rays

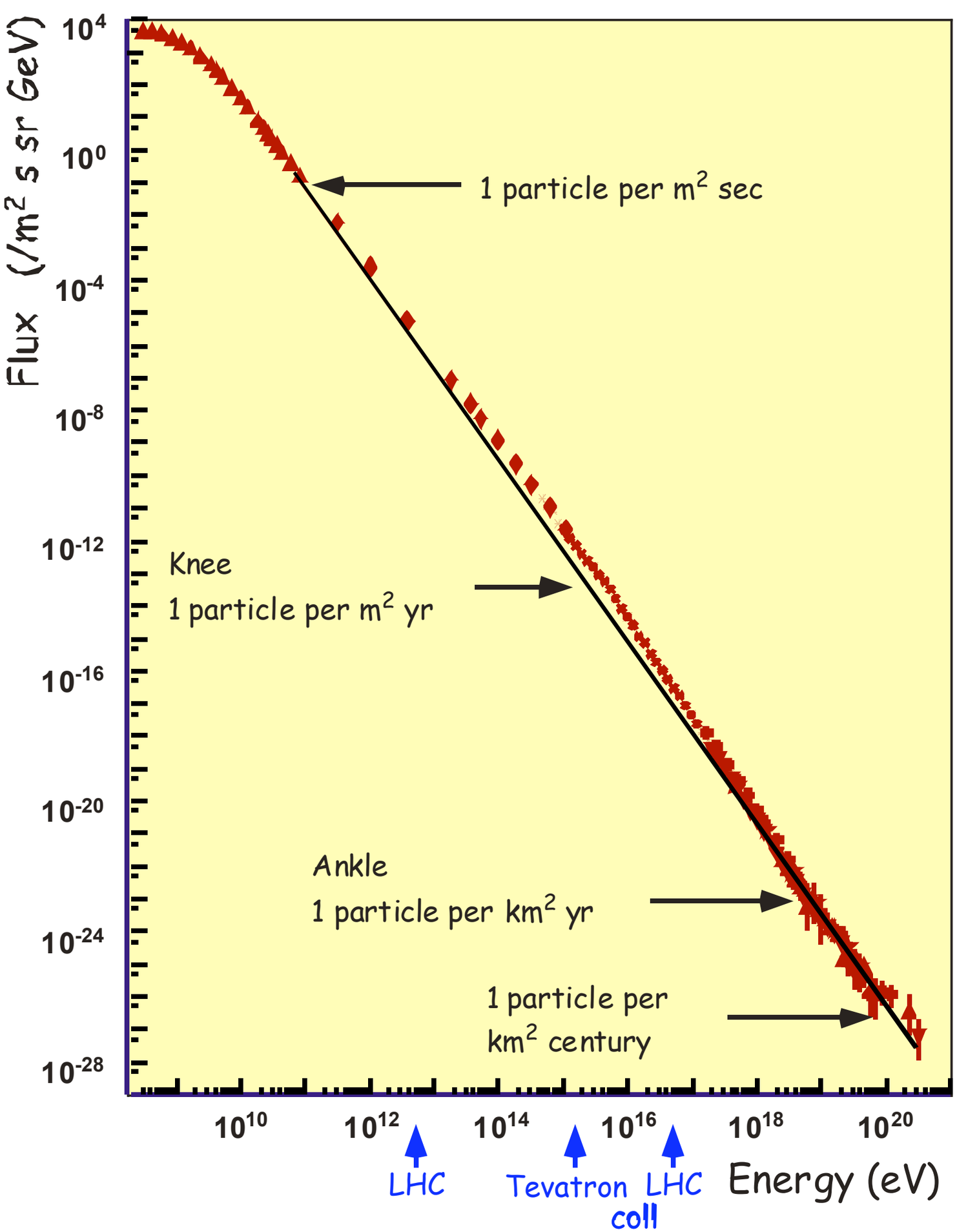
ν : low interaction cross section

atmospheric neutrinos from atmosphere

Universal photon spectrum



Flux of Cosmic Rays



11 orders of magnitude in energy,
32 in flux !!!!

Power law with almost no structure.
(makes it difficult to interpret)

Highest energy events:

AGASA ~3 x 10^{20} eV

Fly's Eye ~3 x 10^{20} eV

One detector set-up can hardly span more than ≈2 decades in energy, i.e. it is difficult to see the "greater picture".

N_{evts} = flux x area x time

> 100

low, given by nature

$\approx 1\ m^2$ for space exp.

≈ 3 yrs

size of detector limits the fluxes that can be observed

$$N_{evts} = flux \times area \times time \times p$$

> 100

low, given by nature

$\approx 1\ m^2$ for space exp.

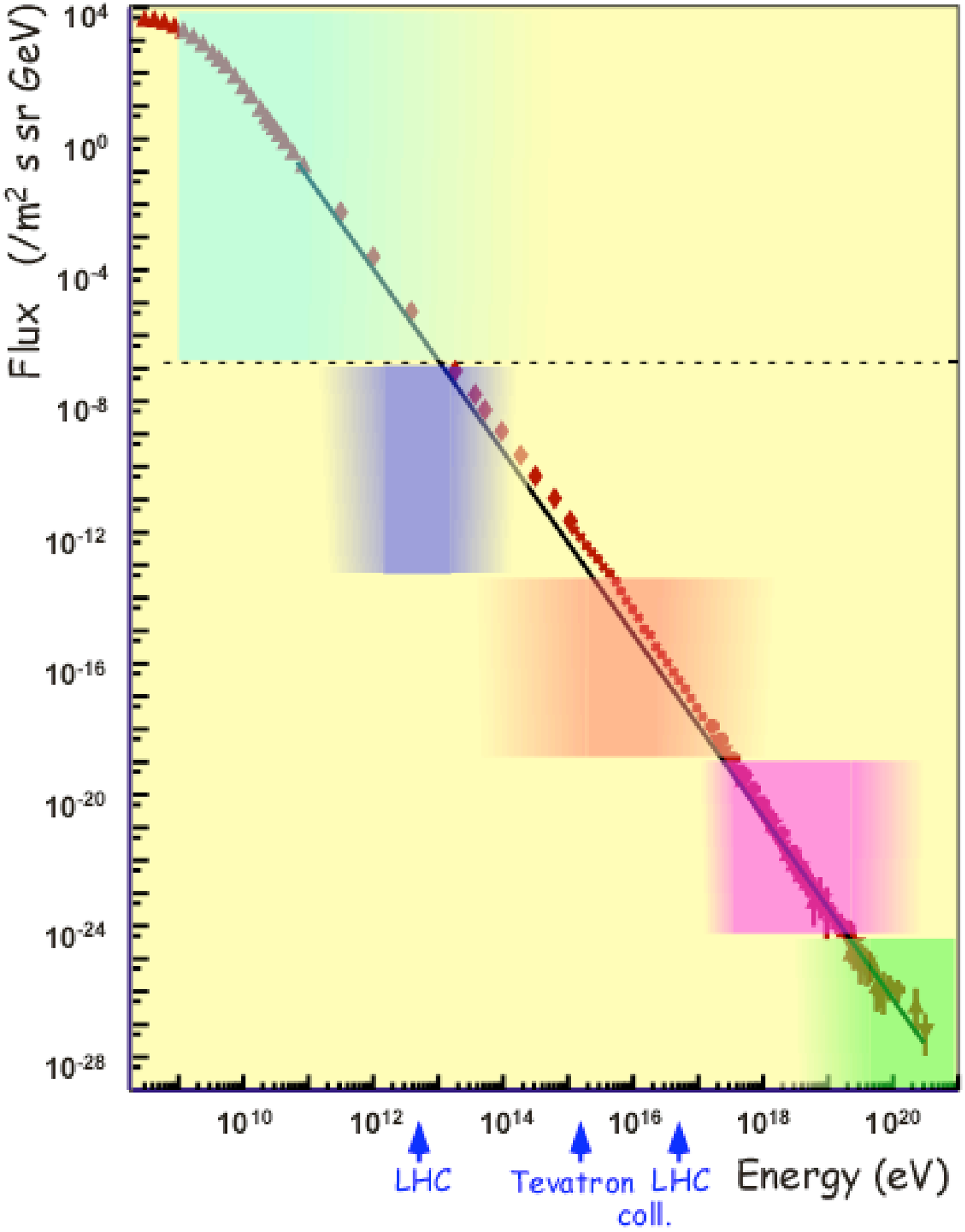
≈ 3 yrs

size of detector limits the fluxes that can be observed

p : probability to interact in detector :

for CRs and gammas: $p \approx 1$

for neutrinos: $p \ll 1$



Direct Measurements:

balloon & satellite experiments
particle identification,
elements, isotopes

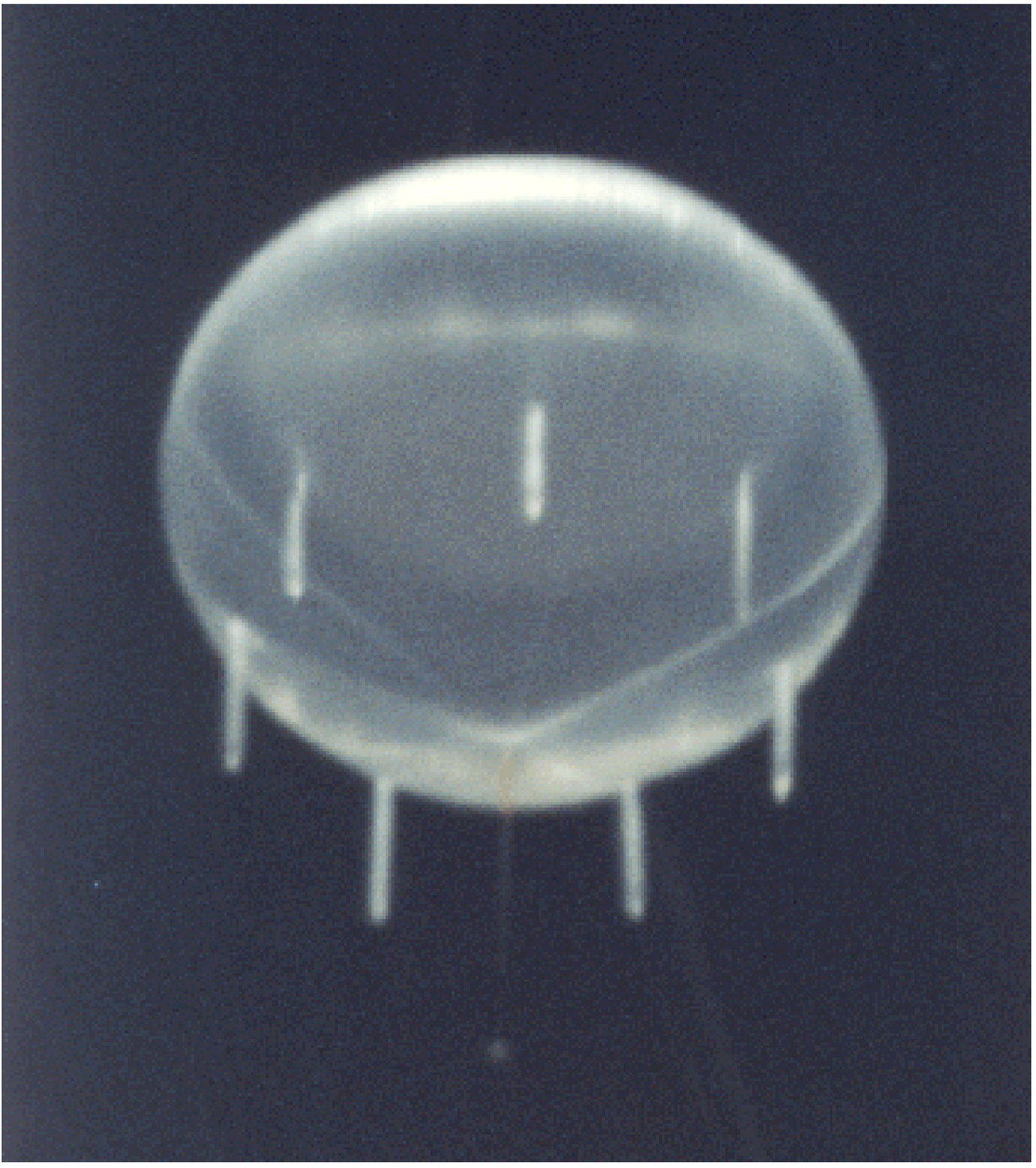
Air Shower Experiments:

MAGIC, HESS, VERITAS, ...
Tibet, Milagro

KASCADE, KASCADE-GRANDE

Haverah Park, Akeno,
Telescope Array

HIRES
AGASA
Auger
EUSO / OWL



Scientific Ballooning

balloon: 10^6 m^3 filled with Helium
payload: up to 3500 kg,
height: 30-40 km
flight time: few days, soon 100 days ?

CR Mass Composition

(in GeV range)

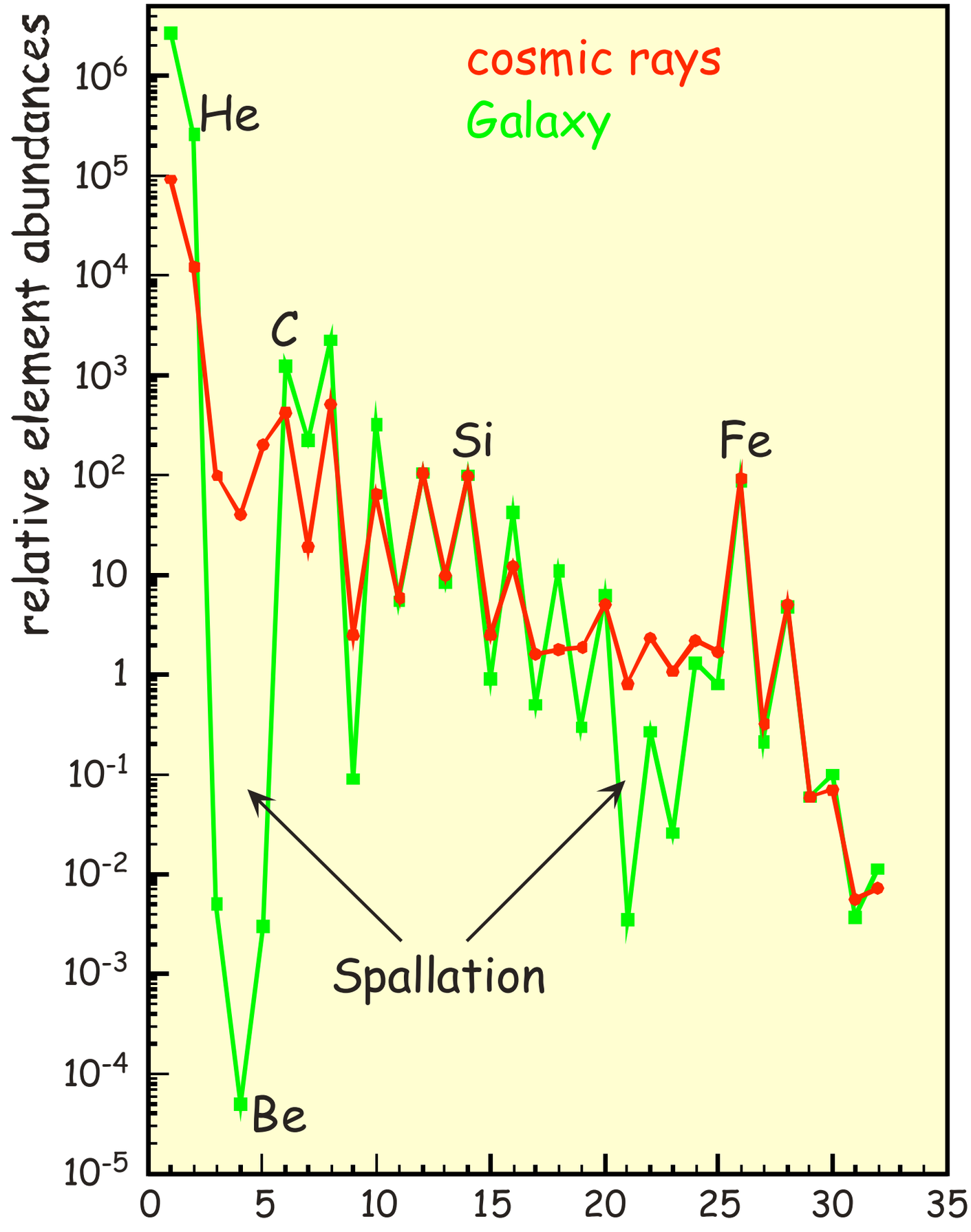
element and isotope composition
well known (for E < GeV)

89% p, 9% He, 2% other nuclei
<1% electrons

"CRs are star matter"

secondary/primary nuclei:
~ 10 g/cm^2

unstable/stable secondaries:
~ 10^7 years
(decreases with ~$E^{-0.6}$)



The currently favoured model:

Fermi Acceleration (1st order) in shock fronts

$$dN/dE \sim E^{-2.1} \cdot E^{-0.6} \approx E^{-2.7}$$

in sources

"residence" time in galaxy

measured at Earth

prime source candidates: SNR (up to $\approx 10^{14}$ eV)

frequent & powerful enough to account for observed CR density

low-energy CRs are galactic, diffusing in gal. magnetic field

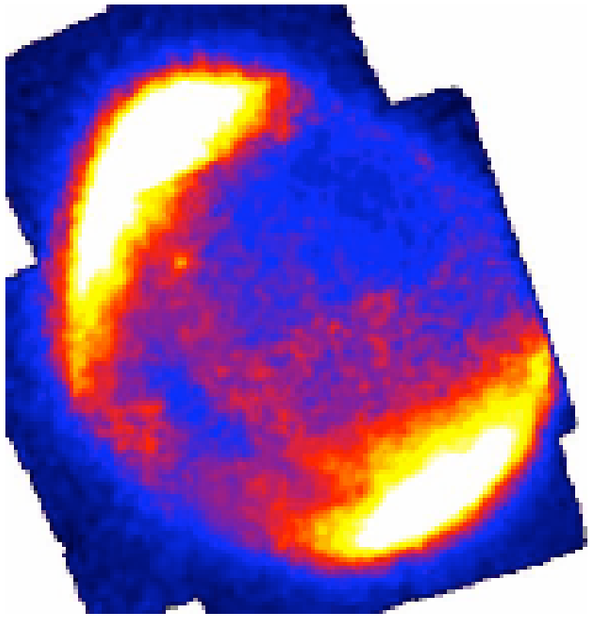
direct evidence ?

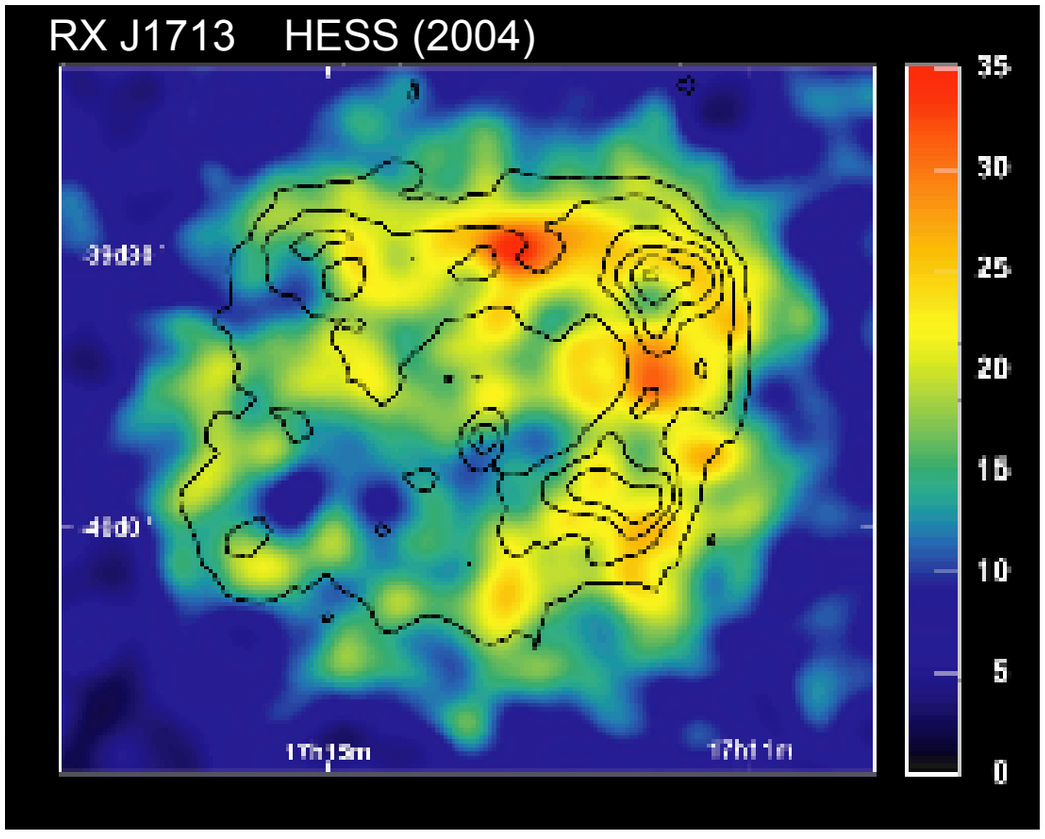
synchrotron & IC radiation from relativistic electrons

Not much evidence for CR acceleration yet.

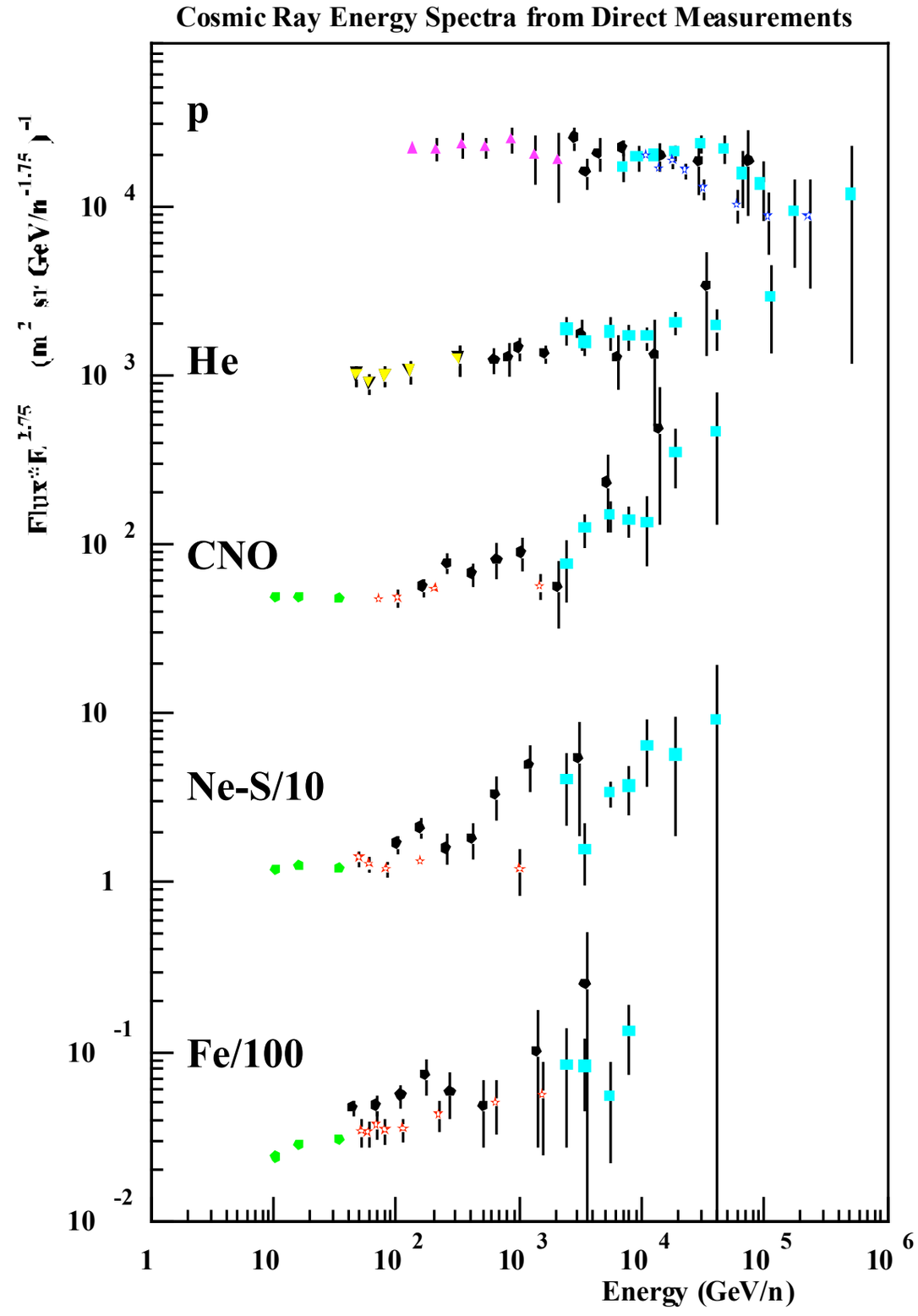
(hope for gamma-ray experiments)

SN1006 ASCA (1995)



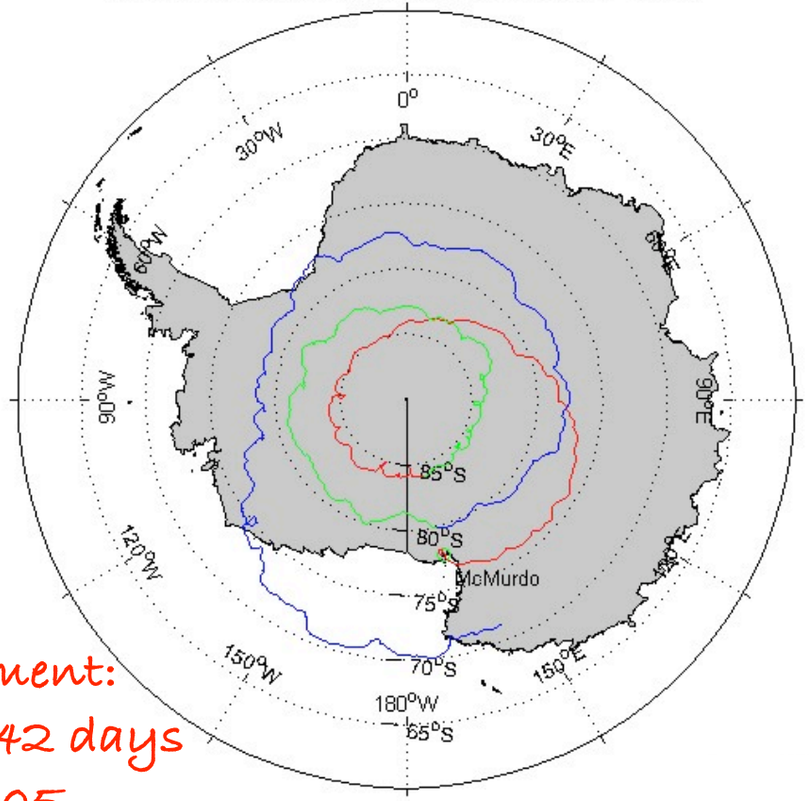


various balloon and satellite experiments ...

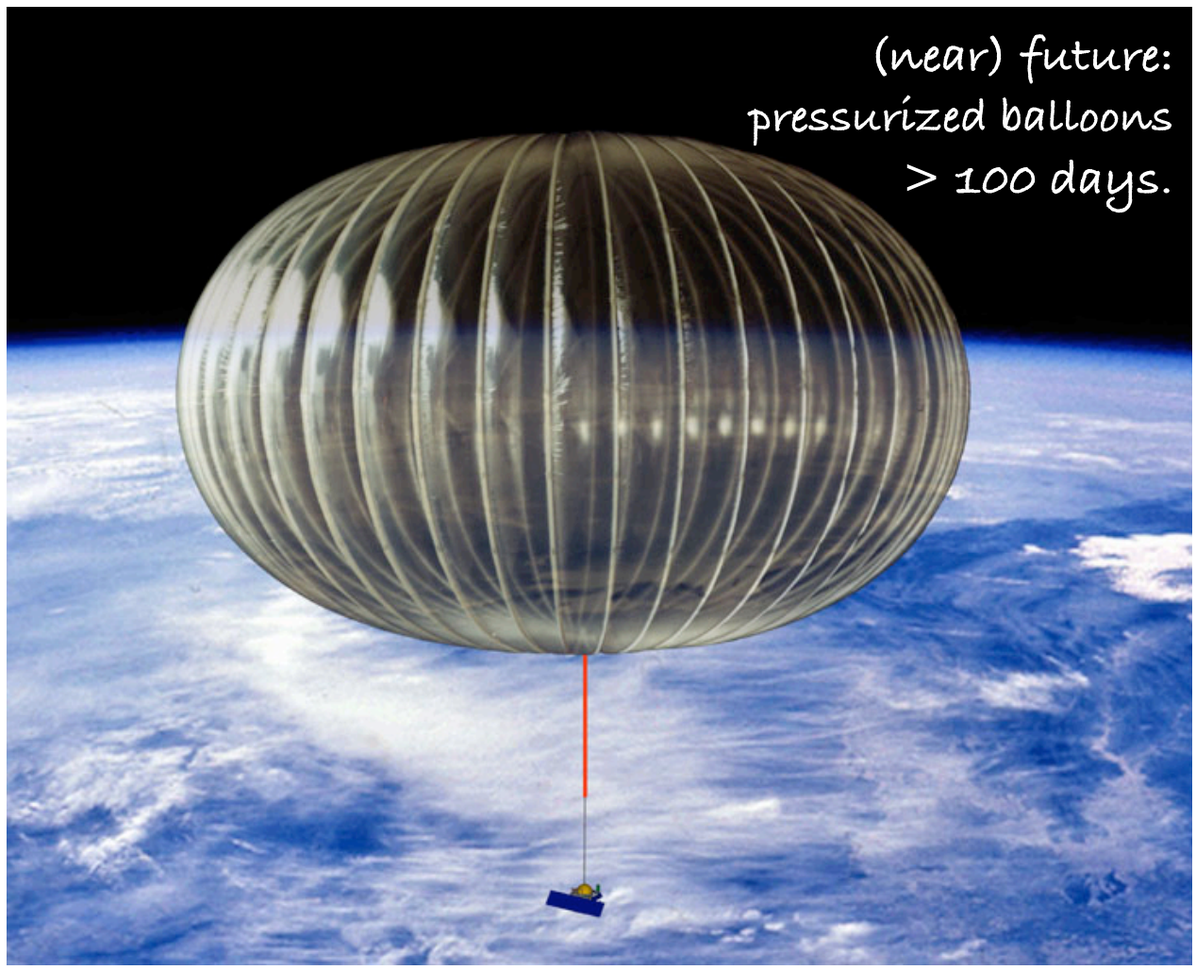


larger detectors?

longer times?



CREAM Experiment:
World record: 42 days
Jan 2005



Satellites, Space Station ?

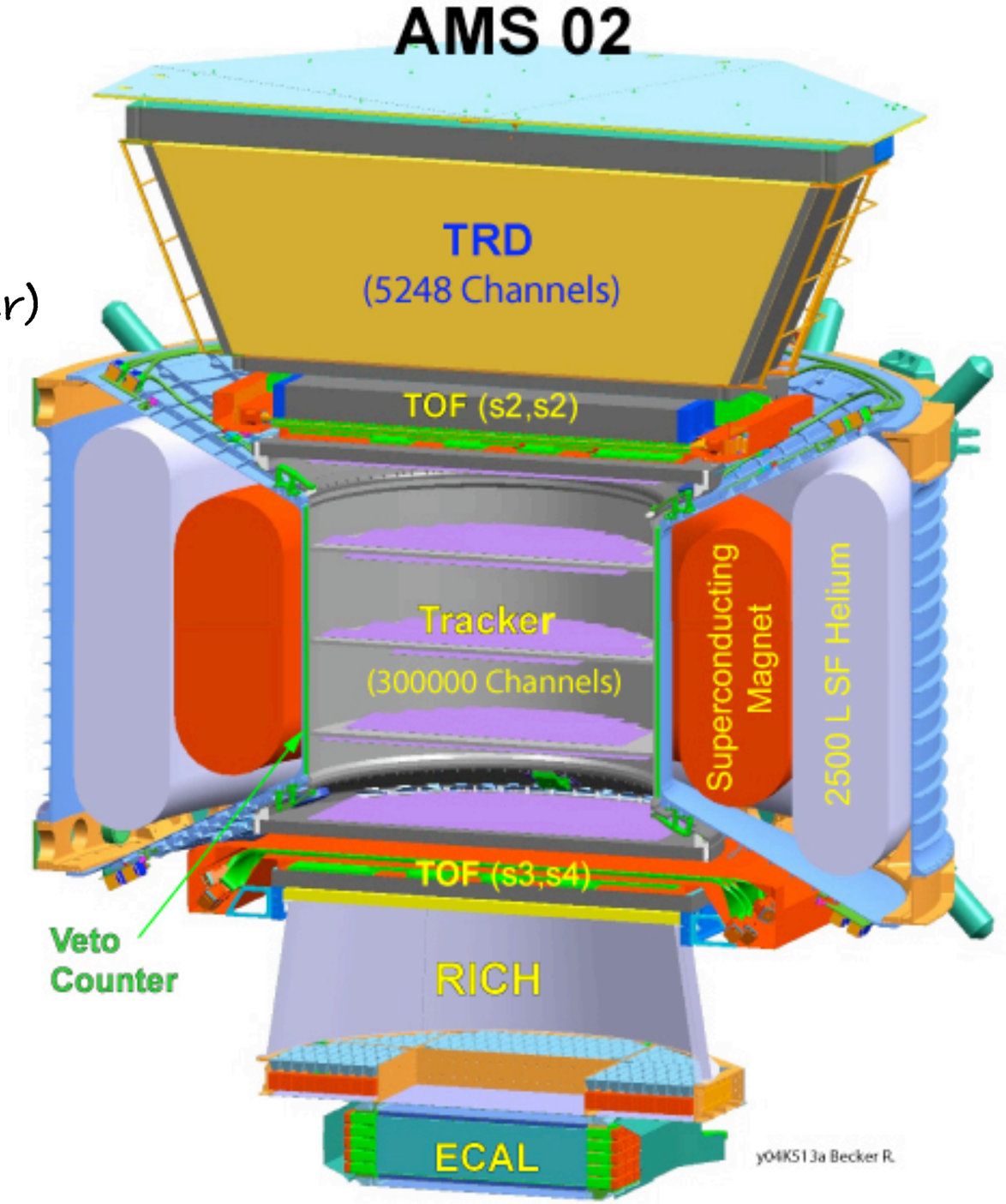
detector size ≈ m^2, as for balloon experiments

measurement times ≈ 1-5 years

but ≈ 100x more expensive ...

e.g. AMS (Antimatter Magnetic Spectrometer)
to be deployed on
International Space Station

when ???



Steeply falling spectrum: 10 x in energy / 500 in flux

Higher energies require very large detectors:

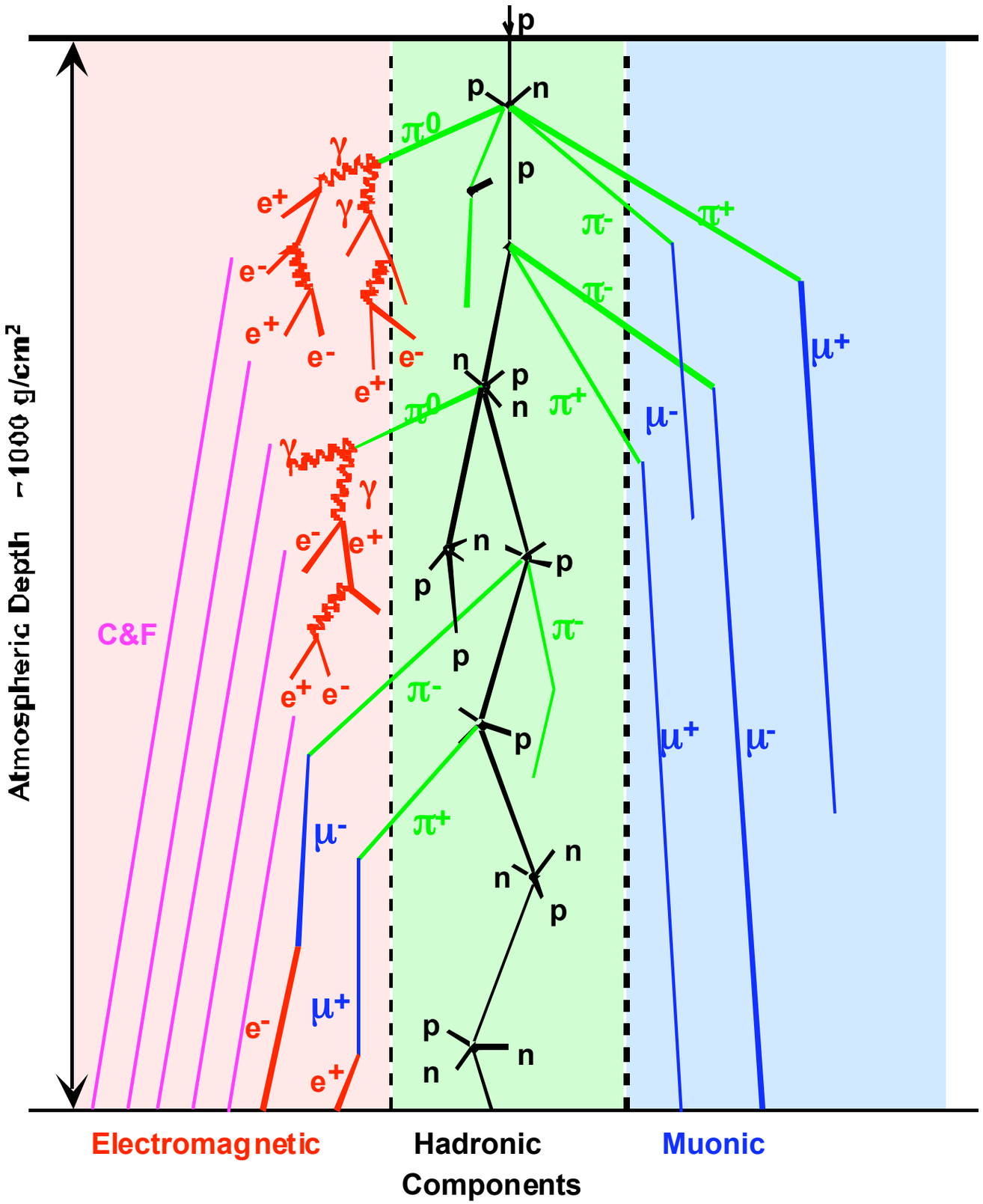
Instrument large natural absorbers
(e.g. atmosphere, water, ice)

Indirect Measurements: Air Showers

Deduce properties of primary CRs
from the shape and particle content of
the shower of secondaries produced.

this is tricky:
it requires knowledge on how a shower forms
depending on energy, angle, primary particle,
hadronic interaction, ...

Air Shower Experiments



p, n, π : near shower axis

μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV

μ : from $\pi^{\pm}$, K, ... decays ~ 1 GeV

$N_{e,\gamma} : N_{\mu}$ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
- interaction cross-sections,
- hadronic and el.mag. particle production,
- decays, transport, ...

at energies of MeV to 10^{20} eV

well above man-made accelerators.

Complex interplay with many correlations
- requires MC simulations

Detection Techniques 1

Particles at ground level

large detector arrays (scintillators, wire chambers, calorimeters…)

small sample of secondary particles are recorded

(numbers of particles, densities, angles, arrival times, …)

e.g.	area	coverage
Kascade	0.04 km^2	1.5 x 10^{-2}
Haverah Park	12 km^2	
Yakutsk	25 km^2	
AGASA	100 km^2	2.5 x 10^{-6}
Auger SD	3000 km^2	5.3 x 10^{-6}

100% duty cycle, relatively easy to operate

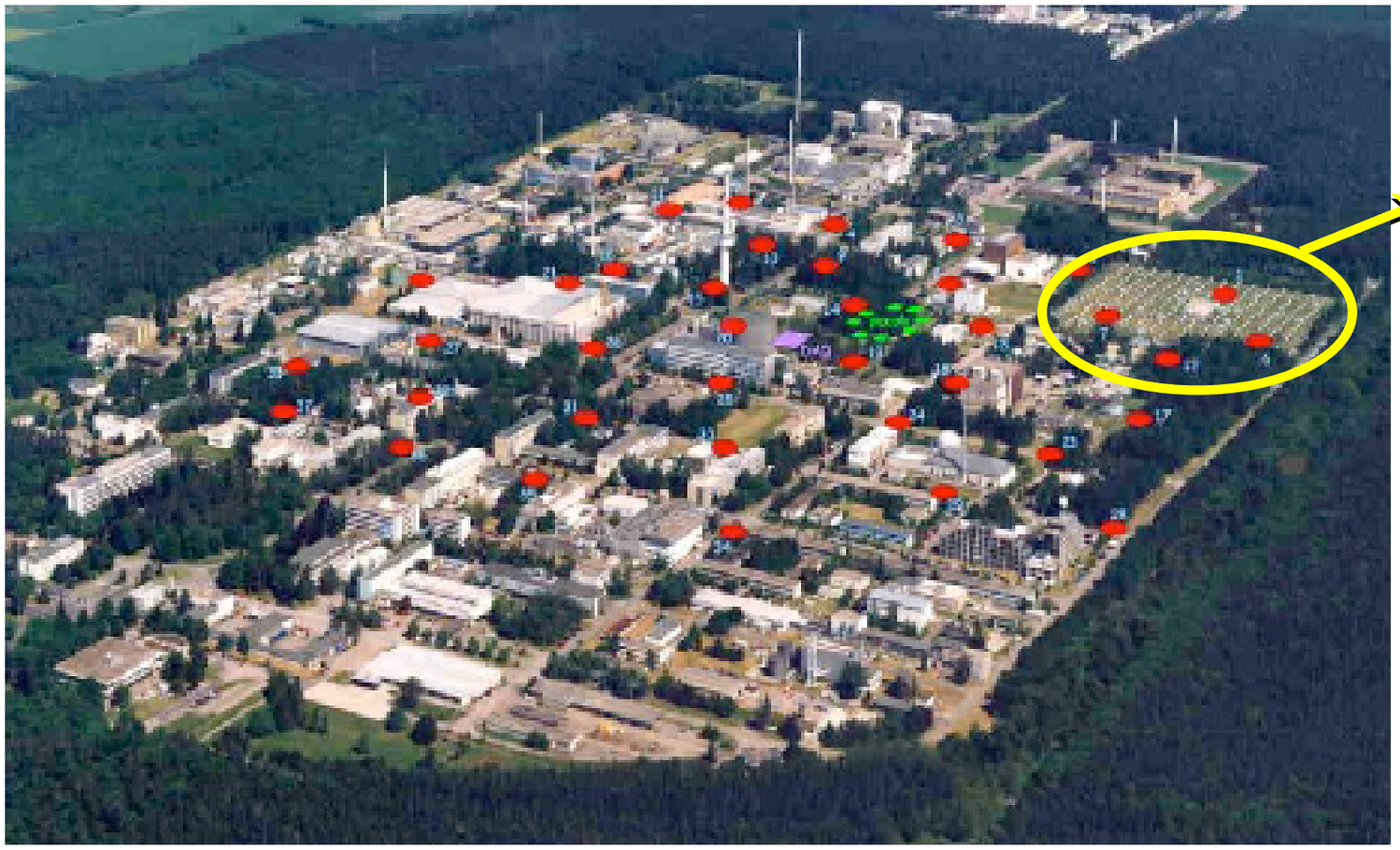
aperture = area of array (independent of energy)

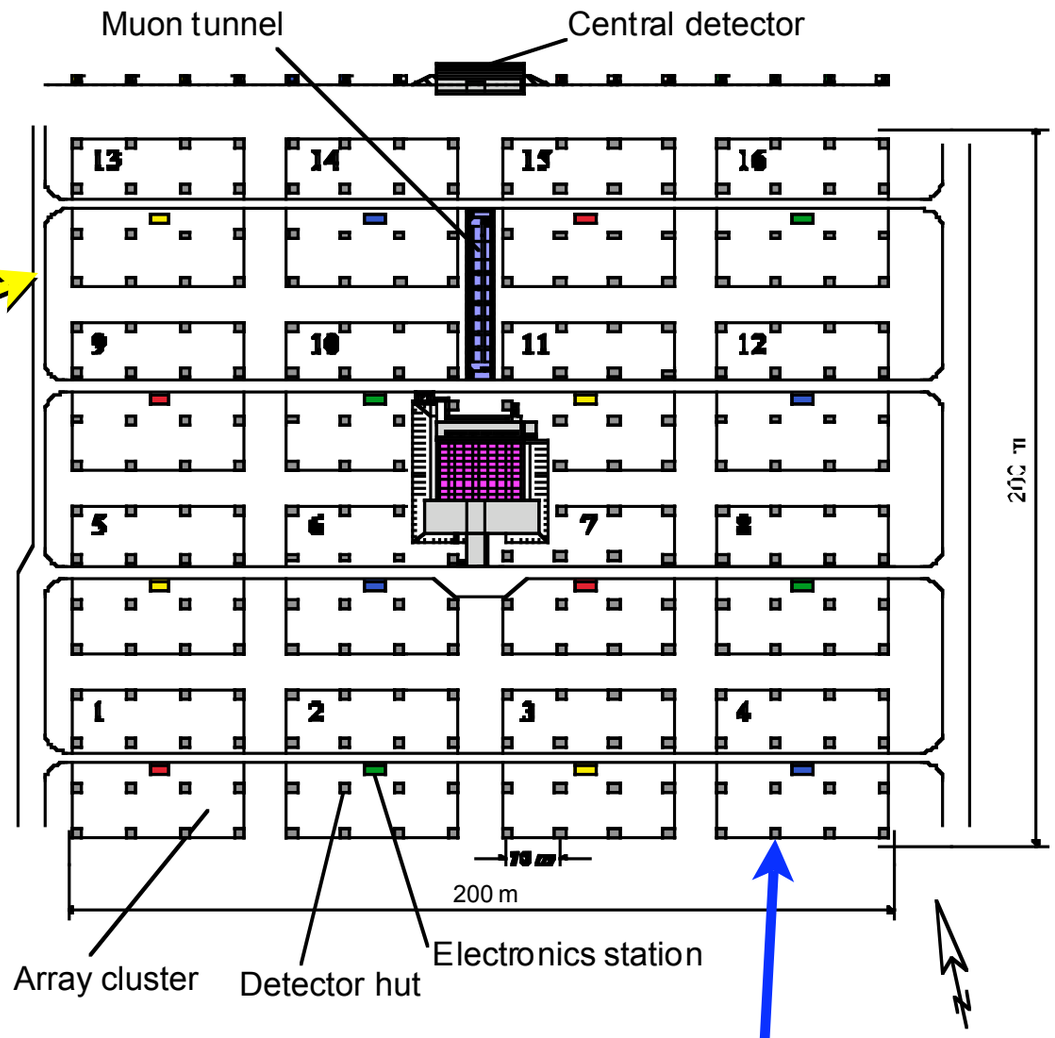
energy resolution $\sigma(E)/E \approx 30\%$

but: primary energy / mass composition is model dependent

KASCADE & KASCADE GRANDE

$\approx 10^{14} - 10^{16}$ eV $\approx 10^{15} - 10^{17}$ eV





Total area of array determines
- the maximum energy (statistics)

Detector spacing determines
- low-energy threshold
- quality of the sampling

Limiting factor: the cost

Detection Techniques 2

Fluorescence of N_2 molecules in atmosphere

calorimetric energy measurement as fct. of atmospheric depth

$\sigma(E)/E \approx 20\ \%$

works only for $E > 10^{17}$ eV, only in dark nights (10%)

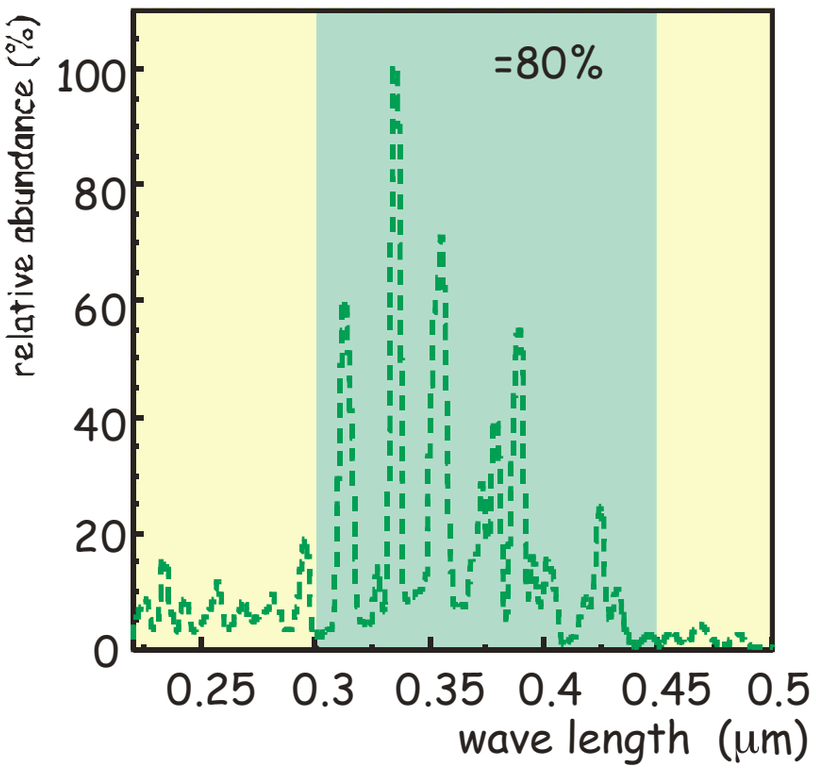
requires good knowledge of atmospheric conditions

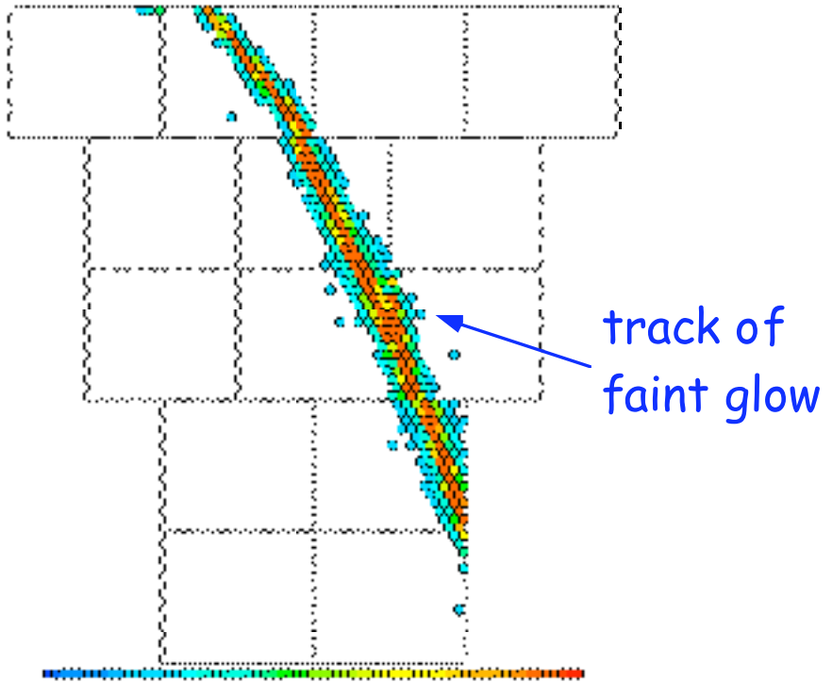
aperture grows with energy, varies with atmosphere

e.g. Fly's Eye,

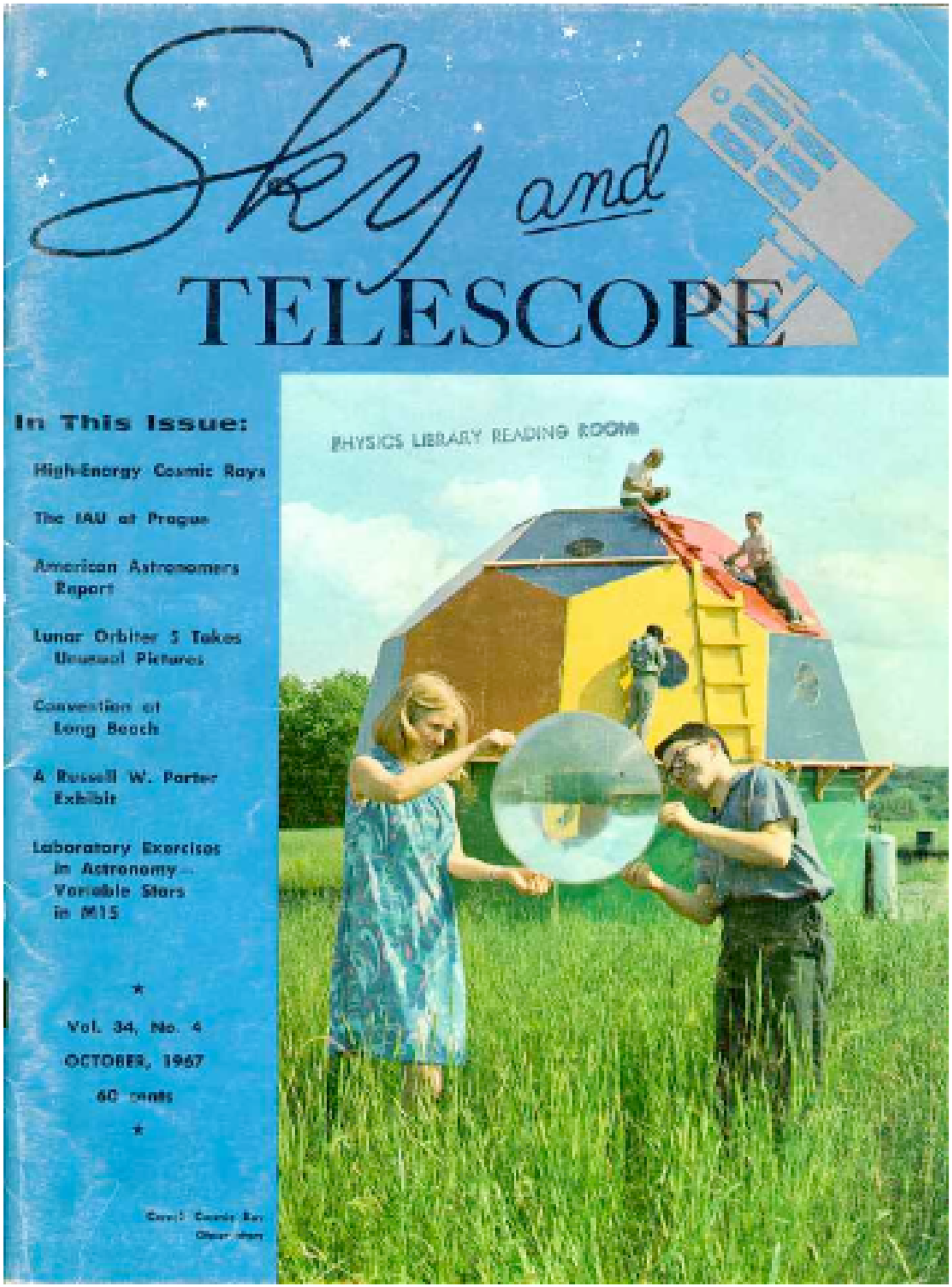
High Resolution Fly's Eye (Utah)

Auger FD





c.f. 100 W light bulb
moving with c
at 30 km distance
through atmosphere



The First
Fluorescence Detector:

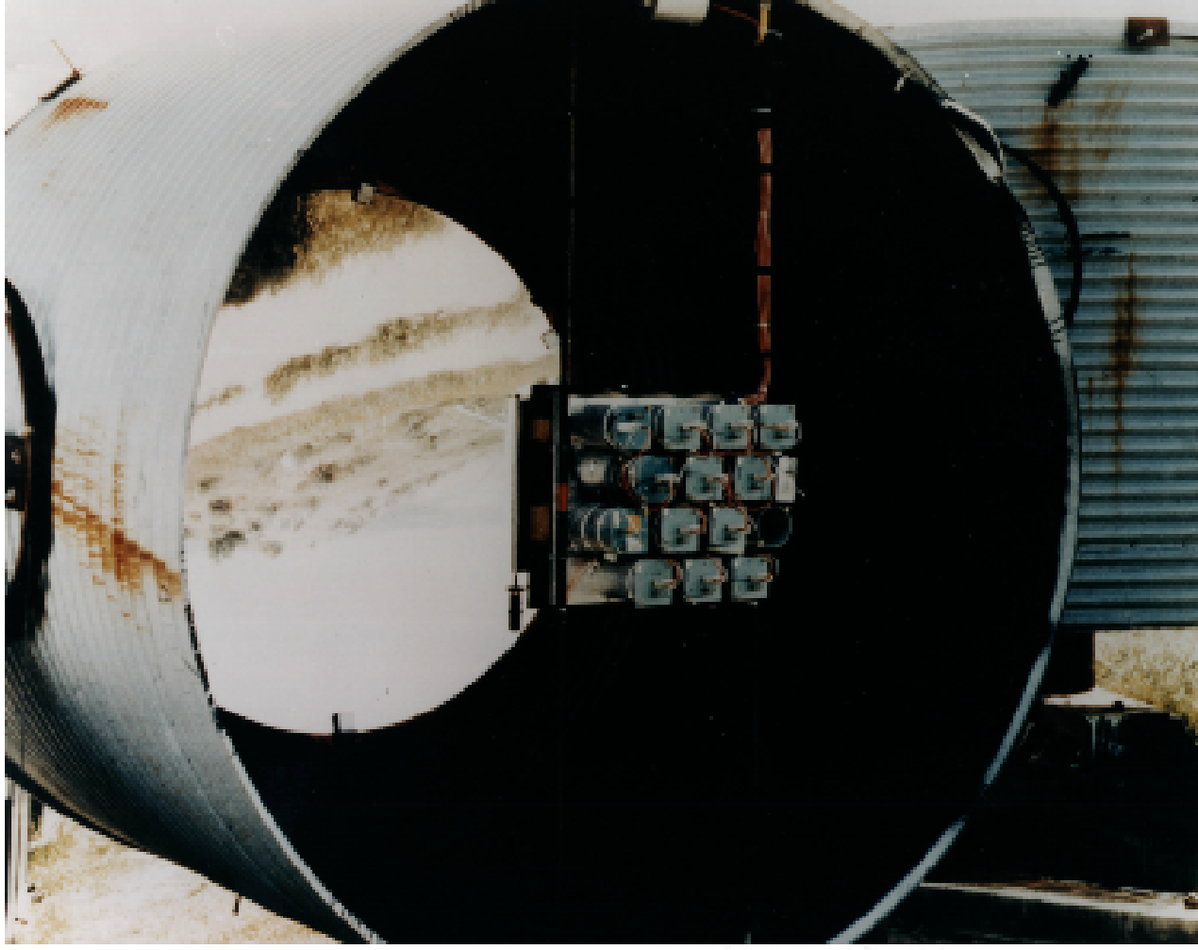
Cornell University
K. Greisen, 1967

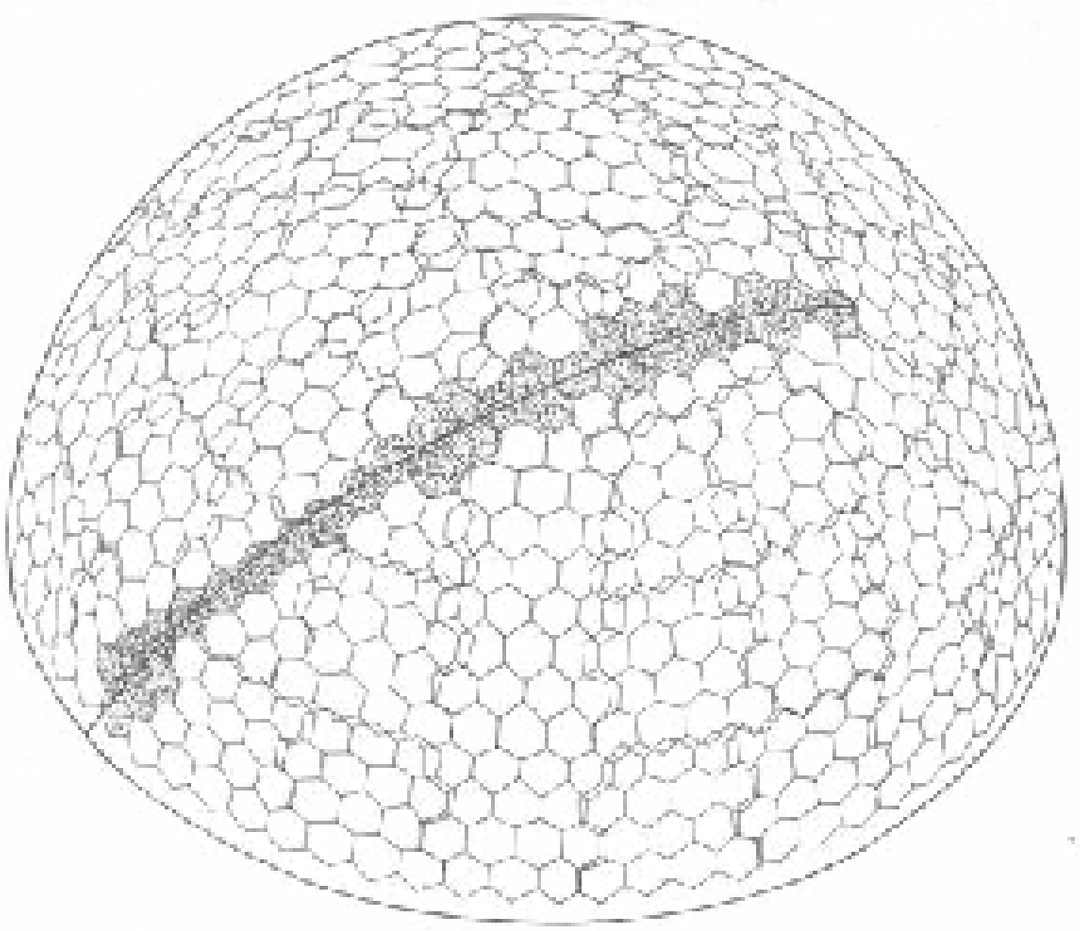
10 x 50 PMTs
6°x6° pixels
0.1 m^2 Fresnel lenses

(not successful)

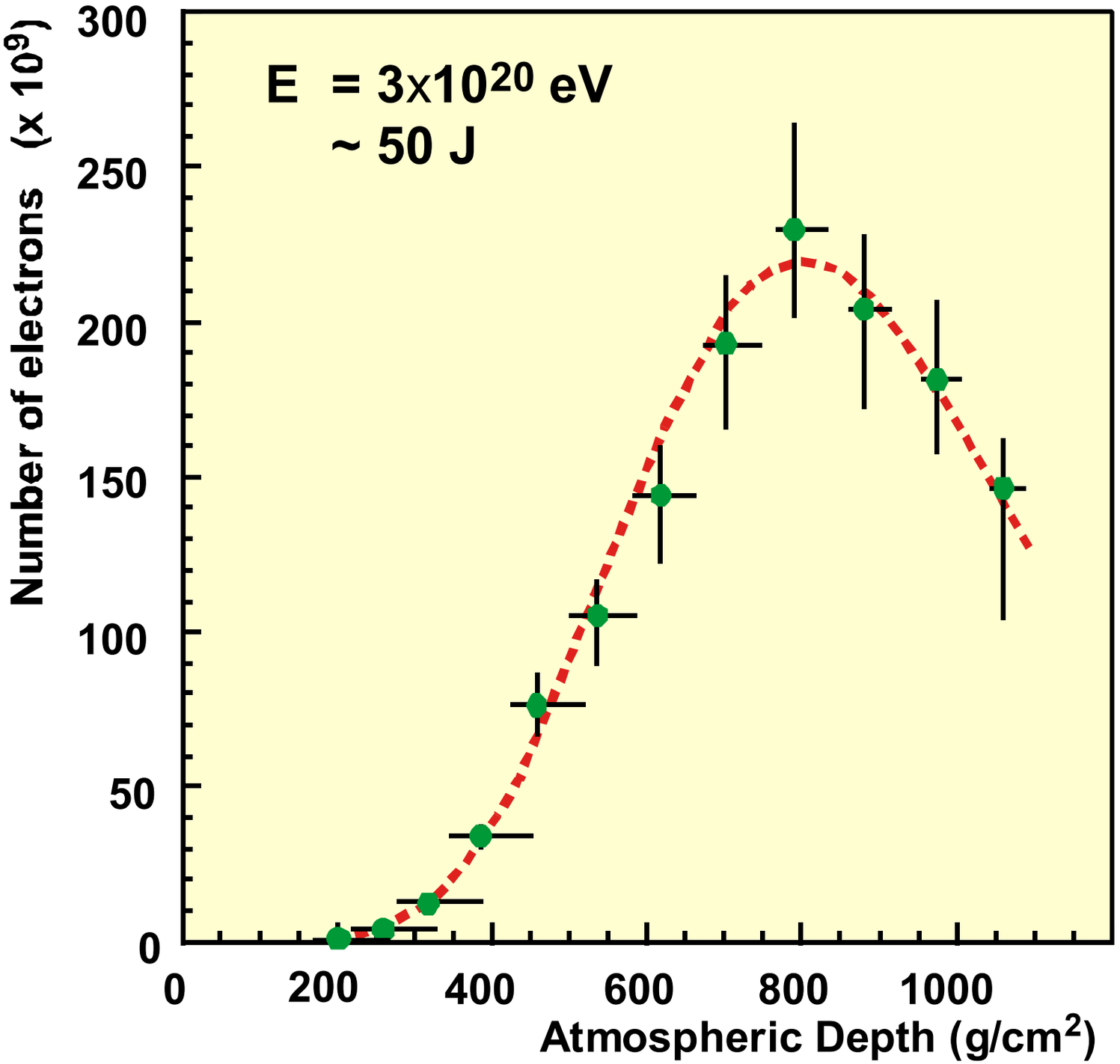
Fly's Eye (Utah)

2 stations, 3.4 km apart
101 mirrors, 1.5 m Ø
12-14 pixels each (PMTs)
5° field of view per pixel
operational: 1980-1993





The Big Fly's Eye Event



50 J !!!!

> 200 billion secondaries

Catalogue of UHECRs i.e. $E > 10^{20}$ eV

(2004: pre-Auger)

Volcano Ranch/USA	Scintillator Array 1962	
	1 event	$E > 100$ EeV
Haverah Park/UK	array of water-Cherenkov detectors 1970 - 1980	
	4 events	$E > 100$ EeV
Yakutsk/Sibiria	Scintillators & atmospheric Cherenkov 1989 -	
	1 event	$E > 120$ EeV
Fly's Eye/Utah	atmospheric fluorescence 1991	
	1 event	$E > 320$ EeV
Akeno/Japan	Scintillators & Muon Detectors 1990 - 2004	
	≈10 events	$E_{max} > 330$ EeV

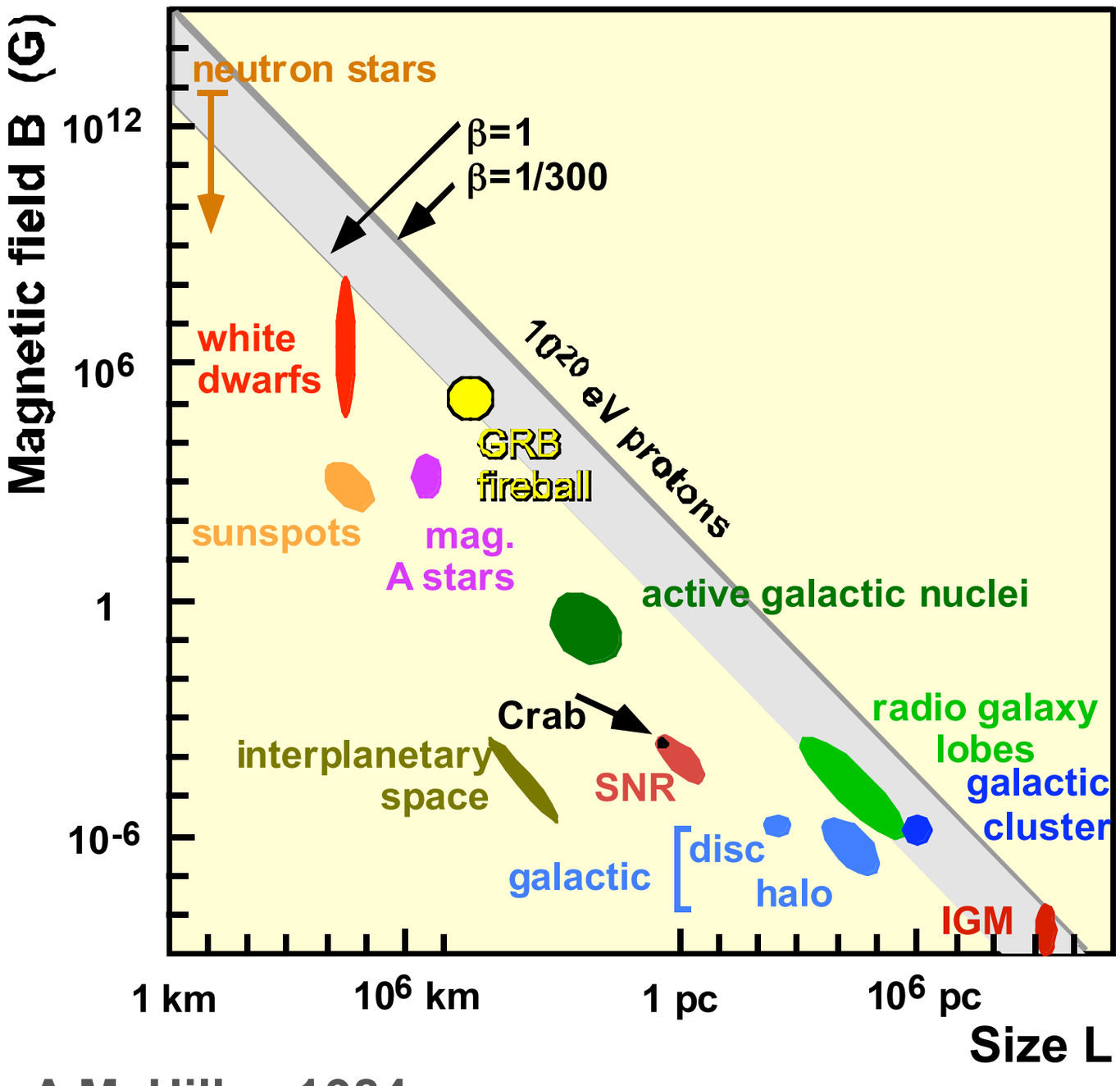
Energy resolution : ≈ 30%

Flux at $E > 100$ EeV : ≈ 1 per km² and century

These events are no artefacts !!!!

There are "accelerators" out there that make $> 10^{20}$ eV particles.

Where ??? How ???



A.M. Hillas 1984

$B_{\mu G} \times L_{kpc} > 2\, E_{EeV} / Z$

$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

to fit gyro radius within L and
to allow particle to wander around
during acceleration time

But also:
gain should be more rapid than
losses due to magnetic field
(synchrotron radiation)
and photo-reactions.

No obvious candidates ....

Particle Type ?

- no neutrinos,

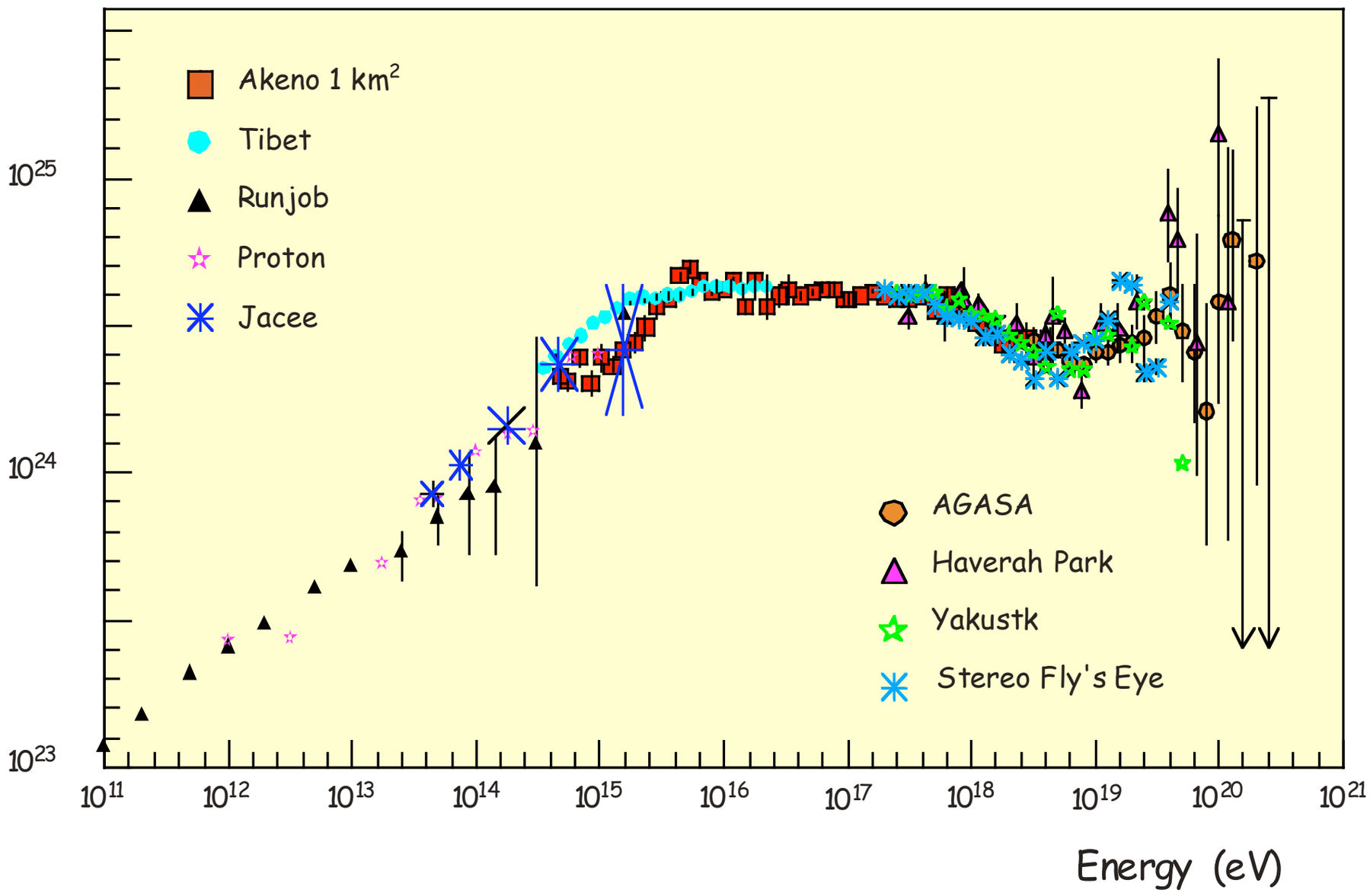
  since start points of showers are near top of atmosphere

- no photons,

  since shower form is different from expectation for photons
  (electromagnetic interaction is well known; QED)

Showers look like showers from p and nuclei
at lower energies, ... just much larger.

Differential Energy Spectrum

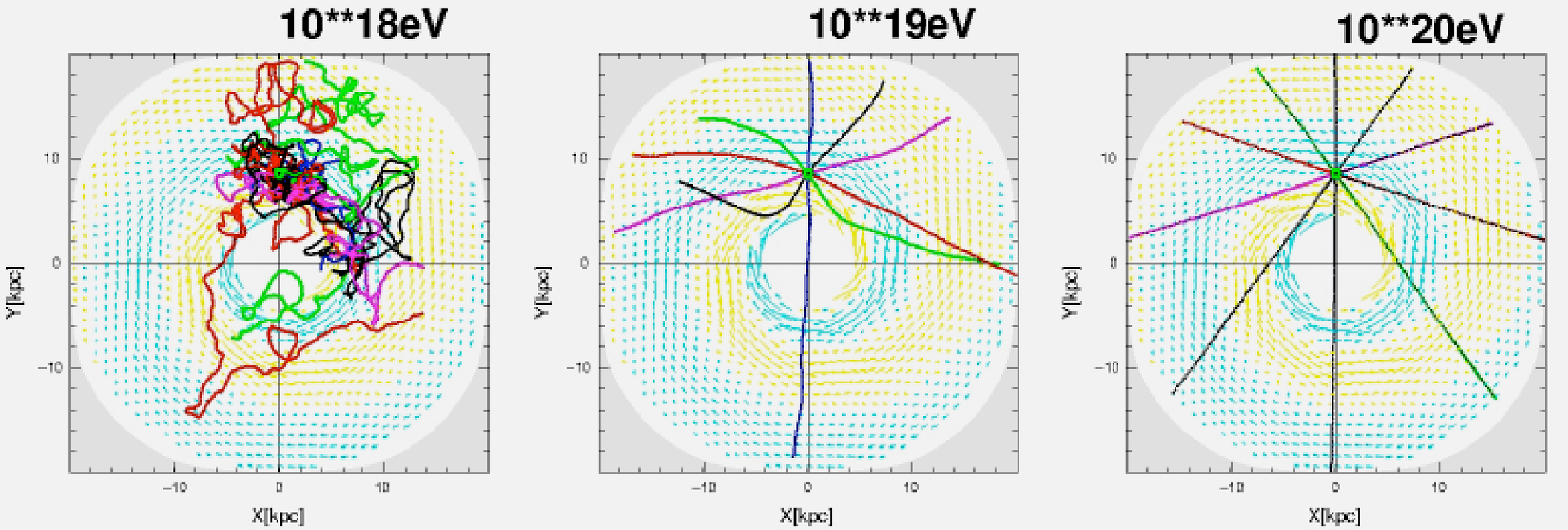


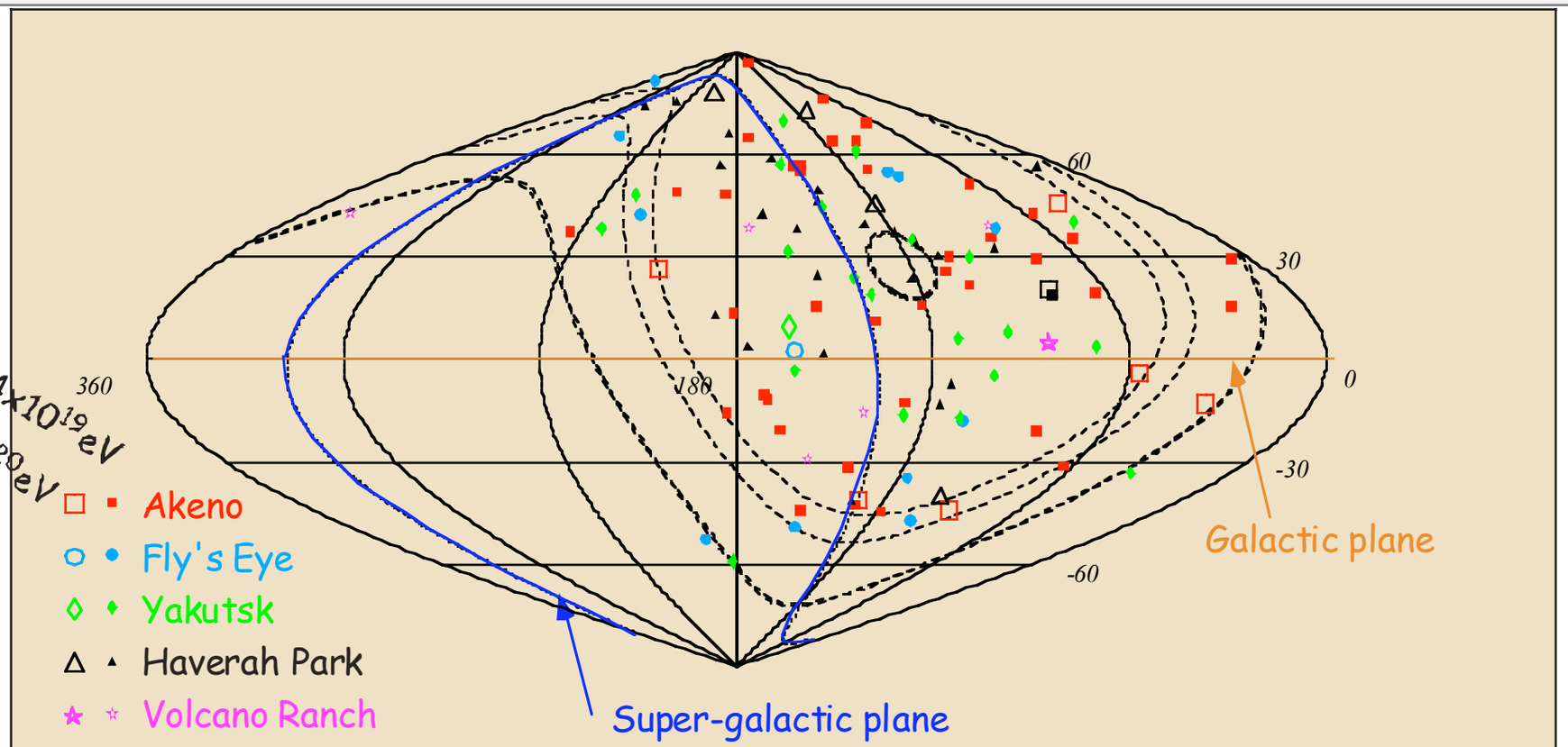
adjusted by
± 15% in energy

(within respective
energy resolution)

Agreement: $< \pm 45\%$ in flux at 10^{19} eV
$< \pm 15\%$ in energy

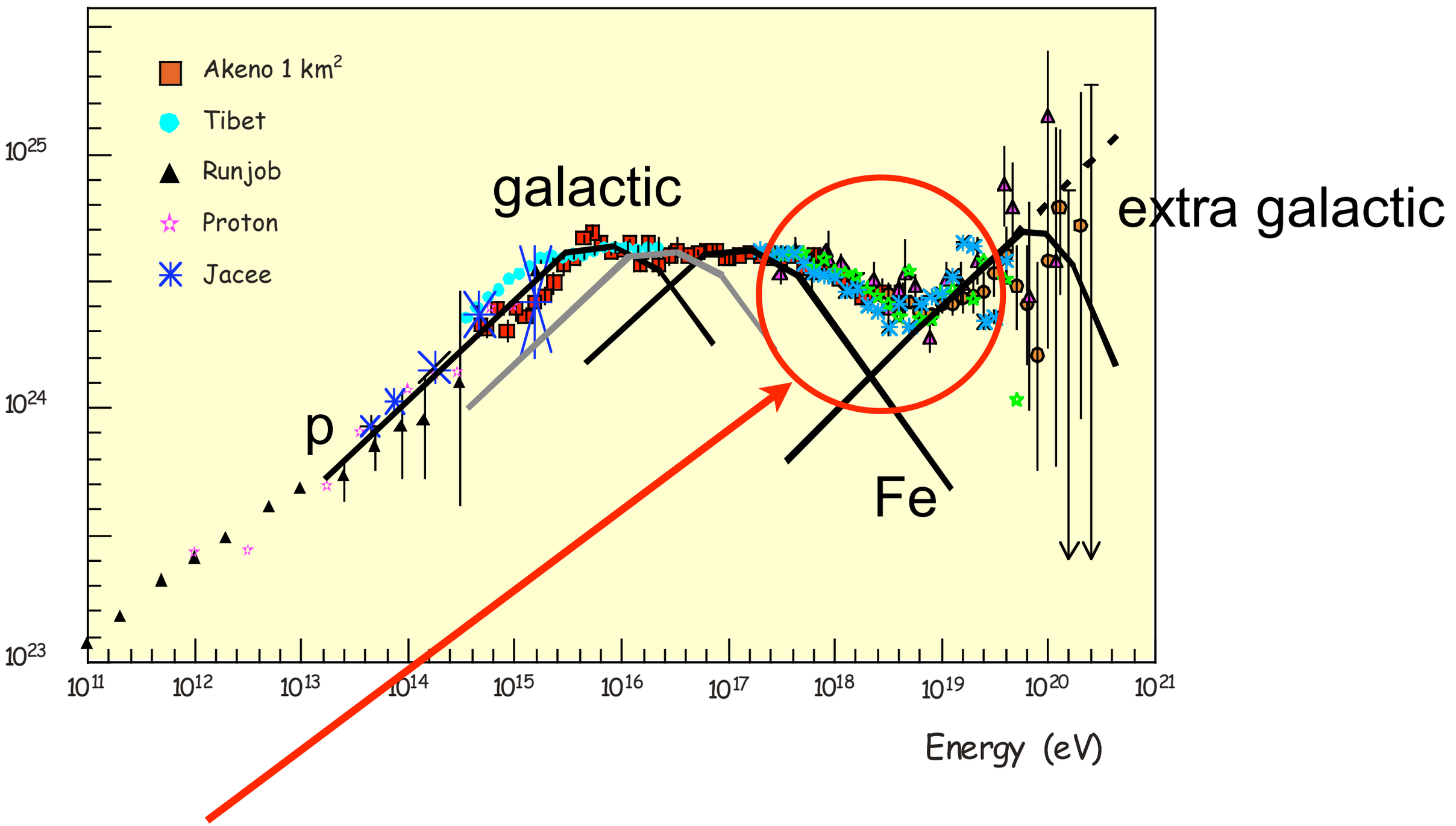
Highest-energy particles must be extragalactic





deflection < 1°

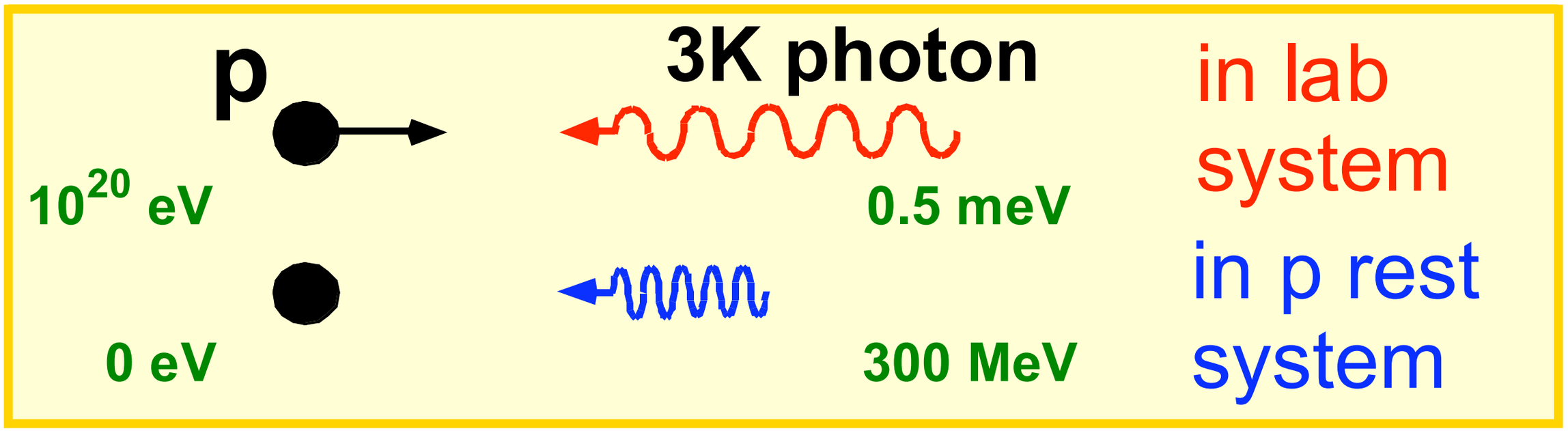
no apparent preference for galactic plane



Details not yet clear: dip due to e^+e^- production?
need comp. measurement across transition region

GZK Cut-Off

Greisen Zatsepin Kuzmin



$p + \gamma_{3K} \longrightarrow \Delta^+ \longrightarrow p + \pi^0$ → γ

$\longrightarrow n + \pi^+$ → ν

$^{56}Fe + \gamma_{3K} \longrightarrow {}^{55}Fe + n$

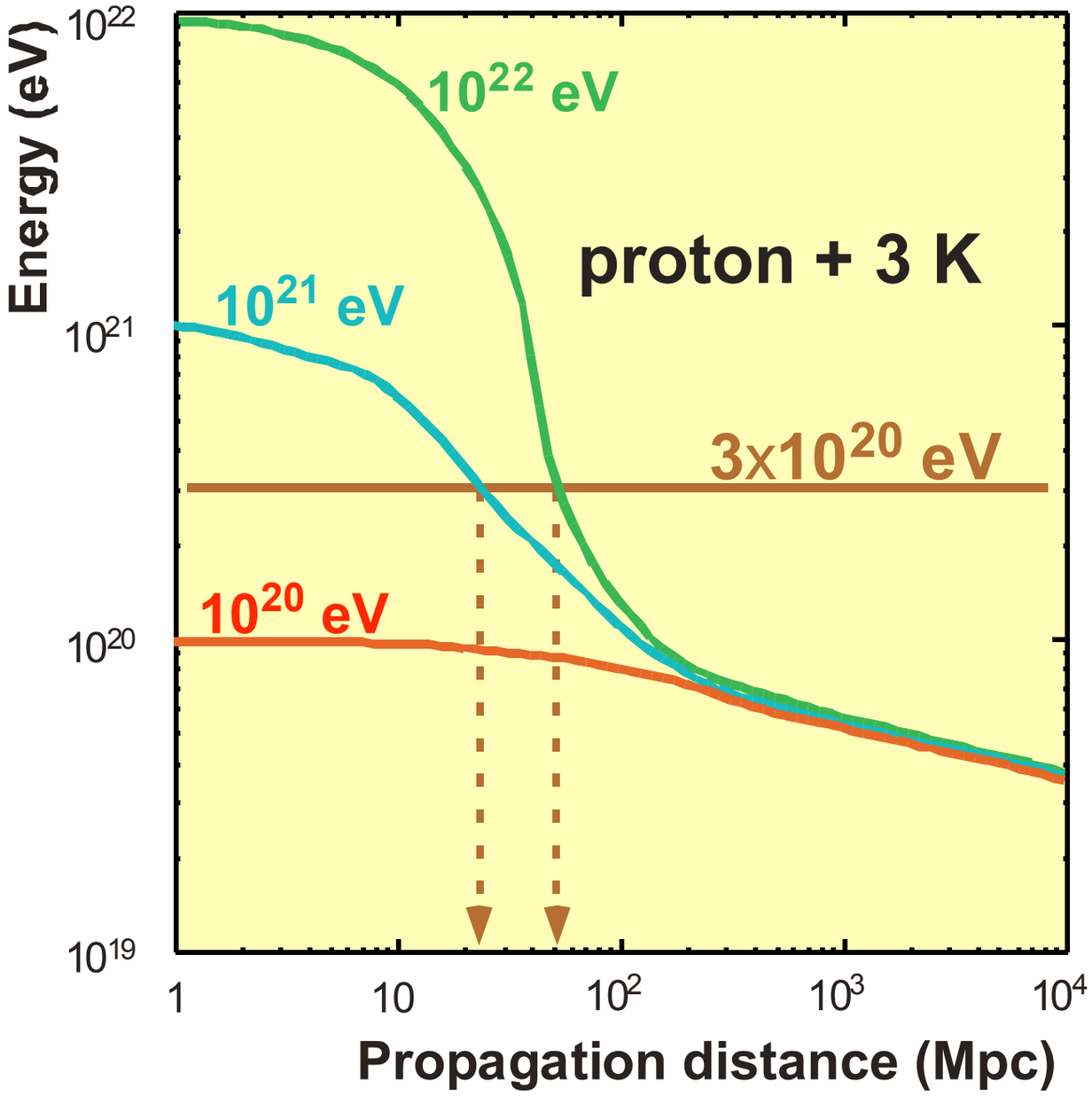
Photo-pion production

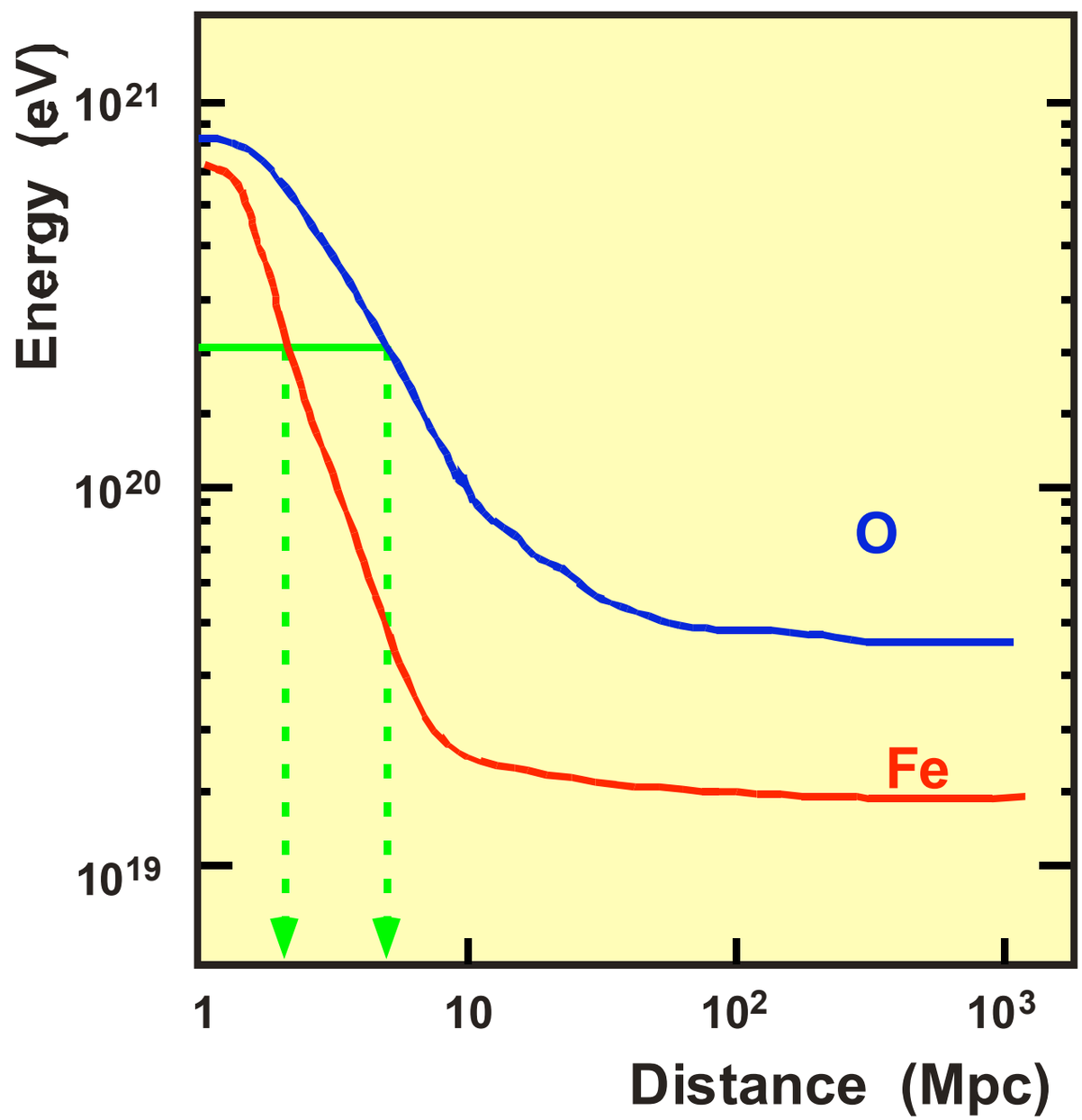
Photo dissociation

Universe is opaque for $E > 5 \times 10^{19}$ eV.

Test of Lorentz Invariance for $\gamma \approx 10^{11}$!

Energy Loss of Protons .... and Nuclei

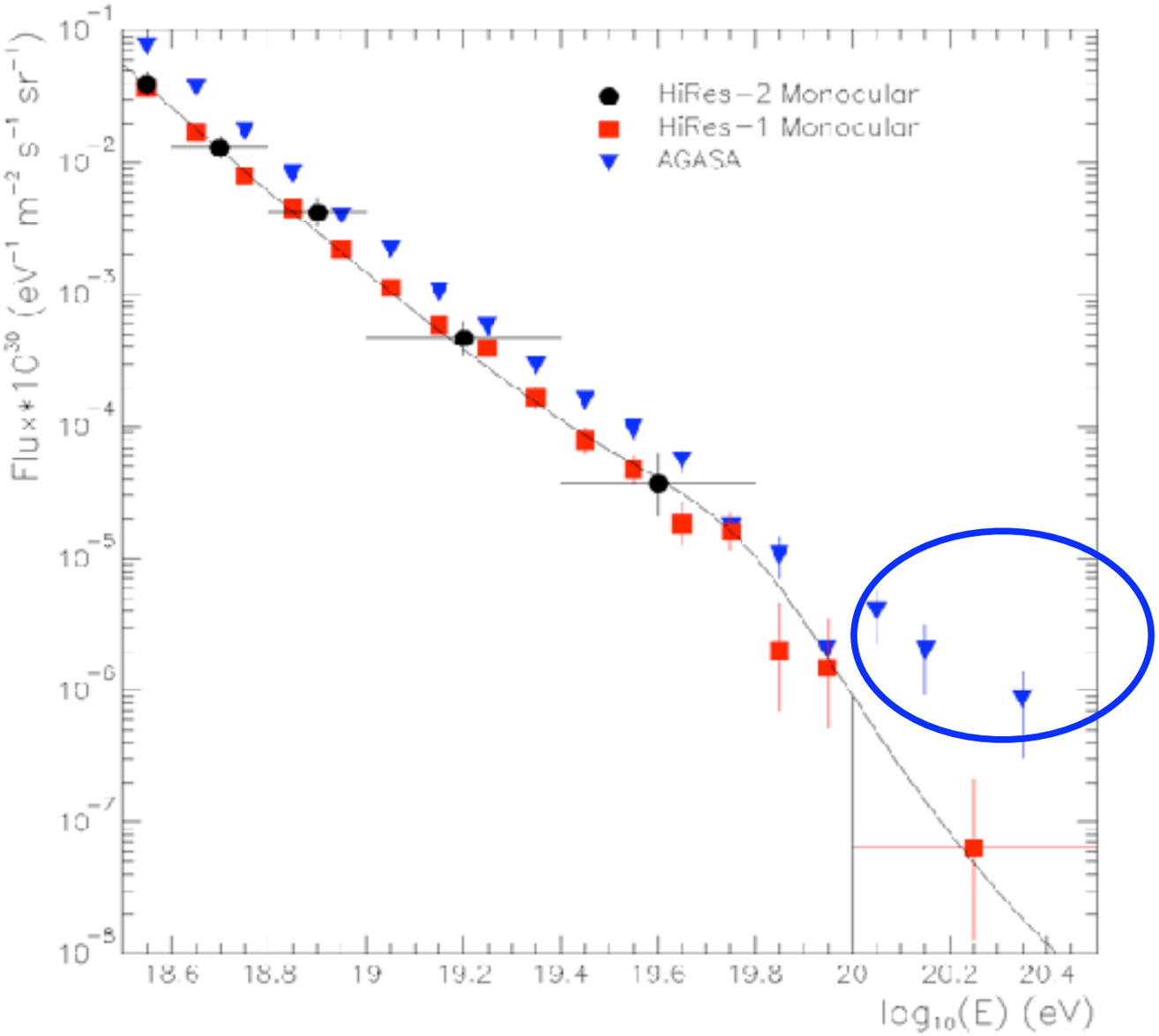




i.e. sources must be close (d < 50-100 Mpc, z < 0.01)

but: no suitable energetic objects known

GZK cut-off or not ?



AGASA vs HiRes

different techniques,
small statistics,
results inconclusive.

many speculations
why spectrum
continues

Theoretician's feast:

Proposed Solutions (1/week)

Hot Spots in AGN-Jets	Biermann
AGNs	Biermann
Pulsars	Bell
Galaxy collisions, wind shocks	Cesarsky, Morfill, Jokipii
Shocks at formation of gal. clusters	Biermann et al
GRBs	Milgram, Usov, Waxman, Vietri

Astrophysical solutions (bottom-up)

ν annihilation with relic-ν	Weiler et al.
Superheavy relic particles	Ellis, Sarkar et al.
Topologic defects - Monopoles	Schramm, Sigl
- Necklaces	Berezinsky et al.
Dirac Monopoles	Weiter & Kiphart et al

Heavy particle decays (top-down)

New SUSY particles S_0 (uds+gluino: 2 GeV)	Farrar et al.
UHECRON (m ~ 10 GeV)	Farrar & Kolb
Deviation from Lorentz invariance	Coleman & Glashow

New Physics Exotica

needed:

much more statistics,
good energy resolution,
control of systematics,
mass composition

Auger

>300 PhD physicists / 70 institutions from

Argentina, Australia, Brazil, Bolivia, Czech Republic, France,
Germany, Italy, Mexico, Netherlands, Poland, Portugal,
Slovenia, Spain, United Kingdom, USA, Vietnam

first ideas: Workshop in Paris 1992
design study: 1994-1995

Collaboration forming, fund raising, site selection

1998 begin of funding
2001 engineering array operational
2002 begin of mass production and construction
2007 southern site complete

Auger: unprecedented statistics and precision

~30 evts/yr with $E > 10^{20}$ eV (based on AGASA flux)

Hybrid Detector:

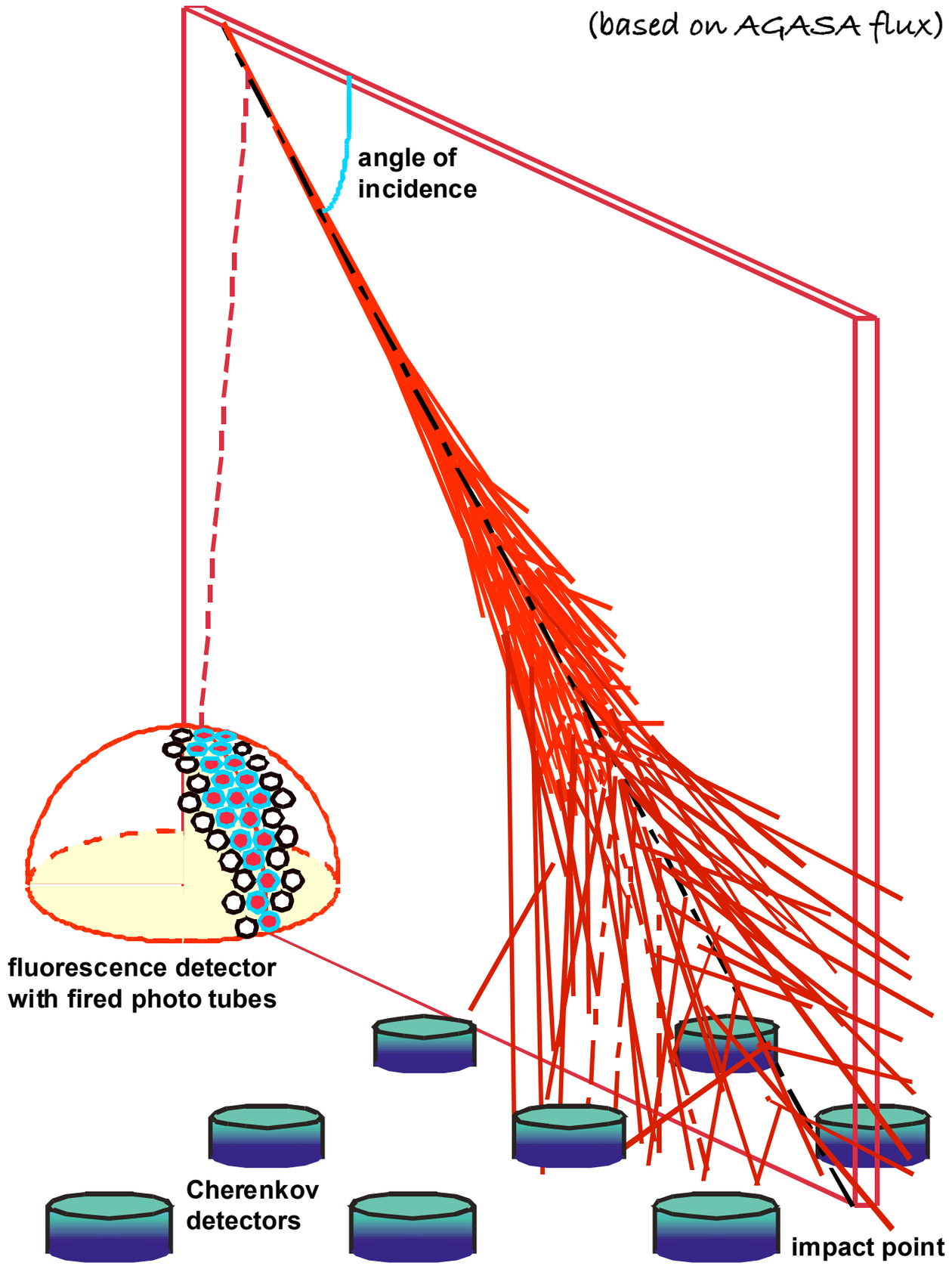
Array of 1600 water Cherenkov detectors
- covering 3000 km²
- duty cycle: 100%

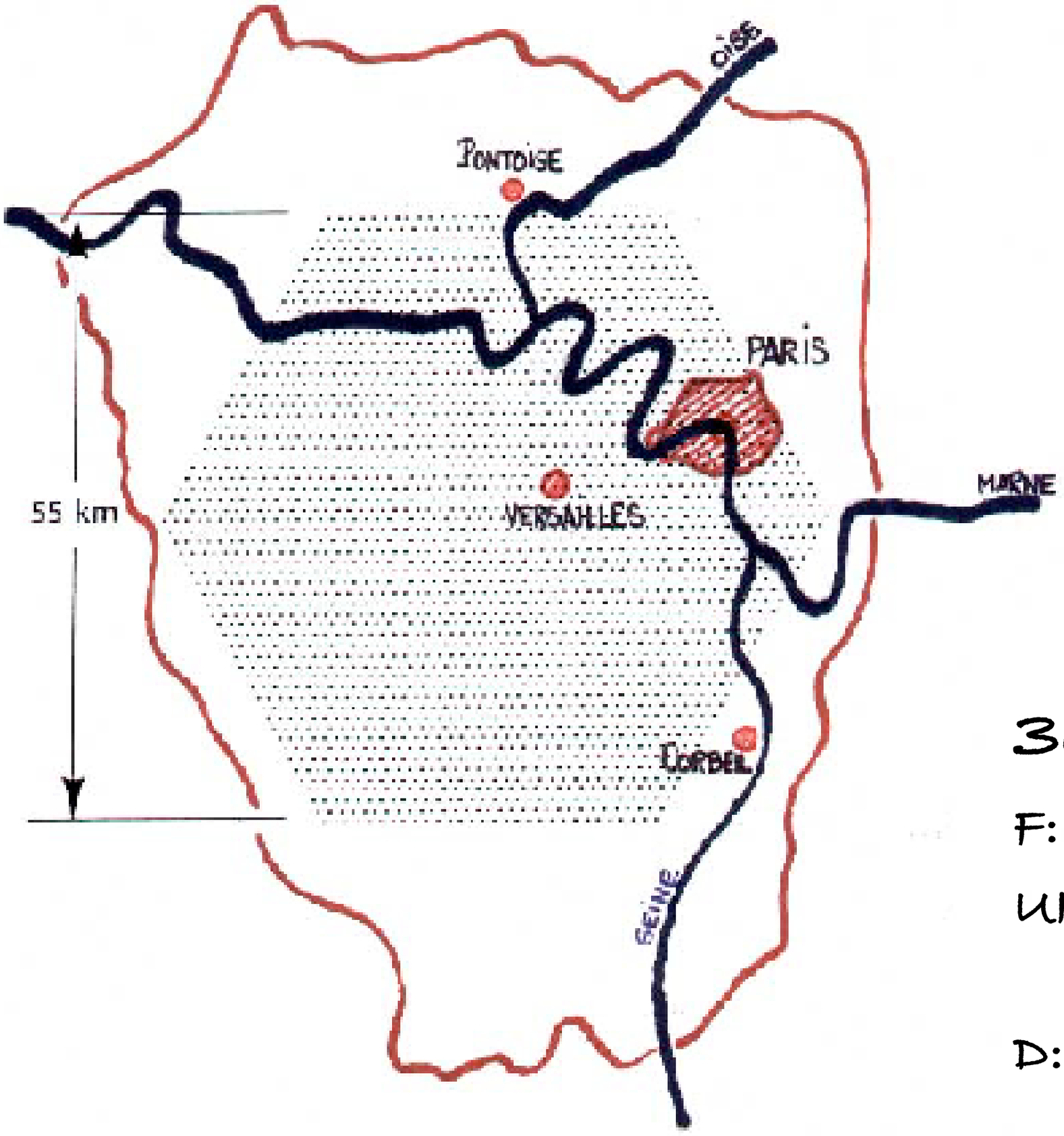
Fluorescence telescopes
- 24 FDs (30°x30° each)
- duty cycle: 10%

Better geometric reconstruction, cross-calibration, control of systematics.

Full-sky coverage with 2 observatories in northern and southern hemisphere.

Shape of the spectrum? Cut-off?
Anisotropy in arrival directions?
Mass composition ?





3000 km²

F: 25x size of Paris

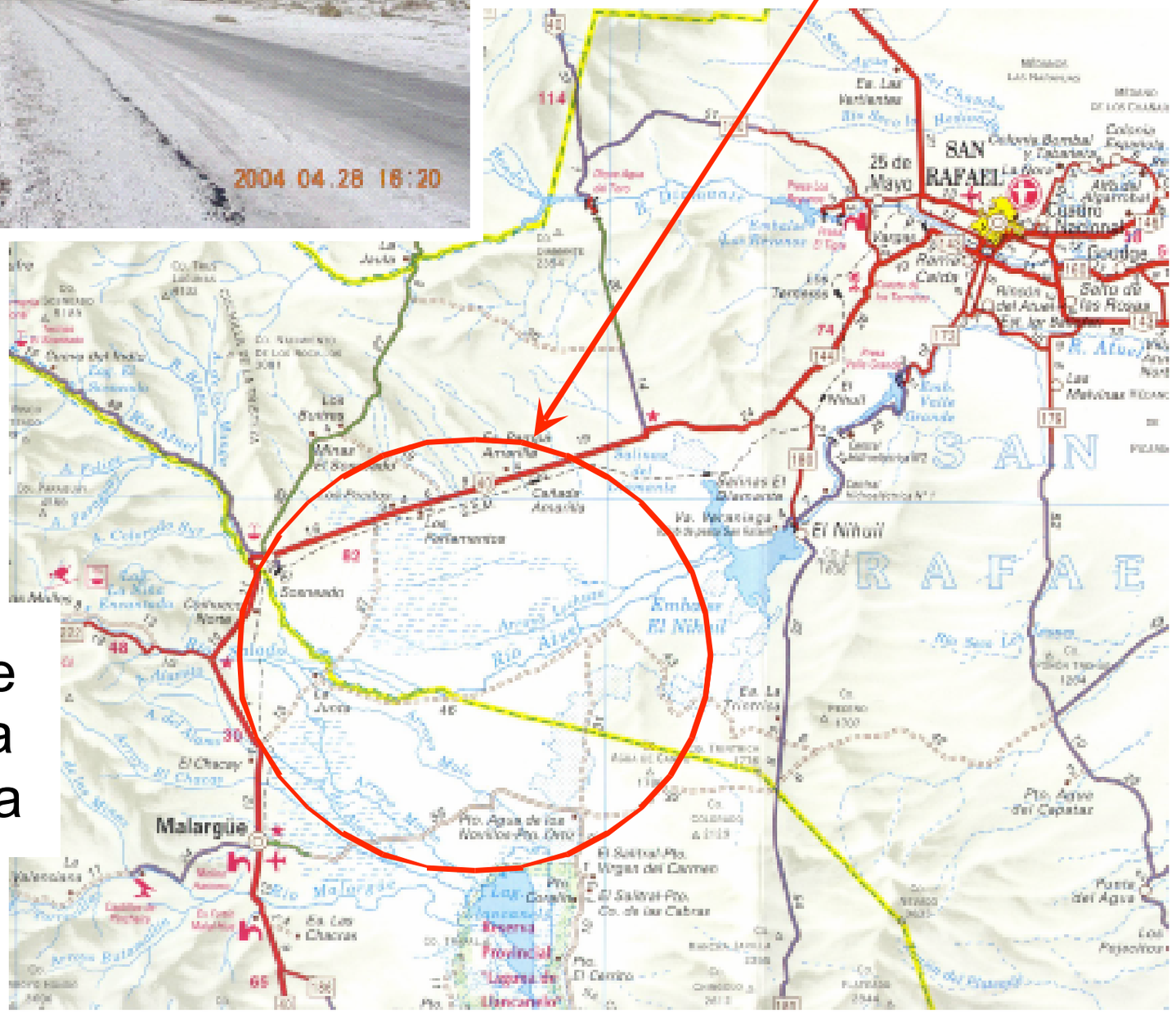
UK: size of Lancashire, area inside M25

D: size of Saarland

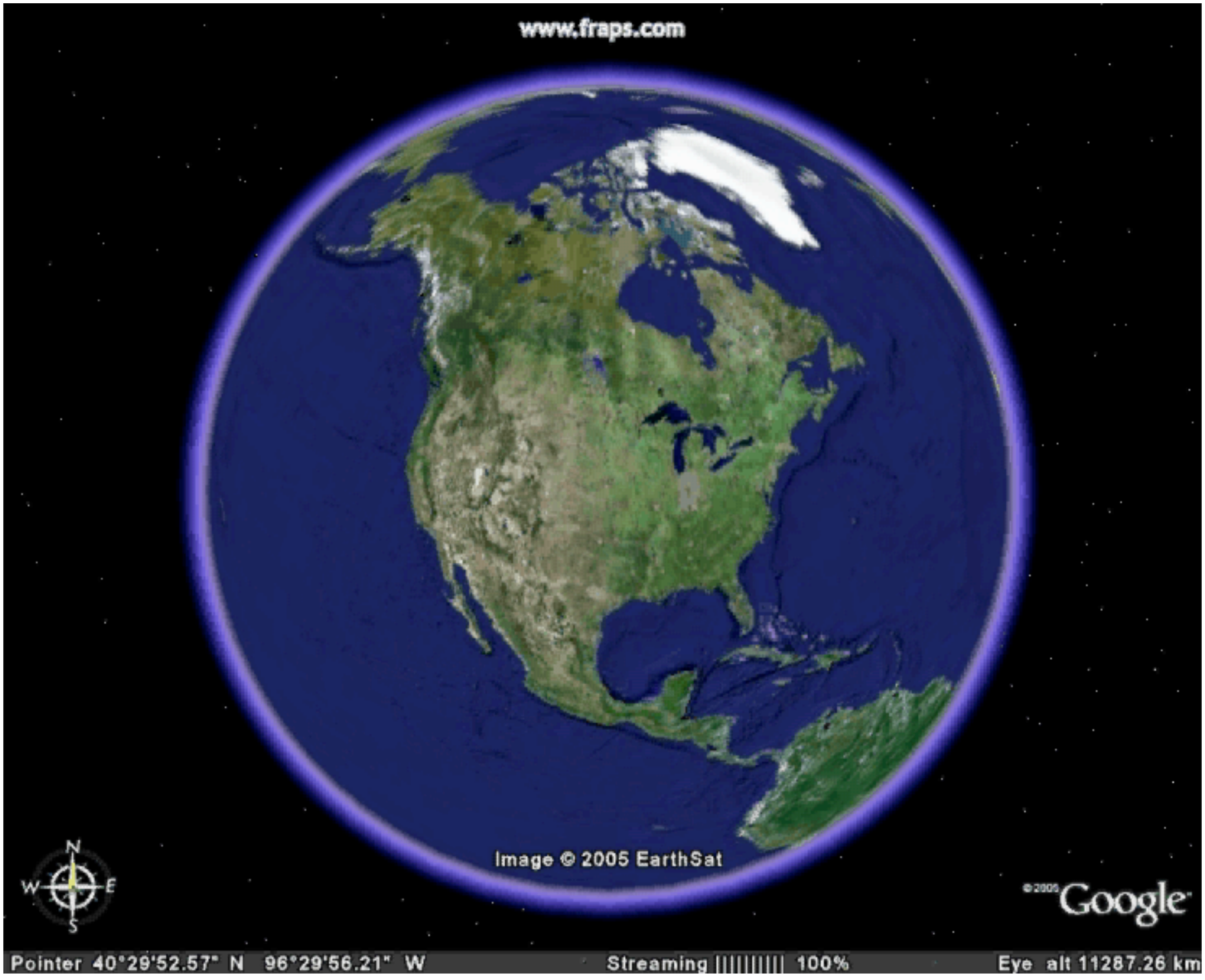
Gr: 2 x size of Lesbos

Auger South

(1400 m a.s.l.,
35.2° S, 69.2° W)



Malargüe
Mendoza
Argentina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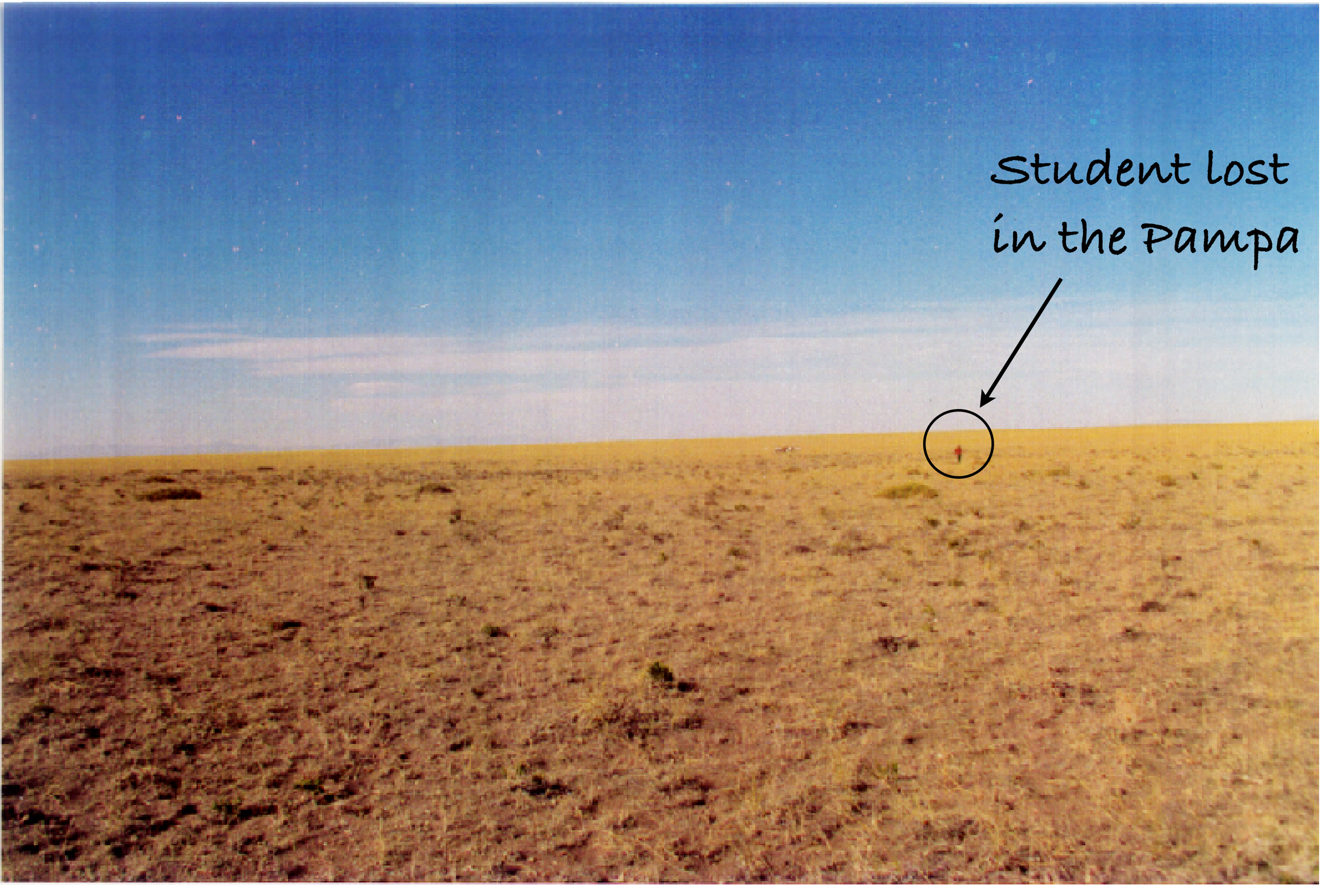
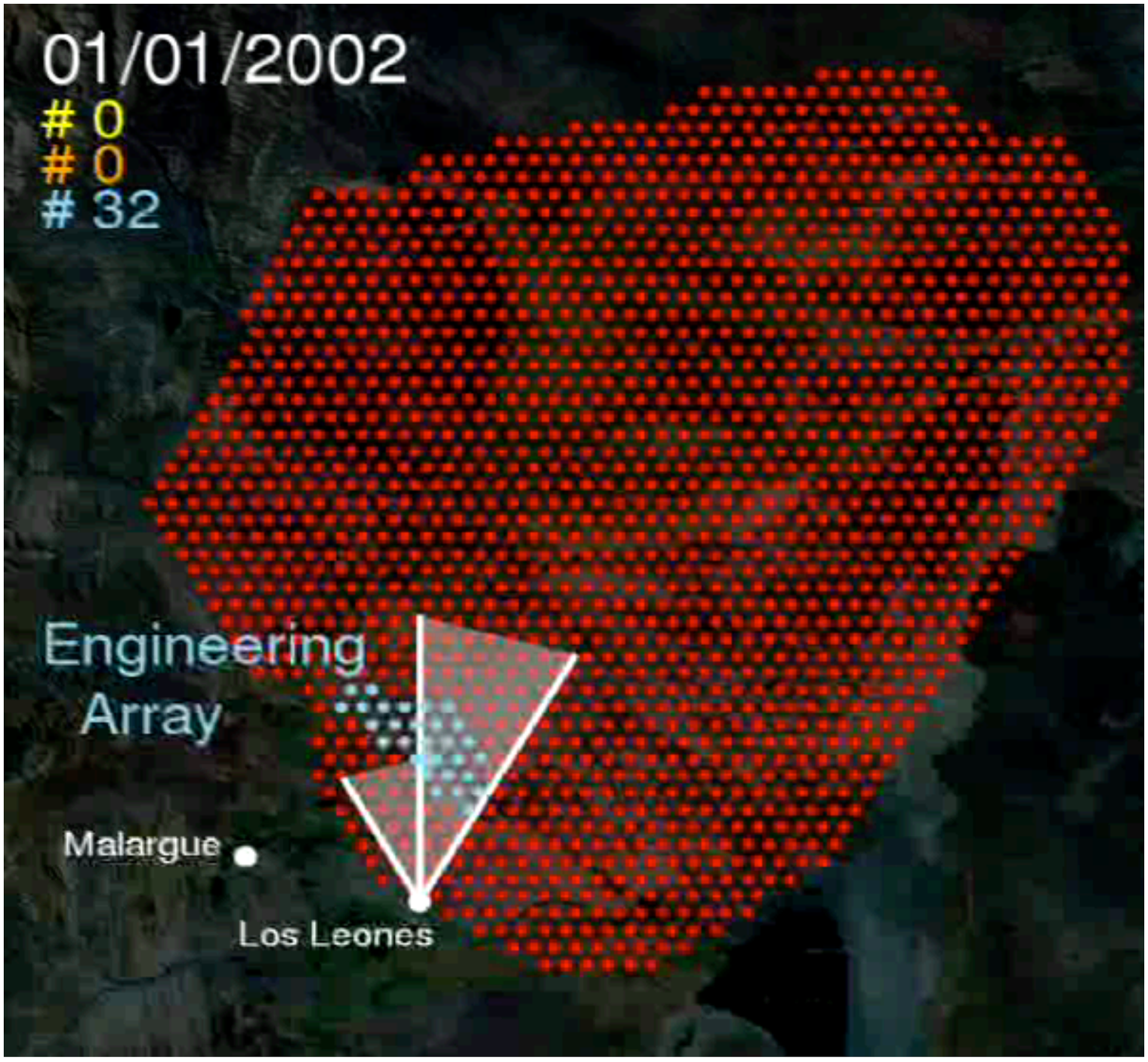
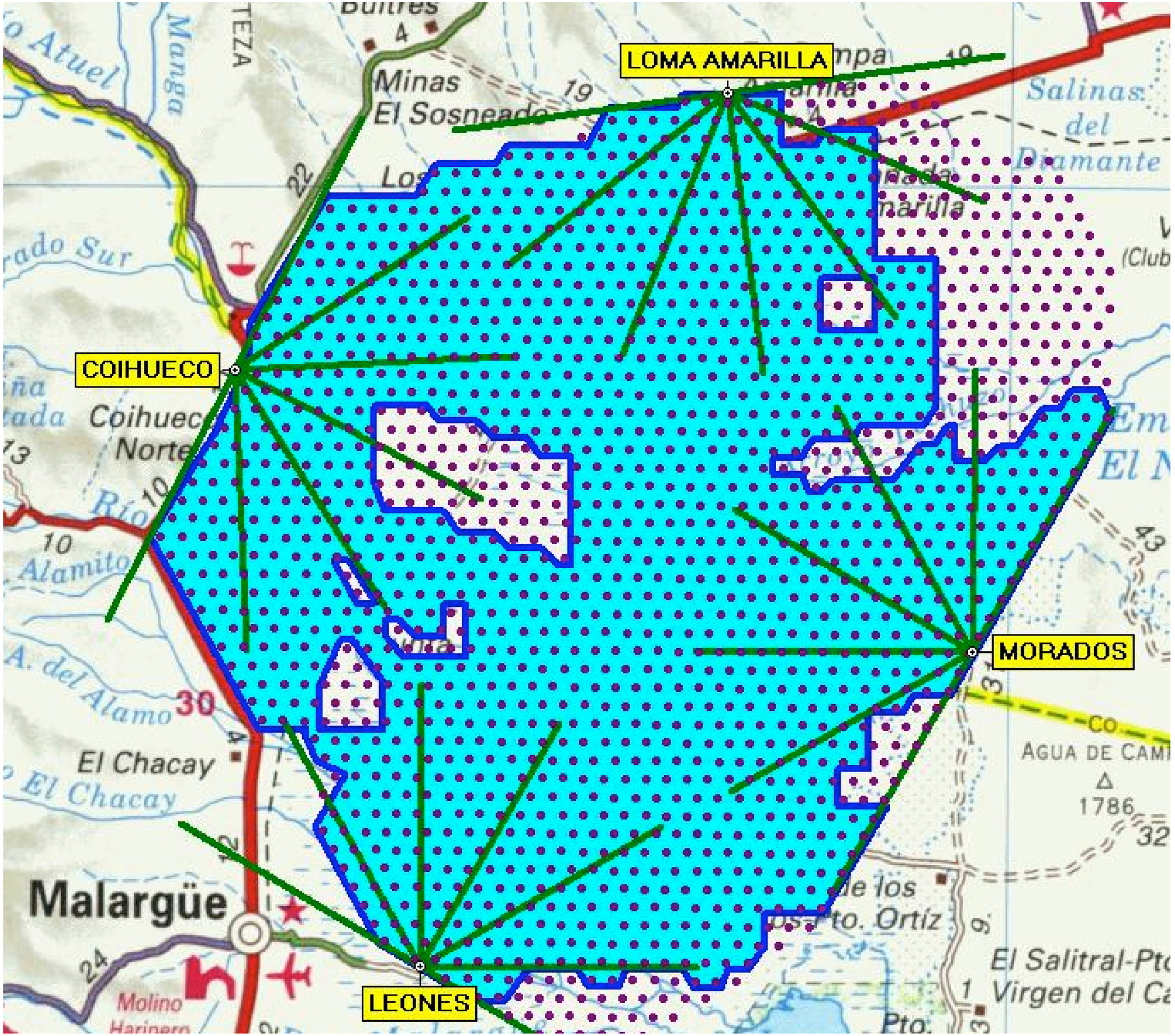
Pointer 40°29'52.57" N 96°29'56.21" W
Streaming ||||||||| 100%
Eye alt 11287.26 km


Student lost
in the Pampa

Installation of Auger detectors: the movie

planned
tank deployed
with water
send data



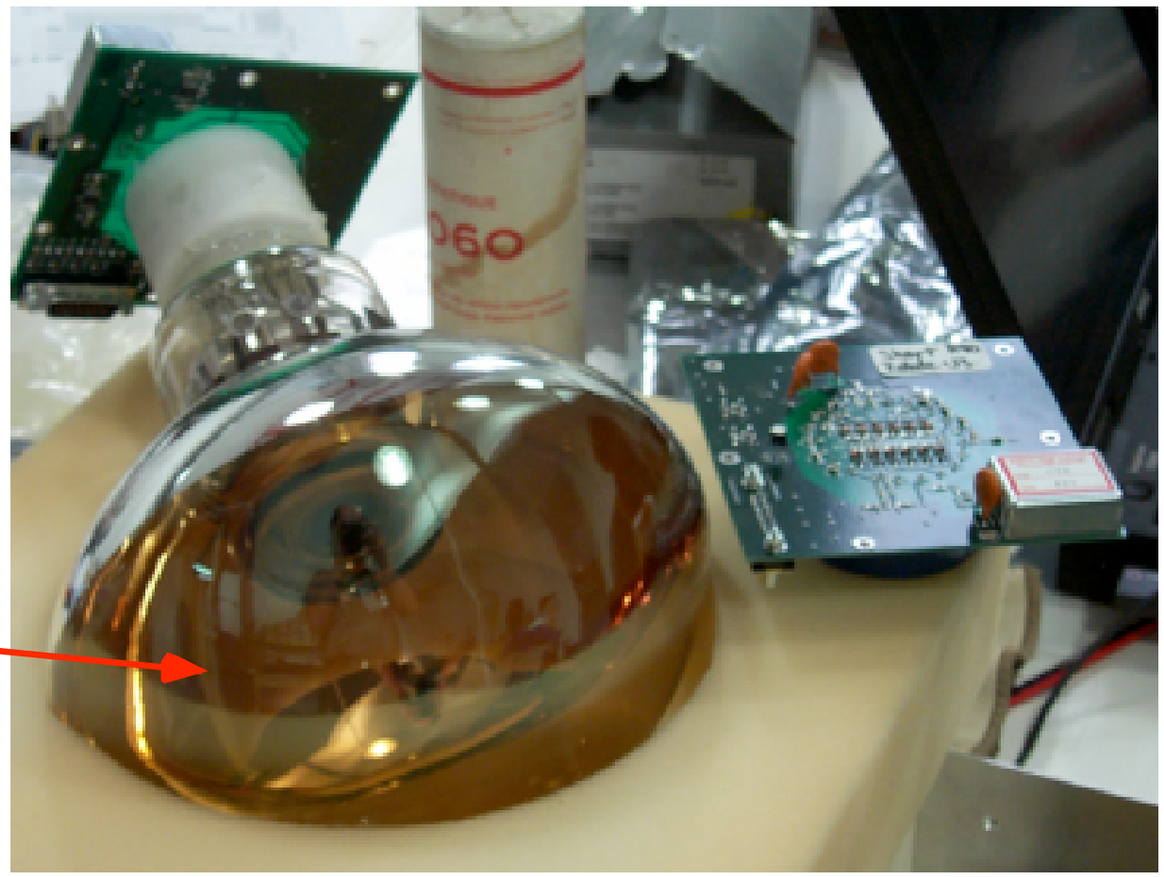


Status:
July 2007

1438 deployed
1400 filled
1364 taking data

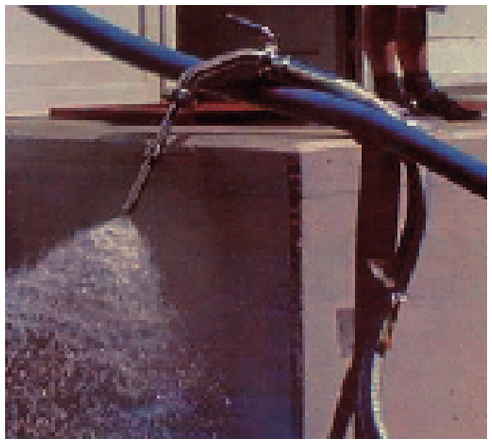
all 24 FD complete

10 m^2 x 1.2 m water
viewed by 3 PMTs,
solar panel & batteries
(power budget 10 W)
electronics box
radio antenna



three
9" PMTs

Tank deployment

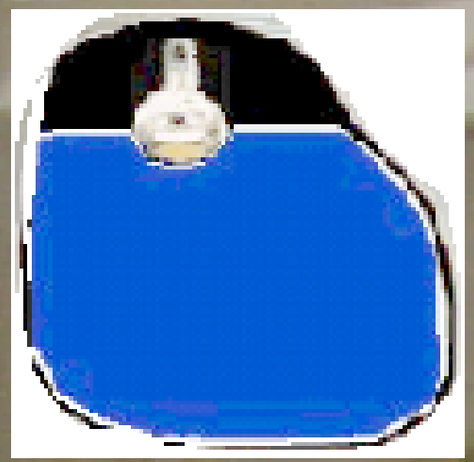


Communications antenna

GPS antenna

Electronics enclosure

Solar Panels



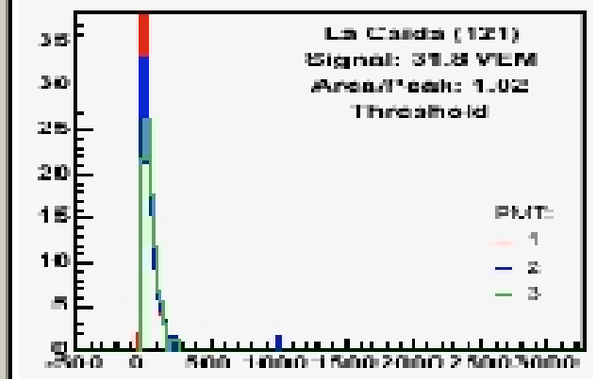
3 x 9" PMTs

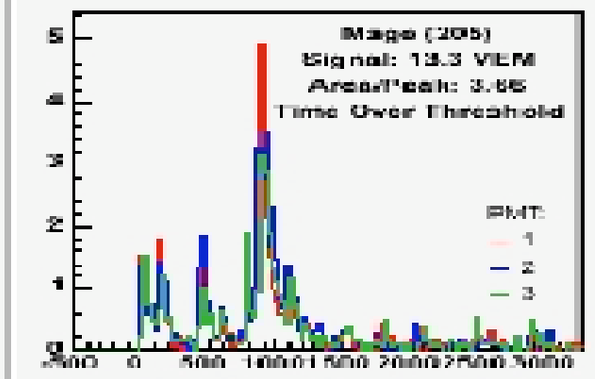
Plastic tank
12 m^3 water

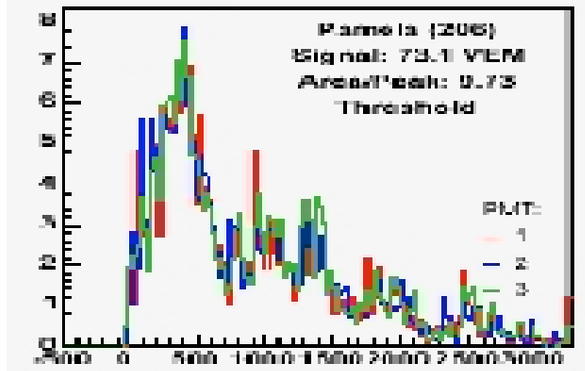
Battery box

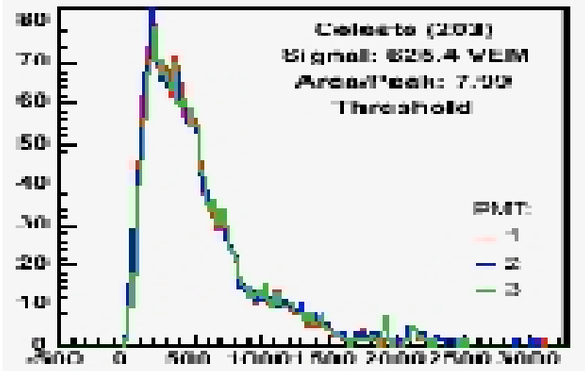
water Cherenkov detectors:
12 m^3 water, 3 PMTs, GPS,
radio, electronics,
solar panel & battery

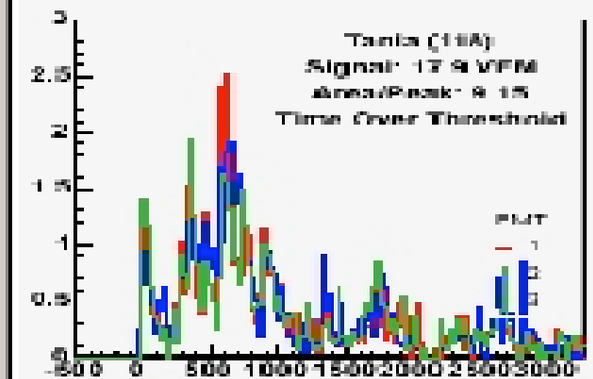
1600 tanks on 3000 km^2

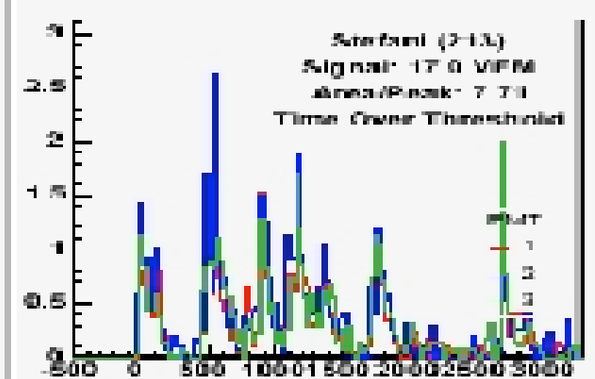


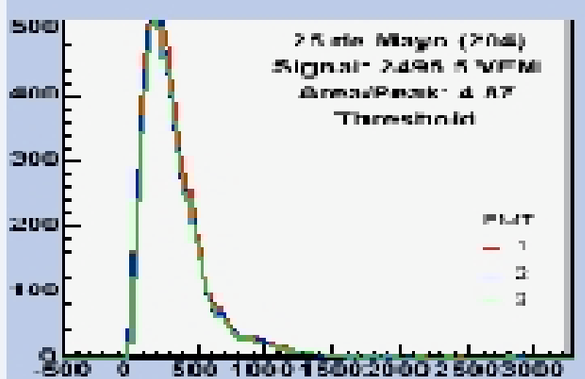


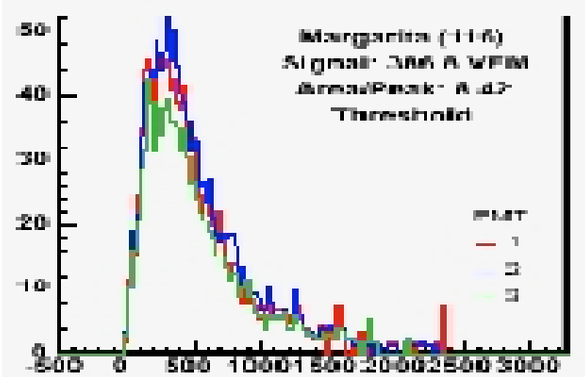


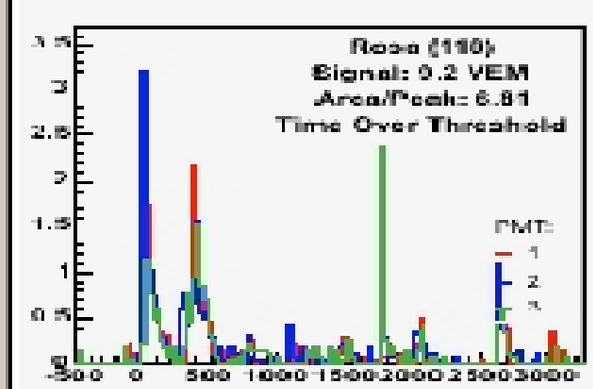


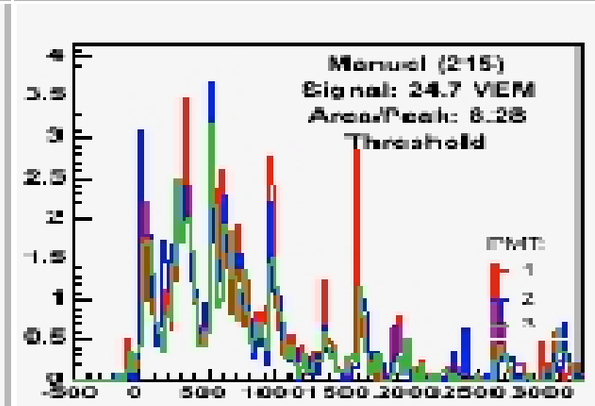


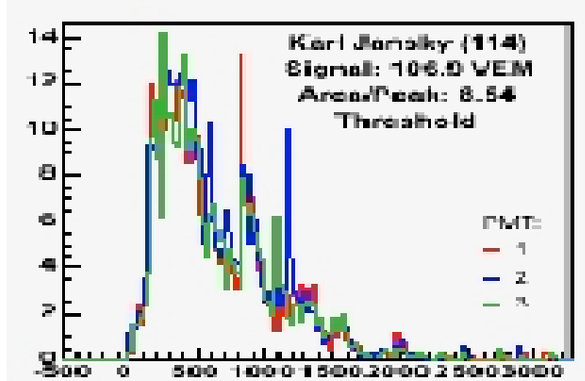


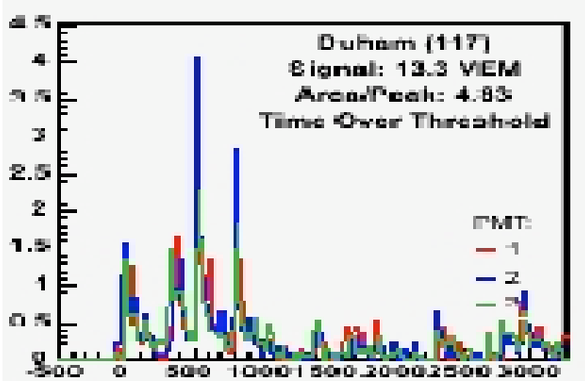


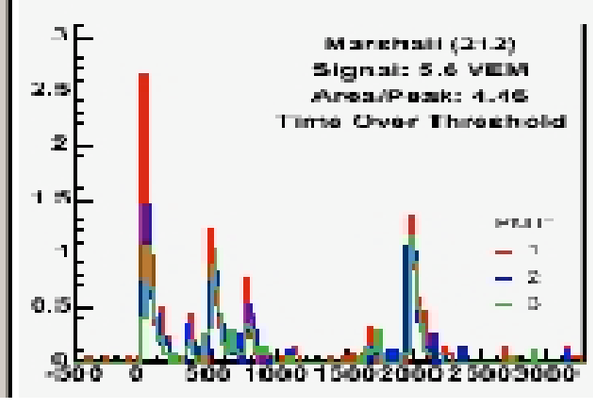


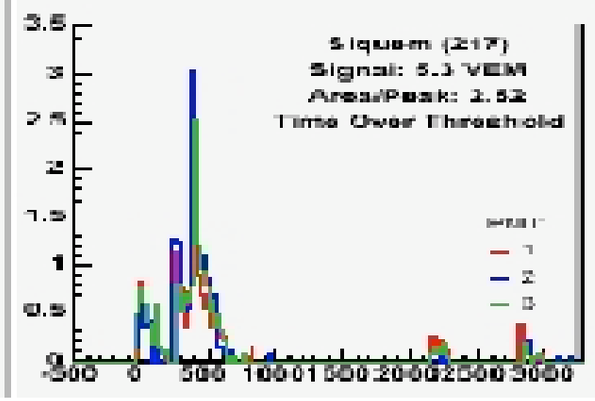


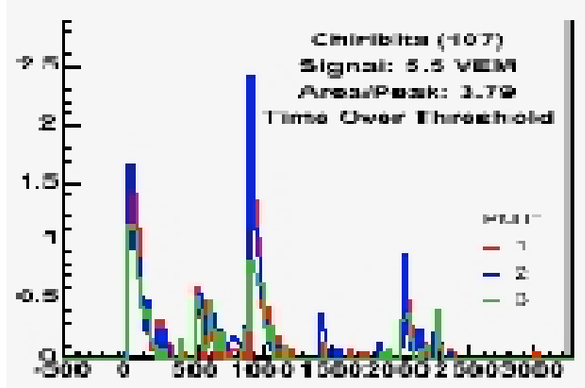


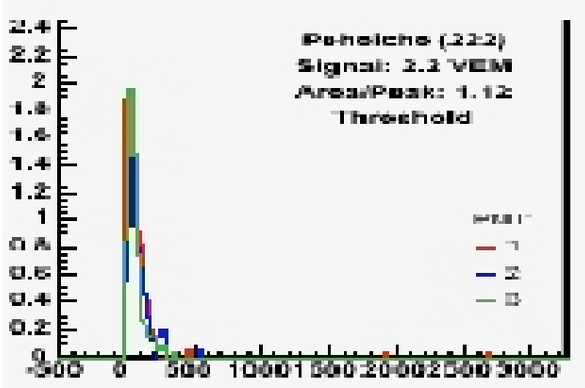








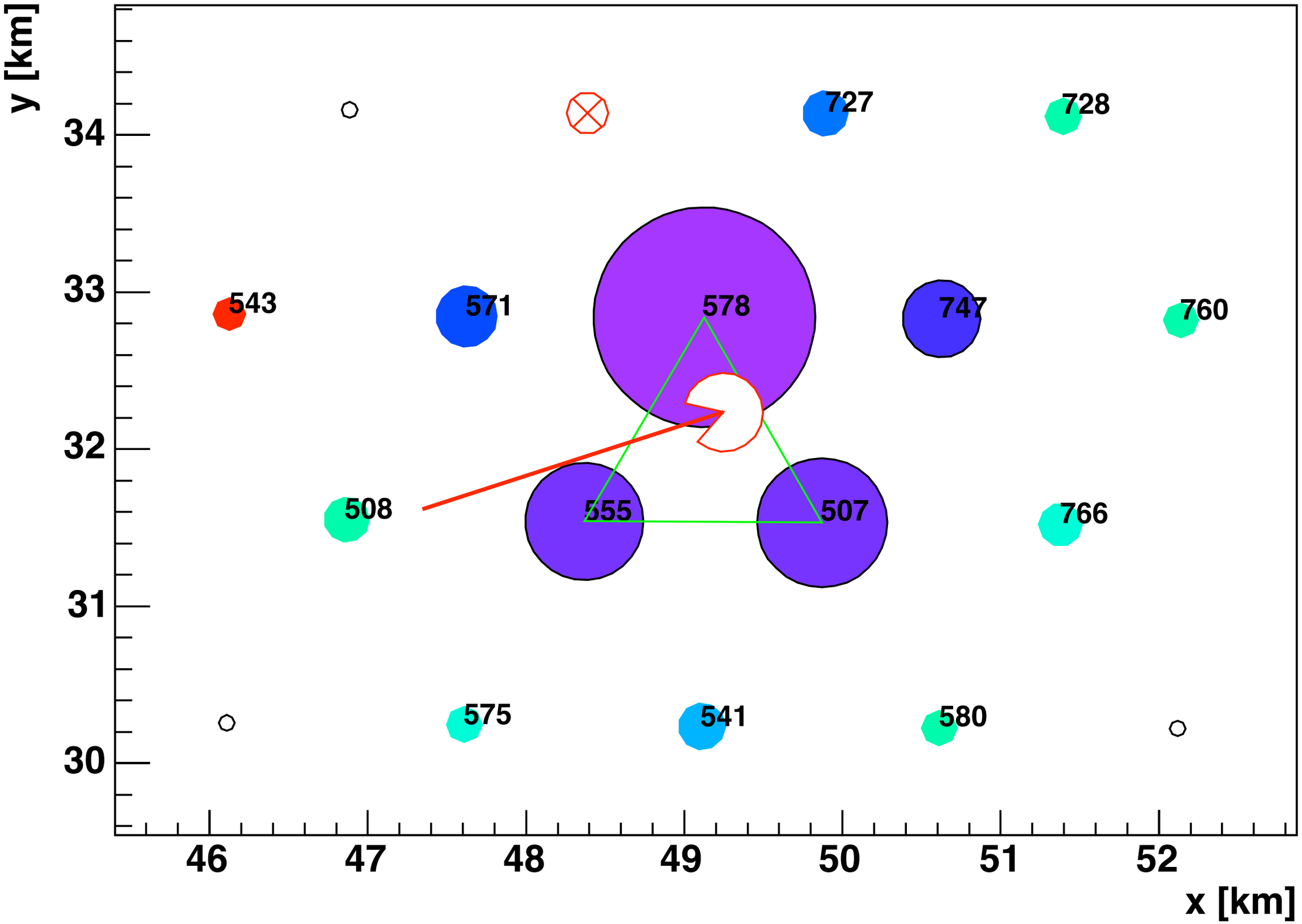




High & smooth pulses close to shower core, low & spiky pulses far away.

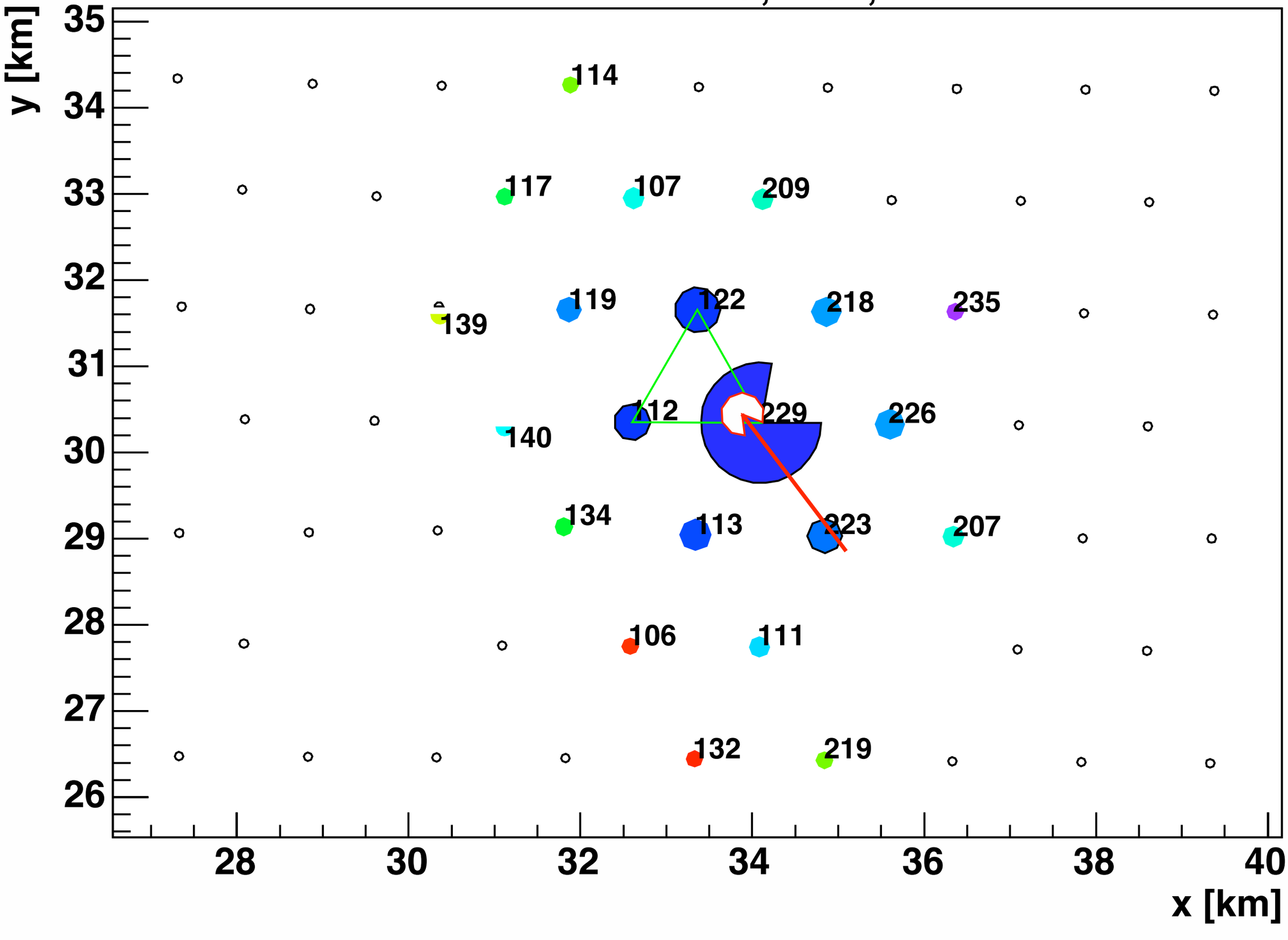
Event 1225537

14 tanks, 34°, 79 x 10^{18} eV



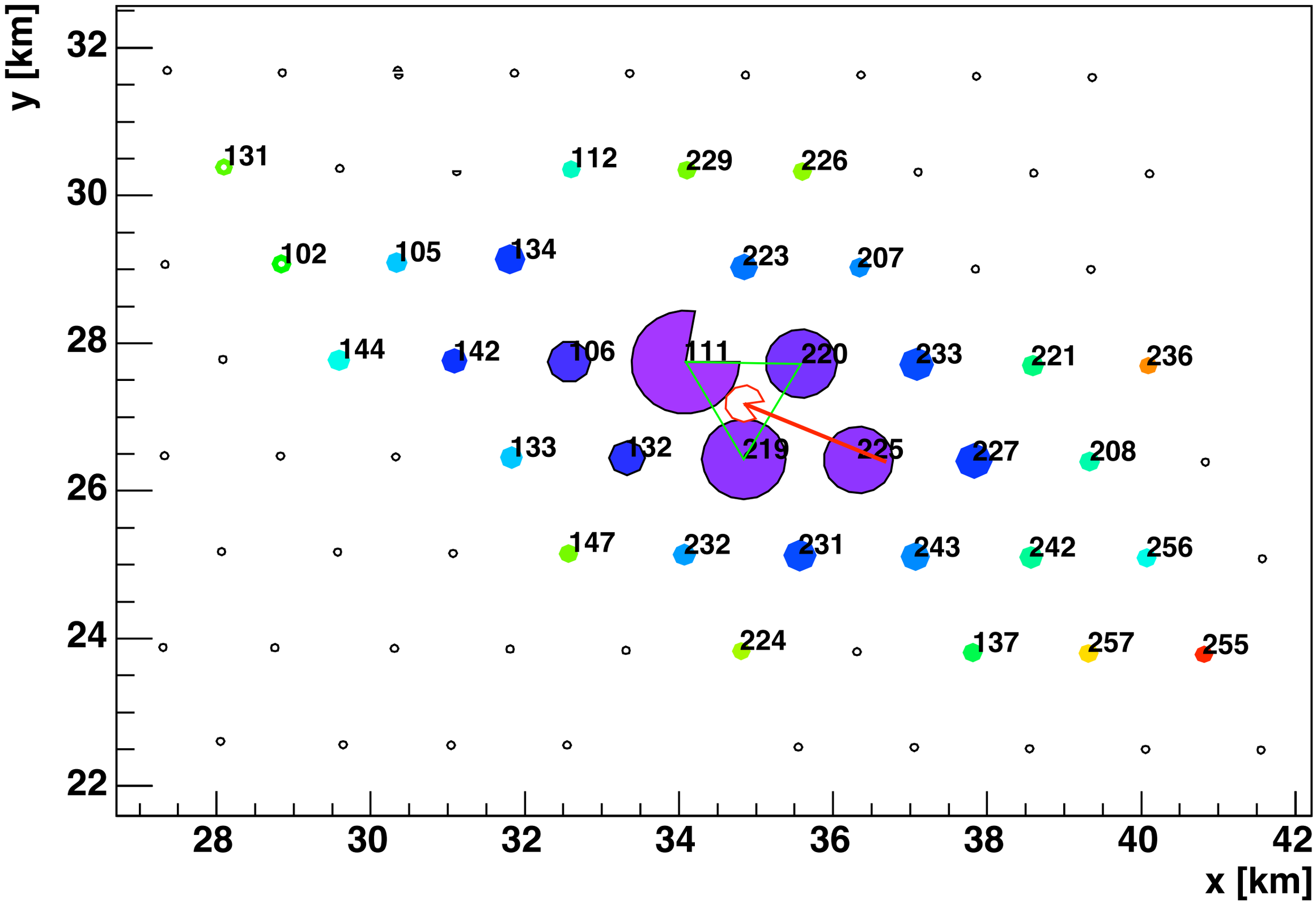
Event 1096757

21 tanks, 45°, 86 x 10^{18} eV



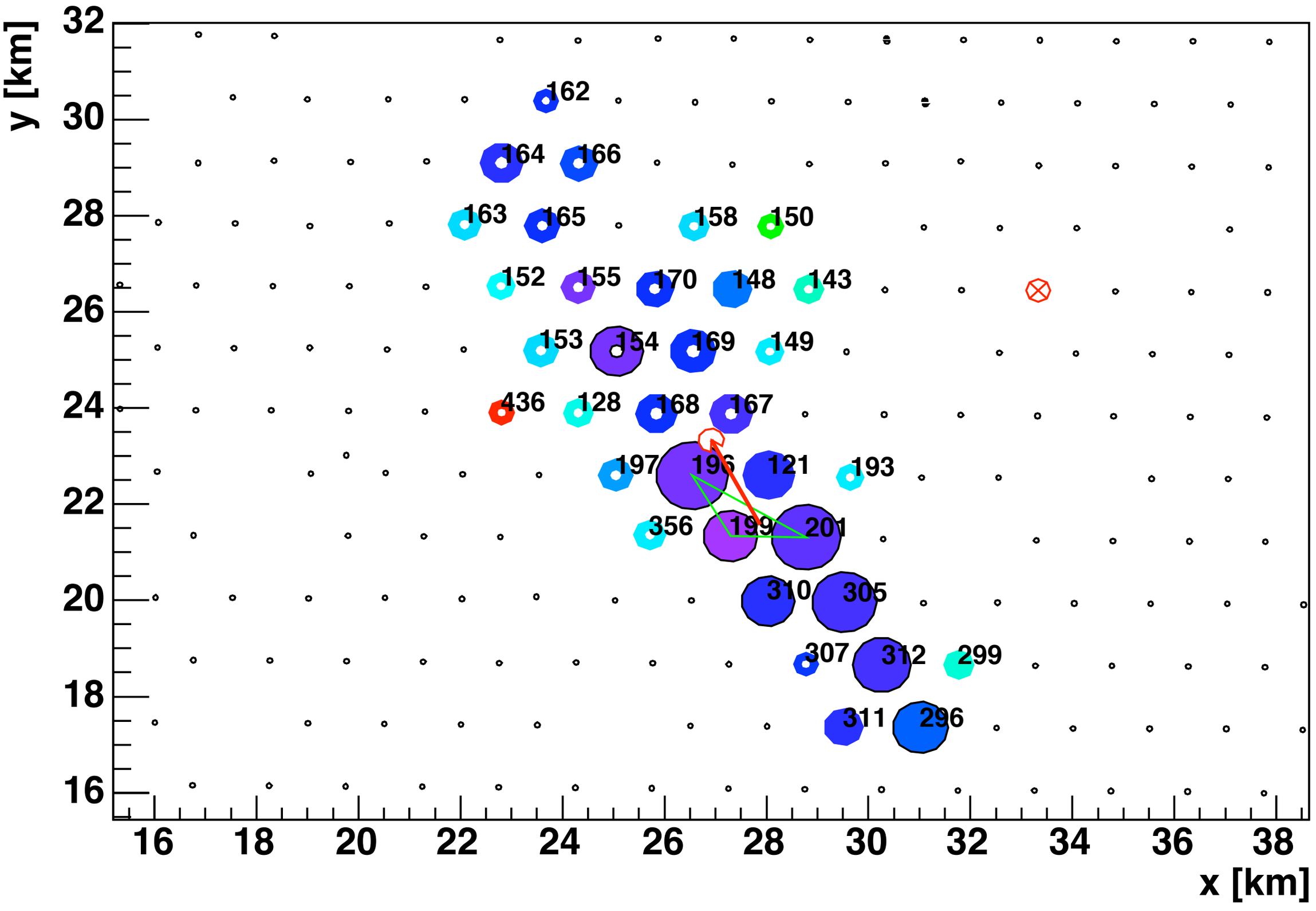
Event 787469

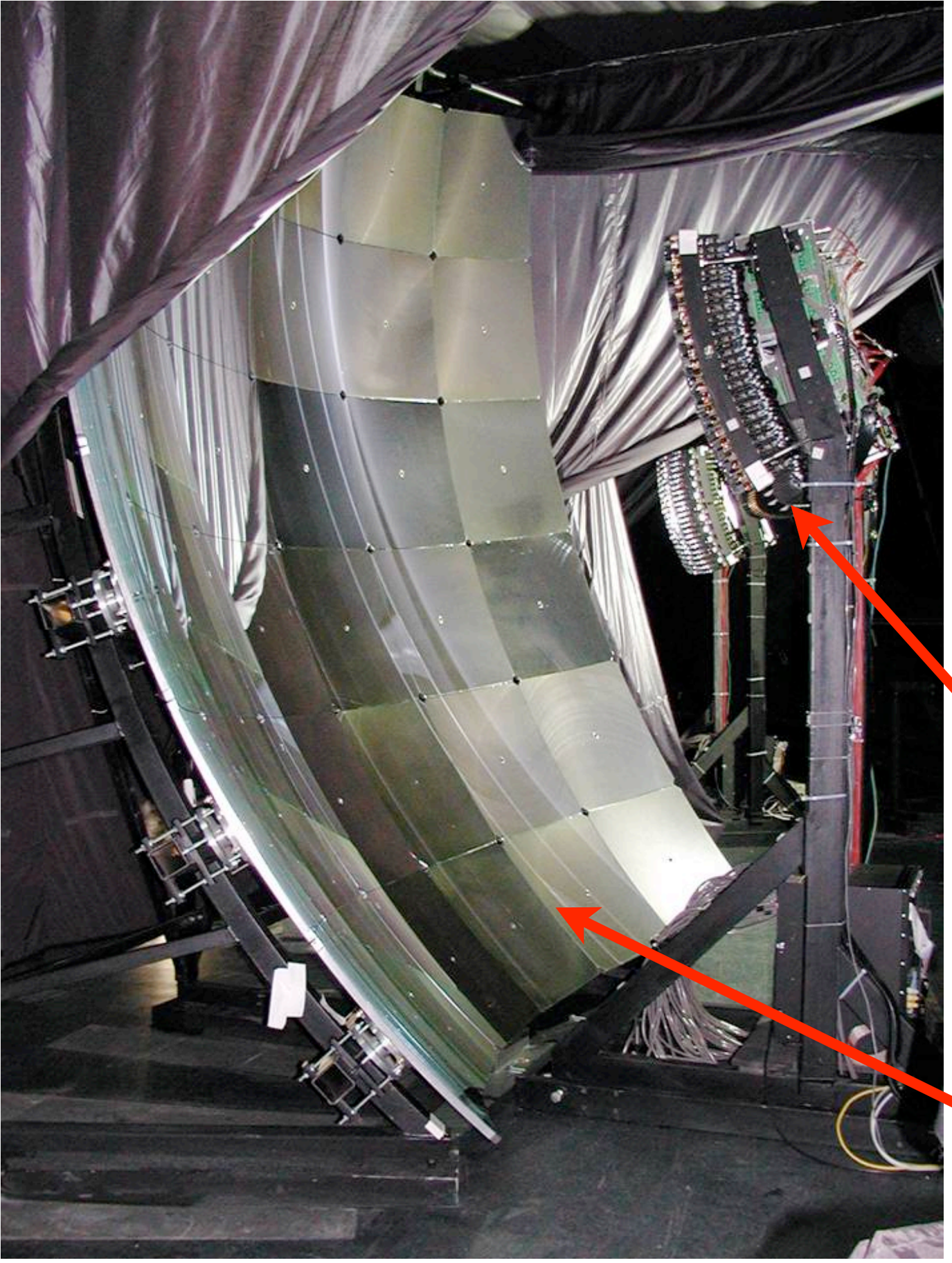
31 tanks, 60º, 76 x 10^{18} eV

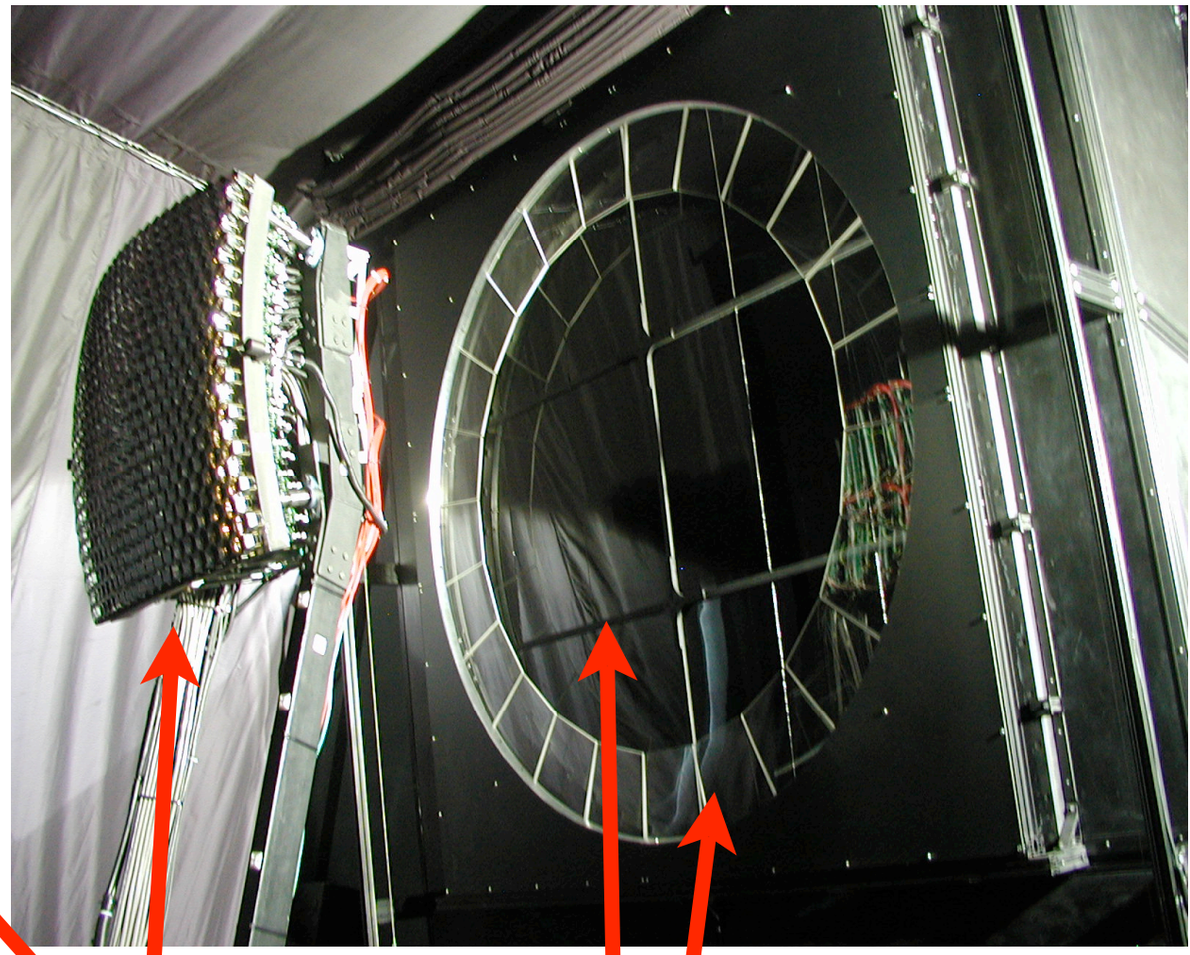


Event 1099180

34 tanks, 82°, ~10 x 10^{18} eV



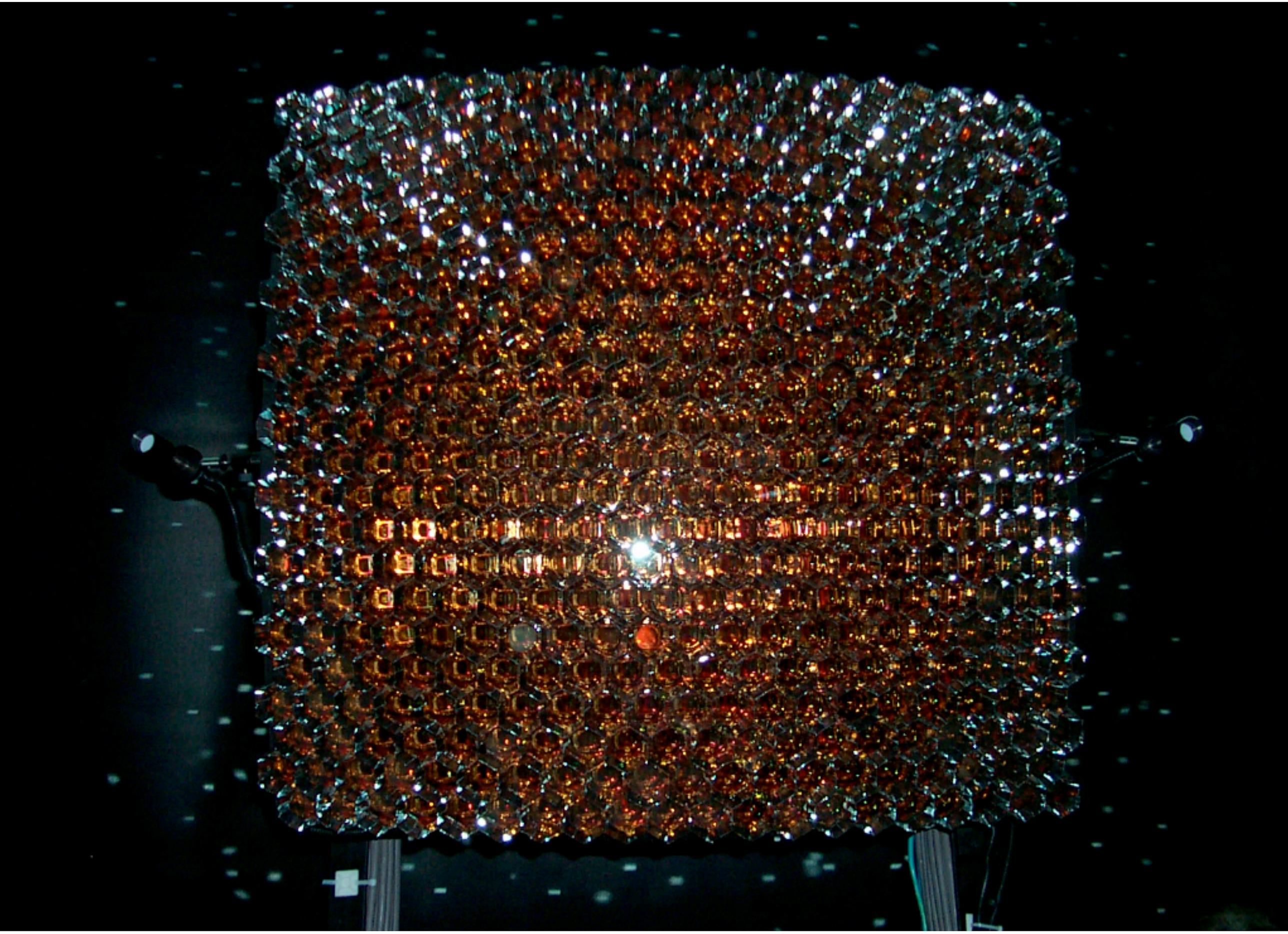


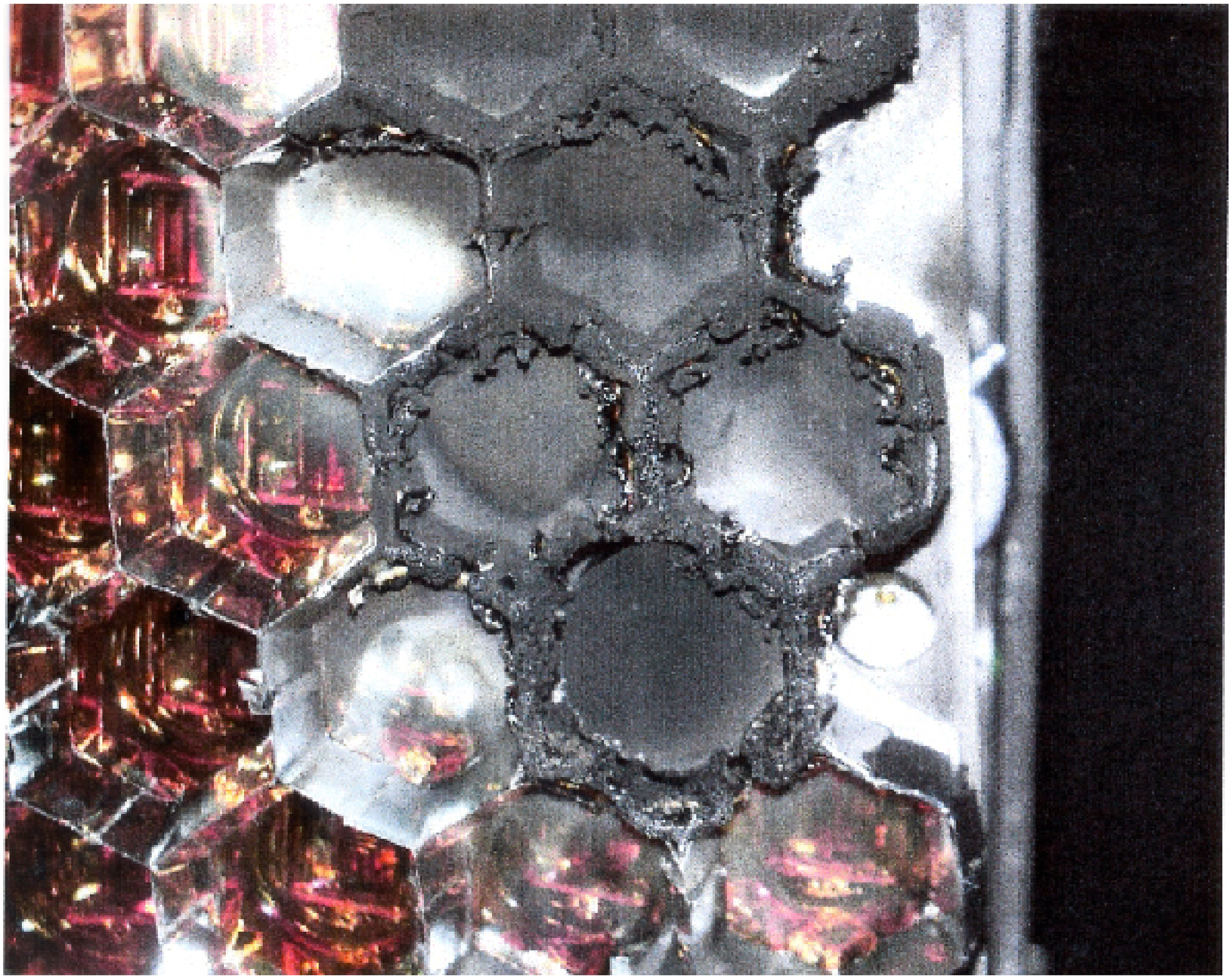


440 pixel
PMT camera

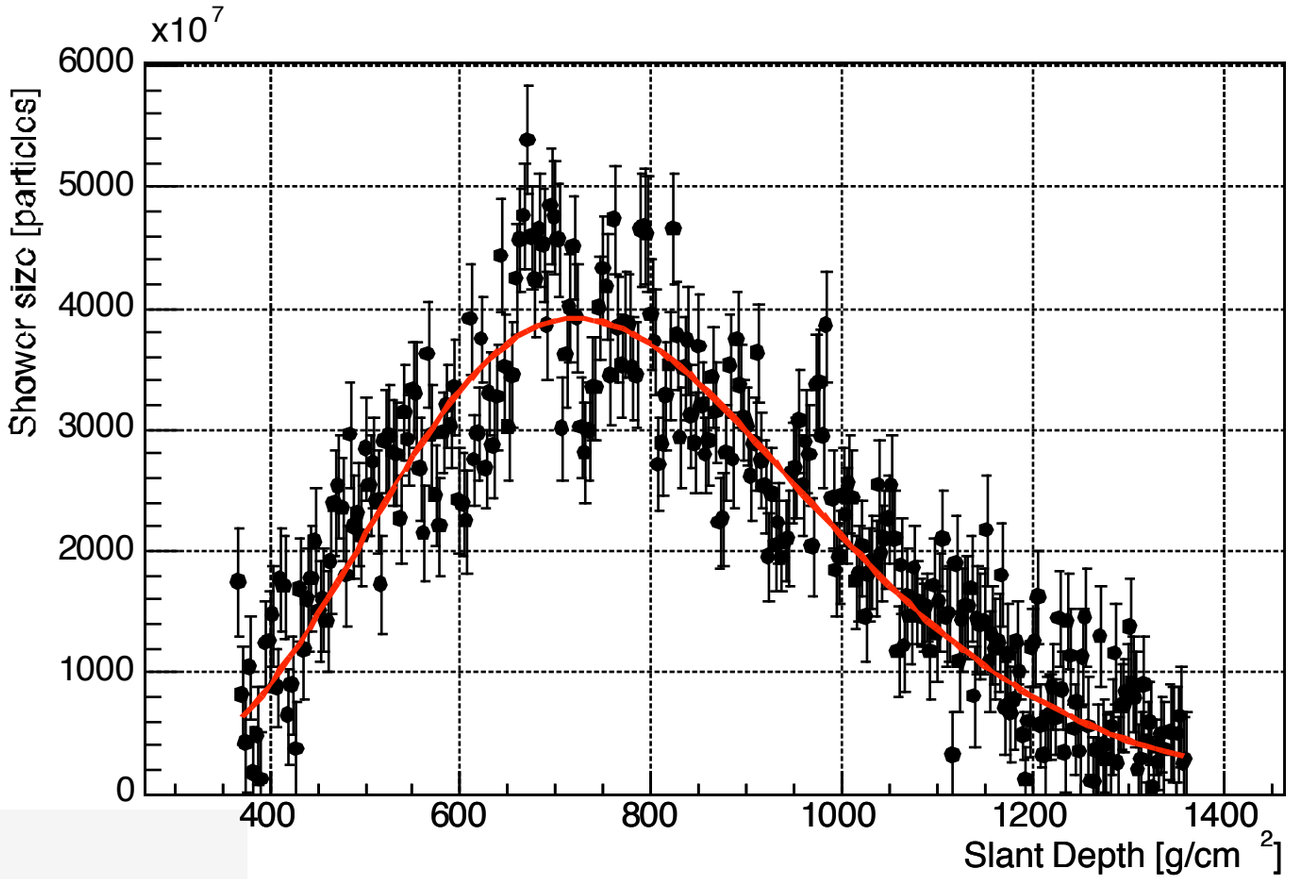
aperture with ring
of corrector lenses

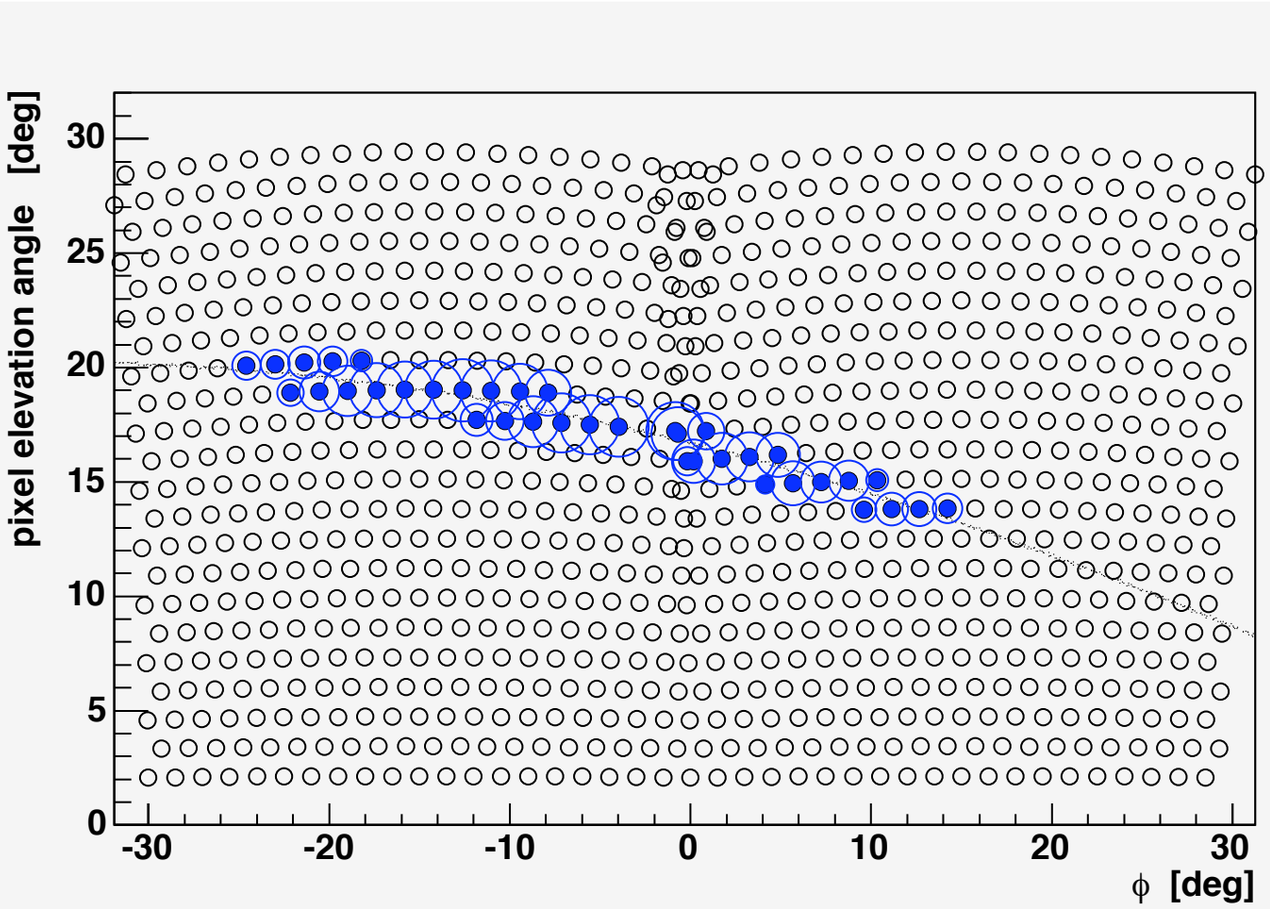
focusing, facetted
Aluminium mirror





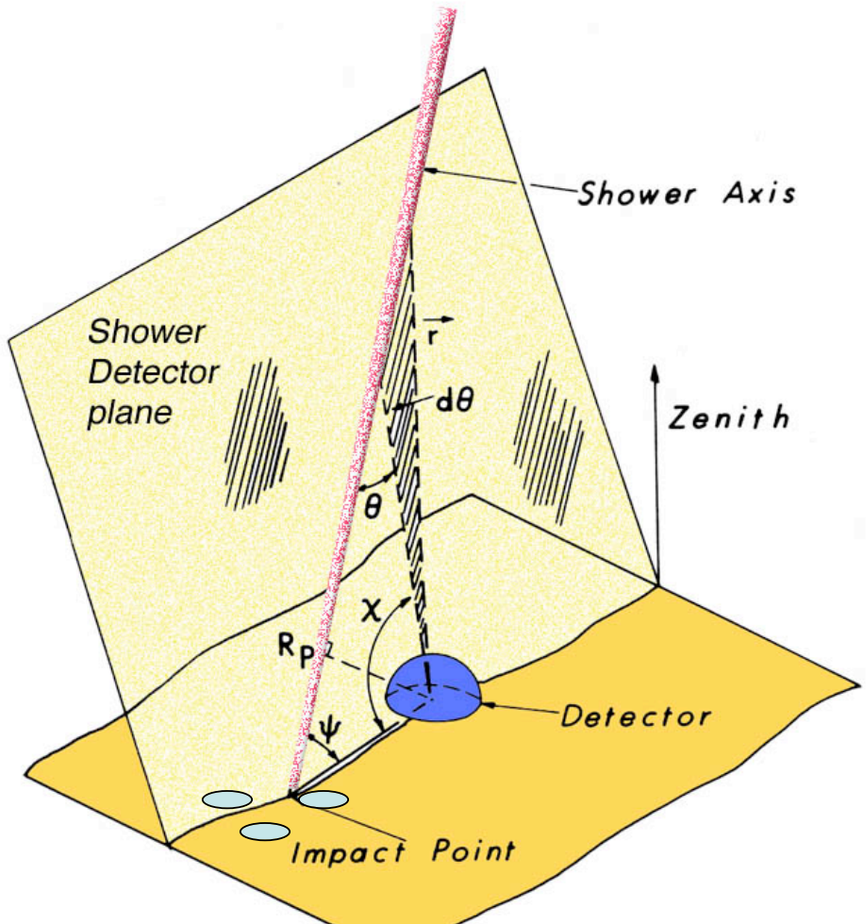
FD: longitudinal profile
calorimetric energy
X_{max} for mass comp.

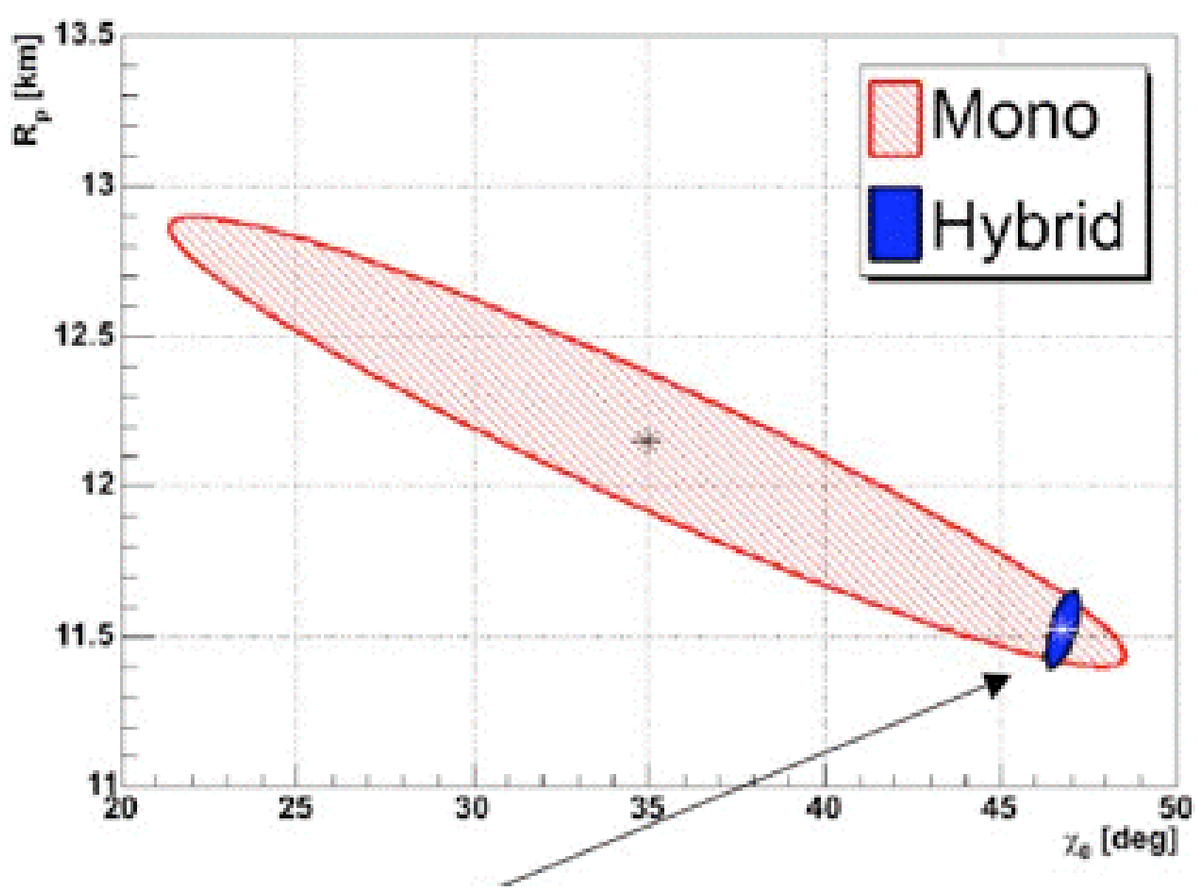




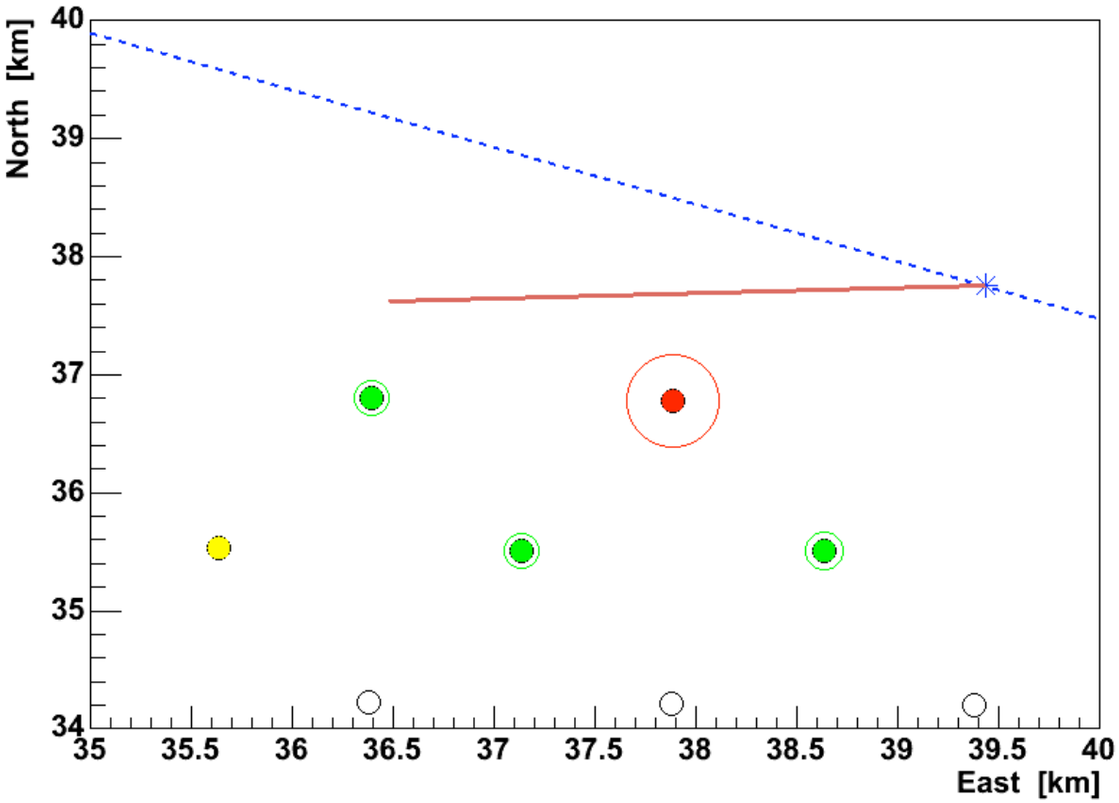
SD &FD: hybrid,
very good geometry
cross-calibration

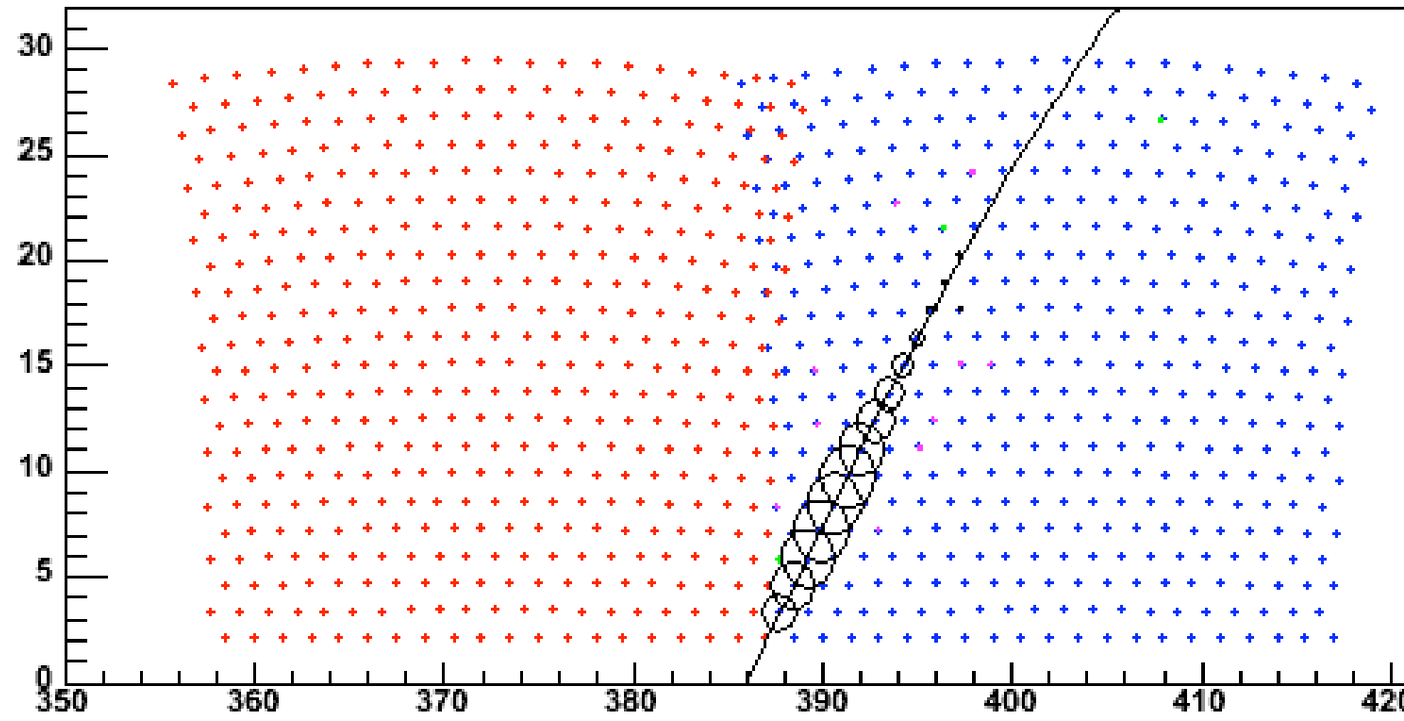
	hybrid	SD only	FD only
angular resolution	0.2°	1-2°	3-5°
aperture	independent of E, mass, models	independent of E, mass, models	dependent of E, mass, models and spectral slope
energy	independent of mass, models	dependent of mass, models	independent of mass, models

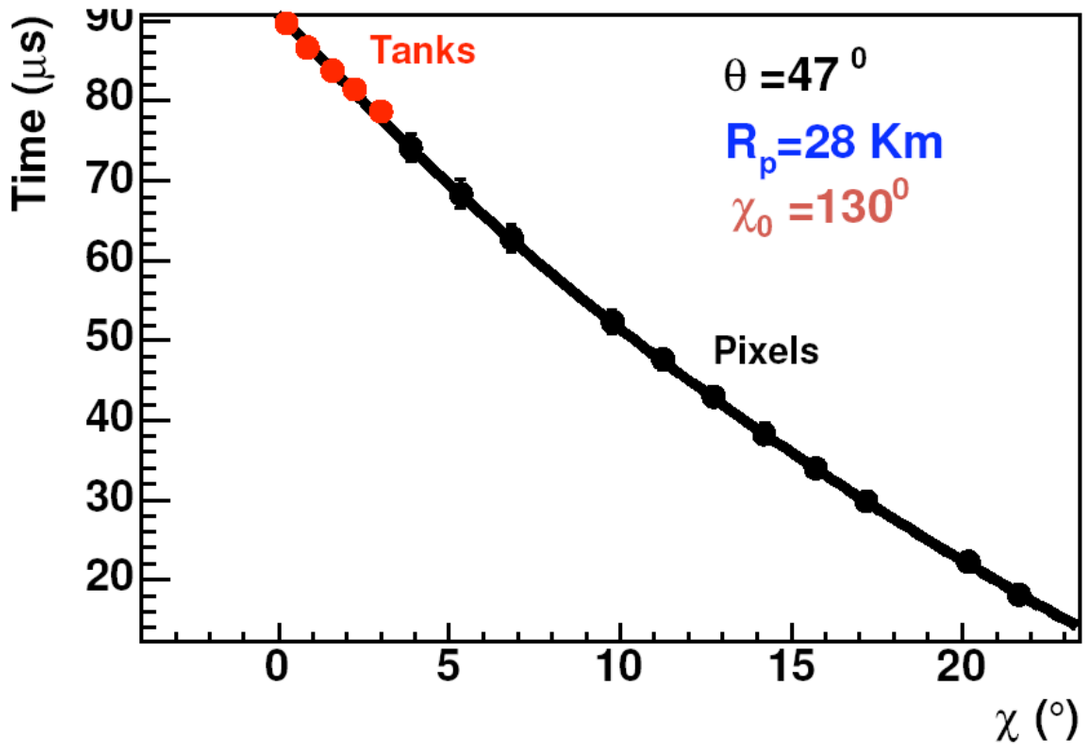


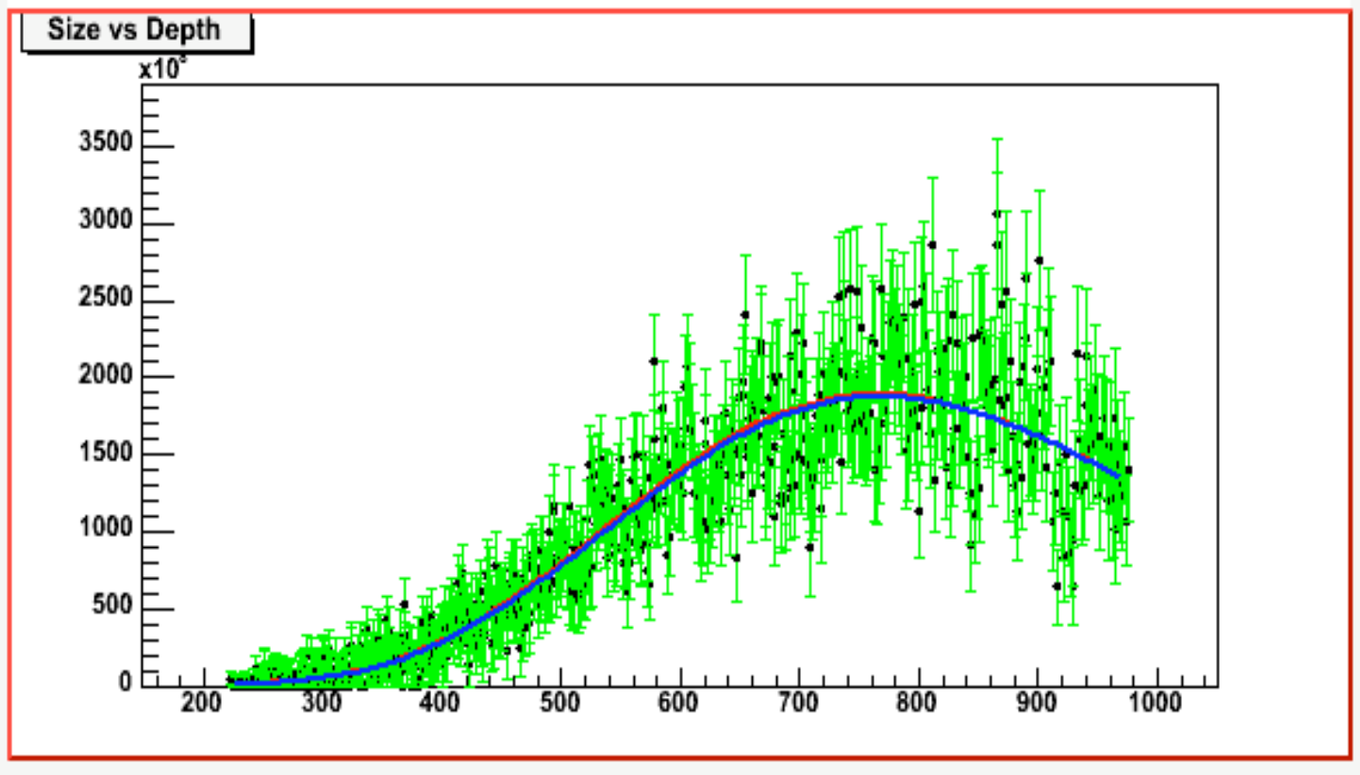


A big event that got away: E ≈ 140 EeV









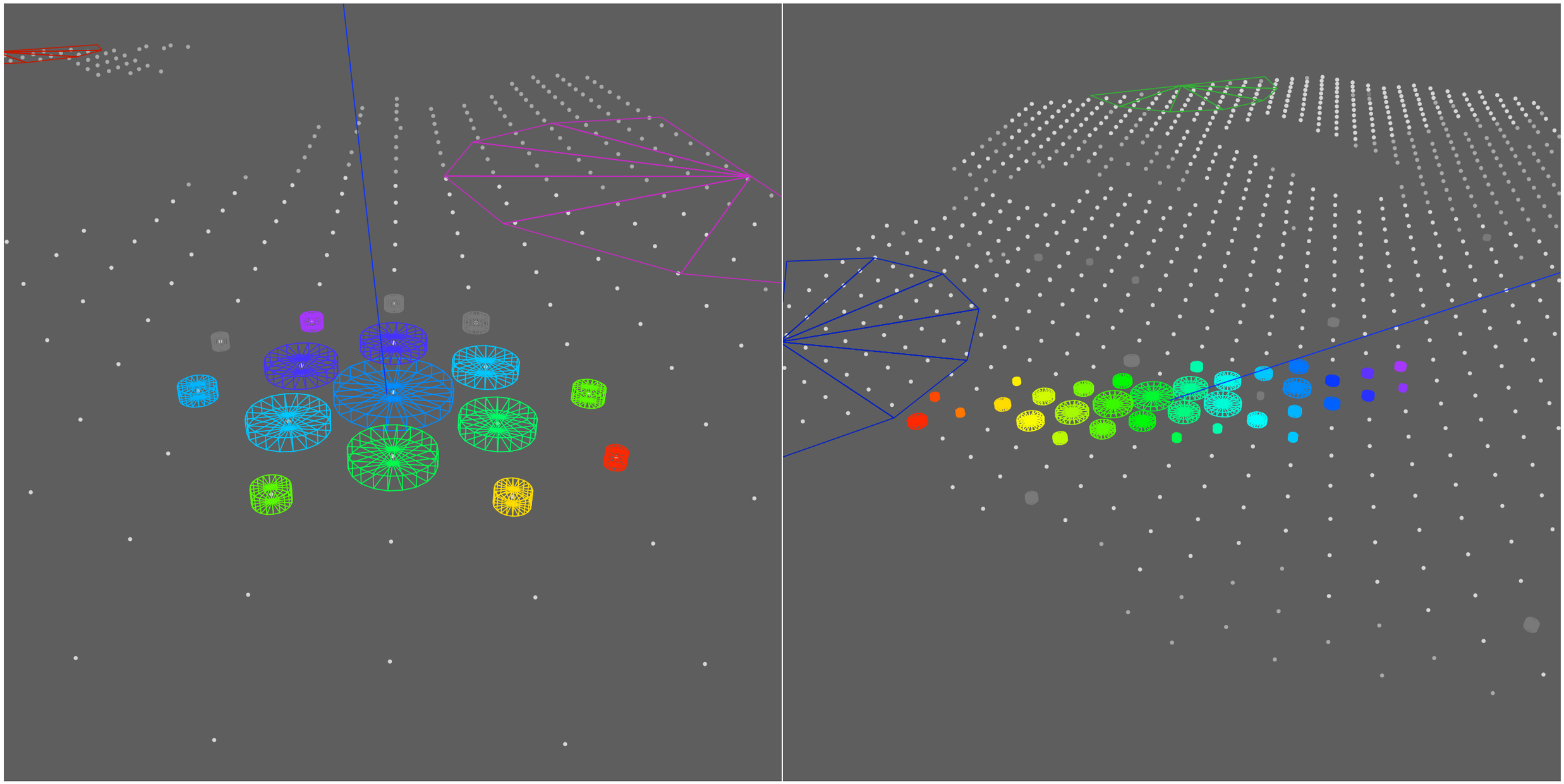
highest energy events so far:

near vertical

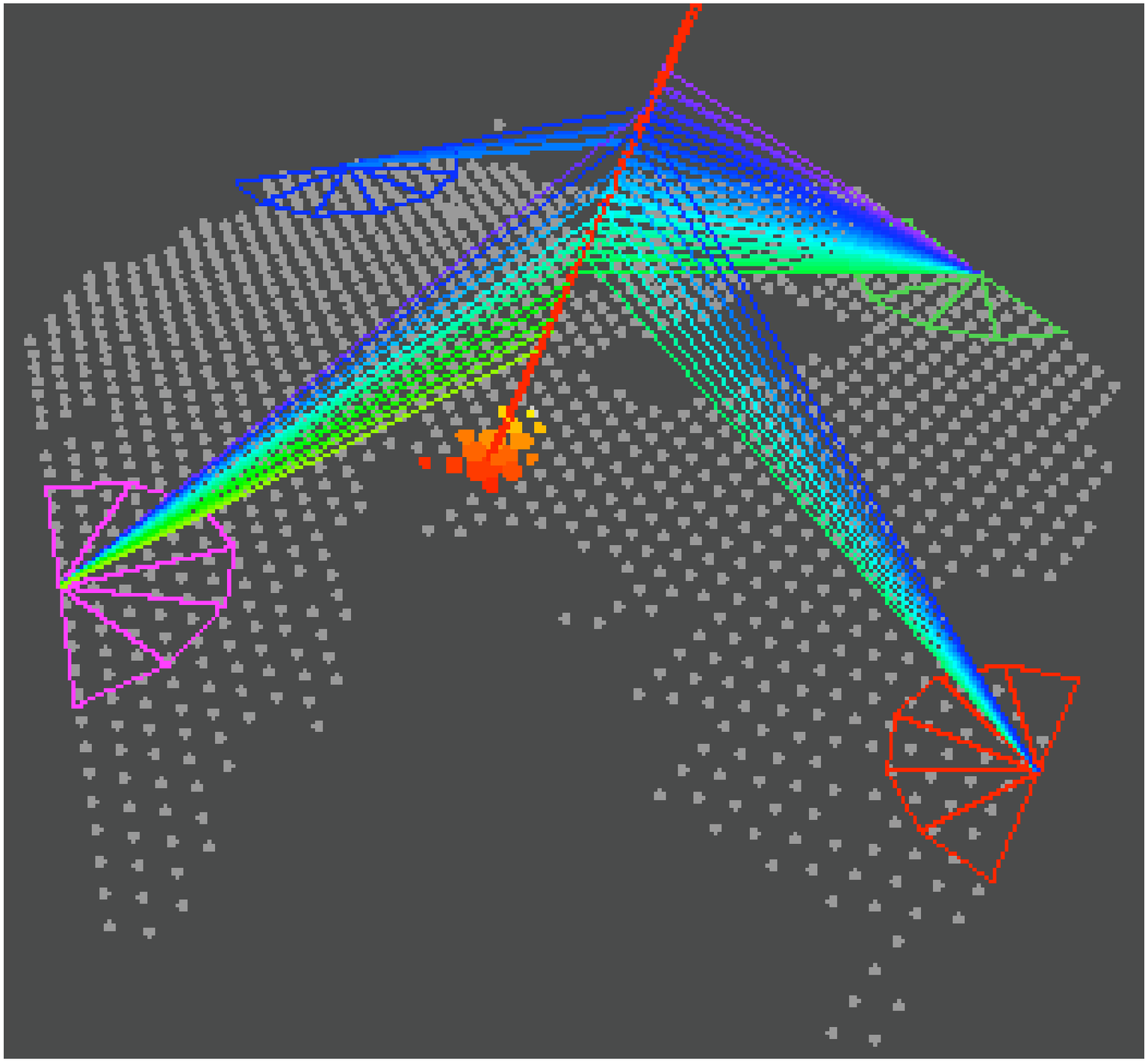
$E = 1.67 \times 10^{20}$ eV $\theta = 14°$

inclined

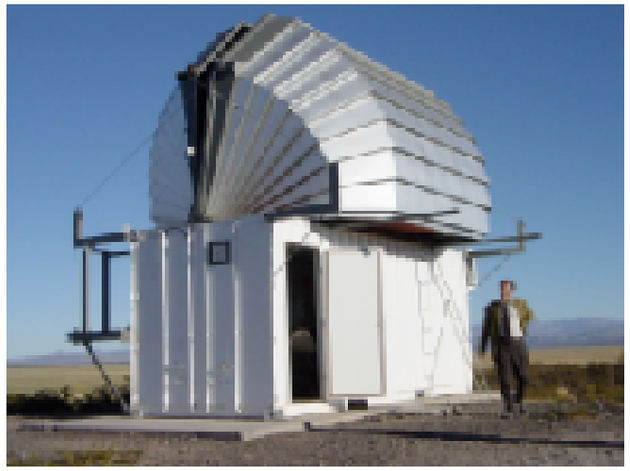
$E = 0.37 \times 10^{20}$ eV $\theta = 74°$



20 May 2007 E ~ 10^{19} eV
Shower seen by array and all 4 FDs



Atmospheric Monitoring and Calibration



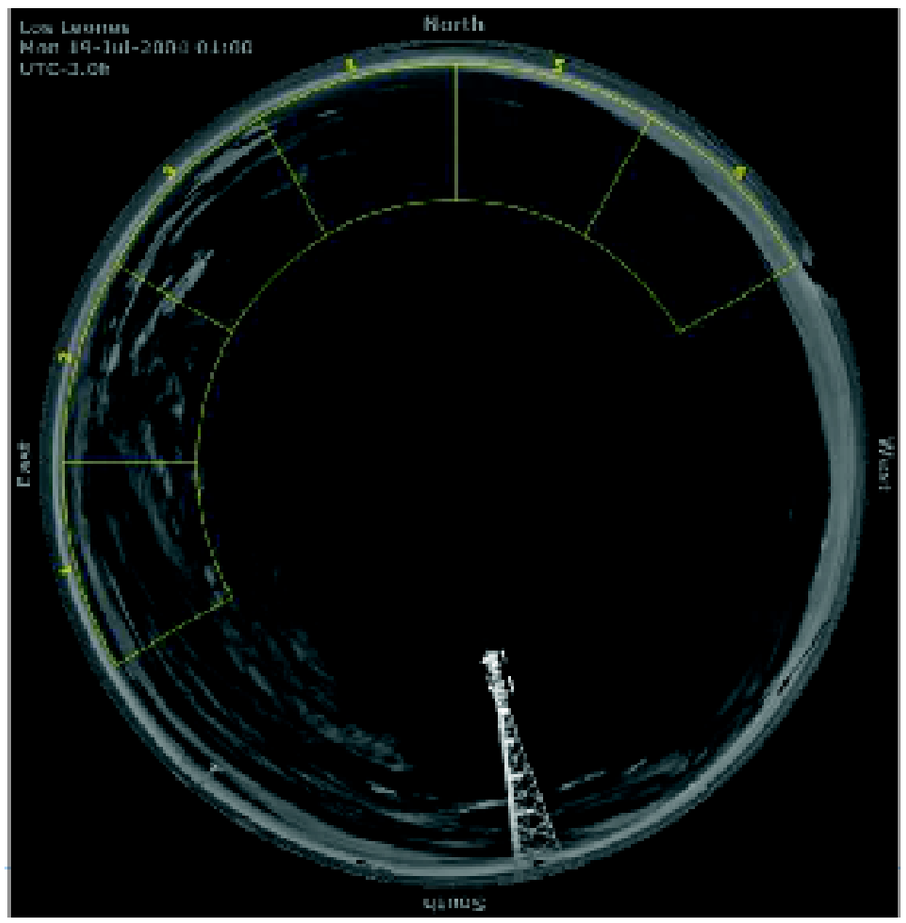
Lidar for atmospheric profiling and
“shooting the shower”
at each Fluorescence building

Central Laser Facility
(laser linked to adjacent tank)

End-to-end absolute calibration
(Drum for uniform illumination
of FD camera)

Balloon borne
atmospheric measurements

Cloud monitor



First Results

- Spectrum
- Composition
- Anisotropy

Energy: straight forward (?) from FD

(but FD only active for 10% of time)

model dependent from SD

(SD active for 100% of time)

get energy calibration from FD

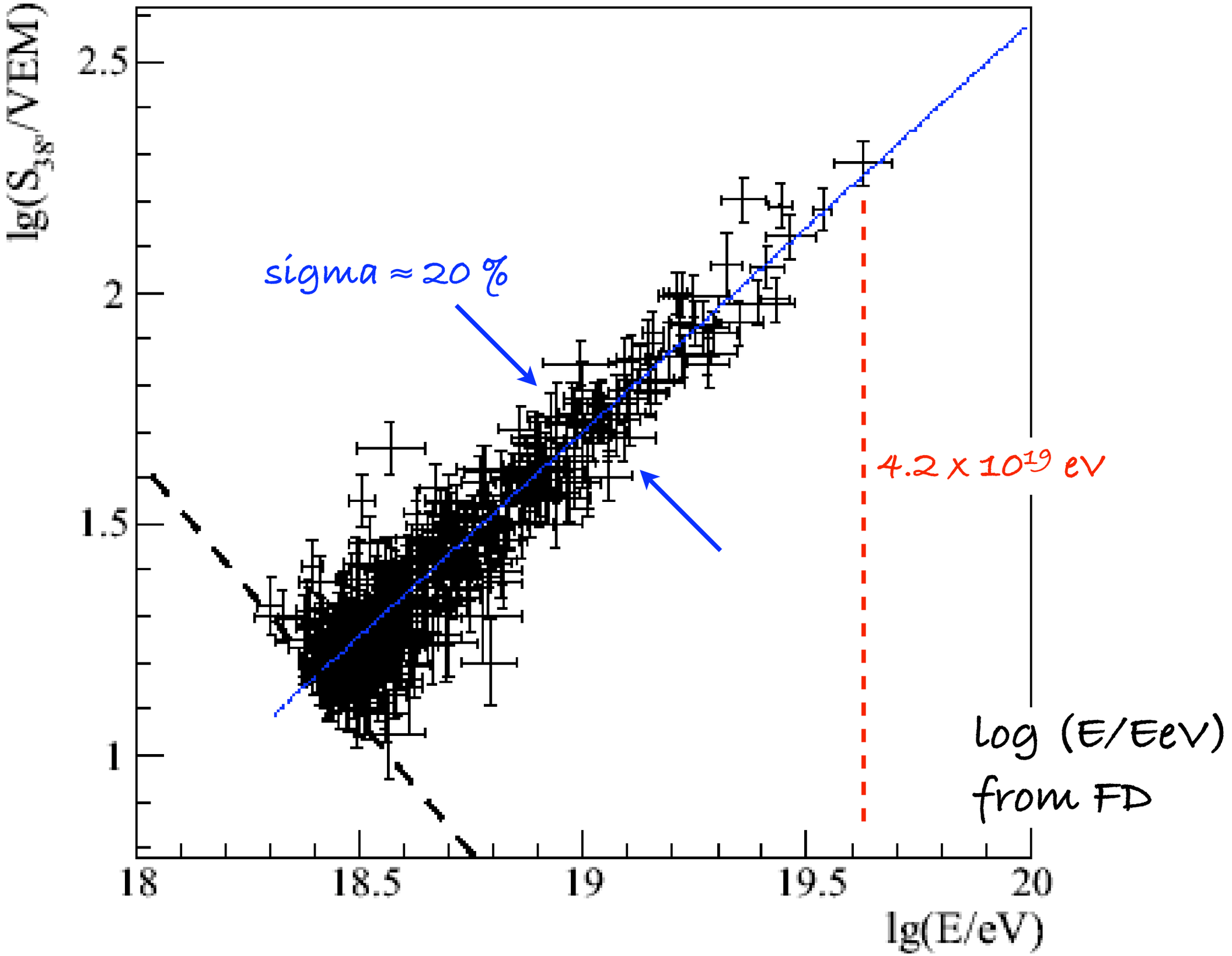
for high statistics from SD

Aperture: directly from size of SD

(above 3×10^{18} eV)

log (S1000) from SD

387 hybrid events



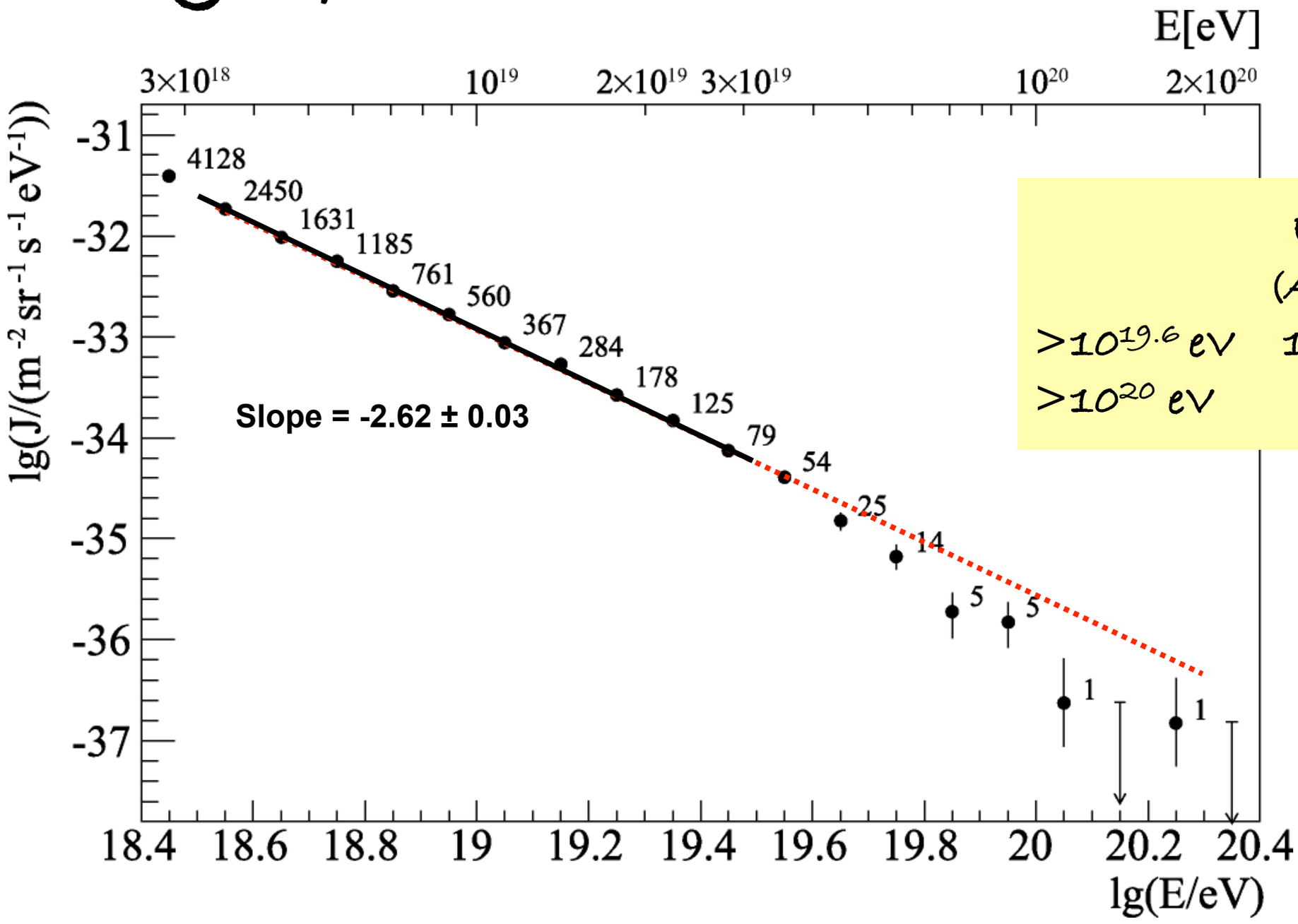
model independent; error on S(1000) decreases with energy

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%

model dependent

Several activities to decrease these uncertainties

Energy spectrum from SD



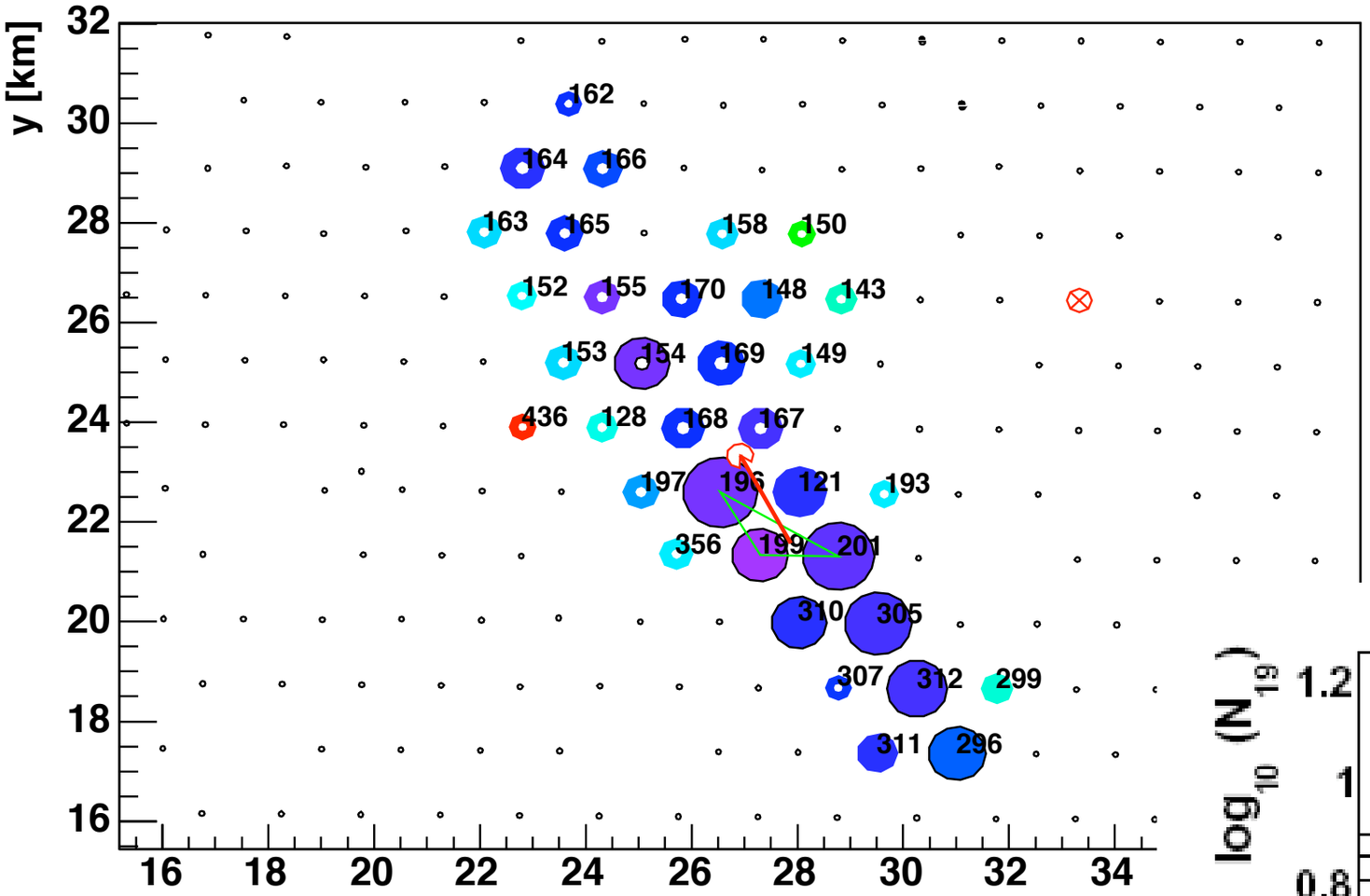
	Exp (AGASA)	Obs (Auger)
$>10^{19.6}$ eV	132 ± 9	51
$>10^{20}$ eV	30 ± 2.5	2

5165 km² sr yr ≈ 0.85 full-Auger years

zenith angle: 0-60°

7725 events > $10^{18.5}$ eV

Event 1099180



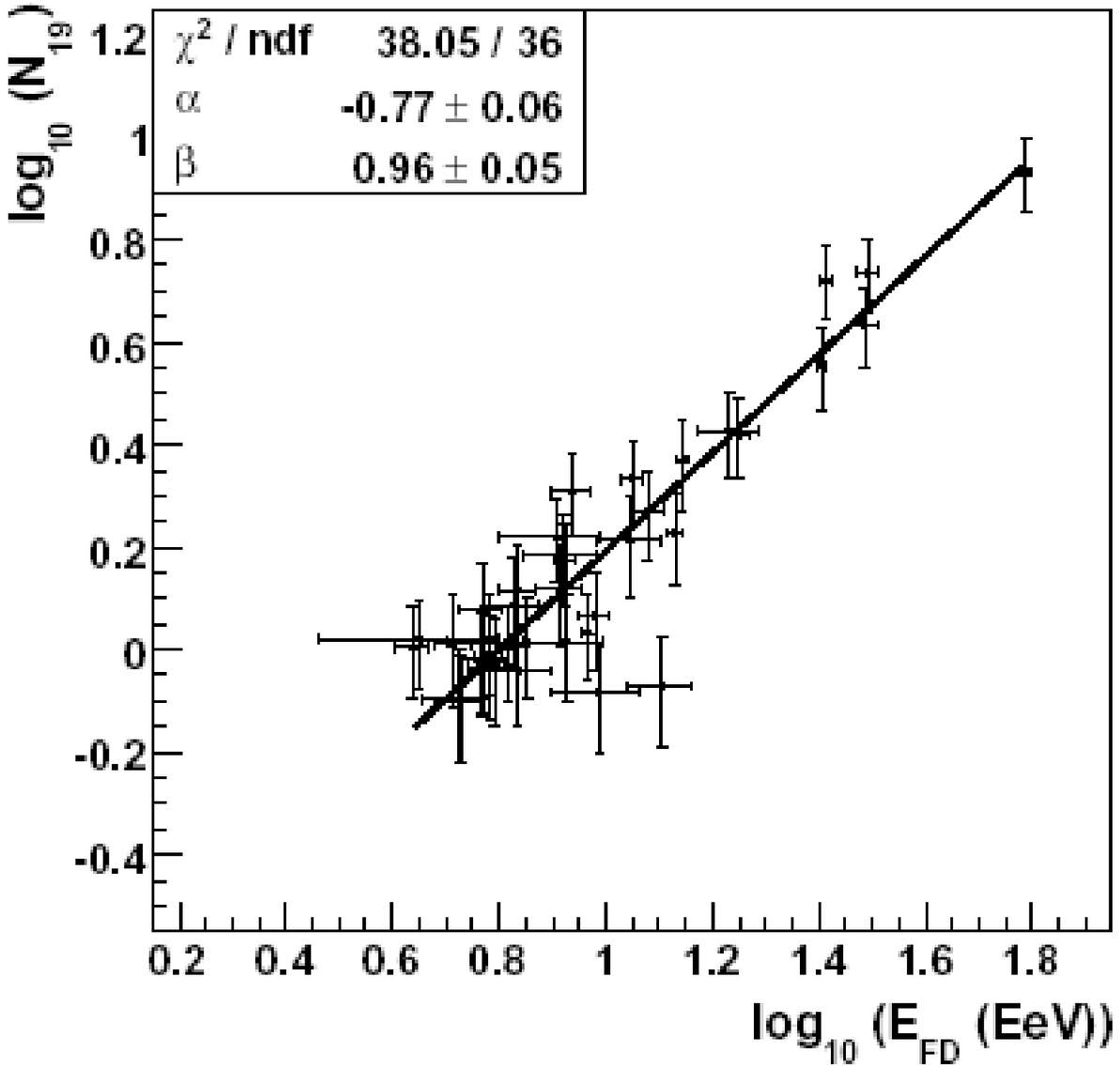
34 tanks, 82°,

$E \approx 10^{19}$ eV

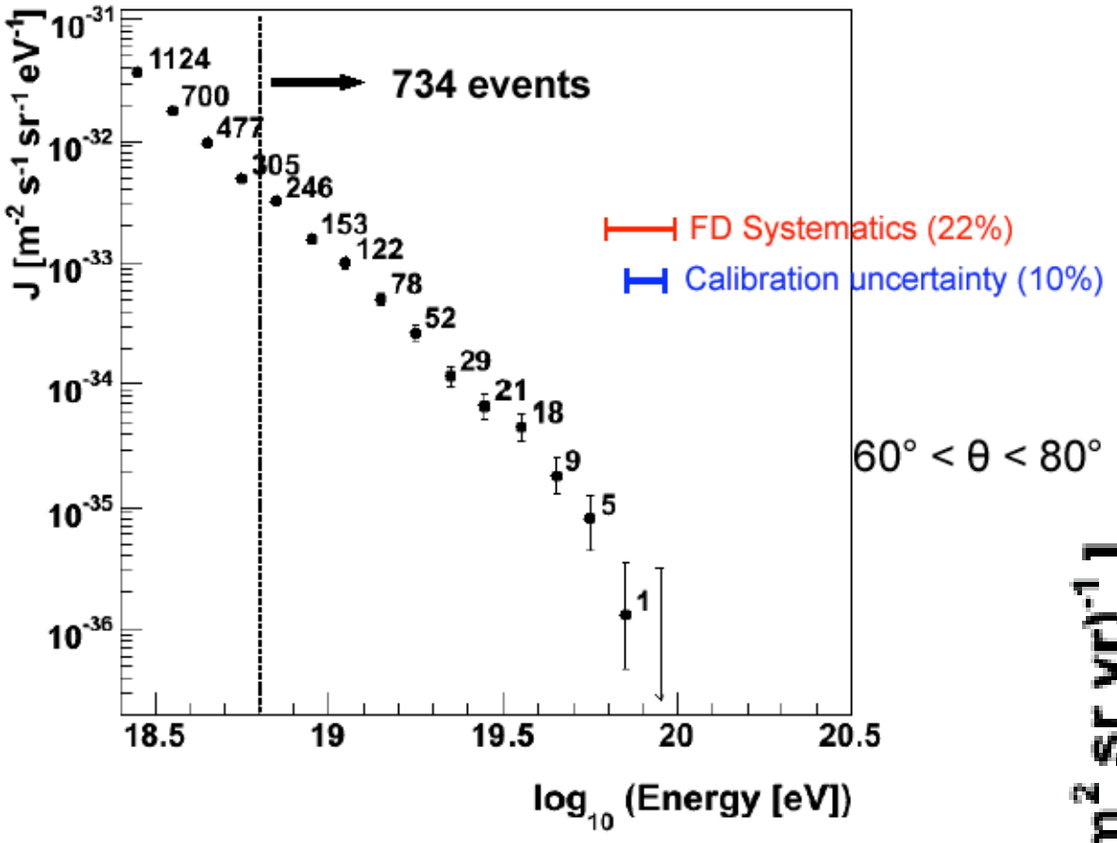
inclined showers add to aperture

only muons survive at ground

N_{19} is suitable energy parameter

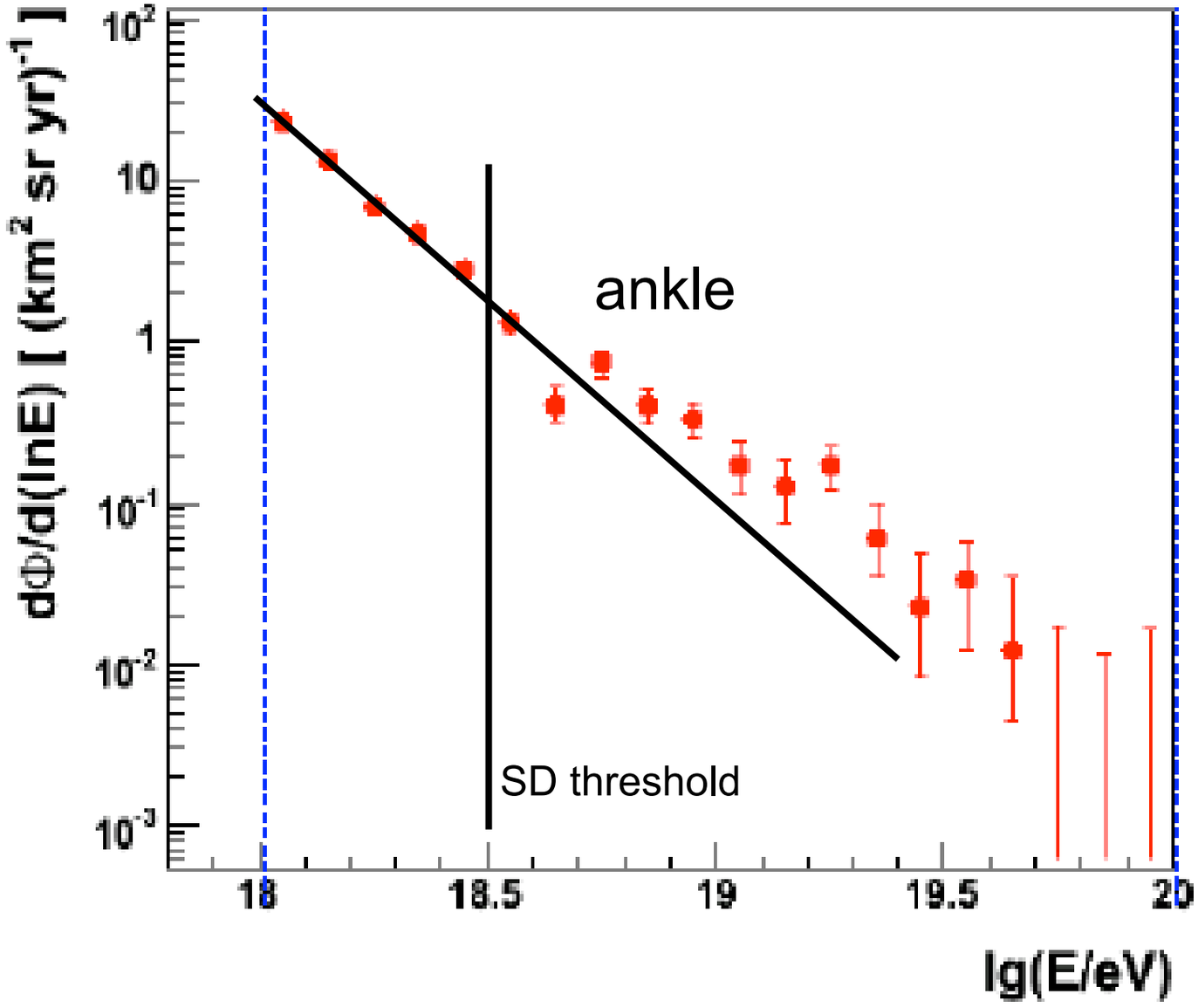


Inclined events energy spectrum



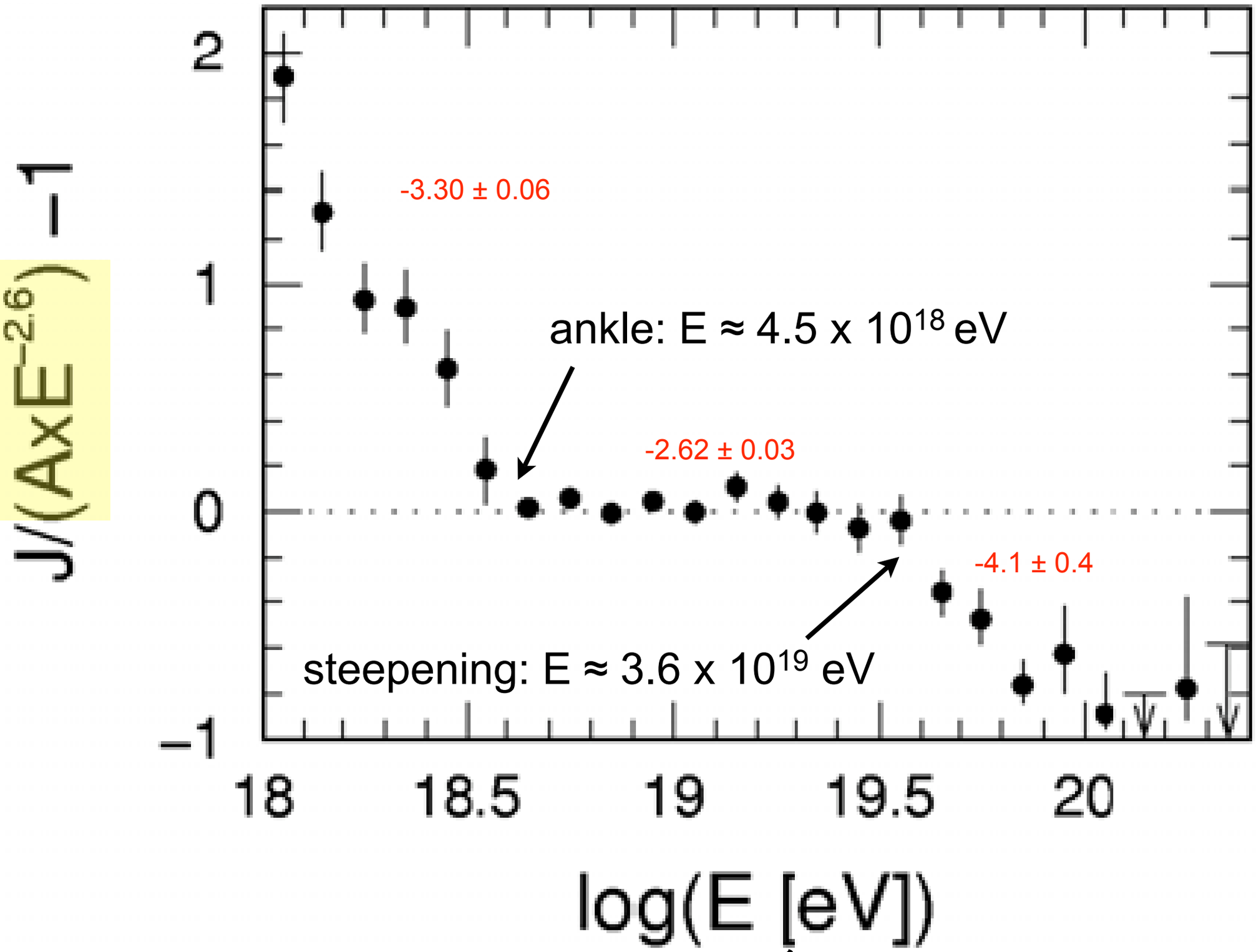
Exposure 1510 km^2 yr sr (29% of θ<60°)

Hybrid Spectrum



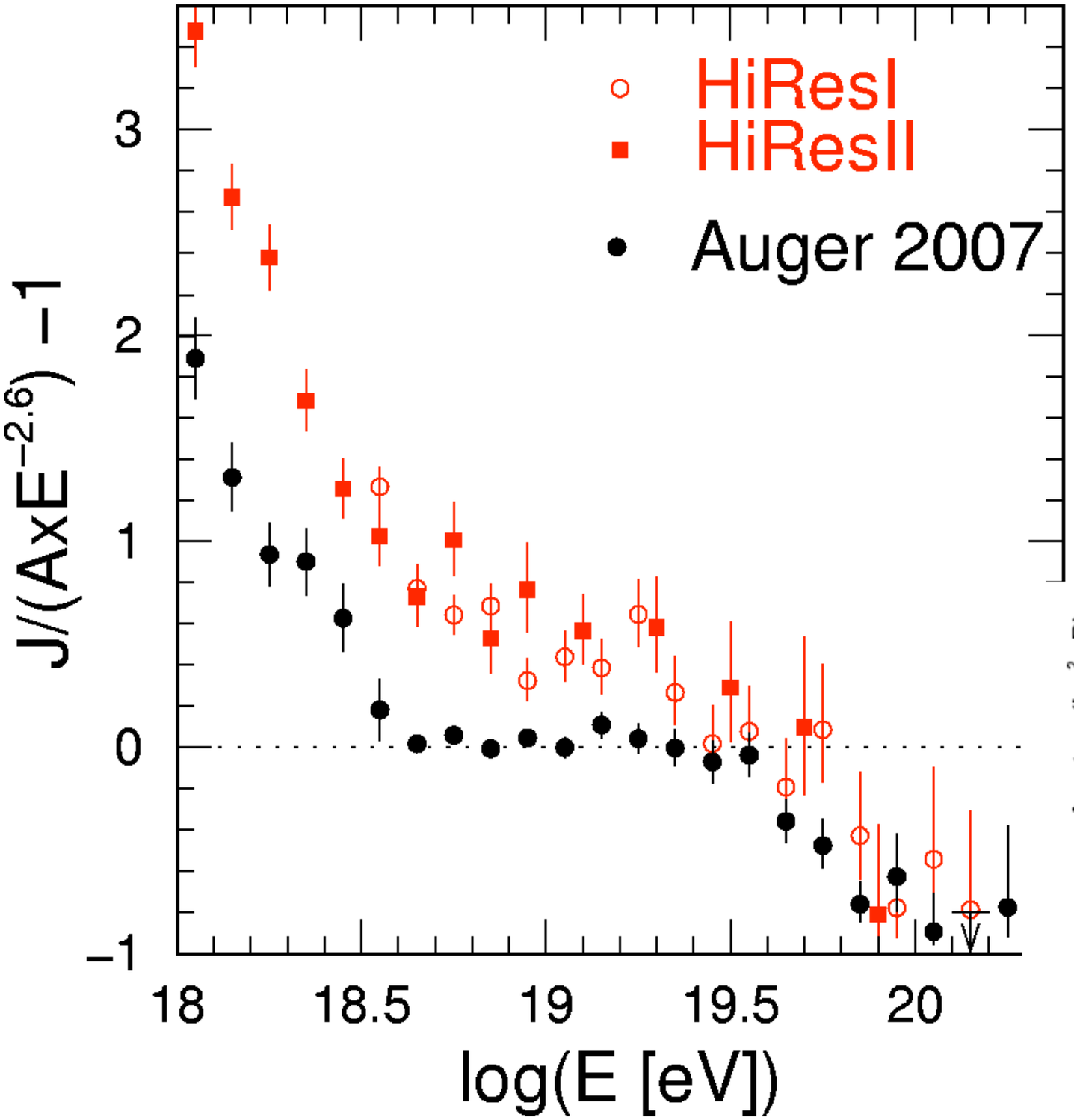
SD vertical
SD inclined
Hybrid
log(JxE^3 [m^{-2}s^{-1}eV^2])
log(E [eV])
25
24.5
24
23.5
18
18.5
19
19.5
20

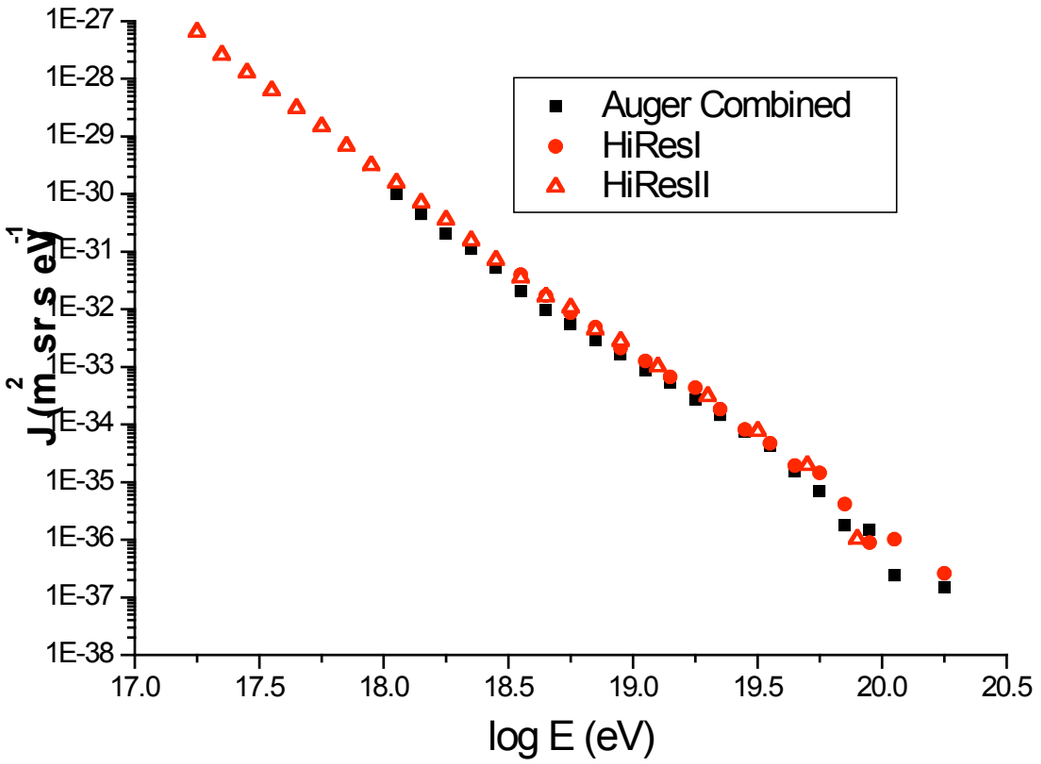
Residuals (combined spectrum)

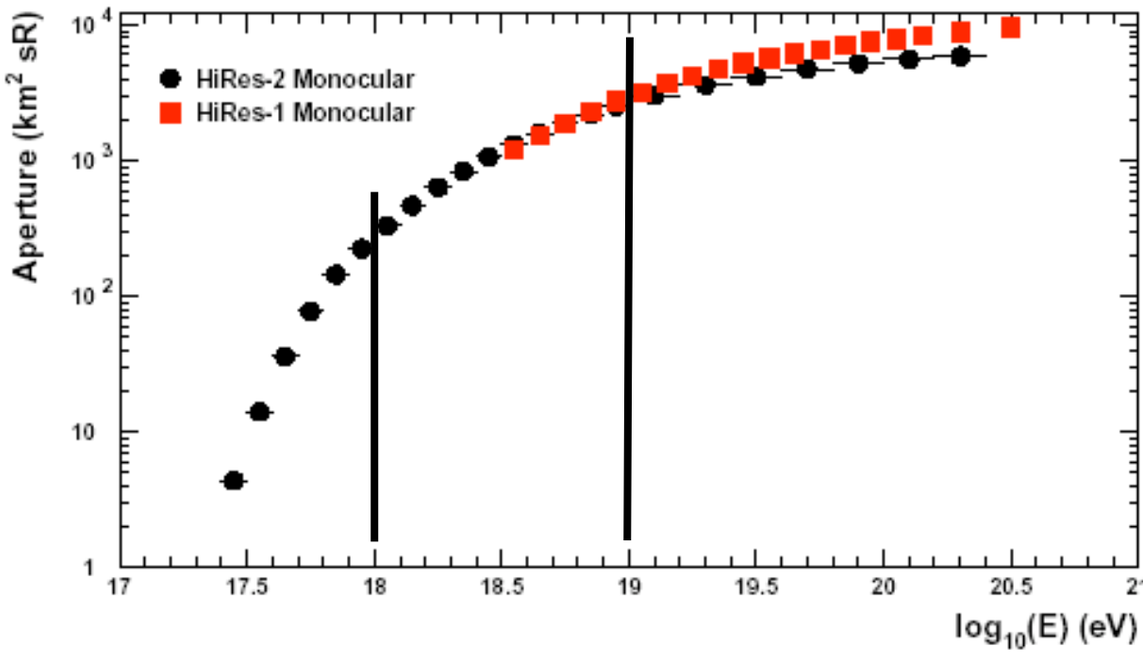


Auger sees a spectral steepening at $E \approx 3.6 \times 10^{19}$ eV.

- model and mass independent ! -







Is HiRes aperture known well enough ?

changes by 10x from 1 to 10 EeV

depends on mass composition, models, spectral slope

Does Auger see the GZK cut-off ?

GZK cut-off: if CRs are protons
power-law spectrum at source, $> 10^{20}$ eV
sources are universally distributed
depression by about a decade at $\approx 5 \times 10^{19}$ eV

Also nuclear primaries would be absorbed,
but not quite in the same way (propagation)

Alternatives:

- maximum energy of accelerator
- effect of a local source

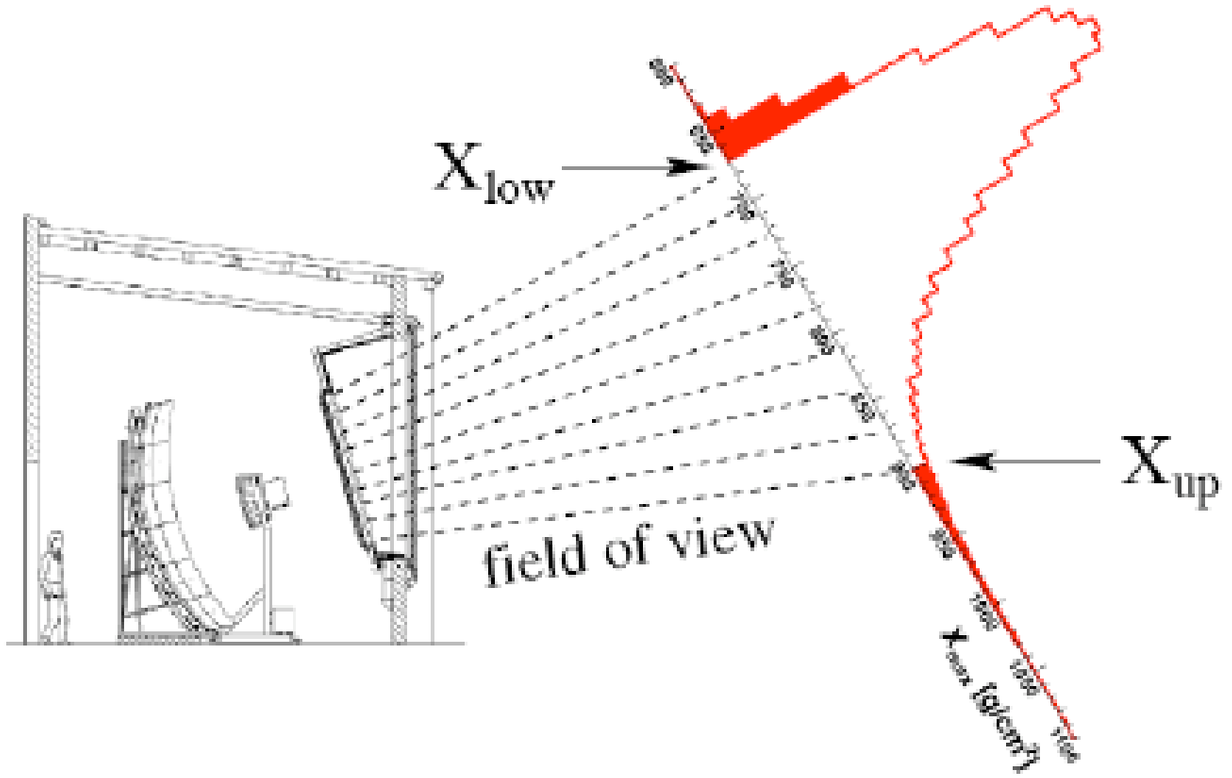
Is ankle the transition point between galactic and extragalactic CRs ?

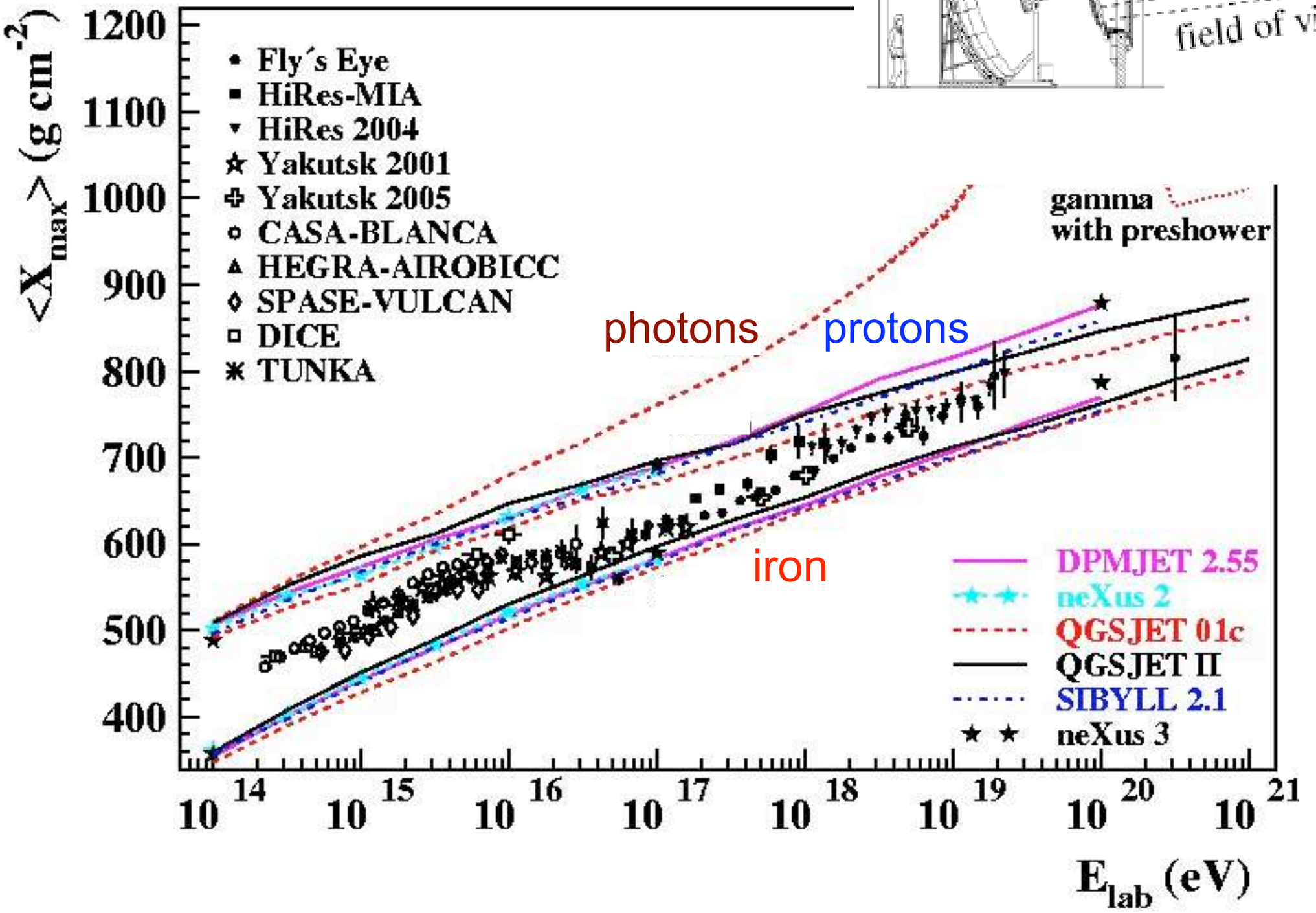
... need more info on **composition** ...

FD: measure X_{max}

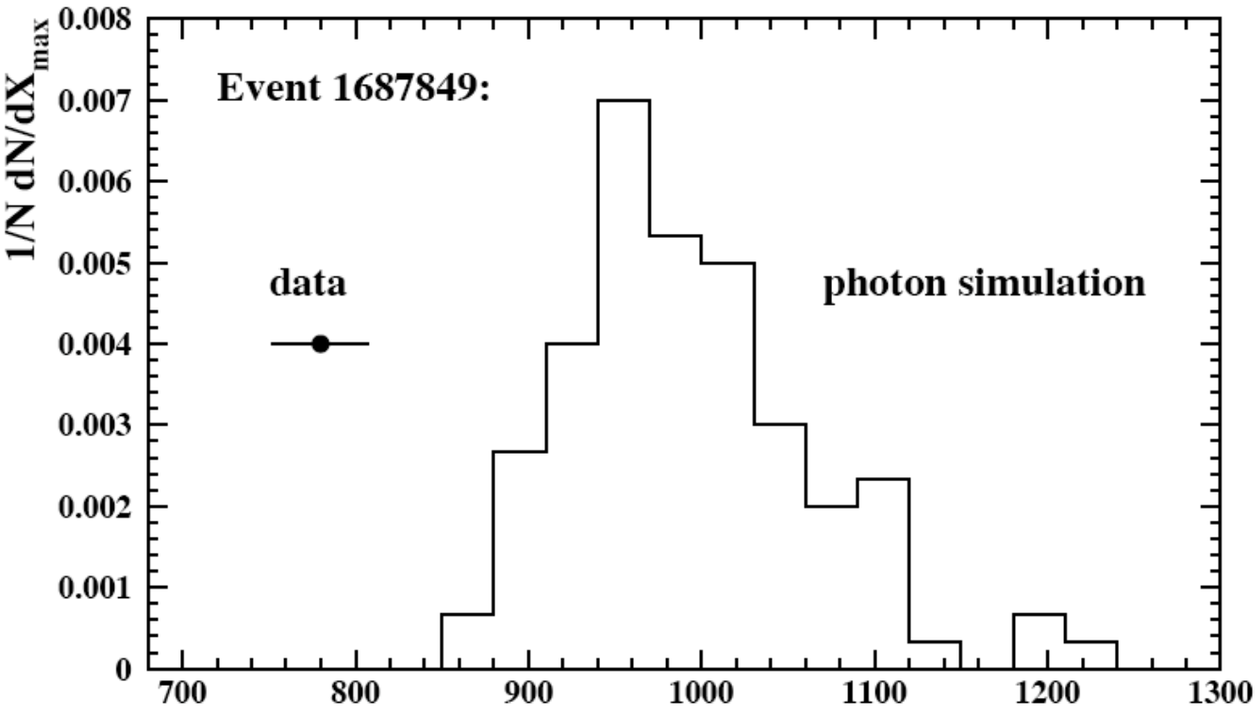
photons maximise deeper than nuclei

protons maximise deeper than iron



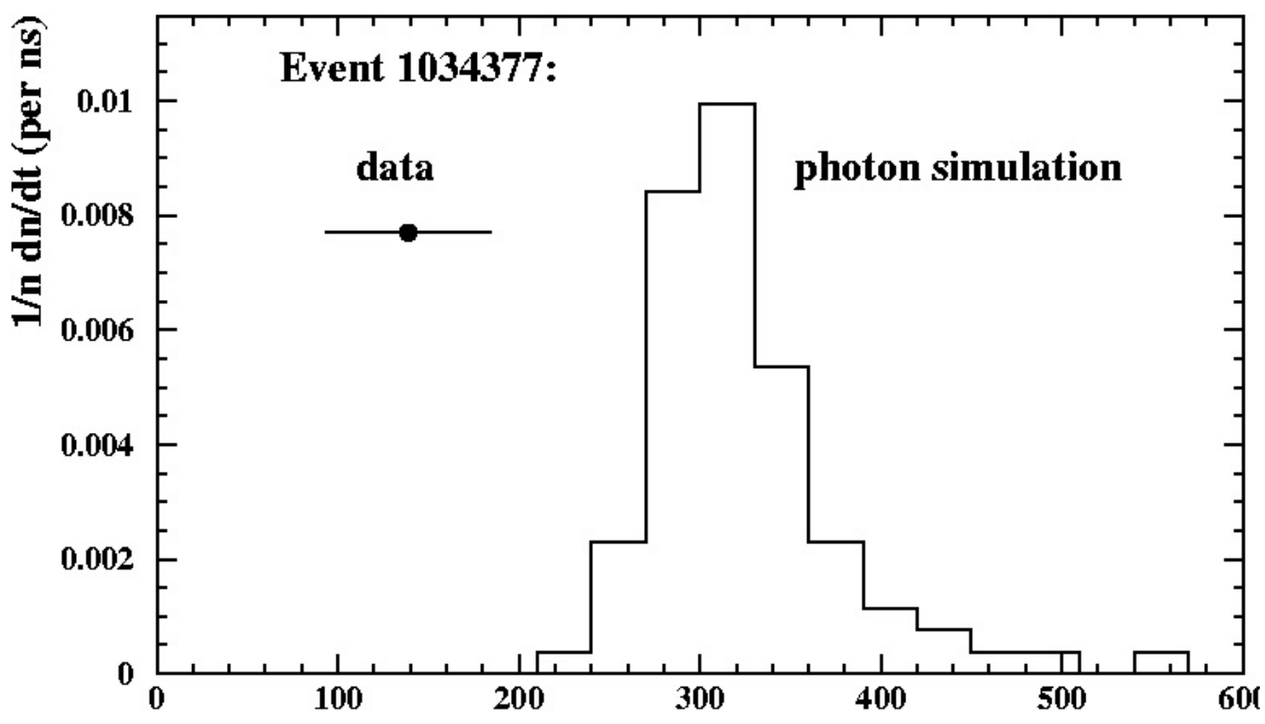


Hybrid events



Xmax (g/cm²)

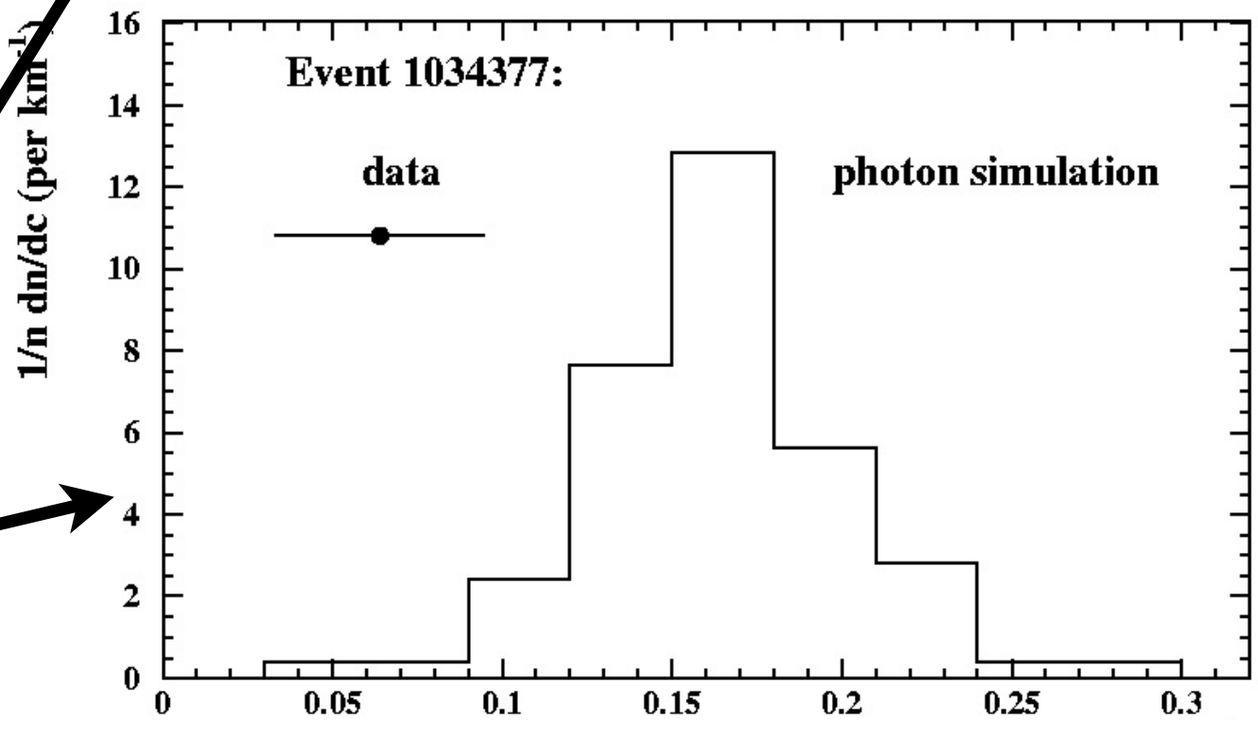
SD events



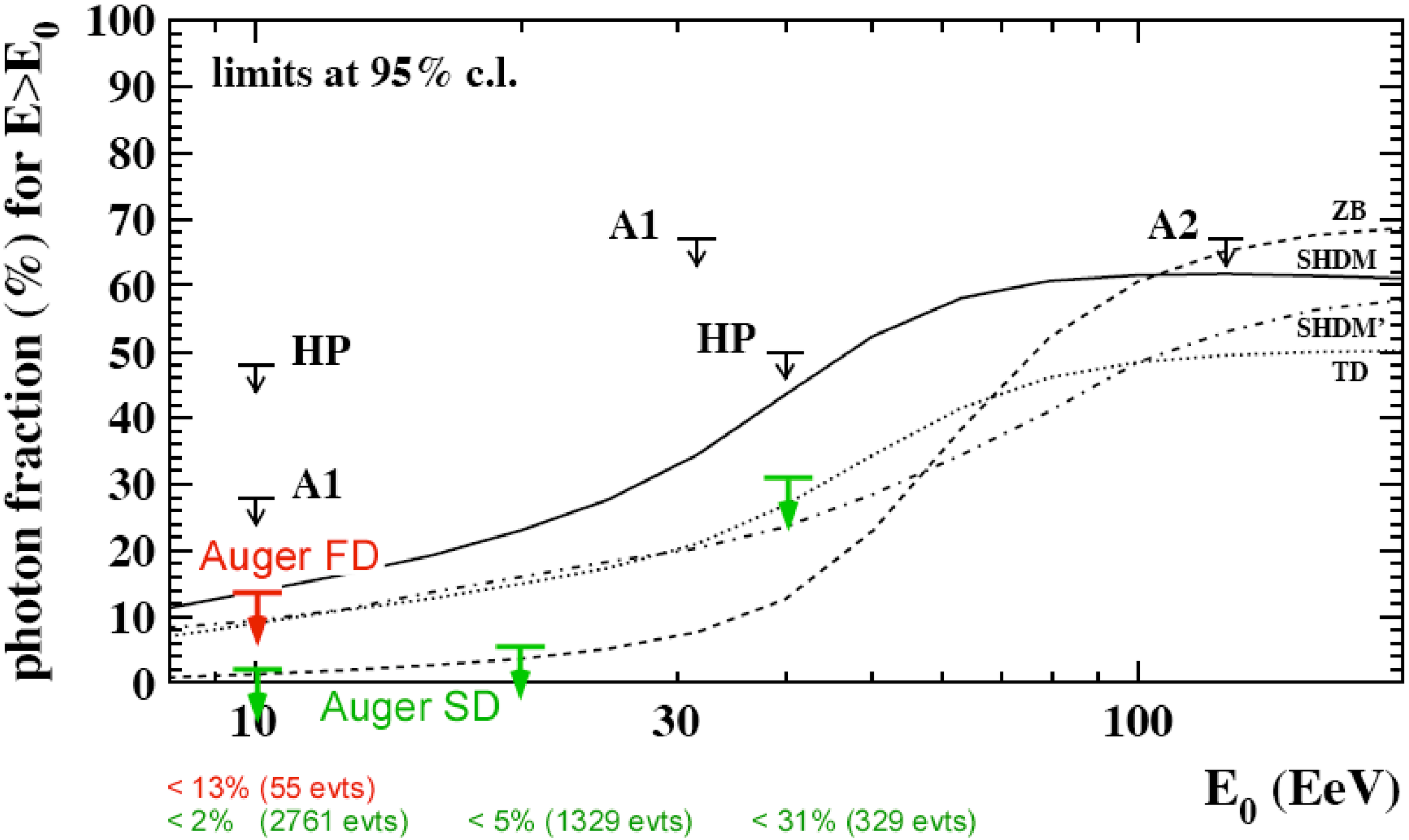
signal rise time (ns)

Compare each event with photon MCs,
Combine probabilities for all events

SD: much larger statistics,
but reconstruction not mass independent

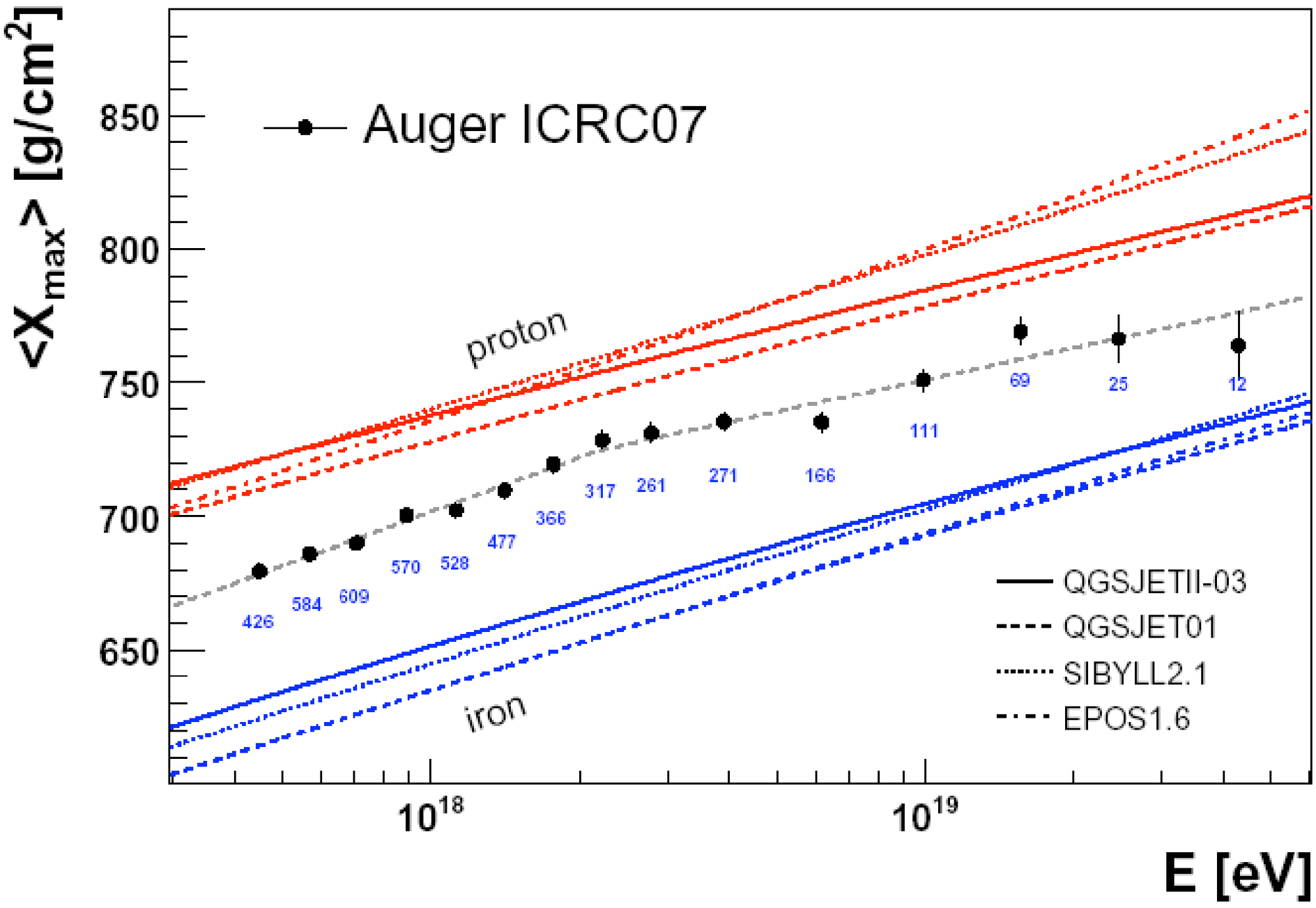


curvature of shower front (1/km)



Auger Collaboration
Astrop. Phys. 27 (2007) 155
to be submitted to Astrop. Phys.

Hadronic composition from $X_{max}(E)$



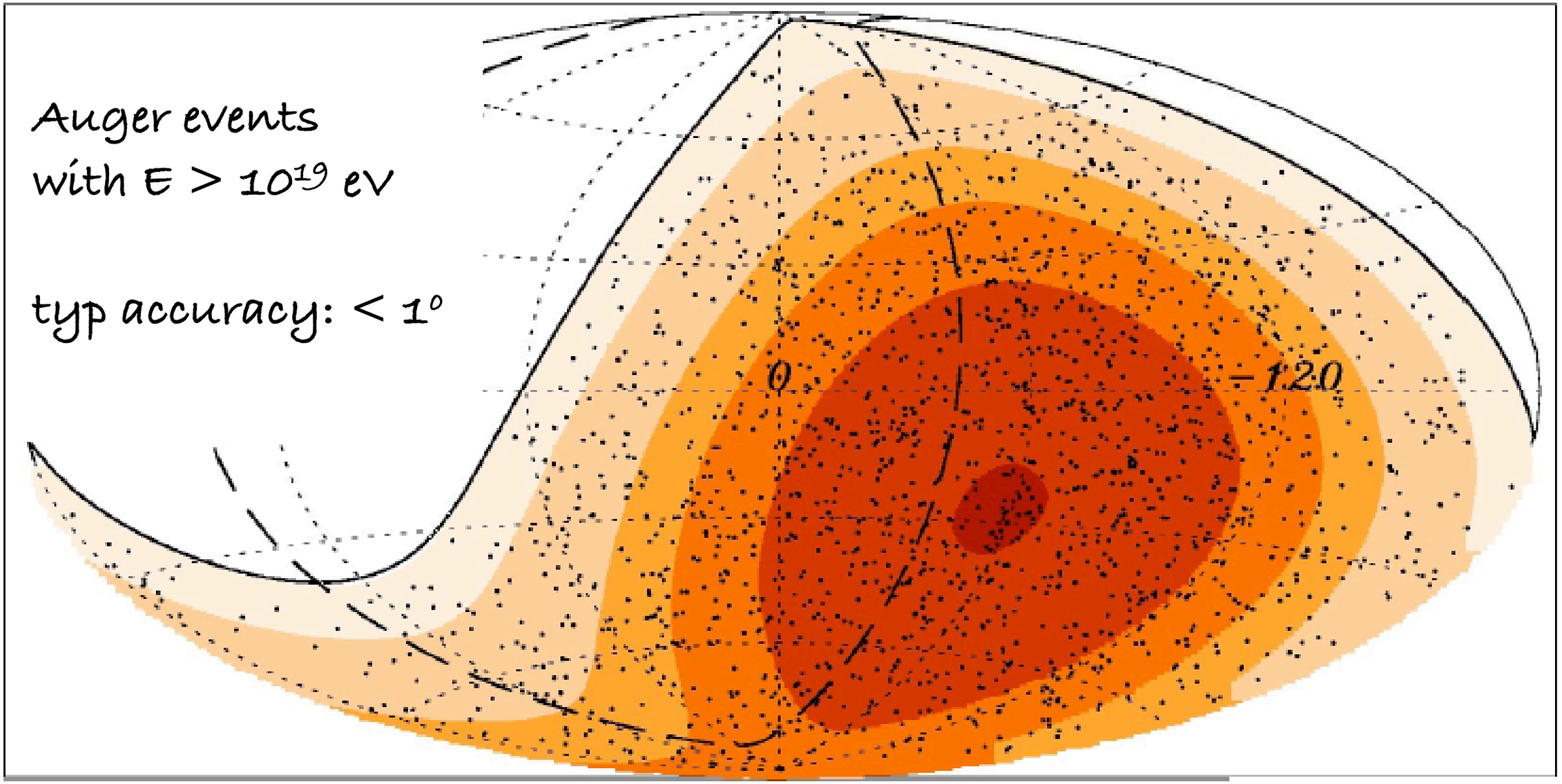
Mixed composition up to highest energies ? not expected

(Results strongly model dependent)

needs more work: fluctuations in X_{max}, SD events, ...

Auger events
with $E > 10^{19}$ eV

typ accuracy: < 1°



Clusters, point sources ? (AGASA)

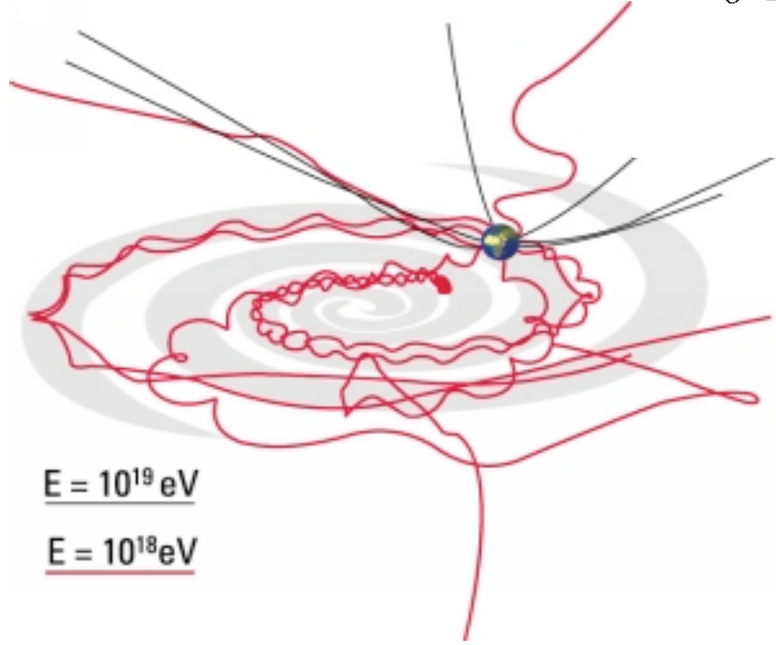
Large-scale anisotropies ? (AGASA, Sugar)

Correlations with potential source populations ?

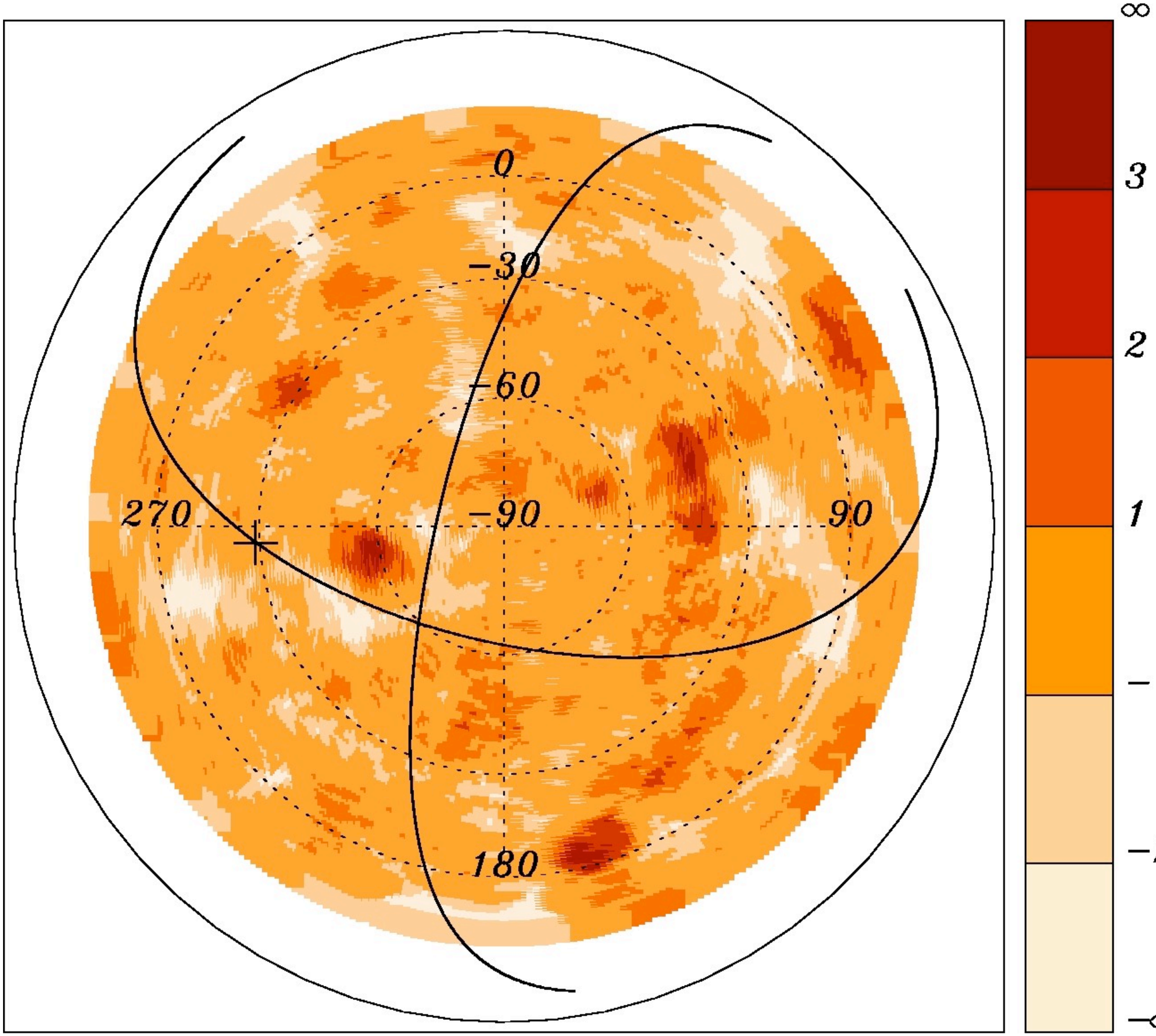
e.g. Blazars, AGNs, ... (HiRes)

Alignment & ordering in energy ?

- expected for real cosmic ray sources
- "spectroscopy" in cosmic magnetic fields

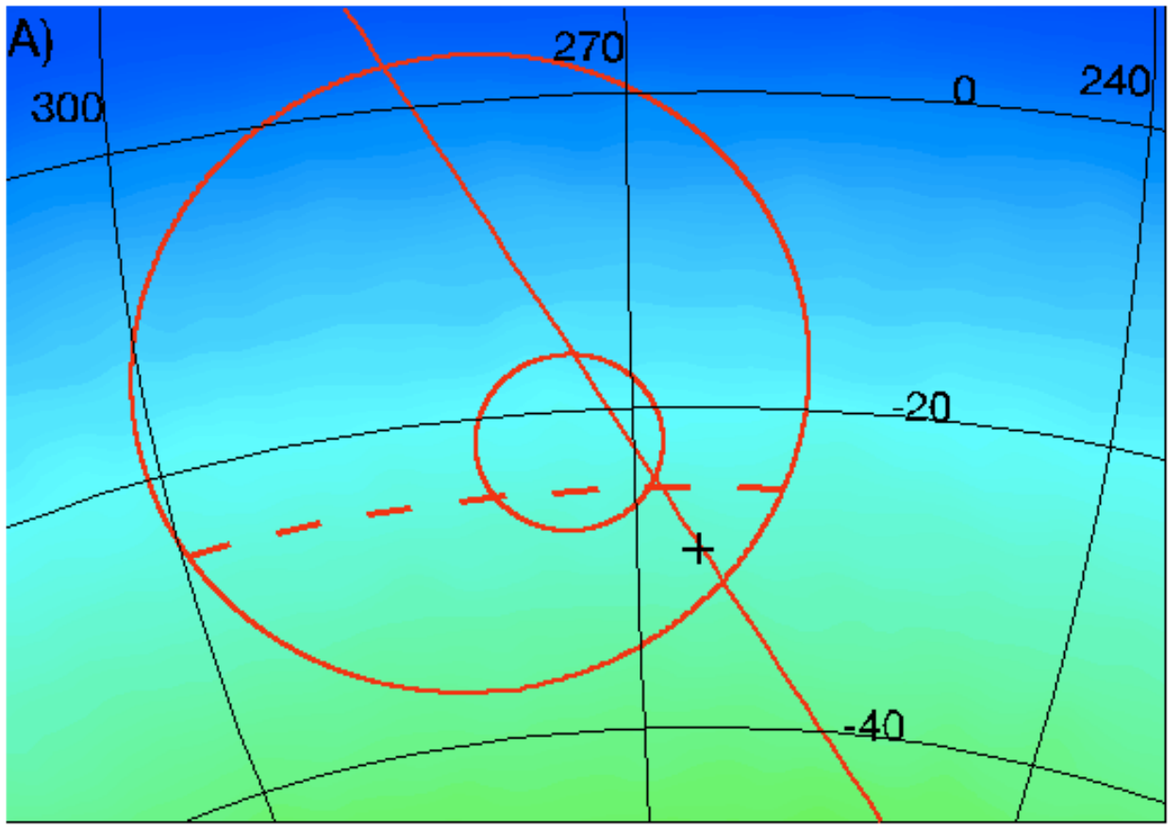


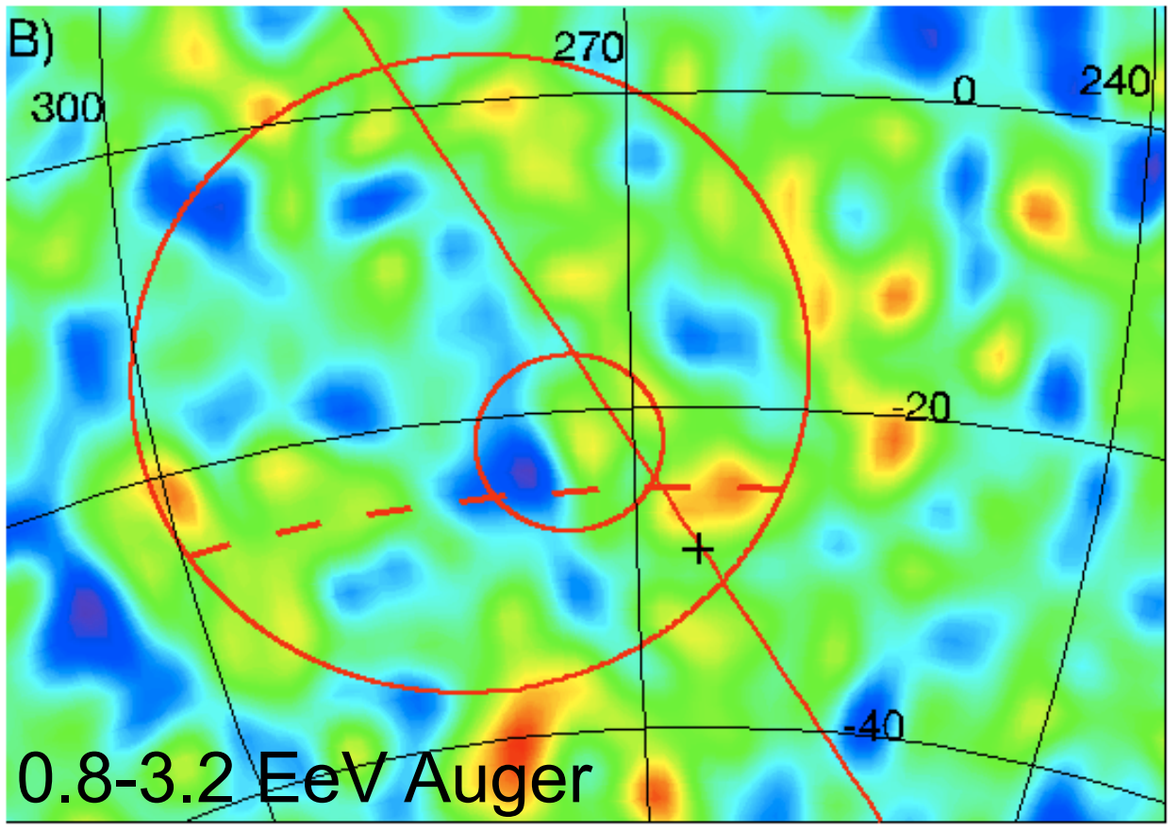
No large over-densities or dipoles

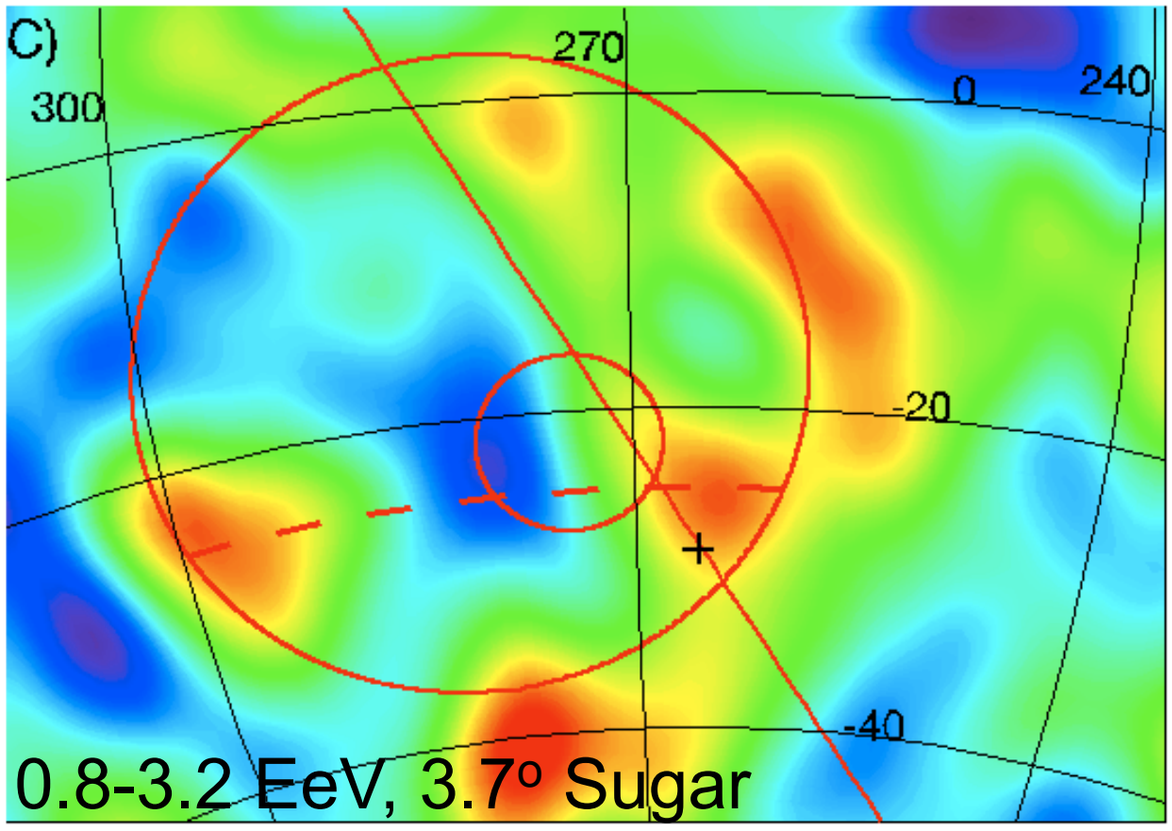


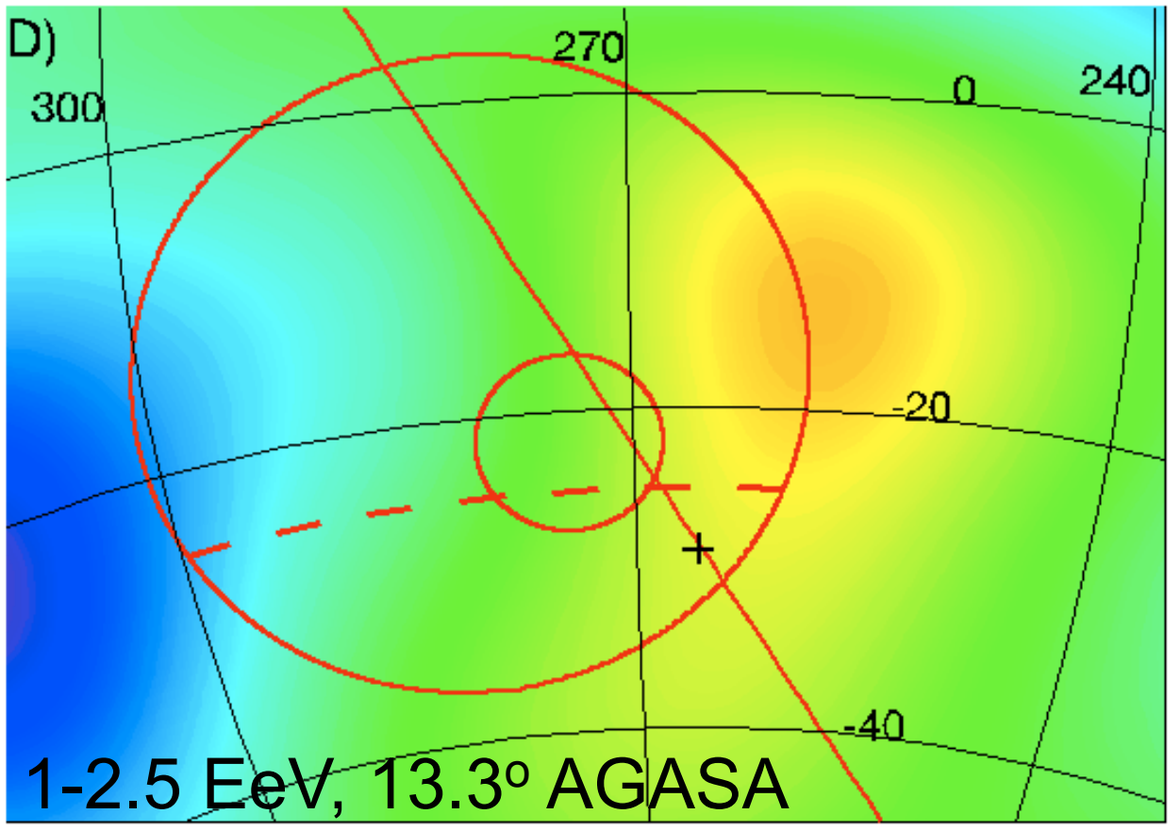
Auger: Galactic Centre

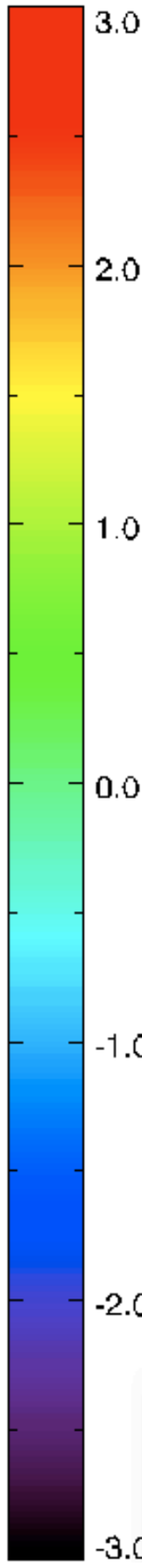
see Astrop. Phys. 27 (2007) 244











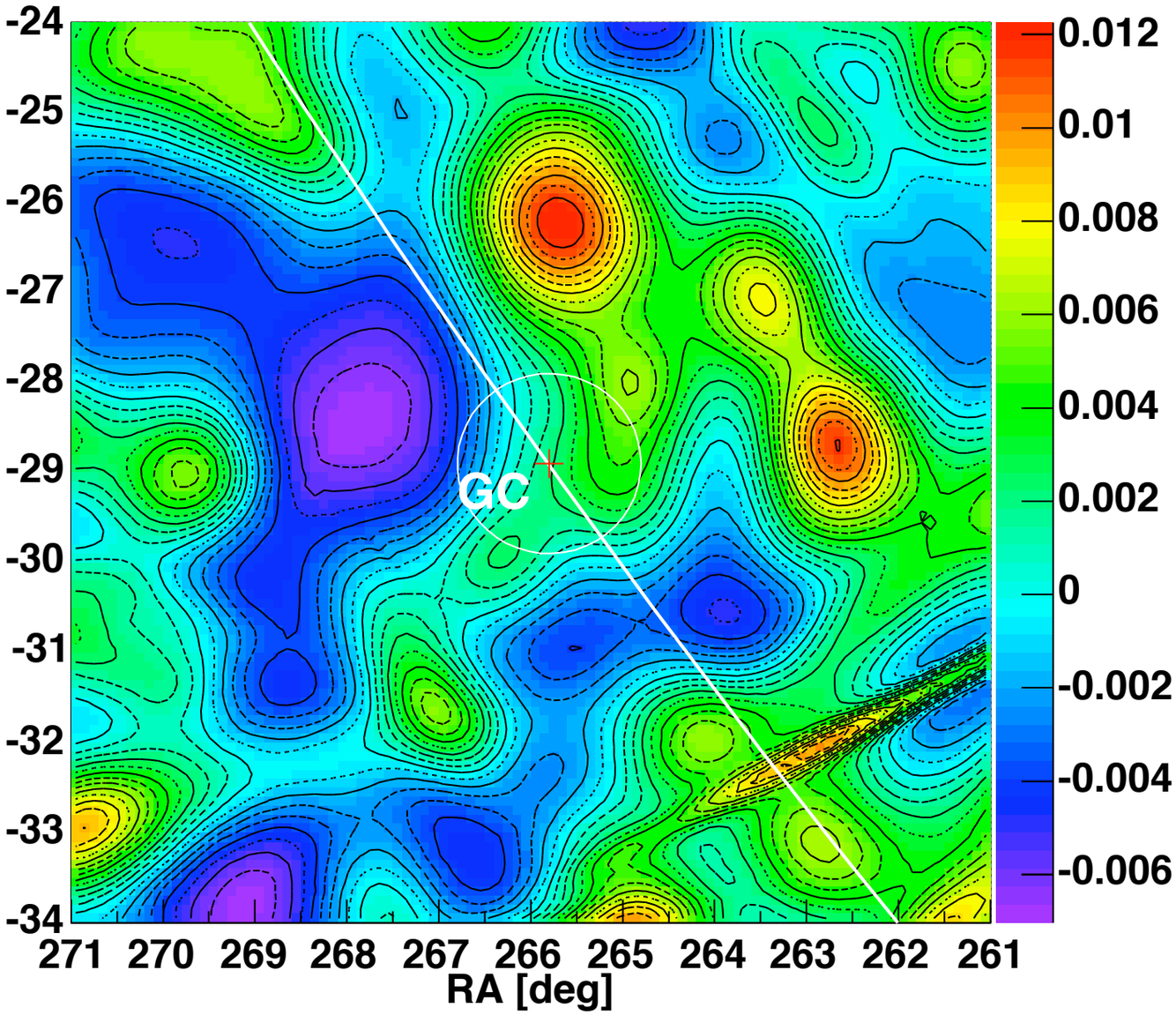
1.0-2.5 EeV AGASA:
506/414
+4.5σ or +22%

Auger:
1155/1160
(22% excess would give +1415 evts. or +7.5σ)

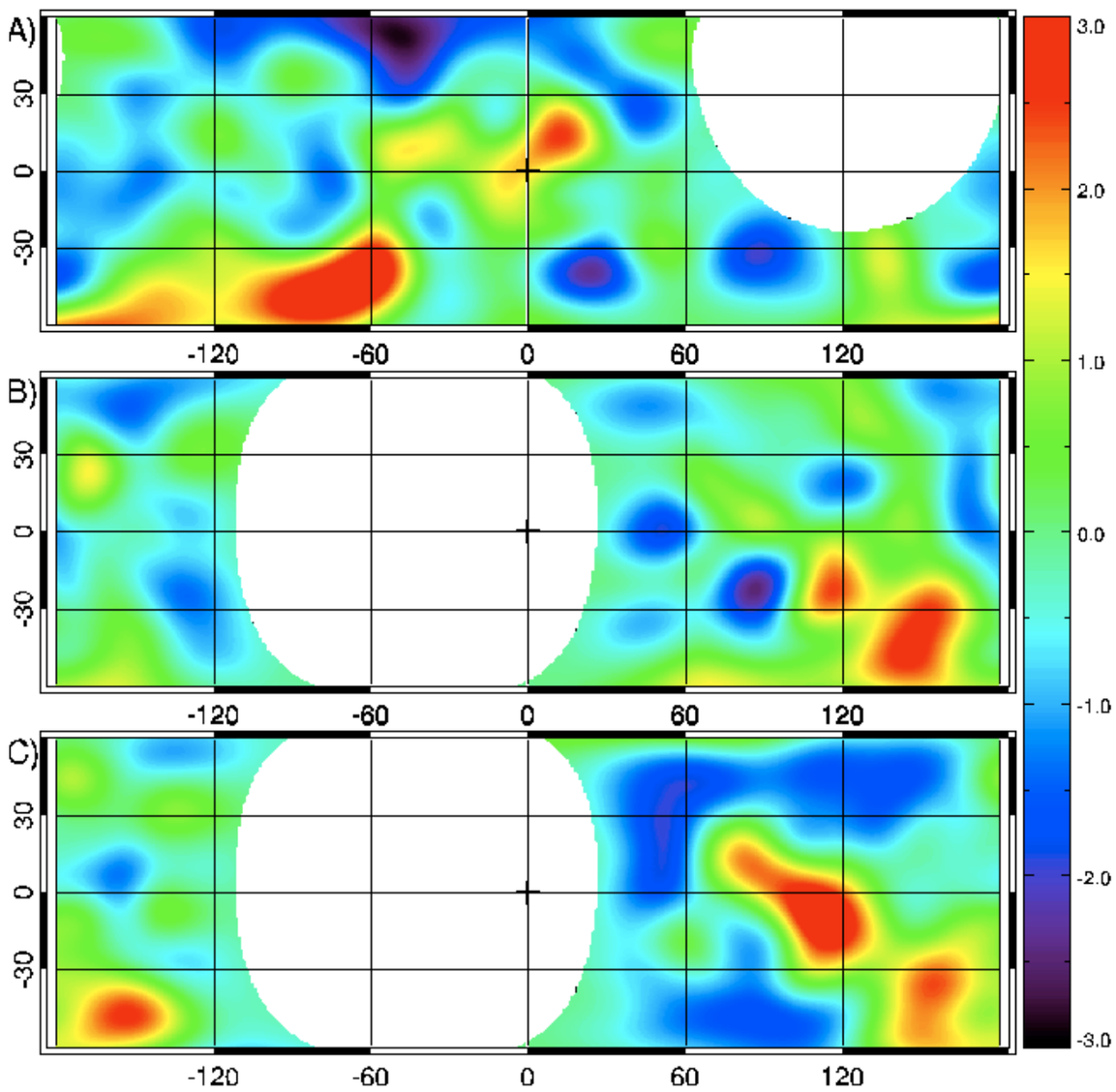
0.8-3.2 EeV Sugar:
22/12
+2.9σ or +85%

Auger:
144/151
(85% excess would give +279 evts. or +10.5σ)

no point source



no correlation with galactic or super galactic plane



No dipoles or large-scale excesses

No significant emission from Galactic Centre
as claimed by AGASA and Sugar

No small-scale clustering as claimed by AGASA

No signal from BL Lacs as claimed by HiRes

but:

Some first hints for anisotropy at are seen:

2 prescriptions are set up
to be tested with independent data sample
(answer very soon)

...and
Auger will increase event number 5-10x in next few years

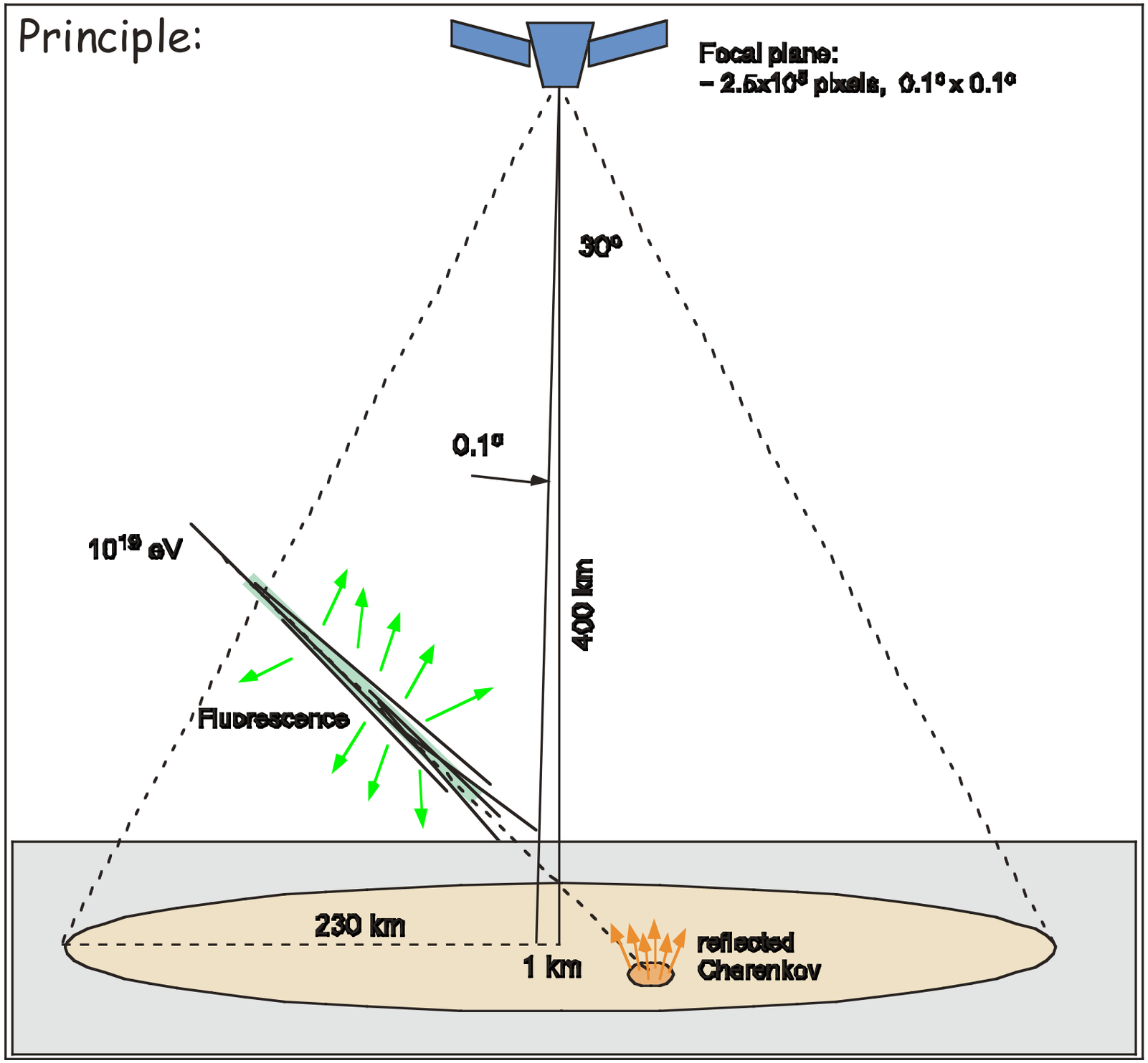
even larger: Space-based UHECR Experiments

e.g. EUSO

$A\Omega \approx 10^6$ km^2 sr

$> 10^3$ Events/year
with $E > 10^{20}$ eV

(50-100 x Auger)



EUSO as neutrino detector

Target mass:

$\approx 10^{16}$ kg Air !!!

$\approx 10^{4}$ km^3 Water/Ice

$\approx 10^{4}$ x IceCube