Lectures at Dublin Summer School: 7 July 2011

Cosmic Rays

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OUTLINE

Lecture 1

Some History

Properties of Low Energy Cosmic Rays

Tutorial on physics of air showers

Cosmic rays at ≈ 10^{15} eV – the ‘knee’

Lecture 2

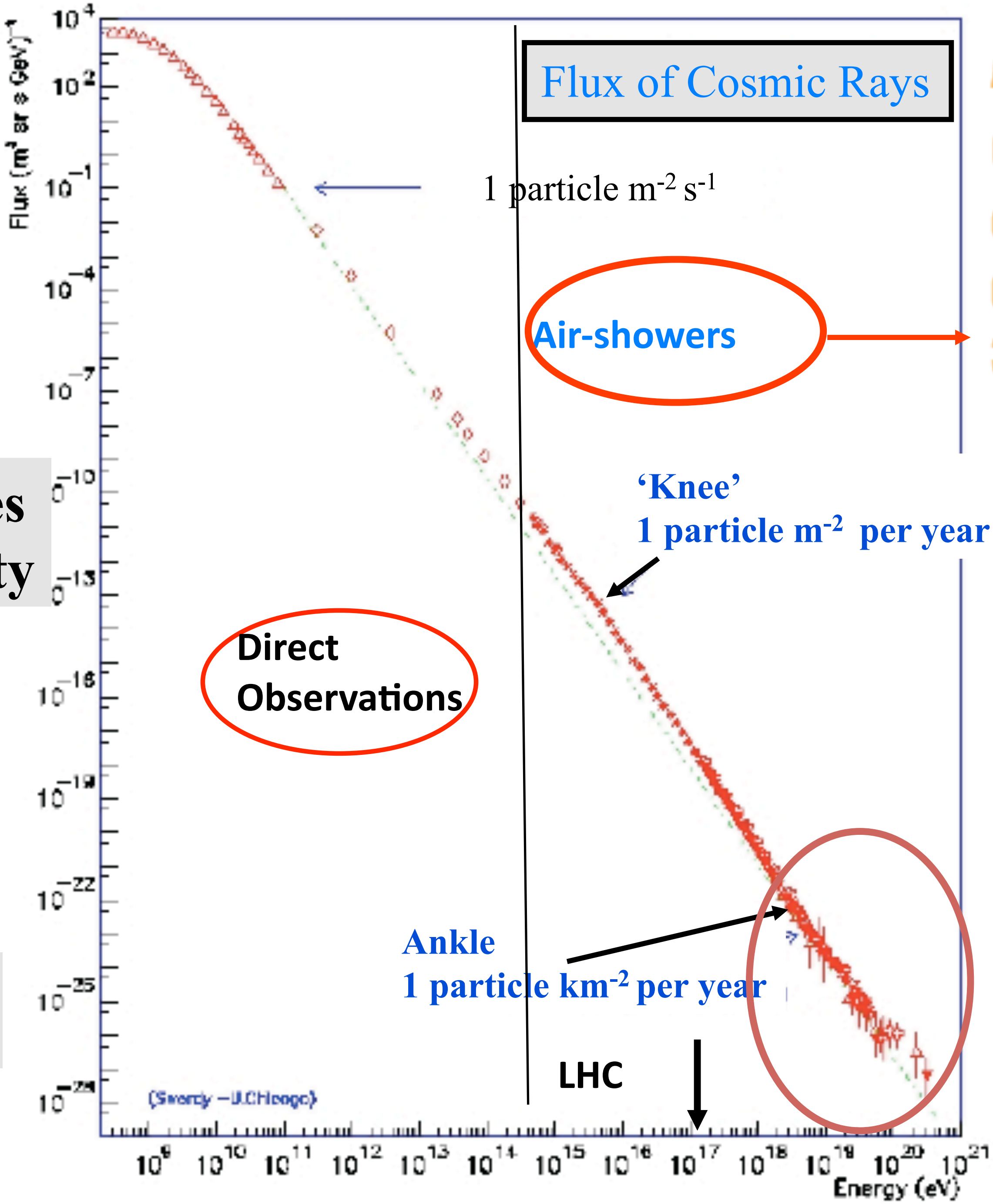
The Highest Energy Cosmic Rays

Why study them?

Pierre Auger Observatory

Results

Flux of Cosmic Rays



1 particle m^{-2} s^{-1}

Air-showers

'Knee'
1 particle m^{-2} per year

Direct Observations

Ankle
1 particle km^{-2} per year

LHC

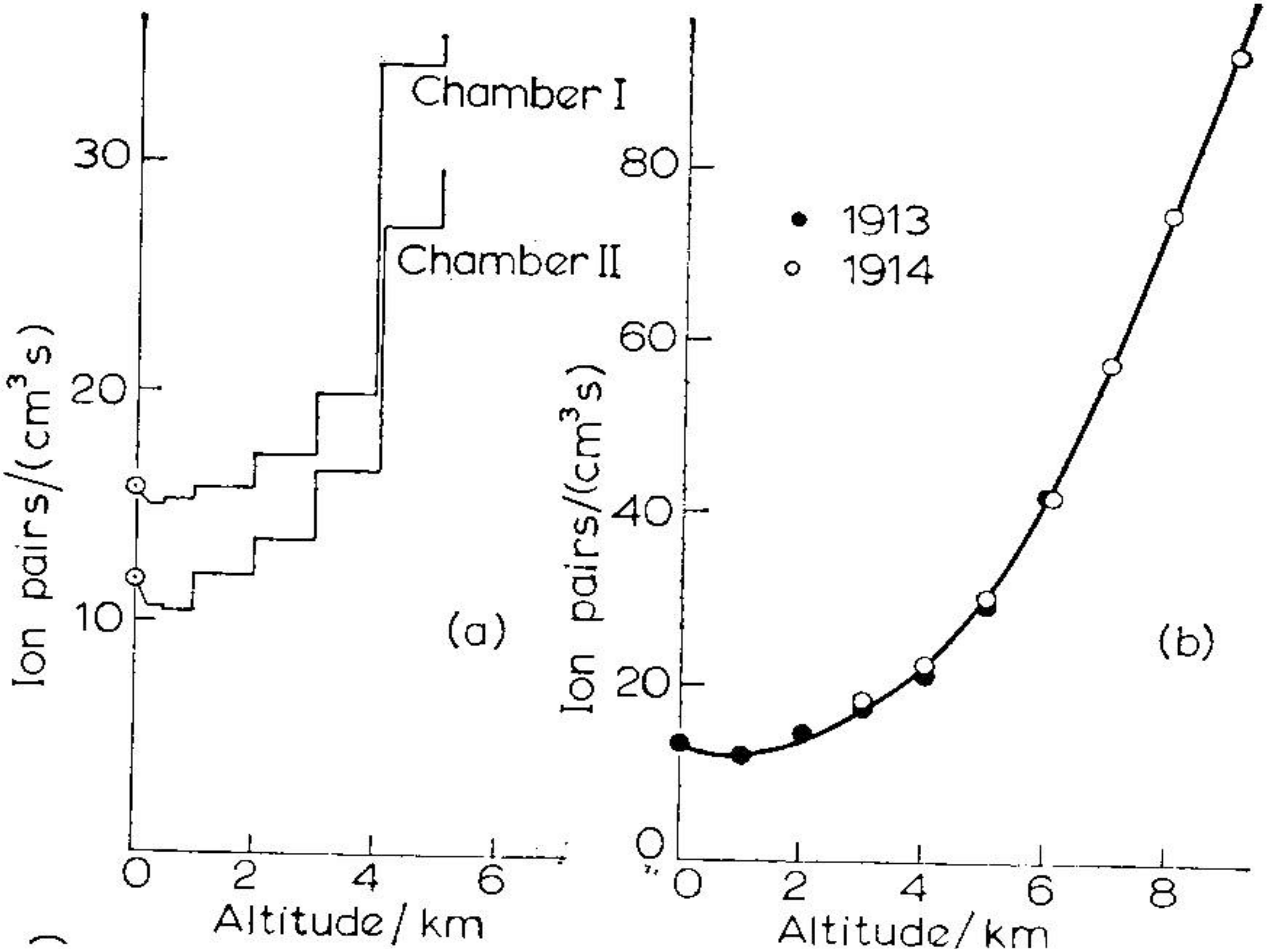
25 decades in intensity

S Swordy
(Univ. Chicago)

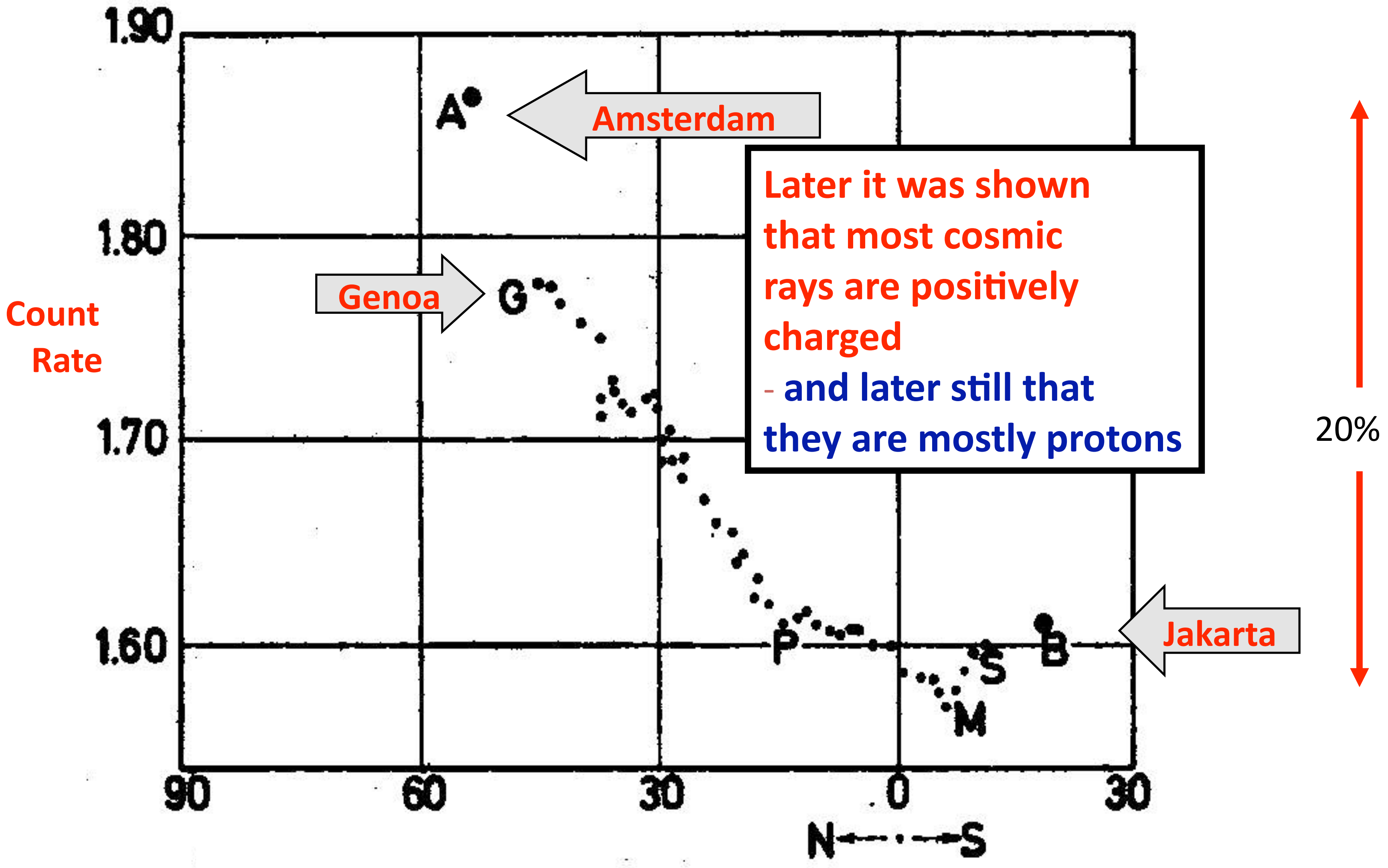
11 Decades in Energy

Hess bei Ballonlandung (1912).

Hess Data **Kolhöster Data**

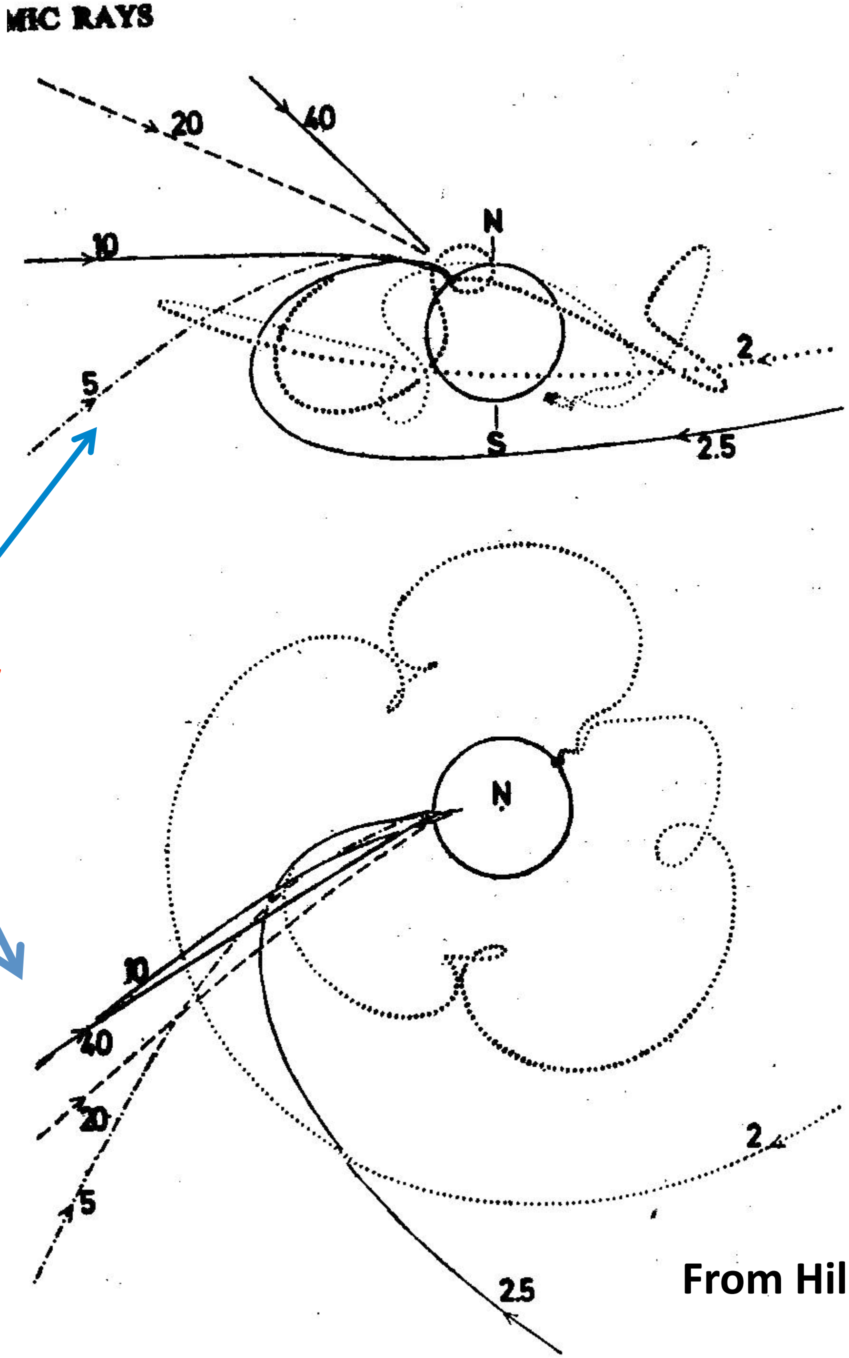


Clay's Results, taken by Berlage (~1926)



Later it was shown that most cosmic rays are positively charged
- and later still that they are mostly protons

Counting Rate at sea-level as a function of the position of the ship with respect to the earth's magnetic field which is nearly horizontal at the earth's equator



Energies in GeV

Vallarta 1932

From Hillas 'Cosmic Rays'

Some properties of low energy cosmic rays

- Energy density of cosmic rays ≈ 1 eV cm^{-3}

- Similar to energy density in 2.7 K radiation, starlight, turbulent gas motions and magnetic fields – only the last two are significant equalities

- 1 eV cm^{-3} through out Universe faces us with a daunting problem

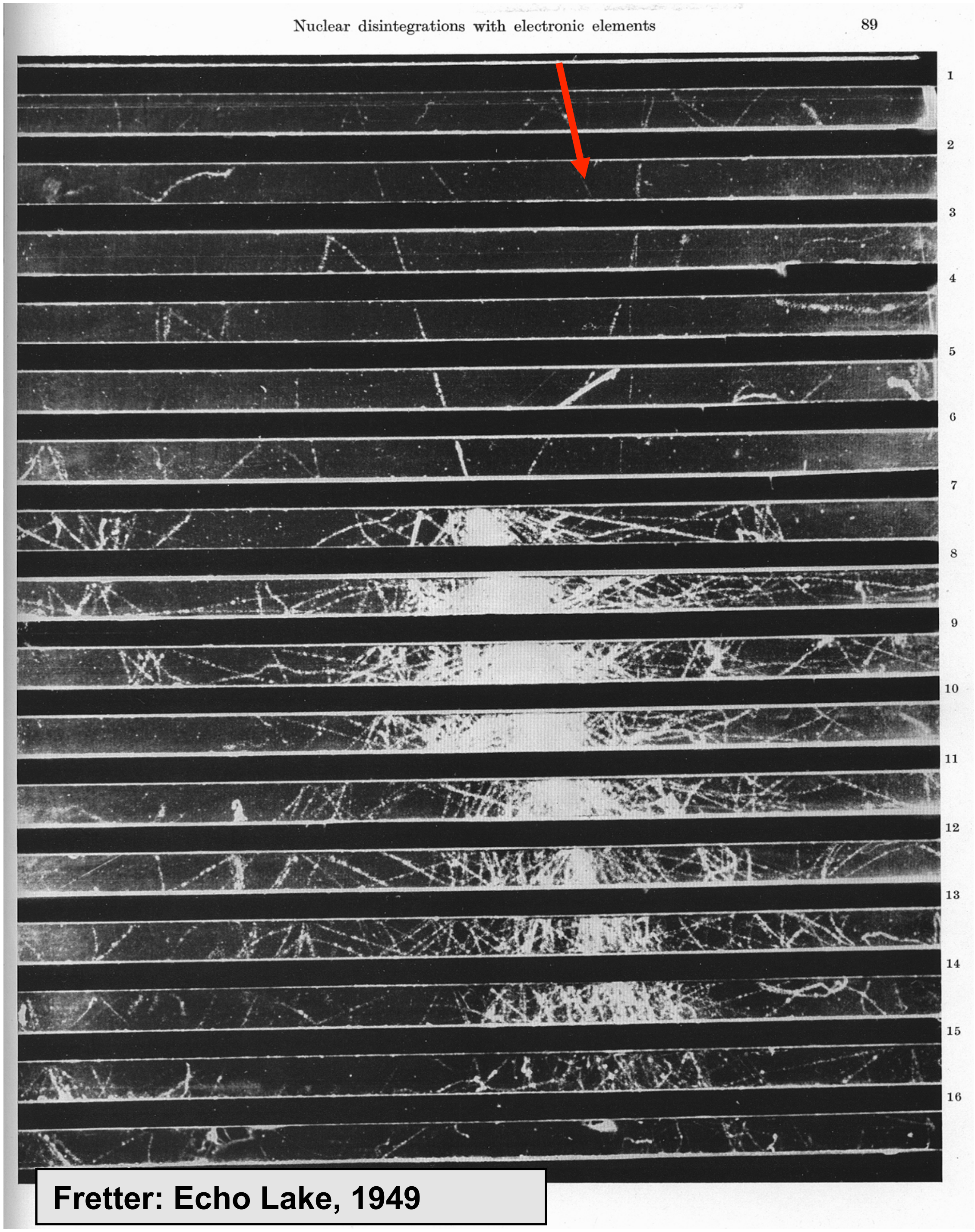
- For low energy cosmic rays , our galaxy is a place where sources are likely to be located: for the highest energy cosmic rays???

- Can be observed directly up to ≈ 100 TeV from balloons (e.g. ATIC) and from space (e.g. AMS – watch out for results from this)

- Detectors are used to measure –dE/dx and the charge, with the energy being measured in a variety of ways, often with a calorimeter

- Electrons≈ 10^{-2} and gamma rays ≈ 10^{-4}

(Im)Practical example of how it is done


Nuclear disintegrations with electronic elements 89

Fretter: Echo Lake, 1949

1.3 cm Pb

- **Incoming particle is highly likely to be a proton**
- **Level of ionisation excludes heavier nucleus (dE/dx) ~Z^2**
- **Traversal of the particle through 6 Pb-plates (about 88.5 g cm^{-2} or 13.9 rad. lengths) without interaction strongly excludes an electron.**

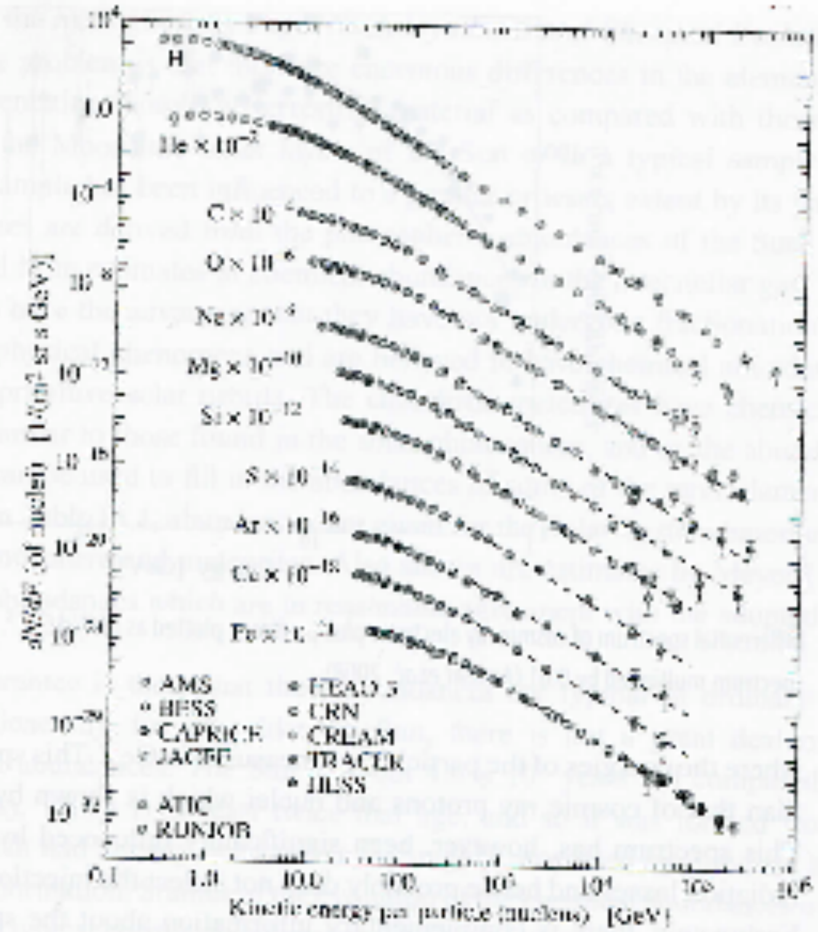
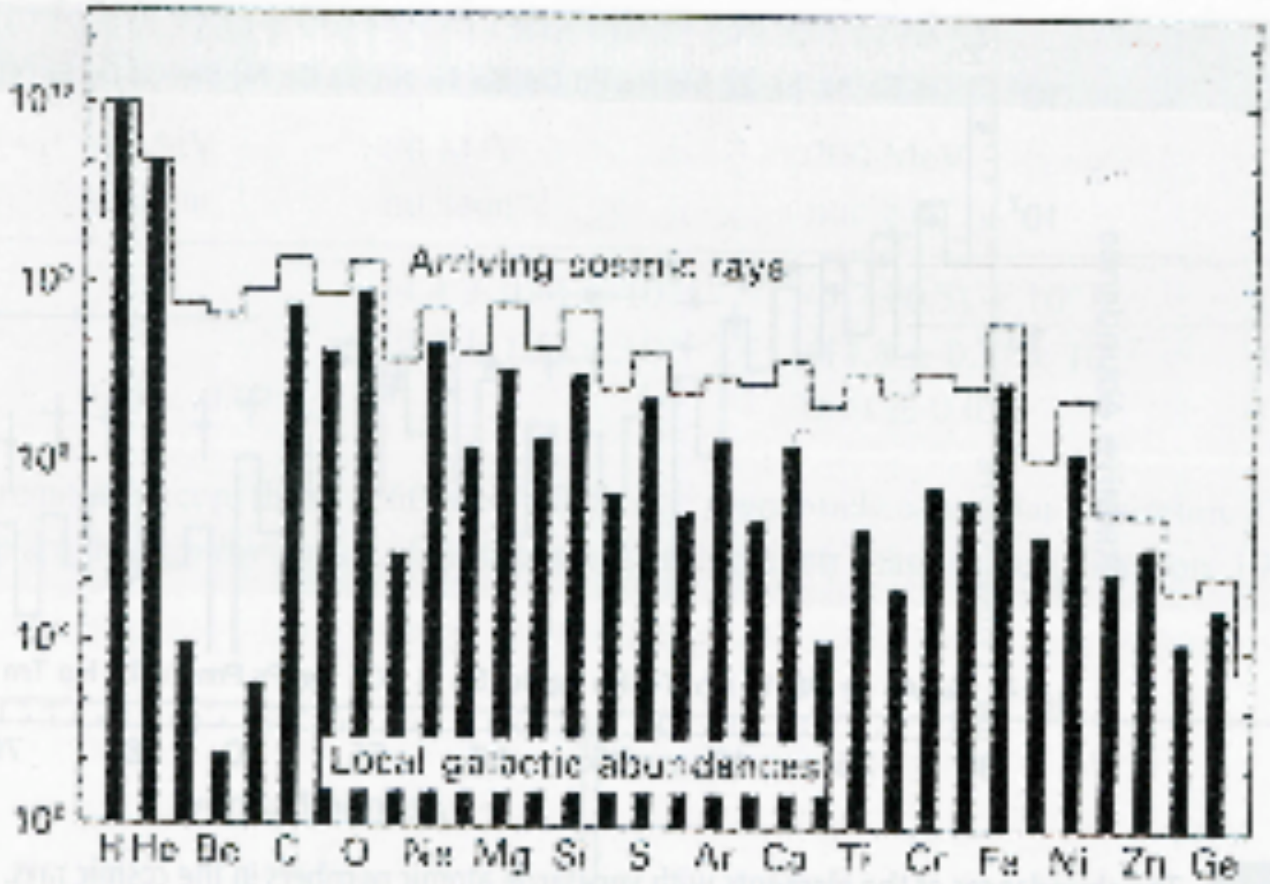


Fig. 15.2 The differential energy spectra of different cosmic ray species as a function of kinetic energy (Hörandel *et al.*, 2008). Note that these data refer to the energy per particle rather than the energy per nucleon (see Table 7.1). The scaling factors used to display the spectra of the different elements are clearly shown on the diagram.

Longair p499



The cosmic abundances of the elements in the cosmic rays (solid line) compared with the Solar System abundances (solid histogram). The data have been normalised to a relative abundance of hydrogen of 10^{12} (Lund, 1984).

Longair p 495

The comparison of the distribution of the elements shows some striking features

- **Presence of Li, Be and Boron in relatively large quantities**

- **Presence of elements just lighter than Fe**

- **Ratio of ^{3}He to ^{4}He (needs sensitivity to isotopes)**

Spallation:

Interaction of parent nuclei with hydrogen of ISM

See analysis in Longair pp 507 to 517

From the observed abundances, using a set of transfer equations, Longair pp 507 et seq

One finds that typically these cosmic rays have traversed ≈ 5 g cm^{-2}

Assuming that there is 1 atom of H per cm^3

This sets the lifetime of the cosmic rays at 3 x 10^6
to 3 x 10^7 years

This age can be confirmed by using various radioactive nuclei, such as ^{10}Be as a radioactive clock ($\tau = 1.51 \times 10^6$ years)

Study of the transport equations is also important for appreciating manner in which electrons propagate: study them

- Direct measurements are possible up to about 100 TeV
e.g. ATIC experiment

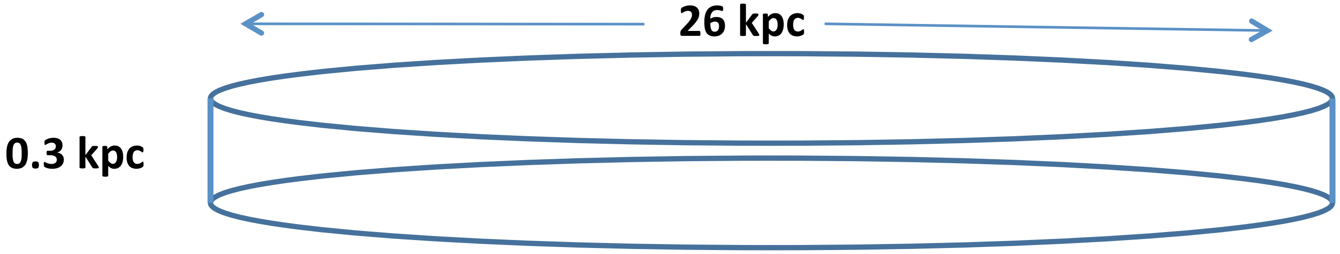
- In terms of energy per nucleus

p: He: 2 x CNO: 2 x Ne-Si : 2 x Z>17 : 4 x Fe

- Lifetime, energy density and storage volume give us
an estimate of the power of the cosmic ray sources

We need to assume the storage volume and the indications from the lifetime points to the galactic plane

Galaxy:



- Total energy in this volume is about 5 x 10^{54} ergs

- Ginsburg in 1960s argued that Supernovae (SN) could power the cosmic rays

- 1 per 30 years in the galaxy (to within about x2)

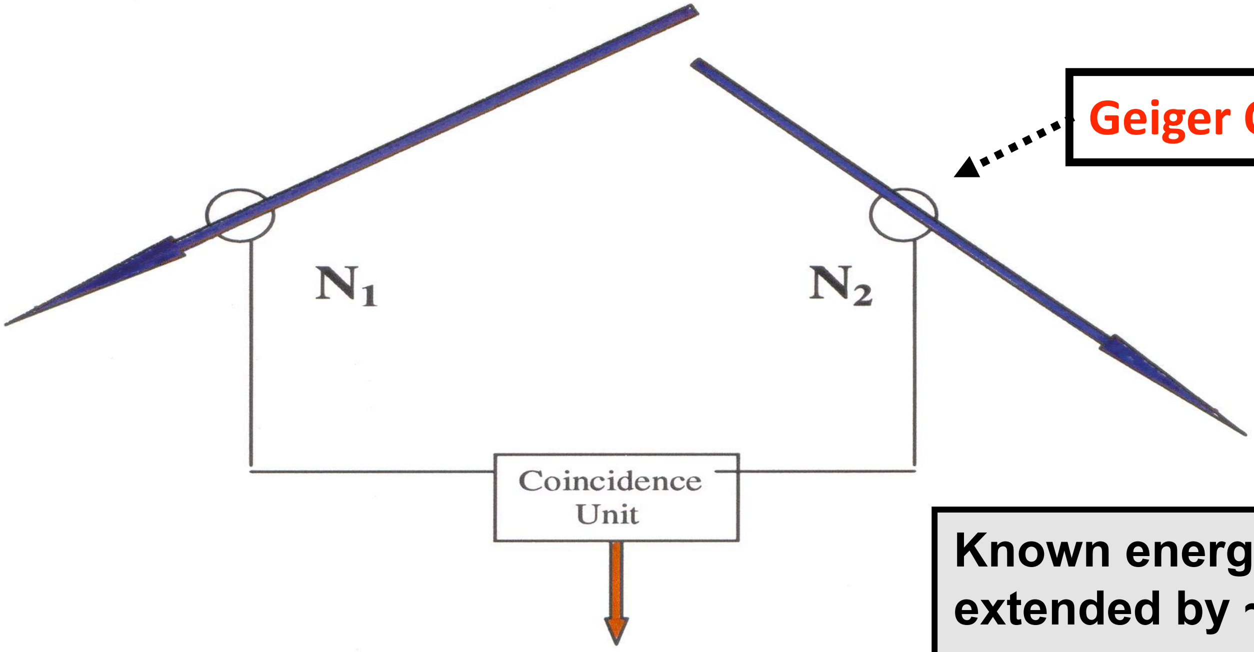
- So about 2.5 x 10^{49} ergs in cosmic rays from each SN

- This is about the same as the energy in visible light

  and about 2% of kinetic energy output of SN

(You will hear discussion about evidence of whether or not SN ARE the source of cosmic rays from Jim Hinton)

Discovery of Extensive Air Showers: Pierre Auger (1938)



Geiger Counters

Known energy scale extended by ~10^5

Chance Rate = $2N_1N_2\tau$,

Resolving time = 10 millionth of a second (10^{-5} s)

Observed Rate was found to be much higher than the Calculated Chance Rate

– even when the counters were as far as 300 m apart (at Jungfrauhoch)


Nuclear disintegrations with electronic elements 89

Plate 92

~ 1 TeV

Fretter: Echo Lake, 1949

Reasonable to have point of interaction in 7th plate (this depends on p- Pb cross-section)

$p_{CR} + p \rightarrow p + p \text{ (or n)} + N(\pi^{+} + \pi^{-} + \pi^{0})$

Also K, Λ, η, Ω, Σ…. are undoubtedly created

What is the energy of the particle?

- **a MUCH harder question to answer in larger showers**

How can we understand shower development?

Electromagnetic part of the cascade (i)

Key processes are bremsstrahlung and pair production: cross-sections calculable from QED

$\lambda_{pair} = 1/n\sigma_{pair}$, where

$\sigma_{pair} \cong ((Z^2 r_e^2)/137)(28/9)\ln(183/Z^{1/3})$ cm^2

or $\sigma_{pair} \cong 5.7\, r_e^2 = 6 \times 10^{-26}$ cm^2 , for air

$\sigma_{pair} = (7/9)\sigma_{brem}$

Electromagnetic part of the cascade (ii)

- gamma ray disappears in pair production
- opening angle: $\theta \approx mc^2/h\nu$

-

- bremsstrahlung energy spectrum is ‘flat’
  - electron can lose all of its energy at once
- opening angle $\approx mc^2/E$, where E is energy of radiated photon

The Radiation Length

$E = E_o \exp(-x/X_o)$, where X_o is the radiation length

if, $-dE/dx)_{brem} = -dE/dx)_{ionisation}$

electron is said to be at the critical energy, $E = \varepsilon_c$

(Good source for derivations of relations discussed in last few slides:
Longair ‘High Energy Astrophysics’, Second Edition, Volume 1)

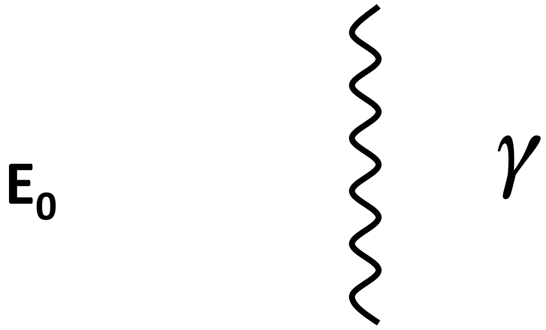
The following discussion and slides are due to Jim Matthews (LSU). The treatment is an approximation intended to exhibit some of the physics driving the main features of air showers plainly and simply

It does not replace full simulations

It is a useful pedagogic tool from which we can learn a lot

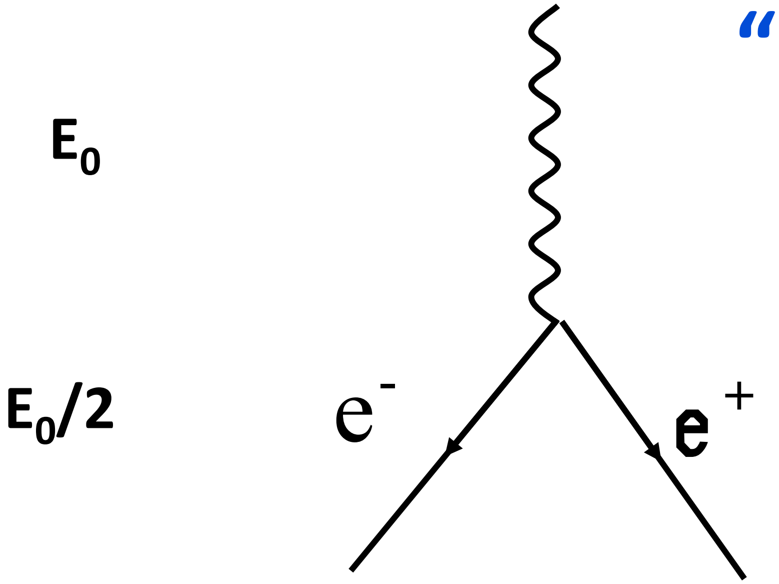
J Matthews: Astropart. Phys. **22** (2005) 387.

The Heitler Model



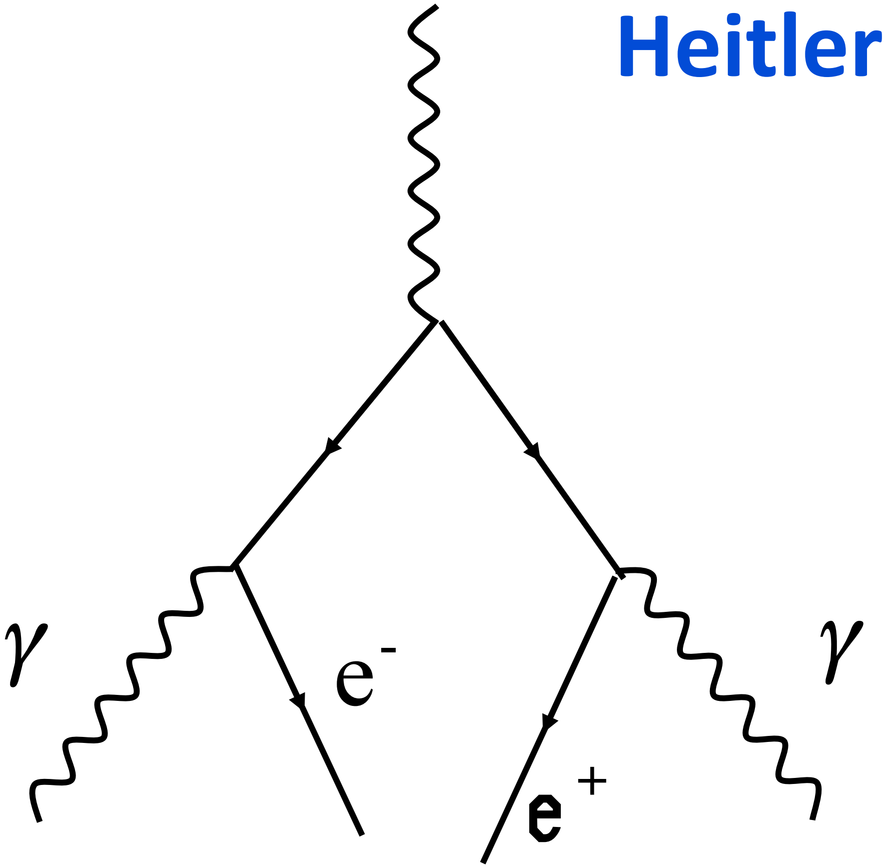
W. Heitler, *The Quantum Theory of Radiation ,3rd Ed.*, (1954), p.386.

"Heitler's Model"



W. Heitler, *The Quantum Theory of Radiation* ,3rd *Ed.*, (1954), p.386.

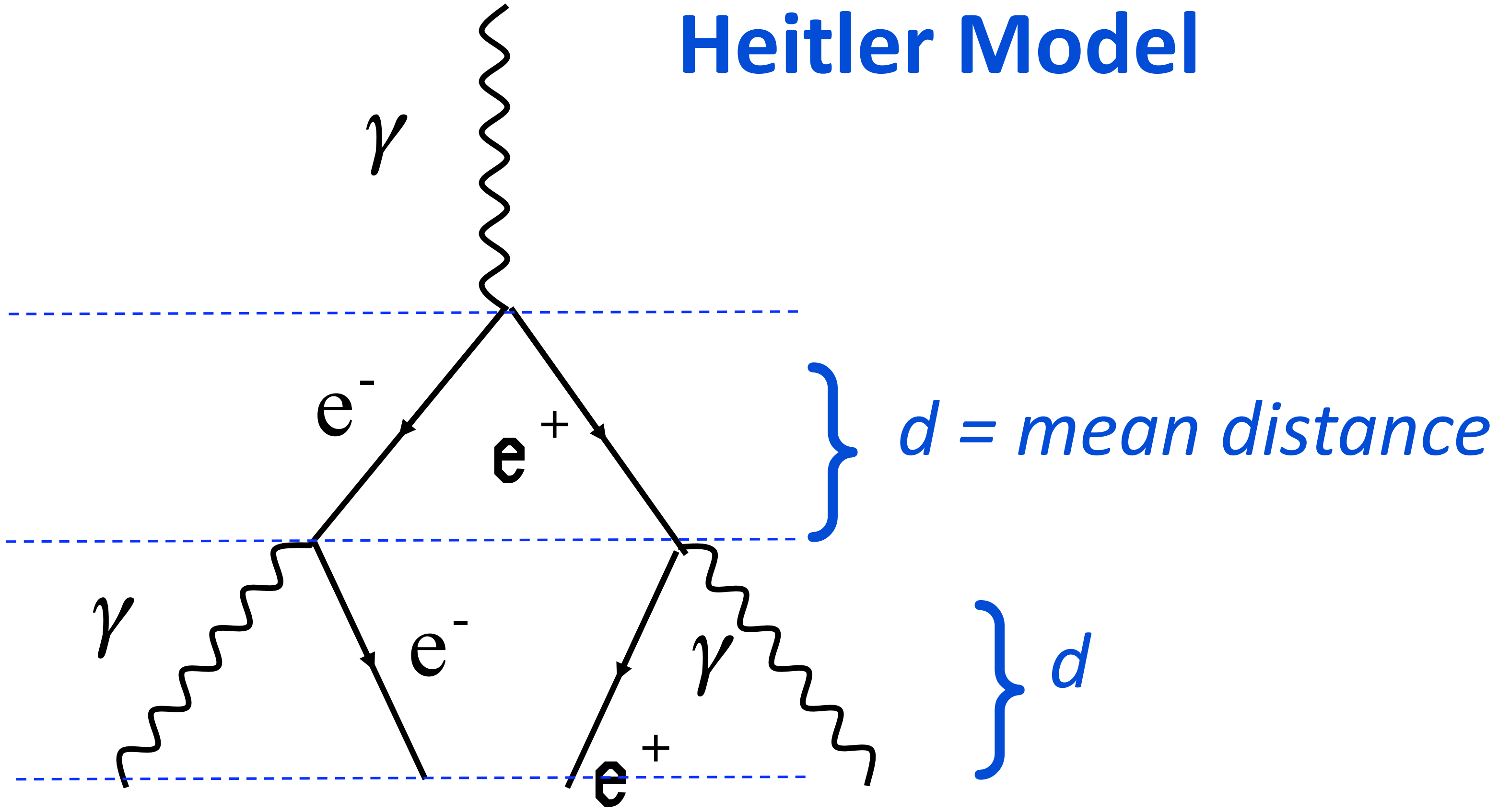
Heitler Model



$E_0/4$

W. Heitler, *The Quantum Theory of Radiation ,3rd Ed.*, (1954), p.386.

Heitler Model



$$d = \lambda_r \ln 2$$

$\lambda_r = 37$ g cm^{-2} in air

(radiation length)

After “n” splits, there are “N” particles (e^+, e^-, and photons):

$$N = 2^n = e^{x/\lambda_r}$$

After “n” splits, there are “N” particles (e^+, e^-, and photons):

$$\boxed{N = 2^n = e^{x/\lambda_r}}$$

- **Energy is evenly split between two secondaries.**

- **Cascade *stops* after “n_c” splits when individual energies are too low: *critical energy ξ_c*.**

$$\boxed{N_{max} = 2^{n_c}}$$

$$\boxed{E_\circ = \xi_c^e N_{max}}$$

(ξ_c is when collision losses > radiative losses: 85 MeV in air)

$$\boxed{n_c = \ln[E_\circ/\xi_c^e]/\ln 2}$$

Things the Heitler Model does well:

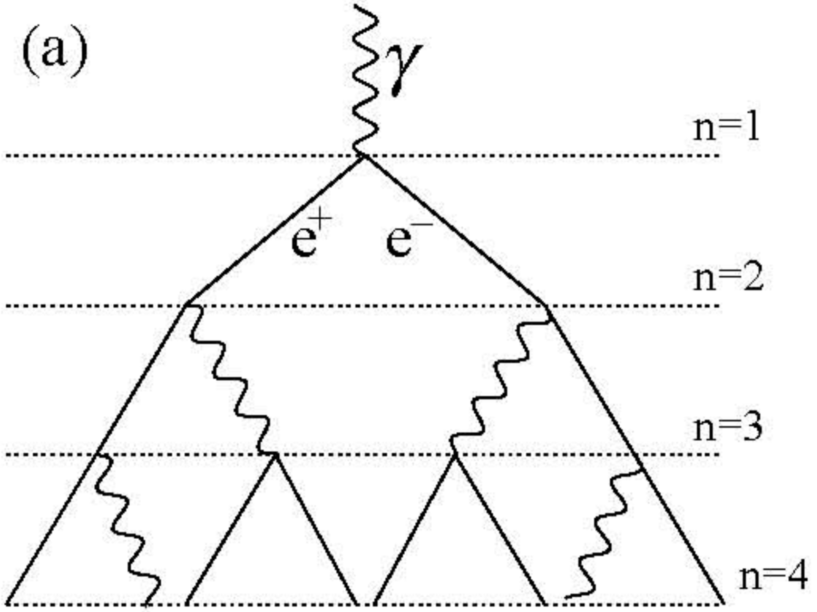
$N_{max} \sim E_o$ - but not constant of proportionality

$X_{max} \sim \log E_o$

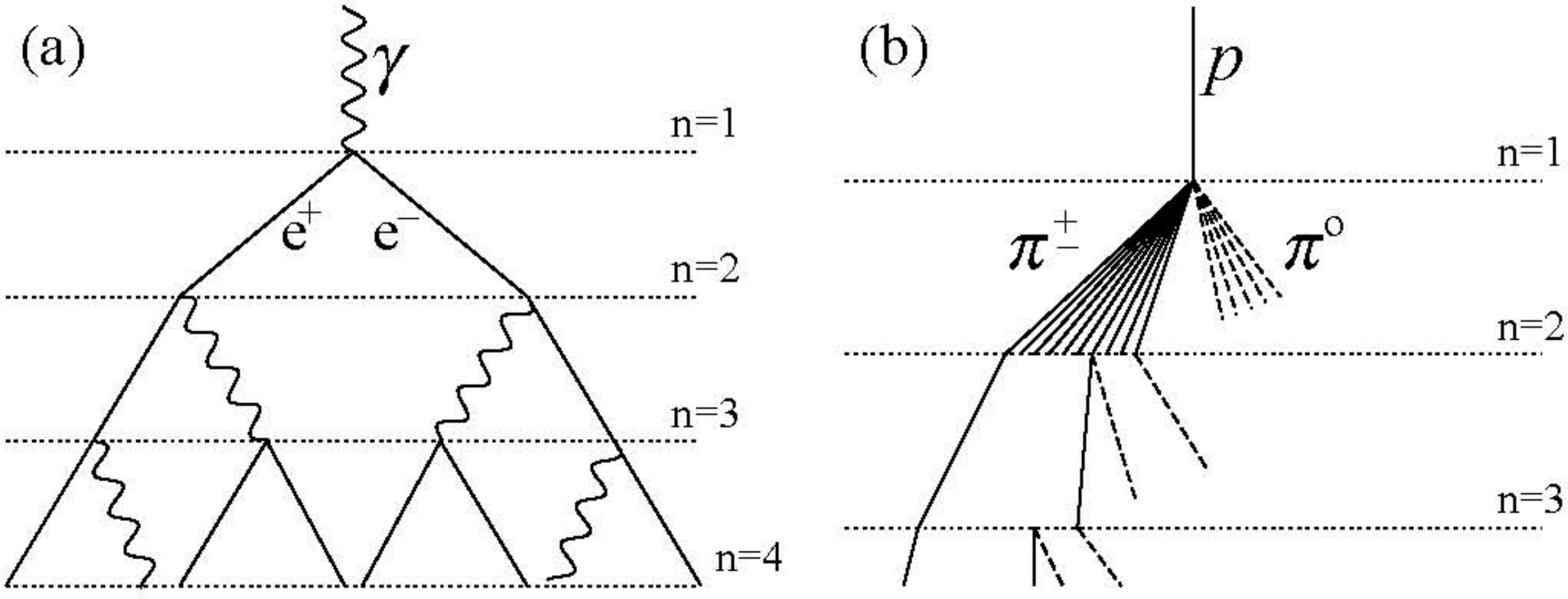
$$\Lambda \equiv \frac{\mathrm{d}\, X_{max}}{\mathrm{d}\log_{10} E_\circ} = 2.3\, \lambda_r = (85\ \mathrm{g\ cm^{-2}})/\mathrm{decade}$$

Things it does not do:

- relative numbers of photons/electrons
- attenuation, especially after maximum



$$\boxed{E_\circ = \xi_c^e N_{max}}$$



Extension to hadronic cascade is Jim Matthews's original contribution

$N_{ch}=N_{\pi\pm}=10$, $N_{\pi o} = 5$

$N_{\mu} = N_{\pi\pm}$

$$\boxed{E_\circ = \xi_c^e N_{max}}$$

$$\boxed{E_\circ = \xi_c^e N_{max} + \xi_c^\pi N_\mu}$$

For pions, the distance between events is defined by the *interaction length*

$$\boxed{d = \lambda_I \ln 2}$$

λ_I = 120 g cm^{-2}

(c.f. λ_p = 80 g cm^{-2})

The hadronic ***critical energy*** is reached when the distance to the next interaction exceeds the (**dilated**) lifetime

$$\boxed{\xi_c = 20 \text{ GeV}}$$

After n generations, there are N_π charged pions:

$$N_\pi = (N_{ch})^n$$

Total energy carried by all these pions:

$$(2/3)^n E_o$$

e.g. ~ 10% after 5 generations

So each pion has:

$$E_\pi = \frac{E_\circ}{(\frac{3}{2} N_{ch})^n}$$

When pions drop below their critical energy :

$$\boxed{E_\pi = \xi_c = 20\ \text{GeV}}$$

all π± decay to muons

$$\ln N_\mu = \ln N_\pi = n_c \ln N_{ch} = \beta \ln[E_\circ / \xi_c^\pi]$$

$$\beta = \frac{\ln[N_{ch}]}{\ln[\frac{3}{2}N_{ch}]} = 0.85$$

$$\boxed{N_\mu = \left(\frac{E_\circ}{\xi_c^\pi}\right)^\beta \approx 10^4 \left(\frac{E_\circ}{1\ \mathrm{PeV}}\right)^{0.85}}$$

(Full simulations give $\beta = 0.85 - 0.92$)

(n.b.: logarithmic dependence on N_{ch})

The growth of N_μ with E_o is less-than-linear ($\beta < 1$).

Lower energy showers are more "efficient" in muon production

This is why Fe primaries make more muons than protons do (superposition model: 56 showers each with $E = E_p/56$)

β depends on the (logarithmic) ratio of charged to neutral pions

The primary energy of the shower is divided into EM and hadronic channels:

$$E_\circ = \xi_c^e N_{max} + \xi_c^\pi N_\mu$$

Use observed $N_e = N_{max} / g$, $g \approx 10$:

$$\boxed{E_\circ = g\xi_c^e \left(N_e + \frac{\xi_c^\pi}{g\xi_c^e} N_\mu\right) \approx 0.85 \text{ GeV} (N_e + 24 N_\mu)}$$

A great deal can be learned by measuring N_e and N_μ in the same events

Depth of shower-maximum must be treated a little more carefully because it strongly depends on the *first* interaction.

1. Do an EM shower with $(1/3\ E_o)/N_{ch}$
2. Use increasing multiplicity $N_{ch} \sim E_o^{1/5}$
3. Use energy dependent p-air λ_I

$$\begin{aligned} X^p_{max} &= X_\circ + \lambda_r \ln[E_\circ/(3N_{ch}\xi^e_c)] \\ &= (470 + 58\log_{10}[E_\circ/1\ \mathrm{PeV}])\ \mathrm{g\ cm}^{-2} \end{aligned}$$

Not deep enough by ≈ 100 g cm^{-2}

Express in terms of EM-shower $X_{\mathbf{max}}$:

$$\boxed{X^{p}_{max} = X^{\gamma}_{max} + X_{\circ} - \lambda_{r} \ln[3N_{ch}]}$$

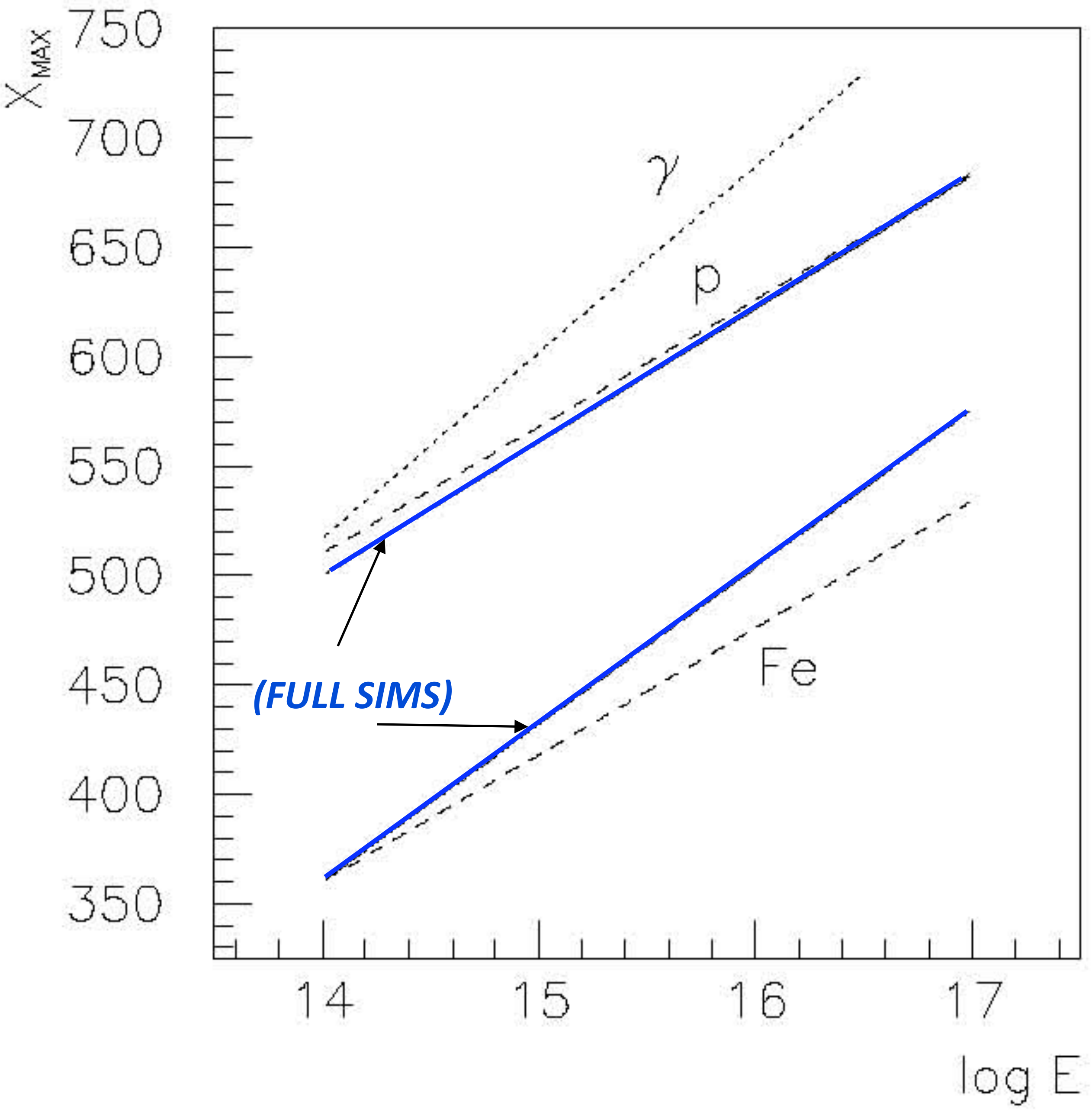
Elongation rate **is in very good agreement with detailed simulations:**

$$\boxed{\Lambda^{p} = \Lambda^{\gamma} + \frac{\mathrm{d}}{\mathrm{d}\log_{10} E_{\circ}}\{X_{\circ} - \lambda_{r} \ln[3N_{ch}]\} = 58 \text{ g cm}^{-2} \text{ per decade}}$$

p, Fe lines shifted (up) by 100 g/cm^2

gamma line not shifted

slopes **are in good agreement**

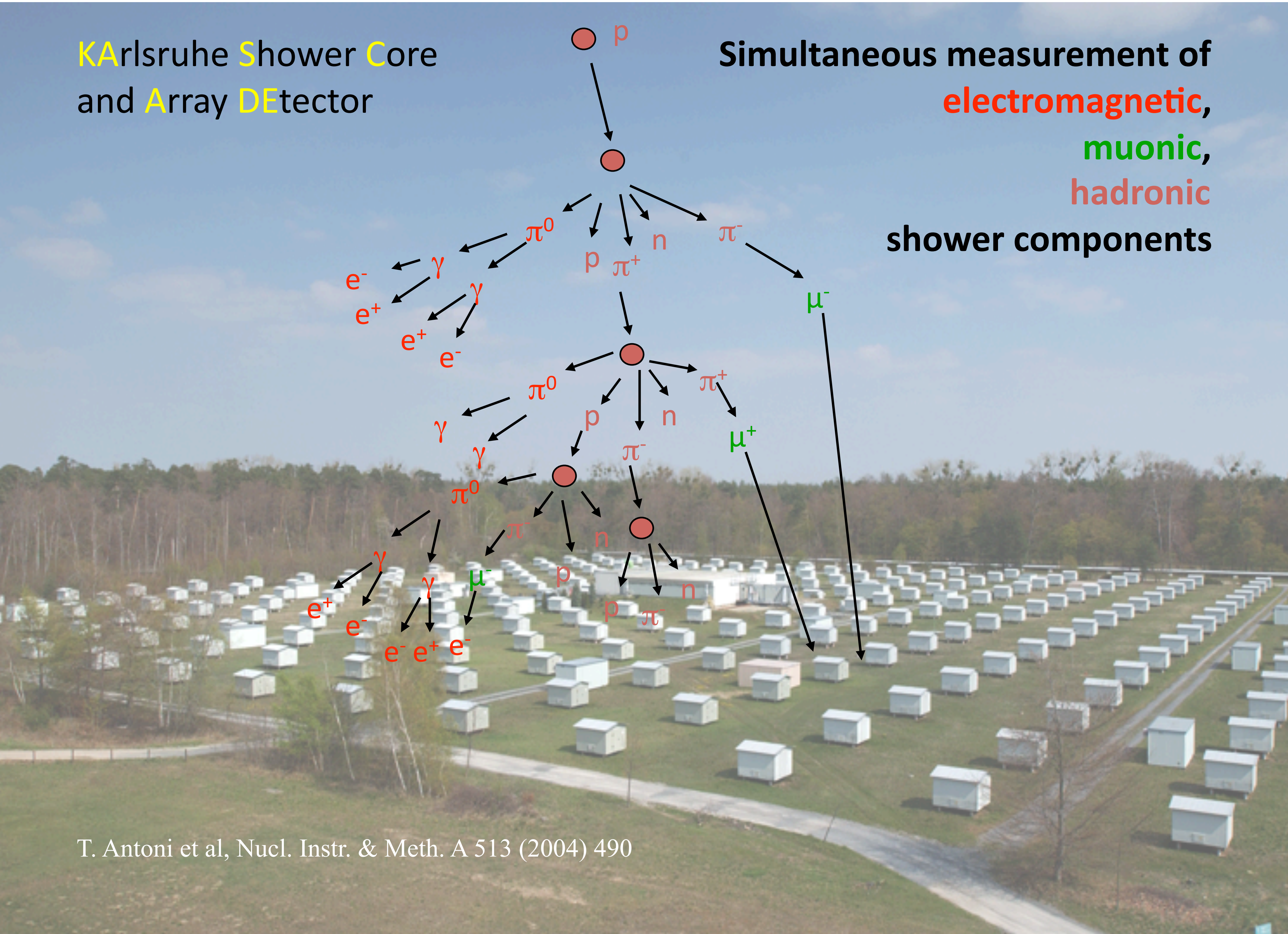


"Full Sims" ***from:***

Heck et al., Hamburg ICRC (p.233); Fowler et al., Ast.P.Ph. 15 (2001),49.

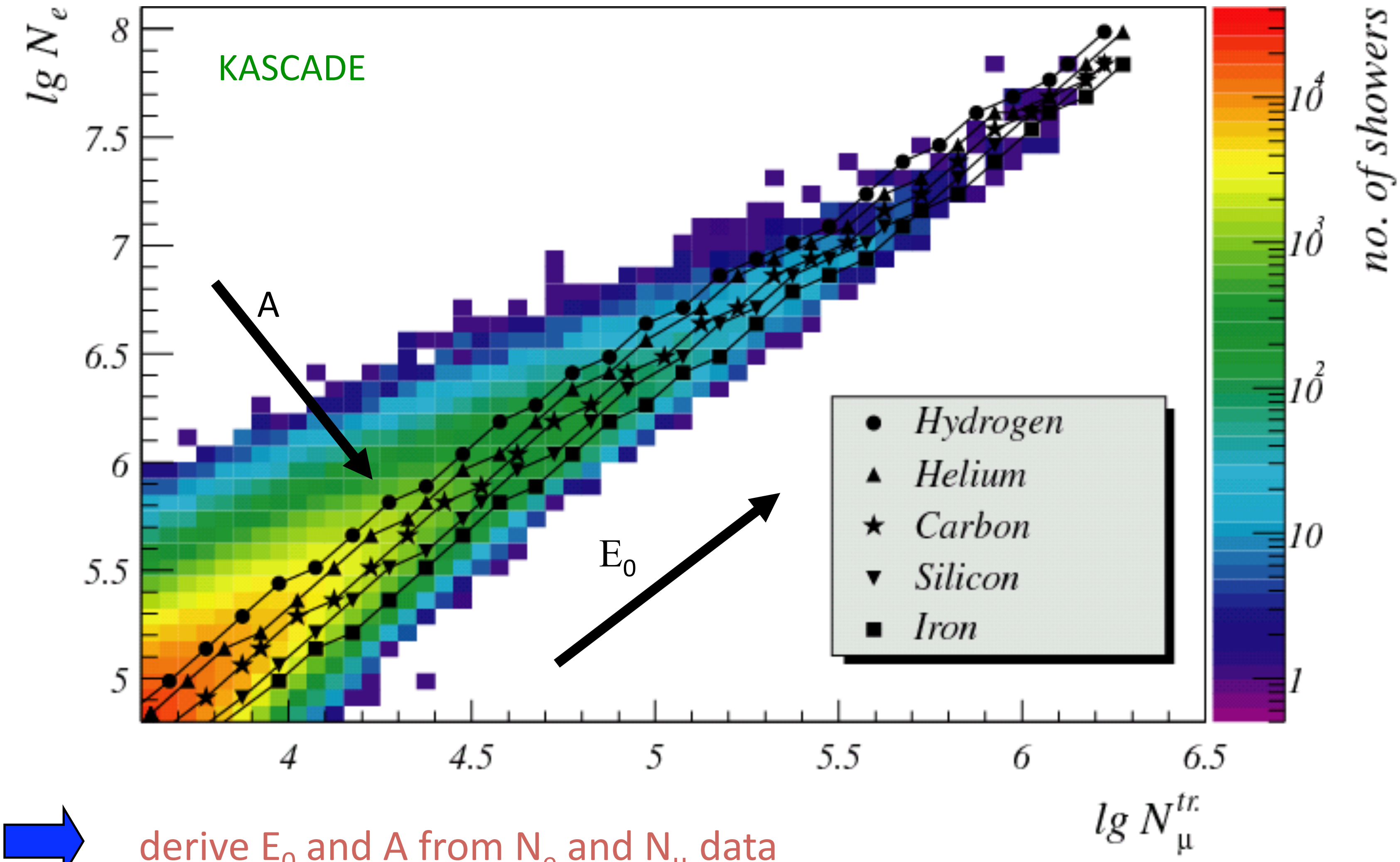
KArlsruhe Shower Core and Array DEtector

Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components



T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

Two dimensional shower size spectrum lg N_e vs. lg N_μ



- derive E_0 and A from N_e and N_μ data
- Fredholm integral equations of 1st kind:

$$g_i(\lg N_e, \lg N_\mu) = \int_0^\infty t_i(\lg N_e, \lg N_\mu \mid E)\, p_i(E)\, dE$$

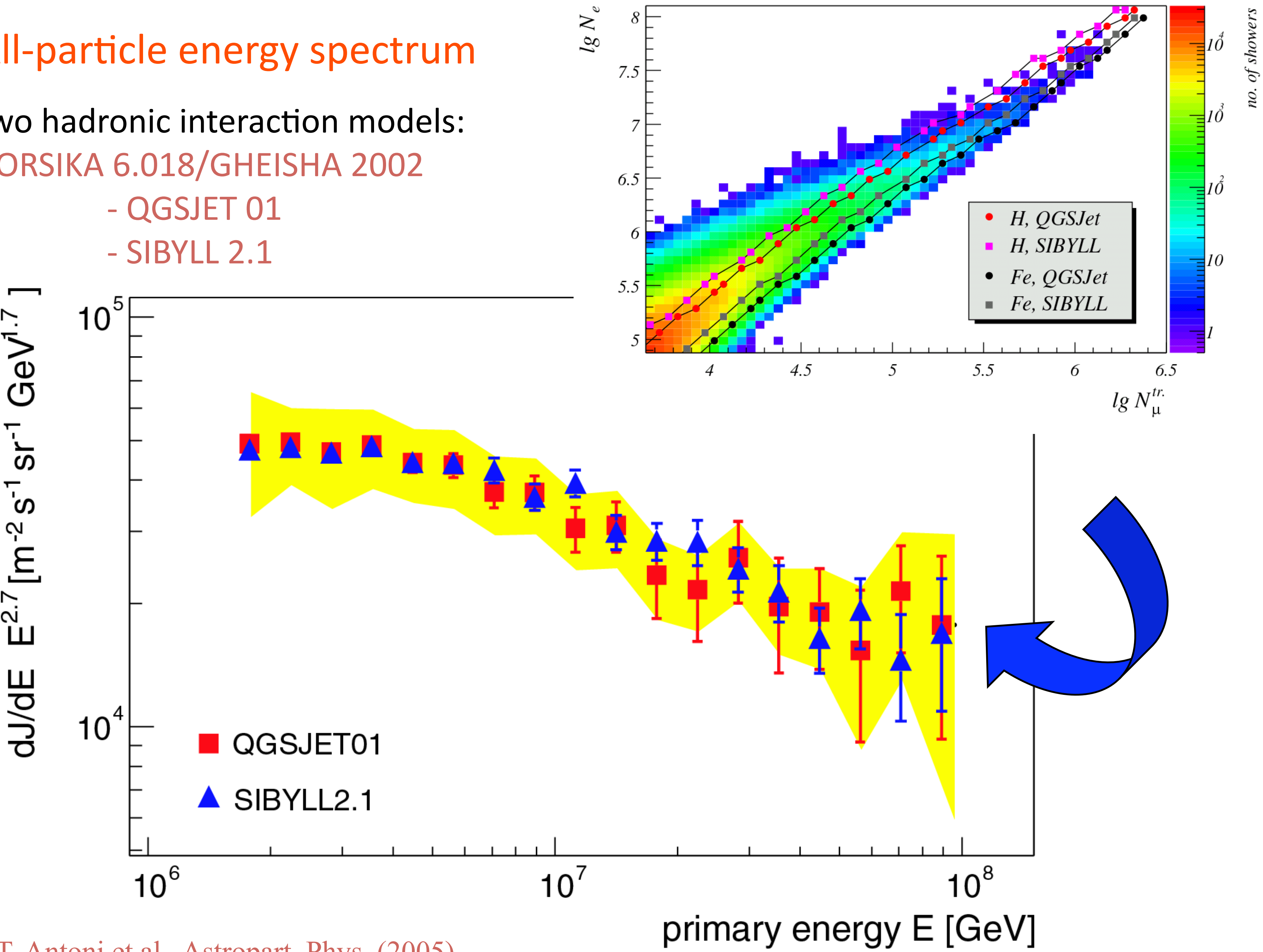
M Roth et al, 28th ICRC, Tsukuba 1 (2003) 139

All-particle energy spectrum

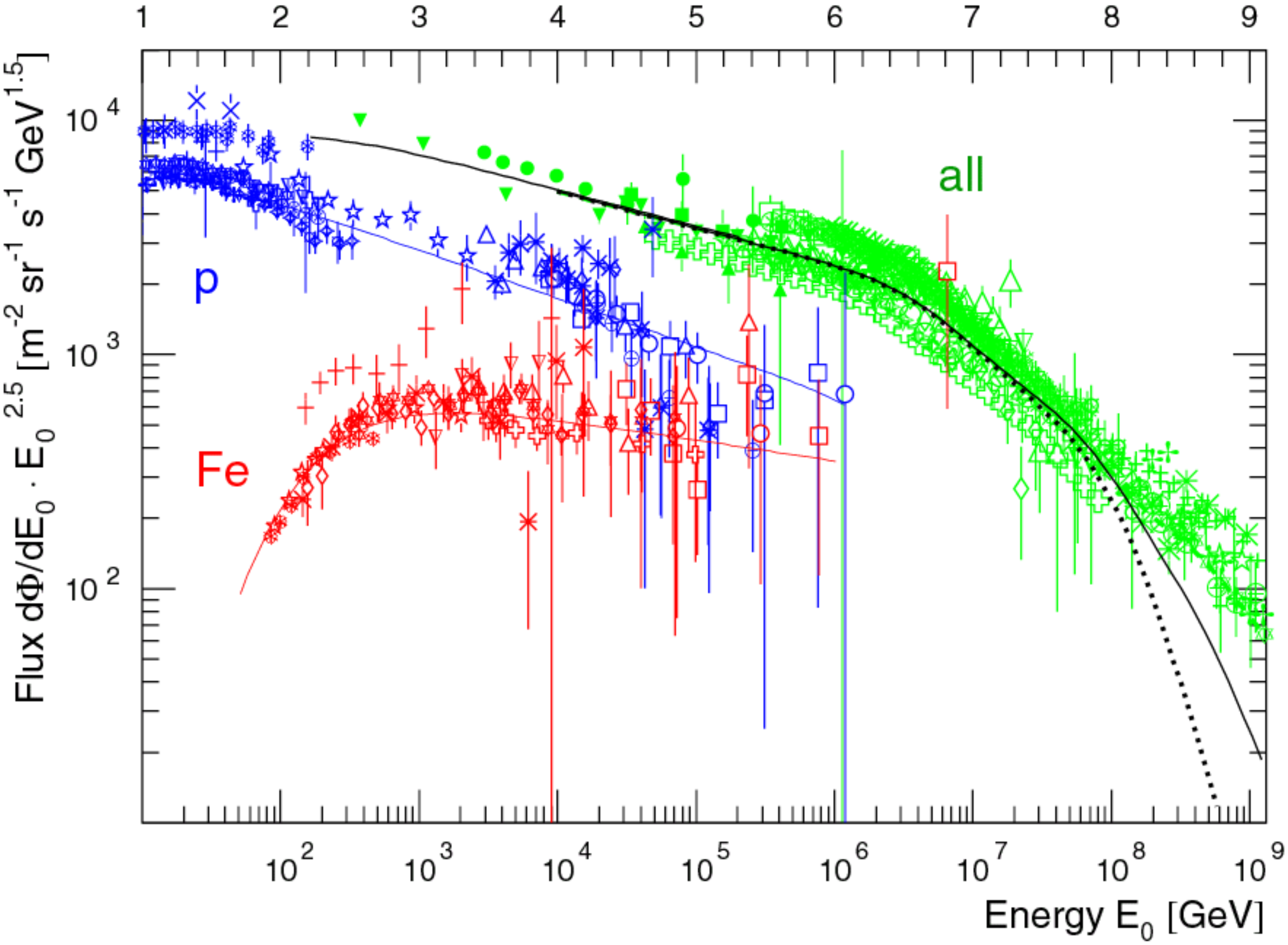
two hadronic interaction models:

CORSIKA 6.018/GHEISHA 2002

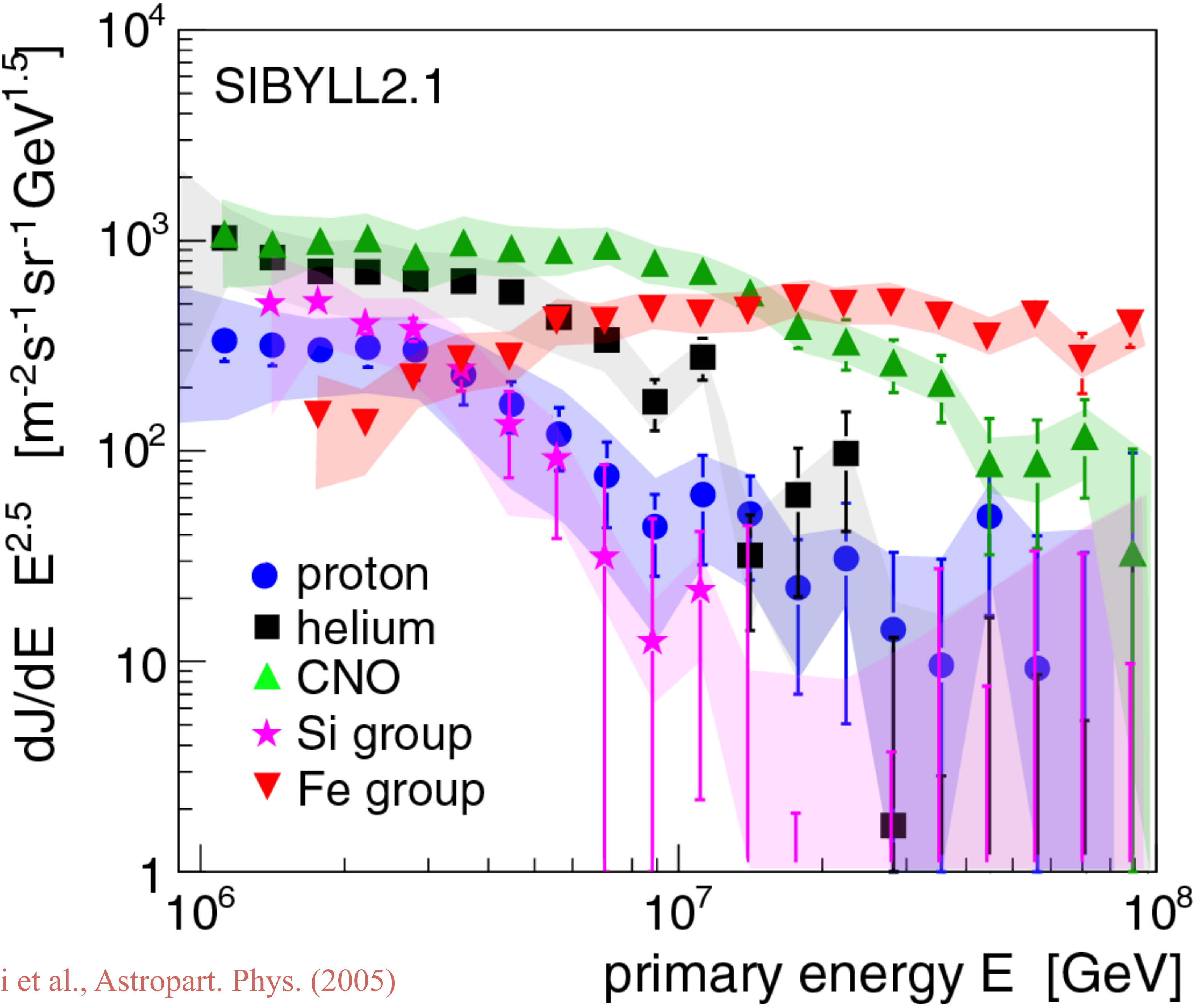
- QGSJET 01
- SIBYLL 2.1



T. Antoni et al., Astropart. Phys. (2005)


1
2
3
4
5
6
7
8
9
10^4
10^3
10^2
Flux $d\Phi/dE_0 \cdot E_0^{2.5}$ [m^{-2} sr^{-1} s^{-1} $GeV^{1.5}$]
p
Fe
all
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Energy E_0 [GeV]

KASCADE: Energy spectra for individual elemental groups



T. Antoni et al., Astropart. Phys. (2005)

For many years there was a huge debate as to whether or not the bend in the spectrum, the knee, was due to particle physics (bend at energies increasing by A) or bend was at energy increasing by Z

The KASCADE results strongly suggest that the spectrum is changing because of a rigidity effect – change depends on Z

But not yet clear that this is a source or a leakage effect

In my view different types of sources can't be excluded

and that's the end of part I

Giving a golf ball the energy of a high-energy cosmic ray: South Pole, Jan 1988

Why study Ultra-High Energy Cosmic Rays?

- no idea of their origin
- how to accelerate to 10^{20}eV?
- steepening of spectrum at highest energies?

PROPAGATION EFFECTS or SOURCES?

Difficulties:

Above 10^{19} eV the rate is ~ 1 km^{-2} per year

- energies are hard to measure
- mass spectrum is unknown
- anisotropies are hard establish

Spectrum shape:

$$E = 2\,\Gamma\varepsilon_{2.7\,K}$$ (for head-on collision)

Steepening above 4 x 10^{19} eV? (GZK-effect: 1966)

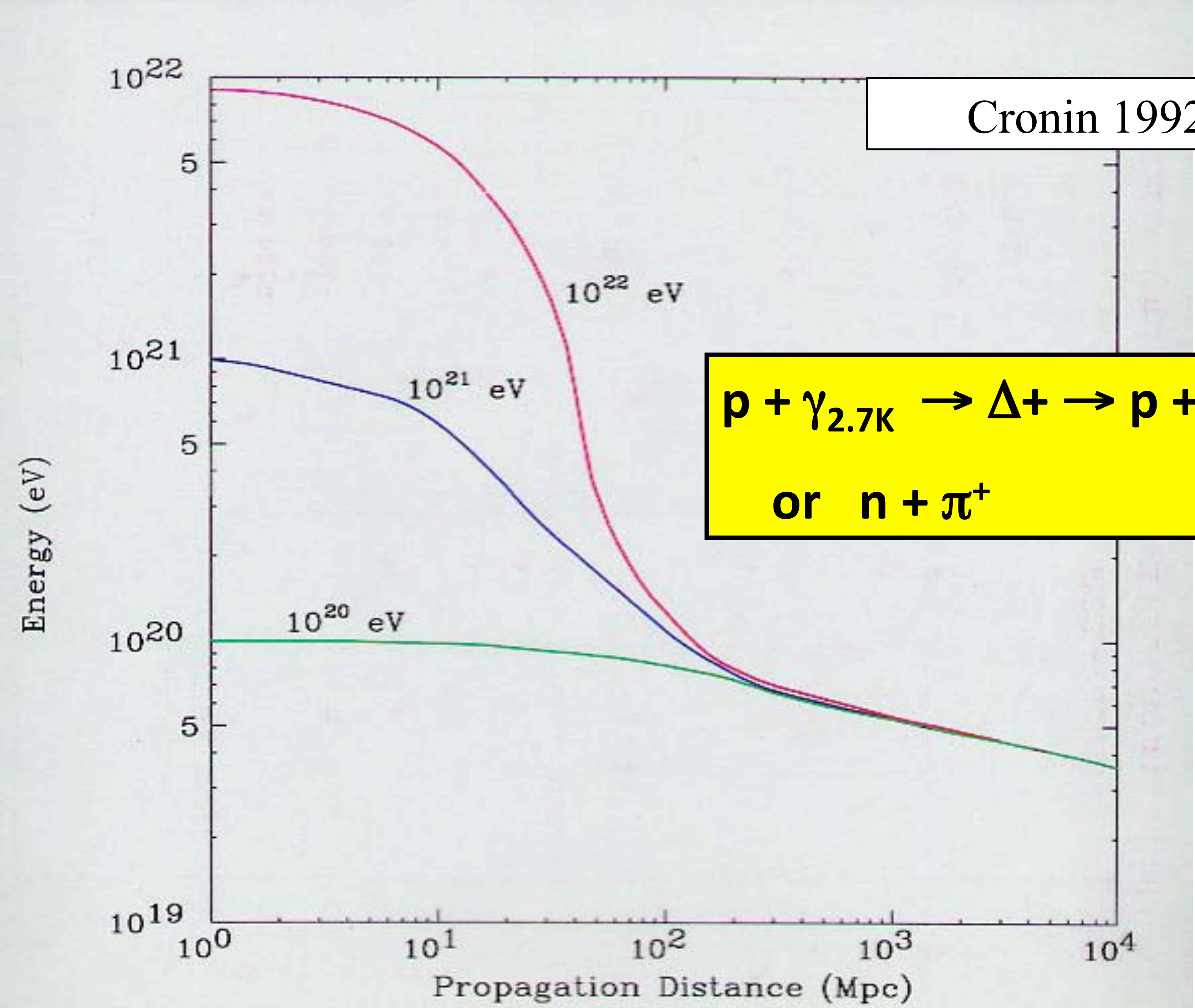
$\gamma_{2.7\,K} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$ or $p + \pi^{-}$ (CMB well-known)

or

$\gamma_{IR} + A \rightarrow (A - 1) + n$ (IR background poorly known)

Also $\gamma_{2.7K} + Z \rightarrow Z + e^{+} + e^{-}$ (pair production)

$\gamma + \gamma_{radio} \rightarrow e + e$ (but 100 MHz background at UHECR unknown)

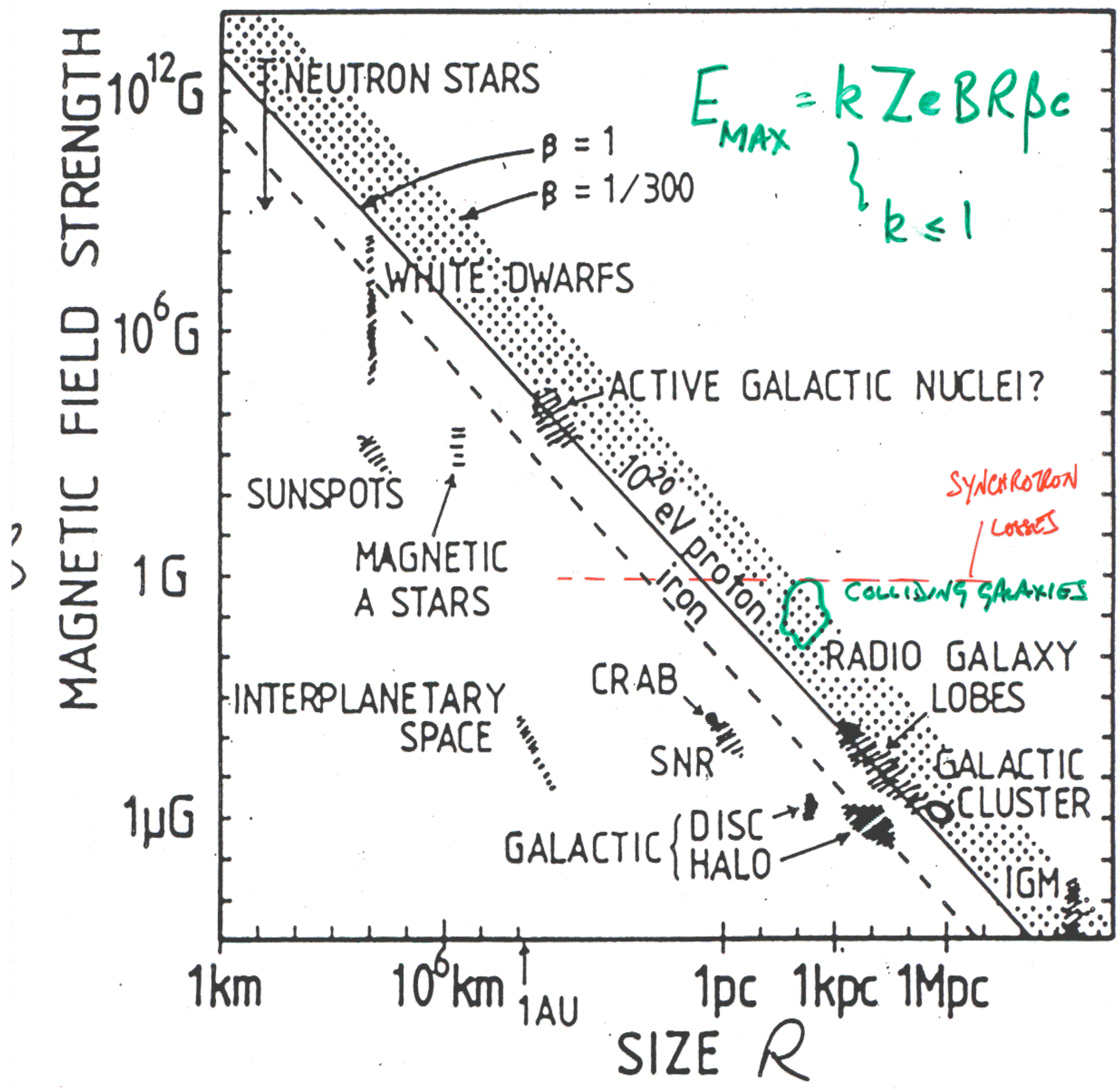


Cronin 1992

$p + \gamma_{2.7K} \rightarrow \Delta+ \rightarrow p + \pi^0$

or $n + \pi^+$

THE HILLAS PLOT (Ann Rev As. Ap 1984)



Hillas 1984
ARA&A
B vs R

Magnetars?

GRBs?

Particles in region of predicted GZK-steepening could tell us about sources within 100 – 200 Mpc

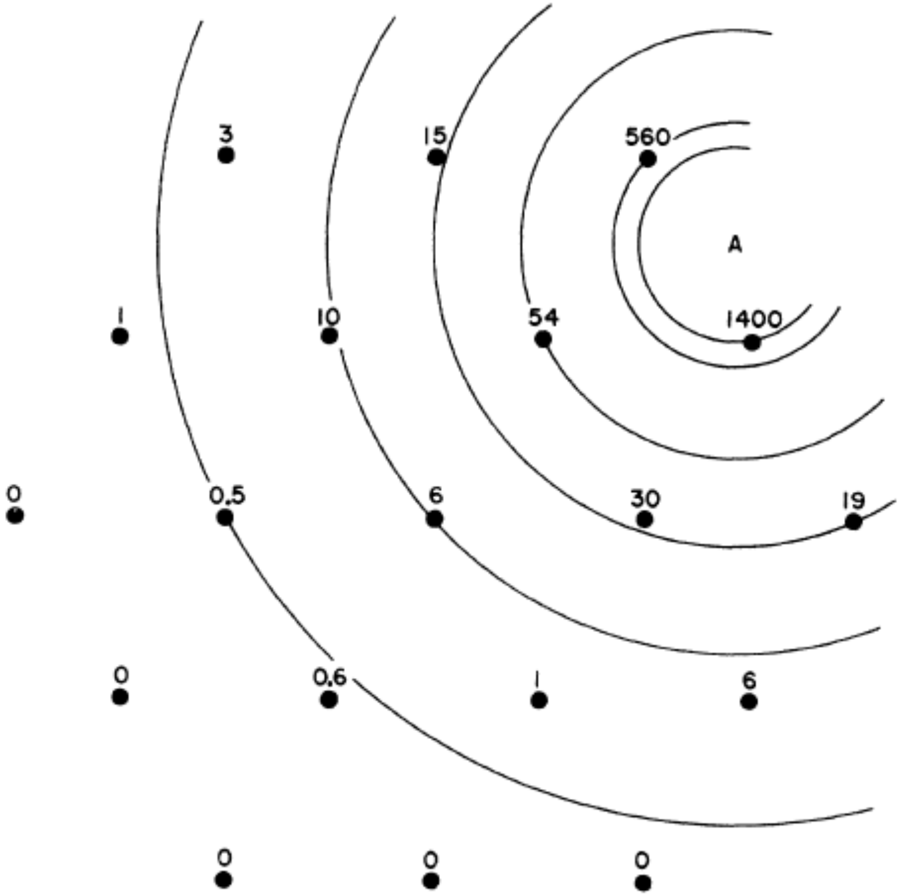
- depending on the energy.

IF particles are protons, the deflections are expected to be small enough above ~ 5 x 10^{19} eV (~ 2°) that point sources might be seen – provided there are not too many.

So, measure:

- **energy spectrum - to look for GZK-prediction**
- **arrival direction distribution - explore**
- **mass composition – for interpretation**

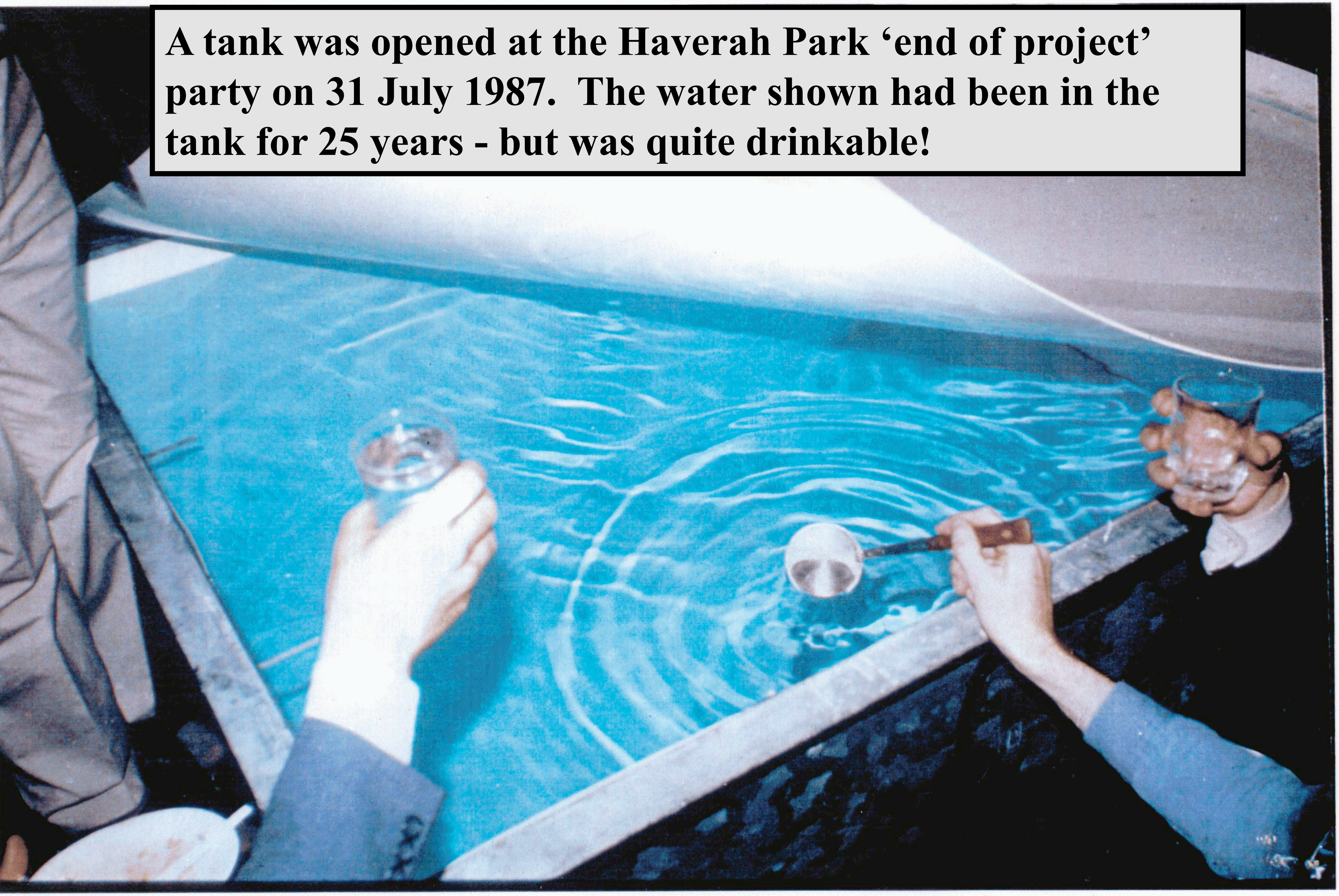
Credit: M Panasyuk



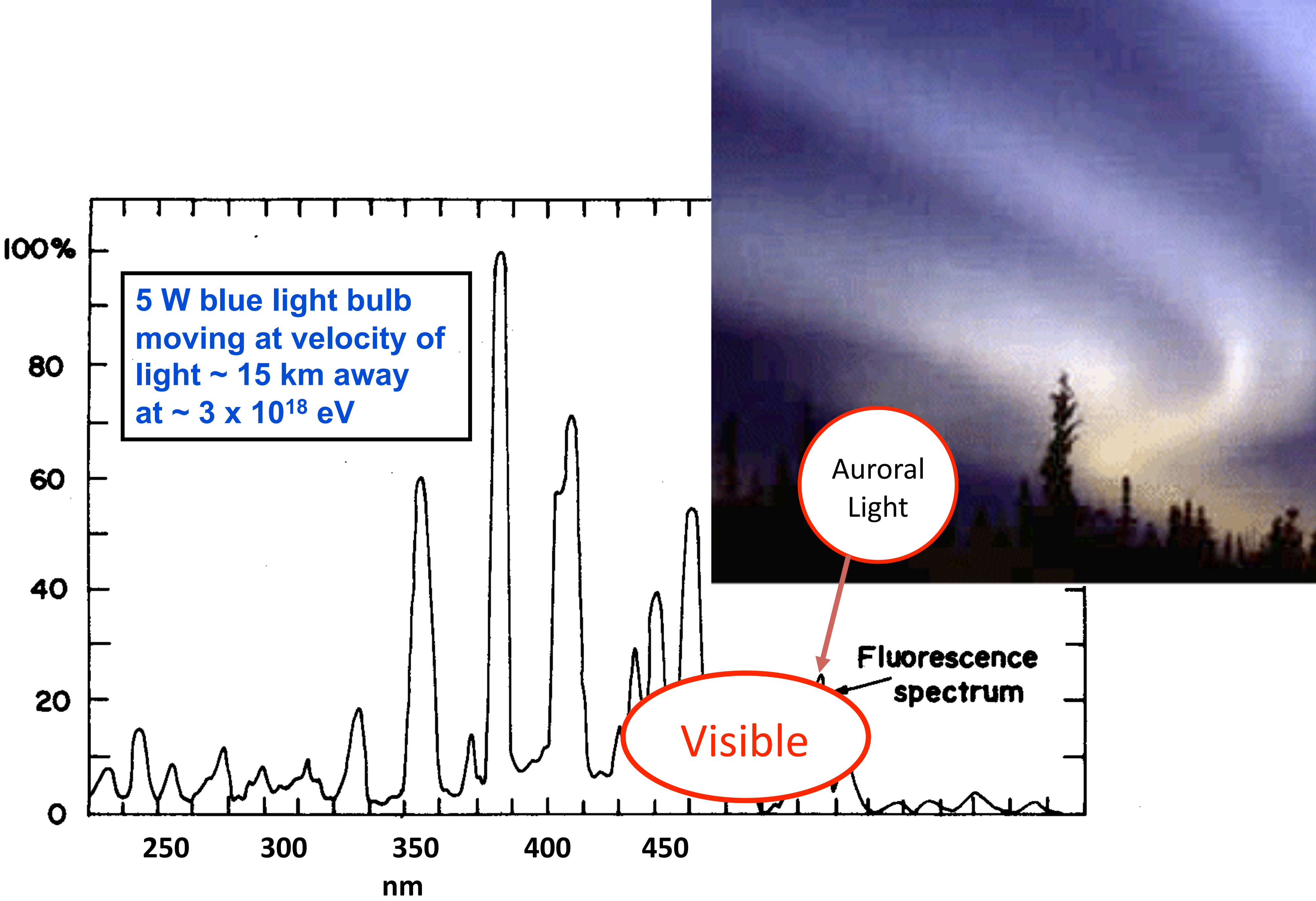
John Linsley (1927 – 2002)

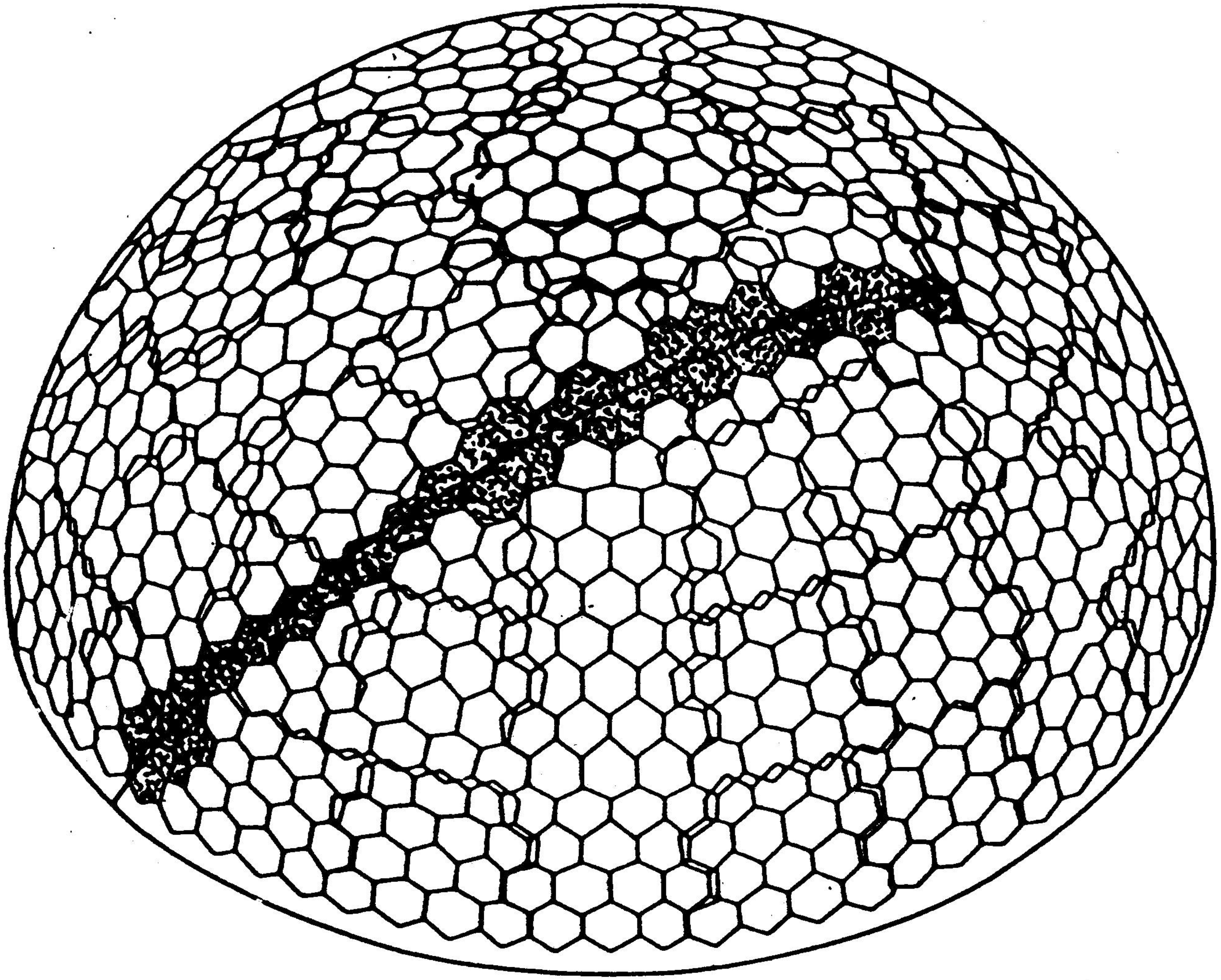
Pioneer of Large Shower Arrays

Volcano Ranch: 10^{20} eV



A tank was opened at the Haverah Park 'end of project' party on 31 July 1987. The water shown had been in the tank for 25 years - but was quite drinkable!

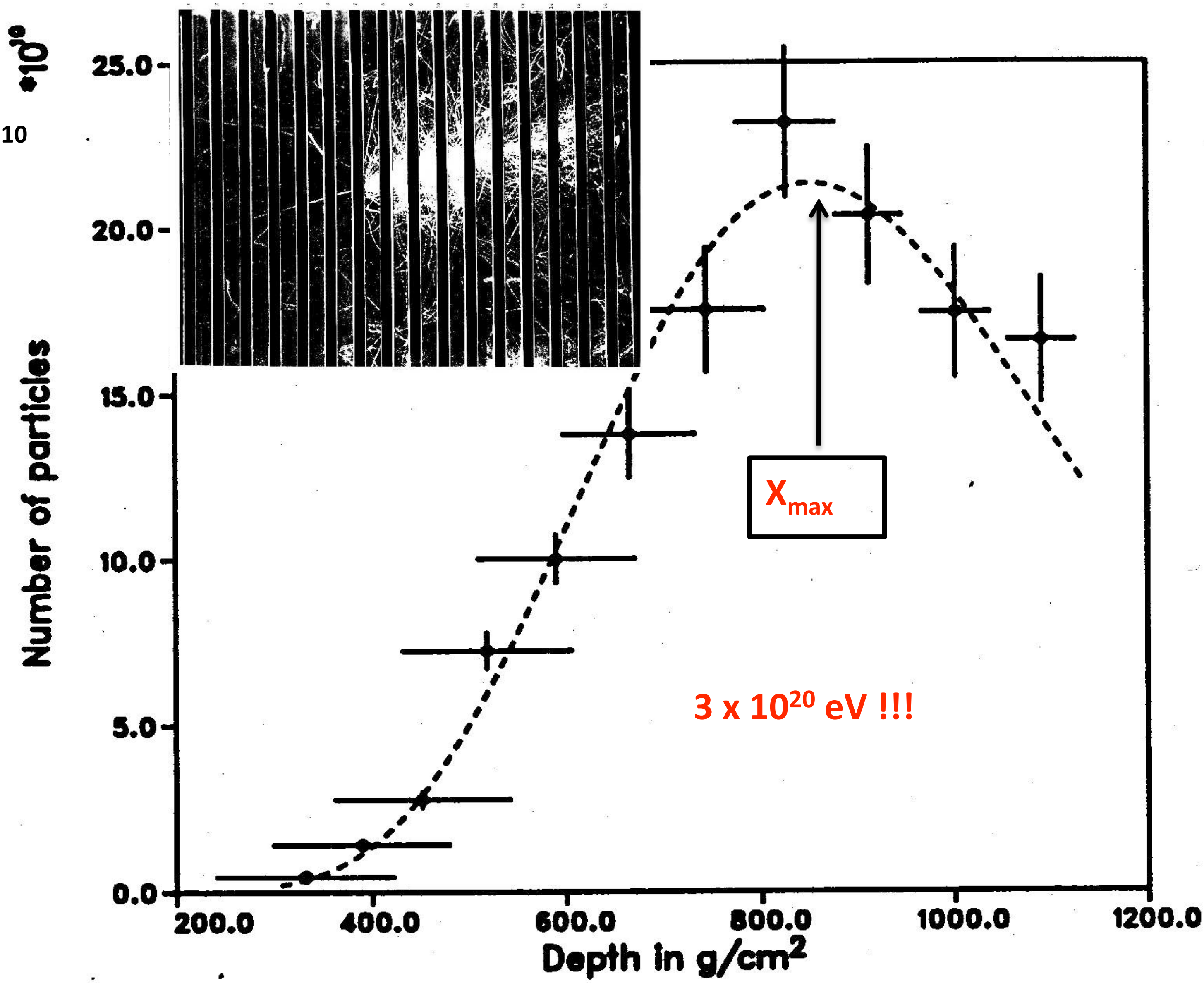

5 W blue light bulb moving at velocity of light ~ 15 km away at ~ 3×10^{18} eV



Idea of Fly's Eye Detector (University of Utah): 880 photomultipliers

HiRes: detector of fluorescence light

x 10^{10}

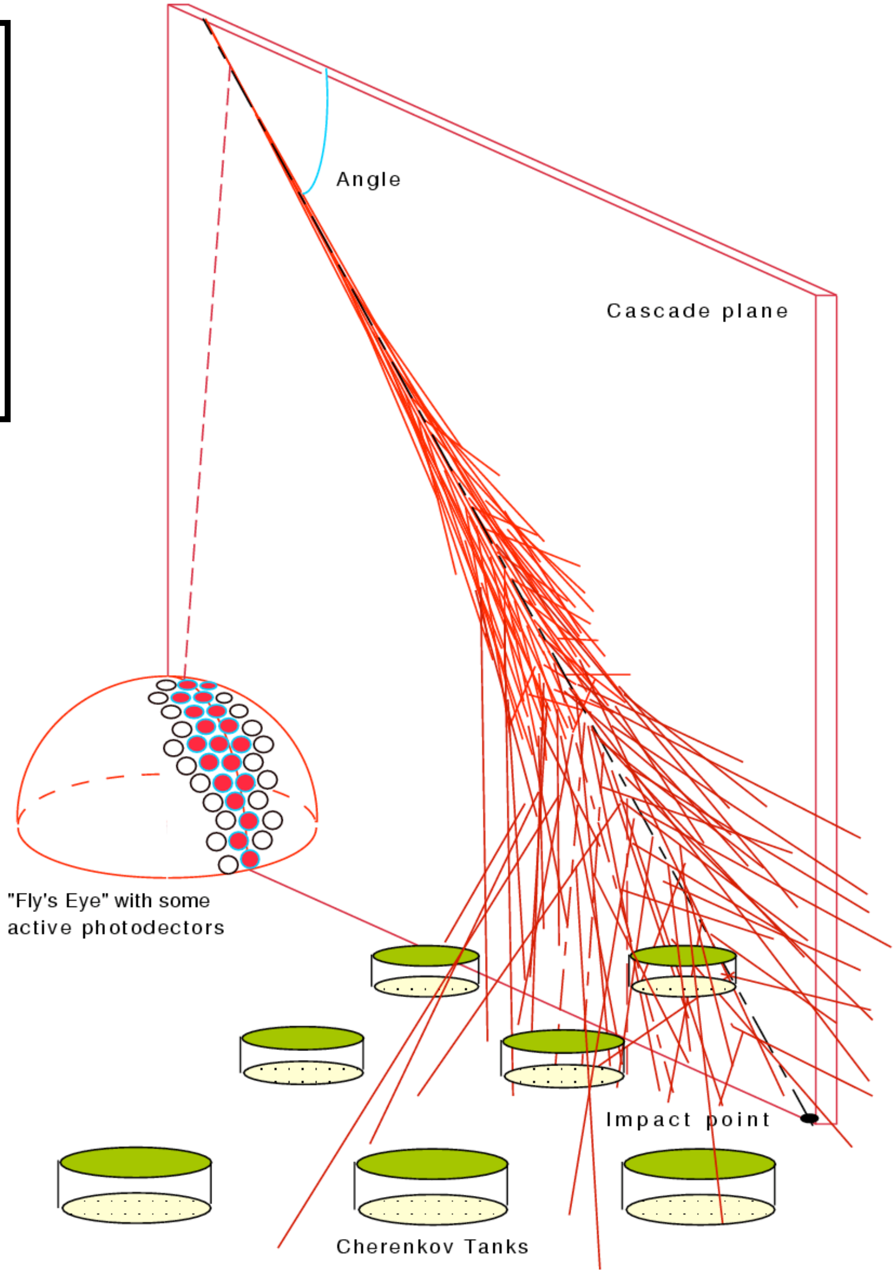


X_{max}

3 x 10^{20} eV !!!

The Design of the Pierre Auger Observatory marries the two techniques just described in

the 'HYBRID' technique



Fluorescence →

AND

Array of water-Cherenkov detectors →

The Pierre Auger Collaboration

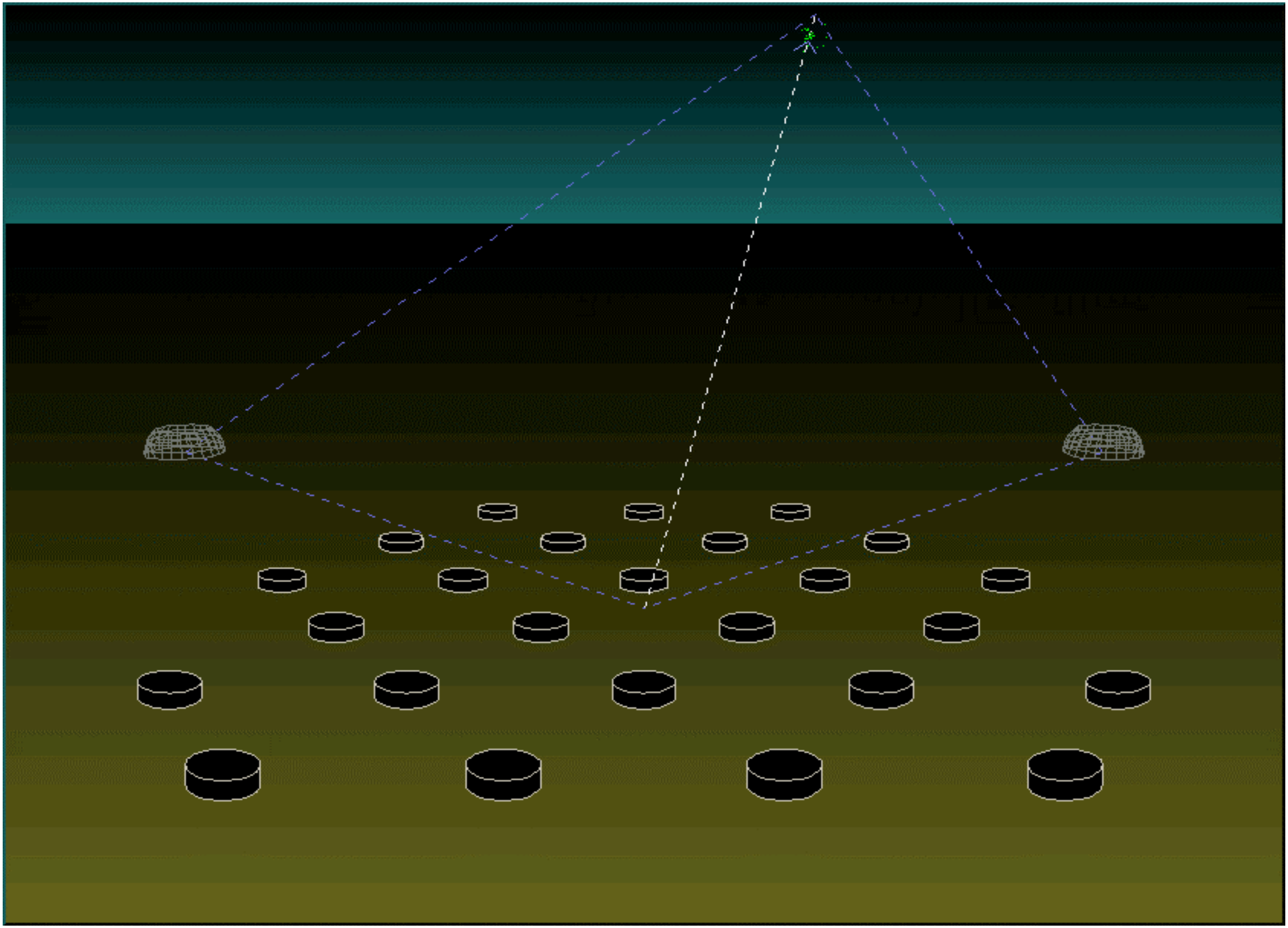
Czech Republic
France
Germany
Italy
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom

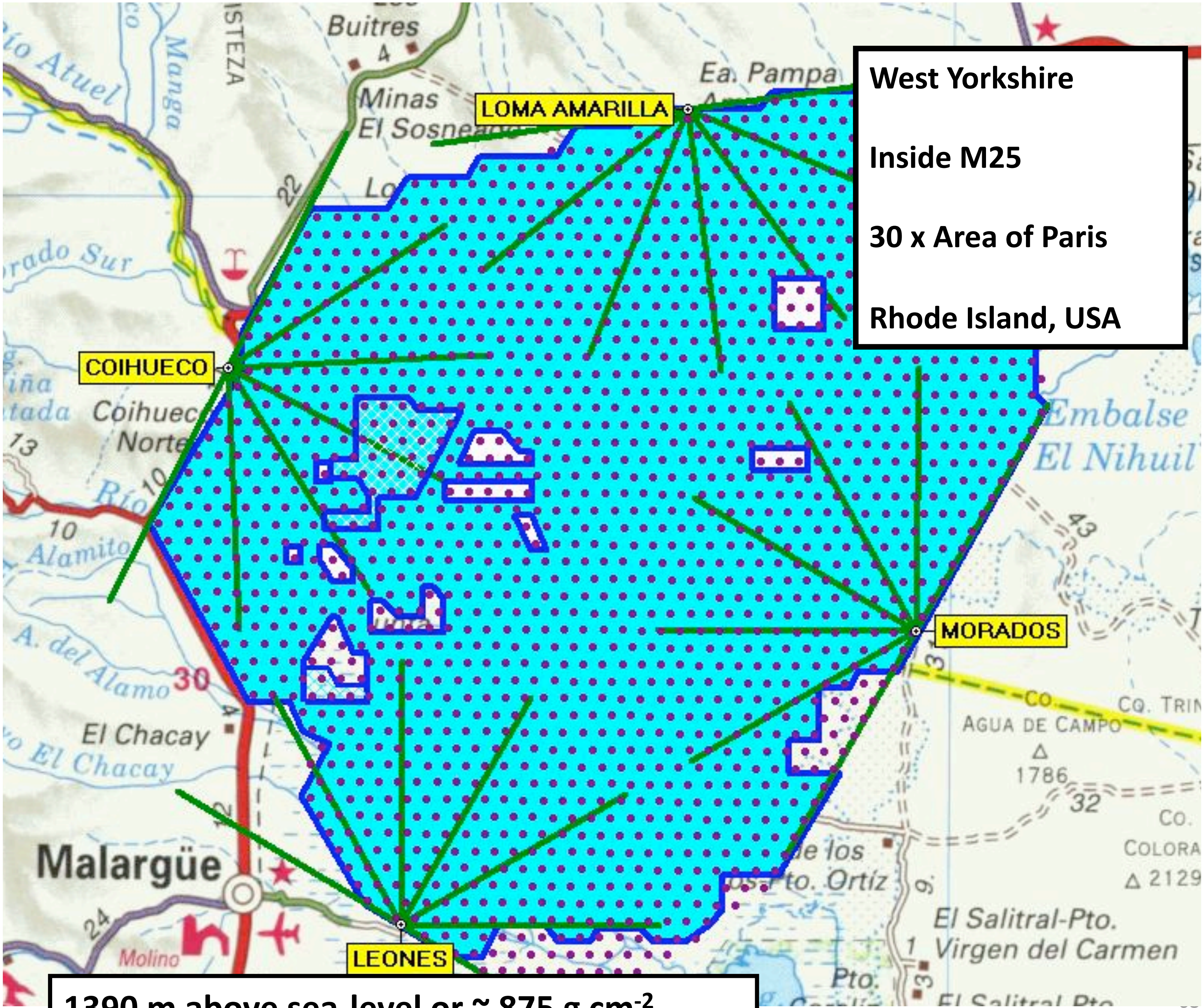
Argentina
Australia
Brasil
Bolivia*
Mexico
USA
Vietnam*

**Associate Countries*

~ 400 PhD scientists from
~ 100 Institutions in 17 countries

Aim: To measure properties of UHECR with unprecedented statistics and precision – first discussions in August 1991 in Trinity College, Dublin – Jim Cronin and Alan Watson





West Yorkshire

Inside M25

30 x Area of Paris

Rhode Island, USA

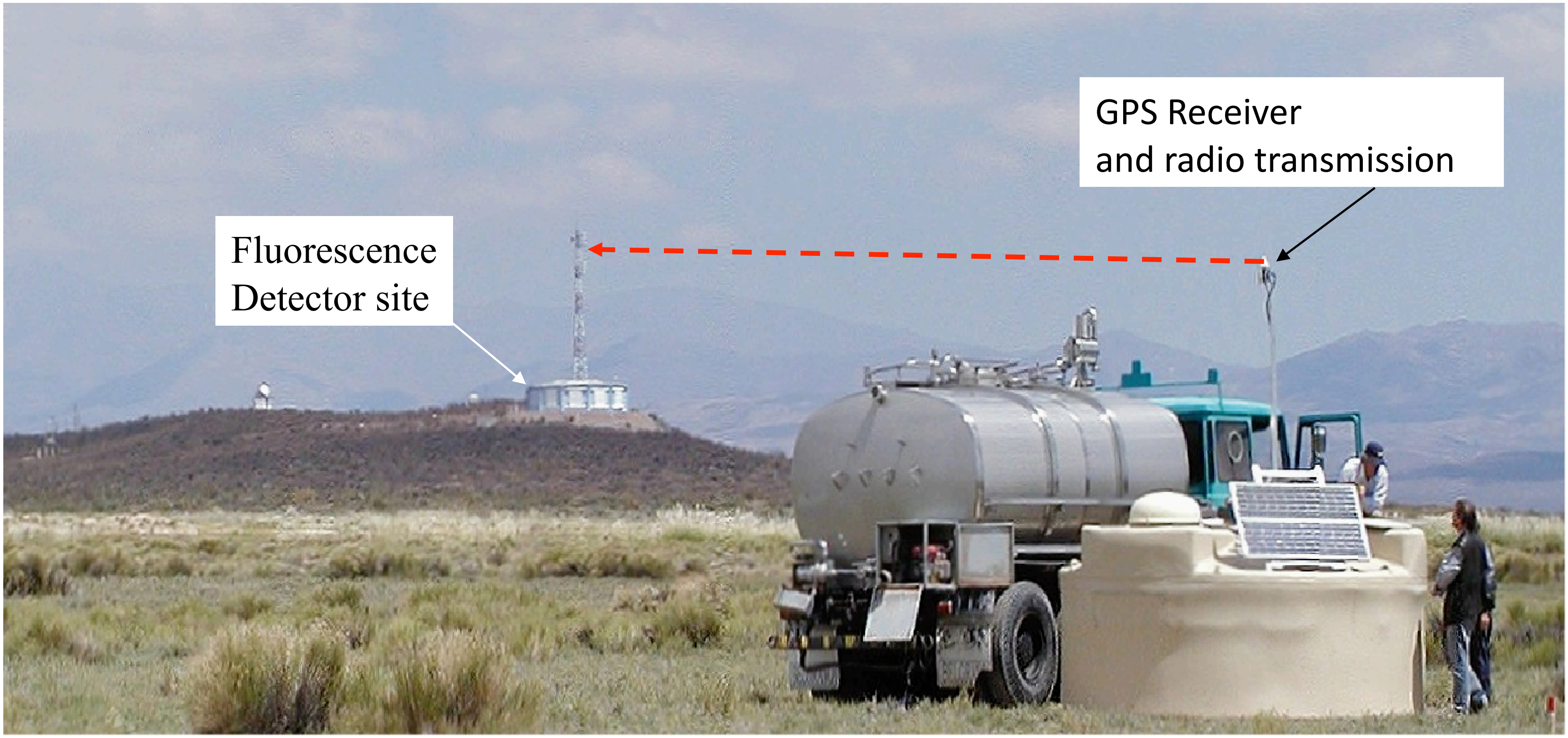
1390 m above sea-level or ~ 875 g cm^{-2}

Campus of Auger Observatory in Argentina

The Office Building in Malargüe
- funded by the University of Chicago ($1M)

Tank liner and tank

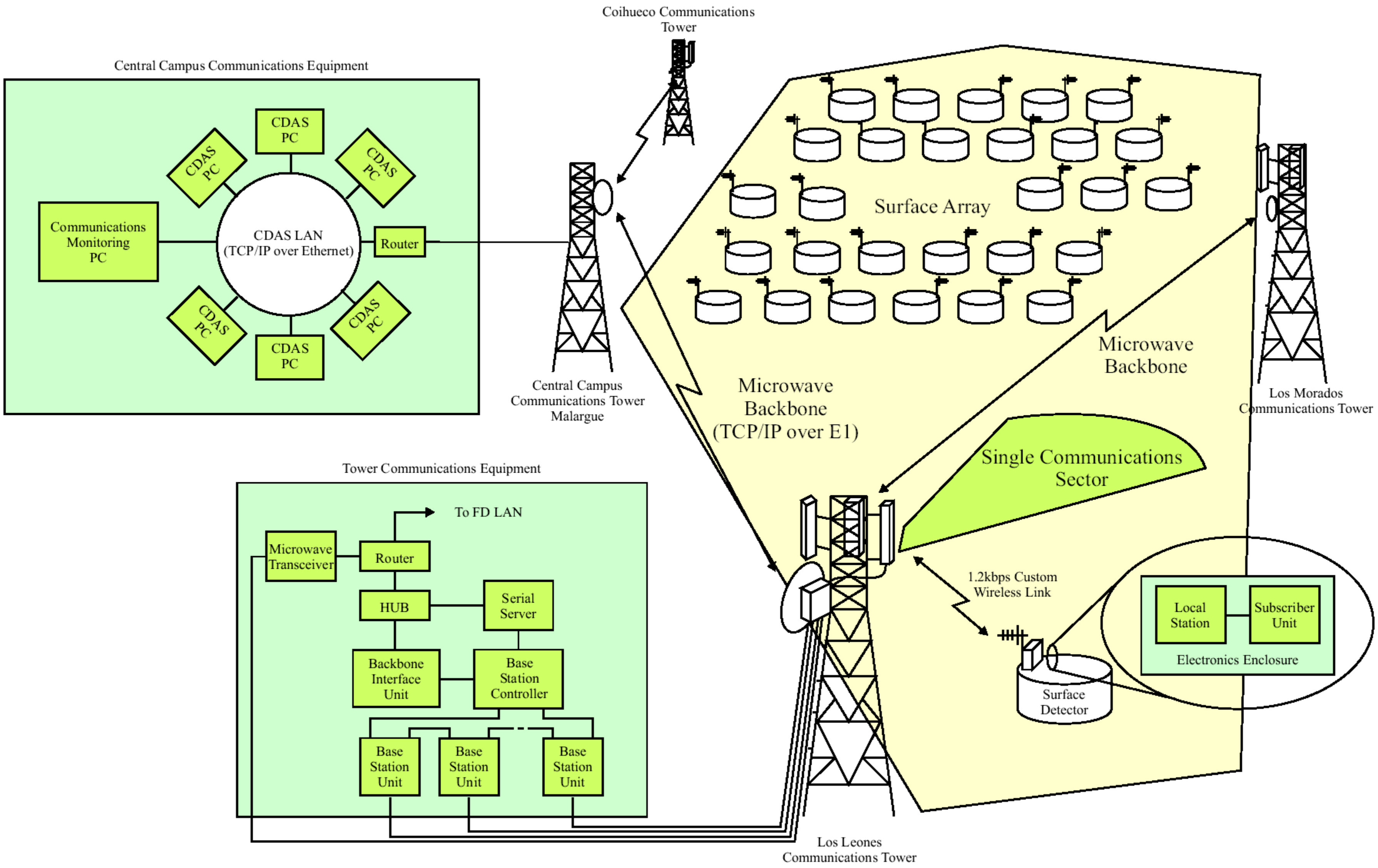
Last tank deployed: 13 June 2008



Fluorescence Detector site

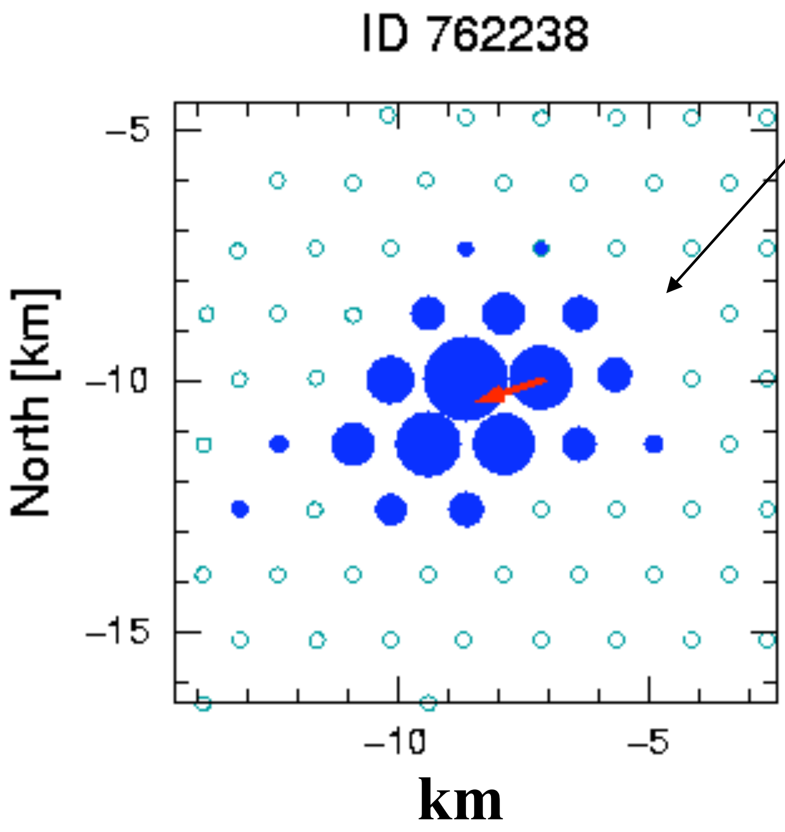
GPS Receiver
and radio transmission

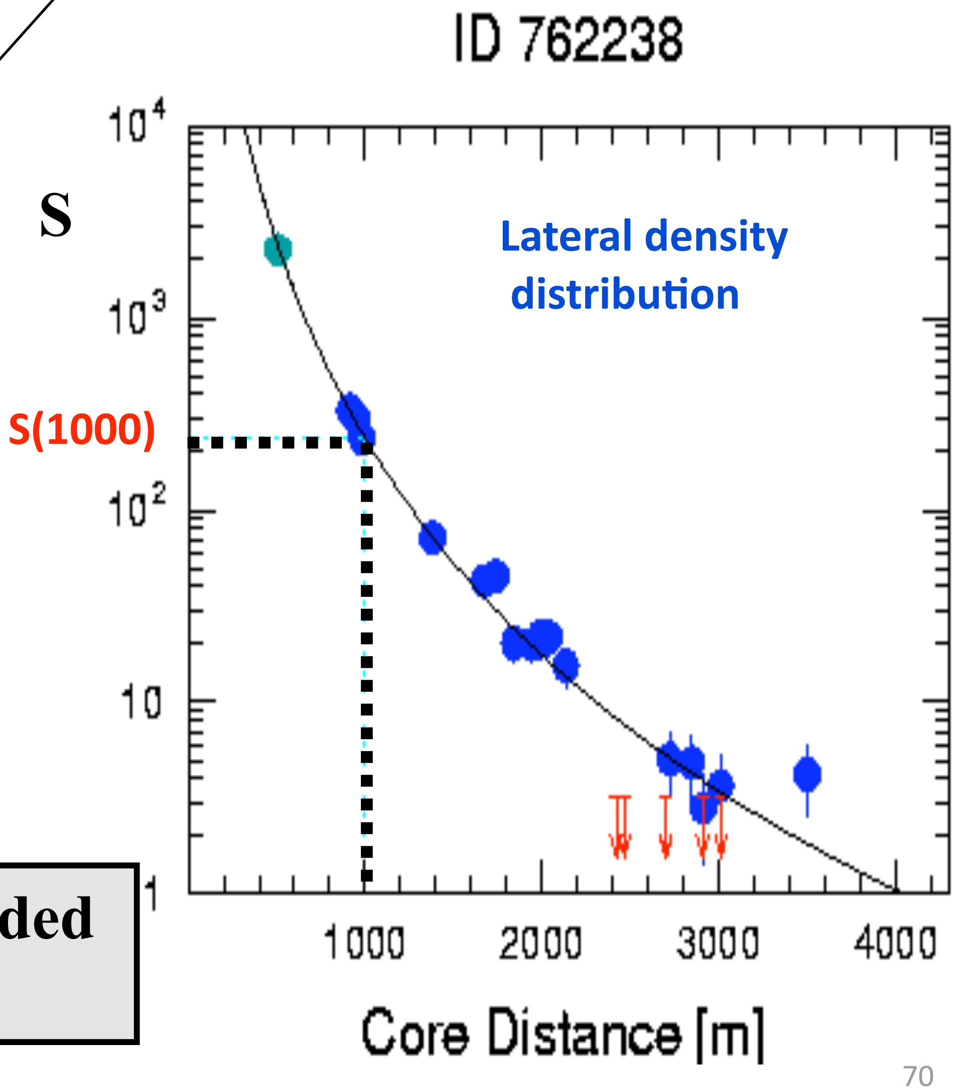
Telecommunication system



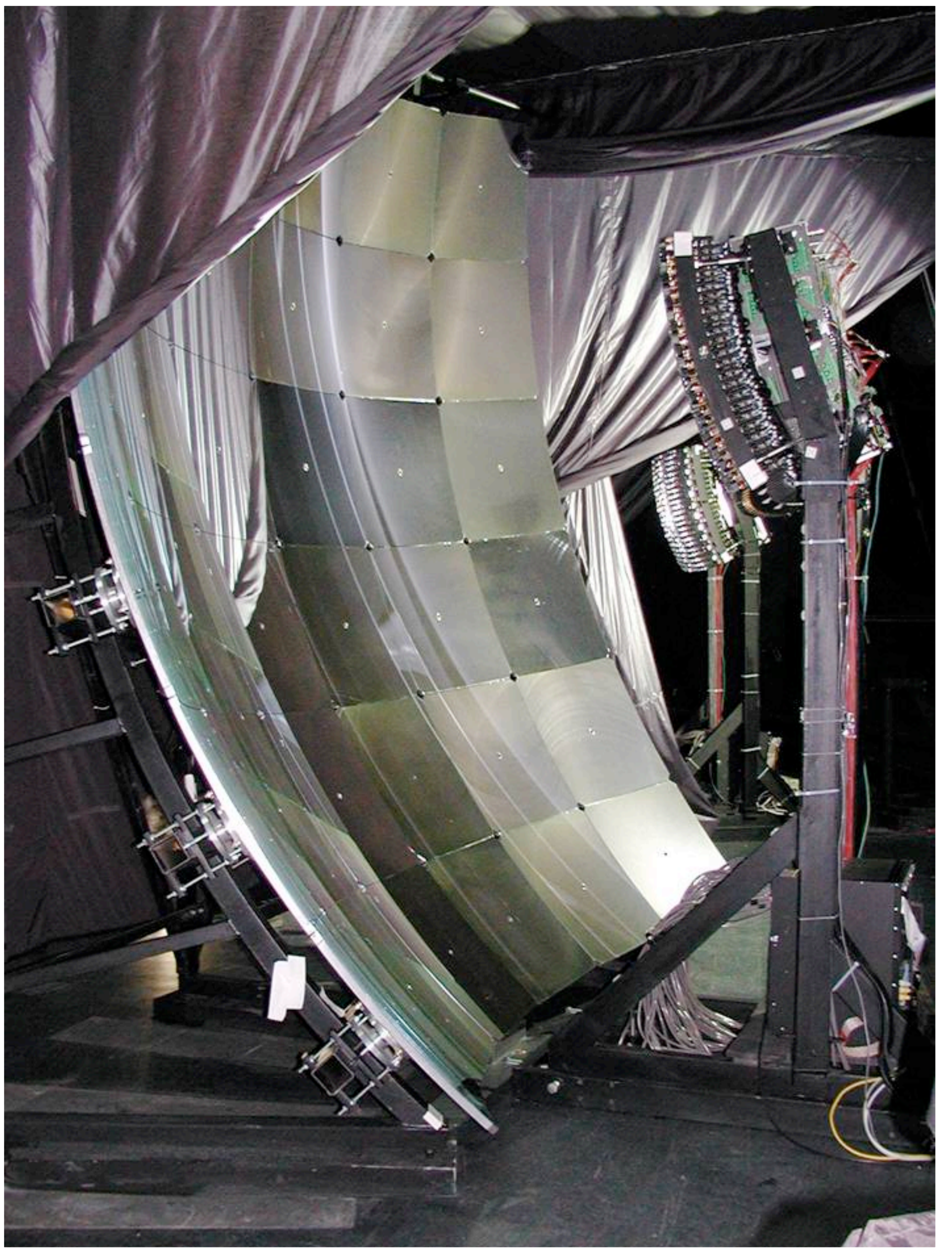
Zenith Angle ~ 48º Energy ~ 7 x 10^{19} eV

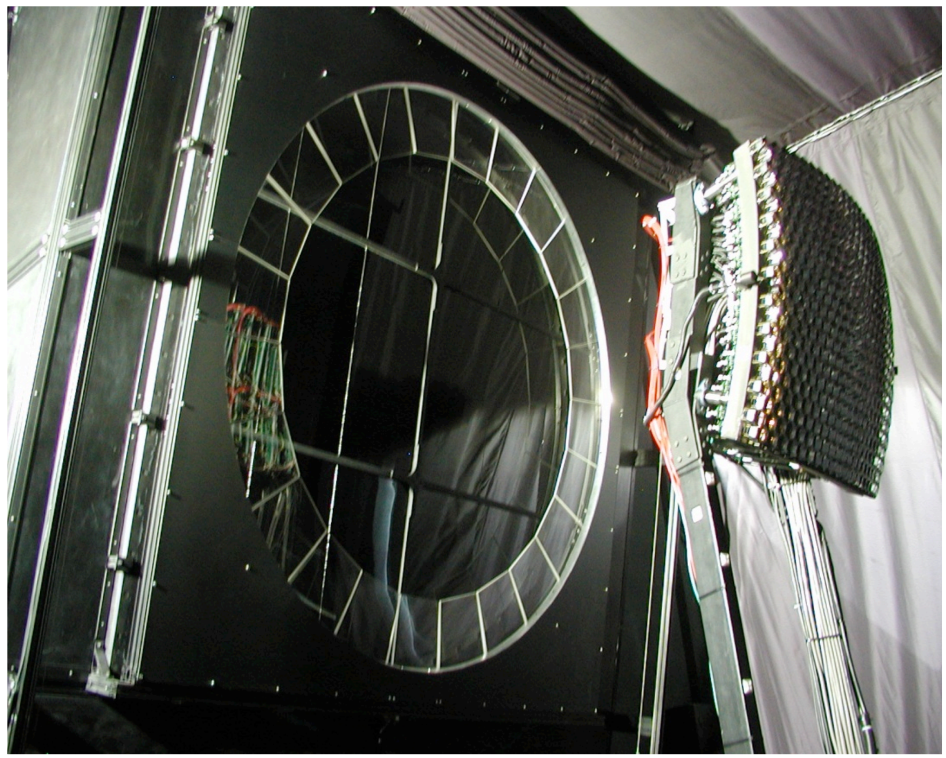
18 detectors triggered





An example of an event recorded with the Cherenkov detectors

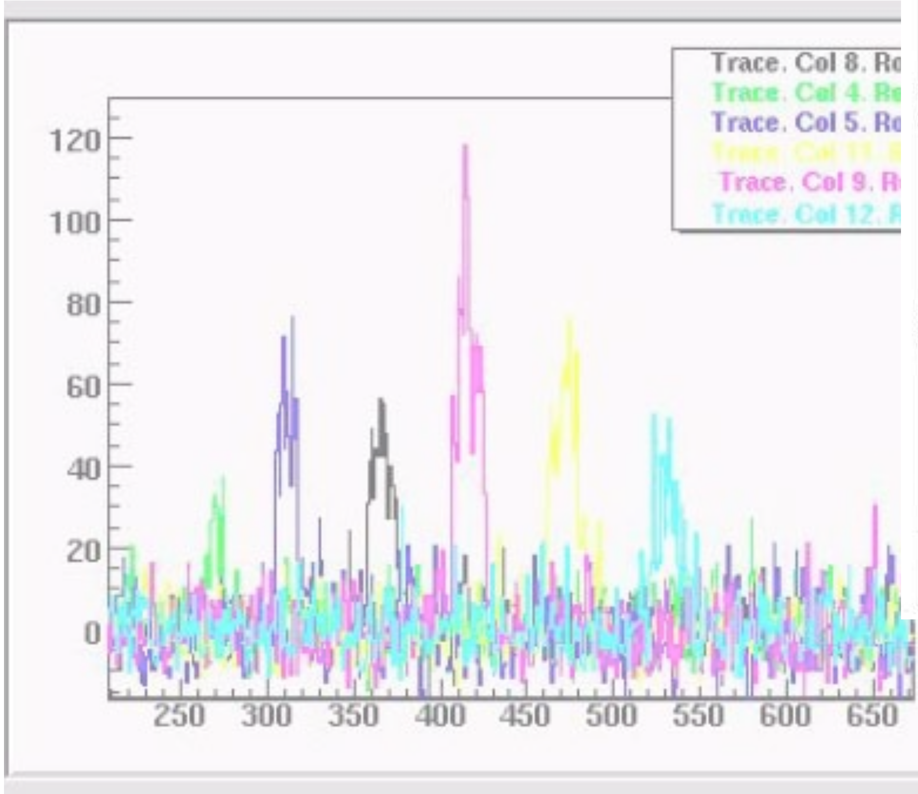


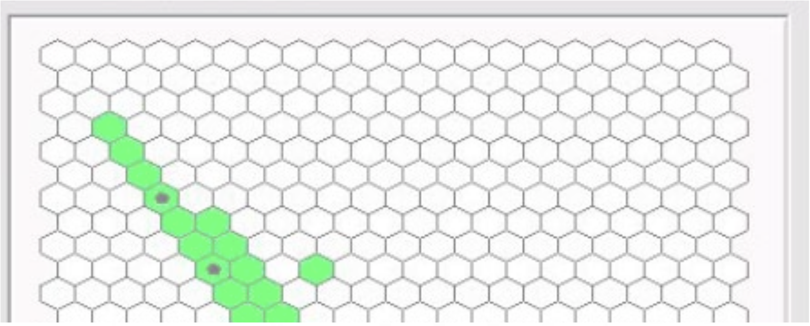


Fluorescence telescopes:
***Number of telescopes:* 24**
***Mirrors:* 3.6 m x 3.6 m with field of view 30º x 30º, each telescope is equipped with 440 photomultipliers.**

FD reconstruction

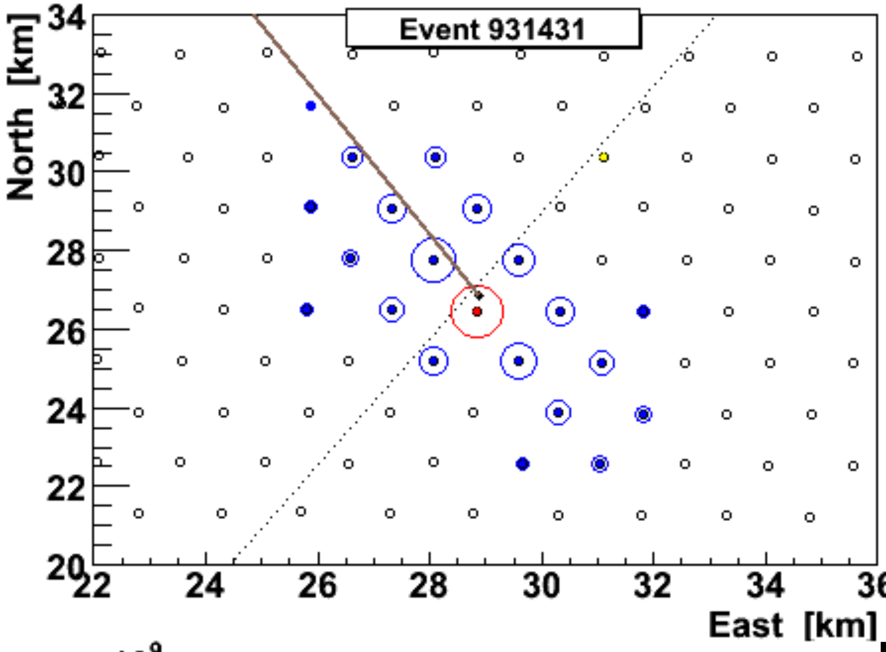
Signal and timing:- Direction and energy





Pixel geometry
shower-detector plane

A Hybrid Event



Core location

Easting 468693 ± 59

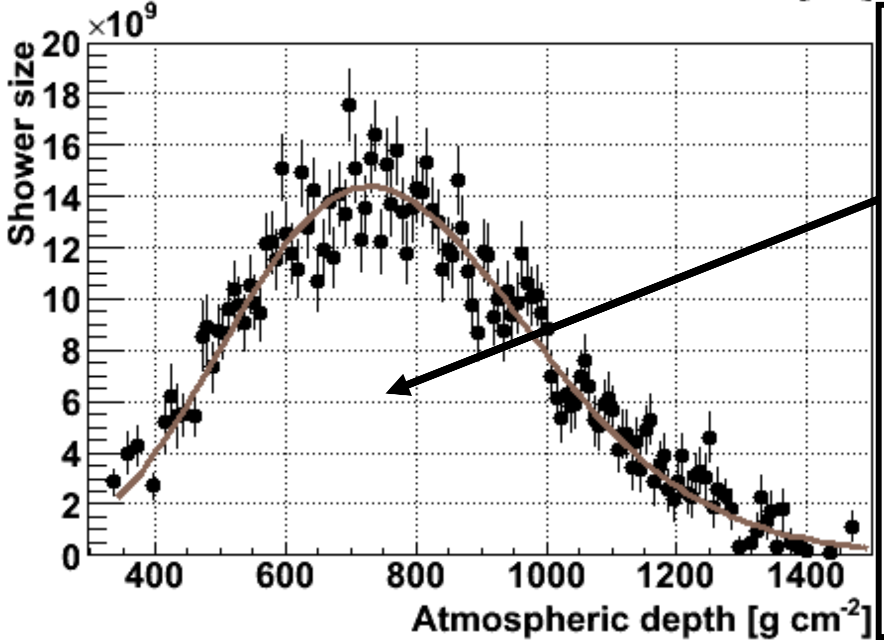
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

$\theta = (62.3 \pm 0.2)^\circ$

$\phi = (119.7 \pm 0.1)^\circ$

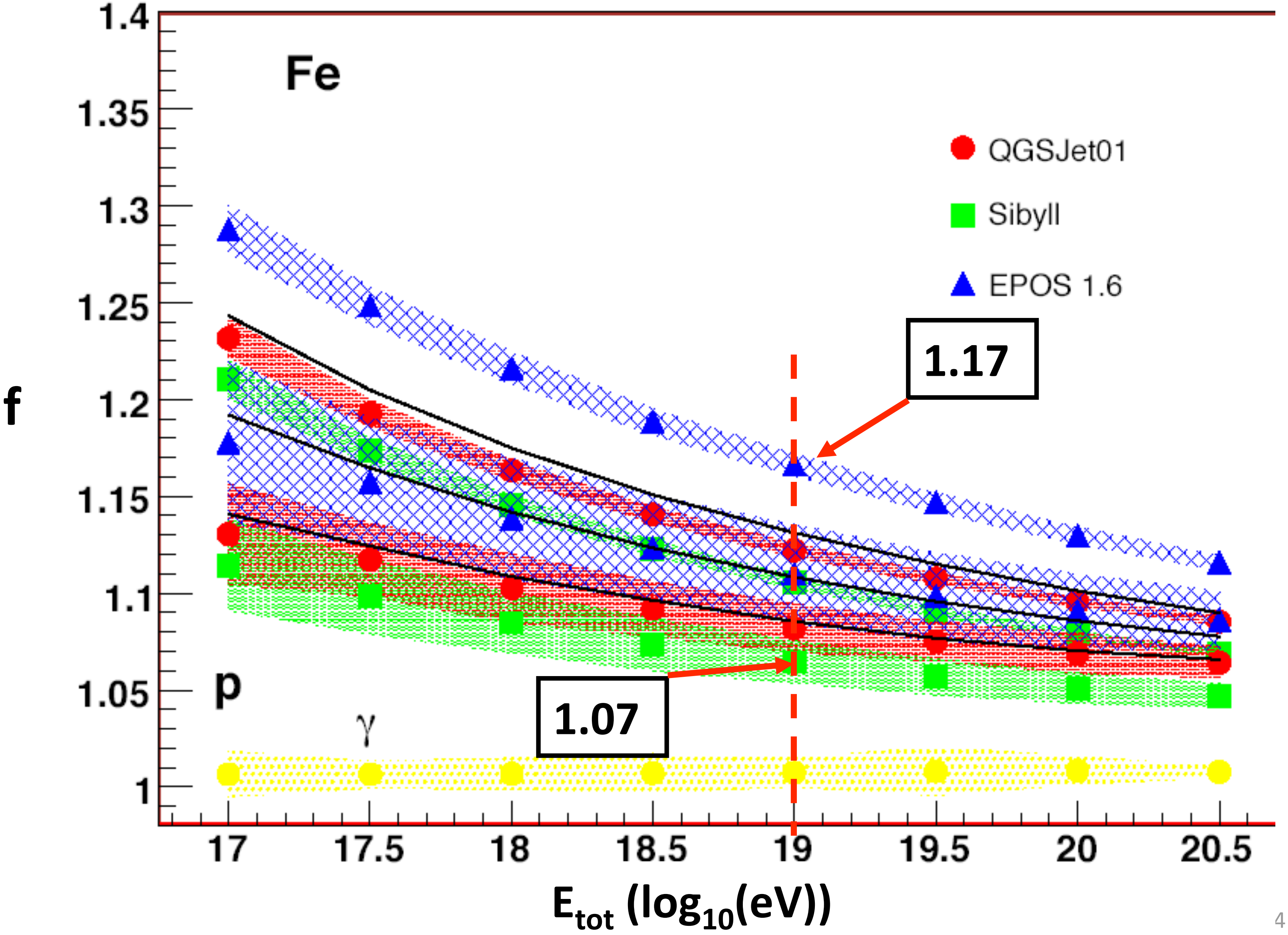


Energy Estimate
- from area under
curve

(2.1 ± 0.5) x 10^{19} eV

must account for
'missing energy'

$f = E_{tot}/E_{em}$


f
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
Fe
p
γ
● QGSJet01
■ Sibyll
▲ EPOS 1.6
1.17
1.07
17
17.5
18
18.5
19
19.5
20
20.5
E_{tot} ($\log_{10}$(eV))

Results from Pierre Auger Observatory

Data-taking started on 1 January 2004 with

125 (of 1600) water-Cherenkov detectors

6 (of 24) fluorescence telescopes

more or less continuous operation since then

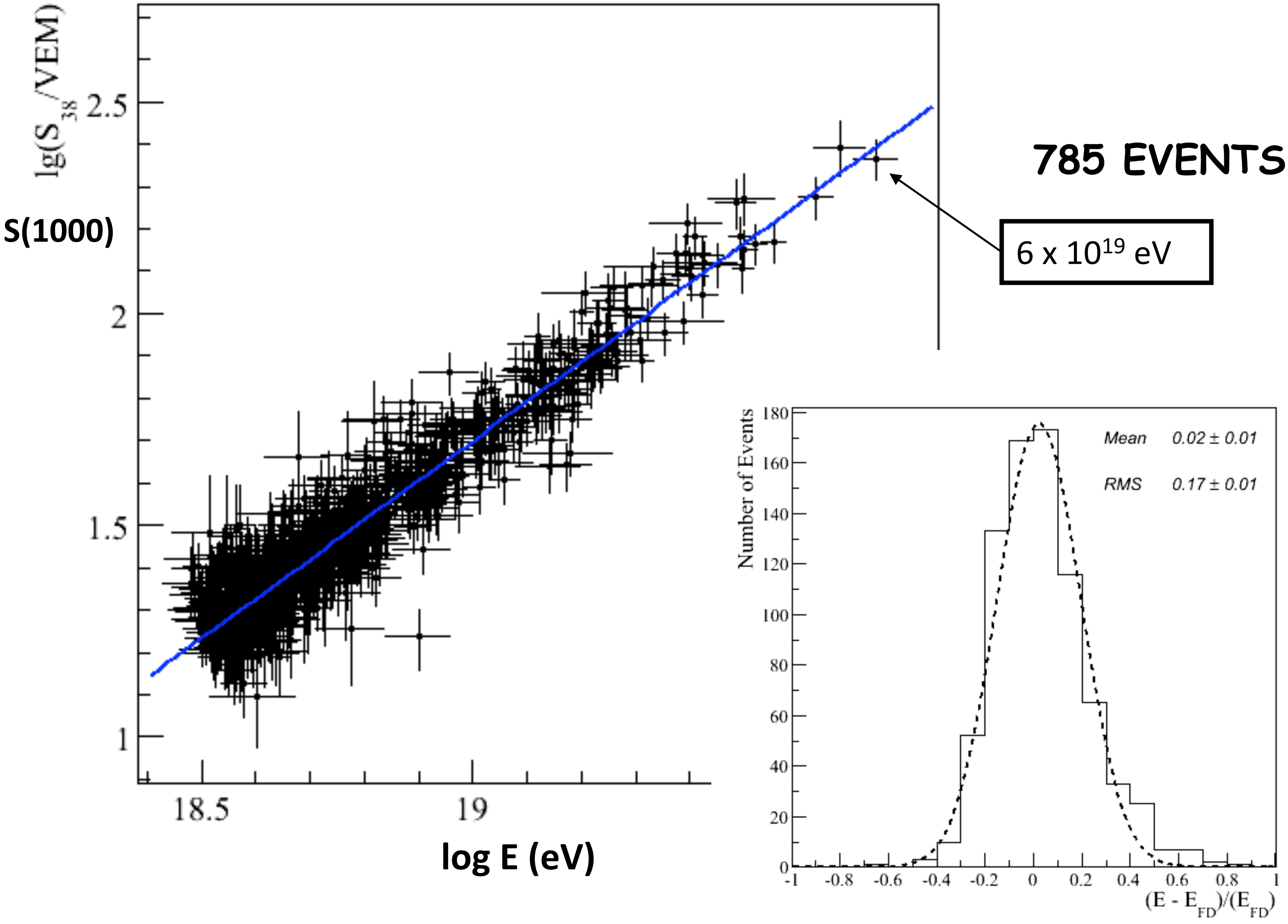
At end of 2009, 12,790 km^2 sr yr

> 10^{19} eV: 4440 (HiRes stereo: 307
> 5 x 10^{19} eV: 59 : 19
> 10^{20} eV: 3 : 1)

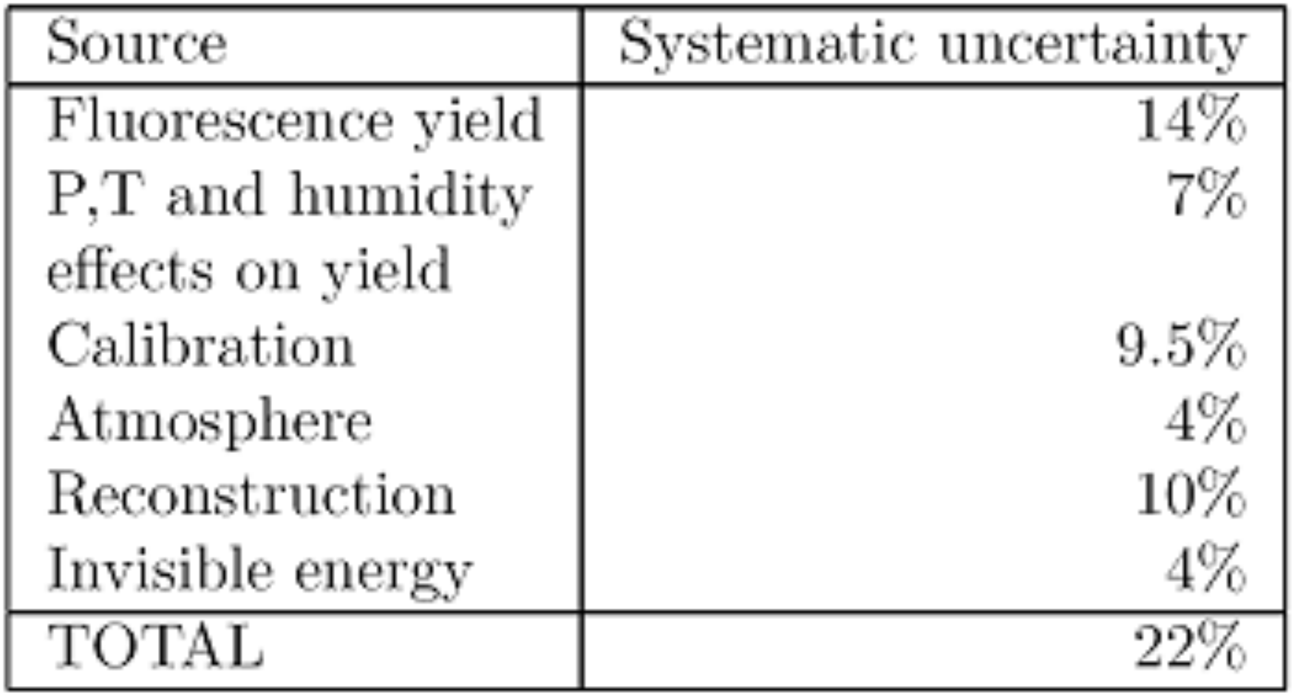
HiRes Aperture: x 4 at highest energies

x 10 AGASA

Auger Energy Calibration



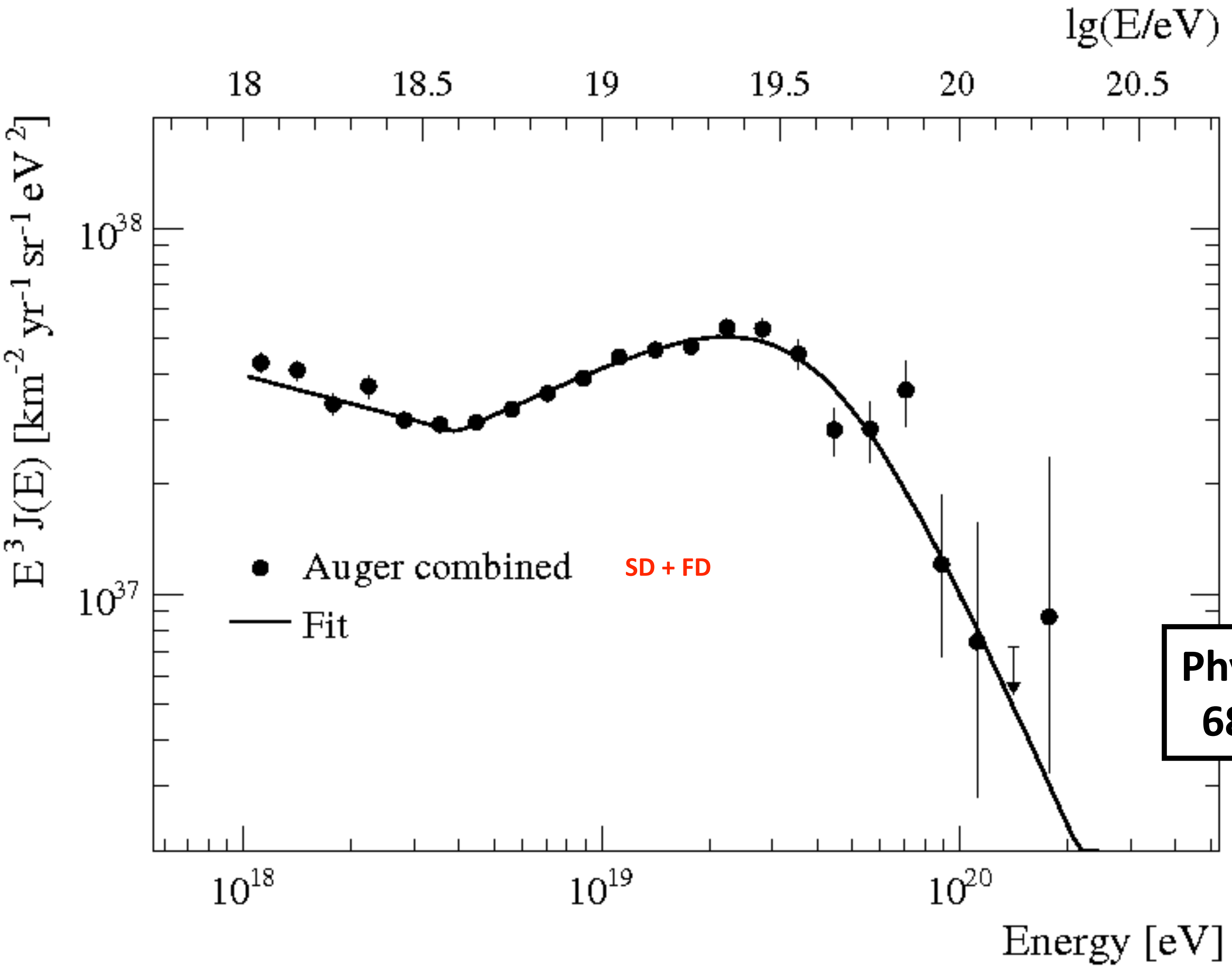
Summary of systematic uncertainties



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%

Fluorescence Detector Uncertainties Dominate

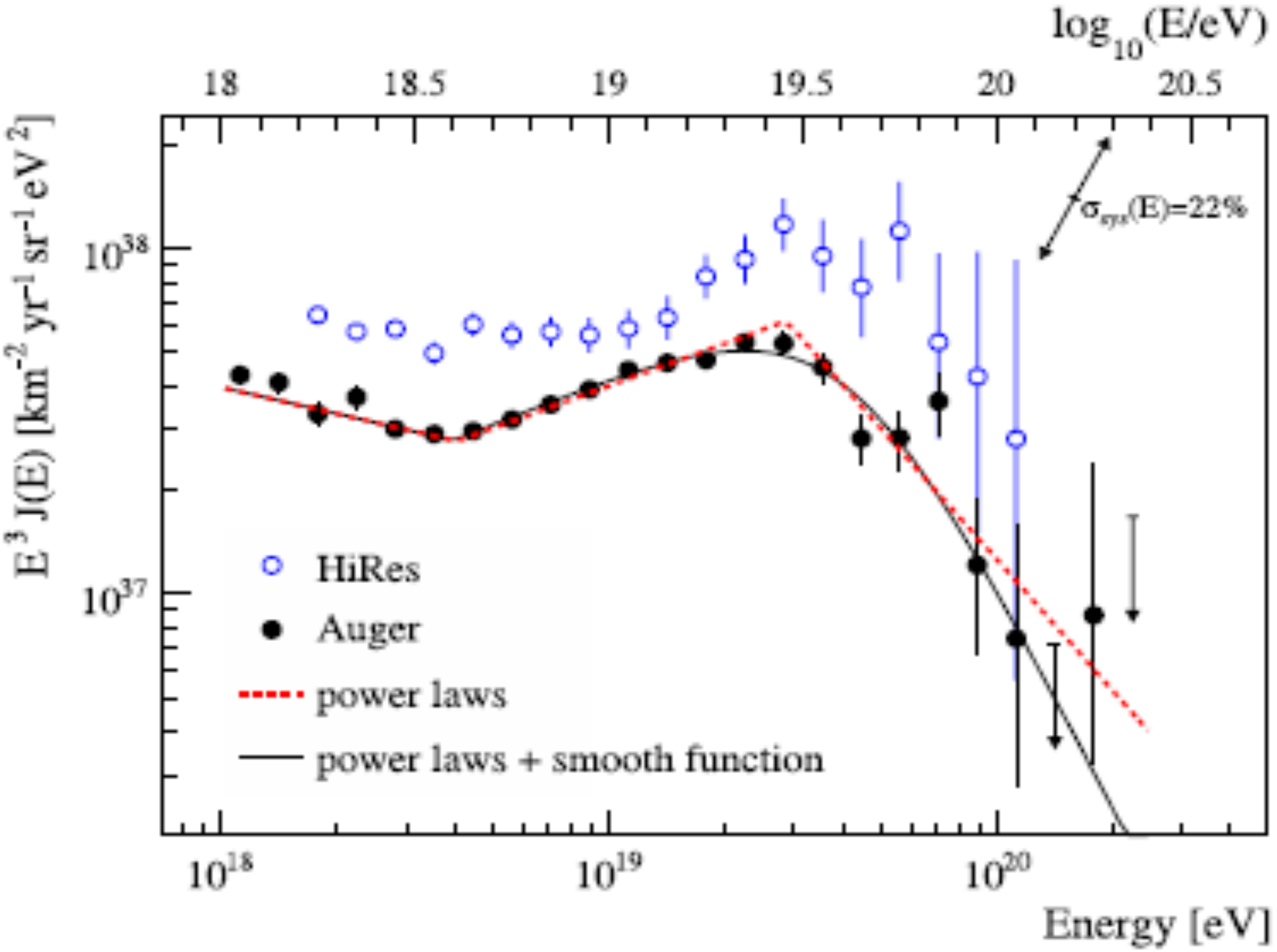
Energy Spectrum from Auger Observatory



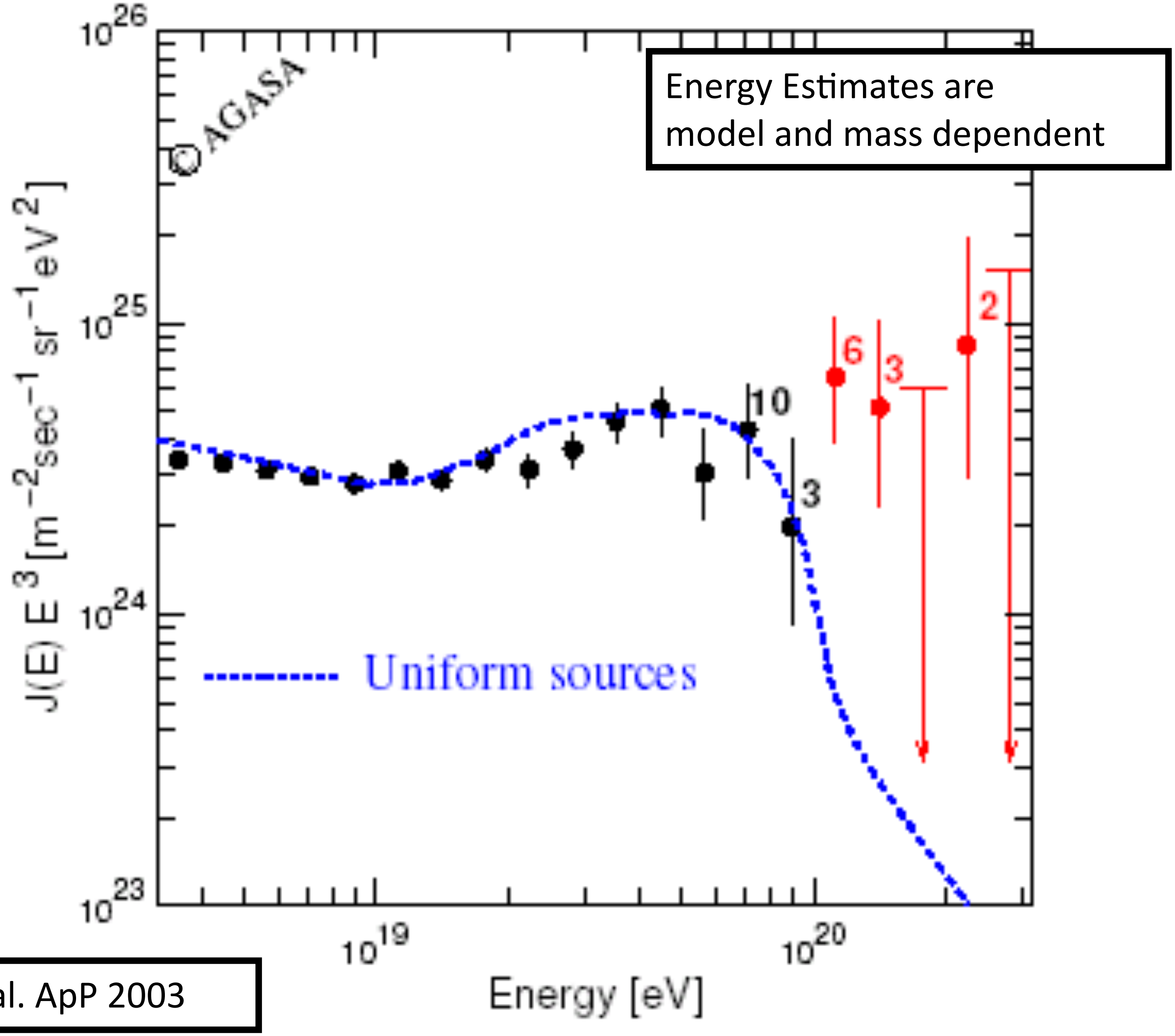
SD + FD

Physics Letters B
685 239 2010

Above 3 x 10^{18} eV, the exposure is energy independent: 1% corrections in overlap region



Auger and HiRes Spectra



Energy Estimates are
model and mass dependent

Takeda et al. ApP 2003

For the few events above 10^{20} eV

Auger (3) and HiRes stereo (1)

Integral flux is **$(2.4 \pm 1.9/1.1) \times 10^{-4}$ km^{-2} sr^{-1}yr^{-1}**

11 AGASA events

$(6.4 \pm 1.9) \times 10^{-3}$ km^{-2} sr^{-1} yr^{-1}

a factor of more than 25

Even a factor of x 2 increase in Auger energies would not be enough to explain difference

Consensus is that Auger and HiRes have got it right

But the steepening itself is INSUFFICIENT for us to claim that we have at last (predicted in 1966) seen the Greisen-Zatsepin-Kuz'min effect

It might simply be that the sources cannot raise particles to energies as high as 10^{20}eV – Nature could be teasing us!

But, if the steepening IS caused by the GZK-effect then we might expect to find that cosmic ray sources are relatively nearby

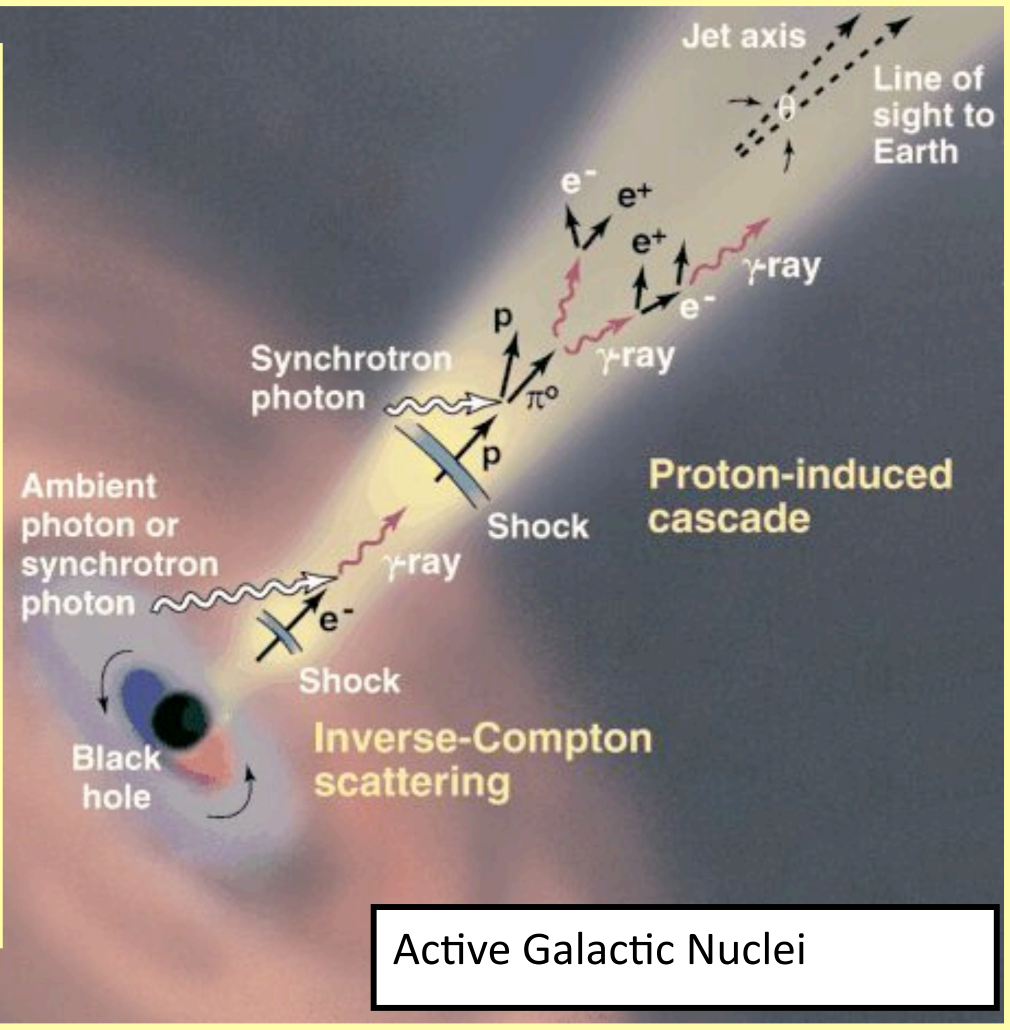
So, look to see if we can find likely accelerators lined up with the direction of the highest energy events

But what might the acceleration mechanism be?

Searching for Anisotropies

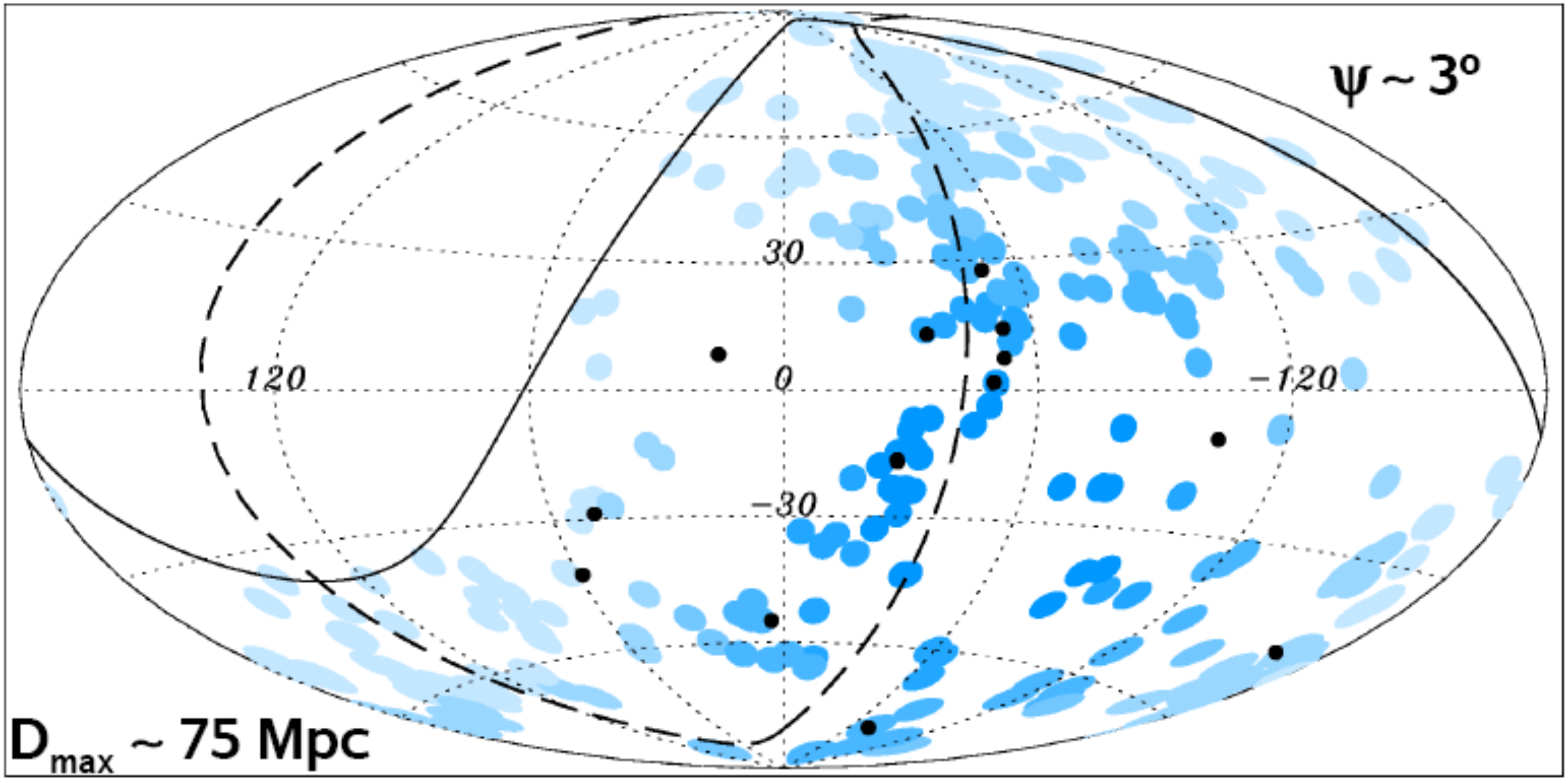
Image of M87 with Hubble Space Telescope

Decided to use catalogue of galaxies like this and see if they lined up with the directions of our event



Active Galactic Nuclei

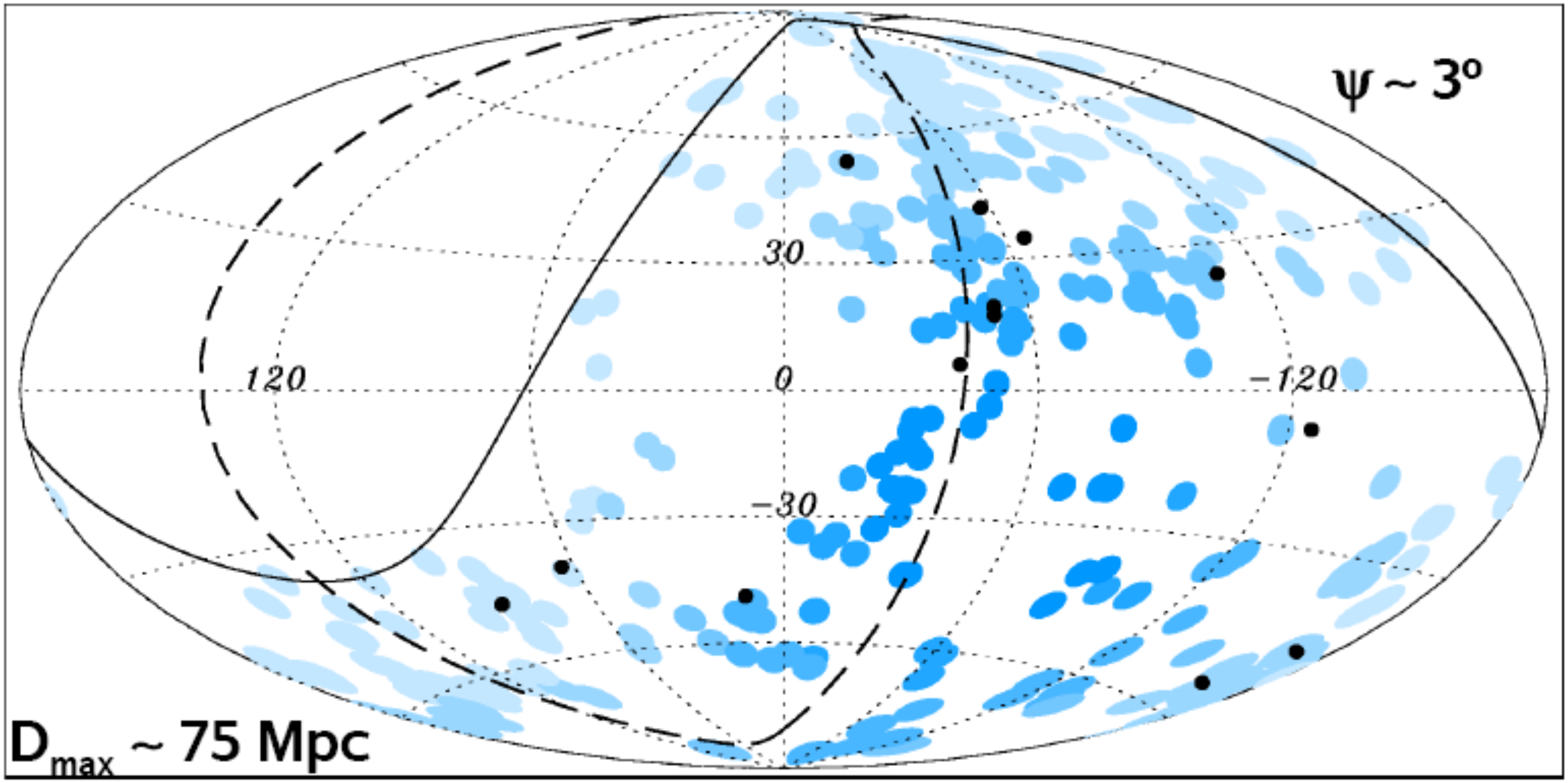
Exploratory scan: data until 27 May 2006



Largest significance for E_{th} ~ 6x10^{19} eV ψ ~ 3° D_{max} ~ 75 Mpc

12/15 events close to AGNs in Véron-Cetty & Véron Catalogue

Test Using Independent Data Set



Data from 27 May 2006 until 31 August 2007

8/13 events lined up as before: chance 1/600

Using Veron-Cetty AGN catalogue

First scan gave ψ < 3.1°, z < 0.018 (75 Mpc) and E > 56 EeV

Period	total	AGN hits	Chance hits	Probability
1 Jan 04 - 26 May 2006	15	12	3.2	1st Scan
27 May 06 – 31 August 2007	13	8	2.7	1.7×10^{-3}

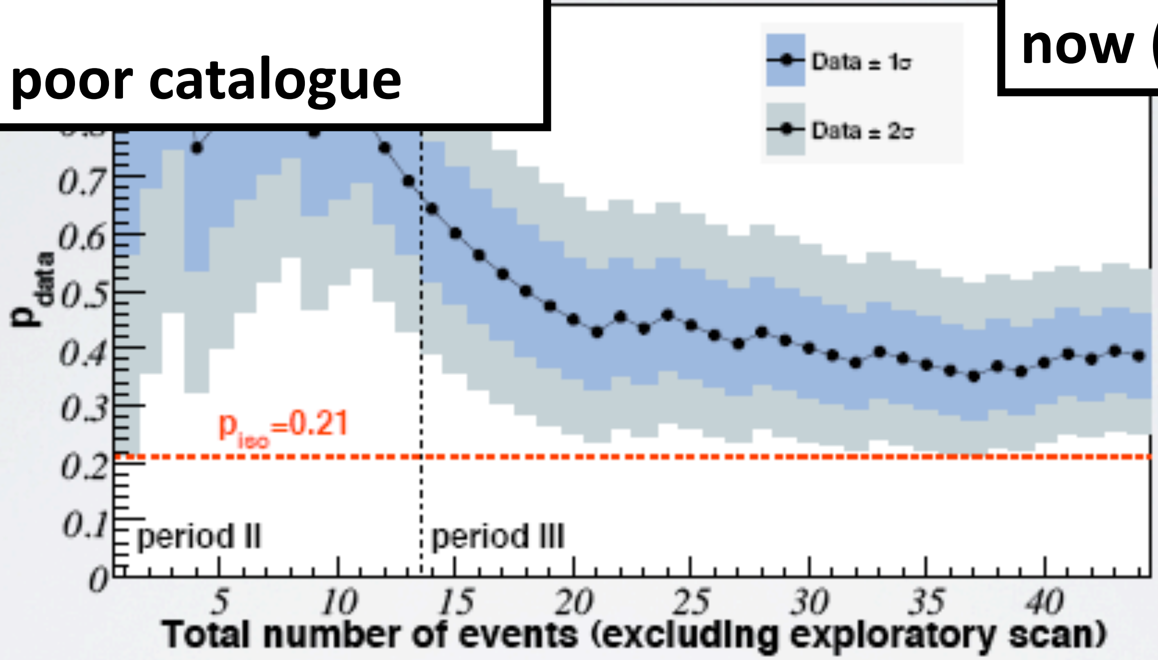
Each exposure was 4500 km^2 sr yr

6 of 8 'misses' are with 12° of galactic plane

CURRENT STATUS

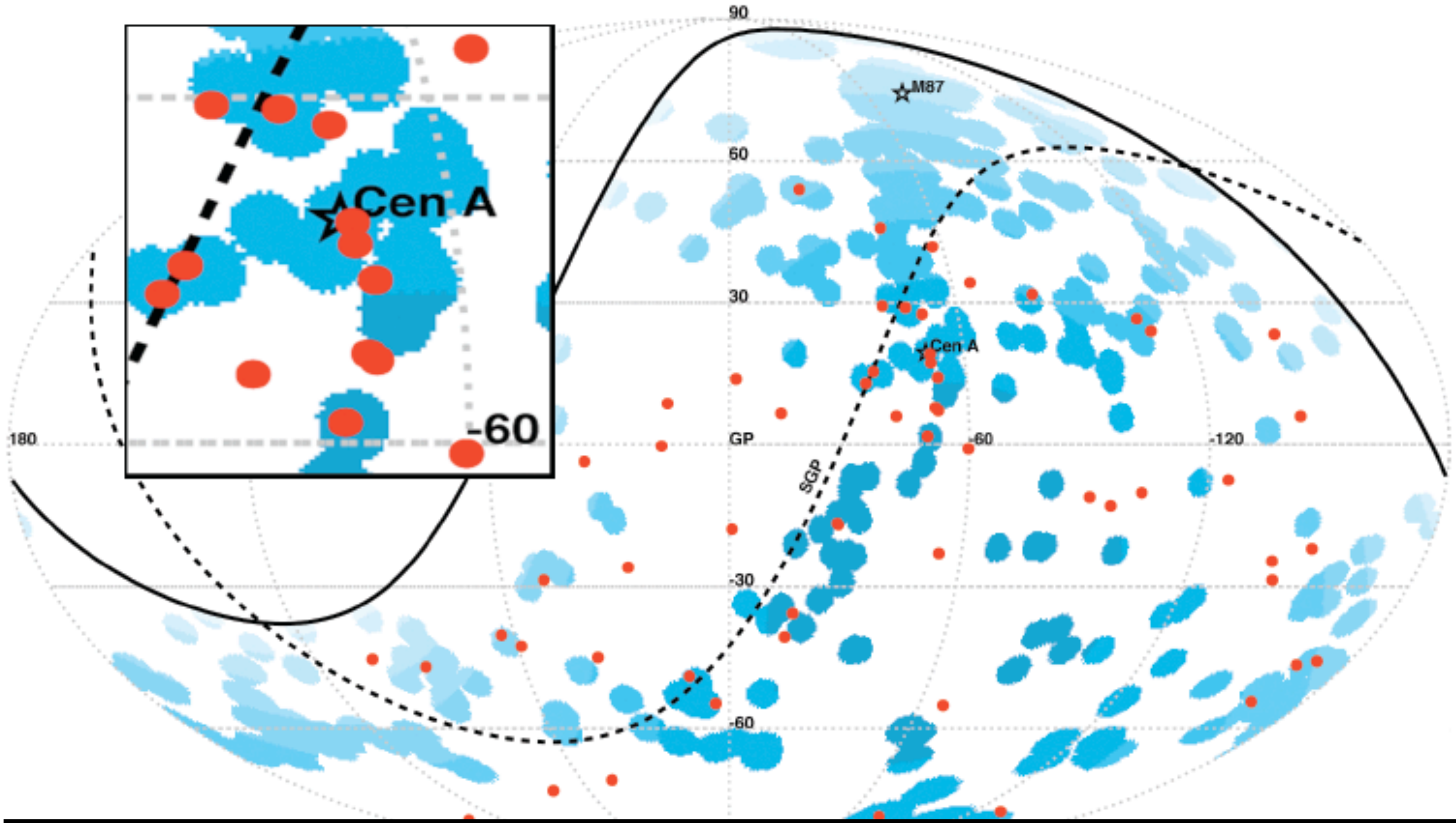
Nature has been unkind (?)
AND
we chose a poor catalogue

(69 ± 12)%
now (38 ± 6)%S



p = 17/44 = 0.38 more than 2 s.d. from isotropy
(expected from isotropy 9.2/44)

The degree of correlation has decreased, but still provides evidence for anisotropy of UHECRs @ E > 55 EeV at 99% C.L.



A clear message from the Pierre Auger Observatory is that we made it too small

Rate of events that seem to be anisotropically distributed is only ~ 2 per month

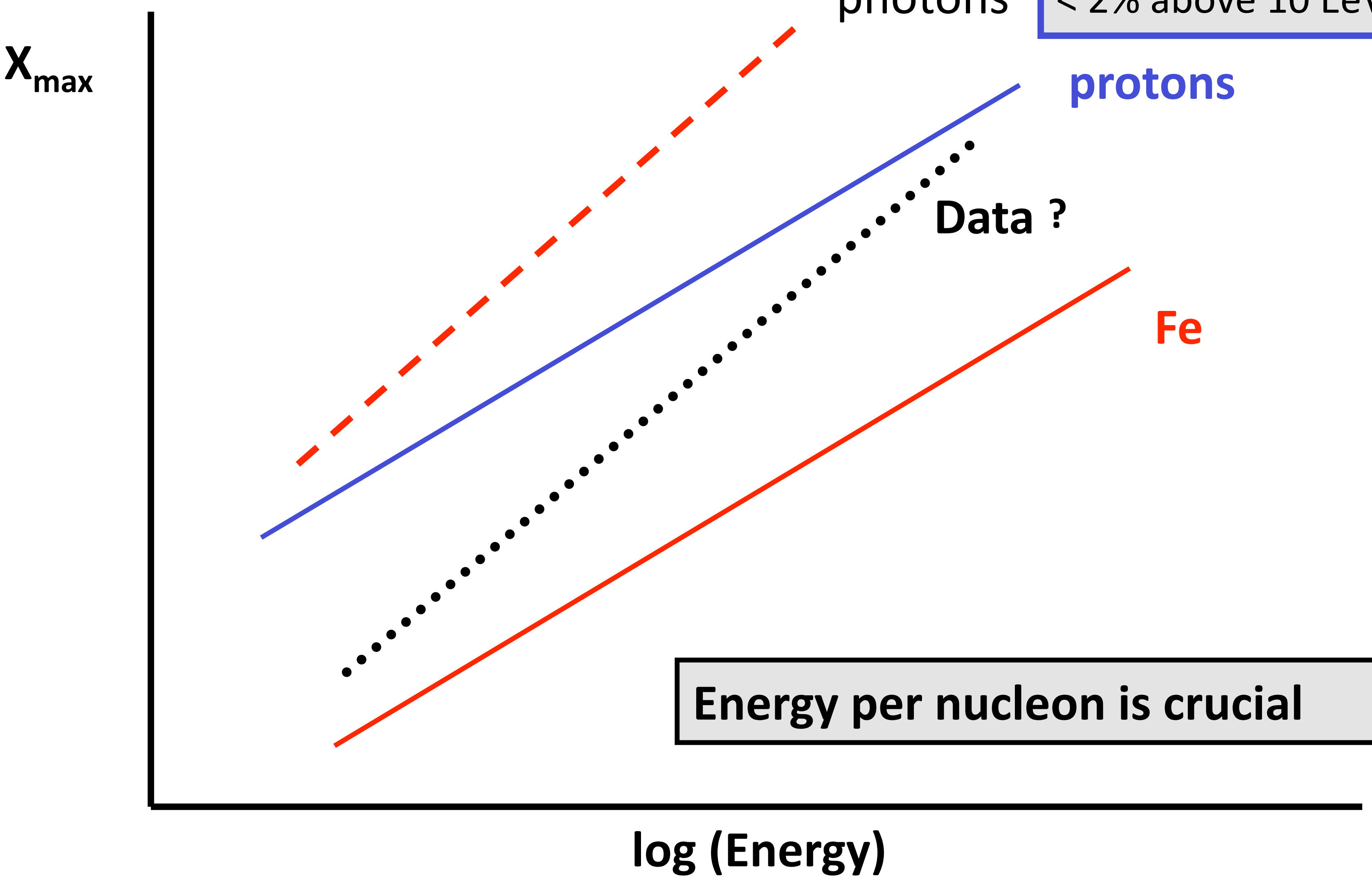
Indications on Mass Composition

- **Anisotropy suggests a proton fraction of ≈ 40%**

- **Most unexpected result from Pierre Auger Observatory so far points in another direction**

- ***Could* be indicative of interesting new physics (??)**

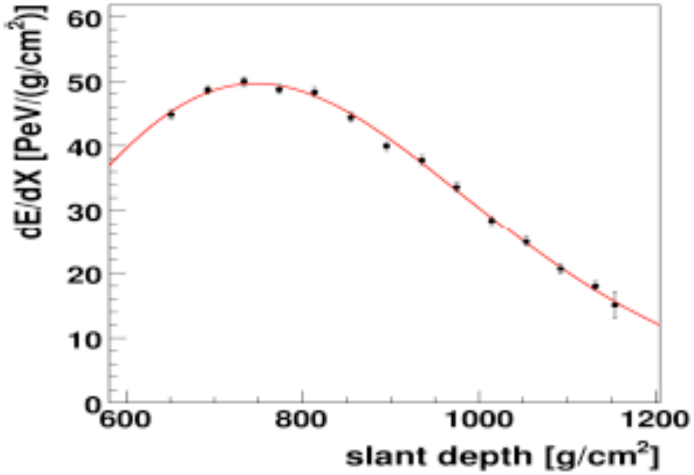
How we try to infer the variation of mass with energy

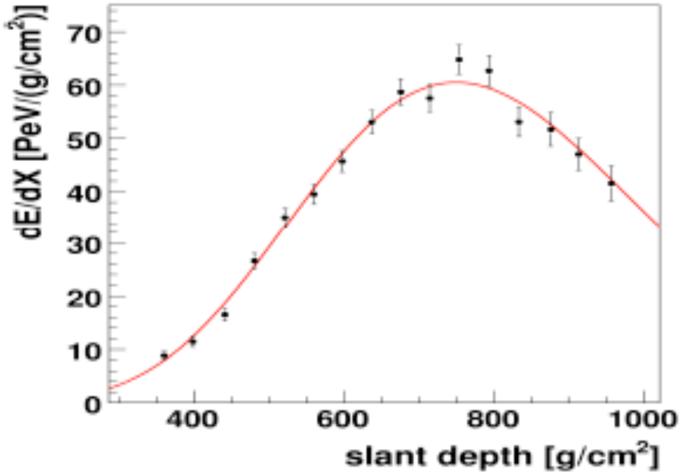


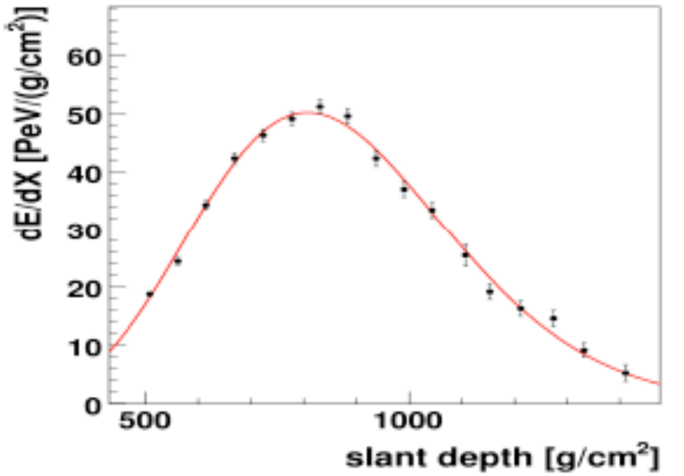
< 2% above 10 EeV

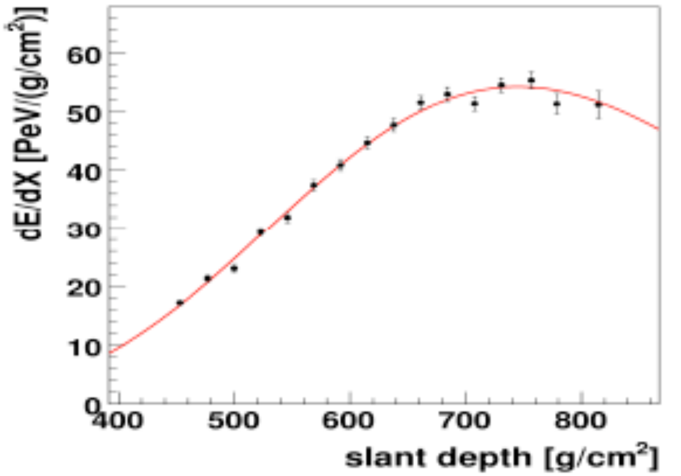
Energy per nucleon is crucial

Some Longitudinal Profiles measured with Auger

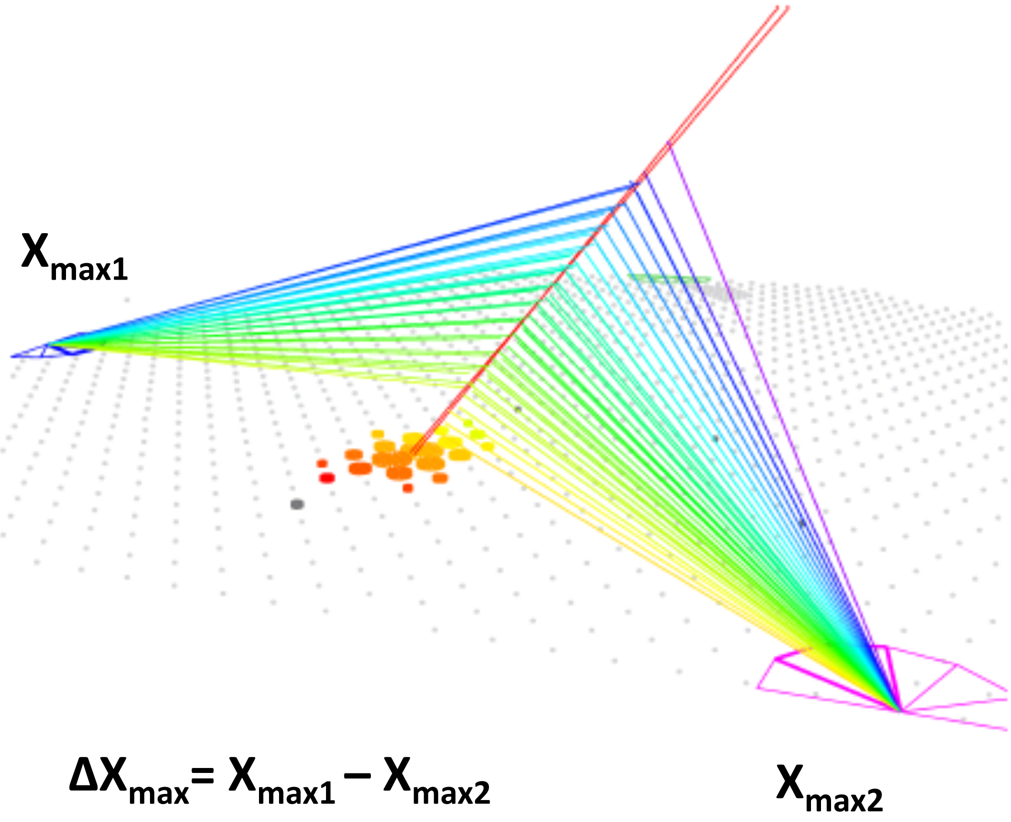




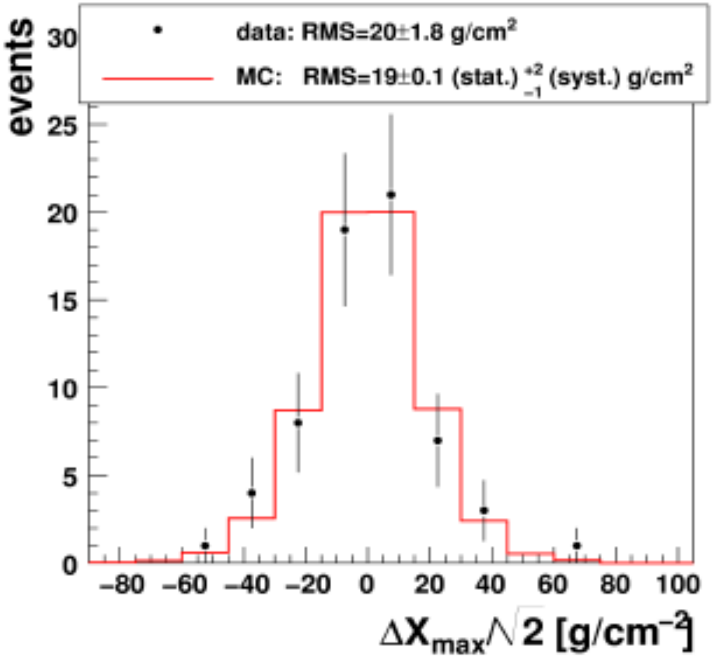


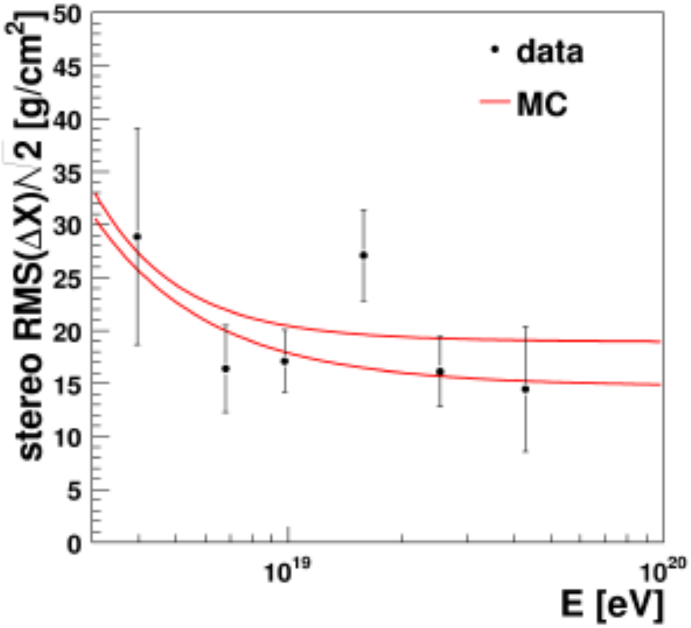


X_{max} Resolution



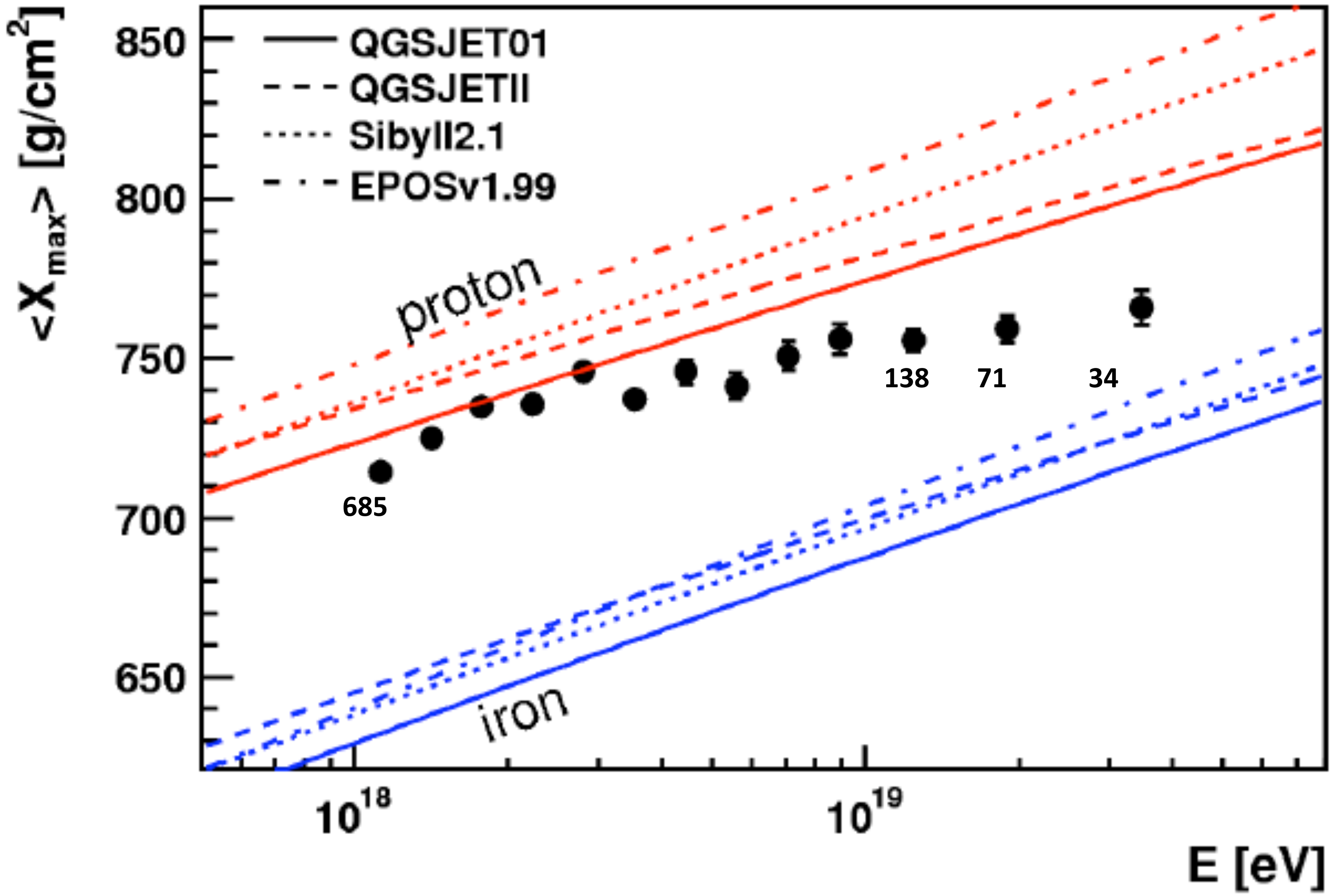
$\Delta X_{max} = X_{max1} - X_{max2}$



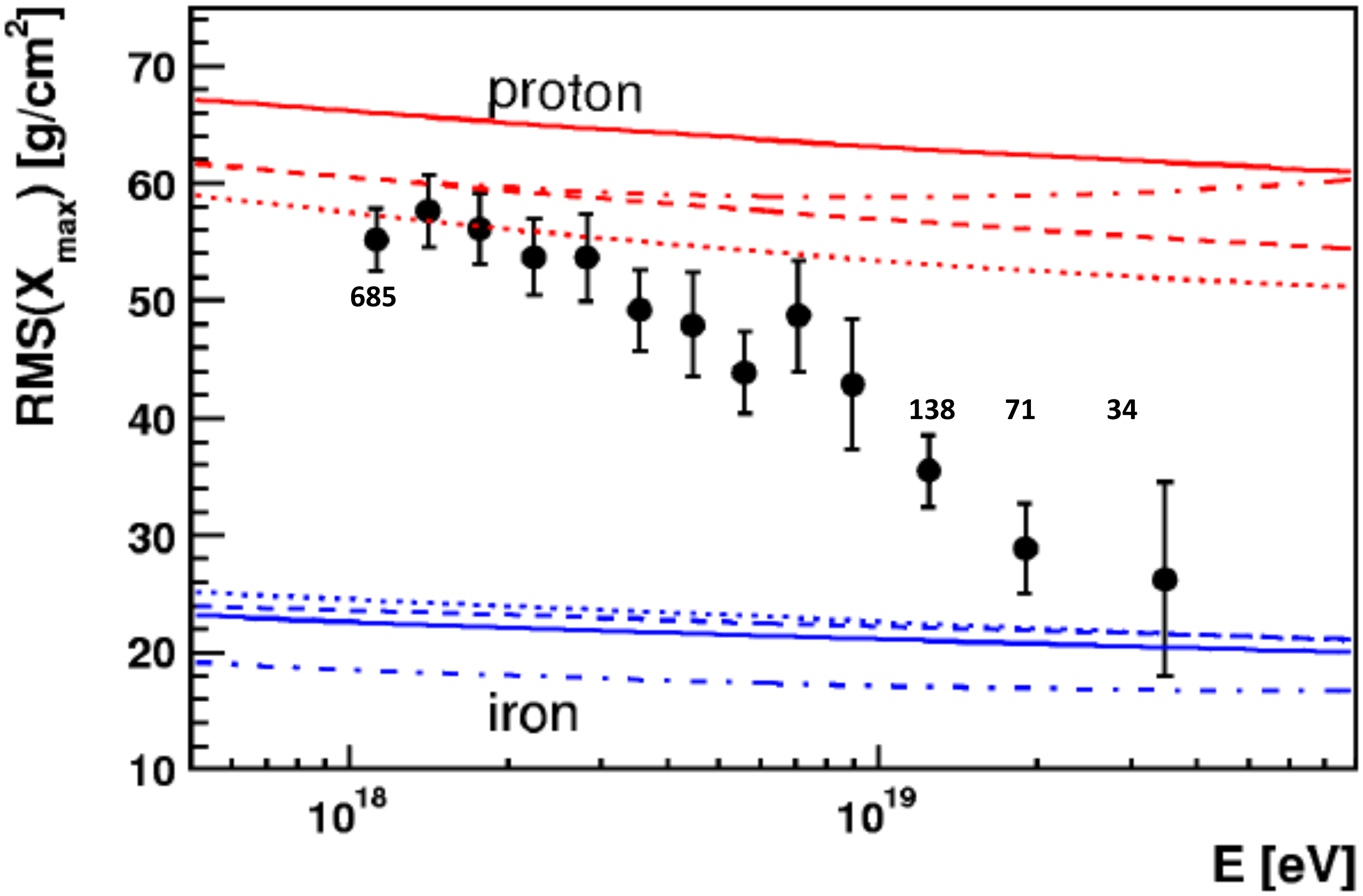


Check using Simulations

Mean X_{max} from 3754 events



RMS($X_{max)}$ for same events



Aloisio, Berezinsky and Gazisov Astroparticle Physics 34 620 2011

"Ultra High Energy Cosmic Rays: the disappointing model"

Assumes extra-galactic origin

Protons dominate 1 – 3 EeV

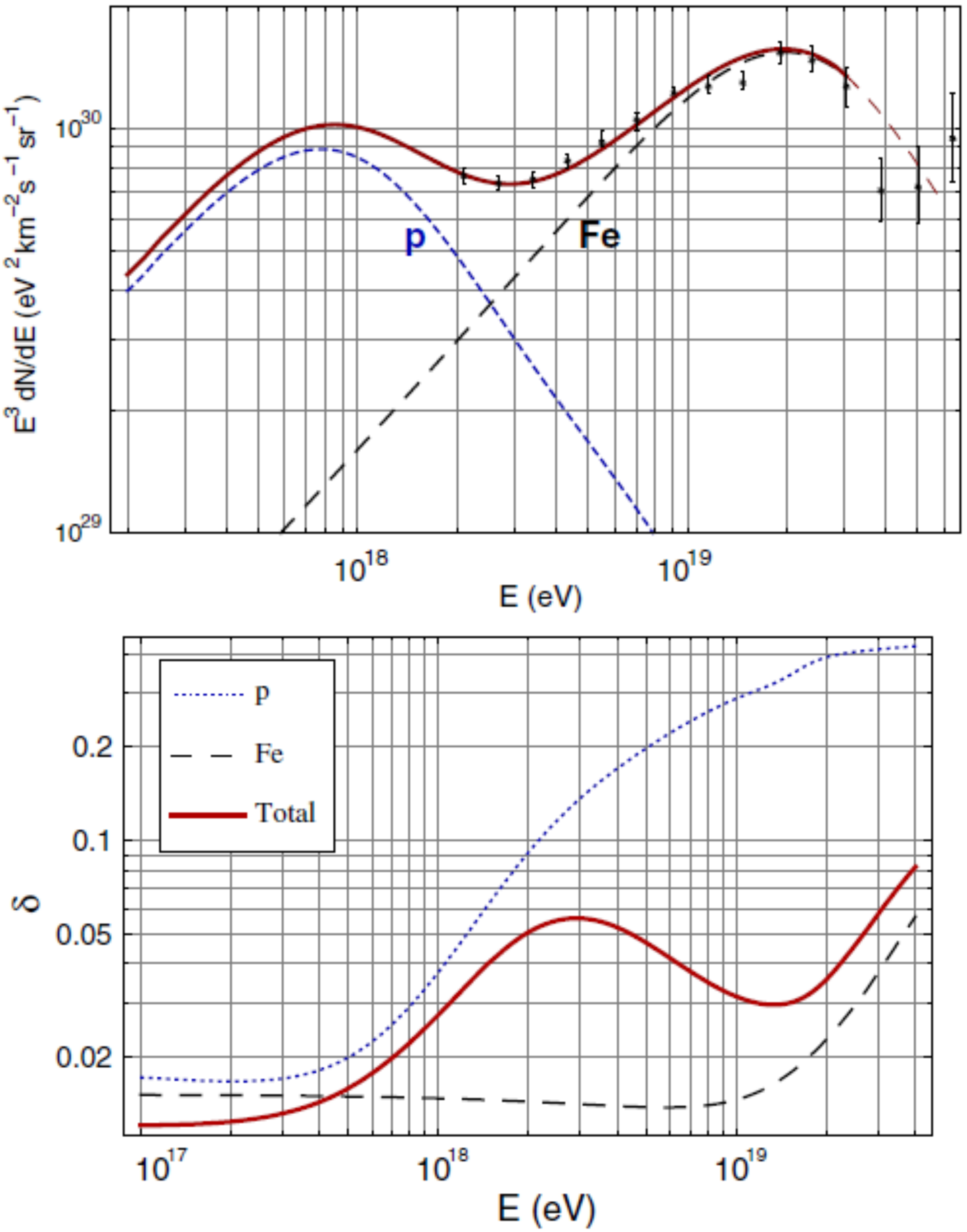
Low Maximum Energy of Acceleration: E(max) = ZE_p

No photo-pion production in Intergalactic space

GZK steepening does not exist

Absence of cosmogenic neutrinos

No anisotropy at high energies



Calvez et al.

PRL 2010 105 09101

Consider a bursting source, GRB or rare types of SN explosions

Arrival Direction data cannot exclude this

Carlo Crivelli (1430 – 1490): ‘The Annuciation with St Edimus’