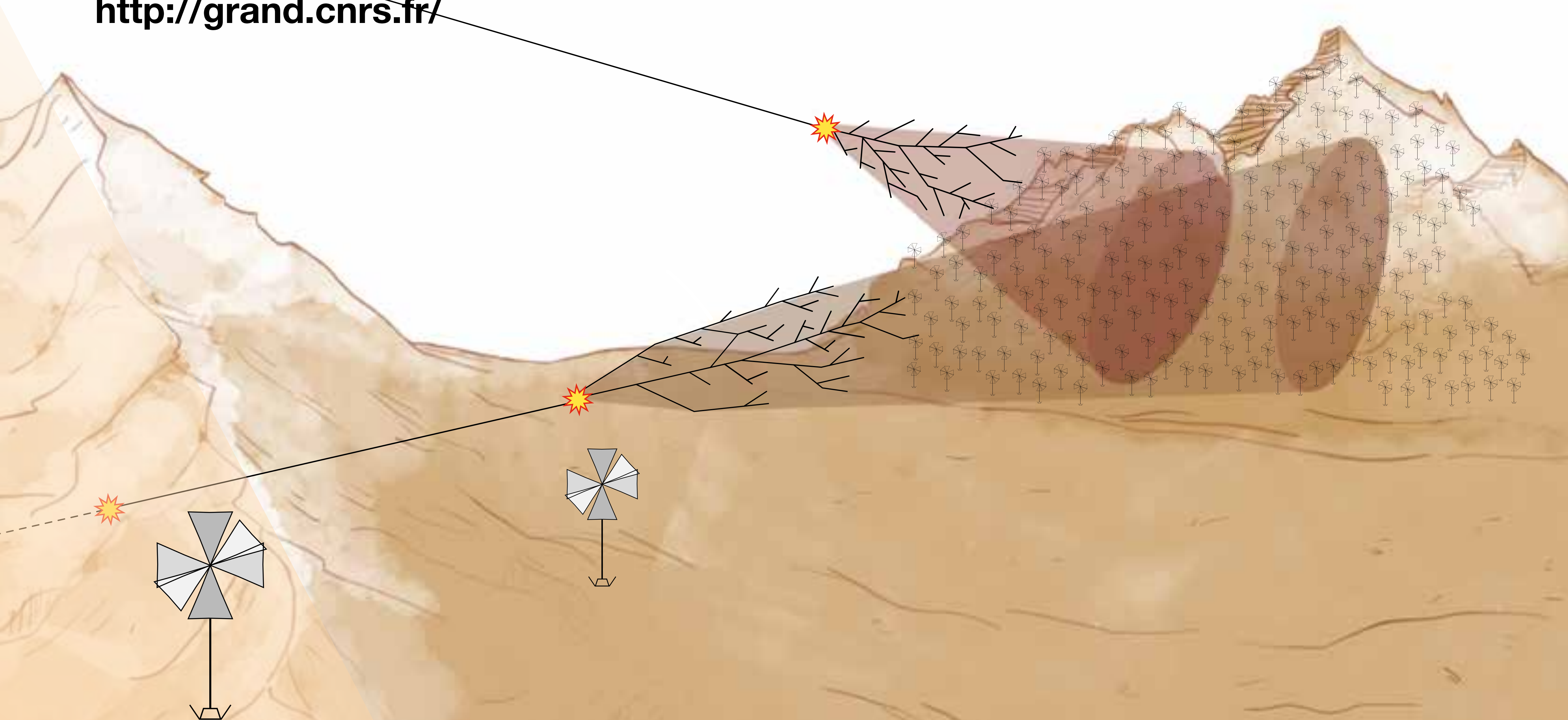
GRAND

The Giant Radio Array for Neutrino Detection

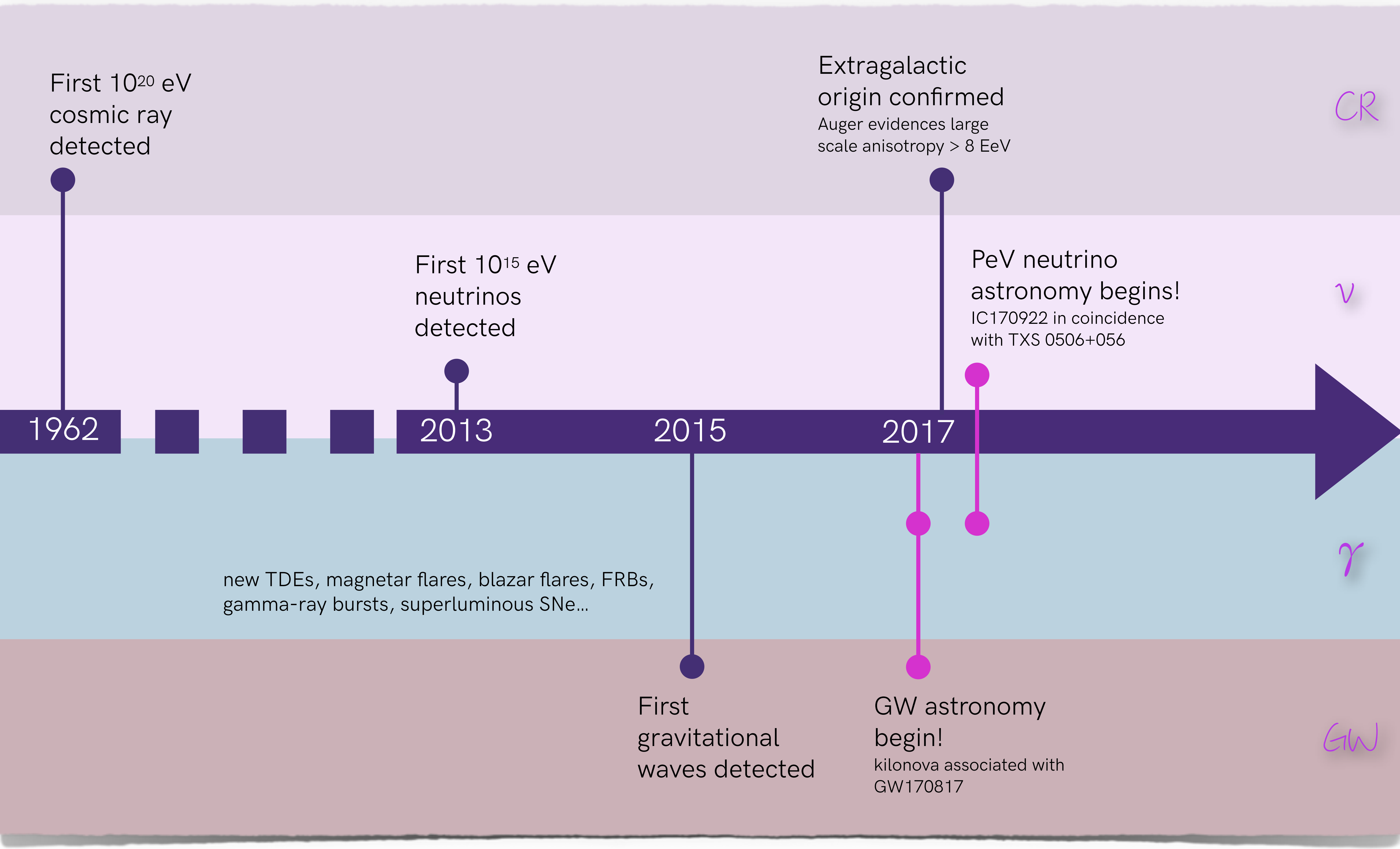
http://grand.cnrs.fr/



Kumiko Kotera - Institut d'Astrophysique de Paris

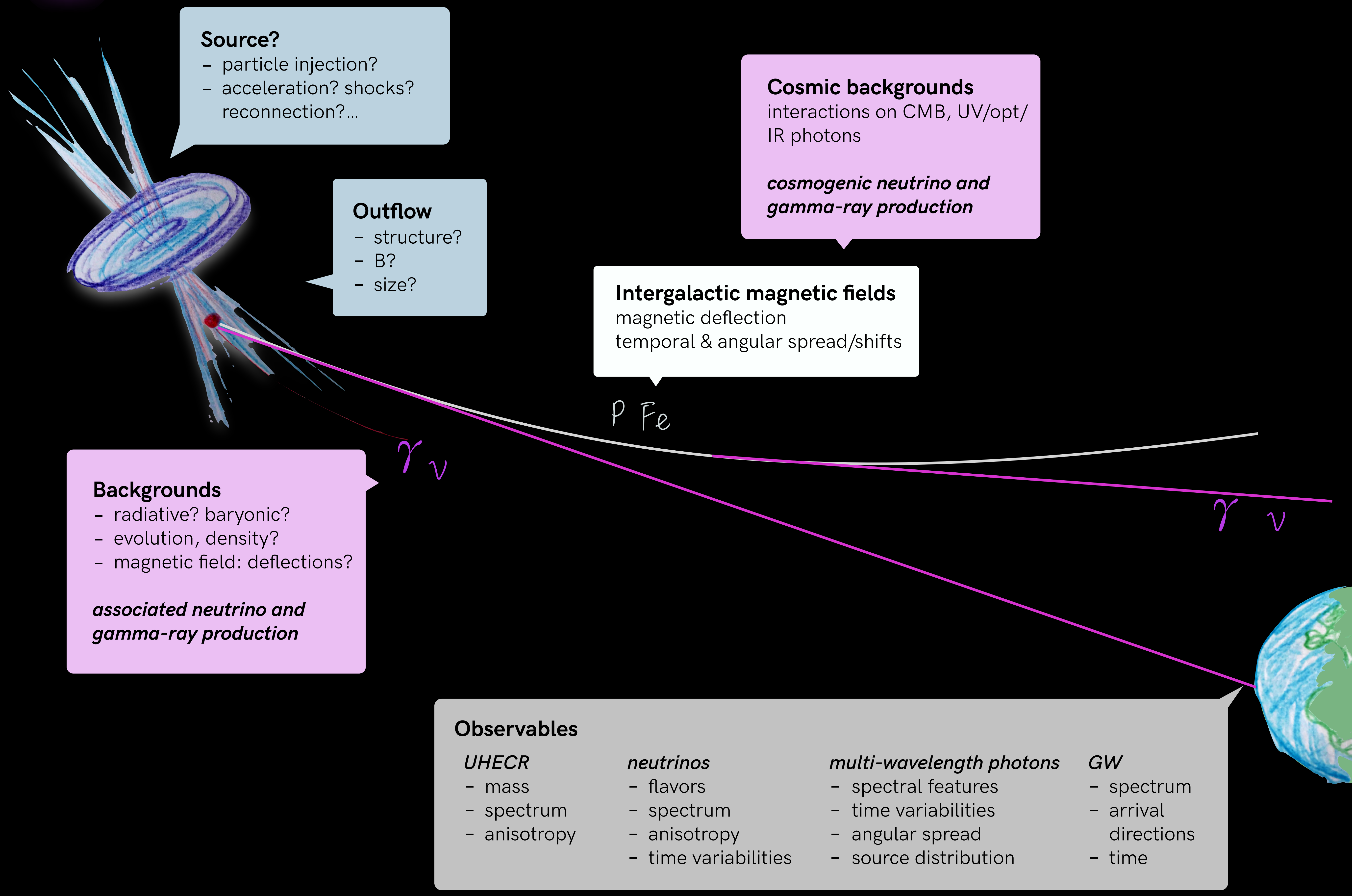
ICRR - 25/02/2019

Exciting times!

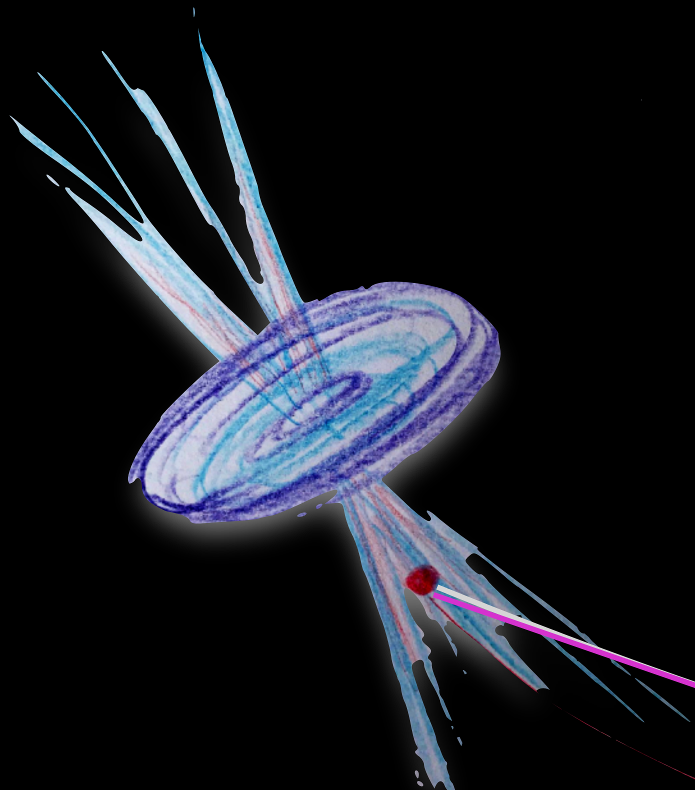


And we still don't know the origin of UHECRs

A UHECR journey



Current multi-messenger data: useful to understand UHECRs?



Cosmic backgrounds
interactions on CMB, UV/opt/IR photons

cosmogenic neutrino and gamma-ray production

Backgrounds
- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

associated neutrino and gamma-ray production

γ ν

Secondaries take up 5-10% of parent cosmic-ray energy

$E_\nu \sim 5\%\ E_{CR}/A$

$E_\gamma \sim 10\%\ E_{CR}/A$

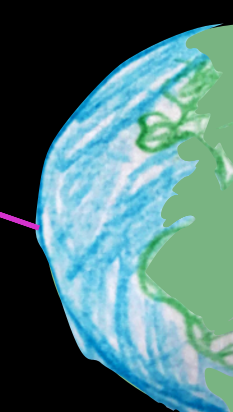
$E_{CR} > 10^{18}$ eV

$E_\nu > 10^{16}$ eV

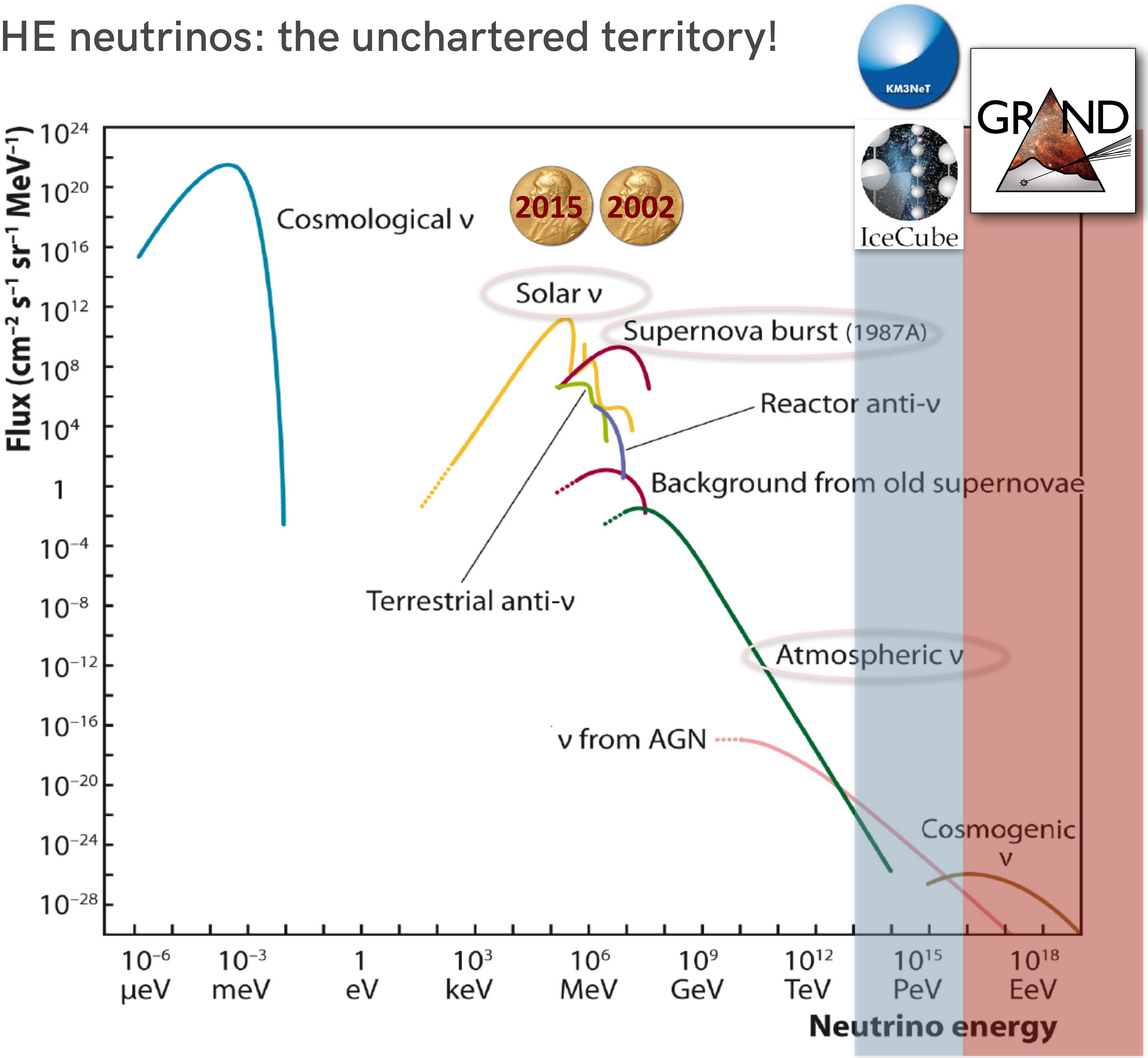
γ ν

IceCube neutrinos do not directly probe UHECRs

Actually, none of the current multi-messenger data (except UHECR data) can directly probe UHECRs ... but they help :-)

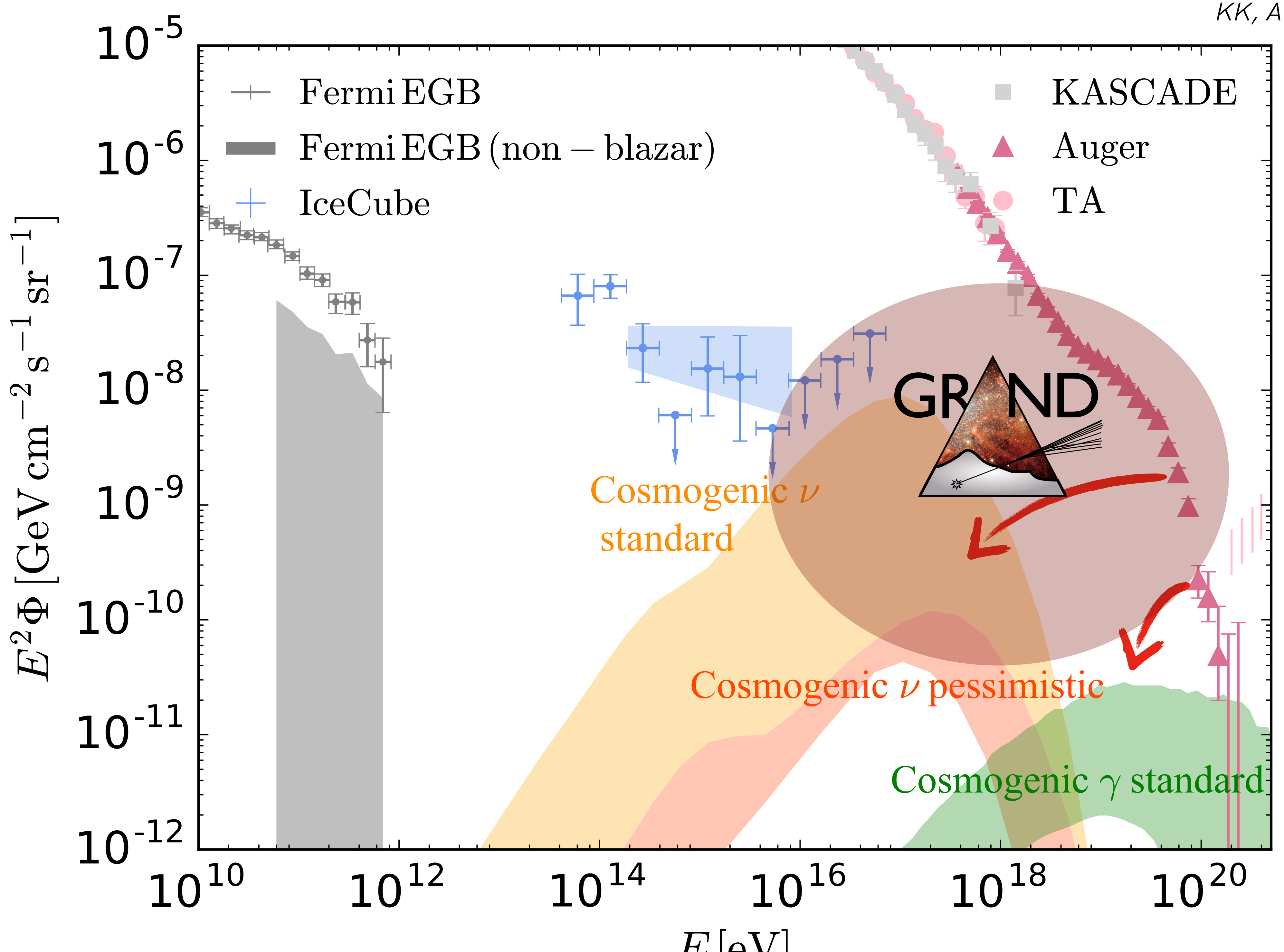


UHE neutrinos: the unchartered territory!



The guaranteed cosmogenic neutrinos

Alves Batista, de Almeida, Lago, KK, 2018
GRAND Science & Design, 2018
KK, Allard, Olinto 2010



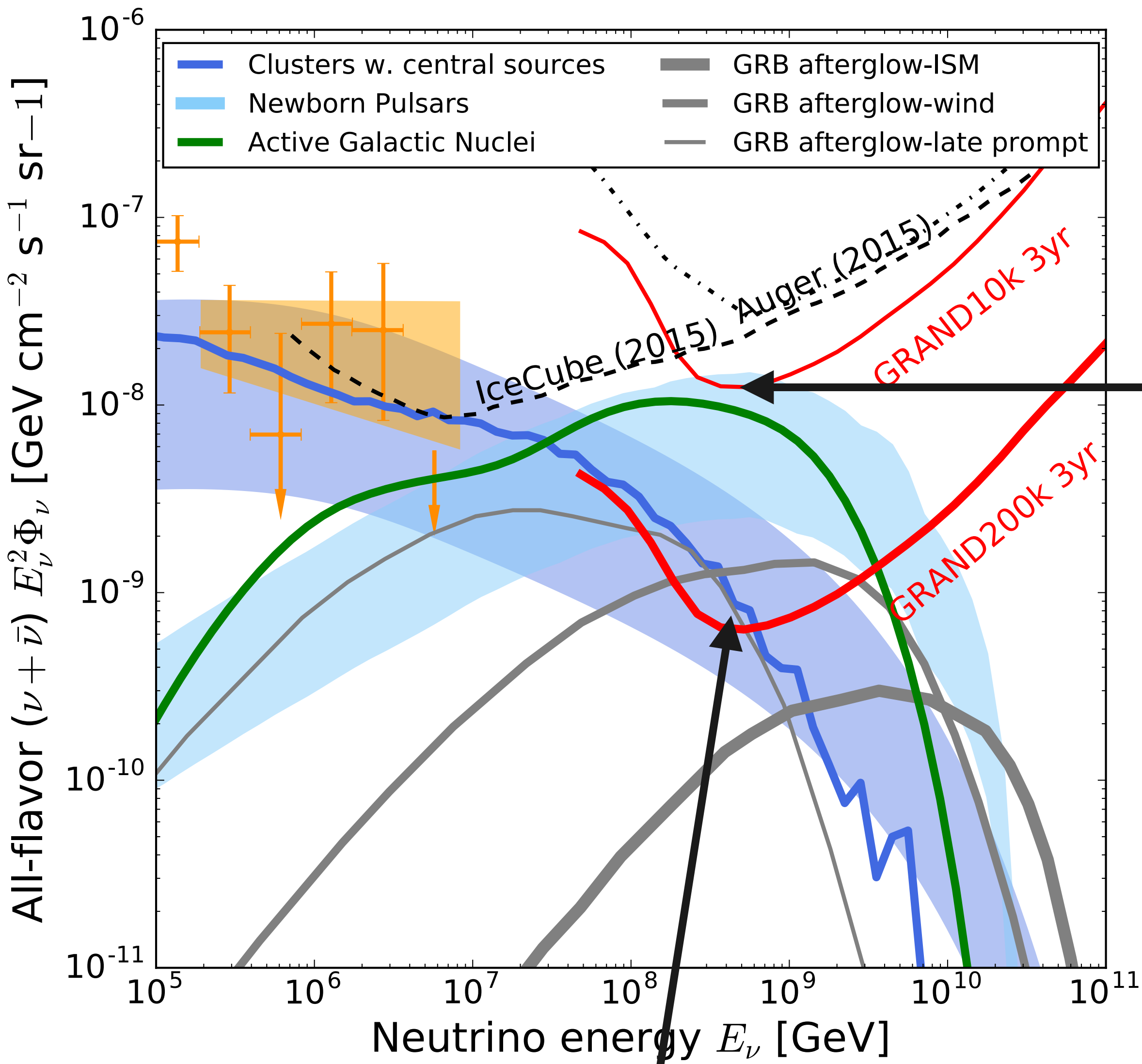
What we can aim to do with future observatories

cosmogenic:
guaranteed

direct from source:
likely more abundant

pessimistic scenarios
of cosmogenic neutrinos = good!

low background for source neutrinos

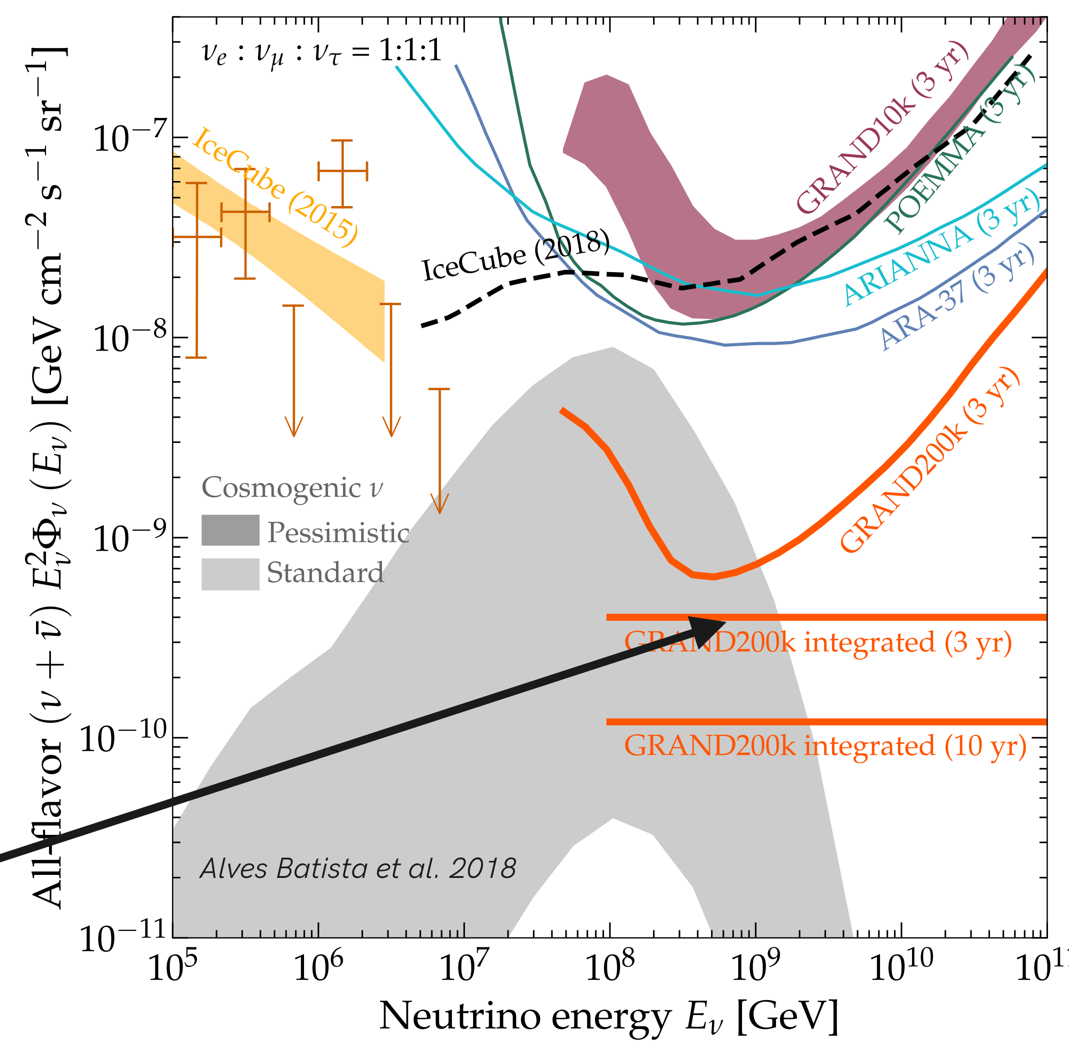


detect the
first EeV
neutrinos

detect EeV neutrino **point sources**

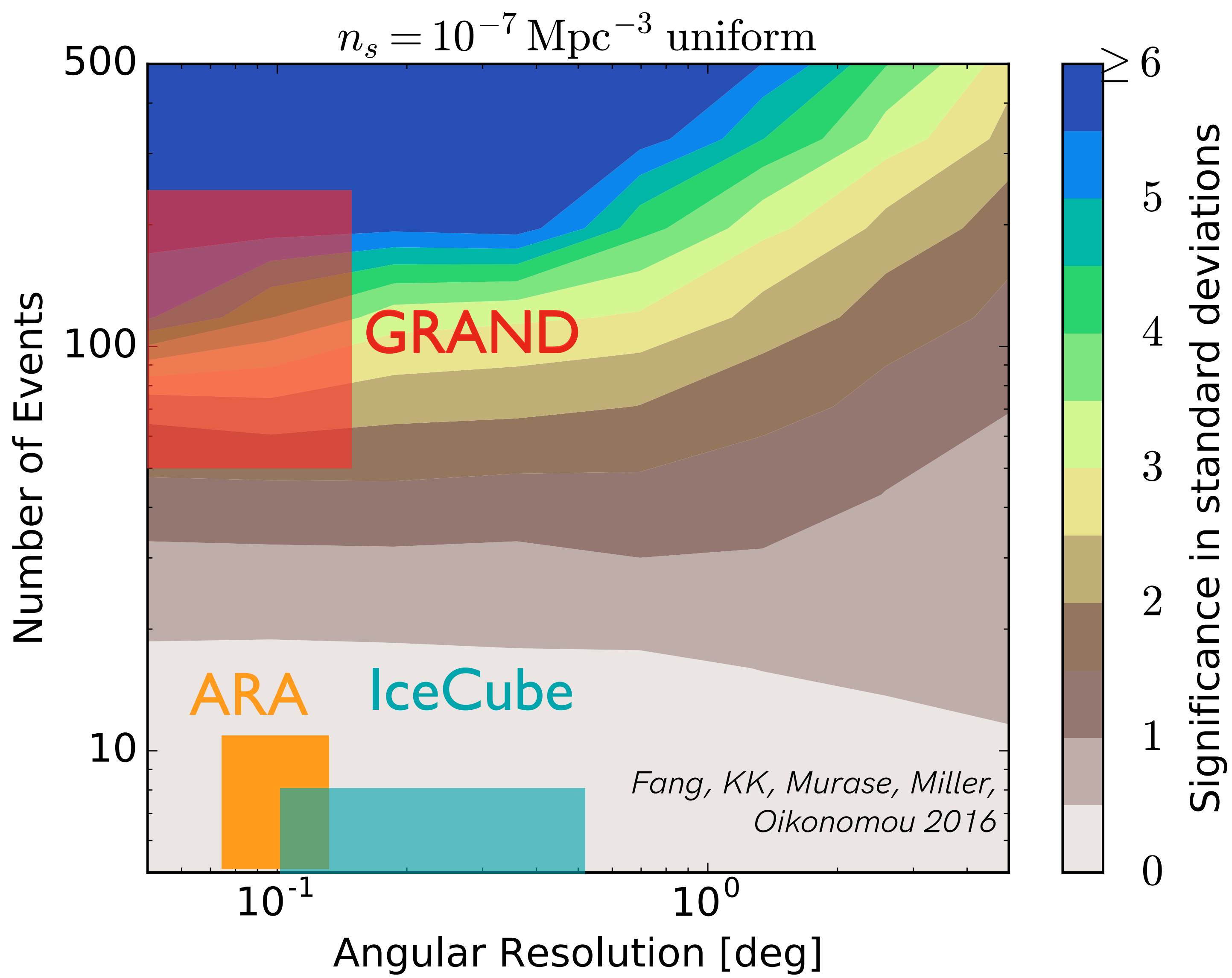
100s of events
~0.3° angular resolution

detect **cosmogenic** neutrinos



Can we hope to detect very high-energy neutrino sources?

Neutrinos don't have a horizon: won't we be polluted by background neutrinos?



boxes for experiments assuming neutrino flux: 10^{-8} GeV cm^{-2} s^{-1}

YES if

- good angular resolution (< fraction of degree)
- number of detected events > 100s

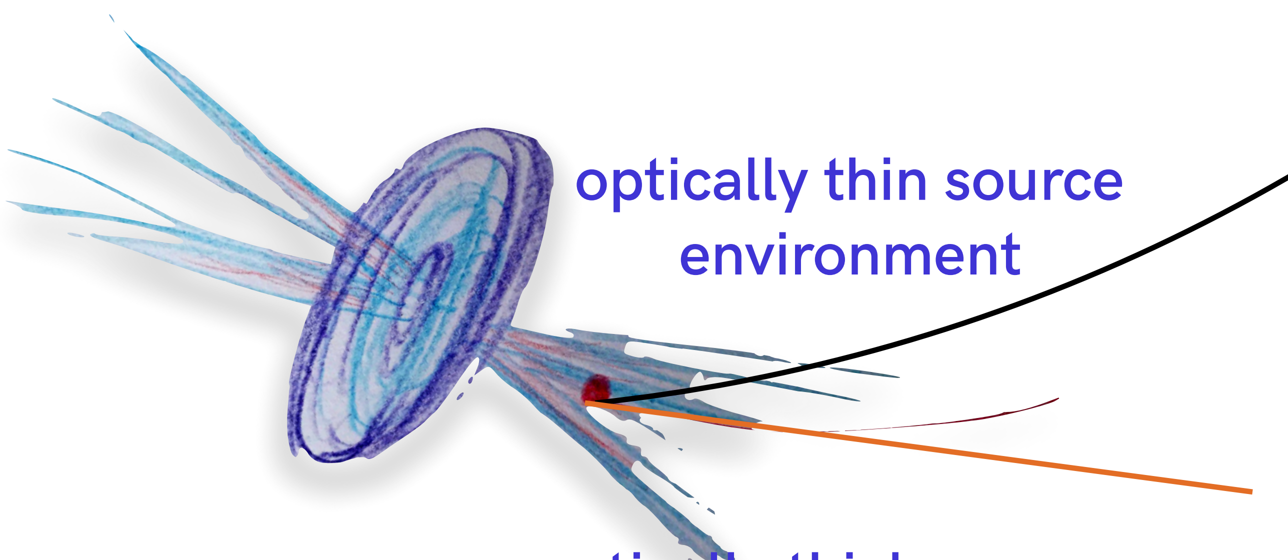
If the **measured** UHECR composition is not protons

it is NOT the end of the world at all!

- sources emitting observable UHECRs and UHE neutrinos **are likely not the same!**
  - a source will be opaque to UHECR protons to produce abundant UHE neutrinos
  - **observable** UHE (>10^{17} eV) neutrino sources are sources of UHECRs
  - **but they are likely NOT observable sources of UHECRs!**

if measured **UHECR composition** heavy
UHE neutrino astronomy completely possible

not really related

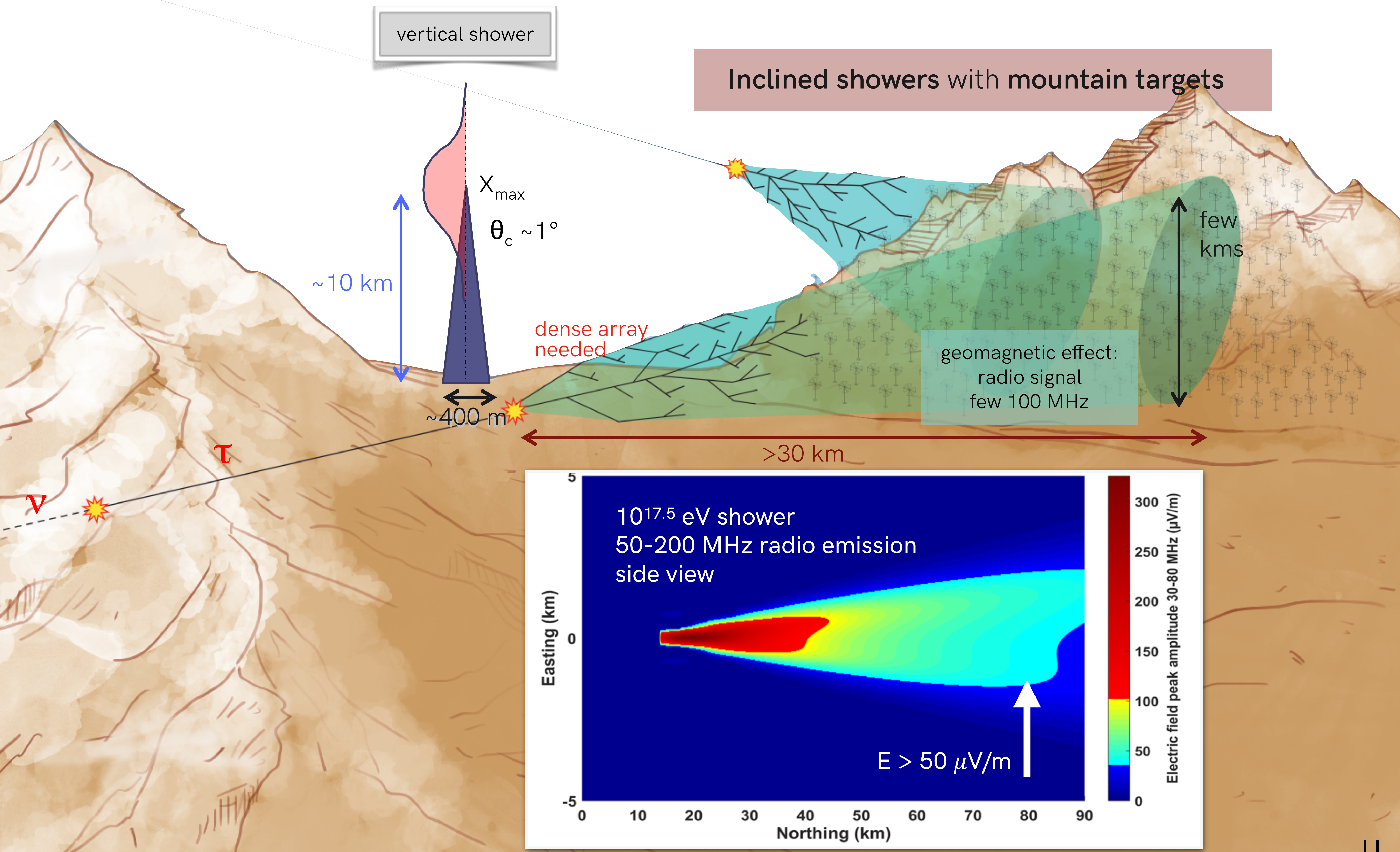


The GRAND Project

The GRAND Concept

radio detection: a mature and autonomous technique
AERA, LOFAR, CODALEMA/EXTASIS, Tunka-Rex, TREND

radio antennas cheap and robust: ideal for giant arrays



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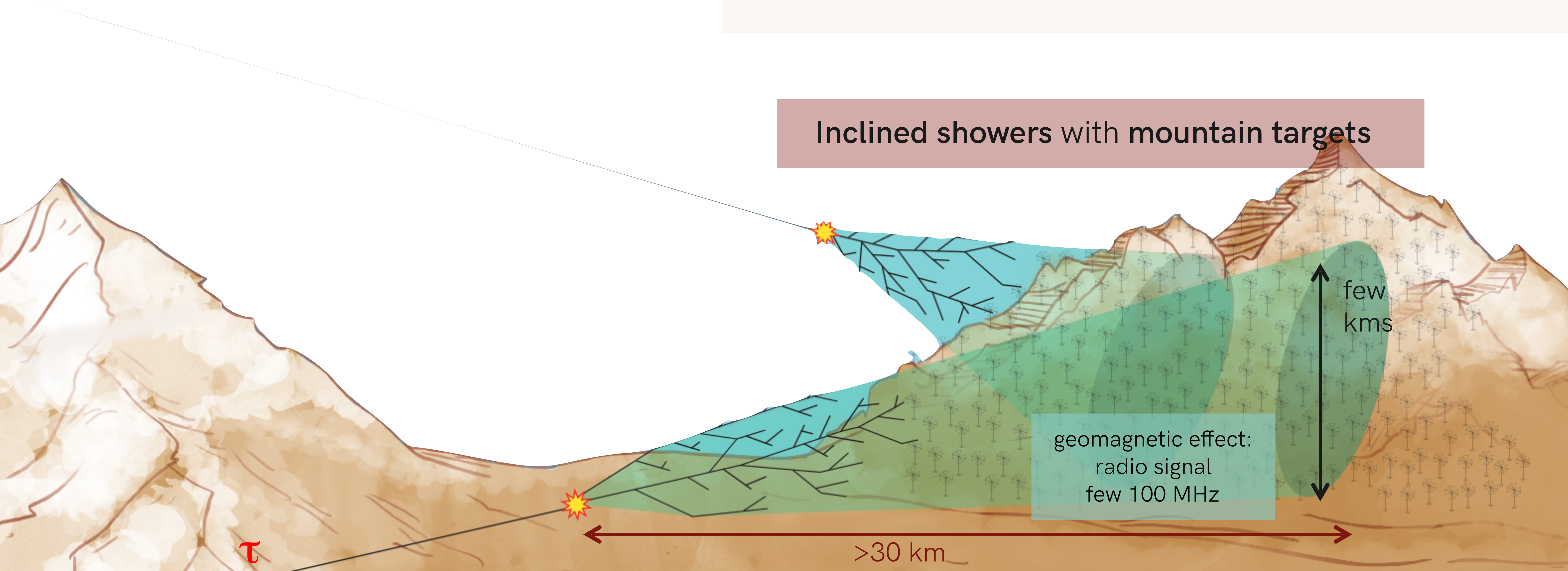
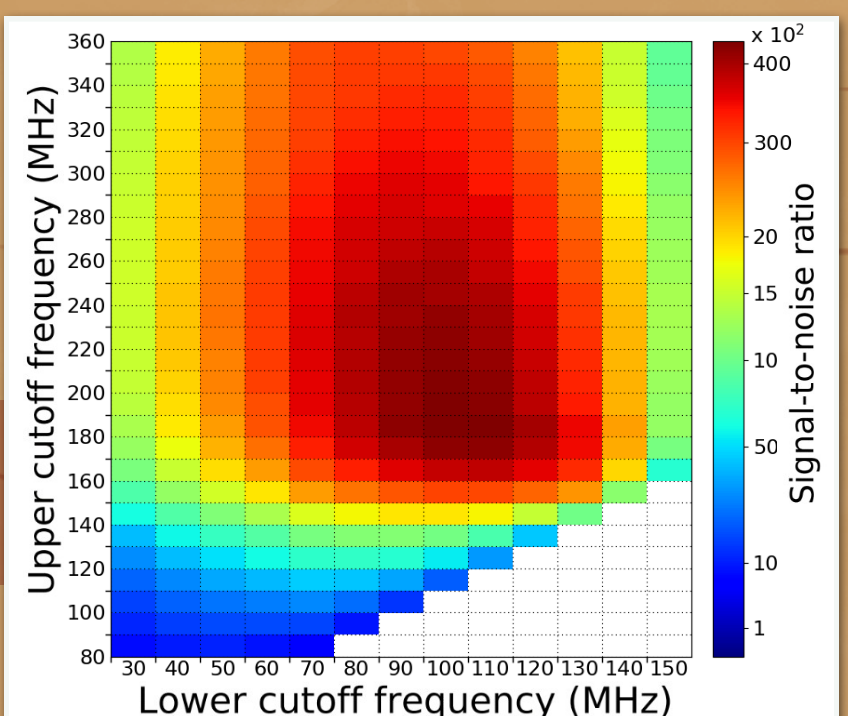


Antenna response of a dipole antenna
ZHAireS simulations with 1ns binning
antenna @ cone
neutrino 5×10^{17} eV, zen=87° h=2800m

Galactic noise + thermal noise (300K) included
Optimal frequency band 50-200 MHz

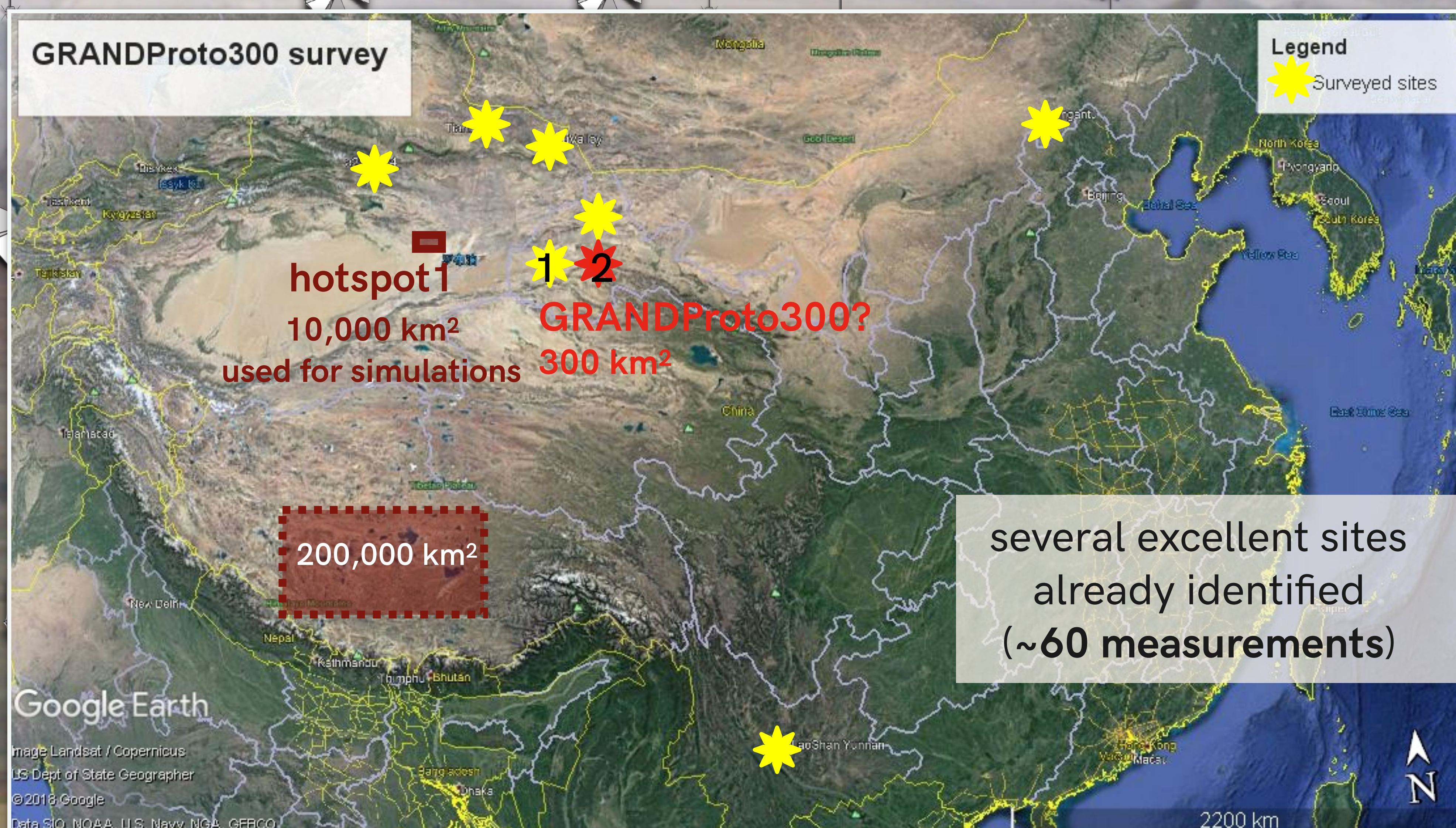
A. Balagopal (KIT)



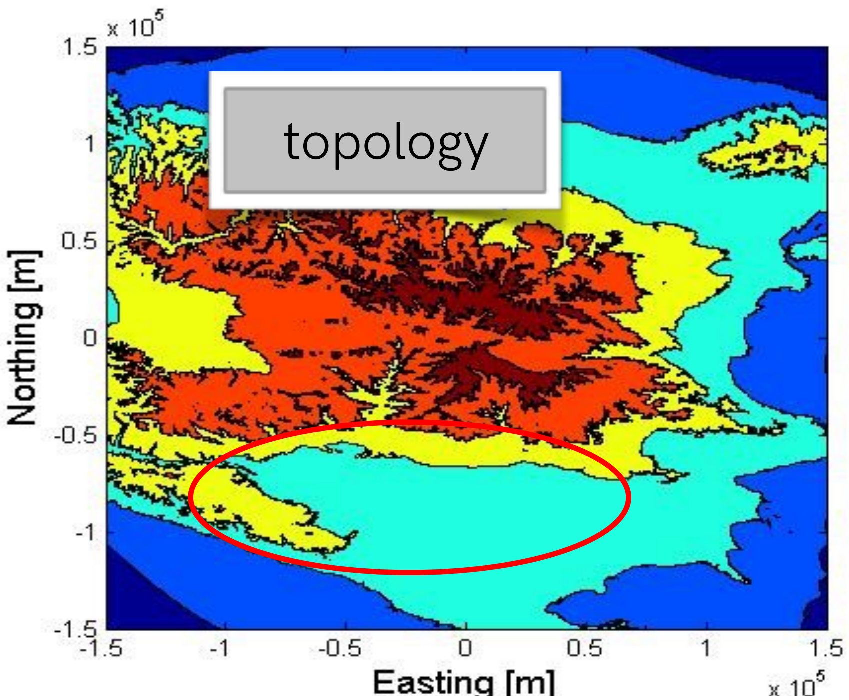
The GRAND Concept

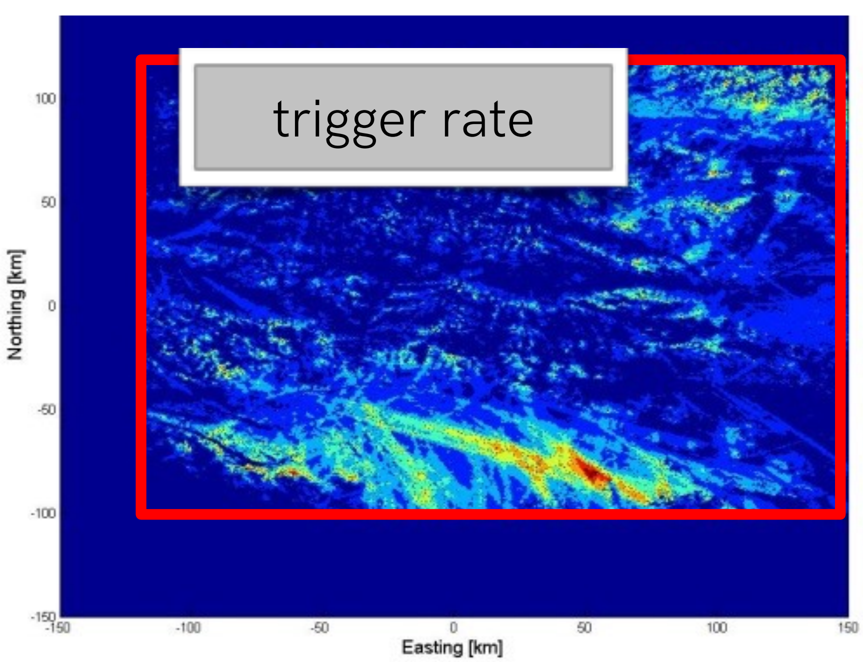
200,000 radio antennas over 200,000 km²
~20 hotspots of 10k antennas
in favorable locations in China & around the world

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



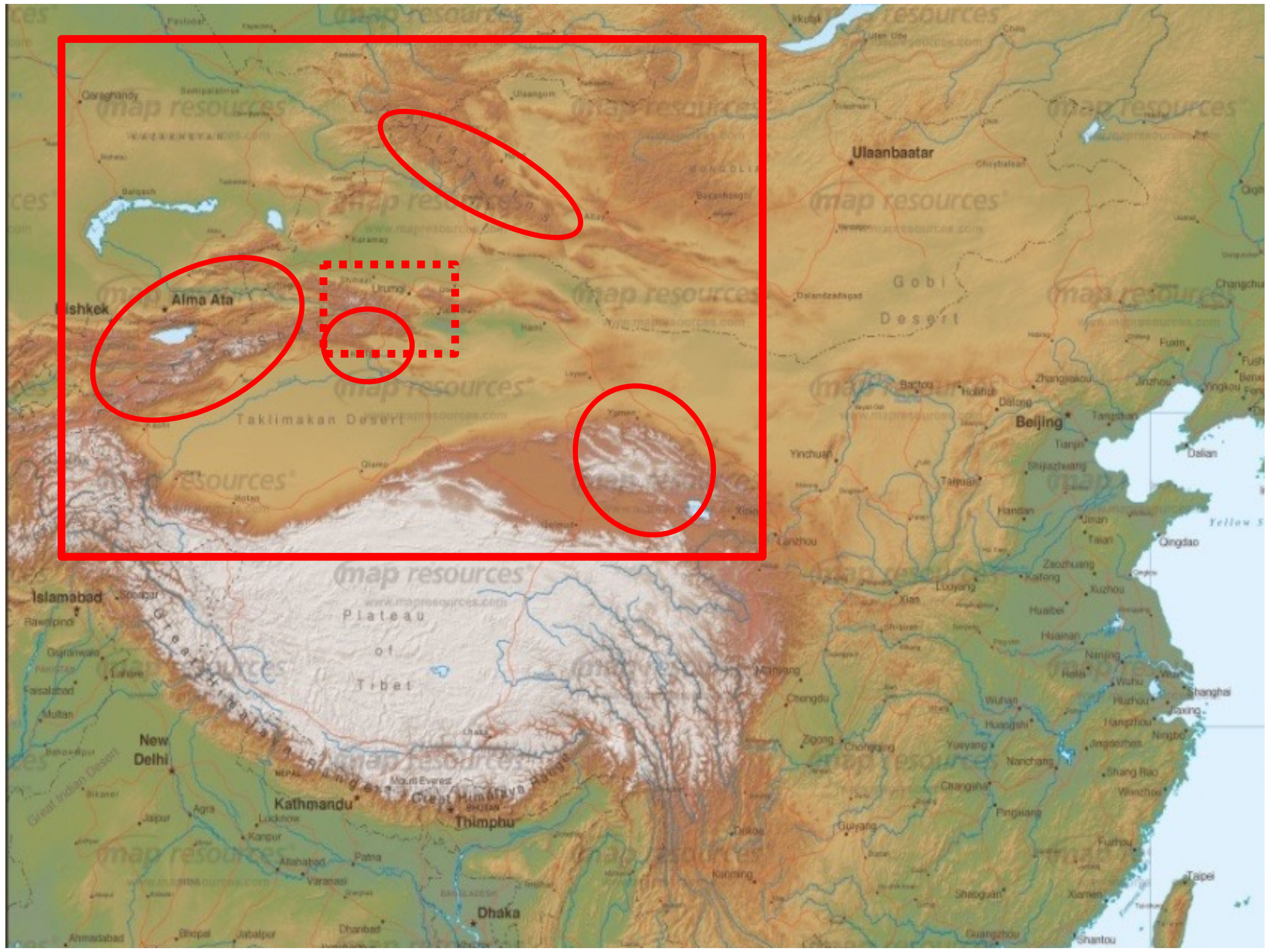
Deployment in hotspots



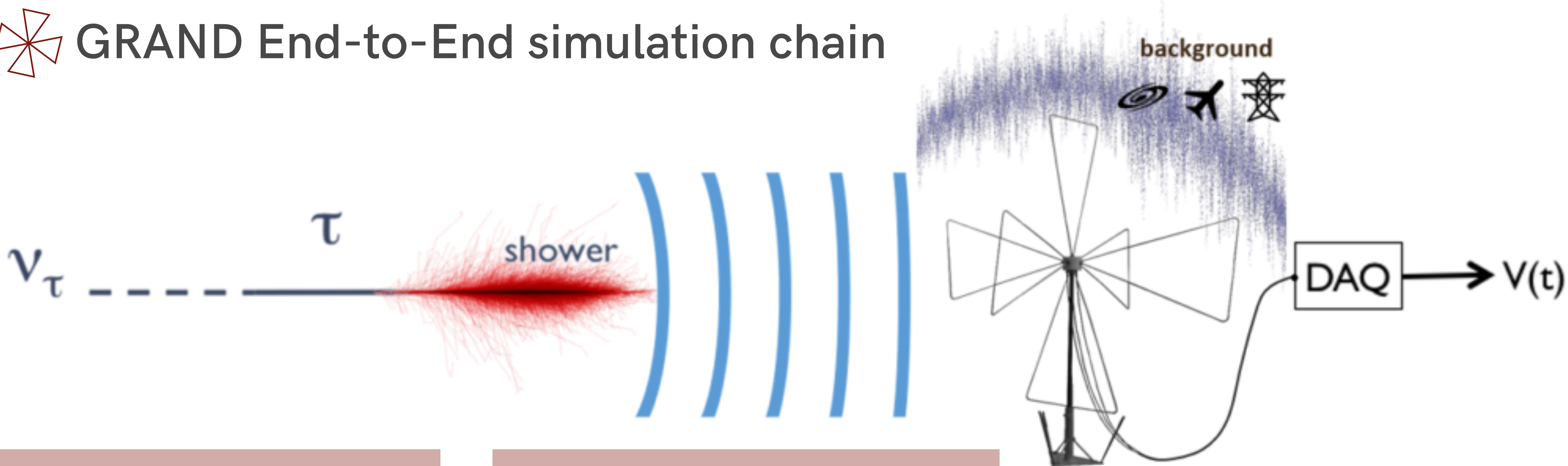


Hotspot with favorable topology
⇒ enhanced detection rate!

- Target sensitivity: φ_0 = 1.5x10^{-11} GeV/cm^2/sr/s
- Driver: go for hotspots! Then 200’000km^2 may be enough to reach target sensitivity
- Giant simulation area (1’000’000 antennas over 1’000’000 km^2? Full Earth?) to identify hotspots.



GRAND End-to-End simulation chain



- Topography along track
- CC & NC ν_τ interactions
- τ energy losses
- τ decay through **backward** simulation

➔ **DANTON**

➔ **RETRO**
(GRAND specific framework for backward propagation)

V. Niess, LPC Clermont Ferrand

- Shower development
- Radio emission

Zilles et al. submitted to Astropart. Phys.

➔ ZHaireS + EVA

➔ **Radio-morphing**

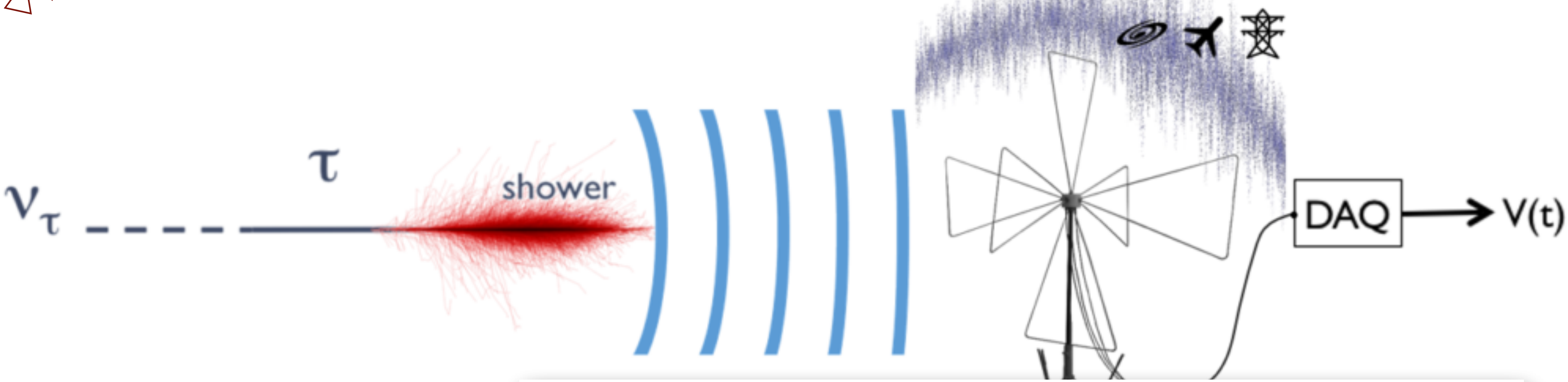
W. Carvalho, K. Kotera, K. de Vries, O. Martineau, M. Tueros, ***A. Zilles***
(IAP, Paris)

- Antenna response
- Antenna trigger
(background noise sim)

➔ **NEC**

D. Charrier (Subatech Nantes),
S. Le Coz, O. Martineau

GRAND End-to-End simulation chain



- Topography along track
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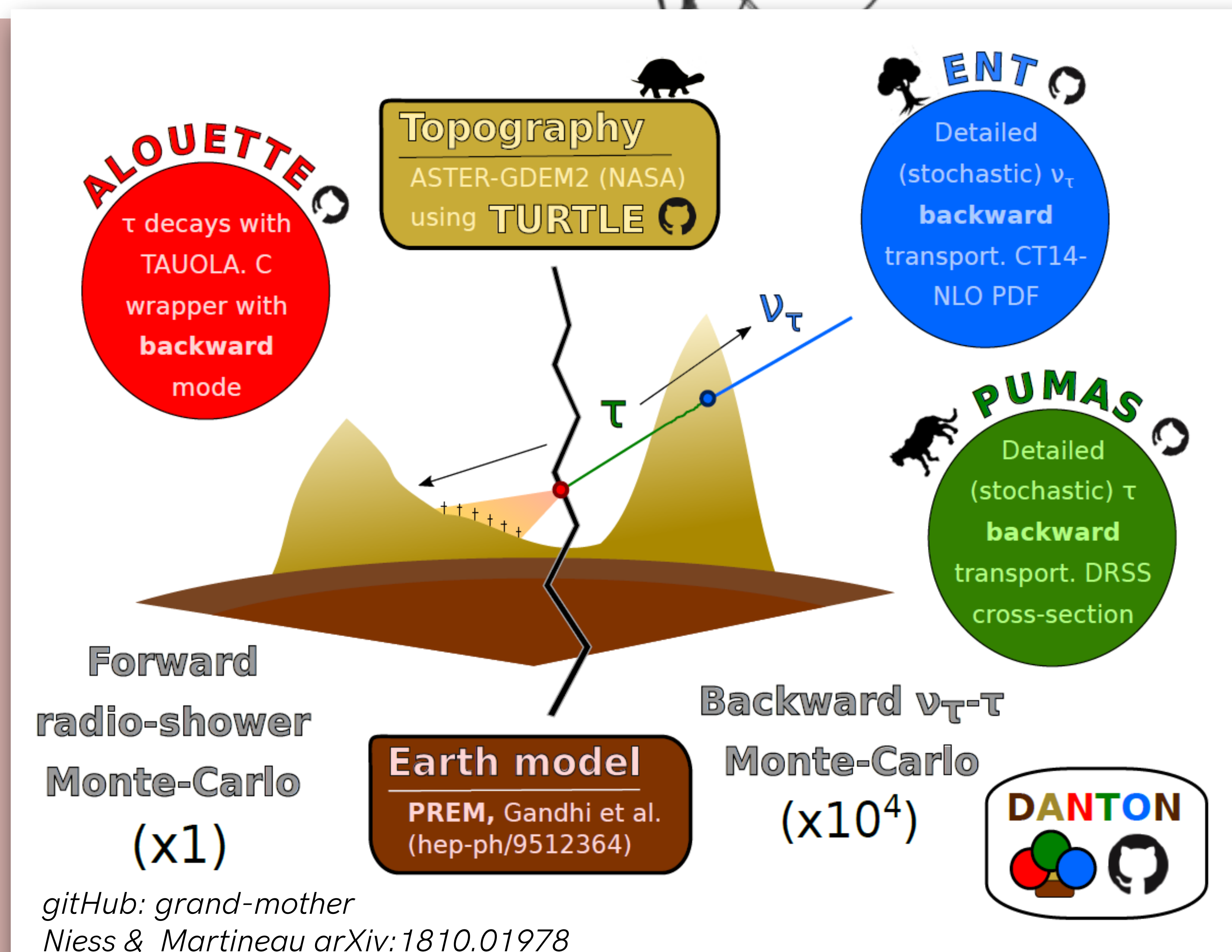
V. Niess, LPC Clermont Ferrand



GRAND End-to-En

- Topography along track
- CC & NC ν_τ interactions
- τ energy losses

Antenna trigger
(background noise sim)

→ **NEC**
D. Charrier (Subatech Nantes),
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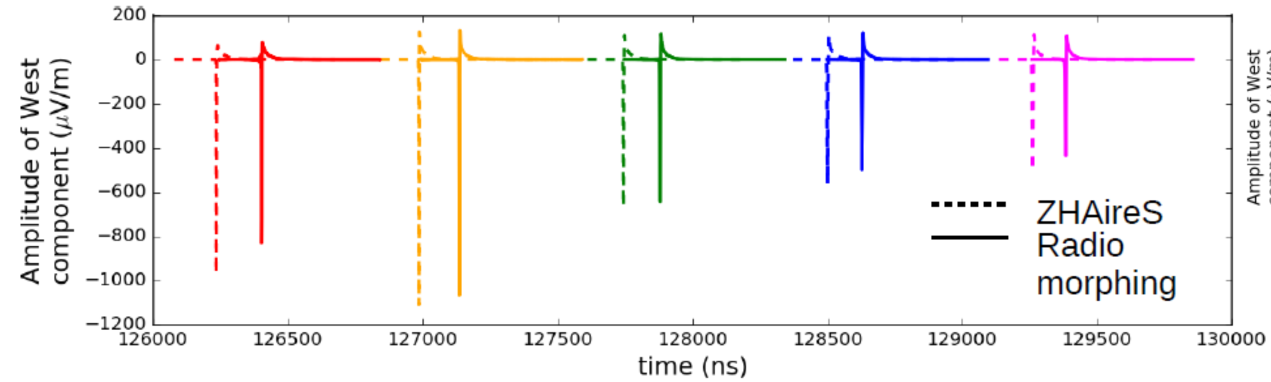
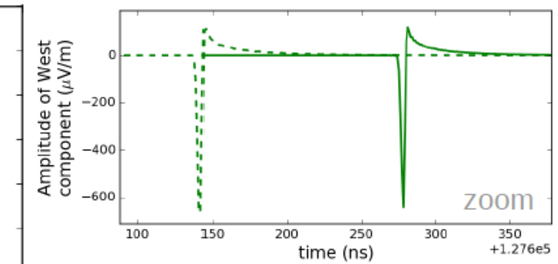
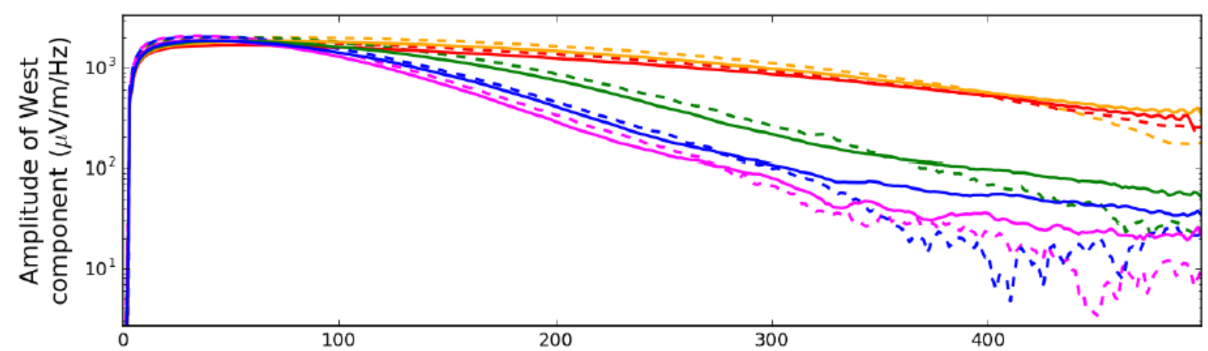
Comparison to microscopic simulation

Example shower, randomly picked antenna positions







Simulated signal
(1ns time binning, not filtered)

→ **Amplitude, pulse shape and polarisation can be reproduced!**

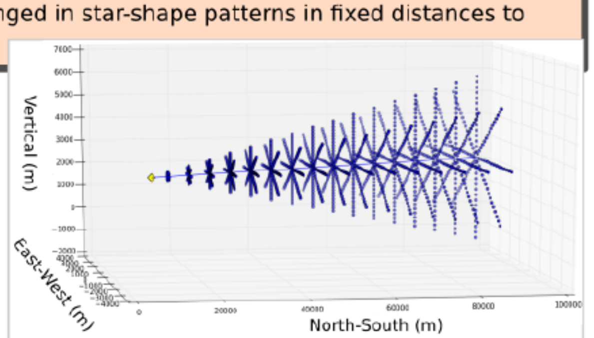
Zilles et al. submitted to Astropart. Phys. Anne Zilles, ARENA2018 14

The Radio Morphing recipe

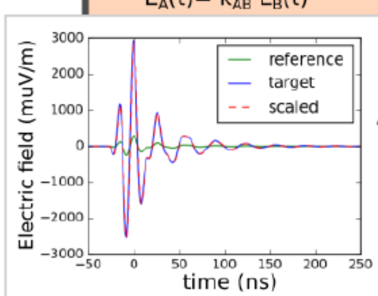
Not GRAND specific!
→ universal method

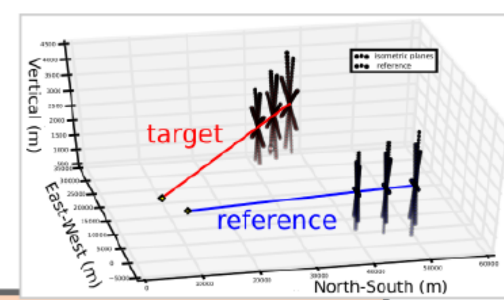
Preparing the reference shower: simulated electric field traces for antennas positions arranged in star-shape patterns in fixed distances to X_{max}

1



Scaling of the electric field amplitude according target shower parameters:
$E_A(t) = k_{AB}\ E_B(t)$





2

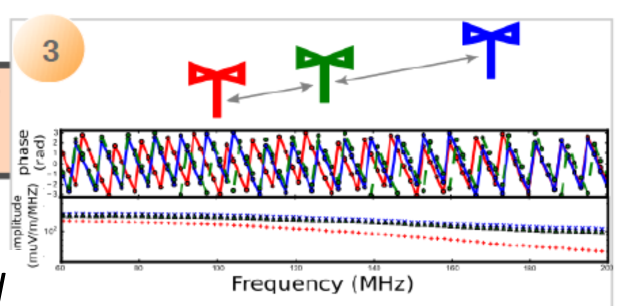
Isometry of reference positions: translation and rotation according target shower direction

Desired shower parameters

Desired antenna positions

Interpolation of pulse shape at desired antenna position:
$E_A(x_i,t) \longrightarrow E_A(x_j,t)$

3



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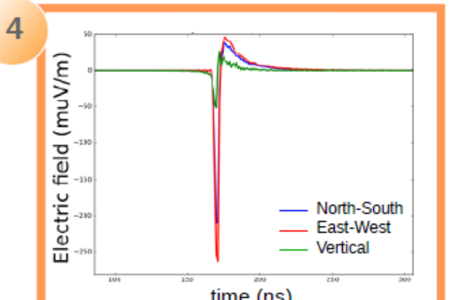
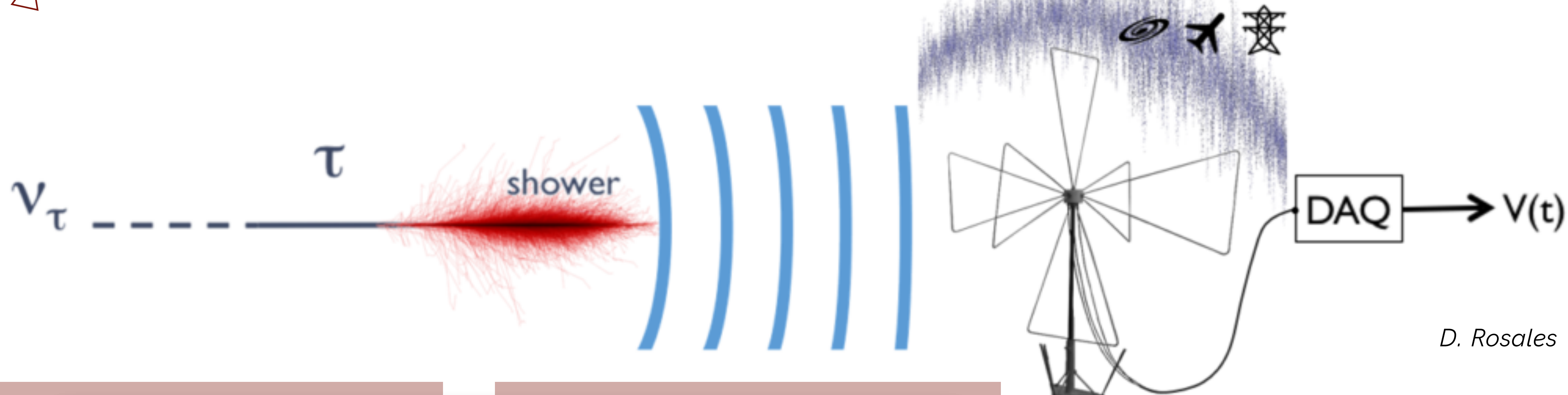


Electric field traces at desired antenna positions

Zilles et al. submitted arXiv:1811.01750

Anne Zilles, ARENA2018

GRAND End-to-End simulation chain



- T
- C
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  si

➔ D

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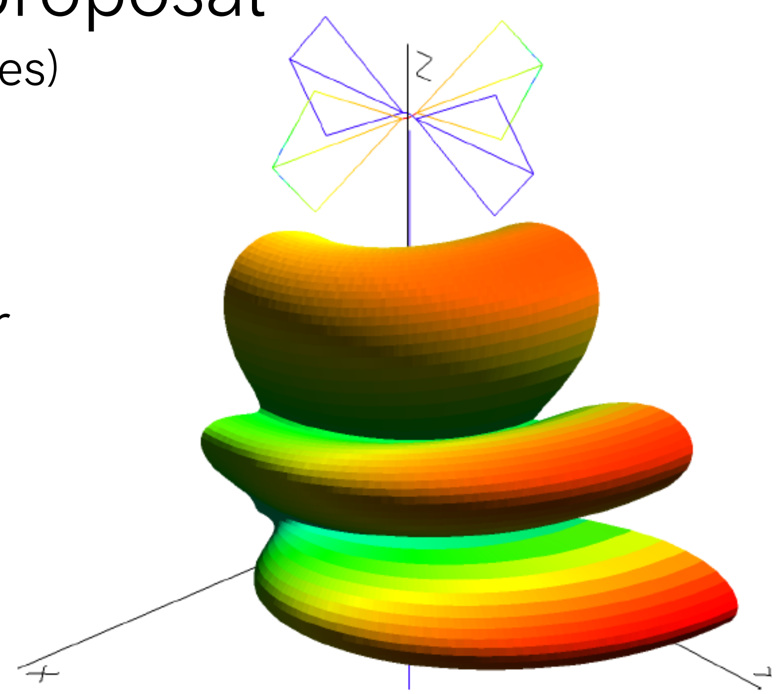
V. N

HorizonAntenna proposal

D. Charrier (Subatech Nantes)

- Active bow-tie antenna (*a la* CODALEMA)
- Dimension optimized for the **50-200 MHz** frequency range
- Antenna height: 4.5 m



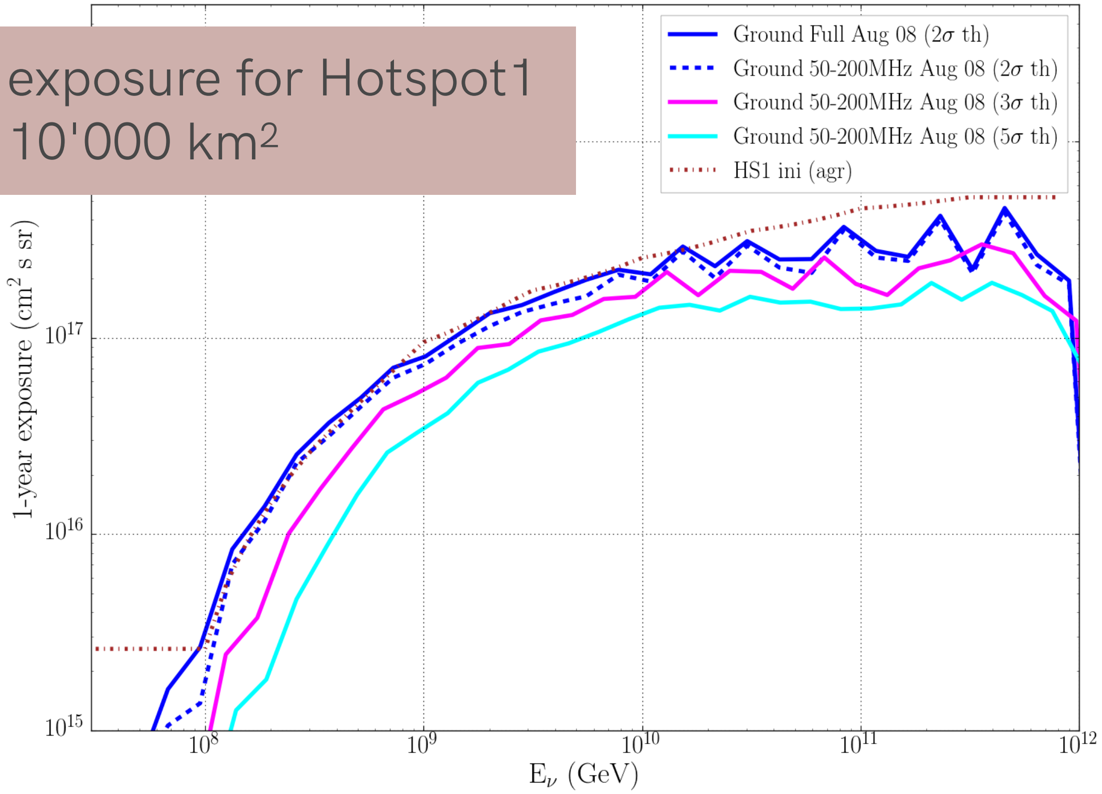
- **optimized for ~horizontal waves**
- 3 arms: full polarization measurement
- Detailed (stationnary) noise level estimate: 15μV rms

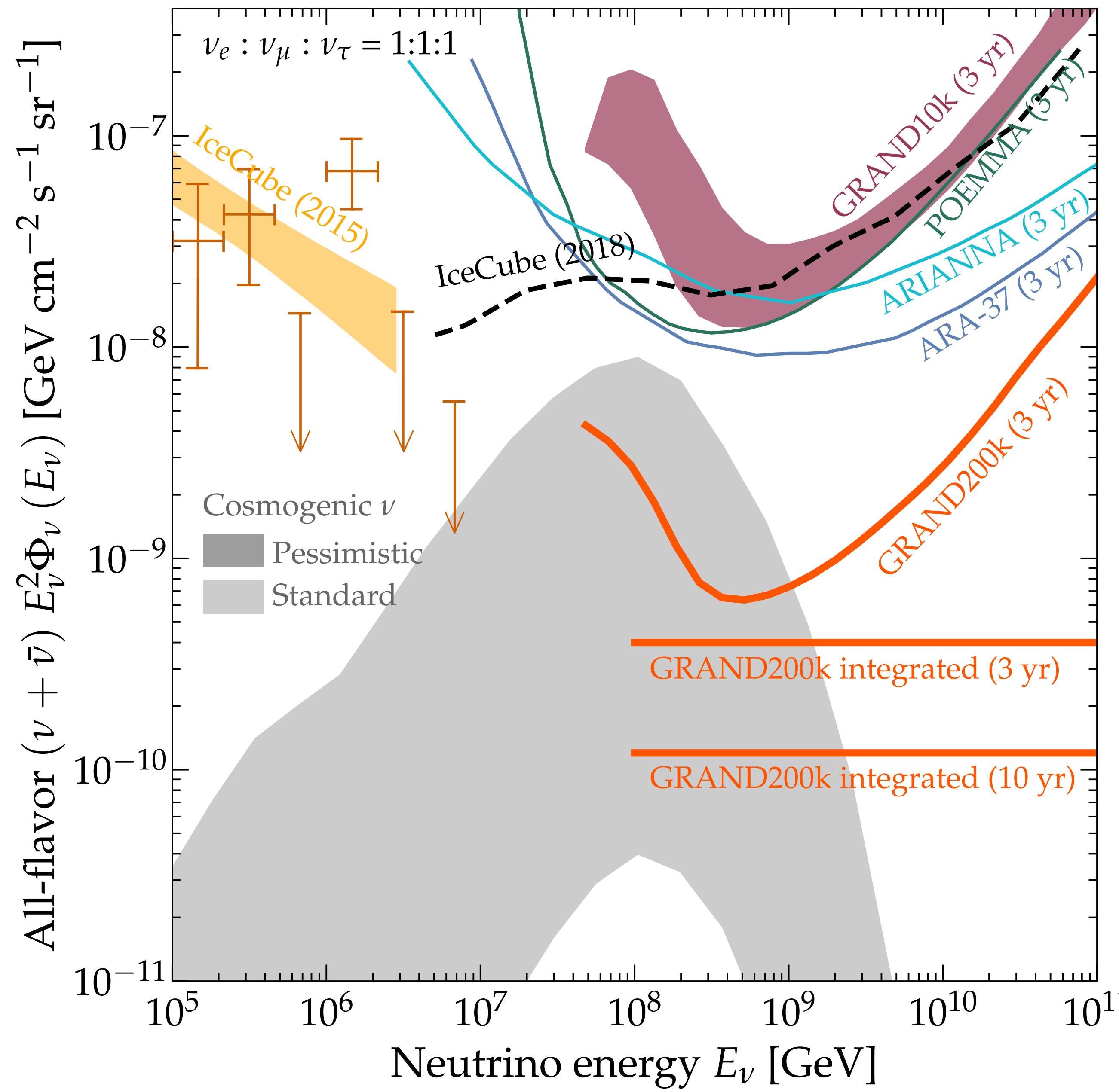
- Antenna response
- Antenna trigger
  (background noise sim)

➔ **NEC**
D. Charrier (Subatech Nantes),
S. Le Coz, O. Martineau

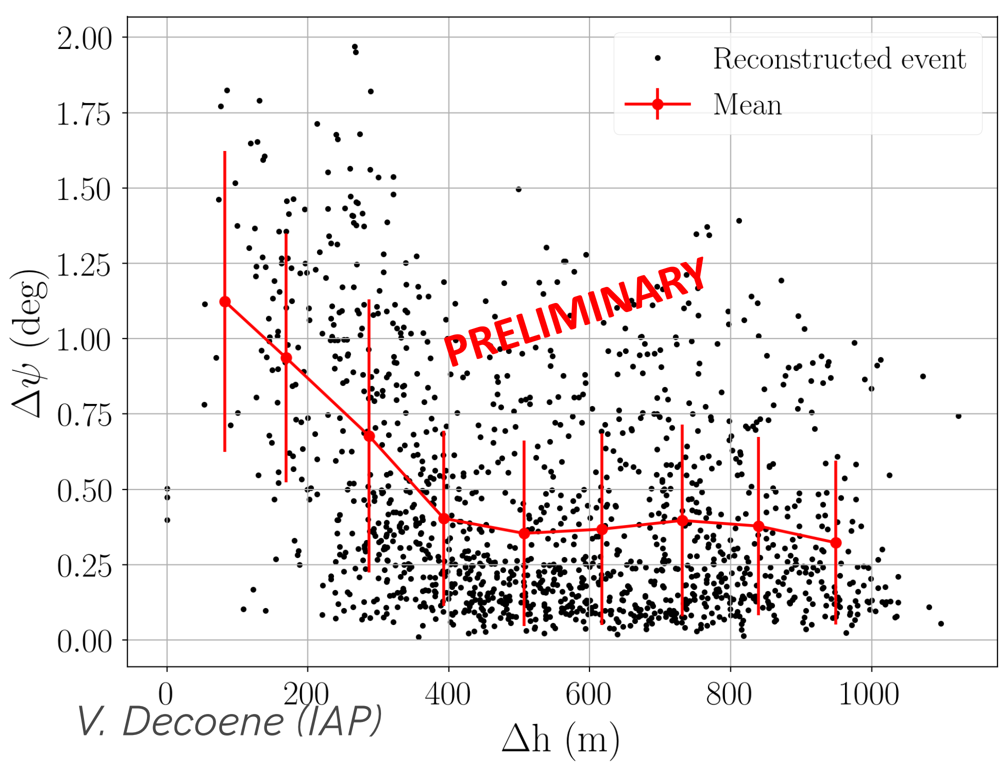
Simulated performances

exposure for Hotspot1
10'000 km²





~0.1-0.3° angular resolution for GP300 also achievable for Hotspot1



$<\psi>$< **0.5°**
(Plane wave approx)
➔ **Astronomy!!!**

GRAND full sensitivity ($E>10^{17}$ eV)
~4x10^{-10} GeV cm^{-2} s^{-1} sr^{-1}

X_{max} resolution:
< 40 g/cm^2 achievable for $E>10^{19}$ eV
with GP300 & further stages

V. Decoene (IAP)

A. Zilles, C. Guépin (IAP)

GRAND Technical Challenges

- How to collect data?
  - Optimised trigger (machine learning (?), see Führer et al. ARENA2018) to improve selection @ antenna level
  - Optimised informations to be transmitted to central DAQ
- How to identify air showers out of the ultra dominant background ?
  - Specific signatures of air shower radio signals vs background transients demonstrated (TREND offline selection algorithm: 1 event out 10^8 pass & final sample background contamination < 20%)
  - Improved setup (GRANDproto35, being deployed) should lead to even better performances
  - Deep learning techniques
- How well can we reconstruct the primary particle information
  - Simulations promising (similar performances as for standard showers) + deep learning technique

Need for an experimental setup to test and optimize techniques

GRAND

GRANDProto300

- How to deploy and run 200,000 units over 200,000km²?
- How much will it cost? Who will pay for it?

go for industrial approach! answers to be studied at later stage

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

GRANDProto300

GRANDProto35

GRAND10k

GRAND200k

2018 | 2020 | 2025 | 203X

Goals

Setup

Budget & stage

GRANDProto35 (2018)

standalone radio array: test efficiency & background rejection

35 radio antennas
21 scintillators

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

GRANDProto300 (2020)

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

- 300 HorizonAntennas over 200 km²
- Fast DAQ (AERA+ GRANDproto35 analog stage)
- Solar panels + WiFi data transfer
- Ground array (a la HAWC/Auger)

1.3 M€

to be deployed in 2020

GRAND10k (2025)

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

DAQ with discrete elements, but mature design

for trigger, data transfer, consumption

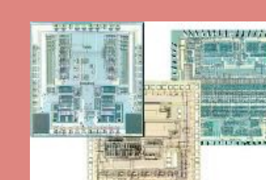
1500€ / detection unit

GRAND200k (203X)

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

200,000 antennas over 200,000 km², ~ 20 hotspots of 10k antennas, possibly in different continents

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

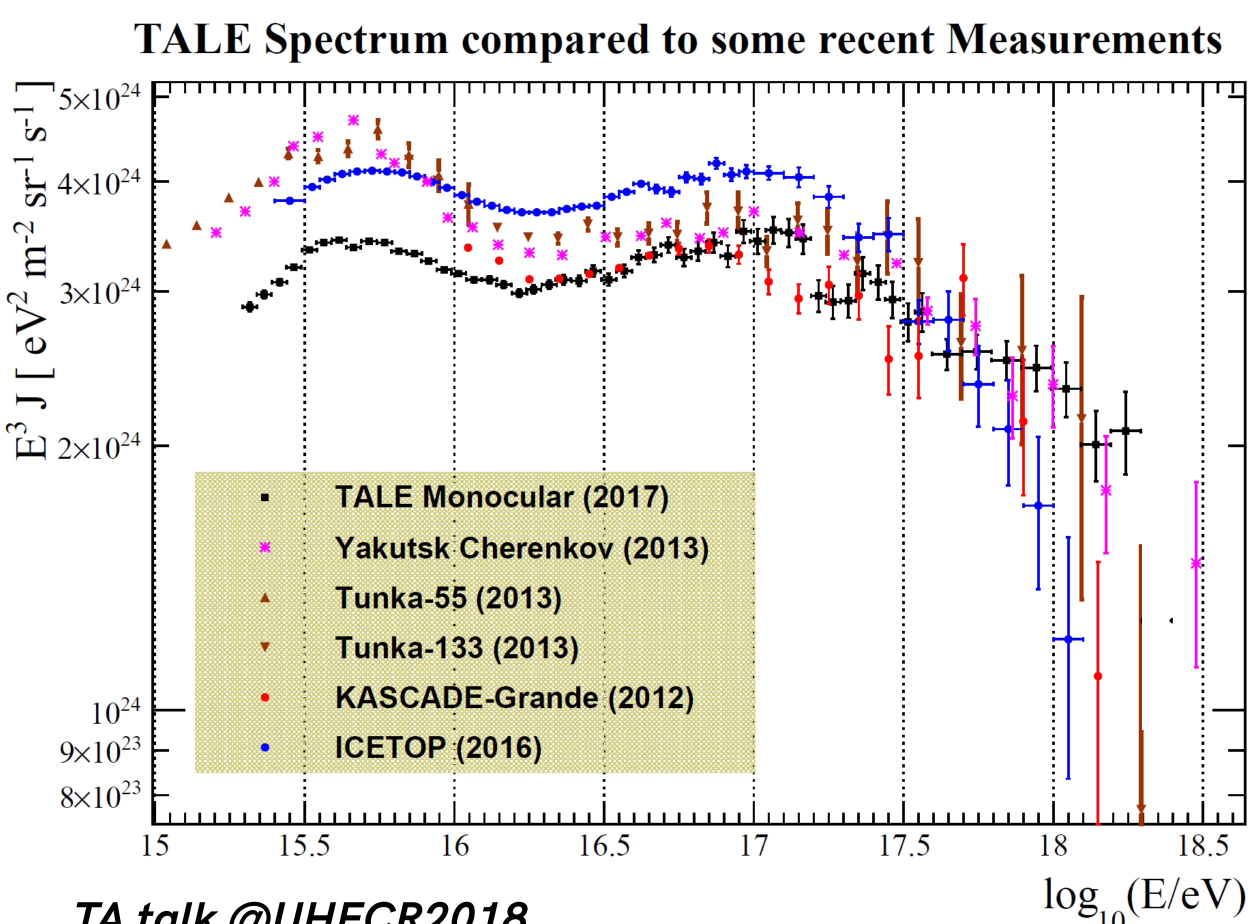


ASIC
Cost ~10M€ ➔ few 10€/board
Consumption < 1W
Reliability

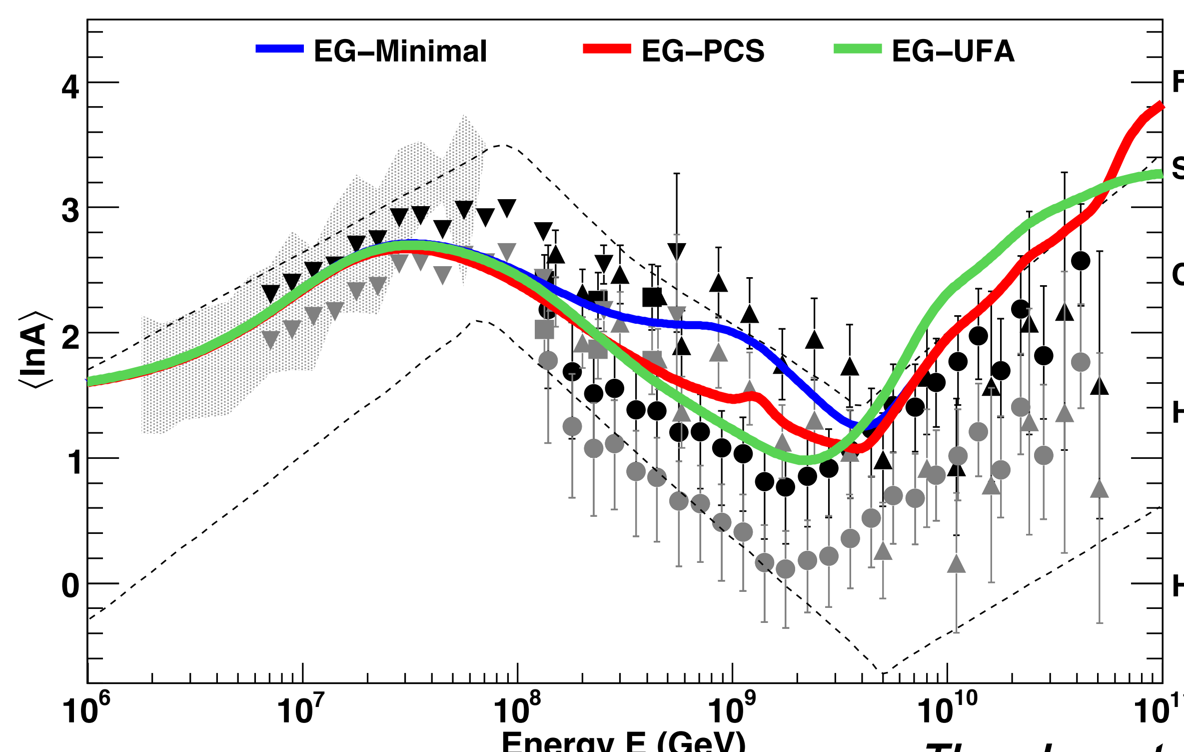
Status of GRANDProto300

The Galactic to extragalactic transition region

- bumpy spectrum
- emerging and vanishing mass elements?
- most theory models fit because of systematic uncertainties
- experimental gap around 10^{17}eV
- **a single setup covering $10^{16.5-18}$ eV?**



TA talk @UHECR2018



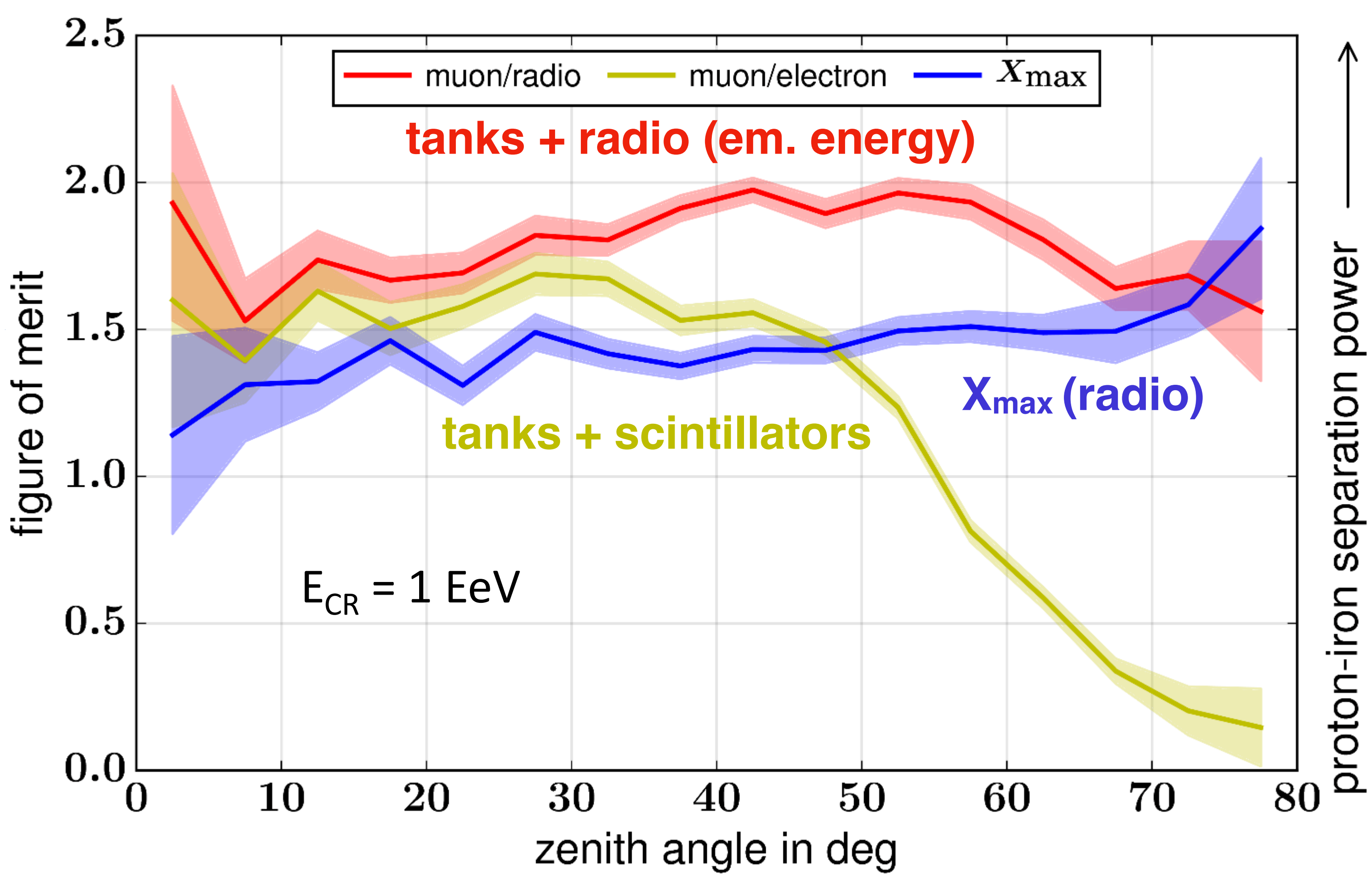
Thoudam et al. 2016

How to reach an exquisite accuracy on mass composition?

- a single setup covering $10^{16.5-18}$ eV?

Yes, and combining radio + muon detectors
—> best for inclined showers (>60°)
—> add also standalone radio measurement of X_{max}
for exquisite accuracy!

radio self trigger —> no dependency on the primary nature for trigger efficiency (ex : light primaries inducing muon-poor showers)



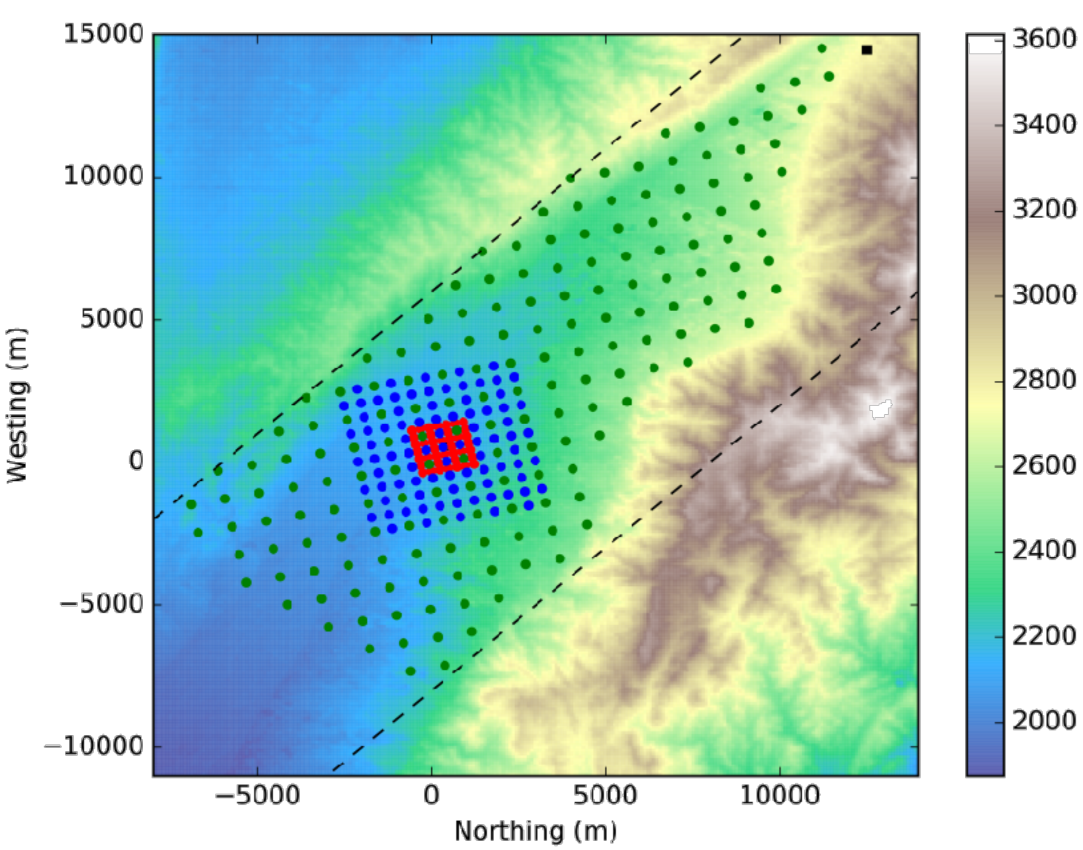
Ewa Holt PhD thesis

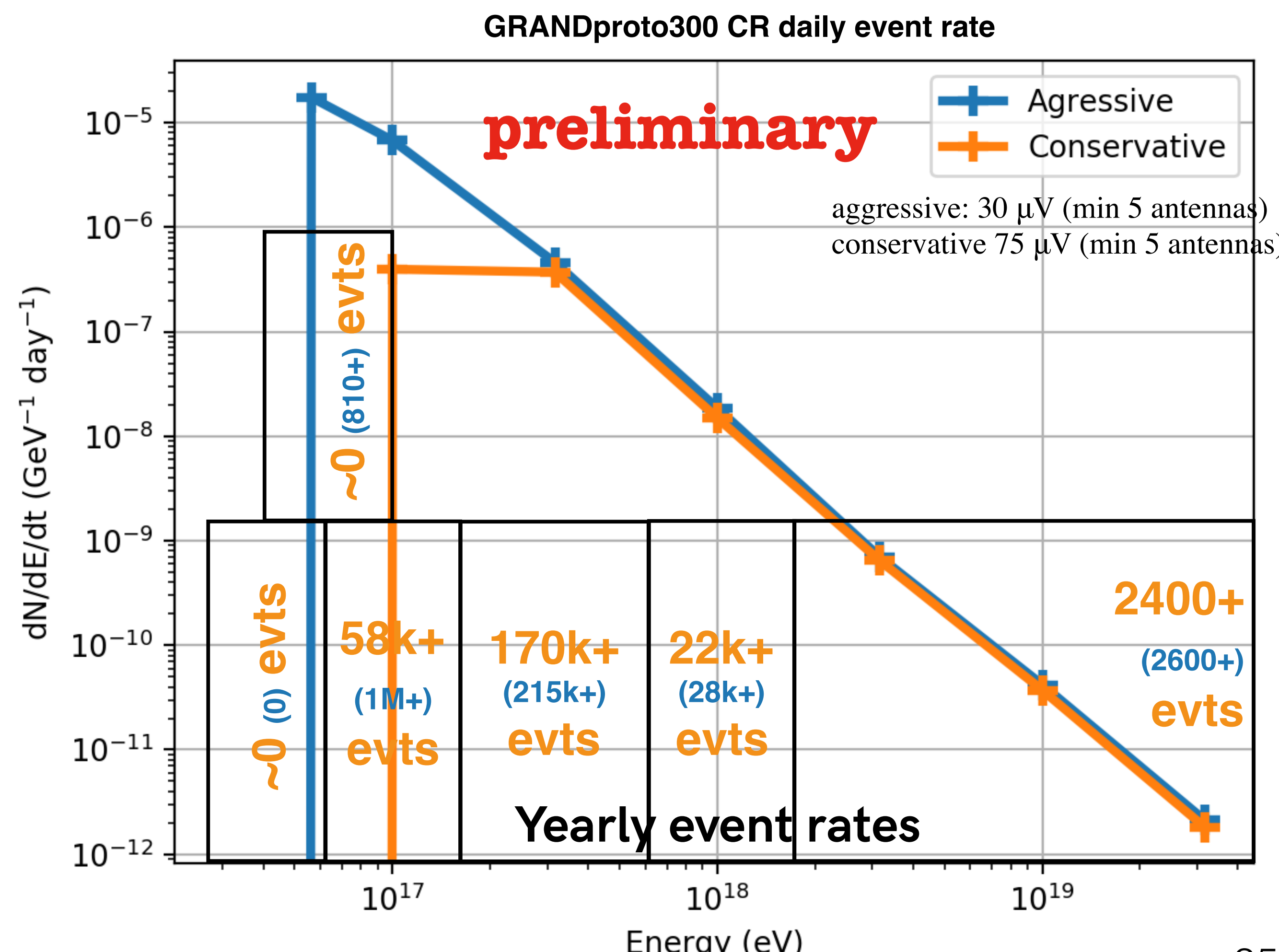
GRANDProto300

- an autonomous radio array
- for inclined air-showers
- with denser infill to reach low energies and cover $10^{16.5-18}$ eV
- a hybrid ground array for muon detection

Possible preliminary layout

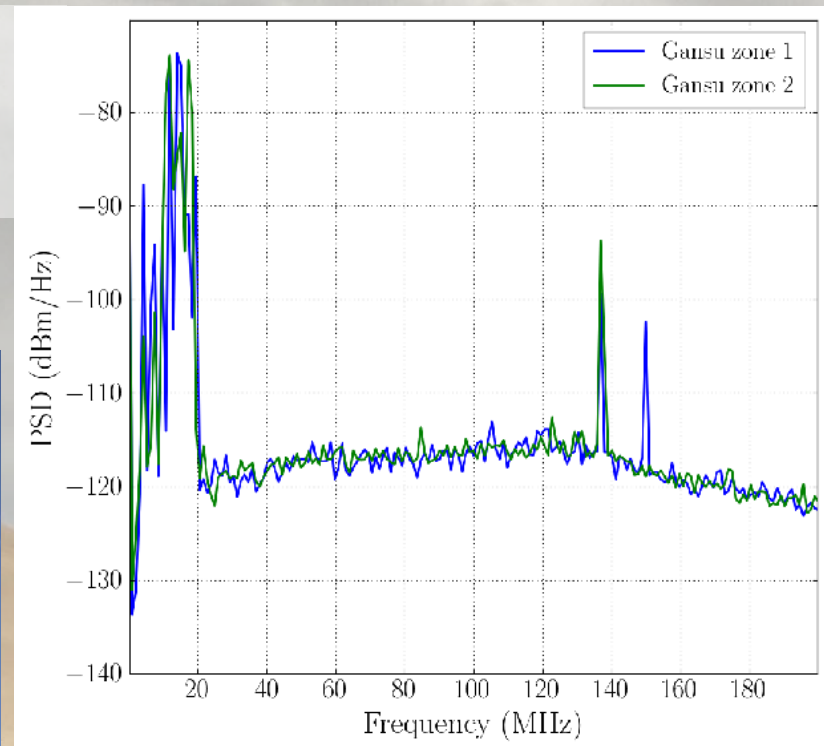
- 200 km² with 196 detection units
- 25 km² infill of 85 antennas with 500-m spacing
- 2 km² infill with 26 antennas with 250-m spacing
- + water tanks - configuration to be studied



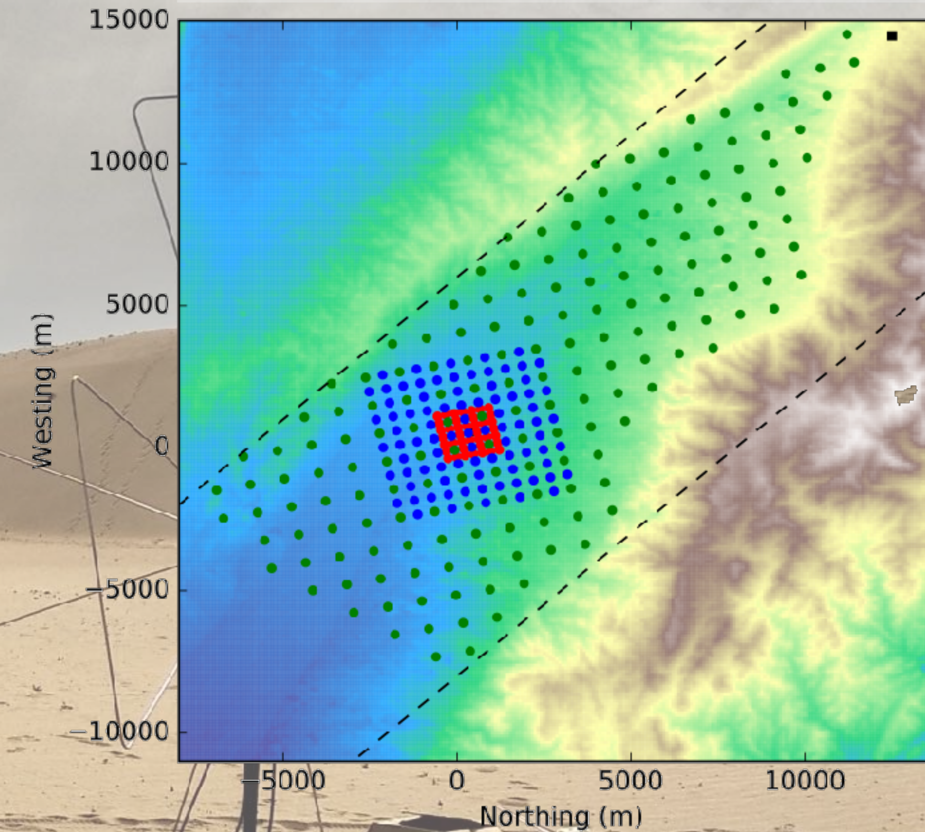


GRANDProto300: experimental setup almost ready

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

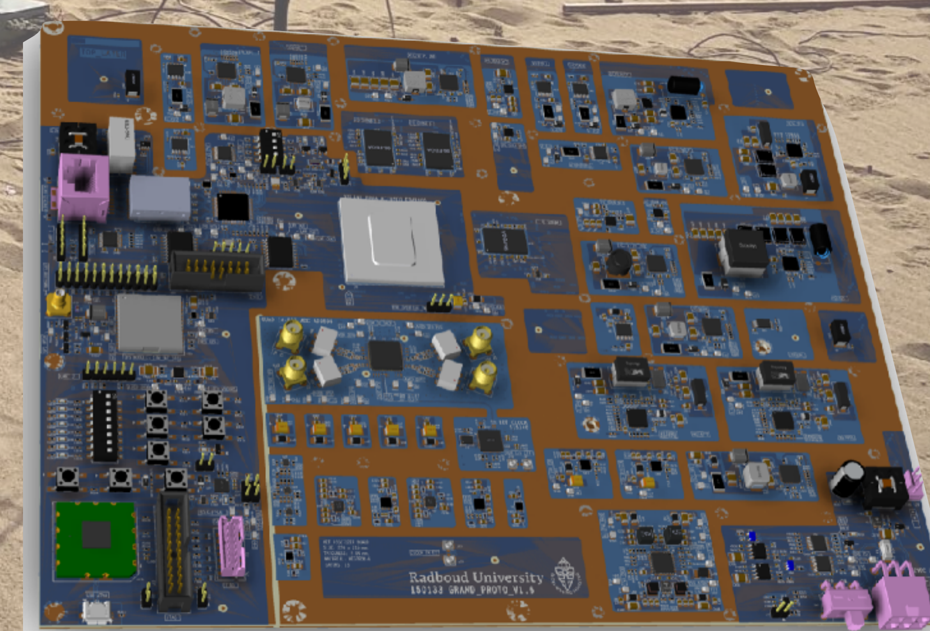


Layout: 300 antennas, 200km², 1km step size with denser infield
➔ Erange = $10^{16.5}$-10^{18}eV



HorizonAntenna, successfully tested in the field (August, December 2018)

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



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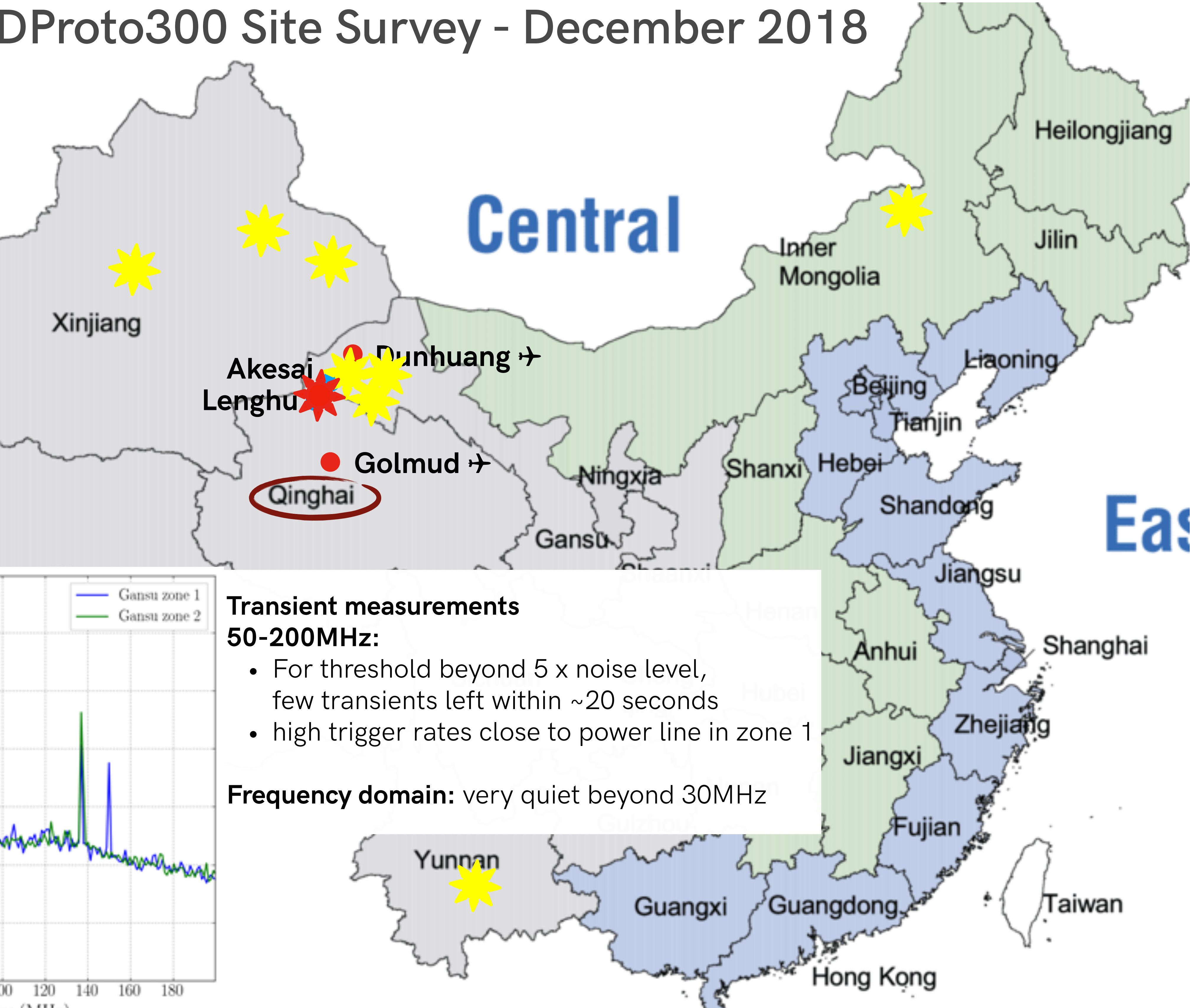
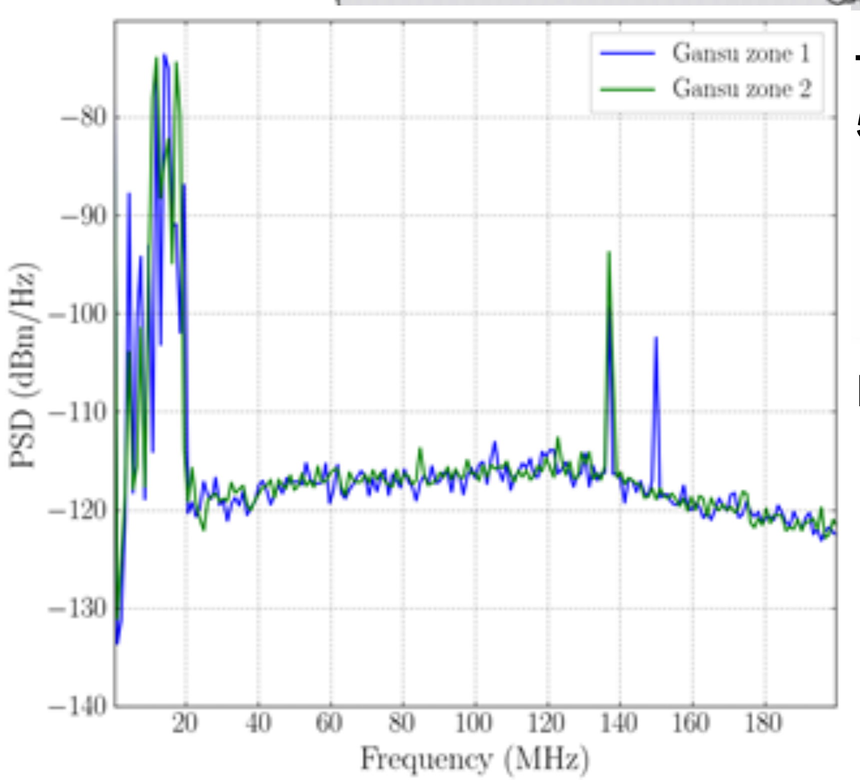
GRANDProto300 Site Survey - December 2018





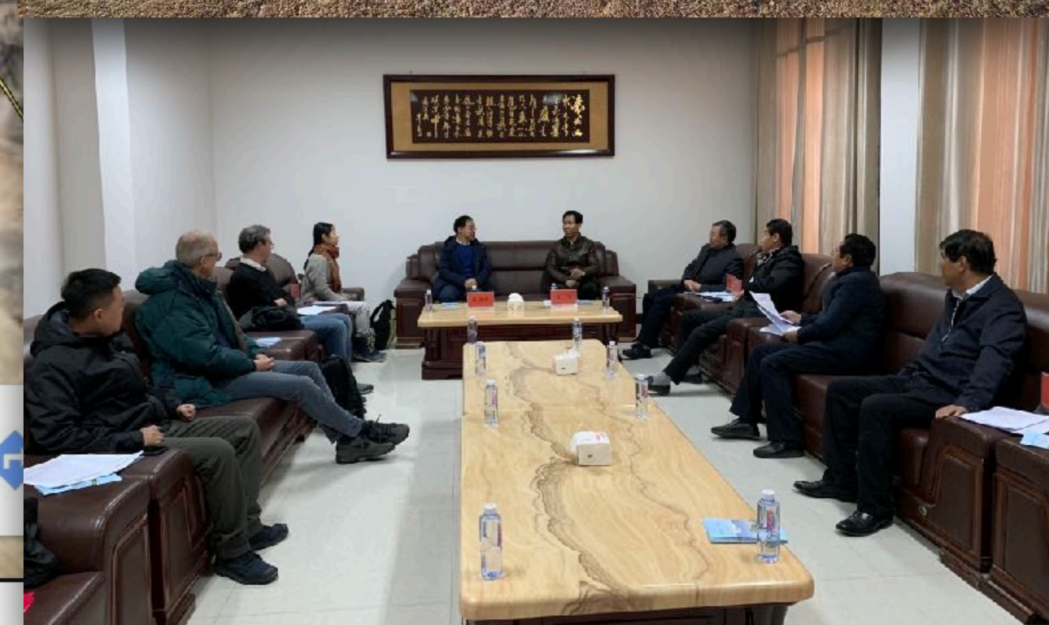
Transient measurements 50-200MHz:
- For threshold beyond 5 x noise level, few transients left within ~20 seconds
- high trigger rates close to power line in zone 1

Frequency domain: very quiet beyond 30MHz

- ~50 measurements in 50-200 MHz range (April 2017-December 2018)
- **7/9 tested sites are very good candidates for 10k-antenna hotspots**
- deployment of several antennas next spring in Gansu Province

GRANDProto300 Site: strong political support in Qinhai

- Qinhai province propose that we take **mostly any site around the Lenghu town**
- very strong support (Province-level)
- no long-term plans for industry (very remote area, ancient dead petrol industry)
- history of supporting astronomy: active mm-Observatory in Qinhai since 1980s http://english.dlh.pmo.cas.cn/
- Active help from professional engineers from Radio Regulatory Commission



GP300 muon detector array

Penn State group

- tanks à la HAWC/Auger
—> size (height) closer to HAWC than Auger (inclined showers)
—> inside (especially liners) Auger-style (with reflective Tyvek to collect light)

- rather traditional technique —> low risk, high gain

Next GRAND Collaboration Meeting in China

April 24-27 2019

https://indico.in2p3.fr/event/18766/

Dunhuang:
airport, 4-hour drive to Qinhai site, nice touristic city

GRAND Today

France China Particle Physics Laboratory | Natural Science Foundation of China | France China Particle Physics Laboratory | Chinese Academy of Science

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~50 collaborators from 10 countries

France (15), China (7), USA (7), Netherlands (2), Germany (2), Copenhagen (1), Spain (2), Brazil (2), Belgium, Argentina, Sweden

GRAND Workshop, IAP, August 2018

electronics prototyping: Nikhef/Radboud U., NAOC
antenna prototyping: Subatech, Xidian U.
production: NAOC, Xidian U.
simulations: IAP, LPNHE, KIT, Clermont-Ferrand, VUB
particle detectors: Penn State U.
computing resources: KIT
site management: NAOC

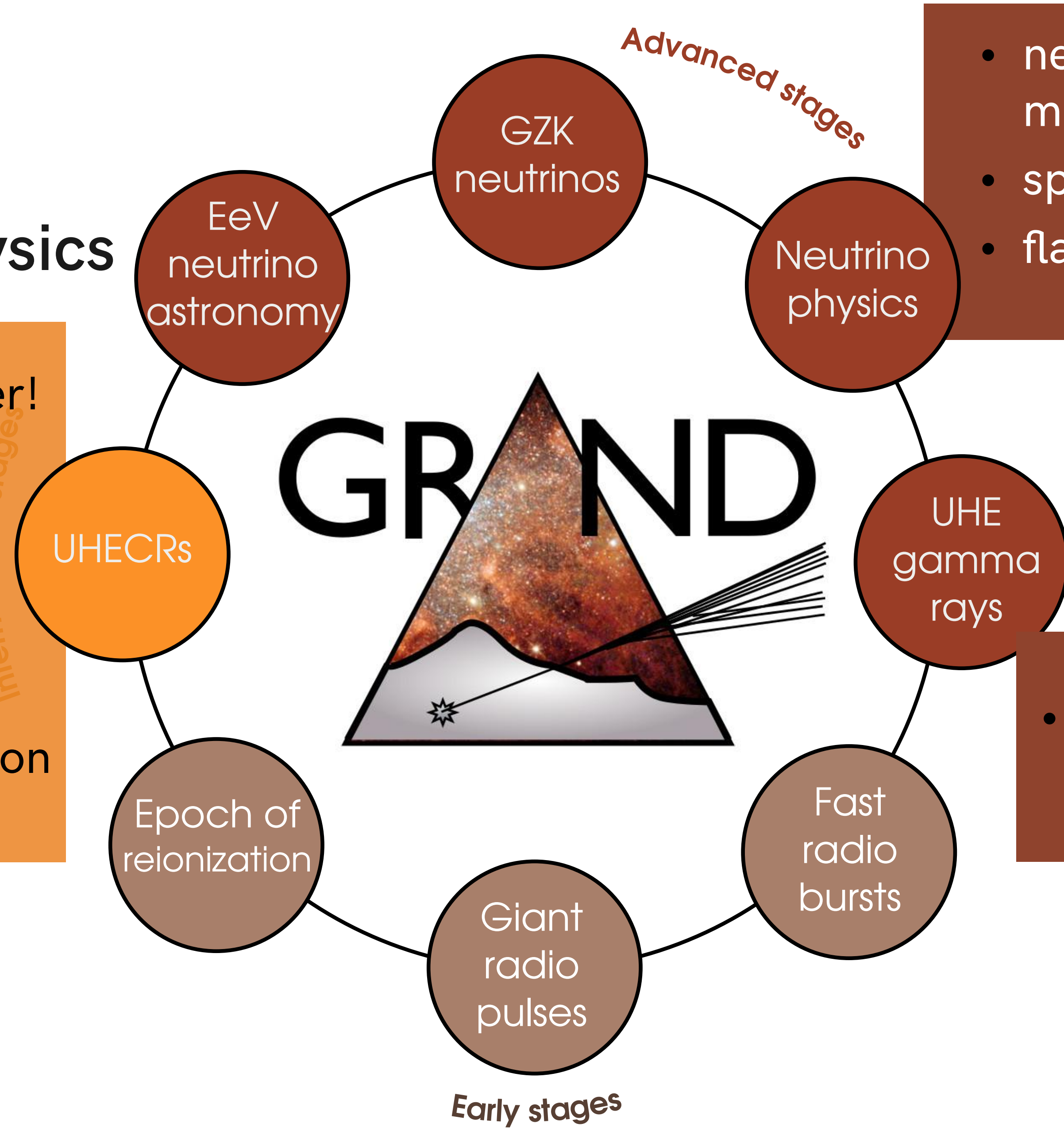
A rich science case

neutrino physics

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

UHECR, hadronic physics

- 20 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

- 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

What instrumental approach will be suited for what purpose, and what approaches should be supported by the community given the significant increase in cost per experiment?

- astronomy possible only with a **giant array**
- affordable giant array possible with **radio** detection of **inclined** air-showers
- goal of GRANDProto300: demonstrate **autonomous** radio detection of inclined air-showers
- if this works, in principle, **radio alone could suffice** to do EeV neutrino astronomy
(cheaper + avoid difficulties related to other detection techniques)
but hybrid detection could be implemented in subset arrays for richer data

- beyond GRANDProto300, **challenges** are related to **large arrays**
(e.g. communication, power supply)**: common to all other large-array projects**

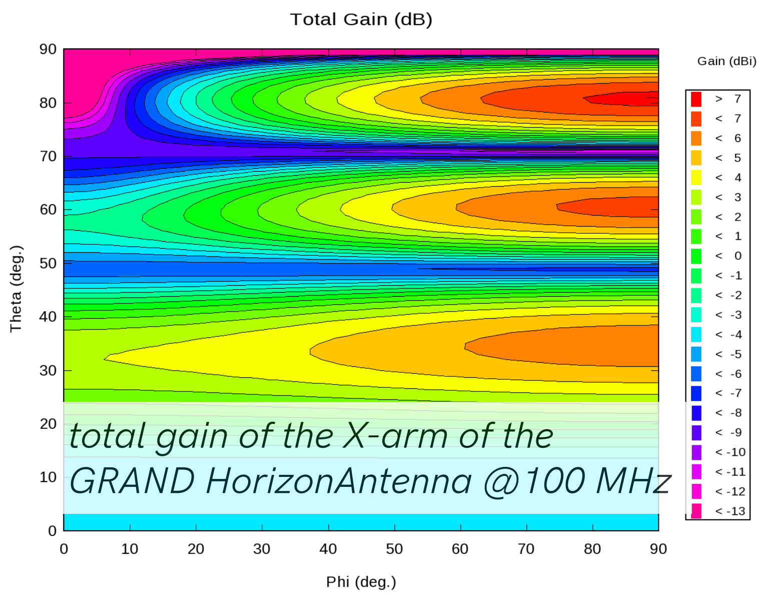
GRAND

join us and bring your ideas!

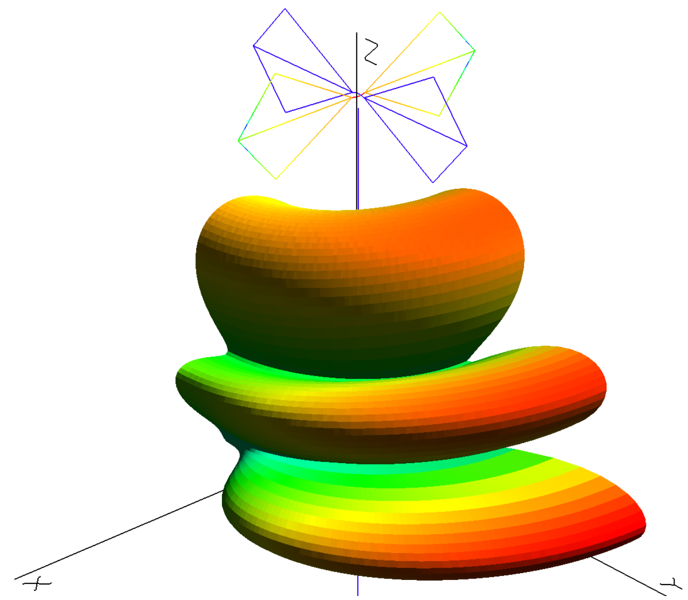
http://grand.cnrs.fr/

HorizonAntennas

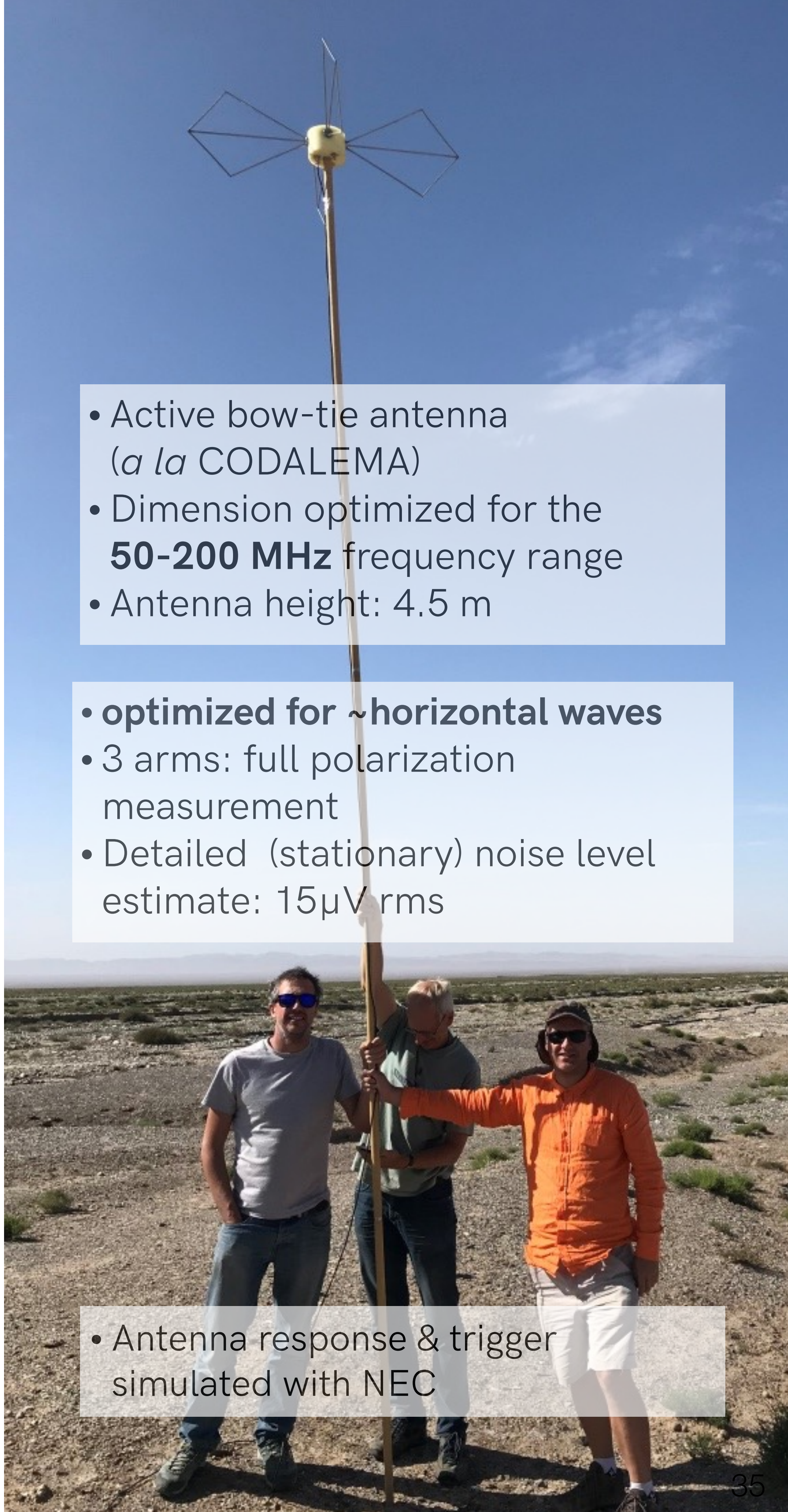
- designed and tested (D. Charrier, SUBATECH)
- to be fully characterized + mechanical design (Xidian University?)
- will be produced by Xidian University (group of Guo Lixin & Jinya Deng)
- will be calibrated by Xidian University



total gain of the X-arm of the GRAND HorizonAntenna @100 MHz



Jinya Deng @Xidian University



- Active bow-tie antenna (*a la* CODALEMA)
- Dimension optimized for the **50-200 MHz** frequency range
- Antenna height: 4.5 m

- **optimized for ~horizontal waves**
- 3 arms: full polarization measurement
- Detailed (stationary) noise level estimate: 15μV rms

- Antenna response & trigger simulated with NEC

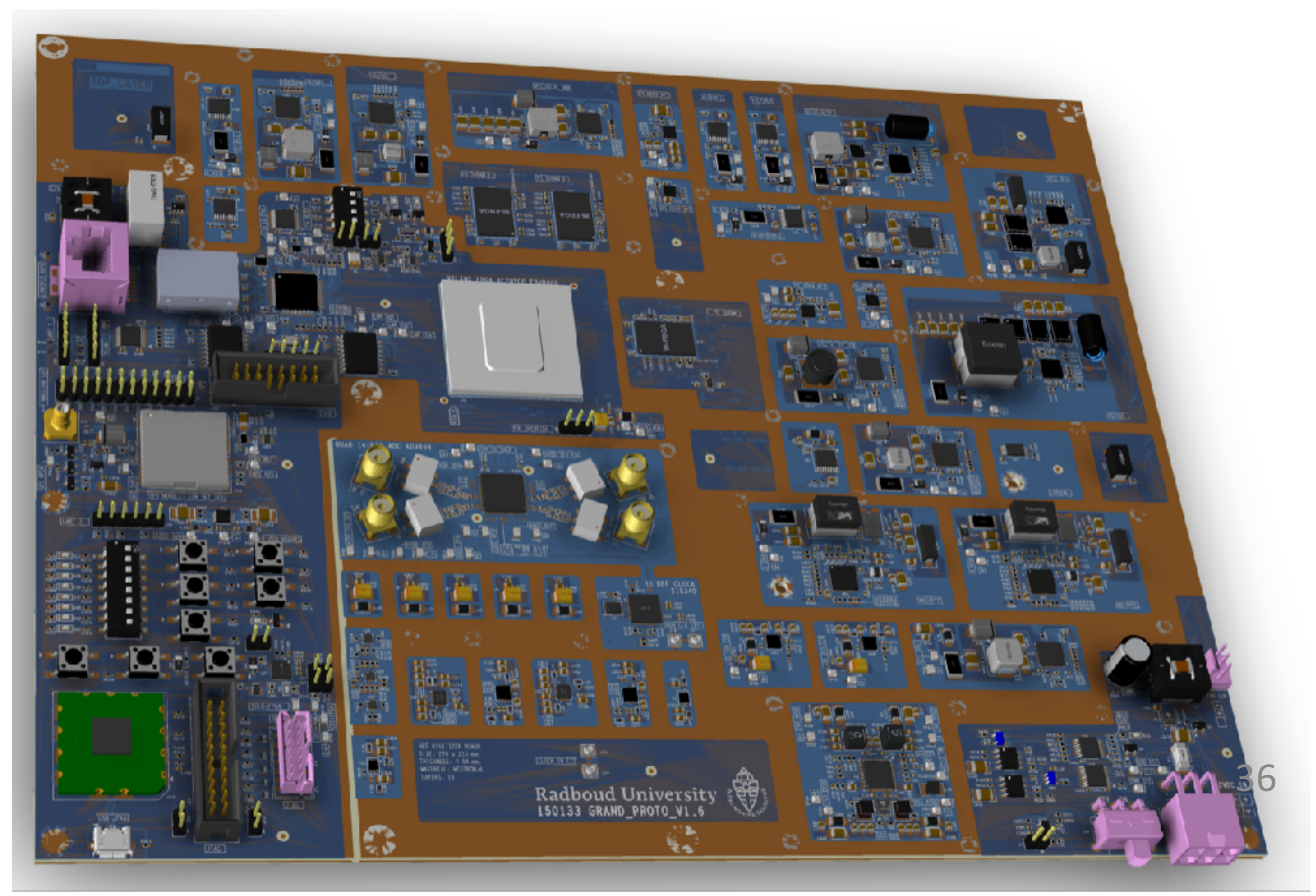
35

GP300 electronics

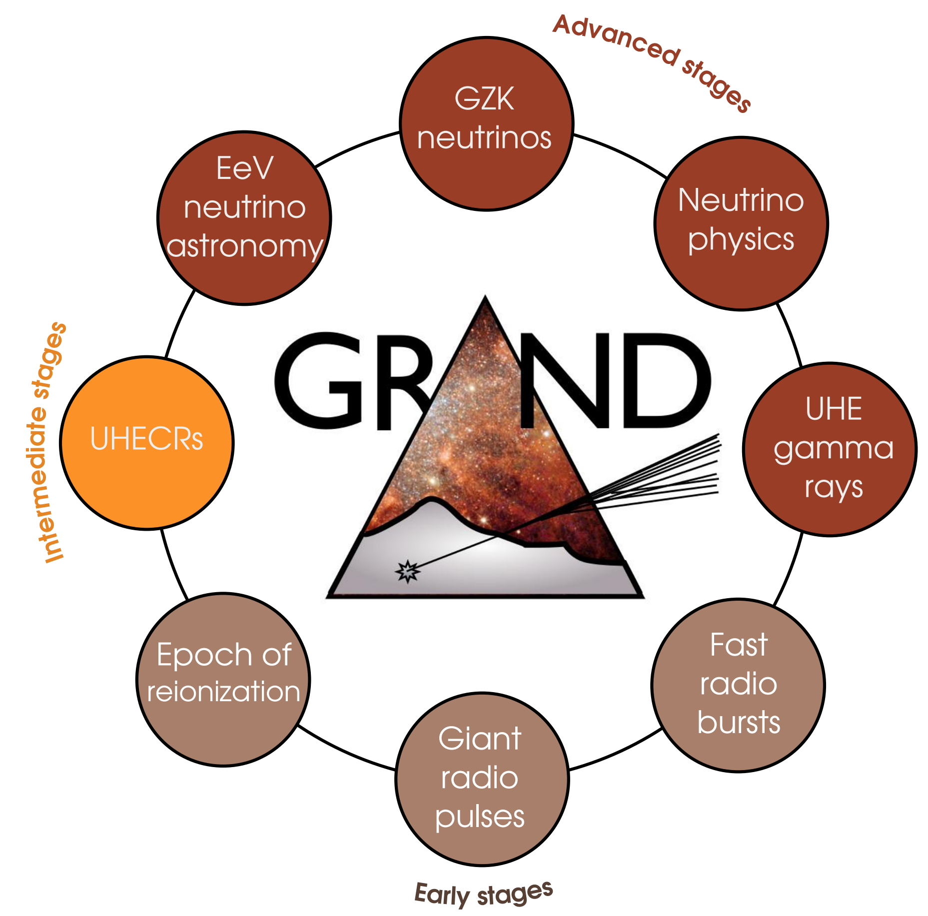
Nijmegen group

- **design of the prototype board ready (Rene Habraken)**
- based on the AERA Dutch electronics
- currently: production of 3 units (in Europe)
  production of a second batch for testing later in 2019
- **Nikhef is advancing money for production**
- at later stages: production to be done in China and managed by China

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



GRAND Science Case: What else can we do?



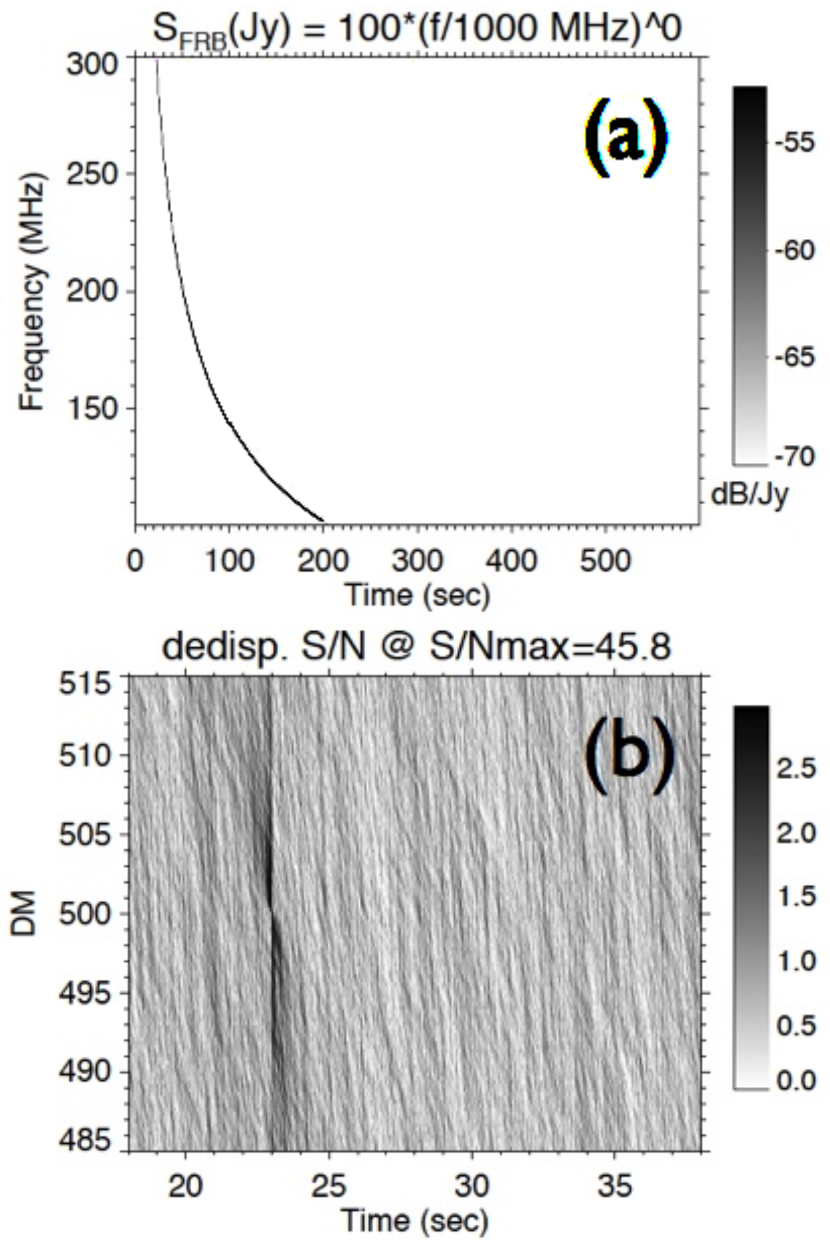


FIG. 7 The top panel (a) shows a (i) dispersed (DM = 500 pc.cm^{-3}) and (ii) diffused 100 Jy and 5 ms long FRB pulse (the simulated galactic noise is not shown since its power largely dominates the signal). The bottom panel (b) shows the result of a blind search. GRAND would detect that event with an SNR of ∼ 50. The FRB dispersive drift lasts for ∼ 185 s (against ∼ 370 s for DM = 1000 pc.cm^{-3})

Simulations by P. Zarka for GRAND

- The largest UHECR detector on ground
- Fast Radio Bursts and Giant Radio Pulses!
  - 30 Jy + flat spectrum FRBs should be detectable by GRAND (incoherent sum of 200’000 antenna pulses in 100-300MHz)
  - GRAND sales argument: good sensitivity, unexplored frequency band, large field of view (= single antenna FoV thanks to incoherent summing) opening possibilities for HUGE stats…