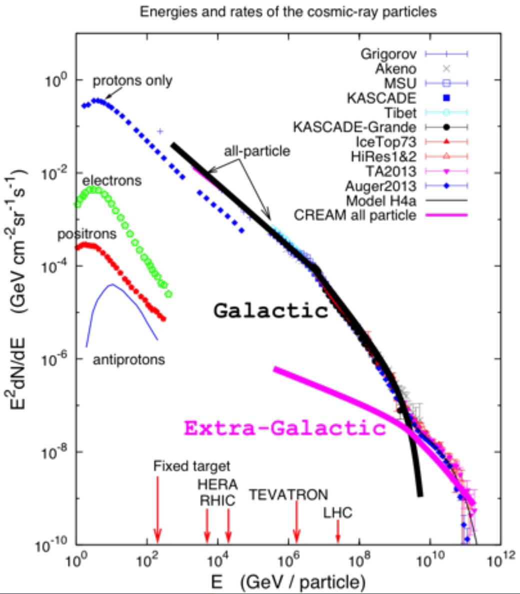
Towards identifying the sources of Ultra-High Energy Cosmic Rays with the GRAND experiment

Lech Wiktor Piotrowski

University of Warsaw

HEP seminar, 19.V.2023

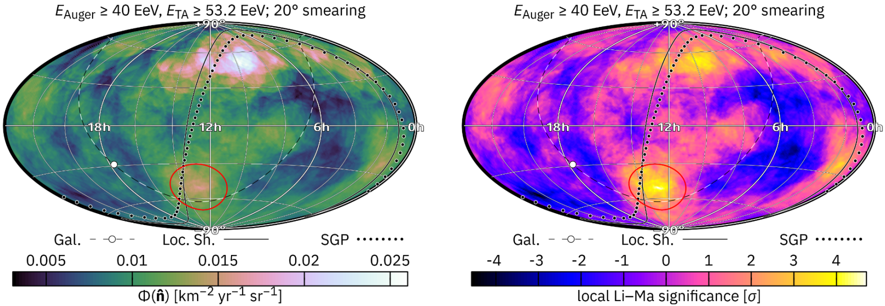
Cosmic rays spectrum



Main UHECR questions:

- Sources
- Composition
- Spectrum

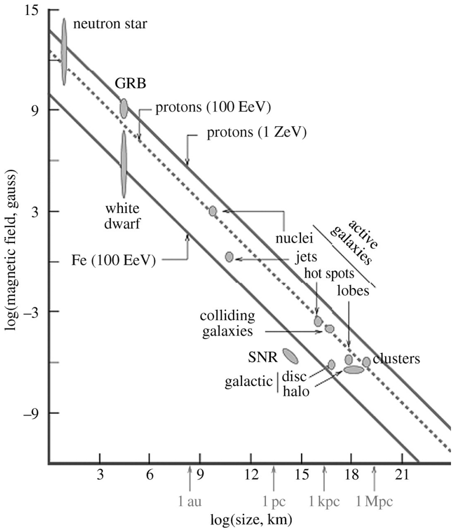
UHECR sky map



A. di Matteo et al., ICRC 2019

Possible UHECR sources

- Bottom-up scenarios – acceleration in electromagnetic fields



Possible UHECR sources

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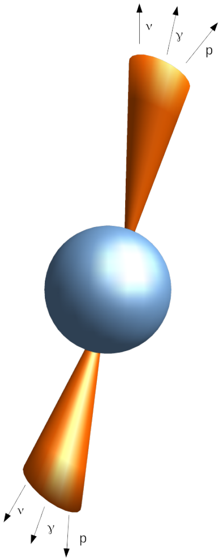
- Top-down scenarios
  - Super-heavy Dark Matter – mass $>10^{21}$ eV, decays to UHECR/UHEν/UHEγ



Possible UHECR sources

- Bottom-up scenarios – acceleration in electromagnetic fields
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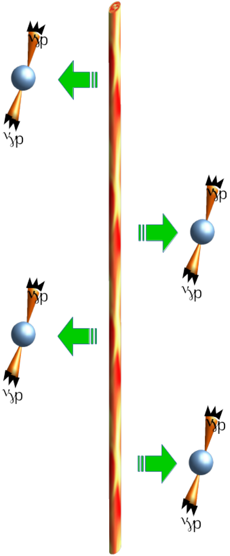
  - Topological defects – decays to super-heavy particles which decay to UHECR/UHEν/UHEγ



Possible UHECR sources

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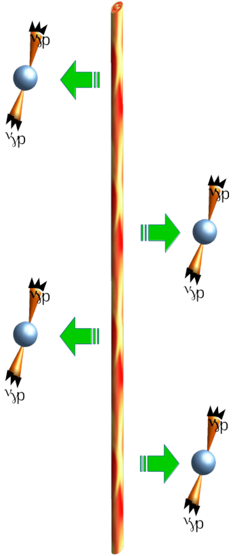
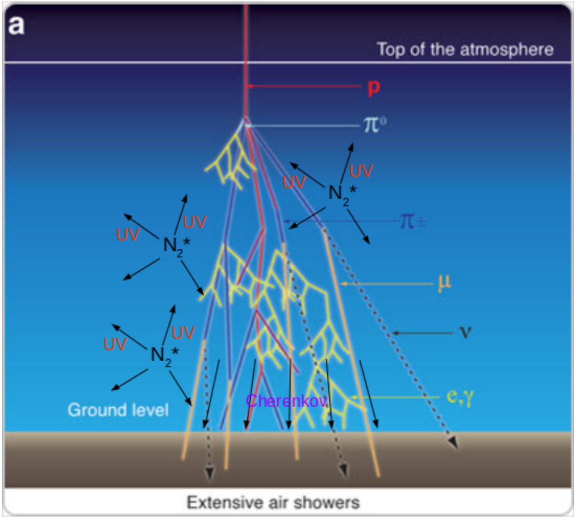
- Top-down scenarios
  - Super-heavy Dark Matter – mass $>10^{21}$ eV, decays to UHECR/UHEν/UHEγ
  - Topological defects – decays to super-heavy particles which decay to UHECR/UHEν/UHEγ
- Limits on UHE gammas and neutrinos strongly favour bottom-up scenarios as the main source of UHECR



Extensive Air Shower



Cascade of secondary particles (EAS) produces UV radiation (excited nitrogen fluorescence), Cherenkov radiation and... radio waves

EAS observables

What do we try to measure/estimate?

- EAS axis direction → incoming direction of the primary particle
- EAS energy → primary particle's energy
- EAS Xmax – distance to where the number of secondaries was maximal → mass and thus type of incoming particle

What these observables tell us?

- Direction – possible astrophysical source identification
- Energy and Xmax – physical mechanism of acceleration / astrophysical source type

Direct detection of secondary particles

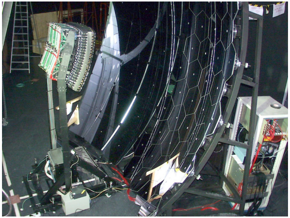
- Secondary particles reaching the ground: muons (>50%), electrons, gammas, positrons, neutrinos...
- Surface detectors detecting them through direct interaction

Auger surface detector: a water cherenkov tank

Telescope Array surface detector: a plastic scintillator

Fluorescence (luminance) detection

- Secondaries excite atmospheric nitrogen
- Nitrogen emits isotropic light mostly in near-UV ($\sim 320, 340, 360$ nm)
- An EAS travelling through the sky is seen by telescopes from the side



Auger fluorescence telescope

Telescope Array fluorescence telescope

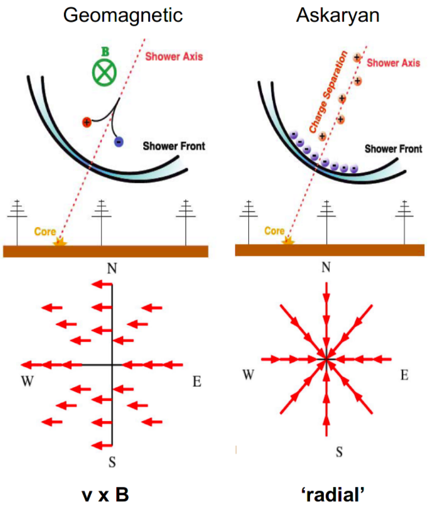
Detection of Cherenkov emission

- A cone of 300-1000 nm light is produced along the EAS axis
- Can be detected by a fast ($\sim$ 10 ns res.) telescope
- Cone diameter is $\sim$ 120 m on the ground – not feasible for on-ground in-air detection
- Could be detected from space
    - Direct Cherenkov – for Earth-skimming neutrinos induced EAS (upward-going). Cone much bigger due to distance and thin air.
    - Reflected Cherenkov – from downward going EAS, scattered light
- The main method for detection of neutrinos in ice and water

IceCube's PhotoMultiplier Tube

Radio emission from EAS

- **Geomagnetic:** Main contribution from electric current perpendicular to the EAS axis from separations of e^+ and e^- by geomagnetic field
- **Askaryan / charge excess:** $\sim$ 10% contribution from excess of e^- in the EAS front due to e^+ annihilation
- In both cases we have an "electrical current" generating a $\sim$ 10 ns radio pulse
- "Cherenkov"-like effects: radio pulse is compressed due to varying refractive index of air



Credit: T. Huege, ICRC2013

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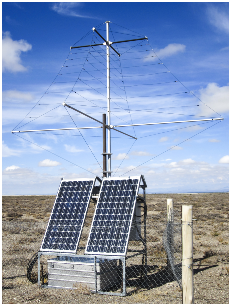
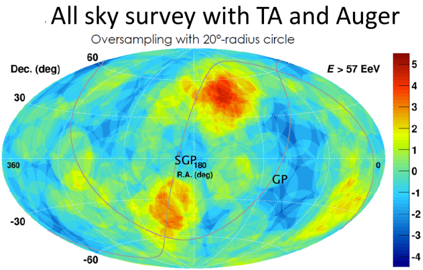
- In both cases we have an "electrical current" generating a ~ 10 ns radio pulse
- "Cherenkov"-like effects: radio pulse is compressed due to varying refractive index of air
- The radio waves can be detected by simple radio antennas

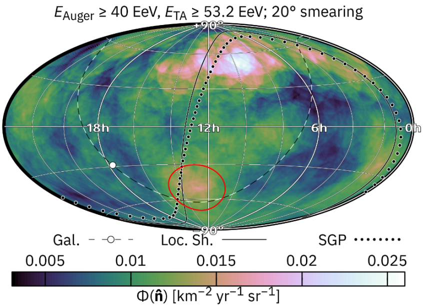


AERA antenna (AUGER)

LOFAR antenna



H. Sagawa, CRIS 2015

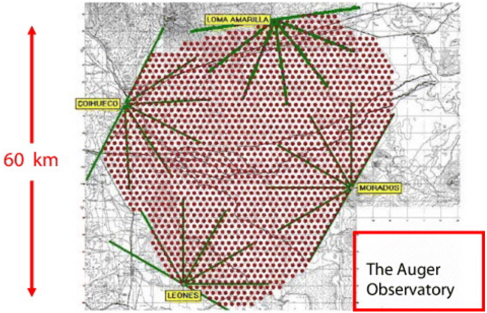


A. di Matteo et al., ICRC 2019

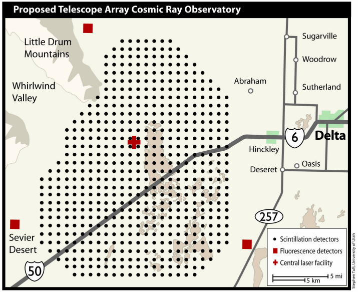
Not much closer to detecting sources in 4 years...

How to find UHECRs sources?

...and that despite huge covered areas



Pierre Auger Observatory – $\simeq 3000$ km^2



Telescope Array – $\simeq 762$ km^2

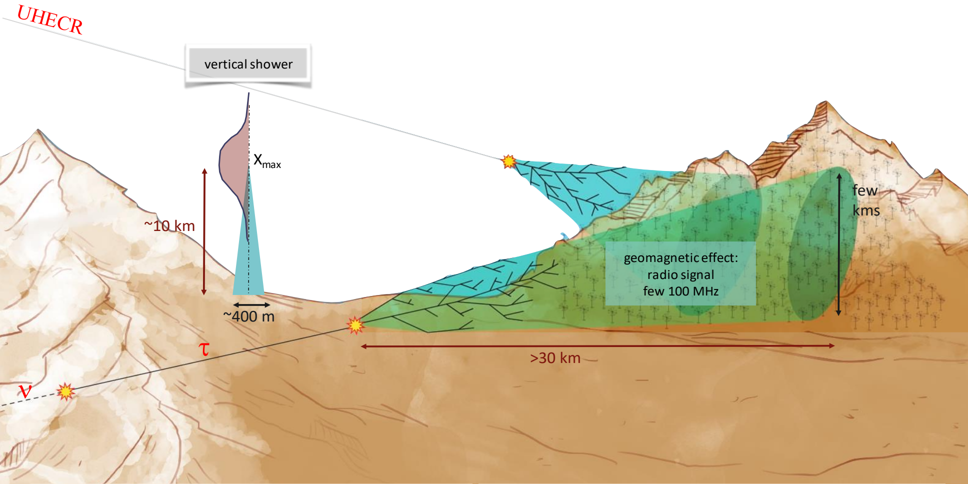
How to find UHECRs sources?

Solutions

- Increase the atmosphere coverage
  - Use a different experimental idea (eg. observations from the orbit with JEM-EUSO/Poemma)
  - Use different (more efficient and cheaper) detection methods to cover more ground
- Reduce the angular uncertainty
  - Observe UHE neutrinos from UHECR ($\sim$ 5% of the primary energy) that travel in straight line from the source

Giant Radio Array for Neutrino Detection – GRAND – aims at both increasing the atmoshpere coverage and observing the UHE neutrinos

Radio detection of ultra-high-energy air-showers in GRAND

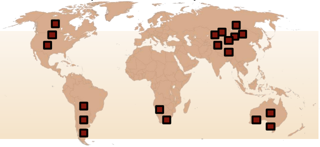


radio detection: a mature technique
AERA, LOFAR, CODALEMA, Tunka-Rex, TREND

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

slide by Kumiko Kotera

The GRAND Concept



200'000 radio antennas over 200'000 km^2
~20 sub-arrays of 10'000 antennas
over favorable sites worldwide

China

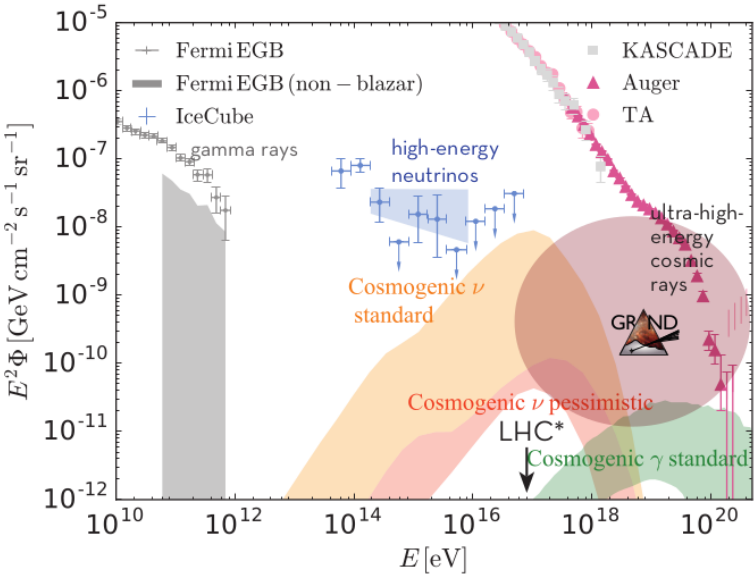
Argentina

- ✓ 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)

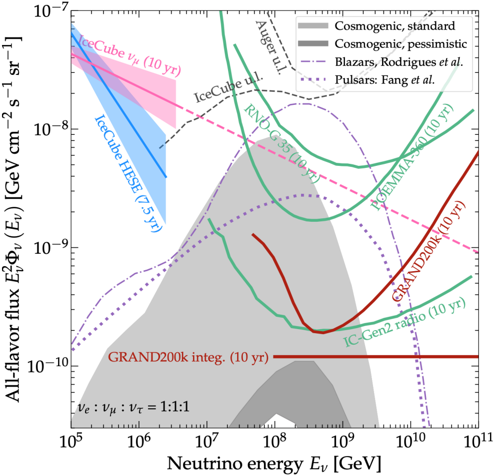
slide by Kumiko Kotera 8

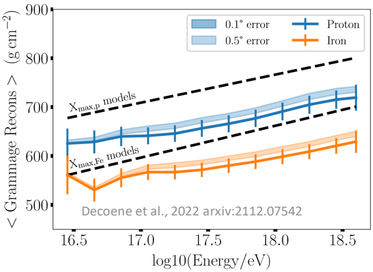
GRAND spectral range

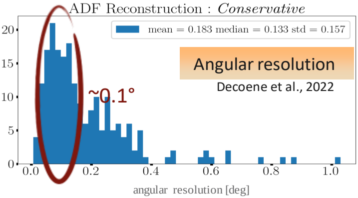


Simulated performances

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







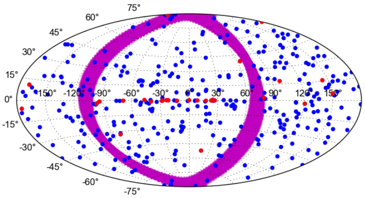
- GRAND full sensitivity to neutrinos (E>10^{17} eV) ~4 x 10^{-10} GeV cm^{-2} s^{-1} sr^{-1}
- Angular resolution ~0.1° for GP300 & GRAND — Decoene et al., 2022
- Energy resolution < 10% on air-showers for GP300 & GRAND — B. Lago & Rio GRAND team
- X_{max} resolution < 40 g/cm² for E>10^{17} eV (comparable to other methods) — Decoene et al., 2022

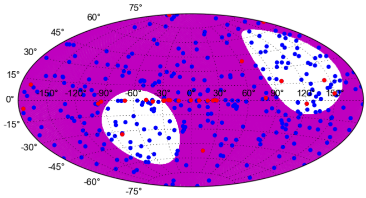
slide by Kumiko Kotera

GRAND sky coverage

Visibility for 1 sub-array (10,000 antennas) @ 43°N

1 h | 24 h





- 80% full sky coverage in 24 h for GRAND10k
- 107,000 km^2 sr exposure per year above 1 EeV for GRAND200k

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 30 d	6	<2.8°
ARA	3.6×10^{-9} (2030)	35	5°
RNO-G	1×10^{-8} in 5 yr	30	2°×10°
ARIANNA-200	8×10^{-9} in 5 yr	50	2.9–3.8°
RET-N	3×10^{-10} in 5 yr	50	?
IceCube-Gen2 Radio	4×10^{-10} in 5 yr	43	2°×10°
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°

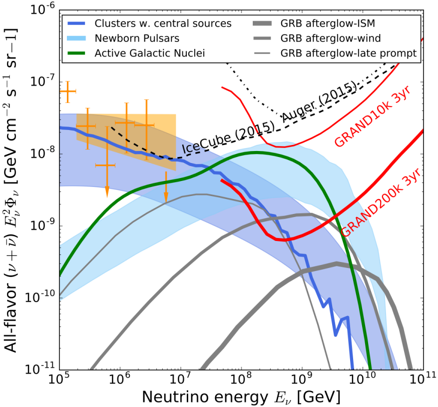
adapted from Guépin, KK, Oikonomou, Nature Phys. Rev. 2022

	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 deg²	0.2°
gamma	INTEGRAL SPI-ACS	4π	-
X	XMM-Newton	0.5°	6"
X	Athena-WFI	0.4 deg²	< 5"
multi	Swift BAT	1.4 sr	0.4°
multi	Swift XRT	0.1 deg²	18"
multi	Swift UVOT	0.1 deg²	2.5"
multi	SVOM ECLAIRs	2 sr	< 0.2°
multi	SVOM MXT	1 deg²	13"
multi	SVOM VT	0.2 deg²	< 1"
IR/optical/UV	ASAS-SN	72 deg²	7.8"
IR/optical/UV	ATLAS	29 deg²	2"
IR/optical/UV	Pan-STARRS	14 deg²	1.0–1.3"
IR/optical/UV	ZTF	47 deg²	2"
IR/optical/UV	Vera Rubin Obs. (LSST)	9.6 deg²	0.7"
IR/optical/UV	MASTER-II(VWF)	8(400) deg²	1.9" (22")
IR/optical/UV	TAROT	4 deg²	3.5"
IR/optical/UV	GEMINI (GMOS)	30.23'²	0.07"/pix
IR/optical/UV	GTC (OSIRIS)	0.02 deg²	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 deg²	0.12"
radio	MWA	610 deg²	0.9'
radio	SKA1(2)-MID	1(10) deg²	0.04°–0.7"

slide by Kumiko Kotera

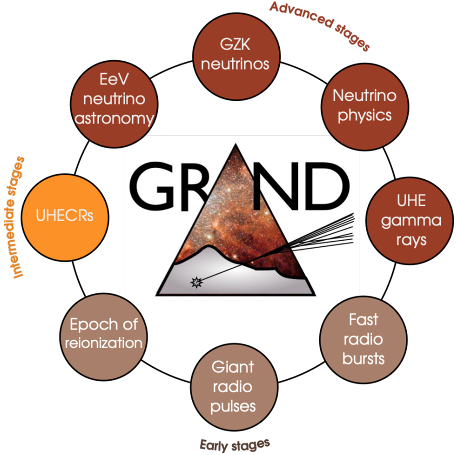
Detection of neutrinos from point sources

- GRAND10k have a chance to detect ν from pulsars after 3 years
- GRAND200k should see ν from clusters, AGNs and some GRBs
- Achievable with 100s of events and $\sim 0.3^\circ$ angular resolution
- Pessimistic cosmogenic ν scenarios help point sources' detection (lower background)



GRAND science case

- UHE neutrinos
  - point sources
  - cosmogenic flux
- UHECR
  - 20 times the exposure of Auger
    - 1 yr: GRAND 6400, Auger 320 events $> 10^{19.5}$ eV, GRAND 150, Auger 8 events $> 10^{20}$ eV
  - transition from galactic to extragalactic, north-south anisotropy
  - hadronic physics
- neutrino physics (cross-sections, flavour ratios)
- UHE gamma-rays observations/competitive limits
- Radio astronomy
  - almost full-sky survey
  - FRBs and Giant Pulses



A staged approach with self-standing pathfinders

	Prototyping	GRAND10k	GRAND200k
	2023	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-arrays (x2) • 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

slide by Kumiko Kotera

Autonomous triggering on radio signal

Status for existing experiments:

- Antarctic (super low-noise) experiments, like ANITA, trigger on radio signal
- All non-antarctic experimens (AERA, LOFAR, etc.) are externally triggered (particle detectors)
- But past TREND experiment (a precursor to GRAND) managed to register UHECR with a radio trigger

To trigger on radio signal, we need:

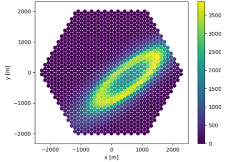
- Very radio-quiet environment
- Optimised antennas
- Electronics and software capable of 10^8 rejection rate
- Motivation – we can not do it differently

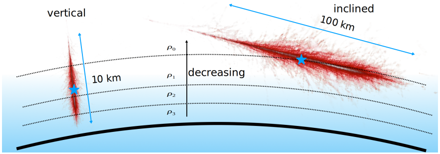
TREND showed that it can be done, GRAND needs to (vastly) optimise it

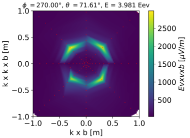
Very inclined EAS reconstruction

How to find primary particle's direction, energy and mass (Xmax)?

- Mature methods for radio for... vertical showers
- Current experiments' sensitivity to very inclined shower is very low
- For very inclined showers terra incognita, but we can start with same methods, and add "our" features







- Strong, accessible Cherenkov-like ring in our frequency range
- Assymetric atmosphere for the shower → synchrotron effect → cloverleaf pattern
- Still studied in simulations

Other challenges

- How to deploy 200,000 antennas
- How to put them on slopes
- Power/connectivity
- How to maintain a huge site
- Finding sites
- Financing...

Hardware

100 detector units ready for deployment:

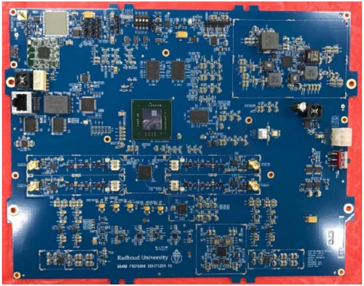
- A butterfly antenna
  - 3 arms: x,y: 2×65 cm, z: 65 cm
  - On a 3.5 m pole

5 detection units tests at Xi'An (by Zheng PengFei)

Hardware

100 detector units ready for deployment:

- A butterfly antenna
  - 3 arms: x,y: 2×65 cm, z: 65 cm
  - On a 3.5 m pole
- Front-end electronic:
  - 30-230 MHz analogue filtering (to be used: 50-200 MHz)
  - 500 MS/s digitisation
  - Xilinx Zync MPSoC (FPGA+2 CPUs+2 RT CPUs)
  - Bullet WiFi data transfer



GRAND: software/simulations/other status

Software

Data format:
- *Idea:* raw/sim → ROOT TTrees
- *Status:* in validation for raw data and ZHAireS, in preparation for CoREAS

Data analysis:
- GRANDlib – Python + C(++) speedups/alternatives
- *Status:*
  - Preliminary energy reconstruction with GRANDlib and CoREAS working
  - Own topography module
  - GRANDlib enhancements in progress (electronic chain simulation, reconstruction, etc.)

Other

Carbon footprint:
- Estimated in 10.1016/j.astropartphys.2021.102587
- GRAND Green Policy validated

Simulations

ZHAireS:
- Migration to ZHAireS 1.0.30a on Aires 19.04.06 now
- For big studies, interpolation used (*M. Tueros and A. Zilles 2021 JINST 16 P02031*)
- ZHAireS 1.1 in progress → more accurate description of the atmosphere using GDAS

CORSIKA7/CoREAS:
- Generated big library of inclined showers
  - Up-going showers handling in progress (*Chao Zhang et al., PoS(ICRC2021)248*)

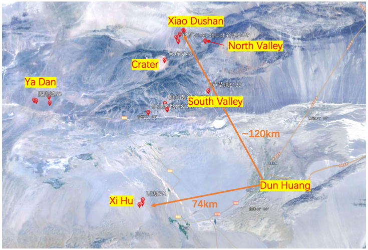
Radio-morphing:
(*A. Zilles et al., 10.1016/j.astropartphys.2019.06.001*)
- Good agreement with microscopic simulations
- New scaling laws and new interpolation → better accuracy of the peak time and amplitude of the interpolated pulse (*Chiche et al., PoS(ICRC2021)194*)

MGMR3D:
(*O. Scholten et al., Phys. Rev. D 97, 023005*)
- Some effort on adaptation from LOFAR to GRAND

Slide by Kumiko K

GRANDProto13

- 13 antennas deployed on private land in Xiao Dushan 3 months ago (by Xidian University and Purple Mountain Observatory)
- No remote access possible (because the site is remote)



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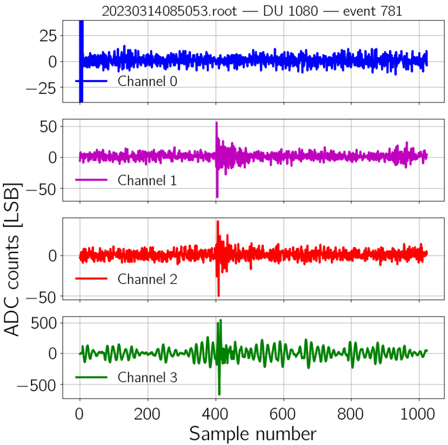
  - Boards overheating
  - Incoherent LNA gains



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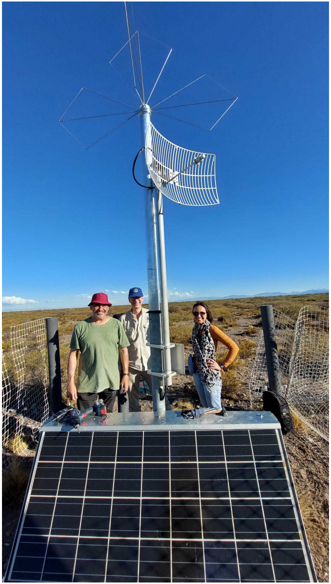
- Main, quickly identified issues:
  - Boards overheating
  - Incoherent LNA gains
- Cooling and new LNAs being installed now

GRAND@Auger

- 4 antennas at the Auger site in Malargue, Argentina (by Radboud University and Univeridad Federal do Rio de Janeiro)
- Attached to AERA infrastructure
- Hardware tests, cross calibration with Auger
- Data transfer and remote access possible through 4G



GRAND@Nancey

- 4 antennas deployed in Nancay Radio Observatory, France

GRAND@Nancey

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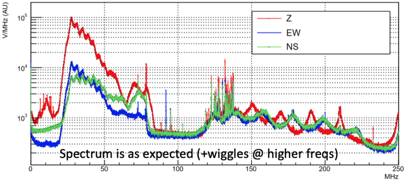
- Easy access (for Europeans)

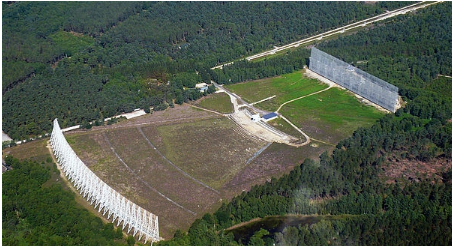
GRAND@Nancey

- 4 antennas deployed in Nancay Radio Observatory, France
- Easy access (for Europeans)
- Hardware tests only with easy access, too noisy for EAS



GRAND@Nancey

- 4 antennas deployed in Nancay Radio Observatory, France
- Easy access (for Europeans)
- Hardware tests only with easy access, too noisy for EAS
- Working on reducing EM noise



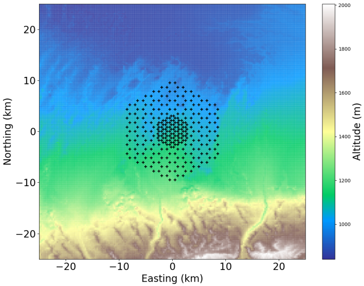
GRANDProto300

We are aiming to have 300 antennas deployed in 2024:

- In a hexagonal pattern with a 850 m side
- Over 200 km^2
- With a denser infill of 100 antennas to decrease the energy threshold
- In Gobi desert, Gansu province, China
- First 80 units still in 2023, hopefully

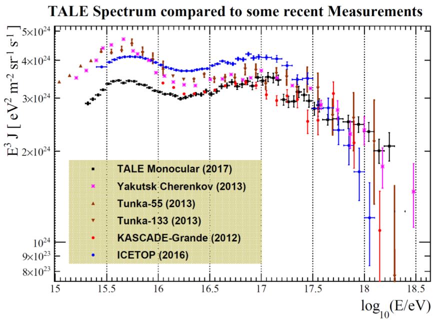
Goals:

- Large scale hardware test
- Autonomous level1 triggering
- Collection of events & bg for level2 design
- Inclined EAS reconstruction
- UHECR comparison with known results
- But also valuable new UHECR & UHEγ results



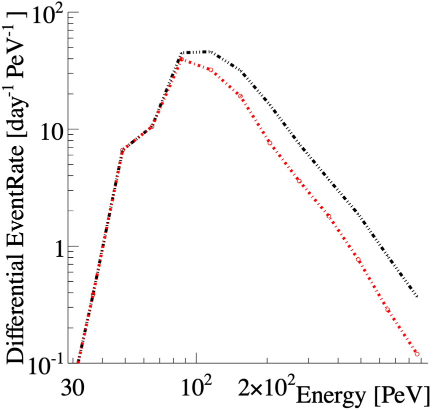
GRANDProto300 science

- GP300 will fill the instrumental gap in $10^{16.5} - 10^{18}$ eV range



GRANDProto300 science

- GP300 will fill the instrumental gap in $10^{16.5} - 10^{18}$ eV range
- Discover/constraining of low-energy large-scale Northern-Hemisphere anisotropy of size 0.01 (constraining existence of nearby UHECR sources)



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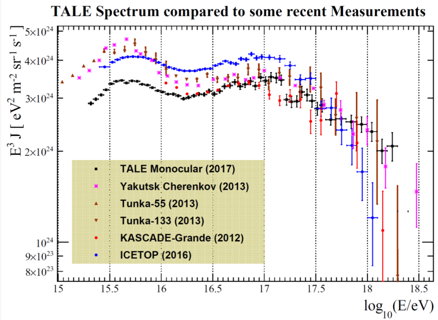
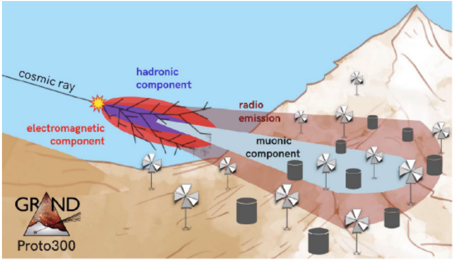
- GP300 will fill the instrumental gap in $10^{16.5} - 10^{18}$ eV range
- Discover/constraining of low-energy large-scale Northern-Hemisphere anisotropy of size 0.01 (constraining existence of nearby UHECR sources)
- With muon detectors:
    - study of transition between the Galactic and extra-galactic cosmic rays





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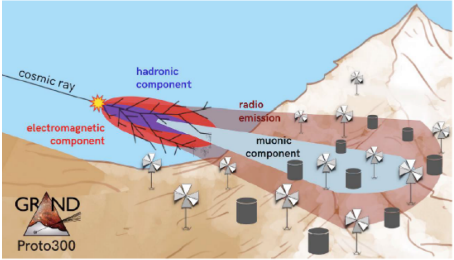
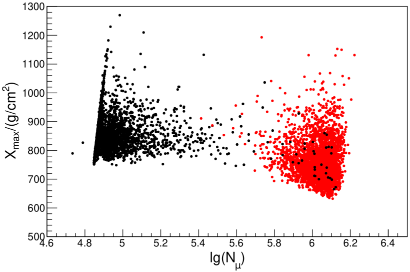
  - detection/limits on UHE gamma rays





Protons red, gamma black

GRANDProto300 science

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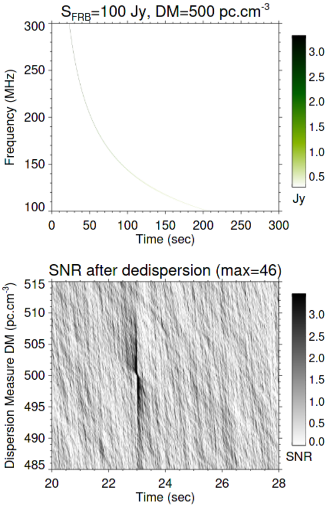
- Discover/constraining of low-energy large-scale Northern-Hemisphere anisotropy of size 0.01 (constraining existence of nearby UHECR sources)
- With muon detectors:
  - study of transition between the Galactic and extra-galactic cosmic rays
  - detection/limits on UHE gamma rays
- Radioastronomy: FRBs, giant pulses

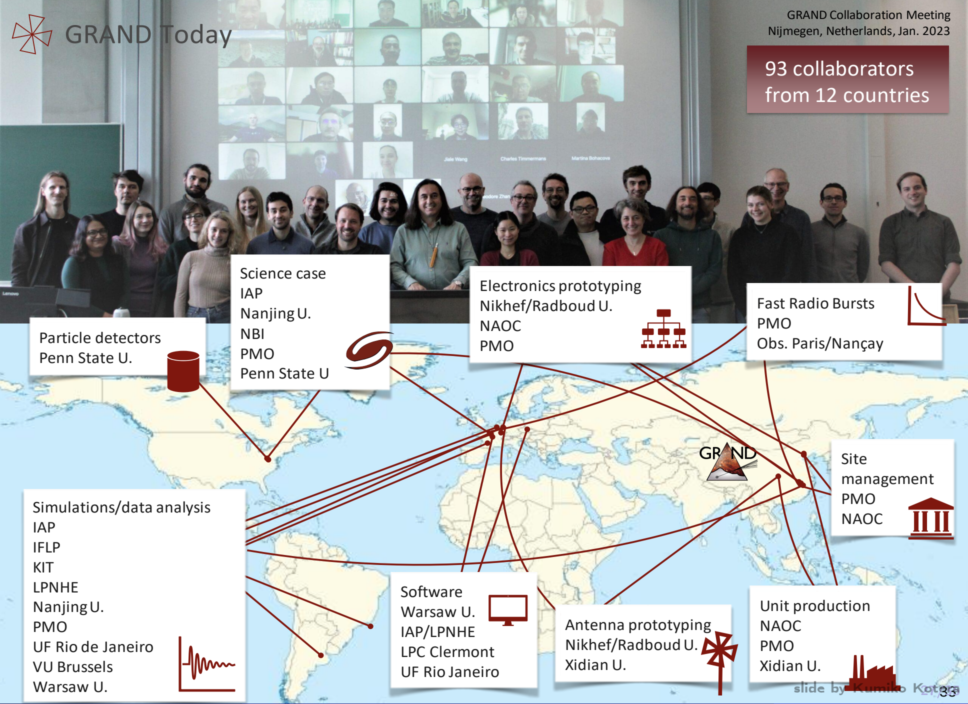


This is for GRAND200k. Peak SNR for the blind search is 46

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
Warsaw U.

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

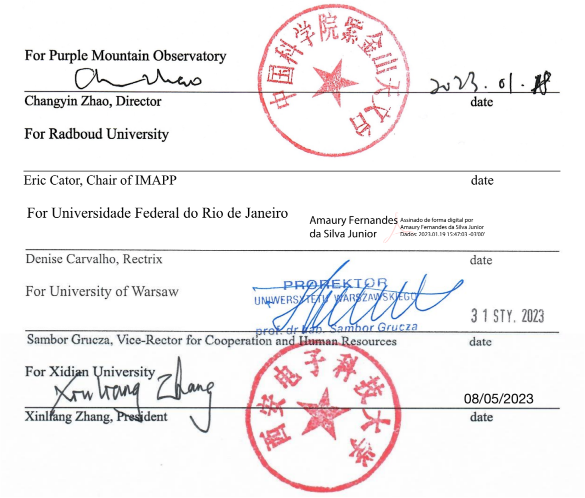
Antenna prototyping
Nikhef/Radboud U.
Xidian U.

Unit production
NAOC
PMO
Xidian U.

slide by Kumiko Kotera

GRAND Today

- Recently joined by Greece
- Memorandum of Understanding signed by 12 parties, including UW



For Purple Mountain Observatory

中国科学院紫金山天文台

Changyin Zhao, Director — 2023. 01. 18 — date

For Radboud University

Eric Cator, Chair of IMAPP — date

For Universidade Federal do Rio de Janeiro

Amaury Fernandes da Silva Junior — Assinado de forma digital por Amaury Fernandes da Silva Junior Dados: 2023.01.19 15:47:03 -03'00'

Denise Carvalho, Rectrix — date

For University of Warsaw

PROREKTOR UNIWERSYTETU WARSZAWSKIEGO prof. dr hab. Sambor Grucza — 31 STY. 2023

Sambor Grucza, Vice-Rector for Cooperation and Human Resources — date

For Xidian University

西安电子科技大学

Xinlfang Zhang, President — 08/05/2023 — date

Members of the Polish group

University of Warsaw, Faculty of Physics

- Lech Wiktor Piotrowski (PI)
- Pragati Mitra
- Szymon Sławiński (Master's Student)

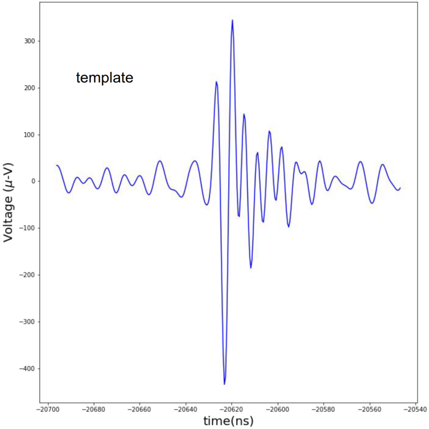
Our contributions: Software

- Data format definition and coding
  - Need to store ADC counts, Voltage, Efield, at different levels of processing
  - A ROOT based format with 11 ROOT TTrees
  - Conversion from hardware binary blob to TTrees
  - Conversion from simulators' data to TTrees (almost done)
- Inerfaces to data
  - Most people code in Python
  - Most people don't want to use ROOT directly
  - Python classes for i/o of TTrees → pure pythonic (no ROOT) syntax
  - An analysis oriented "Event" class that reads/writes data from/to multiple trees automatically
- A "clean", simulated Efield to ADC counts conversion chain

https://github.com/grand-mother

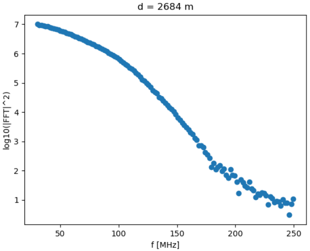
Our contributions: Offline signal identification

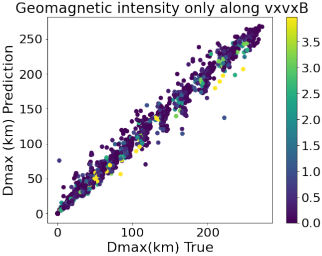
- GRANDProto300 will collect a lot of false events for study
- We need to find UHECR among them, offline
- Template matching algorithm based on simulations prepared and tested
- CNN based one class classifier in plans



Our contributions: Xmax reconstruction

- Available data:
  - Time tracers (signal vs time) of pulses for each antenna
  - Spectrum (FFT) of a pulse for each antenna
- Conventional:
  - Parametrize spectrum slope vs antenna position
  - Parametrize the above vs xmax
- Machine learning:
  - Feed integrated pulses, spectra slopes and antenna positions to decision trees





Possible collaborations with GRAND

- Data analysis preparation
  - Development of data analysis pipeline
  - Signal treatment - trigger
  - Methods and tools for air-shower parameter reconstruction
- Scintillators on GRANDProto300?
  - Development and installation of particle detectors
  - Testing coincident events
  - Drastically improved science case (muon discrepancy, UHE rays)
- GRAND10k R&D
  - Optimisation of mechanical design
  - Optimisation of power management
  - Optimisation of communications & trigger
- Developing multi-messenger analysis in GRAND
  - Messenger discrimination
  - Developing the alert system
  - Synergies with other instruments: TA, CTA, ALPACA, Tibet AS , ASHRA

Summary

The origin of cosmic rays of highest energies still remains a mystery

- Current on-ground experiments (Auger, TA) have small chances of finding it
- GRAND aims to solve it with:
  - A huge exposure (20 times that of Auger in UHECR)
    - covering vast amounts of ground with cheap, low-density radio antennas
    - observing very inclined EAS
  - Detection of UHE neutrinos, vastly reducing direction uncertainty

GRAND status:

- 3 small prototypes started data gathering recently
- With luck, 80 antennas of the GRANDProto300 still this year $\leftarrow$ UHECR science in $10^{16.5} - 10^{18}$ eV region
- With 10,000 antennas in $\sim$ 2025 a chance for first UHE neutrinos discovery
- With 200,000 antennas in 2030's a chance for UHE neutrinos astronomy
- GRAND appears in several roadmaps (APPEC, Snowmass 2022, ESPP 2020, etc.)

More details about the analysis in GRAND during HEP seminar by Pragati Mitra on 16.06.2023.

It is very exciting time with GRAND prototypes collecting first data!

You are most welcome to join the Polish GRAND group!

http://grand-observatory.org

GP300 HorizonAntenna and electronics

Antenna:

- Radiator size optimised for 50-200 MHz (2 times smaller than optimal for >30 MHz)
- Placed on 5 m pole
- diffraction scales as λ/h

Electronics:

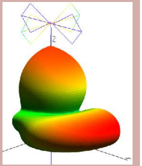
- Filtering analogue signal in 30-230 MHz
- Digitisation using 14-bit ADC (AD9694) with sampling rate of 500 Msamples/s
- Procesing in Zynq FPGA with CPU (Xilinx XCZU5CG)
  - removing narrow-band sources
  - fast logic trigger
  - real-time Fourier transform
  - timestamp of <10 ns (5 ns aim)
- CPU
- DAQ (expected 10 mHz, can accept 10 Hz)

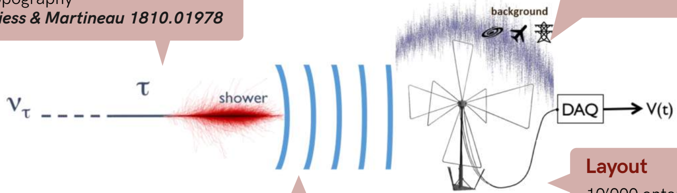
GRAND End-to-End simulation chain

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

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

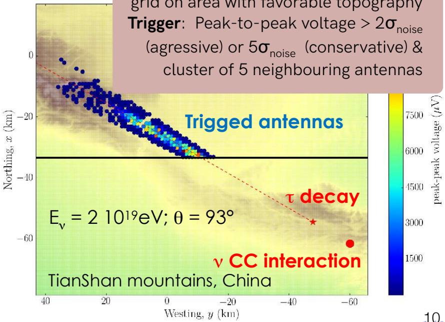




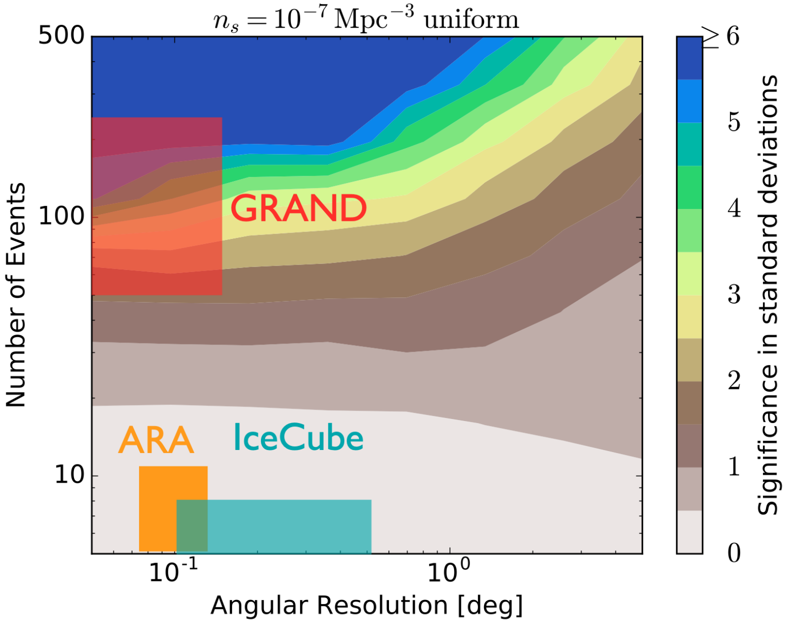
Radio-Morphing
semi-analytical computation of the air-shower-induced Efield transient signal.
A. Zilles et al. 2020, 1809.04912

Interpolation of radio signals
Tueros & Zilles arXiv:2008.06454

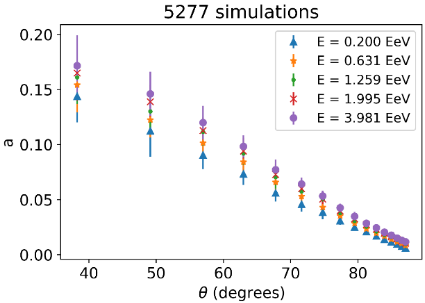
Layout
10'000 antennas with 1 km step square grid on area with favorable topography
Trigger: Peak-to-peak voltage > $2\sigma_{noise}$ (agressive) or $5\sigma_{noise}$ (conservative) & cluster of 5 neighbouring antennas

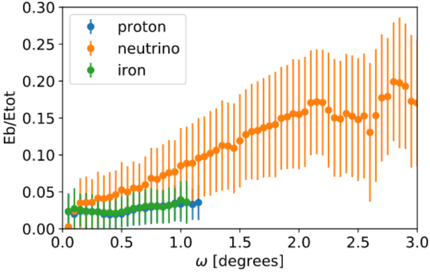


UHE neutrino sources - can we detect?



Polarisation helps





Source: S. Chiche

FRBs

- 580 – 2000 MHz
- Few dozens detected
- Few thousands should happen per day
- Few hundreds per day expected in GRAND (without pointing)
- ...if they extend below 200 MHz