Seminar at University of Birmingham: 19 January 2011

The Properties of Ultra High Energy Cosmic Rays and the Problems that they pose

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OVERVIEW

- **Why there is interest in cosmic rays > 10^{19} eV**

- **The Auger Observatory**

- **Description and discussion of measurements:-**

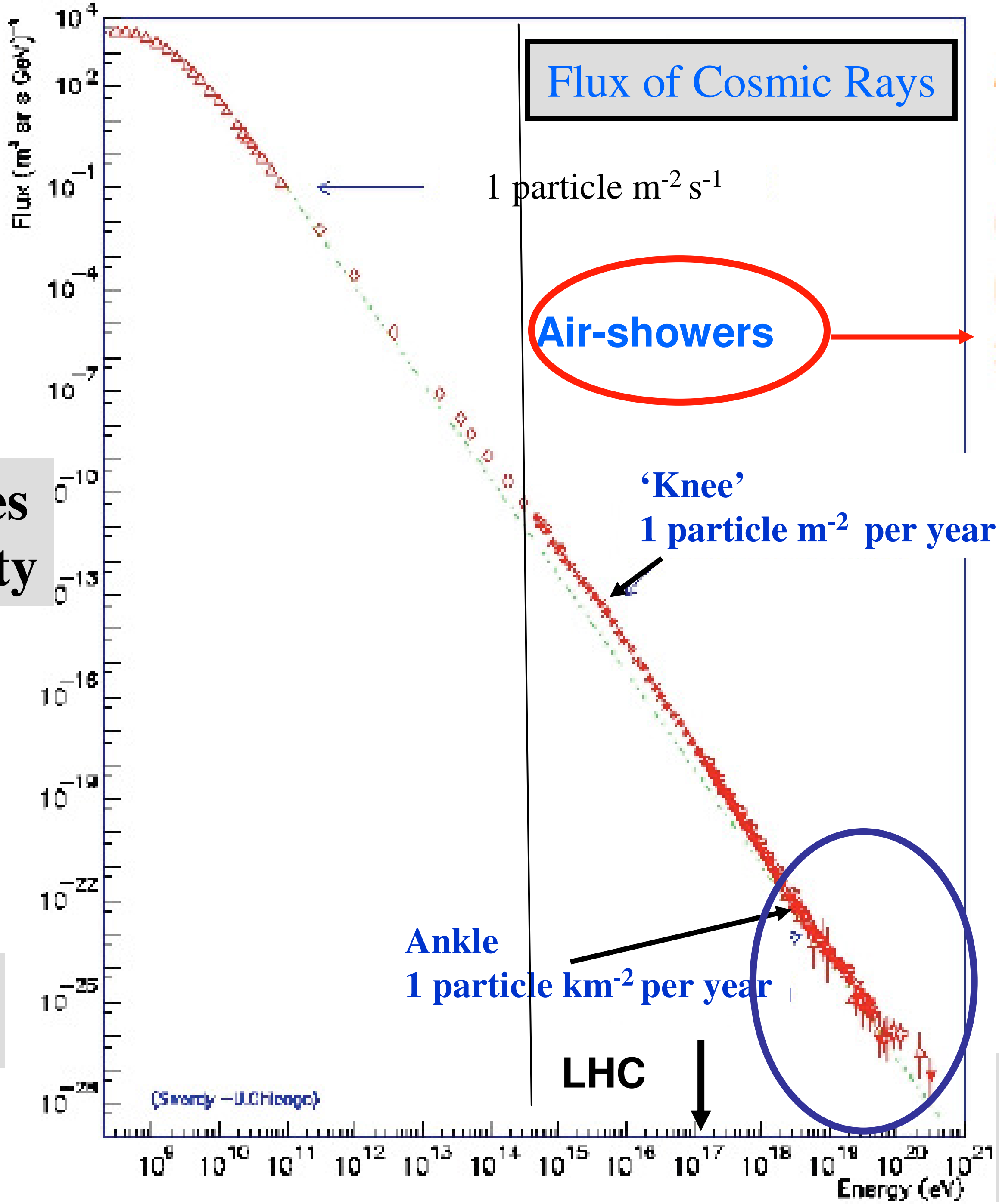
  Energy Spectrum

  Arrival Directions

  Primary Mass (not photons or neutrinos)

- **Can we learn anything about Particle Physics?**

25 decades in intensity



11 Decades in Energy

S Swordy (Univ. Chicago)

Why the interest?

(i) Cosmic Ray Astronomy above 10^{19} eV?
Deflections ~ 10º for protons at 10^{19} eV

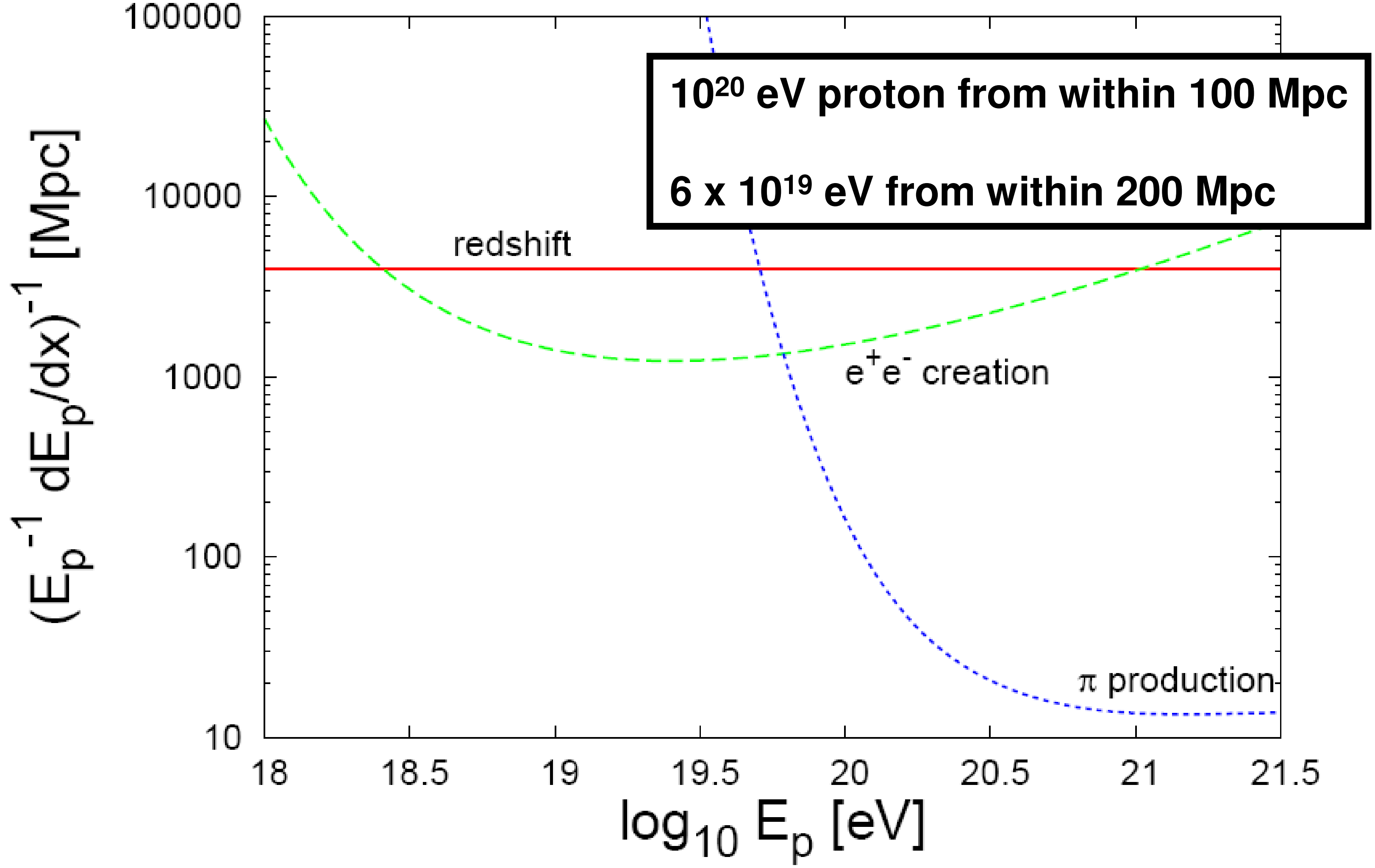
(ii) Spectral steepening above 5 x 10^{19} eV predicted

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

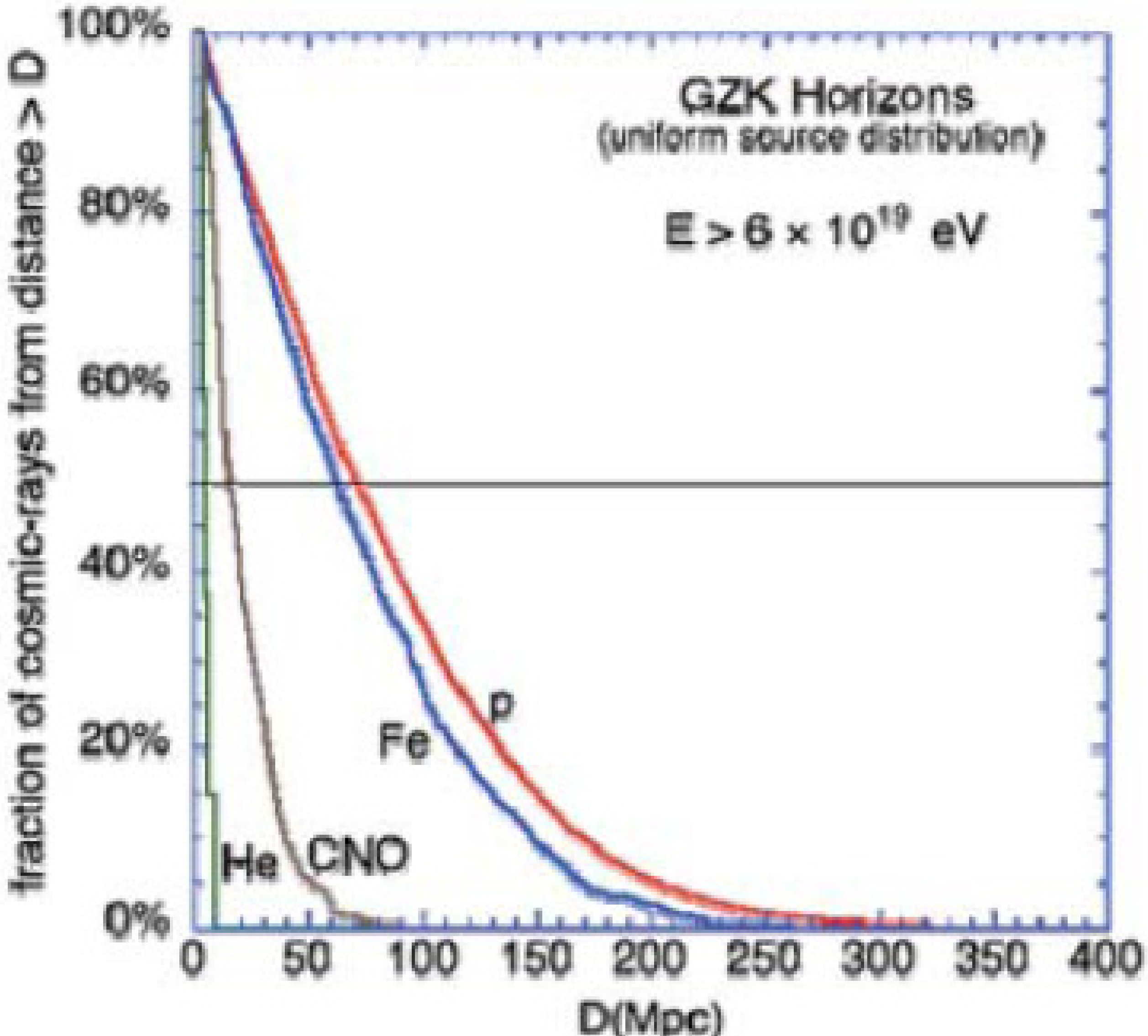
These reactions lead to the <u>ONLY</u> firm prediction in cosmic rays: spectral steepening

(iii) How are particles accelerated?

Interaction Length of protons as function of energy



Taylor and Aharonian 2008



Globus and Allard, private communication 2009

How are CR particles accelerated?

(i) Synchrotron Acceleration at CERN

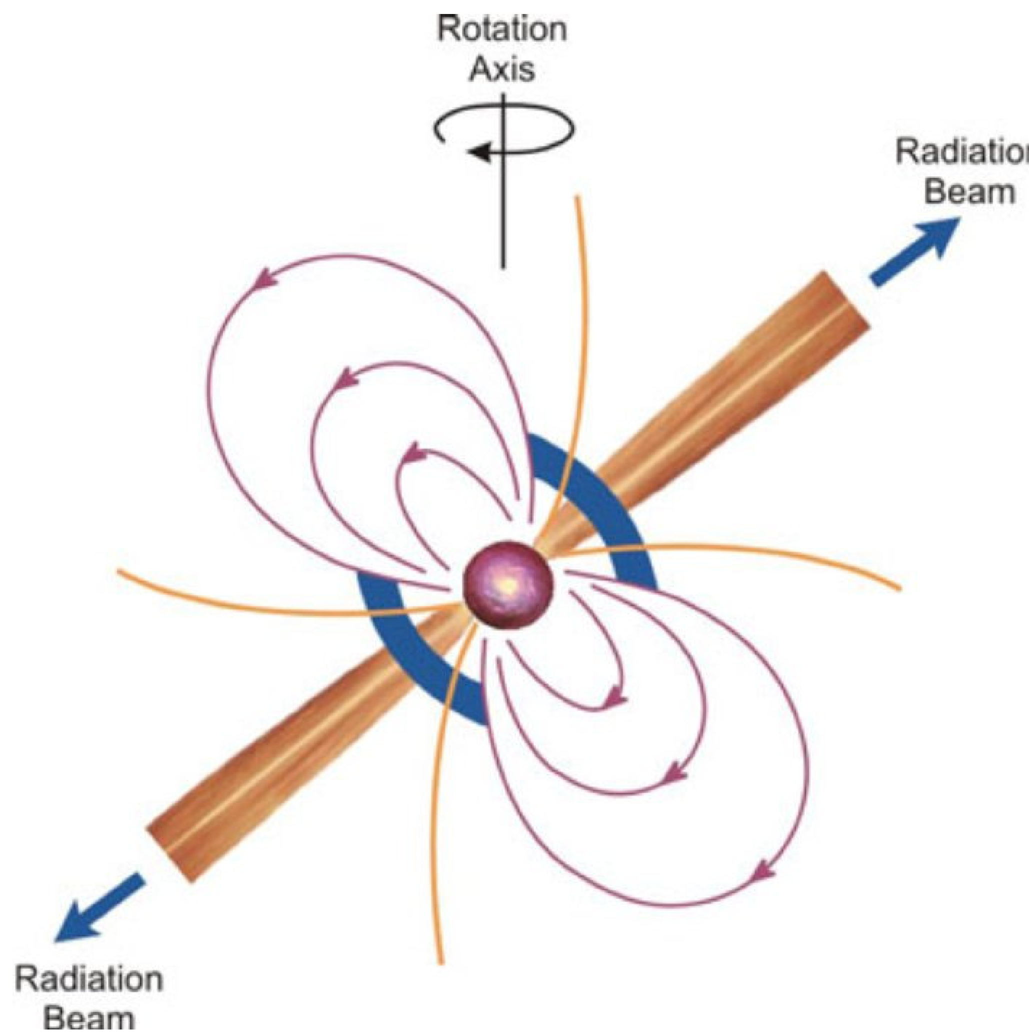
$$E_{max} = ZeBR\beta c$$

7 TeV in LHC (7 x 10^{12} eV)

(ii) **Single Shot Acceleration**
(e.g. Neutron Star)

$$E_{max} = ZeBR\beta c$$

Chandra X-ray image



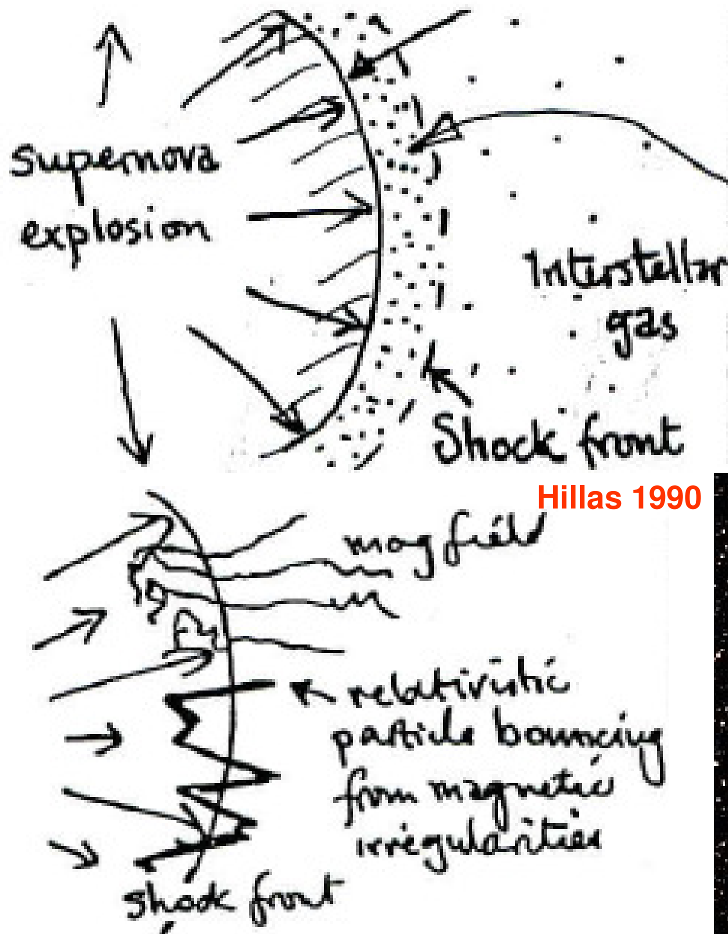
R = 10 km

B = 10^{12} Gauss (10^{8} T)

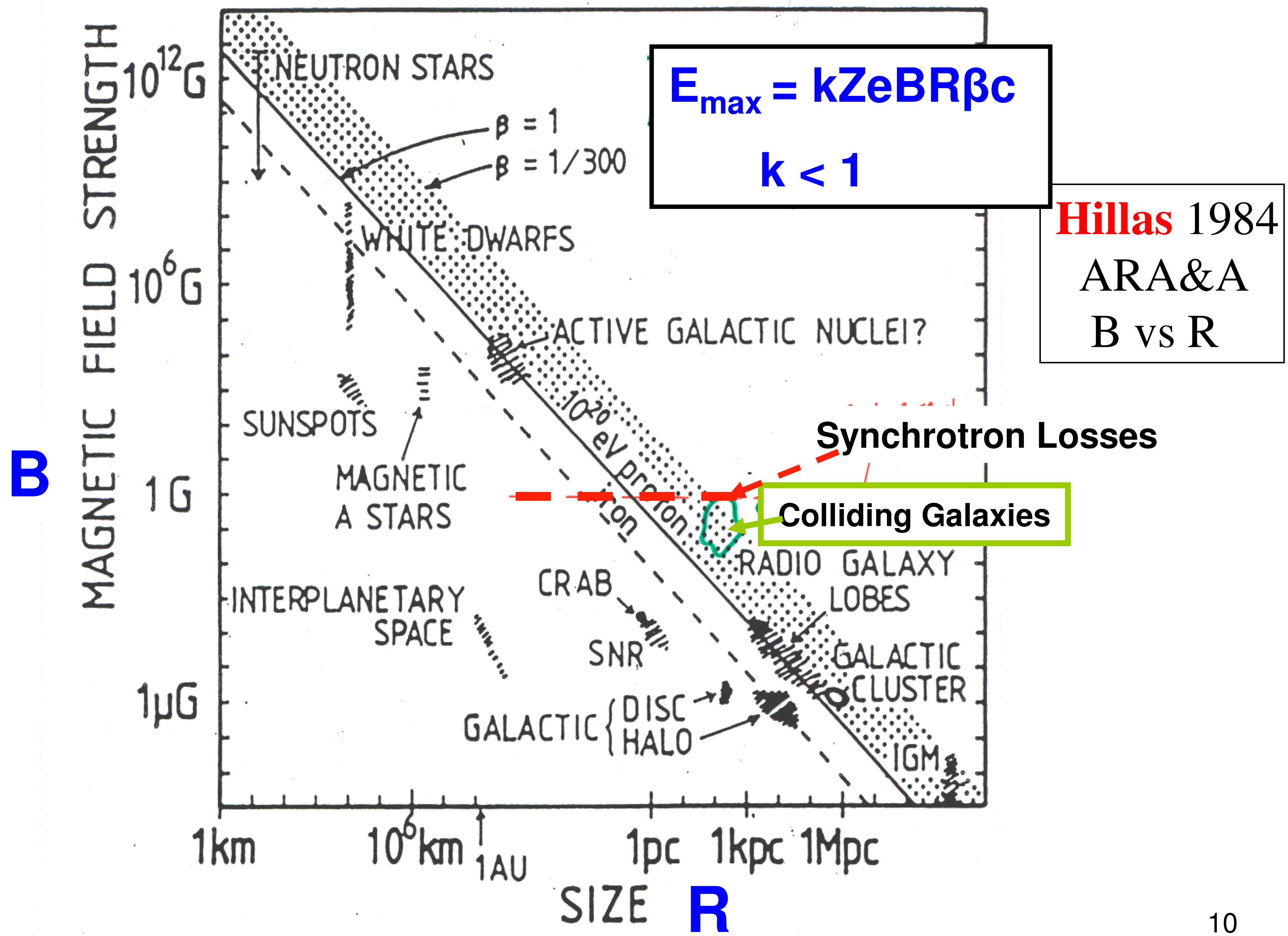
(iii) Diffusive Shock Acceleration

$$E_{max} = kZeBR\beta c, \text{ with } k<1$$

(e.g. Shocks near AGNs, near Black Holes, Supernova……?)



Hillas 1990



E_{max} = kZeBRβc
k < 1
Hillas 1984
ARA&A
B vs R
B
MAGNETIC FIELD STRENGTH
10^{12}G
10^{6}G
1G
1μG
NEUTRON STARS
β = 1
β = 1/300
WHITE DWARFS
ACTIVE GALACTIC NUCLEI?
SUNSPOTS
MAGNETIC A STARS
10^{20} eV proton
Synchrotron Losses
Colliding Galaxies
RADIO GALAXY LOBES
INTERPLANETARY SPACE
CRAB
SNR
GALACTIC CLUSTER
GALACTIC DISC
HALO
IGM
1km
10^{6}km
1AU
1pc
1kpc
1Mpc
SIZE
R

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**

But rate at 10^{20} eV is < 1 per km^2 per century   **- only detectable through extensive air showers**

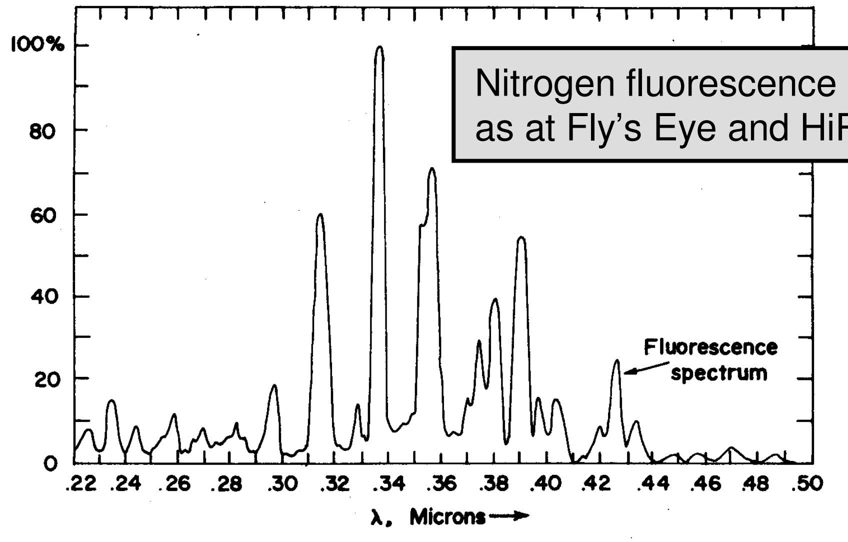
The Pierre Auger Collaboration

*Croatia	Argentina
Czech Republic	Australia
France	Brasil
Germany	*Bolivia
Italy	Mexico
Netherlands	USA
Poland	*Vietnam
Portugal	**Associate Countries*
Slovenia	
Spain	~330 PhD scientists from
United Kingdom	~100 Institutions and 18 countries
(until 31 Dec 2011)	

Aim: Find properties of UHECR with unprecedented precision

First discussions in 1991 (Jim Cronin and Alan Watson)

Shower Detection Methods



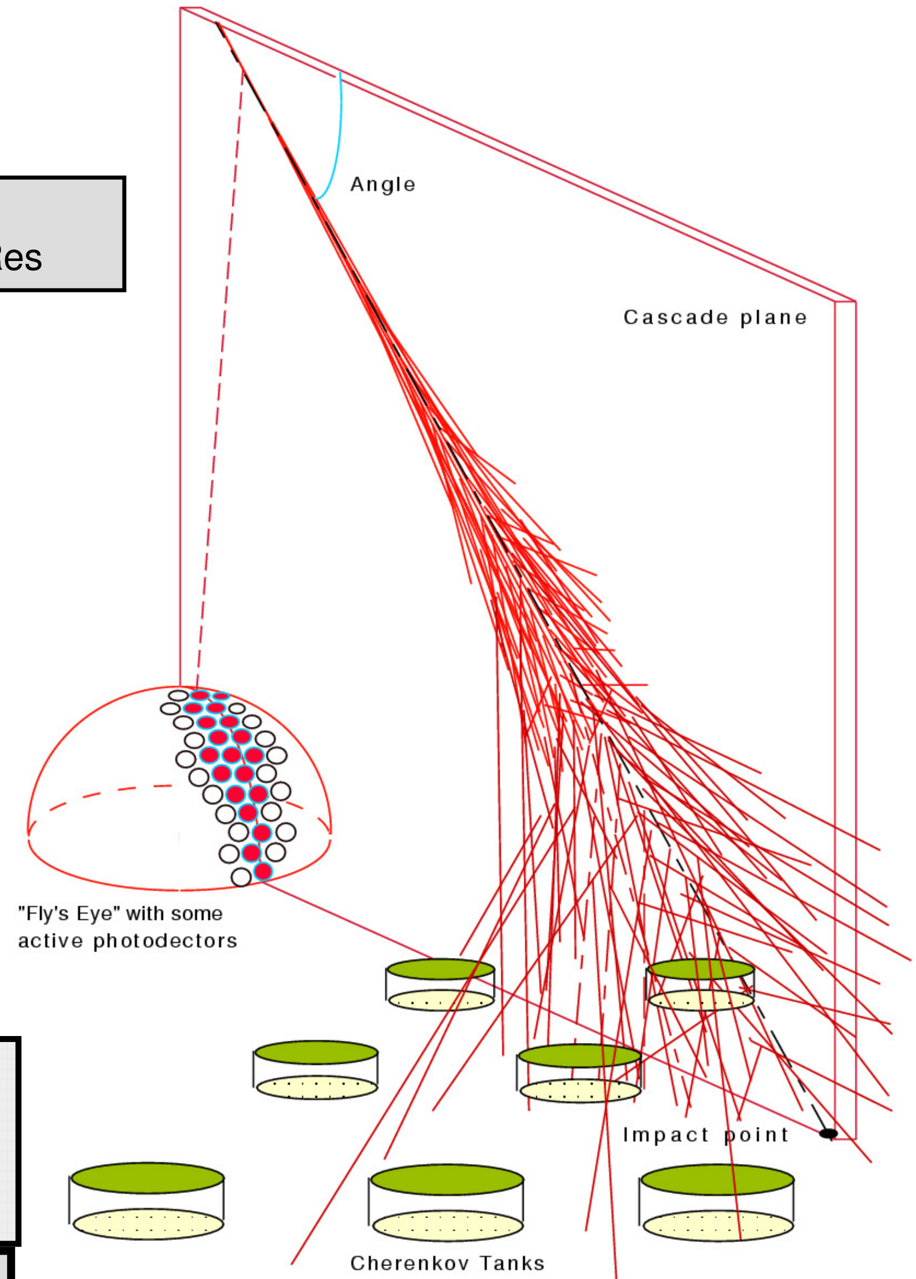
Nitrogen fluorescence
as at Fly's Eye and HiRes

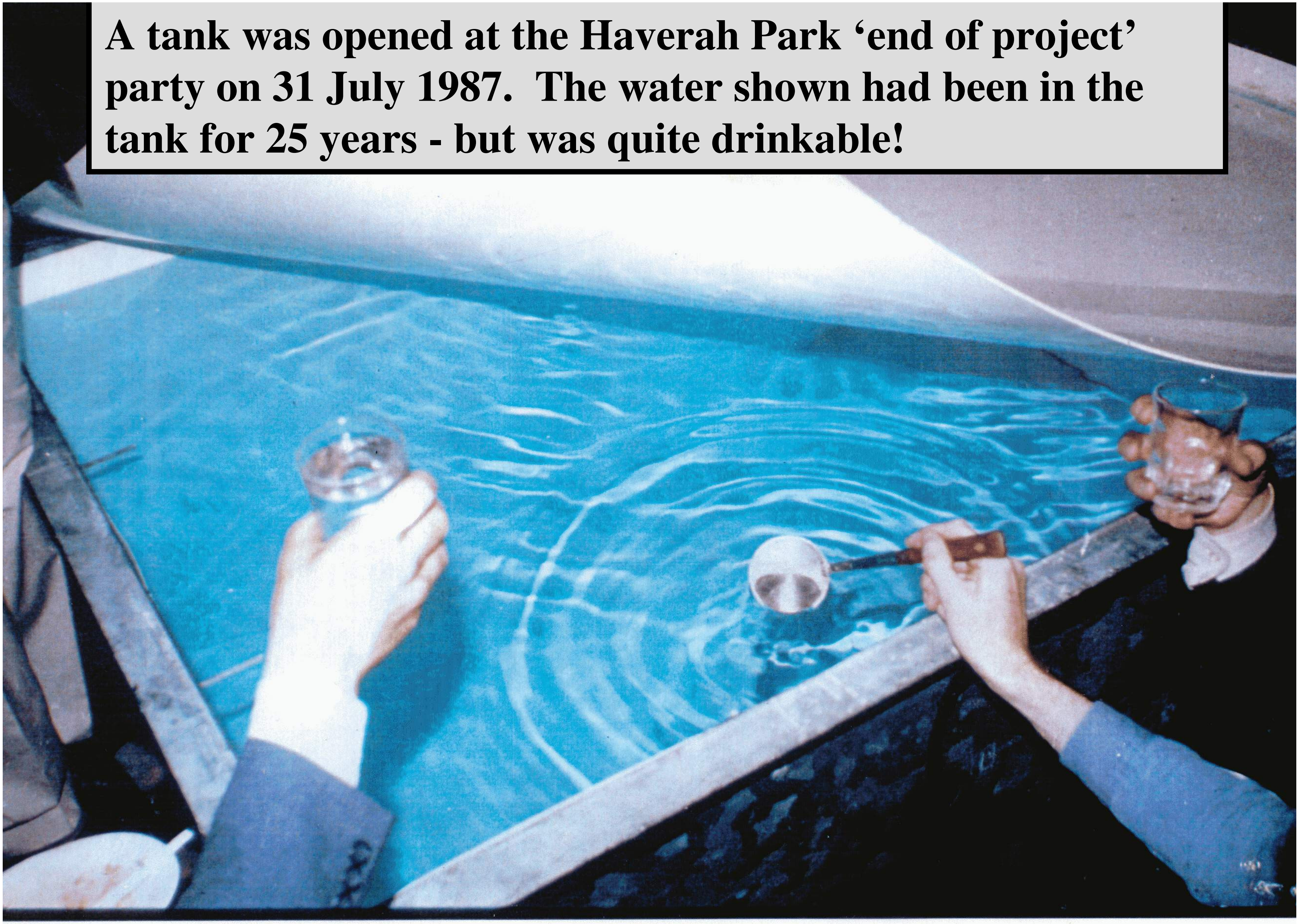
Fluorescence →

OR AND

Arrays of water-Cherenkov detectors →

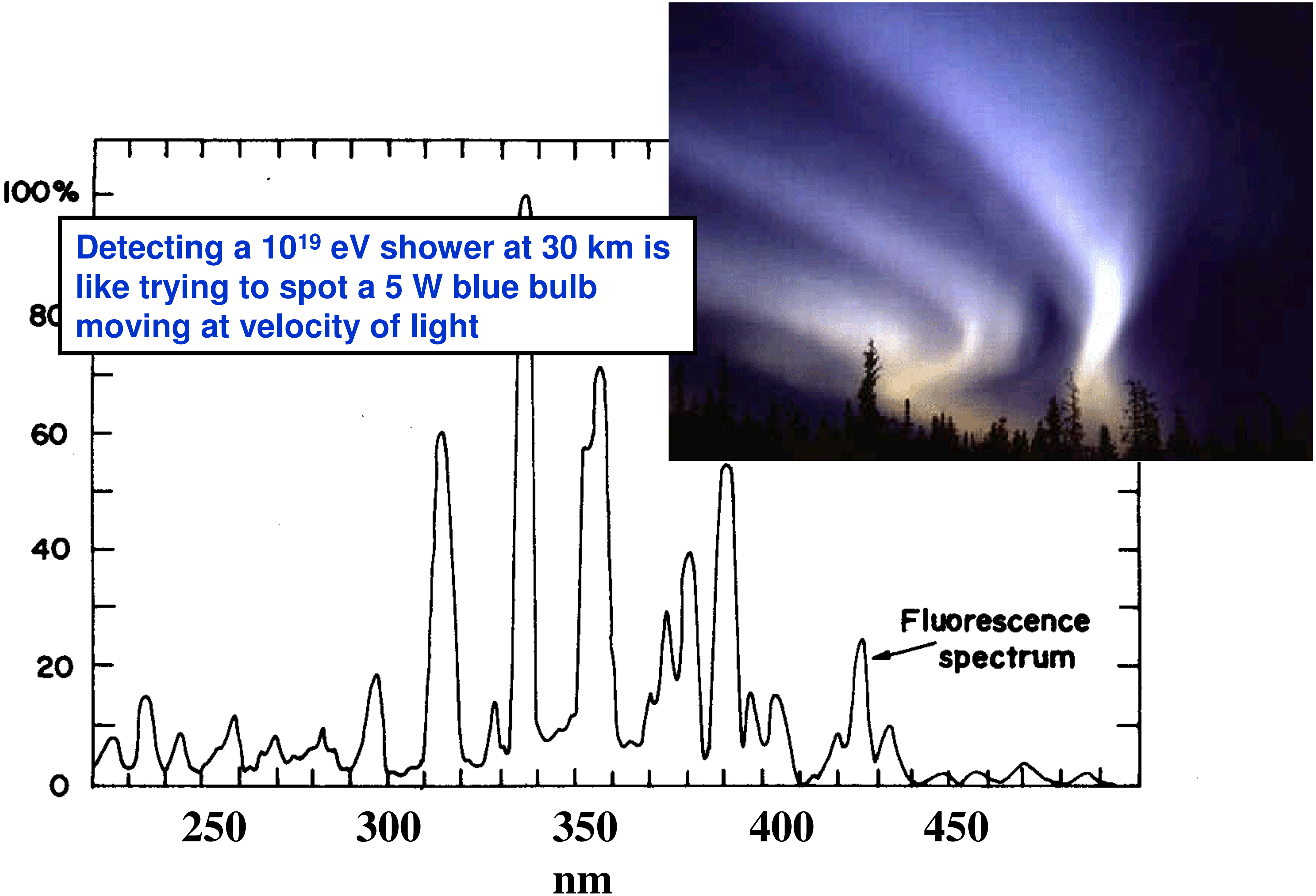
or Scintillation Counters

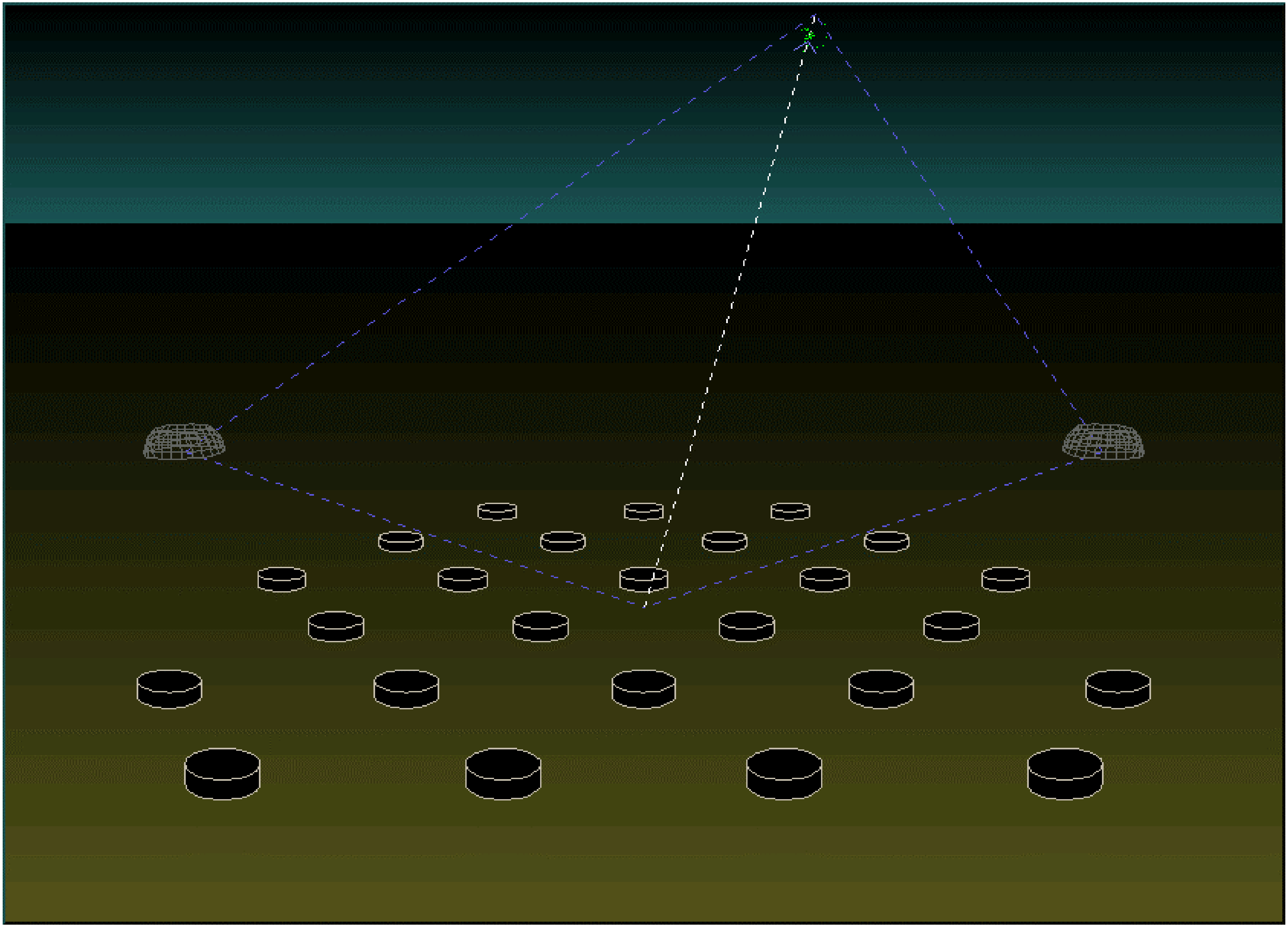




A tank was opened at the Haverah Park 'end of project' party on 31 July 1987. The water shown had been in the tank for 25 years - but was quite drinkable!

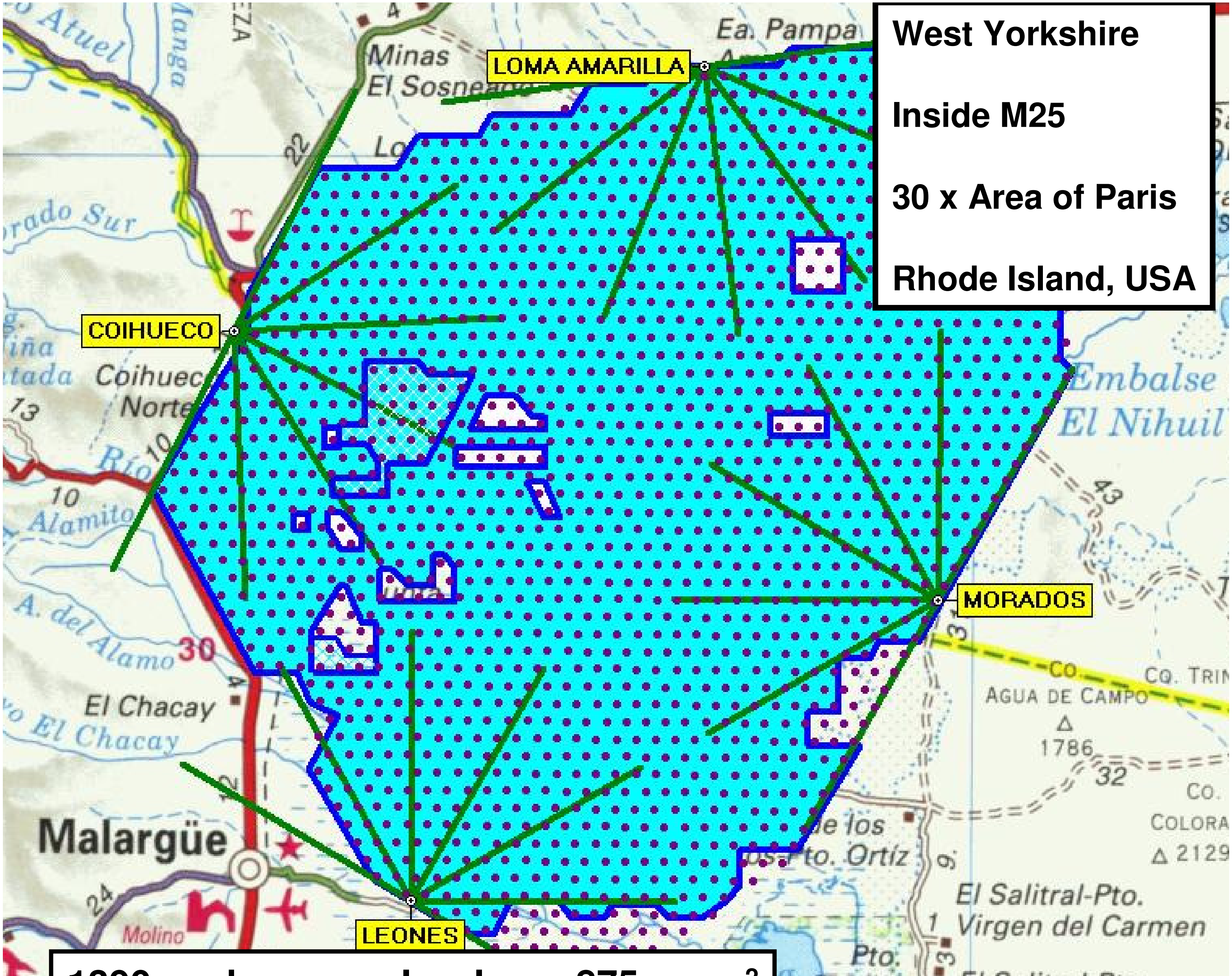
Detecting a 10^{19} eV shower at 30 km is like trying to spot a 5 W blue bulb moving at velocity of light





Campus of Auger Observatory in Argentina

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



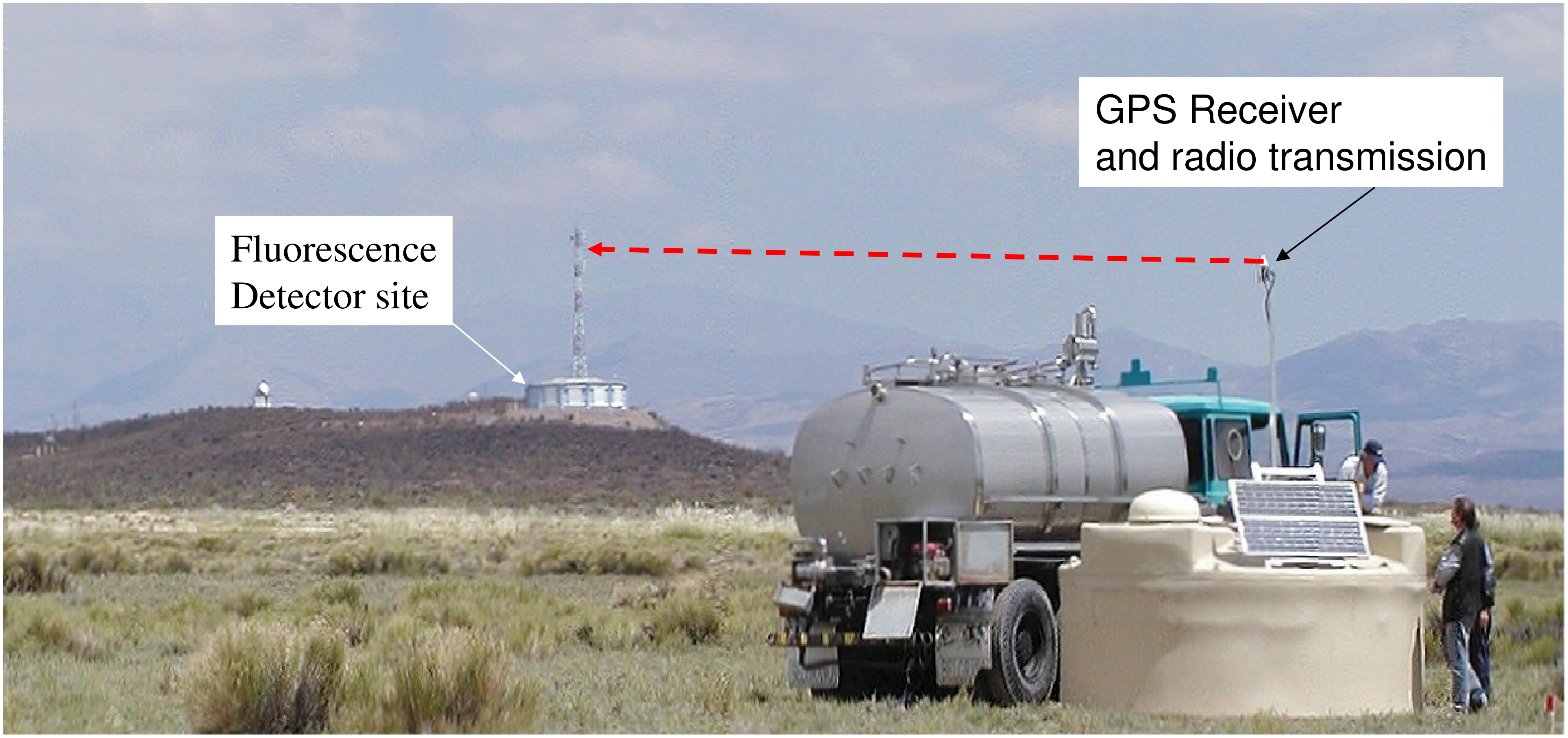
West Yorkshire

Inside M25

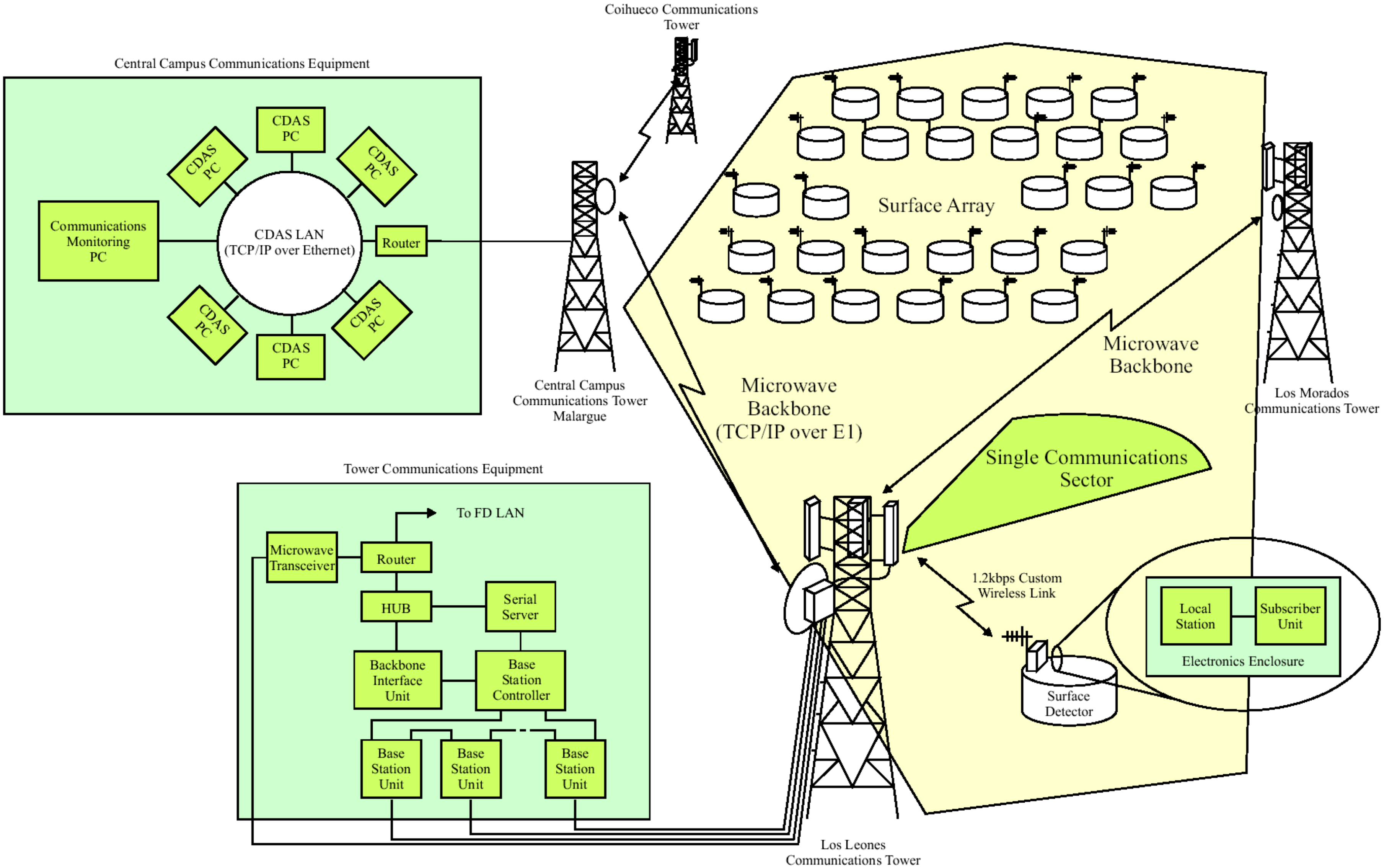
30 x Area of Paris

Rhode Island, USA

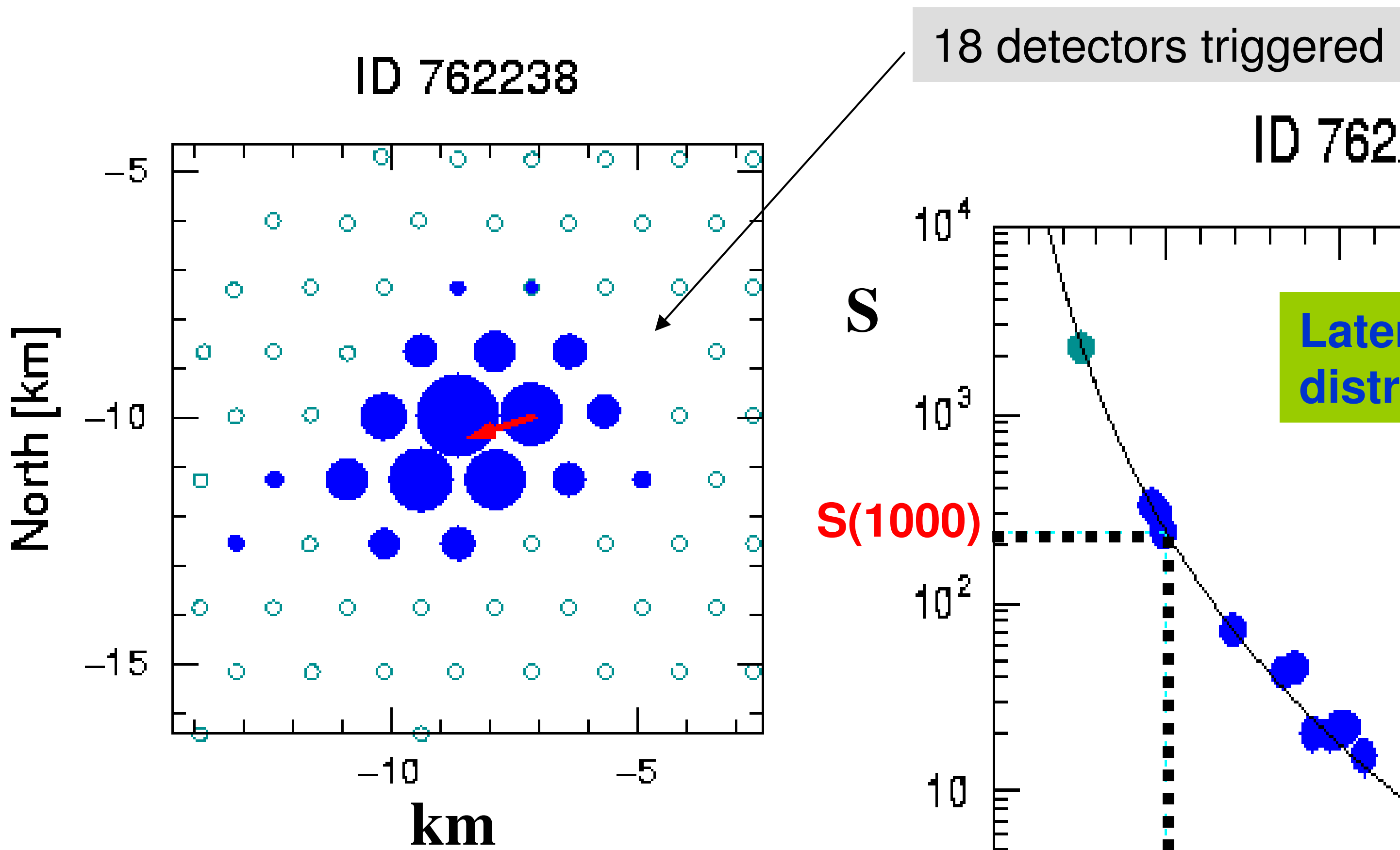
1390 m above sea-level or ~ 875 g cm^{-2}

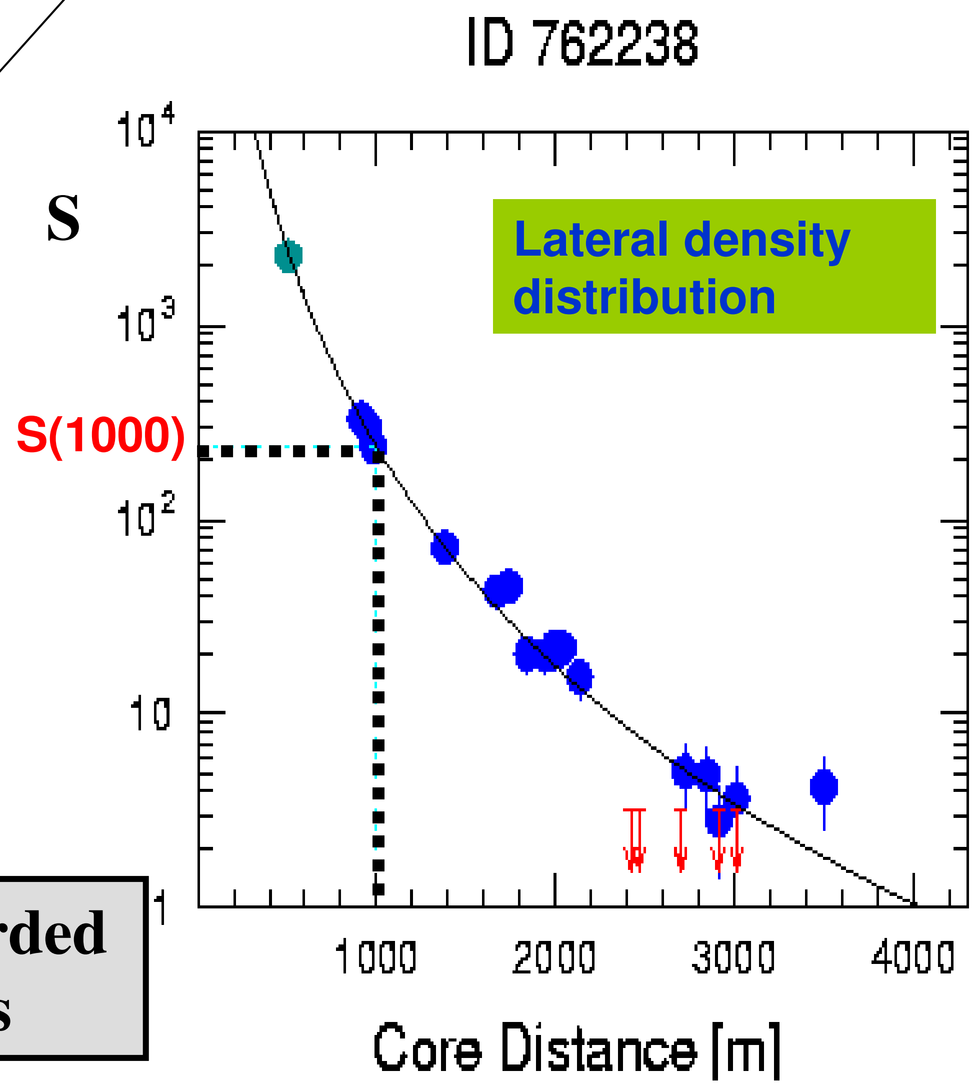

GPS Receiver
and radio transmission
Fluorescence
Detector site

Telecommunication system

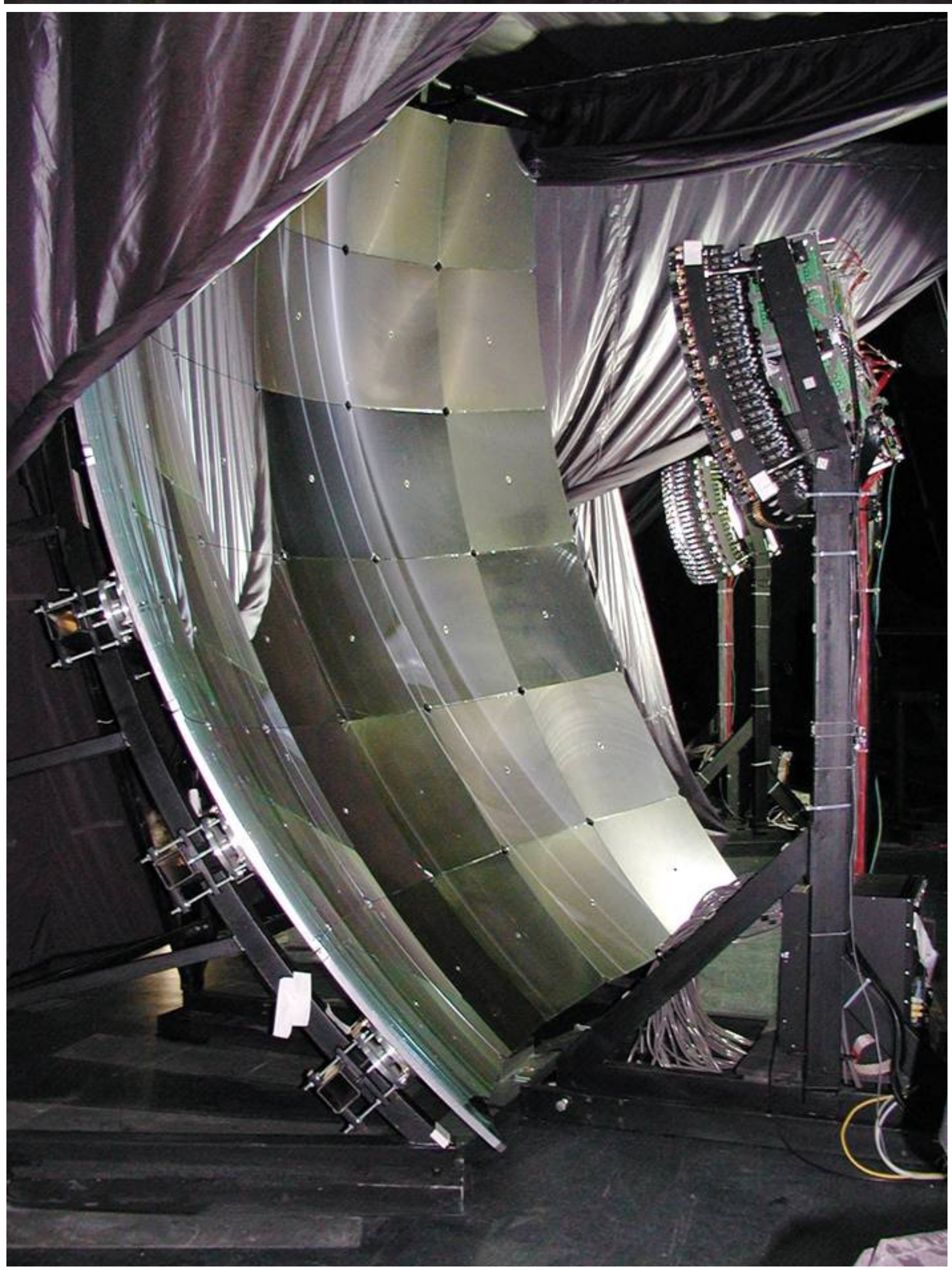


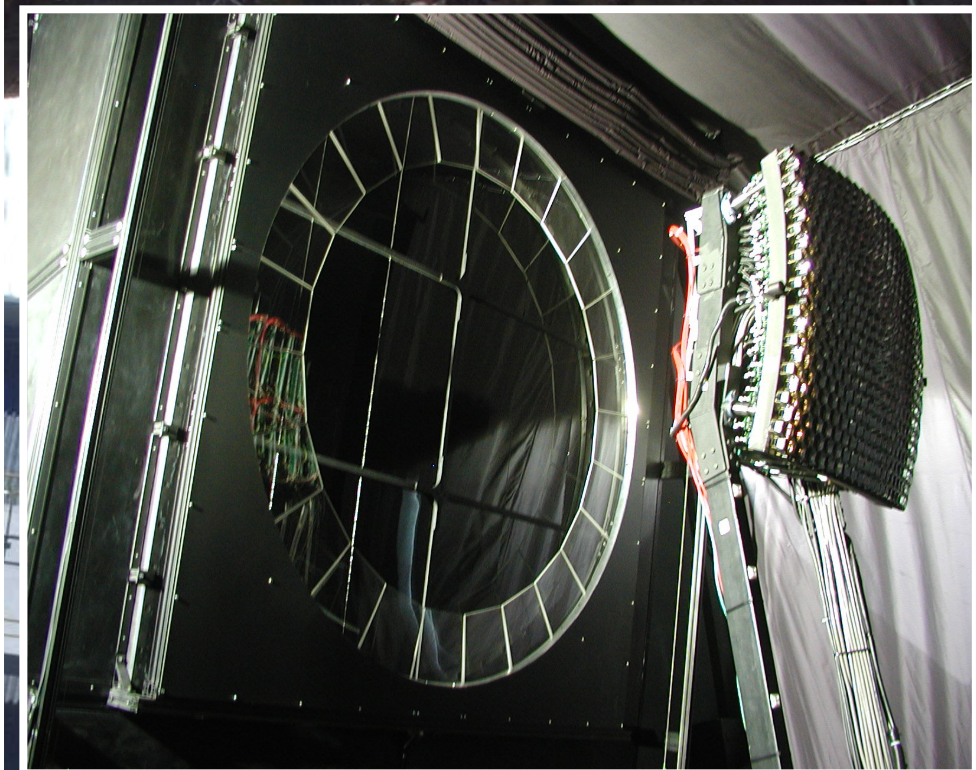
Zenith Angle ~ 48º Energy ~ 7×10^{19} eV





An example of an event recorded with the Cherenkov detectors

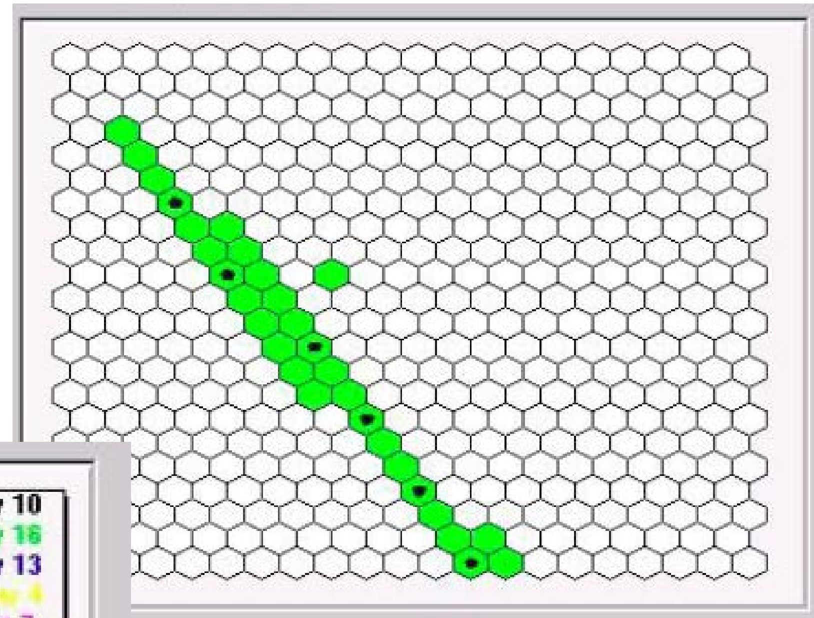


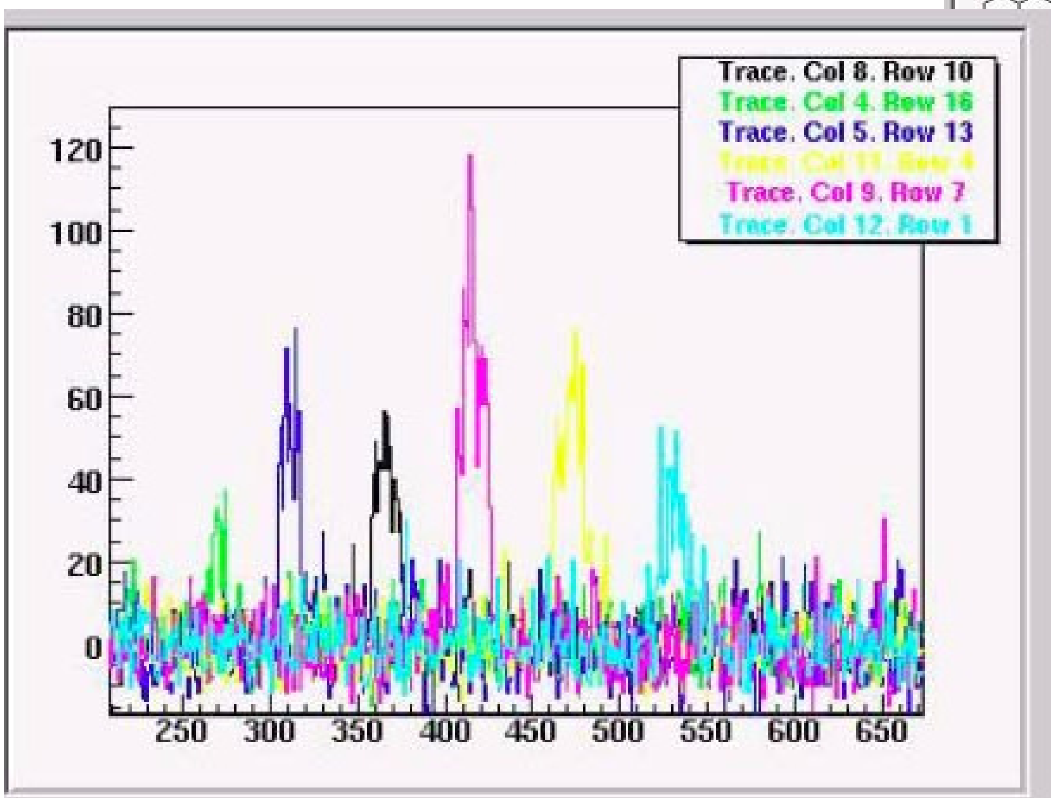


Fluorescence telescopes:
Number of telescopes: **24**
Mirrors: **3.6 m x 3.6 m with field of view 30º x 30º, each telescope is equipped with 440 photomultipliers.**

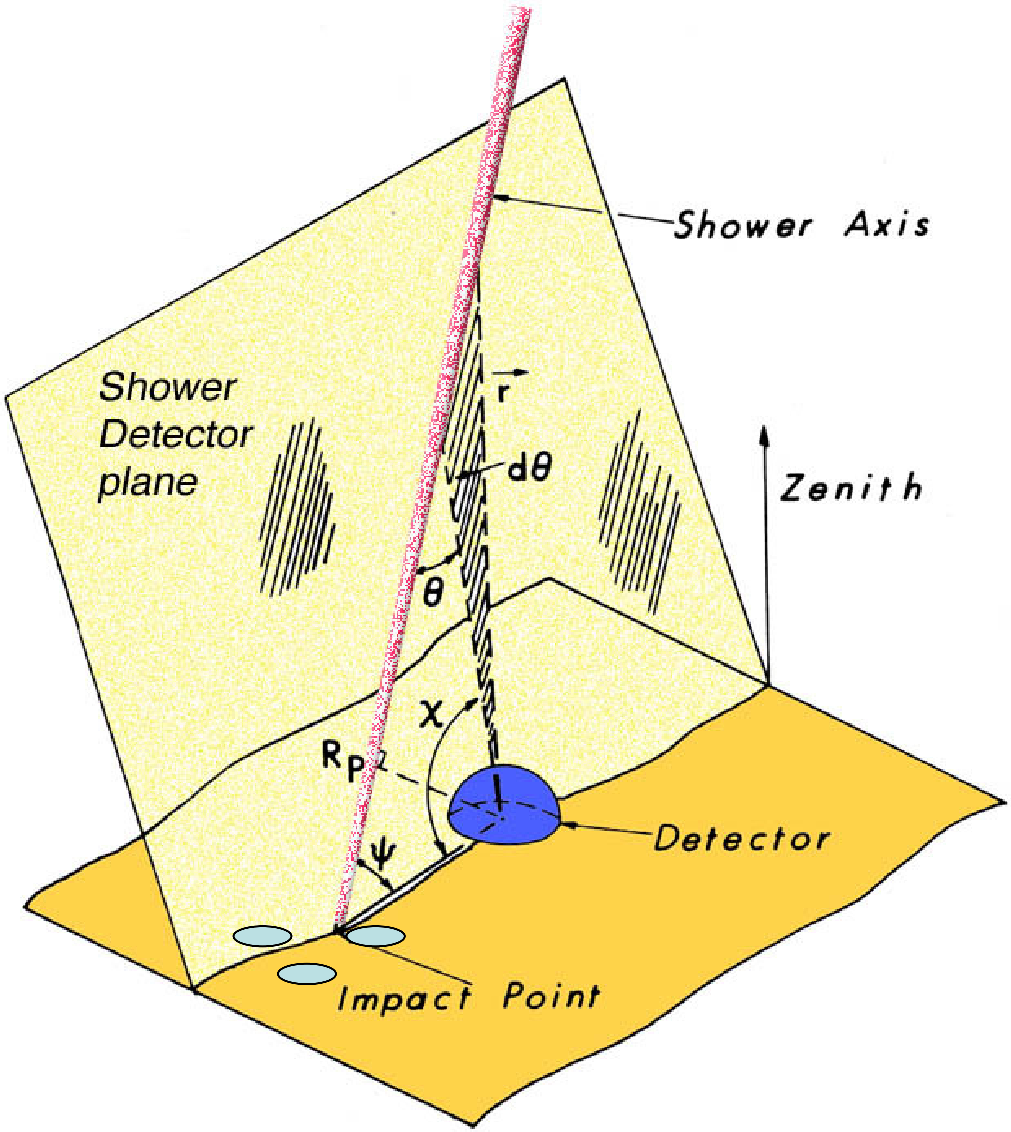
FD reconstruction

Signal and timing
Direction & energy





Pixel geometry
shower-detector plane



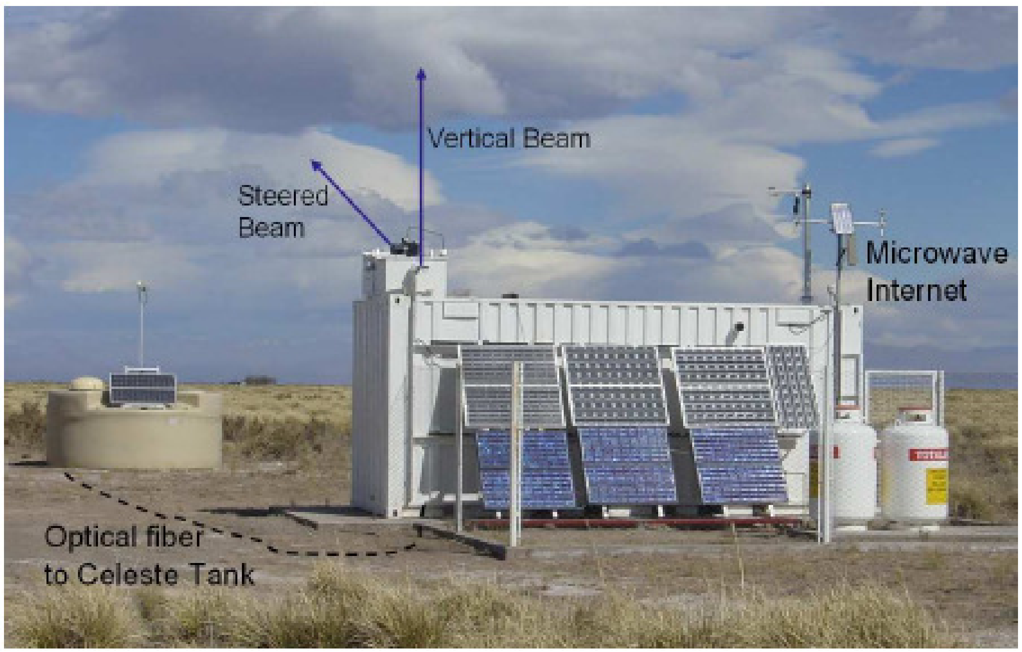
The essence of the hybrid approach

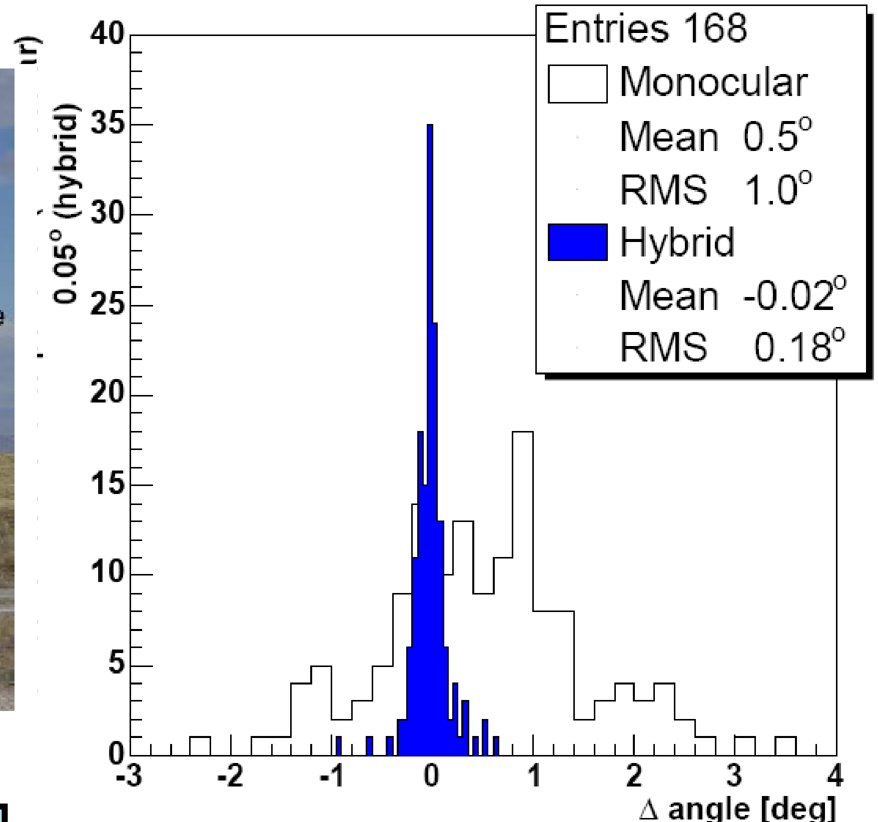
Precise shower geometry from degeneracy given by SD timing

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

Times at angles, χ , are key to finding R_p

Angular Resolution from Central Laser Facility

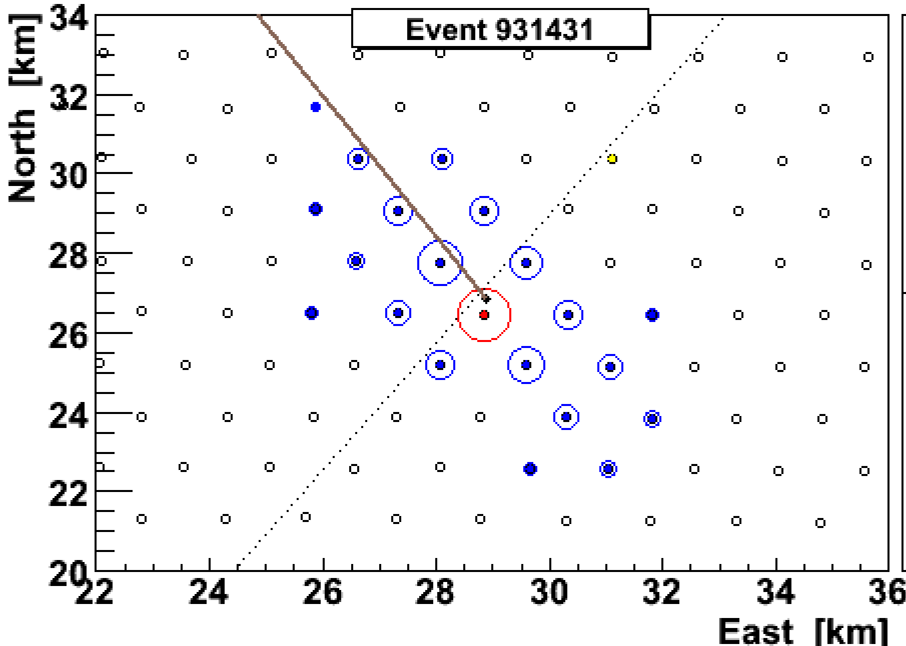




355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

Mono/hybrid rms 1.0°/0.18°

A Hybrid Event



Core location

Easting 468693 ± 59

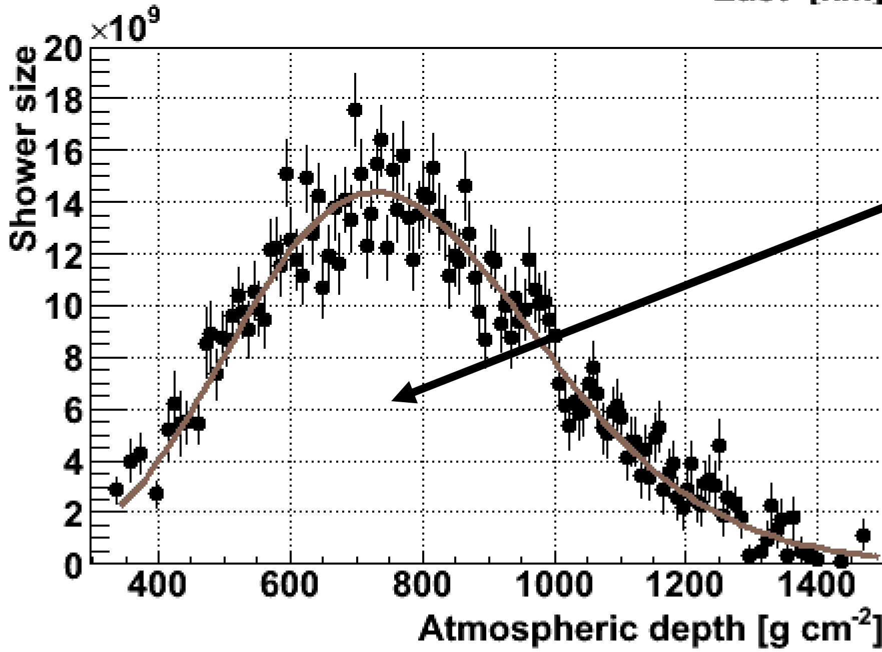
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

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

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

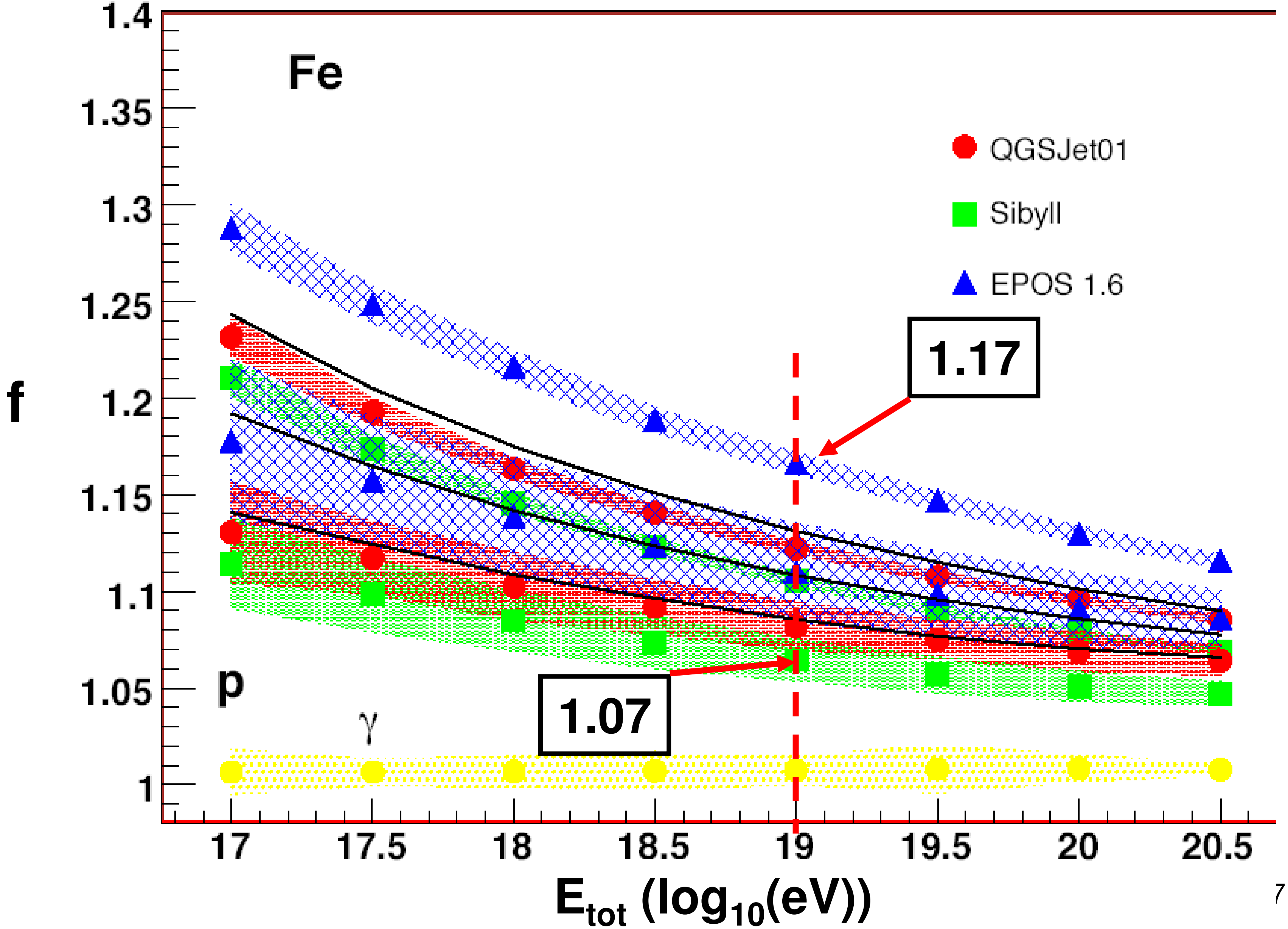


Energy Estimate
- from area under curve

$(2.1 \pm 0.5) \times 10^{19}$ eV

must account for 'missing energy'

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



Fe
p
γ
QGSJet01
Sibyll
EPOS 1.6
1.17
1.07
f
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
17
17.5
18
18.5
19
19.5
20
20.5
E_tot (log10(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

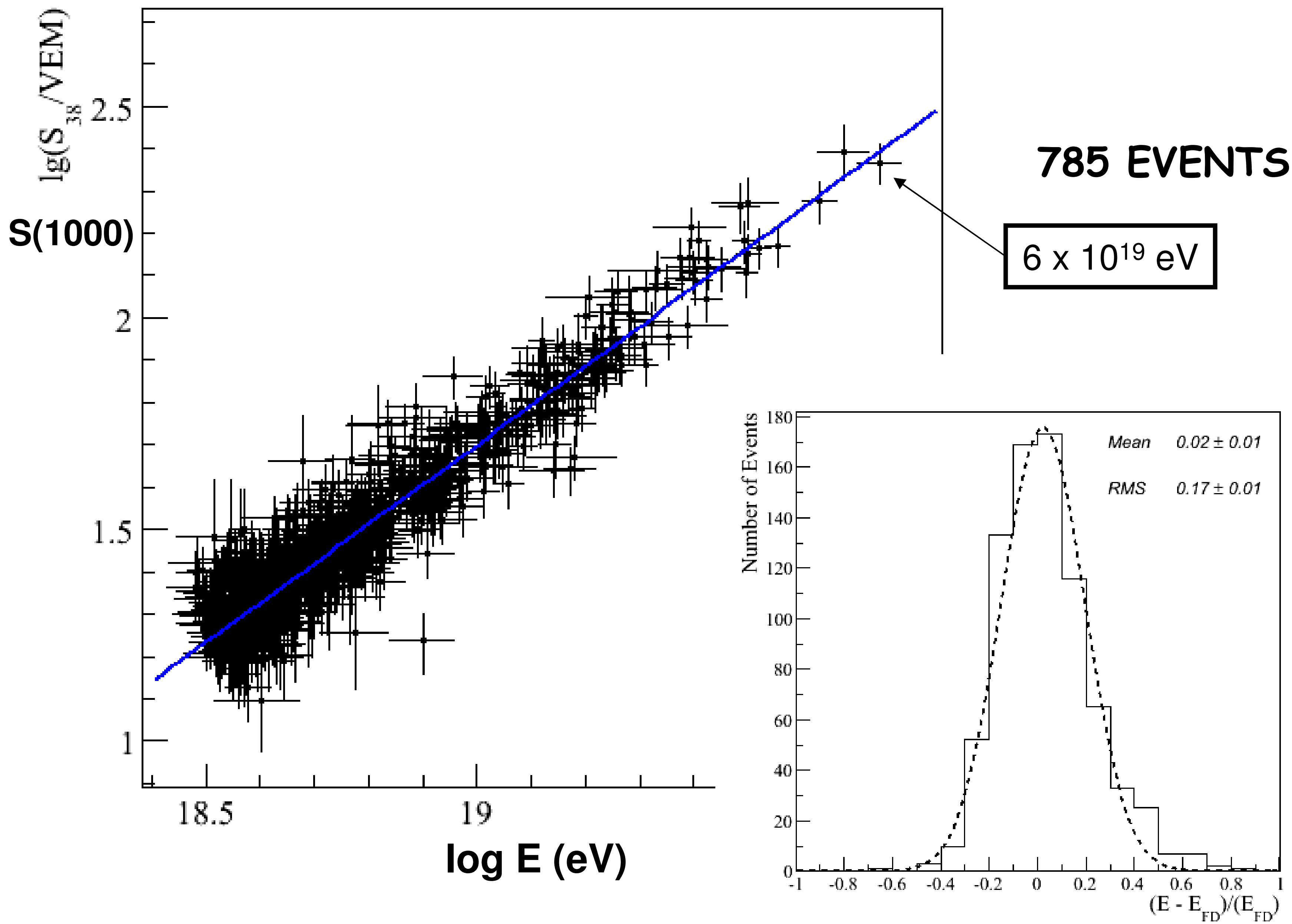
more or less continuous operation since then

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

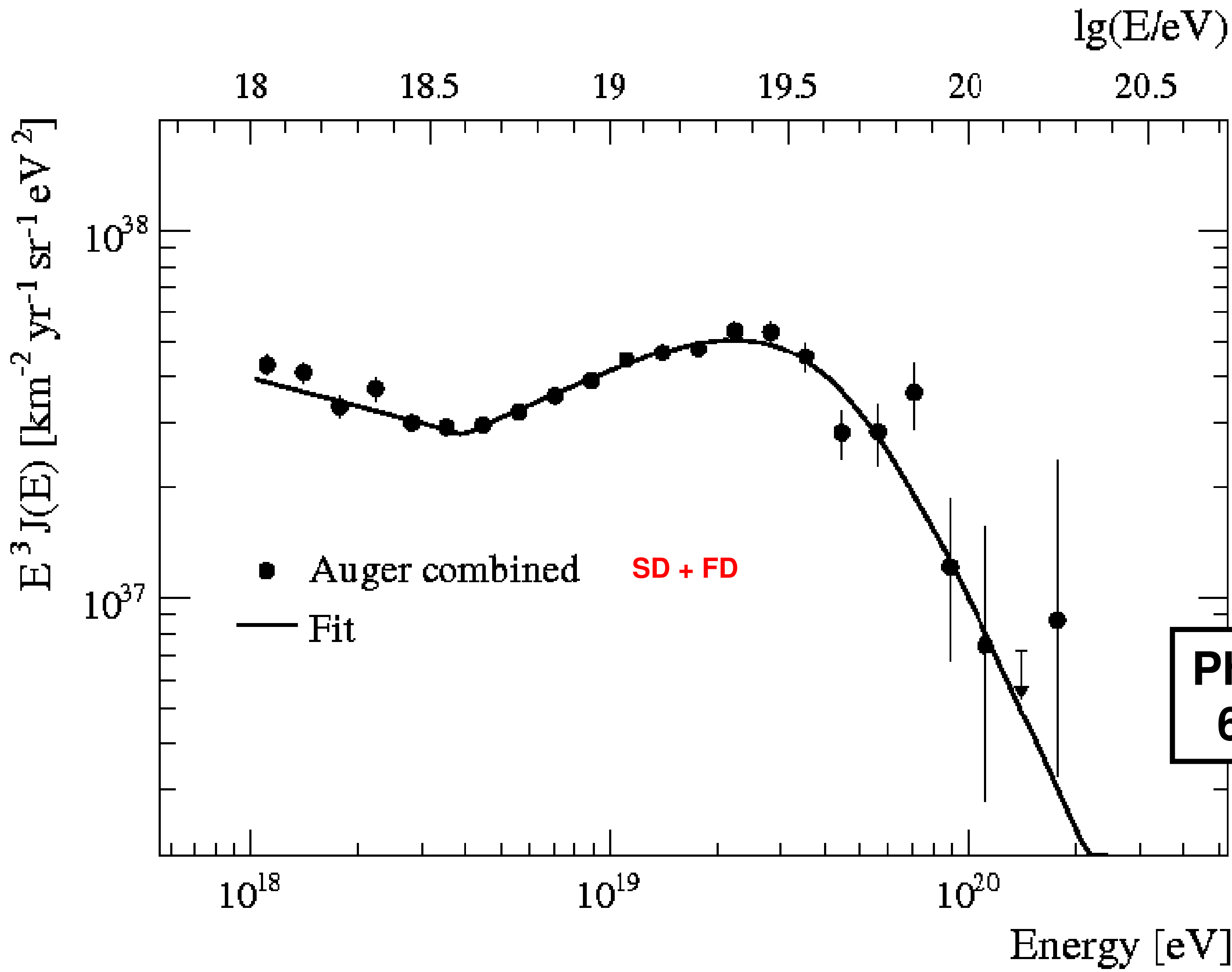


Summary of systematic uncertainties

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%

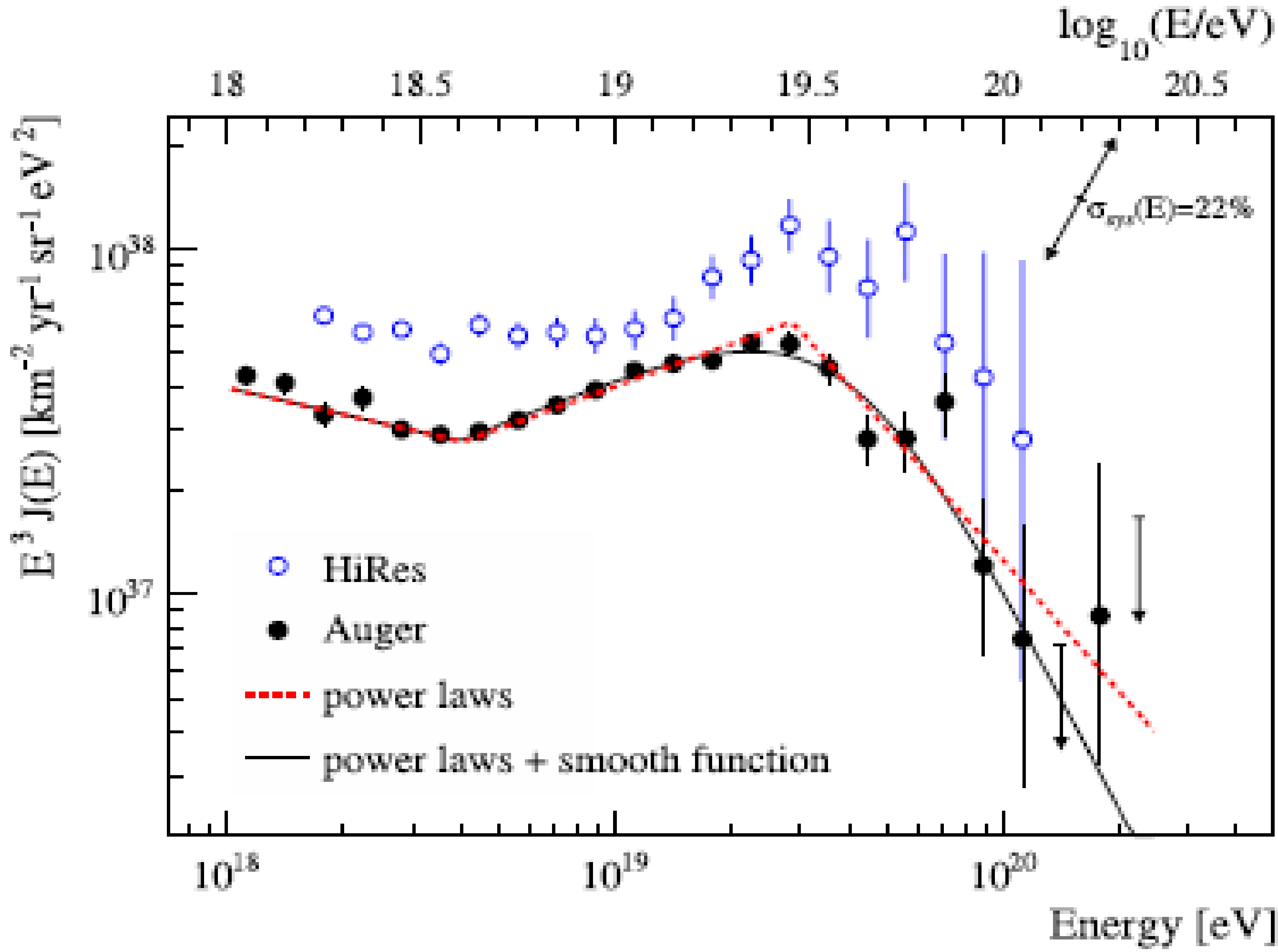
Fluorescence Detector Uncertainties Dominate

Energy Spectrum from Auger Observatory

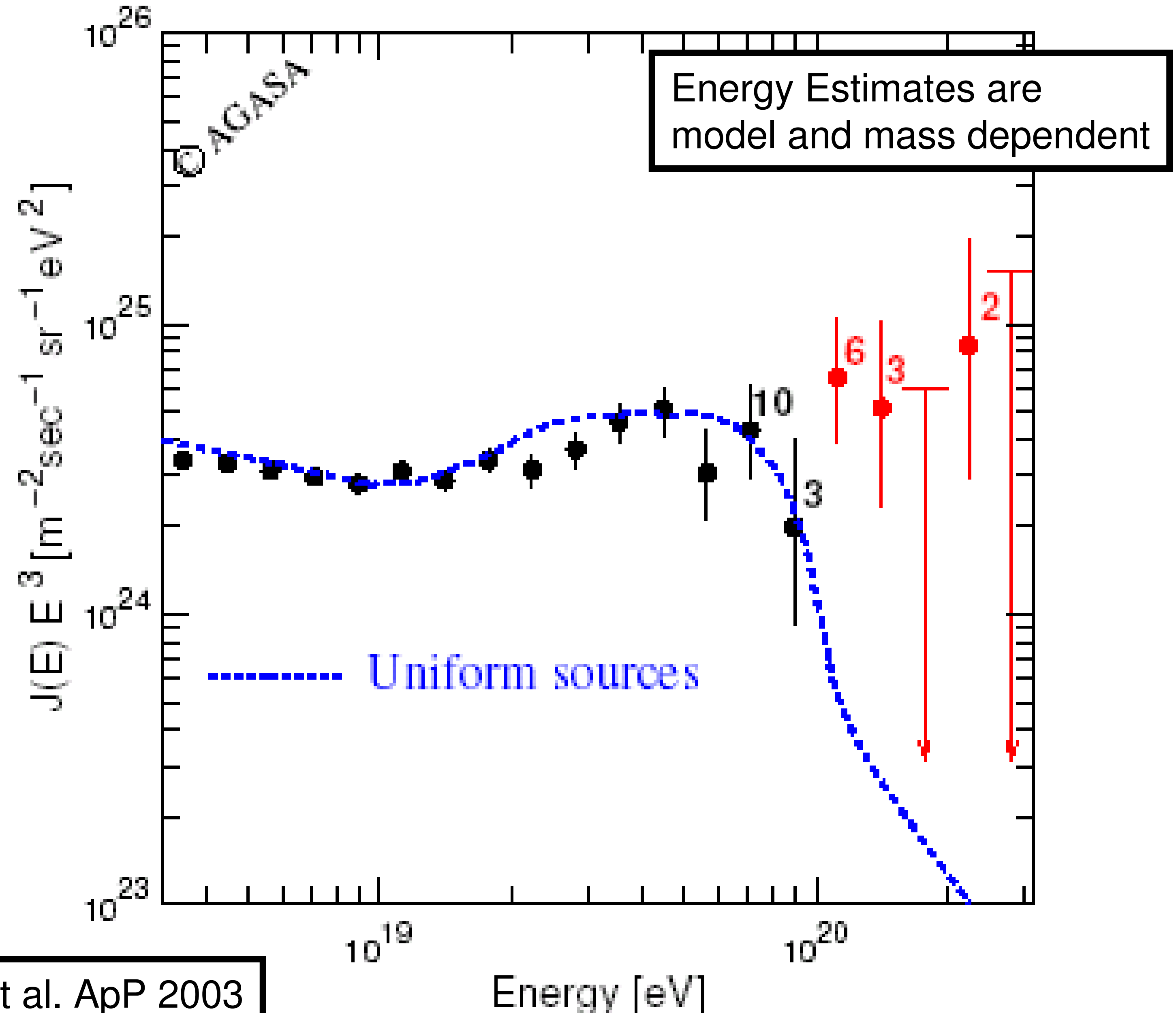


Physics Letters B 685 239 2010

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



Auger and HiRes Spectra



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

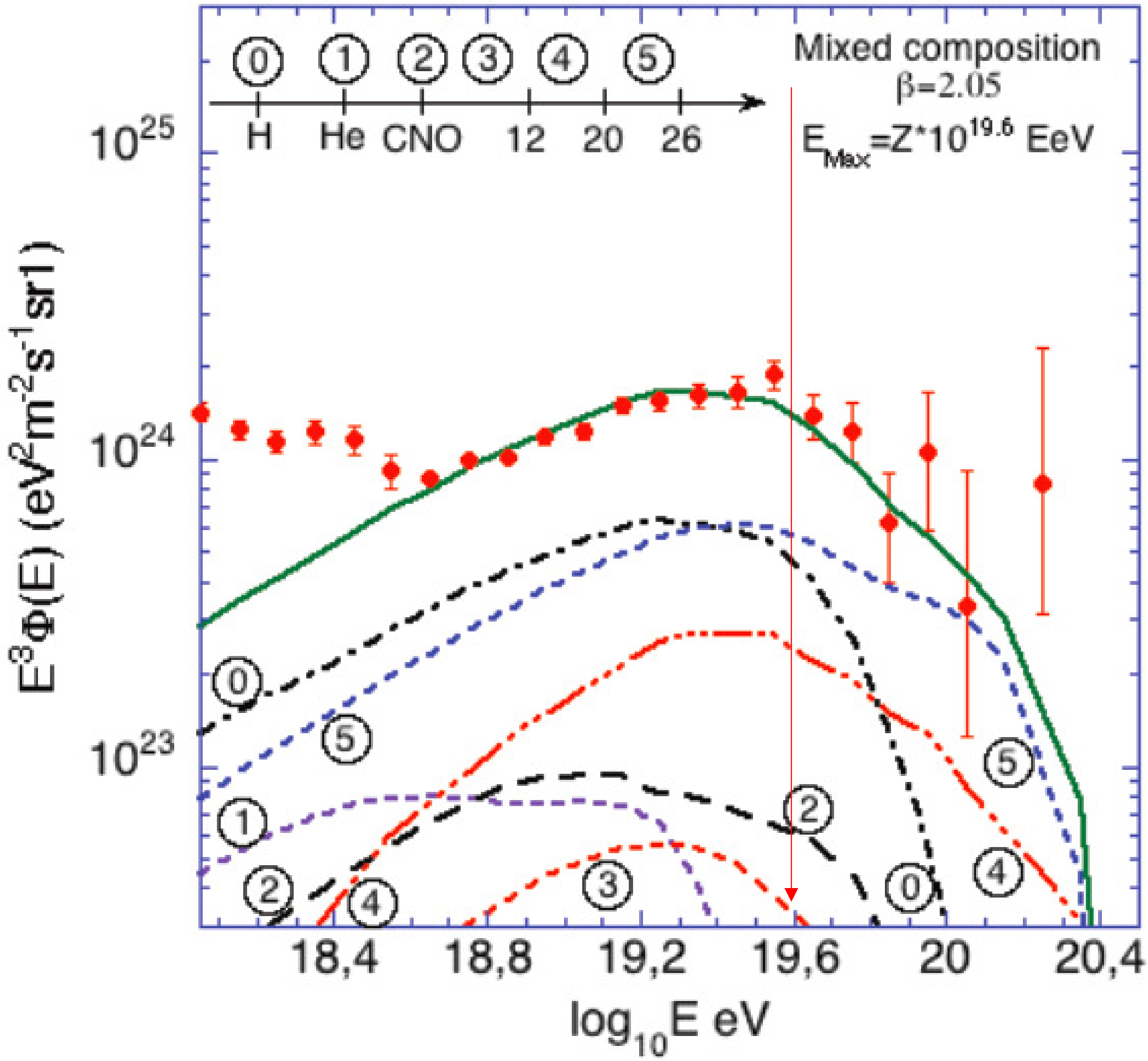
$(6.4 \pm 1.9) \times 10^{-3}$ km^{-2} sr^{-1} yr^{-1}

a factor of more than 25

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

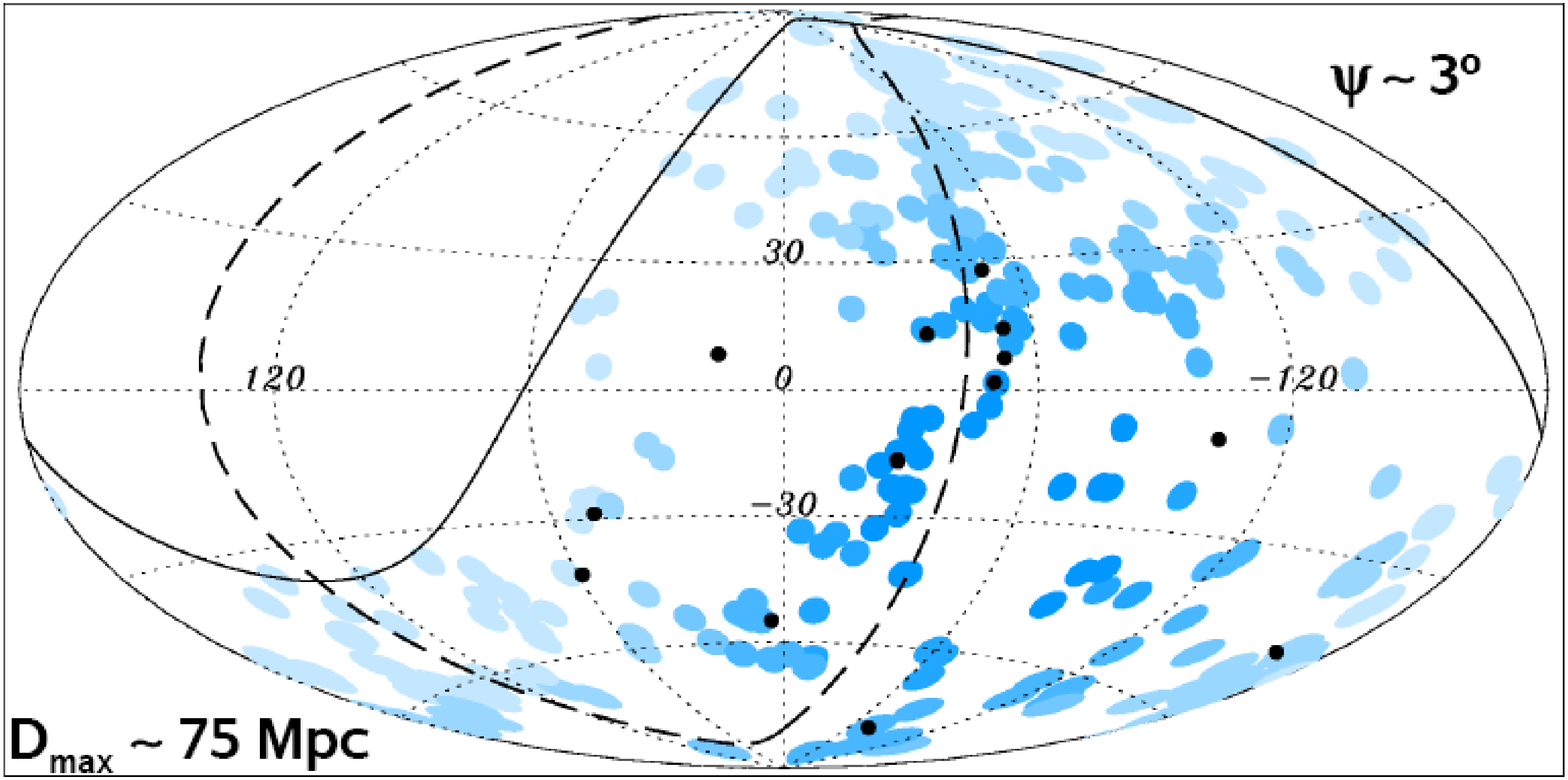
Consensus is that Auger and HiRes have got it right

Spectrum shape does NOT give insights into mass



Searching for Anisotropies

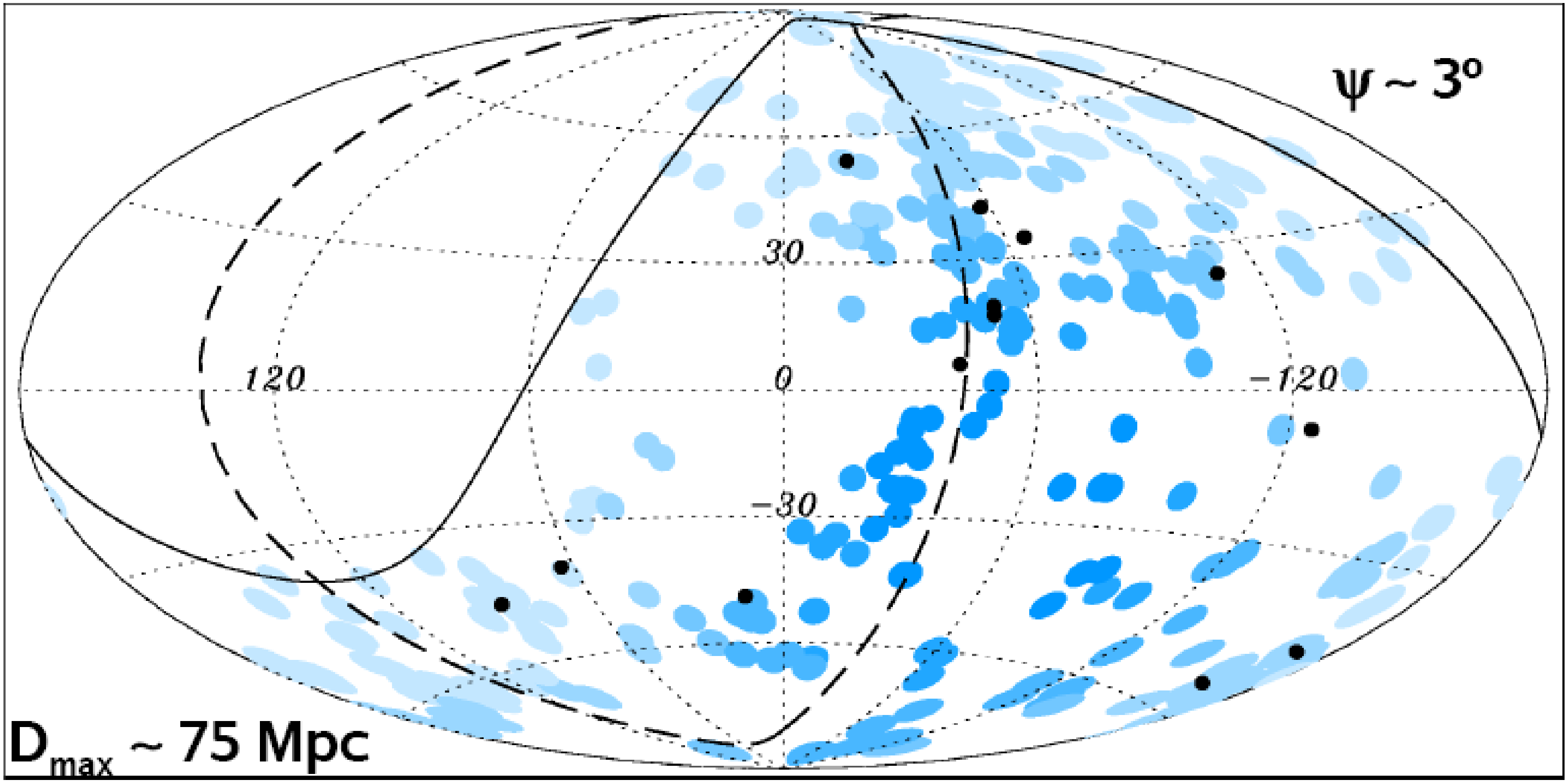
Exploratory scan: data until 27 May 2006



Largest significance for $E_{th} \sim 6\times10^{19}$ eV $\psi \sim 3^{o}$ $D_{max} \sim 75$ 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}

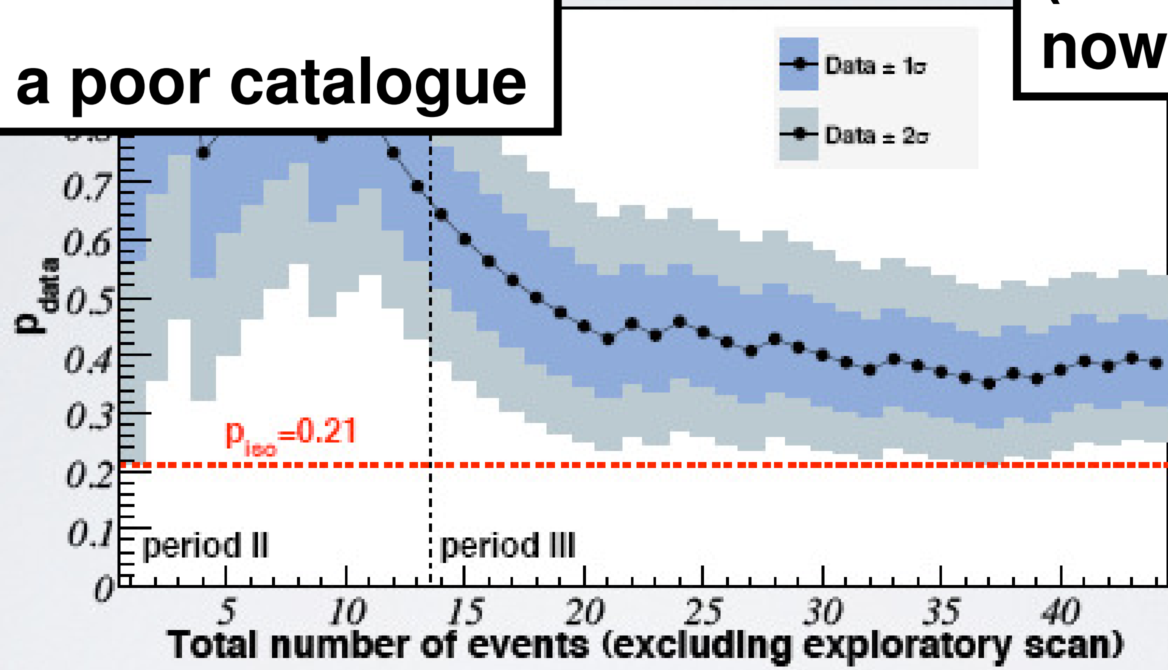
Each exposure was 4500 km^2 sr yr

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

CURRENT STATUS

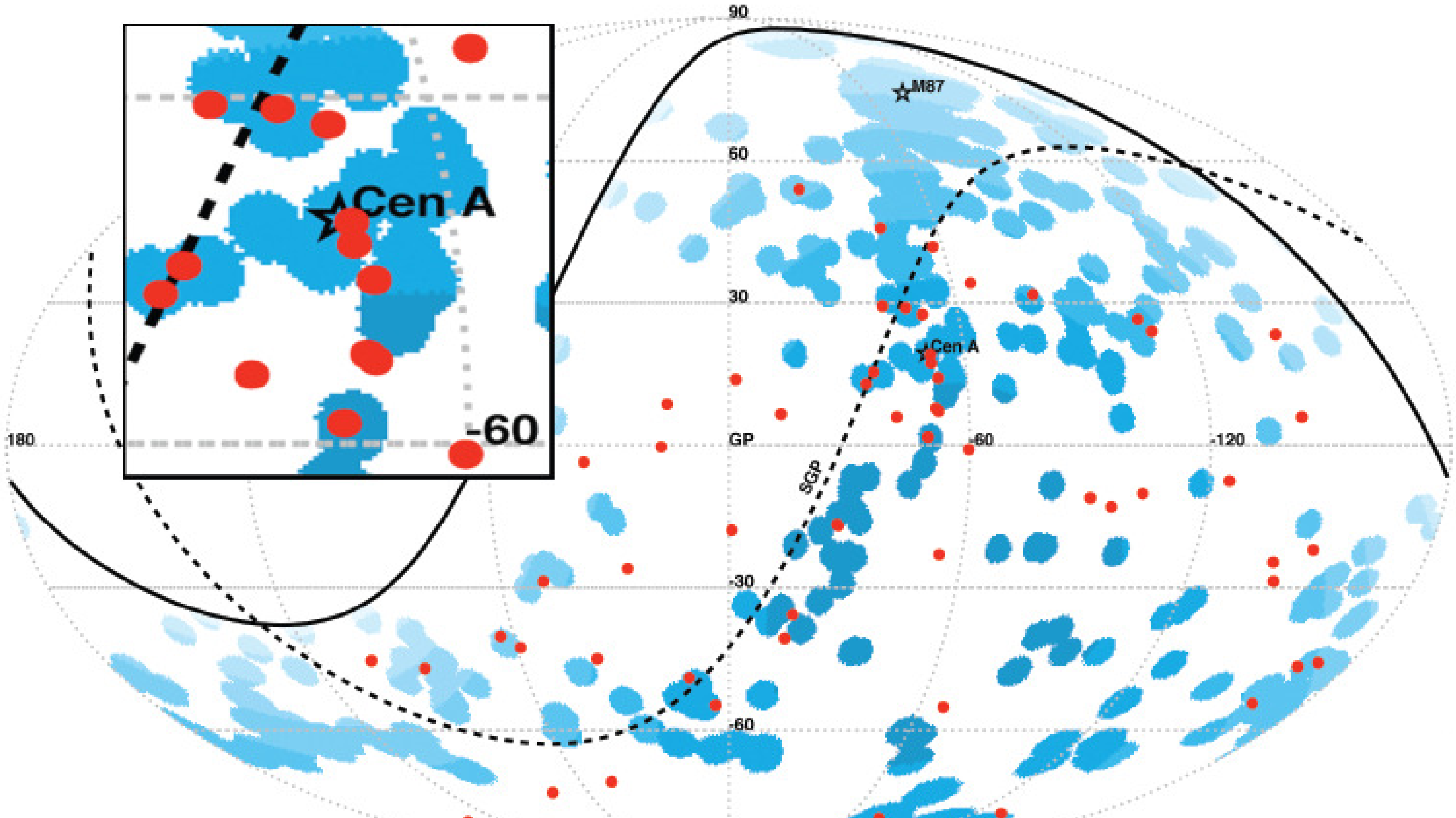
Nature has been unkind (?)
AND
we chose a poor catalogue

(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.



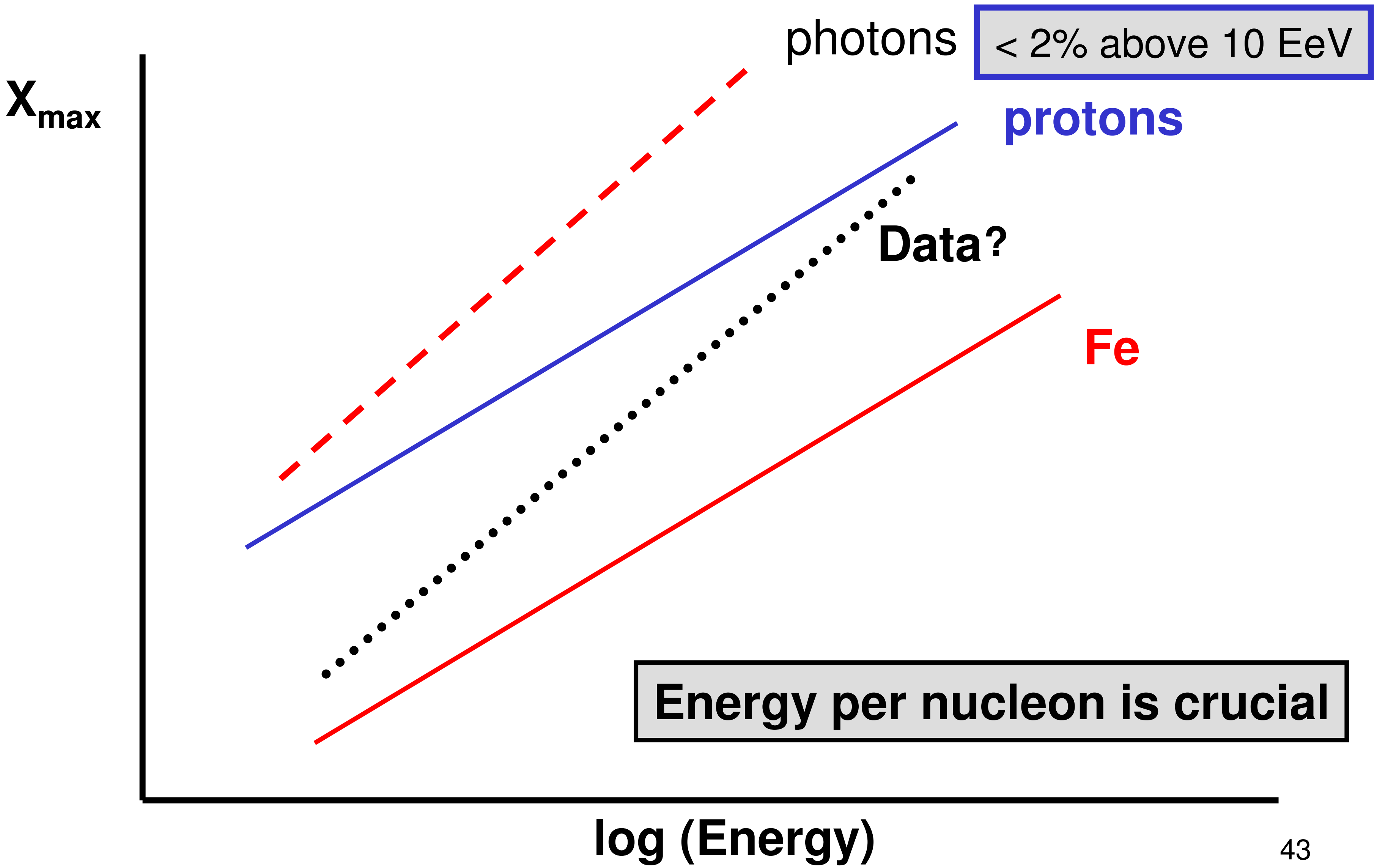
A clear message from the Pierre Auger Observatory is that we made it too small

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

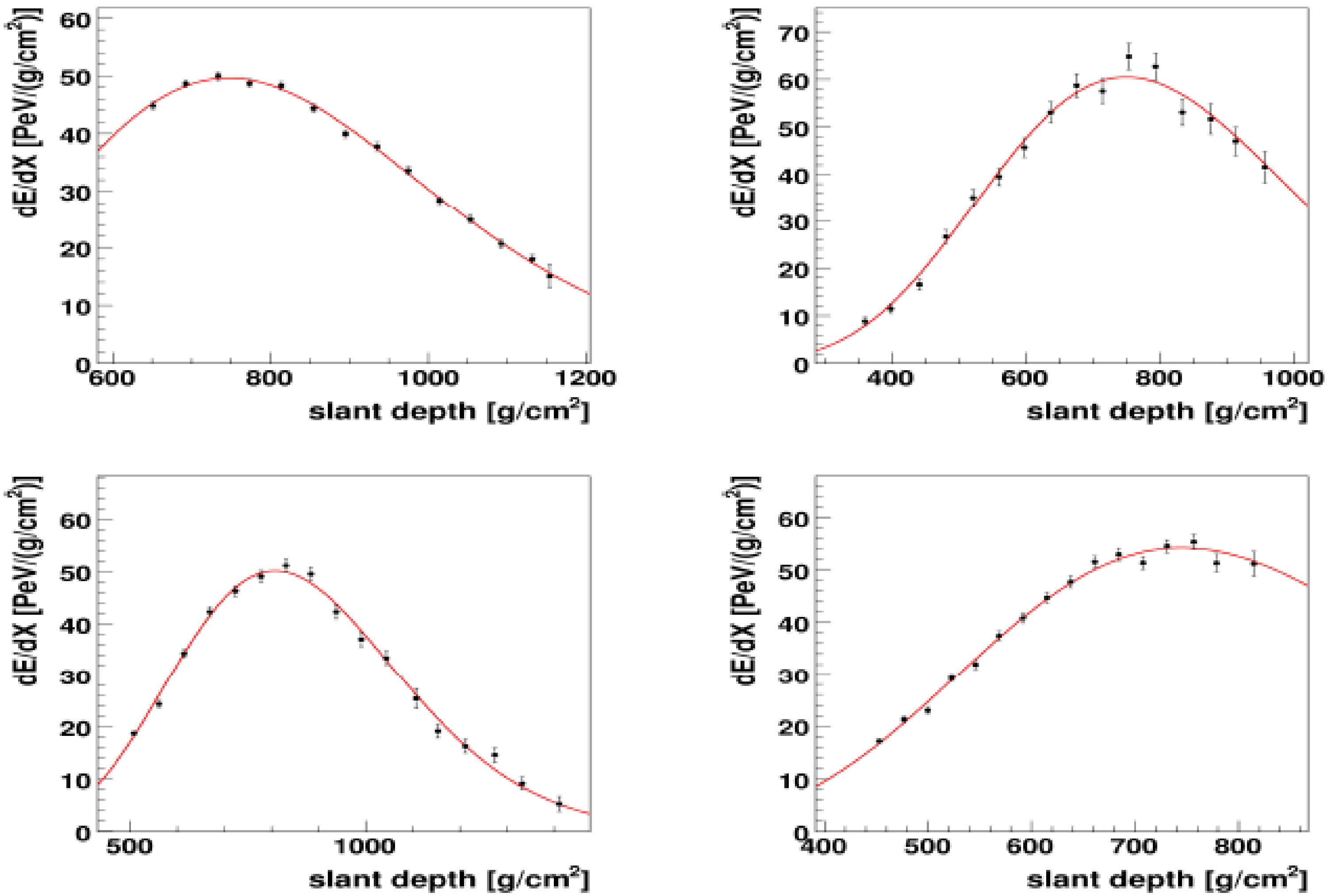
Indications on Mass Composition

- **Anisotropy suggests a proton fraction of ~ 40%**
- **Most unexpected result from Pierre Auger Observatory so far points in another direction**
- ***Could* it be indicative of interesting new physics (??)**

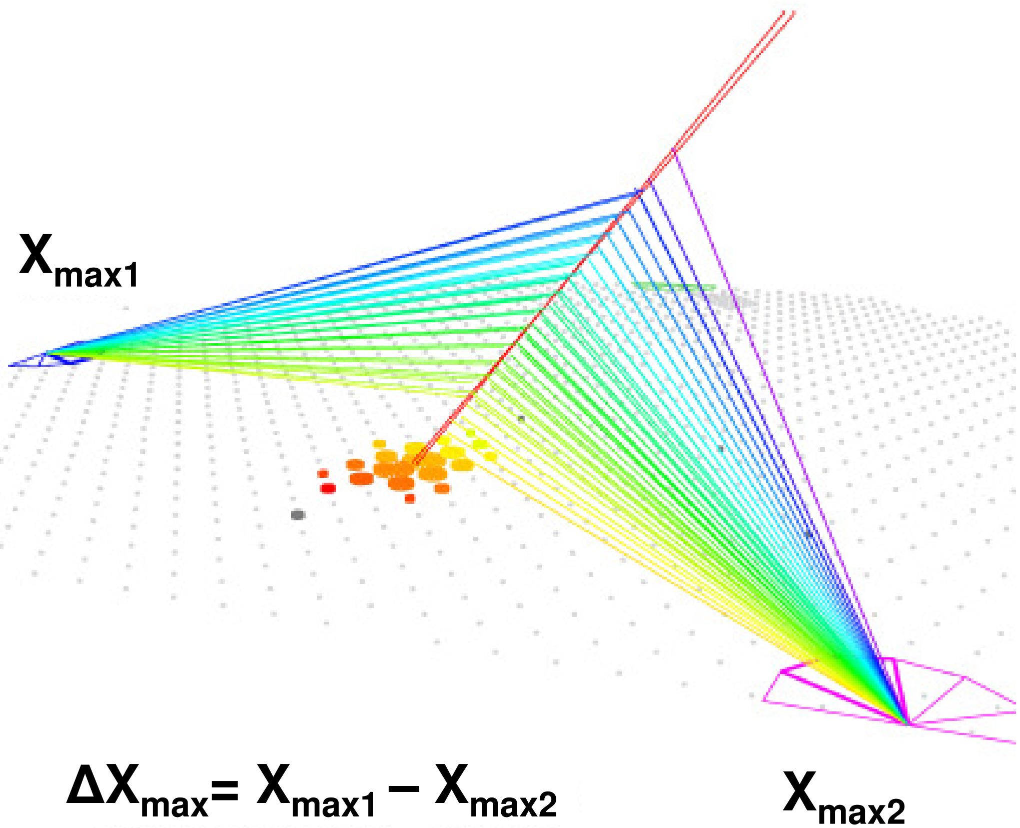
How we try to infer the variation of mass with energy



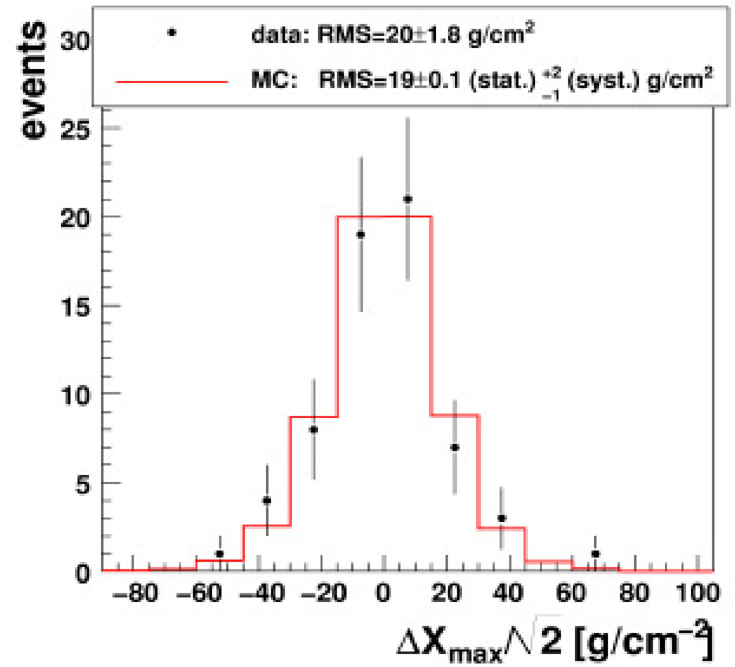
Some Longitudinal Profiles measured with Auger

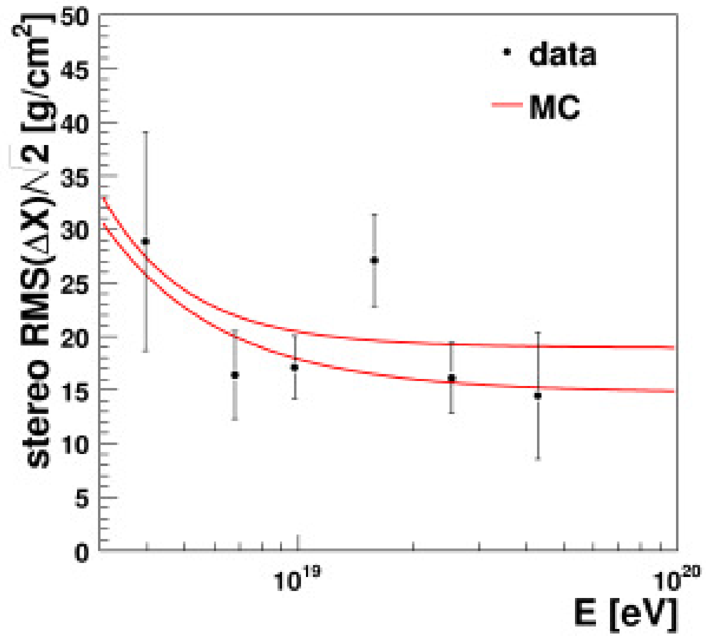


X_{max} Resolution



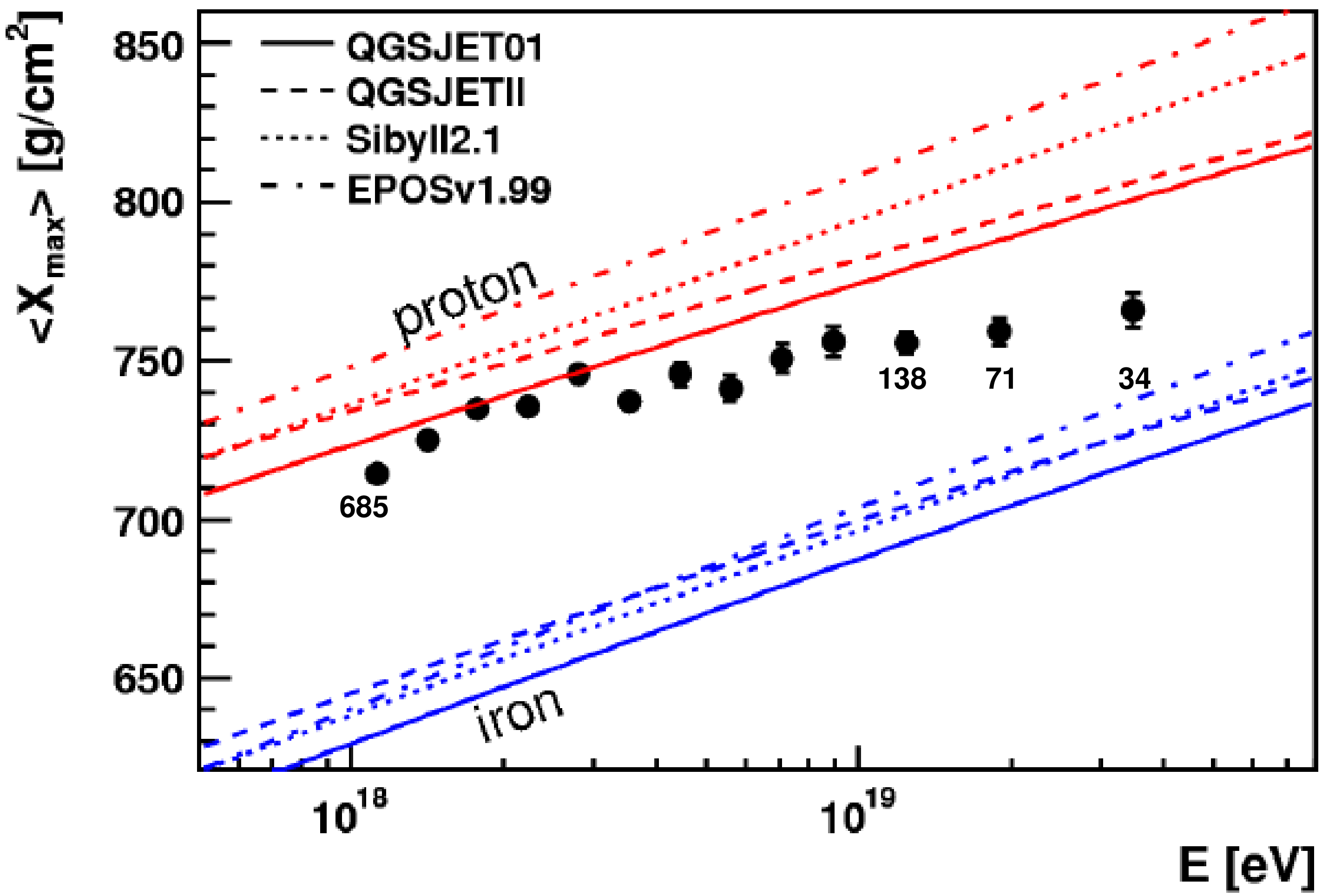
$\Delta X_{max} = X_{max1} - X_{max2}$



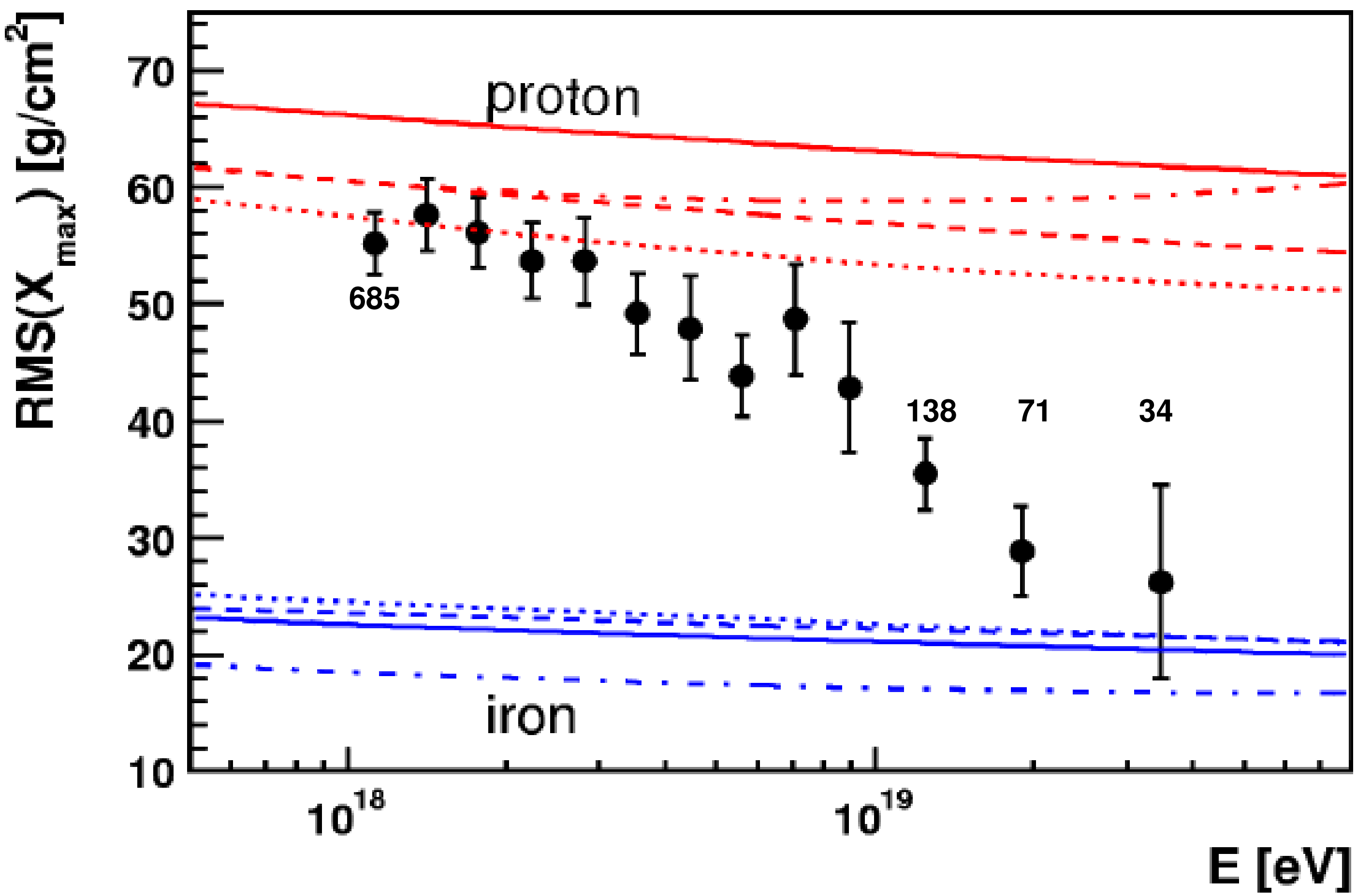


Check using Simulations

Mean X_{max} from 3754 events



RMS(X_{max}) for same events



Spectrum

- **Clear evidence of ankle at ~ 3 x 10^{18} eV**
  - ***common assumption*: galactic to extragalactic cosmic rays**
- **Clear evidence of steepening at ~ 5 x 10^{19} eV**
  - ***common assumption*: GZK-effect seen**

Arrival Direction Distribution

- ~ 40% of UHECR above 5.5 x 10^{19} eV are associated with AGNs

***common assumption*: large fraction of these CR are protons**

Mass Composition

Measurements of <X_{max}> and rms X_{max} suggest:

large fraction of heavier nuclei at highest energies

(But some disagreement with HiRes and TA)

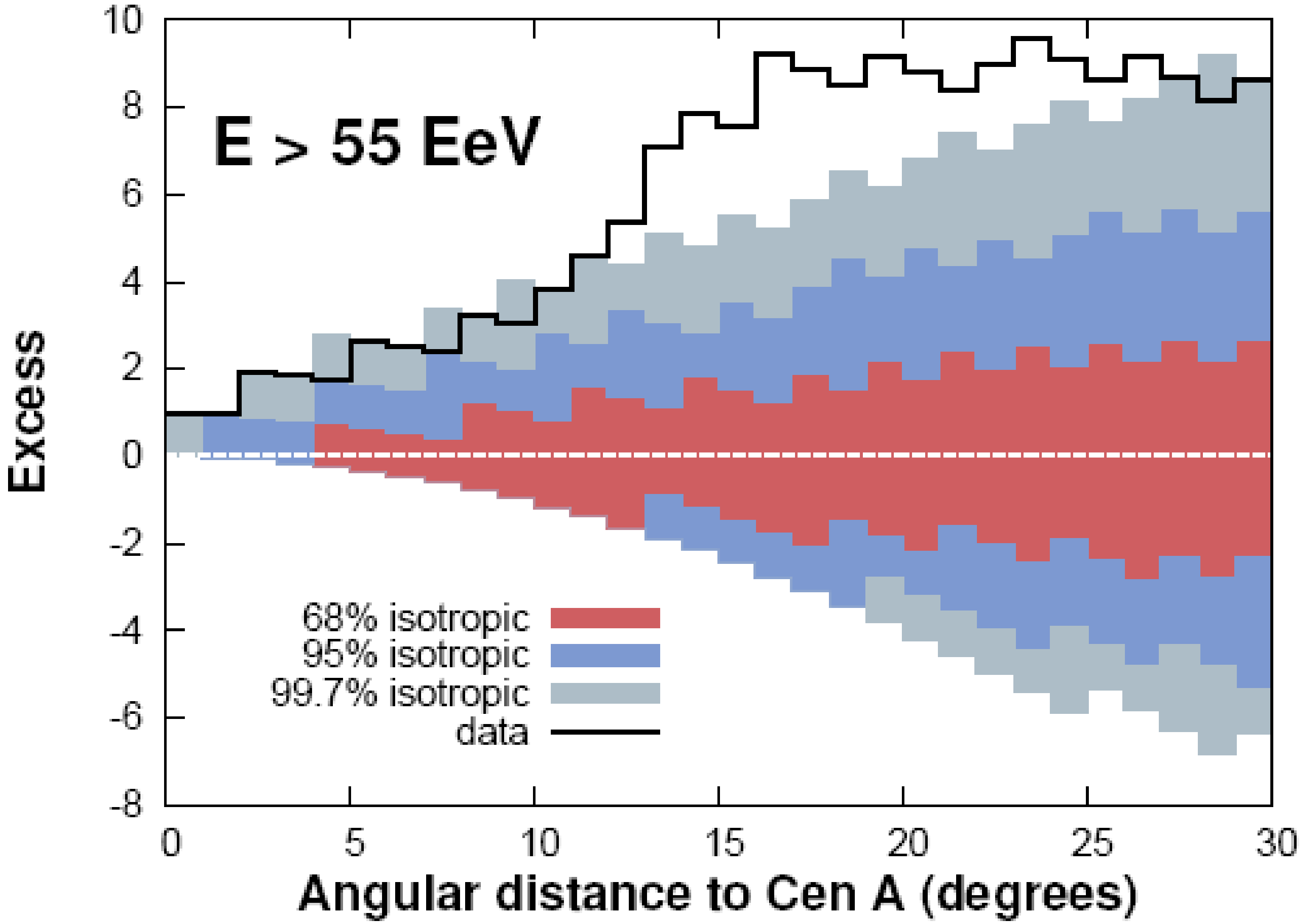
Further Astrophysical Test

Lemoine and Waxman (2009 JCAP 11 009)

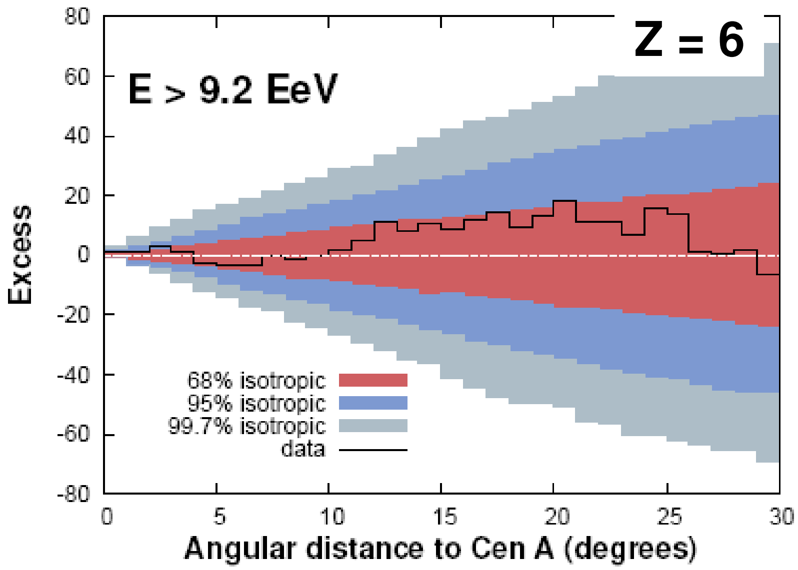
If anisotropy is due to heavy nuclei, then anisotropy expected at energy ~ E/Z

Statistics are greater at lower energies so this should be detectable

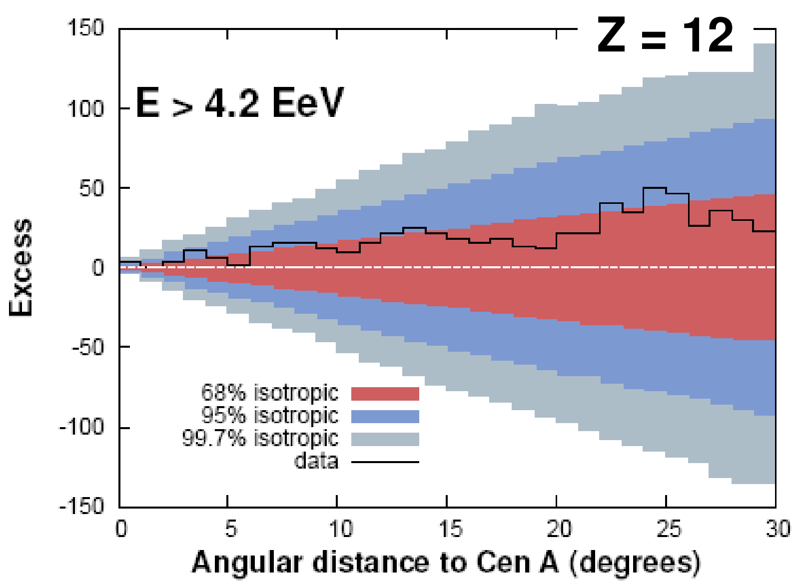
VERY preliminary results from Auger

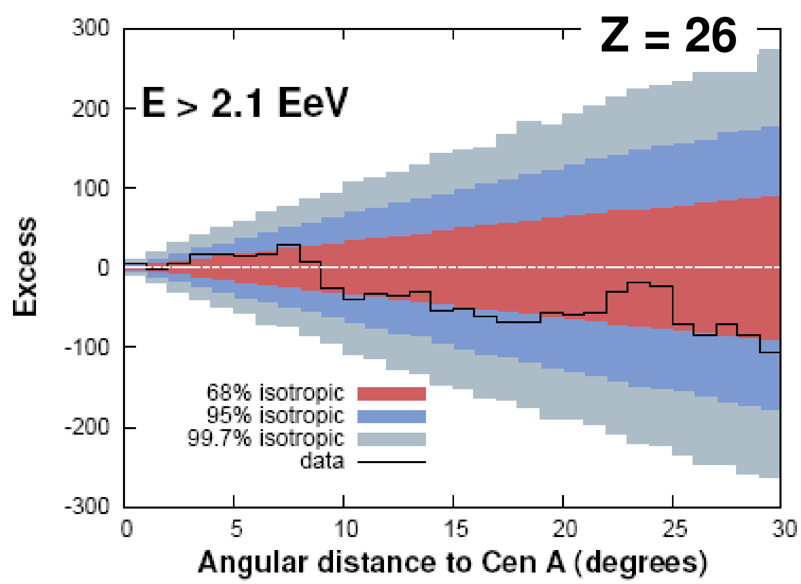

E > 55 EeV
Excess
Angular distance to Cen A (degrees)
68% isotropic
95% isotropic
99.7% isotropic
data
10
8
6
4
2
0
-2
-4
-6
-8
0
5
10
15
20
25
30

PRELIMINARY!



Z	E_{min} [EeV]	N_{tot}	N_{obs}	N_{bkg}	$N^{2\sigma}$
6	9.2	3626	763	768.7 ± 27.7	49.6
13	4.2	13482	2852	2858.2 ± 53.4	100.7
26	2.1	51641	10881	10947.9 ± 104.6	142.4





Tentative Conclusion: Protons from Cen A

- Anisotropy might suggest protons

- X_{max} data suggest diminishing fraction of protons

- Could cross-section (p-air) be much higher than from usual extrapolations?

- Could leading particle take very little energy?

- Could the multiplicity be unexpectedly high?

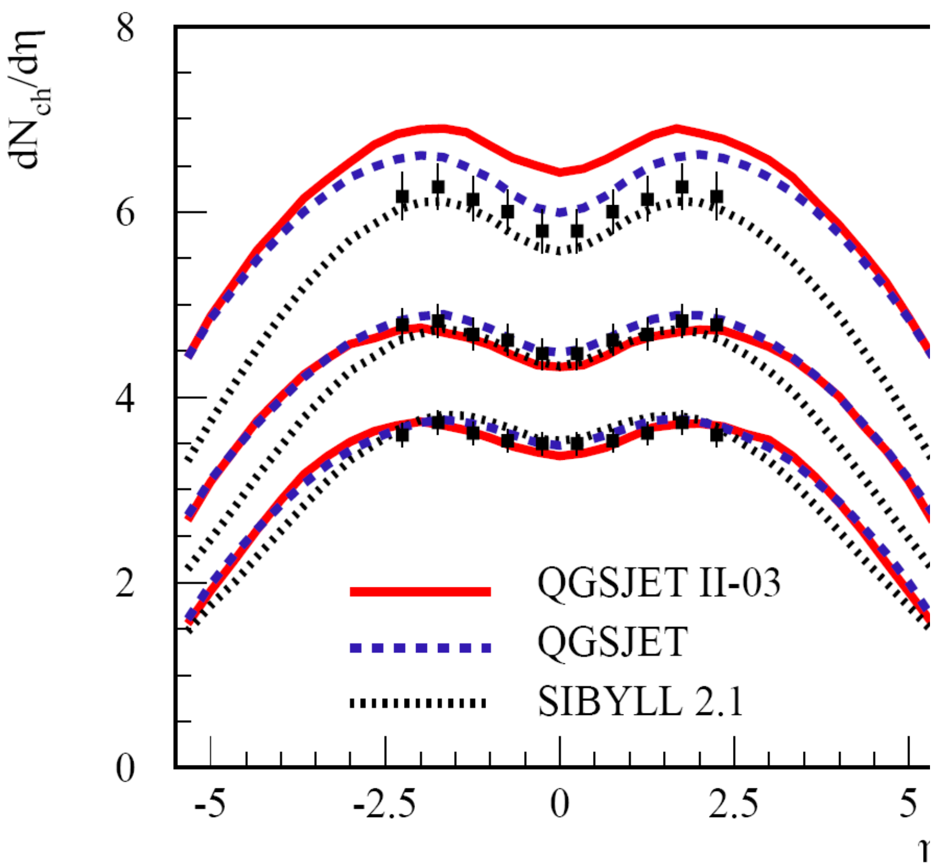
These features would give:-

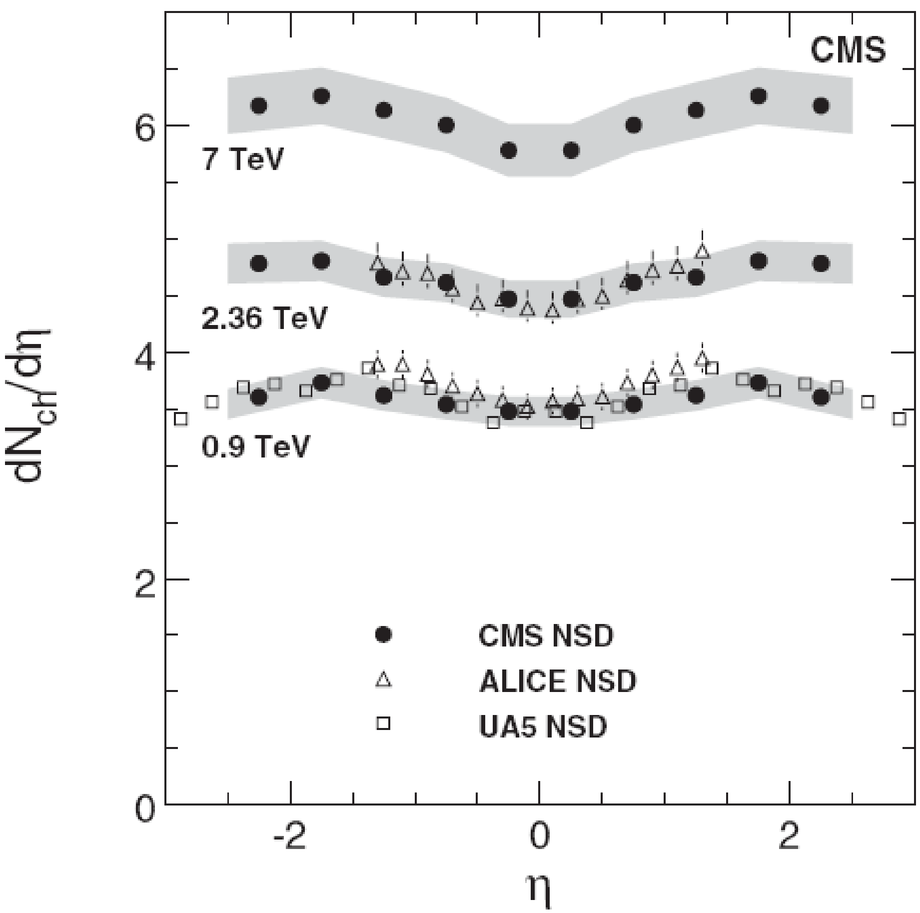
- X_{max} higher in atmosphere than current models

- Reduce fluctuations in X_{max}

Can the LHC help us?

CMS Rapidity Plots

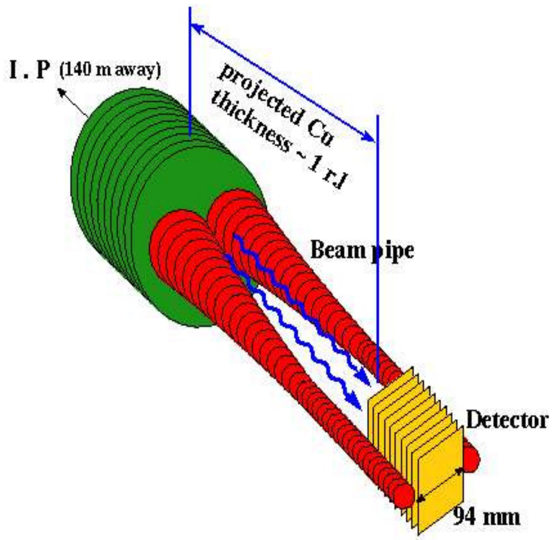




Ostapchenko arXiv: 1010.01372

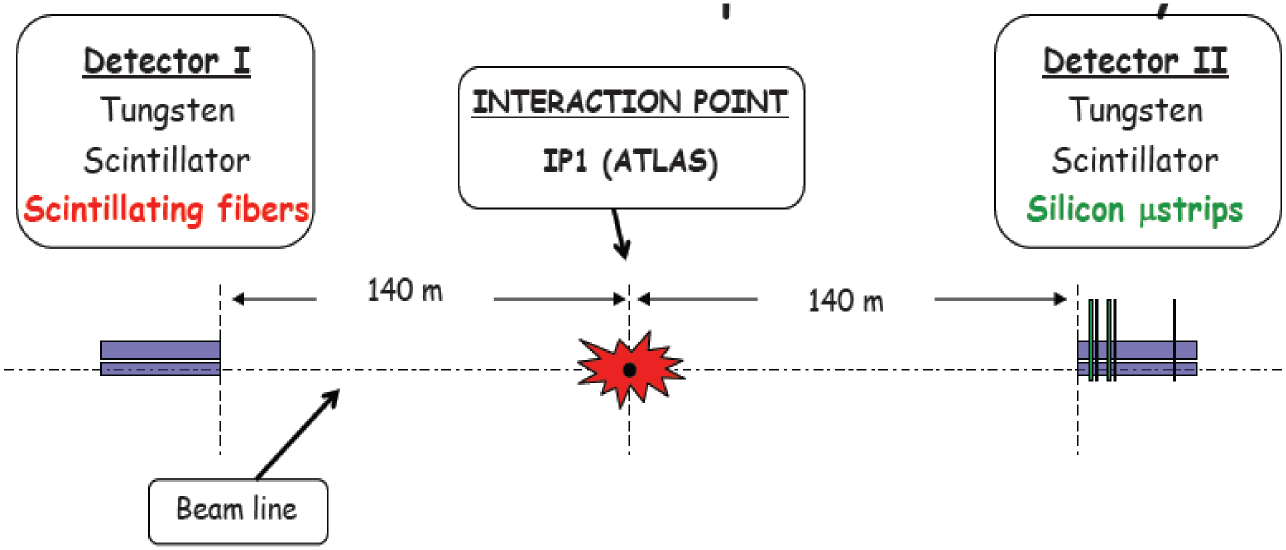
CMS Collaboration: PRL 105 022002 2010

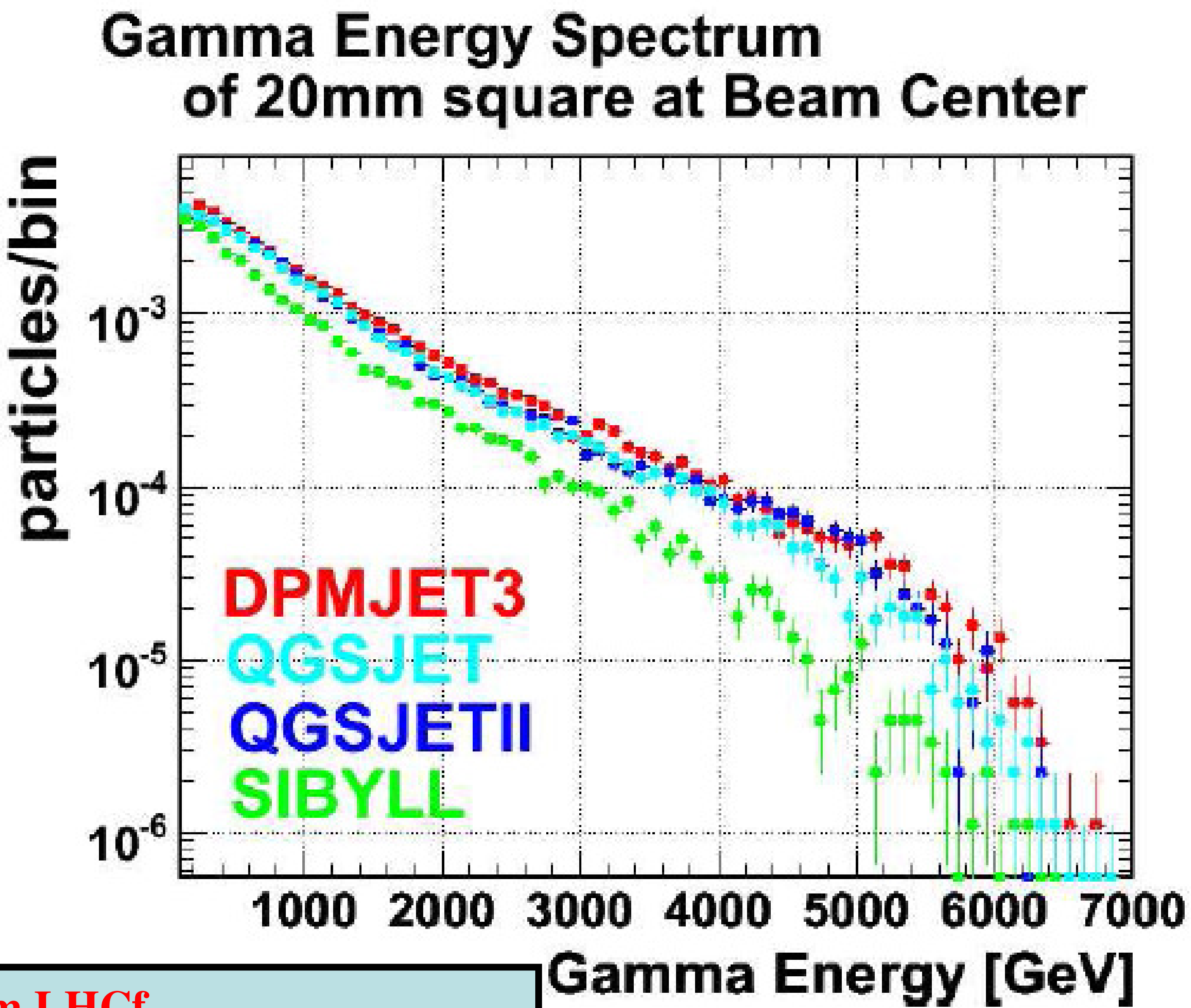
LHCf: an LHC Experiment for Astroparticle Physics



LHCf: measurement of photons and neutral pions and neutrons in the very forward region of LHC

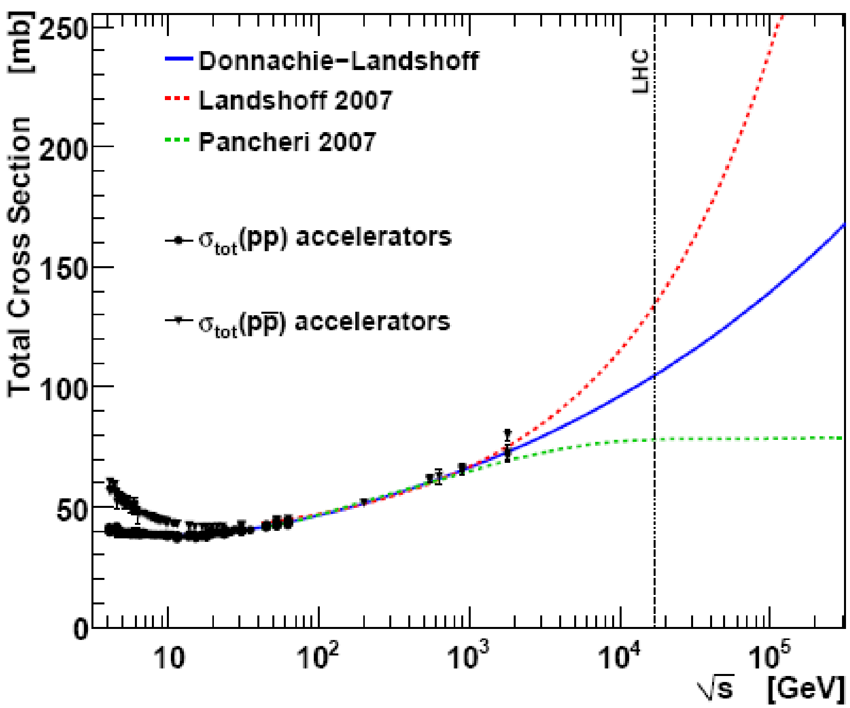
Add an EM calorimeter at 140 m from the Interaction Point (IP1 ATLAS)
For low luminosity running

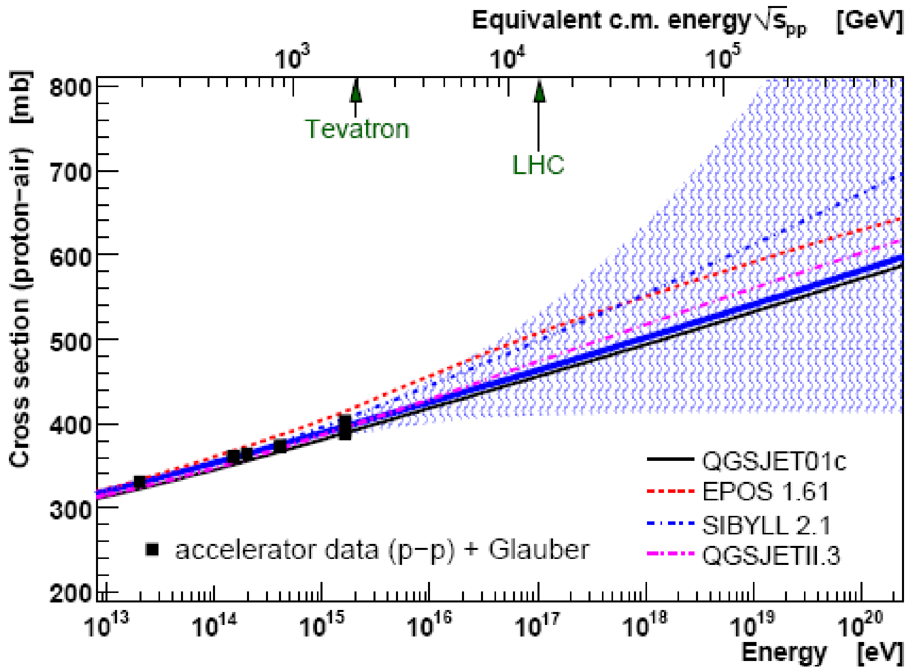




Prospects from LHCf
Results will possibly be reported in Japan in December – haven't yet heard

The Cross-Section Problem





From Ulrich, Engel and Unger 2010

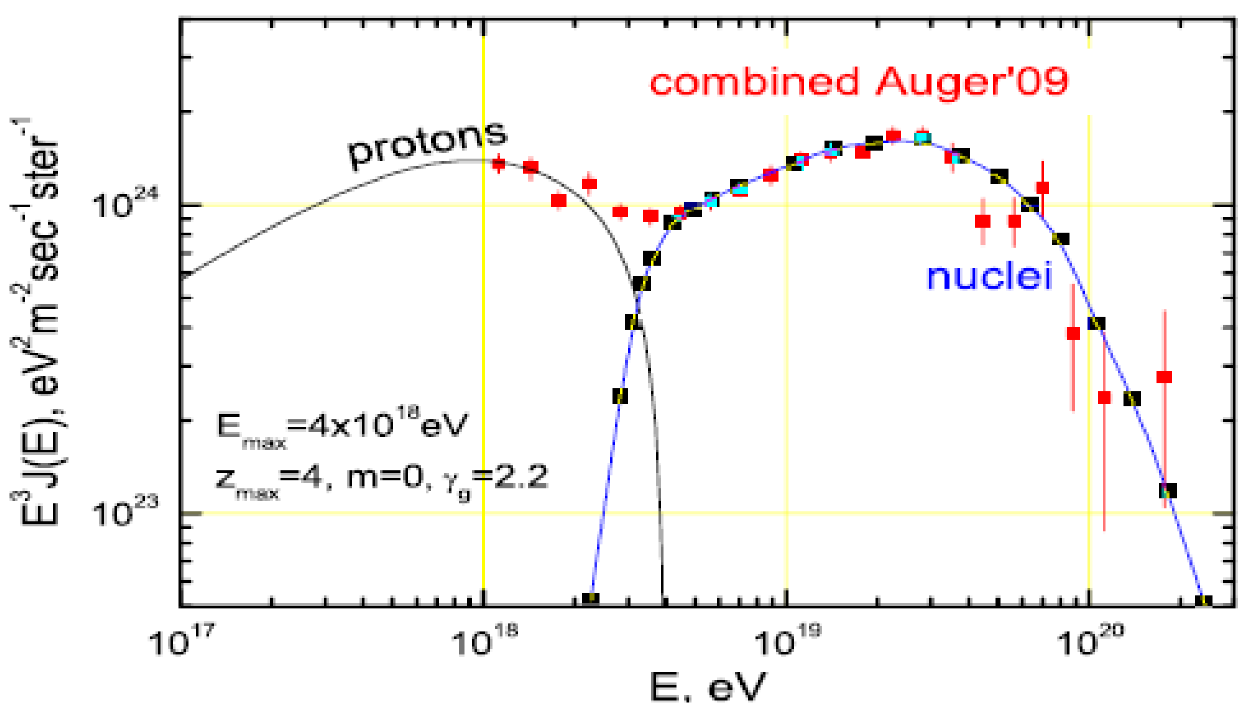
Aloiso, Berezinsky and Gazizov: arXiv 0907.5194

"DISAPPOINTING" MODEL FOR UHECR

based on interpretation of the Auger mass composition.

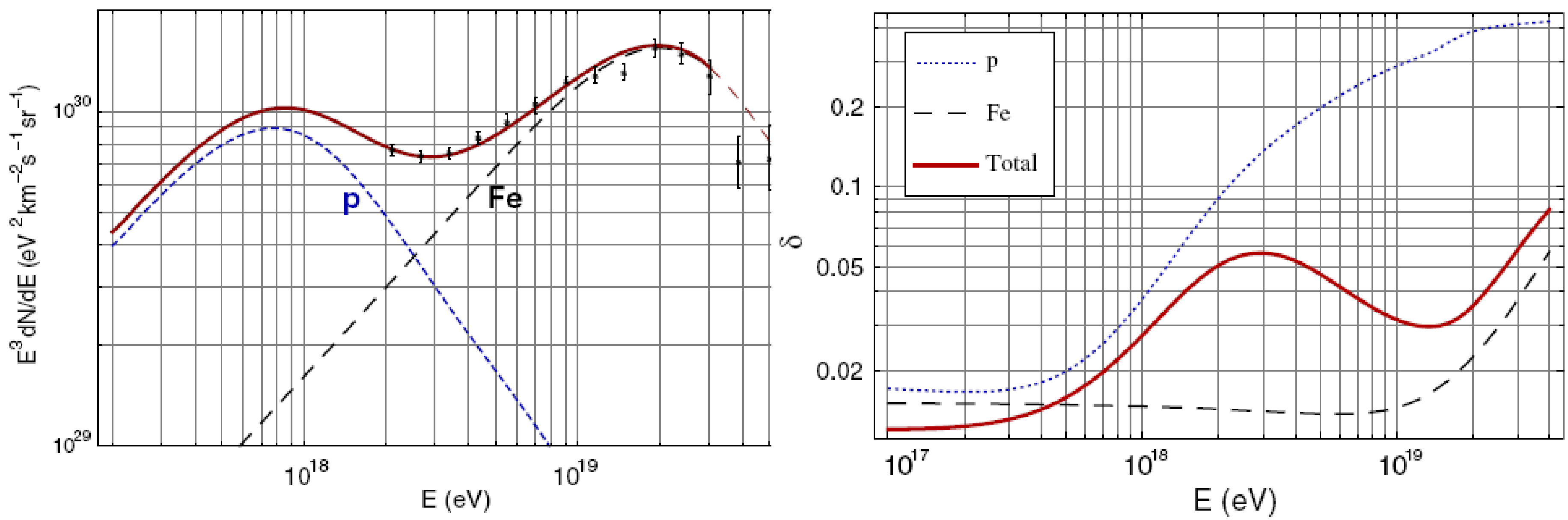
- At $1 \times 10^{18} \lesssim E \lesssim 3 \times 10^{18}$ eV: **almost pure proton composition**
- At $4 \times 10^{18} \lesssim E \lesssim 4 \times 10^{19}$ eV: **A increases up to $A \approx 56$.**

Model: very low acceleration energy $E_{\max}^{\rm acc} = 4 \times 10^{18} Z$ eV.

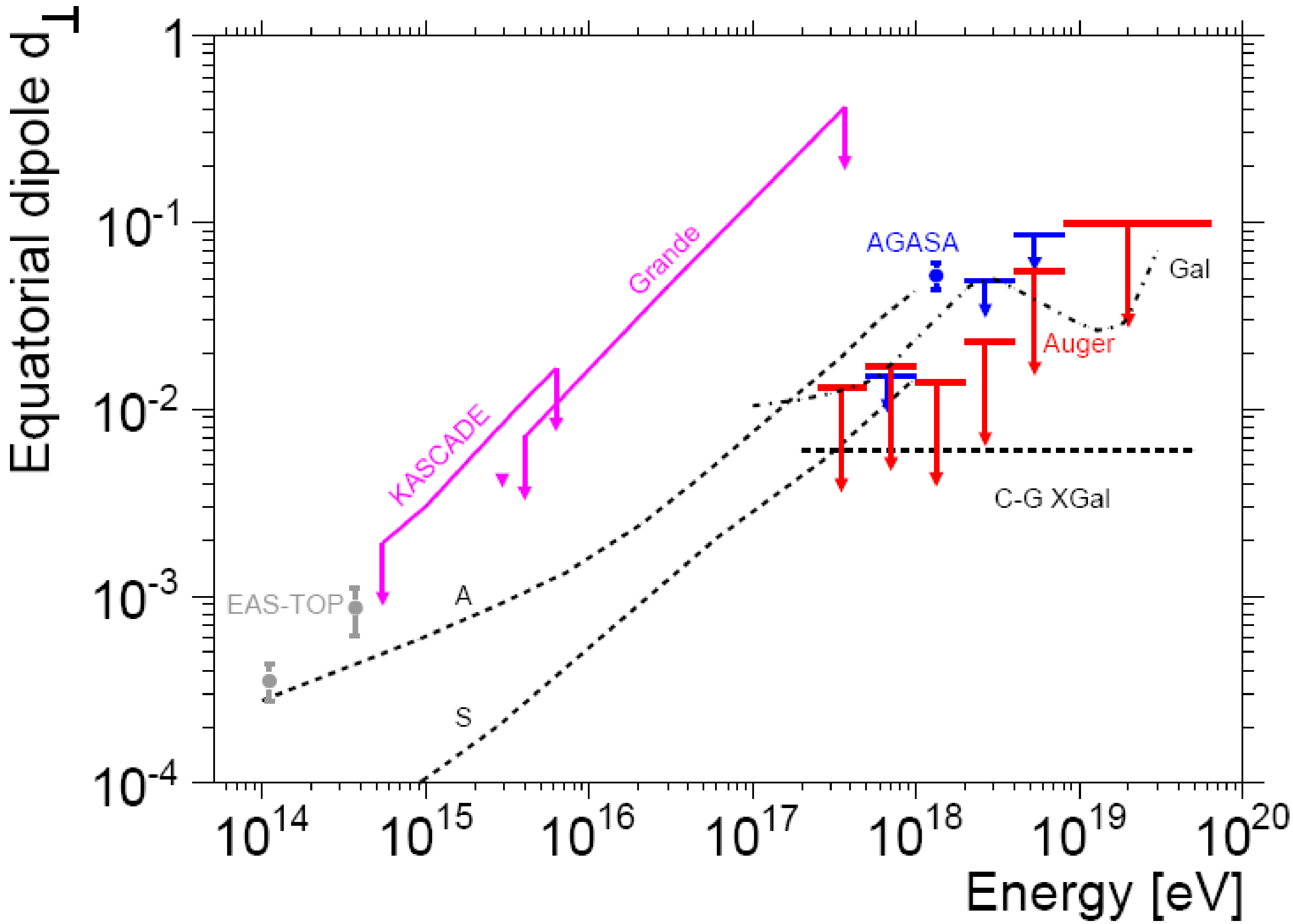


Also Calvez et al. PRL 105 091101 2010

GRBs in our galaxy about every 10^5 years



Auger Large Scale Anisotropy: Submitted for publication, 061210



Next steps:

- **Run Auger South until at least 2015**
- **Build Auger North (at least x7 AS)**
  but NOT in South East Colorado
- **Go into space: JEM-EUSO on ISS (2015) and**
  free-flyer in 2020s?

There are still lots of questions to answer as the data pose several puzzles