The Giant Radio Array for Neutrino Detection

http://grand.cnrs.fr/

Olivier Martineau-Huynh, LPNHE
Irfu, DPhP, January 7, 2019

Menu de rentrée

<u>Apéritif:</u>

Motivation scientifique pour GRAND saupoudrée de son contexte expérimental

<u>Mise en bouche:</u>

Bouchées de principe de détection

<u>Hors d'œuvre:</u>

Objectifs scientifiques de GRAND sauce gravlax

<u>Plat de résistance:</u>

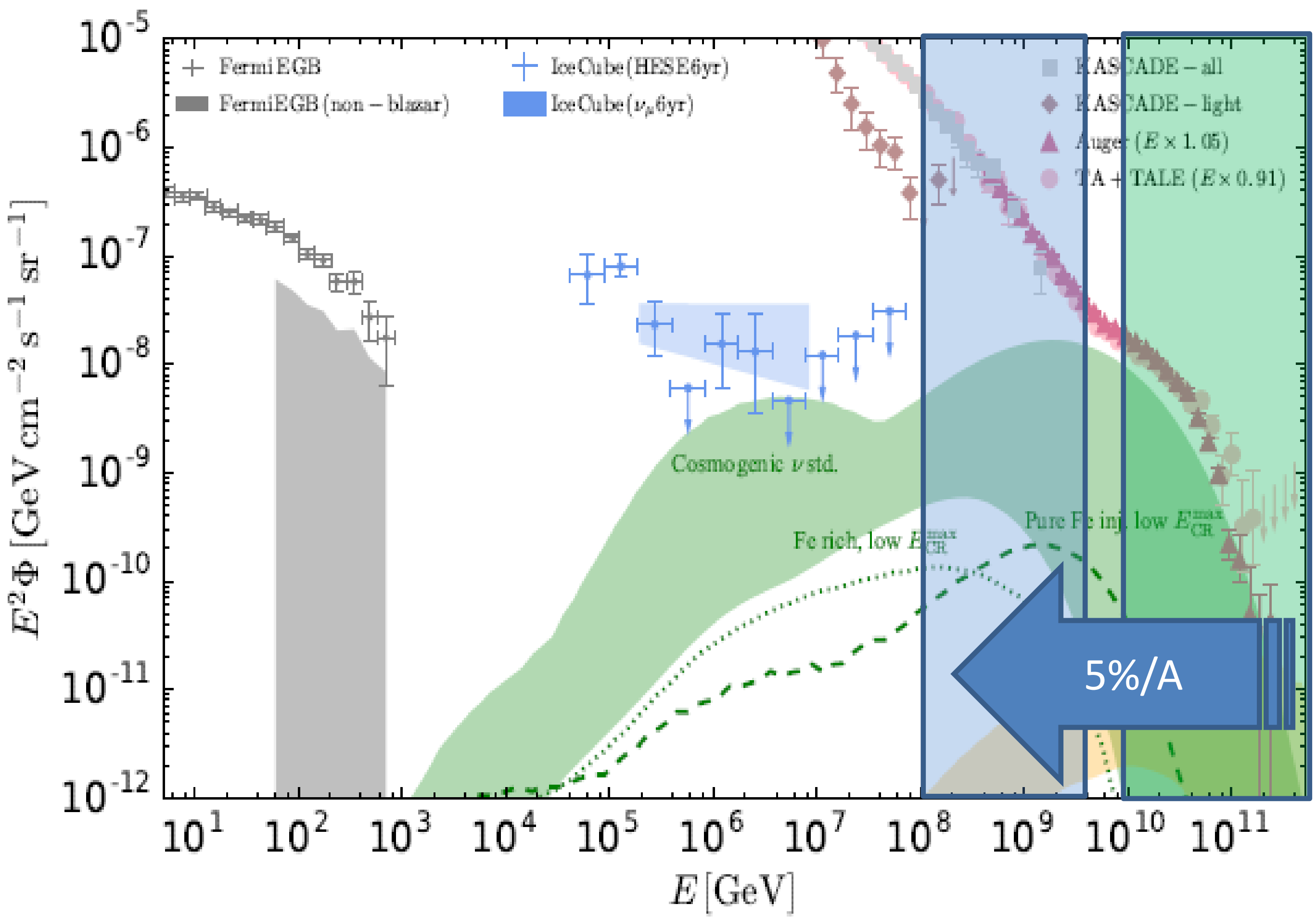
Fricassée de défis expérimentaux de GRAND

<u>Dessert:</u>

Galette des rois (fève = GRANDProto300)

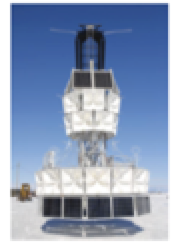
Why UHE neutrinos?

- «Cleanest probe» of the Universe (no deflection, no attenuation, hadronic…).
- Direct link to UHECRs (5% of primary energy)



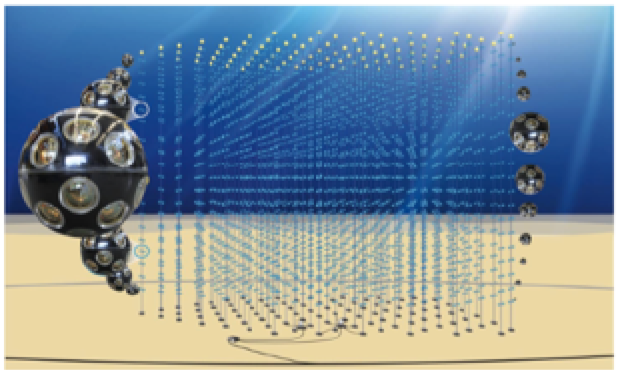
Future project overview

complementarity,
sensitivity to
neutrino sources
“precision frontier”



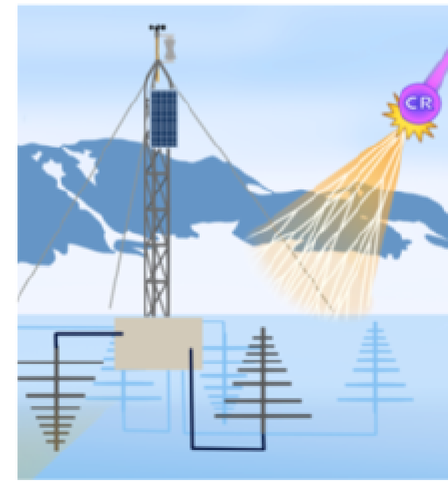
Present neutrino detectors

sensitivity at EeV
and beyond
“energy frontier”

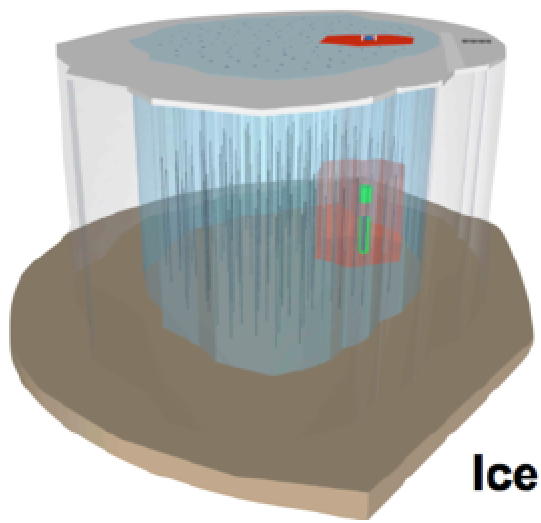


KM3NeT, GVD

sensitivity at
PeV energies
“intensity frontier”



**ARA, ARIANNA,
EVA, GRAND**

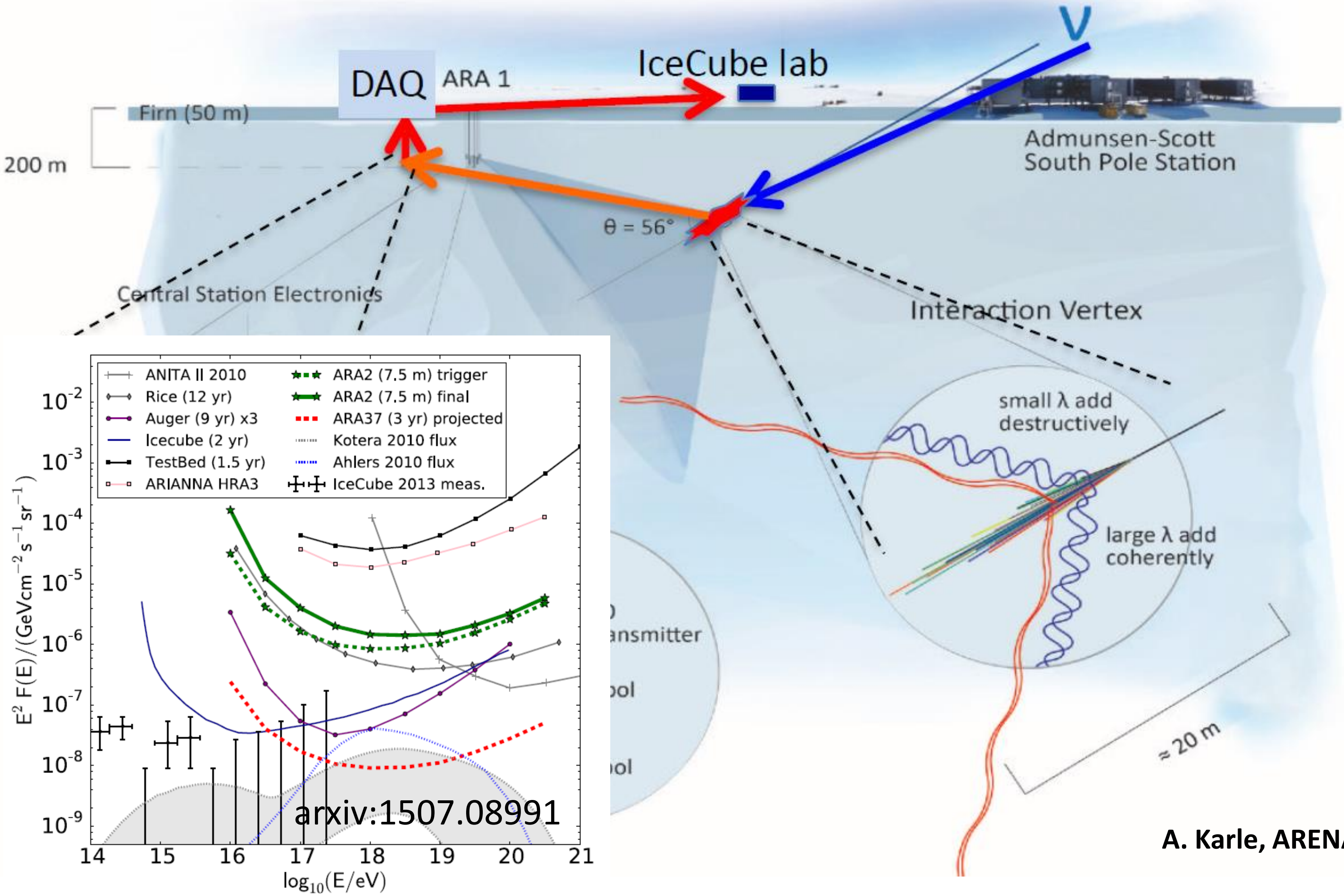


IceCube-Gen2

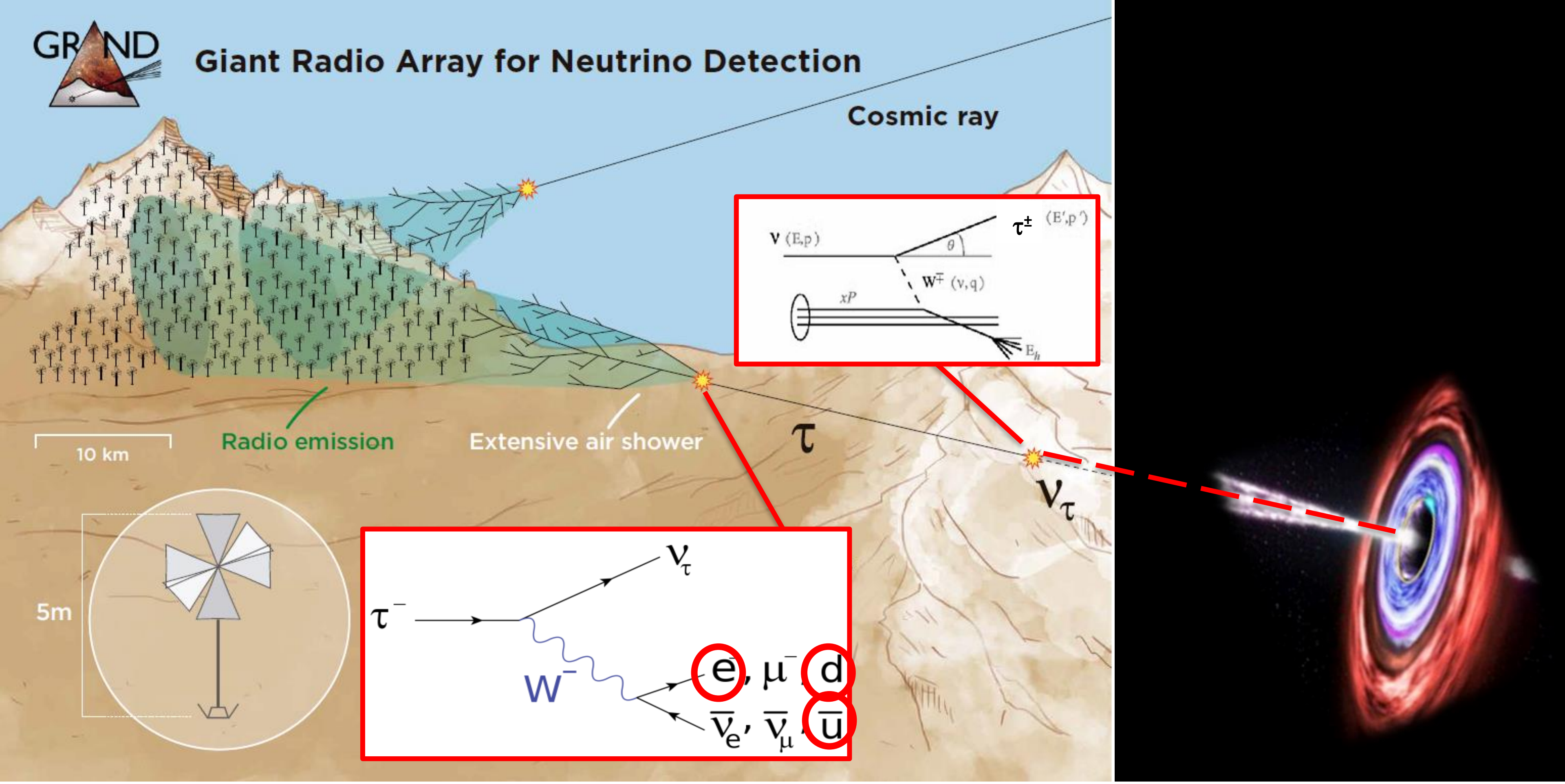
Kowalski@TeVPA2017

credit: M. Ackerman

Detection of ultrahigh-energy neutrinos in ARA



A. Karle, ARENA2018



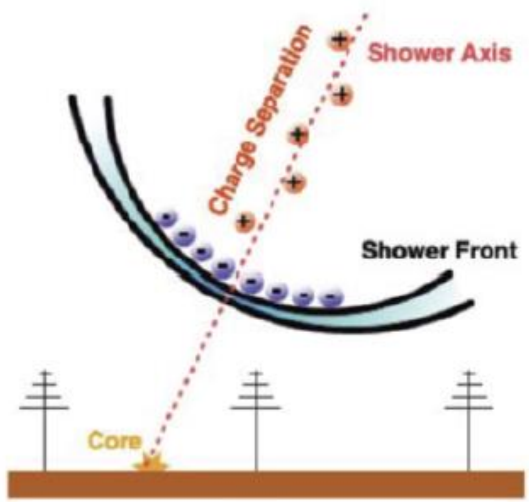
- Detection principle:
  - ν-induced tau decays in atmosphere generate ~horizontal extensive air showers [Fargion astro-ph/99066450]
  - Issues:
    - **VERY seldom events ➔** giant detector
    - <u>**Earth-skimming trajectories**</u> (λ_ν <~1000km)

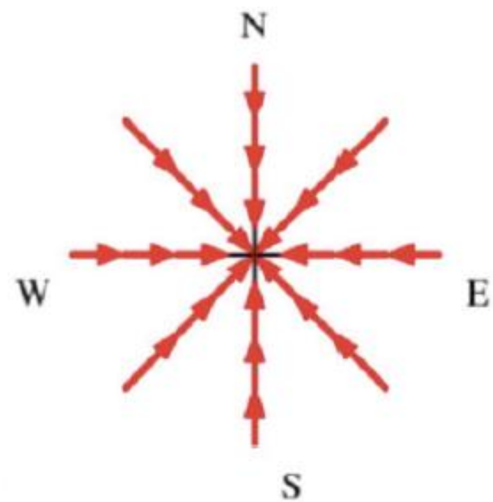
⇨ **Radio-detection**

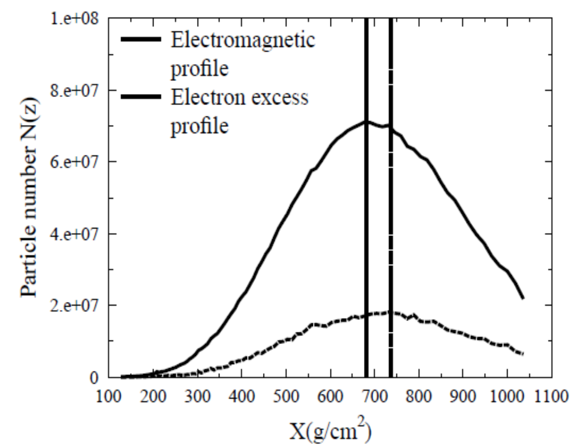
Radio emission by air showers

- Charge excess ⇔ Askaryan effect

De Vries et al.,
astro-ph/1304.1321

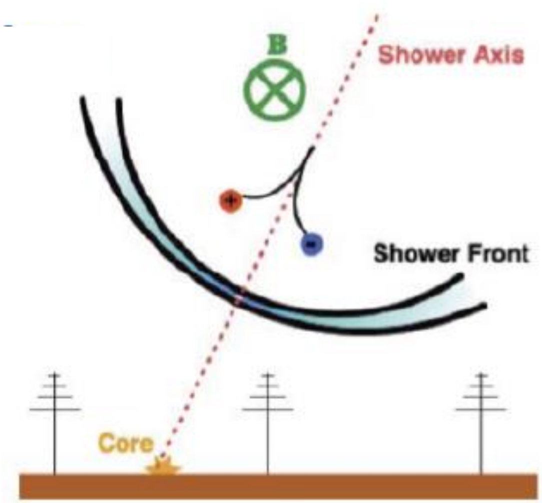


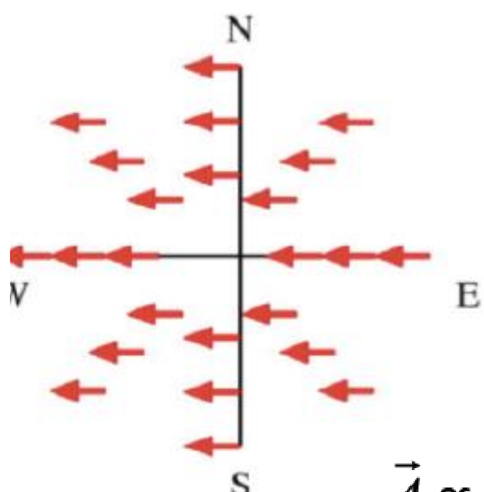




$$A \propto J^0 \qquad \vec{E} = \frac{dA^0}{d\vec{x}} \propto \vec{x}$$

- Geomagnetic effect (dominant)



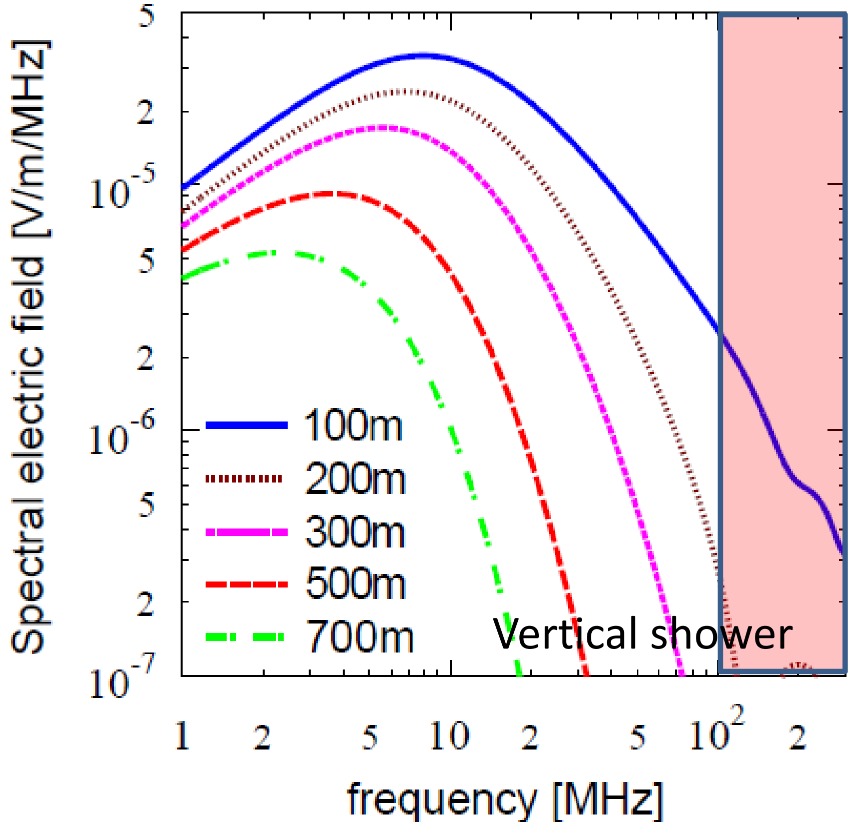


$$\vec{A} \propto \vec{J}_{Lorentz} \qquad \vec{E} = \frac{d\vec{A}}{dt} \propto \vec{v} \times \vec{B}$$

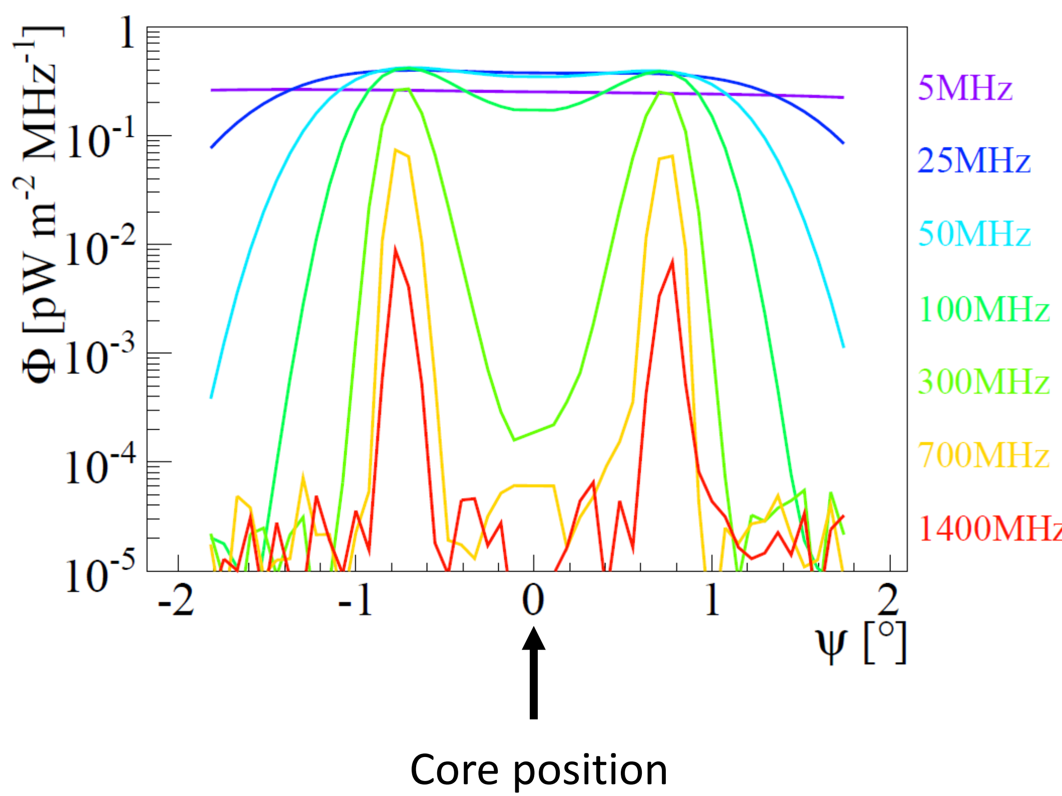
Frequency bandwidth

Emission coherent for λ>>d~3m⇔f<<100MHz.
Exception: high frequencies along Cerenkov ring.
Below 30MHz: short waves

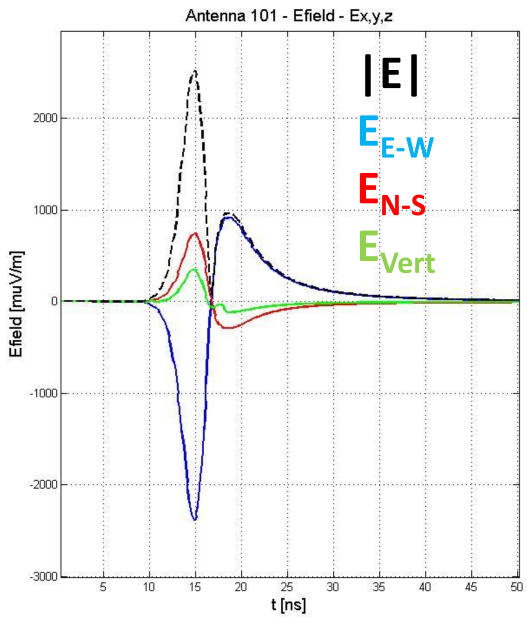
T. Huege, astro-ph/1601.07426

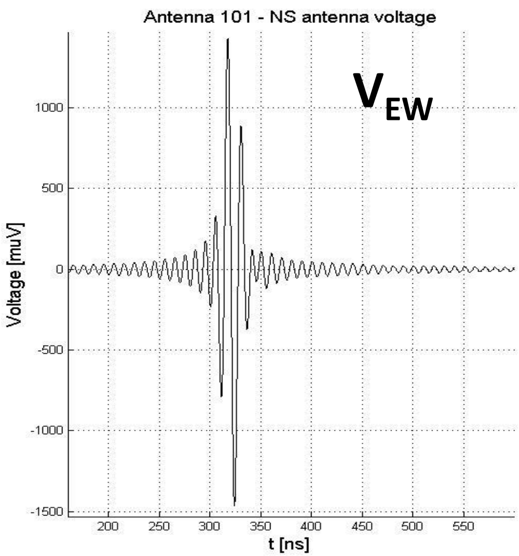


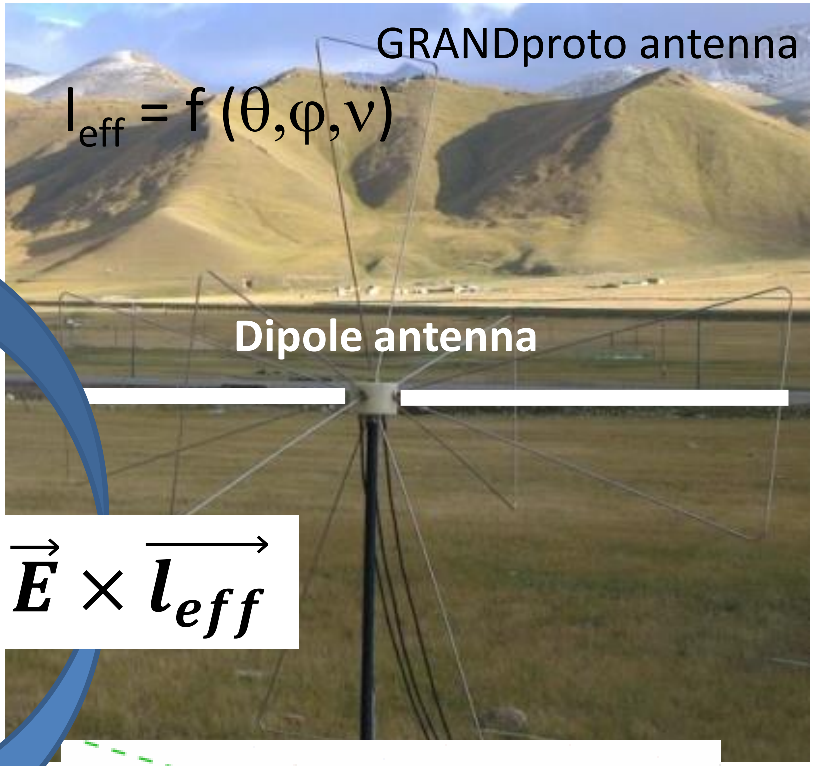
J. Alvarez-Muniz et al, astro-ph/1502.02117



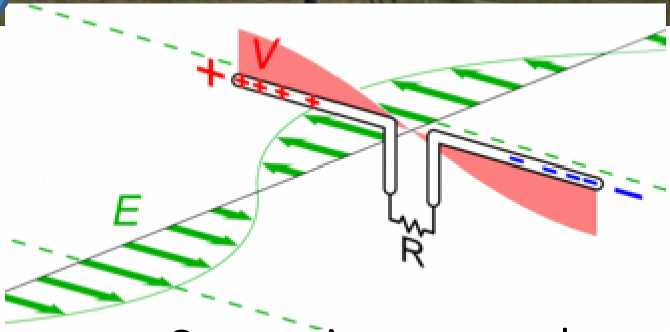
Radio detection







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



Current in antenna due to Efield generates voltage at load output

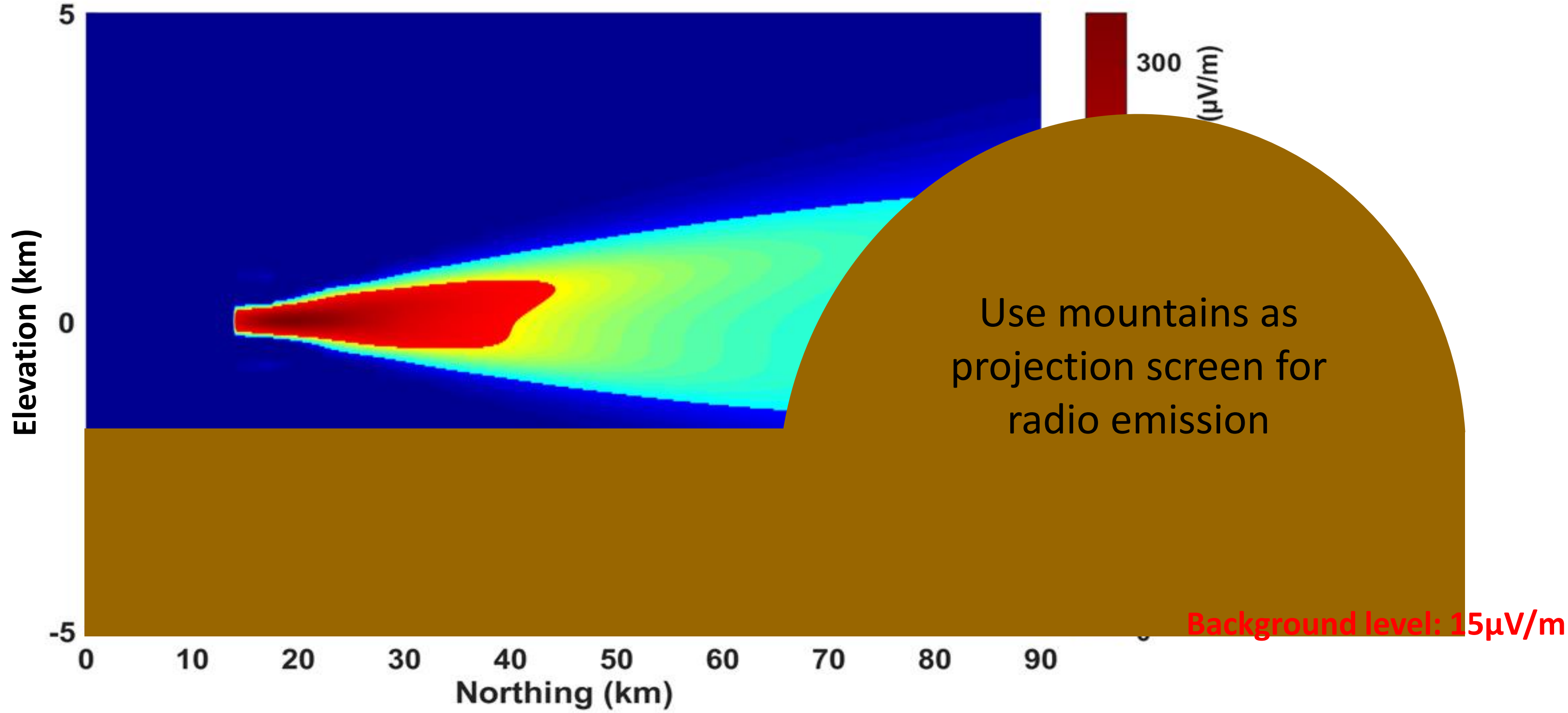
Why radio? Because it is cheap!

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!!



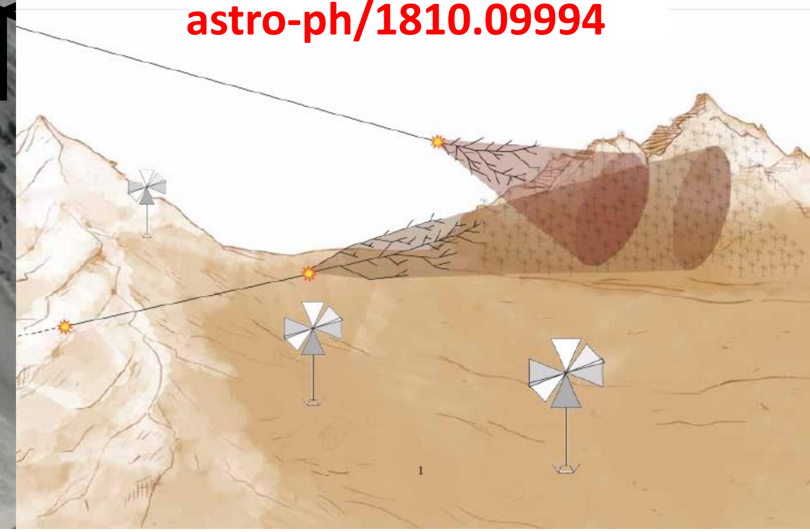
The GRAND project

GRAND

Giant Radio Array for Neutrino Detection

Science and Design

astro-ph/1810.09994



Author list

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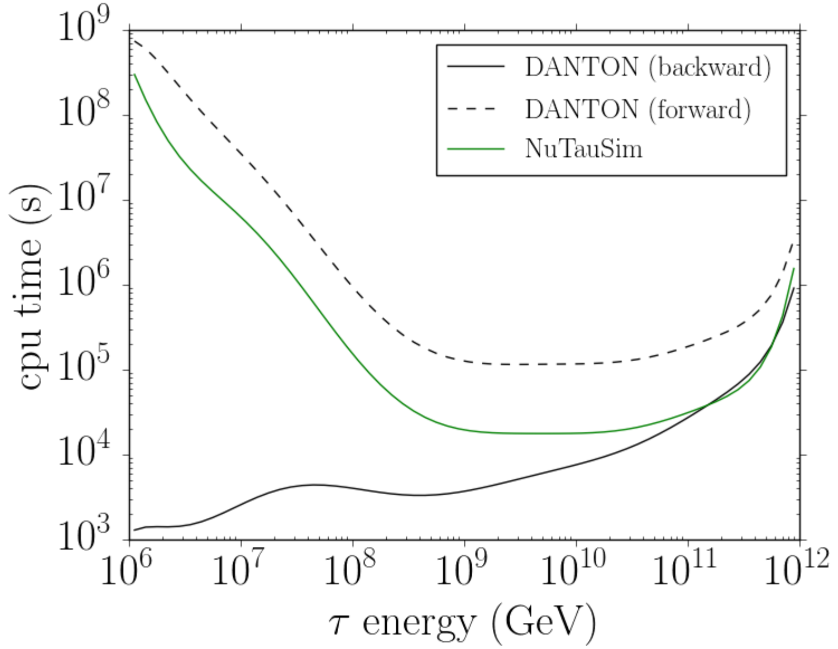
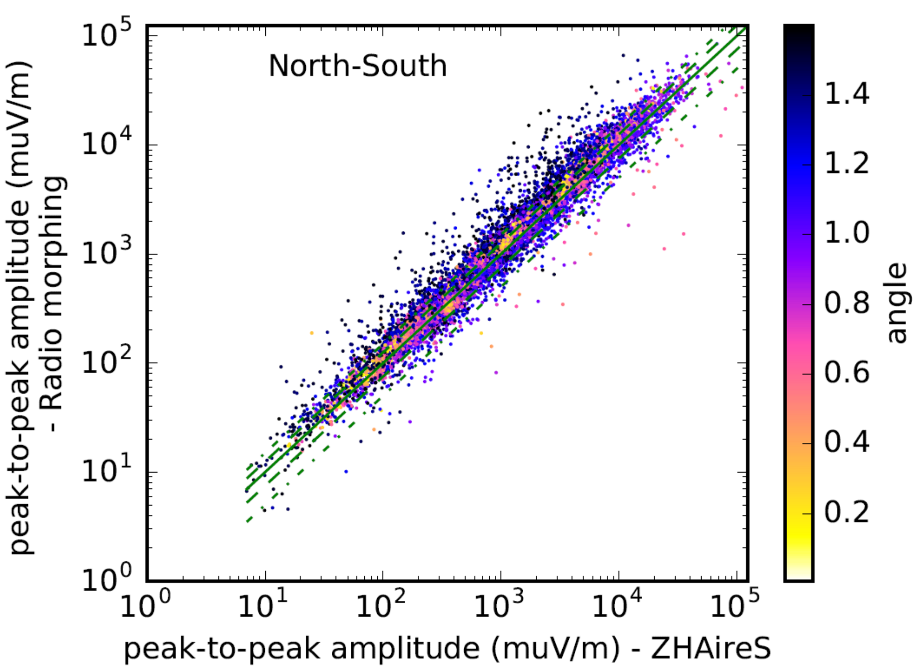
GRAND neutrino sensitivity computation

- **End-to-end custom simulation**

A- DANTON: $\nu \rightarrow \tau$ decay
backward MC over realistic topography.
V. Niess and OMH, astro-ph/1810.01978 .



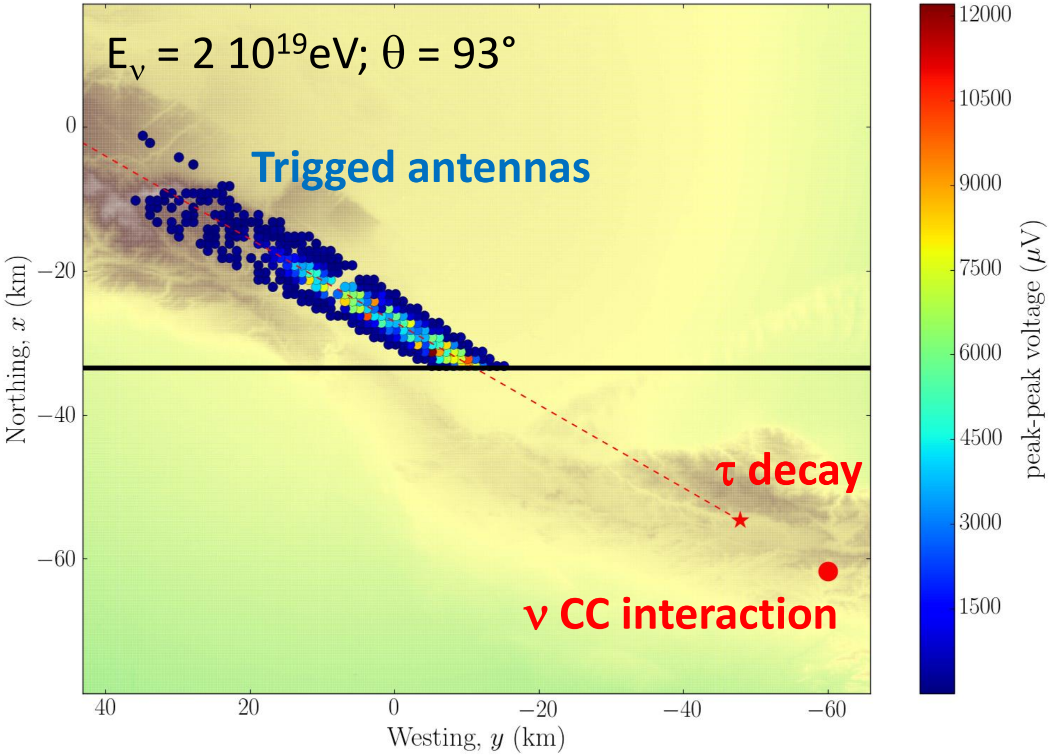


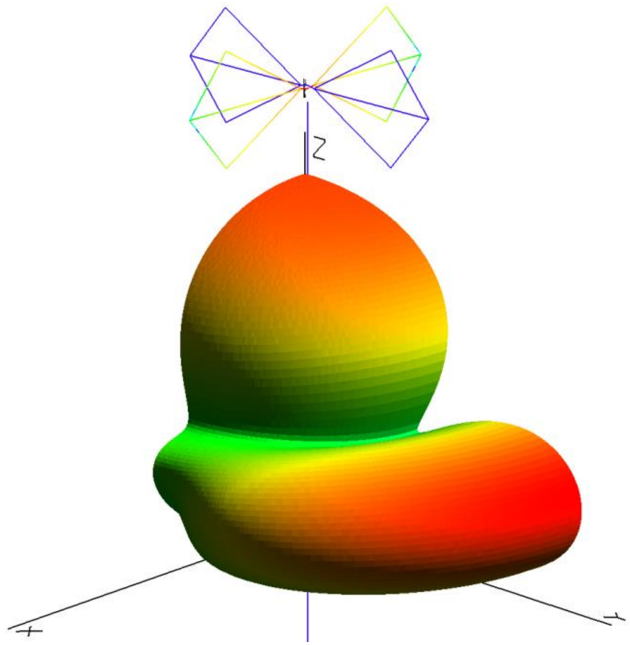
B- RadioMorphing: semi-analytical computation of the air-shower-induced Efield transient signal.
A. Zilles et al., astro-ph/1811.01750

GRAND neutrino sensitivity computation

- **End-to-end custom simulation**

C- Antenna response:
HORIZONANTENNA, h=5m, f = 50-200MHz, optimized for very inclined trajectories. Response simulated in NEC4.

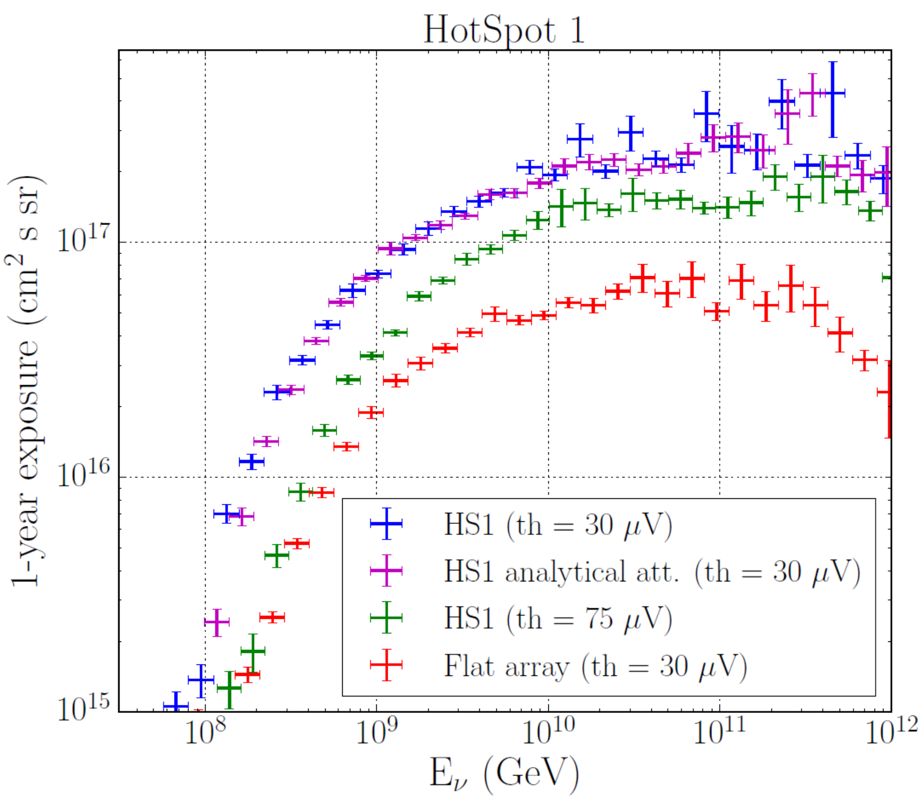


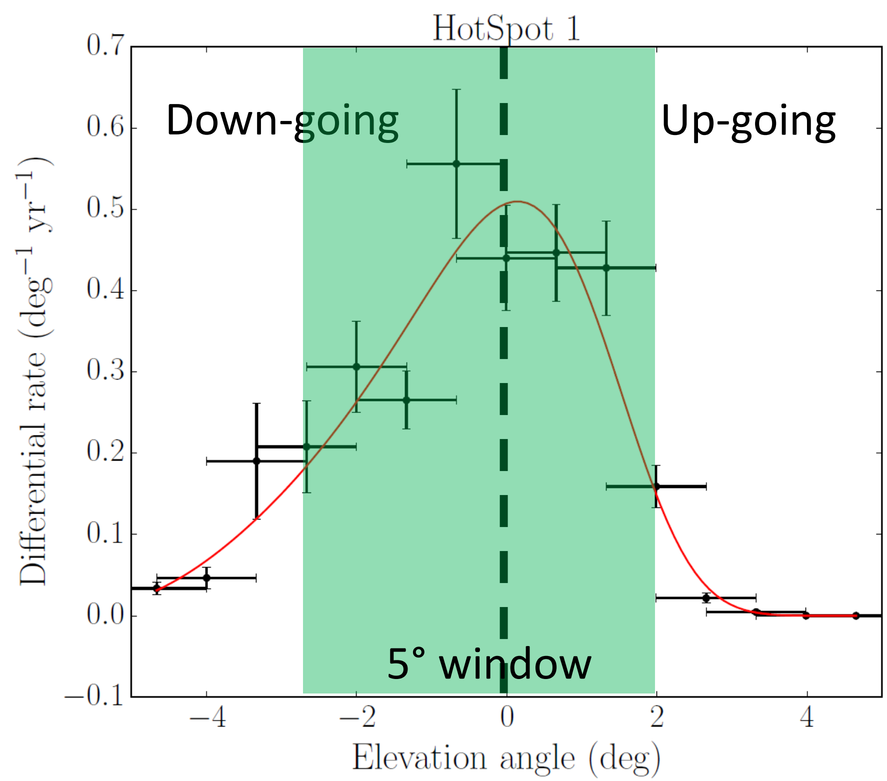


Antenna gain (NEC4)

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

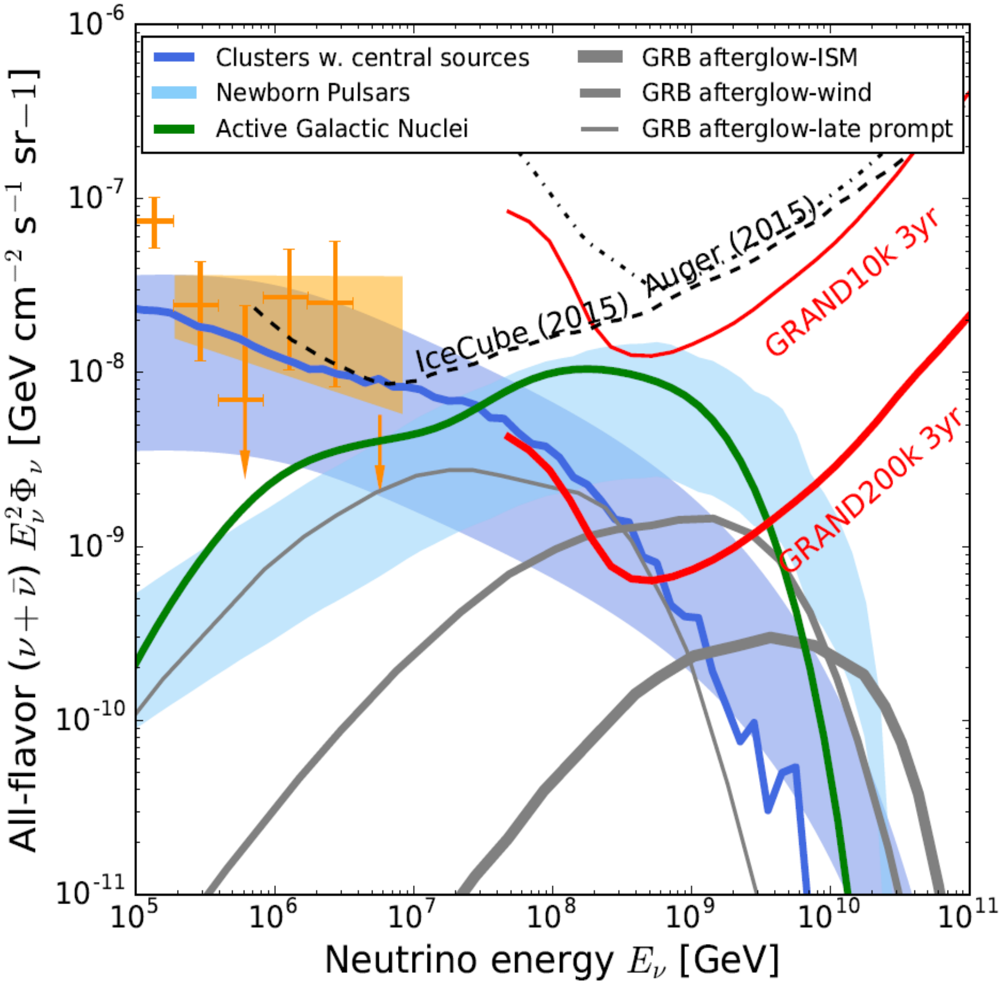
Simulation results





Exposure increase by factor ~4 thanks to topography.

GRAND science case: neutrinos



- GRAND10k (10'000 km²) competitive with ARA-ARIANNA.
- **Cosmogenic neutrinos** guaranteed flux

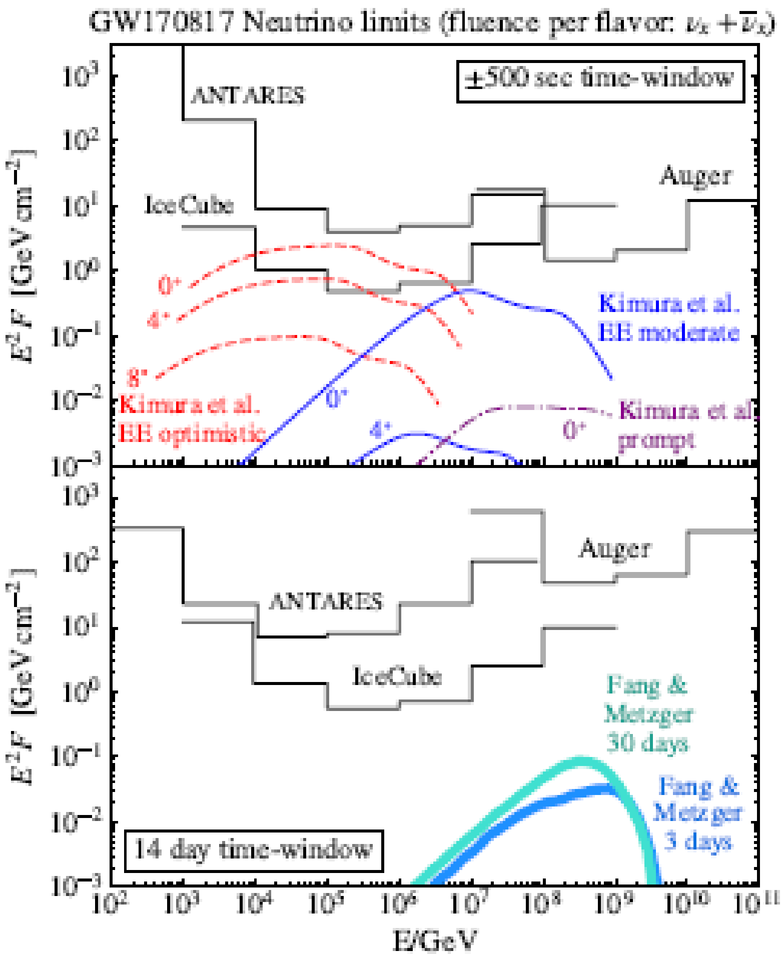
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \boldsymbol{\upsilon}$$

- Prediction based on experimental results (AUGER) + source evolution hypothesis.
- ***Aiming at ~20 subarrays such as HotSpot 1 deployed in areas with favorable topography at different locations in the world***

➔ **GRAND200k (20 x 10 000 km²)**

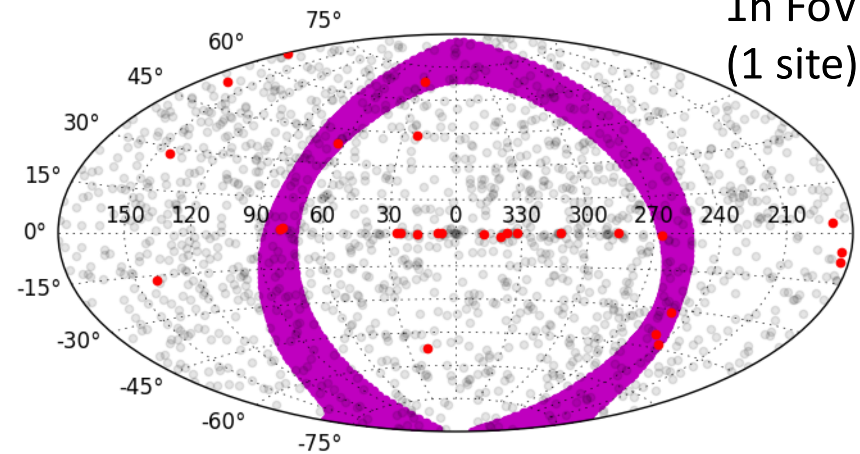
- Sensitivity of full array good enough for GRAND to detect cosmogenic neutrinos for standard hypothesis (up to tens/year)
- Also in range to detect neutrinos directly emitted from sources

GRAND science case: transient events & multi-messanger analysis

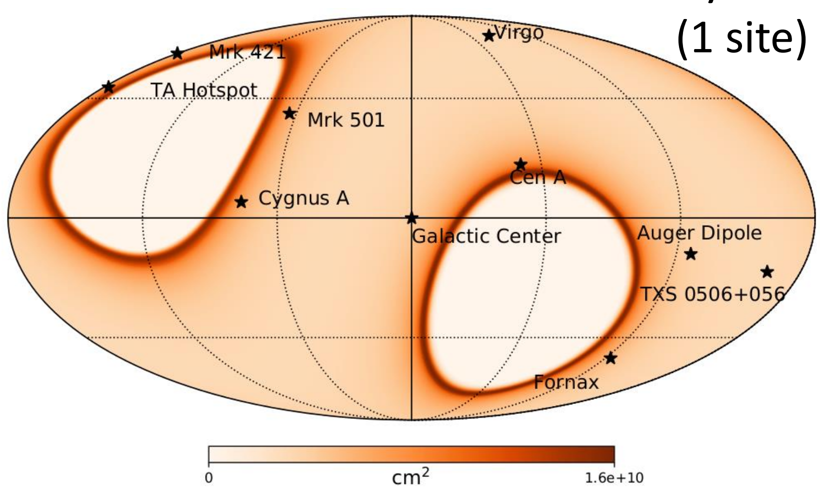


NS merger GW170817

1h FoV (1 site)



1-day FoV (1 site)

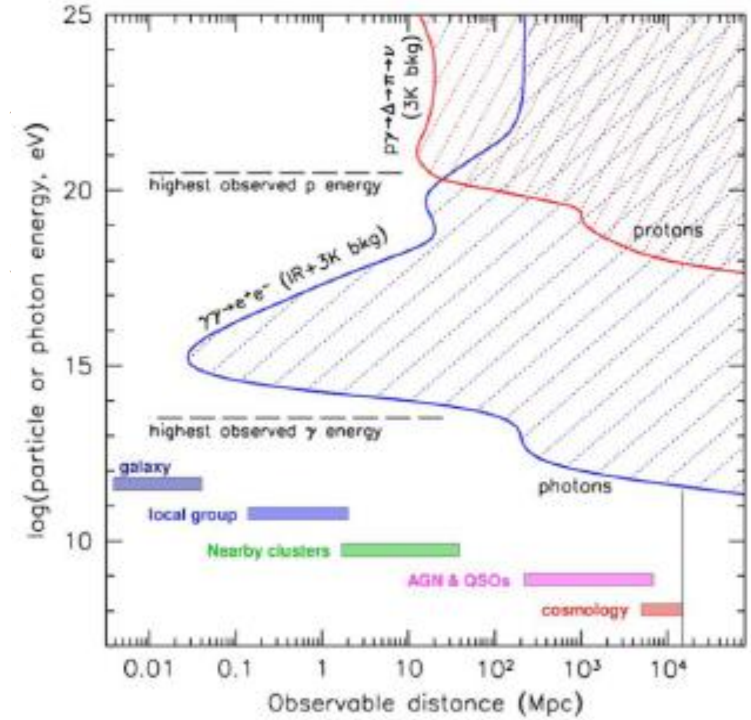


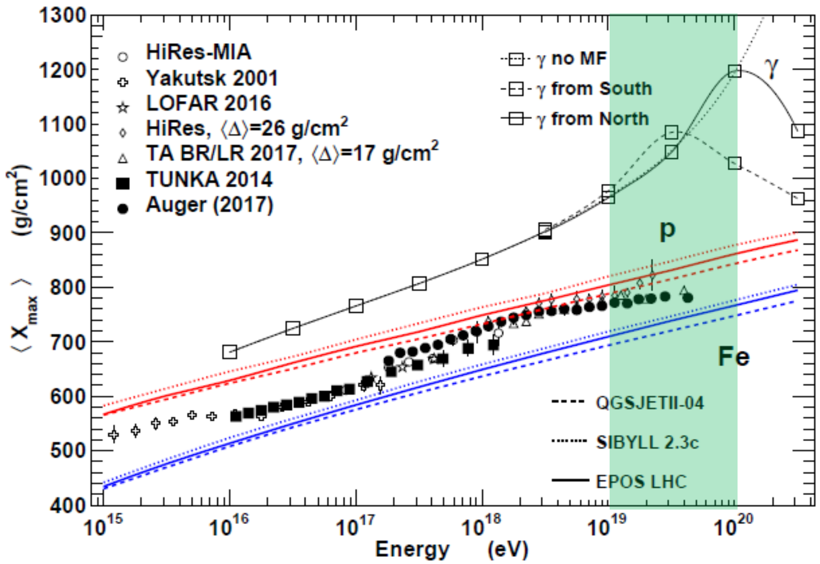
+ GRAND expected angular resolution: $\Delta\psi$~0.1°

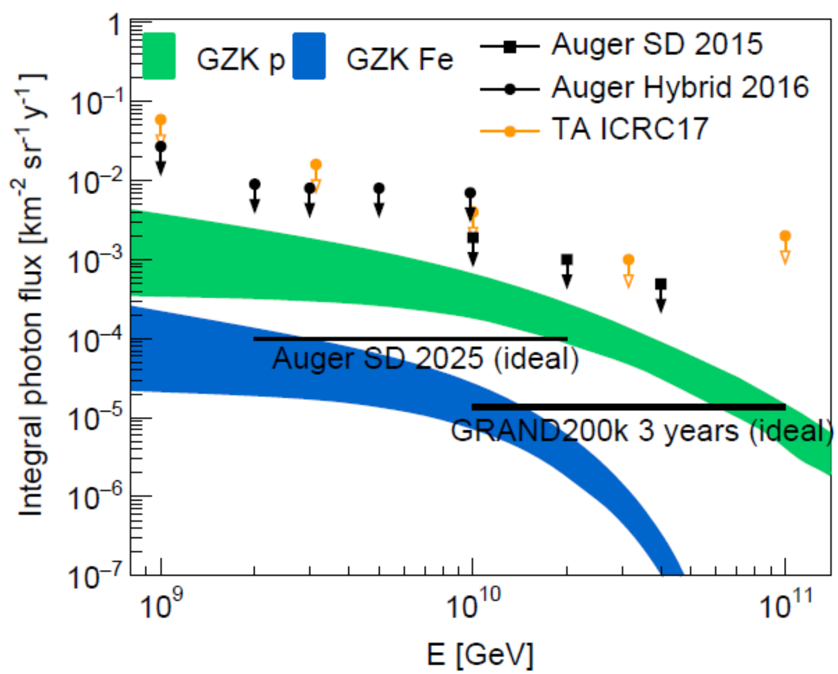
GRAND science case: UHECRs and gammas

- UHECRs: cut-off & transGZK
  - 200 000km² detection area, 60<θ<90°
    ➔ exposure = 15xAUGER
  - Full sky coverage
  - Xmax resolution ~40g/cm² (see later)
- Gamma rays
  - 100% seperation between UHECRs and gammas if we reach 20g/cm² Xmax resolution
  - **Cosmogenic gammas:**

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma$$

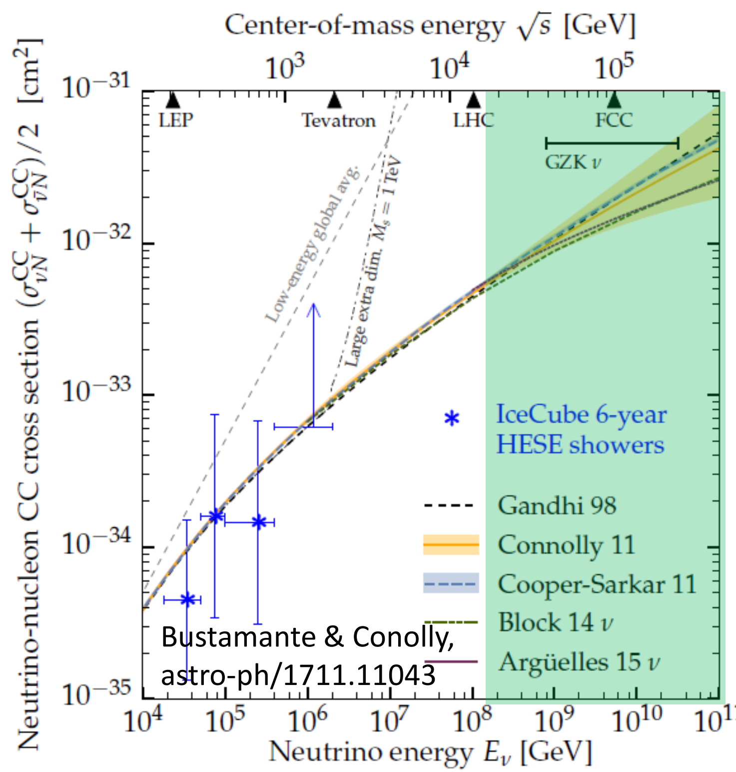


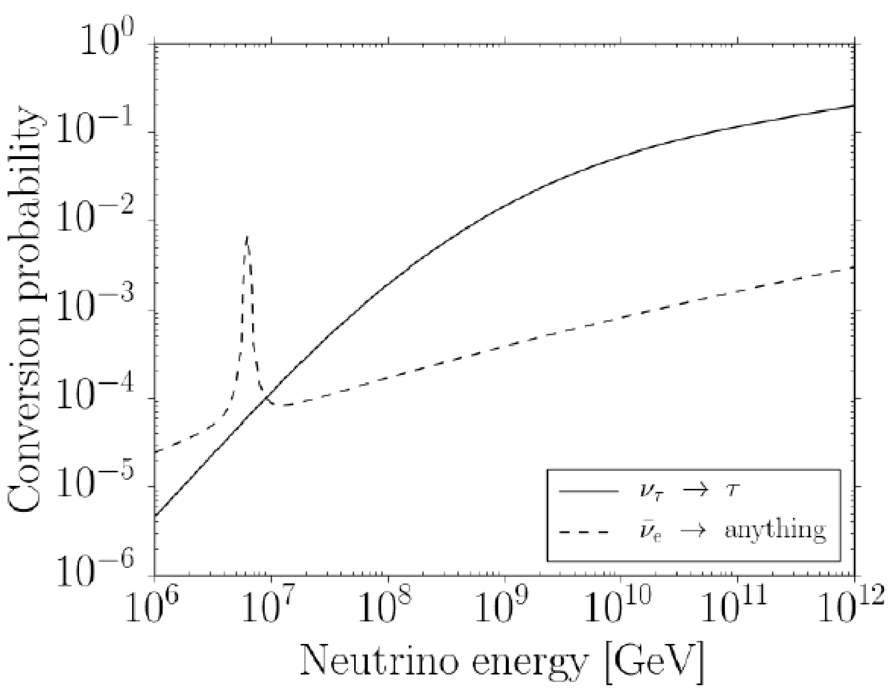


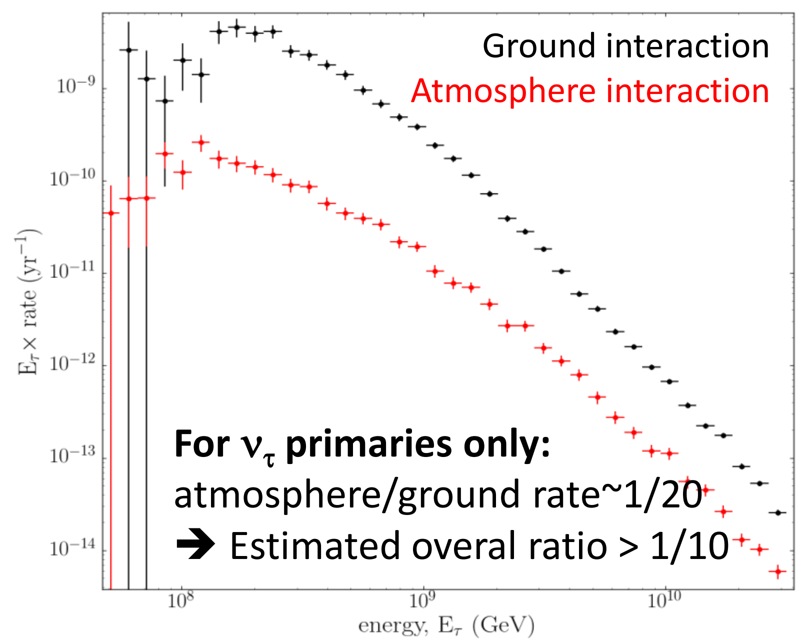


GRAND science case: neutrino physics

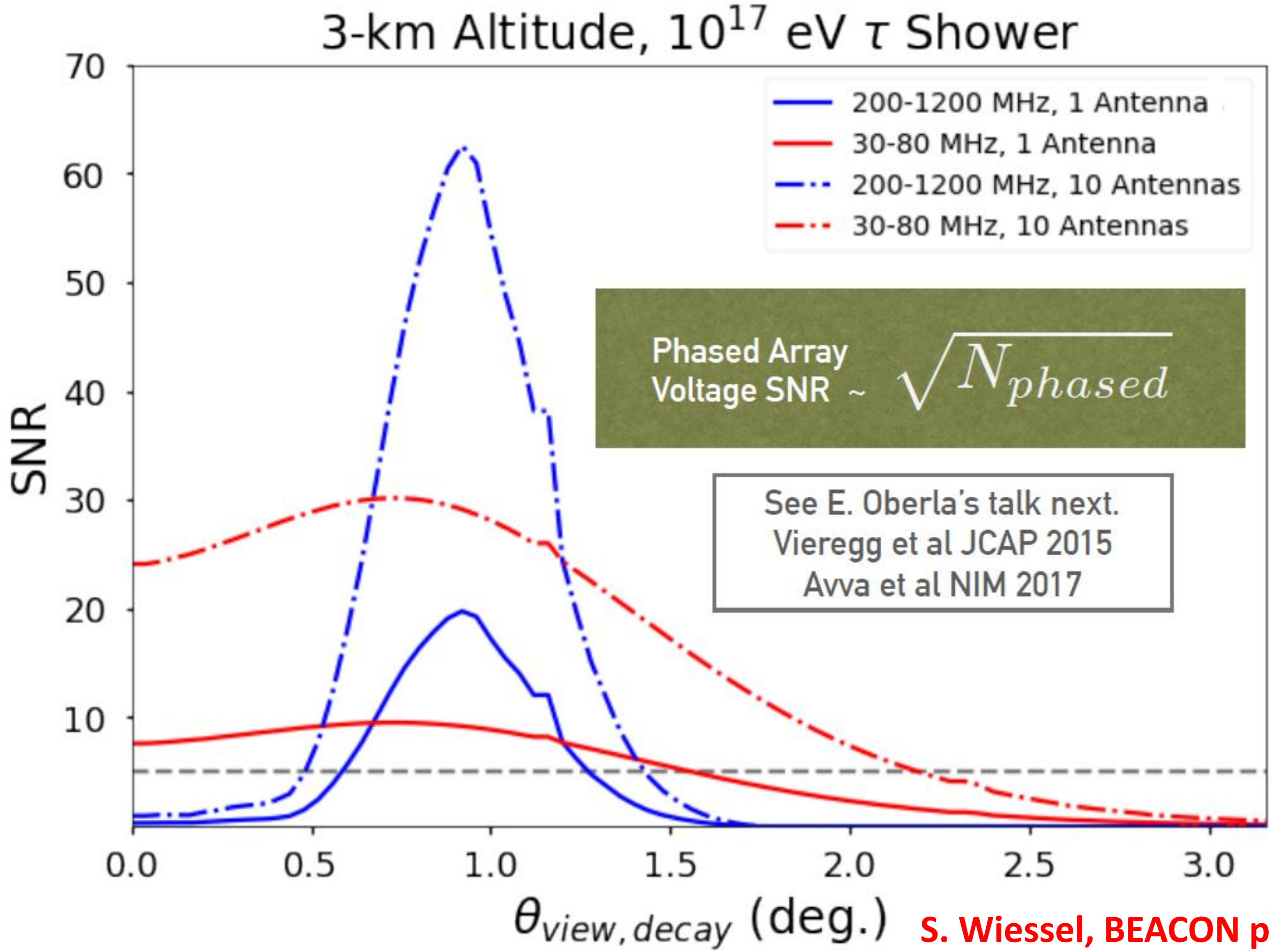
- Measurement of ν-p cross section
- Flavor study by comparison with other experients or *if* atmospheric events (all flavors) detected in addition to ground (ν_τ) (?)
- Search of physics beyond SM:
  - effect on spectrum or arrival directions $\alpha\ \kappa_n E^n\ L$ (??)
- Glashow resonance (???)







Phased Array to Increase SNR

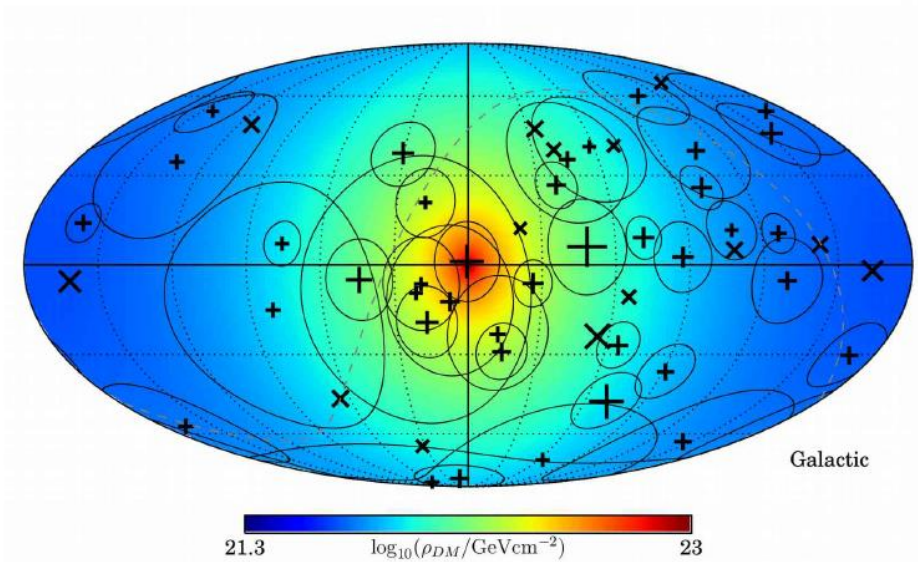


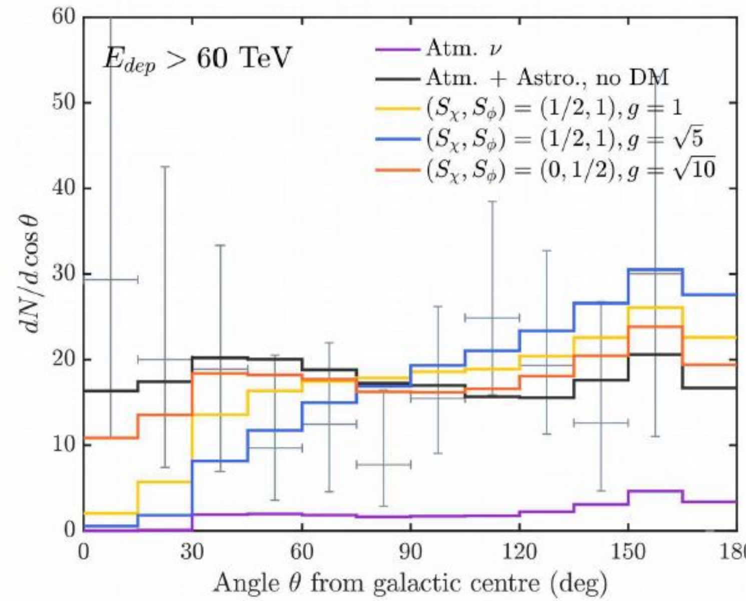
S. Wiessel, BEACON project
ARENA2018

GRAND science case: DM (???)

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





Argüelles *et al.*, *PRL* 2017

Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Mauricio Bustamante (Niels Bohr Institute) 25

+ many others (FRBs, EoR, HE atmospheric events…)

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!!!

But we have several very robust leads

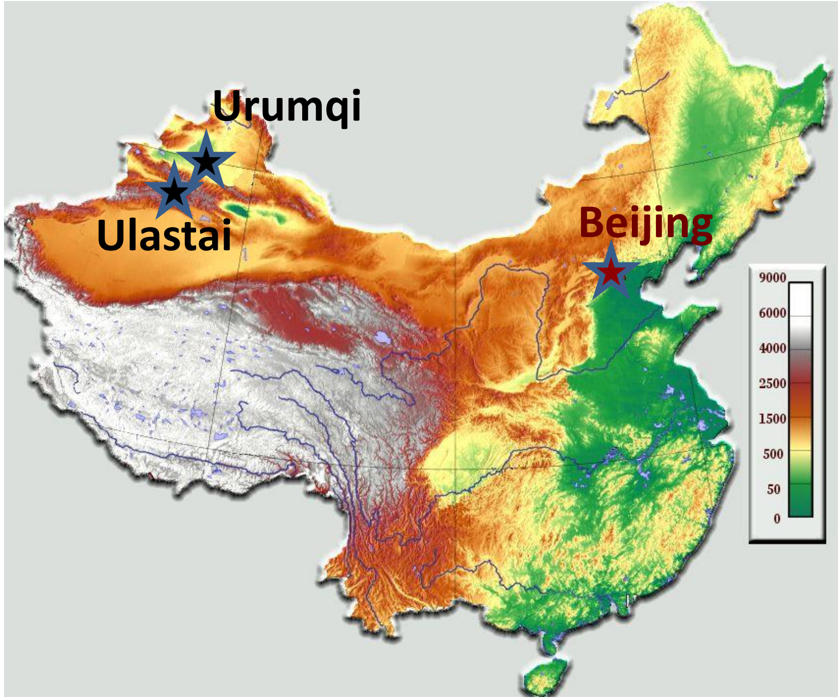
➔ **Time + R&D needed (GRAND not completed before 203x)**

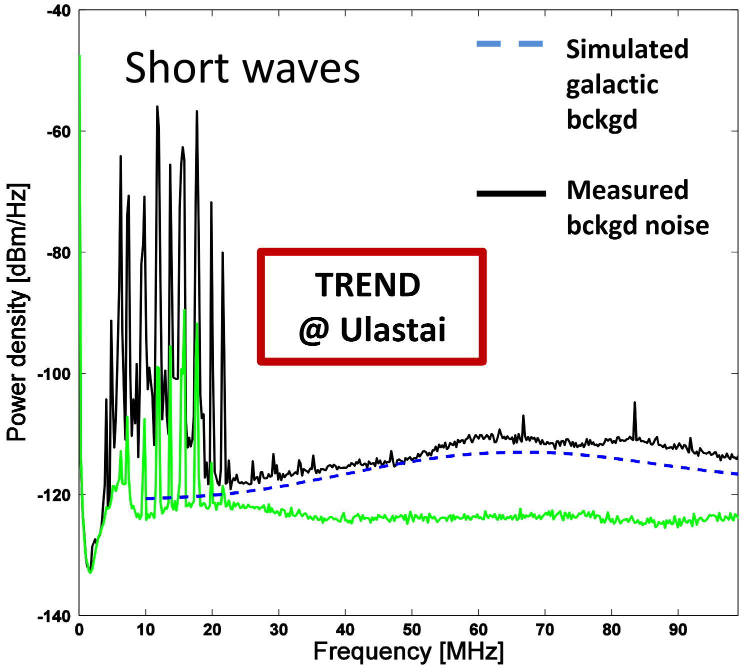
Challenge 1:
autonomous radio detection

The TREND experiment

(2009-2013-2018, 21CMA site)

- A very remote & quiet site.



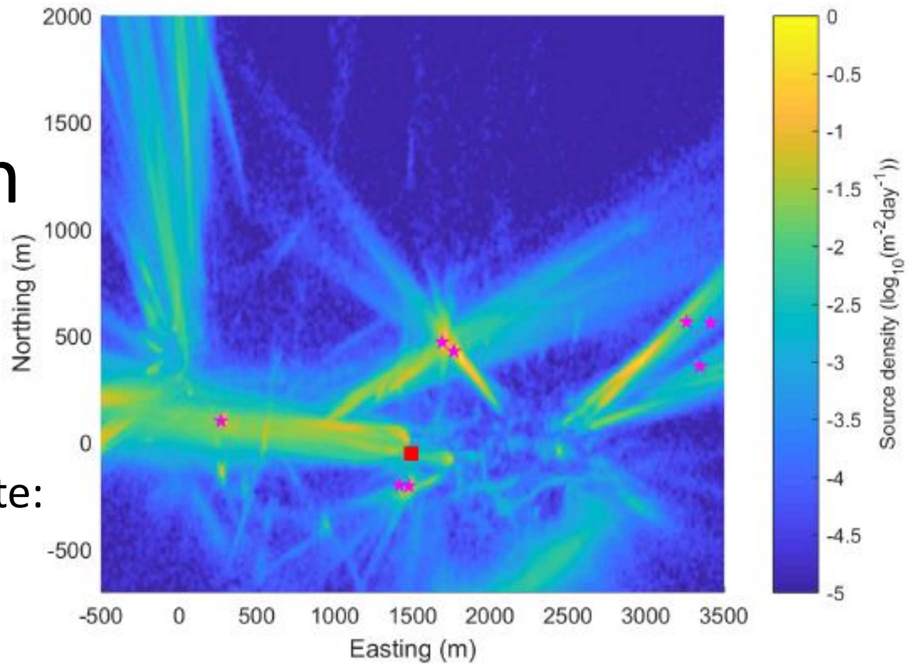


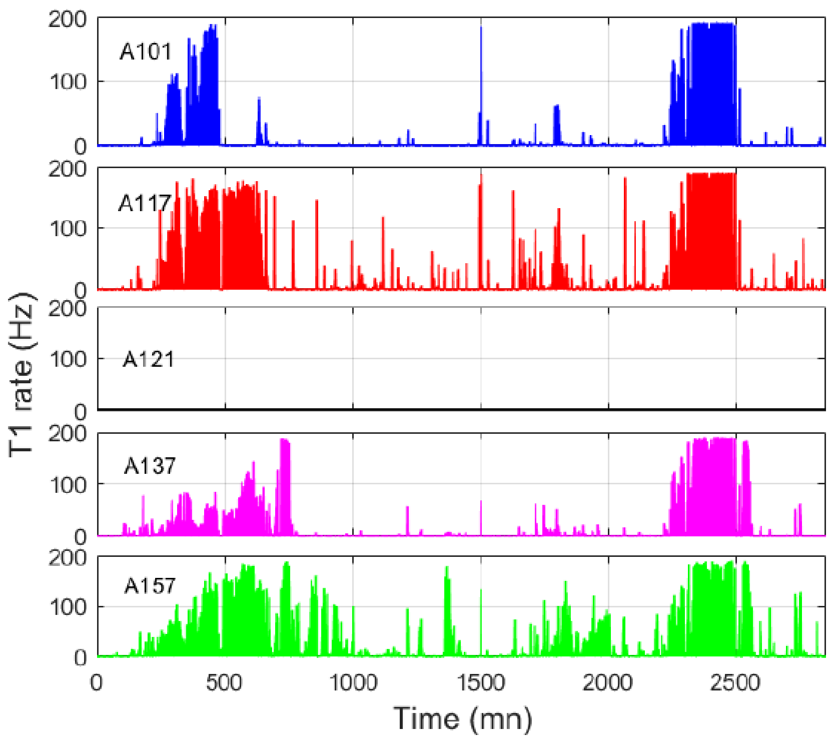
Challenge 1:
autonomous radio detection

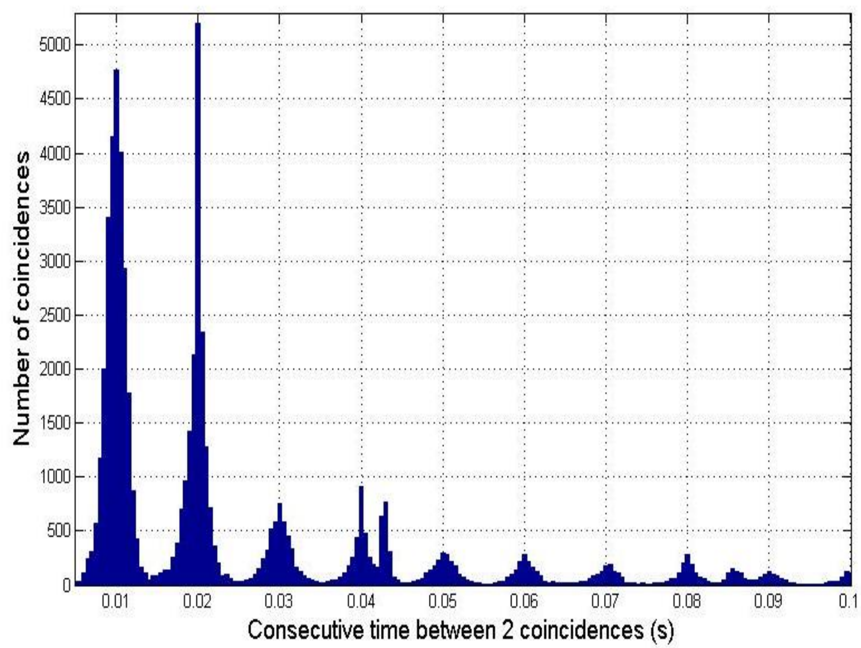
The TREND experiment

(2009-2013-2018, 21CMA site)

- A very remote & quiet site.
- Still: radio coinc rate = tens of Hz while EAS rate: ~20/day





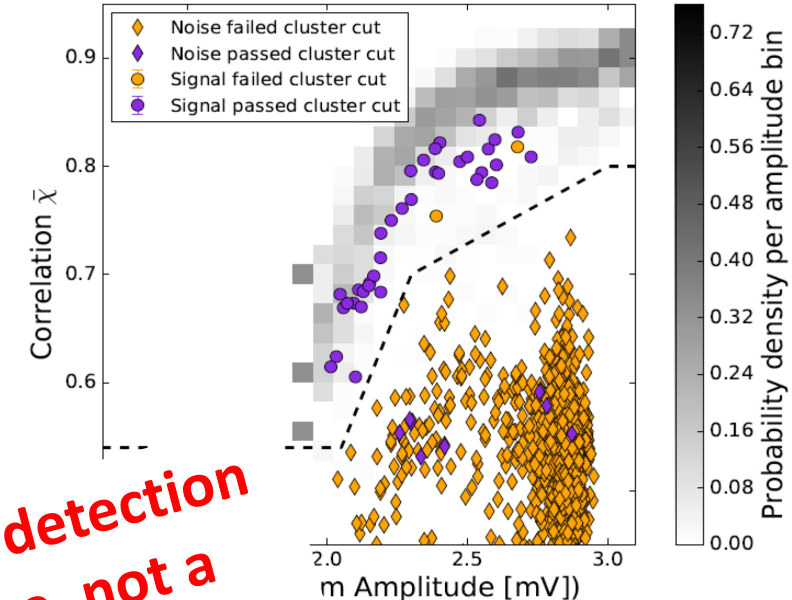


Challenge 1:
autonomous radio detection

The TREND experiment

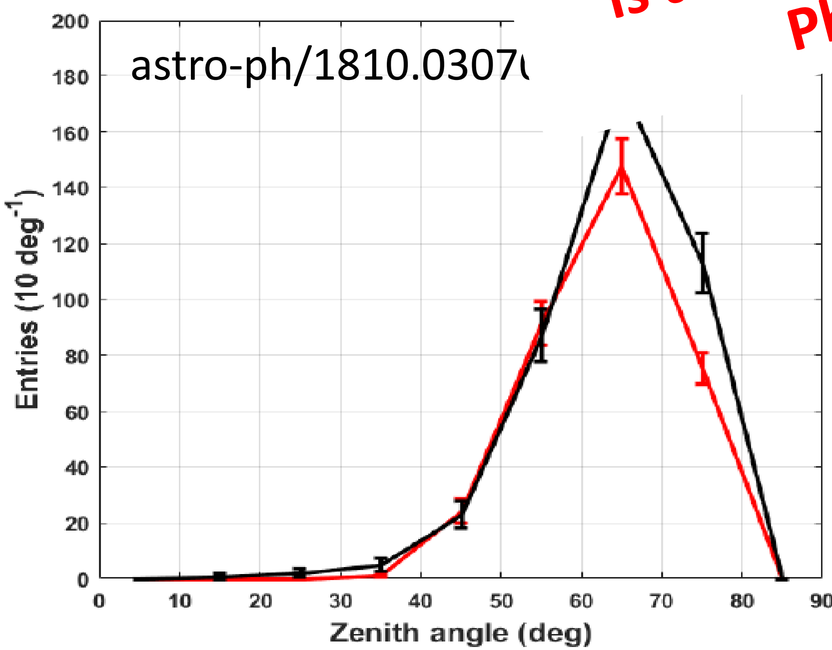
(2009-2013-2018, 21CMA site)

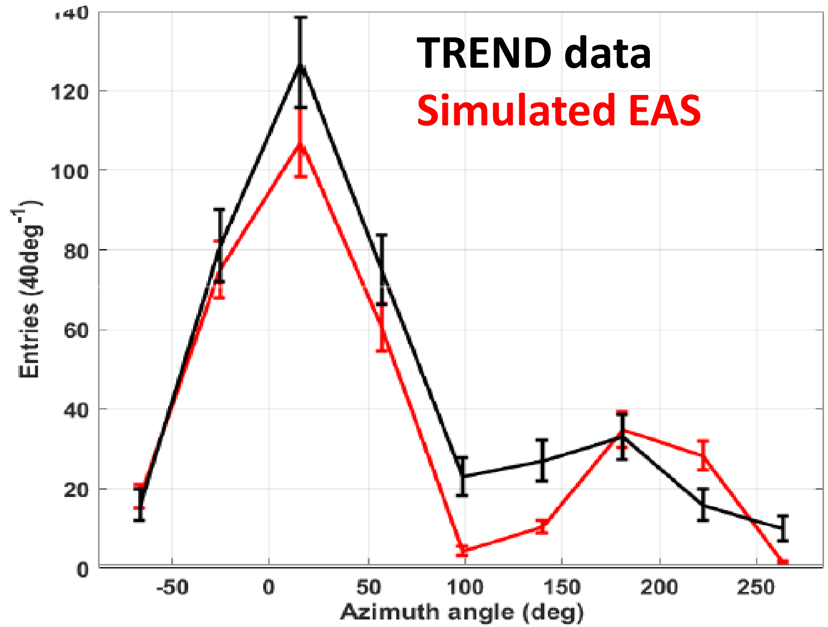
- A very remote & quiet site.
- Still: radio coinc rate = tens of Hz while EAS rate: ~20/day
- BUT distinct EAS & backgro… for excellent discrimin…



…ɔ ARIANNA!
(astro-ph/1612.04473)

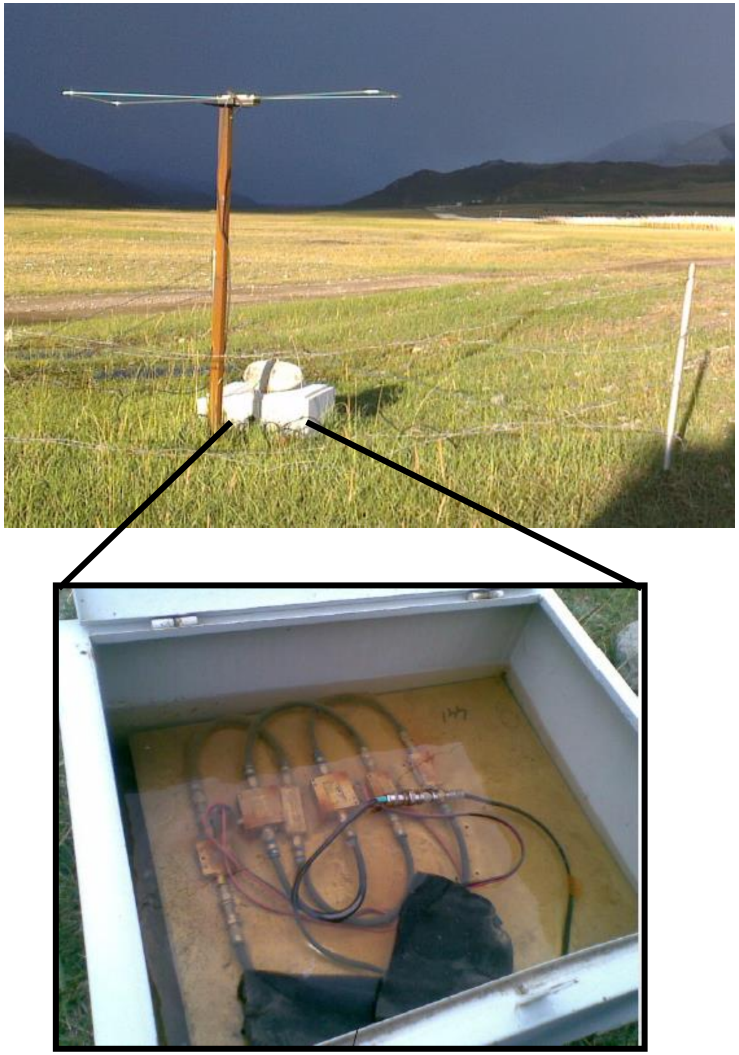
Autonomous radio detection is a technical issue, not a Physics one.

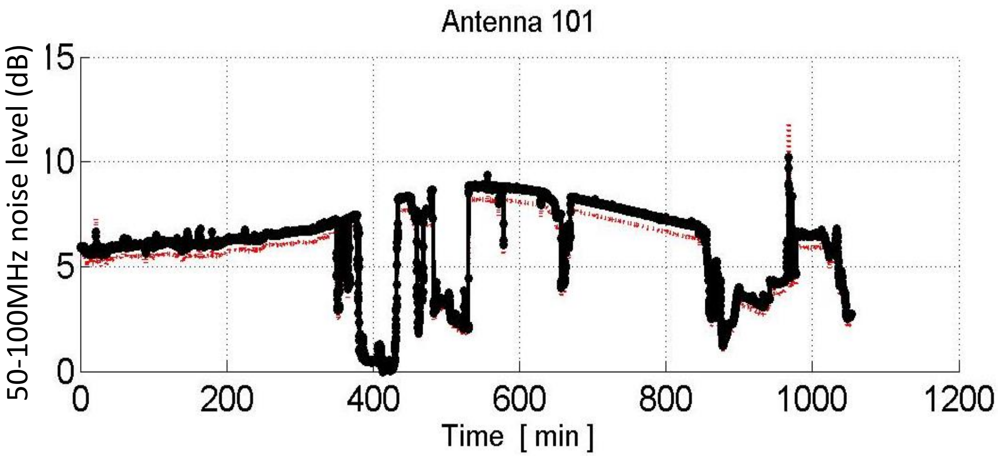


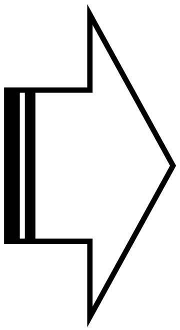


TREND limitations

- «You get what you pay for»:
  system reliability questionnable
  - Sudden drops in gain
  - Aging (antennas, amplifiers, optical system, computers…)



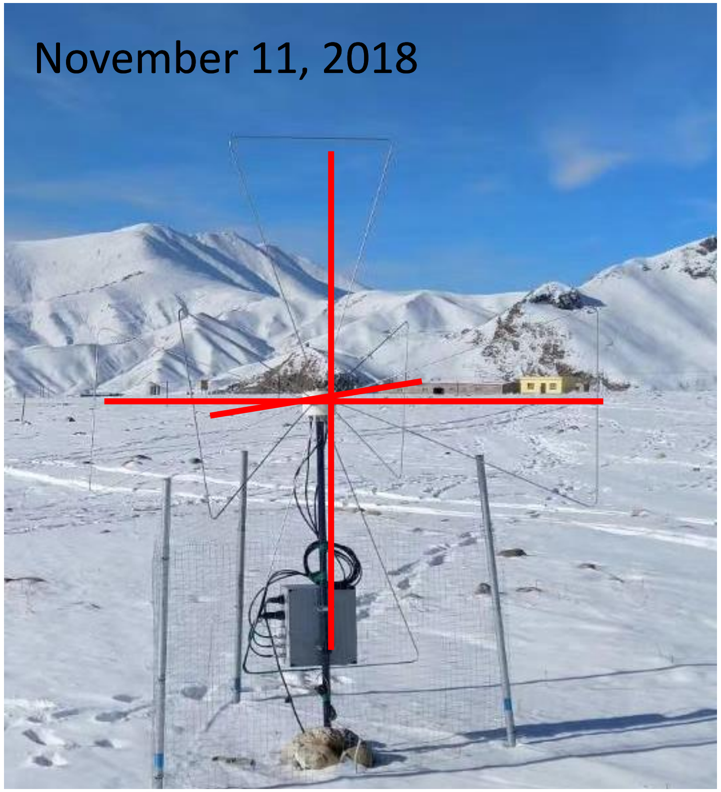


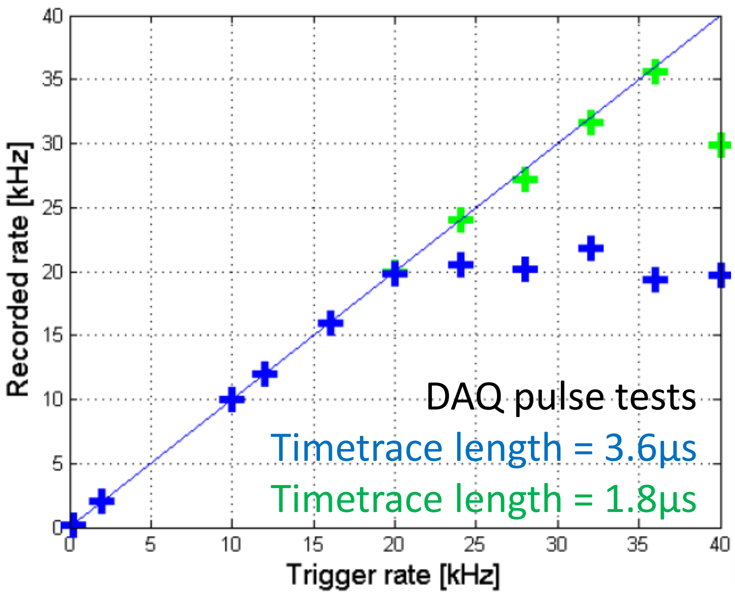


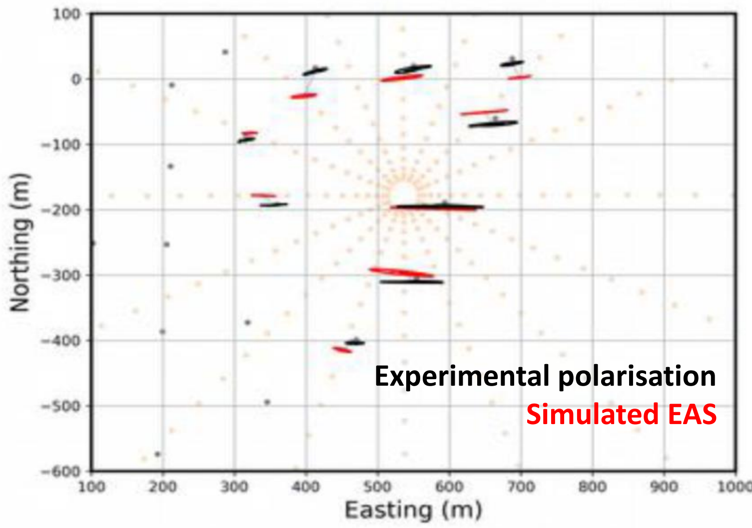
- Significant maintenance effort required
- Determination of efficiency & absolute calibration (very) chalenging: loooong analysis!
- **Reduced detection efficiency: 3% only** (=10%[hardware] x 30%[selction cuts])

GRANDProto35

- Goal: air shower radio detection with <u>high efficiency & high purity</u>
- Methods
  - 3D polarization measurement
  - Fast DAQ
- Cross-check with ground array
- Presently in commissioning phase, but site access issues!
- **Just a first step!!! More in GP300.**



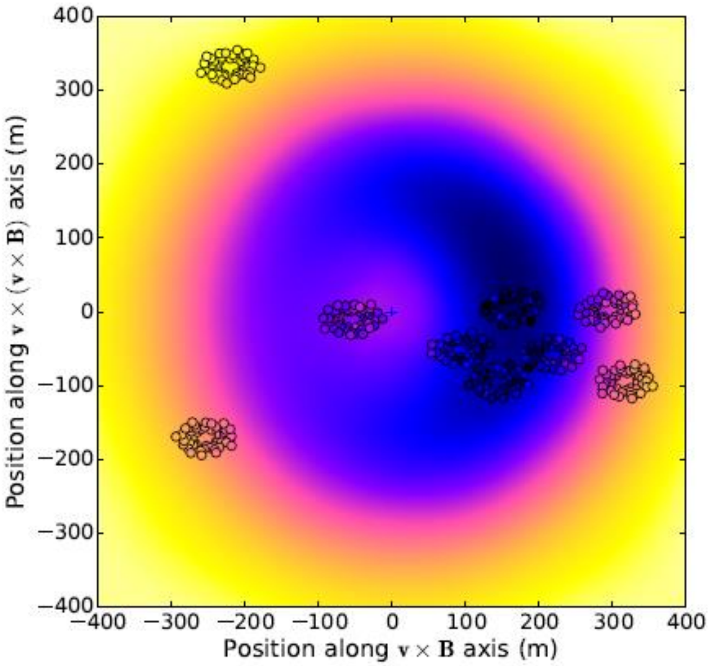


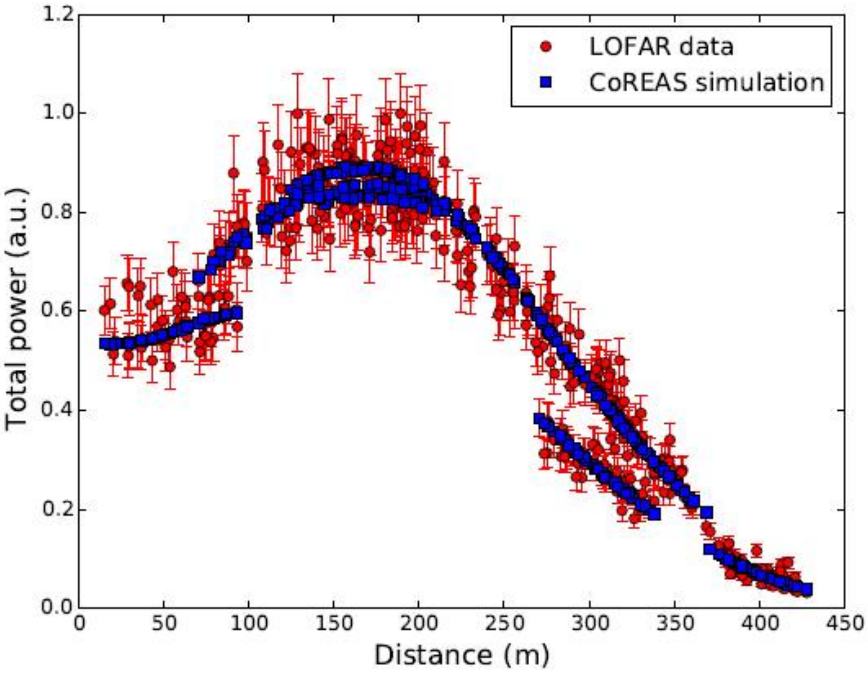


CODALEMA, astro-ph/1710.02487

Challenge 2: EAS reconstruction from radio data

- Simulations now converge to good description of experimental data.





Buitink et al., astro-ph/1408.7001

Radio reconstruction performance

- X_{max} from radio lateral profile, $\langle \Delta X_{max} \rangle \sim \pm 15 g/cm^2$ sys

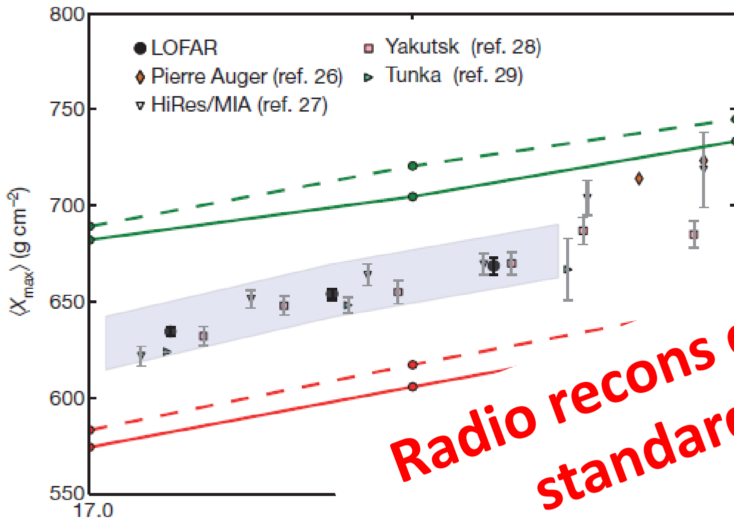
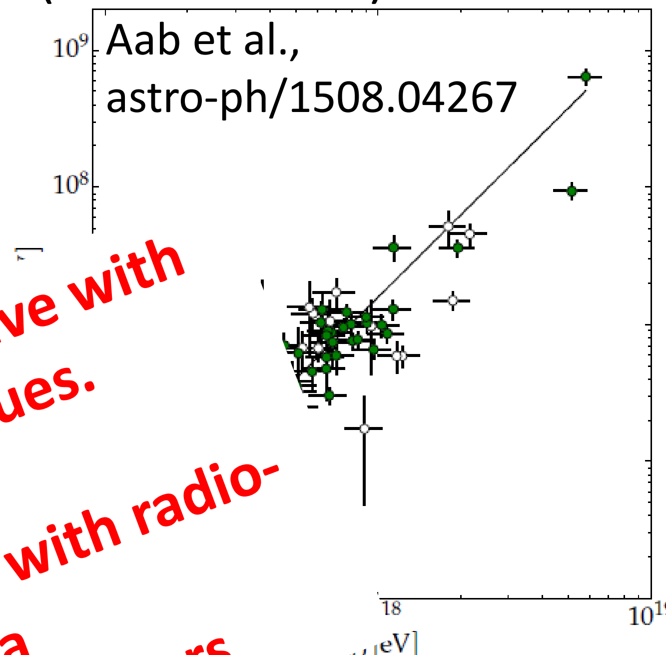


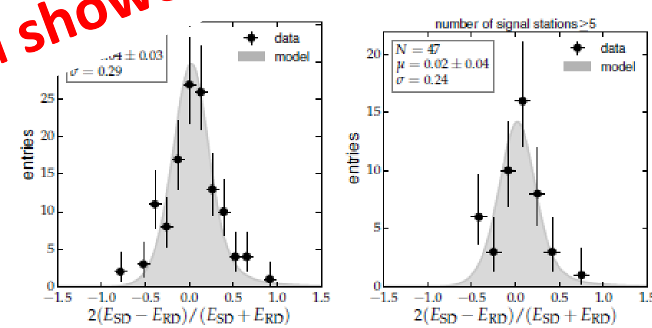
Figure 2 | Measurements of $\langle X_{max} \rangle$. X_{max} as a function of energy E for LOI… that used different techniques[26–29]. Err… The systematic uncertainties are $^{+14}_{-10}$g cr… indicated by the shaded band. The Pierre… the fluorescent light emitted by atmosphe… air-shower particles. HiRes/MIA[27] used a c… technique and muon detection. The Yakutsk non-imaging Cherenkov detectors. The gree… for proton showers simulated using QGSJETI… (dashed); the red (lower) lines are for showers i… …max⟩ …OS-LHC …, iron nuclei.

Buitink et al., Nature

- Energy reconstruction using SD core position: $\Delta E/E<20\%$ (AUGER-AERA)

Aab et al., astro-ph/1508.04267





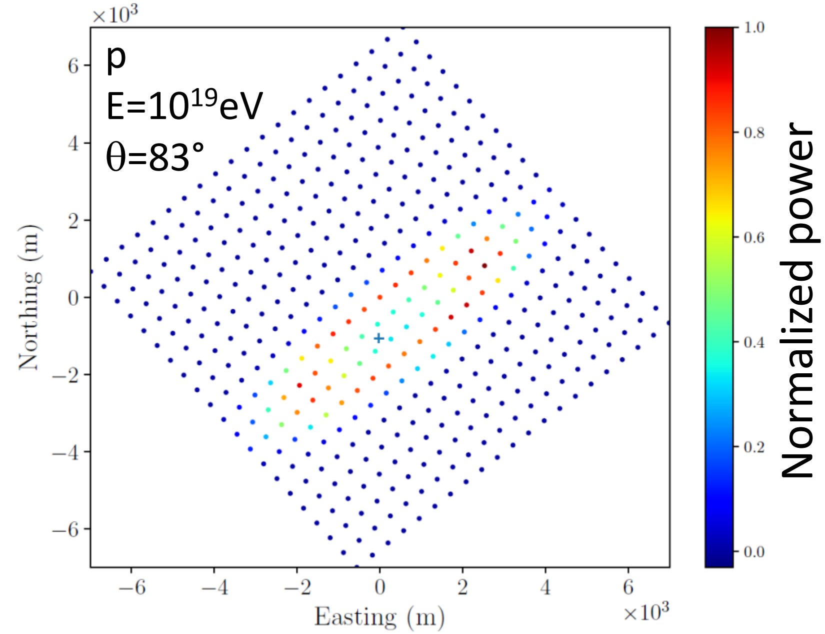
Radio recons competitive with standard techniques.

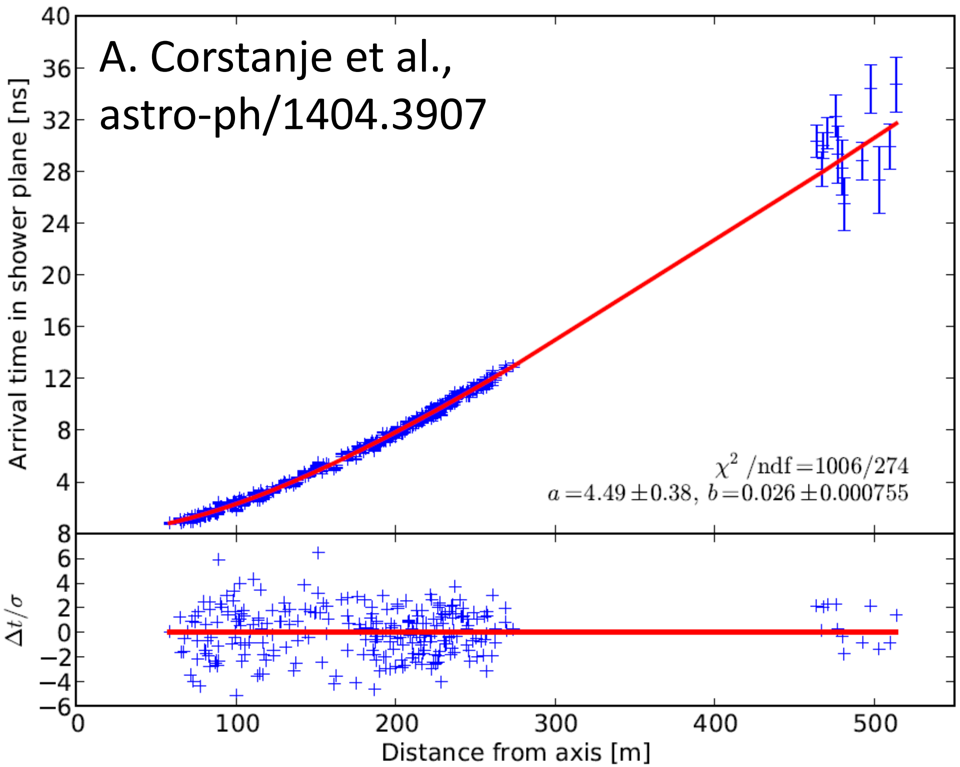
Has to be confirmed with radio-only data + very inclined showers

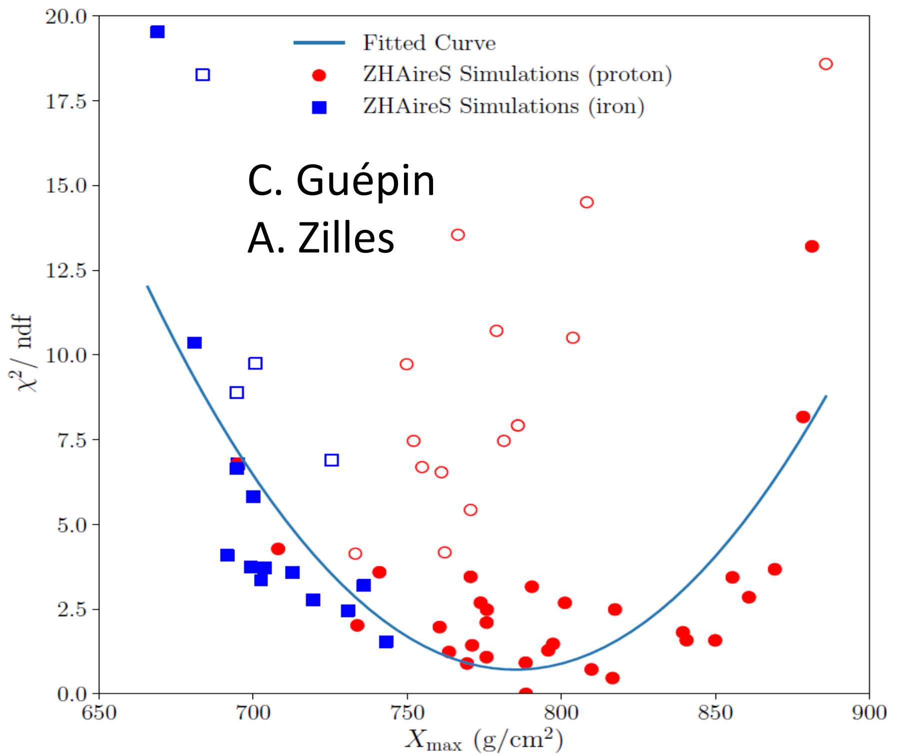
Reconstruction in GRAND

Using CR+neutrino simulations

- Angular resolution :
    - $<\Delta\psi><0.5°$ for plane wave hypothesis thanks to **height difference.**
    - ~0.1° expected with hyperbolic treatment
- Shower maximum: at present $<\Delta x_{max}>$~40g/cm²
- **Work in progress**

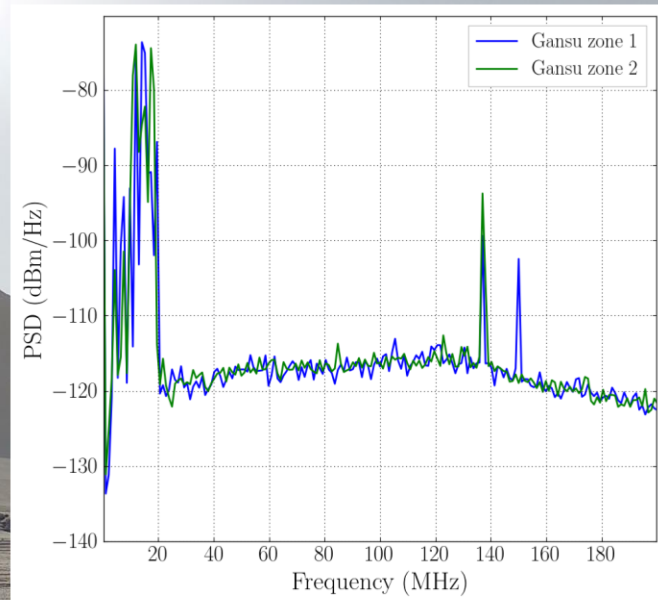




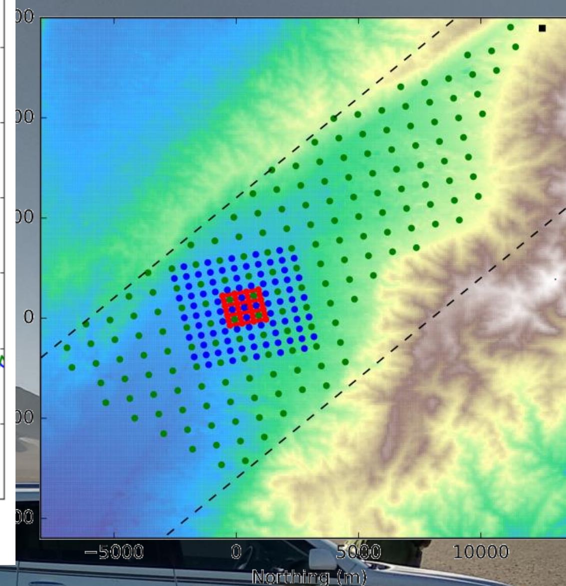


GRANDProto300

Site: 9 sites surveyed in China, 7 with excellent electromagnetic conditions

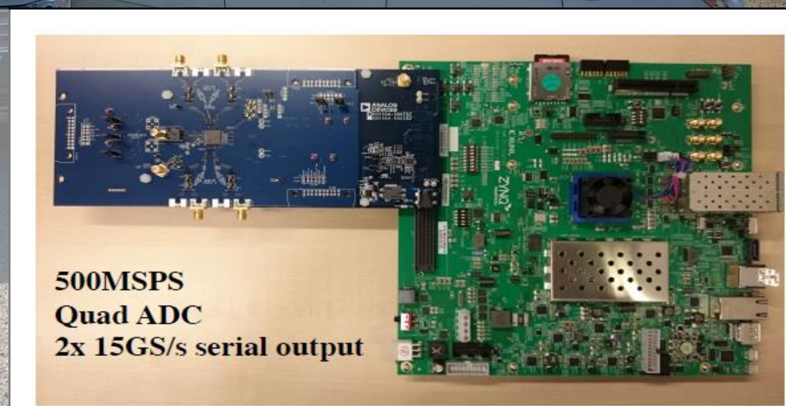


Layout: 300 antennas, 200km^2, 1km step size with denser infield
➔ Erange = $10^{16.5}$-10^{18}eV



HorizonAntenna, succesfully tested in the field (August 2018)

Electronics:
- 50-200MHz analog filtering
- 500 MSPS sampling FPGA+CPU
- WiFi data transfert
- 3 prototype board in prod.



QingHai (China), December 3rd, 2018

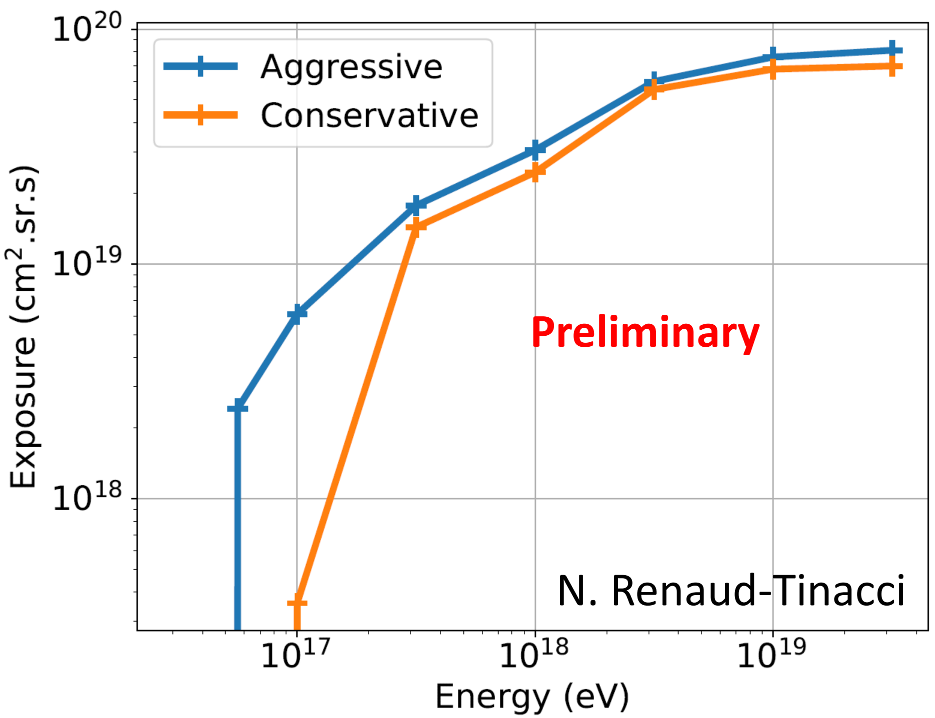
GRANDProto300 goals

GRAND pathfinder, but also a <u>standalone, independent project</u>.
Targeted run period: 2020-2025.

- Autonomous proof-of-principle of autonmous radio-detection of air showers. Trigger, selection and reconstruction of very inclined CRs in $10^{16.5}$-10^{18}eV.

  ➔ validation thru comparison of primary properties -spectrum, direction of arrival & composition- to known results.

- Testbench for further GRAND stages: advanced methods for trigger+background rejection (Machine Learning, etc) and data collection. Power consumption optimization.

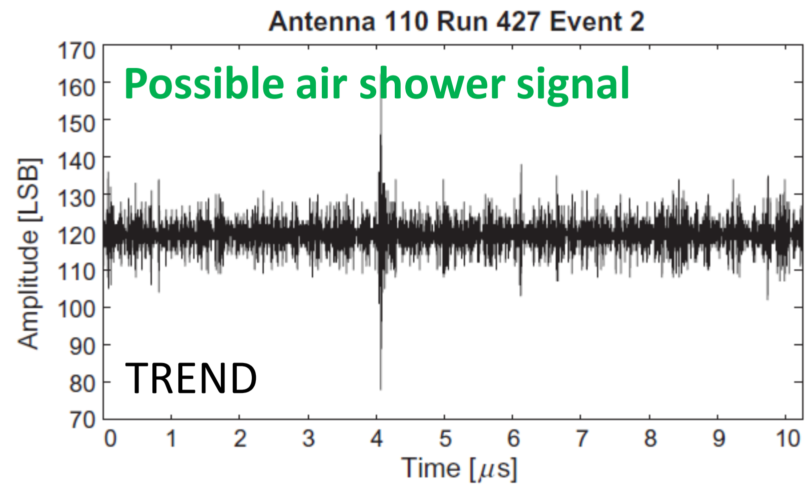


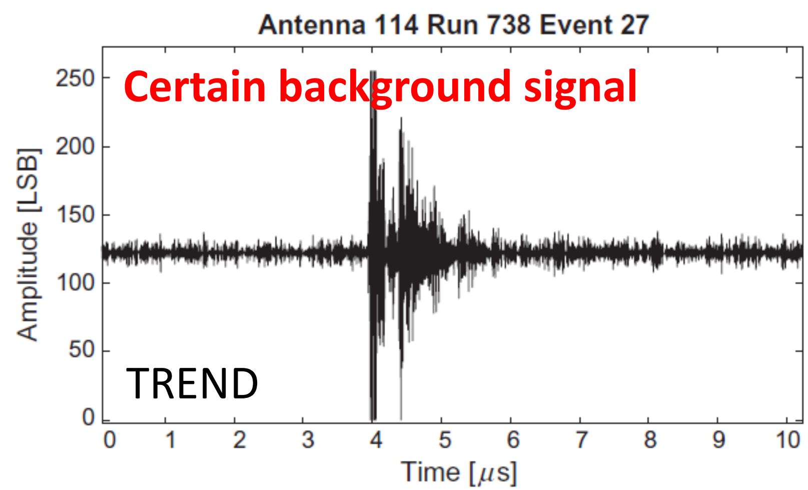
GRAND trigger

- 2 levels for GP300
  - Selection on pulse shape (100% DAQ live time up to 1kHz)
  - Search for antenna coincidences

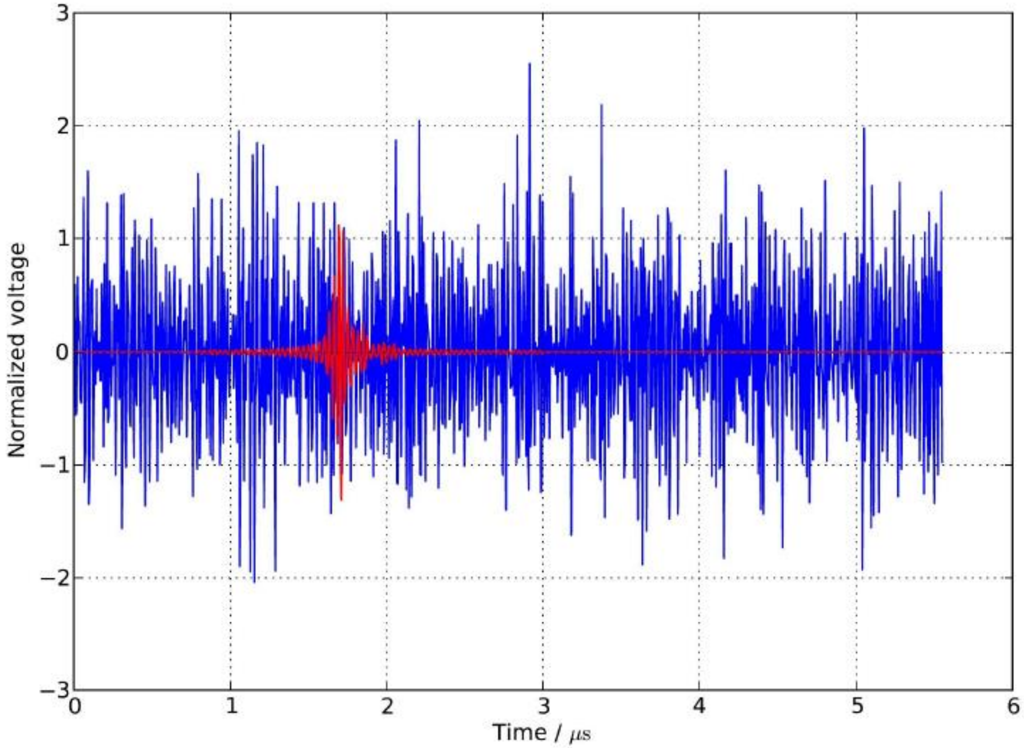
    (128kB/s Wifi transfer allows for 10Hz+4µs traces)

    ➔ Will provide a better insight on typicall background conditions
- Further stages:
  - Reduce data volume?
  - **Better event selection?**
  - Select appropriate data transfer technology





Data



Noise

- Normal distribution
- Different components
- Bandpass filter

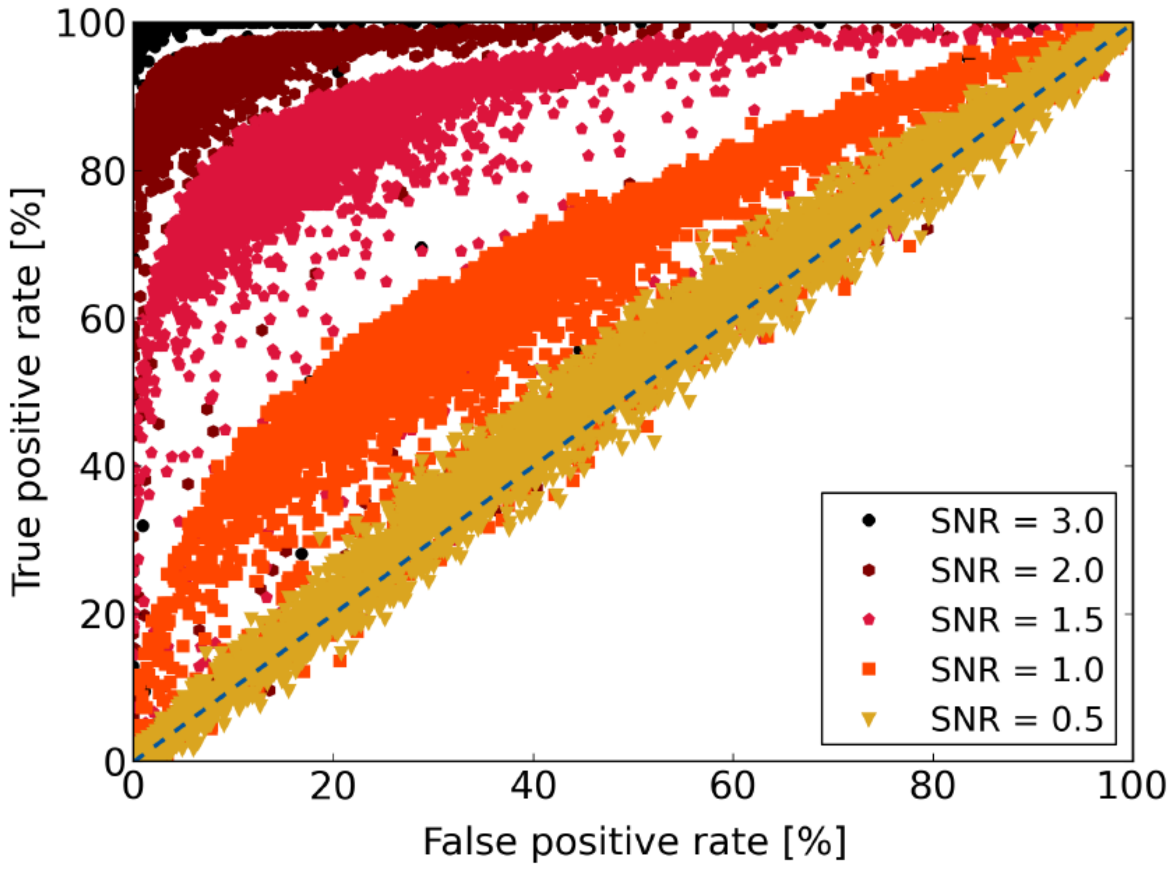
Air shower

- Simulated for AERA (thanks to C. Glaser)
- Scaling the amplitude

↓

Signal-to-noise ratio (SNR)

Evaluation

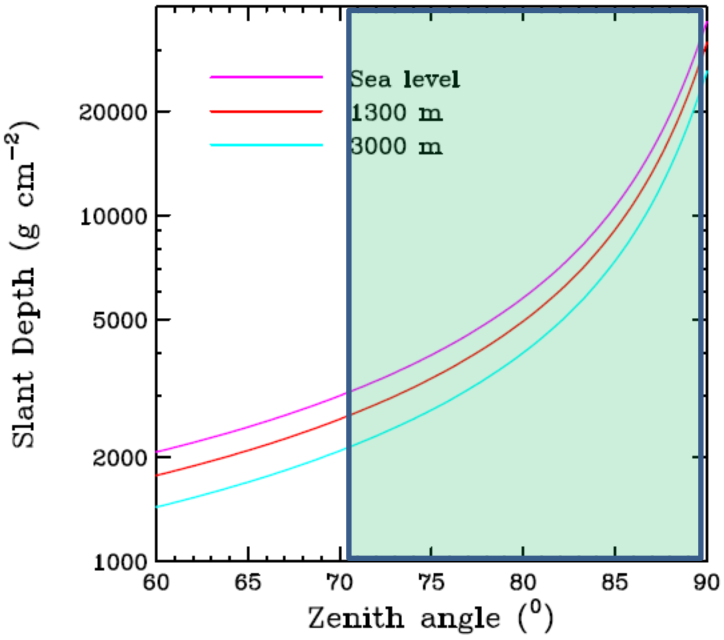


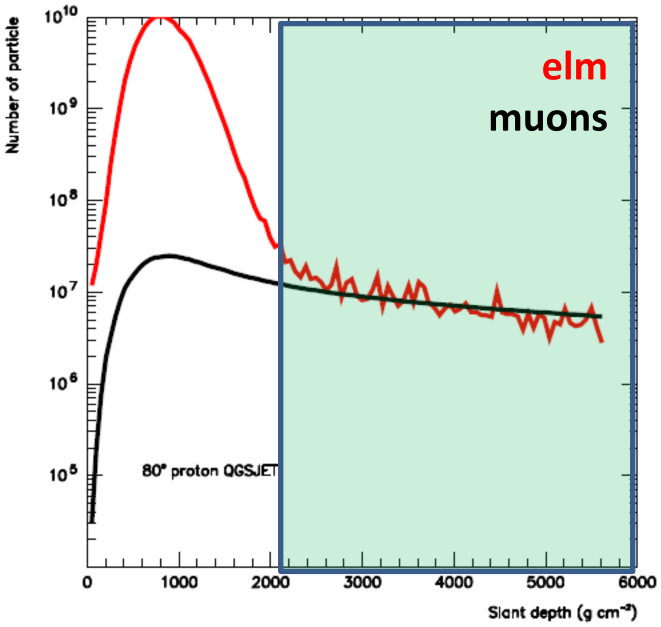
100
80
60
40
20
0
True positive rate [%]
0
20
40
60
80
100
False positive rate [%]
SNR = 3.0
SNR = 2.0
SNR = 1.5
SNR = 1.0
SNR = 0.5

GRANDProto300 hybrid array

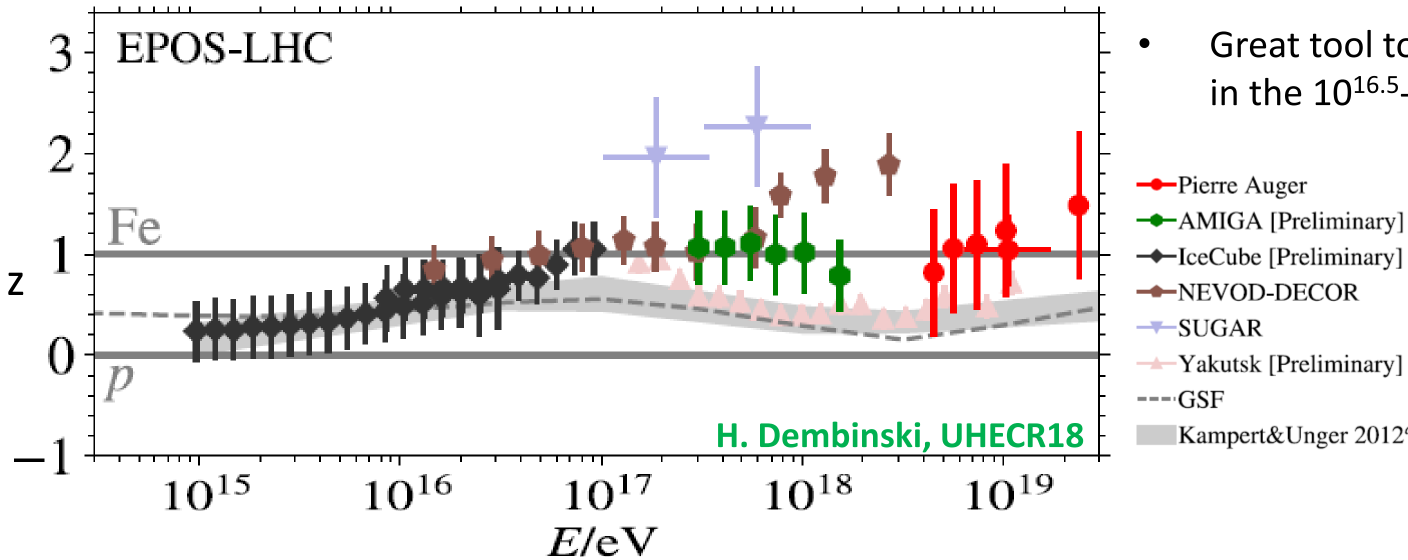
- GRANDProto300 will be complemented by an independant, autonomous **<u>ground array</u>** with large acceptance to inclined showers.
- Independant detection of electromagnetic & muon components on a shower-to-shower basis

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



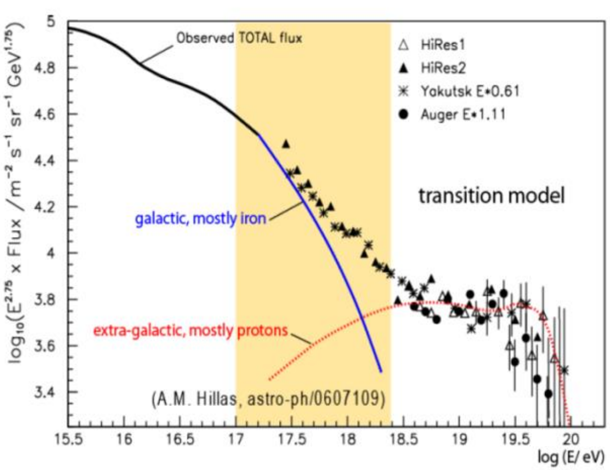


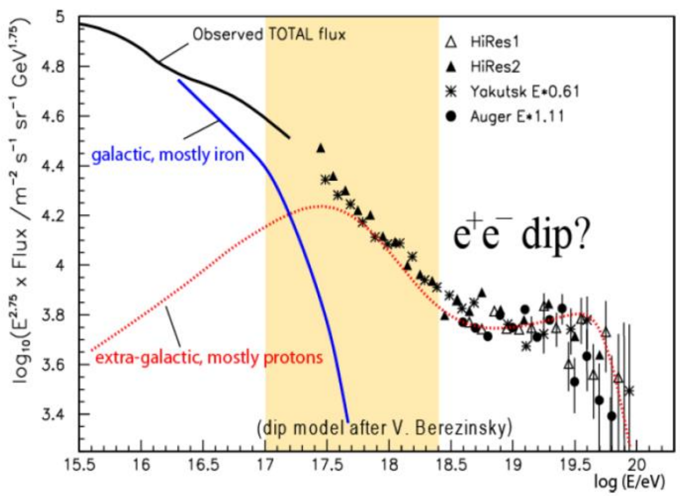
GRANDProto300 physics program



- 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)

GRANDProto300

GRANDProto35

GRAND10k

GRAND200k

2018 | 2020 | 2025 | 203X

2018 — GRANDProto35

Goals

standalone radio array: test efficiency & background rejection

Setup

35 radio antennas
21 scintillators

Budget & stage

160k€, fully funded by NAOC+IHEP, deployment ongoing @ Ulastai

2020 — GRANDProto300

Goals

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

Setup

- 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)

Budget & stage

1.3 M€
to be deployed in 2020

2025 — GRAND10k

Goals

first GRAND subarray, sensitivity comparable to ARA/ARIANNA on similar time scale, allowing discovery of EeV neutrinos for optimistic fluxes

Setup

DAQ with discrete elements, but mature design

for trigger, data transfer, consumption

Budget & stage

1500€ / detection unit

203X — GRAND200k

Goals

first neutrino detection at 10^{18} eV and/or neutrino astronomy!

Setup

200,000 antennas over 200,000 km^2, ~ 20 hotspots of 10k antennas, possibly in different continents

Budget & stage

Industrial scale allows to cut down costs: 500€/unit
➔ 200M€ in total

ASIC
Cost ~10M€ ➔ few 10€/board
Consumption < 1W
Reliability

Take-home message

- GRAND is an ambitious project for a giant array of 200’000 radio antennas deployed at several locations in the world.
- Very rich science case centered on UHE cosmic particles.
- Huge experimental challenge ➔ staged approach over 10-15 years.
- Next step: 300 antennas for the autonomous radio-detection of inclined showers. Exciting science case if complemented by ground array.
- **We need more people to carry out GRAND’s large task list**
- Want to know more/keep in touch?
  - Suscribe to our info list GRAND-ALL-L@IN2P3.FR
  - Check our website: www.grand.cnrs.fr