Radio detection of air showers with

AERA, Pierre Auger Radio Detector, GCOS

characterize cosmic rays:
-direction
-energy
-mass (particle type)
@~100% duty cycle

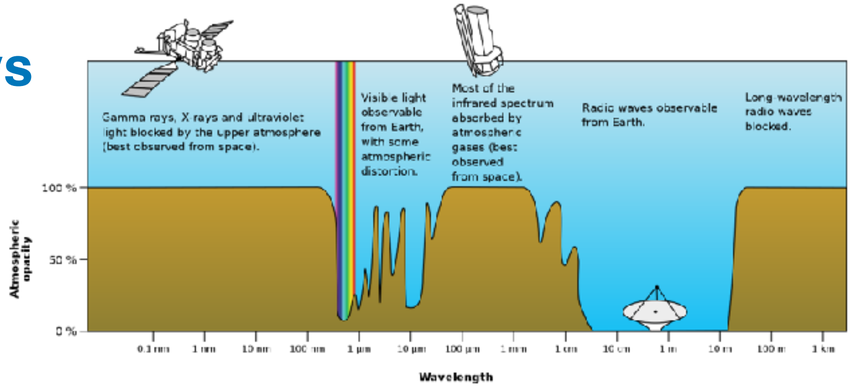
Global Cosmic Ray Observatory - GCOS
(60000 km²) 2035

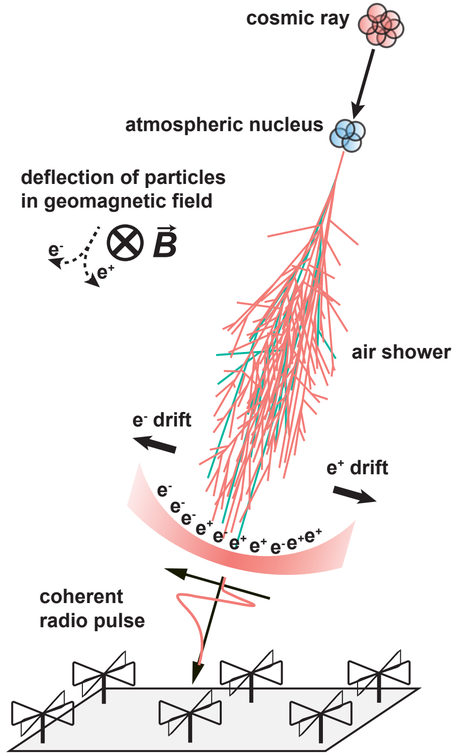
Pierre Auger Radio Detector
(3000 km²) 2023

Auger Engineering Radio Array - AERA
(17 km²) 2010

LOFAR Cosmic Rays
(5 km²) 2007

LOPES
(0,5 km²) 2001

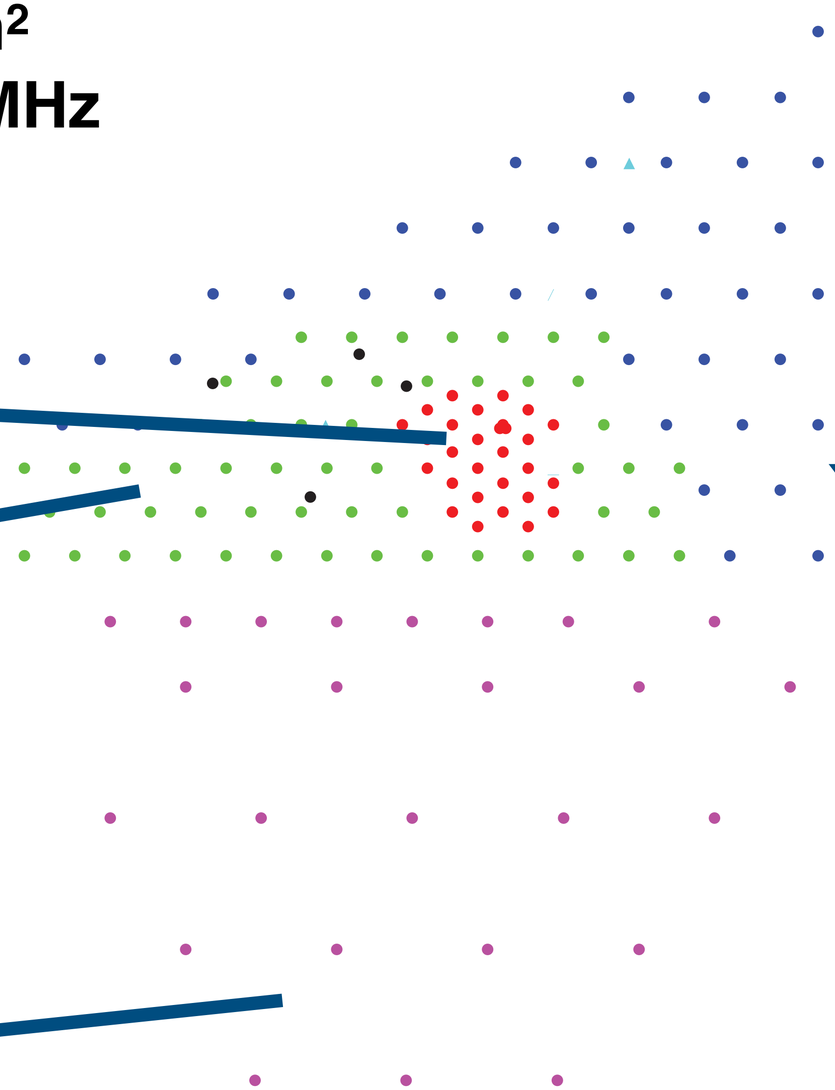


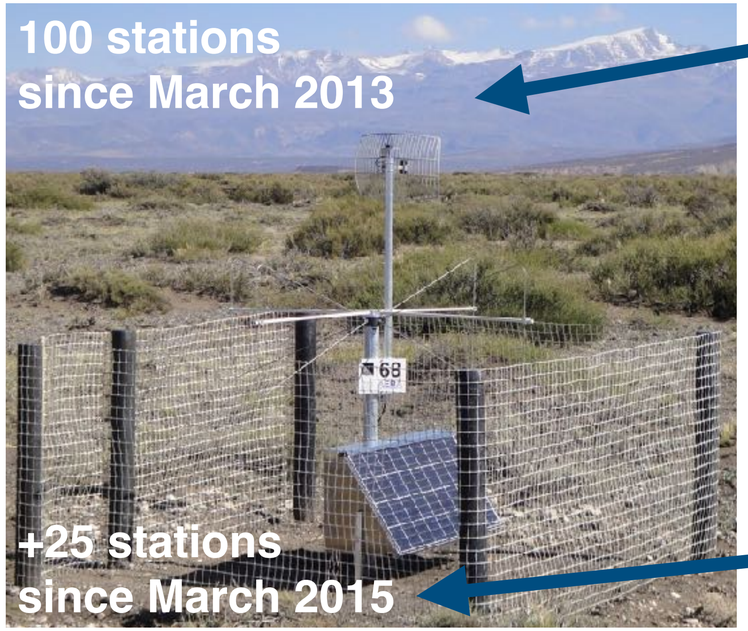


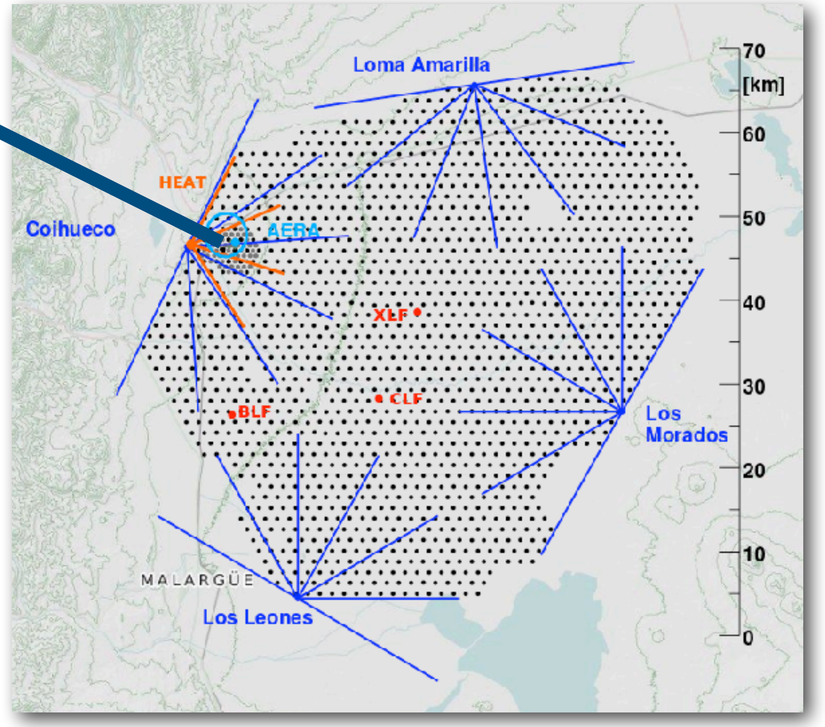
The Auger Engineering Radio Array

~150 antennas
~17 km²
30-80 MHz

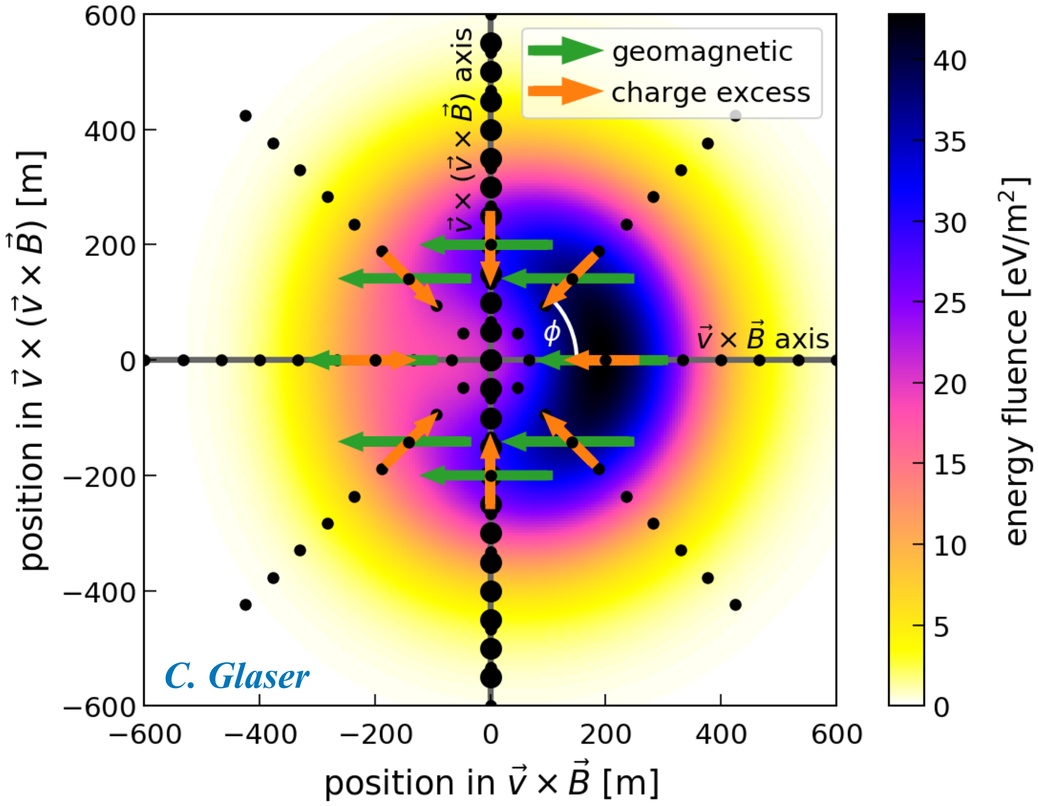
cross calibration with SD & FD

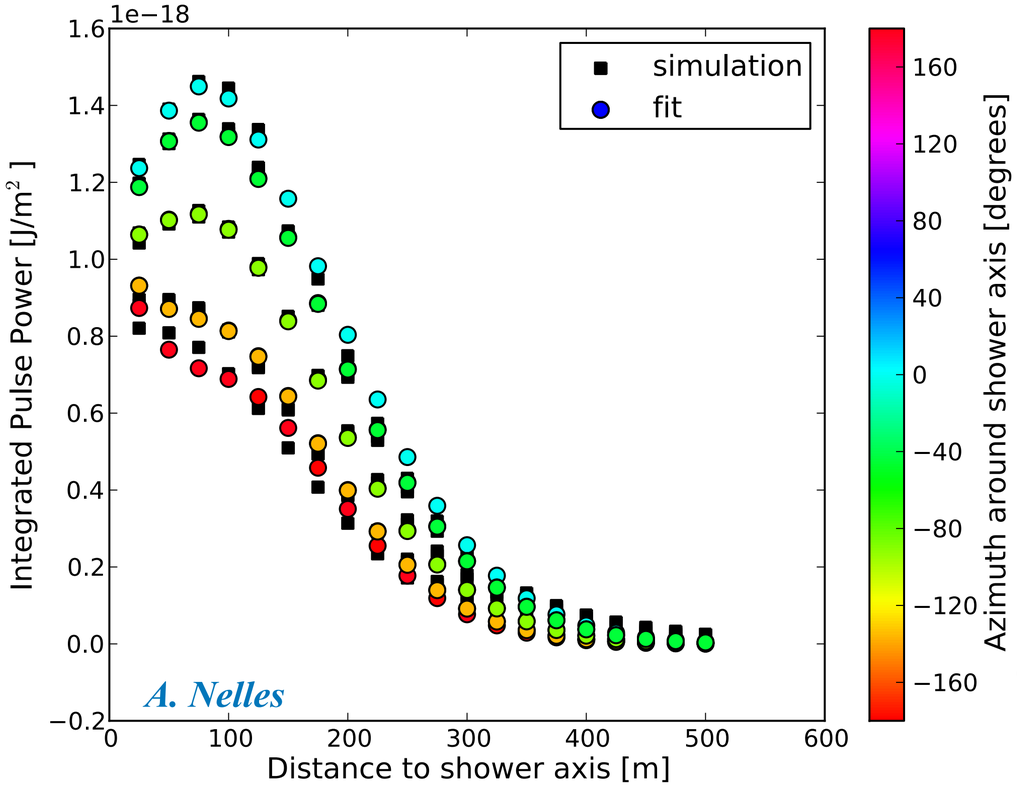


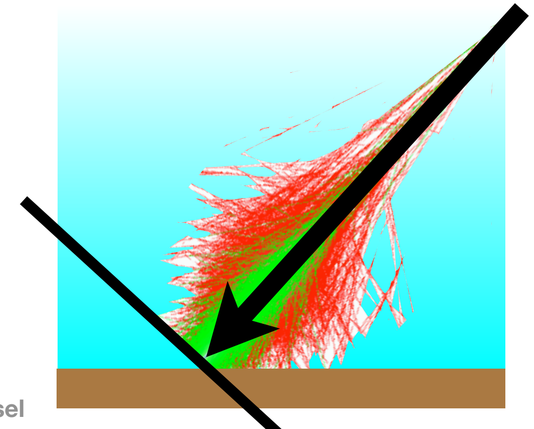


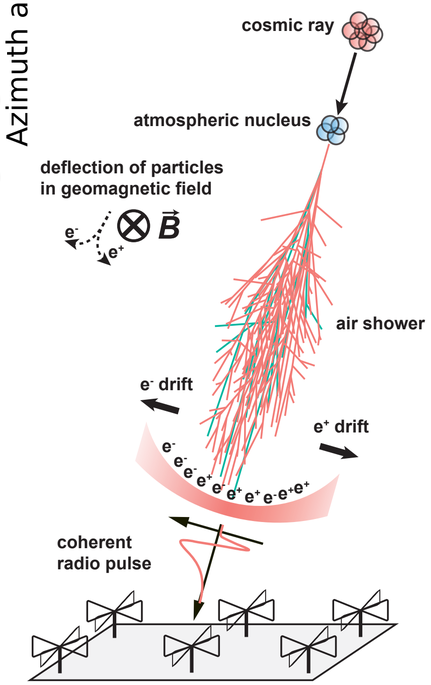


Footprint of radio emission on the ground

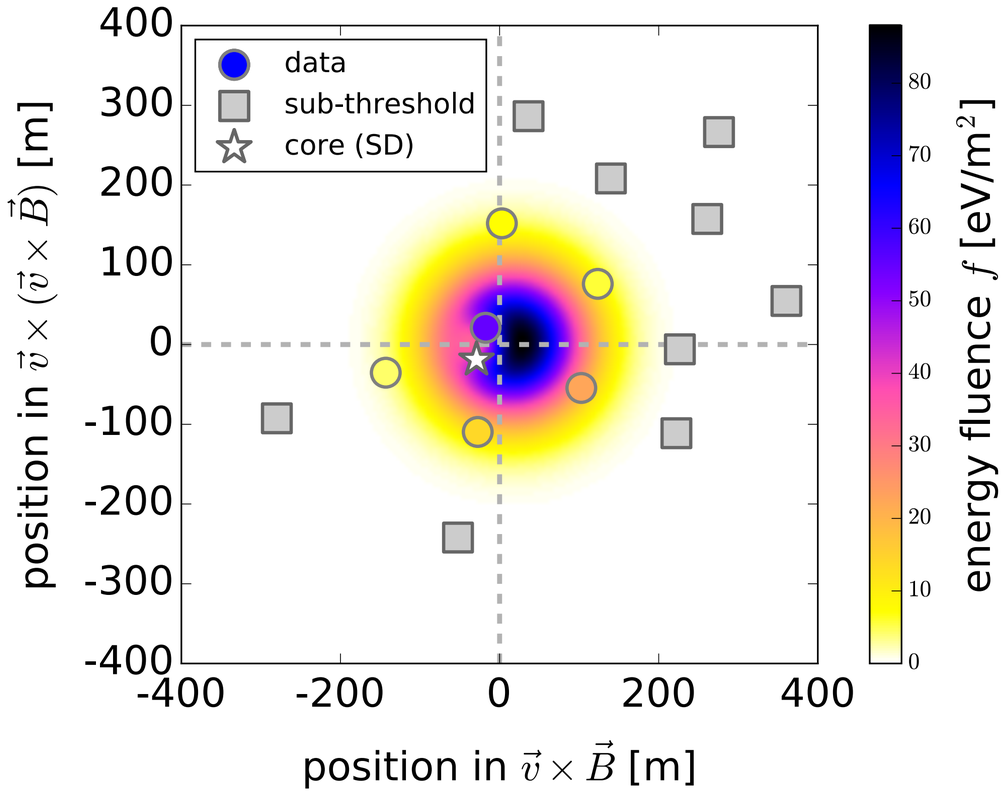


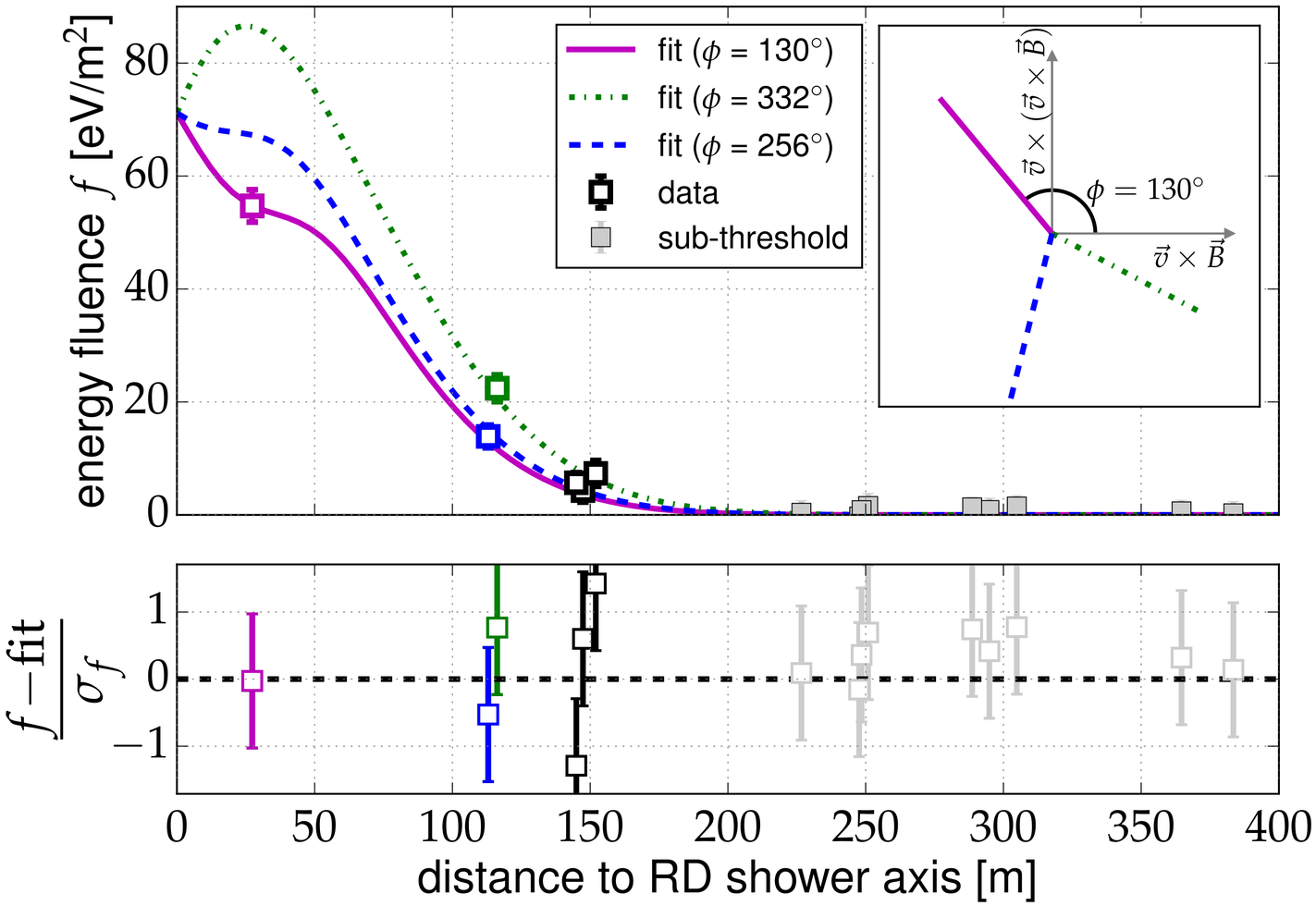






Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy



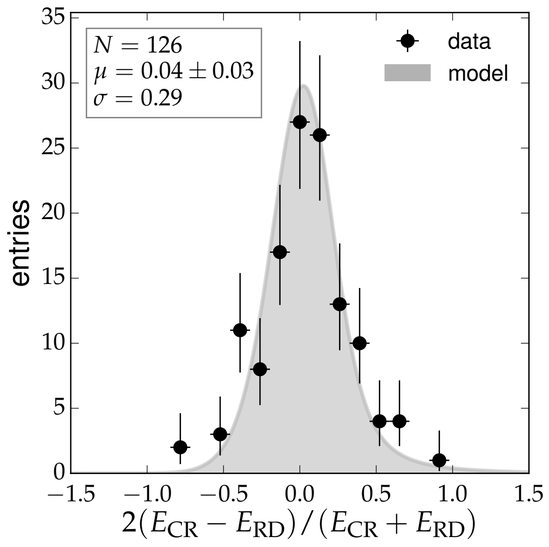


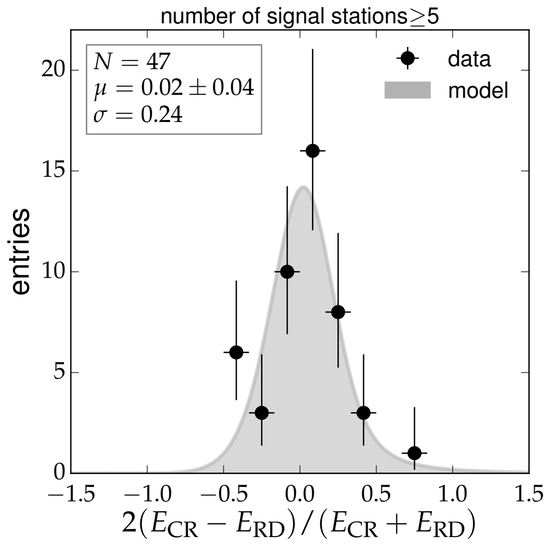
A. Aab et al., PRL 116 (2016) no.24, 241101

Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy

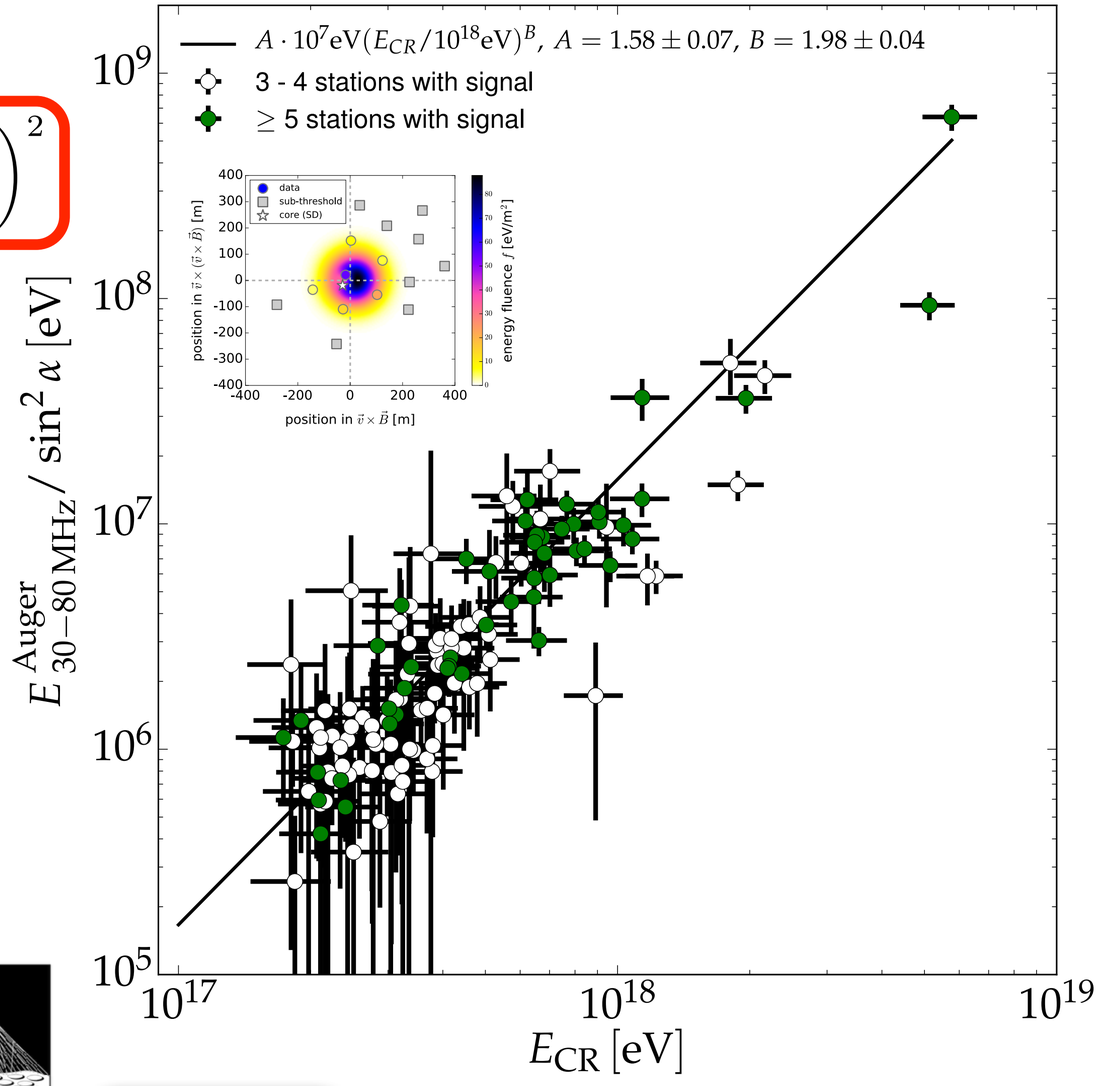
$$E_{30\text{-}80\ \mathrm{MHz}} = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{syst})\ \mathrm{MeV}) \times \left(\sin\alpha \frac{E_{CR}}{10^{18}\ \mathrm{eV}} \frac{B_{Earth}}{0.24\ \mathrm{G}}\right)^2$$

$E_{30\text{-}80}$ MHz = 15.8 MeV @ 10^{18} eV





$\sigma \approx 24\%$



A. Aab et al., PRL 116 (2016) no.24, 241101

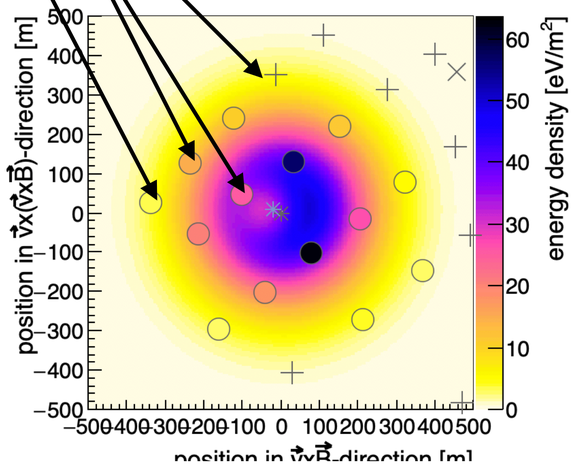
Reconstructing X_{max} from the radio footprint

Reconstruction Air Shower

E_{SD}, θ, ϕ, …

Antennas

Measured



B. Pont, UHECR symposium 2022

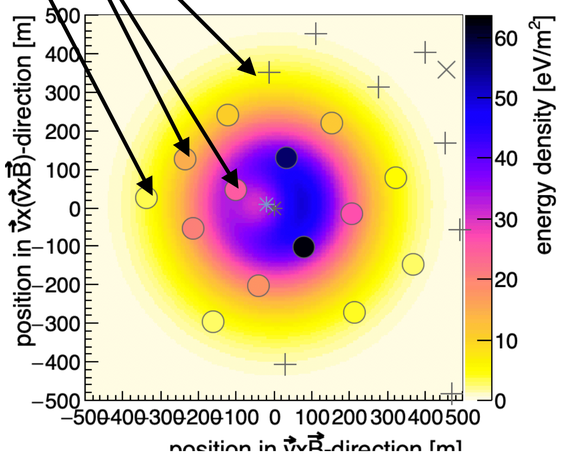
Reconstructing X_{max} from the radio footprint

Reconstruction Air Shower → CORSIKA

E_{SD}, θ, ϕ, … {X_{max}}

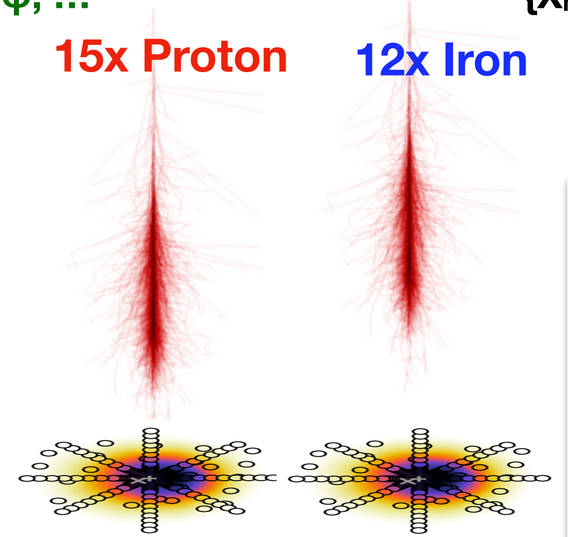
Antennas

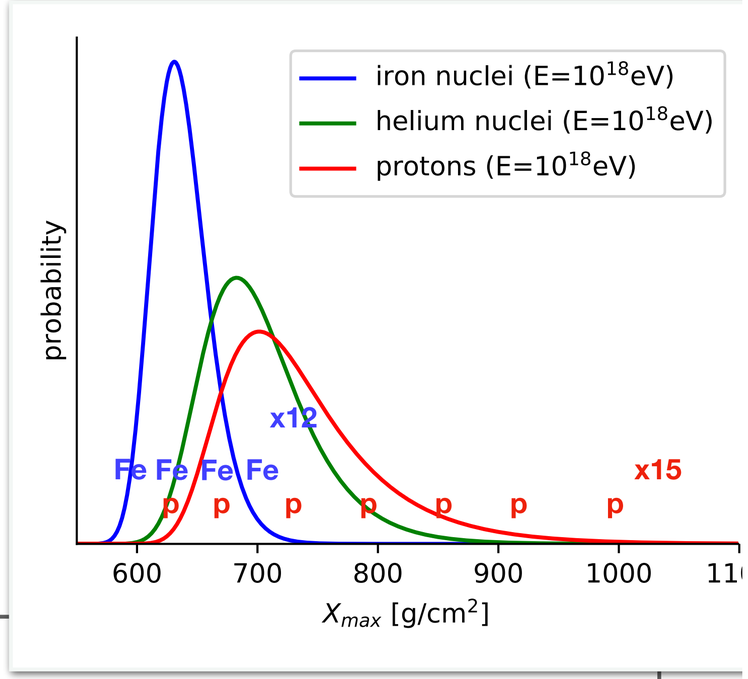
Measured



15x Proton

12x Iron





Technical details

- **CORSIKA** 7.71 (QGSJetII-04, UrQMD 1.3cr, CoREAS)

Event-specific setup:

- + **AERA station layout** + 240 additional '**star-shape**' stations centered around core (for interpolation)
- + **GDAS atmospheres** (**G**lobal **D**ata **A**ssimilation **S**ystem) at Auger at time of data
- + **Magnetic field** model at time of data

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Reconstructing X_{max} from the radio footprint

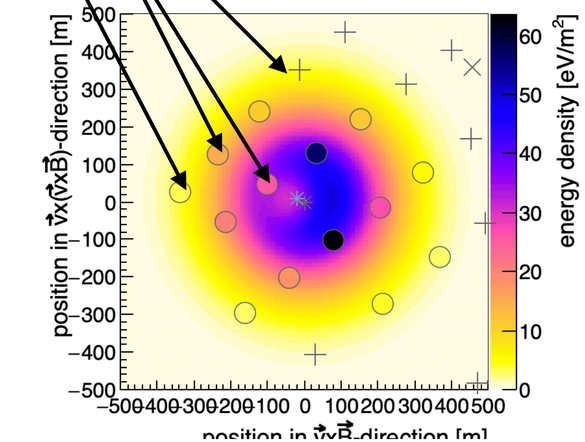
Reconstruction Air Shower → CORSIKA → Reconstruction Simulations

E_{SD}, θ, ϕ, … → {X_{max}}

Using same reconstruction code
(includes detector and reconstruction effects)

Antennas

Measured



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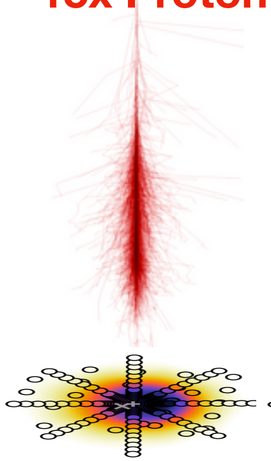
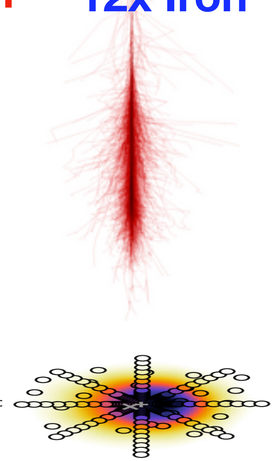
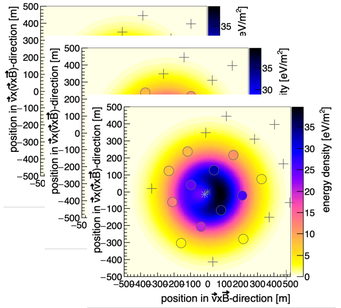


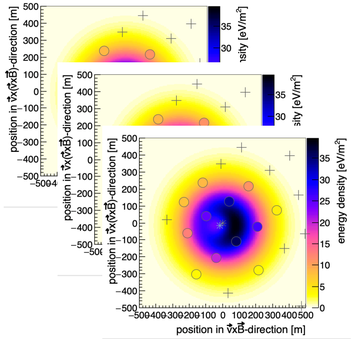
12x Iron



Proton



Iron



B. Pont, UHECR symposium 2022

Reconstructing X_{max} from the radio footprint

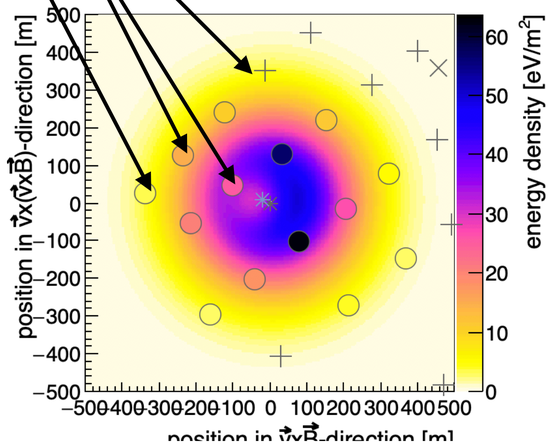
Reconstruction Air Shower → CORSIKA → Reconstruction Simulations

E_{SD}, θ, ϕ, … → {X_{max}}

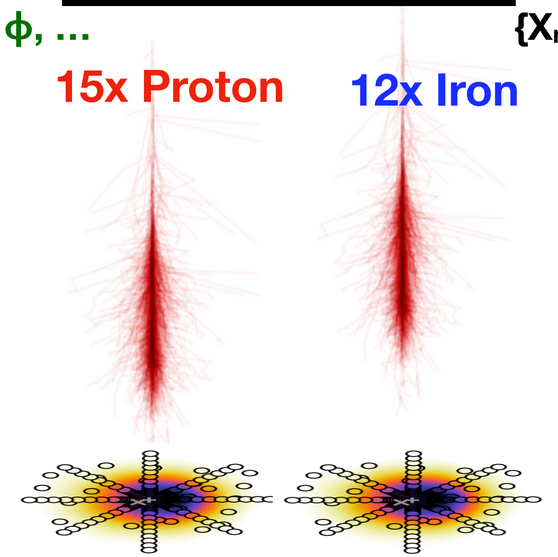
Using same reconstruction code
(includes detector and reconstruction effects)

Antennas

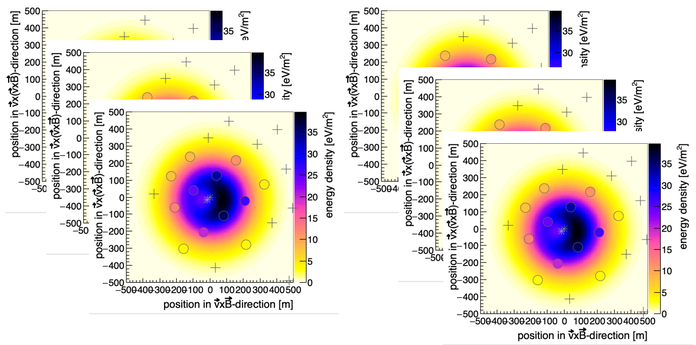
Measured



15x Proton **12x Iron**

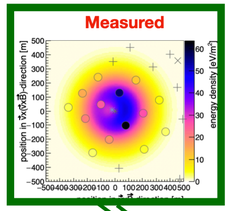


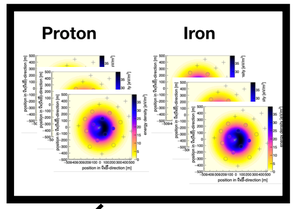
Proton **Iron**



Based on Buitink+(2016)

Minimise to find X_{max} of measured shower:

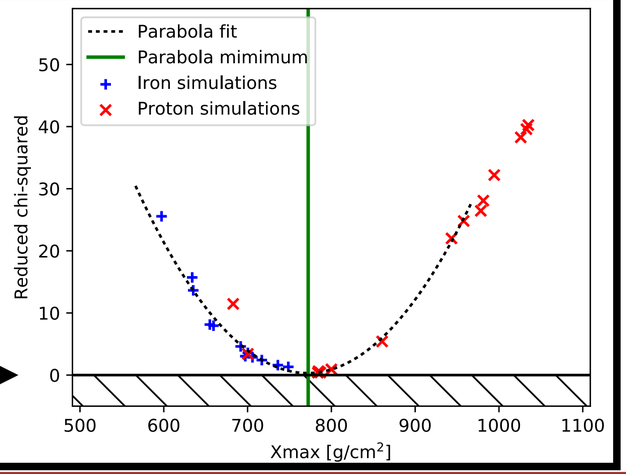




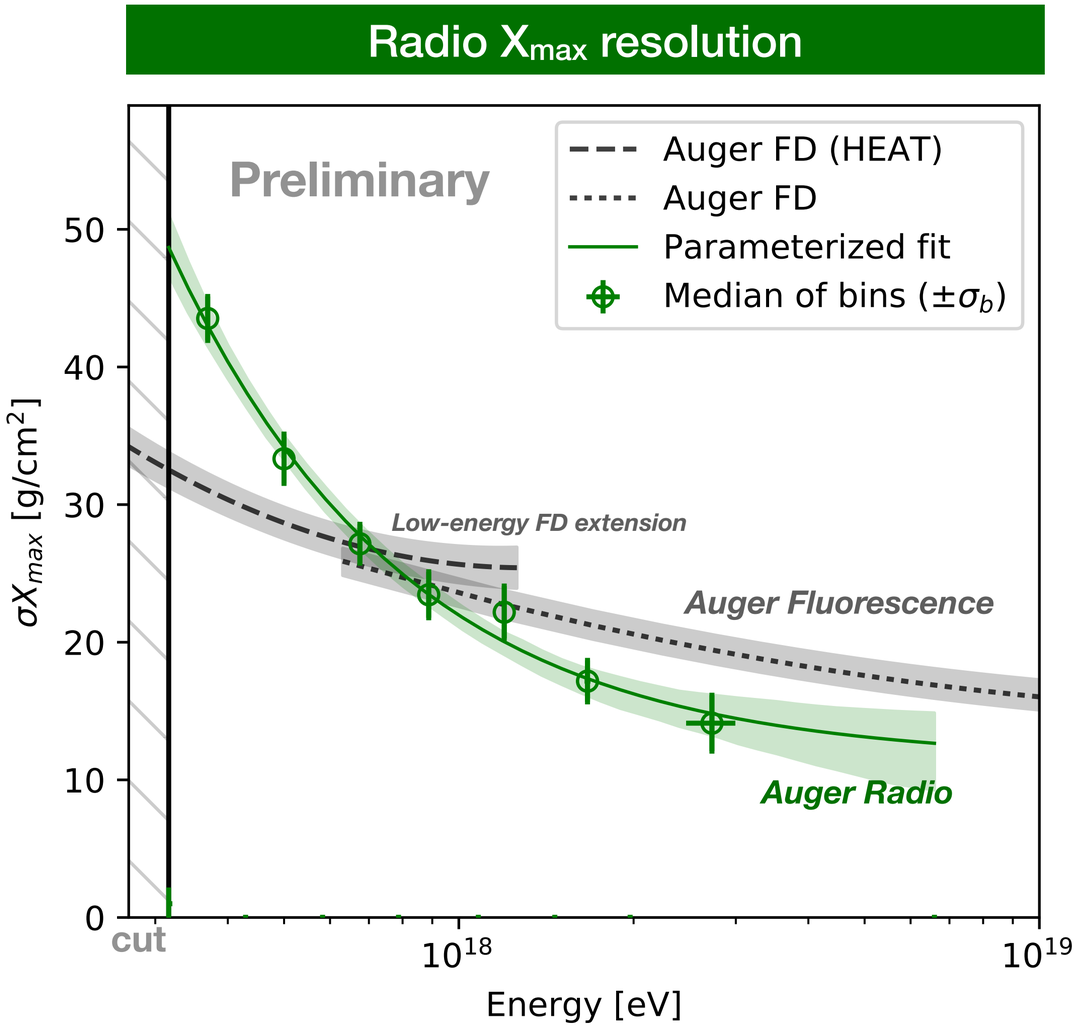
$$\chi^2 = \sum_{\text{AERA Stations}} \left(\frac{u_{\text{data}} - S \cdot u_{\text{sim}}(\Delta \vec{r}_{\text{core shift}})}{\sigma u_{data}} \right)$$

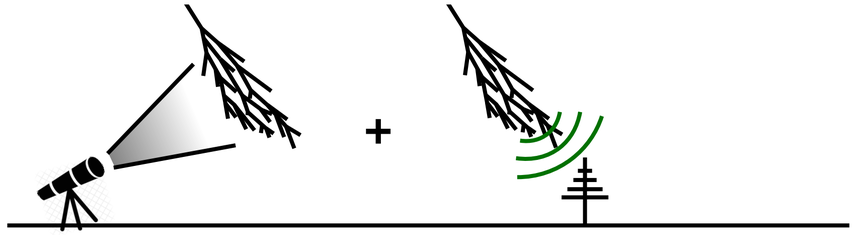
S: *energy scaling*
$r_{core...}$ **:** *core pos. shift*

Minimize →



Resolution of AERA X_{max} method





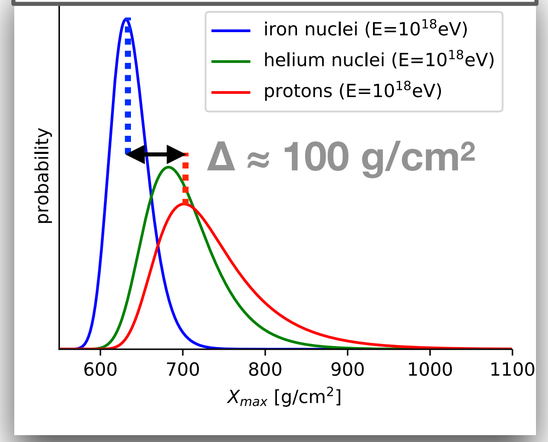
Resolution improves with energy.

- Up to 'better than 15 g/cm² '
- Trend driven by low SNR at low energy.

Resolution competitive with e.g.:

- Auger fluorescence
  [arXiv:1409.4809]

Side note:
High resolution is crucial for mass composition studies.



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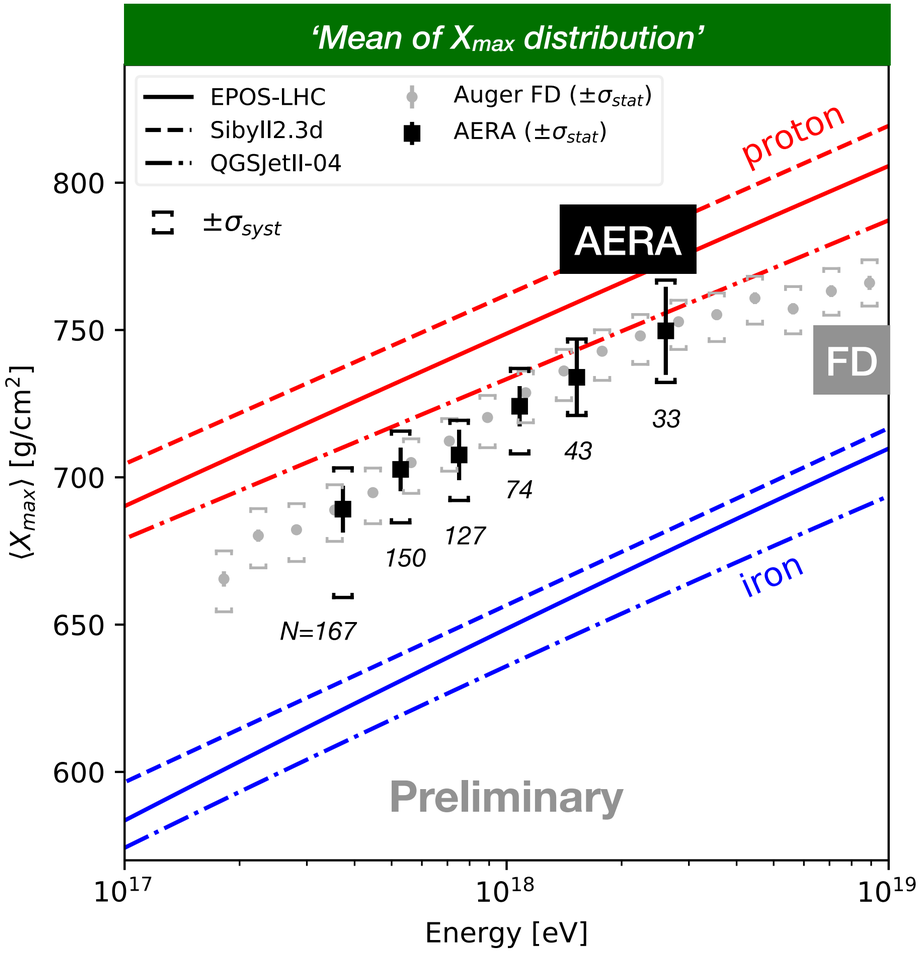
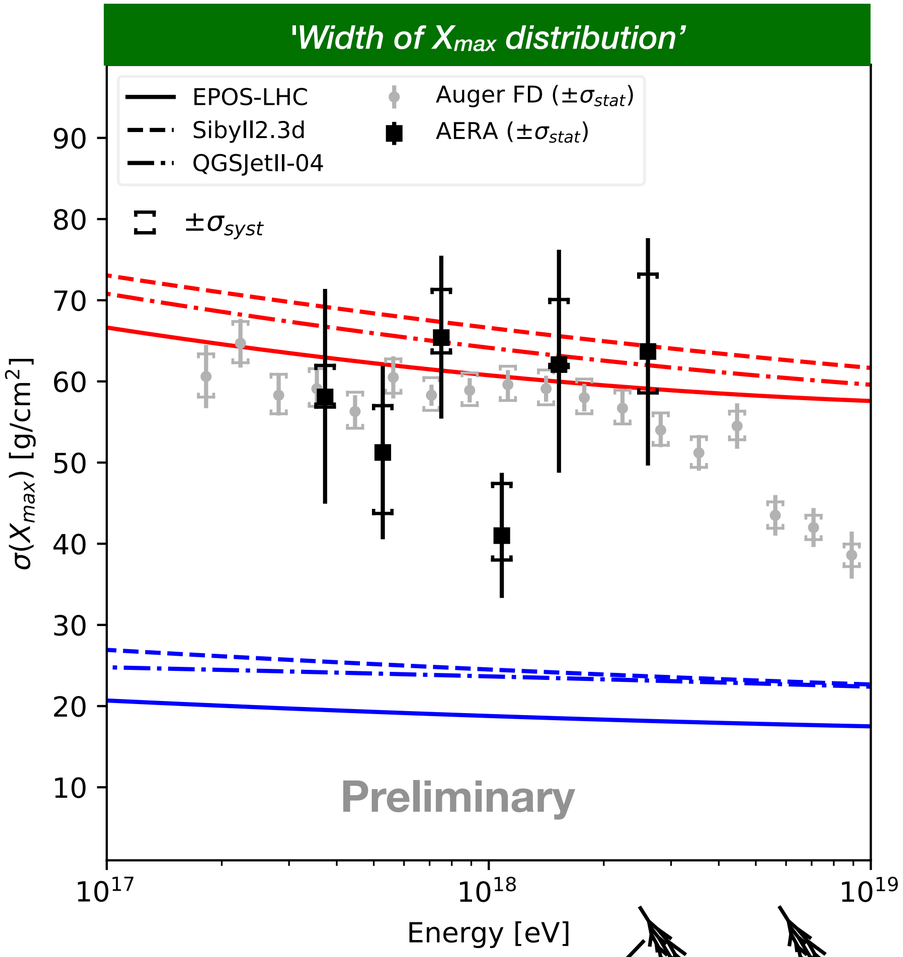
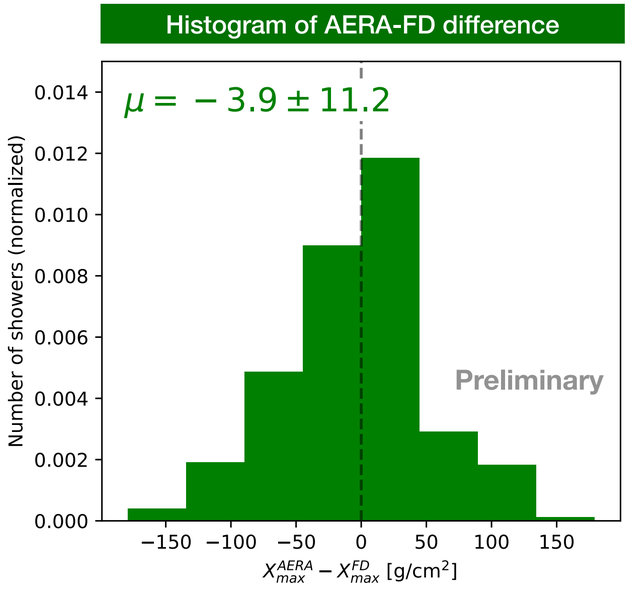
Measured AERA X_{max} distribution







good agreement shower by shower fluorescence vs radio

- ~600 showers after quality and anti-bias cuts.
- In agreement with Auger FD in mean and width.
- (Mixed)-light composition at E=$10^{17.5}$ -$10^{18.5}$ eV.

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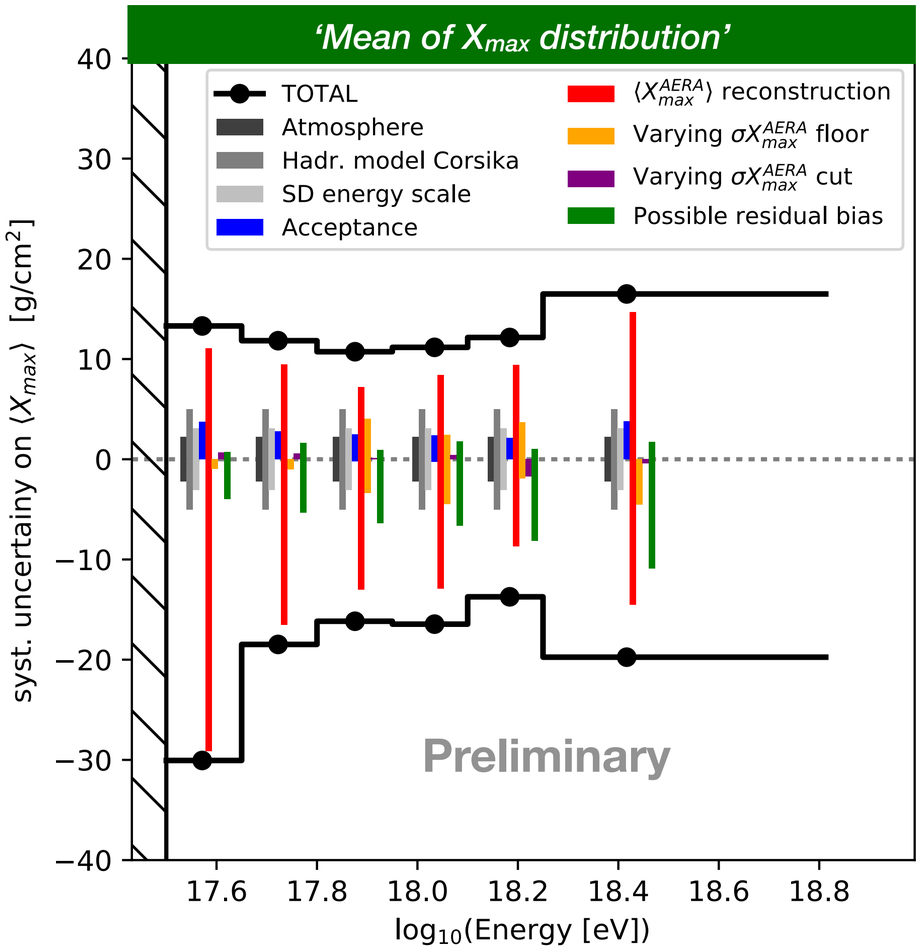
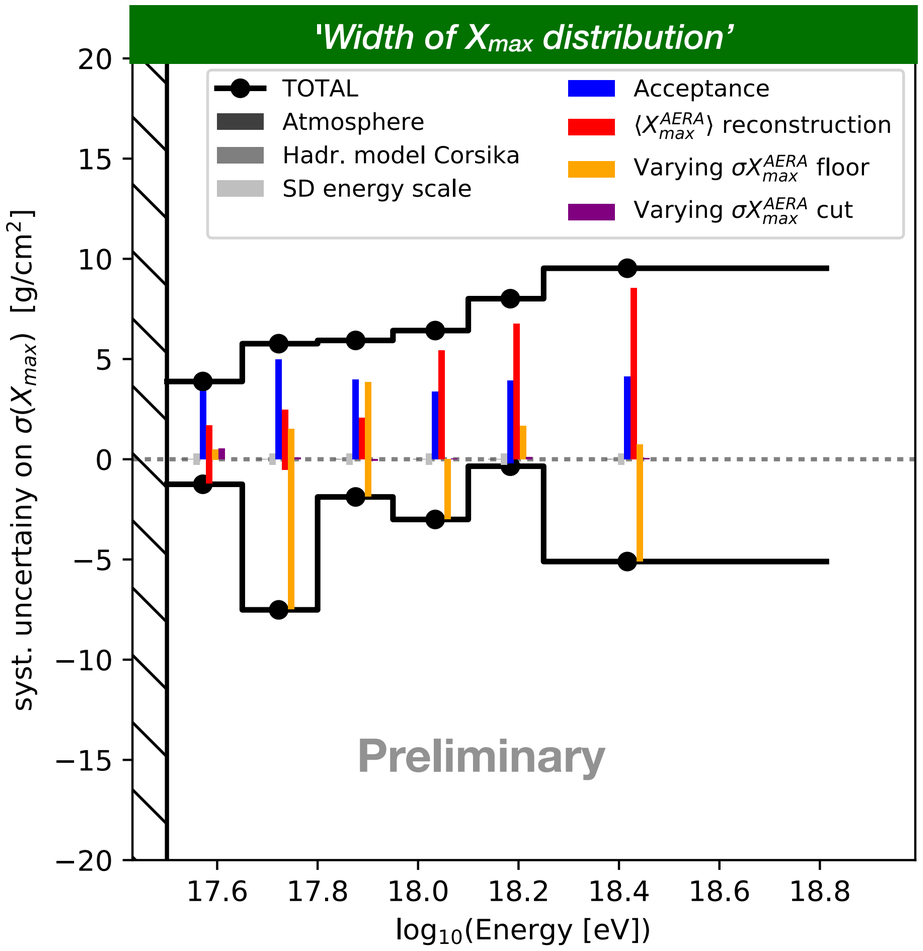
Systematic uncertainties on X_{max}





- **Basic effects** : *hadronic model in CORSIKA, GDAS atmosphere, Auger SD energy scale*
- **Method specific effects** : *data selection (acceptance), X_{max} reconstruction*
- **low-number statistics** : effects of *possible outlier values* and *reconstruction quality cuts*
- **Cross-checks** : *residual bias checks with Zen/Az/core/… vs <X_{max}> and E*

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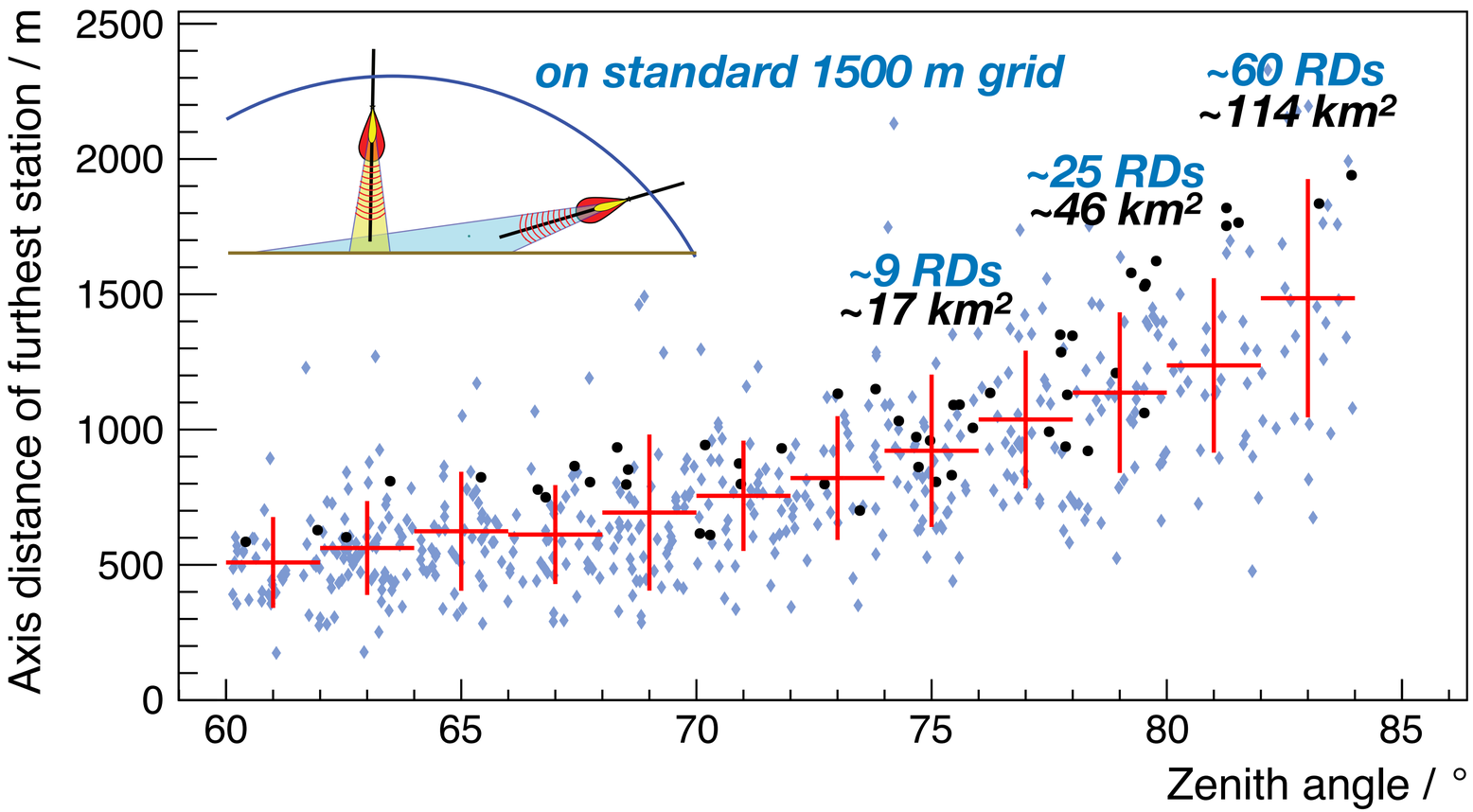
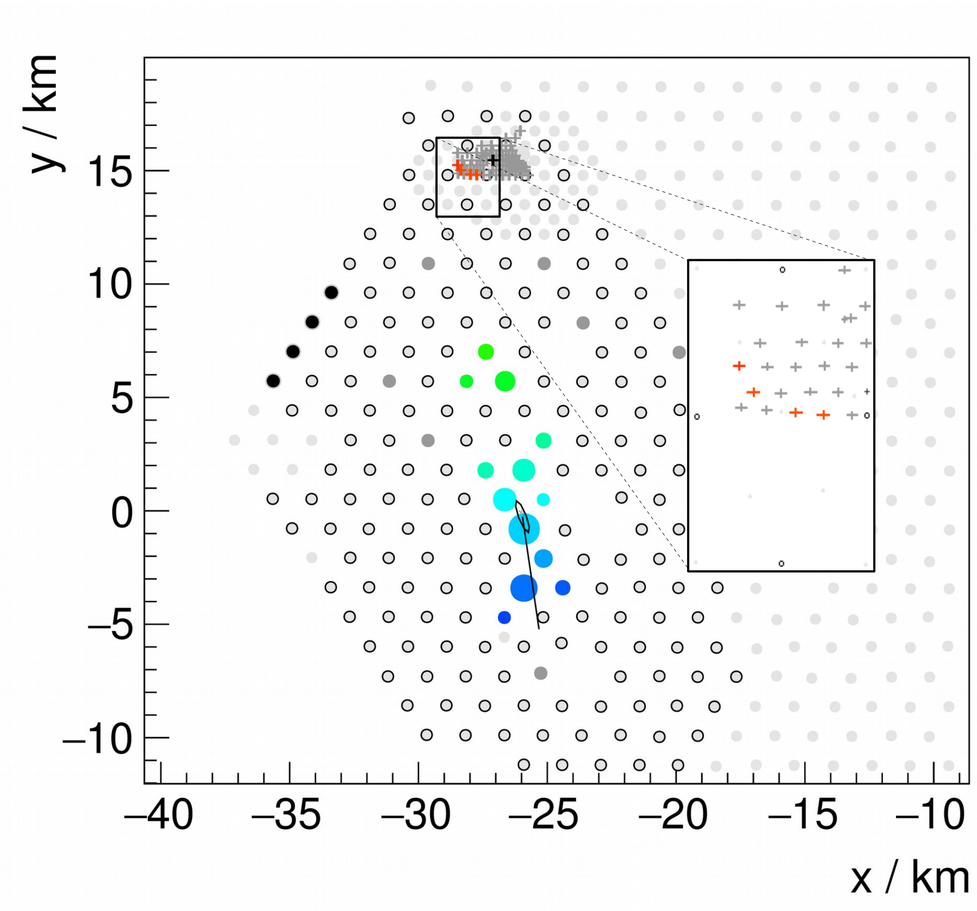
Horizontal air showers have large footprints in radio emission

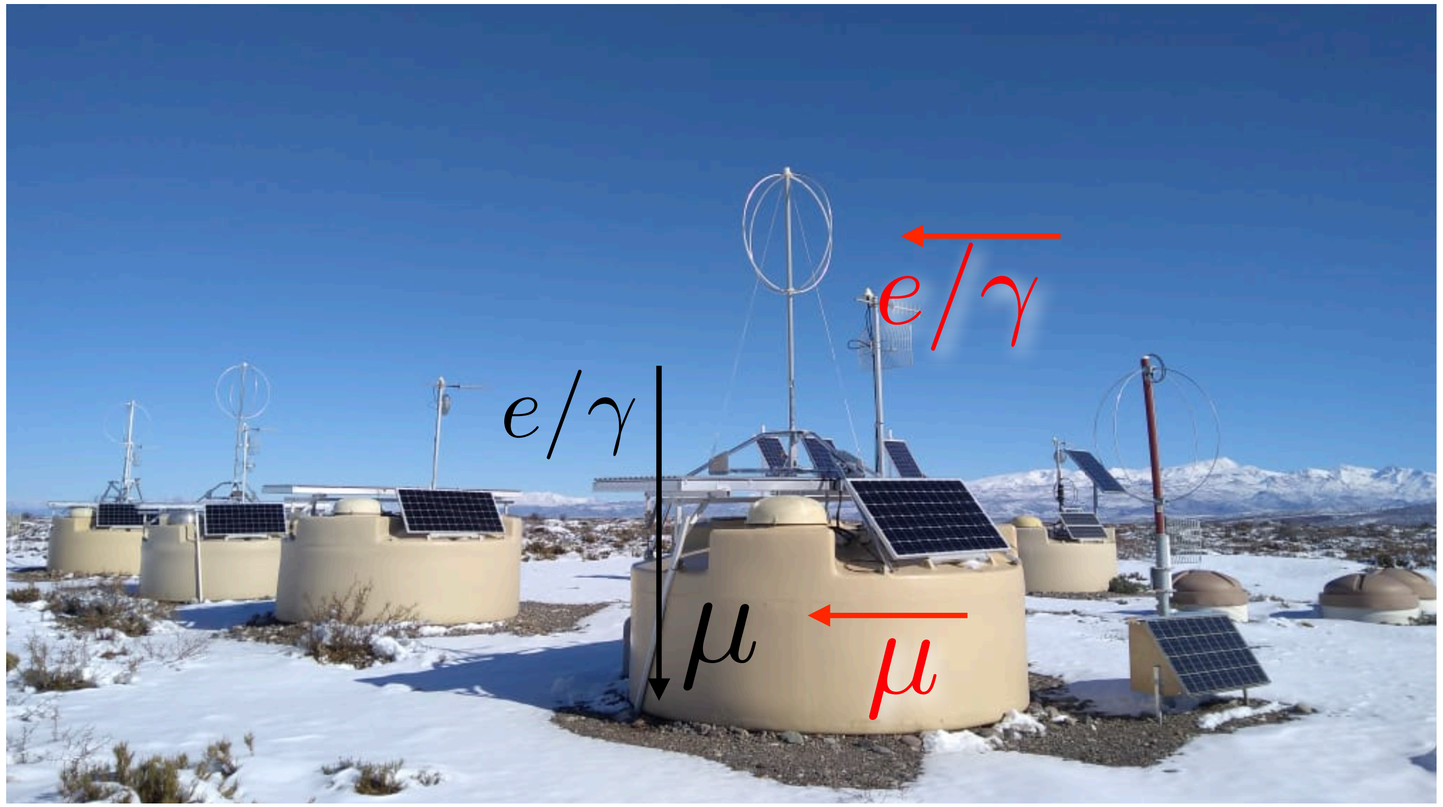




this is MEASURED with the *small* 17km² AERA

A. Aab et al., JCAP10(2018)026

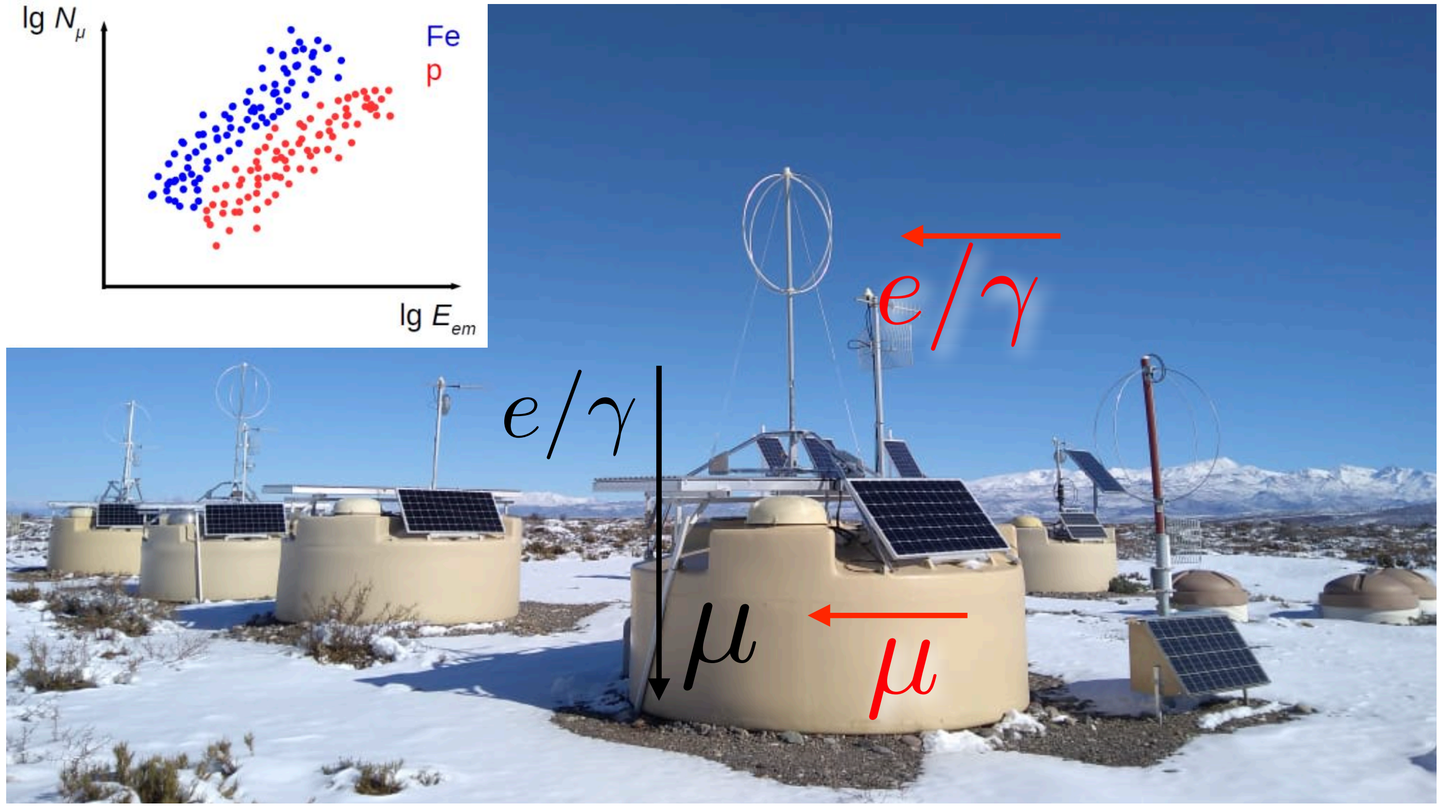
The Radio Detector of the Pierre Auger Observatory



Key science questions

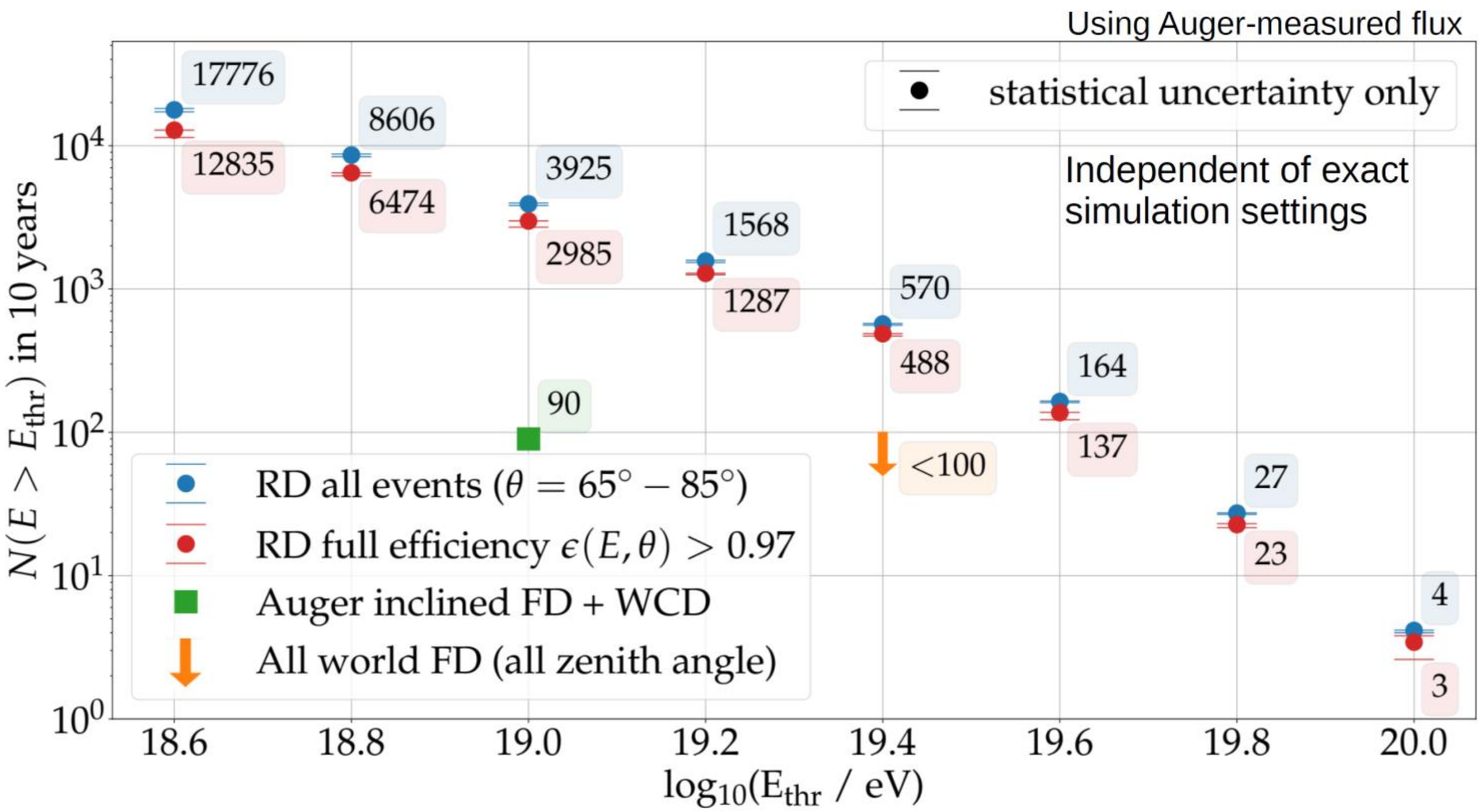
- What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?
- Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale?
- What is the fraction of protons, photons, and neutrinos in cosmic rays at the highest energies?

The Radio Detector of the Pierre Auger Observatory



- dual polarized radio antenna (30-80 MHz) on each SD station
- 1661 positions over 3000 km²
- mass sensitivity for inclined air showers
  radio: e/m
  WCD: muons
- complementary to SSD/WCD

Expected number of cosmic rays in 10 years



- **integral spectrum from folding flux with aperture**
- **expect ~4000 cosmic rays above 10^{19} eV**

T. Huege, UHECR symposium 2022

Expected mass composition sensitivity

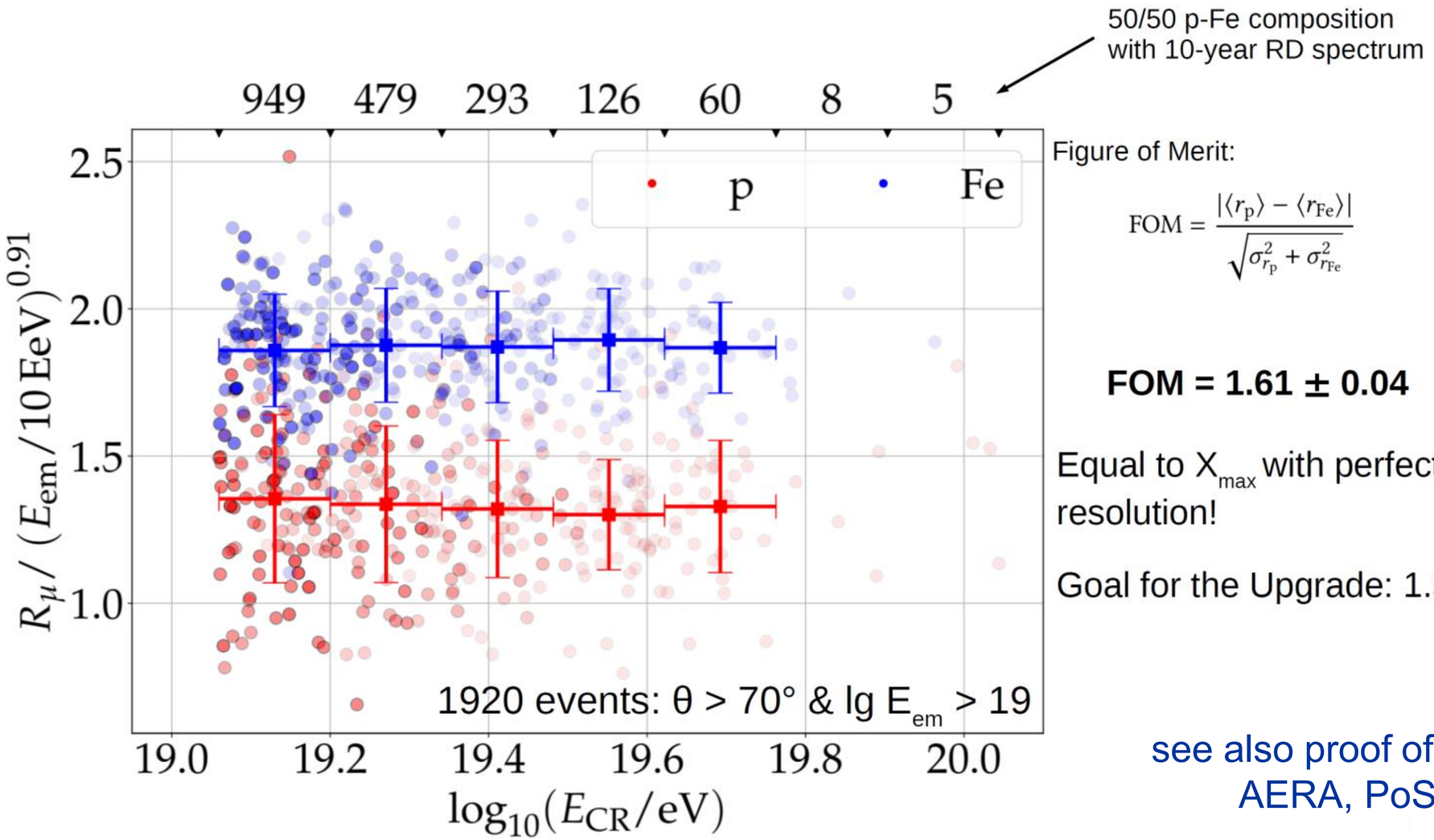


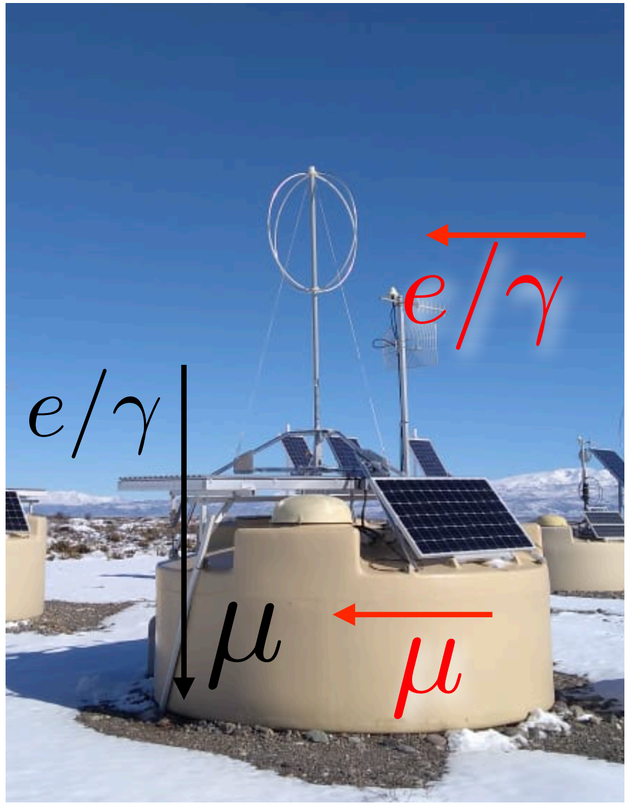
Figure of Merit:

$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma^2_{r_p} + \sigma^2_{r_{Fe}}}}$$

FOM = 1.61 ± 0.04

Equal to X_{max} with perfect resolution!

Goal for the Upgrade: 1.5



see also proof of principle study with AERA, PoS(ARENA2022)

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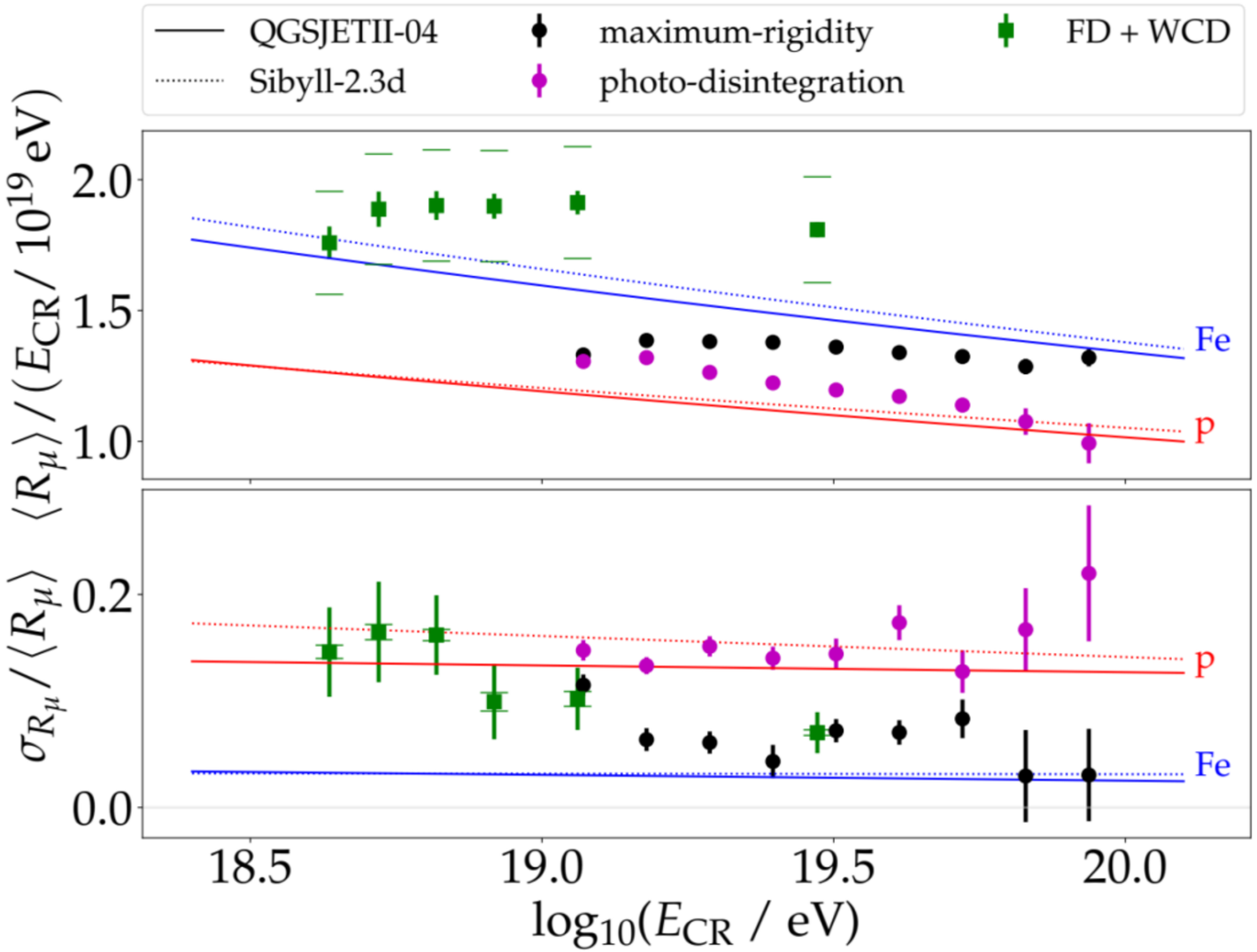
Precision measurement of muon number



- very precise measurement of muon number with WCD & RD at highest energies
- especially measurement of the variation of the muon number will be very powerful

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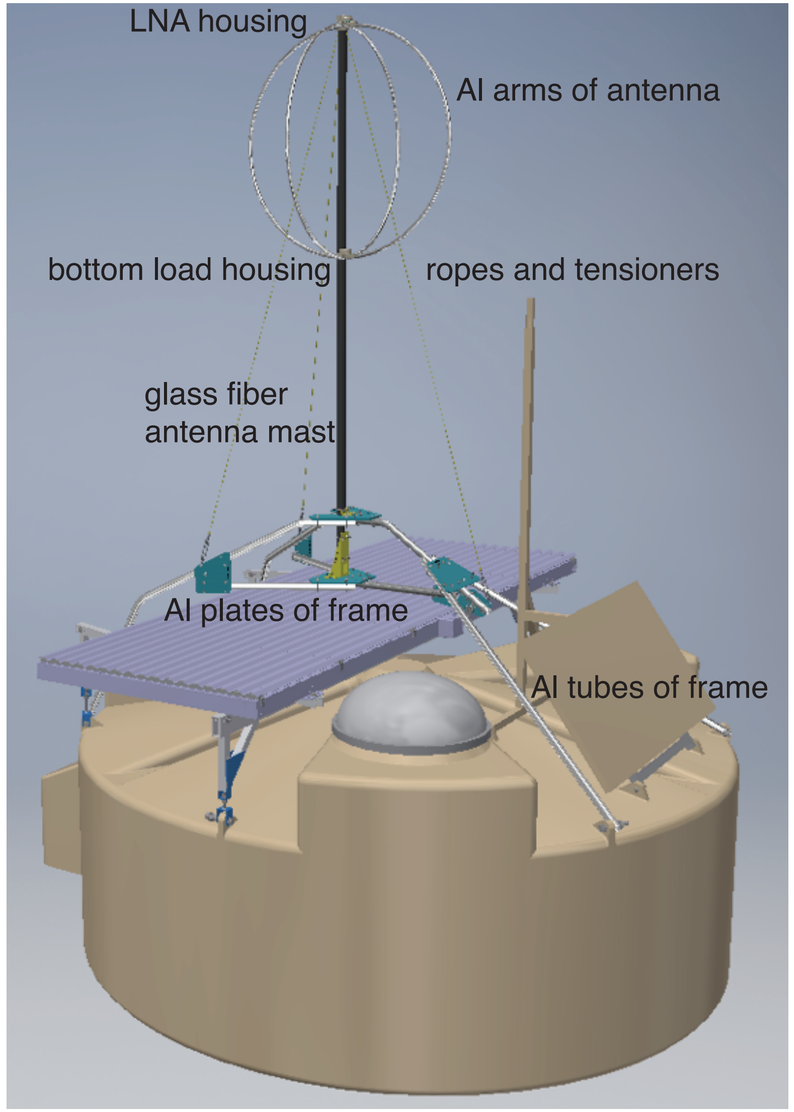
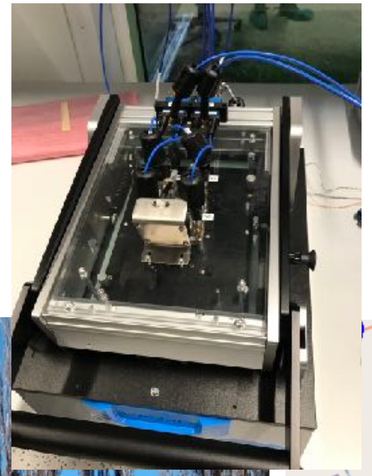
Serious logistics effort to get all components to the Observatory

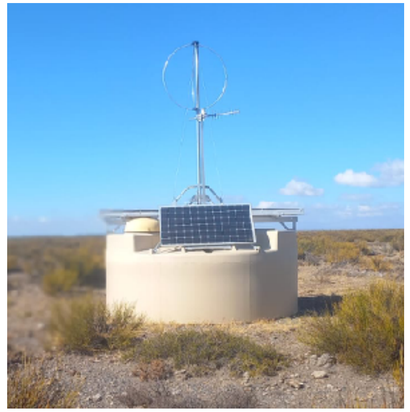
- solar panels - 2000 units
- antenna arms - 6800 parts
- ropes (6 km) and tensioners for the mast
- Al tubes for frame - 13600 parts
- Al plates and antenna foot - 8500 parts
- small parts, u-bolts, nuts, screws, … ~400000 pieces
- housings for digitizers - 2000
- pigtail cables for the LNA - 4000
- housings for LNAs and bottom loads - 12000 parts
- glass fiber antenna masts - 1700
- ferrites - 8500
- mounting brackets for solar panels - 3400 pieces
- L-ground bracket inside the dome - 1700 pieces
- bottom load PCBs - 2000 pieces
- LNAs - 2000 units
- signal cables from LNA to digitizer - 10200 cables
- digital cable from digitizers to UUB - 1700 cables
- fixtures to assemble ferrites - 24 units
- digitizers - 2000 units

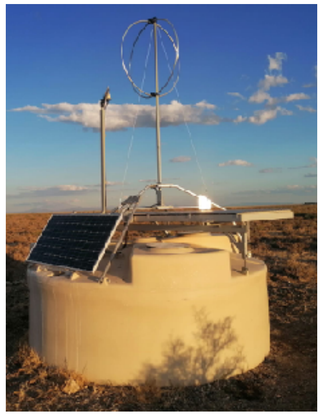


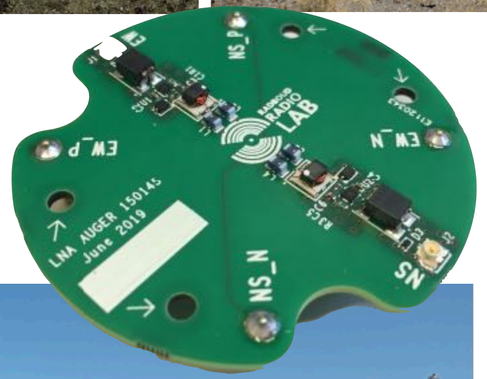
—> 6 sea containers, 75 m³ each & several (~5-10) air freight cargos

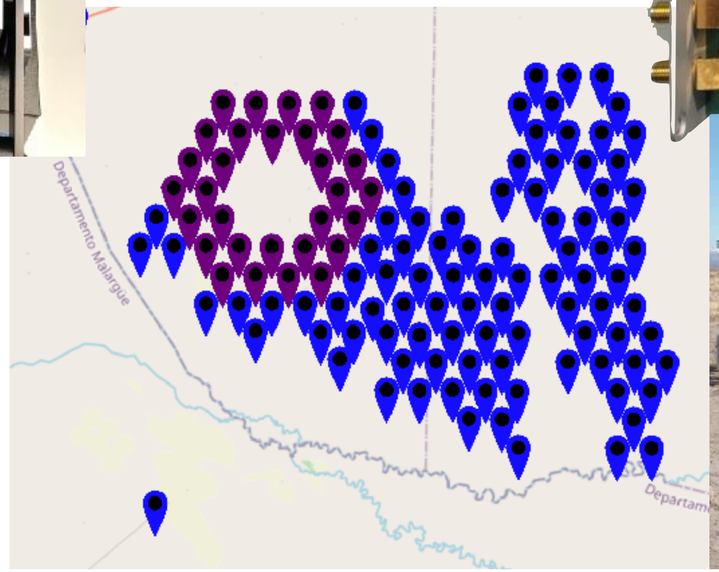
Roll out in field ongoing







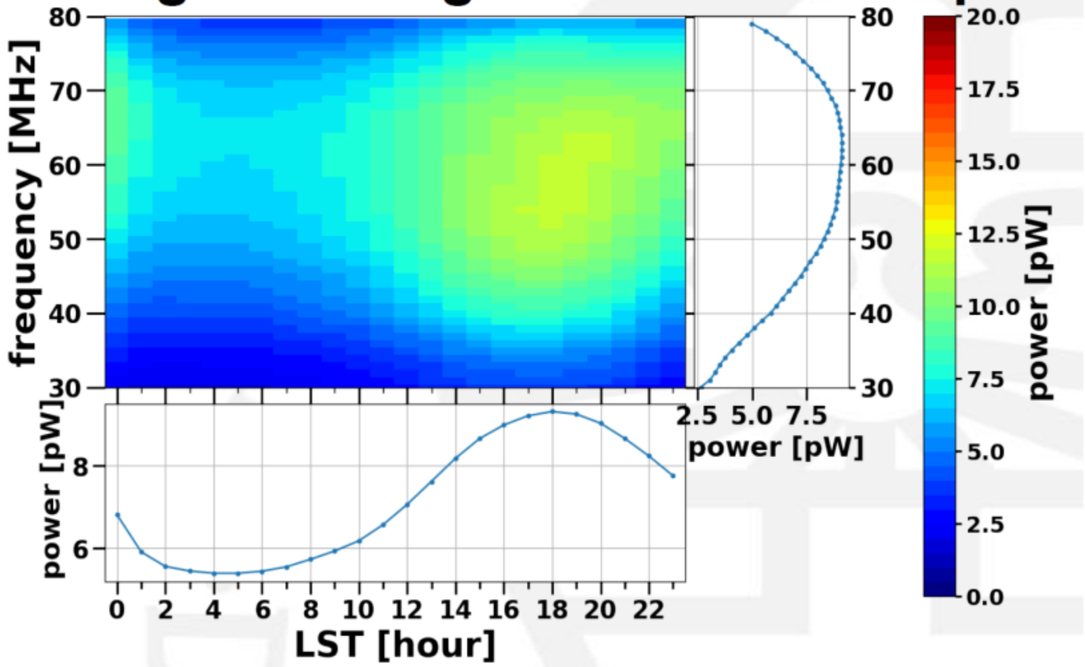




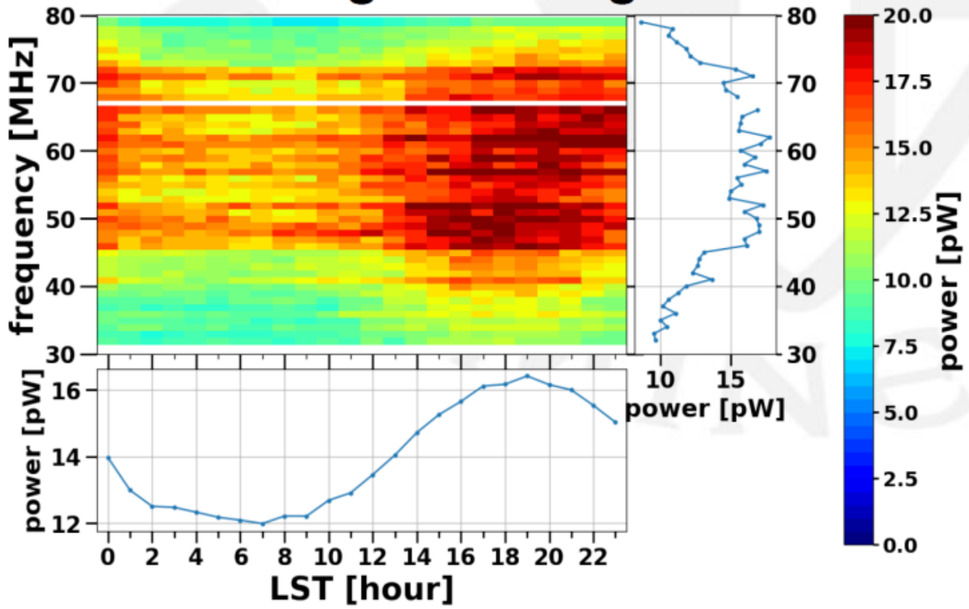
aim to complete RD in early 2024

Calibration with Galactic signal

Simulated galactic signal in the EW loop



Measured noise & galactic signal in the EW loop

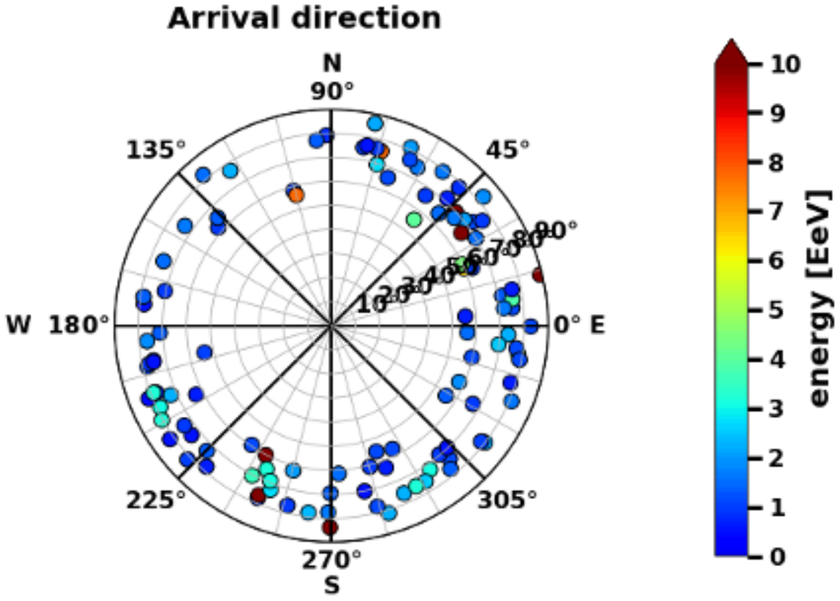


- **EW calibration constant: 1.03 ± 9.6% ± 2%**
- **NS calibration constant: 0.96 ± 9.7% ± 2%**
- **<u>Uncertainty caused by the Antenna model: max 1.5%</u>**

T. Fodran, ICRC 2022 T. Fodran, ARENA 2022

Air showers measured with engineering array

Nice 3-fold event above lg(18.4/eV)



Event 67742721 :-)
Time (UTC): 2022/4/19 18:14:47
Time (GPS): 1334427305 s 414520000 ns
Trigger: 4C1; 6T5 T5Has
Stations: 18 (Acc: 3, Bad: 41)

Global reconstruction (LDF + axis) (5)
E = (7.74 ± 1.10) × 10^{18} eV
(θ, ϕ) = (75.4 ± 0.1, 74.1 ± 0.1) deg

(x,y) = (-19.10 ± 0.10, 9.82 ± 0.27) km
N19 = 1.4 ± 0.2
radius = 46.75 ± 0.27 km

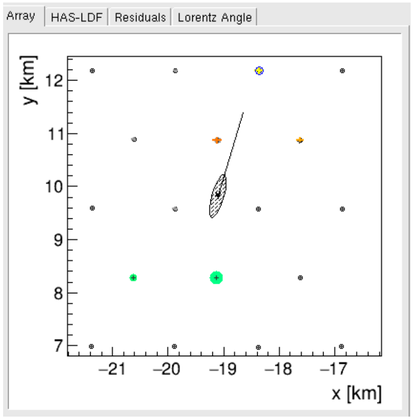
Monitoring
average stations age: 15.7 yr
T = 6.0°C; T (day) = 6.0°C

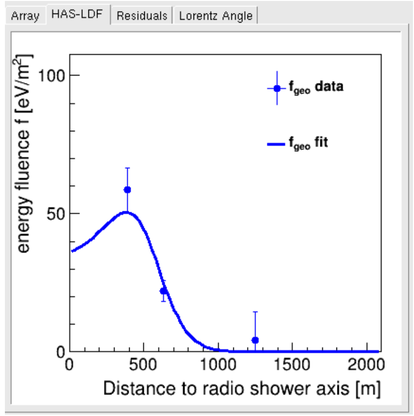
Event Info | MC Info | HAS LDF Info

Run: 0, Event: 67742721
GPS Time 1334427305 s 414520000 ns
UTC Date: 2022/04/19 - 18:14:47
Signal stations: 3 (3 with pulse)

Wavefront: (sphere)
(θ, ϕ) = (76.49 ± 3.3, 74.08 ± 10.49) deg
geomagnetic angle α = 114.1°
χ^2 / ndf = (< 0.01) / 1
radius = 30 ± 334 km

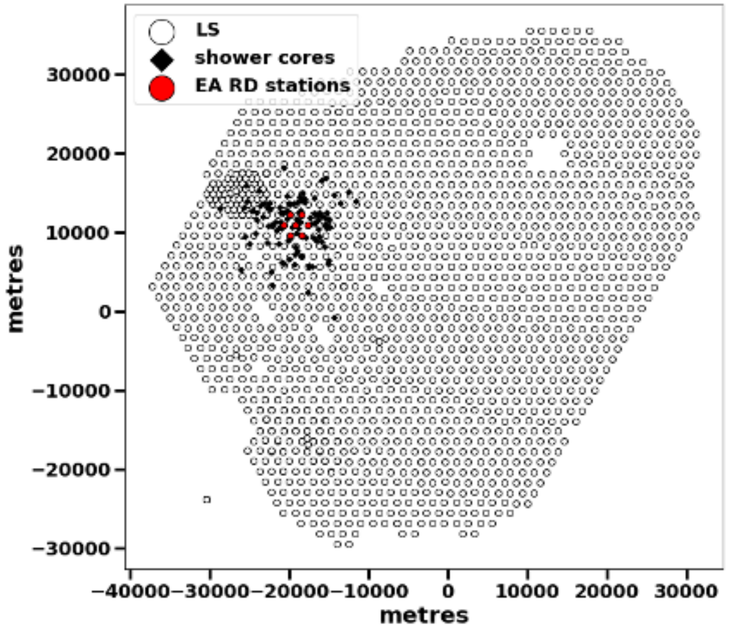
LDF: (HAS)
Emag energy = (3.96 ± 0.43) × 10^{18} eV
Core (x, y) = (-19.10, 9.82) km

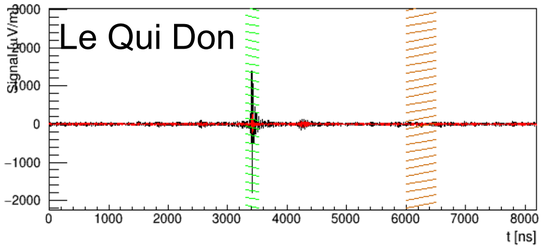


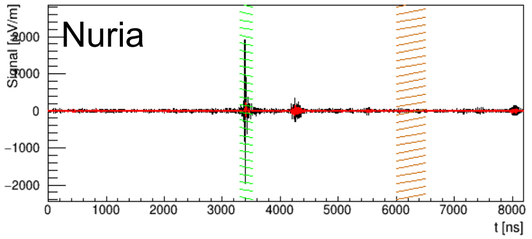


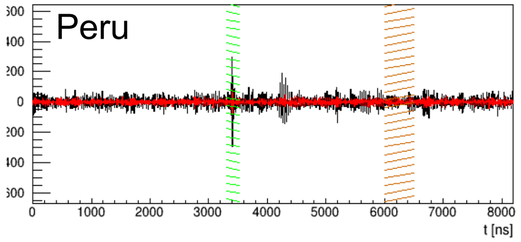
Station List | Options

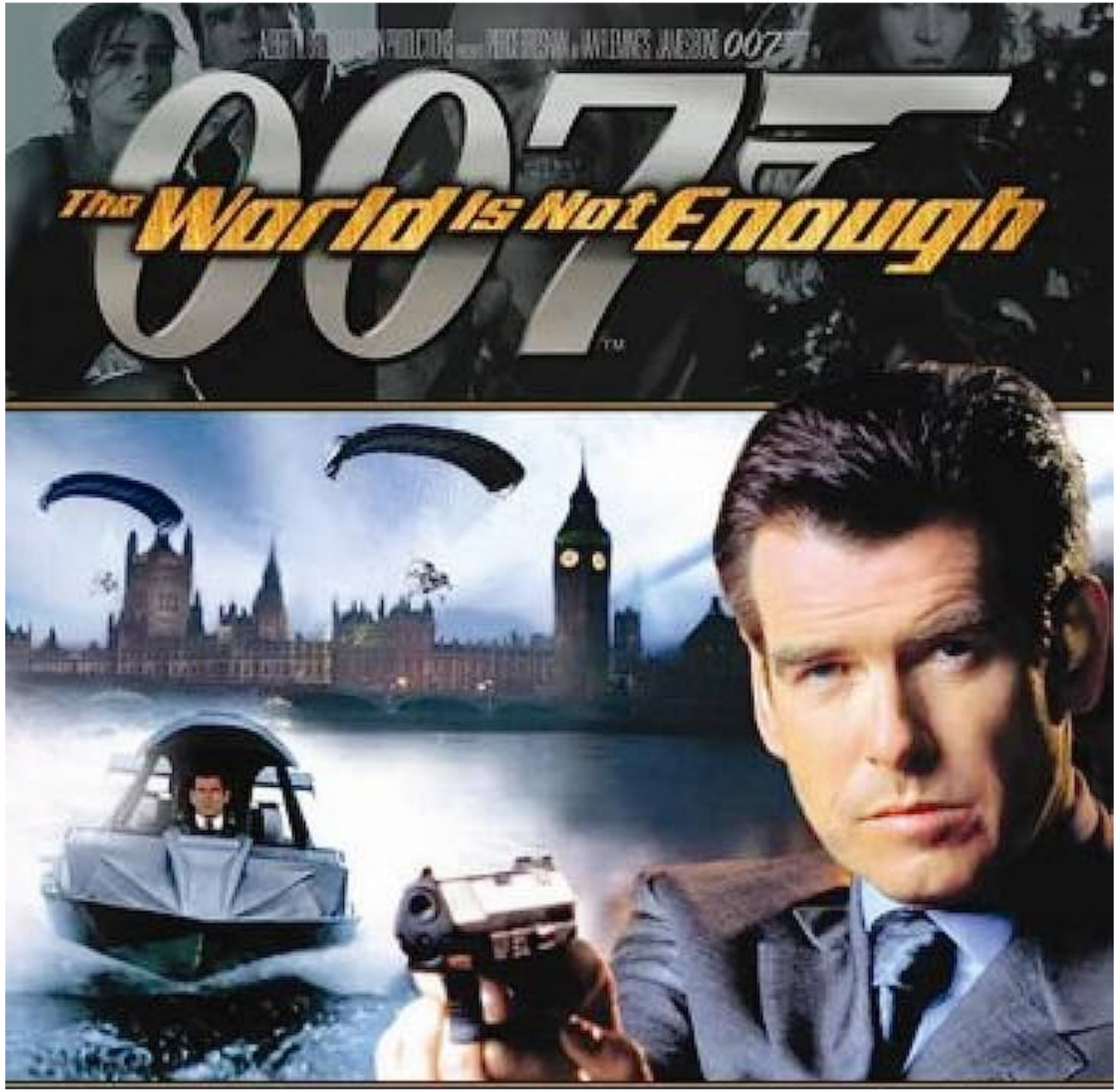
Le Qui Don: fluence = 2397.0 +/- 272.5 eV/m^2, SNR = 3798.2, d = 583 m
Nuria Jr.: fluence = 2274.0 +/- 258.9 eV/m^2, SNR = 3418.4, d = 375 m
Peru: fluence = 120.8 +/- 19.1 eV/m^2, SNR = 134.6, d = 1196 m
Granada: fluence = -0.5 +/- 7.3 eV/m^2, SNR = 2.2, d = 1749 m
Ruca Malen: fluence = 0.4 +/- 3.2 eV/m^2, SNR = 1.8, d = 677 m
Jaco: fluence = -0.3 +/- 4.3 eV/m^2, SNR = 1.8, d = 1448 m





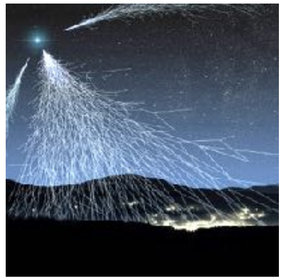






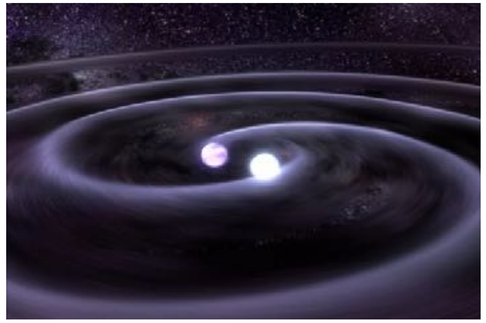
beyond 3000 km²?

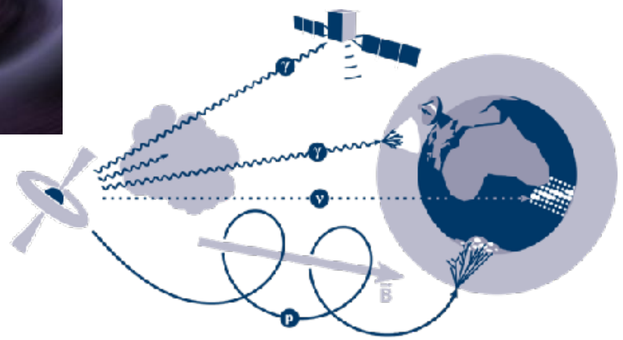
GCOS - The Global Cosmic Ray Observatory

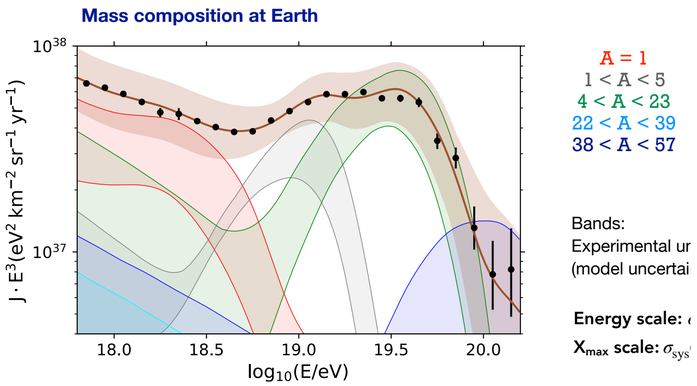


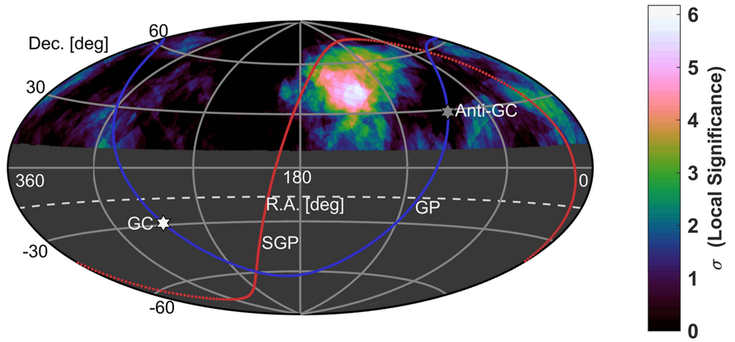
Multi-messenger astroparticle physics beyond 2030

protons, nuclei, gamma rays, neutrinos, (gravitational waves)







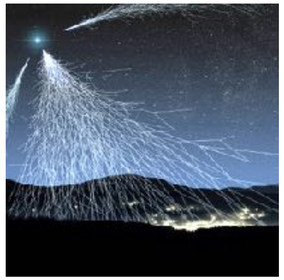


GCOS homepage: http://particle.astro.ru.nl/GCOS

3rd GCOS workshop, Brussels, June 2023

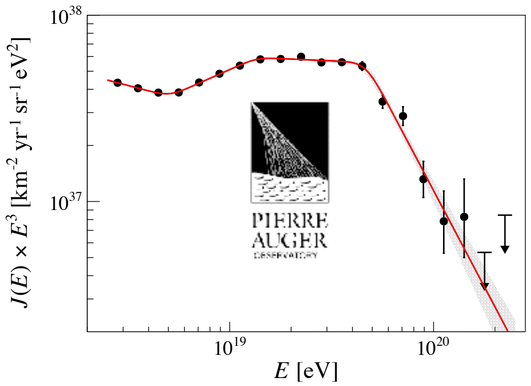
Multi-messenger astroparticle physics beyond 2030

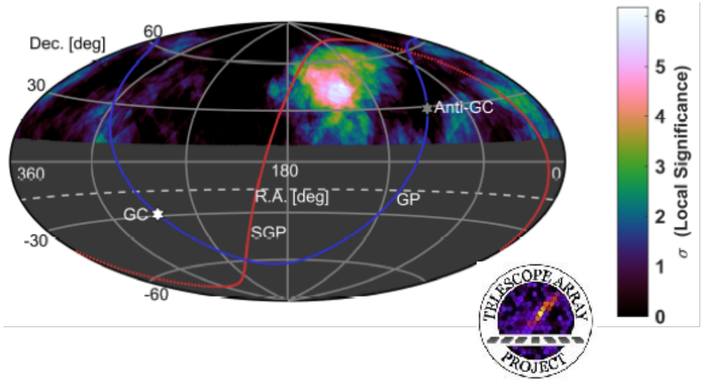
protons, nuclei, gamma rays, neutrinos, (gravitational waves)

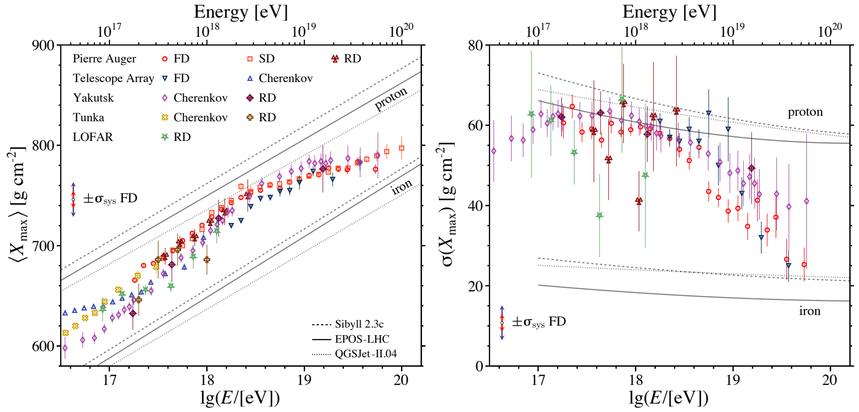


The road ahead as outlined in a Snowmass white paper:

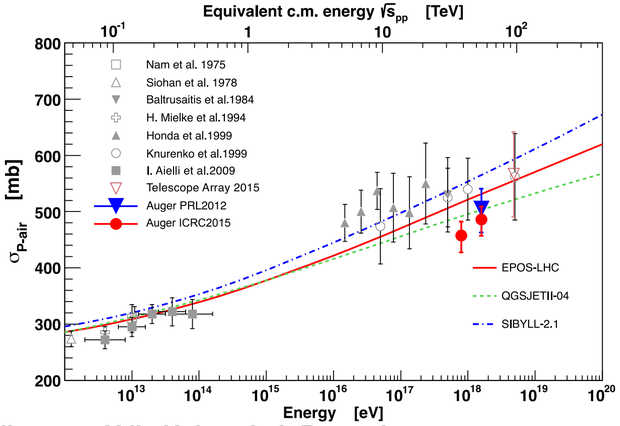
- **Twenty years of UHECR discoveries**

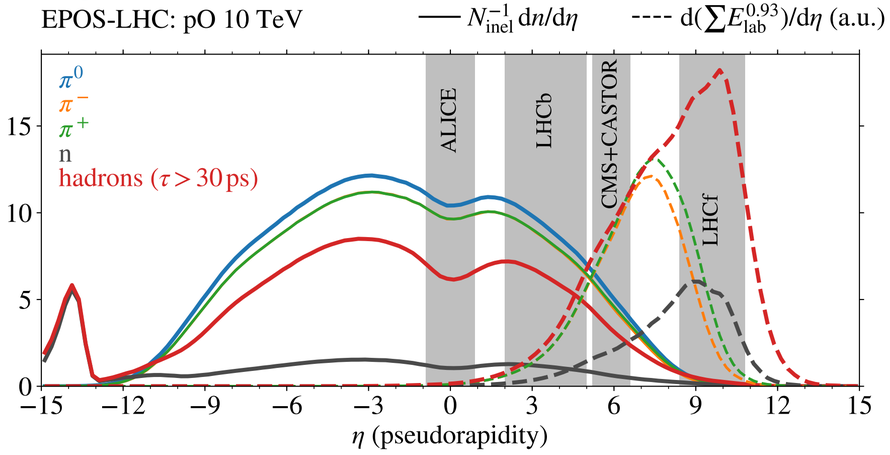


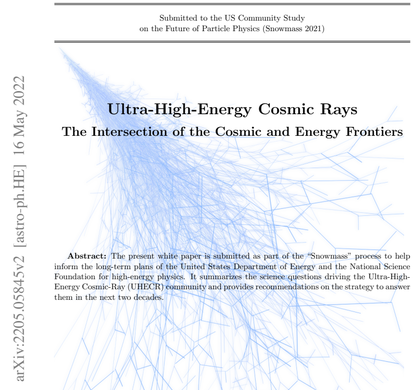




- **Particle physics at the cosmic frontier**







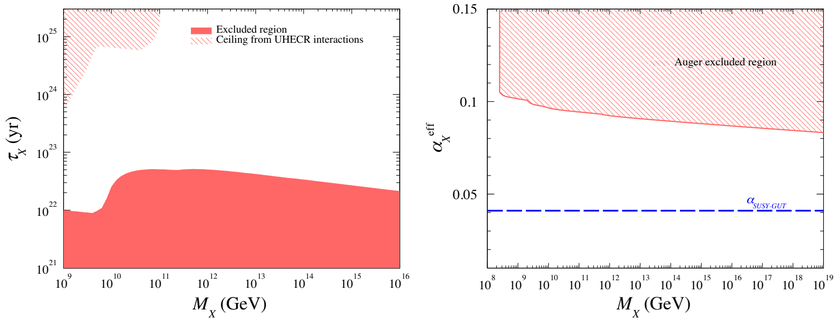
arXiv: 2205.05845

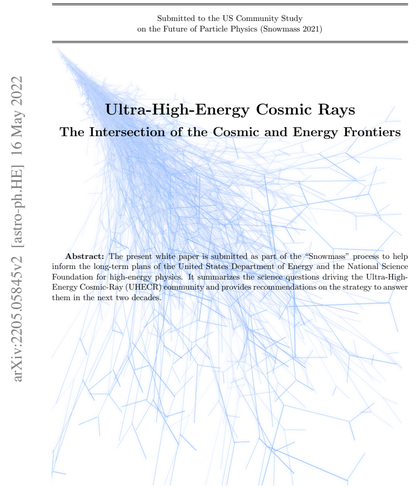
Multi-messenger astroparticle physics beyond 2030

protons, nuclei, gamma rays, neutrinos, (gravitational waves)

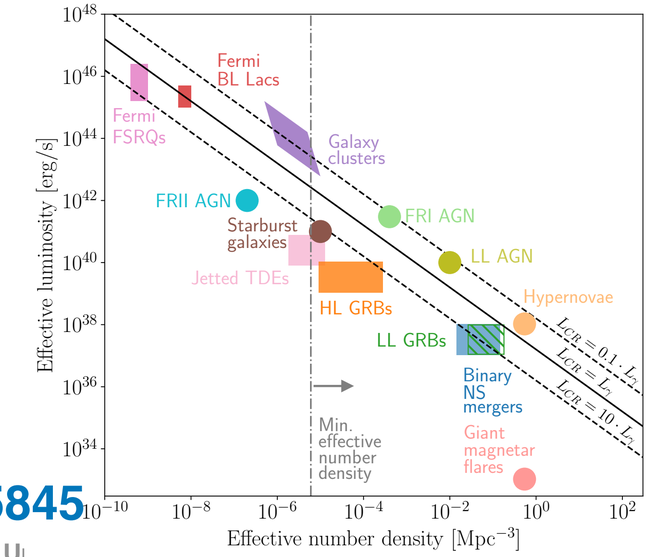
The road ahead as outlined in a Snowmass white paper:

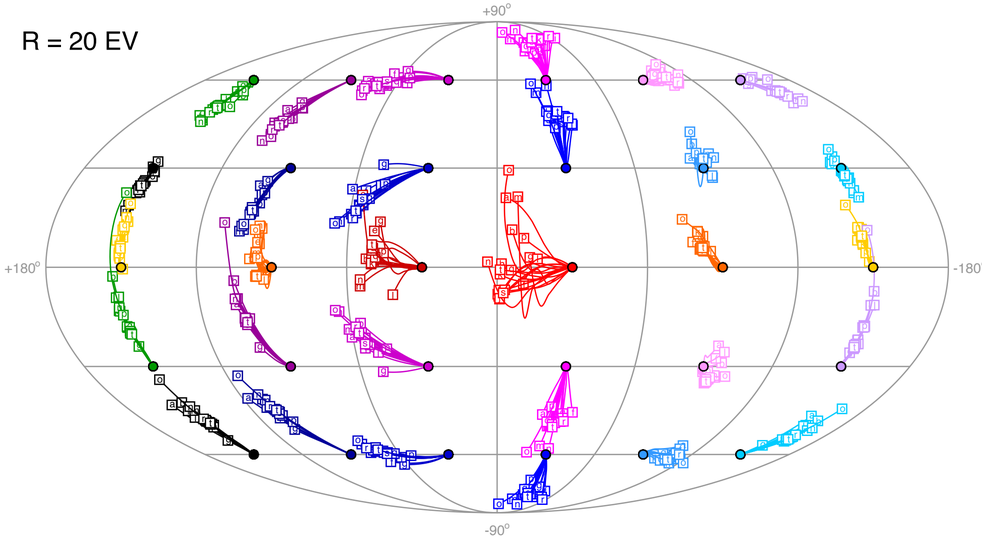
- **A sensitive probe to BSM physics and dark matter**

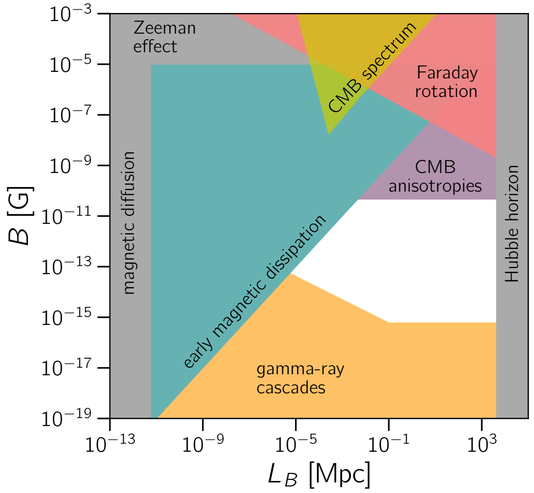




- **Astrophysics at the energy frontier**







arXiv: 2205.05845

Multi-messenger astroparticle physics beyond 2030

protons, nuclei, gamma rays, neutrinos, (gravitational waves)

The road ahead as outlined in a Snowmass white paper:

- **Upgrades of the current giant arrays**

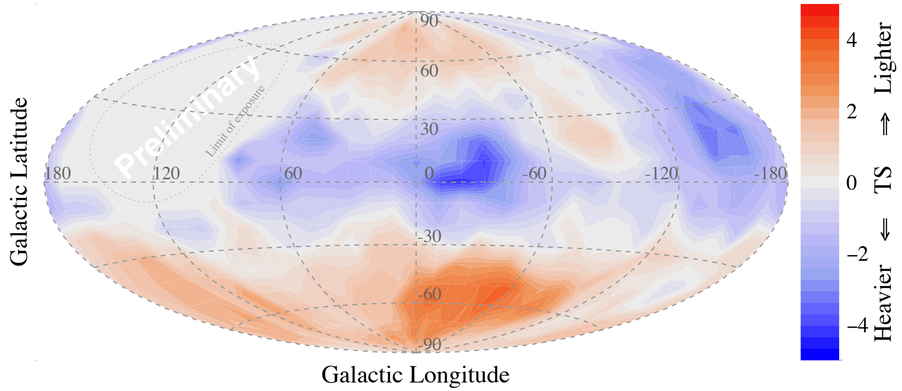
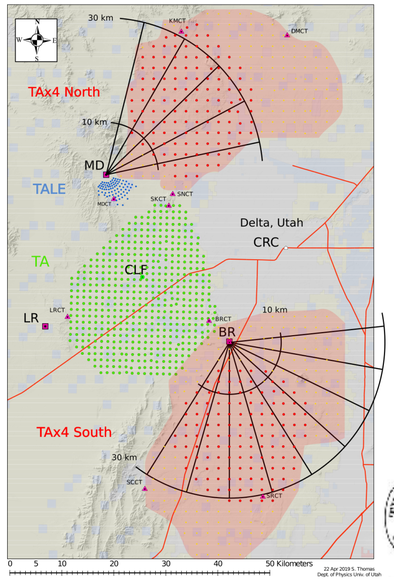
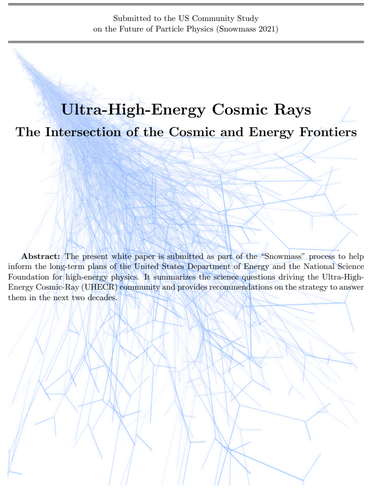
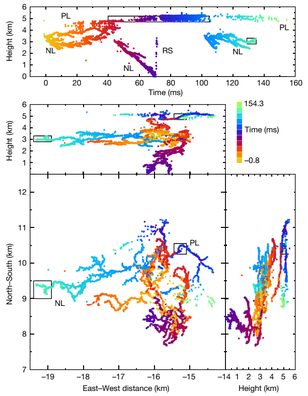


Figure 5.14: Map showing the relative cosmic-ray composition detected by the Pierre Auger Observatory above $10^{18.7}$ eV with the FD, in Galactic coordinates. From Ref. [54].





- **Interdisciplinary science**



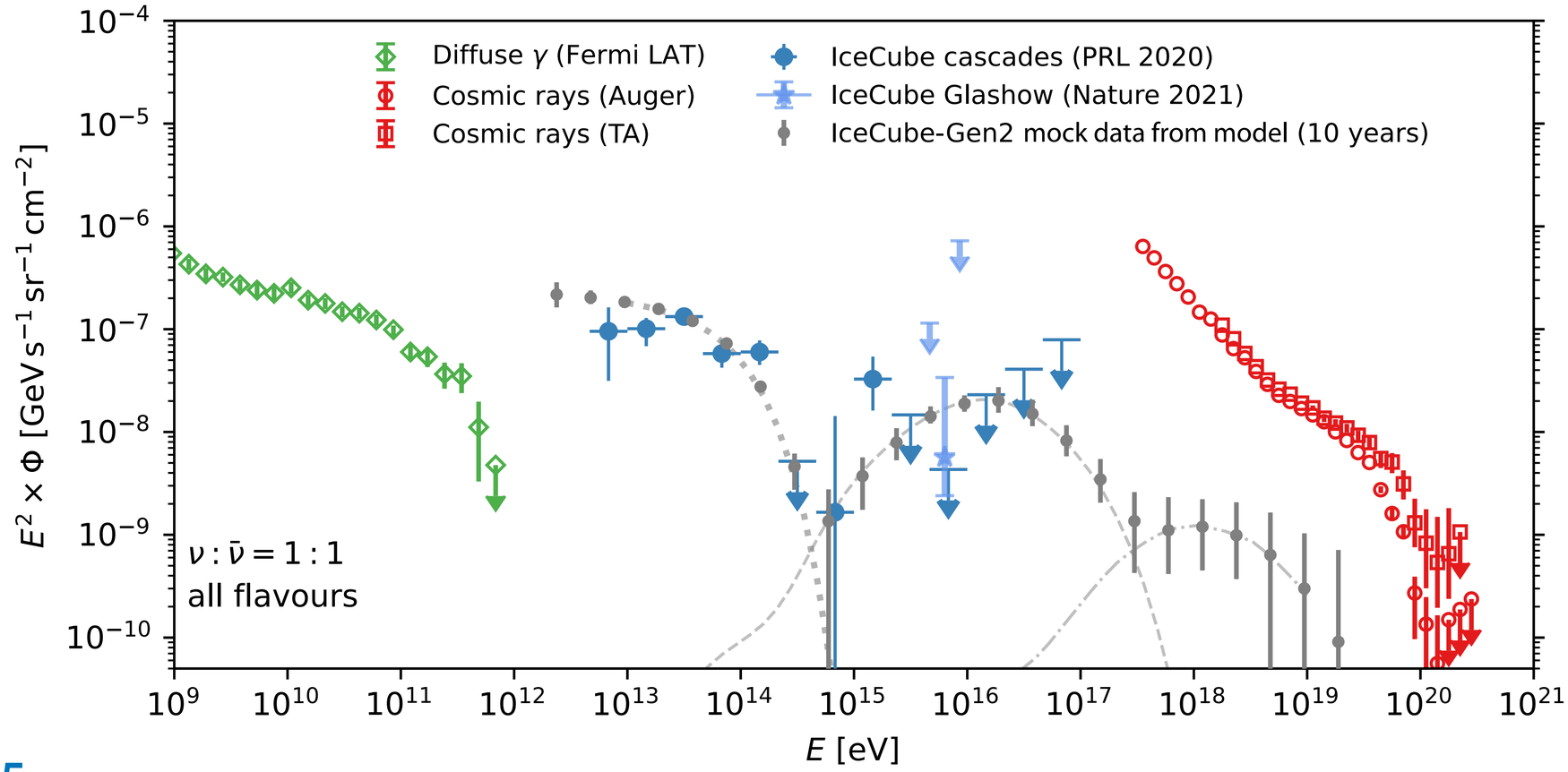
arXiv: 2205.05845

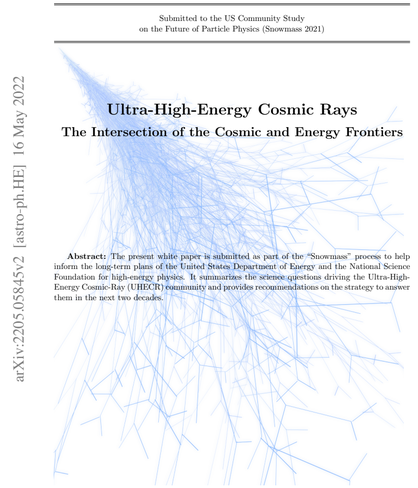
Multi-messenger astroparticle physics beyond 2030

protons, nuclei, gamma rays, neutrinos, (gravitational waves)

The road ahead as outlined in a Snowmass white paper:

- **Multi-messenger astroparticle physics**



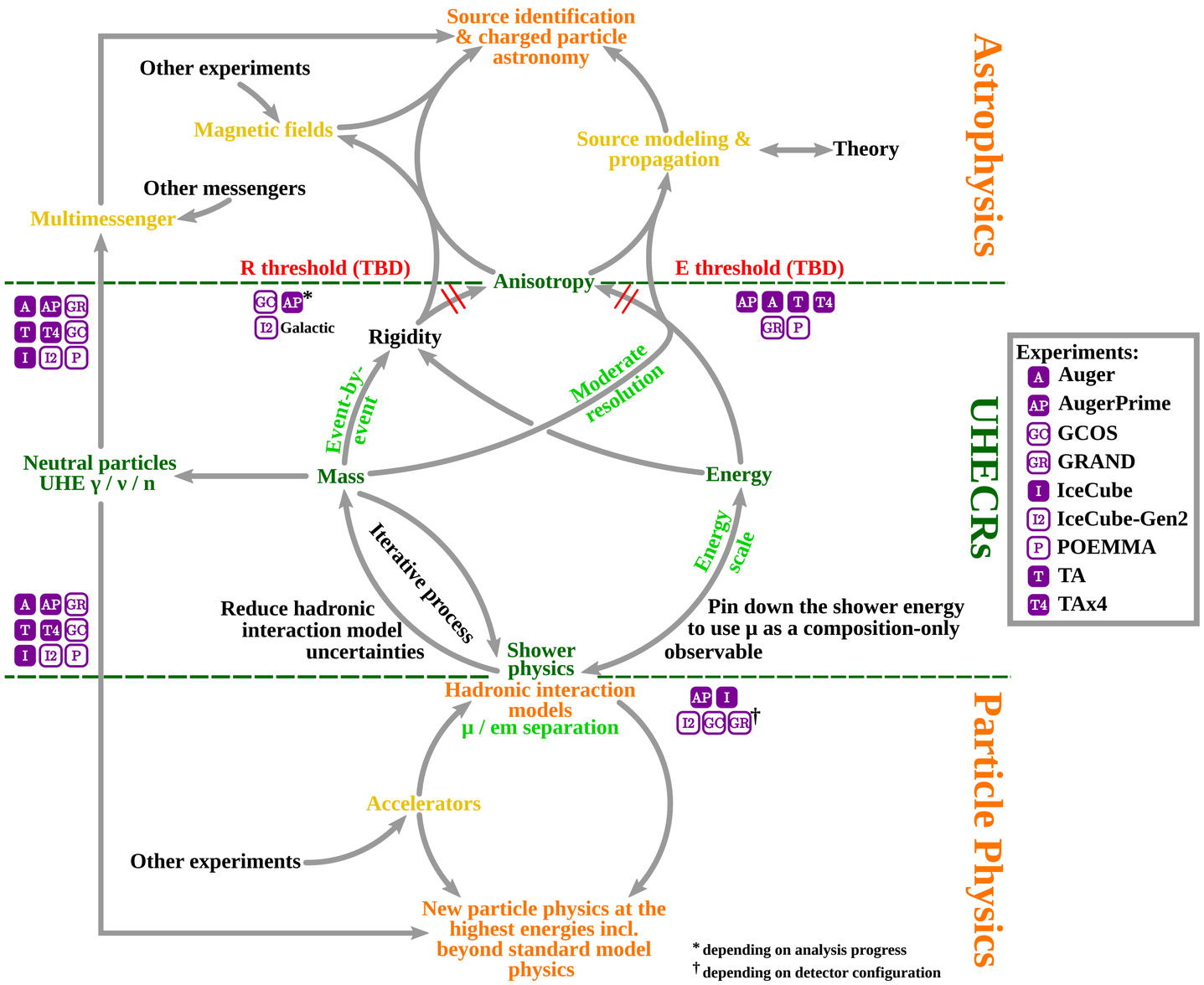

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

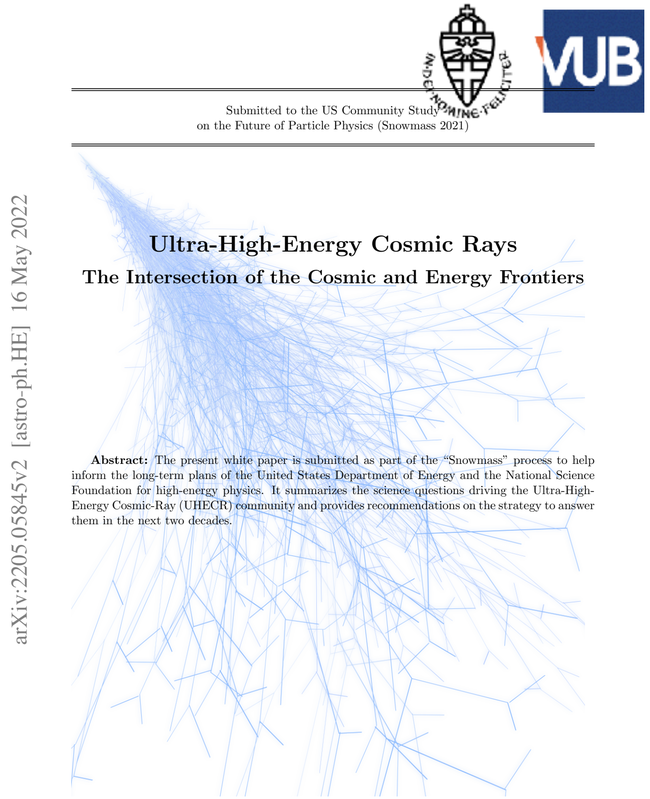
Ultra-High-Energy Cosmic Rays
The Intersection of the Cosmic and Energy Frontiers

Abstract: The present white paper is submitted as part of the "Snowmass" process to help inform the long-term plans of the United States Department of Energy and the National Science Foundation for high-energy physics. It summarizes the science questions driving the Ultra-High-Energy Cosmic-Ray (UHECR) community and provides recommendations on the strategy to answer them in the next two decades.

arXiv:2205.05845v2 [astro-ph.HE] 16 May 2022

arXiv: 2205.05845

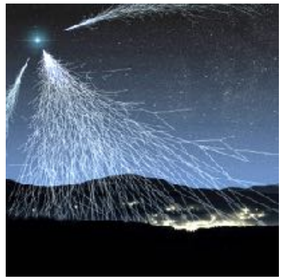




arXiv: 2205.05845

Figure 1: Diagram summarizing the strong connections of UHECRs with particle physics and astrophysics, the fundamental objectives of the field (in orange) for the next two decades, and the complementarity of current and next-generation experiments in addressing them.

GCOS - The Global Cosmic Ray Observatory



UHECRs observatory covering more than 60,000 km^2 (40,000 -80,000 km^2)

With $60,000$ km^2 we can reach the integrated Auger 2030-exposure in 1 years
AugerPrime expected exposure in 6 months

Targeting very good quality events for energies $\geq$ 30 EeV (5-fold) and full efficiency at 10 EeV (3-fold events)

Resolutions per event: energy better than 10%, muon resolution better than 10%, X_{max} better than 30 g/cm^2, and angular resolution better than 1°

Full sky coverage with sites in both hemispheres and surrounded by mountains

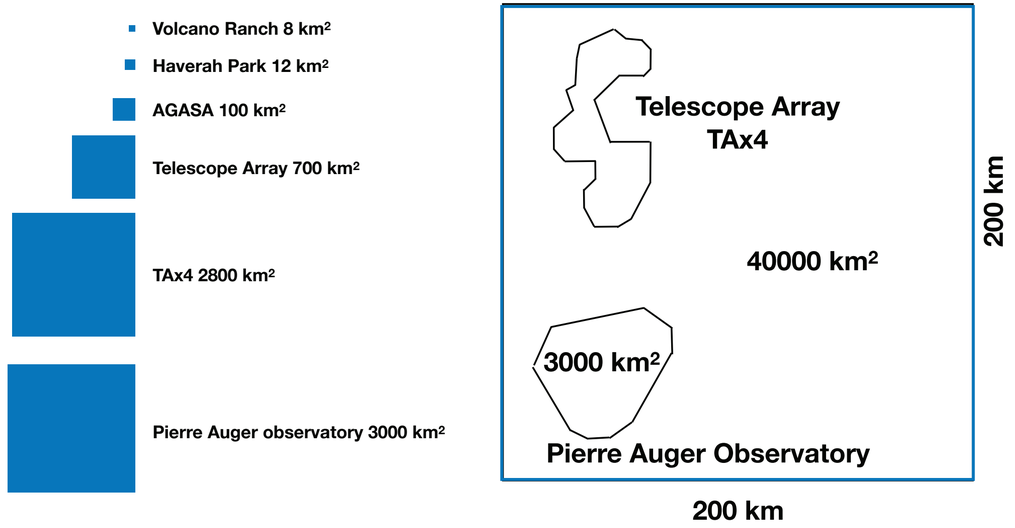
I. Maris, UHECR symposium 2022

How to reach the physics case with a ground array?

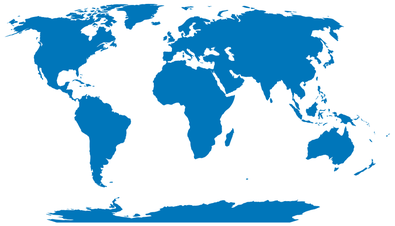
Acceptance/exposure?
What statistics will we need?

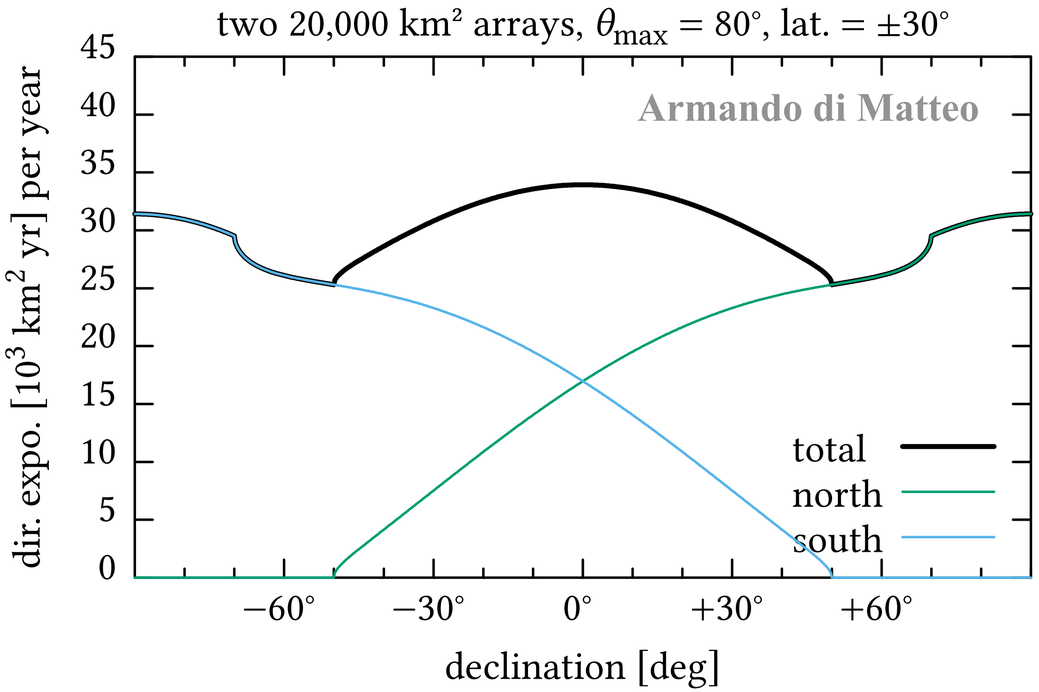
E>$10^{19.5}$ eV ~100 /yr (1000 km² and 2π)
- **~5% light particles**
- **~50% efficiency**
- **40000 km²**

—> 1000 light particles/decade (E>$10^{19.5}$ eV)



Where: full sky coverage?
—> equator, several sites, …

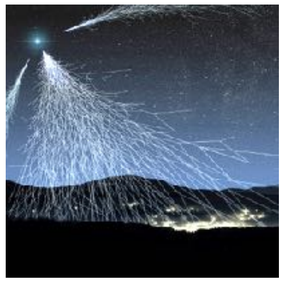


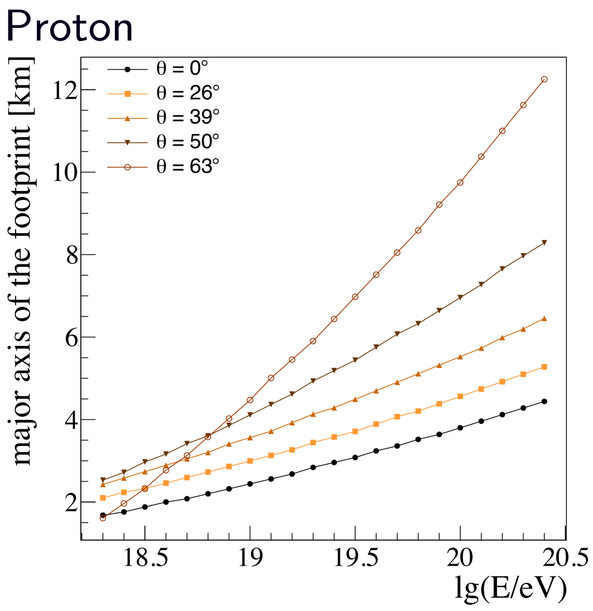


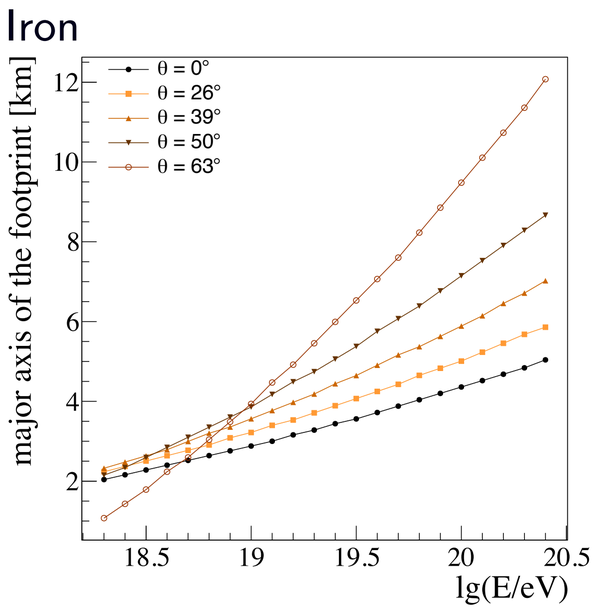
What is realistic in terms of area and number of detectors?

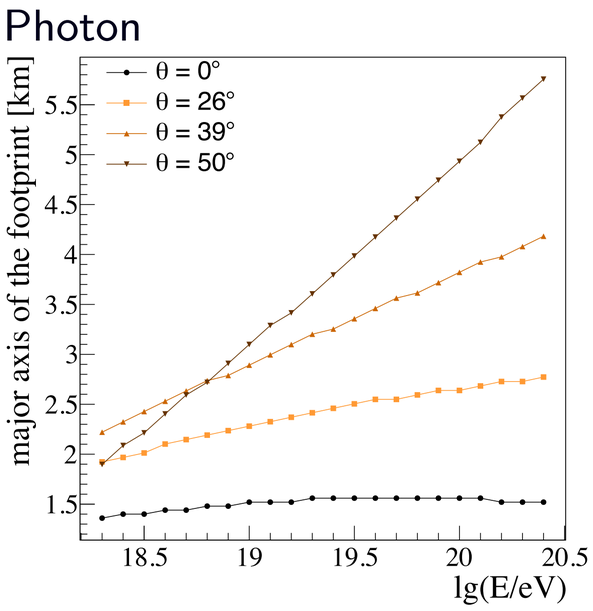
10x existing arrays? —> 40 000 - 60 000 km²
10x number of units? —> 15 000 - 22 000 detectors
2,0 - 2,5 km spacing

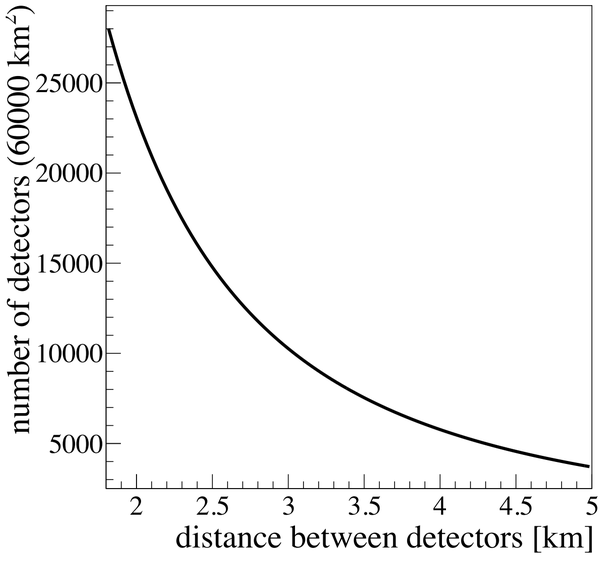
Spacing - How large is the air shower foot print on the ground?











Spacing between detectors cannot be larger than about 2-2.5 km to reach 100% efficiency at 10-30 EeV

On an hexagonal grid: 15k-22k detectors for 60000 km^2

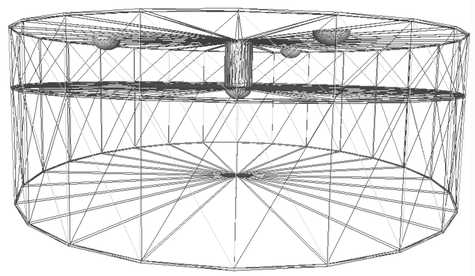
I. Maris, UHECR symposium 2022

12

Advanced water Cherenkov detectors

The idea: optical separation of a Water Cherenkov Tank

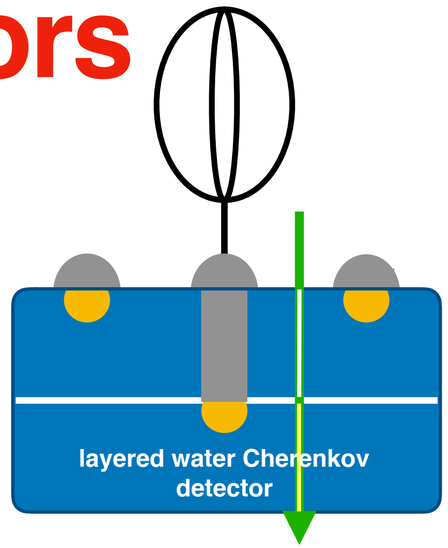
A water volume responds different to photons, $e^{\pm}$ and $\mu^{\pm}$

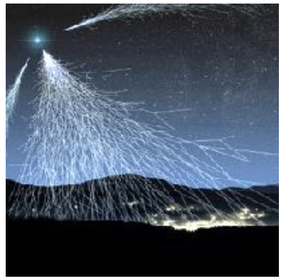


$$\begin{pmatrix} S_{\text{top}} \\ S_{\text{bot}} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix}$$

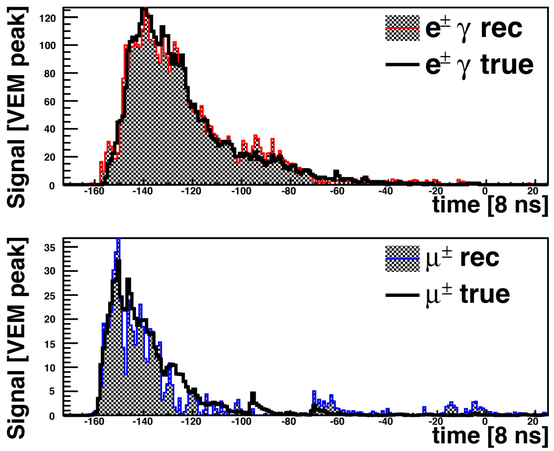
$$\begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix} = \mathcal{M}^{-1} \begin{pmatrix} S_{\text{top}} \\ S_{\text{bot}} \end{pmatrix}$$

2

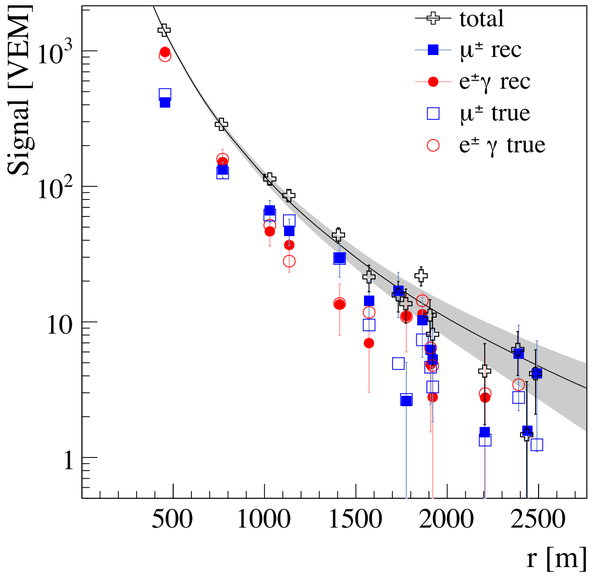




Not only total signal, but also time distributions



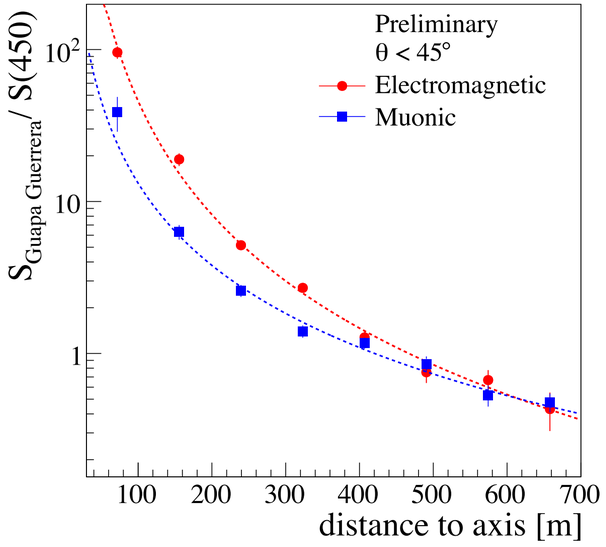
Based on Universality or DNN we can get $X_{\max}$



prototype measurements at Auger Observatory

Mean LDFs for the electromagnetic and muonic components

900 events ($E > 0.03\,\text{EeV}$, $\theta < 45°$)



5

13

Ioana Maris

Antoine Letessier-Selvon et al., Nucl. Instr. Meth. A 767 (2014) 41–49

Advanced WCD complemented by fluorescence and radio detectors

fluorescence light detection

GCOS Cyclops FD: Small elevation, large area, small pixels

e.g. MACHETE Design J. Cortina et al. APP (2016) 46

Nepomuk Otte PoS ICRC19

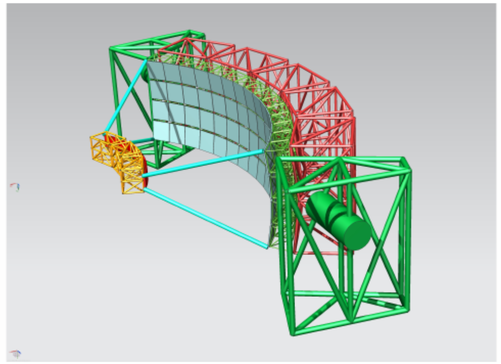


Figure 7: Proposed optics for *Trinity* based on the MACHETE optics. The primary mirror is composed of 68, 1 m^2 mirrors. the focal plane (red curved surface) is populated with 3,300 pixels each consisting of a solid non-imaging light concentrator coupled to an SiPM. The field of view covered by one telescope is $5° \times 60°$.

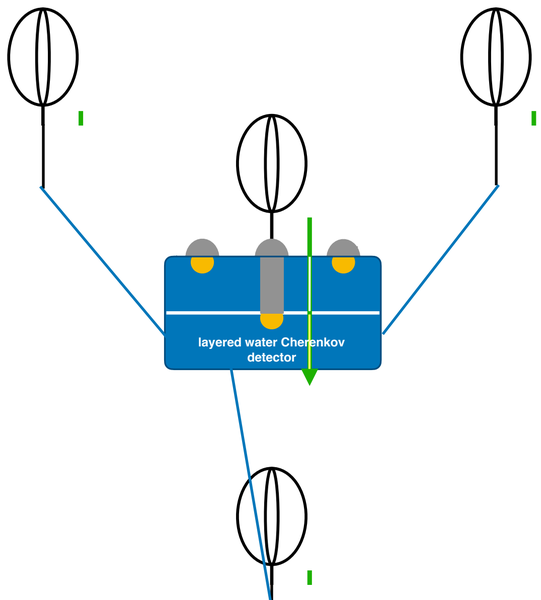
- 2 MACHETE rings $\rightarrow 360° \times 10°$ FoV
- cost: $\sim$ 10 M$ Trinity whitepaper arXiv:1907.08727
- $0.3°$ pixel, effective aperture 10 m^2
- $(S/N)_{\text{FD}} \propto \sqrt{A/\Omega_{\text{pix}}} \rightarrow (S/N)_{\text{Cyclops}}/(S/N)_{\text{Auger}} = \sqrt{10\ \text{m}^2/0.3°^2}\Big/\sqrt{3\ \text{m}^2/1.5°^2}$ = **9**

$\rightarrow$ optimization for GCOS needed & check dual use ν+UHECR

M. Unger

radio detection

- **large spacing of 2,0 - 2,5 km challenging for radio detection**
- **try to record sufficient information from one position**
  —> broad frequency range, see e.g. ARIANNA
- **have radio outriggers around SD position**



Radio detection of air showers with

AERA, Pierre Auger Radio Detector, GCOS

characterize cosmic rays:
-direction
-energy
-mass (particle type)
@~100% duty cycle

Global Cosmic Ray Observatory - GCOS
(60000 km²) 2035

Pierre Auger Radio Detector
(3000 km²) 2023

Auger Engineering Radio Array - AERA
(17 km²) 2010

LOFAR Cosmic Rays
(5 km²) 2007

LOPES
(0,5 km²) 2001

- **significant progress over last two decades**
- **enables us to look optimistically towards the next decade and beyond**