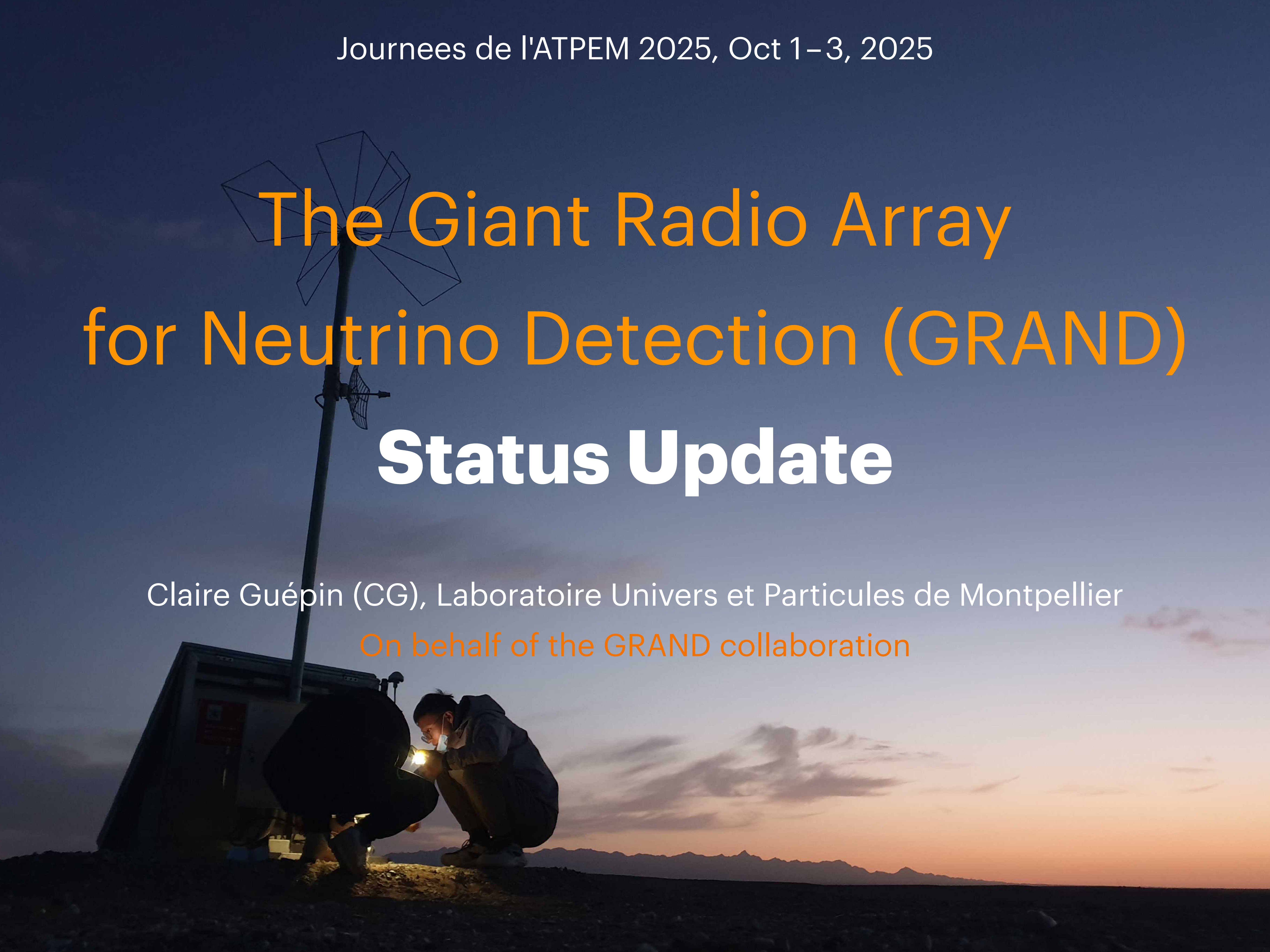


Journees de l'ATPEM 2025, Oct 1–3, 2025

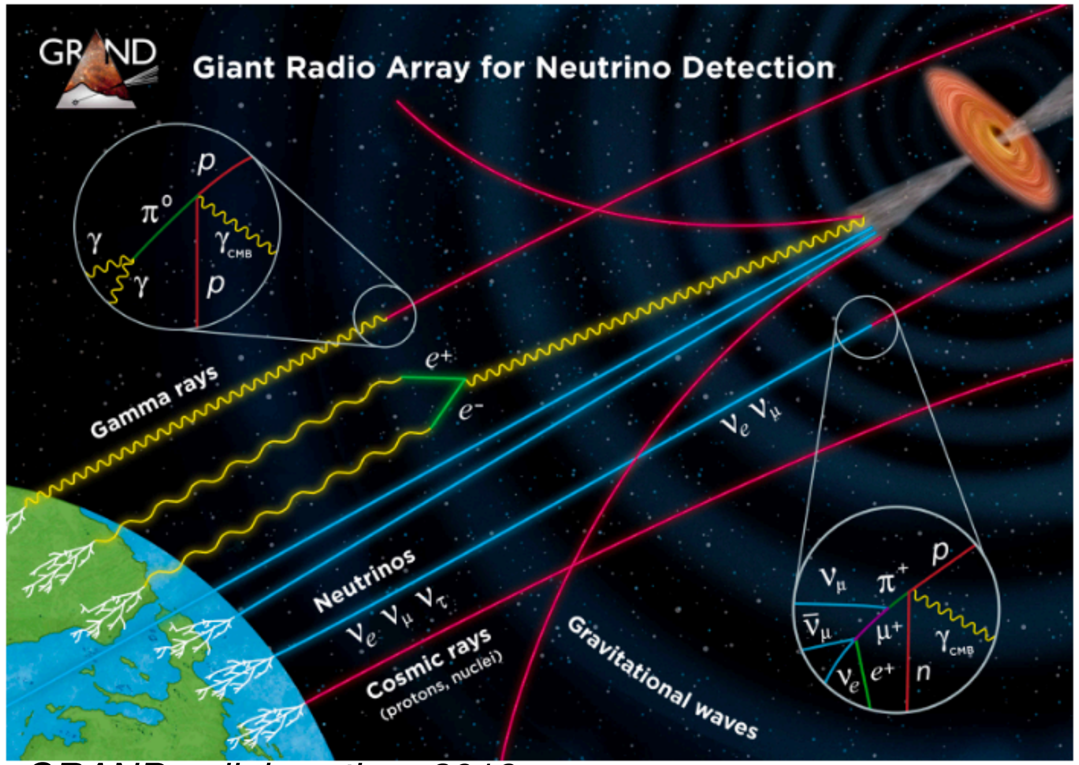
The Giant Radio Array for Neutrino Detection (GRAND)

Status Update

Claire Guépin (CG), Laboratoire Univers et Particules de Montpellier

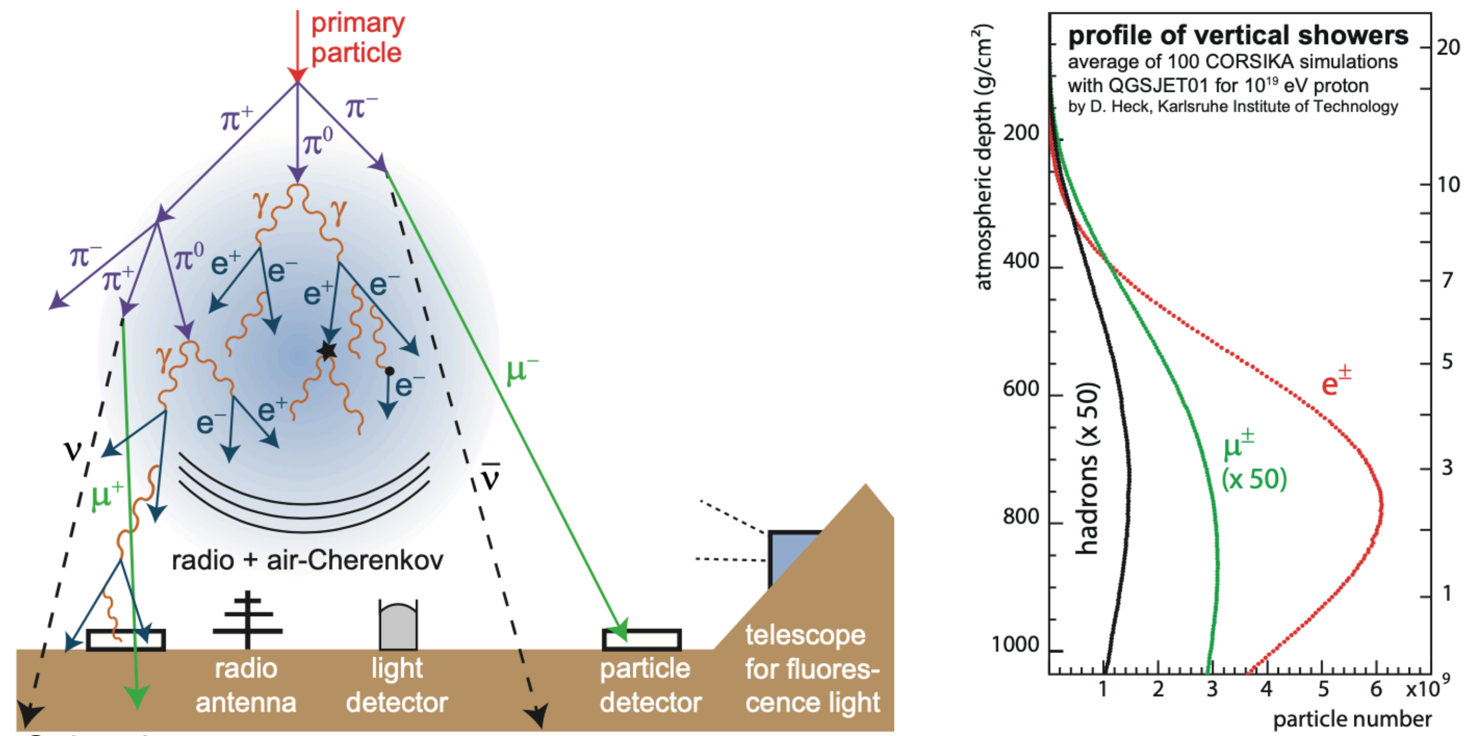
On behalf of the GRAND collaboration

HE-UHE multi-messenger astronomy



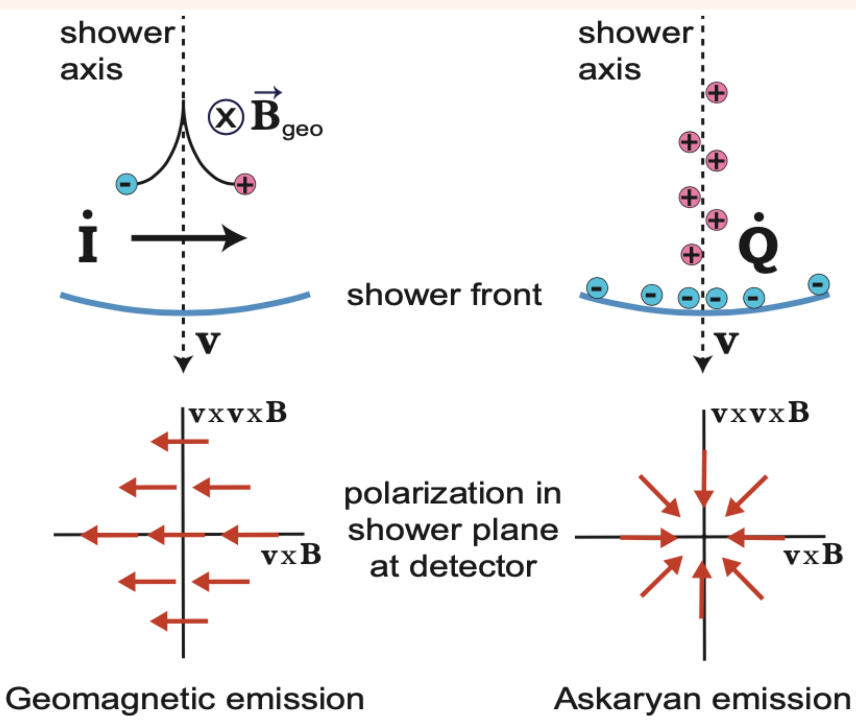
GRAND collaboration, 2019

air shower detection techniques



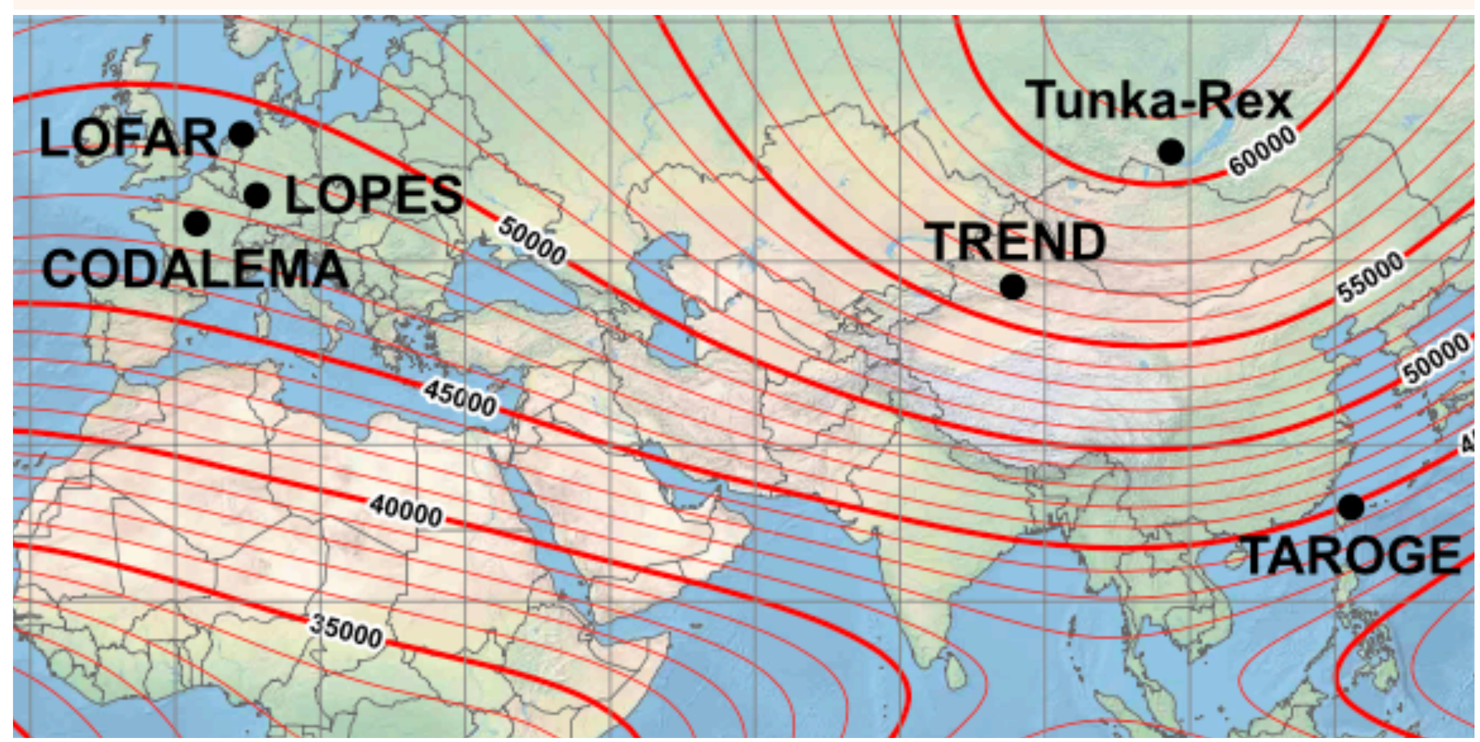
Schröder, 2016

radio detection principe



Schröder, 2016

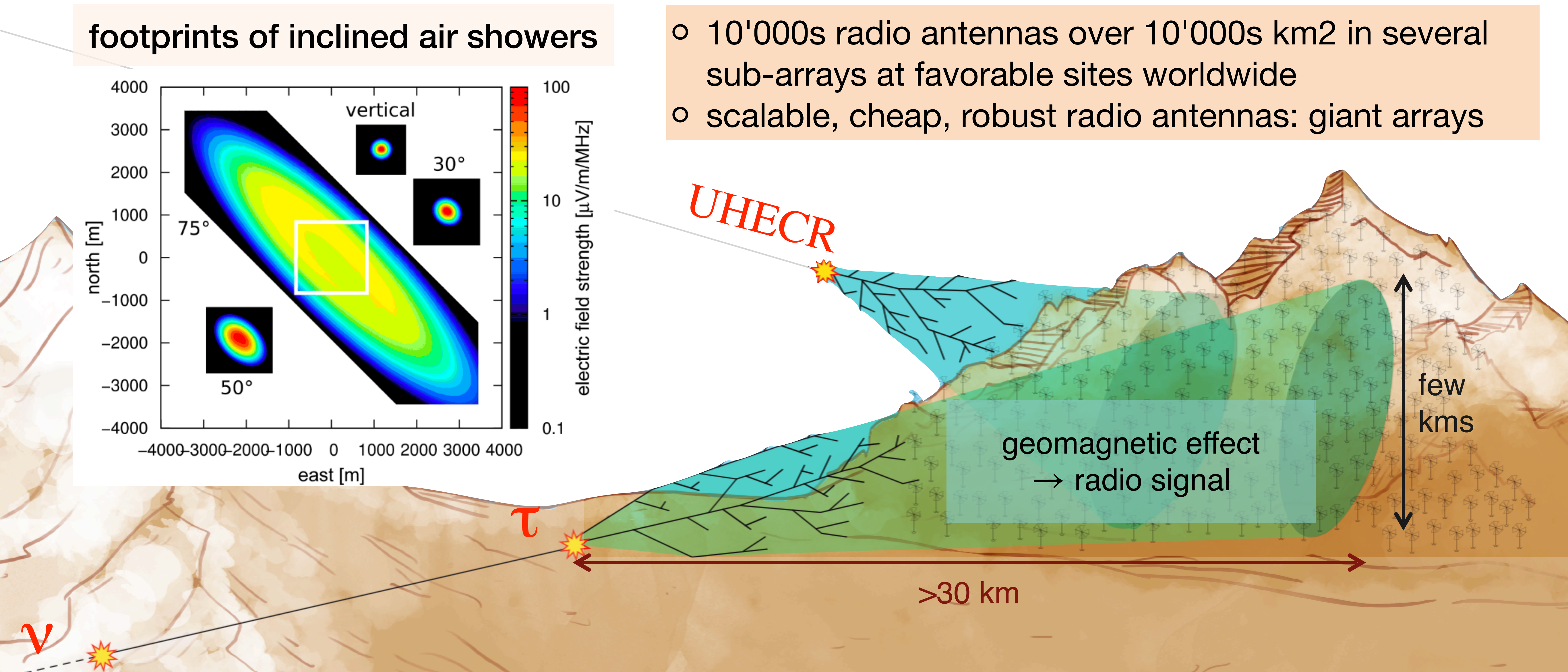
total geomagnetic field strengths



Schröder, 2016

GRAND Concept

- 10'000s radio antennas over 10'000s km2 in several sub-arrays at favorable sites worldwide
- scalable, cheap, robust radio antennas: giant arrays



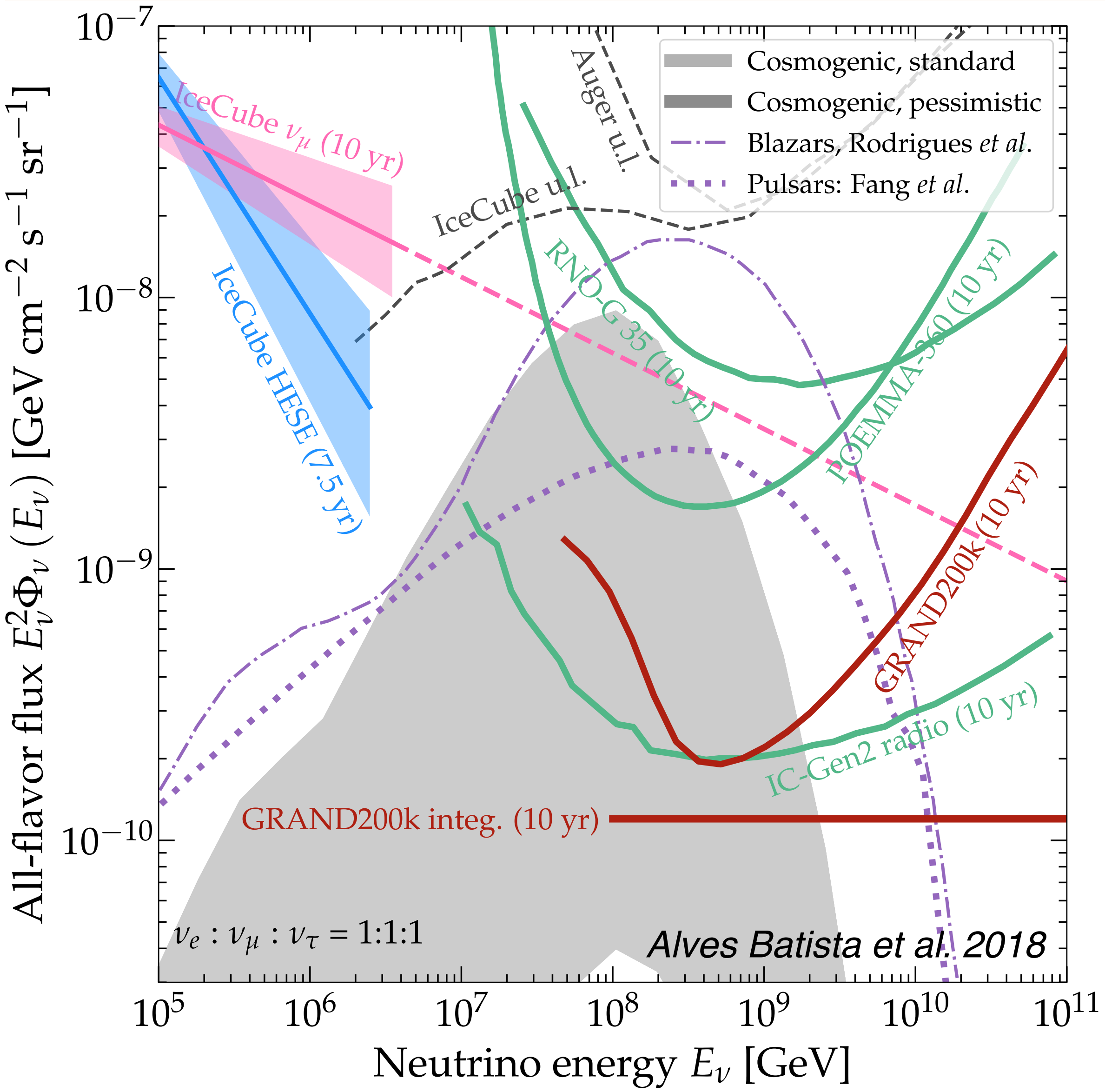
3 Prototypes	GRAND10k	GRAND
2023	2028	203X
cosmic rays $10^{16.5-18}$ eV **autonomous** radio detection of **very inclined** air-showers	**discovery of EeV neutrinos** for optimistic fluxes 10k antennas (Argentina?)	**1st EeV neutrino detection and/or neutrino astronomy!** 2 detectors of 10k antennas: GRAND-North (China) GRAND-South (Argentina?)

Expected performances

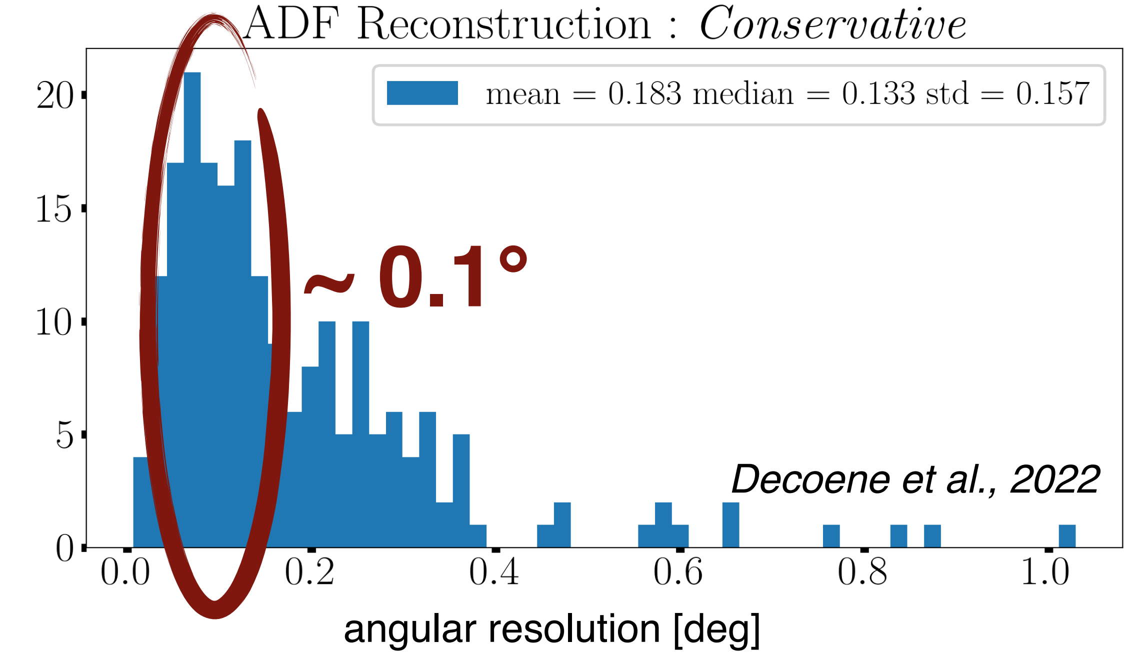
What do we need for UHE neutrino astronomy?

- excellent sensitivity
- sub-degree angular resolution
- wide instantaneous field of view

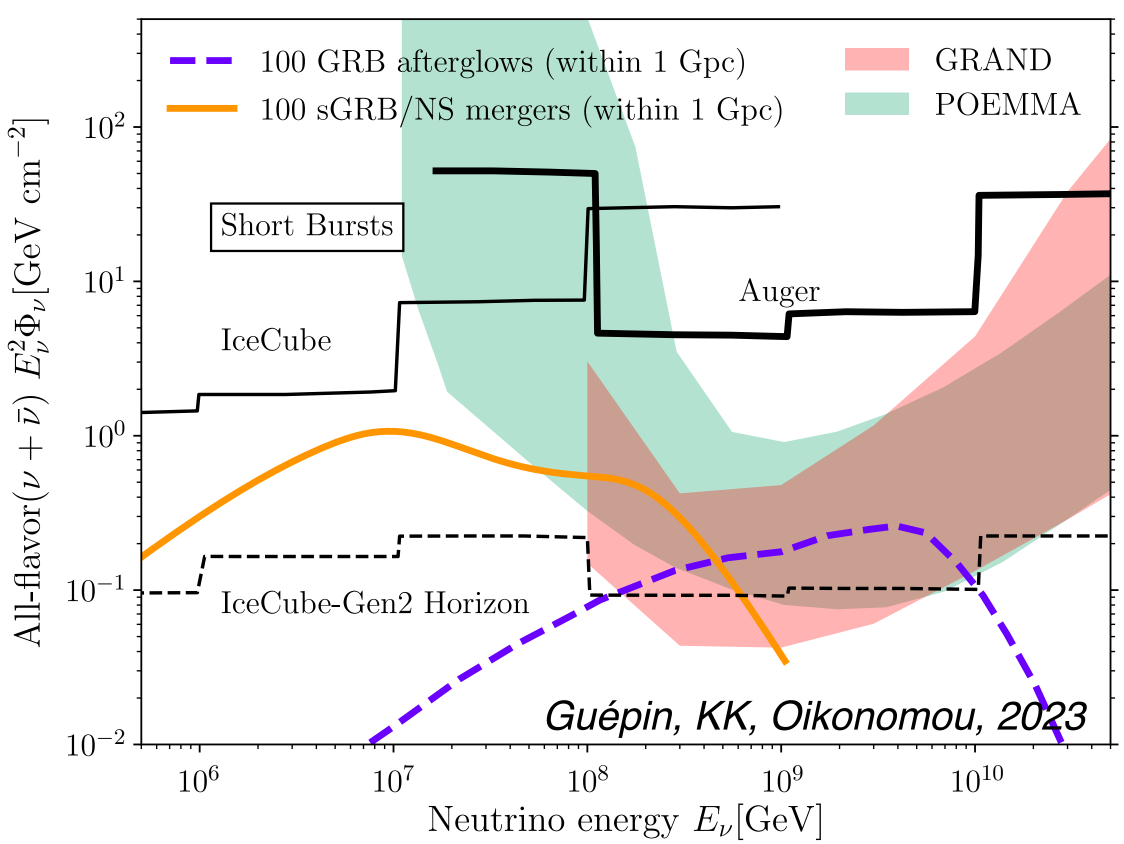
diffuse sensitivity



Angular resolution



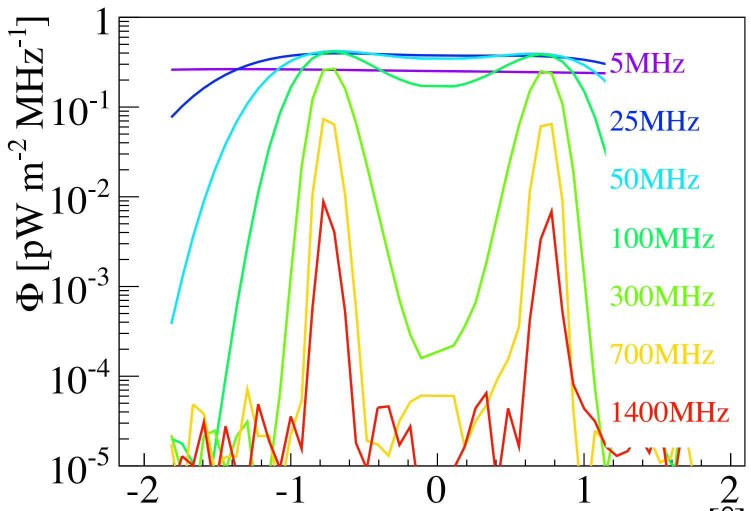
fluence sensitivity



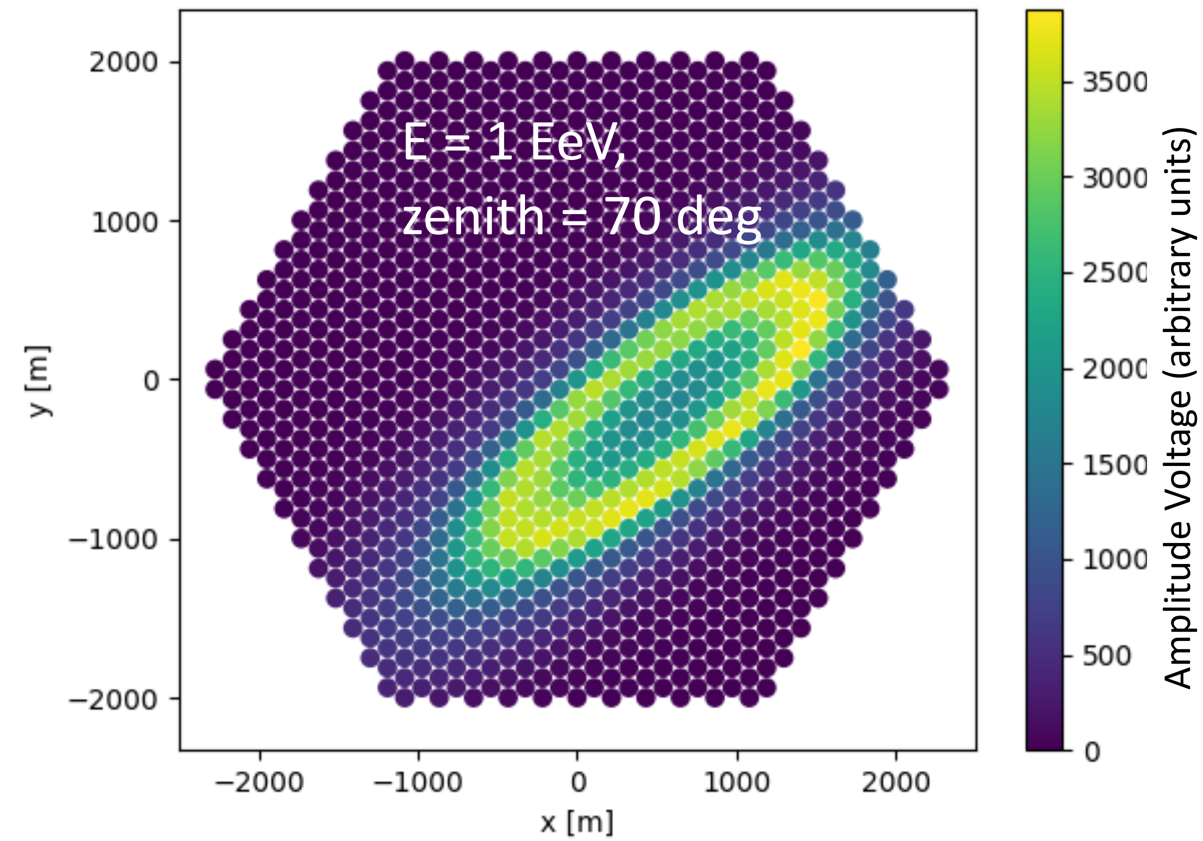
Experience: LOPES, LOFAR, AERA, CODALEMA, TREND, AugerPrime Radio…

Footprint

- Emission ~ point-like around shower max.
- Spherical wavefront
- Emission in few deg. cone around shower axis
- "Cherenkov ring": around 1° at highest frequencies

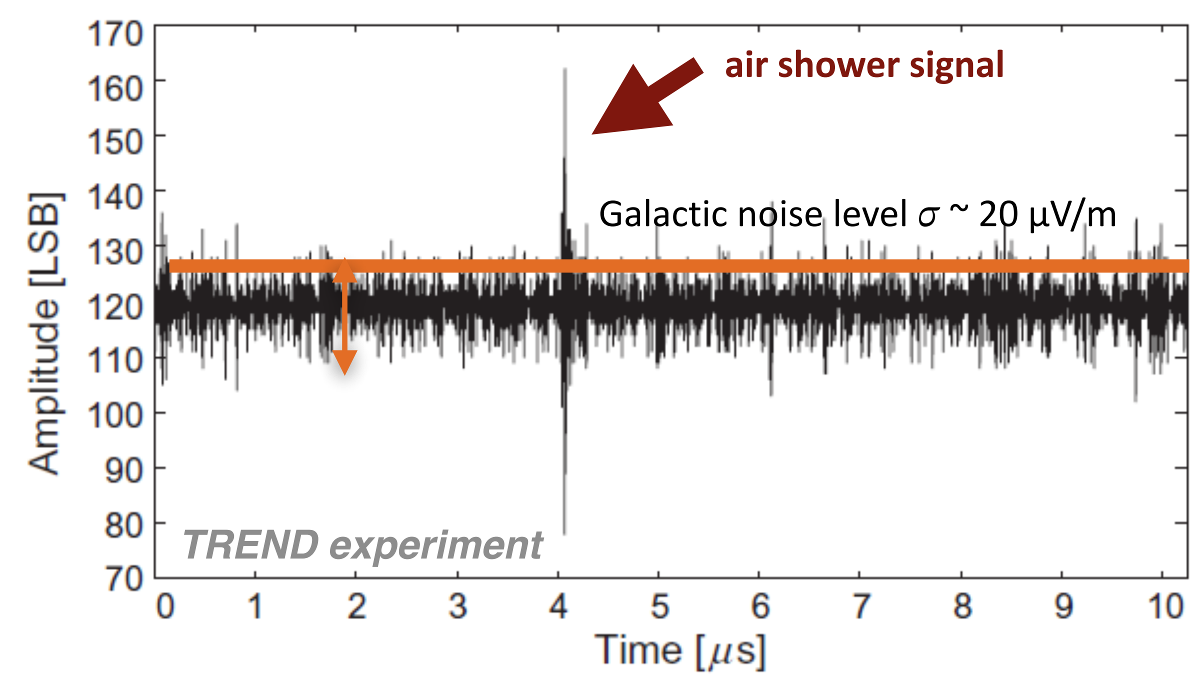


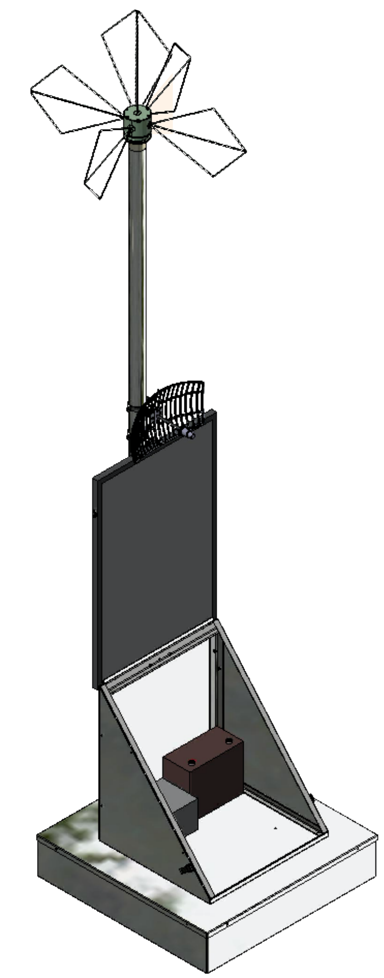
Alvarez-Muñiz et al. 2015



Traces & Pulses

- Frequency range : 50-200 MHz
- Transient pulses, duration: <~ 100ns
- Amplitude of detectable signals at unit level: > 3-5 σ above stationary Galactic background
- Amplitude scales linearly with particle energy
- Detection energy threshold with 5 units: $10^{16.5}$ eV





Low-complexity, robust, low-cost detection units

- Low noise system
- Robust for desert environments & temperature fluctuations
- Simple deployment for large numbers

Autonomous triggering on radio signals

- Ultra-dominant noise: ideal quiet sites
- New electronics development necessary: high sampling rate & autonomous triggering
- Identification of signals + R&D NUTRIG
- Online processing for lower data rate
- Previous successful efforts in other contexts: ANITA, TREND

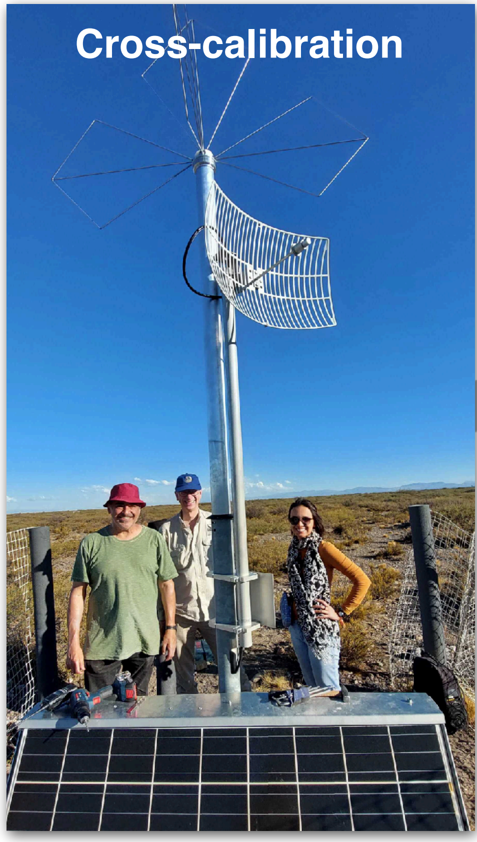
Reconstruction of shower parameters

- Different physics, asymmetries, ground reflections; for very inclined air-showers (B field effects Chiche et al. 2023, Guelfand et al. 2024)
- New reconstruction methods to develop & test (Decoene et al. 2022…)

Data volume & transfer: low-rate, low-power

- Huge data volume (~10 kBy/trigger)
  - GP300 (nominal) rate: L1 trigger: 1 kHz, L2 trigger: 10 Hz
  - NUTRIG target: L1 trigger: 100 Hz, L2: 1 Hz
- Offline treatment reduction to few infos (trigger time, amplitude, polar) —> to implement online

2023-2024: turning point for GRAND



Deployment on 3 sites and first experimental data!
- Commissioning phase. GRAND@Auger: 10 antennas. GRANDProto300: 65 antennas

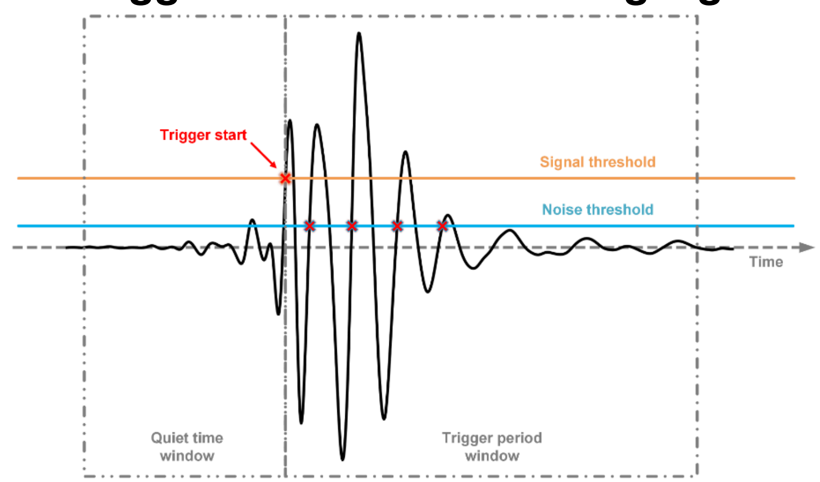
Development of Software & Analysis tools
- GRANDlib: Python library for GRAND data analysis & simulation
- Data Challenge 2: realistic simulation library & reconstruction tools for data analysis

Beginning of R&D for the next phases

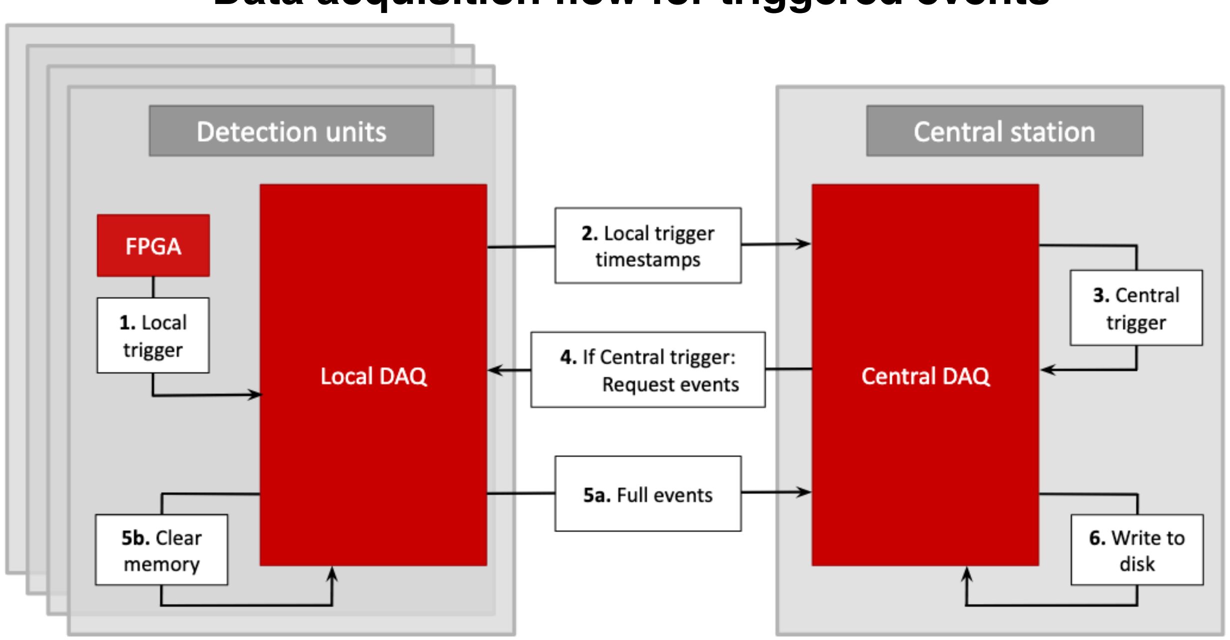
GRAND Coll. arXiv:2509.21306

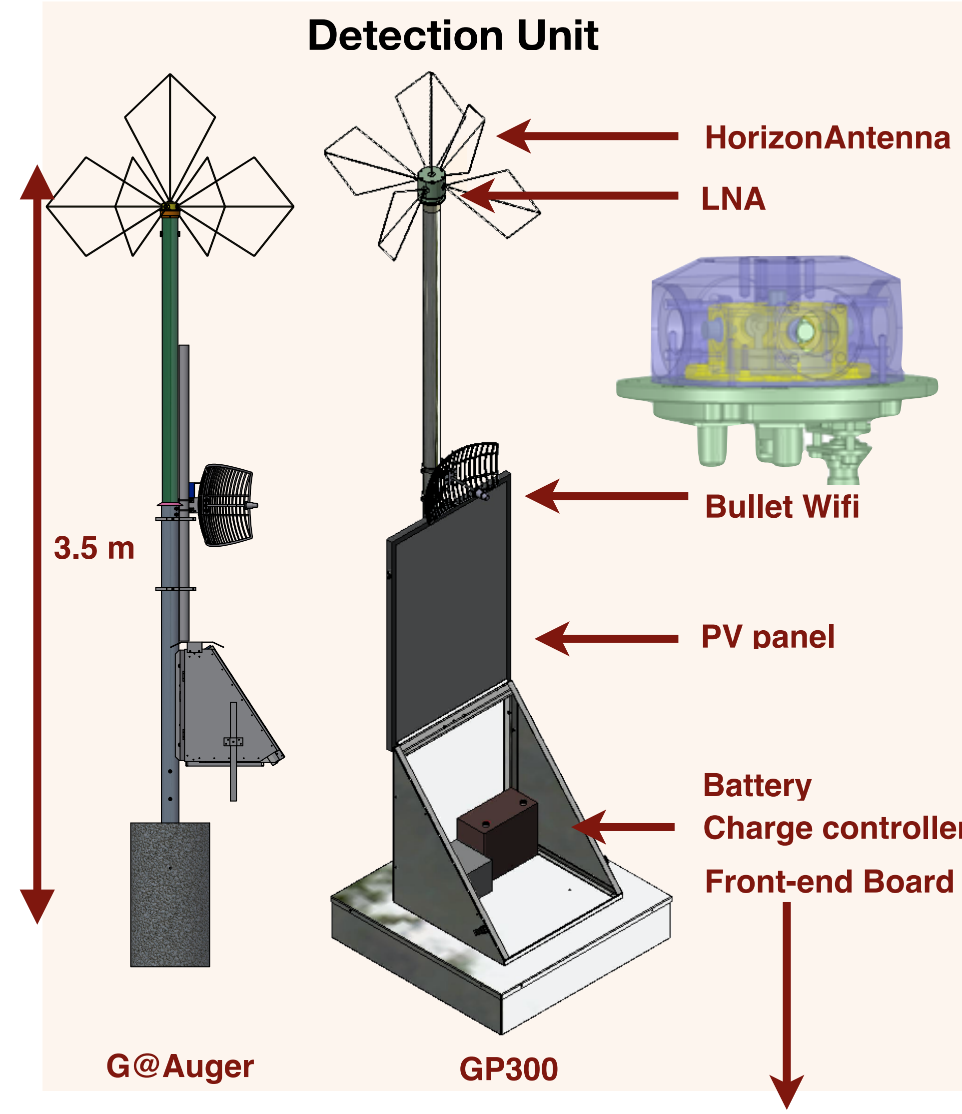
- Same overall components, common data format
- Antenna arms: response differ due to mechanical structure
- Front-End Board: ADC 500MS/s,14 bits, FPGA + 4 CPUs
- Trigger algorithm: unbiased trigger, 10 s, 20 Hz mode
- Testing robustness to environments: heat, humidity, noise level (LNA), stability, coincident trigger

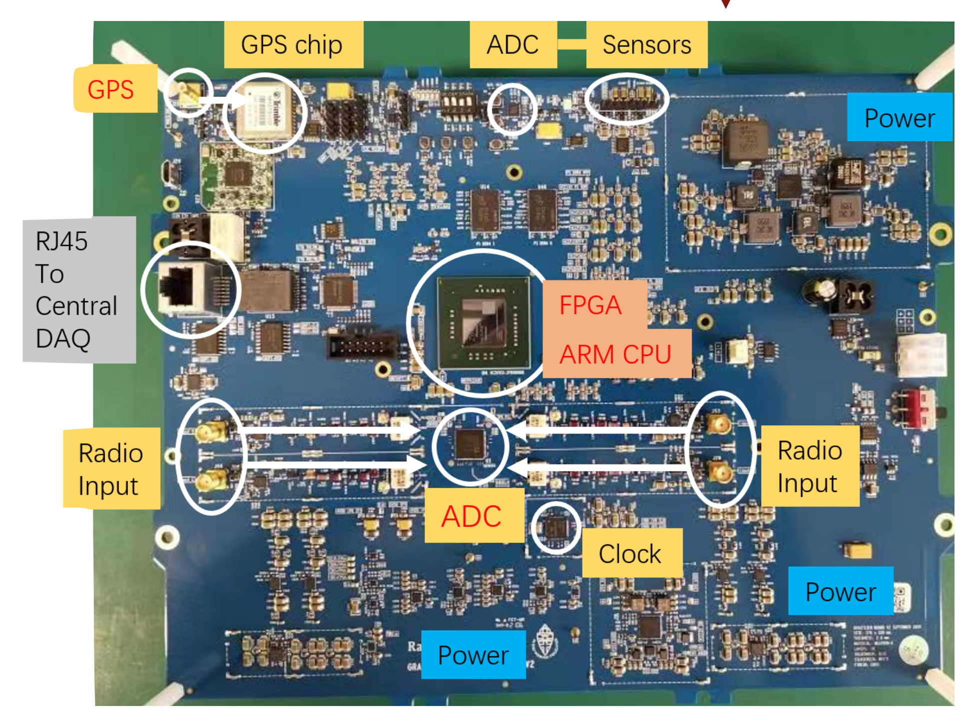
Local Trigger flow for an incoming signal



Data acquisition flow for triggered events





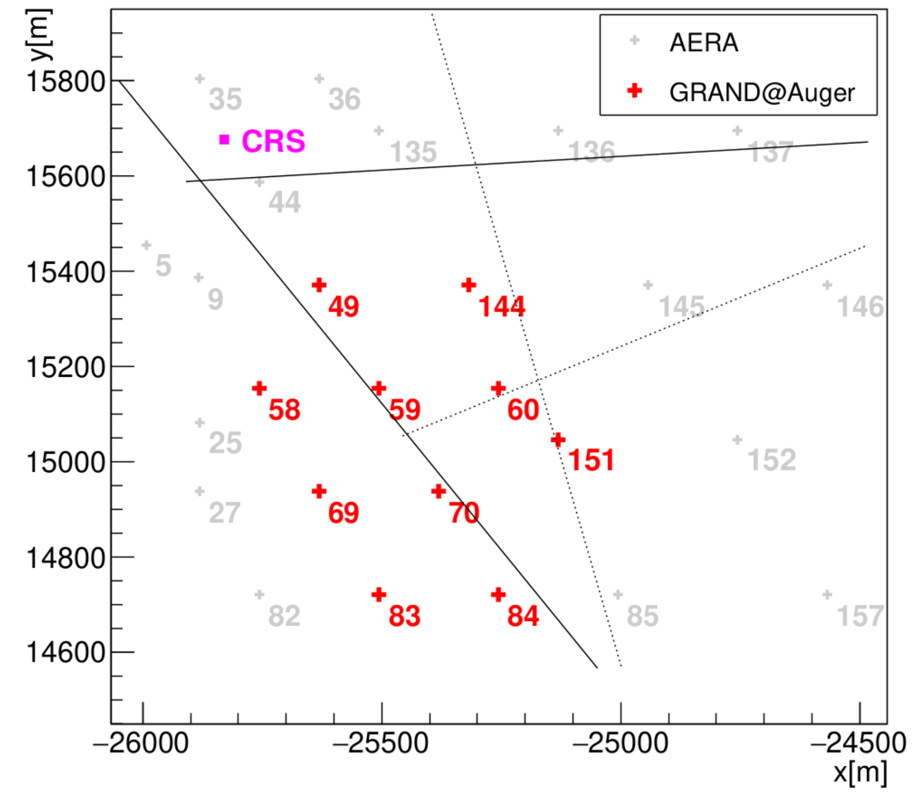


GRAND Coll. arXiv:2509.21306

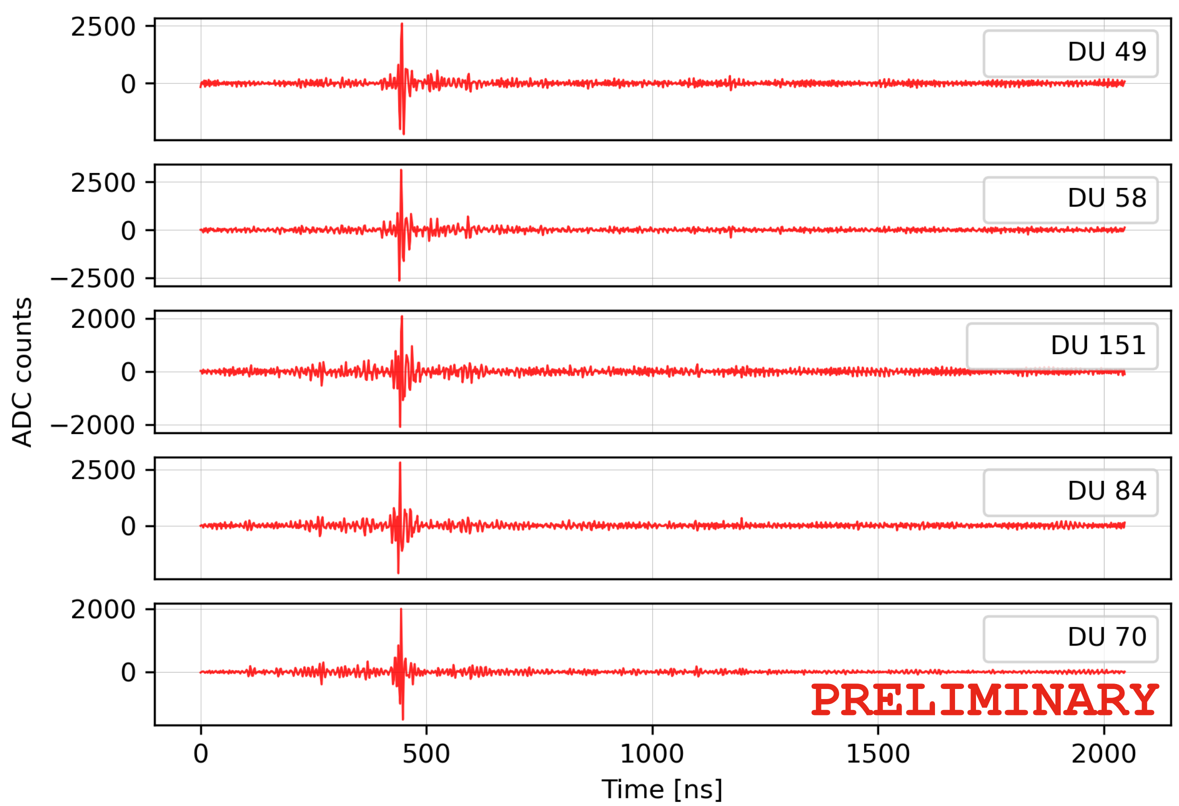
Cross-calibration with Auger detectors:
1 coincident event/day expected

10 antennas deployed:
Auger mechanical structure + infrastructure
- Hardware tests: set-up stability
- Firmware tests, trigger / transient detection

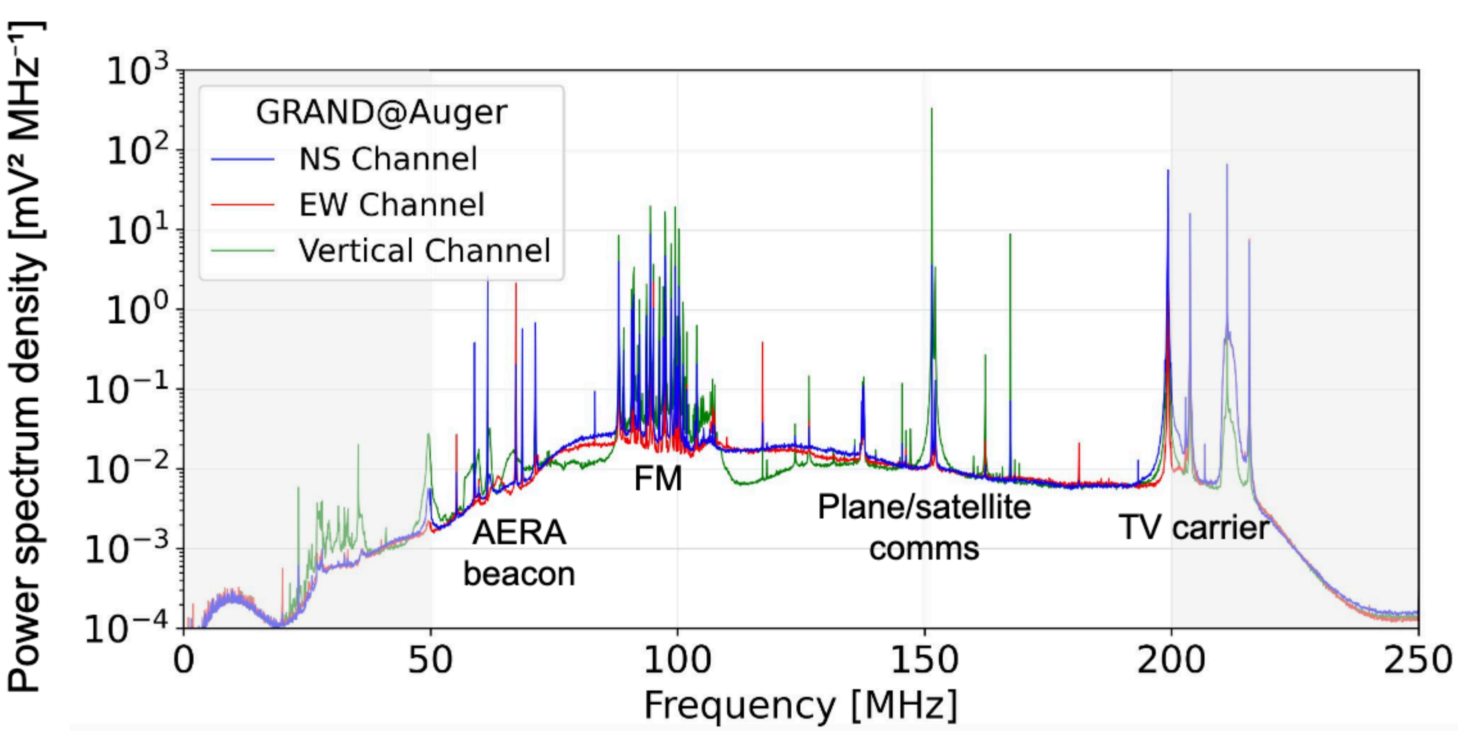
Layout GRAND@Auger



Triggered ADC traces of a time-coincident event with 5 Detection Units (DUs)



Power Spectrum Density



Prototypes: GRANDProto300

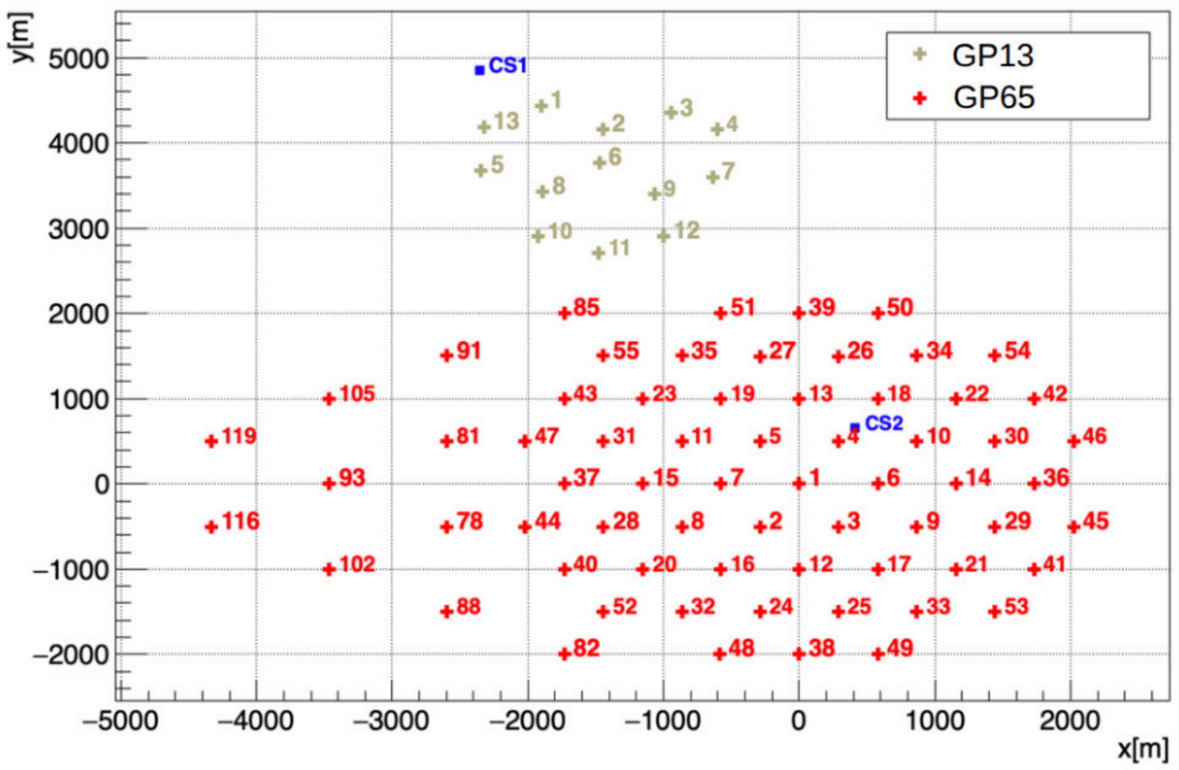
GRAND Coll. arXiv:2509.21306

GRAND detection concept validation:
Autonomous triggering & inclined EAS reconstruction

65 antennas deployed

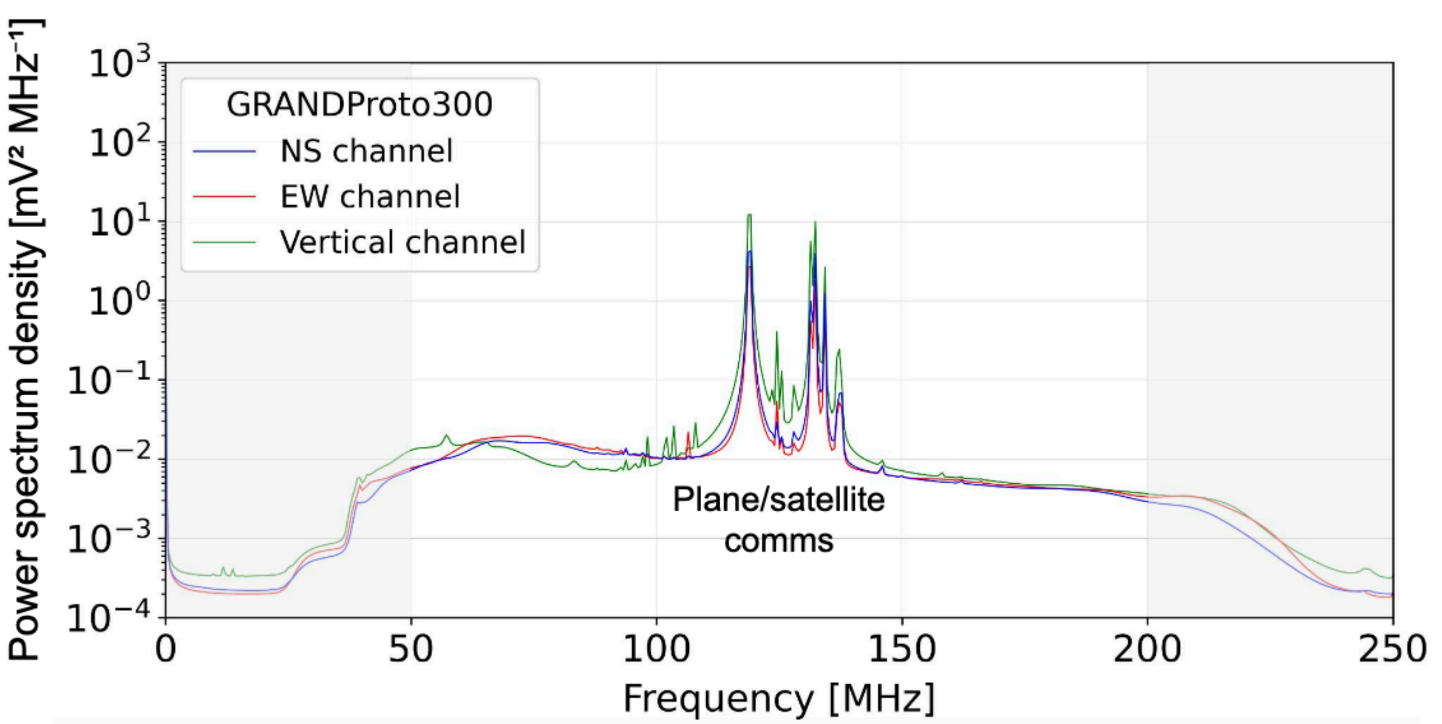
- Hardware tests: long-term stability, self-made noise control, LNA optimization
- Firmware tests, trigger / transient detection
- Cosmic ray search

Layout GRANDProto300



- Clean spectra for all antenna arms [30 - 250 MHz]
- Peaky lines from airplanes, FM, etc.
- Galactic noise + instrumental noise

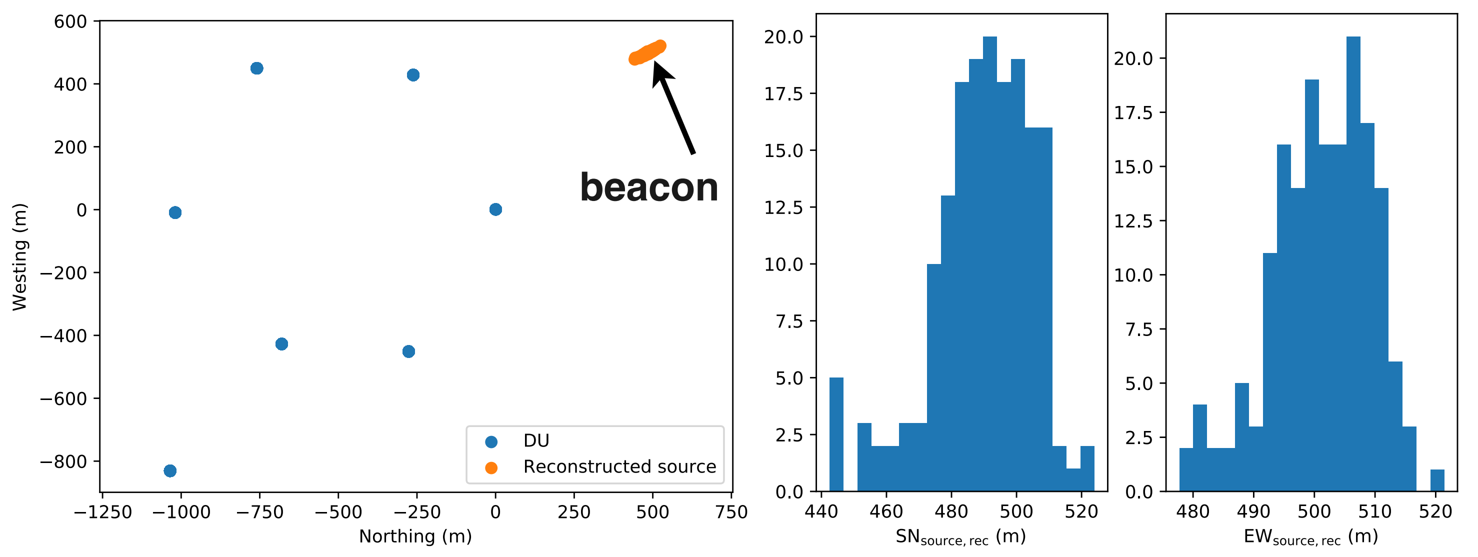
Power Spectrum Density



slide by Sei Kato Vietnam 2024

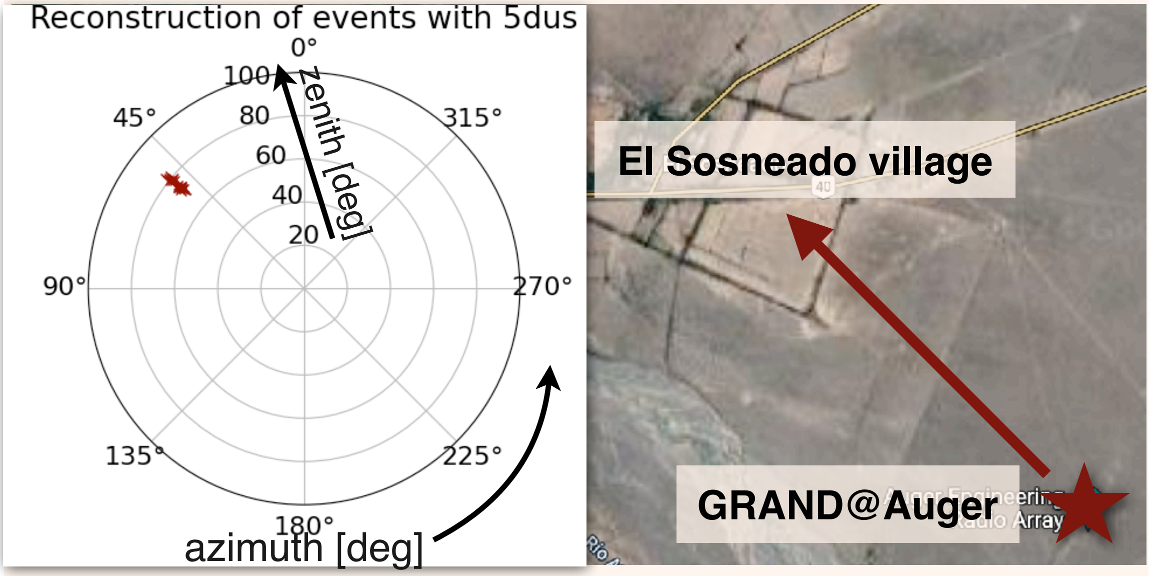
First set of reconstructed events

GRANDProto300



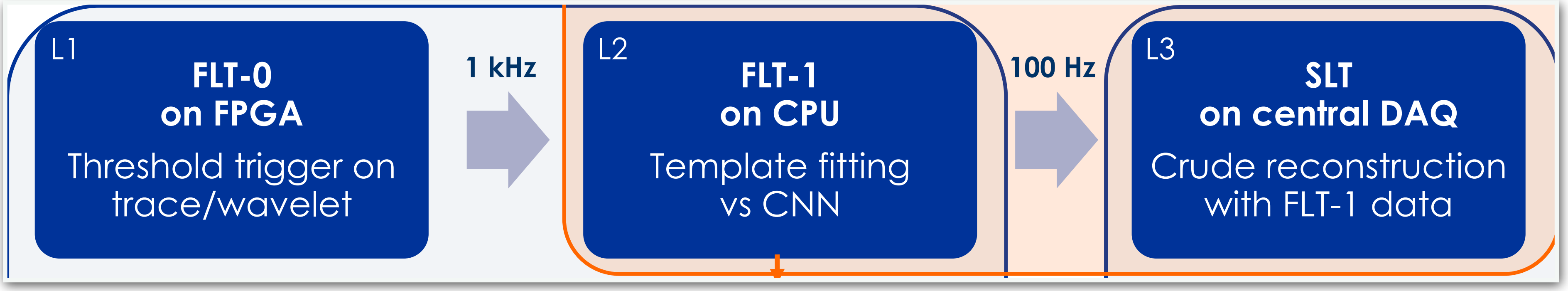
offline coincidence search from beacon
- spherical wave front model (SWF)
- 171 events reconstructed /173 pulses emitted in time window
- 10 m std deviation on Northing/Westing positions

GRAND@Auger



online coincidence search at central DAQ (L3)
- 3 consistent independent analysis (Analytic PWF, PWF/SWF)
- azimuth and zenith consistent with direction of village, towards ground

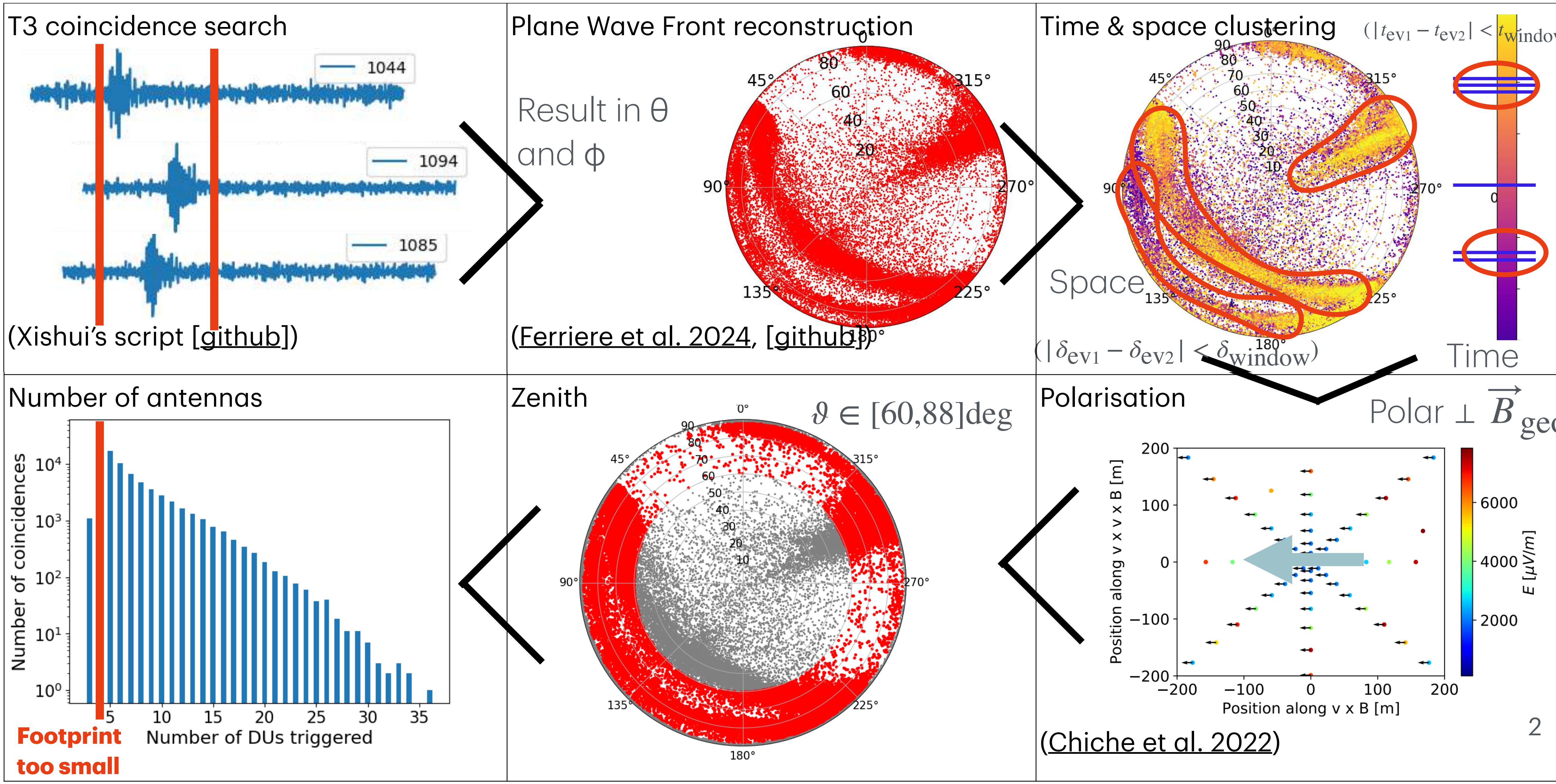
Conclusions:
- **Trigger system works**: L1 for GP300, L1 + L3 for GRAND@Auger
- **GPS timing works**
- Work in progress: coincidence detection efficiency, system stability, sensitivity (Galactic noise)



For more detail:
Mitra et al., PoS(ICRC2023)236,
Duan et al., PoS(ICRC2023)298,
Ma et al., PoS(ICRC2023)304,
Chen et al., PoS(ICRC2023)1023,
Xuet al., PoS(ICRC2023)1024,
Chiche et al., PoS(ARENA2024)059,
Kotera et al., arXiv:2408.16316v2

Cosmic-ray (CR) event search

PRELIMINARY



slide by J. Lavoisier

Realistic simulation libraries: GRAND "Data Challenge 2"

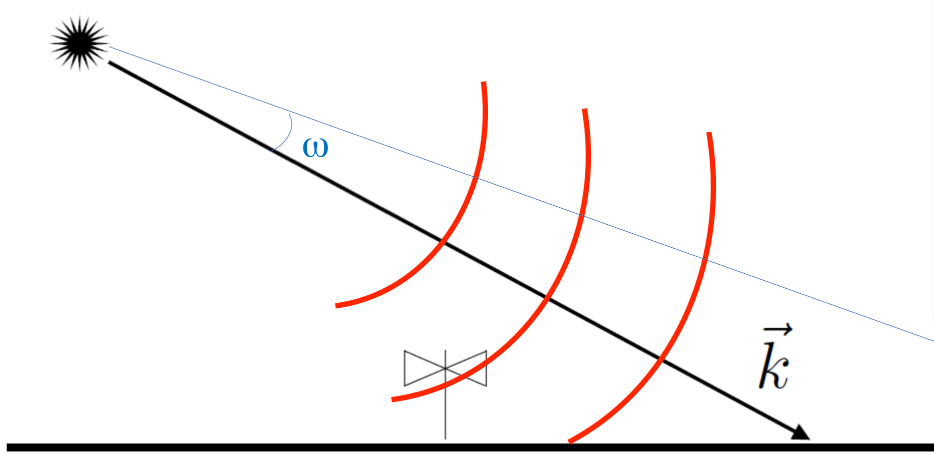
- > 200,000 simulations: raw/hardware like, ADC/Efield traces
- Traces: 4.096 us, downsampled to 500Mhz, with saturation
- Antenna response and RF chain included
- Jitter: 22uV/m Gaussian noise, 5 ns Gaussian smeared “trigger” time, “Amplitude Calibration” gaussian smeared 7.5%

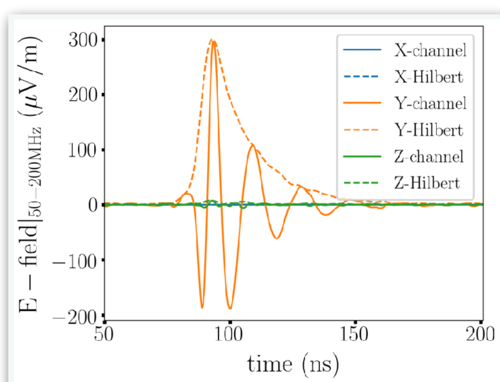
Electric field reconstruction

- E-field reconstruction with CNN
- Direction reconstruction based on polarization
- De-noising of E-field/ADC using ML

Inclined Air Shower Reconstruction

- Plane Wave Front (PWF): fast timing & direction reconstruction (analytical, with error calc.)
- Fitting (empirical and Physics informed) of Angular Distribution Function (ADF)
- Empirical fitting of lateral distribution function
- GNN for EAS studies





V. Decoene PhD. thesis 2021

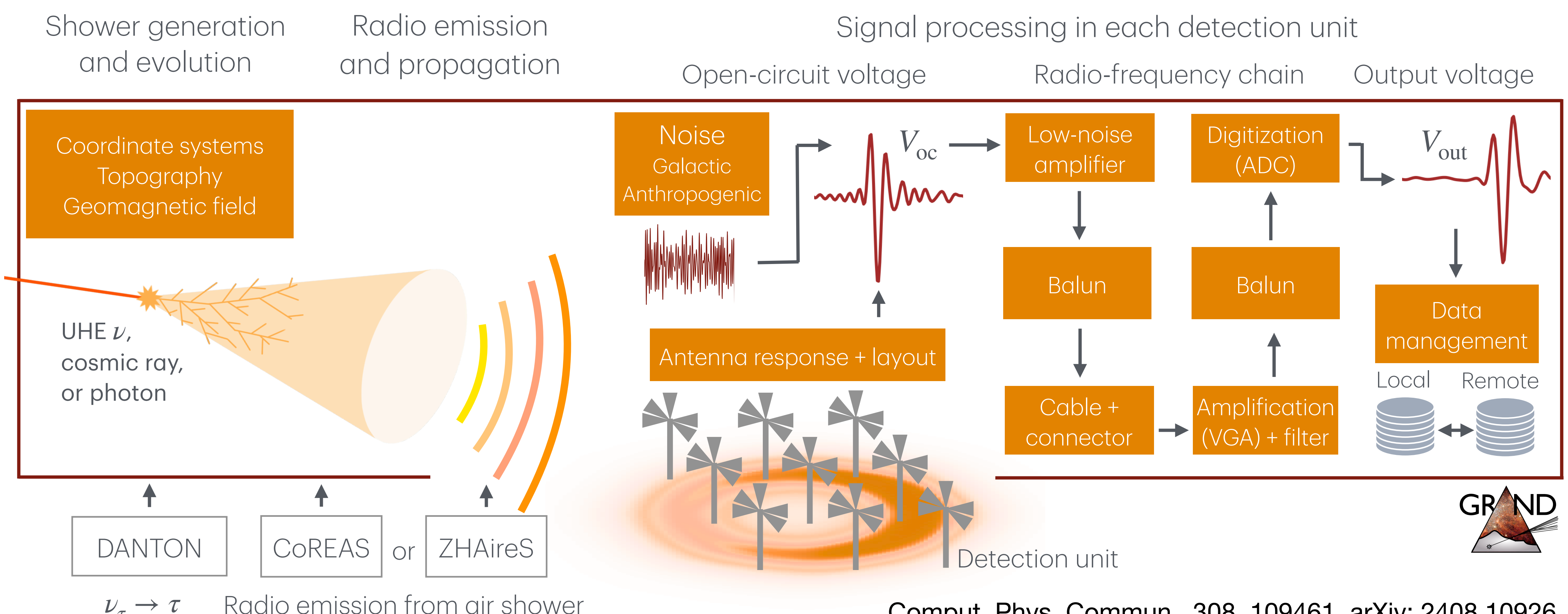
For more detail:
Decoene et al., Astroparticle Physics145, 102779 (2023)
Chiche et al., PRL 132, 231001 (2024)
Guelfand et al JCAP 5, 055 (2024)
Alvarez-Muniz et al., arXiv:1810.09994 (2018)
Macias et al., Pos(ARENA2024)062
Benoit-Lévy et al., JINST19(4), P04006 (2024)

Software pipeline: GRANDlib

Python offline software package for the GRAND collaboration: tool to manage and analyze data

GRAND Coll. 2024, *https://github.com/grand-mother/grand*

- User friendly tool. No need to install ROOT
- Modules for coordinate systems, topography and geomagnetism
- Includes galactic noise and RF chain parameters
- Standard code for signal processing
- Tools to store data in a standard file format and manage them
- Refer to grand/examples for example scripts

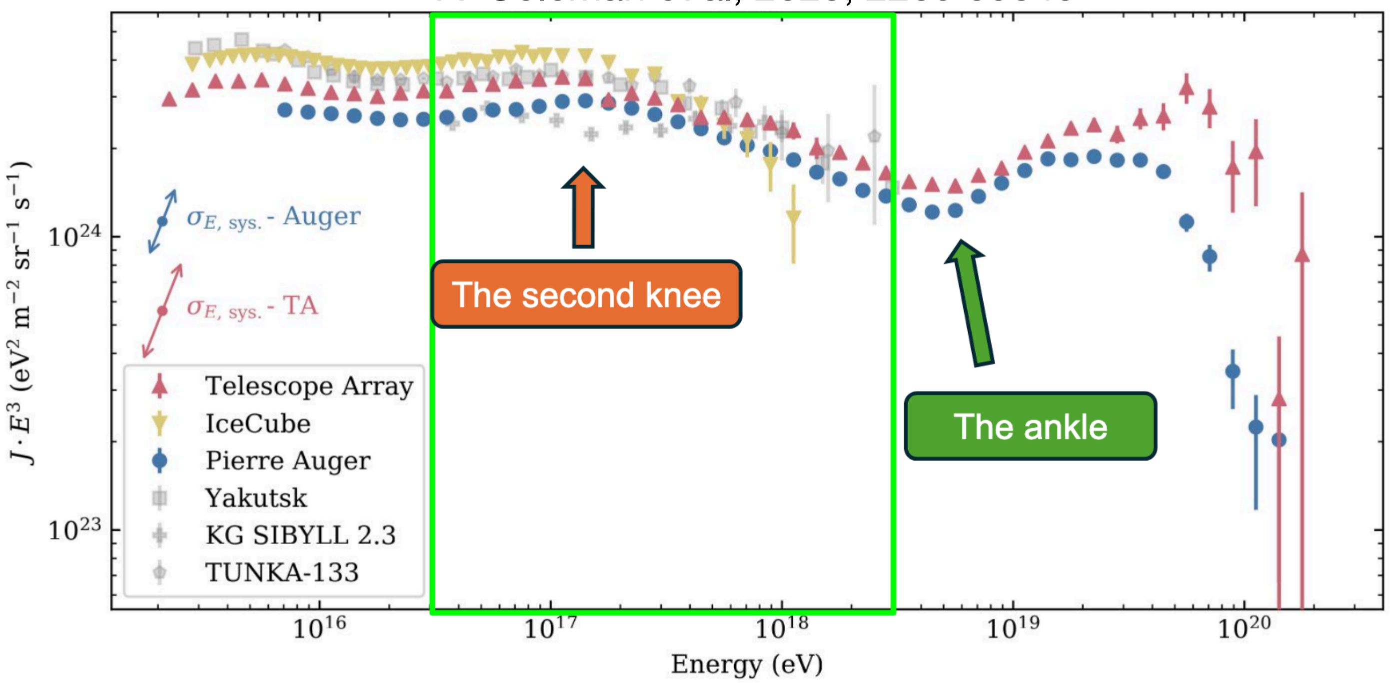


Comput. Phys. Commun., 308, 109461, arXiv: 2408.10926

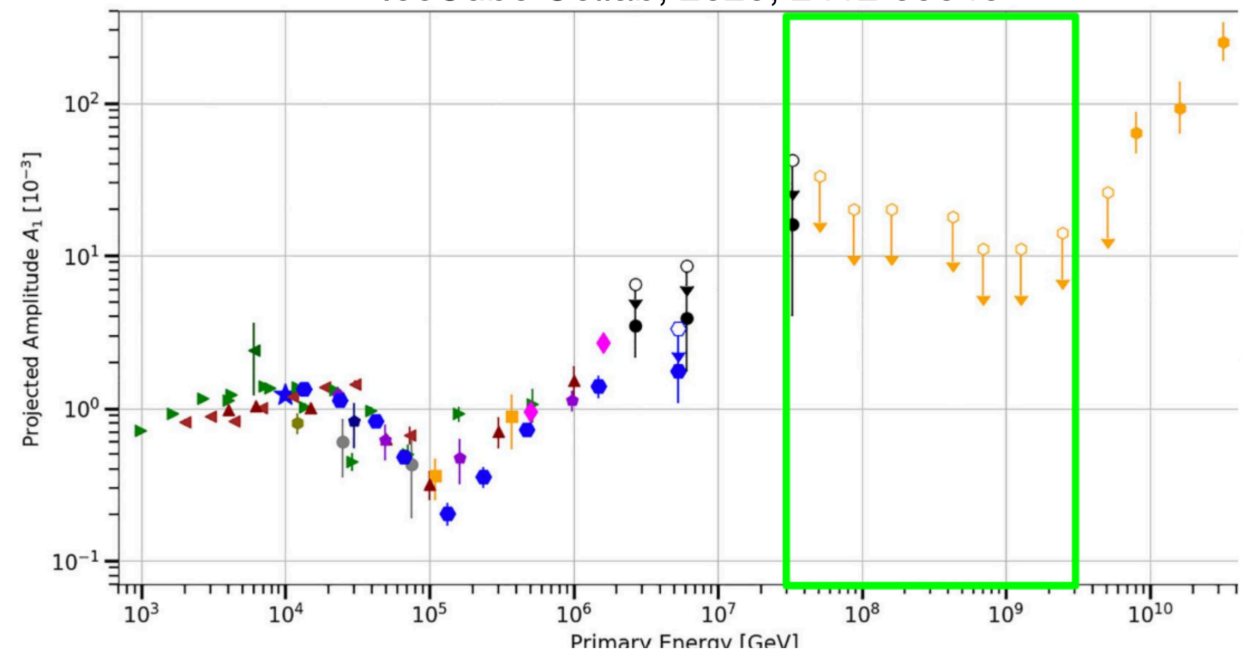
Cosmic-ray transition from Galactic to extra-galactic components
Current work by **Clément Prévotat**, R. Alves Batista, M. Guelfand, CG, A. Marcowith, K. Kotera

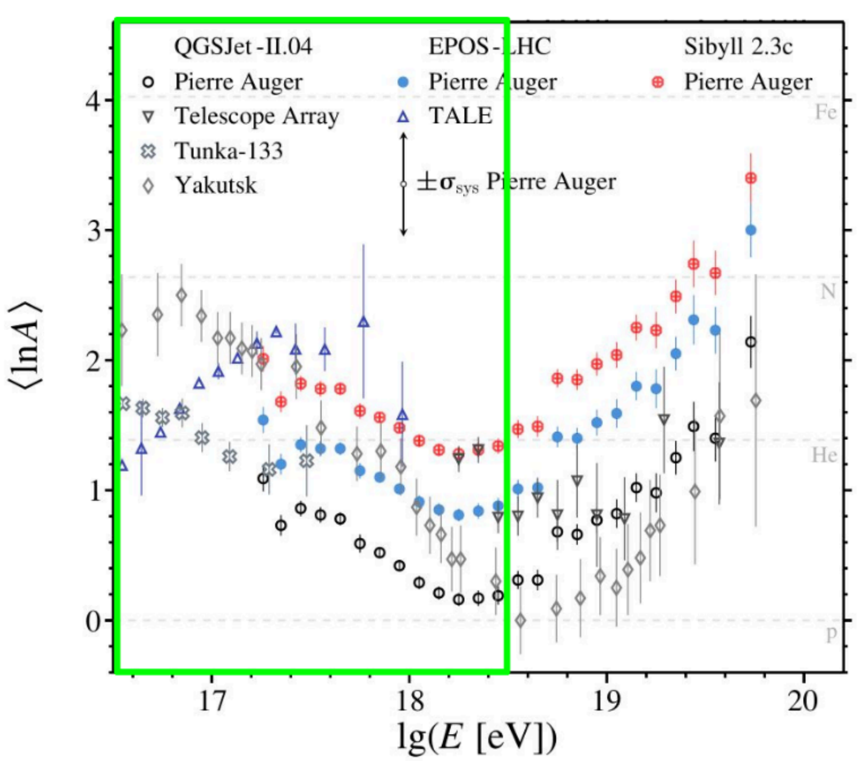
Sources? Anisotropy? Composition? GP300: larger exposure than LOFAR or AERA expected

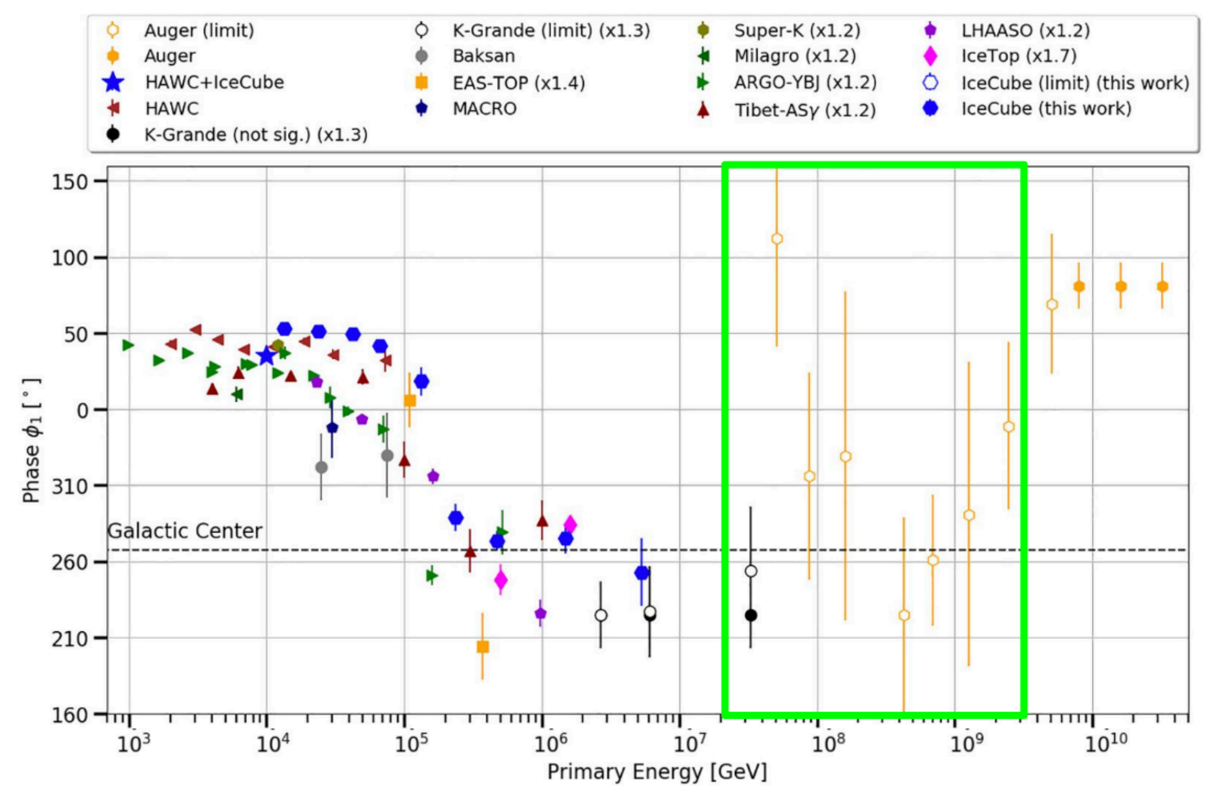
A. Coleman et al, 2023, 2205.05845



IceCube Collab, 2025, 2412.05046



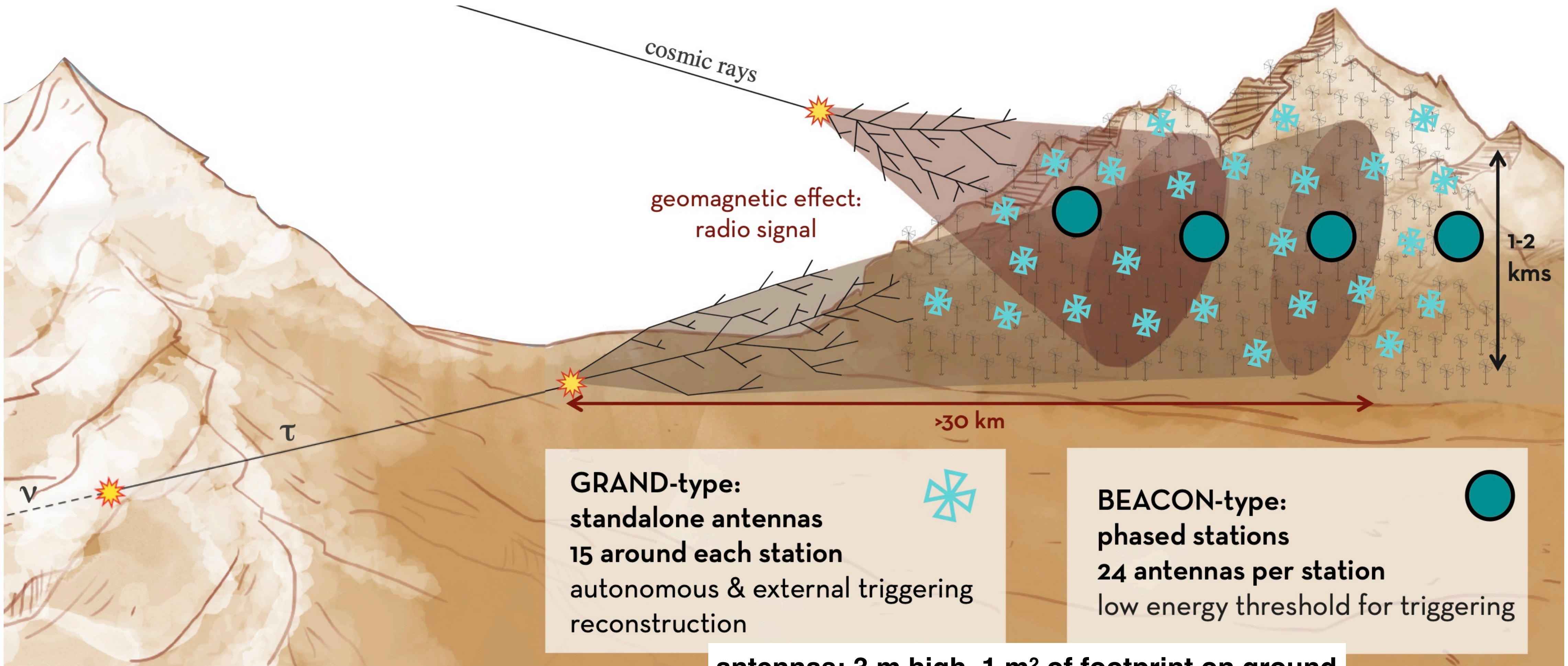




Perspectives: HERON

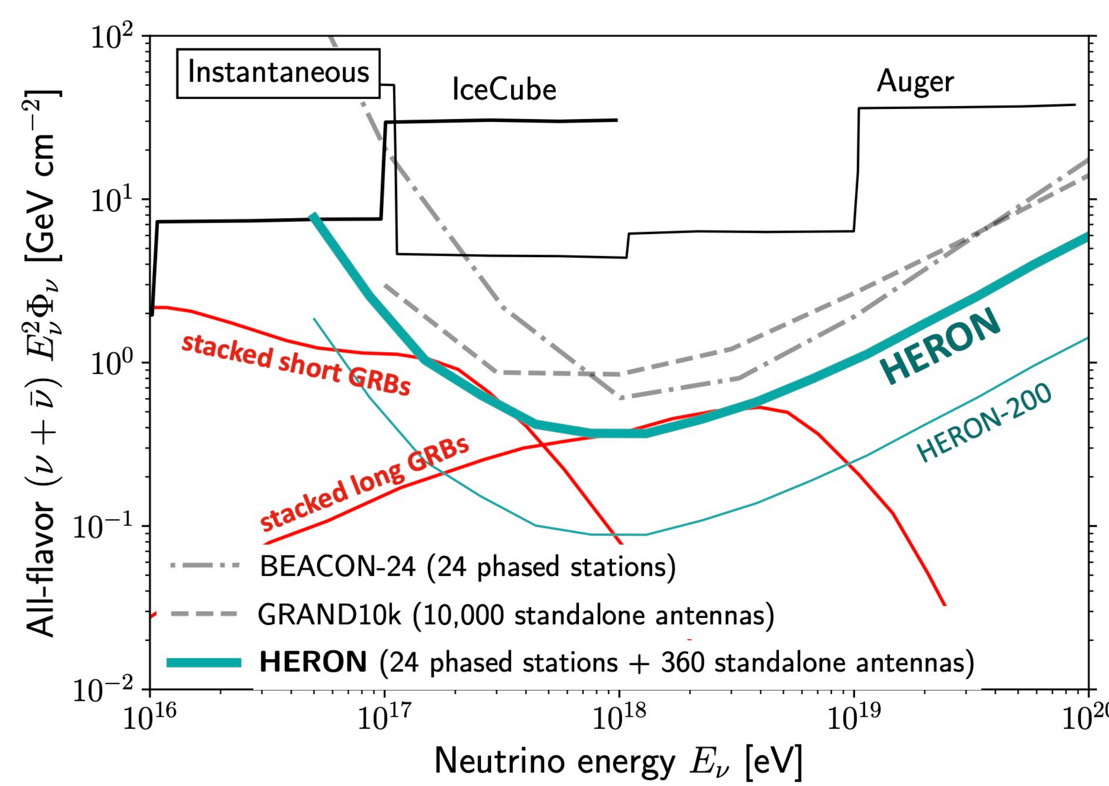
HERON

Detecting the most violent astrophysical sources



antennas: 3 m high, 1 m² of footprint on ground

- **24 phased stations** ("BEACON-type")
  - 70 km linear along mountain, altitude 1000 m
  - each station contains: 24 compact radio antennas
  - station surface: ~100 m2 each
  - separation between stations: ~ 3 km
- **360 standalone antennas** ("GRAND-type")
  - altitudes between 500 m and 1500
- **R&D for GRAND**: external trigger plugged on autonomous GRAND systems & interferometry



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

18 Member & Associate Institutes represented at the Board

- Hellenic Open University (HOU)
- Institut d'astrophysique de Paris (IAP)
- Institute of Physics of the Czech Academy of Sciences (FZU)
- Inter-University Institute for High Energy at Vrije Universiteit Brussel (IIHE-VUB)
- Karlsruhe Institute of Technology (KIT)
- Laboratoire de Physique Nucléaire et des Hautes Energies (LPNHE)
- Laboratoire Univers et Particules de Montpellier (LUPM)
- Radboud University
- University of Warsaw

- Nanjing University
- National Astronomical Observatories, Chinese Academy of Sciences (NAOC)
- Purple Mountain Observatory (PMO)
- Xidian University

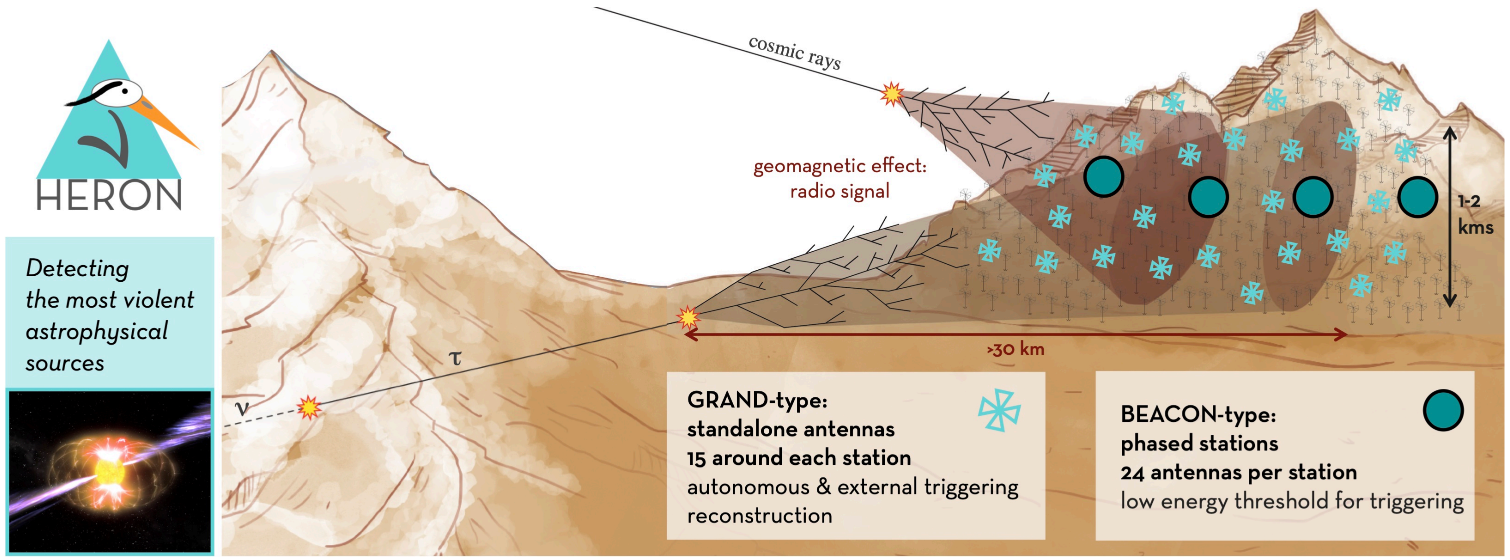
- Pennsylvania State University (PSU)
- San Francisco State University (SFSU)

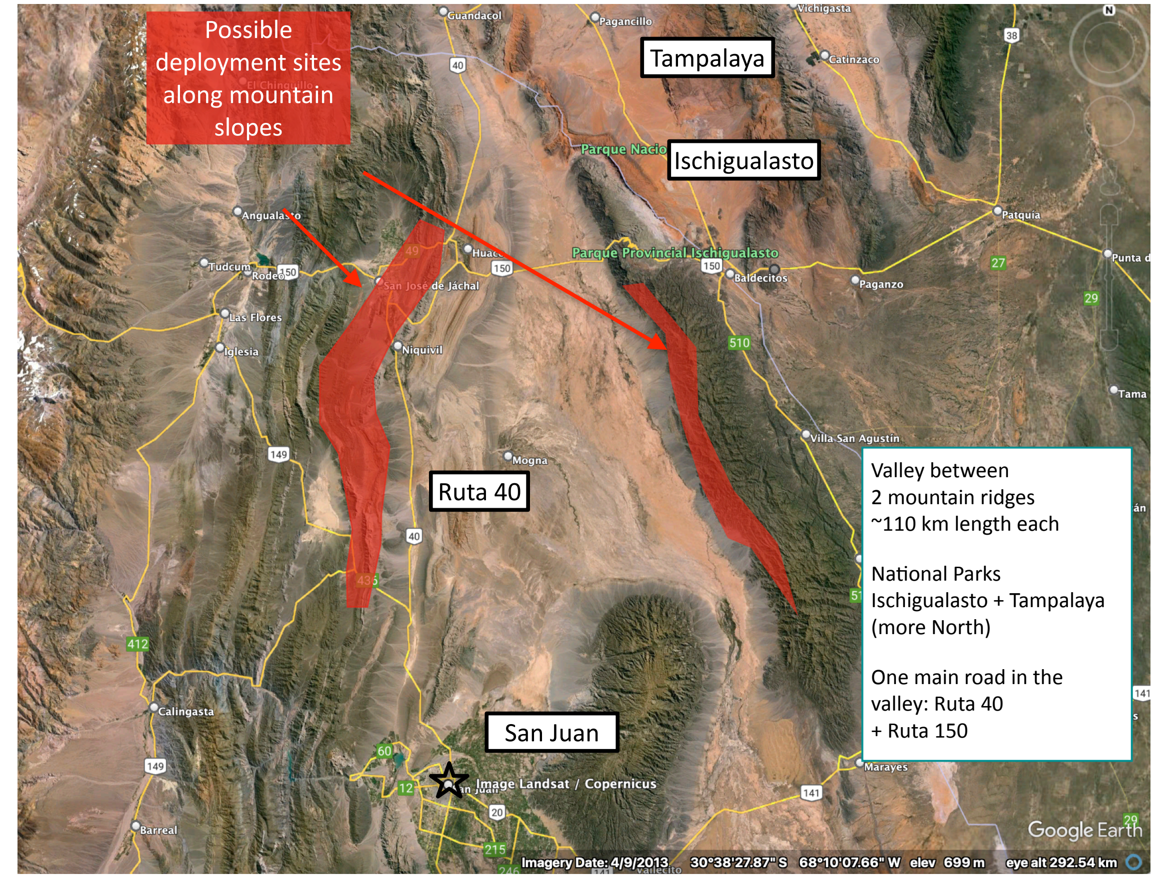
- Universidade Federal do Rio de Janeiro (UFRJ)

Nanjing Collaboration Meeting @ Purple Mountain Observatory, May 2024

Back-up slides

GRAND collaboration, 2019





Where? – San Juan Province, Argentina

Province government supportive of the HERON project

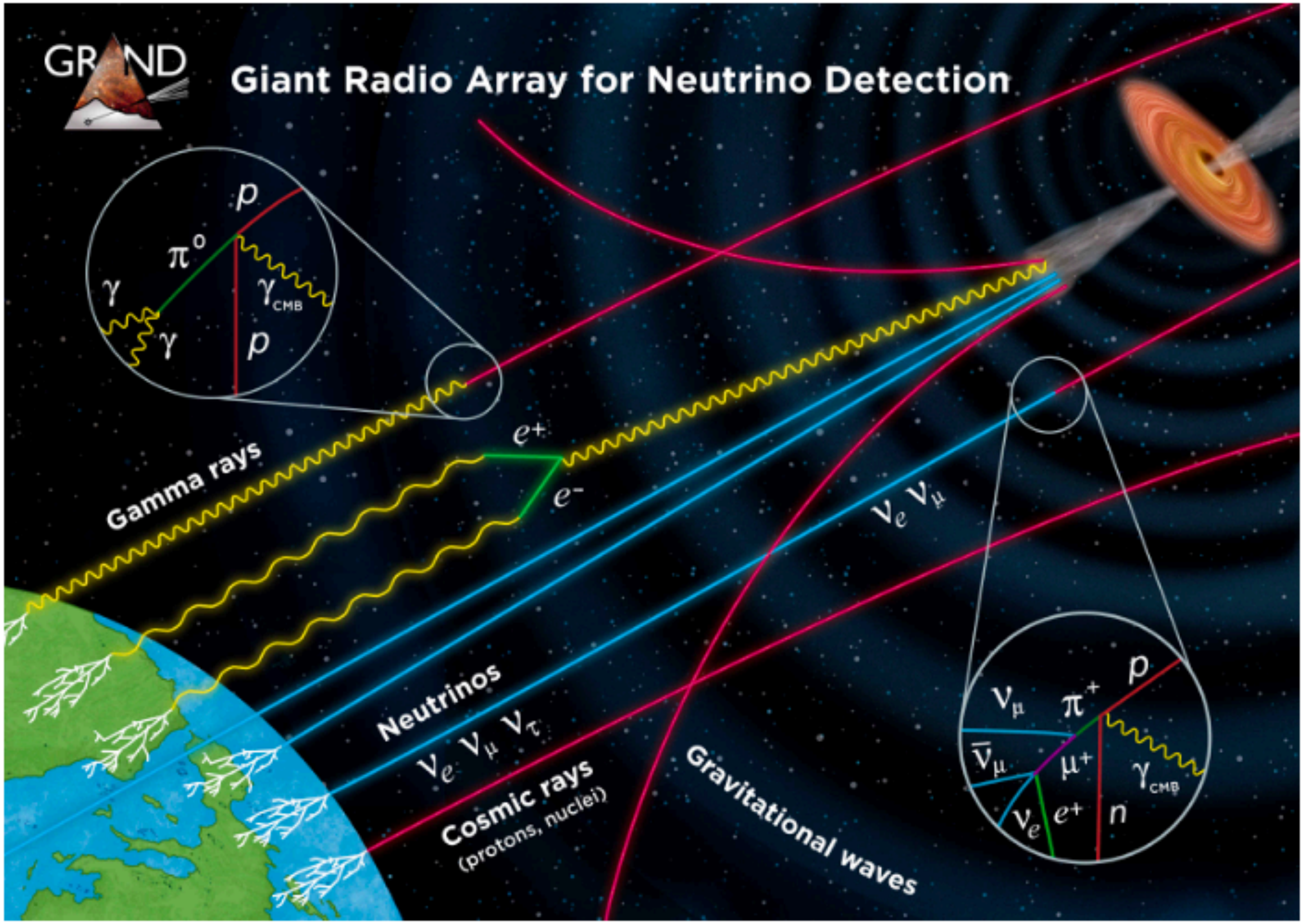
Requirements:

- A non-populated valley surrounded by 2 mountains of elevation > 1000 m, of 30-60 km wide
- Radio-quiet environment (no power lines, no industries, no big road, no major town)
- Possibility to establish a base near the site, to deploy our antennas, access, dig holes & pour concrete to install antennas.

Support & funding

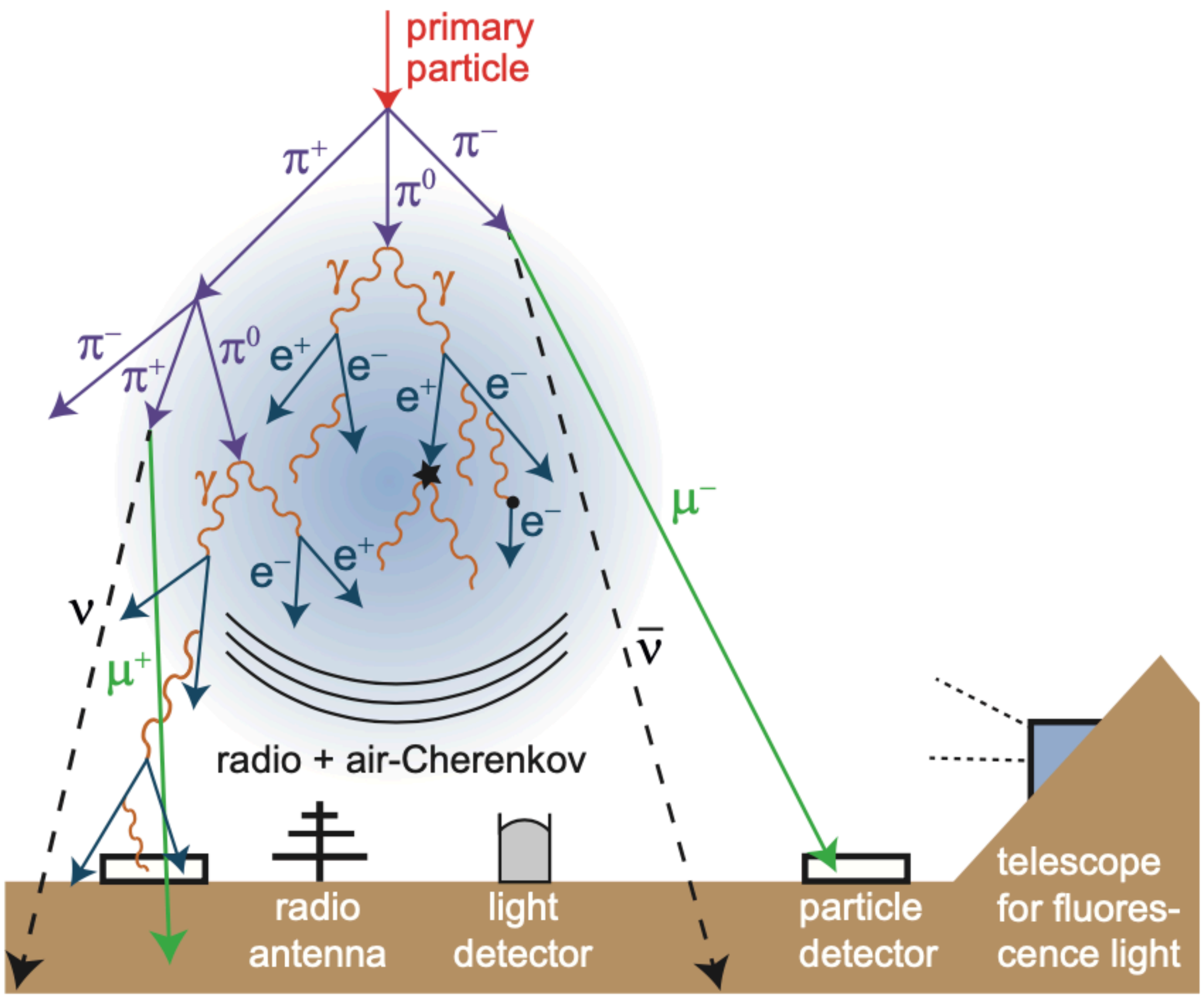
- International consortium (from GRAND & BEACON Collaborations) to bring funding of ~ 15 M€ for equipment & material.
- Active contribution of CNEA, CONICET, UNSAM (ITeDA, Bariloche…)
- Establish international scientific community in San Juan Province
- Members will be actively involved in outreach for the province (schools, universities, museums etc.), similarly to the Pierre Auger Collaboration in Malargüe.
- Local contribution in funding, in-kind, in personnel, for infrastructure by the province to be discussed

HE-UHE multi-messenger astronomy

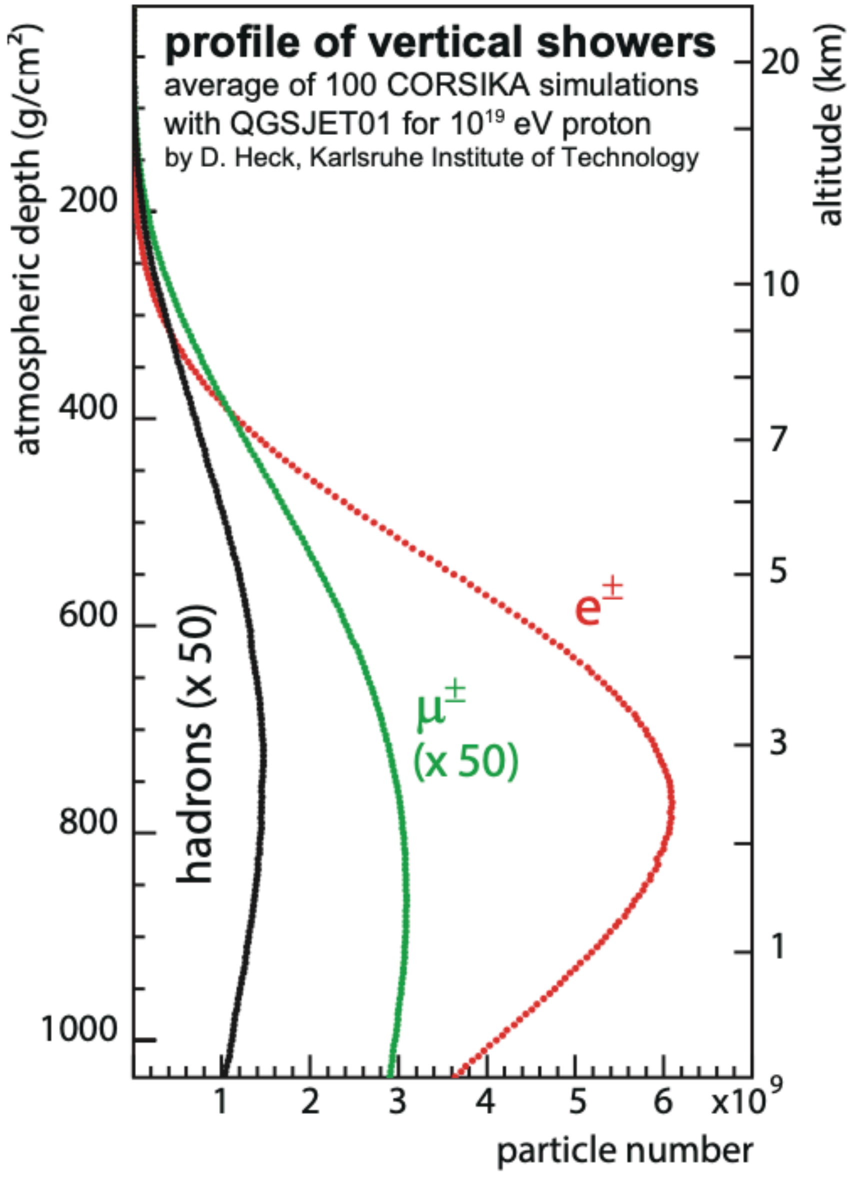


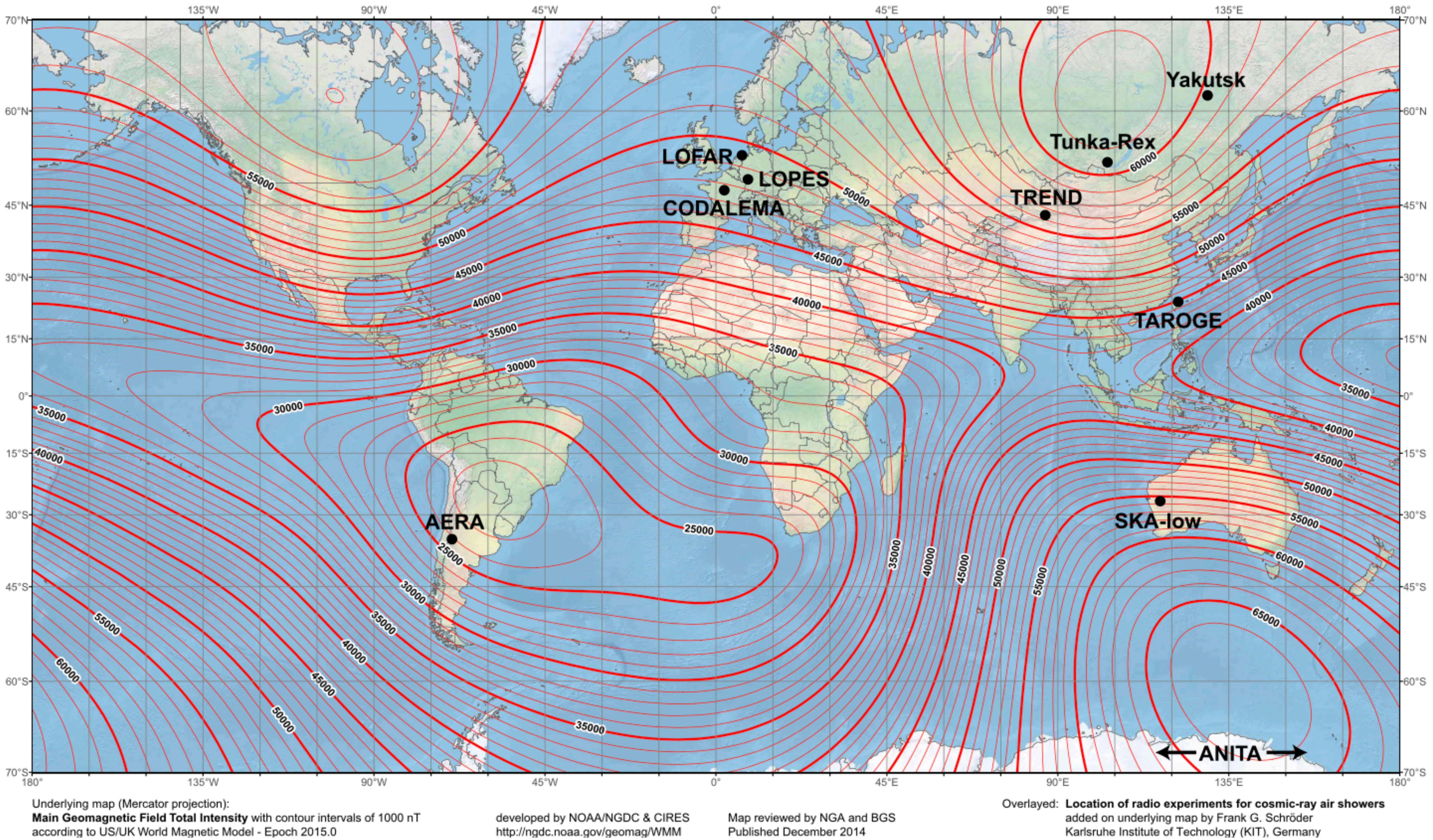
GRAND collaboration, 2019

air shower detection techniques



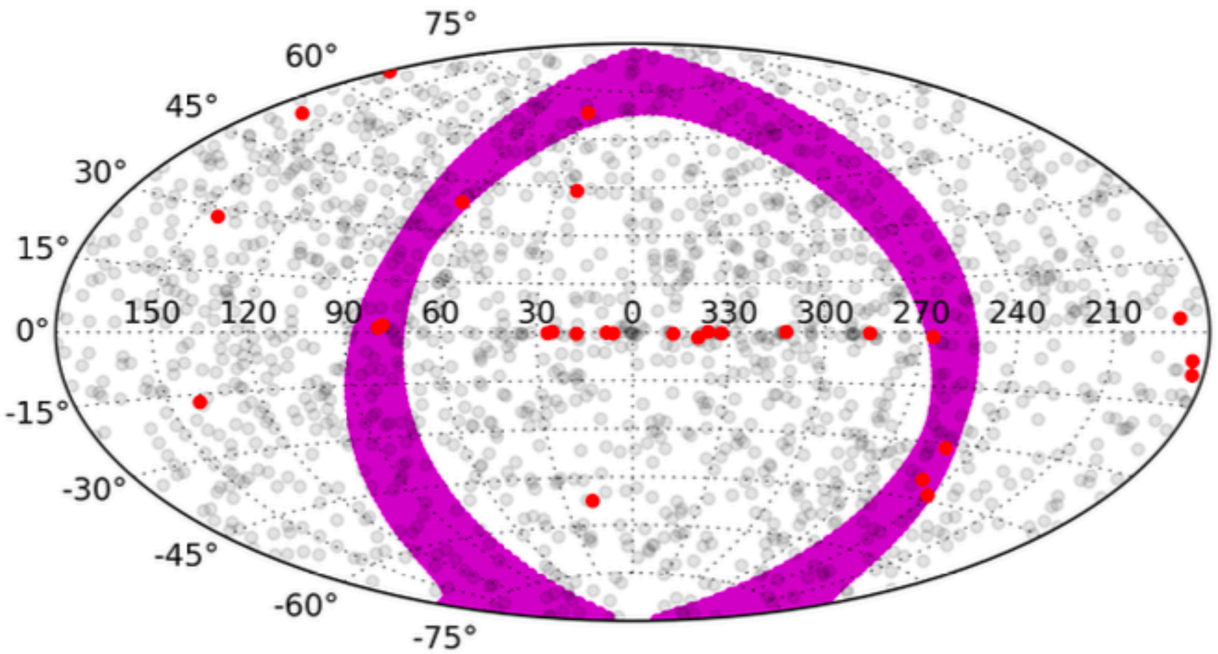
Schröder, 2016

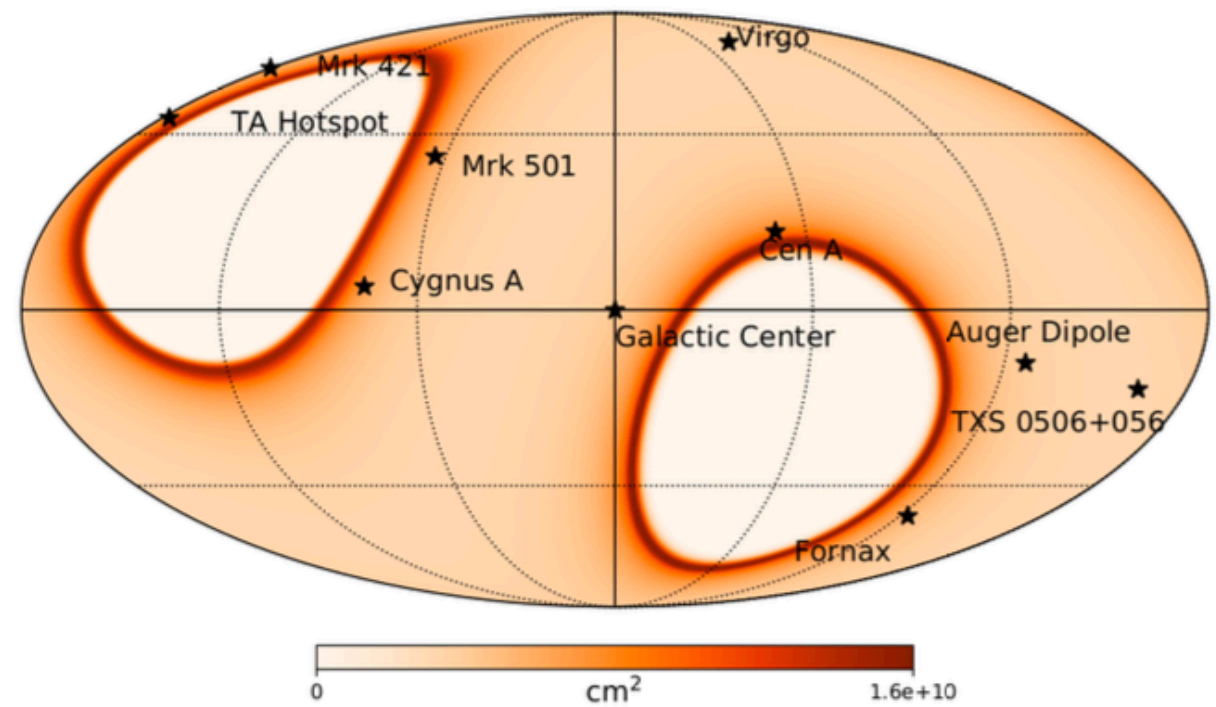




Schröder, 2016

instantaneous f.o.v. (left) and averaged sky sensitivity (right)





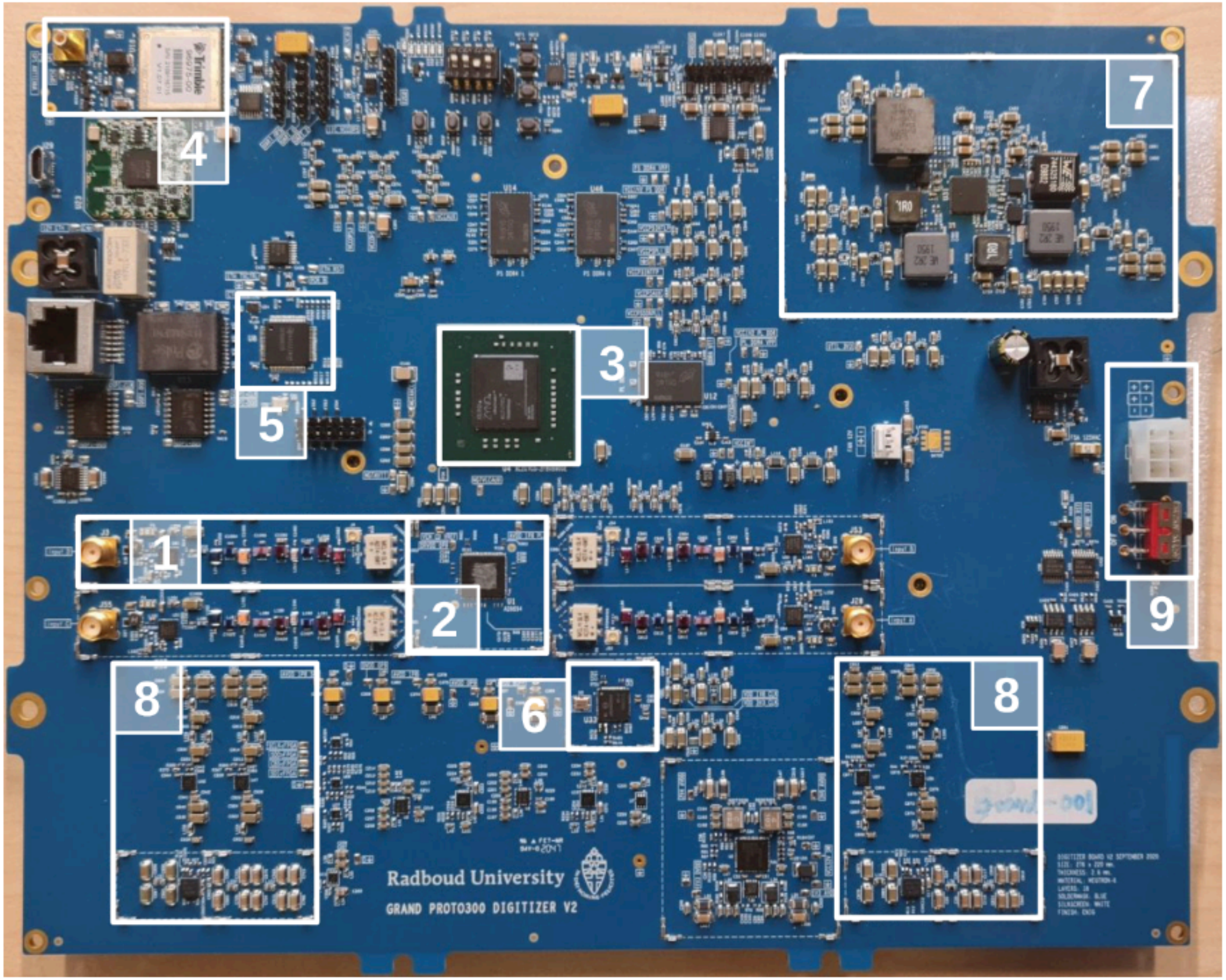
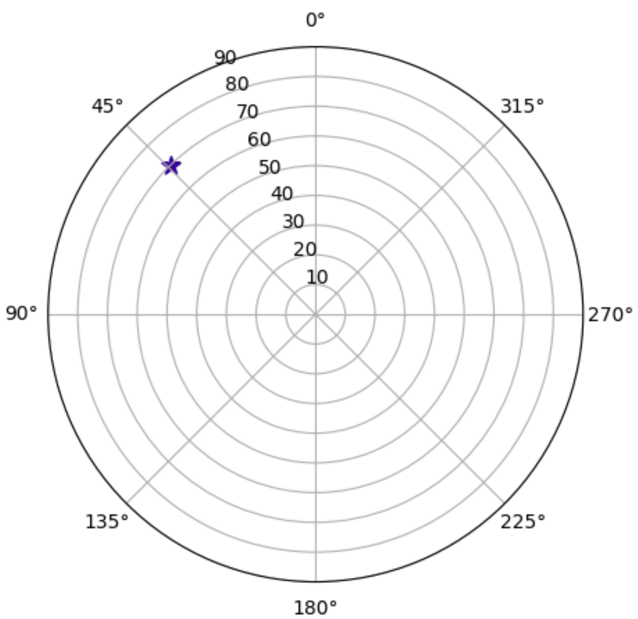
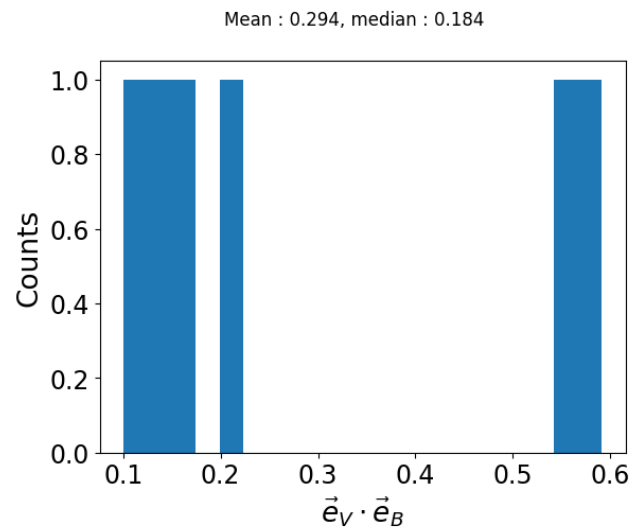


Figure 10. **The GRAND front-end board (FEB).** The main components: (1) signal input and filter chain, with four inputs available; (2) analog-to-digital (ADC) chip; (3) system on chip: field-programmable gate array (FPGA) and central processing unit (CPU) ; (4) Global Positioning System (GPS) chip and connector; (5) Ethernet chip; (6) clock; (7) power supply for the digital part of the board; (8) power supply for the analog part of the board; and (9) power connector and switch. See Section 3.3 for details.

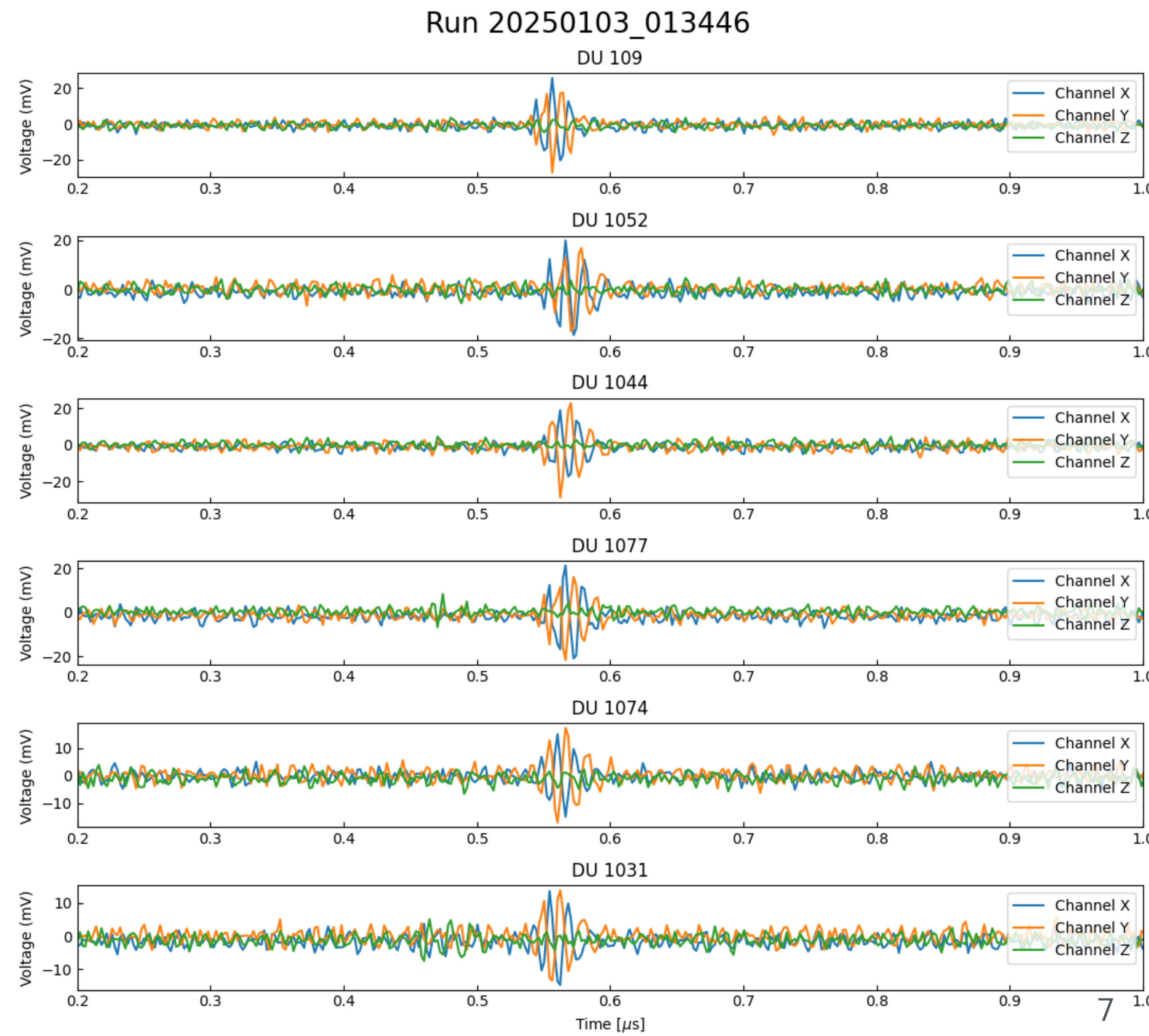
CR events search: first candidates

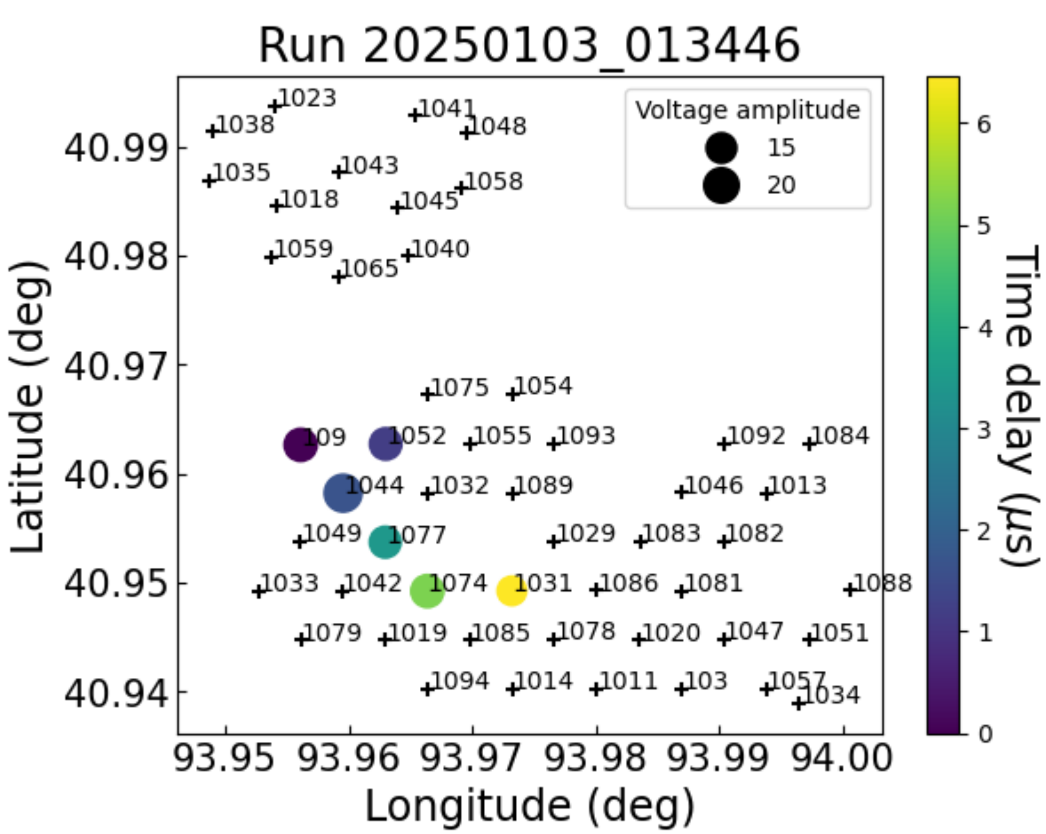
PRELIMINARY





Candidat : 20250103_013446





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slide by J. Lavoisier