LengHu, QingHai province, China
Home of the GRANDProto300 experiment

The Giant Radio Array for Neutrino Detection

http://grand.cnrs.fr/

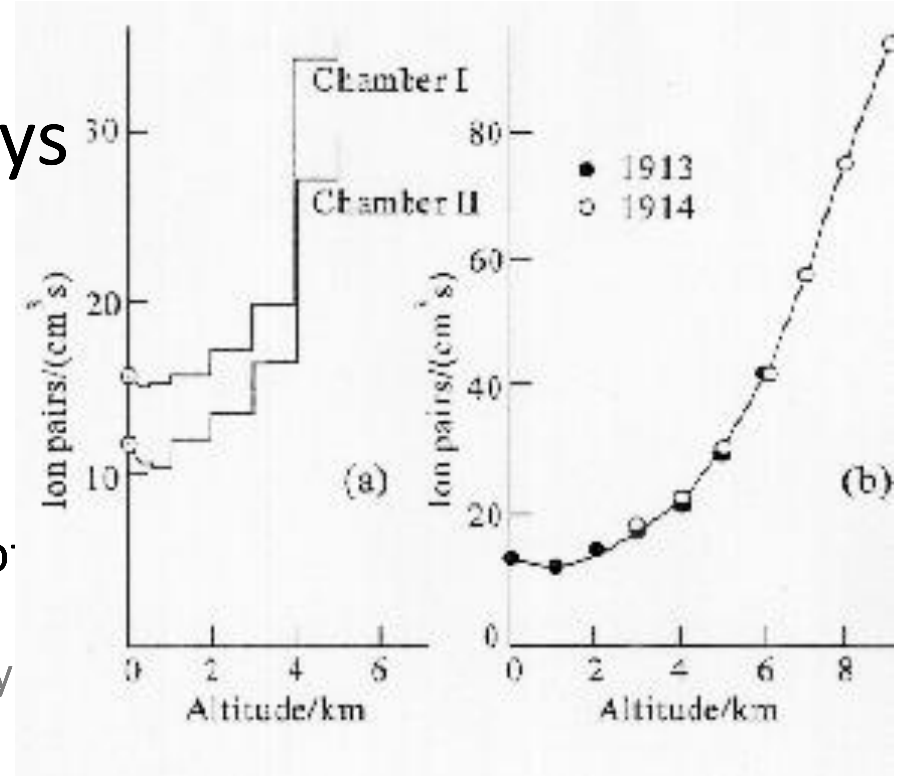
1. Why we want to detect cosmic neutrinos
2. How we are going to do that
3. The road to GRAND

Olivier Martineau, LPNHE, CNRS-Sorbonne Université
GRAND workshop, DunHuang, April 25

The mystery of Ultra High Energy Cosmic Rays

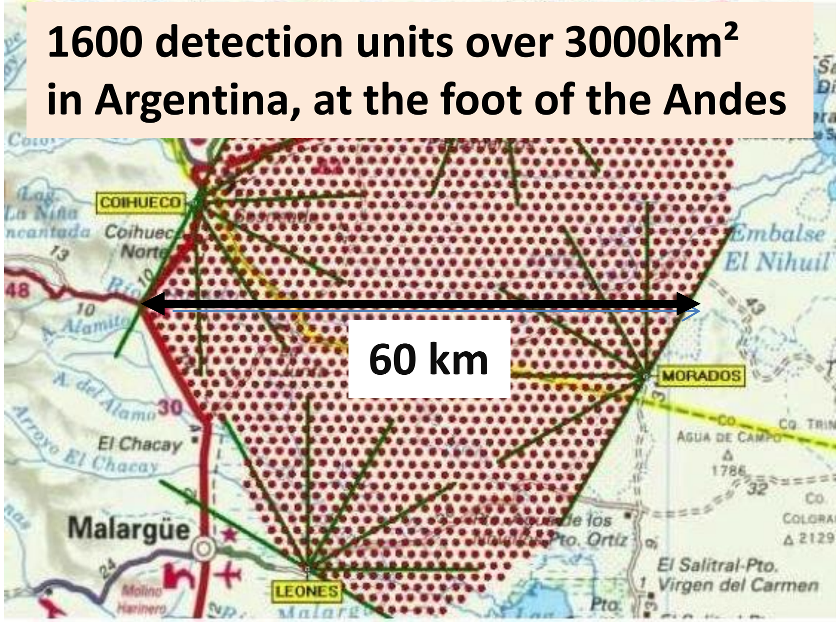
- Ionising particles of cosmic origin constantly received on Earth (Hess, 1911)
- **Macroscopic energies (1960s)!**
  - E>10^{20}eV ⬄ ~50 J: kinetic energy of a tennis ball @ 110 km/h

(LHC accelerator @ CERN: max particle energy ~10^{13}eV ⬄ mosquito in flight)



Results of AUGER

- Huge experiment
  - 3000 km² in Argentina
  - 500 people from 14 countries
- «Complex» results:
  - UHECRs are charged nuclei (H to Fe)
  - Produced by extragalactic astrophysical sources



1600 detection units over 3000km² in Argentina, at the foot of the Andes

<u>Still many open questions:</u>

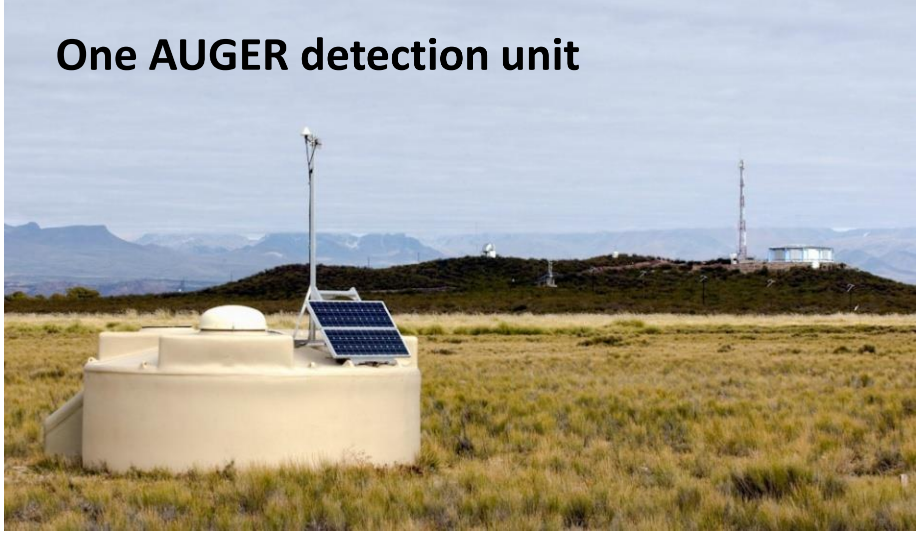
➔ What nuclei exactly?

➔ What type of sources?

➔ Few individual bright sources or population of many sources?

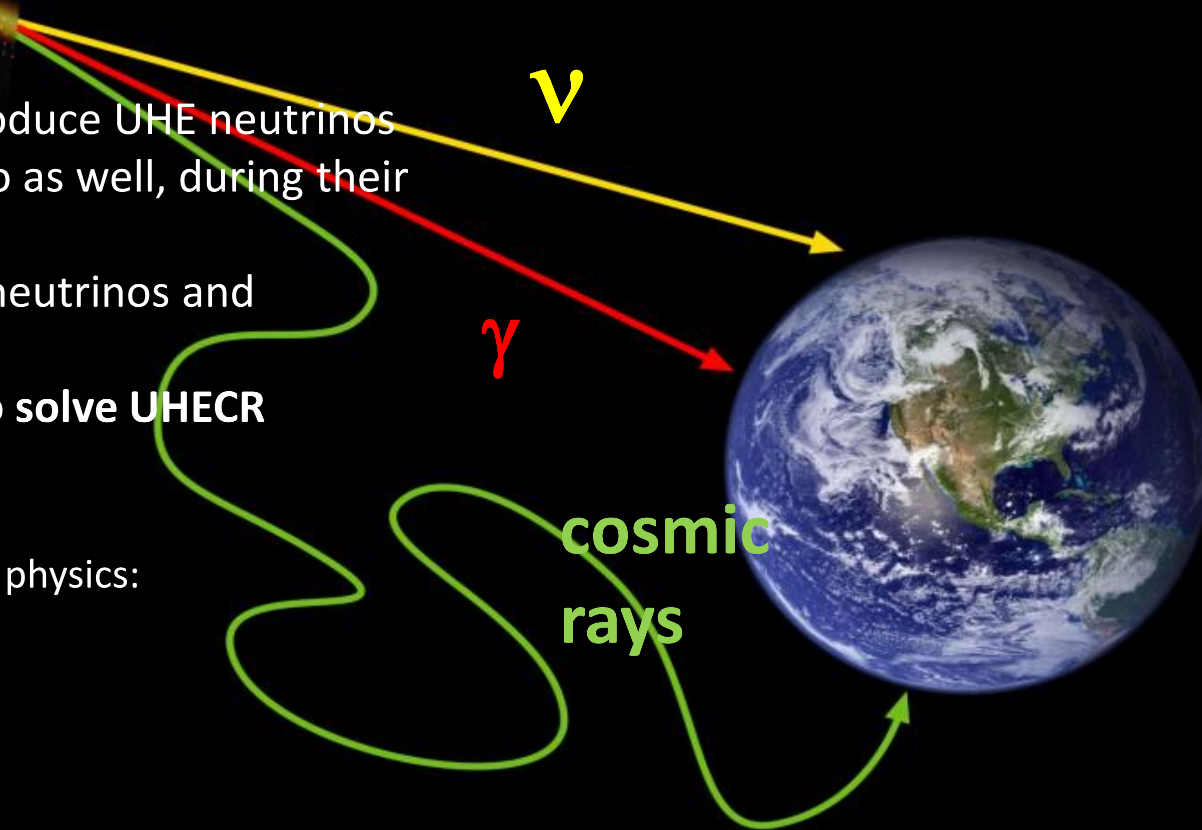
➔ Continous emission or flares?

The mystery is not solved yet!


One AUGER detection unit

UHECRs are charged particles ➔ deviate from source during travel in space because of magnetic fields.
Neutrinos are neutral ➔point back to their sources .
+ very weak interaction probablity: very distant sources can be seen!

➔ **very clean probe of the violent phenomena in the Universe**



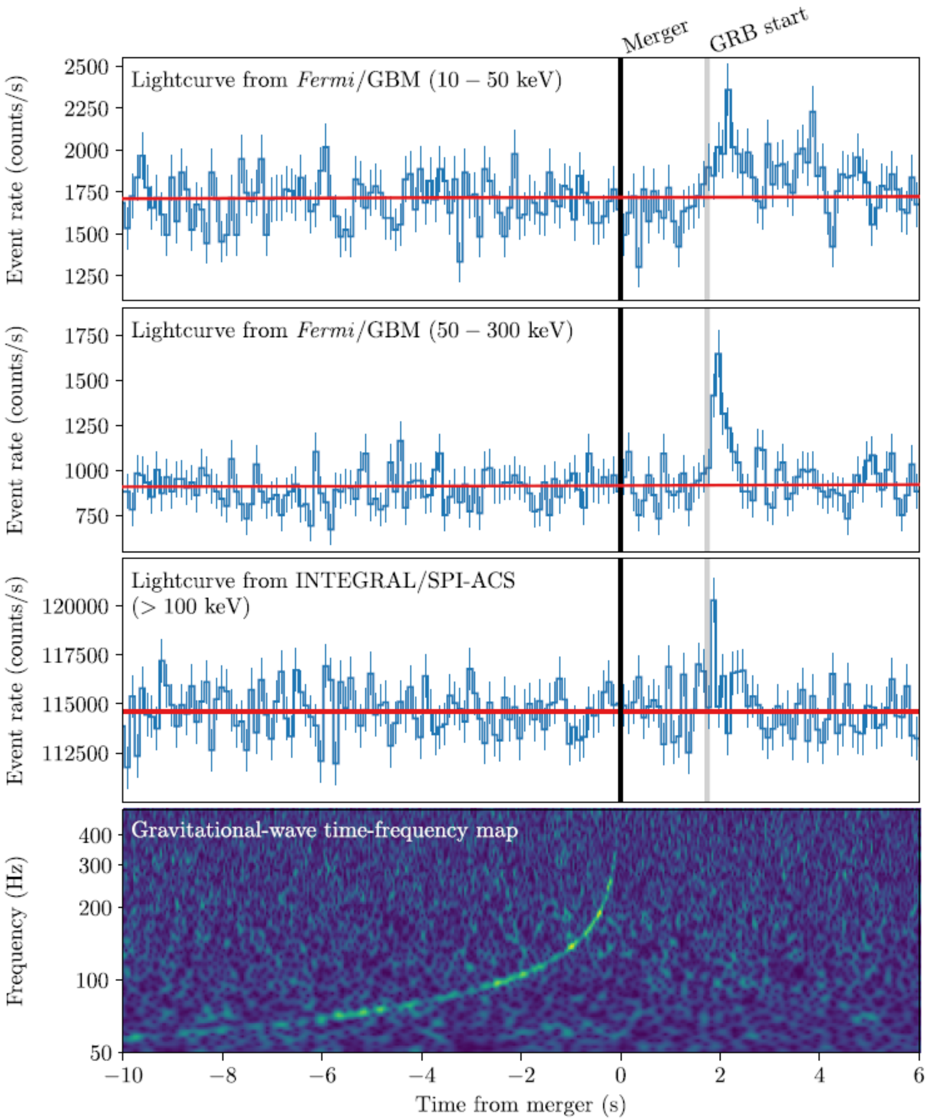
Sources of UHECRs <u>must</u> also produce UHE neutrinos with energy ~10^{18}eV. (UHECRs do as well, during their propagation in the Universe).

➔ Very tight link between UHE neutrinos and UHECRs

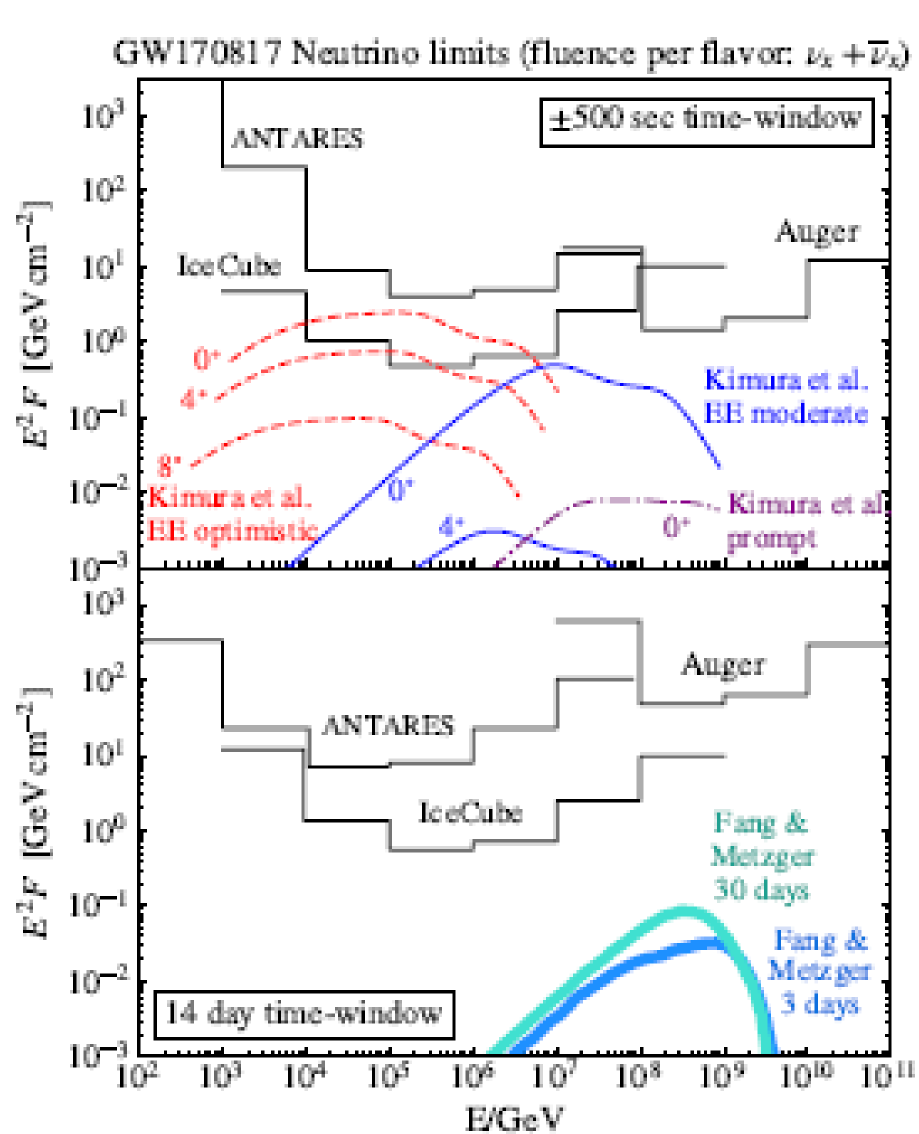
➔ **Neutrinos are key element to solve UHECR mystery.**

Neutrino is a very important tool for physics:
2 Nobel Prizes in the last 20 years
- Solar neutrinos (2002)
- Neutrino oscilations (2017)

Multi-messenger astrophysics
combine informations to solve Nature's mystery



NS merger GW170817



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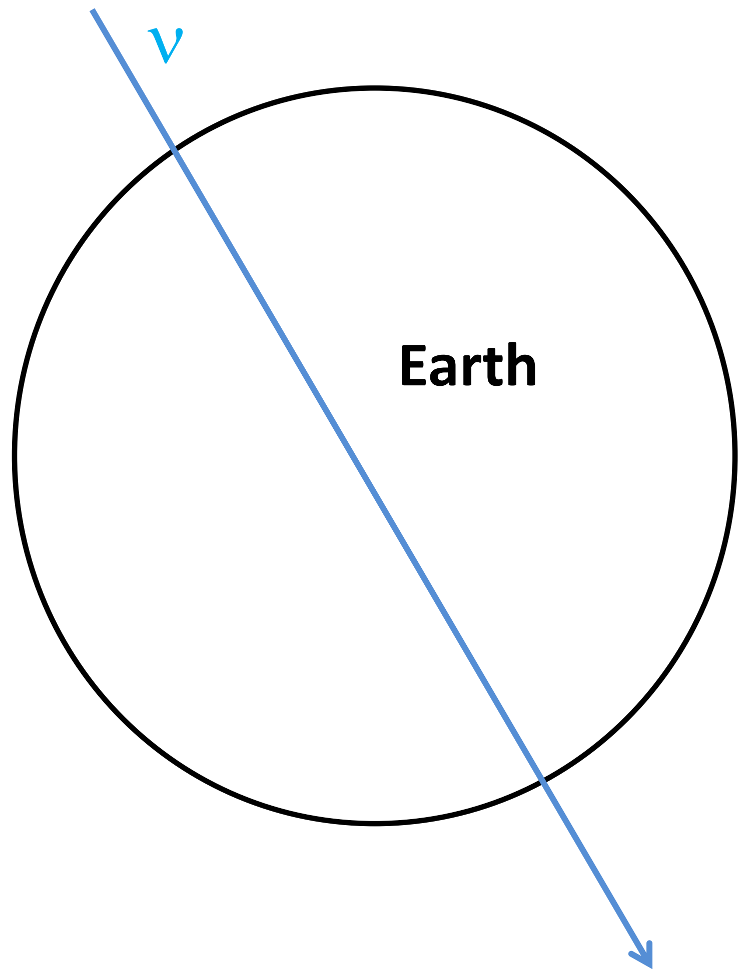
UHE neutrino astronomy: basics

- Three of the 12 elementary particles of the Standard Model of Physics. Neutral & light (~1eV/c², vs 5 10^5 eV/c² for electrons).
- Huge cosmic neutrino flux @ Earth: ~10^{11} /cm²/s (mostly from the Sun)
- But very tiny interaction probability!
  - For E = 10^9 eV:
    - p(ν interaction) = p(proton interaction)x10^{-12}

    ➔ Cosmic neutrinos have a very large chance to cross the Earth without interaction!



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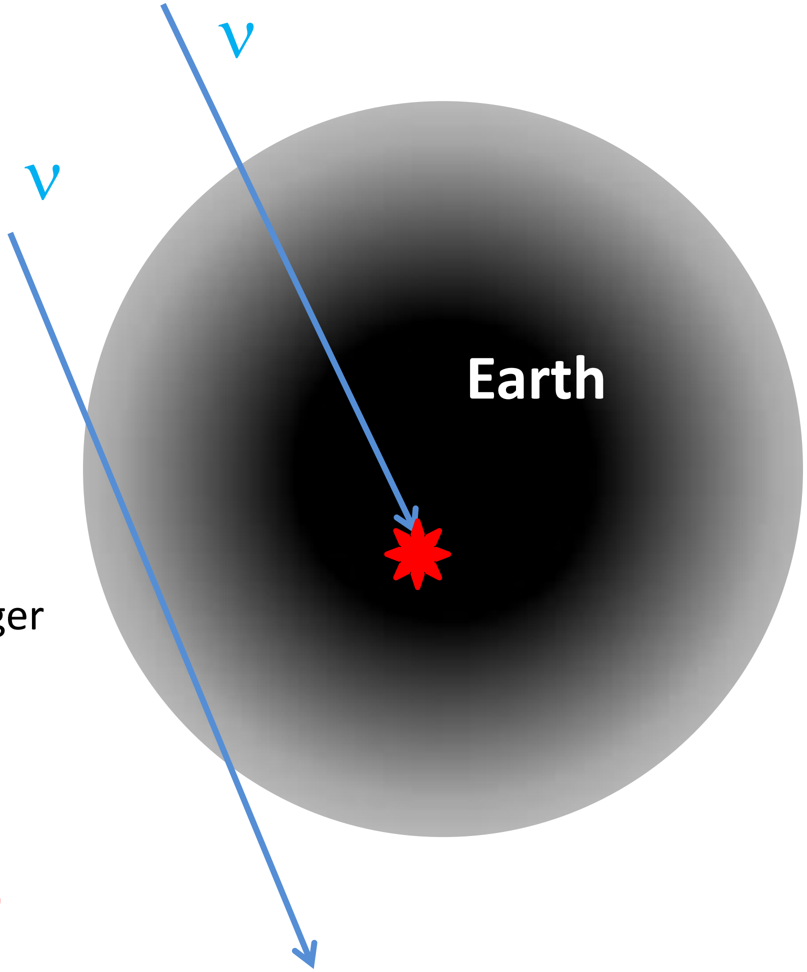
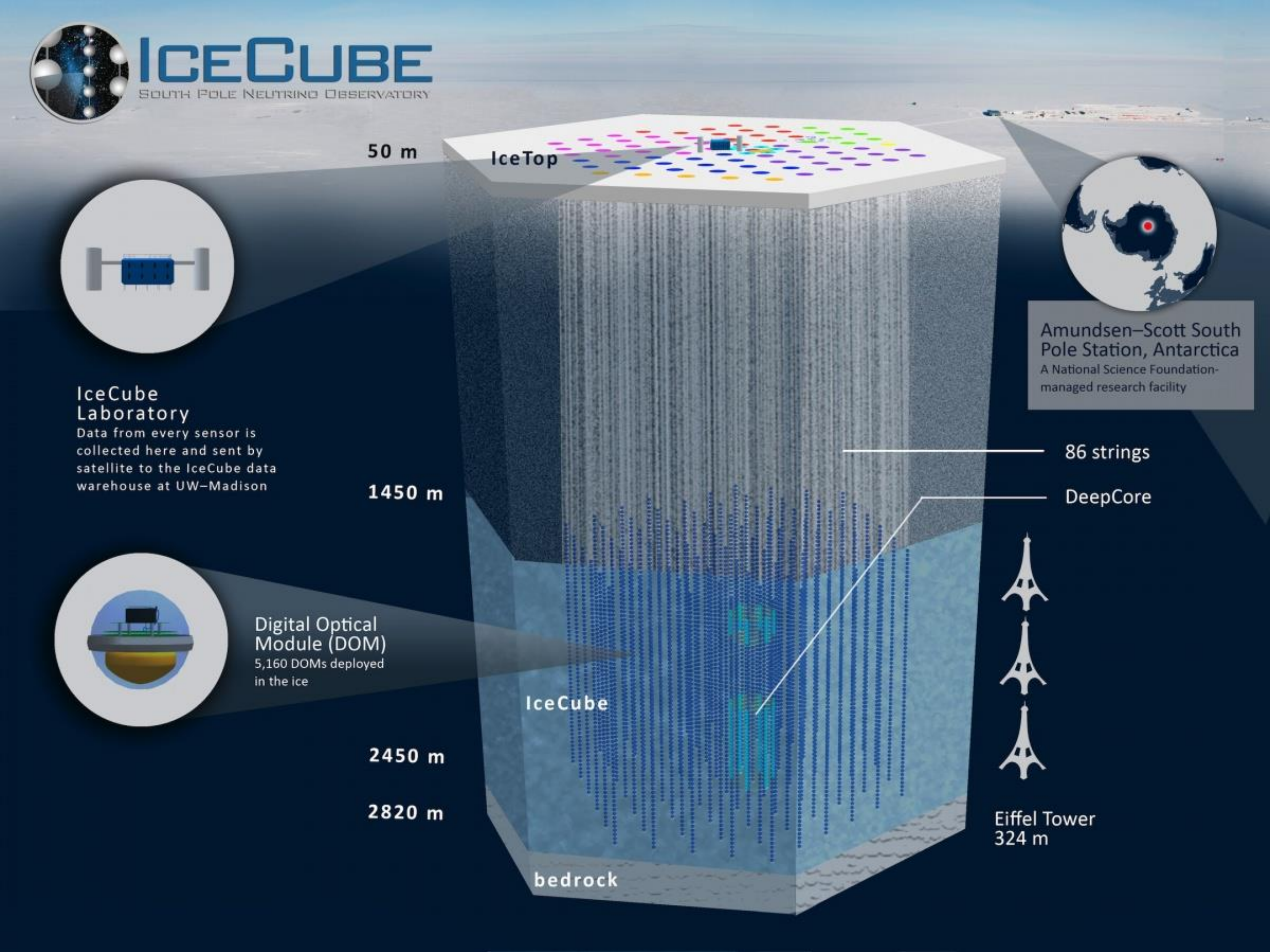
    ➔ Cosmic neutrinos have a very large chance to cross the Earth without interaction!
  - For E>10^{18}eV:
    - Interaction probability increases: 10^6 times larger compared to E=10^9eV

    ➔Earth opaque to neutrino if d>1000km.
    - BUT flux drops: at most ~100/km²/year.

➔ We need a GIANT detector to catch 10^{18} eV neutrinos.



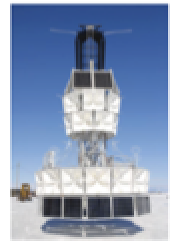

IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube
2450 m
2820 m
bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
Eiffel Tower
324 m

Future project overview

complementarity, sensitivity to neutrino sources **"precision frontier"**

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

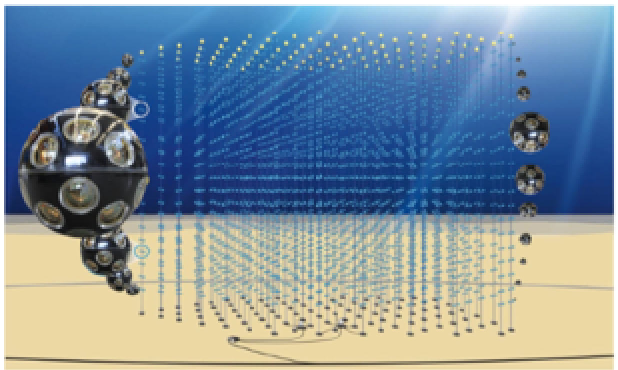
ANTARES



PIERRE AUGER OBSERVATORY

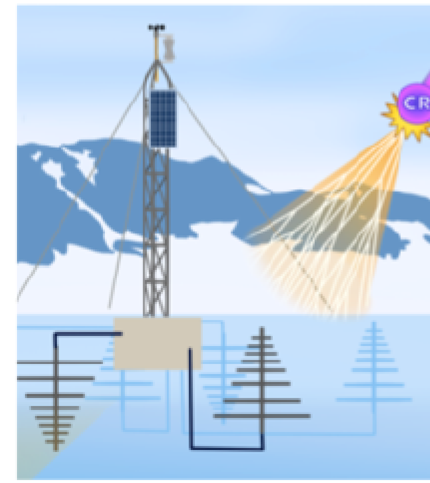
Present neutrino detectors

sensitivity at EeV and beyond **"energy frontier"**

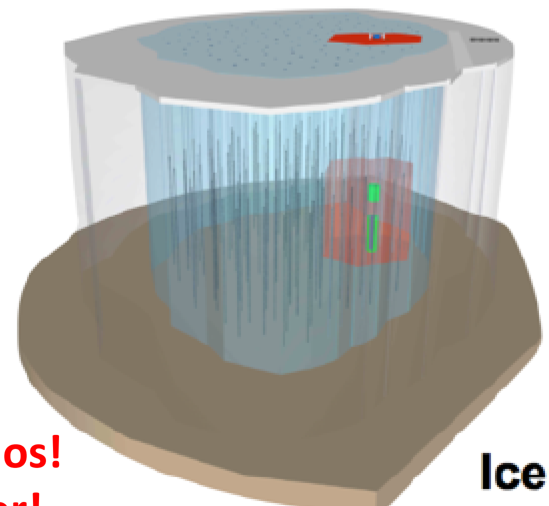


KM3NeT, GVD

sensitivity at PeV energies **"intensity frontier"**



ARA, ARIANNA, EVA, GRAND

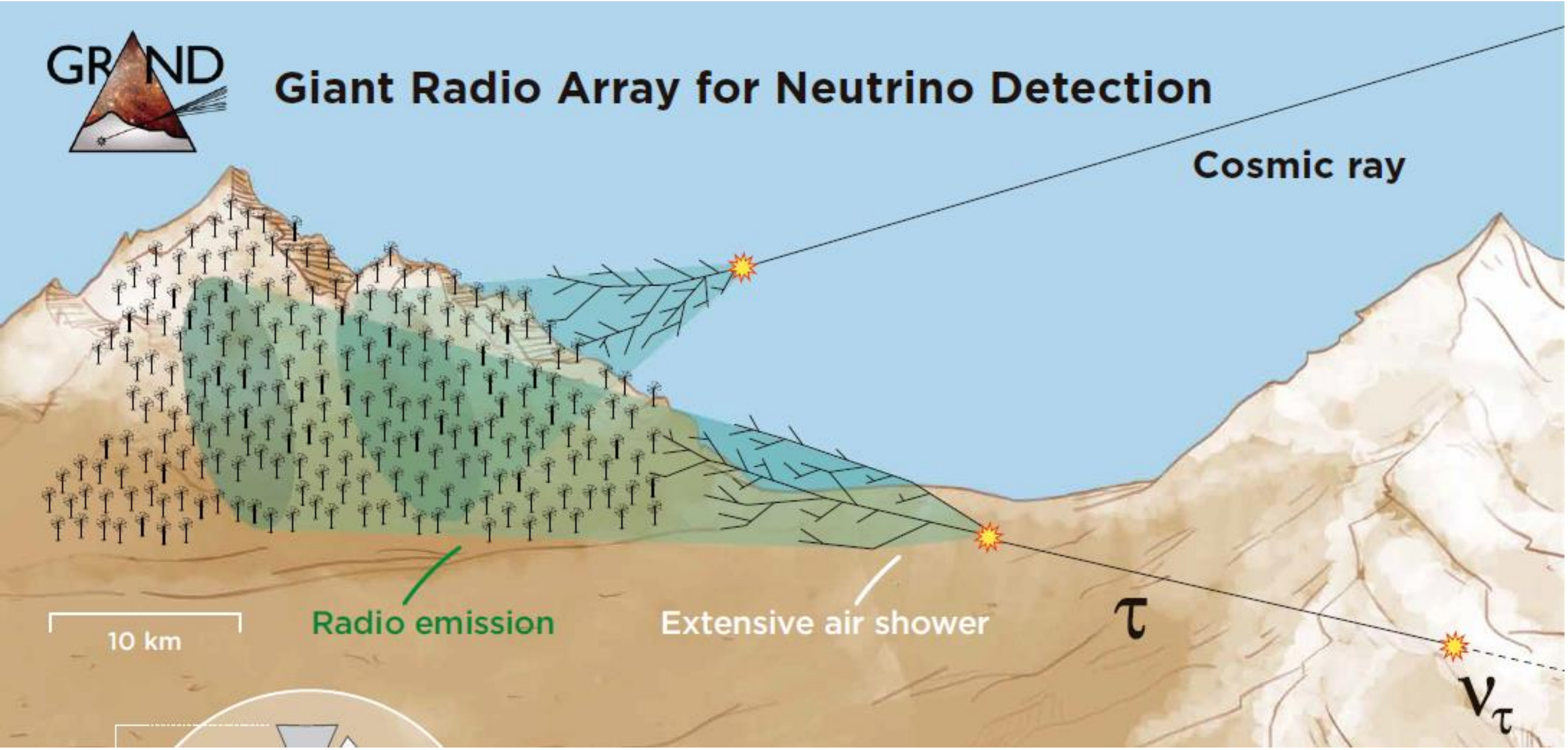


IceCube-Gen2

Only 2 events with E>10^{15}eV:
IceCube too small for UHE neutrinos!
We need a MUCH LARGER detector!

credit: M. Ackerman

Neutrino detection by GRAND



- Very indirect process ➔ very unlikely ➔ need a GIANT^2 detector.
- The tau particle has to be produced less than ~100km from Earth surface in order to emerge. Only possible for short underground travels
  ➔ showers with <u>horizontal trajectories.</u>

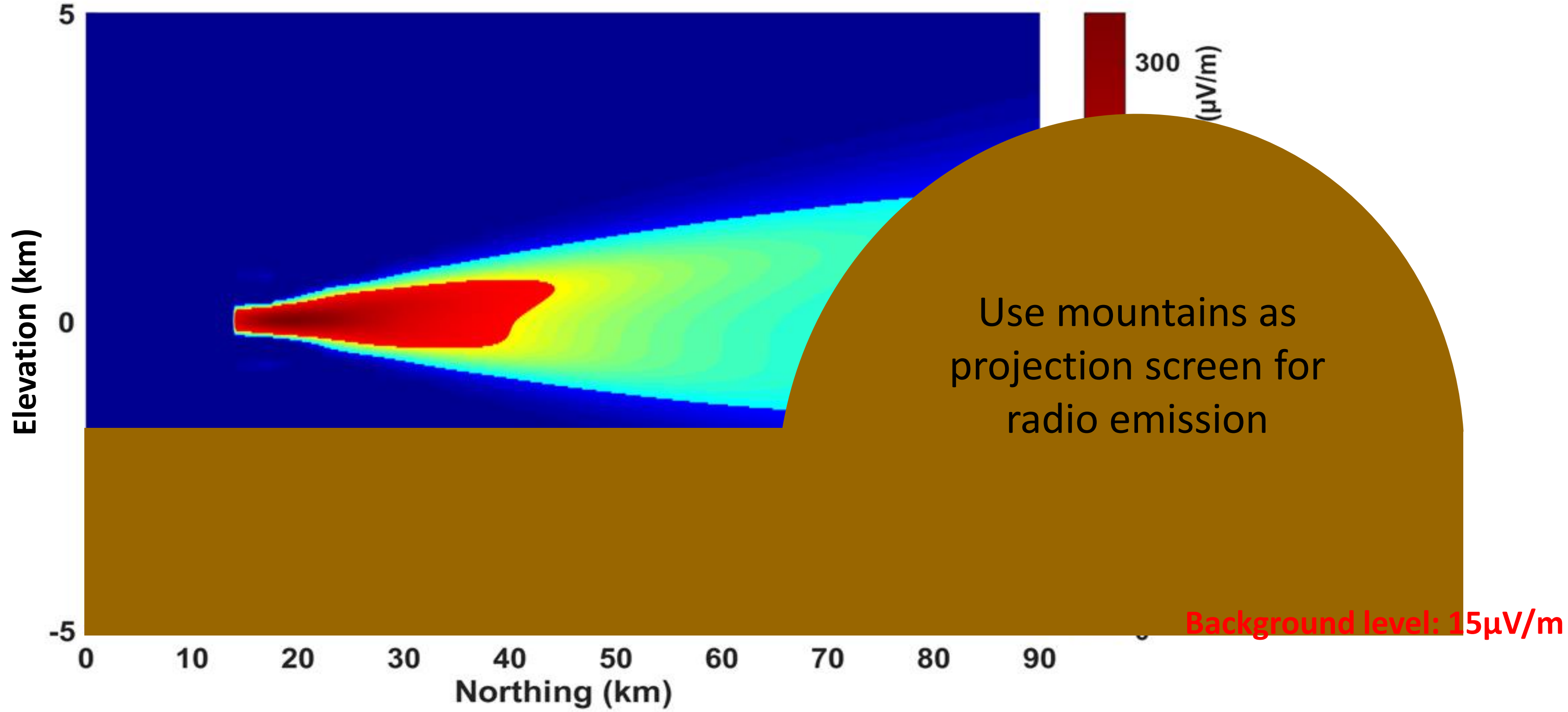
Why radio? Because it is cheap!
➔ perfect for giant detectors

Why radio?

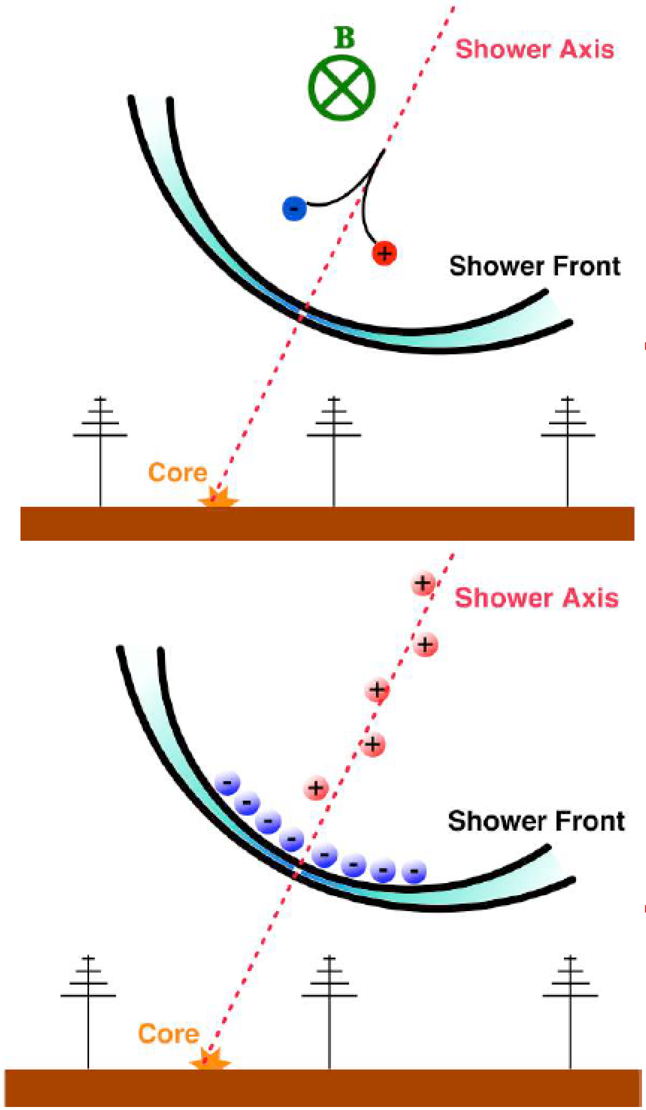
Because it is perfect for horizontal air showers!

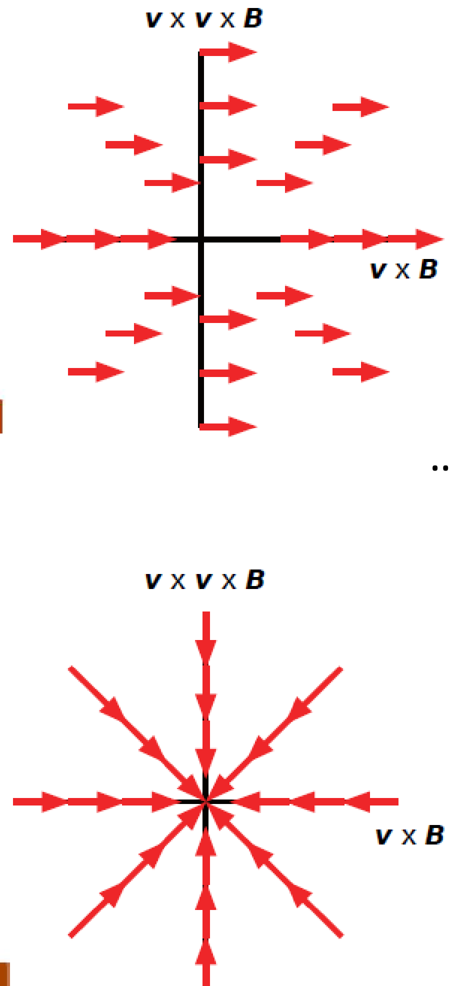
50-200MHz radio emission of a $10^{17.5}$eV shower viewed from the side:

~10s of km² detectable footprint @ ~100 km!!



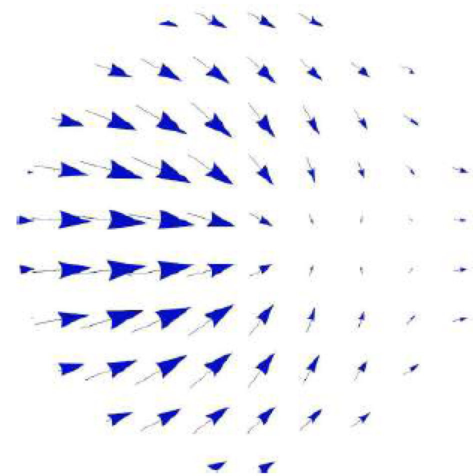
Measuring air showers with radio antennas



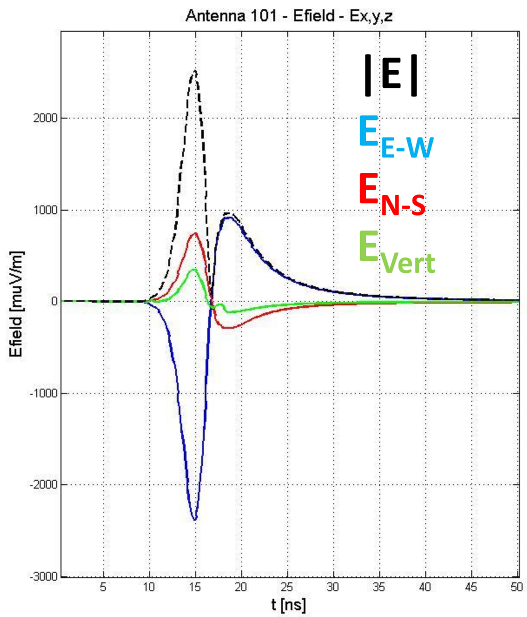


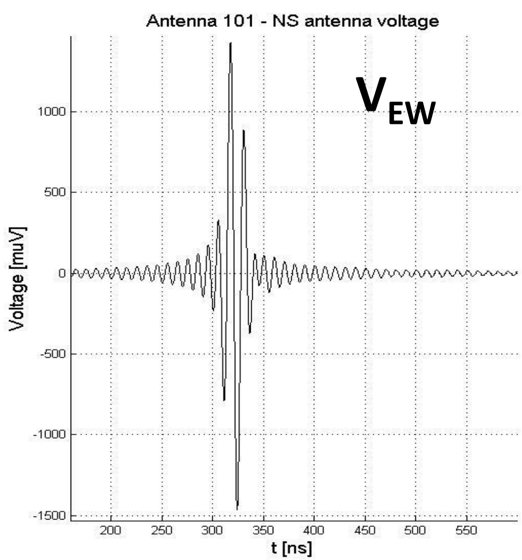
Both mechanisms create polarized signals. This causes interference and complicates the measurements.

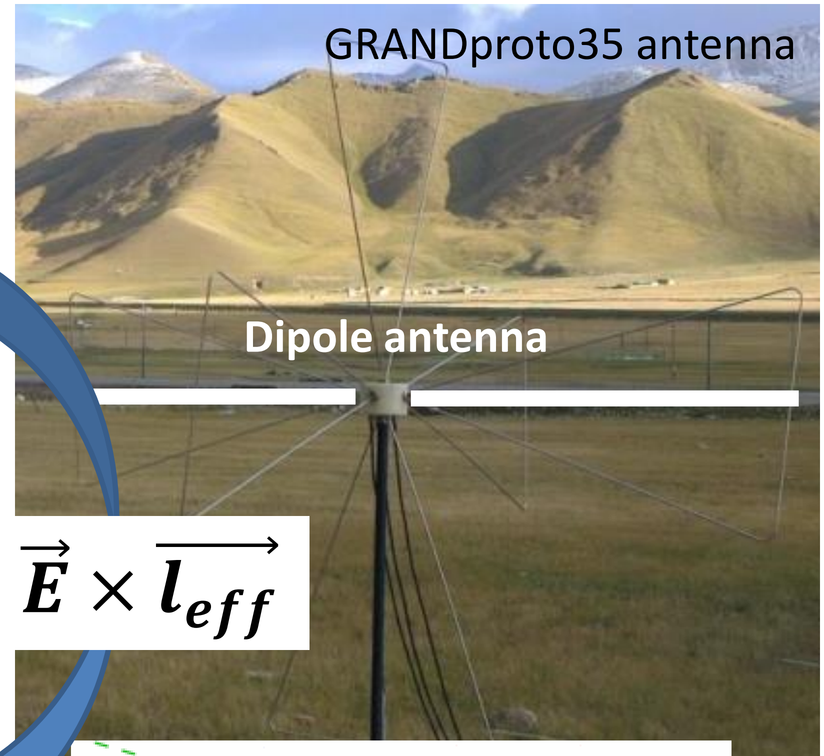
… but also provides a unique signature!!!



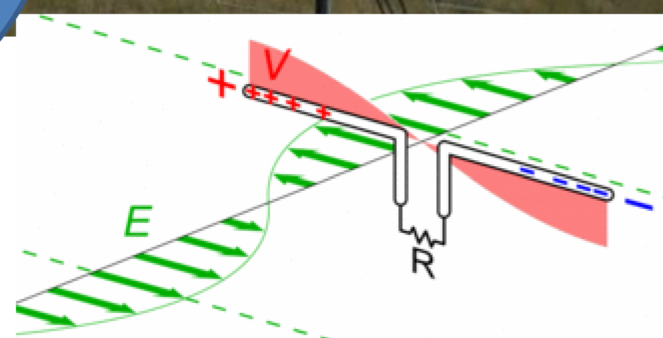
Radio detection







$$V = \vec{E} \times \overrightarrow{l_{eff}}$$



Current in antenna due to Efield generates voltage at load output

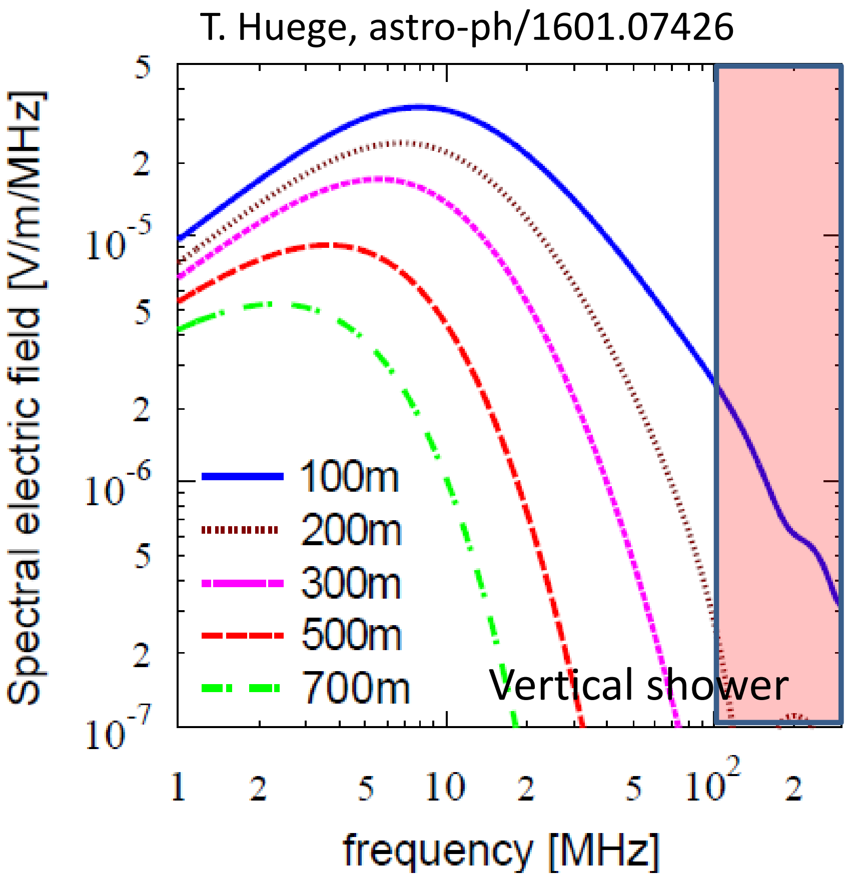
Frequency bandwidth

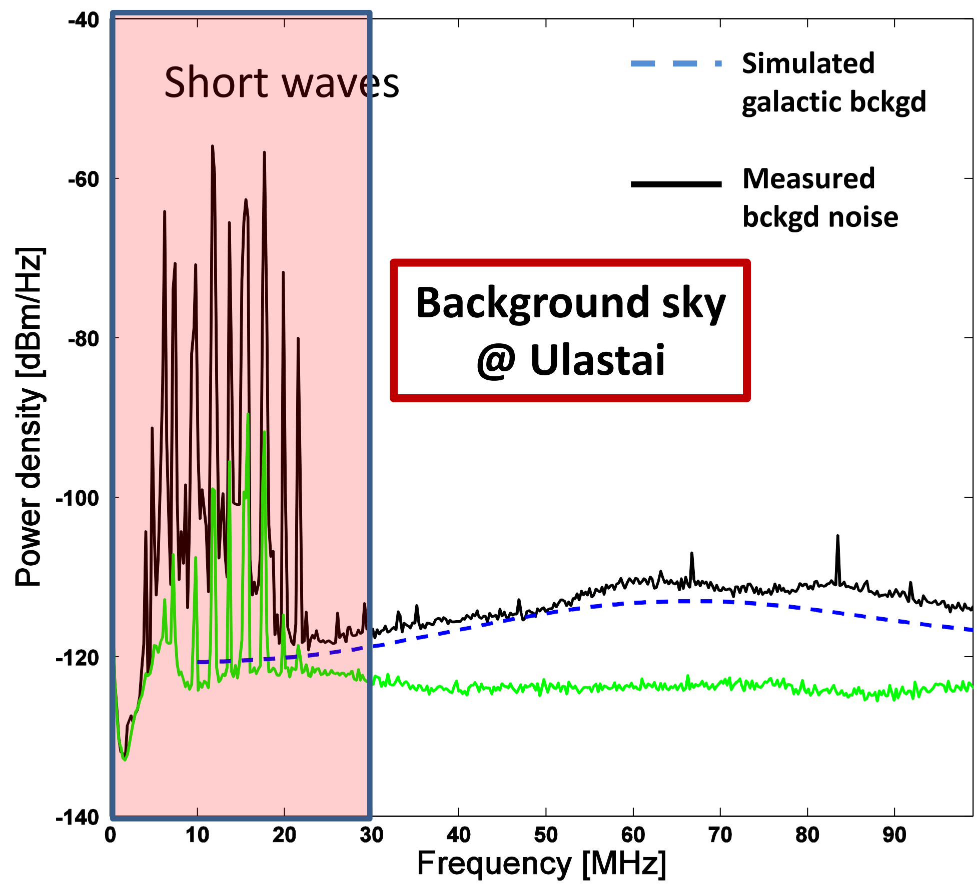
Emission coherent for λ>>d~3m⇔f<<100MHz

➔ **max frequency = 200MHz**

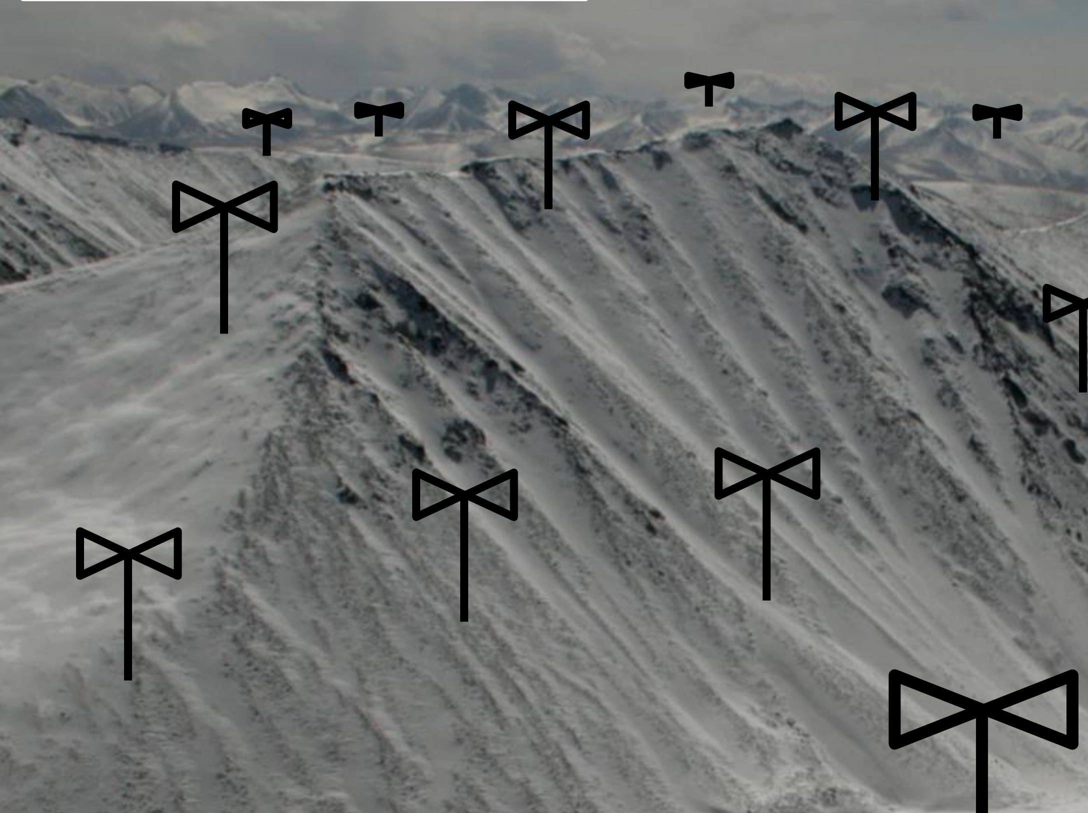
Below 30MHz: short waves

➔ **min frequecy = 50MHz (see further slides)**





The GRAND project

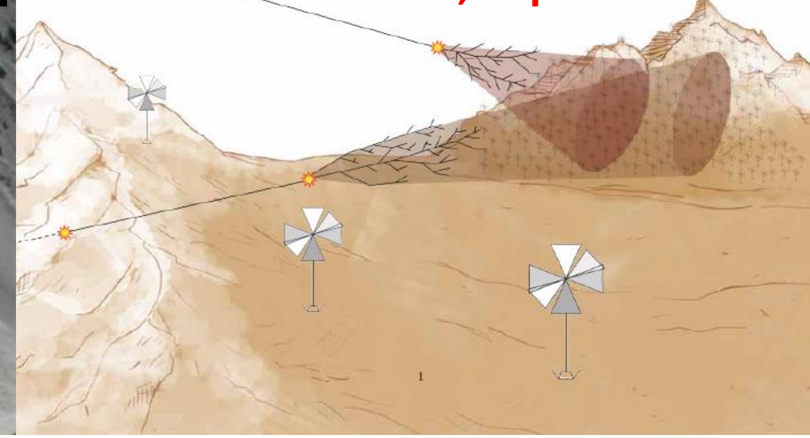


GRAND
Giant Radio Array for Neutrino Detection

Science and Design

astro-ph/1810.09994

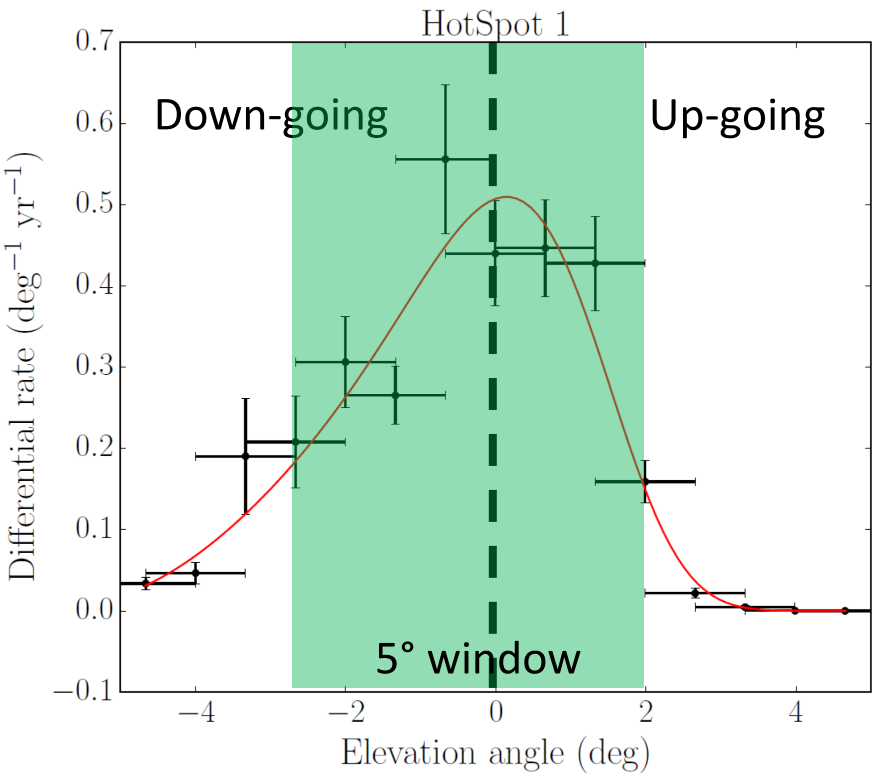
Science China, in press

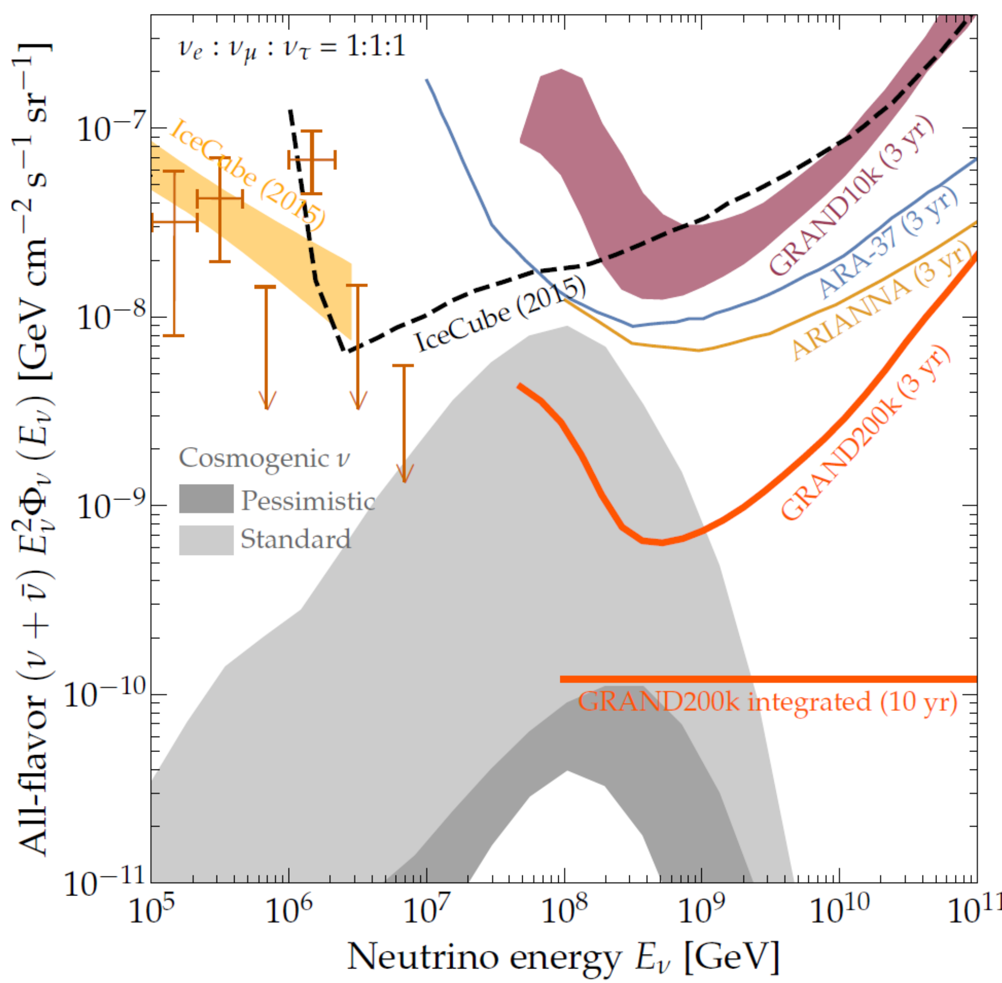


Author list

Jaime Álvarez-Muñiz[1], Rafael Alves Batista[2,3], Aswathi Balagopal V.[4], Julien Bolmont[5], Mauricio Bustamante[6,7,8,†], Washington Carvalho Jr.[9], Didier Charrier[10], Ismaël Cognard[11,12], Valentin Decoene[13], Peter B. Denton[6], Sijbrand De Jong[14,15], Krijn D. De Vries[16], Ralph Engel[17], Ke Fang[18,19,20], Chad Finley[21,22], Stefano Gabici[23], QuanBu Gou[24], Junhua Gu[25], Claire Guépin[13], Hongbo Hu[24], Yan Huang[25], Kumiko Kotera[13,26,*], Sandra Le Coz[25], Jean-Philippe Lenain[5], Guoliang Lü[27], Olivier Martineau-Huynh[5,25,*], Miguel Mostafá[28,29,30], Fabrice Mottez[31], Kohta Murase[28,29,30], Valentin Niess[32], Foteini Oikonomou[33,28,29,30], Tanguy Pierog[17], Xiangli Qian[34], Bo Qin[25], Duan Ran[25], Nicolas Renault-Tinacci[13], Frank G. Schröder[35,17], Fabian Schüssler[36], Cyril Tasse[37], Charles Timmermans[14,15], Matías Tueros[38], Xiangping Wu[39,25,*], Philippe Zarka[40], Andreas Zech[31], B. Theodore Zhang[41,42], Jianli Zhang[25], Yi Zhang[24], Qian Zheng[43,24], Anne Zilles[13]

GRAND simulation results





Horizontal trajectories only!

We need antennas sensitive along the horizon

➔ min frequency = 50MHz

We want a GUARANTEED detection of cosmic neutrinos by GRAND

➔ we need a <u>200’000km² detector</u> (2% of China),

➔ **great physics program ahead (and huge technical challenge)!**

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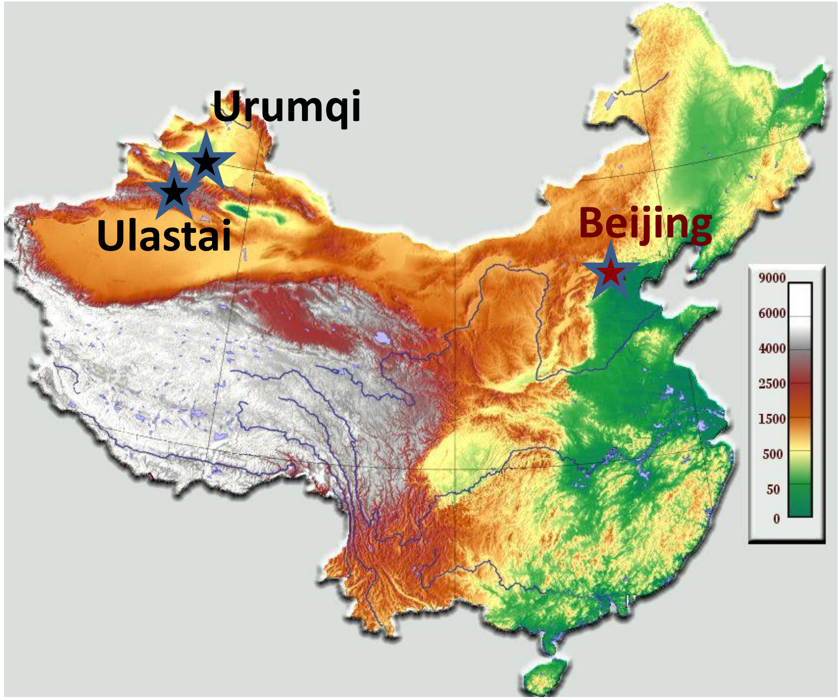
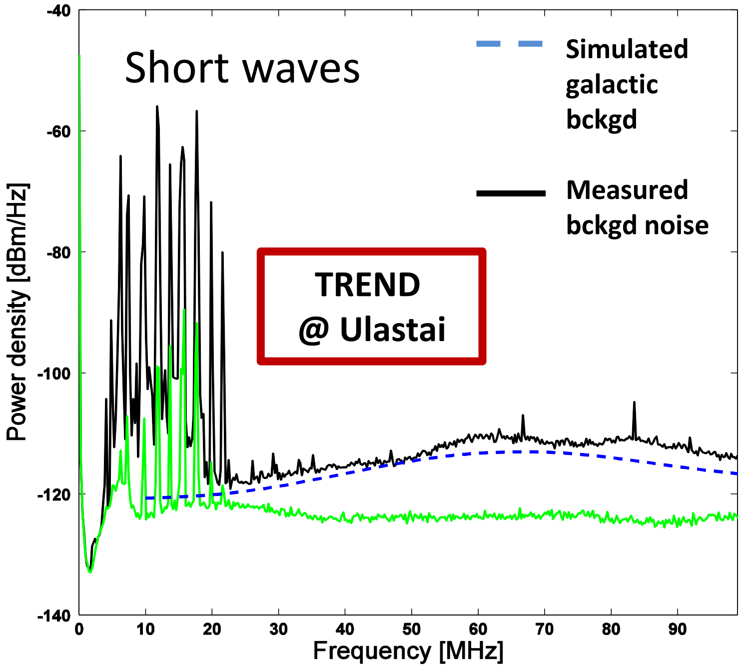
Autonomous radio detection of air showers

The TREND experiment, seed for GRAND

(2009-2013-2018, 21CMA site)

- A very remote & quiet site.



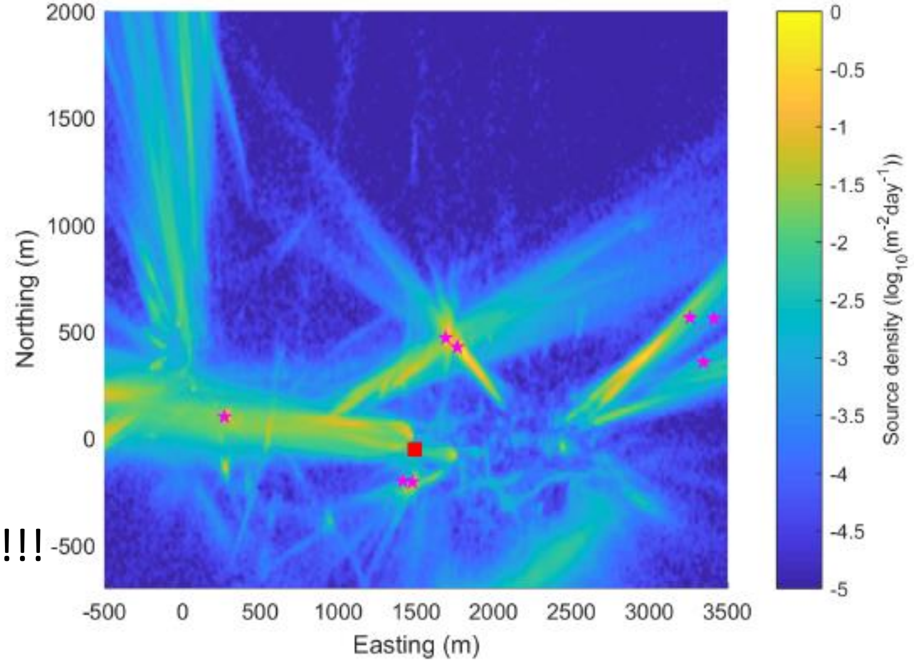


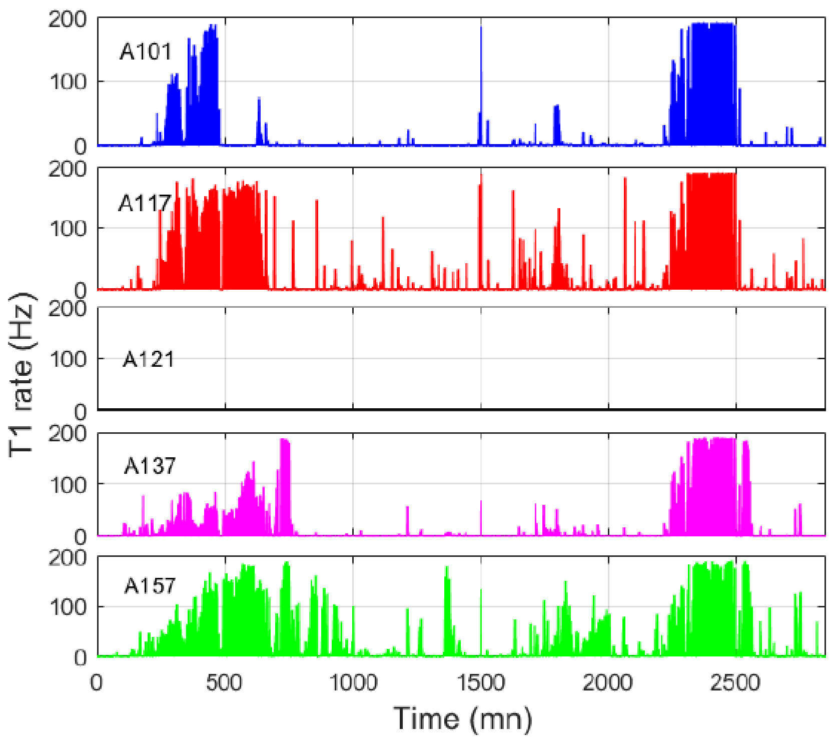
Autonomous radio detection of air showers

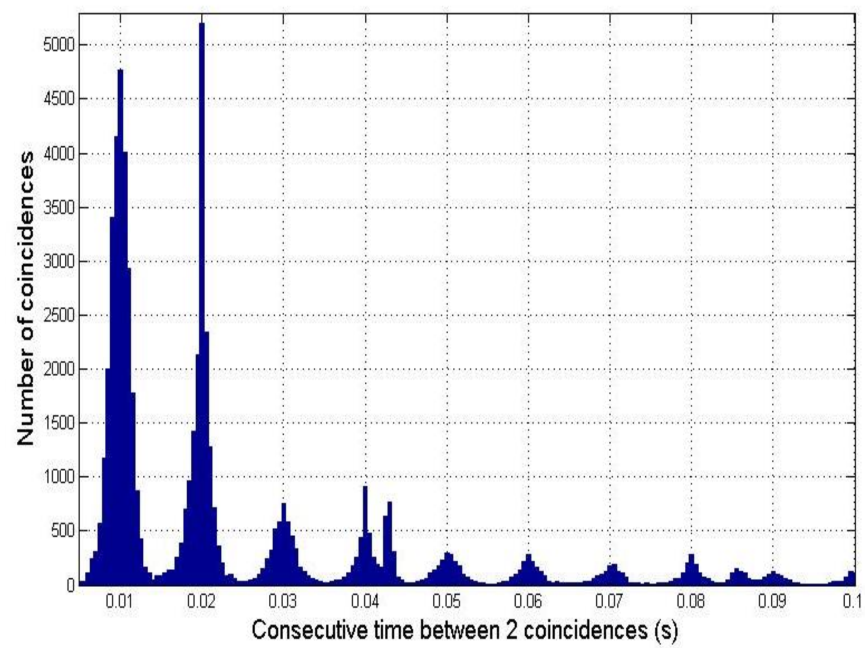
The TREND experiment, seed for GRAND

(2009-2013-2018, 21CMA site)

- A very remote & quiet site.
- Still: radio coinc rate = tens of Hz while air shower rate = ~20/day: huge background rate!!!





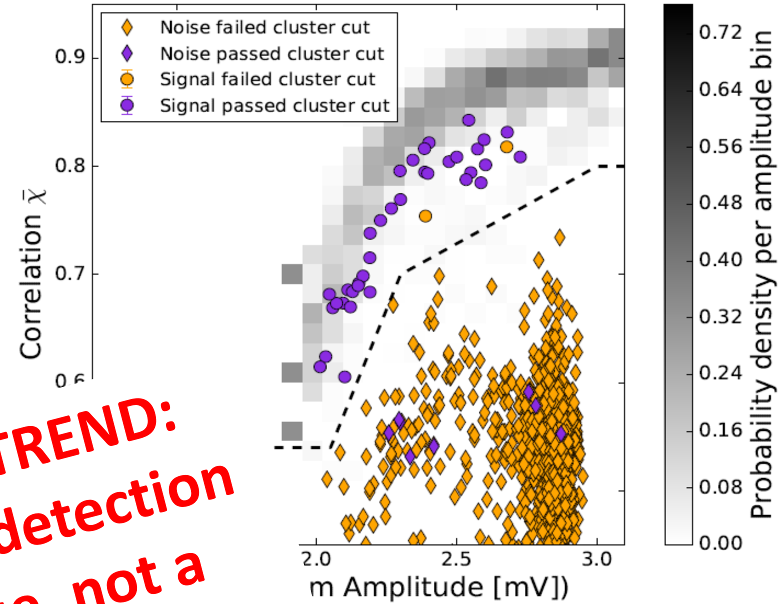


Autonomous radio detection of air showers

The TREND experiment, seed for GRAND

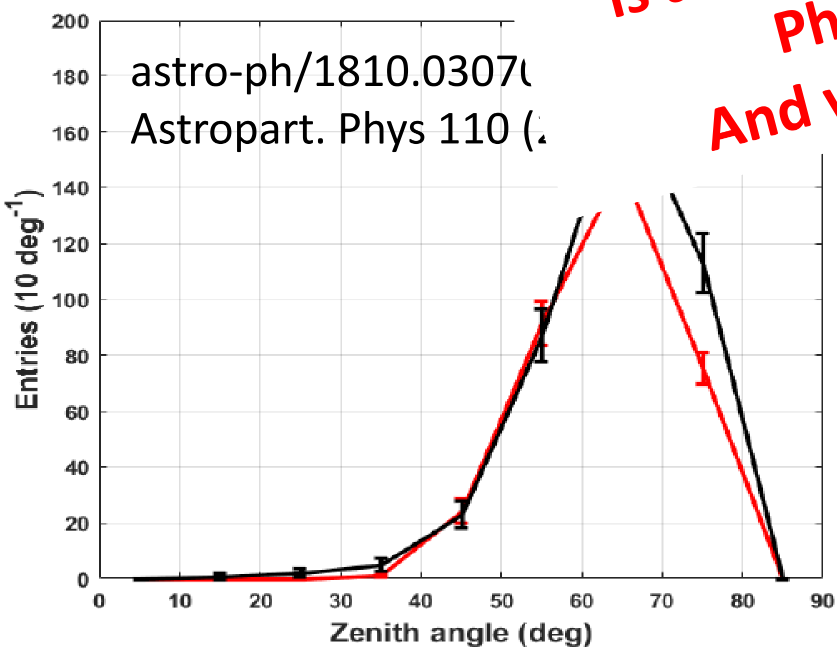
(2009-2013-2018, 21CMA site)

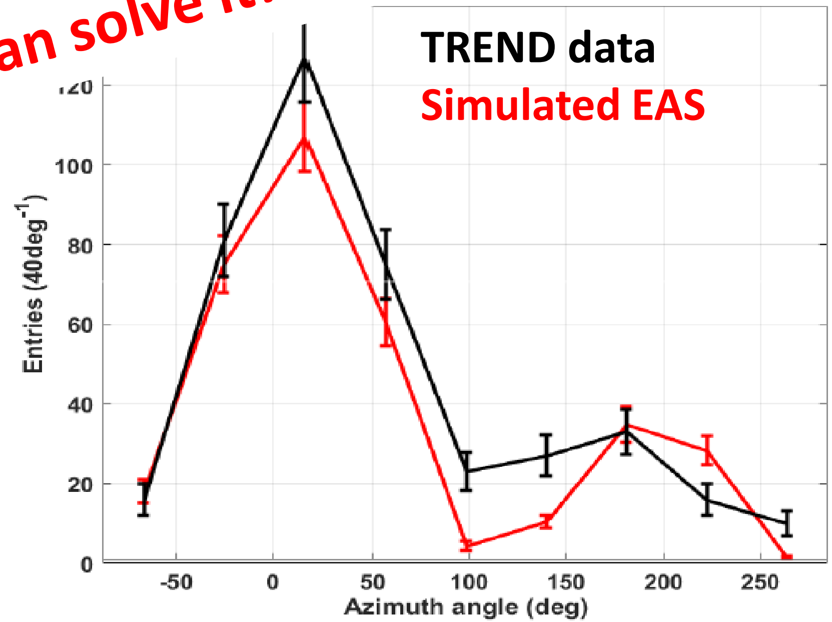
- A very remote & quiet site.
- Still: radio coinc rate = tens of Hz whi[...] rate = ~20/day : huge bac[...]
- BUT distinct EAS & ba[...] for excellent discrimin[...]



[...] ARIANNA!
[...]h/1612.04473)

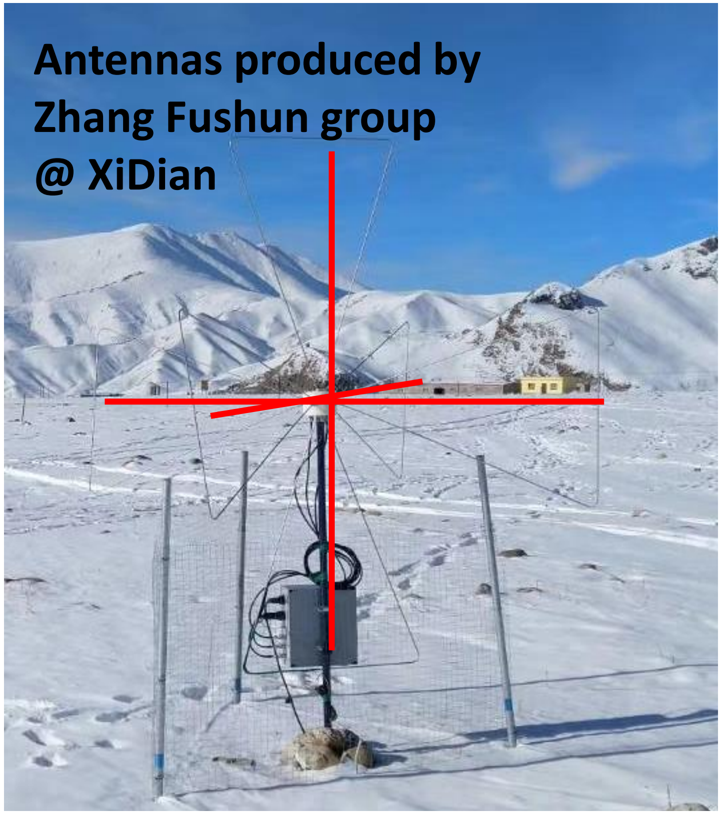
Main lesson from TREND: autonomous radio detection is a technical issue, not a Physics one… And we can solve it!





TREND succesfull, but…

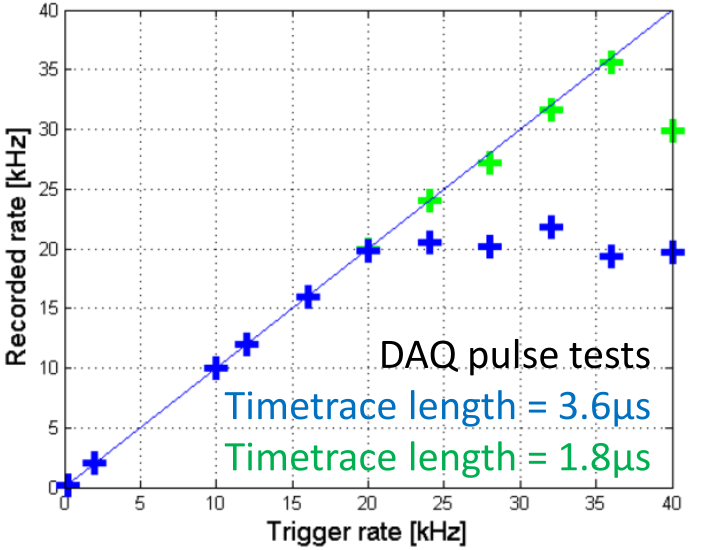
Unreliable setup	+	Poor discrimination	=	Poor detection efficiency
10%		30%		**3%**



GRANDProto35

Robust setup + fast DAQ	+	Polarization measurement	=	(Much) better detection efficiency

GP35 presently in commissioning phase @ Ulastai…
But just a first step towards GRAND!



	2018 — GRANDProto35	2020 — GRANDProto300	2025 — GRAND10k	203X — GRAND200k
Goals	standalone radio array: test efficiency & background rejection	standalone radio array of very inclined showers (θ_z>70°) from cosmic rays (>$10^{16.5}$ eV) + ground array to do UHECR astro/hadronic physics	first GRAND subarray, sensitivity comparable to ARA/ARIANNA on similar time scale, allowing discovery of EeV neutrinos for optimistic fluxes	first neutrino detection at 10^{18} eV and/or neutrino astronomy!
Setup	35 radio antennas 21 scintillators 	• 300 HorizonAntennas over 300 km^2 • Fast DAQ (AERA+ GRANDproto35 analog stage) • Solar panels (day use) + WiFi data transfer • Ground array (à la HAWC/Auger)	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	200,000 antennas over 200,000 km^2, ~ 20 hotspots of 10k antennas, possibly in different continents Industrial scale allows to cut down costs: 500€/unit ➔ 200M€ in total
Budget & stage	160k€, fully funded by NAOC+IHEP, deployment ongoing @ Ulastai	1.3 M€ to be deployed in 2020	1500€ / detection unit 	 ASIC Cost ~10M€ ➔ few 10€/board Consumption < 1W Reliability

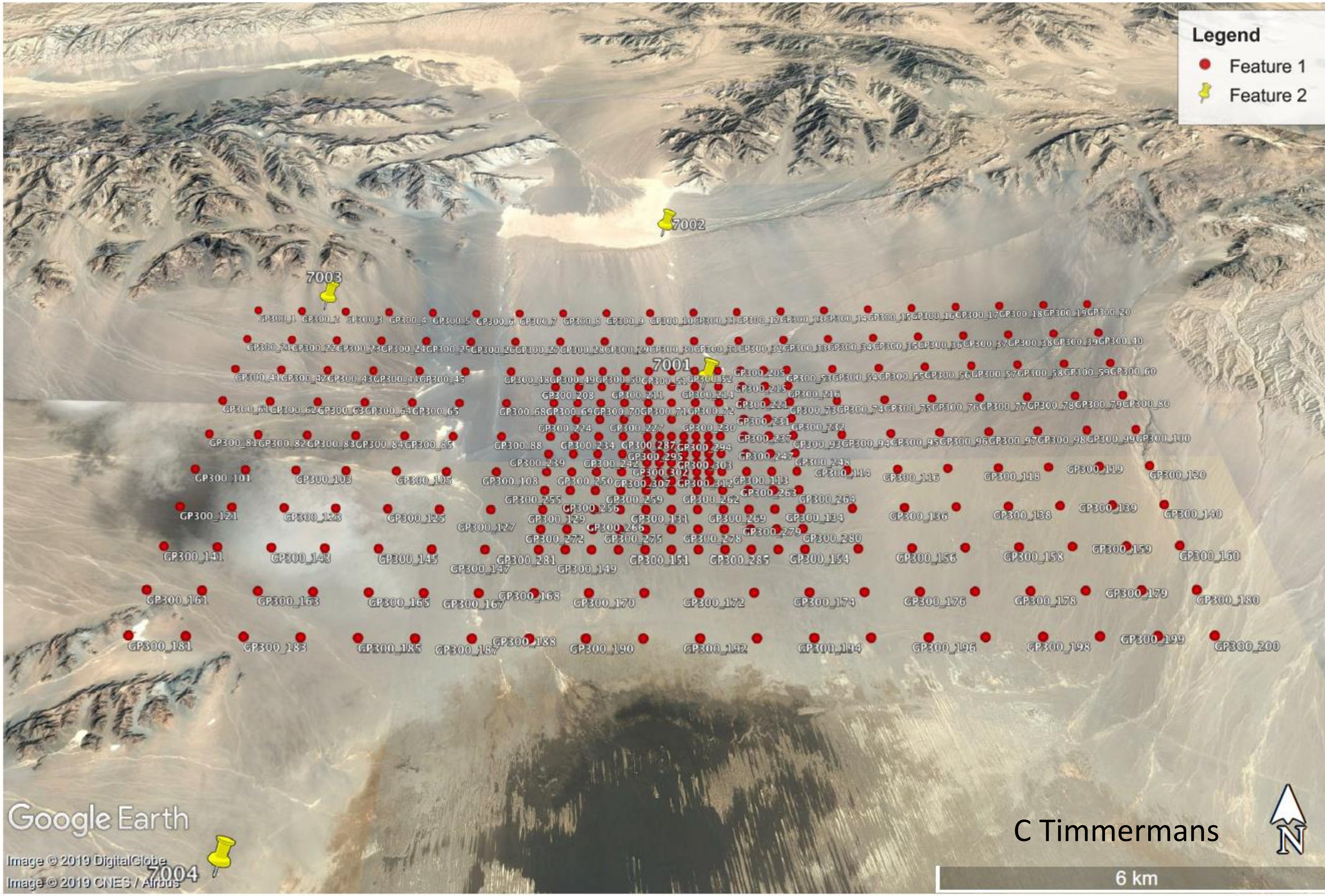
GRAND: still a long way to go

- **How to deal with the HUGE transient event rate** ***[estimated 1kHz/antenna]*****?**
- **How to identify air showers out of the ultra dominant background ?** ***[<100 neutrinos/year vs >1Hz background]***
- **How to detect radio signals propagating along the horizon ?** ***[diffraction + attenuation on ground]***
- How to reconstruct the primary particle information *[Very inclined events]*?
- **How to collect data** ***[1kHz/antenna & tens of kms to DAQ center]*****?**
- **How to deploy and run 200'000 units over 200'000km^2** ***[Logistics, reliability]*****?**
- How much will it cost? Who will pay for it?

➔ A huge experimental, technical, logist & financial challenge

WE DON'T KNOW (yet) the answers!!!

➔ GP300 first goal: find definite answers to these questions

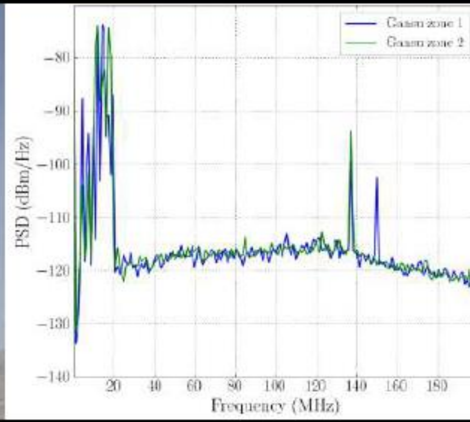

Legend
Feature 1
Feature 2
7001
7002
7003
7004
Google Earth
Image © 2019 DigitalGlobe
Image © 2019 CNES / Airbus
C Timmermans
N
6 km

GP300

<u>Horizon Antenna</u>
(D. Charrier)
3 arms
LNA
4.5m height

XiDian U: unit integration

<u>Site: QingHai</u> (China)
~3000m asl
Radio quiet
Full local support
Possible extension to
1000s km²



<u>Electronics:</u> (Nijmegen)
50-200MHz analog filtering
500MS/s ADC
GPS timing
FPGA+CPU
WiFi transfer
10W (100W-0.7m² solar panel)

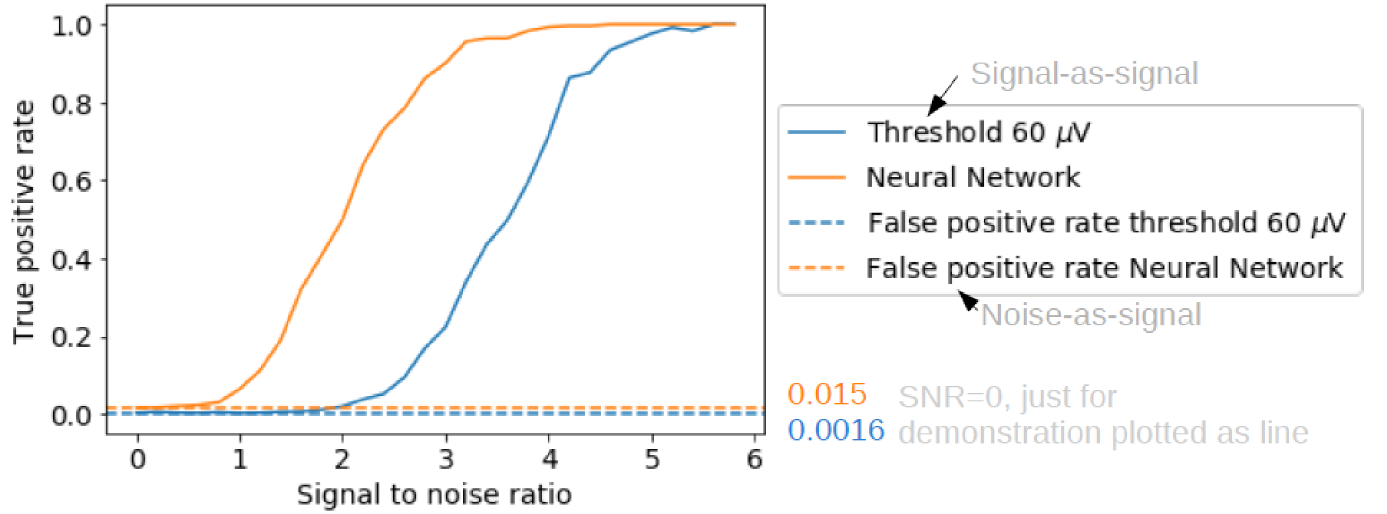
1 km

<u>Layout:</u>
200 km² @ 1km step (GRAND layout)
+ 25km² infield @ 500m step
+ 4km² @ ~200m step
(preliminary)

GRANDProto300

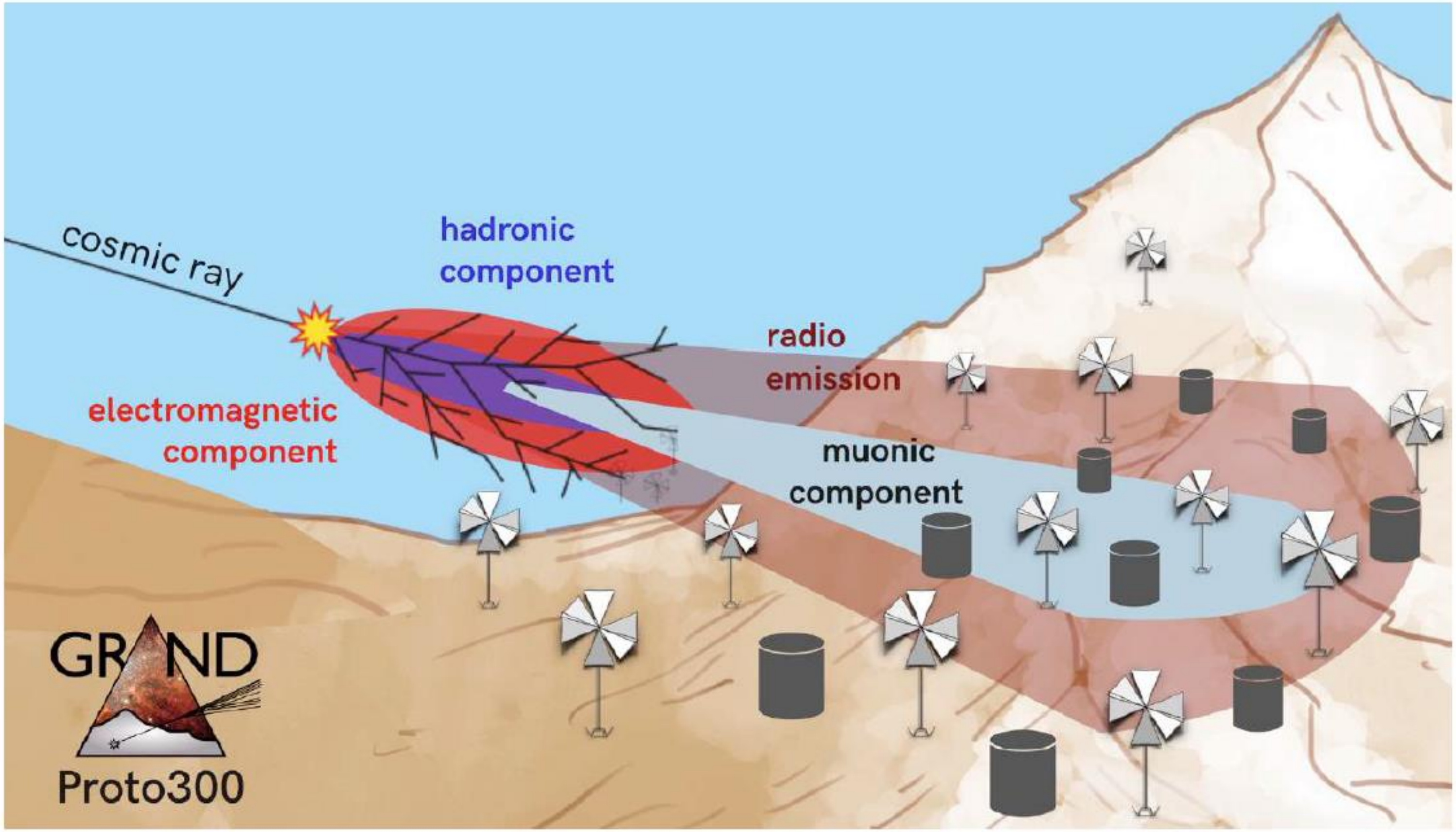
- First goal: validate GRAND detection concept
- Second goal: testbench for GRAND10k because solutions chosen for trigger & data transfer are not scalable to 10000 units!

DeepLearning for trigger?
T. Charnock, F. Führer & A. Zilles , IAP



GRANDProto300

- Third goal: do nice physics!
  - Air shower physics in $10^{16.5} – 10^{18}$eV
  - Transition between Galactic & Extragalactic origin of CRs

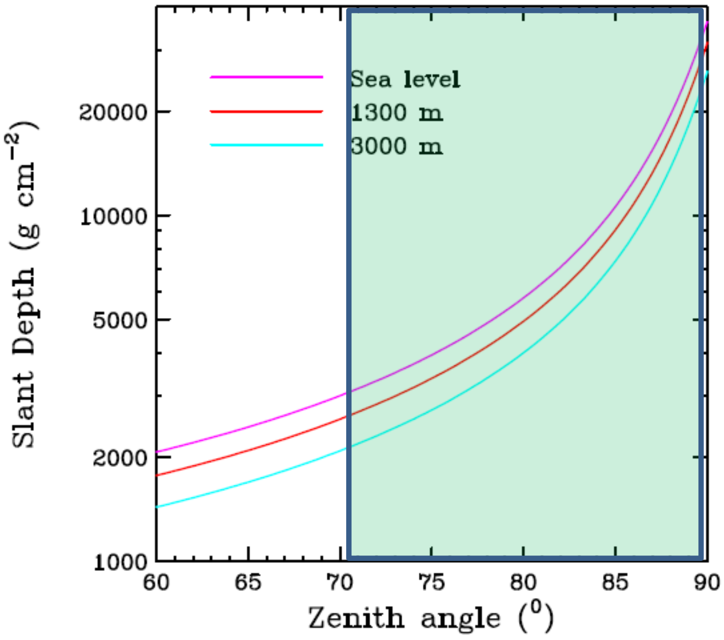


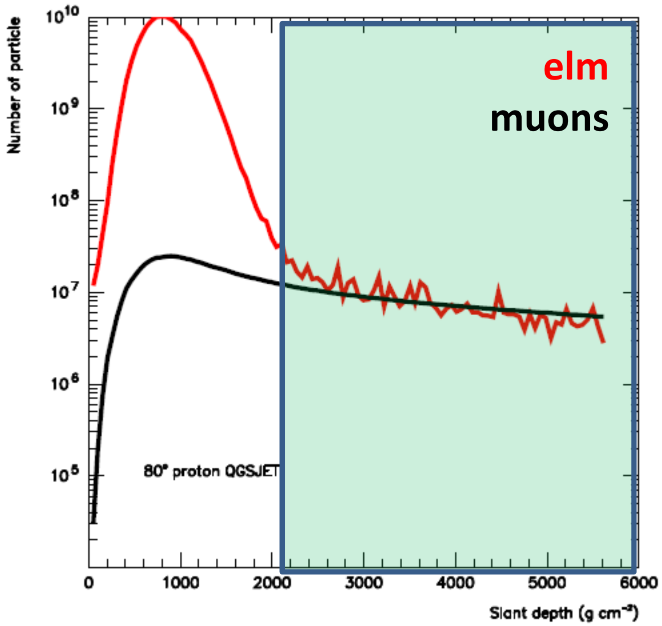
GRANDProto300 hybrid array

- GRANDProto300 will be complemented by an independant, autonomous **particle detector array** with large acceptance to inclined showers (after 2022)
- Independant detection of electromagnetic & muon components on a shower-to-shower basis, at the detector level.

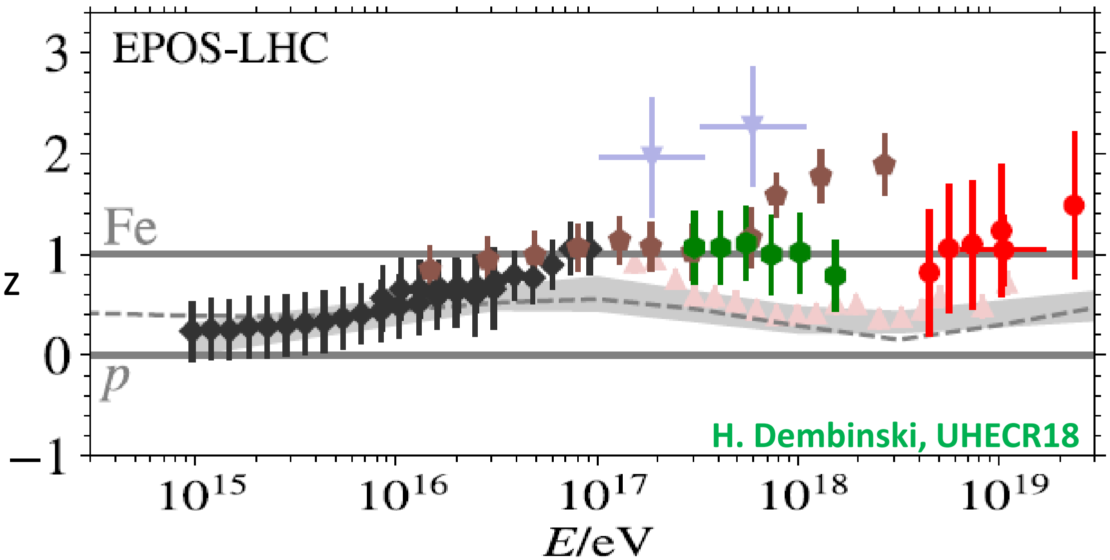
➔ Model-independant measurements of E ($\approx E_{elm}$), X_{max}, X_{max}^{μ} and N_{μ}

➔ Optimized & redundant measurement of primary nature



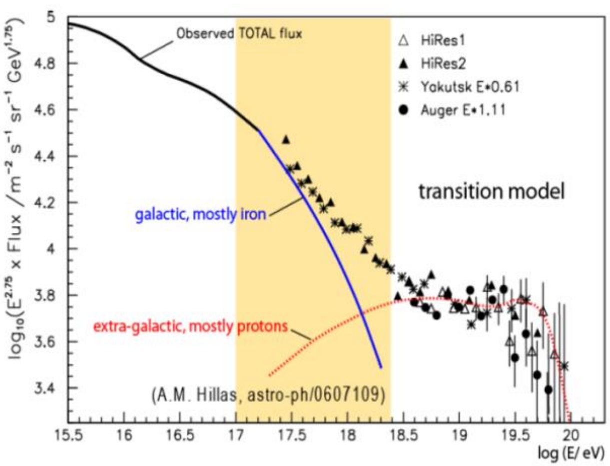


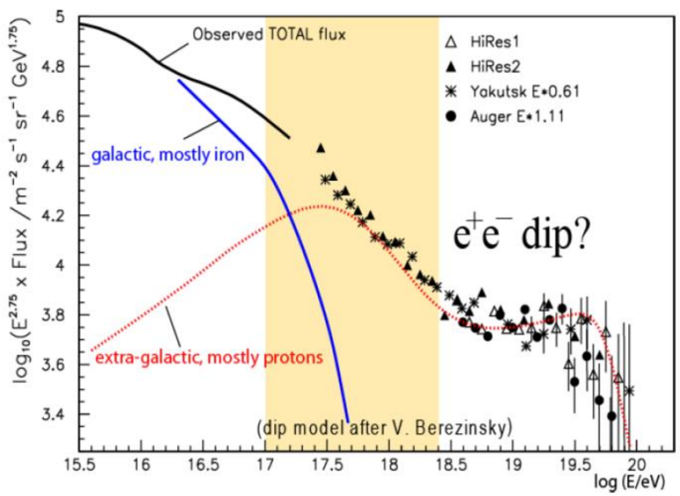
GRANDProto300 physics program (to be refined)



- Great tool to study air shower physics in the $10^{16.5}$-10^{18} eV energy range.

$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$





- Insight on the Galactic-extragalactic transition (large stat+full sky coverage + excellent primary determination)