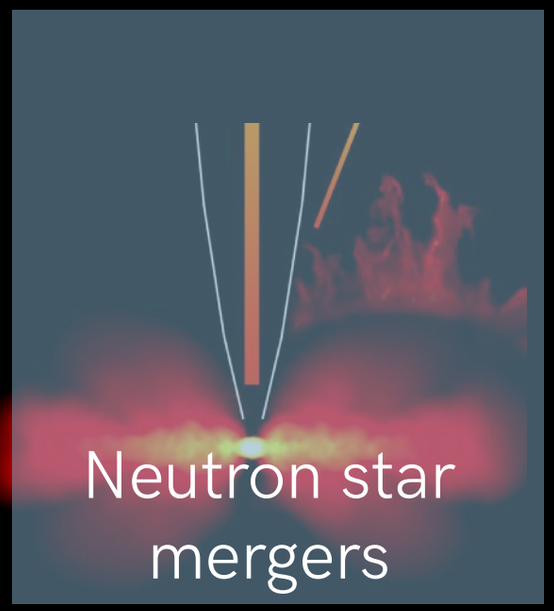
Kumiko Kotera - Institut d'Astrophysique de Paris - CNRS

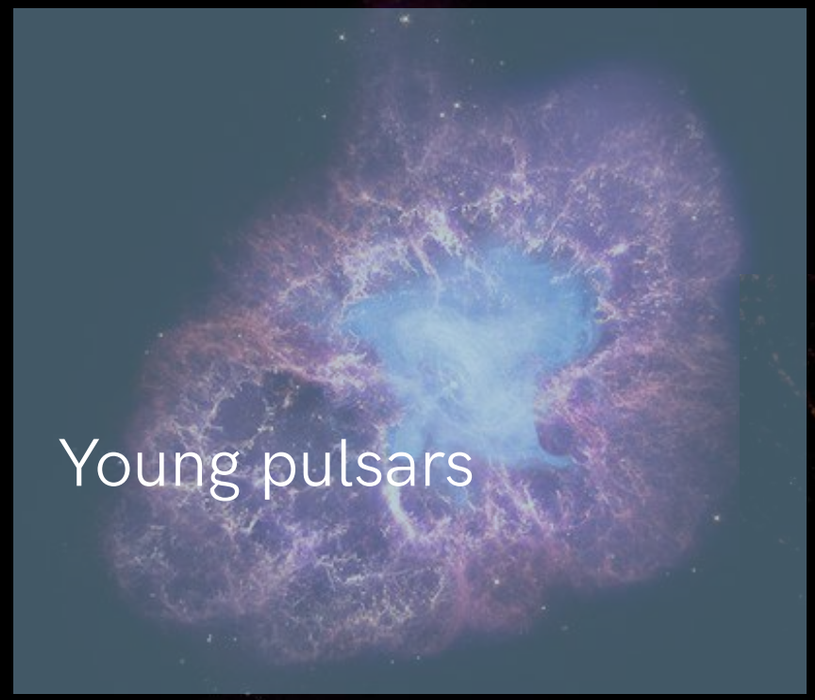
OCA - 28/03/2023

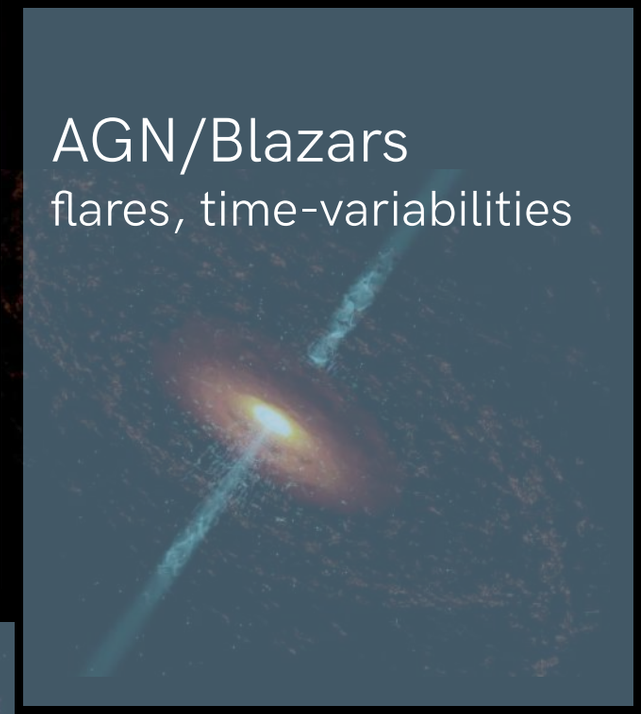
Towards EeV Neutrino Astronomy with GRAND

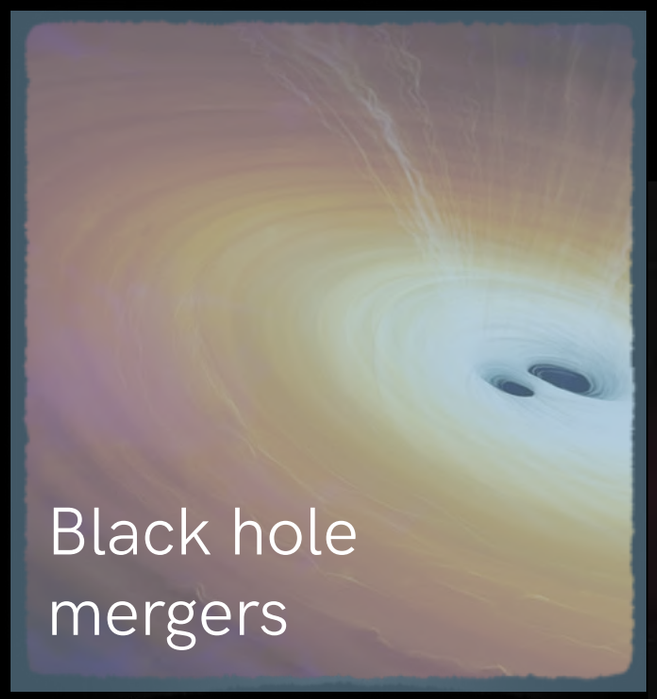
(Giant Radio Array for Neutrino Detection)

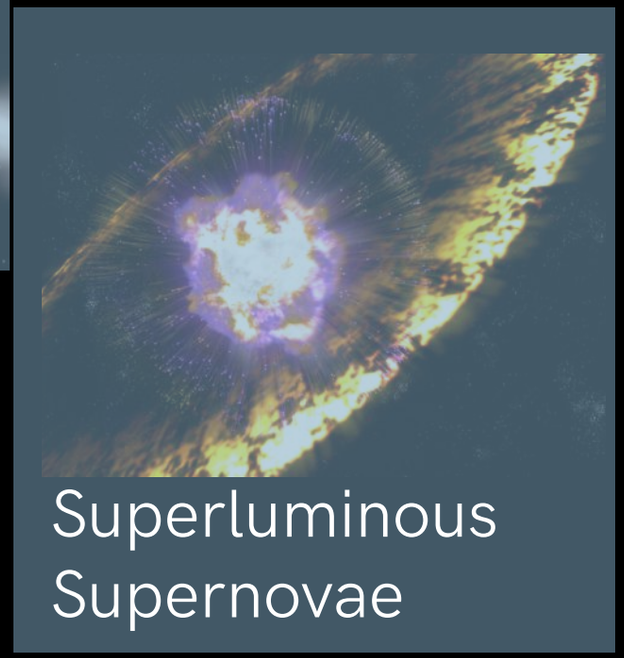
Understanding the violent Universe?











Exploring the high-energy Universe with multi-messengers

Gravitational waves

Cosmic rays

Cosmogenic neutrinos
produced during propagation in the intergalactic medium

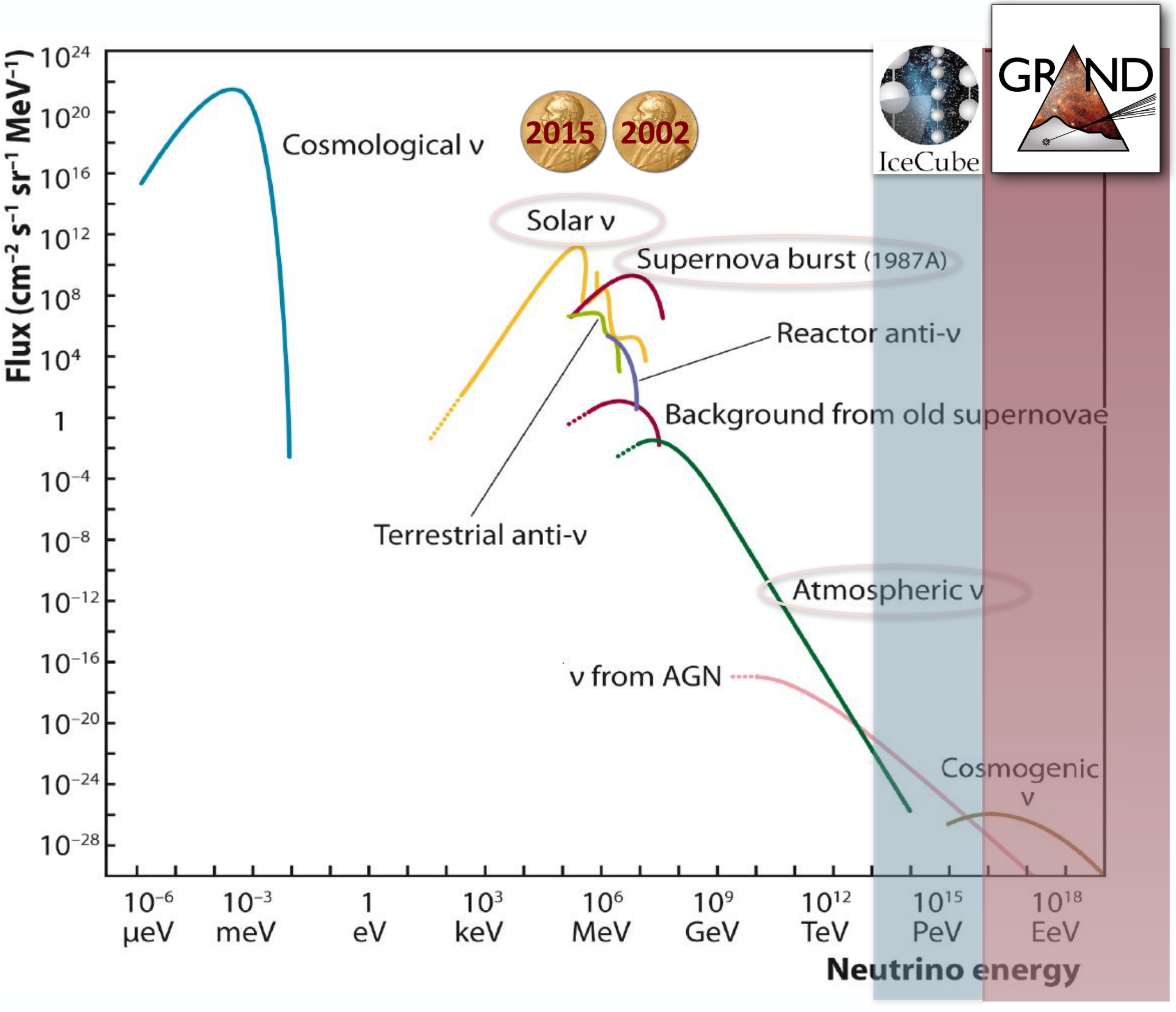
Astrophysical neutrinos
produced at the source

Gamma rays

Neutrinos

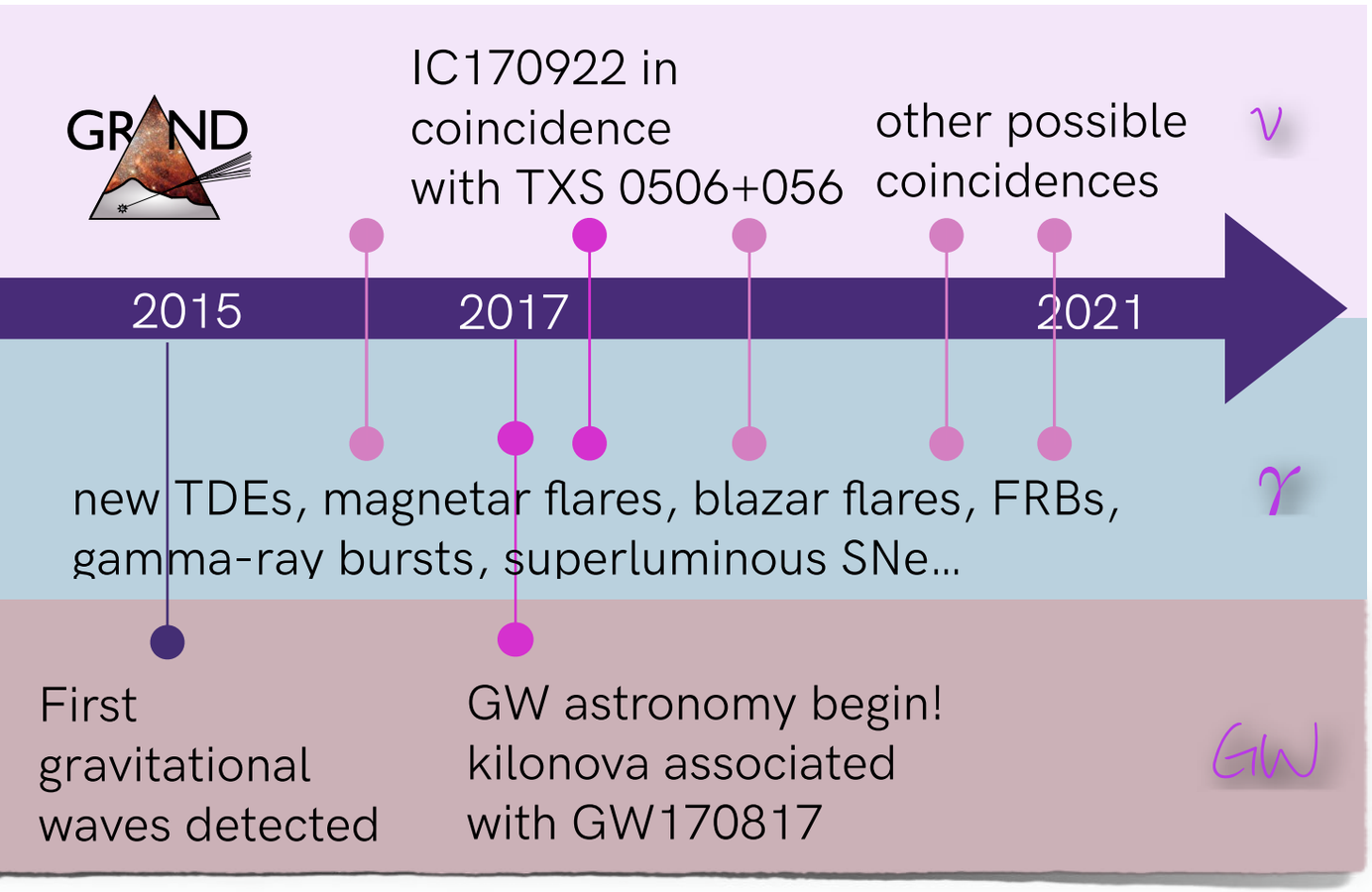
- not deflected by magnetic fields
- allow us to see farther in the Universe
- allow us to see deeper in objects
- clear hadronic acceleration signature

UHE neutrinos: the unchartered territory!



Evolution of UHE neutrino science case

BOOM of multi-messenger astronomy + time domain astronomy at HE



e.g., ***Møller et al. 2018, van Vliet et al. 2019***

of course very interesting, but less of a priority?

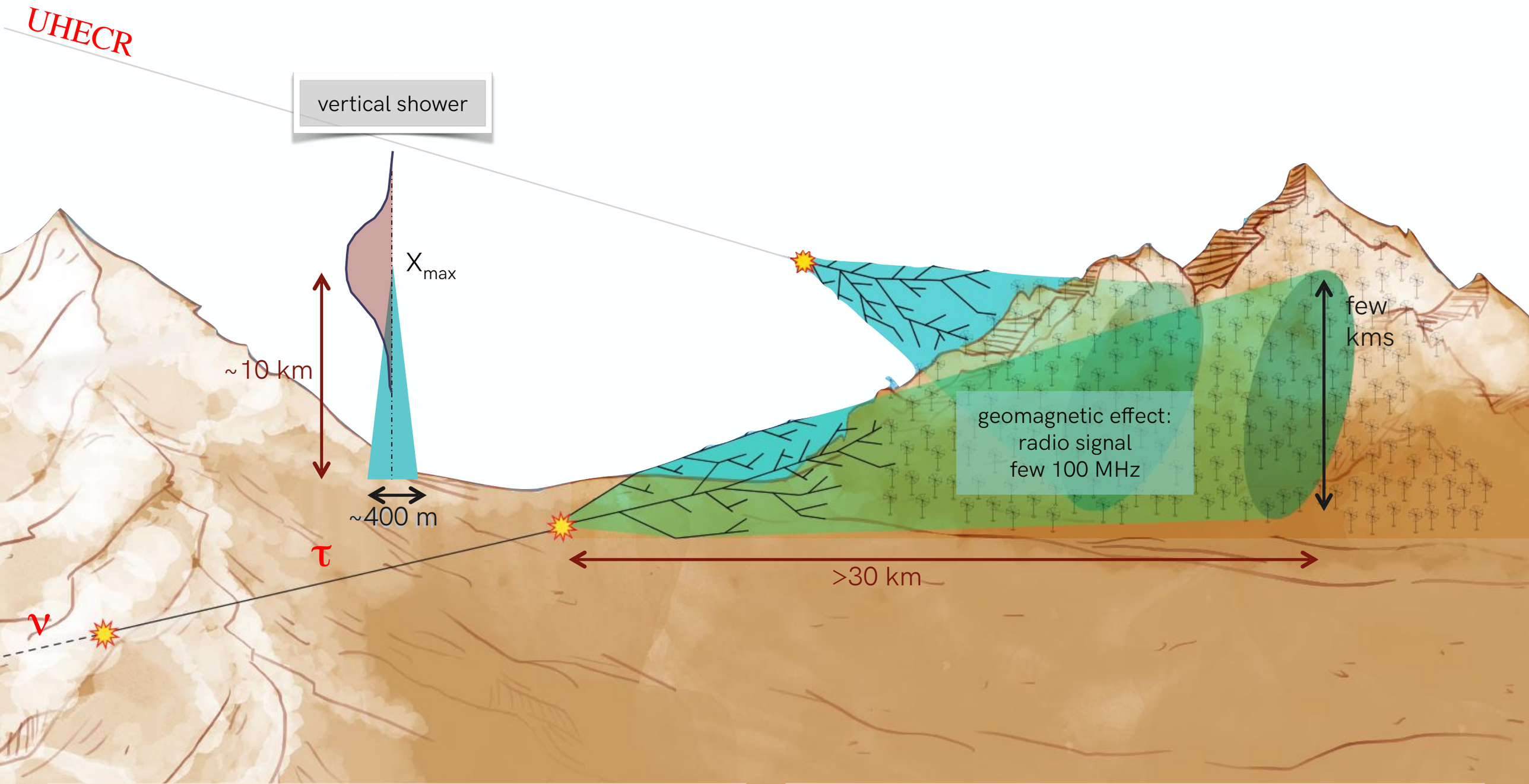
Let's catch the diffuse cosmogenic neutrino flux!

Point sources! Transient neutrino sources!

What will we need?

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

Radio detection of ultra-high-energy air-showers

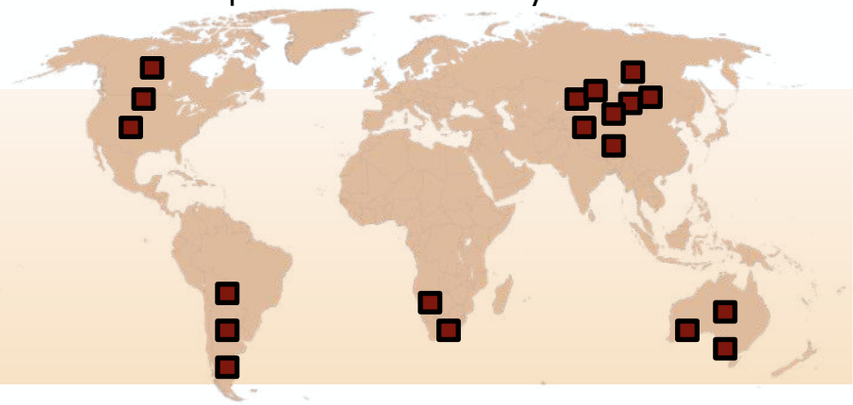


radio detection: **a mature technique**
AERA, LOFAR, CODALEMA, Tunka-Rex, TREND

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

Le concept de GRAND

example of sub-array locations



200'000 radio antennas over 200'000 km²
~20 sub-arrays of 10'000 antennas
over favorable sites worldwide

China

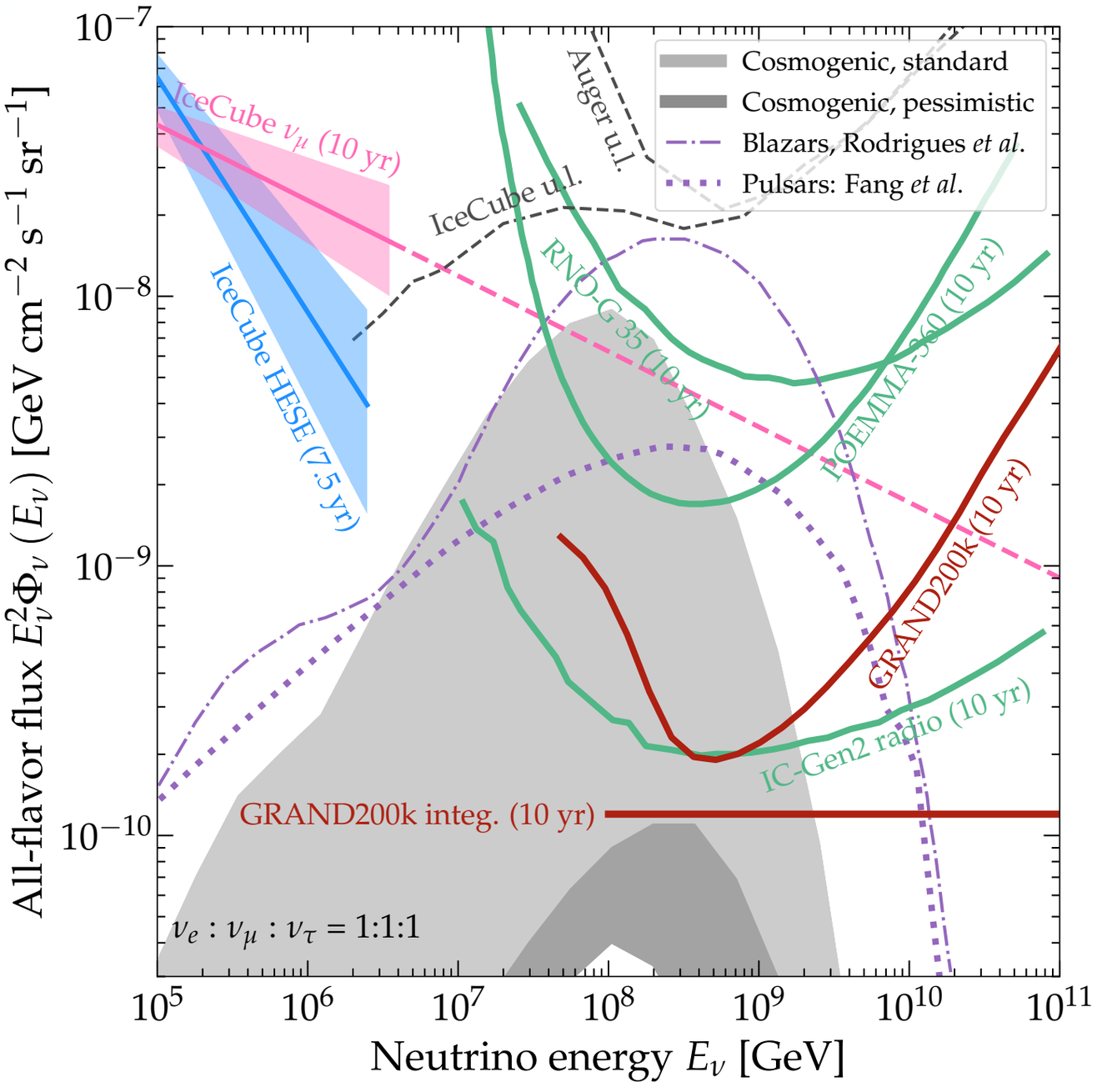
Argentina

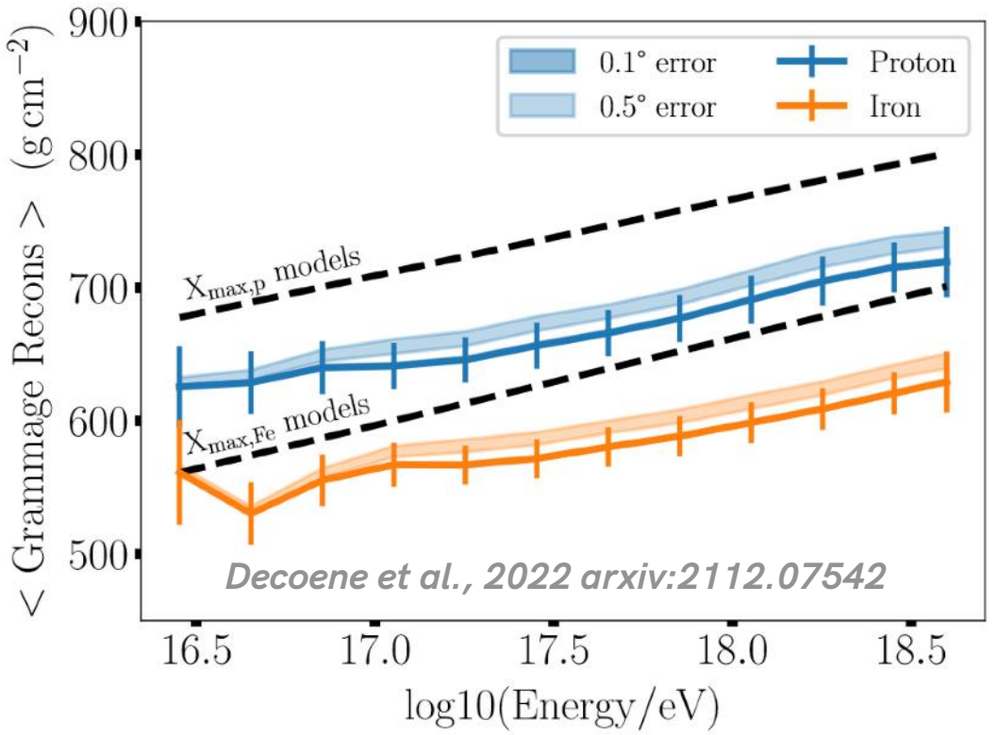
- ✓ Radio environment: radio quiet
- ✓ Topography: mountains/slopes
- ✓ Access, Installation and Maintenance
- ✓ Other issues (e.g., political)

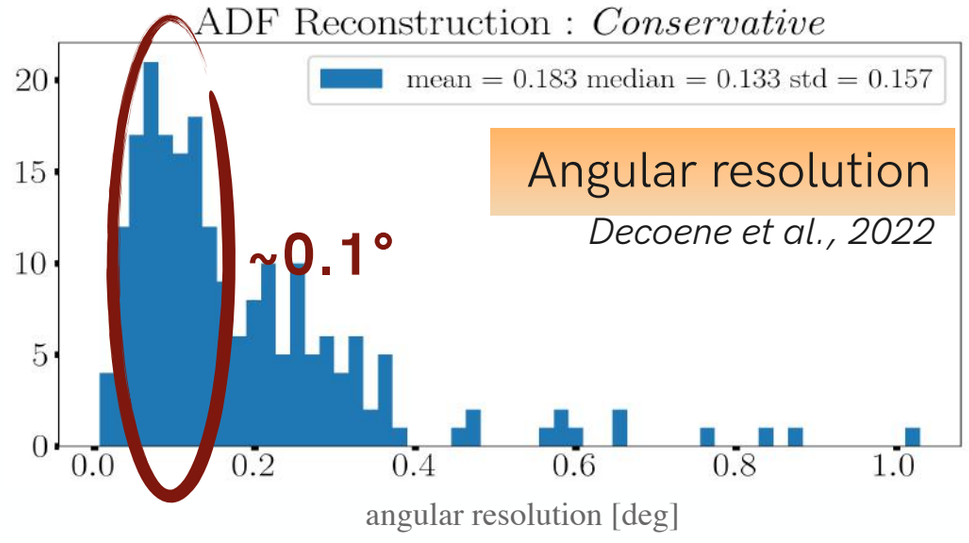
several excellent sites identified
in Argentina & China
(**~100 measurements, 14 campaigns**)

Simulated performances

GRAND Science & Design, GRAND Coll. Science China, arXiv:1810.09994







Angular resolution

Decoene et al., 2022

- **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*

The angular resolution is key for multi-messenger networks

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

2021 2025 >2030	Diff. sens. lim. in GeV cm^{-2} s^{-1} sr^{-1}	iFoV in sky %	ang. res.
PUEO	4.2×10^{-8} in …	…	<2.8°
ARA	…	…	…
RNO-G	…	…	…
ARIANNA-200	…	…	…
RET-N	…	…	…
IceCube-Gen2 Radio	4×10	…	$2^\circ\times10^\circ$
BEACON	1.2×10^{-8} in 5 yr	6	0.3°–1°
GRAND10k	1×10^{-8} in 5 yr	6	0.1°
GRAND	4×10^{-10} in 5 yr	45	0.1°
Auger	[1.5×10^{-8} (2019)]	30	<1°
TAMBO	?	27	1°
POEMMA Cerenkov	7×10^{-8} in 5 yr	0.6	0.4°
Trinity	1×10^{-10} in 5 yr	6	<1°
Ashra-NTA	2×10^{-10} in 5 yr	30	0.1°

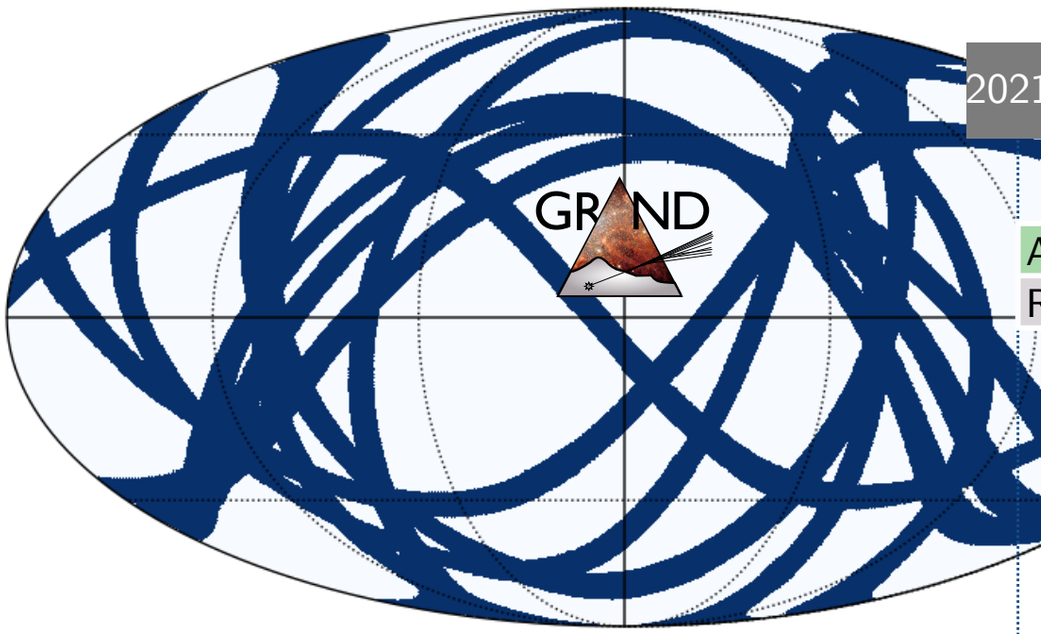
difficult to reach sub-degree resolution for in-ice instruments

adapted from ***Guépin, KK, Oikonomou, Nature Phys. Rev. 2022***

	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 deg^2	0.2°
	INTEGRAL SPI-ACS	4π	-
X	XMM-Newton	0.5°	6”
	Athena-WFI	0.4 deg^2	< 5”
multi	Swift BAT	1.4 sr	0.4°
	Swift XRT	0.1 deg^2	18”
	Swift UVOT	0.1 deg^2	2.5”
	SVOM ECLAIRs	2 sr	< 0.2°
	SVOM MXT	1 deg^2	13”
	SVOM VT	0.2 deg^2	< 1”
IR/optical/UV	ASAS-SN	72 deg^2	7.8”
	ATLAS	29 deg^2	2”
	Pan-STARRS	14 deg^2	1.0–1.3”
	ZTF	47 deg^2	2”
	Vera Rubin Obs. (LSST)	9.6 deg^2	0.7”
	MASTER-II(VWF)	8(400) deg^2	1.9” (22”)
	TAROT	4 deg^2	3.5”
	GEMINI (GMOS)	30.23’^{2}	0.07”/pix
	GTC (OSIRIS)	0.02 deg^2	0.127”/pix
	Keck (LRIS)	46.8’^{2}	0.135”/pix
	VLT (X-shooter)	2.2’^{2}	0.173”/pix
radio	VLA	0.16 deg^2	0.12”
	MWA	610 deg^2	0.9’
	SKA1(2)-MID	1(10) deg^2	0.04°–0.7°

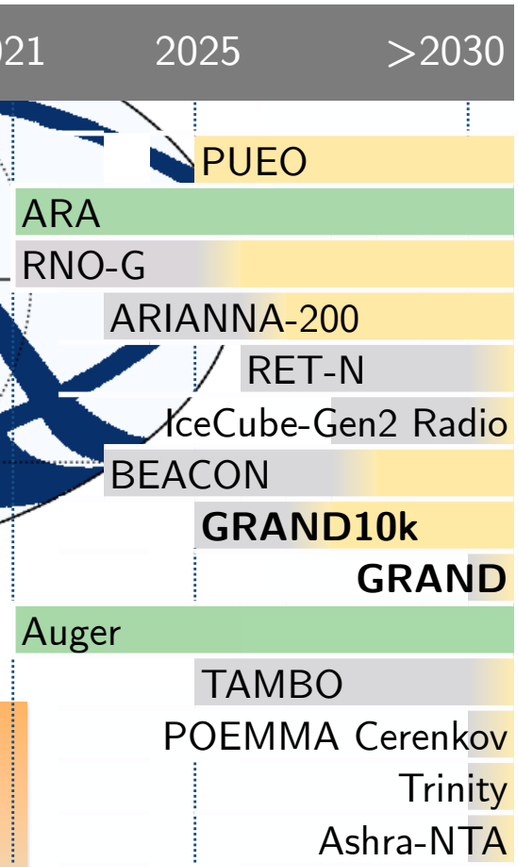
A wide **instantaneous** field of view
for more chances of spotting short transients

A wide **daily** field of view for more chances of spotting longer transients



by Foteini Oikonomou

instantaneous FoV (45% sky)
10 random* site locations



No gain from Earth rotation for South Pole instruments (but iFoV very good!)

in Ge…			…g. res.
4.2×10^{-8} in 30 d	6	19	$<2.8°$
3.6×10^{-9} (2030)	35	20	$5°$
1×10^{-8} in 5 yr	30	35	$2°\times10°$
8×10^{-9} in 5 yr	50	>50	$2.9-3.8°$
3×10^{-10} in 5 yr	50	>50	?
4×10^{-10} in 5 yr	43	43	$2°\times10°$
1.2×10^{-8} in 5 yr	6	19.5	$0.3°-1°$
1×10^{-8} in 5 yr	6	80	$0.1°$
4×10^{-10} in 5 yr	45	100	$0.1°$
[1.5×10^{-8} (2019)]	30	92.8	$<1°$
?	27	62	$1°$
7×10^{-8} in 5 yr	0.6	18–36	$0.4°$
1×10^{-10} in 5 yr	6	62	$<1°$
2×10^{-10} in 5 yr	30	>50	$0.1°$

adapted from ***Guépin, KK, Oikonomou, Nature Phys. Rev. 2022***

*uniformly spaced between 60N and 40S

impossible to reach full-sky with a single site

A rich science case

UHE neutrinos

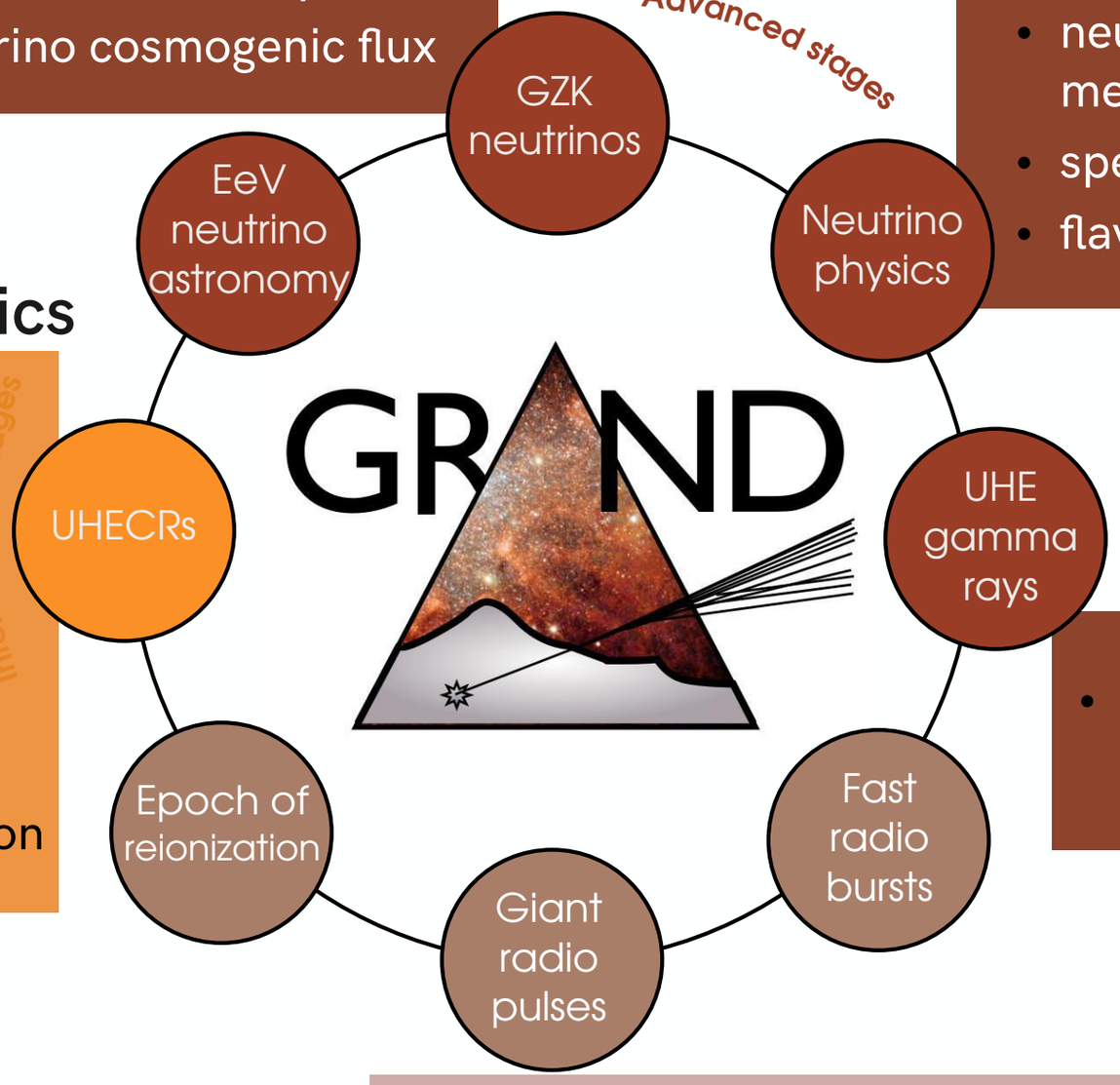
- UHE neutrino astronomy
- UHE neutrino cosmogenic flux

neutrino physics

- neutrino cross-section measurements
- spectral, angular distortions
- flavor ratios

UHECR, hadronic physics

- 20-80 times the exposure of Auger!
- GRANDProto300: transition from Galactic/ extragalactic
- hadronic physics: muon discrepancy, UHECR mass composition, p-air cross-section



UHE gamma rays

- competitive with Auger at GRANDProto300 stage

radio-astronomy in a novel way

Early stages

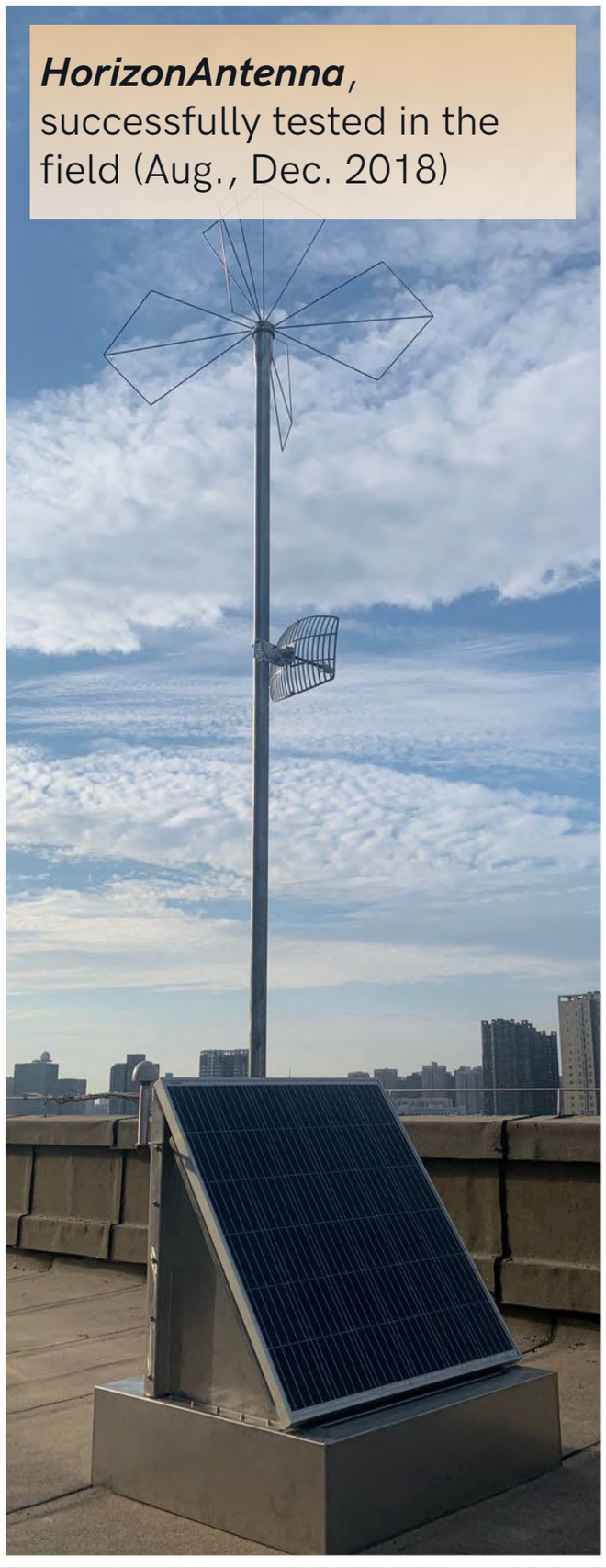
- unphased integration of signals: an almost full-sky survey of radio signals
- can detect FRBs and Giant Radio pulses of the Crab already at the GRANDProto300 stage

A staged approach with self-standing pathfinders

	Prototyping	GRAND10k	GRAND200k
	2022	2025	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-array** • **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

GRANDProto300 & other prototypes: experimental setup

HorizonAntenna, successfully tested in the field (Aug., Dec. 2018)



Deployment of 13 antennas in Gansu (China)

deployed 2 weeks ago!

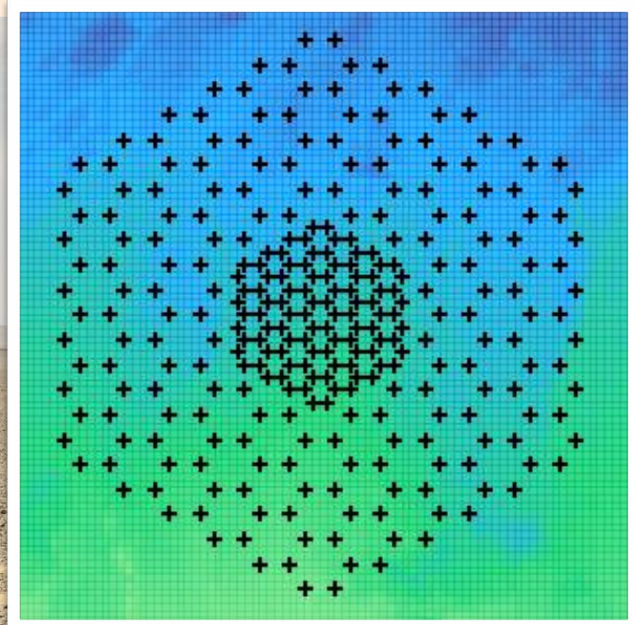
Deployment of 4 antenn this summer in Nançay radio observatory (France)
trigger testing

deployed 6 months ago!

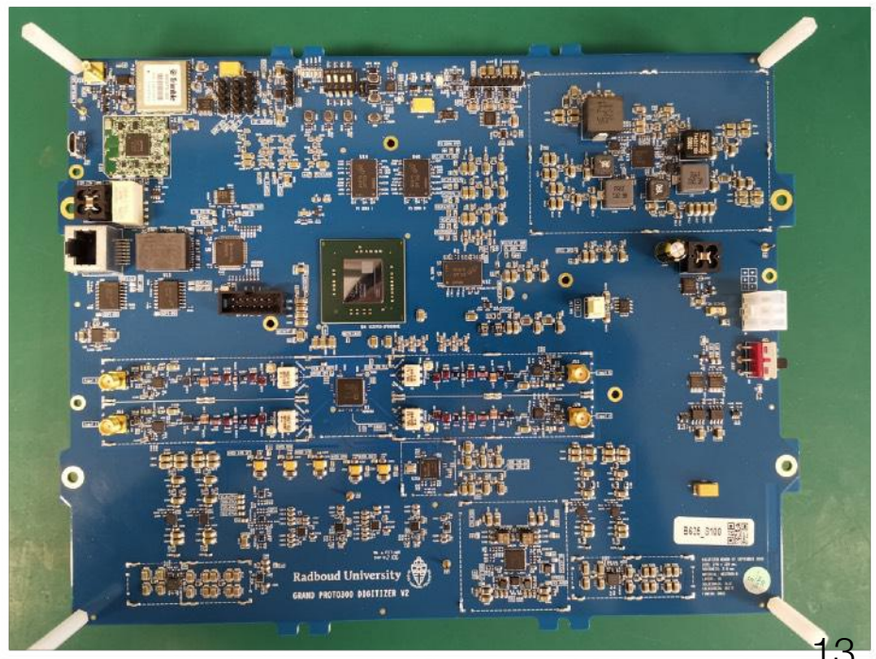
Deployment of 10 antennas on the Auger site in Malargüe, Argentina
cross-calibration

deployed last week!

Layout: 300 antennas, 200km², 1km step size with denser infill
Erange = $10^{16.5}$-10^{18}eV

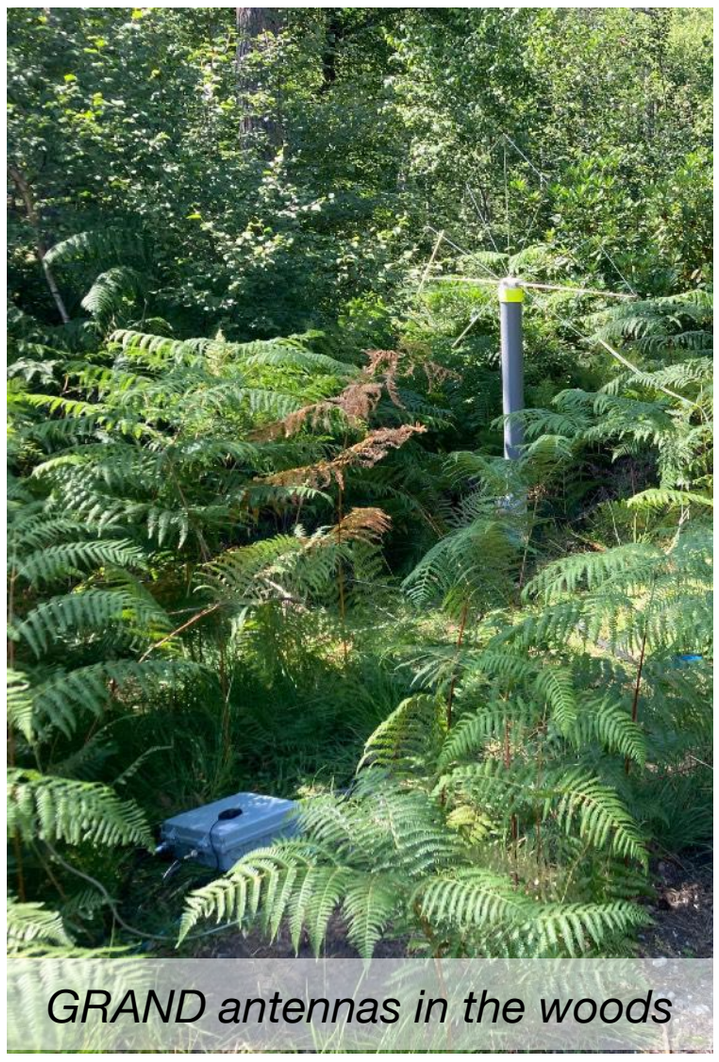


Electronics:
50-200MHz analog filtering,
500MSPS sampling
FPGA+CPU
Bullet WiFi data transfert

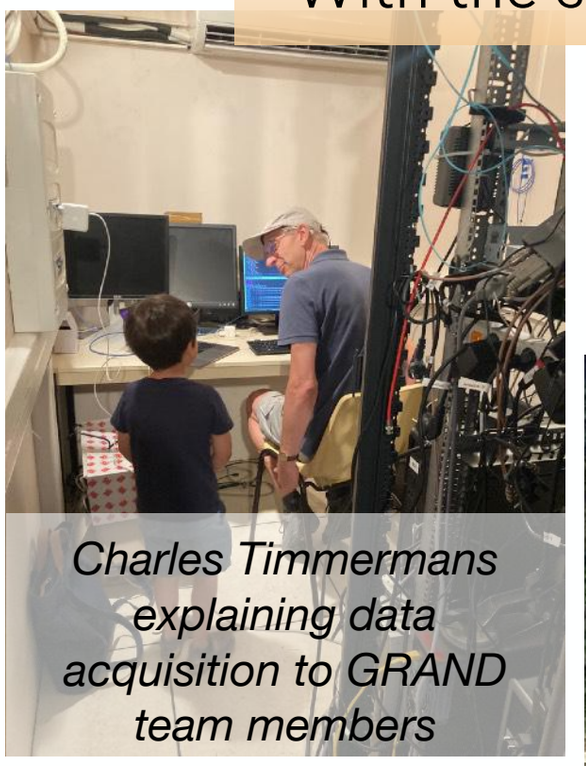


GRAND@Nançay

With the support of ANR-DFG "NUTRIG" program



GRAND antennas in the woods



Charles Timmermans explaining data acquisition to GRAND team members

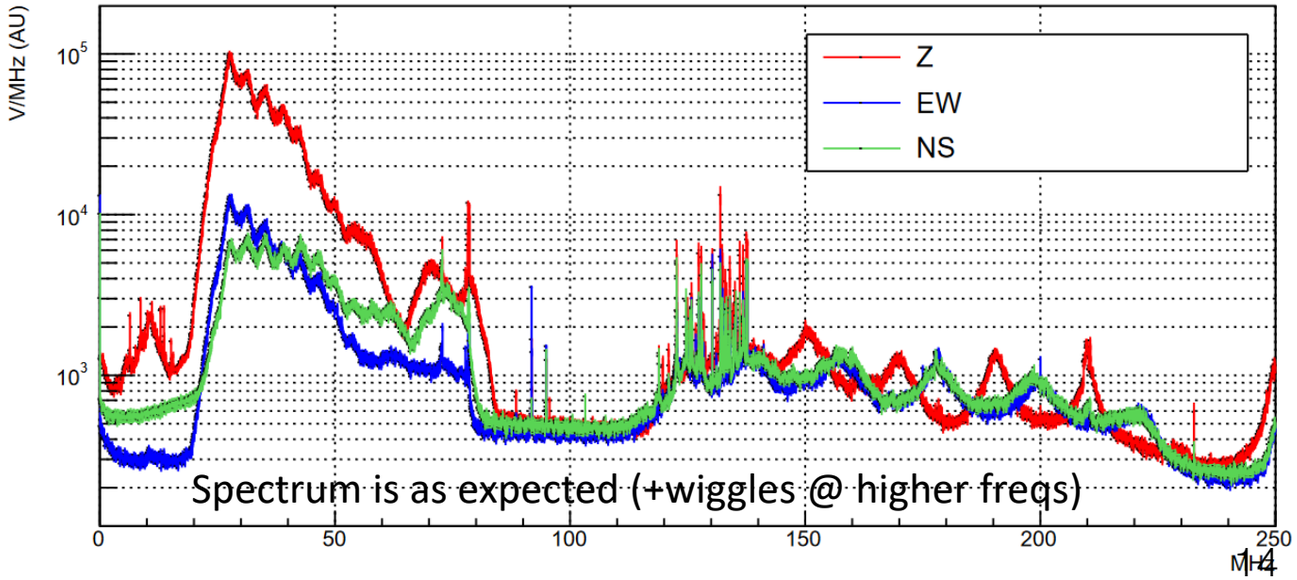
- **4 antennas deployed in Nançay!**

by LPNHE and Radboud University

- Test bench for triggering and hardware
- Currently working on lowering radiation of stations

Marion Guelfand installing cables

Pablo Correa & Olivier Martineau & a GRAND antenna



GRANDProto13 in Xiao Dushan

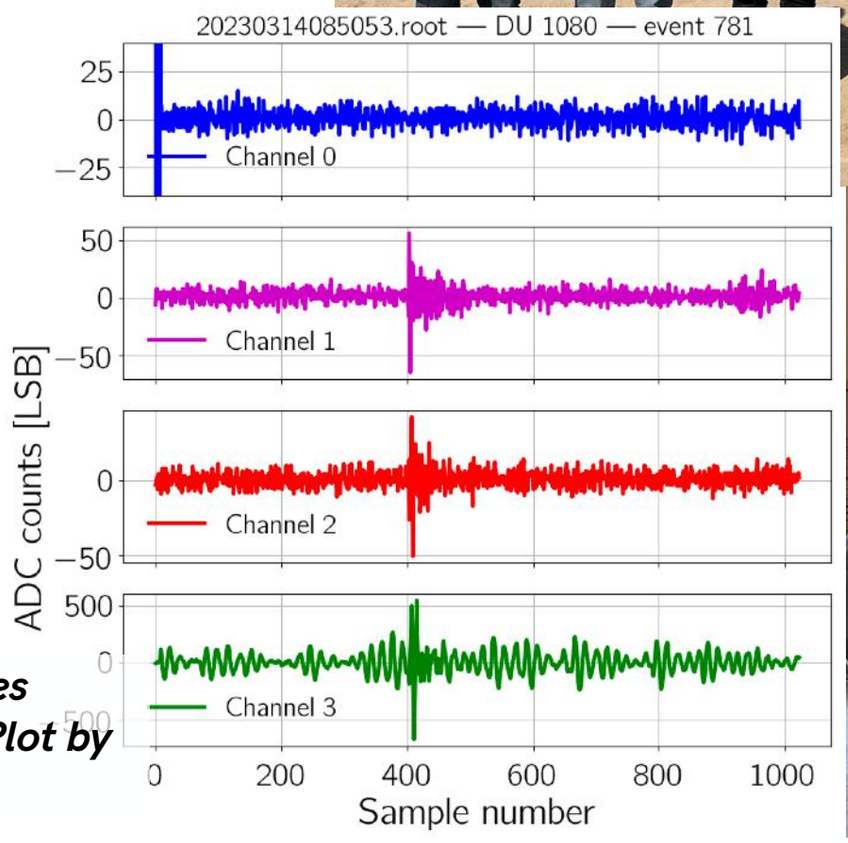
- **13 antennas deployed in Xiao Dushan!**

by Xidian U. & Purple Mountain Observatory

- Data being taken
- Data being processed/analyzed by PMO, Xidian, Paris groups

Yiren Chen, Bohao Duan, Pengxiong Ma, Pengfei Zhang, Yu tang, Shen Wang, Xiaoyuan Huang

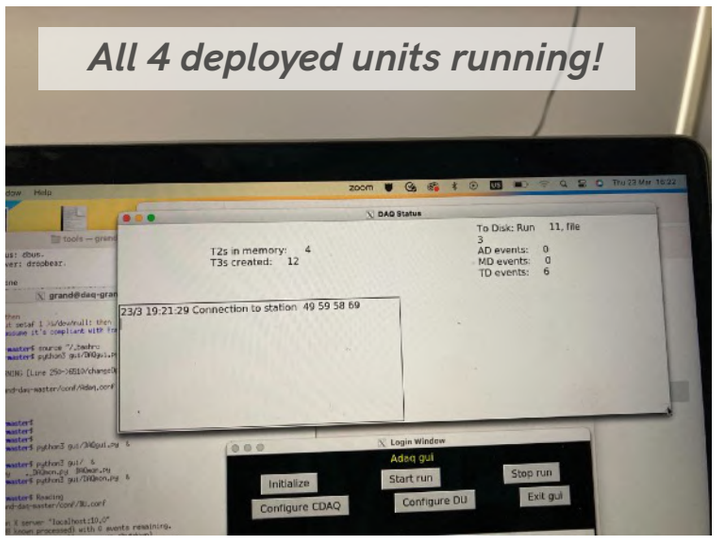
Few nice transient pulses identified in the data - Plot by Pablo Correa



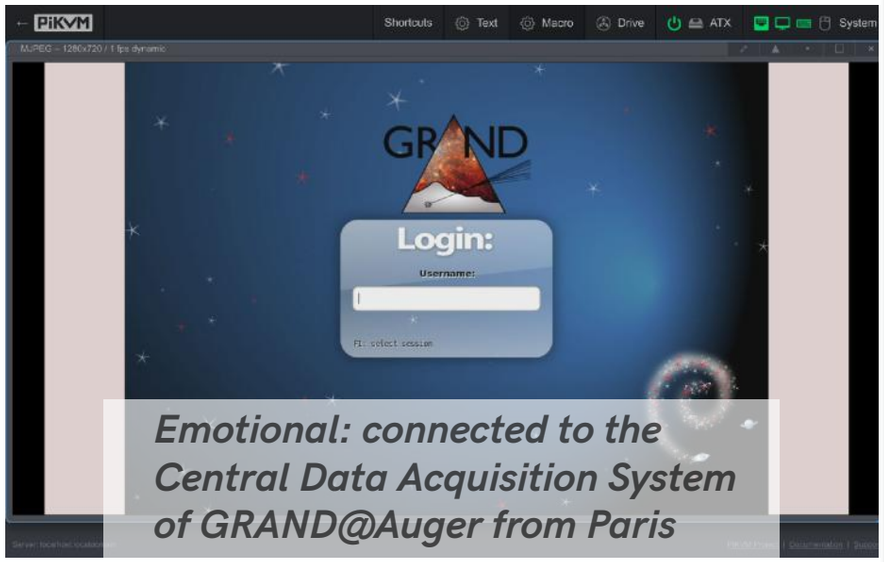
Shen Wang and Bohao Duan taking data

GRAND@Auger - Malargüe, Argentina

- **Deployment of 4 units last week** by Radboud U.
  + U. Federal do Rio de Janeiro
- Data transfer will be possible by 4G
  remote access to the Central DAQ possible

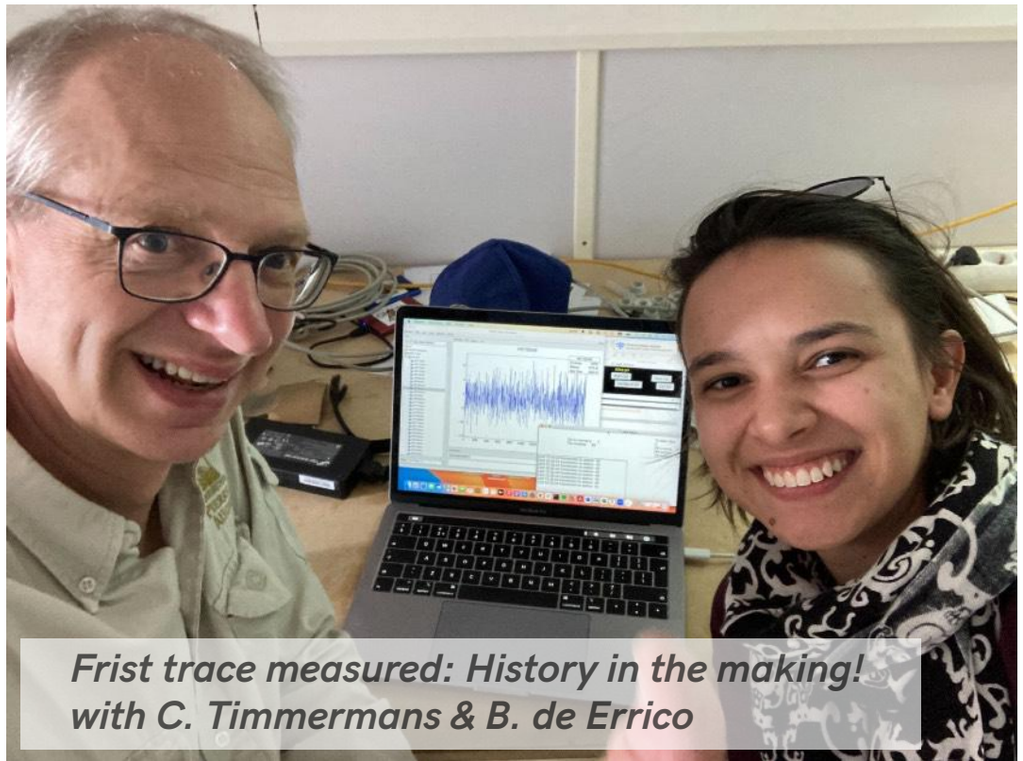


All 4 deployed units running!

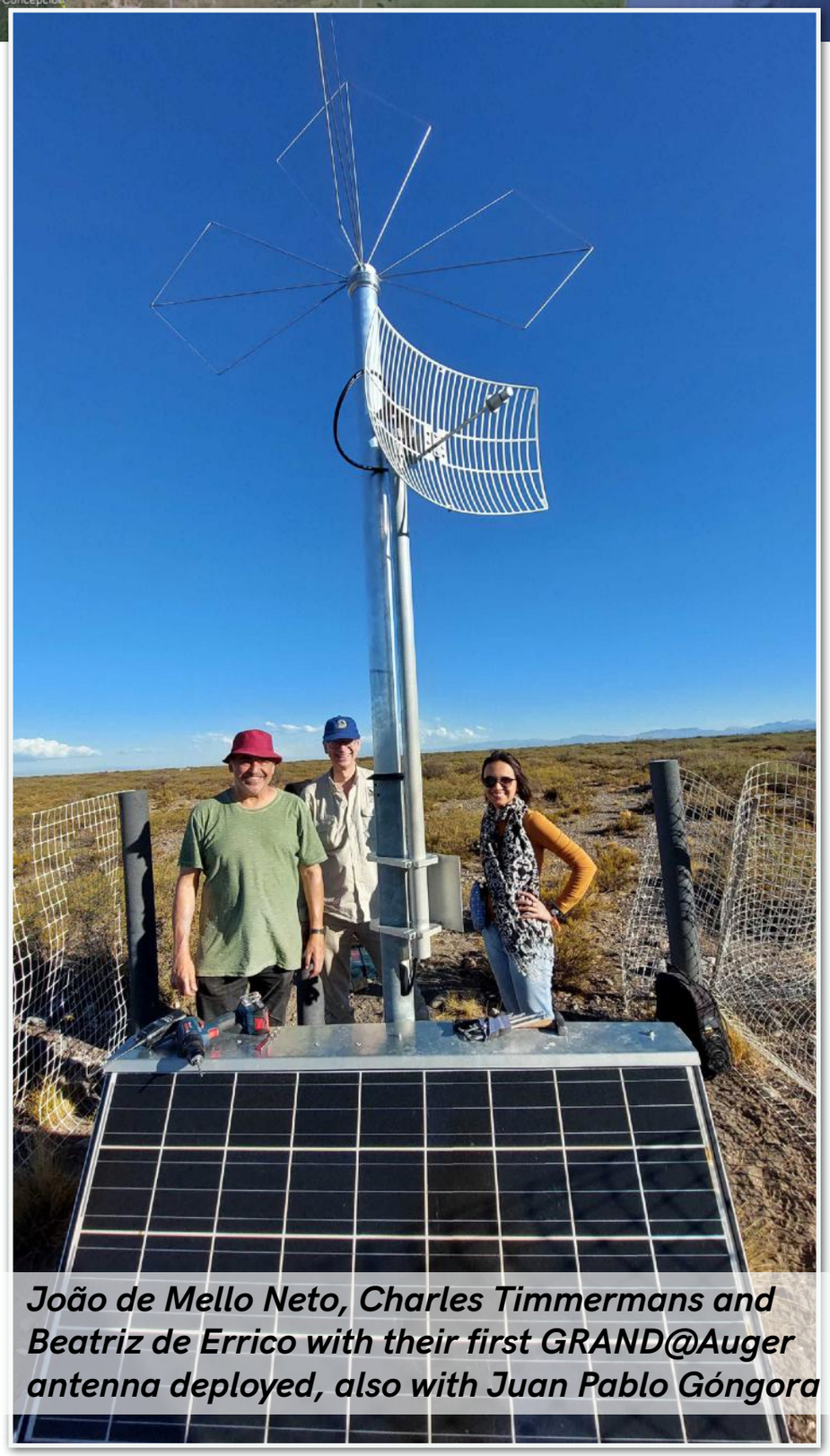


Emotional: connected to the Central Data Acquisition System of GRAND@Auger from Paris

Fred Magnard installing a PiKVM to the DAQ at IAP



Frist trace measured: History in the making! with C. Timmermans & B. de Errico



João de Mello Neto, Charles Timmermans and Beatriz de Errico with their first GRAND@Auger antenna deployed, also with Juan Pablo Góngora

GRAND@Auger: an international prototyping effort

International agreement for the GRAND@Auger project

amended *22/12/2022*

For Fundación Ahuekna

Rubén Denza, Director — Dec 14th, 2022 — date

For Institut d'Astrophysique de Paris

François Bouchet, Director — Dec 13th, 2022 — date

For Karlsruher Institut für Technologie - Institut für Astroteilchenphysik

Ralph Engel, Director — 2022 – 12 – 14 — date

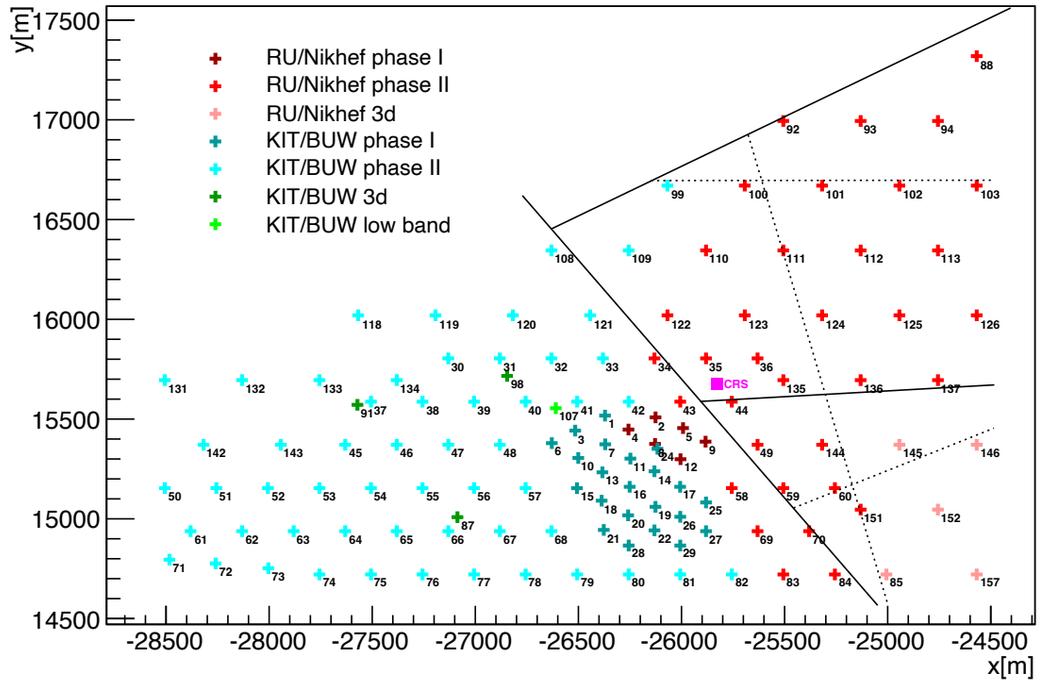
For National Astronomical Observatories, Chinese Academy of Sciences

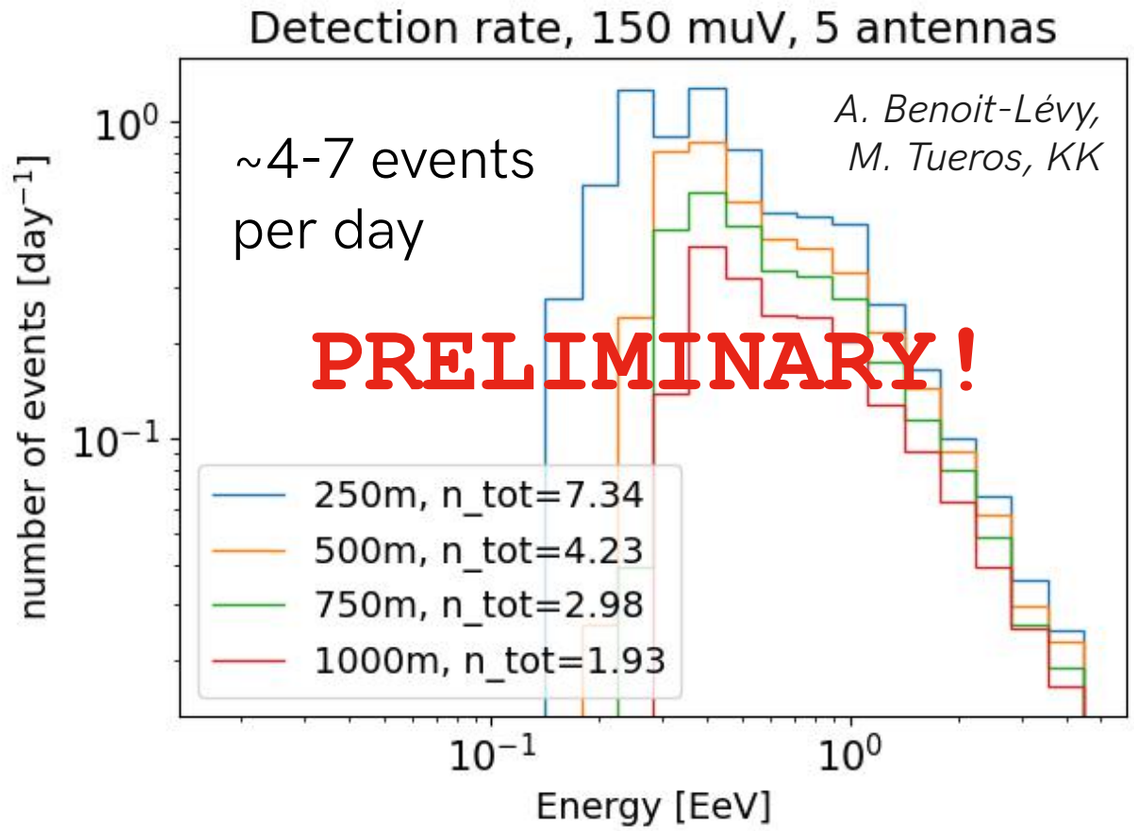
Jin Chang, Director — date

For Radboud University

Charles Timmermans, Chair of Department of High-Energy Physics — 14-12-2022 — date

Deployment at the AERA (Auger) site





GRAND in Argentina

With the support of CNRS IEA Argentina program

Deployment of 10 GRAND antennas at the Pierre Auger Observatory site

Perspectives: hosting one or more GRAND10k sites in Argentina

GRAND Technical Challenges

Autonomous trigger on radio signals

- TREND: ~32% offline identification efficiency
- Noise = ultra-dominant: rejection $1/10^8$
- Identification of signals at various trigger levels, methods to be developed *e.g., Chiche et al. 2022*
- Optimization of data collection

Reconstruction of primary particle parameters

- good performances for vertical air-showers
- no-man's land for inclined air-showers

Develop new "conventional" and machine learning methods

How to deploy/run 200k units over 200k km²?
How much will it cost? Who will pay for it?

Need for an experimental setup to test and optimize

GRAND

@Nançay
@Auger
Proto300

Industrial approach!
low failure rates
deployment ~ electric poles

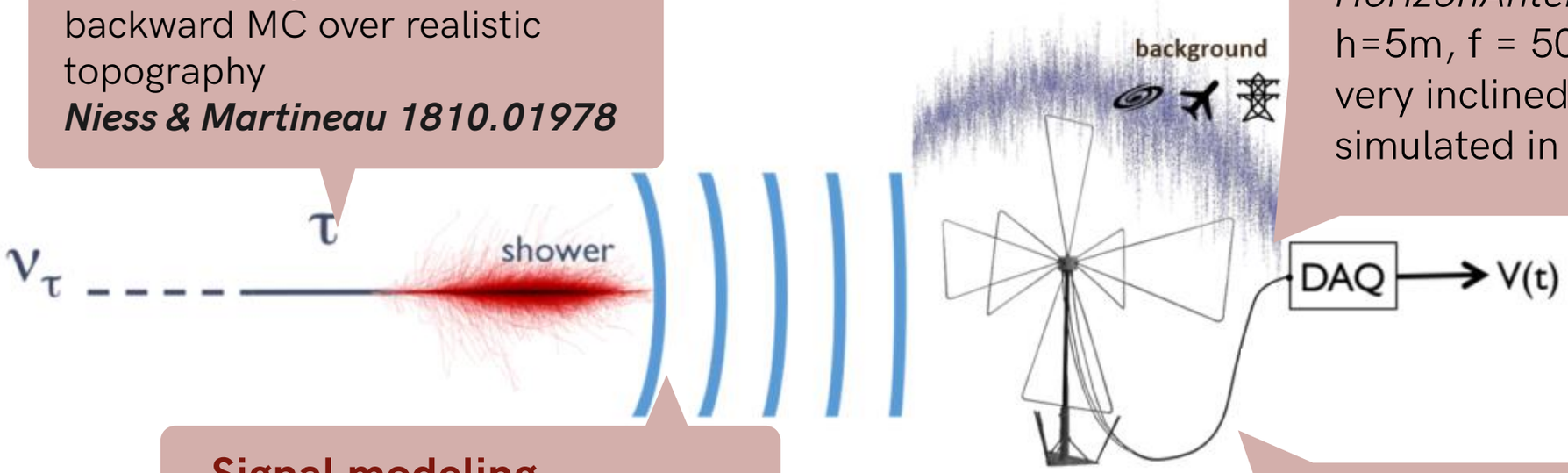
The GRAND Software

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

Developing tools to manipulate GRAND data:
- A (ROOT) file structure
- A database to manage simulations and data
- End-to-end simulation and reconstruction pipeline in development

➔ **Data challenges** to foster developments with 3 segments:
DC0 (Electric field simulations → GRAND file)
DC1 (Voltage computation)
DC2 (Electric field computation & shower reconstruction)

DANTON
ν —> τ decay
backward MC over realistic topography
Niess & Martineau 1810.01978



Antenna response

HorizonAntenna
h=5m, f = 50-200MHz, optimized for very inclined trajectories Response simulated in NEC4

Signal modeling
A. Zilles et al. 2020, 1809.04912
Chiche et al. ICRC 2021
Tueros & Zilles arXiv:2008.06454

Layout

For GP300 with/without infill, for G10k

Effects of topography ***Decoene et al. NIMA 2020***

Signal modeling & air shower reconstruction

GRANDPa team (IAP+Obs. Nice)
S. Chiche, M. Guelfand, K. Kotera, **S. Prunet**, C. Zhang et al.

IFLP (Argentina)
M. Tueros

KIT
T. Huege

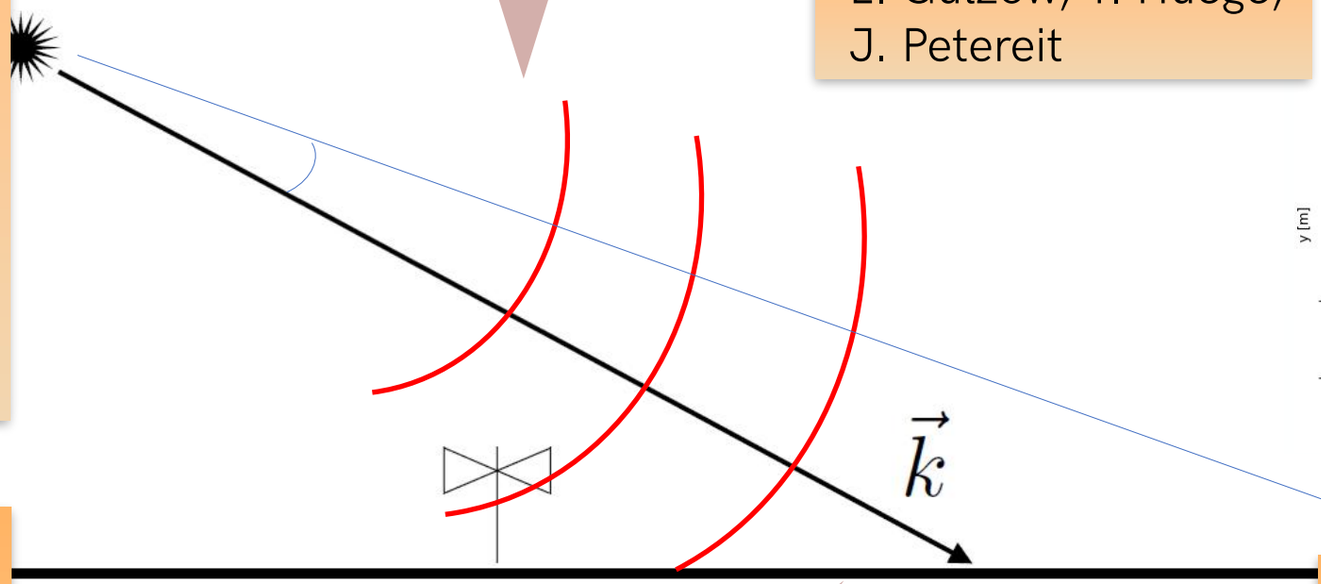
PMO
Kewen Zhang

VUB (Belgium)
K. de Vries, F. Schlüter

Radio-signal modeling (theory)

for very inclined air-showers

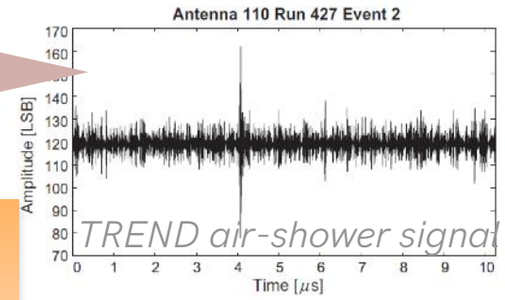
Chiche et al. 2022
Chiche, Zhang et al. in prep.
Guelfand et al. in prep.

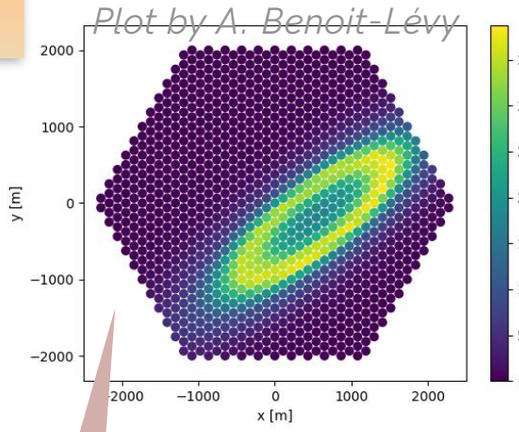


Signal modeling for triggering

within the NuTRIG project

KIT
L. Gülzow, T. Huege, J. Petereit





GRANDPa team
(LPNHE+IAP+Obs. Nice)
J.-M. Colley, **V. Decoene**, C. Guépin, E. Hivon, K. Kotera, O. Martineau, **S. Prunet**, et al.

IFLP (Argentina)
M. Tueros

PMO
K. Zhang

Rio-GRAND team
B. Lago, R. M. de Almeida

Parameter reconstruction framework

Methodology development
Decoene PhD 2020
Decoene et al. 2112.07542

Implementation for a fast code

Machine Learning methods for trigger & reconstruction

Führer, Charnock & Zilles, 2019
Le Coz ARENA 2022

GRANDPa team
(CEA-List, LPNHE)
A. Benoit-Lévy, S. Le Coz, G. Lévy, O. Martineau

Nanjing U.
R. Koirala, S. Wang

U. Chicago/LUPM
C. Guépin

Rio-GRAND team
B. Errico, B. Lago

GRAND at OCA? data analysis, signal treatment & MM opportunities

Data analysis preparation (already @OCA via Simon Prunet)

Development of data analysis pipeline

Methods and tools for air-shower parameter reconstruction

Science Case: GRANDProto300, multi-messenger for GRAND10k, with synergies with GRANDMA, SKA, LIGO-Virgo…

Triggering: GRAND@Nançay

- Developing & testing the triggering system
- Development of trigger criteria for different levels
- Instrumental/signal modeling points of views

GRAND10k R&D

- Optimisation of mechanical design
- Optimisation of power management
- Optimisation of communications & trigger
- Reconstruction of very inclined air-showers
- Trigger and shower identification

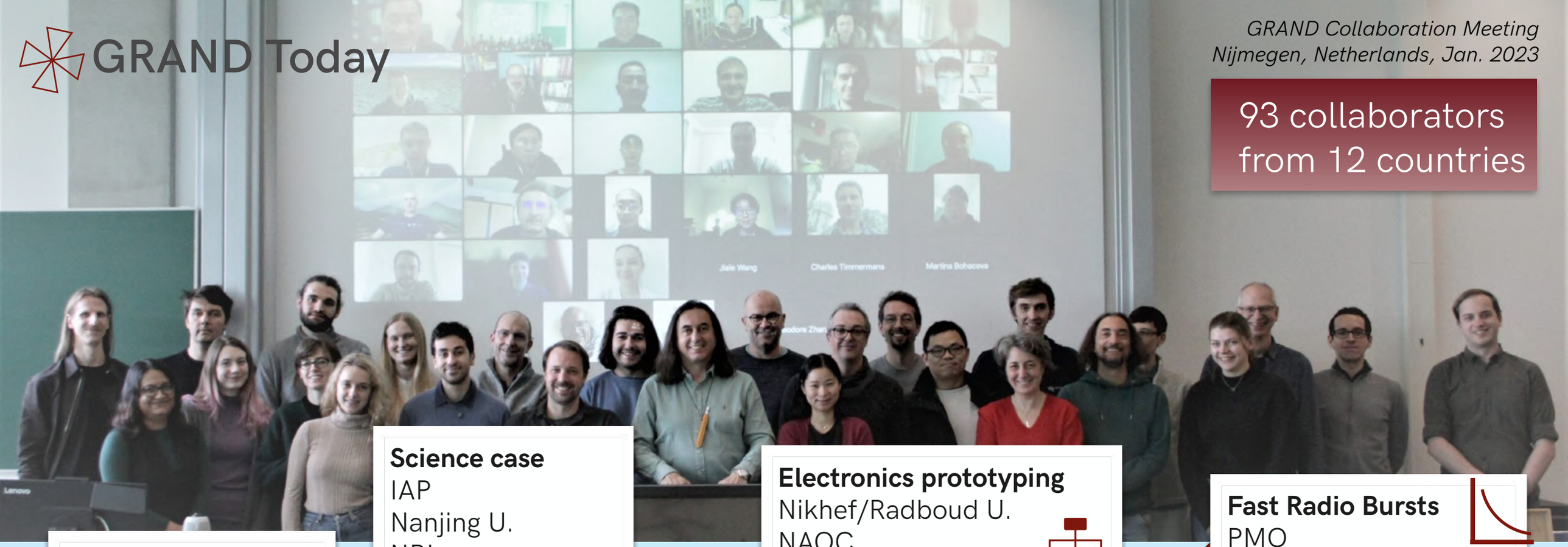
Developing multi-messenger analysis in GRAND

- Messenger discrimination
- Developing the alert system
- Chaire Professeur Junior at Sorbonne Université IAP/LPNHE on GRAND, deadline April 17th!

GRAND Today

GRAND Collaboration Meeting
Nijmegen, Netherlands, Jan. 2023

93 collaborators
from 12 countries



Particle detectors
Penn State U.

Science case
IAP
Nanjing U.
NBI
PMO
Penn State U

Electronics prototyping
Nikhef/Radboud U.
NAOC
PMO

Fast Radio Bursts
PMO
Obs. Paris/Nançay

Site management
PMO
NAOC

Simulations/data analysis
IAP
IFLP
KIT
LPNHE
Nanjing U.
PMO
UF Rio de Janeiro
VU Brussels

Software
Warsaw U.
IAP/LPNHE
LPC Clermont
UF Rio Janeiro

Antenna prototyping
Nikhef/Radboud U.
Xidian U.

Unit production
NAOC
PMO
Xidian U.

GRAND Memorandum of Understanding

Memorandum of Understanding
for the Giant Radio Array for Neutrino Detection (GRAND) Collaboration

2022 version

(ended 27/01/2022)

1. **Parties** *(listed in alphabetical order)*

committing themselves to the agreement including the full names, the names of their organisations, and their addresses

A. **Institut d'Astrophysique de Paris (IAP)**
CNRS/INSU et Sorbonne Université, 98 bis boulevard Arago, 75014 Paris, France

B. **Inter-University Institute For High Energies at the Vrije Universiteit Brussel (IIHE-VUB)**
Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

C. **Laboratoire de Physique Nucléaire et des Hautes Énergies (LPNHE)**
CNRS/IN2P3, Sorbonne Université, Université de Paris, 4 place Jussieu 75005 Paris, France

D. **Nanjing University**
163 Xianlin Avenue, 210023, Nanjing, Jiangsu, China

E. **National Astronomical Observatories, Chinese Academy of Sciences (NAOC)**
20A Datun Road, Chaoyang District, Beijing 100101, China

F. **Xidian University**
No. 2 South Taibai Road, Xi'an, Shaanxi 710071, China

For Institut d'Astrophysique de Paris (INSU/CNRS)
Nov 26th 2021
François Bouchet, Director — date

For Inter-University Institute for High Energies at the Vrije Universiteit Brussel
27 JAN 2022
Jorgen D'Hondt, Director — date

For Laboratoire de Physique Nucléaire et des Hautes Énergies (IN2P3/CNRS)
Marco ZITO Directeur du LPNHE
11/01/2022
Marco Zito, Director — date

For Nanjing University
Xiangdong Li 2021-09-29
Xiangdong Li, Director — date

For National Astronomical Observatories, Chinese Academy of Sciences
2021-11-22
Jin Chang, Director — date

For Xidian University
28/10/2021
Zongkai Yang, President — date

2023 version in progress
(13 parties)

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committing themselves to the agreement including the full names, the names of their organisations, and their addresses

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CNRS/IN2P3, Sorbonne Université, Université de Paris, 4 place Jussieu 75005 Paris, France

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163 Xianlin Avenue, 210023, Nanjing, Jiangsu, China

E. **National Astronomical Observatories, Chinese Academy of Sciences (NAOC)**
20A Datun Road, Chaoyang District, Beijing 100101, China

F. **Pennsylvania State University**
Center for Particle and Gravitational Astrophysics, Pennsylvania State University, University Park, PA 16802, USA

G. **Purple Mountain Observatory (PMO)**
Chinese Academy of Sciences (CAS), No.10 Yuanhua Road, Qixia District, Nanjing 210023, China

H. **Radboud University**
Faculty of Science, P.O. Box 9010, 6500 GL Nijmegen, Netherlands

I. **Universidade Federal do Rio de Janeiro**
Av. Pedro Calmon, 550 - Cidade Universitária, Rio de Janeiro - RJ, 21941-901, Brazil

J. **University of Warsaw**
Krakowskie Przedmieście 26/28, 00-927 Warsaw, Poland

K. **Xidian University**
No. 2 South Taibai Road, Xi'an, Shaanxi 710071, China

+ LUPM (Montpellier) + Hellenic Open University

GRAND in the international community

GRAND appears in several roadmaps

- Mid-term review of the **APPEC** strategy
- Physics briefing book: Input for the **European Strategy for Particle Physics** Update 2020, section 7.3
  http://cds.cern.ch/record/2691414
- **Nikhef** strategic plan 2017-2022 and beyond, p. 43
  https://www.nikhef.nl/strategisch-plan/
- **CNRS** Prospective INSU Astronomie & Astrophysique 2020-2025, p. 34
  https://www.insu.cnrs.fr/sites/institut_insu/files/news/2021-04/Prospective_INSU_AA_2019.pdf
- **Latin American** Strategy for Research Infrastructures for High Energy, Cosmology, Astroparticle Physics LASF4RI for HECAP https://drive.google.com/file/d/1muqdLMMQaZ-yBxFdYLPuCpOQgeSfsvtV/view
- White Paper in the **Decadal Survey** 2020, **Snowmass** 2022

Environmental responsibility

GRAND evaluates its environmental impact

One R&D goal: reduce the environmental impact of the detector

GRAND Carbon Footprint Study
arXiv:2101.02049
arxiv:2105.04610 (Nature)

References:

Website:
http://grand.cnrs.fr

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

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

GRAND Carbon Footprint Study
https://arxiv.org/abs/2101.02049

Documentary by Jean Mouette *The Road to the Neutrino*:
https://www.youtube.com/watch?v=8tDnwq8gAe4