The Giant Radio Array for Neutrino Detection – experimental status and plans

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Particle Astrophysics in Poland
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How to find UHECRs sources?

Problem

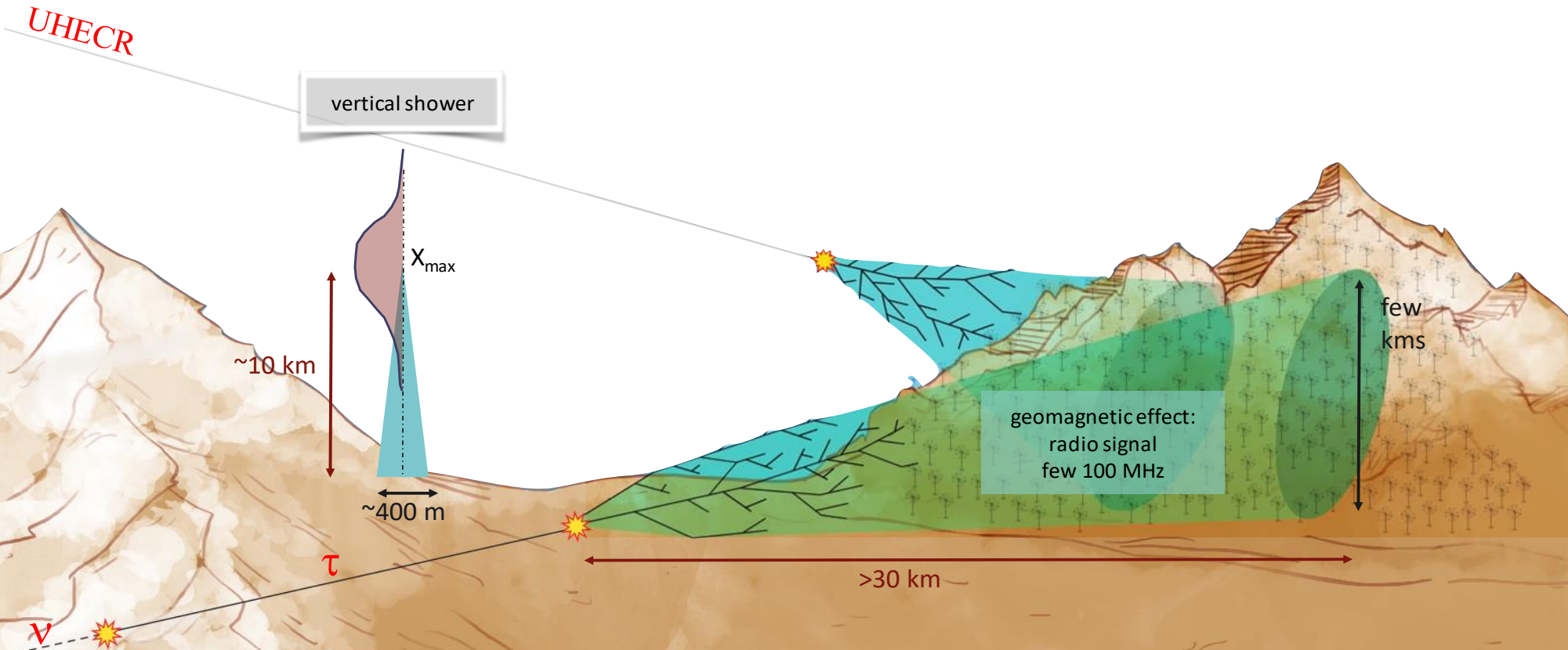
So many years, no UHECRs sources identified

Solutions

- Increase the atmosphere coverage
  - Use a different experimental idea (eg. observations from the orbit with JEM-EUSO/Poemma)
  - Use different (more efficient and cheaper) detection methods to cover more ground
- Reduce the angular uncertainty
  - Observe UHE neutrinos from UHECR ($\sim 5\%$ of the primary energy) that travel in straight line from the source

Giant Radio Array for Neutrino Detection – GRAND – aims at both increasing the atmosphere coverage and observing the UHE neutrinos

Radio detection of ultra-high-energy air-showers in GRAND



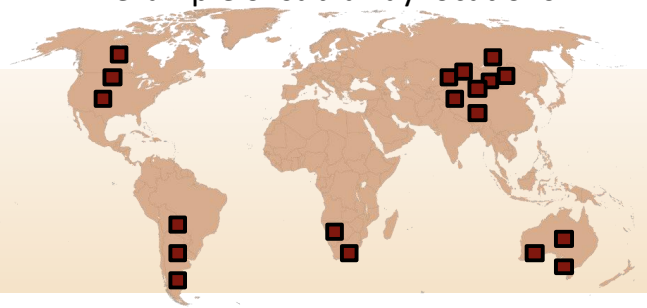
radio detection: a mature technique
AERA, LOFAR, CODALEMA, Tunka-Rex, TREND

radio antennas: scalable, cheap, robust
ideal for **giant** arrays

slide by Kumiko Kotera

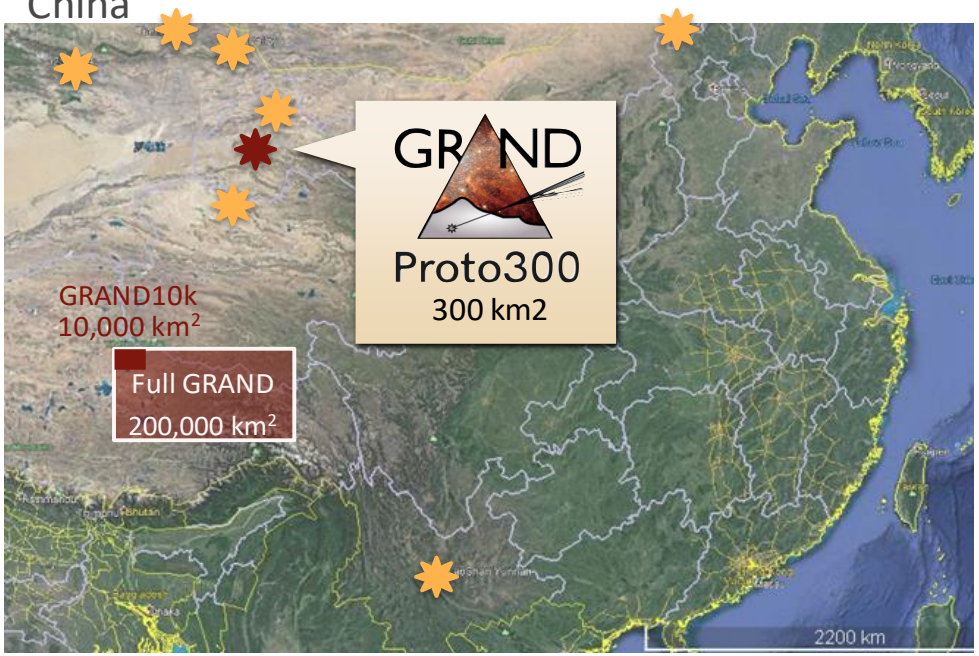
The GRAND Concept

example of sub-array locations



200'000 radio antennas over 200'000 km^2
~20 sub-arrays of 10'000 antennas
over favorable sites worldwide

China



Argentina

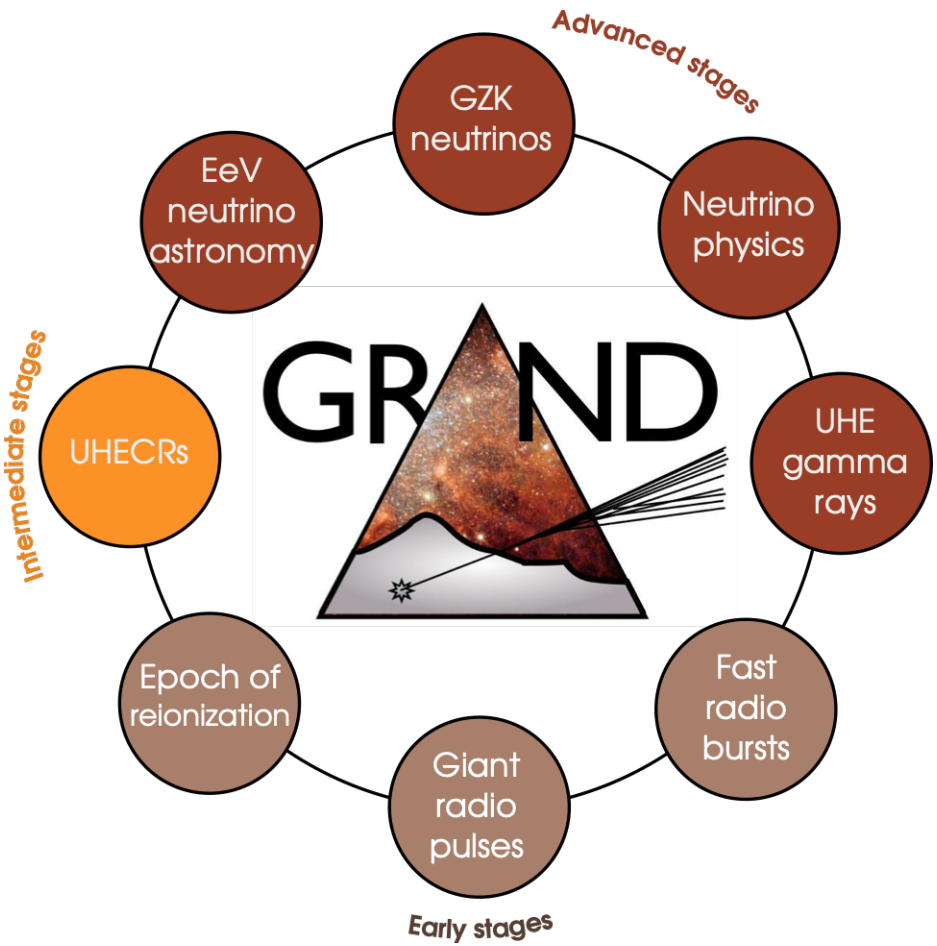
- ✓ Radio environment: radio quiet
- ✓ Topography: mountains/slopes
- ✓ Access, Installation and Maintenance
- ✓ Other issues (e.g., political)

several excellent sites identified
in Argentina & China
(~100 measurements,14 campaigns)

slide by Kumiko Kotera

GRAND science case

- UHE neutrinos
  - point sources
  - cosmogenic flux
- UHECR
  - 20 times the exposure of Auger
    - 1 yr: GRAND 6400, Auger 320 events $> 10^{19.5}$ eV, GRAND 150, Auger 8 events $> 10^{20}$ eV
  - transition from galactic to extragalactic, north-south anisotropy
  - hadronic physics
- neutrino physics (cross-sections, flavour ratios)
- UHE gamma-rays observations/competitive limits
- Radio astronomy
  - almost full-sky survey
  - FRBs and Giant Pulses



A staged approach with self-standing pathfinders

	Prototyping	GRAND10k	GRAND200k
	2025	>2028	203X
Goals	autonomous radio detection of very inclined air-showers cosmic rays $10^{16.5\text{-}18}$ eV • Galactic/extragalactic transition • muon problem • radio transients	1st GRAND sub-arrays (x2) • discovery of EeV neutrinos for optimistic fluxes • radio transients (FRBs!)	sensitive all-sky detector 1st EeV neutrino detection and/or neutrino astronomy!
Setup	• GRAND@Nançay: 4 antennas for trigger testing • GRAND@Auger: 10 antennas for cross-calibration • GRANDProto300: 300 HorizonAntennas over 200 km²	• 10,000 radio antennas over 10,000 km²	• 200,000 antennas over 200,000 km² • 20 sub-arrays of 10k antennas • on different continents
Budget	2 M€ 100 antennas produced funded by China + ANR PRCI NUTRIG (France) + Radboud University	13 M€ 1500€/unit	300M€ in total 500€/unit to be divided between participating countries

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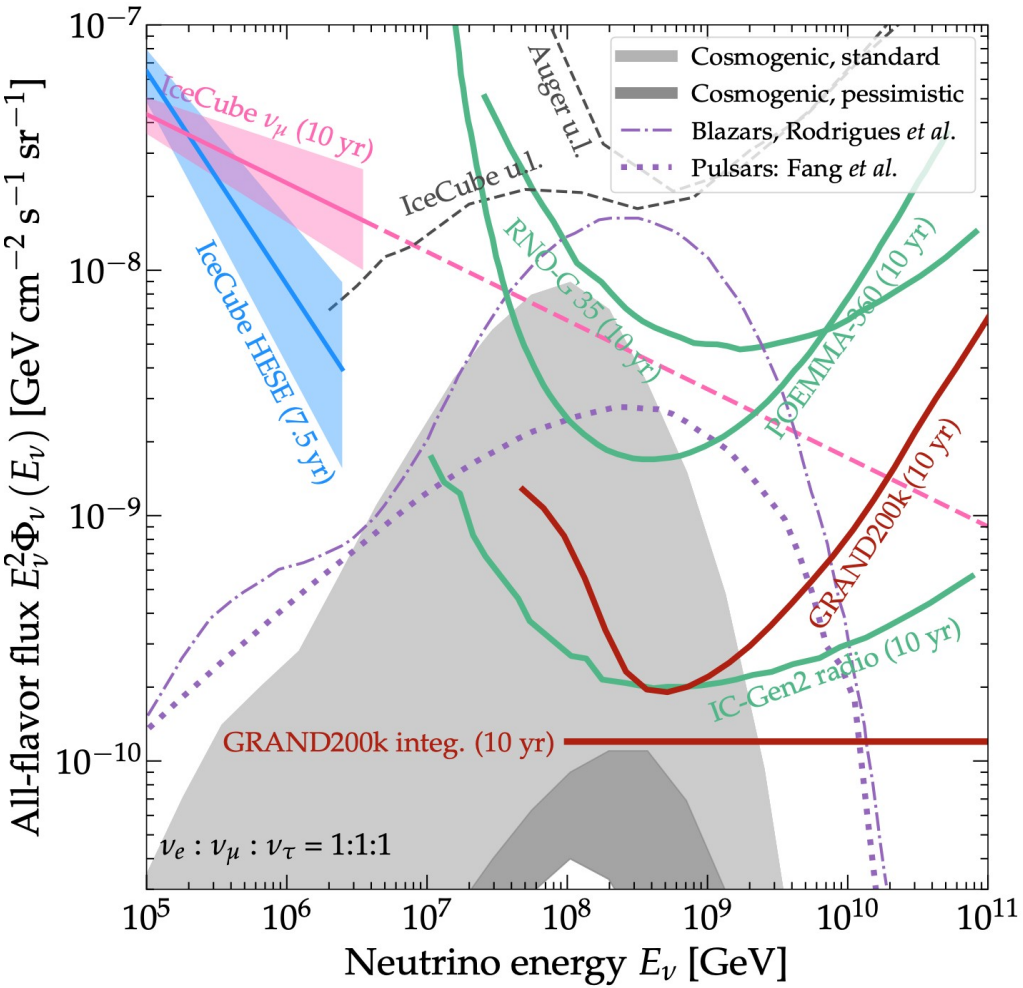
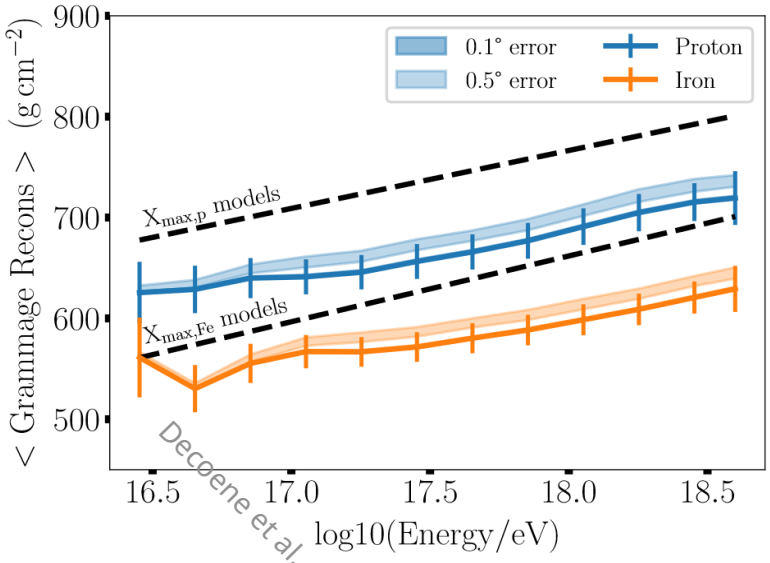
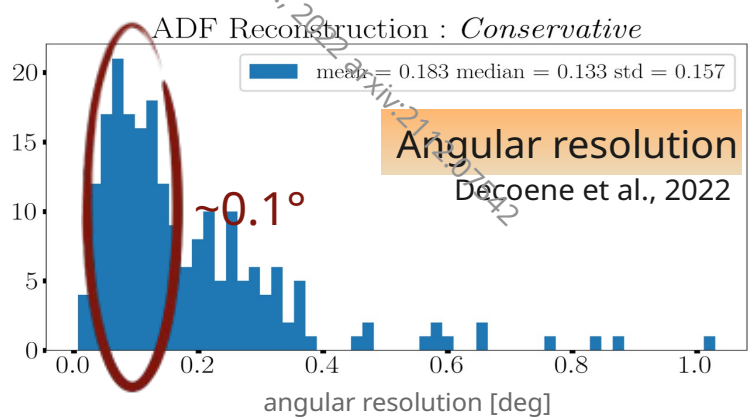
Simulated performances

GRAND Science & Design, GRAND Coll. Science China, arXiv:1810.09994







- GRAND full sensitivity to neutrinos (E>10^{17} eV) ~4 x 10^{-10} GeV cm^{-2} s^{-1} sr^{-1}
- Angular resolution ~0.1° for GP300 & GRAND — Decoene et al., 2022
- Energy resolution < 10% on air-showers for GP300 & GRAND — B. Lago & Rio GRAND team
- X_{max} resolution < 40 g/cm² for E>10^{17} eV (comparable to other methods) — Decoene et al., 2022

slide by Kumiko Kotera

Challenges: Autonomous triggering on radio signal

Status for existing experiments:

- Antarctic (super low-noise) experiments, like ANITA, trigger on radio signal
- All non-antarctic experiments (AERA, LOFAR, etc.) are externally triggered on regular basis (particle detectors)
- But past TREND experiment (a precursor to GRAND) managed to register UHECR with a radio trigger

To trigger on radio signal, we need:

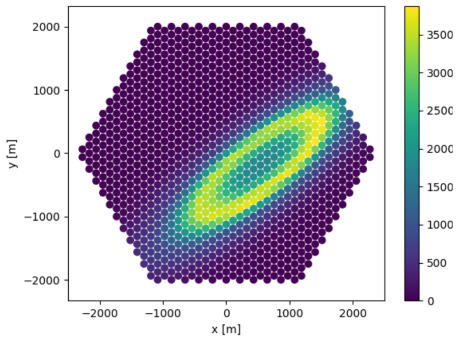
- (intially) Very radio-quiet environment
- Optimised antennas
- Electronics and software capable of 10^8 rejection rate
- Motivation — we can not do it differently

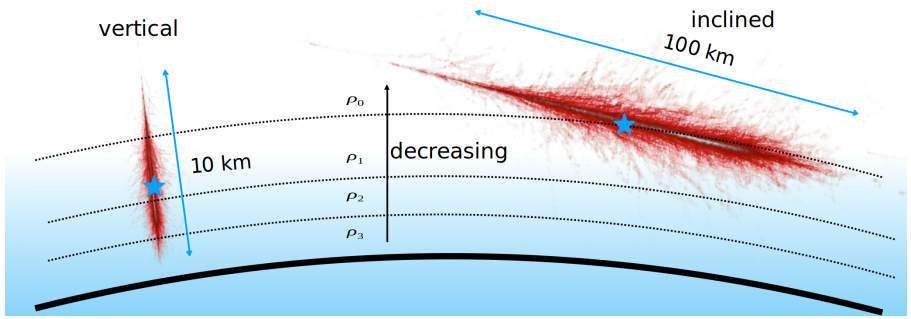
TREND showed that it can be done, GRAND needs to (vastly) optimise it

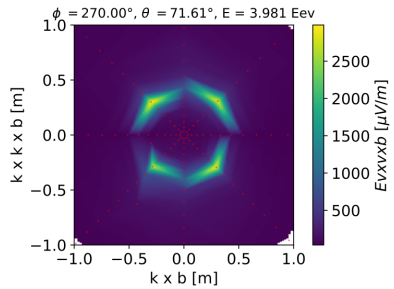
Challenges: Very inclined EAS reconstruction

How to find primary particle's direction, energy and mass (Xmax)?

- Mature methods for radio for... vertical showers
- Current experiments' sensitivity to very inclined shower is very low
- For very inclined showers terra incognita, but we can start with same methods, and add "our" features







- Strong, accessible Cherenkov-like ring in our frequency range
- Asymmetric atmosphere for the shower → synchrotron effect → cloverleaf pattern
- Still studied in simulations, several reconstruction (conventional and ML) methods under development

Other challenges

- How to deploy 200,000 antennas
- How to put them on slopes
- Power/connectivity
- How to maintain a huge site
- Finding sites
- Financing...

Hardware

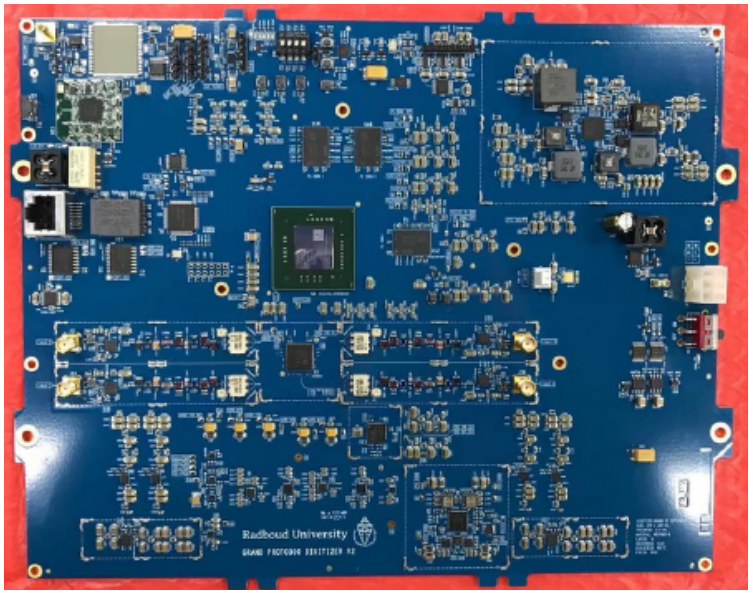
$\sim$ 100 detector units ready, most in use:

- A butterfly antenna
  - 3 arms: x,y: 2×65 cm, z: 65 cm
  - On a 3.5 m pole

5 detection units tests at Xi'An (by Zheng PengFei)

Hardware

- $\sim$ 100 detector units ready, most in use:
  - A butterfly antenna
    - 3 arms: x,y: 2×65 cm, z: 65 cm
    - On a 3.5 m pole
  - Front-end electronic:
    - 30-230 MHz analogue filtering (to be used: 50-200 MHz)
    - 500 MS/s digitisation
    - Xilinx Zync MPSoC (FPGA+2 CPUs+2 RT CPUs)
    - Bullet WiFi data transfer



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  - Xilinx Zync MPSoC (FPGA+2 CPUs+2 RT CPUs)
  - Bullet WiFi data transfer
- LNA, VGA, solar panels, batteries, charge converters, custom filters, etc. $\leftarrow$ very important

GRAND: software/simulations/other status

Software

Data format:
- raw/sim → ROOT TTrees
- *Status:* fully embraced for sims and data from prototypes

Data analysis:
- GRANDlib – Python + C(++) speedups/alternatives
- *Status:*
  - Preliminary energy, direction and Xmax reconstruction with helpf of GRANDlib
  - Own topography module
  - Full electronic chain
  - Know-python-only data access interfaces (data oriented and analysis oriented)

Other

Carbon footprint:
- Estimated in 10.1016/j.astropartphys.2021.102587
- GRAND Green Policy validated

Simulations

ZHAireS:
- For big studies, interpolation used (*M. Tueros and A. Zilles 2021 JINST 16 P02031*)

CORSIKA7/CoREAS:
- Generated similar library to ZHAireS one for GP300, for comparison

Radio-morphing:
(A. Zilles et al., 10.1016/j.astropartphys.2019.06.001)
- Good agreement with microscopic simulations
- New scaling laws and new interpolation → better accuracy of the peak time and amplitude of the interpolated pulse *(Chiche et al., PoS(ICRC2021)194)*

MGMR3D:
(O. Scholten et al., Phys. Rev. D 97, 023005)
- Some effort on adaptation from LOFAR to GRAND, on hold

GRAND@Nancey

- 4 antennas deployed in Nancay Radio Observatory, France

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- Easy access (for Europeans)

GRAND@Nancey

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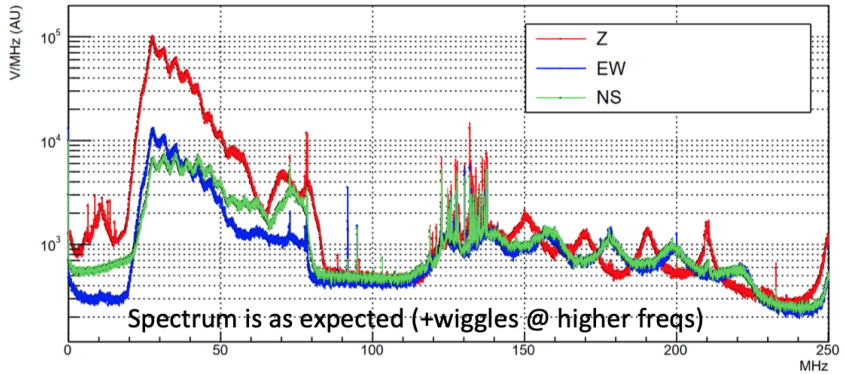
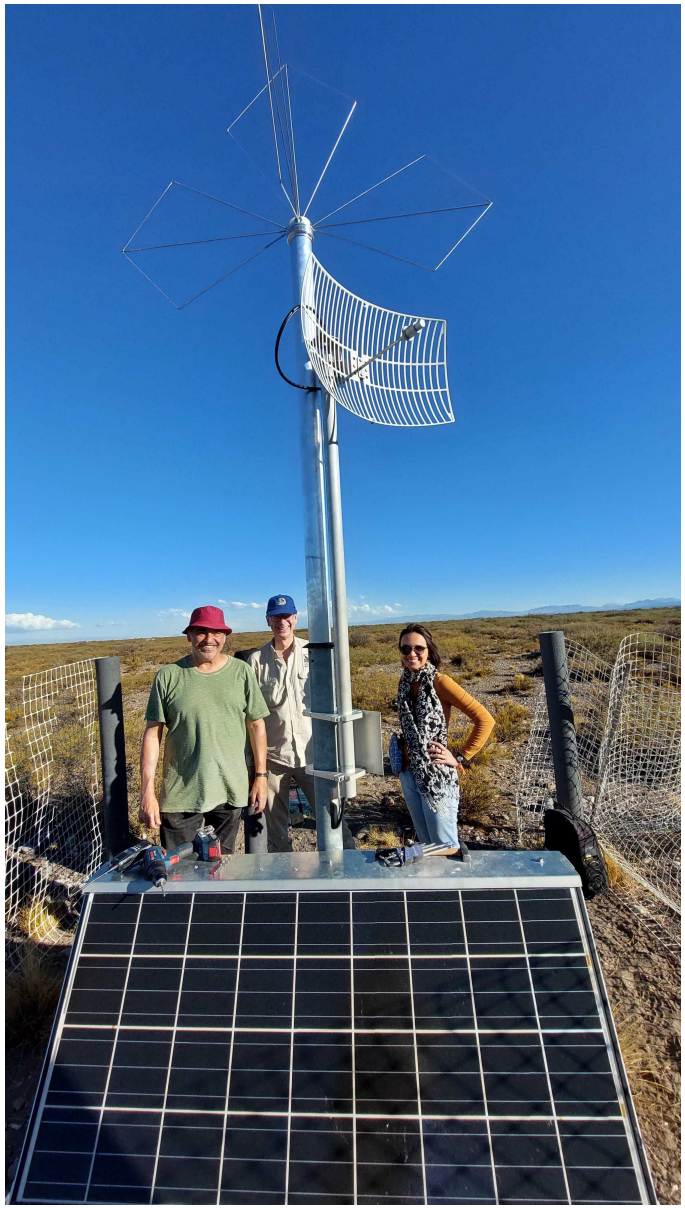
- Easy access (for Europeans)
- Hardware tests only with easy access, too noisy for EAS



GRAND@Auger

- 10 antennas at the Auger site in Malargue, Argentina (by Radboud University and Universidade Federal do Rio de Janeiro)
- Attached to AERA infrastructure



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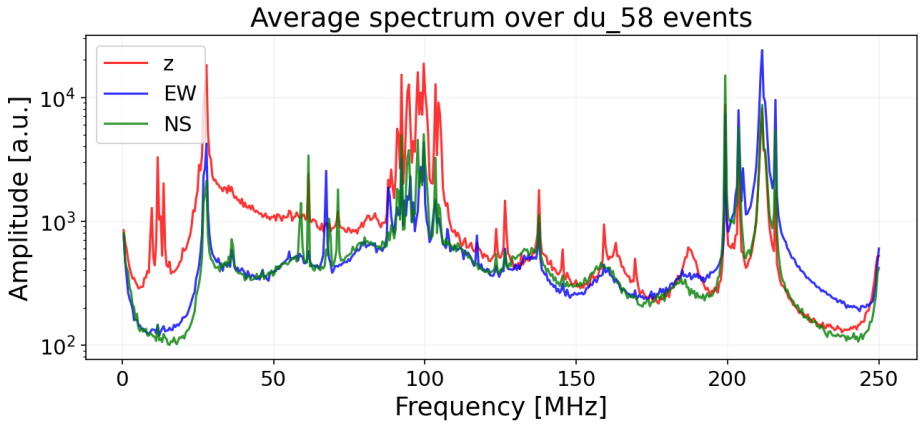

GRAND@Auger

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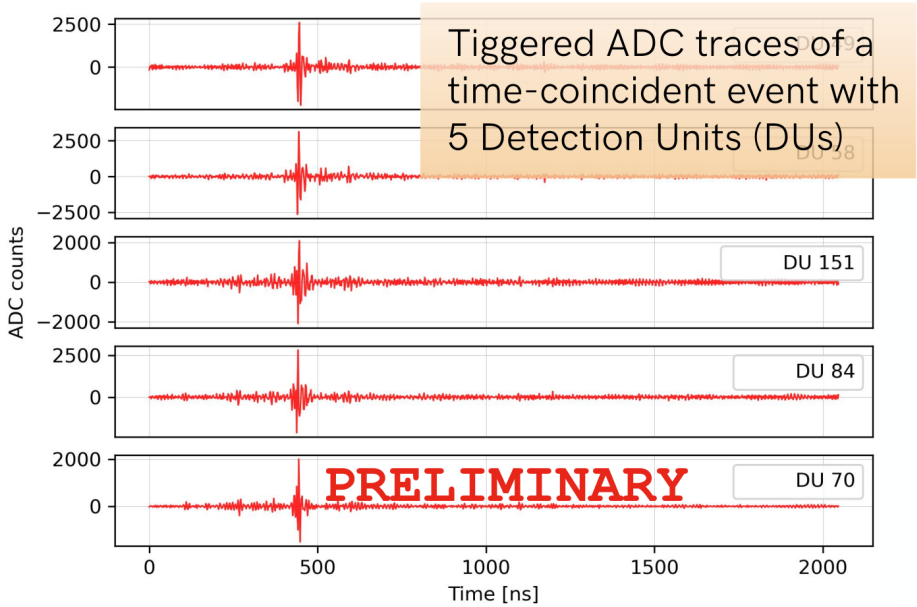
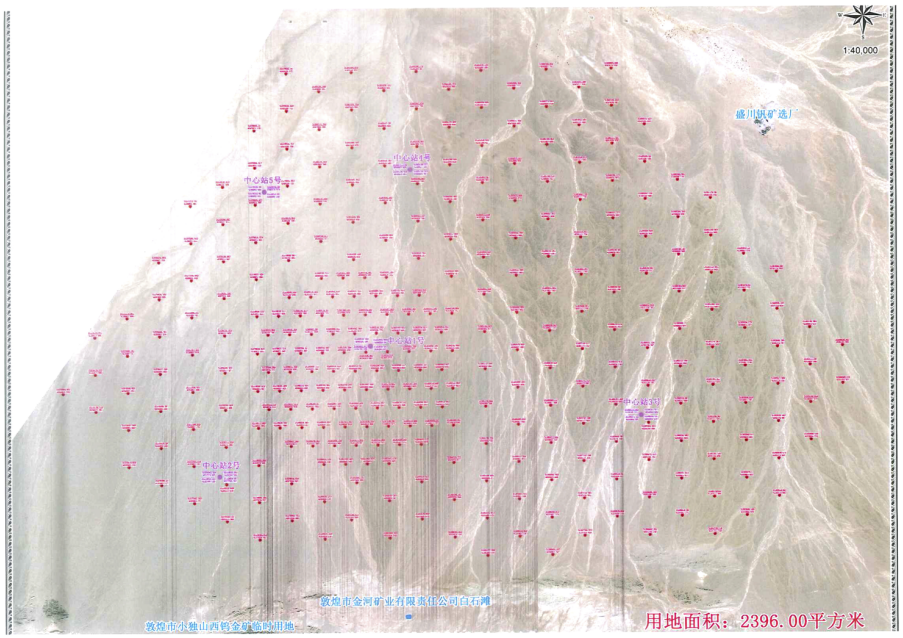
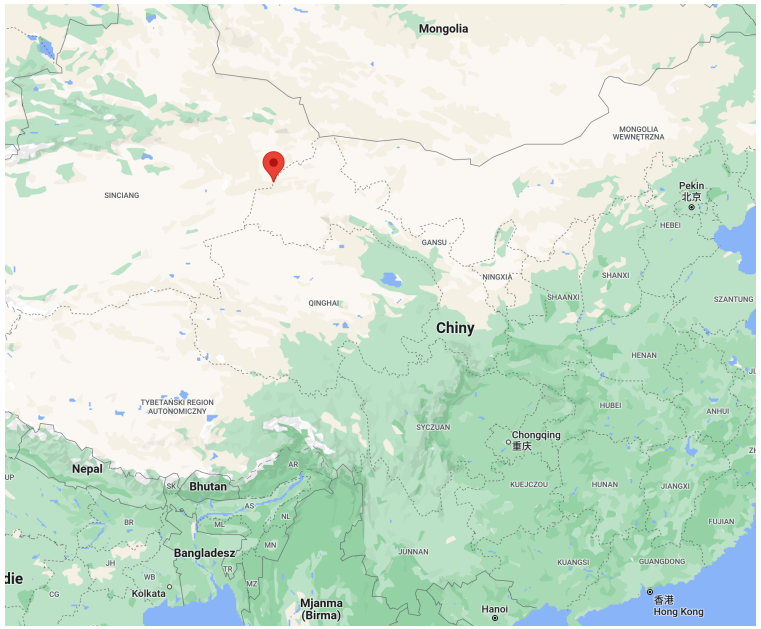
- Attached to AERA infrastructure
- Hardware tests
- Self-triggering, cross calibration with Auger
- Data transfer and remote access possible through 4G

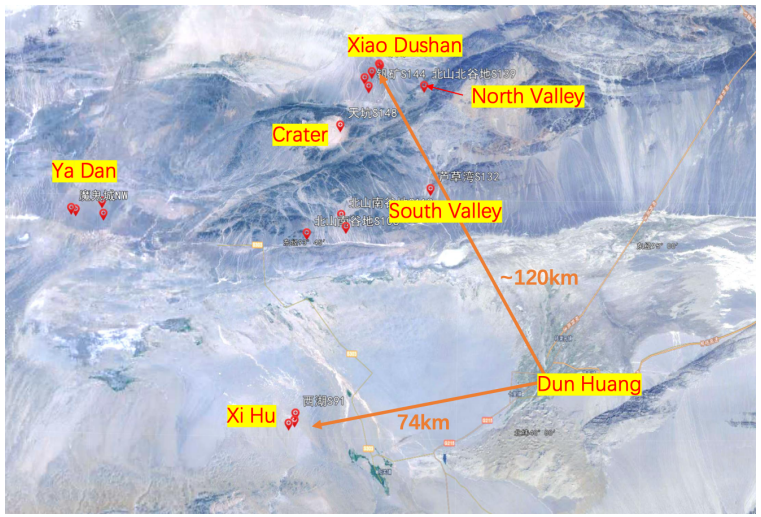


GRANDProto300

- 300 antennas to be deployed in Xiao Dushan, China by $\sim$ 2026 (by Xidian University and Purple Mountain Observatory)







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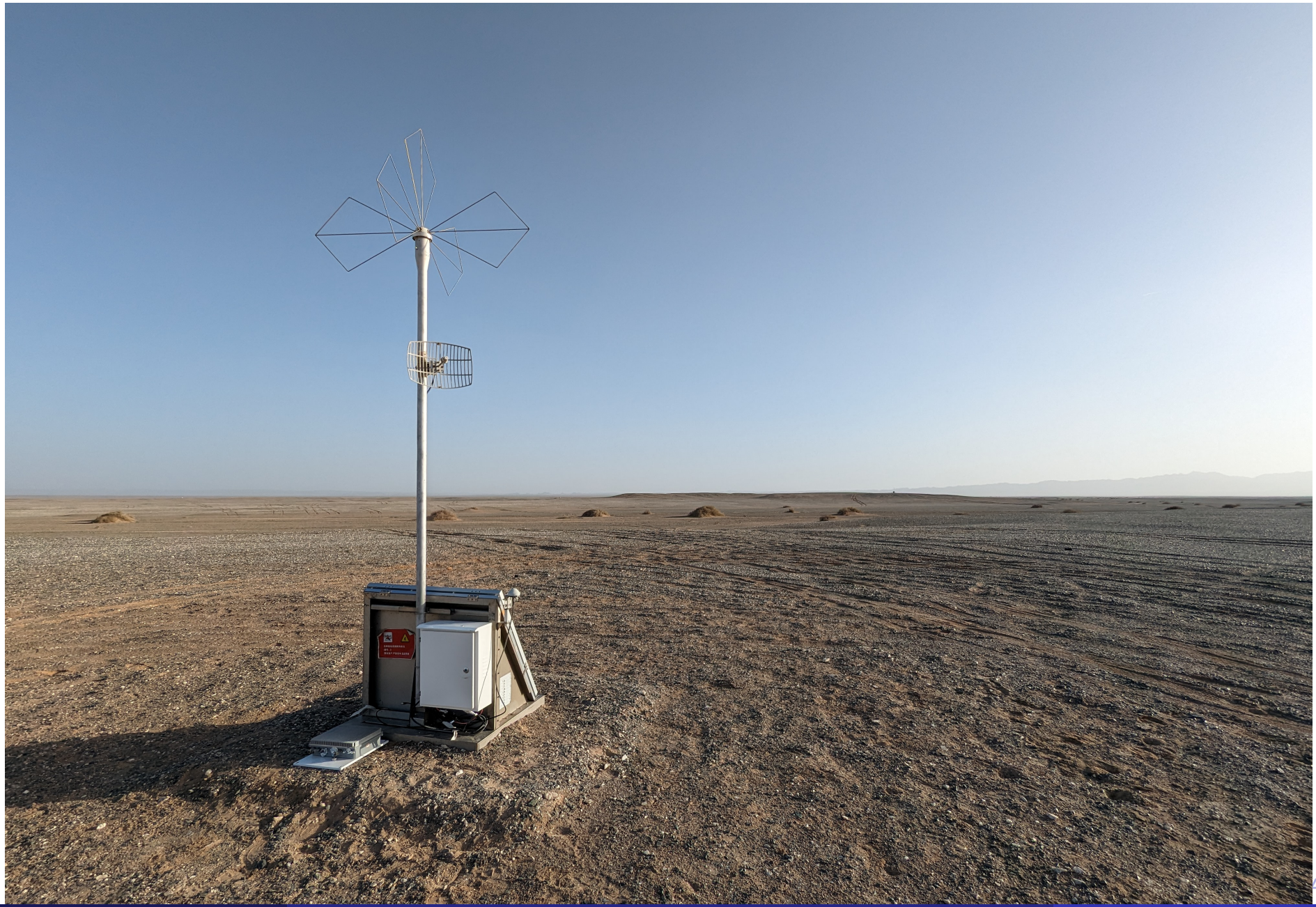

GRANDProto300

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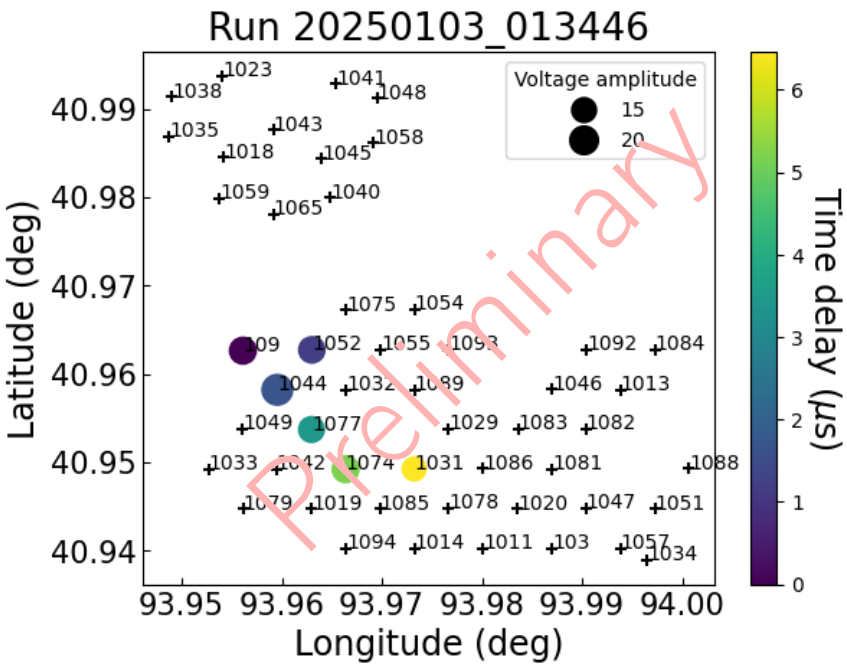
- Currently deployed: 48 antennas
- Hardware development
- Gathered many bias data and single-antenna triggers

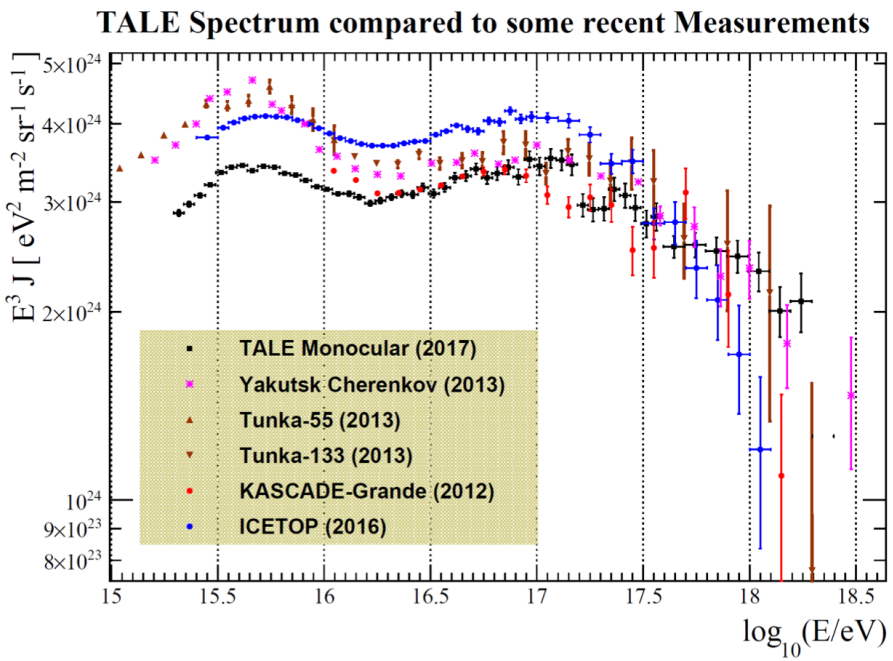
Very preliminary UHECR candidates in GRANDProto300

- GP300 is still in commissioning phase
- Self triggering since late Autumn 2024
- The search for UHECRs in the data has just started
- A few promising events detected, not associated with known sources of bg
- First CR candidates? **Very preliminary** results so far – more study needed!
- No reconstruction/statistics yet



GRANDProto300 science

- GP300 will be crucial in $10^{16.5} - 10^{18}$ eV range in the north



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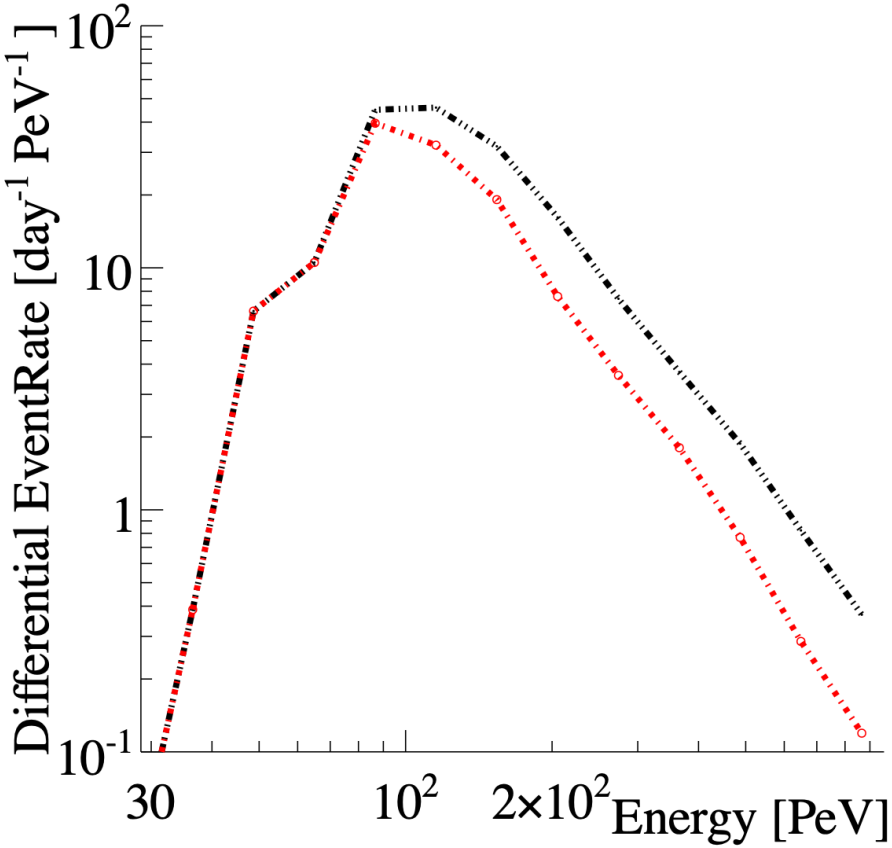

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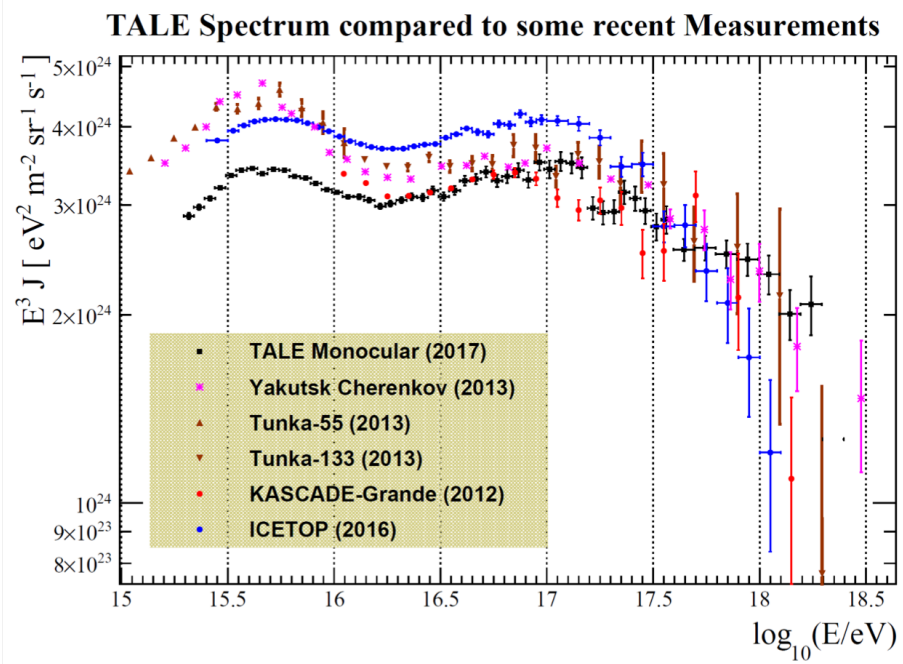

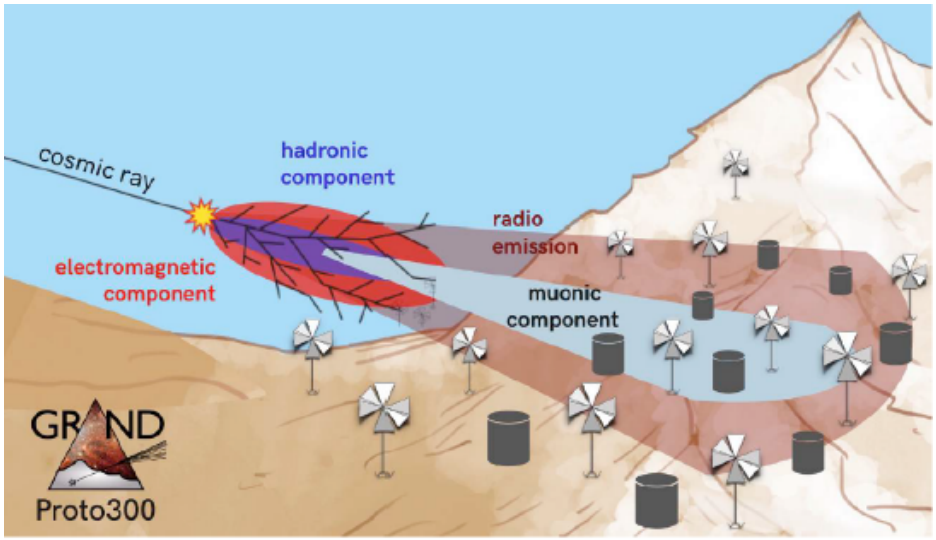

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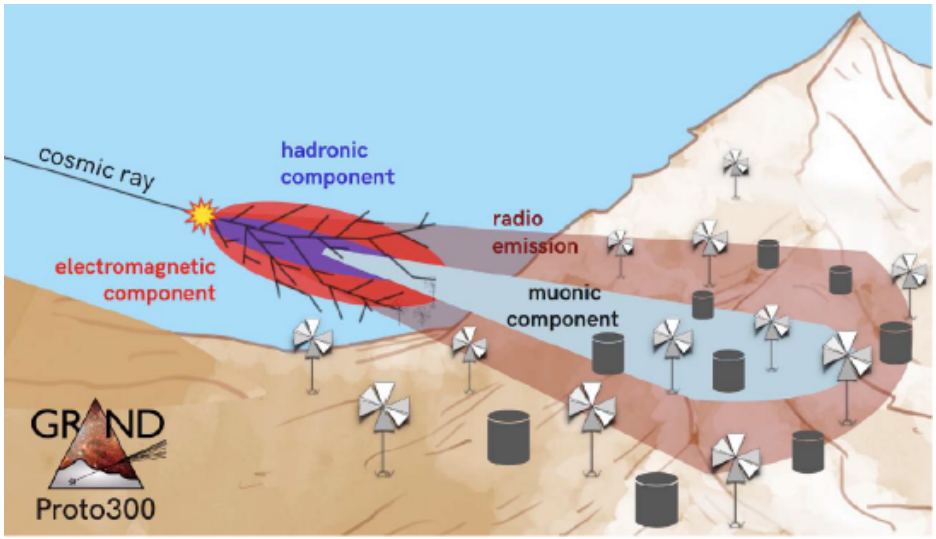

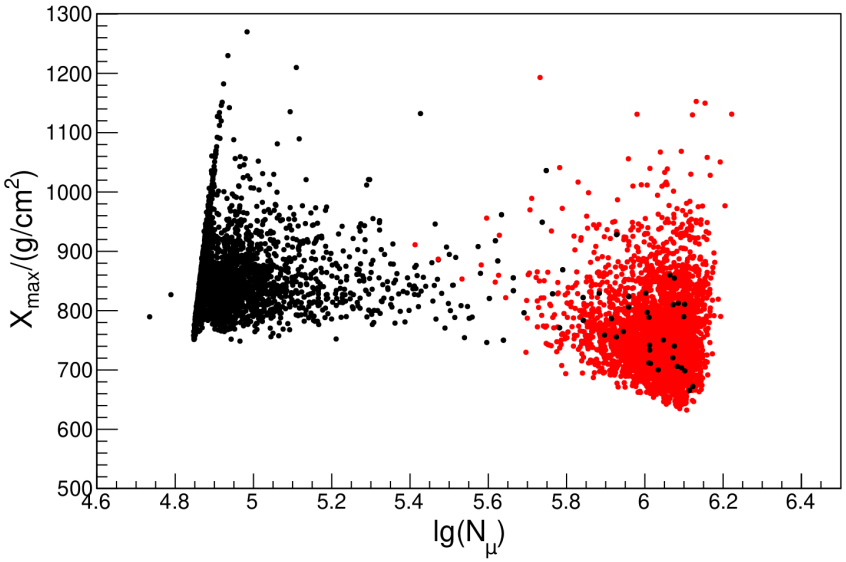

Protons red, gamma black

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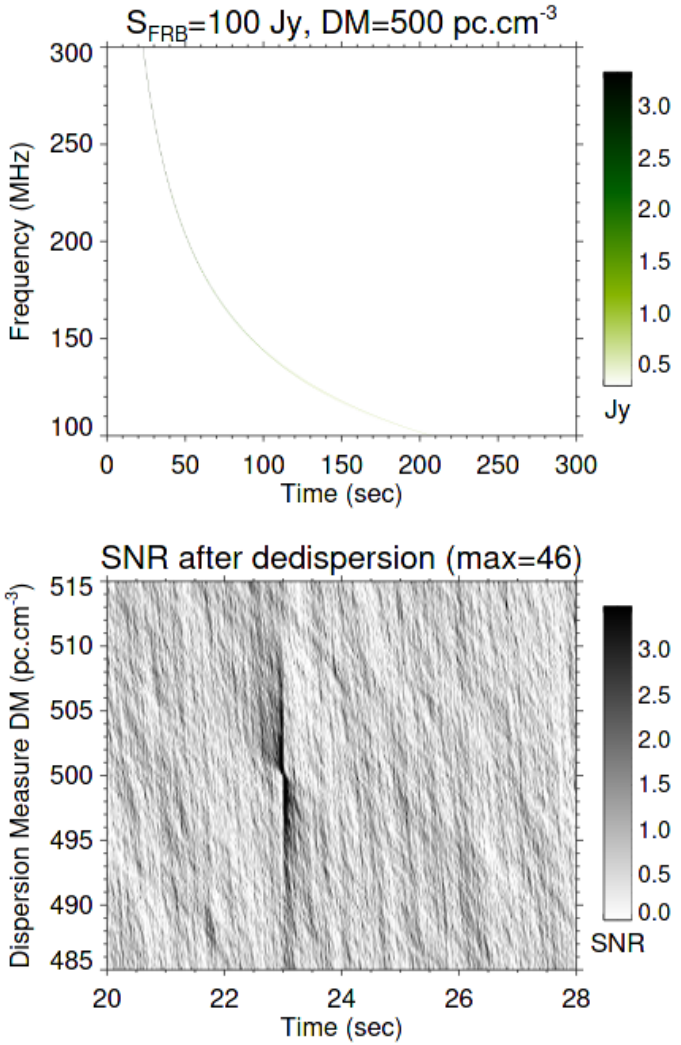
- Radioastronomy: FRBs, giant pulses



This is for GRAND200k. Peak SNR for the blind search is 46

GRAND today

- 15 countries: Argentina, Belgium, Brazil, China, Czech Republic, Denmark, France, Germany, Greece, Japan, Netherlands, Norway, Spain, Poland, USA
- 125 members

The Polish contribution

- X_{max} reconstruction
- Software
- Offline event selection

Please see the X_{max} talk by Washington Carvalho tomorrow, at 14:30!

GRAND meeting in Nanjing, 2024

Summary

The origin of cosmic rays of highest energies still remains a mystery

- Current on-ground experiments (Auger, TA) have small chances of finding it
- GRAND aims to solve it with:
  - A huge exposure (20 times that of Auger in UHECR)
    - covering vast amounts of ground with cheap, low-density radio antennas
    - observing very inclined EAS
  - Detection of UHE neutrinos, vastly reducing direction uncertainty

GRAND status:

- 3 small prototypes started data gathering in 2023
- The first 48 antennas of the GRANDProto300 self-triggerging in coincidence since Autumn 2024
- Very preliminary UHECR candidates detected, giving hope for UHECR science in $10^{16.5} - 10^{18}$ eV region
- With 10,000 antennas in $\sim$ 2028 a chance for first UHE neutrinos discovery
- With 200,000 antennas in the 2030's a chance for UHE neutrinos astronomy
- GRAND appears in several roadmaps (APPEC, Snowmass 2022, ESPP 2020, etc.)

http://grand-observatory.org