

# Ultra-High-Energy Cosmic Rays

**Particle interactions  
at the highest energy  
ever seen**

**?**

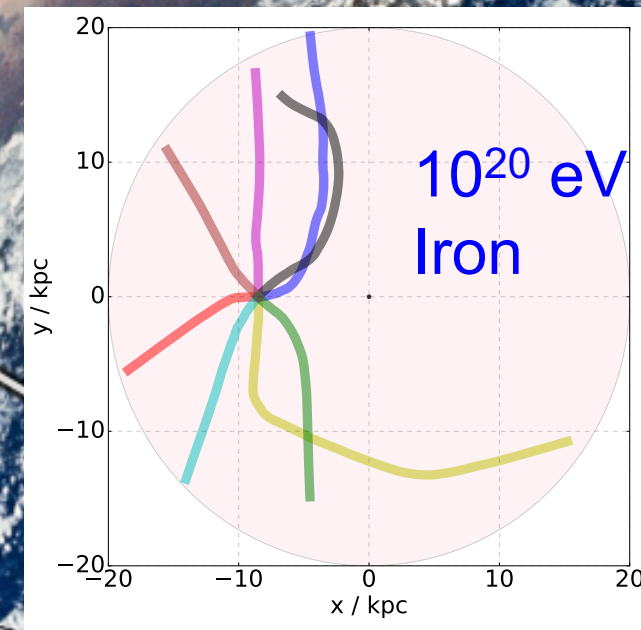
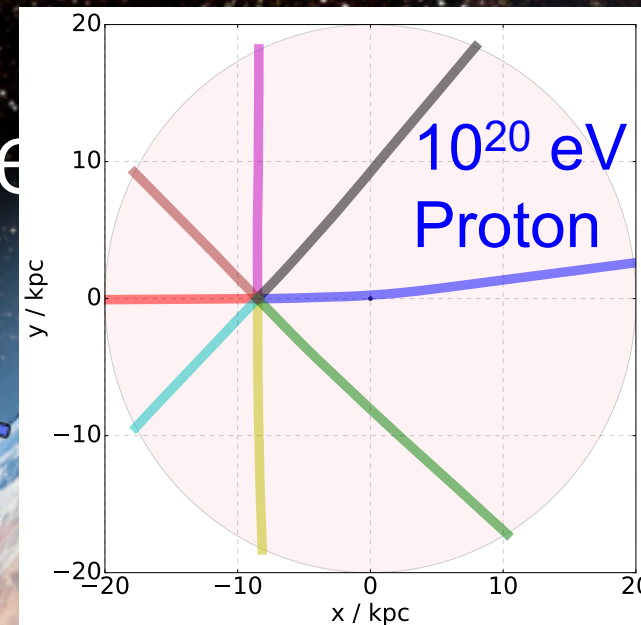
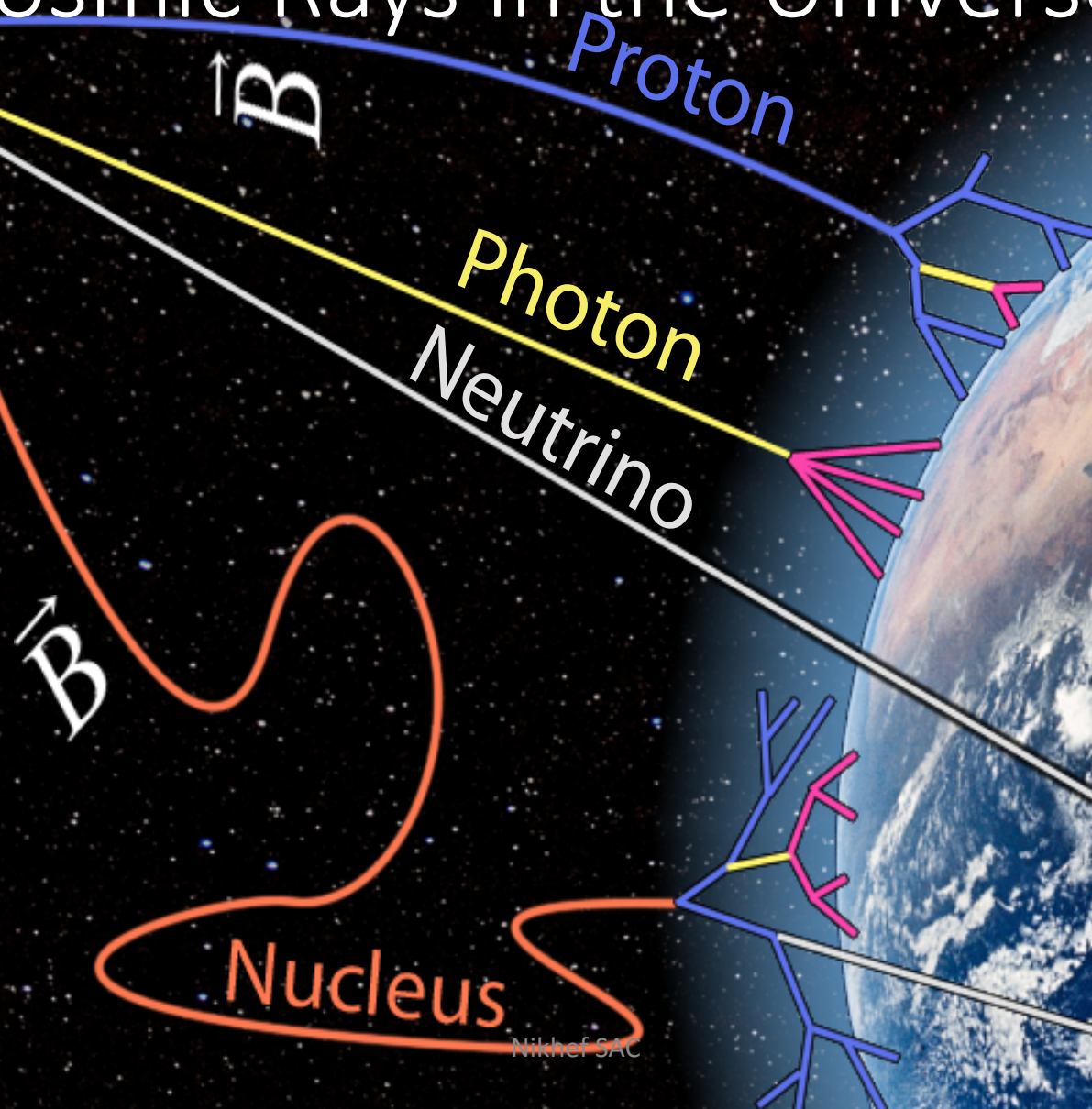
**Origin of highest-energy  
particles in the Universe**

**?**

**Particle type is the key !**



# Cosmic Rays in the Universe



# Ultra-High-Energy Cosmic Rays

## SCIENTIFIC STAFF:

- NWO/Nikhef: NN
- Radboud University/Nikhef: Falcke, Galea, Hörandel, De Jong, Mulrey, Schoorlemmer, Timmermans
- University of Amsterdam: Vink

## TECHNICAL STAFF:

- NWO/Nikhef: 1.1 FTE + 1 FTE from investment budget
- Radboud University: 3.6 FTE

## POST-DOCS:

- Teresa Bister
- Bjarni Pont
- Washington Rodrigues de Carvalho

## GRADUATE STUDENTS

- Fabrizia Canfora (2021)
- Bjarni Pont (2021)
- Mart Pothast (2023)
- Tomas Fodran (2023)
- Abha Kakurdikar (2024)
- Mohit Saharan (2025)
- Mohamed Emam (2025)
- Anthony Bwembya (2025)

## Publications:

119 Auger peer-reviewed papers so far (3 in 2023)  
**8 cited >500 times**

## Dutch Investments:

Entrance FEE	120k	ASTRON/RU/KVI/Nikhef
AERA	808k =	ERC Heino Falcke
	532k	Nikhef
	130k	KVI Groningen
	116k	RU Nijmegen
	30k	RU Nijmegen
Auger comms:	19k	Nikhef
AugerPrime:	4142k =	40k RU Nijmegen
	450k	1000k ERC Jörg Hörandel
		2500k NWO-Groot
		145k KIT
GRAND:	7k	KNAW
	22k	CAS
	5k.	RU Nijmegen

**Dutch investment so far 5116k€5**



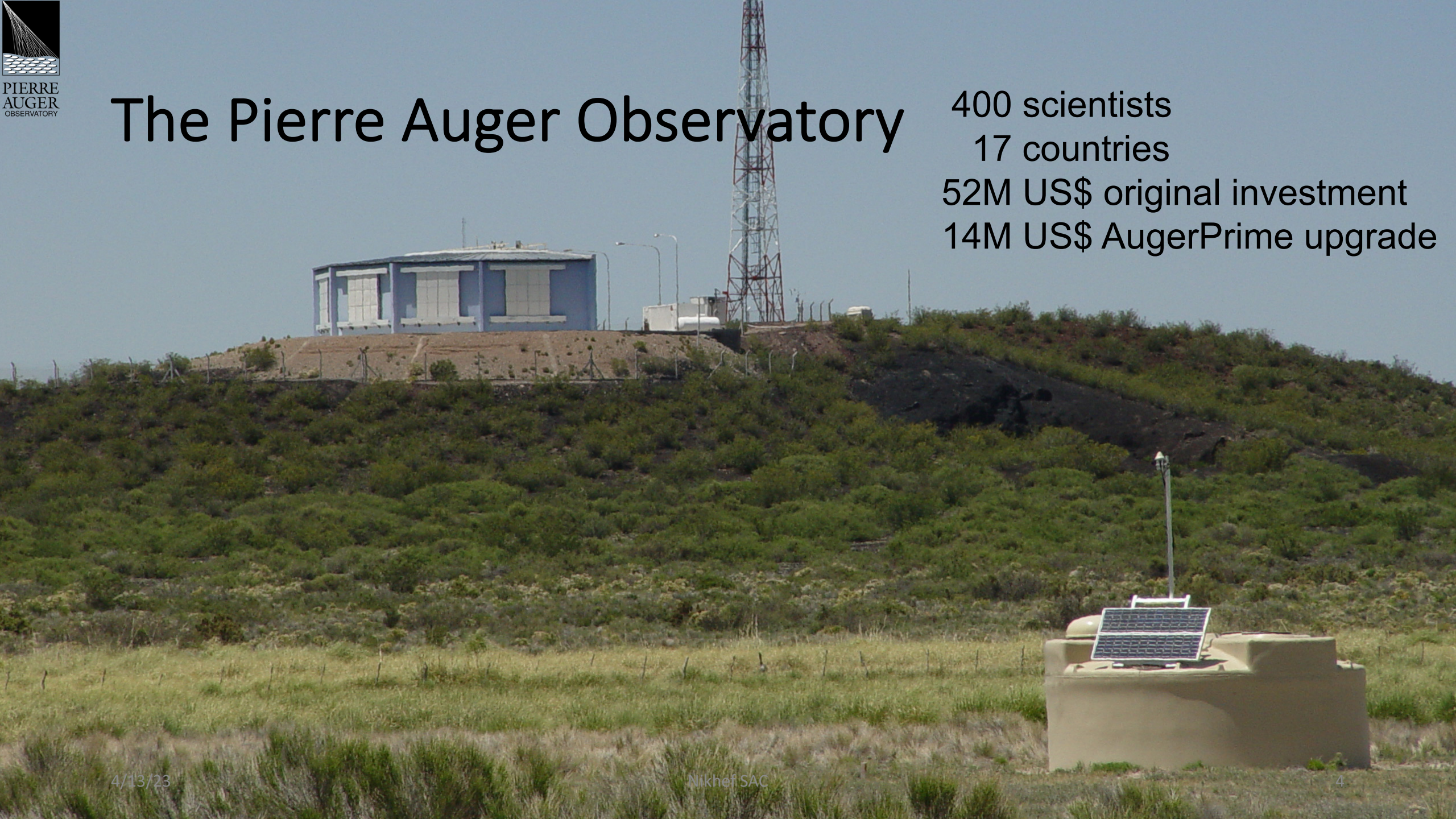
# The Pierre Auger Observatory

400 scientists

17 countries

52M US\$ original investment

14M US\$ AugerPrime upgrade





# Pierre Auger Observatory

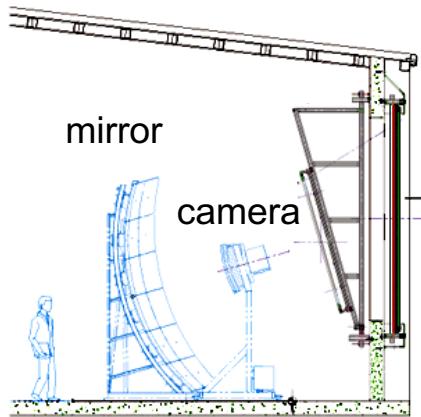
State-of-the-art: **FD**

Energy, direction & **particle type**

$X_{\max}$  using fluorescence light

$$\sigma(X_{\max}) = 20 \text{ g/cm}^2$$

fluorescence  
light

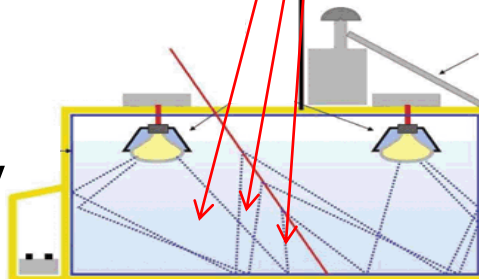


Only in dark nights

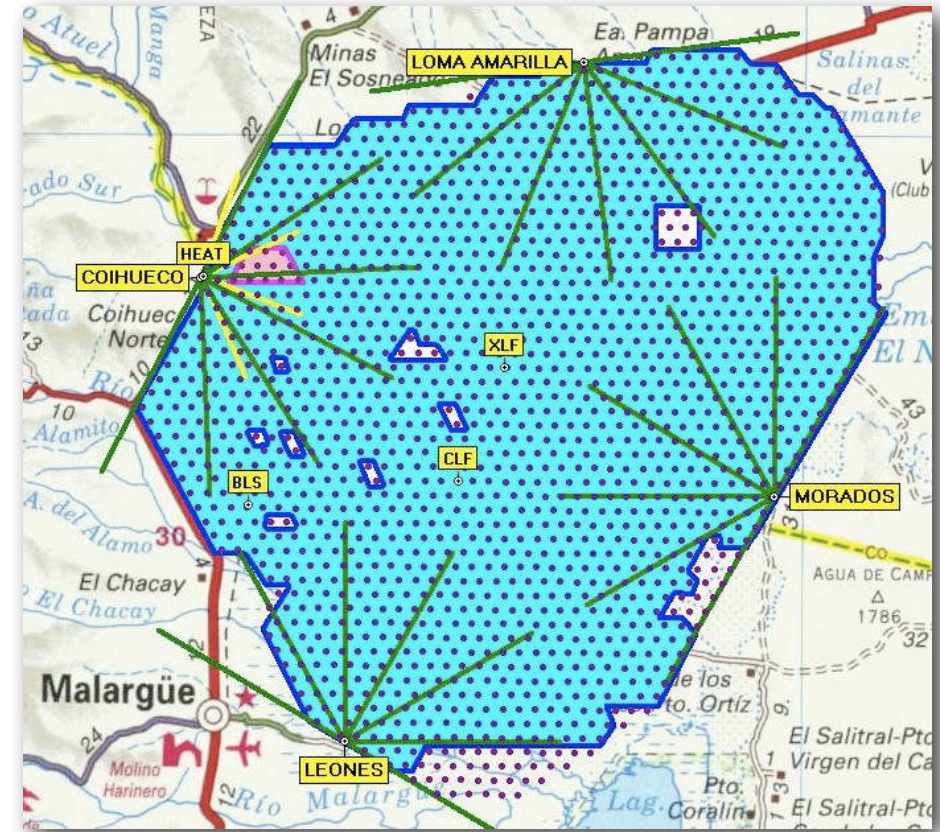
**10% duty cycle**

**SD** measures only  
tail of shower

# particles



Cosmic Ray



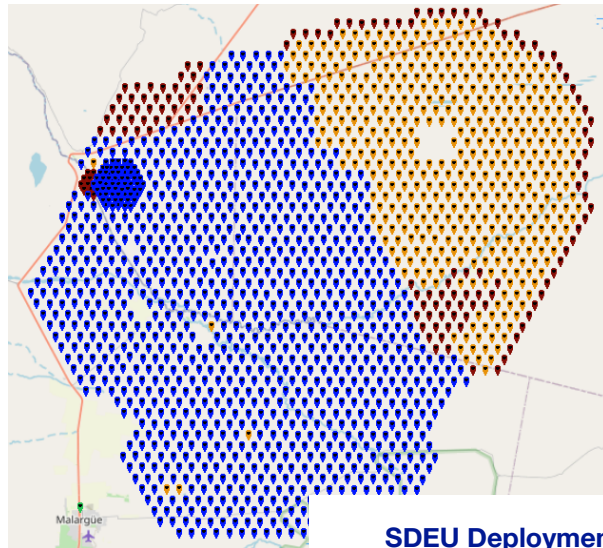
50x60 km = Dutch province

Energy & direction  
**100% duty cycle**



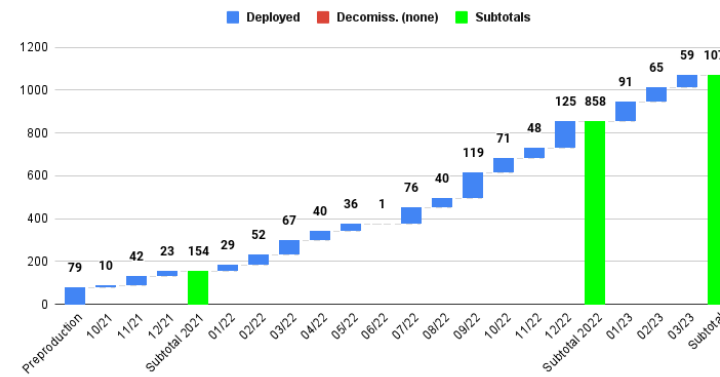
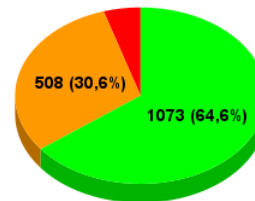
# Status of AugerPrime

## Status of the deployment of UUBs and small PMTs



SDEU Deployment Status  
10 March 2023

● Deployed.  
● To Be Deployed.  
● Not Accessible (79 SD).  
Nominal 1660 SD





# Status of AugerPrime

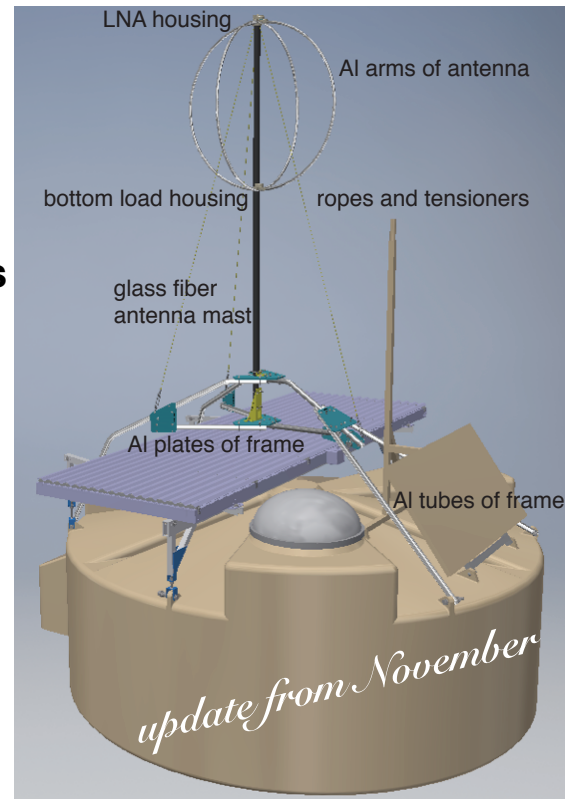
**basically all**  
**RD items are already in Malargüe:**

- 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
- signal cables inside mast - **3400** cables
- fixtures to assemble ferrites - **24** units

—> **6 sea containers, 75 m<sup>3</sup> each**

**for 1700  
stations**

## RD status



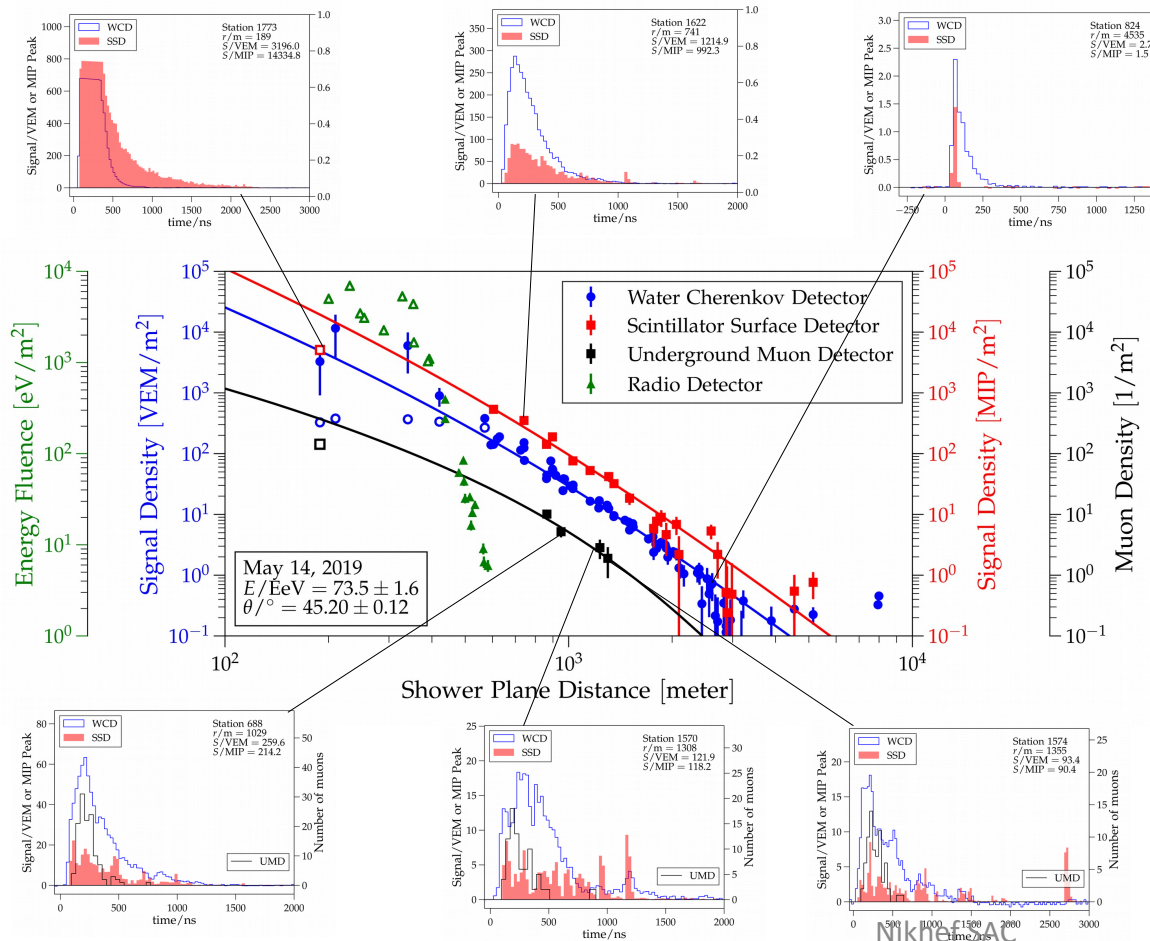
**Aim to complete RD before end of 2023**

**Main bottleneck: Delivery of the science ADC**

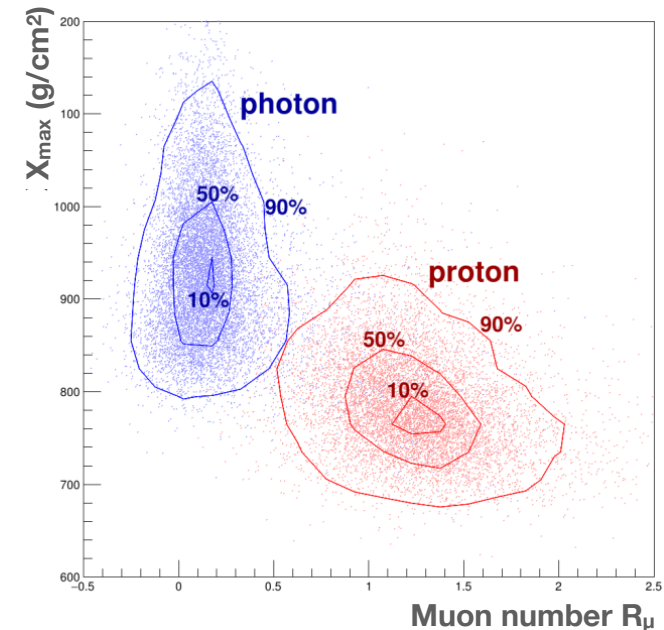


# AugerPrime - Data

## Example of rich information in data of Phase II



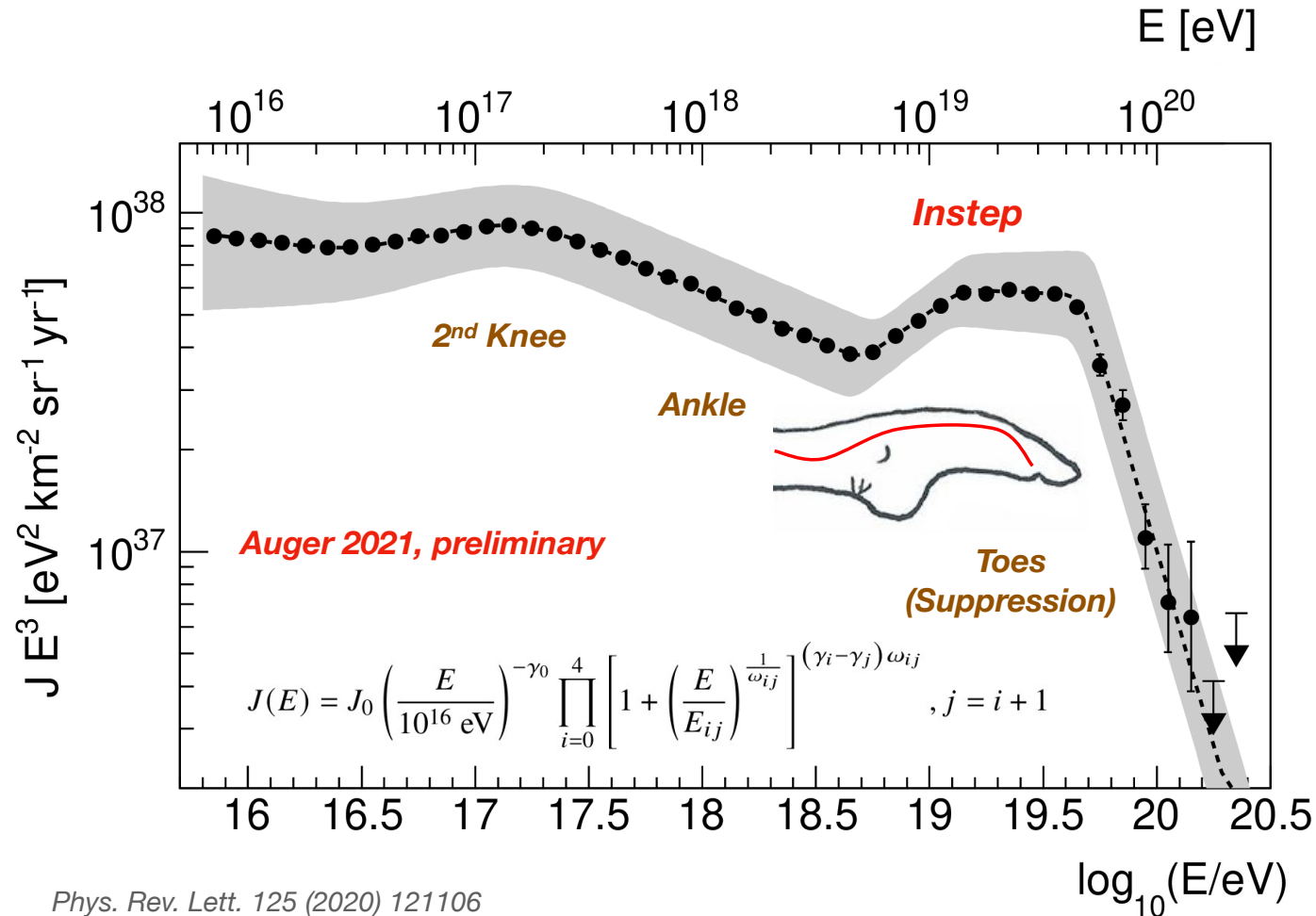
Great physics potential in muons



(Auger, Universe 2022)



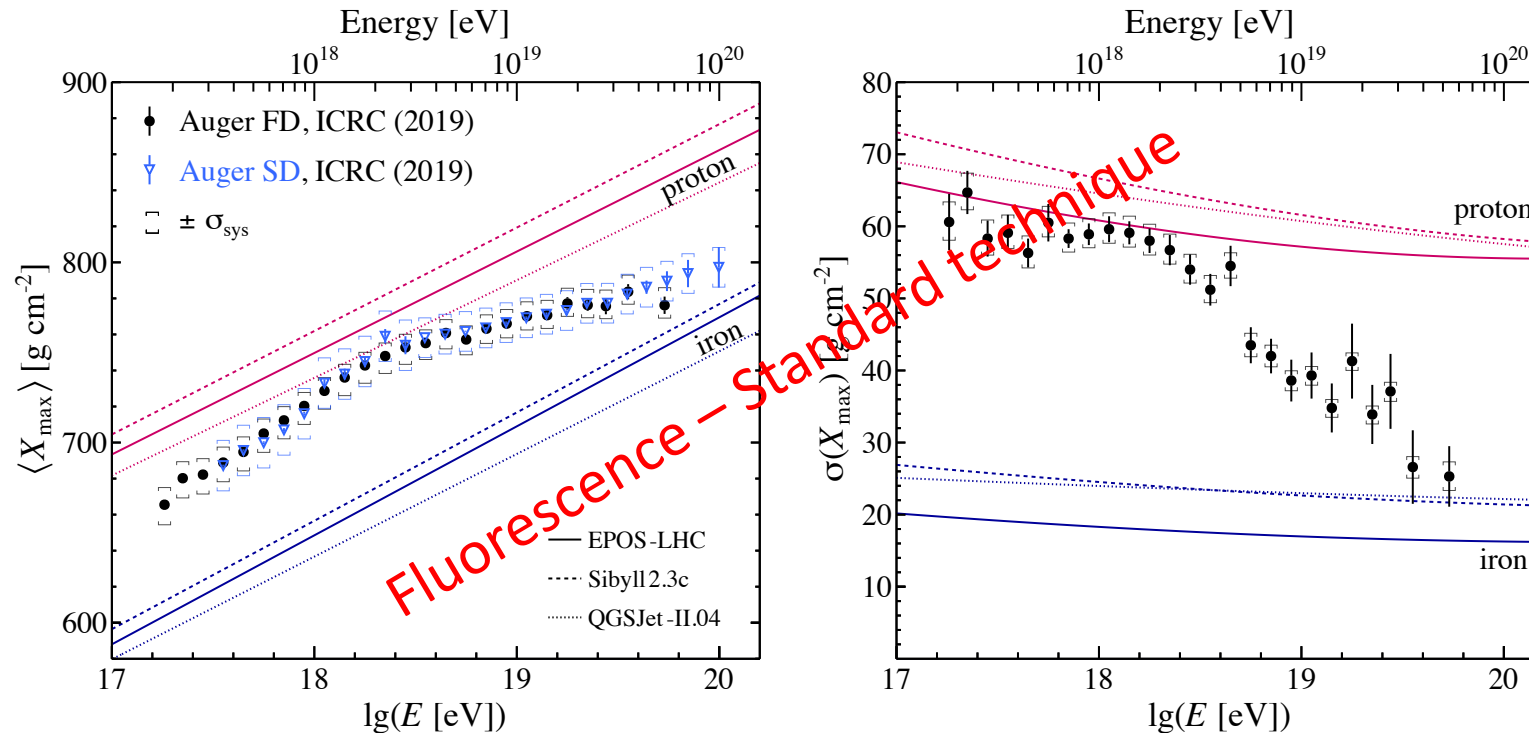
# Highlight Results – Energy Spectrum



Phys. Rev. Lett. 125 (2020) 121106  
 Phys. Rev. D102 (2020) 062005  
 Eur. Phys. J. C81 (2021) 966

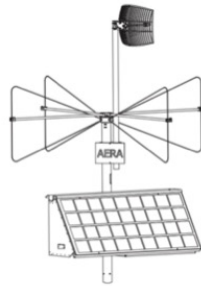
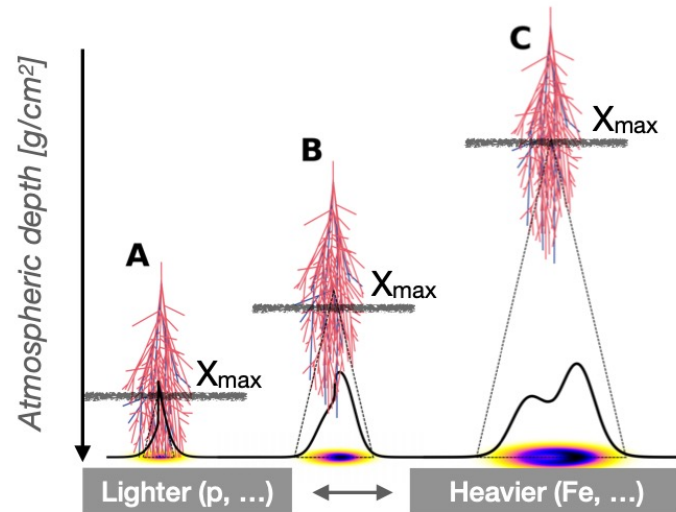


# Highlight Results – Mass Composition

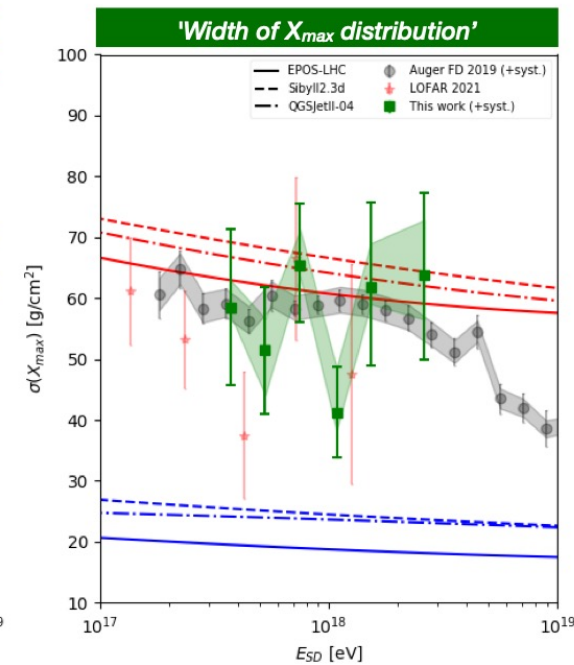
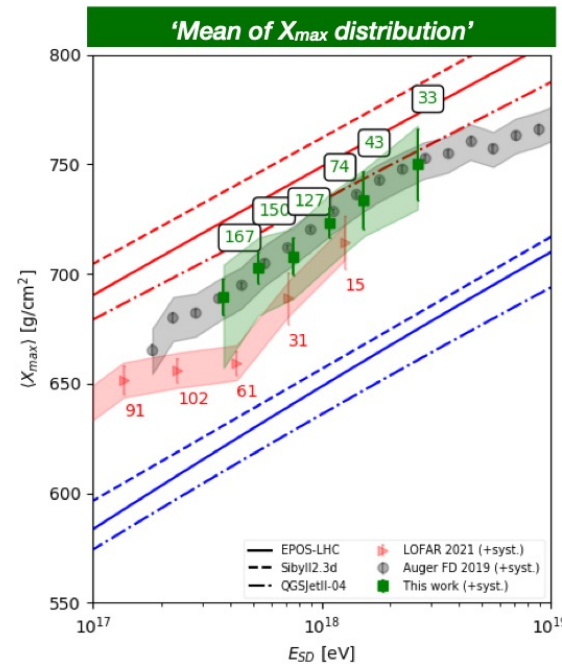




# Highlight Results – Mass Composition



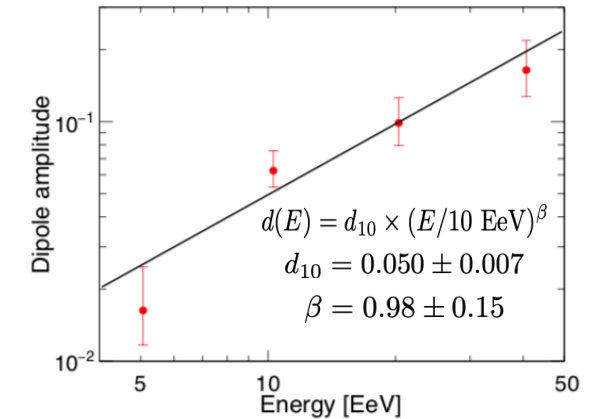
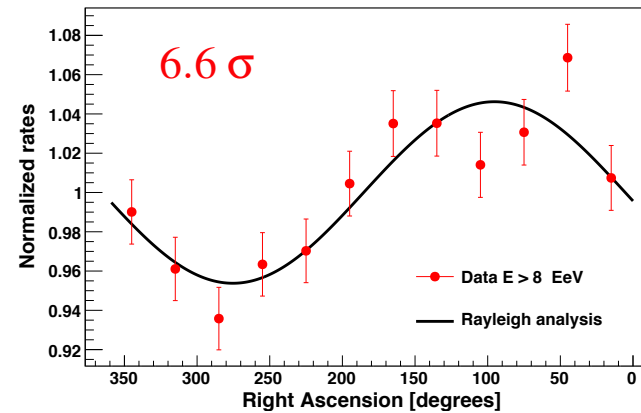
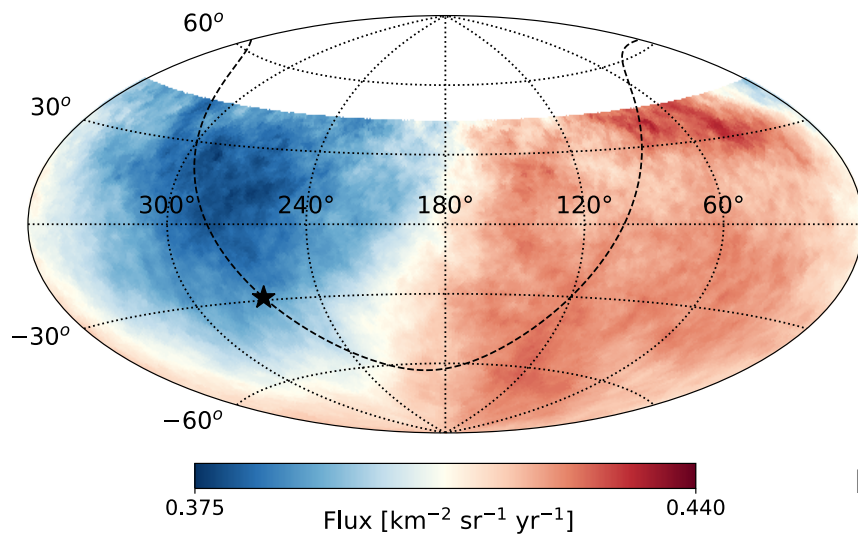
Auger Engineering Radio Array (AERA)



Independent confirmation of earlier Auger results

# Highlight Results - Anisotropy

## Anisotropy on large angular scales – dipole



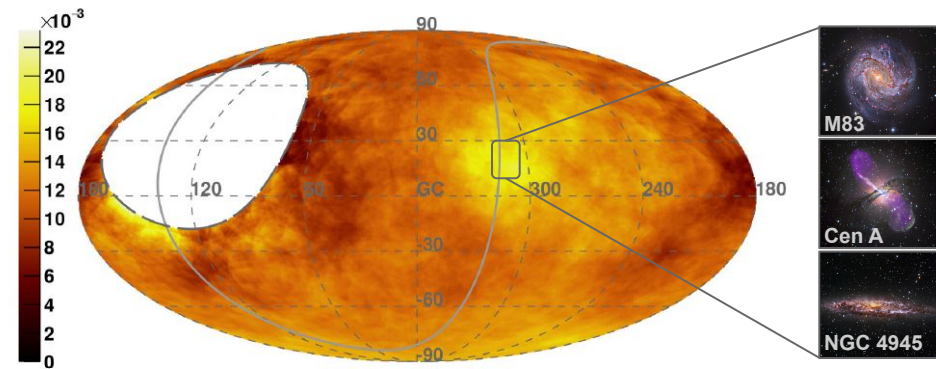
Exposure until end of 2020 ( $\theta < 80^\circ$ ): 110,000 km<sup>2</sup> sr yr  
 $p \sim 5 \times 10^{-11}$



# Highlight Results - Anisotropy

## Anisotropy searches at highest energies – catalogs

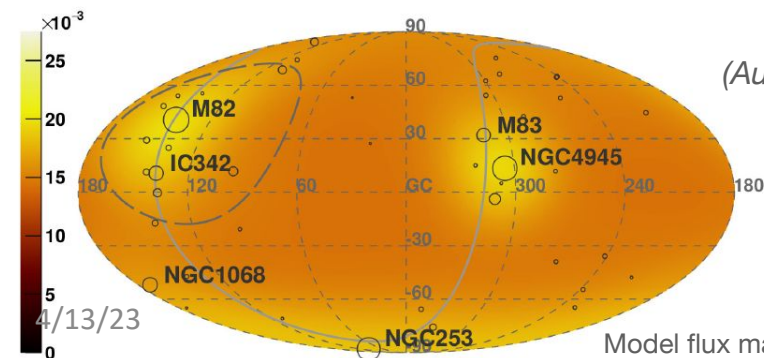
$\Phi(E_{\text{Auger}} > 41 \text{ EeV}) [\text{km}^2 \text{sr}^{-1} \text{yr}^{-1}]$  - Galactic coordinates -  $\Psi = 24^\circ$



**Direction fixed** to that of Cen A, free  $E_{\text{th}}$  and  $\Psi$

$E_{\text{th}} > 41 \text{ EeV}$ ,  $\Psi = 27^\circ$ : **3.9 $\sigma$  post-trial** deviation from isotropy (5% excess)

Starburst galaxies (radio) - expected  $\Phi(E_{\text{Auger}} > 38 \text{ EeV}) [\text{km}^2 \text{sr}^{-1} \text{yr}^{-1}]$

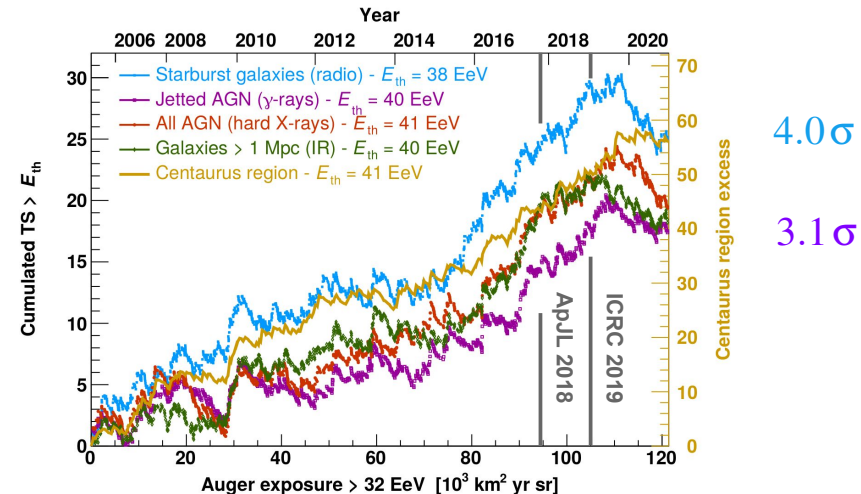


Model flux map

(Auger, *ApJ* 935 (2022) 170)

All data until end of 2020, optimized quality cuts: 120,000  $\text{km}^2 \text{sr yr}$

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

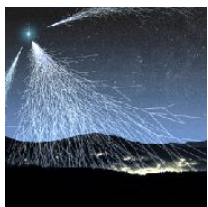


Growth of test statistic (TS) compatible with linear increase  
Discovery threshold of  $5\sigma$  expected in 2025 – 2030 (Phase II)  
Other means to increase sensitivity (Auger 85% sky coverage)

# AugerPrime

- The international agreement on Auger runs until 2025.
- In order to fully benefit from our investments, it needs prolongation
- In November Auger will be evaluated by an external scientific panel, appointed by the finance board
- We hope (expect) to be able to run the Observatory well into the 2030s





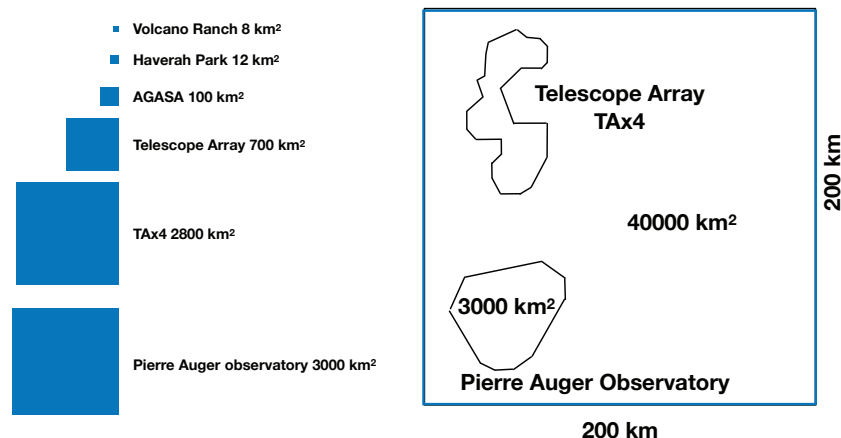
# Next Generation: The Global Cosmic Ray Observatory

## GCOS

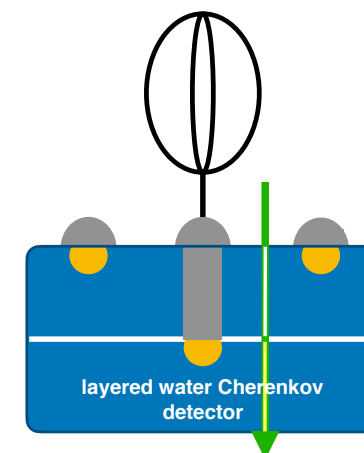
**Multi-messenger astroparticle physics beyond 2030**  
protons, nuclei, gamma rays, neutrinos, (gravitational waves)

**World-wide initiative to build next-generation CR observatory**

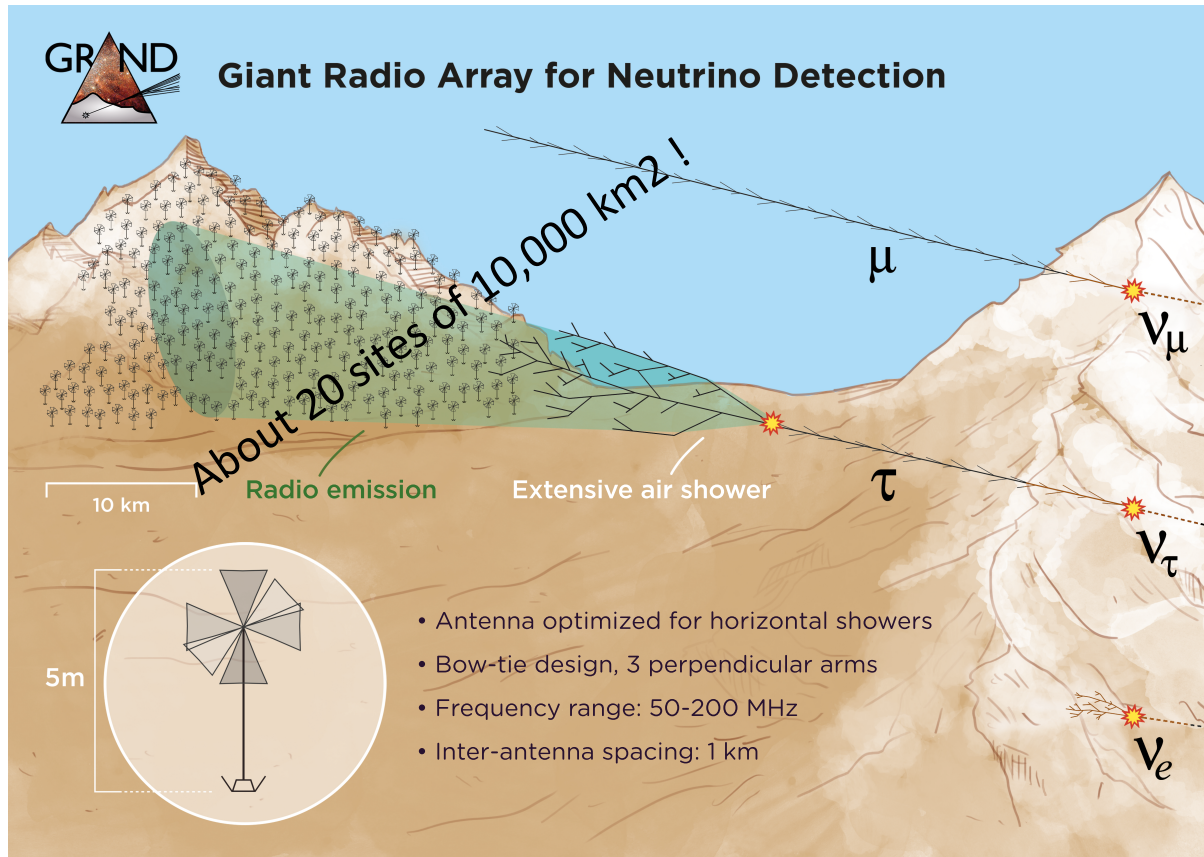
**At present working to define precise science case and detector layout, aiming at least for two sites (northern and southern hemisphere), covering at least 50 000 km<sup>2</sup>**



**Discussing different detection concepts, like segmented water Cherenkov detectors combined with radio antennas, complemented by fluorescence detectors**



# Next Generation: GRAND



- Delays due to COVID and travel restrictions
- Refocus Prototyping:
  - Fully develop a site in the Northern Hemisphere (China) **AND** in the southern hemisphere (Argentina)
  - Create a working engineering setup in Europe (France)



# Next Generation: GRAND

First hardware deployed and first data arriving from China and Argentina



# Status Nikhef Cosmic Ray Programme

- The AugerPrime installation is well underway and first data is promising
- The Auger results are getting close to establishing “small scale” anisotropies, AugerPrime will make a significant impact here
- Radio is a mature addition to AugerPrime
- AERA is able to contribute significantly to the Auger physics output
- GRAND prototypes are coming online
- We have been able to profit significantly from sectorplan money for new graduate students in Nijmegen
- The new hire by Nikhef will hopefully appear soon