Faculté de physique et ingénierie Université de Strasbourg

master PSA Physique Subatomique Astroparticules

Towards multi-messenger measurements at ultra-high energy with GRAND

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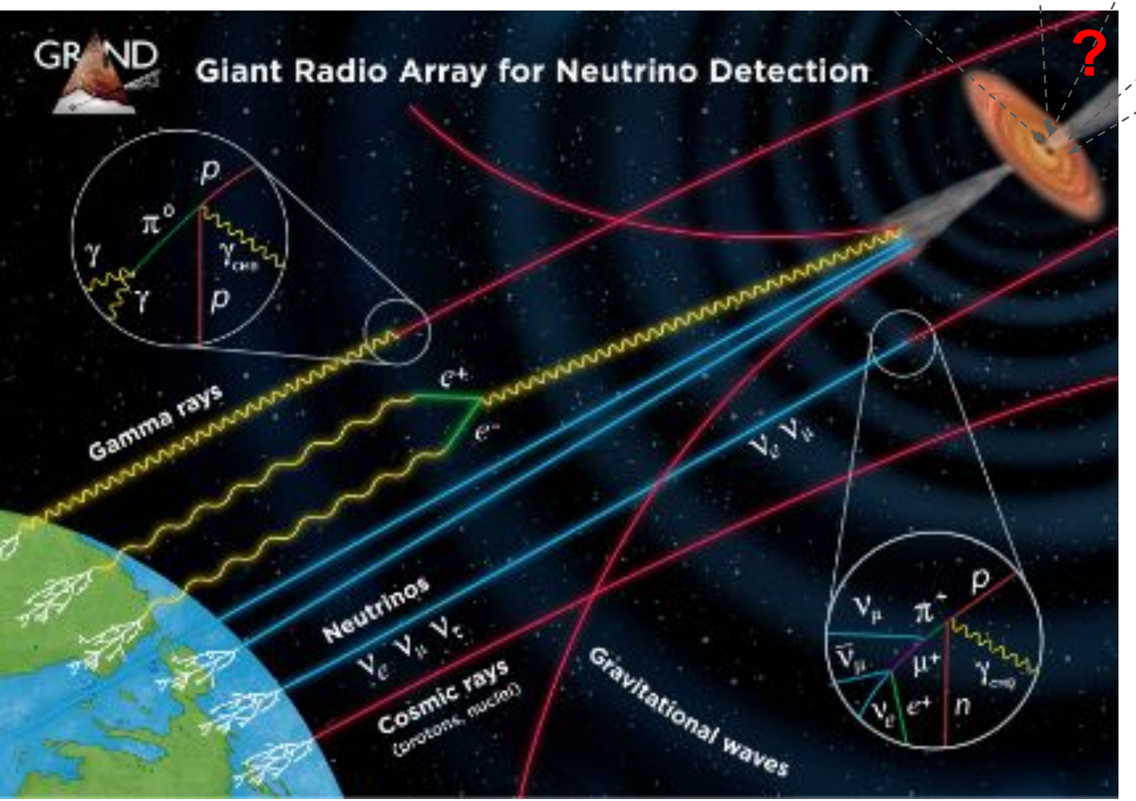
LPNHE PARIS

Supervised by O. Martineau

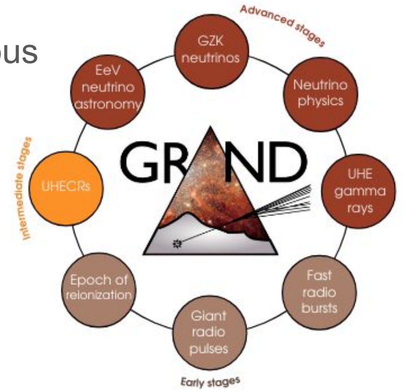
18/06/2025

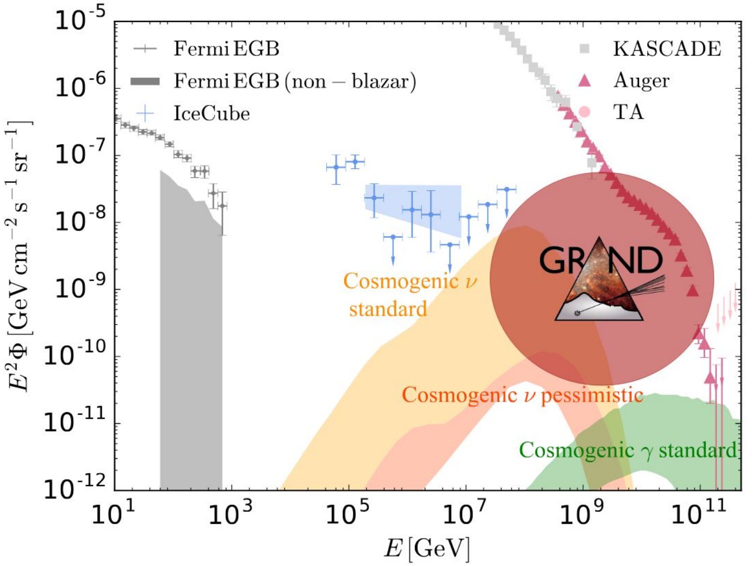
GRAND

GRAND science case



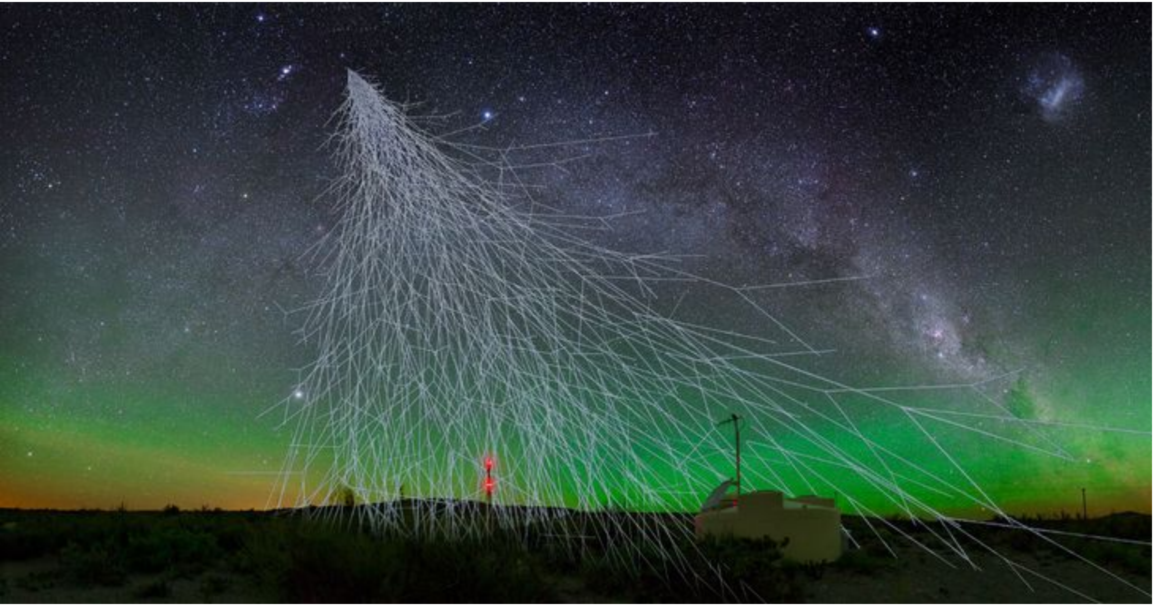
(Álvarez-Muñiz et al. 2019)



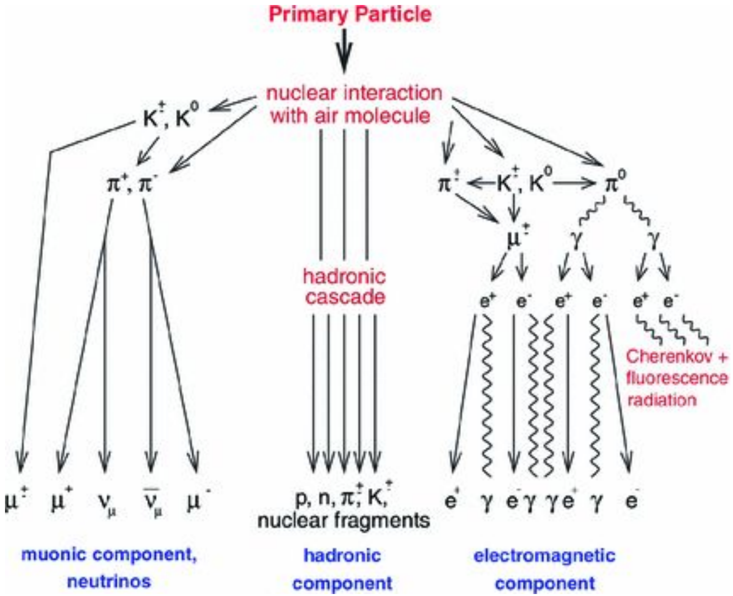


(Álvarez-Muñiz et al. 2019)

Extensive air shower

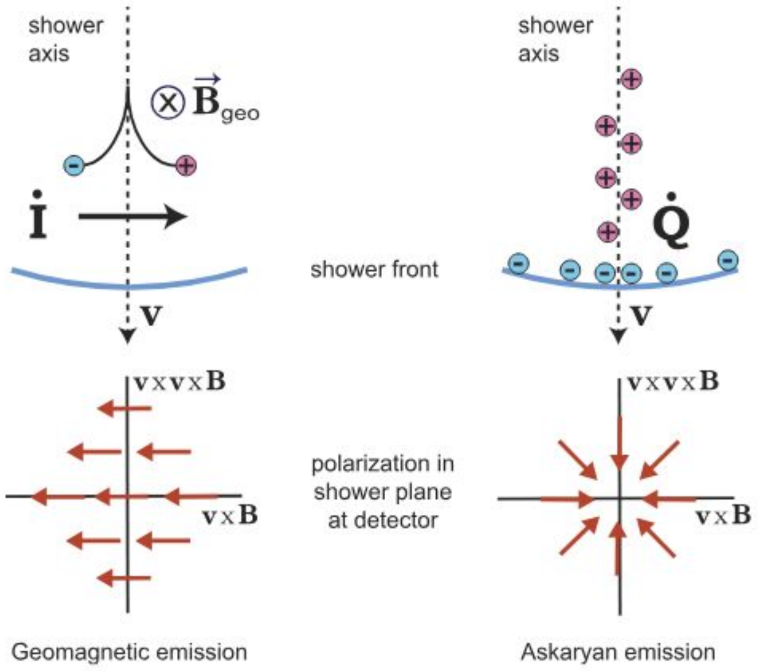


Artist's impression of an air shower over a particle detector at the Pierre Auger Observatory, seen against a starry sky. (A. Chantelauze, S. Staffi, L. Bret)

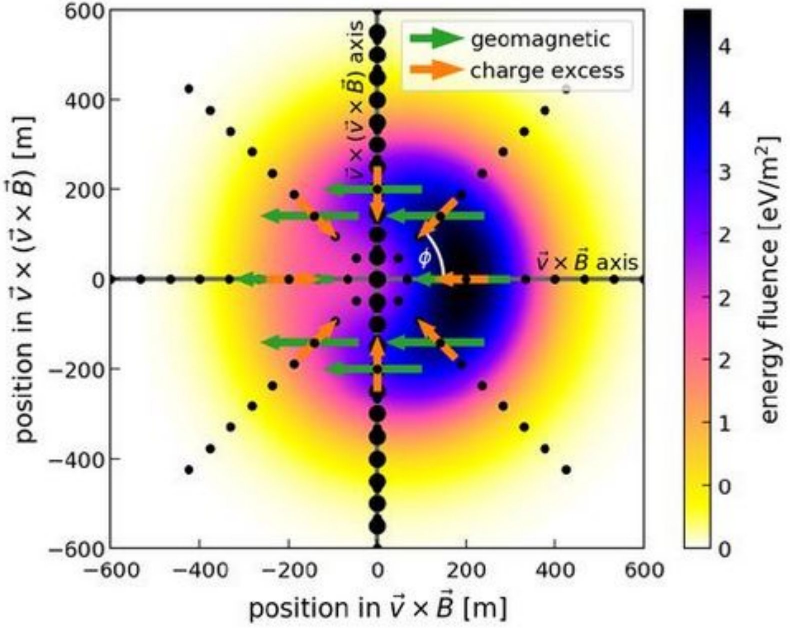


Zilles, A. (2017). Introduction to cosmic rays and extensive air showers.

Geomagnetic & Askaryan effect



(Frank G. Schröder, 2017)



(C.Glaser, 2019)

At MHz–GHz frequencies, air-shower radio signals arise from the coherent superposition of a dominant, Lorentz-force-aligned geomagnetic emission and a radially polarized Askaryan emission, giving constructive or destructive interference.

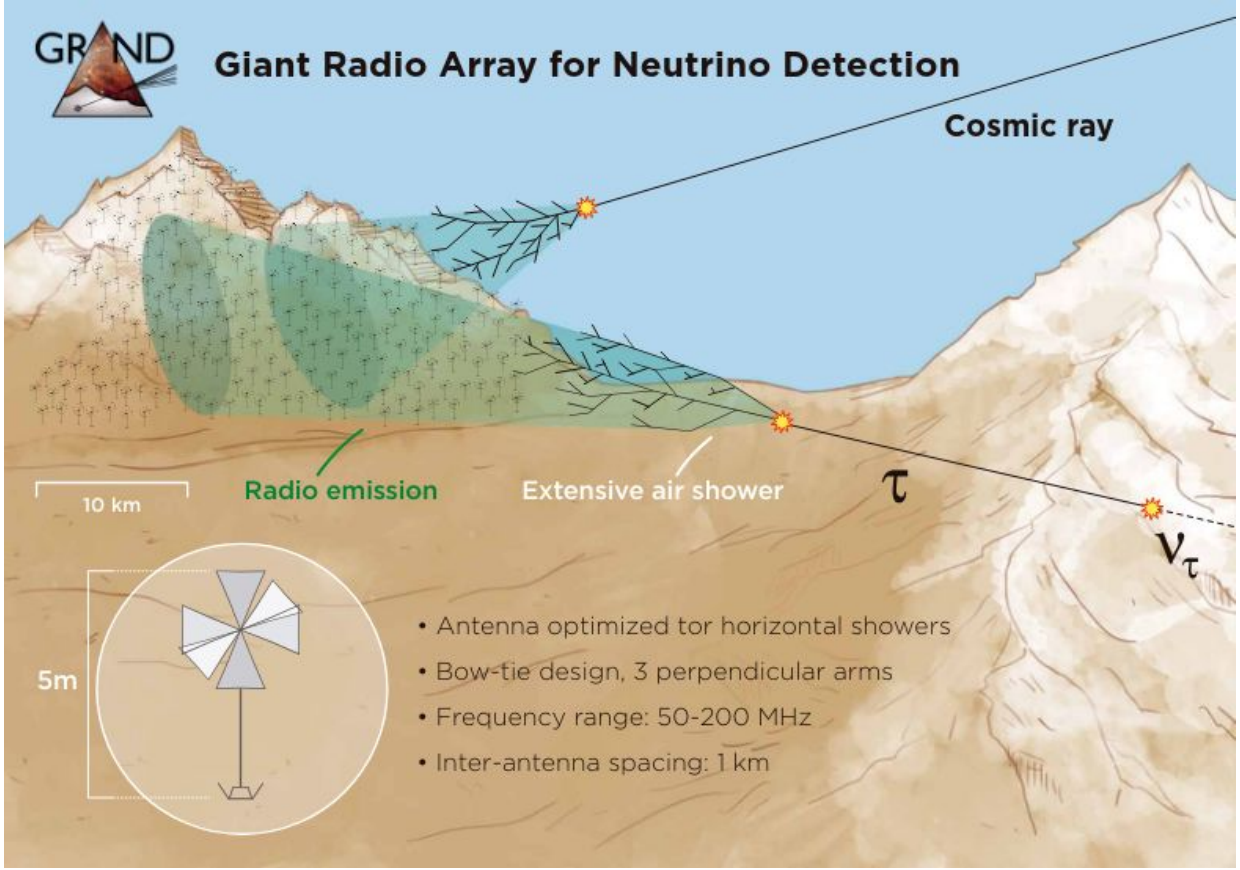
Detection method

- **The aim of GRAND:**

  Build a giant detector **covering 200,000 km² with 200,000 antennas.** Such a large-scale detector suppresses the background from isotropic sources and provides good resolution characteristics. This is why radio detection is promising.

- **Earth-skimming ν_τ channel:**

  ν_τ interacts inside a mountain or the Earth's crust, producing a τ lepton that escapes into the atmosphere and decays, initiating an extensive air shower.

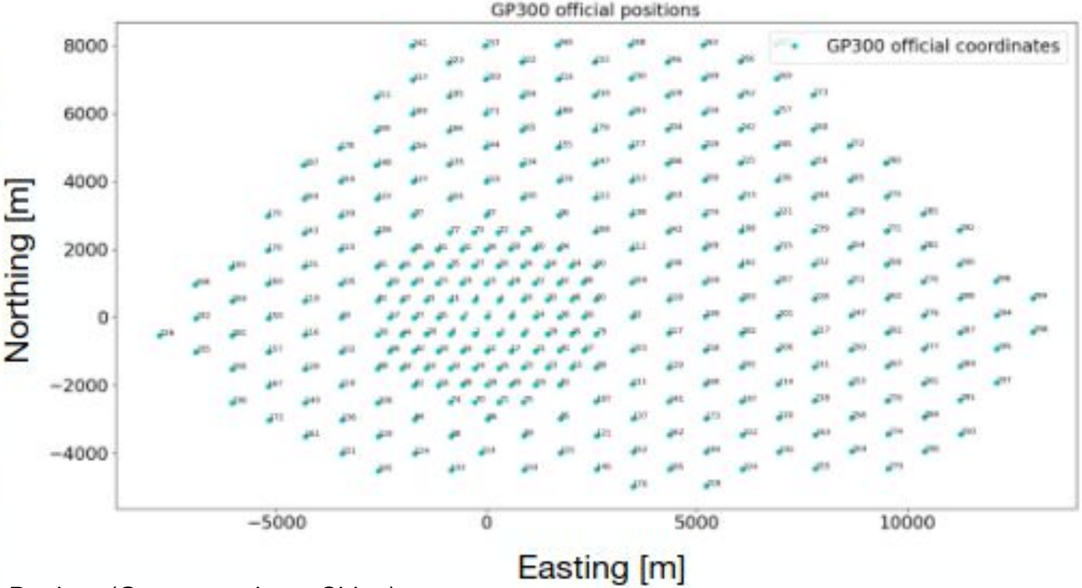


GRAND detection principle, illustrated for one of the 10 000-antenna GRAND10k arrays.

GP300 Overview

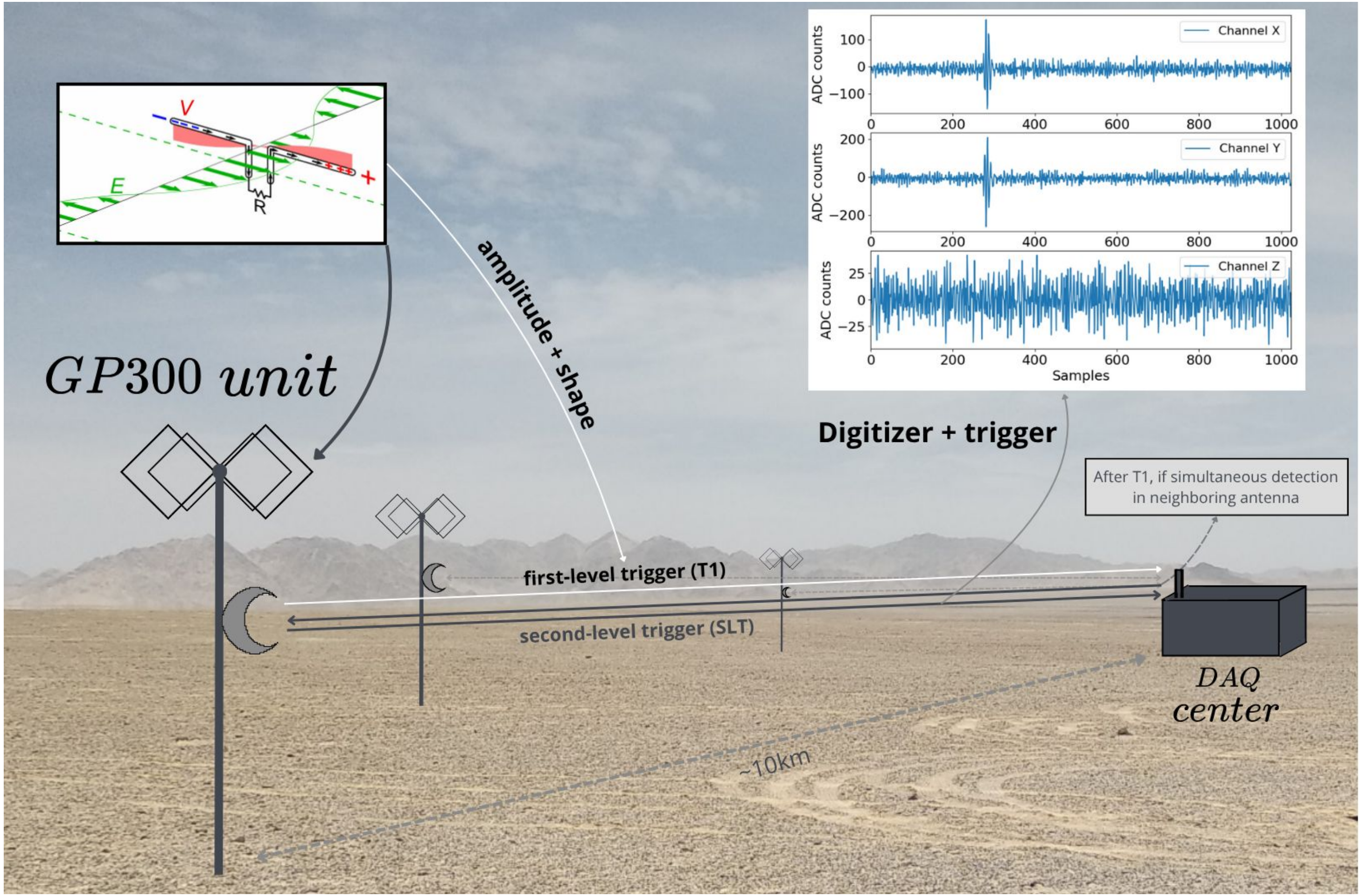
Main Objectives

- Validate the **self-triggering radio detection** concept in real conditions.
- Study the **background noise** and **radio environment**.
- Test and refine **reconstruction algorithms** for extensive air showers (EAS).
- Establish procedures for **data acquisition, storage, and calibration**.

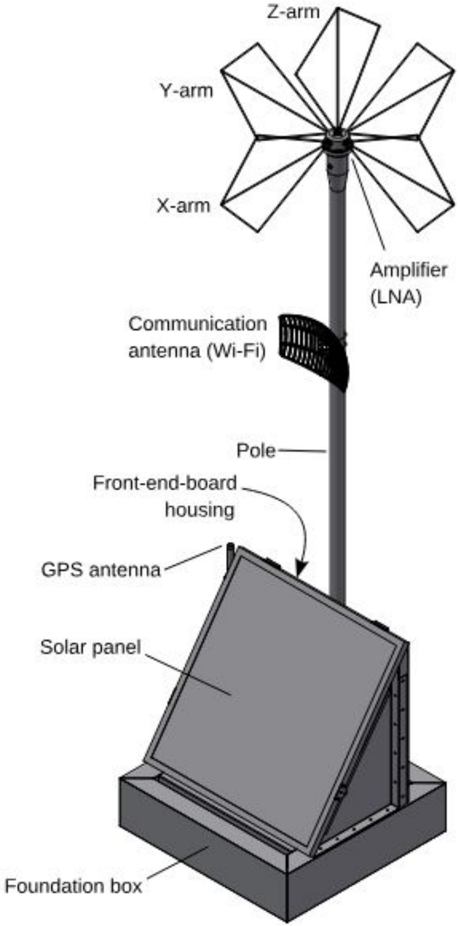


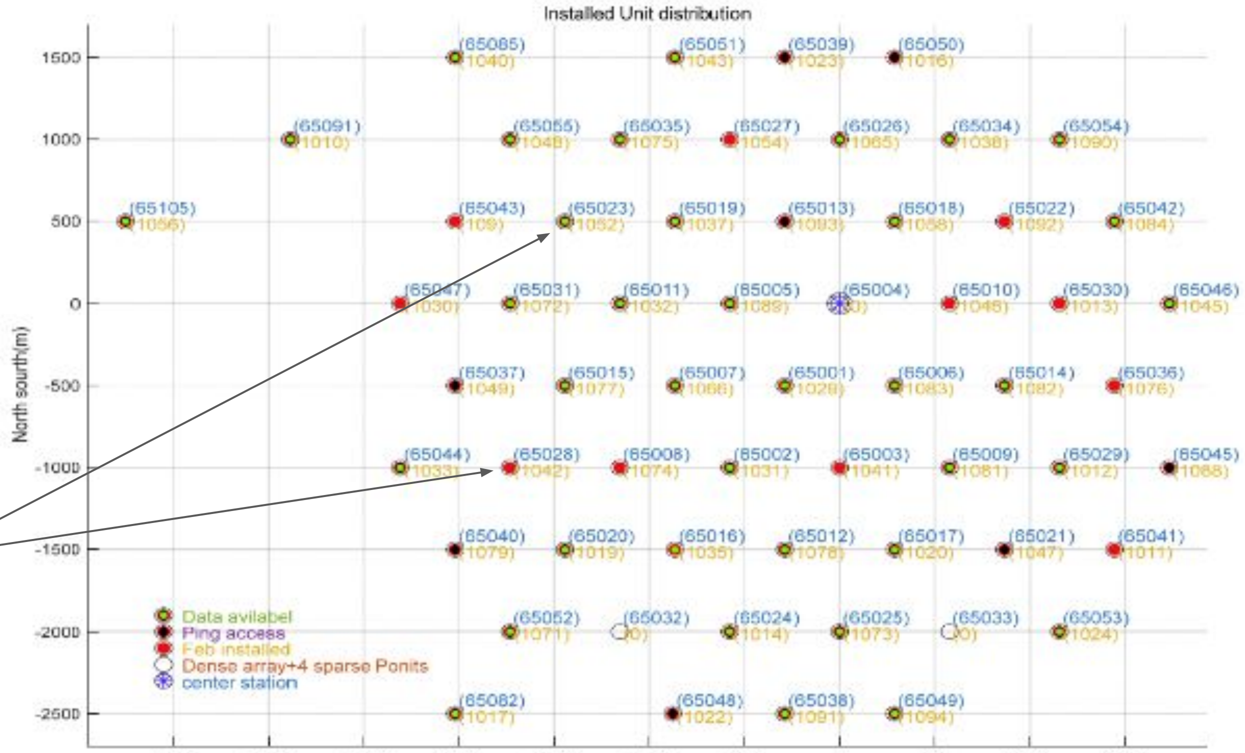
Left: Selected site of the GRANDProto300 radio array in Xiao Dushan (Gansu province, China).
Right: Antenna layout of GRANDProto300. A hexagonal grid was chosen with a sparse array (1 km-step) and a denser infill (577 m-step) (Chiche, S. (2024). GRANDProto300: Status, science case, and Prospects)

Detector details



GP300 status





The first antennas were deployed in February 2023, and the last deployment took place in April 2025. **Currently, 67 antennas deployed.**

My objective during my internship

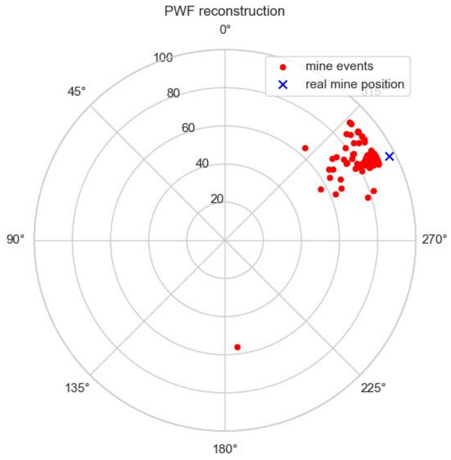
1 Commissioning

Tools to check the status of the detector

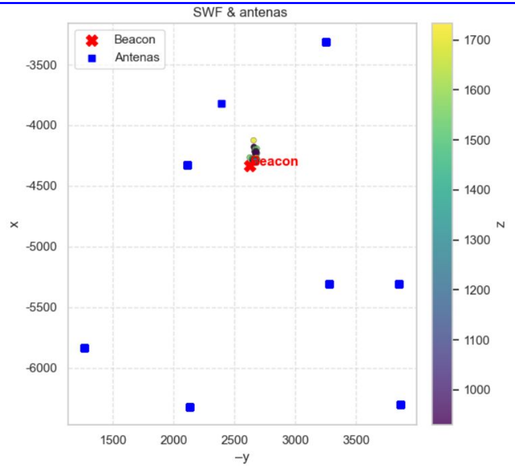
2 Detector qualification

Use well known background sources, to characterise the detector (trigger efficiency, timing accuracy, livetime) and reconstruction methods (PWF, SWF)

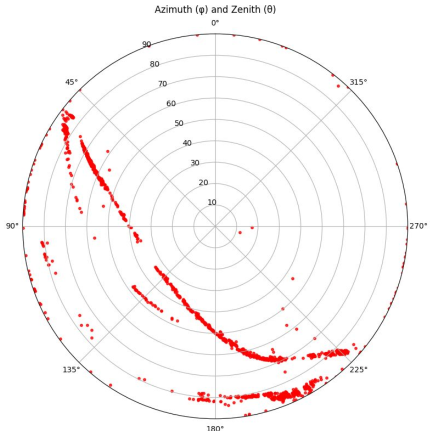
No physics without a good understanding of the detector !



Transformer mine

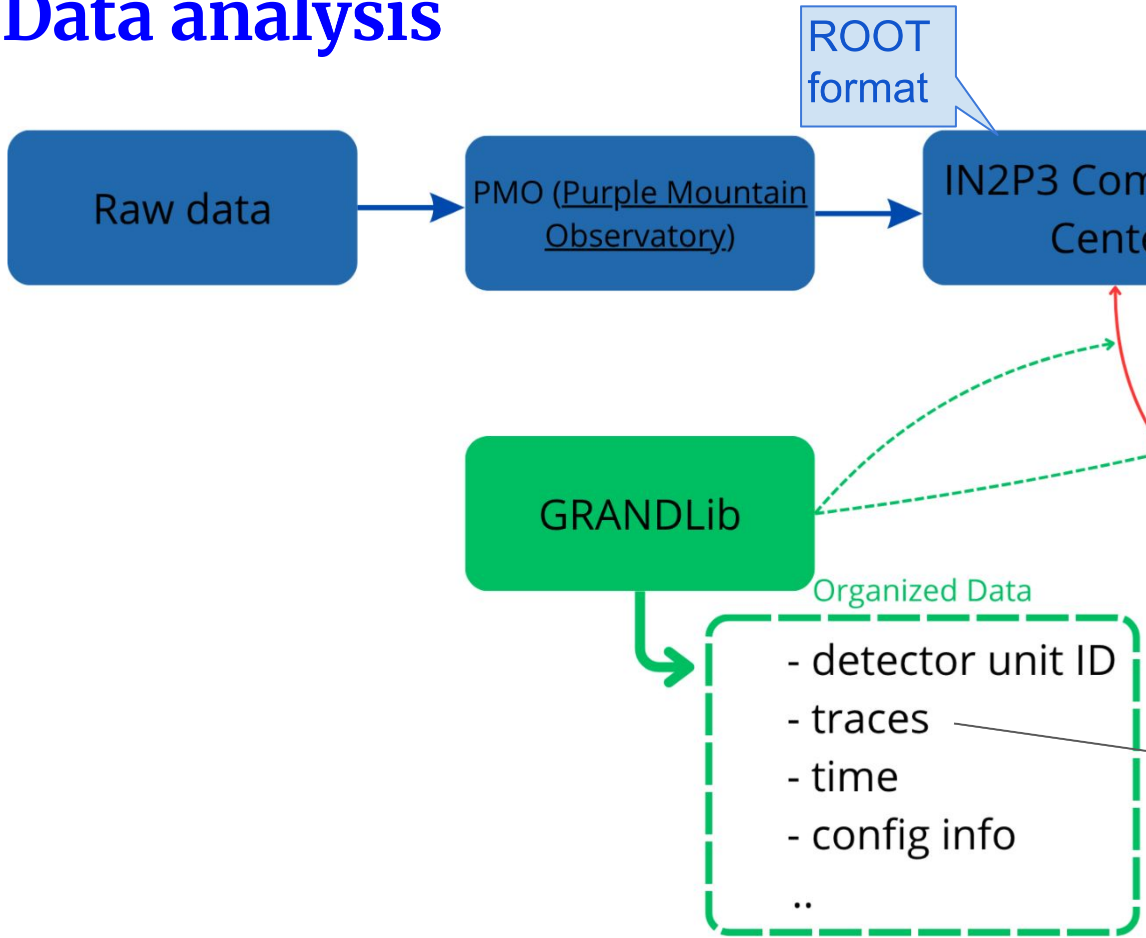


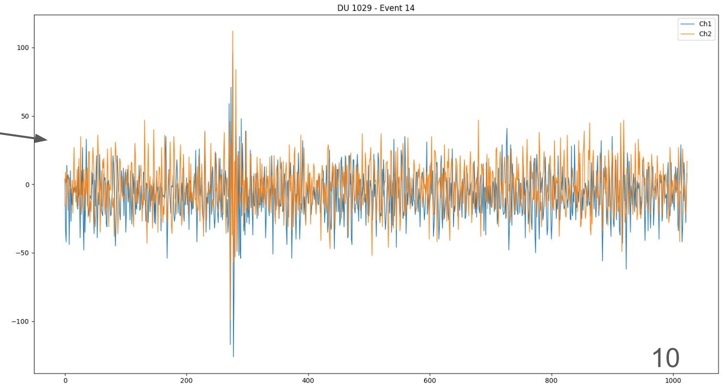
Beacon



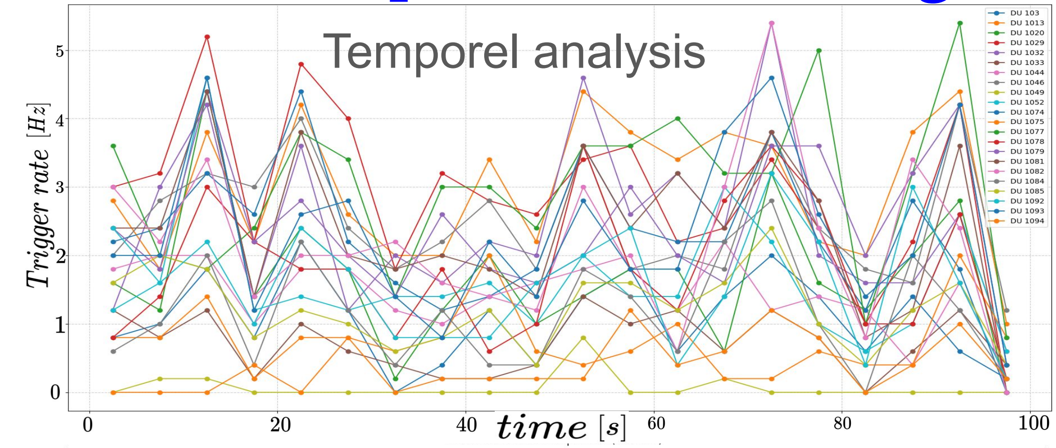
Planes

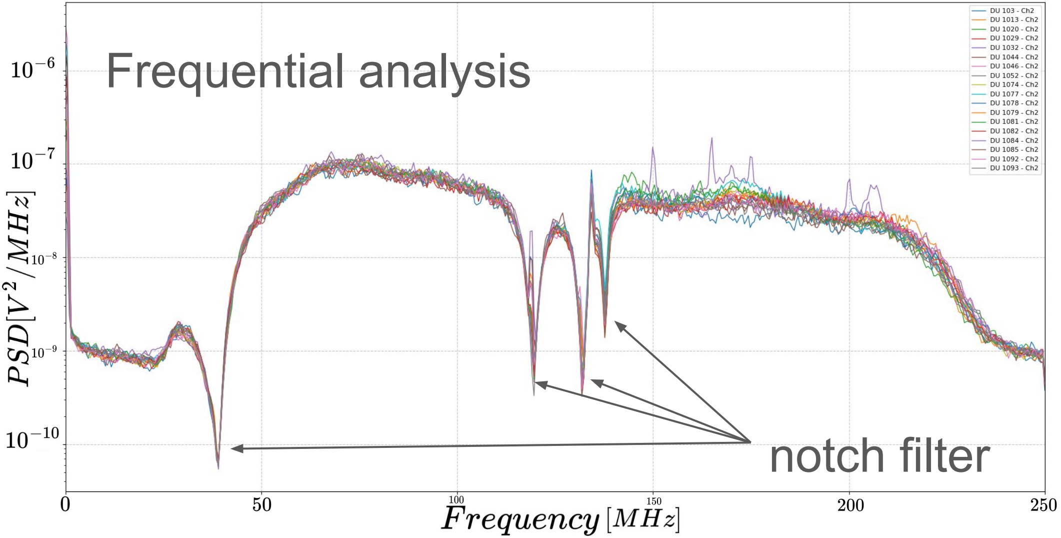
Data analysis



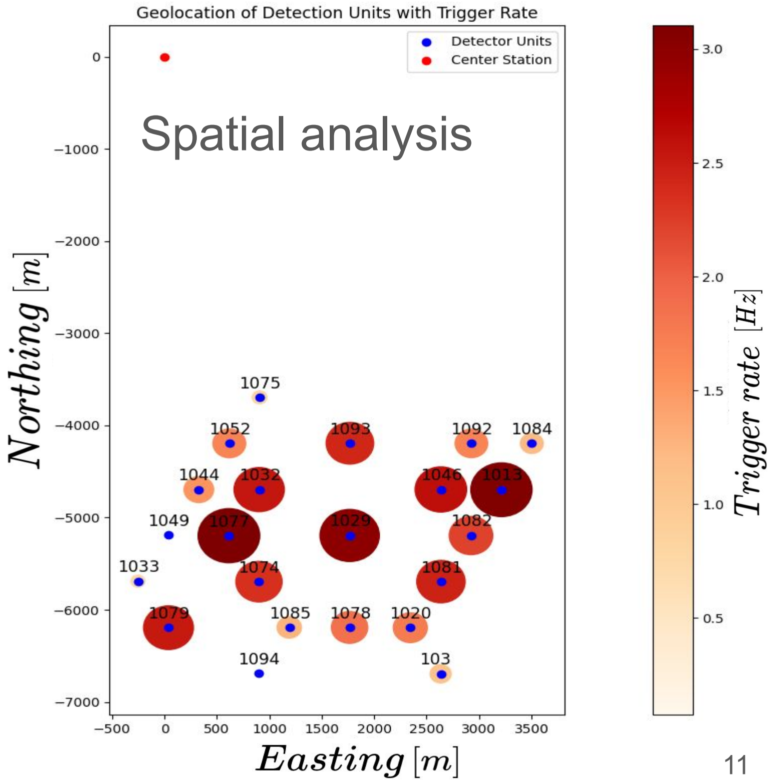


Tools developed for monitoring

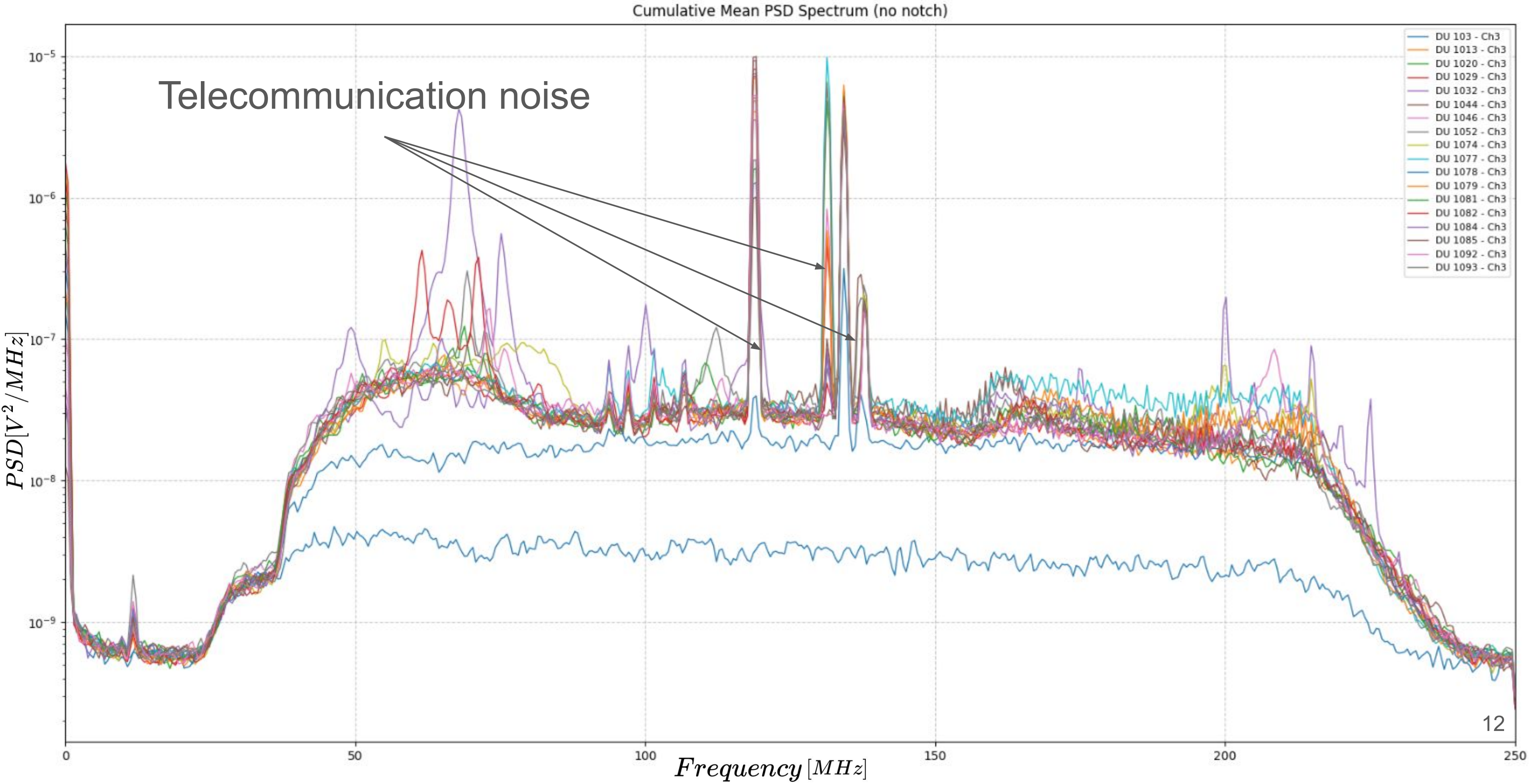




Allows to know the status of the antennas and understand the environment !



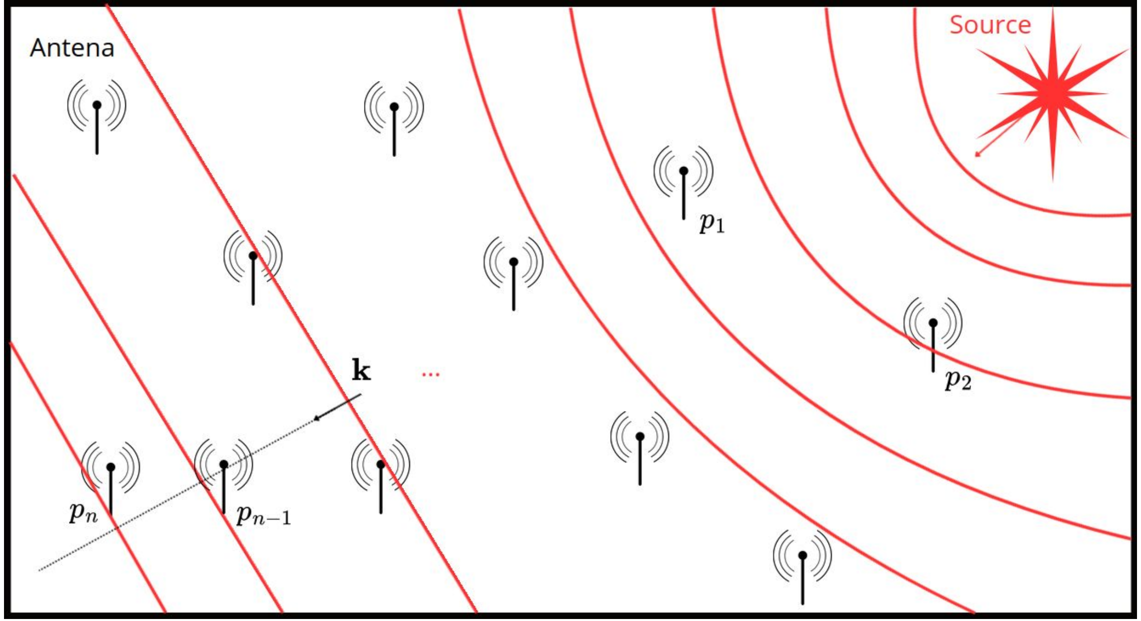
Tools developed for monitoring : Power spectrum density (PSD)



Reconstruction

- The aim is to reconstruct the **direction of cosmic rays.**

- PWF and SWF use the trigger time in their reconstruction algorithms, so it's important to determine it with high precision. It's **crucial** to have a **sub-degree resolution.**



Plane wave function hypothesis (PWF)

minimize

$$\mathcal{L}(\mathbf{k}) \propto (\mathbf{T} - \mathbf{P}\mathbf{k})^T(\mathbf{T} - \mathbf{P}\mathbf{k})$$

Spherical wave function hypothesis (SWF)

minimize

$$\chi^2 \propto \sum_i \left(\frac{t_i - t_0 - \frac{\|\mathbf{p}_i - \mathbf{p}_0\|}{c'}}{\sigma_i} \right)^2$$

PWF : Ferrière, A. et al. "Analytical planar wavefront reconstruction and error estimates for radio detection of extensive air showers."
SWF : V. Niess (2009)

1- Beacon

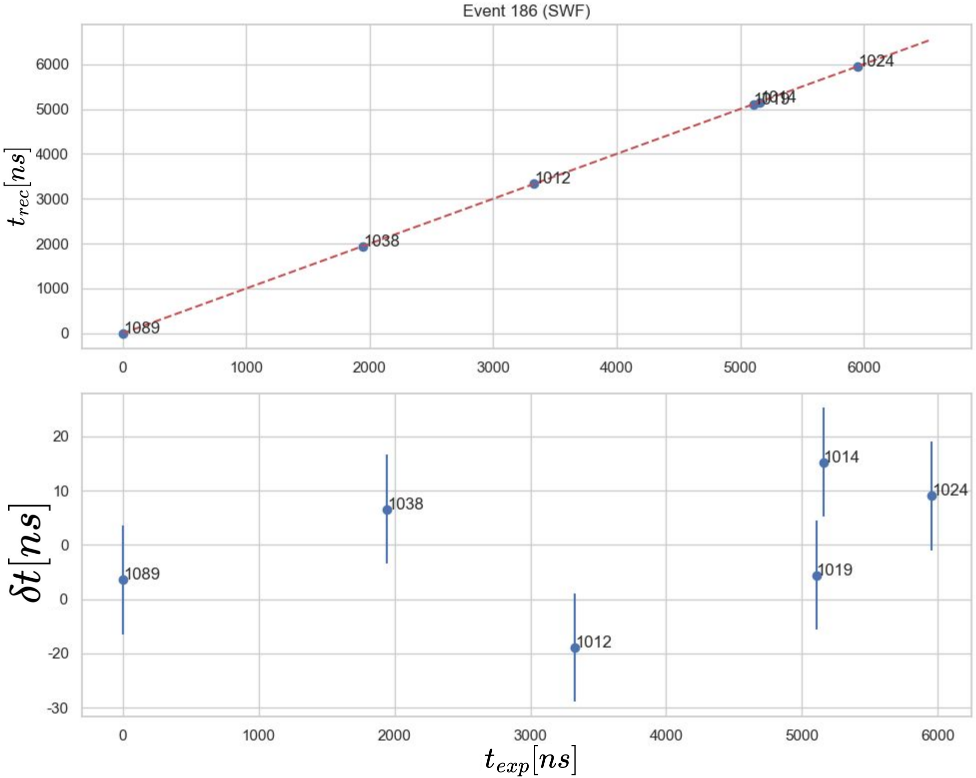
How to assess quality of the reconstruction ?

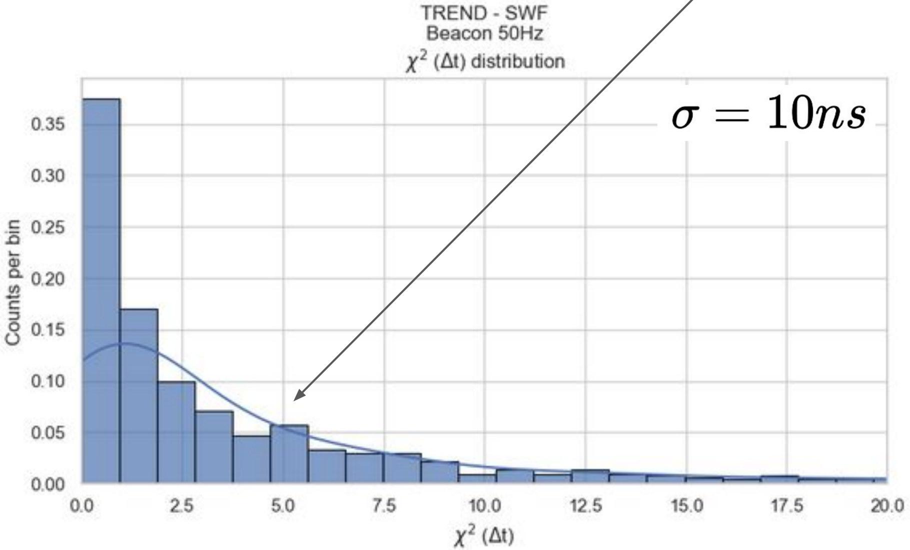
$$t_{simu} = \frac{x_{DU,i} - \boxed{x_{source}}}{c'}$$

Given by the reconstruction

$$t_{\mathrm{rec},i} = t_{simu} + < t_{expe} - t_{simu} >, \qquad \delta t_i = t_{\mathrm{exp},i} - t_{\mathrm{rec},i}$$

$$\chi^2 = \sum_i \left(\frac{\delta t_i}{\sigma}\right)^2$$





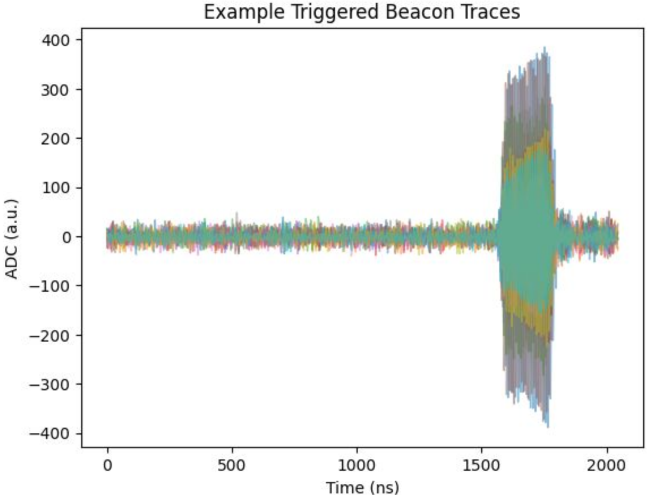
$\sigma = 10ns$

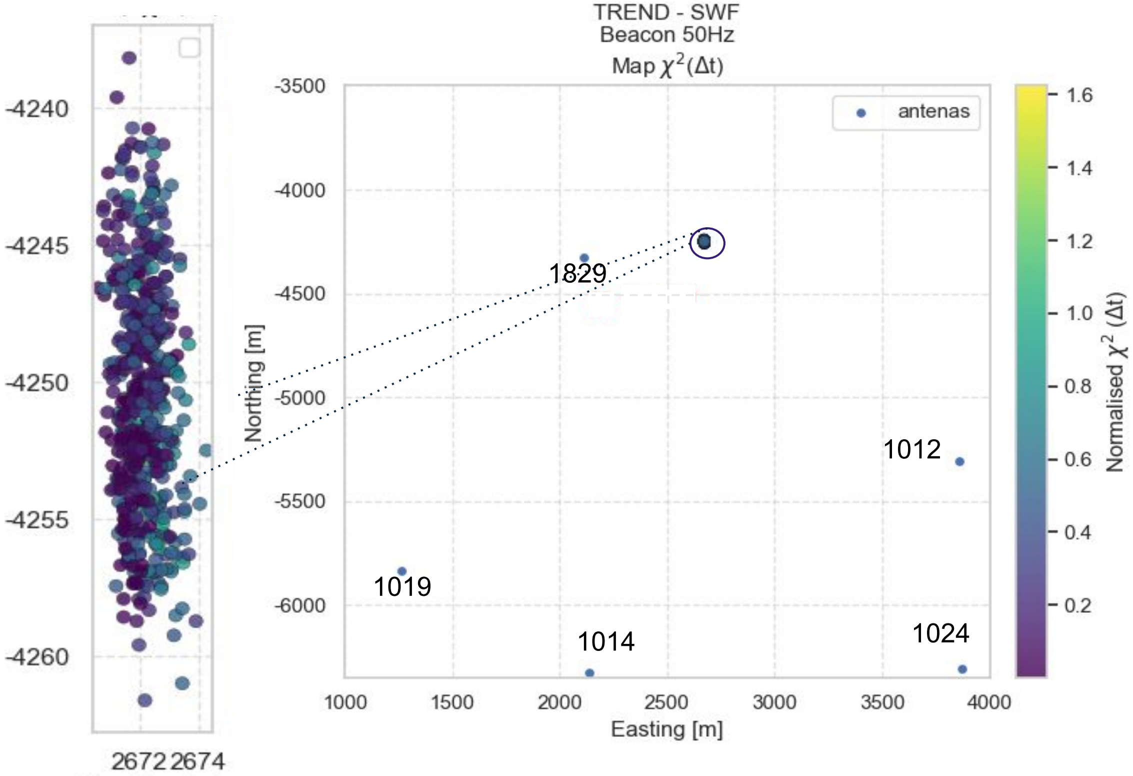
so-called "TREND code", ie developed for TREND by V. Niess (2009)

1- Beacon reconstruction

Using : 20250309_235256_RUN10070

Beacon characteristic : *Sine wave (A=1V, f=100MHz) with 20 periods and repetition rate between 1 and 100Hz.*





1- Beacon analysis

```
std x :  4.16 m
std y :  0.60 m
std z : 12.60 m
```

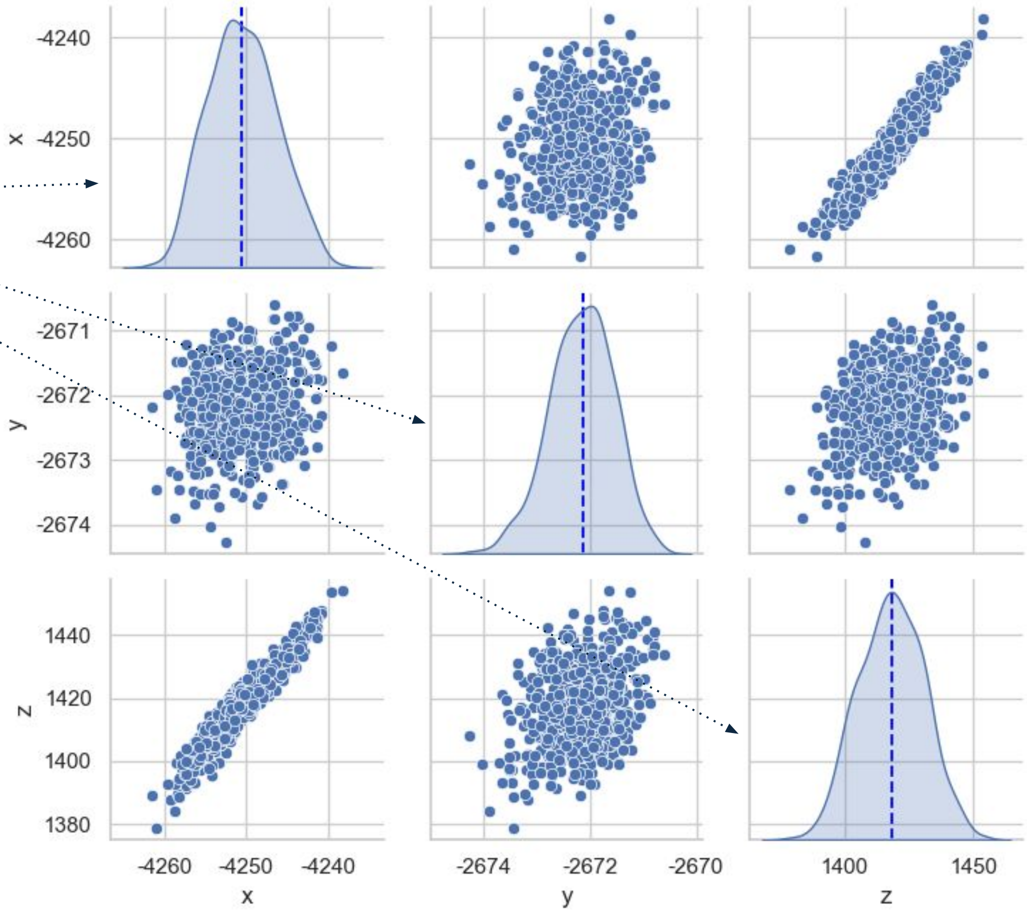
x : has a lower resolution because, for all DUs : $\underbrace{x_{beacon} < x_{DUs}}_{\text{limited constraints on the distance to source}}$

limited constraints on the distance to source

z : limited constraints because source & DUs are nearly in same plane + limited resolution GPS position

bad constraint on orthogonal position

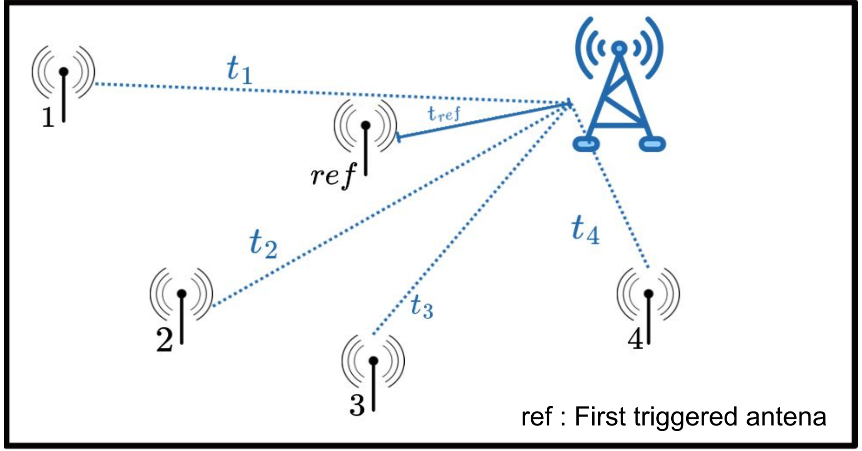
TREND - SWF
Beacon 50Hz
Pairplot with threshold times (N=571 events)



1- Beacon

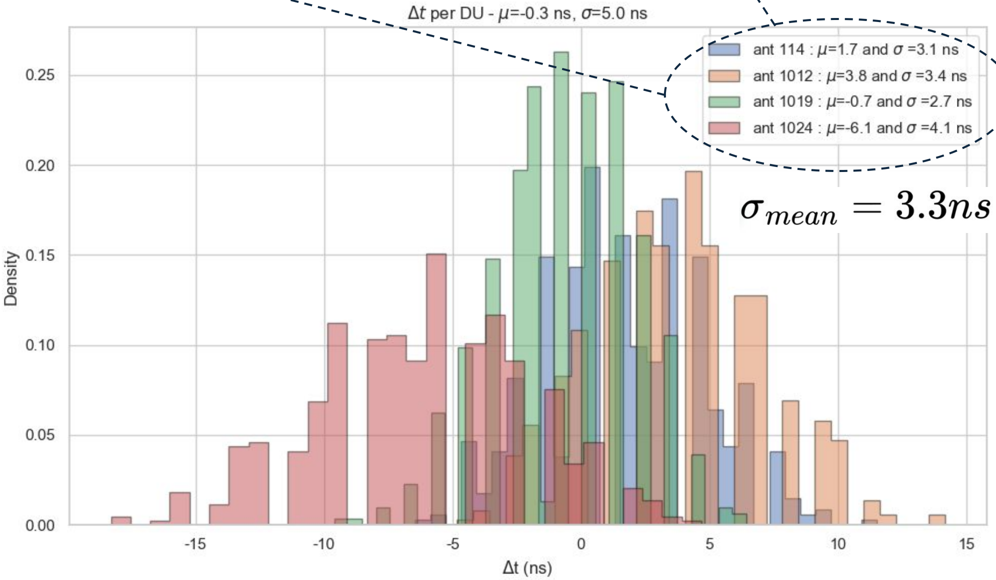
Delay analysis

$$\Delta t_i = (t_i^{sim} - t_{ref}^{sim}) - (t_i^{expe} - t_{ref}^{expe})$$



μ ≠ 0 understood as error on DU position (μ<4ns ≡ ε ~1m)

sigma is understood as the relative time resolution.



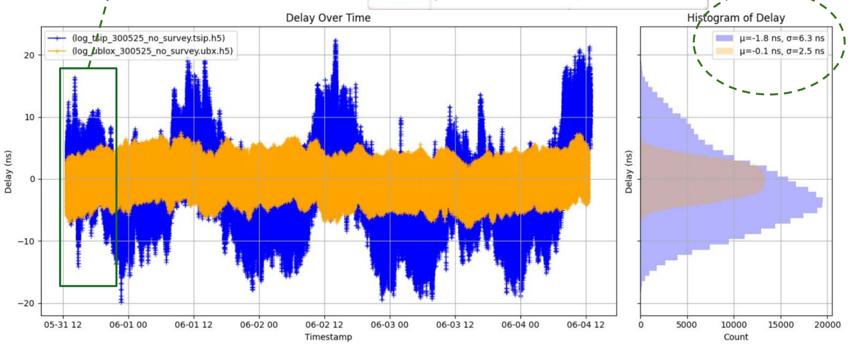
$$\sigma_{mean} = 3.3ns$$

6.3 ns over 3 days but sqrt(2)*2.5 ns = **3.5 ns** at a given instant.

Absolute time GPS Trimble GP300

$\mu = -1.8ns, \sigma = 6.3ns$

$\mu = -0.1ns, \sigma = 2.5ns$

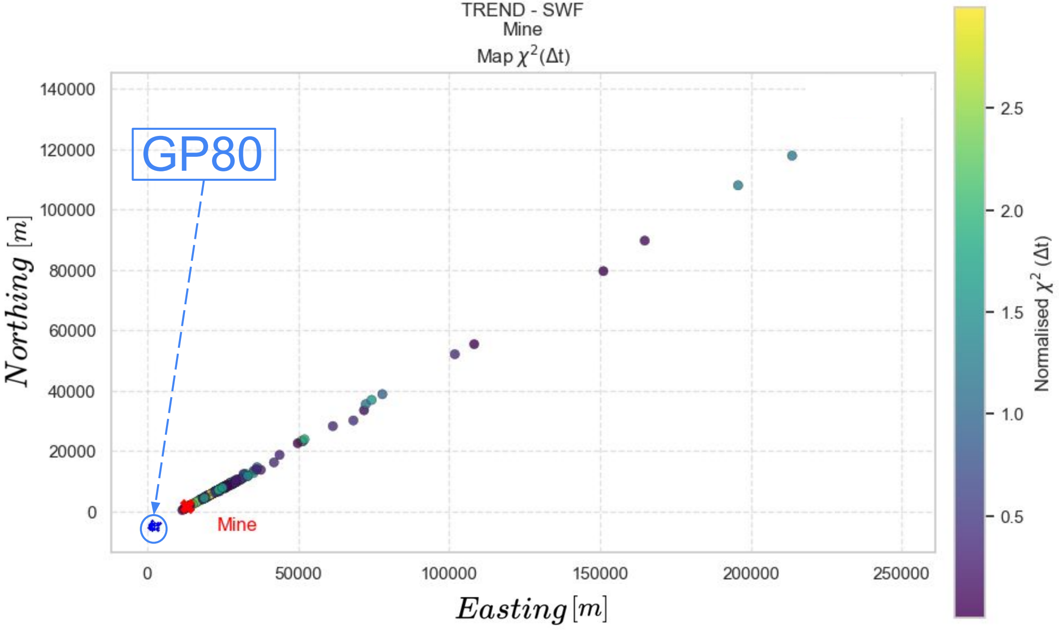


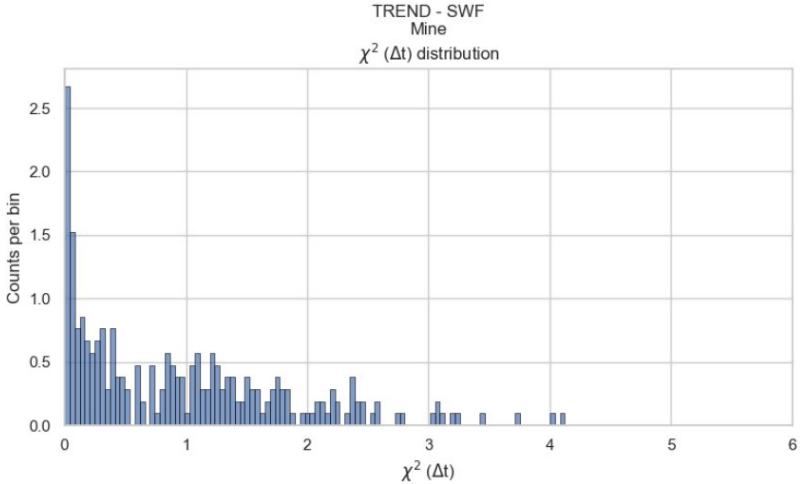
(Vincent Voisin's 2025)

2- Transformer mine

Using : 20250309_235256_RUN10070

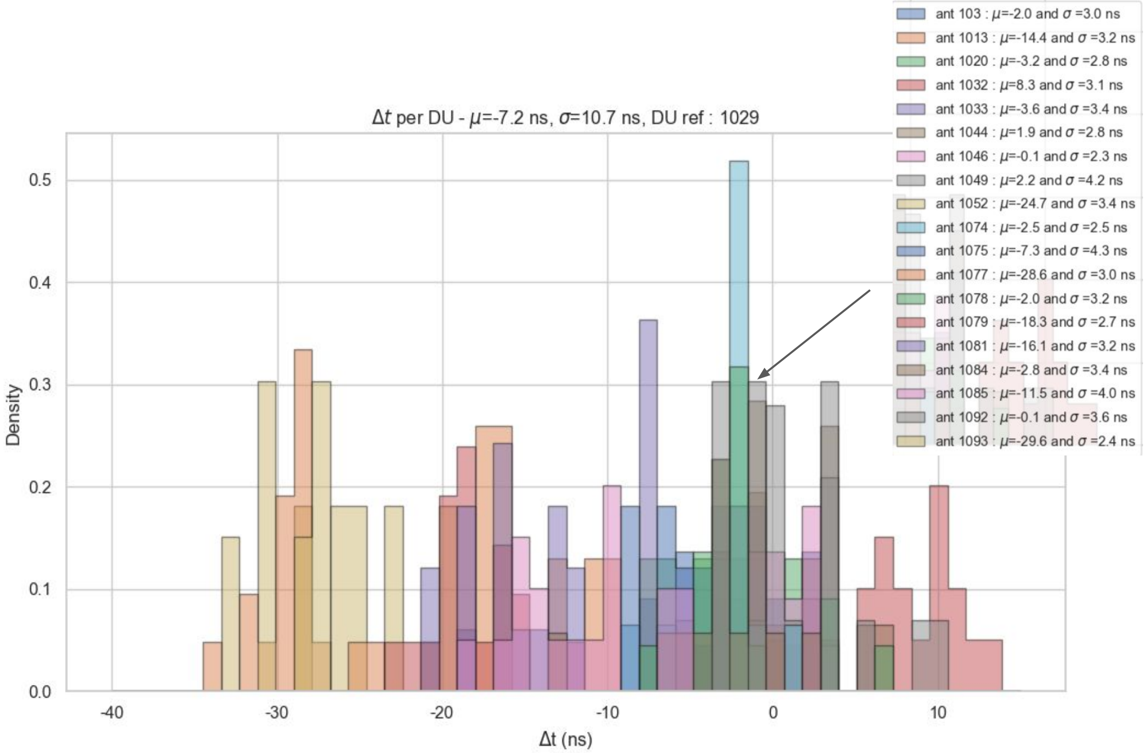
- Few events are reconstructed very far from the transformer mine **but in the right direction**

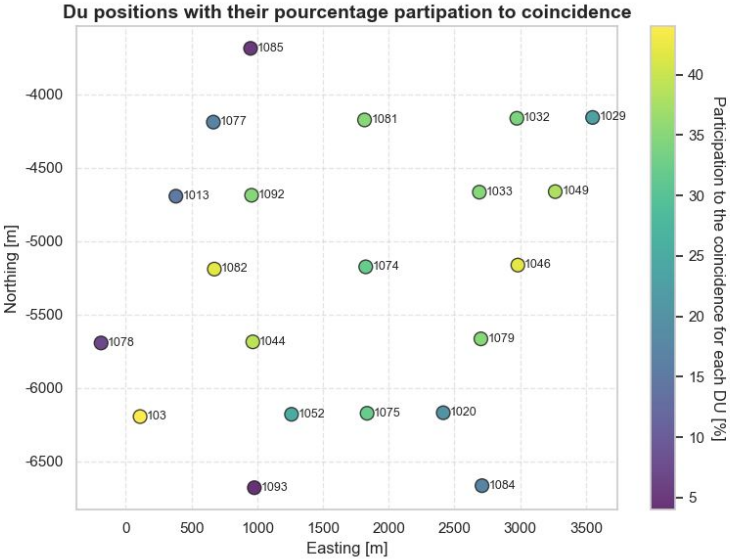




2- Transformer mine

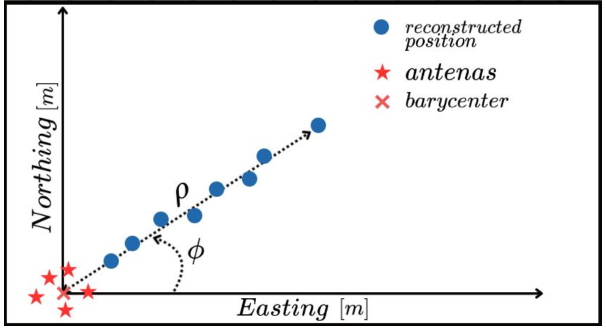
- Coherent sigmas
- Some interrogation about the mean offset (true propagation speed, reflexions ?)

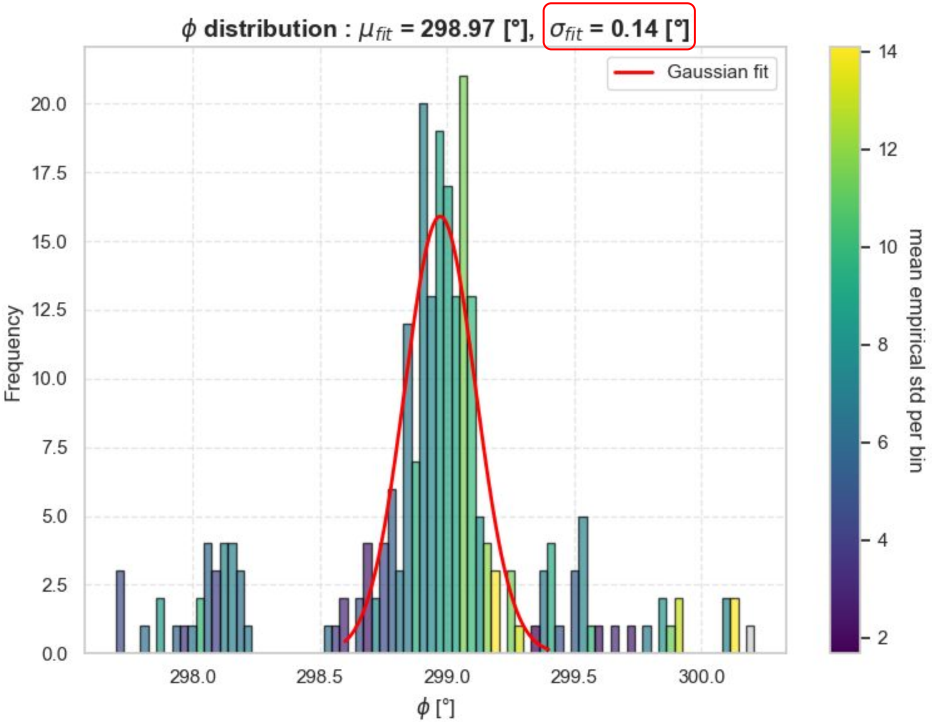


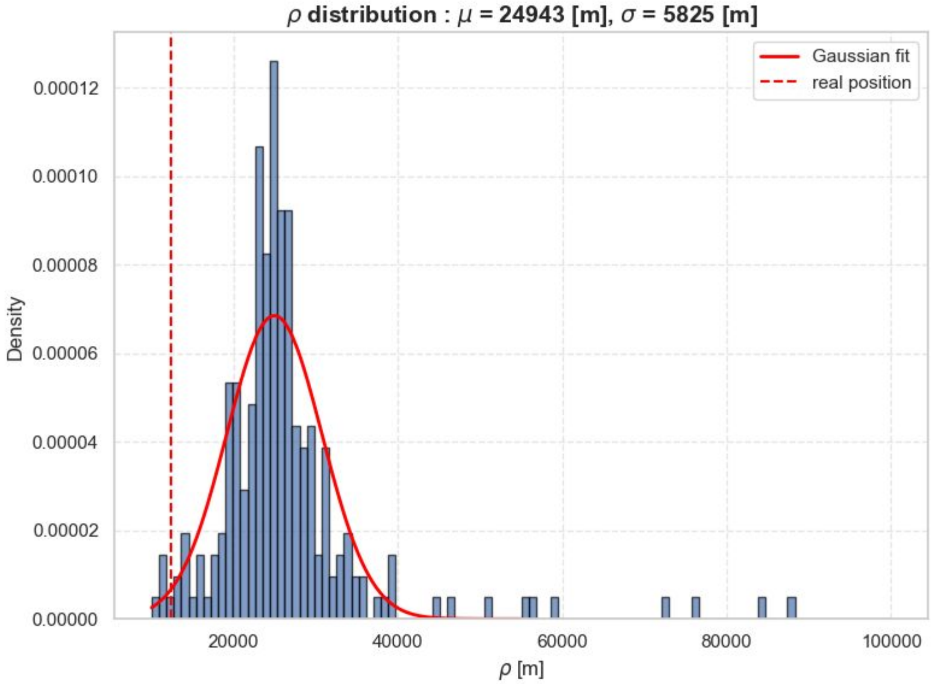


2- Transformer mine

Characterize the detector angular resolution.







Summary

- Measurement of the experimental (relative) timing precision using beacon + mine trigger times. It results a mean standard deviation of < 4 ns.

- Determine the experimental angular resolution by reconstructing known source positions (e.g., transformer-mine runs) and comparing the mean reconstructed direction to the given source, yielding an angular azimuth resolution < 0.2°.

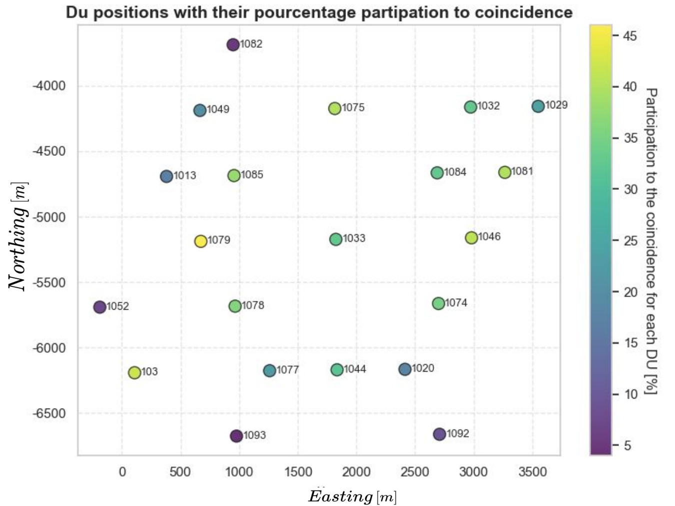
Outlook

- The next step is to pursue this work by studying plane sources. Access to high-precision ADS-B system of their locations will allow us to better characterize the detector.

- Study the temporal evolution of these sources in order to evaluate the detector’s stability over time.

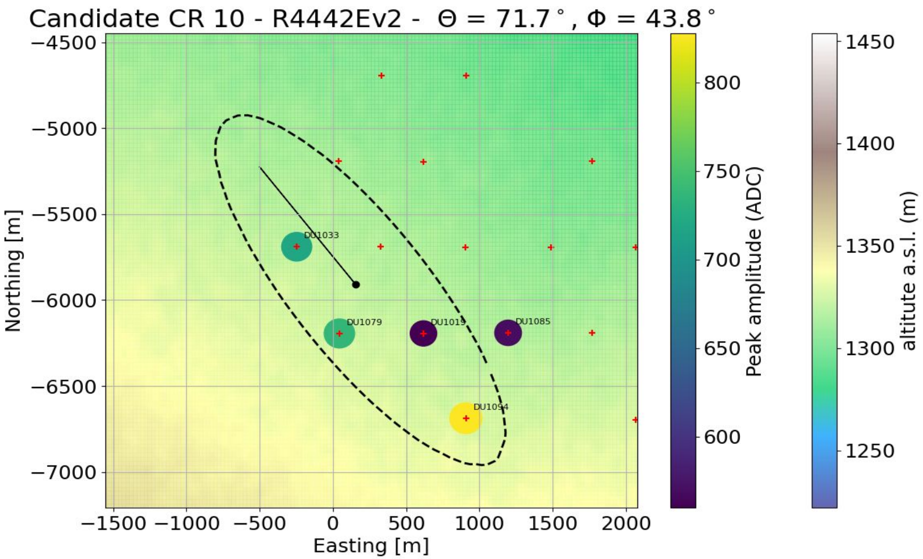
- Continue the analysis to gain a deeper understanding of the trigger pattern and its footprint.

- Investigating inclined extensive air showers to study cosmic rays.

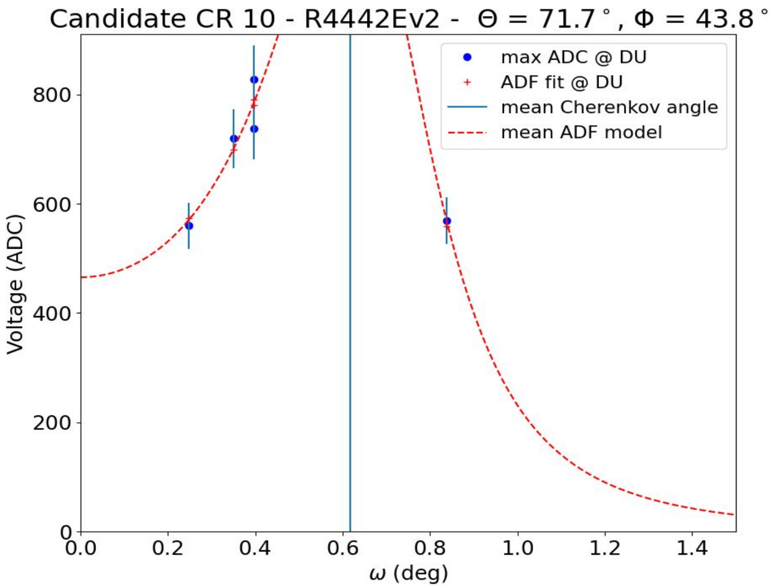


cosmic ray candidates & PhD work

- In parallel, GRAND has detected its first cosmic rays.



Cosmic ray candidate view, showing the peak amplitude and de relief of the site (M.Guelfand, 2025)

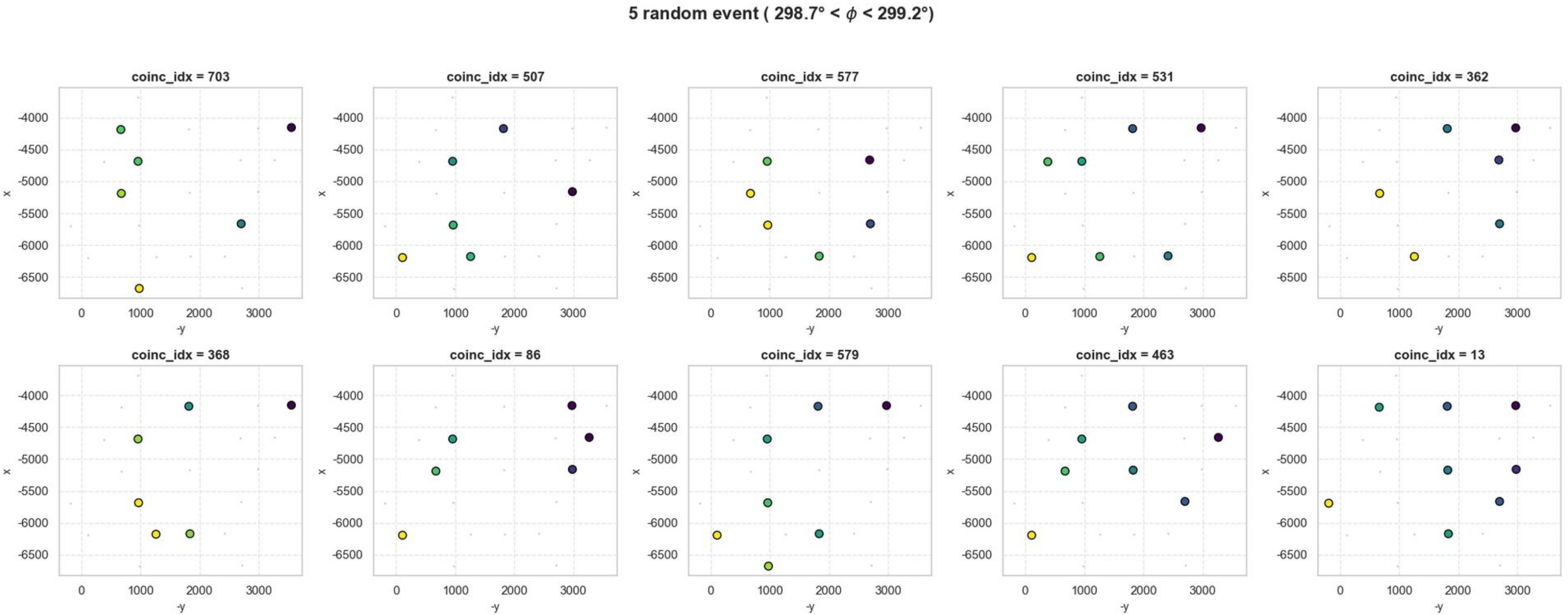


ADF reconstruction of a cosmic ray candidate (M.Guelfand, 2025)

- Then, during my PhD, I will be responsible for continuing the search for cosmic rays, with a particular focus on highly inclined candidates.

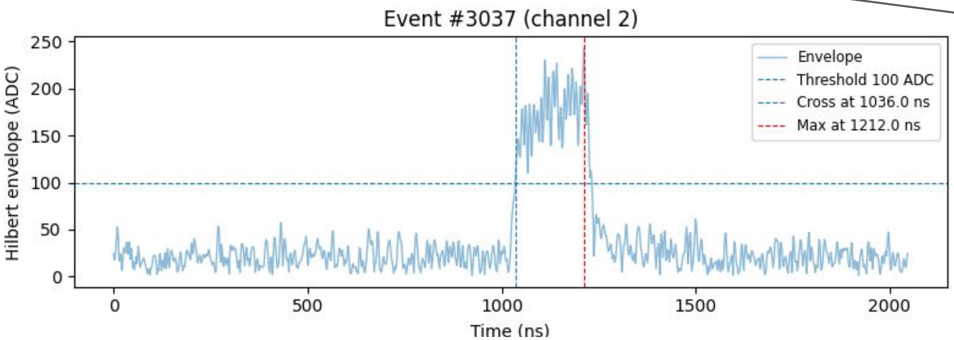
Thanks for your attention !

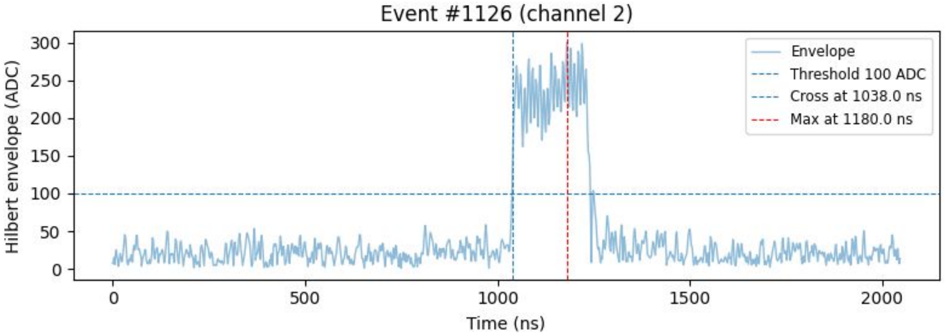
Backup

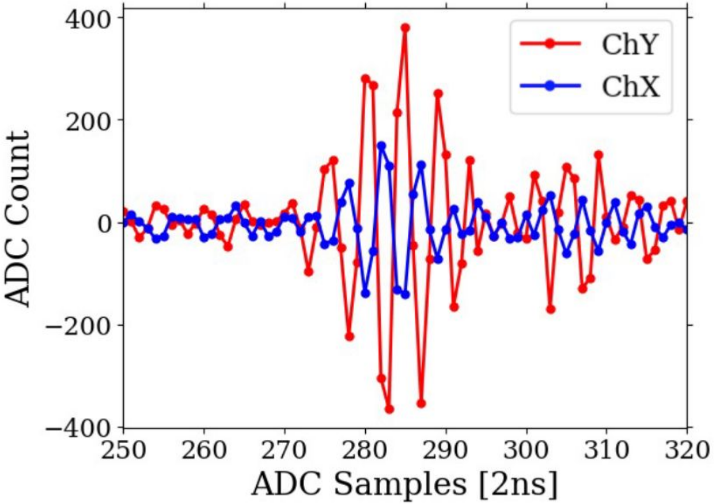

5 random event (298.7° < ϕ < 299.2°)
coinc_idx = 703
coinc_idx = 507
coinc_idx = 577
coinc_idx = 531
coinc_idx = 362
coinc_idx = 368
coinc_idx = 86
coinc_idx = 579
coinc_idx = 463
coinc_idx = 13
-4000
-4500
-5000
-5500
-6000
-6500
x
0
1000
2000
3000
-y

1- Beacon

GP80_20250424_102757_RUN173_CD



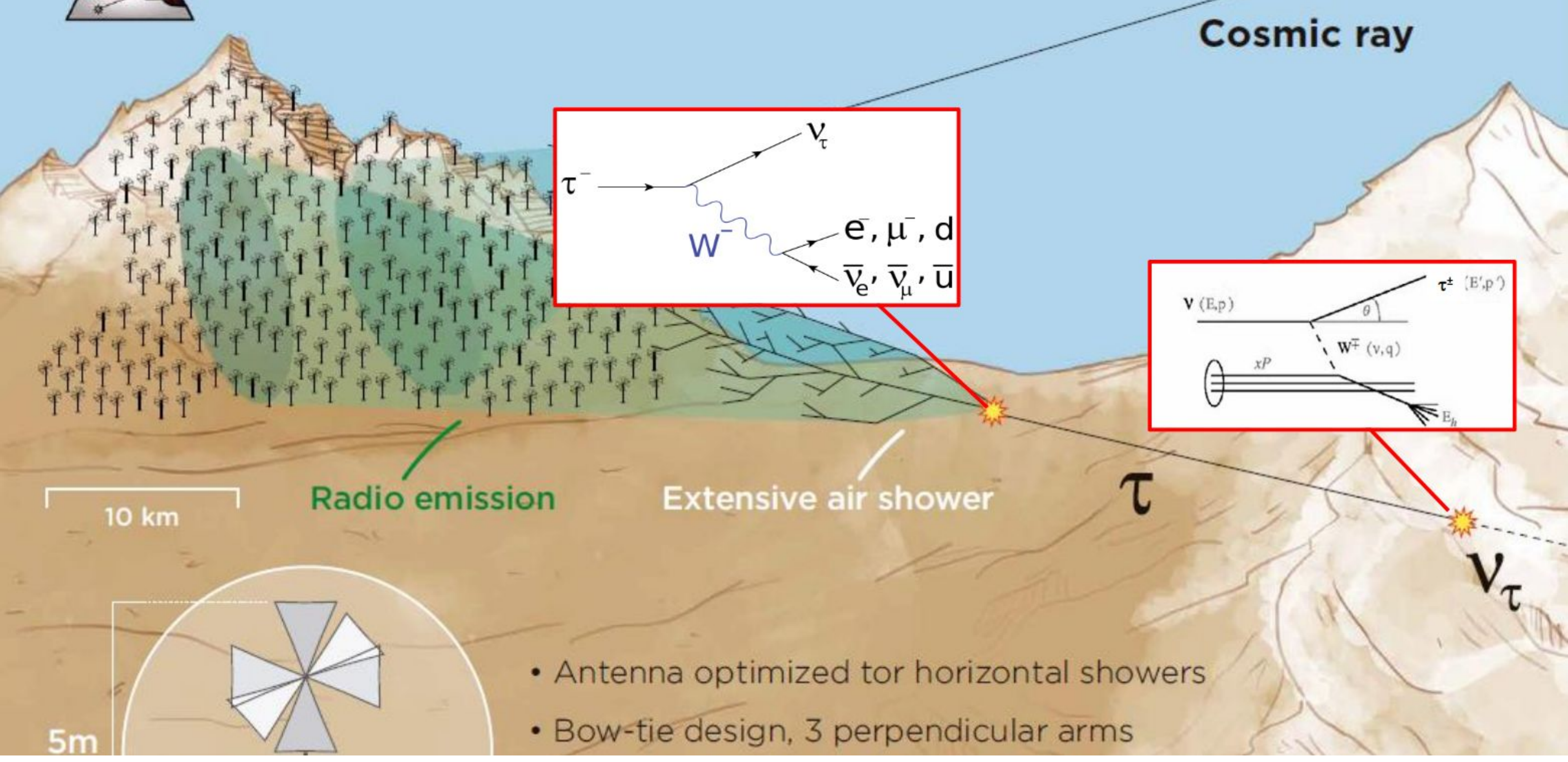




from Xishui Tian

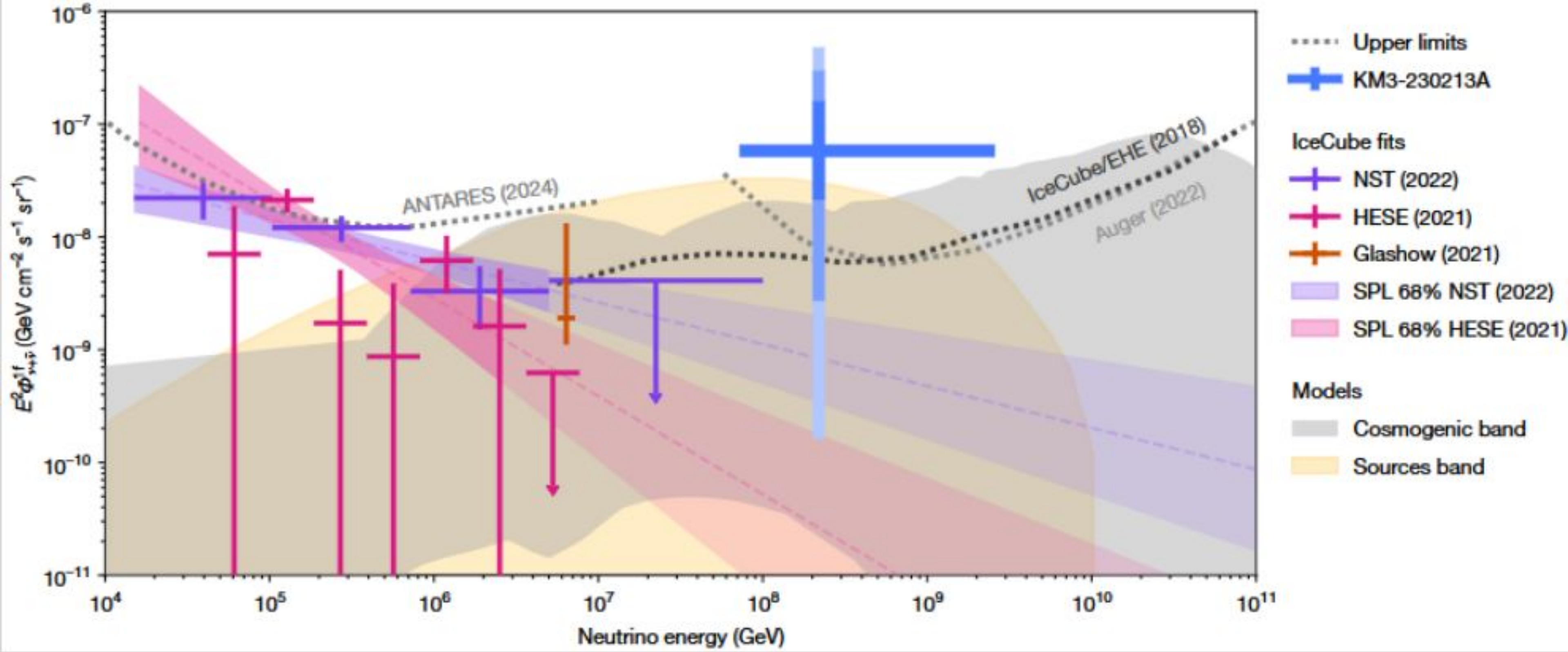
Beacon characteristic : *Sine wave (A=1V, f=100MHz) with 20 periods and repetition rate between 1 and 100Hz.*

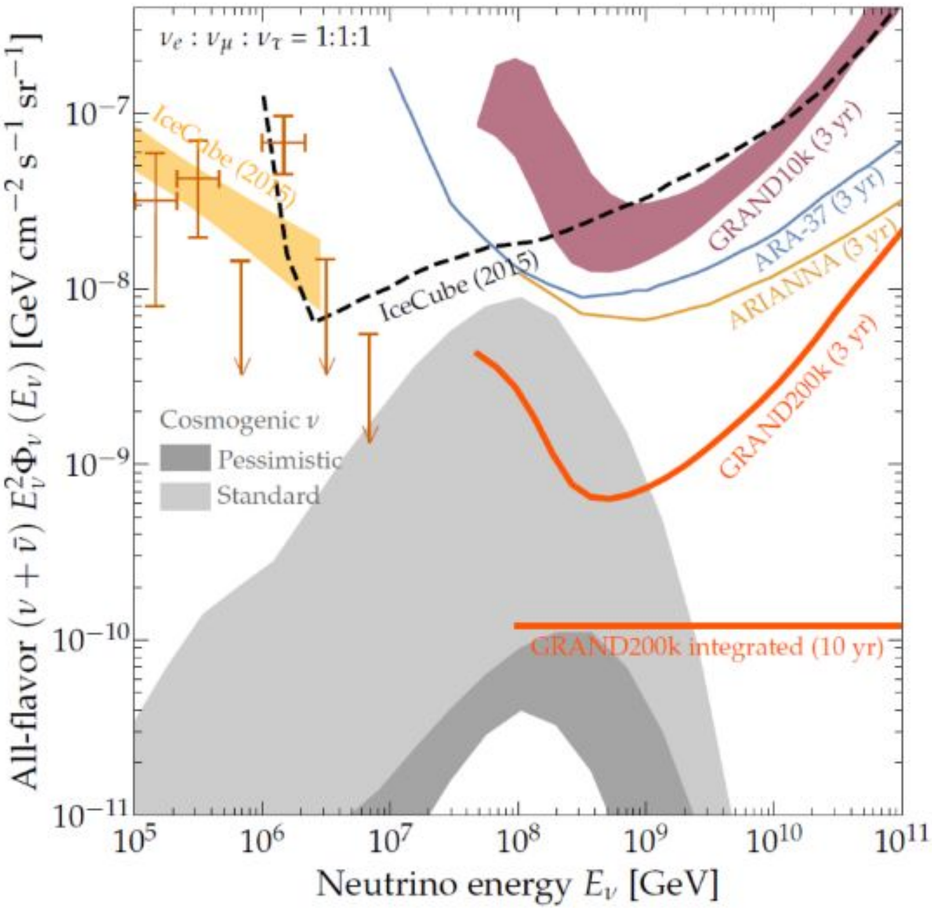
Giant Radio Array for Neutrino Detection



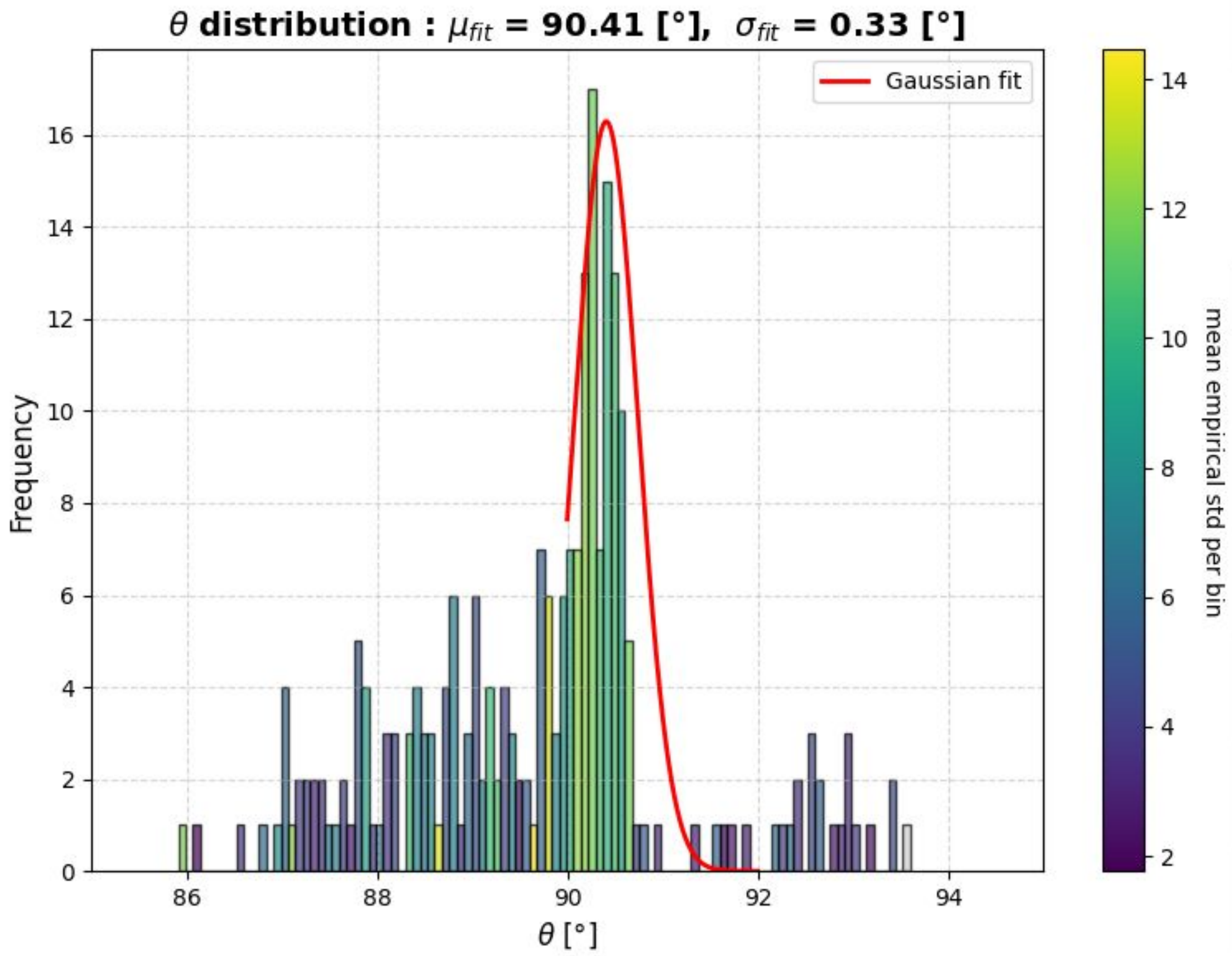
- Antenna optimized tor horizontal showers
- Bow-tie design, 3 perpendicular arms

Km3net event





$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1
IceCube (2015)
IceCube (2015)
GRAND10k (3 yr)
ARA-37 (3 yr)
ARIANNA (3 yr)
GRAND200k (3 yr)
GRAND200k integrated (10 yr)
Cosmogenic ν
Pessimistic
Standard
All-flavor $(\nu+\bar{\nu})$ $E_\nu^2\Phi_\nu(E_\nu)$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]


θ distribution : μfit = 90.41 [°], σfit = 0.33 [°]
Gaussian fit
Frequency
θ [°]
mean empirical std per bin
0
2
4
6
8
10
12
14
16
86
88
90
92
94
2
4
6
8
10
12
14