Ultra-high energy cosmic rays in the multi messenger era

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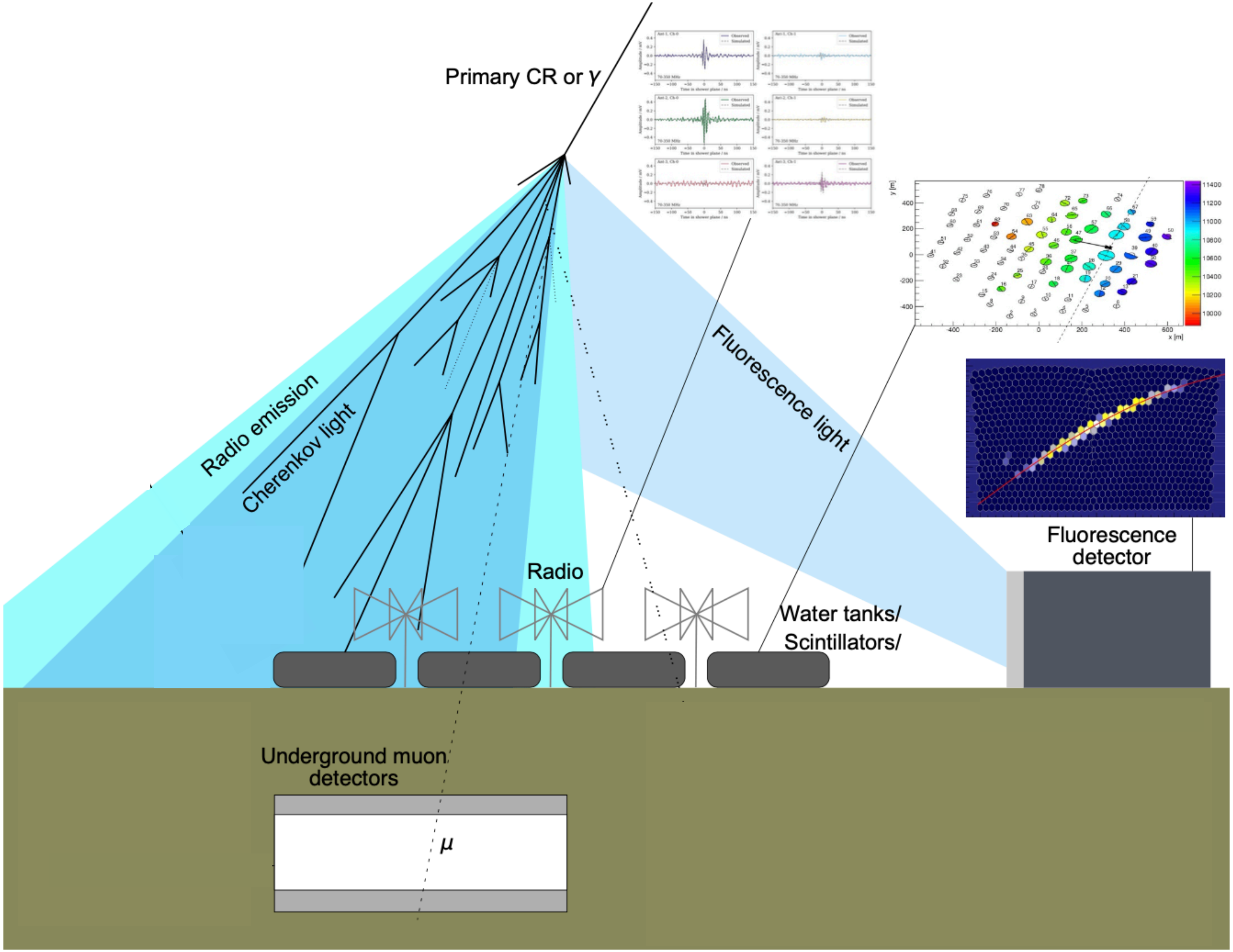
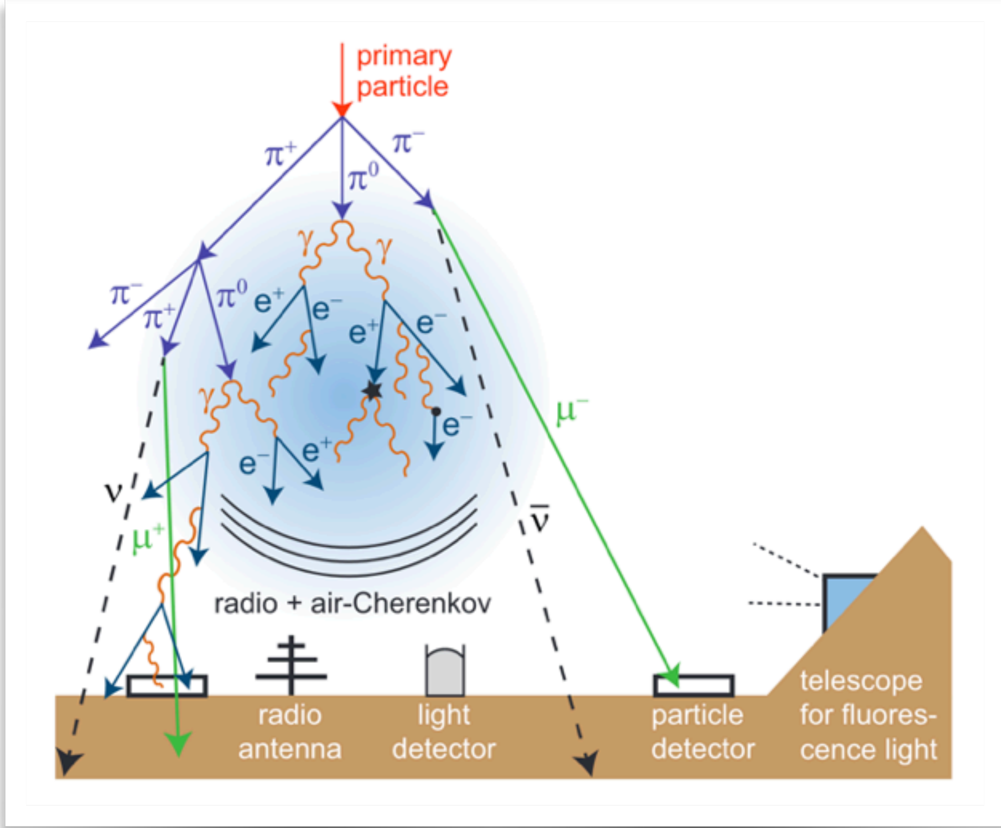
Detectors for UHECRs



Surface detectors

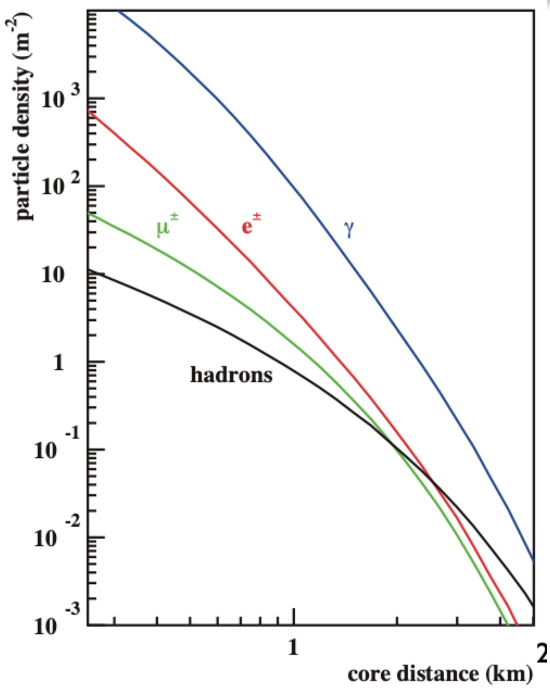
- array of detectors at one atmospheric level

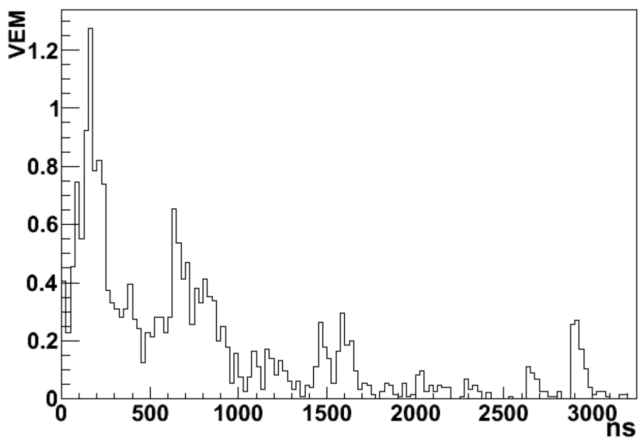


✓ total area chosen depending on the primary energy, and thus on the rate to be studied:
~10^5 m² for the knee region (e.g. EASTOP)
3000 km² for the UHE region (e.g.Auger)

✓ separation between modules matching the footprint of the shower at the observation level:
~tens of m (knee region),
~ hundreds to km (UHE region)

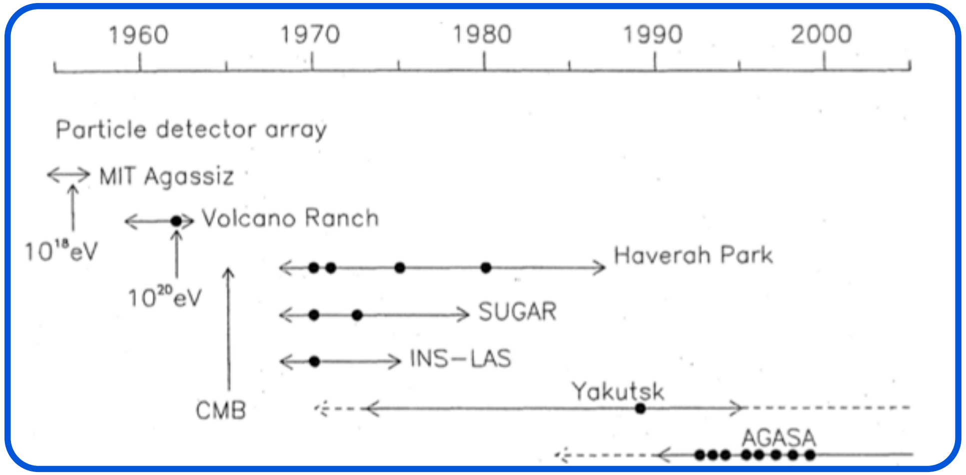
✓ active area << total area :
~3 10^{-3} (EASTOP), ~5 10^{-6} (Auger)



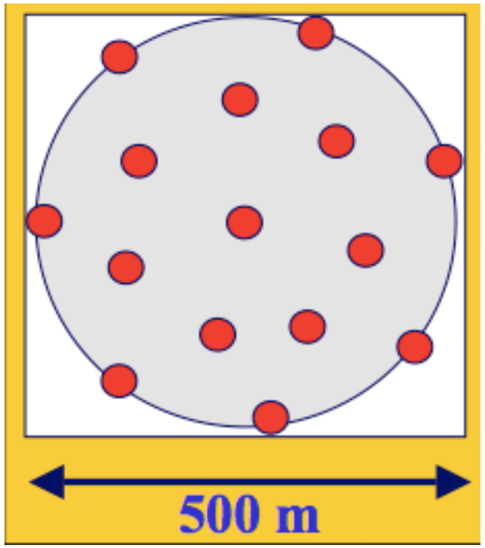


- observables
  ✓ signals (number of charged particles) in the modules : EM, muonic, hadronic components
  ✓ time of arrival of the particles

From small arrays…

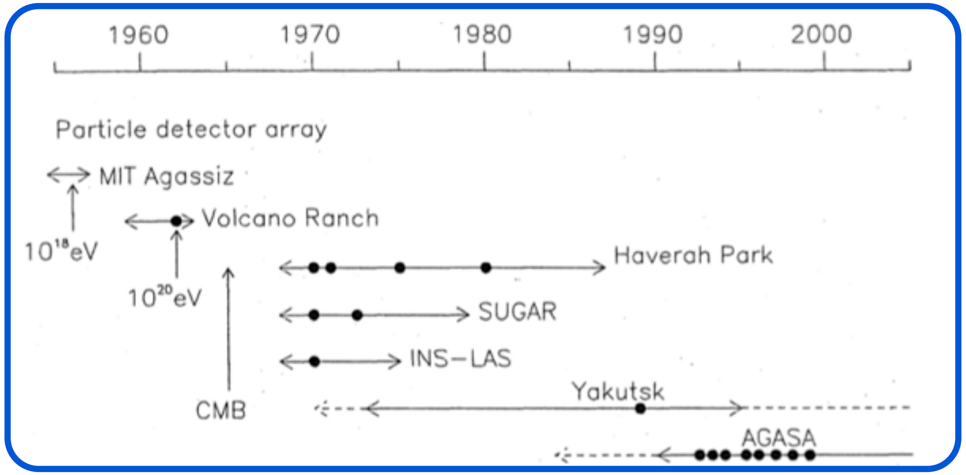


- PAMIR (G.Zatsepin, 1946)
  - ✓ 3860 m asl, USSR
  - ✓ array of Geiger-Muller counters + ionization and cloud chambers
  - ✓ energies up to the knee

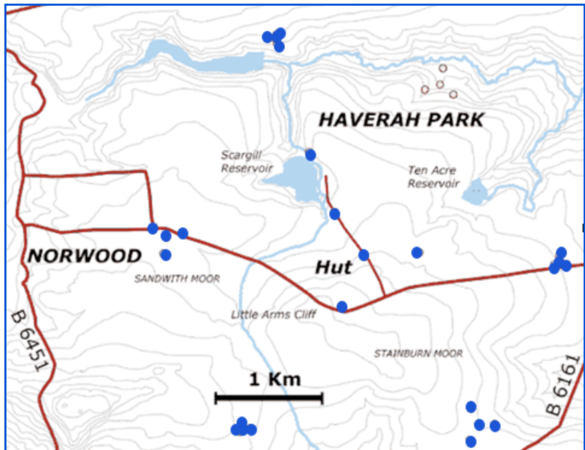


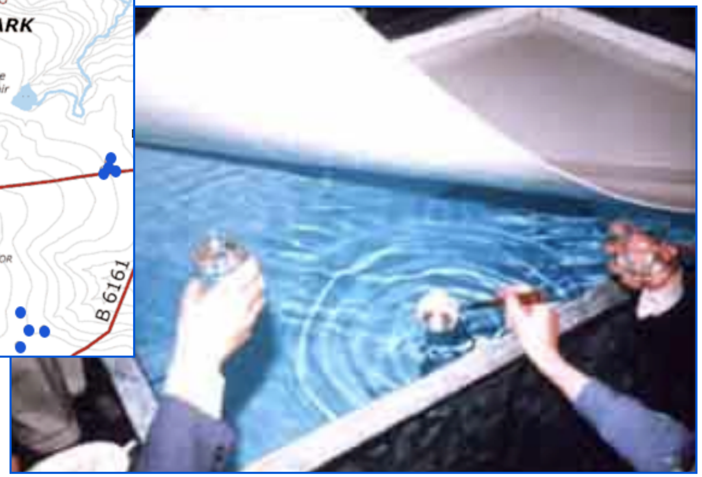
- AGASSIZ (B.Rossi, MIT, 1956)
  - ✓ array of 15 plastic scintillators (1 m^2 each) with PMTs
  - ✓ energies up and above the knee
  - ✓ density sampling ->core
  - ✓ fast timing -> arrival direction

…to giant experiments



- **Volcano Ranch** (New Mexico, 1957-63)
  - ✓ array of 19 plastic scintillators (3.3 m² each) ~**8.1 km²**
  - ✓ **first detection of an event with E ~ 10^{20} eV**

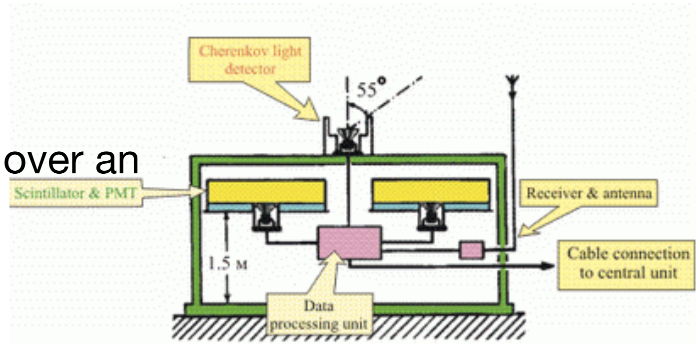


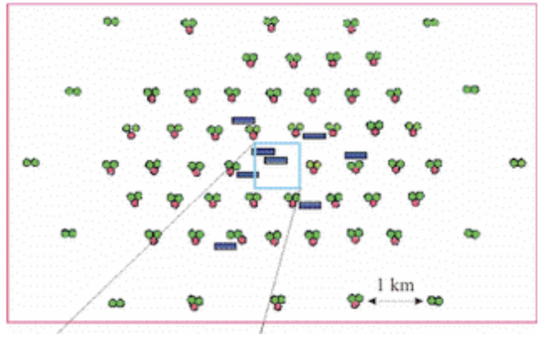


- **Haverah Park** (UK, 1967-87)
  - ✓ array of 200 water Cherenkov tanks over an area ~ **12 km²**
  - ✓ mutual distances from 150 m to 2 km : **4 events with E ~ 10^{20} eV**

…to giant experiments

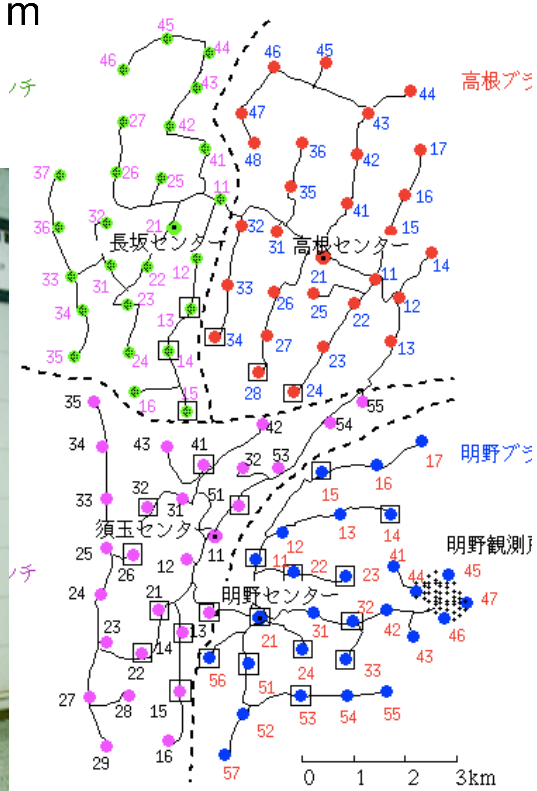
- **Yakutsk** (Siberia, 1969-95)
  - ✓ surface and undergound detectors over an area ~ **18 km²**
  - ✓ mutual distance from 100 to 500 m



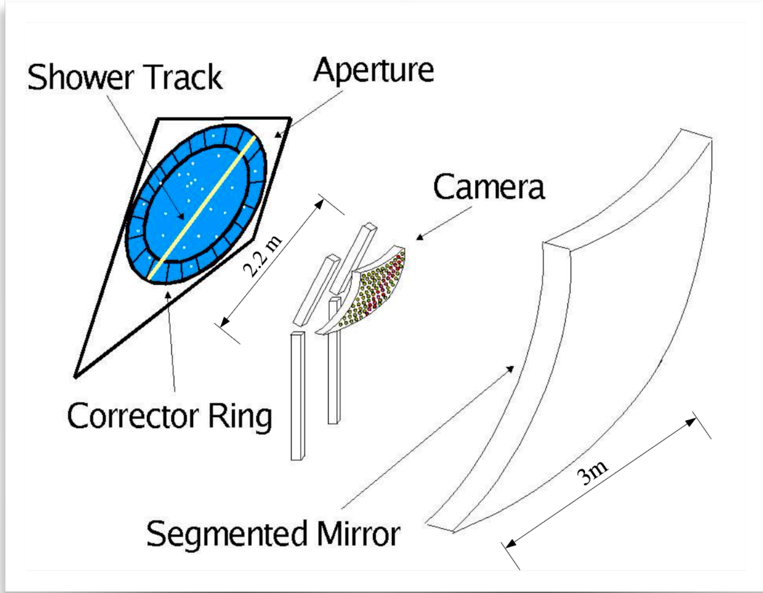


- **SUGAR** (Australia, 1968-79)
  - ✓ array of 56 pairs of scintillators buried 1.7 m underground over an area ~ **60 km²**
  - ✓ mutual distances ~1.6 km, too big

- **AGASA** (Japan, 1990-2004)
  - ✓ array of 111 scintillator stations (2.2 m² each) + 27 muon detectors
  - ✓ over an area ~ **100 km²**
  - ✓ mutual distances ~1 km
  - ✓ ~10 events with E > 10^{20} eV



Fluorescence detectors

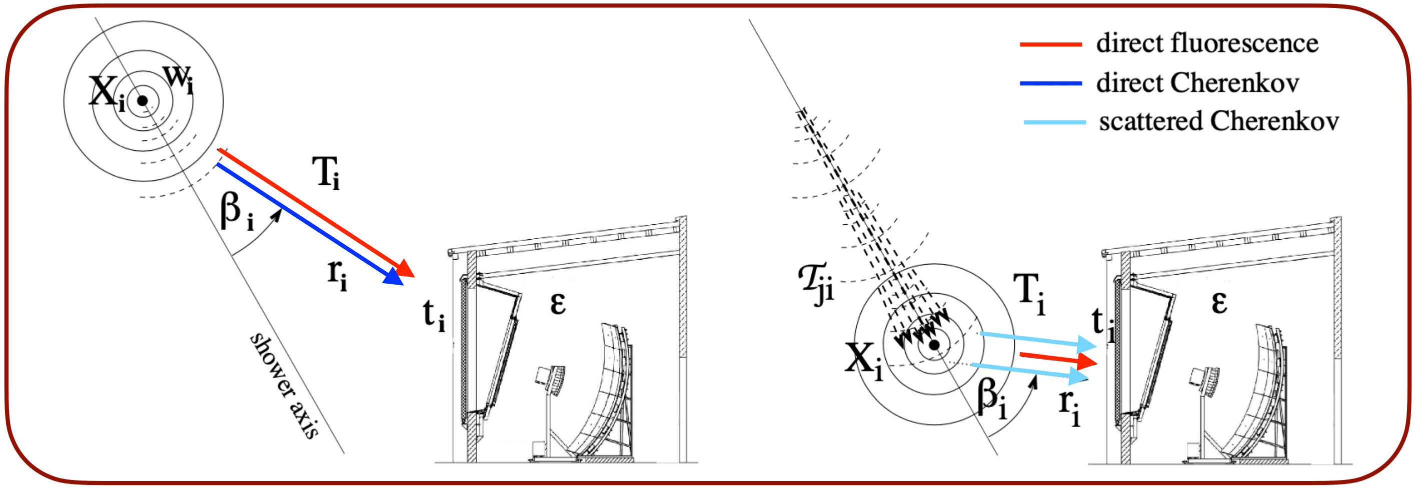


- mirrors collect the total light emitted along the shower track visible in the field of view and focus it onto a multi-pixel (multi-PMT) camera
- several mirrors can be combined for a larger FOV

  ✓ fast and sensitive electronics
  ✓ clear, moonless nights: ~10% duty cycle
  ✓ mandatory monitoring of atmospheric conditions: Rayleigh (molecular) and Mie (aerosol) scattering

- three contributions

  ✓ the particles of an EAS excite nitrogen molecules in the atmosphere, which subsequently radiate ***UV fluorescence light*** isotropically
  ✓ charged shower particles travel faster than the speed of light in air, leading to the emission of ***direct Cherenkov light***.
  ✓ due to the charged particles scattering, ***scattered Cherenkov light*** is also present.



Fluorescence detectors

emitted | recorded at the telescope

$$N_\gamma^{fl}(X_i) = Y_i^{fl}(dE/dX_i)\Delta X_i \longrightarrow y_i^{fl} = \frac{A\epsilon T_i}{4\pi r_i^2} N_\gamma^{fl}$$

$$N_\gamma^{Ch}(X_i) = Y_i^{Ch} N_e(X_i) \longrightarrow y_i^{Ch} = \frac{A\epsilon T_i}{4\pi r_i^2} f_{Ch}(\beta_i) N_\gamma^{Ch}(X_i)$$

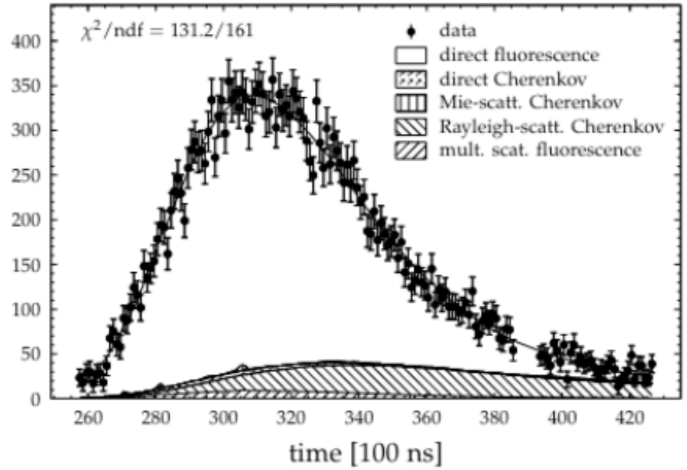
$$(dE/dX)_i = \alpha_i N_e(X_j)$$

$$N_\gamma^{Ch,sc}(X_i) = \sum_{j=0}^{i} T_{ji} Y_j^{C} N_e(X_j) \longrightarrow y_i^{Ch,sc} = \frac{A\epsilon T_i}{4\pi r_i^2} f_{sc}(\beta_i) N_\gamma^{Ch,sc}(X_i)$$

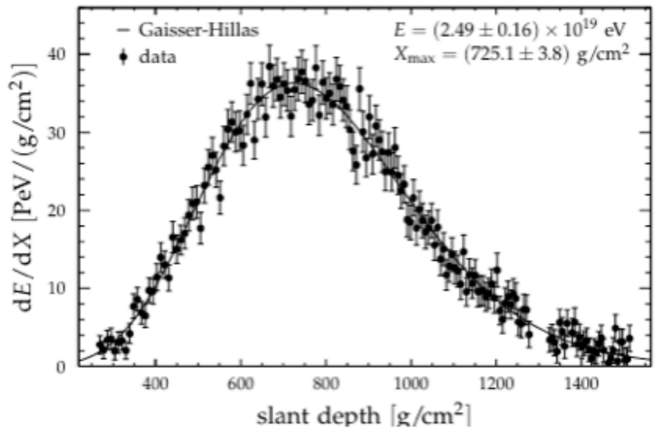
$$y_i = y_i^{fl} + y_i^{Ch} + y_i^{Ch,sc}$$ total light flux at the telescope

$\downarrow$

(dE/dX) in the field of view

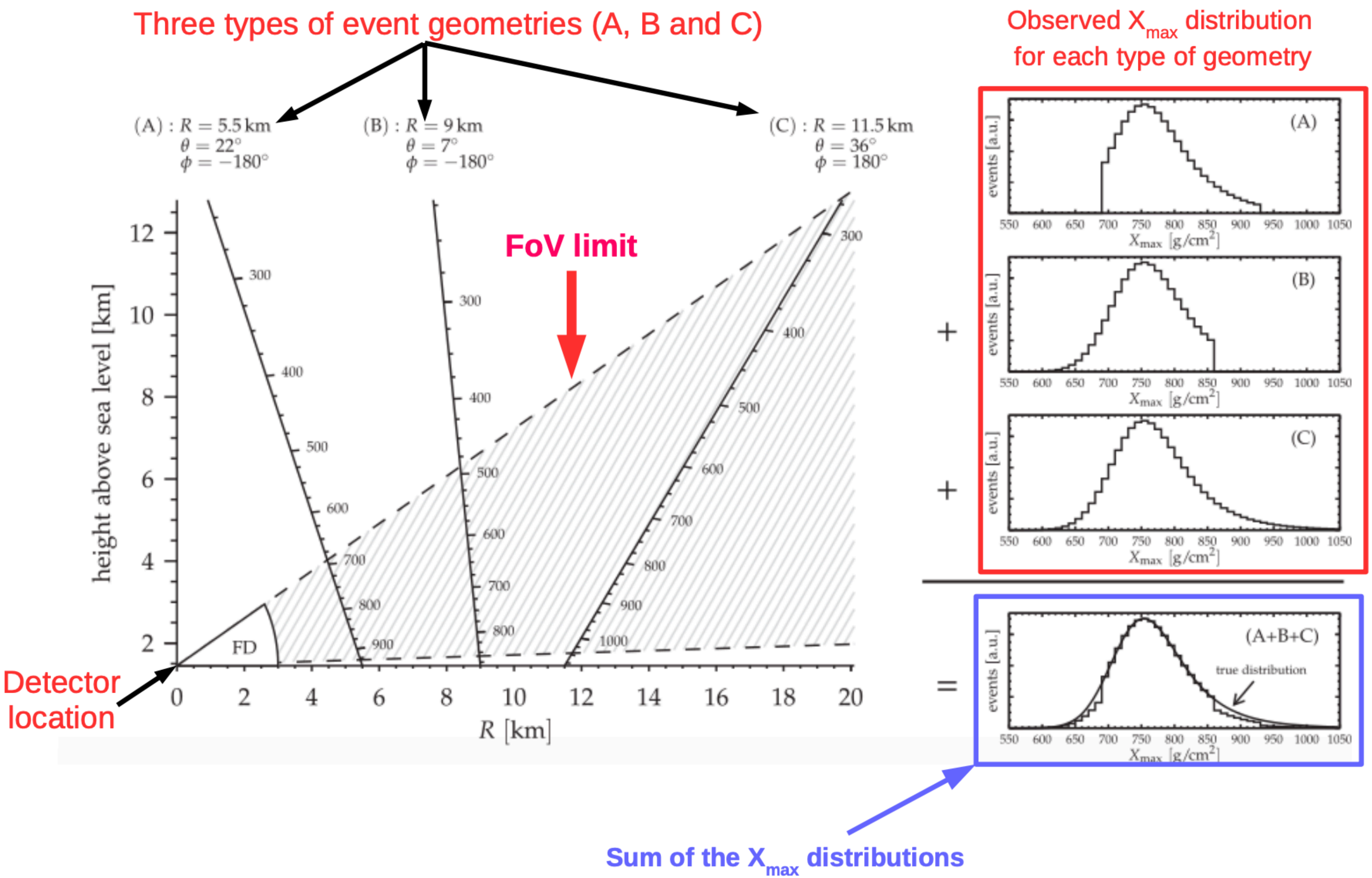


$$f_{GH}(X) = \left(\frac{dE}{dX}\right)_{max} \left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{(X_{max}-X_0)}{\lambda}} exp\left(\frac{(X_{max} - X_0)}{\lambda}\right)$$

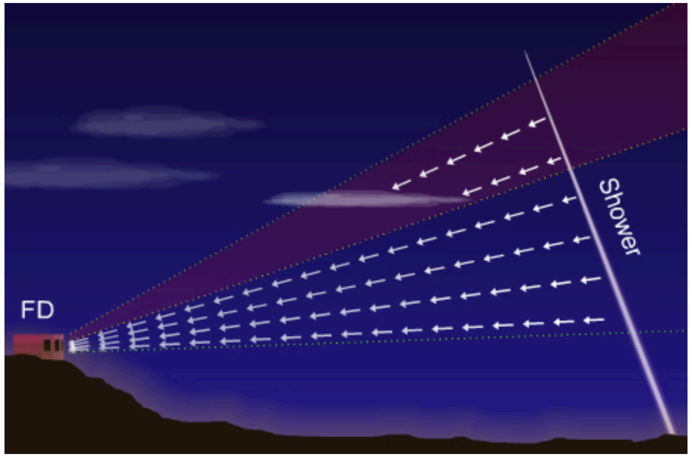


$$\boxed{E_{em} = \int_0^\infty dX f_{GH}(X)}$$

Fluorescence detectors



Atmospheric monitoring

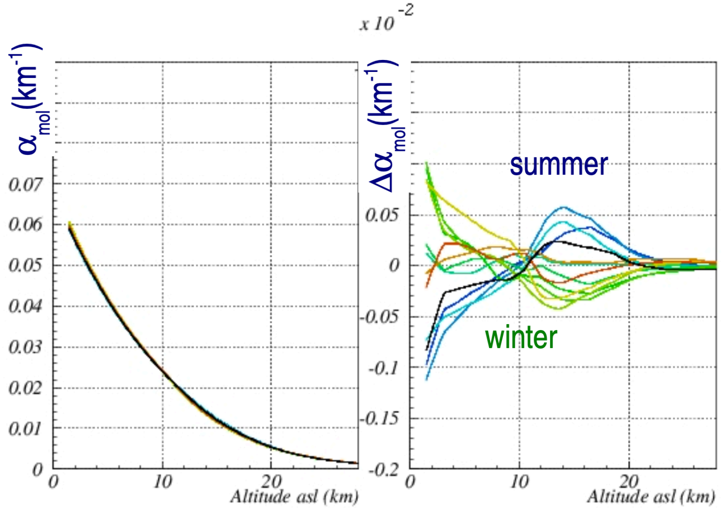


Transmission: $T(x) = e^{-\tau}$

Optical Depth (OD): $\tau = \int_0^X \alpha(r)\, dr = \tau_{molec} + \tau_{clouds} + \tau_{aerosol}$

Attenuation coefficient: $\alpha = \sigma * N(x)$

Attenuation Length: $\Lambda = 1/\alpha$



Molecular attenuation:

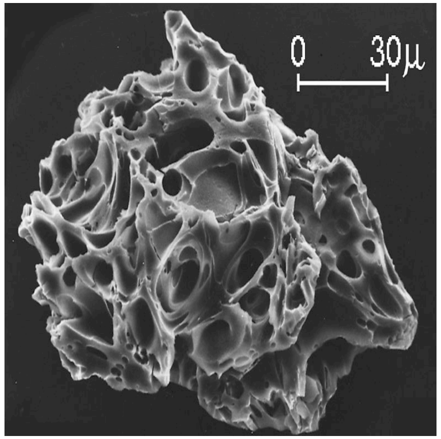
size of molecules << distance between molecules << light wavelength
0.1 nm << 5 nm << 300-400 nm

elastic (Rayleigh) or inelastic (Raman)
Very little dependence on molecular density variations

Aerosols attenuation:

size of spheres > light wavelength
1000nm > 300-400 nm

Most variable term contributing to transmission
Need for extensive monitoring with different instrumentation

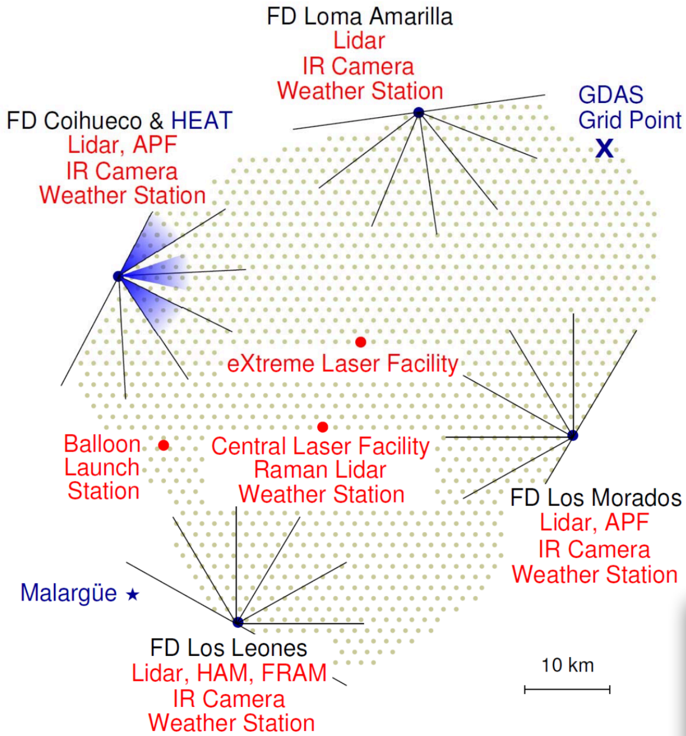


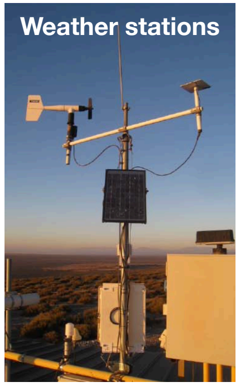
Smoke (landfires)
dust
sand (windborn)

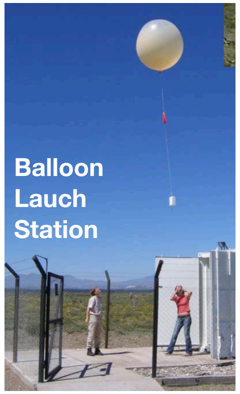
Clouds

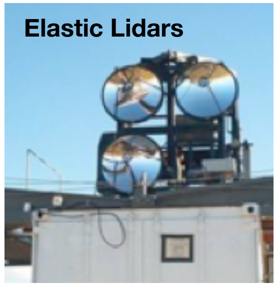
false profiles (holes/bumps) can be induced by absorption of light in clouds or side-scattering of Cherenkov beam

Atmospheric monitoring at Auger







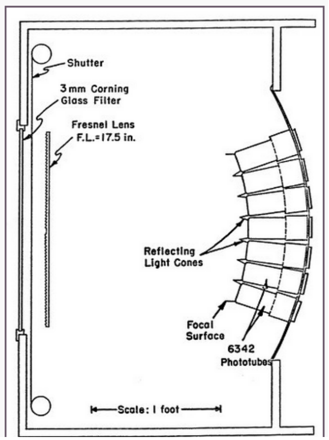


Category	Variable	Frequency	Instrument(s)
State	At ground: pressure, temp., wind, humidity	5 min	Weather stations
	Profile: pressure, temp., humidity	3 h	GDAS[a]
Aerosols	Vert. optical depth (z)	Hourly	CLF, XLF + FD
	Phase function	Hourly	2 APF units
	Ångström coefficient	Hourly	FRAM (HAM)
Clouds	Presence in FD pixels	15 min	4 cloud cameras
	Behind FD sites	15 min	4 lidar stations
	Along select tracks	Avg. 1/night	FRAM, lidar
	Above CLF/XLF	Hourly	CLF, XLF + FD

The old ones…

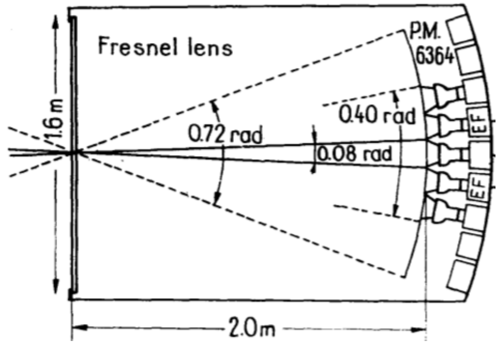
Cornell (USA, 1964-67)

- ✓ triangle of stations at 11, 16, 12 km
- ✓ in 1965, imaging system with mosaic segments
- ✓ too bad atmosphere
- ✓ too small lenses



INS-Tokyo (Japan, 1968)

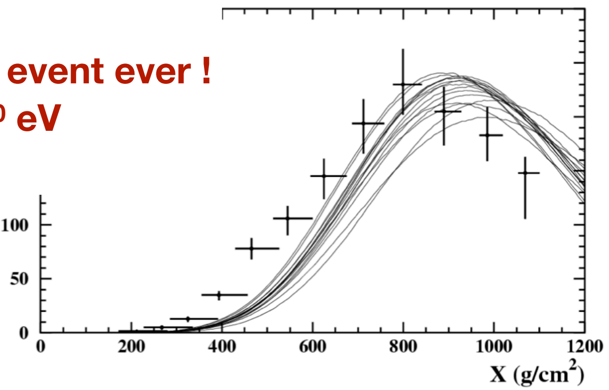
- ✓ Fresnel lens 1.6 m diameter + 27 PMTs in the focal plane
- ✓ **first fluorescence light from EAS> 5 10^{18} eV**
- ✓ technical problem with lenses



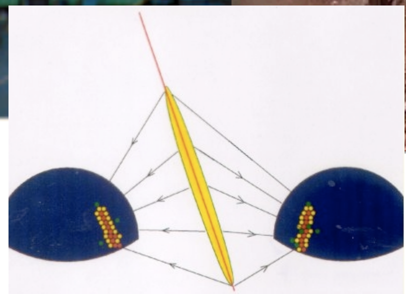
Fly's Eye (Utah, 1981-93)

- ✓ first array: 67 modules each with a spherical mirror (1.6 m diameter) + 12-14 PMTs, 5x5^0 sky region
- ✓ second array: 36 modules at 3.4 km from the other

largest event ever !
$3.2\ 10^{20}$ eV

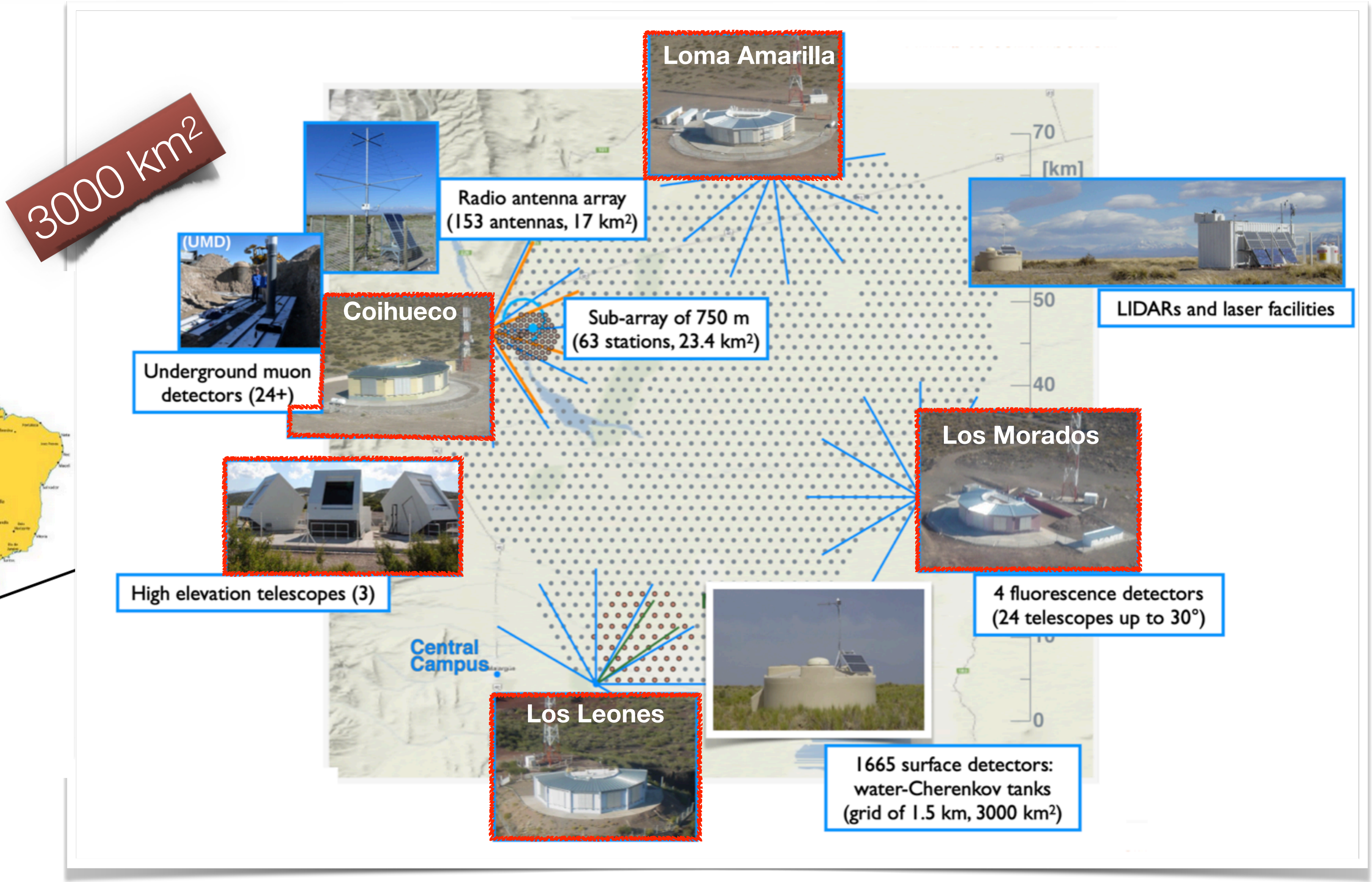


…more recent ones…



- **HiRes** (Utah, 1994-2004)
  - ✓ HR-I: 21 mirrors, 360^0 in azimuth, 3-17^0 in elevation
  - ✓ HR-II: 42 mirrors, 360^0 in azimuth, 3-33^0 in elevation
  - ✓ can see showers up to ~ 40 km

The hybrid approach: Pierre Auger Observatory



- 1661 Water-Cherenkov stations: SD1500 : 1600, 1.5 km grid; SD750: 61, 750 m grid
- 4 Fluorescence Sites: 24 telescopes, 1-30⁰ FoV + 3 High Elevation Telescopes, 30-60⁰ FoV
- Engineering arrays: 153 Radio antennas (AERA); 24 Underground Muon Detectors (UMD)

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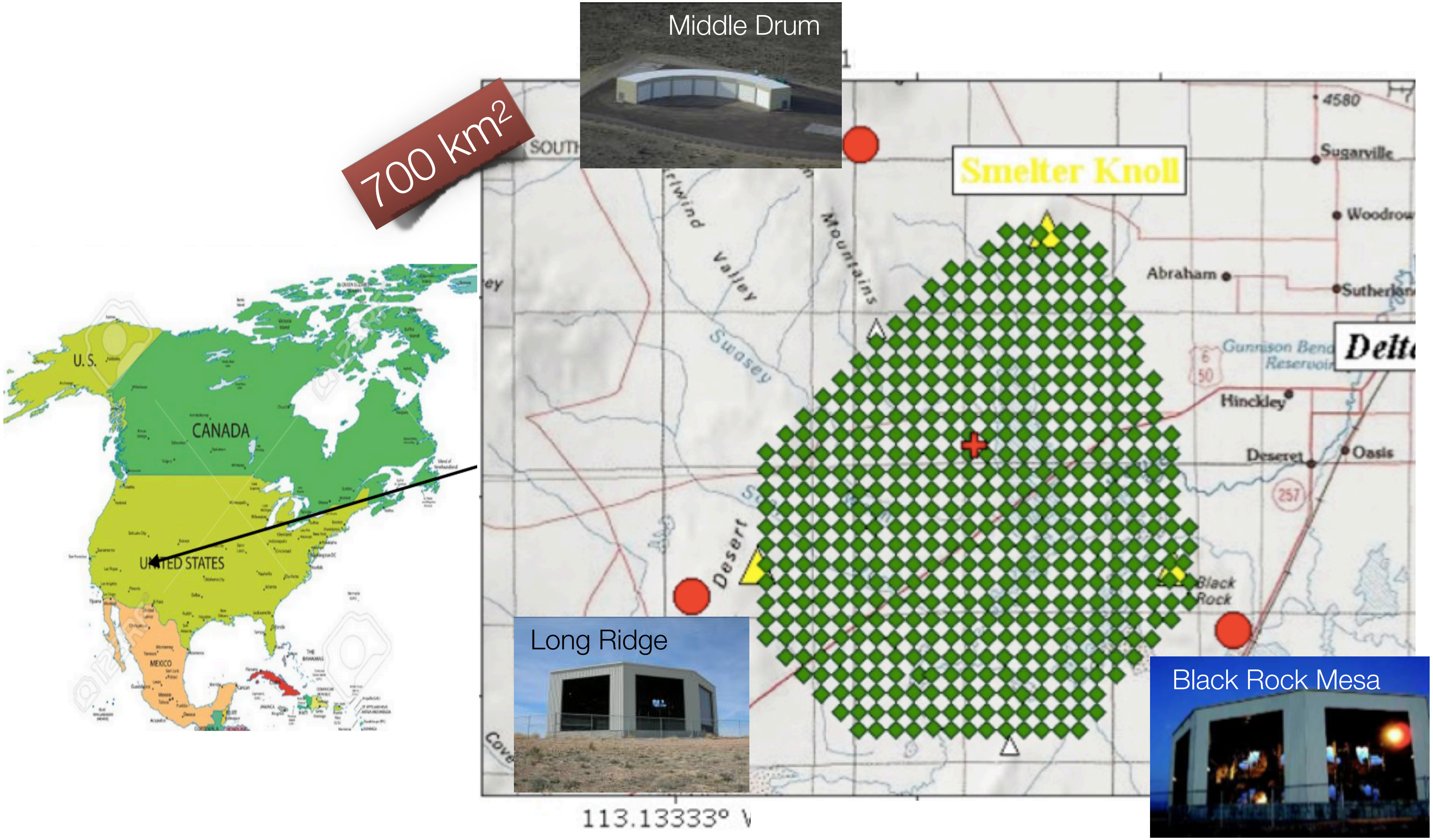
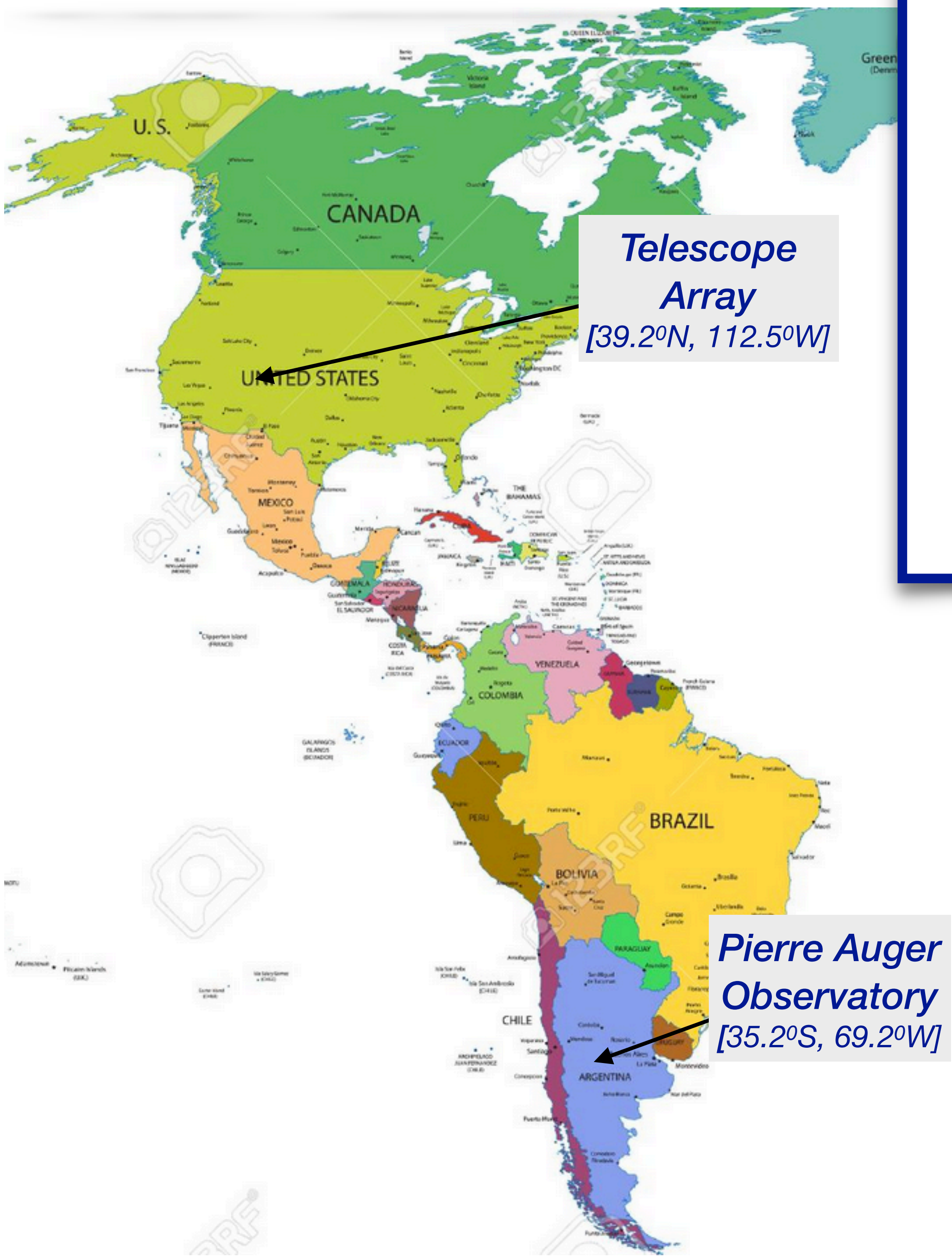
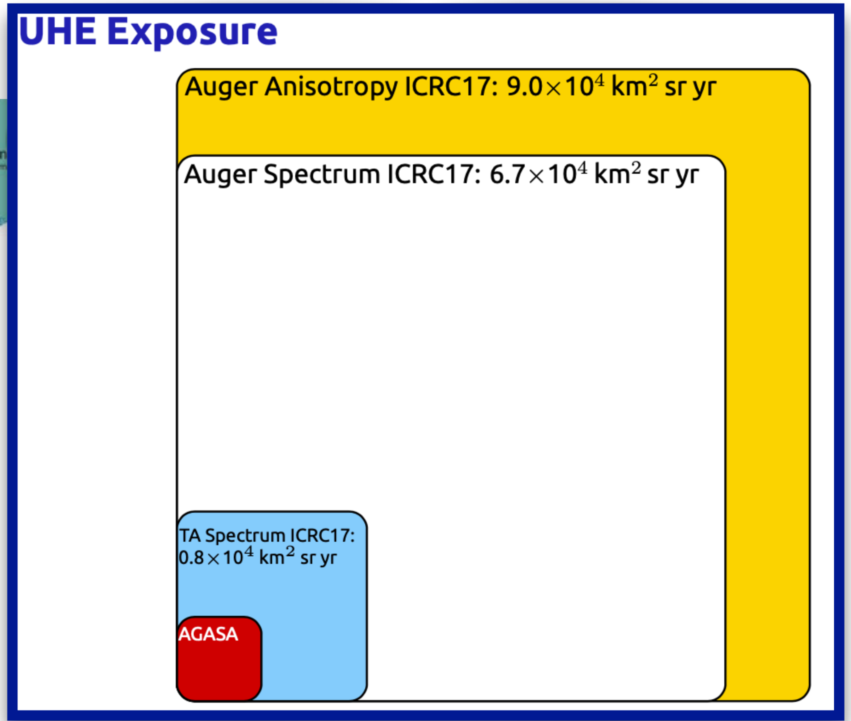
The hybrid approach: Telescope Array

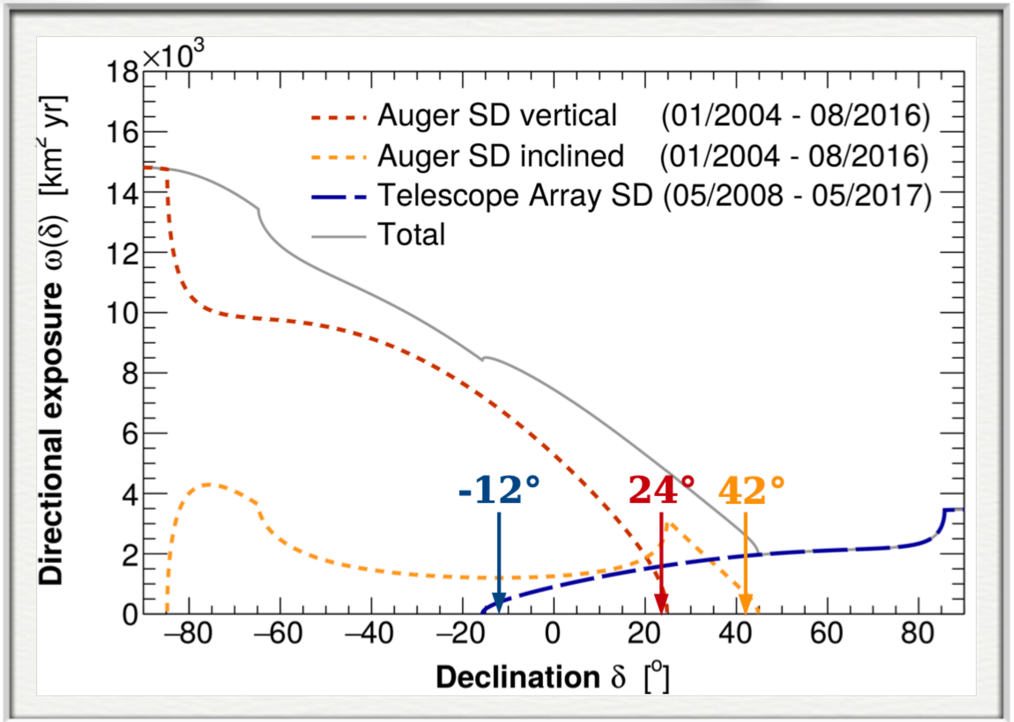


- 507 plastic scintillator detectors: 1.2 km grid, 3000 km^2
- 3 Fluorescence Sites: 38 telescopes, 3-31^0 FoV (MD: refurbished FD from HiRes, LR,BR: new FDs]

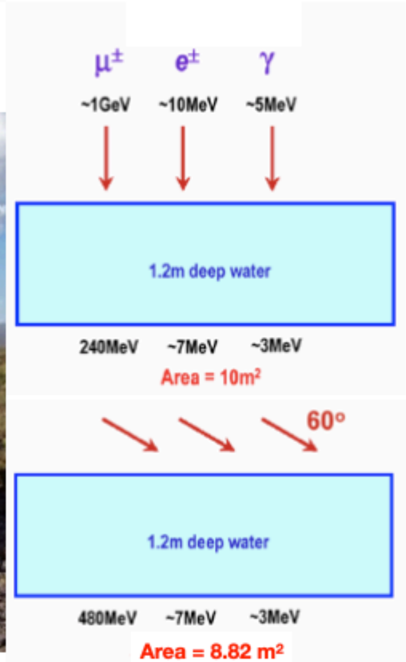
UHECR detectors

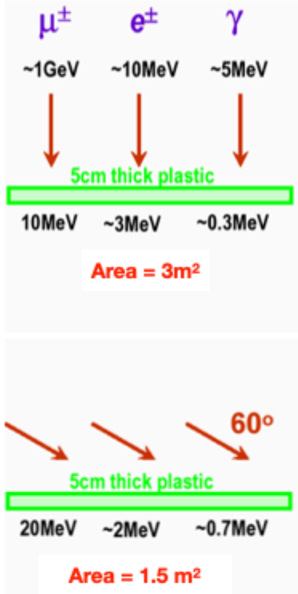






Surface detectors





1.2 m deep —> 3.3 X_0

Gamma flux ~ 1 order of magnitude higher than e± flux

Muon signal enhanced in proportion to water thickness: vertical muons deposit ~240 MeV

Volume detector: $$A = \pi R^2 cos\theta + 2Rhsin\theta$$
$$= 10.2\ cos\theta + 4.3\ sin\theta\ m^2$$

Good sensitivity to horizontal showers (neutrino signature)

1661 stations, separation 1500 m (750m in Infill)

5 cm deep —> 0.12 X_0

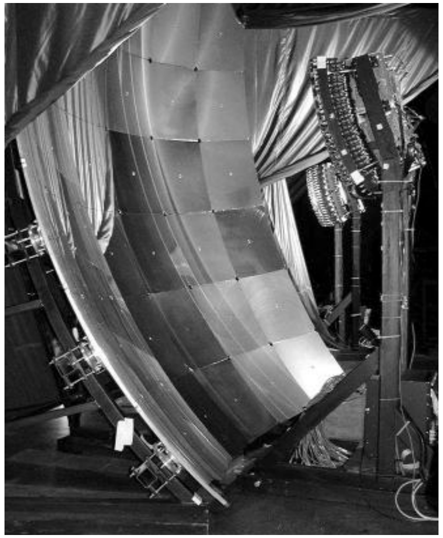
More sensitive to the flux of e±

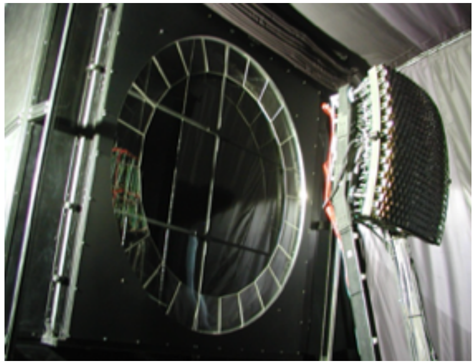
Thin detector: μ energy deposit ~10 MeV, negligible contribution

$$A = 3.0\ cos\theta\ m^2$$

507 stations, separation 1200 m

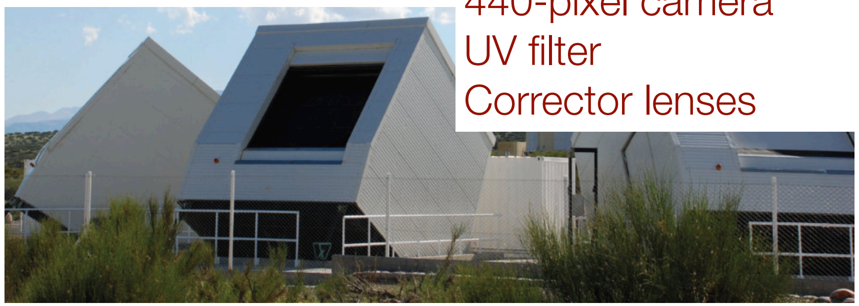
Fluorescence detectors





24 FD in 4 station
+3 high elevation mirrors in HEAT

10 m^2 mirror
440-pixel camera
UV filter
Corrector lenses



48 FD in 3 stations

Mirrors:
14 5.2 m^2 mirrors in site Middle Drum
12 6.8 m^2 mirrors in sites Black Rock Mesa and Long Ridge
256 pixels/camera
+ 10 high elevation mirrors in TALE

Radio antennas - AERA at Auger

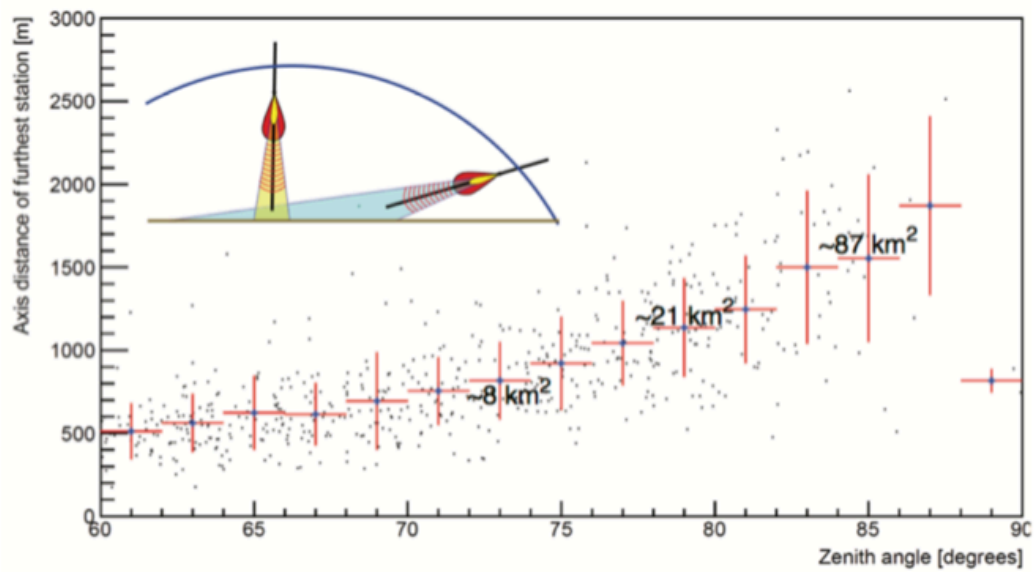
~150 antennas

~17 km^2

30-80 MHz

E (30-80 MHz) =15.8MeV@10^{18} eV

inclined air showers can be detected by a sparse antenna grid (> 1 km mutual distance)

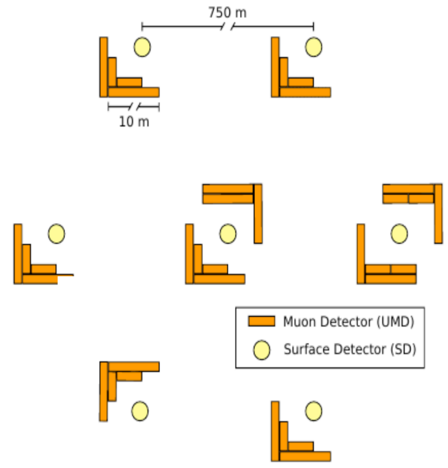


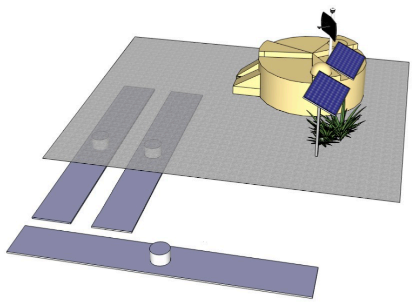
Direct muon detection

61 muon detectors shielded by 2.3 m of soil

Each detector: 30 m^2 - 23.4 km^2 instrumented

750 m spacing

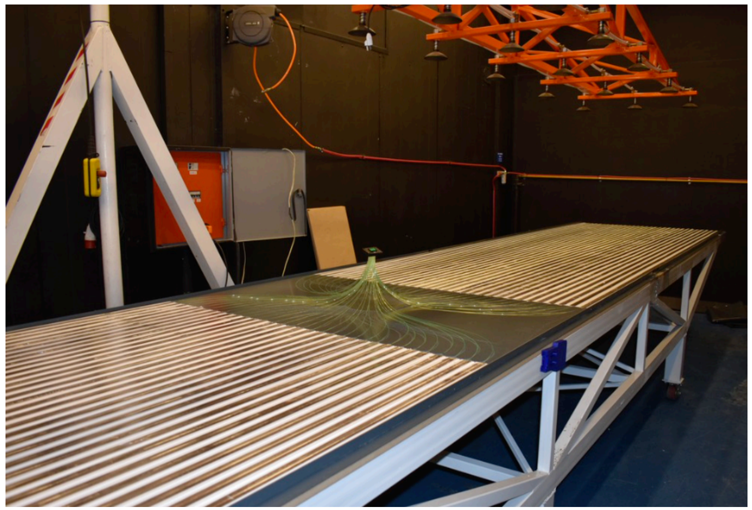




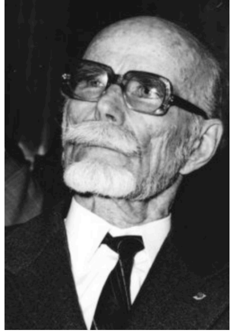
Direct measure of muons

Full efficiency study of the lower energy region (transition)

SD-750m	SD-433m
23.5 km^2	1.9 km^2
61 WCDs	19 WCDs
E_{thr} 0.1 EeV	E_{thr} 0.03 EeV

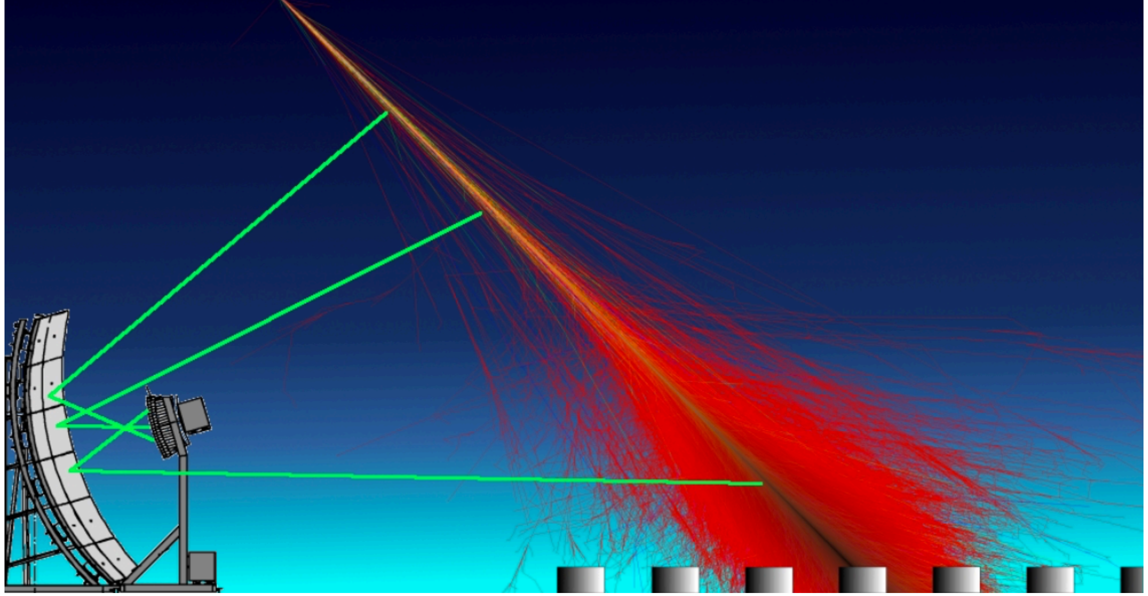


…very unusual labs !

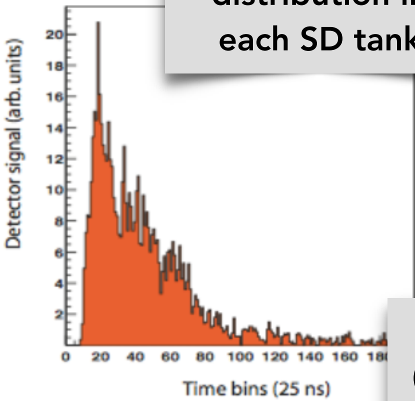


The Pierre Auger Observatory

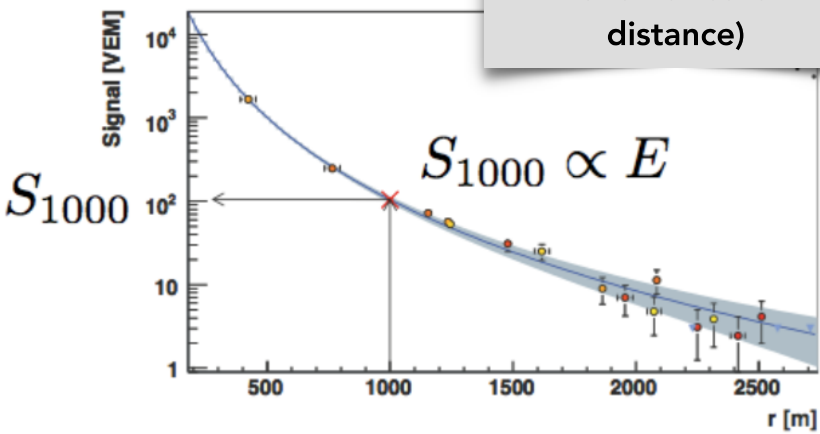
The hybrid approach

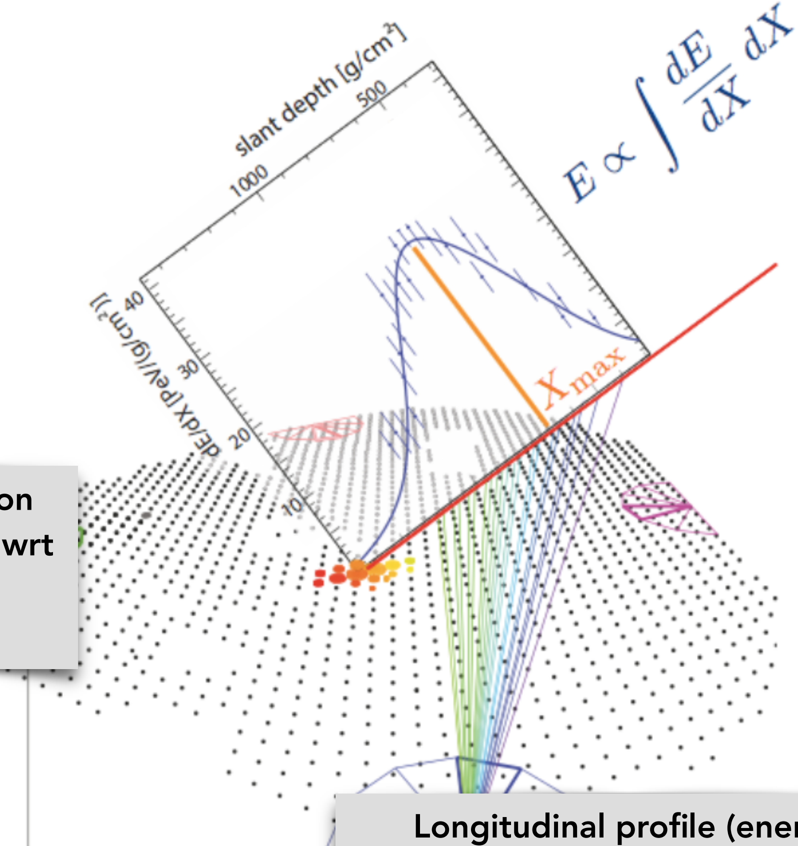


Arrival time distribution in each SD tank



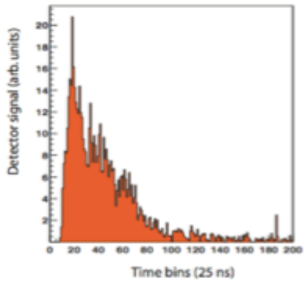
Lateral distribution (particle densities wrt shower core distance)

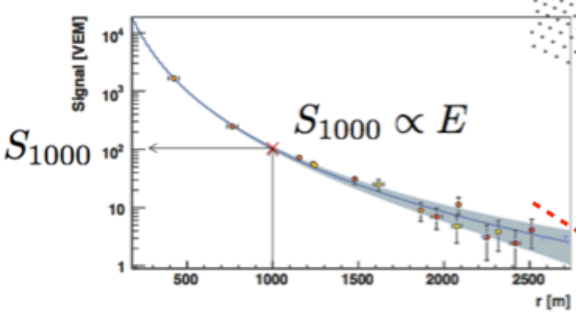


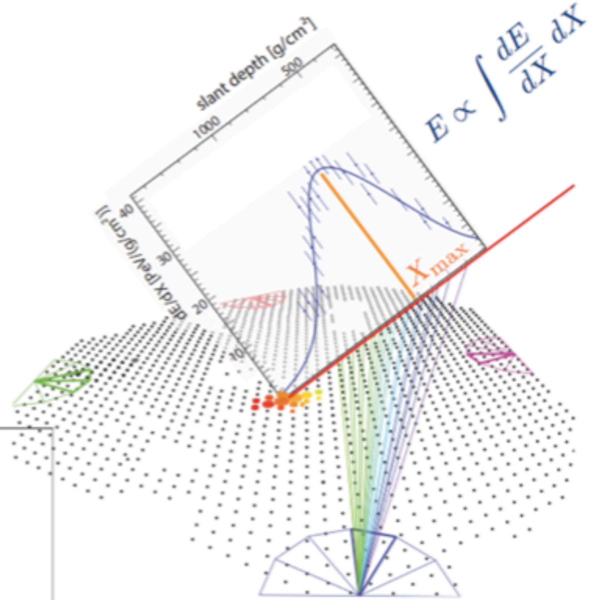


Longitudinal profile (energy release along shower path in atmosphere)

Energy calibration







2. calorimetric energy measurement (FD)
(~10-13% duty cycle)

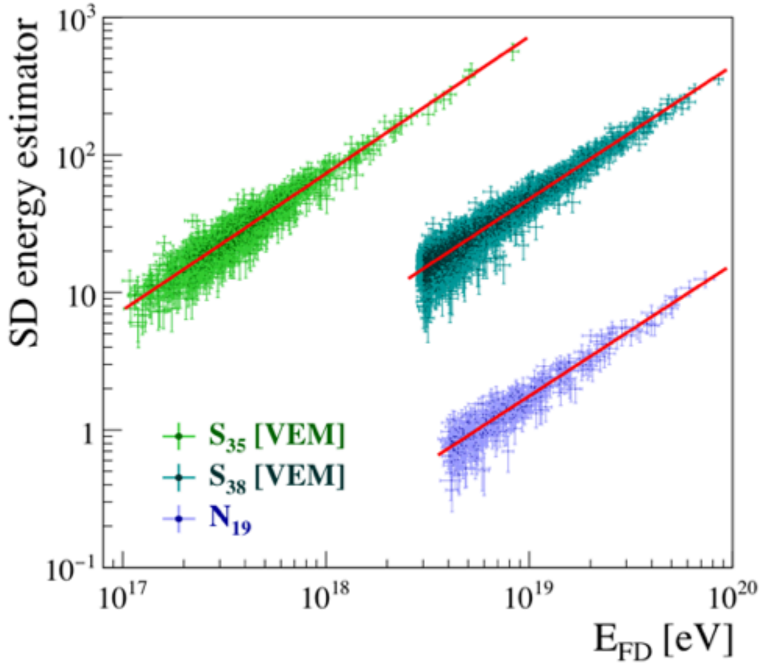
$$E_{cal} = \int_0^\infty dX \frac{dE}{dX}$$

3. evaluate the missing energy

$$E_{tot} = E_{cal} + E_{inv}$$

1. energy-related observable at ground (SD)

$$S_{r_{opt}} \propto E$$



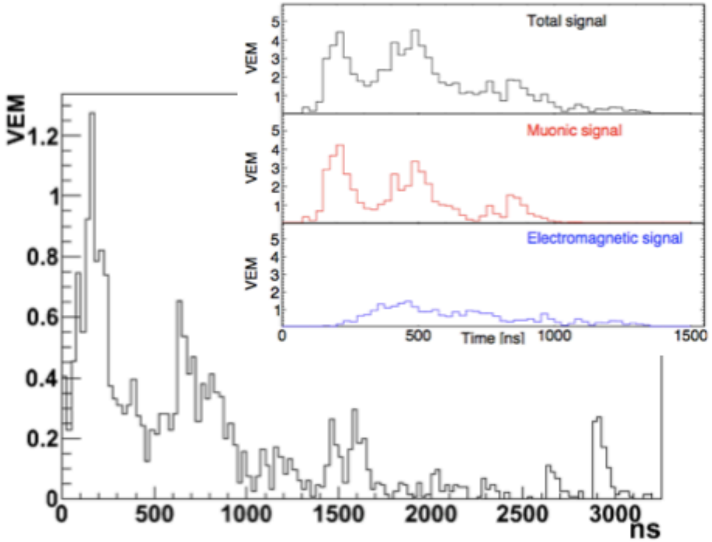
4. Correlation of S_{SD} with E_{FD}

Reconstructing the signals in SD

At station level:

➡Start time : depends on resolution of the GPS time-tagging system (10 ns) + FADC sampling accuracy (~7 ns) + fluctuation of the arrival time of the first particles (due to thickness of the shower front, density of particles therein, cross-section of the station)

➡Size of the signal (VEM) $\sigma_S^2 = f_S^2(\theta) \times S$

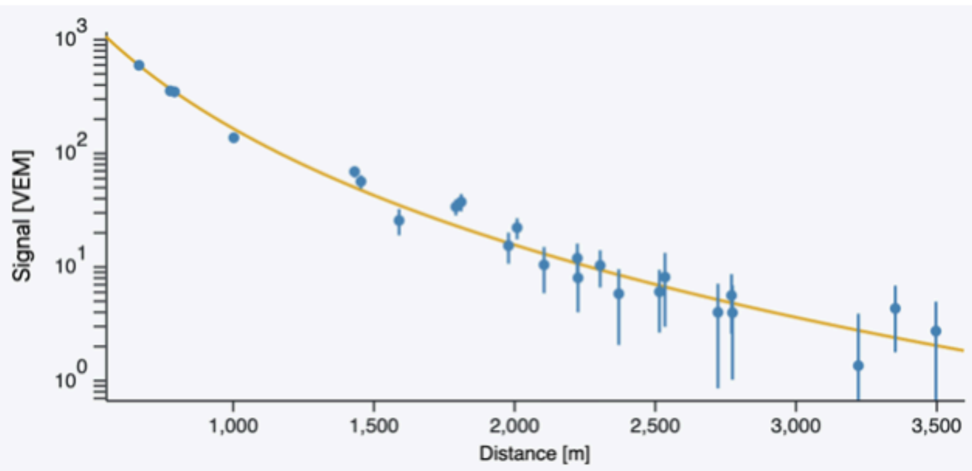


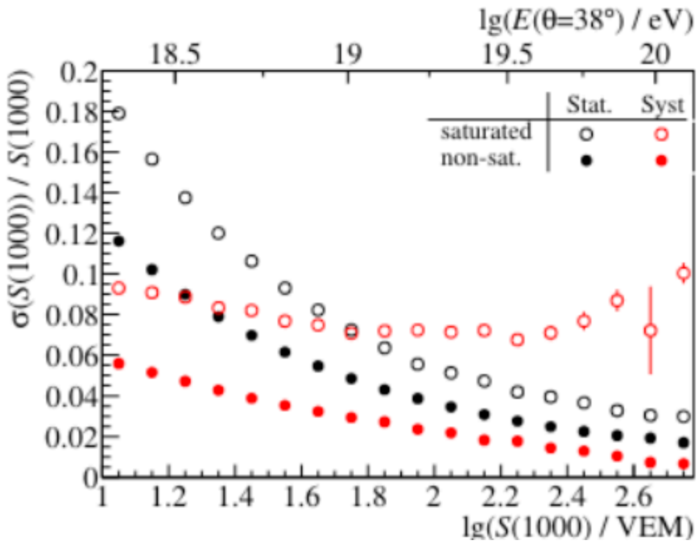
At event level:

From the timing: geometry of the shower **(arrival direction, core position)**

From the signals: lateral distribution

$$S(r) = S(r_{opt}) f_{LFD}(r) \qquad f_{LDF}(r) = \left(\frac{r}{r_{opt}}\right)^{\beta} \left(\frac{r + r_s}{r_{opt} + r_s}\right)^{\beta+\gamma}$$





The “invisible energy”: the Auger data driven approach

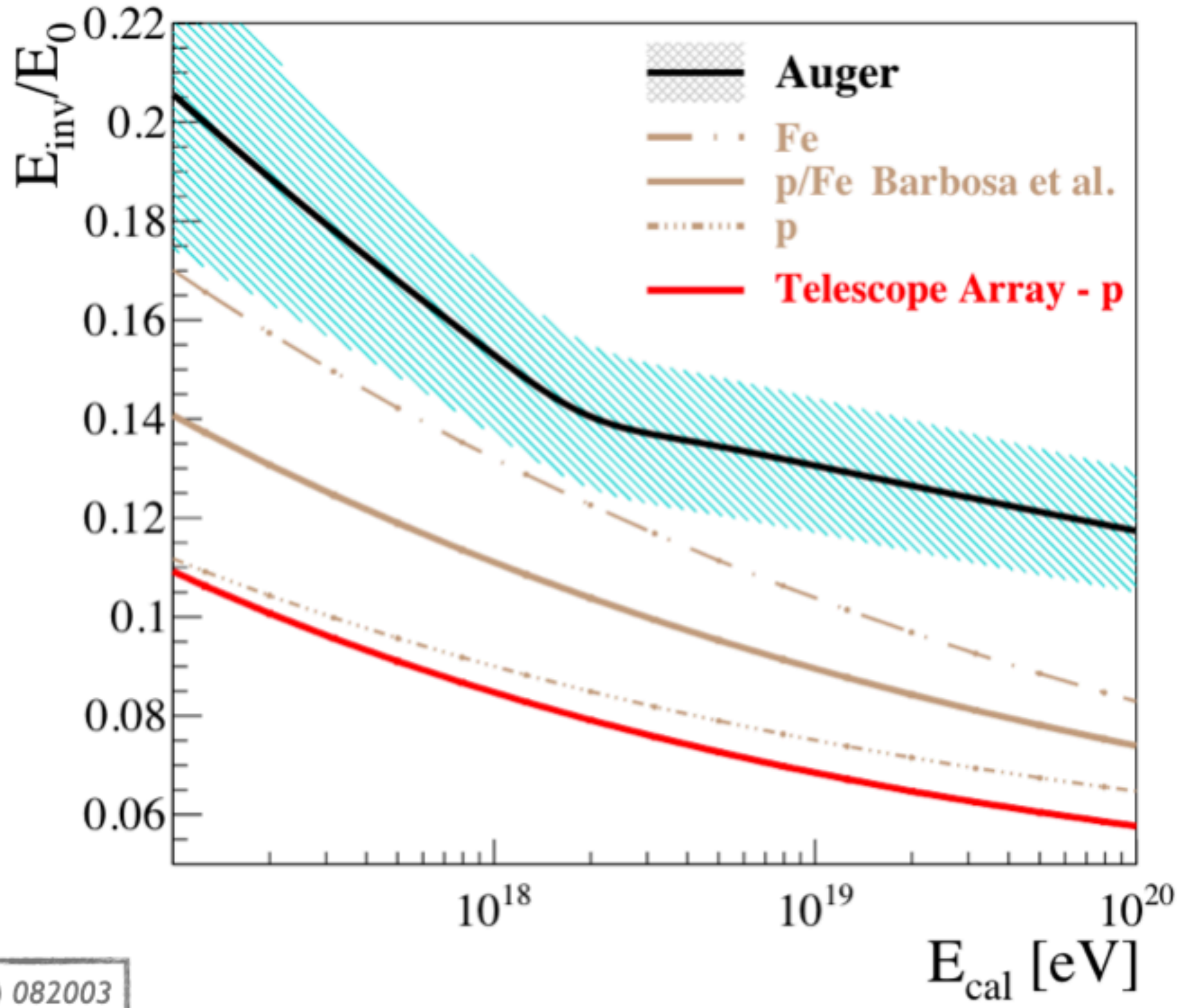
Inclined events (>60⁰)

$$E_{inv} = \epsilon_c^\pi N_\mu$$

Vertical events (<60⁰)

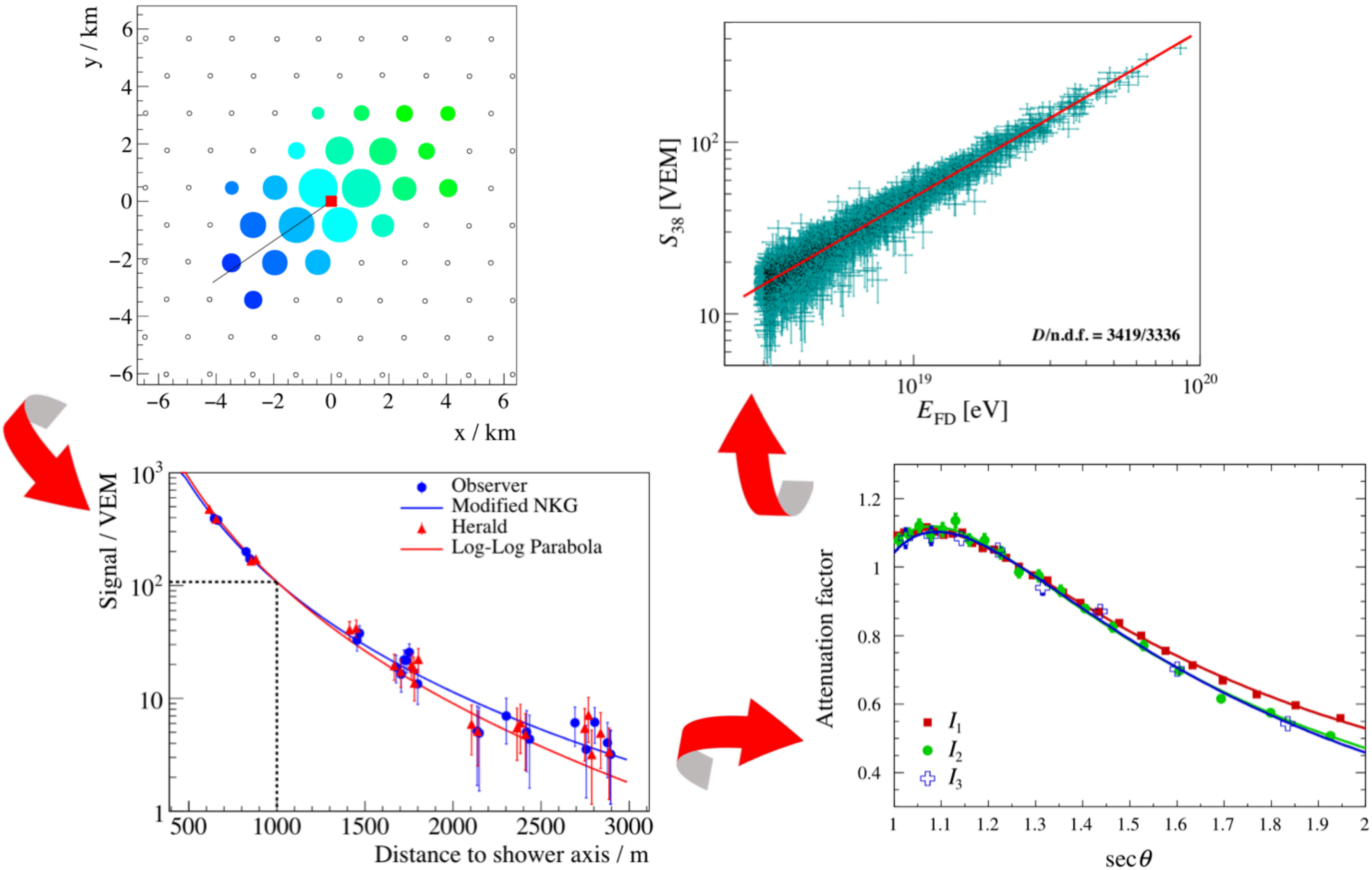
$$E_{inv}^A = \epsilon_c^\pi \left(\frac{E_0}{\epsilon_c^\pi}\right)^\beta A^{1-\beta} \qquad E_0 = \gamma_0(\Delta X) S(1000)^\gamma$$

$$E_{inv} \propto S(1000)^\gamma$$

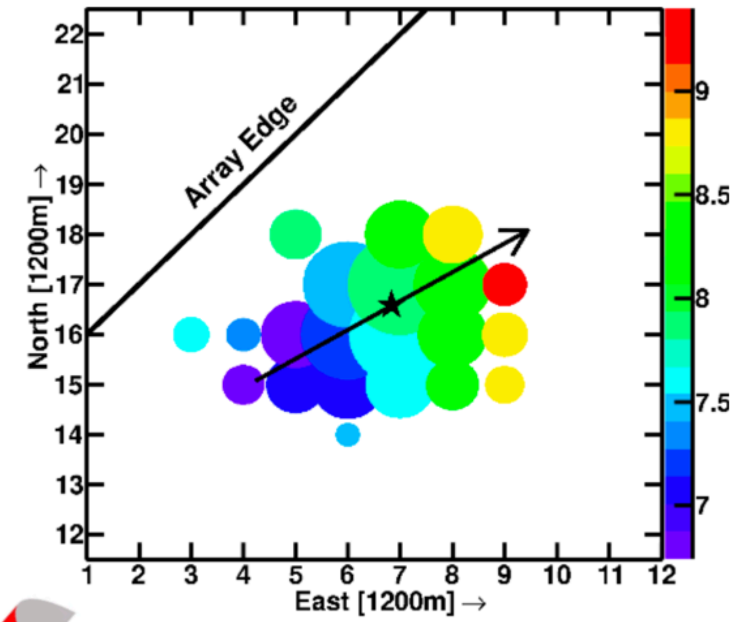


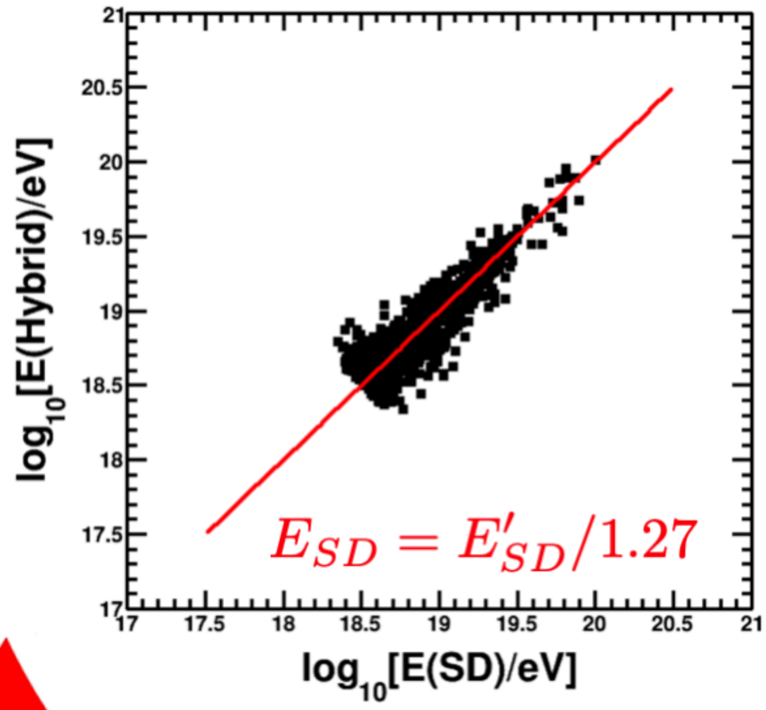
Auger Coll., Phys.Rev.D100 (2019) 082003

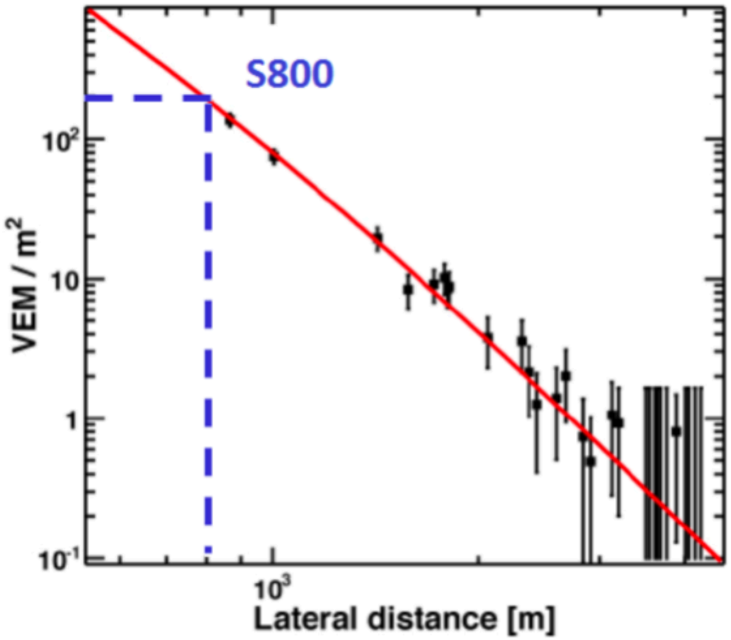
Energy calibration (Auger)

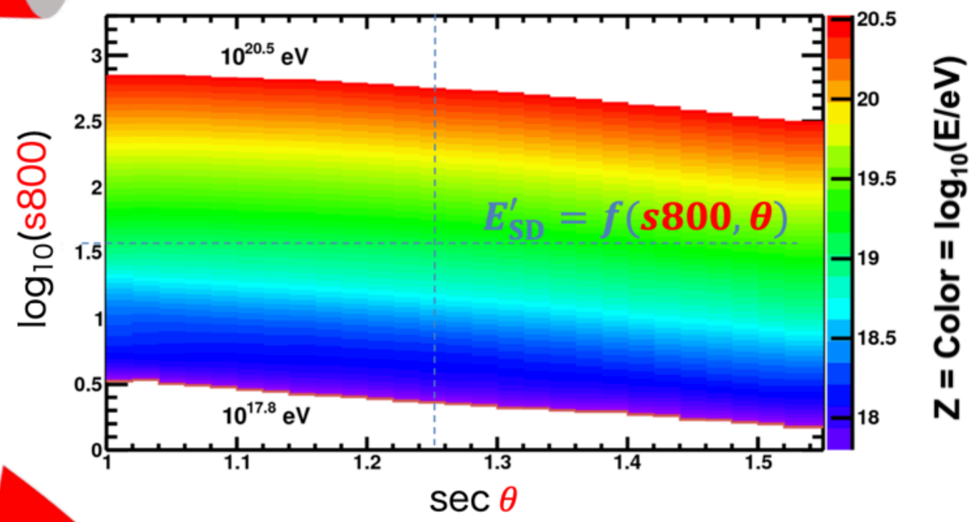


Energy calibration (TA)









[TA, EPJ Web.of Conf.210 (2019) 01001]

Auger Public Data Release

The Pierre Auger 2021 Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data presented at the 36th International Cosmic Ray Conference held in 2019 in Madison, USA, following the Auger Collaboration Open Data Policy. The release also includes 100% of weather and space-weather data collected until 31 December 2020.

This website hosts the datasets for download. A brief overview of the Pierre Auger Observatory and of the Auger Open Data is set out below. An online event display to explore the released cosmic-ray events, and example analysis codes are provided. An outreach section dedicated to the general public is also available.

Datasets

the released datasets and their complementary data

Visualize

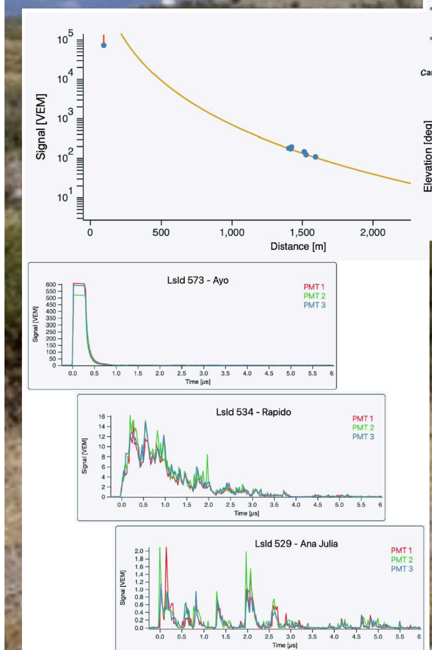
an online look at the released pseudo raw cosmic-ray data

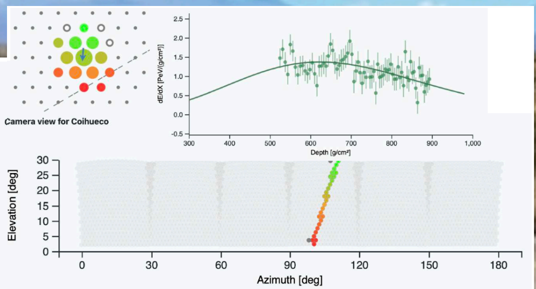
Analyze

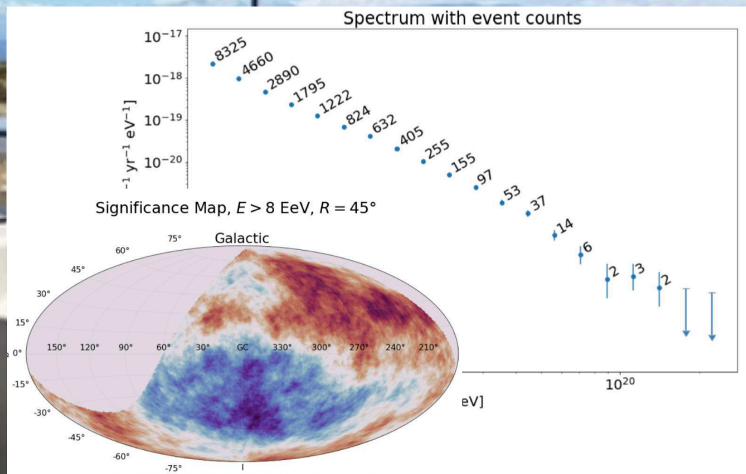
example analysis codes in online python notebooks to run on the datasets

Outreach

a page dedicated to the general public





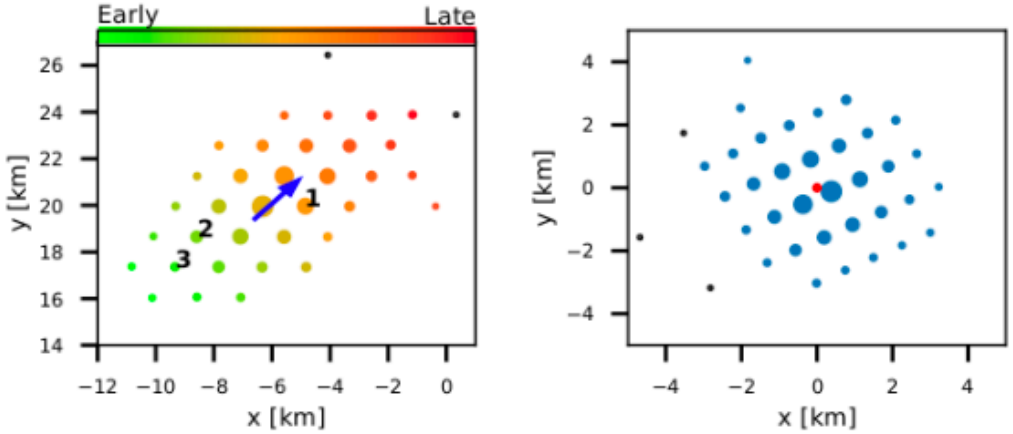


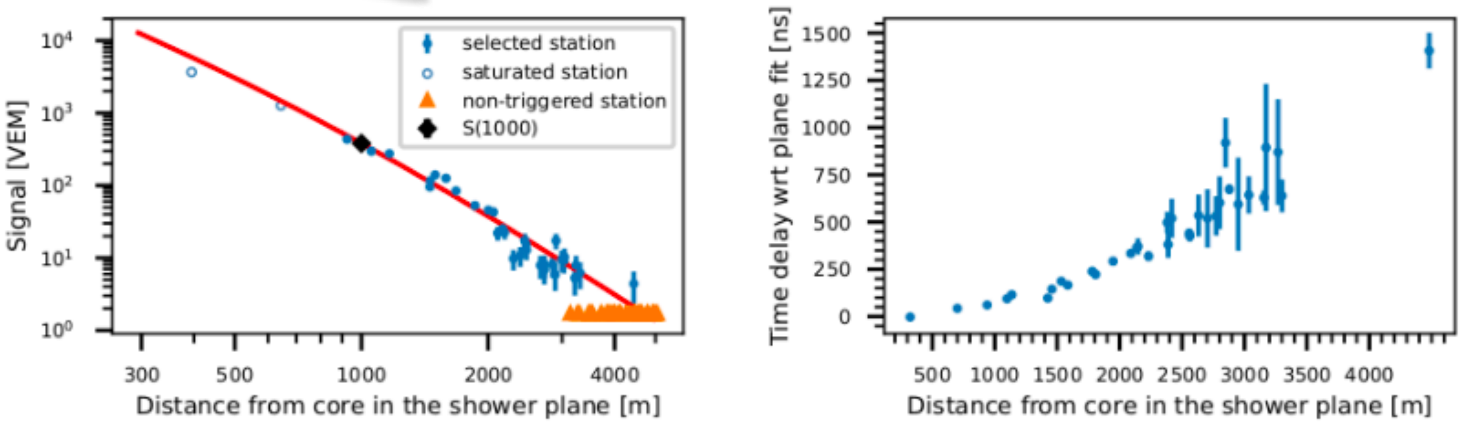
https://opendata.auger.org/

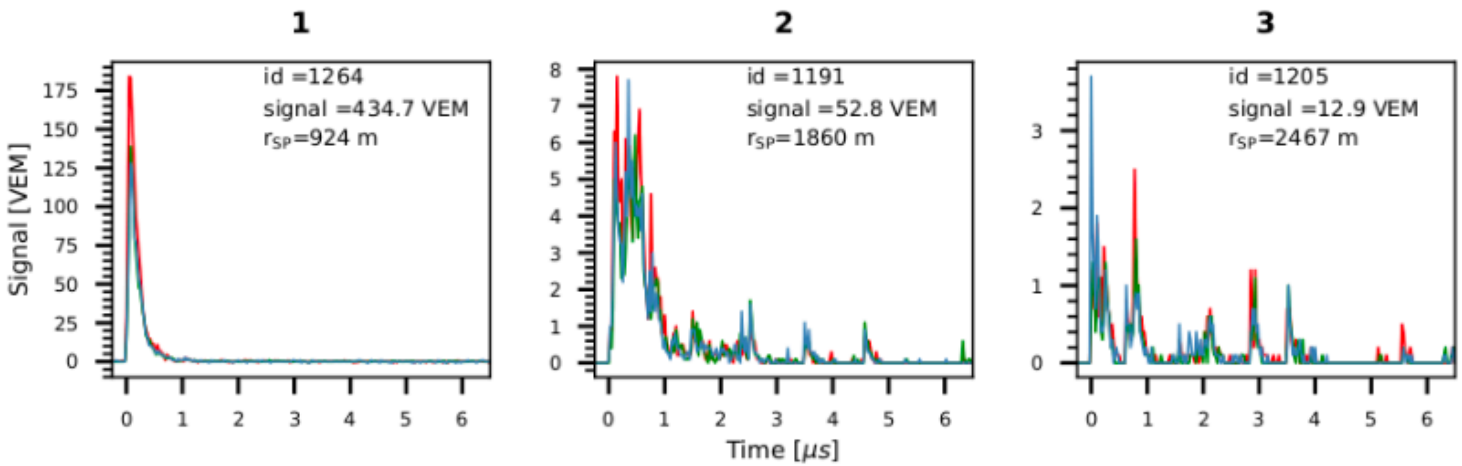
DOI:10.5281/zenodo.4487613

Example : an Auger SD event

Energy [EeV]	166±13
θ [deg]	58.6
φ [deg]	224.4
α [deg]	128.9
δ [deg]	-52.0
β	-2.0
$t_{1/2}(1000)$ [ns]	98±3
Multiplicity	34

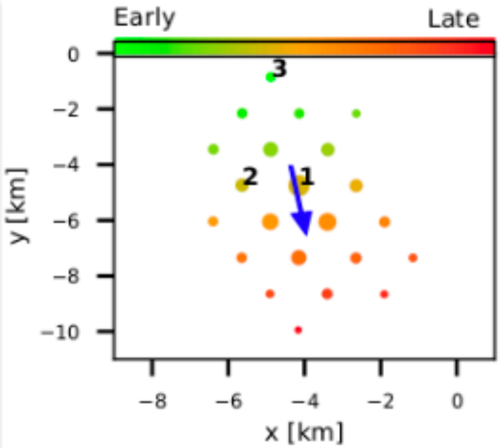


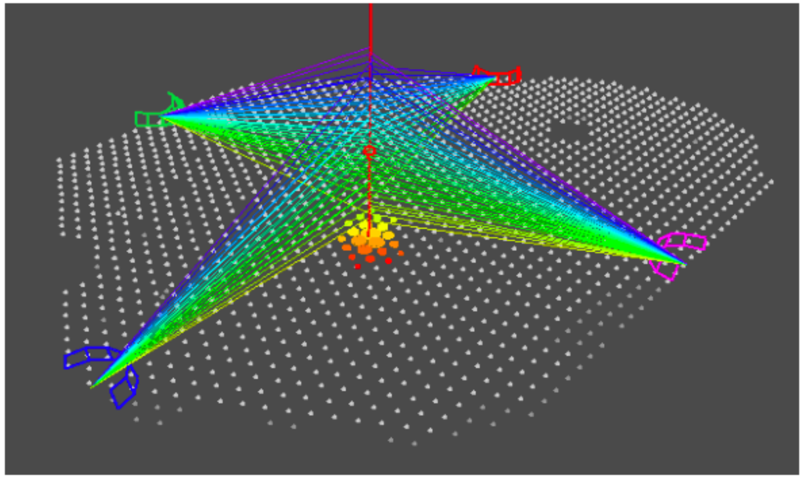


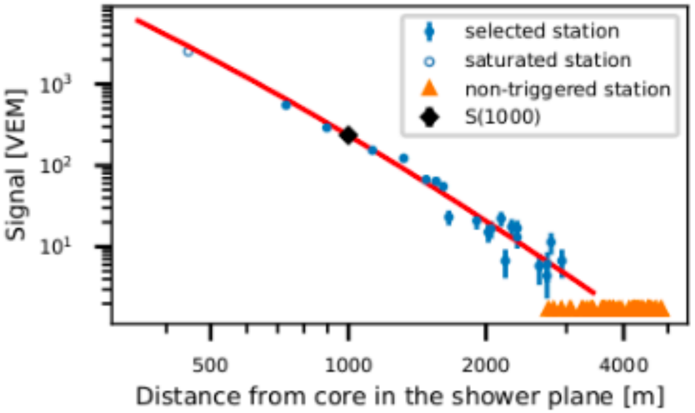


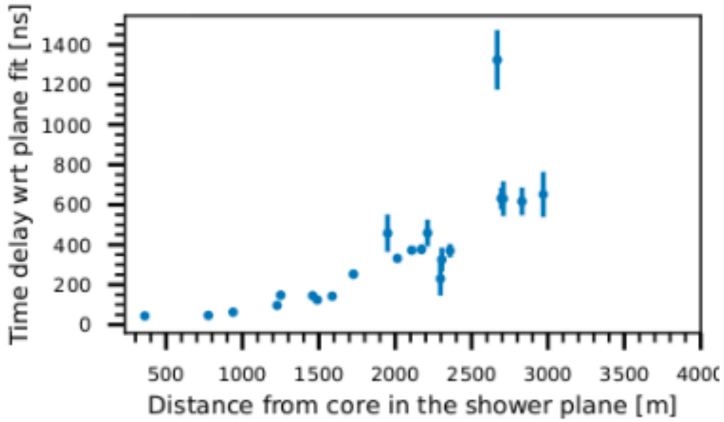
Example : an Auger multi-hybrid (4 FD) event

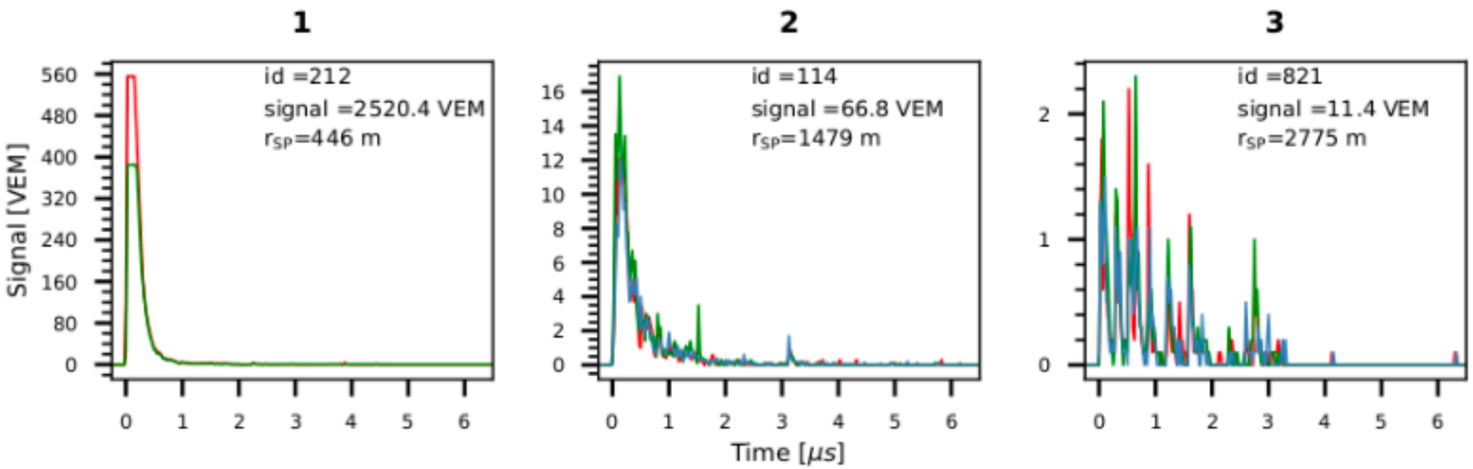
Energy [EeV]	82±8
θ [deg]	53.8
φ [deg]	100.6
α [deg]	324.5
δ [deg]	17.8
β	-2.1
$t_{1/2}(1000)$ [ns]	127±5
Multiplicity	22



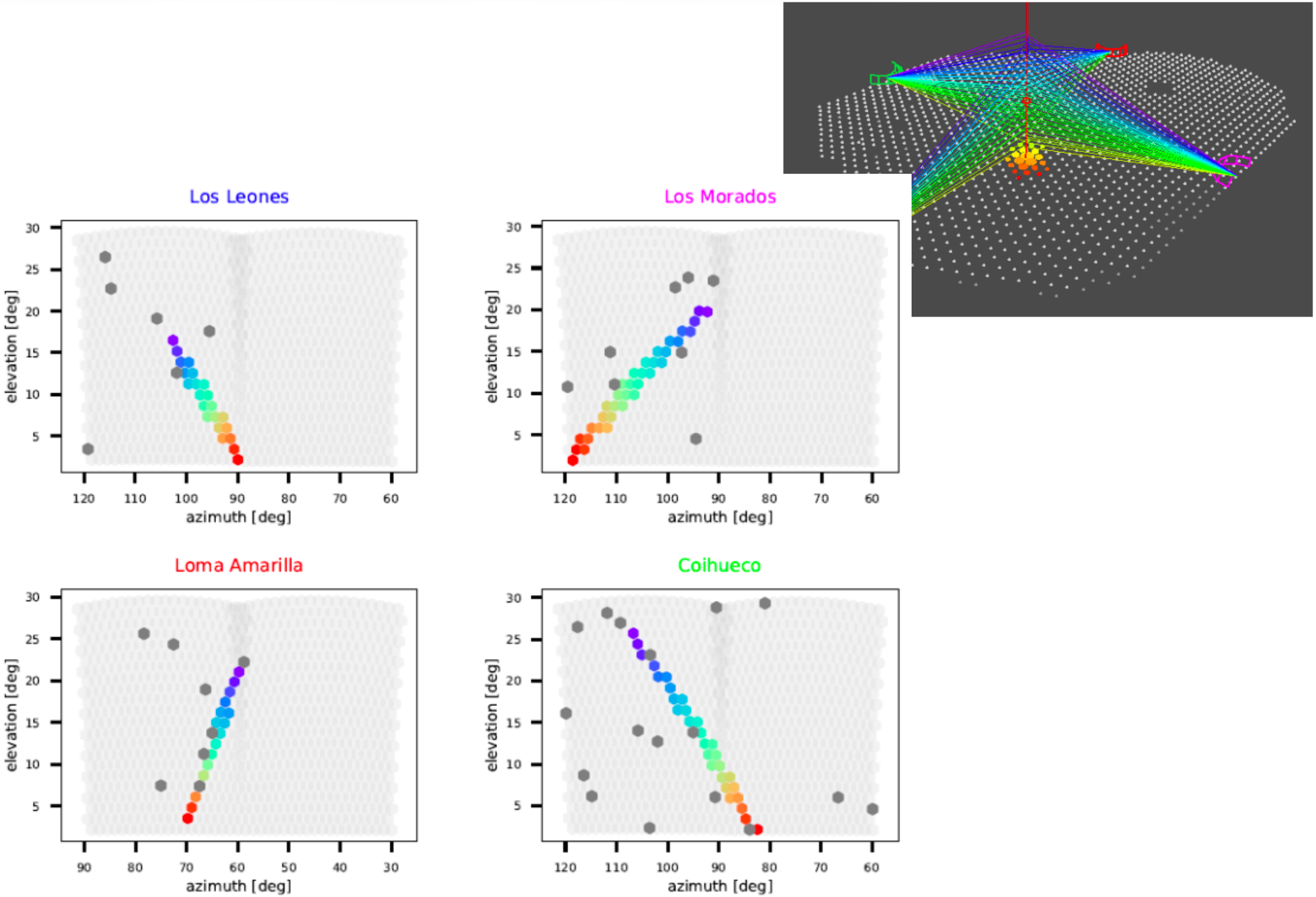




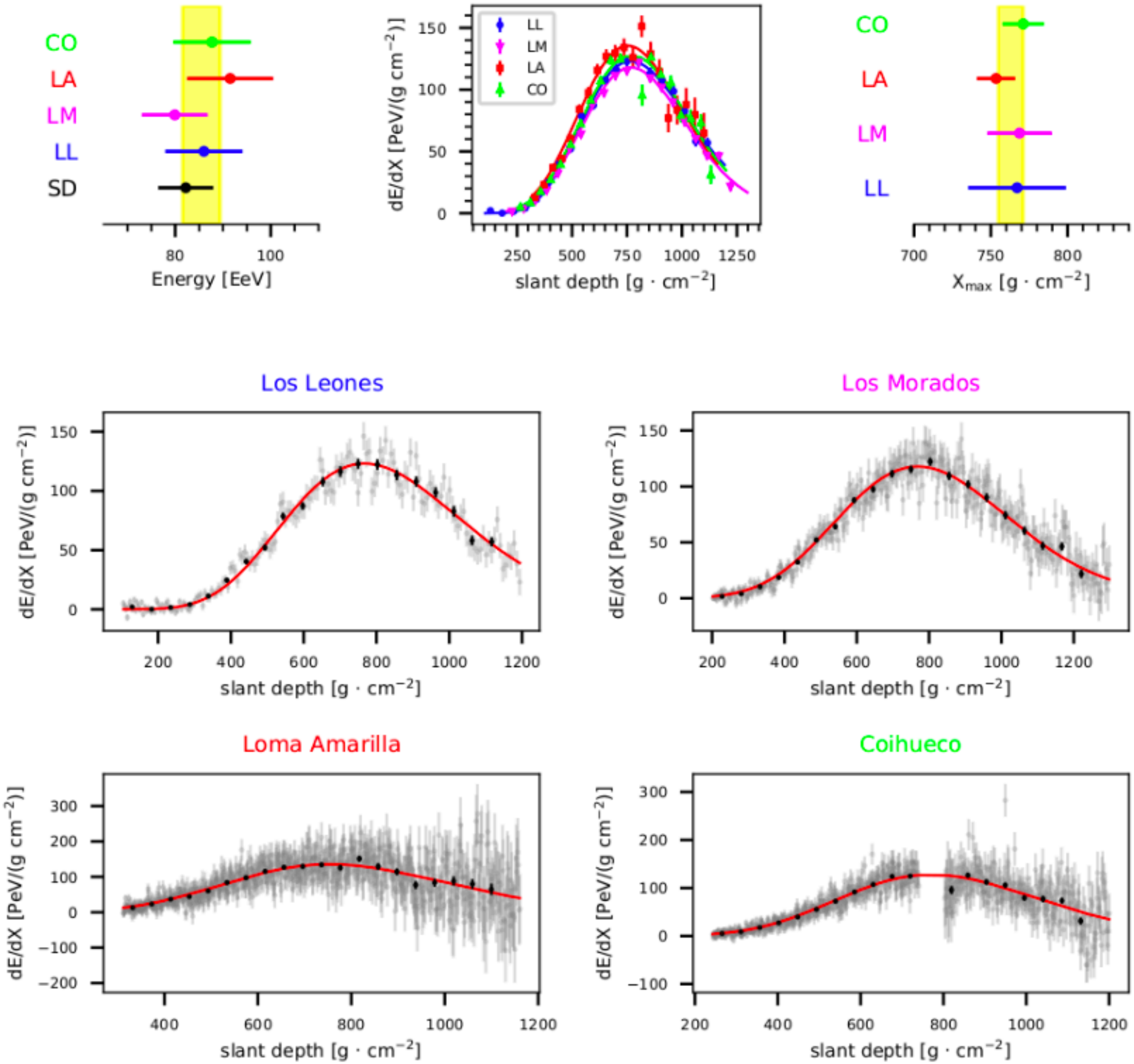




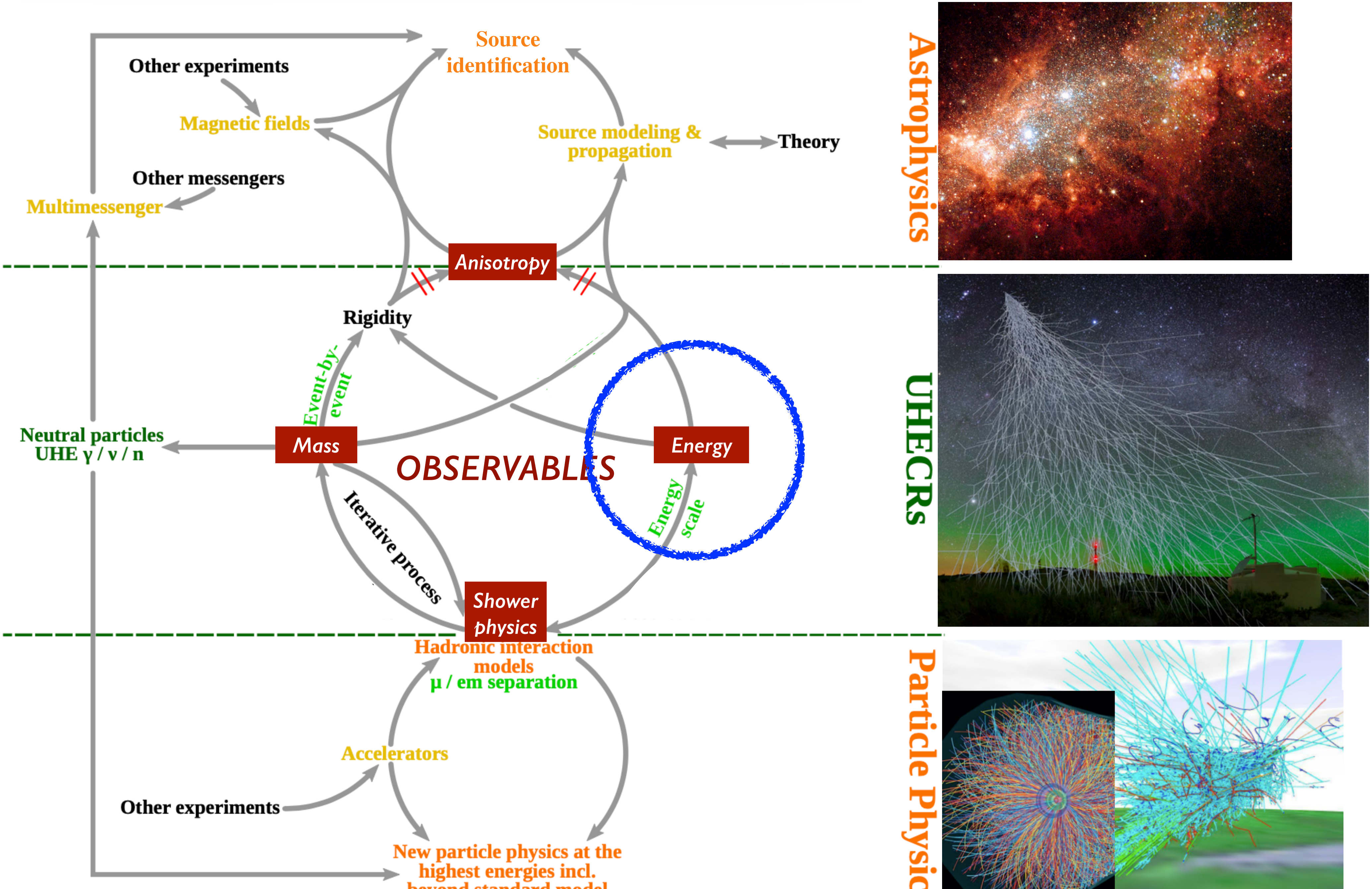
Example 4: an Auger multi-hybrid event



Example 4: an Auger multi-hybrid event



UHECRs (E>10^{17} eV) connections



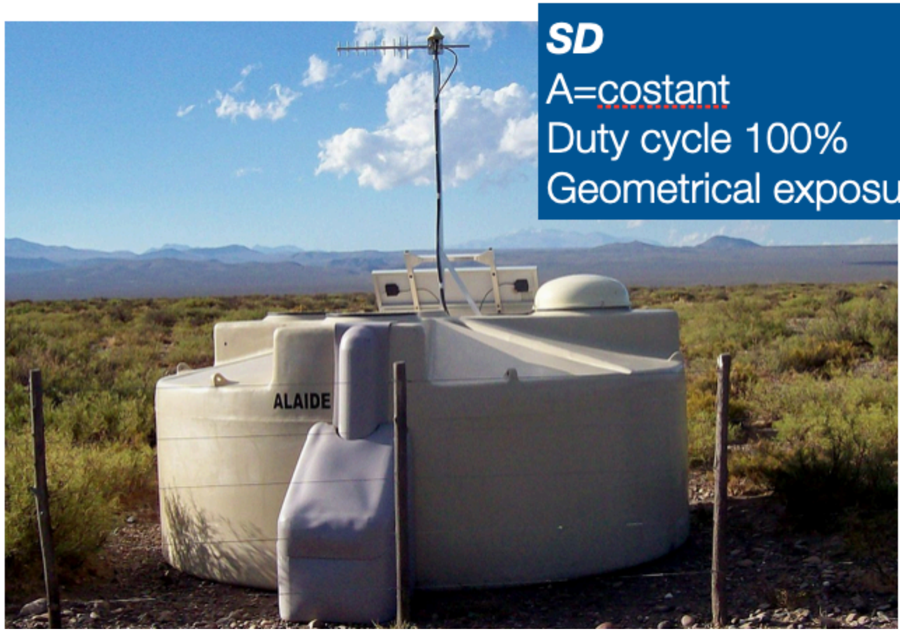
[modified from arXiv:2205.05845]

The energy spectrum

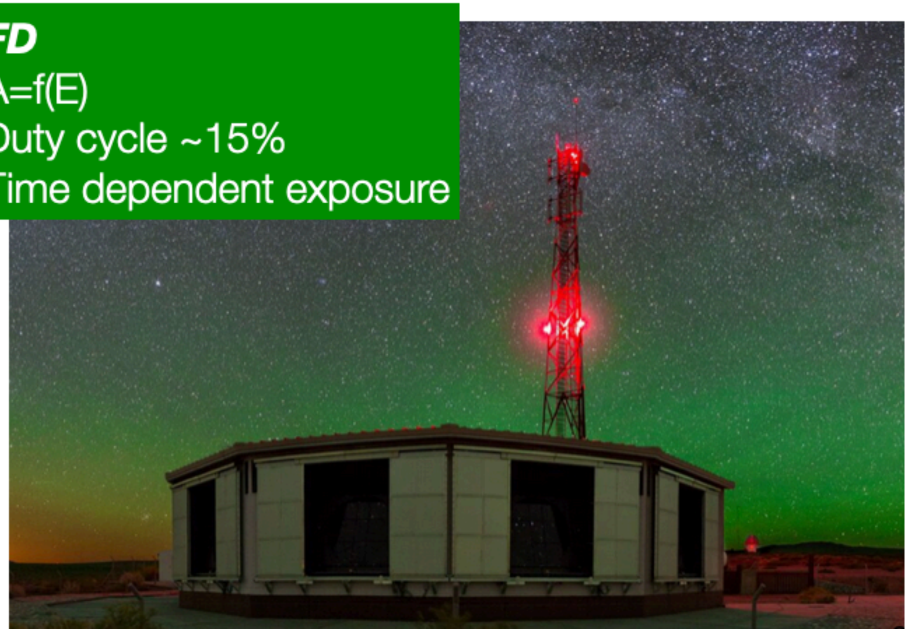
$$\Phi(E) = \frac{N(E, E+\Delta E)}{t\Omega A \Delta E} \equiv \frac{N(E, E+\Delta E)}{\epsilon \Delta E}$$

- N=number of incident particles between E and ΔE
- t= measurement time
- A= area of detection
- Ω=solid angle
- ε= exposure

SD
A=costant
Duty cycle 100%
Geometrical exposure



FD
A=f(E)
Duty cycle ~15%
Time dependent exposure

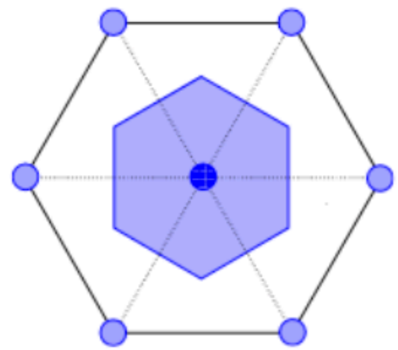


The exposure

Surface detector

- ✓ SD fully efficiency above 3 EeV
- ✓ Hexagonal grid of SD exploited for geometrical evaluation of the aperture:
  - detector cell area a_{cell}~4.6 km^2 sr for $\vartheta<60^0$
  - Ncell(t) monitored every second
- ✓ A=Ncell(t) x a_{cell}
- ✓ ϵ= array aperture x number of live seconds

$$\epsilon = t \int_0^{2\pi} \int_{cos\theta_{min}}^{1} cos\theta A \; dcos\theta = A \; t\pi(1 - cos^2\theta_{min})$$



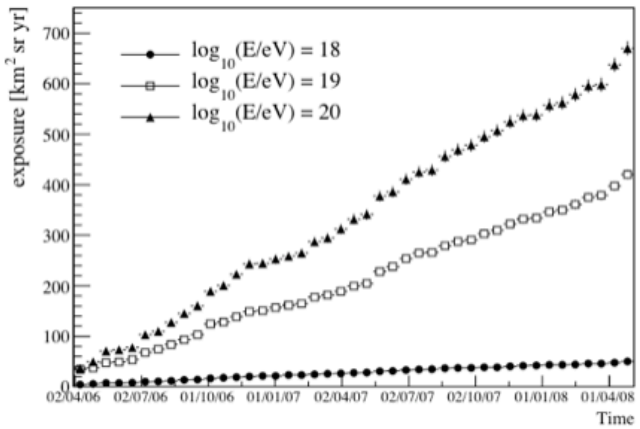
e.g. 01/01/2004 - 31/08/2018

(60,400±1,810) km² sr yr

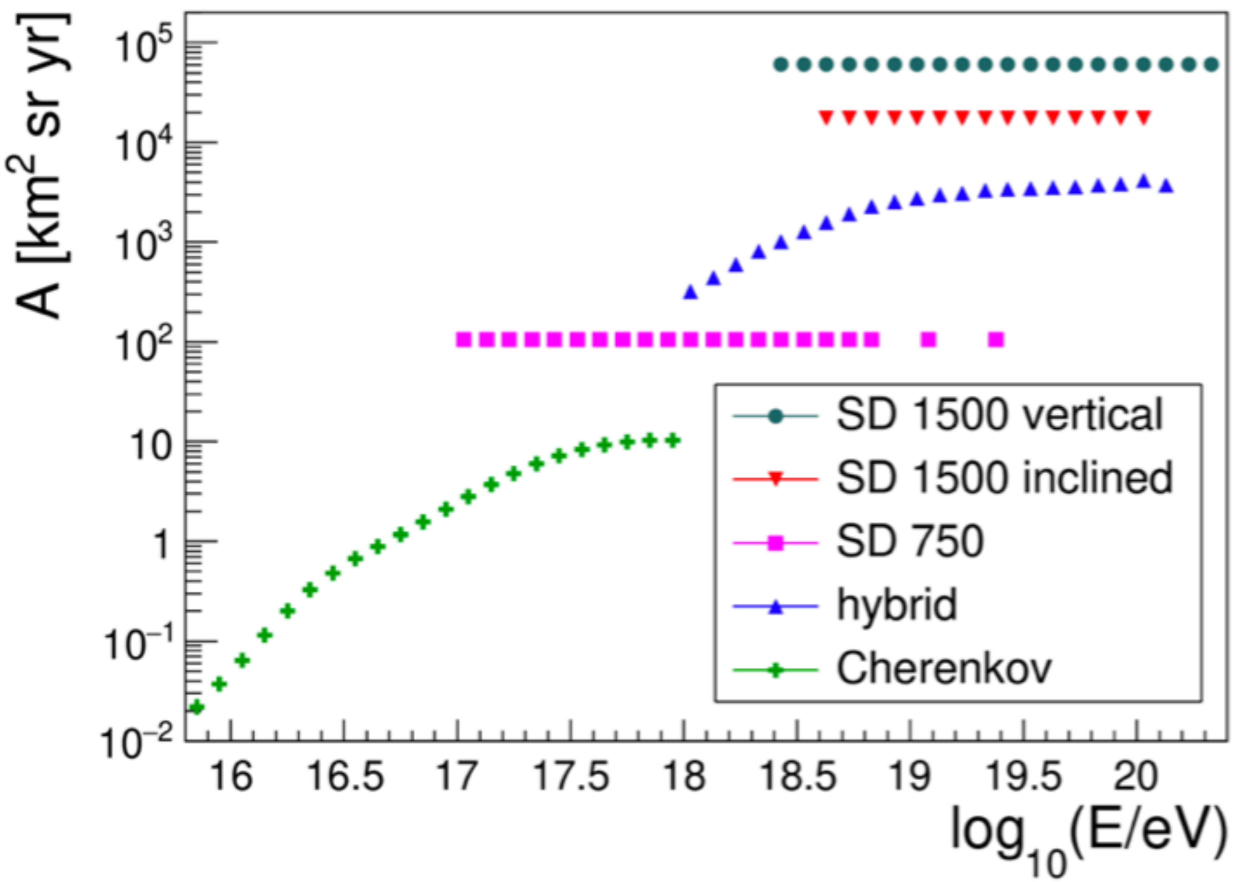
Hybrid detector

- ✓ Time variations of the detection and energy dependence must be carefully taken into account
- ✓ Requires the knowledge on the detector on-time
- ✓ Time dependent detector simulation used

$$\epsilon(E) = \int_T \int_\Omega \int_{S_{gen}} \epsilon(E,t,\theta,\phi,x,y) cos\theta dS d\Omega dt = \int_T A(E,t)dt$$



The exposure



SD – from active hexagon cells

- geometrical calculation
- flat above threshold

FD – realistic MC simulations

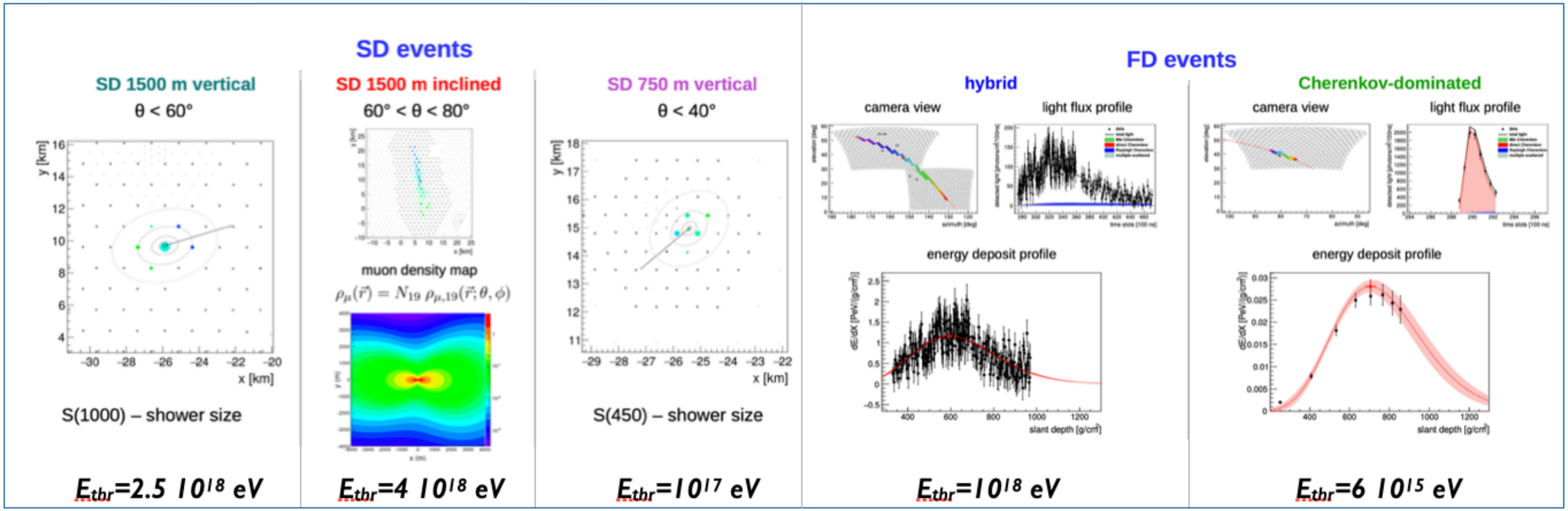
- light from EAS
- atmospheric conditions
- detector status

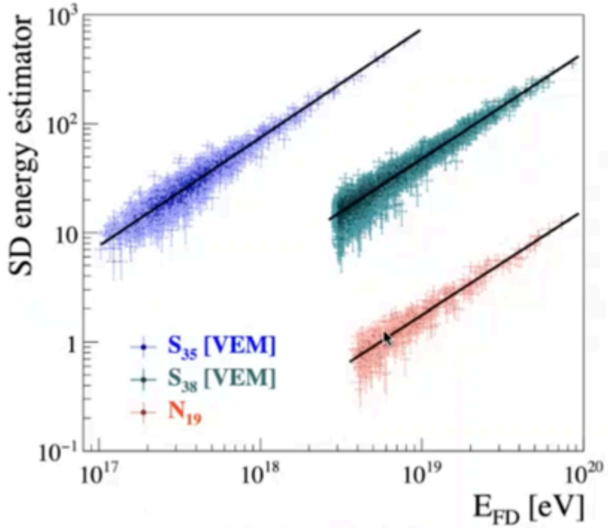
- evolves with energy

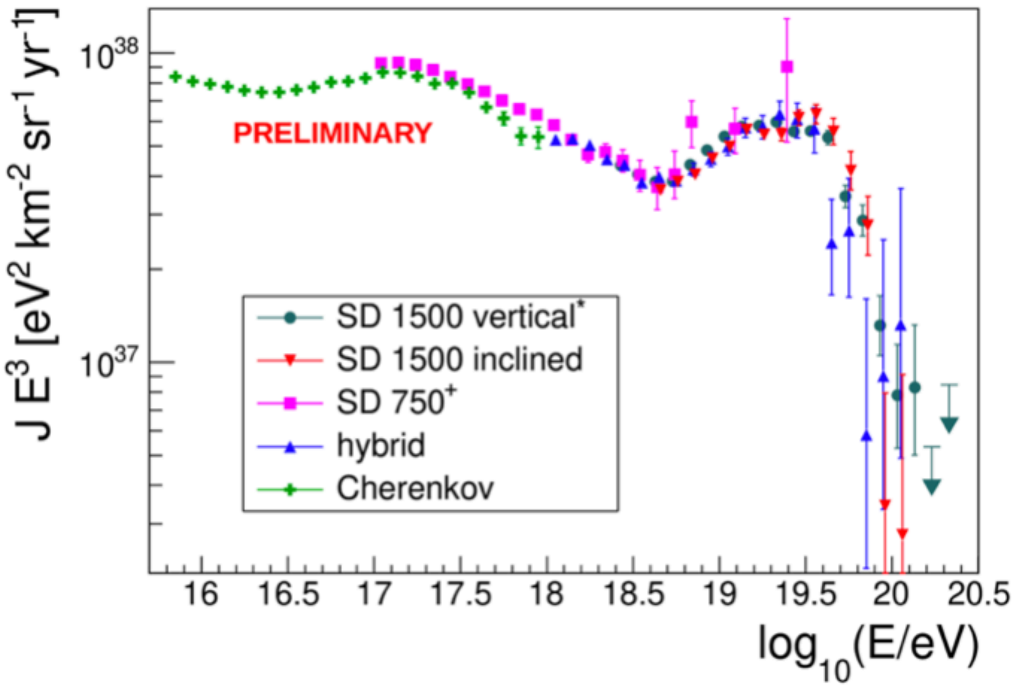
contributions to tolal exposure @ 10^{19} eV:

SD 1500 m vertical	74.8%
SD 1500 m inclined	21.6%
SD 750 m	0.1%
hybrid	3.4%
Cherenkov	0%

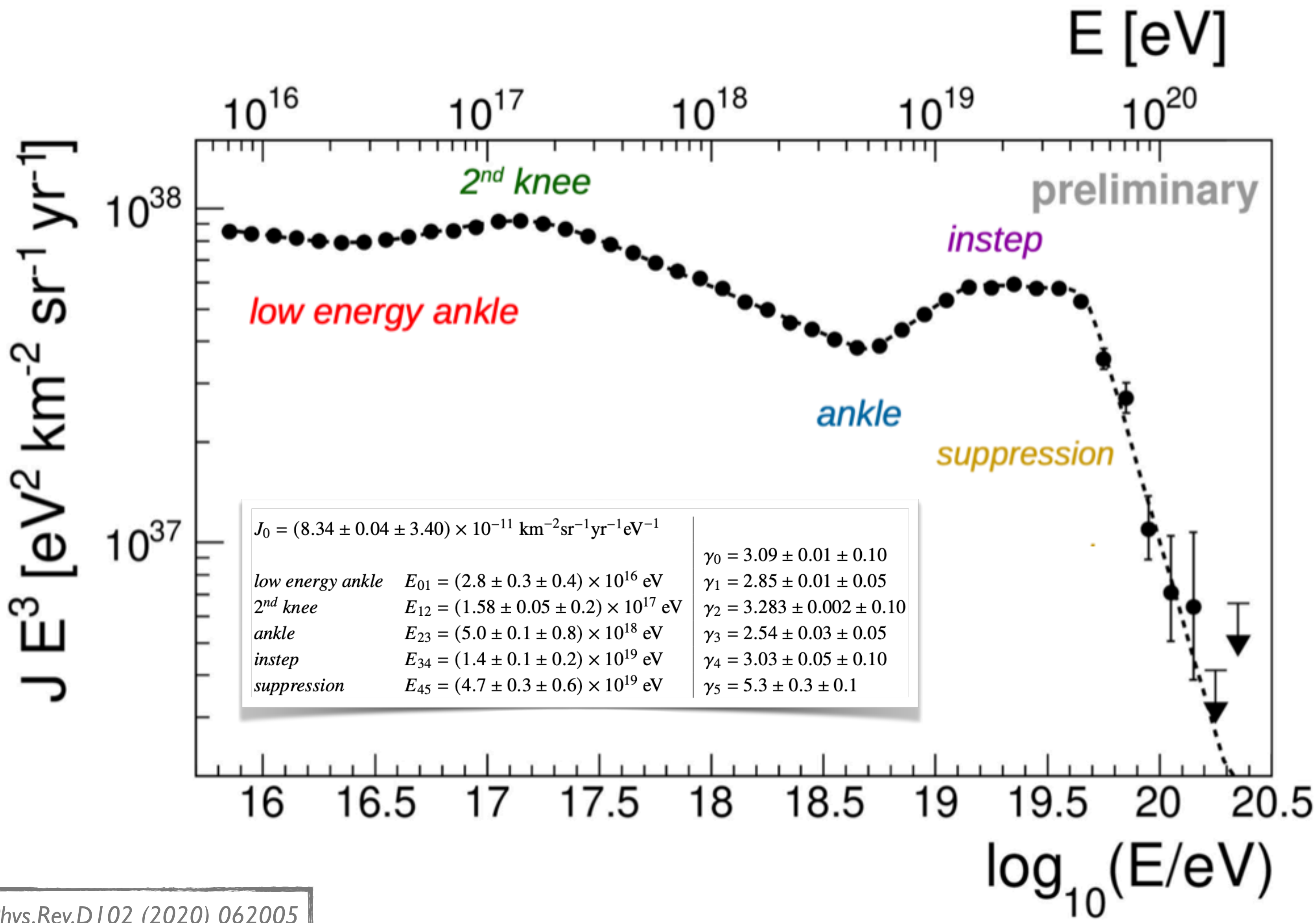
Auger energy spectra





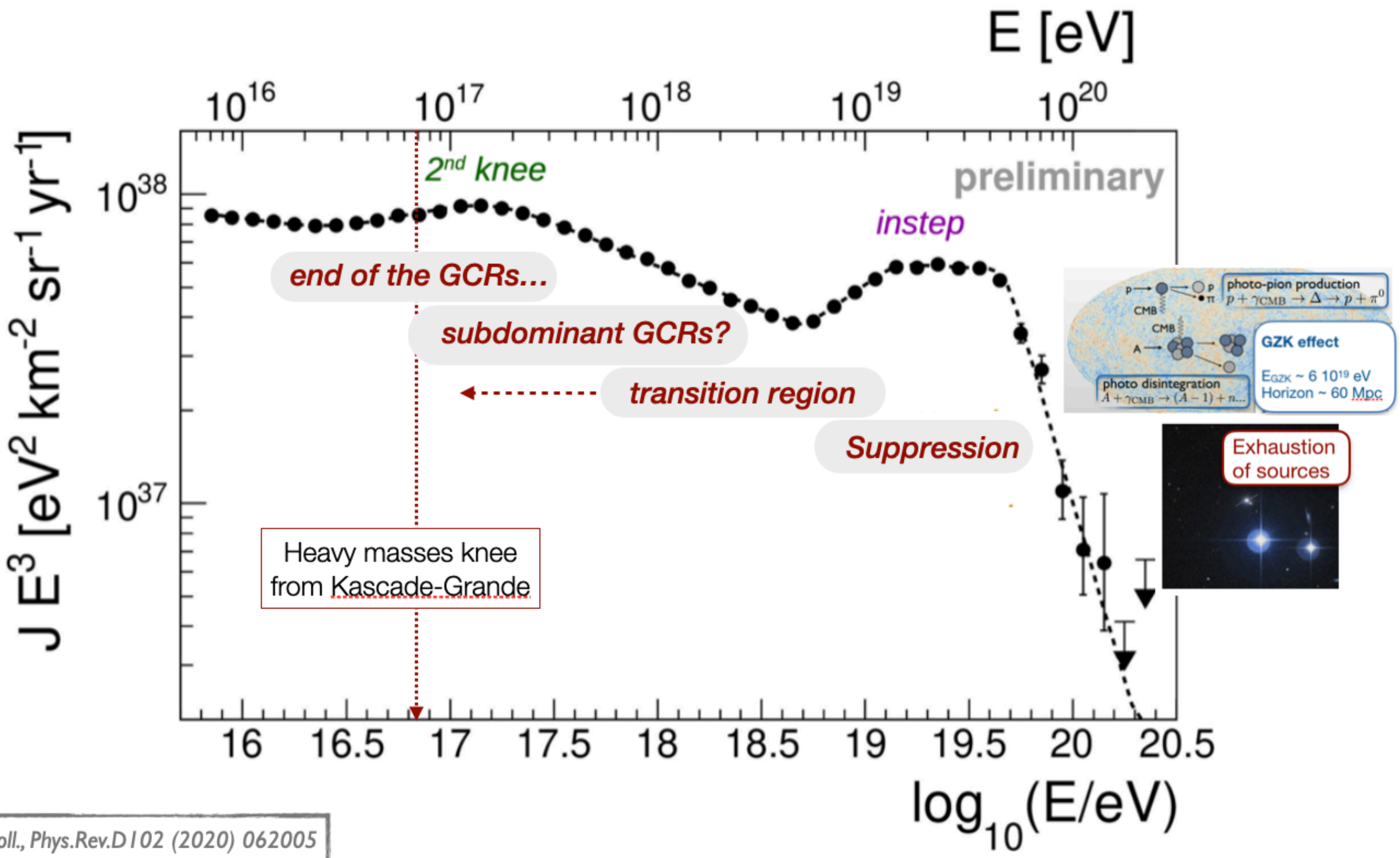


The Auger energy spectrum



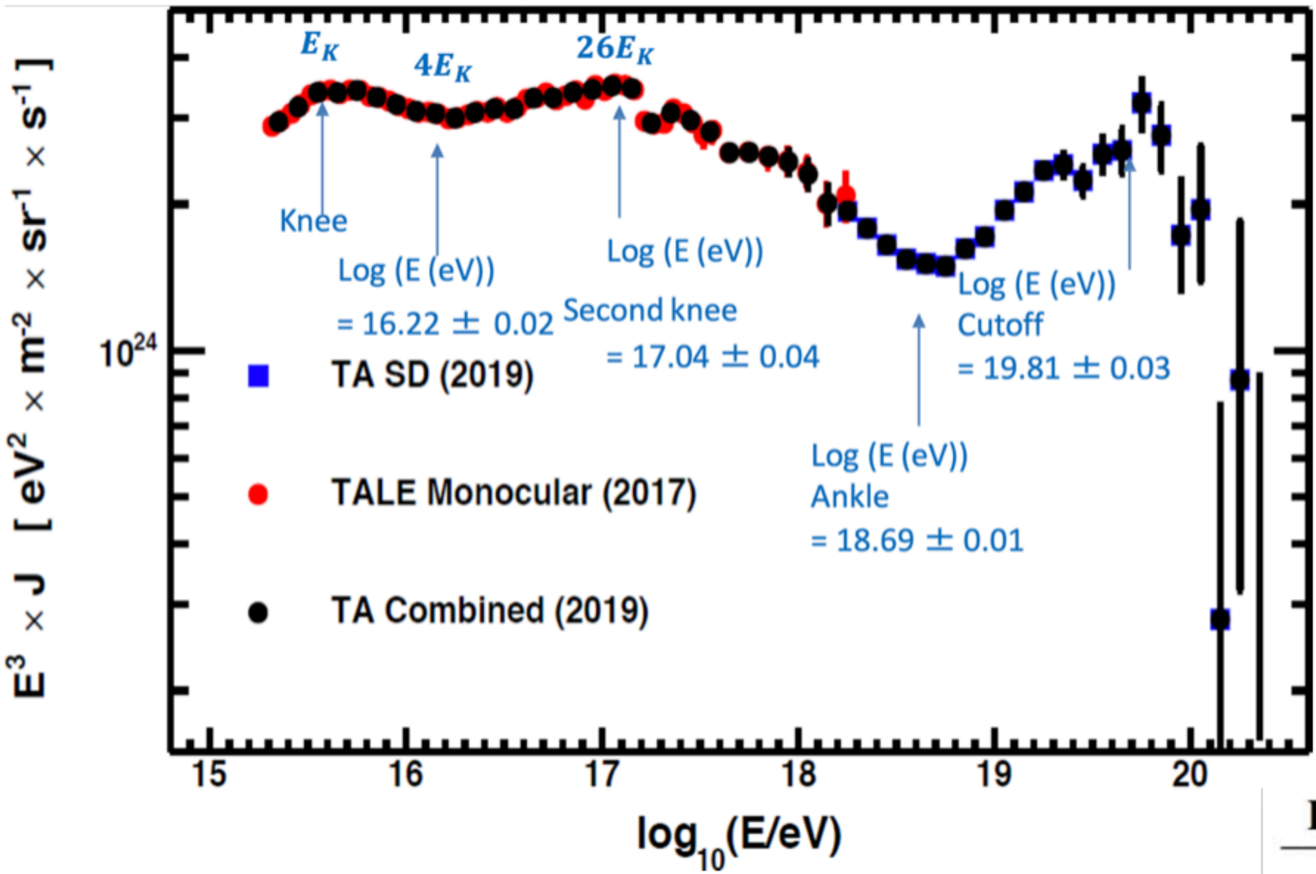
Auger Coll., Phys.Rev.D102 (2020) 062005
Auger Coll., Eur. Phys. J. C 81 (2021) 966
V.Novotny, PoS(ICRC2021) 324

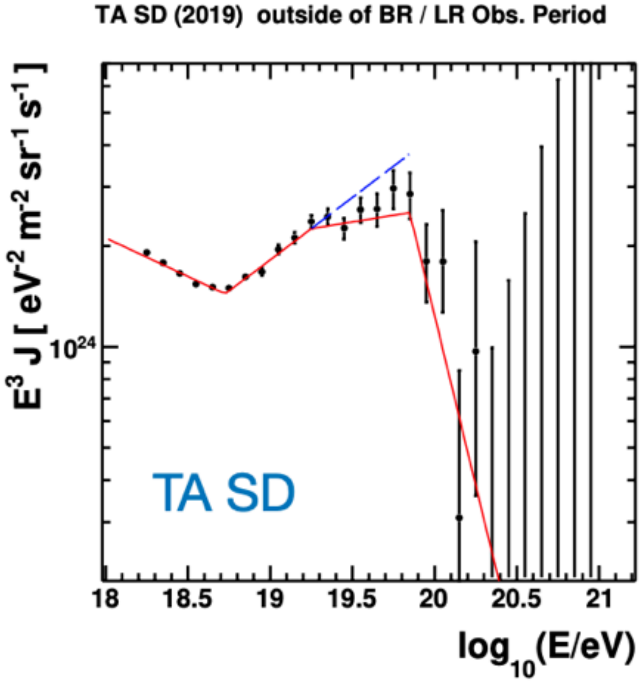
The energy spectrum



Auger Coll., Phys.Rev.D102 (2020) 062005
Auger Coll., Eur. Phys. J. C 81 (2021) 966
V.Novotny, PoS(ICRC2021) 324

The TA energy spectrum

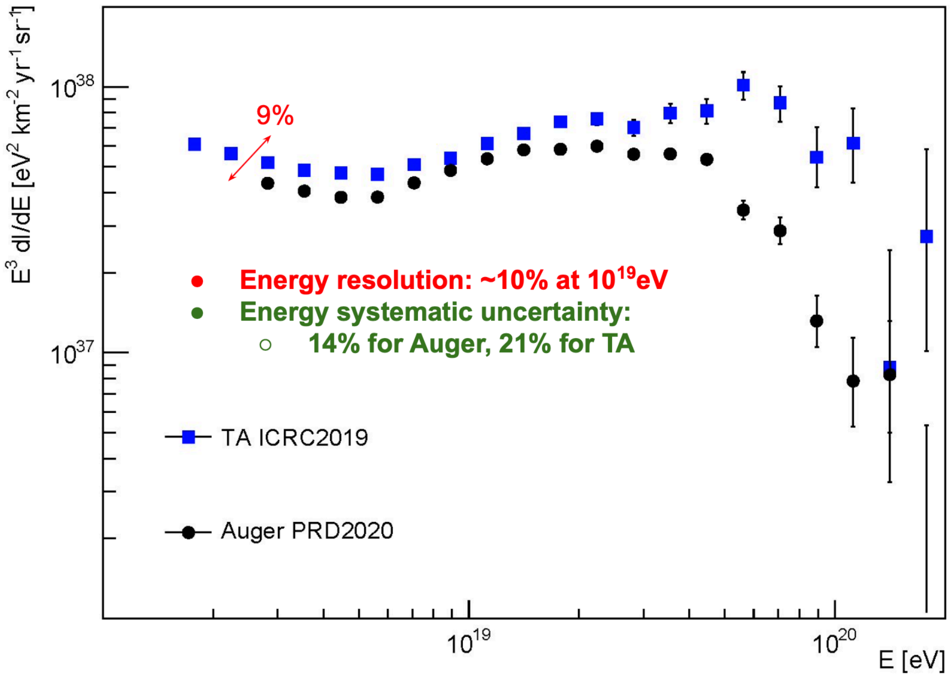


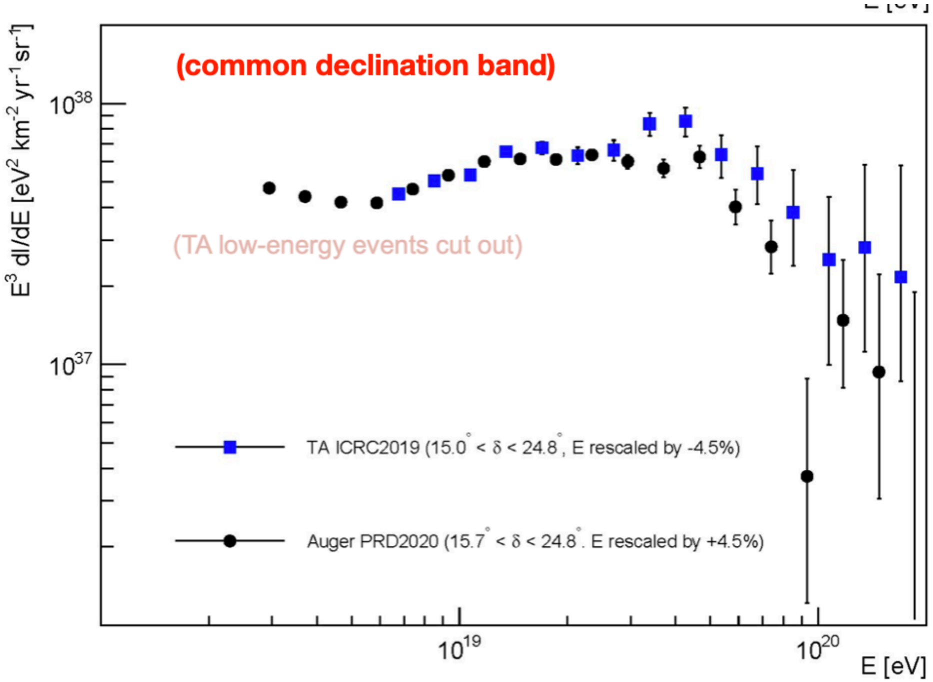


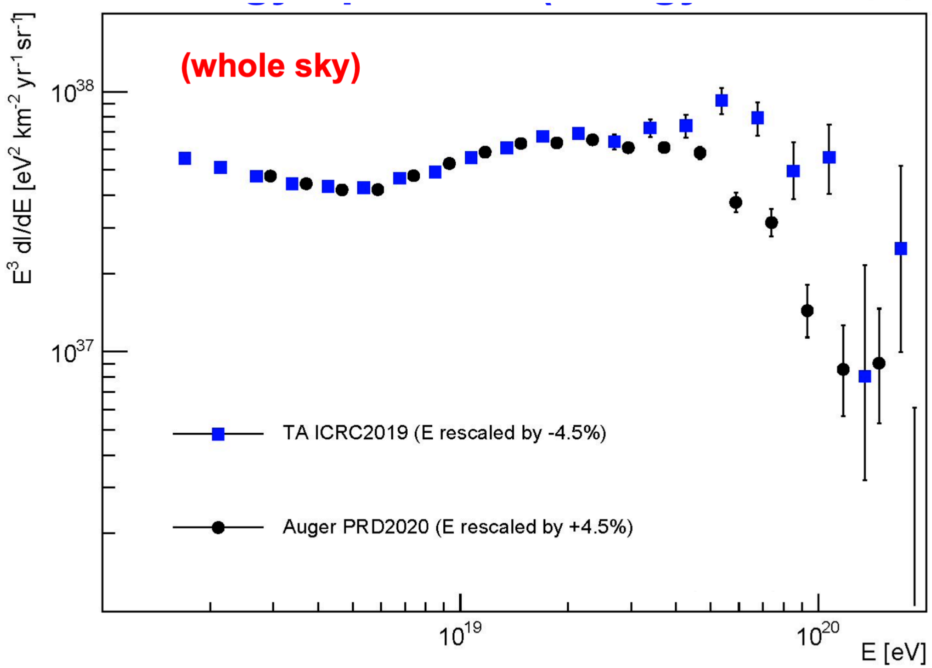
Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
$E_{\text{ankle}}/\text{EeV}$	5.0 ± 0.1	5.4 ± 0.1
$E_{\text{instep}}/\text{EeV}$	13 ± 1	18 ± 1
$E_{\text{cut}}/\text{EeV}$	46 ± 3	71 ± 3

G.Rubtsov (TA Coll.), PoS(2021) 012
D.Ivanov (TA Coll.), PoS(2021) 341

Comparison Auger/TA







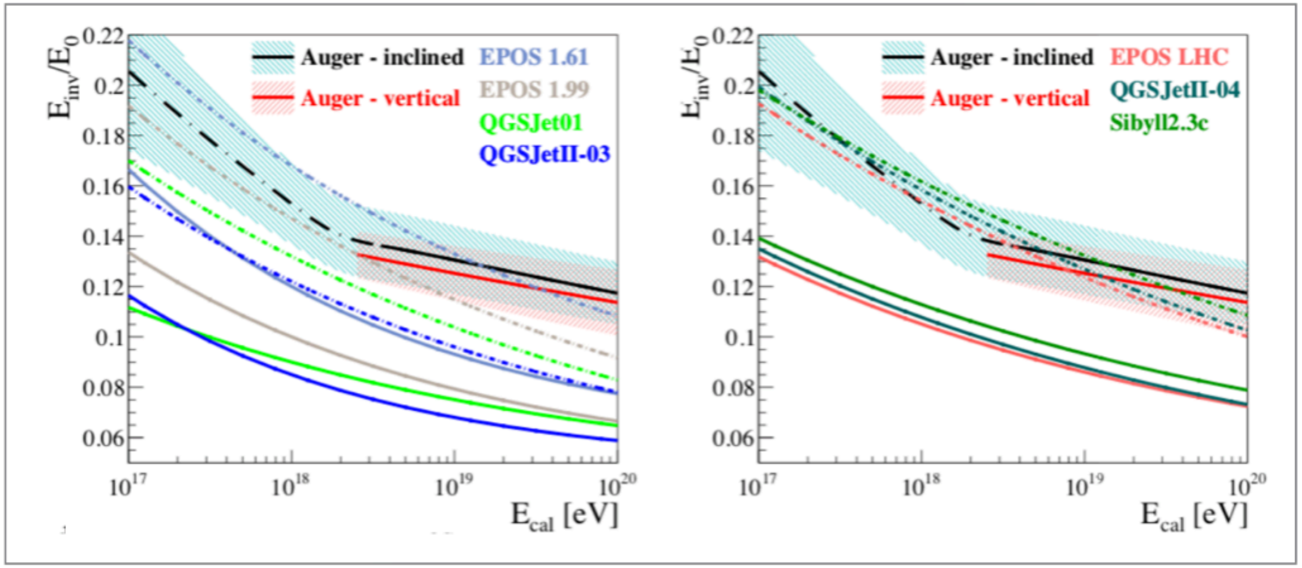
good agreement in the common declination band ($-15^0<\delta<24.8^0$) within systematics up to ~30 EeV
further energy dependent rescaling $\pm$10% per decade needed to restore agreement at the UHE - studies ongoing

Main differences Auger/TA

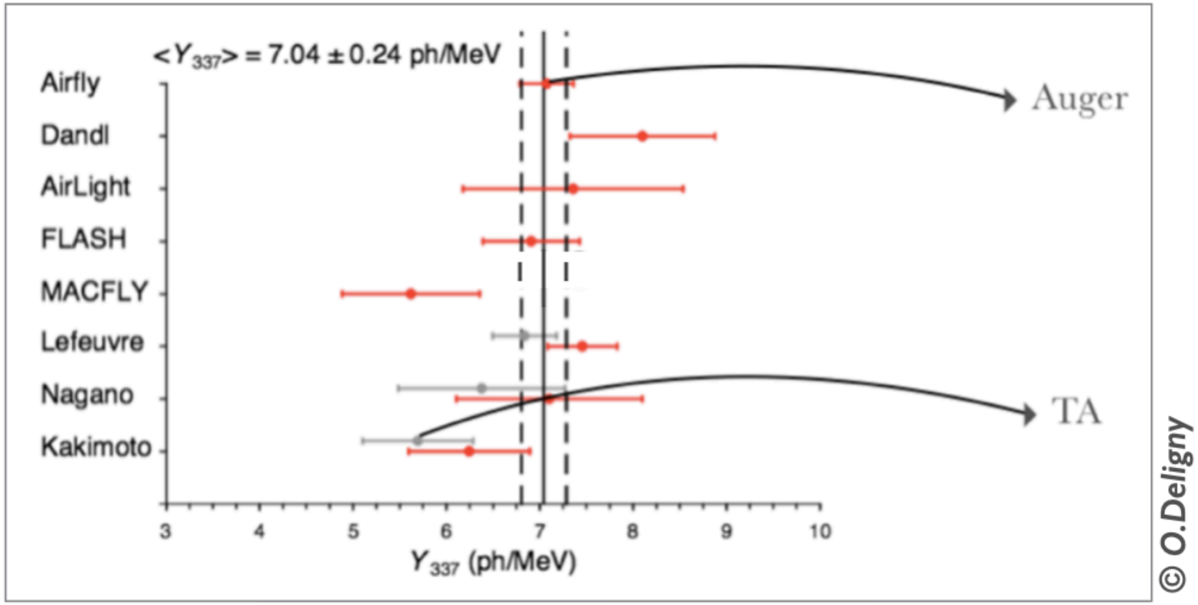
- if E_{inv}(Auger) is used in TA : $E_{TA} \times 1.07$
- if FY(Auger) is used in TA : $E_{TA} \times 0.86$
- + differences in the method of correlating the SD observable with E: constant intensity cut in Auger, look-up tables based on QGSJetII-03(proton) for TA

PAO+TA working group, ICRC2021

Comparison Auger/TA



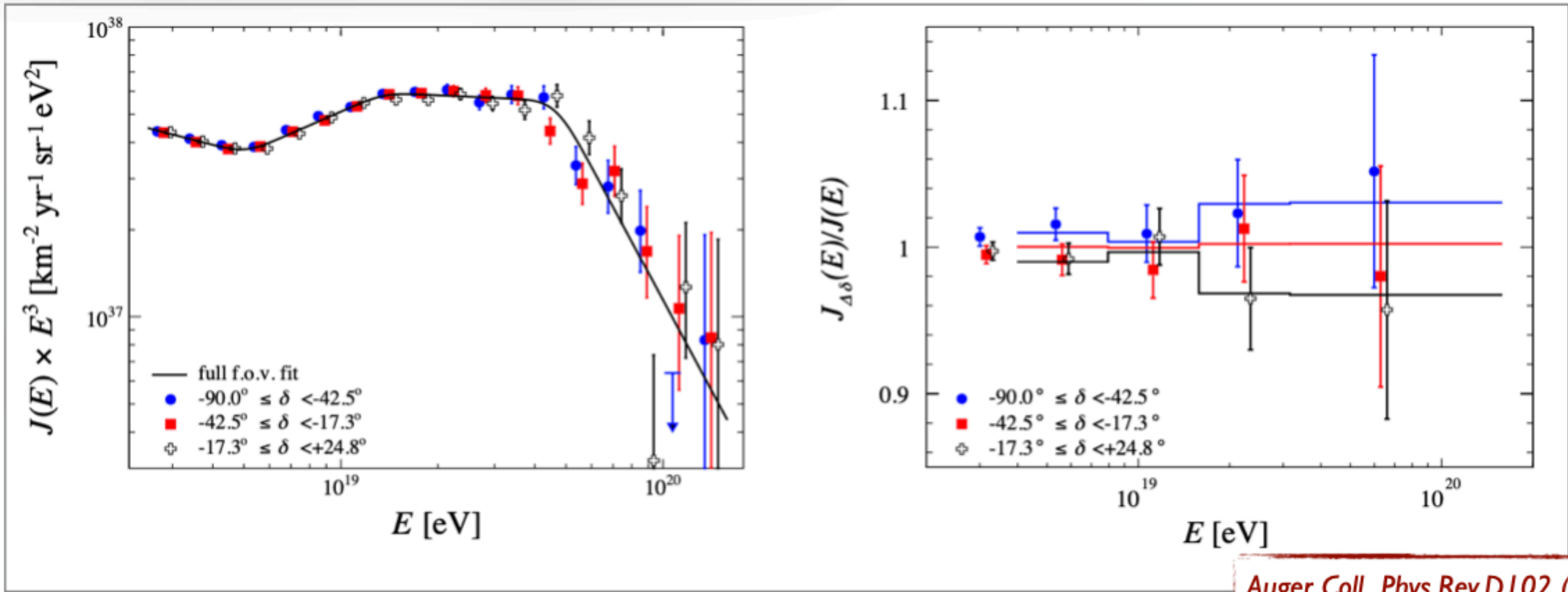
- if E_{inv}(Auger) is used in TA E_{TA} x 1.07



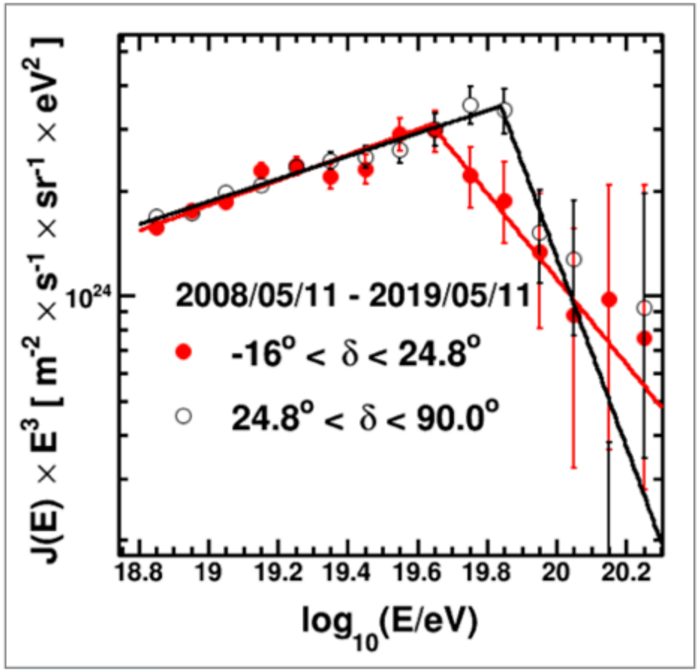
- if FY(Auger) is used in TA E_{TA} x 0.86

- difference in the method to correlate the SD observable with E: constant intensity cut in Auger, look-up tables based on QGSJetII-03(proton) for TA

Comparison Auger/TA



Auger Coll., Phys.Rev.D102 (2020) 062005



TA Coll., PoS(ICRC2019) 298.

Is there a declination dependence?

declination dependence of the spectrum in the highest energy region:

- not seen in Auger (except for differences due to the dipolar anisotropy pattern above 8 EeV)
- seen in TA at ~4.3σ level, currently not explained by systematic uncertainties:
  - ➡ $\log_{10}E_{break}$ (lower δ) = 19.64±0.04
  - ➡ $\log_{10}E_{break}$ (higher δ) = 19.84±0.02

1- Setting the stage

- sources
- acceleration
- propagation from sources to Earth
- extensive air showers

2- Techniques

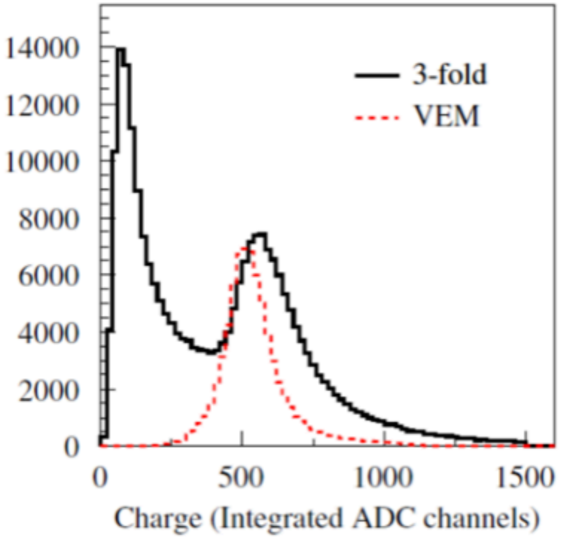
- surface, fluorescence, radio detectors
- from old to modern Observatories
- the experimental observables
- the energy spectrum

3- What have we learnt?

- anisotropy of UHECRs
- mass composition
- multi-messengers
- the future of the field

Backup slides

Calibration of detectors response



SD Calibration

2500 Hz atmospheric muons

Their flux is collected in each WCD and compared to the one obtained in a reference tank equipped with a muon hodoscope

Q_{peak} ~ 1.03 VEM/PMT

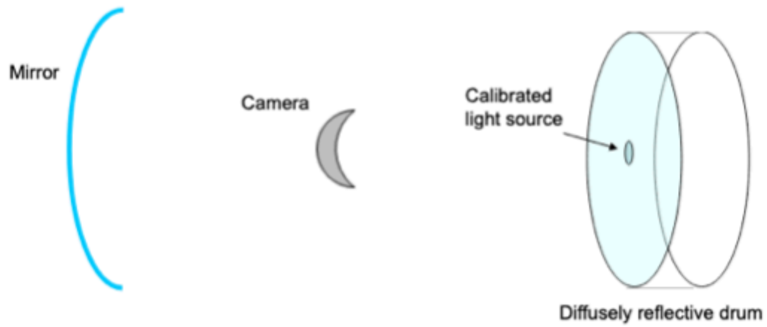
Q_{VEM}= n_{phe} x PMT gain

Q_{VEM} checked on light produced by a decay electron from a stopped muon

FD Calibration

- **Absolute**: End to End Calibration

  The **Drum** device installed at the aperture uniformly illuminates the camera with light from a calibrated source (1/month)



- Relative: UV LED + optical fibers (1/night)
- Alternative techniques for cross checks
  - Scattered light from laser beam
  - Statistical

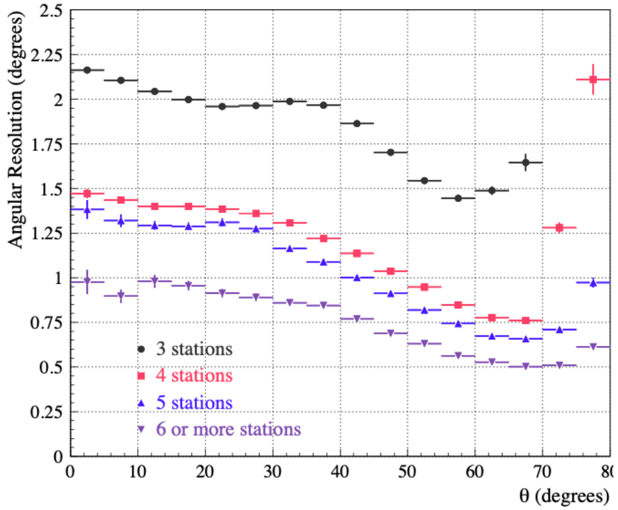
⇨ All agreed within 10% for the EA

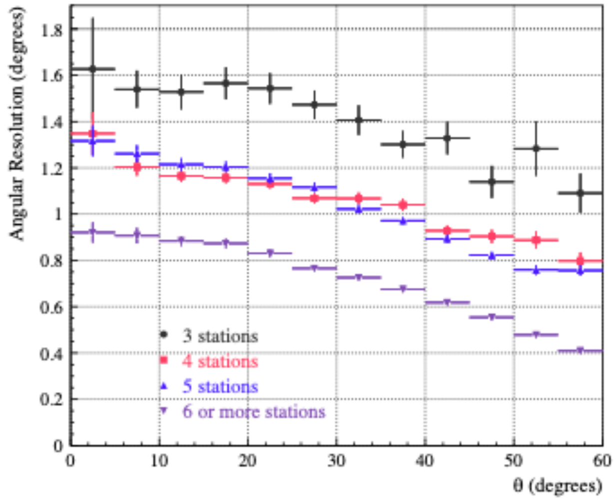
FDs	Overall uncertainty [%]	FDs with same components
Coihueco 2/3	1.5	CO2/3
Coihueco 4/5	1.5	CO1,4-6, LA, HEAT
Los Morados 4/5	1.5	LM
Los Leones 3/4	2.2	LL1-6

The angular resolution

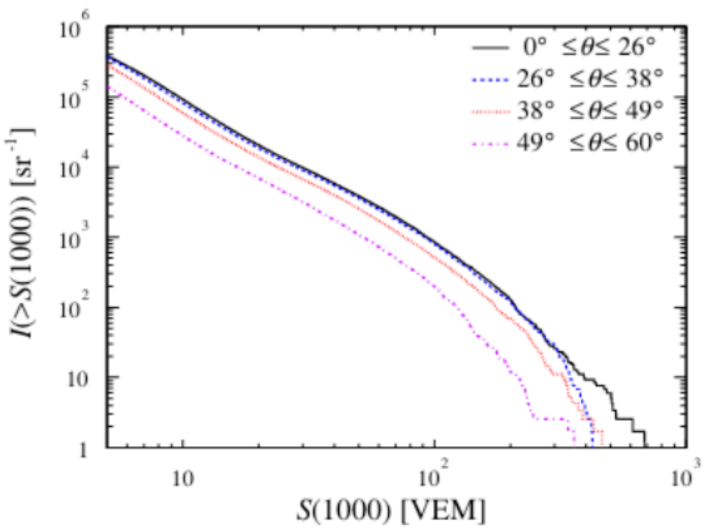
It depends on
- the multiplicity of the triggering stations
- the precision on the arrival times
- the model to fit the shower front

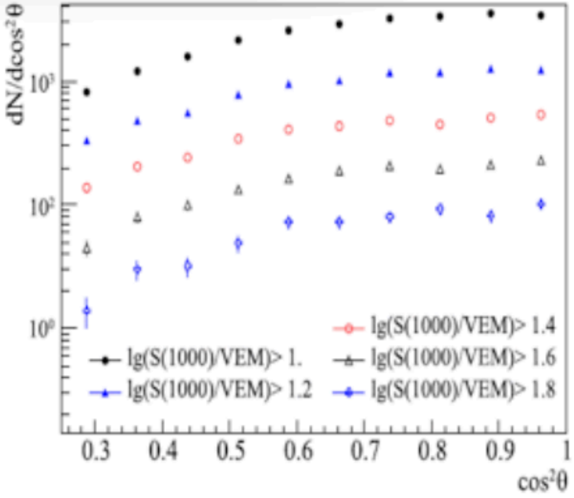
Better than 1^{0} for ≥ 6 stations





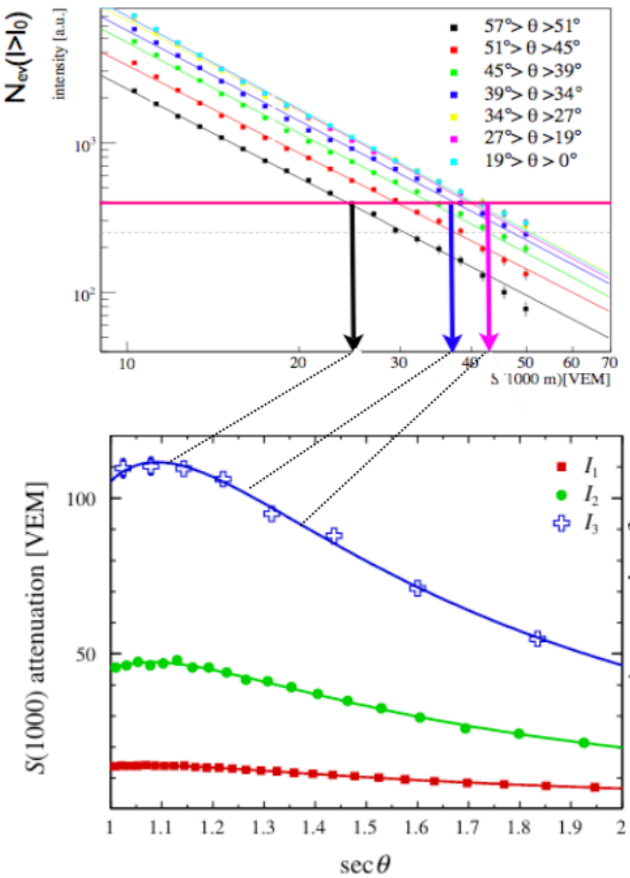
The "Constant Intensity Cut"

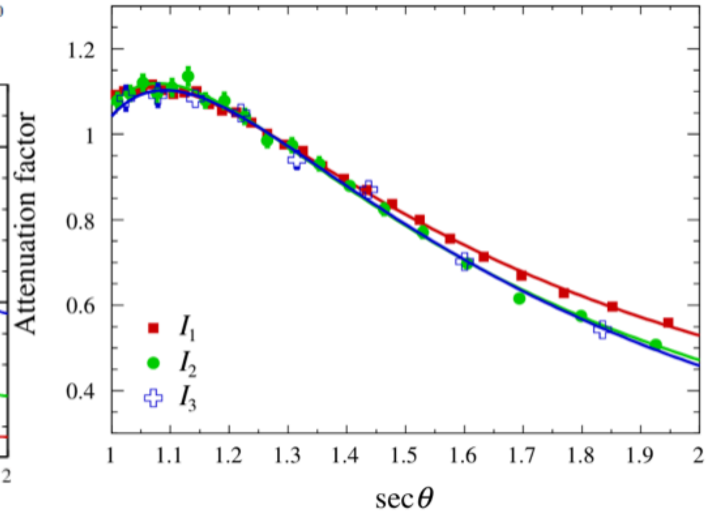




if the CR flux is isotropic
if acceptance(θ) is known

$$\frac{dN}{d\ sin^2\theta} = const$$





$$S_{38^\circ} = \frac{S(1000)}{CIC(\theta)}$$

$$CIC(\theta) = 1 + ax + bx^2 + cx^3$$

$$(x = cos^2\theta - cos^2 38^\circ)$$

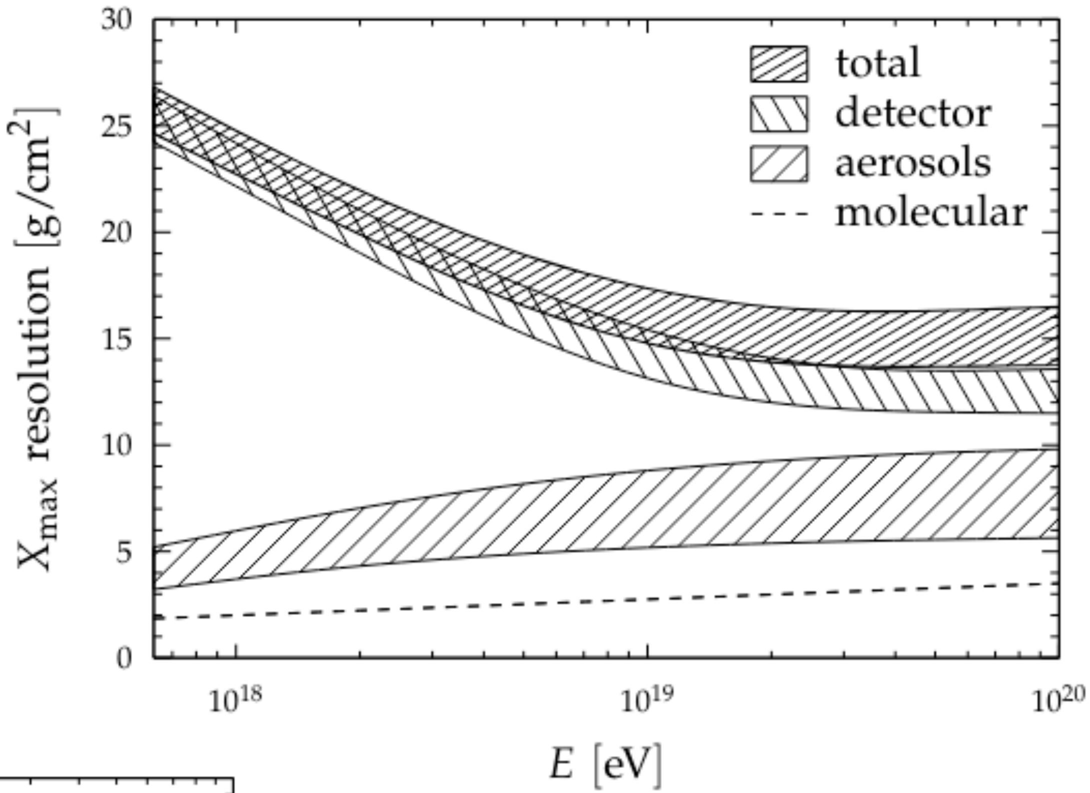
Energy resolution

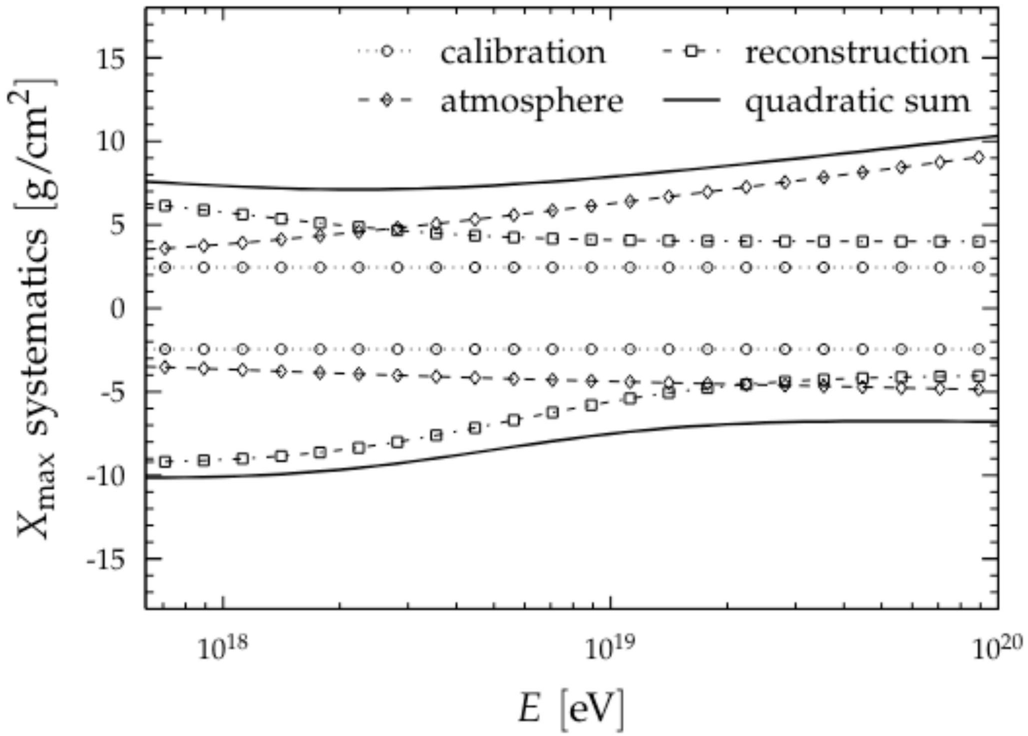
	FD energy resolution	
atmosphere	Aerosol optical depth	1.2% – 3.8%
	Horiz. uniform. of aerosols	1.6% – 5%
	Molecular atmosphere	1%
detector/ reconstruction	Nightly relative calib.	1.3%
	Time drift of FD energies	2.5%
	Mismatch between telescopes	3.5%
	Stat. error from geom. and GH fit	4.6% – 2.8%
	Extrapolation of profile	2.2%
invisible energy	E_{inv} shower-to-shower fluc.	1.1% – 0.6%
	E_{inv} mass uncertainty	2.4% – 0.3%
	TOTAL	7.6% – 8.6%

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

Systematic uncertainties on the energy scale

X_{max} resolution

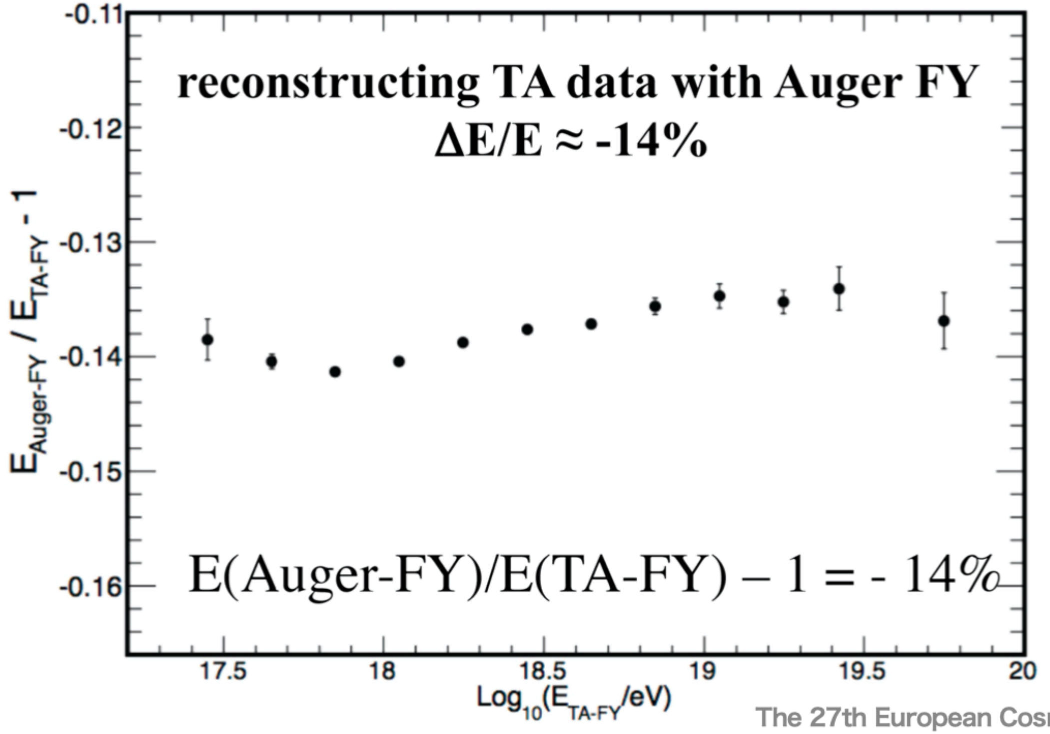




Systematic uncertainties on X_{max}

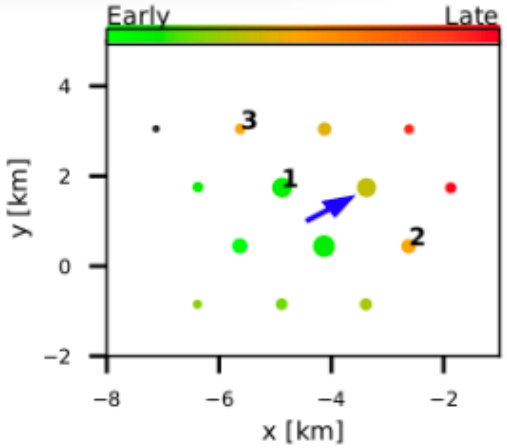
Impact of the Fluorescence Yield Model

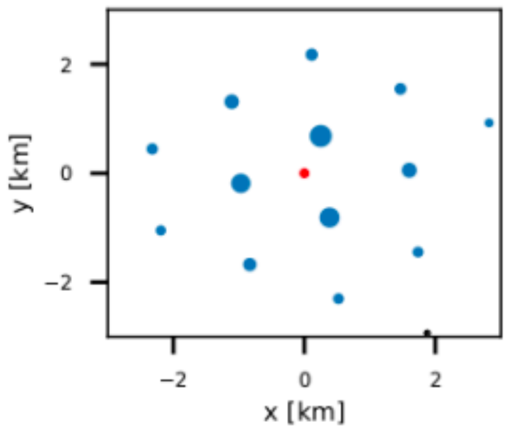
- Auger: AirFly result
  (*Astropart. Phys.* 42 90 2013, 3.6% uncertainty)
- TA: Kakimoto et al. (*NIM-A*, 372 527 1996, 11% uncertainty)
  + FLASH spectrum
- 14% difference

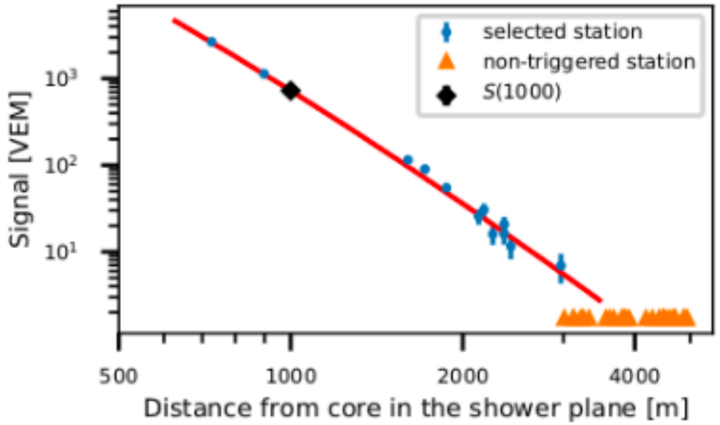


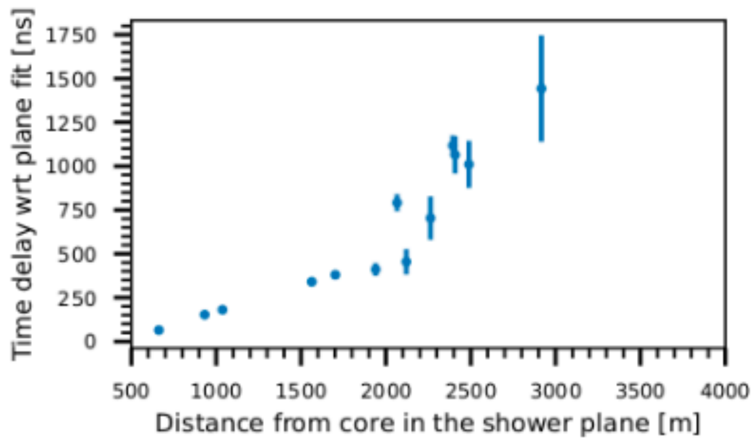
Example : an Auger vertical SD event

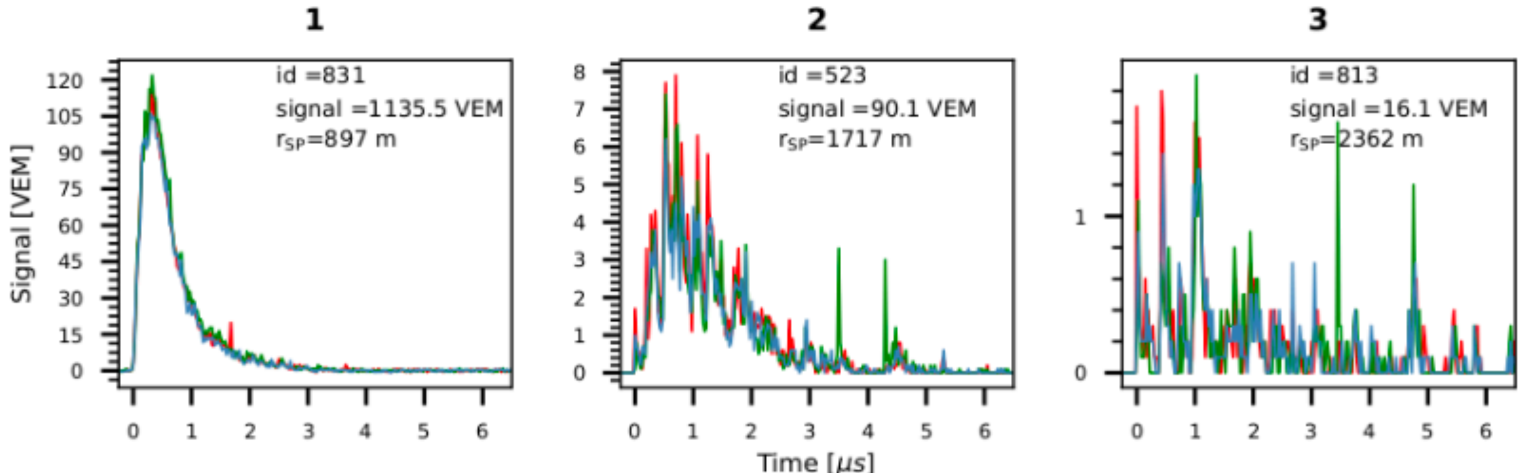
Energy [EeV]	155±12
θ [deg]	6.8
φ [deg]	204.6
α [deg]	102.9
δ [deg]	-37.8
β	-2.6
$t_{1/2}(1000)$ [ns]	360±10
Multiplicity	13











Example : an Auger inclined SD event

Energy [EeV]	113±14
θ [deg]	77.2
φ [deg]	188.0
α [deg]	21.7
δ [deg]	-13.8
Multiplicity	75