Dublin Astrophysics Summer School
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Cosmic Rays above 10^{18} eV

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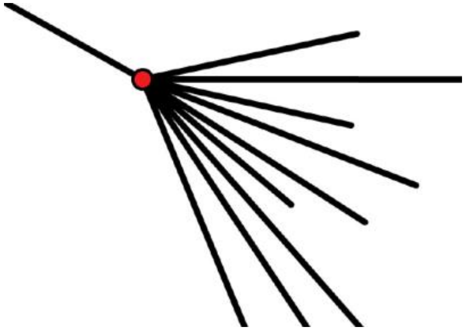
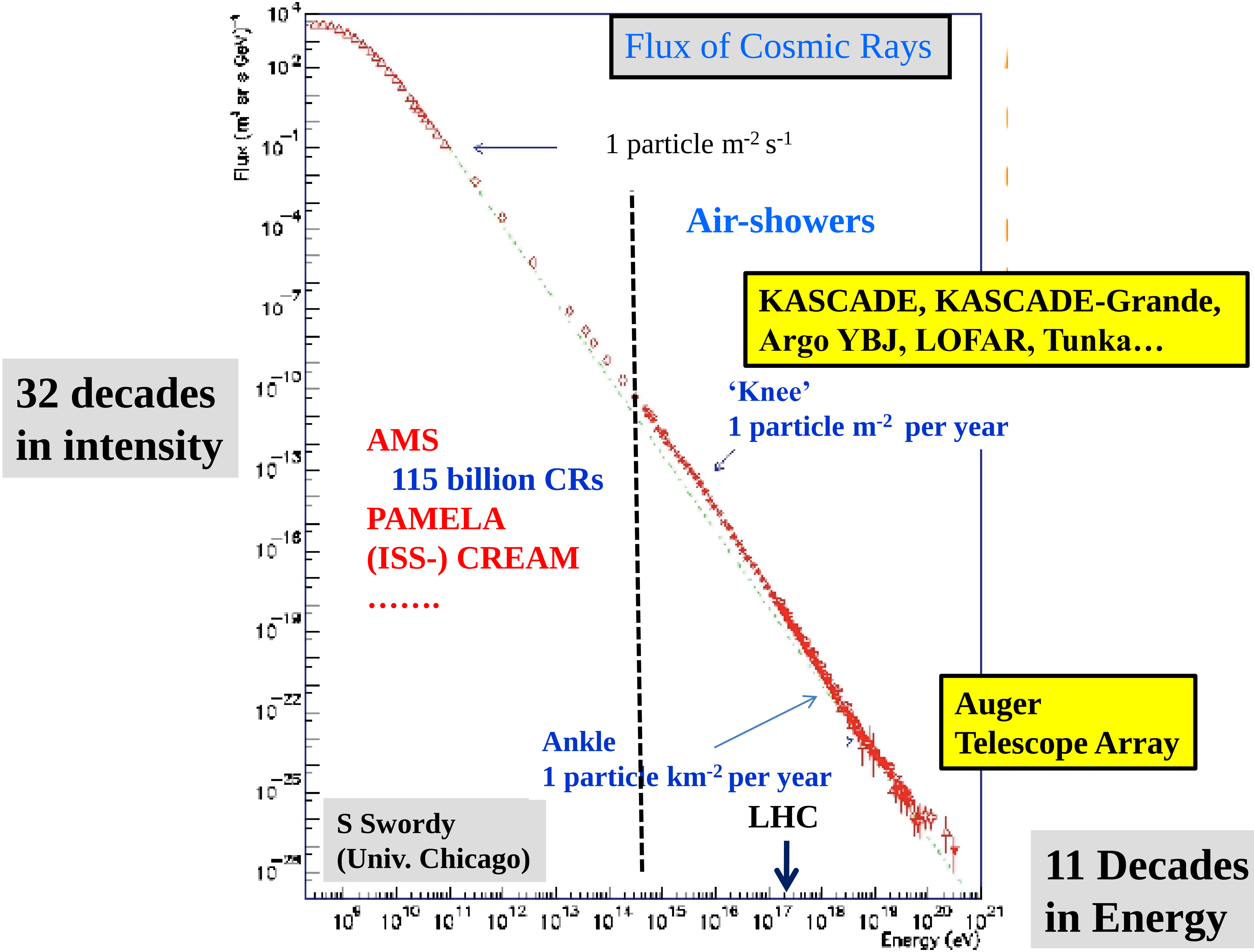


Outline

- **Some background**
- **Why and how we study particles of the highest energies**
- **The Pierre Auger Observatory**
- **Measuring the properties of Extensive Air Showers**
- **The energy spectrum**
- **Arrival Directions**
- **The mass - the problem of hadronic interactions**
- **Neutrinos – Diffuse and Multi-messenger**


Flux of Cosmic Rays
1 particle m^{-2} s^{-1}
Air-showers
KASCADE, KASCADE-Grande,
Argo YBJ, LOFAR, Tunka…
32 decades
in intensity
'Knee'
1 particle m^{-2} per year
AMS
115 billion CRs
PAMELA
(ISS-) CREAM
…….
Auger
Telescope Array
Ankle
1 particle km^{-2} per year
LHC
S Swordy
(Univ. Chicago)
11 Decades
in Energy
Flux (m^2 sr s GeV)$^{-1}$
10^4
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}
Energy (eV)

Questions to answer to discover the origin of the highest energy cosmic rays

(i) Are there excesses from some regions of sky?

Deflections in magnetic fields:

at ~ 10^{19} eV: still ~ 10° for proton in Galactic magnetic field

(ii) Steepening of spectrum above 5 x 10^{19} eV as predicted?

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

$$\gamma_{2.7\,K} + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \;\text{ or }\; p + \pi^o$$

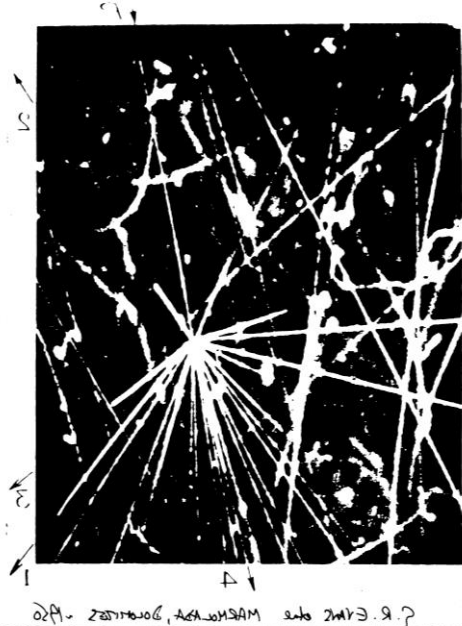
and

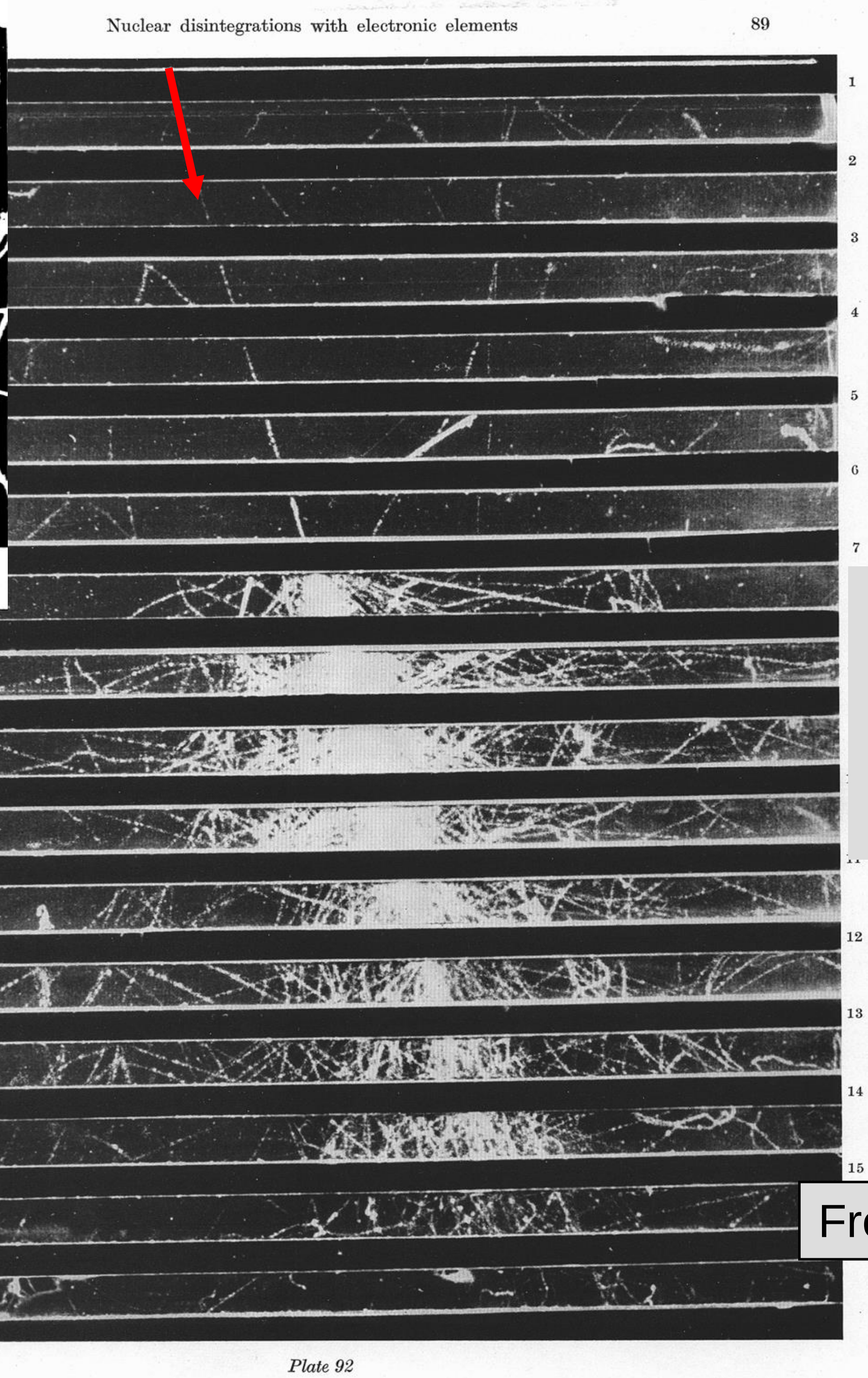
$$\gamma_{IR/2.7\,K} + A \rightarrow (A - 1) + n$$

Sources must lie within about 100 Mpc

(iii) Mass Composition – nuclei, neutrons and photons?

All three observations are needed to infer the origin(s)





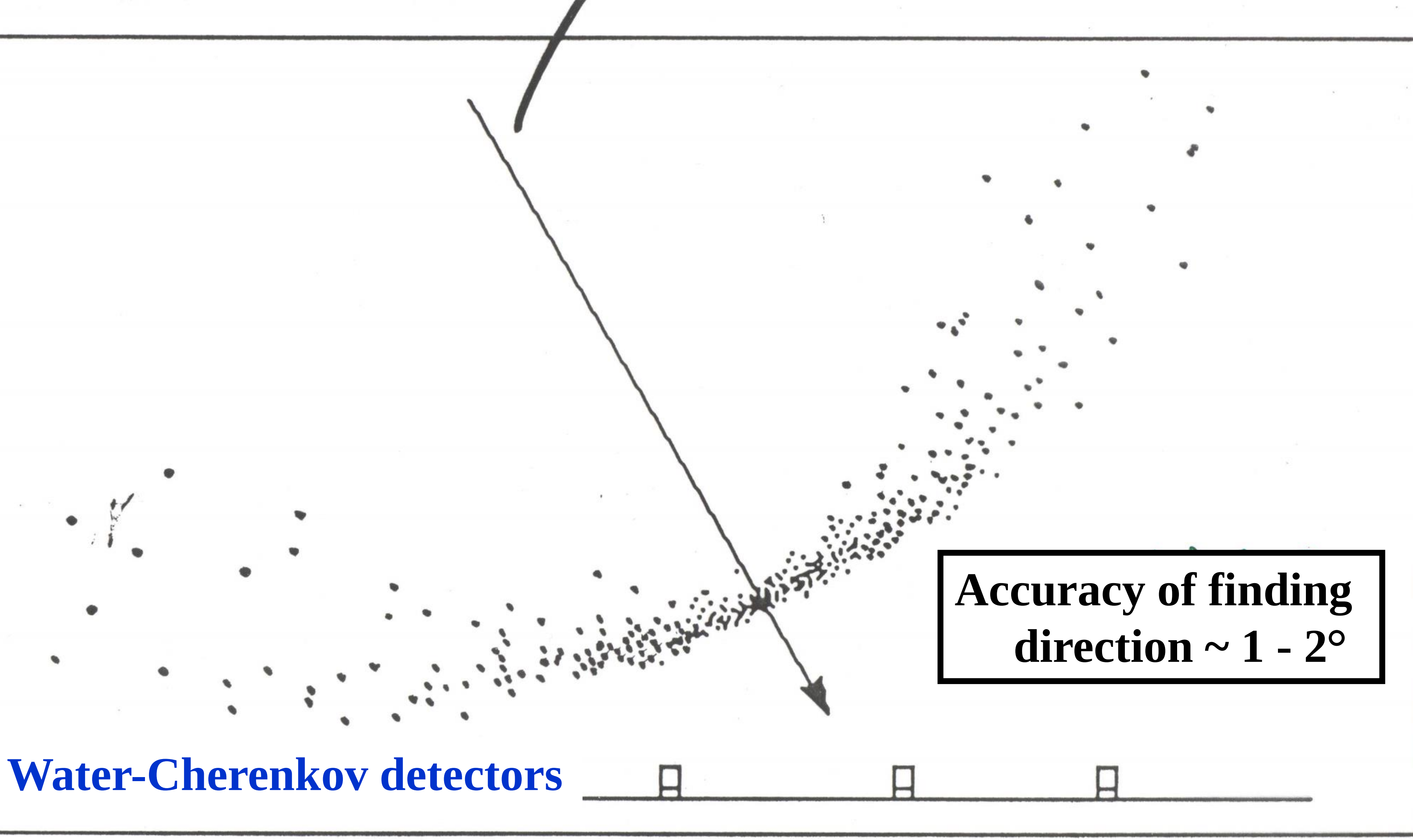
1.3 cm Pb

10 GeV proton

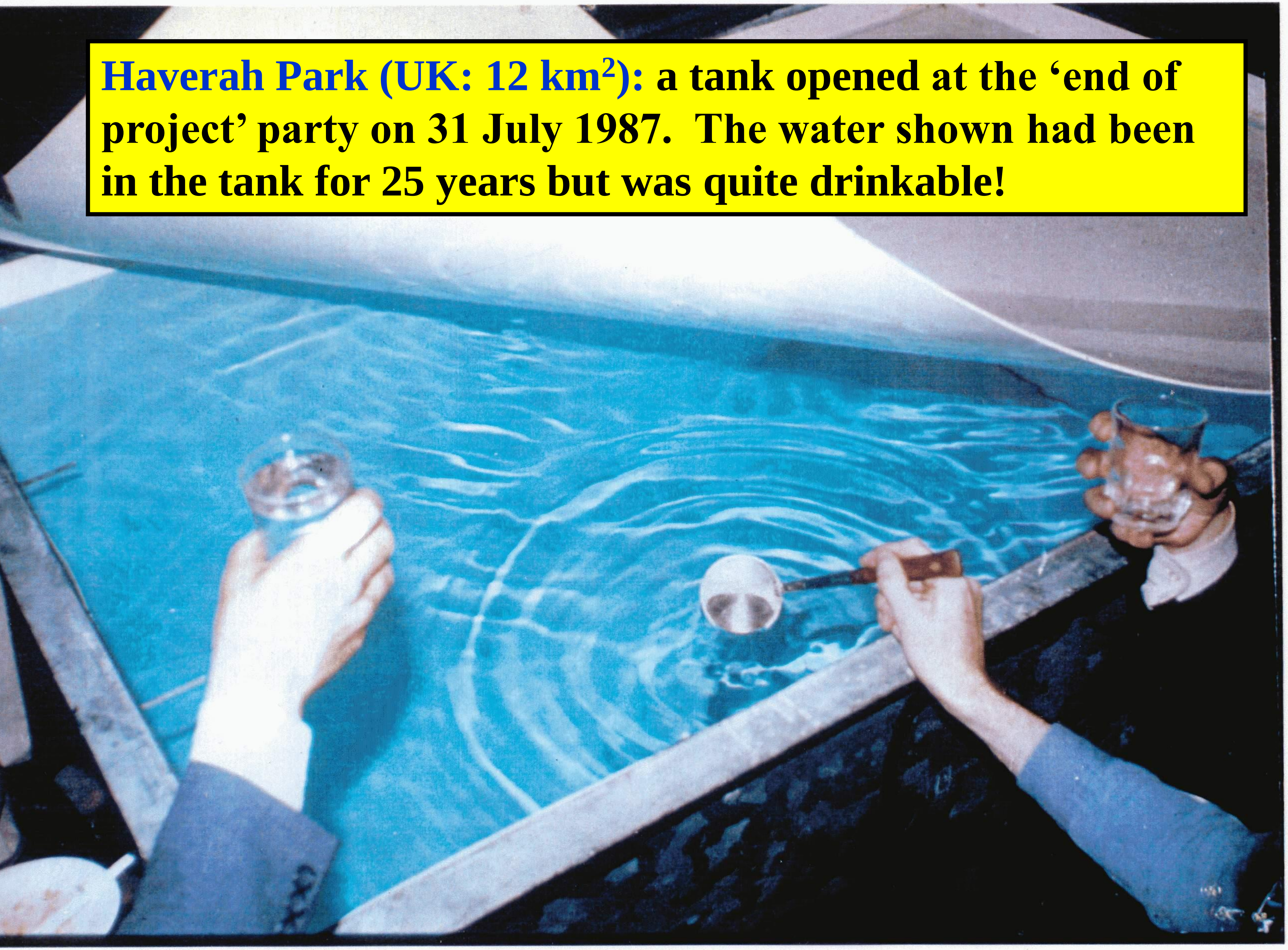
Shower initiated by proton in lead plates of cloud chamber

Detectors can find particle number and arrival times

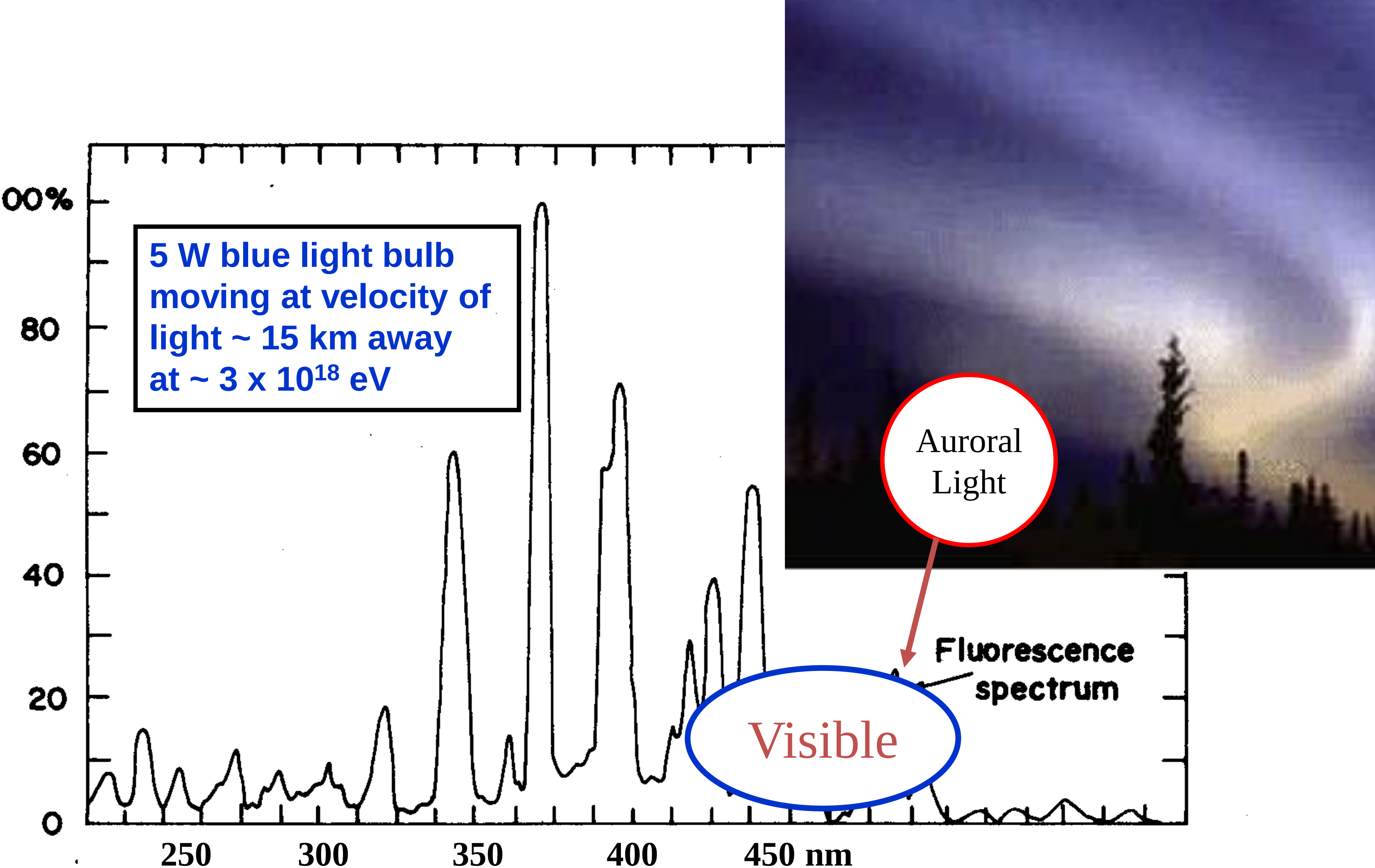
Fretter: Echo Lake, 1949

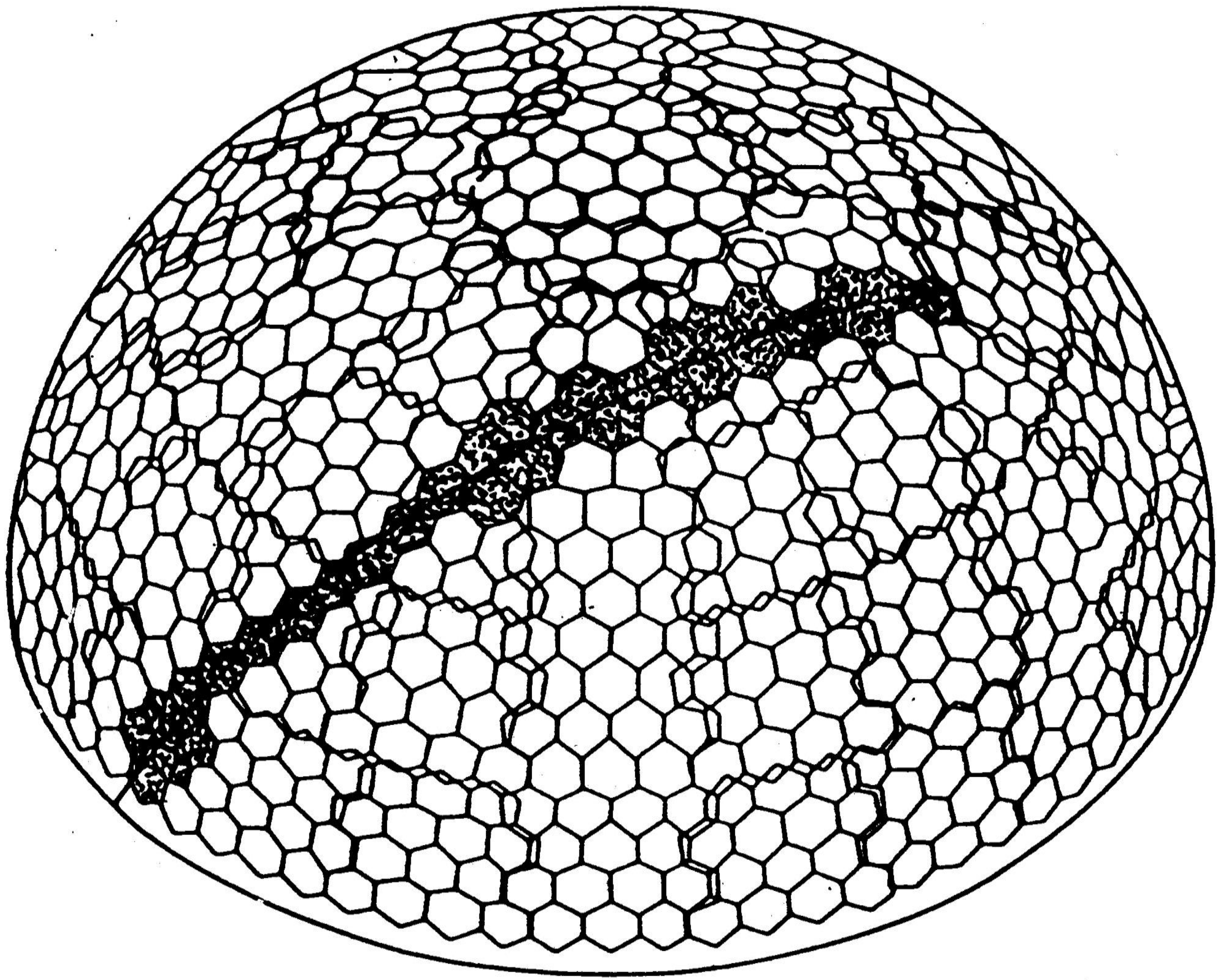


‘Fast timing’ gives the direction



Haverah Park (UK: 12 km^2): a tank opened at the 'end of project' party on 31 July 1987. The water shown had been in the tank for 25 years but was quite drinkable!

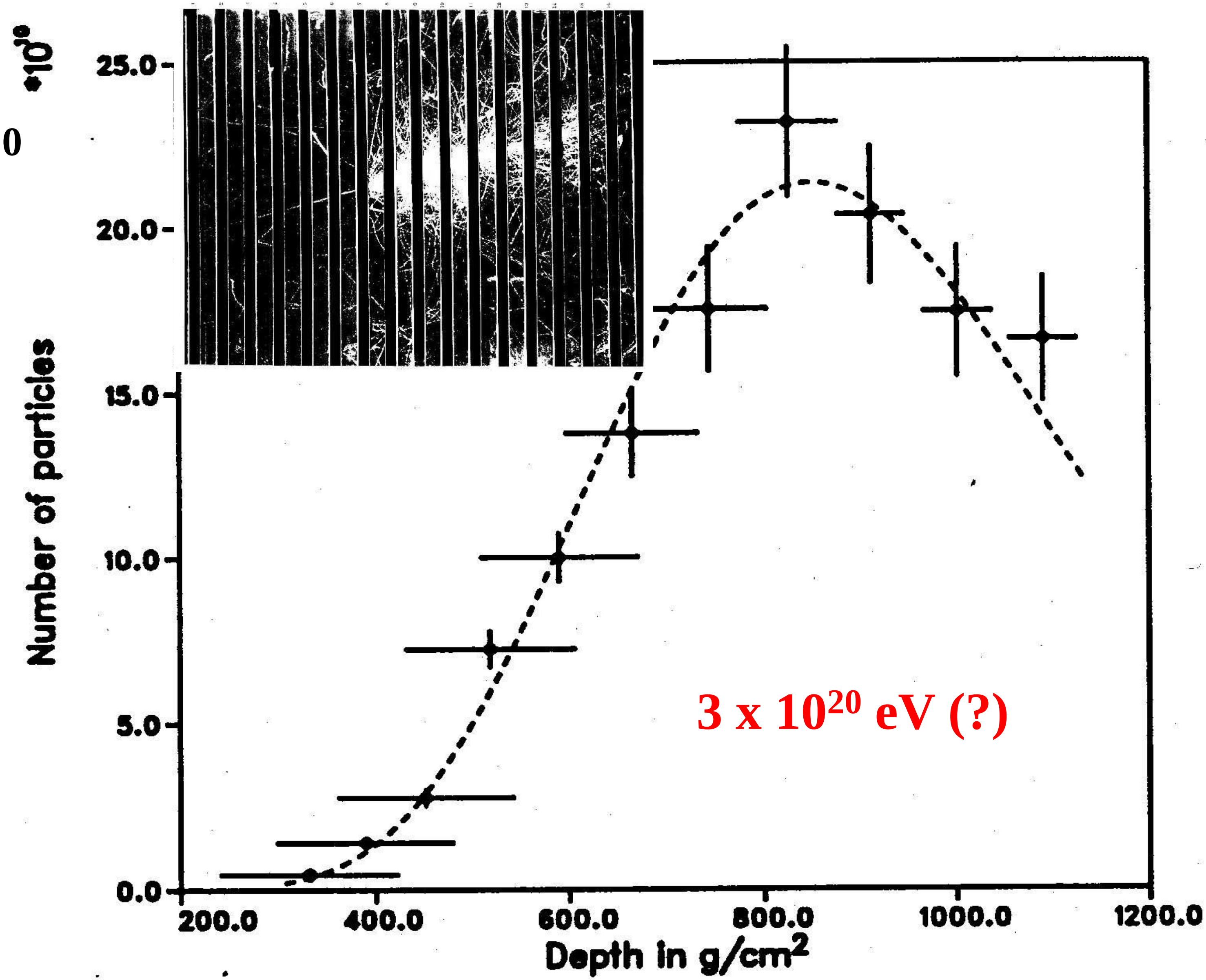

5 W blue light bulb moving at velocity of light ~ 15 km away at ~ 3 x 10^18 eV
00%
80
60
40
20
0
250
300
350
400
450 nm
Fluorescence spectrum
Auroral Light
Visible



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

A Fluorescence Detector of the Utah University Group

x 10^{10}



3 x 10^{20} eV (?)

Different techniques gave different results

- but all agreed that rate of energetic cosmic rays is low:-

< 1 per km^2 per century at 10^{20} eV

(~ 10/min on earth's atmosphere)

1990: Needed larger areas > 1000 km^2

1991: Started working with Jim Cronin (Chicago) to form a collaboration to design and build such an instrument (3000 km^2) - and to raise the money

These efforts helped create the Pierre Auger Observatory

The Auger Schematic Design

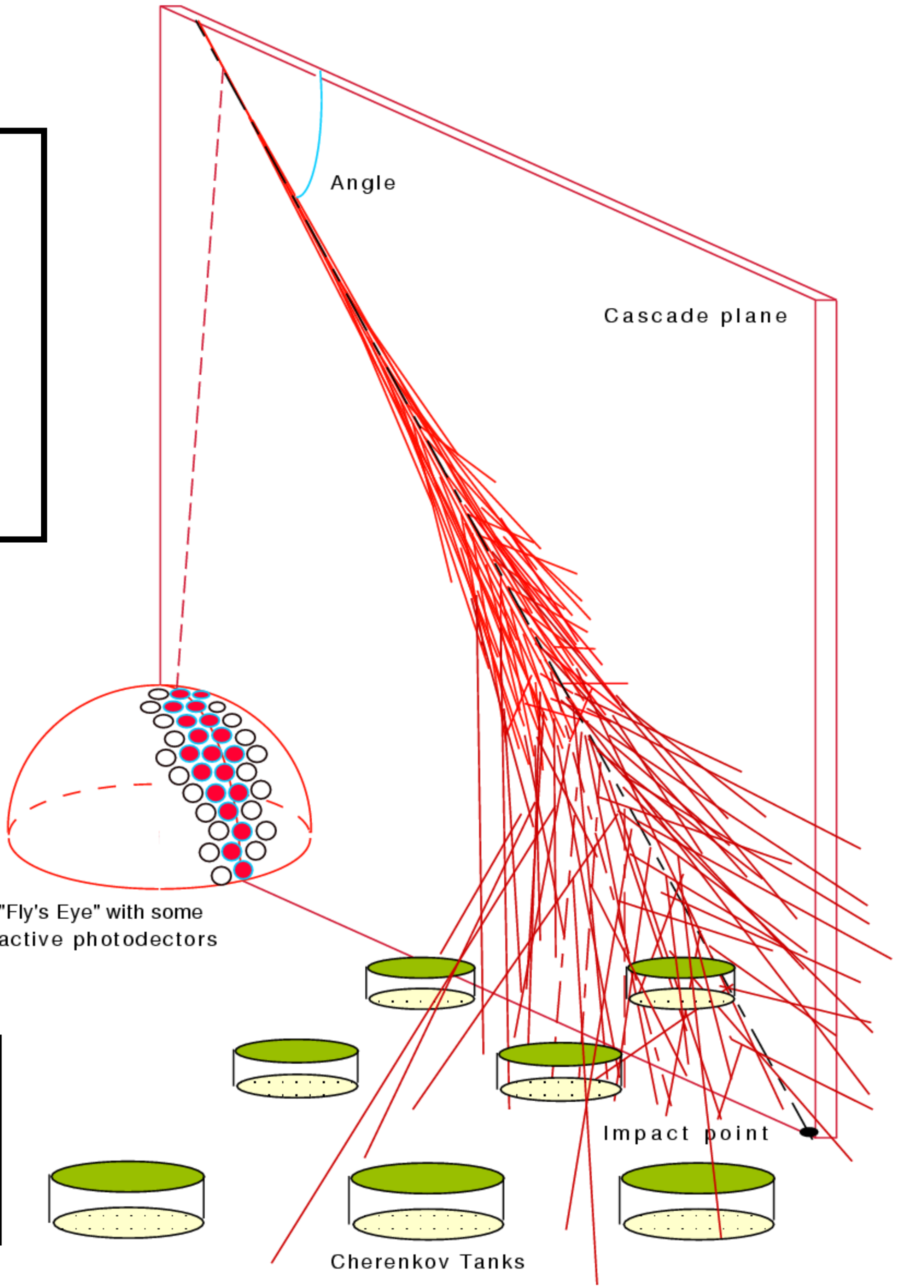
The design of the Pierre Auger Observatory marries two well-established techniques

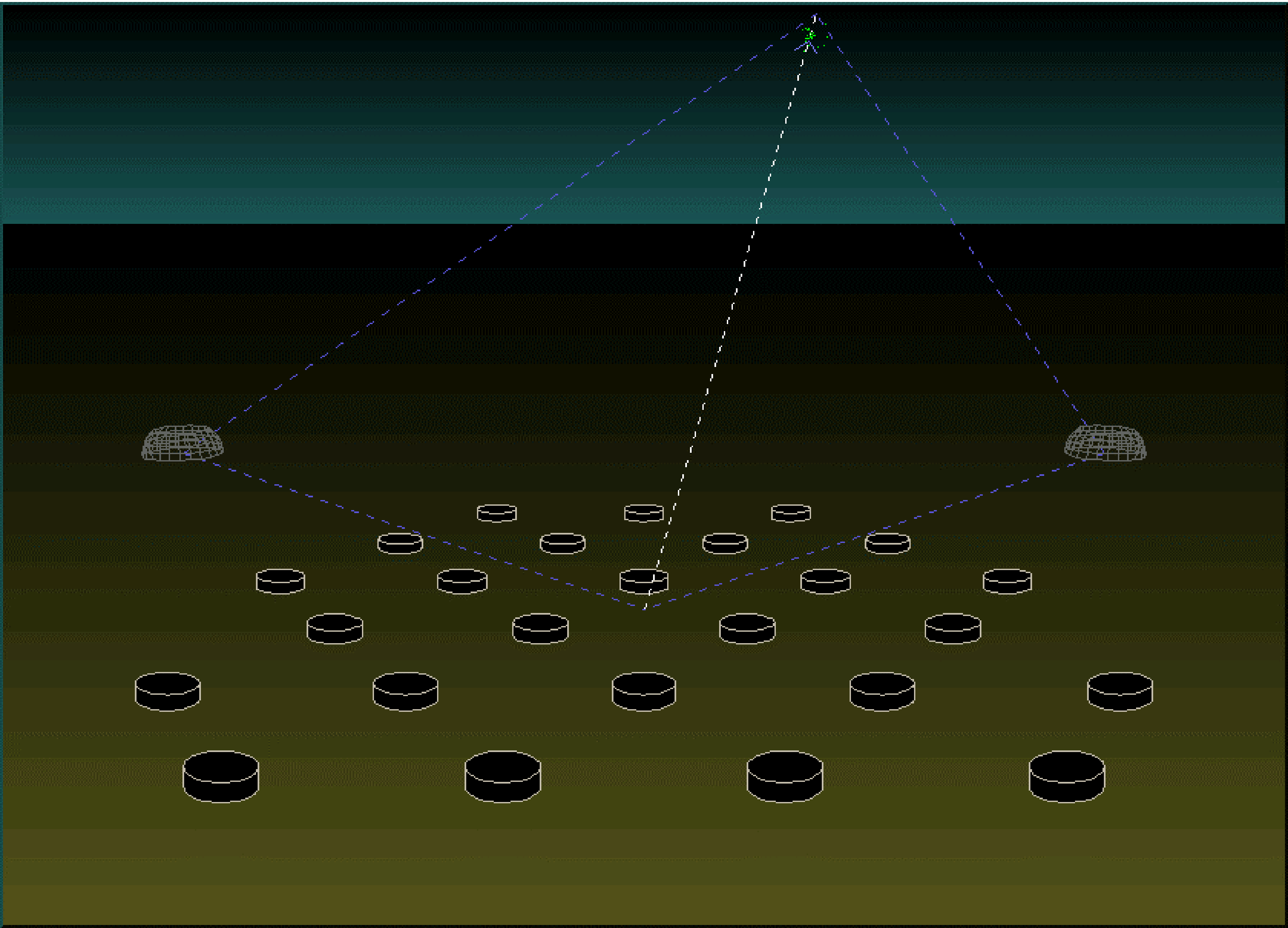
→ the 'HYBRID' technique

Fluorescence →

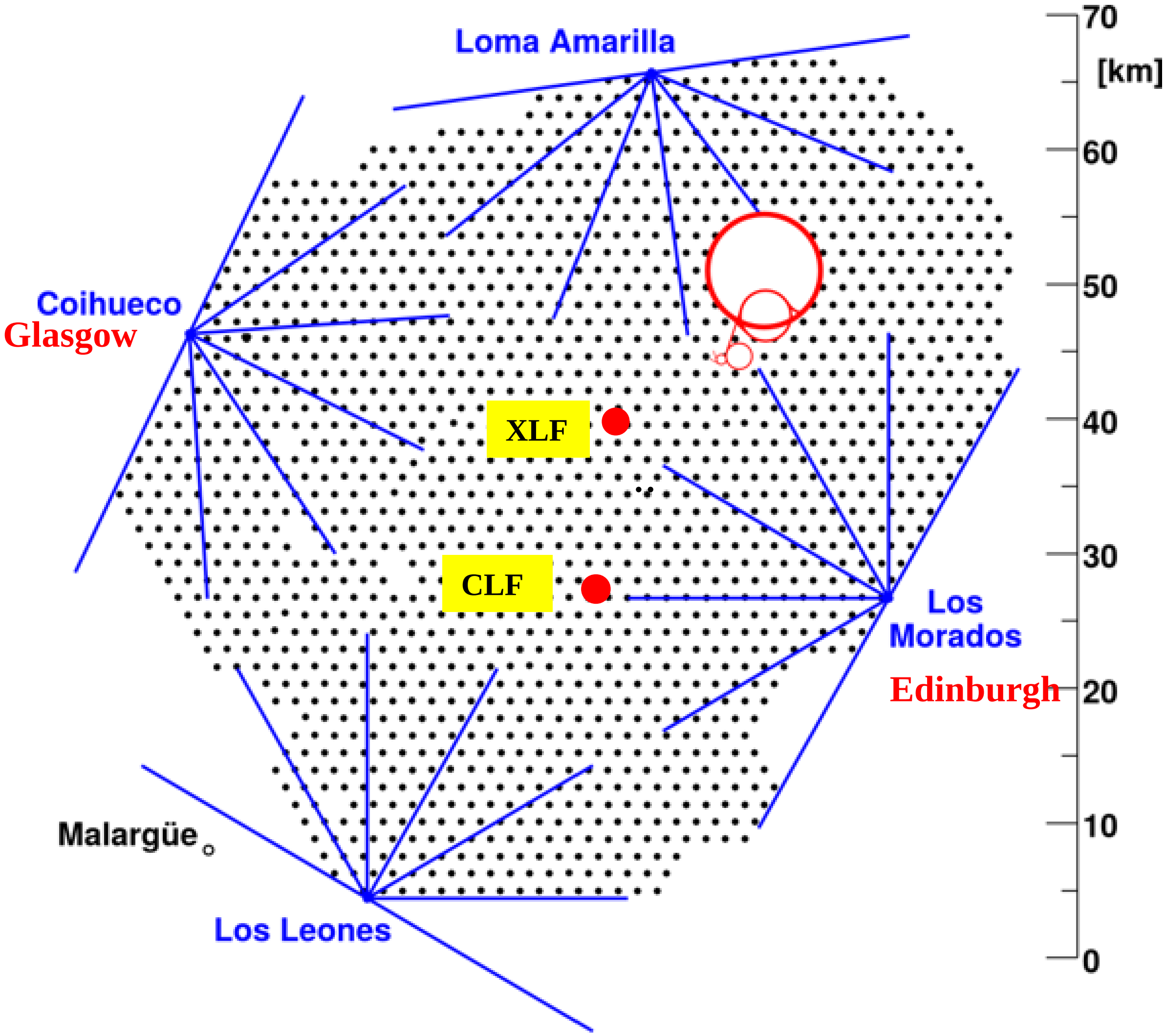
AND

Arrays of water-Cherenkov detectors →





The Pierre Auger Observatory: Malargüe, Argentina

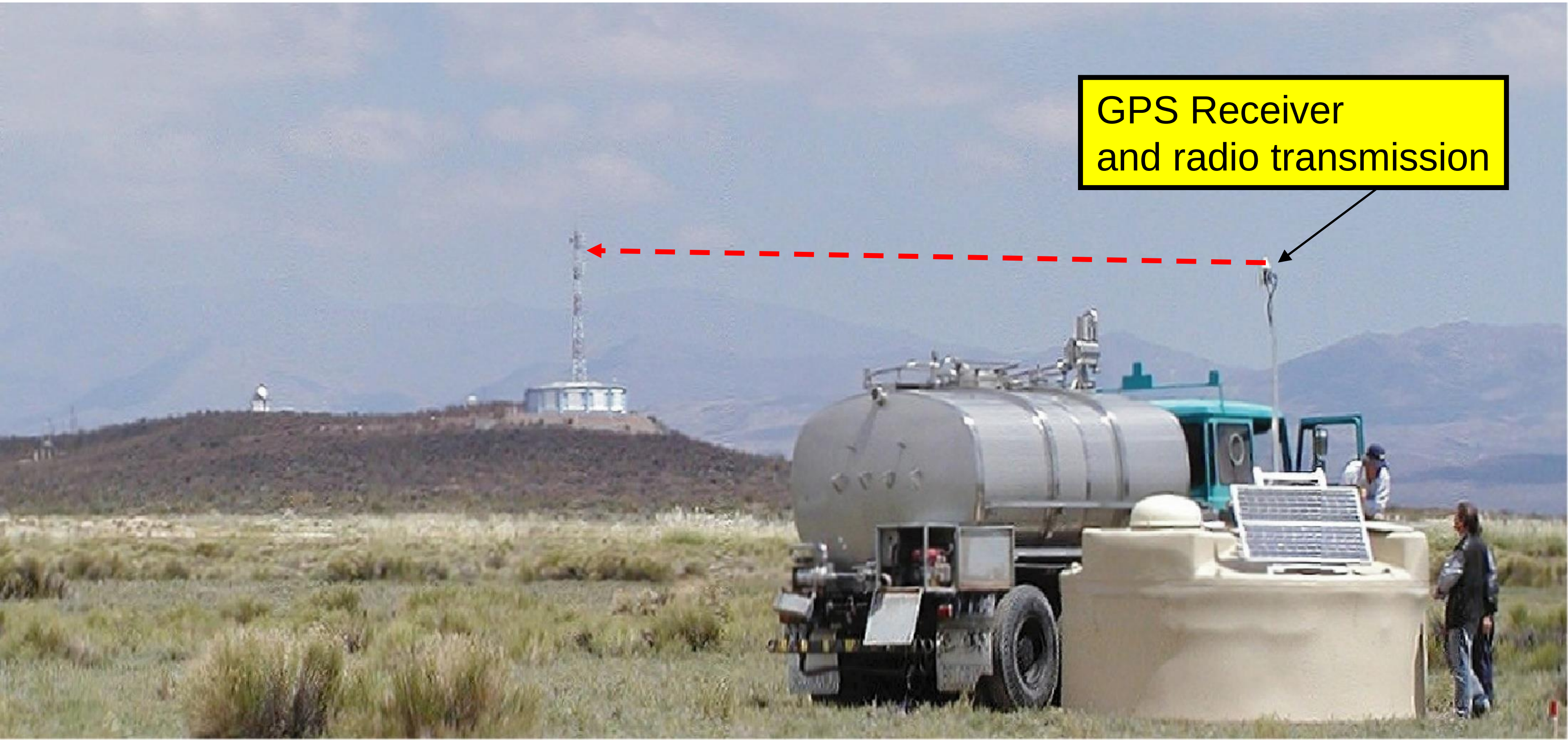


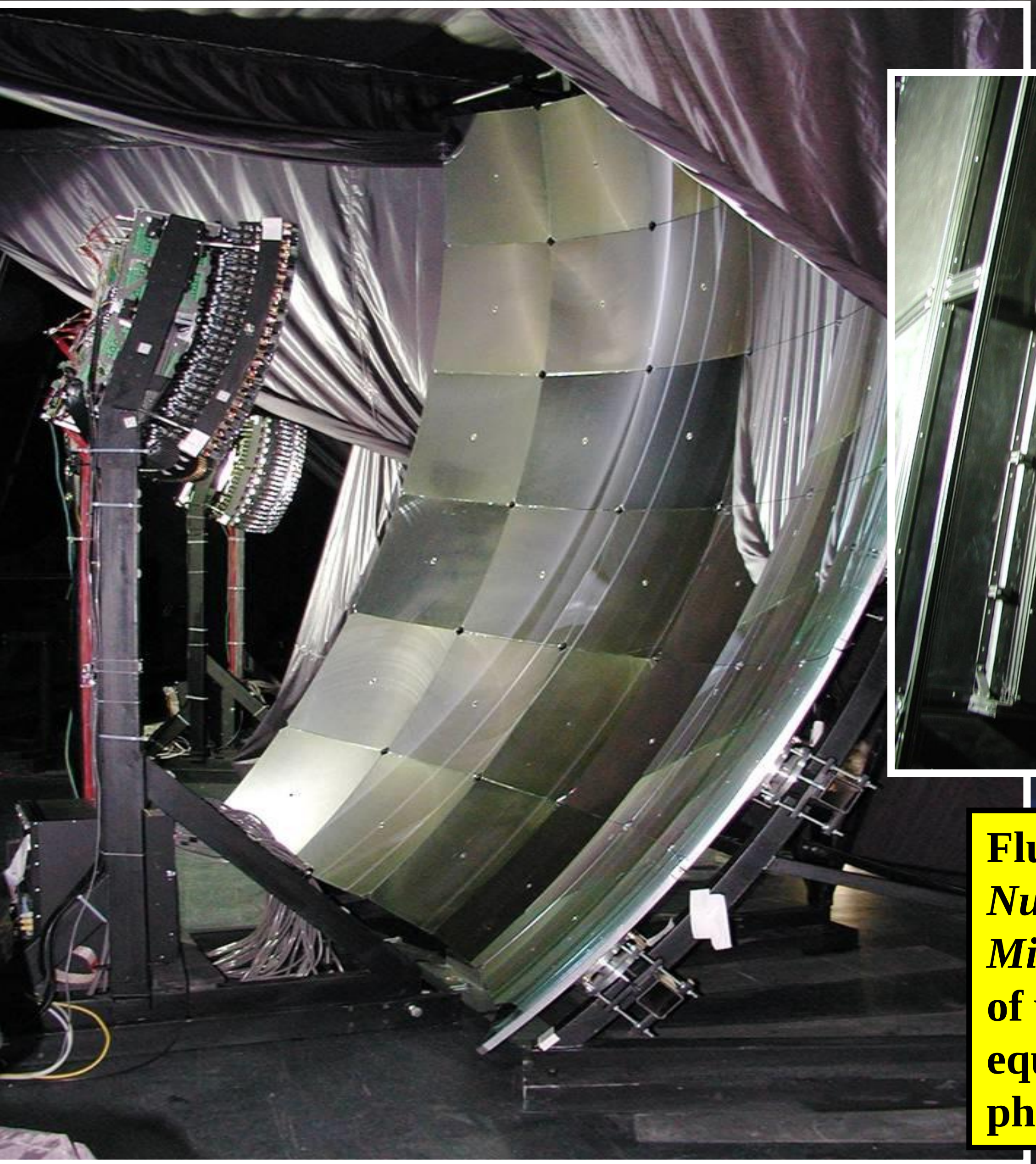
- 1600 water-Cherenkov detectors: 10 m^2 x 1.2 m
- 3000 km^2
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
- Capital cost ~$50M
- About the area of Limerick

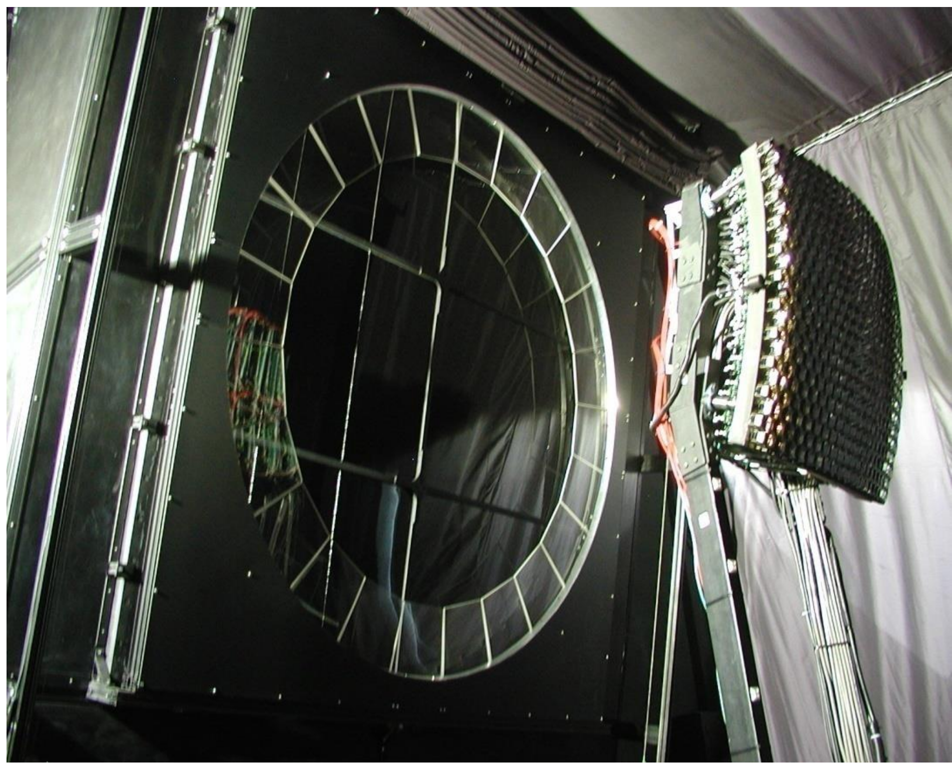
The Auger Observatory Campus in Argentina

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


29. 6. 1999

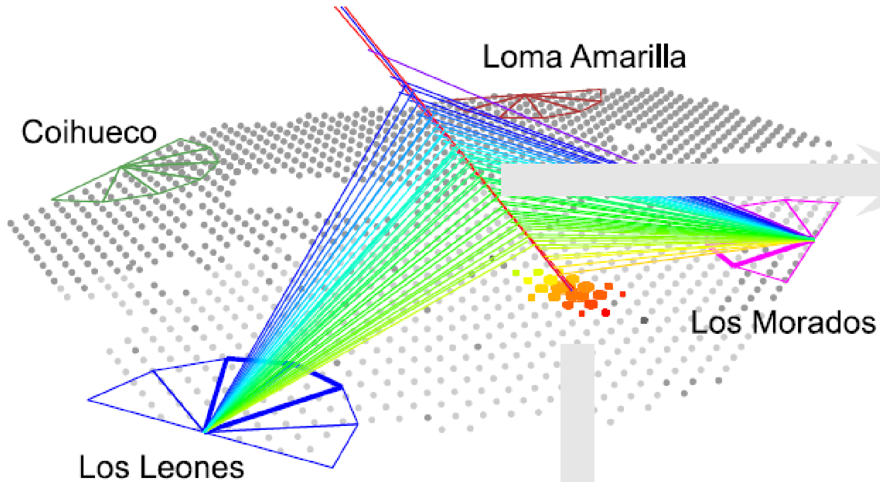

GPS Receiver
and radio transmission

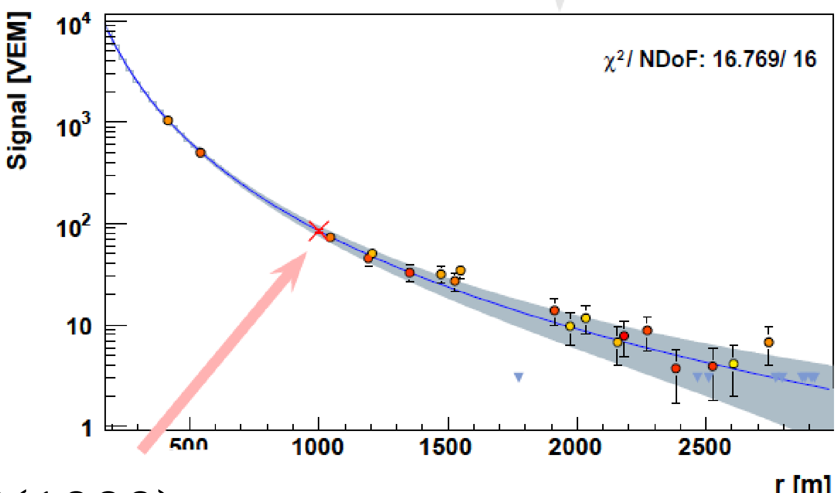




Fluorescence telescopes:
Number of telescopes: **24**
Mirrors: **3.6 m x 3.6 m with field of view 30º x 30º, each telescope is equipped with 440 photomultipliers**

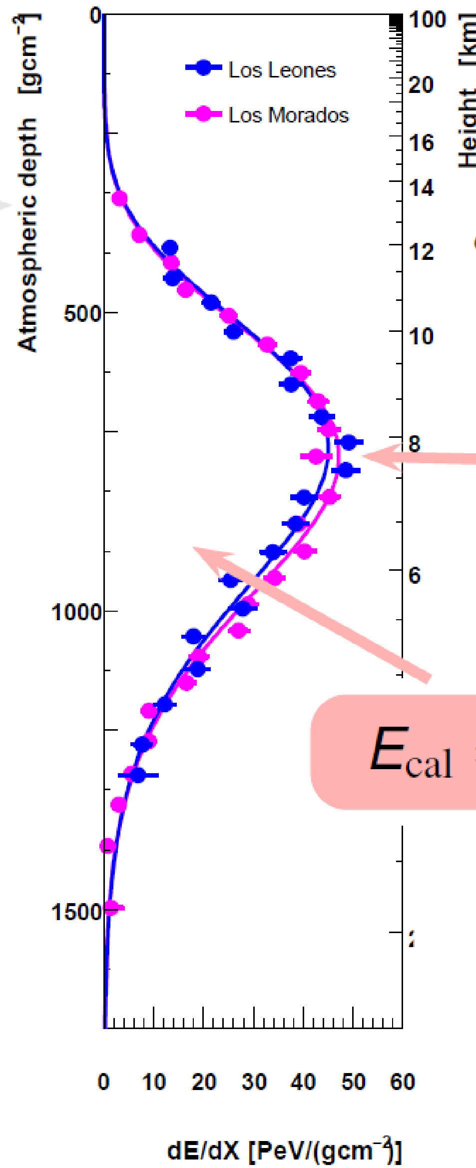
Hybrid Detection of Air Showers





S(1000)

$$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$$



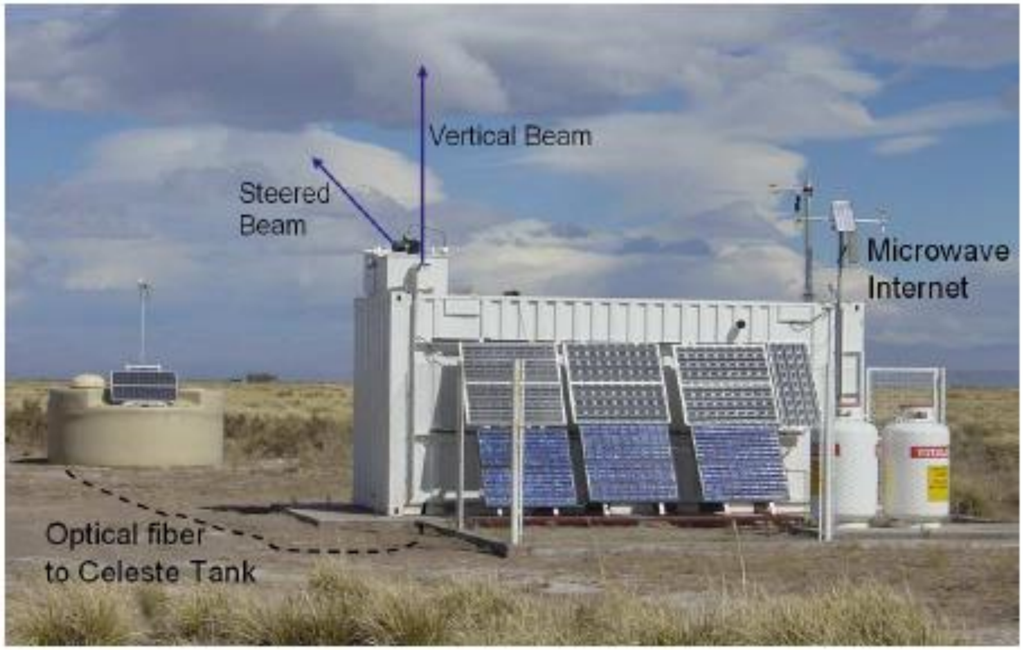
$$\sigma_{X_{\mathrm{max}}} \leq 20\,\mathrm{g/cm^2}$$
$$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$$

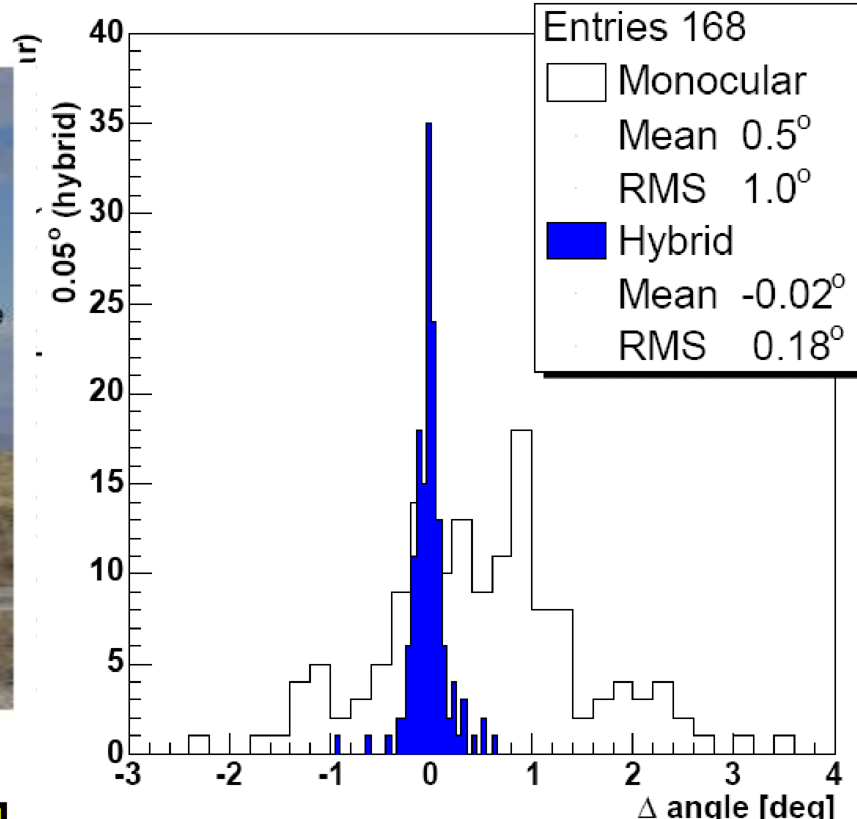
X_{max}

$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$

$$\sigma_E/E \sim 8\,\%$$
$$\Delta_{\mathrm{sys}} \approx 15\,\%$$

Angular Resolution from Central Laser Facility

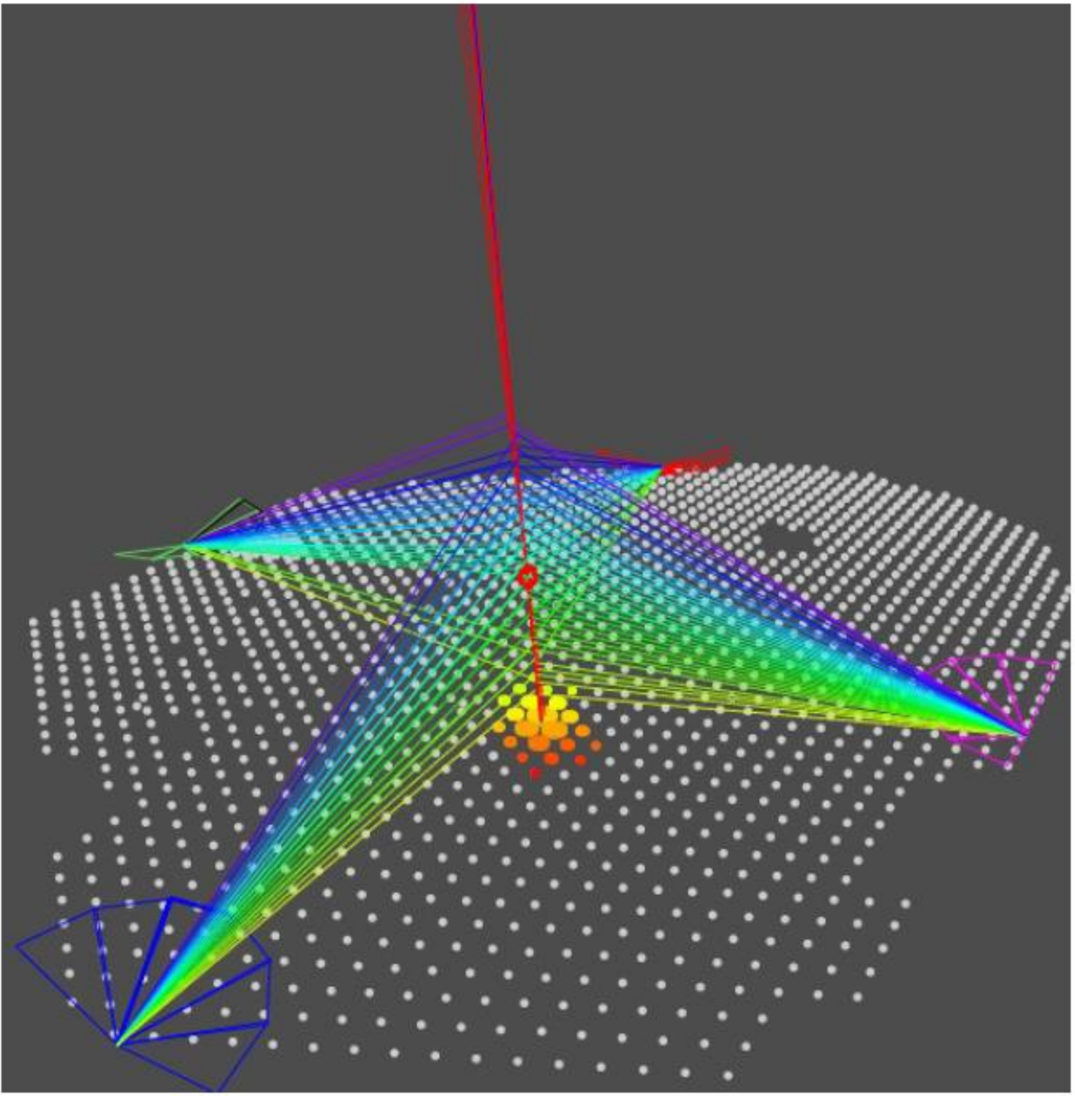


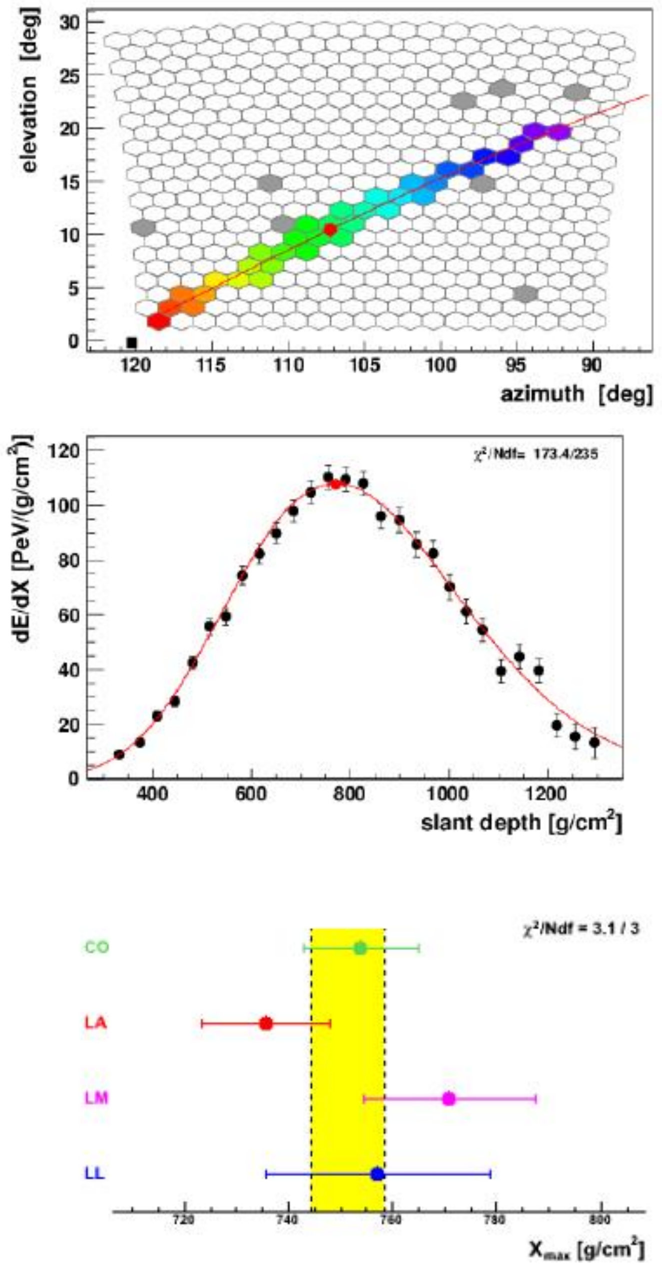


355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

Mono/hybrid rms 1.0°/0.18°

Precision of the energy measurement

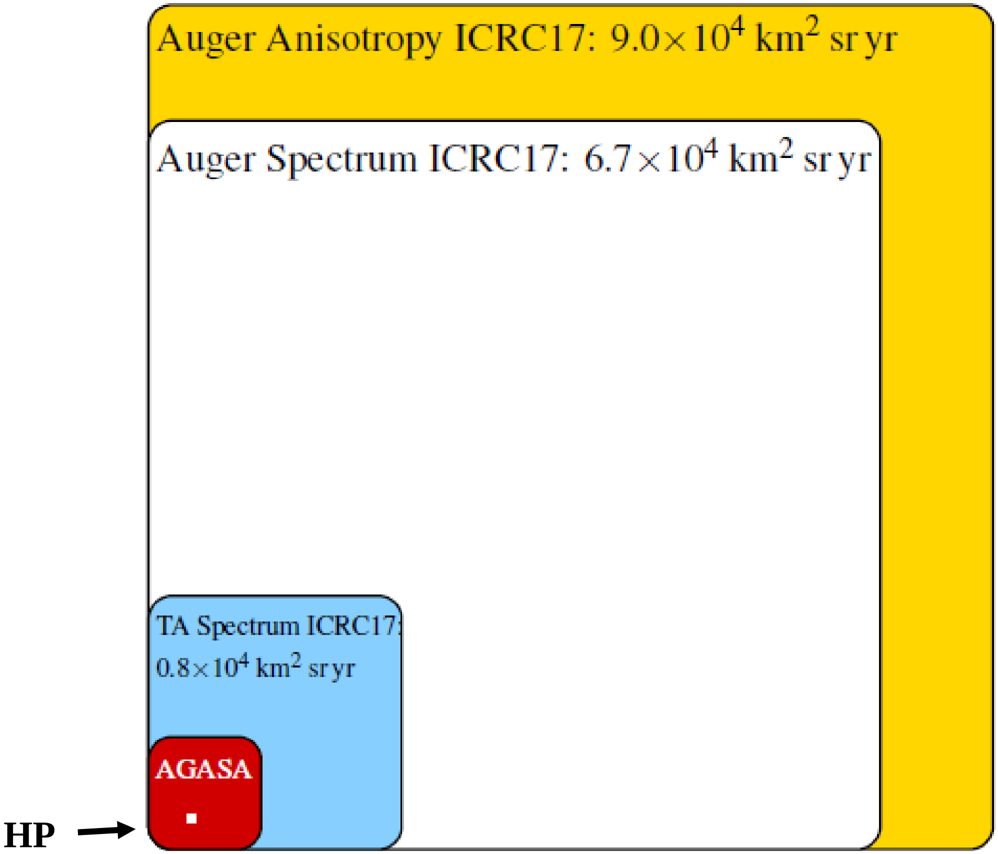




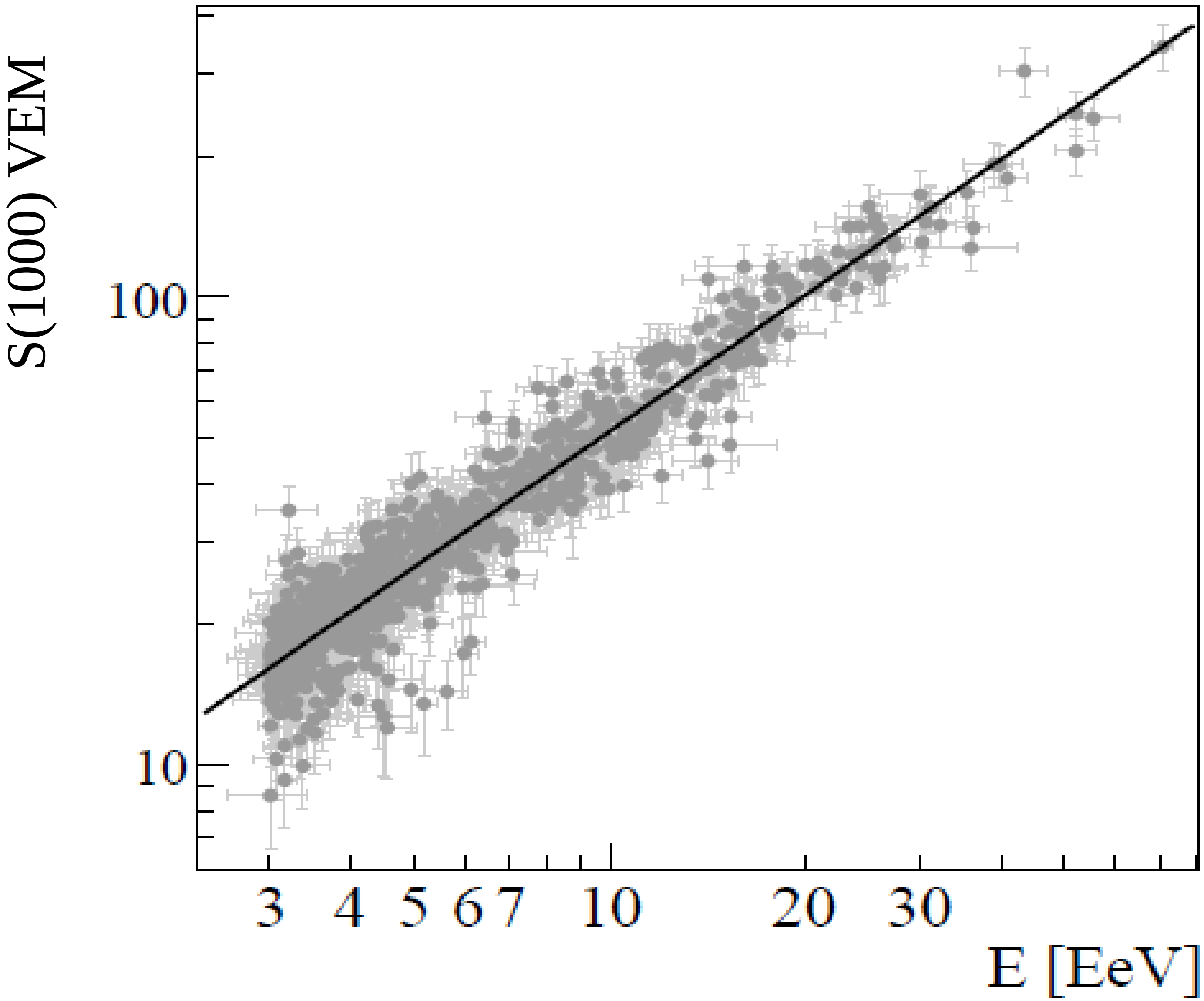
$E = 7.1 \pm 0.2\ 10^{19}$ eV - $X_{max} = 752 \pm 7$ g/cm^2

2004: Data taking started with about 200 water-Cherenkov detectors and two fluorescence telescopes - 13 years after first discussions

Soon surpassed the exposure at Haverah Park accrued in 20 years – now over 67,000 km^2 sr years



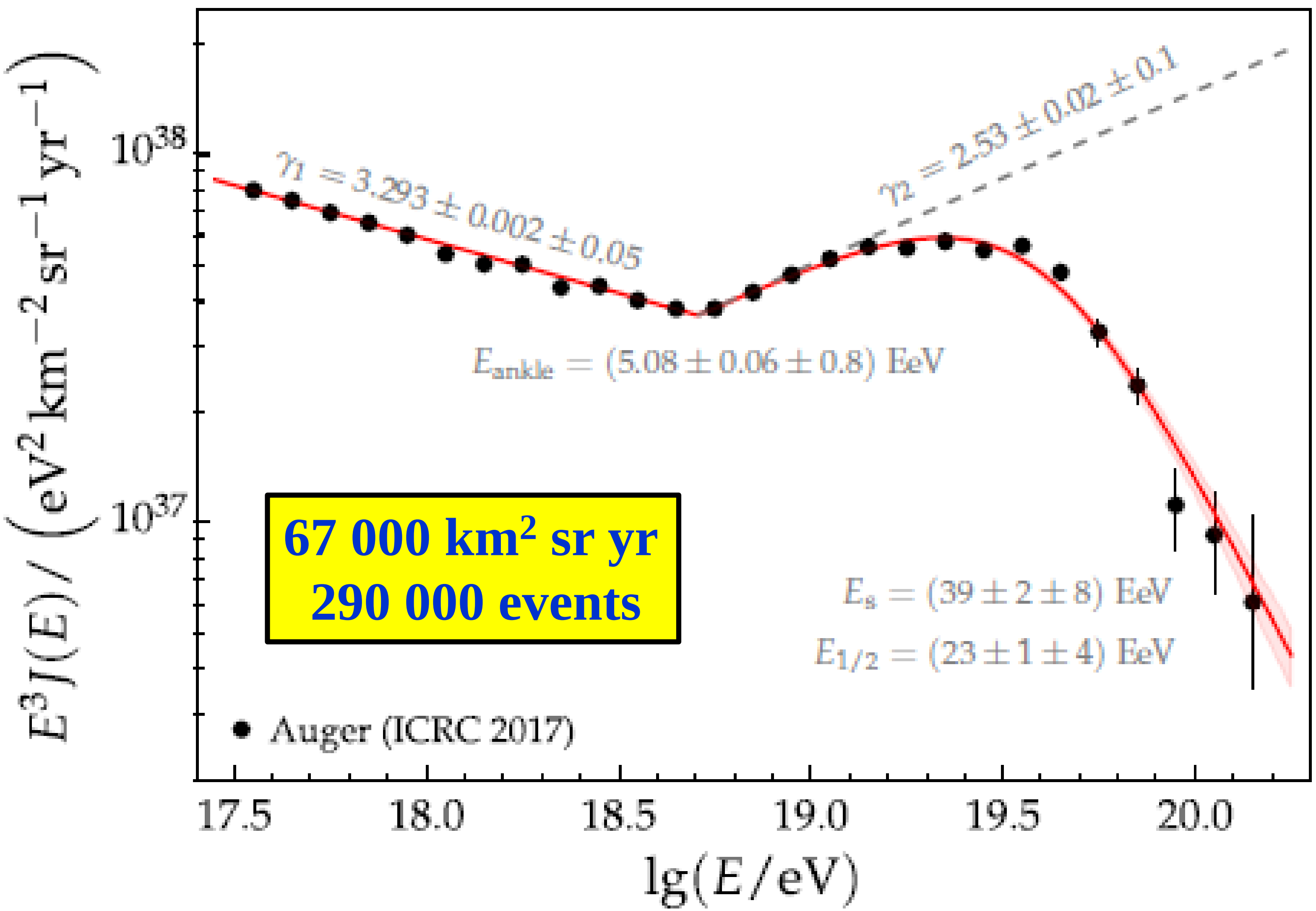
After Michael Unger 2017

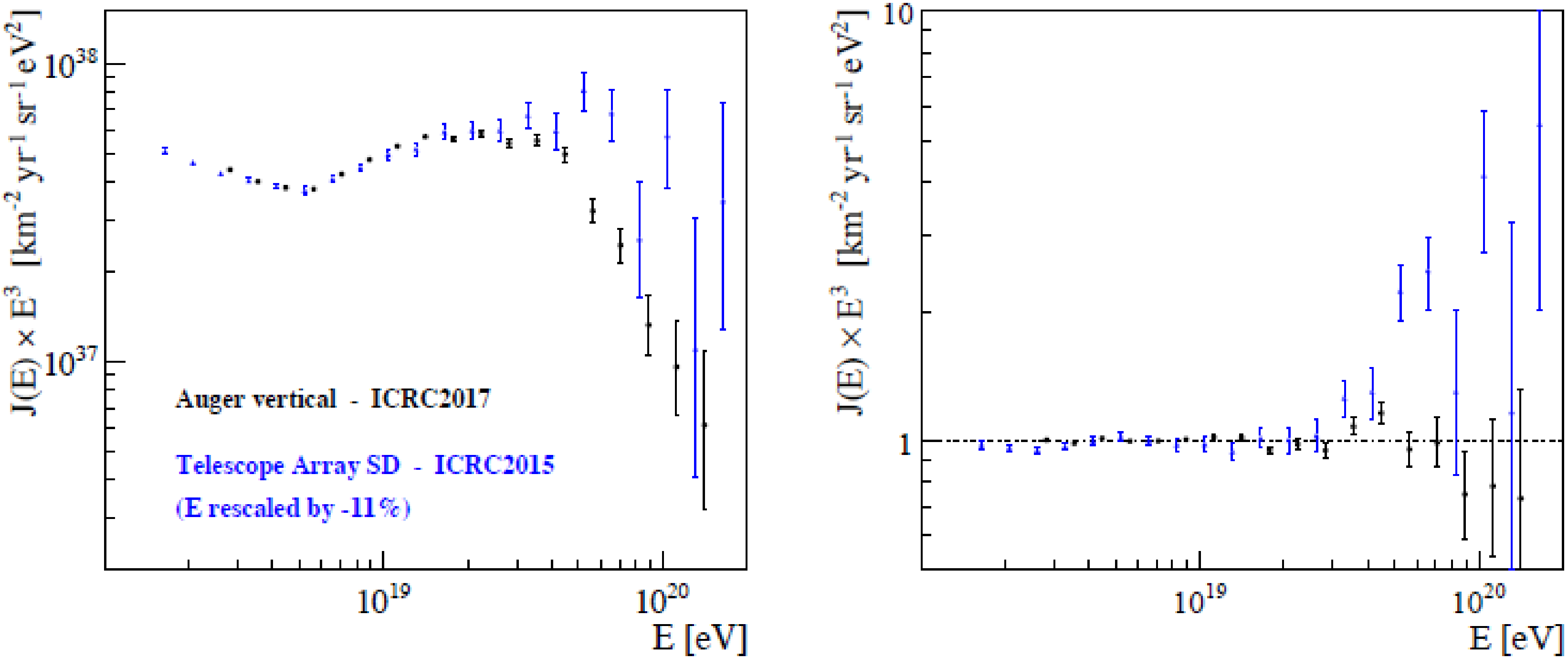


839 events

7.5 x 10^{19} eV

Auger Energy Calibration


$E^3 J(E) / (eV^2 km^{-2} sr^{-1} yr^{-1})$
10^{38}
10^{37}
$\gamma_1 = 3.293 \pm 0.002 \pm 0.05$
$\gamma_2 = 2.53 \pm 0.02 \pm 0.1$
$E_{ankle} = (5.08 \pm 0.06 \pm 0.8)$ EeV
$E_s = (39 \pm 2 \pm 8)$ EeV
$E_{1/2} = (23 \pm 1 \pm 4)$ EeV
67 000 km^2 sr yr
290 000 events
Auger (ICRC 2017)
17.5
18.0
18.5
19.0
19.5
20.0
$\lg(E/eV)$



$J(E) \times E^3$ [$km^{-2}\,yr^{-1}\,sr^{-1}\,eV^2$]
10^{38}
10^{37}
Auger vertical - ICRC2017
Telescope Array SD - ICRC2015
(E rescaled by -11%)
10^{19}
10^{20}
E [eV]
$J(E) \times E^3$ [$km^{-2}\,yr^{-1}\,sr^{-1}\,eV^2$]
10
1
10^{19}
10^{20}
E [eV]

However the steepening itself is INSUFFICIENT for us to claim that we have 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!

probably is!

Energy densities of CMB, galactic magnetic field, cosmic rays and starlight are very similar – this may be another coincidence

- **Are there anisotropies in the arrival direction distributions?**

- **Knowing the mass composition would be useful – but for this we need to extrapolate key features of hadronic interactions to high energies**

- cross-section, multiplicity, inelasticity, pion collisions…

Arrival Direction studies

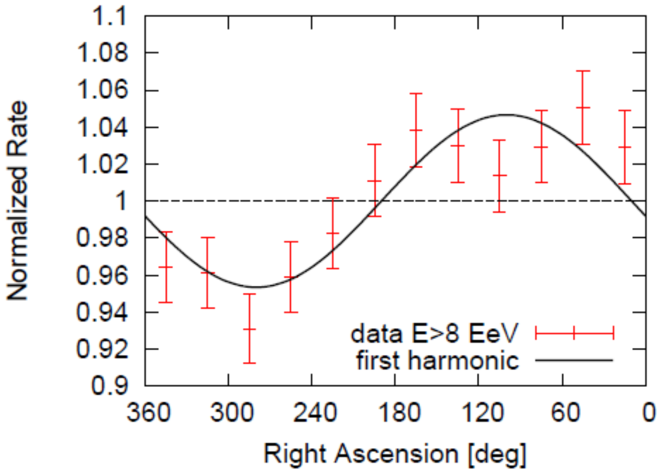
- The cosmic-ray sky is remarkably isotropic, even at the very highest energies
- This surely reflects the high charge of the particles and magnetic fields that lie between us and the sources – or there could be a huge number of sources
- There may be hot-spots in the sky at the highest energies
- There is now very strong evidence for a dipole anisotropy 8 EeV

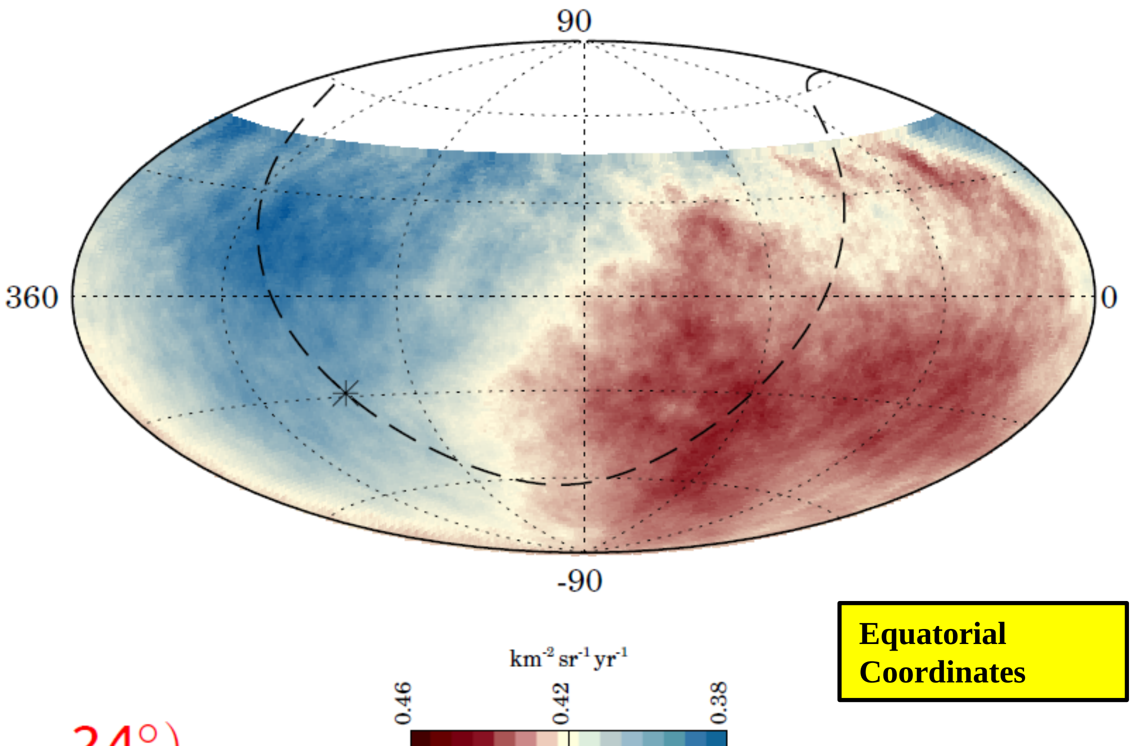
Observation of Dipolar anisotropy above 8 EeV

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2 σ (5.6σ before penalization for energy bins explored)



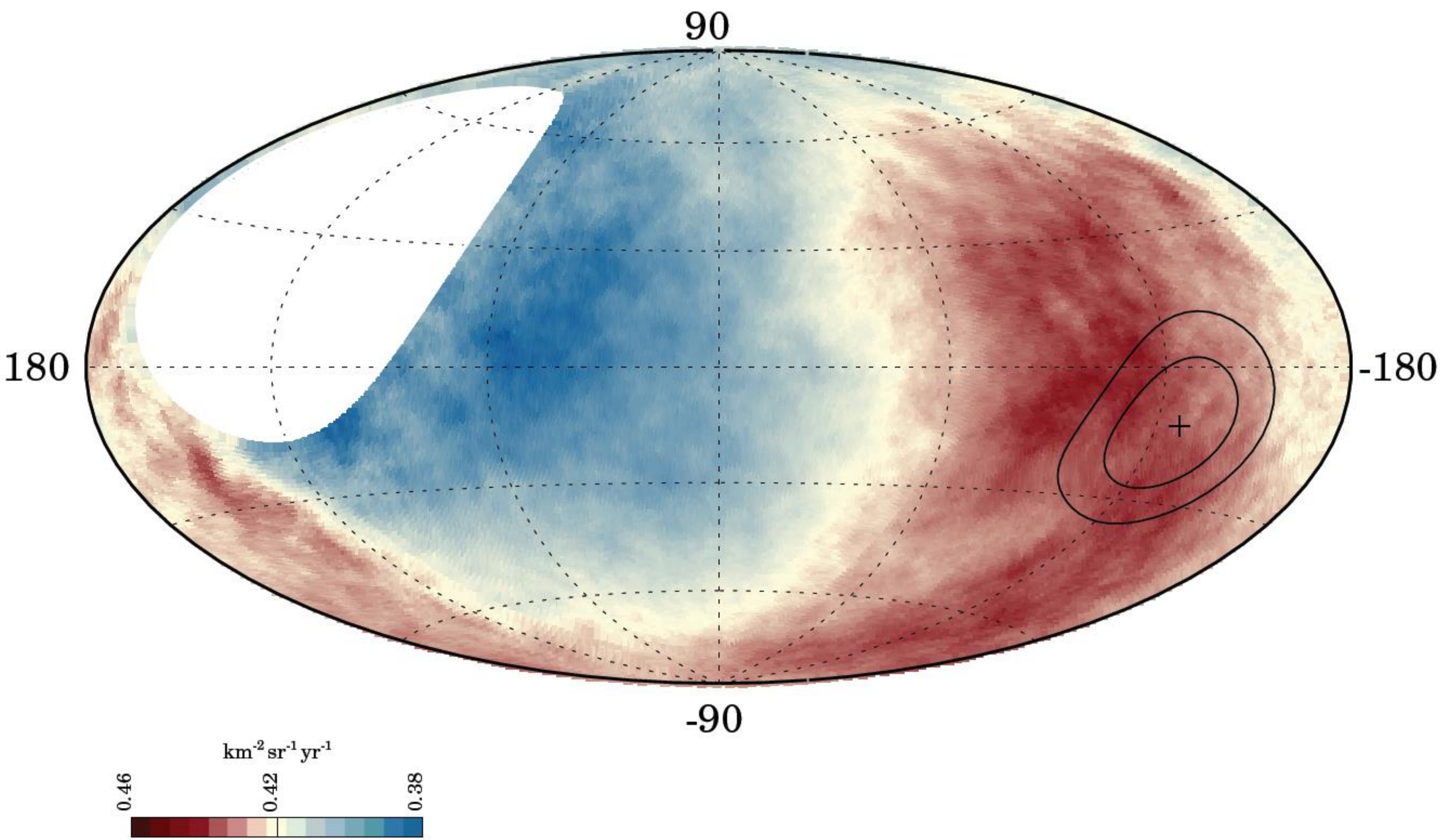


Equatorial Coordinates

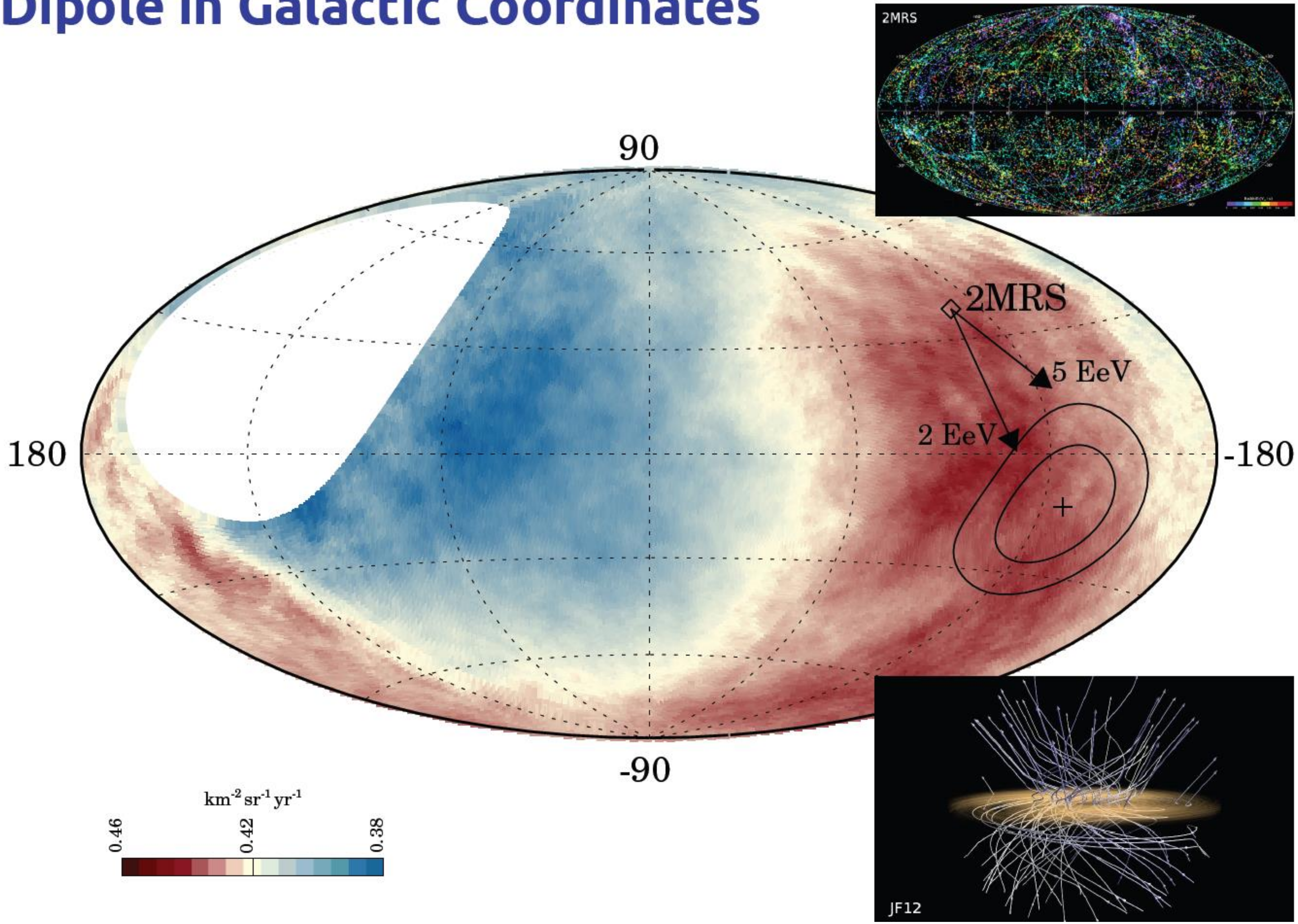
3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

Dipole in Galactic Coordinates



Dipole in Galactic Coordinates



Sur la piste des rayons cosmiques dans la pampa argentine

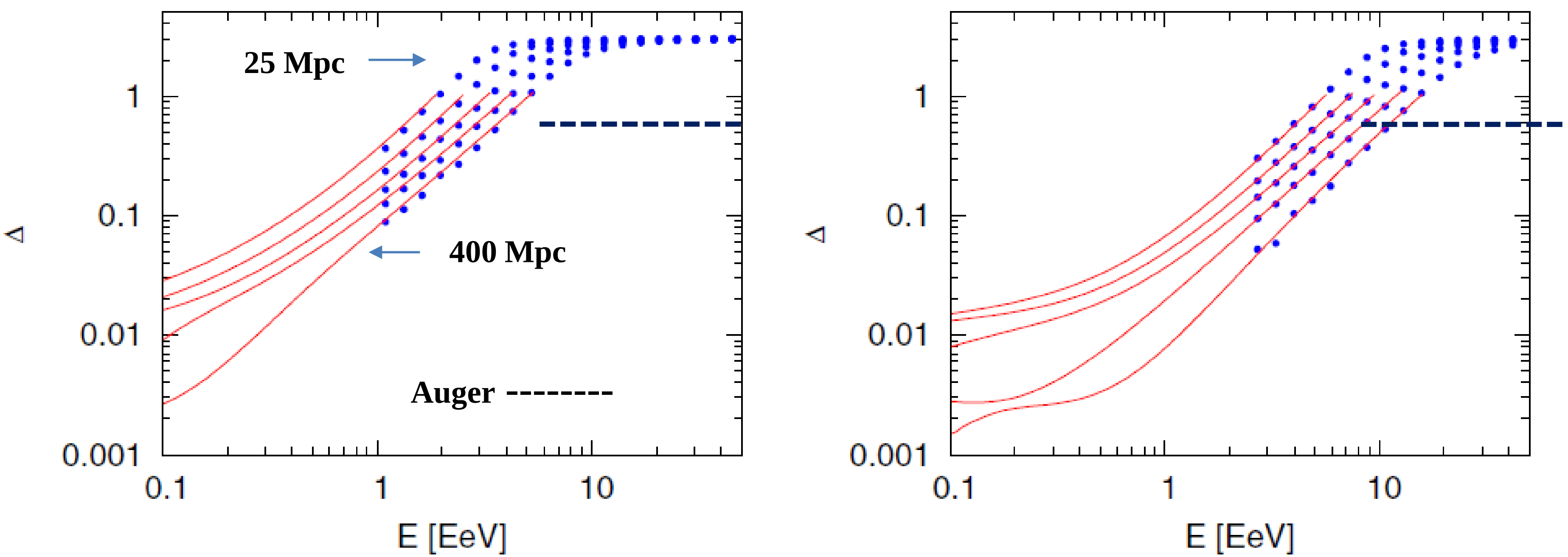
Quelle est l'origine des **rayons cosmiques** *? C'est pour résoudre cette* **énigme** *que des chercheurs ont investi la pampa argentine. Là, ils ont installé* **le plus grand détecteur** *du monde qui, jour et nuit, traque les* **flux de particules** *venues du* **cosmos**. *Une* **quête** *dont les physiciens espèrent beaucoup.*

Cette cuve perdue dans la pampa ici détecte la trace des rayons cosmiques.

Par Claire Martin. Photos: Rodrigo Gomez Rovira/Vu

Harari, Mollerach and Roulet PRD 89 123001 2014

Single Source Model



Coherence length = 1 Mpc. LH B= 1 nG; RH B= 3 nG

-proton primaries are assumed

Harari, Mollerach and Roulet PRD 89 123001 2014

Multiple sources

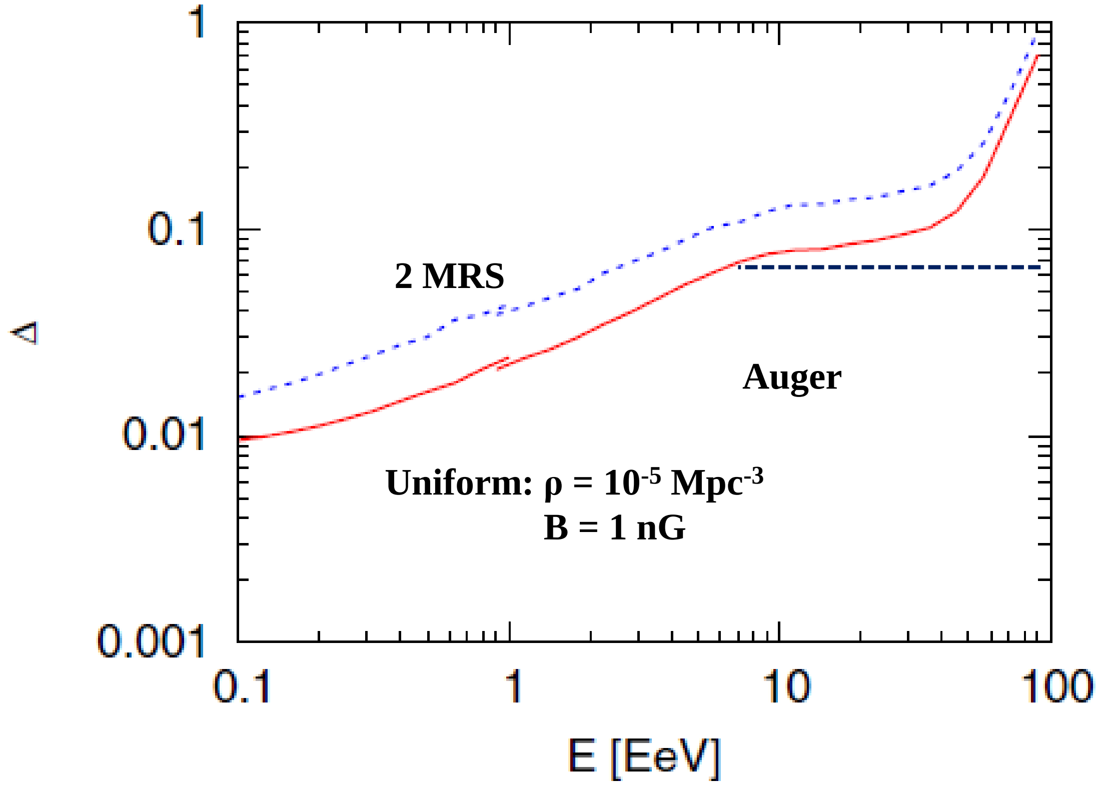
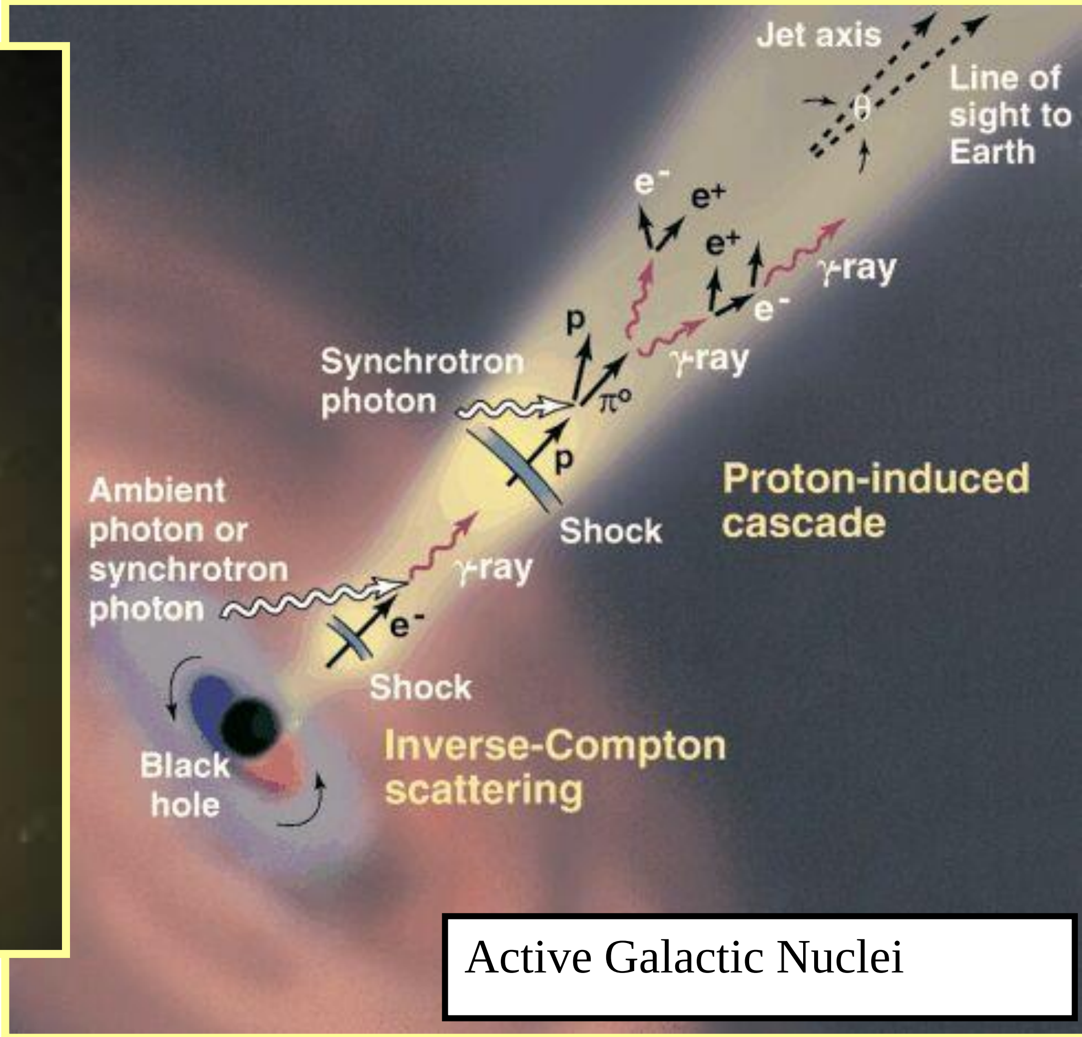


image of M87 with Hubble Space Telescope



Active Galactic Nuclei

Production in Starburst Galaxies ApJ Letters (Jan 2018)

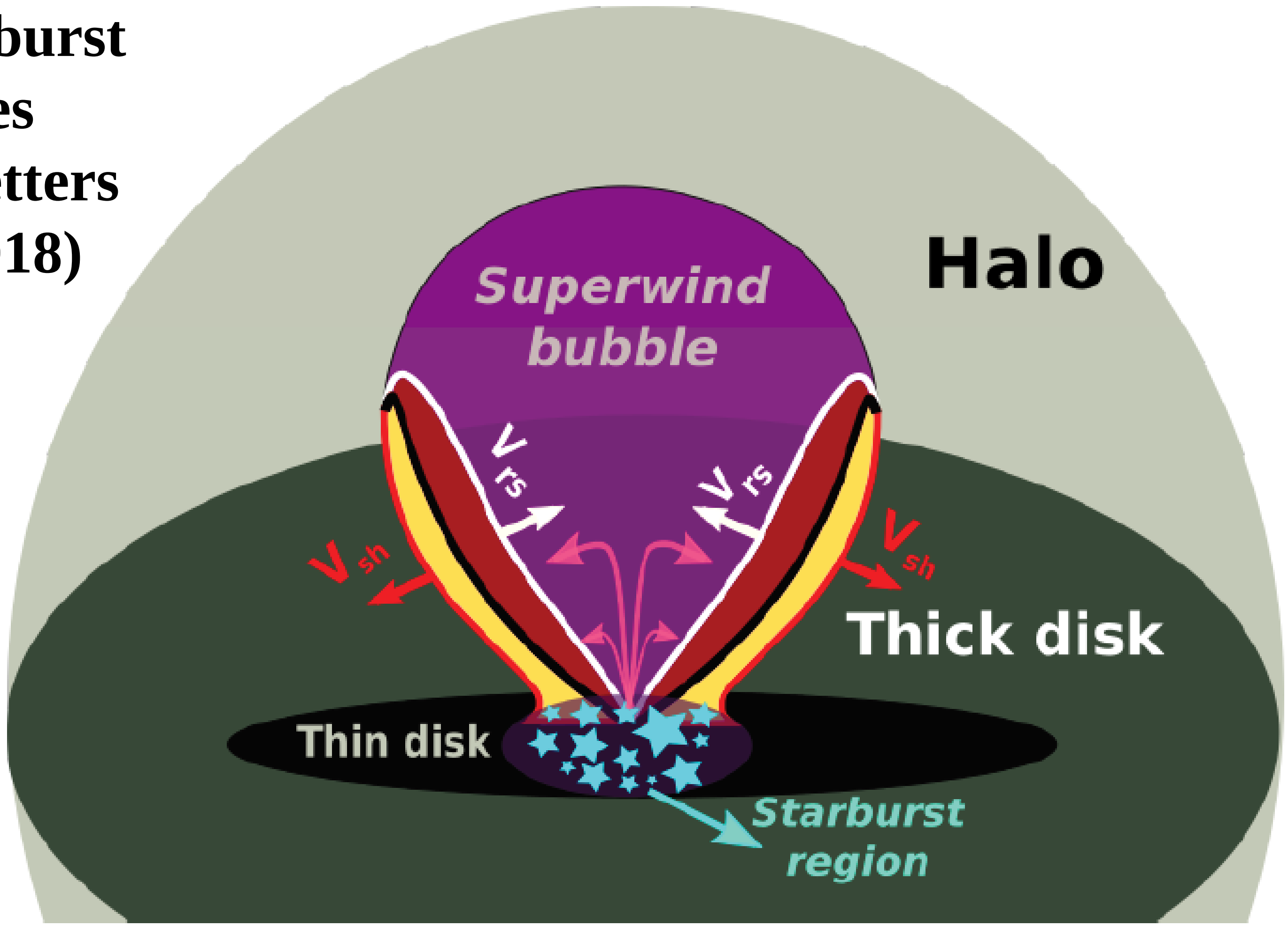
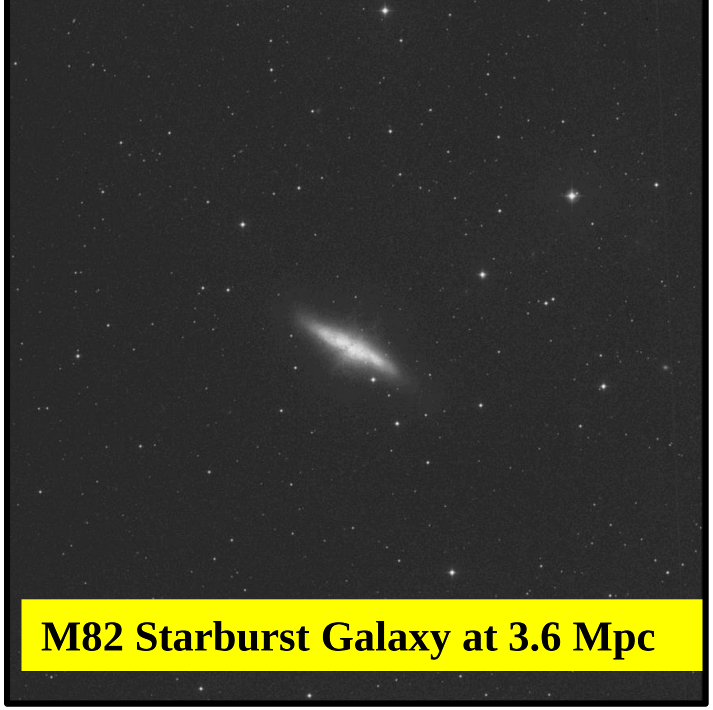


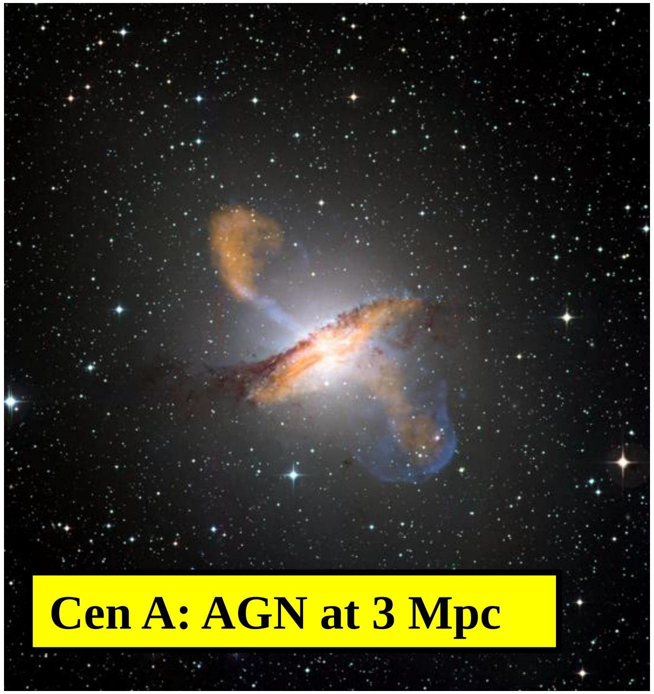
Fig. 1. Scheme of the physical scenario considered in this work. Not to scale. Adapted from Strickland et al. (2002).



M82 Starburst Galaxy at 3.6 Mpc

NGC 253: Sculptor Galaxy at 3.5 Mpc

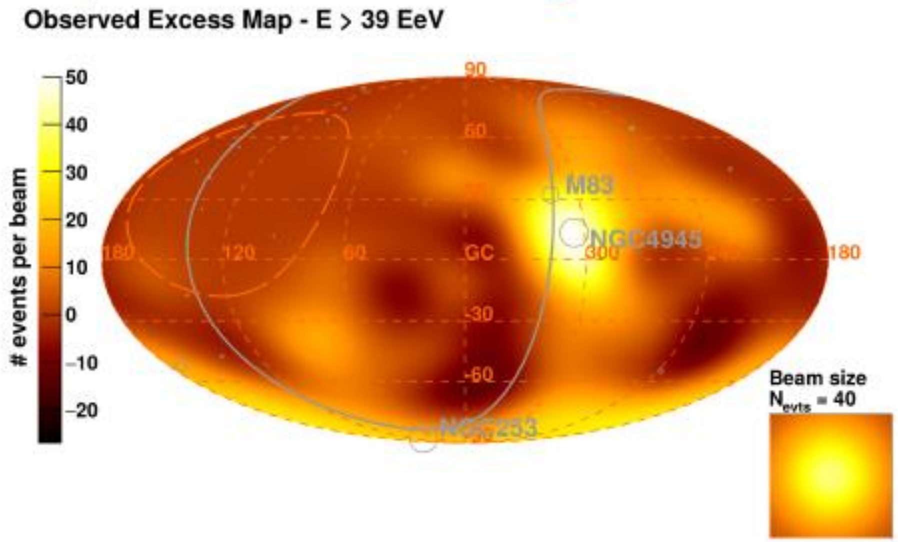
NGC 4945 at 3.6 Mpc

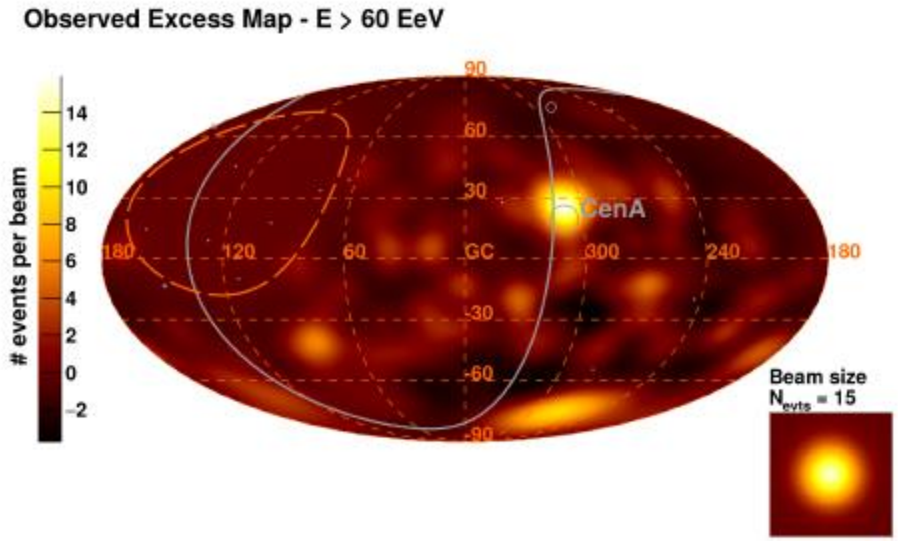


Cen A: AGN at 3 Mpc

UHECR come from Starburst Galaxies and from AG: ApJ Letters January 2018

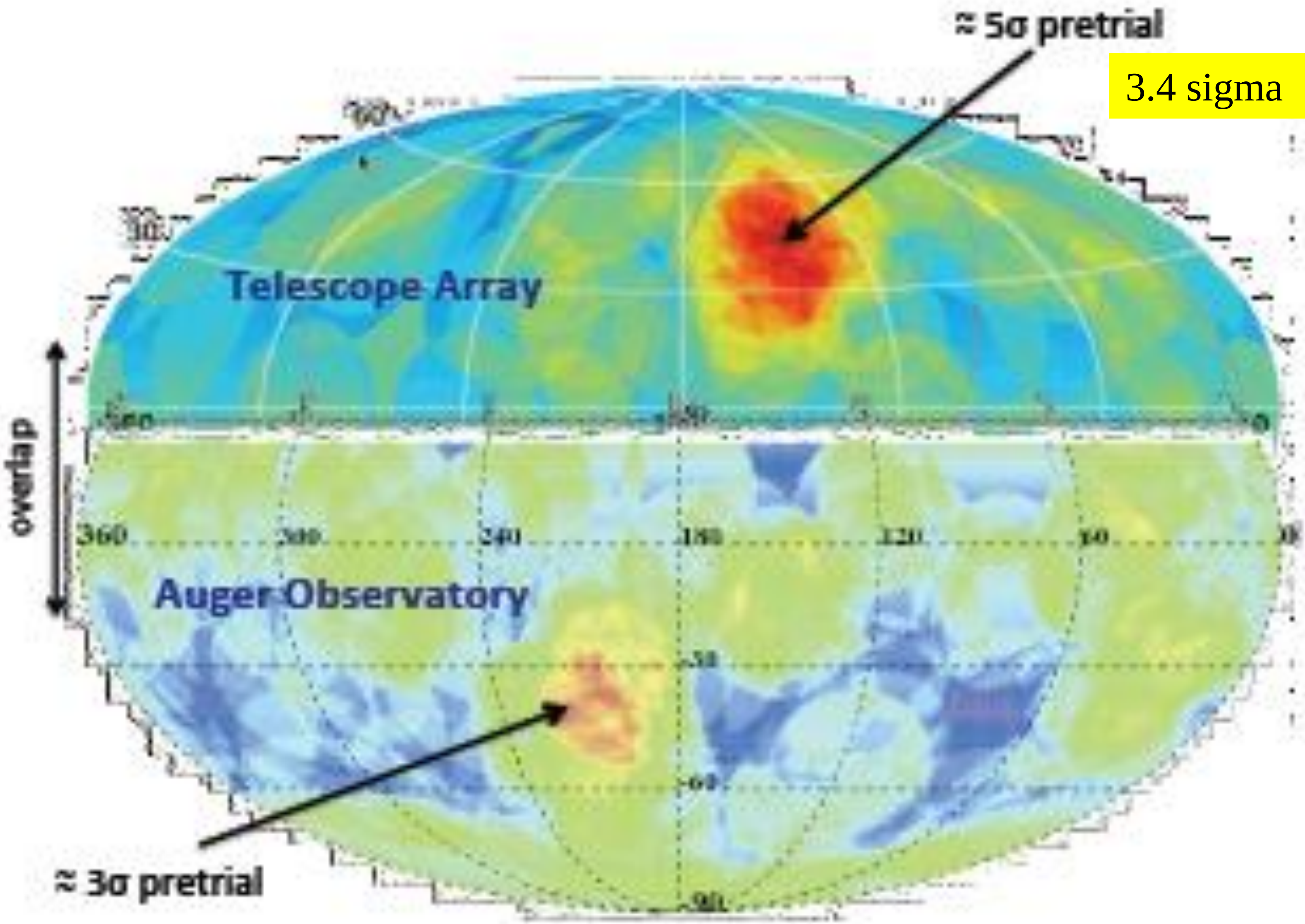
top: starburst galaxies





bottom: γAGN

Auger and Telescope Array Hot-Spots



3.4 sigma

< 2 sigma

It would be enormously useful to know the mass composition

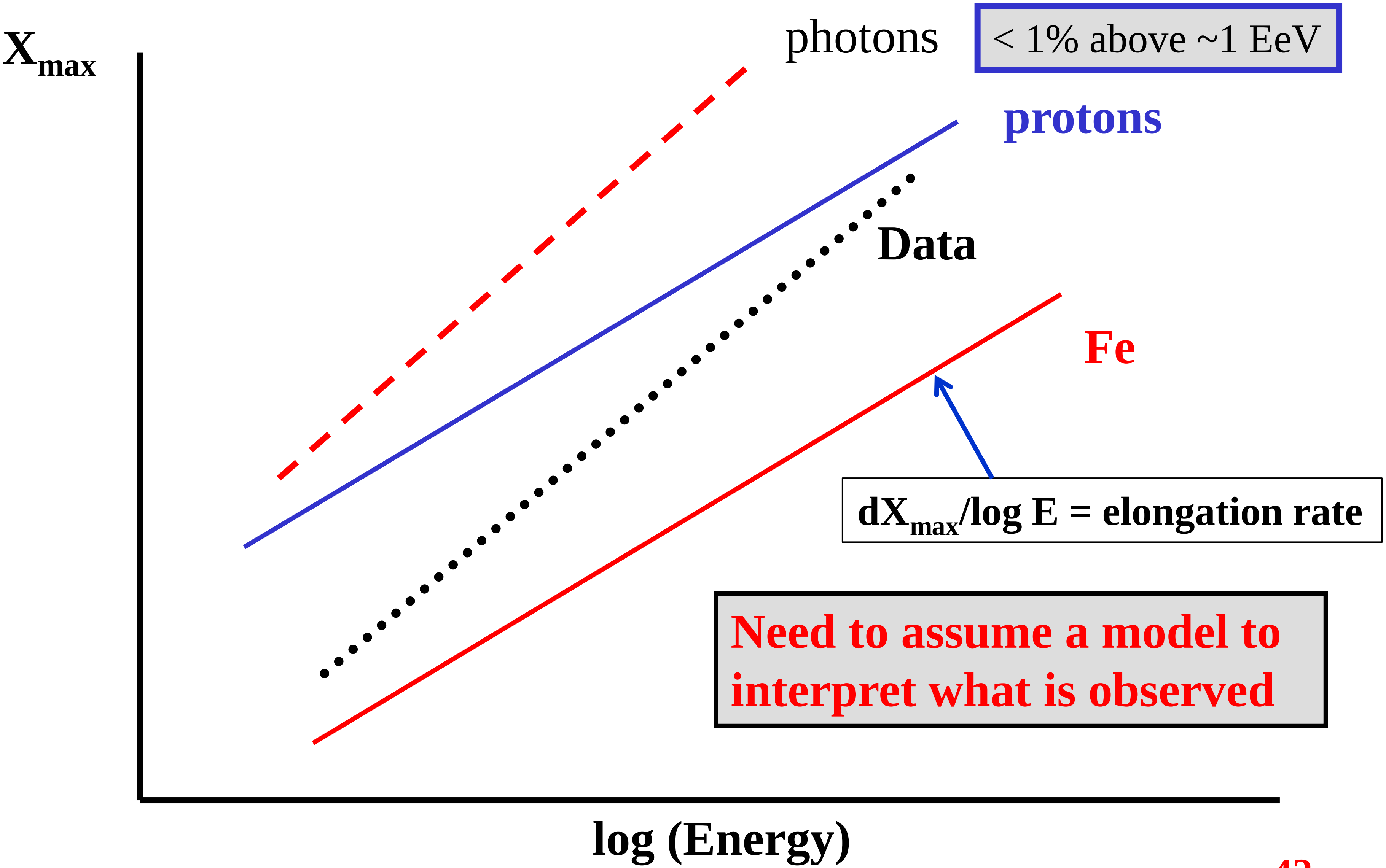
Uncovering the mass composition is extremely difficult

In absence of a strong point-like anisotropy (protons?), one must rely on extrapolations of hadronic physics from accelerators to help interpret the data

Eventually, we will find a hadronic model that fits all of the data

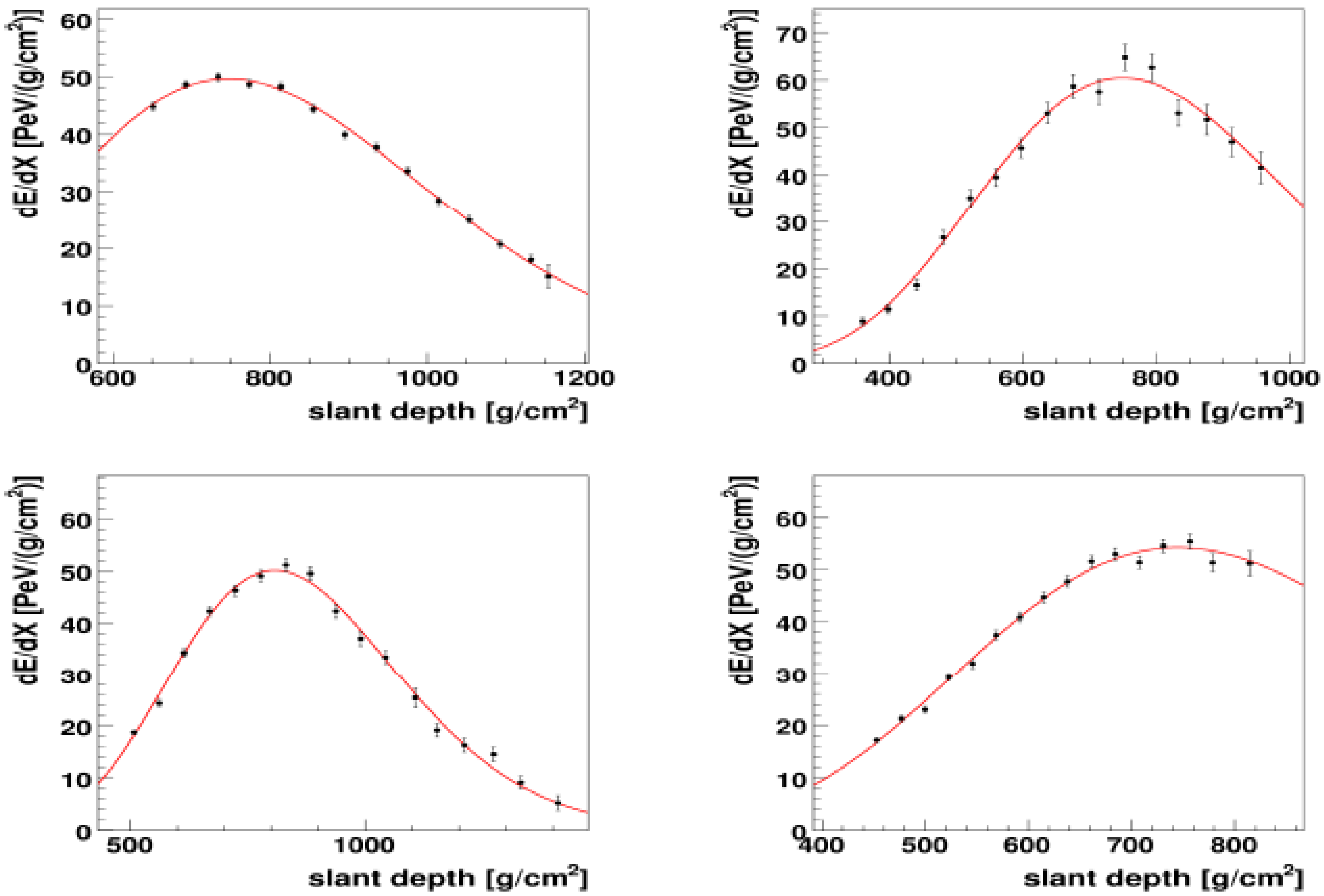
It will give a unique mass composition – but we are not there yet!

One method to try to infer the variation of mass with energy



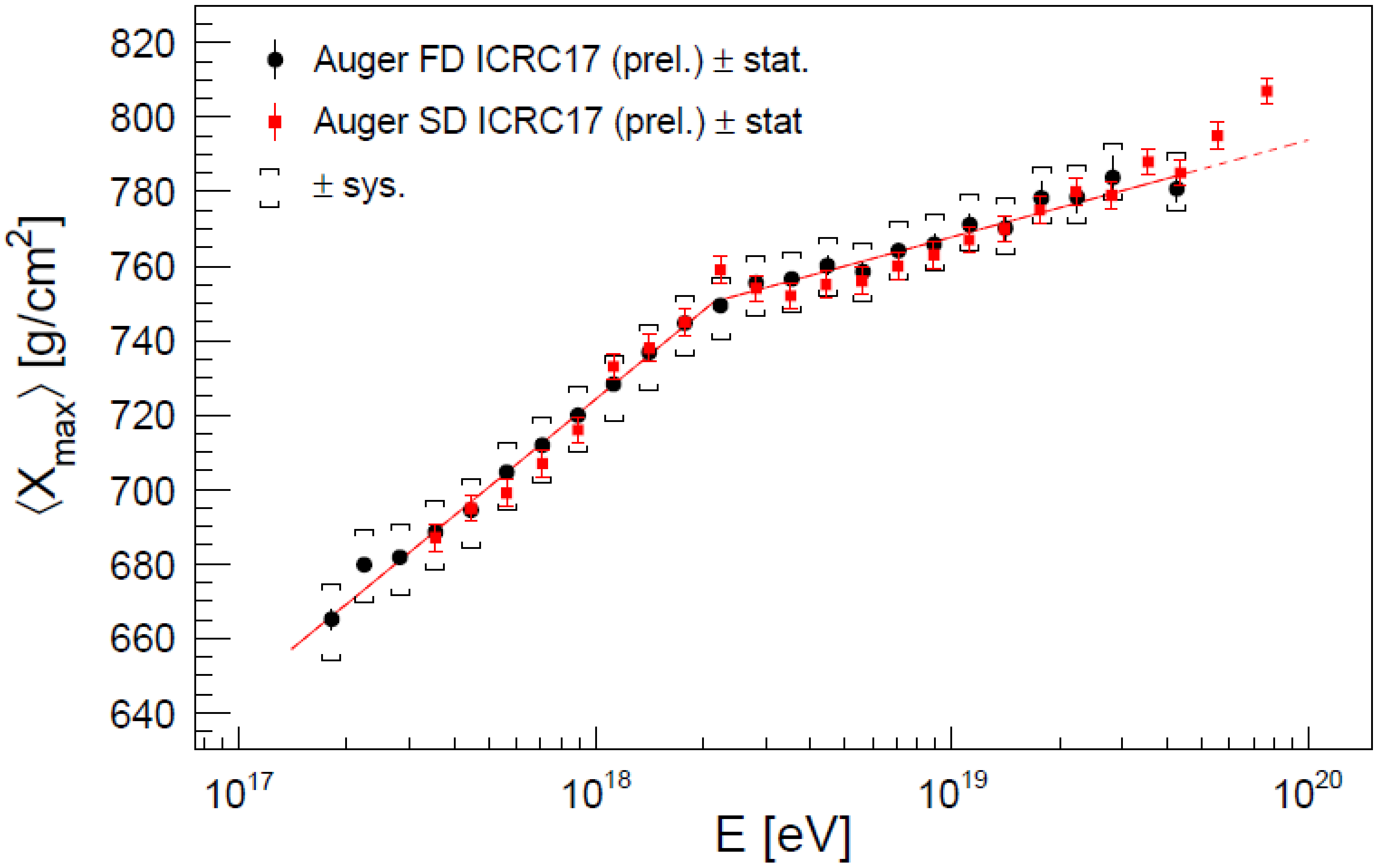
Some Longitudinal Profiles measured with Auger

1000 g cm^{-2} = 1 Atmosphere ~ 1000 mb



rms uncertainty in X_{max} < 20 g cm^{-2} from stereo-measurements

Average X_{max} Fluorescence and Surface Detector



Results on mass from depth of maximum with fluorescence detectors

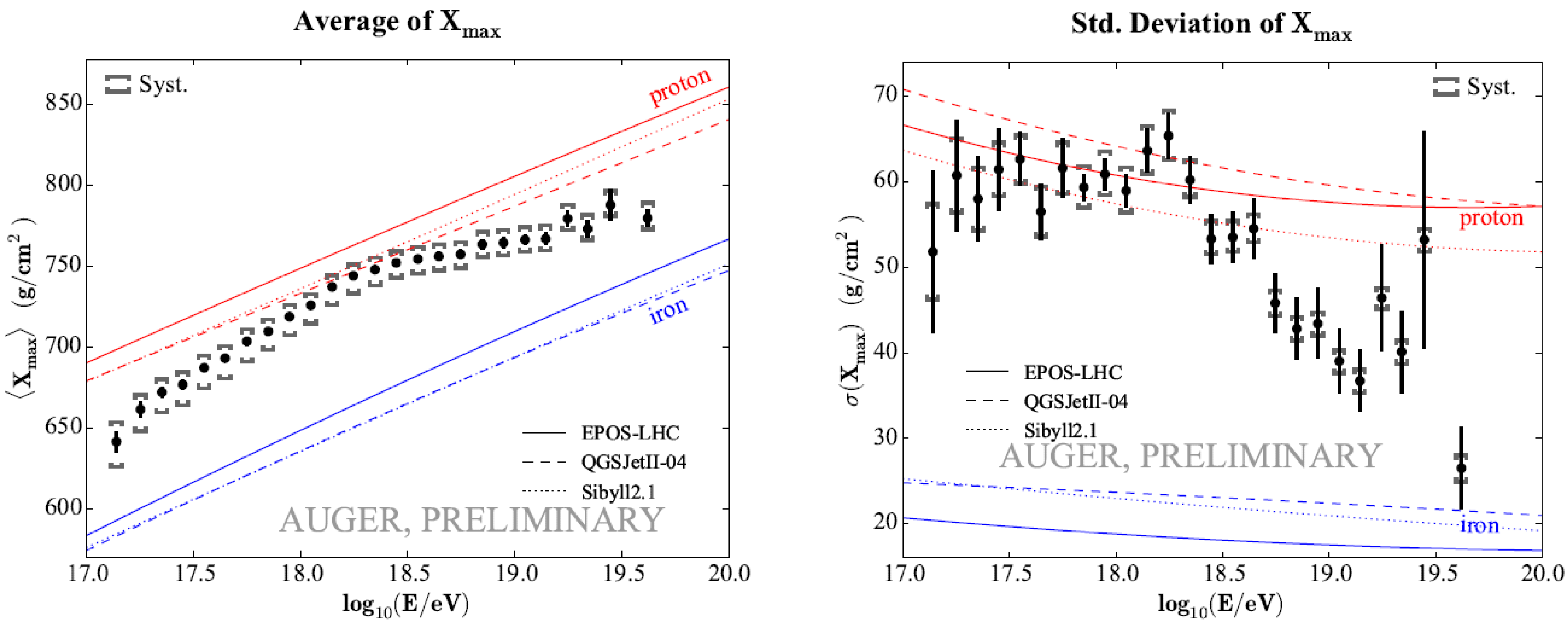
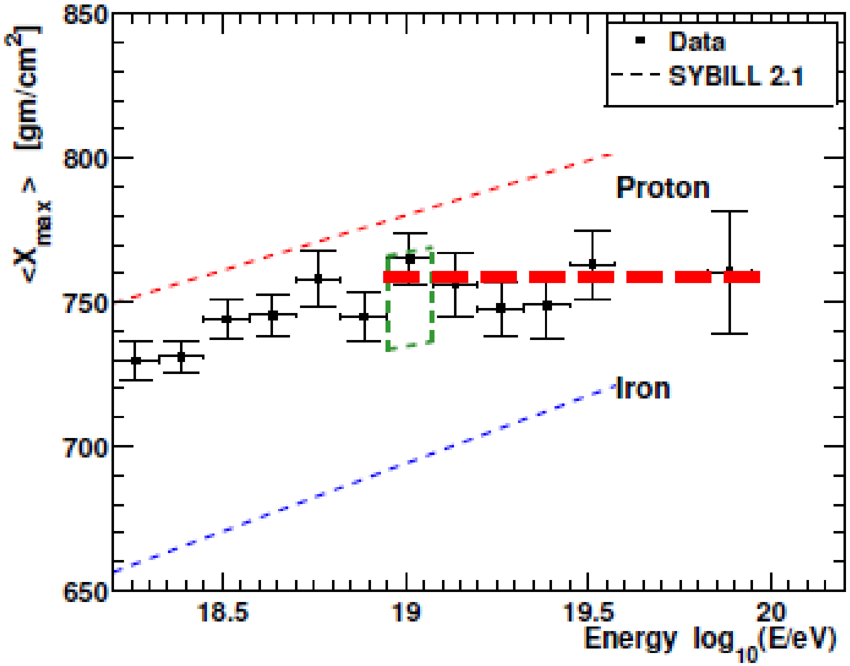


Figure 3: The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

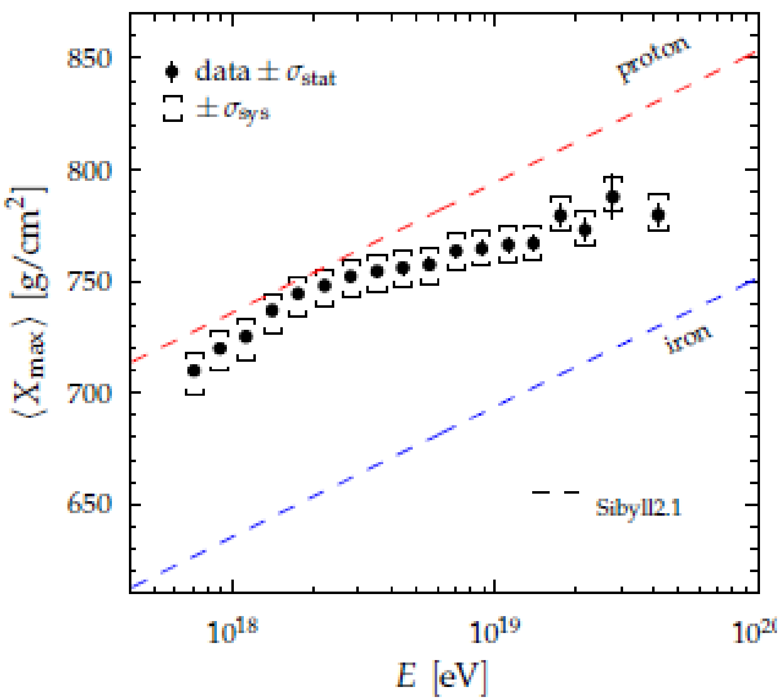
Predictions from Sibyl model lie between those with QGSjet and EPOS-LHC

Comparison of TA and Auger results against a single model

— Michael Unger



Telescope Array Collaboration, APP **64** (2014) 49



Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

- **New Sybil model moves depth of maximum DEEPER into atmosphere and thus *pure proton claims become harder to sustain***

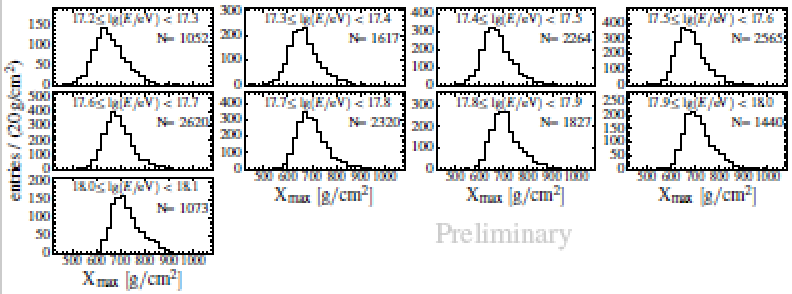
This is a key issue for neutrino experiments

- **Change of elongation rate seen in BOTH data sets**

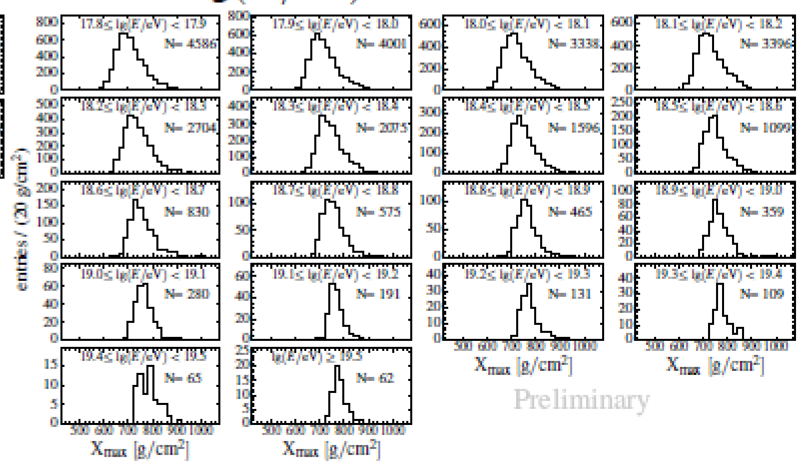
(p-He-N-Fe)-fit of X_{max} Distributions

FD data:

$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

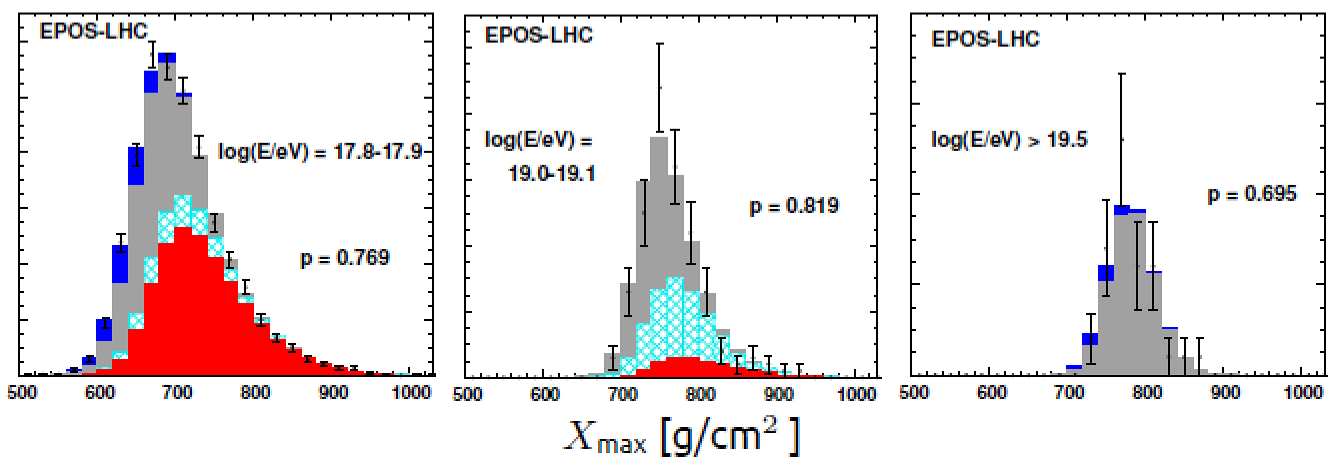


$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$

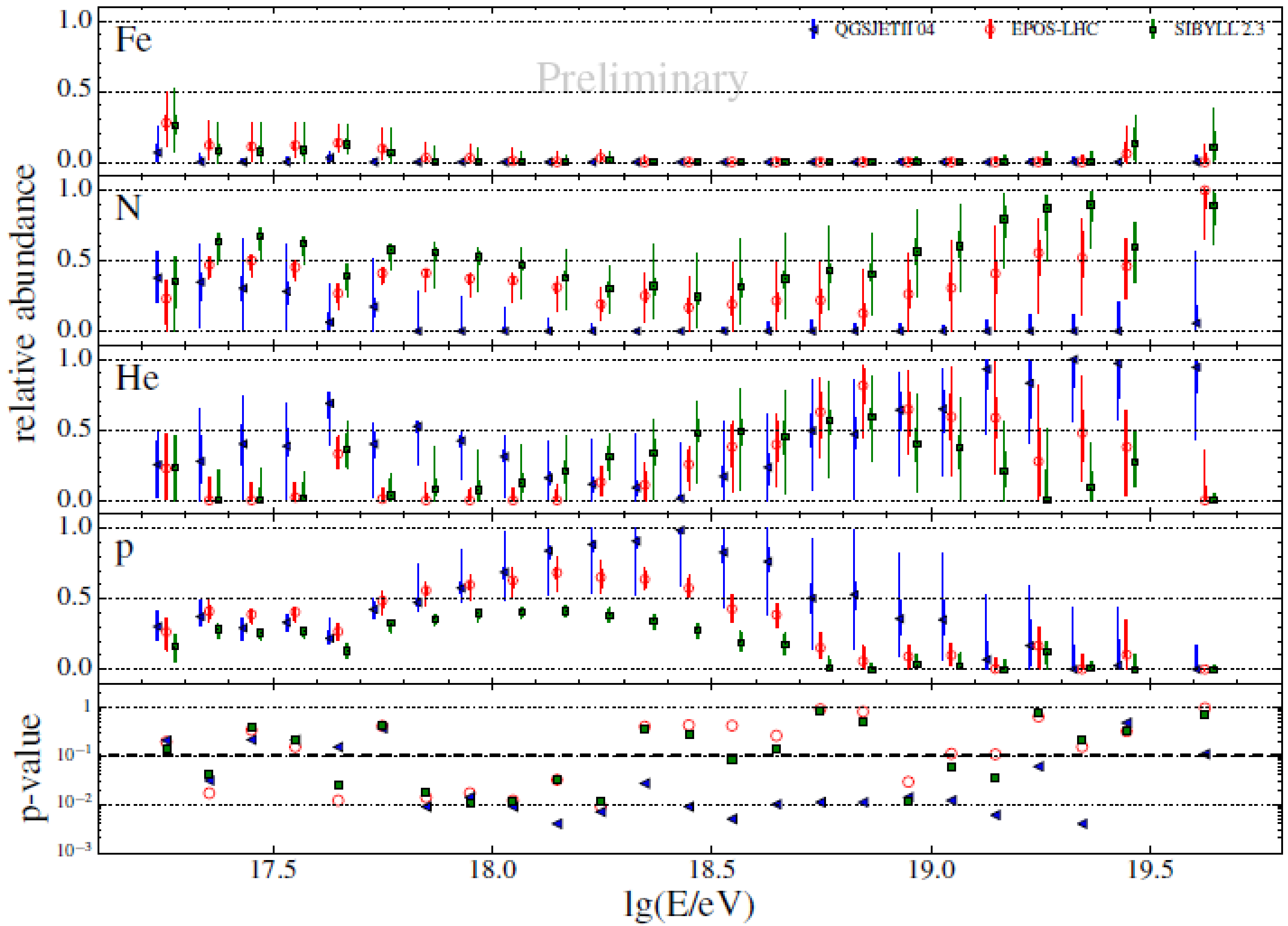


Examples of 4-component fit:

p He N Fe



Composition Fractions



Search for UHE neutrinos at the Auger Observatory

ELSEVIER

Astroparticle Physics 8 (1998) 321–328

On the detection of ultra high energy neutrinos with the Auger observatory

K.S. Capelle[a], J.W. Cronin[a], G. Parente[b], E. Zas[b]

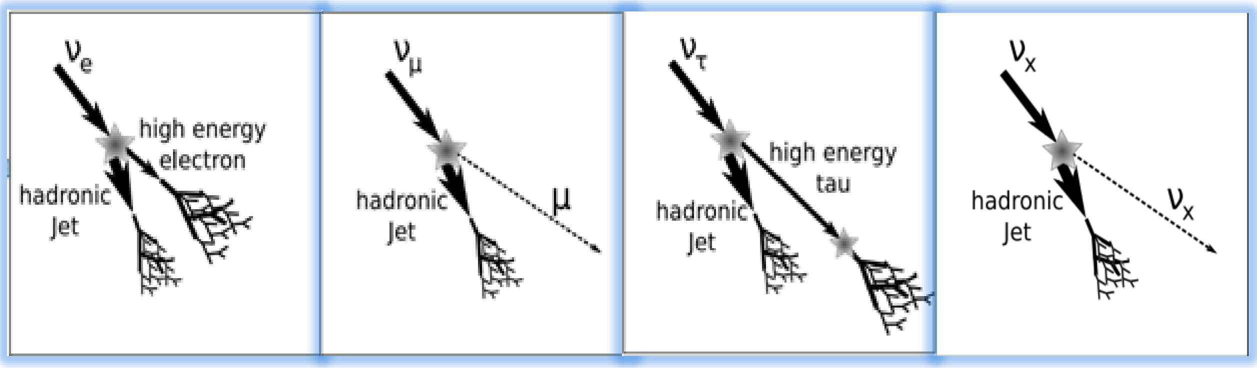
Parente and Zas: Venice Meeting 1996, arXiv 960609

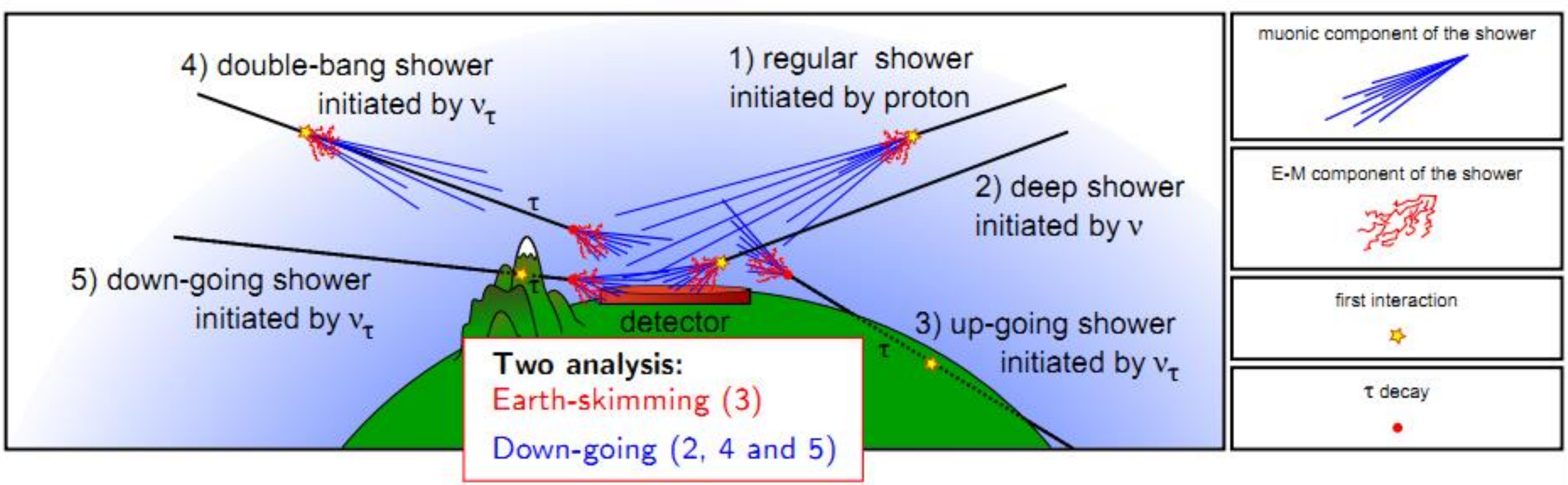
τ at EeV may decay before reaching the ground
→ Secondary shower (Double Bang event)

Also interactions in mountains or upward-going in earth

Letessier-Selvon A 2001 *AIP Conf. Proc.* **566** 157 (*Preprint* astro-ph/0009444)
Fargion D 2002 *Astrophys. J.* **570** 909 (*Preprint* astro-ph/0002453)
Fargion D 2003 *Proc. Int. Conf on Neutrino Telescopes, Venice* vol 2, pp 433–55 (*Preprint* hep-ph/0306238)

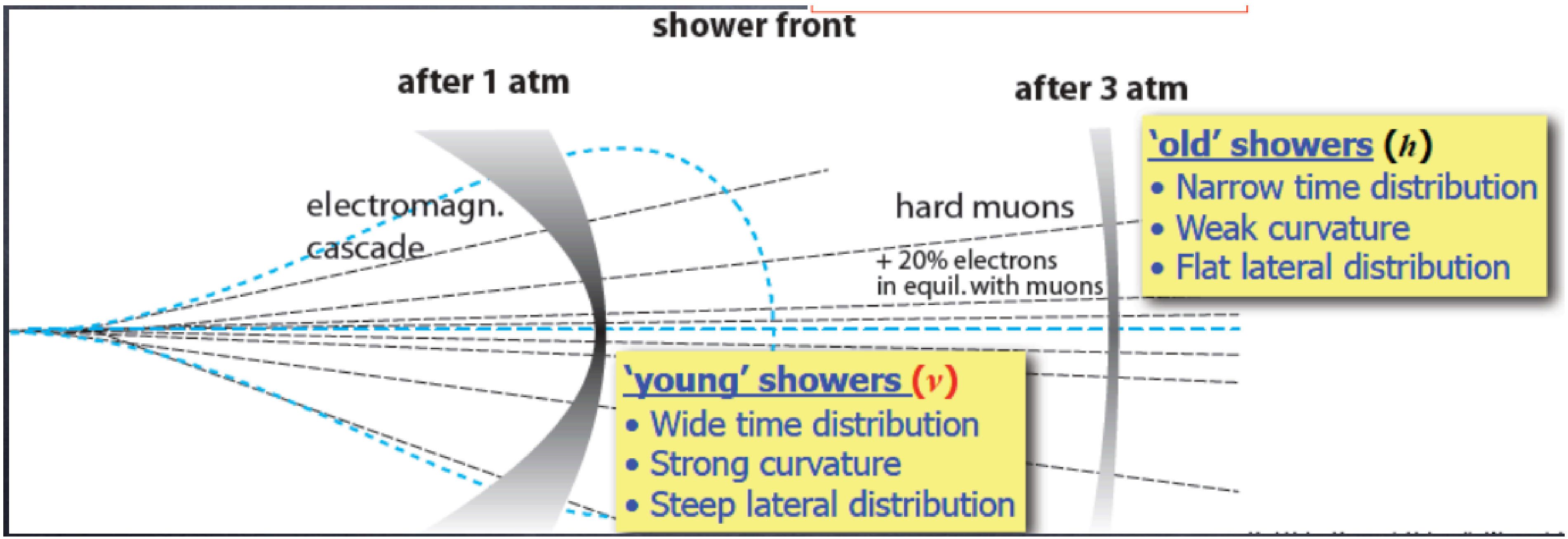
$$p + \gamma_{CMB} \longrightarrow \pi \longrightarrow \nu$$



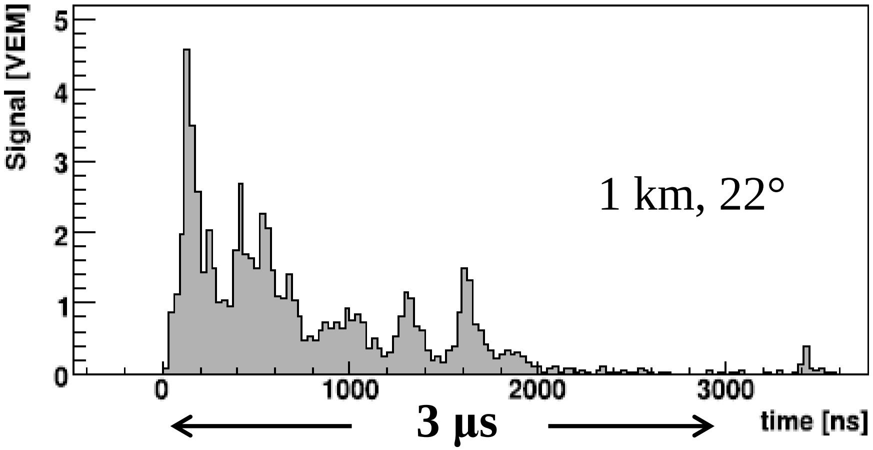


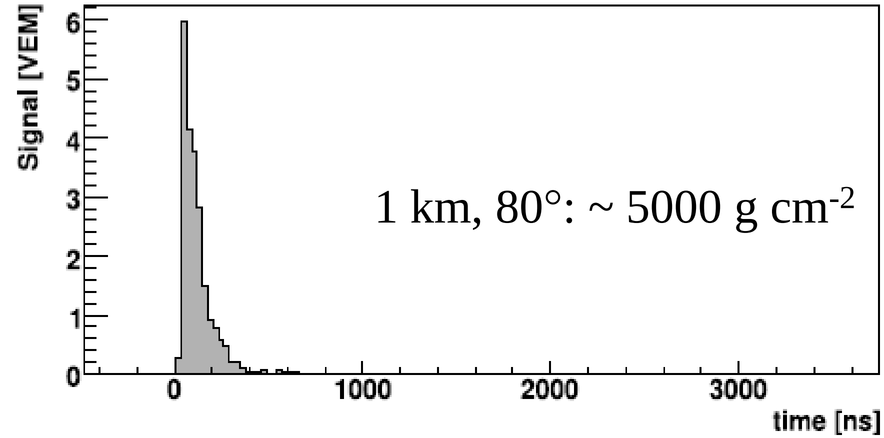
Search Method for neutrinos

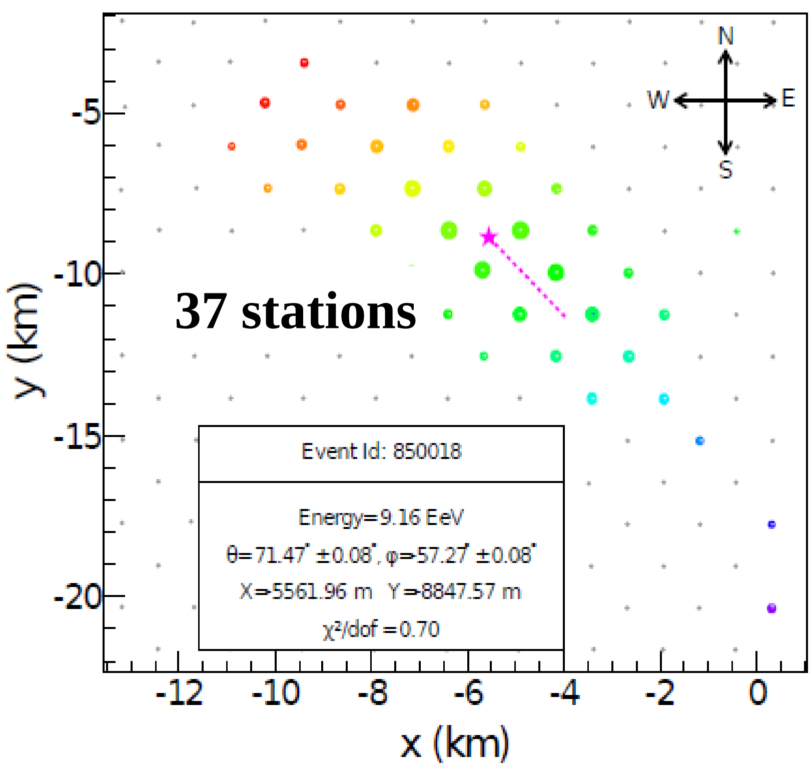
Look for inclined, BUT young, showers

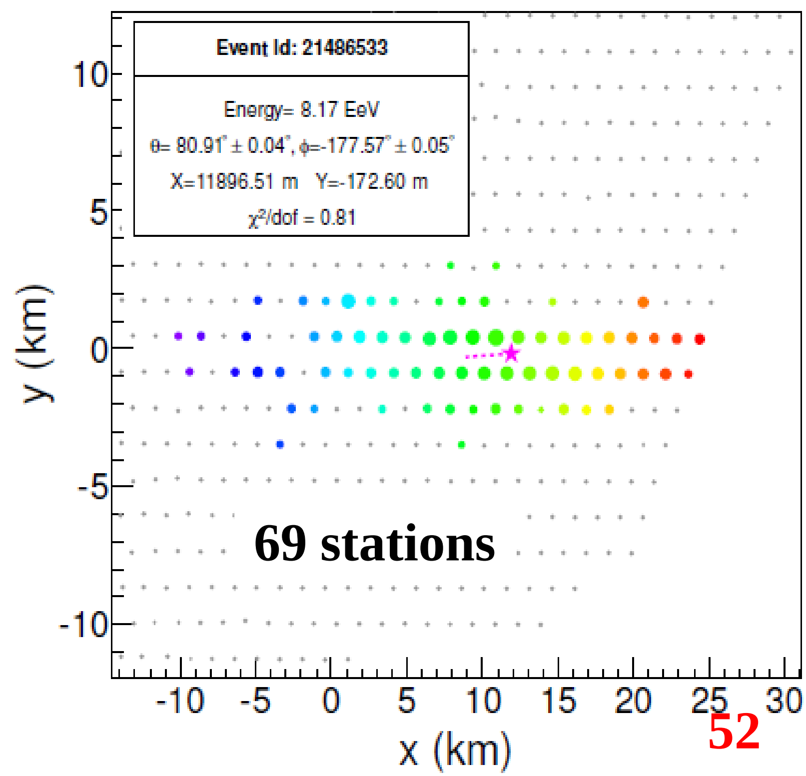


Using inclined showers to look for neutrinos









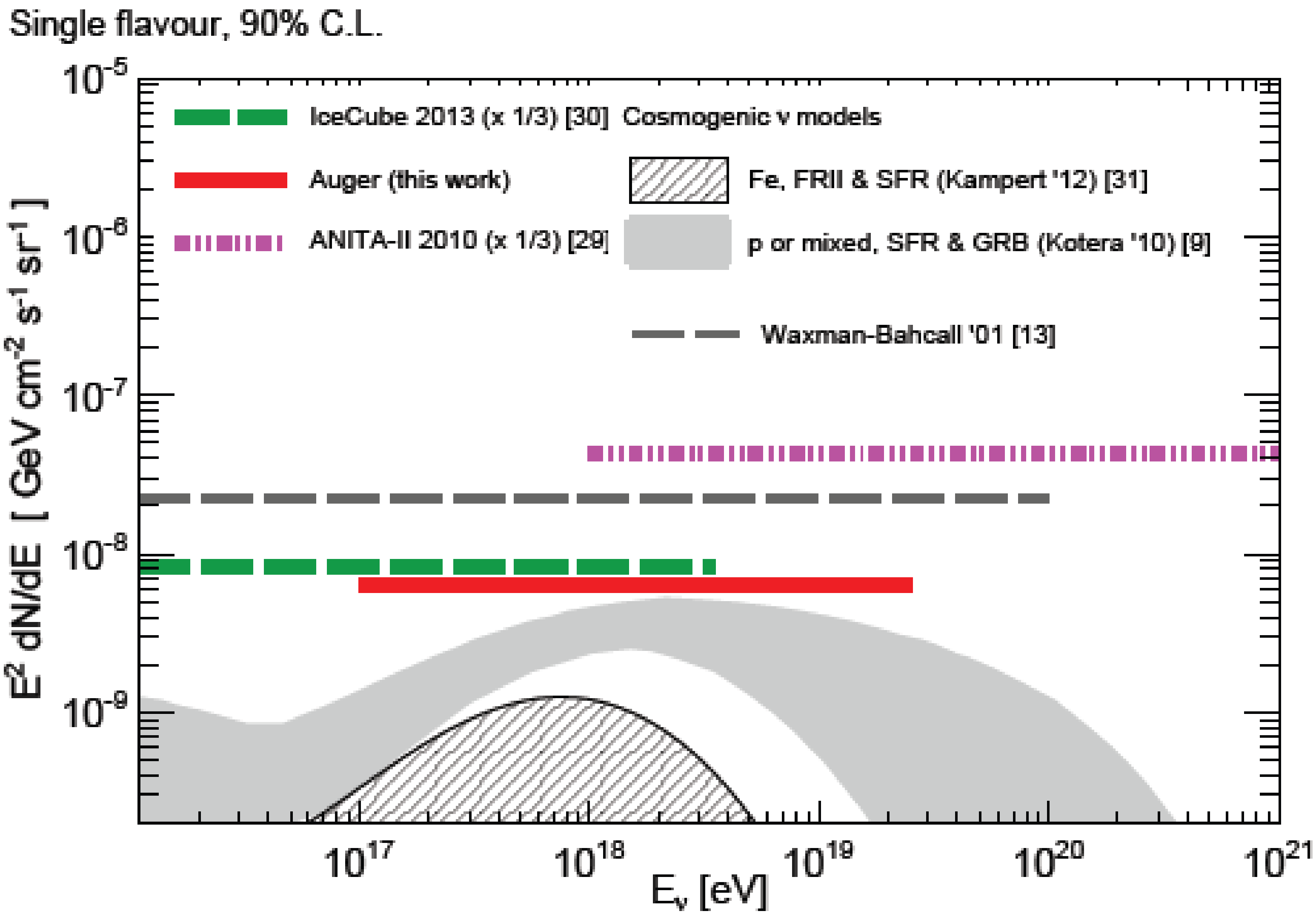


Figure 4. Top panel: Upper limit (at 90% C.L.) to the normalization of the diffuse flux of UHE neutrinos as given in Eqs. (2) and (3), from the Pierre Auger Observatory. We

Searching neutrinos in coincidence with other 'happenings'

1. **GW170817 Superbly positioned for Auger neutrino searches**
   -but only upper limits – joint paper with ~7000 others!

2. **TXS0506+056**
   Again no neutrinos seen. Joint paper with IceCube, ANTARES and Auger

MNRAS 000, 1–10 (2017) Preprint 28 February 2017 Compiled using MNRAS LaTeX style file v3.0

Connecting blazars with ultra high energy cosmic rays and astrophysical neutrinos

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28 February 2017

ABSTRACT
We present a strong hint of a connection between high energy γ-ray emitting blazars, very high energy neutrinos, and ultra high energy cosmic rays. We first identify potential hadronic sources by filtering γ-ray emitters in spatial coincidence with the high energy neutrinos detected by IceCube. The neutrino filtered γ-ray emitters are then correlated with the ultra high energy cosmic rays from the Pierre Auger Observatory and the Telescope Array by scanning in γ-ray flux (F_γ) and angular separation (θ) between sources and cosmic rays. A maximal excess of 80 cosmic rays (42.5 expected) is found at $\theta \leq 10°$ from the neutrino filtered γ-ray emitters selected from the second hard *Fermi*-LAT catalogue (2FHL) and for $F_\gamma(> 50\,\mathrm{GeV}) \geq 1.8\times10^{-11}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$. The probability for this to happen is 2.4×10^{-5}, which translates to $\sim 2.4\times10^{-3}$ after compensation for all the considered trials. No excess of cosmic rays is instead observed for the complement sample of γ-ray emitters (i.e. *not* in spatial connection with IceCube neutrinos). A likelihood ratio test comparing the connection between the neutrino filtered and the complement source samples with the cosmic rays favours a connection between neutrino filtered emitters and cosmic rays with a probability of $\sim 1.8\times10^{-3}$ (2.9σ) after compensation for all the considered trials. The neutrino filtered γ-ray sources that make up the cosmic rays excess are blazars of the high synchrotron peak type. More statistics is needed to further investigate these sources as candidate cosmic ray and neutrino emitters.

Key words: neutrinos — radiation mechanisms: non-thermal — BL Lacertae objects: general — gamma-rays: galaxies — pulsars: general — cosmic rays

Astrophysical Models

There are many and the data are not very constraining

John von Neumann famously said

> With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.

By this he meant that one should not be impressed when a complex model fits a data set well. With enough parameters, you can fit any data set.

Truth ... is much too complicated to allow anything but approximations.

Summary of experimental data discussed above

- **Ankle at ~ 4 EeV and steepening at ~ 50 EeV clearly established**

- **Strong evidence for dipole anisotropy in Auger data above 8 EeV**

- **Weaker evidencs (~4 sigma) for coincidence with starburst galaxies above 39 EeV and some evidence (~2.5 sigma) for γAGNs above 60 EeV**

- **Mass composition getting heavier above the ankle (still some dispute)**

- **No diffuse neutrinos seen (at level similar to IceCube) nor any from specific events (GW170817 or TX0506+56)**