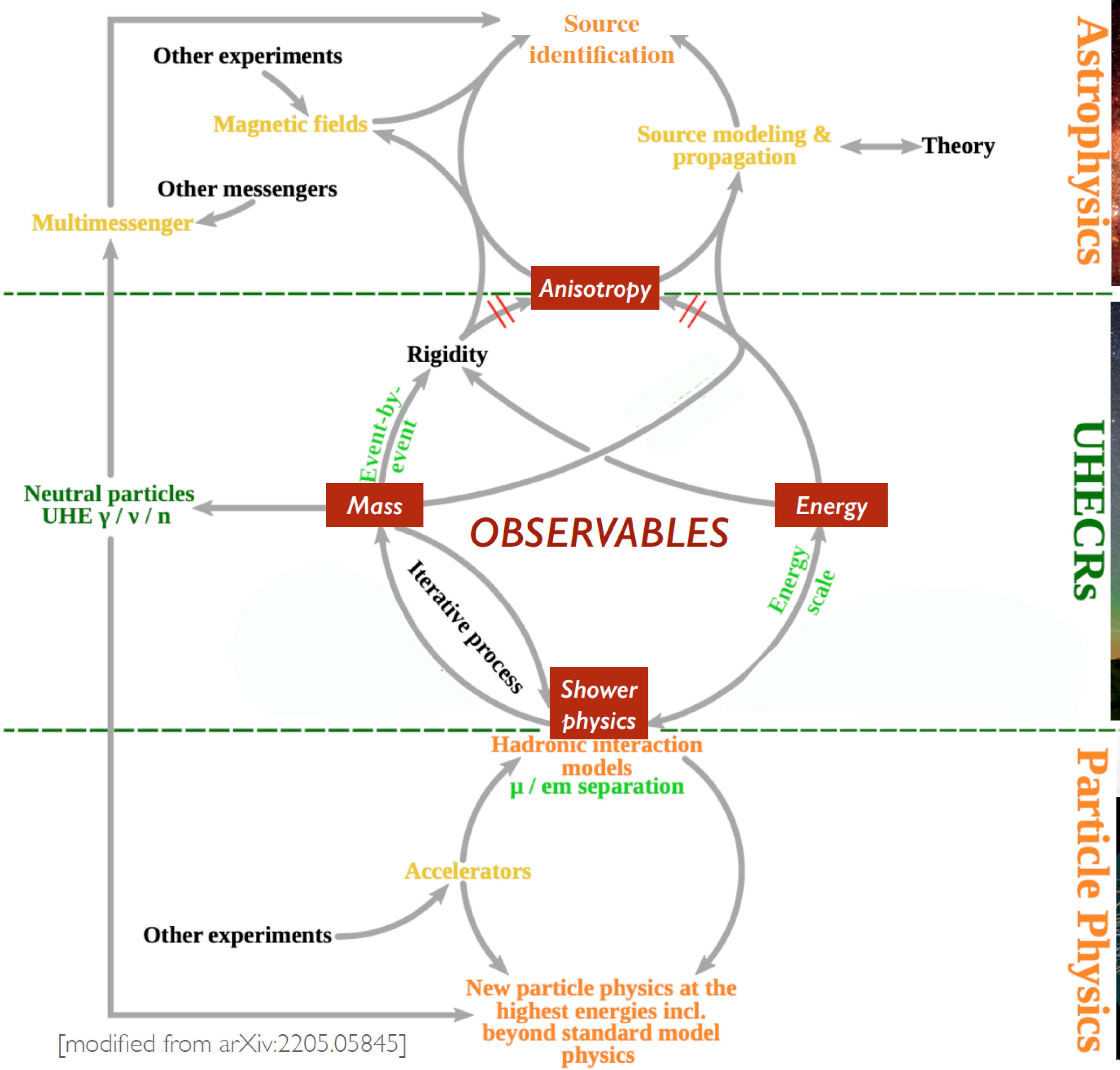
Recent results from the Pierre Auger Observatory

Serguei Vorobiov, University of Nova Gorica, Slovenia

IPA2022, TU Wien, Austria, 5.9.2022

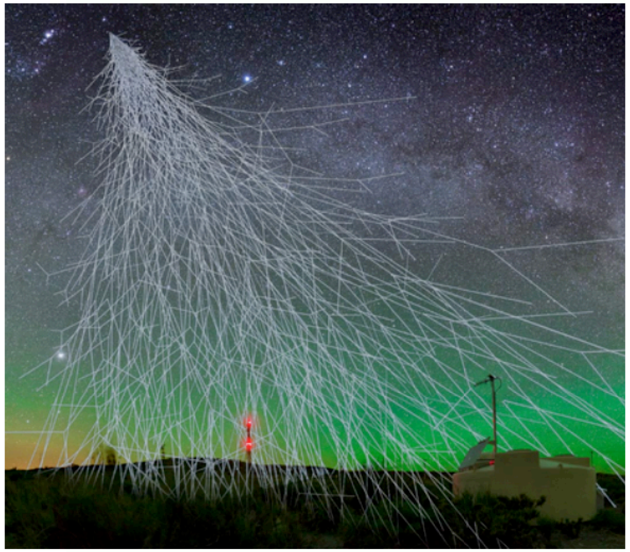
Connections of UHECRs ($E>10^{17}$ eV)



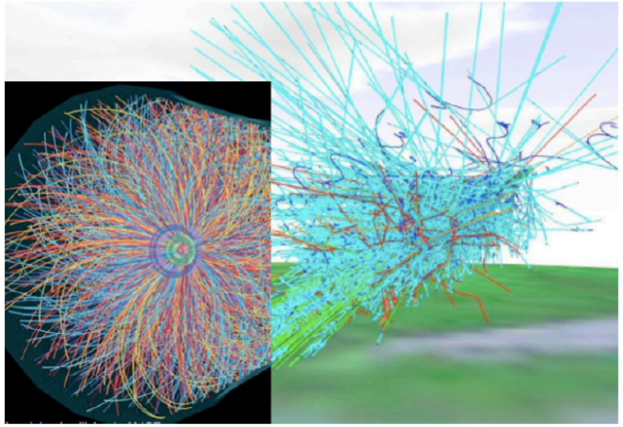
[modified from arXiv:2205.05845]

Astrophysics

UHECRs

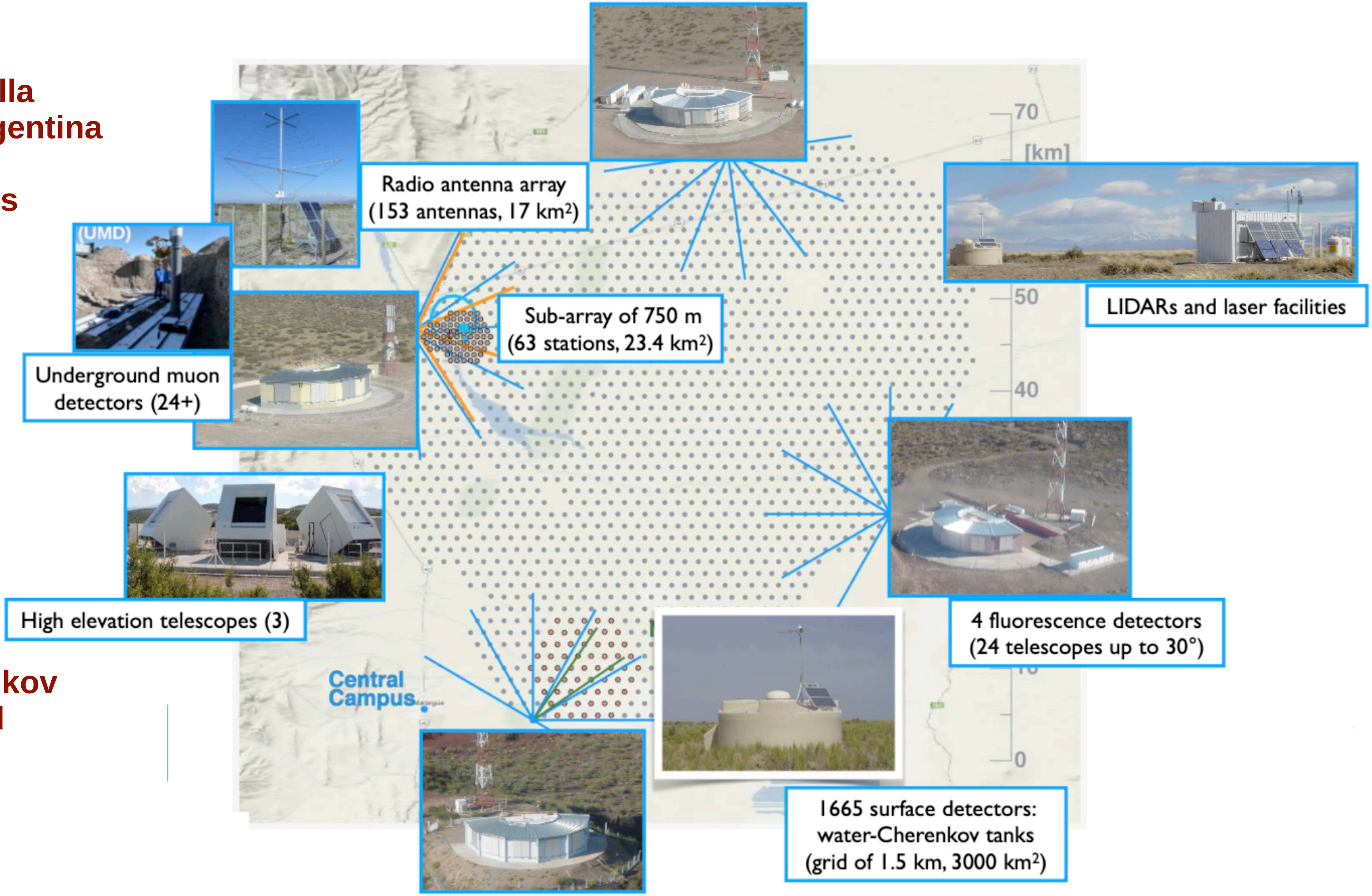


Particle Physics



The Pierre Auger Observatory

Pampa Amarilla
Malargüe, Argentina
17 Countries
>400 members



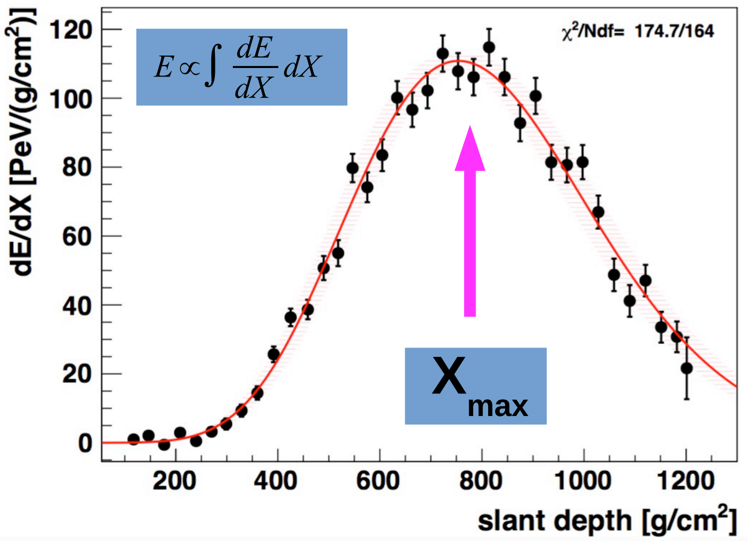
Water Cherenkov detectors and

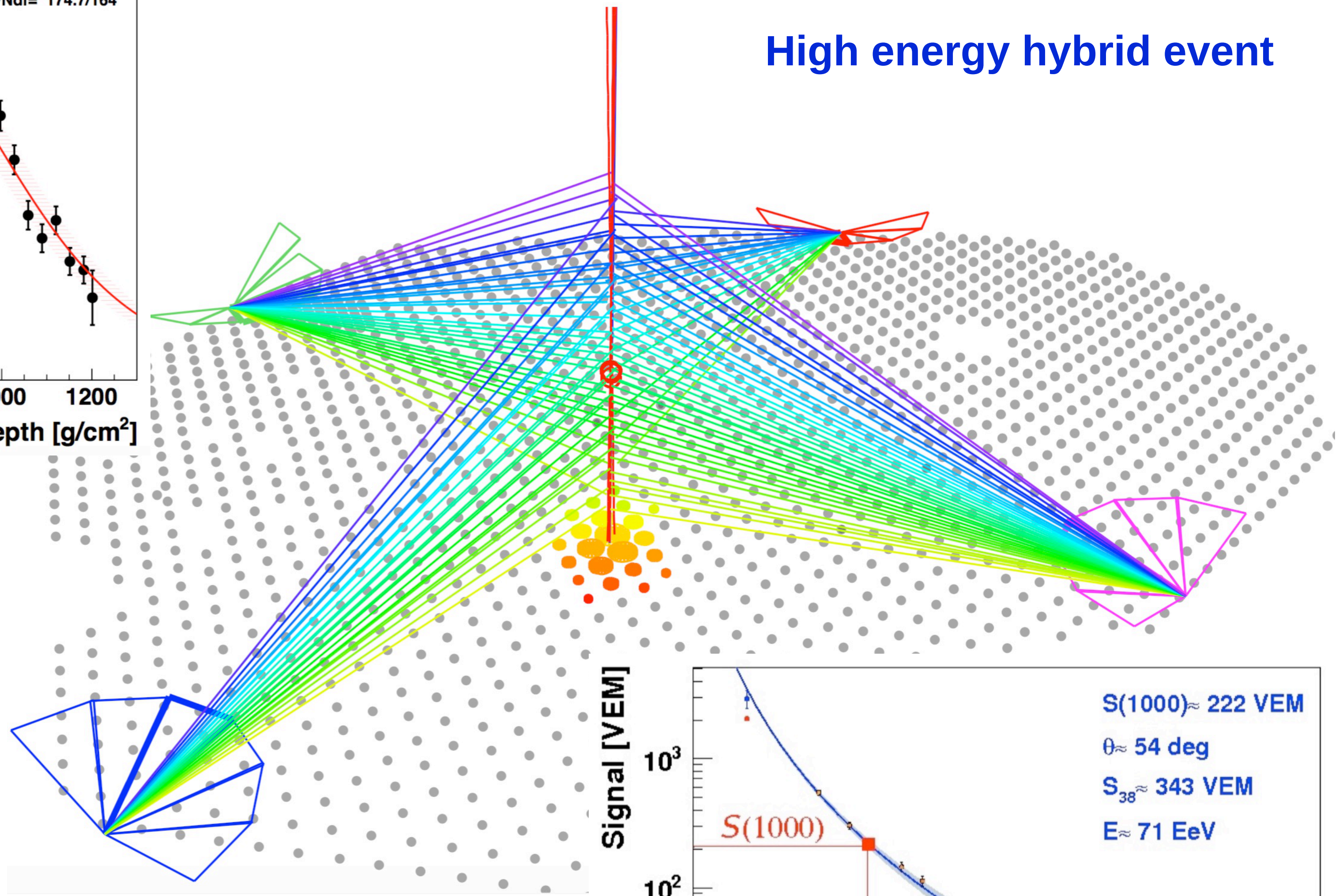
Fluorescence Telescopes

***Phase 1 :* data taking from 2004 on**
(from 2008 with the full array in operation):
✓ Over 120,000 km^2 sr yr for anisotropy studies
✓ Over 90,000 km^2 sr yr for spectrum studies

Phase 2 : the AugerPrime upgrade
Data taking from 2023 to 2030...
✓ +40,000 km^2 sr yr
✓ Multi-hybrid events : FD, SD, SSD, RD, UMD

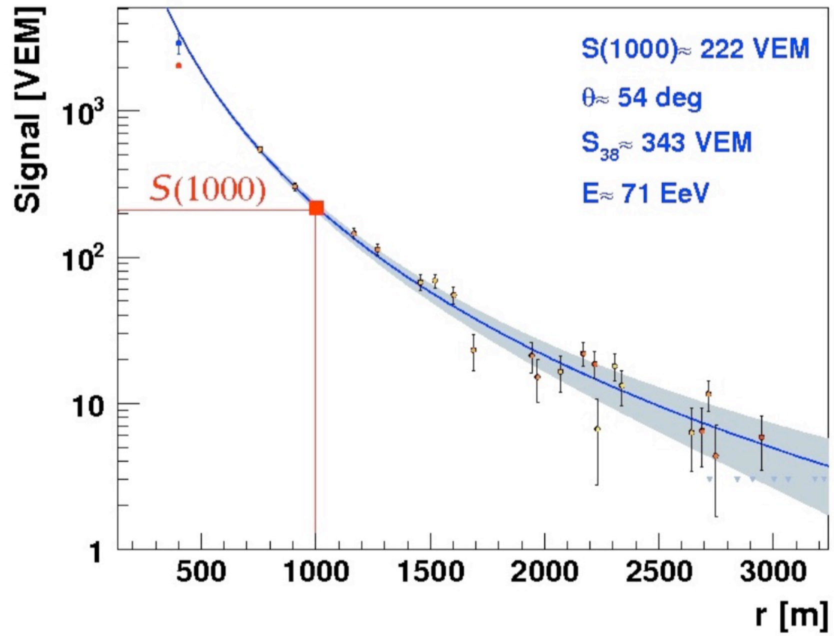
Primary CR reconstruction





FD energy: integral of the longitudinal profile

FD: position Xmax of the shower maximum => information on the primary mass



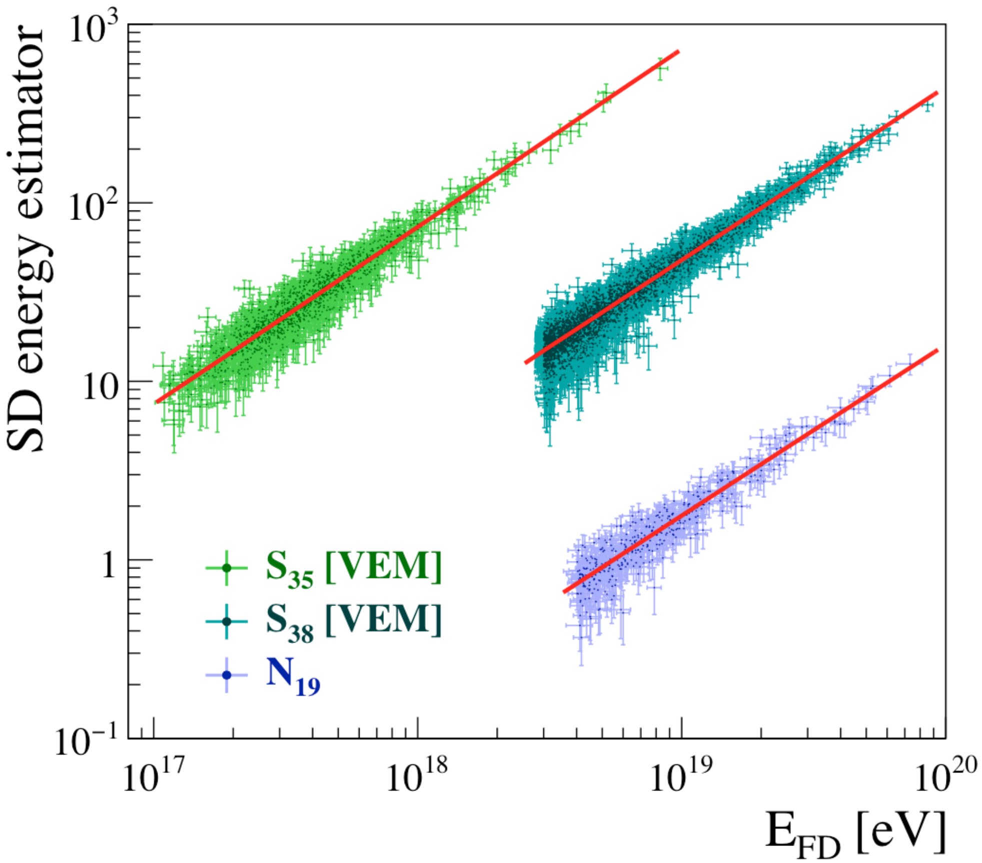
SD energy: ∝ signal S(1000) at 1 km from the shower core

SD: shower geometry (core position and arrival direction)

Auger energy calibration & systematics

FD: the common energy scale

free of SD-related uncertainties (cascade simulation + hadronic interaction models)



Energy systematic uncertainties:

FD calibration: 9.9%

FD profile reconstruction 6.5-5.6%

Atmospheric conditions: 3.4-6.2%

Stability of the energy scale 5%

Fluorescence yield: 3.6%

Invisible energy 1.5%

Statistical error of SD calibration fit 1%

FD energy scale: 14%

SD resolution for energy reconstruction:

Energy: 20% (@2 EeV) to 7% (@ >20 EeV)

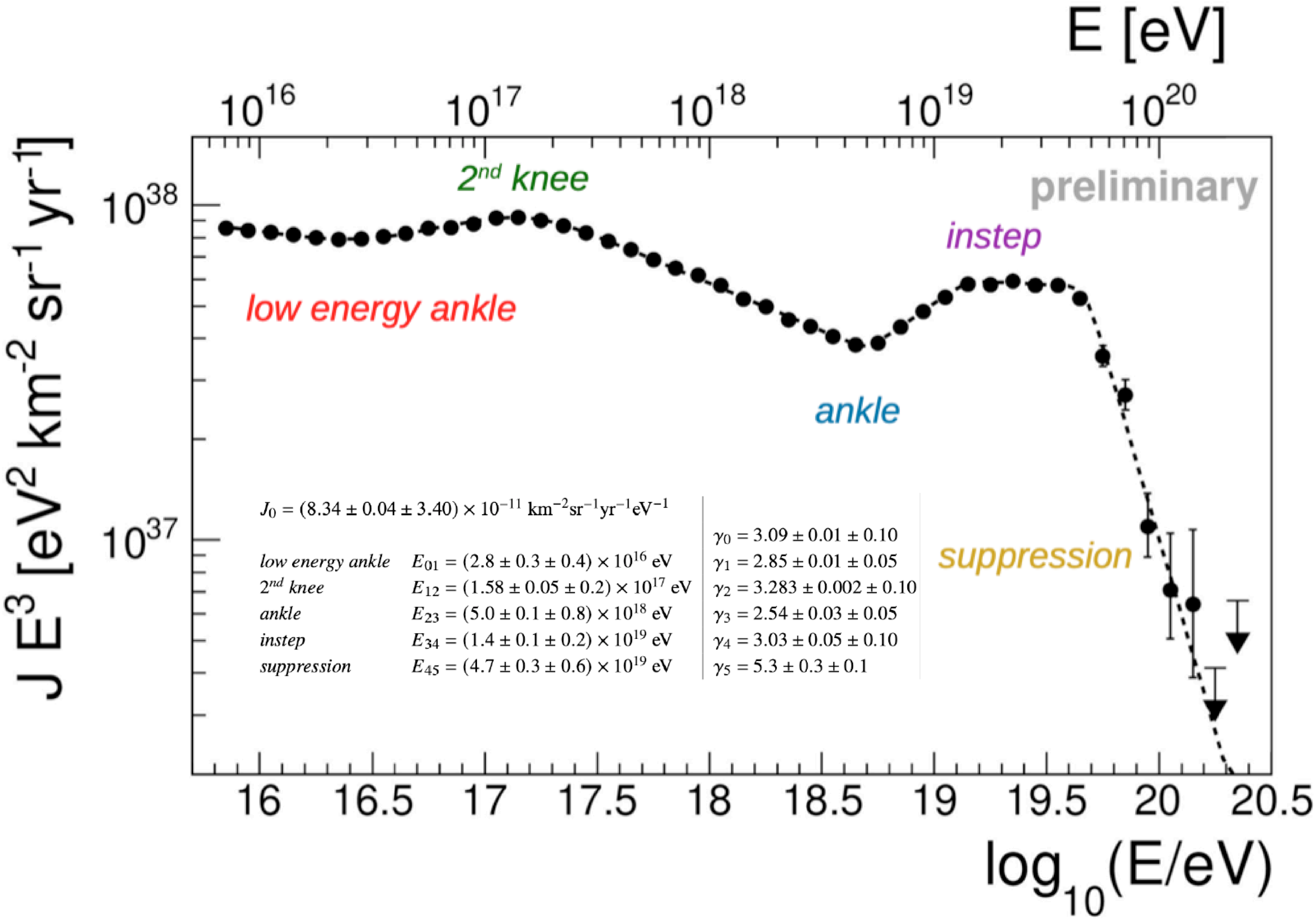
Hybrids (FD + at least 1 SD station):

Energy resolution 7.4%

Features of the energy spectrum of cosmic rays above 2.5 x 10^{18} eV using the Pierre Auger Observatory, Phys. Rev. Lett. 125, 121106 (2020)

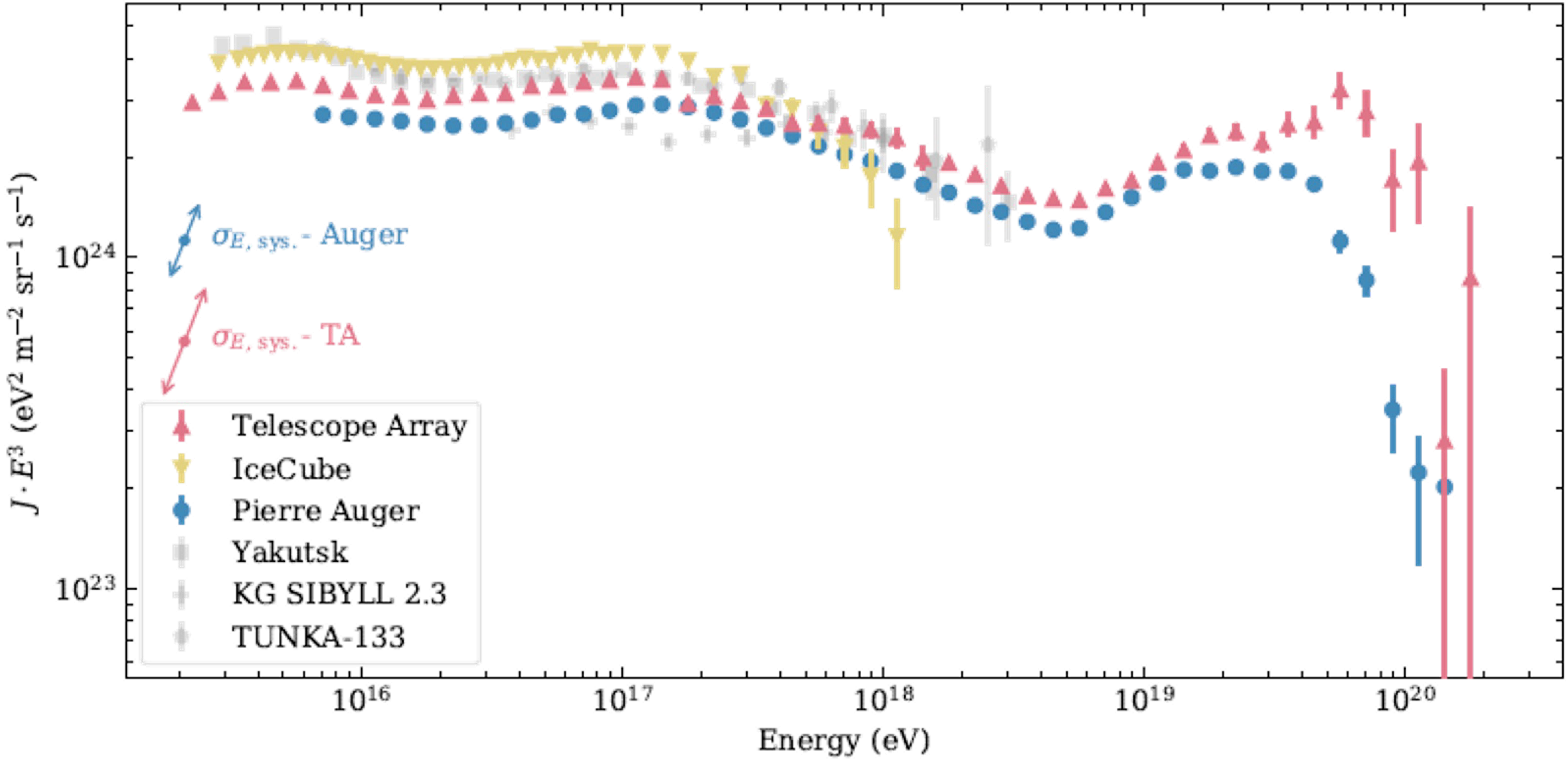
Measurement of the cosmic ray energy spectrum above 2.5 x 10^{18} eV using the Pierre Auger Observatory, Phys. Rev. D 102, 062005 (2020)

UHECR energy spectrum



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

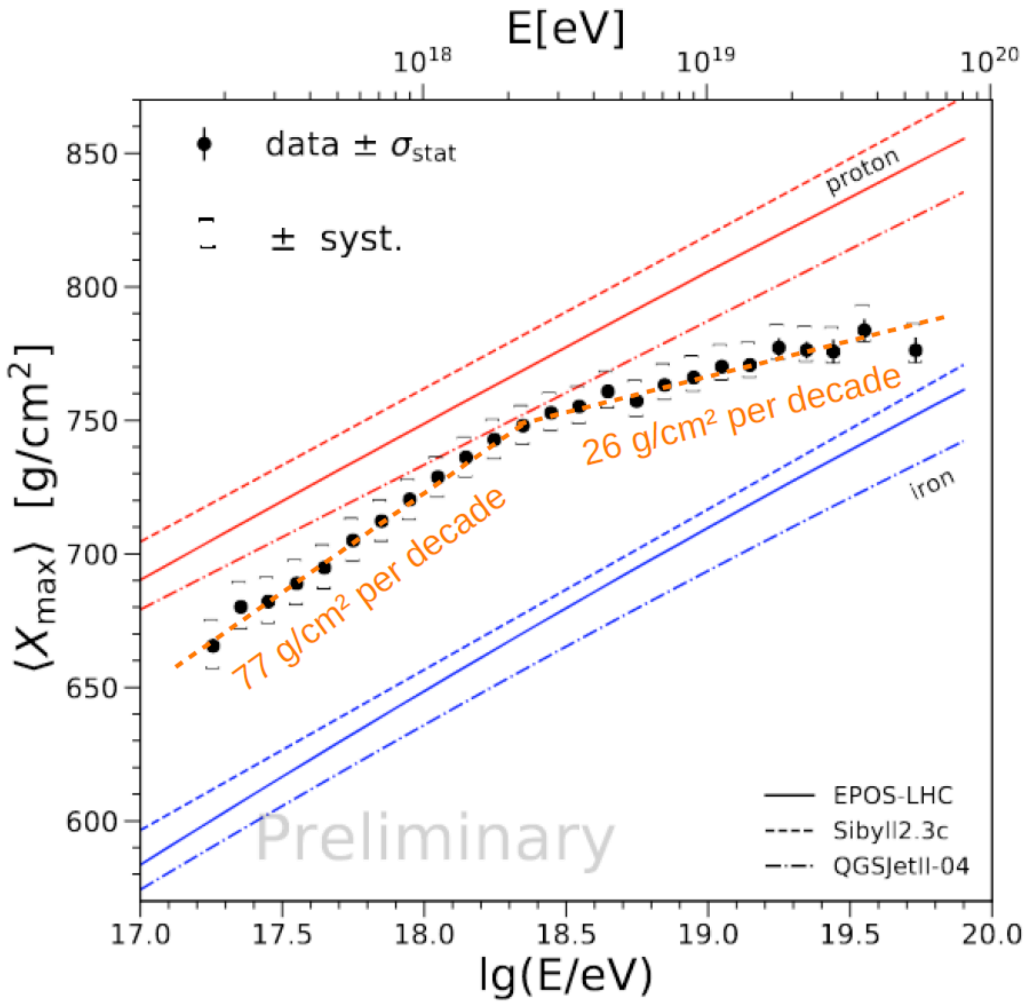
Comparing spectrum to other data

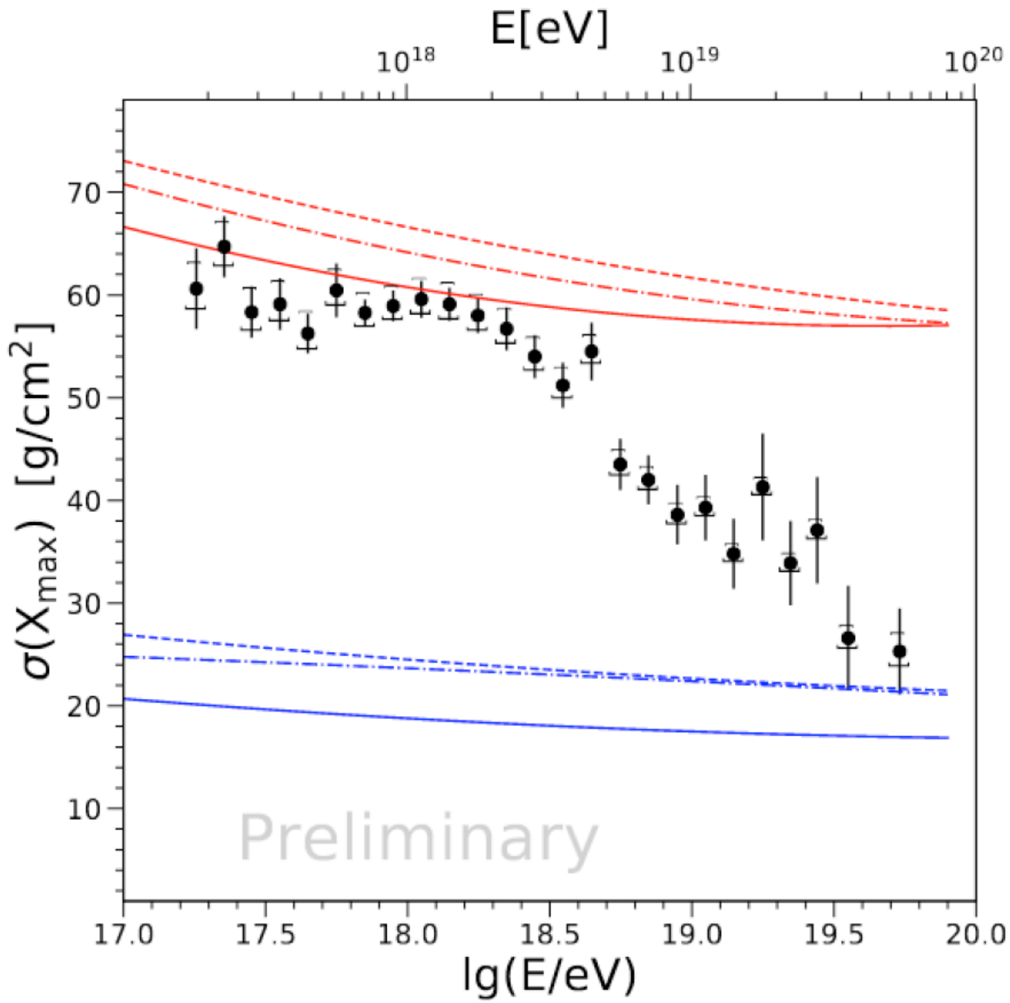


- At the highest energies, Auger and TA data can be brought to better agreement using a +/- 4.5% energy rescaling (well within systematics).
- Even when looking in the common declination band, an energy dependent shift is required to resolve the remaining discrepancies.

Y.Tsunesada (Auger-TA working group), ICRC 2021, #337
Snowmass UHECR white paper, arXiv 2205.05845 (2022)

X_{max} moments

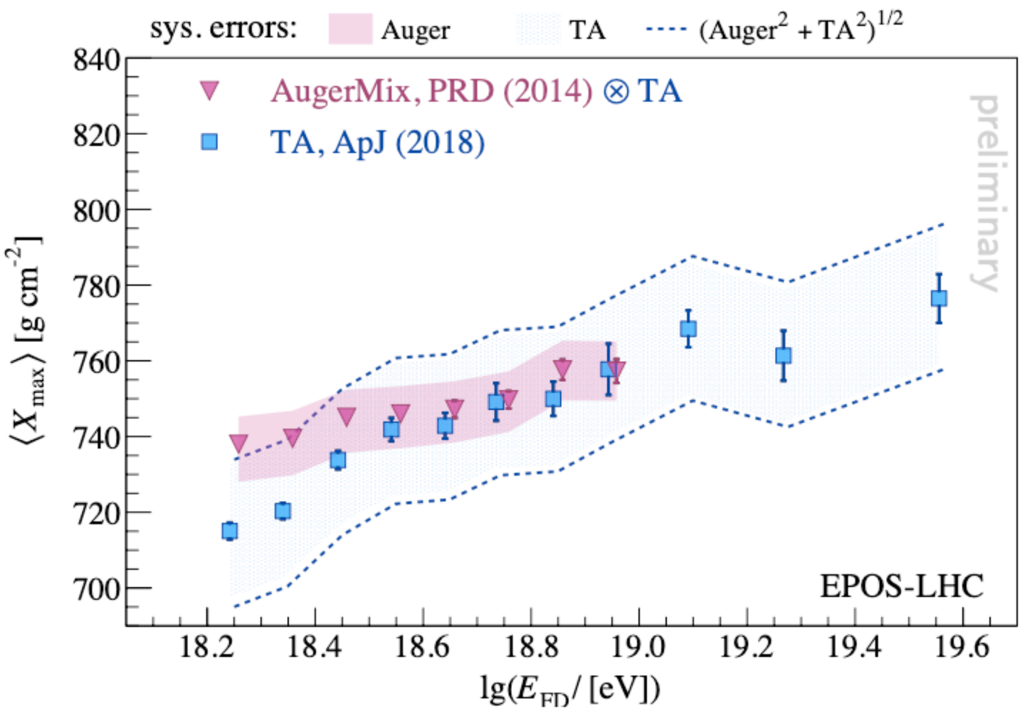


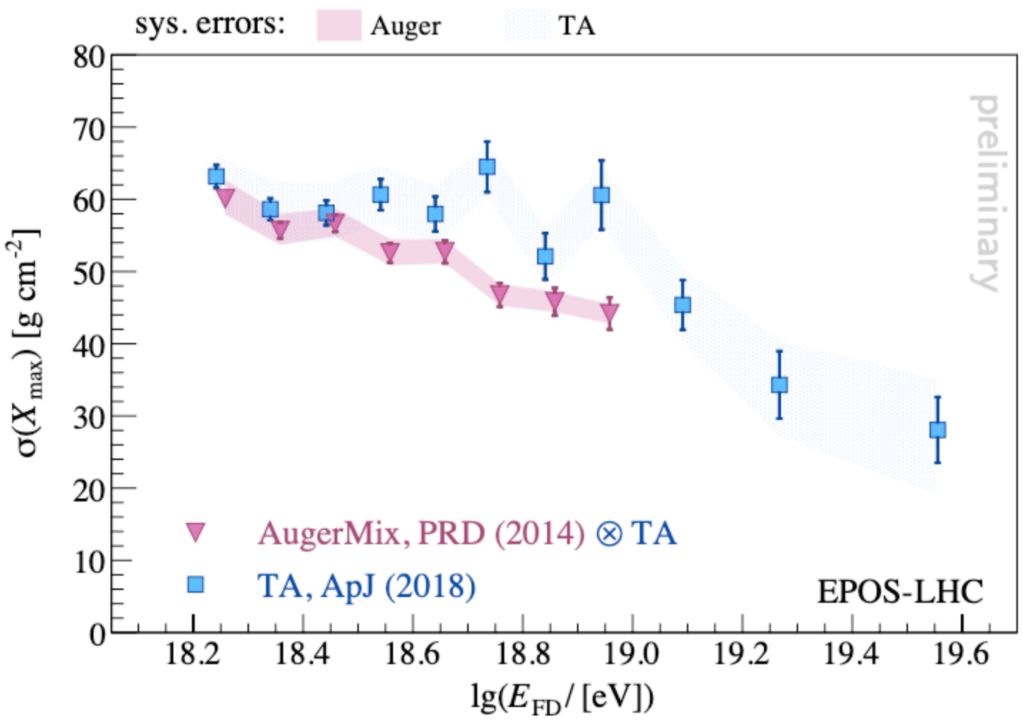


Evidence of a mixed composition - pure composition of light nuclei excluded with > 6σ
Change of slope around $10^{18.3}$ eV : composition first becomes lighter before getting heavier and heavier at the highest energies
Above $10^{18.3}$ eV : distribution of X_{max} become narrower

Comparisons with Telescope Array

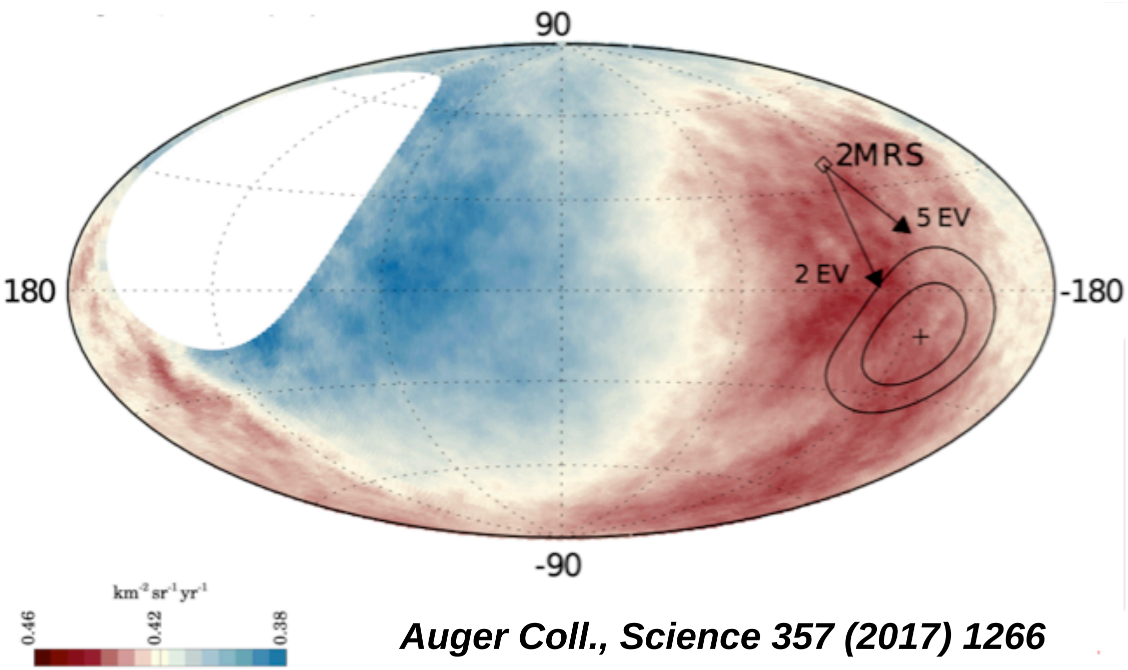
- **The Auger composition fractions input to the TA simulations; the resulting distributions are compared to the TA Xmax results**
- **TA data consistent with proton AND with Auger-mix composition at least up to 10 EeV**





Auger&TA working group, JPS Conf.Proc. 9 (2016) 010016
Auger&TA working group, EPJ Web of Cons. 210 (2018) 010009

Large scale anisotropy

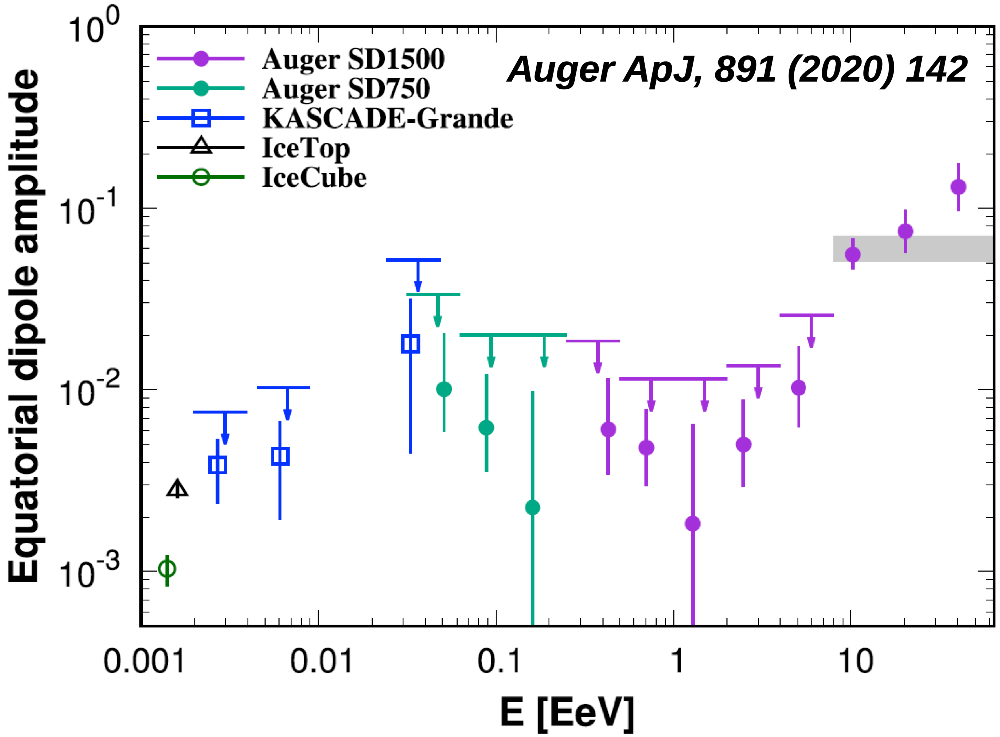


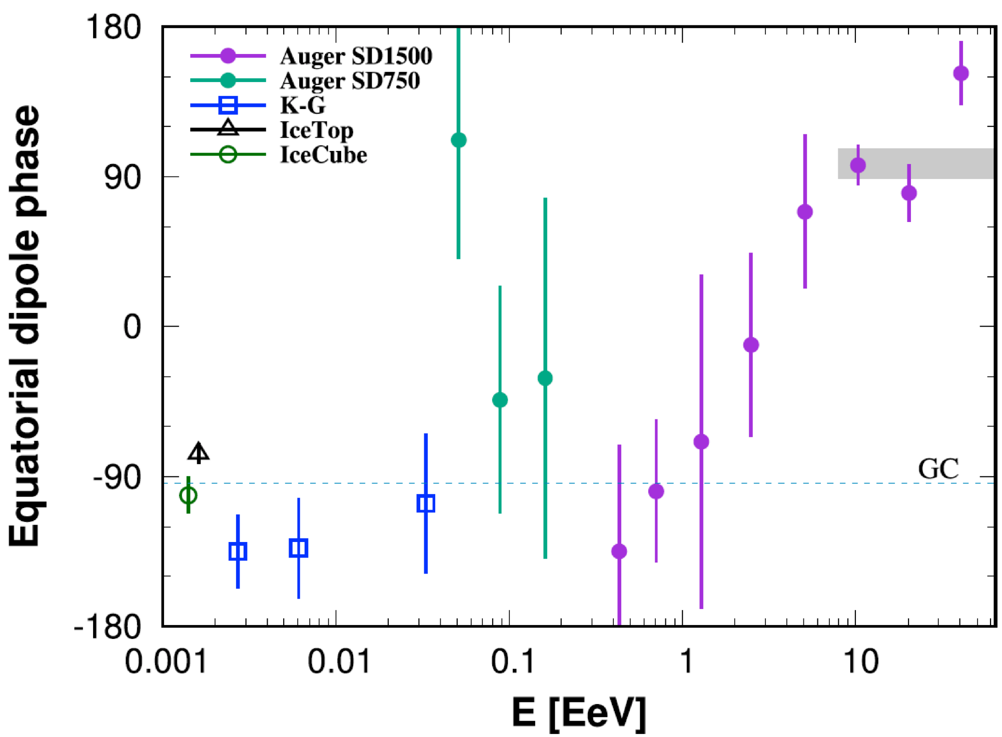
Auger Coll., Science 357 (2017) 1266

➡ exposure 110,000 km^2 sr yr

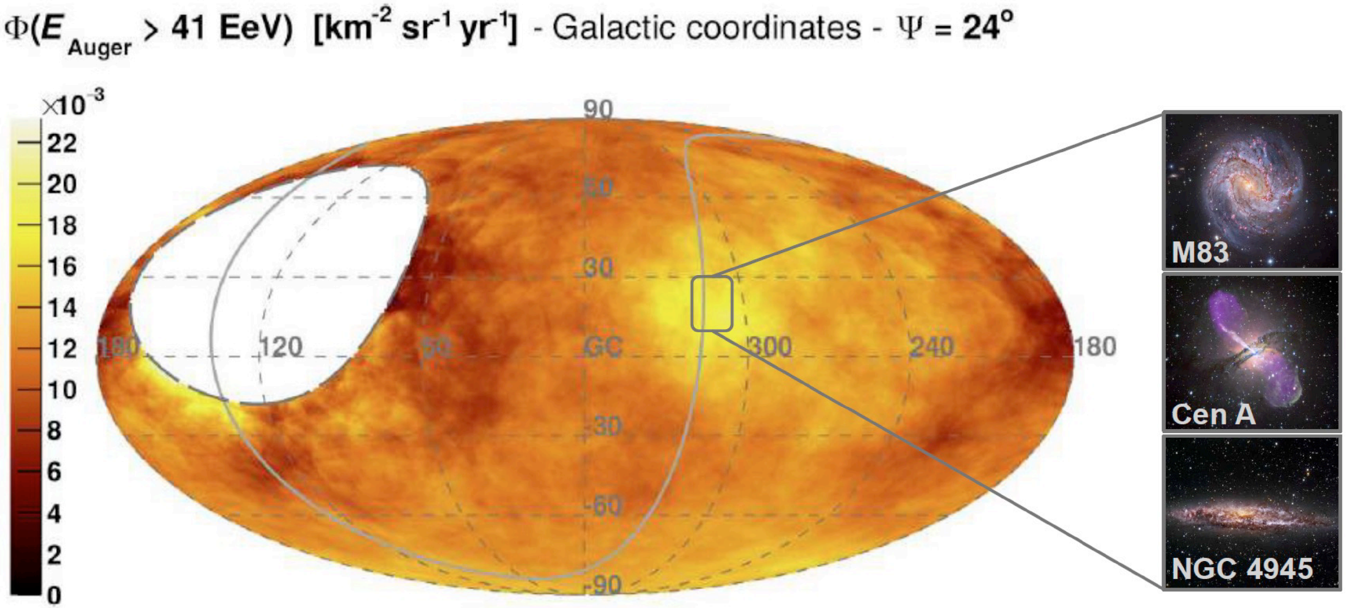
➡ ***OBSERVATION (at 6.6σ): 3D dipole above 8 EeV at (α,δ)=(95°,-36°): $(7.3^{+1.1}_{-0.9})$ %***

➡ UHECRs are extra-galactic above 8 EeV, predominantly Galactic below few EeV





Intermediate scale anisotropy



Catalog	$E_{\rm th}$ [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}

Search parameters

- $1^{\circ} \leq \Psi \leq 30^{\circ}$
- 32 EeV ≤ E ≤ 80 EeV

Whole sky blind search

- Most significant excess:
- Ψ =24° & E = 41 EeV
- 2.2σ post trial

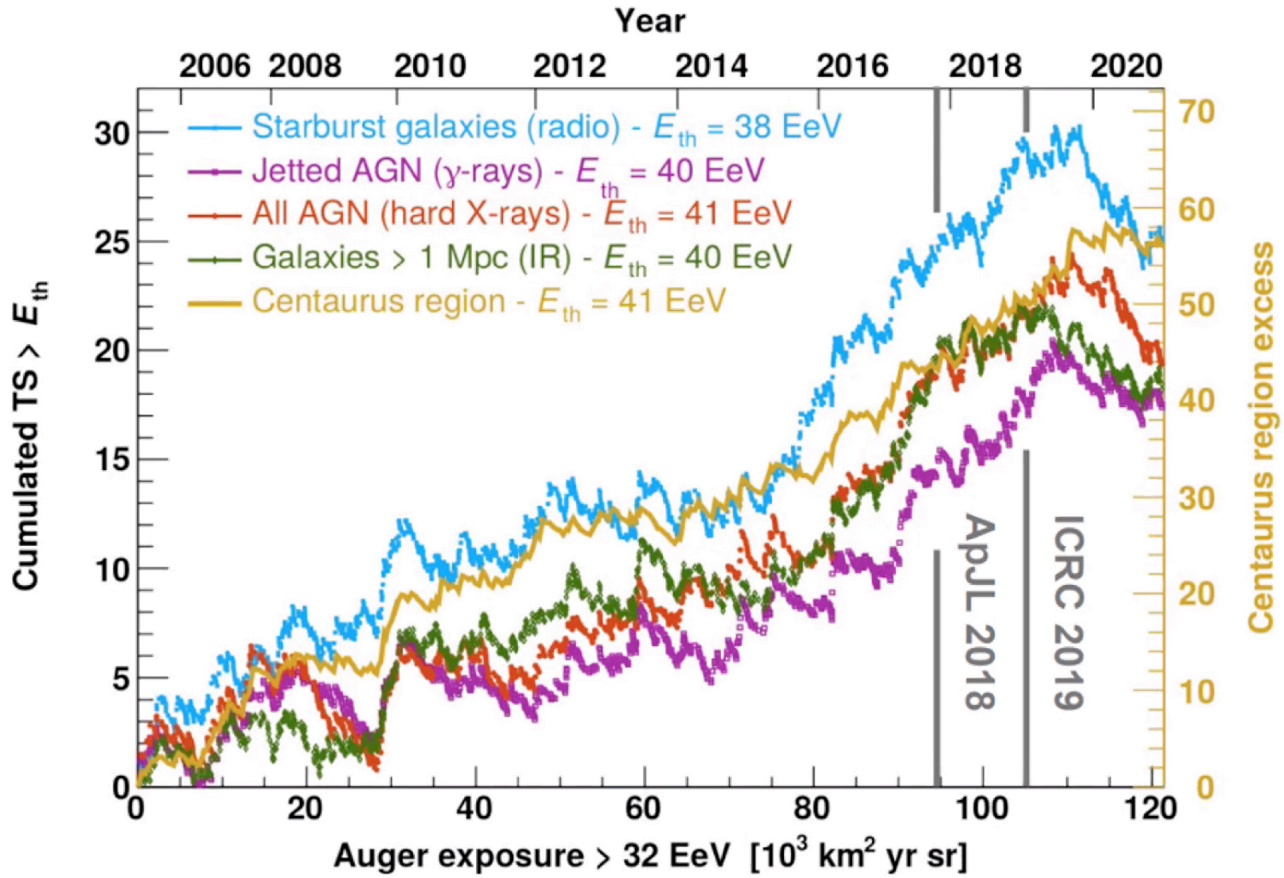
Fixed direction (CenA)

- Most significant excess:
- Ψ =27° & E = 41 EeV
- 3.9σ post trial

Catalog searches (see table)

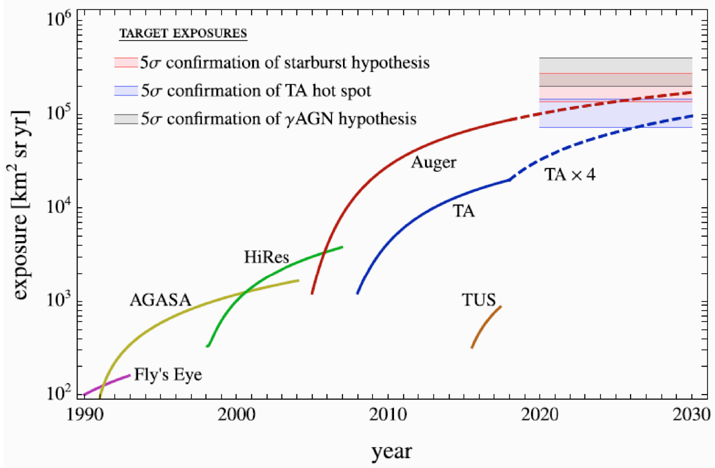
J.Biteau for the Pierre Auger Collaboration, ICRC2021 #307
A.Aab et al., Ap. J. Lett 853 L29 (2018)
Paper accepted to ApJS (2022); see arXiv:2206.13492

Intermediate scale anisotropy



4.0σ

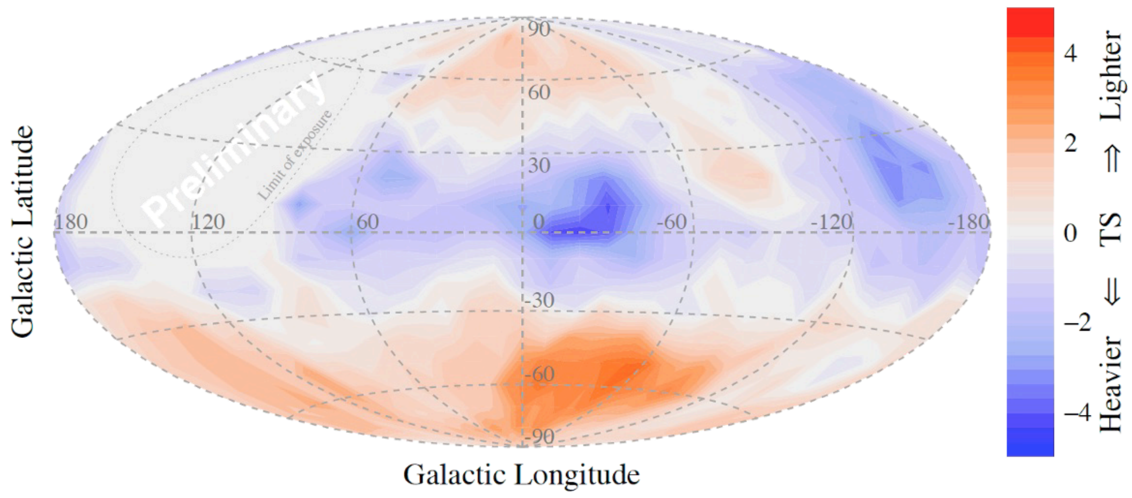
3.1σ

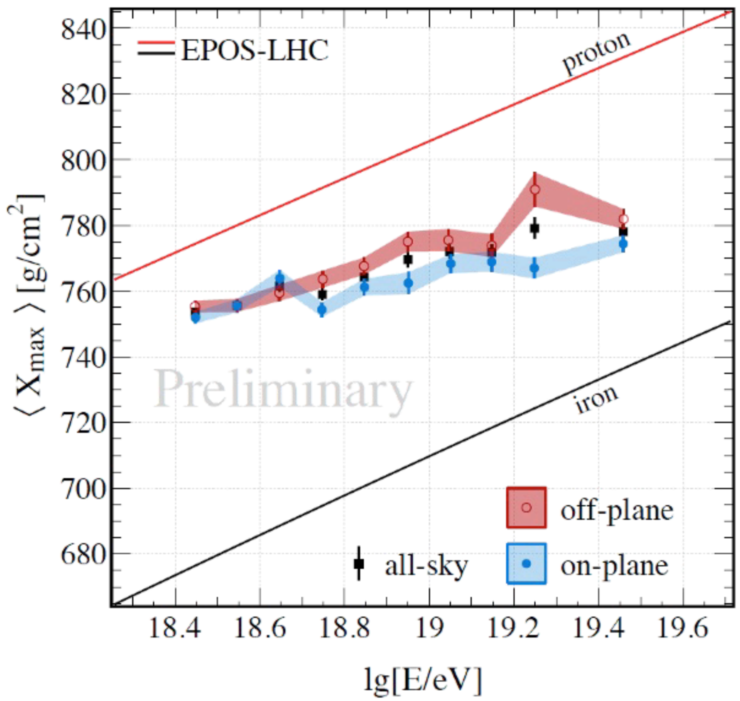


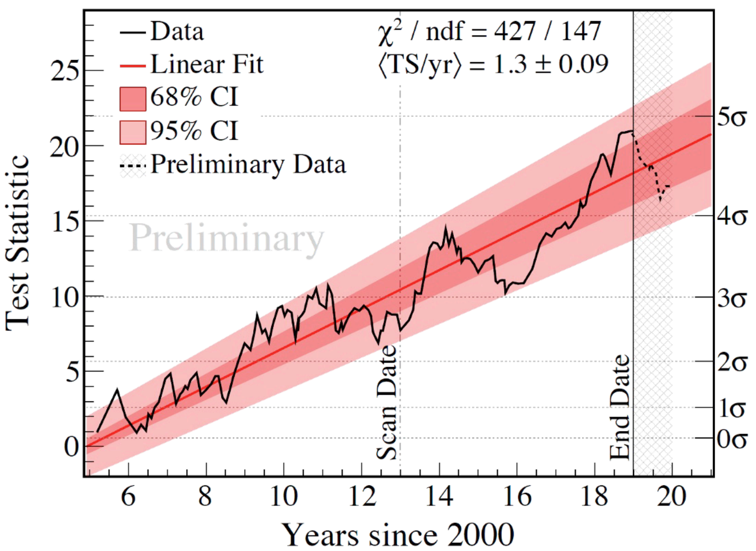
Signal growths consistent with the discovery of one or more classes of UHECR sources by 2025-30

J.Biteau for the Pierre Auger Collaboration, ICRC2021 #307, A.Aab et al., Ap. J. Lett 853 L29 (2018)
F.Sarazin, L.Anchordoqui et al. 2020 Decadal Survey UHECR white paper, arXiv:1903.04063

Composition enhanced anisotropy studies





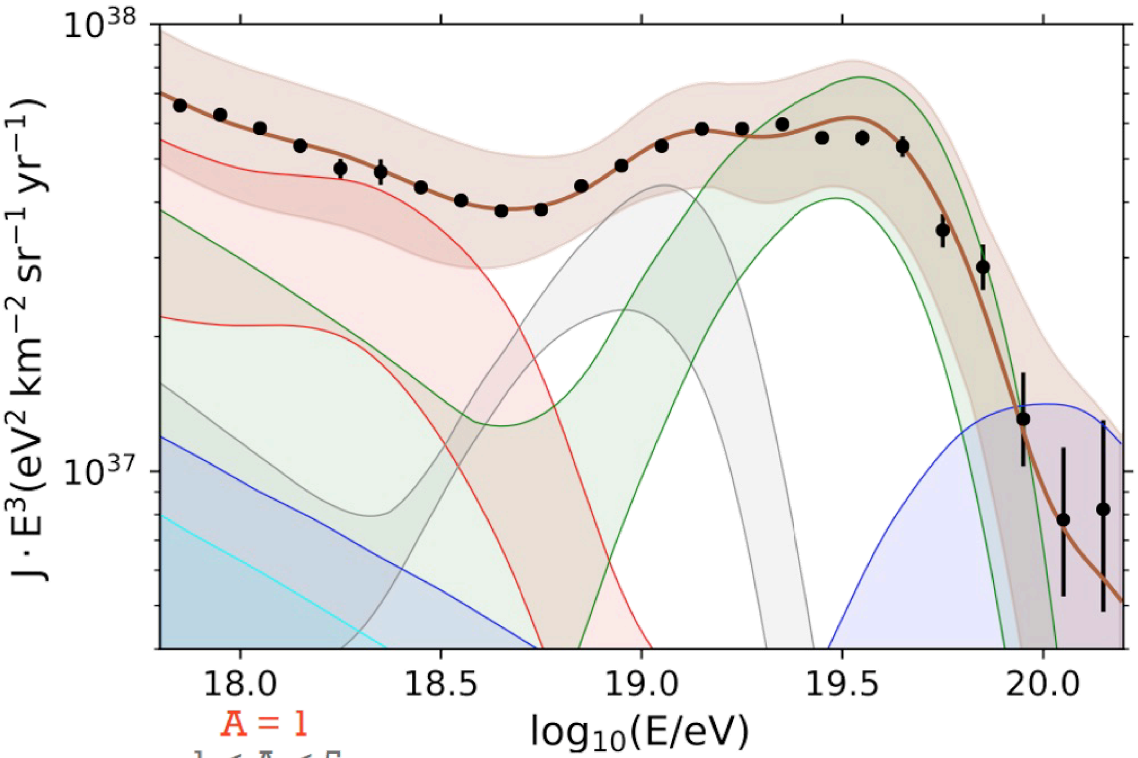


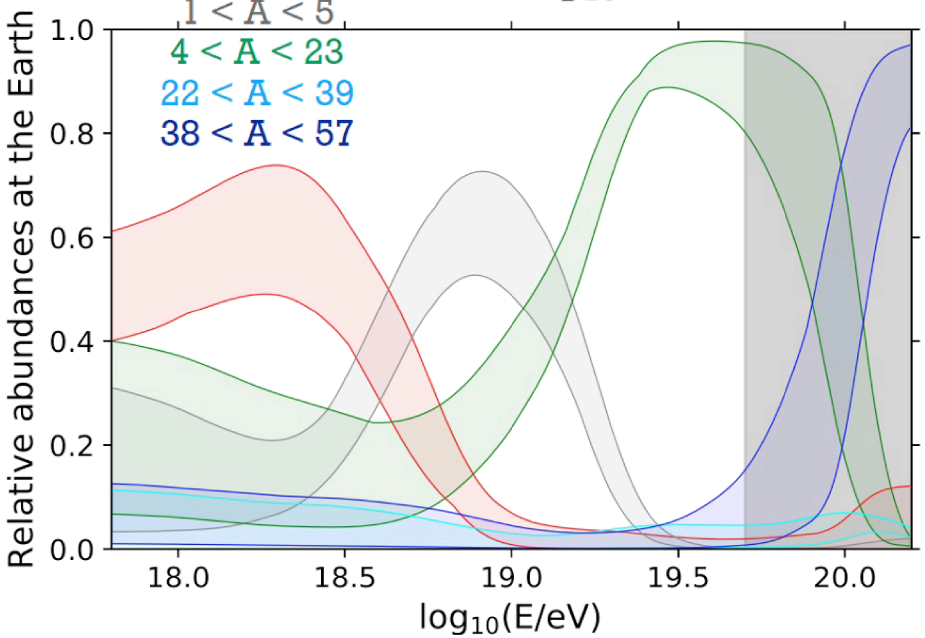
- **Scan of data before Jan 1, 2013 (54% of the data). Highest TS for Log(E_{min}/eV)=18.7 and b_{split}=30º.**
- **Significance at the end date: 4.9σ statistics only, 3.3σ including systematics**
- **Indication of a lighter composition far from the Galactic plane**

Such anisotropy may not be related to the Galactic Magnetic Field. Local source distribution or mass dependent horizons may play a role.

E. Mayotte for the Pierre Auger Collaboration, ICRC 2021 #321

Interpreting the data





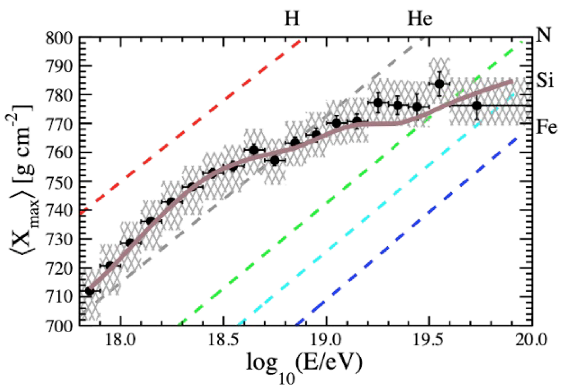
Extension of the combined fit to below the ankle.

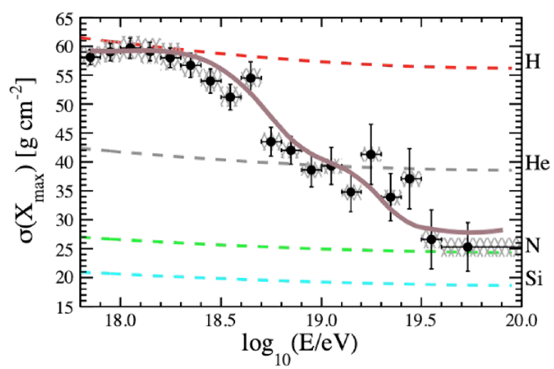
Energy spectrum >6 10^{17} eV
Xmax ~6 10^{17} - 5 10^{19} eV + σ(Xmax)
Propagation from sources

Above the ankle: Maximum rigidity scenario with R_{cut} ~ 1.5 x 10^{18} V and very hard spectral index γ < 1
+ soft extragalactic component below the ankle

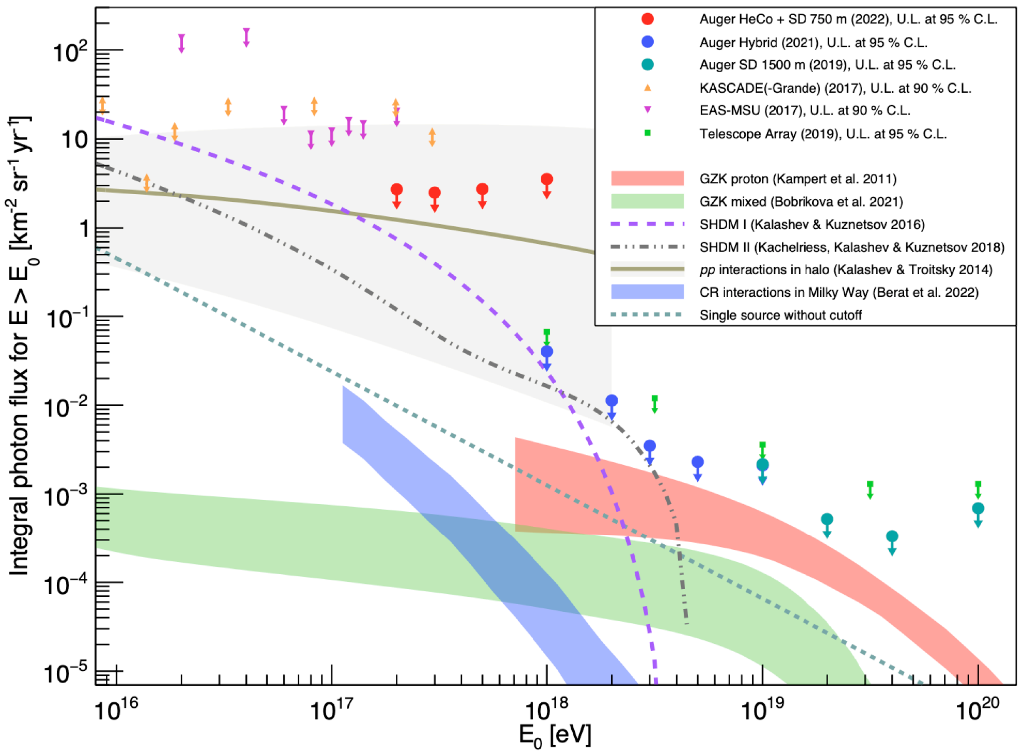
Possible Galactic component (N) below the ankle doesn't constrain the fit well

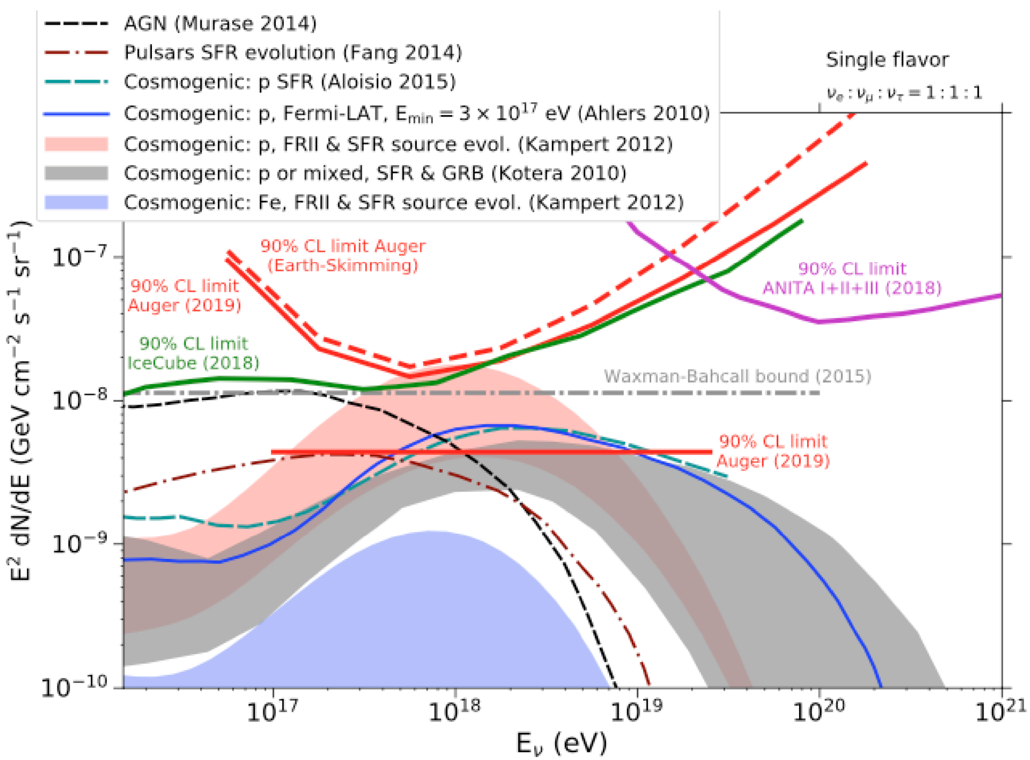
A.Aab et al., PRL 125, 121106 (2020)
E.Guido for the Pierre Auger Collaboration, ICRC2021 #311





UHE photons and neutrinos





Most stringent limits on UHE photons across three decades in energy

Maximum sensitivity to UHE ν's around EeV k (90% CL) < 4.4 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

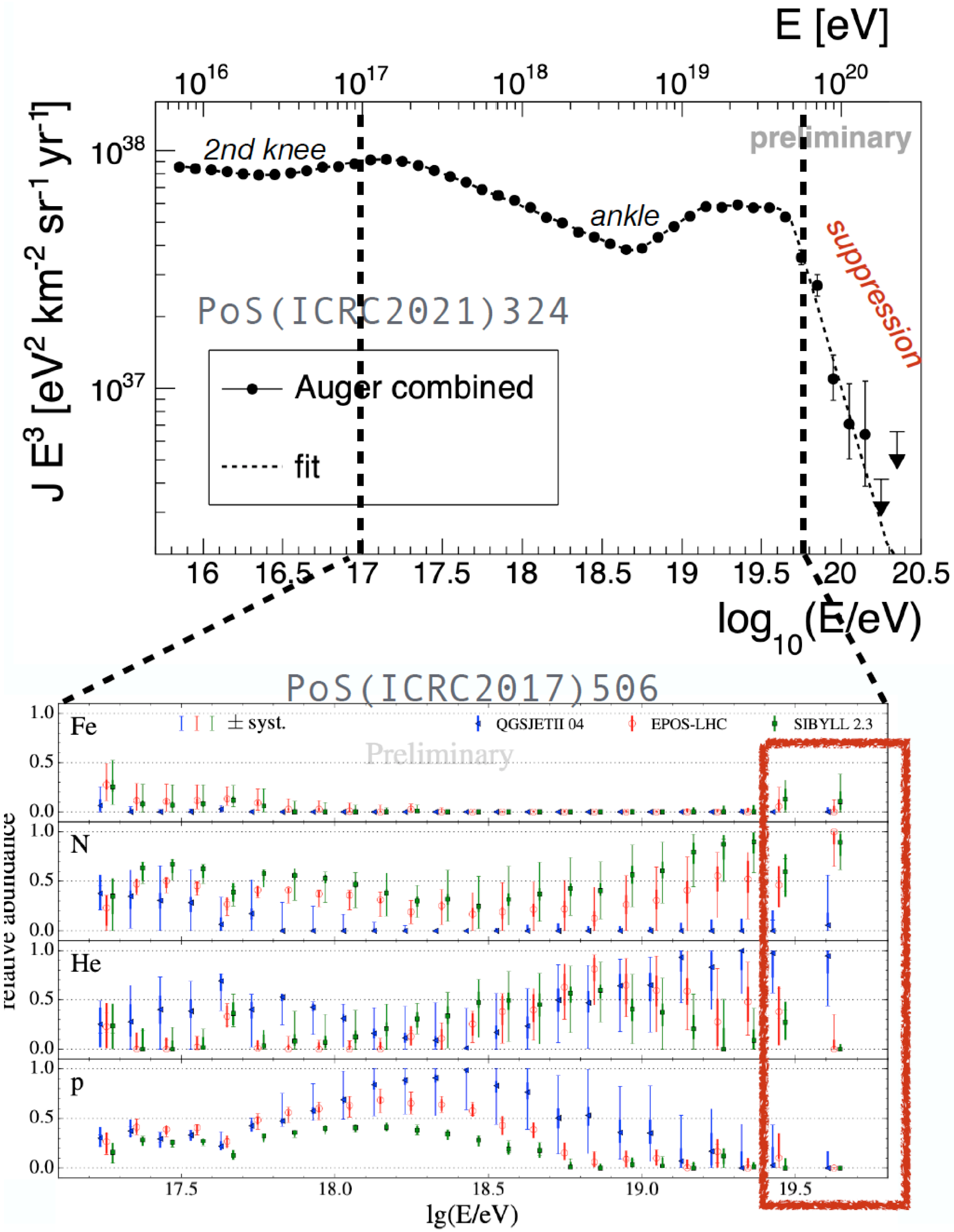
- limits background dominated
- more data for γ/hadron separation needed
- an increased sensitivity to photons required for probing unexpected phenomena, e.g. Milky Way sources, interaction in the halo, decay of SHDM

- different models of cosmogenic and astrophysical neutrino production excluded
- aperture comparable to that of IceCube if source direction is favourable
- neutrinos used (as photons) in multi-messenger studies of transient phenomena

Auger Coll., JCAP04 (2017) 009; JCAP09 (2020) E02
P.Savina (Auger Coll.), PoS(ICRC2021) 373
Auger Coll., ApJ (2022)

Auger Coll., JCAP10 (2019) 022;
JCAP 11 (2019) 004; ApJ 902 (2020)105

Results and lessons from Auger Phase 1



Flux suppression well established :
the UHECR sources must be nearby (< 200 Mpc)

Composition mixed and heavier above ~ 2x10^{18} eV from Xmax measurements
… but statistics too low above ~$10^{19.5}$ eV due to FD duty cycle ~15%.

Large scale dipolar anisotropy (6.6 σ) :
extragalactic origin for UHECR > 8 EeV
+ Hints of correlation with SBG/AGN
➟ Quest for sources still open.

Muon puzzle: muon content in simulations lower than in data
➟ Tension with all hadronic models.

Strong limits on the flux of neutrinos and gammas: "standard" astrophysical scenarios of UHECR production

… and many more

Towards Auger Phase 2: AugerPrime upgrade

Surface Scintillator Detector (SSD)
different response to electromagnetic & muonic shower components w.r.t. WCD

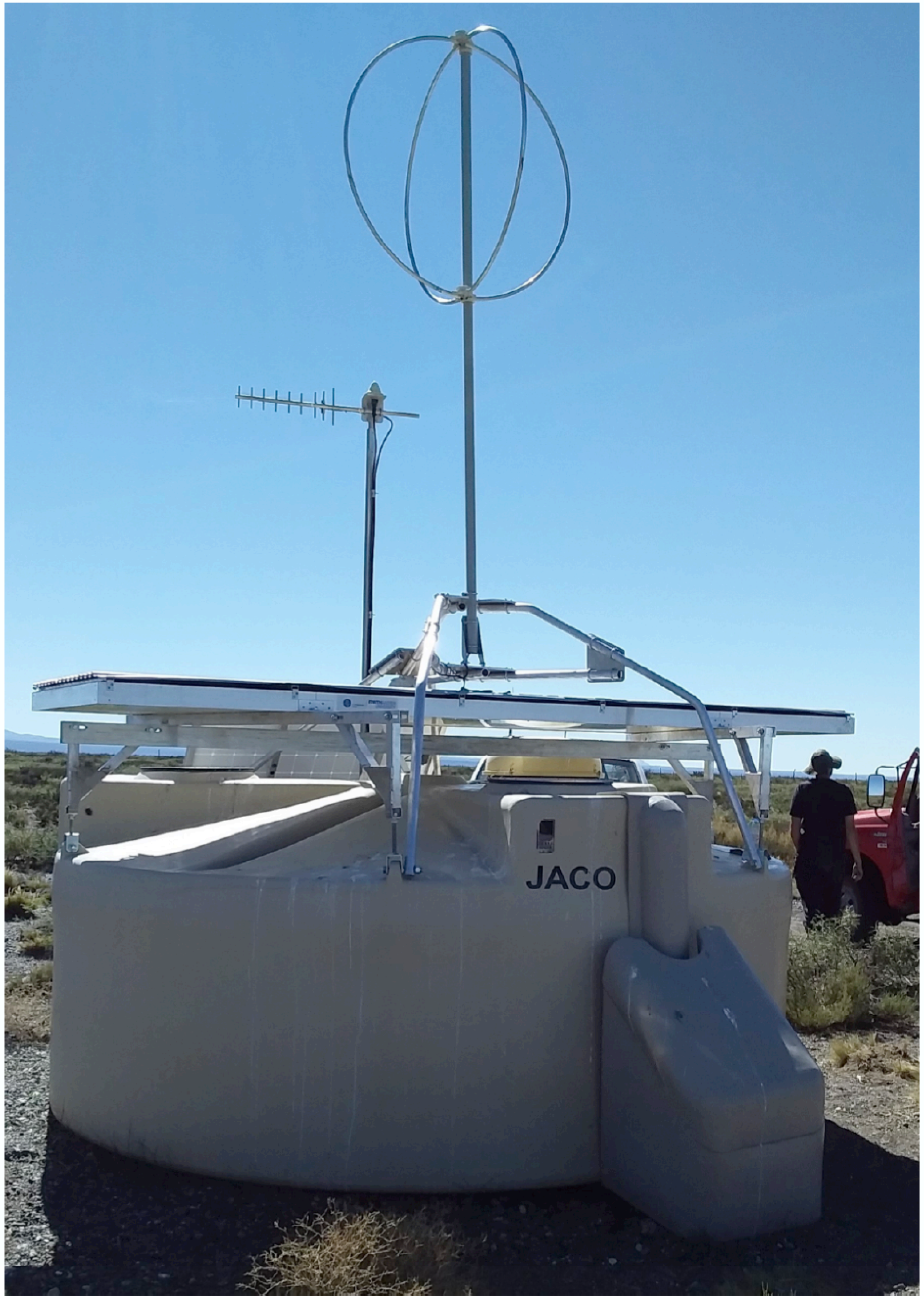
Radio antenna
to measure the radio emission of showers in atmosphere (30-80 MHz)

Underground Muon Detector (UMD)
direct muon measurement and cross-check of SSD-WCD combined analysis

Small PMT (SPMT)
increase of the dynamic range of WCD measurements

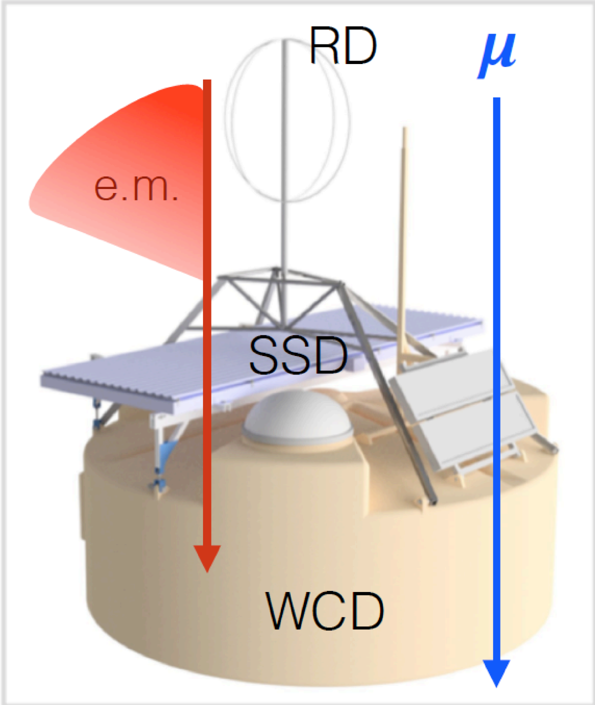
Upgraded Unified Electronics (UUB)
to process the signals from all the new detectors with improved performances

Auger Preliminary Design Report [arXiv:1604.03637]
A. Castellina, EPJ Web of Conf.210 (2019) 06002

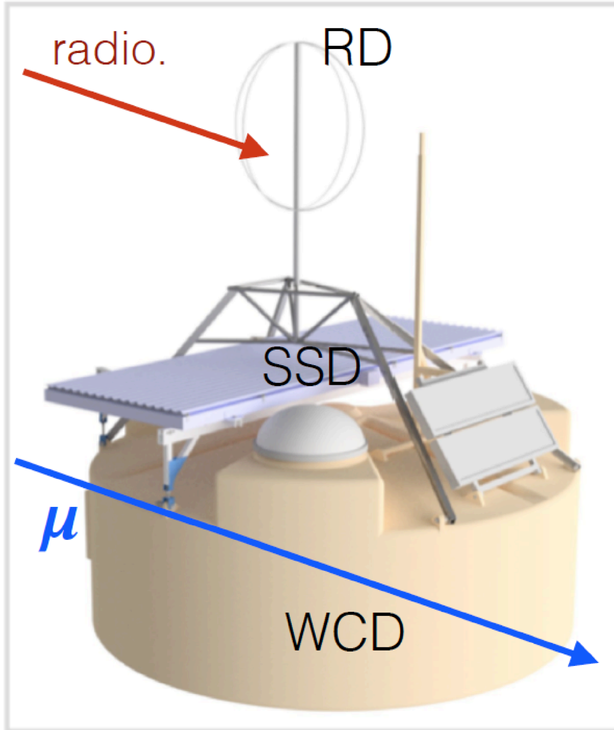


Measurements with AugerPrime

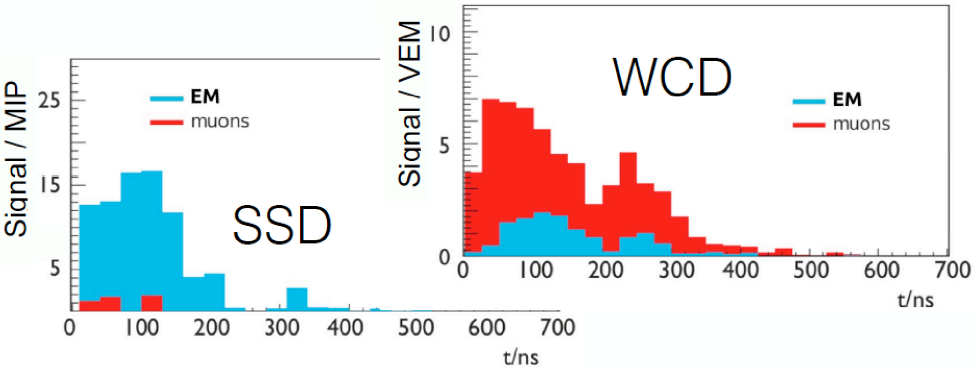
vertical events (0°- 60°)



Simultaneous measurement of a shower with WCD, SSD, RD, UMD (& fluorescence telescopes)



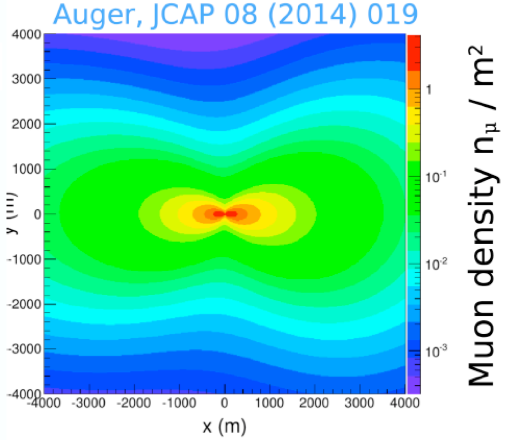
inclined events (60°- 95°)

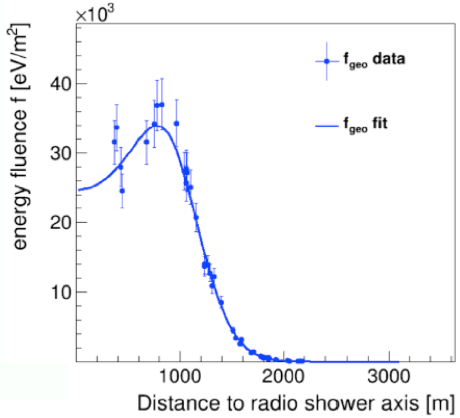


+ RADIO

- top-down method (i.e. comparison with MC)
- radio observables (e.g. LDF slope, wavefront shape)
- comparison with muon density from UMD (lower energies)

density of muons at ground (WCD) ⟶





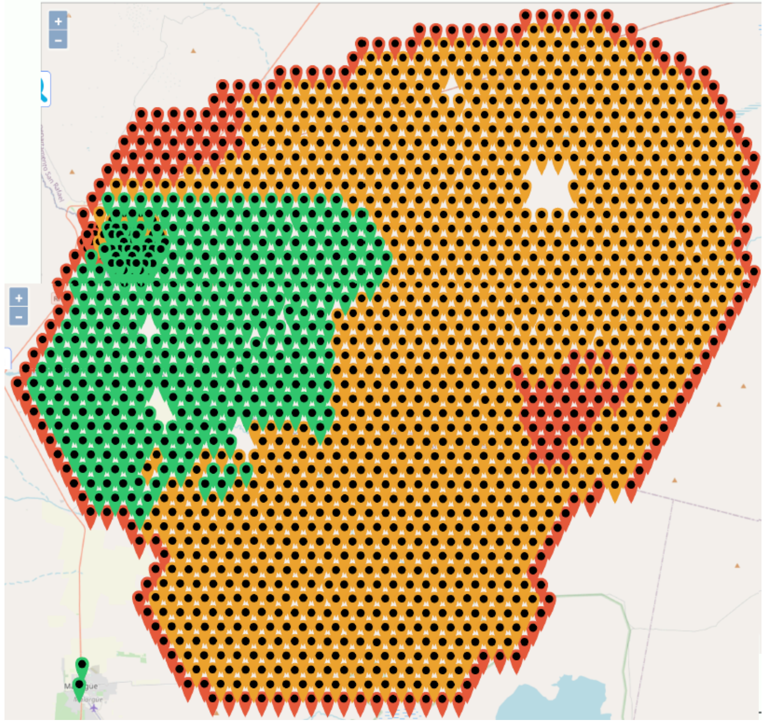
+

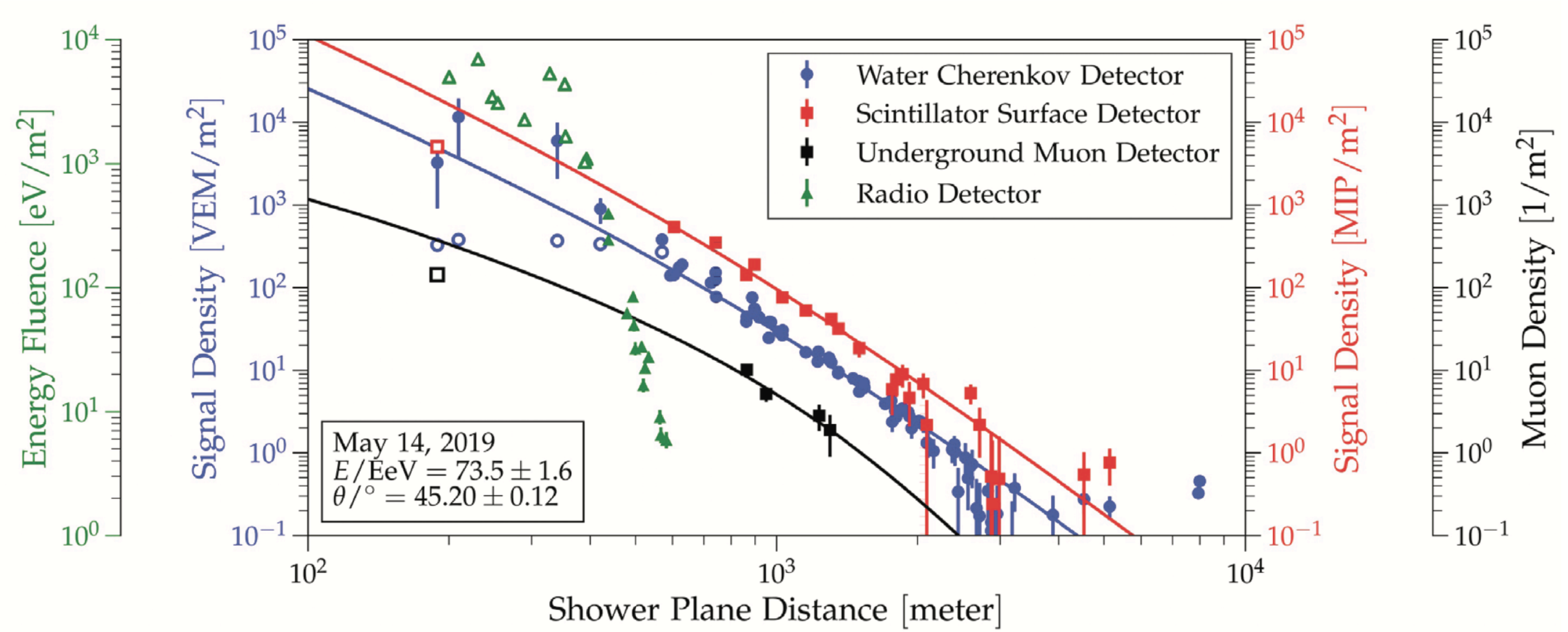
⟵ radiation at ground from e.m. component (RD)

AugerPrime: status and conclusions

AugerPrime : largest exposure UHECR detector with composition sensitivity above 4 x 10^{19} eV

- Deployment and commissioning to be completed by mid 2023.
- Data taking foreseen up to 2030.
- Fundamental input for future experiments.



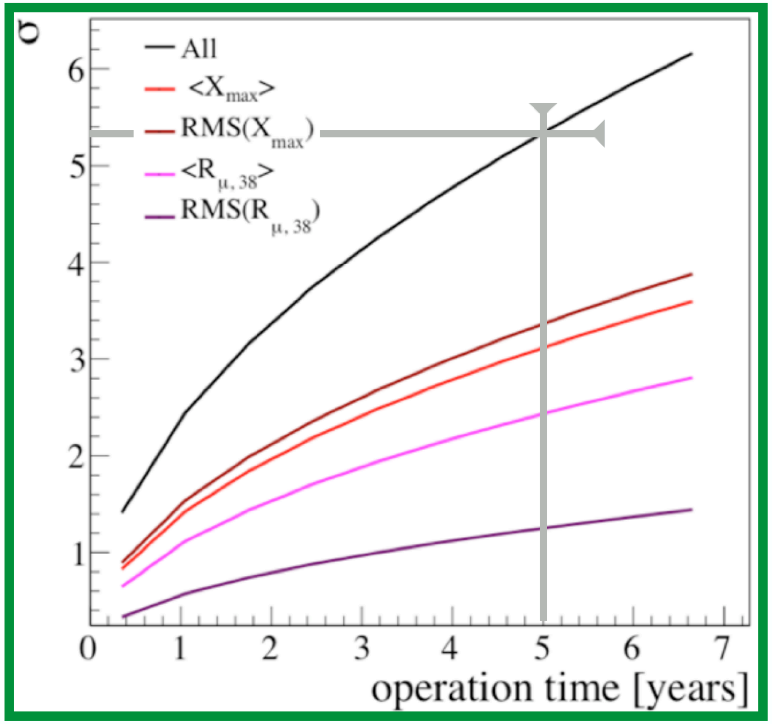


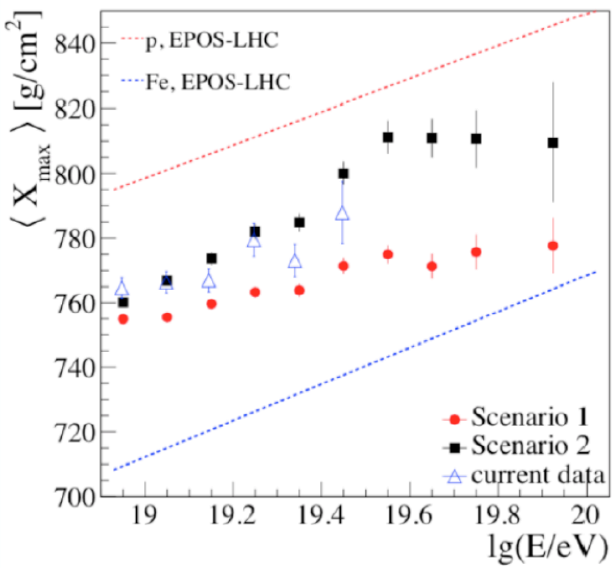
Backup slides

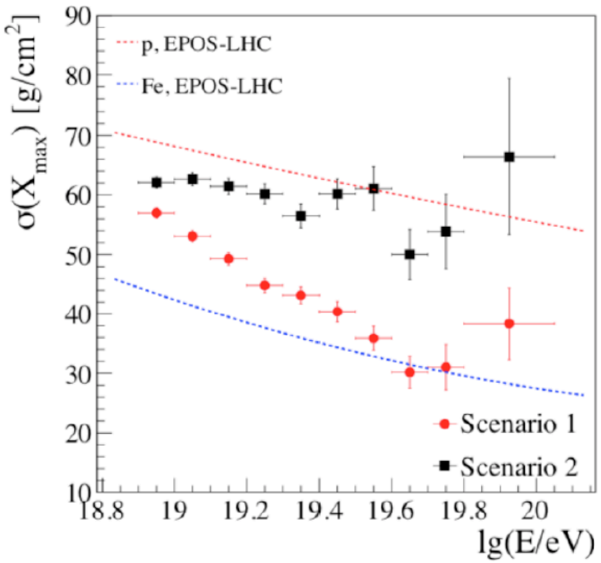
AugerPrime scientific case

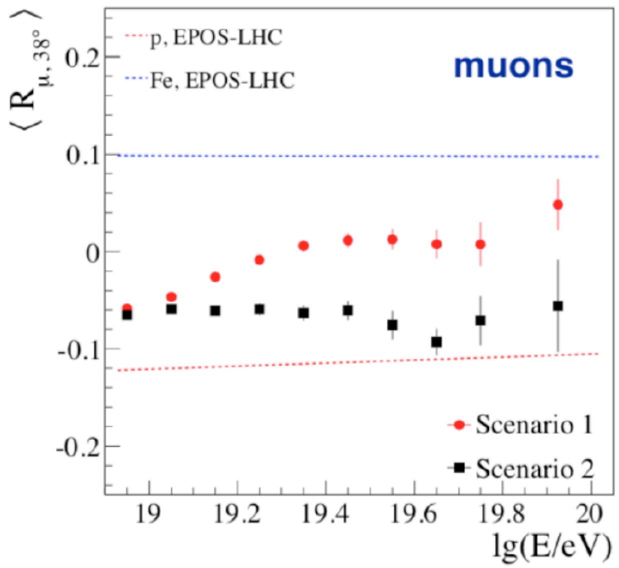
Primary goal : mass composition of UHE

- ➡ to study the origin of the suppression
- ➡ to accomplish composition-driven anisotropy analyses *e.g. if 10% of protons at the highest energies* →
- ➡ to study the hadronic interactions at energy much larger than human made accelerators (hints of new physics ?)
- ➡ to provide better estimates of ɣ and ν flux (explore potential of future experiments)









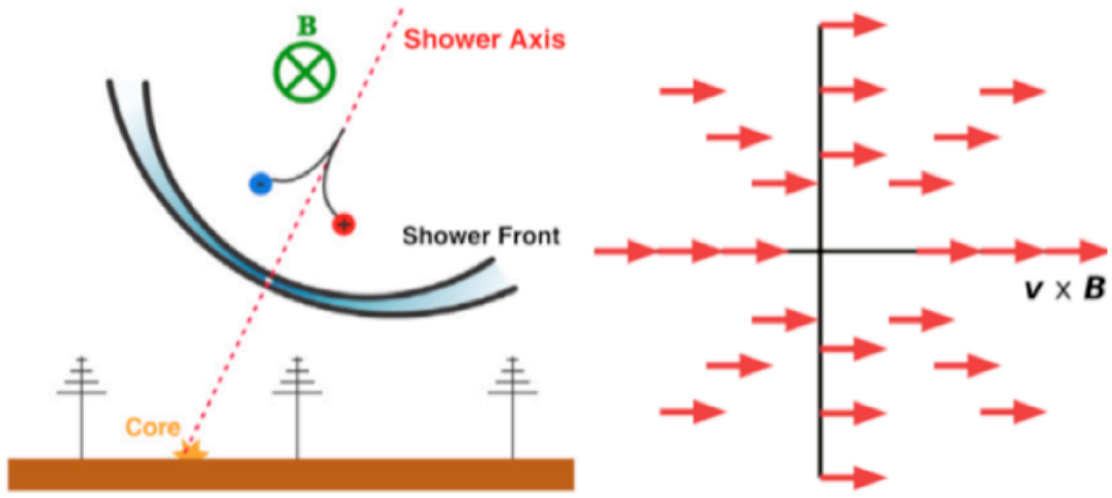
Scenario 1 : maximum rigidity model   Scenario 2 : photo-disintegration model

Radio emission by extensive air showers

The 30–80 MHz band is used by most experiments.
Due to coherence effects, the cosmic-ray-induced radio emission is strongest below 100 MHz.
Atmospheric noise and short-wave band transmitters make measurements below 30 MHz unfeasible.
From 85 to 110 MHz the FM band interferes with measurements.

Geomagnetic emission

- geomagnetic field deflects e- and e+ in opposite directions —> transverse current varying over time
- linear polarisation of the radiation (E aligned along the Lorentz force)
- propagation along the shower axis



Askaryan effect

- ionisation of ambient medium by EAS particles: e+ annihilation —> excess of e- along the longitudinal development
- linear polarisation of the radiation (E radially oriented wrt EAS axis)
- sub-dominant in EAS