Giant Radio Array for (UHE) Neutrino (and UHECR) Detection

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How to find UHECRs sources?

Problem

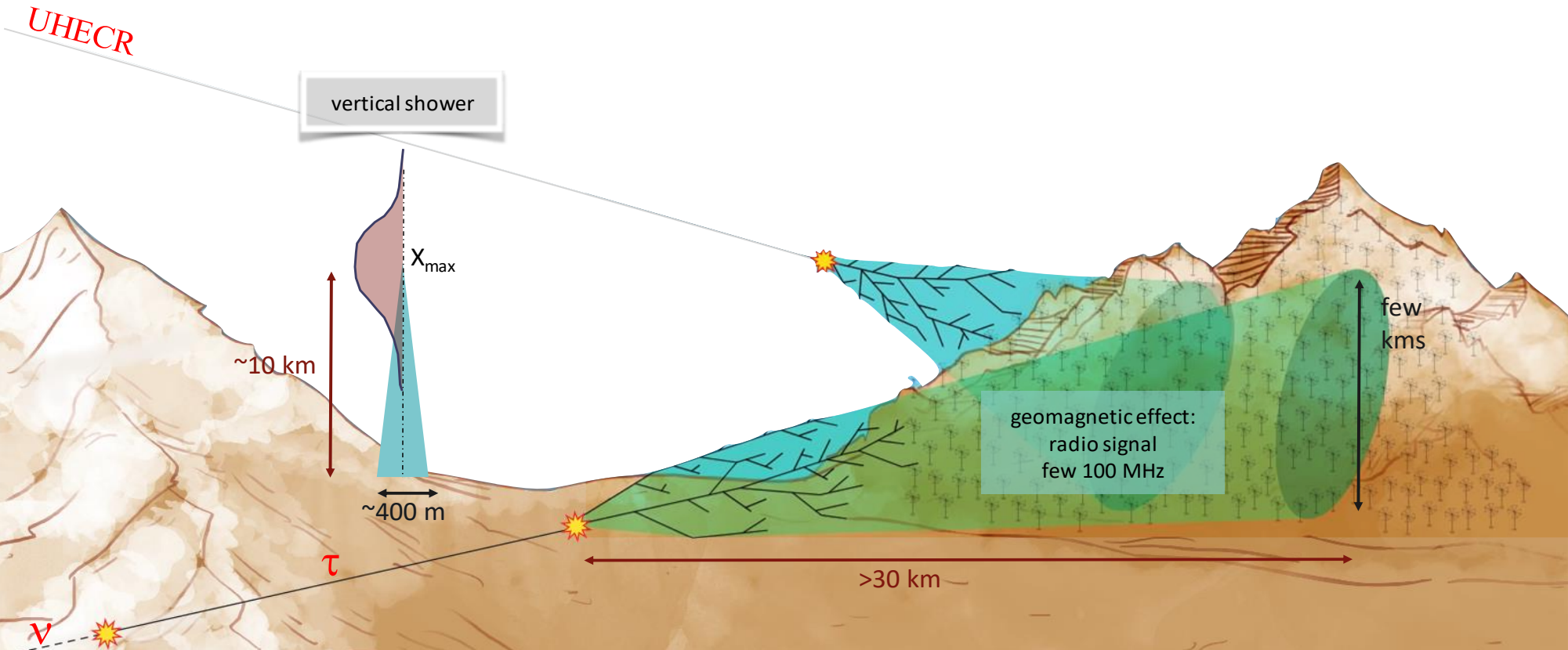
So many years, no UHECRs sources identified

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



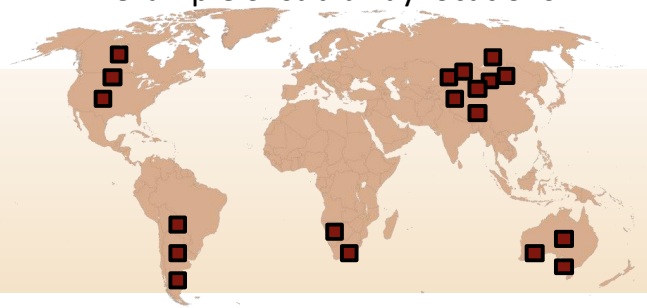
radio detection: a mature technique
AERA, LOFAR, CODALEMA, Tunka-Rex, TREND

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

slide by Kumiko Kotera

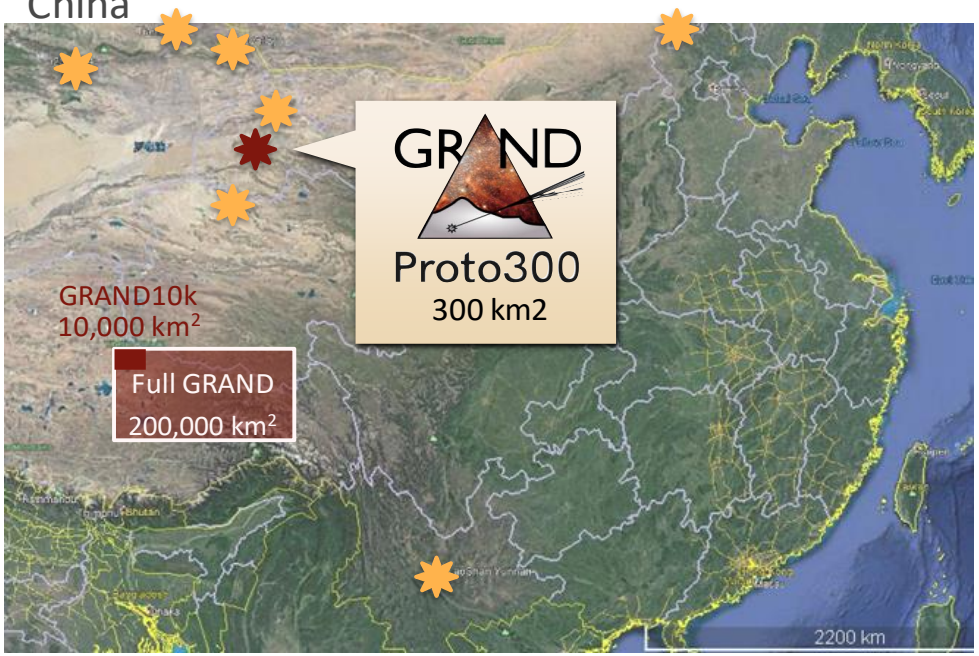
The GRAND Concept

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

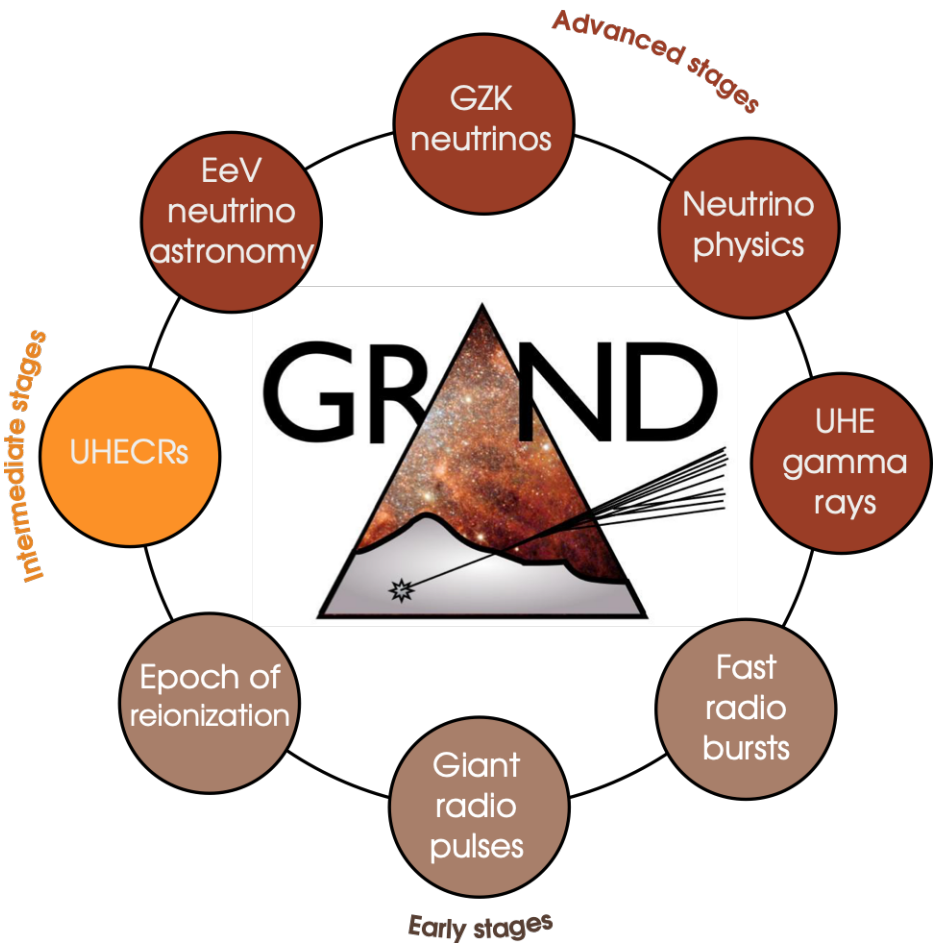
- ✓ Radio environment: radio quiet
- ✓ Topography: mountains/slopes
- ✓ Access, Installation and Maintenance
- ✓ Other issues (e.g., political)

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
	2024	>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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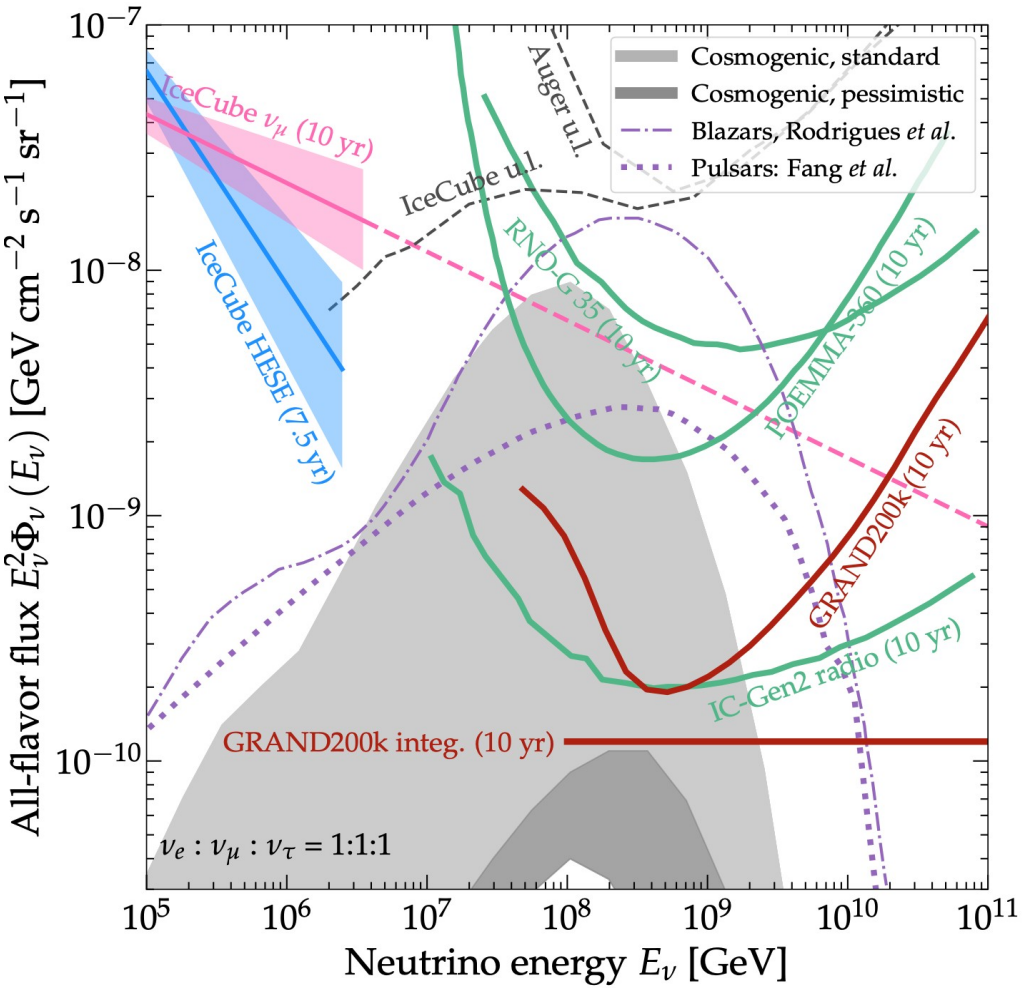
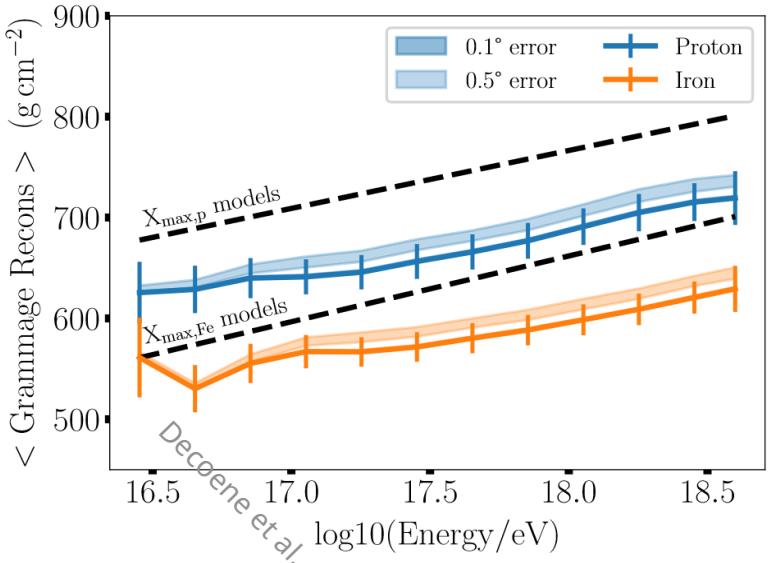
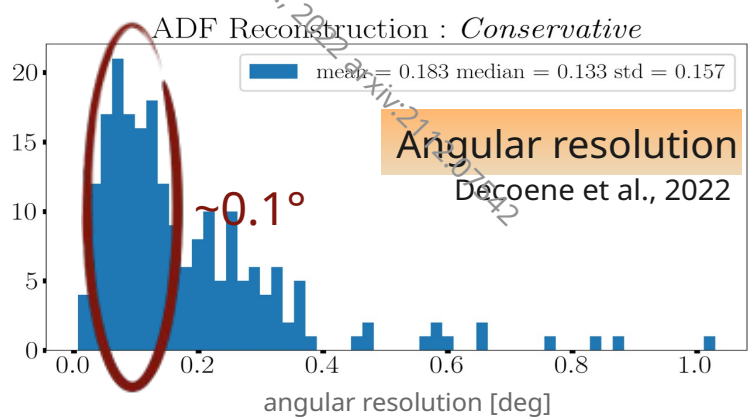
Simulated performances

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

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:

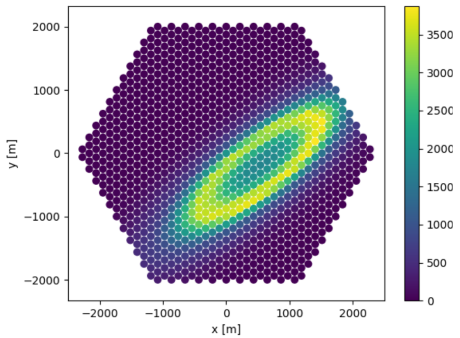
- (intially) Very radio-quiet environment
- Optimised antennas
- Electronics and software capable of 10^8 rejection rate
- Motivation — we can not do it differently

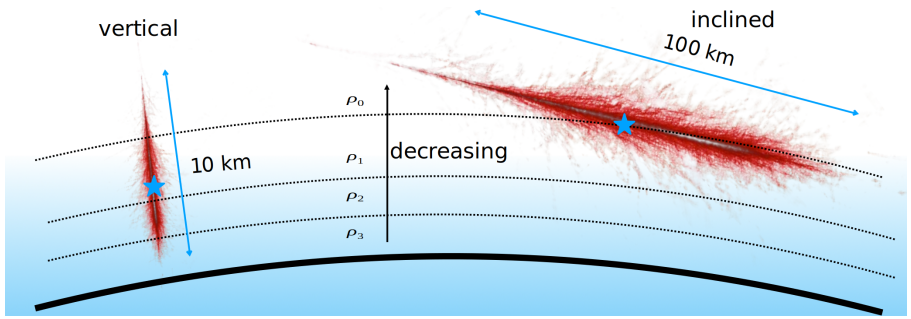
TREND showed that it can be done, GRAND needs to (vastly) optimise it

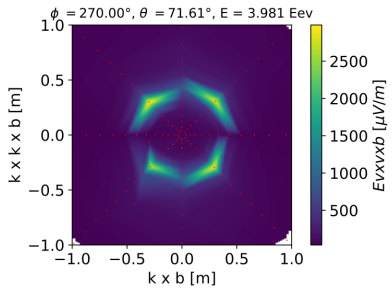
Very inclined EAS reconstruction

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

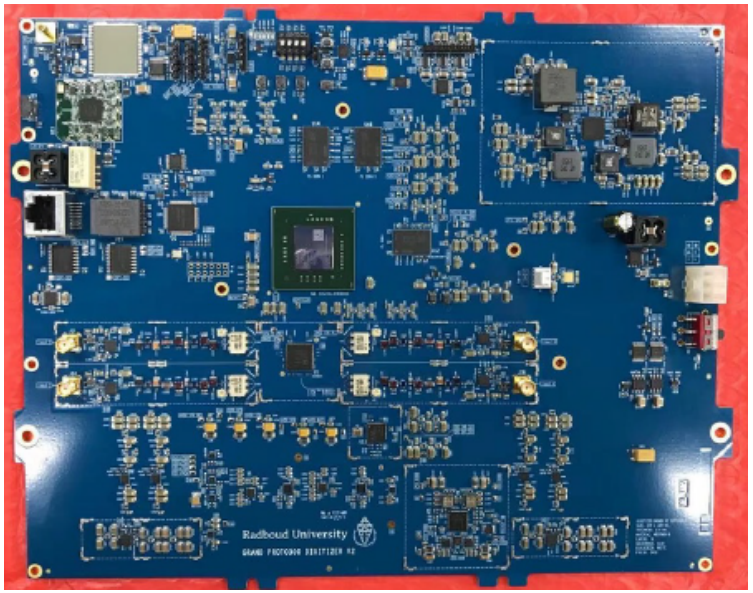
$\sim$ 100 detector units ready, some in use:

- 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, some 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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  - 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*)

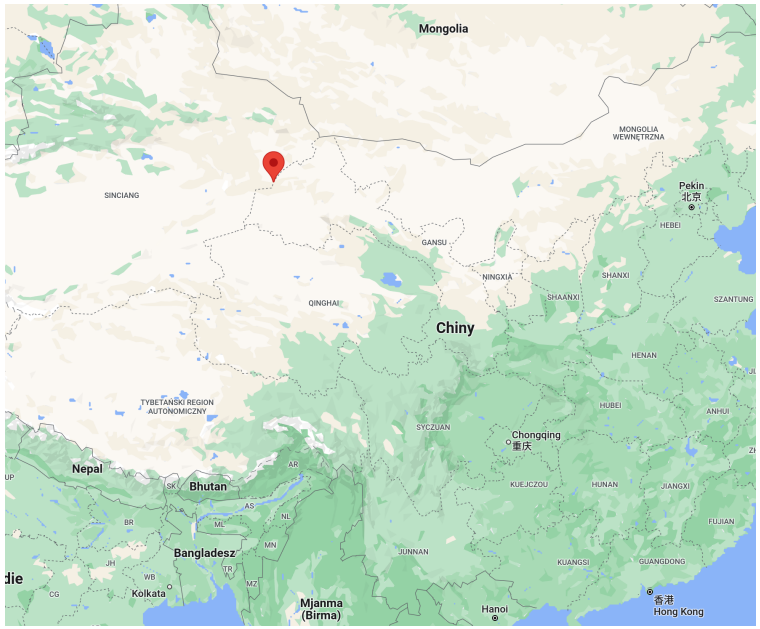
CORSIKA7/CoREAS:
- Generated similar library to ZHAireS one for GP300, for comparison

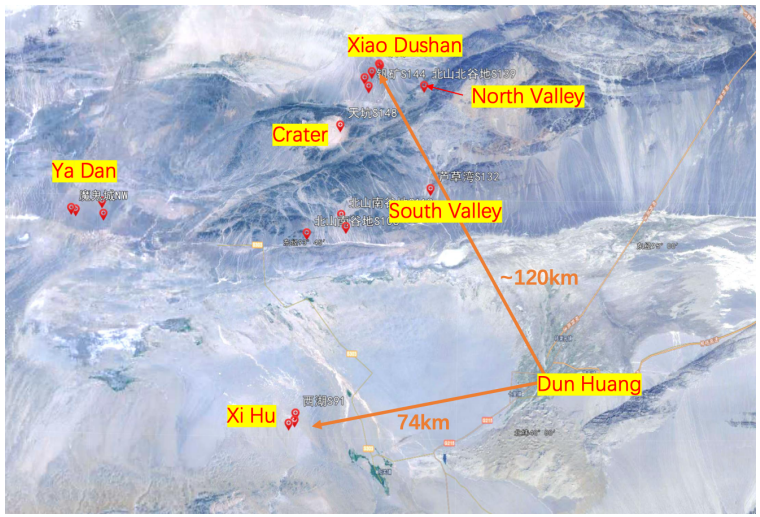
Radio-morphing:
(A. Zilles et al., 10.1016/j.astropartphys.2019.06.001)
- Good agreement with microscopic simulations
- New scaling laws and new interpolation → better accuracy of the peak time and amplitude of the interpolated pulse *(Chiche et al., PoS(ICRC2021)194)*

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

GRANDProto13

- 13 antennas deployed on private land in Xiao Dushan in 2023 (by Xidian University and Purple Mountain Observatory)





GRANDProto13

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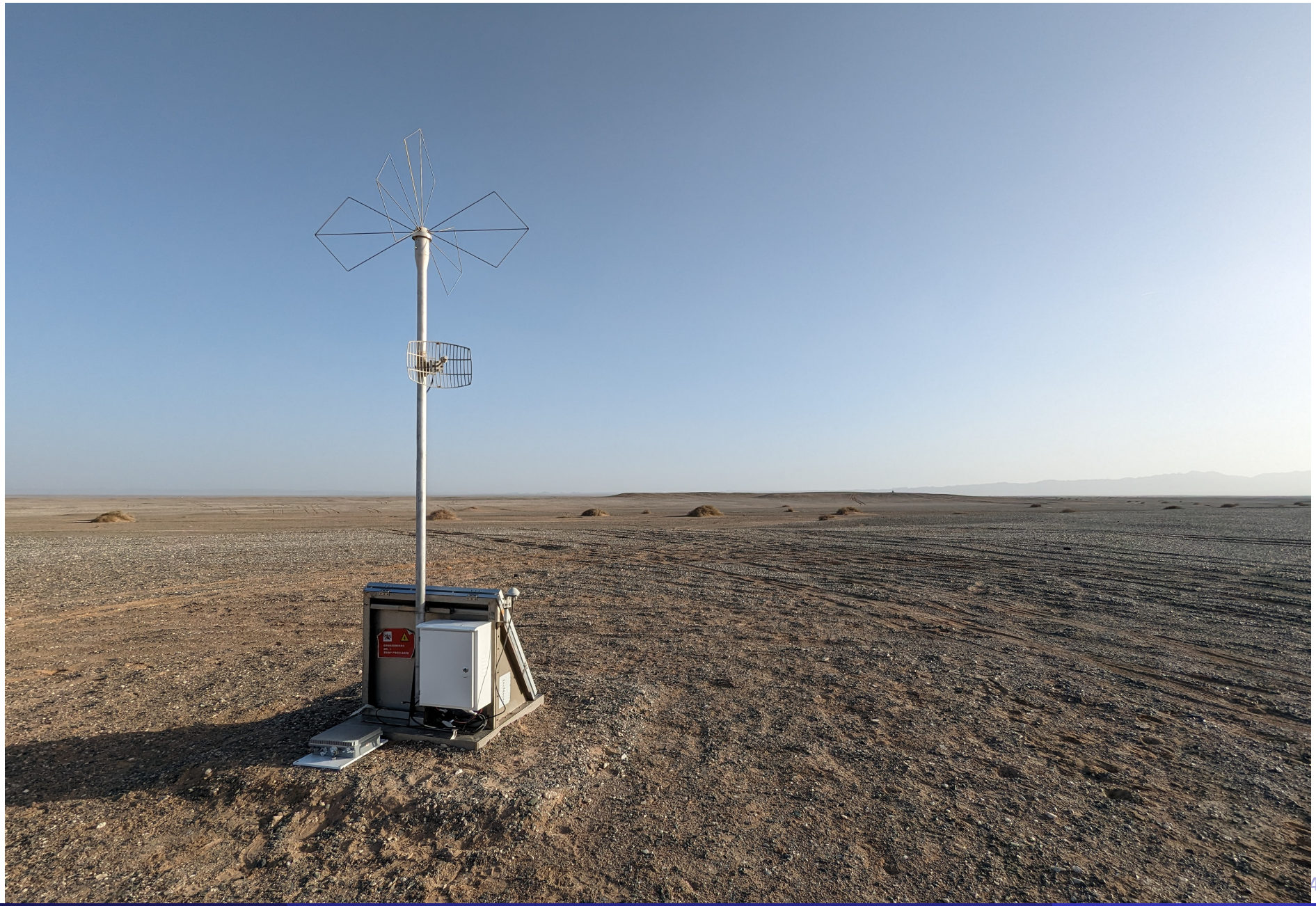

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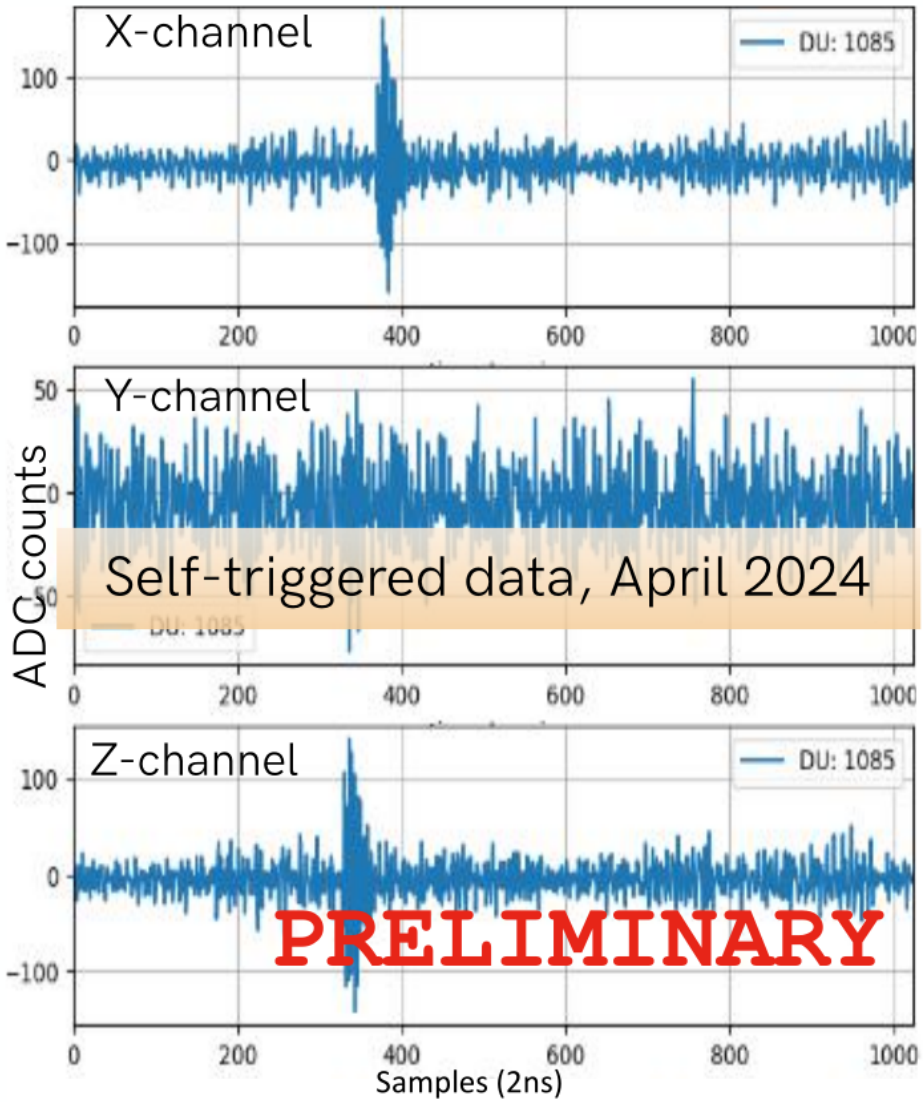
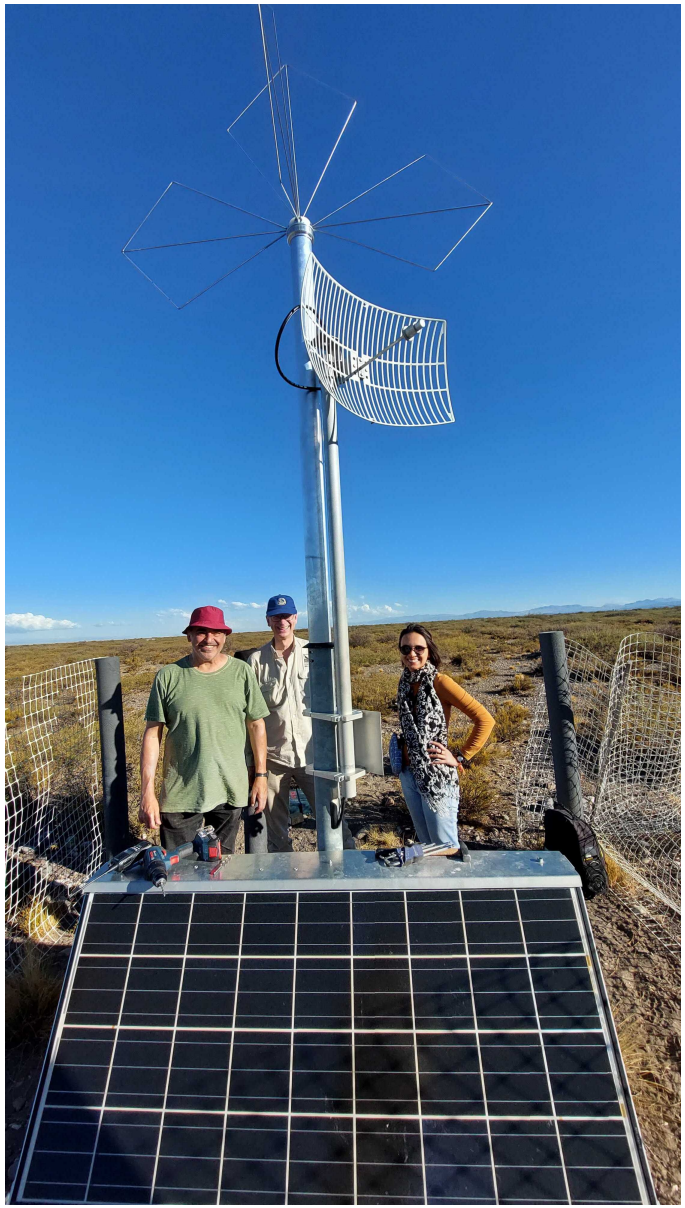
- Triggering and EAS reconstruction (for now too small to do science)
- Hardware development
- Gathered many bias data and single-antenna triggers
- Still in commissioning phase



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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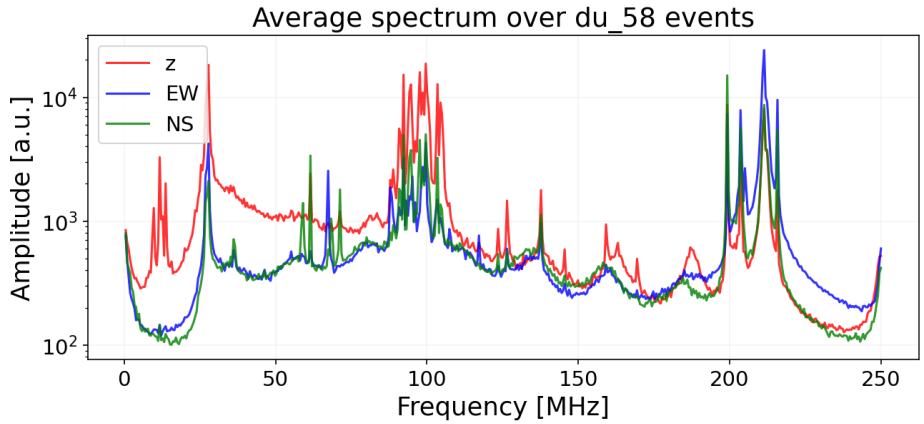

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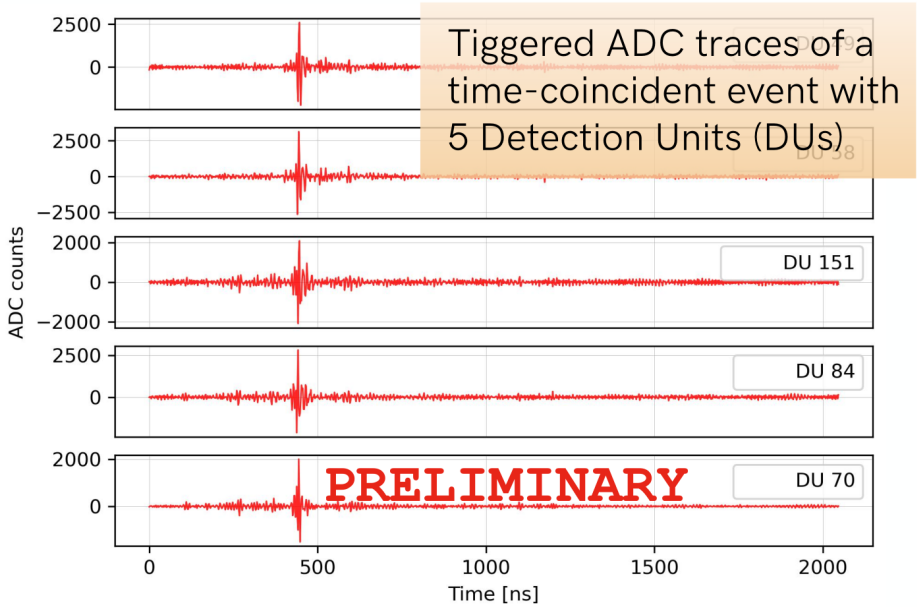
- Hardware tests
- Self-triggering, cross calibration with Auger
- Data transfer and remote access possible through 4G



GRAND@Nancey

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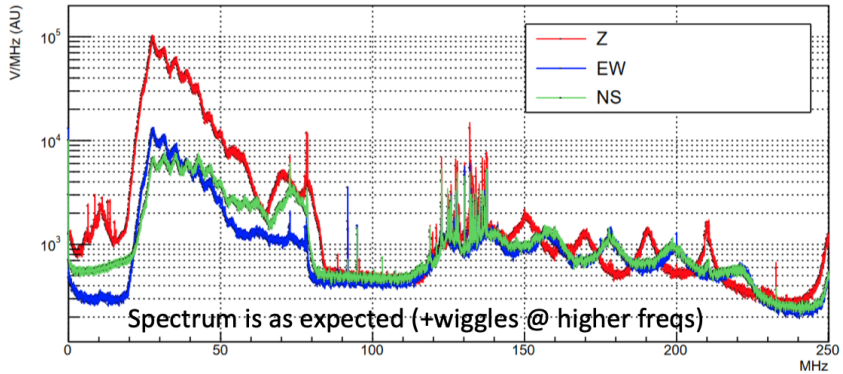
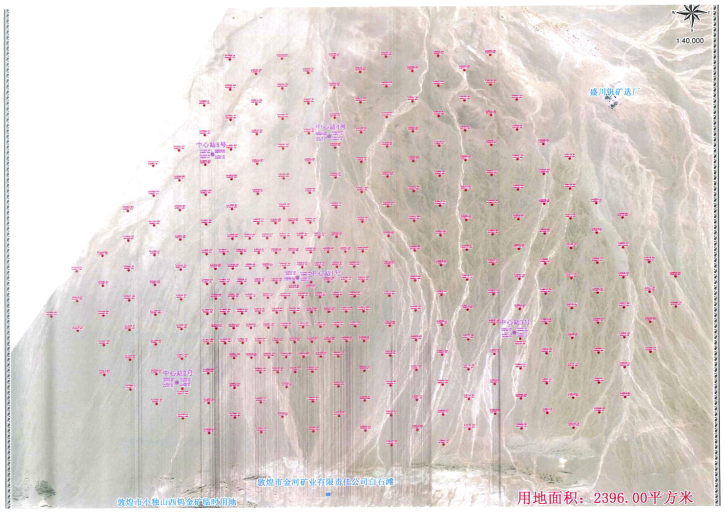
- Easy access (for Europeans)
- Hardware tests only with easy access, too noisy for EAS



GRANDProto300

We are aiming to have $\sim$ 300 antennas deployed in 2025:

- The 200 km^2 site officially approved
- Will incorporate the GP13 site, includes infill
- Extended to 80 antennas this autumn (now too hot)
- Expected $\sim$ 100 UHECRs per day

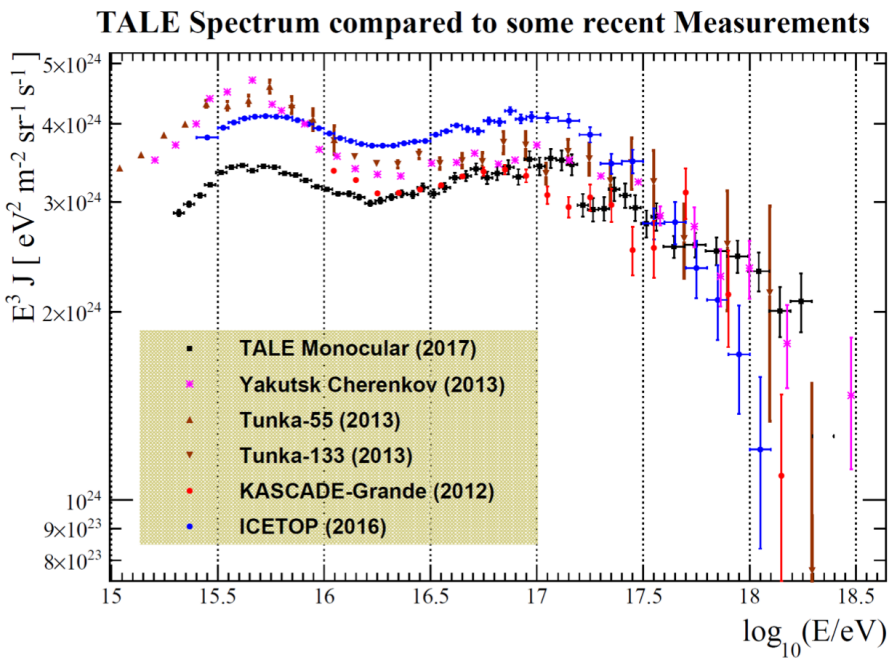


Goals:

- Large scale hardware test
- Autonomous triggering
- Inclined EAS reconstruction
- UHECR comparison with known results
- But also valuable new UHECR & UHEγ results

GRANDProto300 science

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



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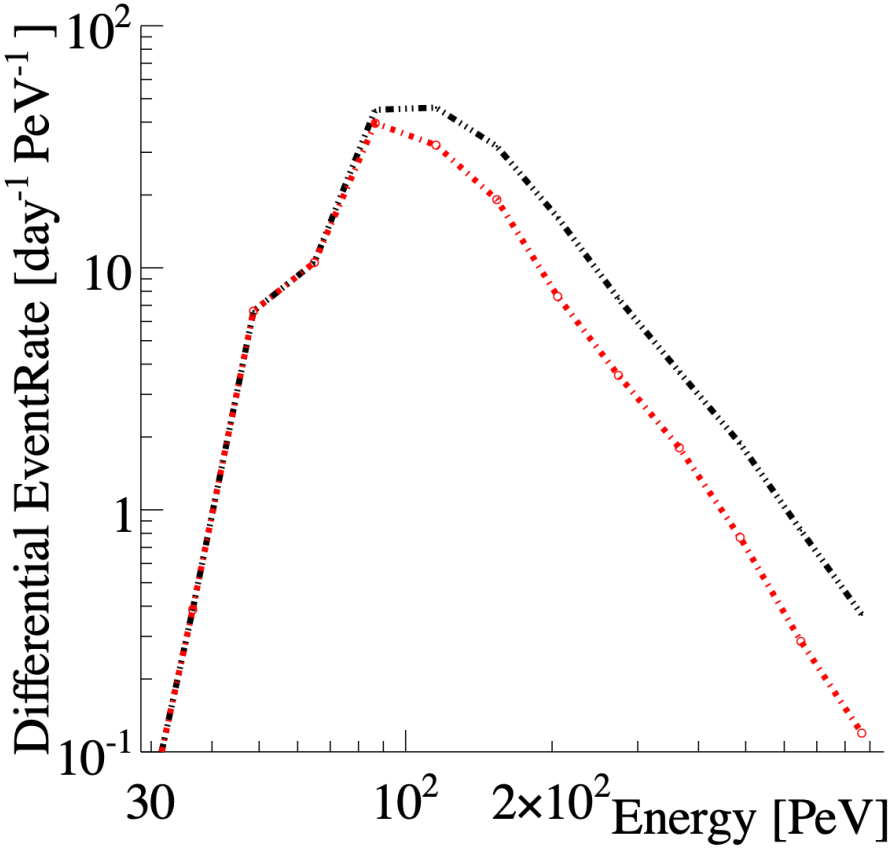
- Discovery/constraining of low-energy large-scale Northern-Hemisphere anisotropy of size 0.01 (constraining existence of nearby UHECR sources)



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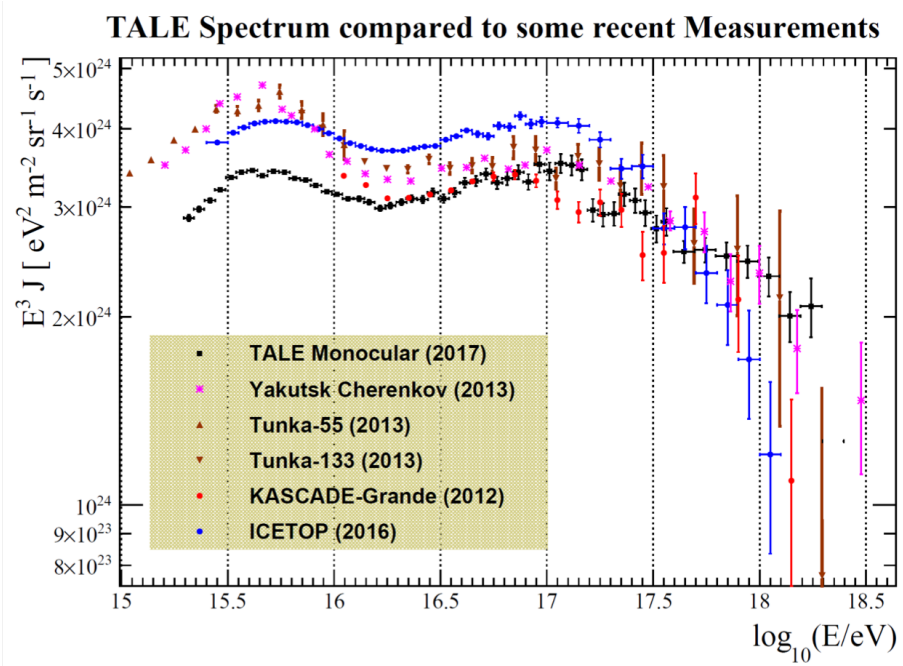
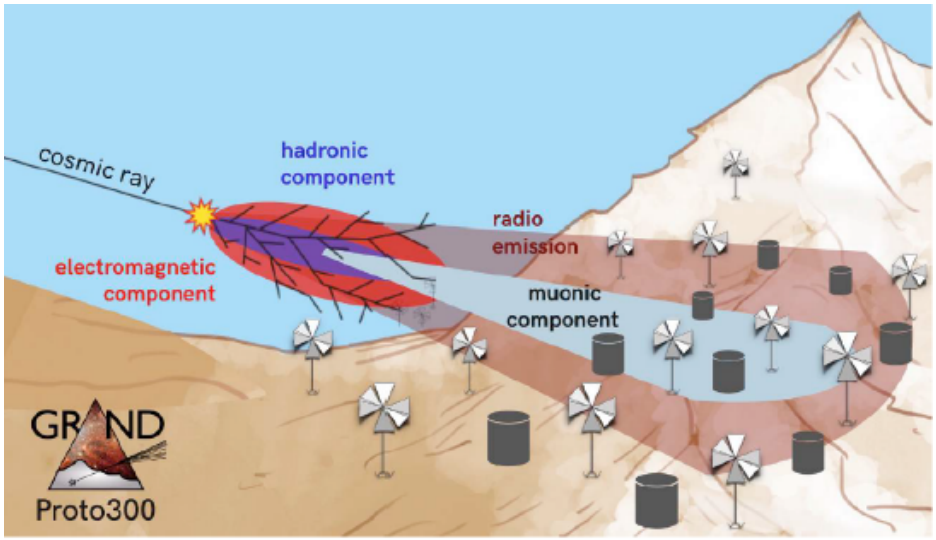
  - study of transition between the Galactic and extra-galactic cosmic rays





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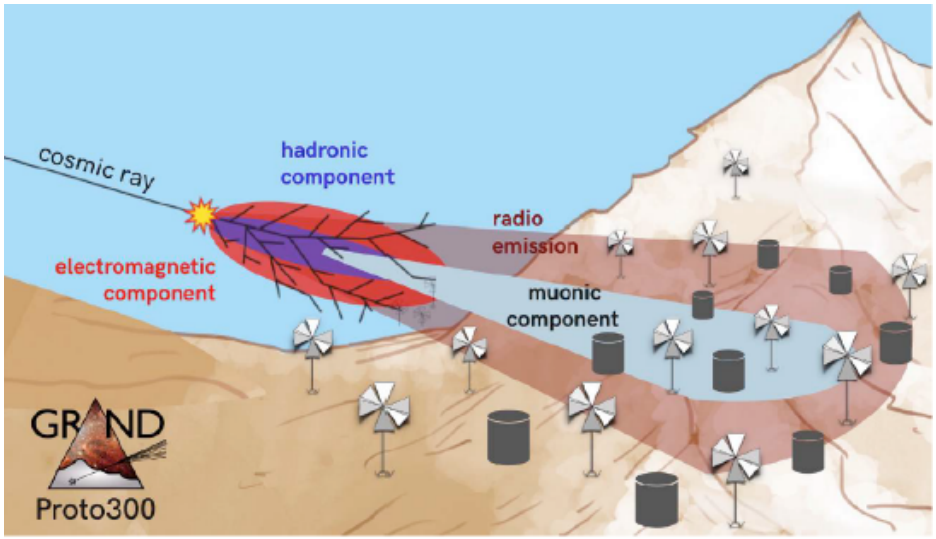

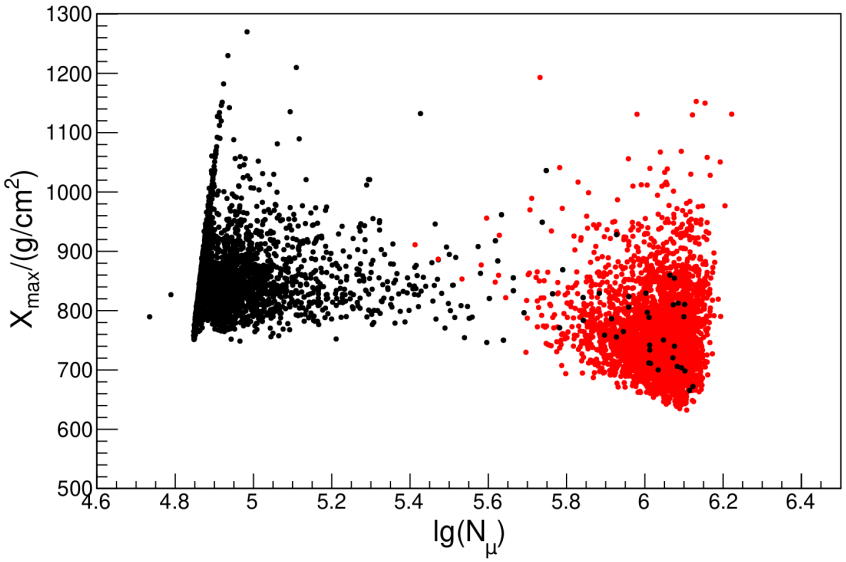

Protons red, gamma black

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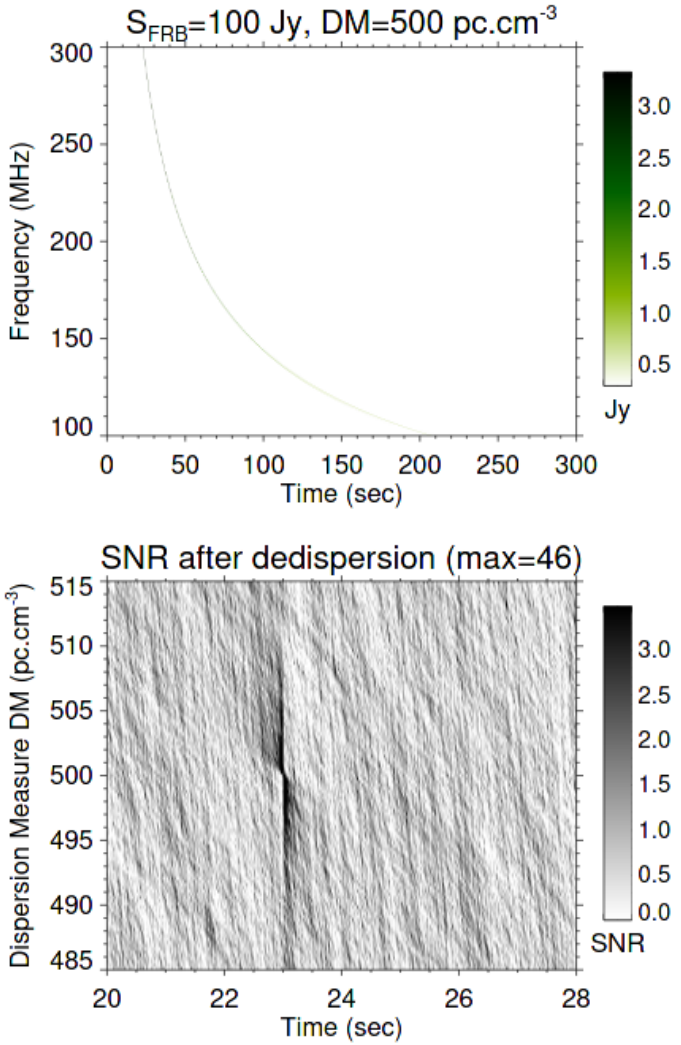
- Radioastronomy: FRBs, giant pulses



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

GRAND today

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

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
- 80 antennas of the GRANDProto300 in the Autumn $\leftarrow$ 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