IceCube meets Particle Astrophysics

Madison, Wisconsin: 28 – 29 April 2011

Cosmic Rays

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Cosmic Rays – a random walk to some remarkable results

Overview

- Historical background of work that led to the Auger Observatory – and not unconnected to IceCube

  Cygnus X-3 in the 1980s

  Searching for 100 TeV γ-ray sources at the South Pole

  SPASE-AMANDA story

- The Auger Observatory

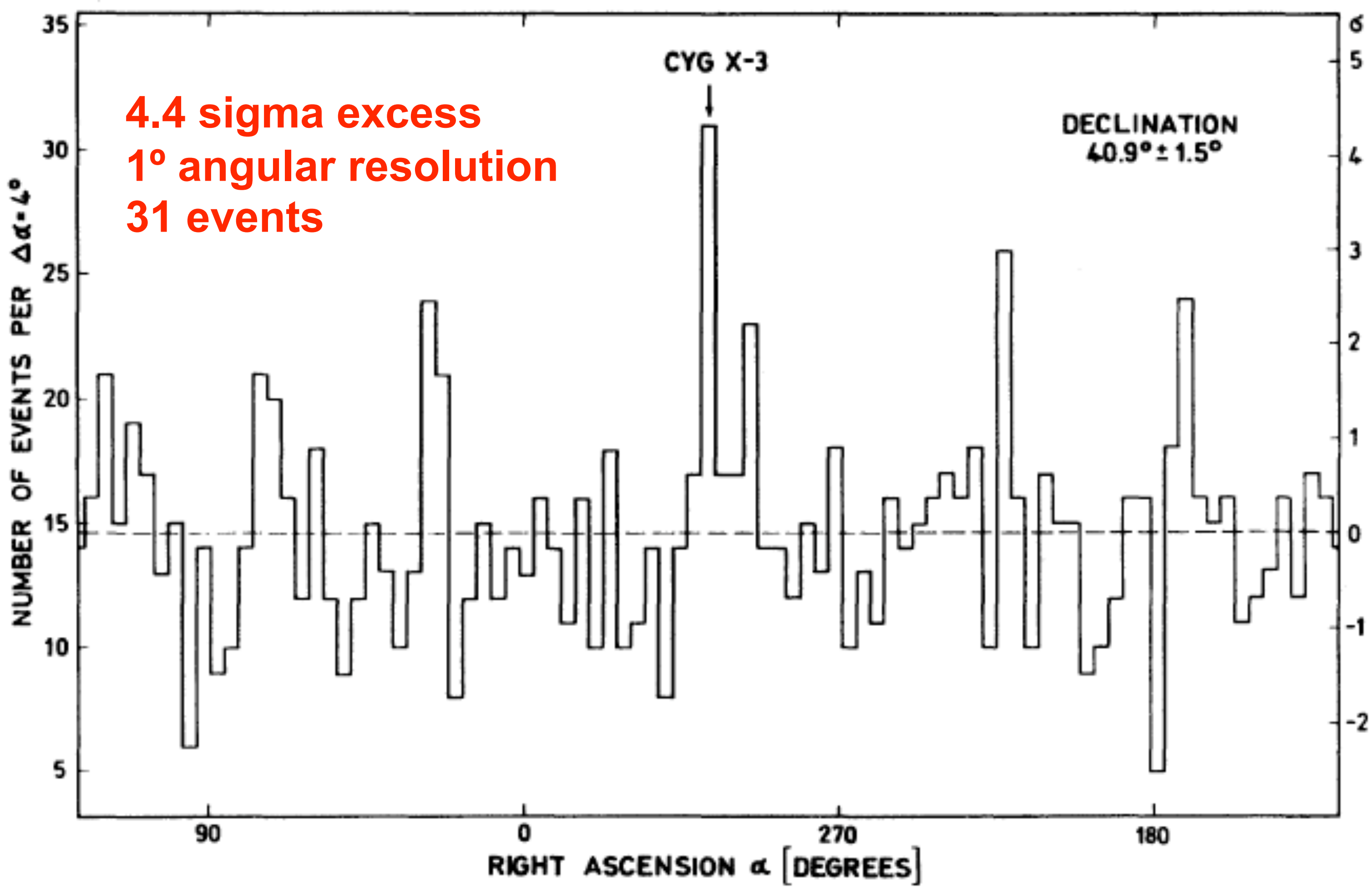
- Results from the Auger Observatory

- The UHECR, gamma-ray and neutrino link

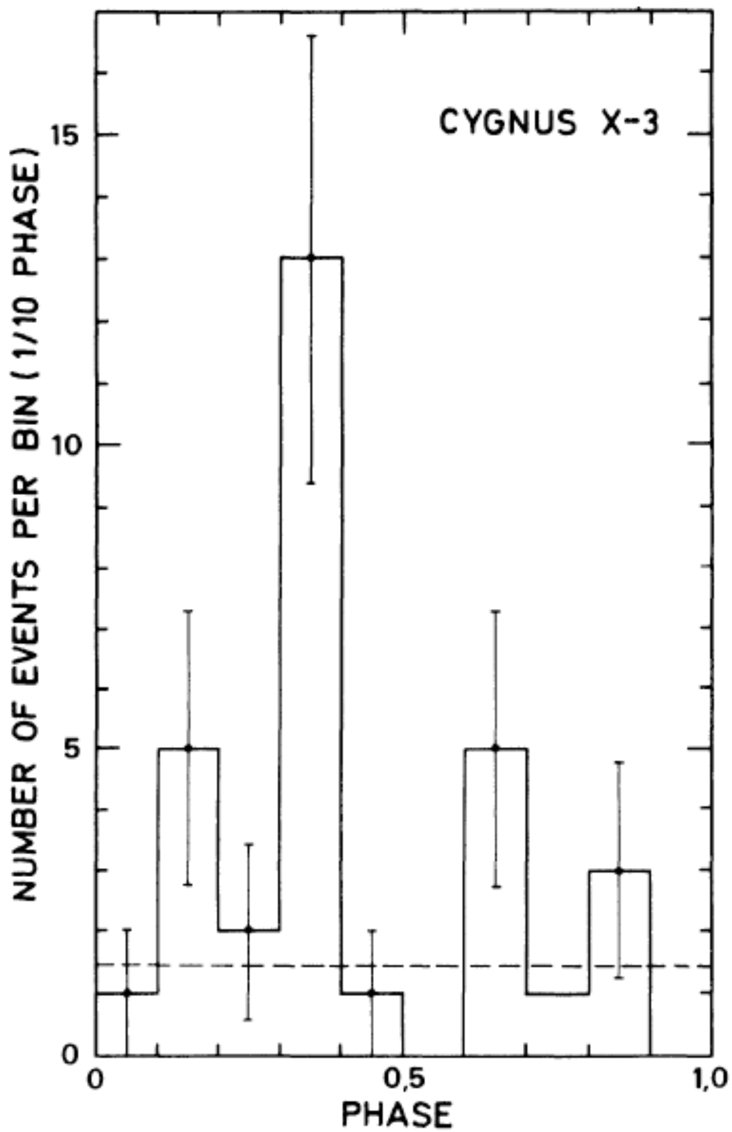
Disclaimer: Not intended to be a review: strong personal bias

Samorski and Stamm: ApJ Letters 268 L17 May 1983

DETECTION OF 2×10^{15} TO 2×10^{16} eV GAMMA-RAYS FROM CYGNUS X-3



31 events



4.8 hours

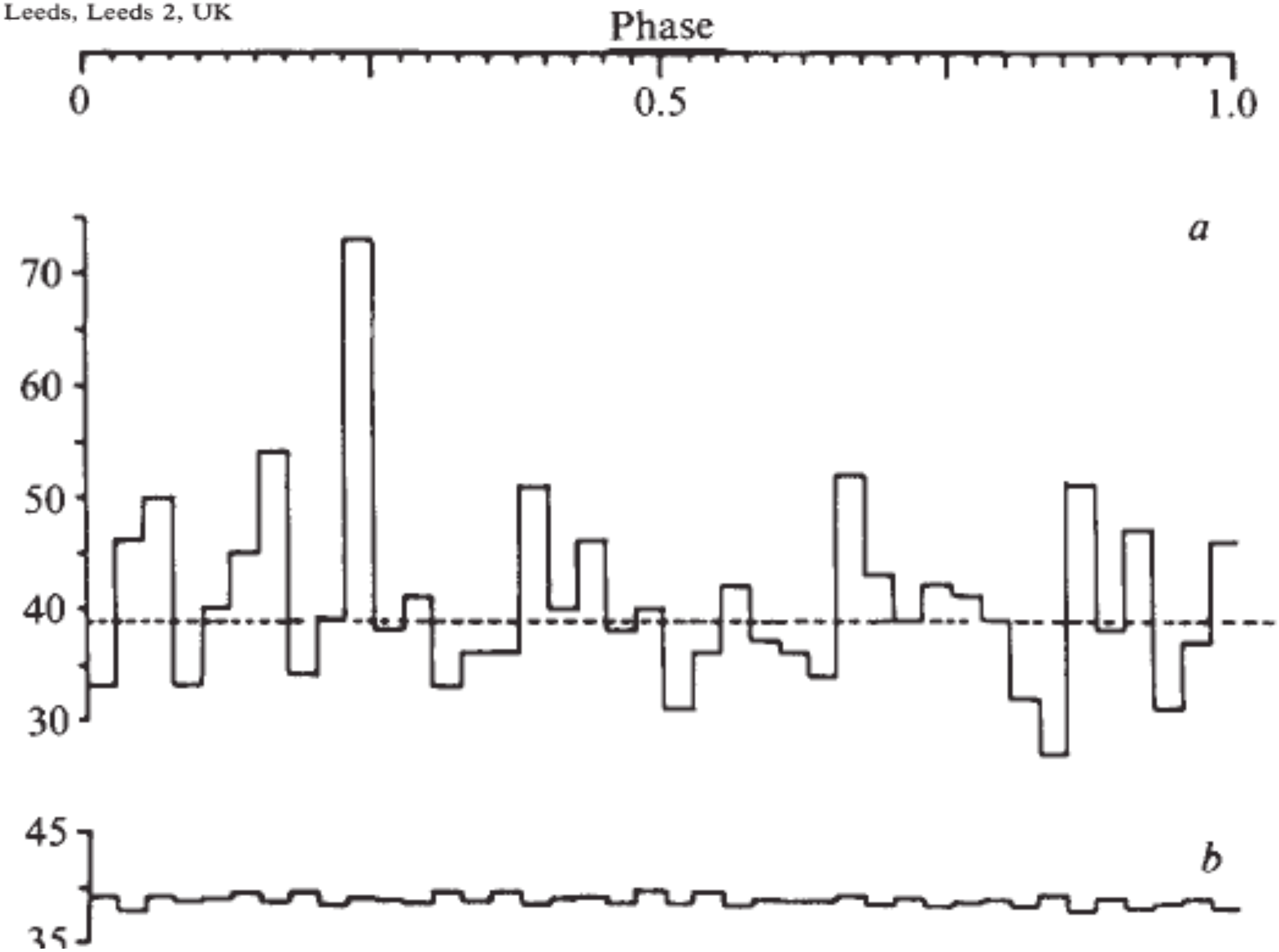
Explained in terms of X-ray binary system including neutron star

Observation of γ rays >10^{15} eV from Cygnus X-3

J. Lloyd-Evans, R. N. Coy, A. Lambert, J. Lapikens, M. Patel, R. J. O. Reid & A. A. Watson

Department of Physics, University of Leeds, Leeds 2, UK

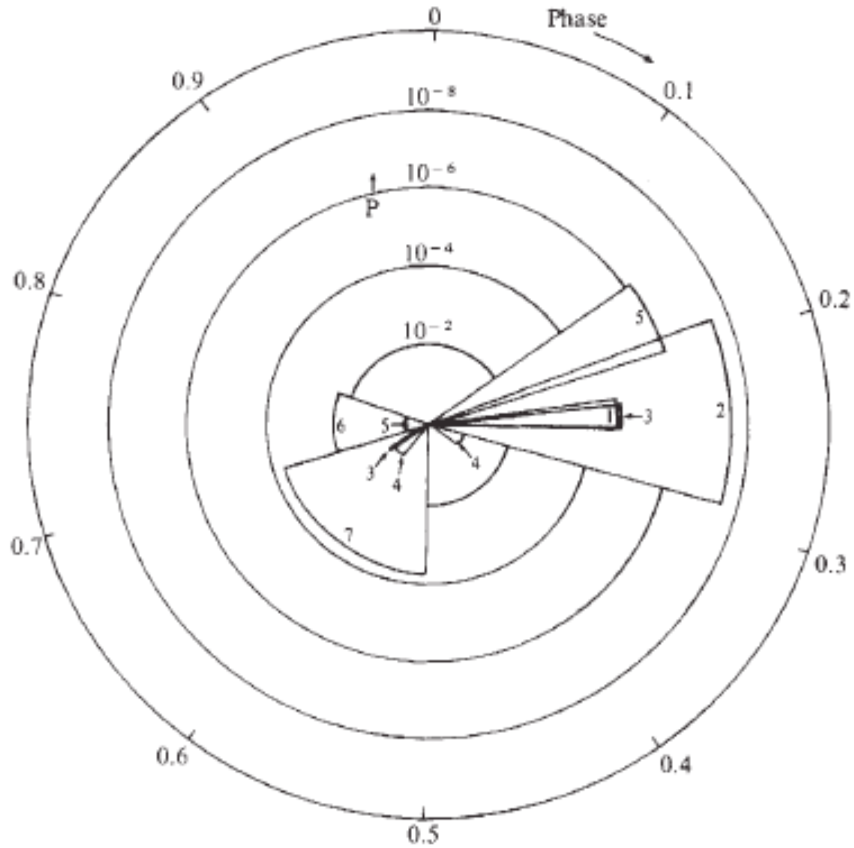
Nature 305 784 October 1983

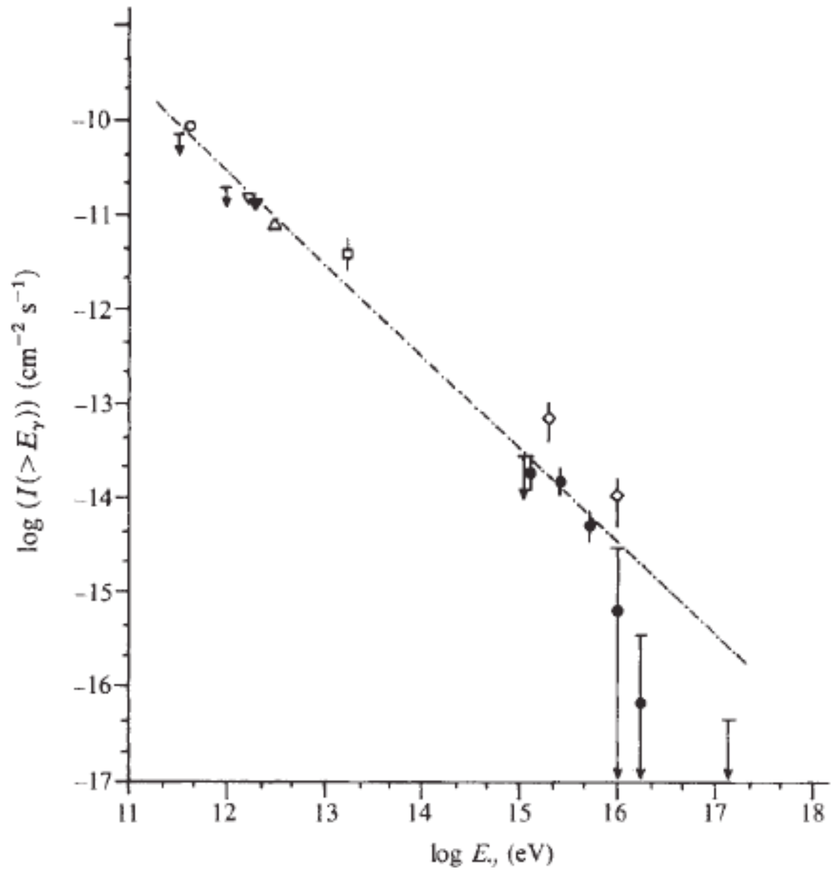


Observations by Haverah Park group appeared to confirm Kiel results

Poorer angular resolution

Very small temporal overlap





Often forgotten – **before Crab detection in 1989 at TeV energies by Whipple - that the air-shower results were consistent with** **prior claims** **at TeV energies**

Many people from particle physics entered field

In USA: Wisconsin, Hawaii, Minnesota groups
at Haleakala and South Pole at TeV energies

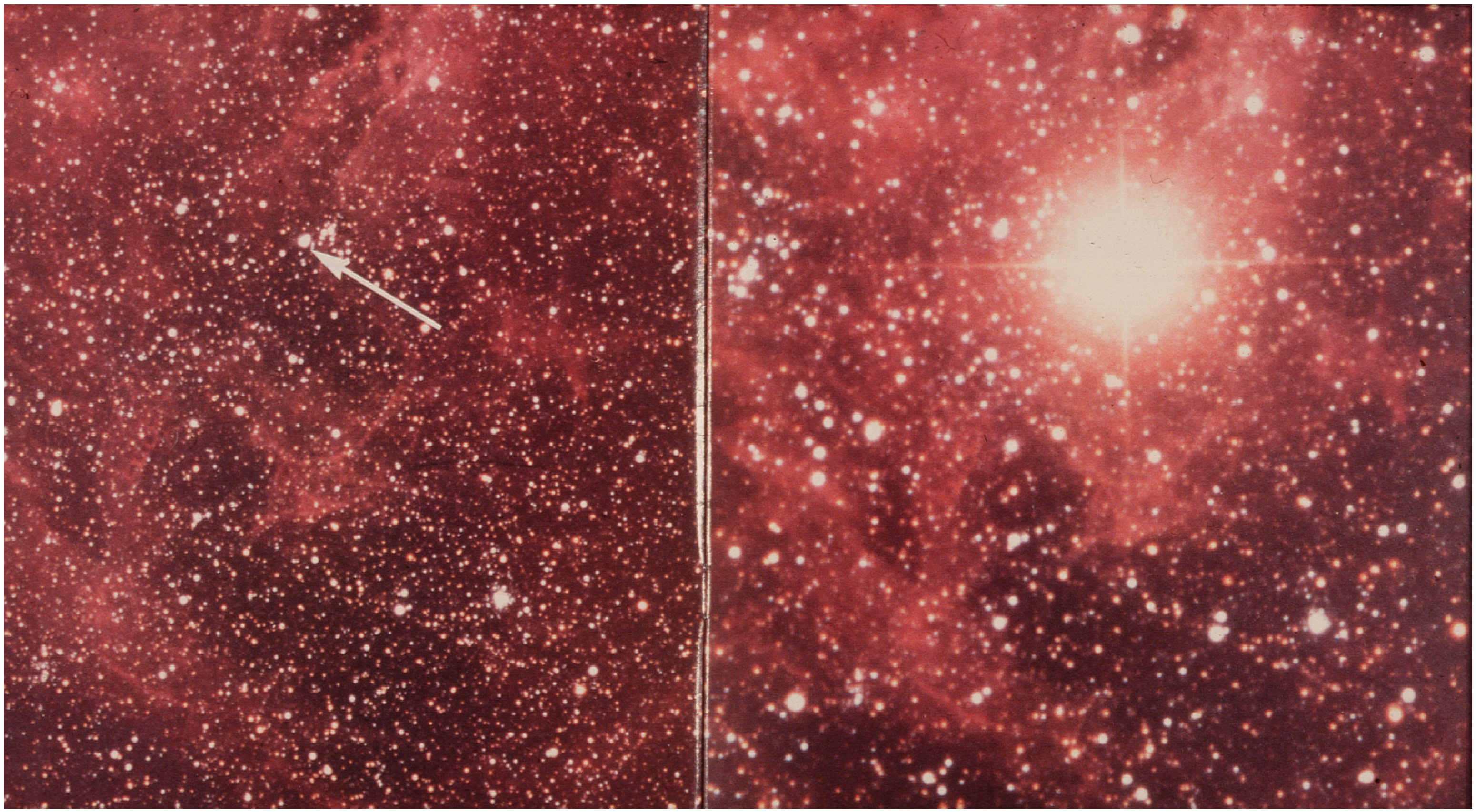
Cronin with CASA at 100 TeV energies
Yodh at Los Alamos with CYGNUS

In Europe: Various groups at La Palma from Germany
Heinrich Meyer
Eckart Lorentz
Werner Hofmann and others

Explorations with existing air-shower arrays – and many 2 to 2.5 sigma results from objects that were in the beam of the array

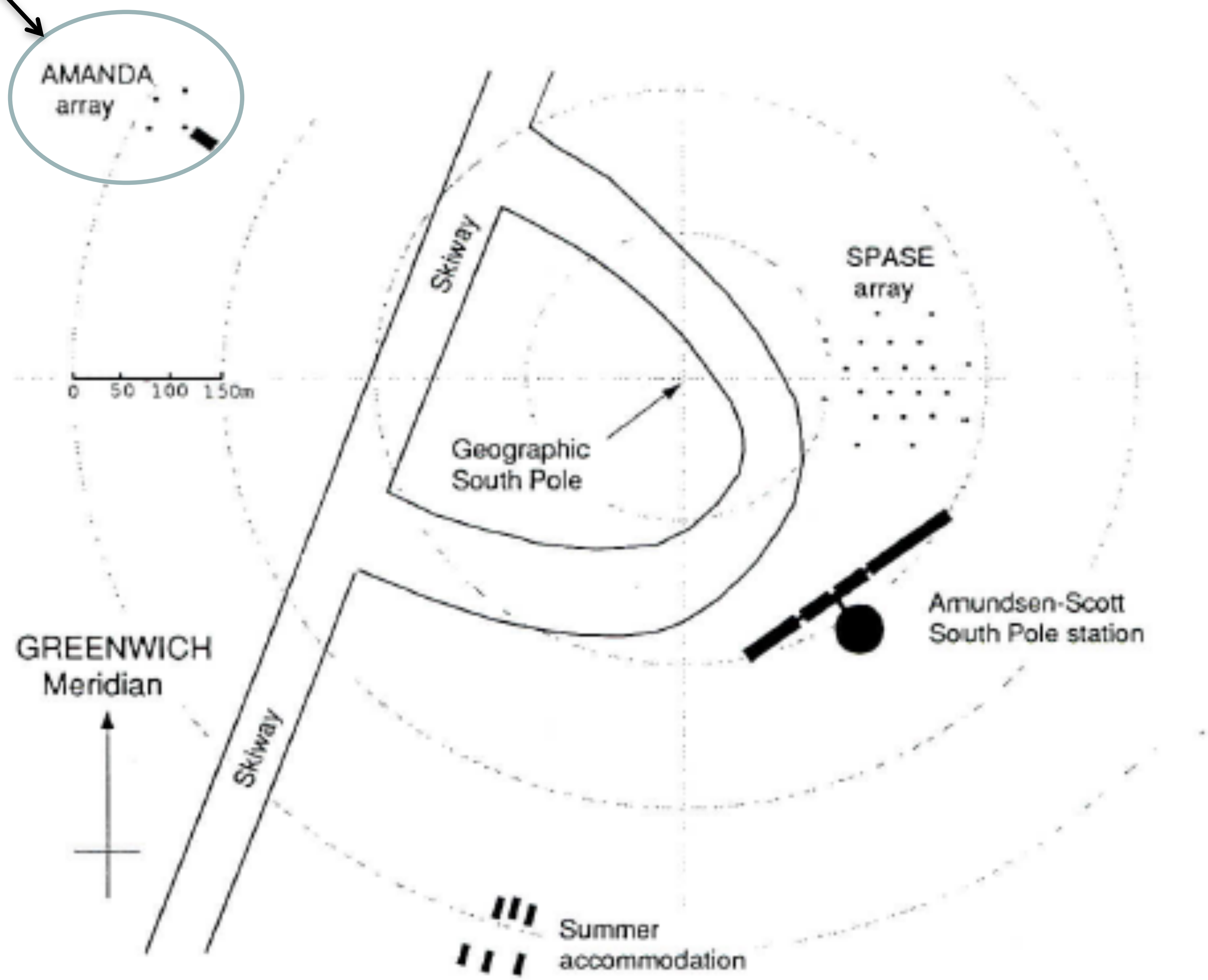
Following a suggestion by Michael Hillas, Leeds group joined with team from Bartol Research Institute (Pomerantz, Gaisser and Stanev) to make search at South Pole for 100 TeV γ from X-ray binaries

Planning and funding of Bartol/Leeds effort began in late 1986 largely supported by NSF – John Lynch



SN1987A: explosion of star in Large Magellanic cloud

Later



AMANDA
array
SPASE
array
0 50 100 150m
Skiway
Skiway
Geographic
South Pole
Amundsen-Scott
South Pole station
GREENWICH
Meridian
Summer
accommodation

Lifting a SPASE scintillator box into position: November 1987

Loading a scintillator block

Some detectors of the SPASE array at the South Pole

Observations started within less than a year of SN1987 explosion

Objects in sky 24 hours per day and observations at 3300 m equivalent

No signals seen from SN1987a – theorists had misled us –

and nothing seen from X-ray binaries

Significant contributions were:-

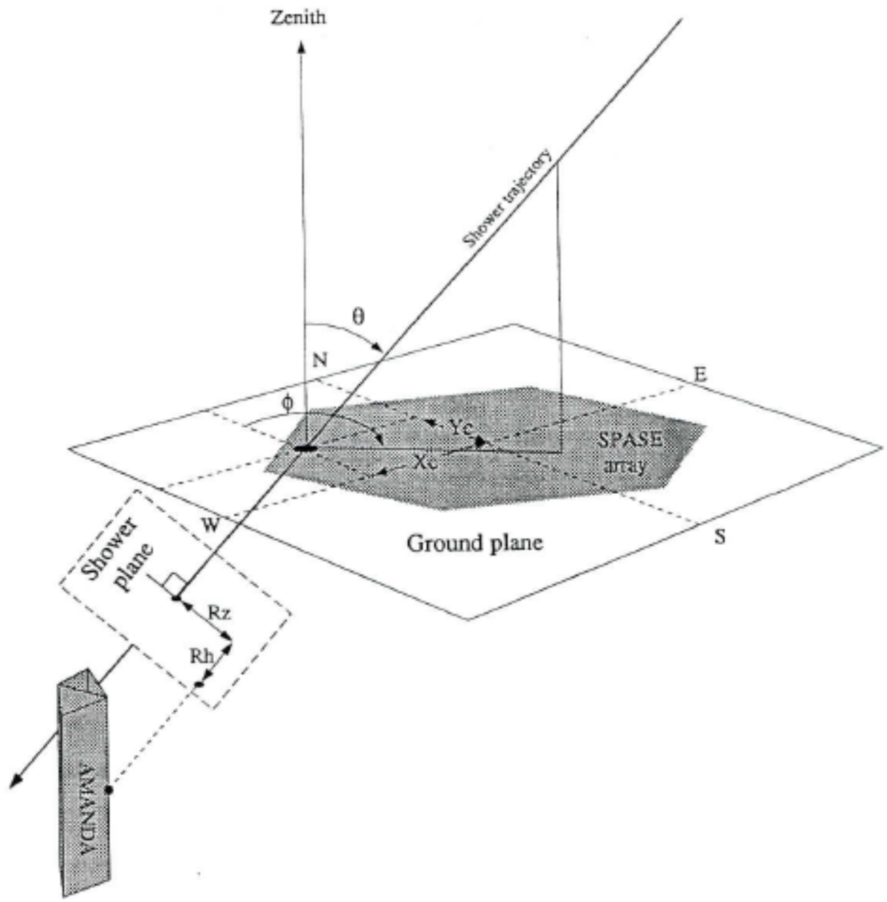
Established direction of Greenwich Meridian (AAW)

With a Cherenkov light receiver (Trevor Weekes) showed that the angular resolution was ~ 1º

Learned how hard it was to freeze water (Bob Morse)

These data were of interest and use to AMANDA and a loose collaboration began – no collaboration meetings, no project management - but a lot of fun work and some science

SPASE Array and AMANDA



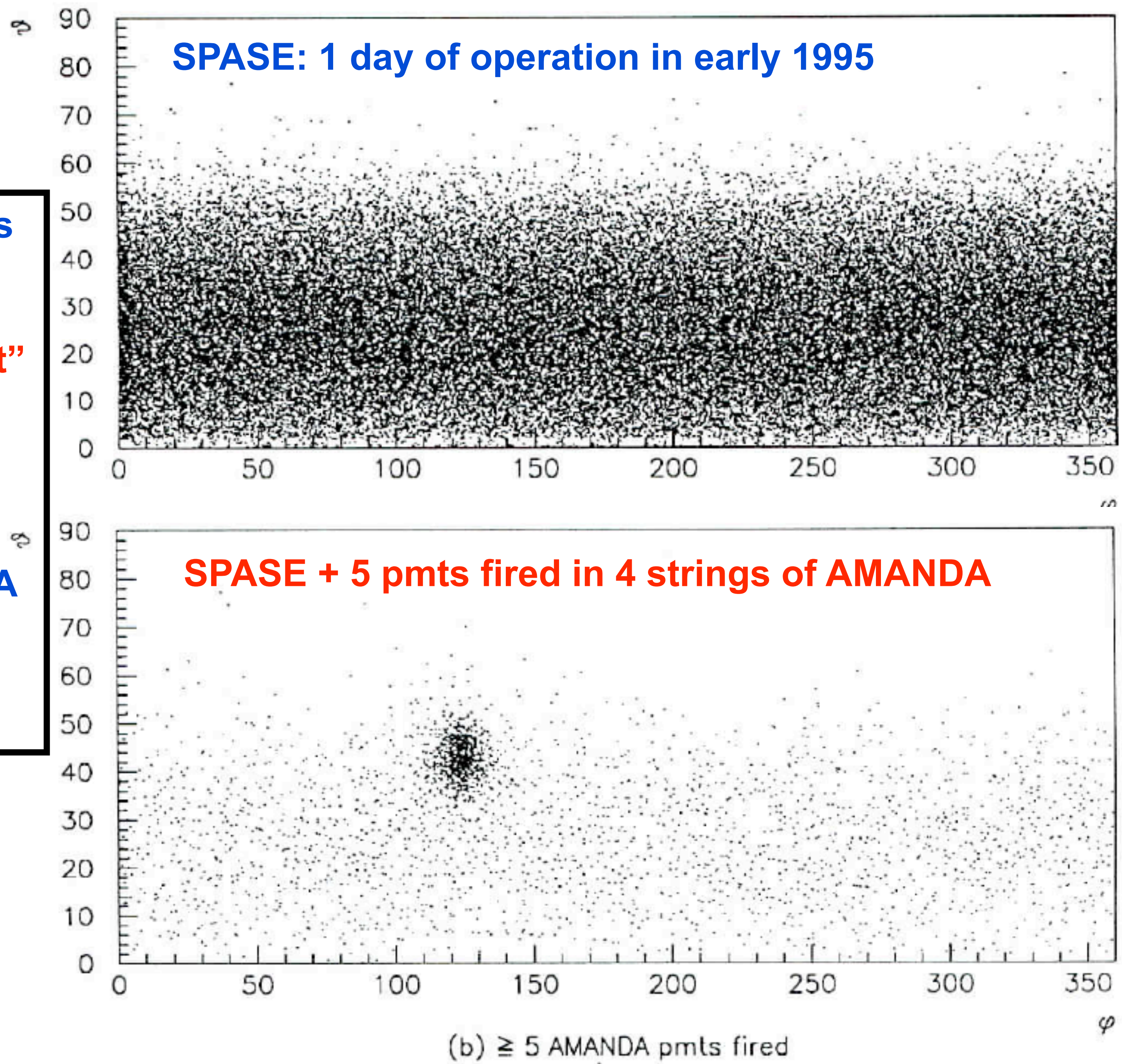
From Simon Hart's PhD thesis:

"a eureka moment"

but

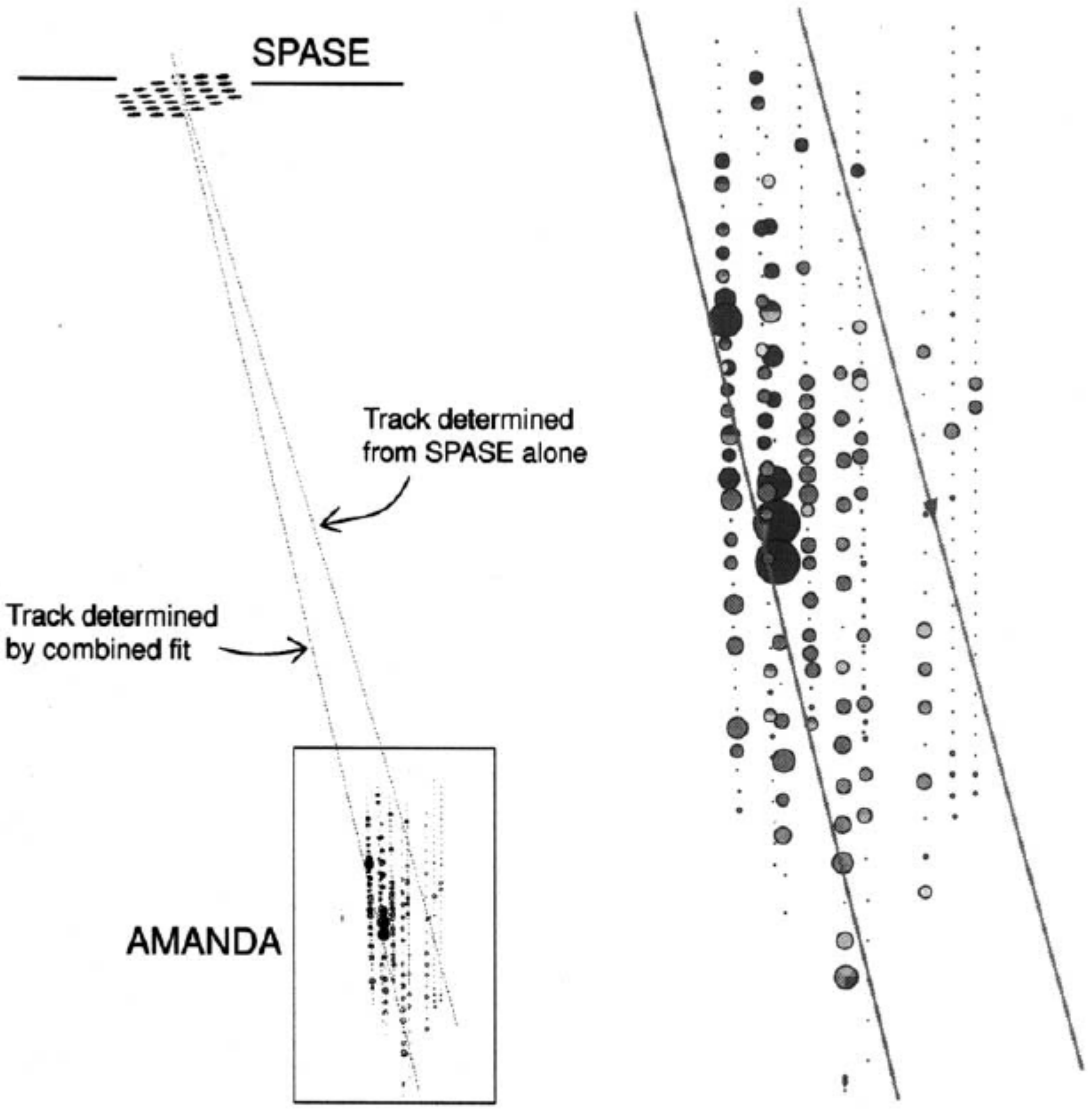
Disappointing result for AMANDA

Detector in layer of air bubbles

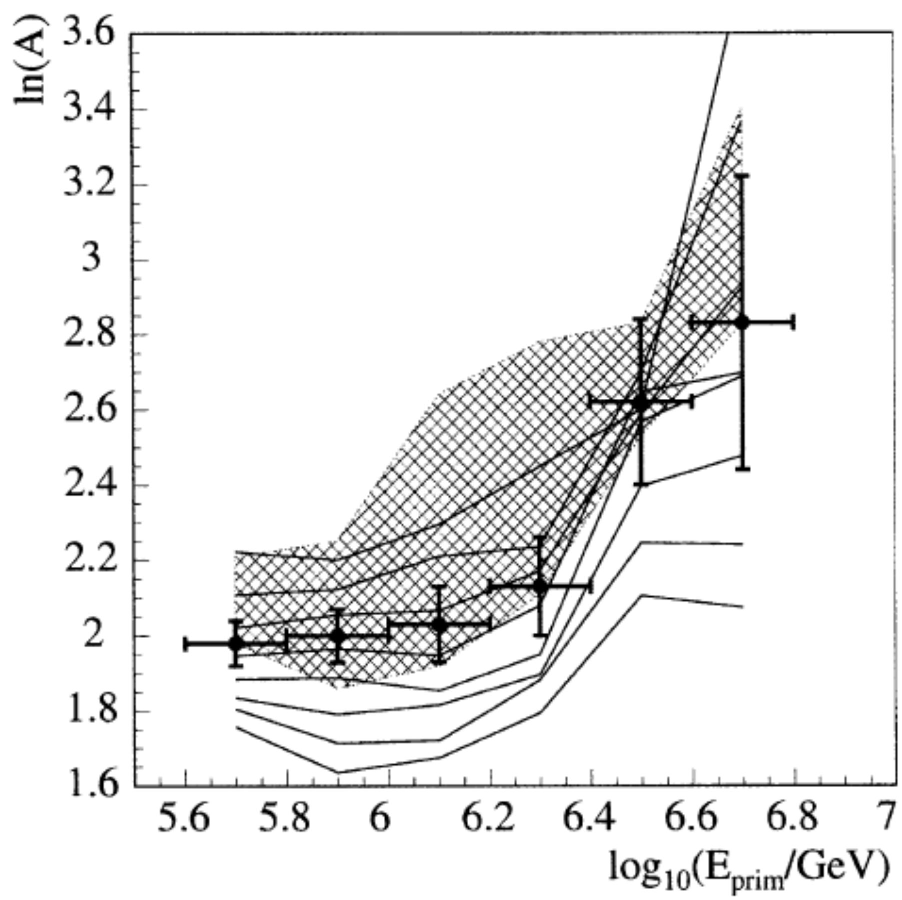


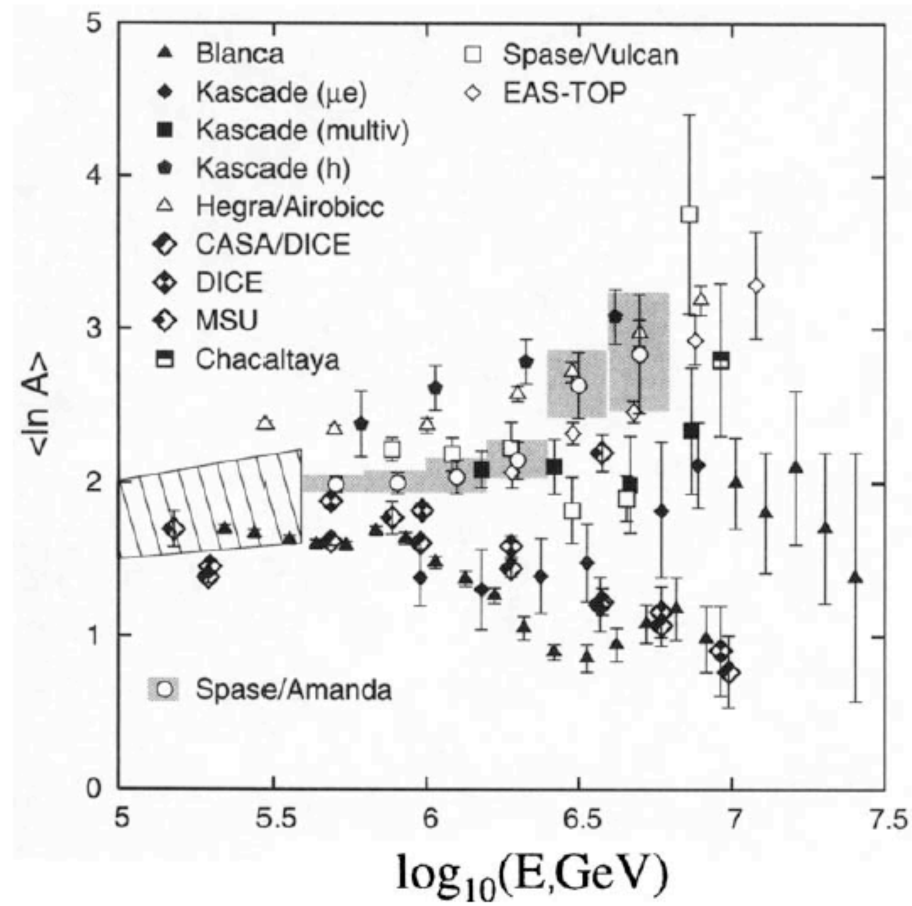
Ahrens et al. Astroparticle Physics 21 565 2004 (126 authors!)

Evolved to study of mass composition with 10 strings



Ahrens et al. Astroparticle Physics 21 565 2004





In 1995, at Rome ICRC, Jim Cronin gave a Review talk describing how gamma-ray astronomy had evolved in terms of detector developments.

- Negative results from CASA which was hugely more sensitive than previous shower arrays

- Studies of the Solar Magnetic field with such as the Tibet array

- AIROBICC at La Plama

- TeV detectors in La Palma

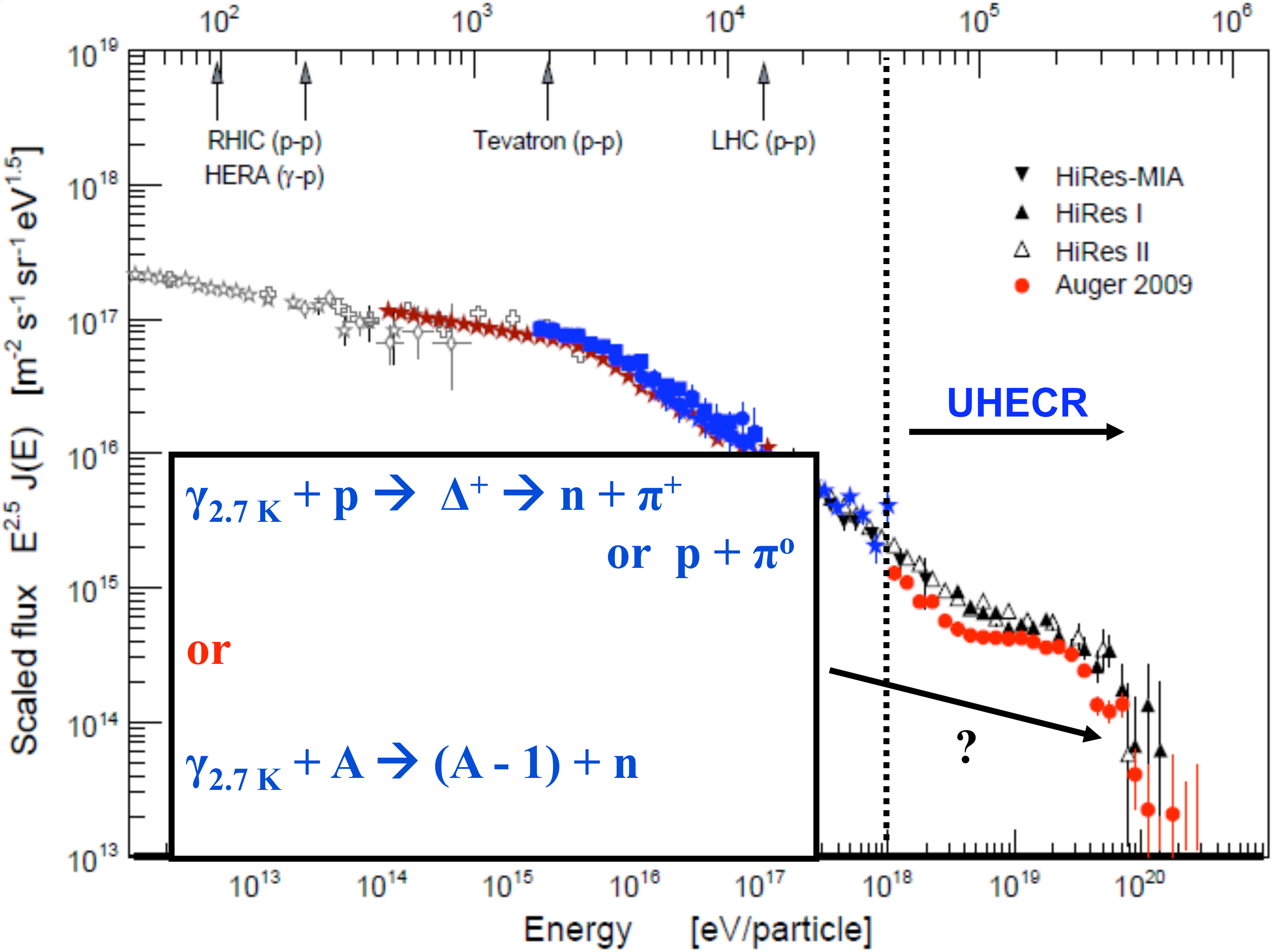
- MILAGRO at Los Alamos

"Old problems remain and new mysteries have appeared and there are new researchers armed with enthusiasm and new technology to solve the old problems and unravel the new mysteries.

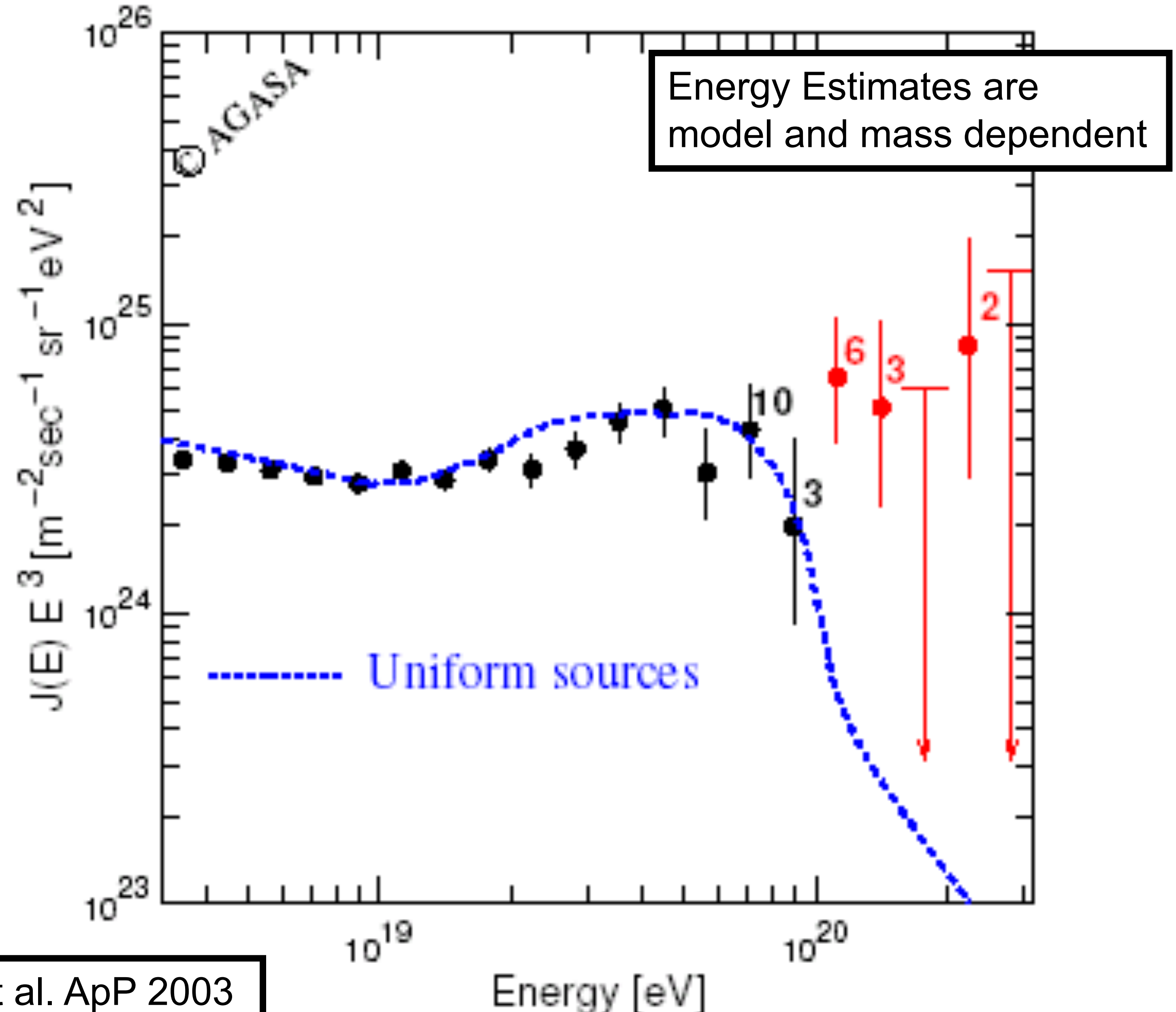
This is the legacy of Cygnus X-3."

Another legacy was the Pierre Auger Observatory

UHECR

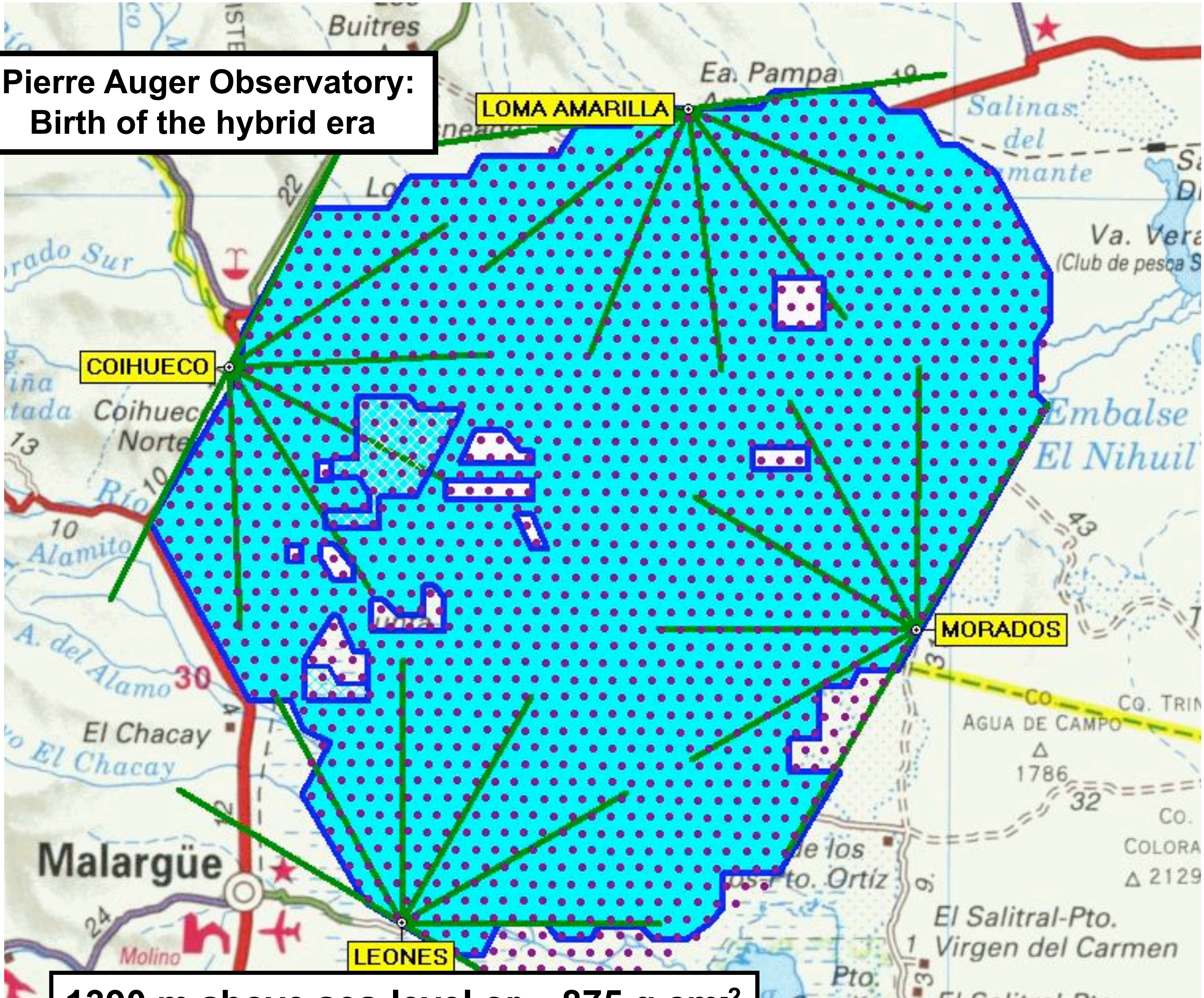


Equivalent c.m. energy √s_pp [GeV]
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2009
UHECR
Scaled flux E^2.5 J(E) [m^-2 s^-1 sr^-1 eV^1.5]
10^19
10^18
10^17
10^16
10^15
10^14
10^13
γ_2.7 K + p → Δ^+ → n + π^+
or p + π^o
or
γ_2.7 K + A → (A - 1) + n
?
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
Energy [eV/particle]



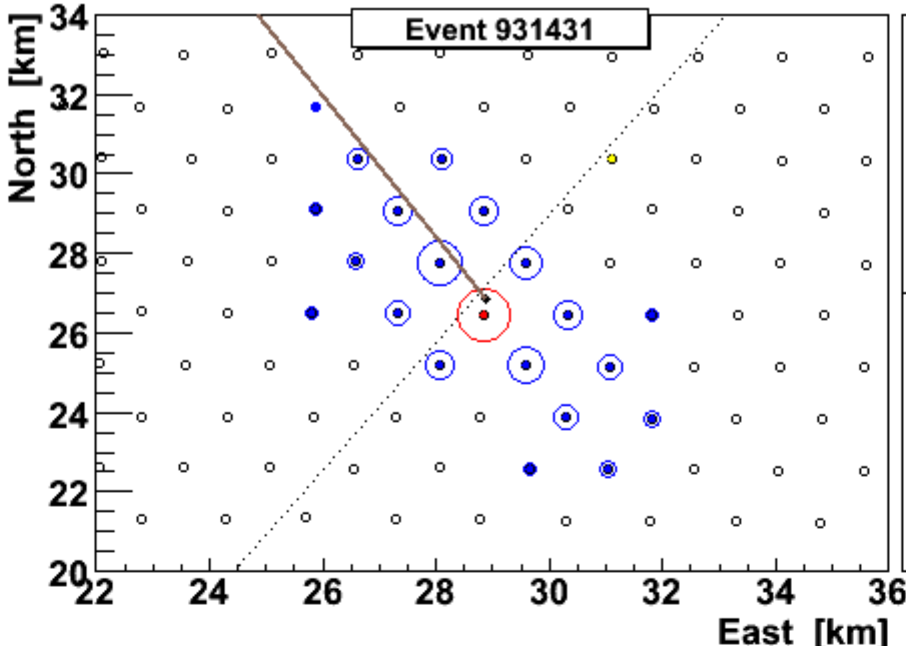
Takeda et al. ApP 2003

Pierre Auger Observatory: Birth of the hybrid era



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

A Hybrid Event



Core location

Easting 468693 ± 59

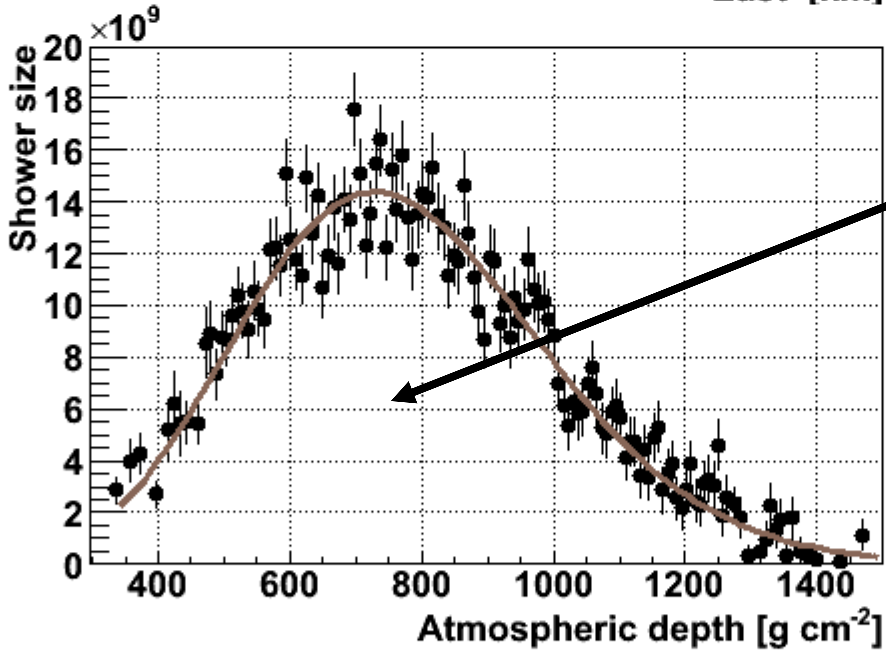
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

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

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

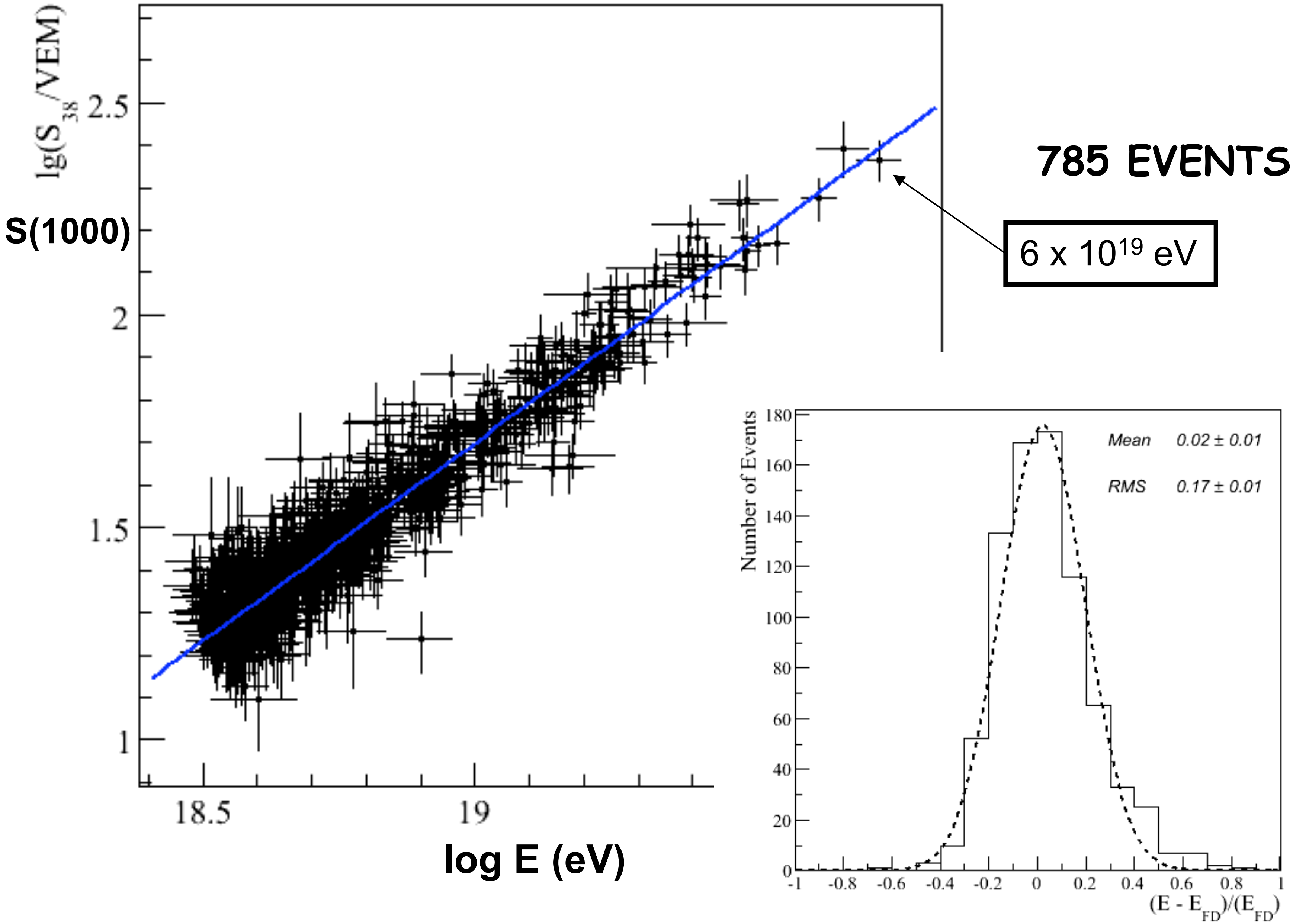


Energy Estimate
- from area under curve

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

must account for ‘missing energy’

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

Results from Pierre Auger Observatory

Data-taking started on 1 January 2004 with

125 (of 1600) water-Cherenkov detectors

6 (of 24) fluorescence telescopes

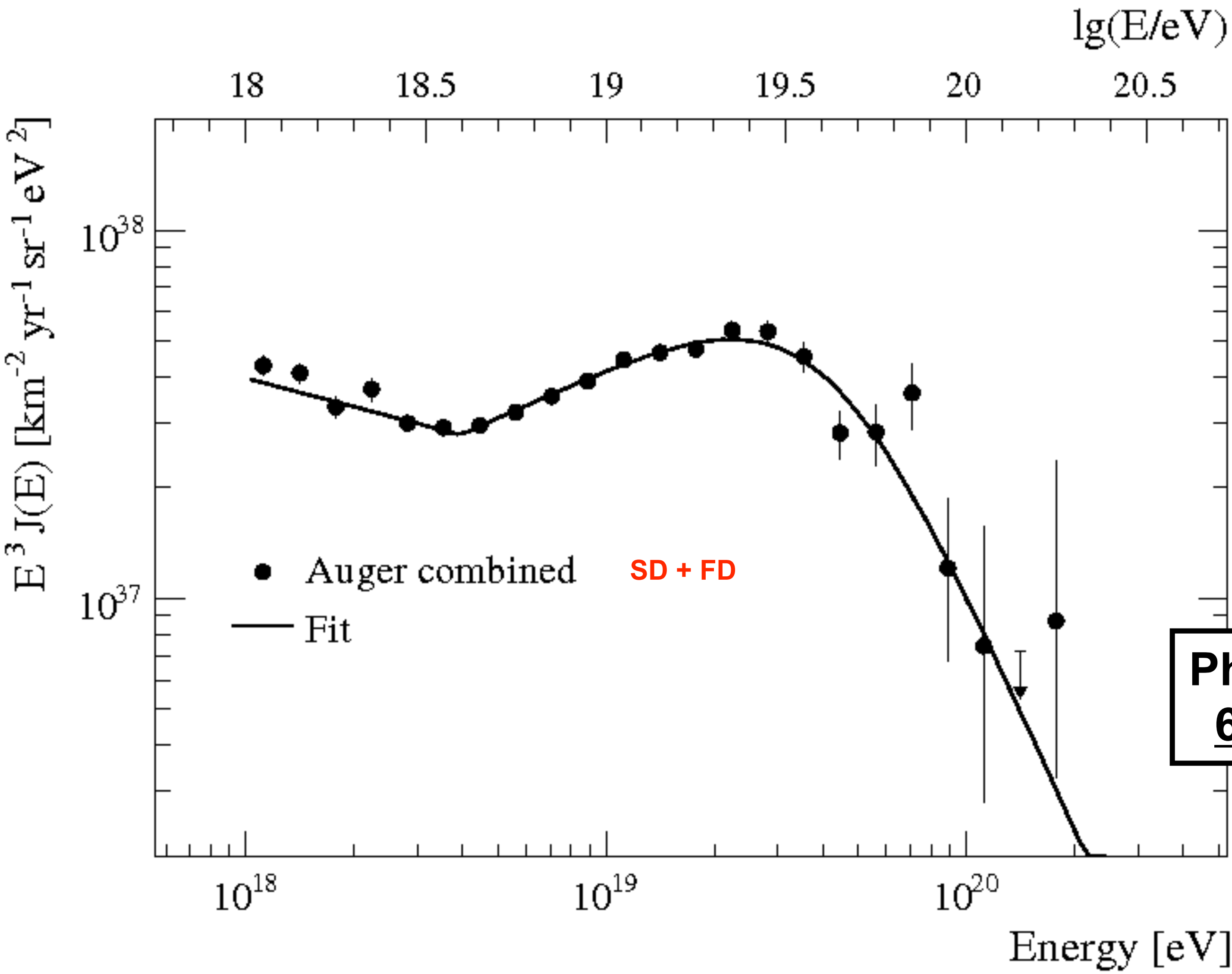
more or less continuous operation since then

At end of 2009,		12,790 km^2 sr yr	
	$> 10^{19}$ eV:	4440	(HiRes stereo: 307
	$> 5 \times 10^{19}$ eV:	59	: 19
	$> 10^{20}$ eV:	3	: 1)

HiRes Aperture: x 4 at highest energies

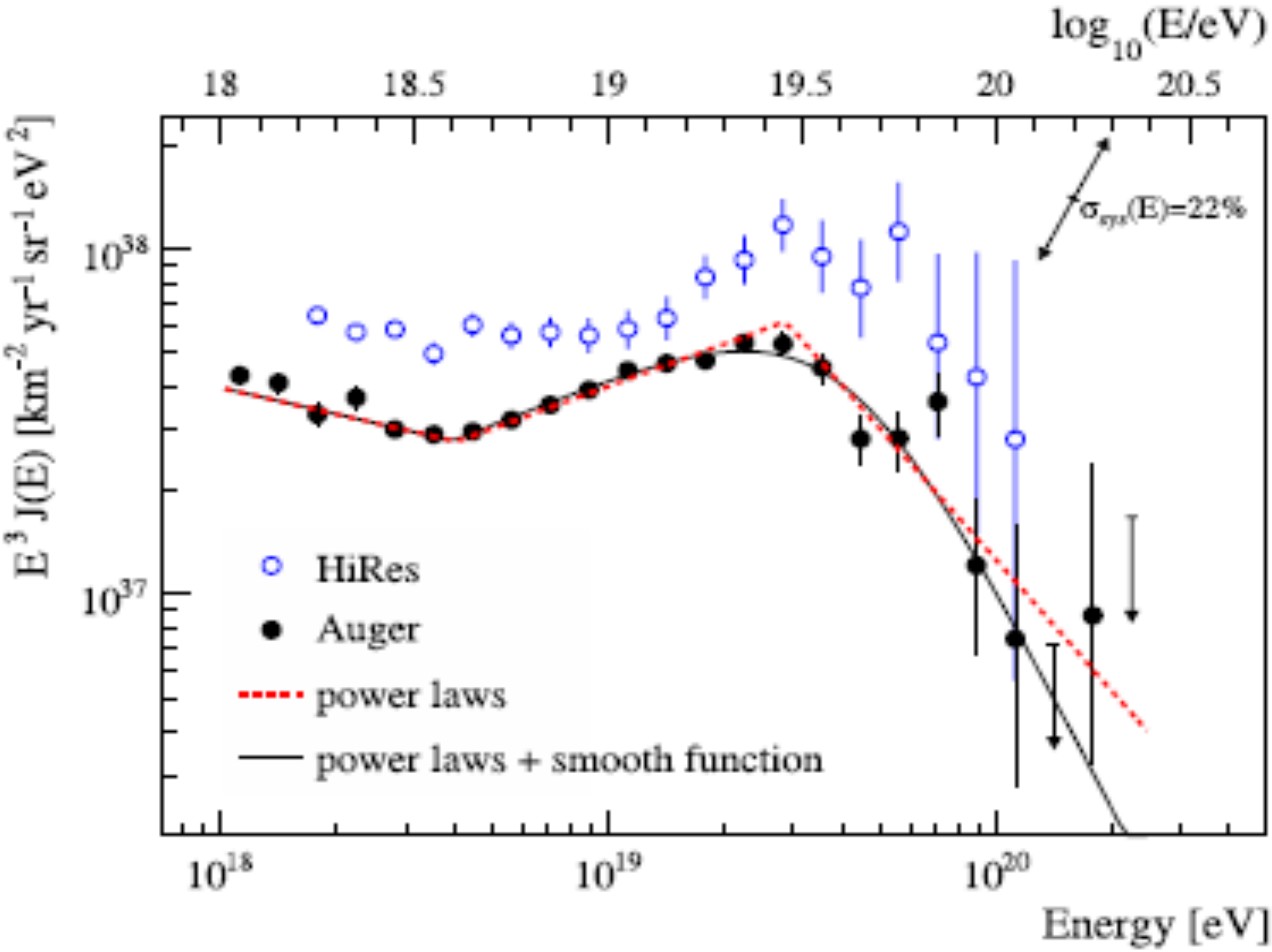
x 10 AGASA

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

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

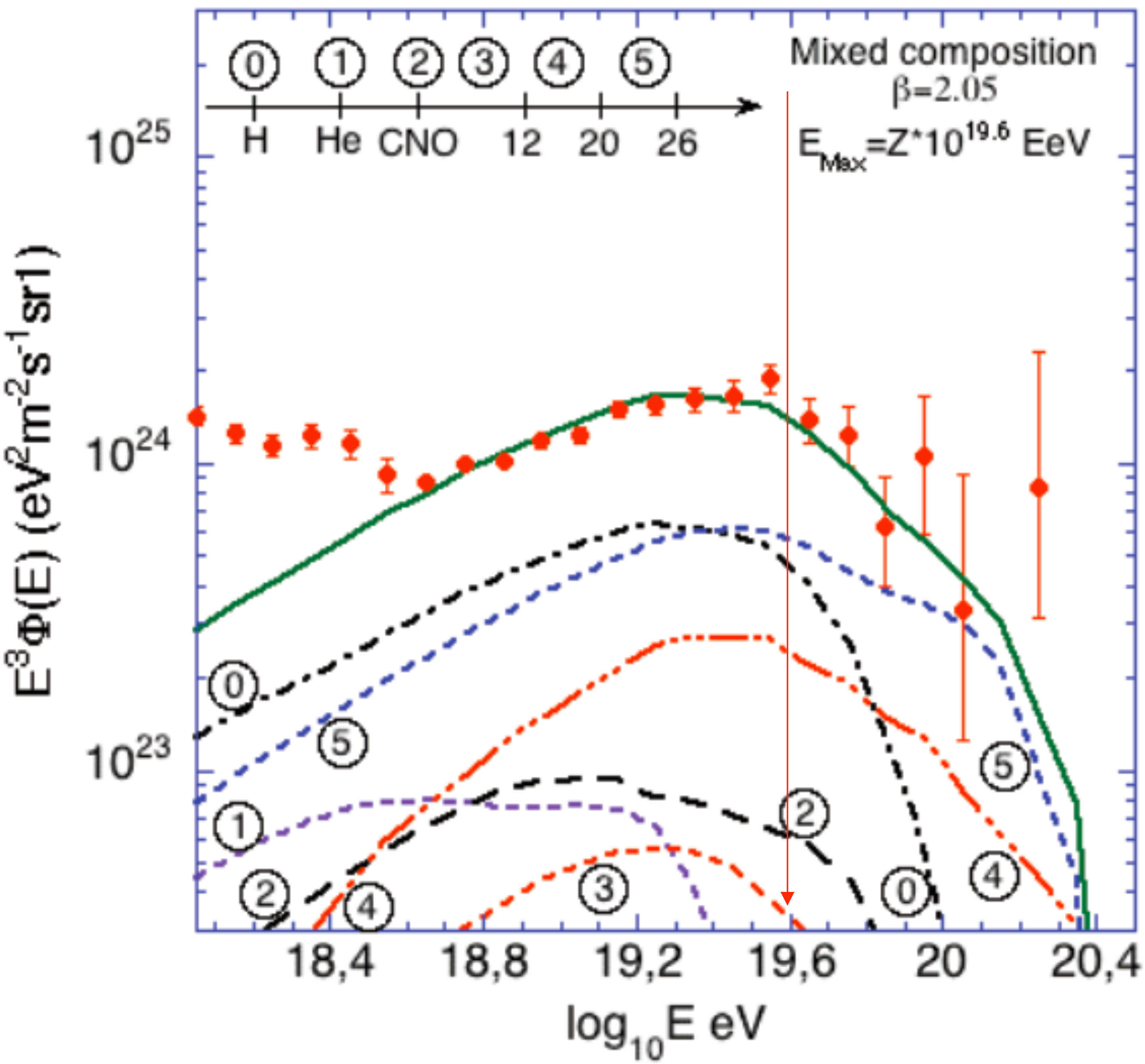
$(6.4 \pm 1.9) \times 10^{-3}$ km^{-2} sr^{-1} yr^{-1}

a factor of more than 25

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

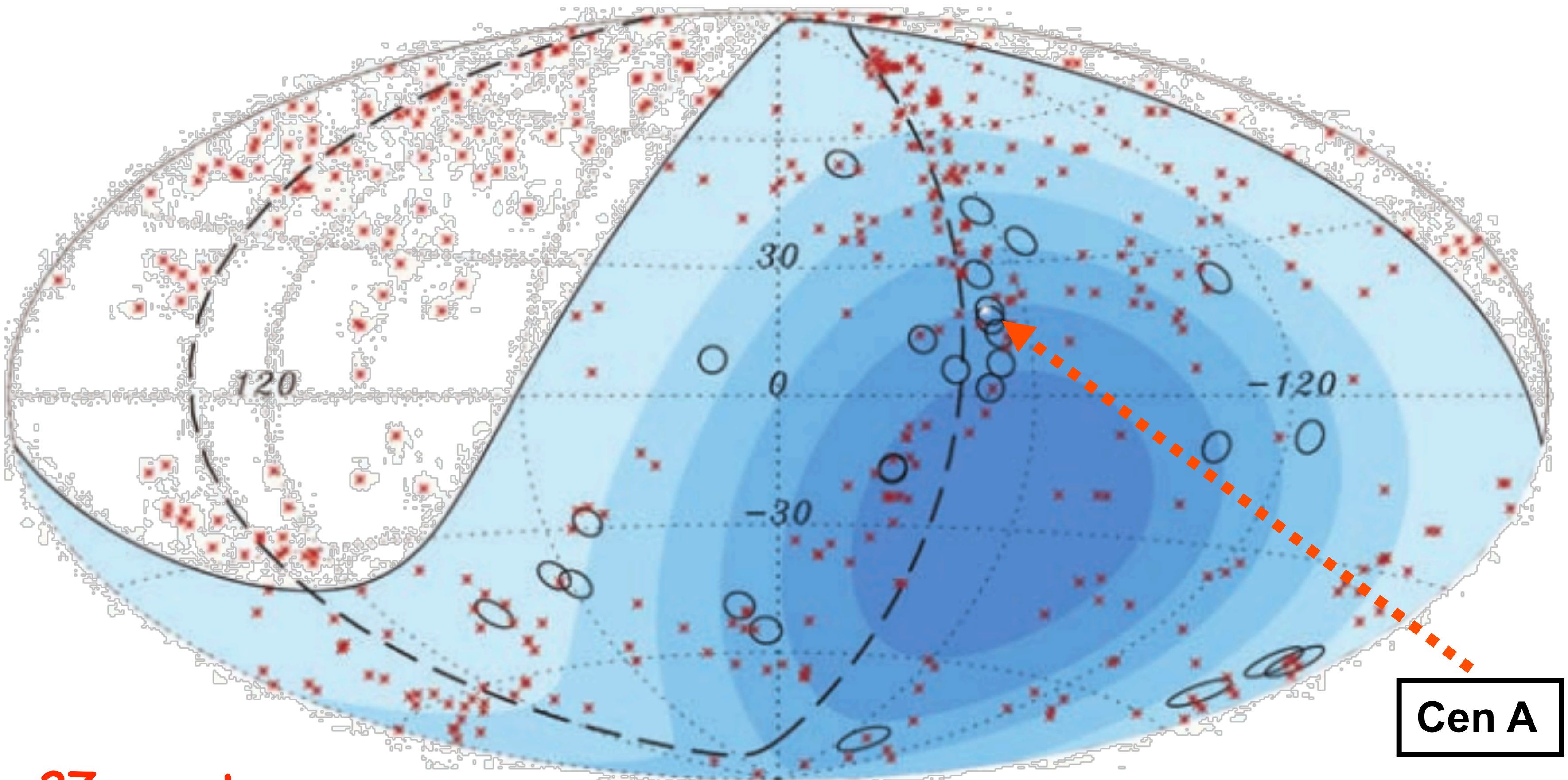
Consensus is that Auger and HiRes have got it right

Spectrum shape does NOT give insights into mass

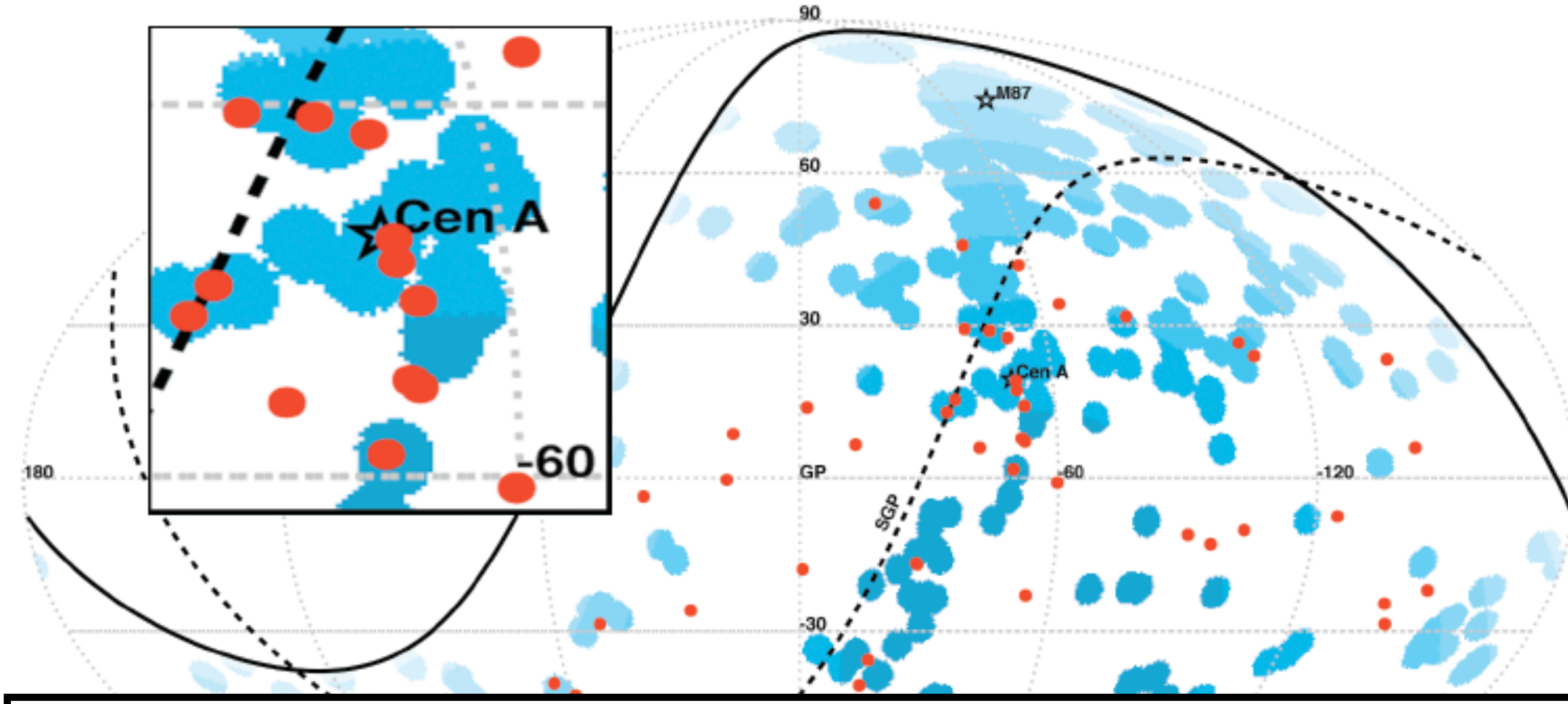


ANISOTROPY

Situation as at November 2007: Science and Astroparticle Physics



27 events



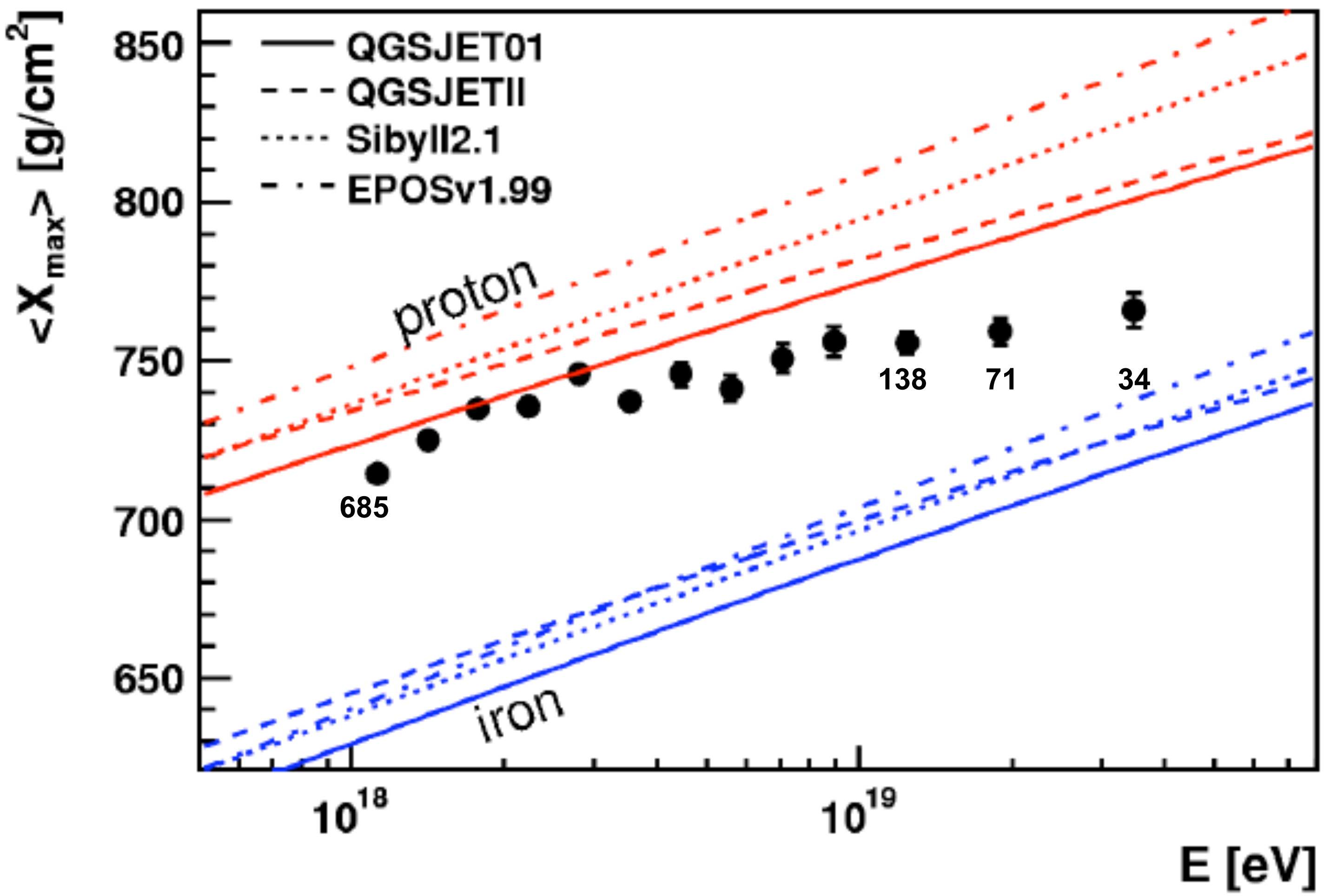
Correlation has fallen from ~ 68% to ~ 38% (2007 –> 2010)

Cen A may be a source: in 13º circle around: 12 seen/1.7

A clear message from the Pierre Auger Observatory is:-

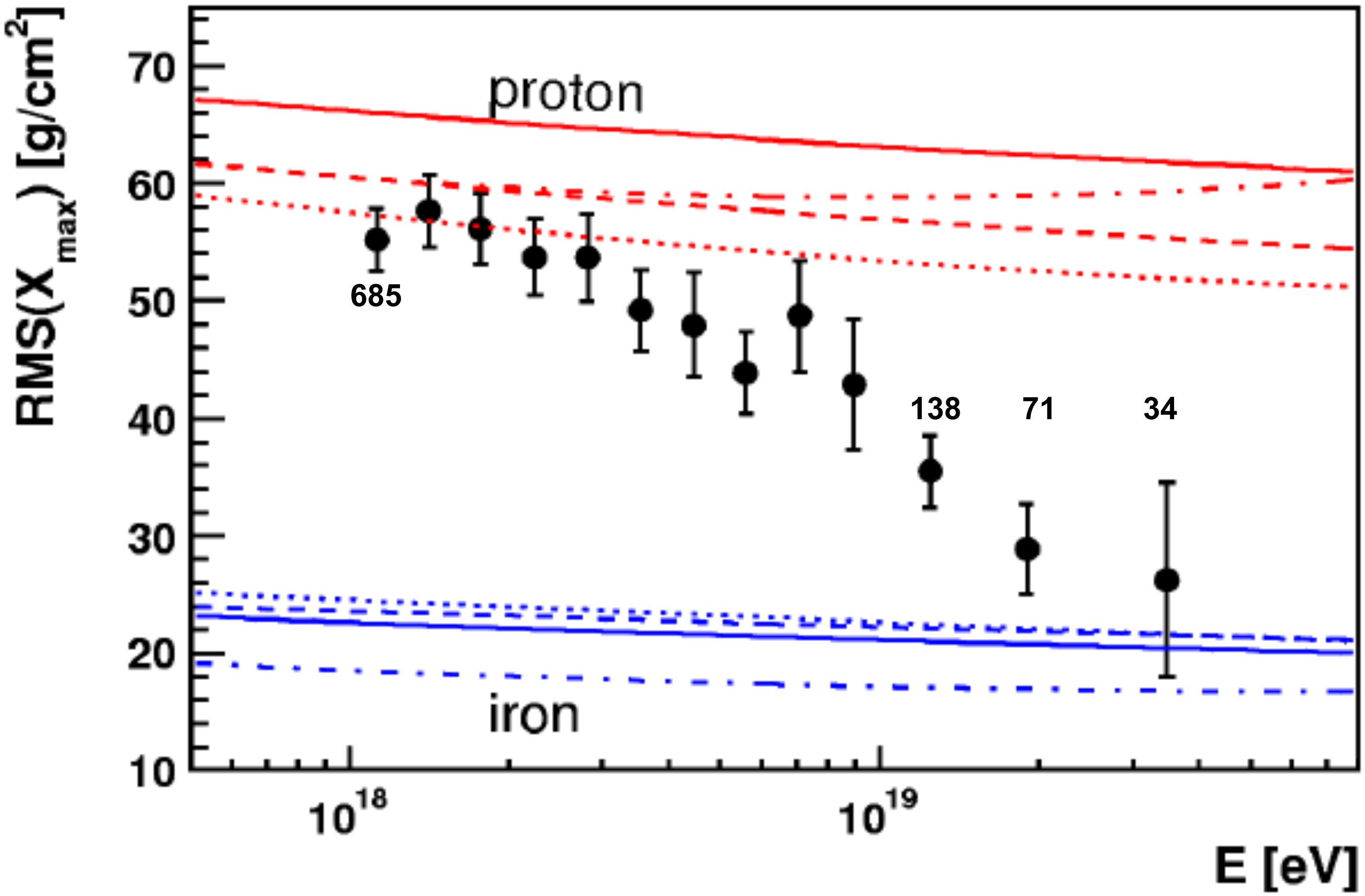
We made it too small (2 per month at energy of interest)

Mean X_{max} from 3754 events



Differences from HiRes remain to be understood

RMS(X_{max}) for same events



Update of these measurements will be reported at Summer Conferences

Anisotropy might suggest protons (PERSONAL VIEW!)

- but 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?**

ALICE: High multiplicity events
Intriguing Press Release from LHCf

These features would give

- **X_{max} higher in atmosphere than current models**

- **Reduce fluctuations in X_{max}**

LHC may help answer these questions (LHCf)

Reasons to doubt present models of hadronic physics

• The cosmic ray models seem generally to be better than Pythia family at describing LHC data

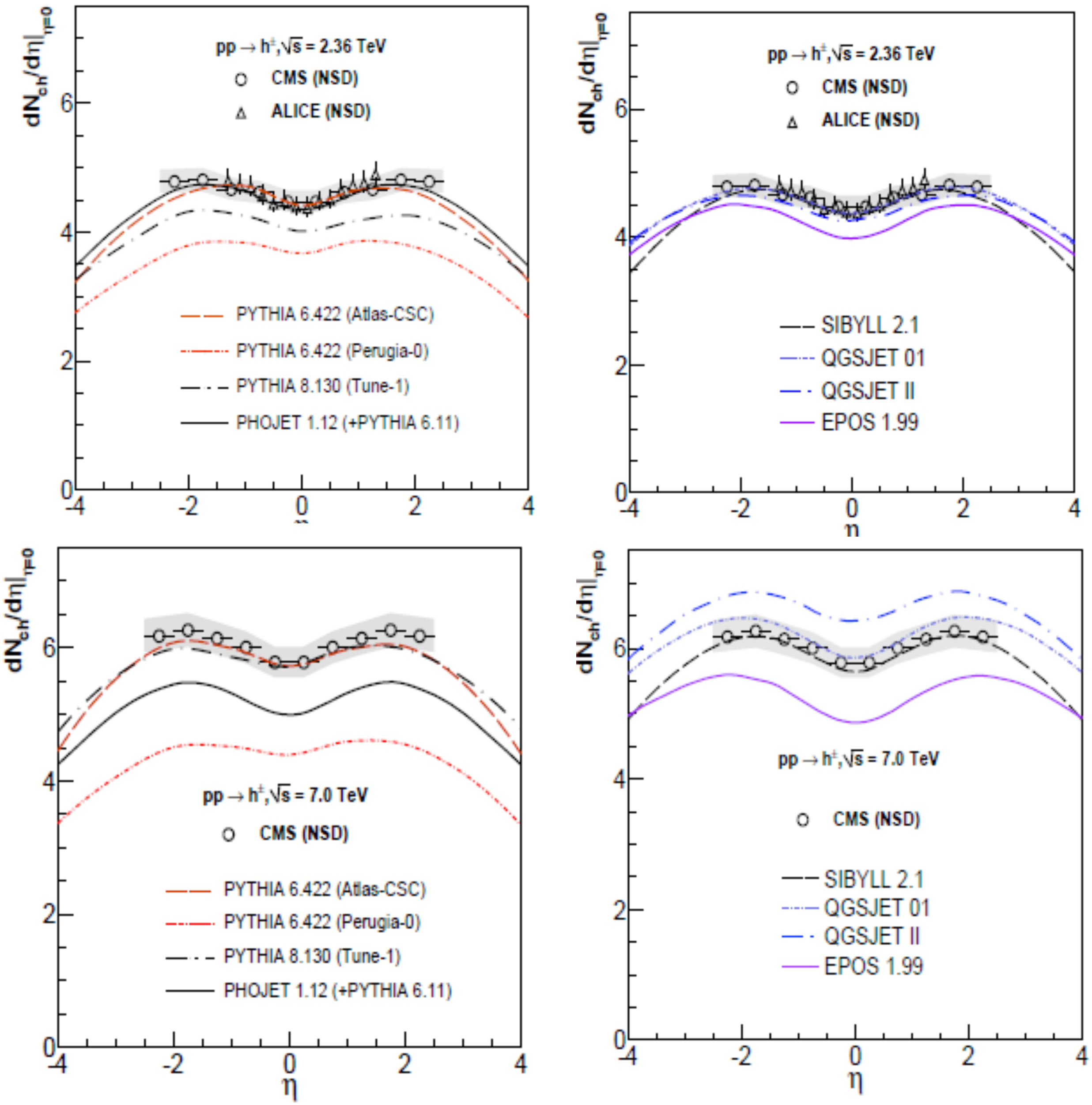
BUT

• Models do not predict the number of muons seen by the Auger Observatory

Assuming protons and QGSjetII deficit is ~ 30%

Several estimates of muon number made including FADC trace and analysis of inclined showers

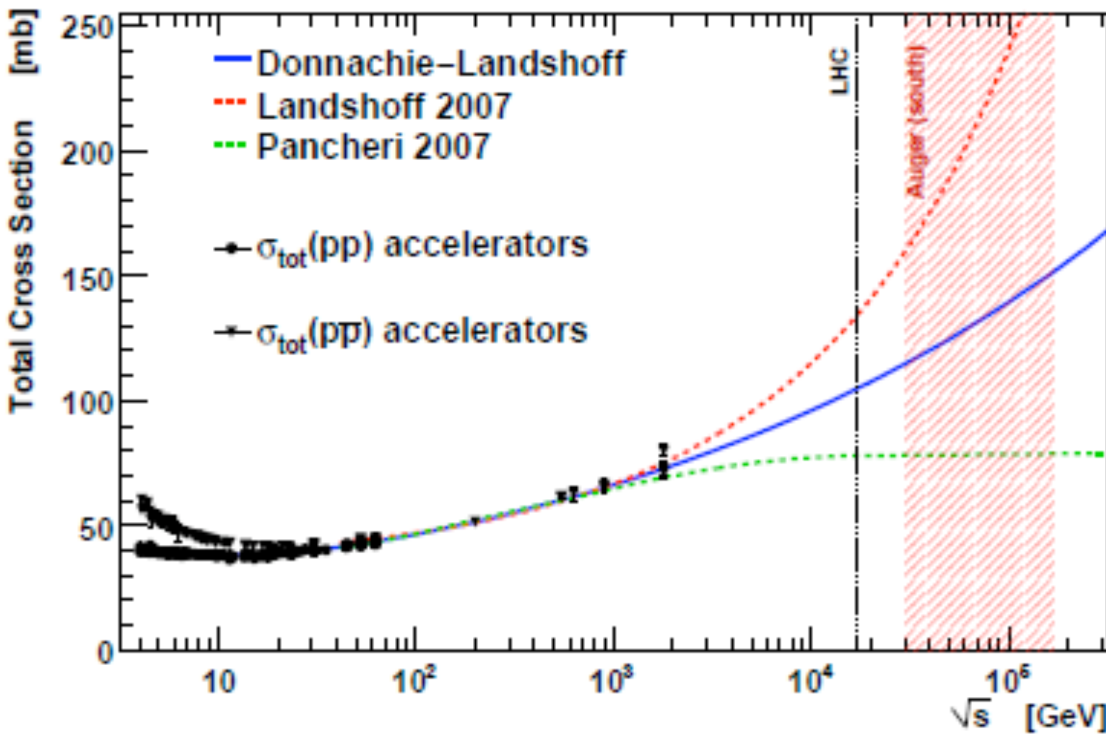
• Primary energy estimated from models is much greater than estimated from fluorescence detector approach, ~ 30%



2.36 TeV

7 TeV

Comparison of Accelerator and Cosmic Ray Models with LHC Rapidity



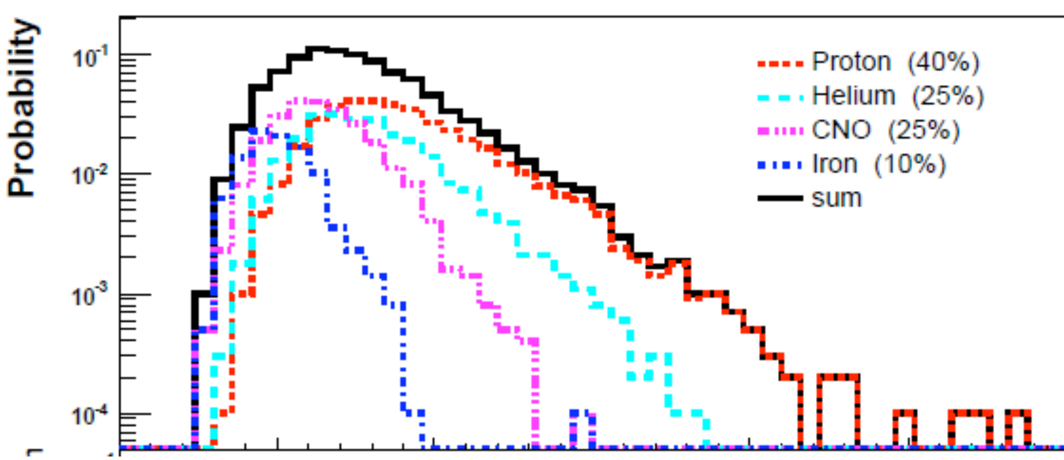
Ulrich, Engel and Unger 2011

Tail of X_{max} distribution can be used to get cross-section.

High statistics and good understanding of systematics

Auger Collaboration will report cross-section measurement this summer, at $\sqrt{s}$ = 60 TeV

favours Pancheri extrapolation



600 X_{max} g cm^{-2} 1200

UHECR, photons and neutrino fluxes

Low Energy: Excluding Sun, nothing since SN1987A

Medium Energy:
No signals yet reported from ANATARES or IceCube

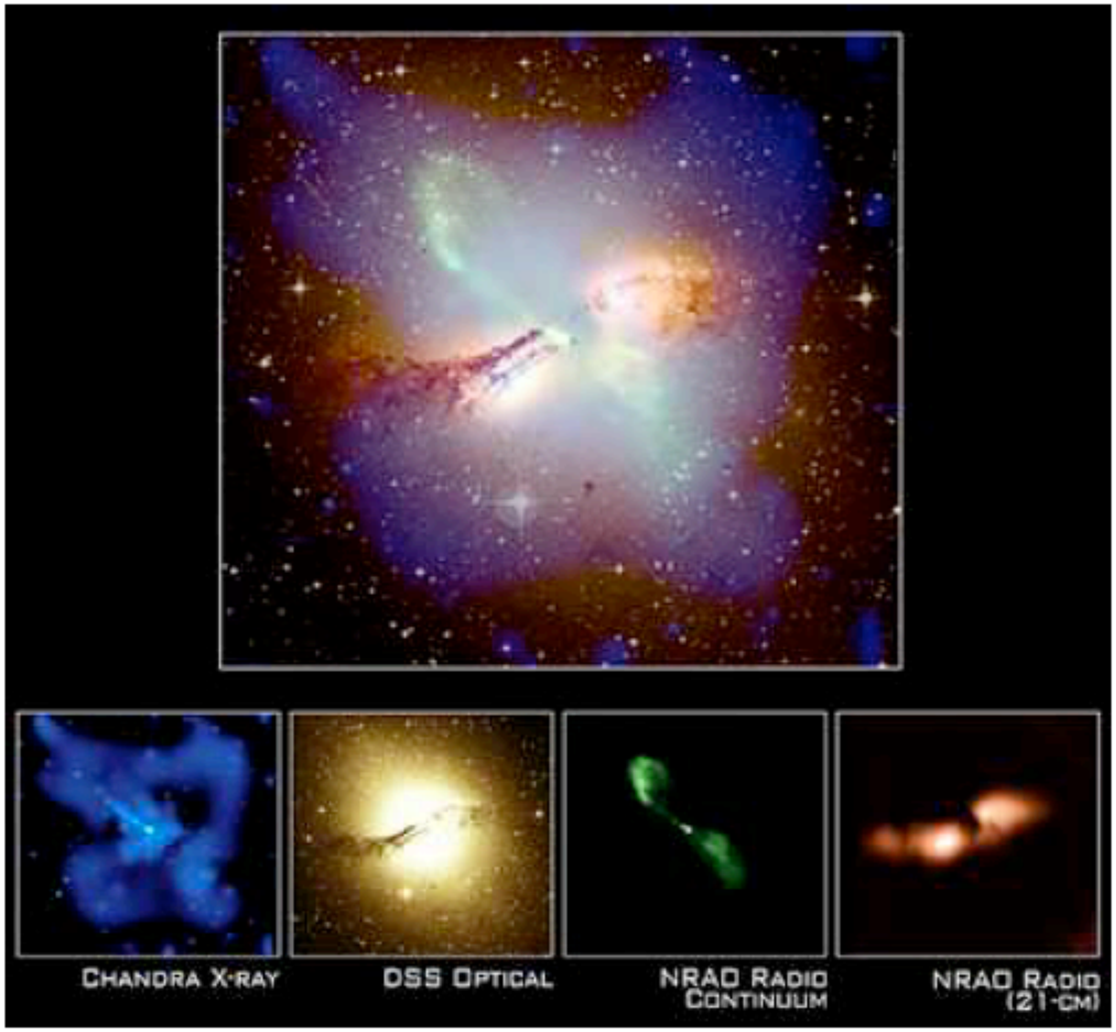
UHE Neutrinos:
Promise of ANITA and radio projects generally

Assuming that Cen A is a source both of TeV gamma-rays

and cosmic rays above 5 x 10^{19} eV:-

Can this tell us something about expected fluxes of neutrinos?

Neutrino Signals from Cen A?



General agreement (admission by modellers):

Modelling is much more uncertain than observations

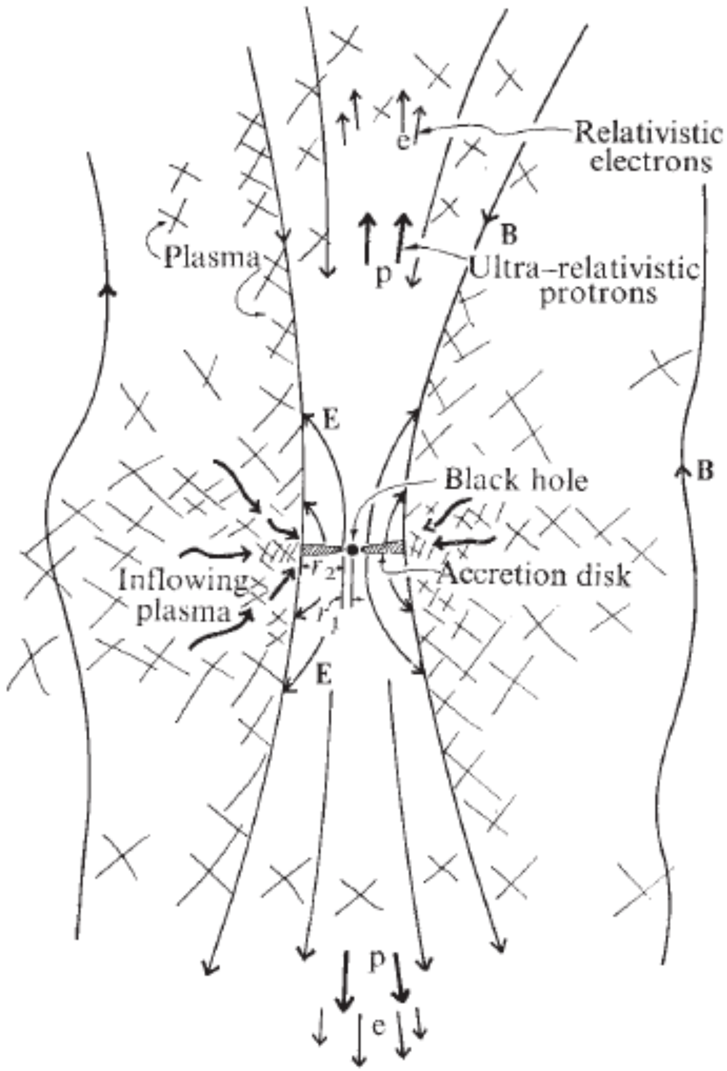
Many studies-

- **Halzen and Murchadha, 2008 arXiv: 0802.0887**
- **Cuoco and Hannested, Phys Rev D: 023007 2008**
- **Fraija, Sahu and Zhang, arXiv: 1007.0455**
- **Biermann et al., arXiv: 1012.0204**
- **Kachelreiss, Ostapchenko and Tomàs,**
  New J Phys 11 065017 2009a (arXiv:0805.2608)
  Int. Journal of Mod Phys 18 1591 2009b (arXiv: 0904.0590)
  PASA 27 482 2010 (arXiv: 1002.4874)

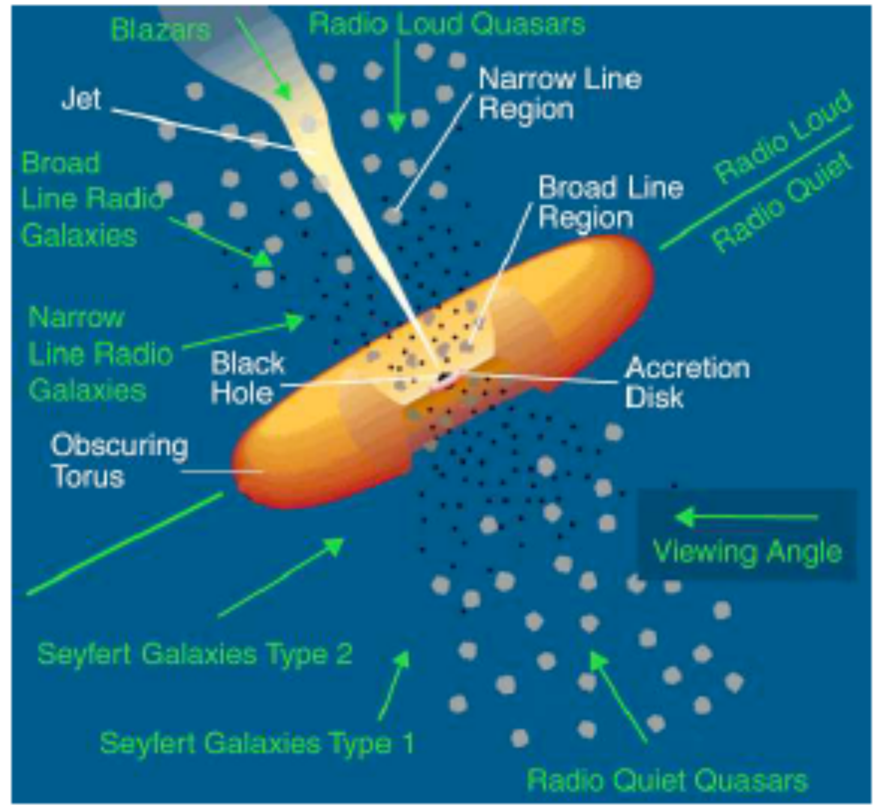
The latter efforts seem to me to be the most detailed and most careful (KOT)

Also only one that has MADE predictions for ν and γ

Paradigm for Active Galactic Nuclei



$= \frac{1}{137}$



Author?

Lovelace: Nature 262 649 1976

Does the emission come from near core or from jet?

TeV measurements cannot yet decide
- but achievable aim of CTA

KOT examined both possibilities
- but there are HUGE assumptions

Near Core: Electromagnetic Acceleration in E-field

(Blandford, Lovelace…)

then $\gamma + p \rightarrow p(n) + \pi^0(\pi^+)$

Neutrons and photons (from π^0) escape but fate of protons depends on magnetic field

In Jet: Shock Acceleration (Fermi)

then $p + p \rightarrow \text{pions} + p + p$

Uncertainties that need to be pinned down by future studies

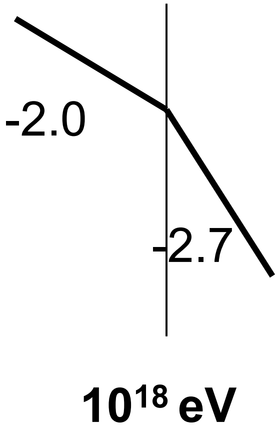
- **Magnetic fields**
- **Matter density**
- **Photon densities**

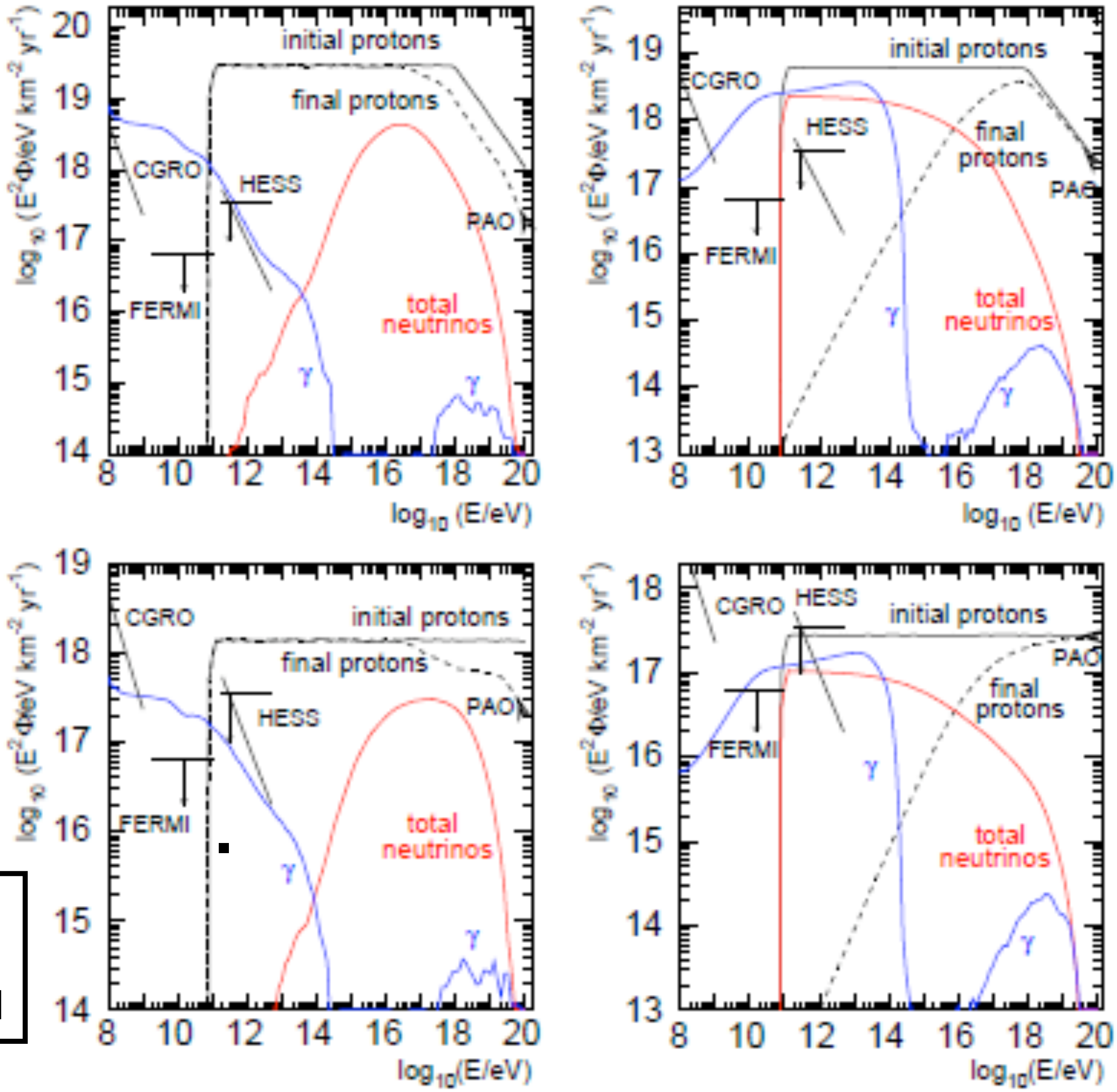
KTO make certain assumptions and calculate fluxes of neutrinos and photons, based on Auger observations of 2 events from within 3º of Cen A: not contradicted by newer data

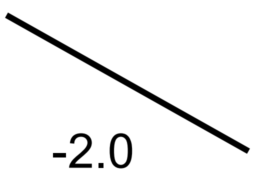
Energy spectrum of accelerated particles assumed

+ first calculations done BEFORE positive H.E.S.S. detection

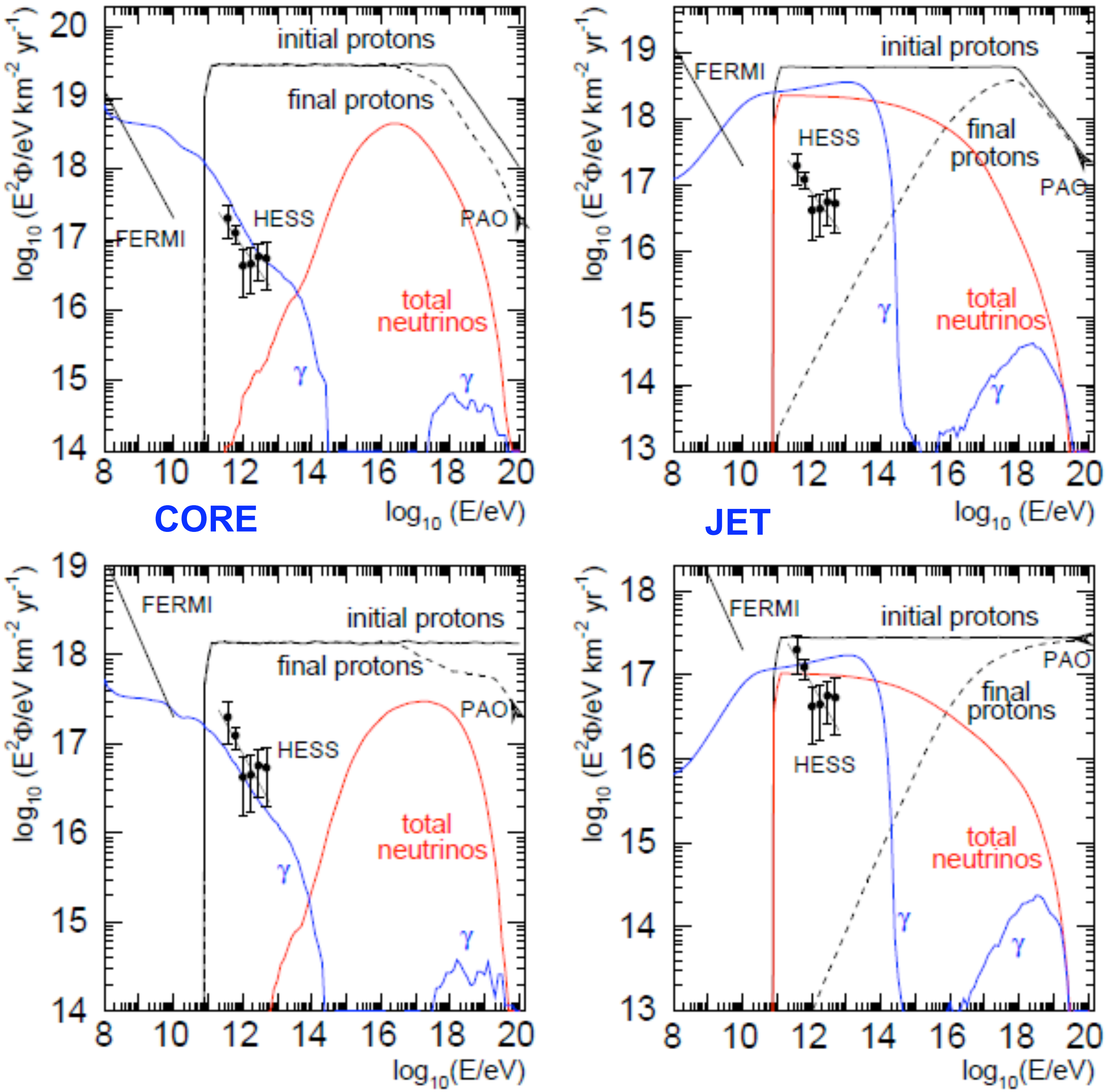
Acceleration Region **CORE** **JET** (KOT 2009A)







also slope of -1.2 - disfavoured



(KOT2009b)

Power law with Break:-

-2.0 to -2.7

Acceleration near core indicated

Power law:-

-2.0

Neutrino Flux can be calculated for different instruments

	Break in spectrum:	No break
IceCube:	Core: 0.3 per year	0.01 per year
	Jet: 0.4	0.02
km3net:	Core: 0.1 per year	7×10^{-2}
	Jet: 0.2	0.2

These numbers are very challenging for any operating, or planned, neutrino observatory

Many questions remain:-

Is the steepening due to GZK-effect?

Need to be cautious about jumping to this conclusion

Berezinsky et al: Disappointing Model (E_{max} proportional to Z)

Calvez et al (2010)

Both have discussed GRBs in galaxy (10^5 years)

Dermer (2010)

Clear that high-energy astrophysics is going to remain a very exciting field for many years

Sources, acceleration mechanisms, magnetic fields...

AND

Real prospects of some particle physics insights.

IceCube has a huge part to play in this exploration:

Good Luck!

Centauraus A with moon and the Parkes Telescope

Credit: Ilana Feain, Tim Cornwell & Ron Ekers (CSIRO/ATNF);
ATCA northern middle lobe pointing courtesy R. Morganti (ASTRON);
Parkes data courtesy N. Junkes (MPIfR);
ATCA & Moon photo: Shaun Amy, CSIRO