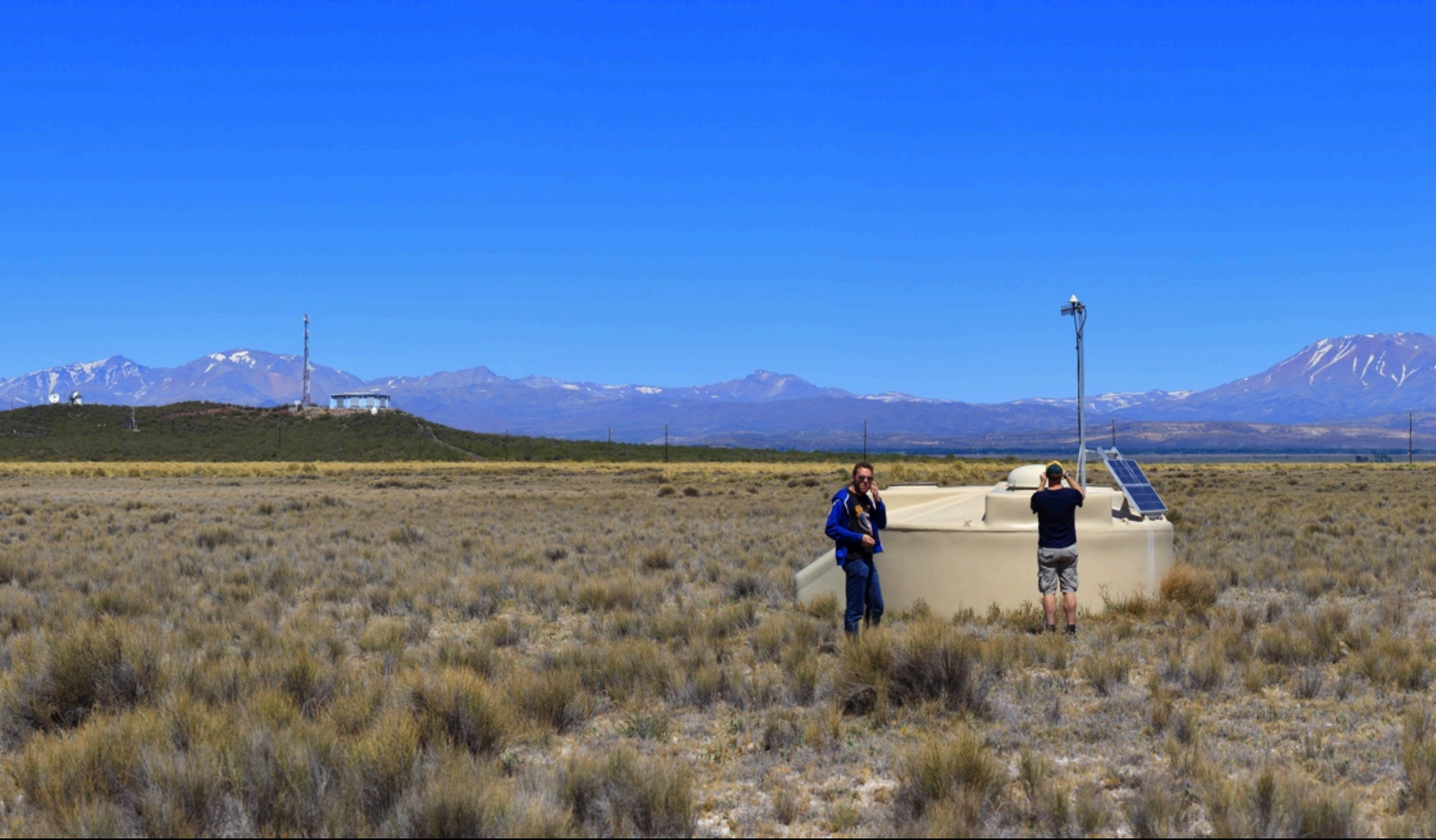
Highlights on UHECRs from the Pierre Auger Observatory

after ≈ 10 years of operation (and ≈ 20 years from the conception)



Piera L. Ghia (LPNHE, Paris and Univ. Paris VI and Paris VII)

Outline

The challenges of UHECRs

Challenging the challenge: The Pierre Auger Observatory

UHECRs after 10 years of Auger data

Conclusions and perspectives

The challenges of UHECRs

Prologue

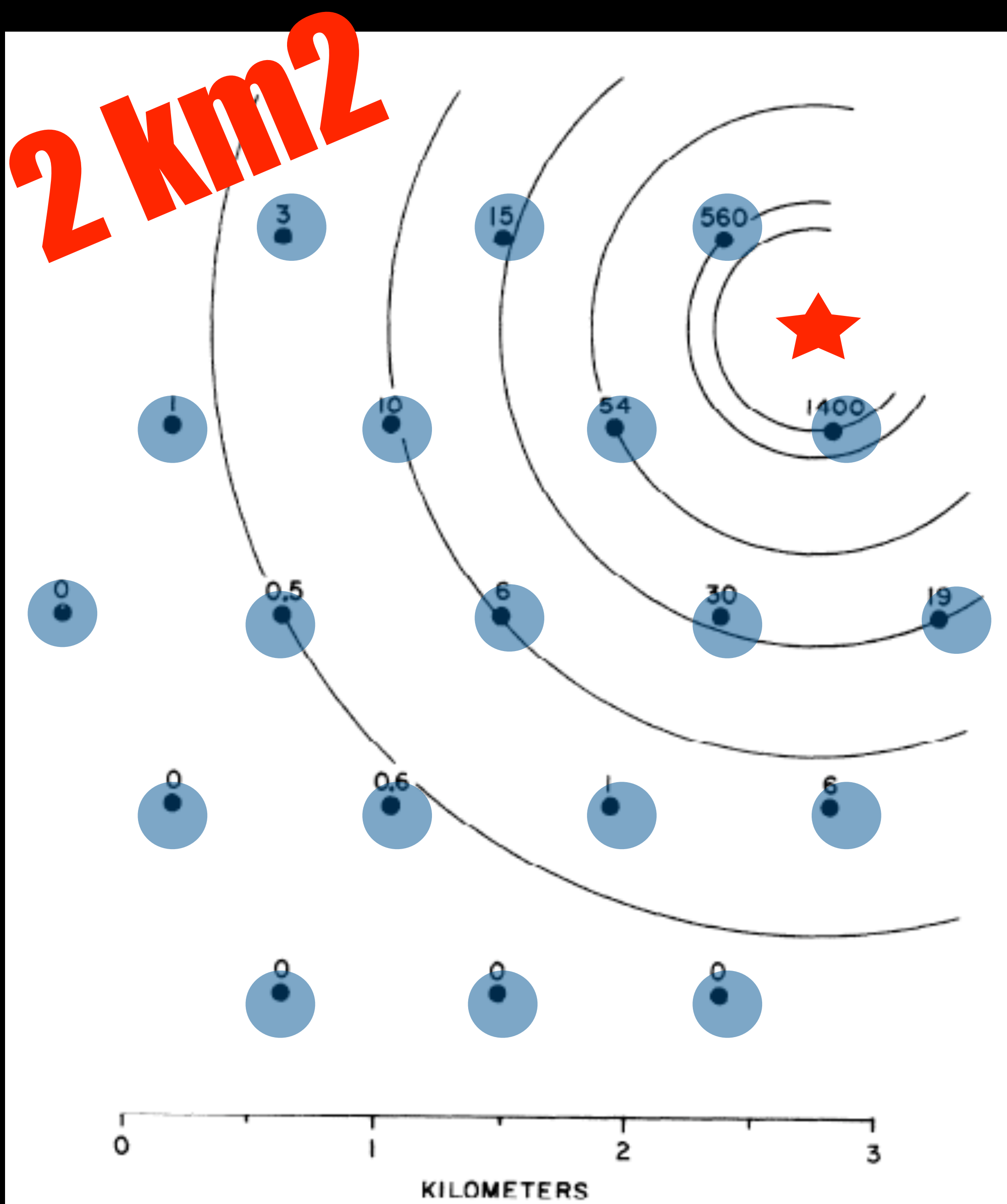
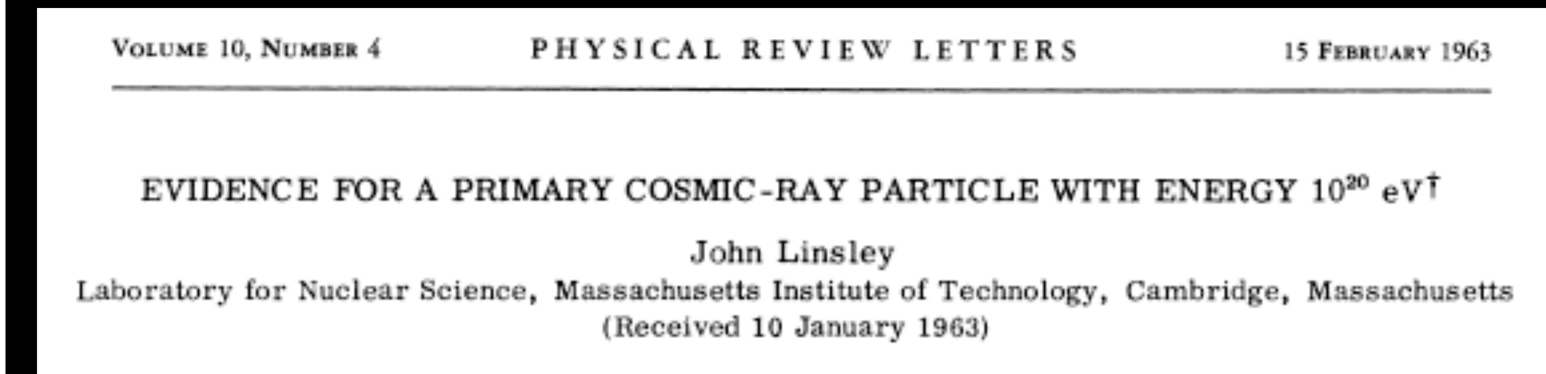


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower

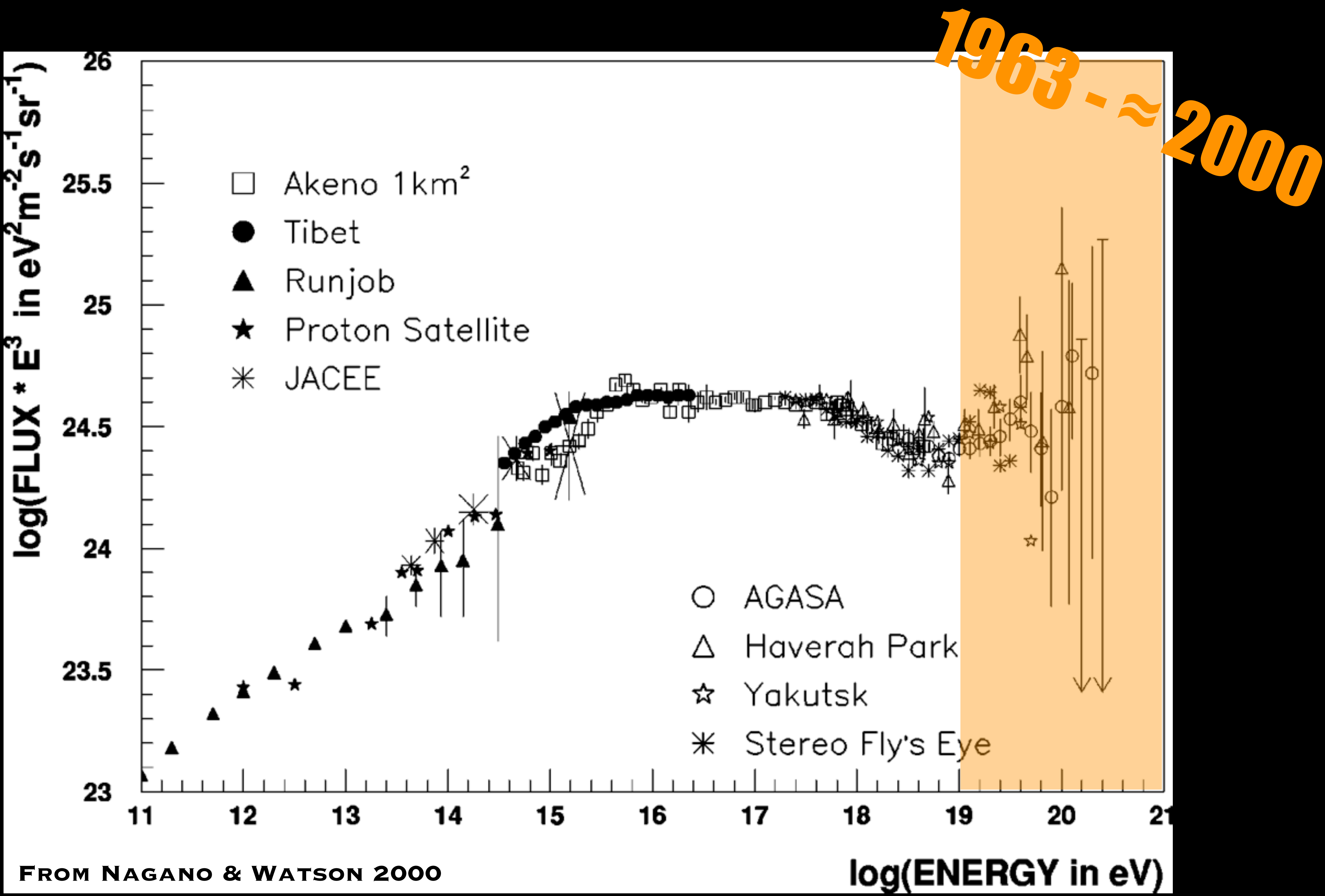

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

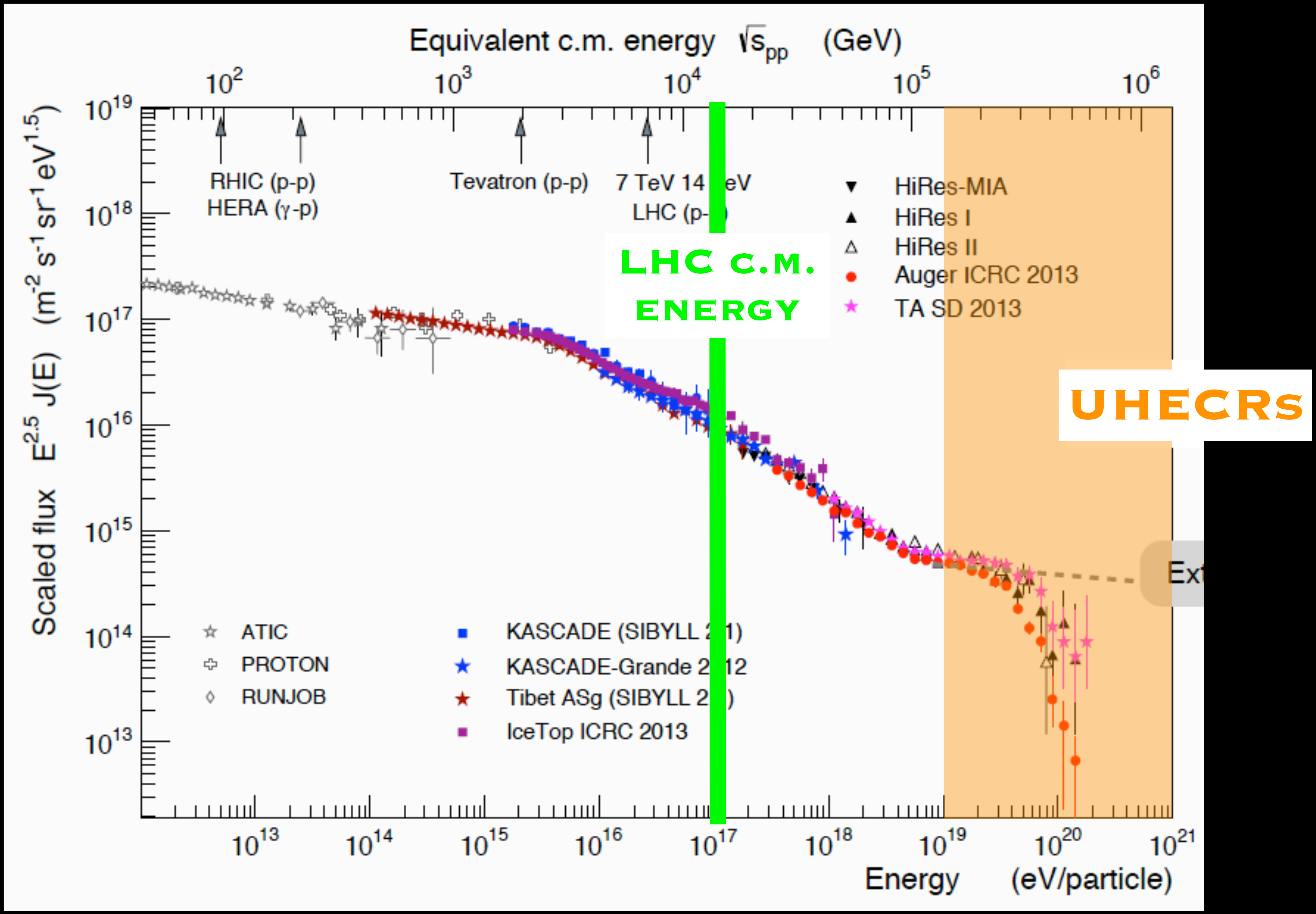
Volcano Ranch, 1963: the first observed CR at 10^{20} eV

Linsley's detection was not a swallow
(that does not make a summer)



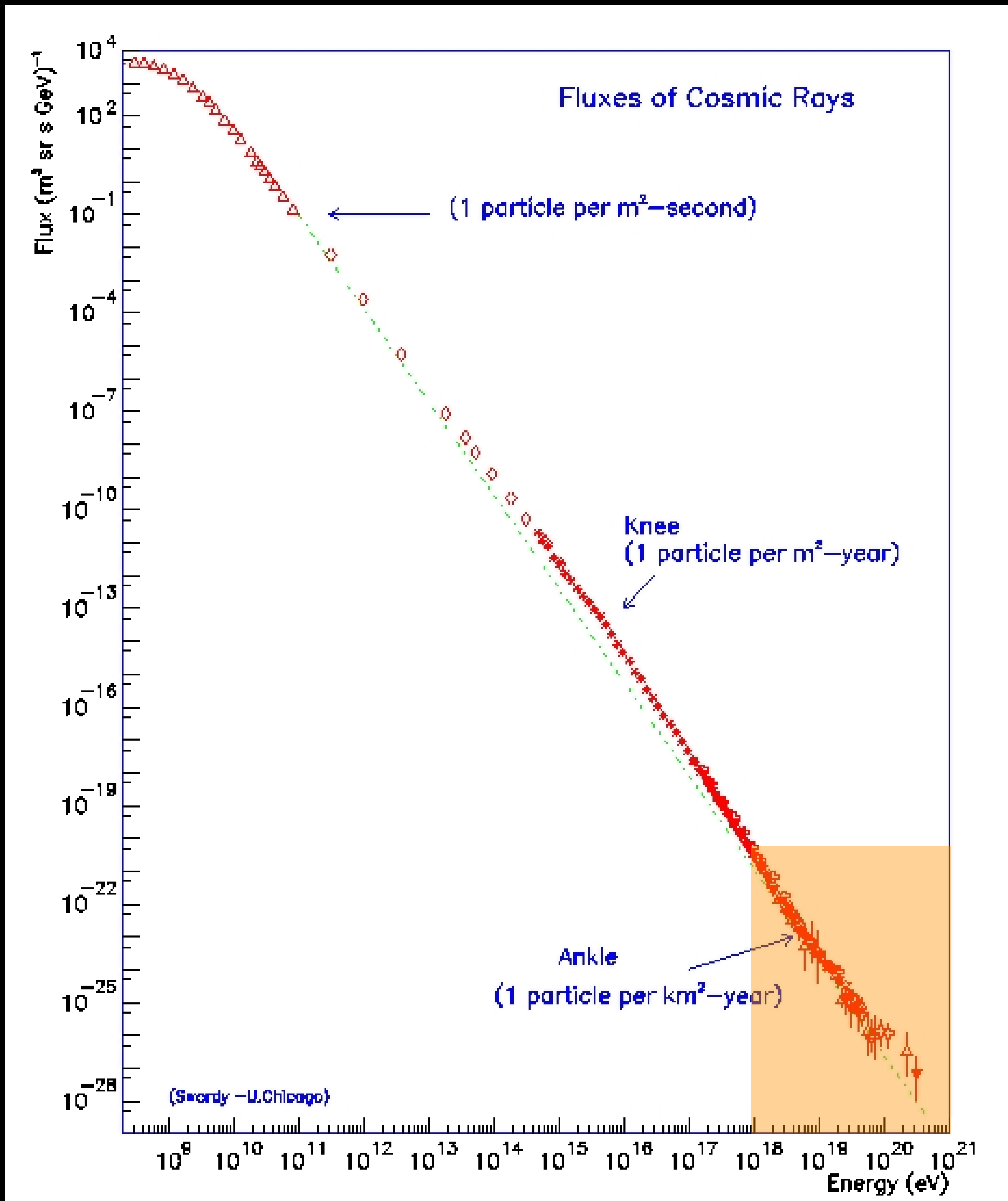
Cosmic rays of ultra-high energies were subsequently observed by several experiments, up to energies well exceeding 10^{20} eV

What produces them?



The Universe's highest energy particles

I Challenge: UHECR detection

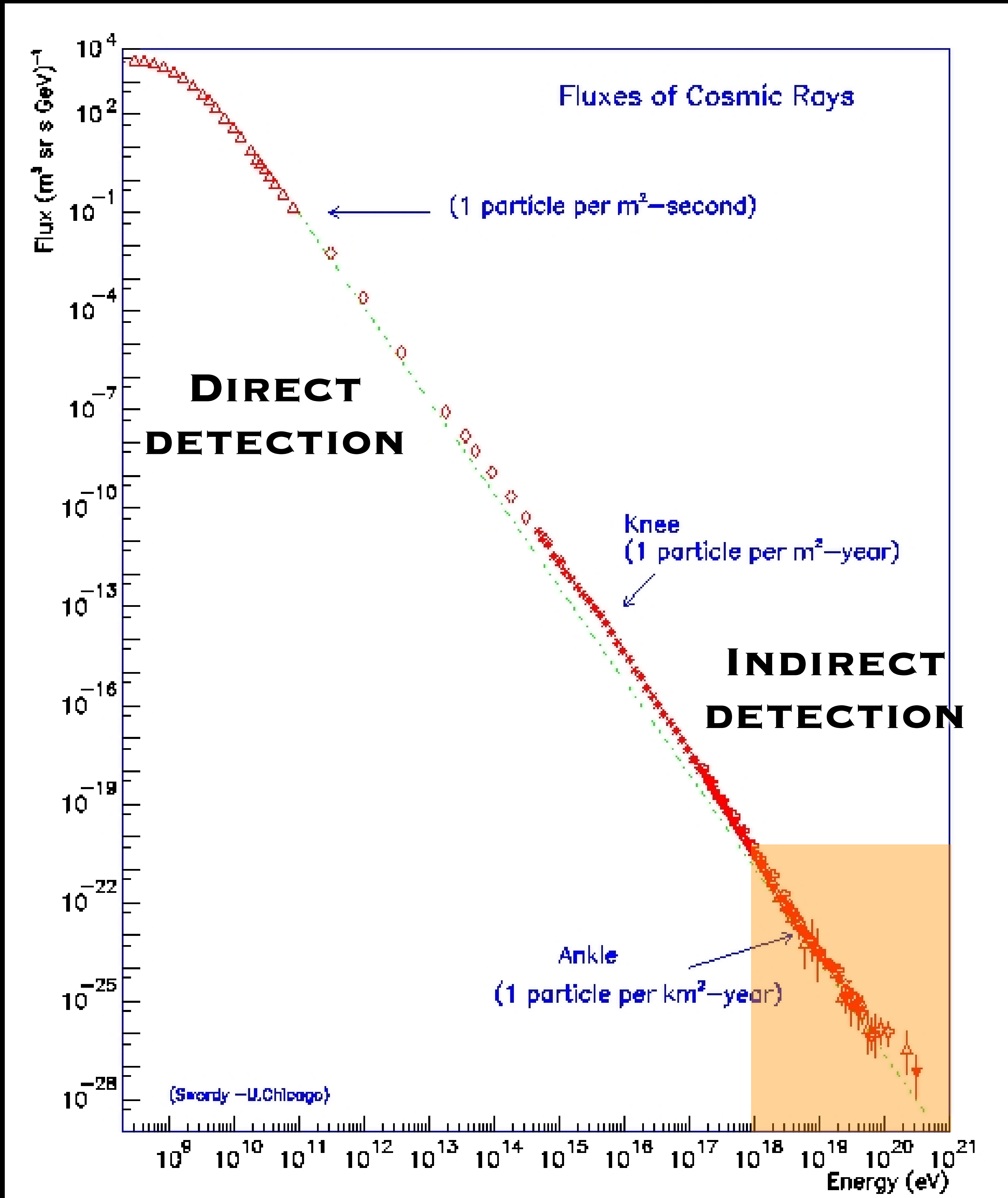


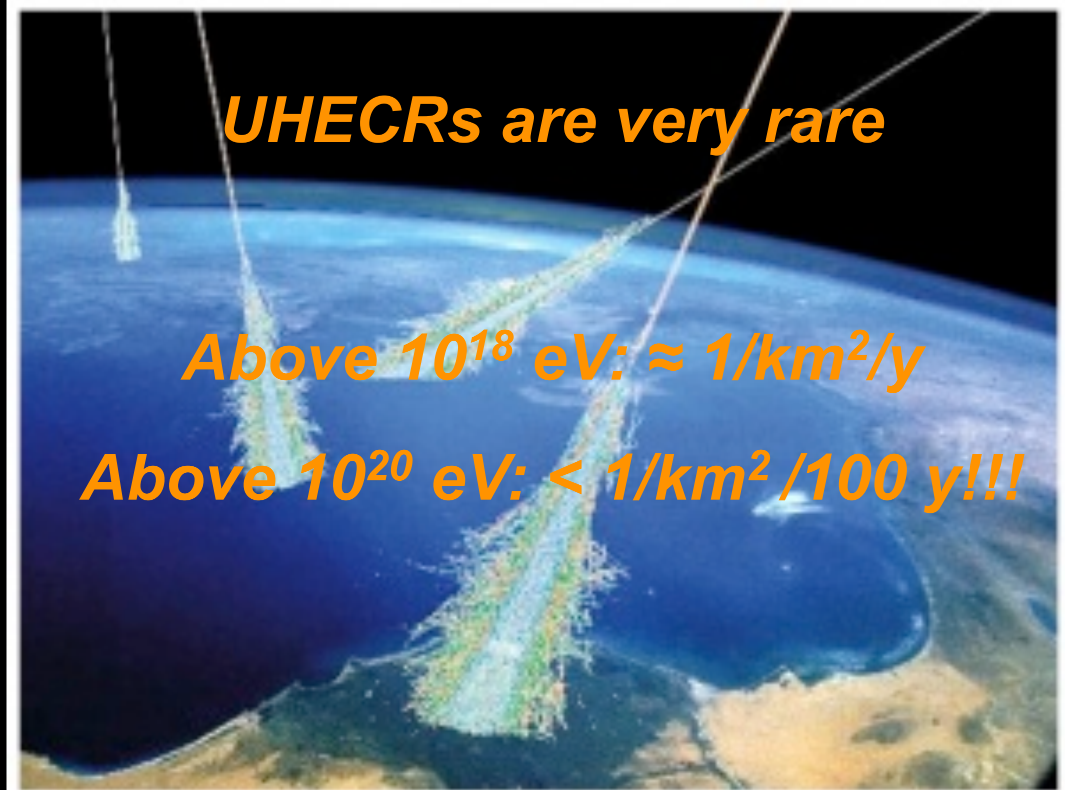
UHECRs are very rare

Above 10^{18} eV: ≈ 1/km^2/y

Above 10^{20} eV: < 1/km^2 /100 y!!!

I Challenge: UHECR detection

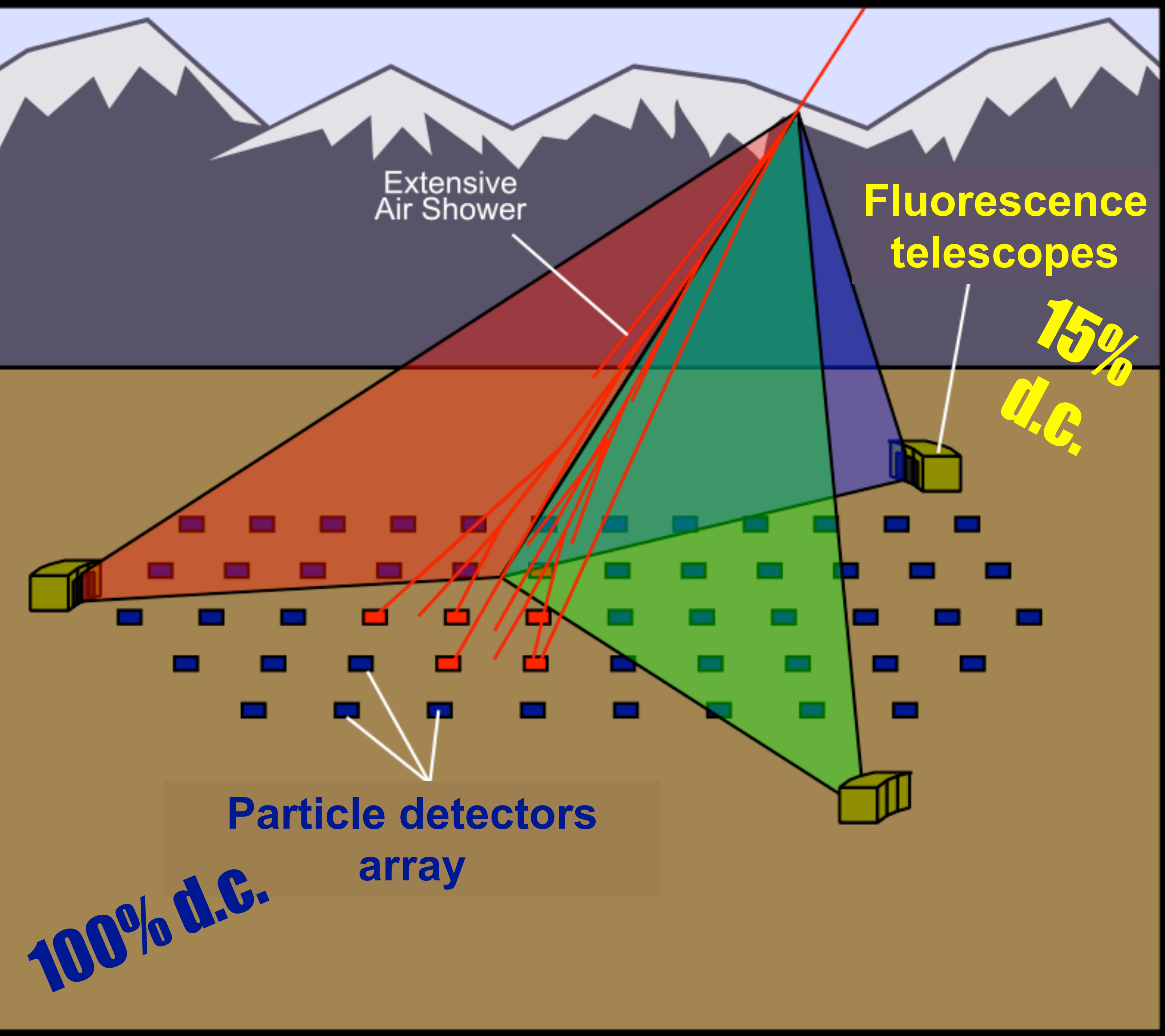




The only way of studying the high-energy region of the CR spectrum is by observing the secondary showers of particles produced by CRs interacting in our atmosphere.

The atmosphere is used as an inhomogeneous calorimeter.

I Challenge: UHECR detection



Extensive air showers can be detected over an extended area. Large detection area compensates the smallness of flux

Huge effective areas needed at UHE, as well as long exposure times ("observatories" more than "experiments")

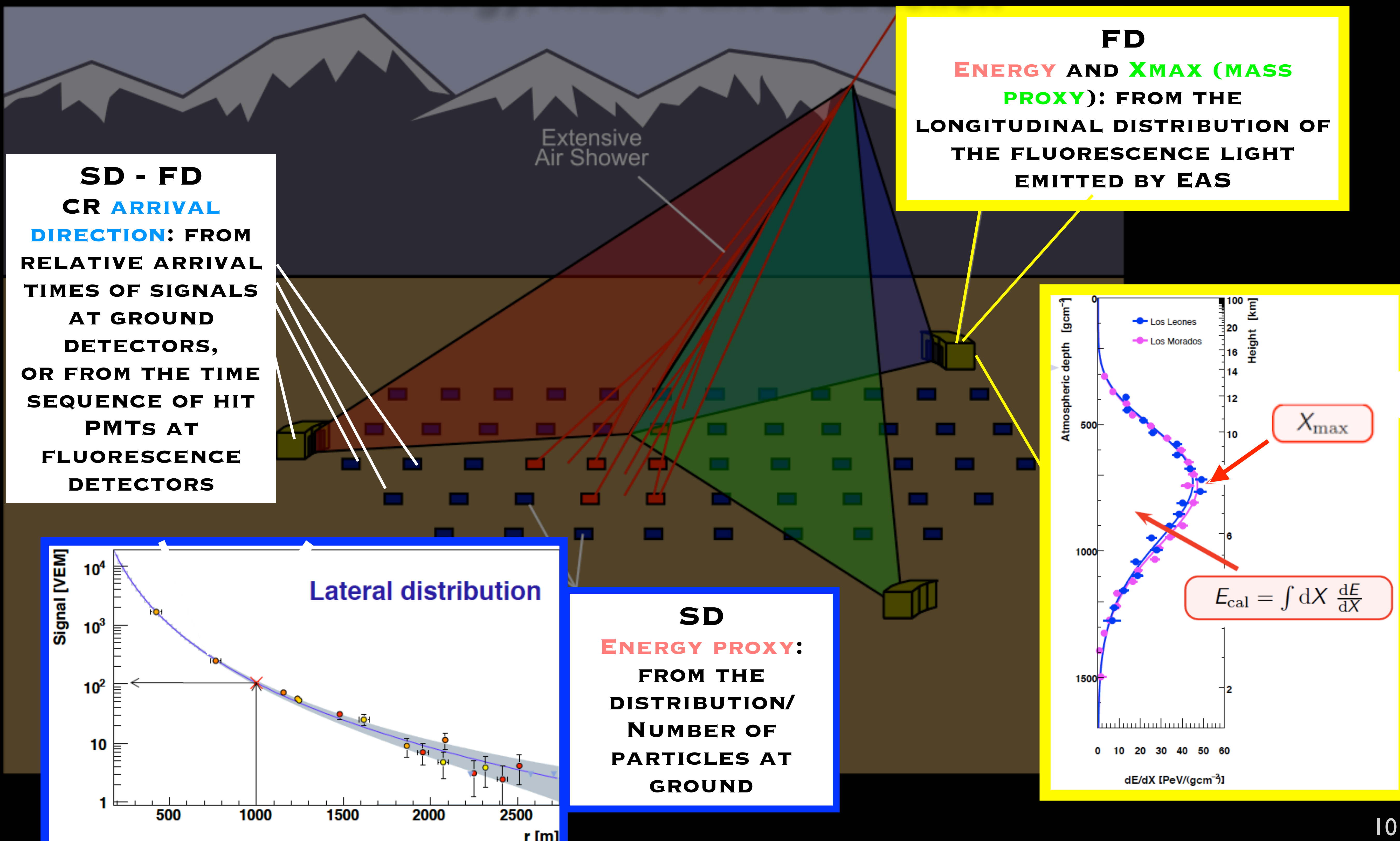
Giant particle detectors arrays on Earth (O(> 100 km^2, 100% d.c.)

and/or

telescopes recording fluorescence light emitted by Nitrogen molecules excited by shower particles (10-15% d.c.)

II Challenge: UHECR (indirect) measurements

How to pass from showers observables to CR properties
Energy, Mass, Arrival Direction



II Challenge: UHECR (indirect) measurements

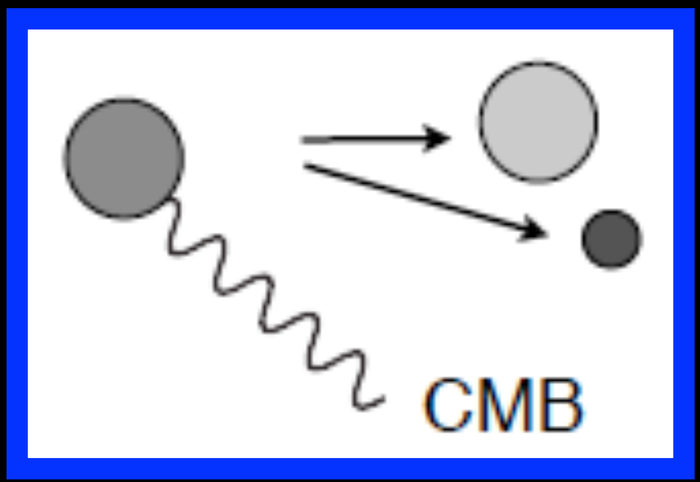
Technique	Particle detectors arrays	Fluorescence telescopes
Duty cycle	100%	15%
Arrival direction	Direct < 1°	Direct < 1°
Energy	Indirect: Need for calibration	Direct: Calorimetric measurement
Mass	Indirect: Shower sampled at a unique depth	Direct: Shower development

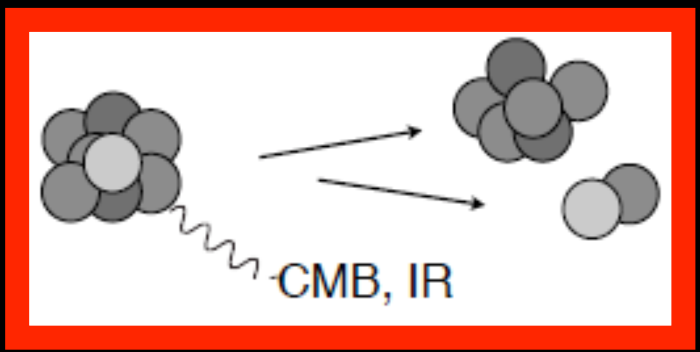
Two complementary techniques

Challenge: inferences on UHECRs

For CRs above ≈ 10^{18} eV, their gyro-radius exceeds Galactic dimensions for typical magnetic fields of O(μG) strength: probable **EXTRA-GALACTIC origin**

PROPAGATION



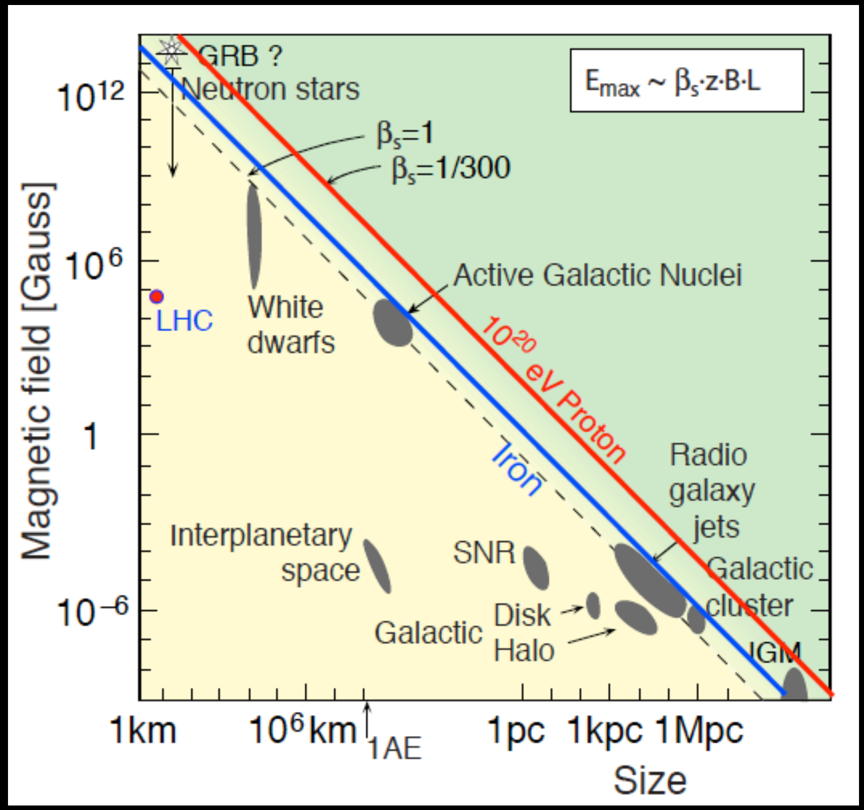


UHECRs interact with CMB photons

Protons (above ≈ 40 EeV) undergo pion photo-production (GZK)

Nuclei are photo-dissociated (similar threshold)

ACCELERATION

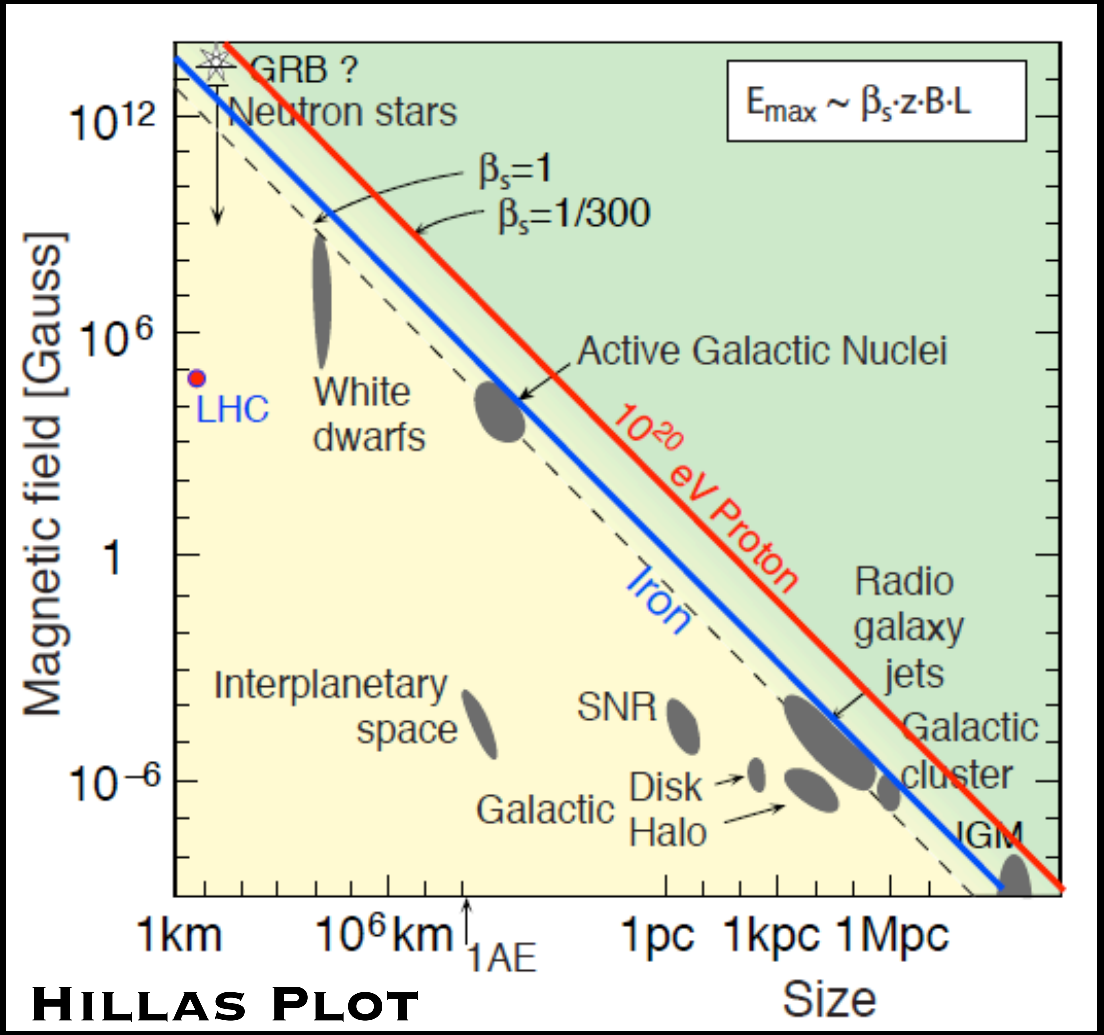


Maximum acceleration energy: depends on the product of B (magnetic field) and L (object size) AND on the charge of the UHECR

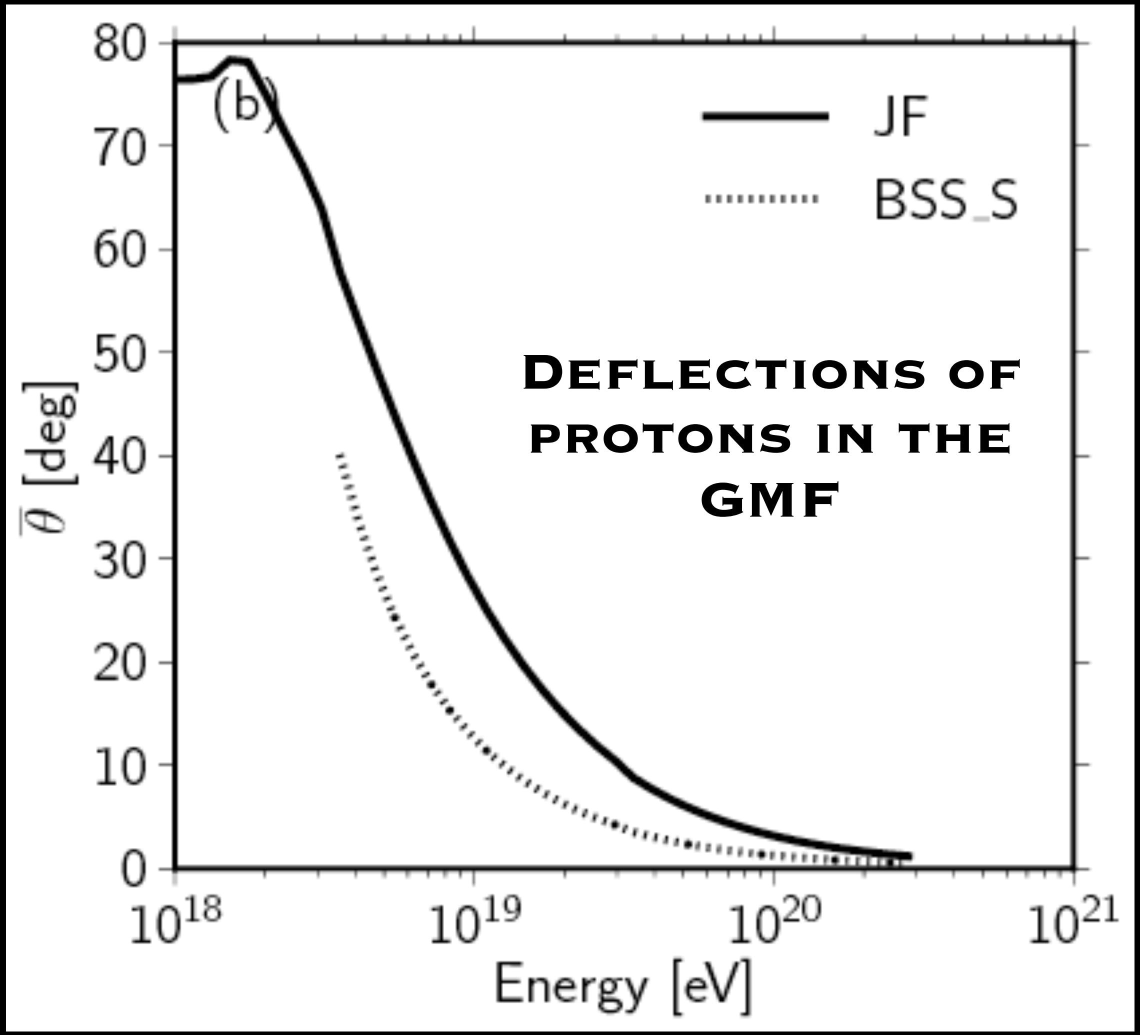
The features of the energy spectrum (flux vs energy) tells us about UHECR propagation and/or their maximum energy at the source

The measurement of the primary mass tells us the origin of features in the energy spectrum

Challenge: inferences on UHECRs



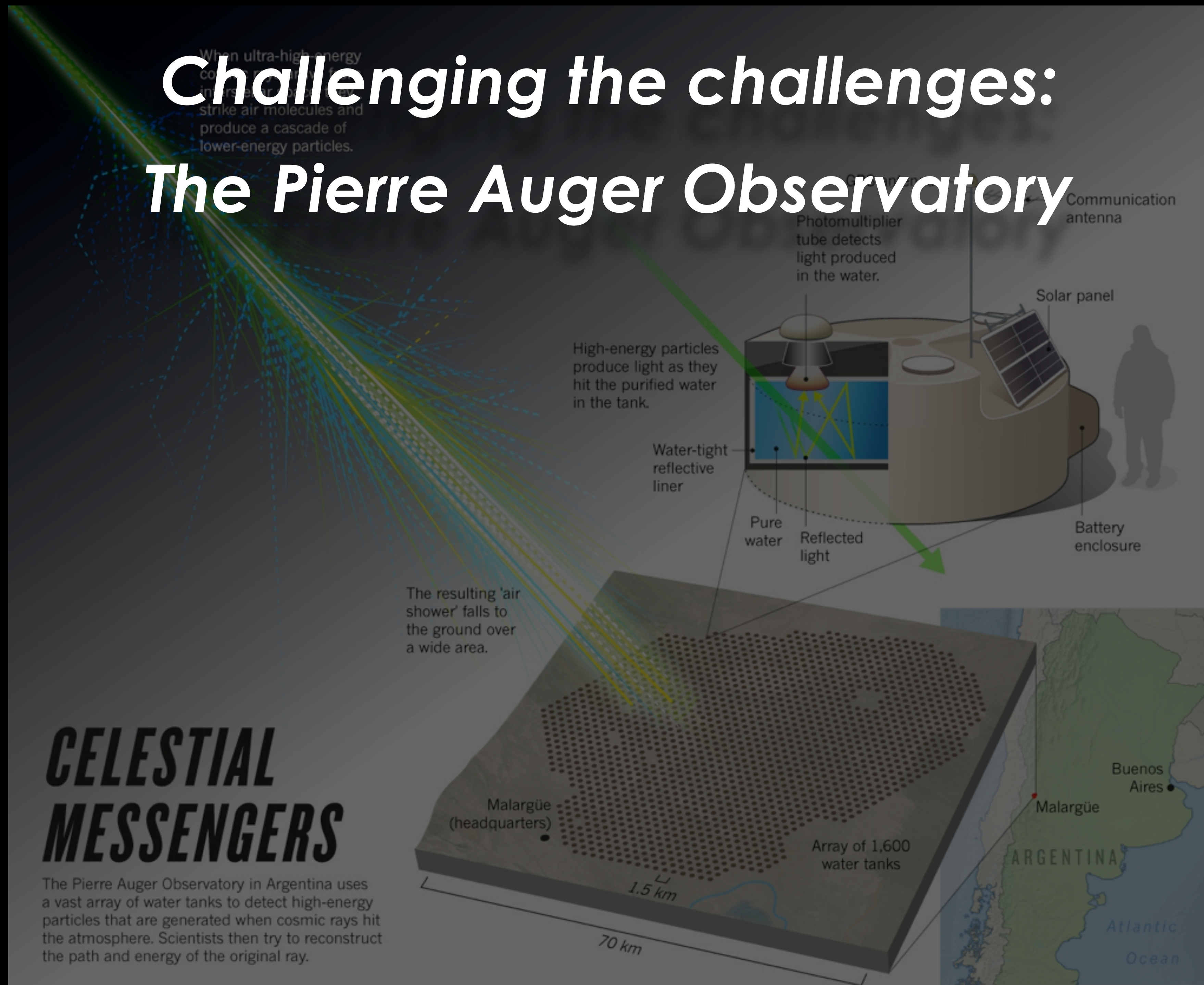
Only few kind of sources might accelerate particles to UHE



The highest energy cosmic rays might point to sources (if they are protons)

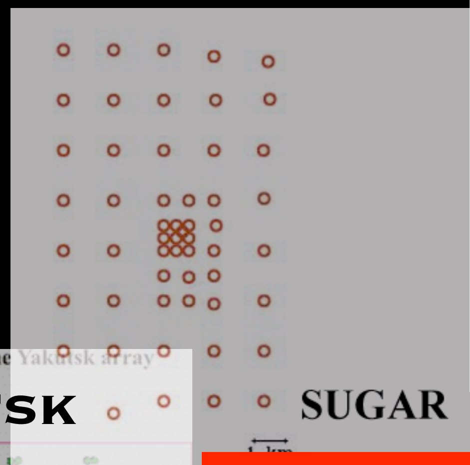
Energy-loss processes on the CMB limit the “horizon” of UHECRs (<200 Mpc). As “nearby” matter is not homogeneously distributed, the **distribution of UHECR arrival directions** might show small-scale anisotropies. If they are low-Z particles indeed.

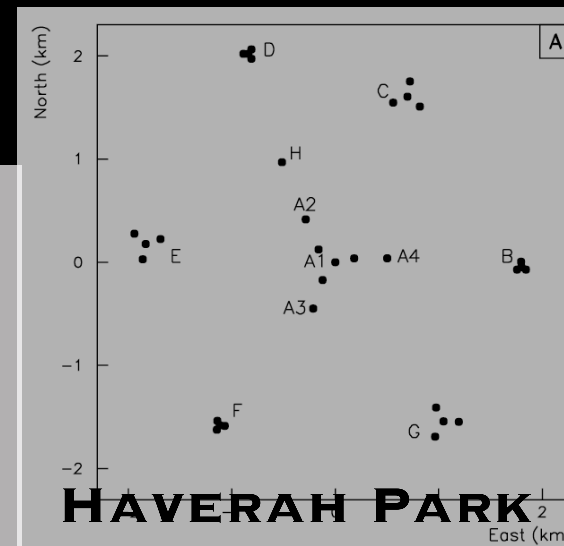
Challenging the challenges: The Pierre Auger Observatory

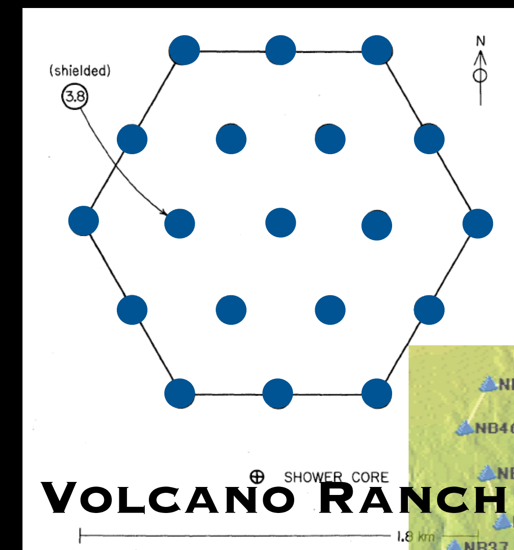


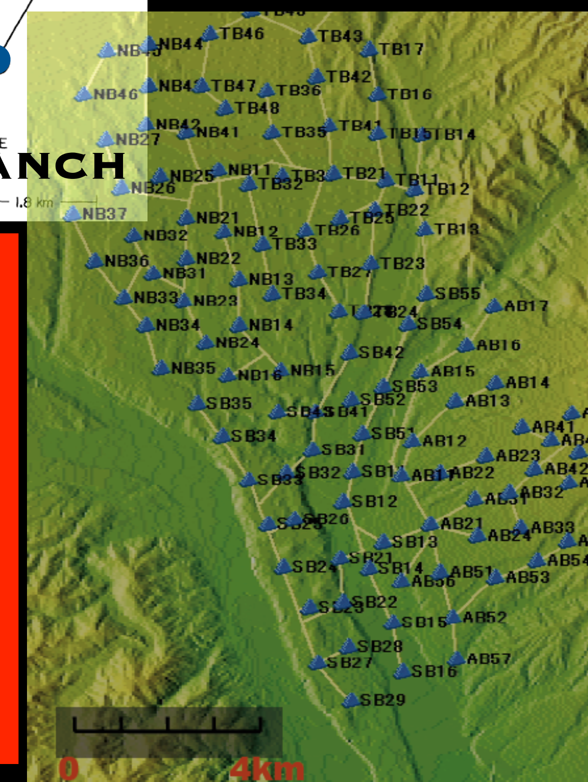
Where did we stand when Auger was conceived?

A few numbers









7 observatories

≈ 40 years of observation,

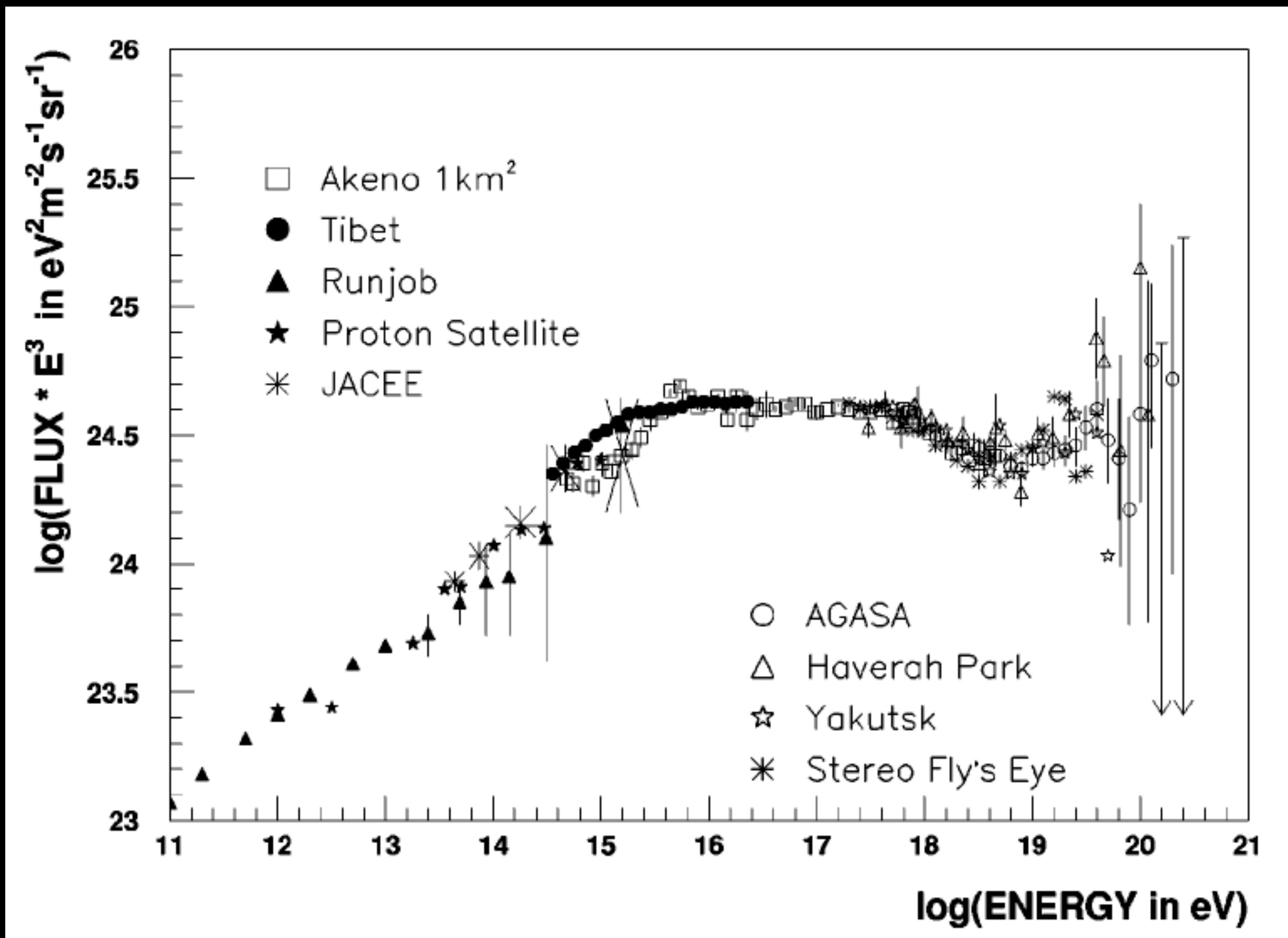
≈ 150* events above 40 EeV

≈ 50* above 55 EeV

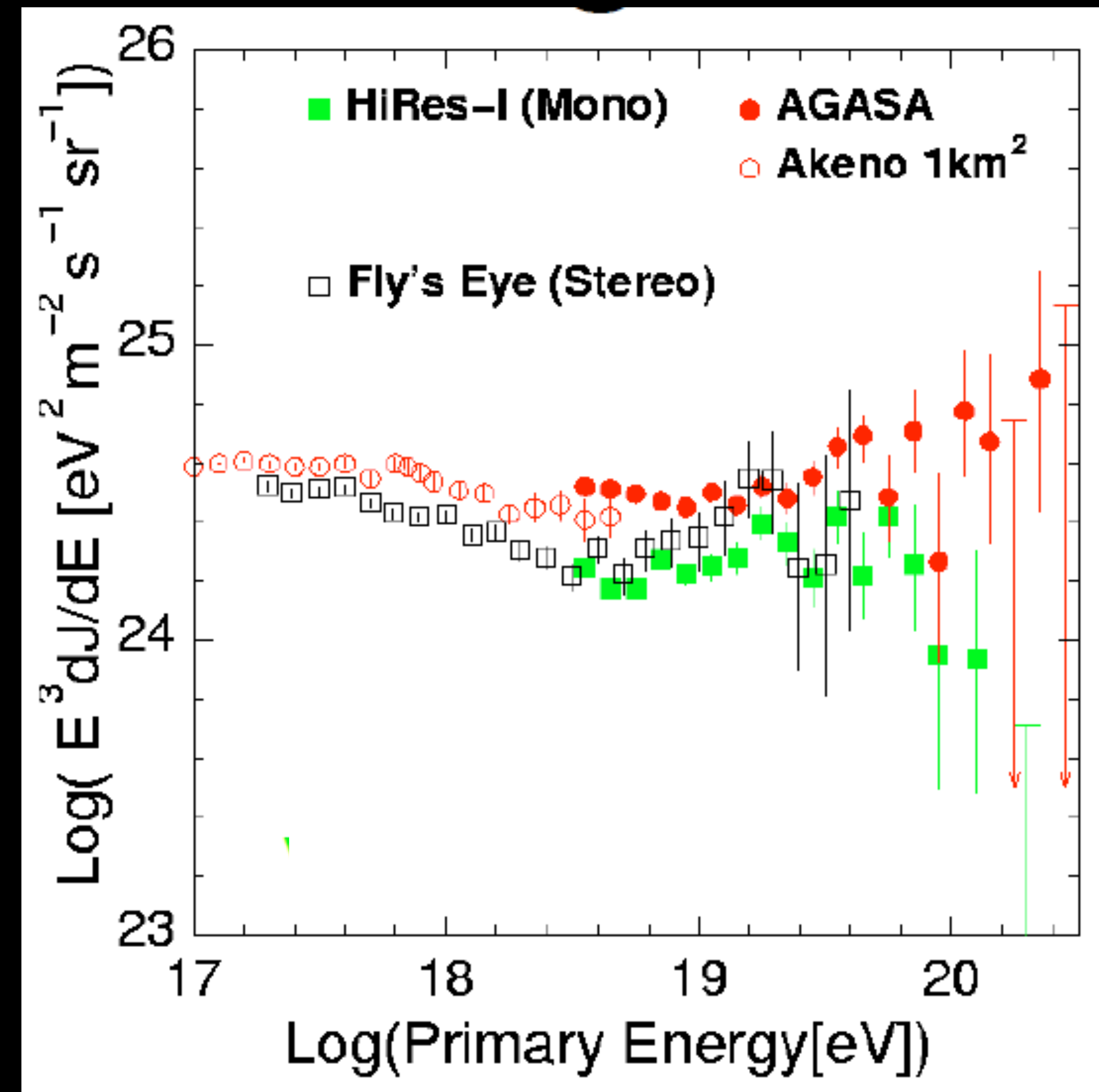
* CAVEAT: THE ENERGY SCALE OF AGASA WAS AFTERWARDS DISCOVERED TO BE OVER-ESTIMATED BY 30%

Where did we stand when Auger was conceived?

UHECR Flux



"I GENERATION"

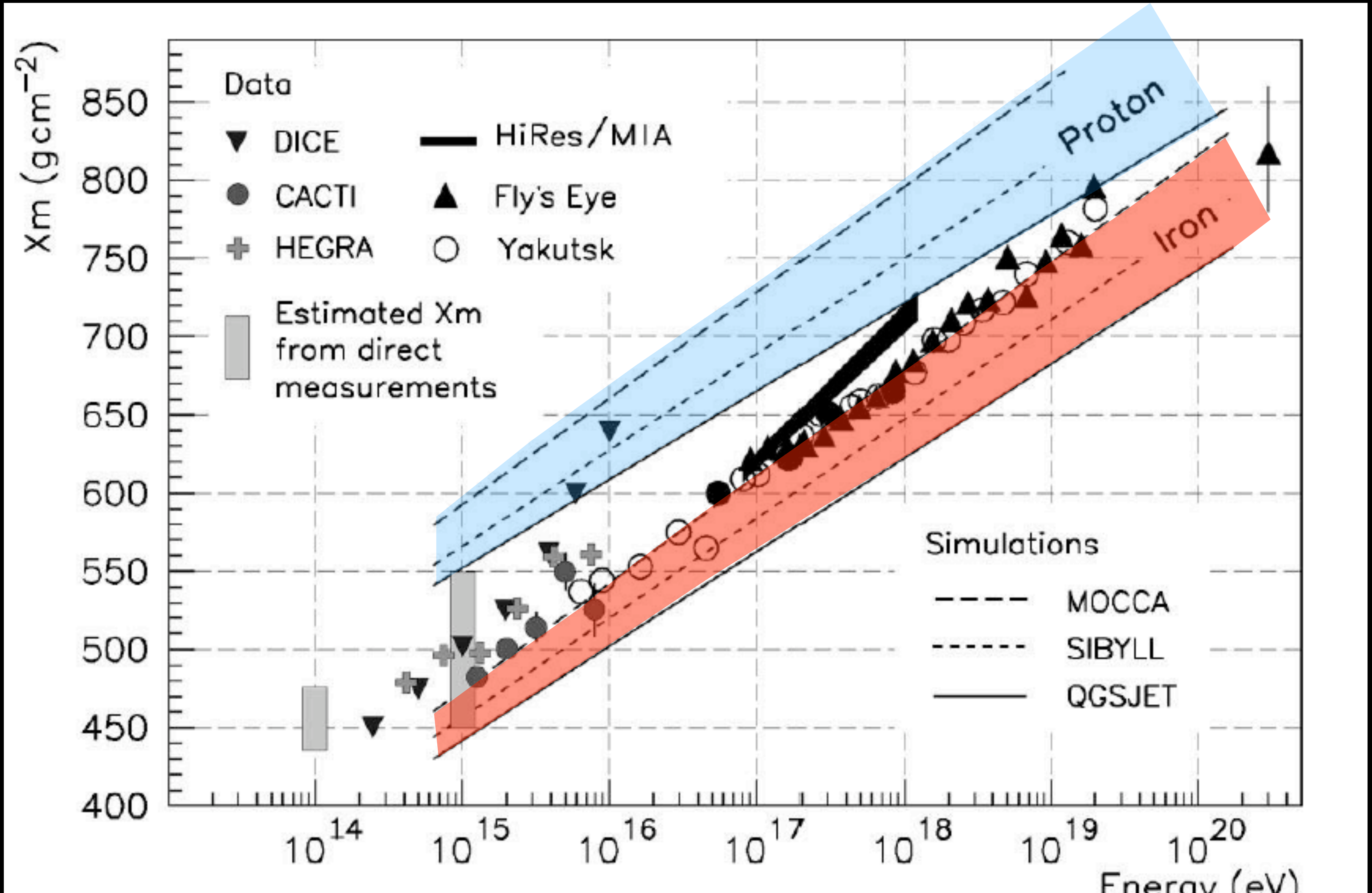


"II GENERATION"

Scarcity of UHE events: impossible to establish the existence of the suppression of the flux

With a larger number of events: AGASA (no suppression) vs HiRes (yes suppression) "controversy"

Where did we stand when Auger was conceived?
UHECR Mass

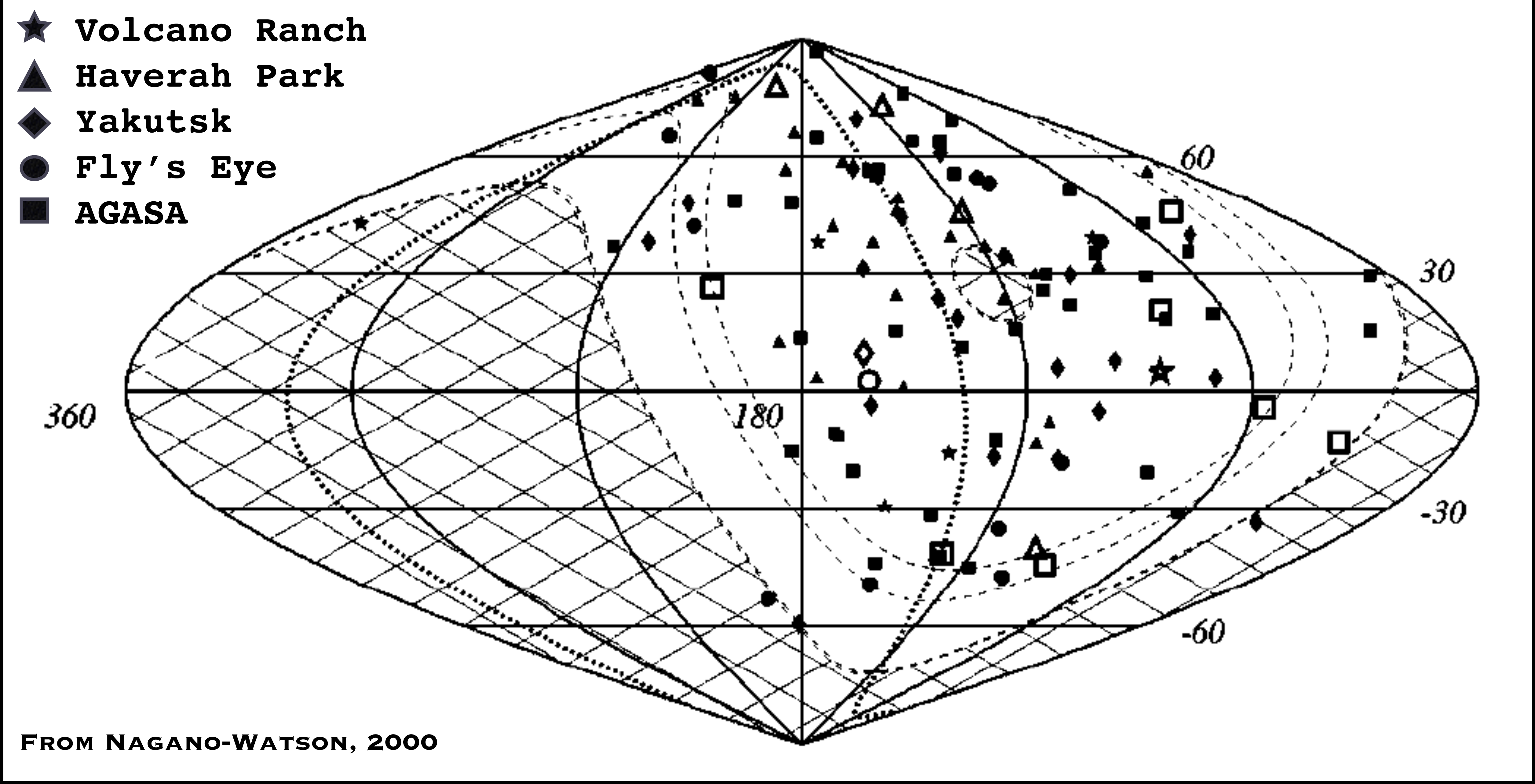


From Nagano & Watson 2000

<Xmax>: Paucity of events above 10 EeV

Large differences between hadronic models hindering mass interpretations

Where did we stand when Auger was conceived?
UHECR arrival directions



40 years of observation, 5 different experiments: 114 events above 40 EeV

Angular resolution: 2.5-5°

No significant deviation from isotropy in galactic and super-galactic coordinates

No correlation with nearby matter distribution

Possible clusters on ≈ 2.5 deg scale? (AGASA Doublets/triplets)

Mid-90s: Conception of the Pierre Auger Observatory

THE PIERRE AUGER OBSERVATORY PROJECT: AN OVERVIEW

M. Boratav (for the Auger Collaboration)

LPNHE, University of Paris VI, 4 Place Jussieu, 75005 Paris, France

ABSTRACT

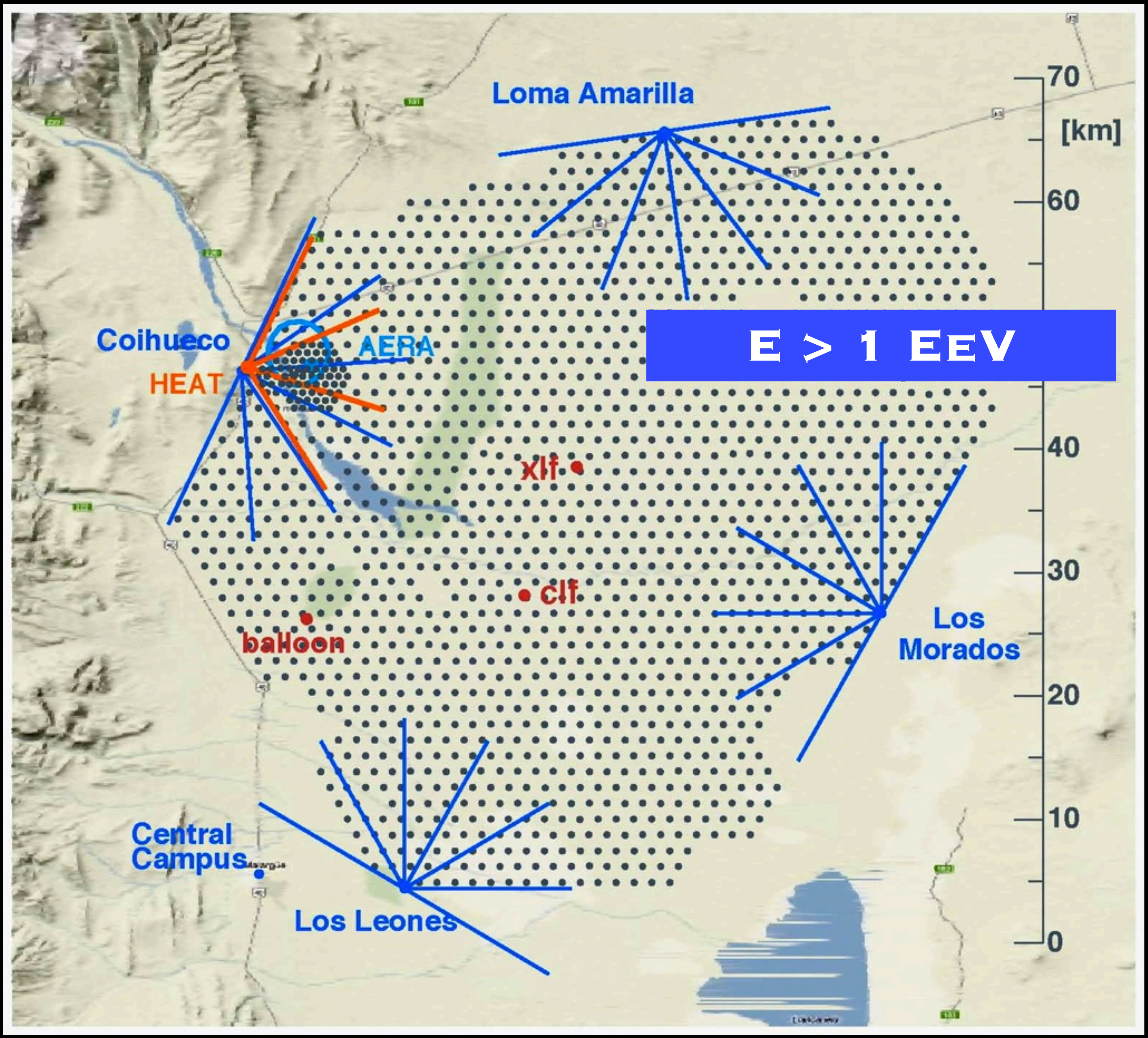
The Pierre Auger Observatory is a project of cosmic ray detector aiming at a high-statistics study of cosmic rays with energies exceeding 10^{19} eV (around and above the so-called Greisen-Zatsepin-Kuzmin spectral cutoff). The origin of the cosmic rays belonging to this extreme region of the energy spectrum is essentially unknown. Therefore, the Observatory is designed so that it will detect, in a few years' time, thousands of events in the relevant region, reconstruct their energy spectrum with unprecedented precision, measure the directions from which they come and, to some extent, study the chemical composition of the incident cosmic rays. The design of the detector is now complete and a world-wide collaboration is ready to build it in five years. We present a brief description of the detector together with its performance and the present status of the project.

25th International Cosmic Ray Conference, 1997, Durban

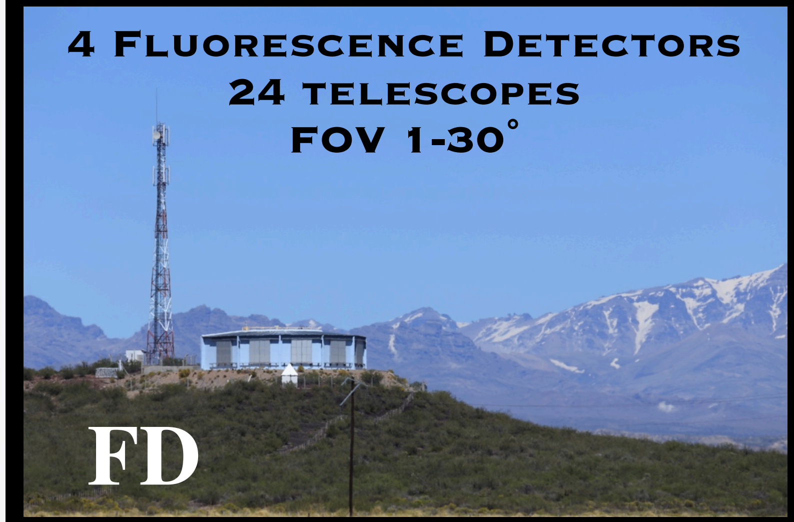
Mid-90s: Conception of the Pierre Auger Observatory

Merging a particle detectors array and fluorescence telescopes into a **giant *hybrid* observatory**

The Pierre Auger Observatory, Argentina

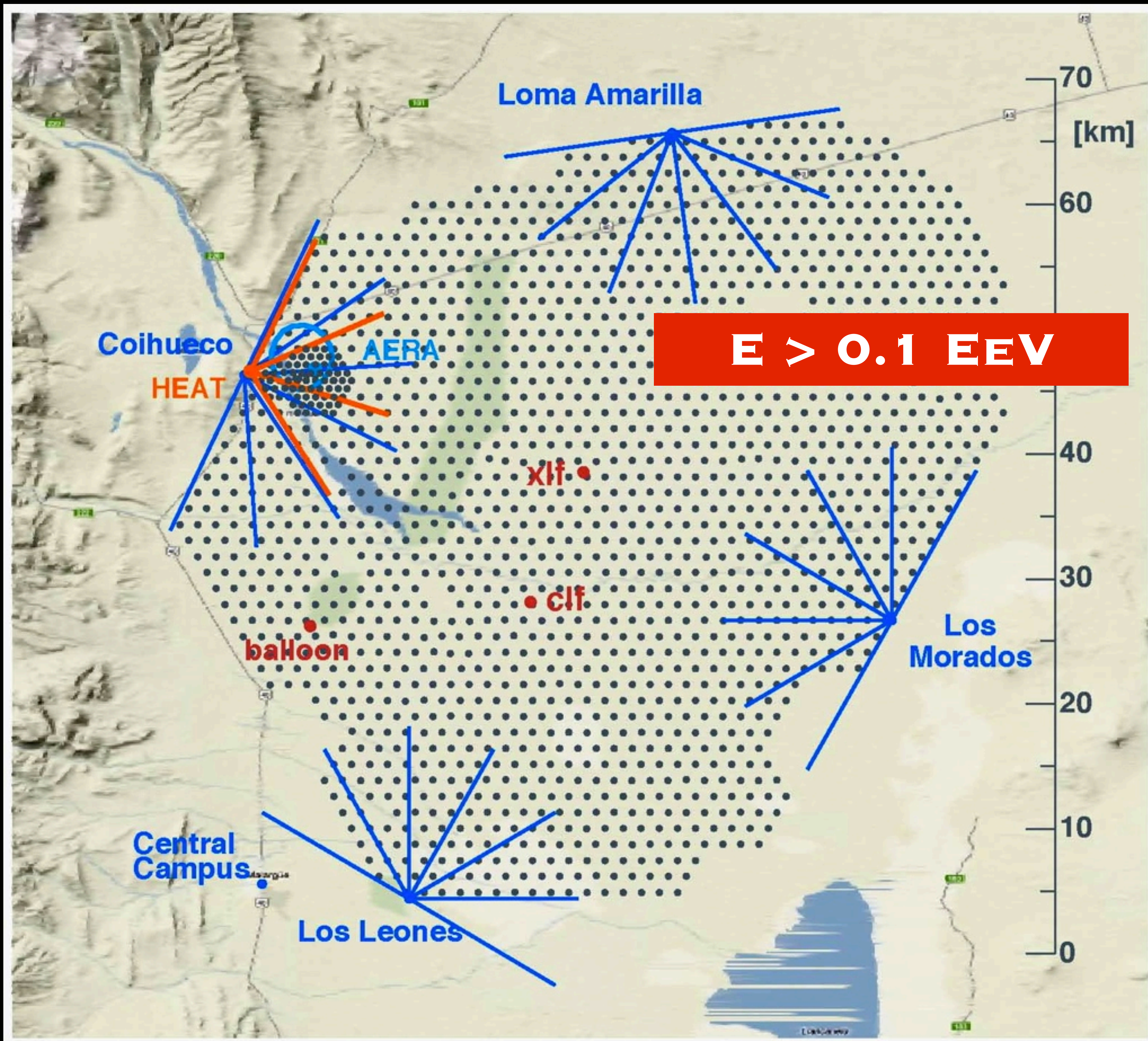


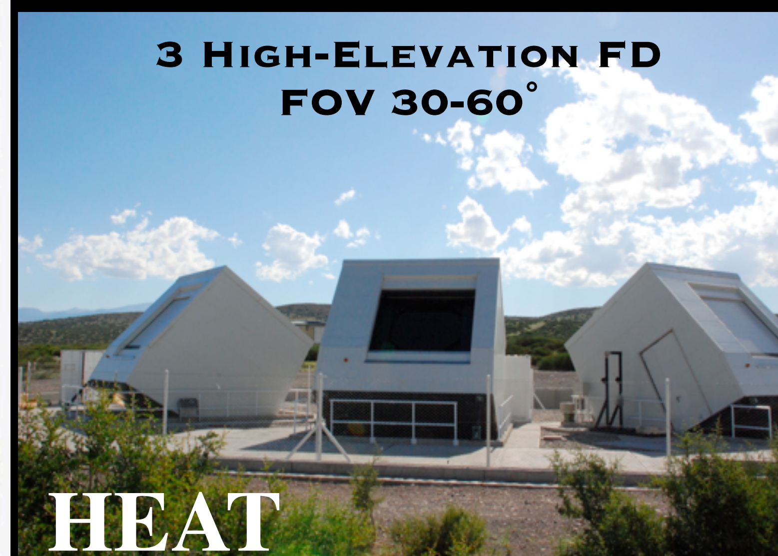
THE INITIAL DETECTORS

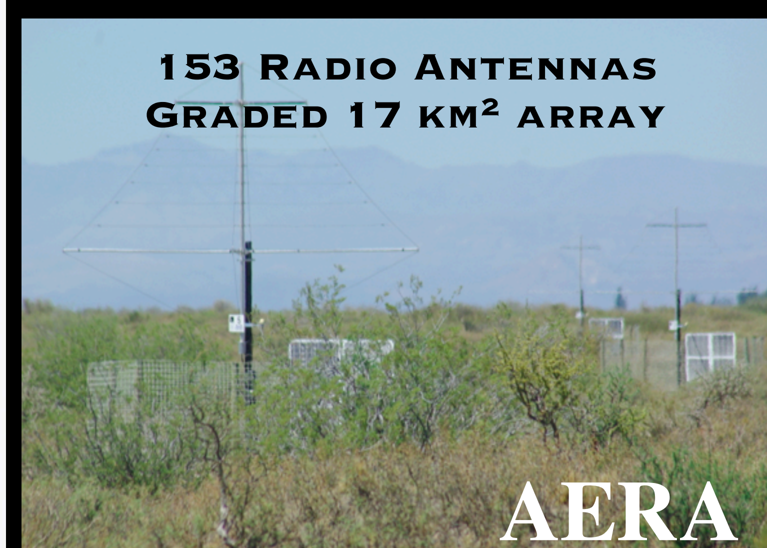


The Pierre Auger Observatory, Argentina

THE NEW DETECTORS

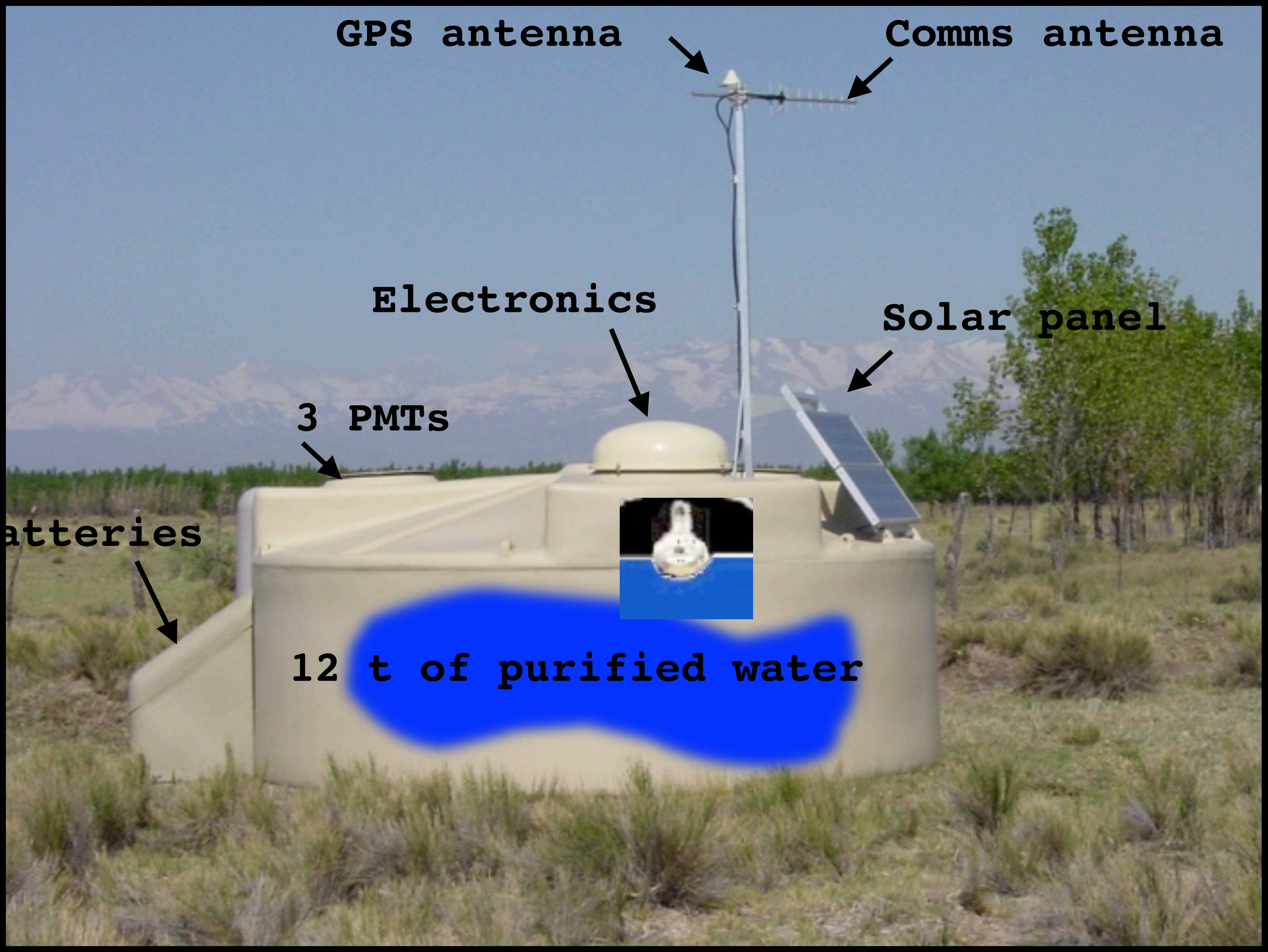






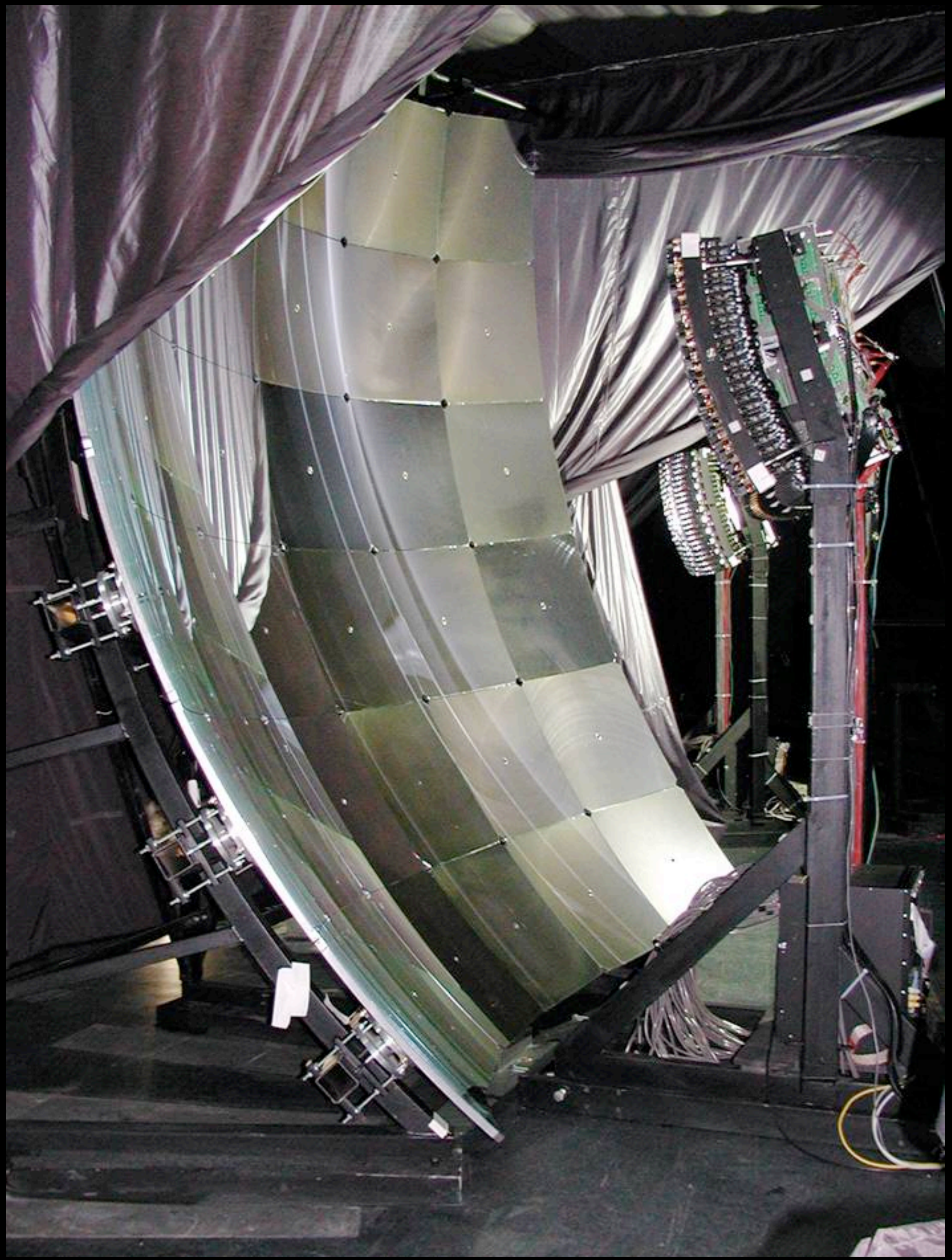
The basic elements of the Observatory

Particle detector



Water (12 t) Cherenkov detector
Area: 10 m2
Thickness: 1.2 m
acceptance up to 90 deg
Sensitive to em and mu component
(light signal larger for mu)

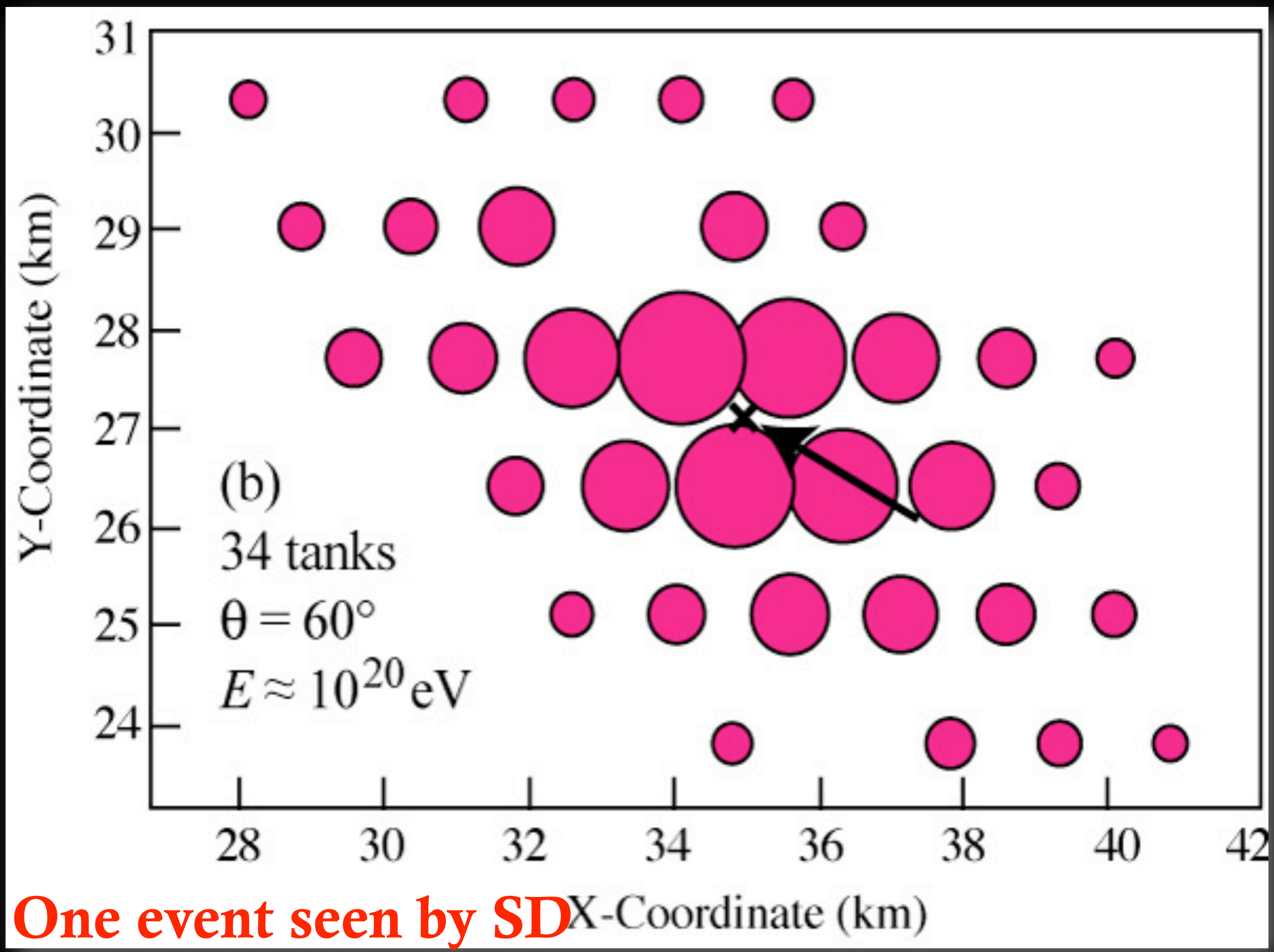
Fluorescence telescope

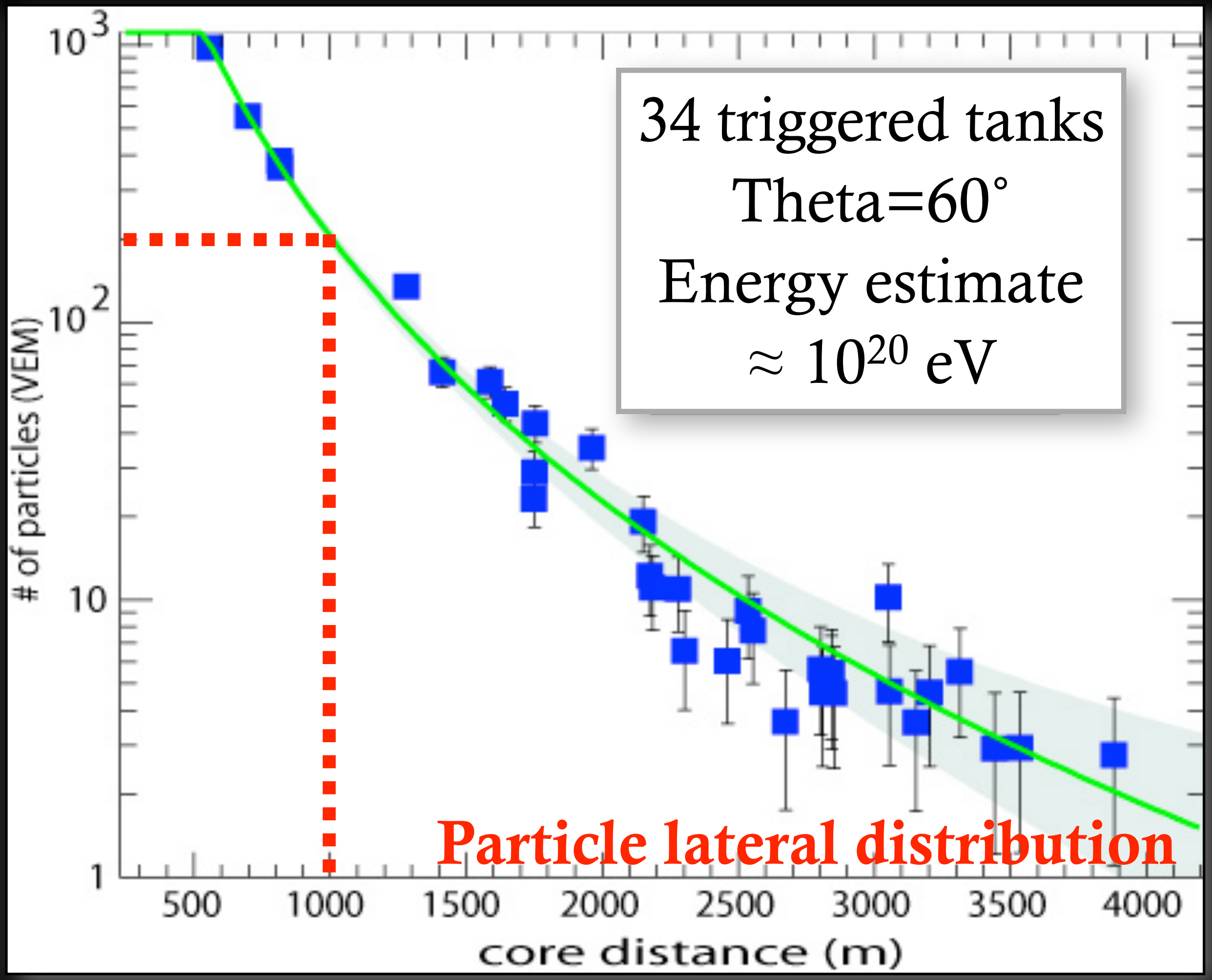


3.4 m segmented mirror
440 PMTs camera
30˚x 30˚ FOV

The basic observables

SD measures the lateral structure of the shower at ground

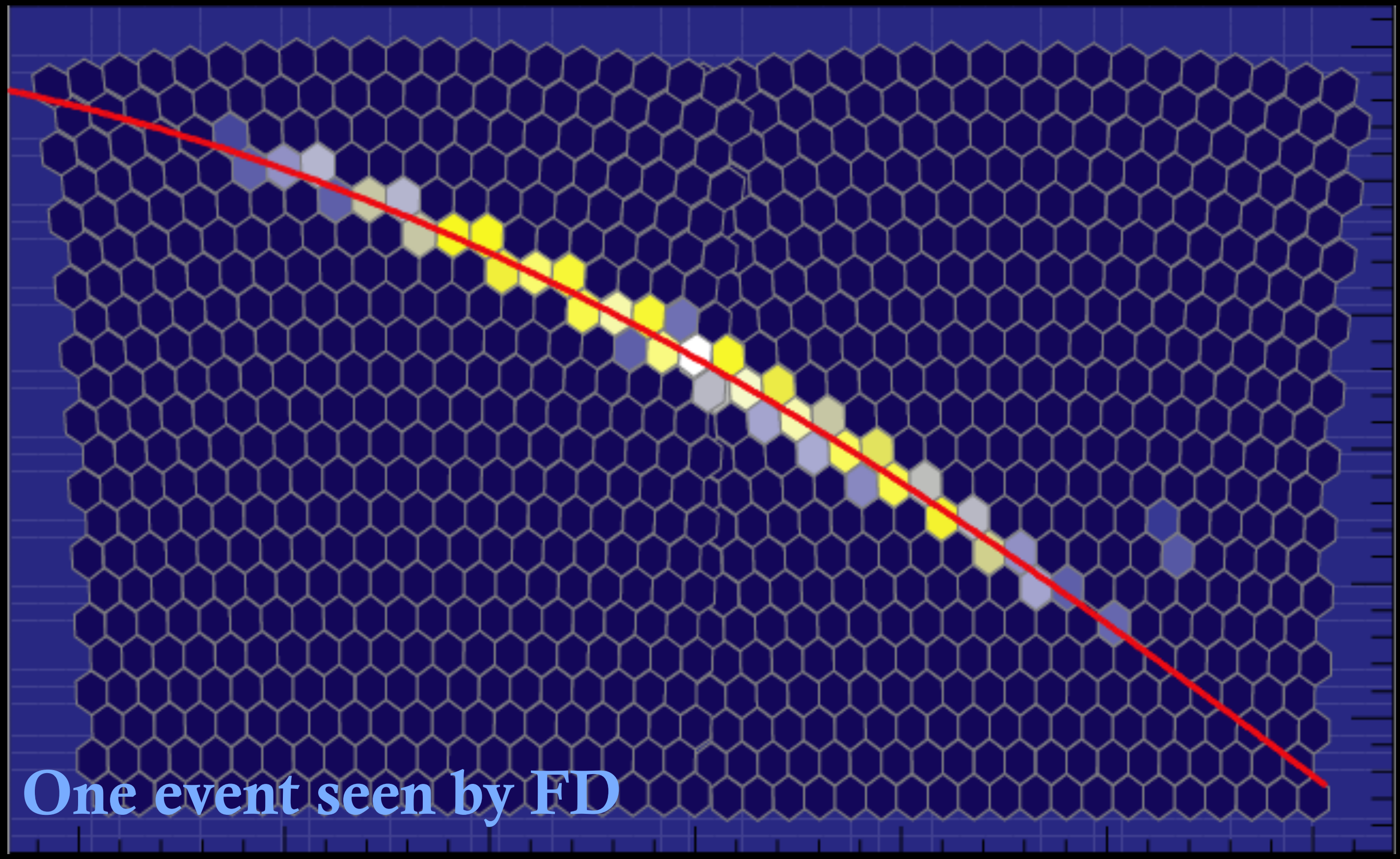


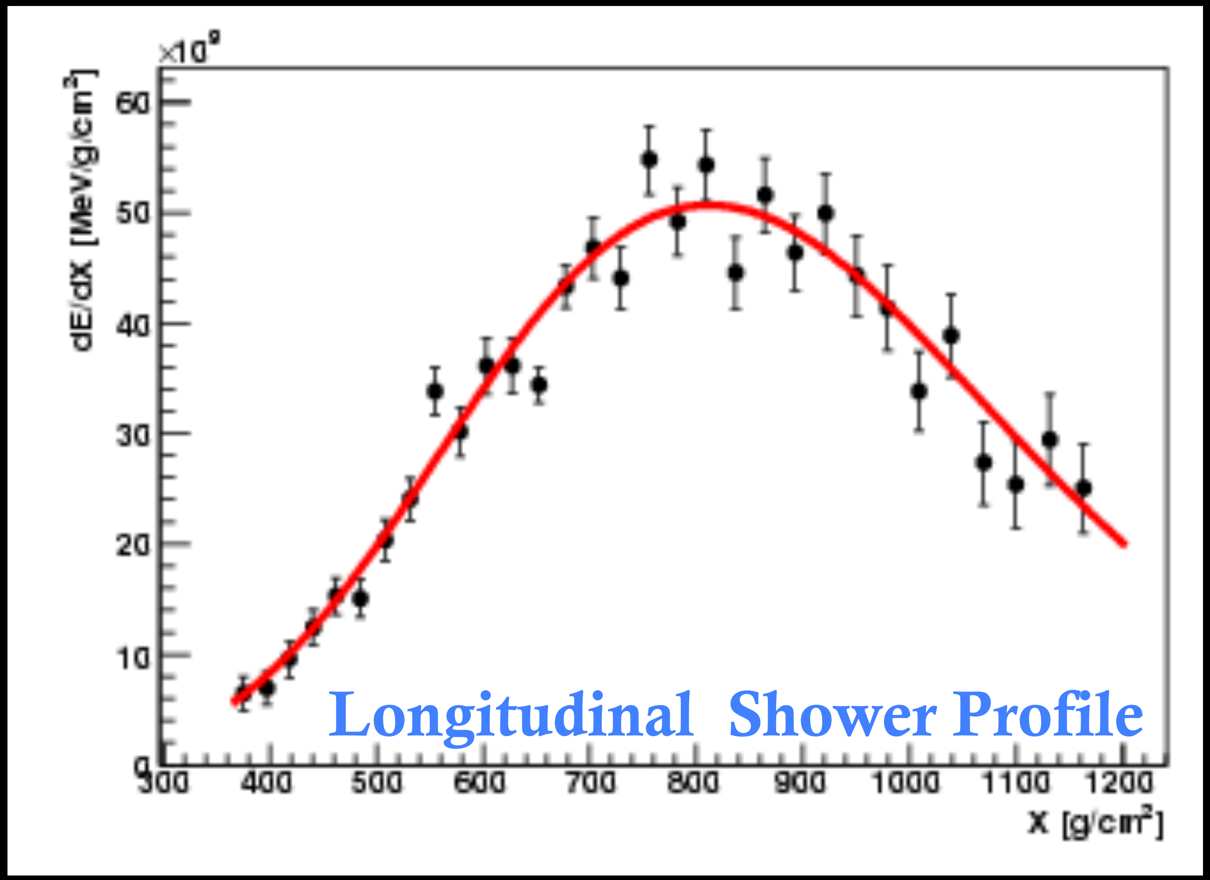


- Reconstruct geometry (arrival direction & impact point)
- Fit particle lateral distribution (LDF)
- S(1000) [signal at 1000 m] is the Auger energy estimator ("ideal" distance depends on detectors spacing)

The basic observables

FD records the longitudinal profile of the shower during its development in atmosphere

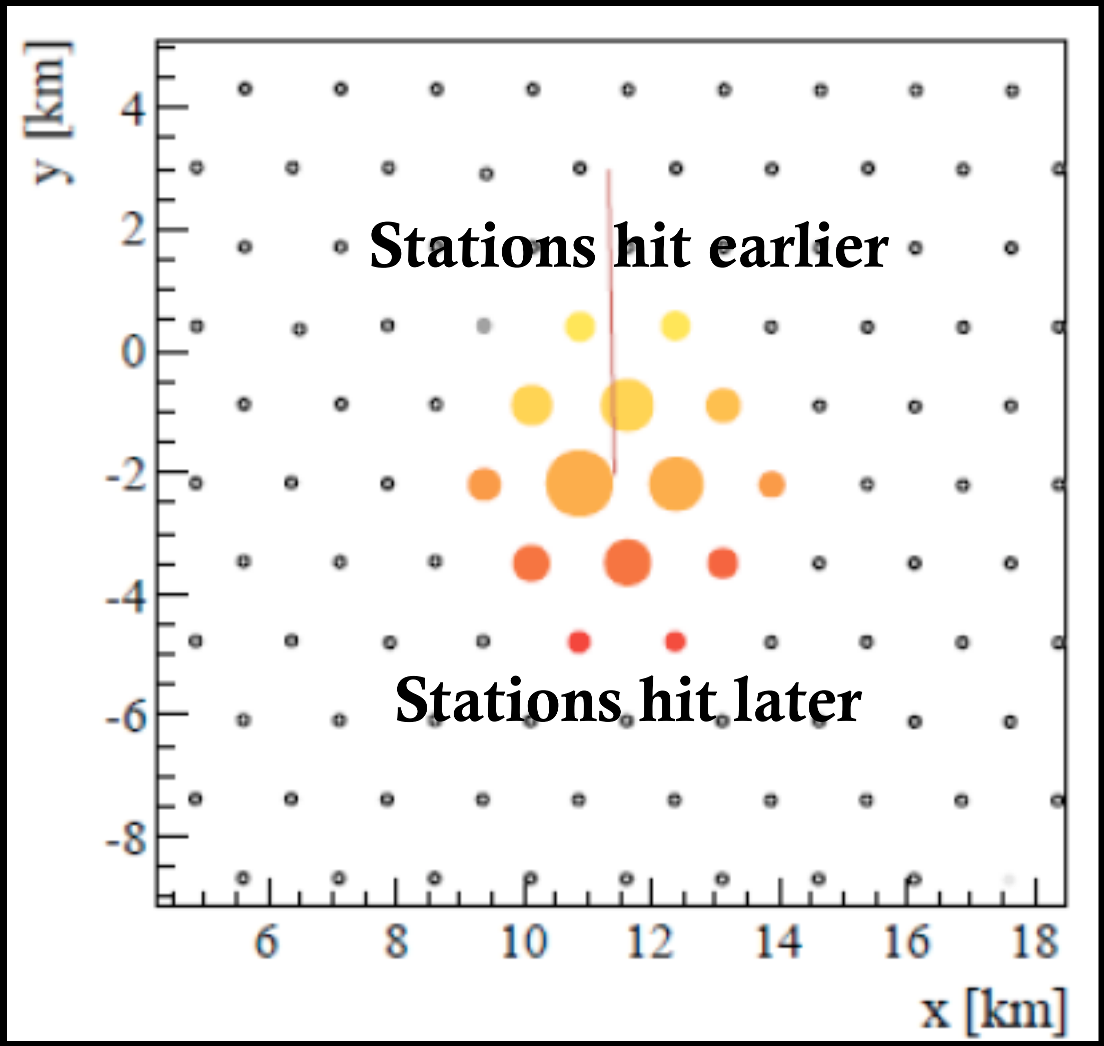




- Reconstruct geometry (arrival direction & impact point)
- Fit longitudinal shower profile
- Calorimetric measurement: Energy $\propto$ integral of the profile
- Depth of the shower maximum (Xmax): Mass estimator

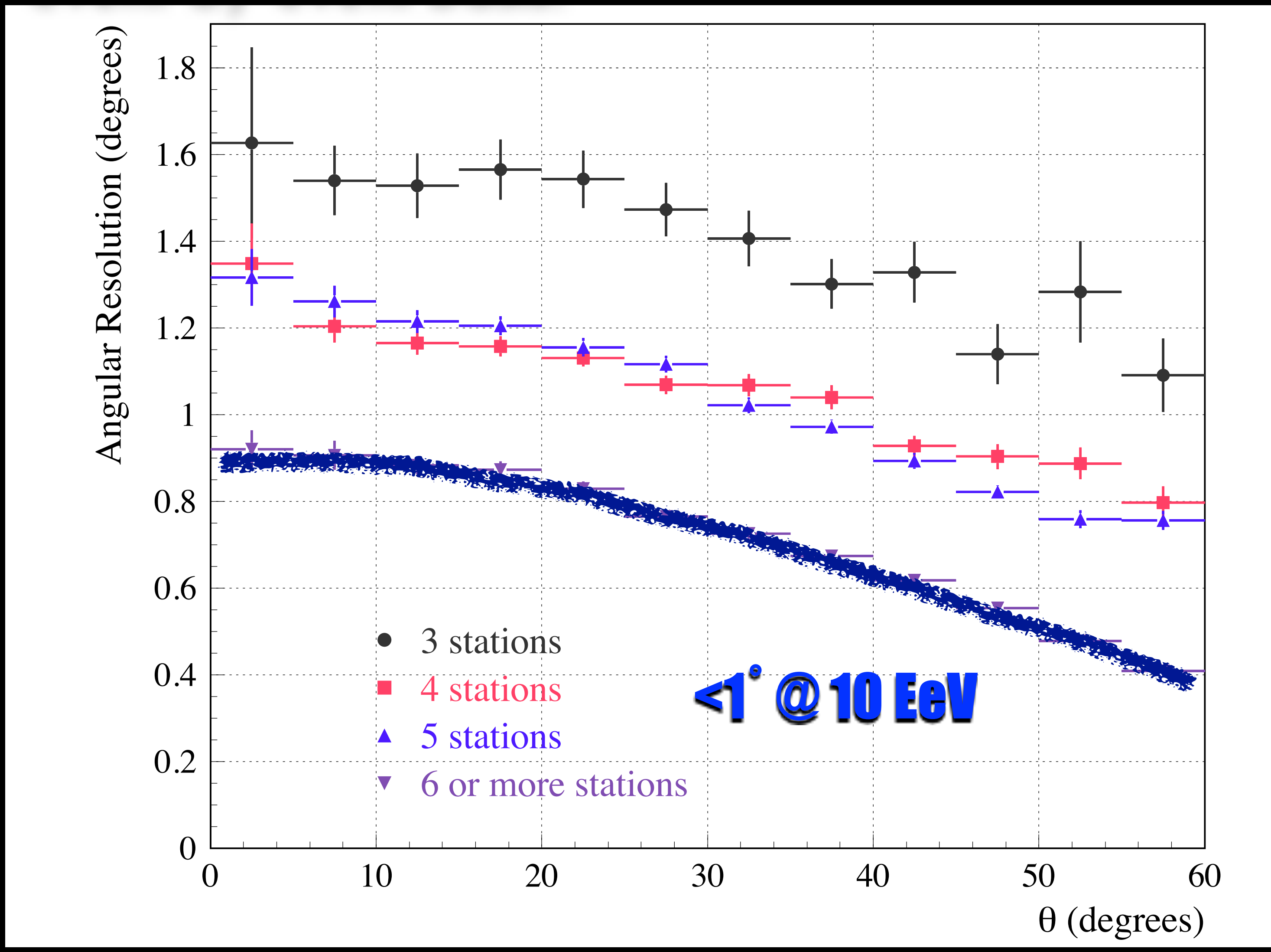
UHECR arrival direction

CR arrival direction: from relative arrival times of signals at ground detectors



Arrival direction: estimated by a fit of the shower front (moving at light speed)

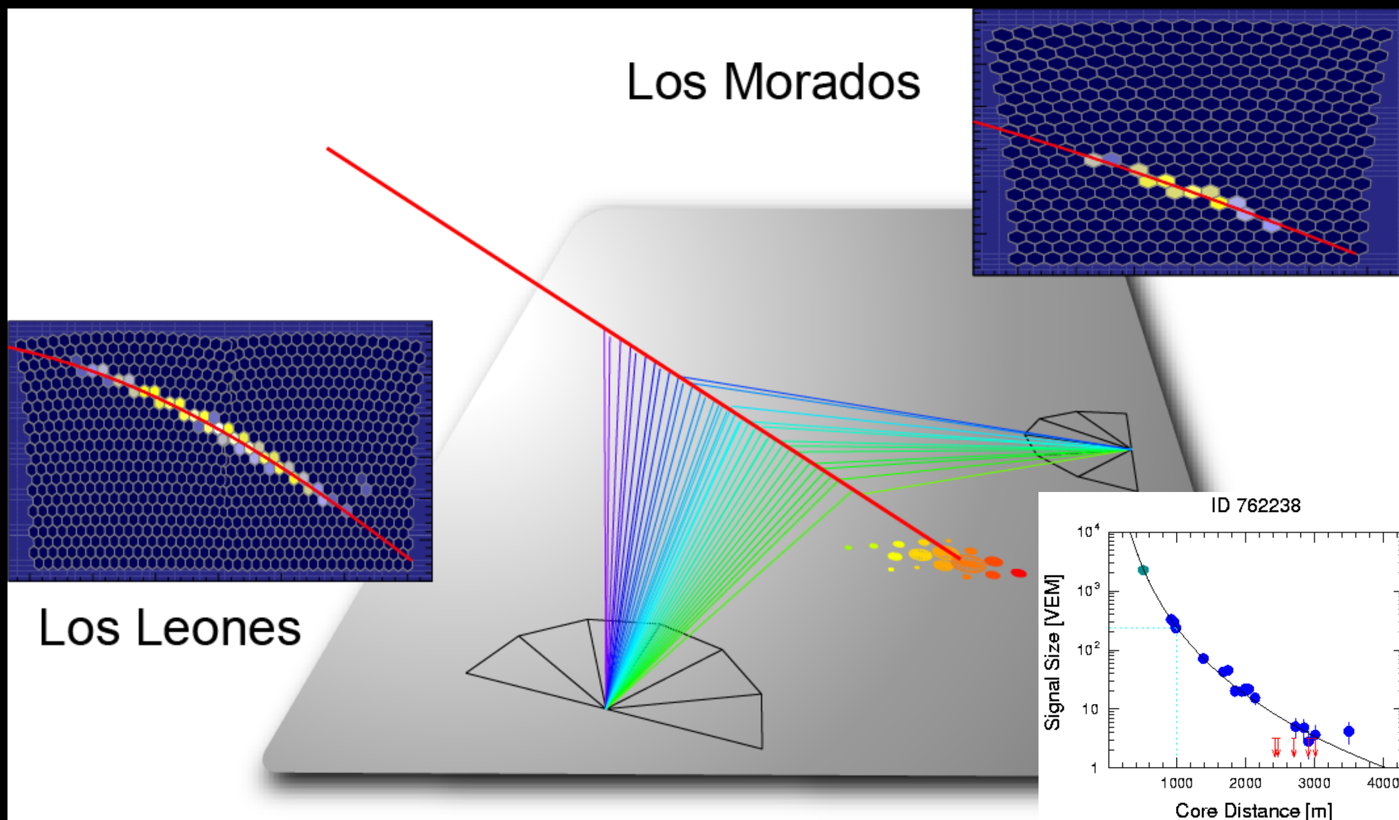
Angular resolution: estimated from the fit on an event-by-event basis.

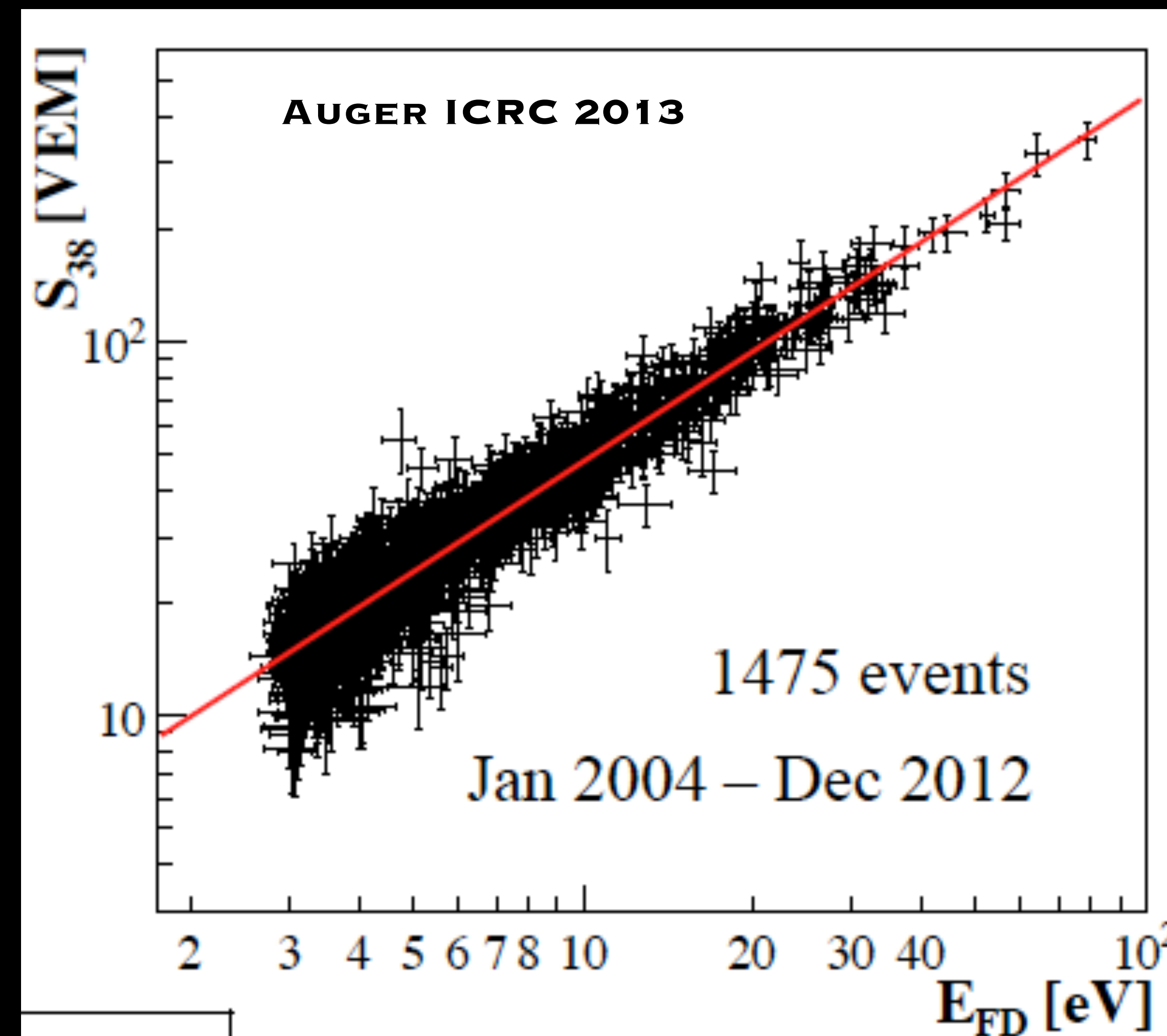


E>10^{18} eV (>10^{19} eV): $\geq$ 3 (6) tanks: < 2° (1°)

UHECR energy

Hybrid event





Systematic uncertainties on the energy	
Fluorescence yield	3.6%
Atmosphere	3.4%-6.2%
FD calibration	9.9%
FD reconstruction	6.5%-5.6%
Invisible energy	3%-1.5%
Stat. error of the	0.7%-1.8%
Stability of the E	5%
TOTAL	**14%**

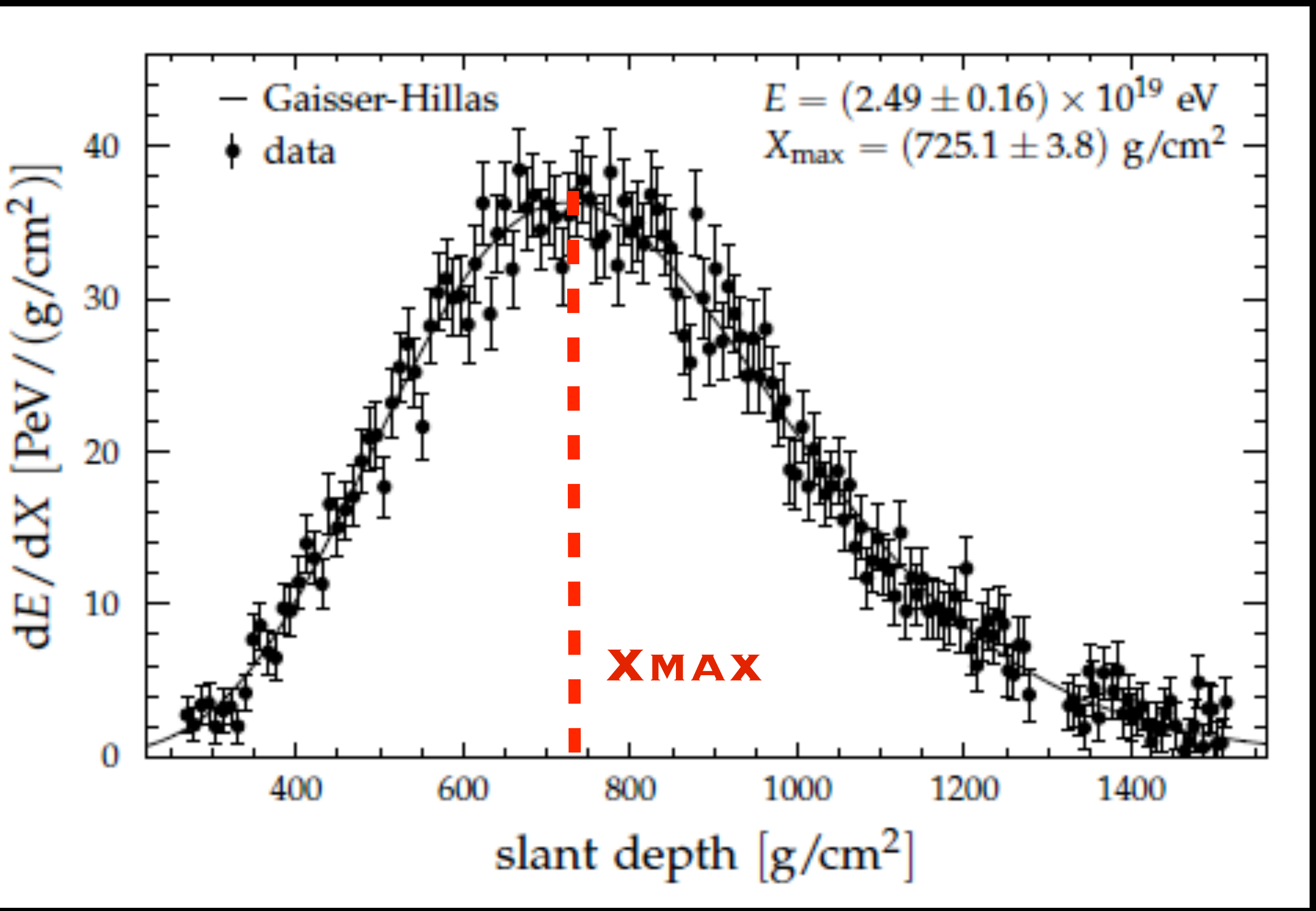
Hybrid Events are used to calibrate the SD energy estimator, S(1000)

[converted to the median zenith angle, S38]

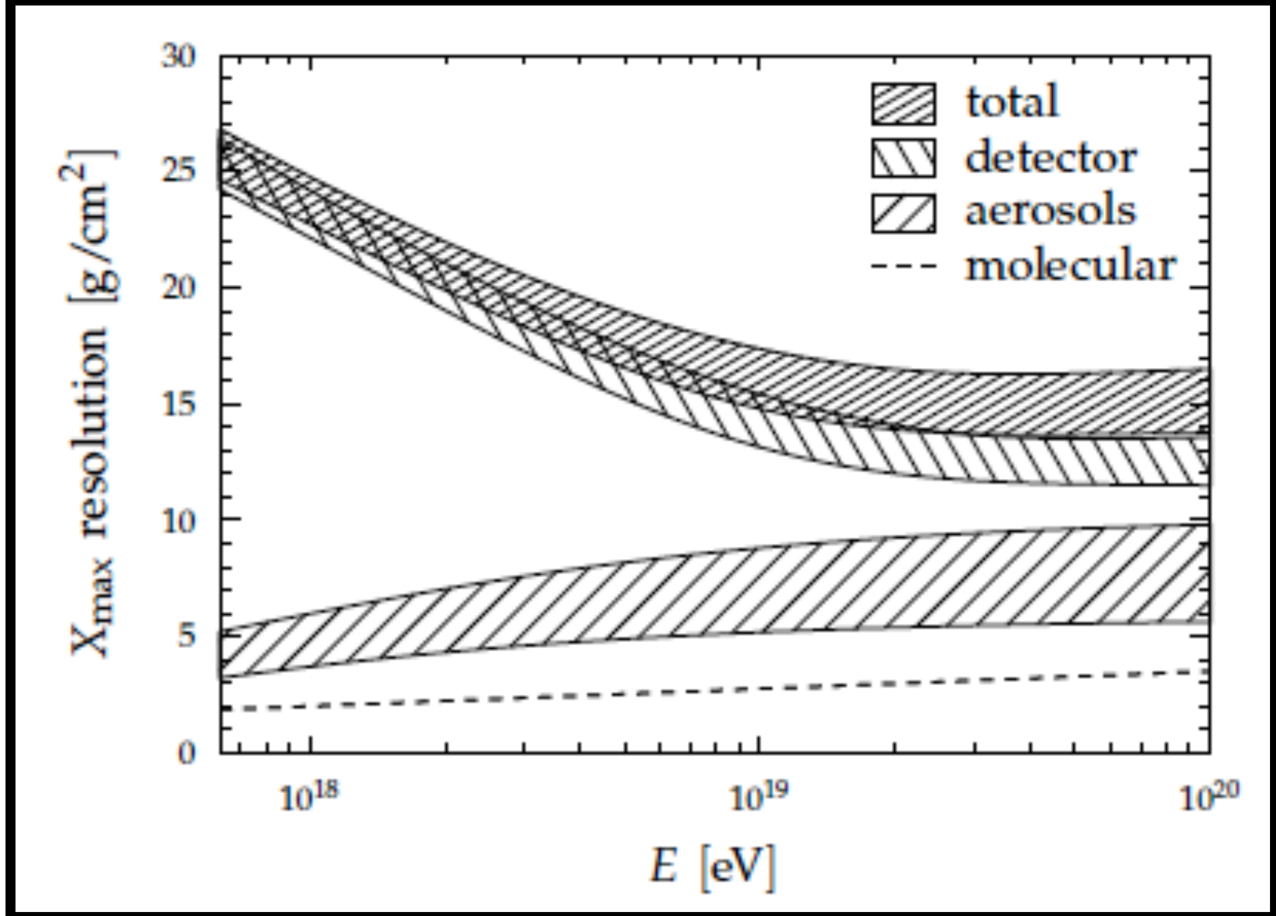
with the FD calorimetric energy

UHECR mass

Shower profile observed by FD



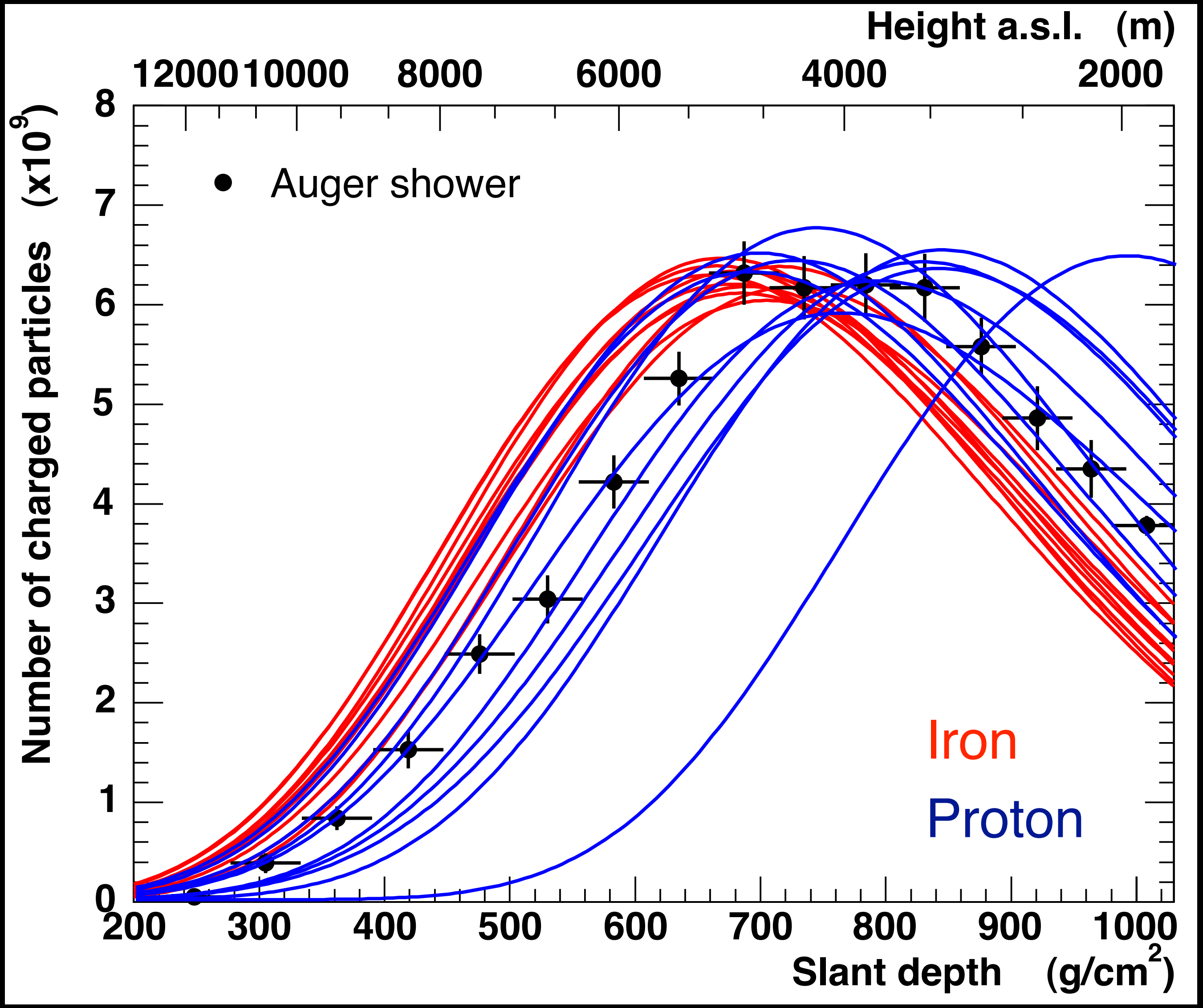
Xmax resolution



Between 25 and 15 g/cm2, getting better with increasing energy

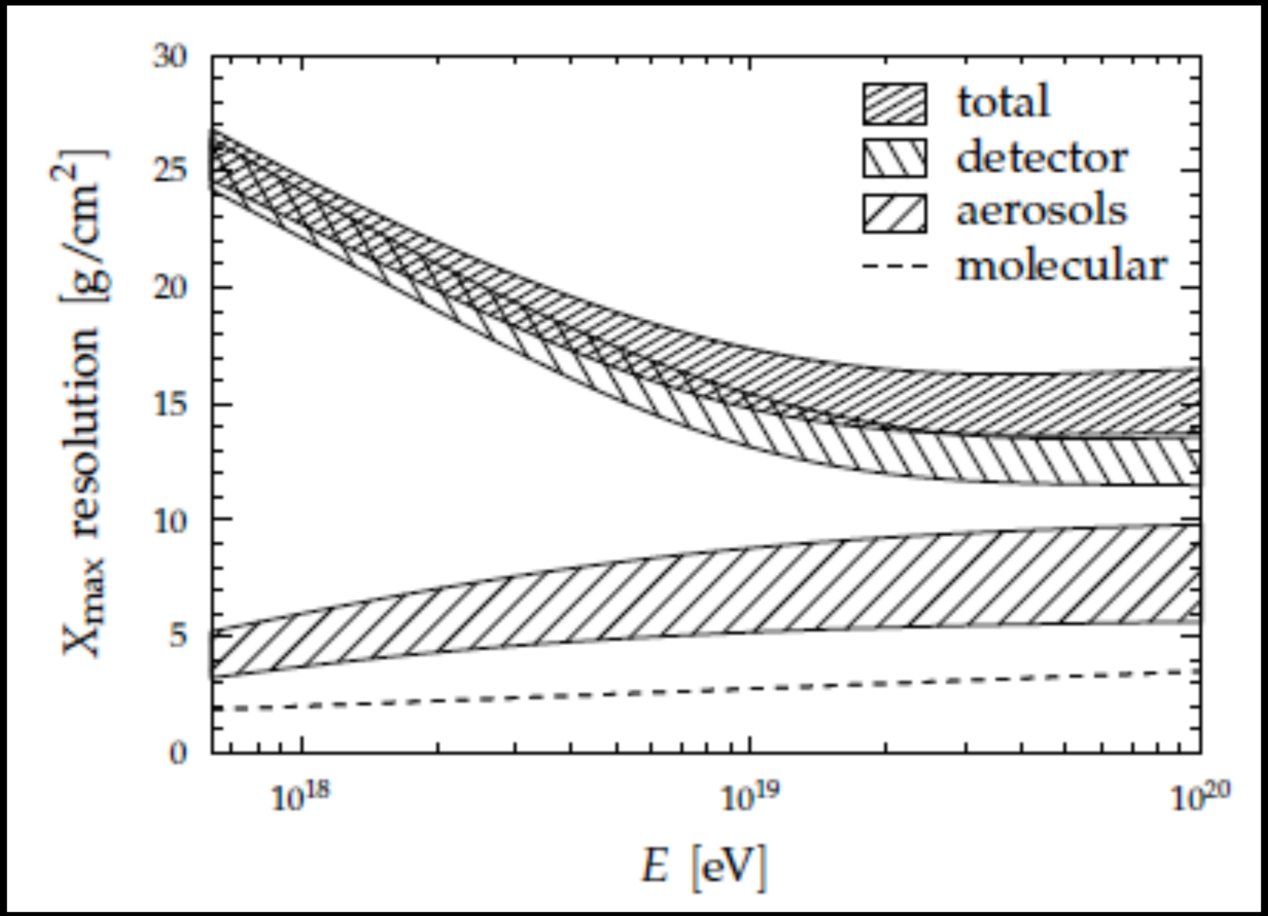
Systematic uncertainty ≈ 10%

UHECR mass



Xmax and its fluctuations are sensitive to mass (smaller Xmax and smaller fluctuations for heavier primaries)

Xmax resolution



Between 25 and 15 g/cm2, getting better with increasing energy

Systematic uncertainty ≈ 10%

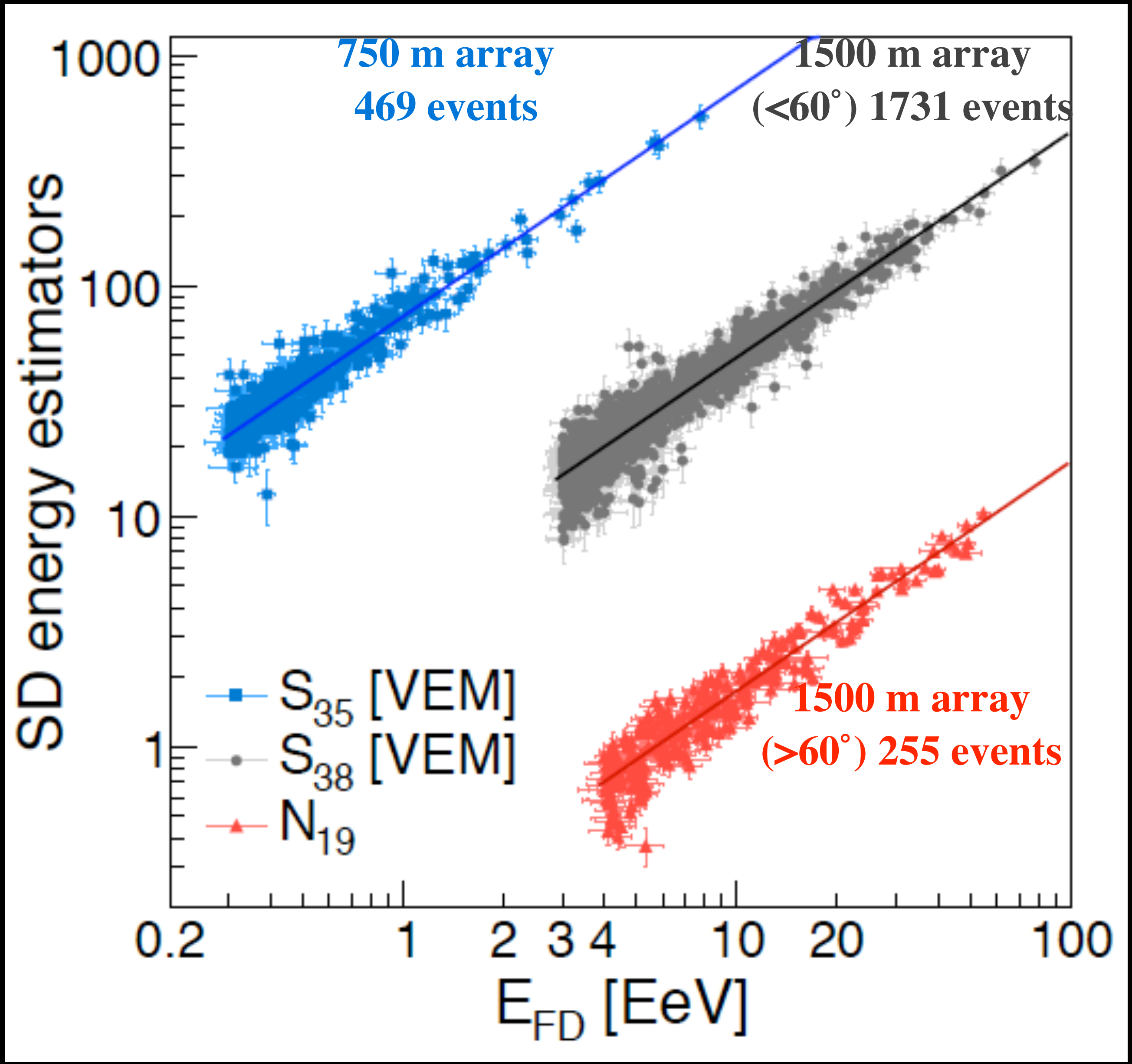
UHECRs after 10 years of Auger data

10-yr data set that covers 3 decades in energy...

> 50000 km² sr yr exposure

Detector	E_{th} [10^{18} eV]	N(E>E_{th})	N(E>40 EeV)
Hybrid (HEAT&SD)	**0.1**	**≈ 6000**	**-**
SD 750 m	**0.3**	**≈ 60000**	**-**
Hybrid (FD&SD)	**1**	**≈ 10000**	**≈ 15**
SD 1500 m (0˚-60˚)	**3**	**≈ 100000**	**≈ 350**
SD 1500 m (60˚-80˚)	**4**	**≈ 15000**	**≈ 100**

Energy calibration

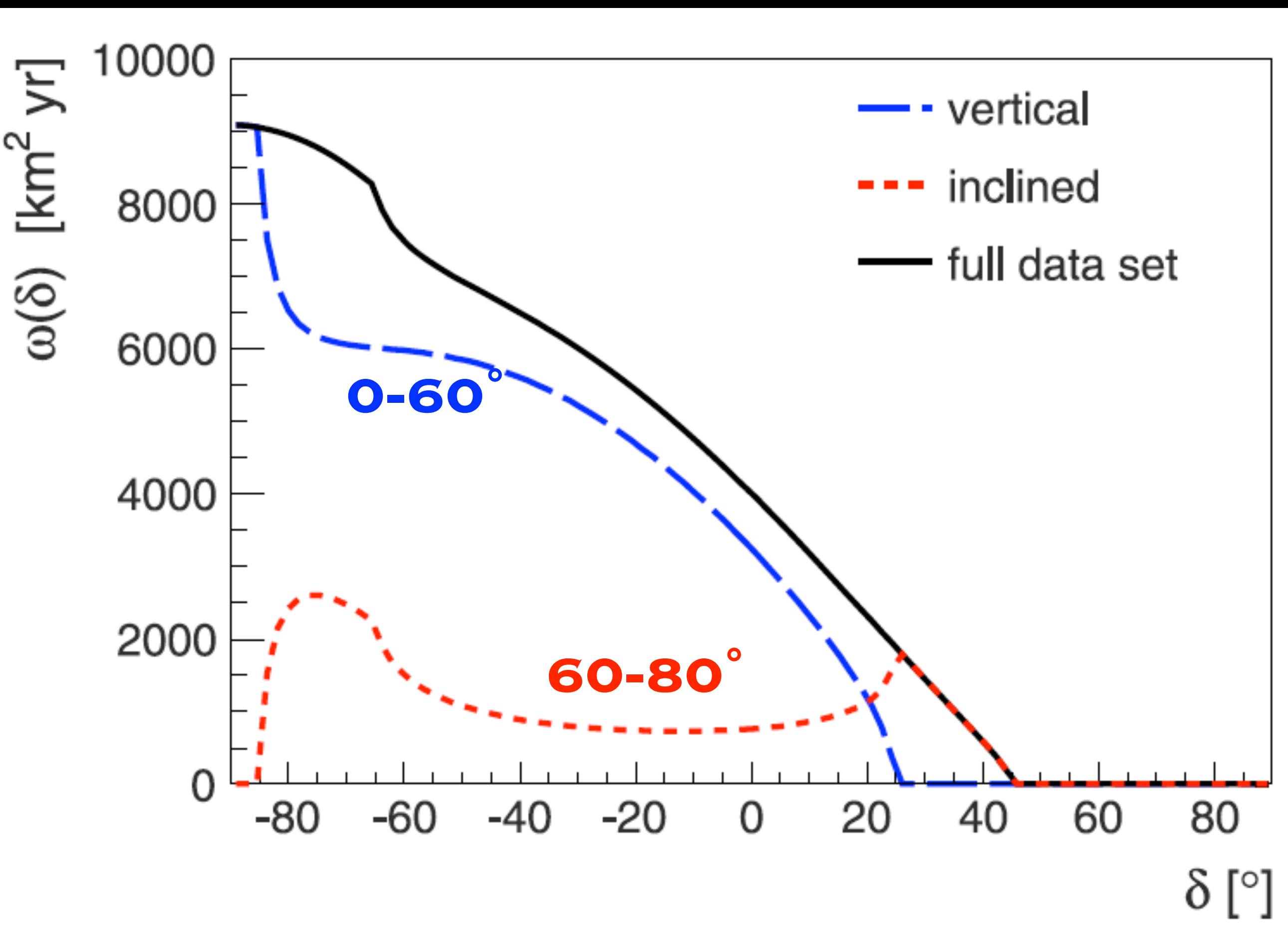


The fluorescence detector provides a common energy scale

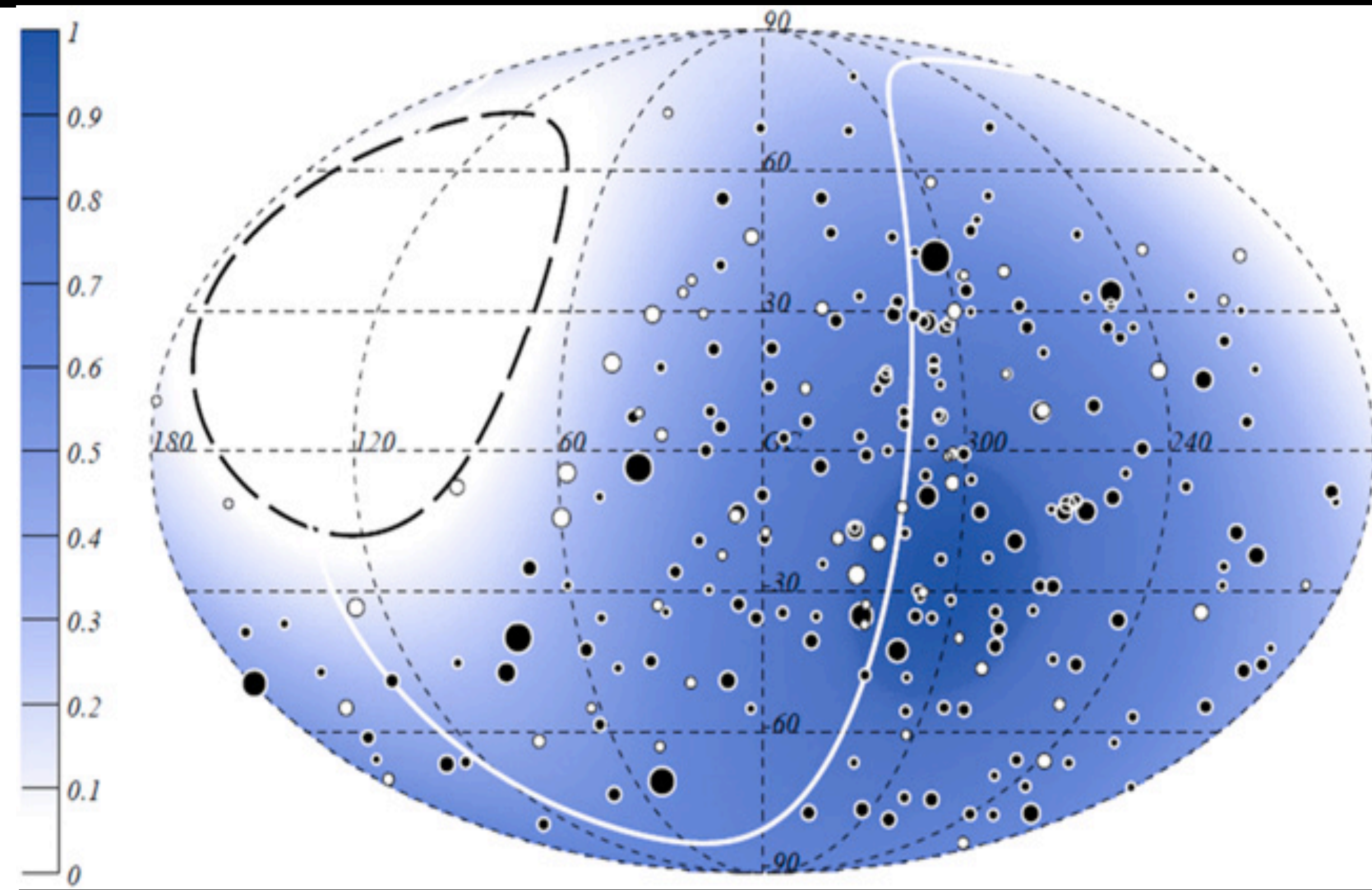
Systematic uncertainty: 14%

...and 85% of the sky

Directional exposure



Sky map (E>52 EeV), Galactic coo

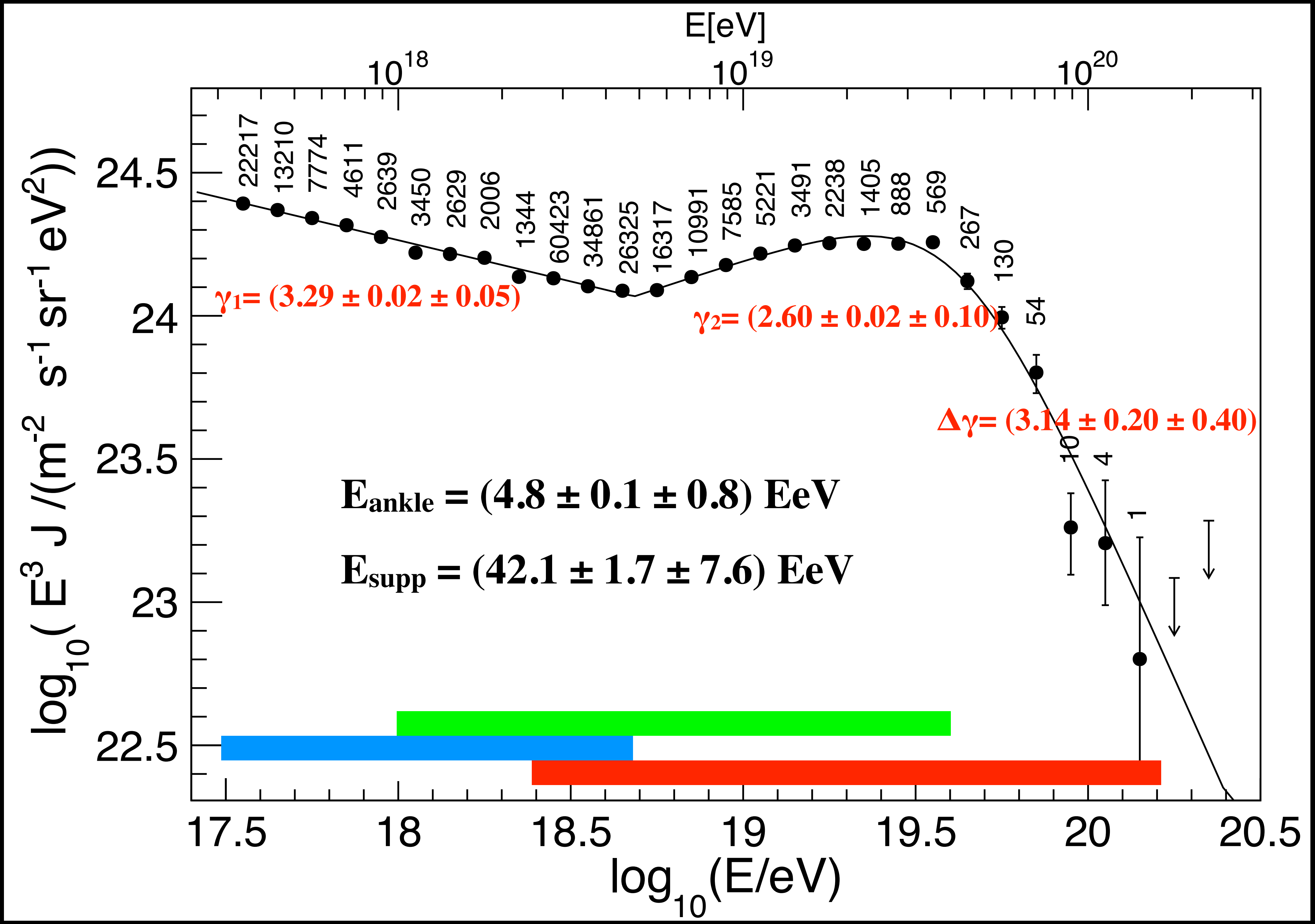


By including cosmic rays with zenith angles up to 80°, the Auger field of view covers from −90° to +45° in declination.

The all-particle spectrum

4 data sets combined: **SD 750 m**, **FD (hybrid)**, **SD 1500 m (0-60˚)**, **SD 1500 m (60-80˚)**

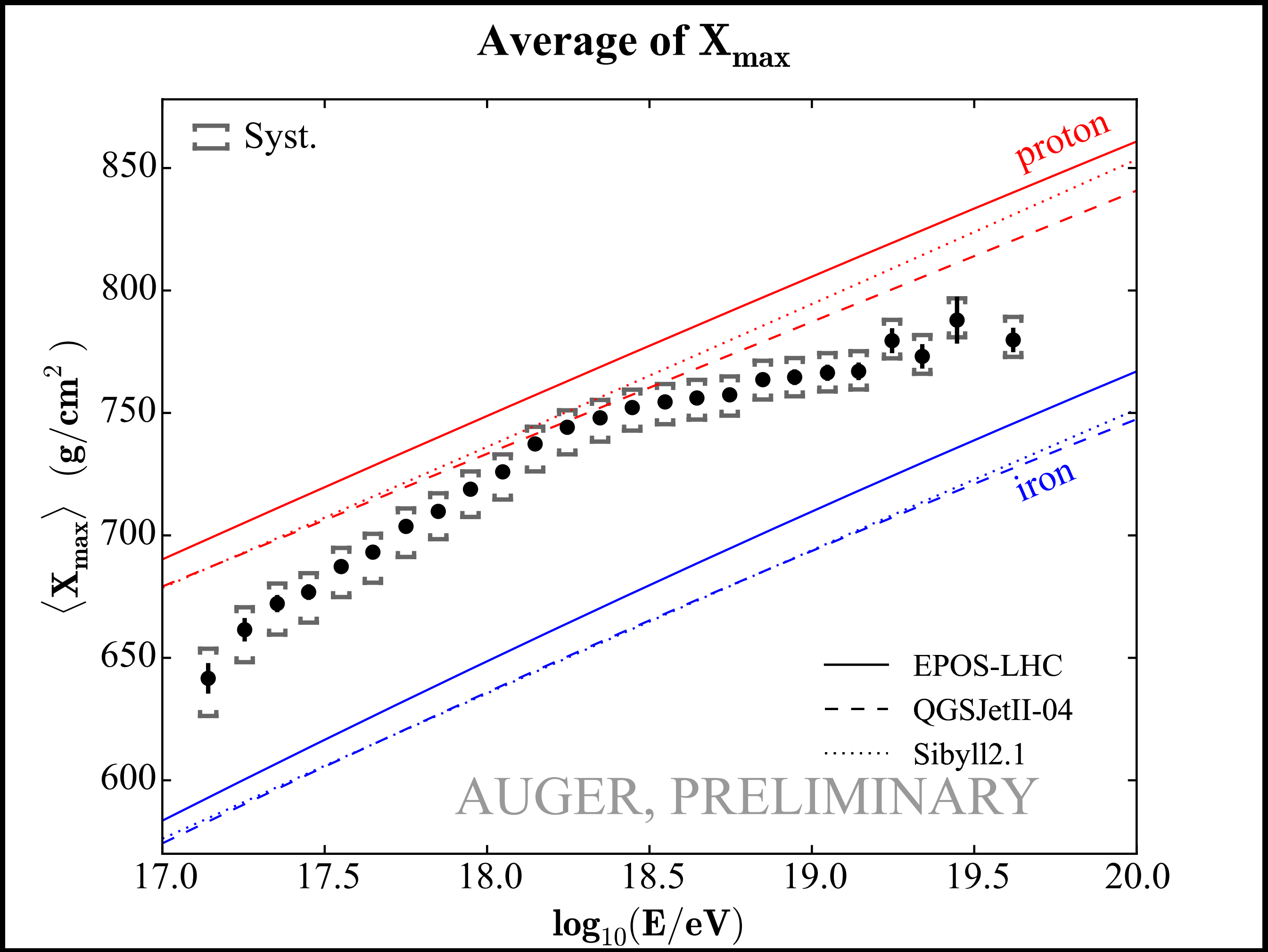
≈ 200 000 events

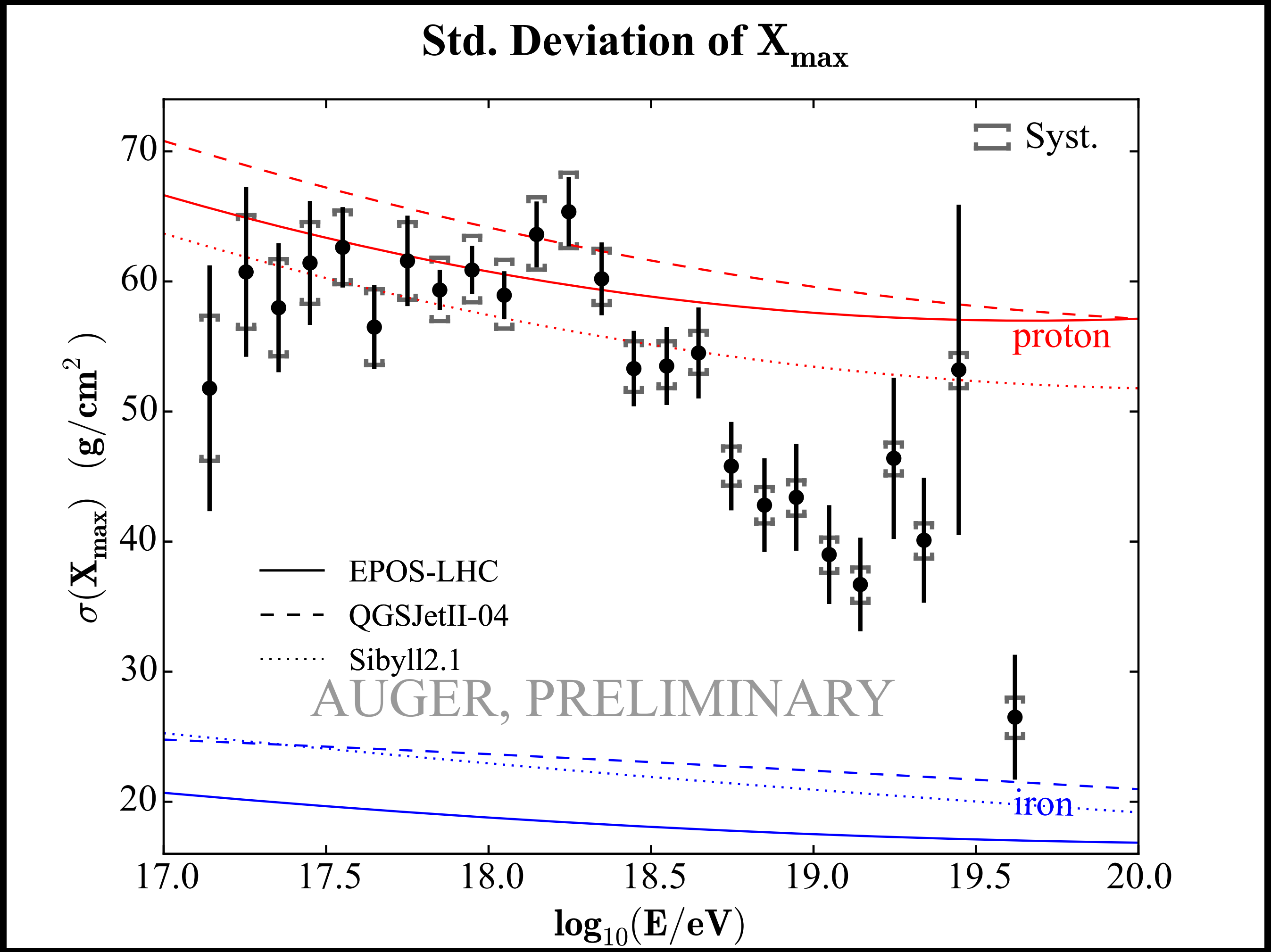


Clear observation of an ``ankle" at ≈ 5 EeV and flux suppression at ≈ 40 EeV

The depth of the shower maximum

Depth of shower maximum premiere observable for mass composition studies
HEAT data extends the FOV of the fluorescence detector up to 60˚
Extension of the depth of shower maximum measurements down to 10^{17} eV

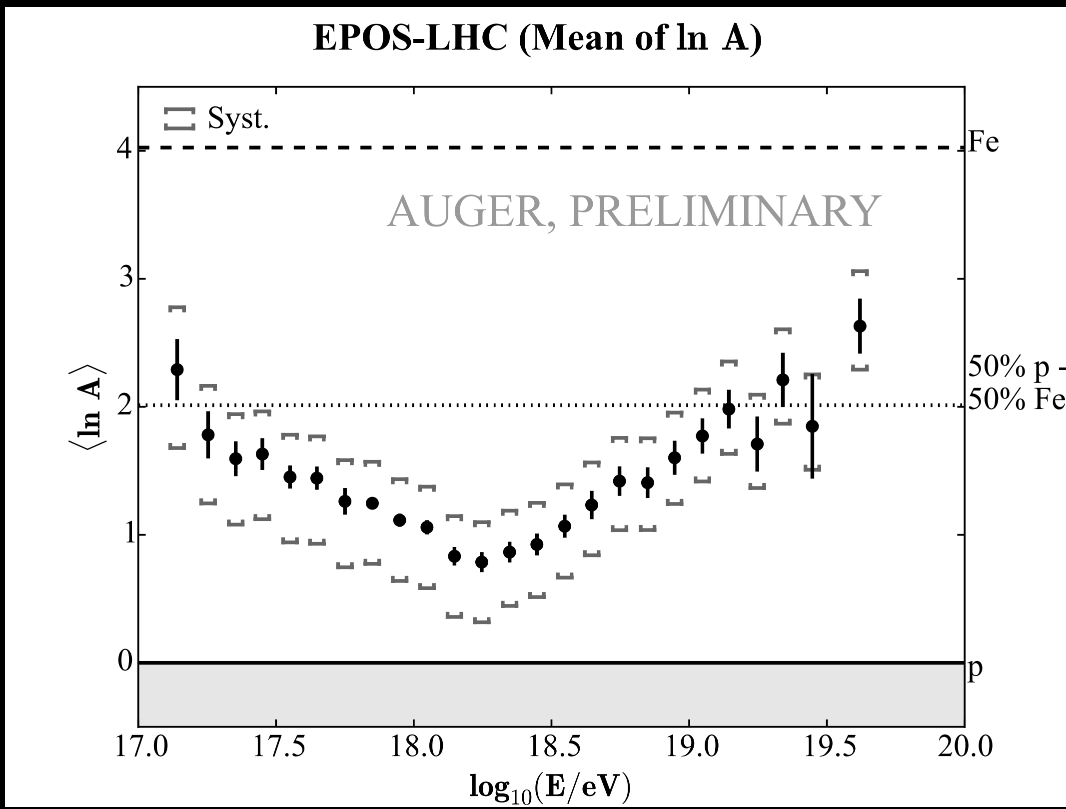


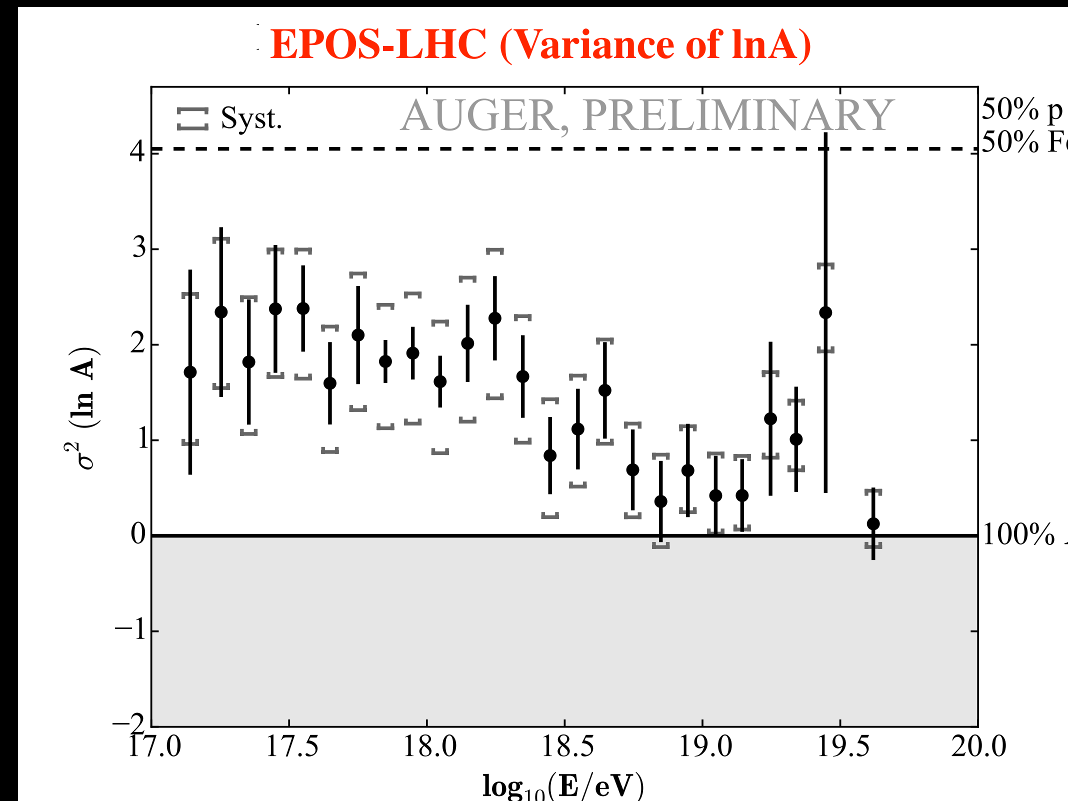


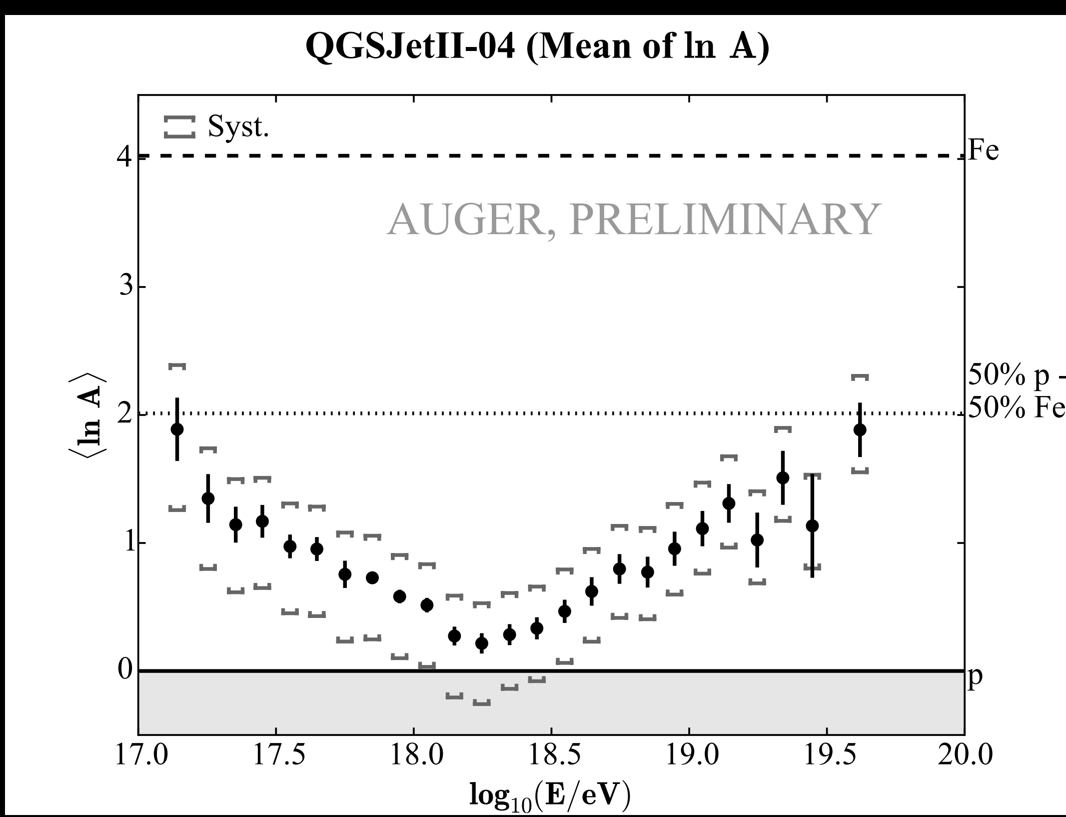
Xmax data (mean and sigma) compared to state-of-the-art models of hadronic interactions) indicate a decrease in mass up to ≈ $10^{18.3}$ eV, after which the mass increases again up to at least ≈ $10^{19.6}$ eV.

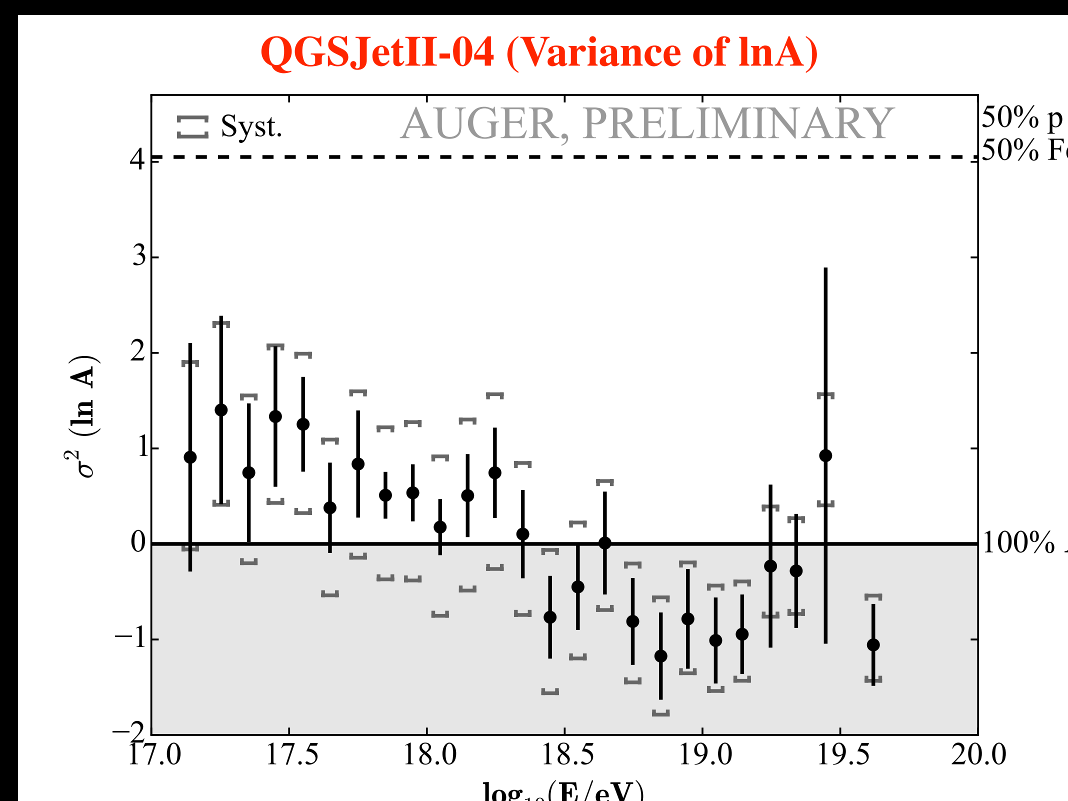
NB: very few data above 40 EeV!

From the depth of shower maximum to primary mass (lnA)









Similar trend for both models: heavier composition at low energies (largest mass dispersion), lightest one at ≈ 2×10^{18} eV, getting heavier again towards higher energies (smaller mass dispersion)

N.B. Not only inferences on mass but test of models too

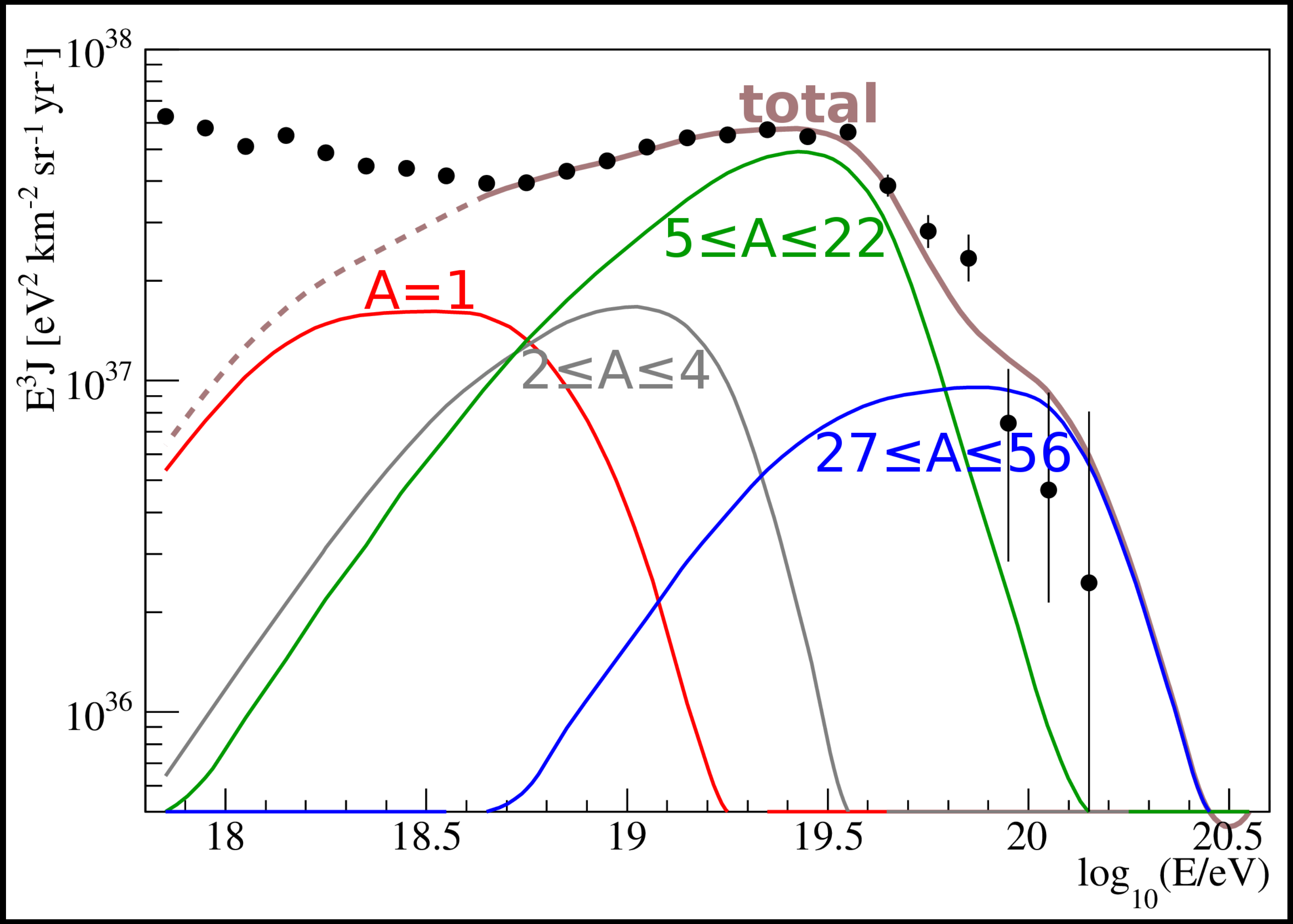
The conversion to σ^2(lnA) through QGSJETII-04 yields unphysical results

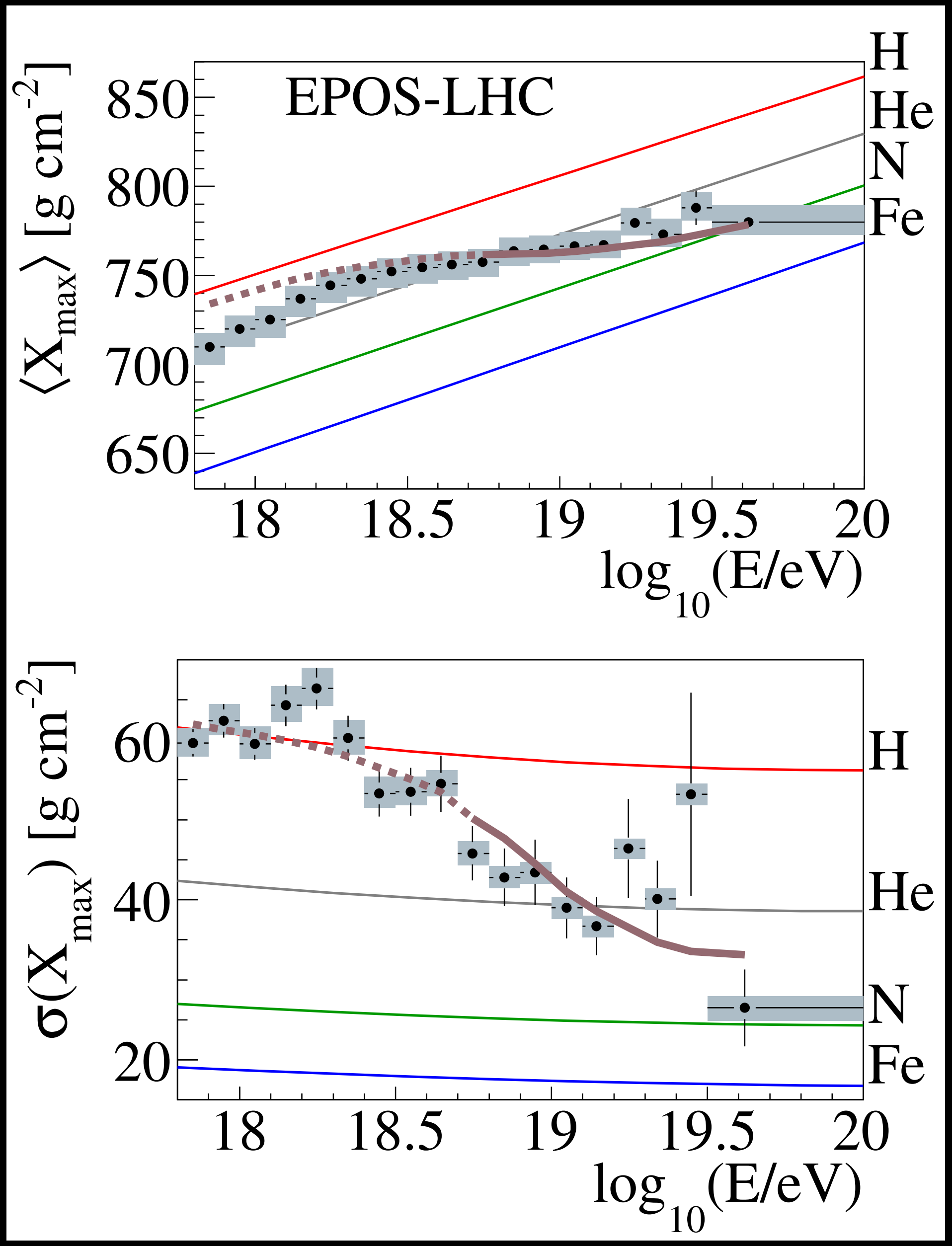
What do spectrum AND composition data tell us?

(Simple) Model of UHECR to reproduce the Auger spectrum and Xmax distributions

Homogeneous distribution of identical sources accelerating p, He, N and Fe nuclei.

Fit parameters: injection flux normalization and spectral index γ, cutoff rigidity Rcut, p-He-N-Fe fractions





Best fit with very hard injection spectra (γ ≤ 1)

Flux limited by maximum energy at the sources (Rcut ≤ $10^{18.7}$ eV)

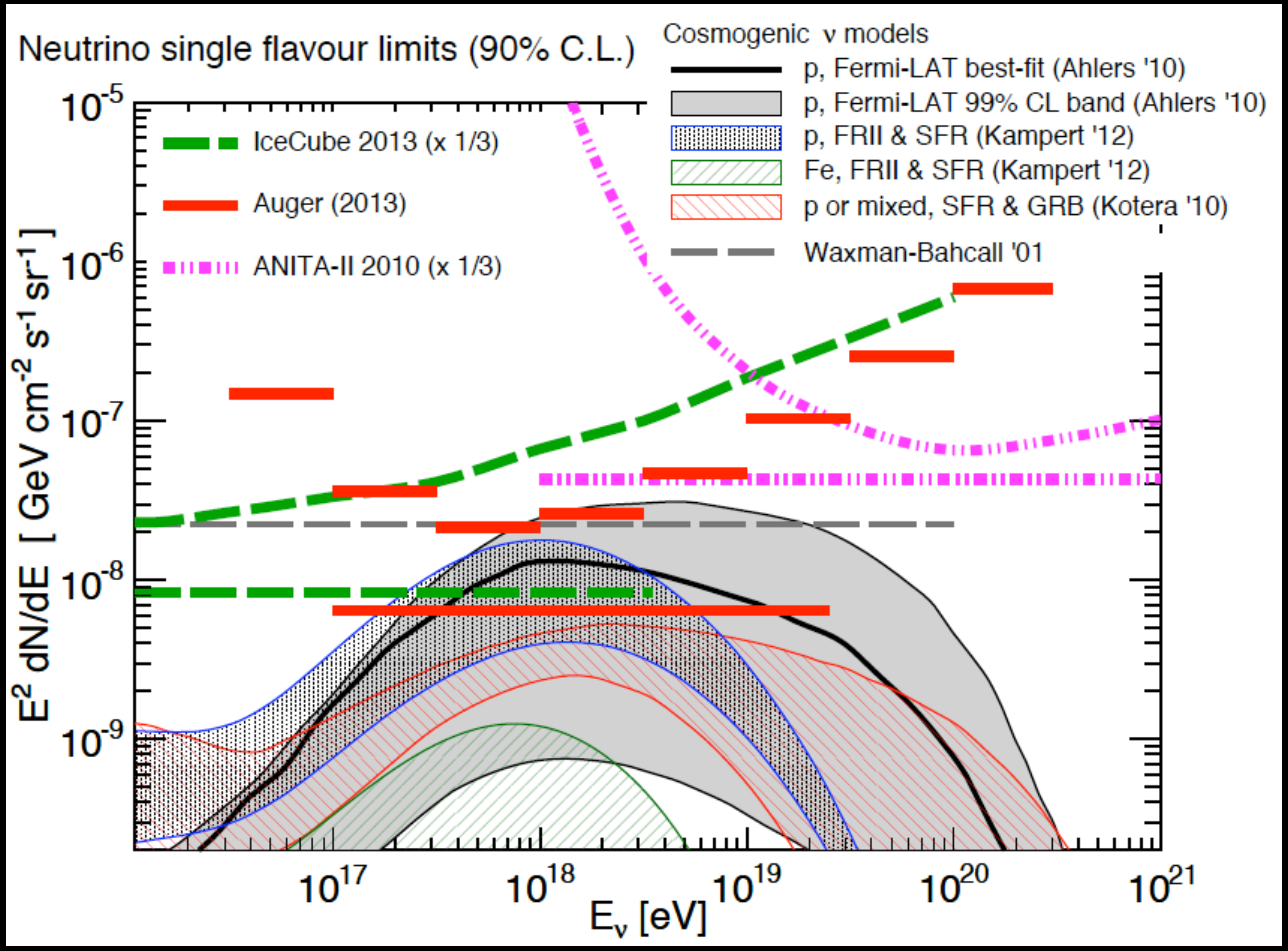
Prevailing intermediate masses at the source

Another handle on UHECR composition and origin: search for cosmogenic photons and neutrinos

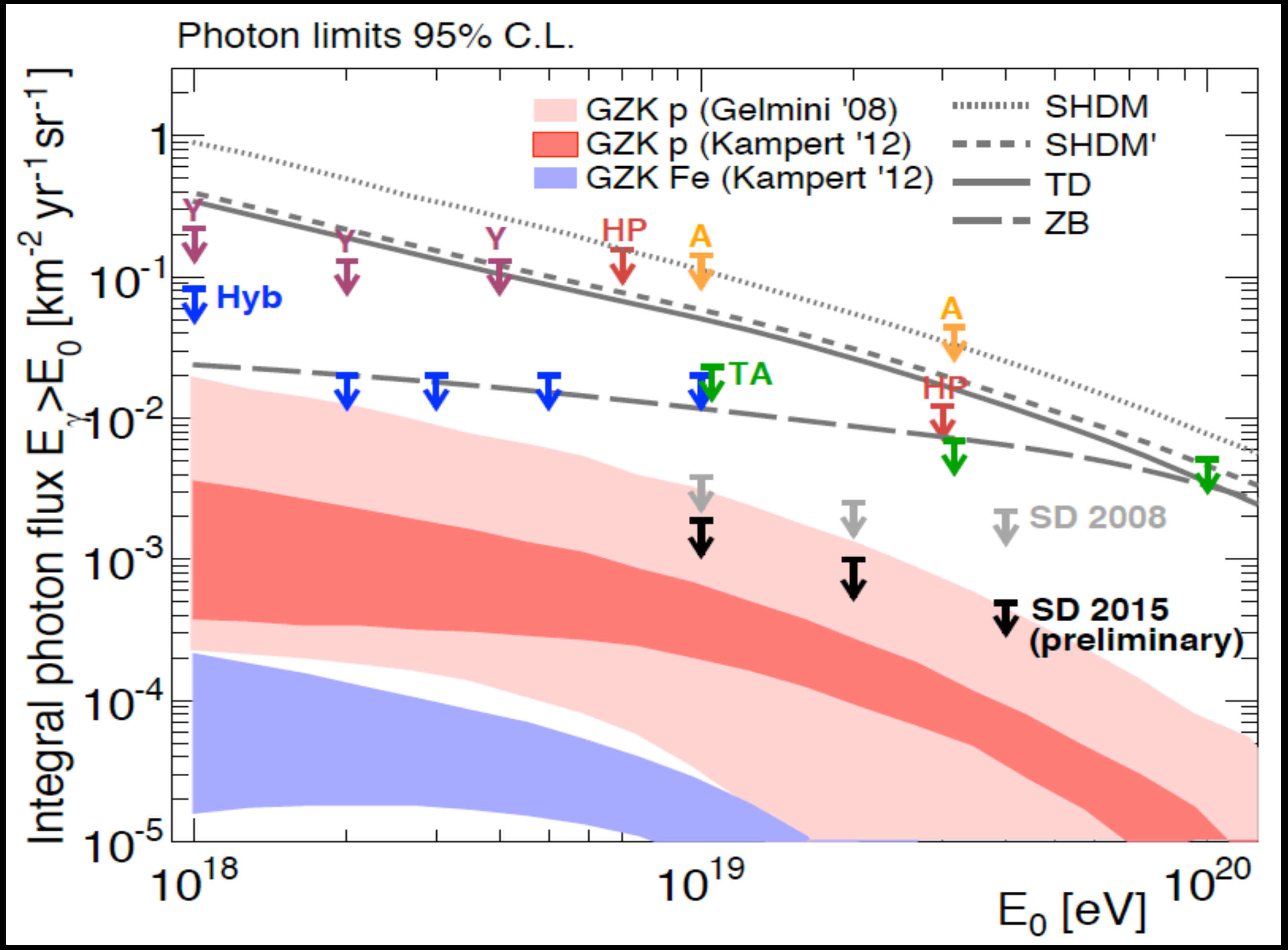
EeV neutrinos and photons produced in the interactions of UHECRs on CMB photons.
The expected fluxes depend on the primary mass

Neutrino and photon search based on the time structure of signals in the SD stations

NEUTRINOS



PHOTONS



Neutrino limits disfavor some models of pure proton production at the sources

Most "exotic" source models ruled out by photon limits

The distribution of arrival directions: small- and intermediate angular scales

The updated fraction of correlations with AGNs in the VCV catalogue
(28.1±3.8)% vs 21% isotropic expectation)
does not substantiate the initial evidence of anisotropy at energies larger than 53 EeV.

Anisotropy tests on the arrival directions of 602 events with E>40 EeV

Exploring a **wide range of angular windows (1-30 deg)**
[lower limit = angular resolution; upper limit: larger deflections if larger-Z nuclei)

Exploring **different energy thresholds (from 40 to 80 EeV)**
[reducing the "horizon", while keeping a sizable statistics]

Studies of "intrinsic" anisotropies
[search for localized excesses; auto-correlation]

Search for correlations with known astrophysical structures
[Galactic plane and center, and super-Galactic plane]

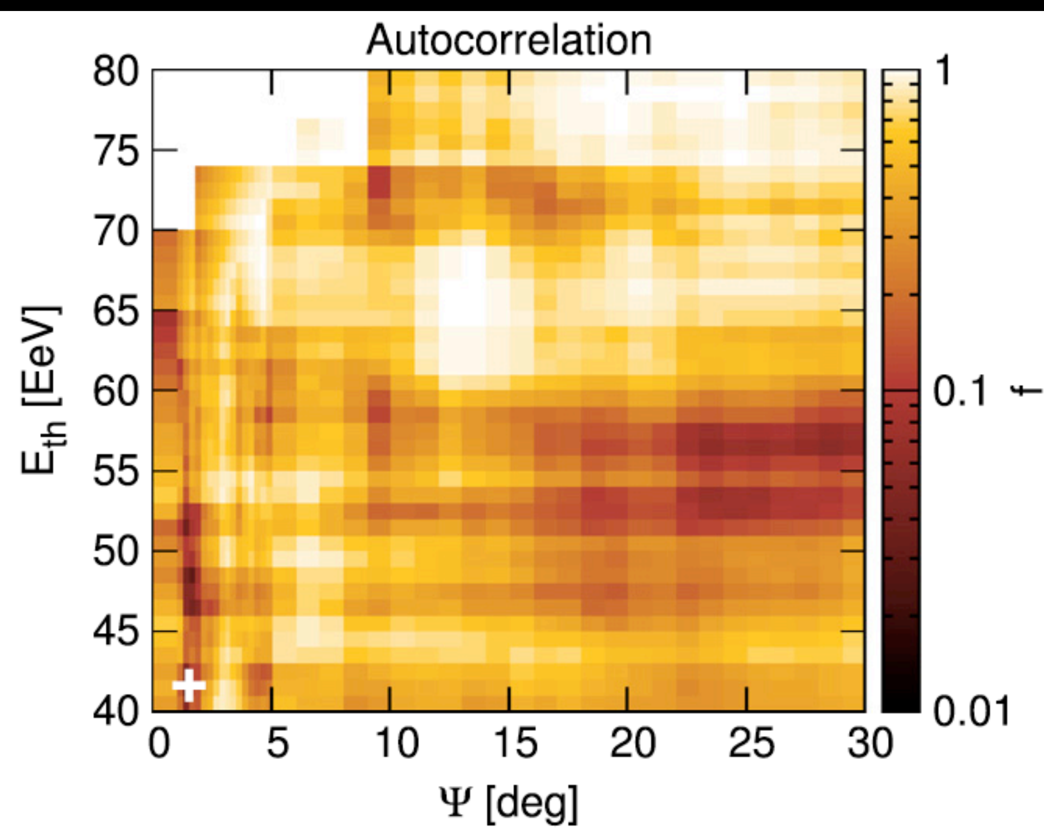
Search for correlations with astrophysical objects
[catalog of galaxies, of AGNs observed in X-rays, of radio-galaxies**]**

Intrinsic anisotropy tests

Autocorrelation (search for pairs of events): look for excesses of "self-clustering"

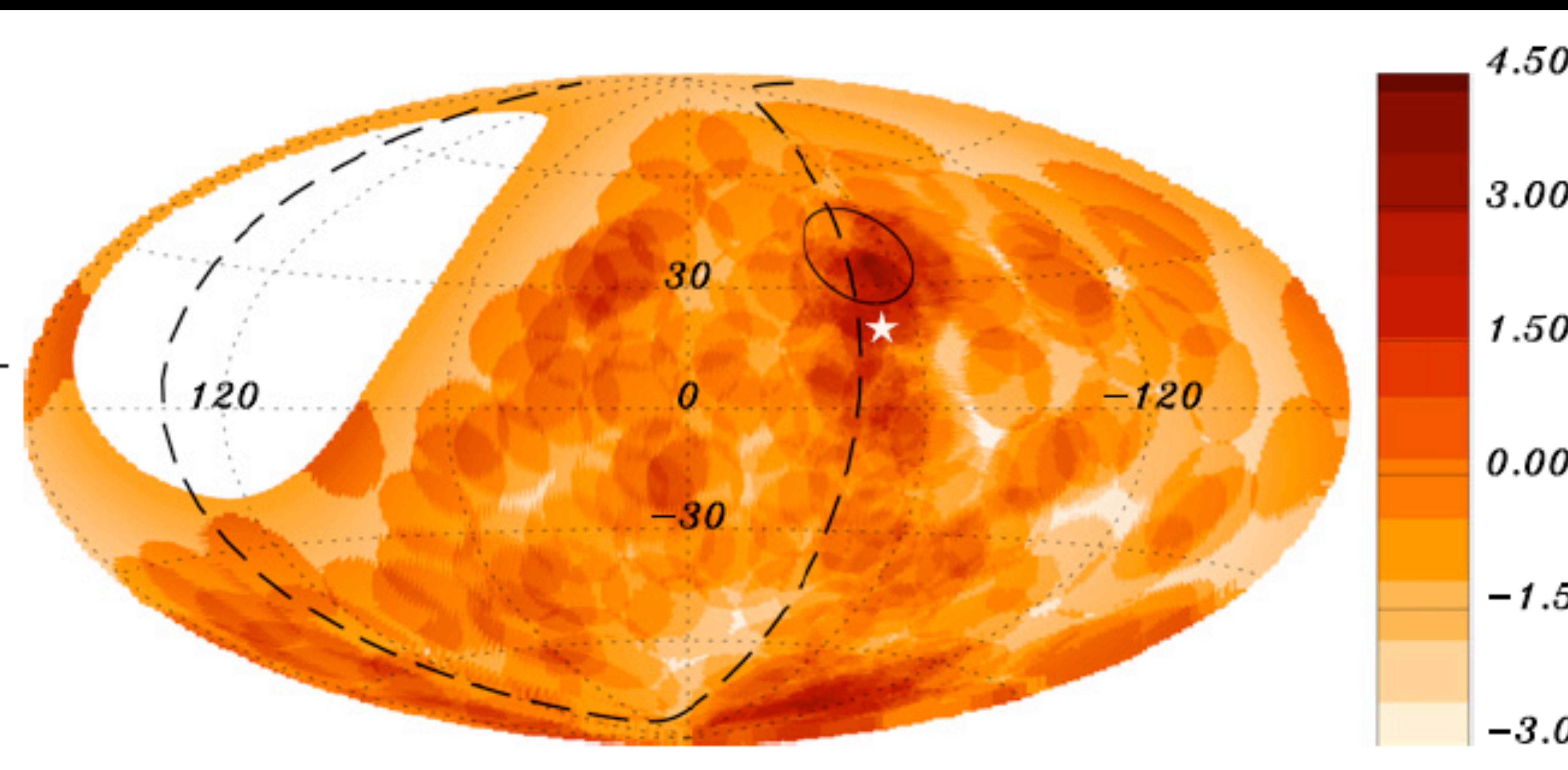
All-sky search: look for localized excesses of events

AUTOCORRELATION



Minimum at 1.5˚ and E_{th} = 42 EeV Post-trial probability: 70%

"BLIND" SEARCH FOR LOCALIZED EXCESSES



Largest excess (4.3 s.d): E_{th}>54 EeV, r=12˚ [18˚ from Cen A]

Post-trial probability: 69%

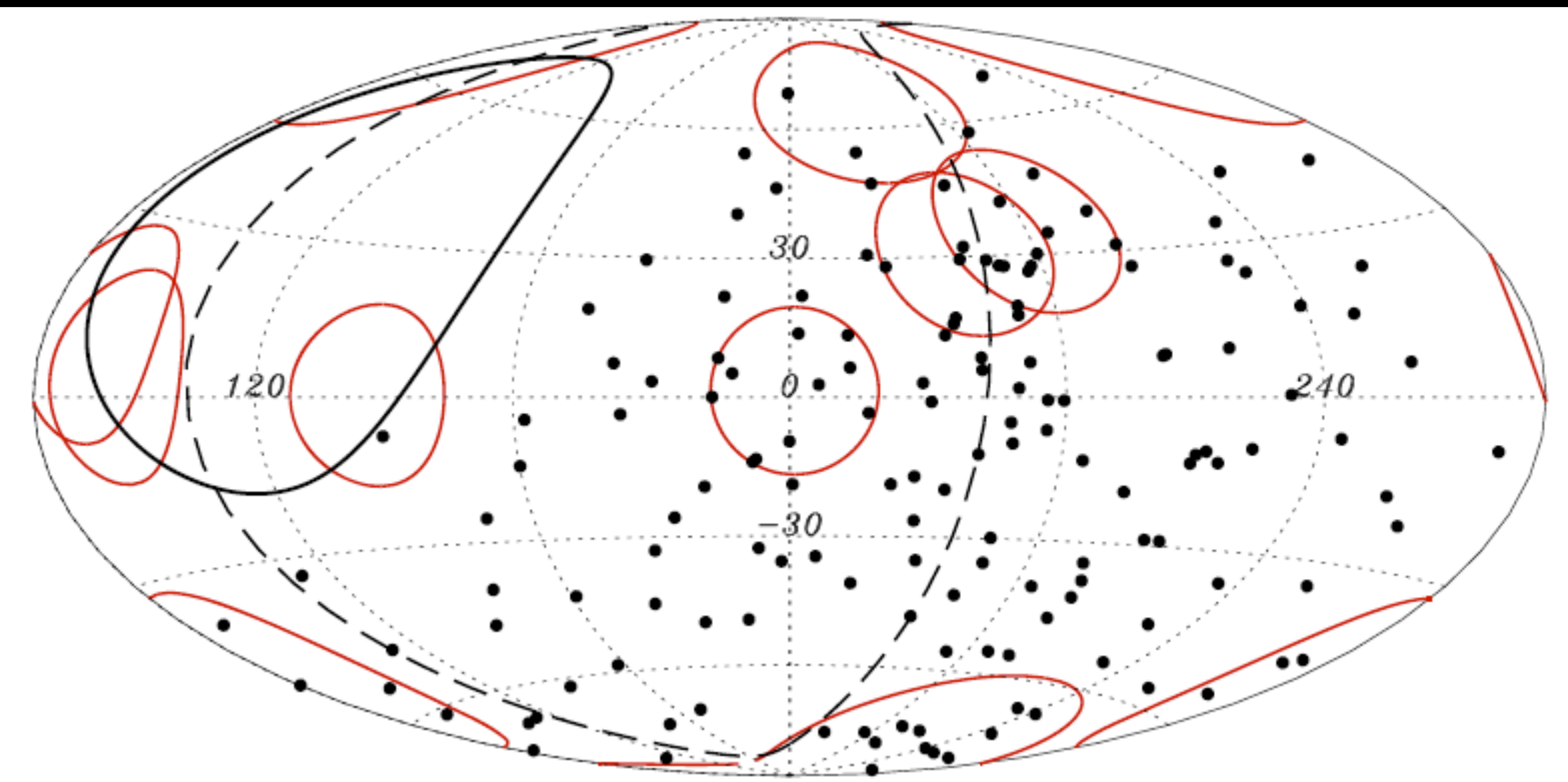
High degree of isotropy challenging the original expectations of few sources and light primaries

Tests vs astrophysical objects

Gal-Xgal planes, 2MRS galaxies, Swift-BAT AGNs, jetted radio galaxies, Cen A

Scan over angles and energy thresholds. Scan over luminosity for AGNs and radio-galaxies

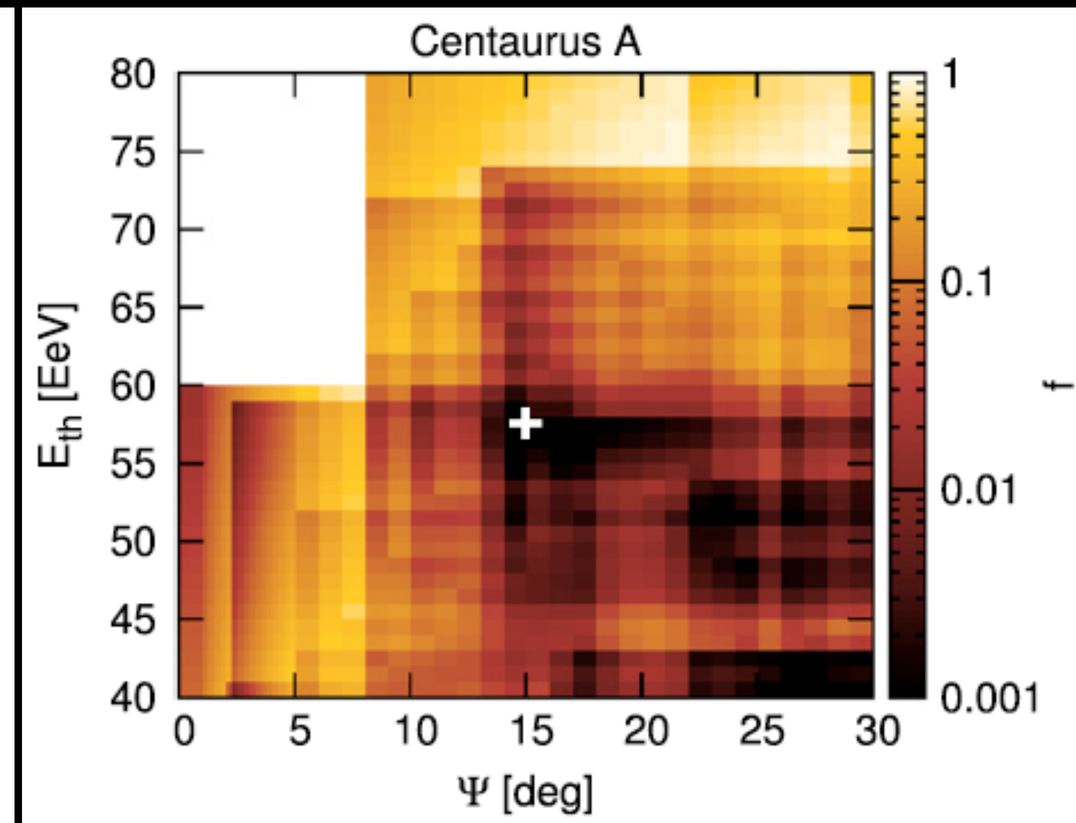
CROSS-CORRELATION WITH SWIFT AGNS



Largest excess for E_{th}>58 EeV, r=18˚, L>10^{44} erg/s

Post-trial probability: 1.3%

CEN A



Minimum at = 15˚ and E_{th} = 58 EeV

Post-trial probability: 1.4%

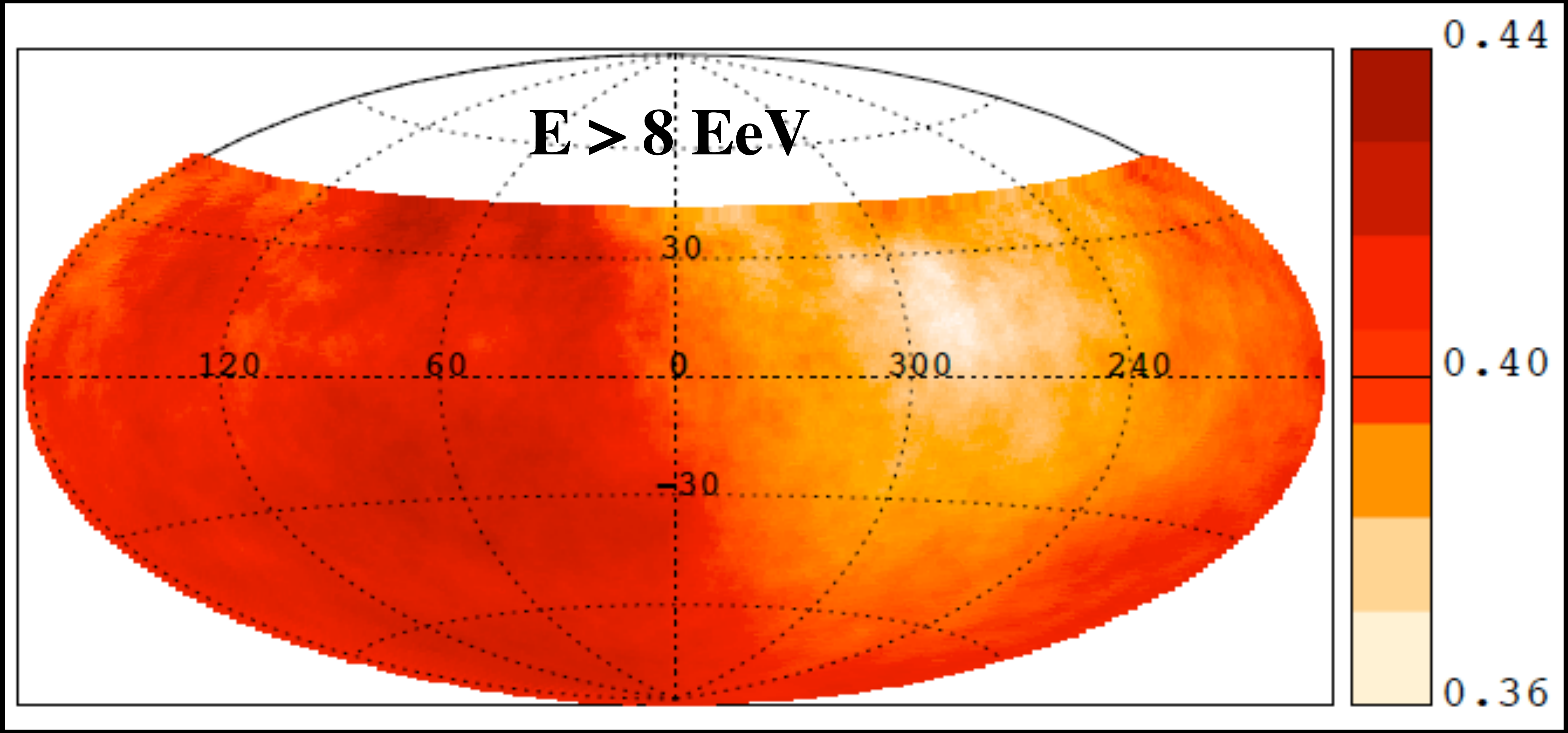
The most significant deviations from isotropy are at intermediate scales

The distribution of arrival directions: large angular scales

AUGER: Harmonic analysis in right ascension and azimuth (declination-sensitive)

≈ 70000 events with E>4 EeV and $\vartheta < 80^\circ$. Two energy bins: 4-8 EeV and > 8 EeV

Sky map of the CR flux (45° smoothing)



Dipole Amplitude: 7.3 ± 1.5% (p=6.4x10^{-5}). Pointing to $(\alpha, \delta) = (95^\circ \pm 13^\circ, -39^\circ \pm 13^\circ)$

Indications of a dipole at E > 8 EeV

Challenging the original isotropy expectations at these energies

Diffusion of large-Z cosmic rays in the Xgal magnetic fields?

Conclusions and perspectives

10 years of Auger measurements (in 1 slide)...

- Clearly observed flux suppression, at ≈ 40 EeV. Evocative of the GZK cutoff

- Gradual shift of the mass towards heavier primaries at the highest energies

- From spectrum AND mass data: the flux suppression seems due a cut-off intrinsically due to exhaustion of the sources rather than to UHECR propagation

- Very stringent limits to the flux of UHE photons: astrophysical sources favored over exotic models

- But: no evidence of small-scale anisotropy or of association with astrophysical sources in the arrival directions of UHECRs above 40 EeV. The two most significant excesses are at 15°-20° scales. Indication of a dipole at E>10 EeV

Mass measurements needed at E > 40 EeV

FD loses statistical power at such energies

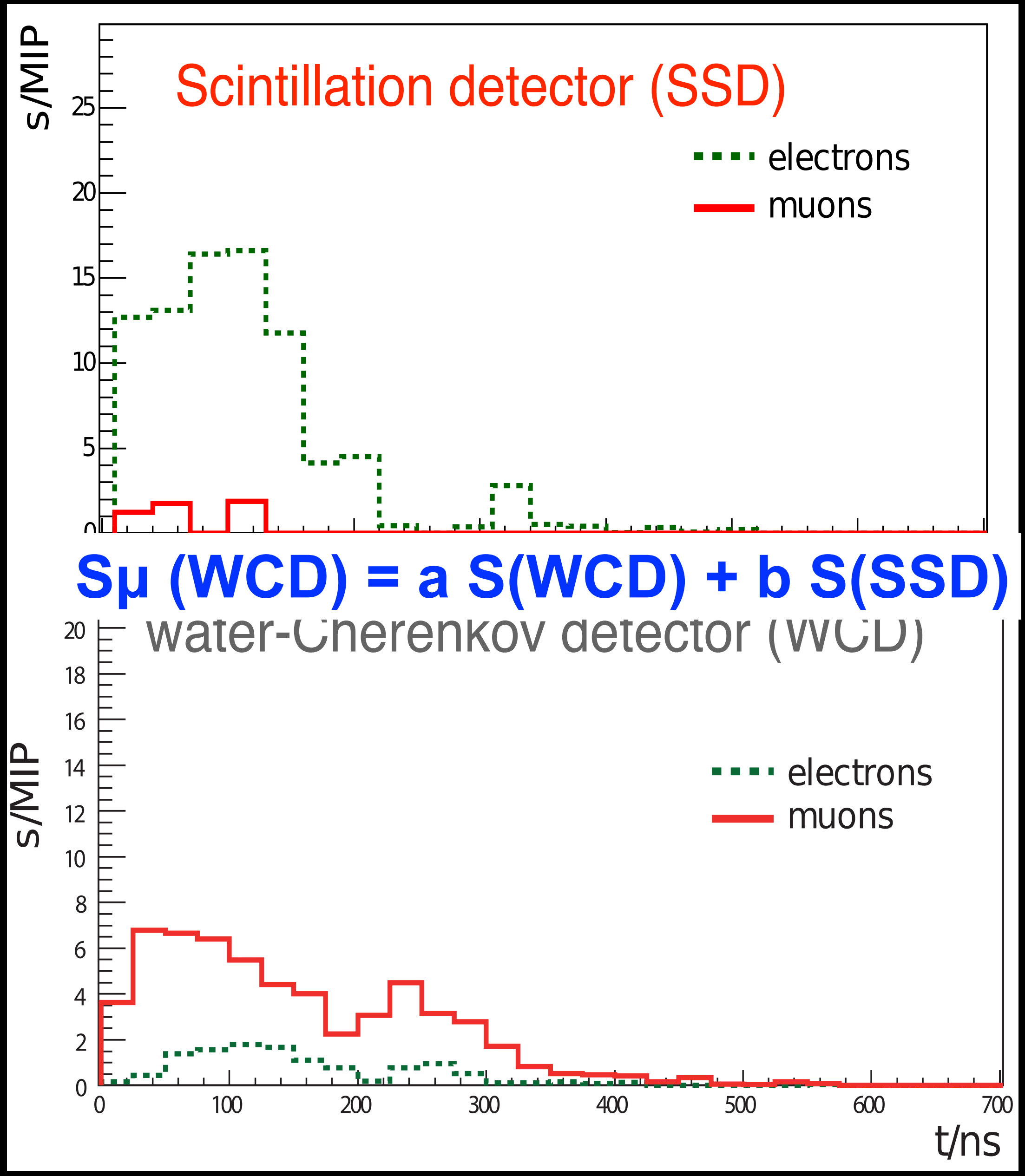
...paving the way for the next 10 years: AugerPrime

• Understand the origin of the flux suppression • Do composition enhanced anisotropy studies

• *Study UHE EAS properties and hadronic interactions*

Composition measurements up to 10^{20} eV by Surface Detector array

Complementarity of response to EAS em and μ components



a and b from simulations
Weak dependence on mass and models