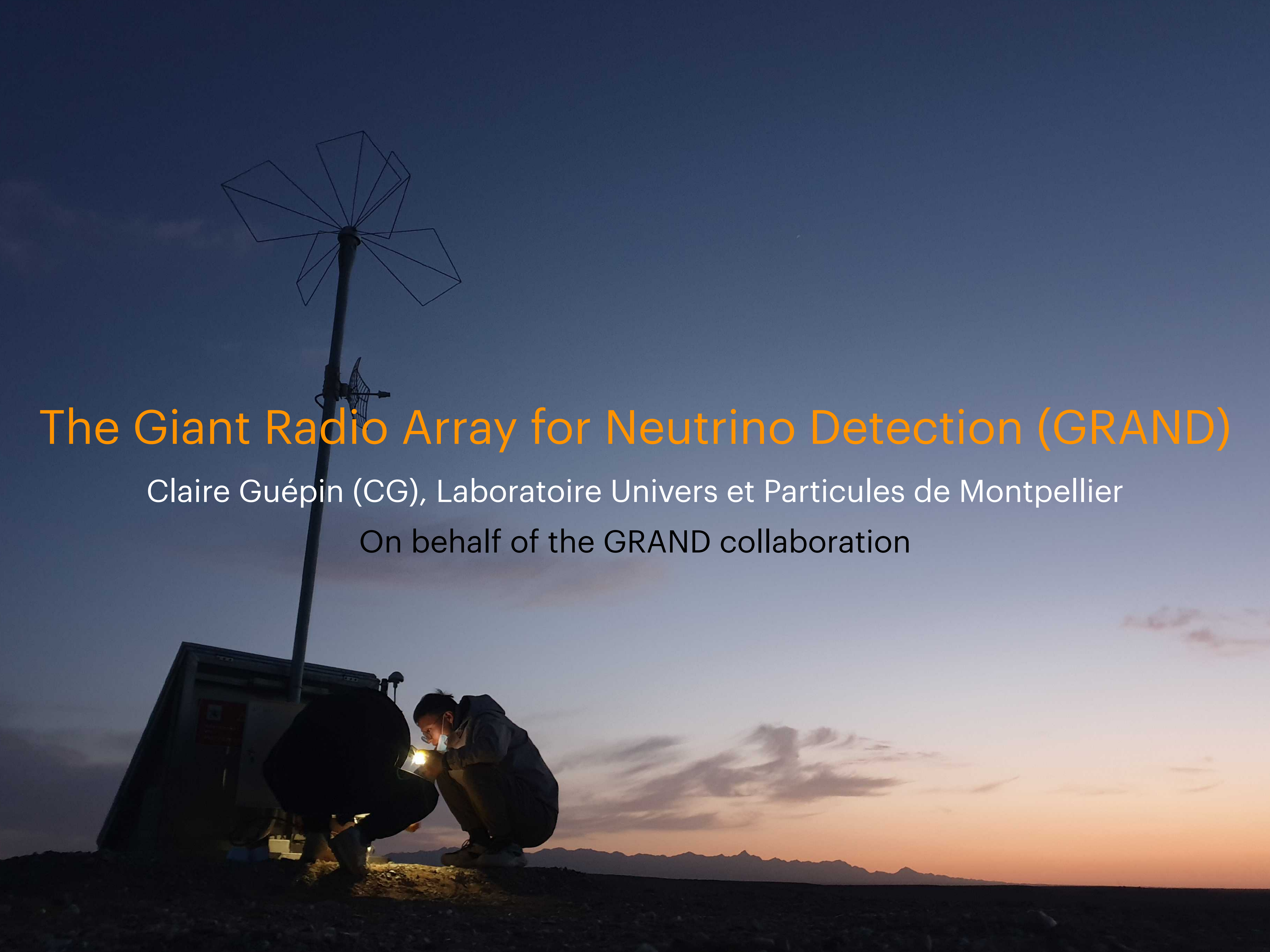


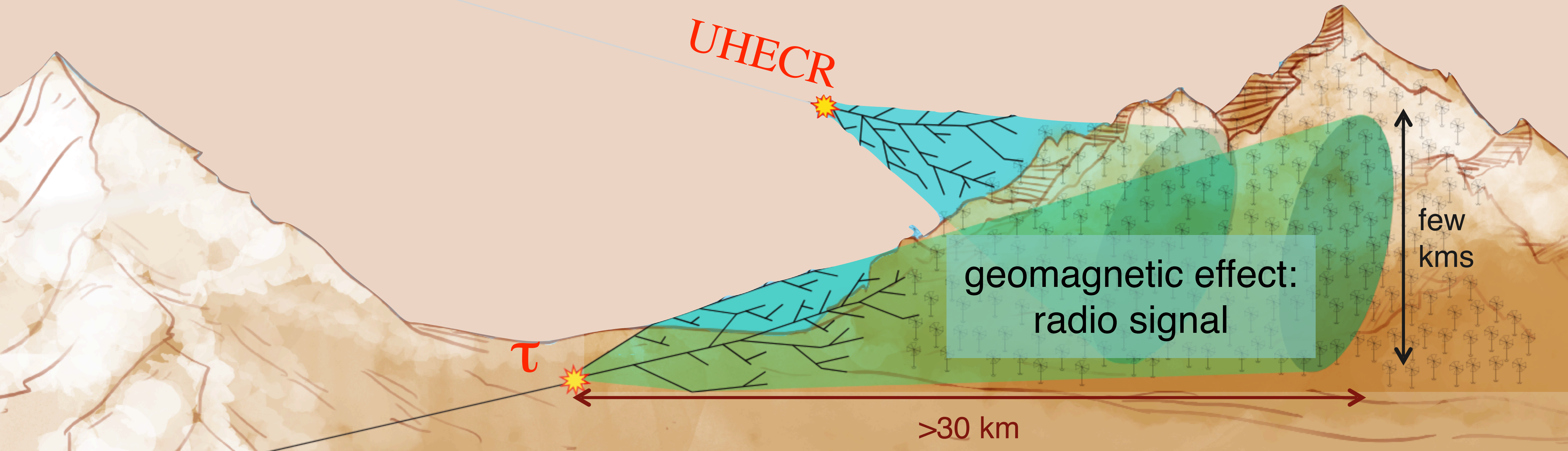
The Giant Radio Array for Neutrino Detection (GRAND)

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

On behalf of the GRAND collaboration

GRAND Concept

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



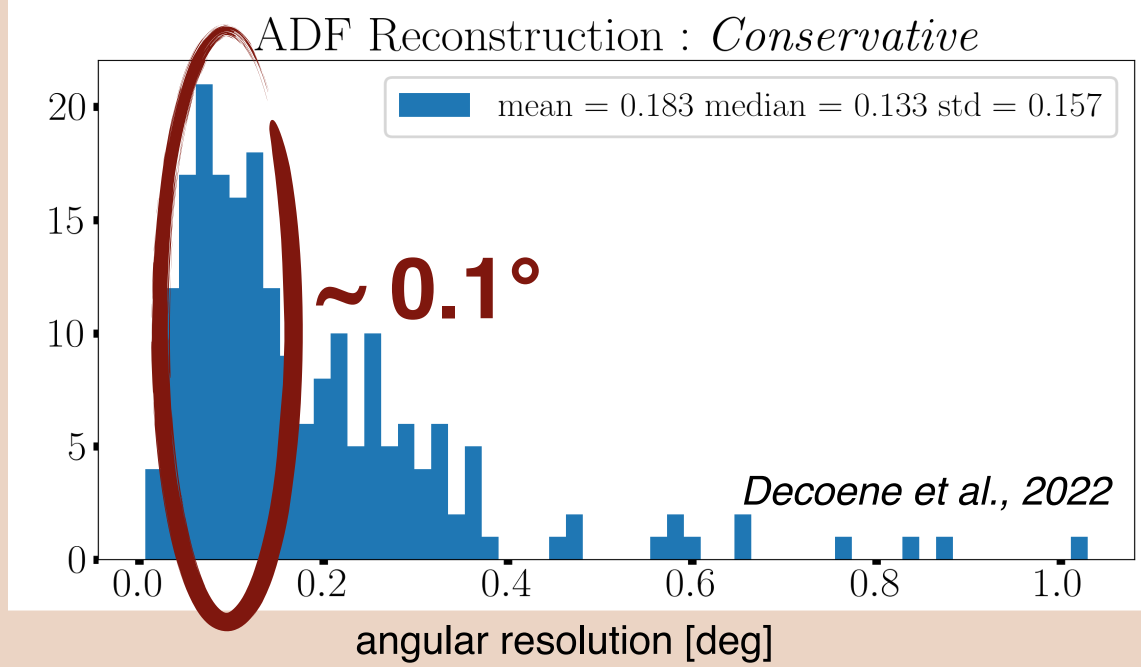
3 Prototypes	GRAND10k	GRAND
2023	2028	203X
cosmic rays $10^{16.5\text{-}18}$ eV **autonomous** radio detection of **very inclined** air-showers	**discovery of EeV neutrinos** for optimistic fluxes 10k antennas (Argentina?)	**1st EeV neutrino detection and/or neutrino astronomy!** 2 detectors of 10k antennas: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

Expected performances

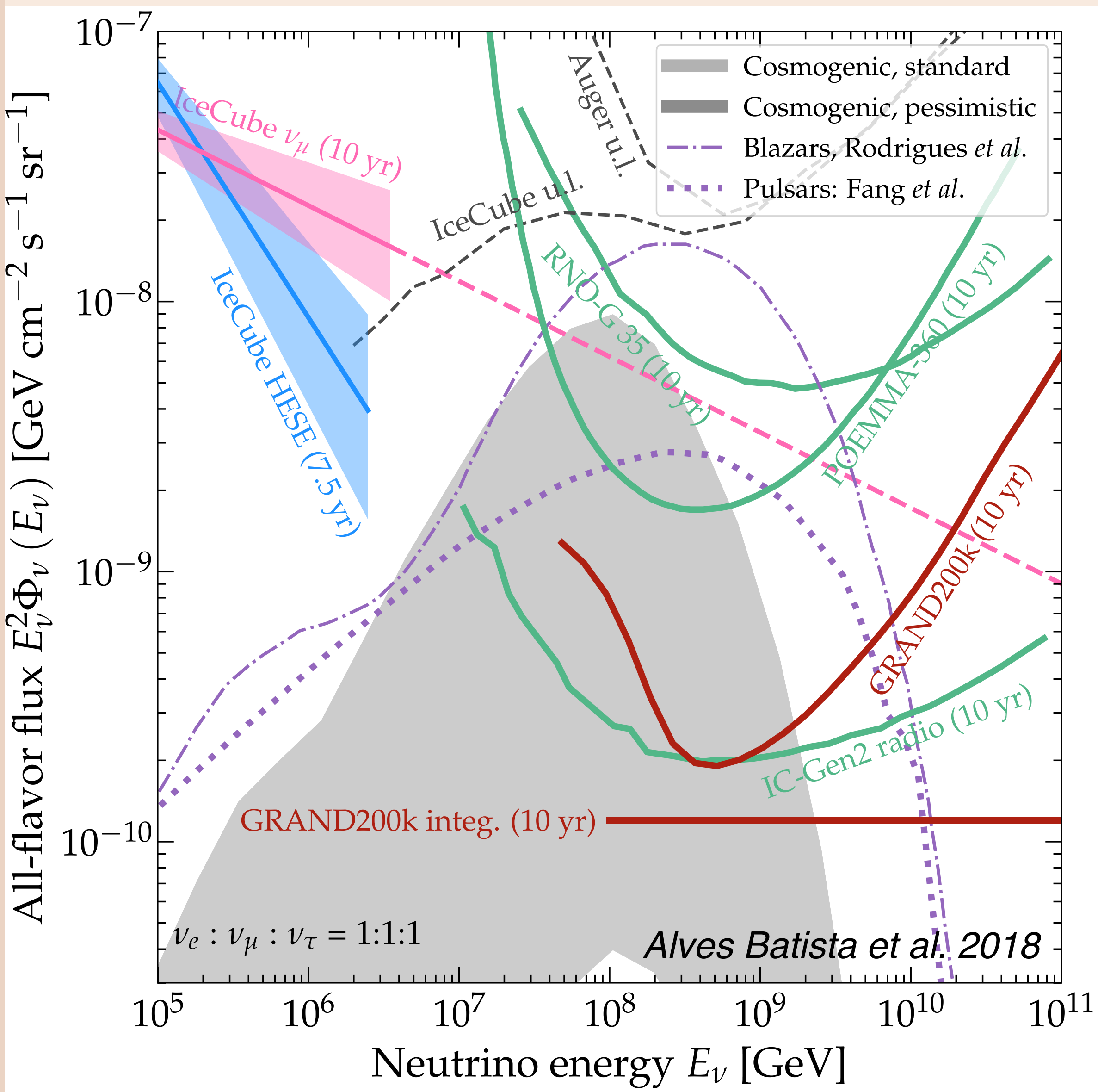
What do we need for UHE neutrino astronomy?

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

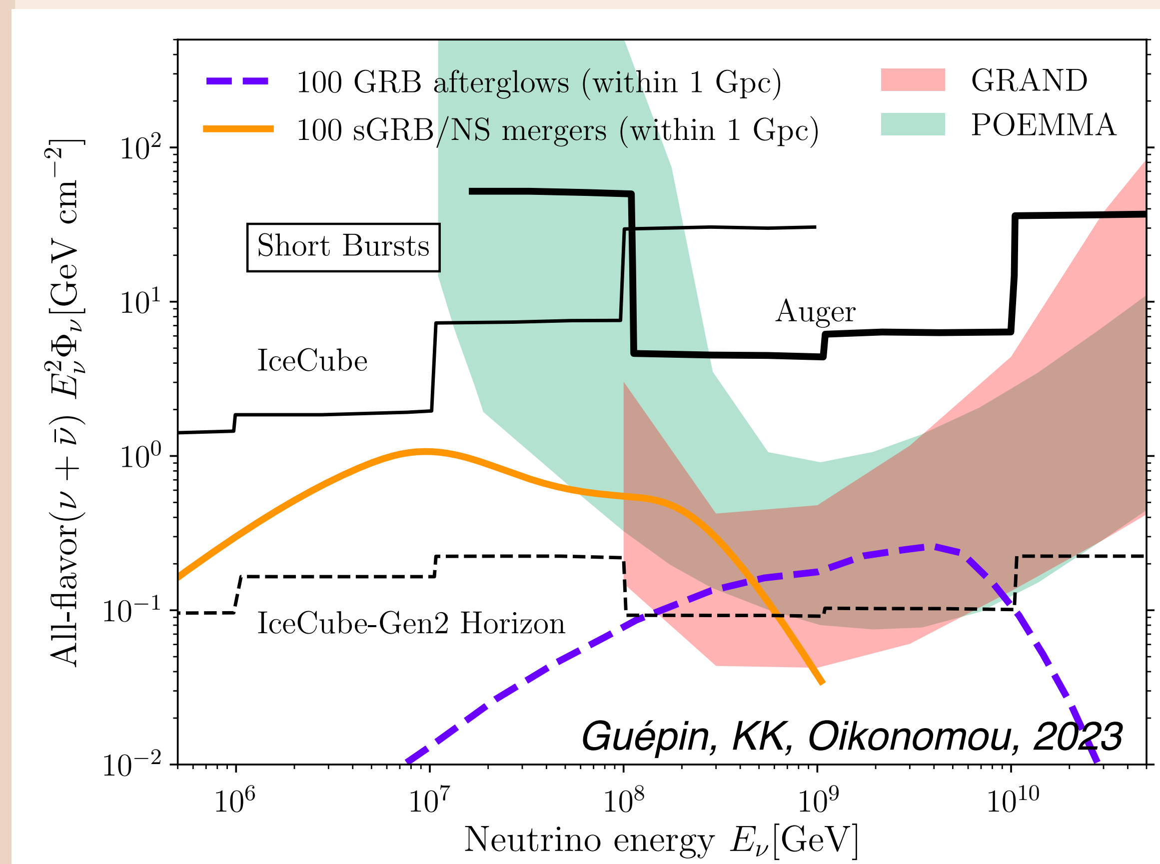
Angular resolution



diffuse sensitivity



fluence sensitivity

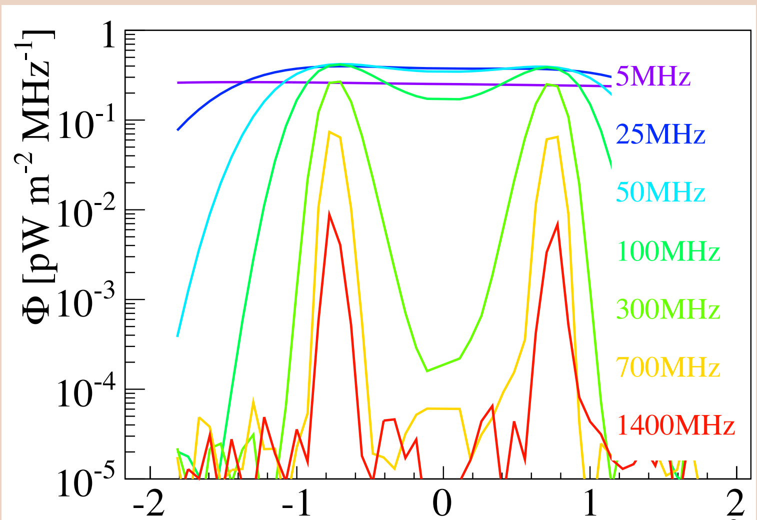


Radio signals at our detectors

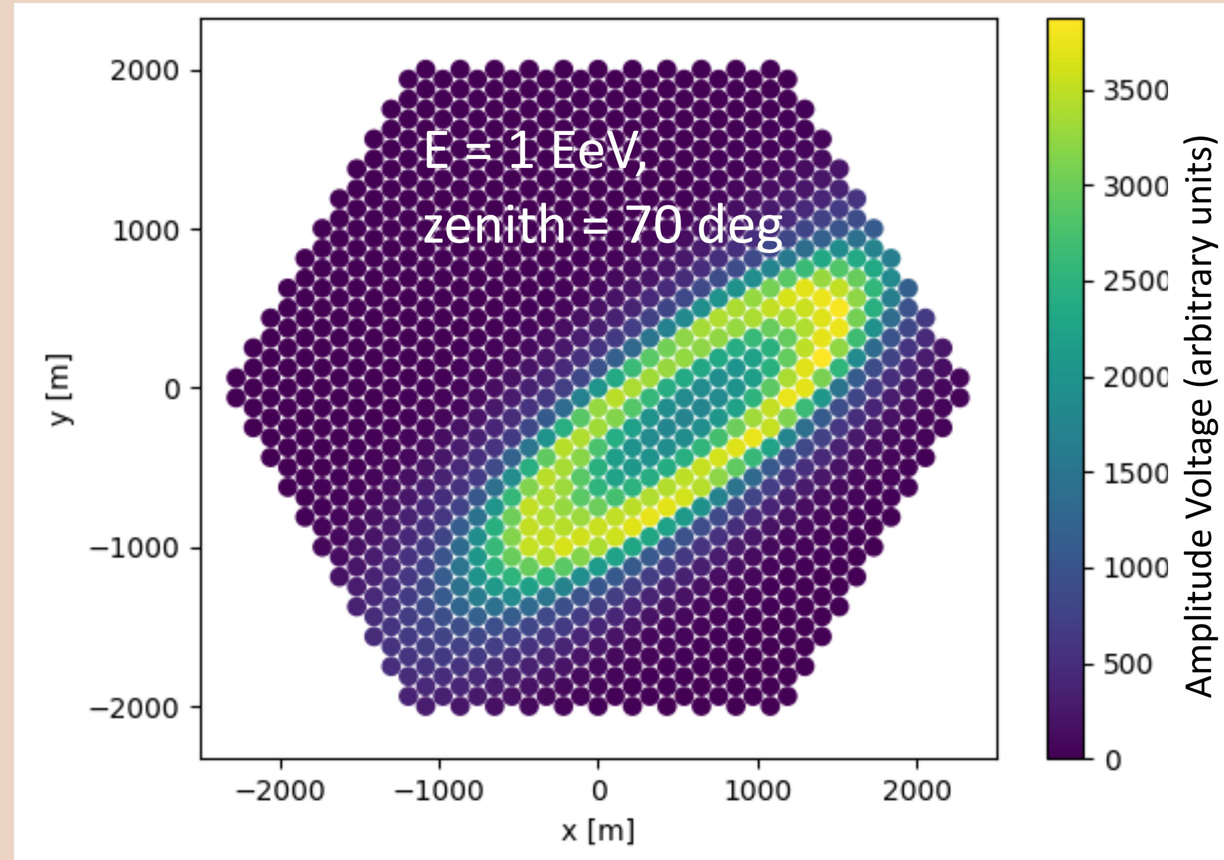
Experience: LOPES, LOFAR, AERA, CODALEMA, TREND, AugerPrime Radio…

Footprint

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

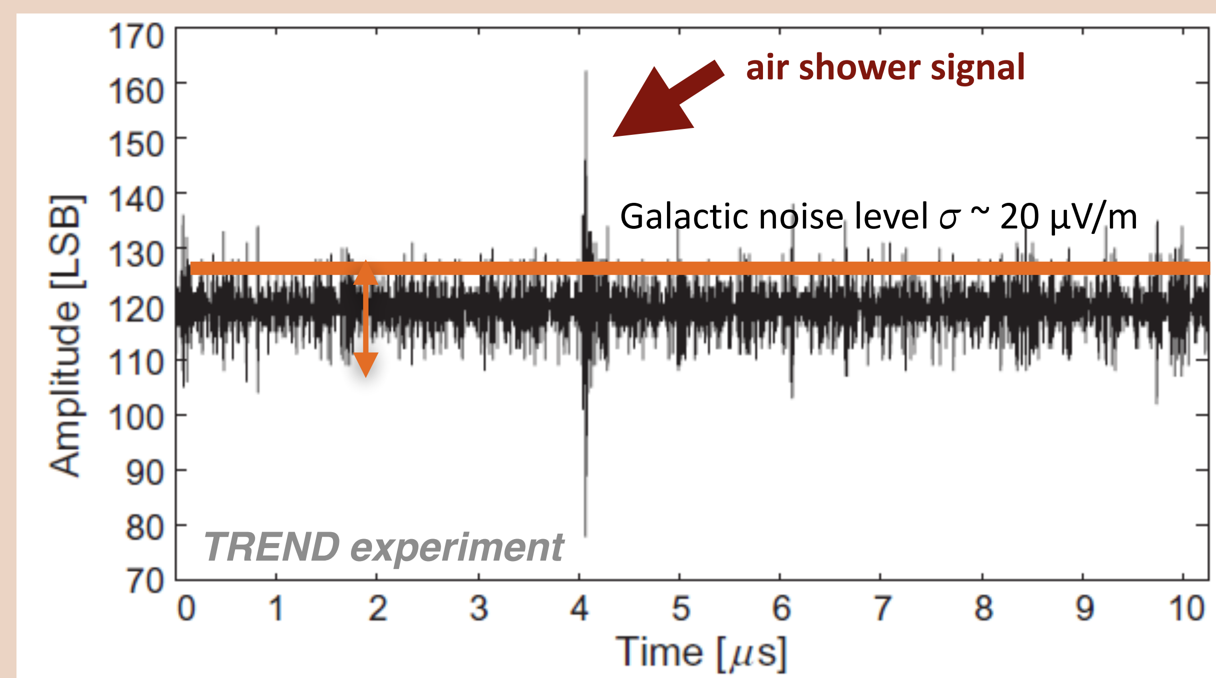


Alvarez-Muñiz et al. 2015



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



GRAND Challenges

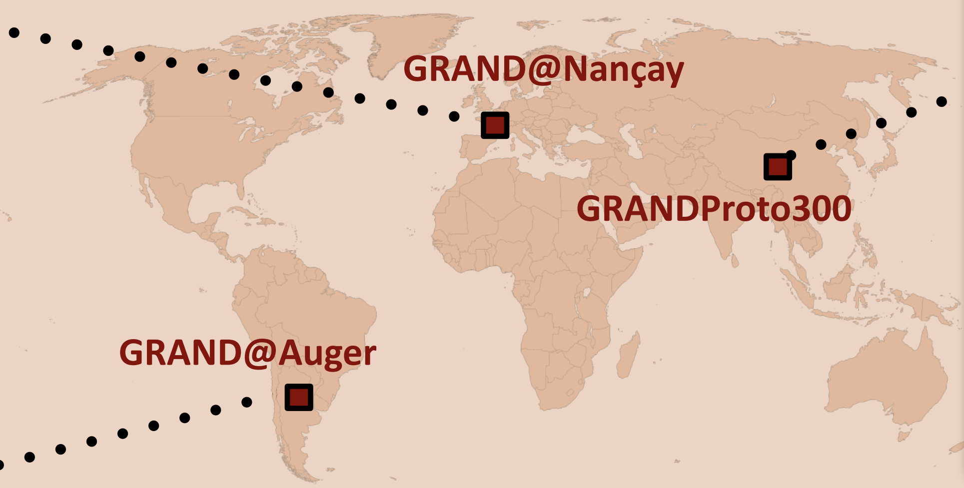
Low-complexity, robust, low-cost detection units
- Low noise system
- Robust for desert environments & temperature fluctuations
- Simple deployment for large numbers

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



Prototypes set-up

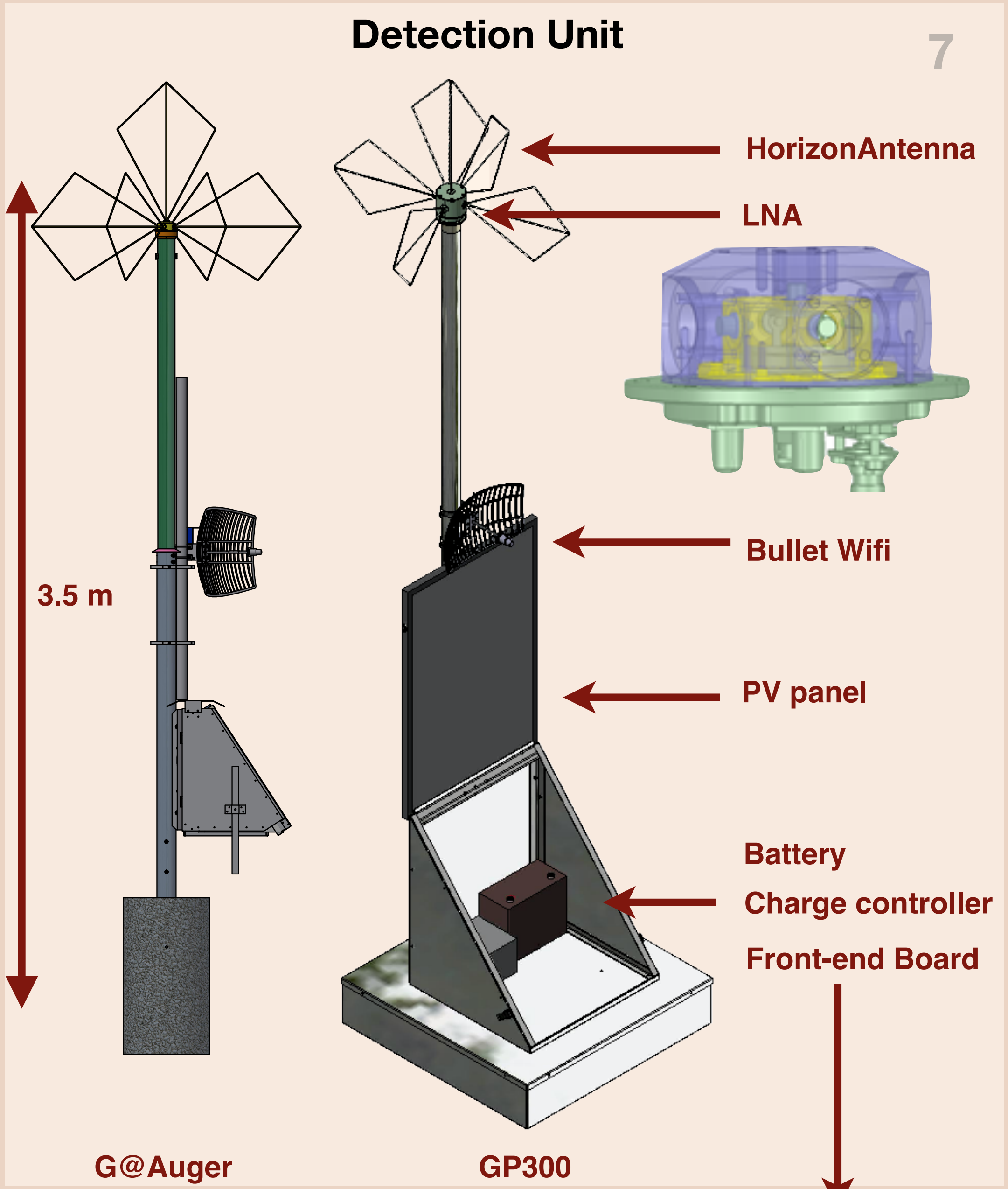
GRAND Coll. in prep.

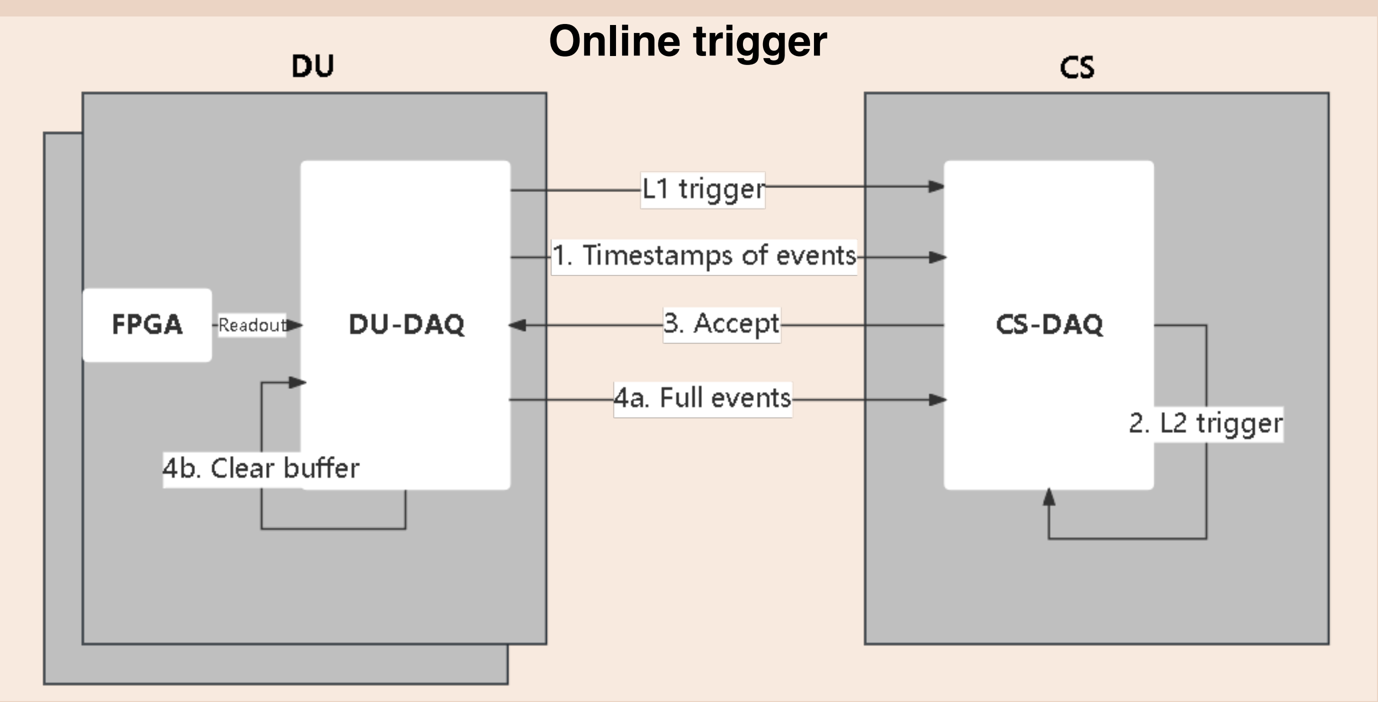
Common set-up

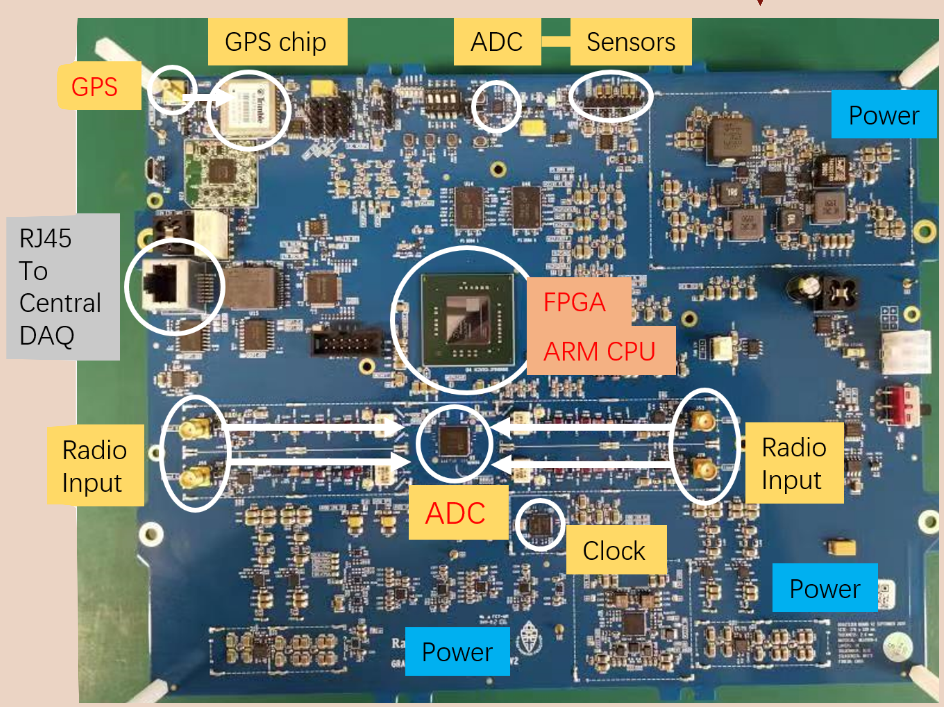
- Same overall components
- Antenna arms: response differ due to mechanical structure
- Front-End Board: ADC 500MS/s,14 bits, FPGA + 4 CPUs
- Trigger algorithm: unbiased trigger, 10 s, 20 Hz mode
- Common data format

Testing robustness to environments

- GRAND@Auger: humidity, noise level (LNA), constraints: mechanical struct., power
- GRANDProto300: stability, coincident trigger
- Firmware (transient trigger) different







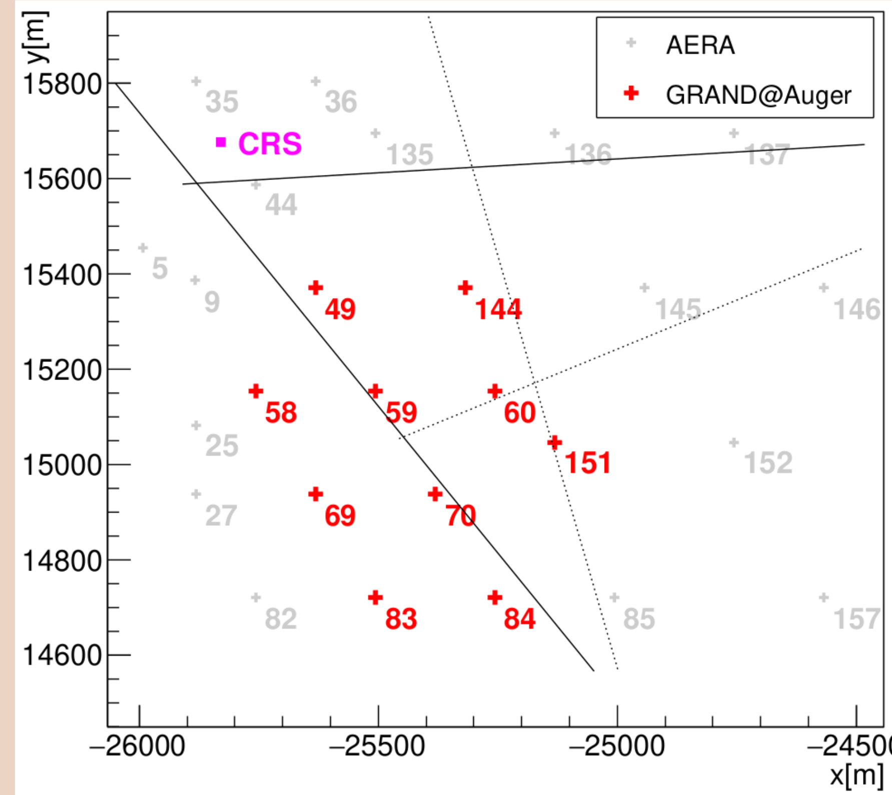
Prototypes: GRAND@Auger

GRAND Coll. in prep.

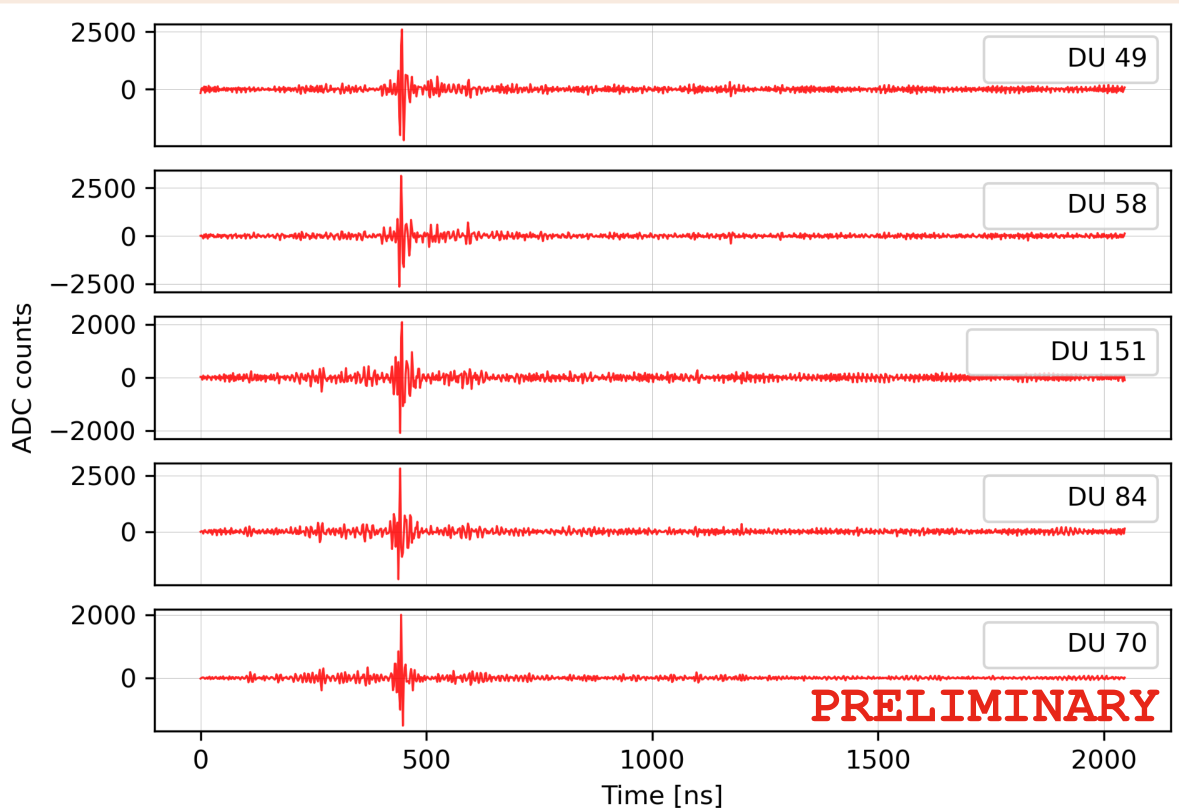
Cross-calibration with Auger detectors:
1 coincident event/day expected

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

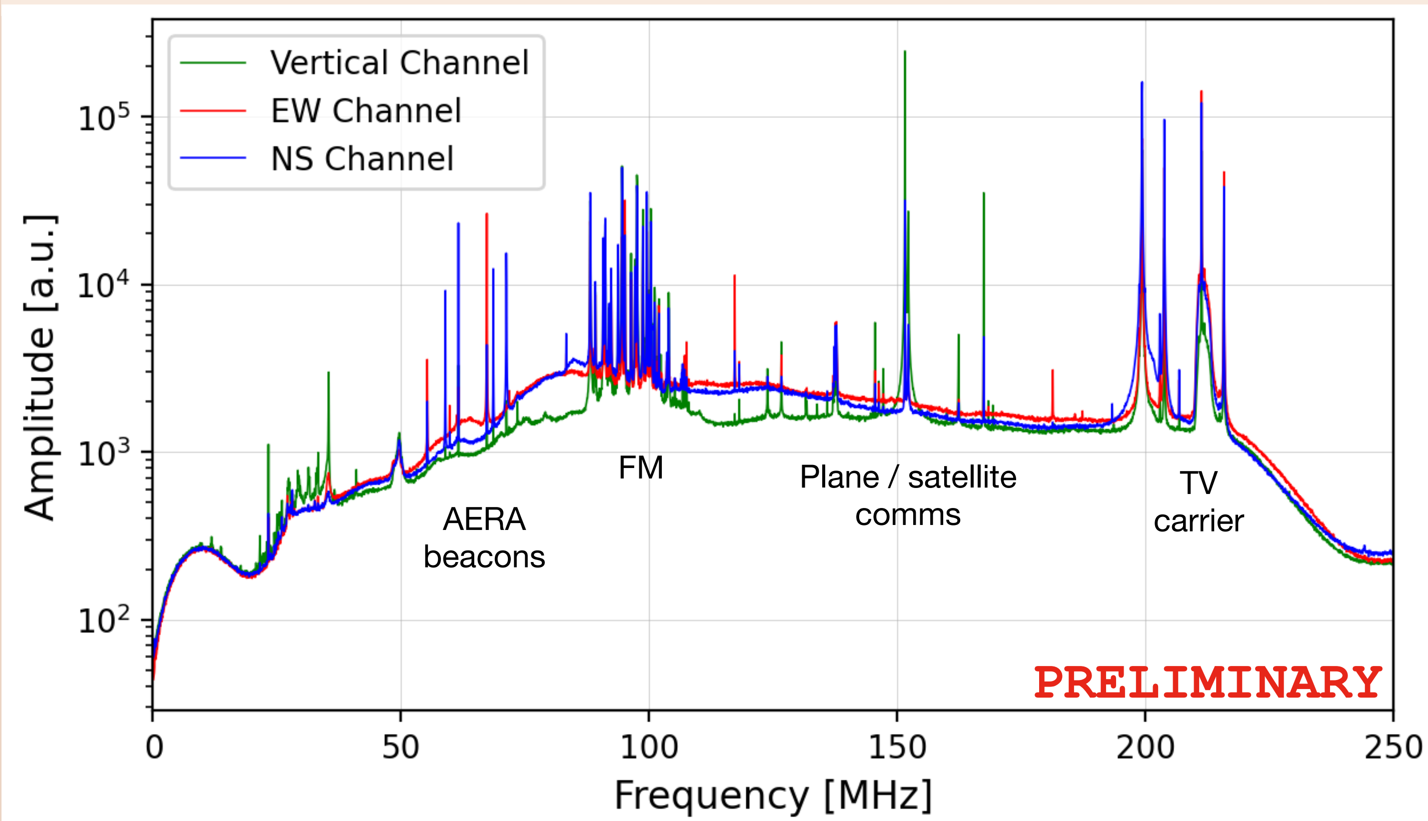
Layout GRAND@Auger



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



Power Spectrum Density



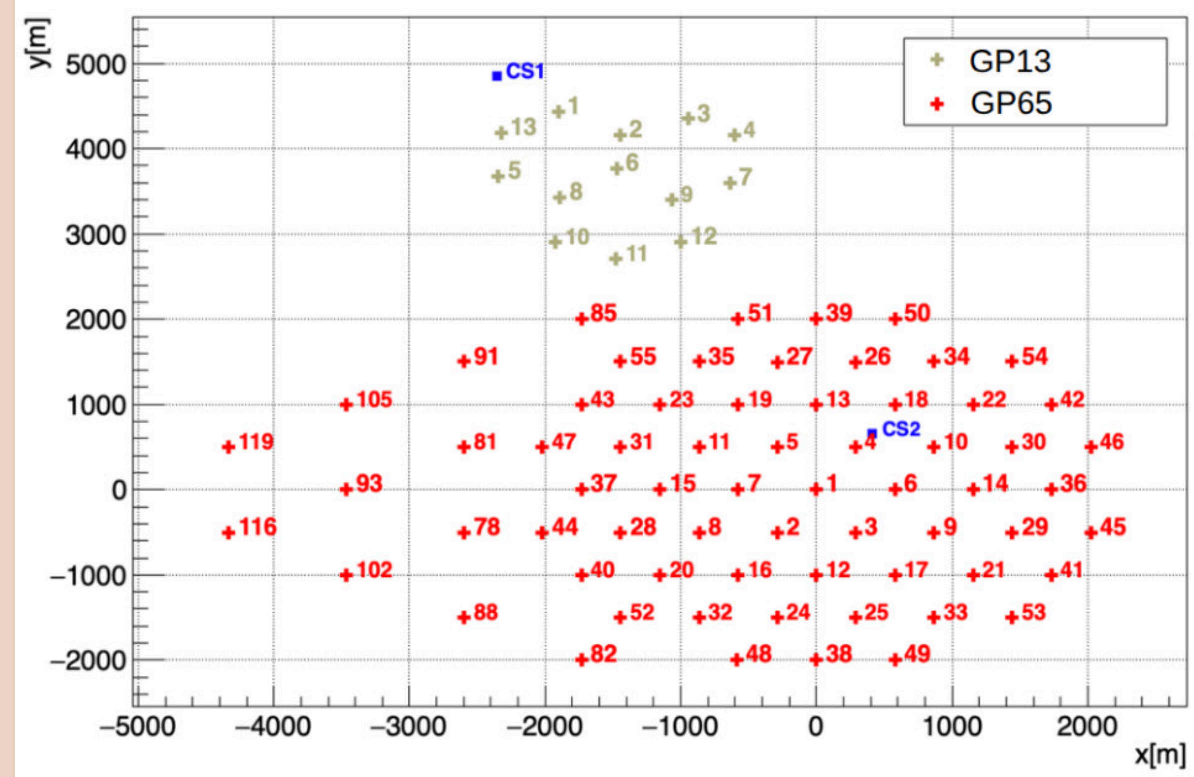
Prototypes: GRANDProto300

GRAND Coll. in prep.

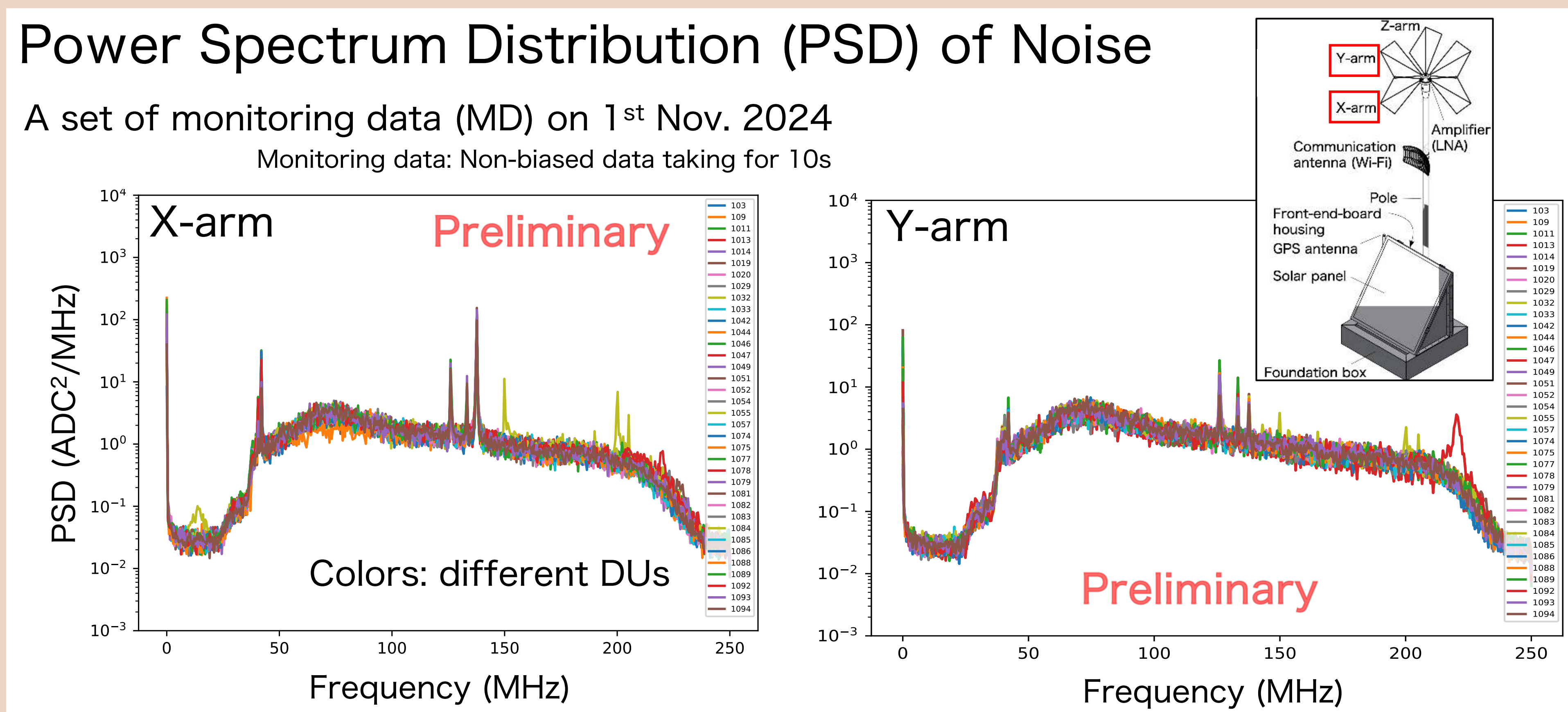
GRAND detection concept validation:
Autonomous triggering & inclined EAS reconstruction

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

Layout GRANDProto300



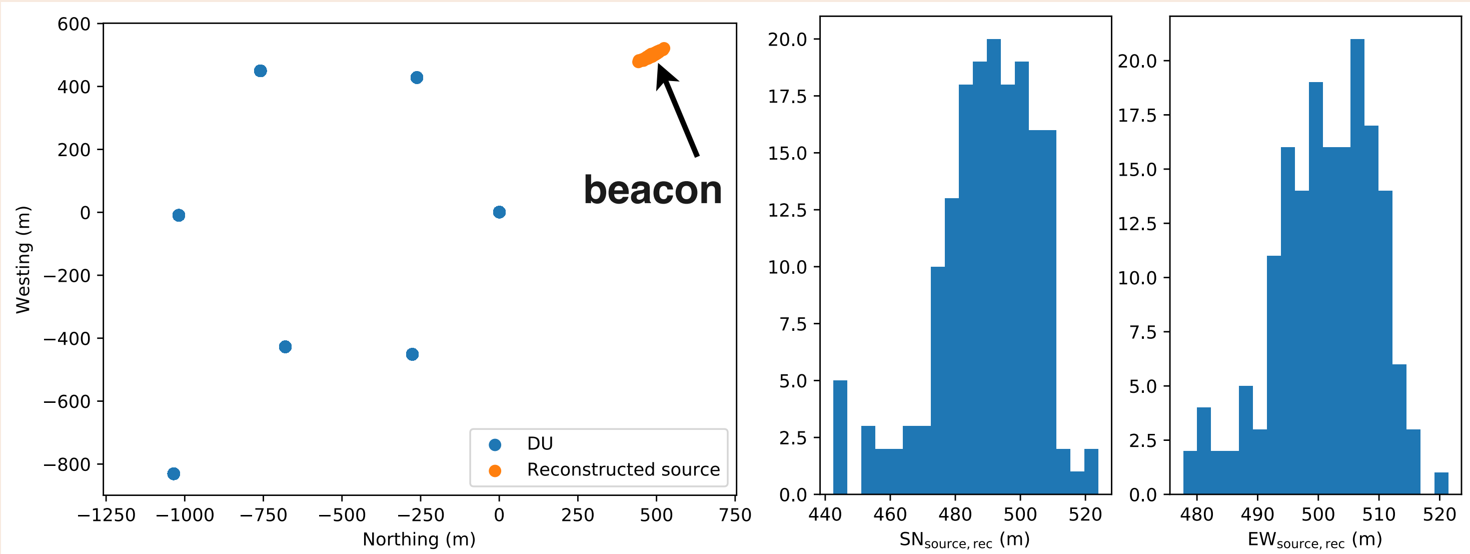
- Clean spectra for all antenna arms [30 - 250 MHz]
- Peaky lines from airplanes, FM, etc.
- Galactic noise + instrumental noise



slide by Sei Kato Vietnam 2024

First set of reconstructed events

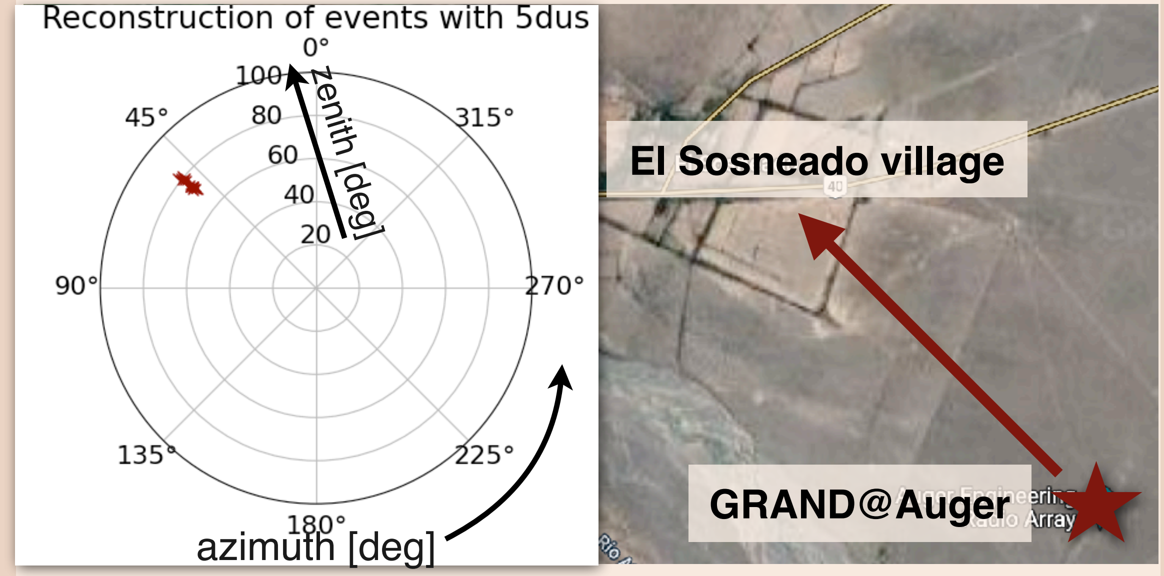
GRANDProto300



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

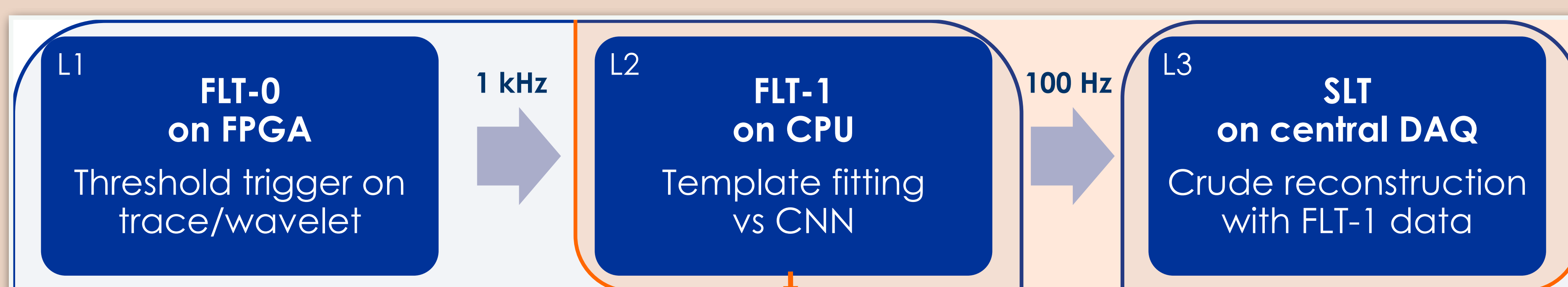


online coincidence search at central DAQ (L3)

- 3 consistent independent analysis (Analytic PWF, PWF/SWF)
- azimuth and zenith consistent with direction of village, towards ground

Conclusions:

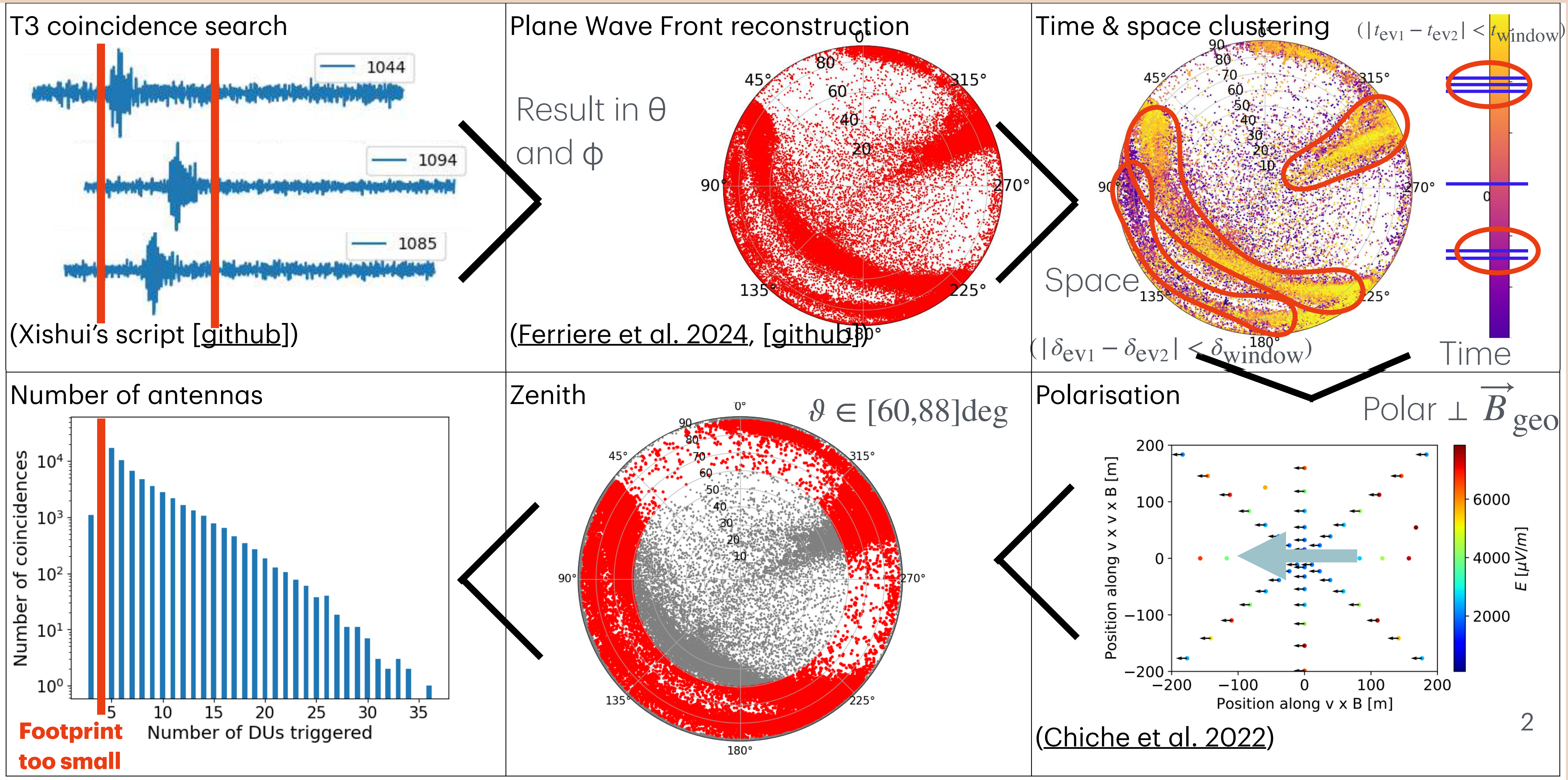
- **Trigger system works**: L1 for GP300, L1 + L3 for GRAND@Auger
- **GPS timing works**
- Work in progress: coincidence detection efficiency, system stability, sensitivity (Galactic noise)



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

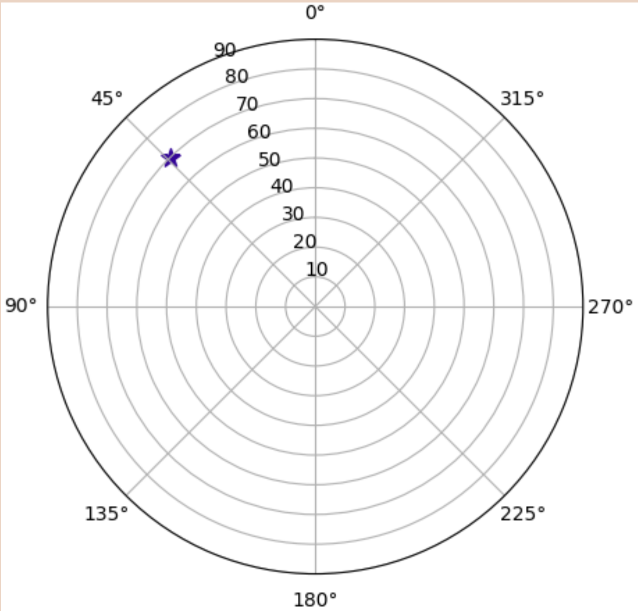
Cosmic-ray (CR) event search

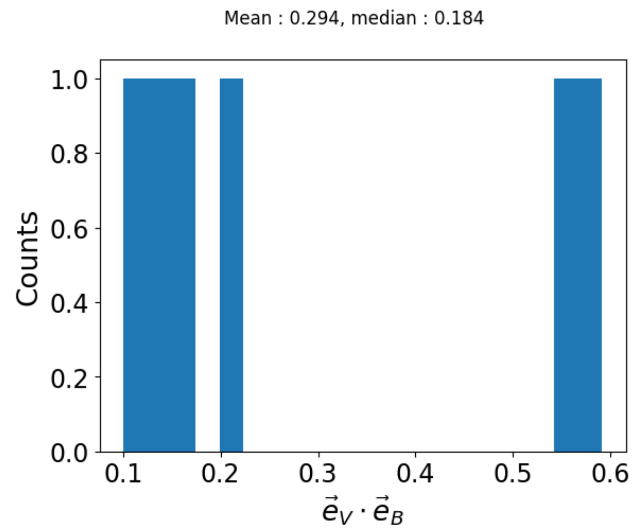
PRELIMINARY

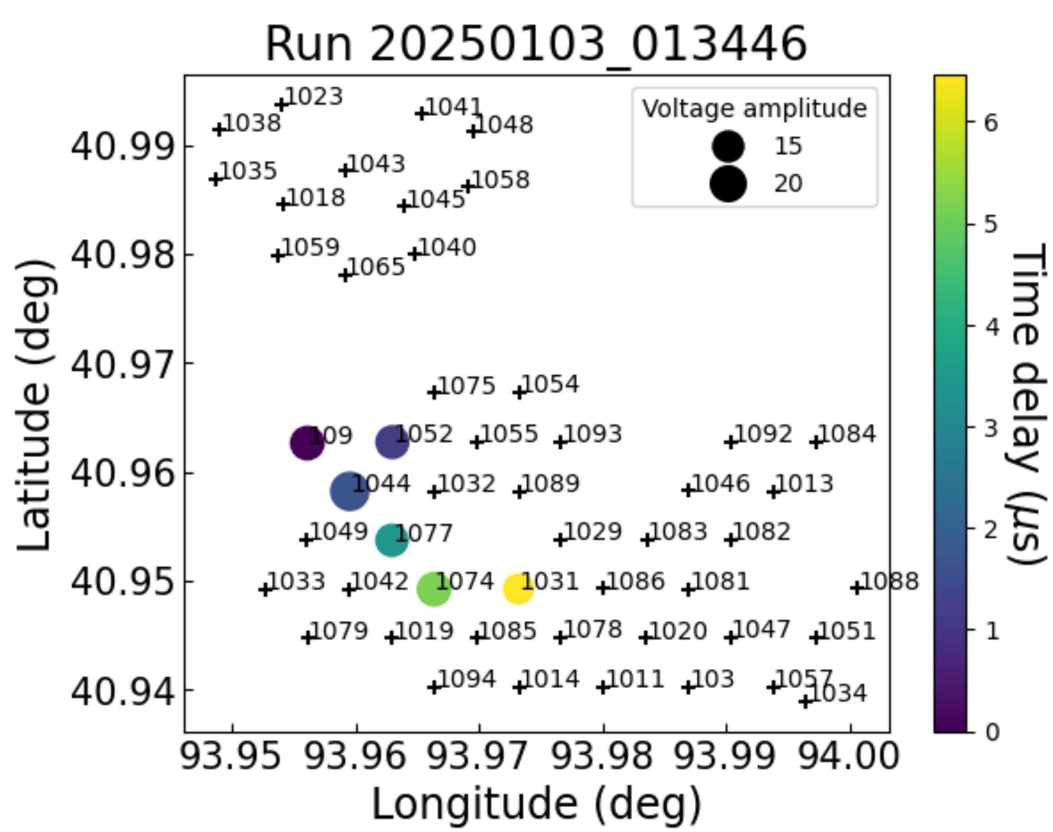


CR events search: first candidates

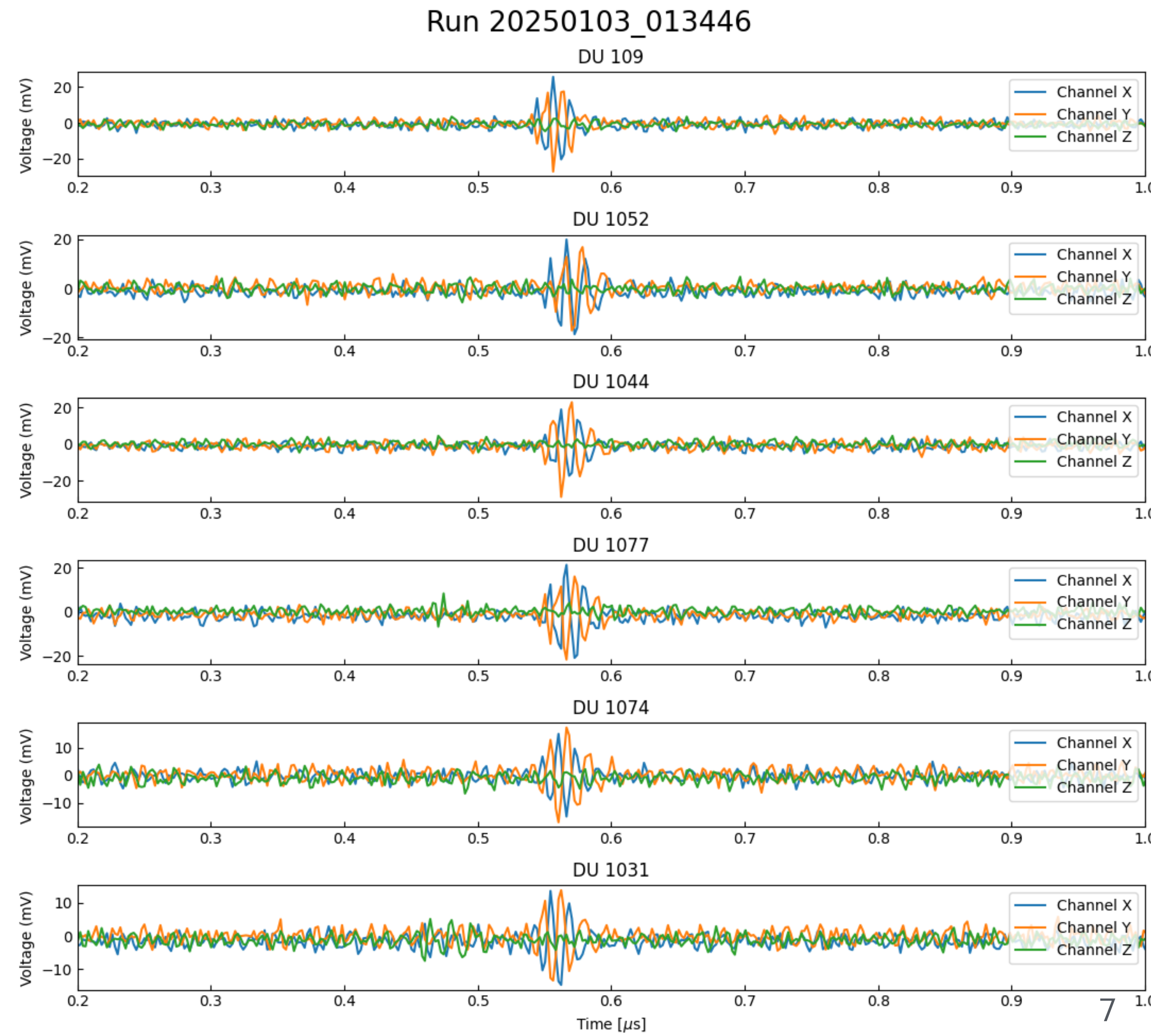
PRELIMINARY







Candidat : 20250103_013446



slide by J. Lavoisier

Reconstruction efforts

Realistic simulation libraries: GRAND "Data Challenge 2"

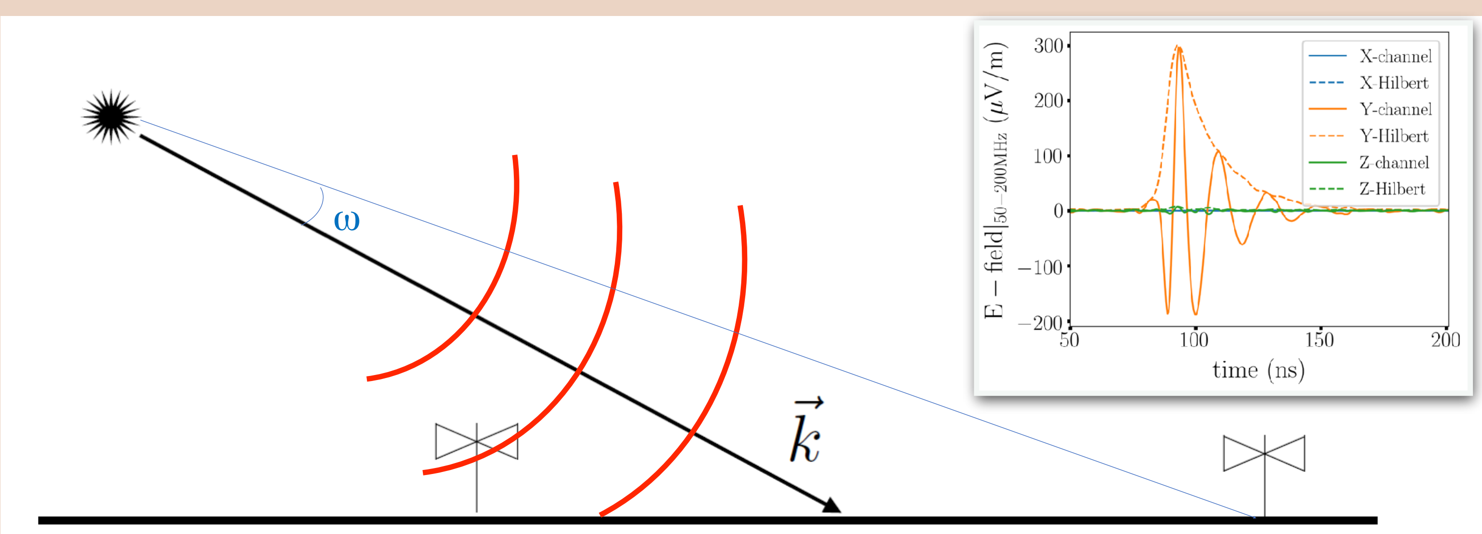
- > 200,000 simulations: raw/hardware like, ADC/Efield traces
- Traces: 4.096 us, downsampled to 500Mhz, with saturation
- Antenna response and RF chain included
- Jitter: 22uV/m Gaussian noise, 5 ns Gaussian smeared “trigger” time, “Amplitude Calibration” gaussian smeared 7.5%

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:

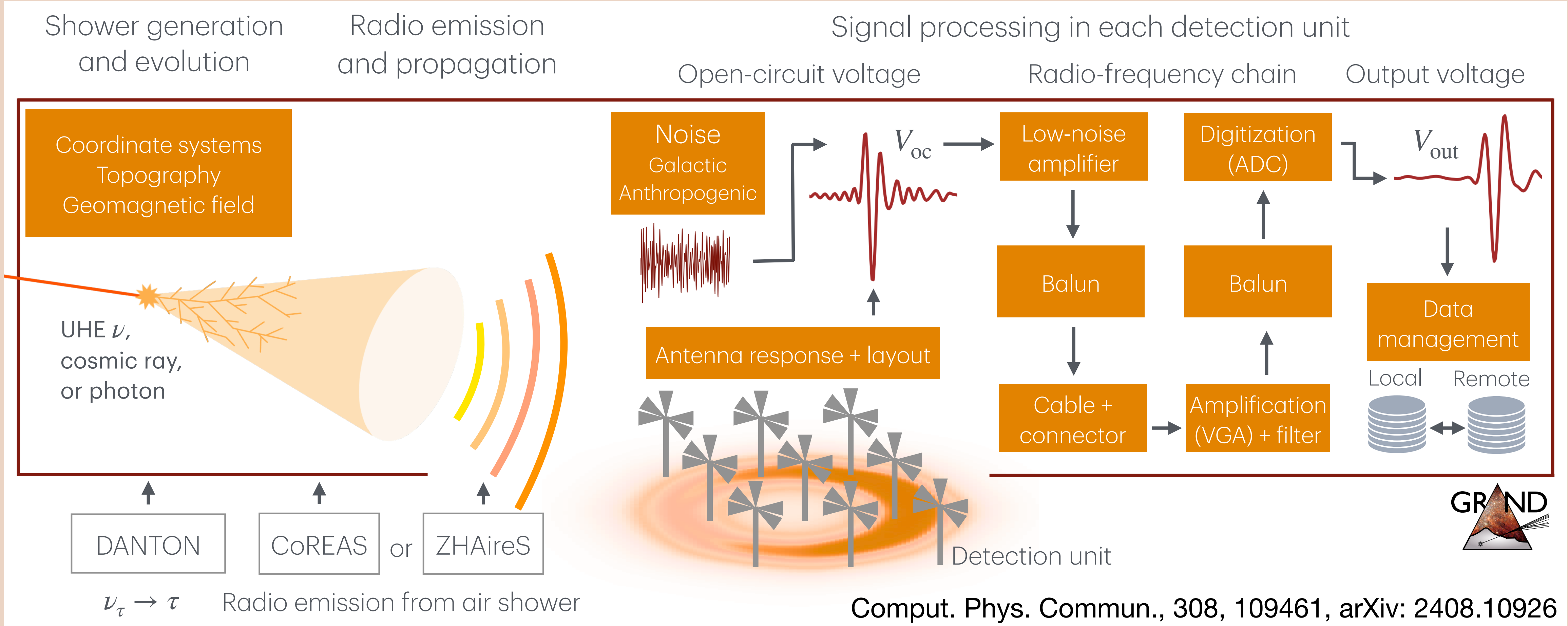
Decoene et al., Astroparticle Physics145, 102779 (2023)
Chiche et al., PRL 132, 231001 (2024)
Guelfand et al JCAP 5, 055 (2024)
Alvarez-Muniz et al., arXiv:1810.09994 (2018)
Macias et al., Pos(ARENA2024)062
Benoit-Lévy et al., JINST19(4), P04006 (2024)

Software pipeline: GRANDlib

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

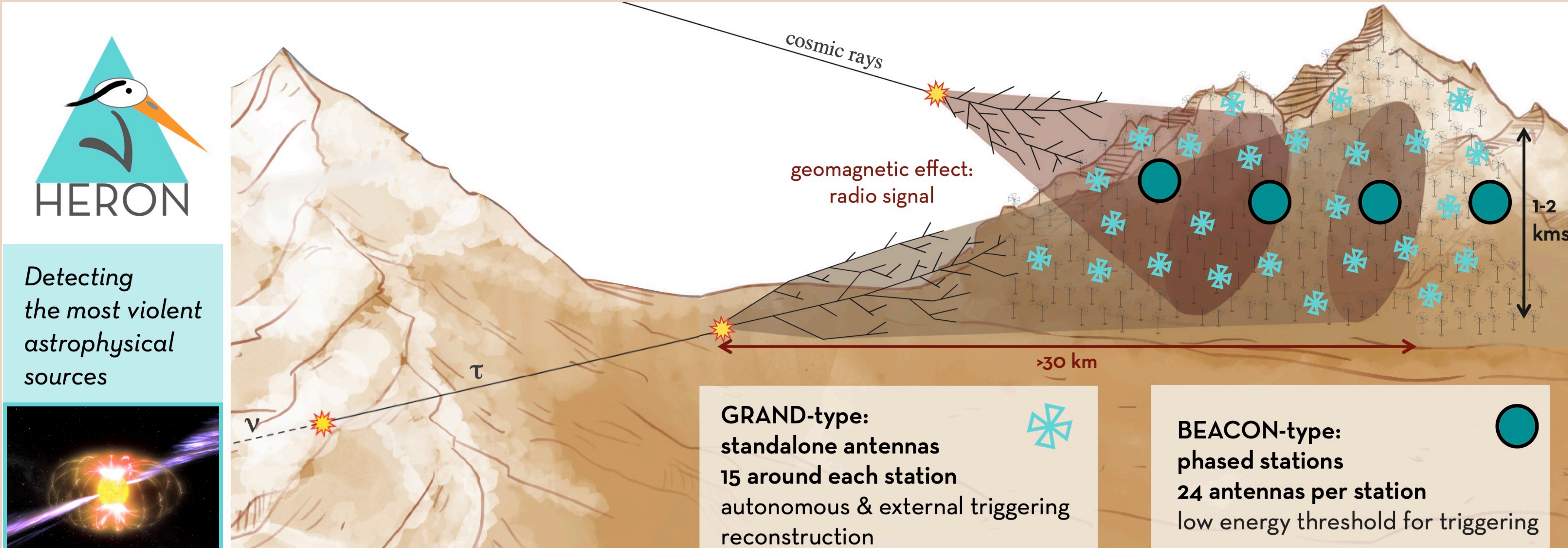
GRAND Coll. 2024
https://github.com/grand-mother/grand

- 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

Perspectives: HERON

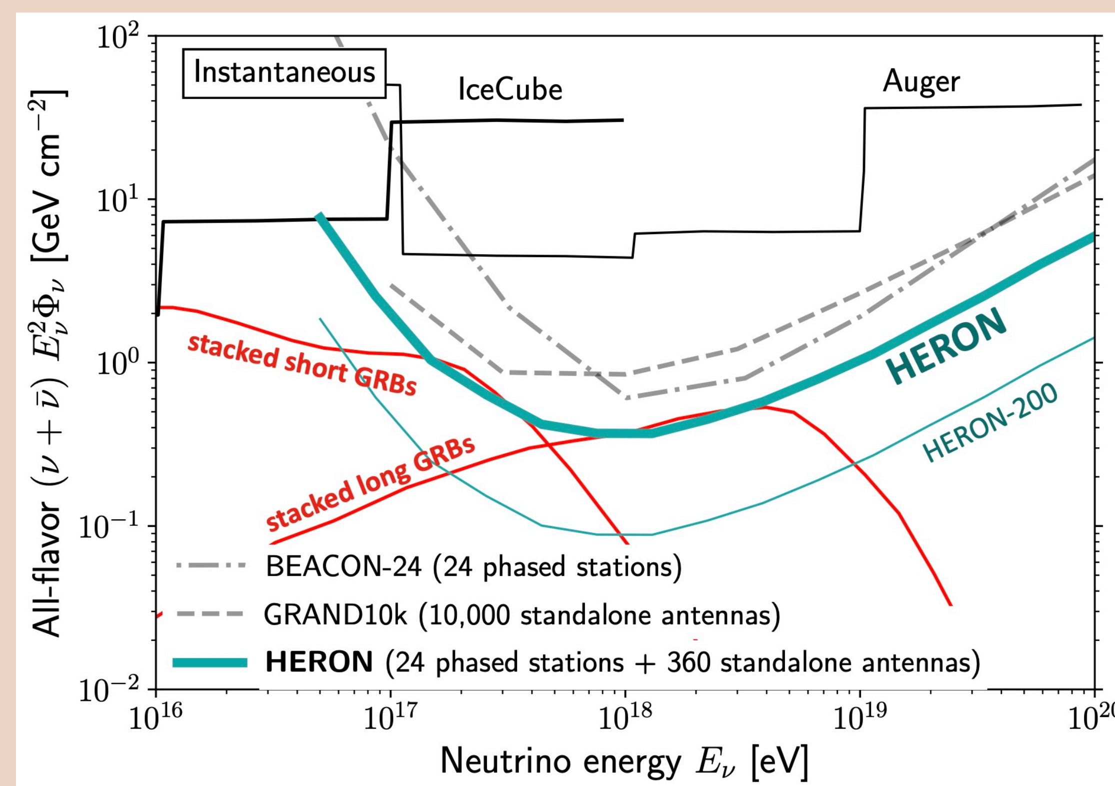


antennas: 3 m high, 1 m² of footprint on ground

- **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



The GRAND Collaboration

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