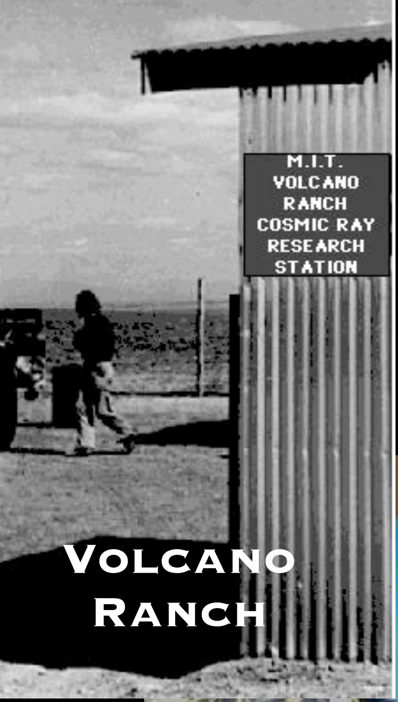
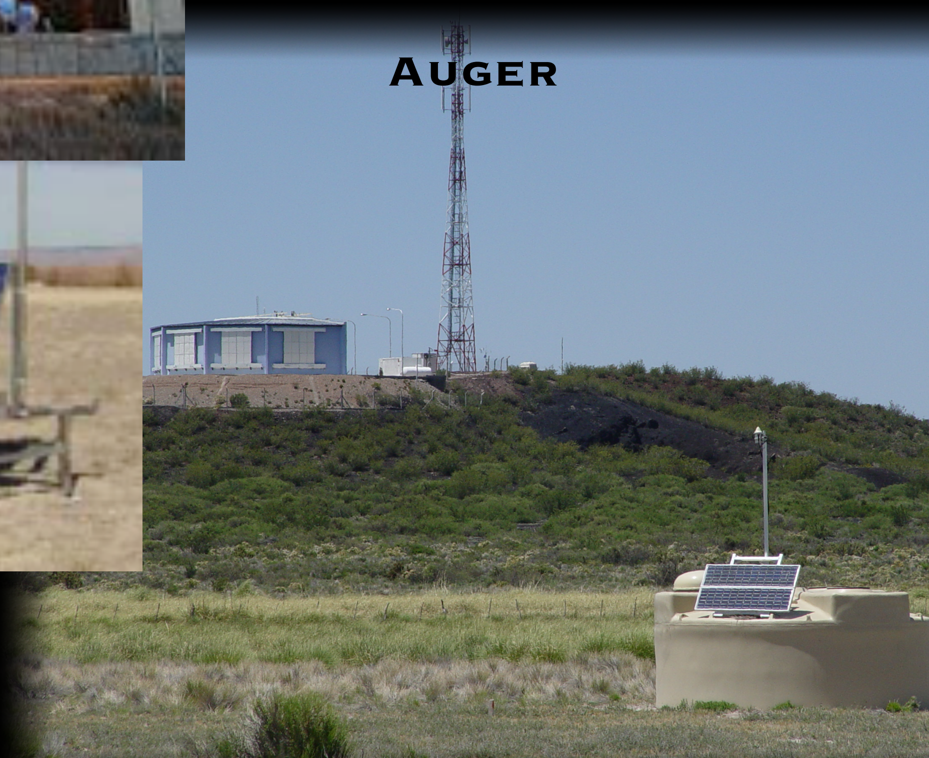
UHECRs
50 years after their first detection

An experimentalist's viewpoint





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

Outline

Introduction:
UHECRs: why and how we study them

Advances in the detectors:
from Volcano Ranch to Auger and Telescope Array

Advances in EAS measurement precision:
arrival direction, energy estimators, depth of the shower maximum

Advances in inferences on UHECRs
(energy spectrum, mass composition and origin)

Conclusions and perspectives

Introduction:

UHECRs: why and how we study them

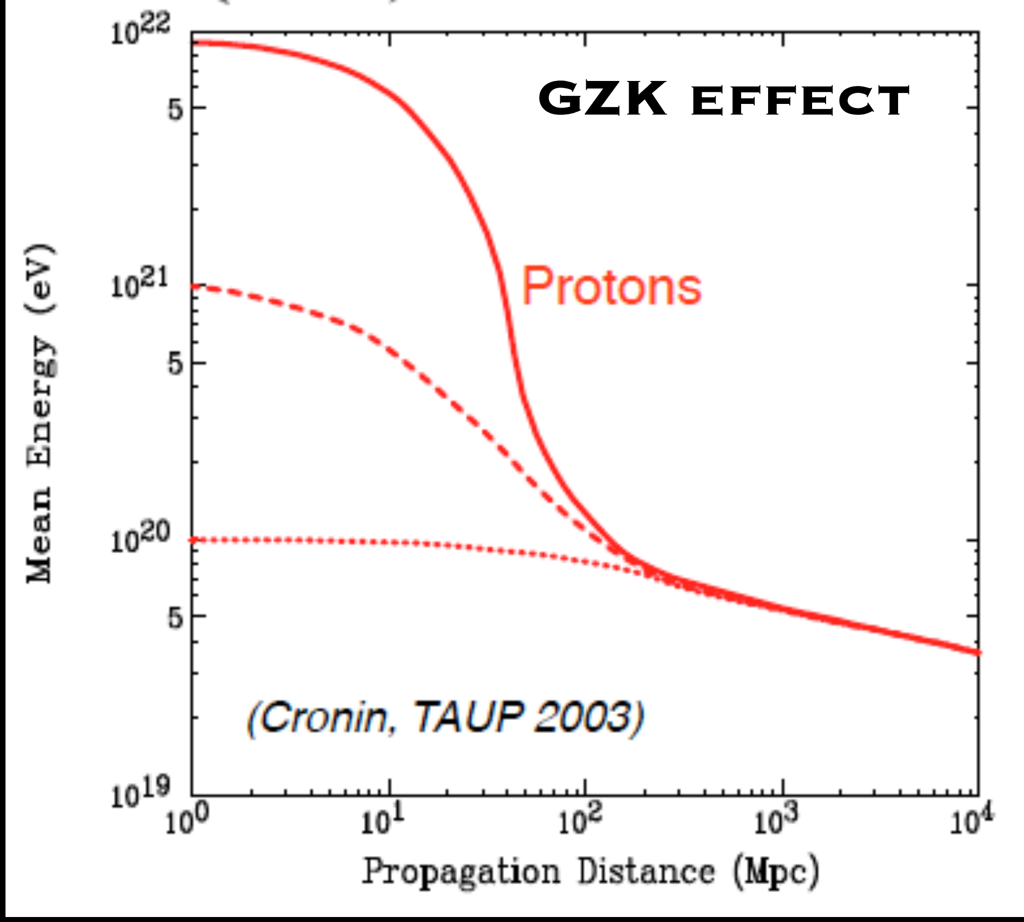
A cutoff in the CR energy spectrum around 60 EeV is expected by CR interaction with CMB photons (GZK effect)

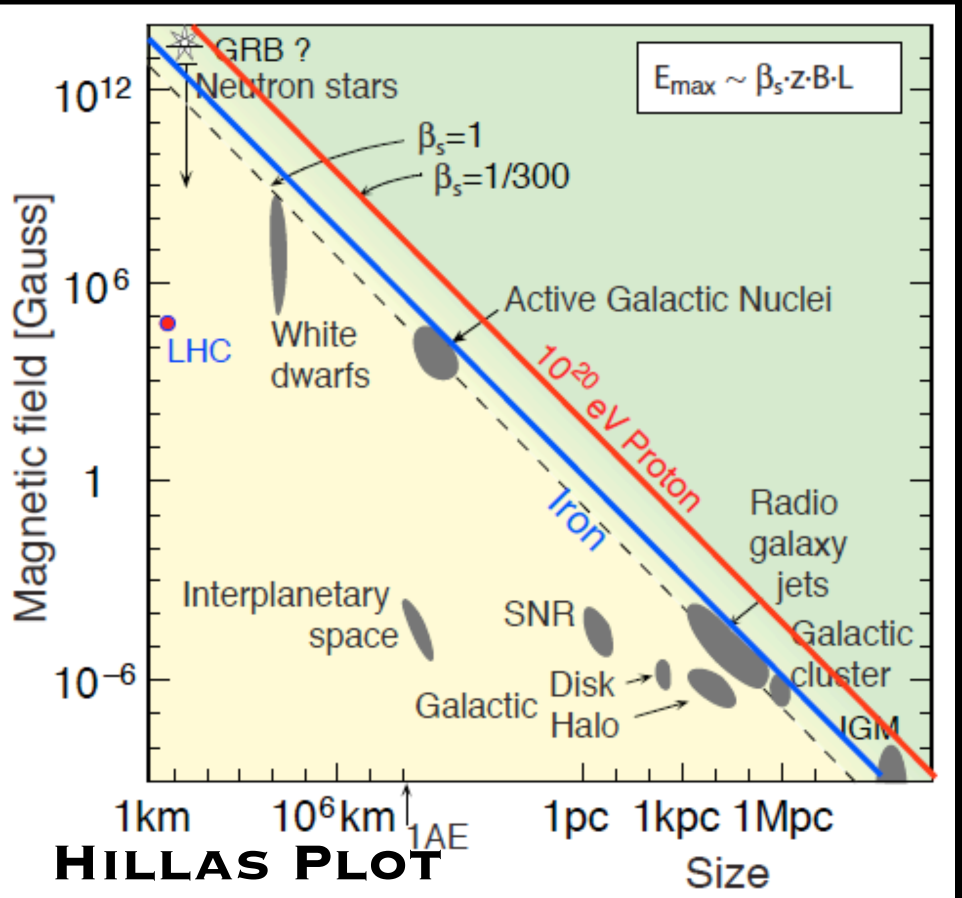
However, experiments (Volcano Ranch first, in 1963) established that CRs with $E>10^{20}$ eV exist!

Only few kind of sources might accelerate particles to these energies (Hillas, 1974). Due to the GZK effect, such sources are thus probably nearby (O(100 Mpc).

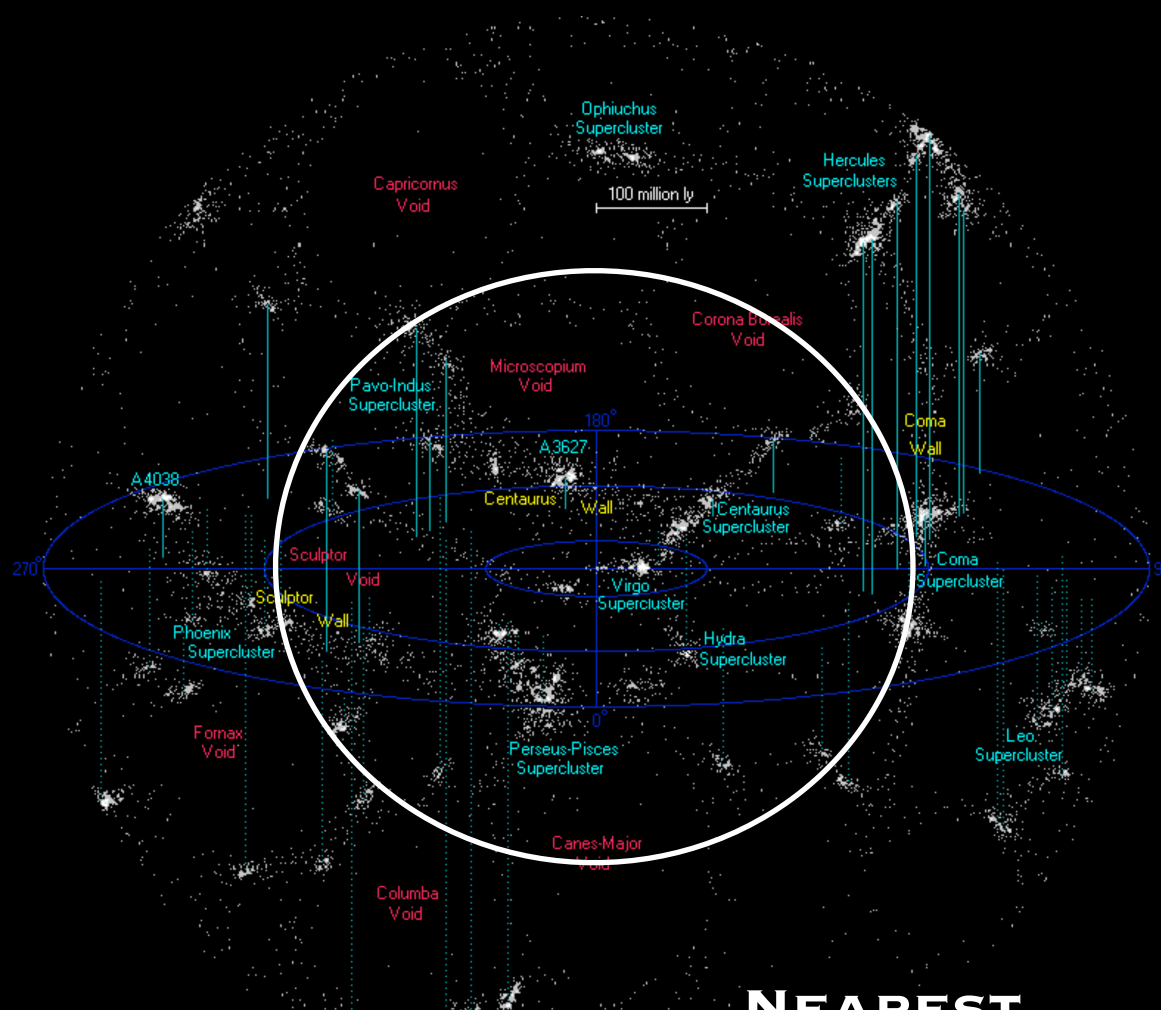
"Nearby" matter is not isotropically distributed. Also, trajectories of (LOW Z) UHECR through galactic and intergalactic magnetic fields may be nearly rectilinear. UHECR anisotropy expected.

But: are UHECRs actually low Z particles?



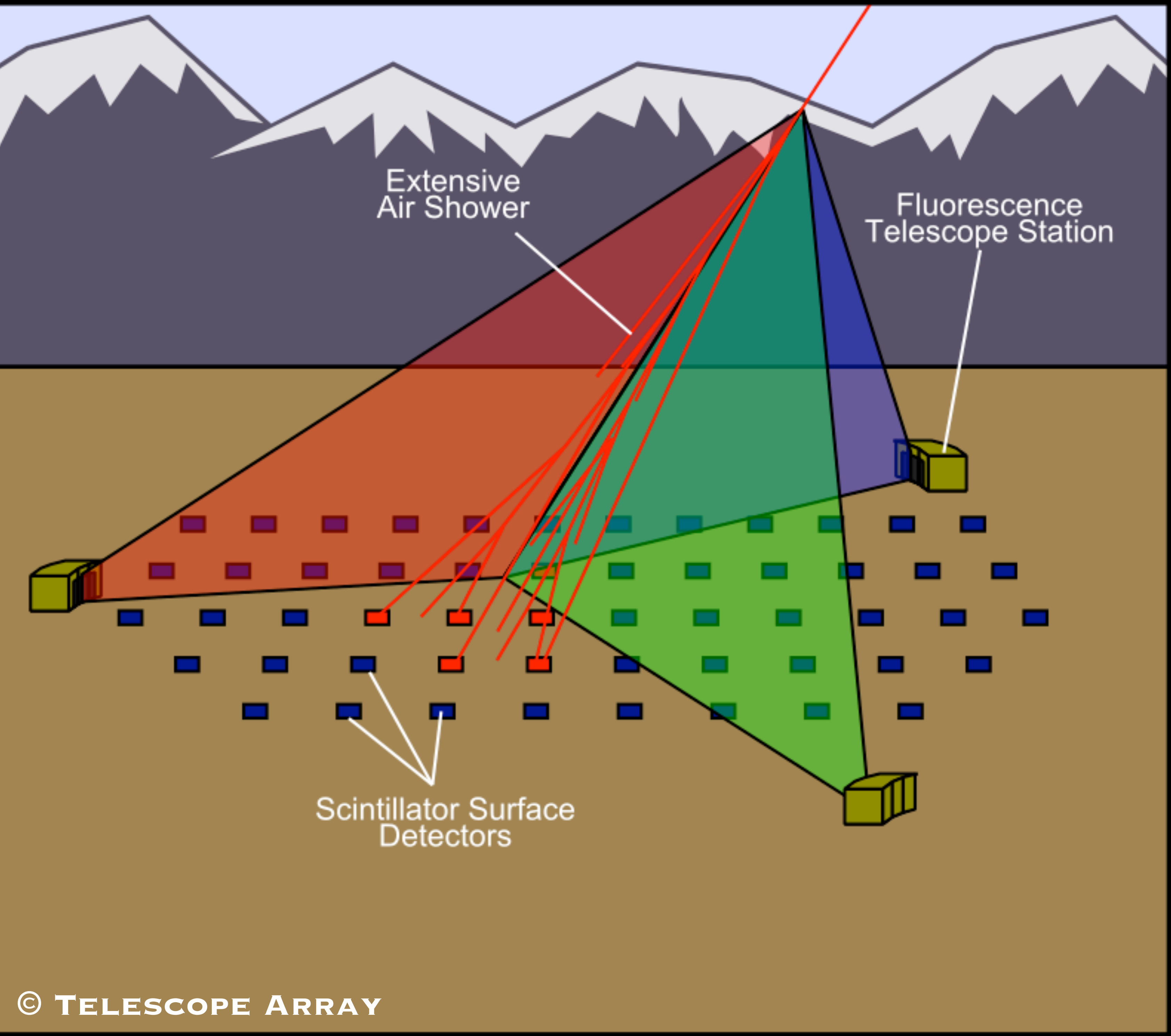


Hillas Plot



Nearest superclusters

UHECRs: how we study them



Ultra High Energy Cosmic Rays (UHECRs, above ≈ 10^{18} eV): very rare, 1/(km^2 y)

But "penetrating" up to ground via a "shower" of particles (extensive air-showers, EAS).

Only "indirect" detection, through EAS, is possible:

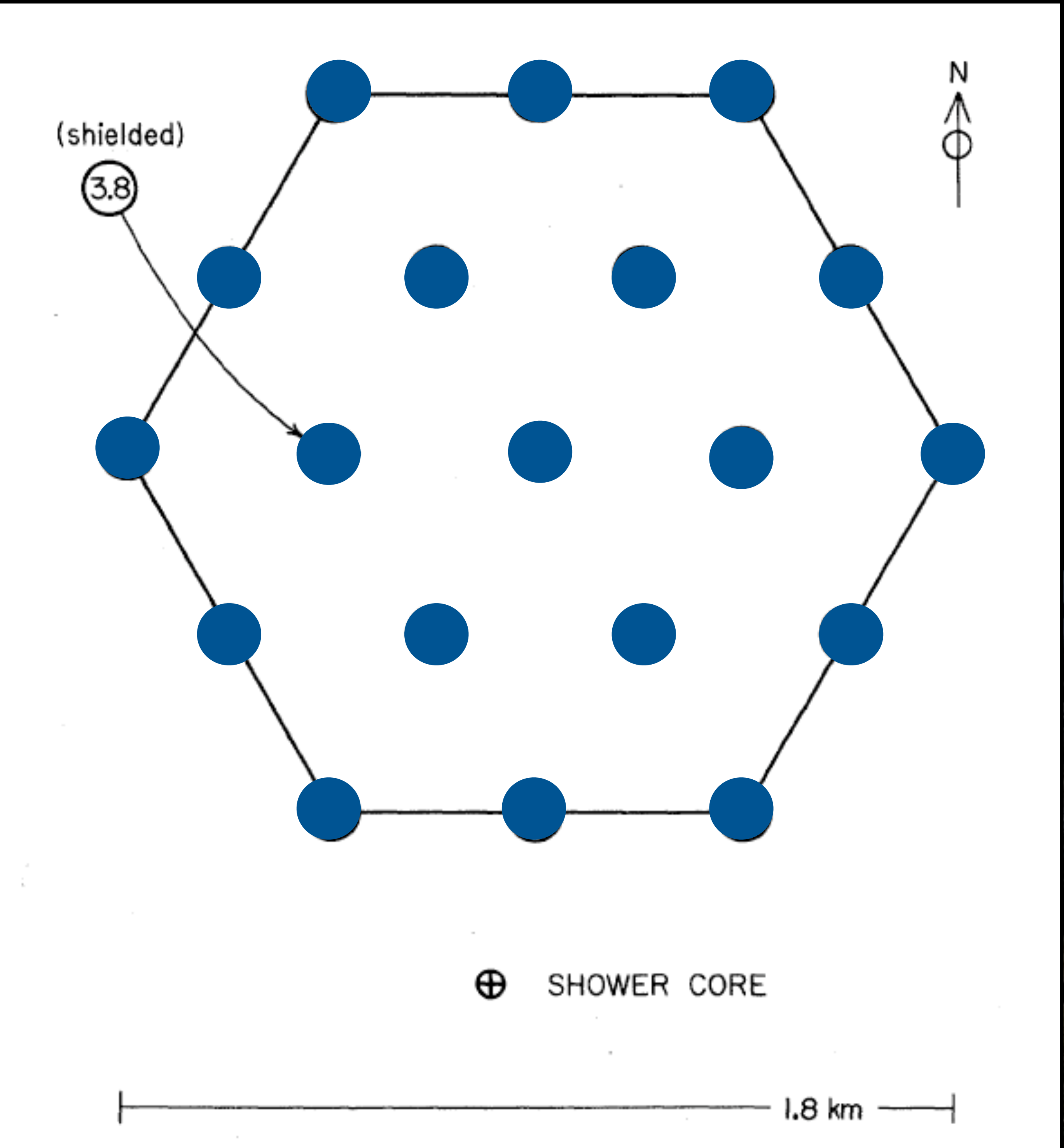
large particle detectors arrays on Earth (O(km^2, 100% d.c.)

and/or

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

Advances in detectors:
from Volcano Ranch to Auger and Telescope Array

The first EAS array covering more than 1 km2



Volcano Ranch (1962-1978)

USA, New Mexico, 1800 m a.s.l.

19 scintillators array

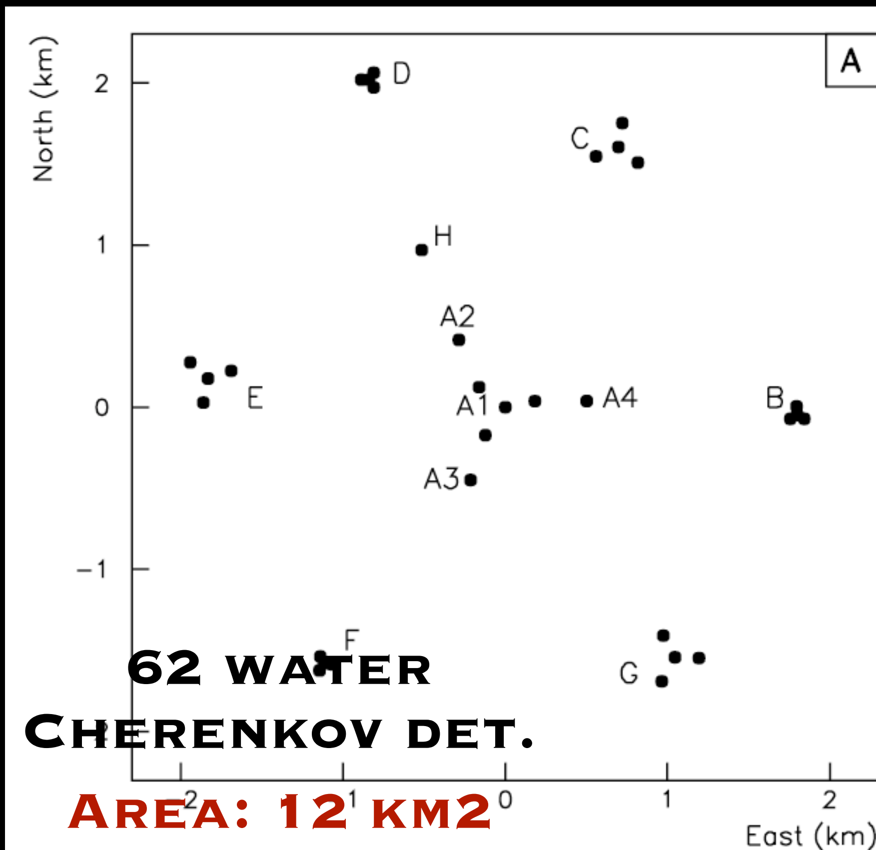
Spacing ≈ 450 m

Enclosed area: 2 km2

(effective area 8 km2)

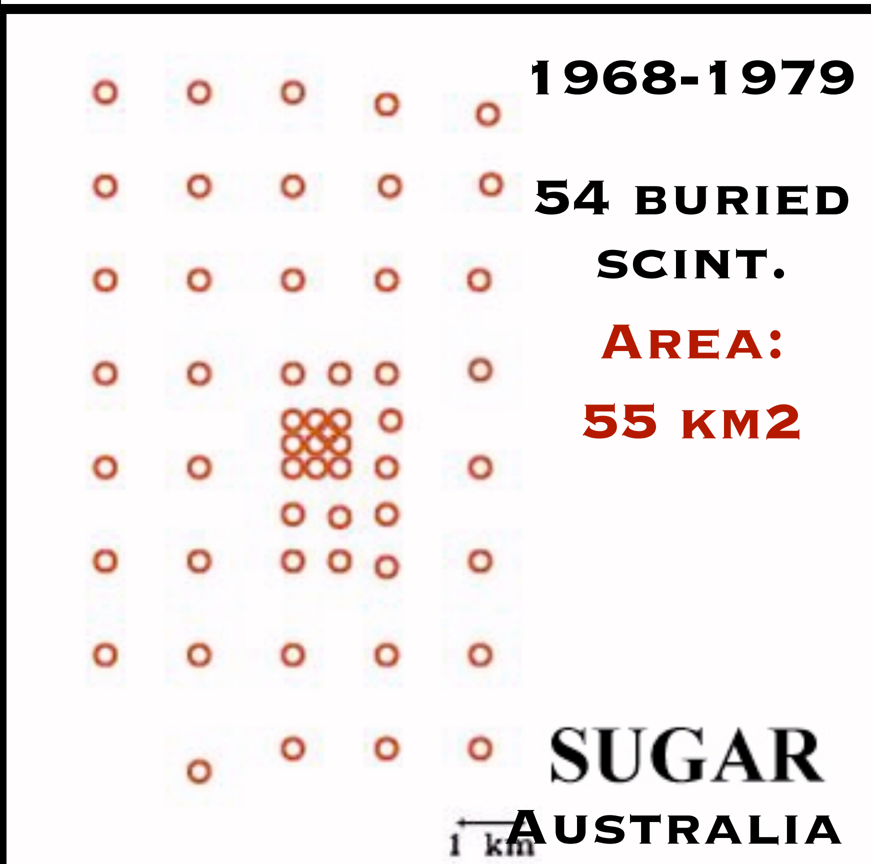
Larger and larger particle-detectors arrays followed...

Haverah Park, UK
1967-1987



62 water Cherenkov det.

Area: 12 km2



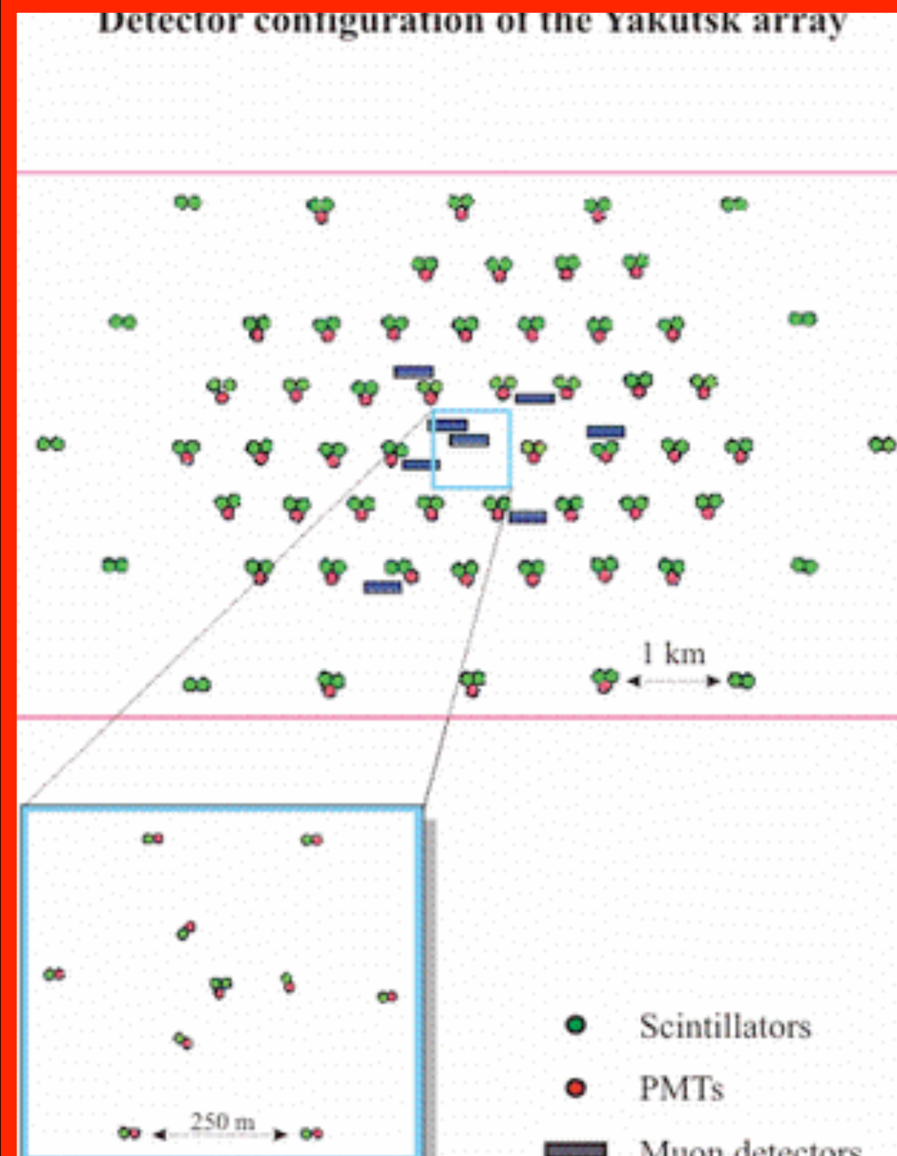
1968-1979

54 buried scint.

Area: 55 km2

Australia

Yakutsk, Russia
1974-NOW!!!

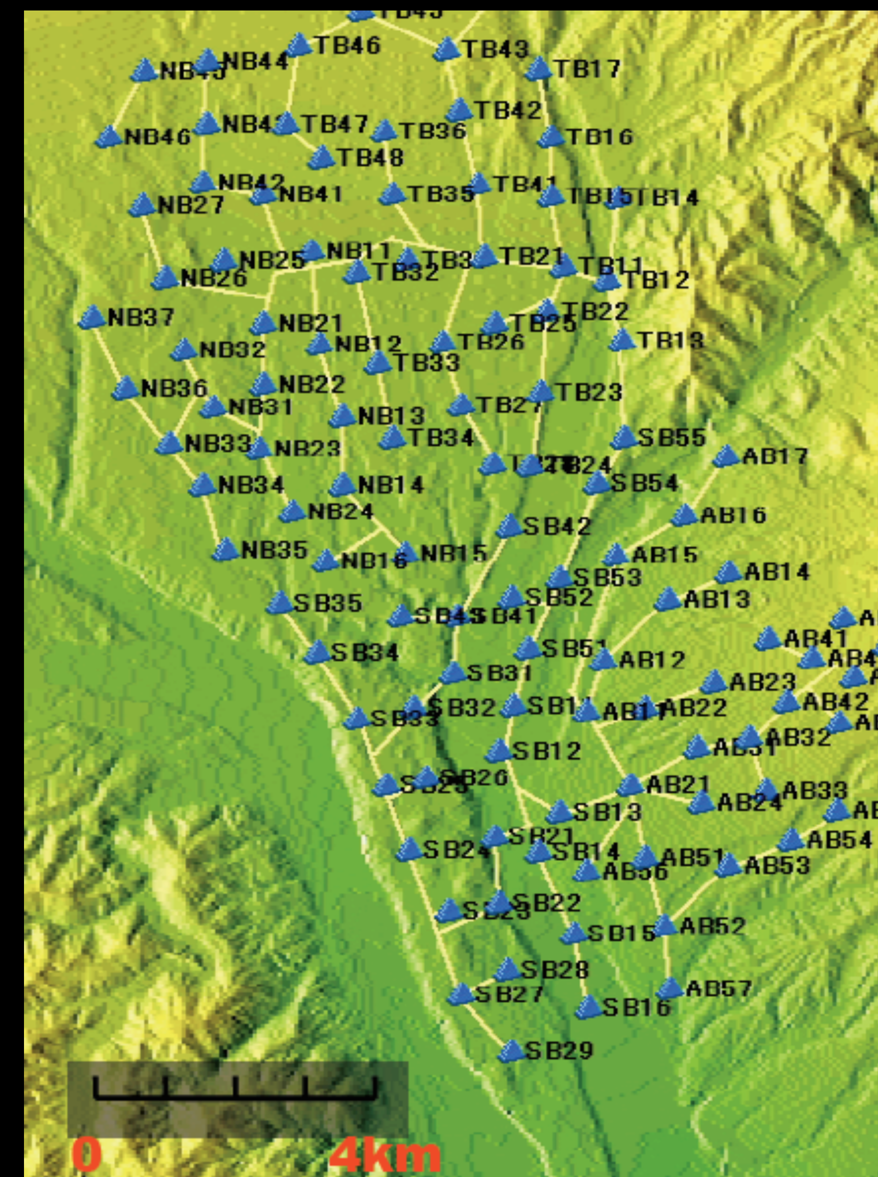


58 scint. + 6 Mu detectors + 45 Cherenkov PMTs

Area: 17 km2

(8 km2 since 1992)

AGASA, Japan
1990-2004



111 scint. + 27 muon detectors

Area: 100 km2

...and starting from early 80s, fluorescence telescopes

1975 - 1995

Fly's Eye

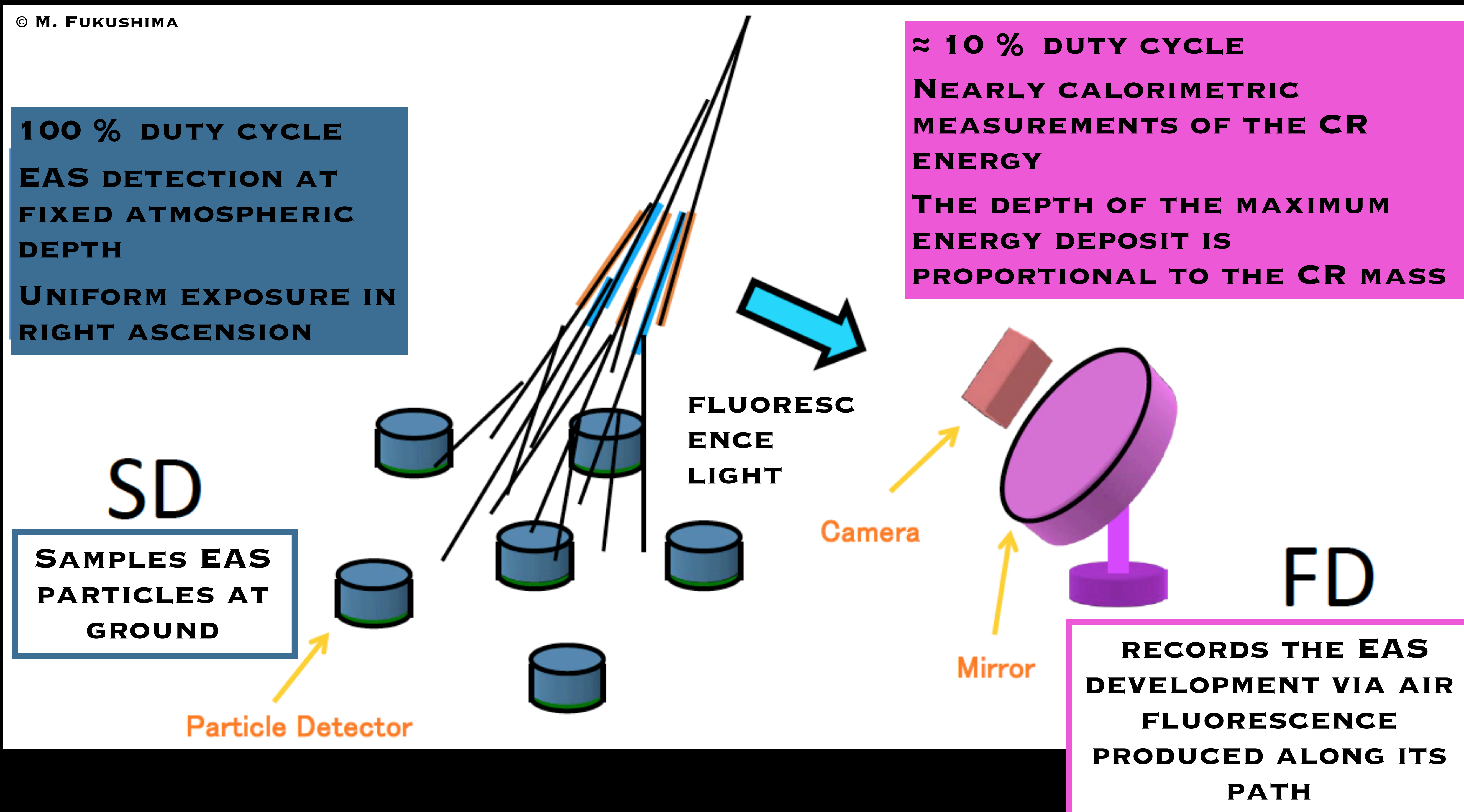
USA, Utah

2 fluorescence telescopes
(67 mirrors & 880 PMTs +
36 mirrors & 464 PMTs)

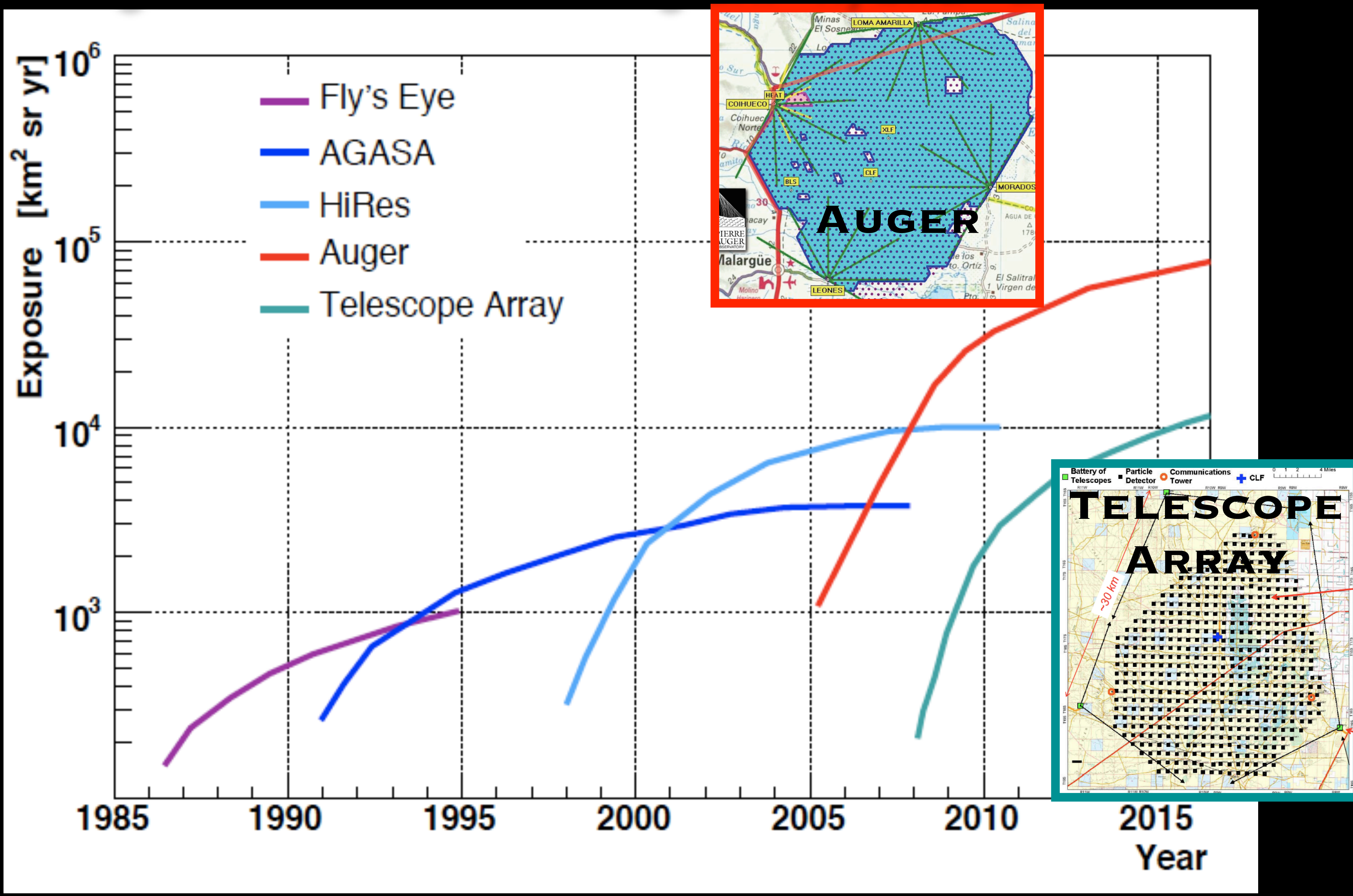
Stereo technique Pioneer

HiRes: USA, Utah (1997-2006)
2 fluorescence telescopes
(HiRES 1 & 2) D=12.6 km

2000s: two well established complementary techniques...



...merged in the two current giant "hybrid" detectors...

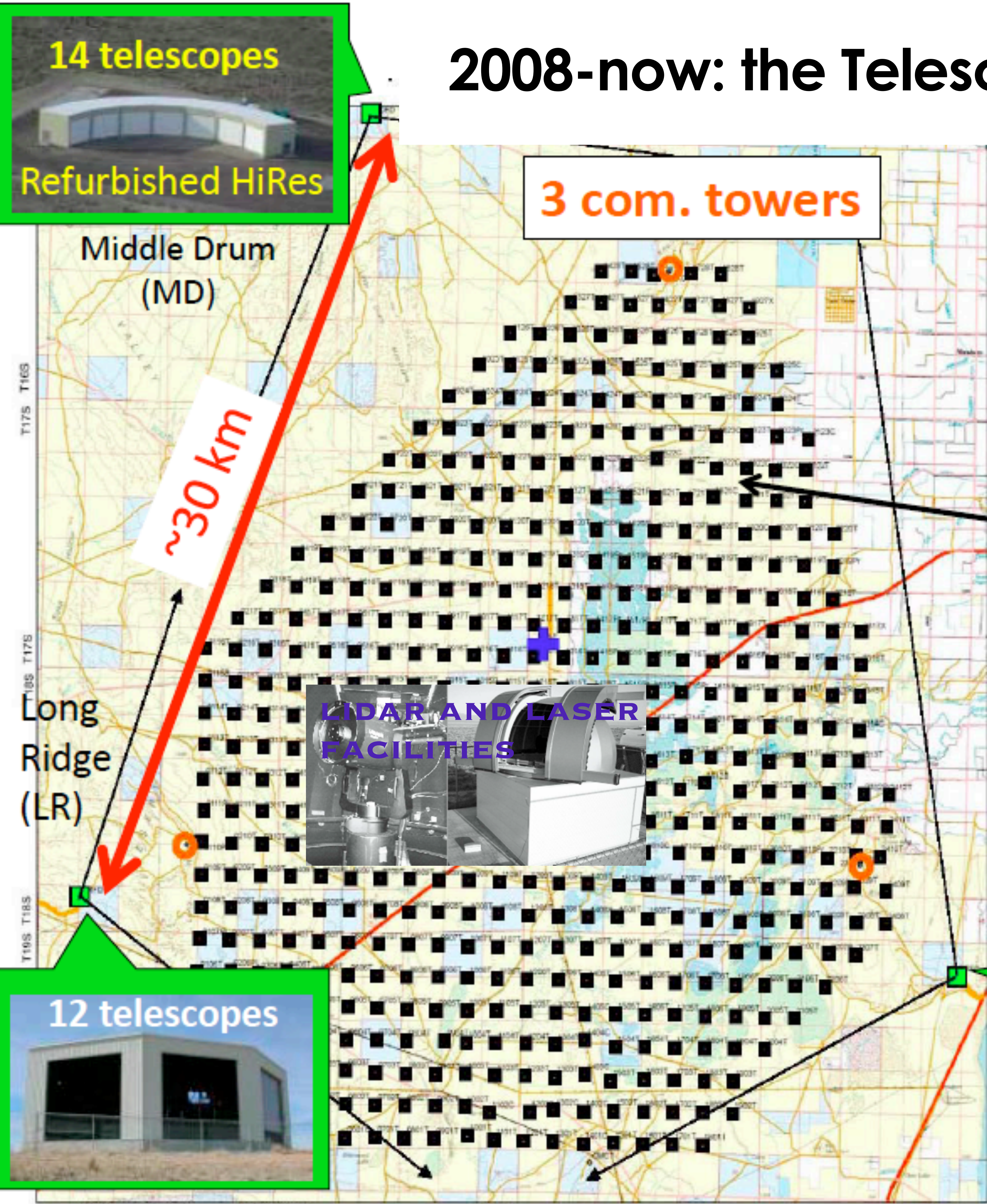


1990 2000 2005 2010

2004-now: the Pierre Auger Observatory

2008-now: the Telescope Array

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

700 km²

Fluorescence Detector(FD)

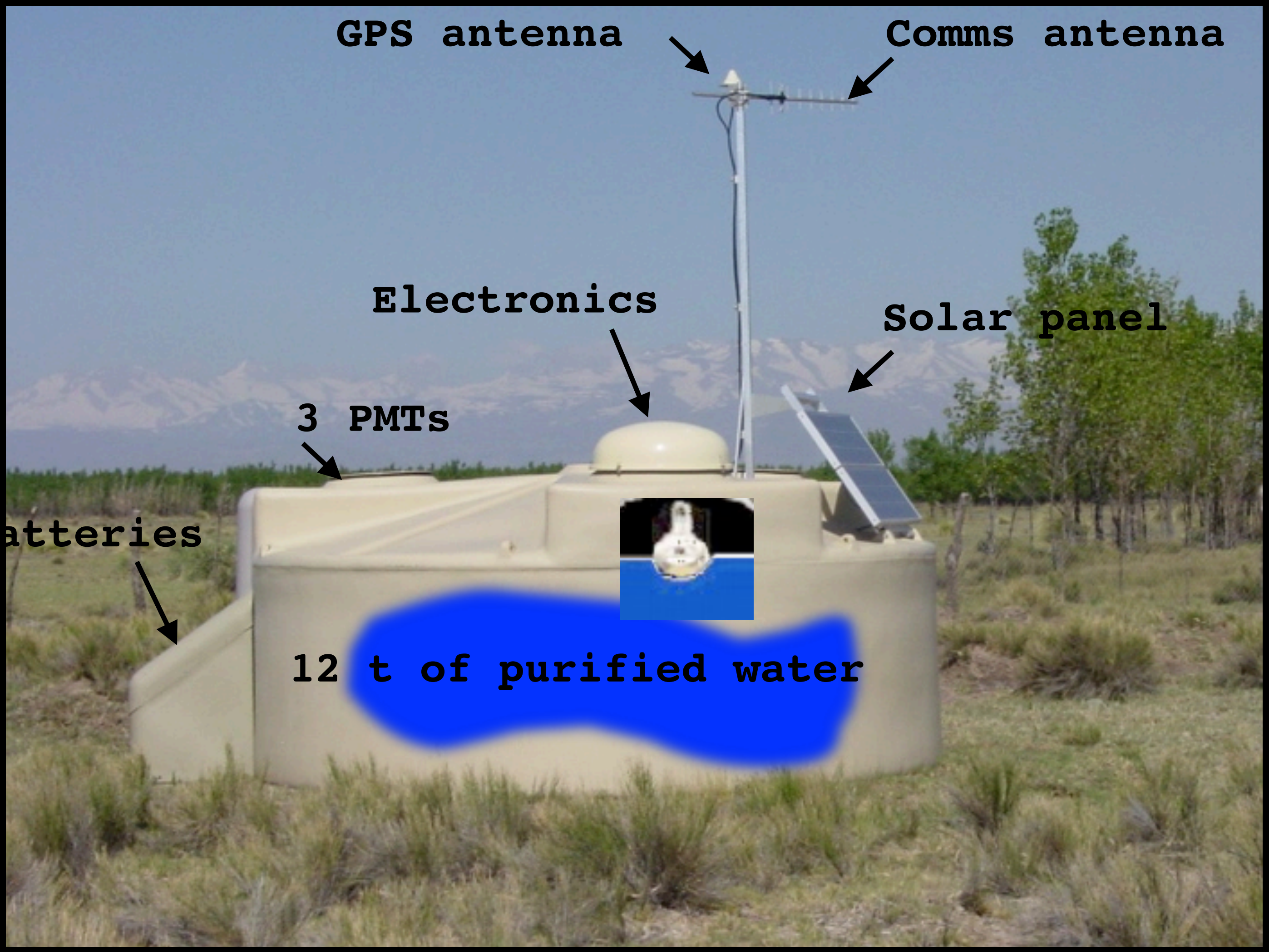
3 stations

38 telescopes

From H. Sagawa, ICRC 2013

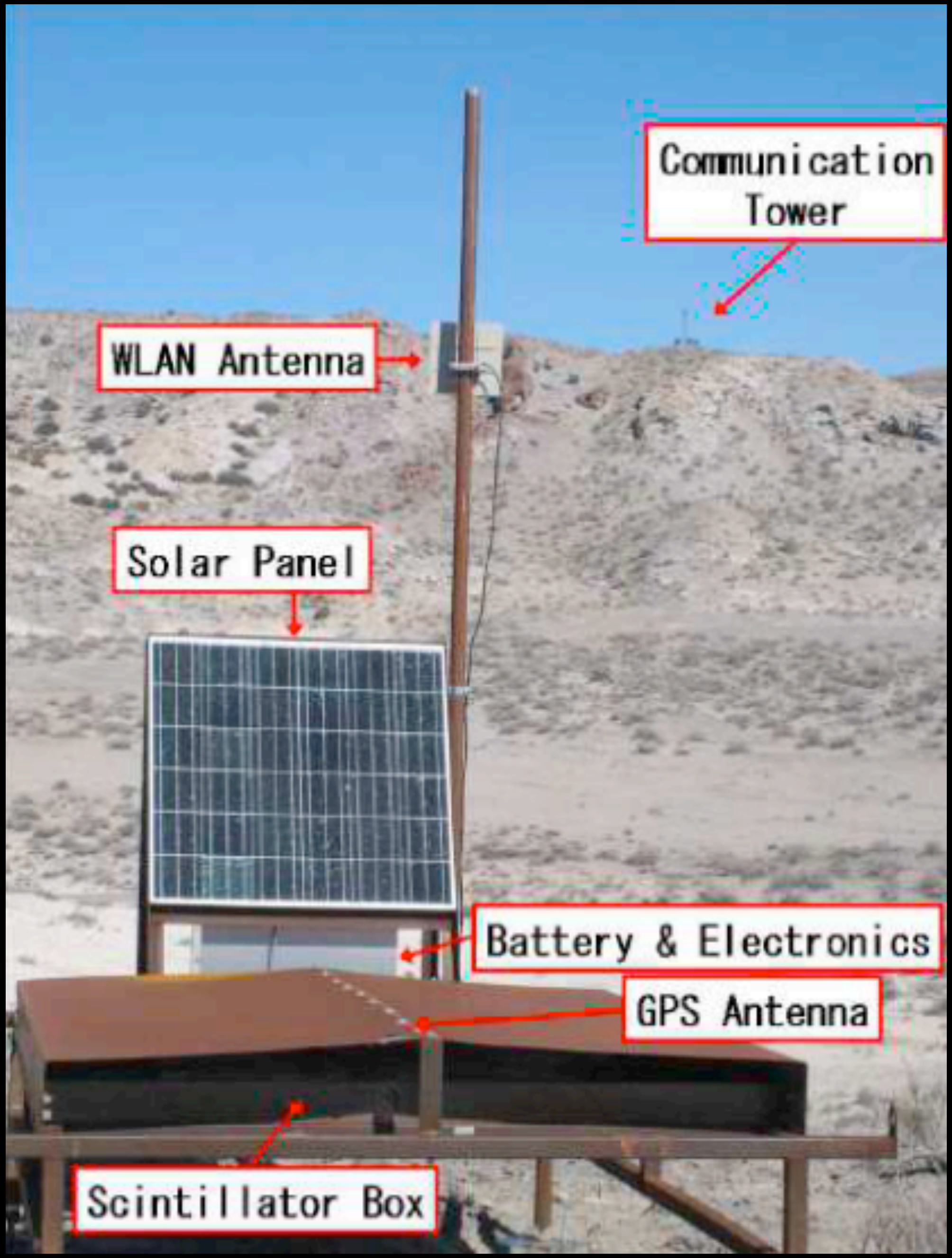
Surface detectors

Auger



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)

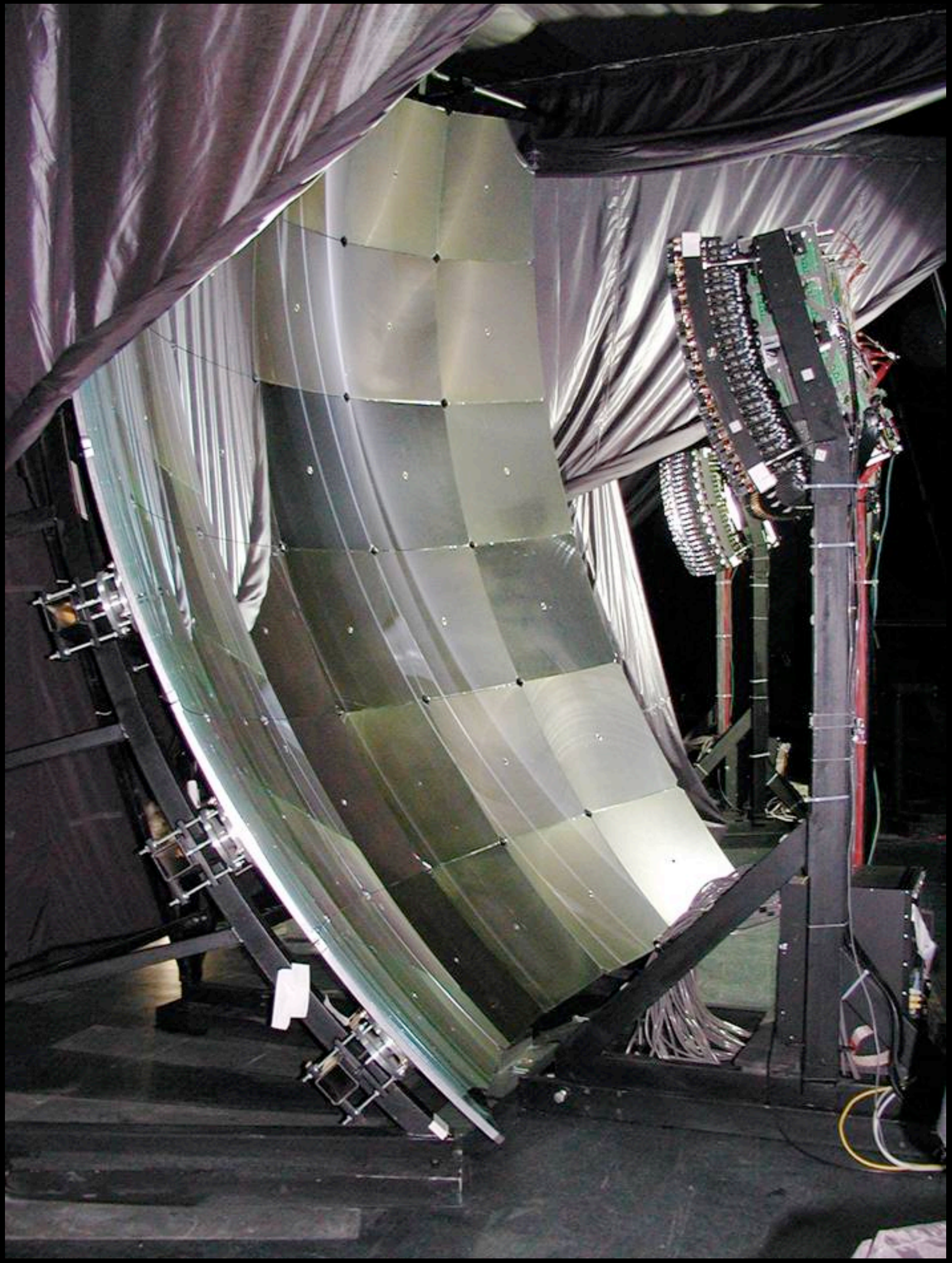
Telescope Array



Scintillators
Area: 3 m2
Thickness: 1.2 cm
acceptance up to 55 deg
More sensitive to em component

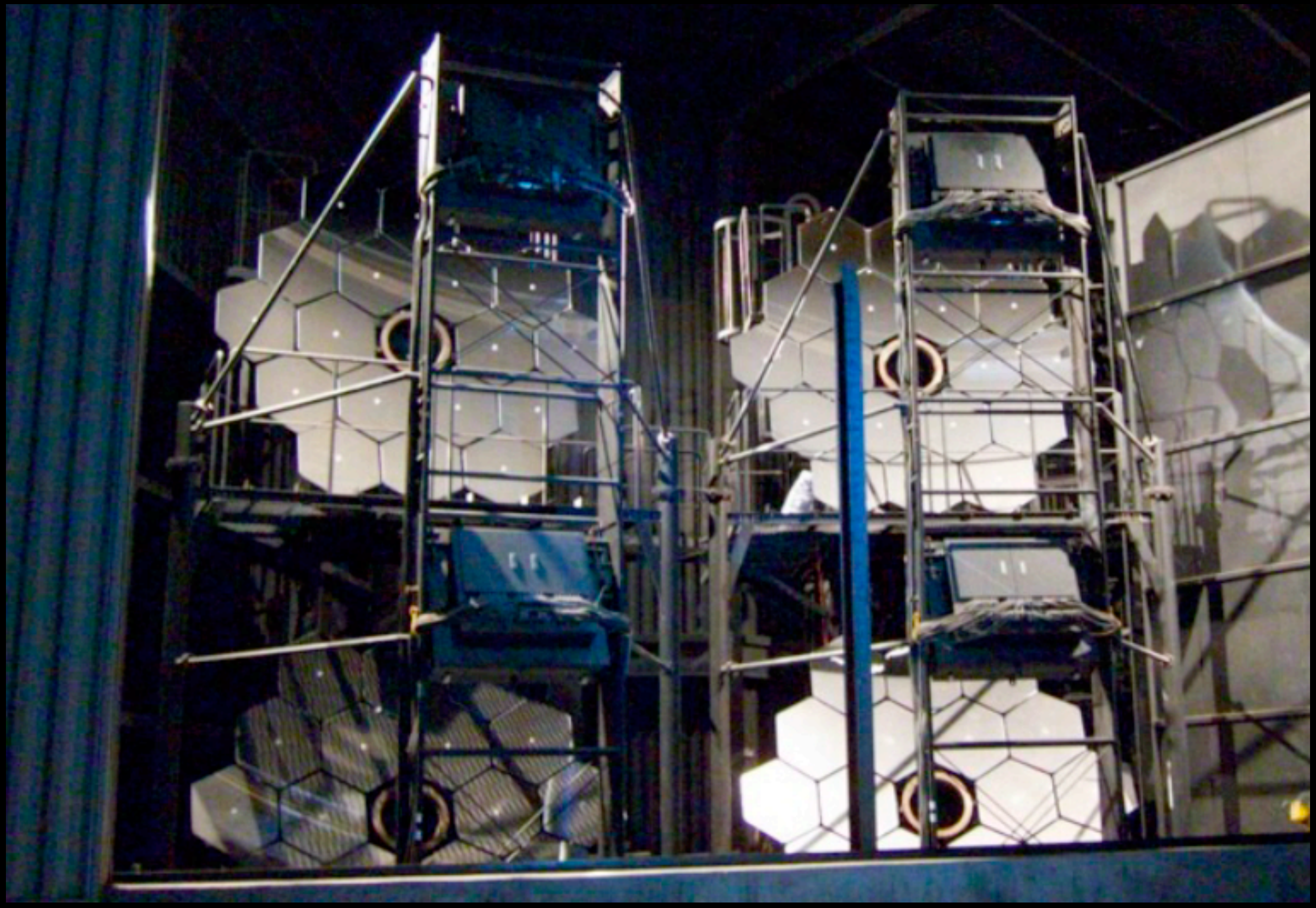
Fluorescence telescopes

Auger



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

Telescope Array



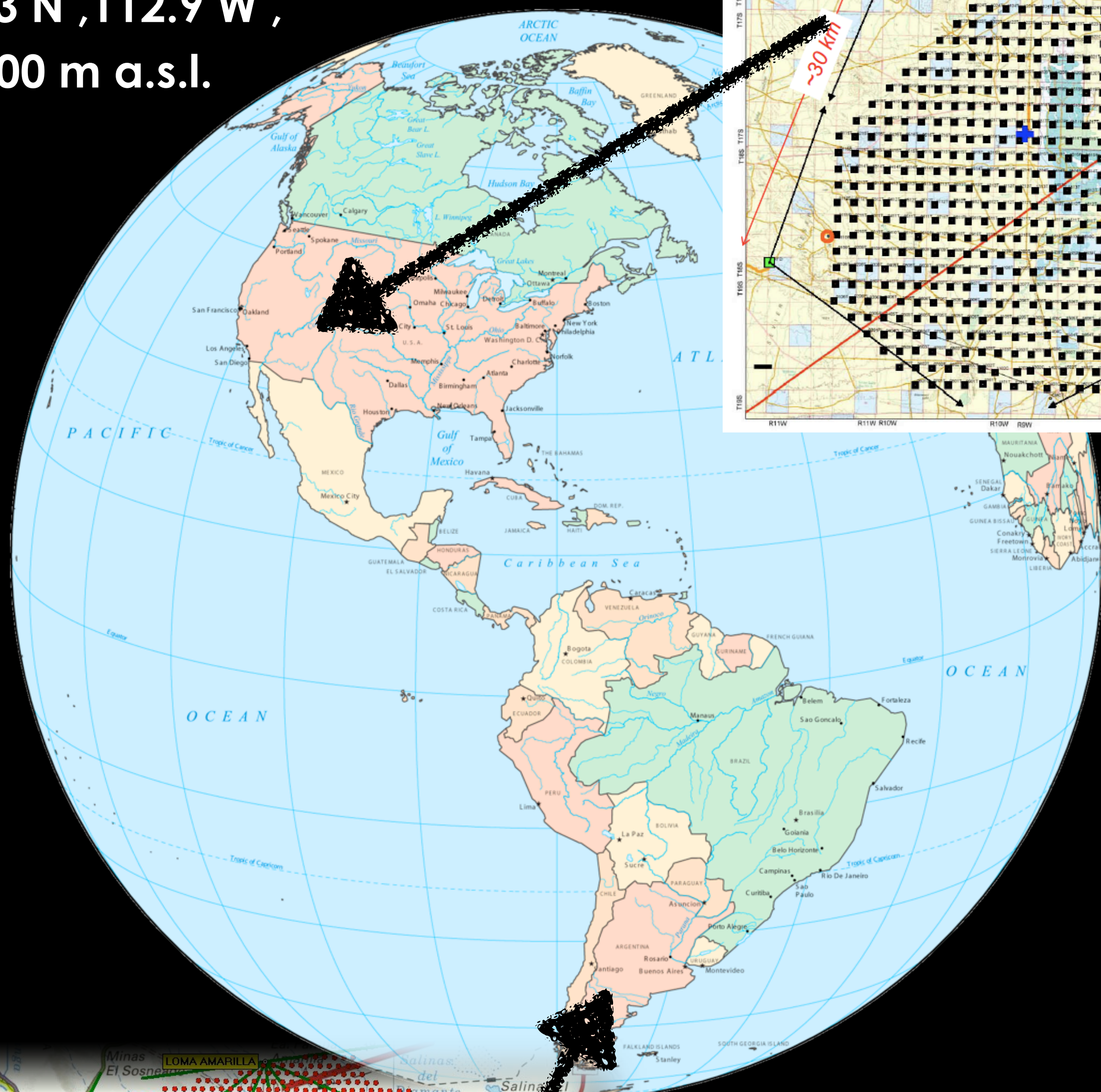
3 m segmented mirror
256 PMTs camera
15° x 18° FOV

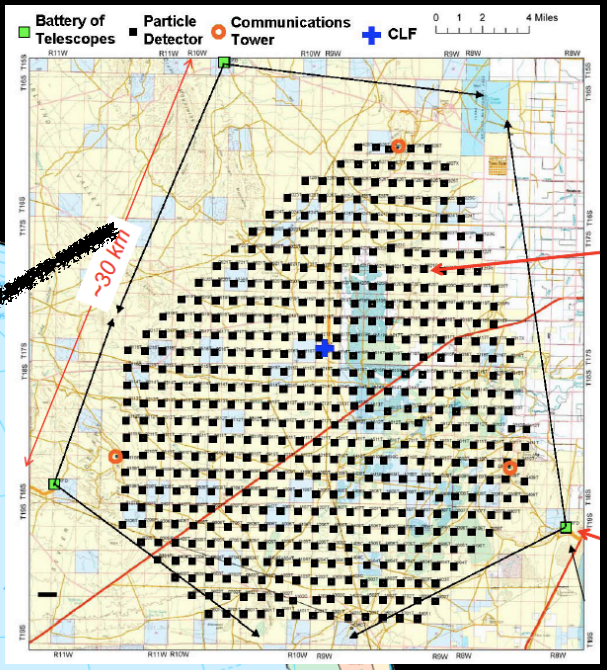
Telescope Array and Auger relative location

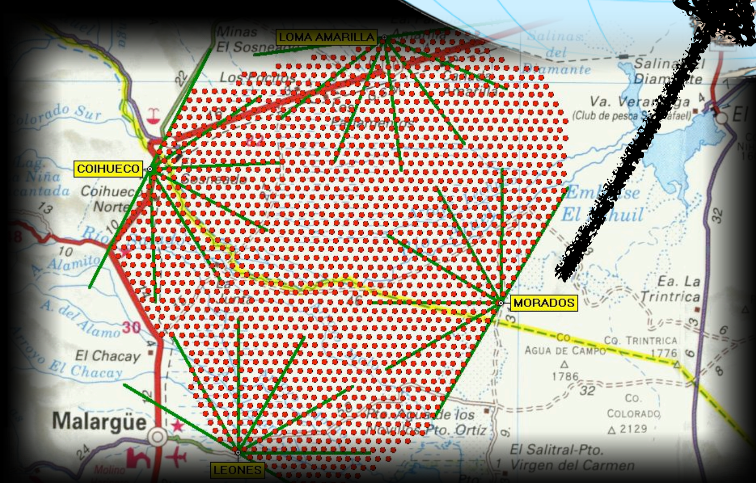
Telescope Array

Millard County,
Utah, USA

39.3 N ,112.9 W ,
1400 m a.s.l.



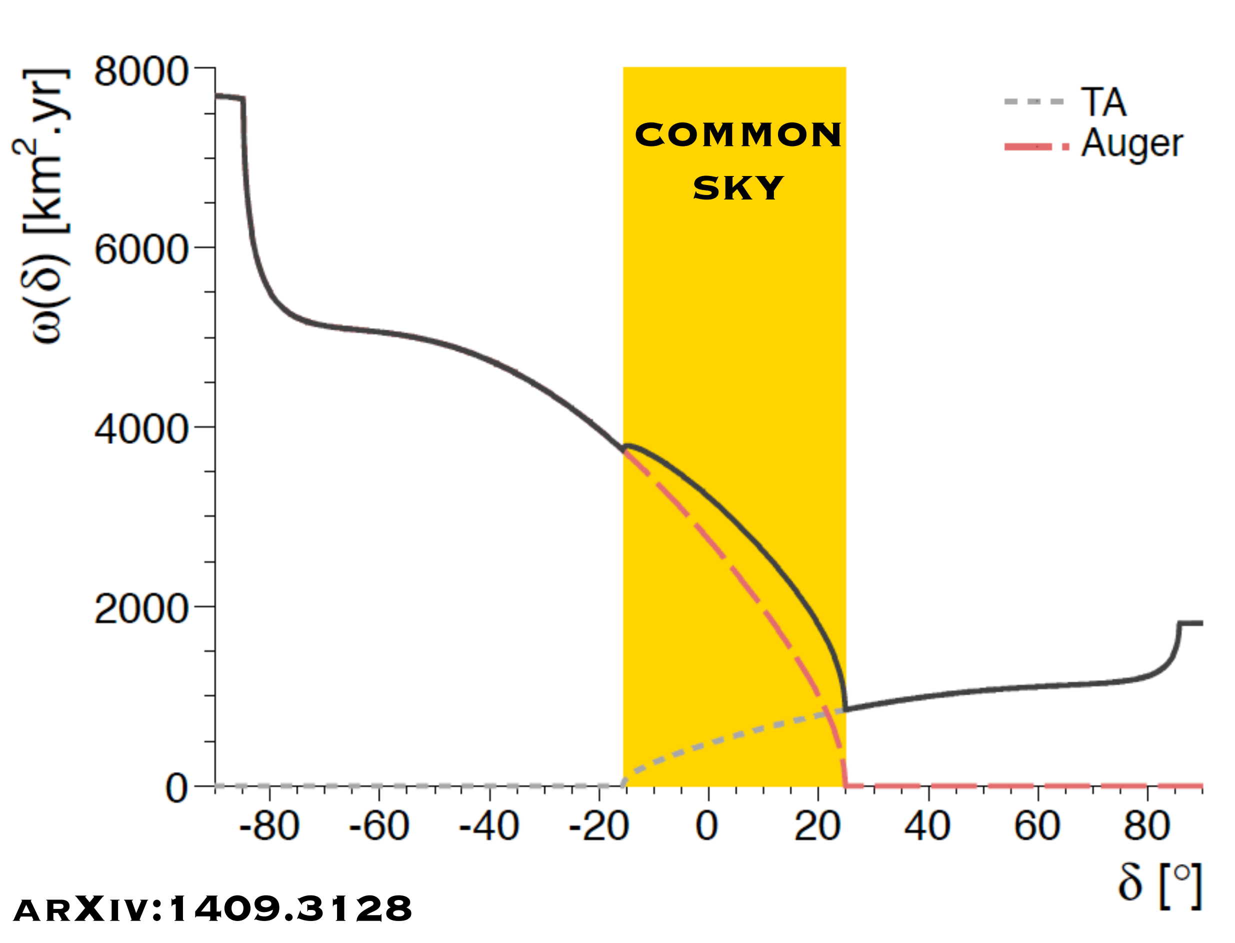




Auger

Malargue, Argentina

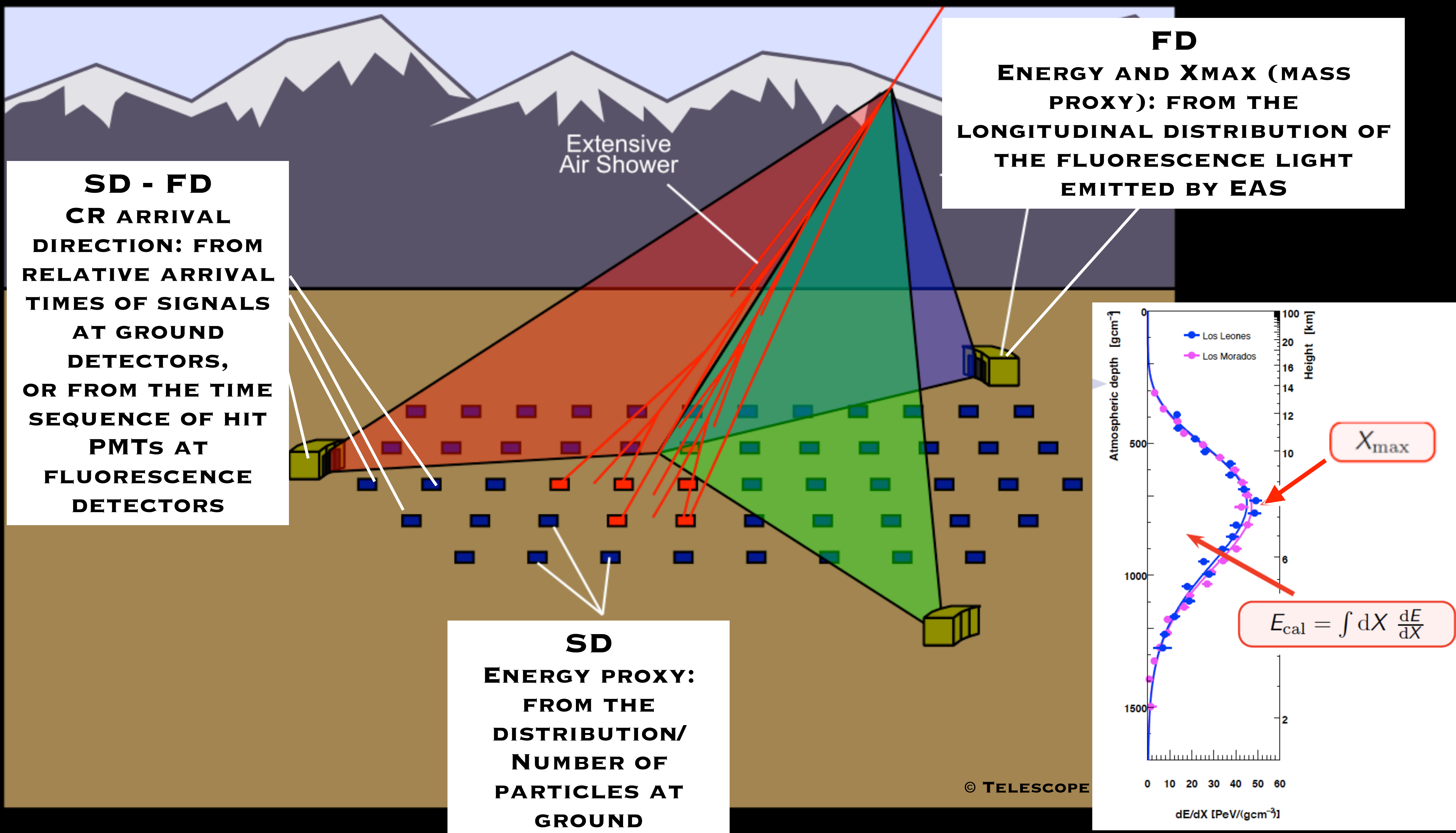
35.1–35.5S, 69.0–69.6W,
1400 m a.s.l.



Auger (0-60 deg)+ TA (0-55 deg)
=
full sky coverage

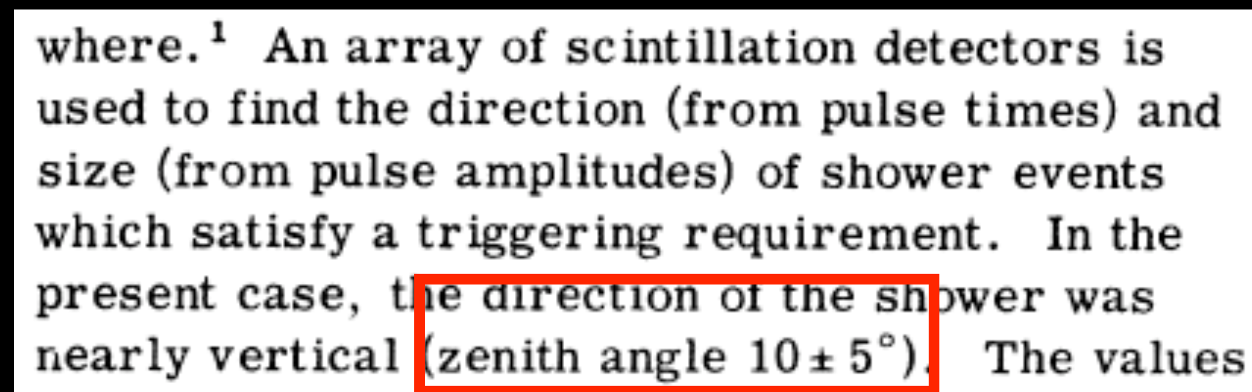
Advances in EAS measurement precision: arrival direction, energy estimators, depth of shower maximum (Xmax)

From EAS observables to CR properties

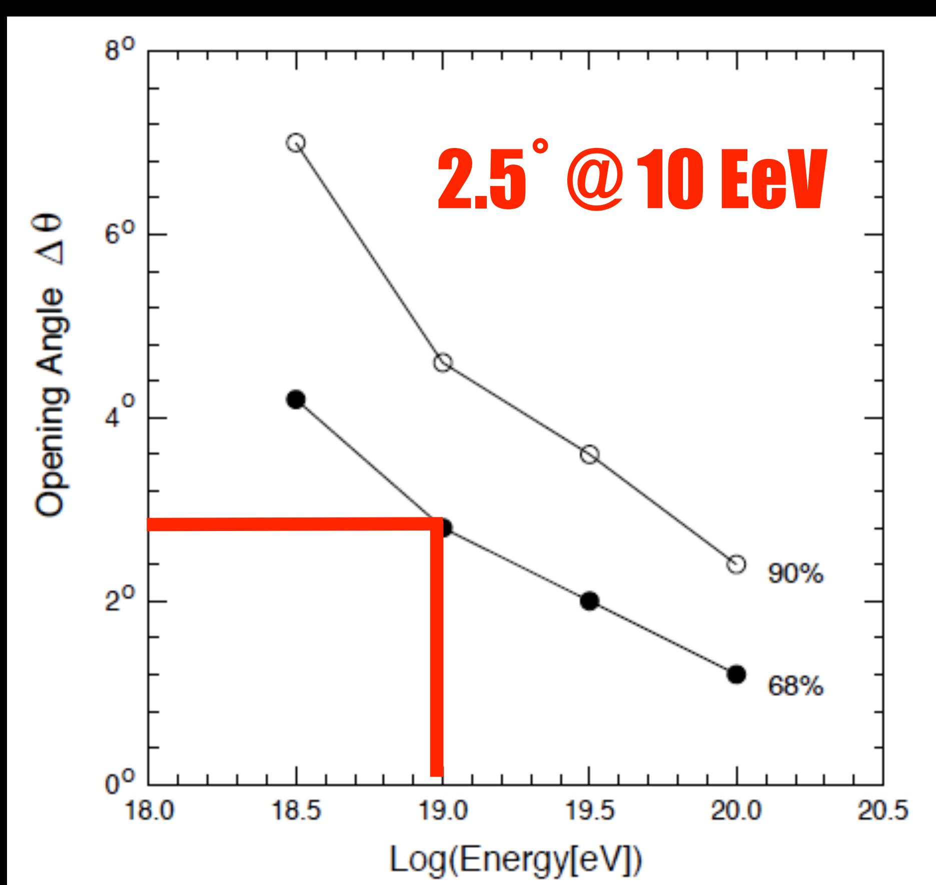


From EAS particles (light) arrival times to primary CR *arrival direction*: the past

Volcano Ranch

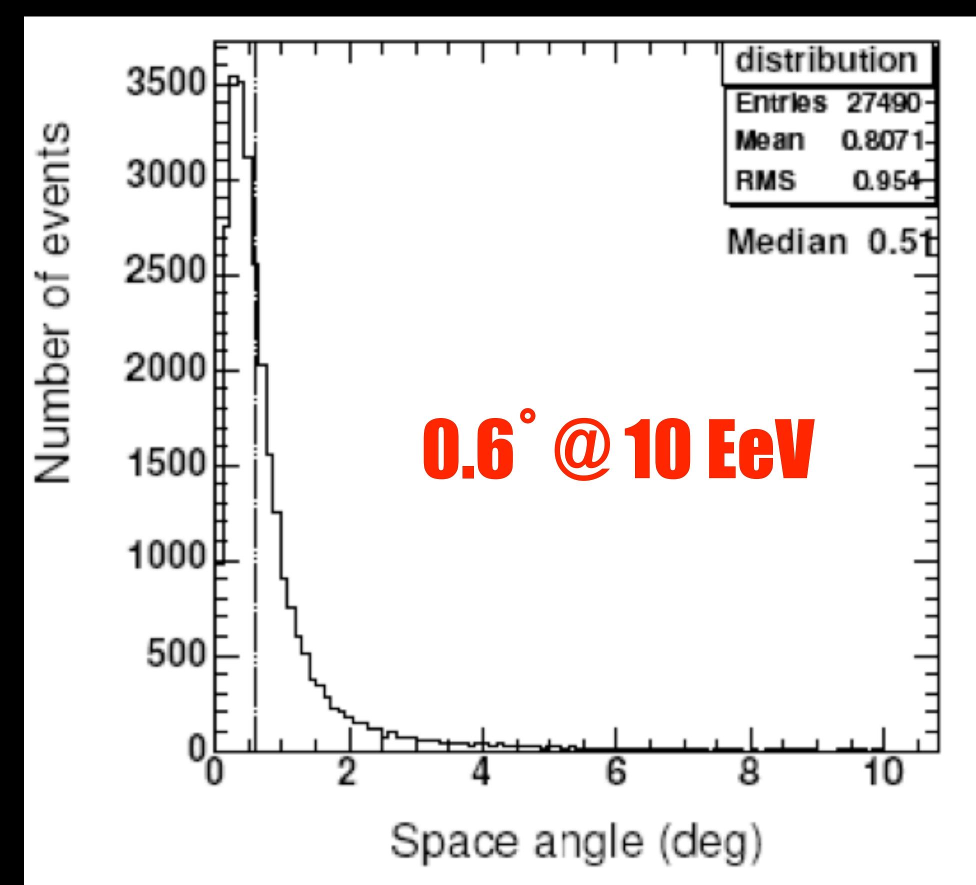

where.[1] An array of scintillation detectors is used to find the direction (from pulse times) and size (from pulse amplitudes) of shower events which satisfy a triggering requirement. In the present case, the direction of the shower was nearly vertical (zenith angle 10 ± 5°). The values

AGASA



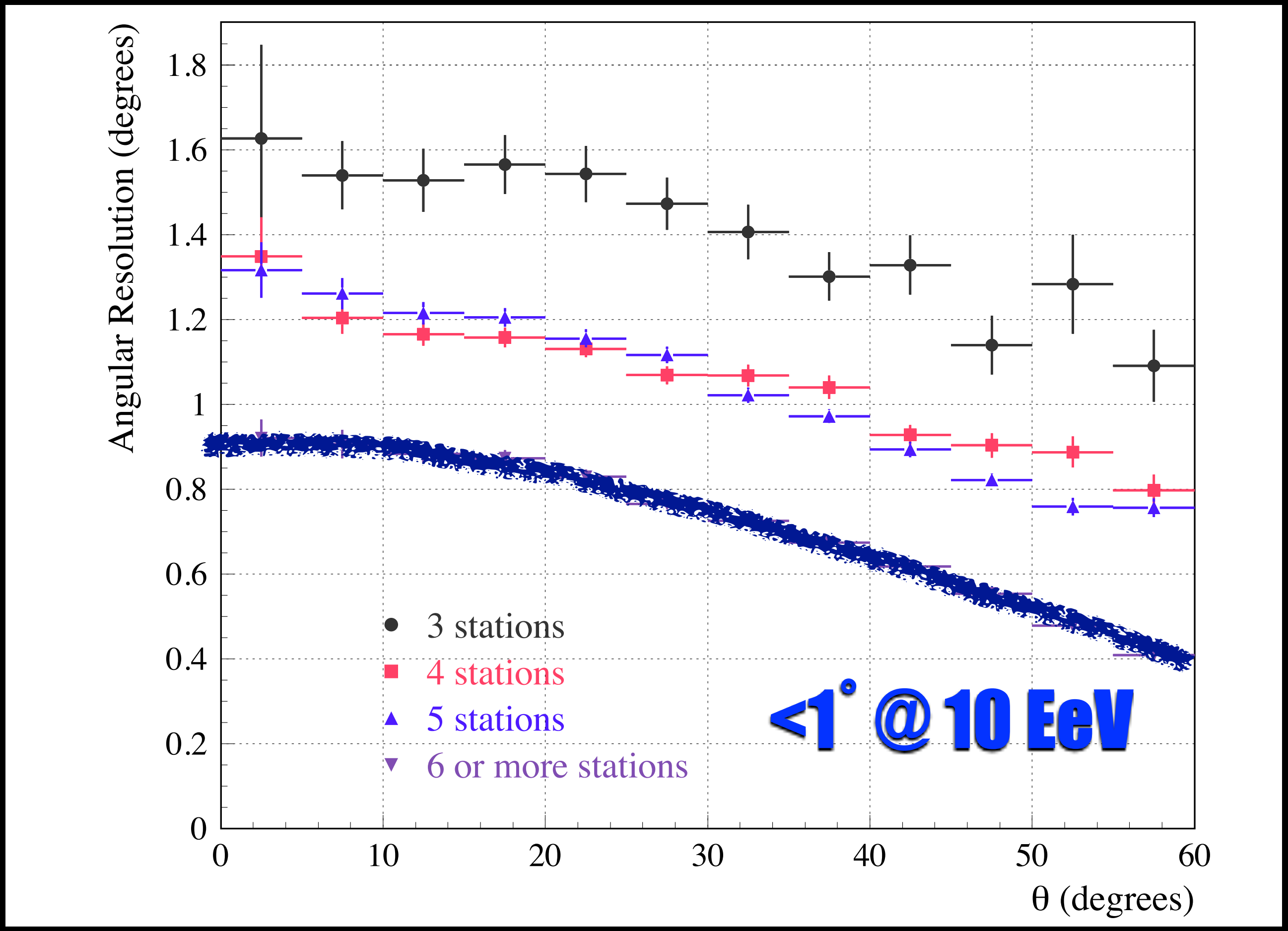
More Precise geometry with stereo fluorescence

HiRes (stereo)

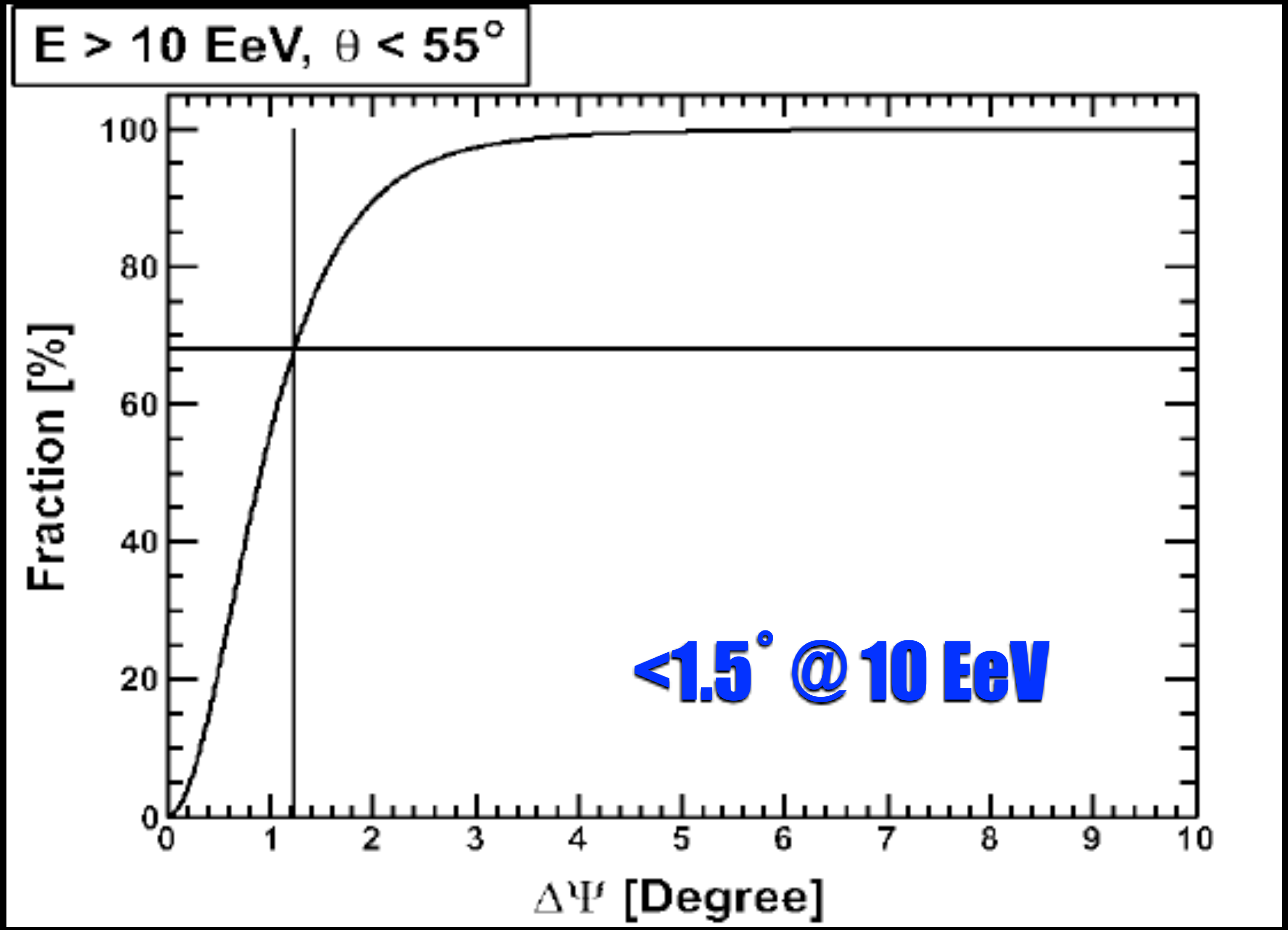


From EAS particles (light) arrival times to primary CR *arrival direction*: the present

Auger (SD)

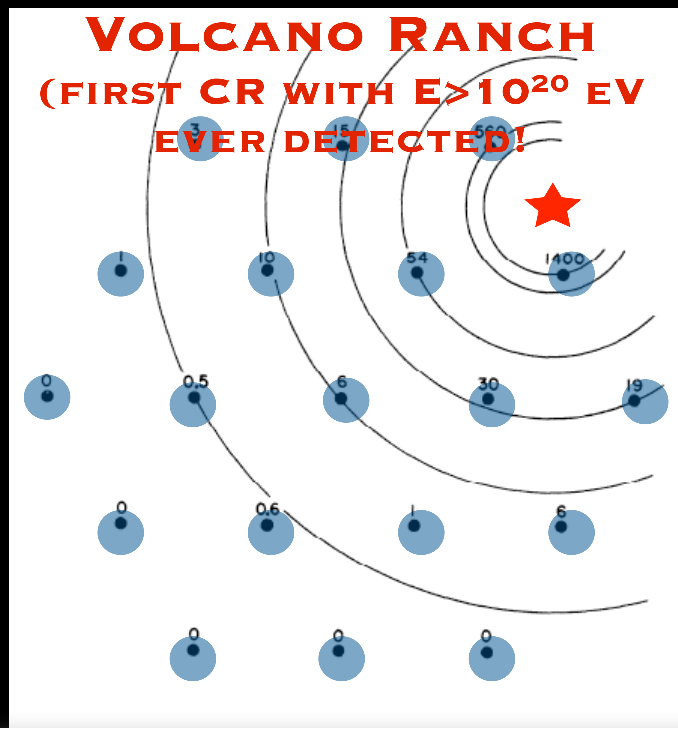


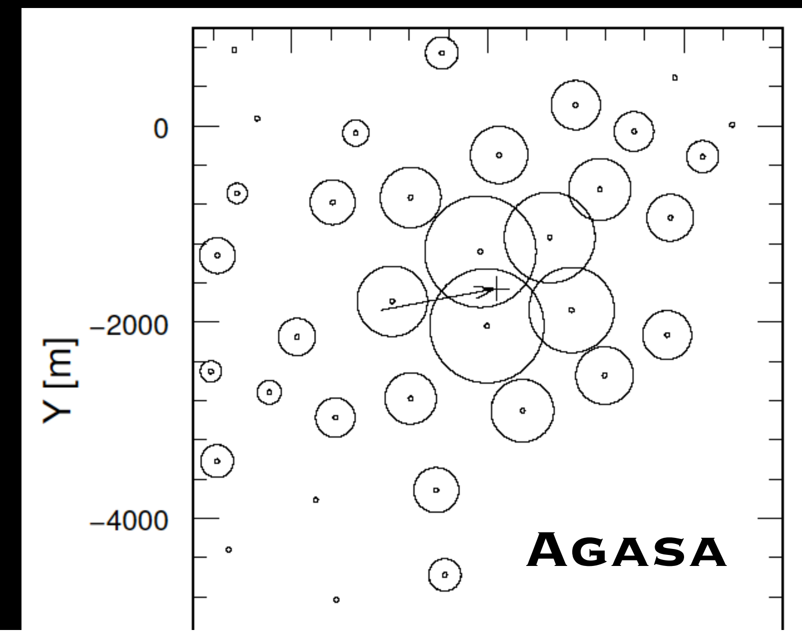
Telescope Array (SD)

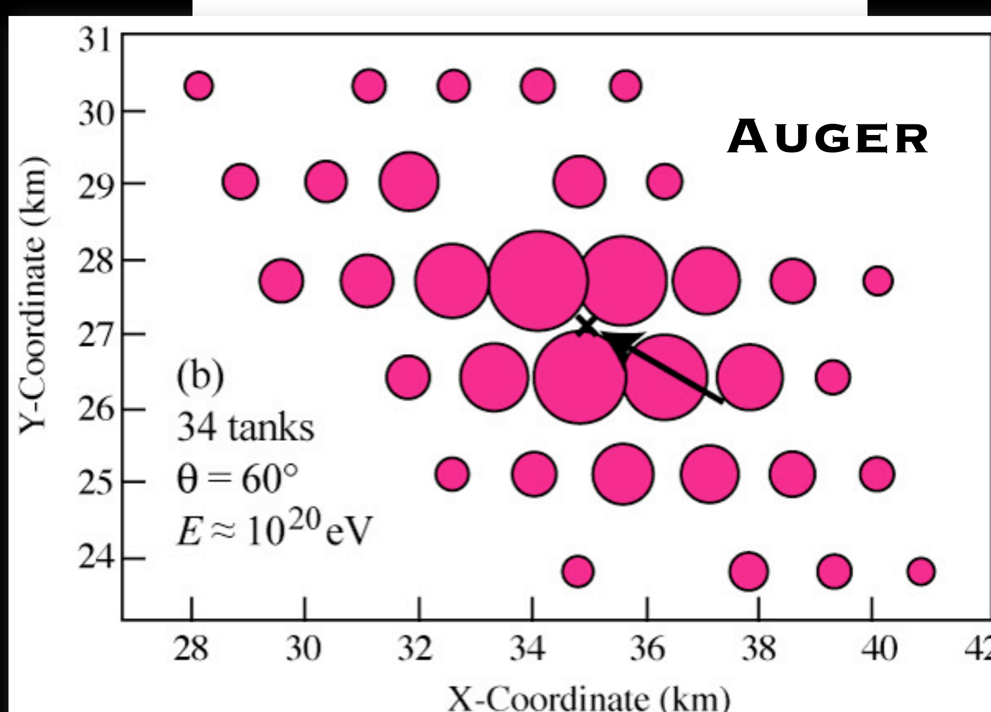


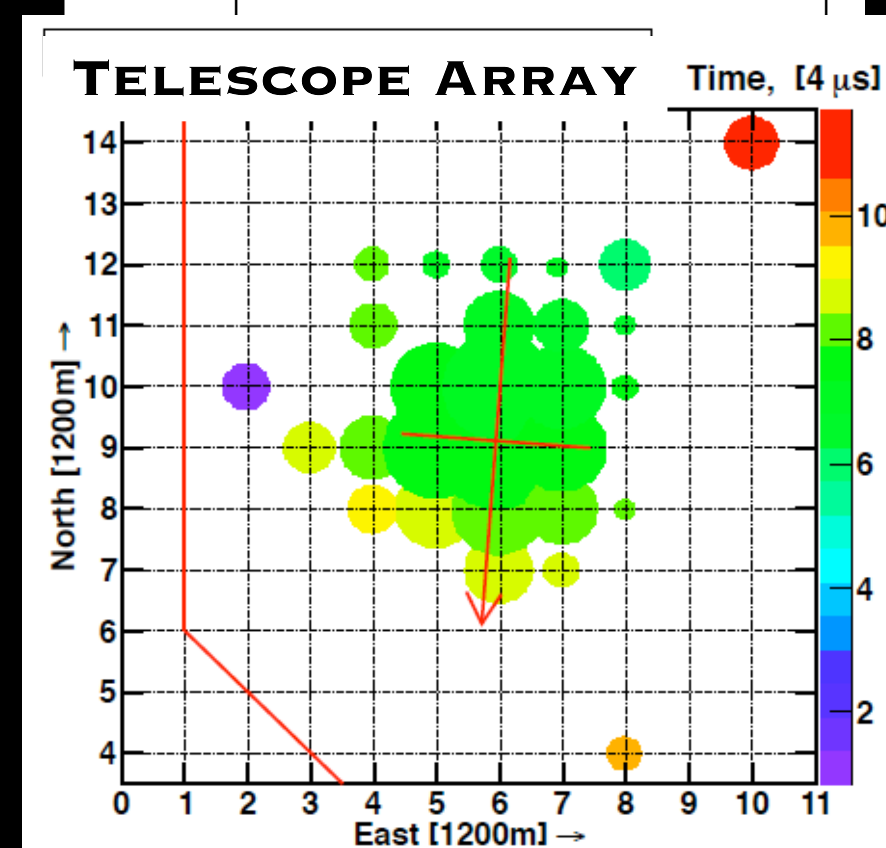
The EAS geometry is even better constrained with hybrid measurements. For both experiments, for hybrid events, the angular resolution improves to ≈ 0.5°

From EAS particles at ground to primary CR *energy*







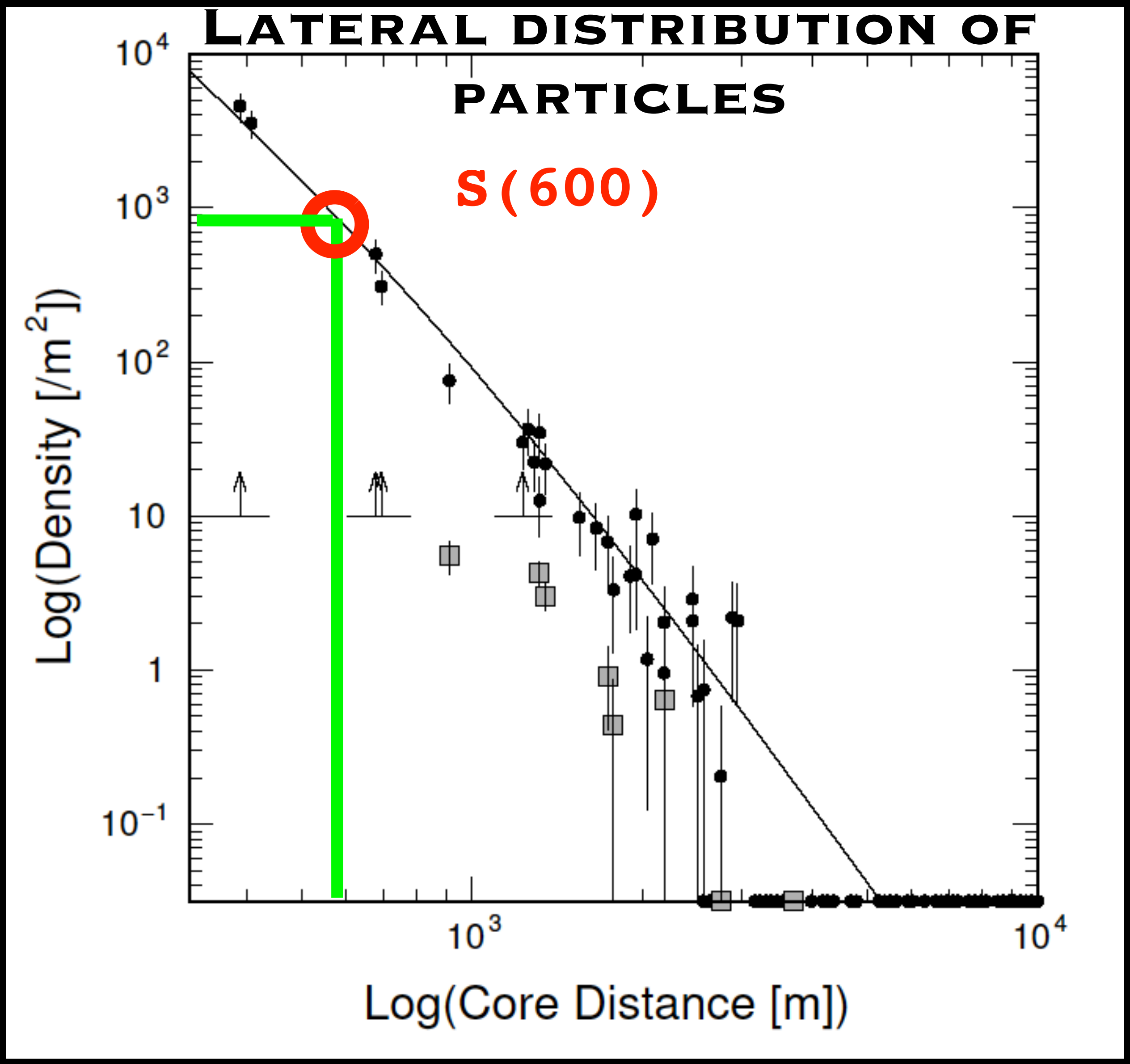


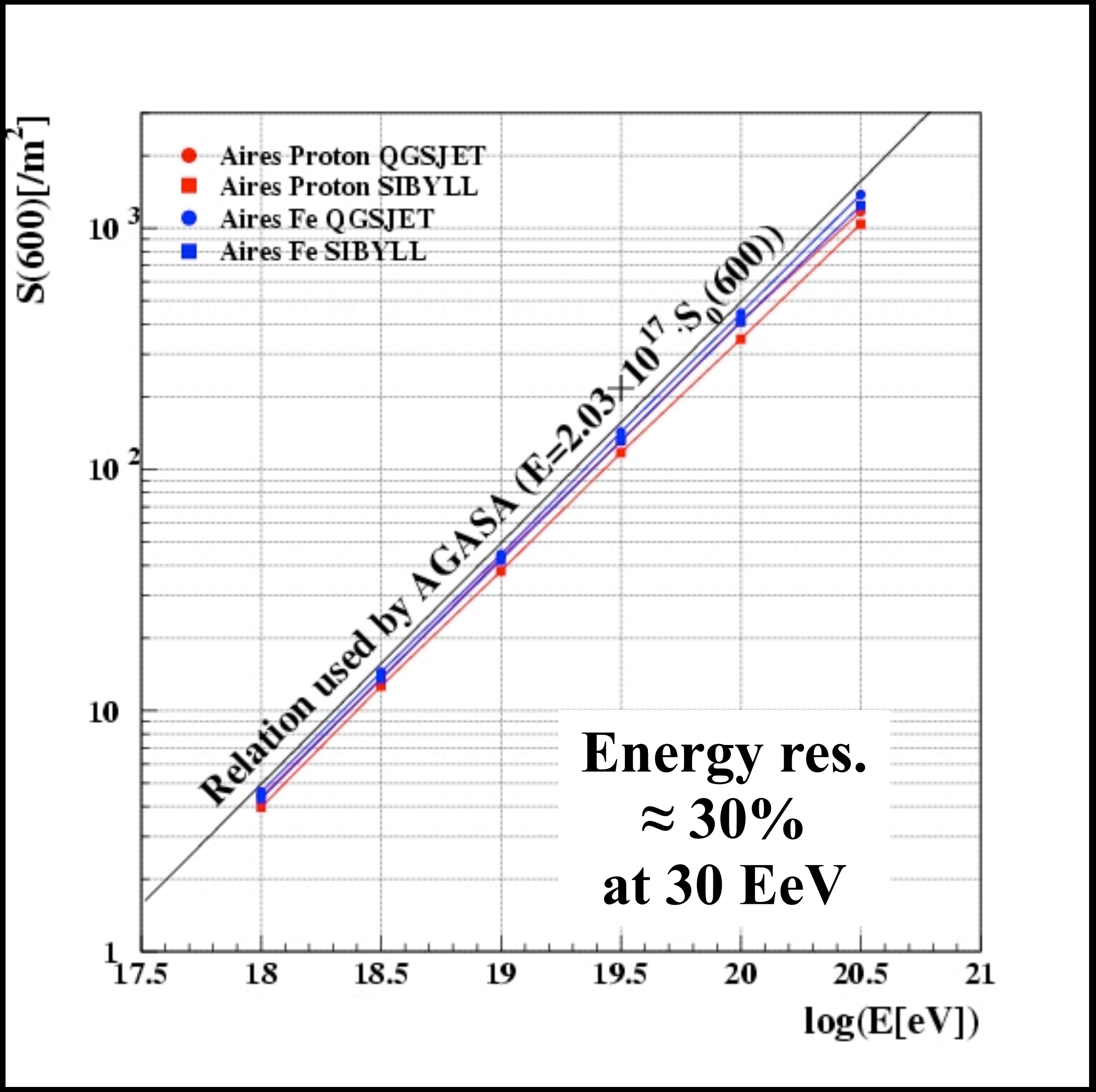
SD samples EAS at fixed depth => the position of depth of shower maximum fluctuates for an event with the same energy and atomic mass.

Summing the total particle density at observation level is inadequate to get the primary energy

From EAS particles at ground to primary CR *energy*: the past

Agasa





Energy estimator == signal @ fixed (large) core distance S(R) [Hillas]

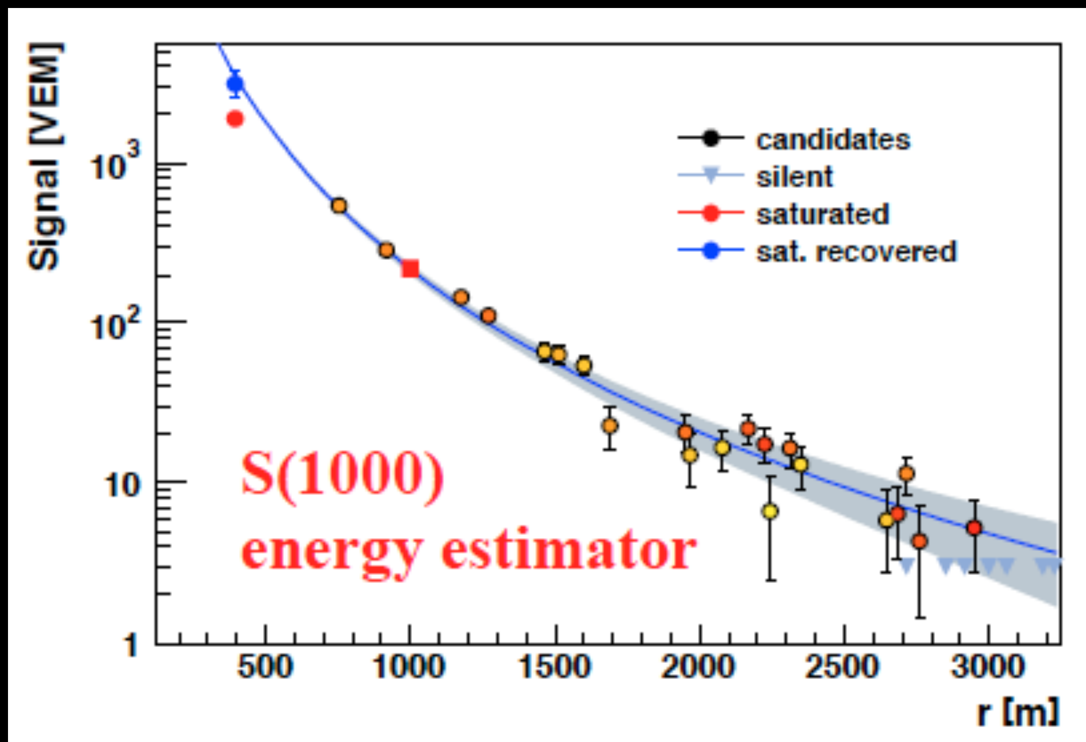
AGASA: Determination of particle density -> LDF -> S(600)

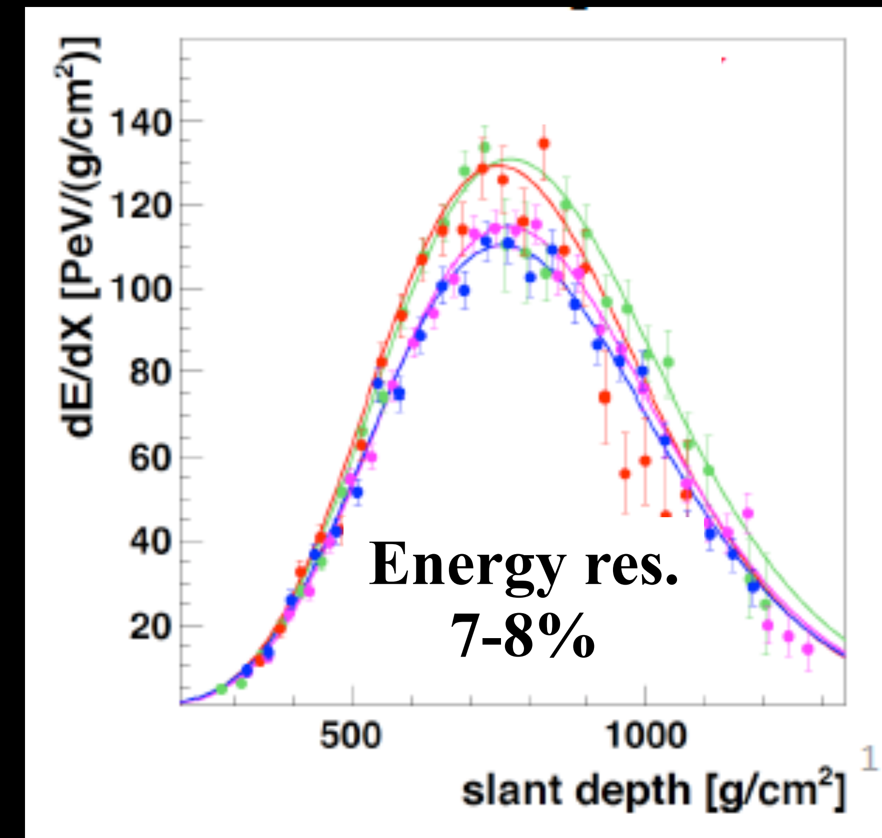
Conversion of S(600) by using cascade models

Largest source of uncertainty: extrapolation of hadronic interactions features from low-energies

From EAS particles at ground to primary CR *energy*: the present

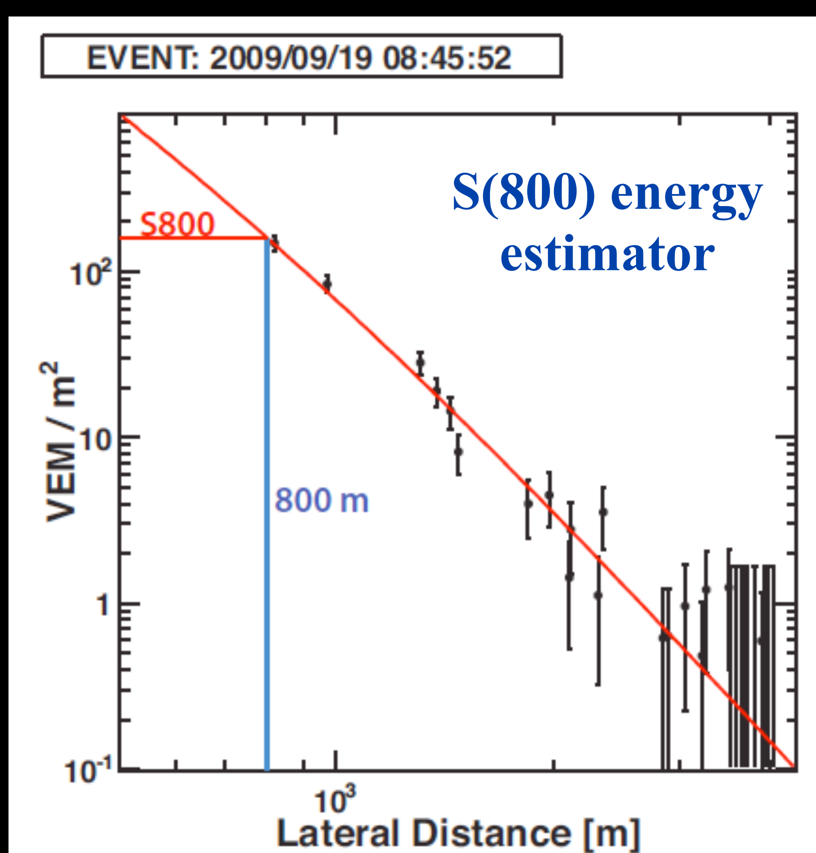
AUGER

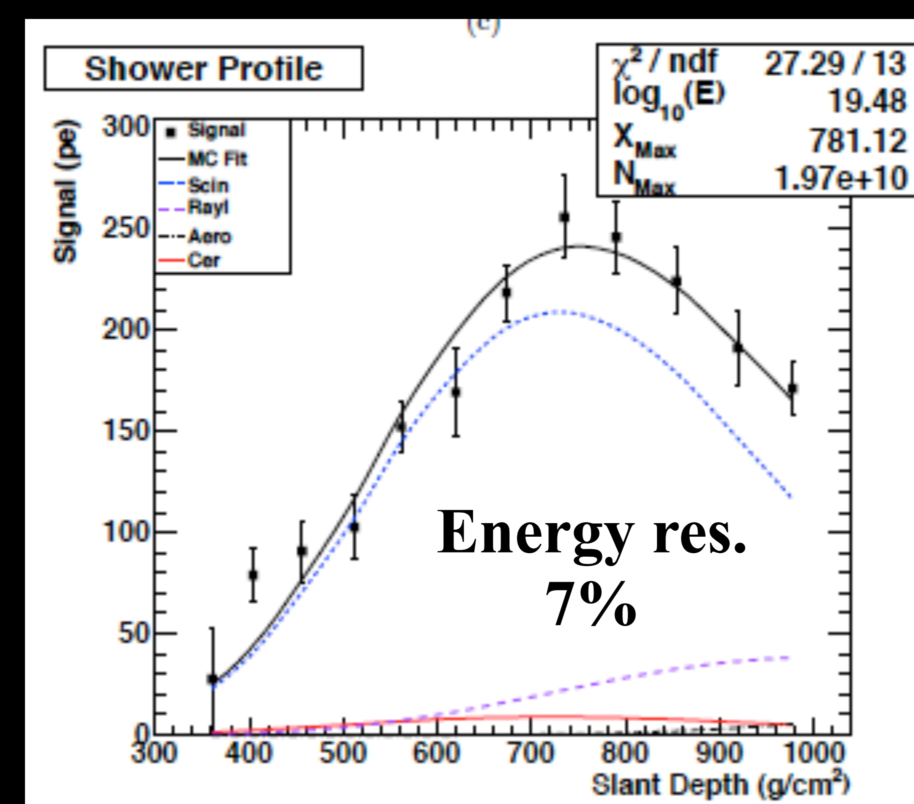




HYBRID EVENTS: CALIBRATION OF SD ENERGY ESTIMATOR WITH FD CALORIMETRIC ENERGY

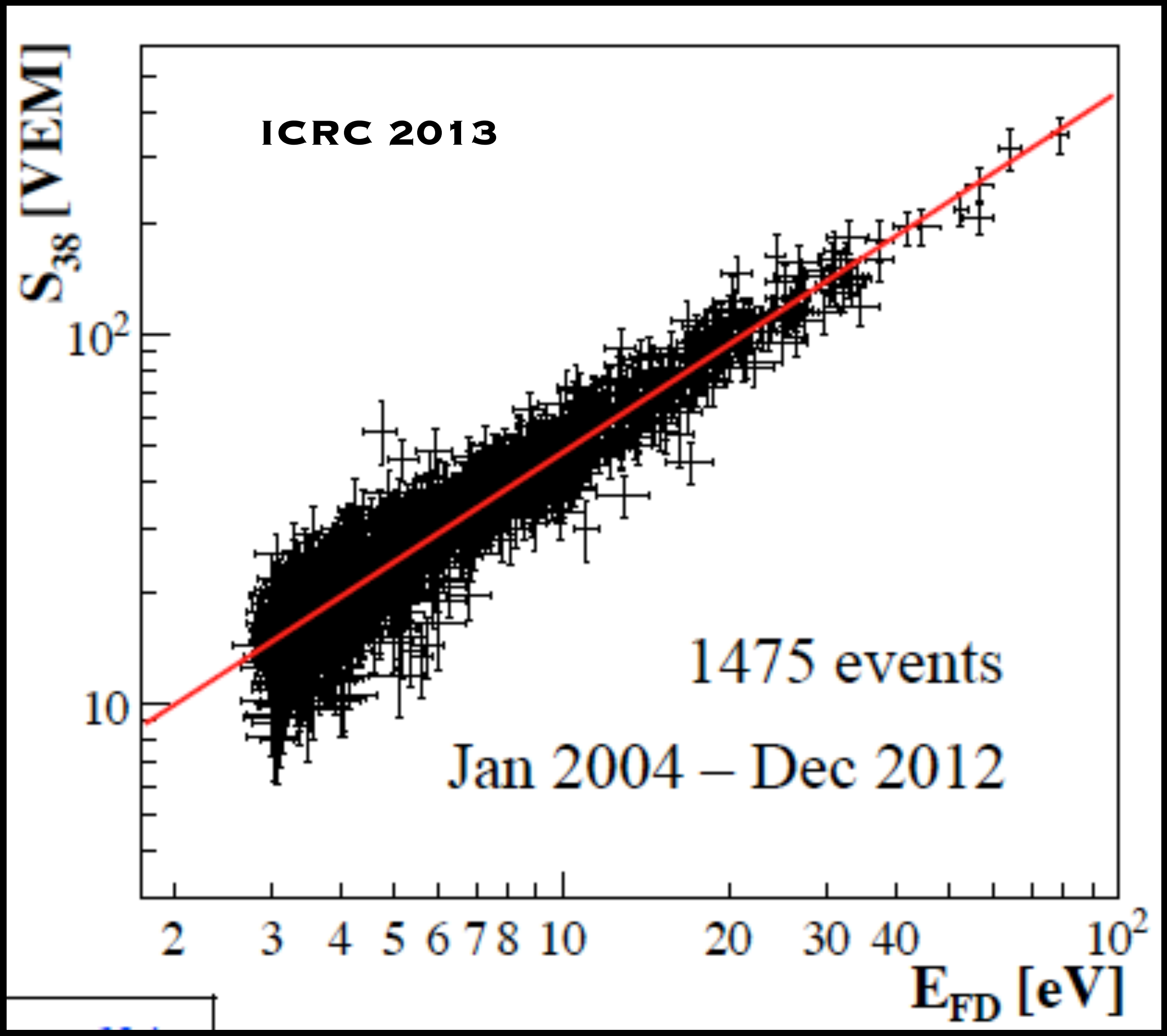
TELESCOPE ARRAY





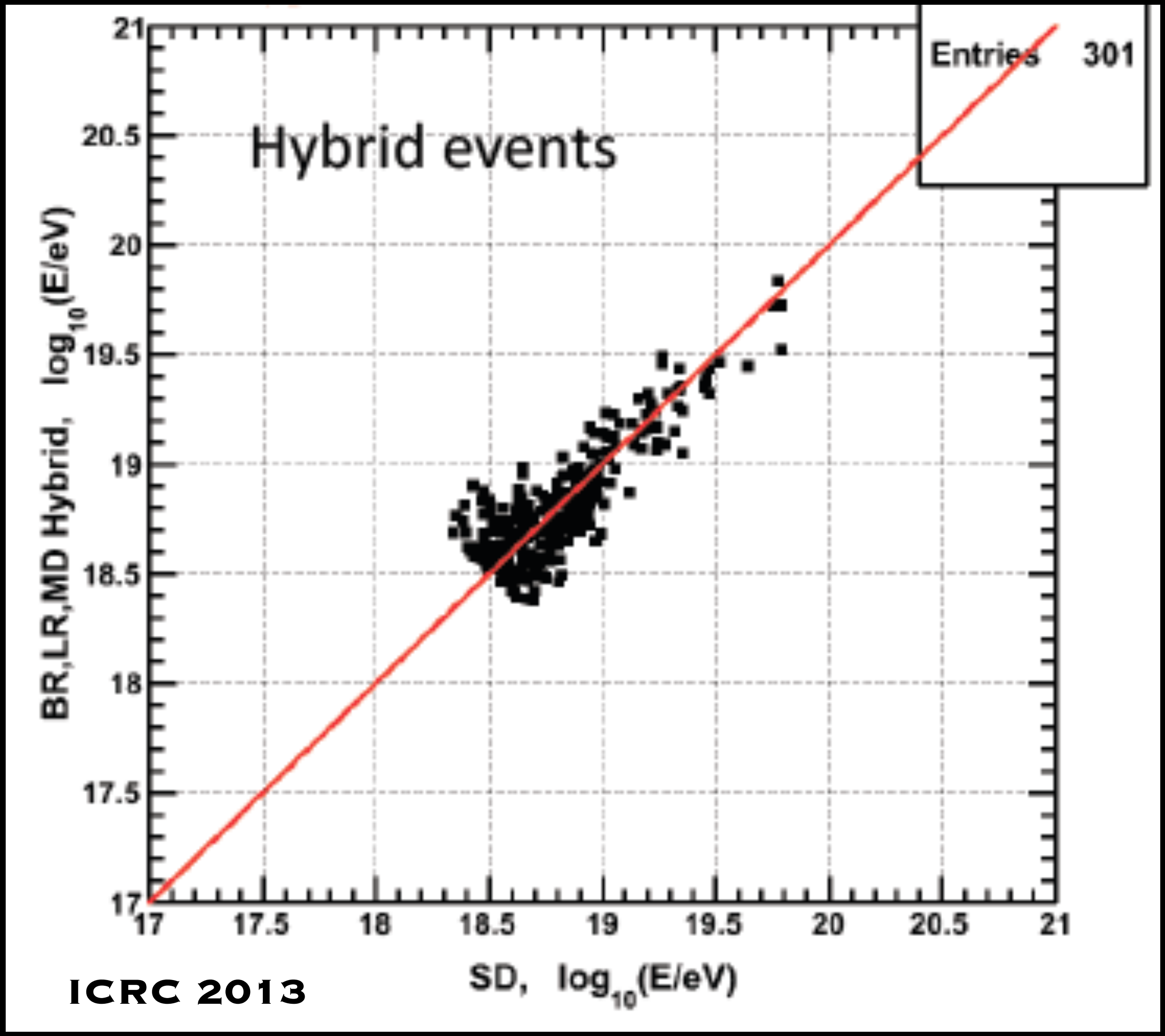
From EAS particles at ground to primary CR *energy*: the present

Auger



Purely data-driven calibration
S(1000) is corrected for attenuation/theta (Constant Intensity Cut) -> S38
S38 is calibrated versus EFD

Telescope Array



S(800) is converted to energy E(S800,theta) through a MC look-up table
The model dependence is removed via the calibration with EFD
The S(800) energy scale requires a downward scaling of 27%

From EAS particles at ground to primary CR *energy*: the present

Auger

Systematic uncertainties on the energy scale	
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 cal. fit	0.7%-1.8%
Stability of the E scale	5%
TOTAL	**14%**

SD energy statistical uncertainty (@10 EeV) ≈ 12%

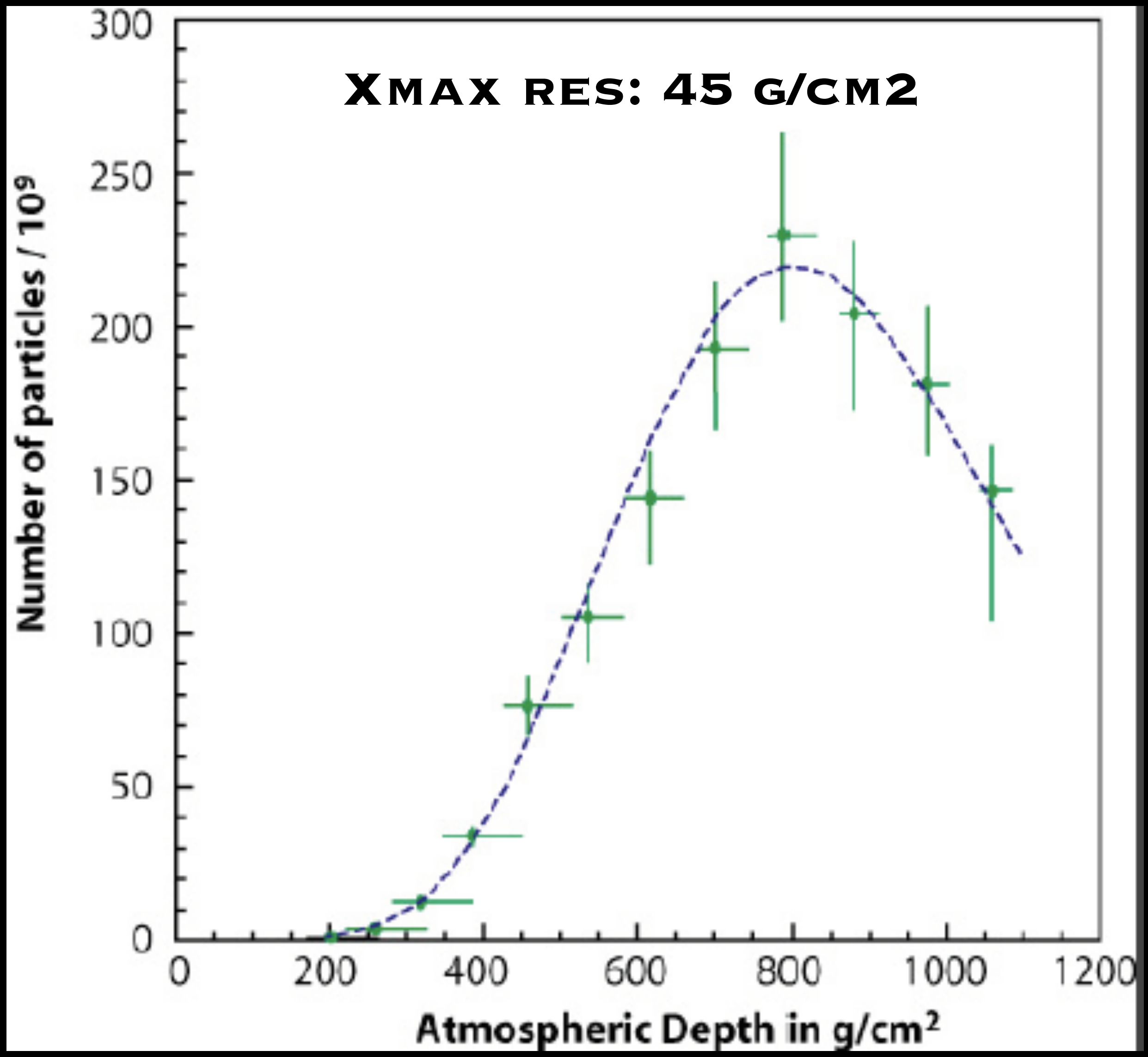
Telescope Array

Systematic uncertainty in energy determination	
Fluorescence yeild	11%
Atmospheric attenuation	11%
Absolute detector calib.	10%
reconstruction	10%
total	21%

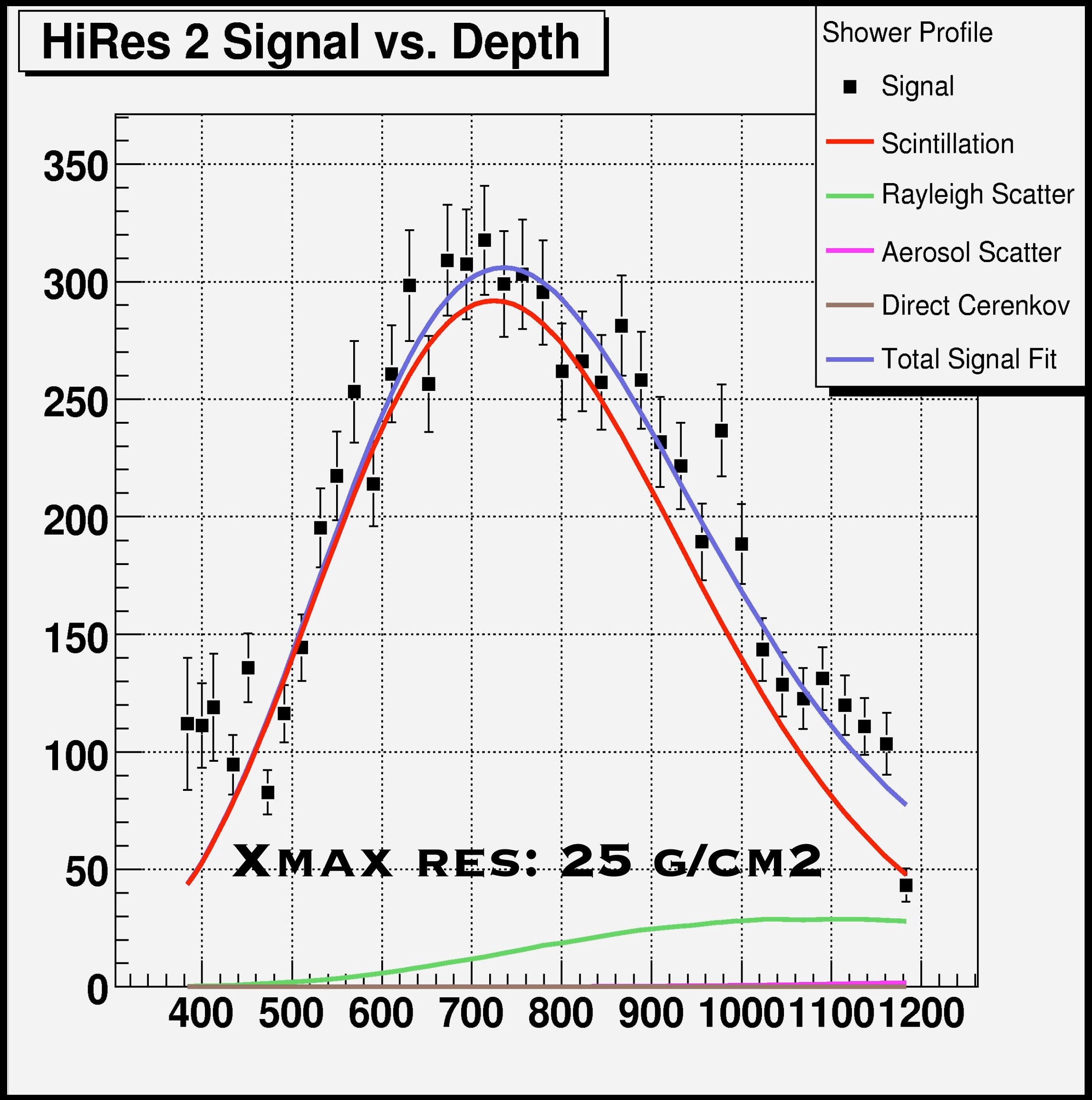
SD energy statistical uncertainty (@10 EeV) ≈ 17%

From EAS longitudinal profile to Xmax: the past

Fly's Eye



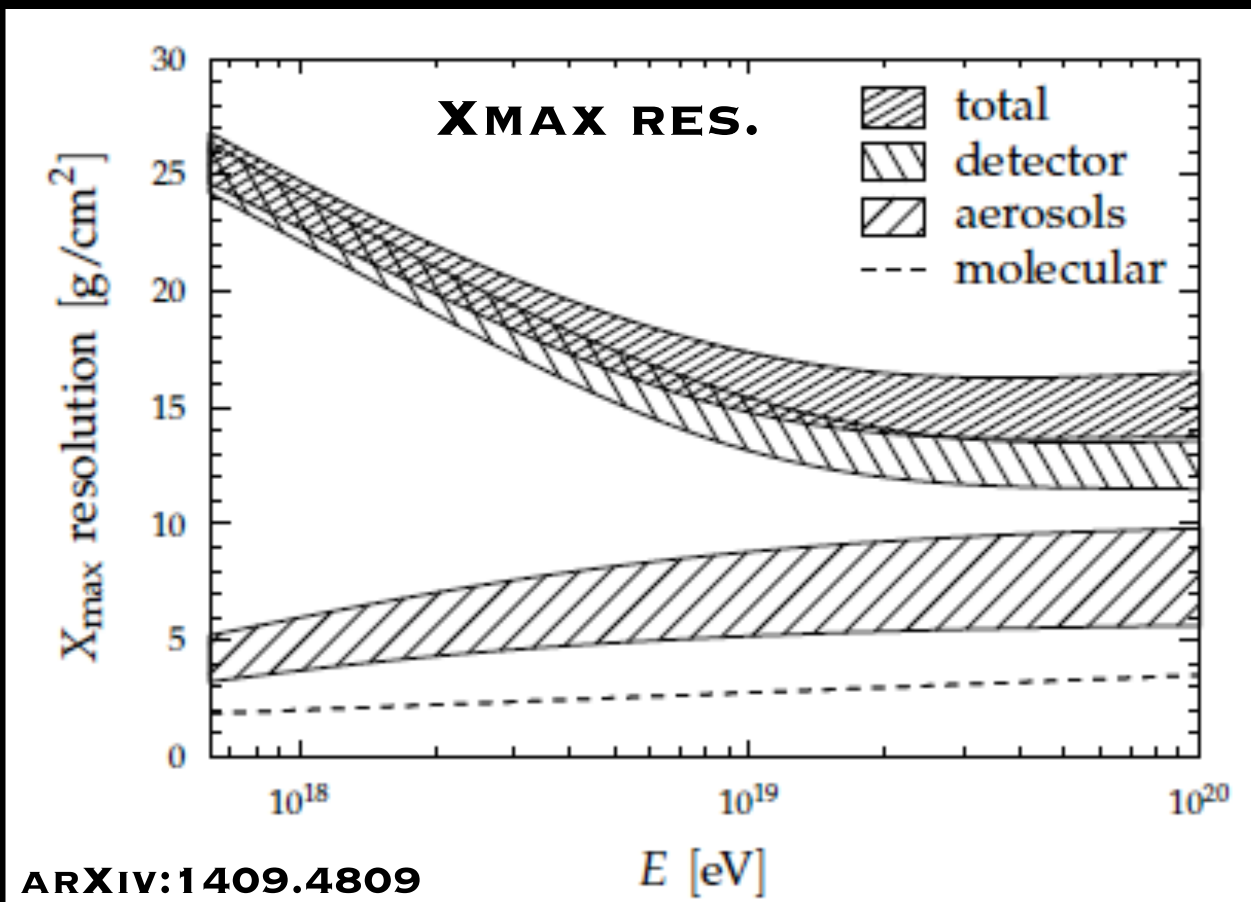
HiRes



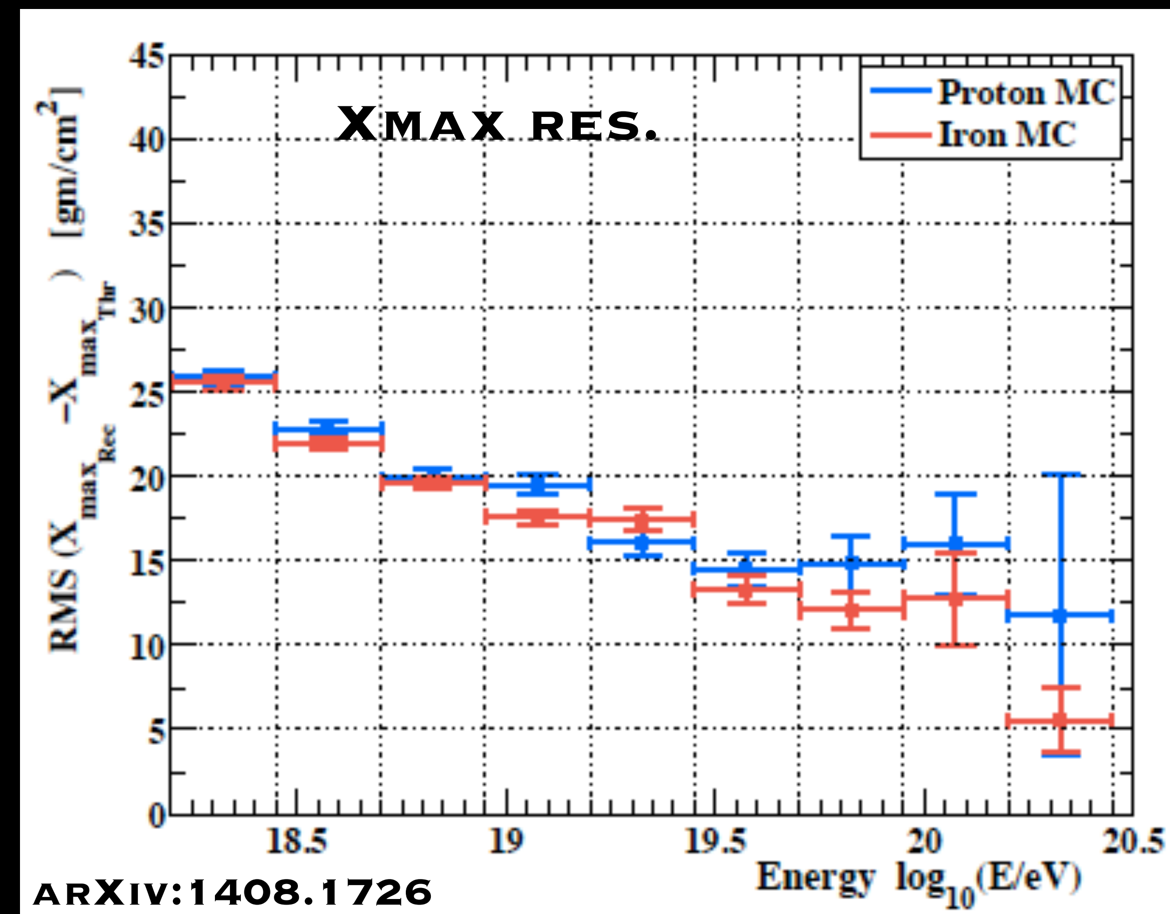
accessibility of Xmax through fluorescence proved by Fly's Eye

From EAS longitudinal profile to Xmax: the present

Auger



Telescope Array



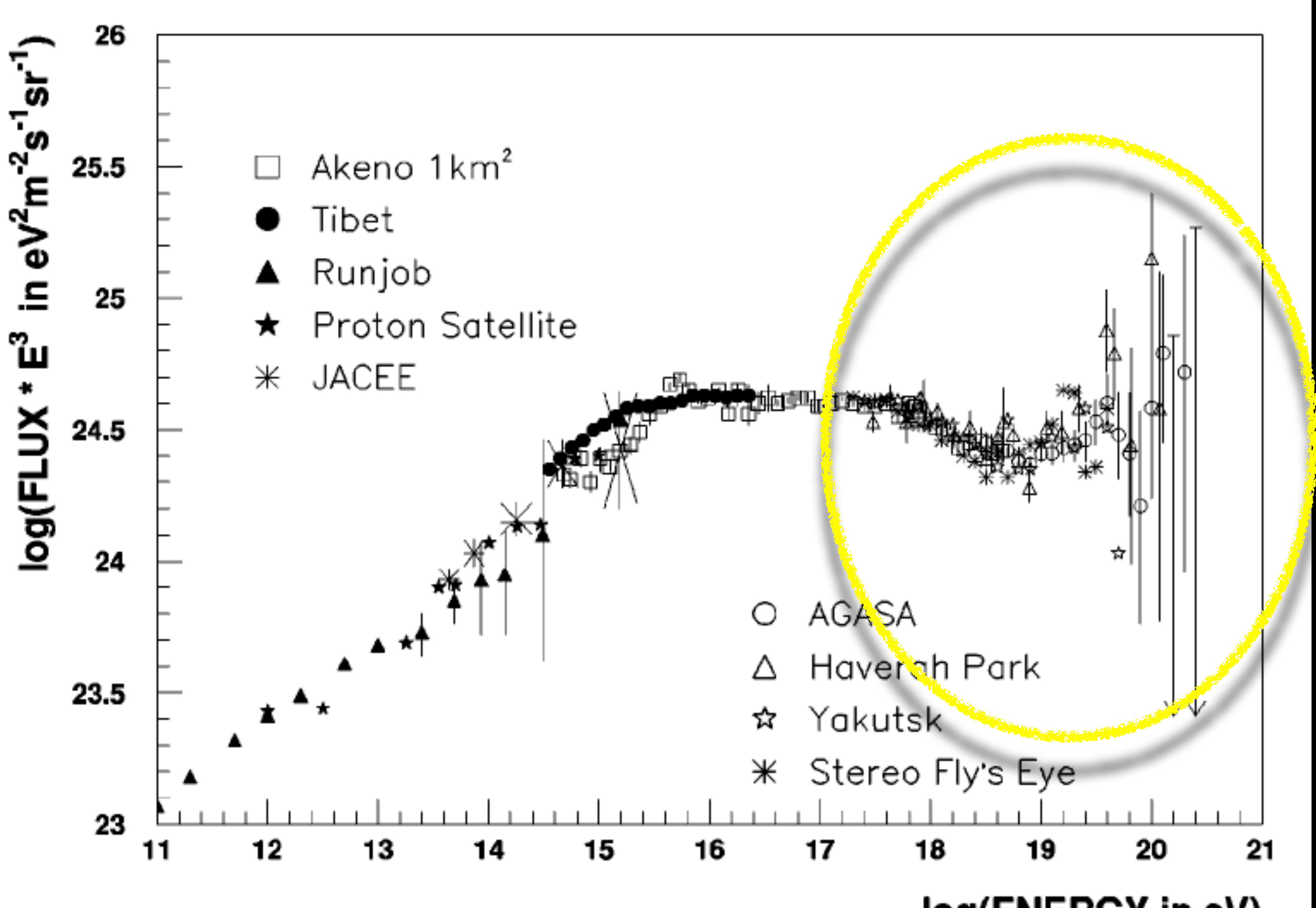
Xmax resolutions improved thanks to the hybrid technique.
Between 25 and 15 g/cm2, getting better with increasing energy

Systematic uncertainty ≈ 10%

Systematic uncertainty ≈ 16%

Advances in inferences on UHECRs
(energy spectrum, mass composition and origin)

UHECR spectrum in 2000

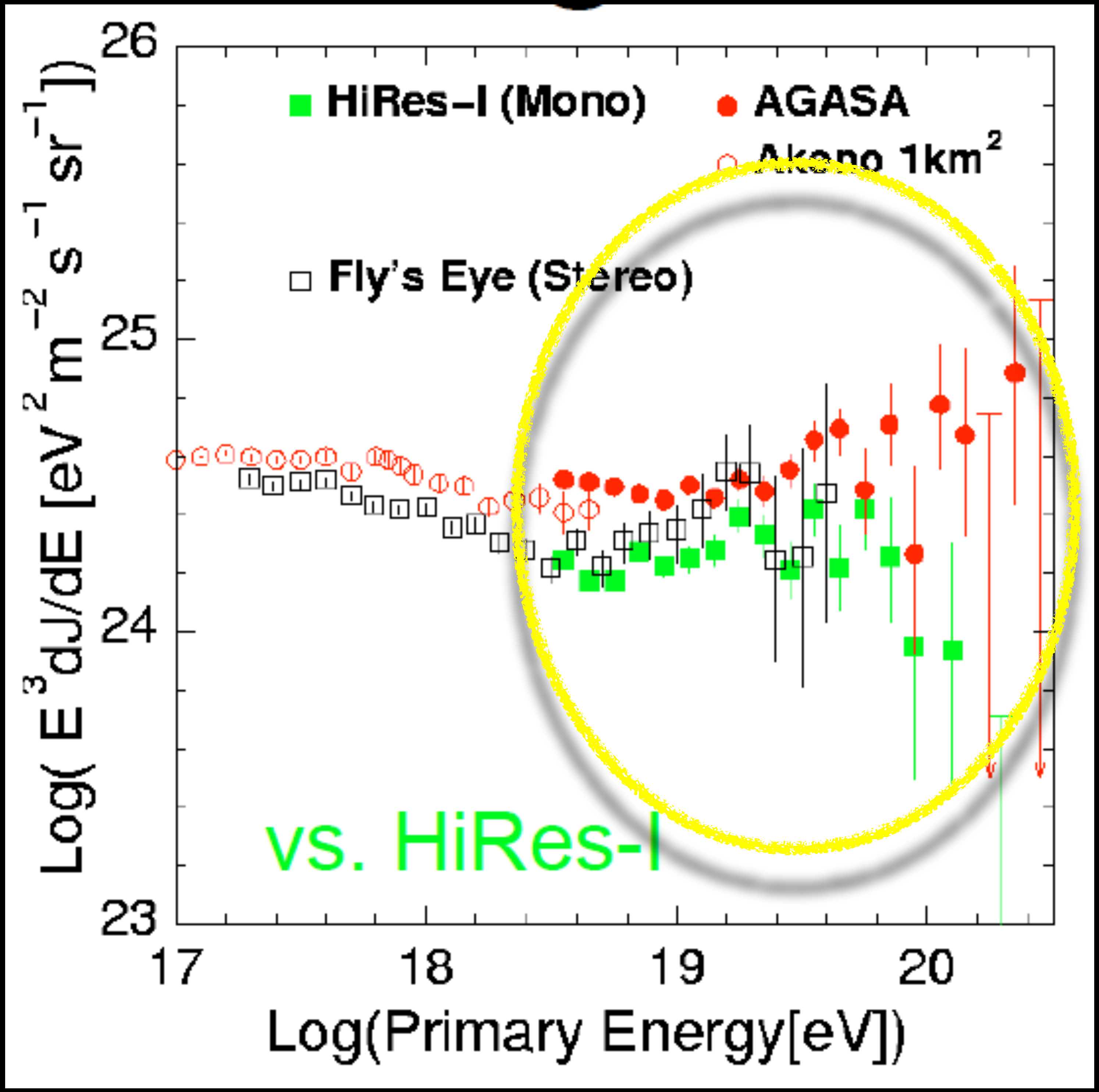


FROM NAGANO-WATSON, 2000

APPEARANCE OF AN "ANKLE" AT FEW EEV

NO FLUX SUPPRESSION ABOVE 50 EEV? (AGASA, HP)

UHECR spectrum in 2003

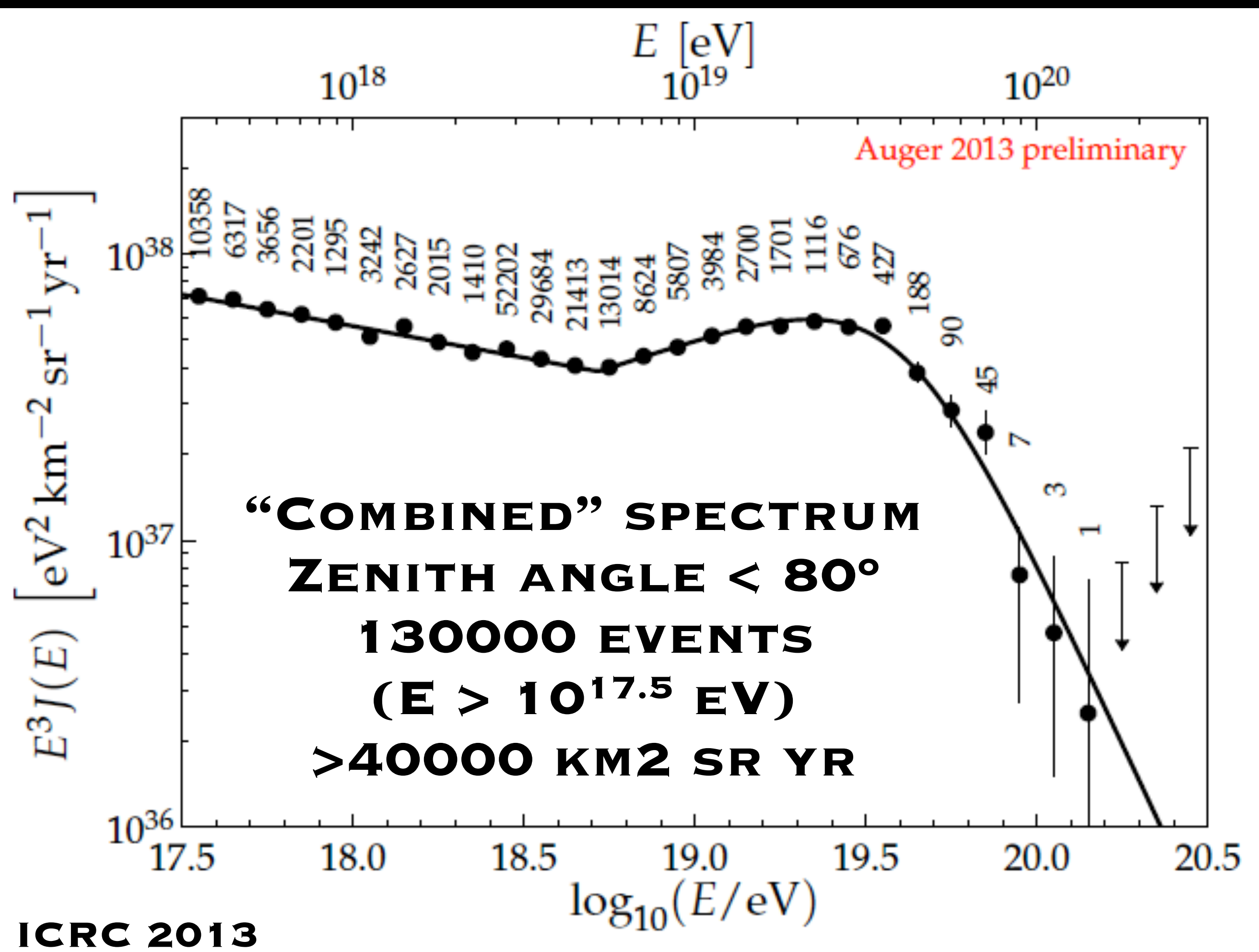


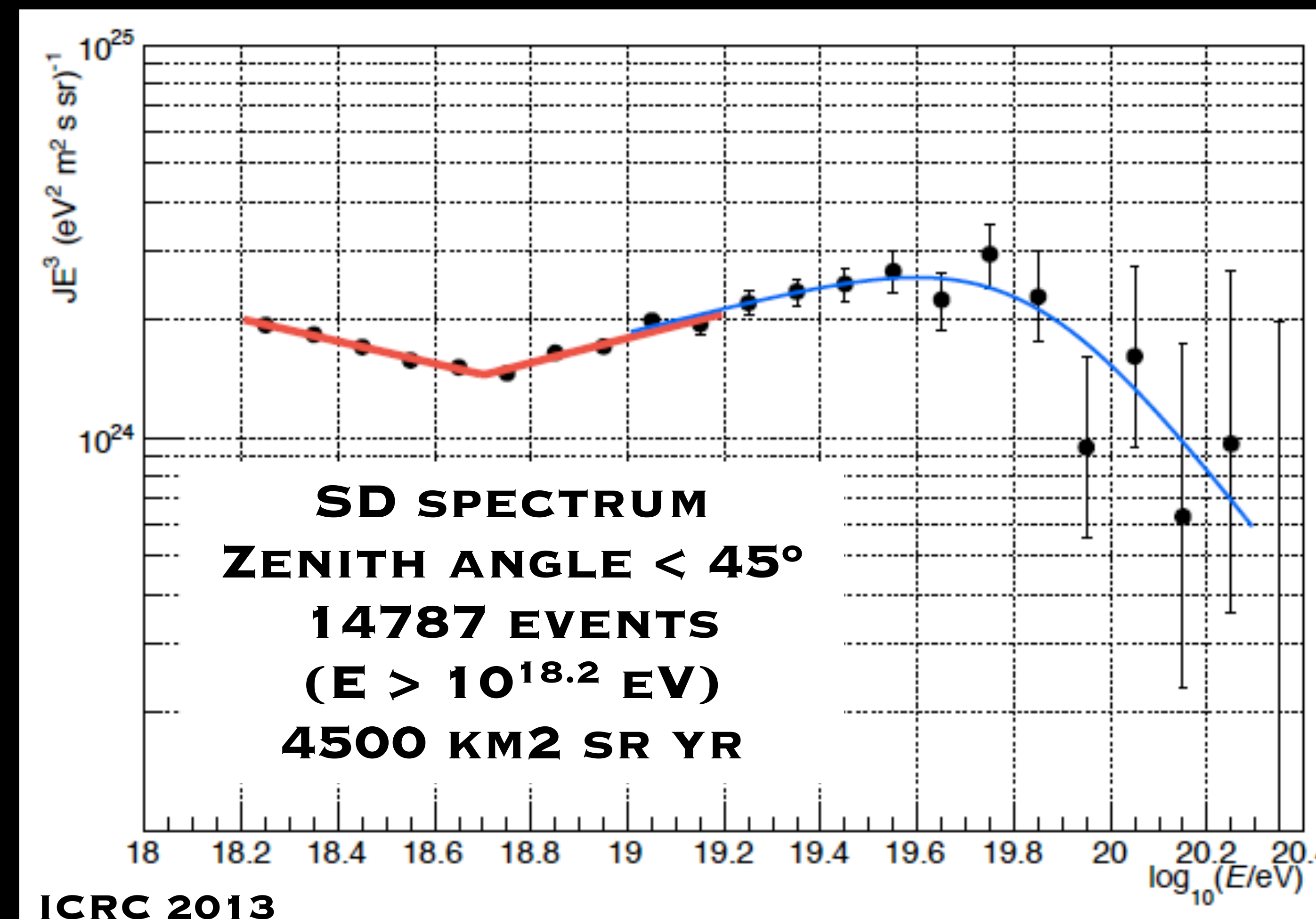
First results from HiRes (ICRC 2003)
discrepancy between AGASA and HiRes

UHECR spectrum now

AUGER

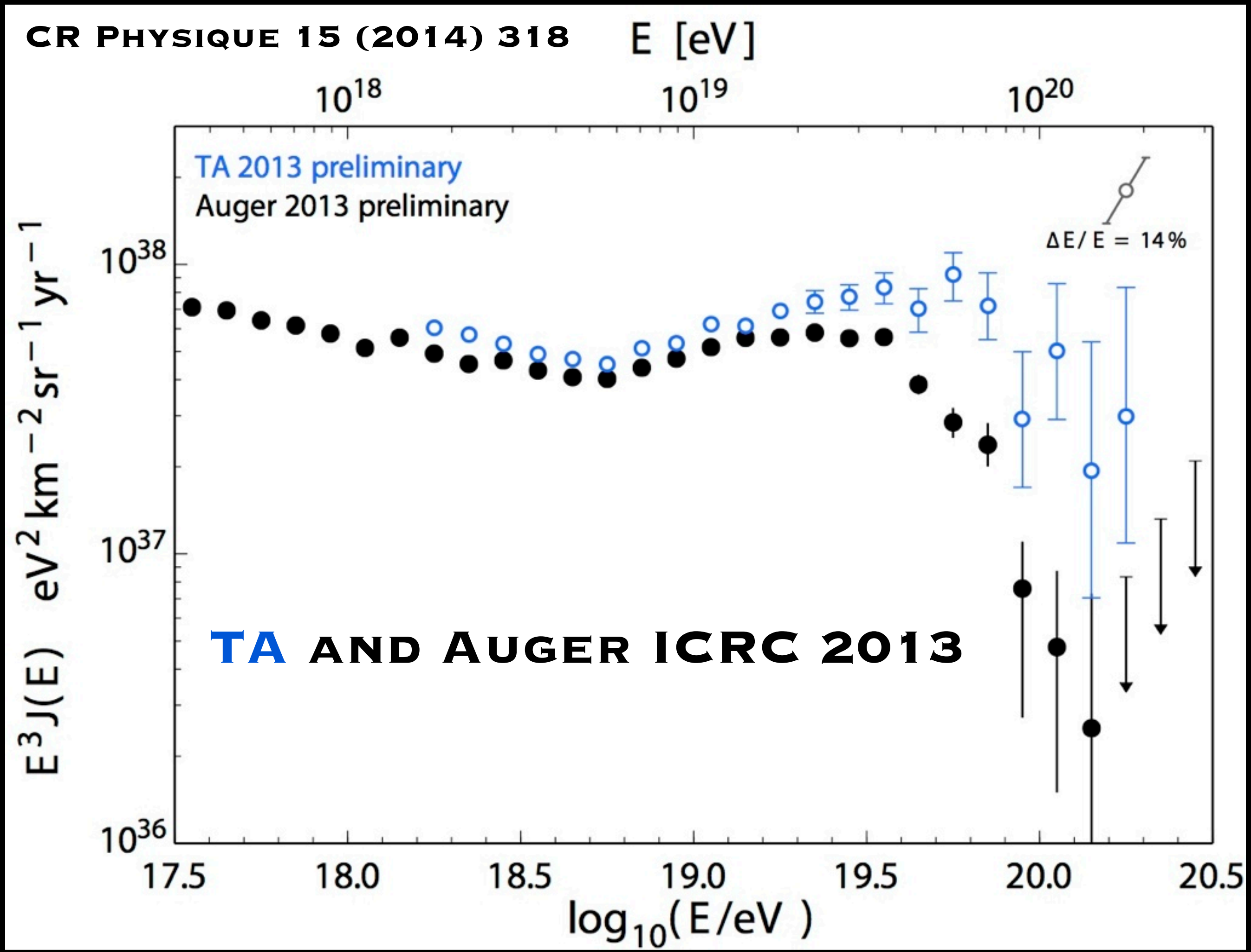
TELESCOPE ARRAY





Clear evidence of an “ankle” at ≈ 5 EeV
Clear observation of a flux suppression at ≈ 40 EeV
(observed by HiRes too, PRL 100 (2008) 101101)

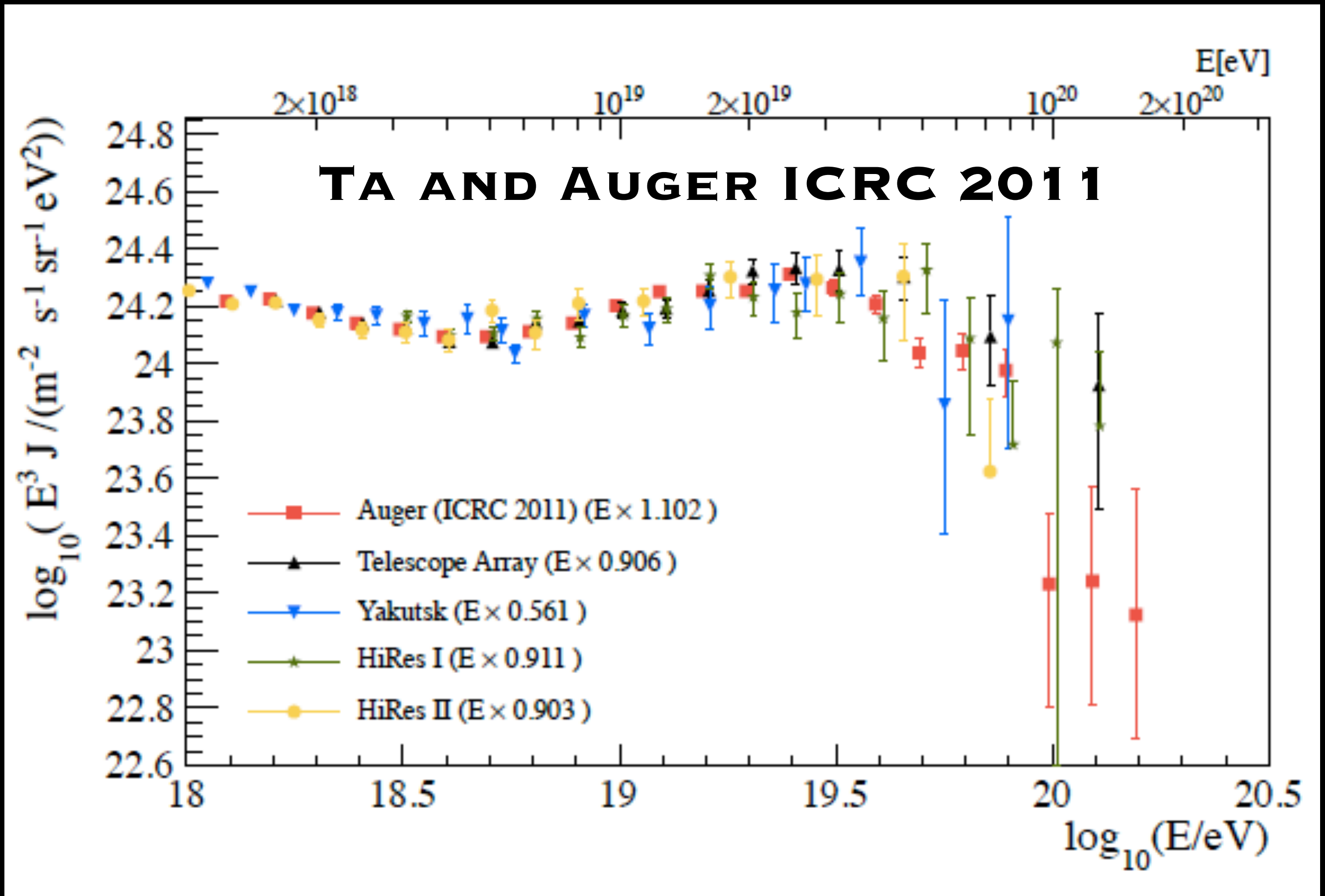
UHECR spectrum now: TA and Auger working together



Auger and TA spectra compatible account taken of relative systematic uncertainties of the two energy scales.

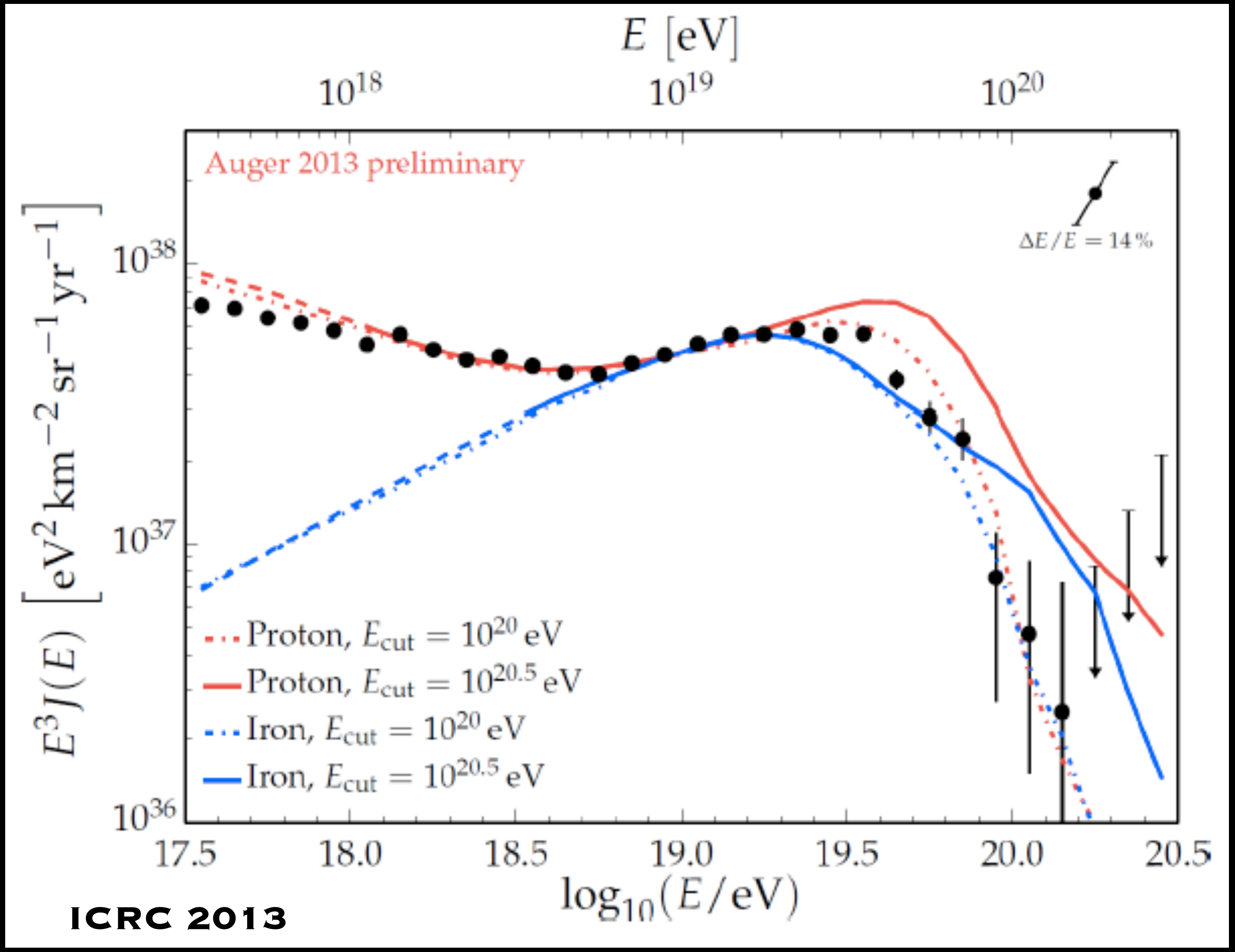
Very good agreement on the ankle.
Auger start of the suppression at slightly lower energy, and falls more strongly than that of TA

Work in progress in a TA/Auger joint working group to compare the two spectra, like it was done earlier (ArXiv 1306.6138)

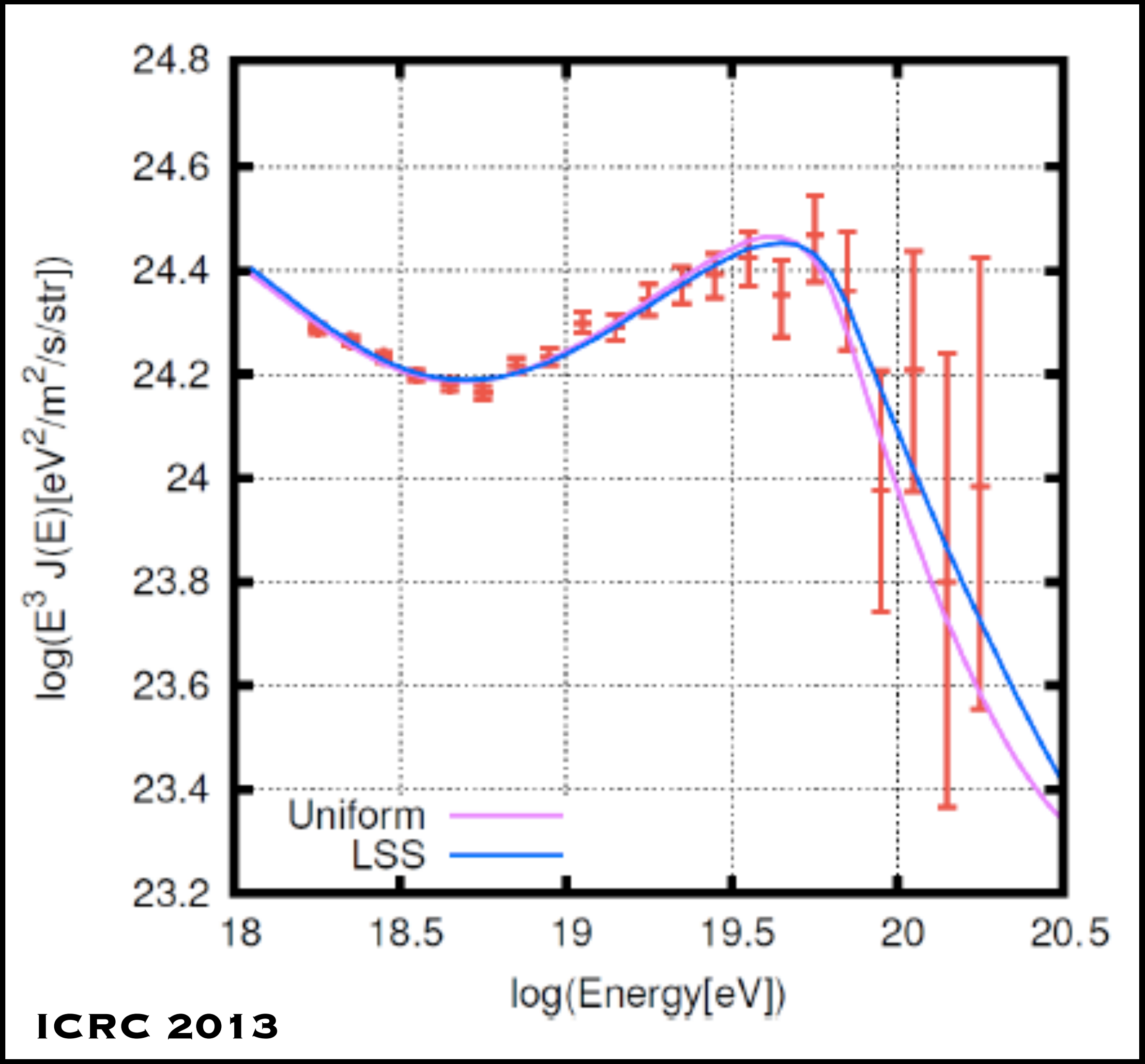


UHECR spectrum now

Auger



Telescope Array



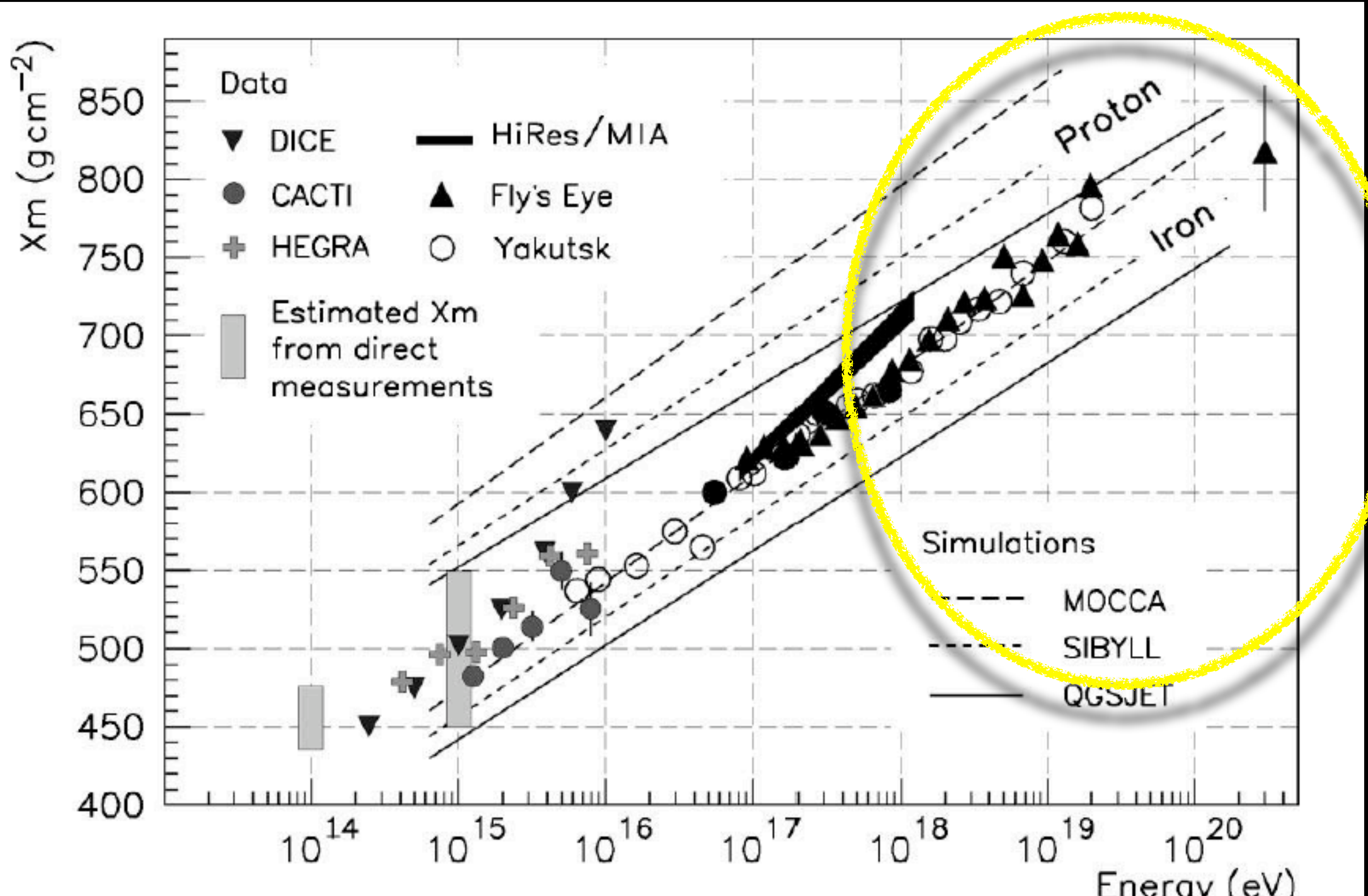
Comparison to pure proton and iron injection (gamma ≈ 2.3) and different cutoff at the source Emax = $10^{20.5}$ eV and 10^{20} eV

Fit to a model with injected proton, assuming a uniform distribution or a distribution following the large-scale structure. Best fit for gamma ≈ 2.4

Measurement of spectra only are not sufficient to fully understand spectral features, that depend on particle spectra (in energy and mass) at the source and their propagation

Mass composition analysis is an essential ingredient

Xmax data in 2000



From Nagano-Watson, 2000

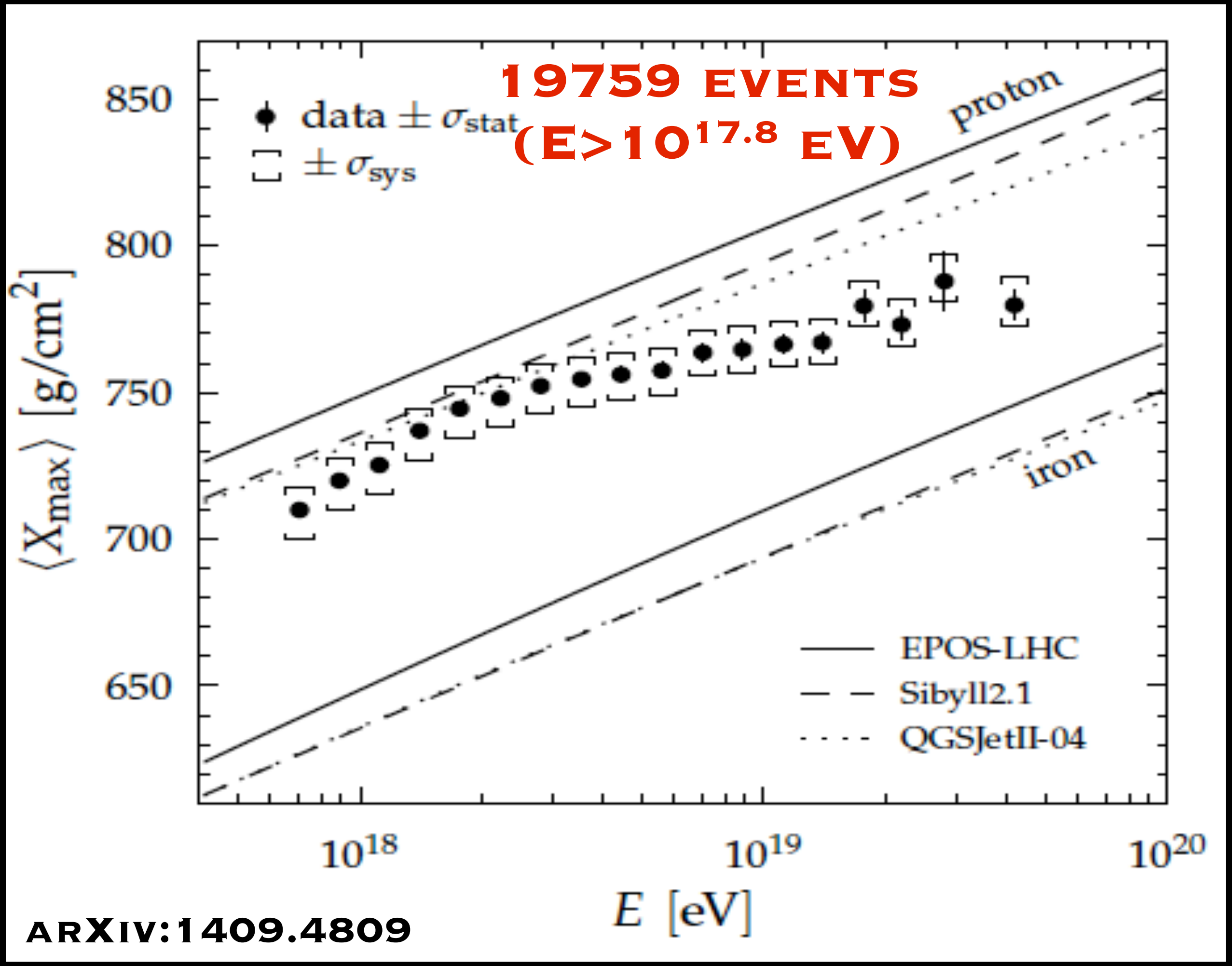
<Xmax>: Paucity of events above 10 EeV

Huge differences between models

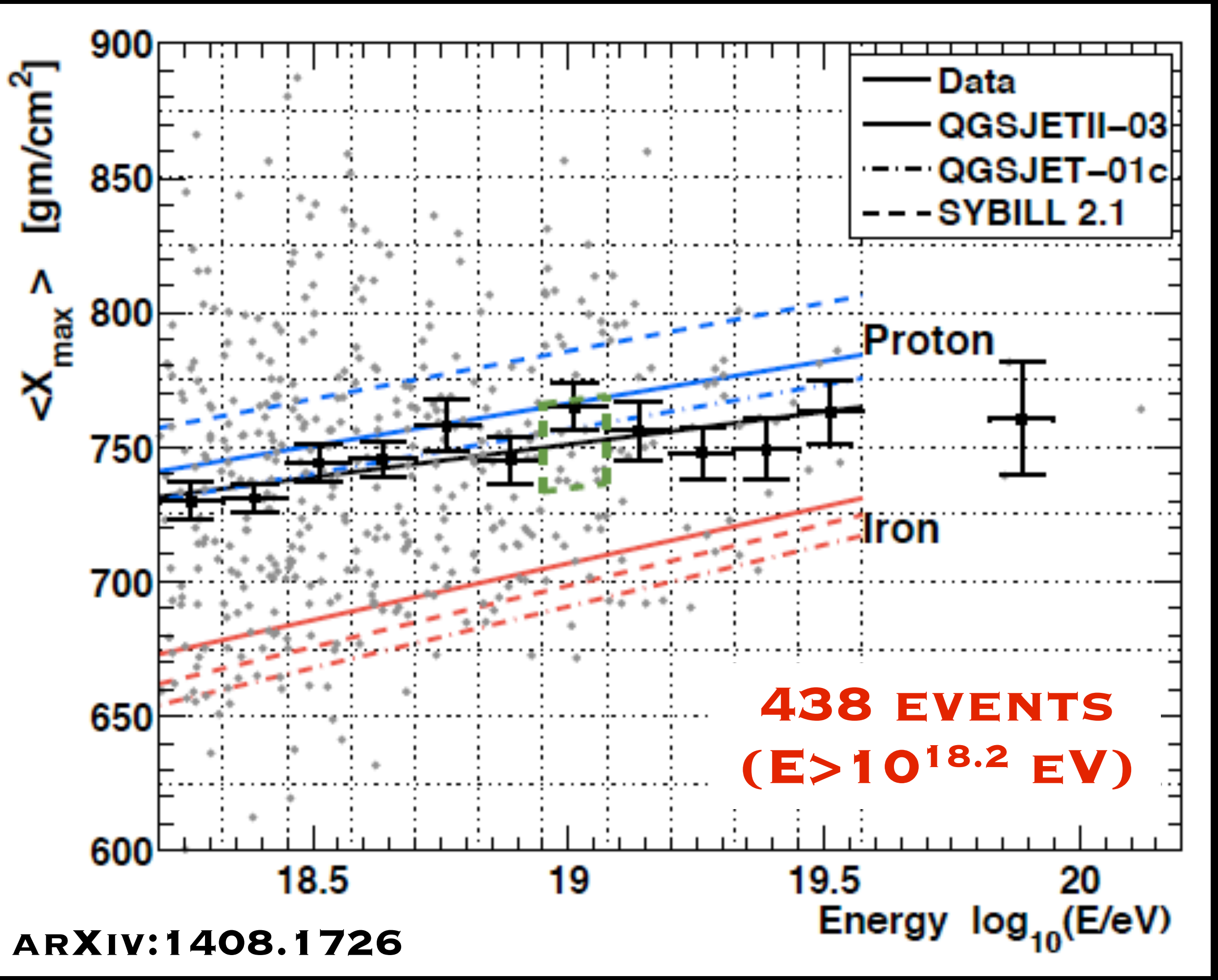
Results difficult to interpret

Xmax data in 2000

Auger:
predominantly light nuclei at ≈ $10^{18.3}$ eV. fraction of heavy nuclei increasing up to energies of $10^{19.6}$ eV.



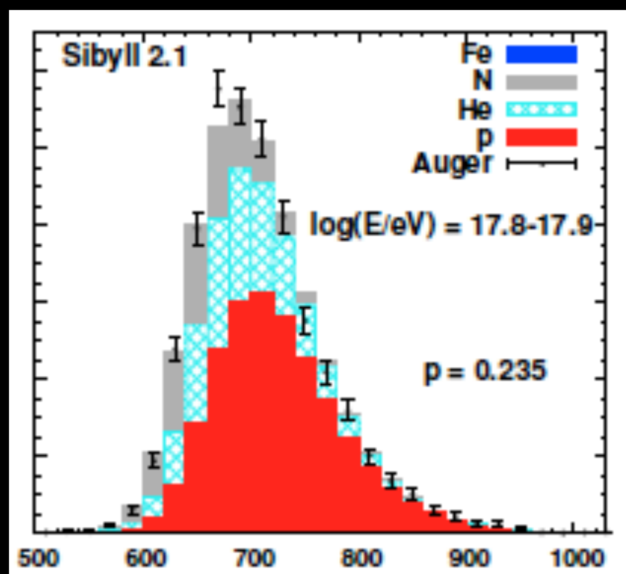
Telescope Array:
light composition, nearly protonic, in good agreement with data.



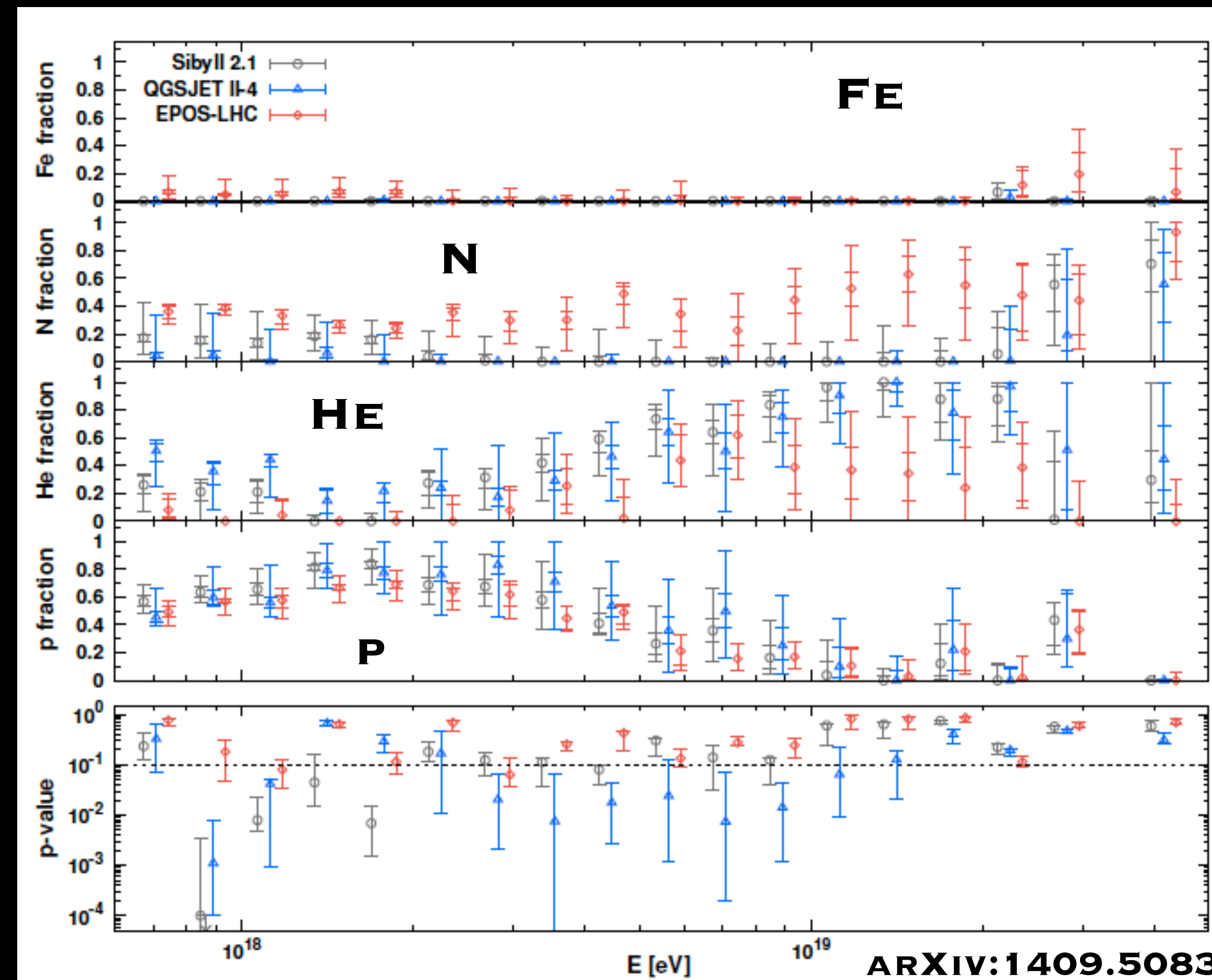
CAVEAT on a direct comparison of datapoint and models
Different treatment of data (bias-free due to fiducial-volume cuts in Auger, acceptance bias in data and model in TA)
Different models used by Auger (post-LHC) and TA (pre-LHC)

Xmax data in 2014: Auger and TA working together

Auger composition mixture
(see I. Lhenry's talk on Wed)

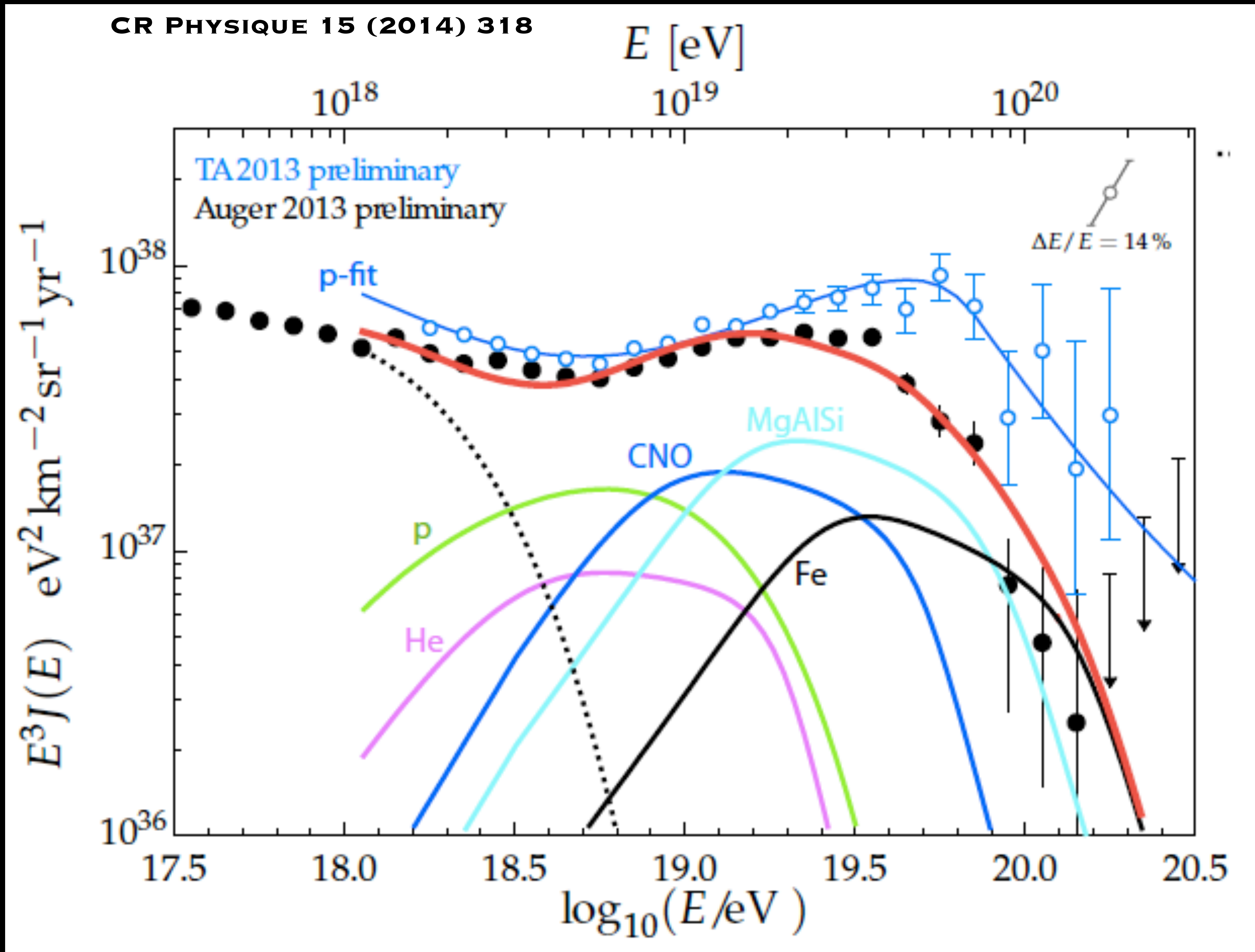


Analysis of Xmax distribution, for each energy bin, in terms of 4-component (p, He, N, Fe) mixture, for different hadronic interaction models



On-going comparison in the TA/Auger WG on mass composition (method in arXiv: 1310.0647) using a set of simulated events from the composition mixture that well-fits Auger Xmax distributions. Such a mix can be injected into the TA hybrid simulation and reconstruction to be then compared to TA data.

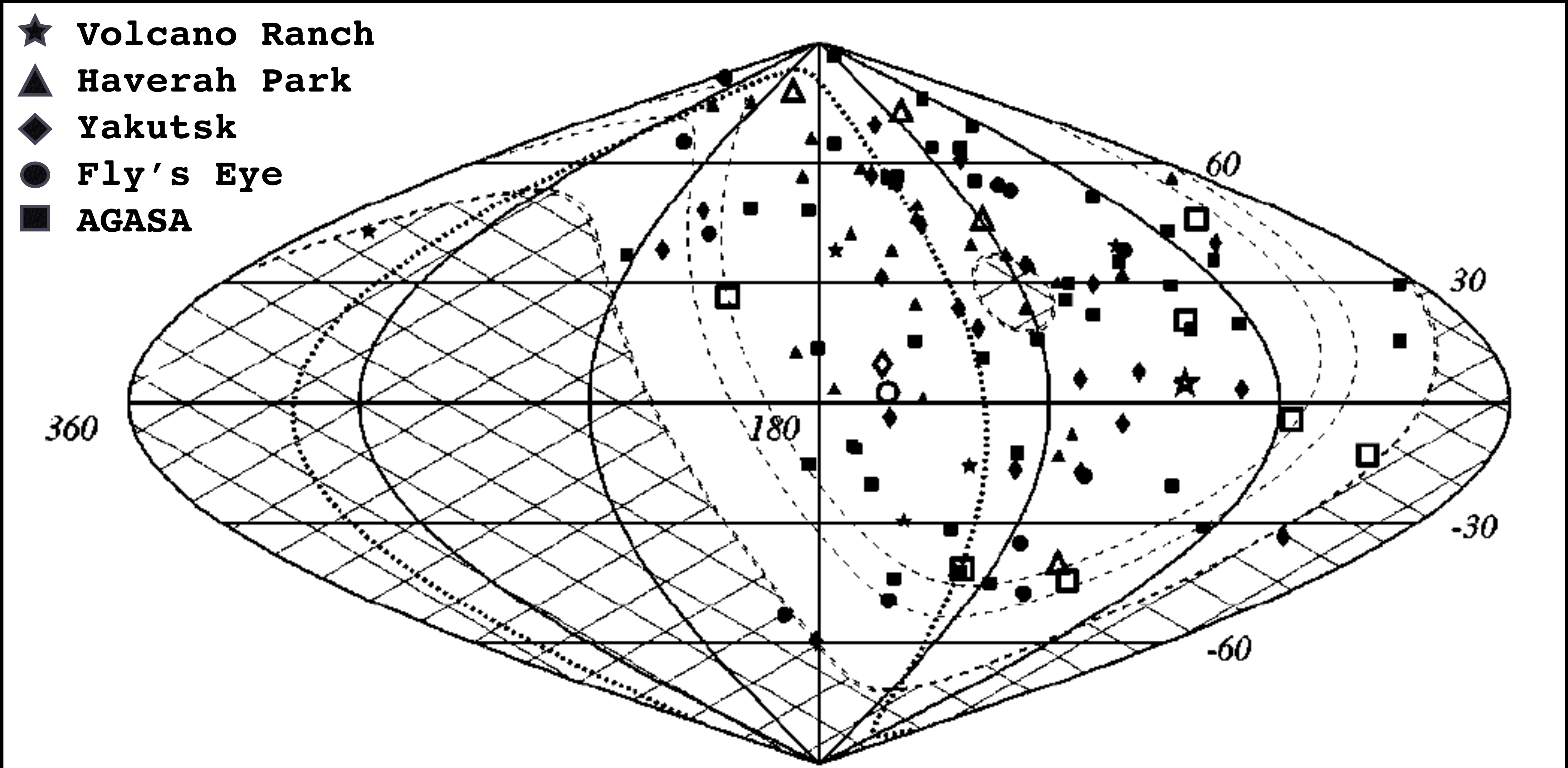
UHECR spectrum now



Even if TA and Auger spectra are compatible within uncertainties, they yield to possible alternative origin of the flux suppression: GZK (propagation) or source limit (Emax of accelerators)?

Emax(p): $10^{18.7}$ eV with a mix of protons and heavier nuclei being accelerated up to the same rigidity, so that their maximum energy scales with Z

Arrival directions in 2000



From Nagano-Watson, 2000

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

Angular resolution: 2.5-5° (N.B.: difficult to be analyzed together)

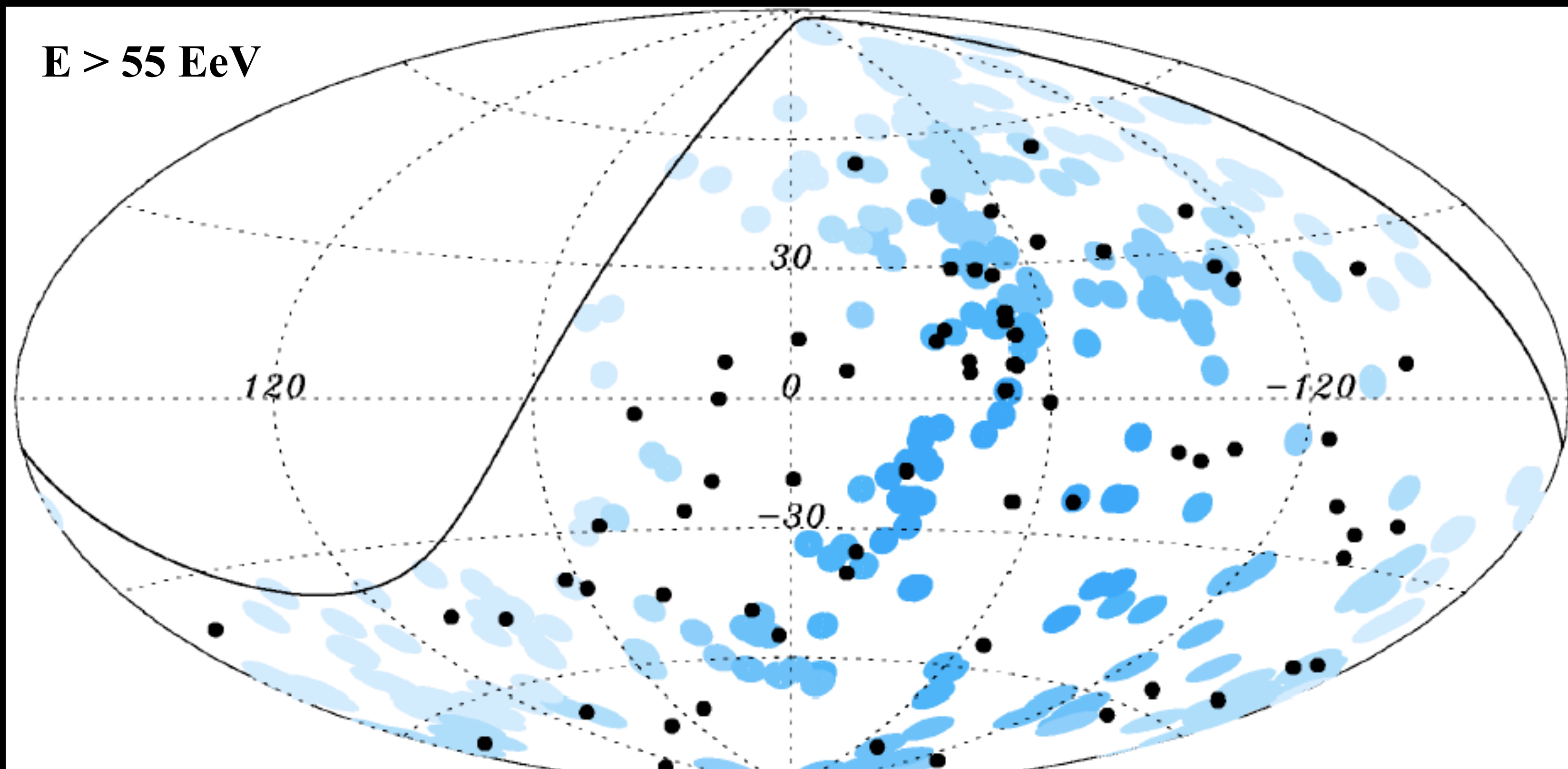
No significant deviation from isotropy in galactic and super-galactic coordinates

No correlation with nearby matter distribution

Possible clusters? (AGASA Doublets/triplets)

Arrival directions now

Auger (2004-2009)



5 years of observation,
69 events above 55 EeV

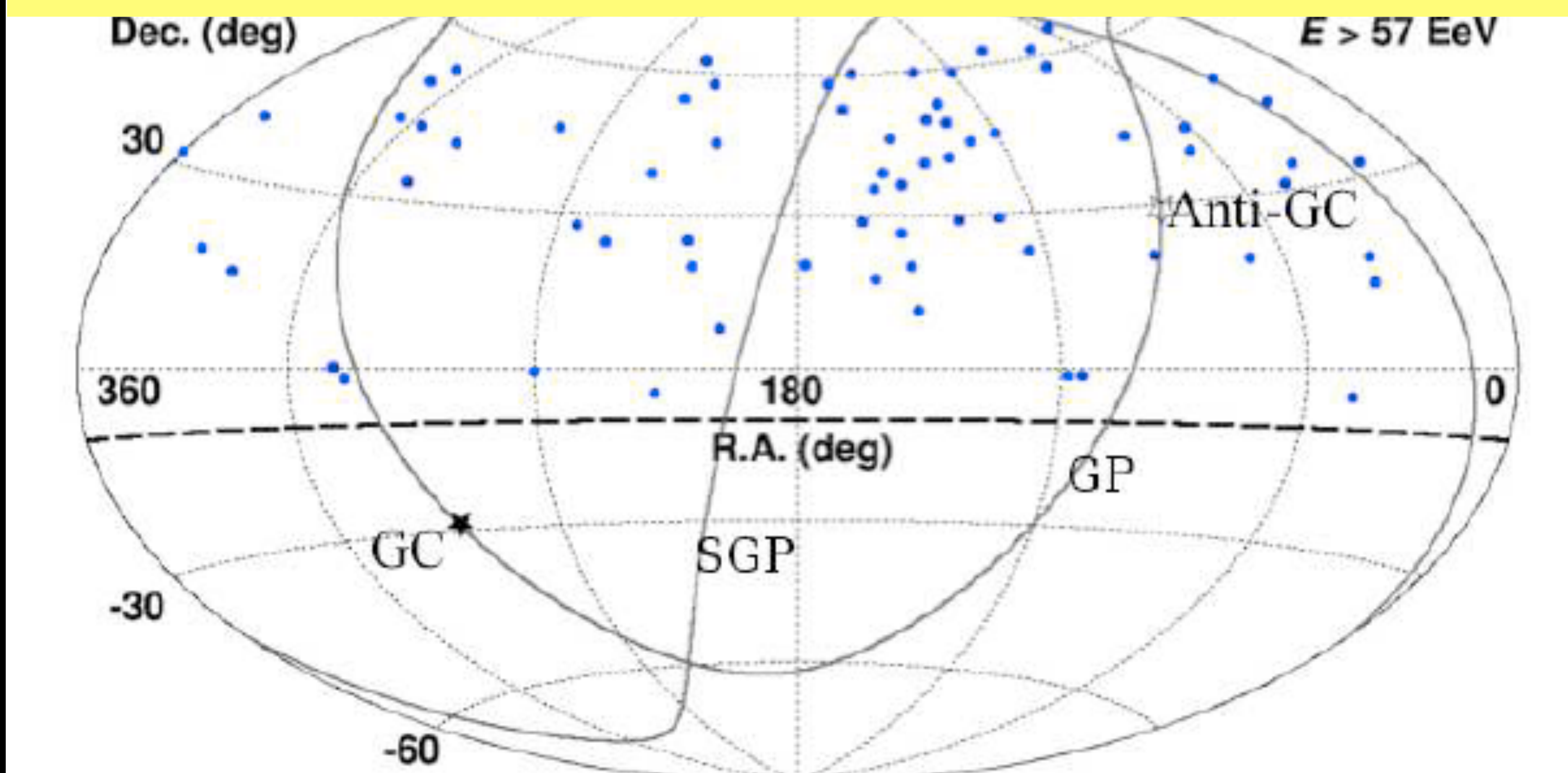
Integrated exposure:
20400 km2 sr y

177 events above 40 EeV

(NOW: a factor > 3 larger,
to be released soon)

5 years of observation, 2 experiments:
≈ 300 events above 40 EeV

TA:2008-2012

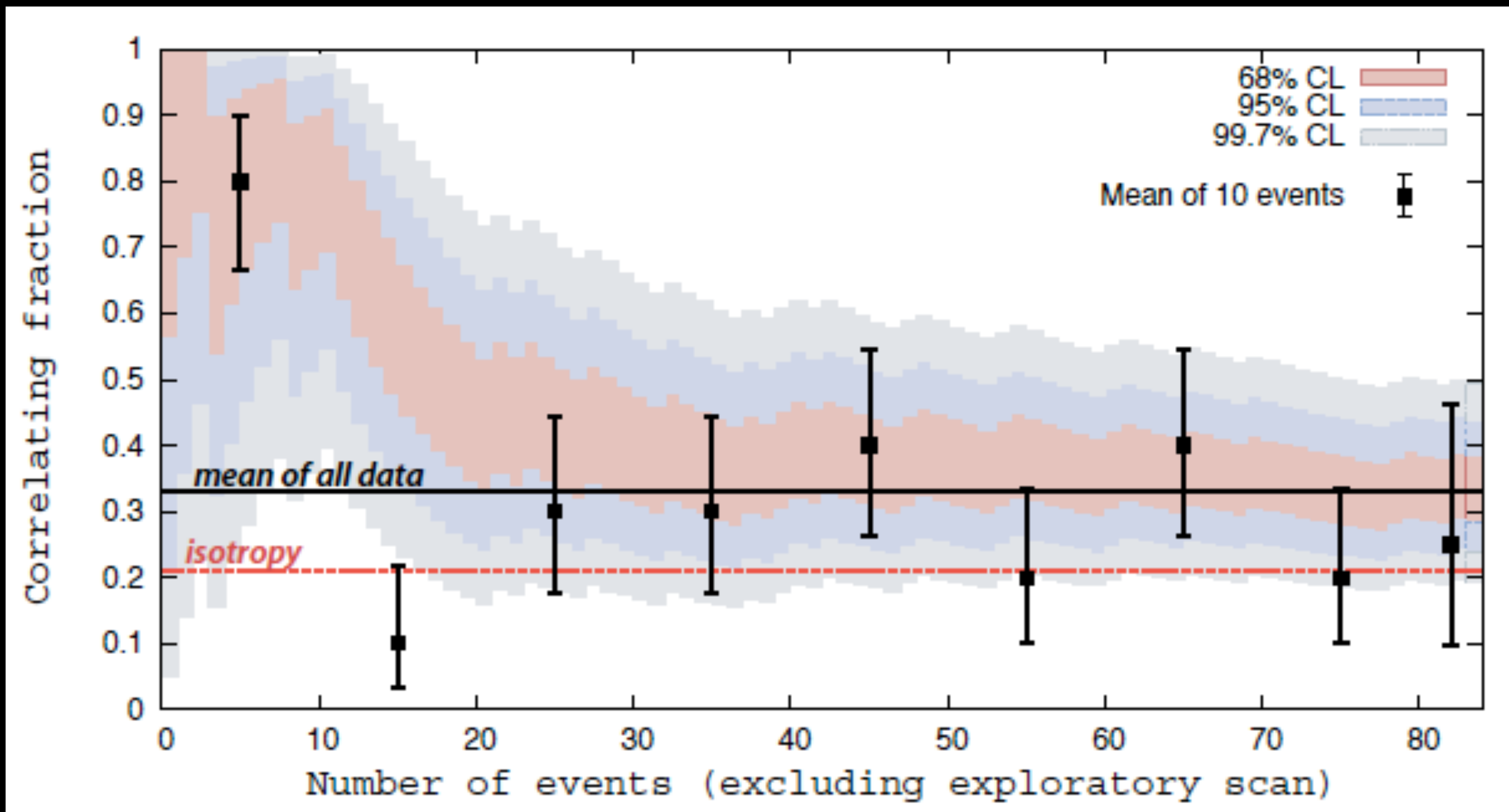


5 years of observation,
72 events above 57 EeV
(+ 15 events in 2013)

132 events above 40 EeV

Correlation between arrival directions and AGNs

AUGER (2004-2010)



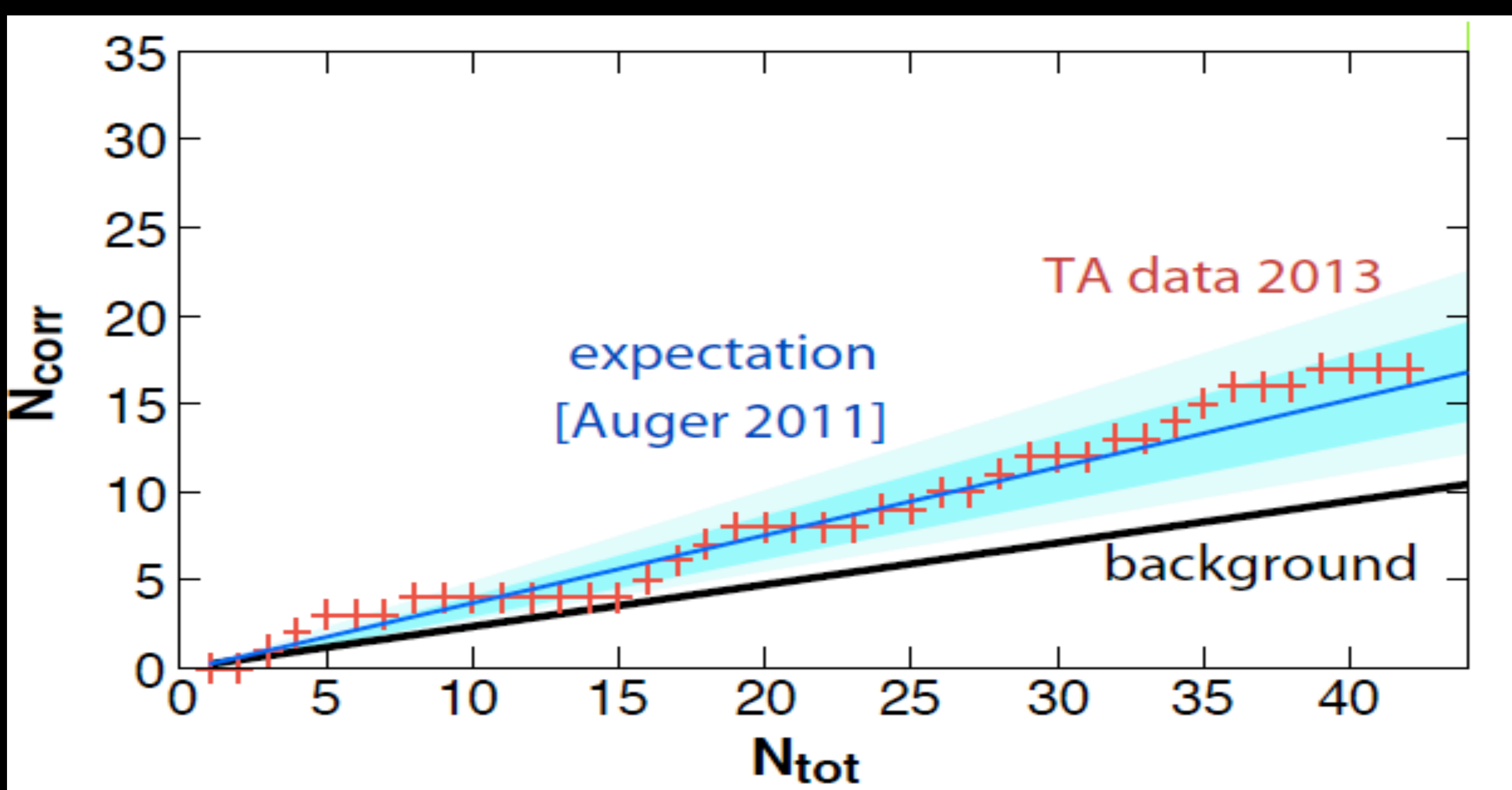
Fraction of UHECR with E>55 EeV correlating with VCV AGNs

isotropic expect.=0.21

data=0.33±0.05

Chance probability p=1 %

TA:2008-2012

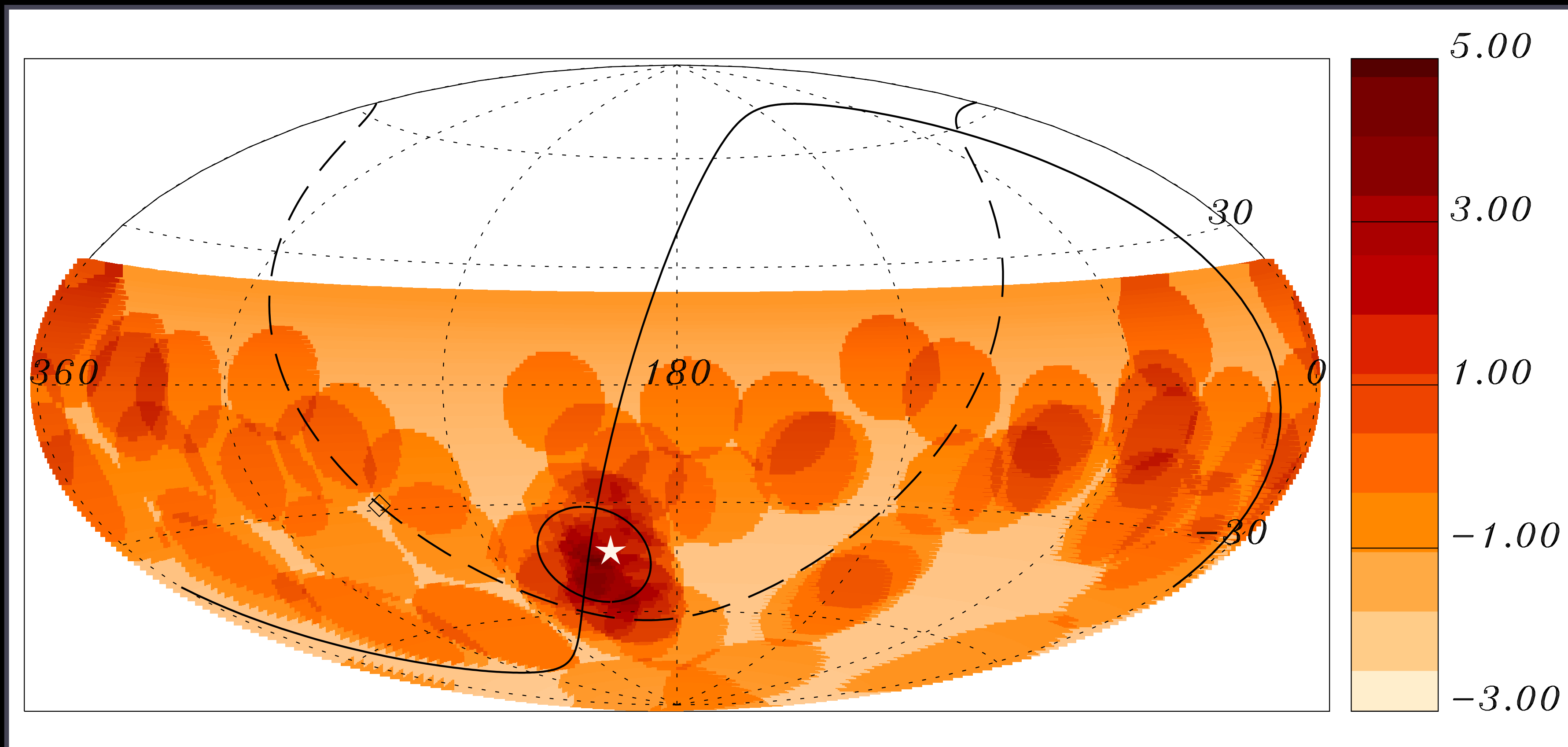


42 UHECR events (>57 EeV, θ<45°, 5 years)
Same set of Agns as Auger
Same correlations parameters

17/42 events correlate
Chance probability p=1.4%

The largest excess in the sky

Auger (2004-2009)

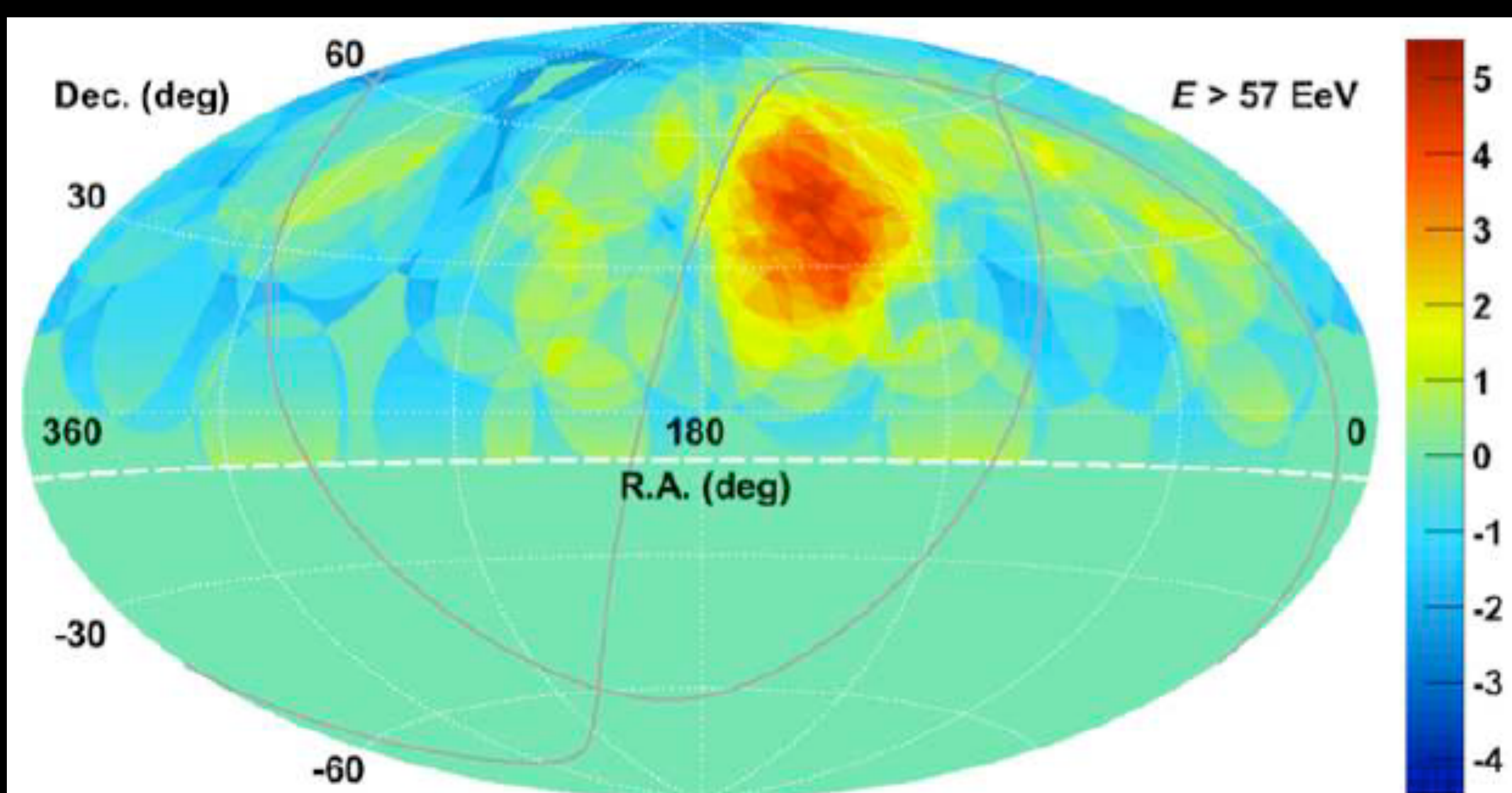


The largest excess (above 55 EeV):

12 events in a 13° cell (1.7 expected): It lies at 4° from Cen A

Chance Probability (penalized for scan in E and angle) ≈ 1%

TA:2008-2012



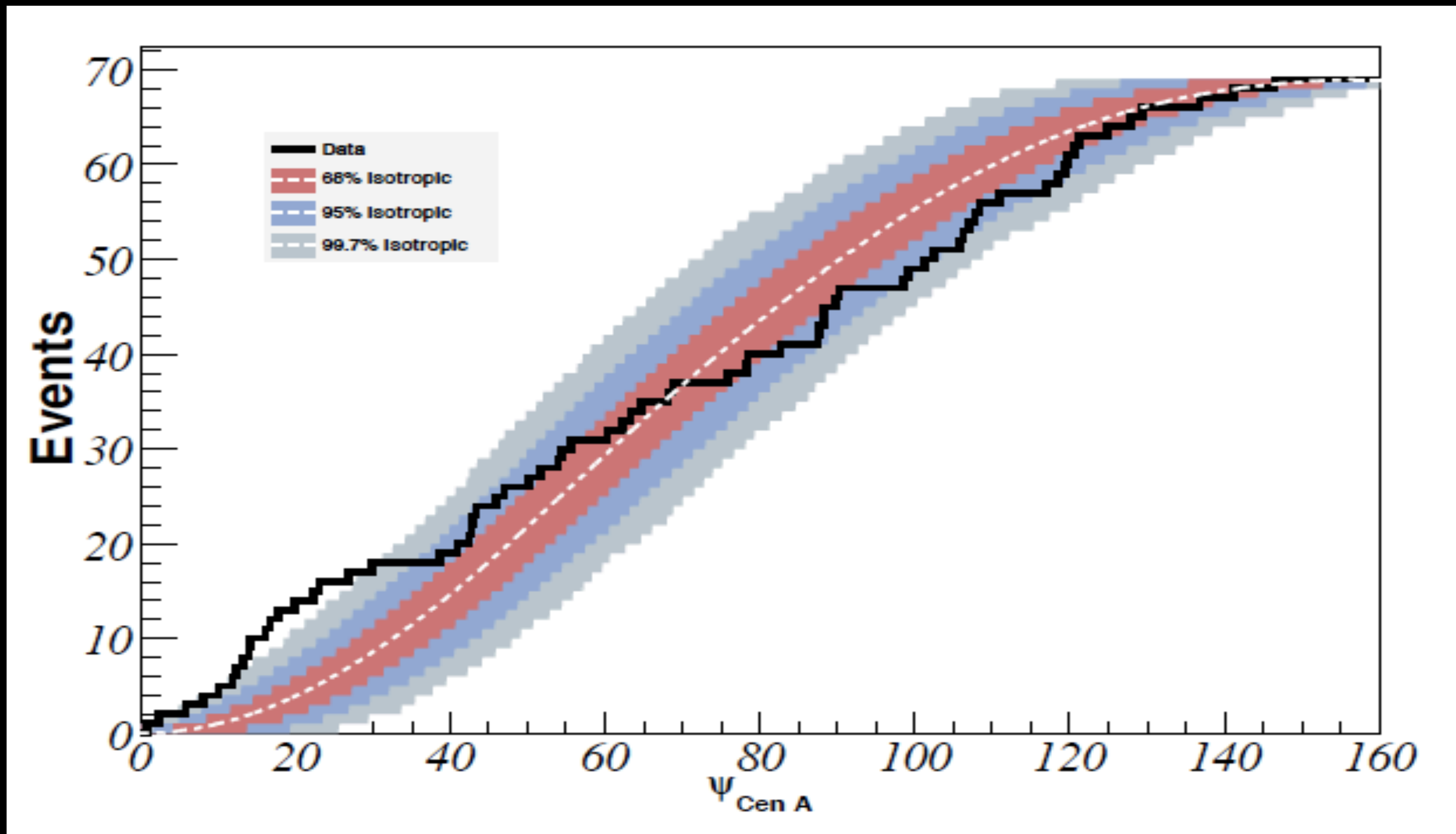
Search for excess above 57 EeV in 20 deg windows

Hotspot : center R.A.=146.7o, Dec. = 43.2o (max. 5.1σ)

Chance probability 3.7×10^{-4}

The largest excess in the sky

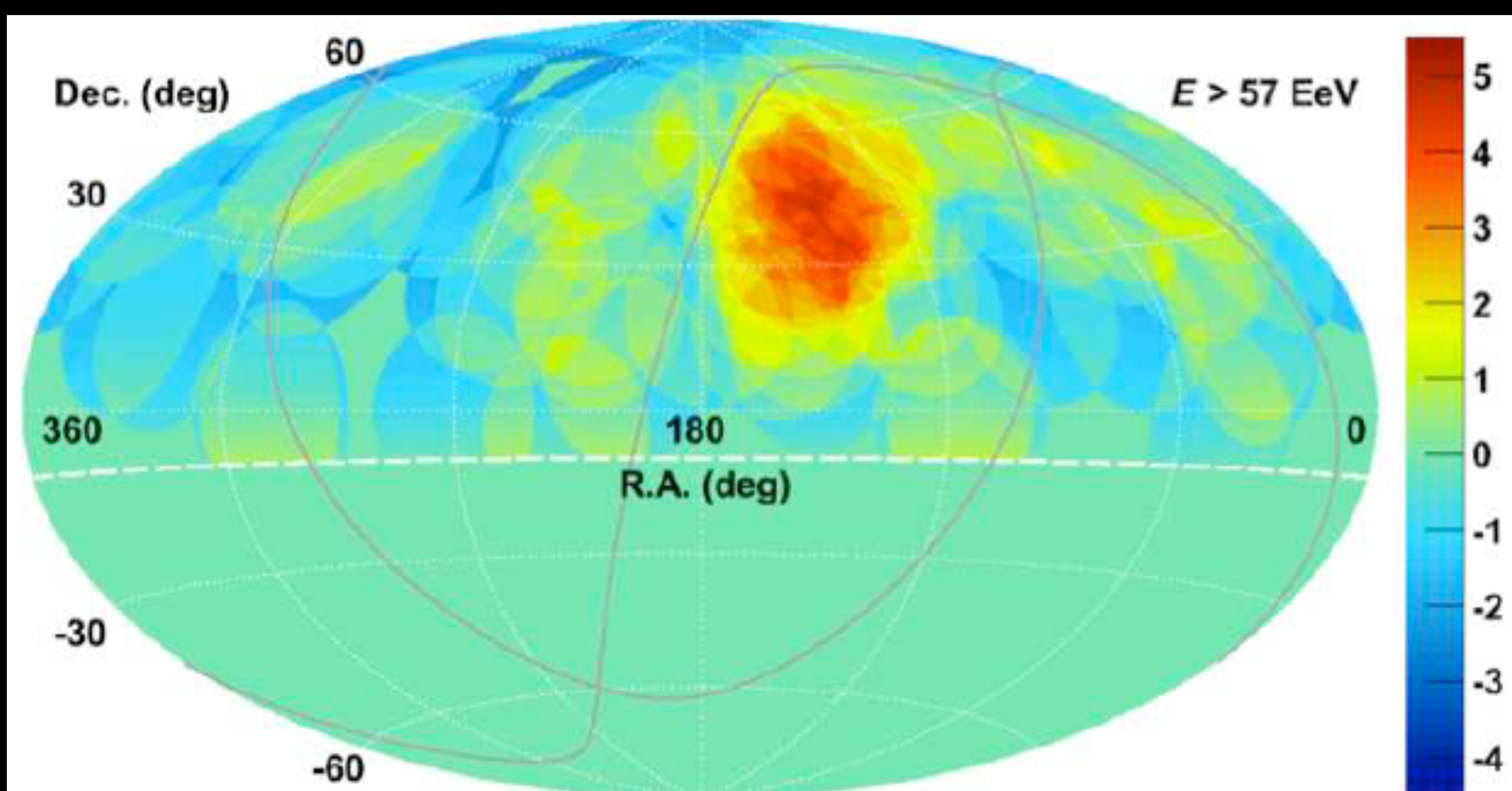
Auger (2004-2009)



Centering on CEN A: largest excess within 18° (13 events vs 3.2 expected)

KS test: 4% probability that the distribution is generated by an isotropic background

TA:2008-2012

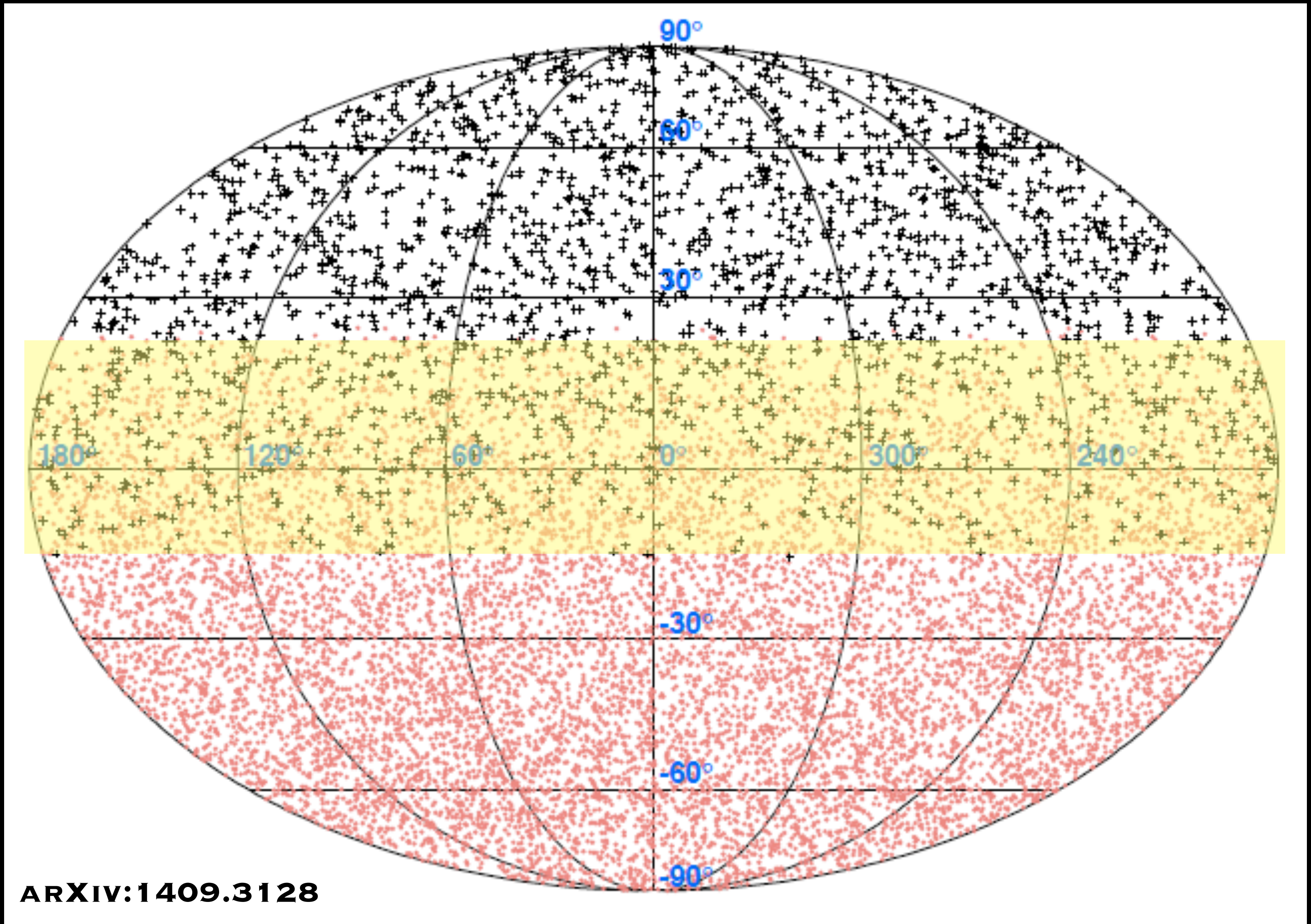


Search for excess above 57 EeV in 20 deg windows

Hotspot : center R.A.=146.7o, Dec. = 43.2o (max. 5.1σ)

chance probability 3.7×10^{-4}

Arrival directions all-sky: TA and Auger working together



EVENTS ABOVE 10 EEV

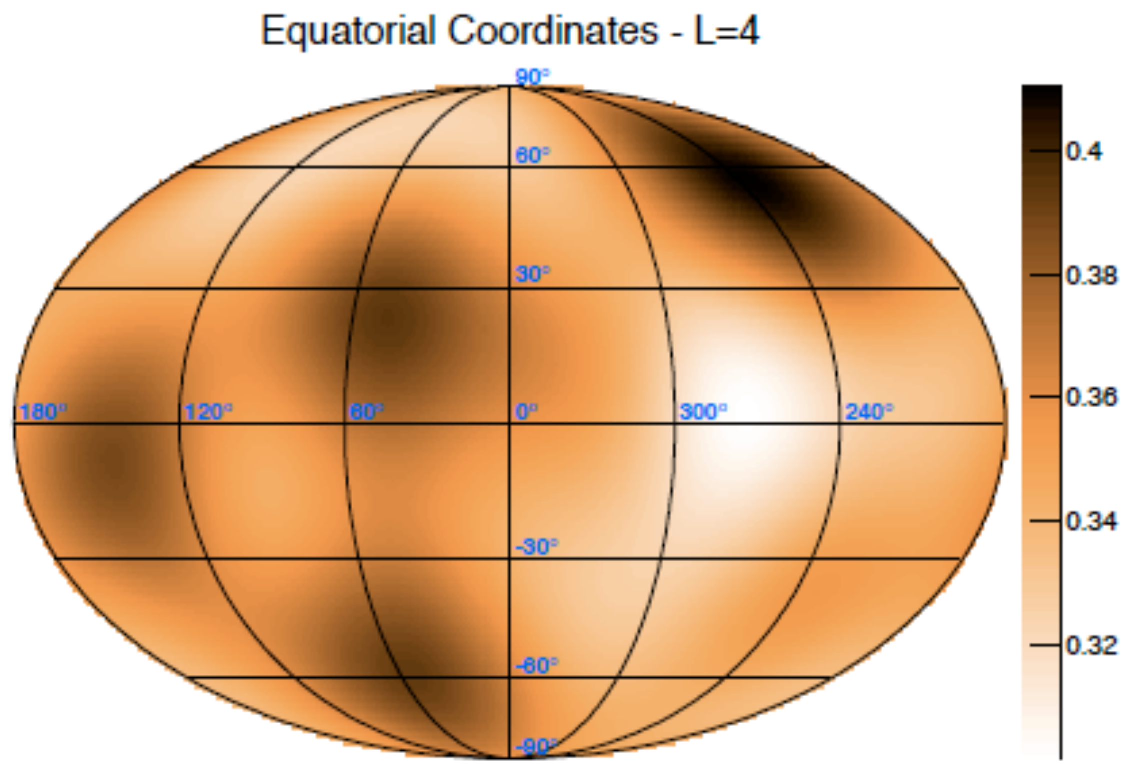
AUGER:
8259 EVENTS
31440 KM2 SR Y

TA:
2130 EVENTS
6040 KM2 SR Y

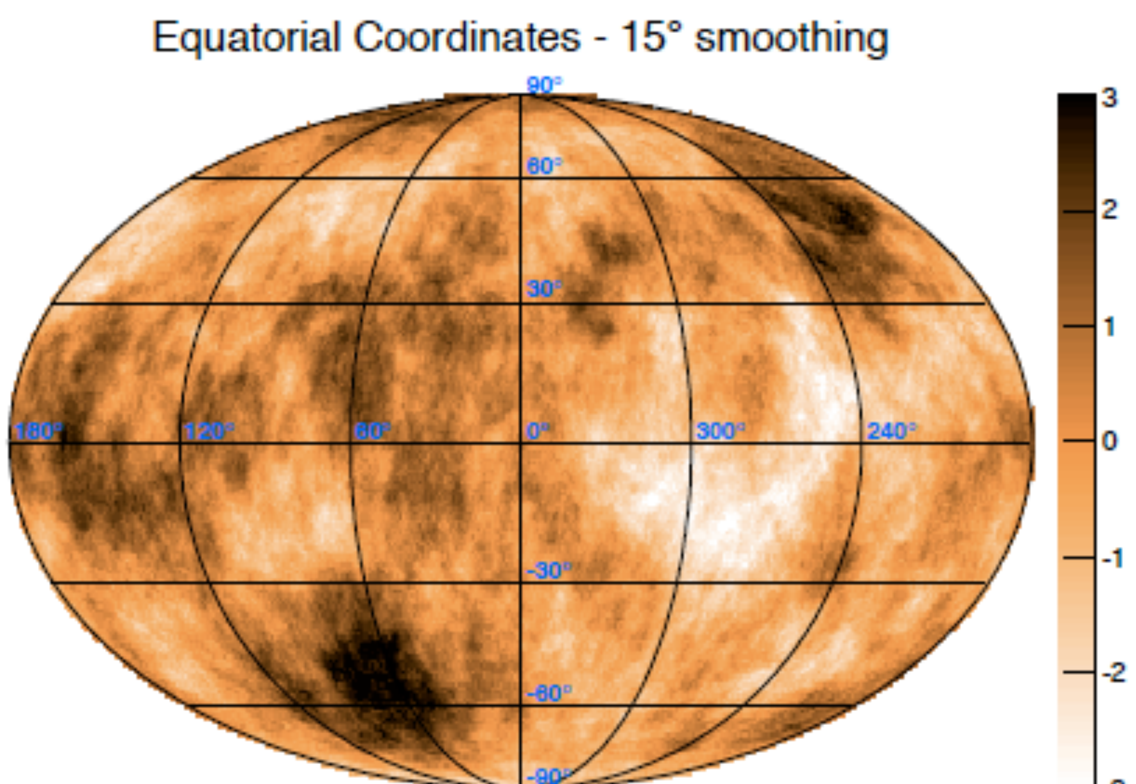
COMMON DECLINATION BAND (-15-25 DEG): USED FOR CROSS-CALIBRATION (EQUAL FLUX):

3435 EVENTS

Arrival directions all-sky: TA and Auger working together



Flux sky map



significance map (smoothed by 15 deg)

arXiv:1409.3128

Search for large-scale anisotropies through a spherical Harmonic analysis

No significant deviation from isotropy

upper limits on amplitudes of dipole and quadrupole moments vs declination have been derived: 7% - 13% for the dipole and between 7% and 10% for a symmetric quadrupole.

Conclusions and perspectives

Conclusions

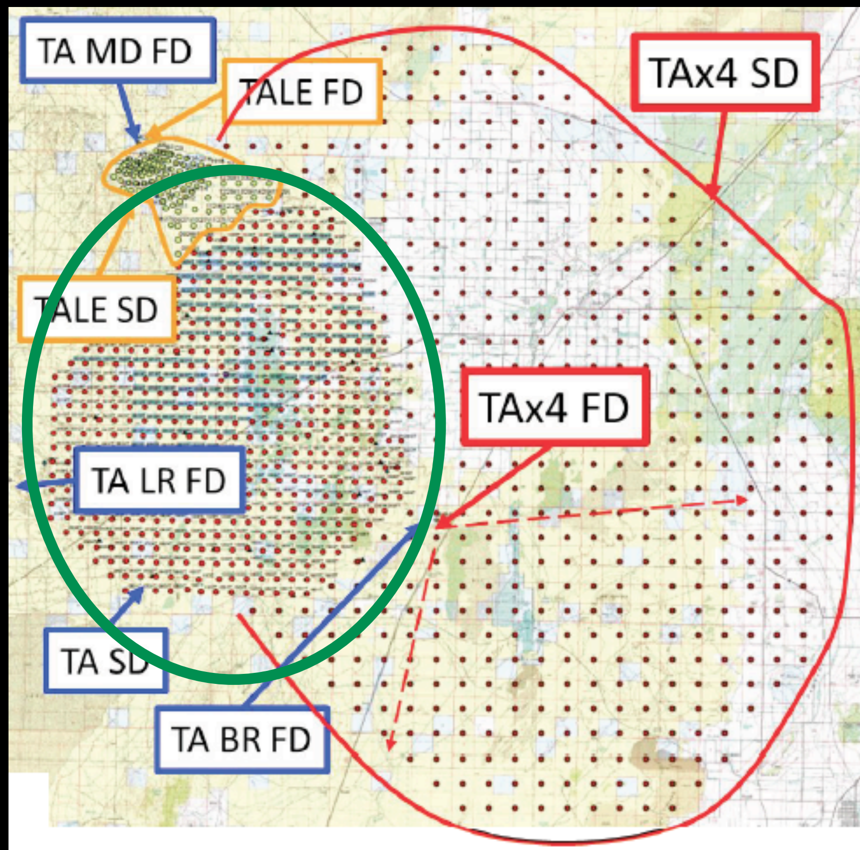
- **Learnt lessons from the past**
- the techniques (date back to 50s-60s!)
- progress not only based on more statistics but also on more accuracy (hybrid technique)

- **Learnt (and to be learnt) lessons from the present**
- Flux suppression clearly observed thanks to statistics AND accuracy: GZK or source exhaustion? Composition measurements essential to answer
- Composition measurement still “critical”: **TA Xmax data consistent with light mass component over the whole energy range. With current statistics cannot prove or disprove the trend towards heavier components compatible with Auger Xmax data.** Lacking statistics at the highest energies.
- Arrival directions: no evidence of large-scale anisotropy, no evidence of small-scale excesses (or multiplets). Correlation with AGNs at ≈ 1% probability. Most interesting sky-regions: TA hotspot, Cen A (intermediate scales, ≈ 20˚).

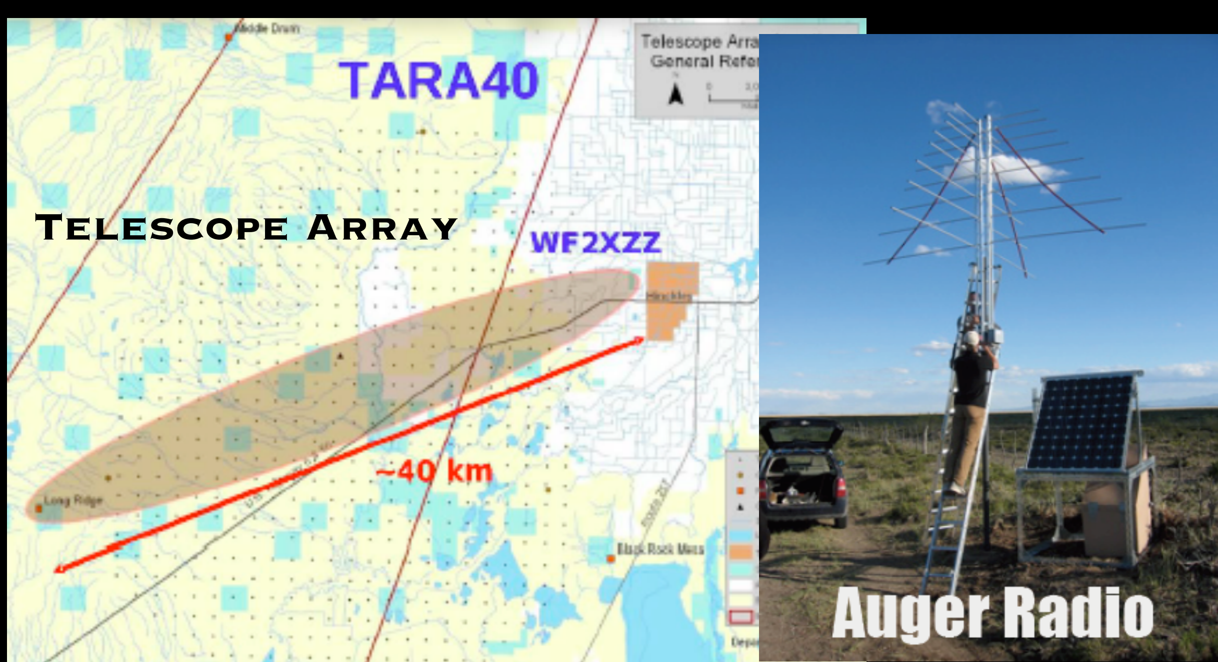
- **Steps for the future**
- larger number of events
- higher precision “multi-hybrid” detectors

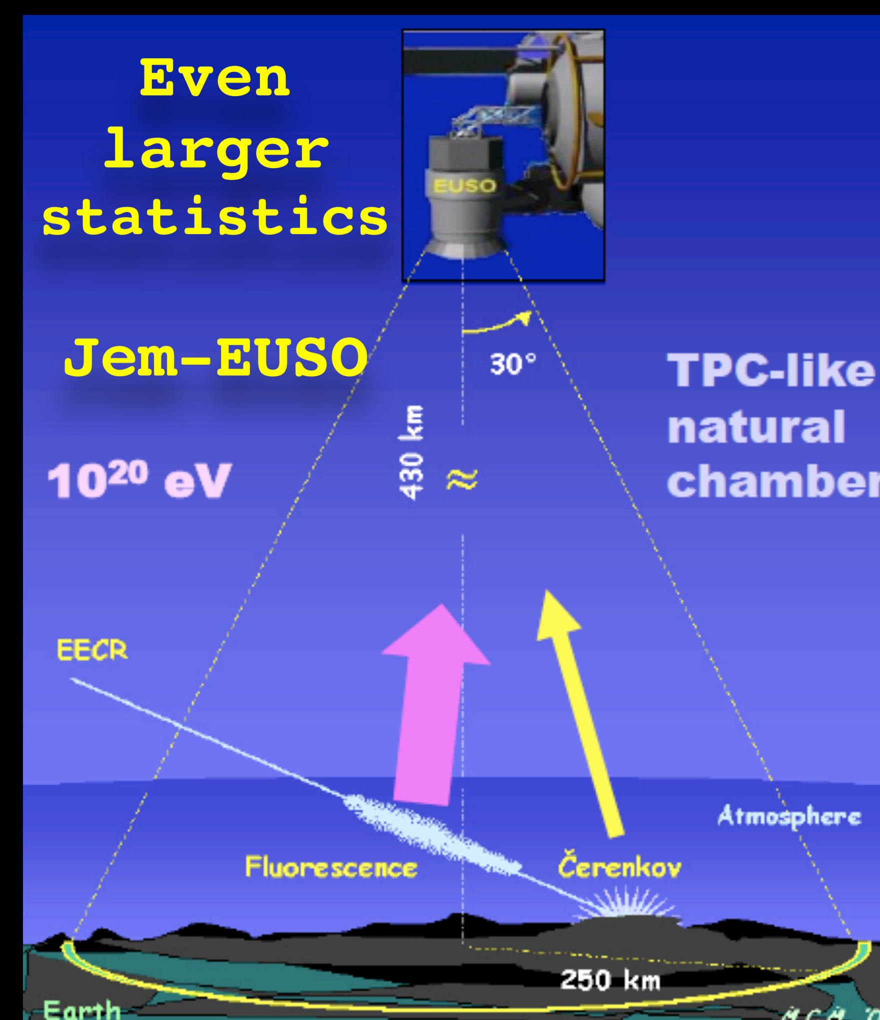
Perspectives

TAx4 (larger area: 3000 km2)



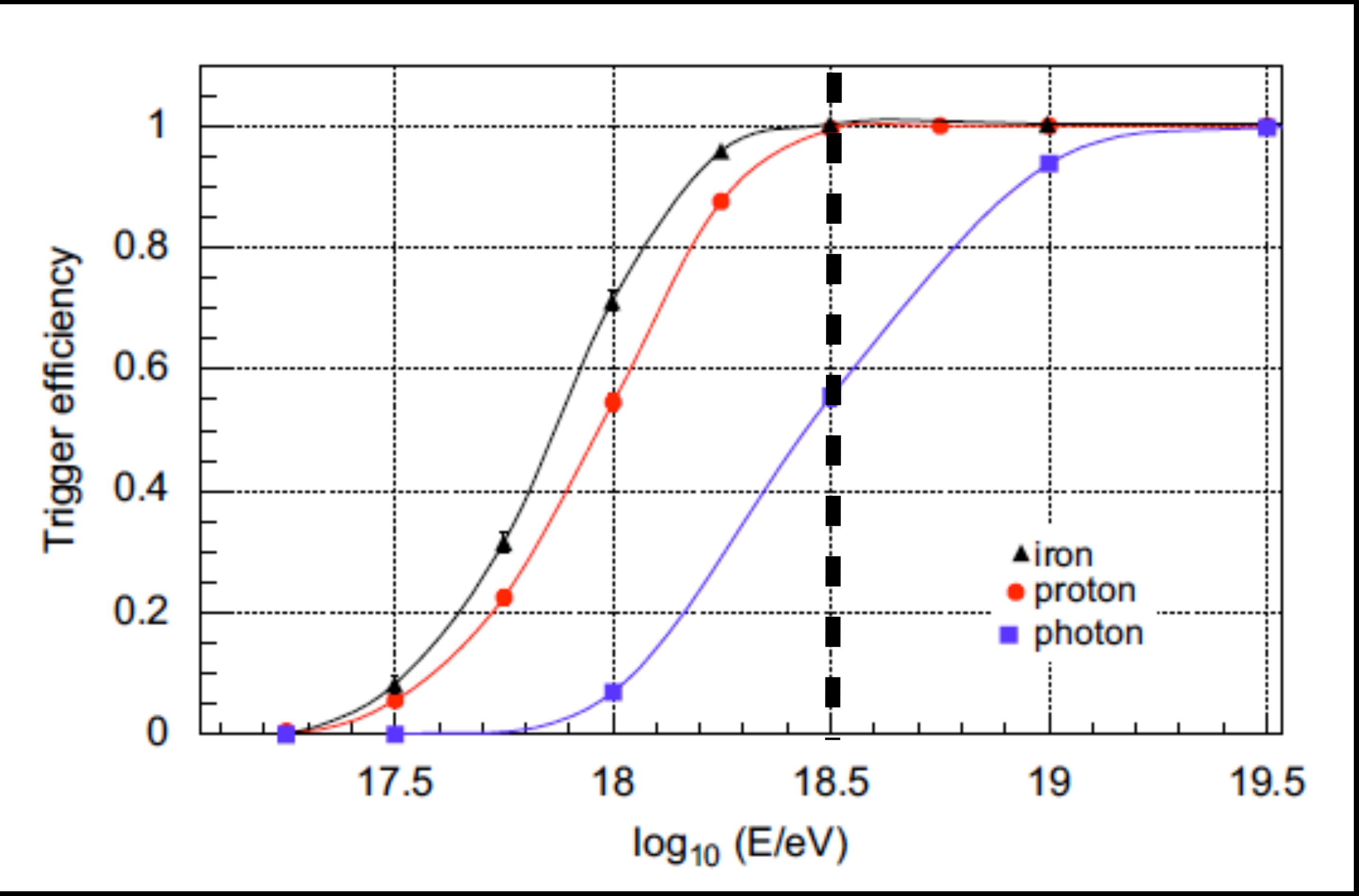
R&D new techniques: radio and radar



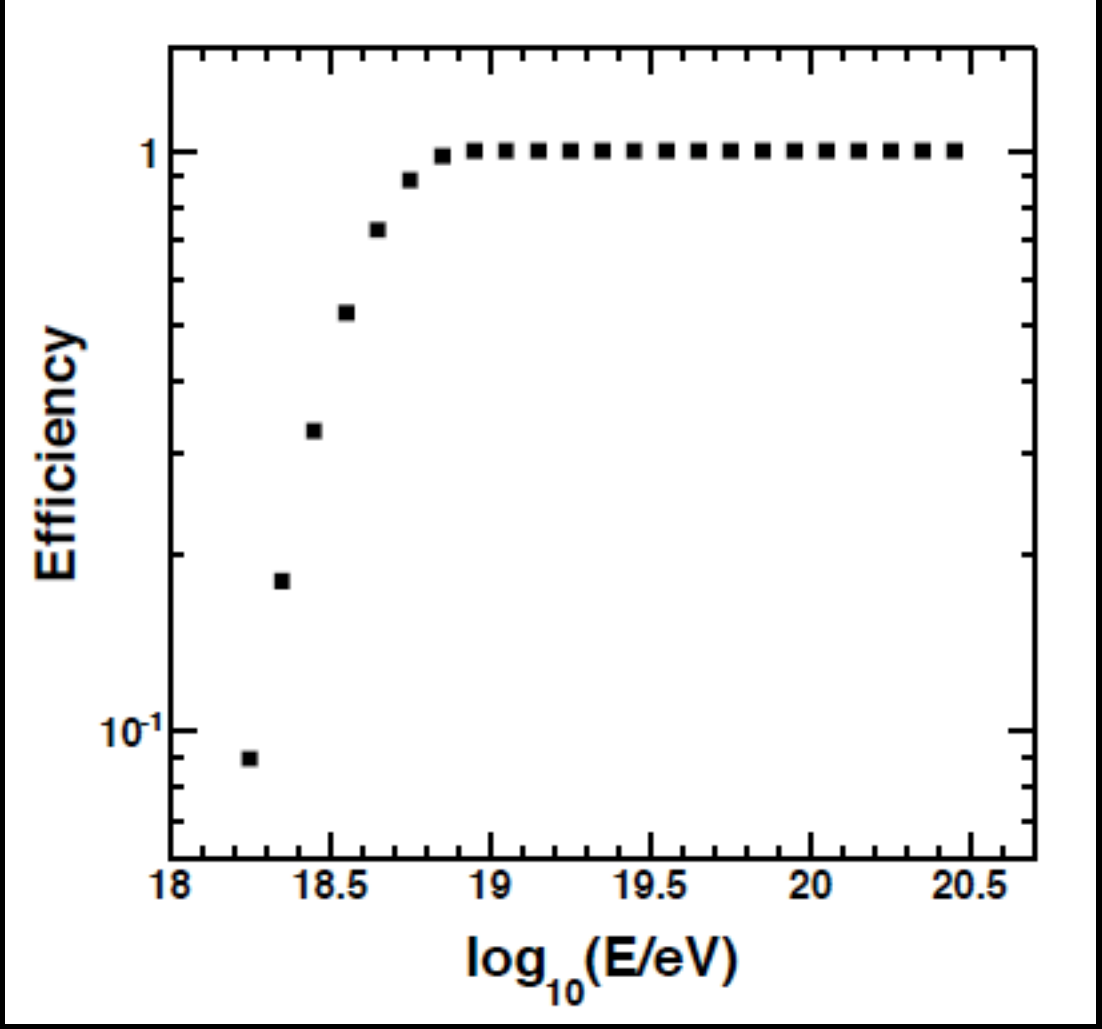


Trigger efficiency

Auger (SD)
[0-60 deg]



Telescope Array (SD)
[0-45 deg]



SD: 3-fold trigger
Fully efficient at E>3 EeV
(hadrons)
Geometry-based exposure Calc.

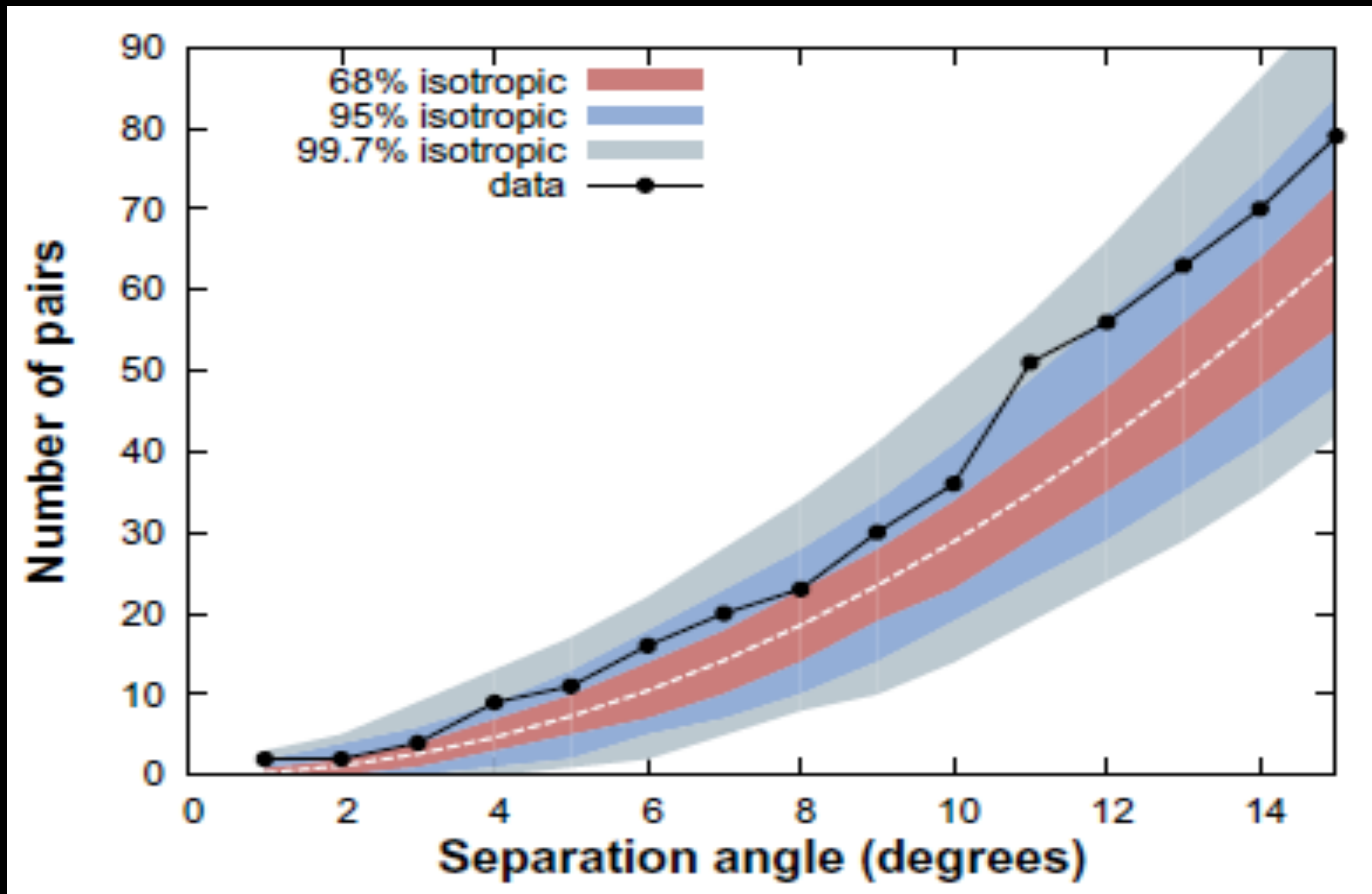
Hybrid: FD+1 triggered WCD
Fully efficient at E>1 EeV
Simulation-based exposure calc.

SD: 3-fold trigger
Fully efficient at E>10 EeV
Simulation-based exposure calc.

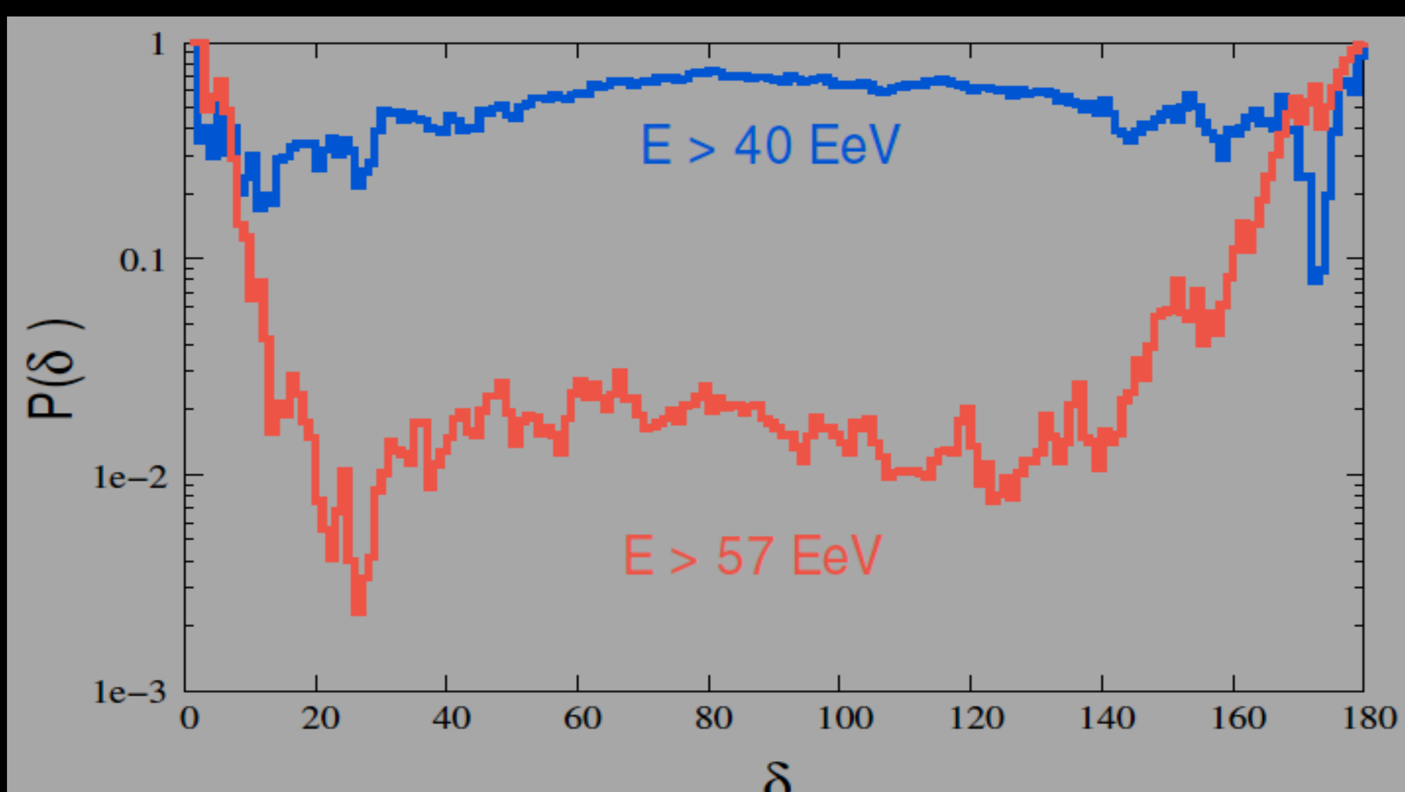
Hybrid: FD+SD trigger
Fully efficient at E>10 EeV
Simulation-based exposure calc.

Small-scale clustering (autocorrelation)

AUGER (2004-2009



TA:2008-2012



AUTOCORRELATION METHOD:

SEARCH FOR PAIRS OF EVENTS WITH WITH DIFFERENT ANGULAR SEPARATION

NO EVIDENCE OF CLUSTERING AT SMALL SCALES (A LA AGASA, VERSUS DOUBLETS REPORTED BY AGASA AT