The Giant Radio Array for Neutrino Detection: Status and Perspectives

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on behalf of the GRAND Collaboration

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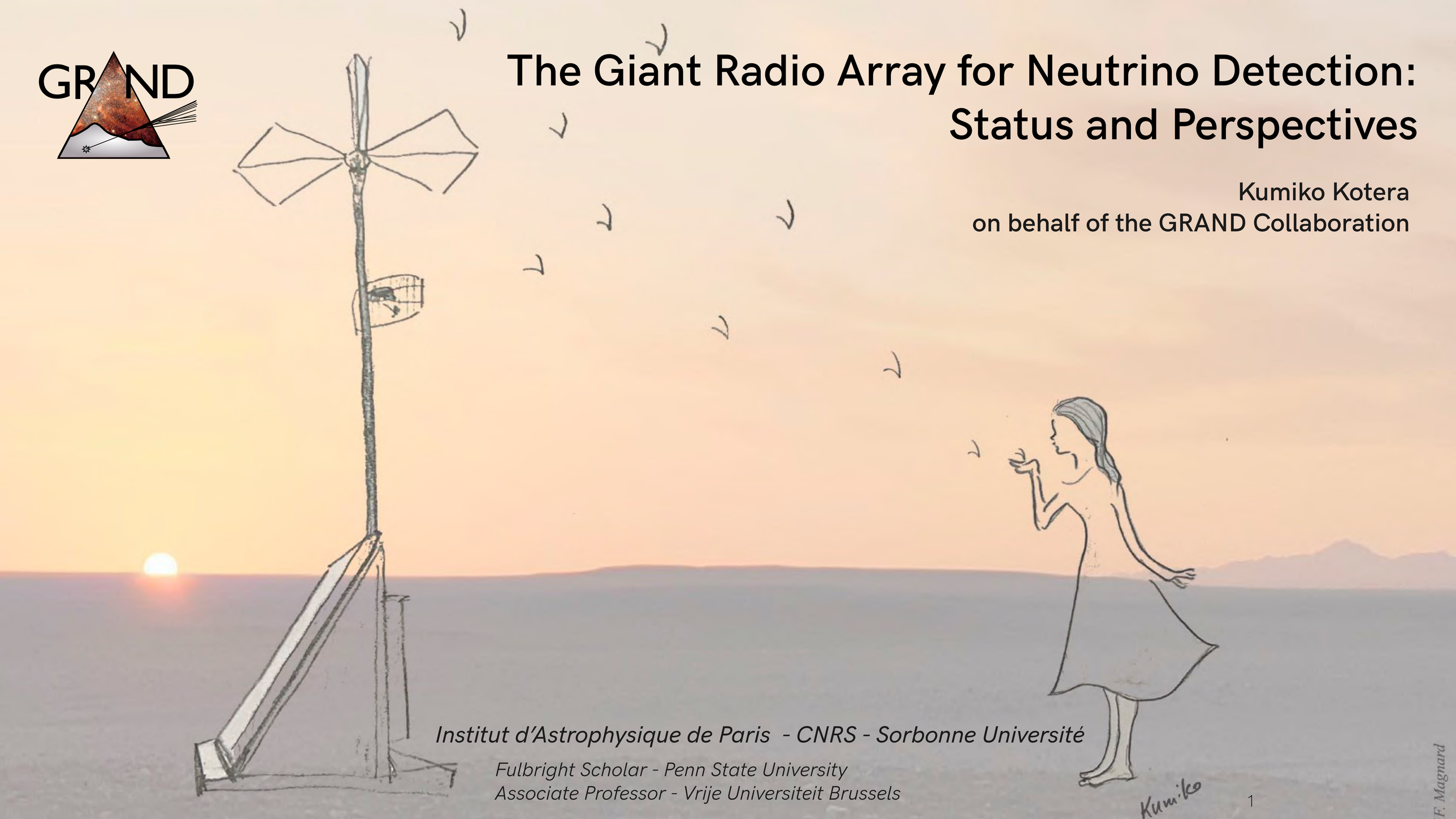
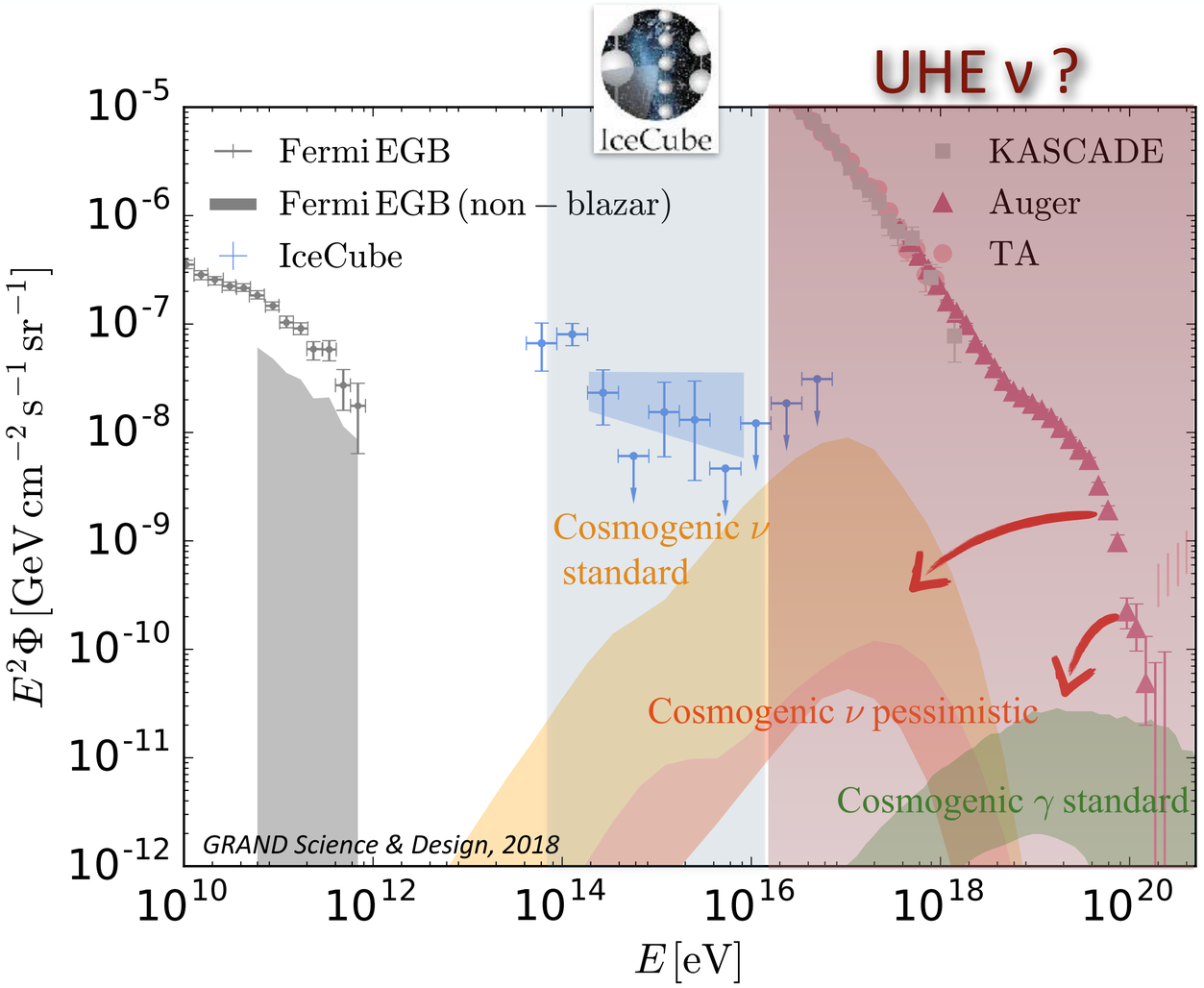


Detecting ultra-high-energy neutrinos – lessons learnt from experiments



A recent endeavor

- UHE neutrino search: ancillary science case of UHECR & HE neutrino experiments
- Recently: dedicated instruments ARIANNA, ARA, ANITA

Summary of recent progress

1. One UHE neutrino has been detected so far (?) (KM3Net event at 120 PeV)

lesson from Auger: target astrophysical fluxes

2. Auger observations of UHECRs constrain the flux of c

lesson from IceCube: require excellent angular resolution to pinpoint sources amid near-isotropic background

3. Two sources have been clearly identified after 10 years of e

lesson from IceCube: aim for the 100 PeV range to extend and connect with IceCube observations

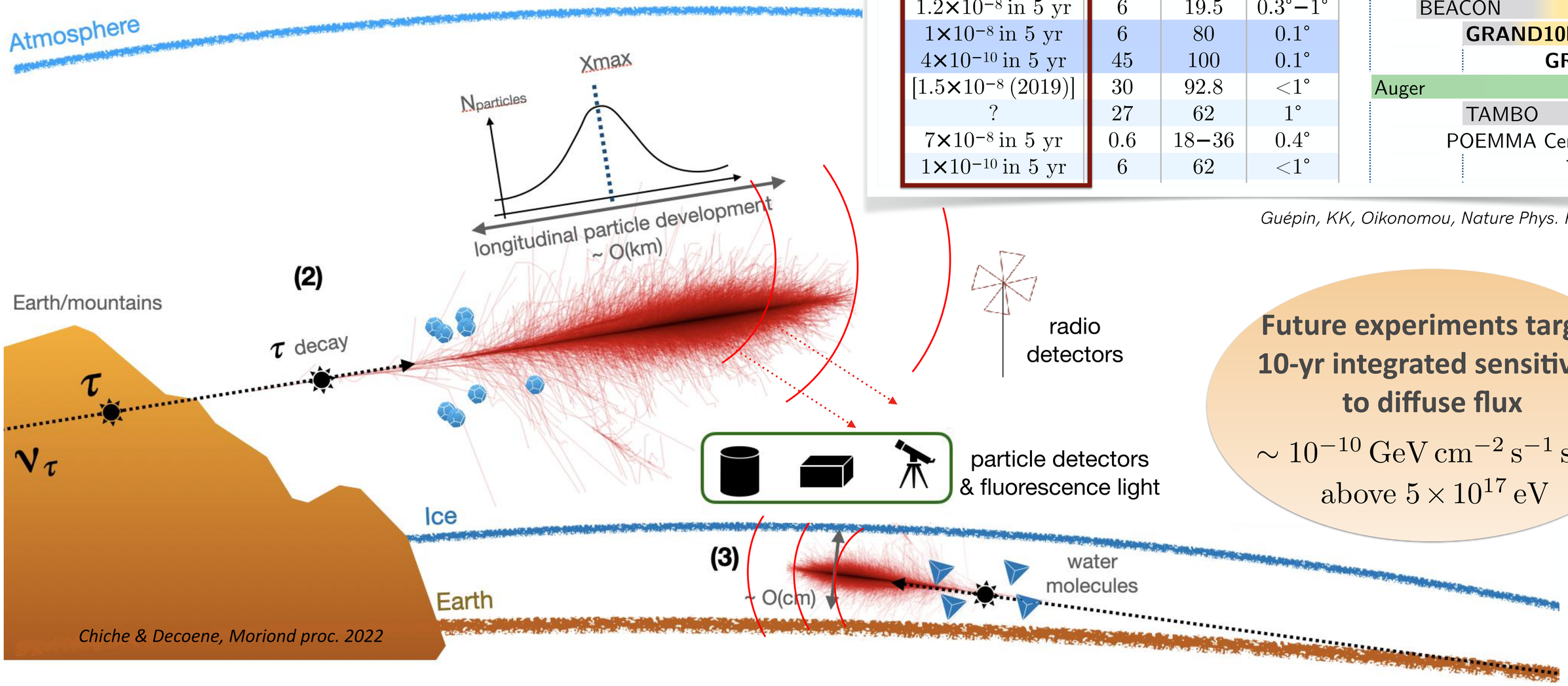
4. E st

lesson from MM: develop follow-up tools and integrate in a MM framework, enabling rapid response and alerts

Experimental perspectives

Diff. sens. lim. in GeV cm^{-2} s^{-1} sr^{-1}	iFoV in sky %	dFoV in sky %	ang. res.	2021 2025 >2030
4.2×10^{-8} in 30 d	6	19	$<2.8^\circ$	PUEO
3.6×10^{-9} (2030)	35	20	5°	ARA
1×10^{-8} in 5 yr	30	35	$2^\circ\times10^\circ$	RNO-G
8×10^{-9} in 5 yr	50	>50	$2.9-3.8^\circ$	ARIANNA-200
3×10^{-10} in 5 yr	50	>50	?	RET-N
4×10^{-10} in 5 yr	43	43	$2^\circ\times10^\circ$	IceCube-Gen2 Radio
1.2×10^{-8} in 5 yr	6	19.5	$0.3^\circ-1^\circ$	BEACON
1×10^{-8} in 5 yr	6	80	0.1°	**GRAND10k**
4×10^{-10} in 5 yr	45	100	0.1°	**GRAND**
[1.5×10^{-8} (2019)]	30	92.8	$<1^\circ$	Auger
?	27	62	1°	TAMBO
7×10^{-8} in 5 yr	0.6	18−36	0.4°	POEMMA Cerenkov
1×10^{-10} in 5 yr	6	62	$<1^\circ$	Trinity

Guépin, KK, Oikonomou, Nature Phys. Rev. 2022

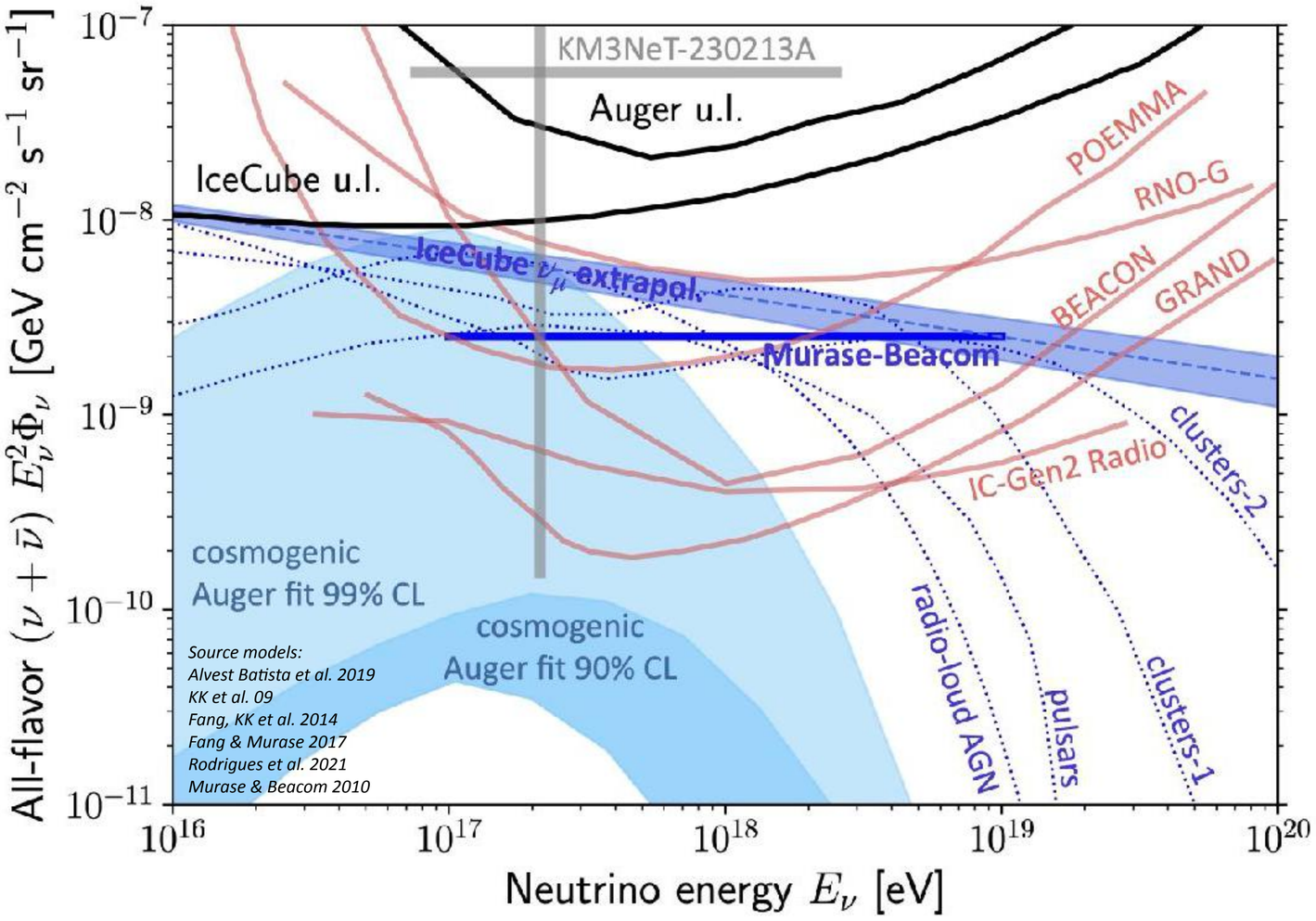


Chiche & Decoene, Moriond proc. 2022

Future experiments target 10-yr integrated sensitivity to diffuse flux

$\sim 10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$
above $5\times10^{17}\,\mathrm{eV}$

Diffuse UHE neutrino fluxes: readjusting our experimental perspectives



- Avoid presenting ruled out cosmogenic fluxes
- Auger constrains cosmogenic fluxes to below

$$\Phi_{\rm cosmo,max} \sim 10^{-8}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\ ,\ \ {\rm at}\ \ 99\%\ {\rm C.L.}$$

- Promising astrophysical fluxes exist

- Which new "Waxman-Bahcall flux" to aim for at UHE?

IceCube extrapolation

$$E_\nu^2\Phi_\nu\ \sim\ 10^{-8}\,(E_\nu/10^{16}\,{\rm eV})^{-2.37}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Murase-Beacom (2010)

$$E_\nu^2\Phi_\nu \lesssim 8.4\times10^{-10} f_z (A/56)^{-0.21}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

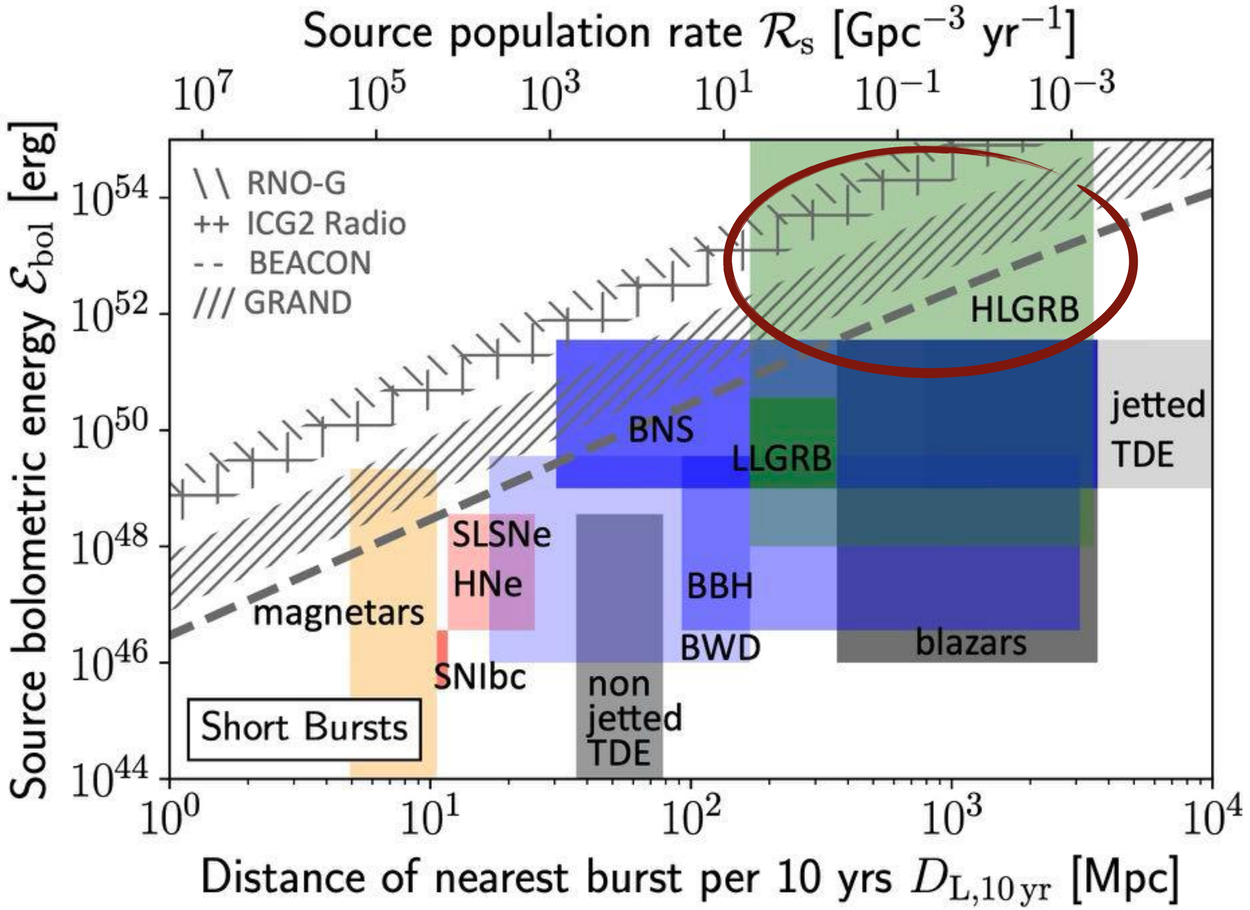
effective (energy-loss) photodisintegration optical depth < 1
here: source evolution factor f_z = 3

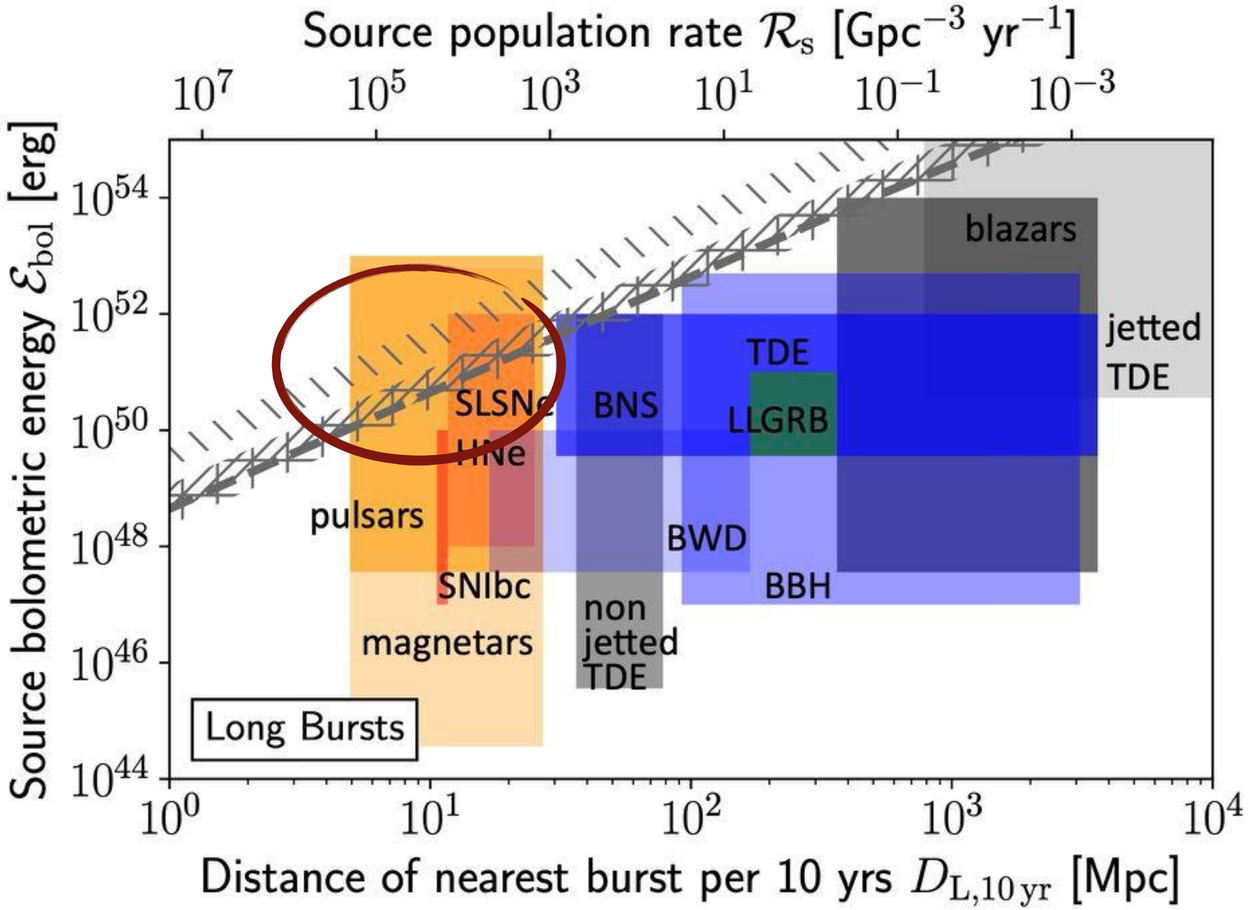
Detector reaching these limits in $10^{17\text{-}19}$ eV can strongly constrain source models.

Whether they can do UHE neutrino astronomy requires to assess additional performances.

What astrophysical sources to aim for in the MM era?

KK, Mukhopadhyay et al. subm.





Short bursts: stay in the instantaneous field of view (FoV) of the instrument (~30 min - 1 day)
Compare source fluences with instantaneous fluence sensitivities

Detectable: Bright rare (distant) sources

Long bursts: any longer transients
Compare source fluences with daily averaged fluence sensitivities

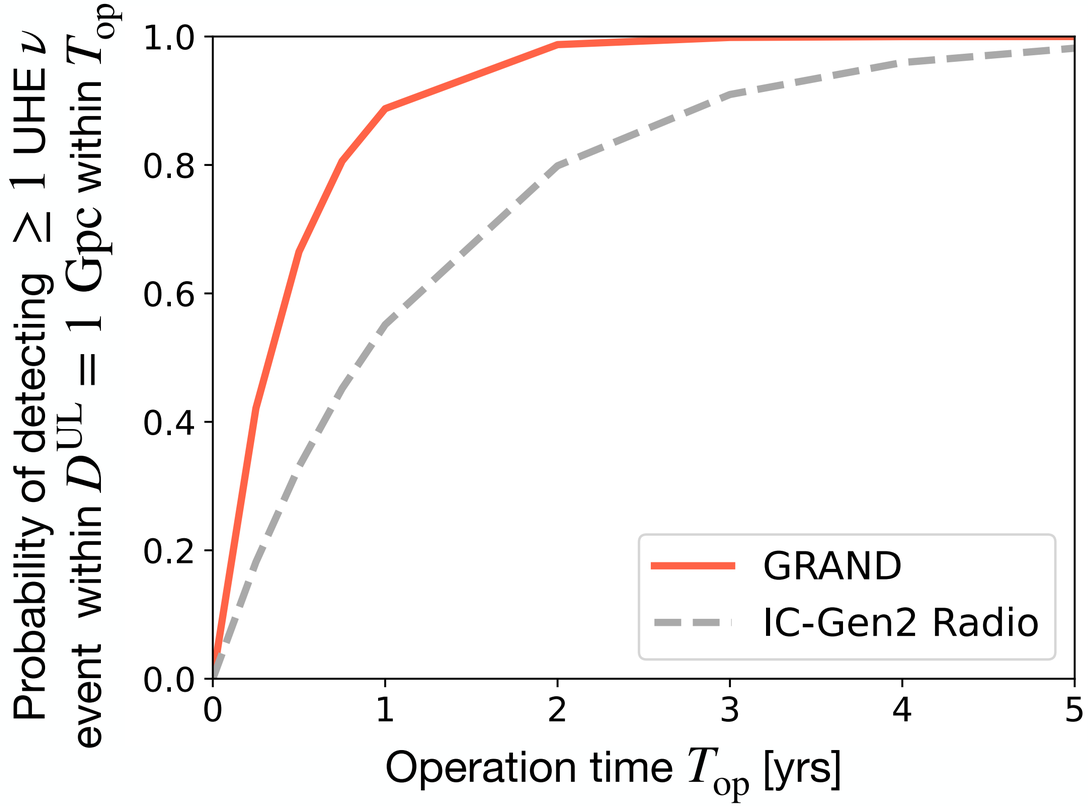
Detectable: Local Group & nearby galaxies

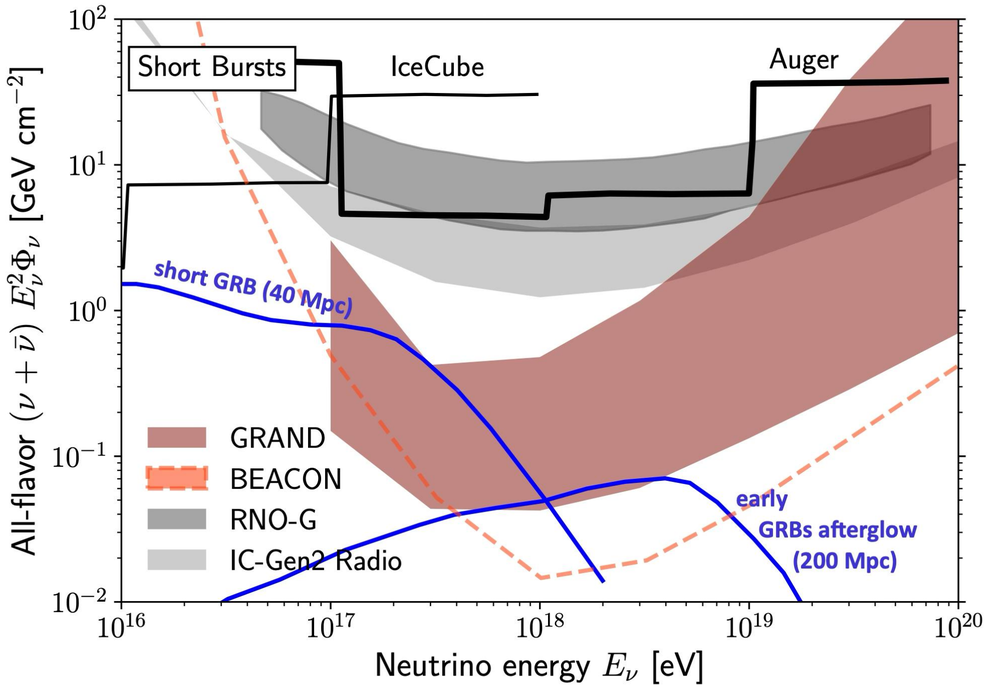
Astronomical observation strategies: Wide & Shallow vs. Deep & Narrow

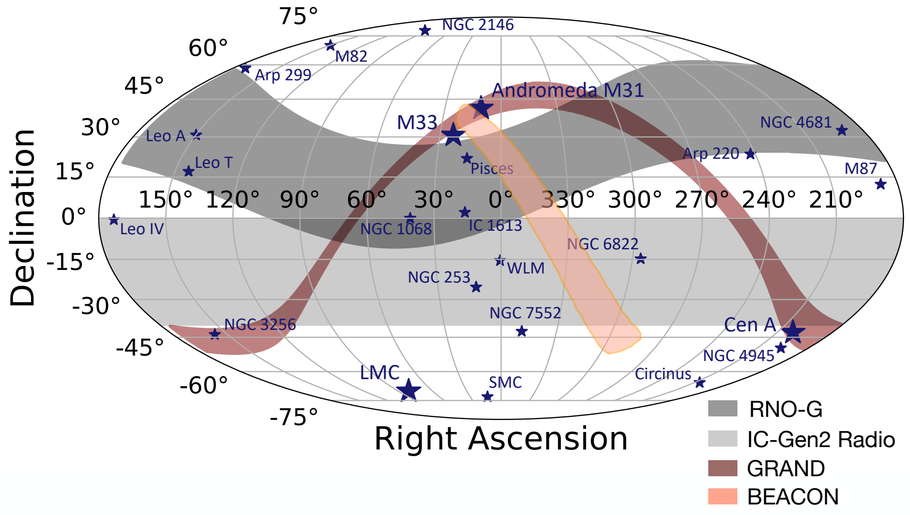
KK, Mukhopadhyay et al. subm.

CAUTION: updated IceCube-Gen2 Radio sensitivities: ~2 orders of magnitude discrepancy found for instantaneous fluence sensitivity

Guépin, KK, Oikonomou, Nat. Phys. Rev erratum



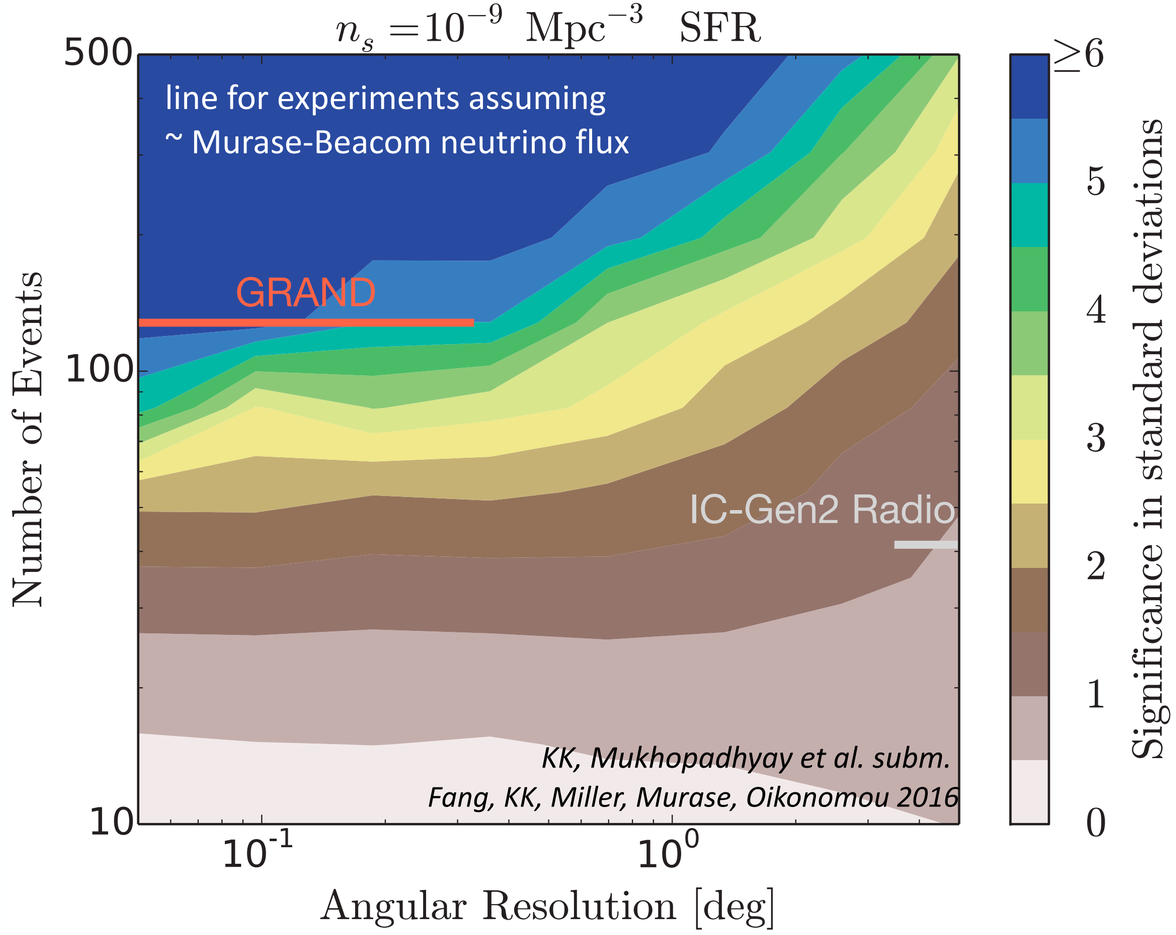




Volume (depth) —> dist^3
Surface (FoV) —> dist^2

Deep & Narrow observatories more powerful for UHE neutrino discovery of known targeted sources
Wide & Shallow: better suited for serendipitous all-sky searches

A necessary angular resolution



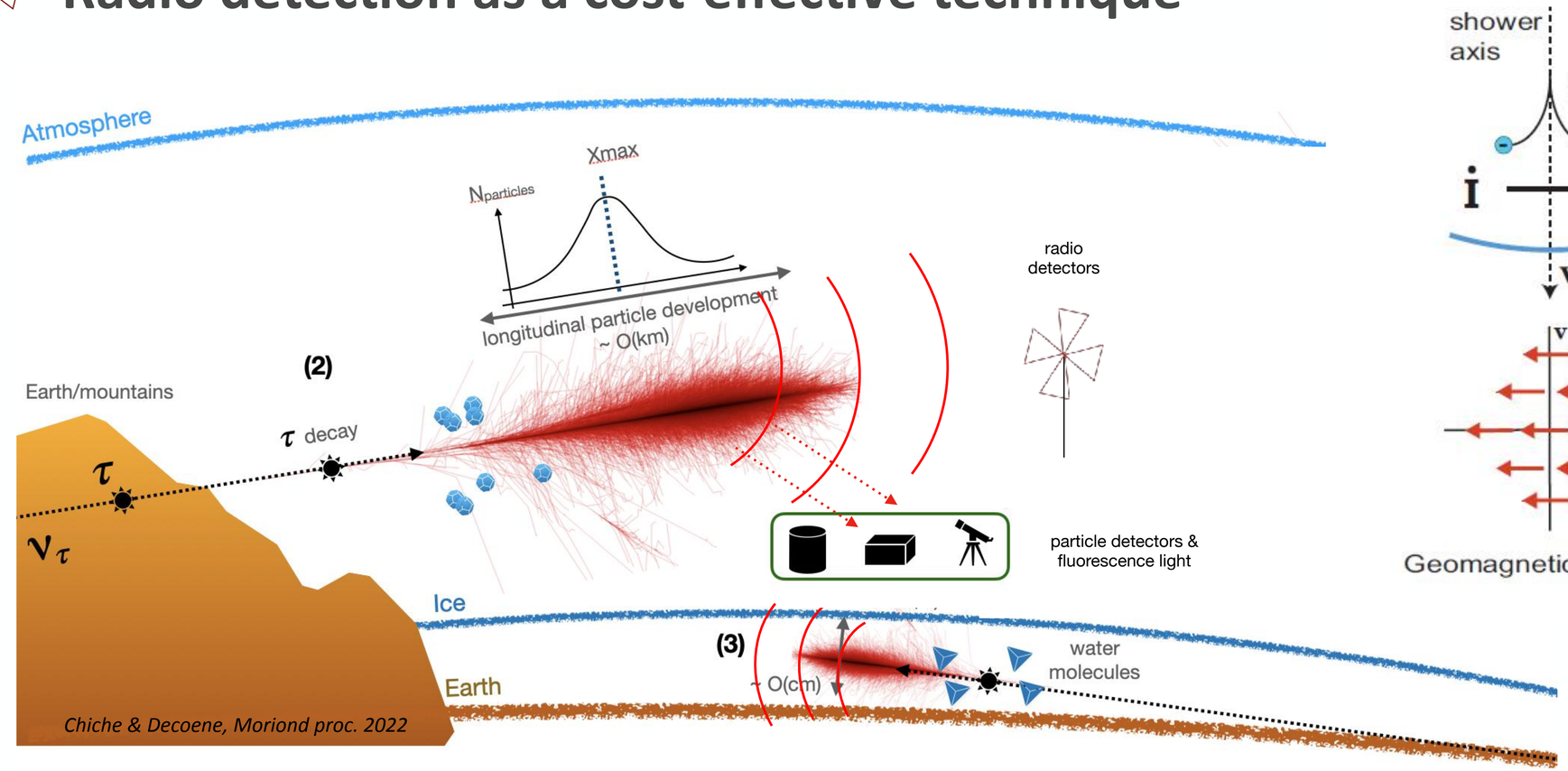
Can we identify a point-source out of a diffuse neutrino sky?

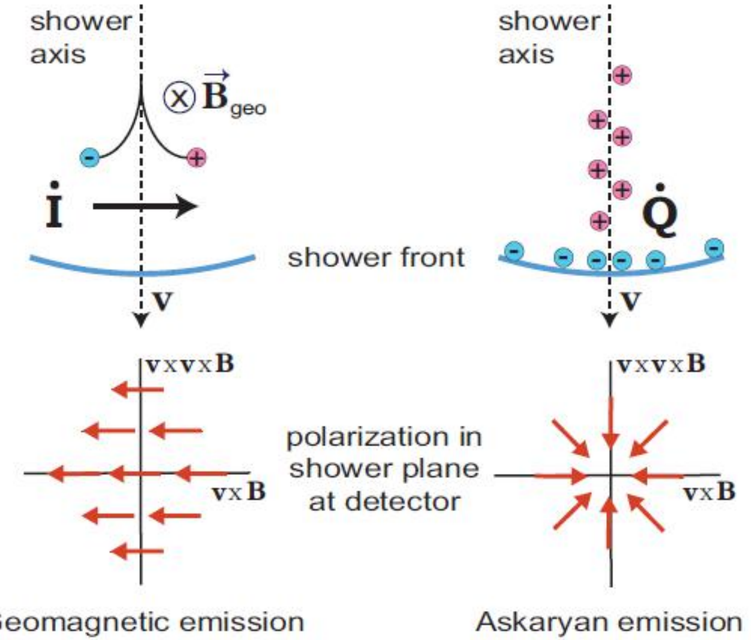
Yes, if we can collect ~100 events with sub-degree angular resolution…

- development of MM-networks, EM instruments —> false associations will be common
- skim interesting events + narrow down search area —> requires angular resolution

		2021	2025	>2030	FoV	ang. res.
gamma	LHAASO				2 sr	0.3°
	CTA				10−20°	< 0.15°
	HAWC				2 sr	0.1°
	H.E.S.S.				5°	0.1°
	MAGIC				3.5°	0.07°
	VERITAS				3.5°	0.1°
	Fermi LAT				2.4 sr	0.15°
	Fermi GBM				9 sr	10°
	INTEGRAL IBIS				64 deg²	0.2°
	INTEGRAL SPI-ACS				4π	-
X	XMM-Newton				0.5°	6”
	Athena-WFI				0.4 deg²	< 5”
multi	Swift BAT				1.4 sr	0.4°
	Swift XRT				0.1 deg²	18”
	Swift UVOT				0.1 deg²	2.5”
	SVOM ECLAIRs				2 sr	< 0.2°
	SVOM MXT				1 deg²	13”
	SVOM VT				0.2 deg²	< 1”
IR/optical/UV	ASAS-SN				72 deg²	7.8”
	ATLAS				29 deg²	2”
	Pan-STARRS				14 deg²	1.0−1.3”
	ZTF				47 deg²	2”
	Vera Rubin Obs. (LSST)				9.6 deg²	0.7”
	MASTER-II(VWF)				8(400) deg²	1.9” (22”)
	TAROT				4 deg²	3.5”
	GEMINI (GMOS)				30.23’²	0.07”/pix
	GTC (OSIRIS)				0.02 deg²	0.127”/pix
	Keck (LRIS)				46.8’²	0.135”/pix
	VLT (X-shooter)				2.2’²	0.173”/pix
radio	VLA				0.16 deg²	0.12”
	MWA				610 deg²	0.9’
	SKA1(2)-MID				1(10) deg²	0.04°−0.7°

Radio detection as a cost-effective technique



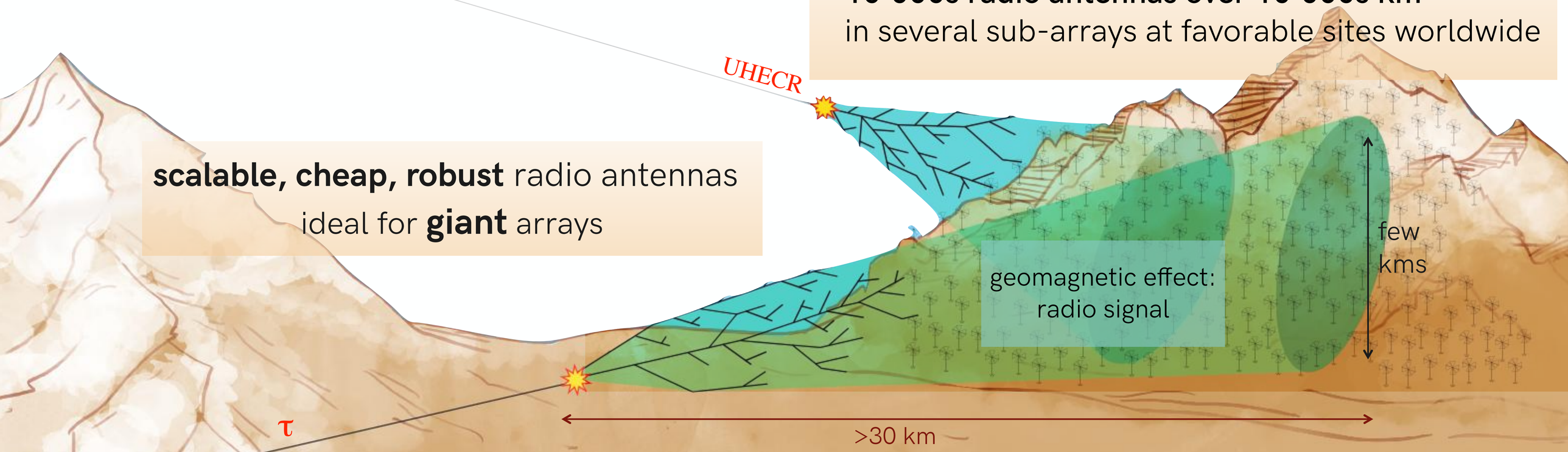


- Radio antennas: cheap, robust, scalable
- 100% duty cycle
- benchmarked technique
  in-ice & in-air for specific configurations

Performances	instantaneous sensitivity	daily aver. sensitivity	iFoV	dFoV	angular resolution
in-ice	+ wide & shallow	++	**+++** wide & shallow	++ no gain by Earth rotation if South Pole	+ reconstruction of polarization difficult
in-air	**+++** deep & narrow	++ equivalent as experiments tuned to diffuse flux	+ deep & narrow	**+++**	**+++** large footprints

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 will we need for UHE neutrino astronomy?

- ✓ Excellent sensitivity
- ✓ Sub-degree angular resolution
- ✓ Wide instantaneous field of view

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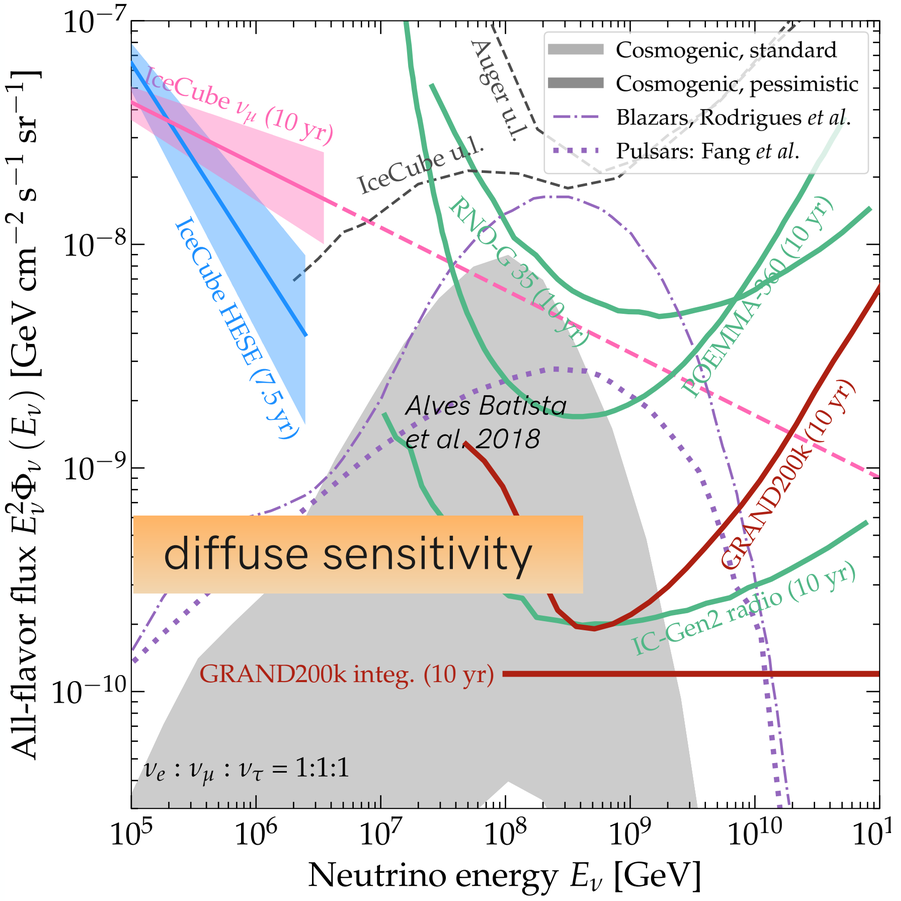
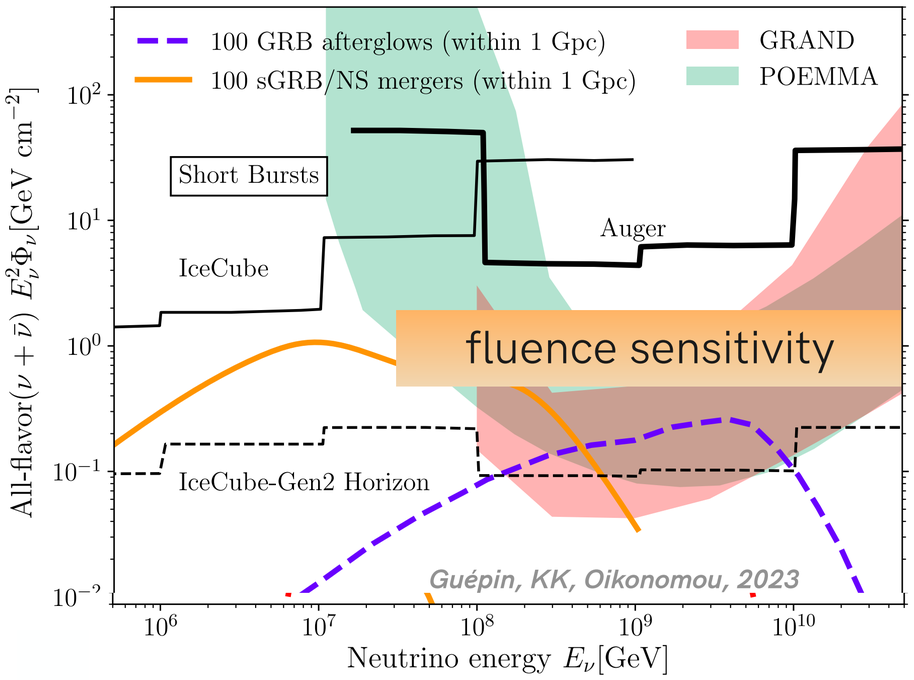
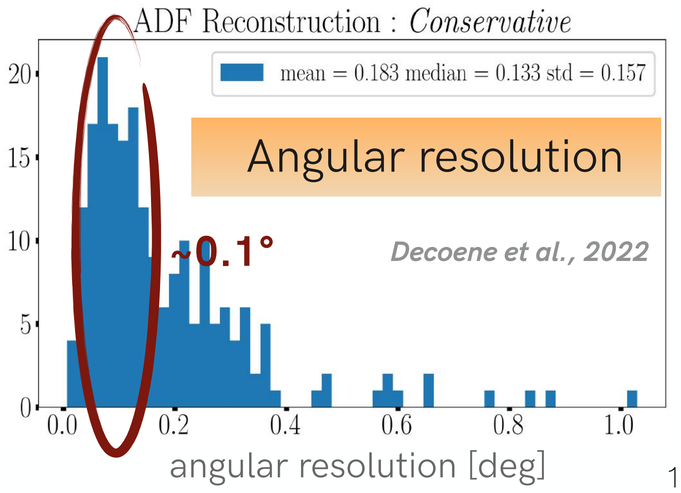
Guépin, KK, Oikonomou, 2023



diffuse sensitivity



fluence sensitivity



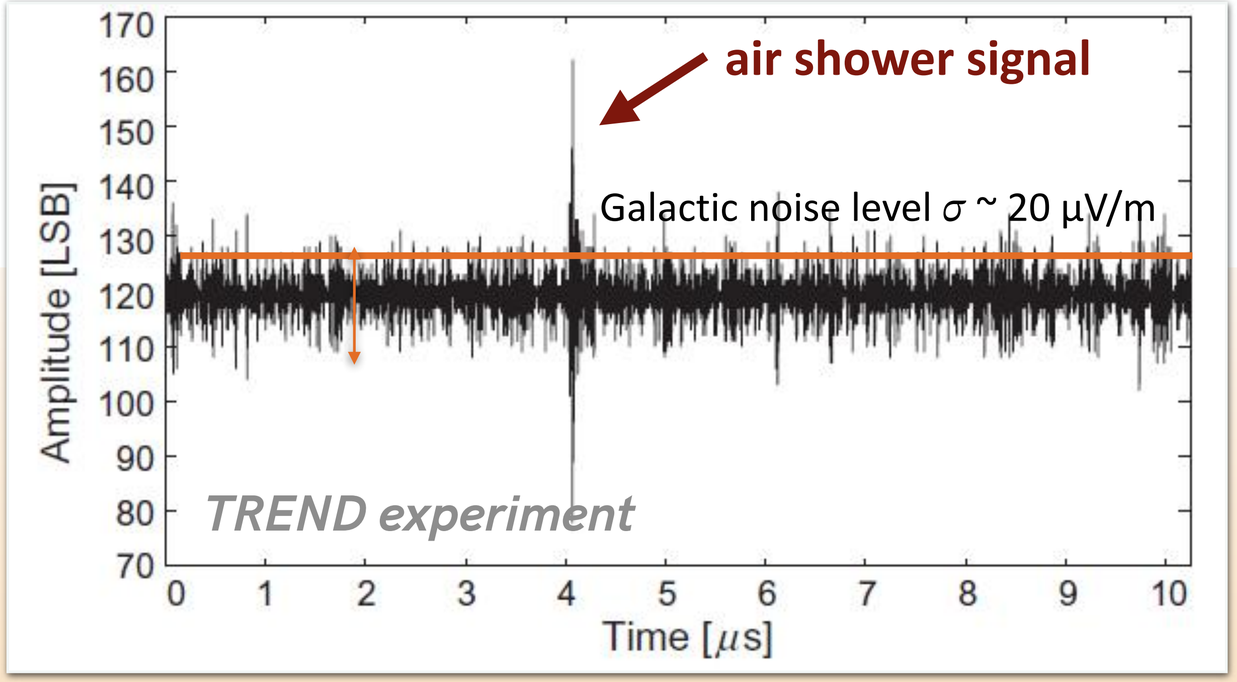
Angular resolution

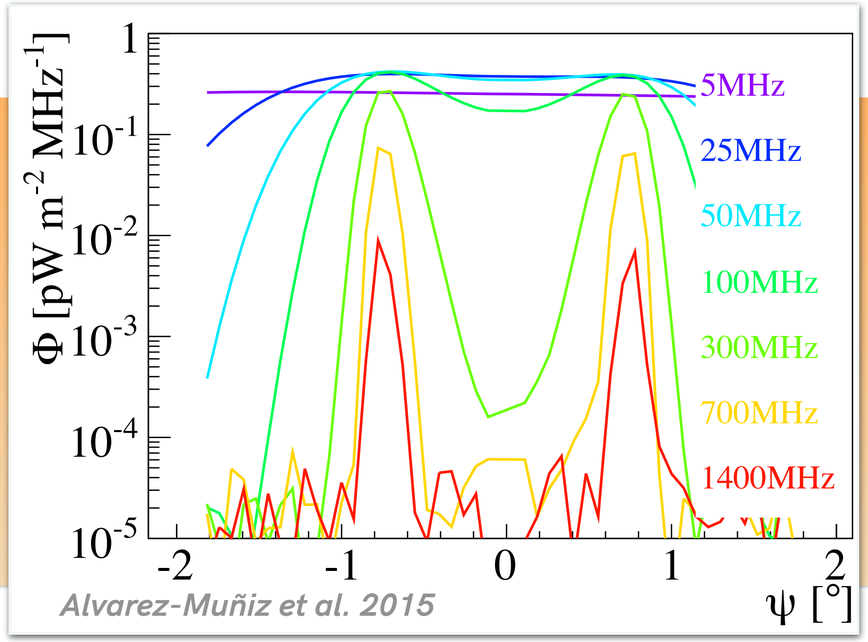
Radio signals at our detectors

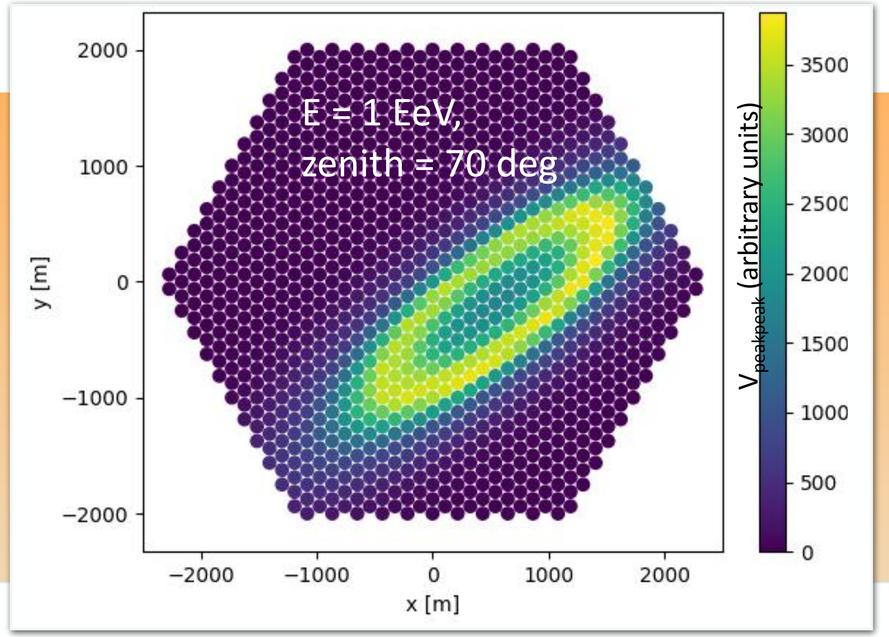
Experience from: LOPES, LOFAR, AERA, CODALEMA, TREND, AugerPrime Radio…

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







Footprint

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

GRAND Challenges

Low-complexity, robust, low-cost detection units

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

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…*)

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

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

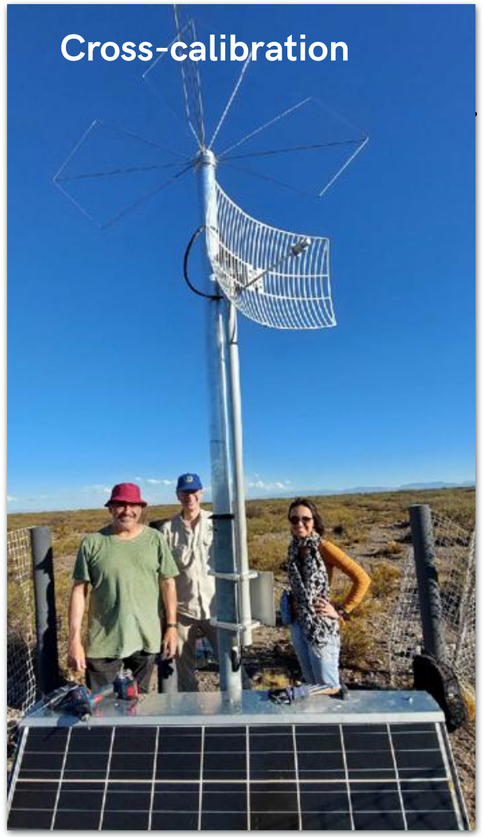
- Huge data volume (~10 kBy/trigger)

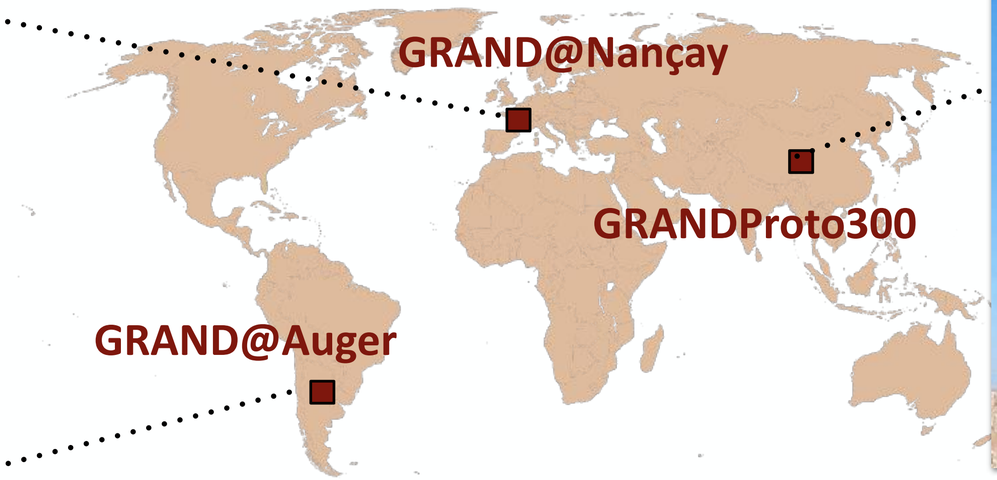
GP300 (nominal) rate:
L1 trigger: 1 kHz
L2 trigger: 10 Hz

NUTRIG target:
L1 trigger: 100 Hz
L2: 1 Hz

- Offline treatment reduction to few infos (trigger time, amplitude, polar)…
—> to implement online

2023-2024: A turning point for GRAND





Prototypes set-up

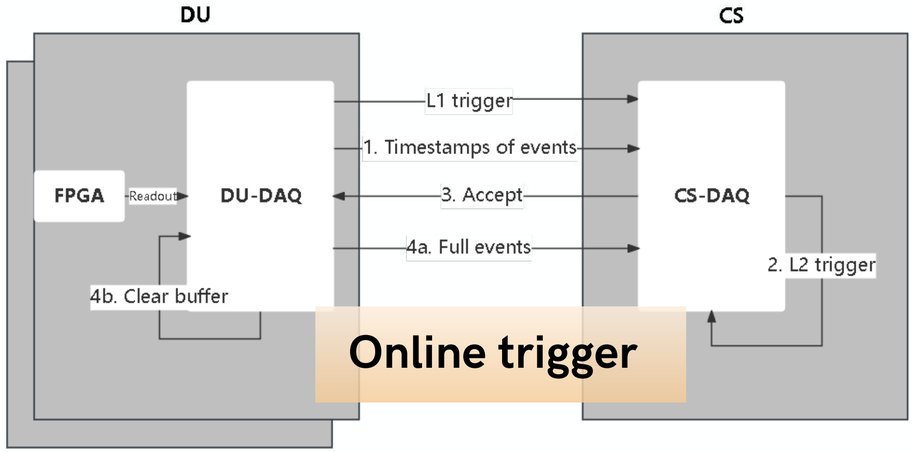
GRAND Coll. in prep.

Common set-up

- Same overall components (simple)
- Antenna arms - response differ due to mechanical structure
- Front-End Board: ADC 500MS/s,14 bits, FPGA + 4 CPUs
- Trigger algorithm: unbiased trigger, ten second, 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

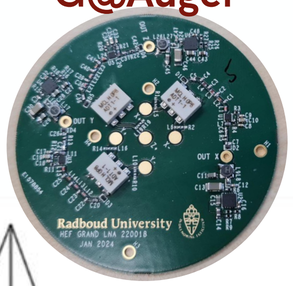


Online trigger

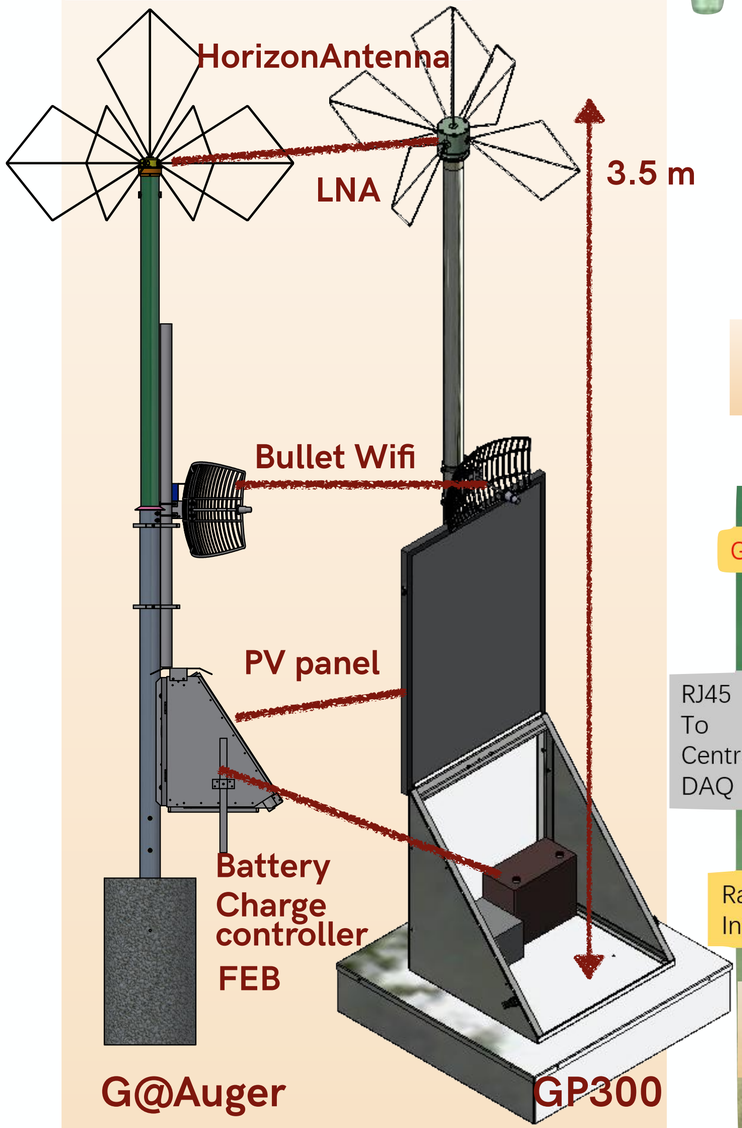
Nut & LNA

GP300

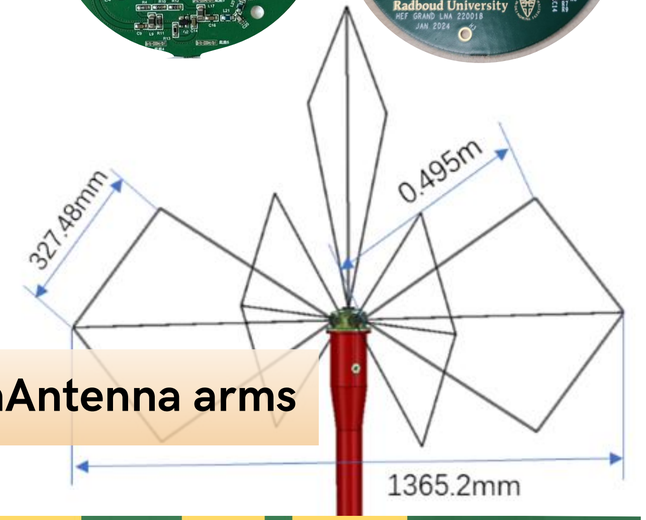
G@Auger



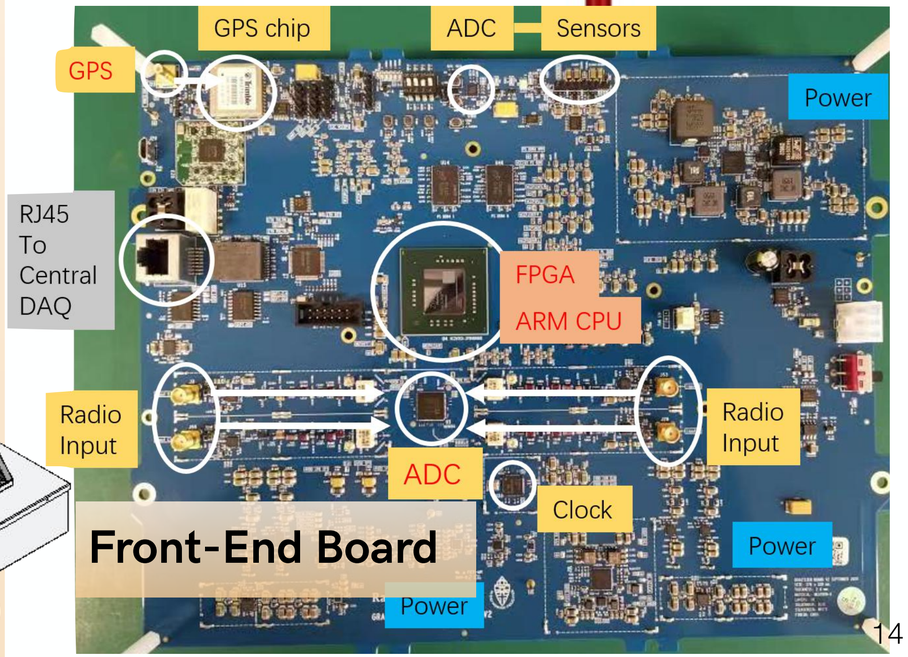
Detection Unit



HorizonAntenna arms

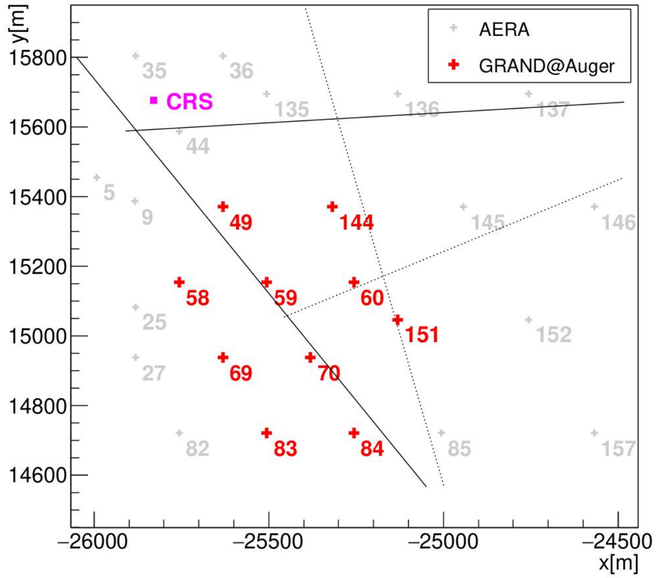


Front-End Board

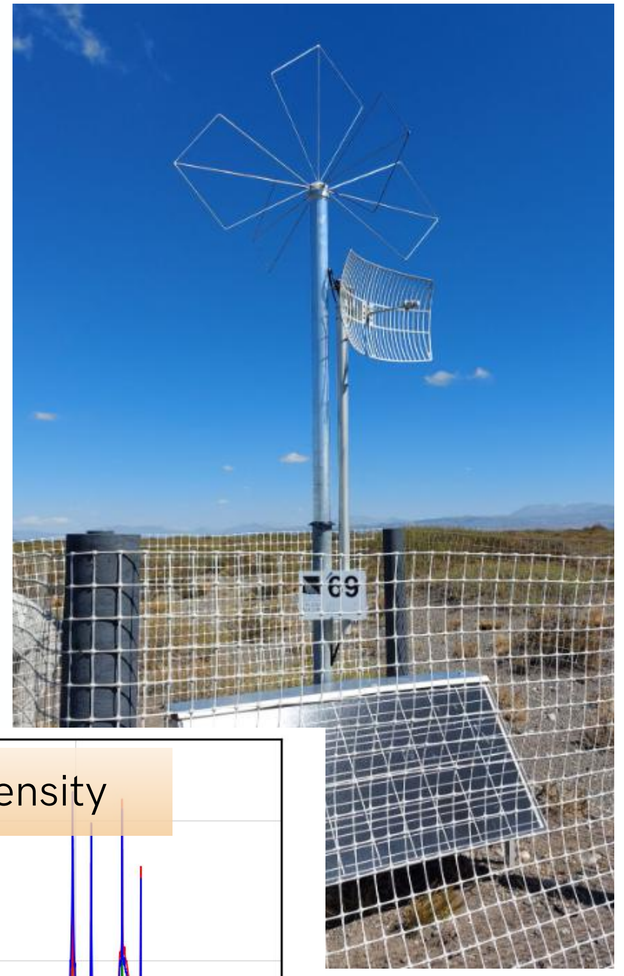


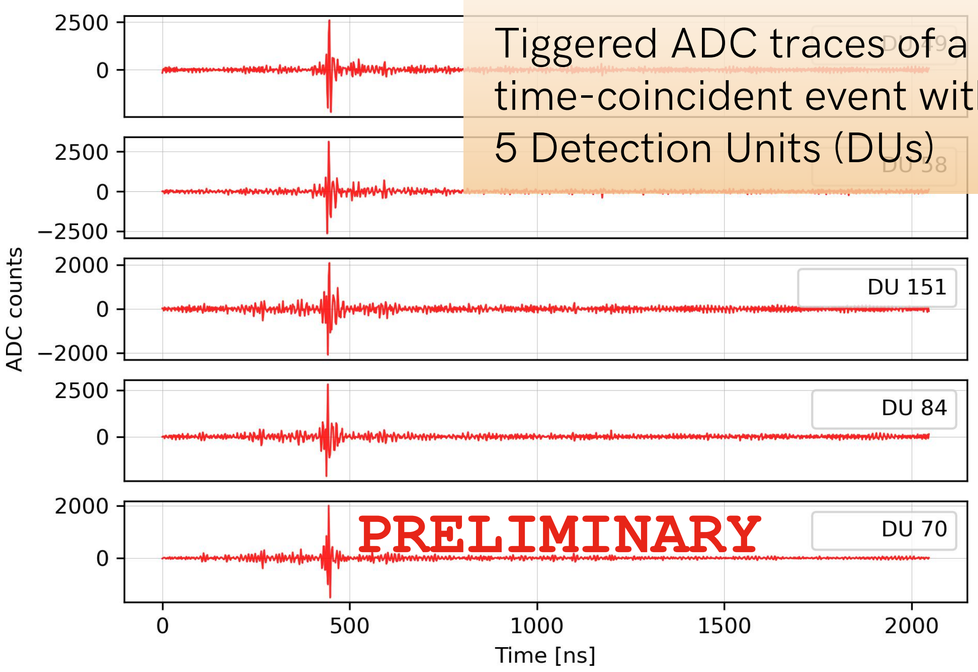
Prototypes: GRAND@Auger

GRAND Coll. in prep.

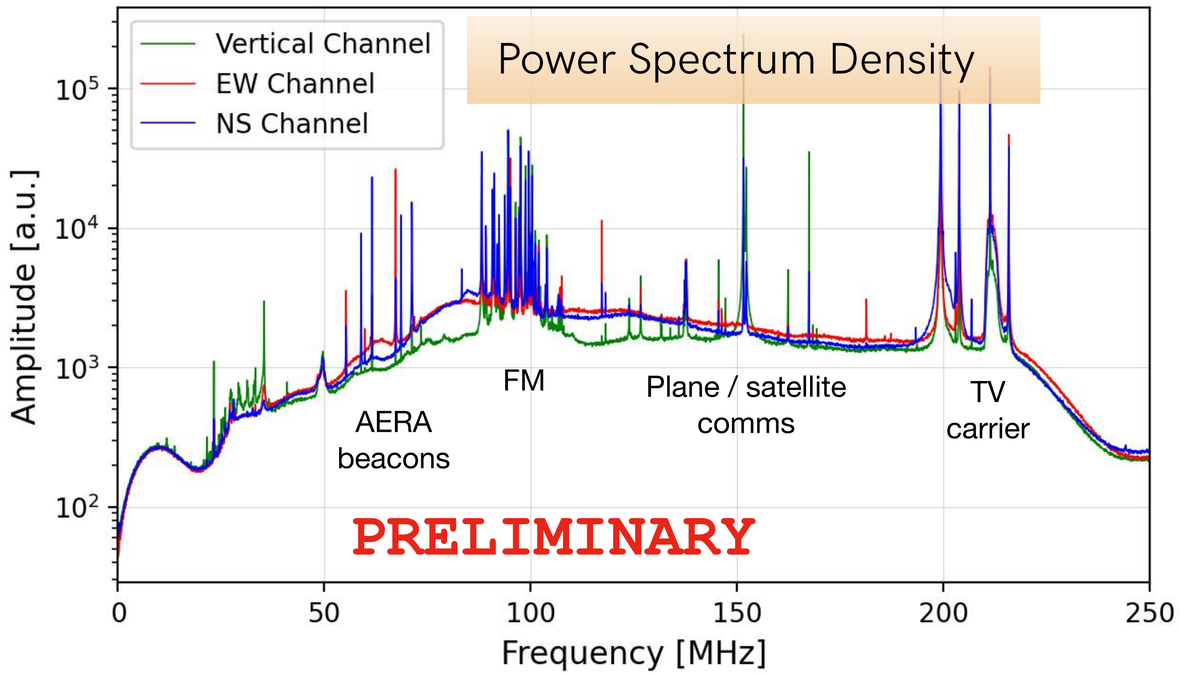


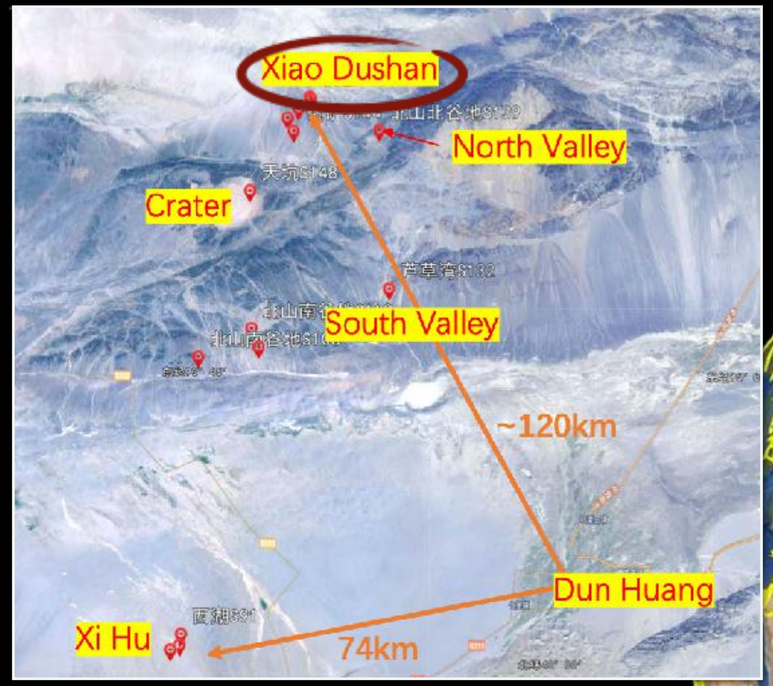
- **Cross-calibration with Auger detectors**
  1 coincident event/day expected
- **10 antennas deployed**
  Auger mechanical structure + infrastructure
- Hardware tests: set-up stability
- Firmware tests, trigger / transient detection

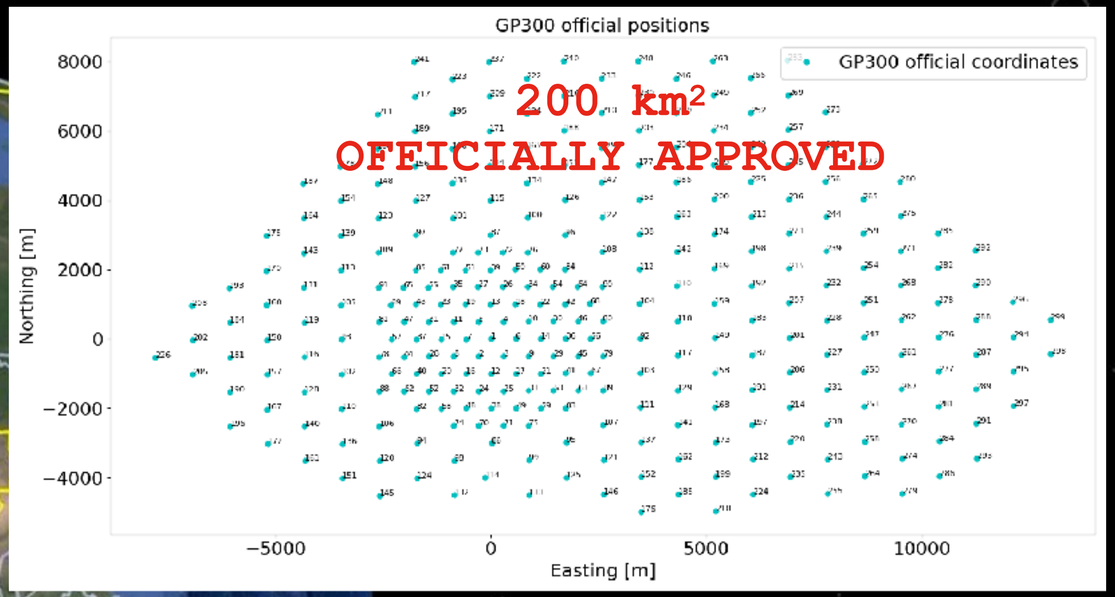




Tiggered ADC traces of a time-coincident event with 5 Detection Units (DUs)







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关于中微子射电观测站二期实验项目用地申请情况的函

敦煌市科技局：

《关于支持中微子射电观测站二期实验项目在敦实施的函》收悉。经审查，现就中微子射电观测站二期实验项目用地审查情况复函如下：

1. 编号为 5 的中心站位于即将出让甘肃省敦煌市白山金矿详查范围，须进行避让重新选址。

2. 编号为 294、291、283、280 的天线单元在甘肃省敦煌市白山金矿详查范围内，须进行避让重新选址。

3. 编号为 63、119、276、278 的天线单元涉及占用草地，须进行避让重新选址。

4. 拟选范围内涉及多条矿区简易道路及高压线路，建设施工过程中须进行避让。

5. 该项目可以现状租赁方式用地，在使用期间不得建设永久性建筑物，不得压占地表、不得改变土地现状；土地年租金每亩约 250 元。

敦煌市自然资源局

2024 年 7 月 12 日

Letter regarding the land application for the second-phase experimental project of the Neutrino Radio Detection observatory

Dunhuang Science and Technology Bureau:

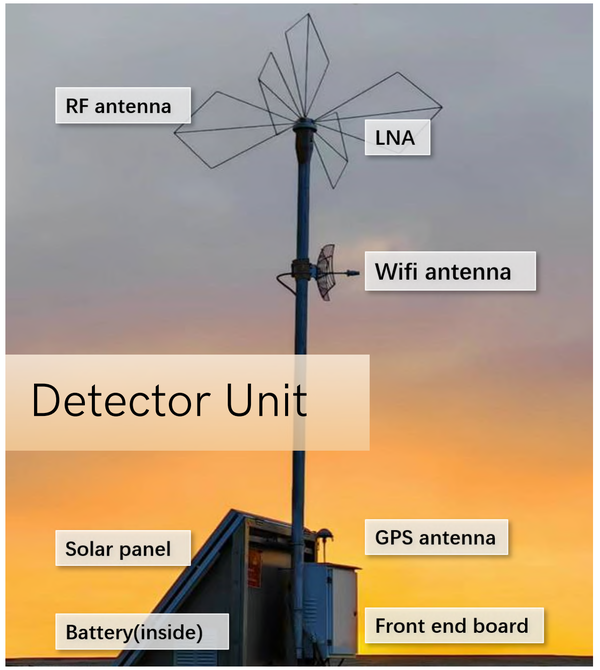
We have received your letter. After review, we are responding to the land review situation for the second-phase experimental project of the Neutrino Radio Detection Observatory as follows:

GRAND Vlog by Pablo Correa
https://www.youtube.com/watch?v=kOSQTb0OJrI&feature=youtu.be

Prototypes: GRANDProto300

GRAND Coll. in prep.

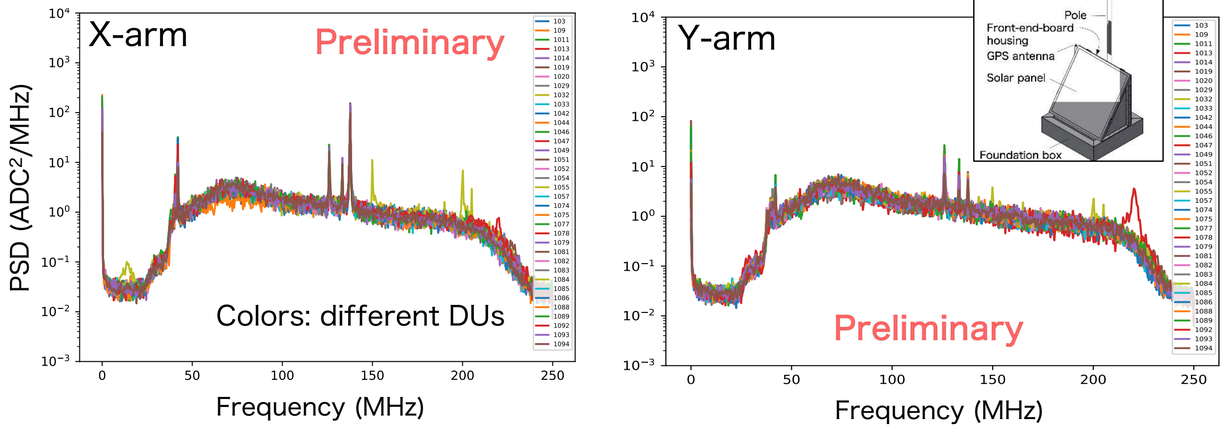
- **GRAND Detection concept validation:** Autonomous triggering & inclined EAS reconstr.
- **65 antennas deployed**
- Hardware tests: long-term stability, self-made noise control, LNA optimization
- Firmware tests, trigger / transient detection
- Cosmic ray search



Power Spectrum Distribution (PSD) of Noise

A set of monitoring data (MD) on 1st Nov. 2024

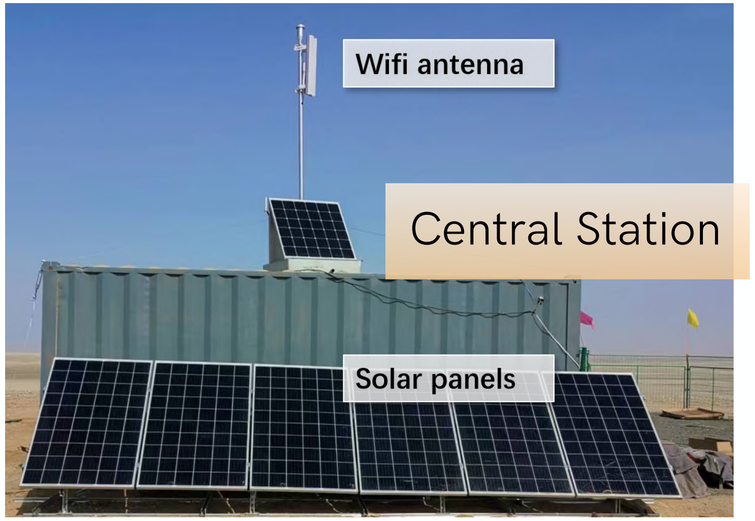
Monitoring data: Non-biased data taking for 10s



- ✓ Very clean spectra for all antenna arms (bandpass = [30MHz, 250MHz])
- ✓ Peaky lines from e.g., airplanes, FM, etc.
- ✓ Global structure = Galactic noise + Instrumental noise (see later)

20

slide by Sei Kato Vietnam 2024



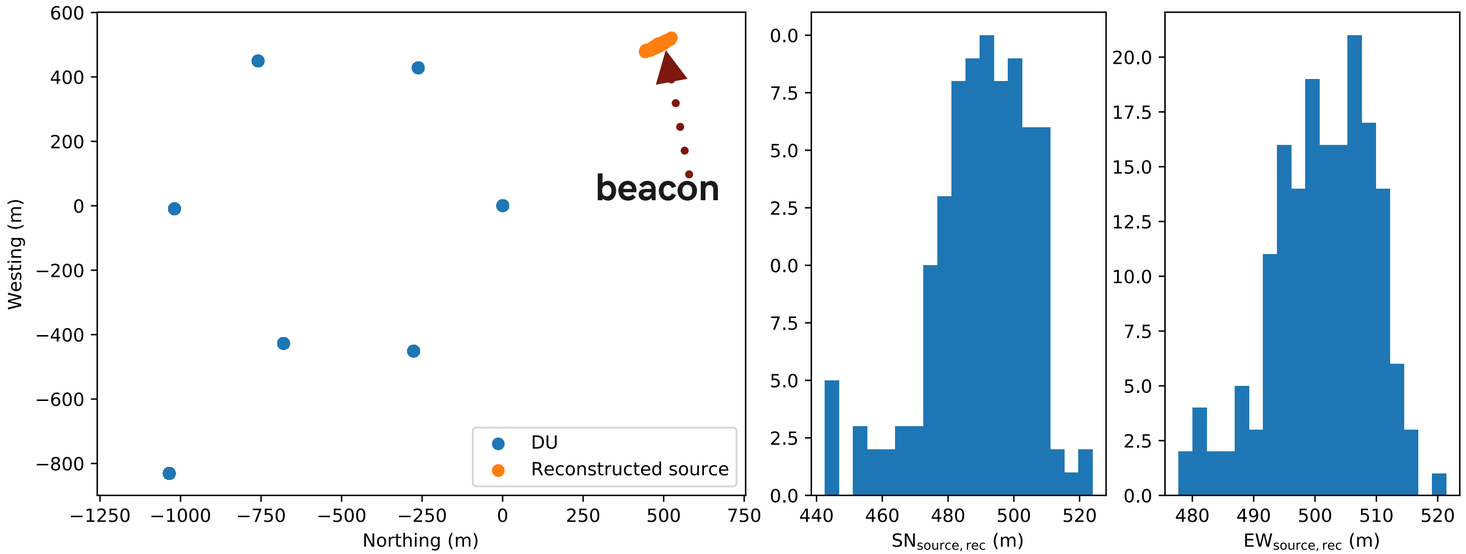
GRAND Vlog by Pablo Correa
https://www.youtube.com/watch?v=kOSQTb0OJrI&feature=youtu.be

First set of reconstructed events

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,

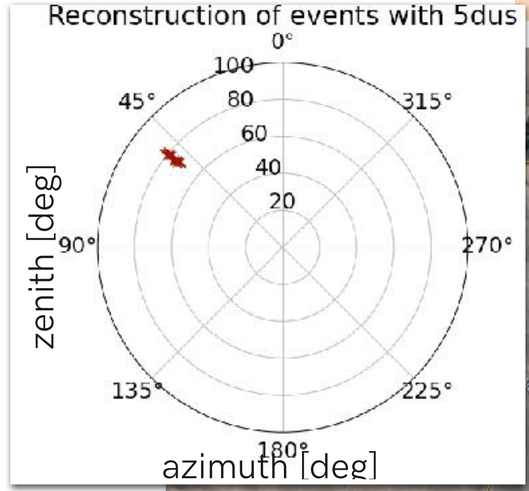
GRANDProto300

GP13



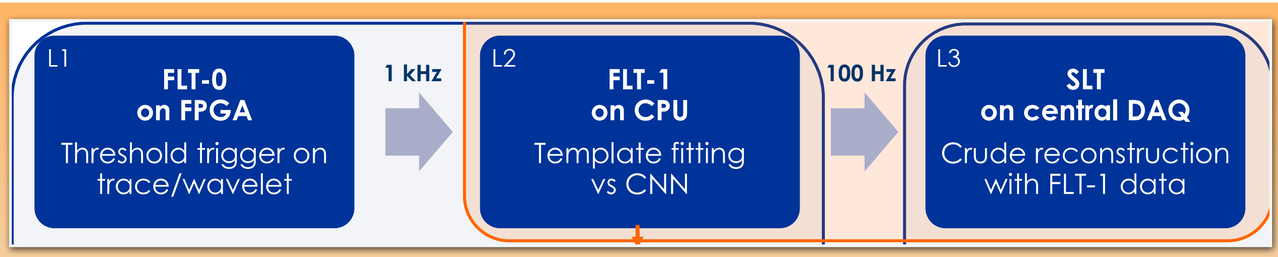
- **offline** coincidence search from beacon
- spherical wave front model (SWF)
- 171 events reconstructed /173 pulses emitted in time window
- 10 m std deviation on Northing/Westing positions

GRAND@Auger



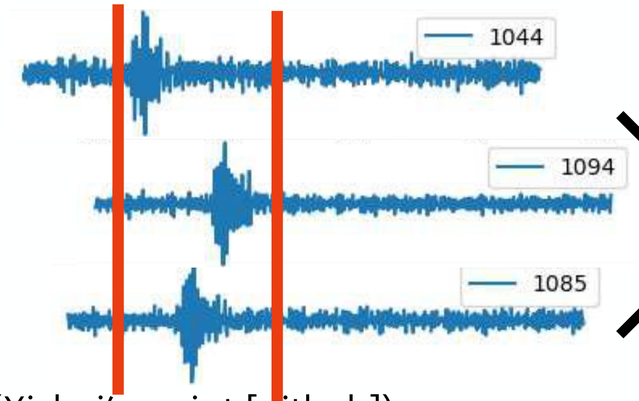
- **online** coincidence search at central DAQ (L3)
- 3 consistent independent analysis (Analytic PWF, PWF/SWF)
- azimuth and zenith consistent with direction of village, towards ground

- **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)



Cosmic-ray event search pipeline **PRELIMINARY**

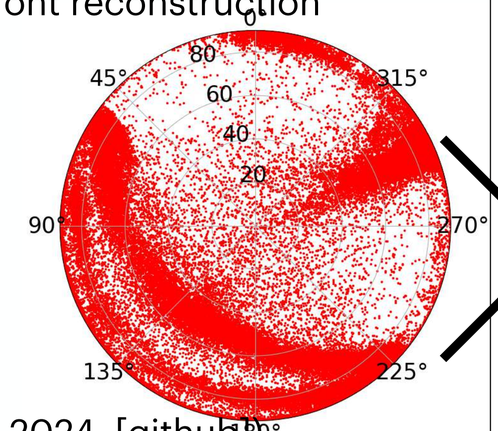
T3 coincidence search



(Xishui's script [github])

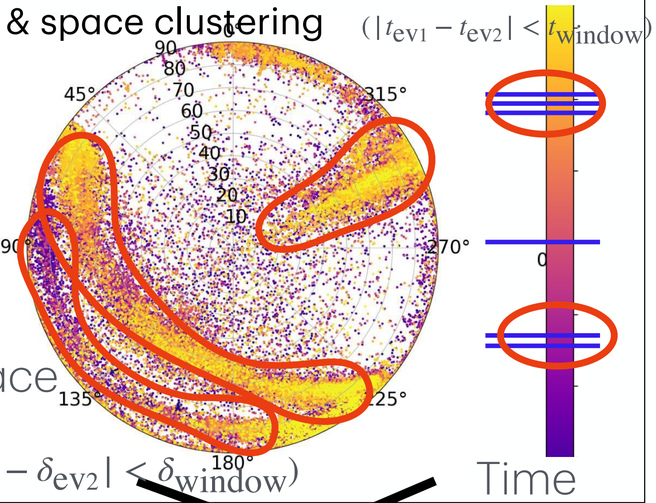
Plane Wave Front reconstruction

Result in θ and ϕ



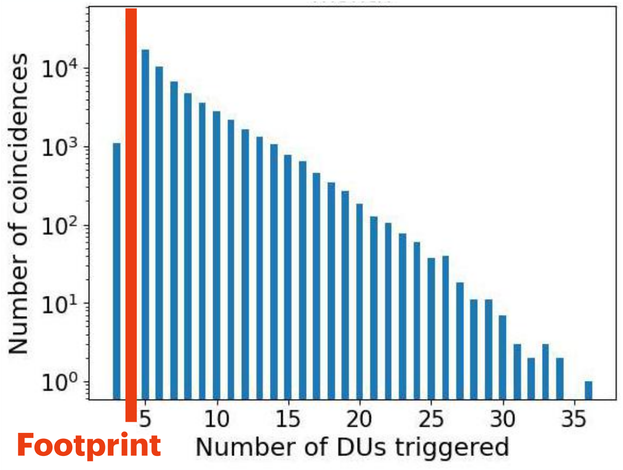
(Ferriere et al. 2024, [github])

Time & space clustering $(|t_{ev1} - t_{ev2}| < t_{window})$



$(|\delta_{ev1} - \delta_{ev2}| < \delta_{window})$

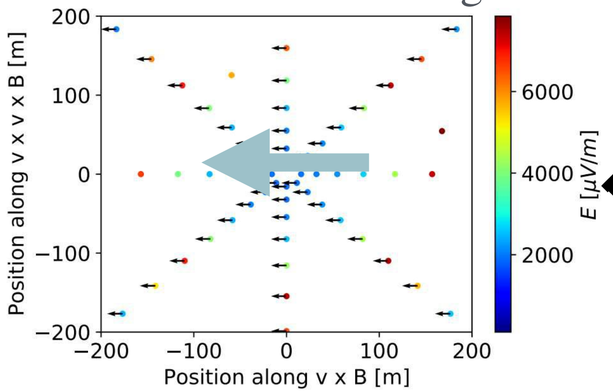
Number of antennas



Footprint too small

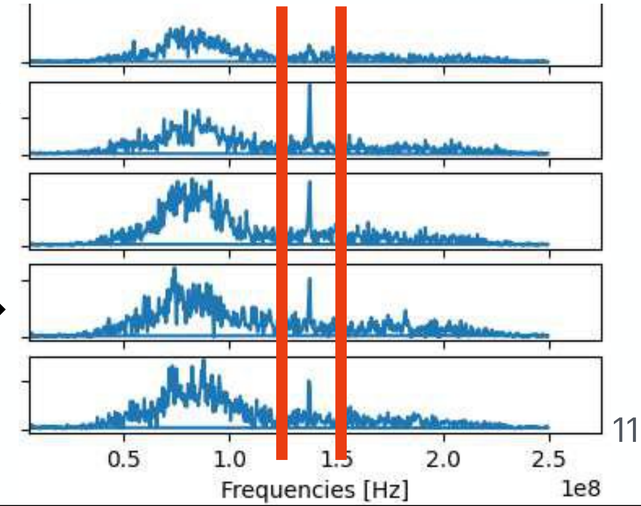
Polarisation

Polar $\perp \vec{B}_{geo}$



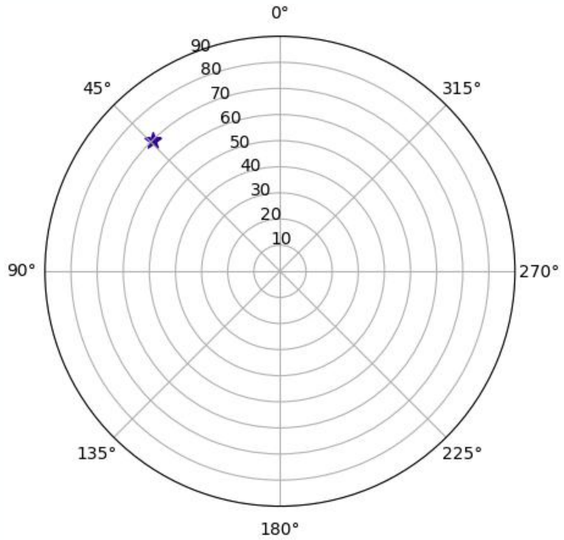
(Chiche et al. 2022)

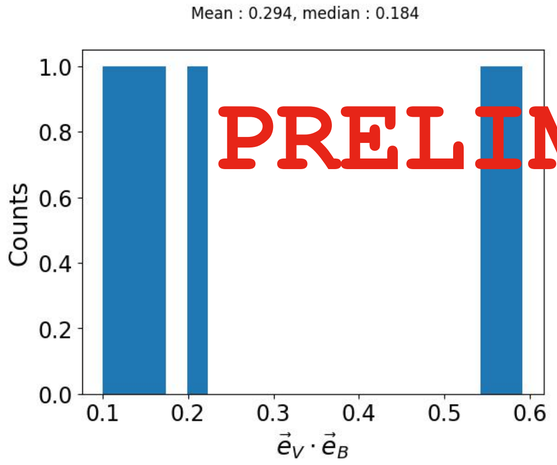
Peak frequency cut



slide by J. Lavoisier

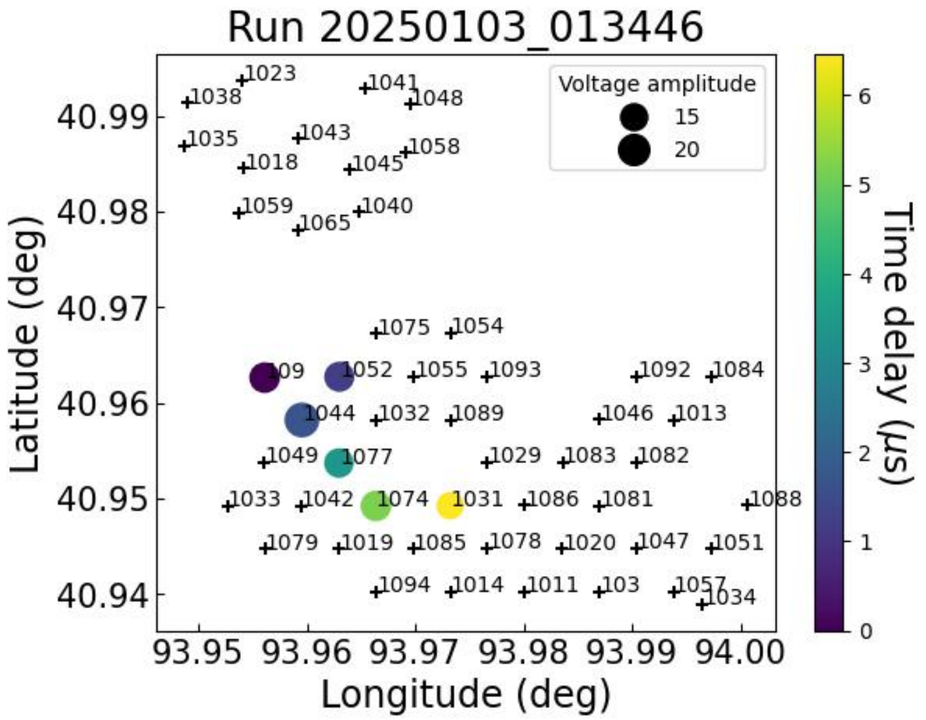
Cosmic ray events search and first candidates

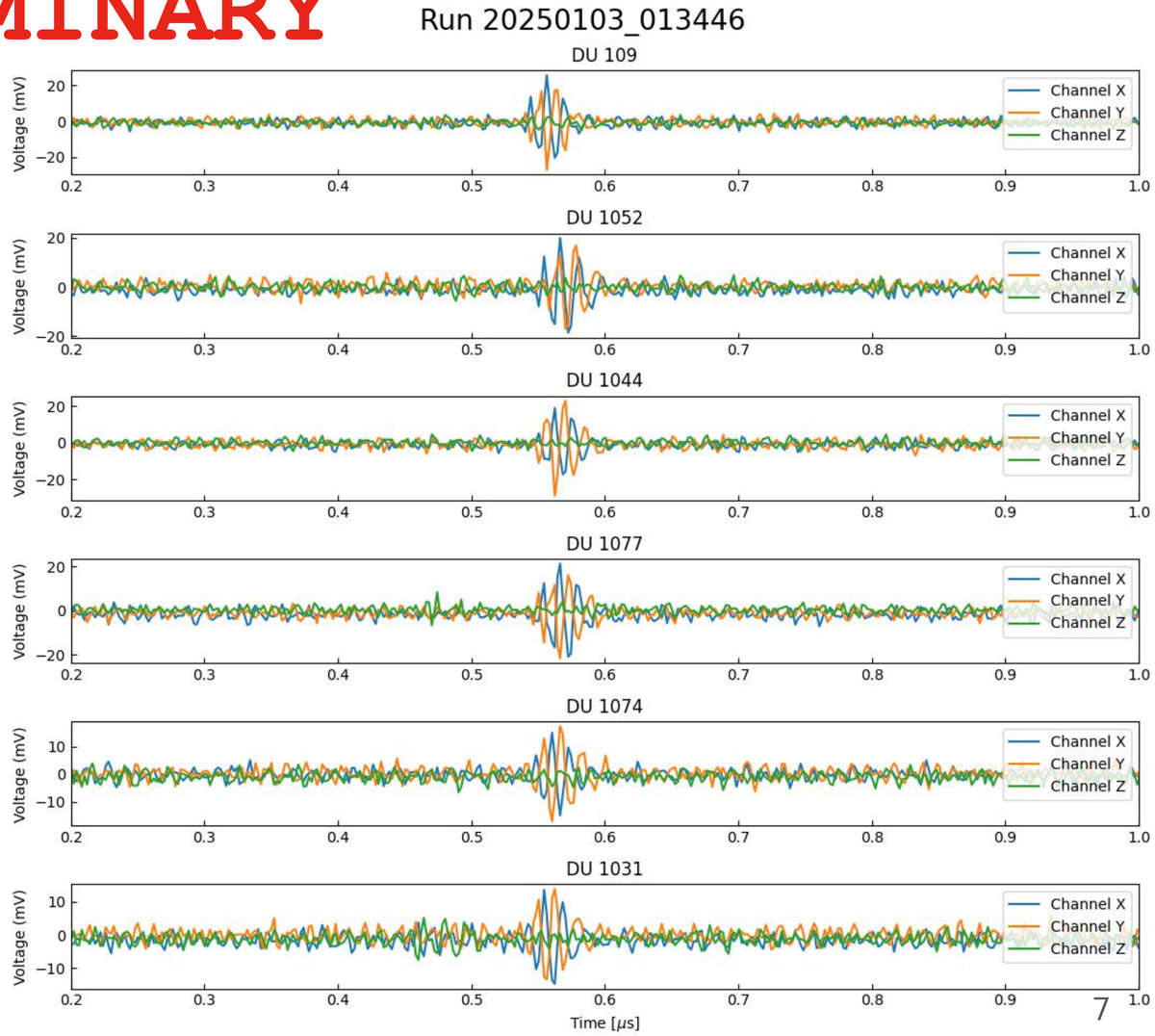




Candidat : 20250103_013446

PRELIMINARY





slide by J. Lavoisier

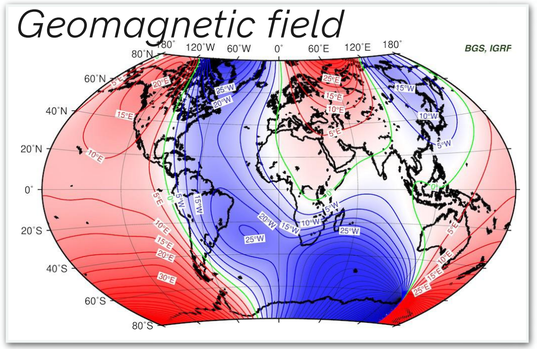
Software pipeline: GRANDlib

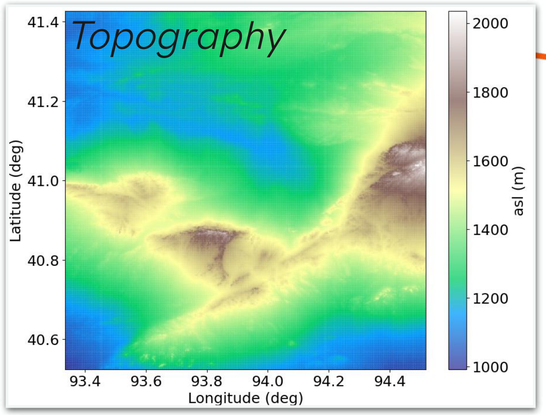
https://github.com/grand-mother/grand

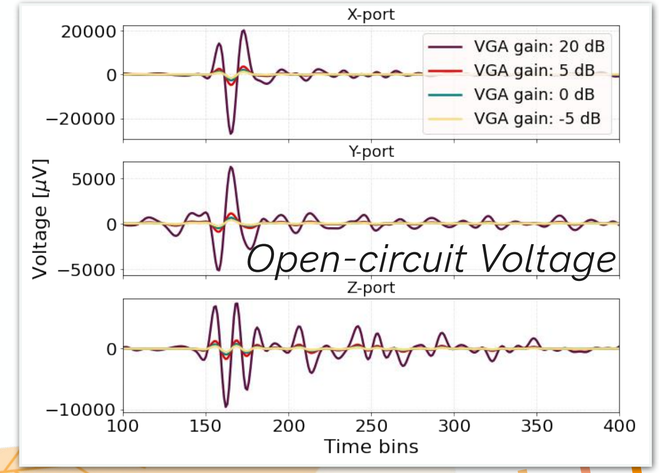
Python offline software package for the GRAND collaboration
Tool to manage and analyze data

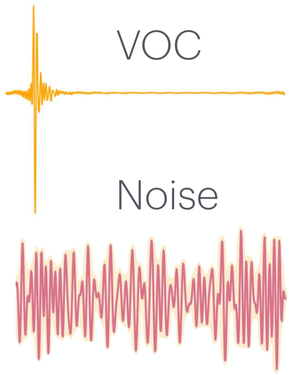
GRAND Coll. 2024

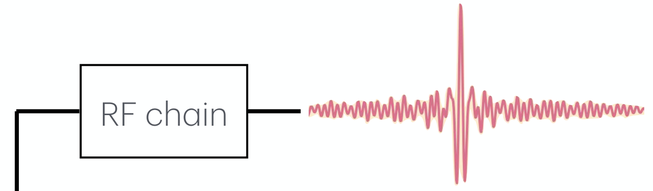
PRELIMINARY FIGURES

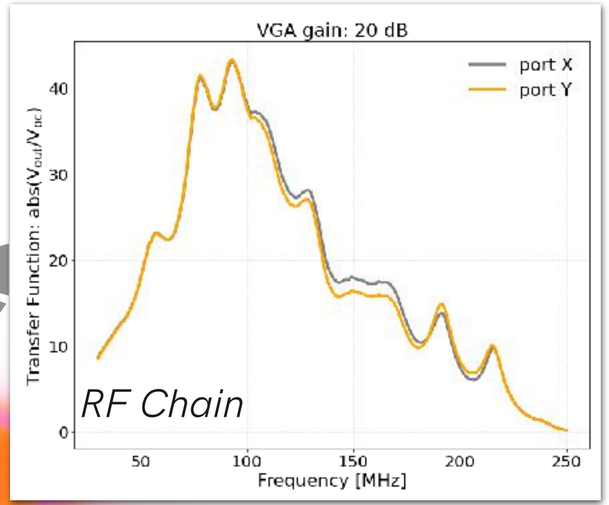


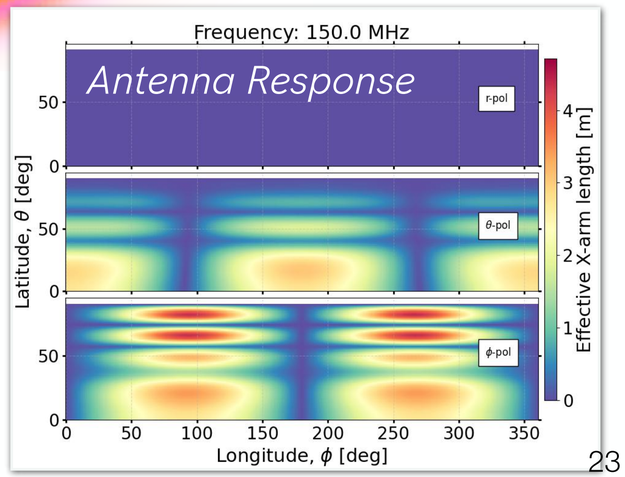












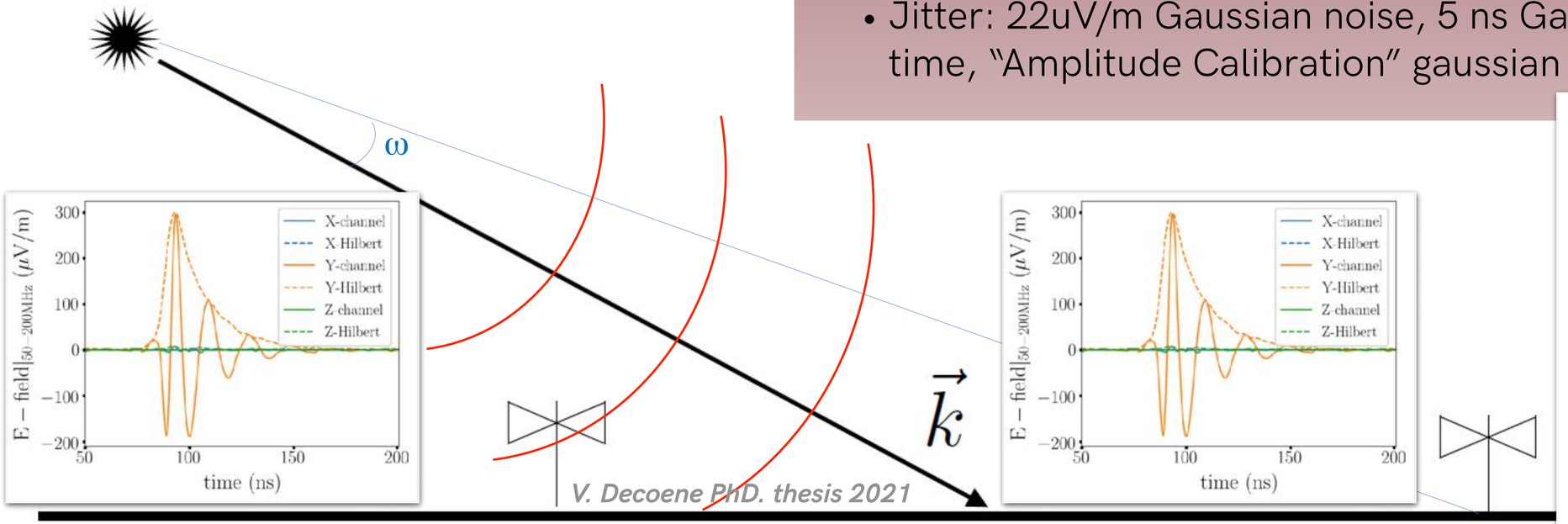
- User friendly tool. No need to install ROOT
- Modules for coordinate systems, topography and geomagnetism
- Includes galactic noise and RF chain parameters
- Standard code for signal processing
- Tools to store data in a standard file format and manage them
- Refer to `grand/examples` for example scripts

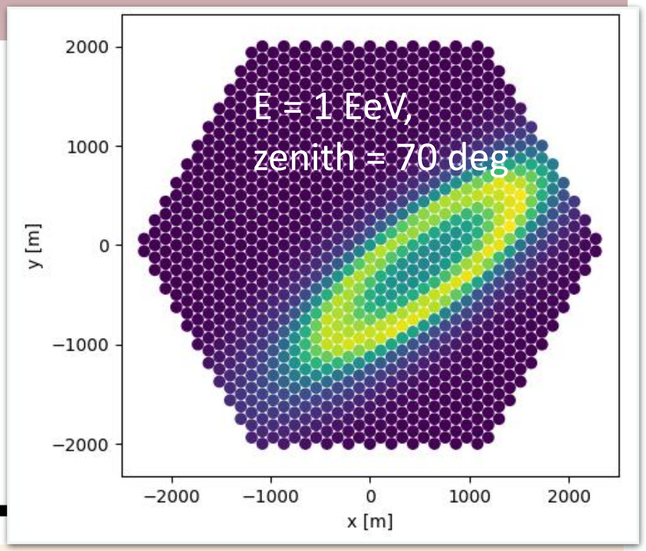
Reconstruction efforts

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 (201
Macias et al., Pos(ARENA2024)062
Benoit-Lévy et al., JINST19(4), P04006 (202

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

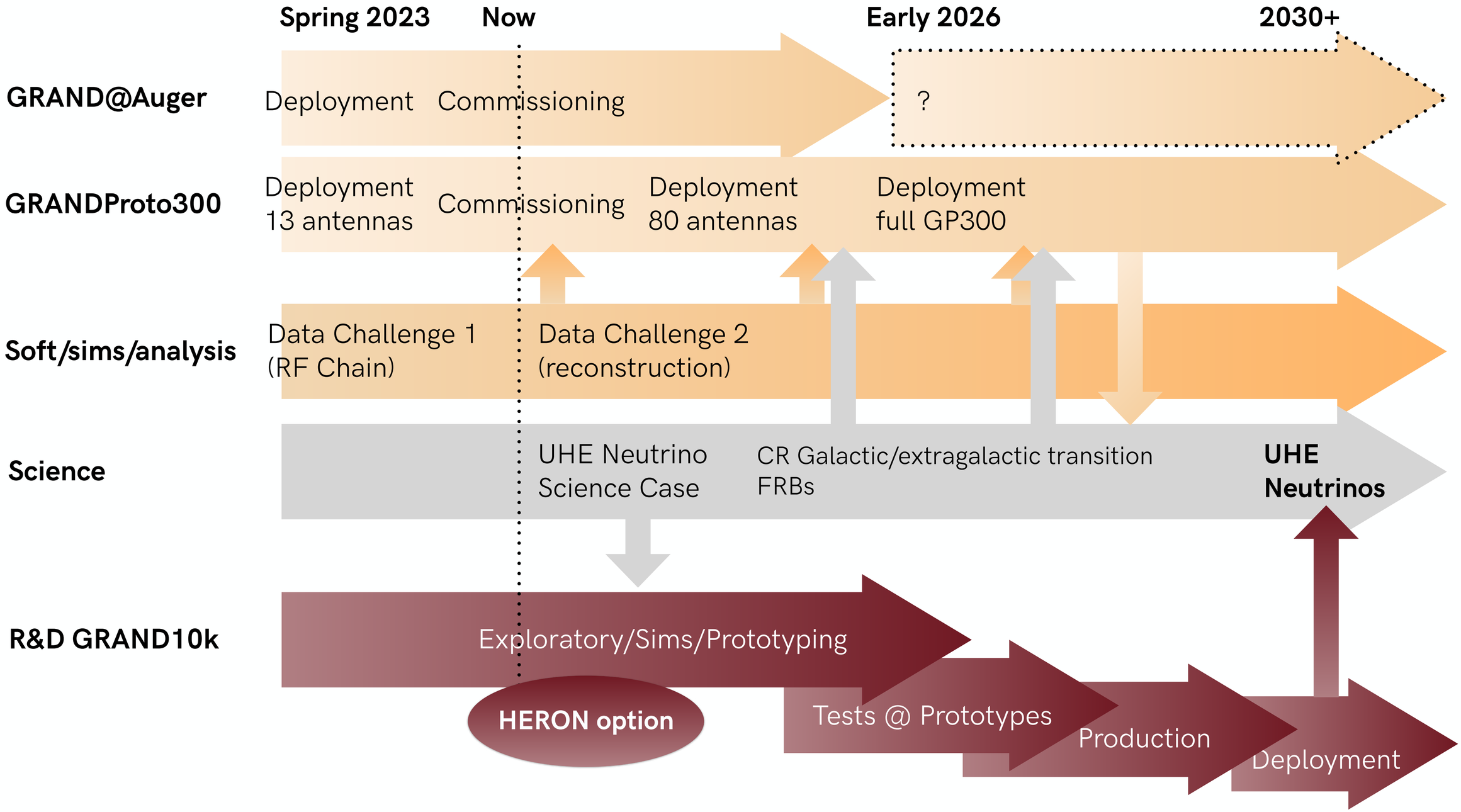
- E-field reconstruction with CNN
- Direction reconstruction based on polarization
- De-noising of E-field/ADC using ML

Inclined Air Shower Reconstruction

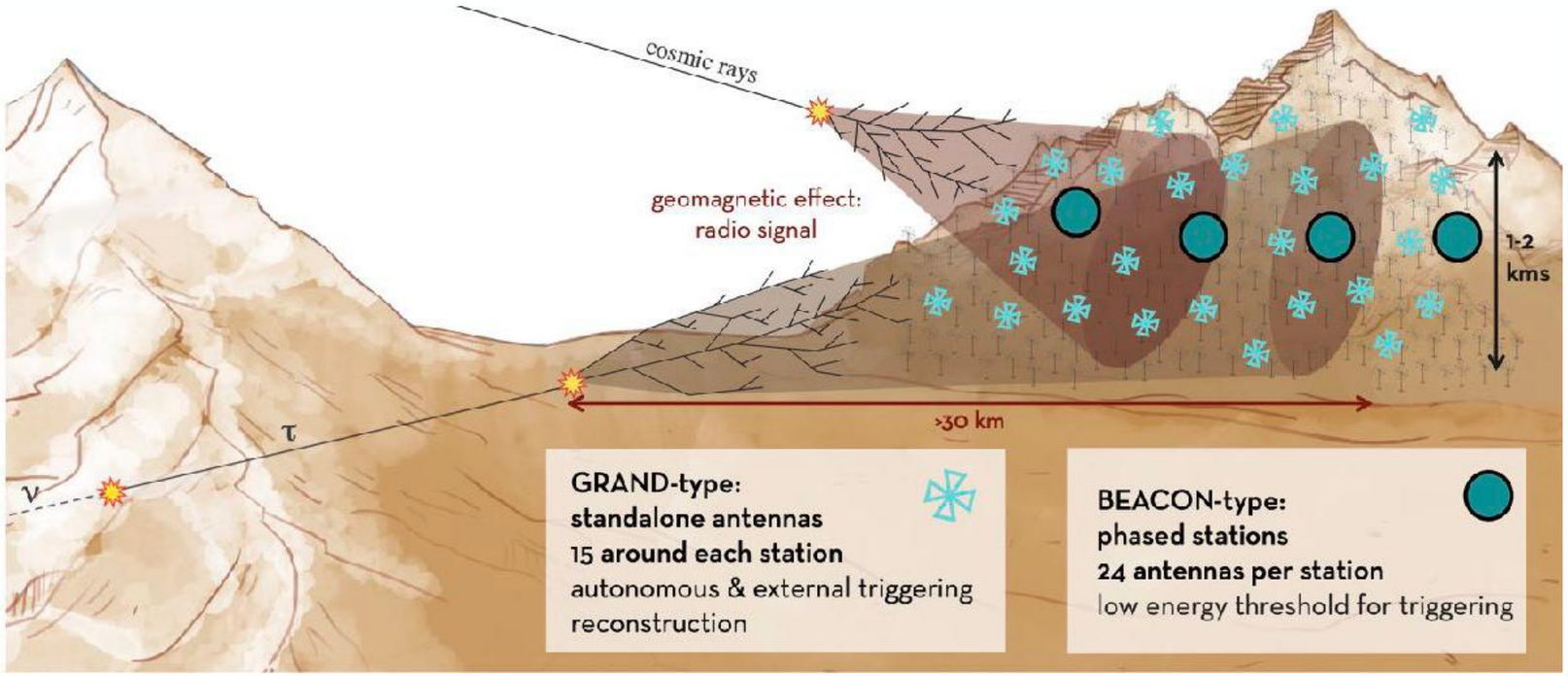
- Plane Wave Front (PWF): fast timing & direction reconstruction (analytical, with error calc.)
- Fitting (empirical and Physics informed) of Angular Distribution Function (ADF)
- Empirical fitting of lateral distribution function
- GNN for EAS studies

Ideal Timeline

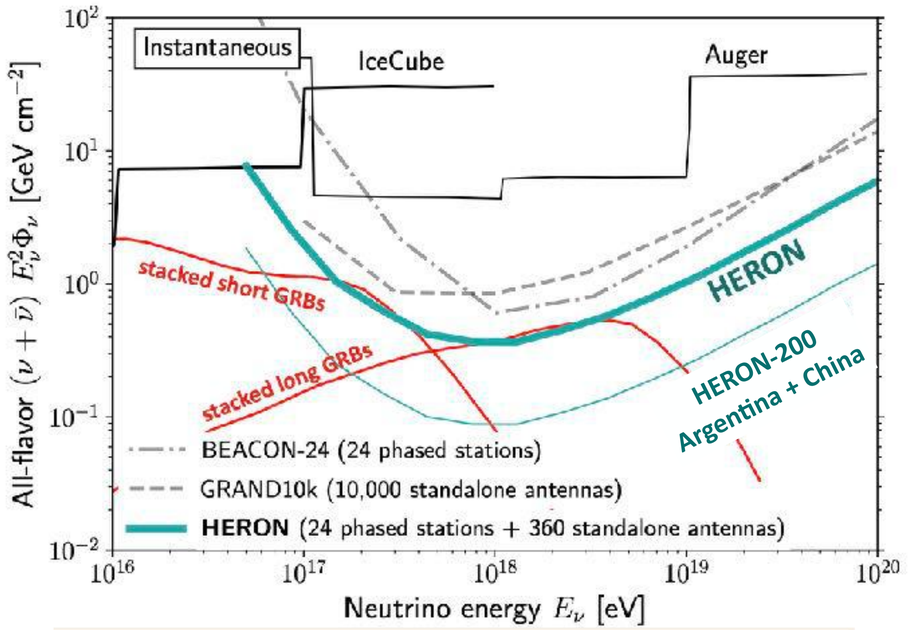
PRELIMINARY



Option for the next stage of GRAND in Argentina: Hybrid Elevated Radio Observatory for Neutrinos (HERON)



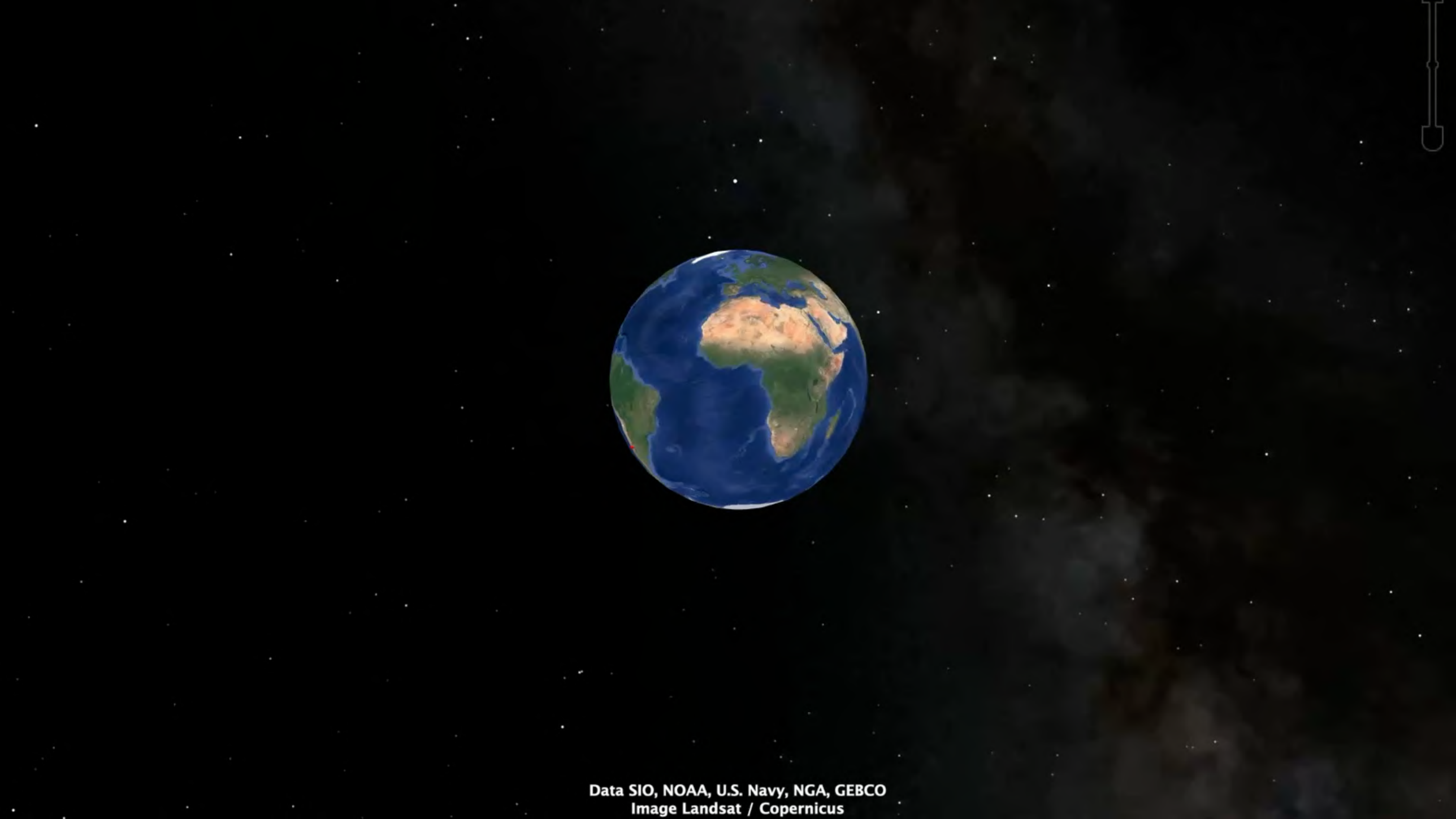
A discovery instrument!



- **24 phased stations** ("BEACON-type" in the figure below) : **70 km linear along mountain**
  each station contains: 24 compact radio antennas (3 m high, 1 m² of footprint on ground)
  station surface: ~100 m² each, separation between stations: ~ 3 km
  altitude 1000 m
- **360 standalone antennas** ("GRAND-type" in the figure below) **at altitudes between 500 m and 1500**
  3m high, 1 square meter of footprint on ground)

R&D for GRAND:
- external trigger plugged on autonomous GRAND systems
- interferometry

2nd site envisioned in China

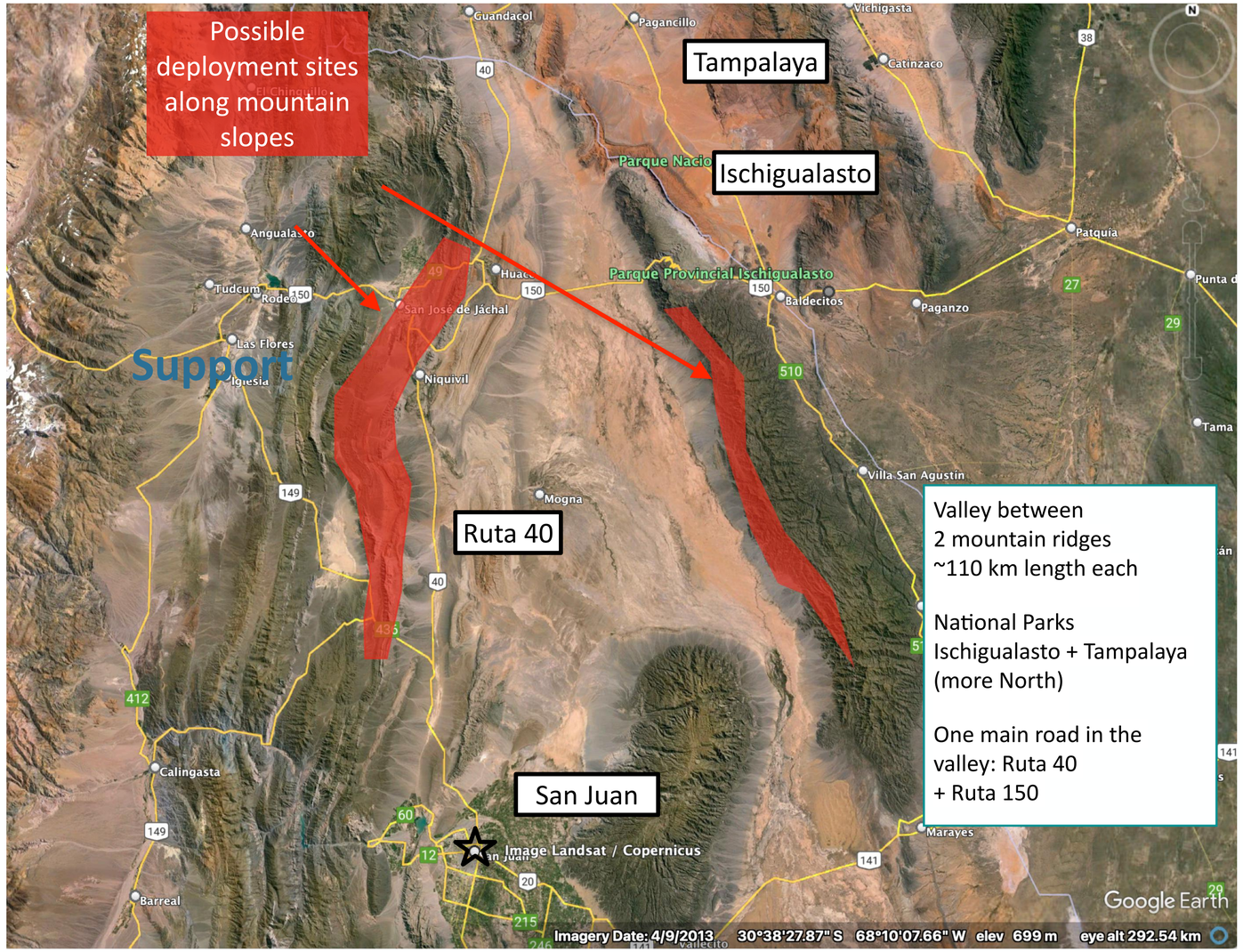

Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

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

The GRAND Collaboration

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

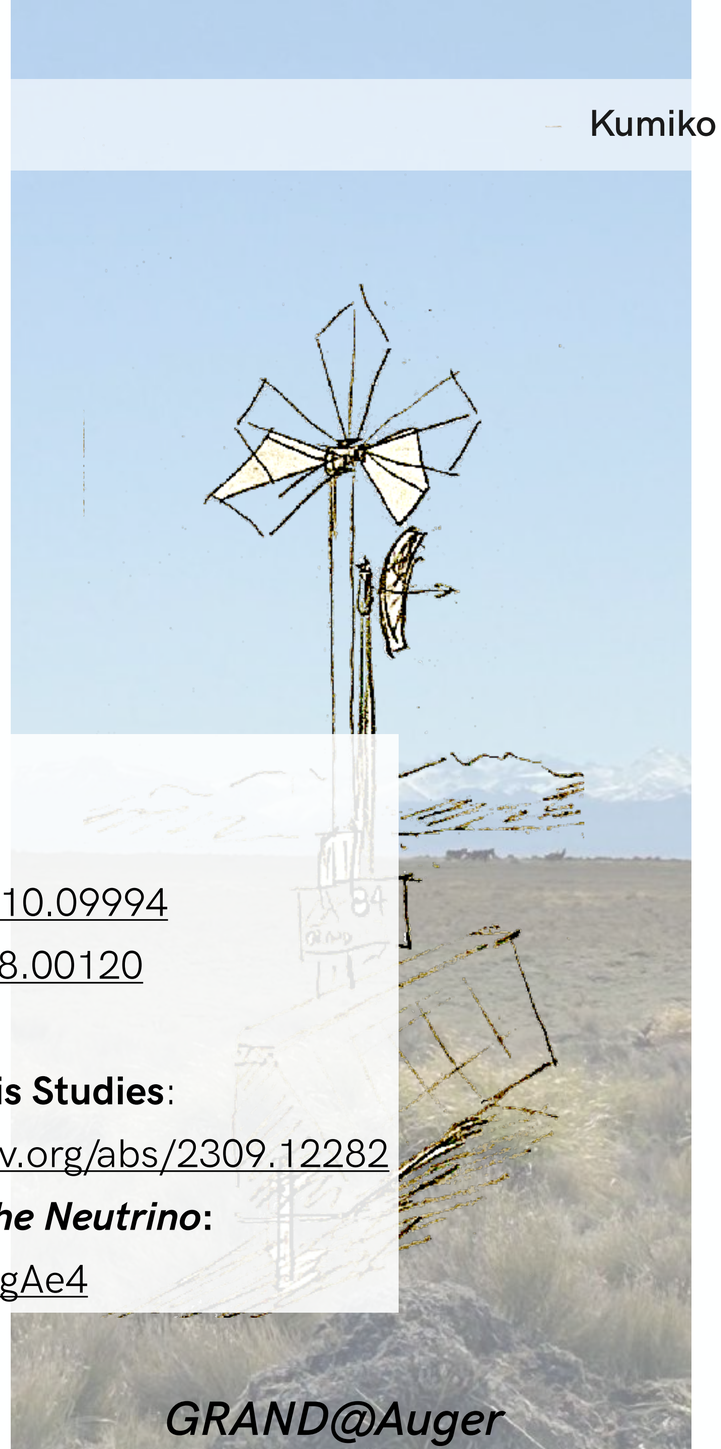
- Pennsylvania State University (PSU)
- San Francisco State University (SFSU)

- Universidade Federal do Rio de Janeiro (UFRJ)

130 members

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

Nanjing Collaboration Meeting @ Purple Mountain Observatory, May 2024



References:

Website: http://grand-observatory.org

GRAND White Paper: https://arxiv.org/abs/1810.09994

GRAND ICRC 2023: https://arxiv.org/abs/2308.00120

Github: https://github.com/grand-mother/

GRAND Carbon Footprint & Life Cycle Analysis Studies:

https://arxiv.org/abs/2101.02049, https://arxiv.org/abs/2309.12282

Documentary by Jean Mouette *The Road to the Neutrino*:

https://www.youtube.com/watch?v=8tDnwq8gAe4

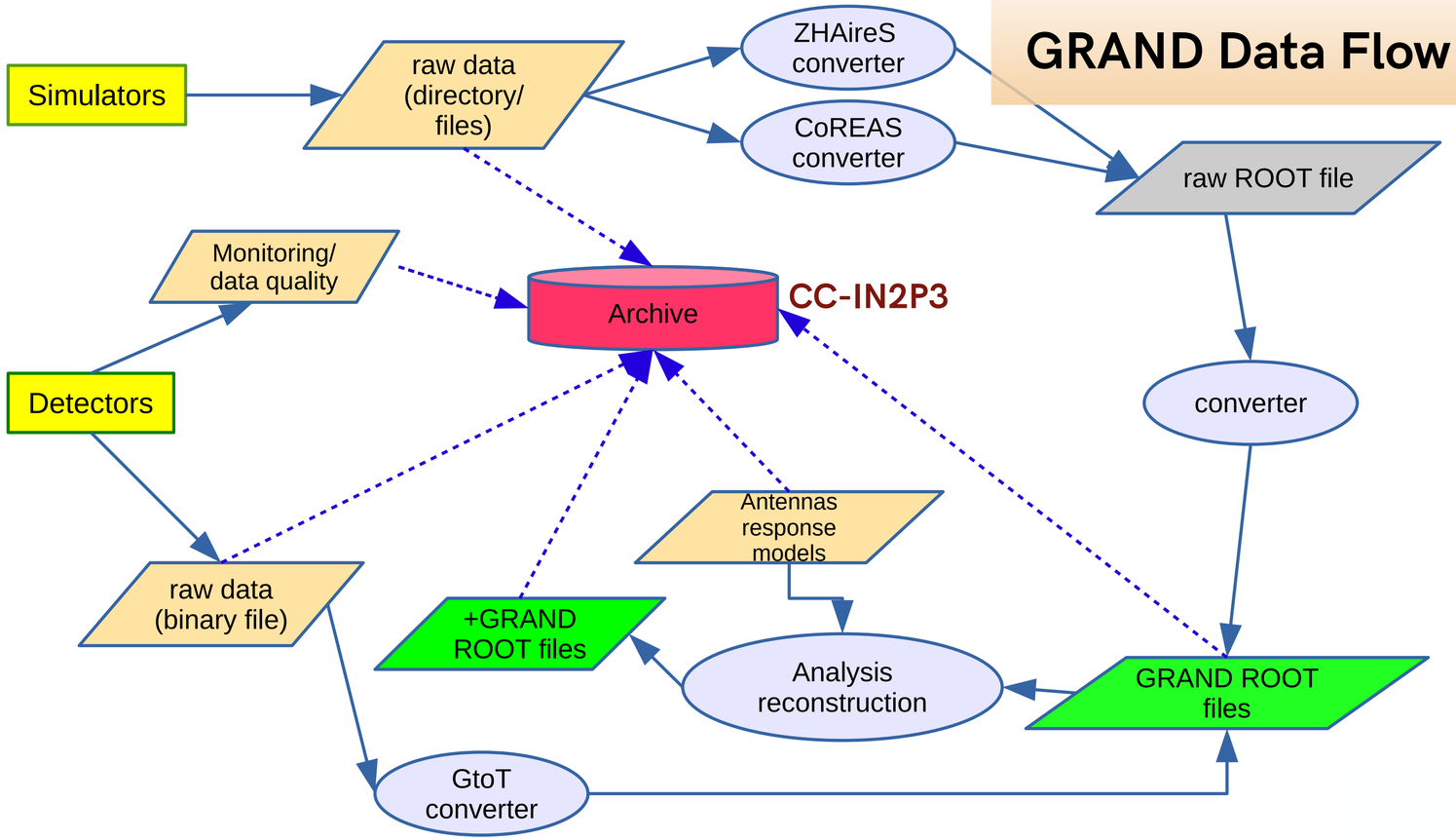
GRAND@Nançay

GRAND@Auger

GRANDProto300

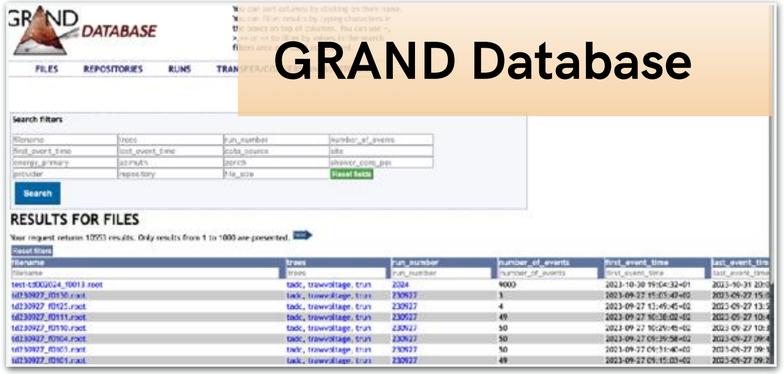
Software pipeline: data flow & online monitoring

GRAND Data Flow

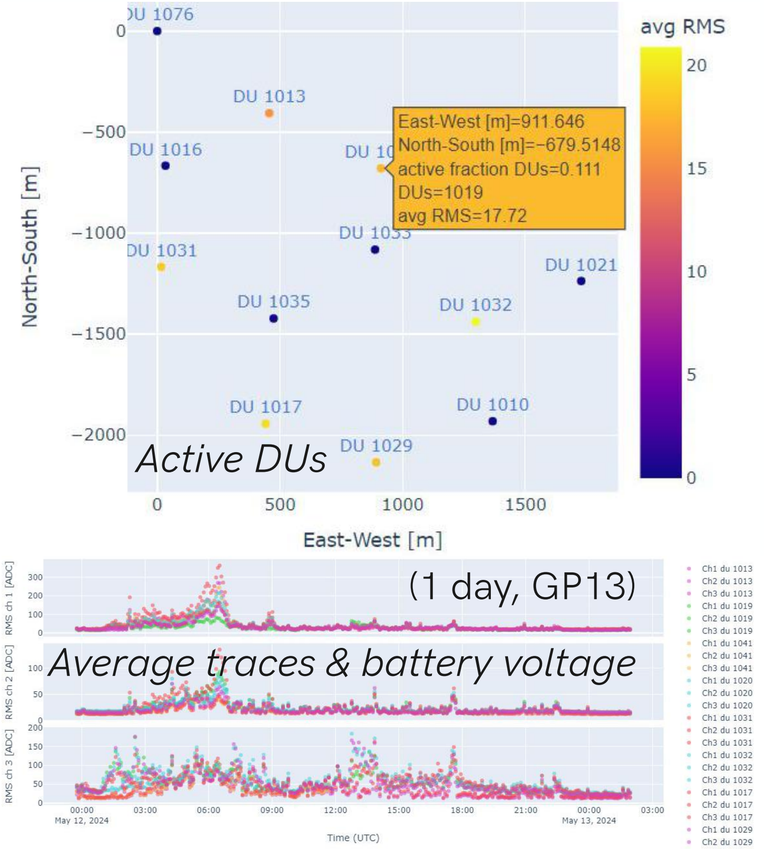


- Automatic/semi-automatic transfer from GRAND@Auger/GP300
- Automatic conversion to GRANDRoot format
- Recorded into GRAND Database, storage at **CC-IN2P3** (Lyon, France)

GRAND Database



GRAND Data Online Monitoring



- Battery & Temperature levels
- Signal RMS levels
- Traces and Frequency domains
- Transient rate, coincidences