The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2036-6

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

25 - 29 May 2009

Ultra-High Energy Cosmic Rays and the Pierre Auger Observatory

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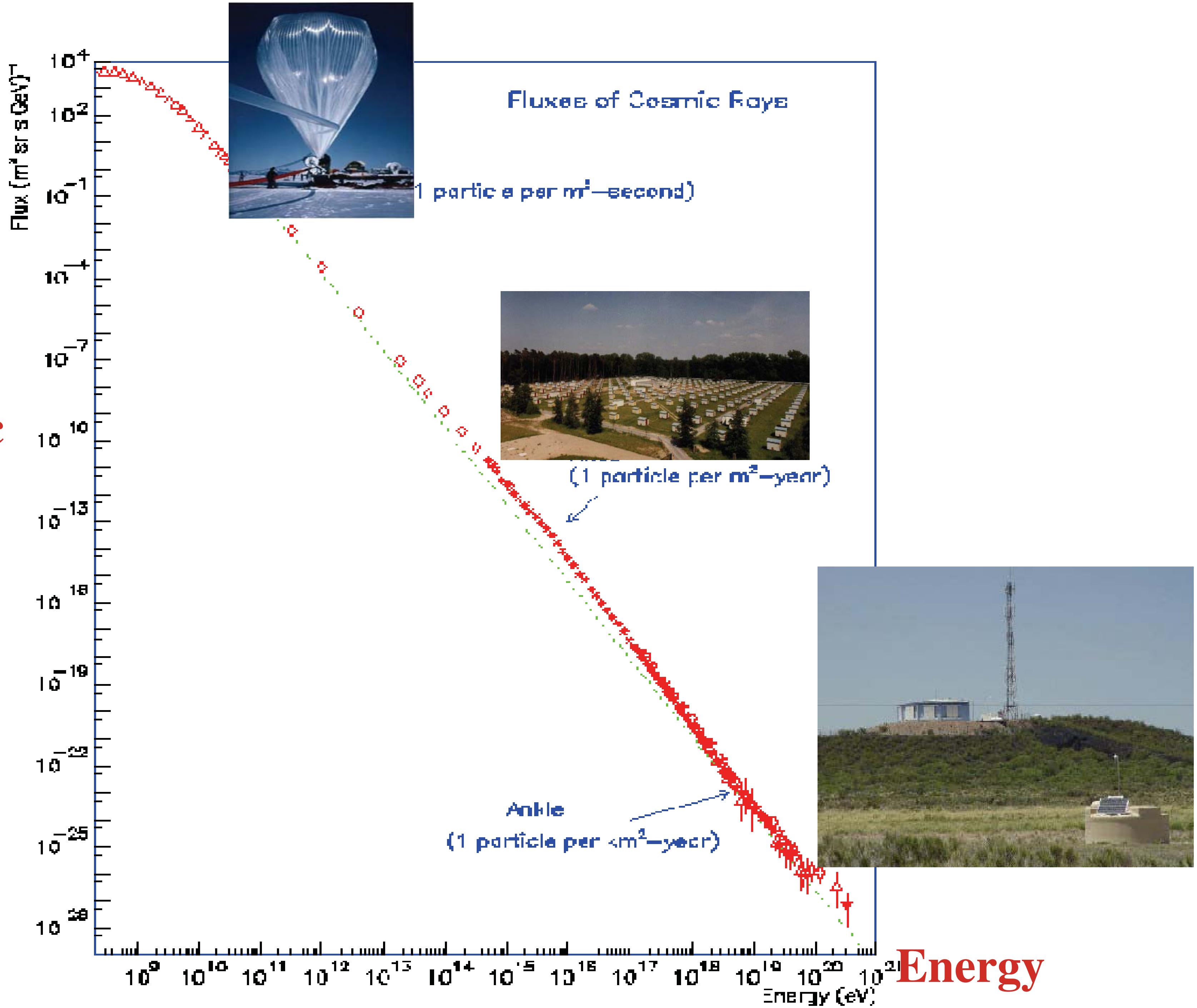
ULTRA-HIGH ENERGY COSMIC RAYS AND THE PIERRE AUGER OBSERVATORY

Esteban Roulet (Bariloche)

the Auger Collaboration: 17 countries, ~100 Institutions, ~400 scientists

Argentina, Australia, Bolivia, Brazil, Czech Rep., France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, UK, USA, Vietnam cosmic ray flux

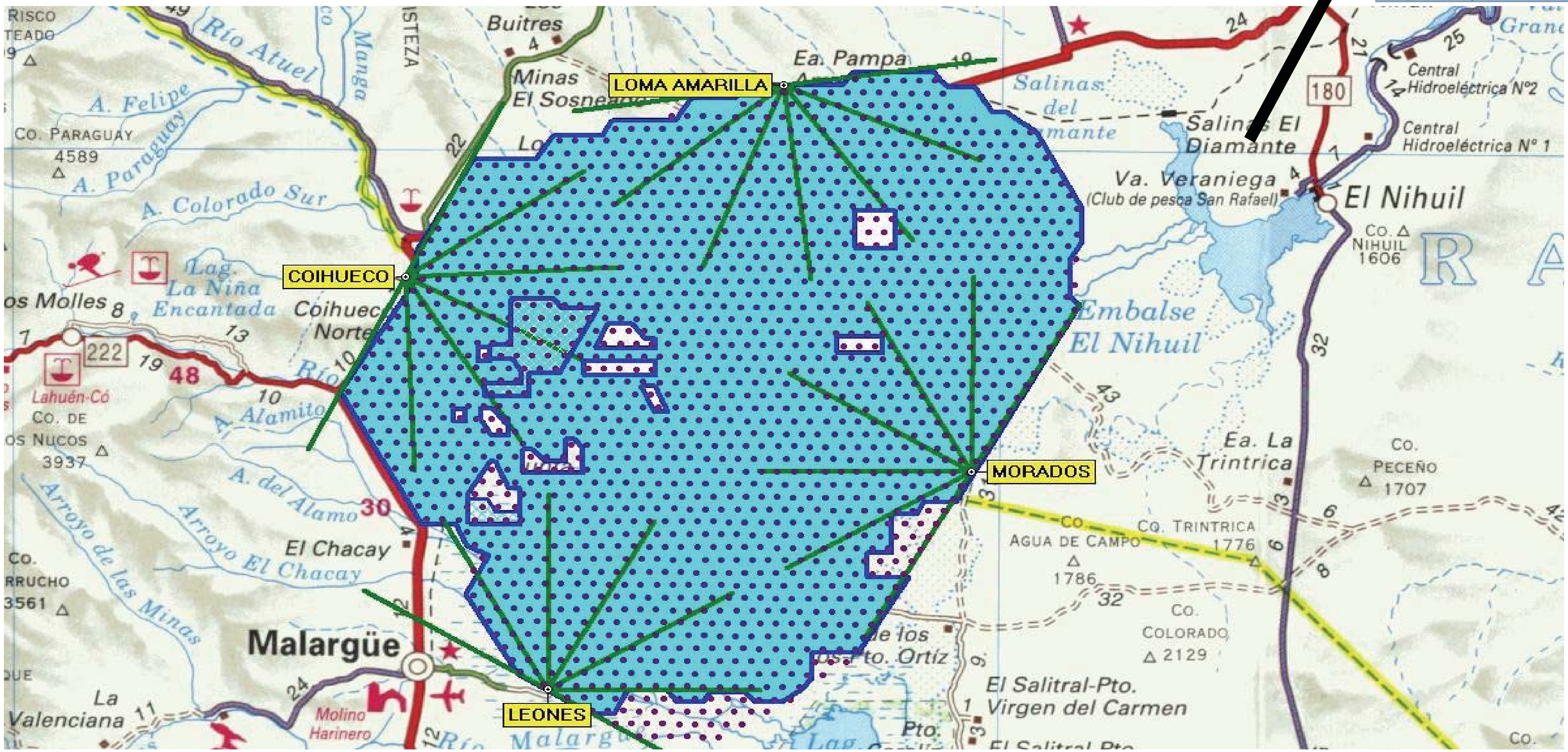


Energy

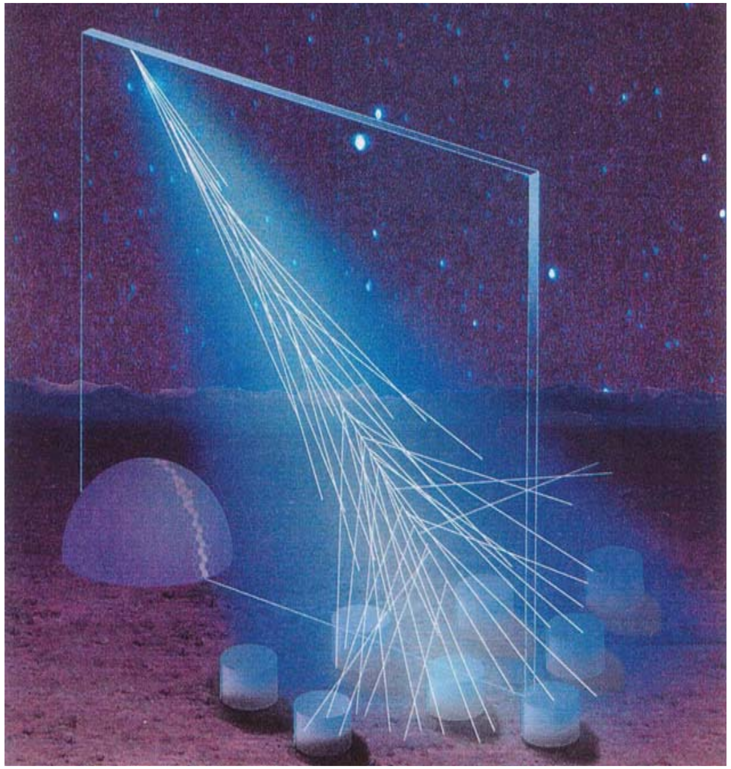
at the highest energies, only few cosmic rays (CR) arrive per km^2 per century !

to see some, a huge detector is required

THE PIERRE AUGER OBSERVATORY



1600 detectors instrumenting 3000 km^2 and 24 telescopes



HYBRID DESIGN

Surface Detectors:
"statistical power" to detect showers on the ground

Fluorescence Detectors:
complementary view of the shower development

energy cross-calibration
angular resolution tests,
X_{max} measurements, etc.

SCIENTIFIC OBJECTIVES:

Spectrum: CR flux for E > 10^{18} eV

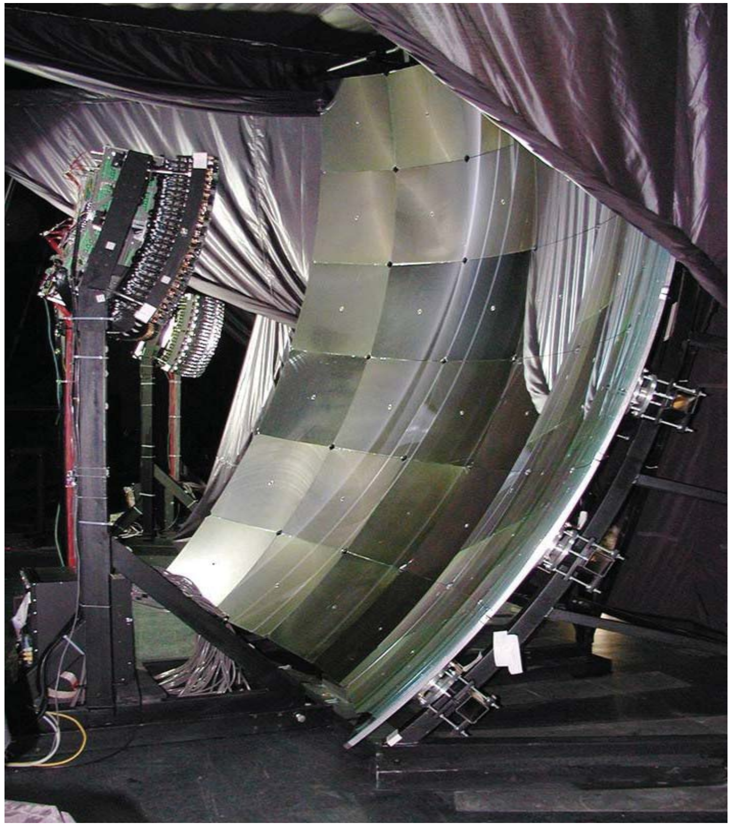
Arrival directions: search for anisotropies (sources)

Composition: light or heavy nuclei, photons, neutrinos, others?

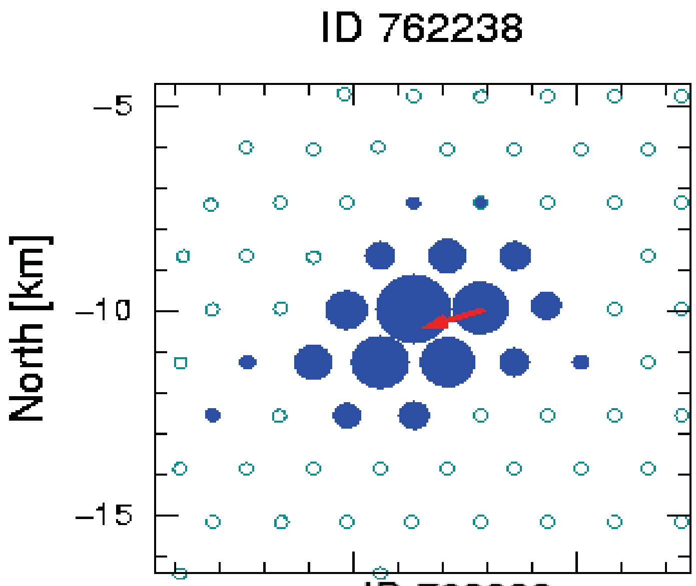
Study of interactions at energies unreachable at accelerators

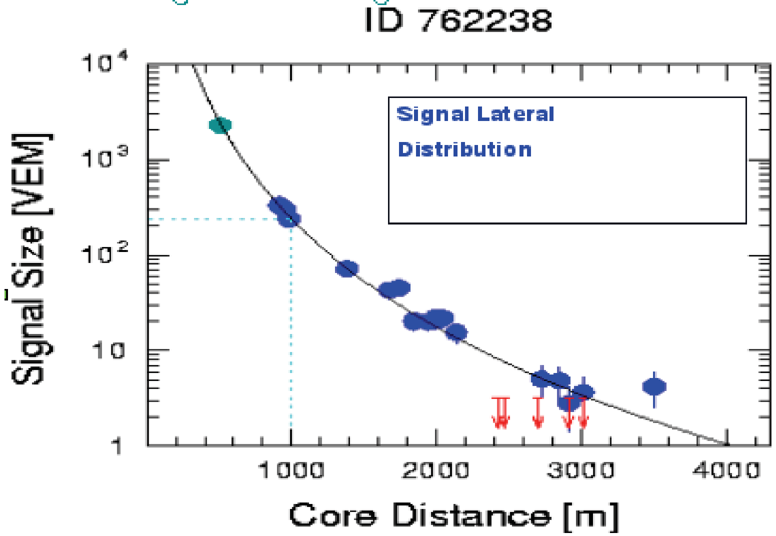
surface detector

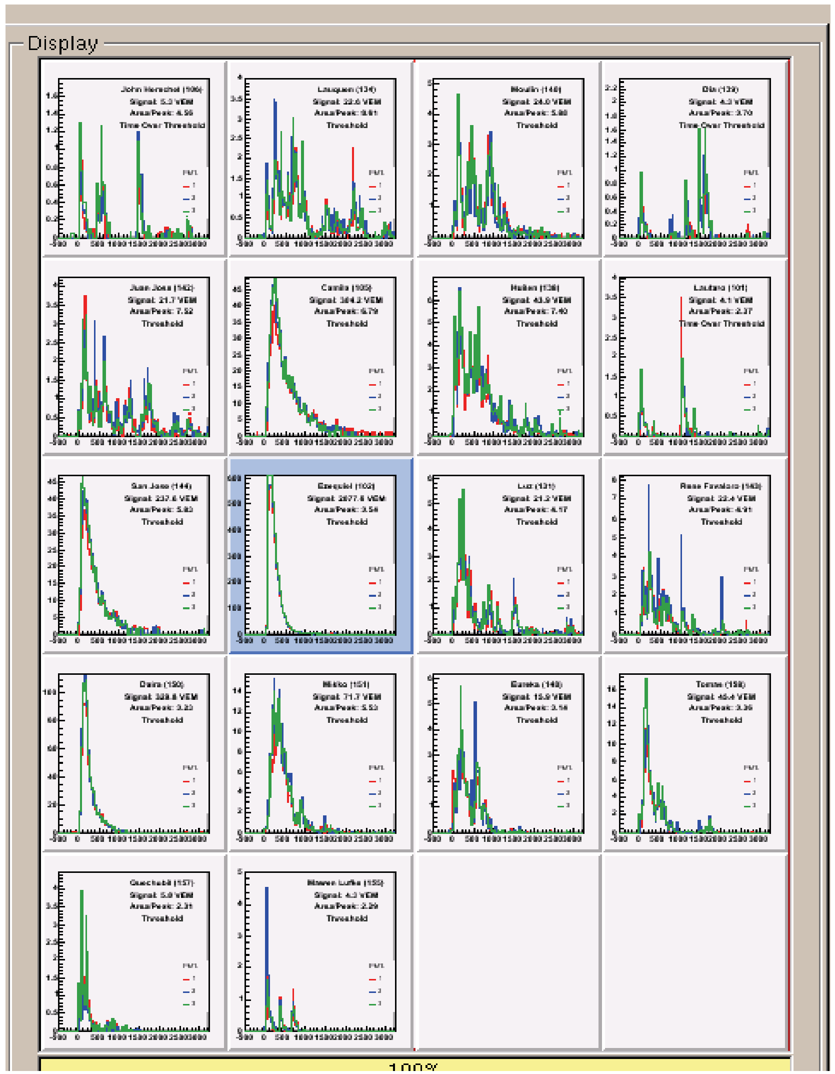
fluorescence detector



event reconstruction with the surface detector



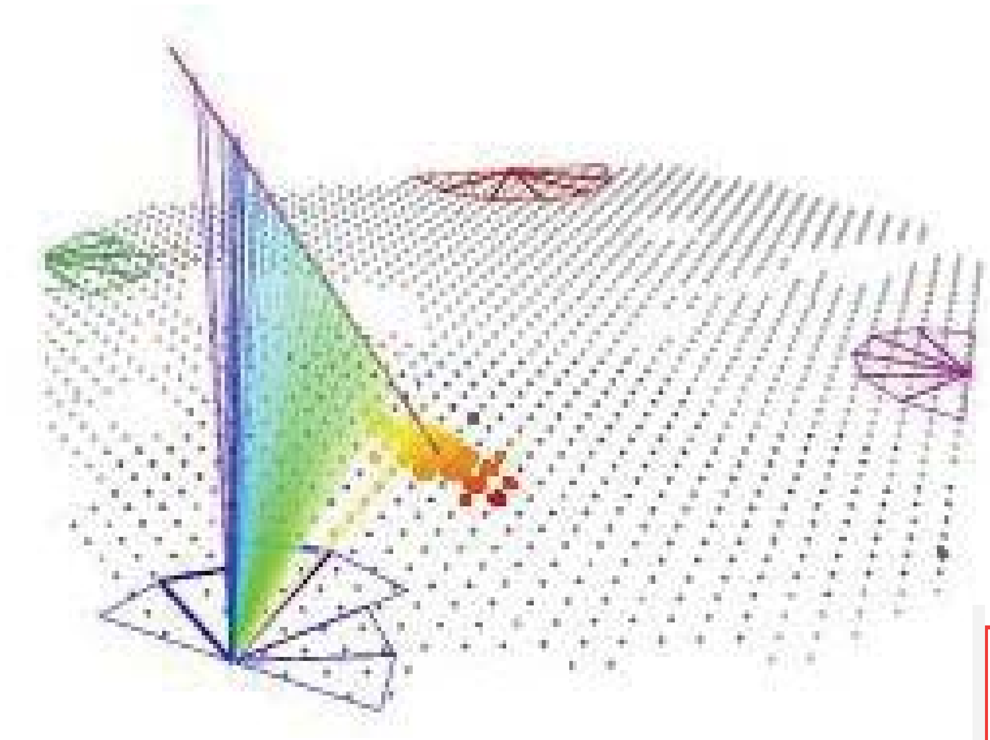


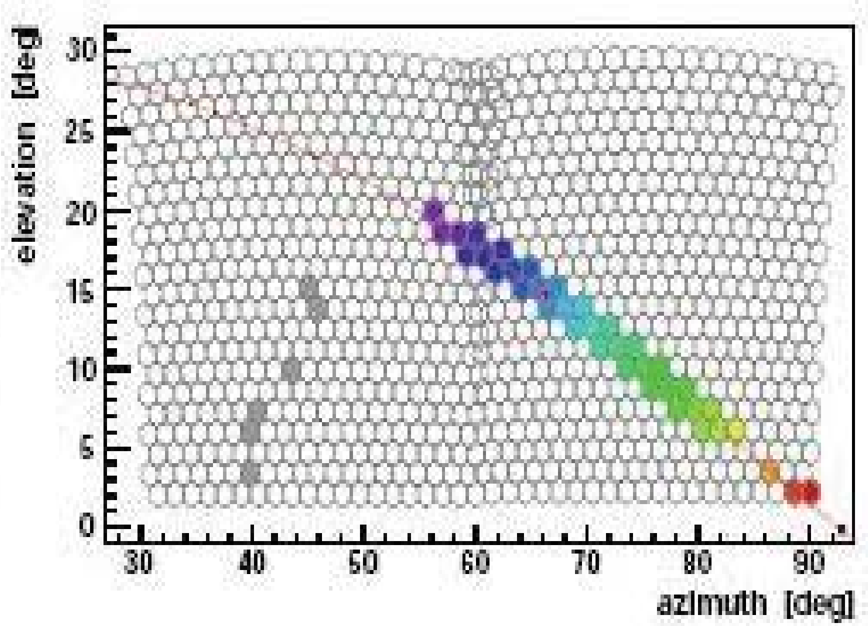


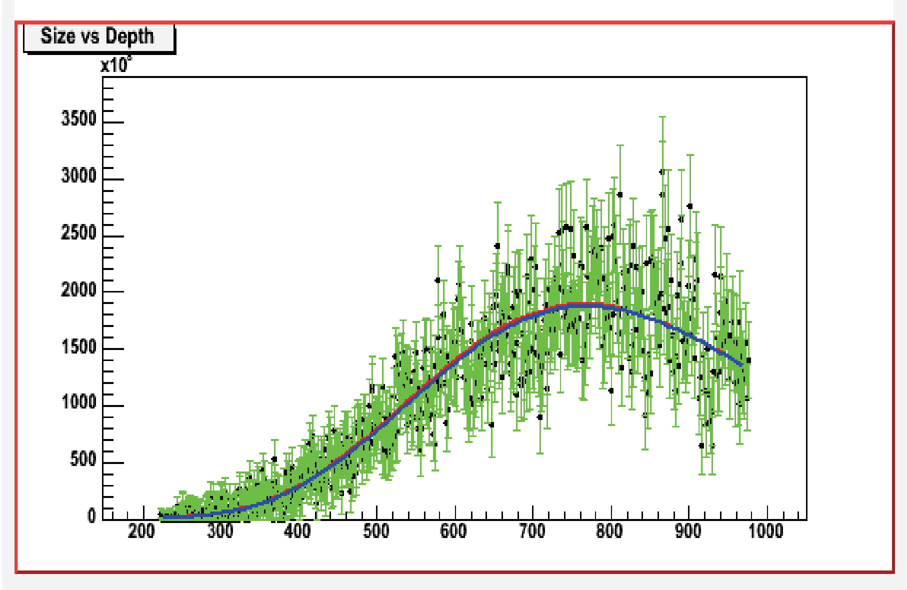
Event with θ~ 48º, E ~ 70 EeV

(1 EeV = 10^{18} eV)

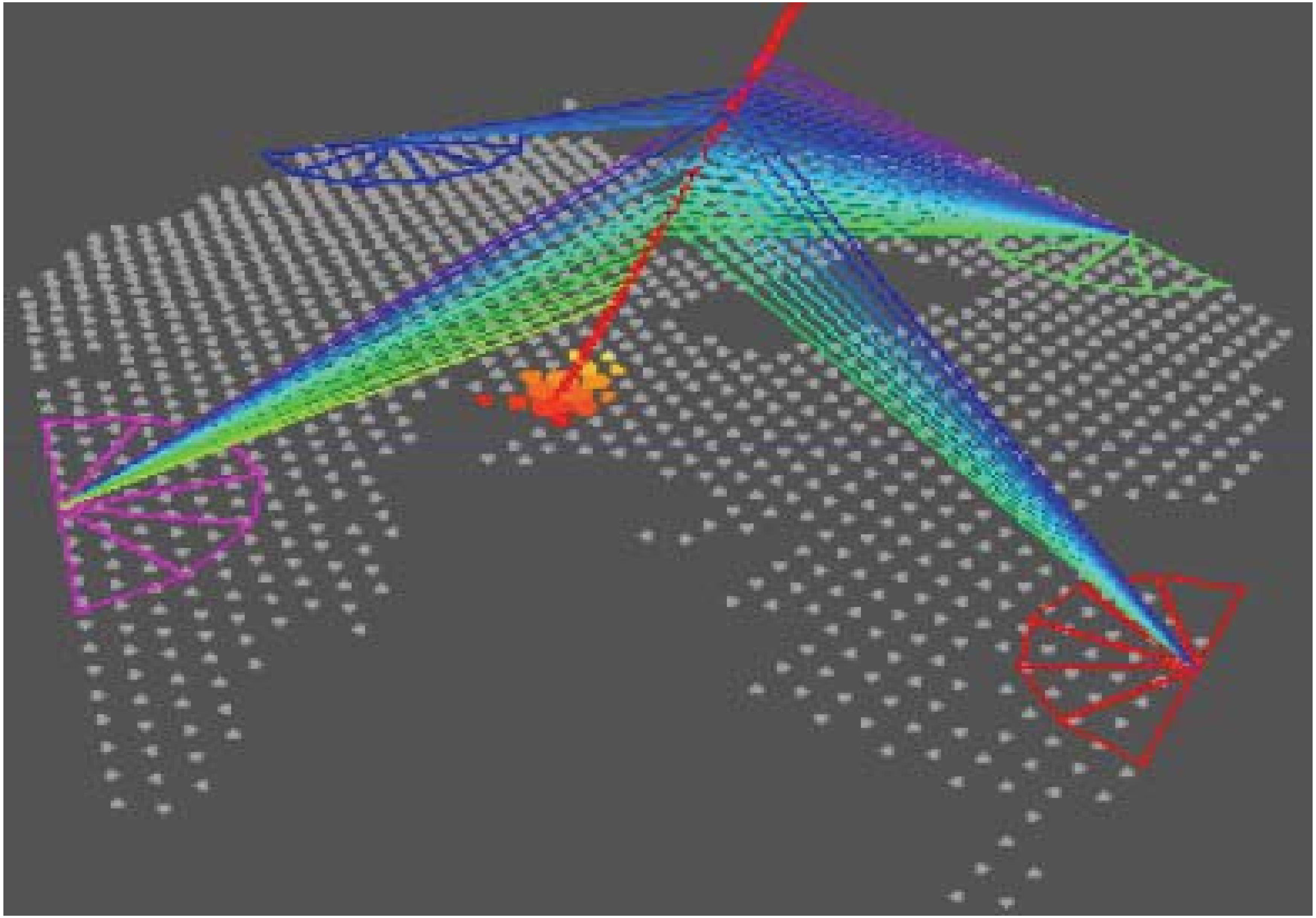
a hybrid event



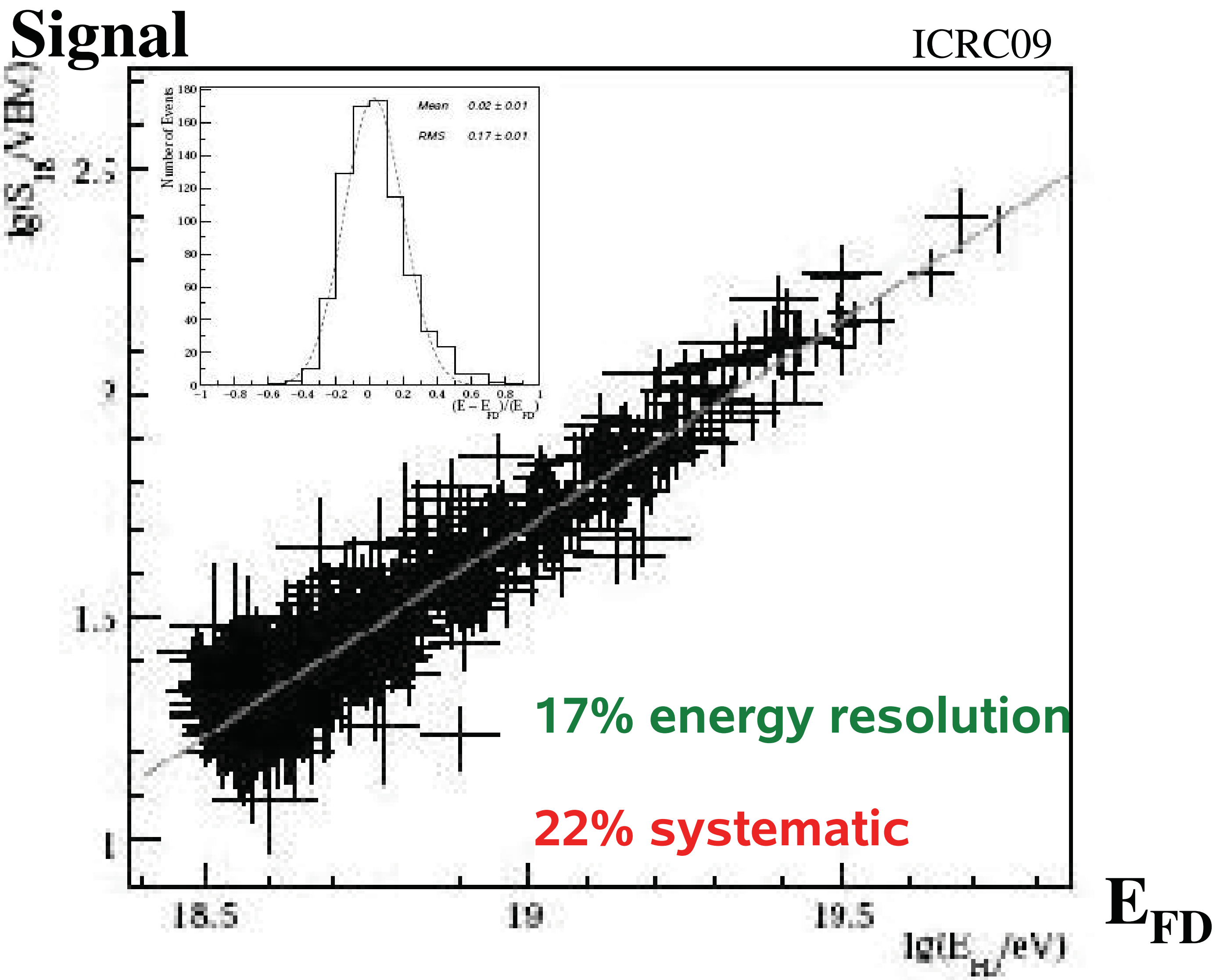




first shower seen by the four telescopes



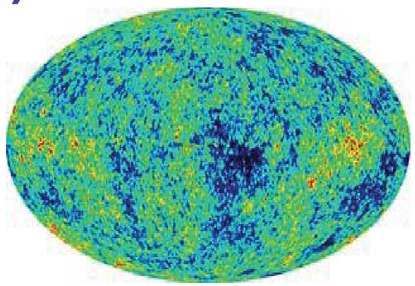
Energy calibrated using hybrid events

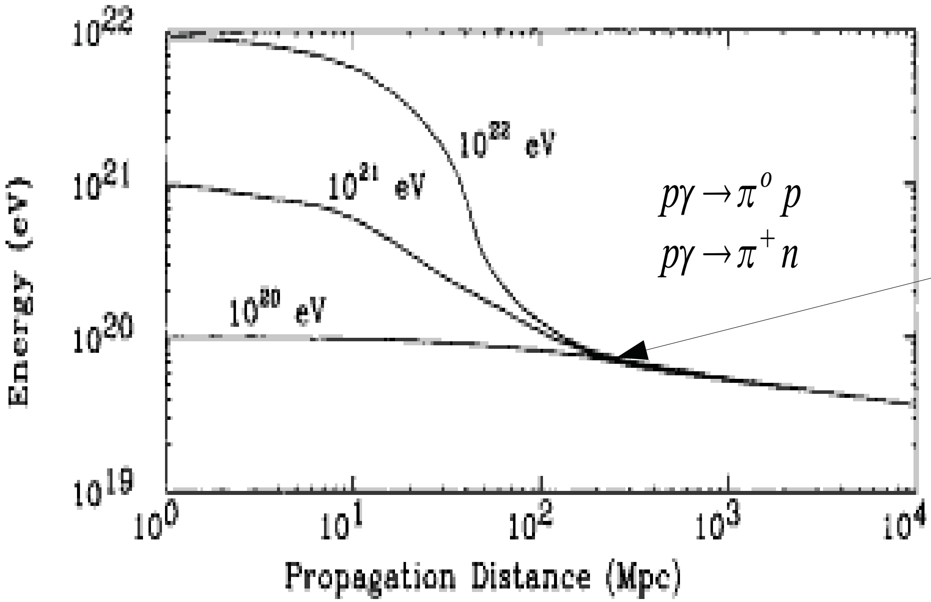


(attenuation in atmosphere accounted with Constant Intensity Cut method)

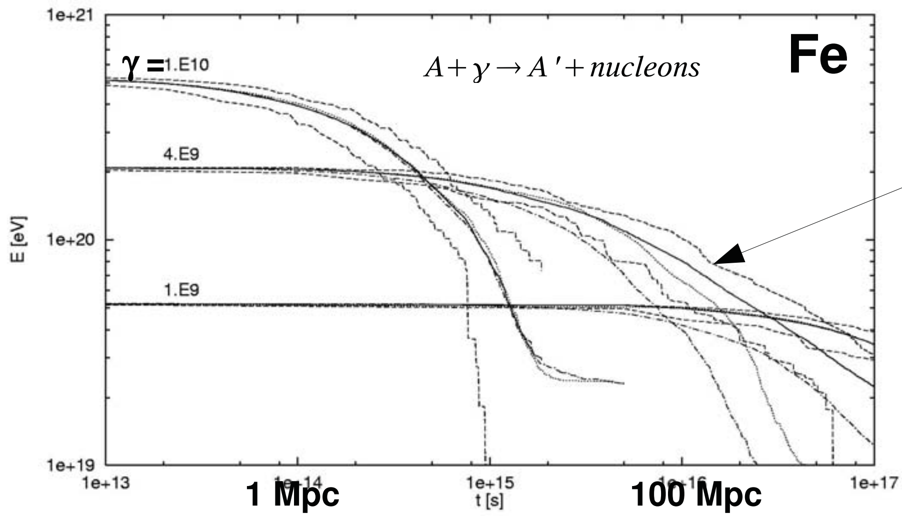
the Greisen-Zatsepin-Kuzmin effect (1966)

AT THE HIGHEST ENERGIES, PROTONS LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND





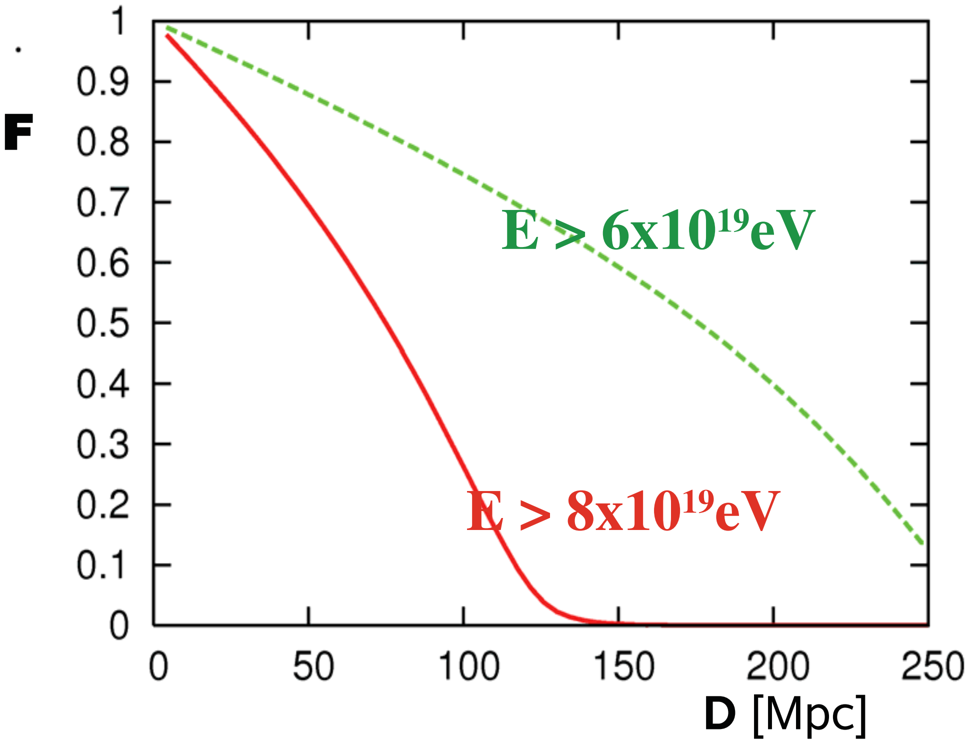
PROTONS CAN NOT ARRIVE WITH $E > 6 \times 10^{19}$ eV FROM D > 200 Mpc



For Fe nuclei:
after ~ 200 Mpc the leading fragment has $E < 6 \times 10^{19}$ eV

ligther nuclei get disintegrated on shorter distances

GZK HORIZON



Fraction of protons arriving with energy > E
from sources at distance D

≈ 90% of events
with E > 6×10^{19} eV
come from sources
at D < 200 Mpc

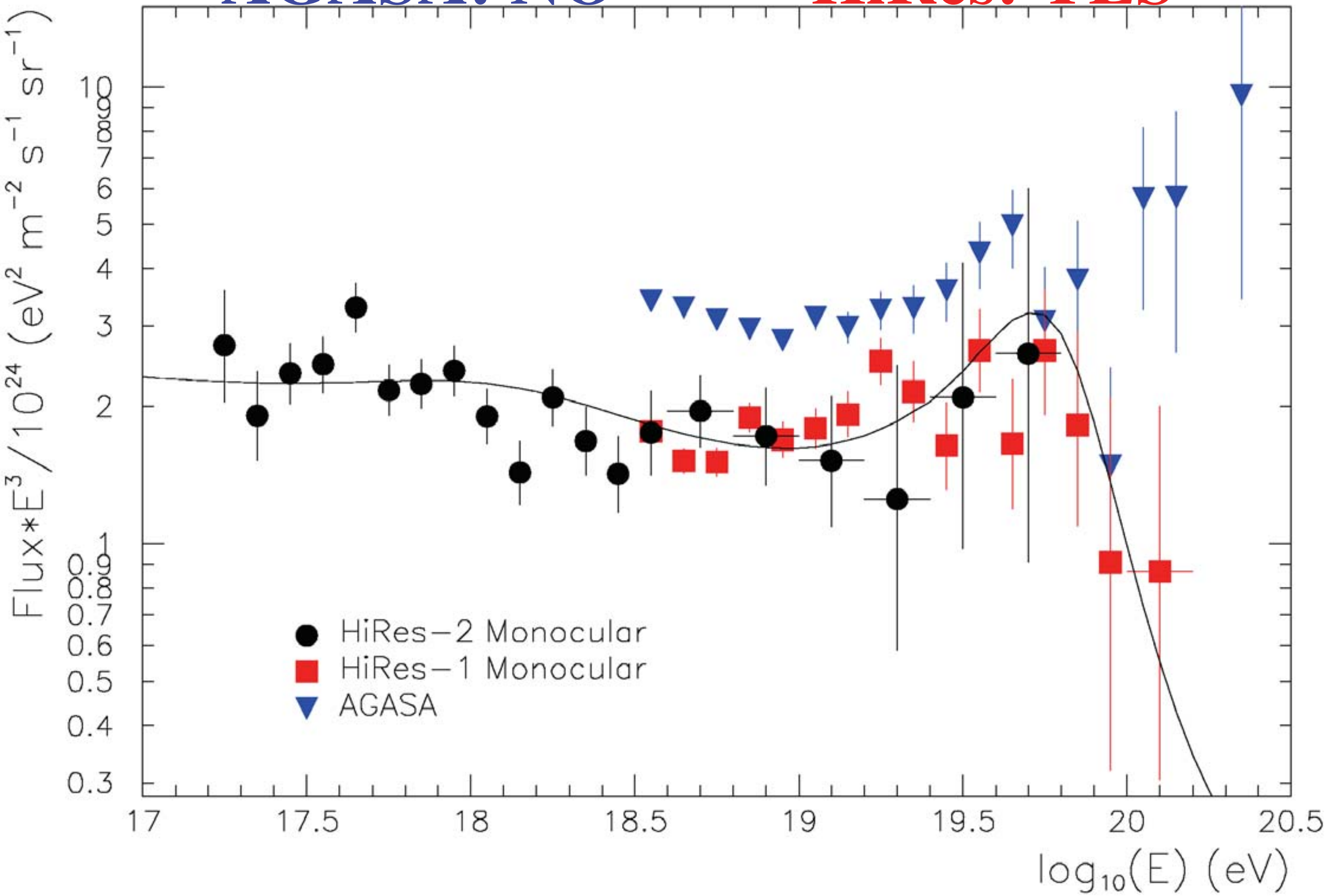
for E > 8×10^{19} eV
90 % from D < 90 Mpc

Diego Harari, Silvia Mollerach, E. R.
JCAP 2006

THE END OF THE SPECTRUM: GZK?

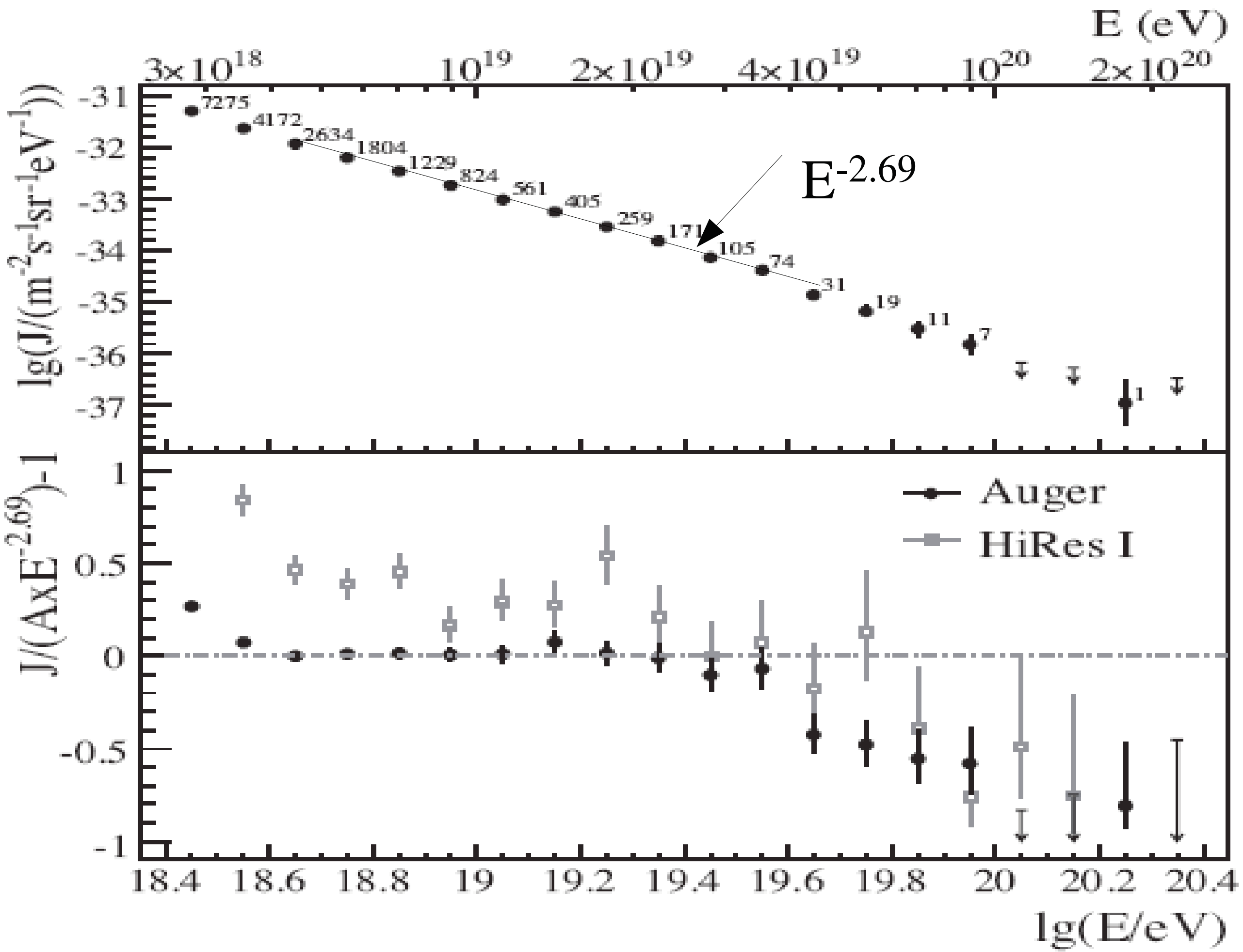
previous results

AGASA: NO **HiRes: YES**



AUGER SPECTRUM FROM SD

(PRL2009)

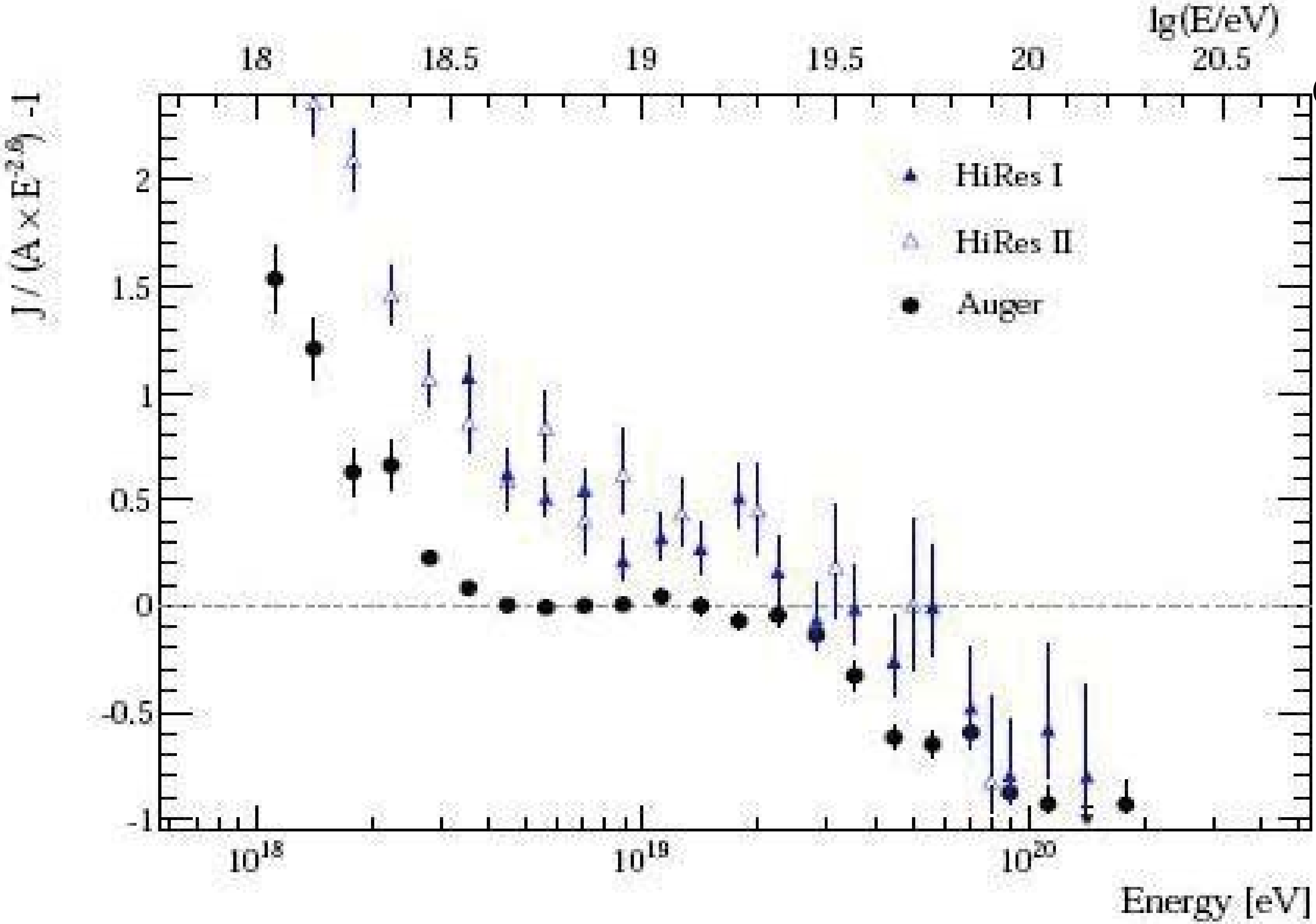


extrapolating $E^{-2.69}$ spectrum expect 167 events above 40 EeV ➔ observe 69

Flux falls to half the extrapolated value for $E \sim 6\times10^{19}$ eV

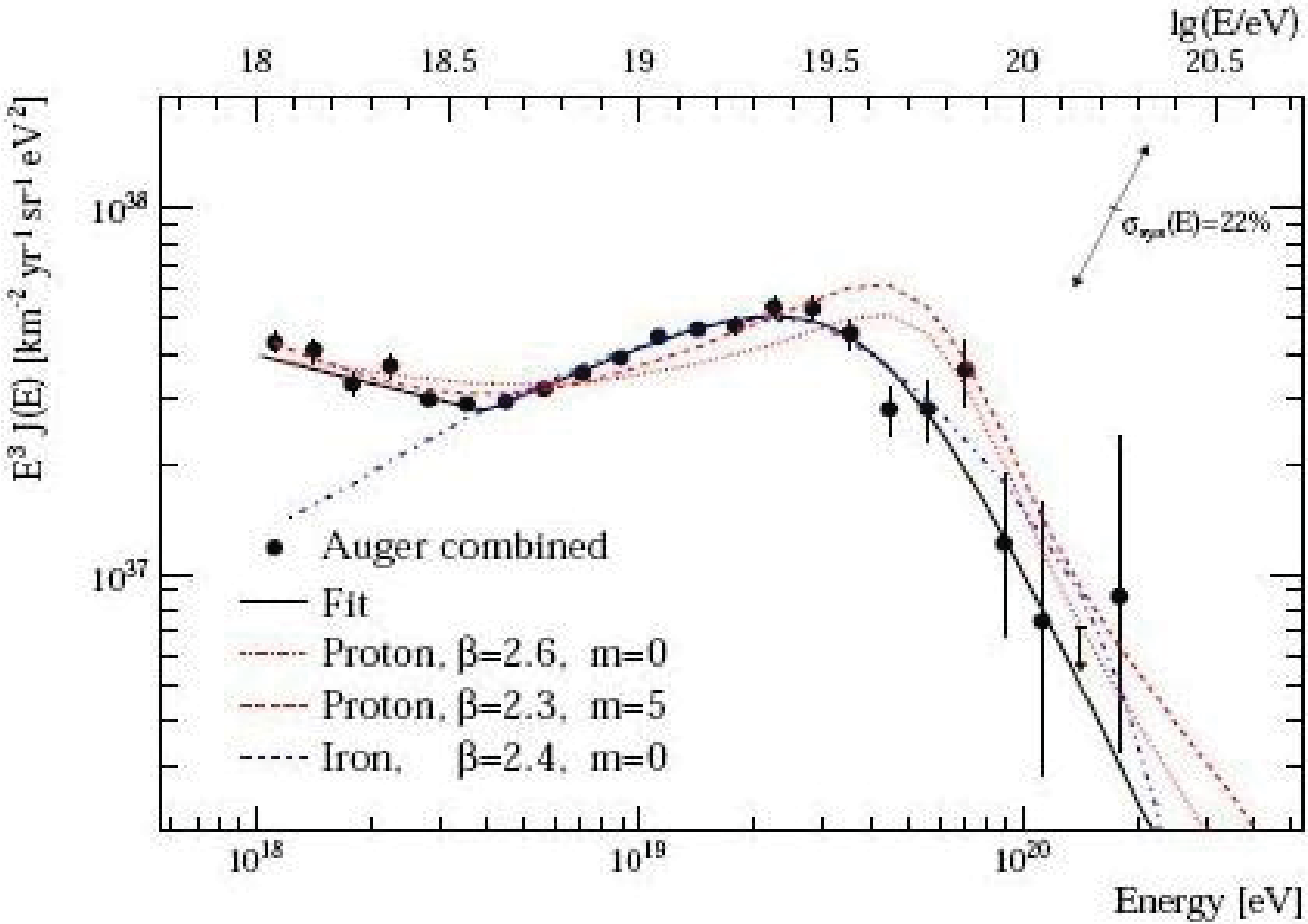
GZK suppression has been observed (> 6σ)

SD + HYBRID SPECTRUM



(ICRC09)

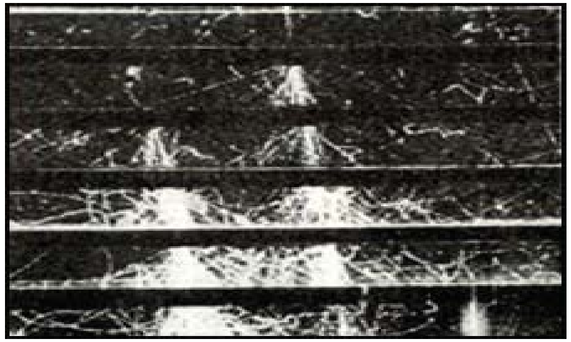
(ICRC09)



lg(E/eV)
18
18.5
19
19.5
20
20.5
E^3 J(E) [km^{-2} yr^{-1} sr^{-1} eV^2]
10^{38}
10^{37}
σ_{sys}(E)=22%
Auger combined
Fit
Proton, β=2.6, m=0
Proton, β=2.3, m=5
Iron, β=2.4, m=0
10^{18}
10^{19}
10^{20}
Energy [eV]

Some basics on air showers:

ELECTROMAGNETIC SHOWERS (e+ , e- , γ)

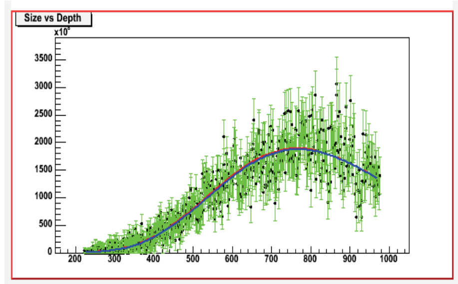


Energy loss of electrons: $$\frac{dE}{dX} = -\alpha(E) - \frac{E}{X_R}$$

Critical E: ionization loss = loss by particle production (brems,pairs)

$$E_c = X_R \langle \alpha(E) \rangle \simeq 86\ MeV \qquad for\ air\ X_R = 37\ \frac{g}{cm^2}$$

Heitler model: after $\lambda_{em} = ln2\ X_R$**, particles split in two**
after n generations, number of particles $N = 2^n$, $with\ n = X/\lambda_{em}$



Shower growth stops when $E_0/N = E_c$,$i.e.\ N_{max} = E_0/E_c$

and depth of maximum is $X_{max} = n\,\lambda_{em} = X_R \ln(E_0/E_c)$

elongation rate: $$D \equiv \frac{dX_{max}}{d \log E_0} = X_R\ ln10 \simeq 85\ \frac{g}{cm^2}$$

Gaisser Hillas longitudinal profile: $$N(X) = N_{max} \left(\frac{X - X_1}{X_m - X_1} \right)^{(X_m - X)/\Lambda} \exp\left((X_m - X)/\Lambda \right)$$

NKG lateral distribution: $$\frac{dN}{r d\phi\, dr} \sim \left(\frac{r}{r_M} \right)^{s-2} \left(1 + \frac{r}{r_M} \right)^{s-4.5}$$

$$age : s = 3X/(X + 2X_m)$$

$$Moliere : r_M \simeq \frac{93\,m}{\rho/(kg\ m^{-3})}$$

HADRONIC SHOWERS

each interaction produces n_{tot} pions (multiplicity)

$n_{neut}=n_{tot}/3 \ \ (\pi^0\rightarrow 2\gamma)$ **em component**

$n_{ch}=2\,n_{tot}/3 \ \ (\pi^\pm)$ **reinteract until** $E<E_{dec} \ (\pi\rightarrow\mu\nu\nu)$

Number of generations from: $E_{dec}=E_0/n_{tot}^n \quad (typically\ n\sim 5-6)$

# of muons = # of $\pi^\pm$ at E_{dec} : $N_\mu=(n_{ch})^n=\left(\frac{E_0}{E_{dec}}\right)^\beta \ with\ \beta=\frac{\ln n_{ch}}{\ln n_{tot}}\simeq 0.86-0.93$

Energy of em component: $E_{em}=E_0-(2/3)^n E_0$ $(\sim 0.8\,E_0\ for\ 10^{16}\,eV)$ $(\sim 0.9\,E_0\ for\ 10^{19}\,eV)$

Estimating X_{max} as the maximum of the first generation π^0 s:

$$X_{max}=\lambda_I+X_R\ln\left(\frac{E_0/n_{tot}}{E_c}\right)$$

depends on $\lambda_I\sim\sigma_{p-air}^{-1}$ and on multiplicity

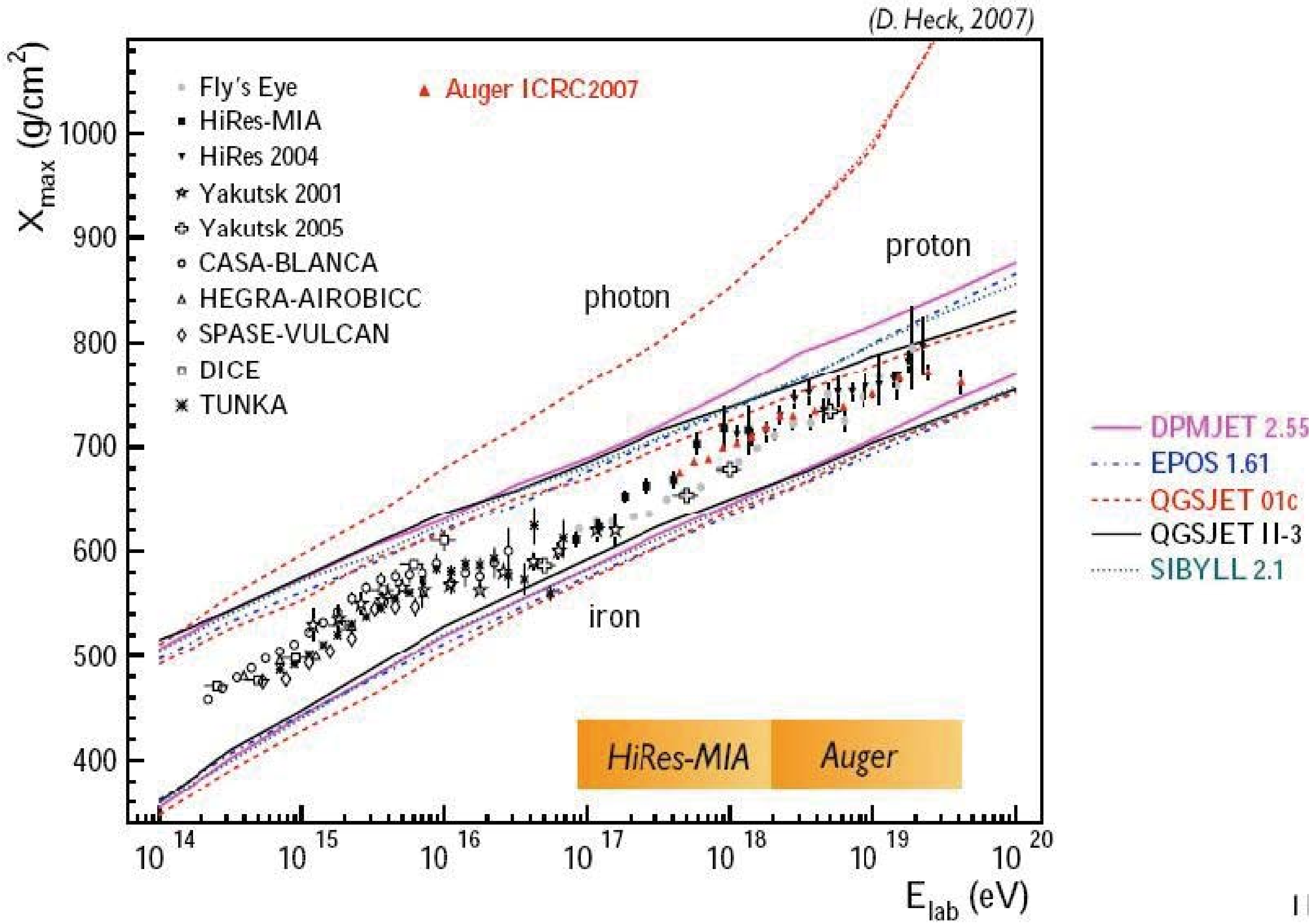
Elongation rate D is smaller than for pure em showers

For nuclei: A nucleons with $E_n=E_0/A$ $X_{max}^A\simeq X_{max}^p-D(E)\log(A)$

Inelasticity: E fraction carried by leading particle $k_{inel}=1-E_{lead}/E_0$

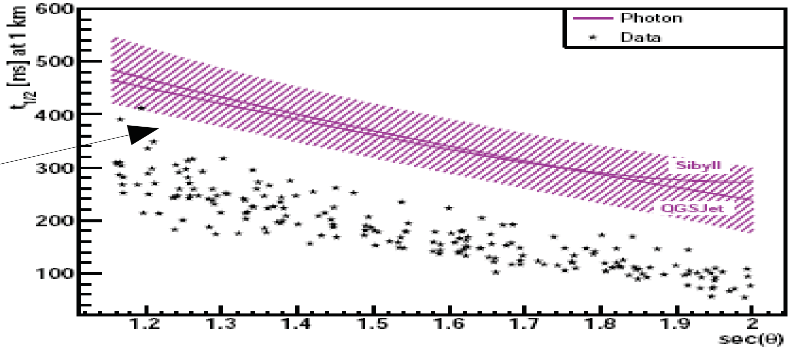
$k_{inel}<1$ **:subsequent interactions influence X_{max} which becomes larger**

COMPOSITION FROM X_{max}

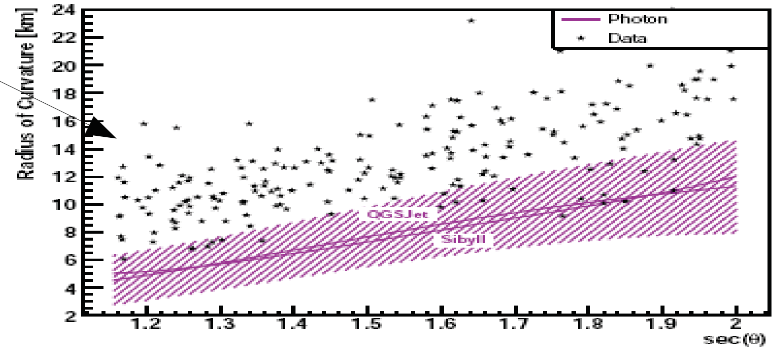


AUGER SD photon bound

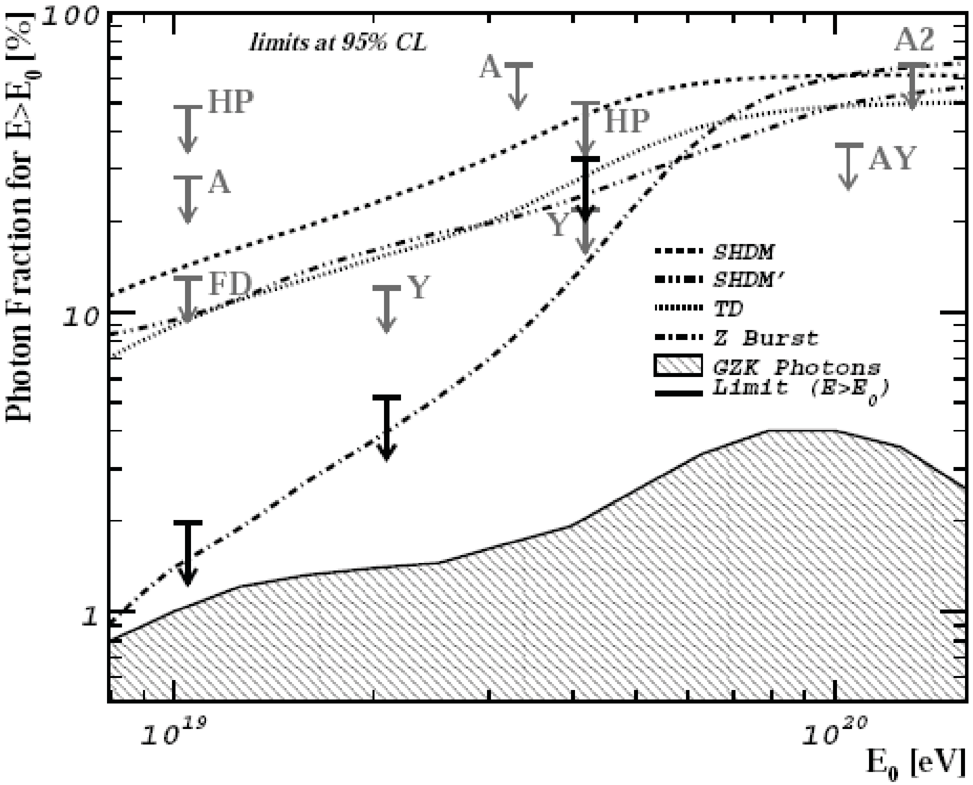
photon showers mostly electromagnetic:
long rise times



and develop later ➔ small curvature radius
(and large X_{max} in FD)



Astroparticle Physics 29 (2008) 243–256



photon fraction:

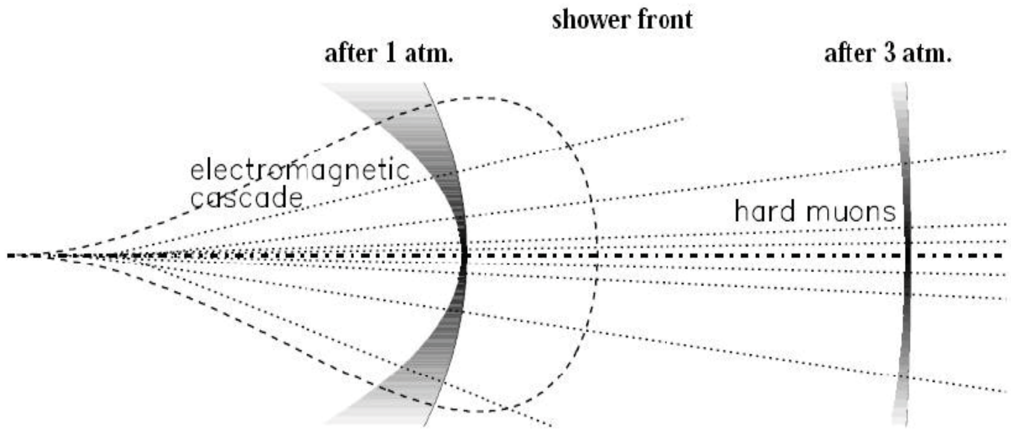
< 2% at E > 10 EeV

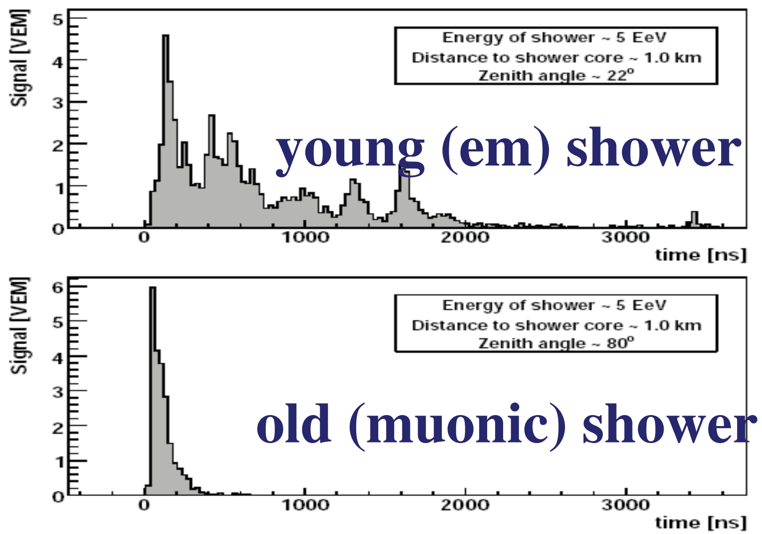
< 31% at E > 40 EeV

excludes most top-down models

AUGER BOUNDS ON DIFFUSE NEUTRINO FLUX

unlike hadronic CRs, neutrinos can produce young horizontal showers above the detector, and upcoming near horizontal tau lepton induced showers



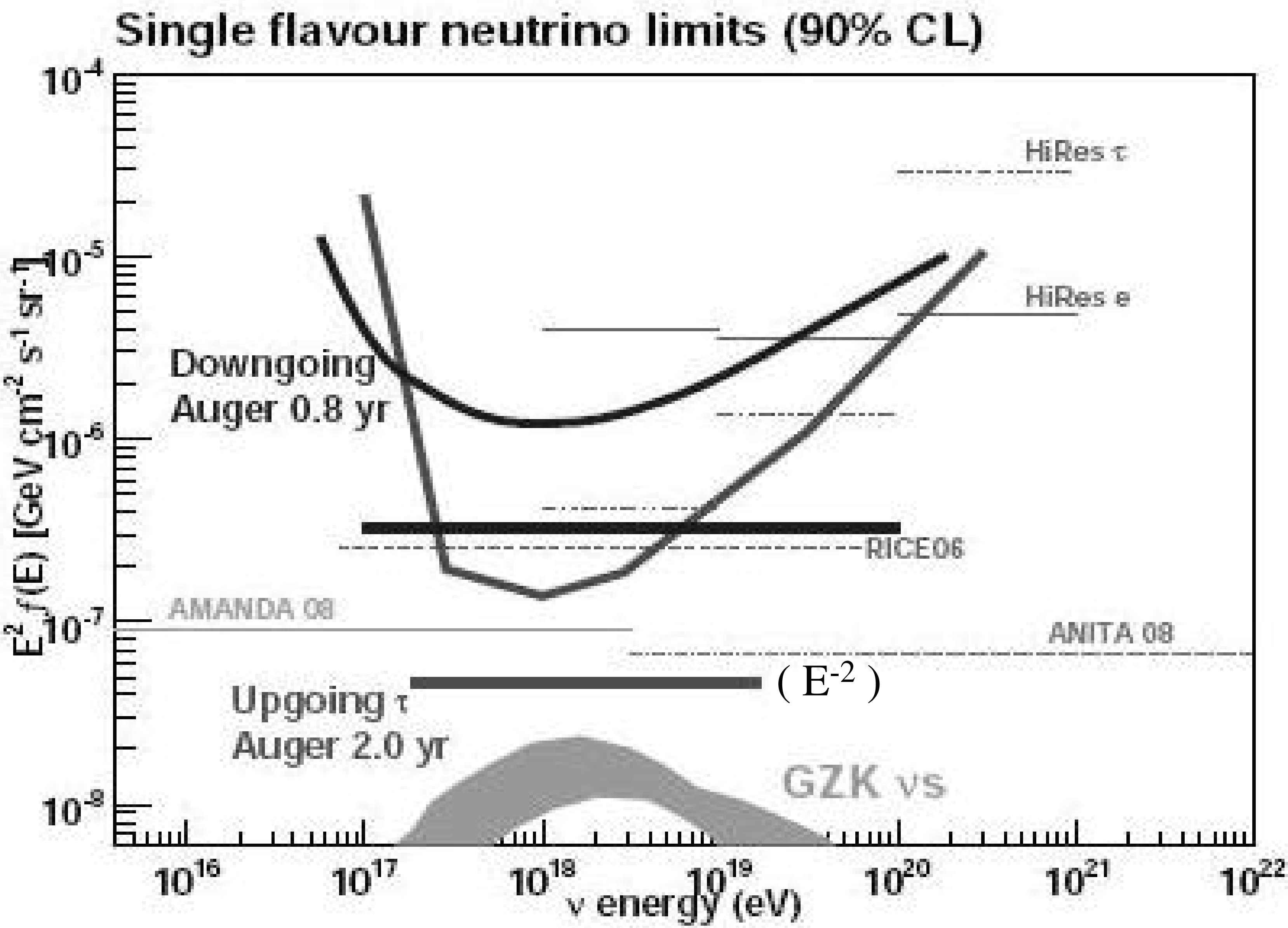


Horizontal young showers?

60% of tank signals with large Area / peak

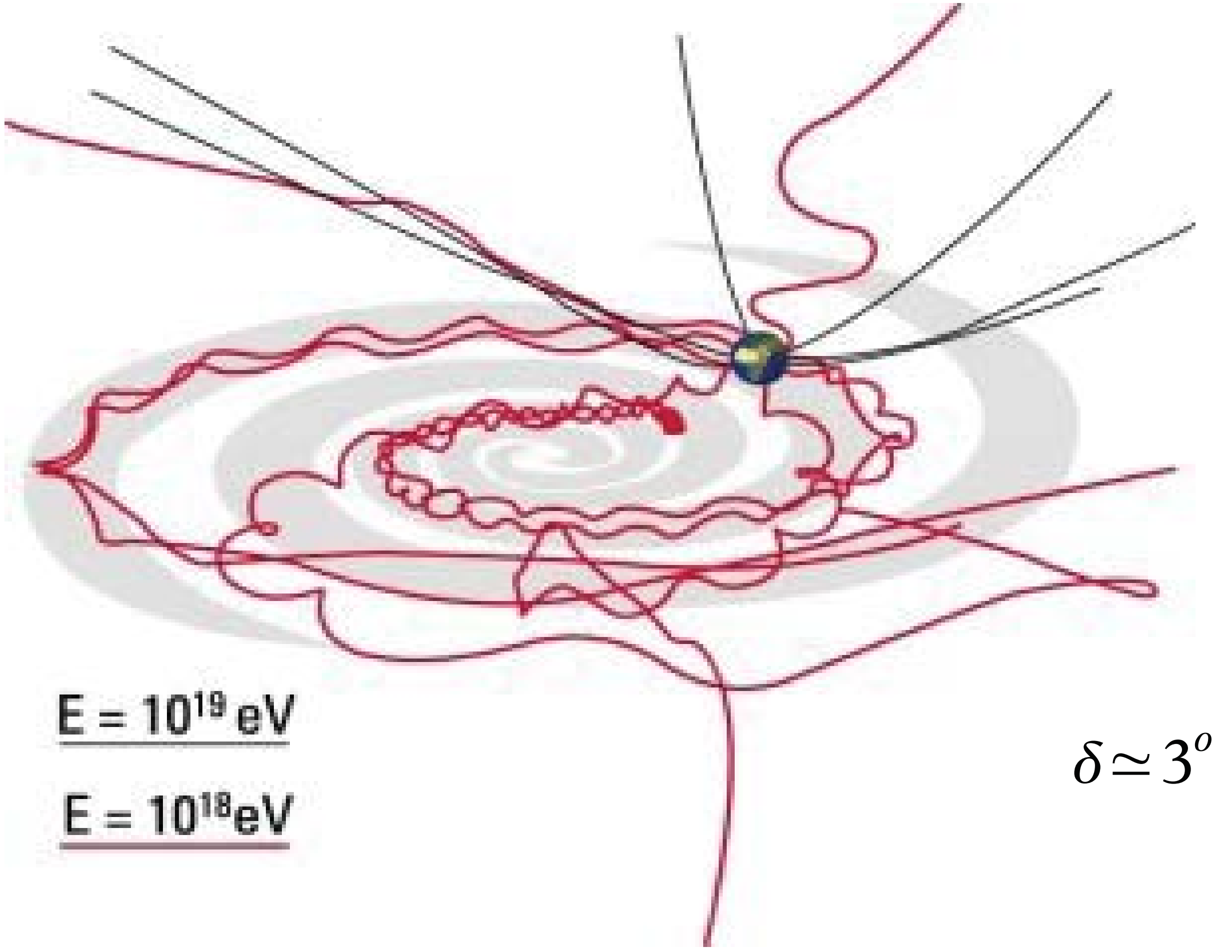
Elongated tracks: L/W > 5 Propagation with v ~ c

ZERO CANDIDATES



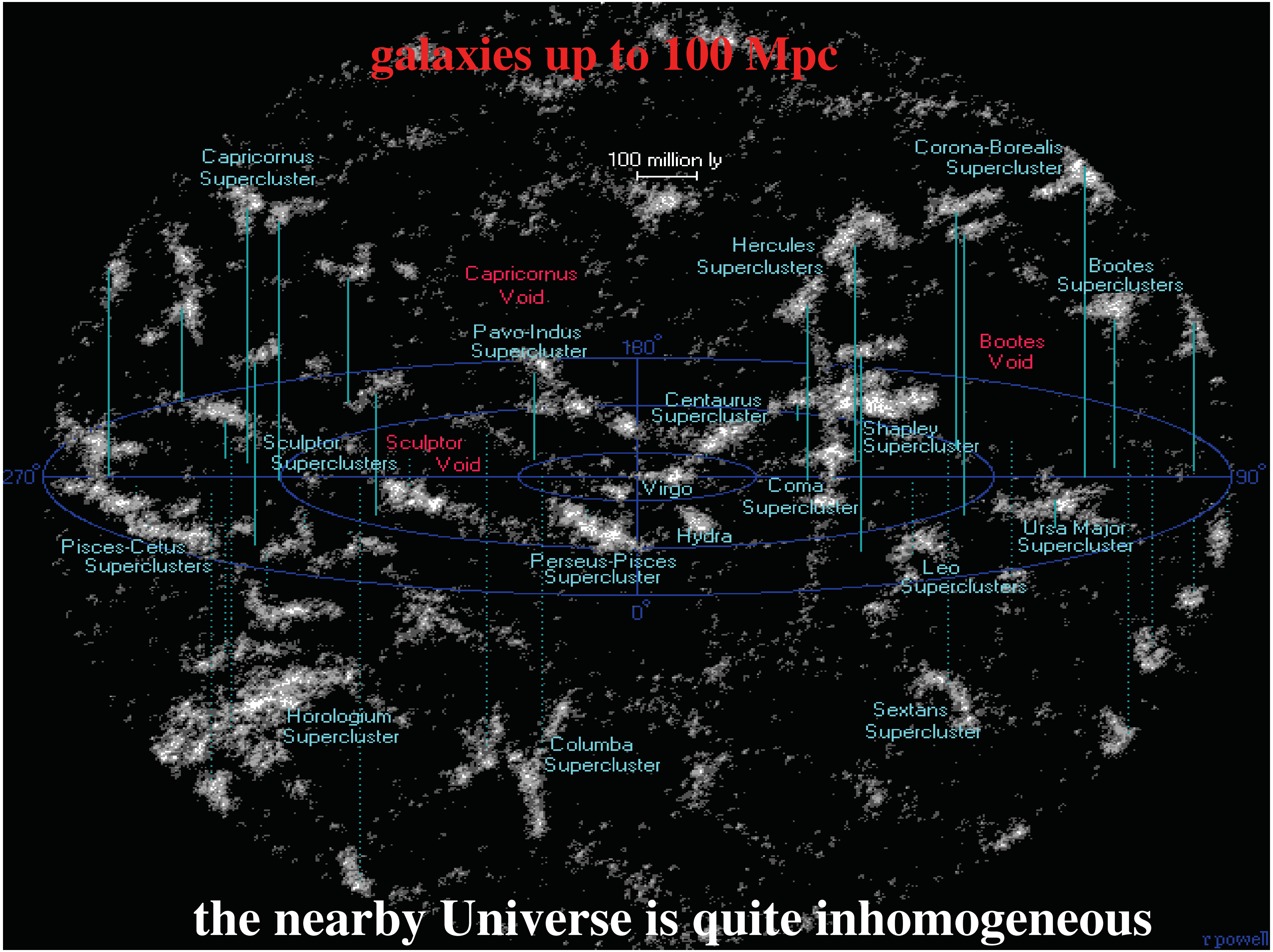
Single flavour neutrino limits (90% CL)
HiRes τ
HiRes e
Downgoing
Auger 0.8 yr
RICE06
AMANDA 08
ANITA 08
(E-2)
Upgoing τ
Auger 2.0 yr
GZK νs
E2 f(E) [GeV cm-2 s-1 sr-1]
ν energy (eV)

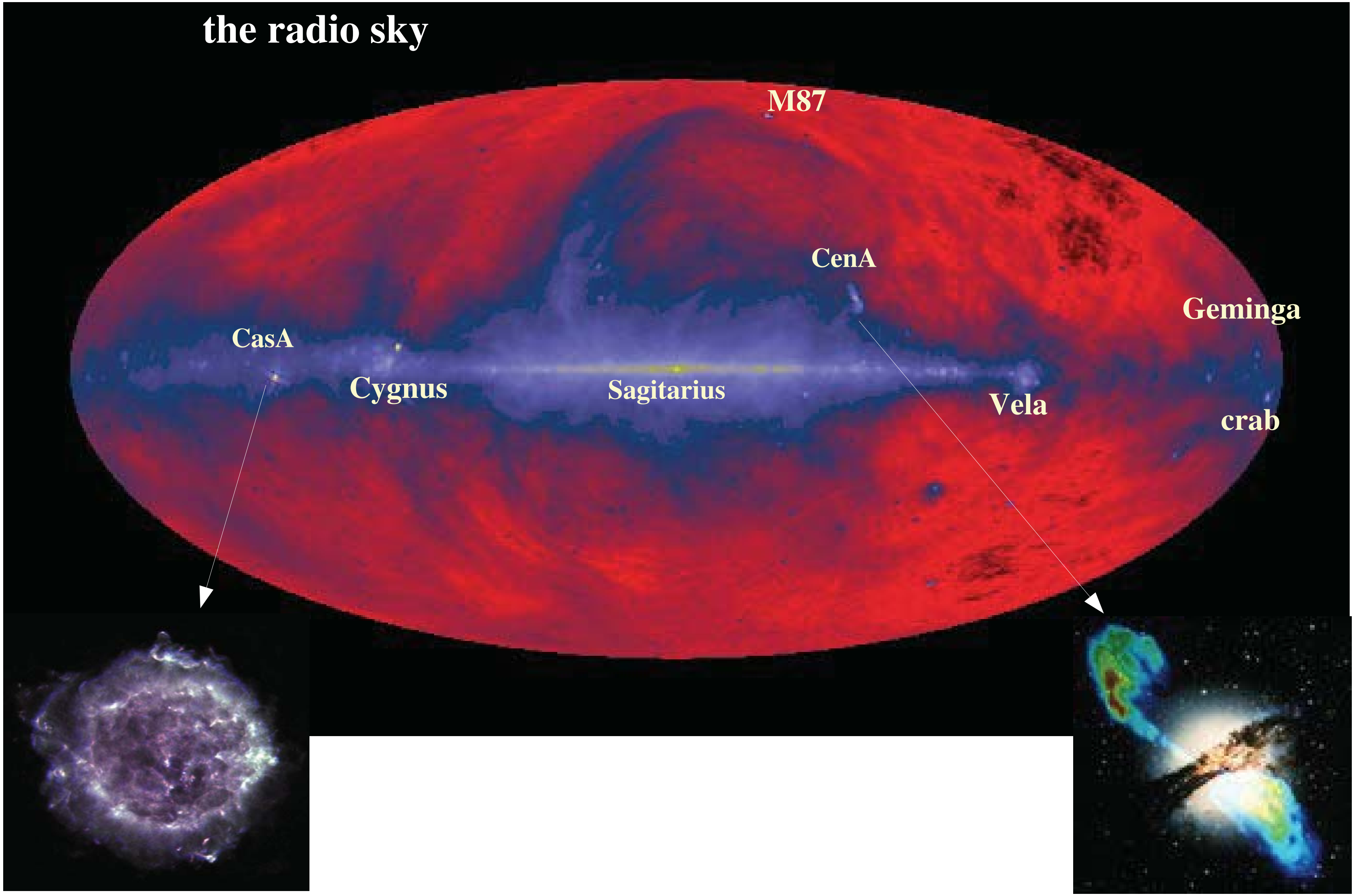
COSMIC RAY ASTRONOMY ?



$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19}\,eV}{E/Z}$$

only for E/Z $\gg 10^{19}$ eV deflections in galactic magnetic fields become less than a few degrees and CR astronomy could become feasible


galaxies up to 100 Mpc
100 million ly
Capricornus Supercluster
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Ursa Major Supercluster
Hydra
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
the nearby Universe is quite inhomogeneous
r powell

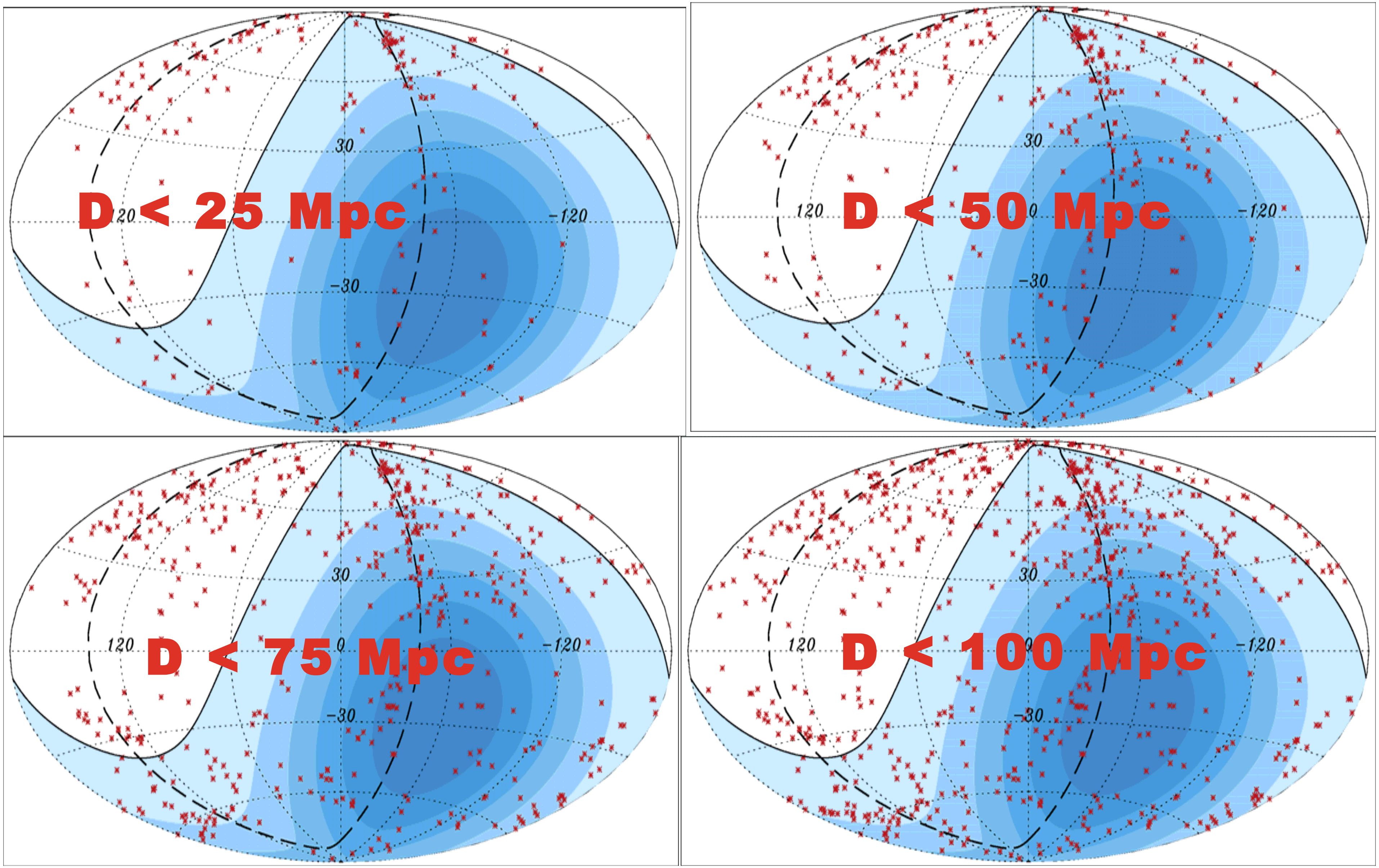


supernovae: preferred candidate sources for E < 10^{18} eV

active galaxies: plausible candidates for E > 10^{18} eV

NEARBY ACTIVE GALAXIES (AGN)

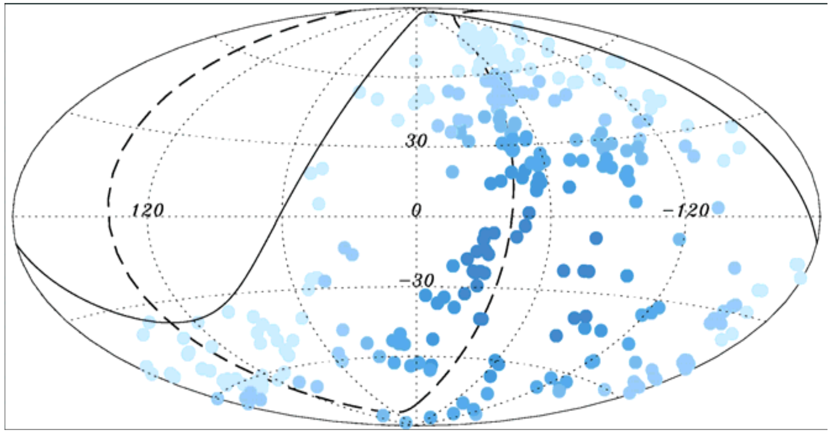
From the Véron-Cetty & Véron catalog (2006)



SEARCH FOR CORRELATIONS WITH NEARBY AGN

Let p be probability that a CR from an isotropic flux arrives with angular separation smaller than ψ from an AGN at a distance smaller than D_{max}

(= Fraction of the area, weighted by the exposure, covered by circular windows of radius ψ)



e.g. $p = 0.21$ for $D_{max} = 75$ Mpc , $\psi = 3.1^o$

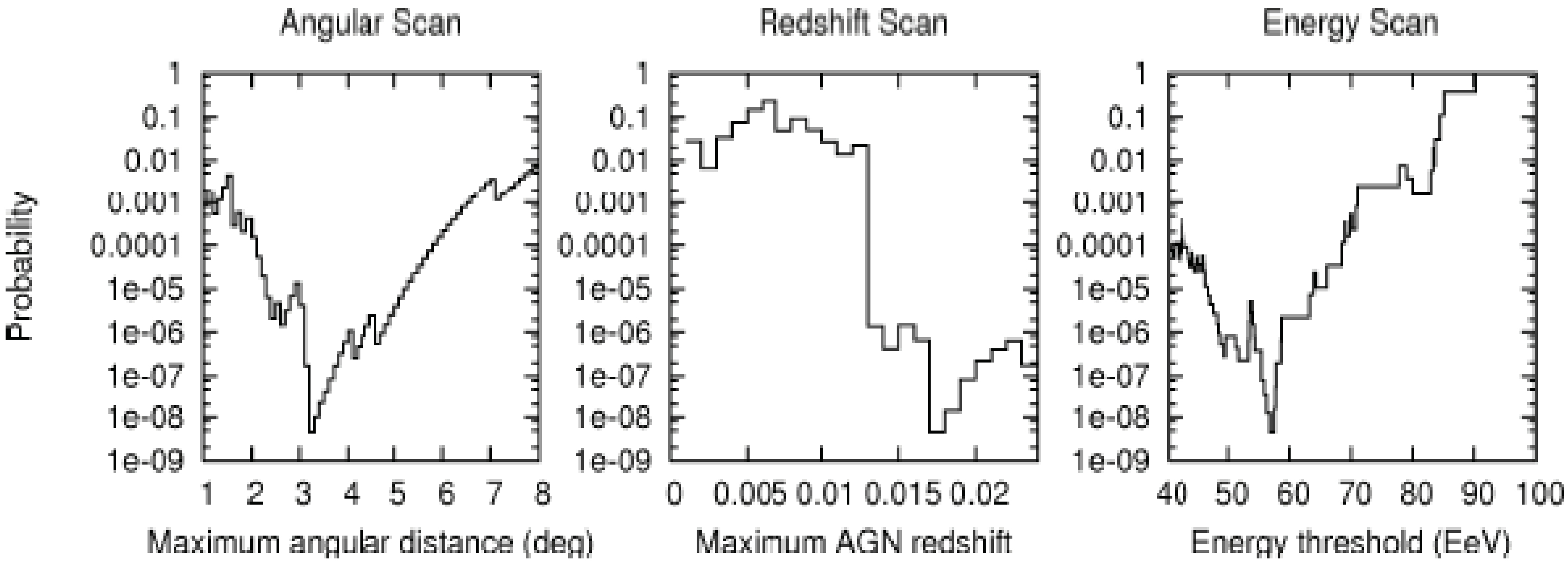
if for the n highest E events ($E > E_{min}$) there are k correlations in the data the probability to find an isotropic realisation more correlated than the data is:

$$P = \sum_{j=k}^{n} \binom{n}{j} p^j (1-p)^{n-j}$$

Minimize P scanning over ψ (deflection), D_{max} (GZK horizon) and E_{min} (Number of highest E events considered)

Data up to august 2007

Minimum of P: $\psi \sim 3^o$; $D \sim 75$ Mpc ; $E_{min} \sim 6x10^{19}$ eV (n = 27)



$F \sim 10^{-5}$ **fraction of isotropic simulations of 81 events (E>40 EeV) which have a smaller P_{min} under the same scan**

HISTORICAL NOTE

Data analysed from Jan 2004 up to 26 May 2006

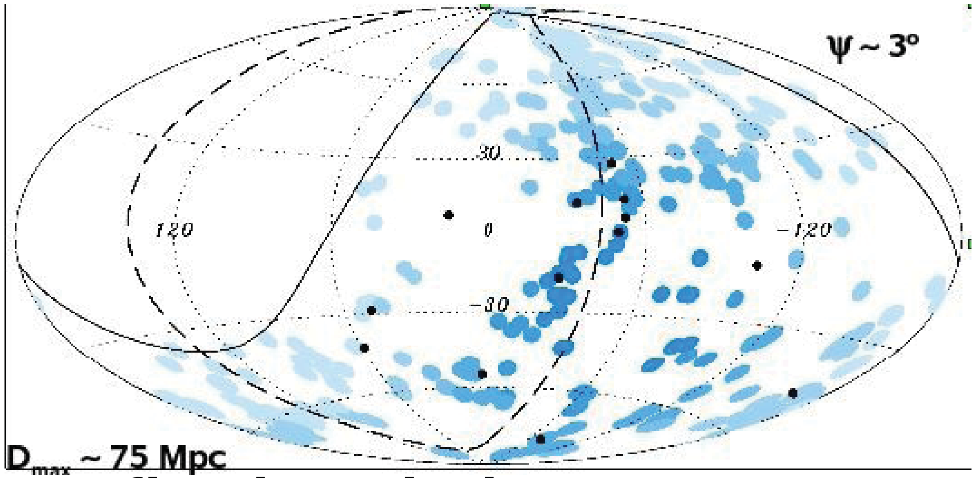
First hints of correlations obtained through this scan

12/15 correlations
(3 expected)

D_{max} = 75 Mpc ψ = 3.1°

$E_{min} = 5.6 \times 10^{19}$ eV

$f \sim 10^{-3}$

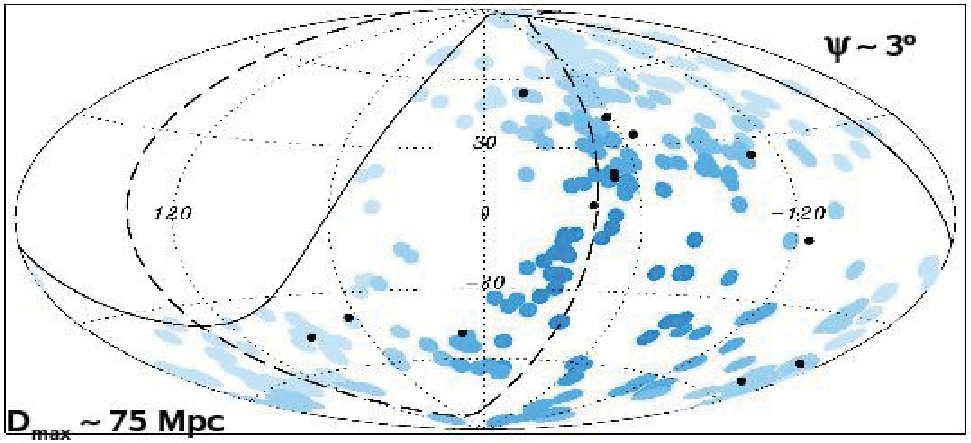


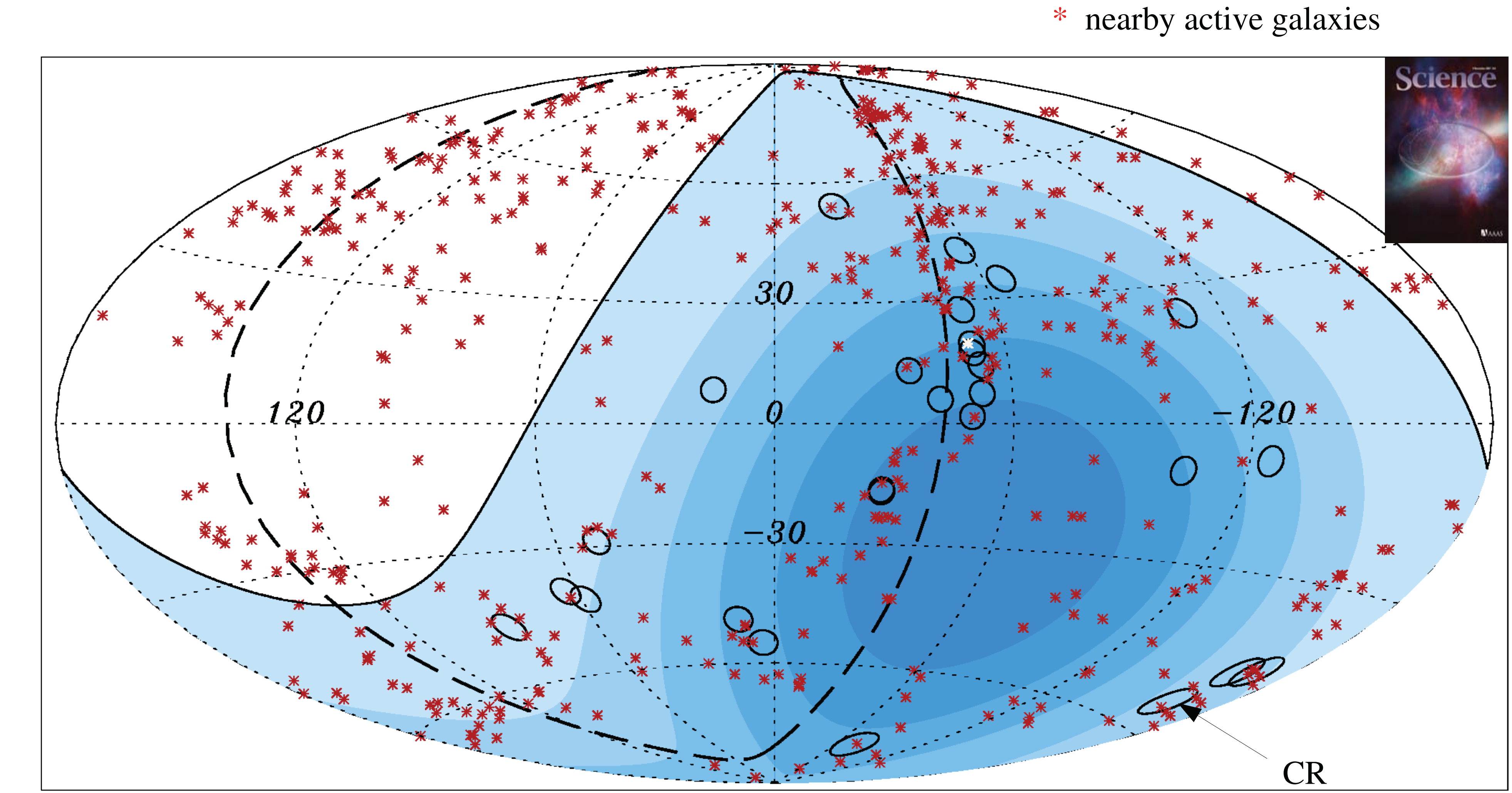
Test with parameters fixed a priori

Data analysed from 27 May 2006 up to 31 Aug 2007

8/13 correlations

in this independent set with parameters specified apriori the probability that flux be isotropic is < 1%





with the data up to 31 august 2007, from the 27 CRs with highest energies, 20 are at less than ~3 degrees from an active galaxy at less than ~ 75 Mpc , while 6 were expected

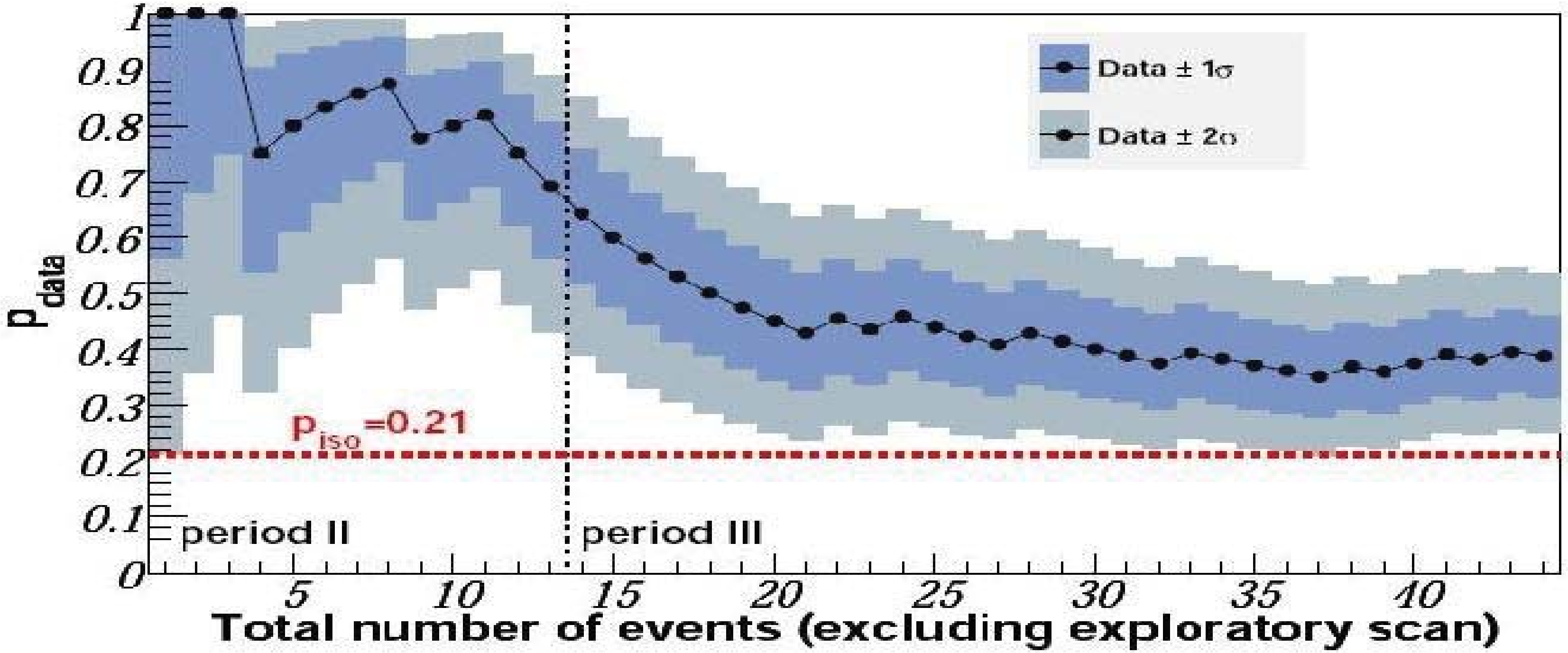
(from the 7 which are not, 5 have $|b_G| < 12$ deg, where catalog is largely incomplete)

(ICRC09)

What happened thereafter ?

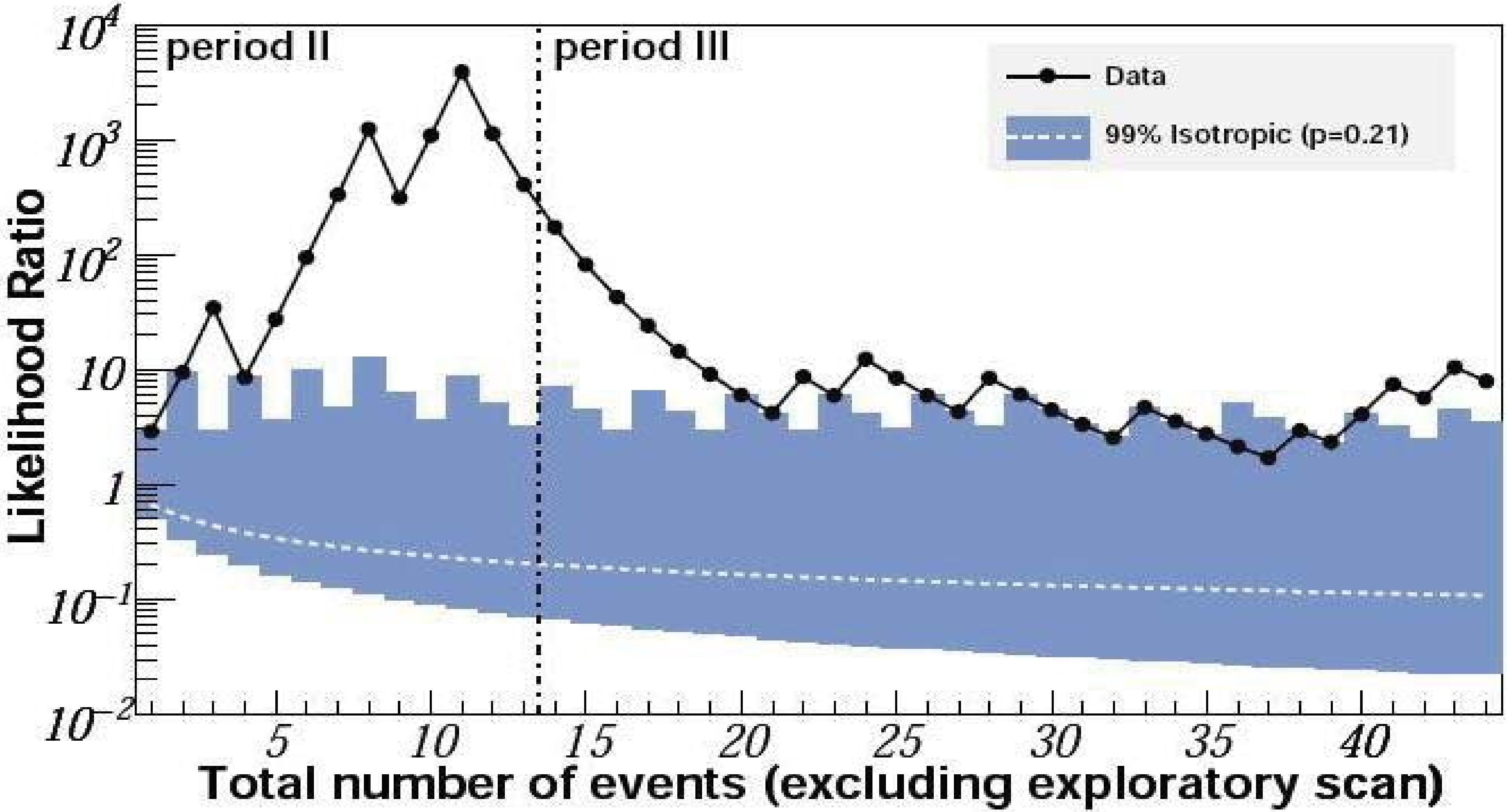
From 31 August 2007 until 31 March 2009:
there are 31 events with E > 55 EeV (new calibration)
and 8 are within 3.1 deg of an AGN closer than 75 Mpc

Fraction correlating (after 5/2006)

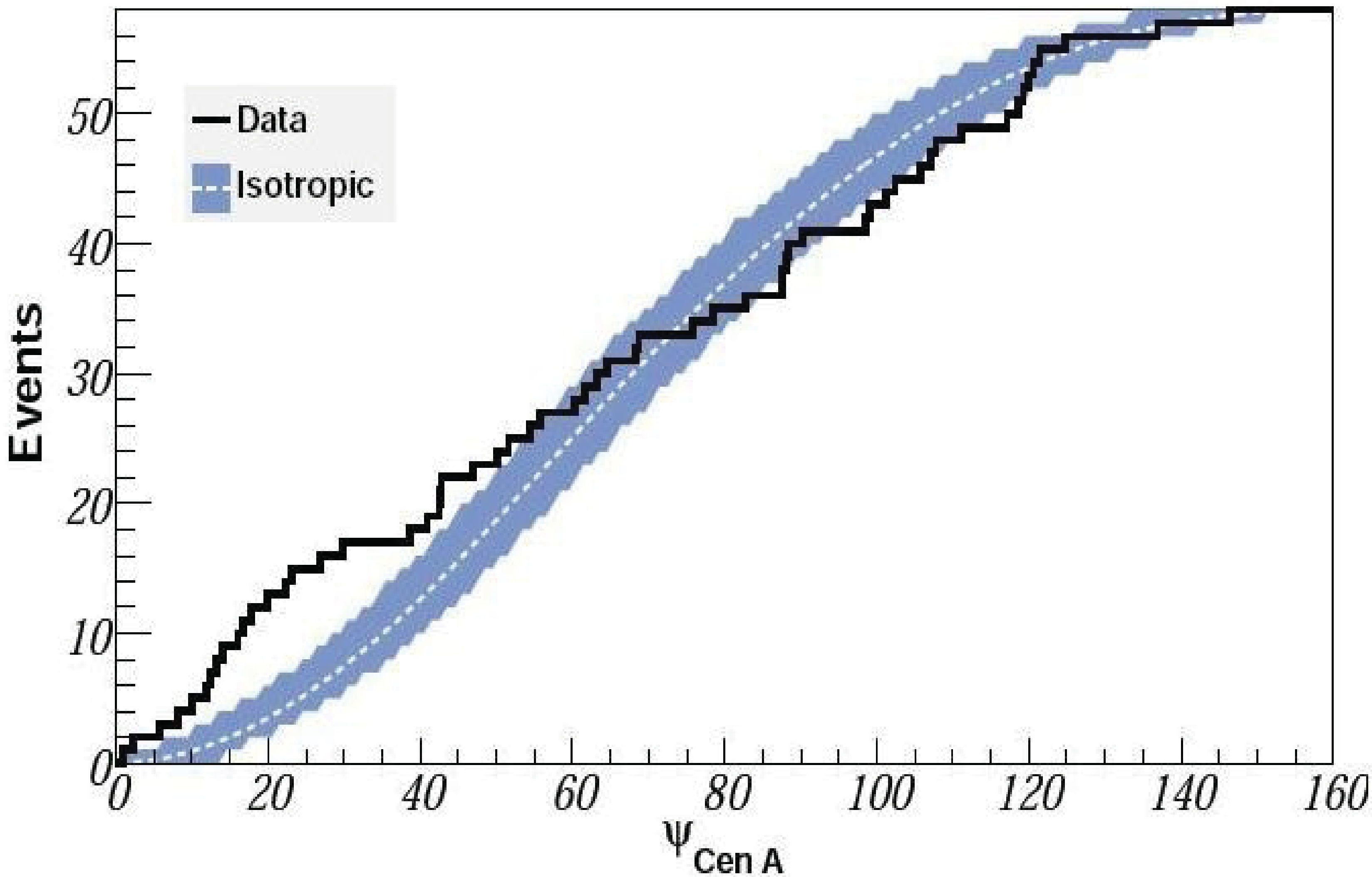


(from the 9 events which have $|b_G|$ < 12 deg, none correlate)

marginalized Likelihood $\equiv \dfrac{\int_{p_{iso}}^{1} dp\ p^{k}(1-p)^{n-k}}{p_{iso}^{\ k}(1-p_{iso})^{n-k+1}}$

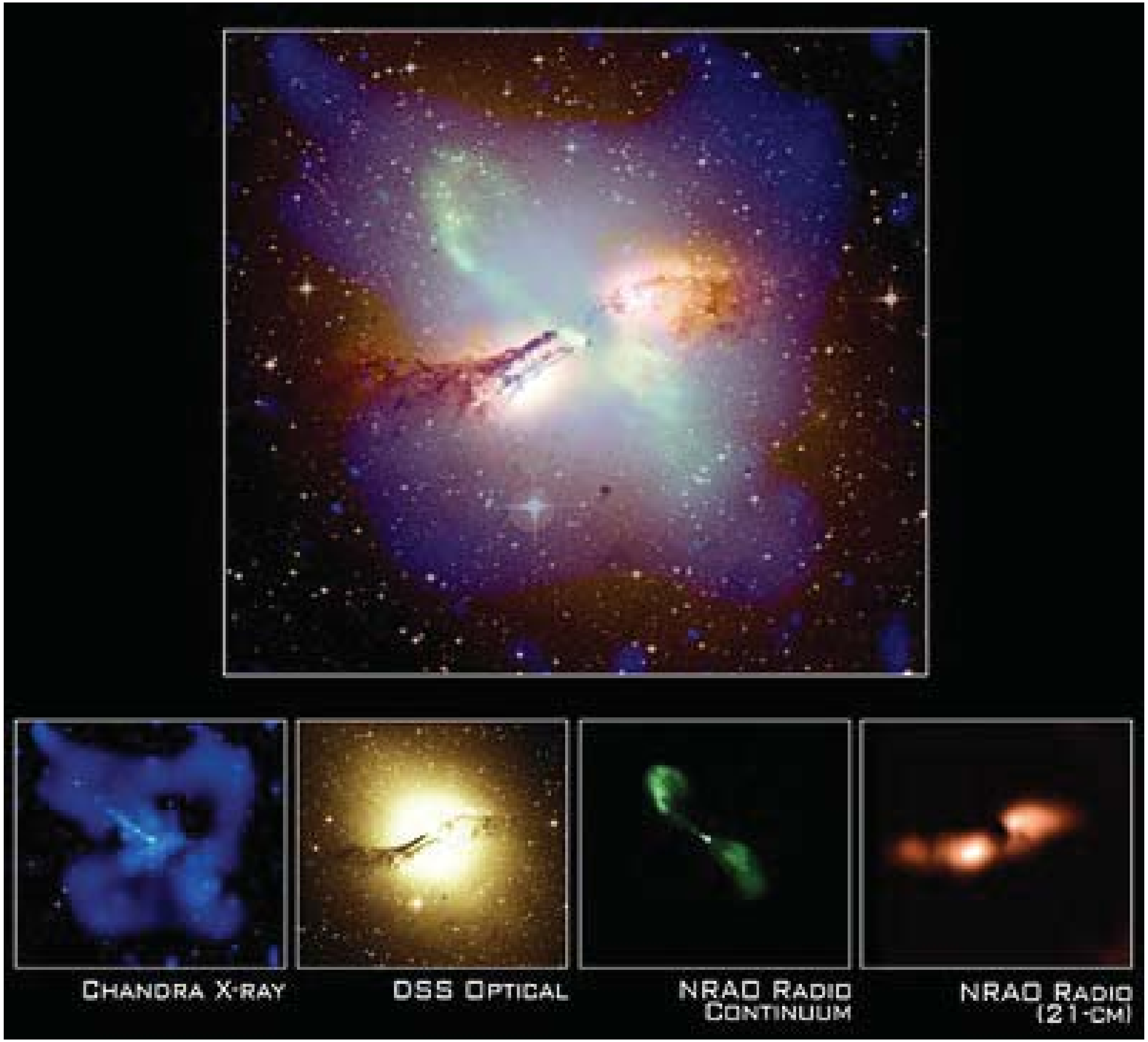


Excess around Centaurus A



Closest Active galaxy: Centaurus A

(~ 3 Mpc)



2 events at less than
3 deg from it

within 18 deg:
12 observed/2.7 expected

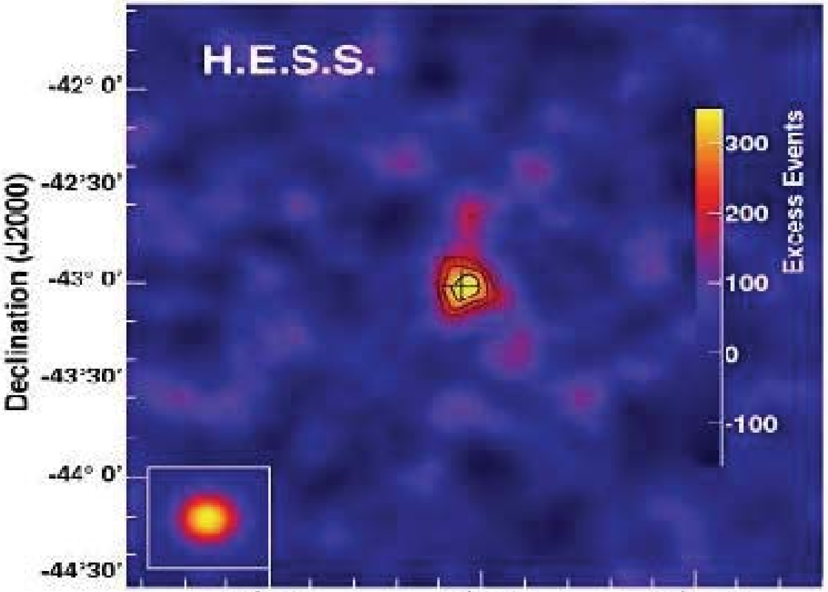
central black hole with
more than 100 million
solar masses !

collision of 2 galaxies

relativistic jet

HESS observation of Centaurus A (0.1 – 10 TeV gammas)

arXiv:0903.1582



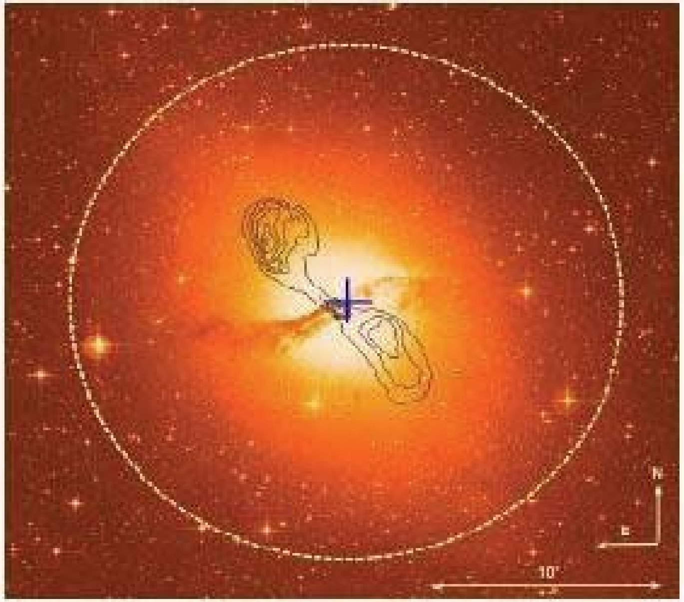


FIG. 2.— Optical image of Cen A (UK 48-inch Schmidt) overlaid with radio contours (black, VLA, Condon et al. 1996), VHE best fit position with 1 σ statistical errors (blue cross), and VHE extension upper limit (white dashed circle, 95% confidence level).

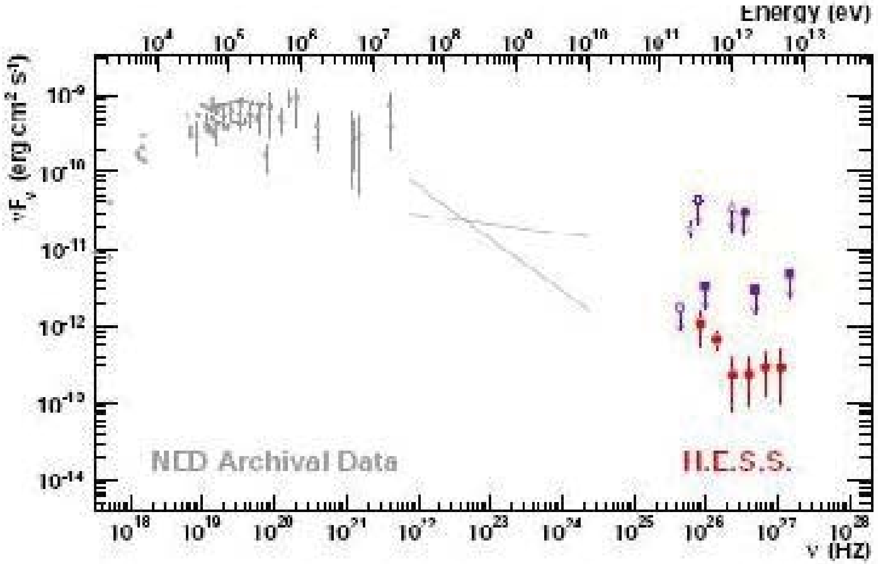


FIG. 4.— Spectral energy distribution of Cen A. Shown are the VHE spectrum as measured by H.E.S.S. (red filled circles), previous upper limits and tentative detections in the VHE regime (purple markers; Grindlay et al. 1975 open diamond; Carramiñana et al. 1990 open cross; Allen et al. 1993 filled circle; Rowell et al. 1999 open triangle; Aharonian et al. 2005 open circle; Kabuki et al. 2007: filled squares). EGRET measurements in the GeV regime

comments:

there is still a 22% systematic uncertainty in E, comparisons with GZK expectations must be done with care

AGNs may be just tracers of nearby large scale structure which may host other CR sources (GRBs, colliding Galaxies, galaxy clusters, ...)

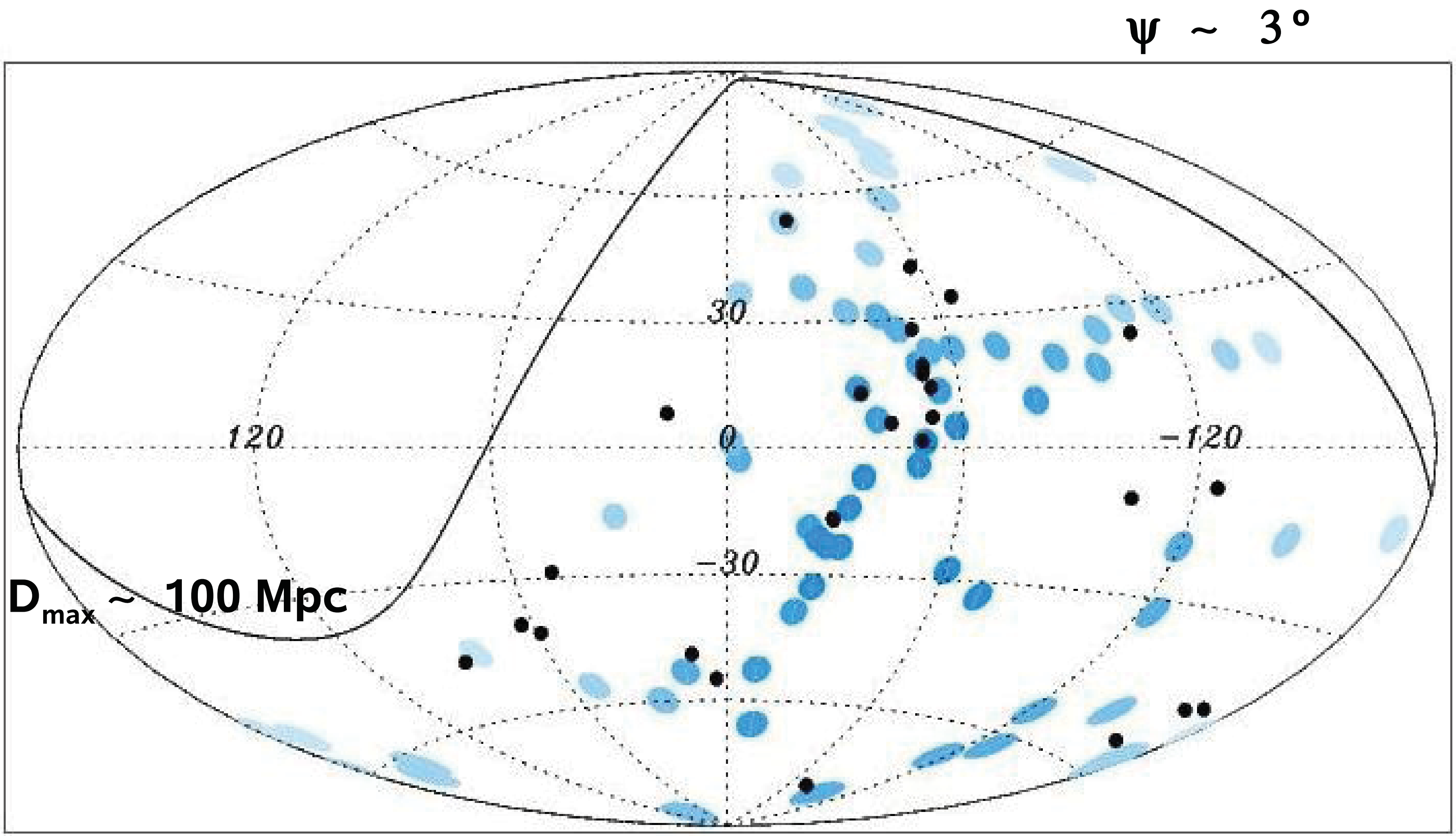
even if AGNs are the sources:

the closest AGN to an event need not be its source (ψ may underestimate the deflections, Dmax may underestimate the GZK horizon)

only a certain AGN subclass may contribute to UHECRs

ILLUSTRATION OF A POTENTIAL AGN SUBCLASS:

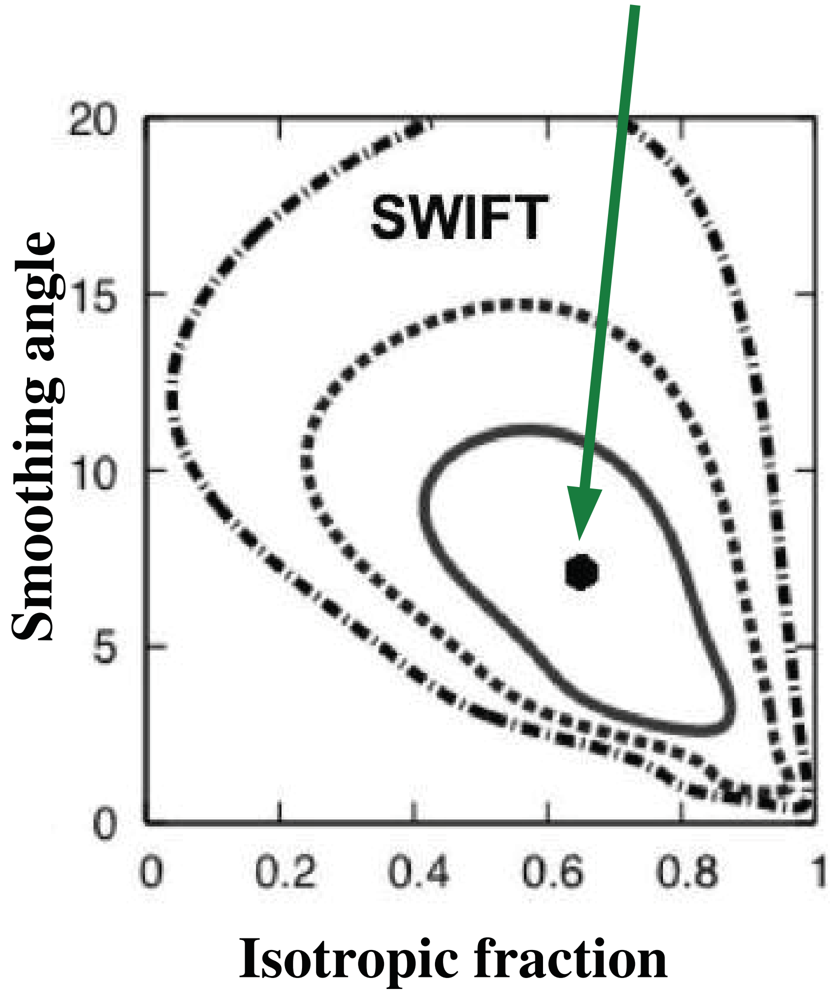
X-RAY IDENTIFIED AGN (SWIFT)

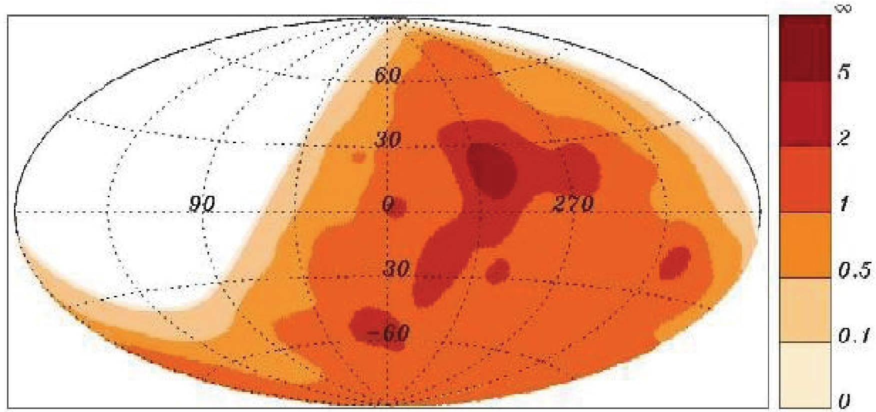


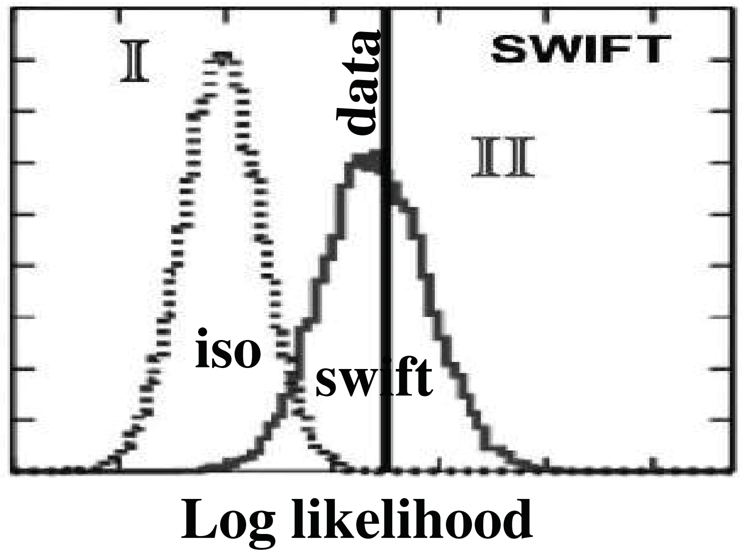
data until 8/07

Adopting a model where fraction f is isotropic, and (1-f) comes from SWIFT sources (flux weighted, GZK suppressed, and smoothed over angular scale α),

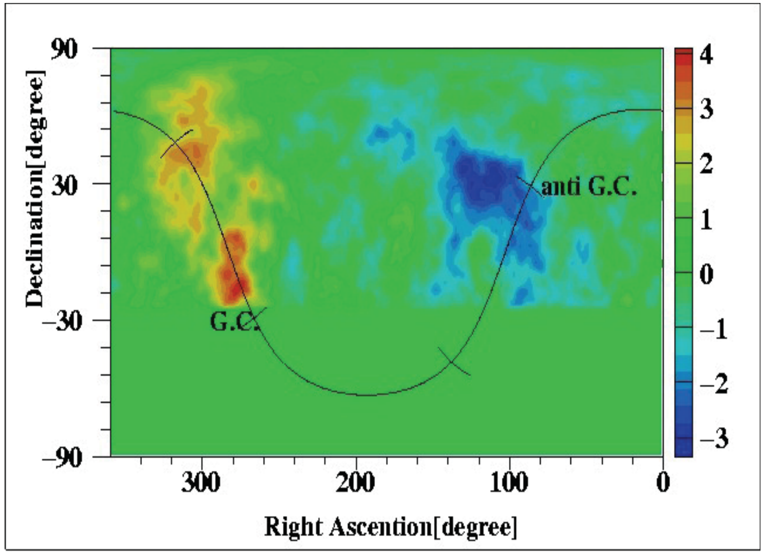
maximizing likelihood of data gives f ~ 0.6 , α ~ 7 deg







AGASA ANISOTROPIES ON 20º SCALES (10^18 – 10^18.4 eV)



$$\frac{observed}{expected} = \frac{506}{413.6} \quad (+4.5\sigma) \quad \textbf{at} \quad (\delta, \alpha) = (-15, 280)$$

(22% excess)

AUGER got $\frac{observed}{expected} = \frac{2116}{2159.6} \quad (-1\sigma)$

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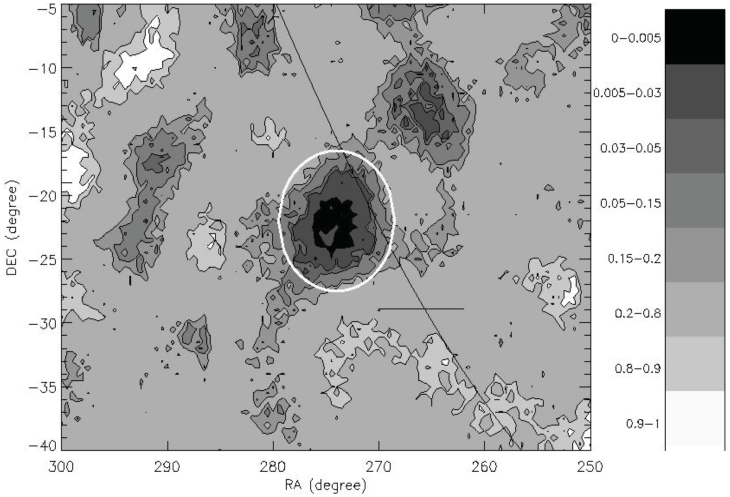
SUGAR galactic center search (5.5º for 10^17.9 – 10^18.5 eV)

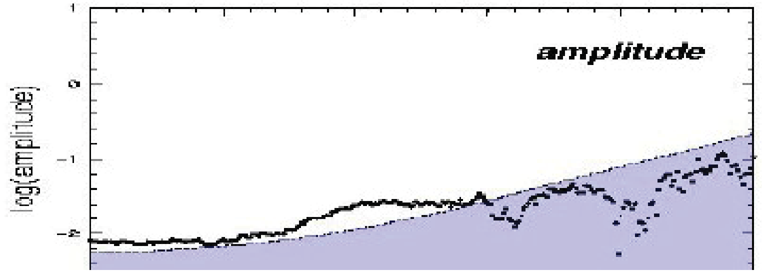


$$\frac{observed}{expected} = \frac{21.8}{11.8} \quad (+2.9\sigma) \quad \textbf{at} \quad (\delta, \alpha) = (-22, 274)$$

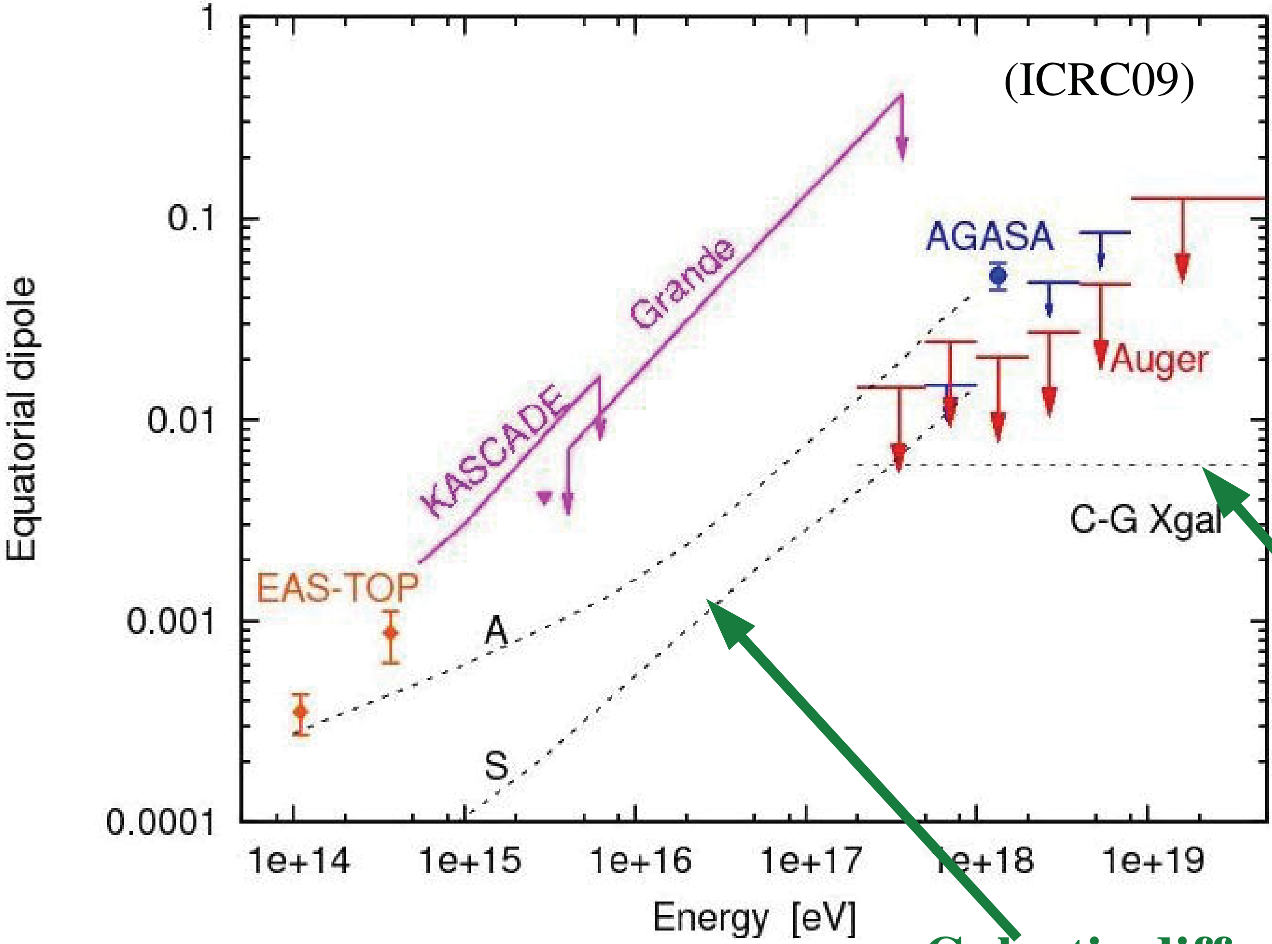
(85% excess)

AUGER got $\frac{observed}{expected} = \frac{286}{289.7} \quad (-0.3\sigma)$

AGASA RAYLEIGH ANALYSIS vs. E



4 % amplitude of 'dipolar' modulation for E > 1 EeV

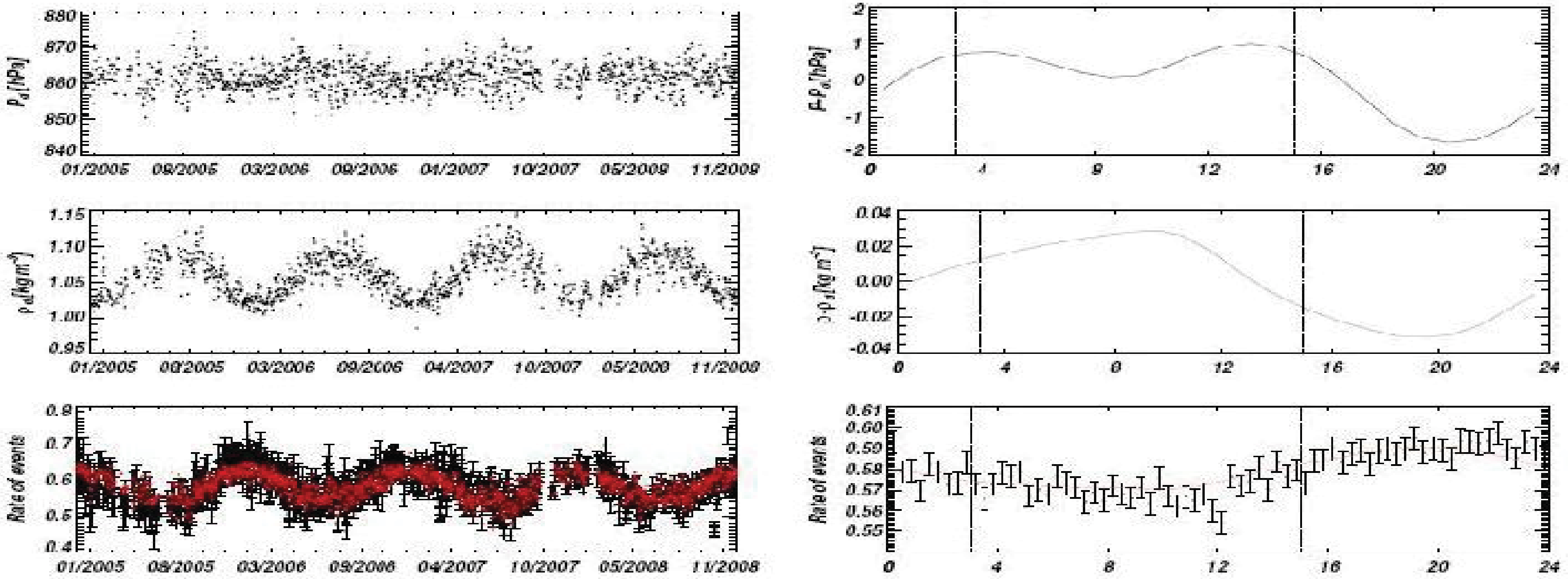


Auger bound:
amplitude < 1.59%
@99%C
for [1,2] EeV

Compton-Getting of isotropic extragalactic

Galactic diffusion models Candia et al.)

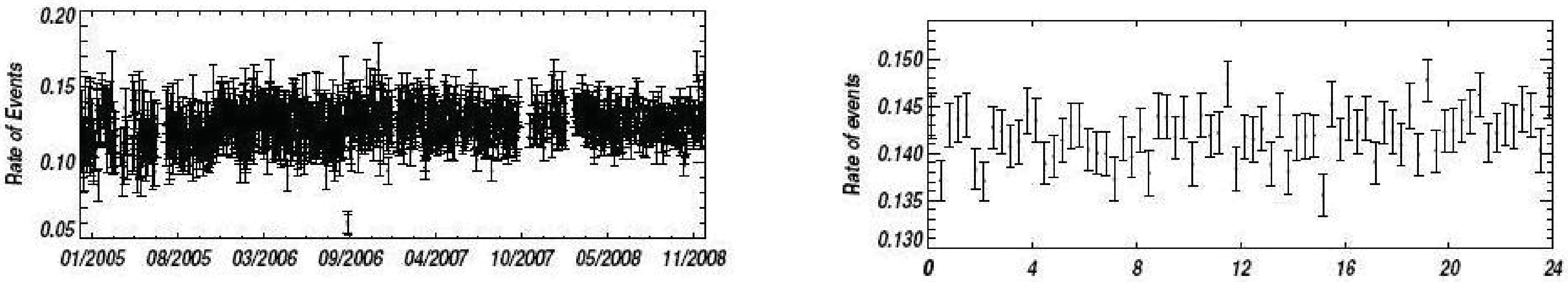
ATMOSPHERIC EFFECTS ON EVENT RATES



Density affects Moliere radius, i.e. lateral spread of shower

pressure affects column density, i.e. age of shower at ground

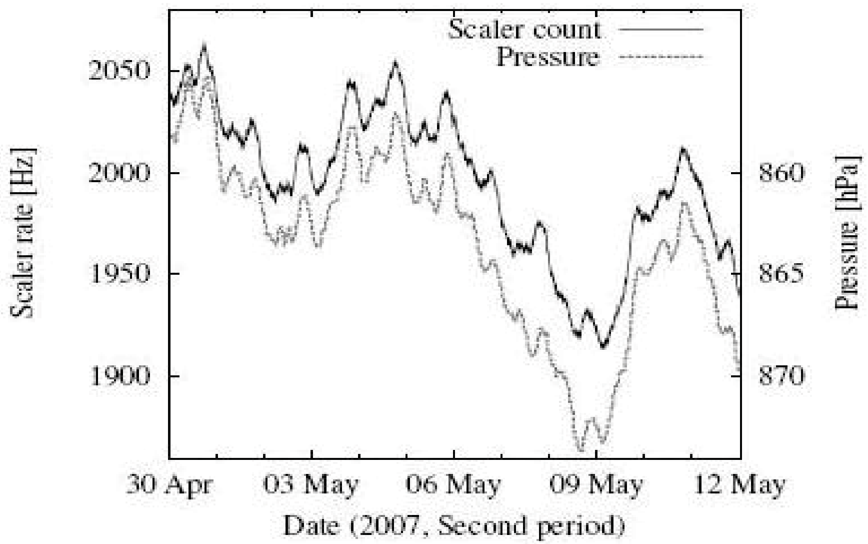
accounting for this in the energy assignment:



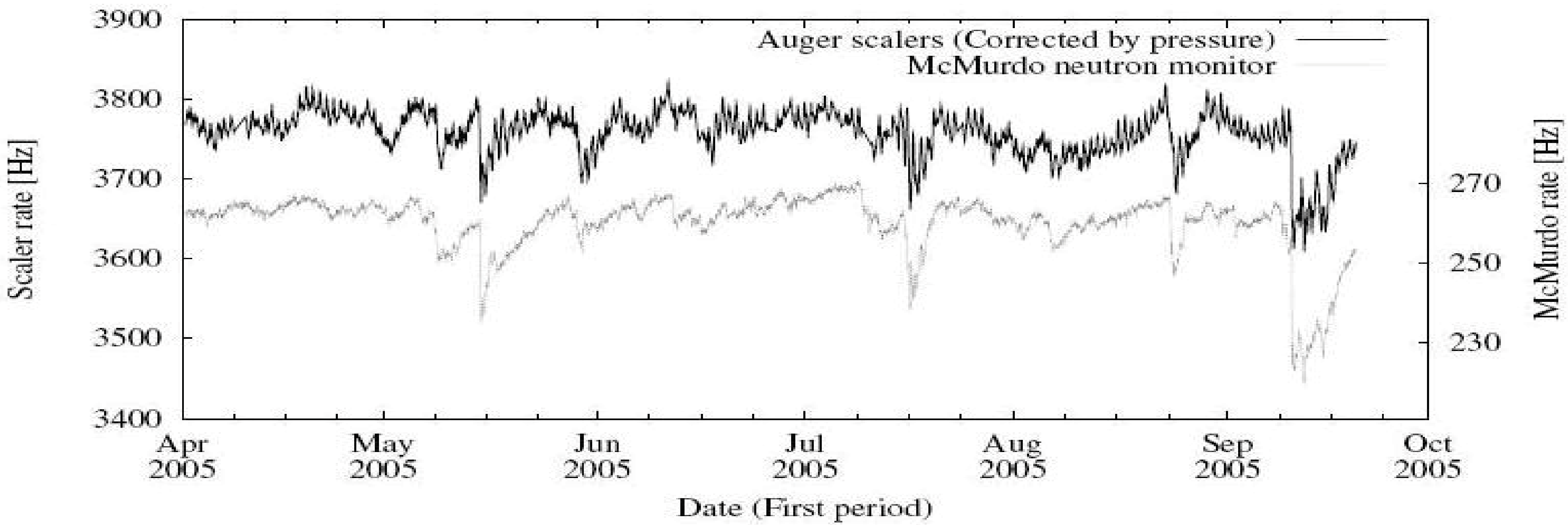
The detector works nicely! e.g.:

Scalers: measure rates of low energy signals (less than 1 muon per tank). Strongly anticorrelated with Pressure.

After correcting for this,...



We see Forbush decreases due to magnetic storms in the Sun!



CONCLUSIONS

Observatory construction essentially accomplished

Evidence that CRs are attenuated by GZK effect

CRs arriving to Earth with $E > 6\times10^{19}$ eV are correlated with the distribution of nearby extragalactic matter

Sources preferentially in regions at less than ~ 100 Mpc in which Active Galactic Nuclei are present
(if other than AGN, sources must have a similar spatial distribution)

Interesting excess in Centaurus A region

No anisotropies observed at EeV energies (galactic/extragalactic?)

photon fraction small (< 2% above 10 EeV)

no neutrinos yet

the charged particle astronomy is being born

providing a new window to observe the Universe

this will allow to study the most violent processes in the Universe, understand the nature of the highest energy cosmic rays, determine magnetic fields, and answer many old questions .....


Where did it all come from?
Where did it all come from?

the questions are similar
the tools are sharper

the answers are closer