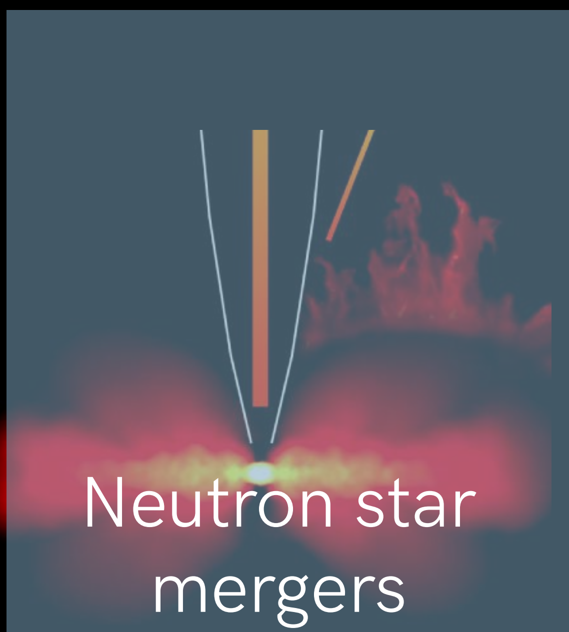
Kumiko Kotera - Institut d'Astrophysique de Paris - CNRS

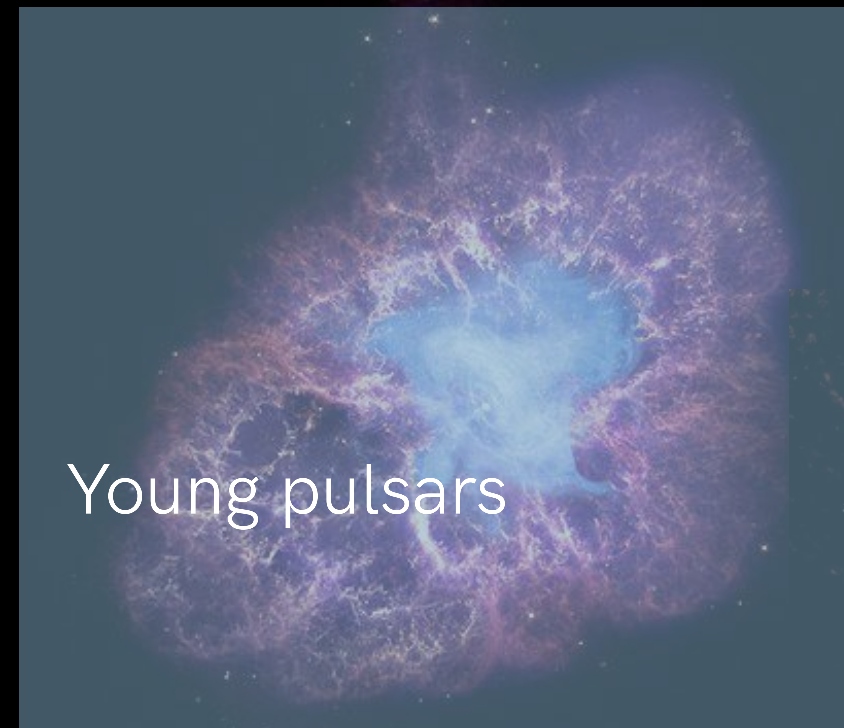
Chiba U. - 19/04/2023

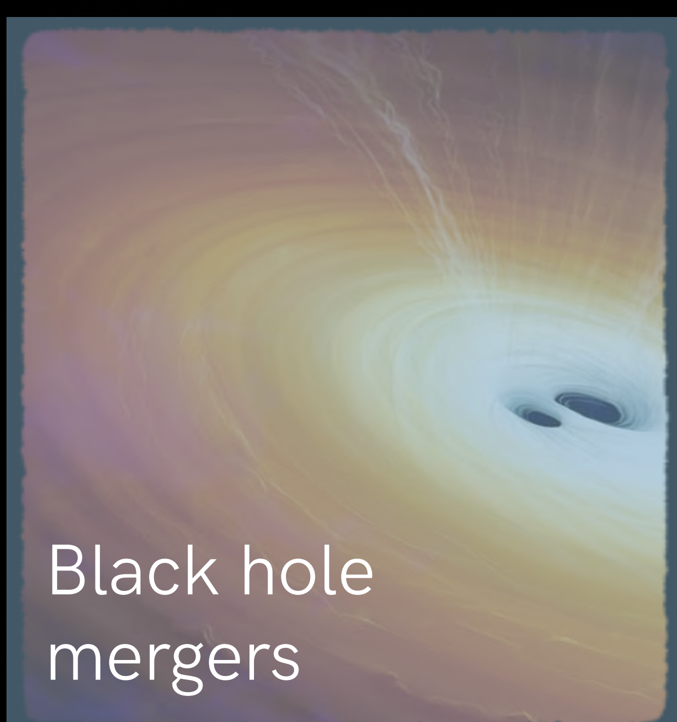
Towards EeV Neutrino Astronomy with GRAND

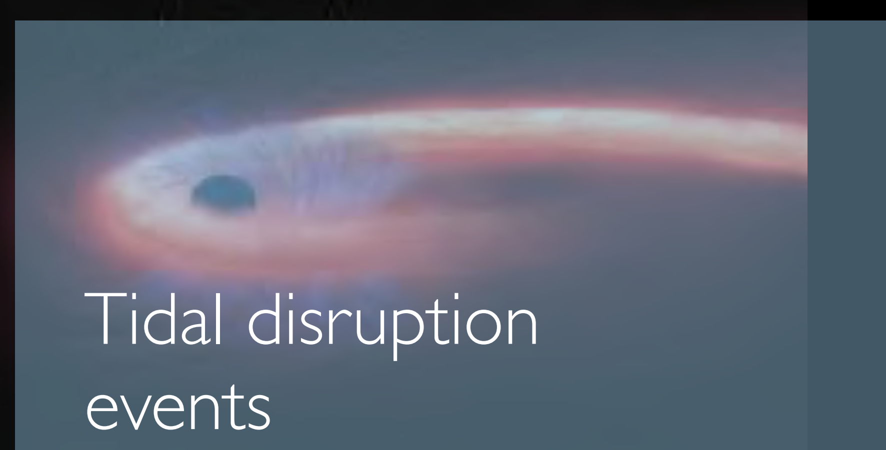
(Giant Radio Array for Neutrino Detection)

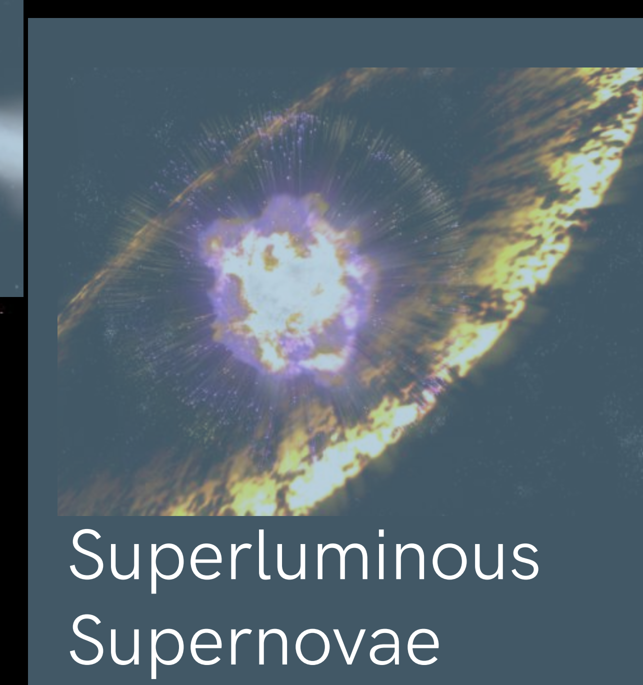
Understanding the violent Universe?



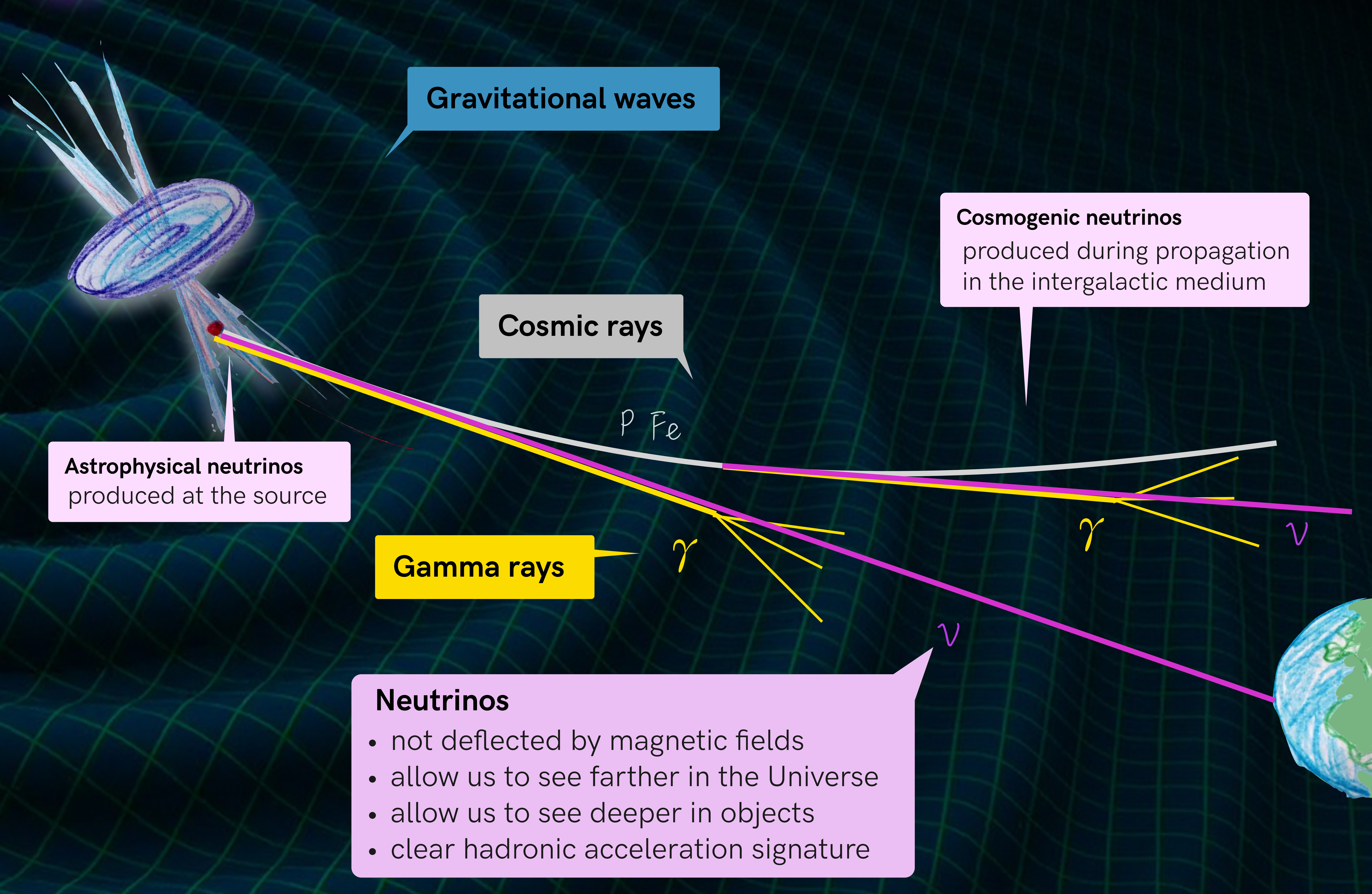




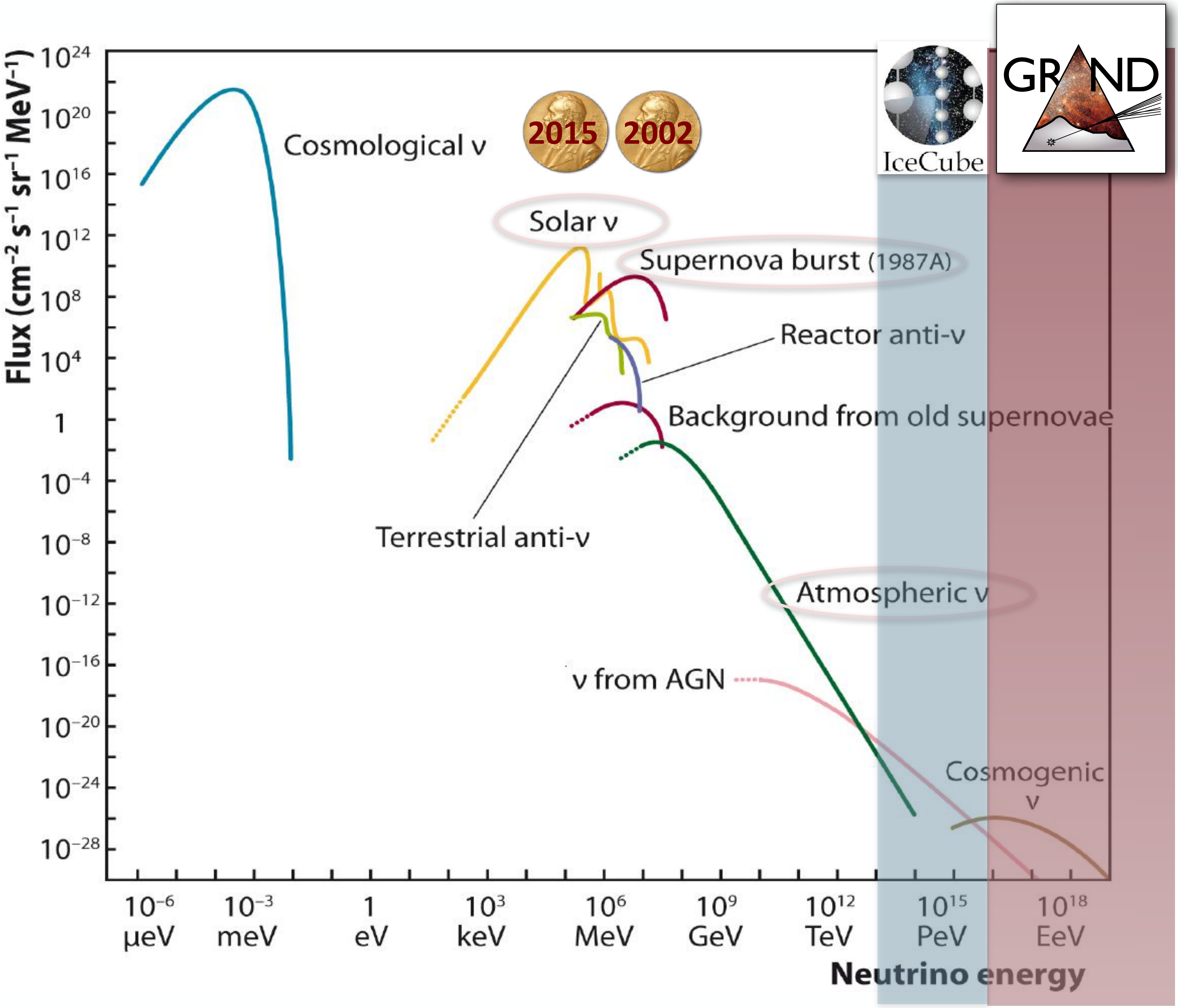




Exploring the high-energy Universe with multi-messengers



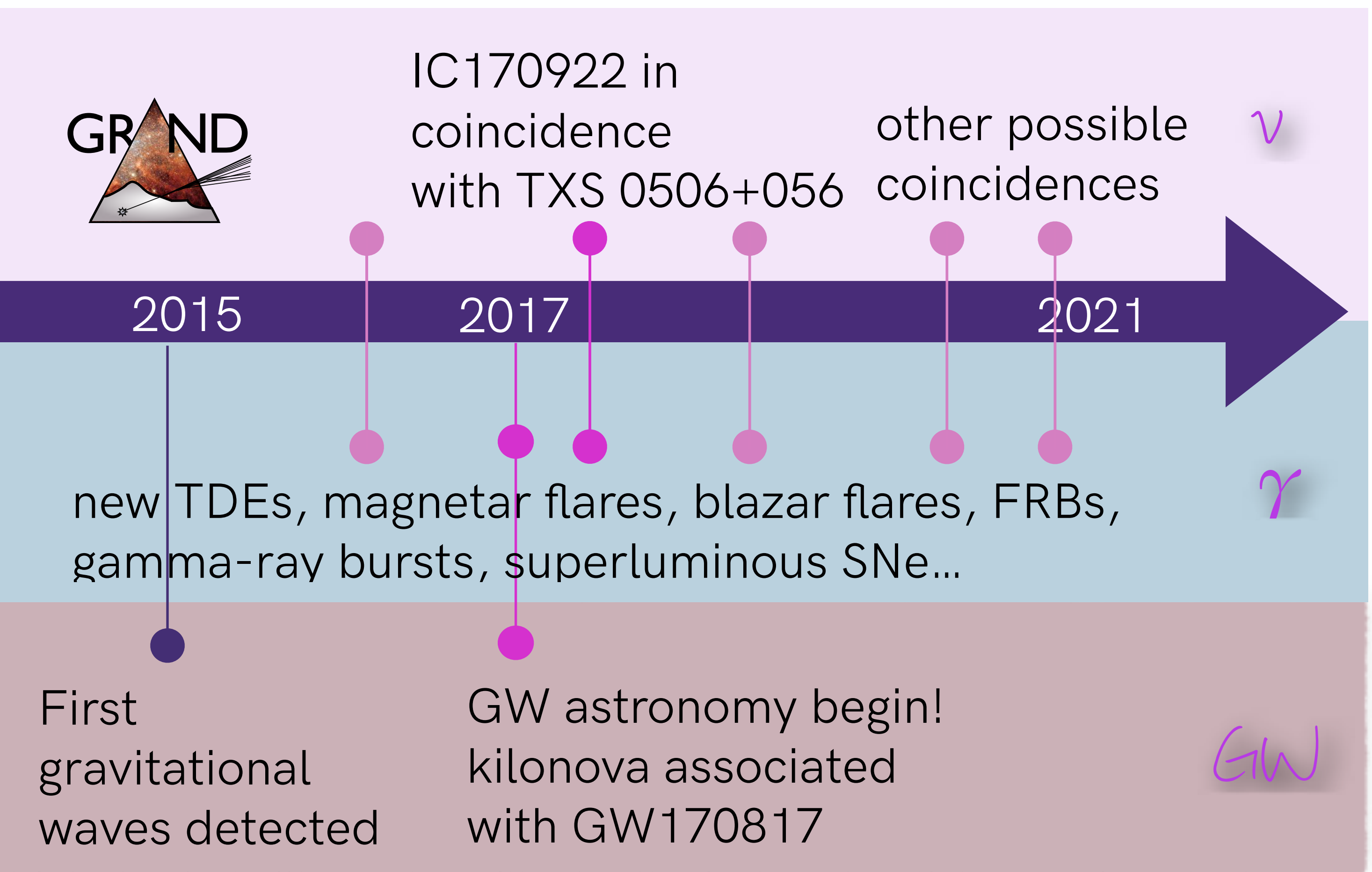
UHE neutrinos: the unchartered territory!



Evolution of UHE neutrino science case

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

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



of course very interesting, but less of a priority?

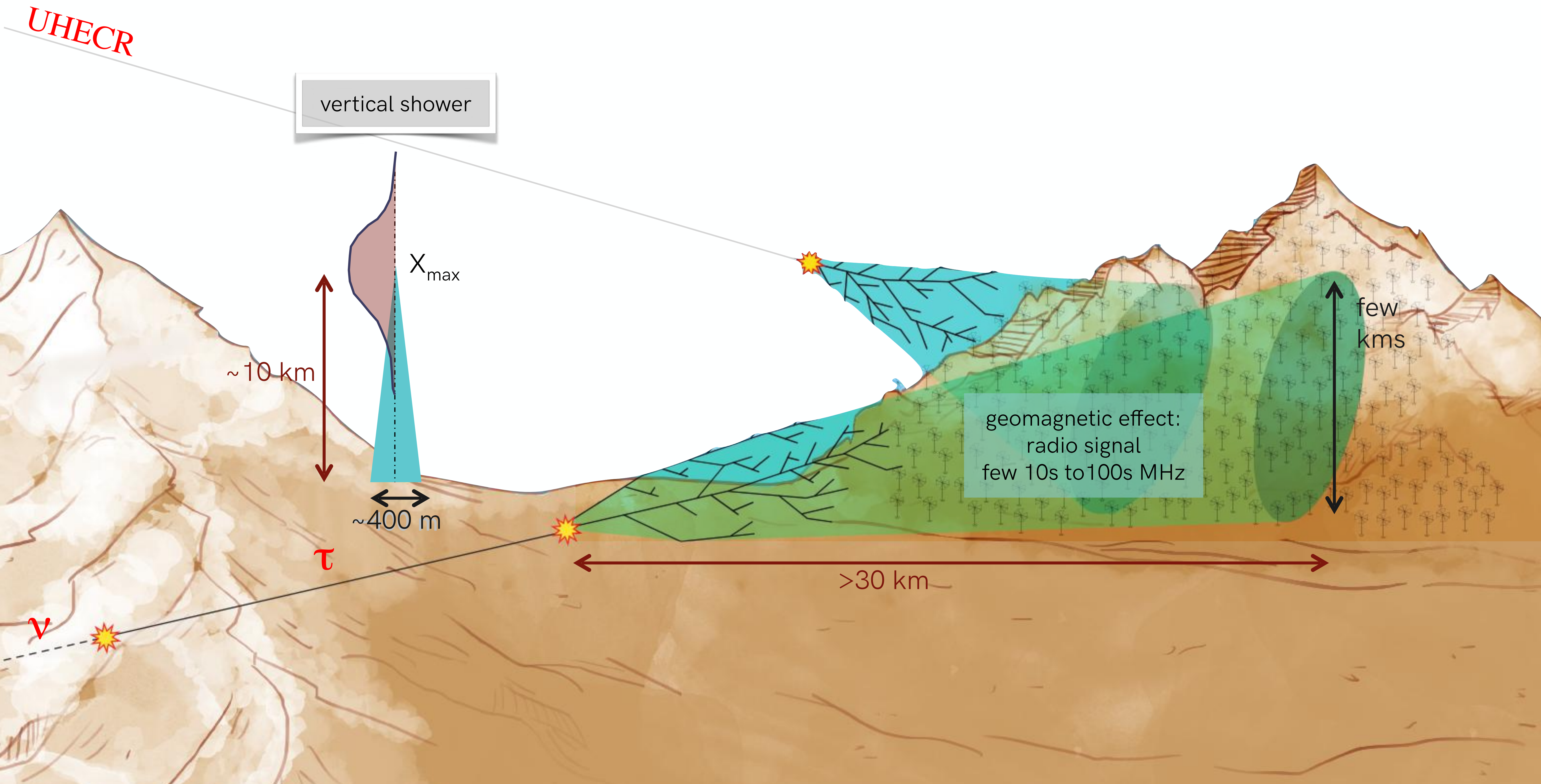
~~Let's catch the diffuse cosmogenic neutrino flux!~~

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



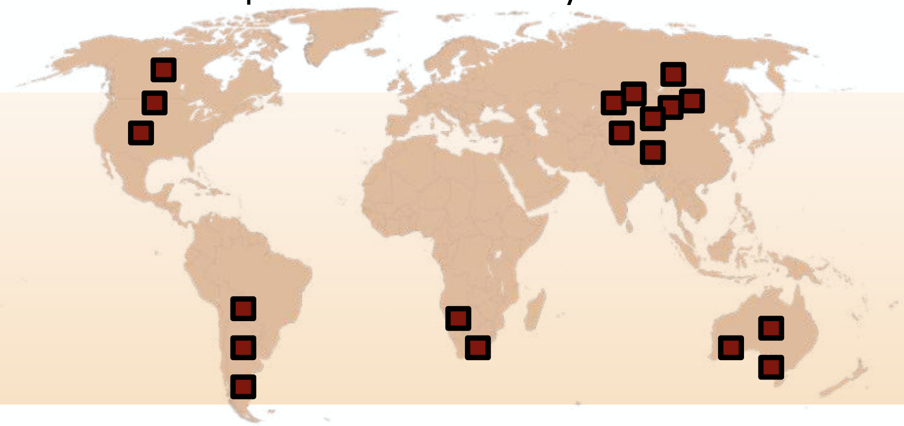
radio detection: **a mature technique**
AERA, LOFAR, CODALEMA, Tunka-Rex, TREND

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

Le concept de GRAND

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

example of sub-array locations



China

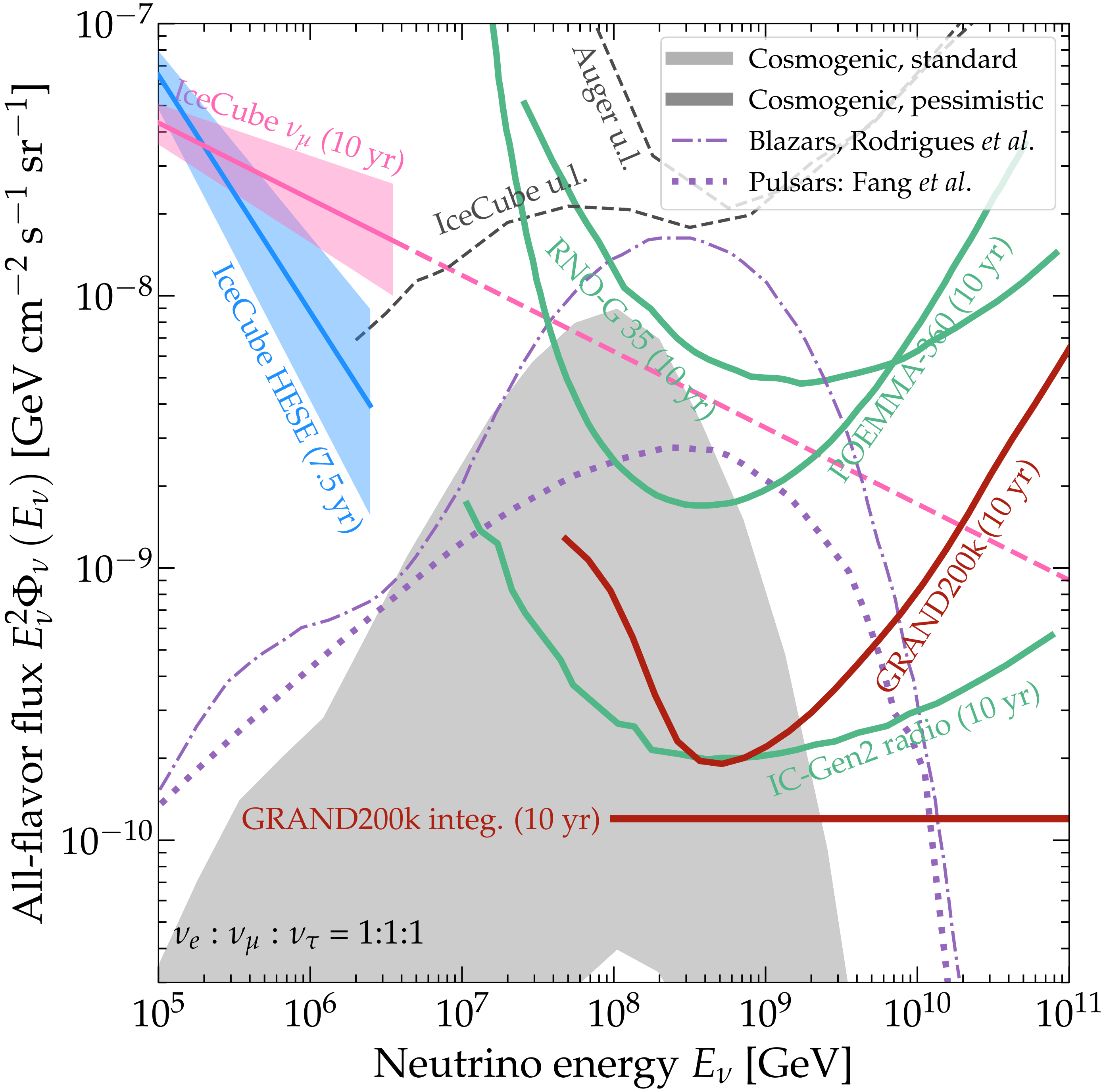
Argentina

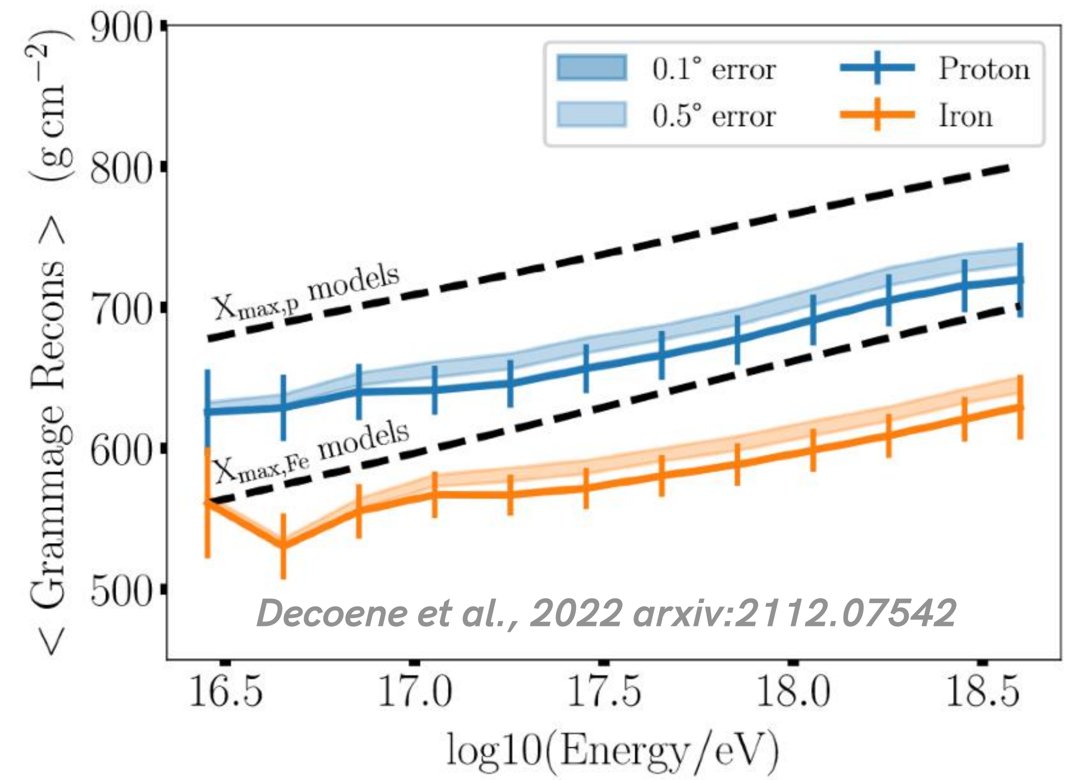
- ✓ Radio environment: radio quiet
- ✓ Topography: mountains/slopes
- ✓ Access, Installation and Maintenance
- ✓ Other issues (e.g., political)

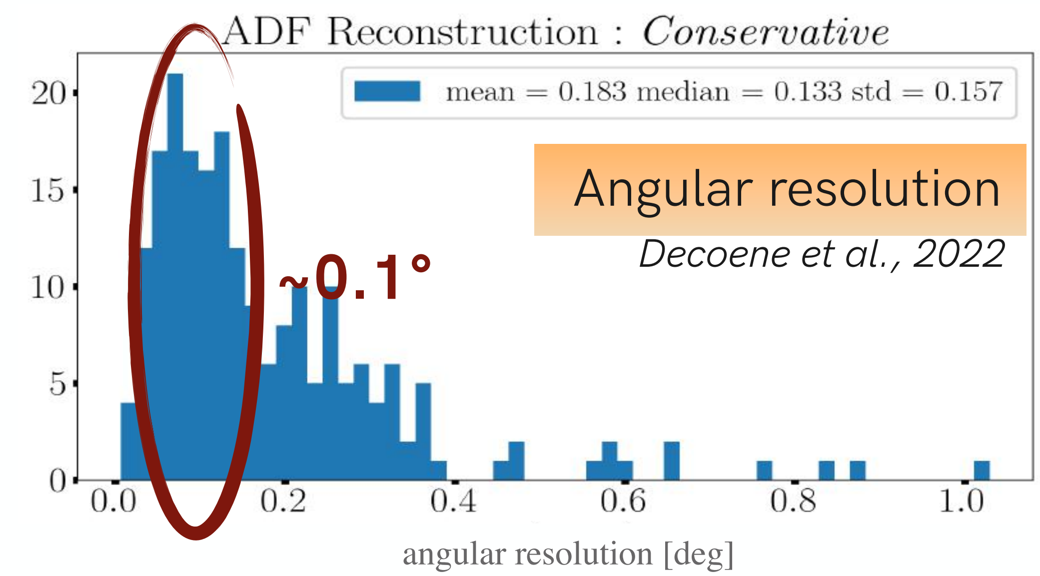
several excellent sites identified
in Argentina & China
(**~100 measurements,14 campaigns**)

Simulated performances

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







- **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

Instrument (2021 – 2025 – >2030)	Diff. sens. lim. in GeV cm^{-2} s^{-1} sr^{-1}	iFoV in sky %	ang. res.
PUEO	4.2×10^{-8} [illegible]	[illegible]	$<2.8°$
ARA	3 [illegible]	[illegible]	[illegible]
RNO-G	[illegible]	[illegible]	[illegible]
ARIANNA-200	[illegible]	[illegible]	[illegible]
RET-N	[illegible]	[illegible]	[illegible]
IceCube-Gen2 Radio	4×10 [illegible]	[illegible]	$2°\times10°$
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	$[1.5\times10^{-8}$ (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	$0.1°$

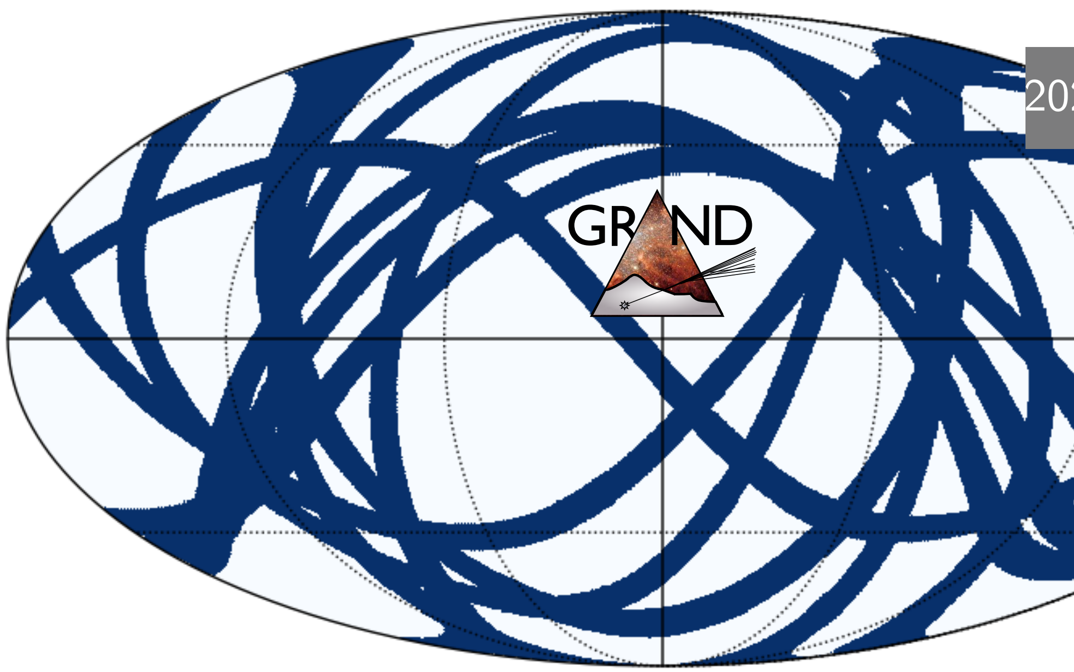
difficult to reach sub-degree resolution for in-ice instruments

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

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

*uniformly spaced between 60N and 40S

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

2021 2025 >2030	in Ge…			…ng. res.
PUEO	4.2×10^{-8} in 30 d	6	19	<2.8°
ARA	3.6×10^{-9} (2030)	35	20	5°
RNO-G	1×10^{-8} in 5 yr	30	35	2°×10°
ARIANNA-200	8×10^{-9} in 5 yr	50	>50	2.9−3.8°
RET-N	3×10^{-10} in 5 yr	50	>50	?
IceCube-Gen2 Radio	4×10^{-10} in 5 yr	43	43	2°×10°
BEACON	1.2×10^{-8} in 5 yr	6	19.5	0.3°−1°
GRAND10k	1×10^{-8} in 5 yr	6	80	0.1°
GRAND	4×10^{-10} in 5 yr	45	100	0.1°
Auger	[1.5×10^{-8} (2019)]	30	92.8	<1°
TAMBO	?	27	62	1°
POEMMA Cerenkov	7×10^{-8} in 5 yr	0.6	18−36	0.4°
Trinity	1×10^{-10} in 5 yr	6	62	<1°
Ashra-NTA	2×10^{-10} in 5 yr	30	>50	0.1°

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

impossible to reach full-sky with a single site

A rich science case

UHE neutrinos

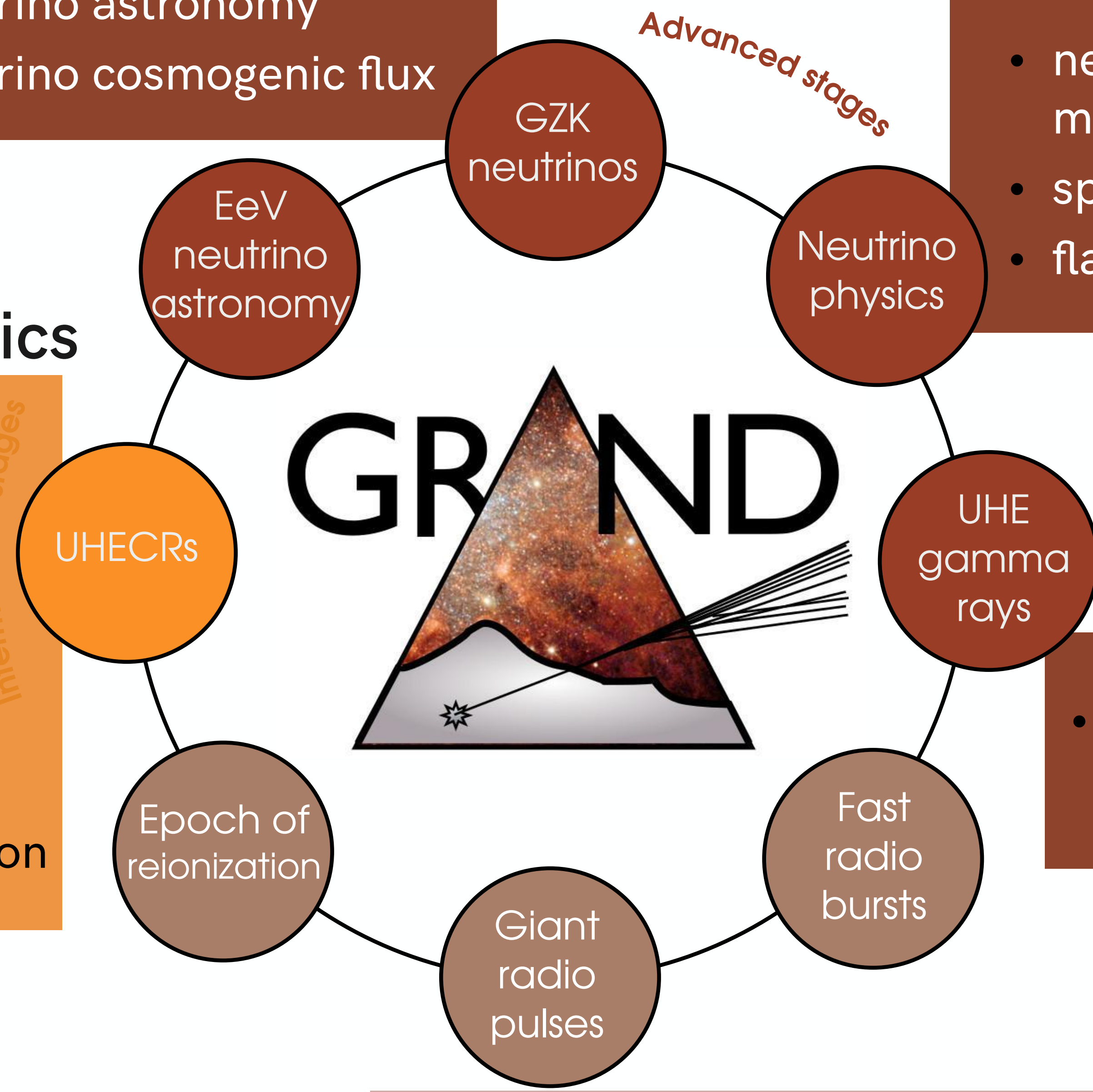
- UHE neutrino astronomy
- UHE neutrino cosmogenic flux

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

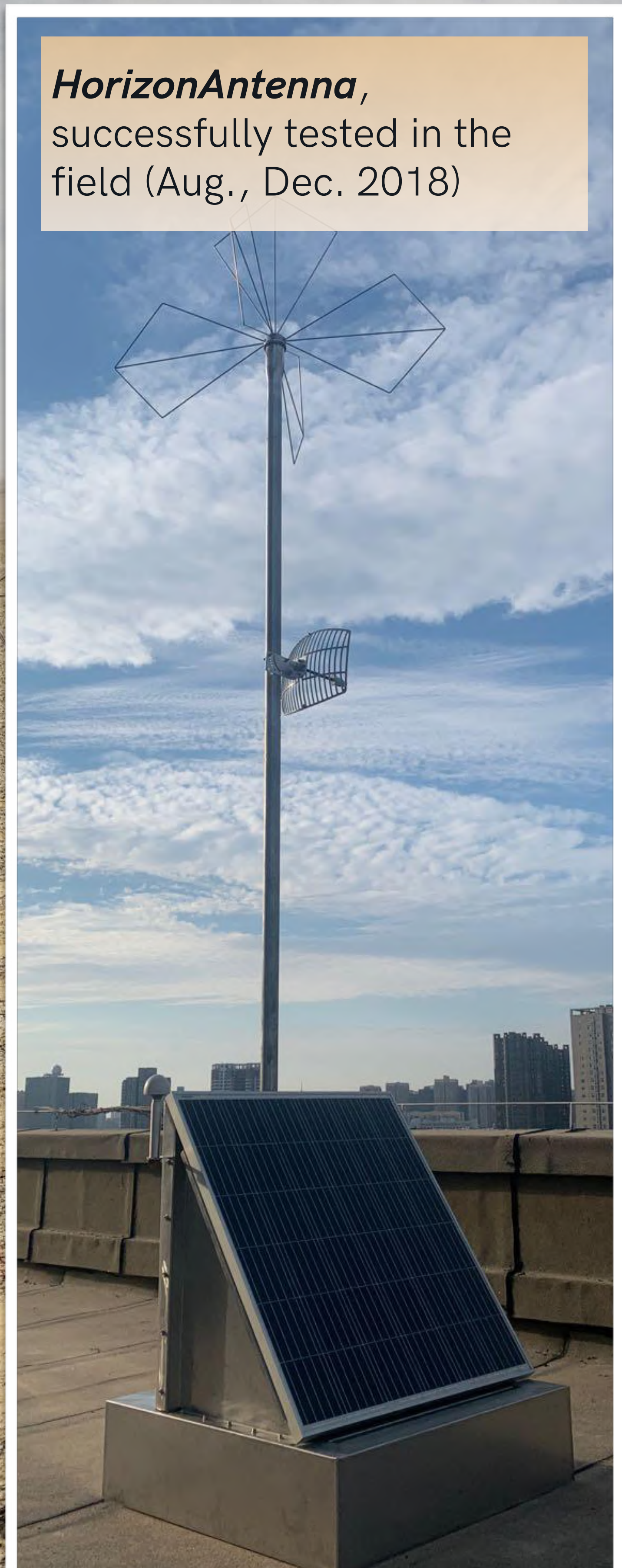
- unphased integration of signals: an almost full-sky survey of radio signals
- can detect FRBs and Giant Radio pulses of the Crab already at the GRANDProto300 stage

A staged approach **with self-standing pathfinders**

	Prototyping	GRAND10k	GRAND200k
	2022	2025	203X
Goals	**autonomous** radio detection of **very inclined** air-showers **cosmic rays $10^{16.5-18}$ 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 km^2	• 10,000 radio antennas over 10,000 km^2	• 200,000 antennas over 200,000 km^2 • 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 month ago!

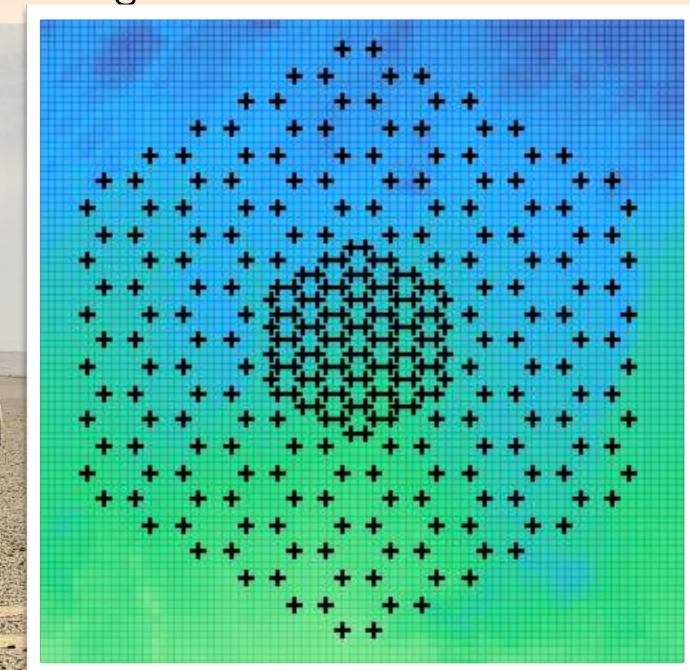
Deployment of 4 antenna this summer in Nançay radio observatory (France)
trigger testing

deployed 6 months ago!

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

deployed 3 weeks ago!

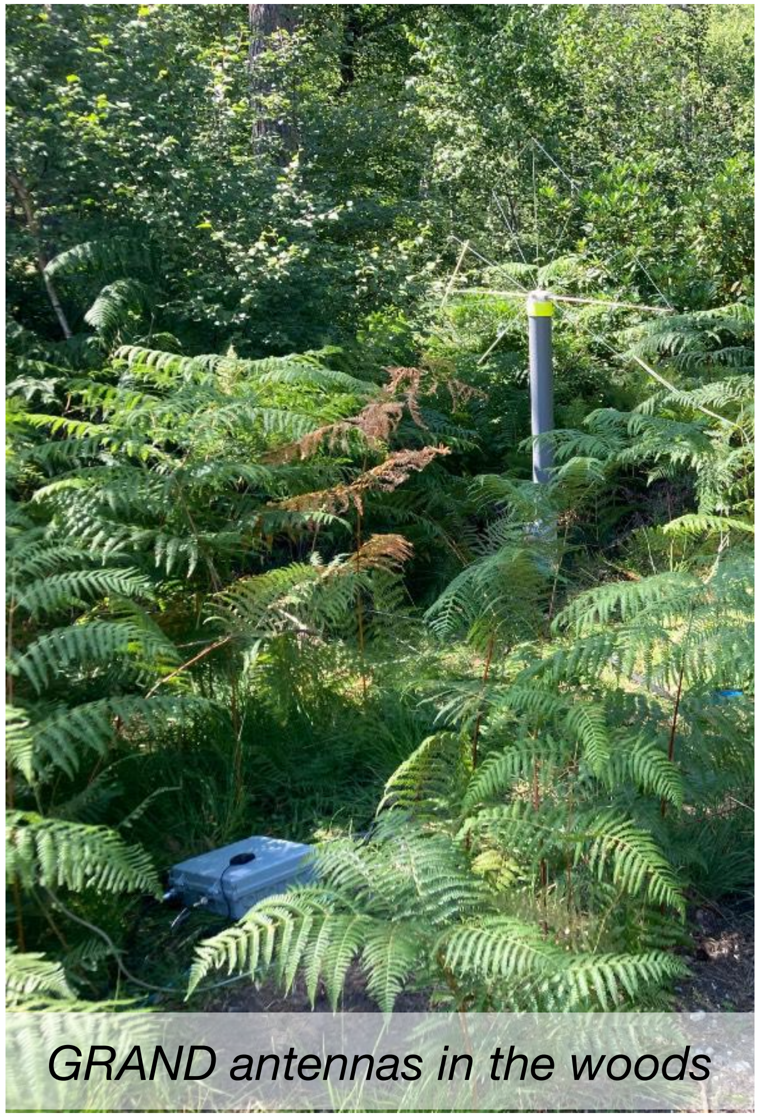
Layout: 300 antennas, 200km², 1km step size with denser infill
Erange = $10^{16.5}$-10^{18}eV

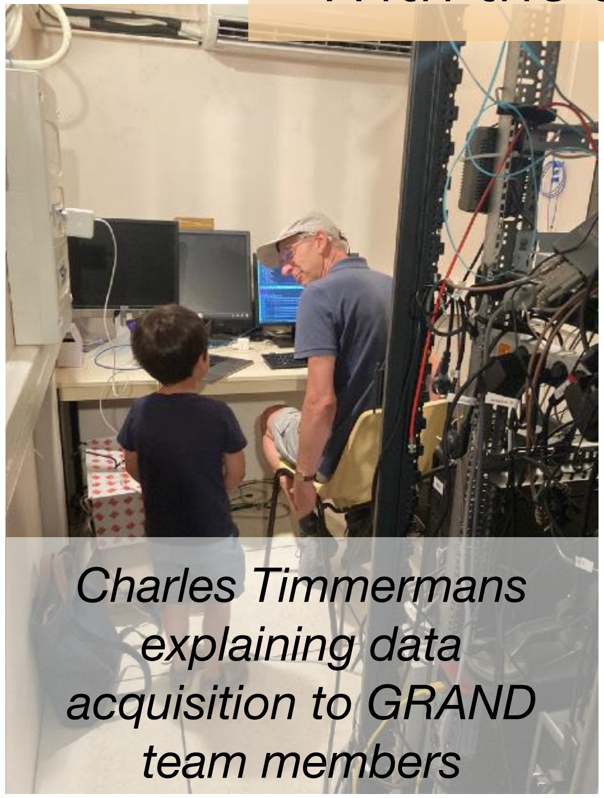


Electronics:
50-200MHz analog filtering,
500MSPS sampling
FPGA+CPU
Bullet WiFi data transfert

GRAND@Nançay

With the support of ANR-DFG "NUTRIG" program

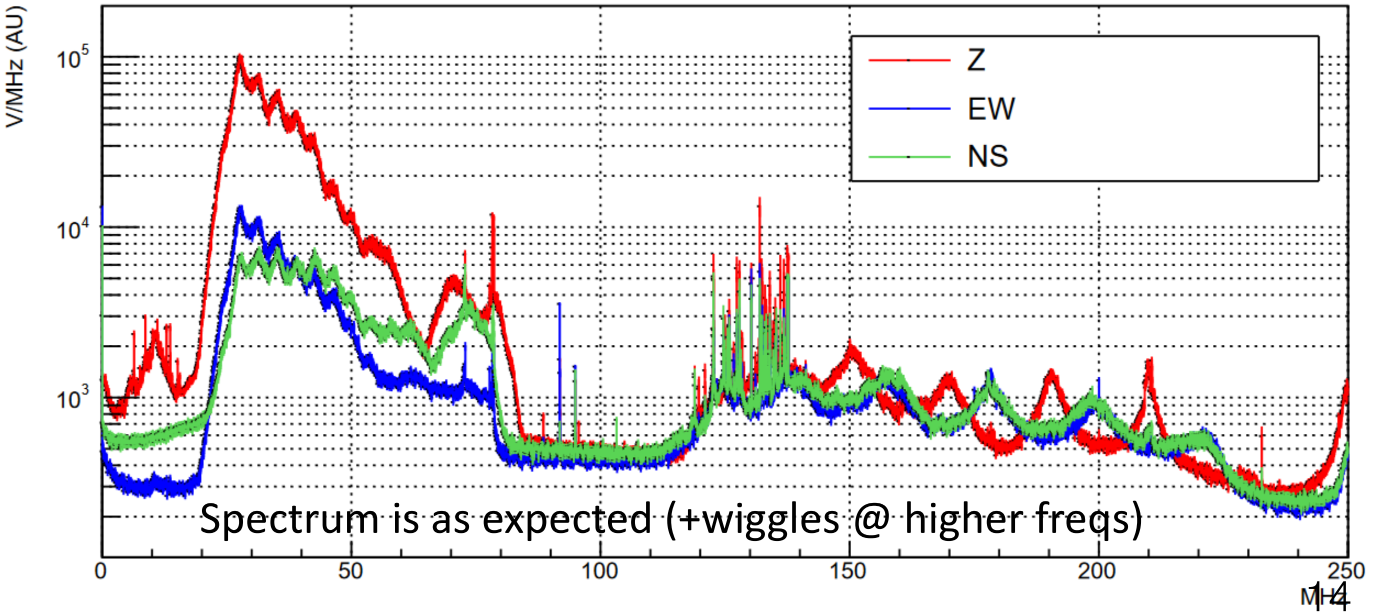

GRAND antennas in the woods


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

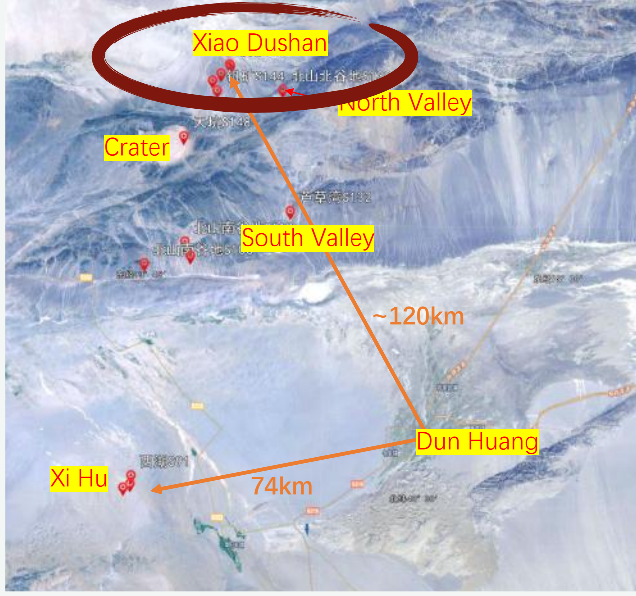


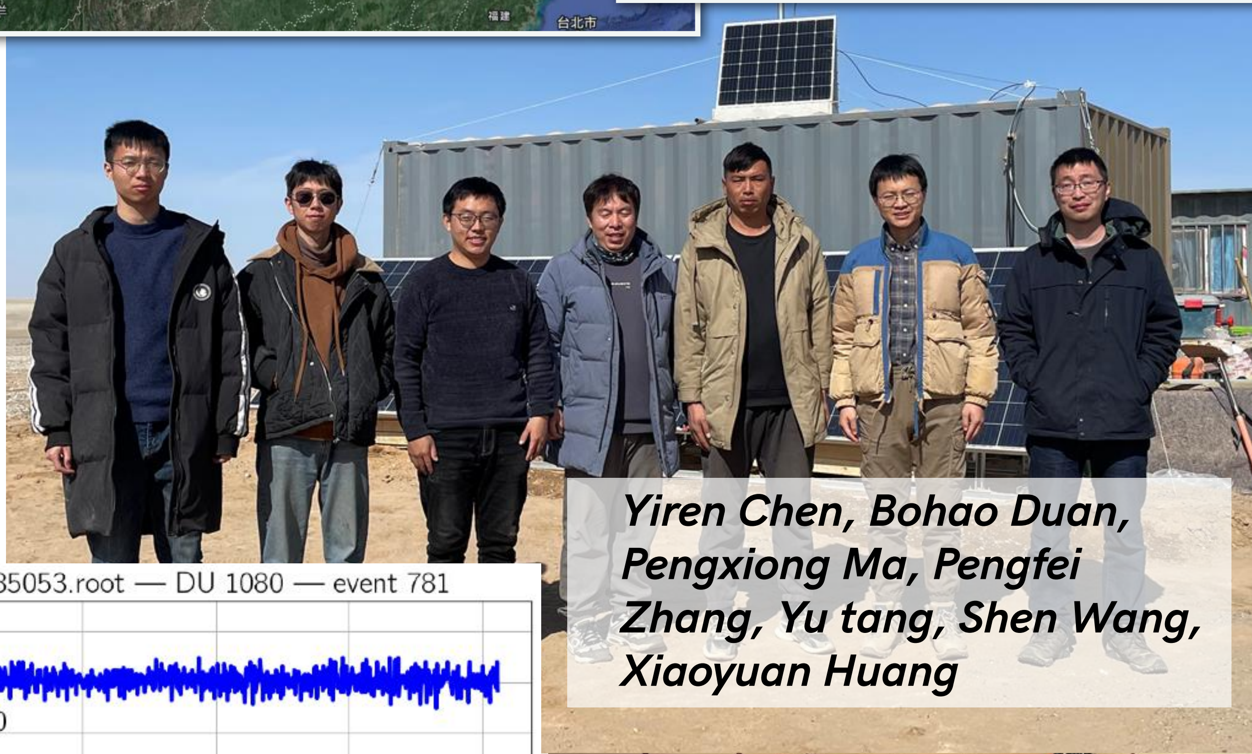
GRANDProto13 in Xiao Dushan

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

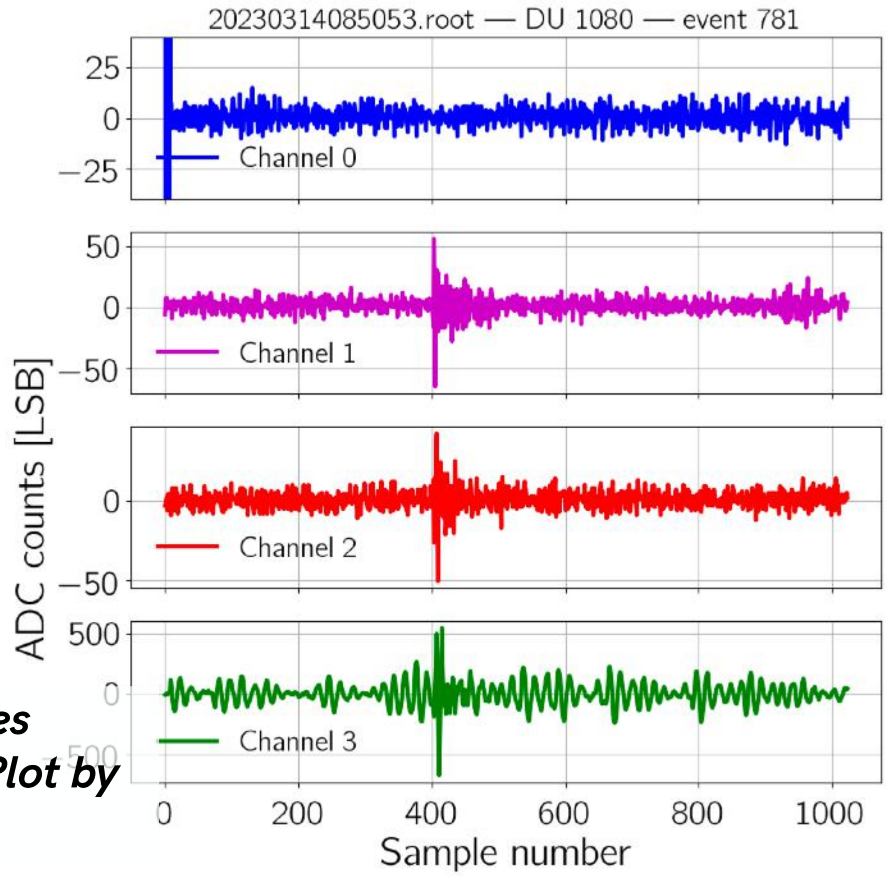
by Xidian U. & Purple Mountain Observatory

- 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

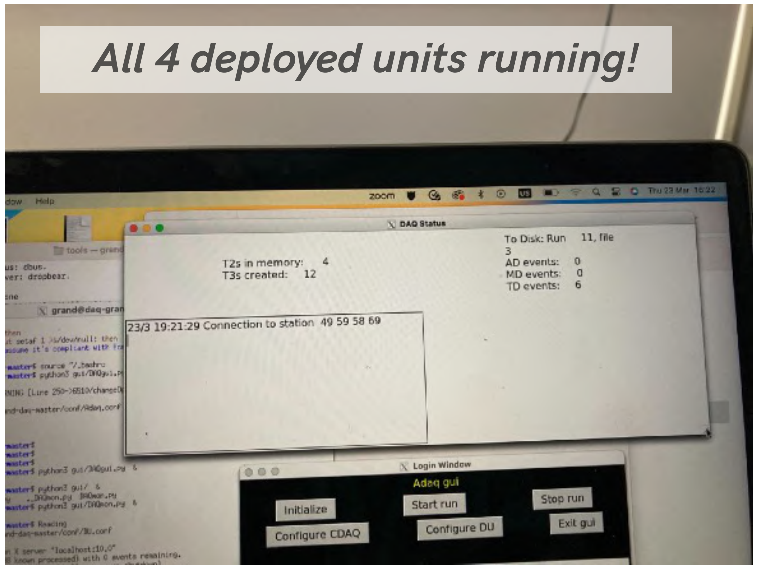


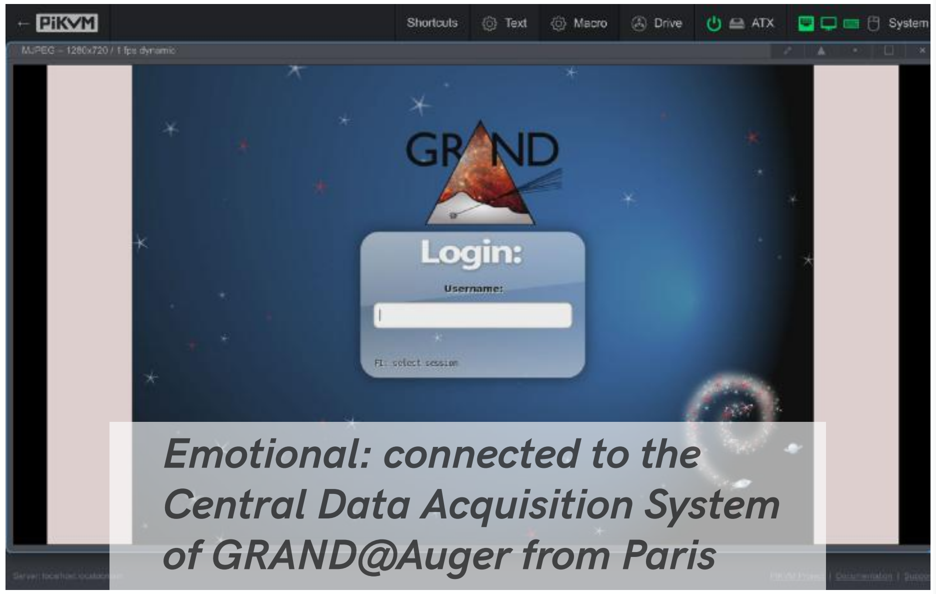
Few nice transient pulses identified in the data - Plot by Pablo Correa

Shen Wang and Bohao Duan taking data

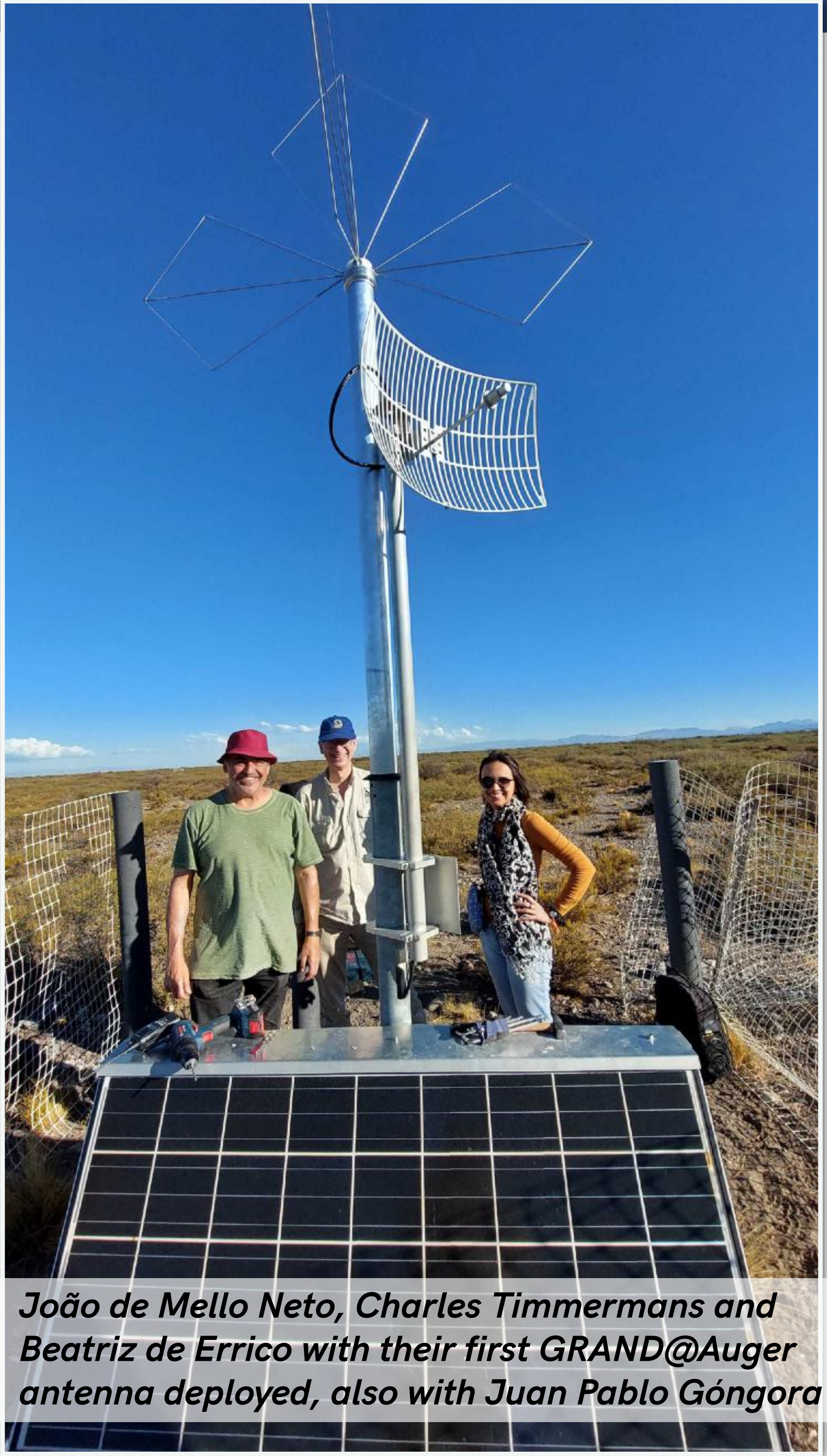
GRAND@Auger - Malargüe, Argentina

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

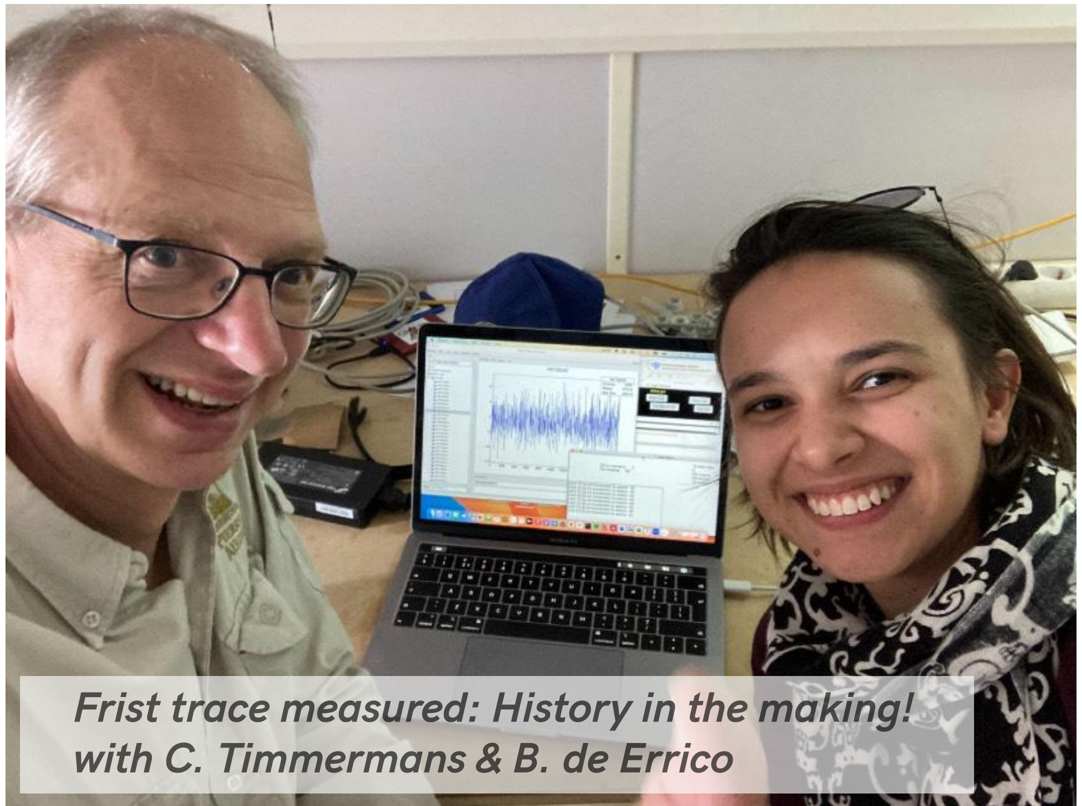

All 4 deployed units running!



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


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


Fred Magnard installing a PiKVM to the DAQ at IAP


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

GRAND@Auger: an international prototyping effort


International agreement for the GRAND@Auger project

amended *22/12/2022*

For Fundación Ahuekna
Ruben Denza, Director — Dec 14th, 2022 — date

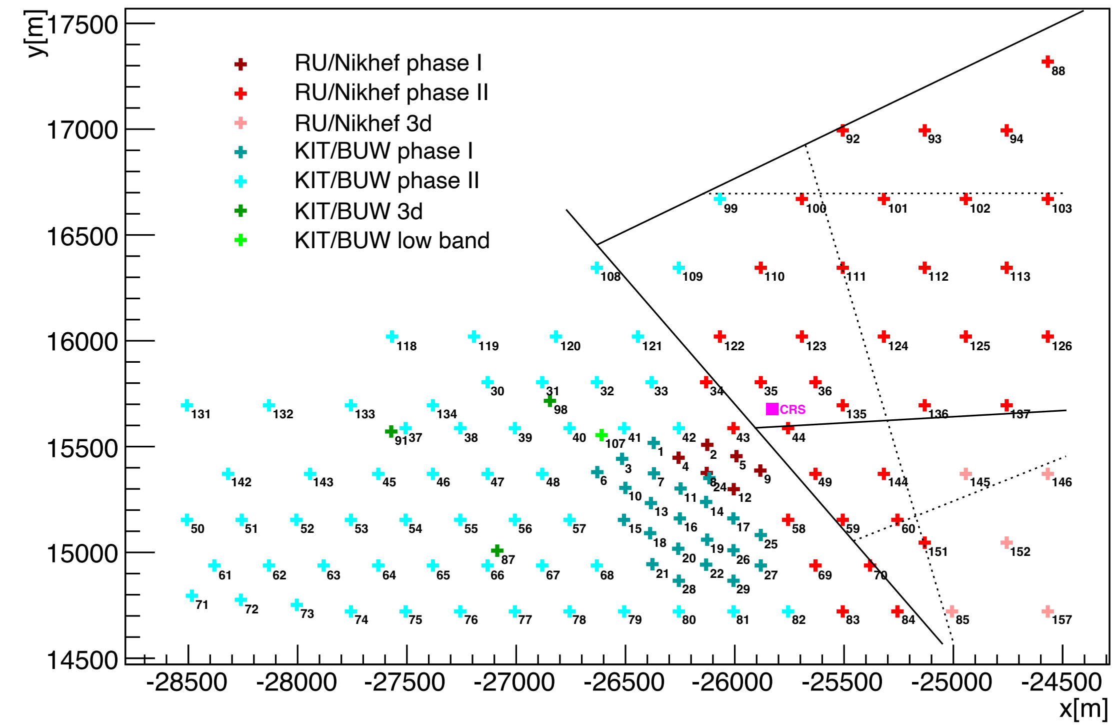
For Institut d'Astrophysique de Paris
François Bouchet, Director — Dec 13th, 2022 — date

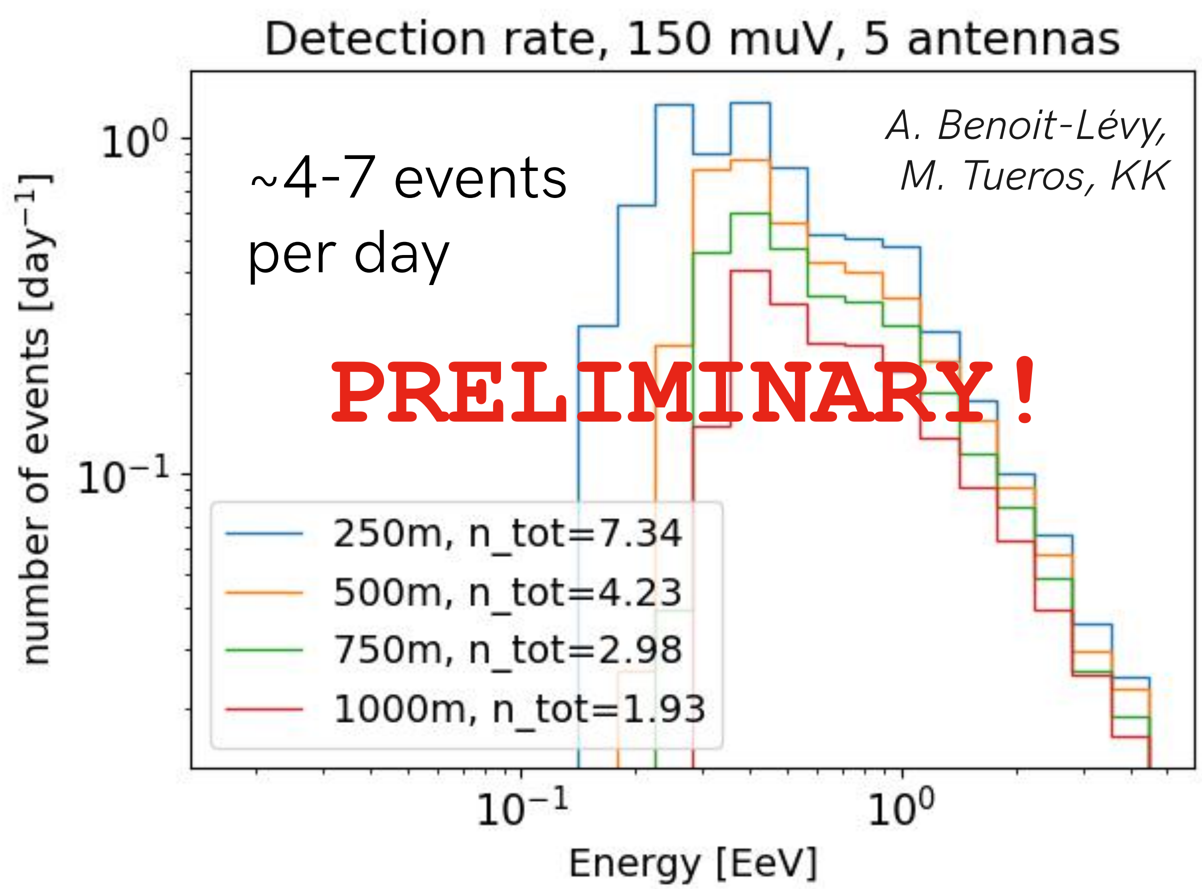
For Karlsruher Institut für Technologie - Institut für Astroteilchenphysik
Ralph Engel, Director — 2022 – 12 – 14 — date

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

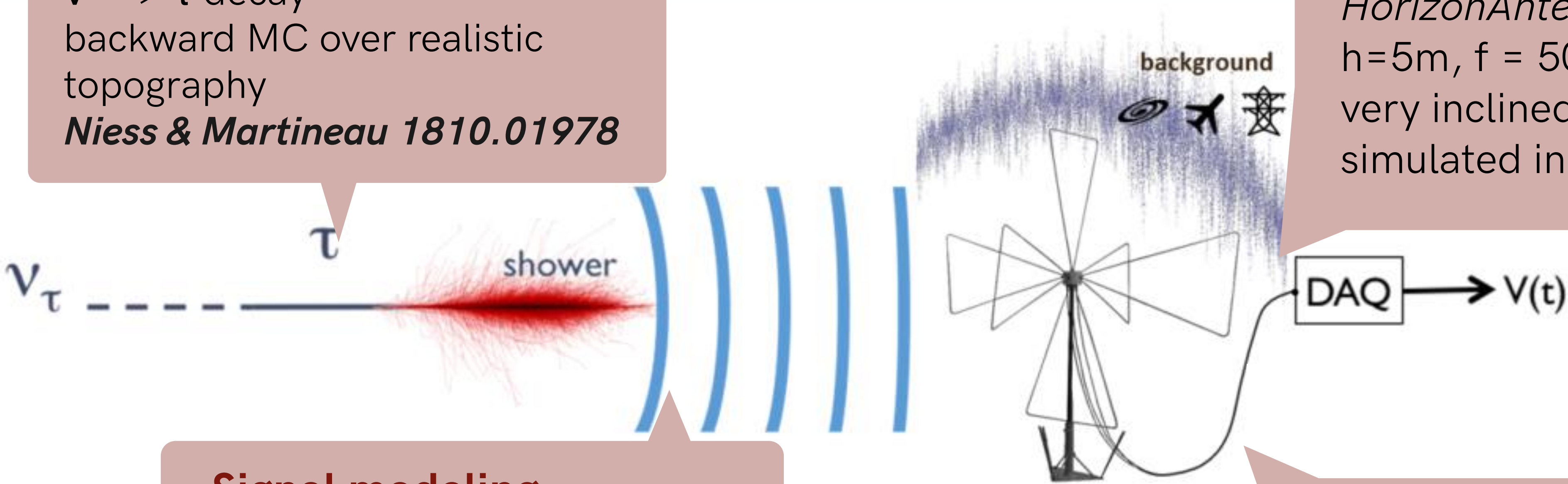
The GRAND Software

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
$\nu \longrightarrow \tau$ 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)

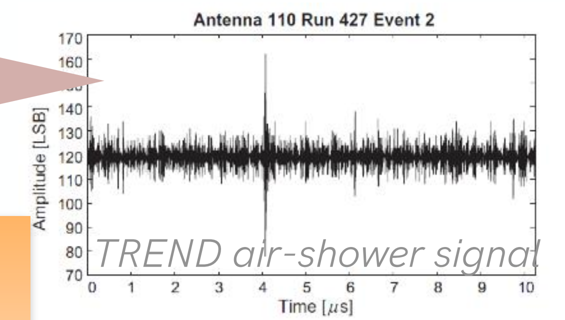
for very inclined air-showers

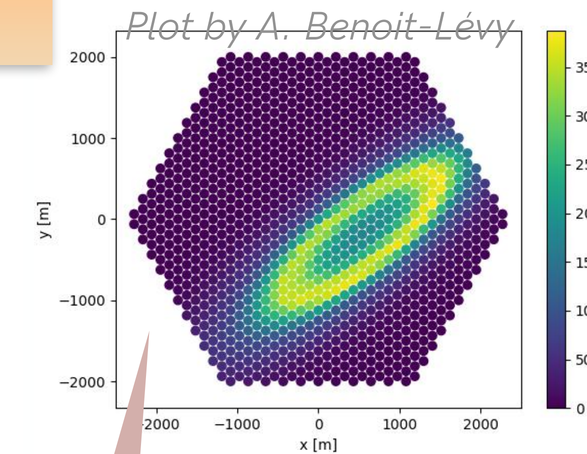
Chiche et al. 2022
Chiche, Zhang et al. in prep.
Guelfand et al. in prep.

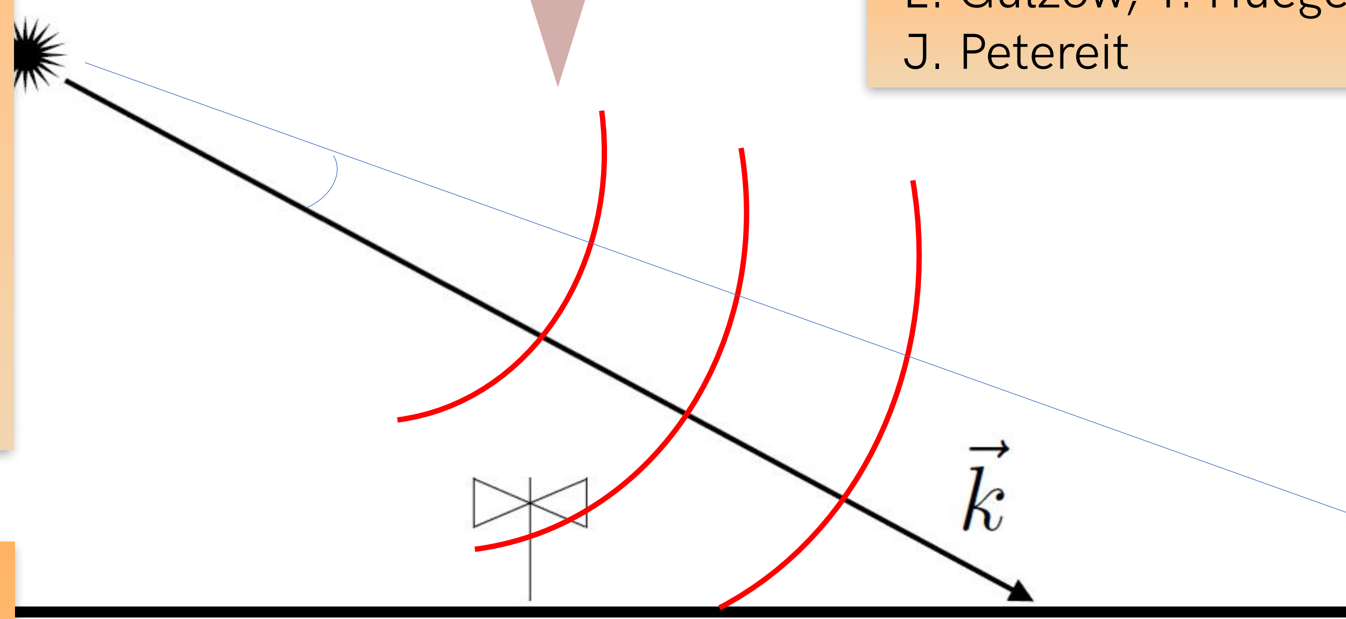
Signal modeling for triggering

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 in Japan?
data analysis, signal treatment & MM opportunities

Data analysis preparation

- Development of data analysis pipeline
- Signal treatment - trigger
- Methods and tools for air-shower parameter reconstruction

Scintillators on GRANDProto300? (Gansu, China)

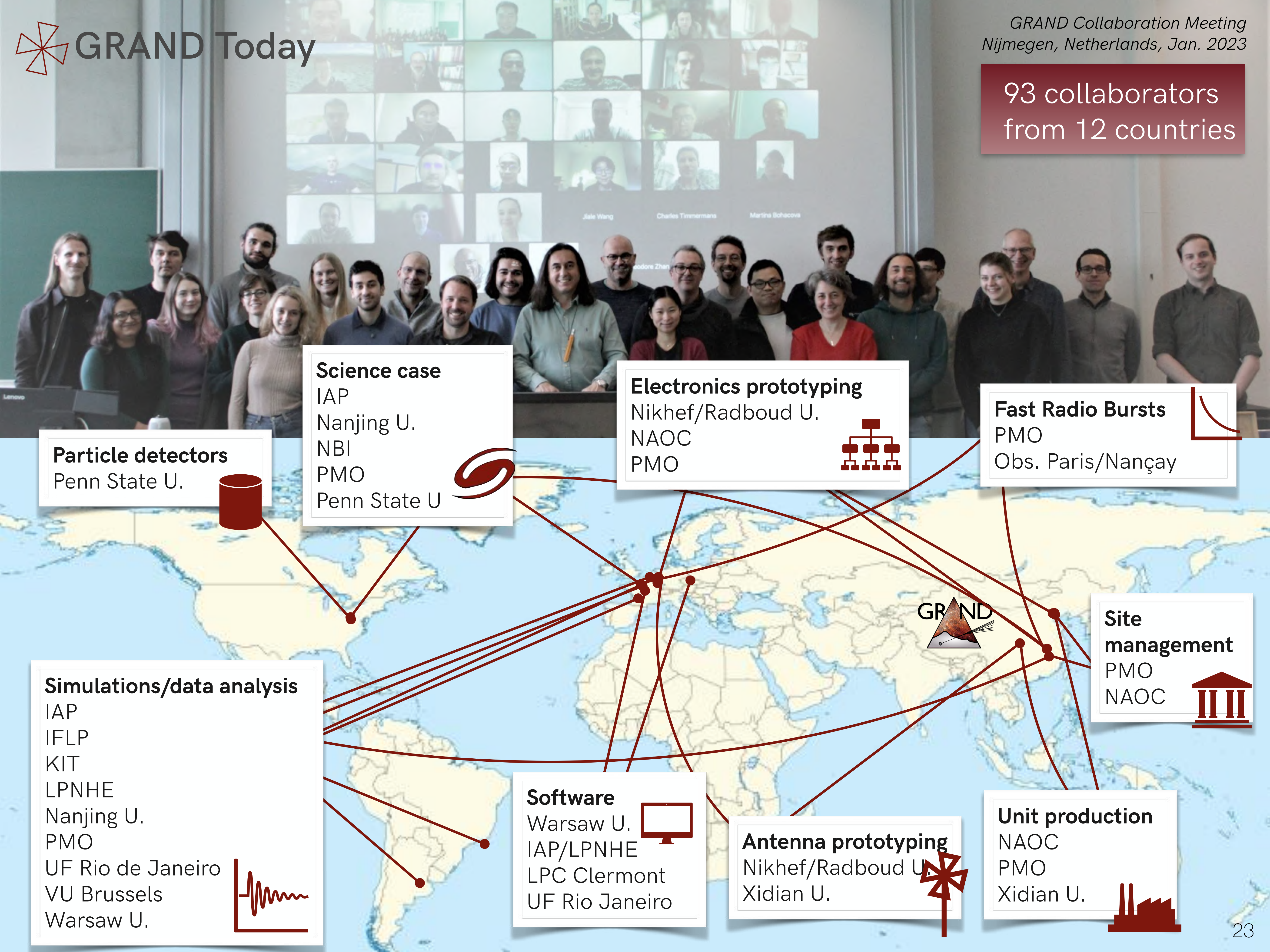
- Development and installation of particle detectors
- Testing coincident events
- Drastically improved science case (muon discrepancy, UHE γ rays)

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
- Synergies with other instruments: IceCube, JEM-EUSO, TA...


GRAND Today
GRAND Collaboration Meeting
Nijmegen, Netherlands, Jan. 2023
93 collaborators from 12 countries
Jiale Wang
Charles Timmermans
Martina Bohacova
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
GRAND
Site management
PMO
NAOC
Simulations/data analysis
IAP
IFLP
KIT
LPNHE
Nanjing U.
PMO
UF Rio de Janeiro
VU Brussels
Warsaw U.
Software
Warsaw U.
IAP/LPNHE
LPC Clermont
UF Rio Janeiro
Antenna prototyping
Nikhef/Radboud U.
Xidian U.
Unit production
NAOC
PMO
Xidian U.
23

GRAND Memorandum of Understanding

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

2022 version

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
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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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

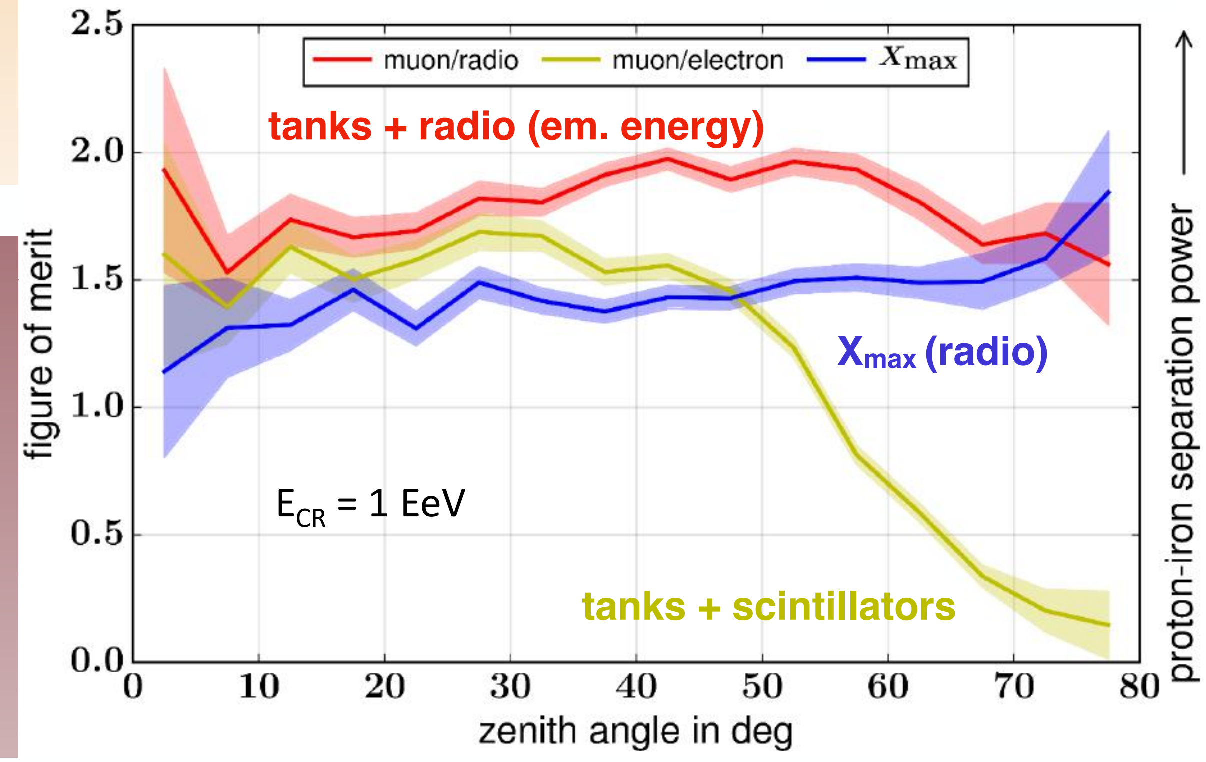
Documentary by Jean Mouette *The Road to the Neutrino*:
https://www.youtube.com/watch?v=8tDnwq8gAe4

GRANDProto300: a self-standing pathfinder

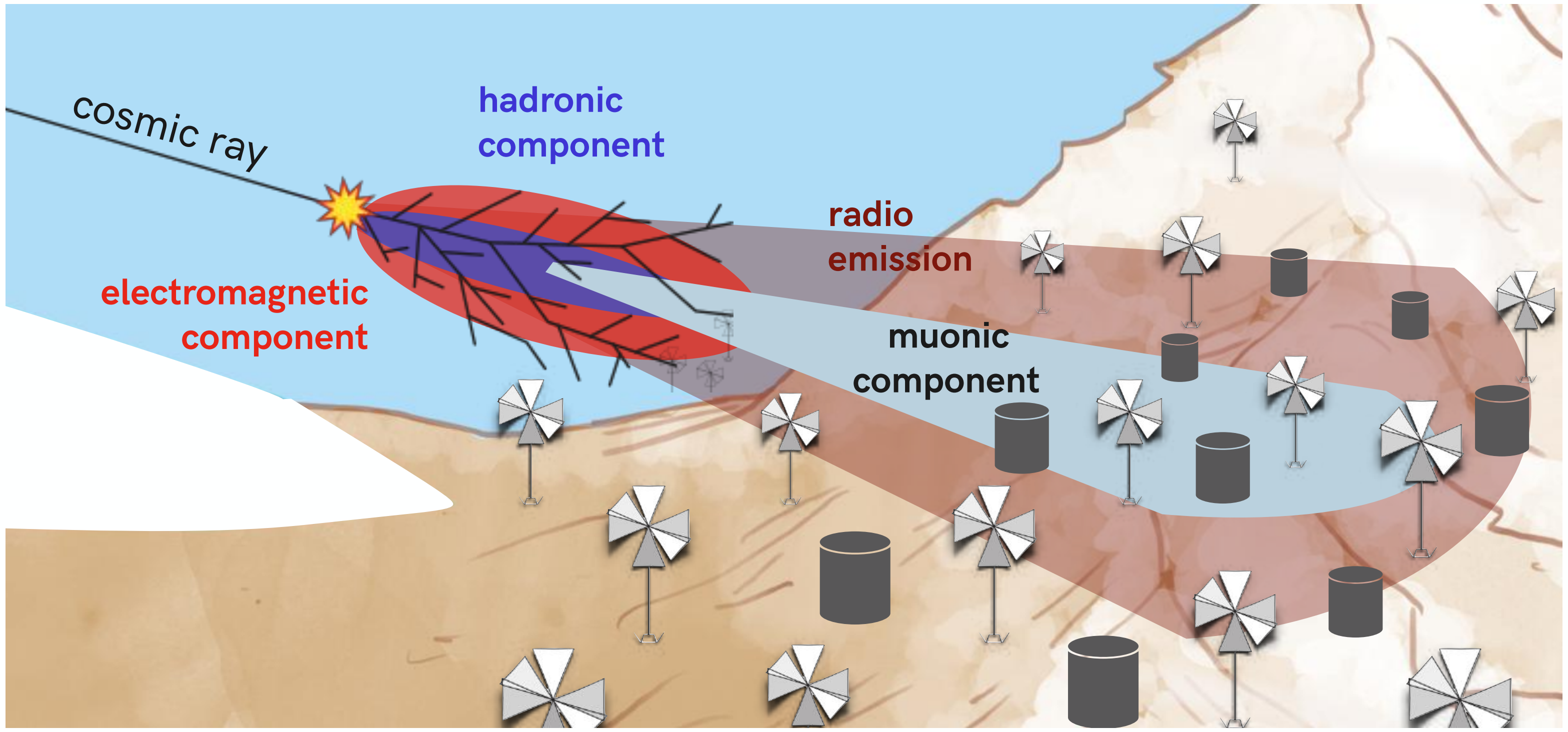
Autonomous detection of **very inclined cosmic rays** E=$10^{16.5}$-10^{18} eV

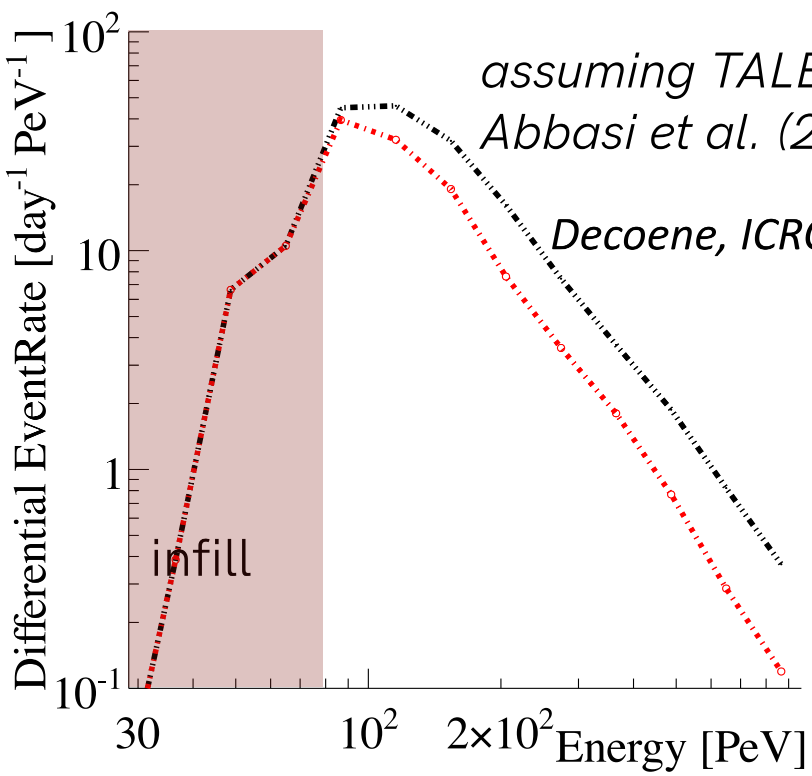
1- reconstructing spectrum, arrival direction & composition
validation via comparison to known results
2 - test bench for further GRAND stages

Holt et al. 2019



Proficient physics instrument
if complemented by **particle detector array**
Galactic/extragalactic transition
hadronic physics (muon content in EAS)
UHE gamma-rays
Fast Radio Bursts





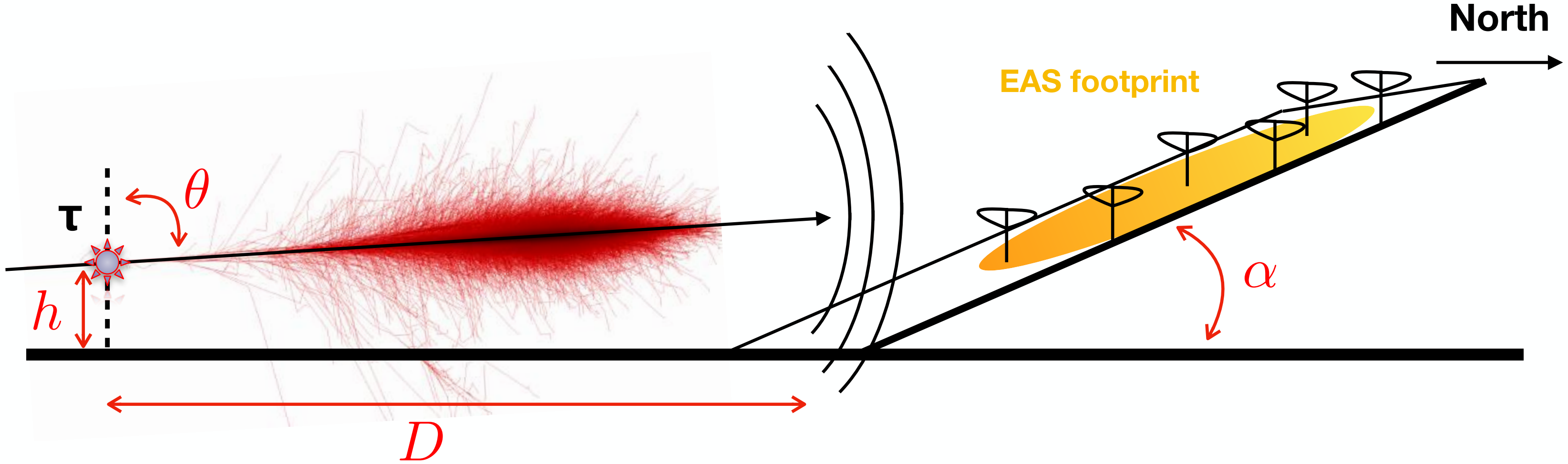
assuming TALE flux Abbasi et al. (2018)

Decoene, ICRC2019

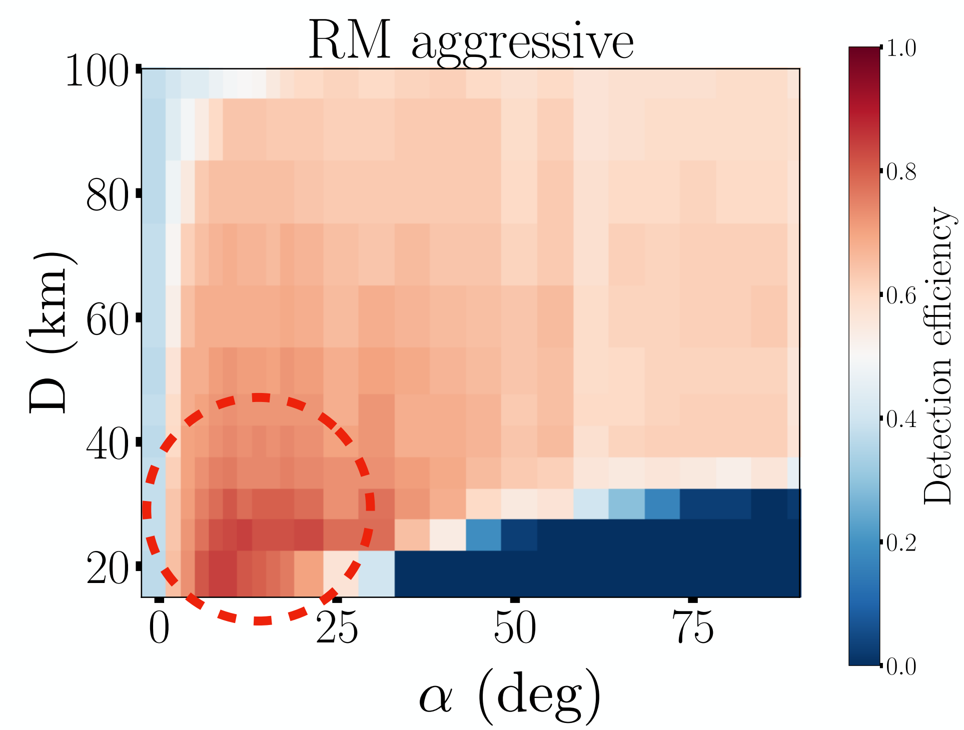
Air-shower parameter reconstruction

- Additional asymetries for very inclined showers (shower age, atmospheric conditions,…)

→ **Dedicated reconstruction methods necessary!**



Decoene et al. NIMA 2020

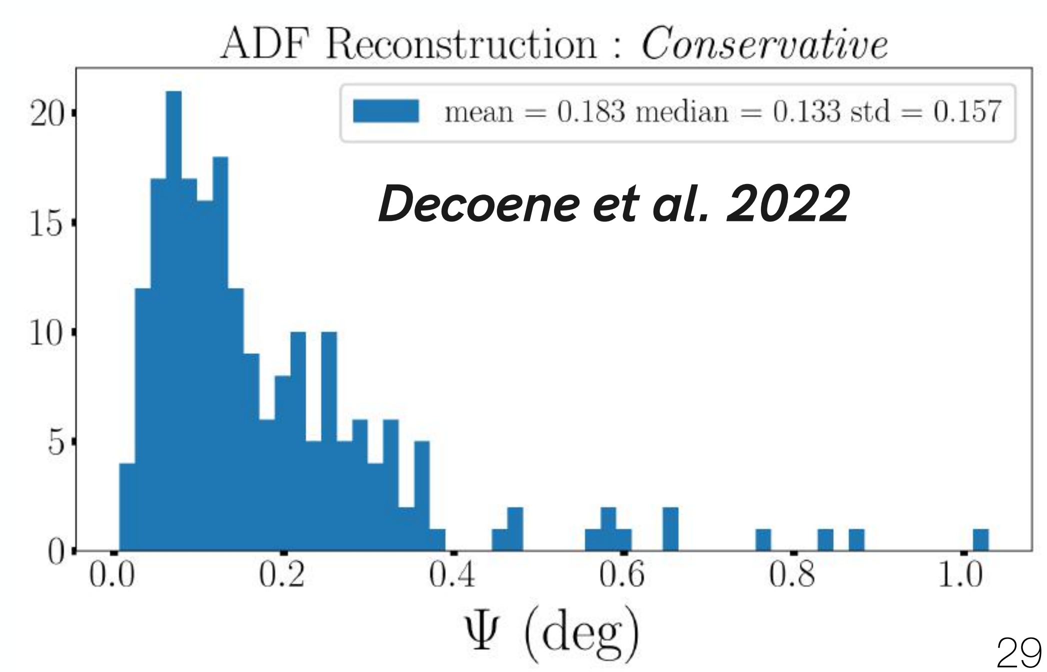


Effects of topography

- Mild slopes (5°-20°) can optimise the UHE neutrino radiodetection efficiency by a factor 3
  Decoene et al. 2020

Angular resolution

- Neutrino astronomy is possible: 0.1° angular resolution on arrival direction achieved
  Decoene et al. 2022

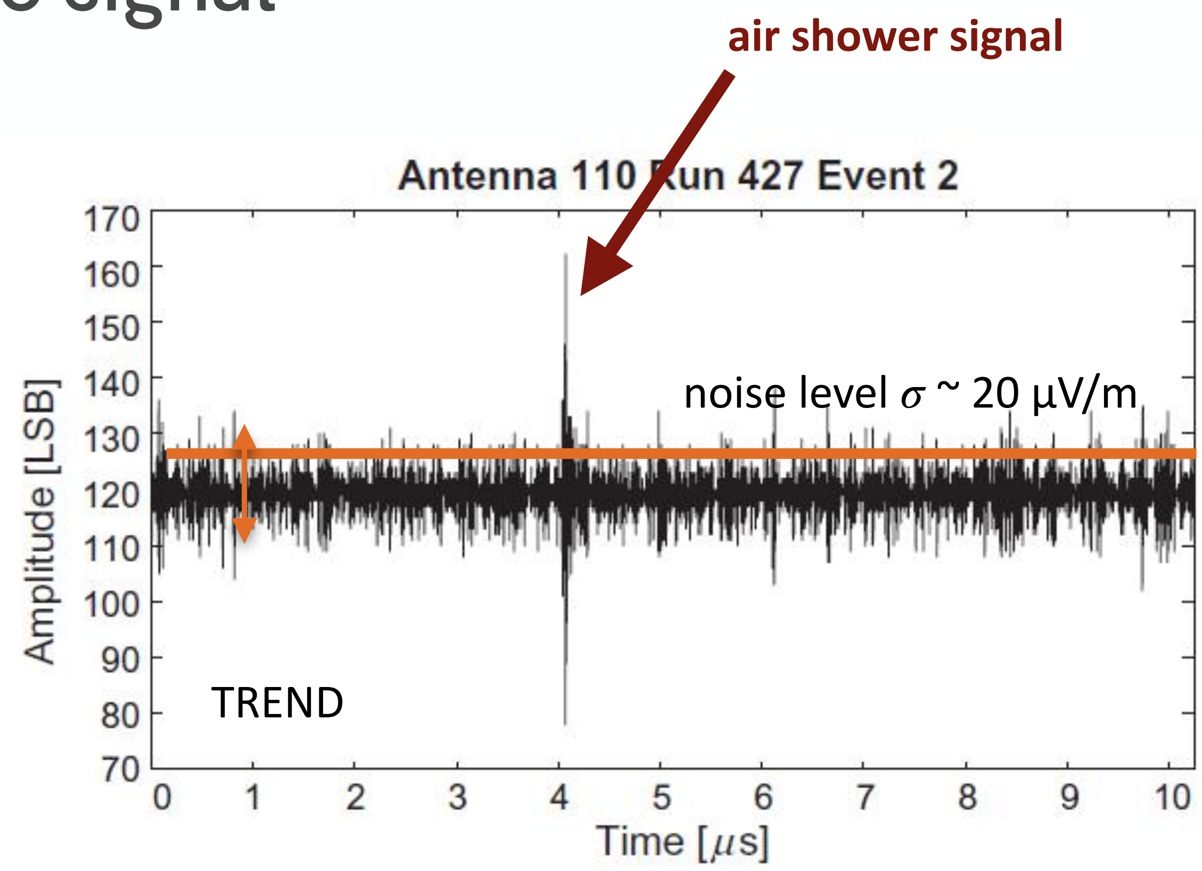


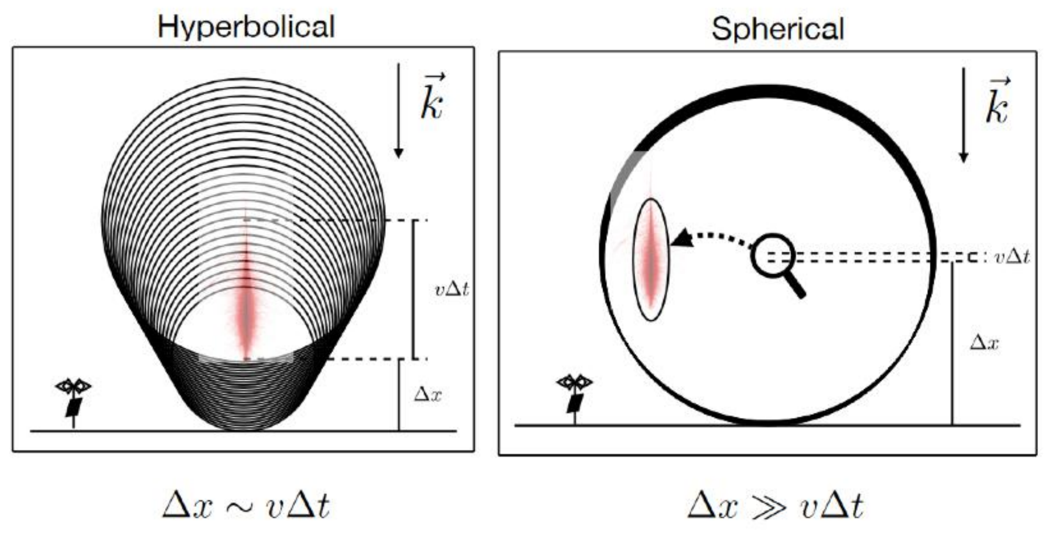
Parameter reconstruction framework

- Preliminary framework for global signal reconstruction (direction, composition, energy)
  V. Decoene PhD 2020

Building on features of the EAS radio signal

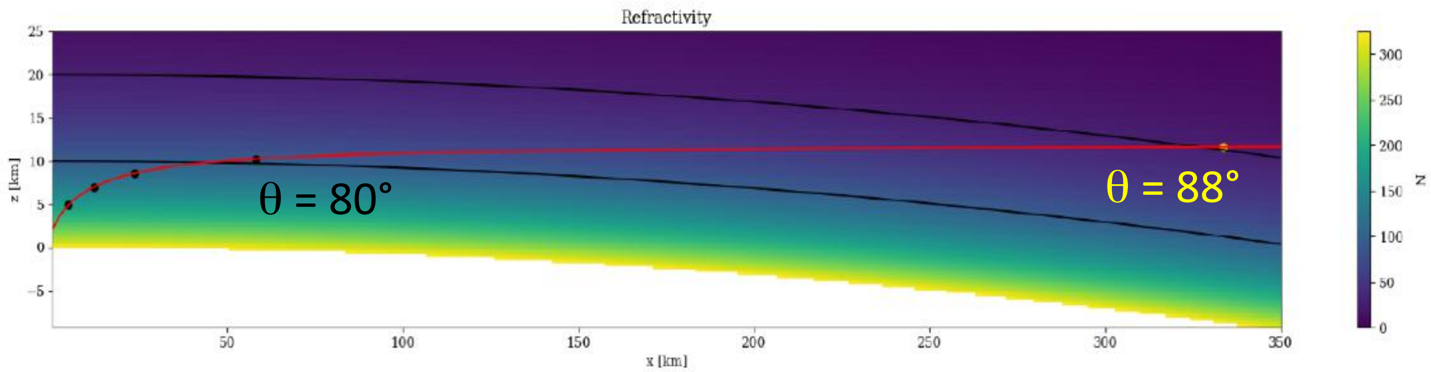
- Frequency range : **30-200 MHz**
- Transient pulses, duration: **<~ 100ns**
- Amplitude of detectable signals at unit level:
  > 3-5 σ above the stationary Galactic background
  (σ[Galactic emission] ~ 20 µV/m in [50-200MHz])
  amplitude scales linearly with primary particle energy
- Detection energy threshold with 5 units in common: $10^{16.5}$ eV





Adapted from Corstanje et al., arXiv:1404.3907

- Emission ~ point-like around shower maximum —> spherical wavefront
- Emission focused in 1° cone around shower axis
- "Cerenkov ring": enhancement around 1° at highest frequencies



Plot by M. Tueros

Technical characteristics of the radio signal

- Frequency range : **30-200 MHz**
- Transient pulses, duration: **<~ 100ns**
- Amplitude of detectable signals at unit level:
  > 3-5 σ above the stationary Galactic background
  (σ[Galactic emission] ~ 20 µV/m in [50-200MHz])
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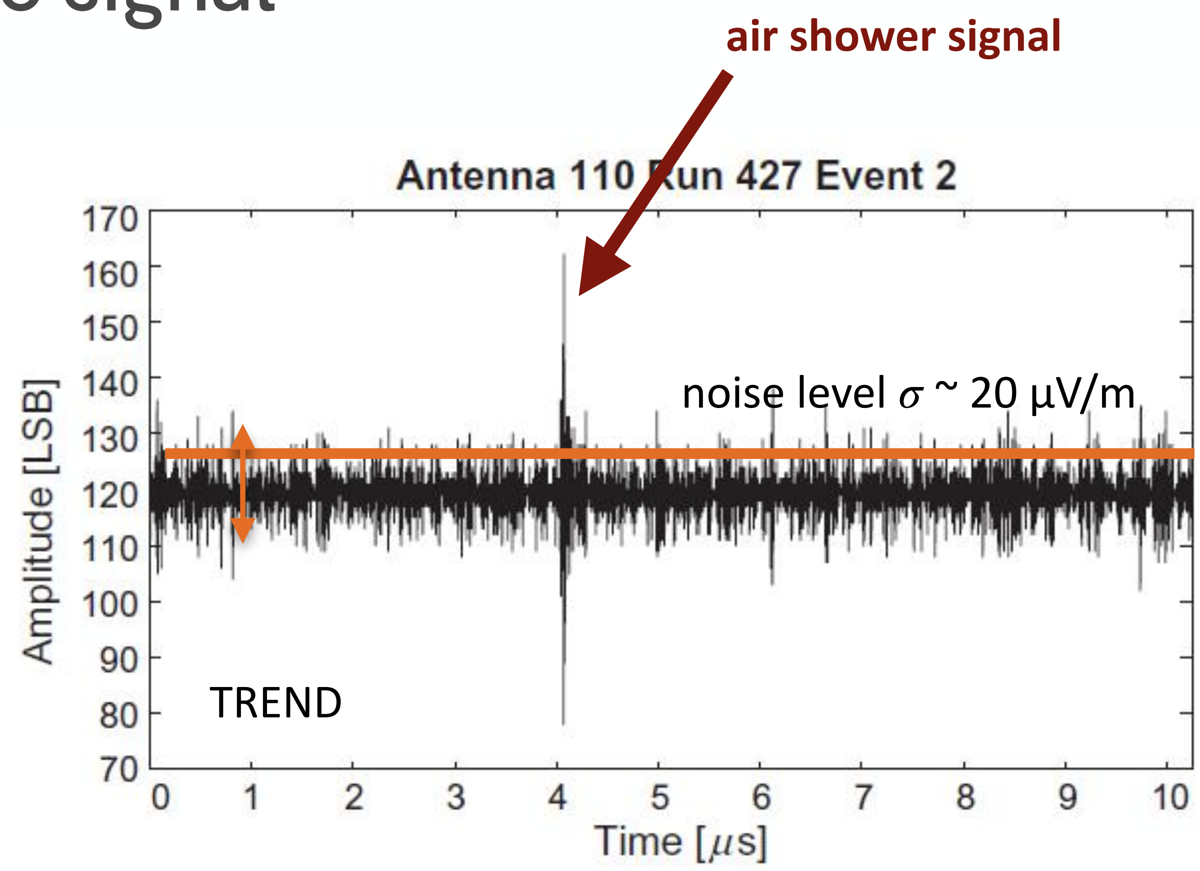
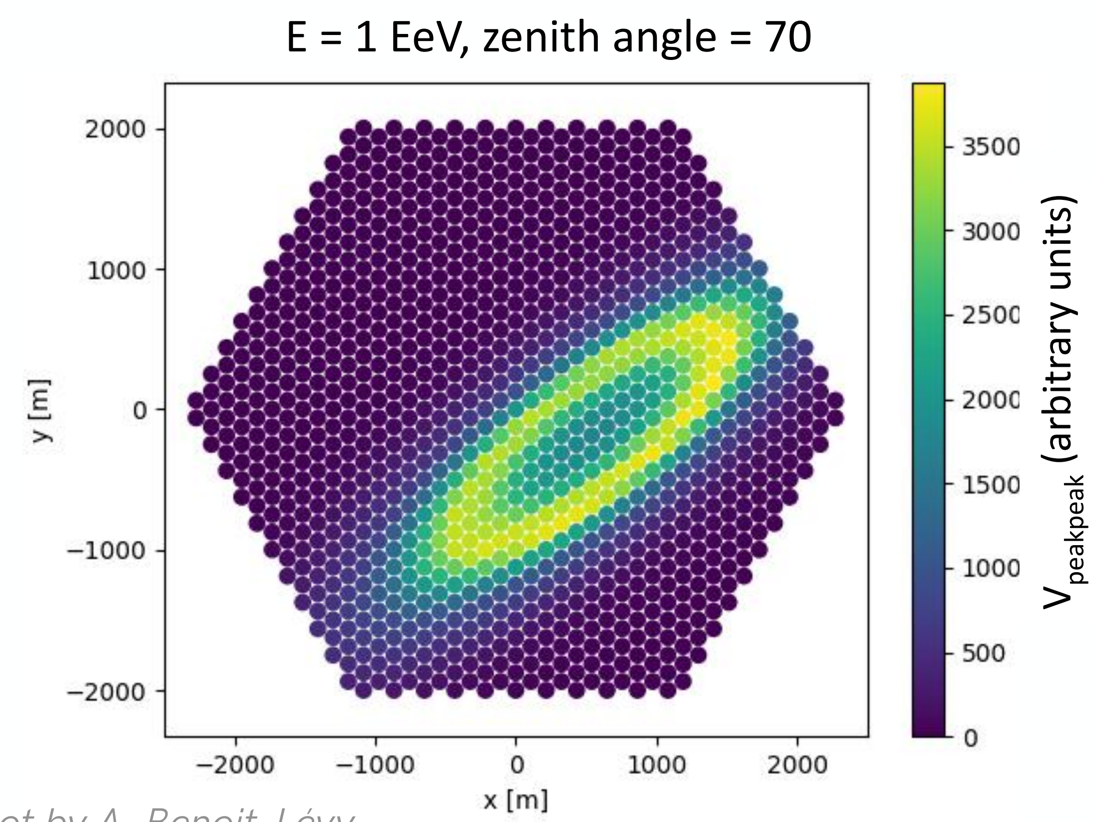
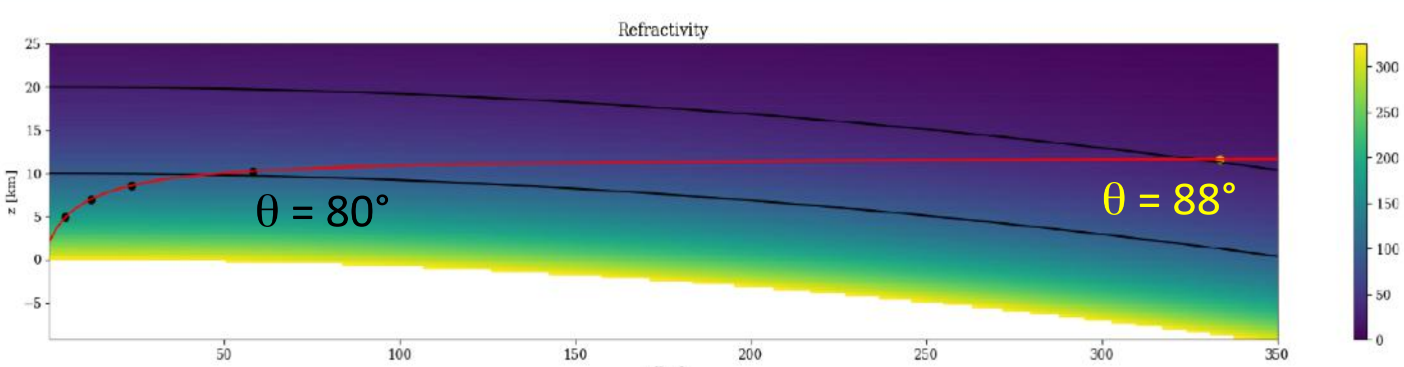




Plot by A. Benoit-Lévy

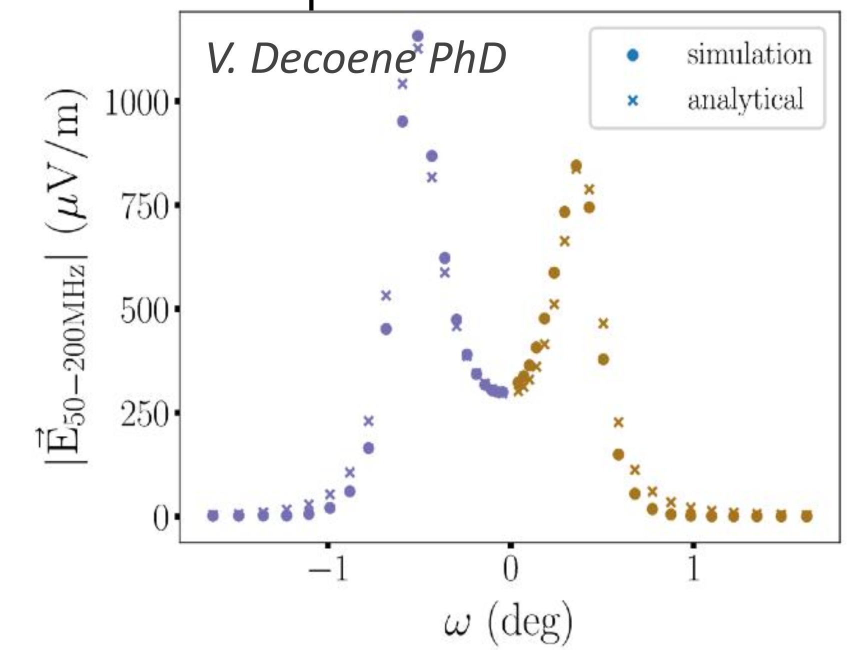
- Emission ~ point-like around shower maximum —> spherical wavefront
- Emission focused in 1° cone around shower axis
- "Cerenkov ring": enhancement around 1° at highest frequencies



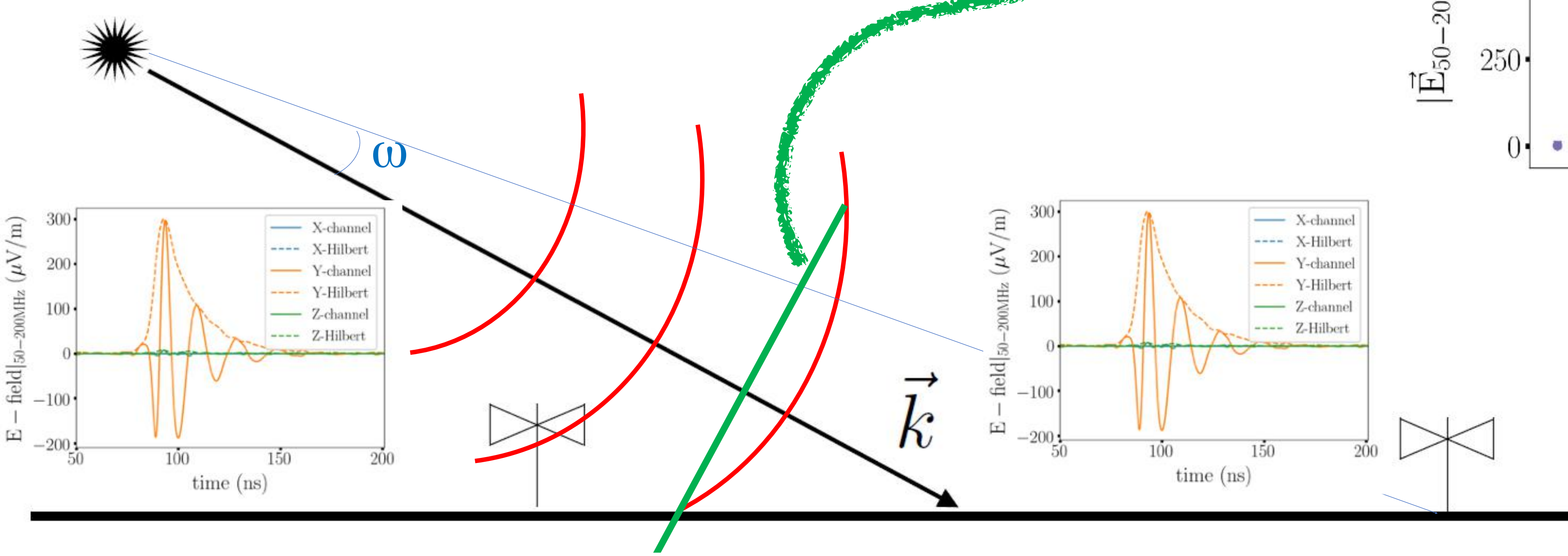
Plot by M. Tueros

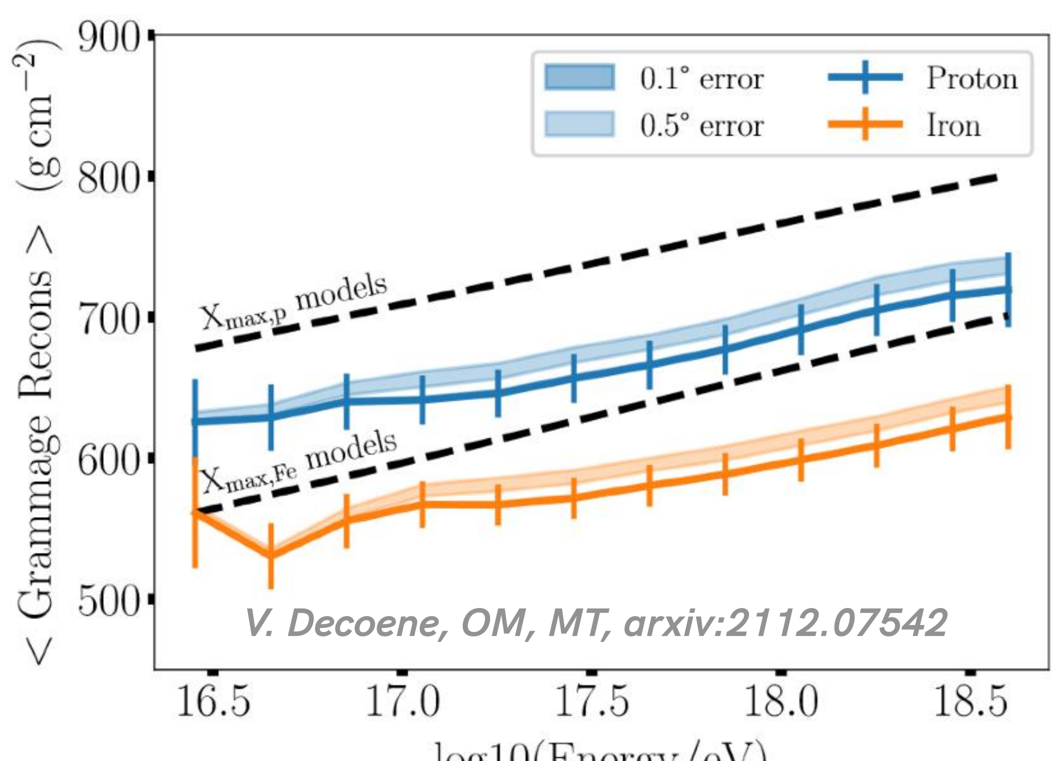
Challenge 1: Air shower reconstruction

Analytical description of amplitude distribution

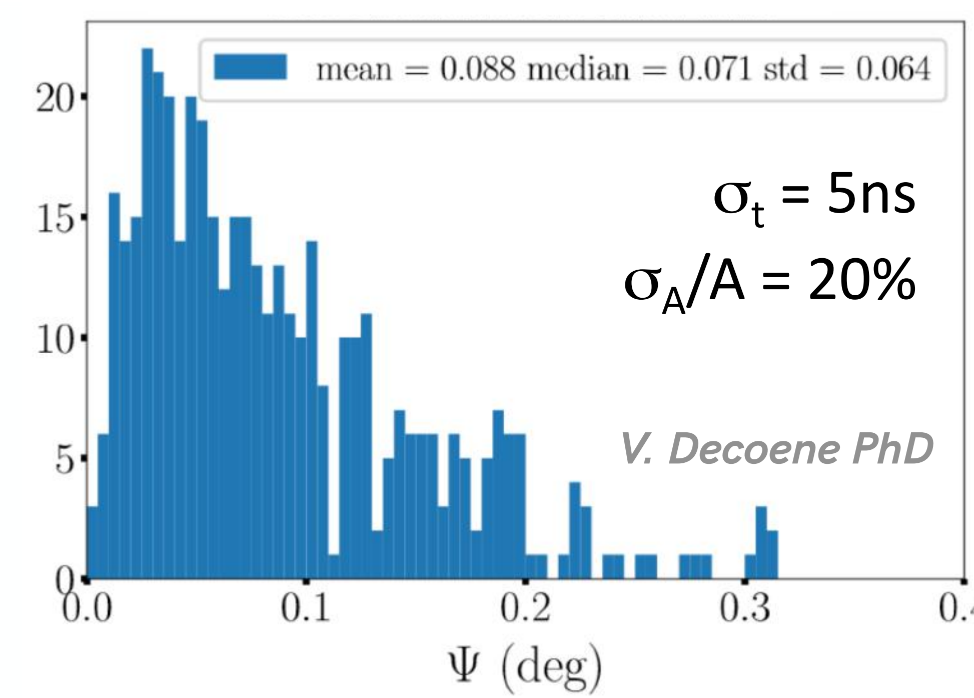


Center of spherical fit of trigger times ⇔ radio emission source





GP300 simulations



Challenge 2: self-triggered radio arrays

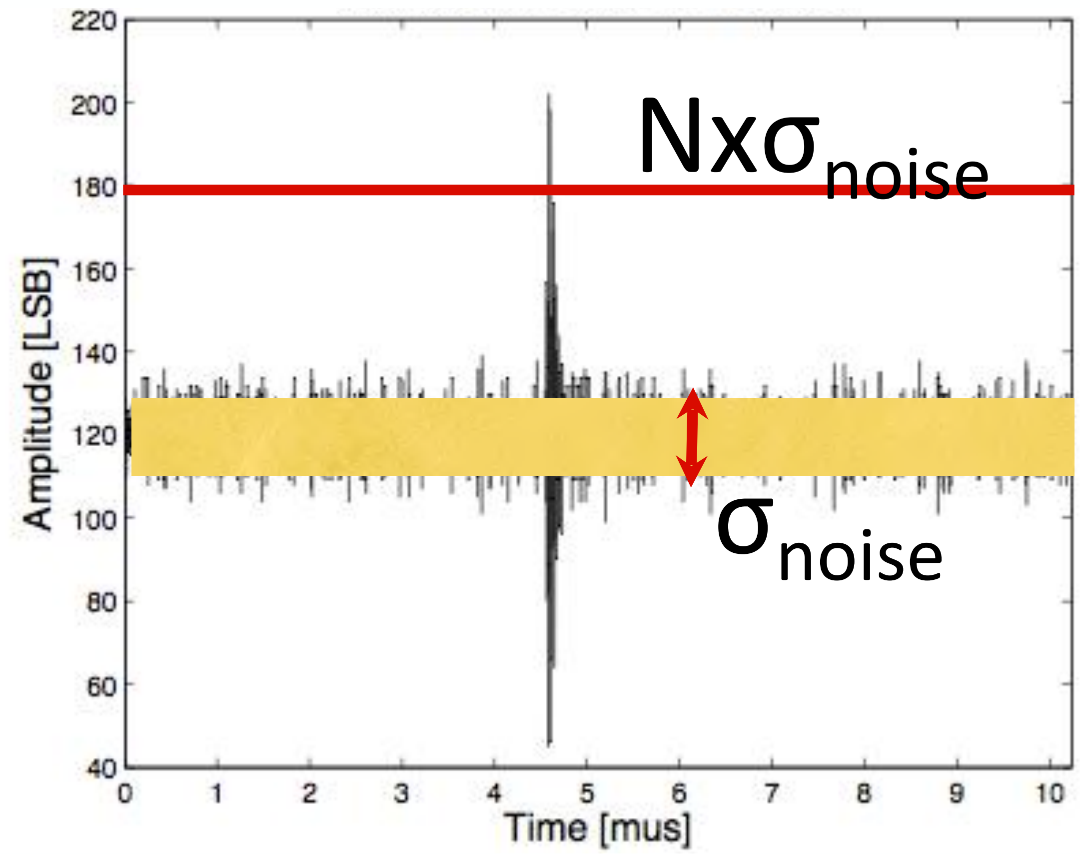
- Only realistic solution for GRAND size
- **At present** (including GP300), only standard methods for triggering:
  - L1 @ unit level: (mostly) signal-over-threshold

    EAS signal known from simulation, background continuously measured
  - L2 @ DAQ level: select causal coincs between L1s (GPS timetags)

    Background is mostly waves rather than random coincs
  - Full time trace collected

    Huge data volume (~10kBy/trigger), while offline treatment reduced to few infos (trig time, amplitude, polar)…

A TREND event

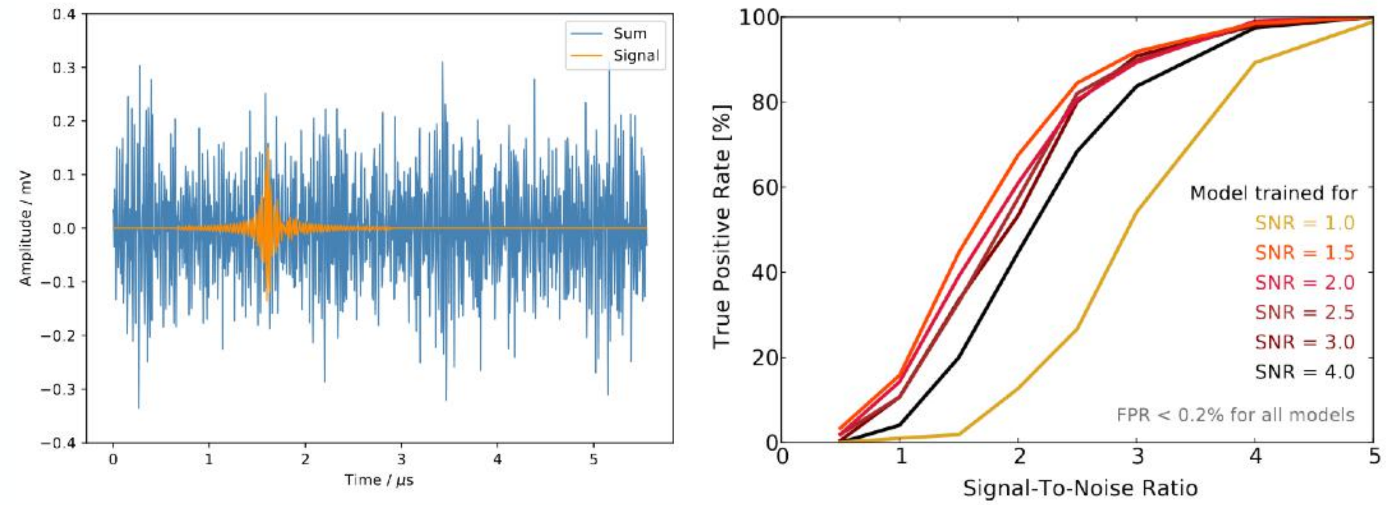


GRANDProto300: large volumes of data ➔ Large bandwidth needed ➔ WiFi
➔ High cost, high power consumption, low range

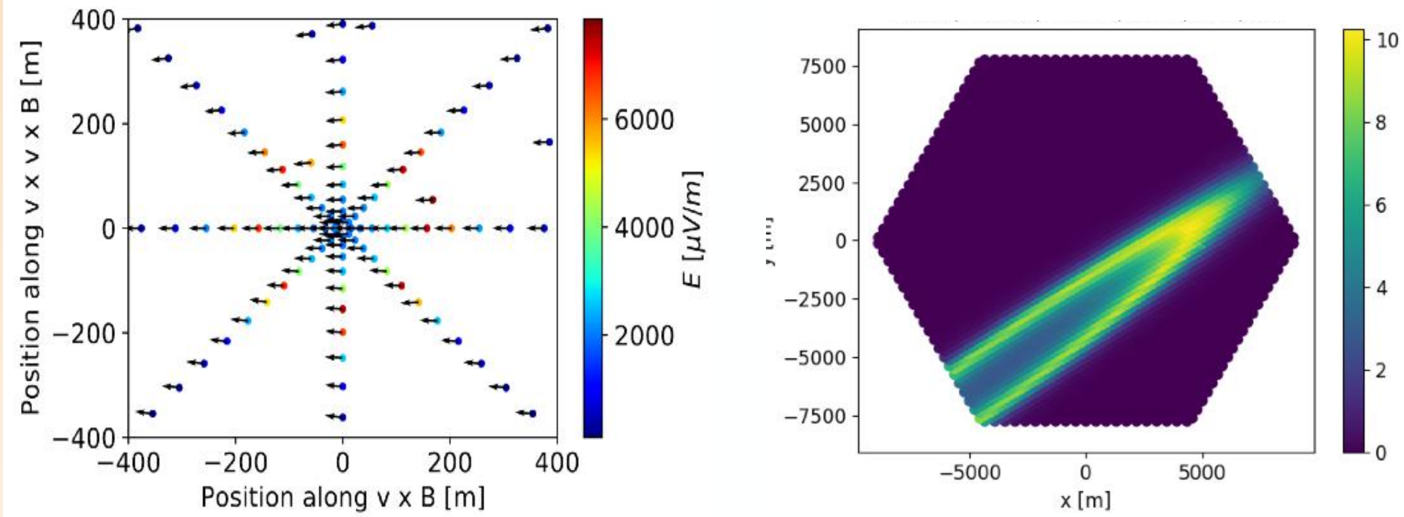
Need for a low-rate, low-power, low-price solution for giant arrays (e.g. GRAND10k)

The NUTRIG proposal
Karlsruhe & Paris (T. Huege, M. Roth, KK & OM)

- L1 trigger (LPNHE lead)
  - Developing innovative methods for:
    - Signal identification (ie fighting against transient noise) ➔ improve purity
    - Signal extraction (ie fighting against stationnary noise) ➔ improve threshold
  - Specific constraints:
    - Online treatment (ie faster that data rate)
    - « Frugality »: low power & limited CPU
    - Noise variability: large range of background pulses, not-so-stationnary baseline conditions
- L2 trigger (KIT lead): use EAS signatures
- Data format (LPNHE + IAP + KIT):
  - Optimize balance between data volume and quality using offline (blind) analysis based on reduced info.

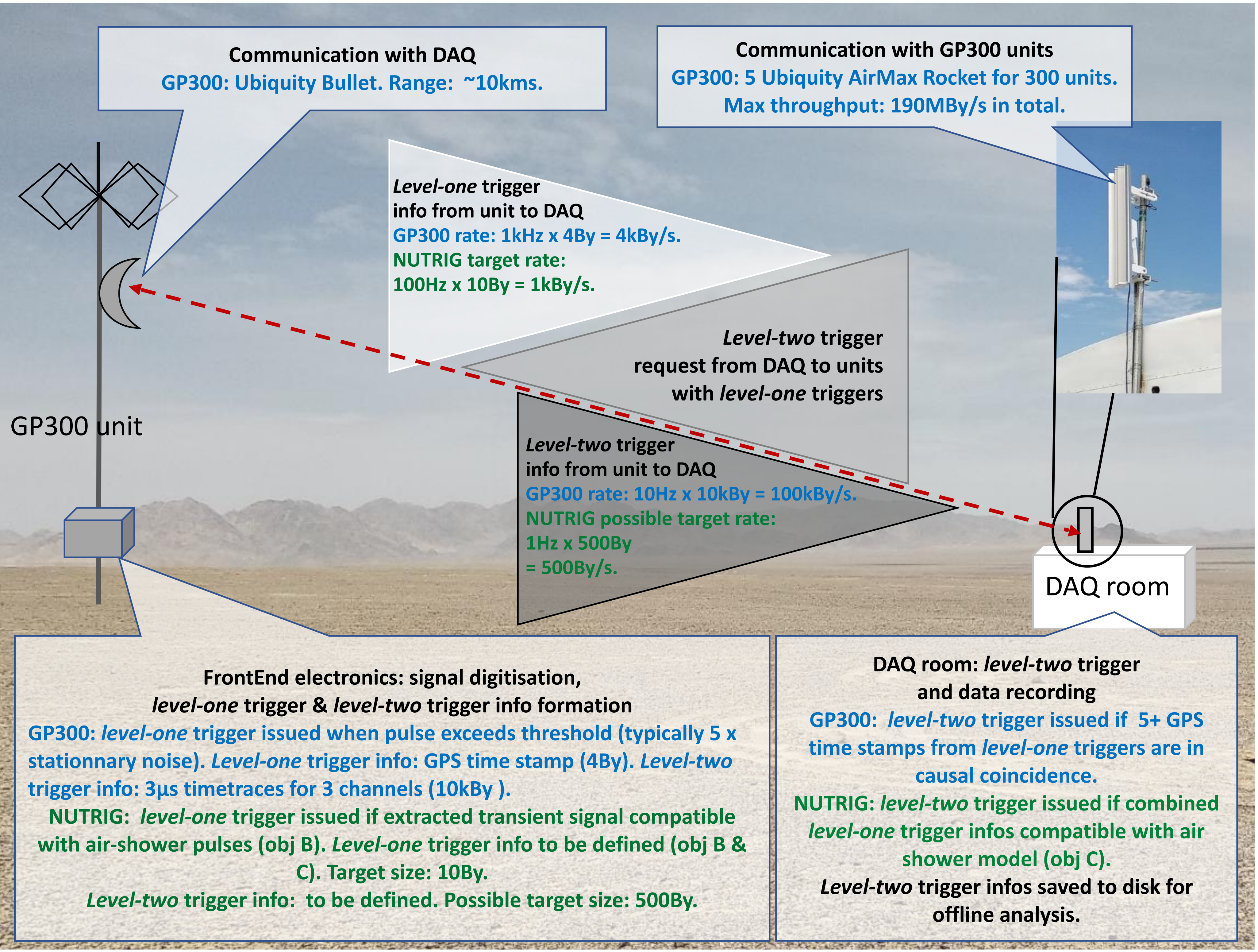


M. Erdmann et al., arXiv:1901.04079



S. Chiche et al., arXiv:2202:06846

The NUTRIG proposal
Karlsruhe & Paris



GP300 (nominal) rate:
L1: 4kBy/s/unit
L2: 100kBy/s/unit
➔ 104kBy/s/unit

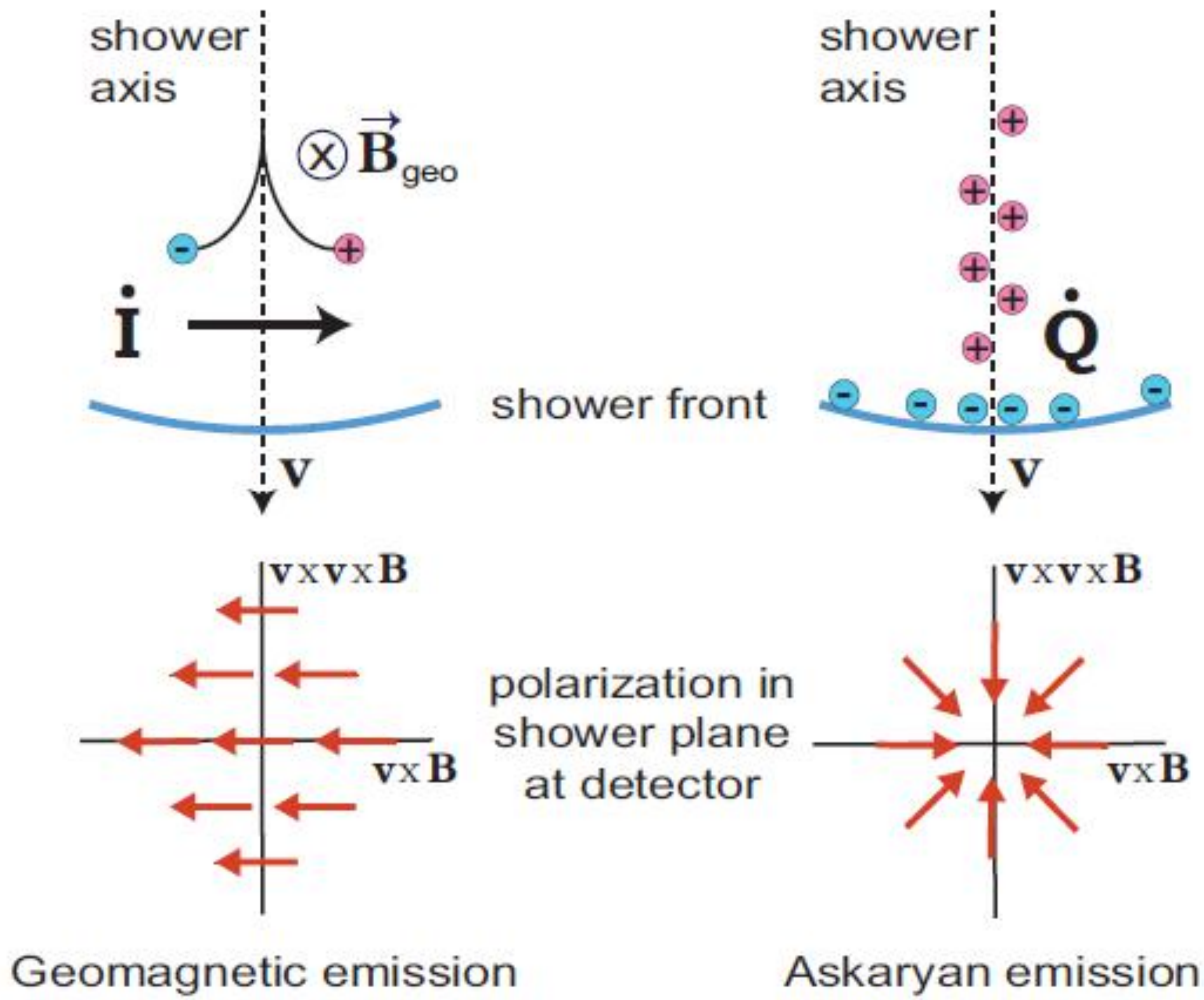
NUTRIG target:
L1: 1kBy/s/unit
L2: 500By/s/unit
➔ 1.5kBy/s/unit

NUTRIG goal (2025):
Optimized trigger methods for autonomous radio arrays
+
Precise quantitative evaluation of data rate

Following step (starting 2024): define hardware layer adapted to data rates
➔ GRAND10k

CLASSICAL picture for radio emission

2 main sources for the radio emission



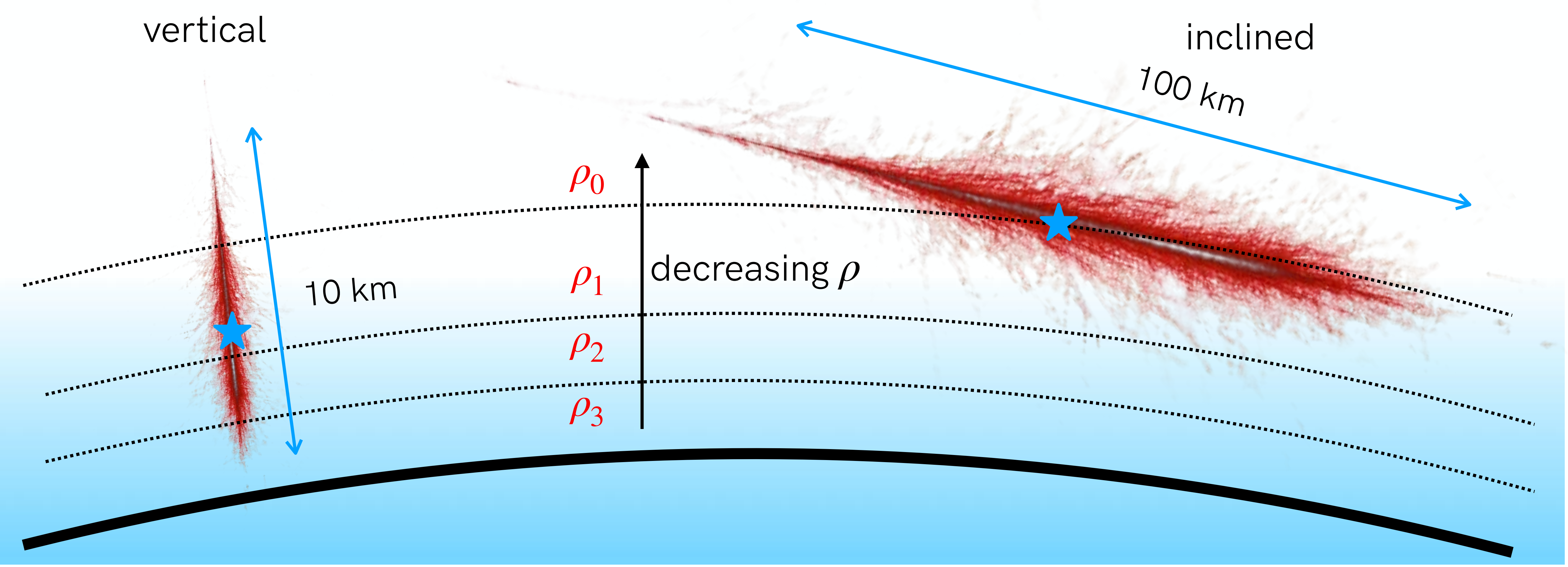
Vertical air-showers: well known, mature and verified

Inclined air showers: still several challenges, trending topic

e.g., Schlüter et al. 2022, Chiche et al. 2022

Characteristics of inclined air showers

- development at **lower air density**
- development over **longer trajectories**



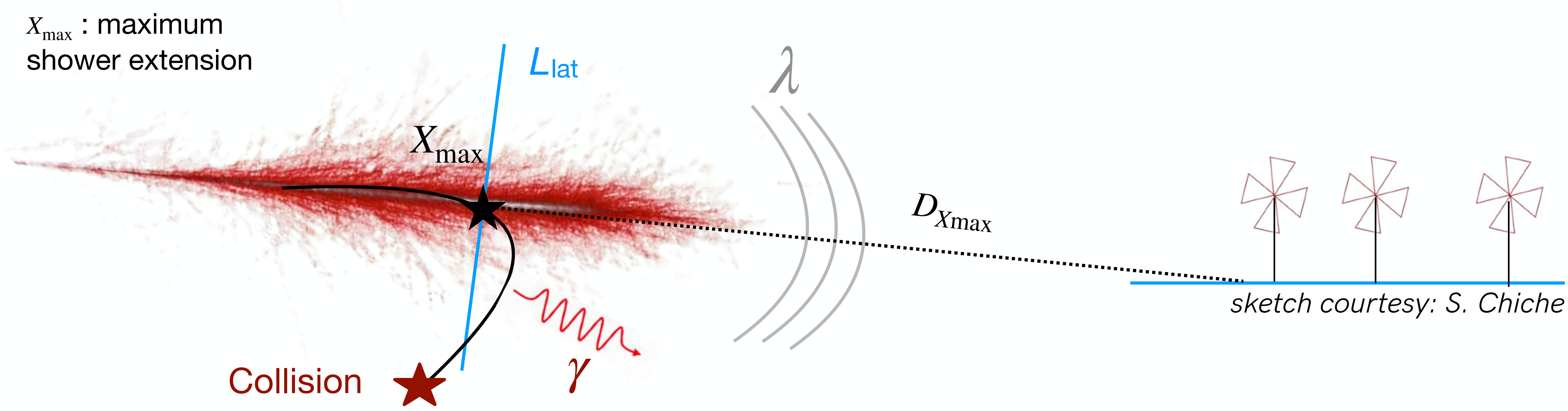
How do all these characteristics affect the radio emission?

Enhanced effect of B!

- particles more deflected —> larger lateral shower extension —> **coherence loss?**
- particles more deflected —> **synchrotron emission?**

slide adapted from S. Chiche

Coherence and synchrotron conditions



Condition for coherent emission

$$L_{lat}(\rho_{air}, B_{Earth}) < l_{coh}$$

Spatial coherence length:

$$l_{coh} = \lambda D_{Xmax} / L_{lat}$$

Shower lateral extent:

$$L_{lat} = x_{transverse}(t = \tau)$$

τ: characteristic time of inelastic collision

Condition for synchrotron emission

$$l_{syn}(B_{Earth}) < l_{rad}(\rho_{air})$$

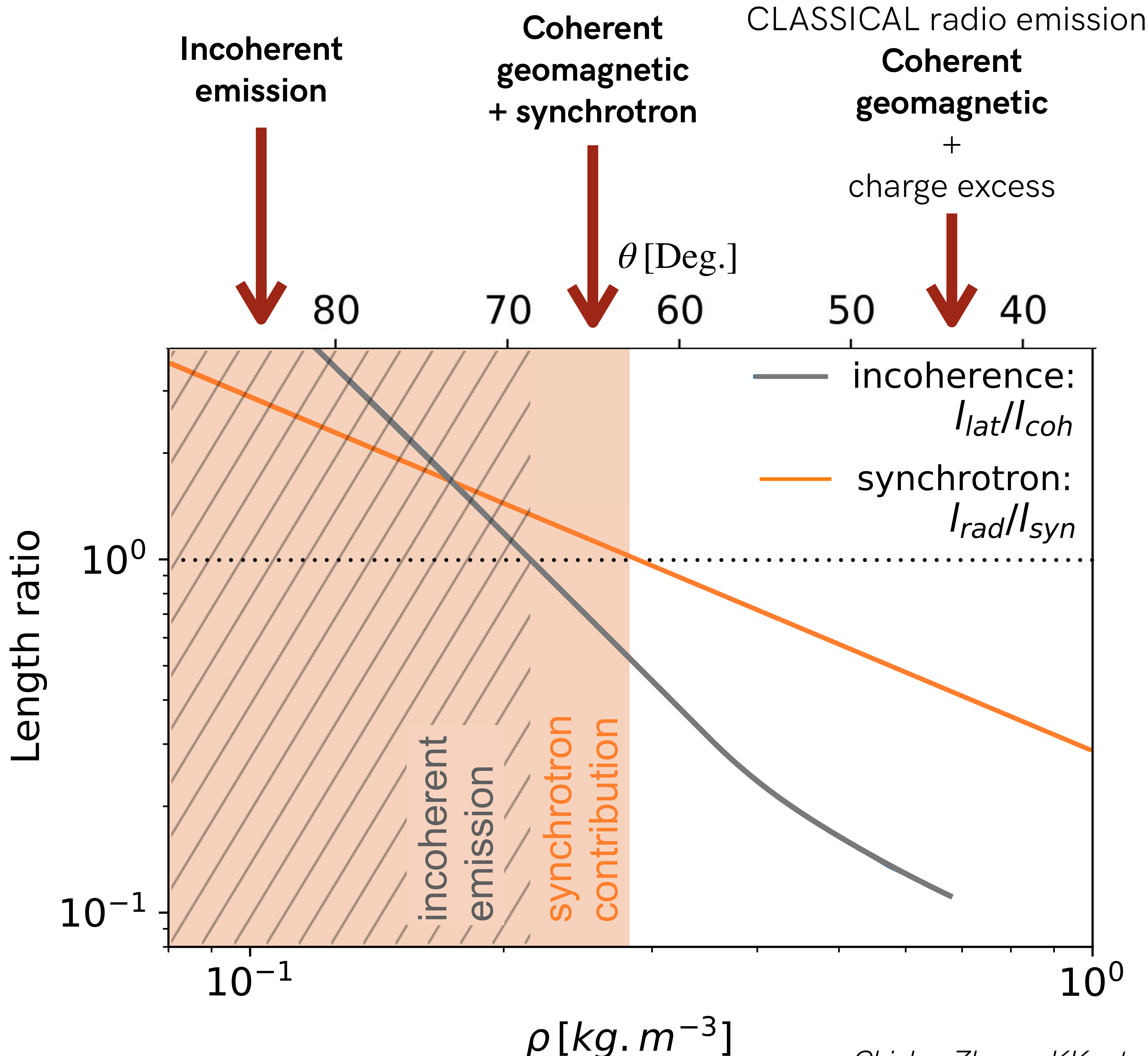
Inelastic collision radiation length

$$l_{rad} = X_0/\rho_{air} \sim 3.67 \times 10^3\,\mathrm{m}\,(\rho_{air}/1\,\mathrm{g\,cm^{-3}})^{-1}$$

Synchrotron cooling length

$$l_{syn} = (\epsilon_e/88\,\mathrm{MeV})^{\frac{2}{3}}(B/50\,\mu\mathrm{T})^{-\frac{2}{3}}(\nu/80\,\mathrm{MHz})^{-\frac{1}{3}}$$

New paradigm for inclined air-showers

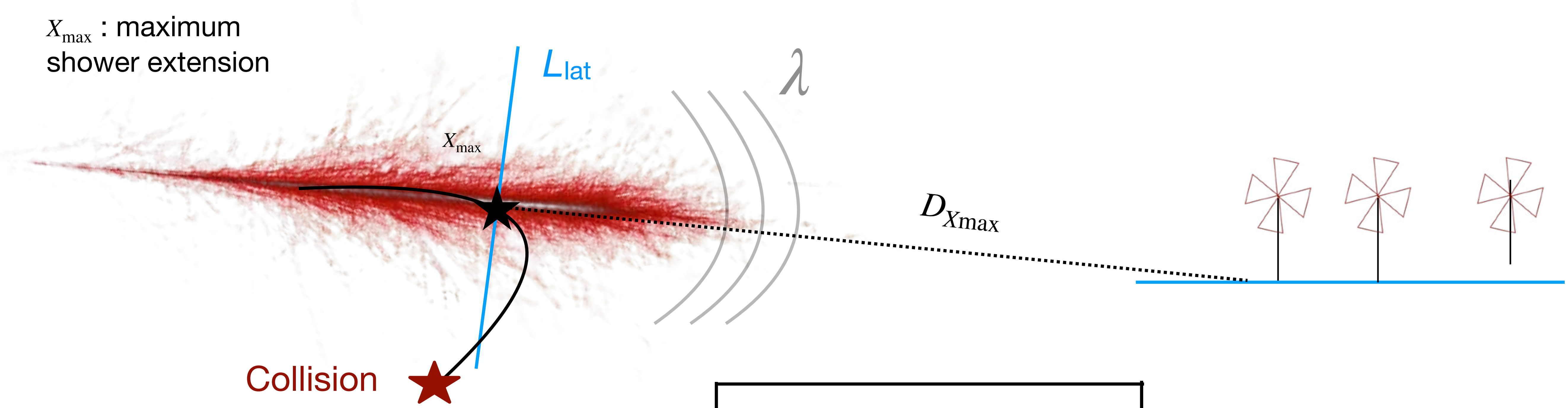


Chiche, Zhang, KK, et al. in prep.

Conditions for a coherent radio signal

→ Strong radio emission only if shower lateral extent shorter than coherence length

$$L_{\rm lat}(\rho_{\rm air}, B_{\rm Earth}) > l_{\rm coh}$$



Spatial coherence length: $$l_{\rm coh} = \lambda D_{\rm Xmax}/L_{\rm lat}$$? From ZHAireS simulations

Shower lateral extent: $$L_{\rm lat} = x_{\rm transverse}(t=\tau)$$ τ: characteristic time of inelastic collision

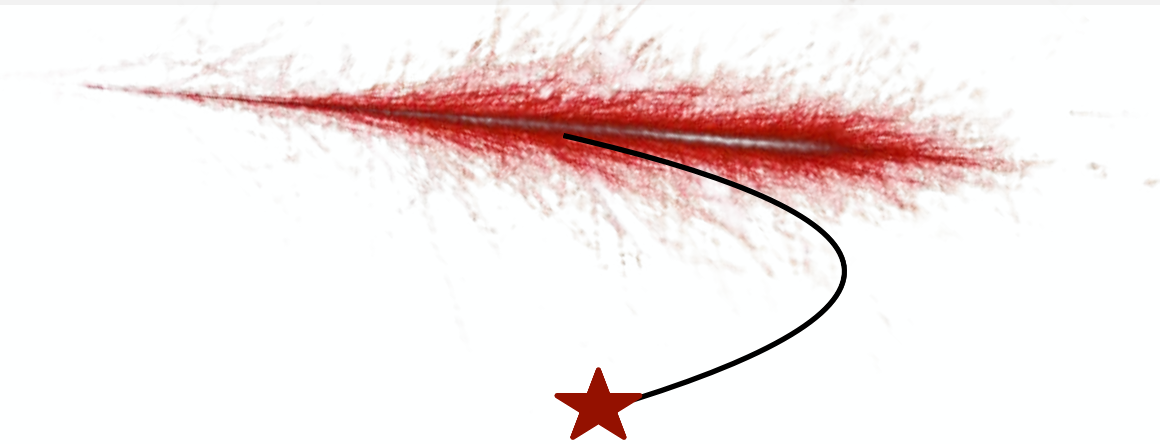
Transverse velocity: $$v_{\rm transverse}(t) = \frac{\tau c^3 e B_{\rm Earth}}{\mathcal{E}(t)}(1 - e^{-t/\tau})$$ (Scholten et al., 2007)

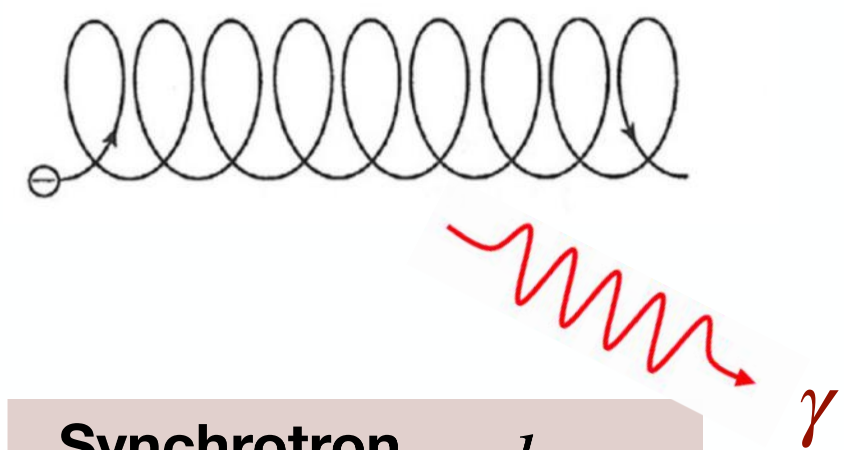
Transverse position: $$x_{\rm transverse}(t) = \frac{\tau^2 c^3 e B_{\rm Earth}}{\mathcal{E}_0}(e^{t/\tau} - 1 - \frac{t}{\tau})$$

see also Marion's studies on particle distribution in air-showers!

Condition for synchrotron emission

see also C. James (2022)





Inelastic collision radiation length $l_{\rm rad}$

Synchrotron cooling length $l_{\rm syn}$

$$l_{\rm rad} = X_0/\rho_{\rm air} \sim 3.67\times10^3\,{\rm m}\,(\rho_{\rm air}/1\,{\rm g\,cm^{-3}})^{-1}$$

$$l_{\rm syn} = 1157\,{\rm m}\,(\epsilon_e/88\,{\rm MeV})^{\frac{2}{3}}\,(B/50\,\mu{\rm T})^{-\frac{2}{3}}\,(\nu/80\,{\rm MHz})^{-\frac{1}{3}}$$

Synchrotron emission becomes important if the synchrotron cooling length is shorter than the inelastic collision length

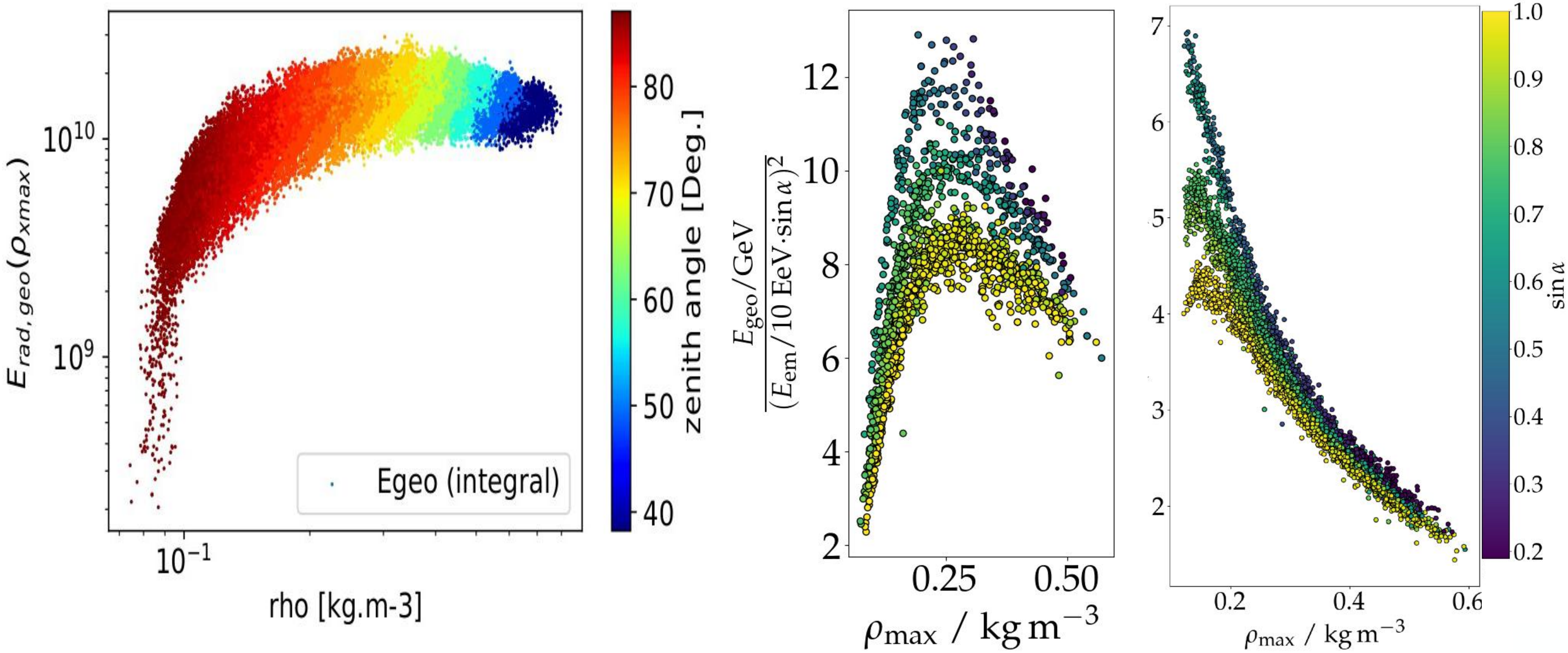
$$l_{\rm syn}(B_{\rm Earth}) < l_{\rm rad}(\rho_{\rm air})$$

$$\frac{l_{\rm syn}}{l_{\rm rad}} \sim 3.15\left(\frac{\epsilon_e}{88\,{\rm MeV}}\right)^{\frac{2}{3}}\left(\frac{B}{50\,\mu{\rm T}}\right)^{-\frac{2}{3}}\left(\frac{\nu}{80\,{\rm MHz}}\right)^{-\frac{1}{3}}\left(\frac{\rho}{1\,{\rm kg.m^{-3}}}\right)$$

Signature of coherence loss

Tests for 2 different B_{Earth} values @GRAND/Auger sites, with ZHAiReS and CoREAS simulations

ZHAiReS, GRAND B_{field} *CoREAs, GRAND* B_{field} *Auger* B_{field}

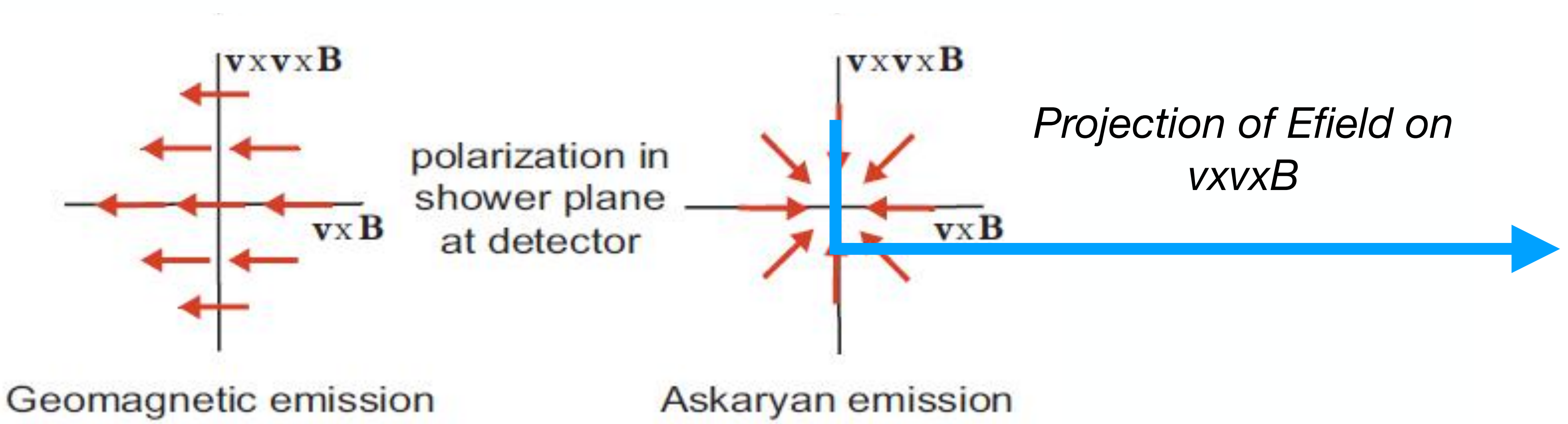


Almost 1.5 order of magnitude cut-off in the signal for GRAND B_{field}!

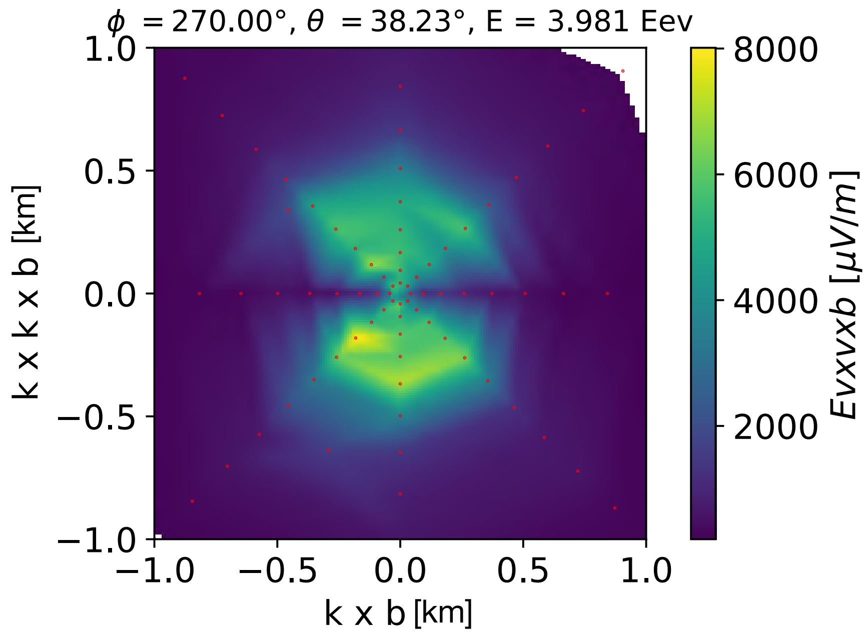
Almost no cut-off in the geomagnetic emission for Auger B_{field}

Synchrotron signature: the clover-leaf pattern

$v \times v \times B$ **component: dominant contribution of Askaryan emission?**

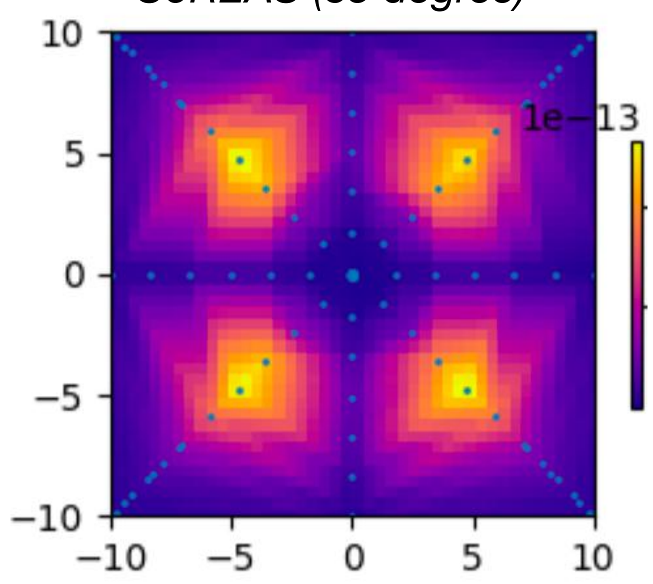


Expected pattern

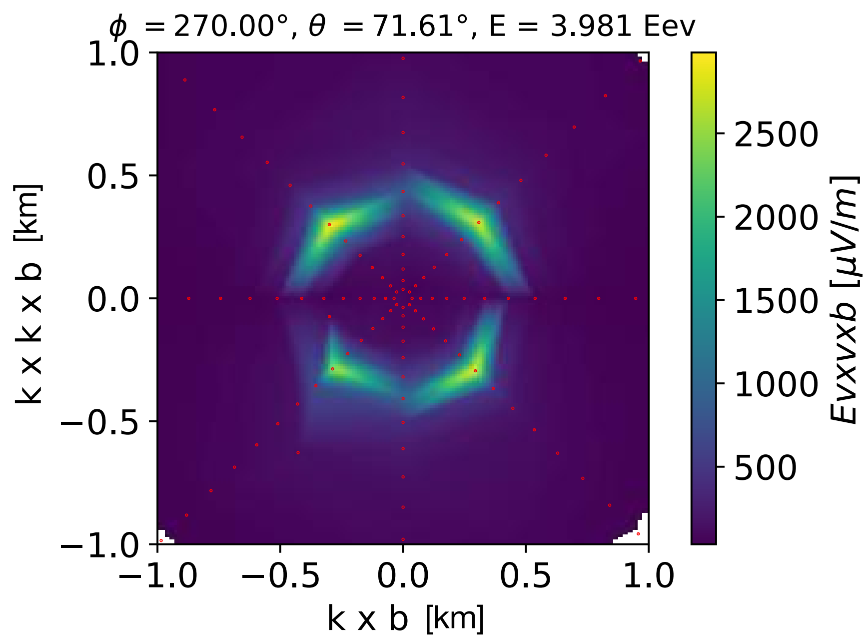


Observed pattern: clover-leaf

CoREAS (85 degree)



ZHAireS



New polarization signature on the $v \times v \times B$ component!

- ~ 10% of the total emission for inclined showers
- Observed in simulations for the 3.4-4.2 GHz band only here $\mathcal{O}(100\,\mathrm{MHz})$

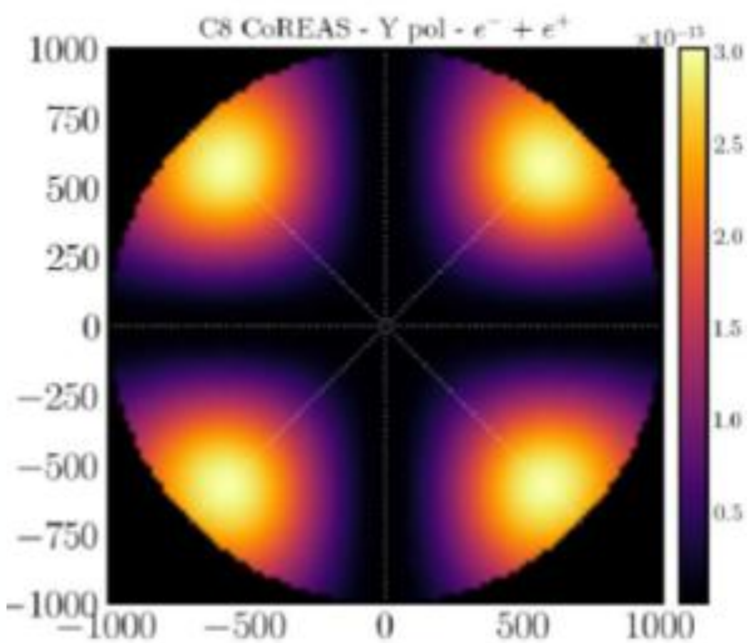
(Huege 2013, CROME data)

Clover-leaf pattern: hints for a third type of emission dominant over the charge excess for inclined EAS

Simulation of an $e^{+/-}$ pair in a uniform B_{field} with Corsika8

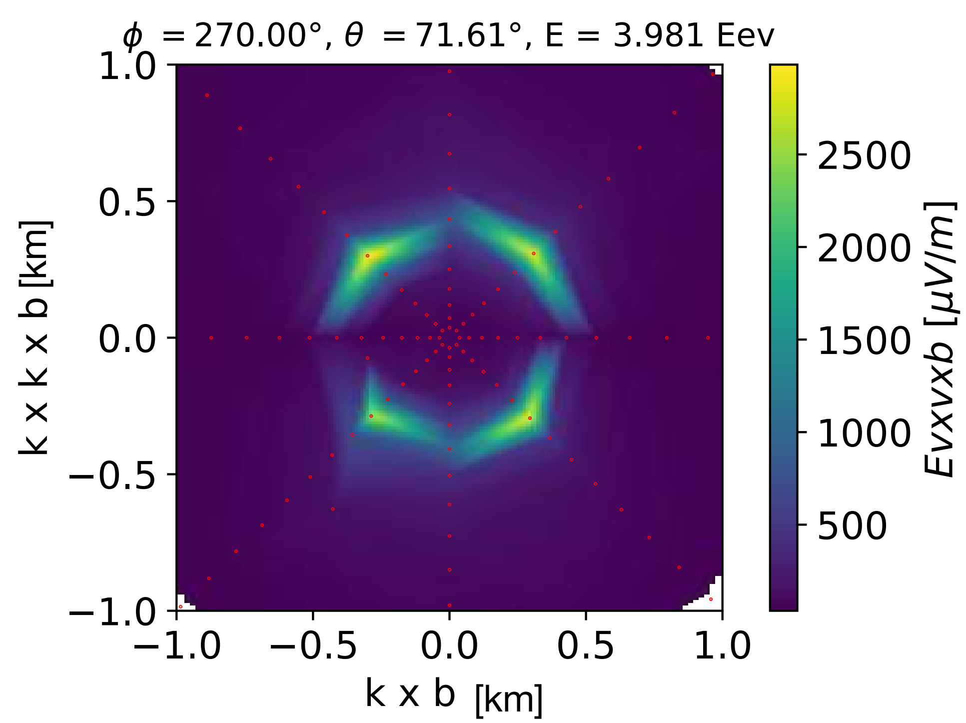
Particles with same energy, starting vertically downwards, observer on the symmetry axis

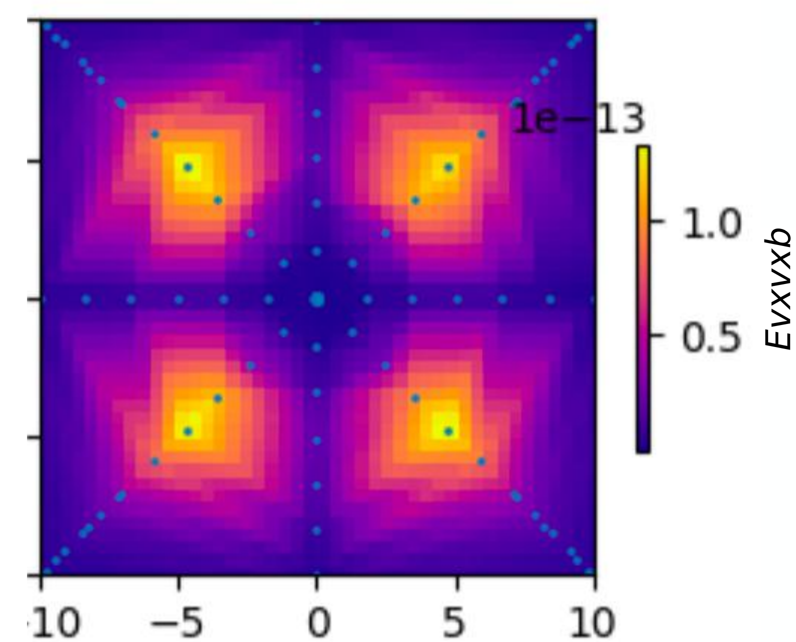
Synchrotron predictions



Credits to Nikolaos Karastathis

Clover-leaf pattern

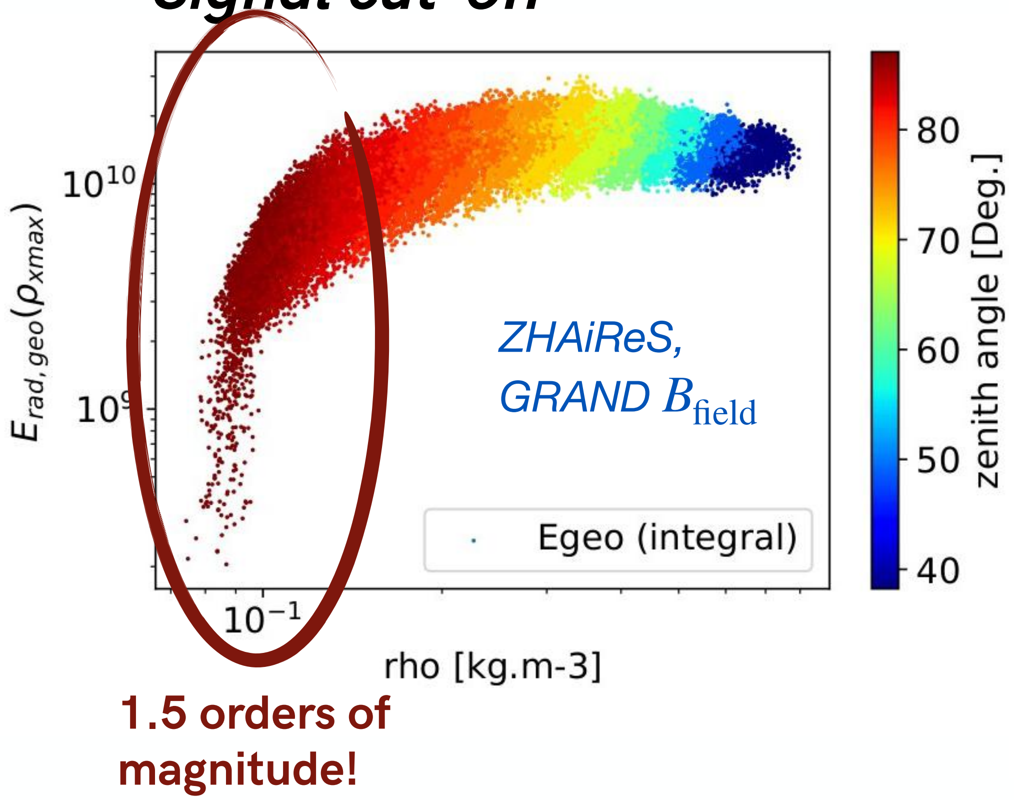


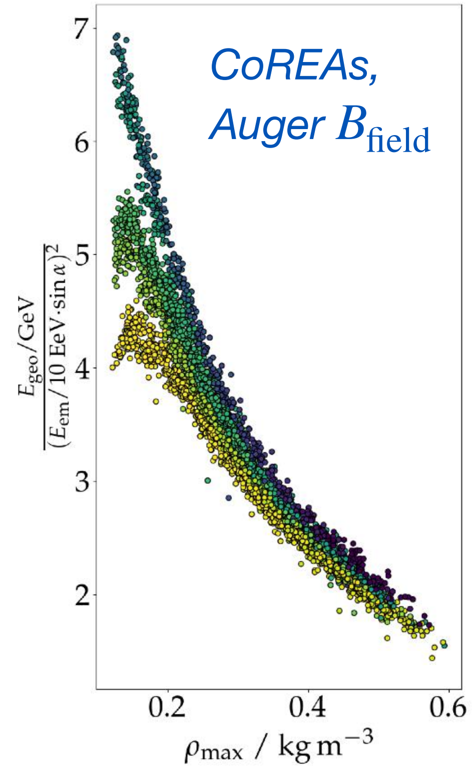


Synchrotron emission of an $e^{+/-}$ pair leads to a clover-leaf like polarization pattern!

New signatures in the radio signal!

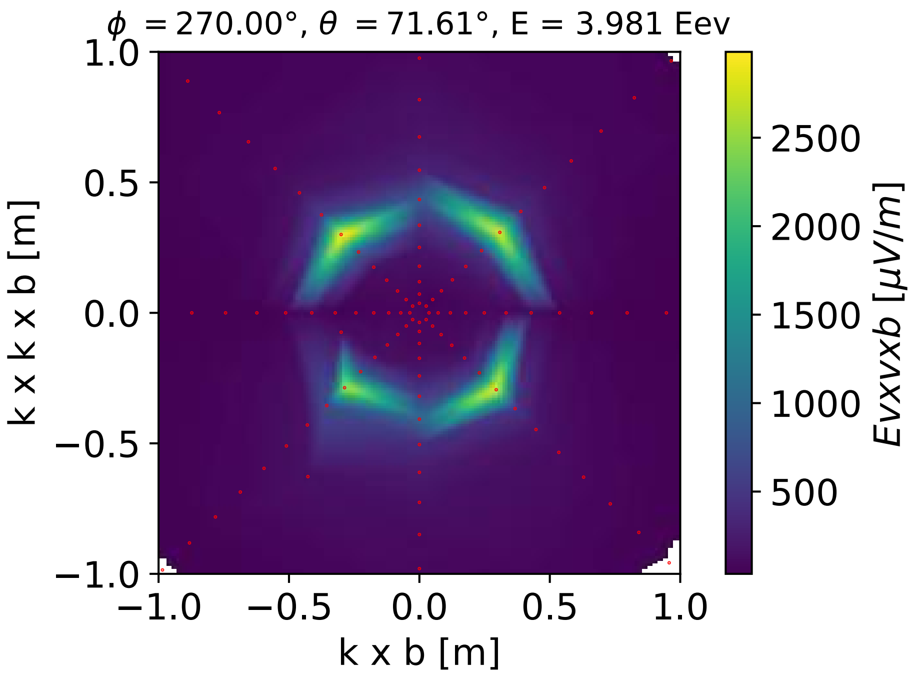
Signal cut-off





Linked to a loss of coherence

Clover-leaf pattern



Linked to synchrotron radiation

Geomagnetic + Askaryan description no longer valid for very inclined air-showers

Could strongly affect detection strategies of future experiments

Could help for cosmic-ray/neutrino discrimination

Simon Chiche, *Zhang, KK, Huege, de Vries, Prunet, Schlüter, Tueros, in prep.*

Marion Guelfand, Simon Chiche, *KK, Prunet, in prep.*