Ultra High Energy Cosmic Rays:
Experimental status and Future Observations

11/7/2022

Charles Timmermans

Radboud University

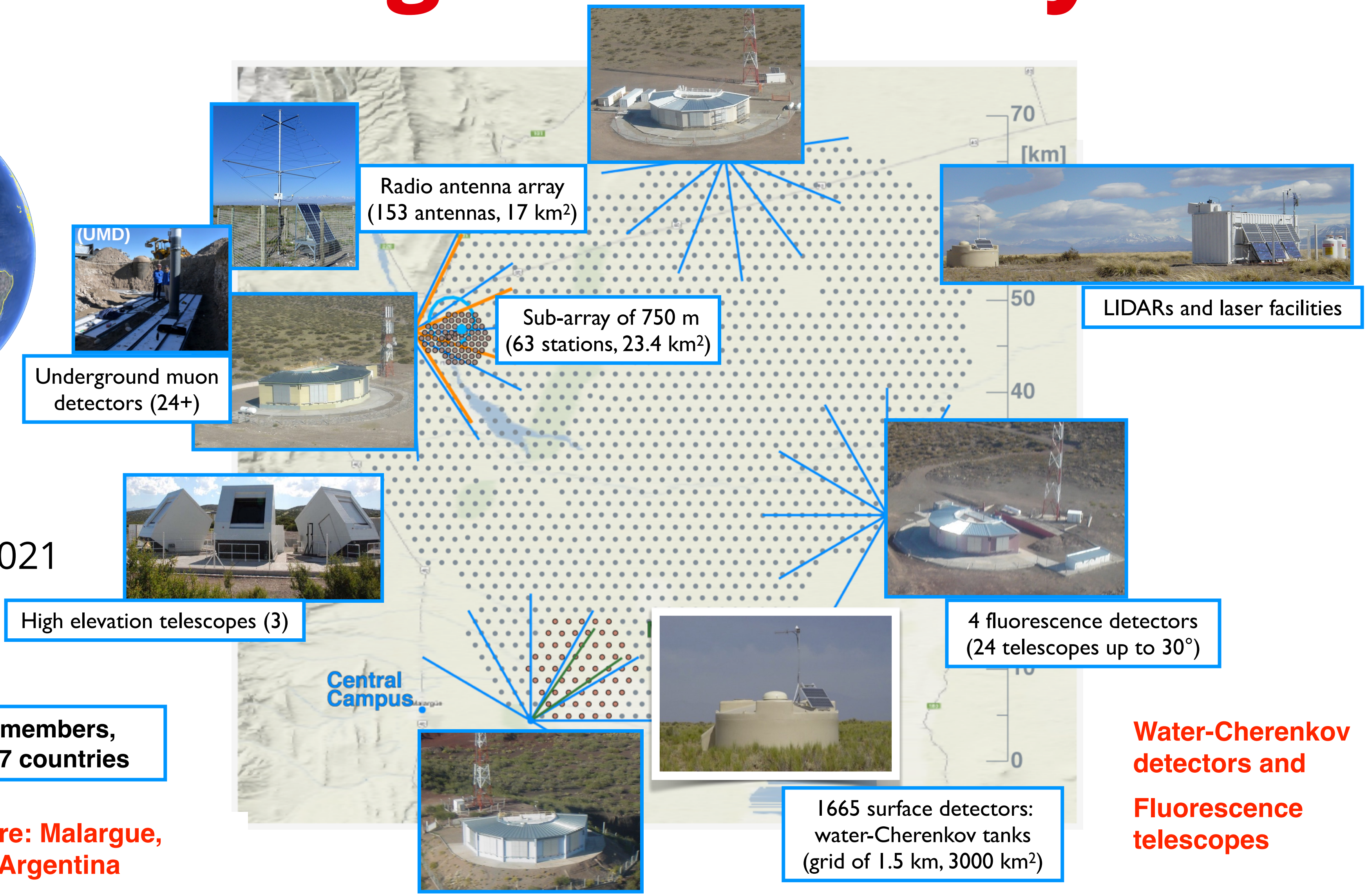
Outline

- The Pierre Auger Observatory and Telescope Array
- Experimental status: Highlights of the recent results
- AugerPrime: The Upgraded Pierre Auger Observatory
- The Next Generation: GRAND

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina

Ralph Engel, ICRC2021



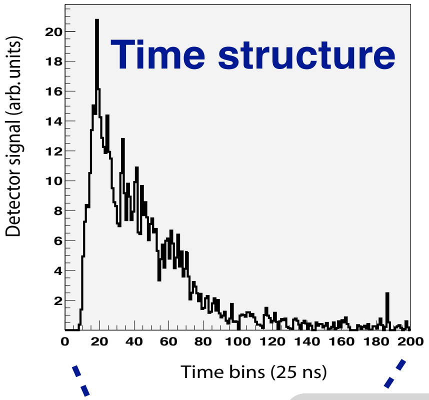
More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

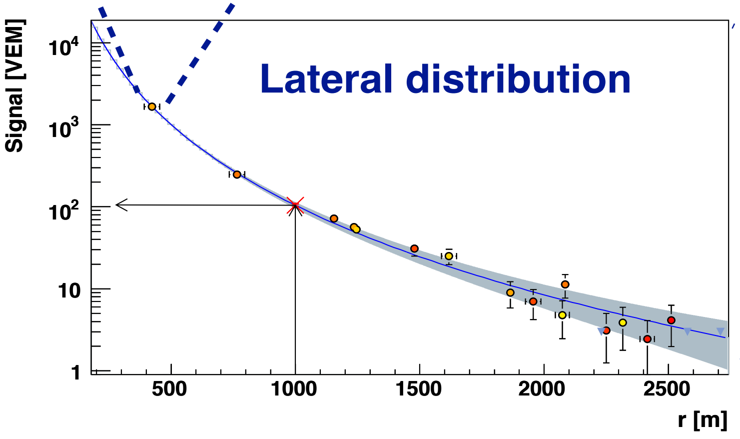
Water-Cherenkov detectors and

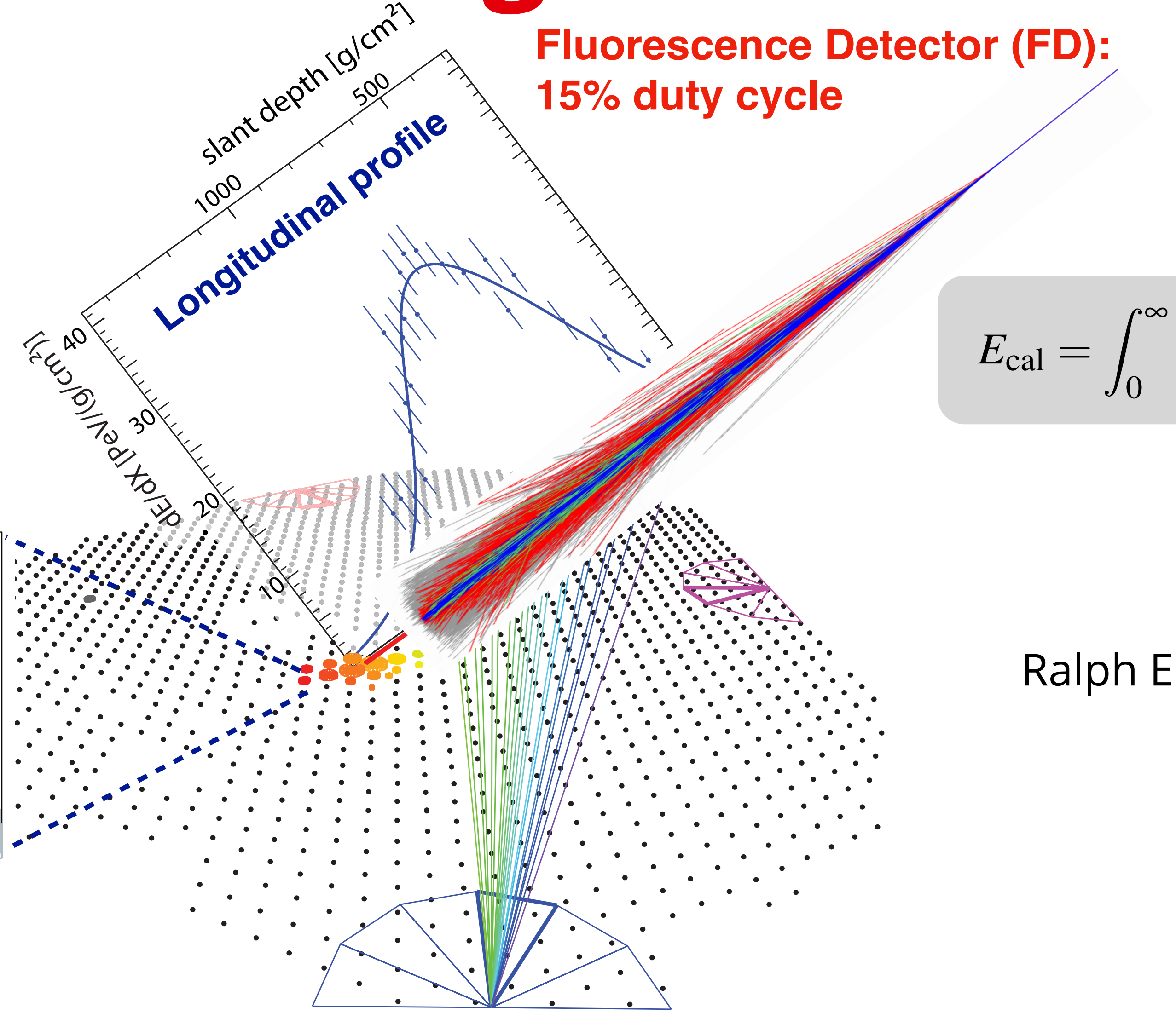
Fluorescence telescopes

Observables Pierre Auger Observatory



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





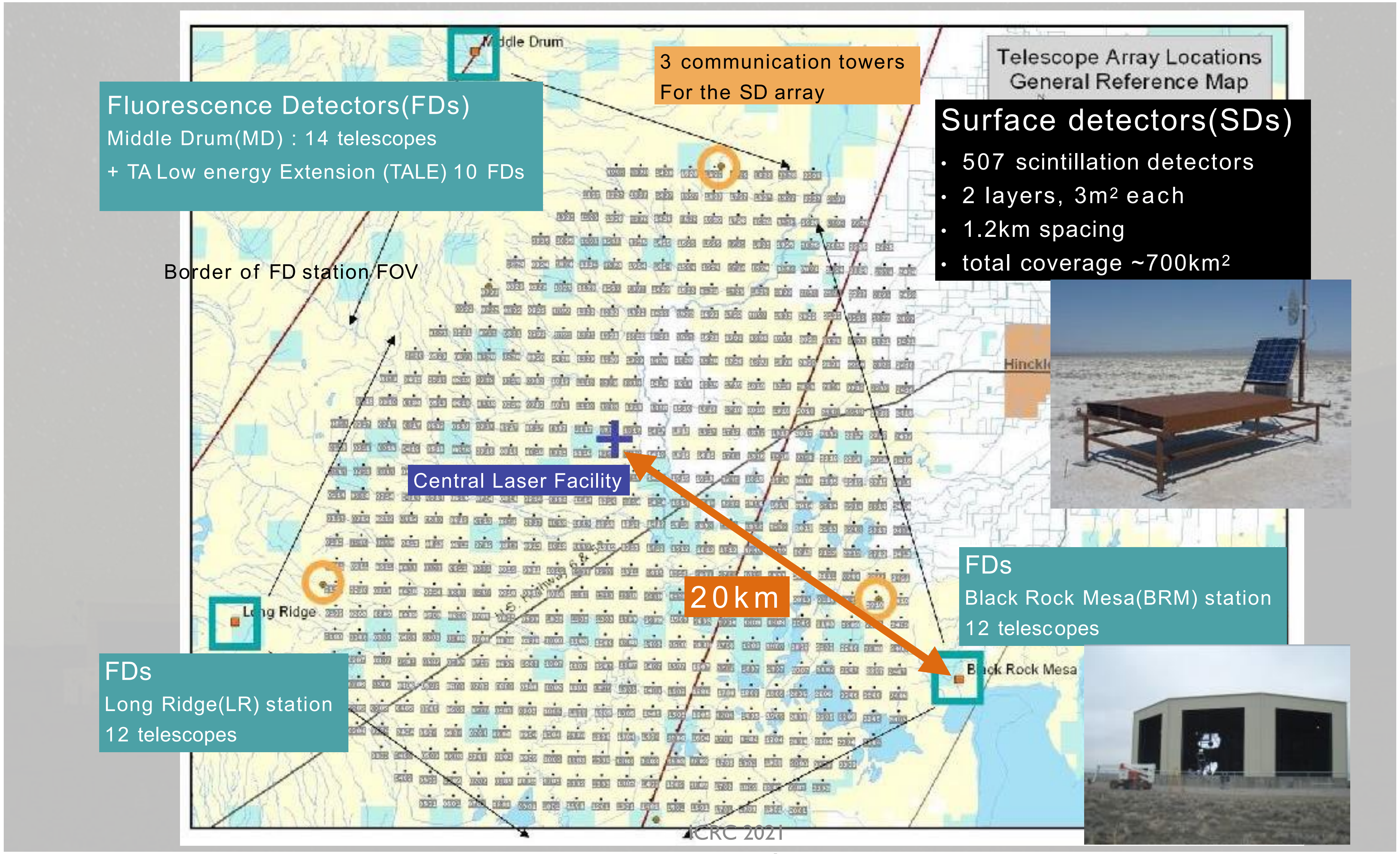
Fluorescence Detector (FD):
15% duty cycle

$$E_{cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{obs} dX$$

Ralph Engel, ICRC2021

Surface Detector (SD)
100% duty cycle

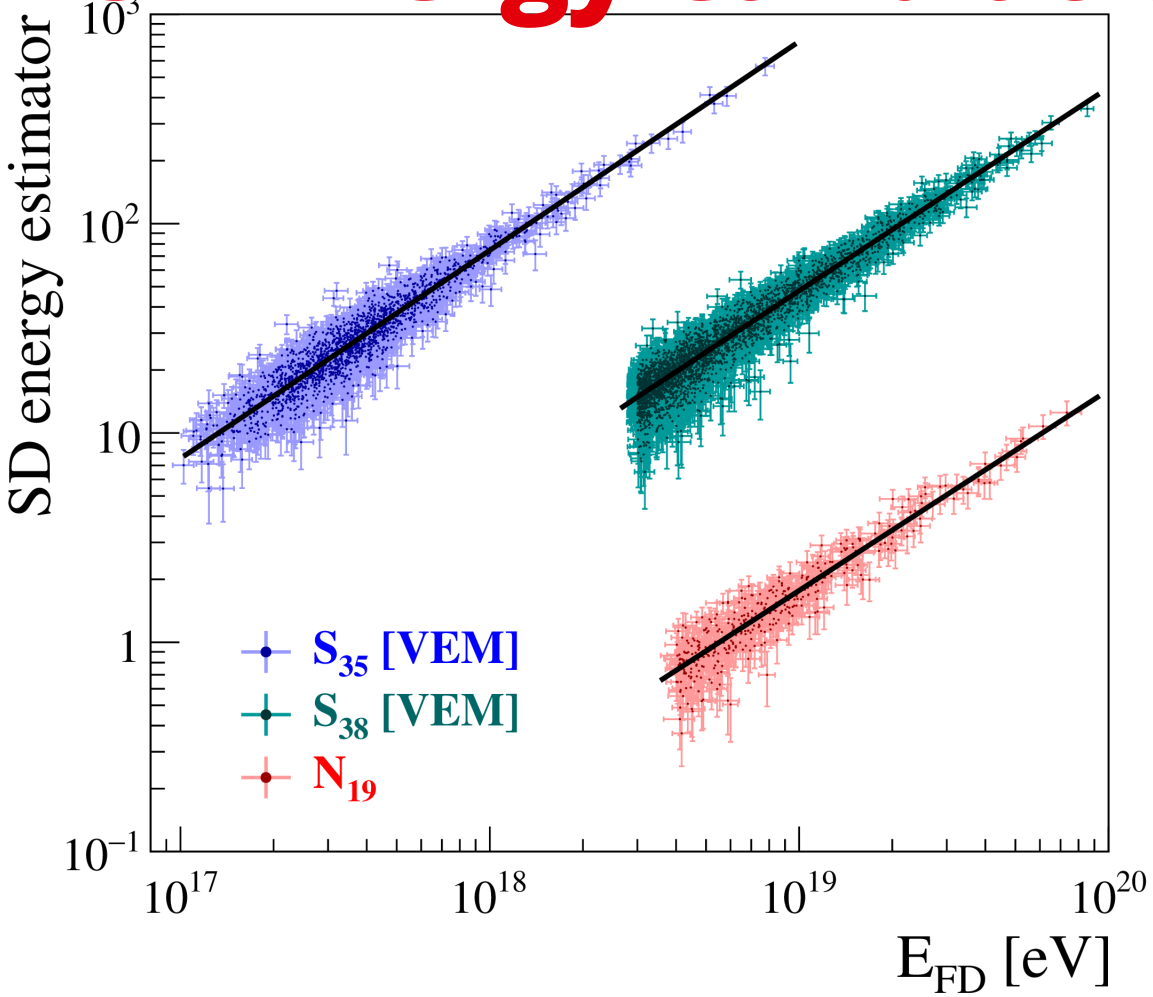
Telescope Array



Grigory Rubtsov, ICRC 2021

The Energy Spectrum

SD Energy Calibration



SD data are calibrated to FD energies

- common energy scale

SD 1500 m vertical – S_{38}

- S(1000)+CIC
- threshold 2.5 EeV

SD 750 m – S_{35}

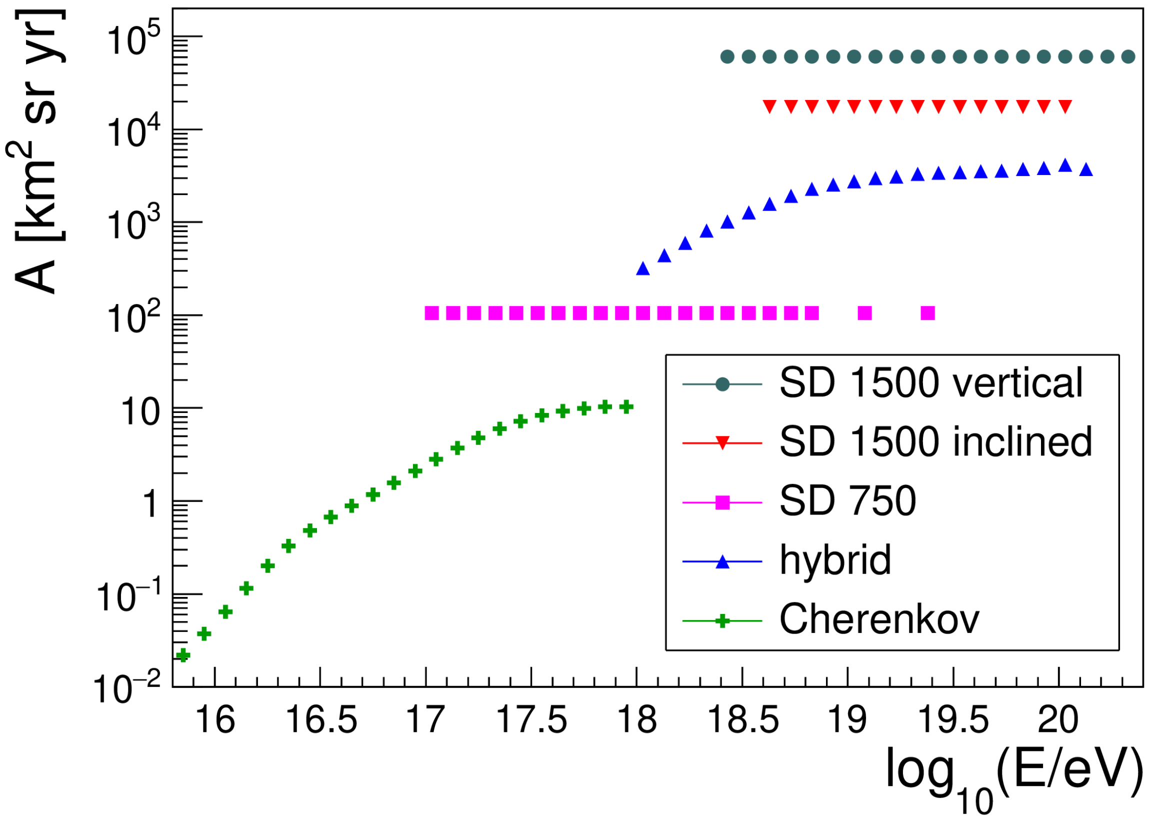
- S(450)+CIC
- threshold 0.1 EeV

SD 1500 m inclined – N_{19}

- scaling parameter
- threshold 4 EeV

Vladimir Novotny
ICRC2021

Exposure



SD – from active hexagon cells

- geometrical calculation
- flat above threshold

FD – realistic MC simulations

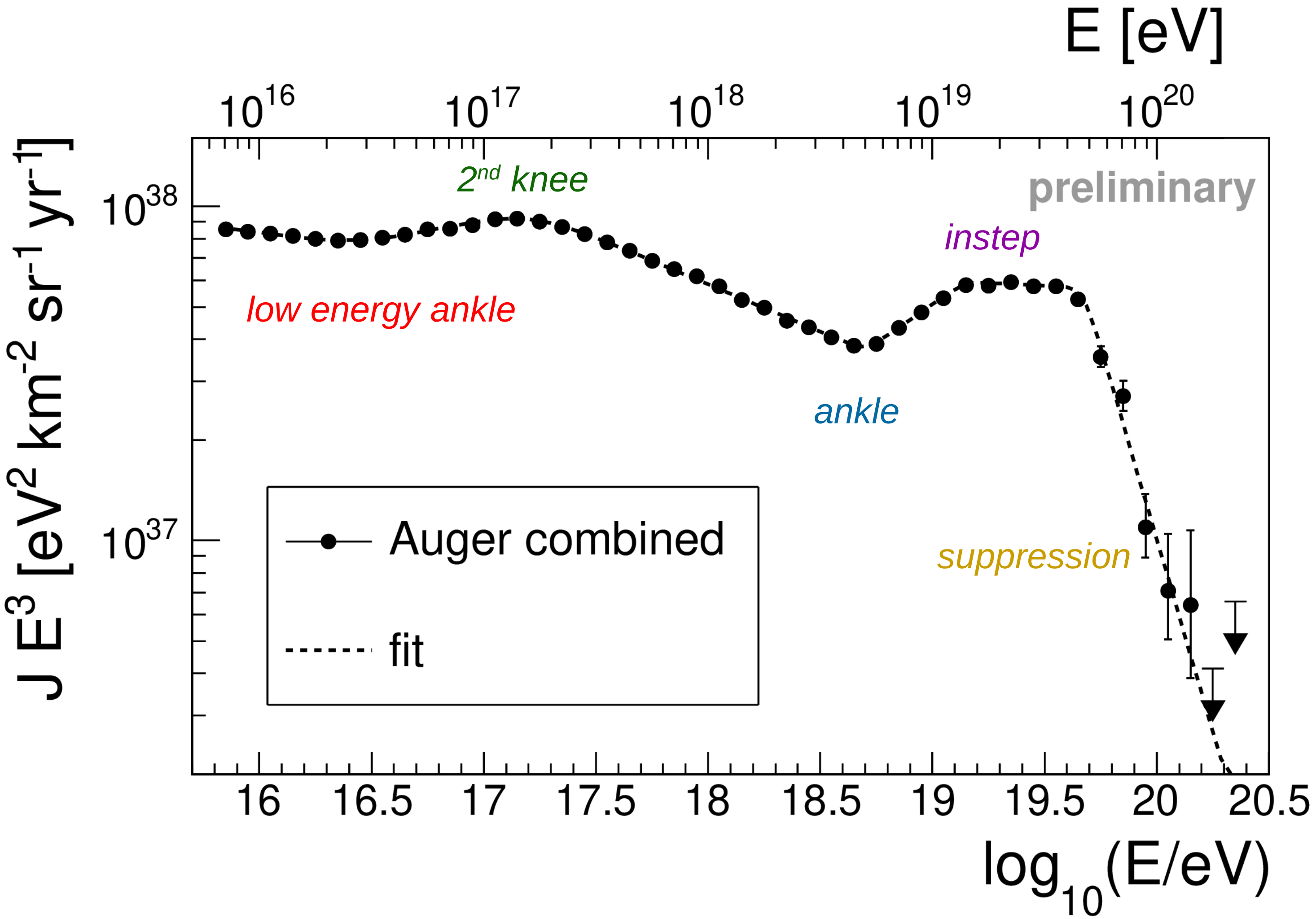
- light from EAS
- atmospheric conditions
- detector status
- evolves with energy

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%

Vladimir Novotny
ICRC2021

Cosmic Ray Energy Spectrum



fit parameters (± stat. ± syst.)

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

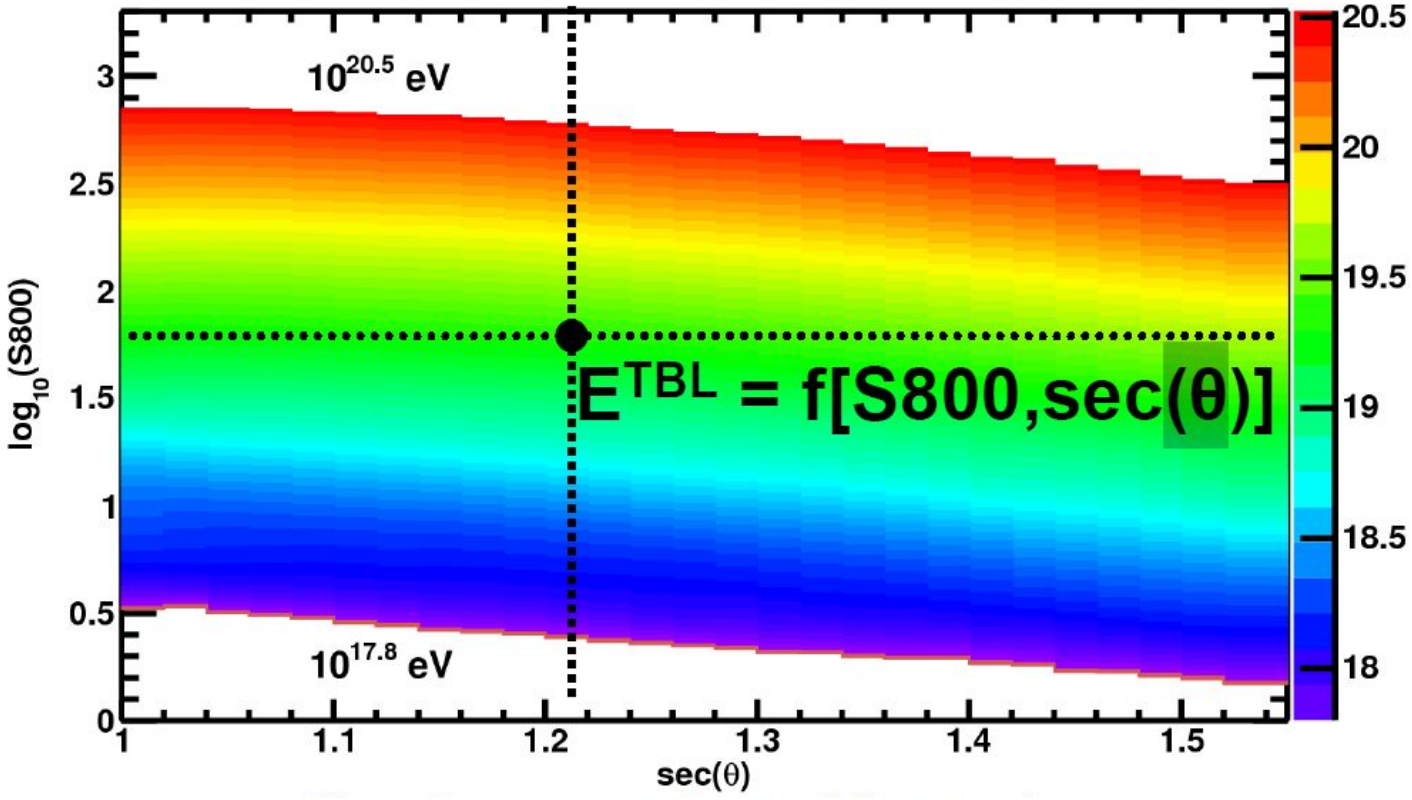
$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

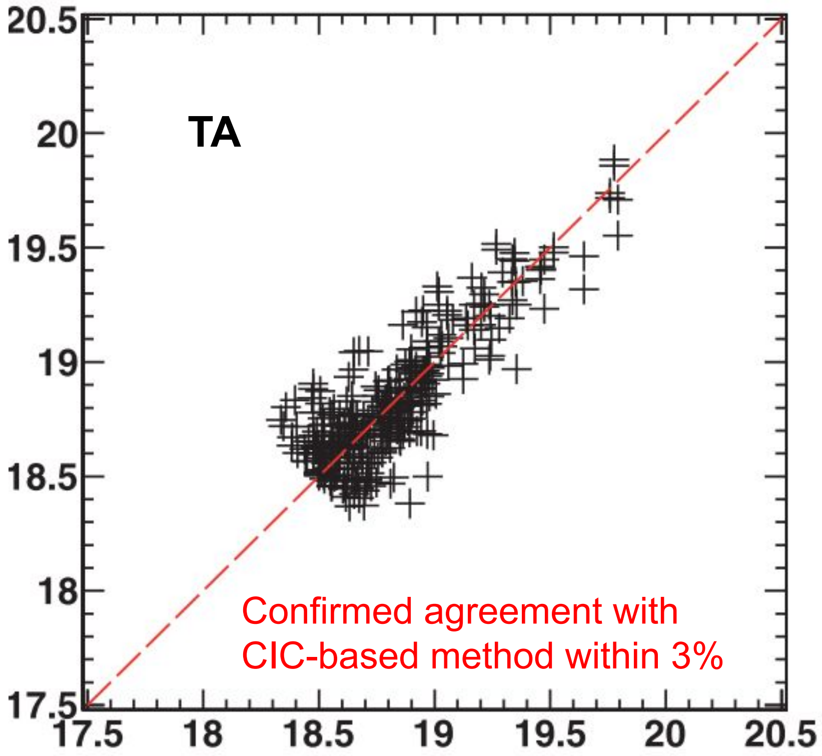
$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ $km^{-2}\,sr^{-1}\,yr^{-1}\,eV^{-1}$

Vladimir Novotny ICRC2021; Eur. Phys. J. C. (2021) 81:966

TA SD Energy Calibration

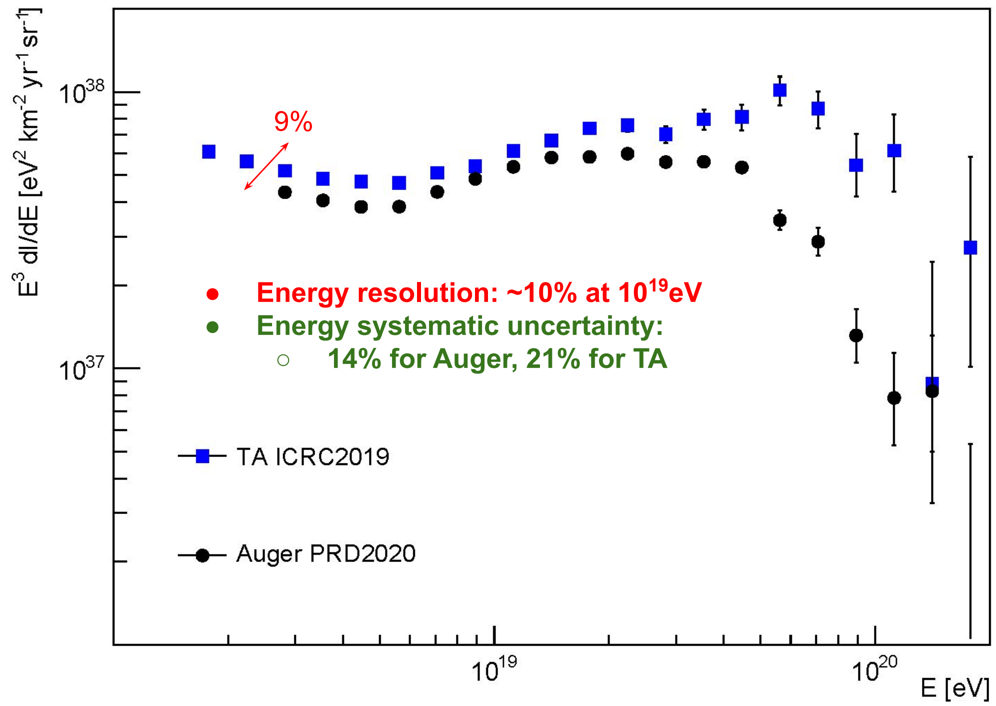




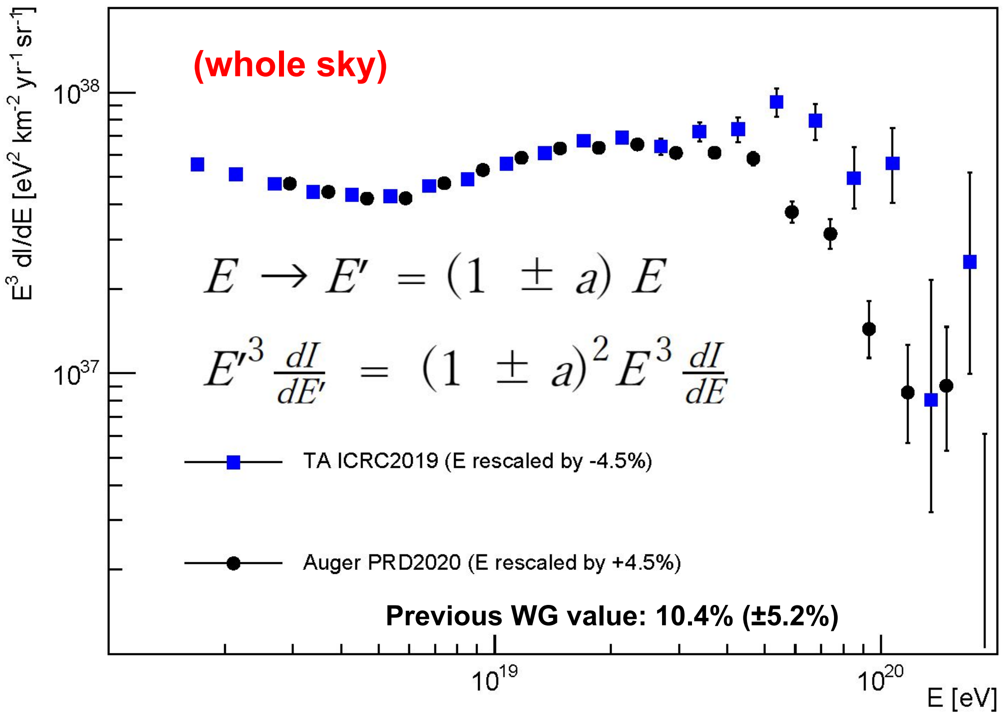
Yoshiki Tsunesada, ICRC2021

Comparison Auger-TA

Auger & TA Energy Spectrum



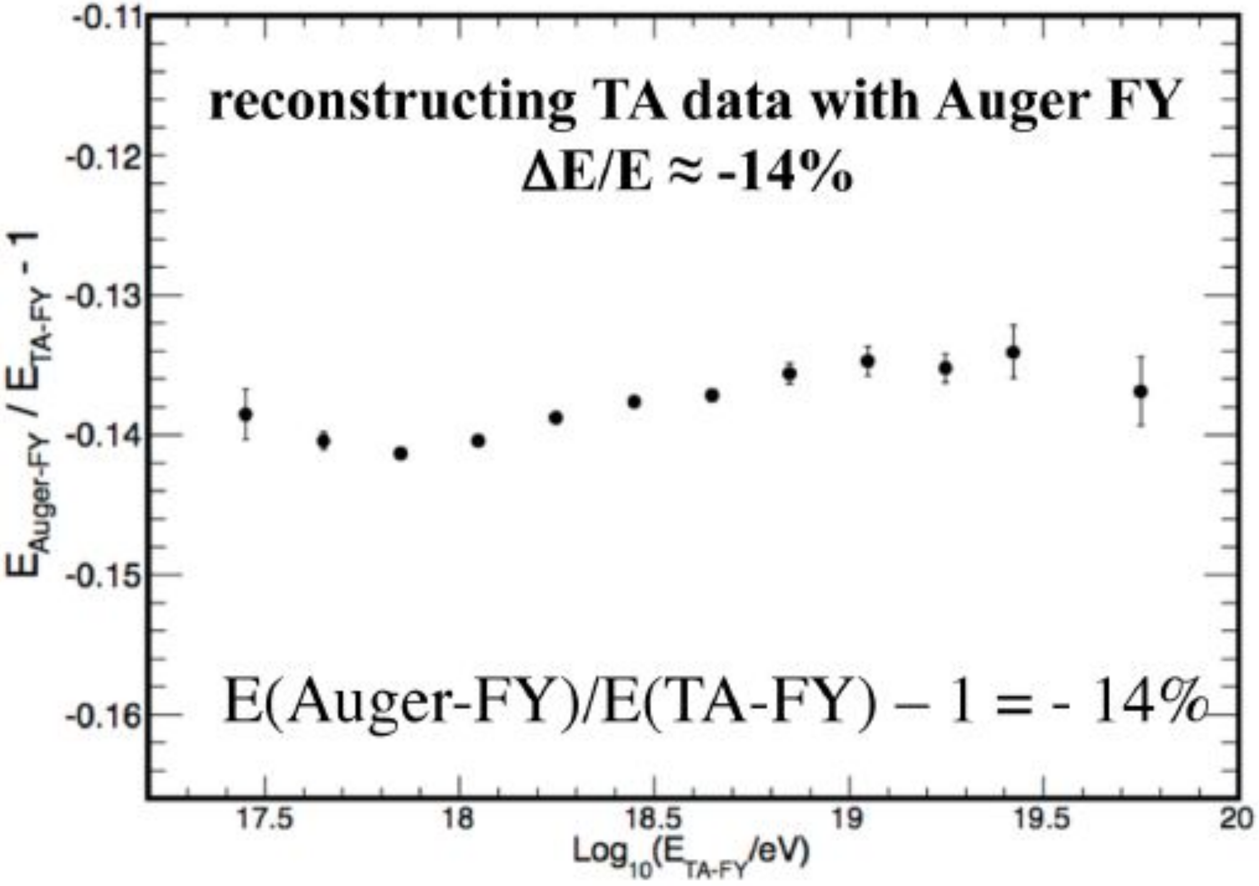
Auger & TA Energy Spectrum (energy ±4.5% rescaled)



Yoshiki Tsunesada, ICRC2021

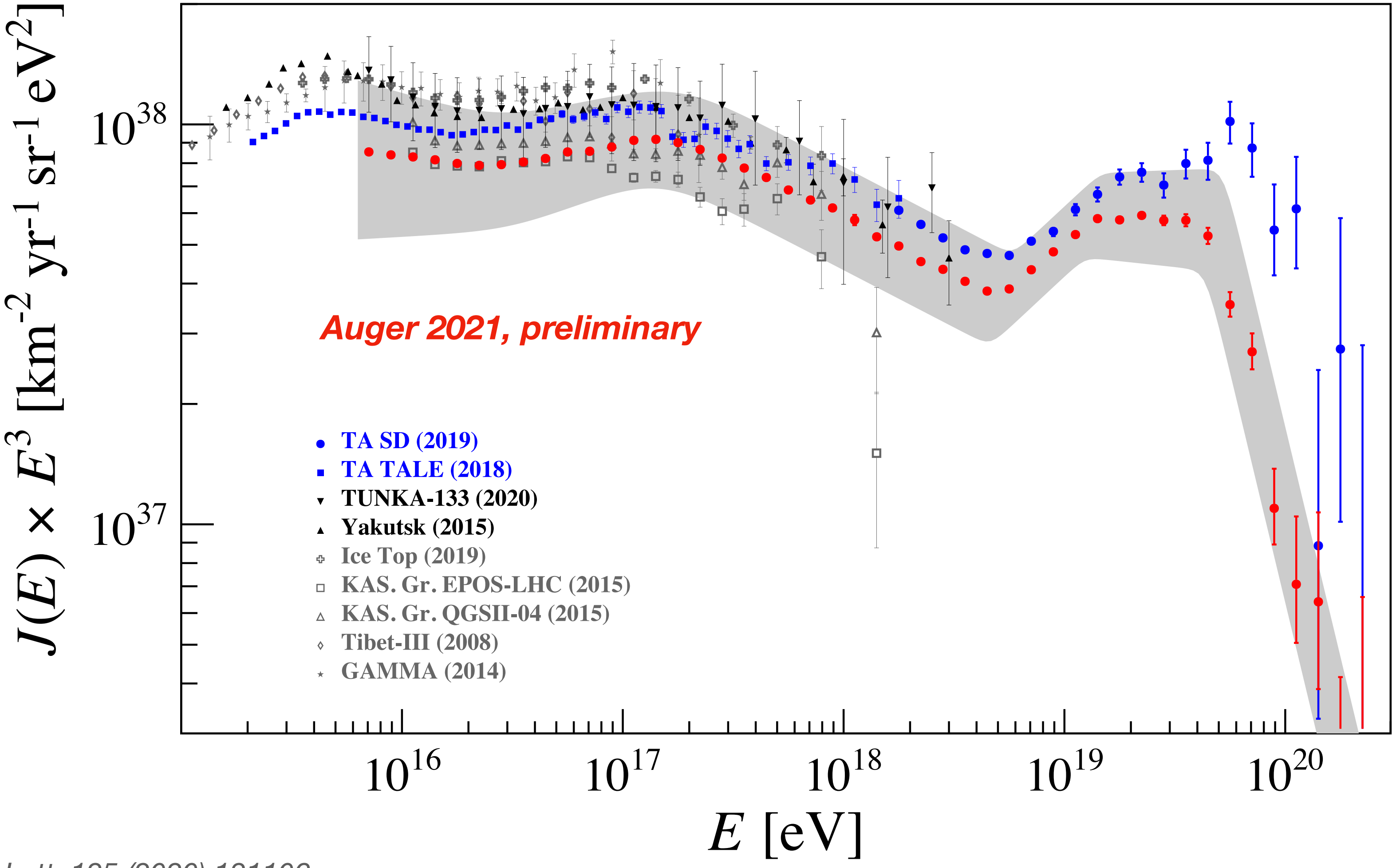
Comparison Auger-TA: Fluorescence Yield

- 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



Yoshiki Tsunesada, ICRC2021

Cosmic Ray Spectra



- Other experiments shown without sys. uncertainties
- Auger has smallest sys. uncertainty on energy scale (14%)

Auger-TA comparison: see presentation of joint working group (Tsunesada et al.)

Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
submitted to Eur. Phys. J. C (2021)

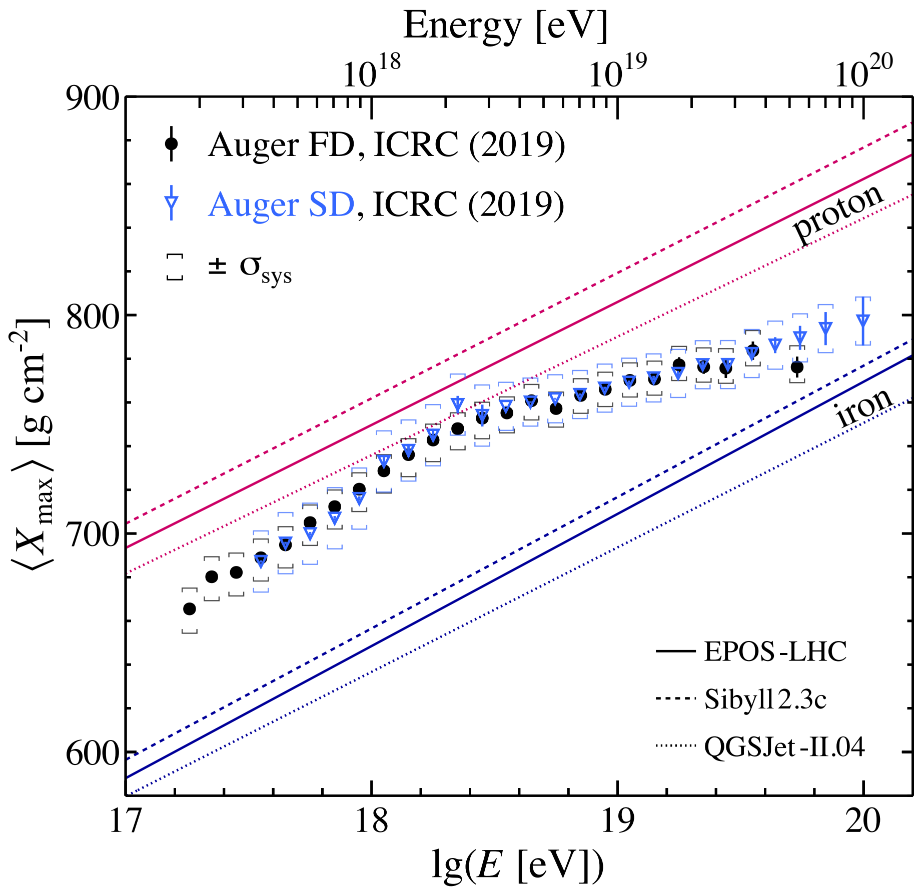
(Vladimir Novotny)

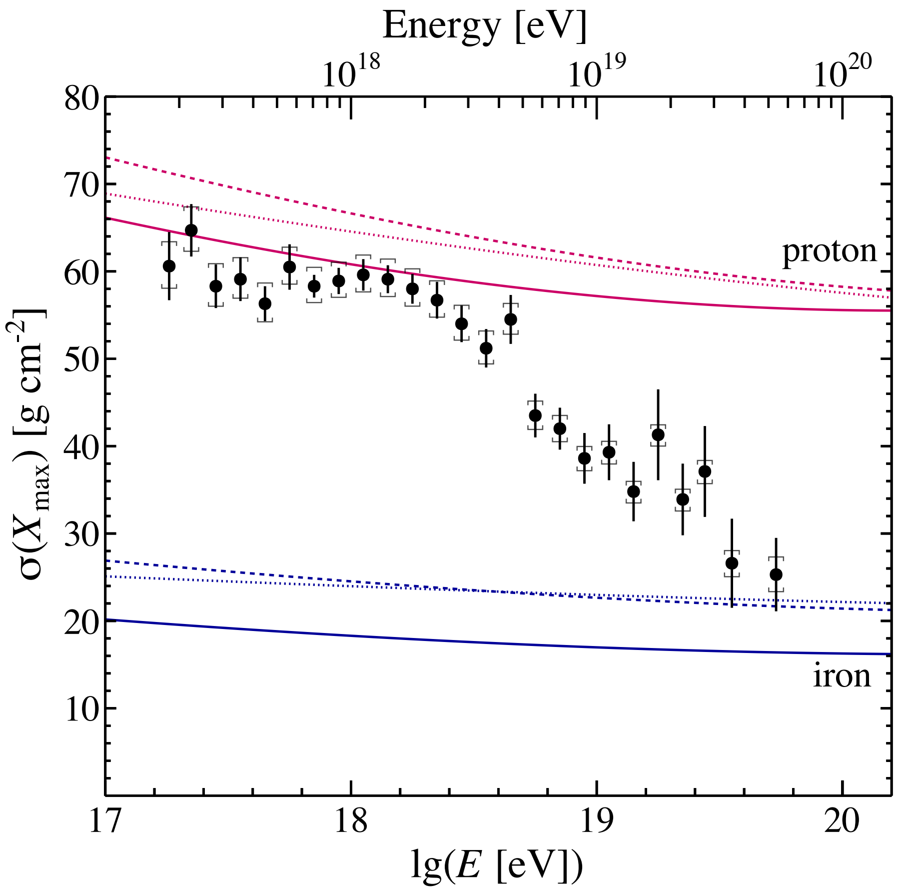
(Yoshiki Tsunesada)

The Cosmic Ray Composition

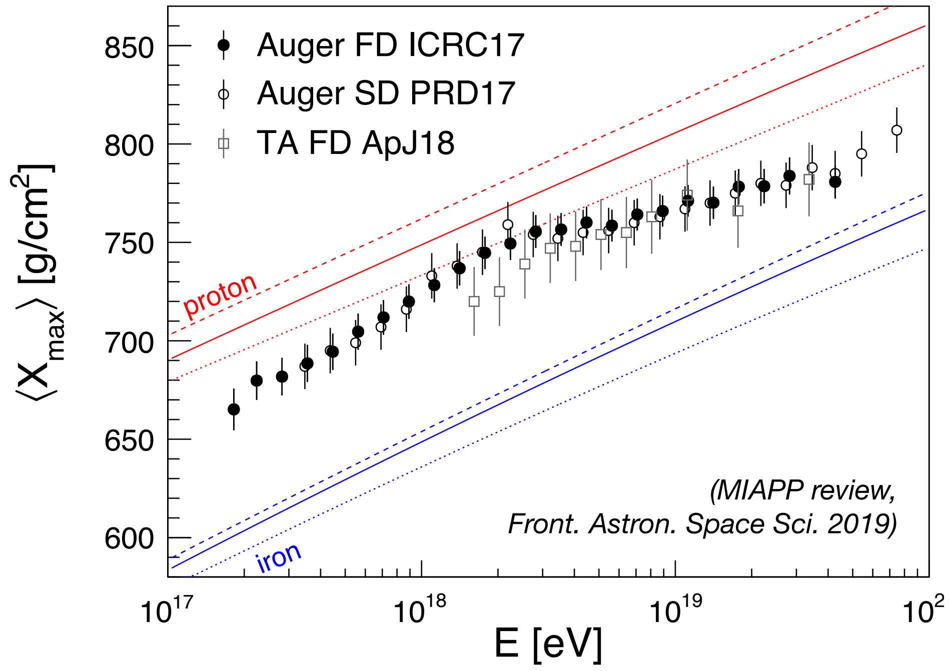
Cosmic Ray Composition –Auger Results

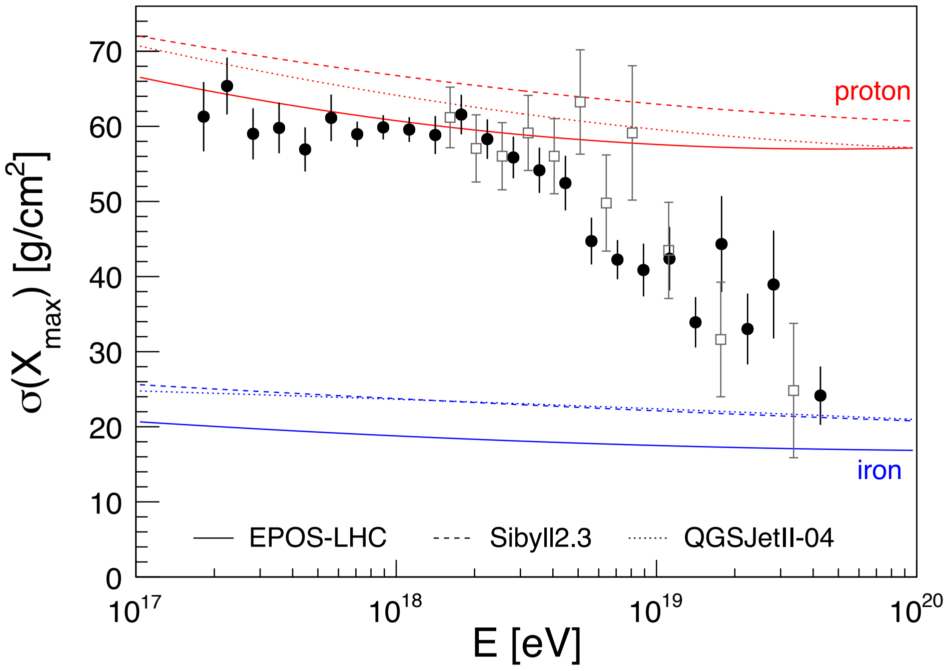
Ralph Engel, ICRC2021

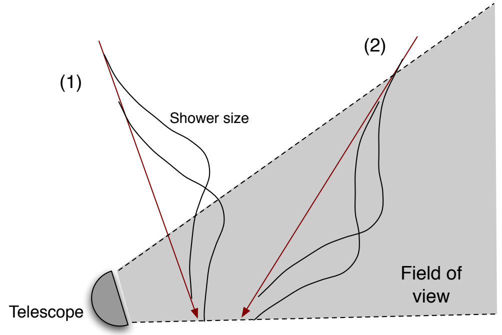




Comparison Auger-TA Composition







Work in progress:
data consistent in energy range with sufficient statistics

(Auger-TA Xmax Working Group, UHECR 2018)

Interpretation Spectrum and Composition

CRs ejected by generic EG accelerators

Assumptions on a simple astrophysical model
(CRs considered **at the escape**)

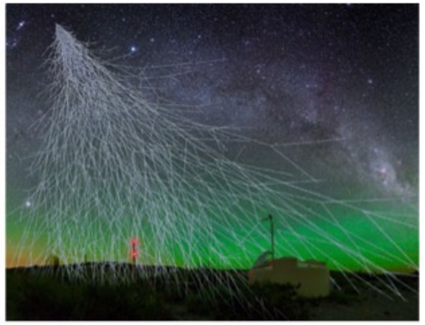
Propagation through the intergalactic medium

+

SimProp simulations

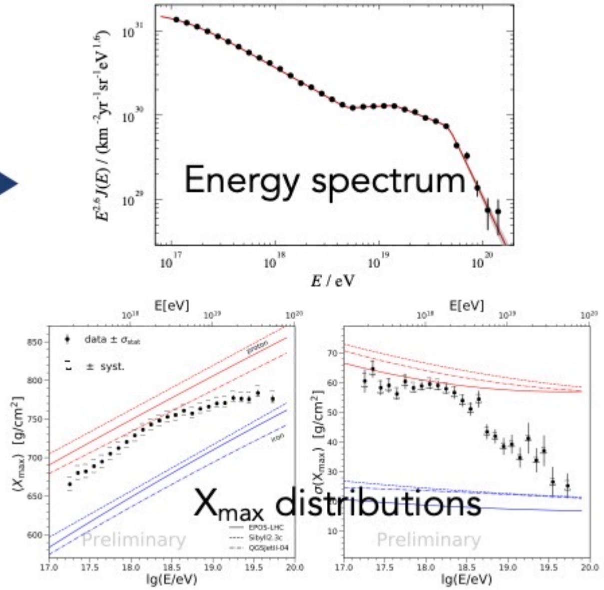
Choice of propagation models for uncertain quantities

Production of showers in the atmosphere



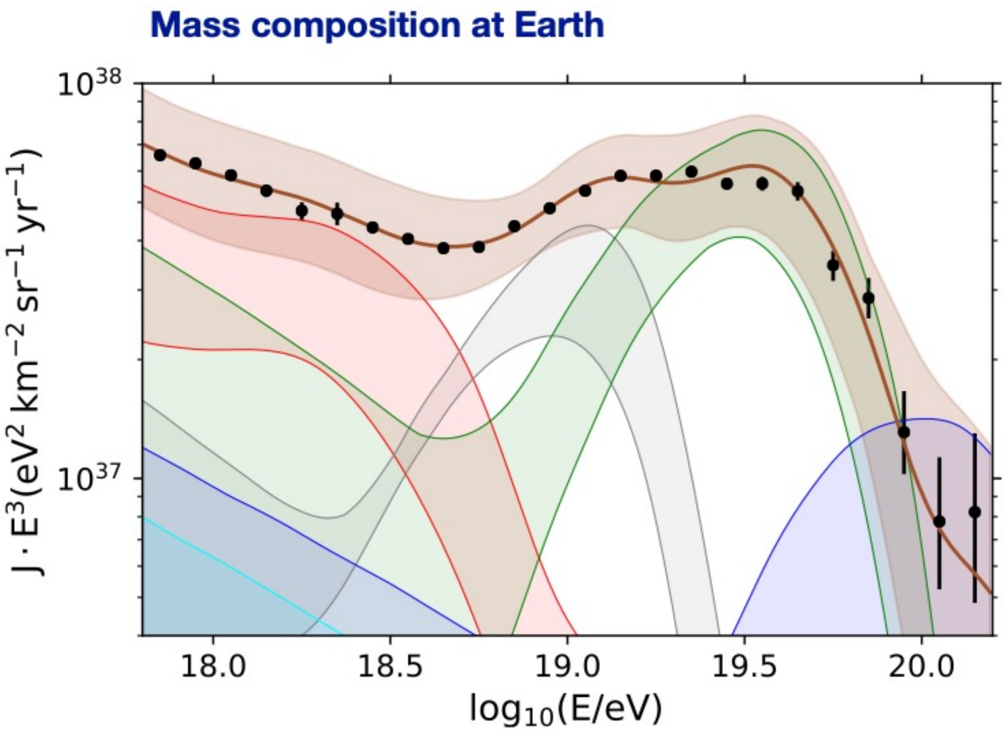
Choice of hadronic interaction models

Comparison with the data (detector effects are included)



Eleonora Guido, ICRC2021

Interpretation Spectrum and Composition

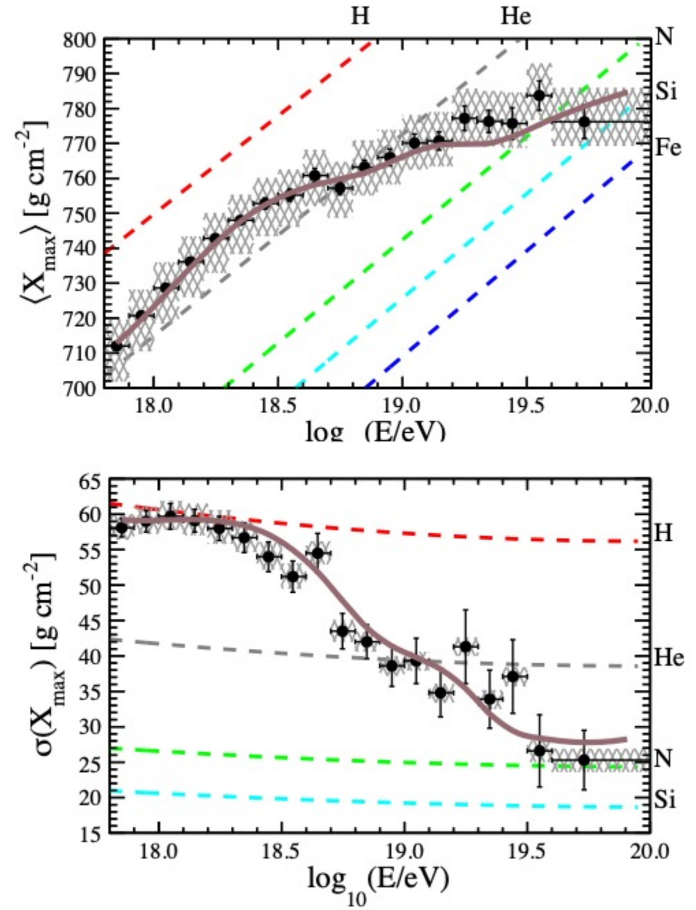


A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9$ g cm^{-2}

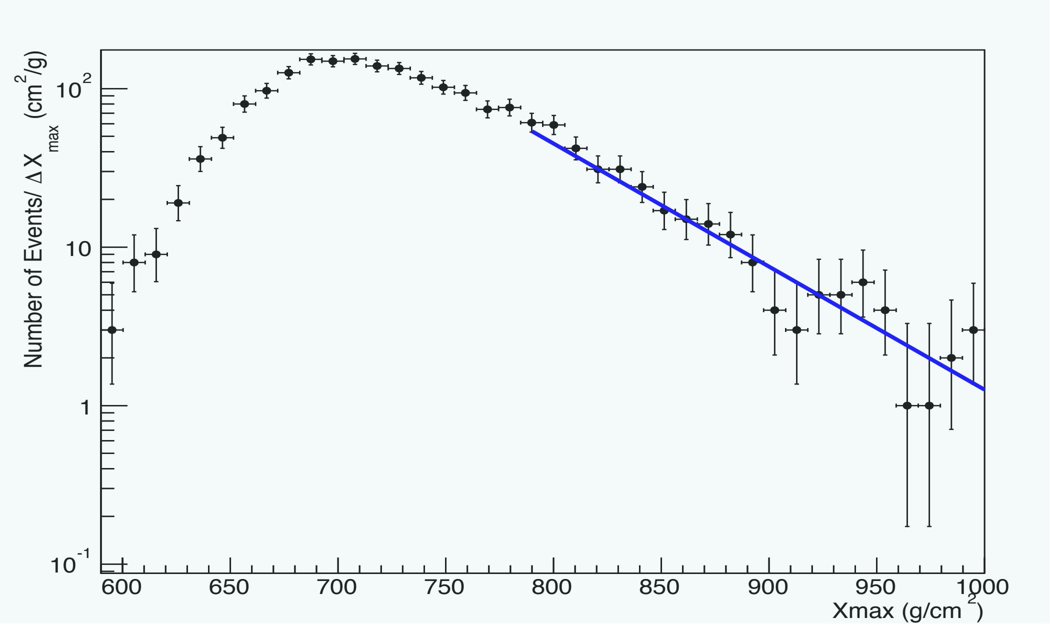


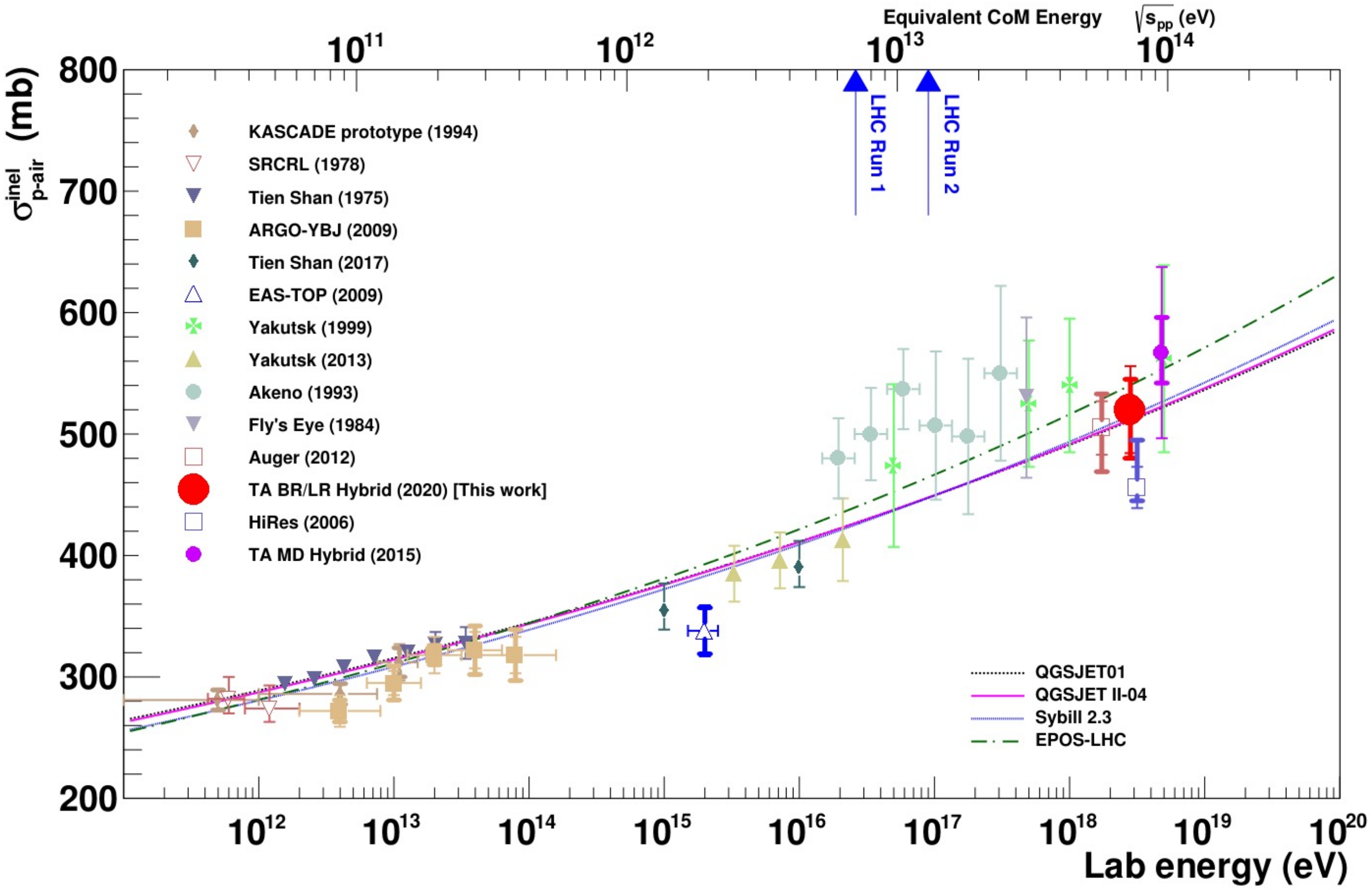
Different model scenarios considered for low-energy part
(transition to galactic component), similar results for total composition obtained

Eleonora Guido, ICRC2021

Cross Section

New TA cross section measurement



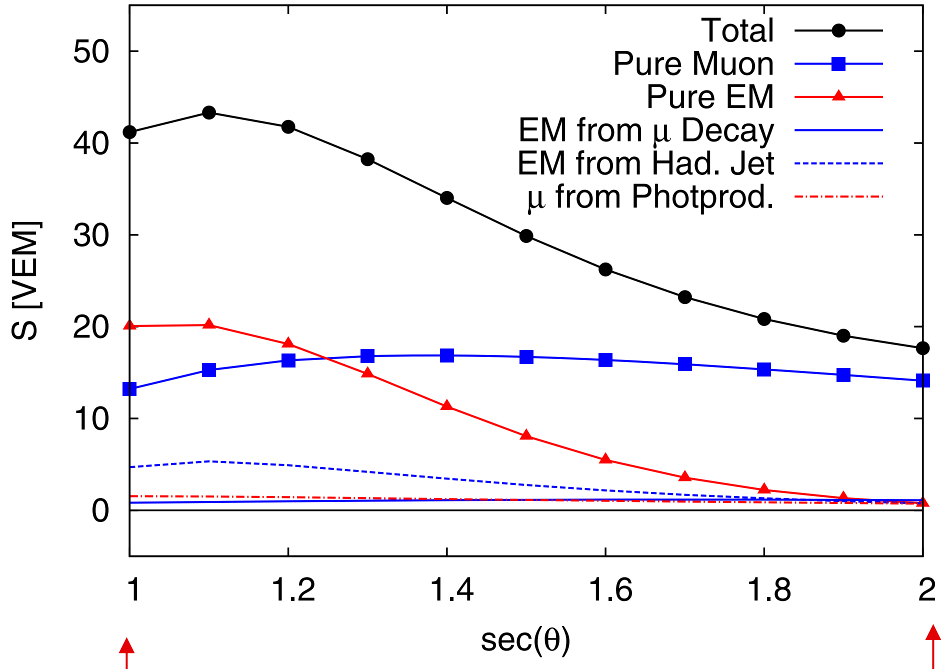


Rasha Abbasi, ICRC2021

The Muon Puzzle

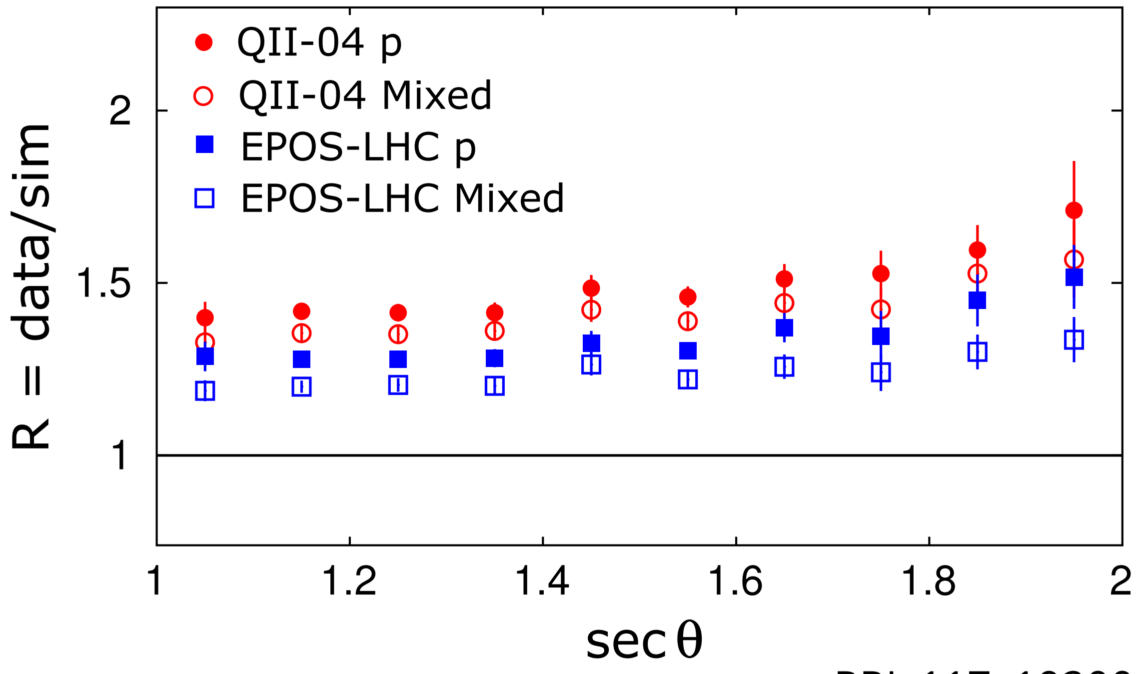
Simulations

QGSJet II-04 simulations,
10 EeV Proton-Air
1 km from shower core



Vertical

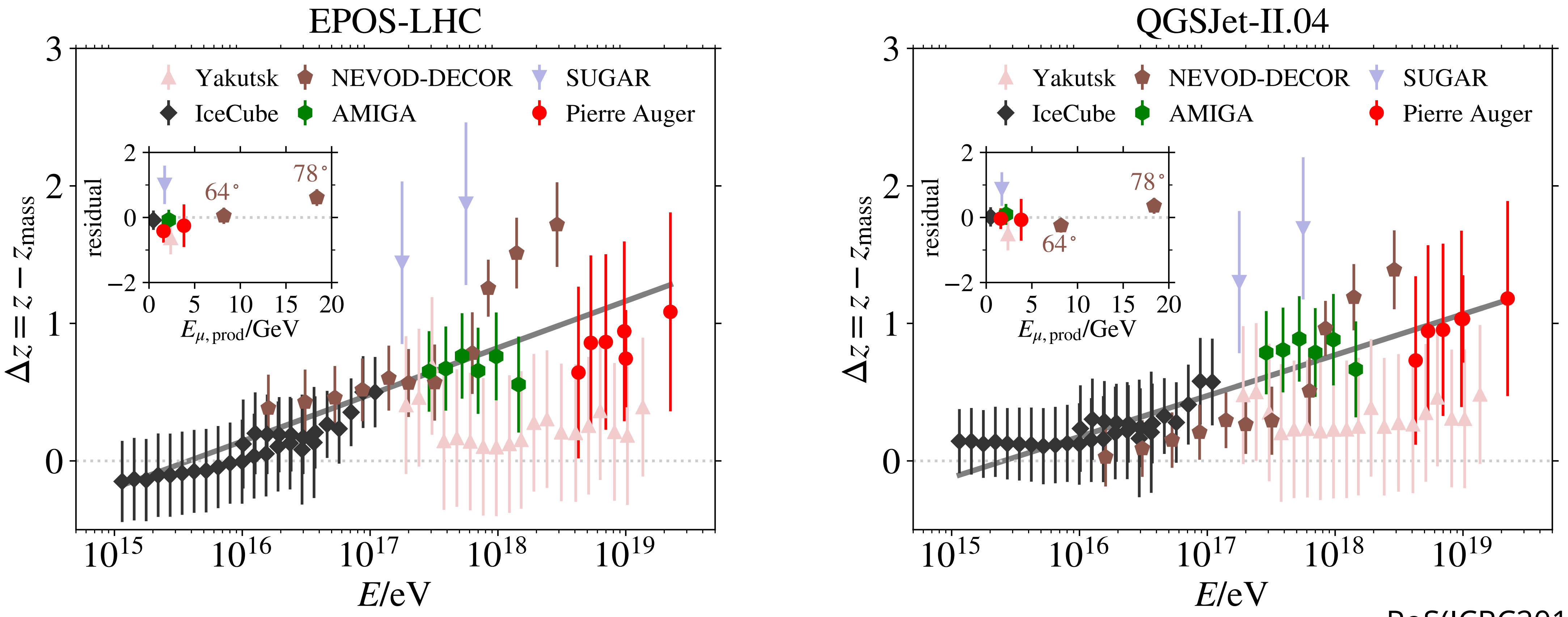
60 degrees
Muon dominated



PRL 117, 192001 (2016)

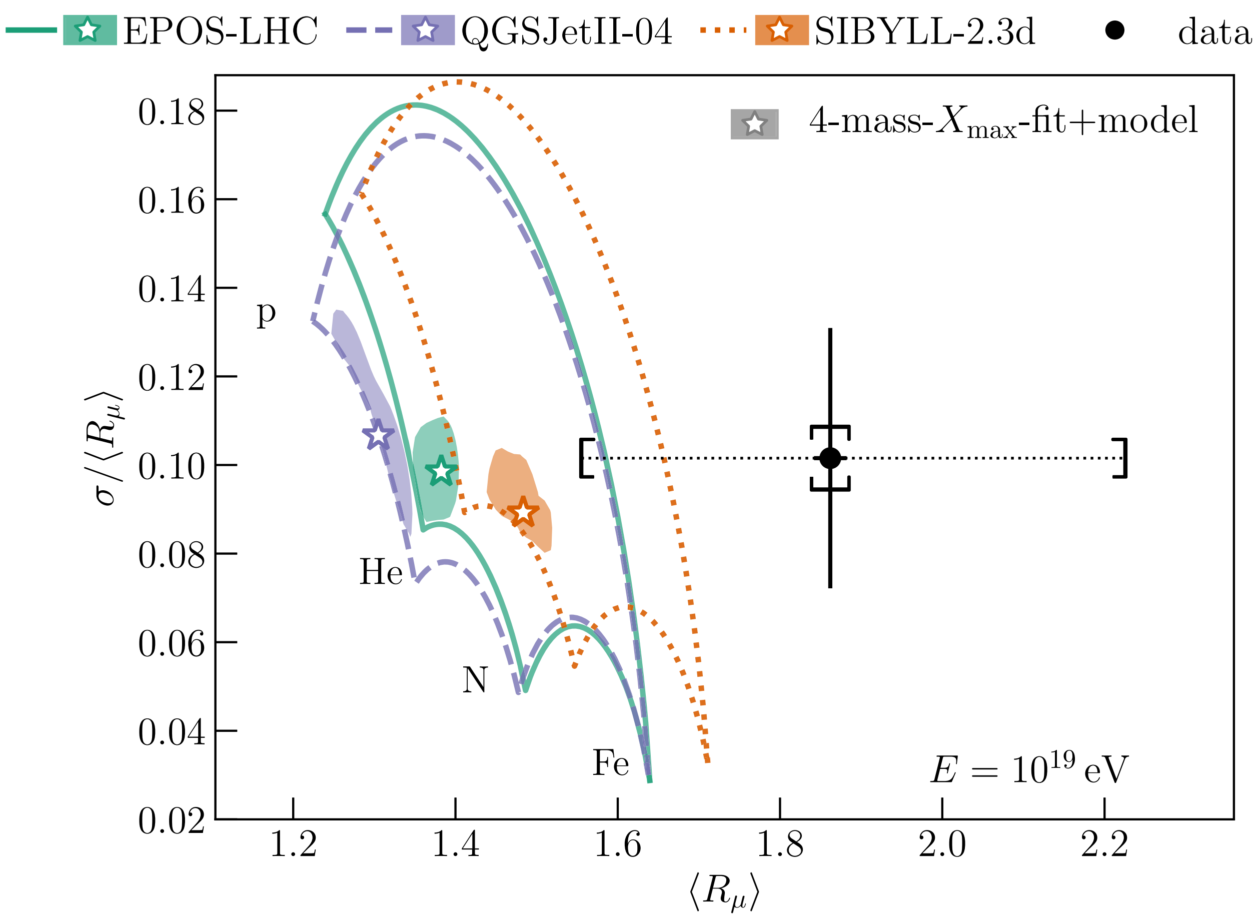
Energy dependence

$$z = \frac{\ln(N_\mu{}^{\text{det}}) - \ln(N_\mu{}_p^{\text{det}})}{\ln(N_\mu{}_{\text{Fe}}^{\text{det}}) - \ln(N_\mu{}_p^{\text{det}})},$$



PoS(ICRC2019),214(2019)

Adding the second moment



Phys. Rev. Lett. 126, 152002 (2021)

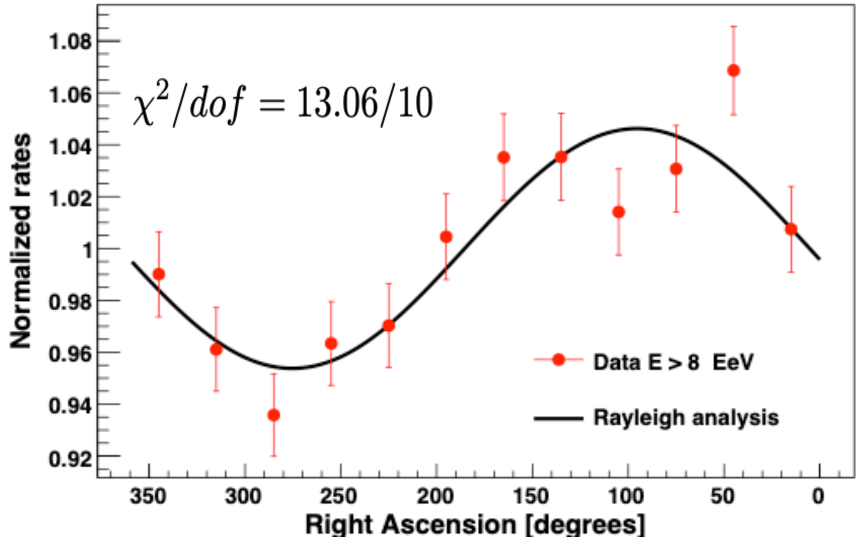
“Low energy”/”Large scale” anisotropies

Dipole Reconstruction

E (EeV)	N	$d_\perp$	d_z	d	$\alpha_d[°]$	$\delta_d[°]$	$P(\geq r_1^\alpha)$
4-8	106, 290	$0.01^{+0.006}_{-0.004}$	-0.012 ± 0.008	$0.016^{+0.008}_{-0.005}$	97 ± 29	-48^{+23}_{-22}	1.4×10^{-1}
8-16	32, 794	$0.055^{+0.011}_{-0.009}$	-0.03 ± 0.01	$0.063^{+0.013}_{-0.009}$	95 ± 10	-28^{+12}_{-13}	3.1×10^{-7}
16-32	9, 156	$0.072^{+0.021}_{-0.016}$	-0.07 ± 0.03	$0.10^{+0.03}_{-0.02}$	81 ± 15	-43^{+14}_{-14}	7.5×10^{-4}
≥8	44, 398	$0.059^{+0.009}_{-0.008}$	-0.042 ± 0.013	$0.073^{+0.011}_{-0.009}$	95 ± 8	-36^{+9}_{-9}	5.1×10^{-11}
≥32	2, 448	$0.11^{+0.04}_{-0.03}$	-0.12 ± 0.05	$0.16^{+0.05}_{-0.04}$	139 ± 19	-47^{+16}_{-15}	1.0×10^{-2}

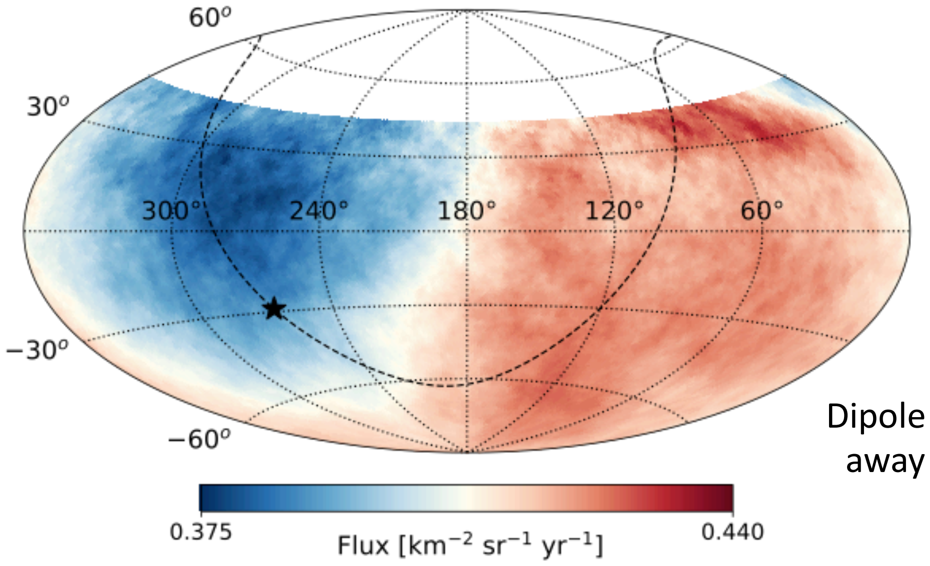
was 1.4×10^{-9} (ApJ 2020) and 2.6×10^{-8} (Science 2017)

Corresponds to 6.6σ



$E \geq 8$ EeV

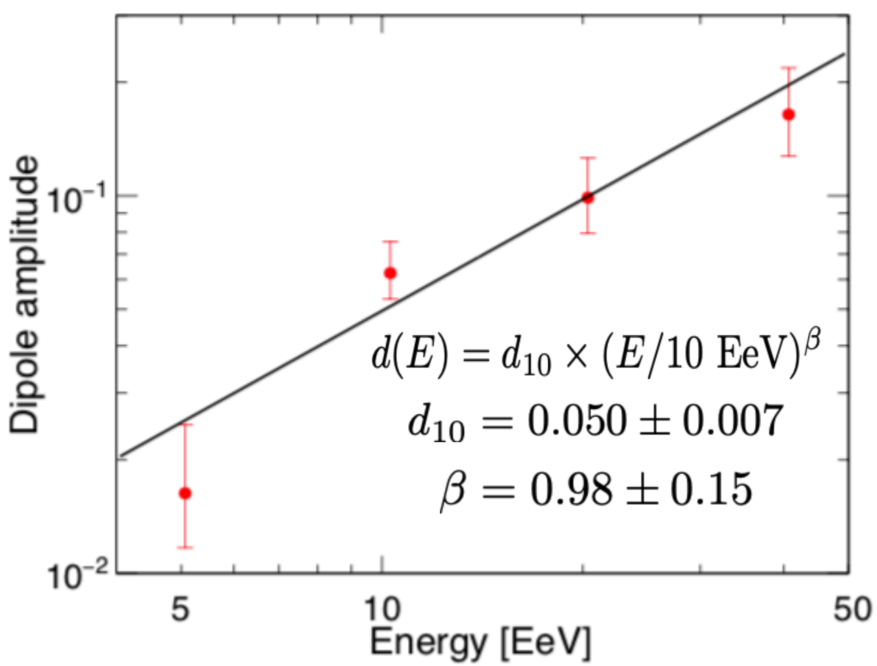
Smoothed by a top-hat window with 45° of radius

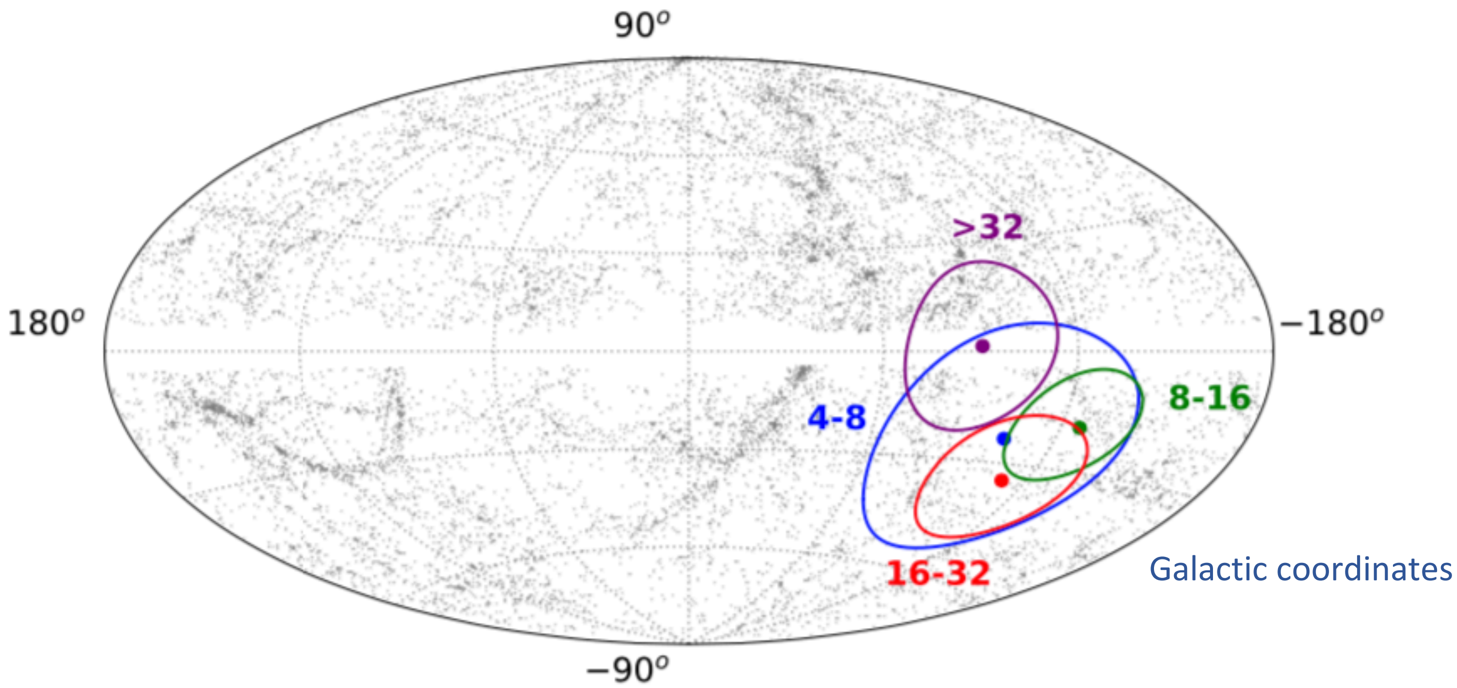


Dipole points ~115° away from the GC

Rogerio de Almeida, ICRC2021

Dipole as function of energy



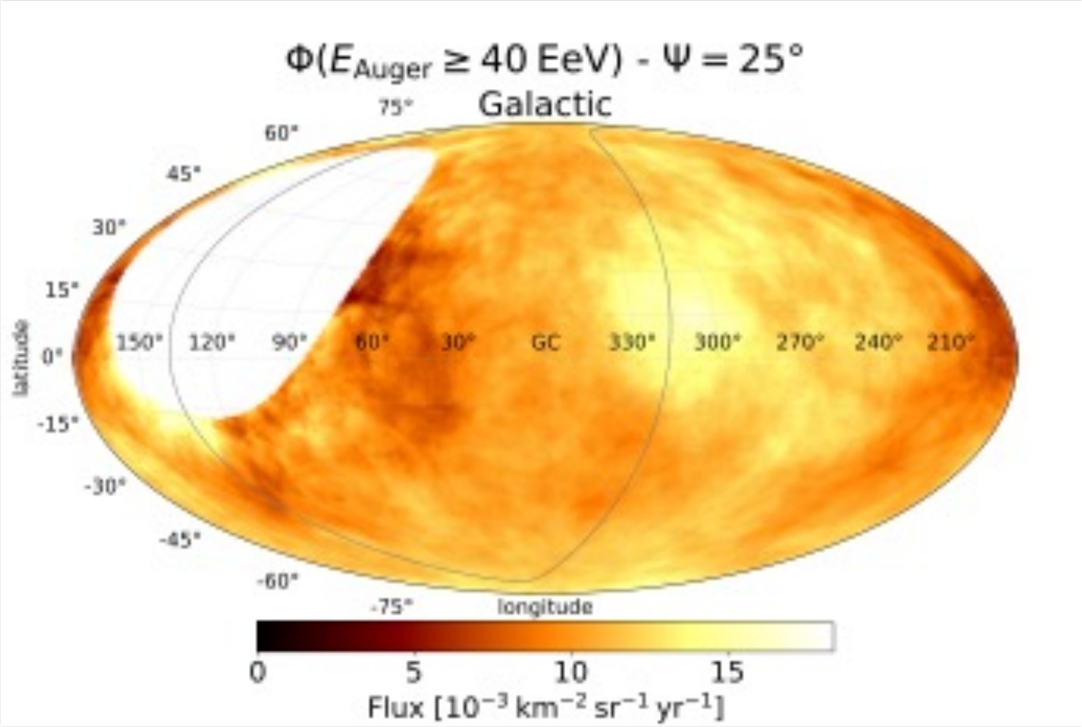


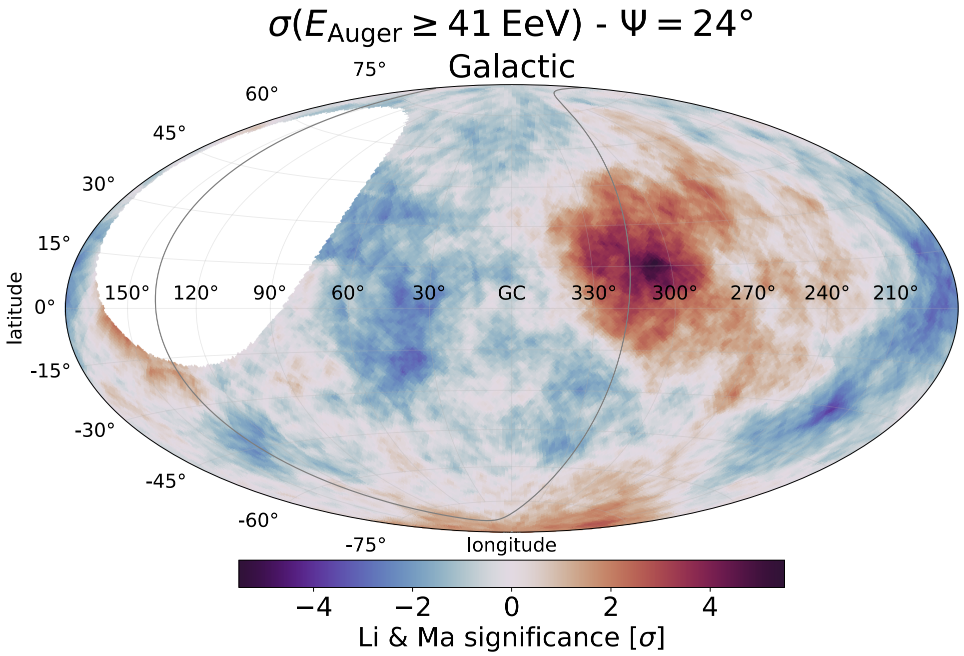
No clear trend in the evolution of dipole direction with energy

Rogerio de Almeida, ICRC2021

High Energy Anisotropies

“High” energy anisotropies

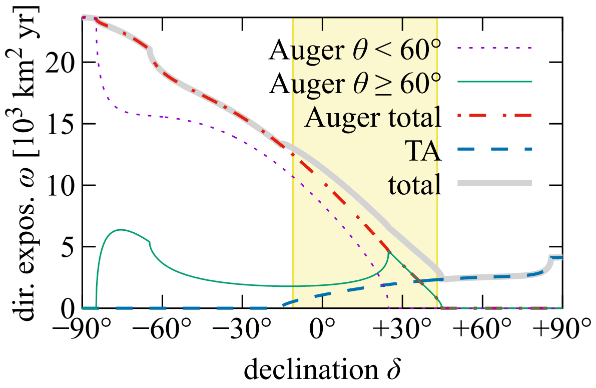




Accepted ApJS (June 2022), ArXiv:2206.13492

4-pi anisotropy

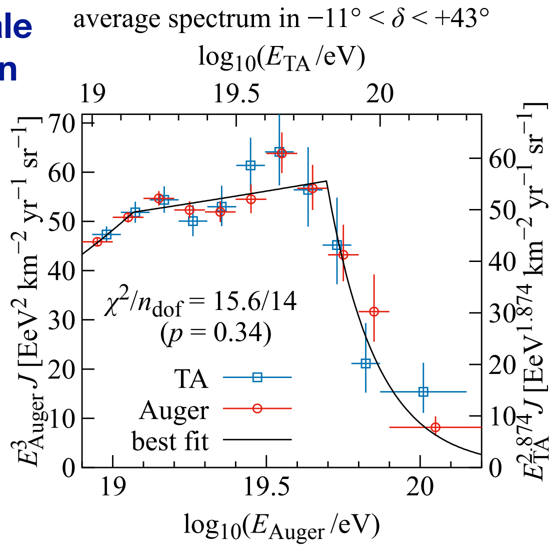
Sky coverage



Auger (θ < 80°): 120,000 km² sr yr

TA (θ < 55°): 14,000 km² sr yr

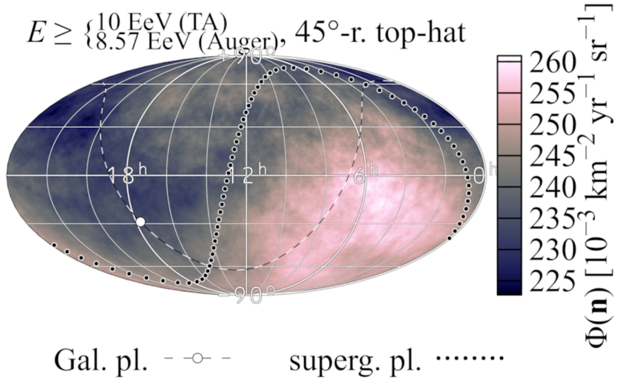
Energy scale conversion



$$\frac{E_{\rm Auger}}{10\ {\rm EeV}} = 0.857 \left(\frac{E_{\rm TA}}{10\ {\rm EeV}}\right)^{0.937}$$

$$\frac{E_{\rm TA}}{10\ {\rm EeV}} = 1.179 \left(\frac{E_{\rm Auger}}{10\ {\rm EeV}}\right)^{1.067}$$

Large angular scales

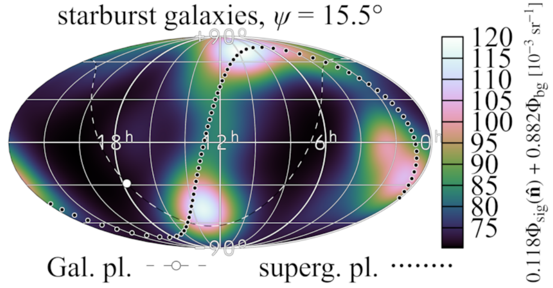


(Peter Tinyakov)

Dipole direction better constrained, compatible with Auger-only result

Catalog correlation searches

(Armando di Matteo)

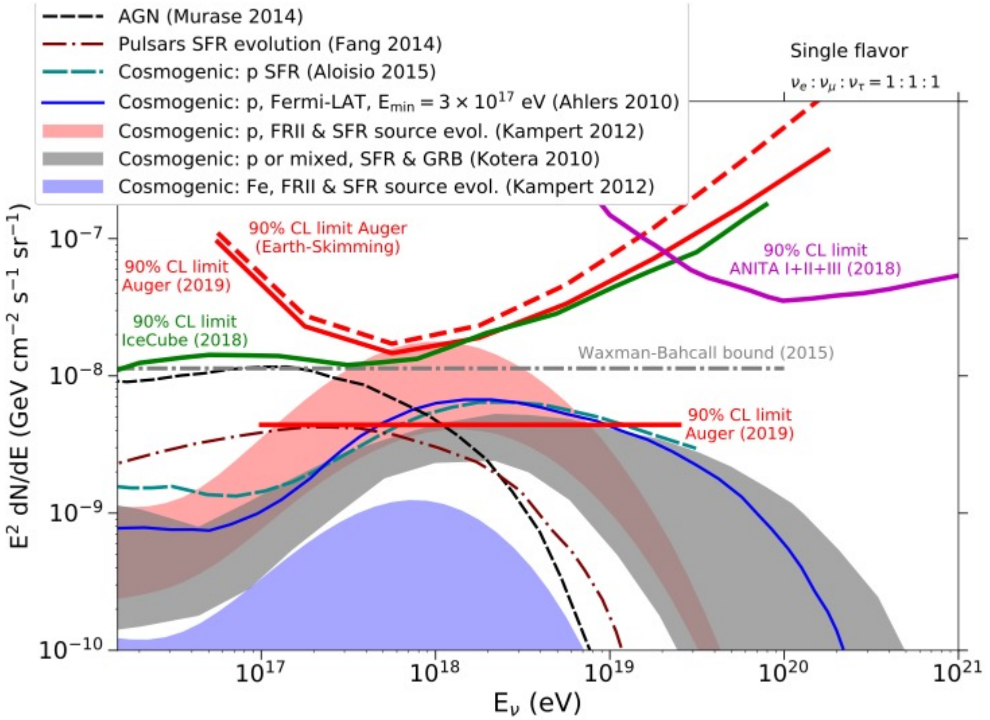


catalog	$E_{\rm min}$ (Auger)	$E_{\rm min}$ (TA)	ψ	equiv. top-hat radius	f	TS
all galaxies	41 EeV	53 EeV	$24^{\circ}{}^{+13^{\circ}}_{-8^{\circ}}$	$38^{\circ}{}^{+21^{\circ}}_{-13^{\circ}}$	$38\%^{+28\%}_{-14\%}$	16.2
starburst galaxies	38 EeV	49 EeV	$15.5^{\circ}{}^{+5.3^{\circ}}_{-3.2^{\circ}}$	$24.6^{\circ}{}^{+8.4^{\circ}}_{-5.1^{\circ}}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2

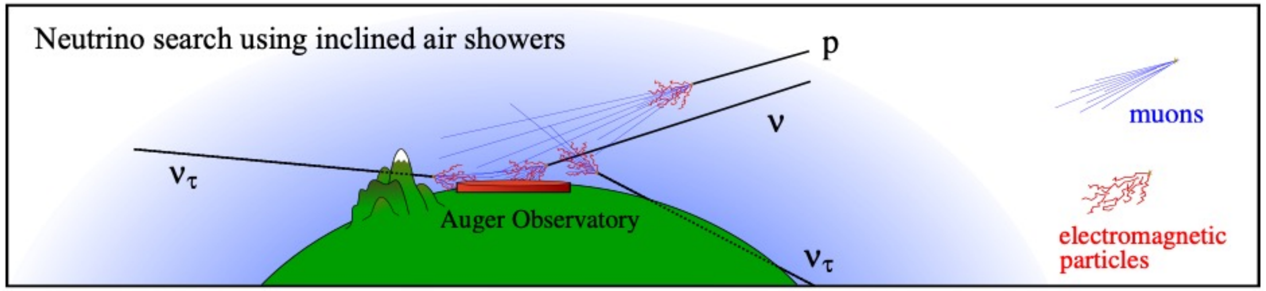
4.2σ for the starburst galaxy catalog $\quad$ 2.9σ for the all-galaxy catalog

Neutrals and Multi Messenger

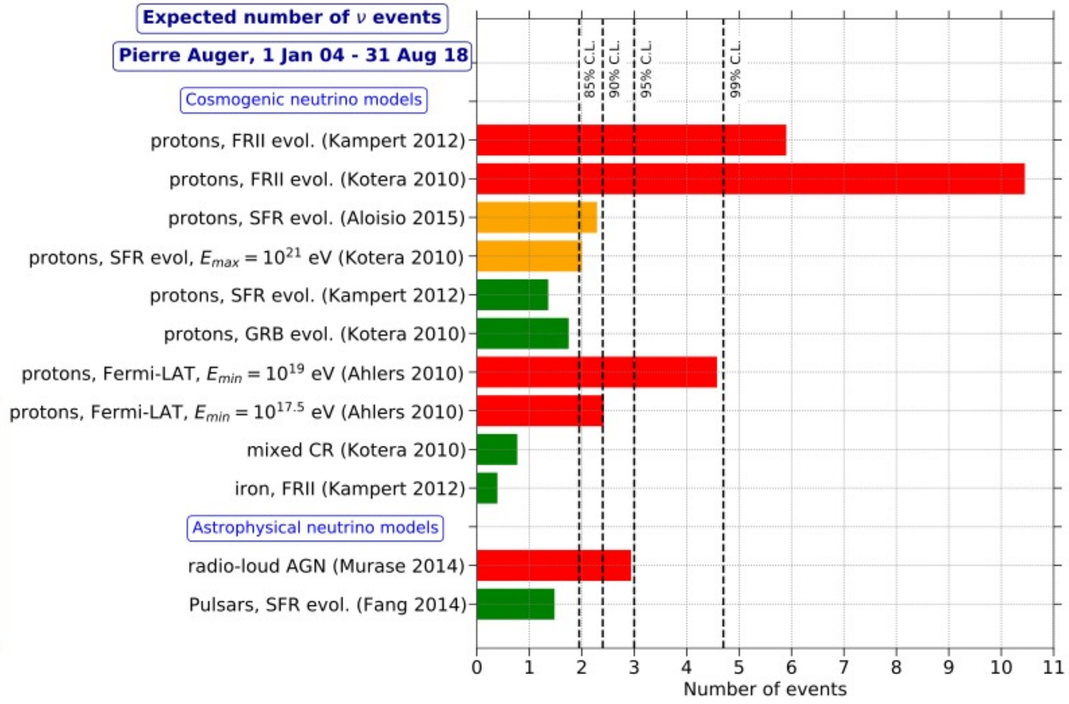
Mostly Sensitive to Tau neutrinos



(Michael Schimp)

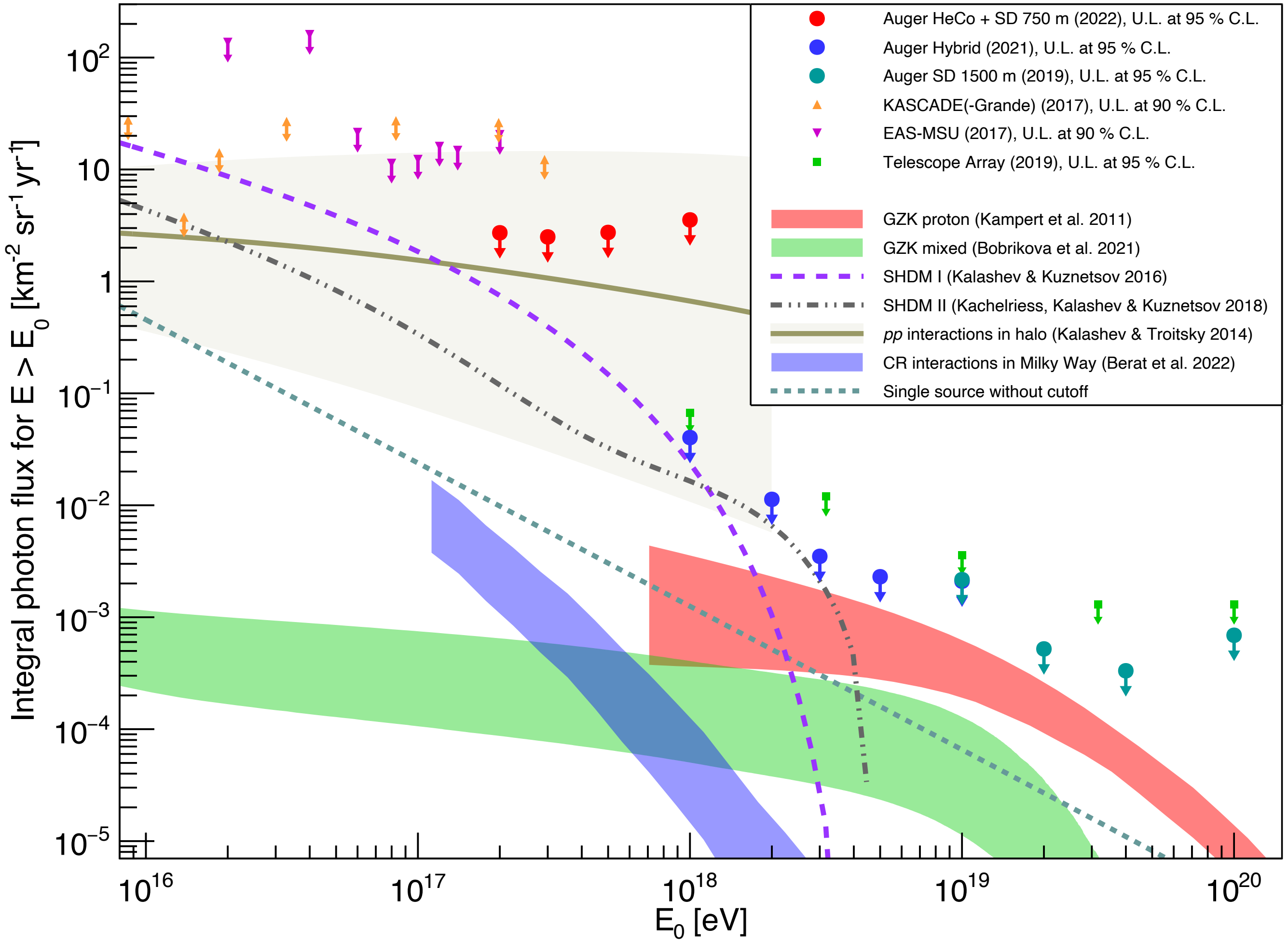


(JCAP 10 (2019) 022, JCAP 11 (2019) 004)



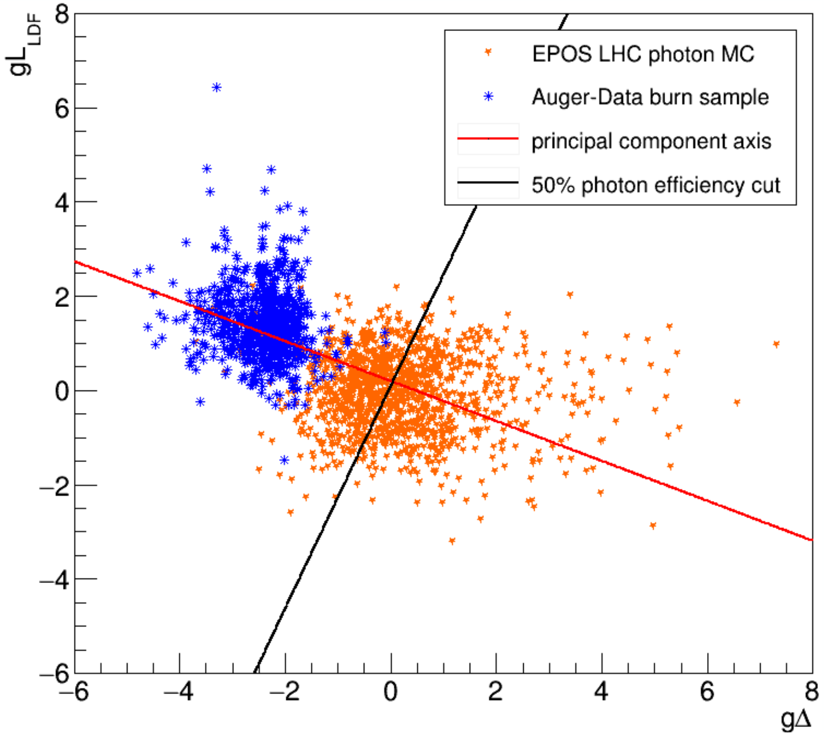
(UHECR 2018, updated)

Photon searches

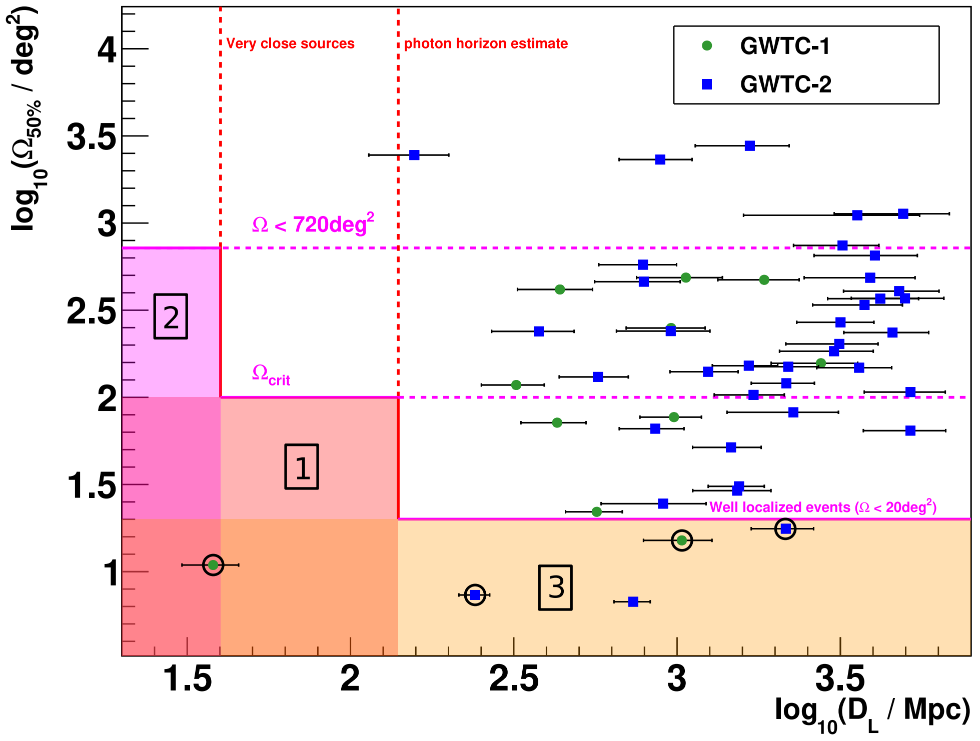


Accepted ApJS (May 2022), ArXiv:2205.14864

Multi-Messenger



Selection of photon-like events between 30 and 60 degrees



Close and well localized GW events

No candidates, upper limits set

Philip Ruehl, ICRC2021

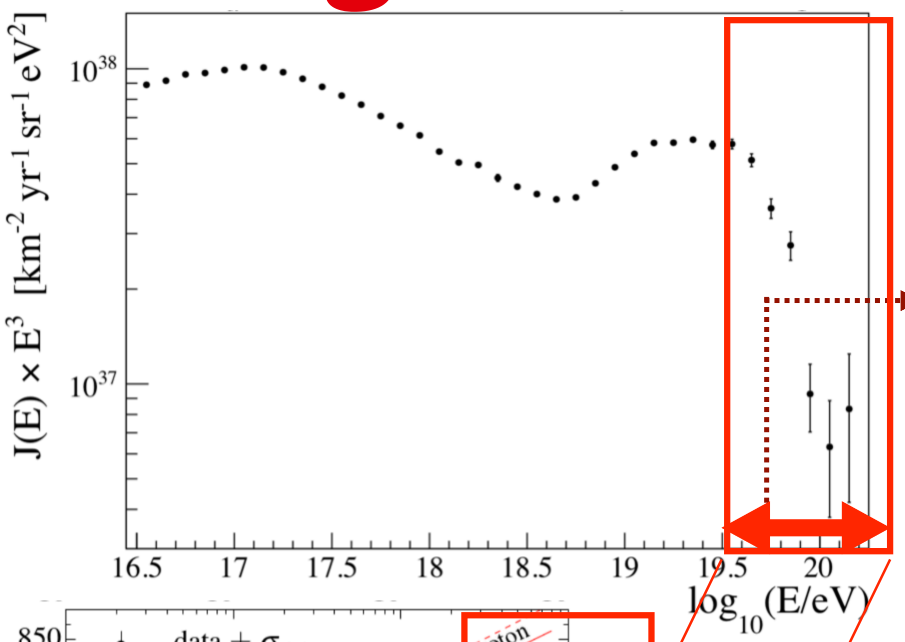
AugerPrime: An Upgraded Observatory

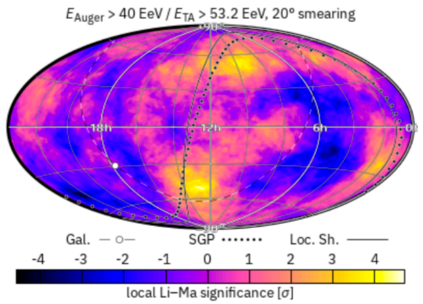
The Science case for Auger Prime

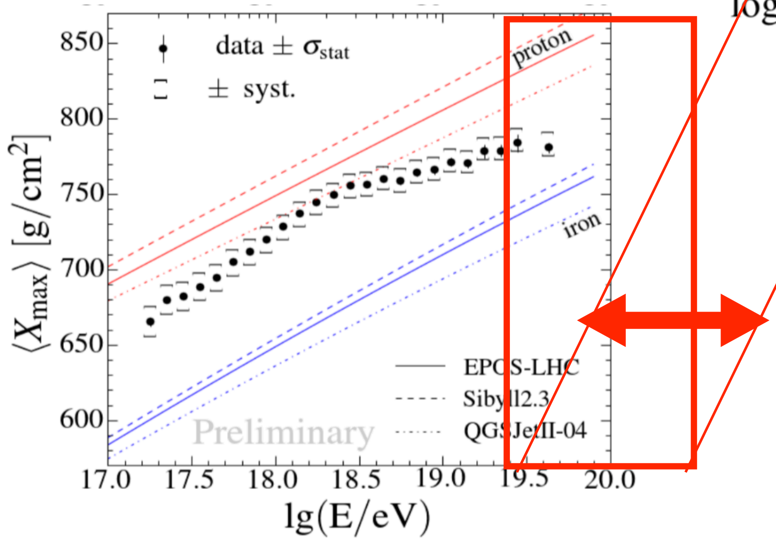
- ➡ study the origin of the suppression
- ➡ select light primaries for charged particle astronomy
- ➡ provide better estimates of the neutrino and γ flux, as such establishing the potential of future CR experiments
- ➡ better measure the shower components to deepen the study of hadronic interactions at UHE and look for non standard physics

Extend operations to >2025, increasing the statistics

Improve the sensitivity to the composition at UHE : disentagle the electromagnetic and muonic components

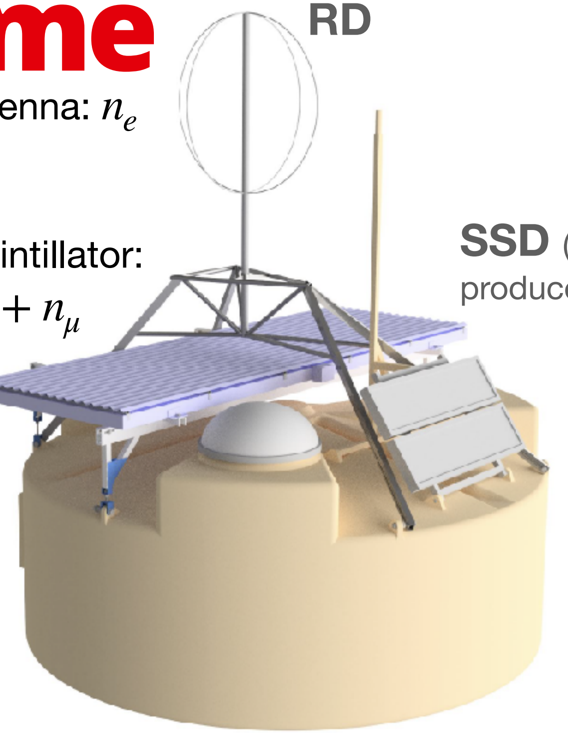






Castellina, ICRC2019

The new Detectors of AugerPrime



Vertical $0^\circ < \theta < 60^\circ$

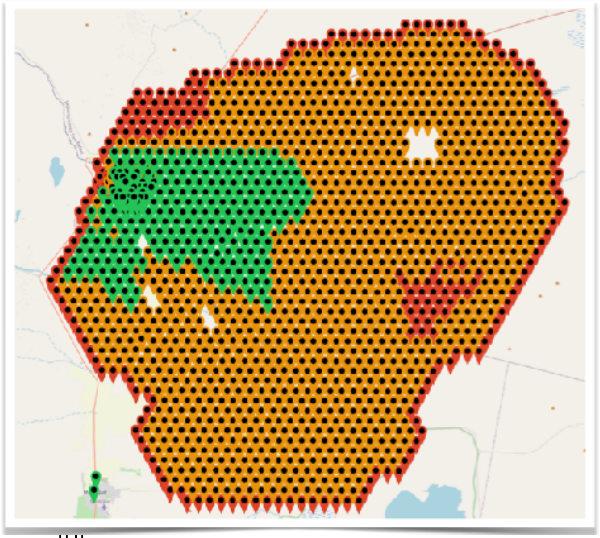
Combination of Scintillators + WCD to disentangle muonic and electromagnetic component

Horizontal $60^\circ < \theta < 85^\circ$

WCD "only" muons
Radio "only" electromagnetic

Status of deployment SSD:

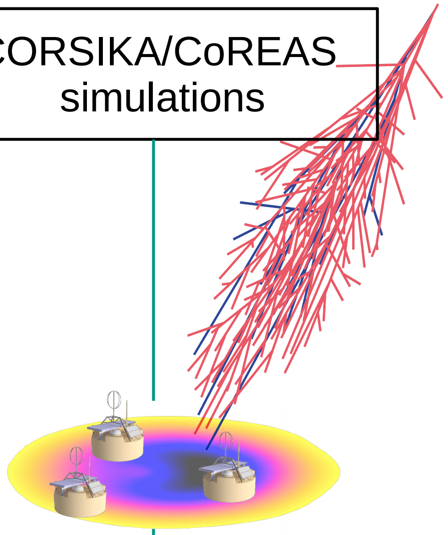
- SSD placed on >75% of stations
- >20% fully equipped
- Finalise installation this year
- In 2023 **only** AugerPrime

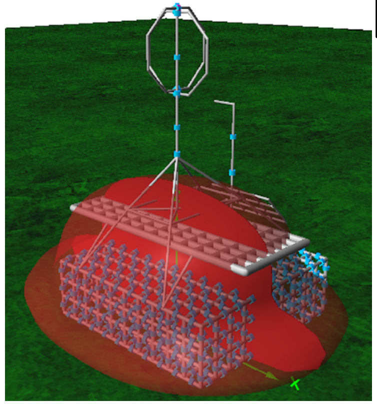


Schoorlemmer, Nikhef 2022

The Radio Upgrade

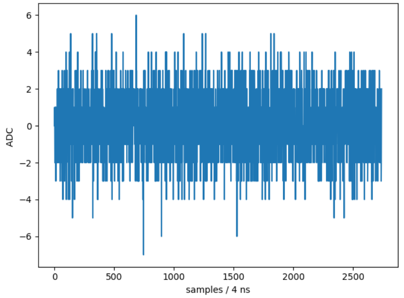
CORSIKA/CoREAS simulations



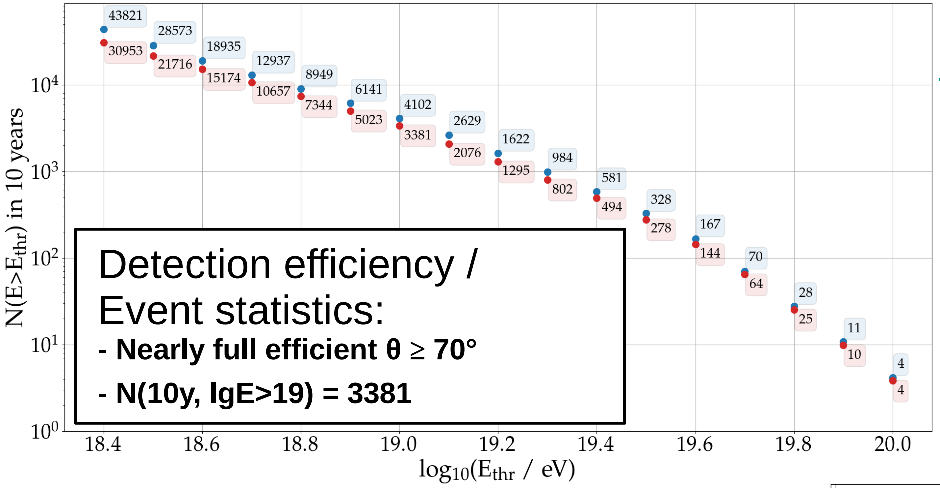


RD Detector simulation

Add measured noise

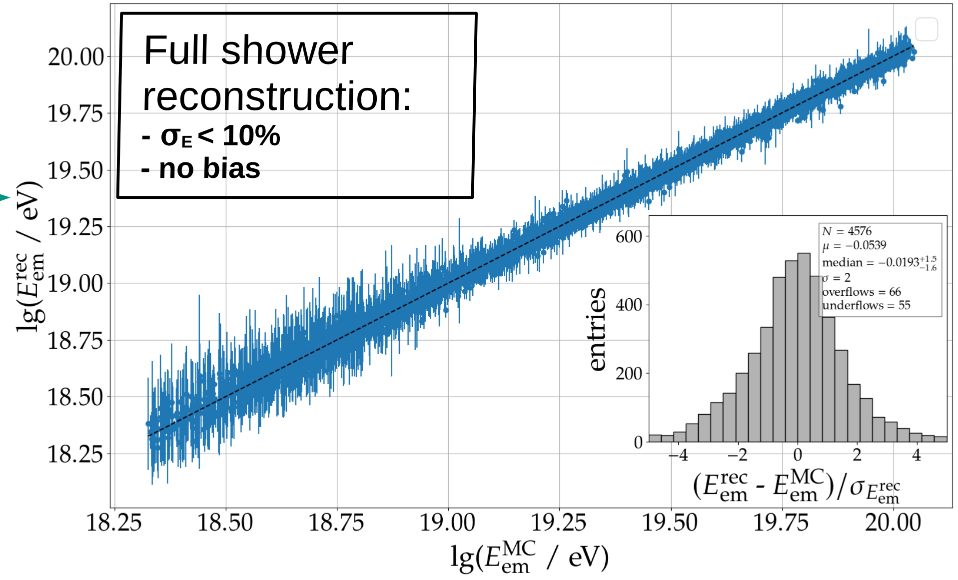


Station signal reconstruction



Detection efficiency / Event statistics:

- **Nearly full efficient θ ≥ 70°**
- **N(10y, lgE>19) = 3381**



Full shower reconstruction:

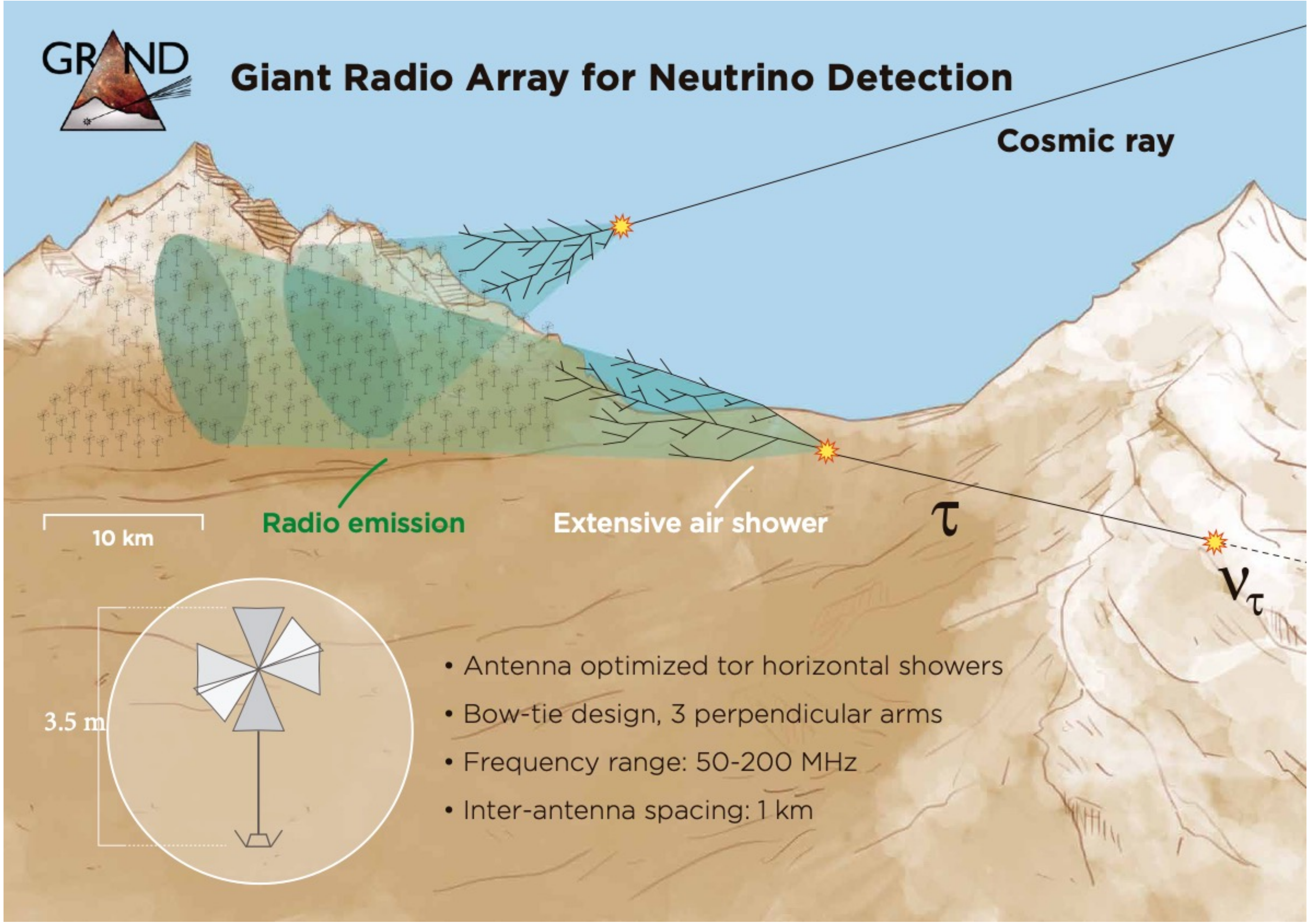
- **σ_E < 10%**
- **no bias**

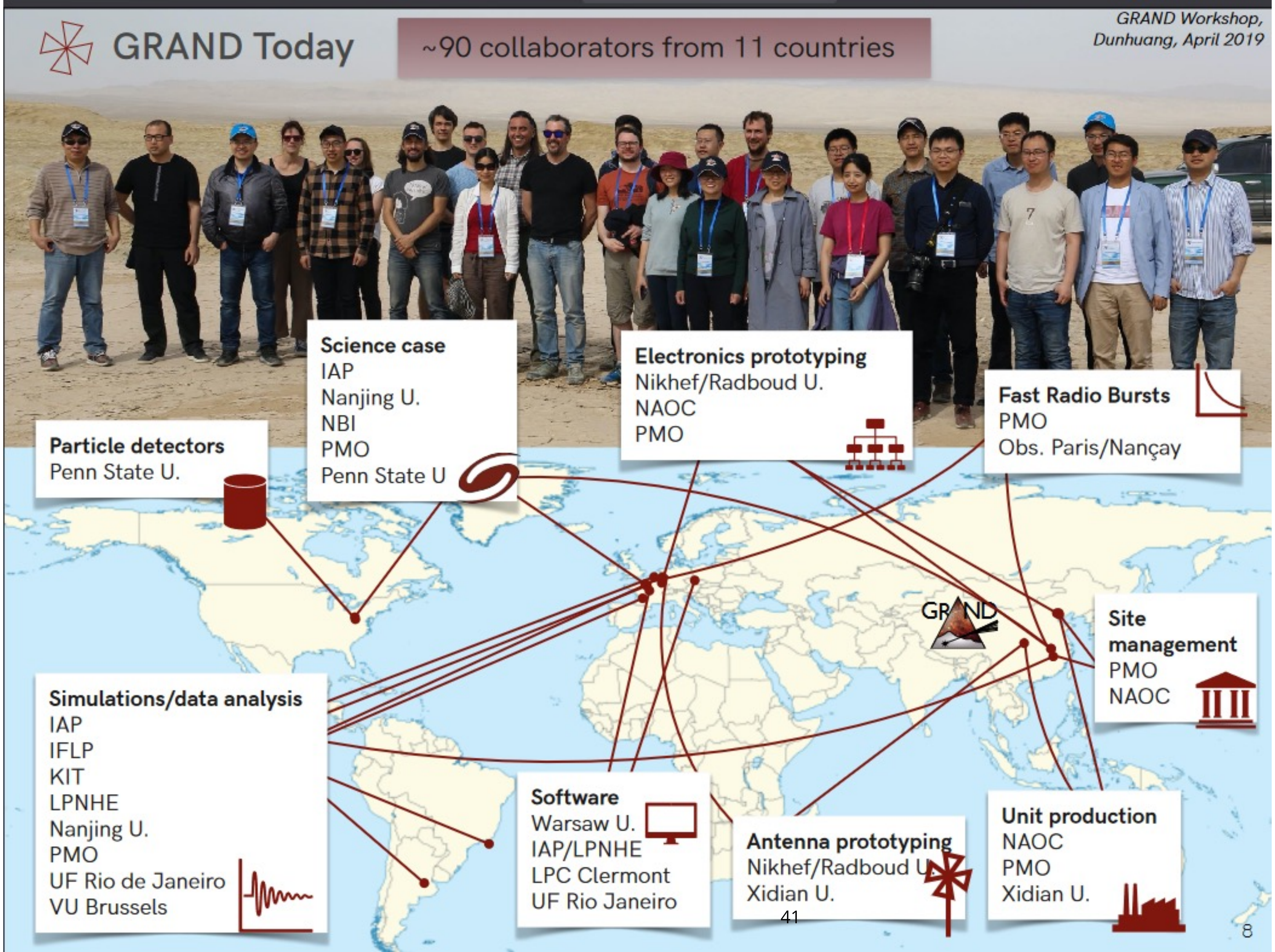
Needs Radio and Muons

Mass composition analysis

Schlueter, ICRC2021

GRAND: A Next generation Observatory


GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
10 km
Radio emission
Extensive air shower
τ
ν_τ
3.5 m
• Antenna optimized tor horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km



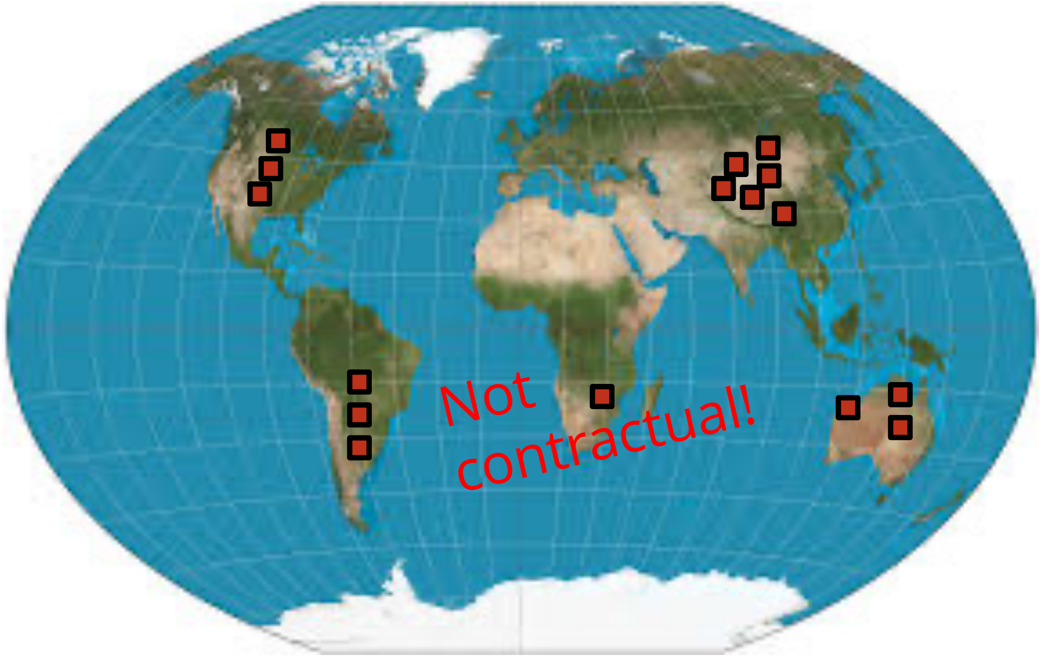
Martineau, ARENA 2022

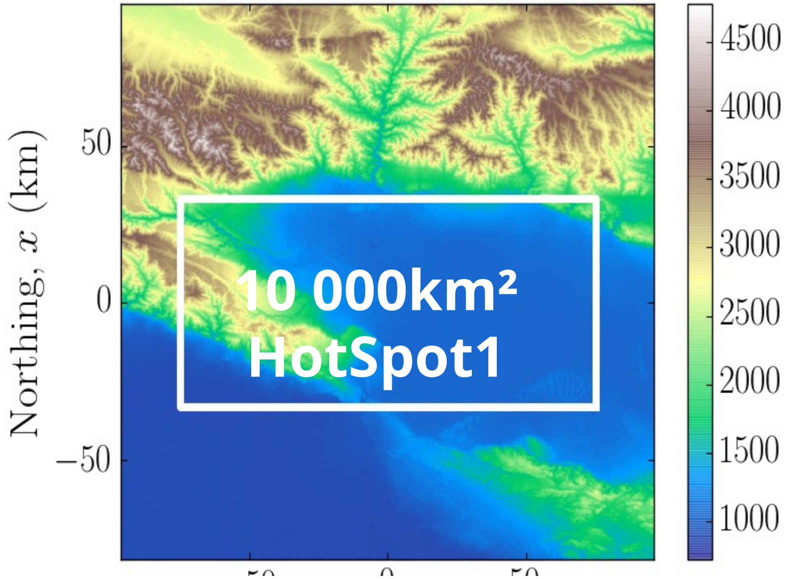
GRAND PROPOSAL

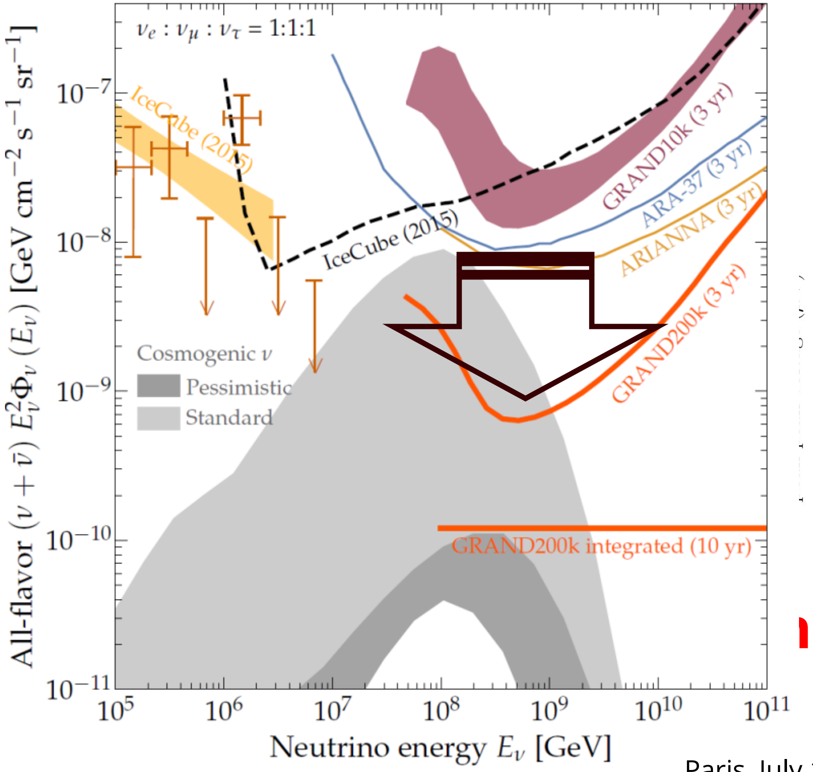
- Sizable effort for end-to-end simulation on a 10000 antennas hotspot (GRAND10k)

➔ Sensitivity in IceCube2015 range.

- **Go for x20!! ➔ Network of o(20) subarrays of o(10000) antennas with sparse density (1/km²) at various favorable locations around the world (« hotspots »)**







Martineau, ARENA 2022

GRAND STAGES

Few km^2 Radio
+
particle
detection
in China

300 km^2
Standalone radio
+
particle detection
in China

10,000 km^2
Standalone radio
in China

200,000 km^2
Standalone
radio
Worldwide

2018 | 2022 | 2028 | 203X

Detector budget:1.5 M€
Development:
- Mechanics
- Electronics
- Power system
- DAQ
- Reconstruction tools

Detector budget:20 M€

Cost Reduction:
- Scale
- Integration (board)

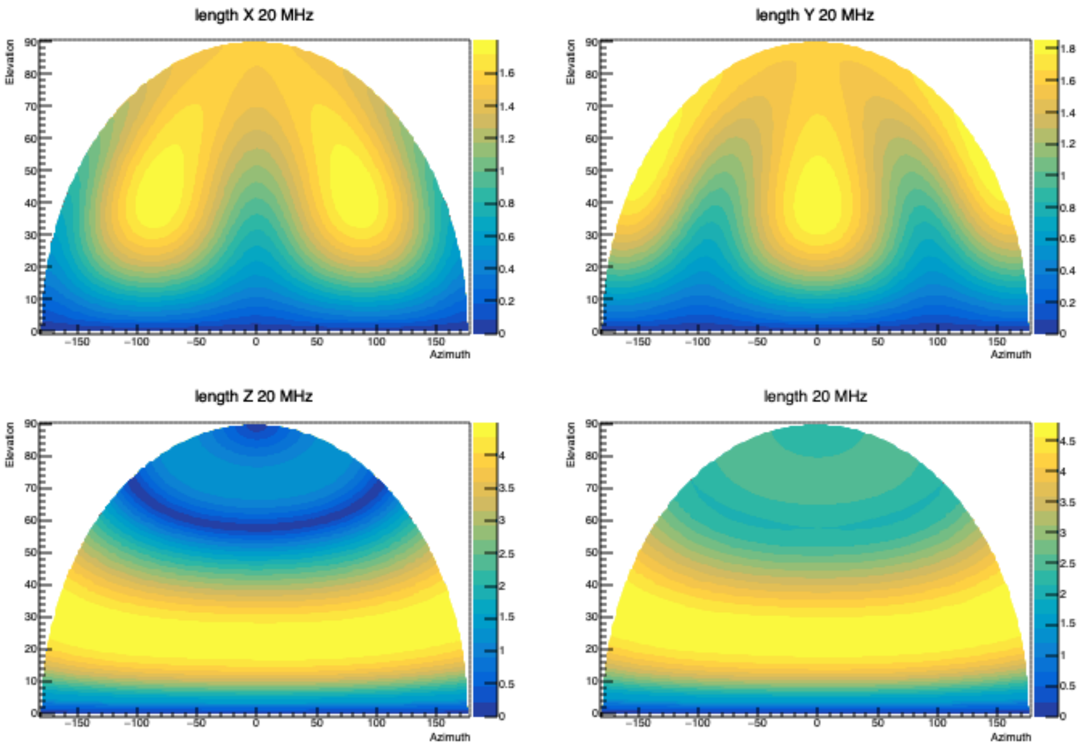
Neutrino and Multi-Messenger physics!

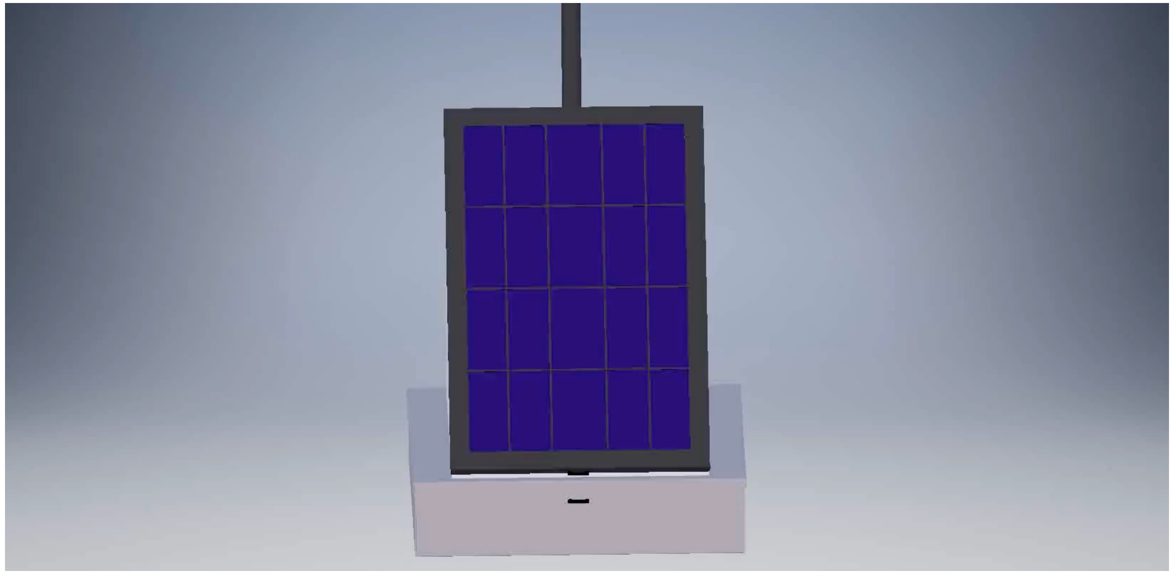
Detector budget:150 M€

Cost Reduction:
- Industrial Scale
- Integration (Chip)

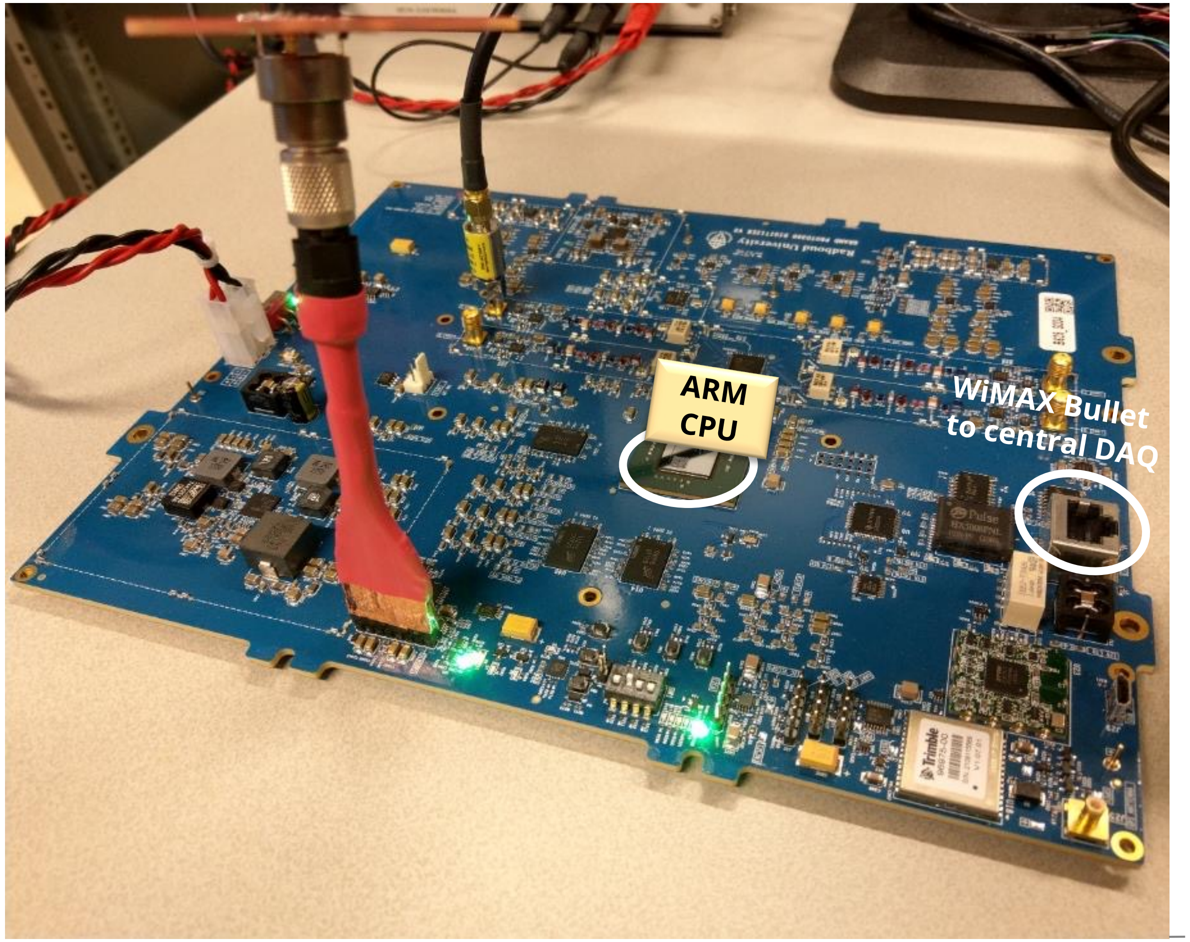
Full physics potential

The Antenna Design





GRAND Digitizer Unit



Analog front end

Control

500 mill. samples per s

GPS 1PPS; RX

Sensors data

Digital electronics - FPGA

Control

Triggered event & metadata

ARM CPU

Control

Triggered event timestamps

Set of buffered triggered events & metadata

Central DAQ

Radio

- 2-level amplification
  - LNA
  - Variable gain amplifier/attenuator
- Filtering 50-200MHz
- ADC (14-bit 500 million samples per second)

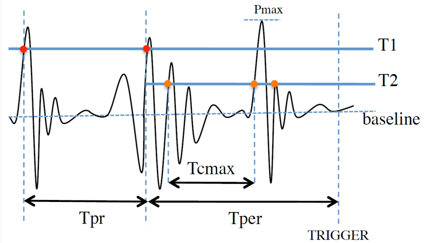
Sensors

- ADC

GPS

- Receiver & ADC

- Notch filters – reduce noise levels and narrow band interfering signals
- L1 Triggering
  - Time-over-Threshold
  - No preceding pulse
  - No succeeding pulse train

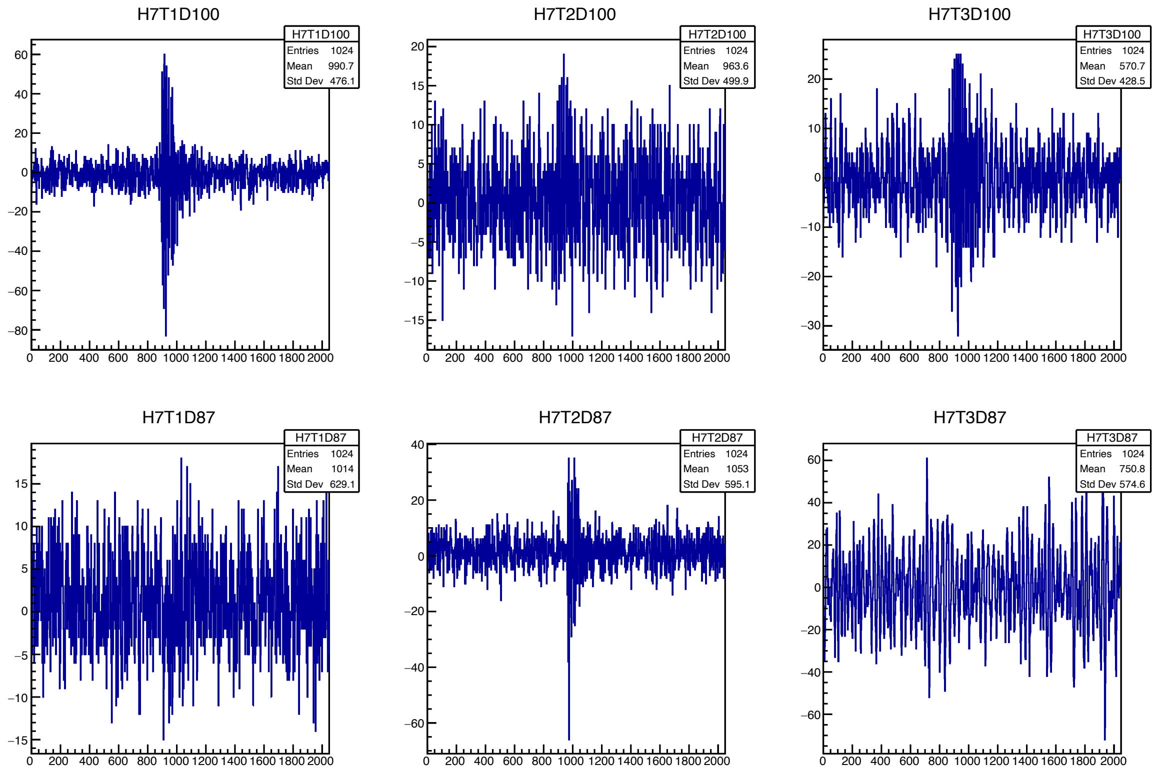


- Buffers 2 events (2 μs event window)

- L2 Triggering (optional)
- Buffers 400 events

- L3 Triggering
  - Compares triggered events timestamps from individual detection units

Nançay: A test station in France

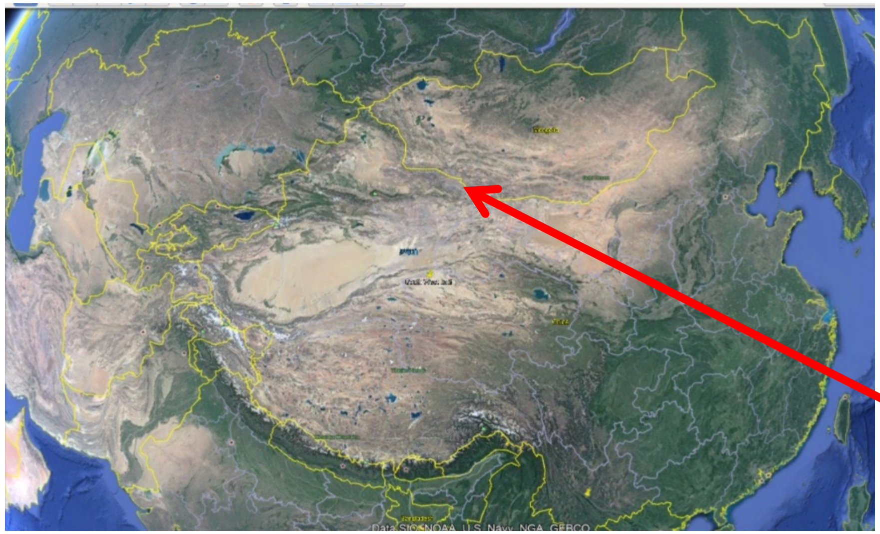


Some first pulses indicating basic functionality!

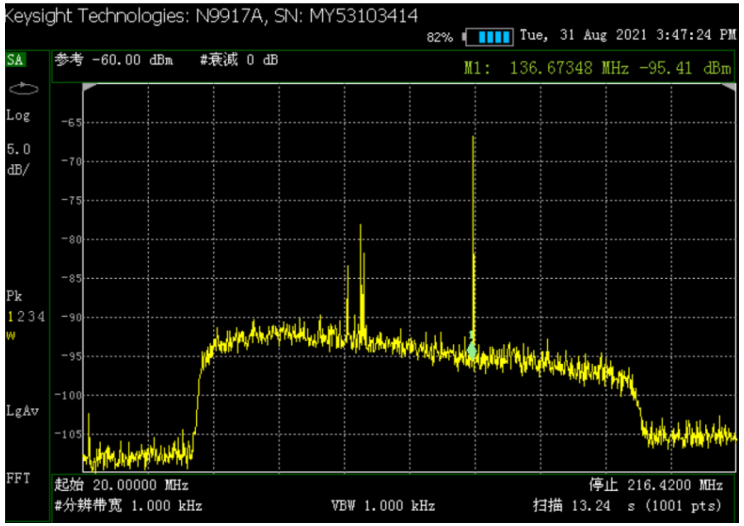
GRAND@Auger: A proposal

- Subarray of **10 GP300 units within PAO array**
- Test GRAND units & trigger system in a different radio environment
- Cross calibration & analysis of Auger (radio) & GRAND data
- Site selection in November 2022, deployment mid 2023 (pending approvall).

The GP300 Site: China



- Subei county, Gansu province:
  - Remote mountain area in the Gobi desert
  - Excellent radio background & topography ideal for deployment
  - Within boundaries of a Nature Reserve
  - **Deployment authorization pending approval**



Martineau, ARENA 2022

Conclusions

- **Current detectors produced a lot of results**
- **Questions remain**
  - What are the sources of UHECR?
  - What is the composition of UHECR?
- **New topics have come up:**
  - UHECR Multi-messenger physics
  - Can we do particle physics beyond LHC energies?
- **Upgrades may provide parts of the answers**
- **A much larger detector will be needed**
  - Preparations are well under way