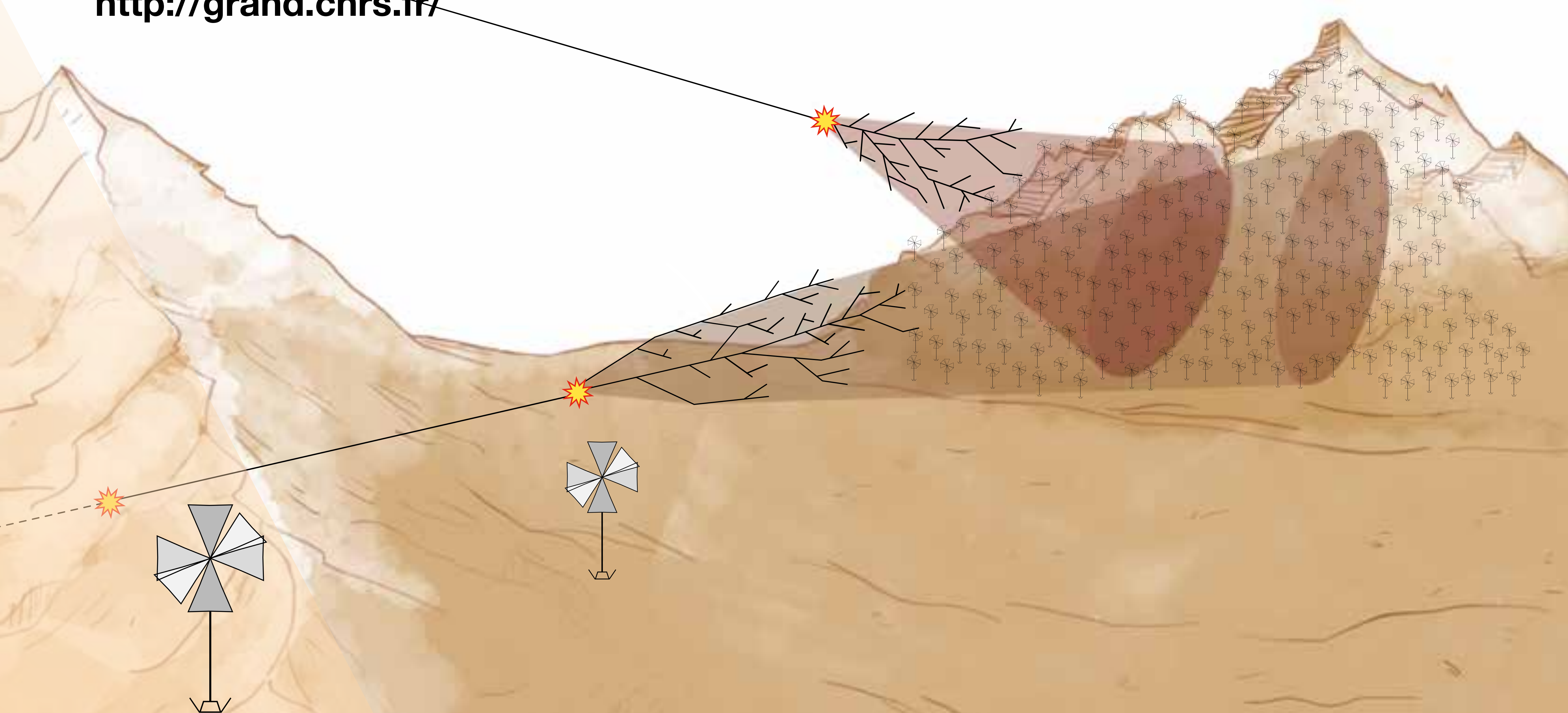
The Giant Radio Array for Neutrino Detection

GRAND

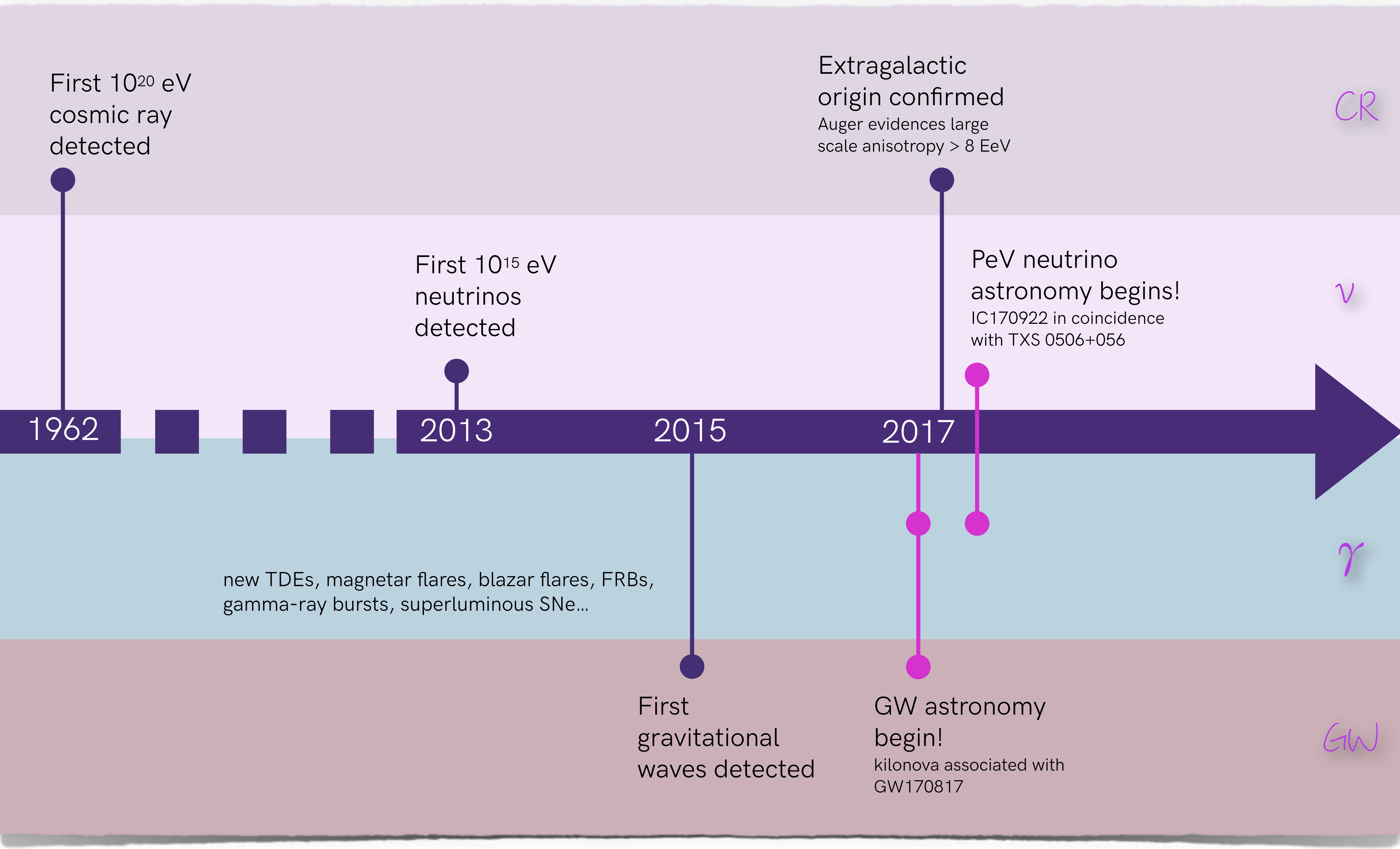
http://grand.cnrs.fr/



Kumiko Kotera - Institut d'Astrophysique de Paris

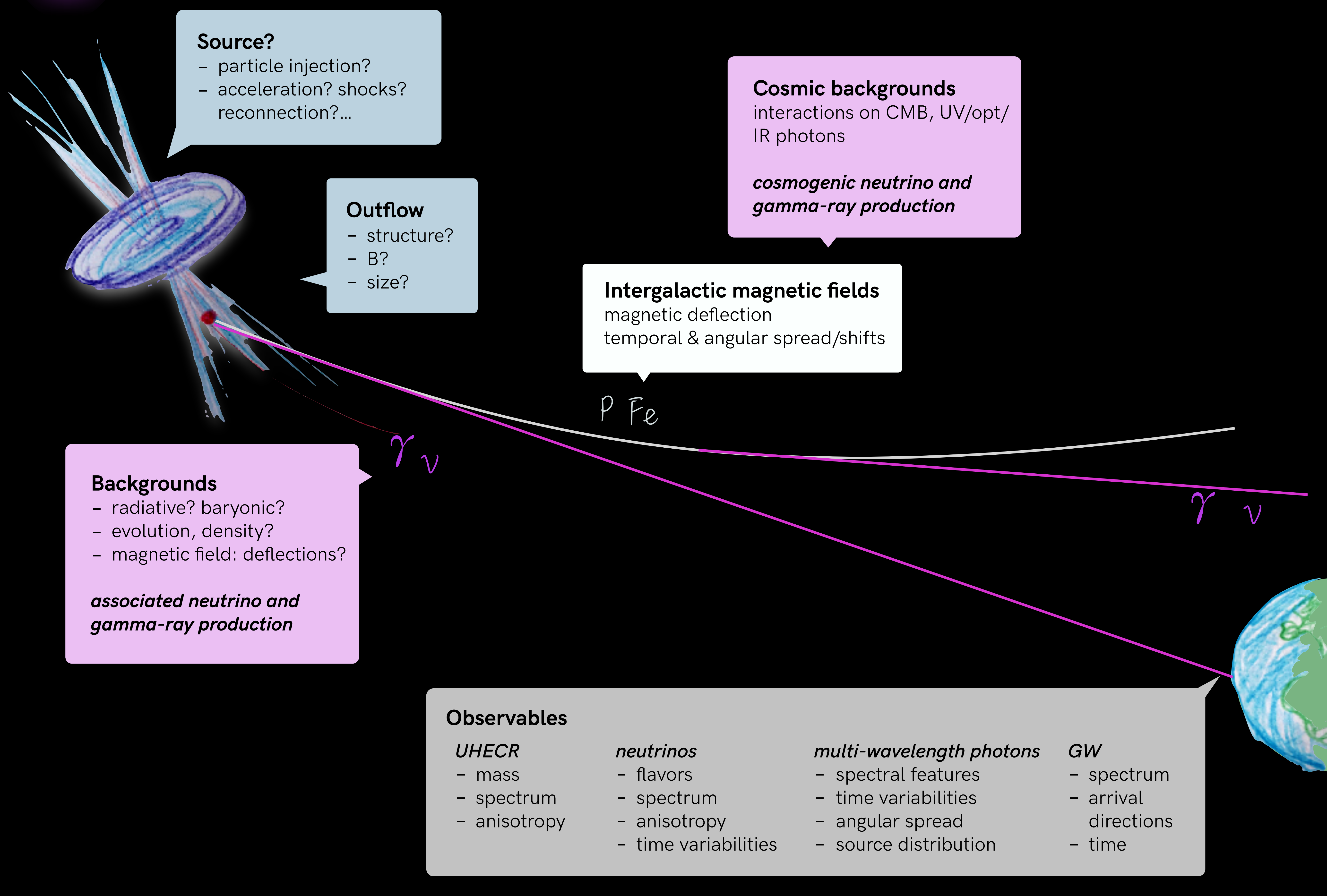
IIHE - 07/12/2018

Exciting times!

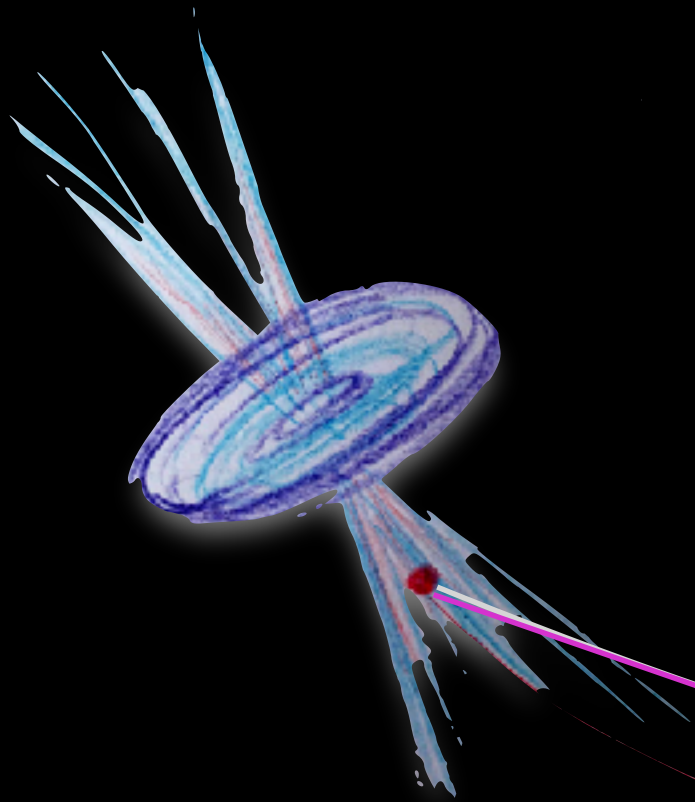


And we still don't know the origin of UHECRs

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

$E_\nu \sim 5\%\ E_{CR}/A$ $\quad$ $E_\gamma \sim 10\%\ E_{CR}/A$

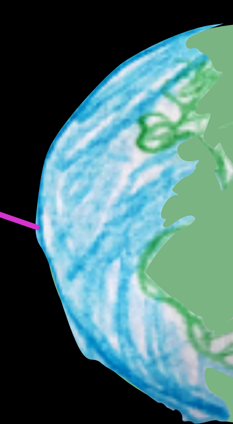
$E_{CR} > 10^{18}$ eV

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

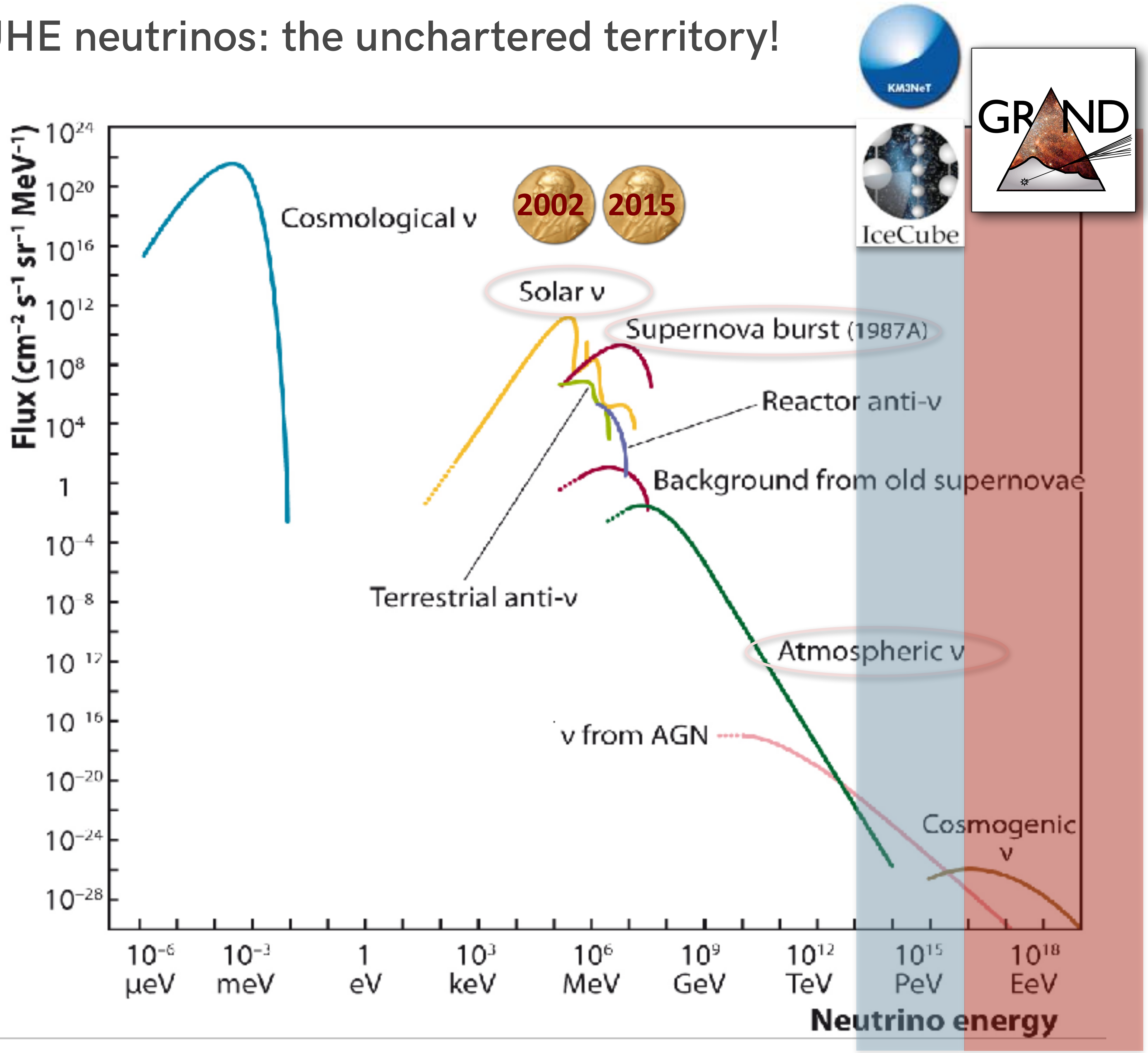
IceCube neutrinos do not directly probe UHECRs

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

γ ν



UHE neutrinos: the unchartered territory!

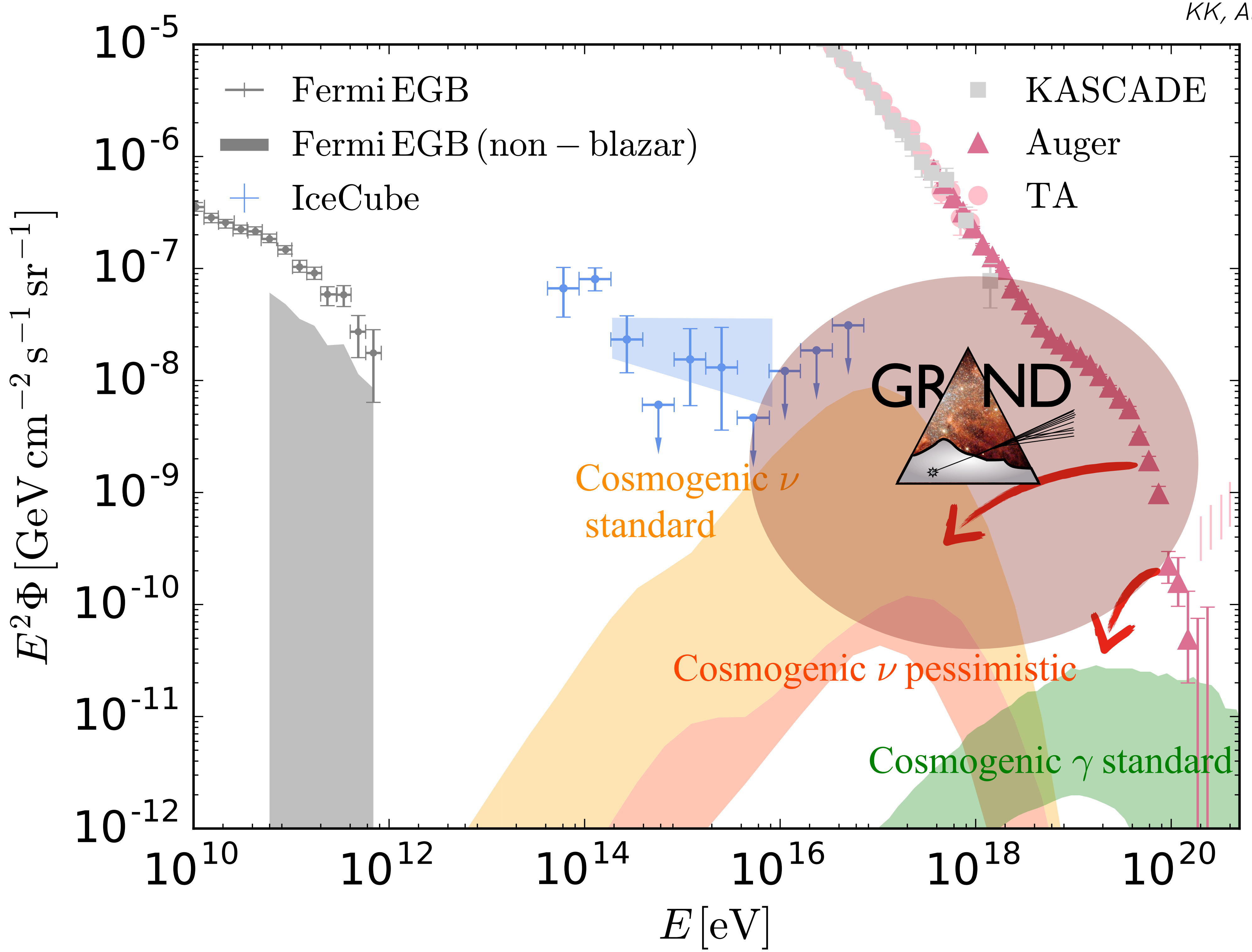


The guaranteed cosmogenic neutrinos

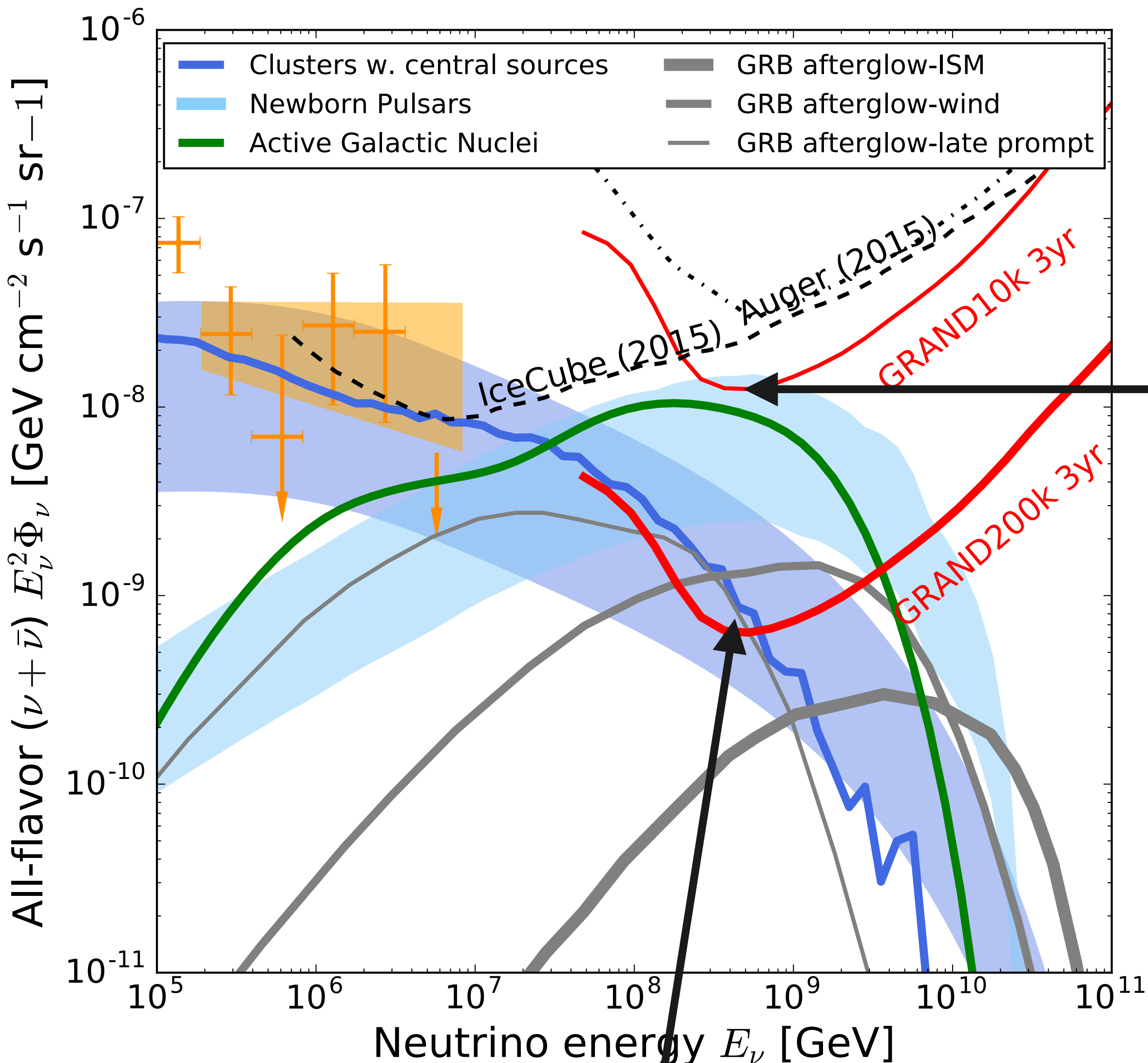
Alves Batista, de Almeida, Lago, KK, submitted

GRAND Science & Design, 2018

KK, Allard, Olinto 2010



What we can aim to do **with future observatories**



detect the first EeV neutrinos

cosmogenic: guaranteed

direct from source: likely more abundant

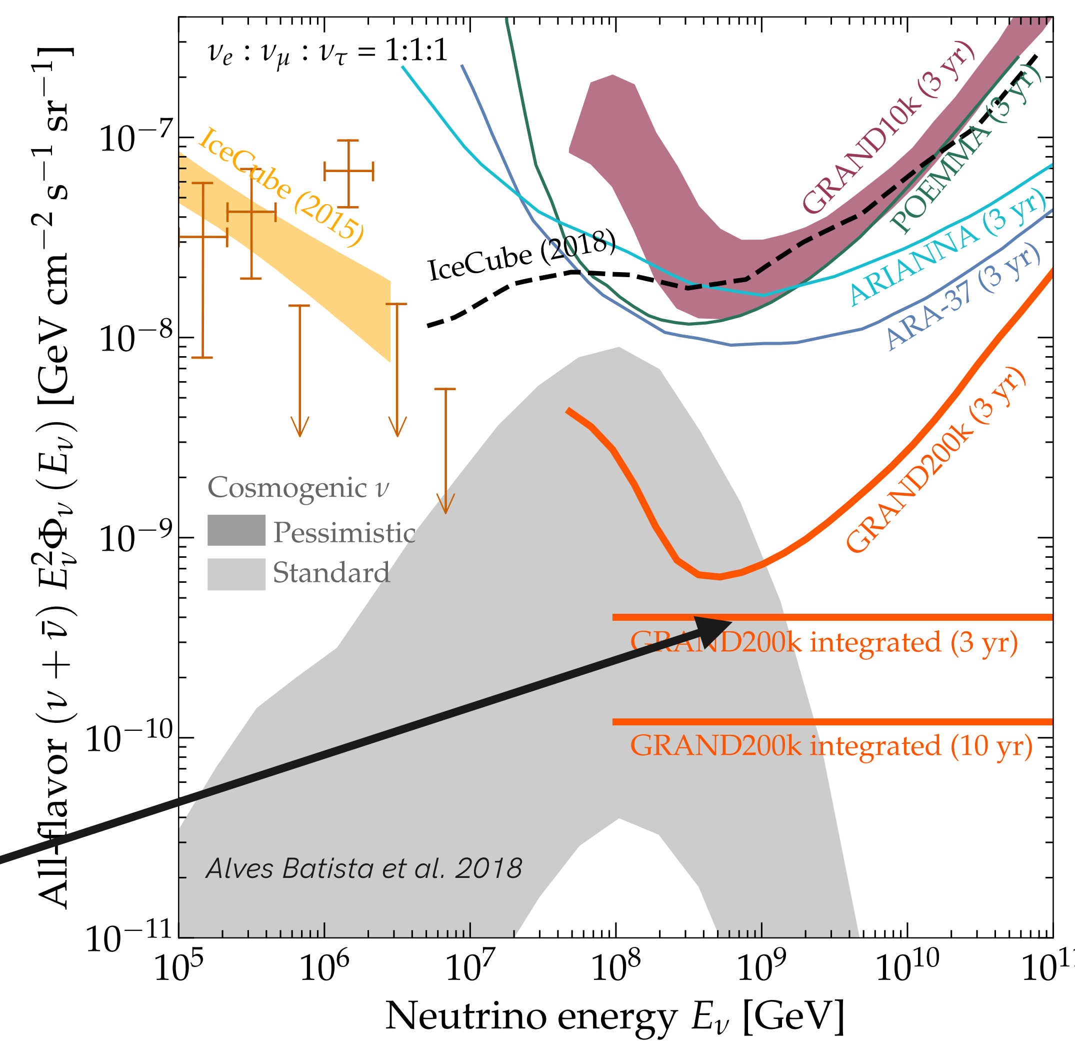
pessimistic scenarios of cosmogenic neutrinos = good!

low background for source neutrinos

detect EeV neutrino **point sources**

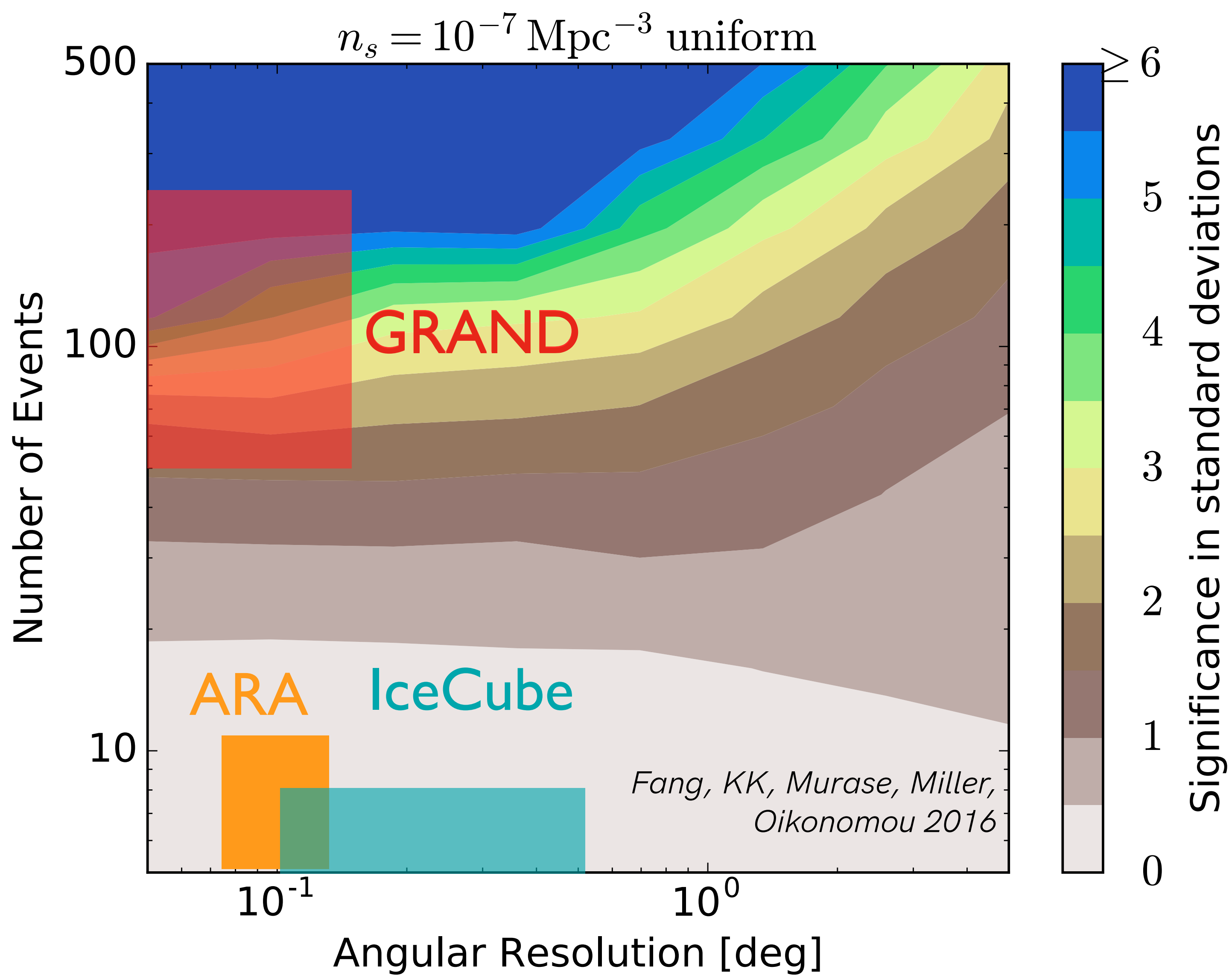
100s of events
~0.3° angular resolution

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

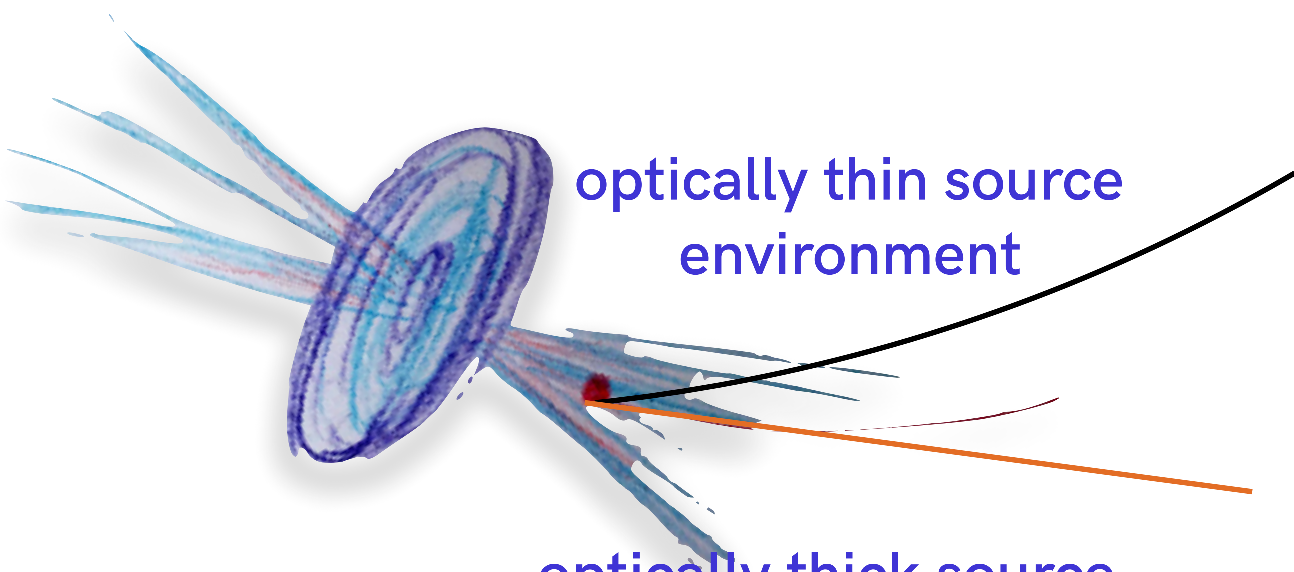
If the **measured** UHECR composition is not protons

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

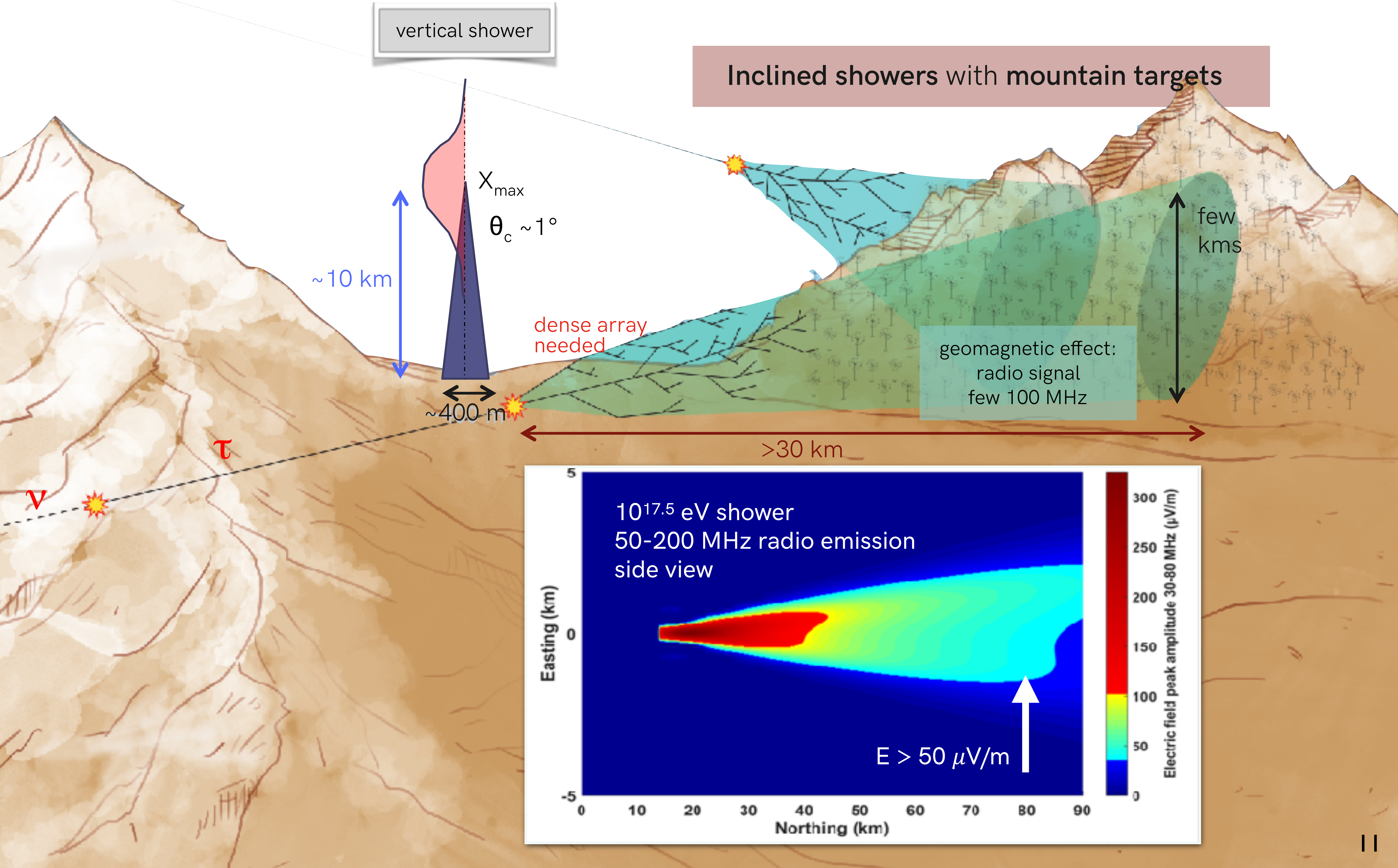


The GRAND Project

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



The GRAND Concept

radio detection: a mature and autonomous technique
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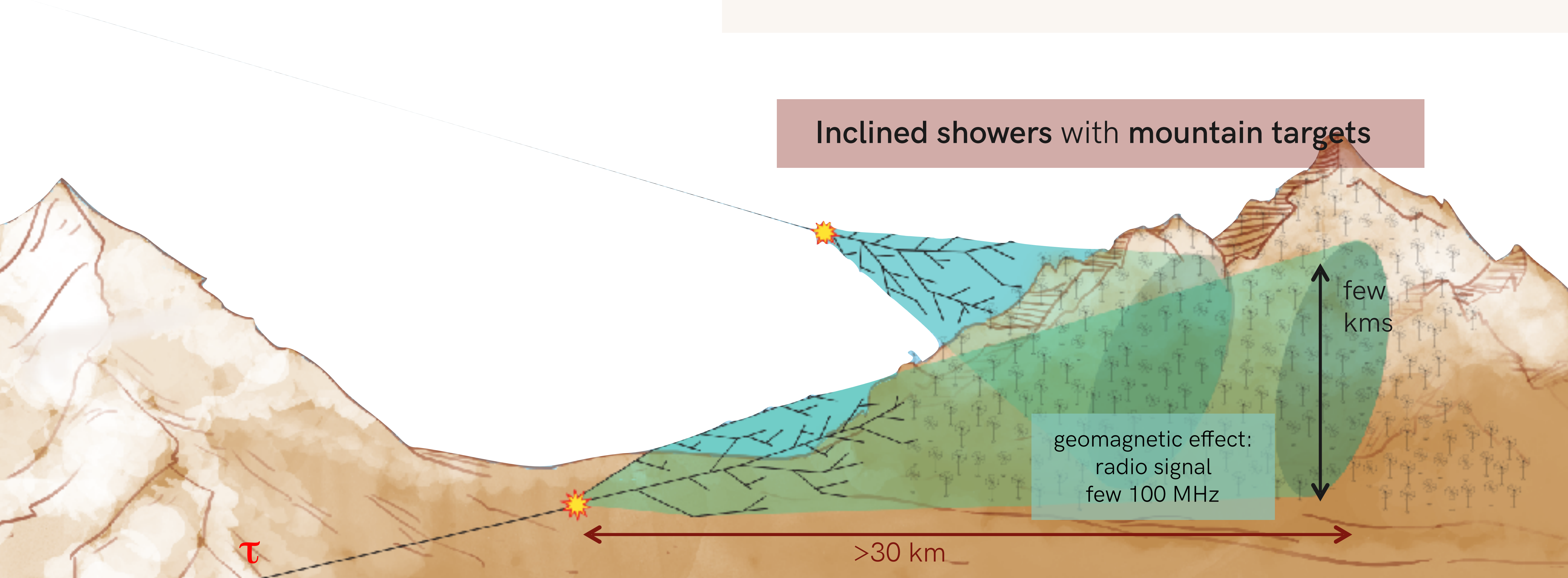
radio antennas cheap and robust: ideal for giant arrays

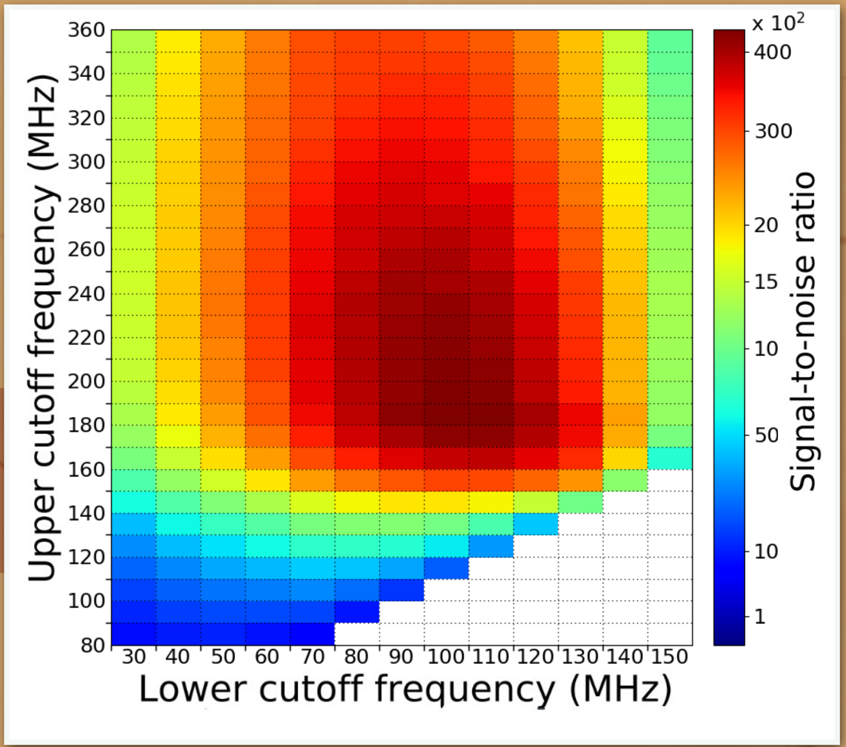
Inclined showers with **mountain targets**



Antenna response of a dipole antenna
ZHAireS simulations with 1ns binning
antenna @ cone
neutrino 5x10^{17} eV, zen=87° h=2800m

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

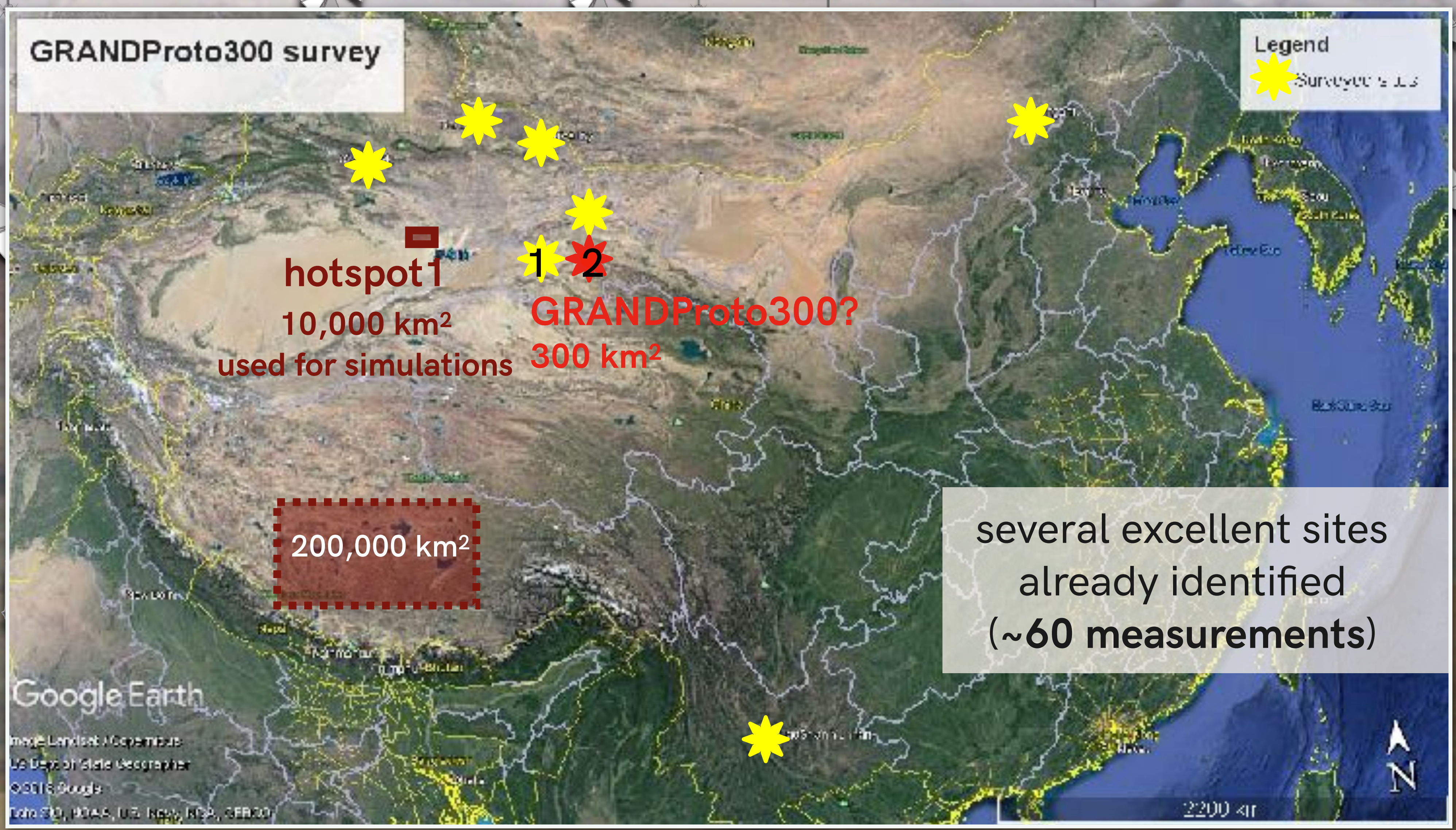
A. Balagopal (KIT)



The GRAND Concept

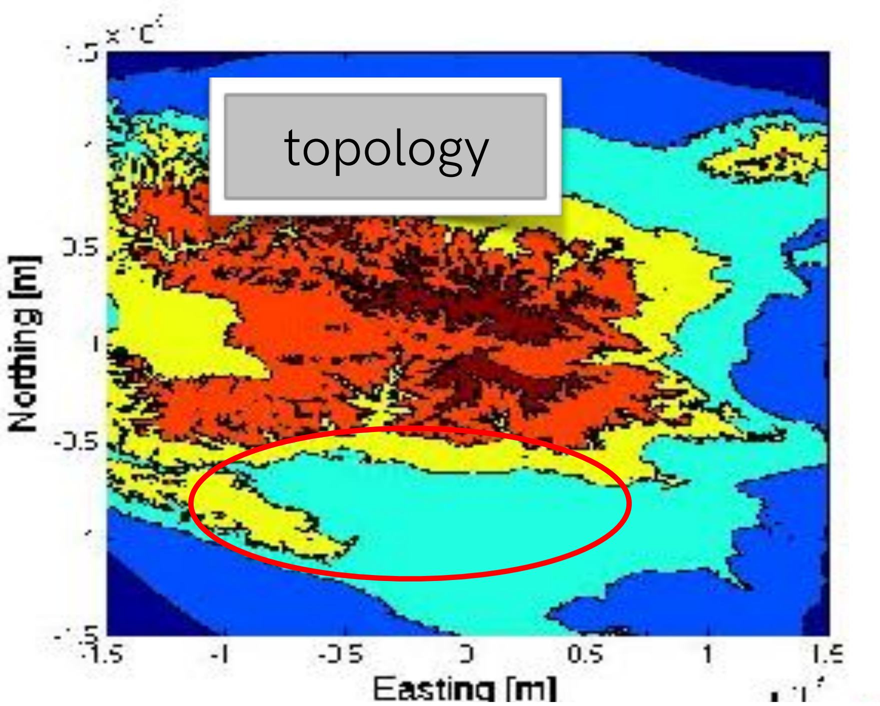
200,000 radio antennas over 200,000 km²
~20 hotspots of 10k antennas
in favorable locations in China & around the world

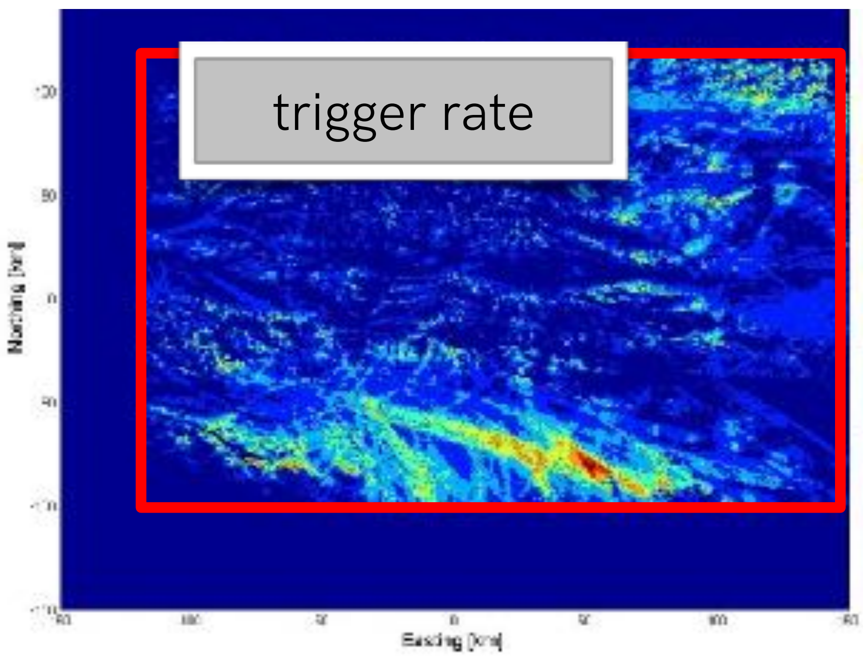
- ✓ Radio environment: radio quiet
- ✓ Physical environment: mountains
- ✓ Access
- ✓ Installation and Maintenance
- ✓ Other issues (e.g., political)



several excellent sites already identified (**~60 measurements**)

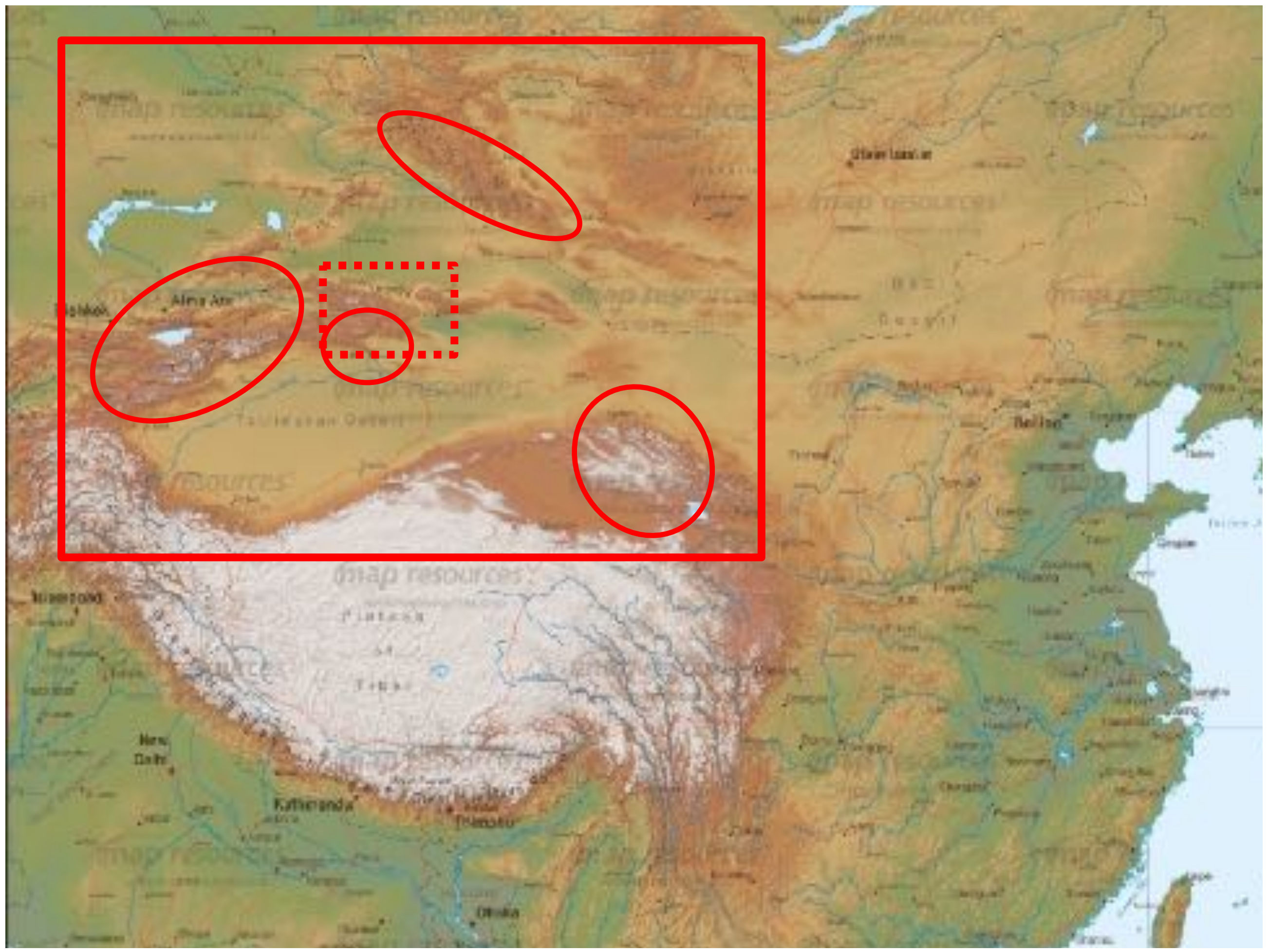
Deployment in hotspots



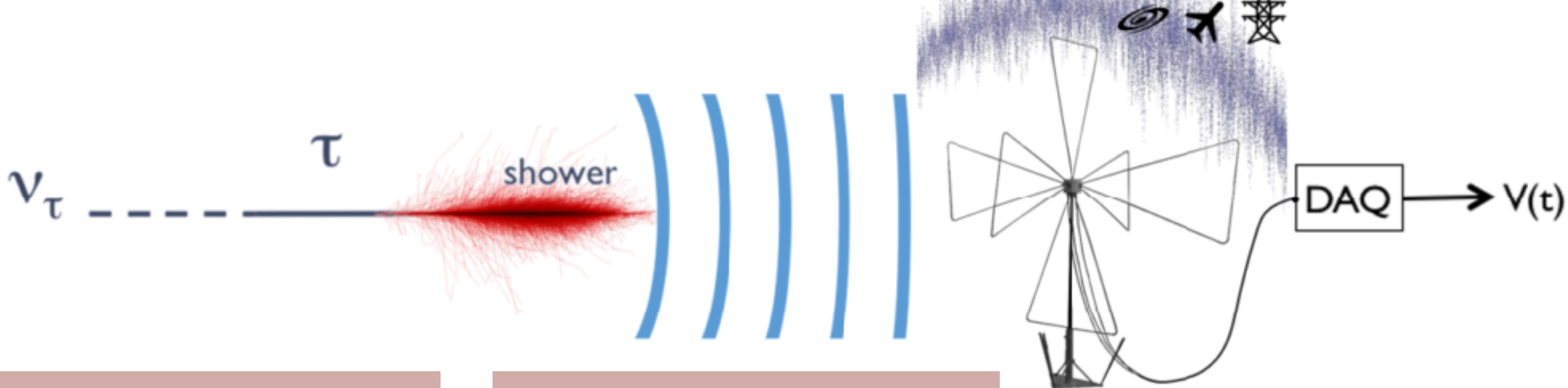


Hotspot with favorable topology
⇒ enhanced detection rate!

- 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**

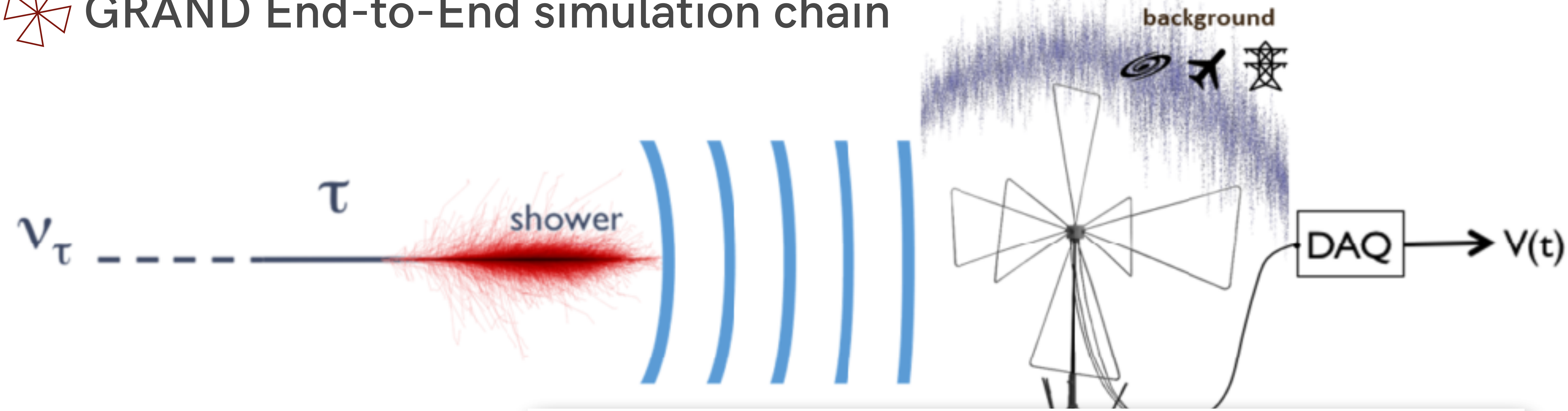
W. Carvalho, K. Kotera, K. de Vries, O. Martineau, M. Tueros, ***A. Zilles***
(IAP, Paris)

- 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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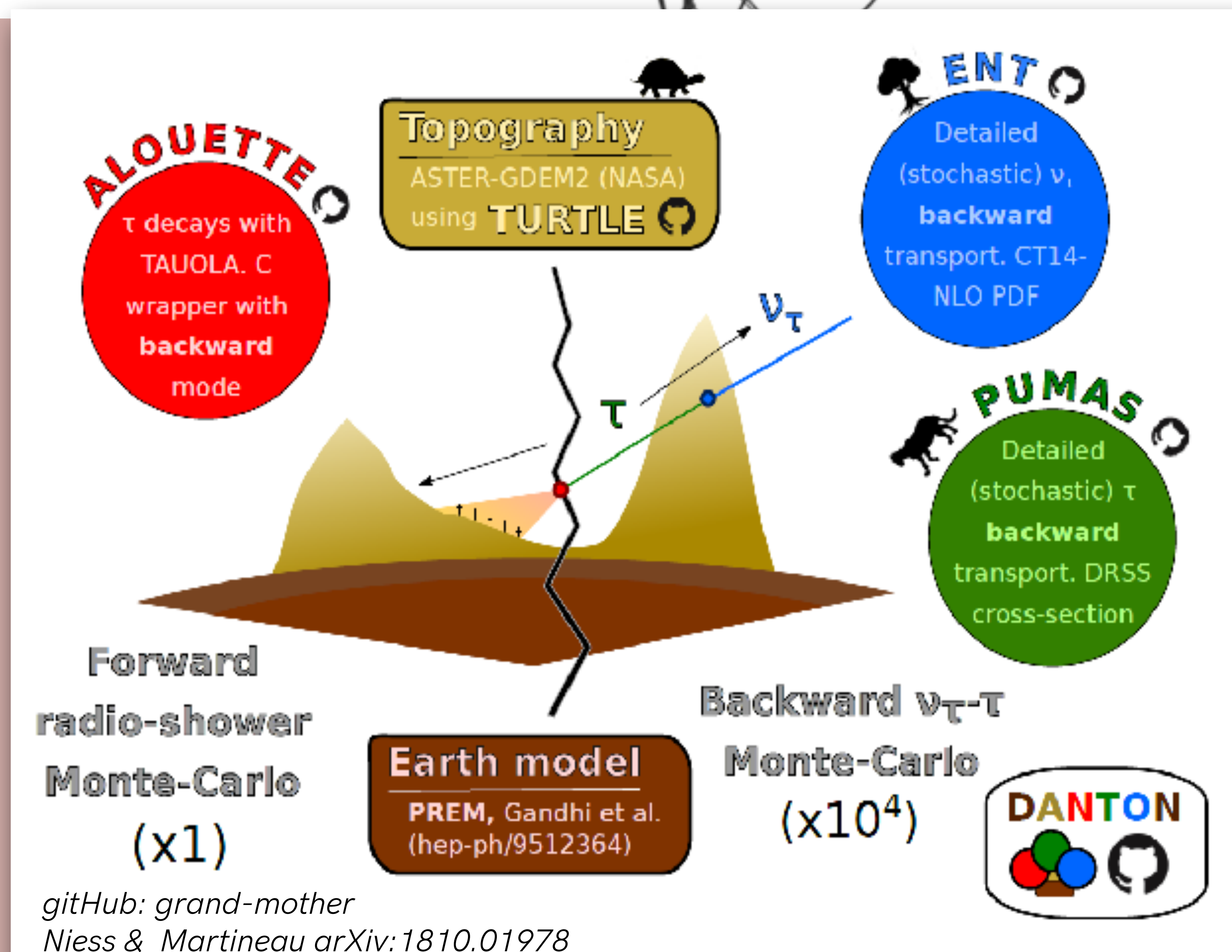
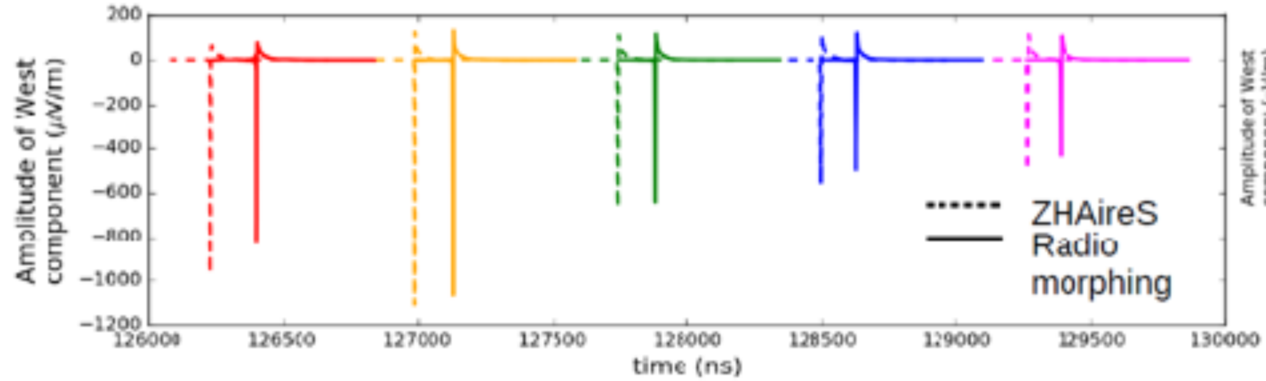


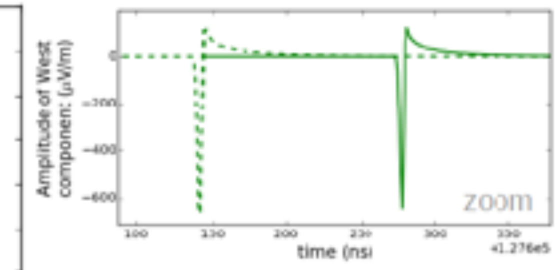
GRAND End-to-En

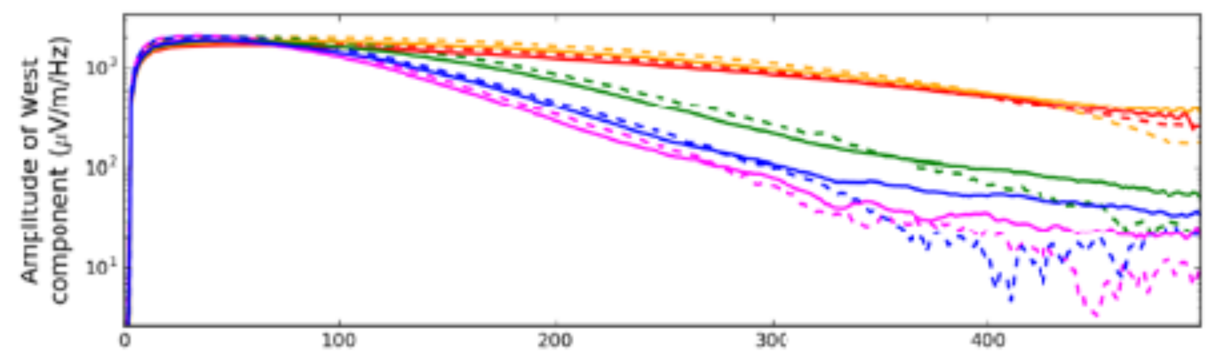
- Topography along track
- CC & NC ν_τ interactions
- τ energy losses

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!**

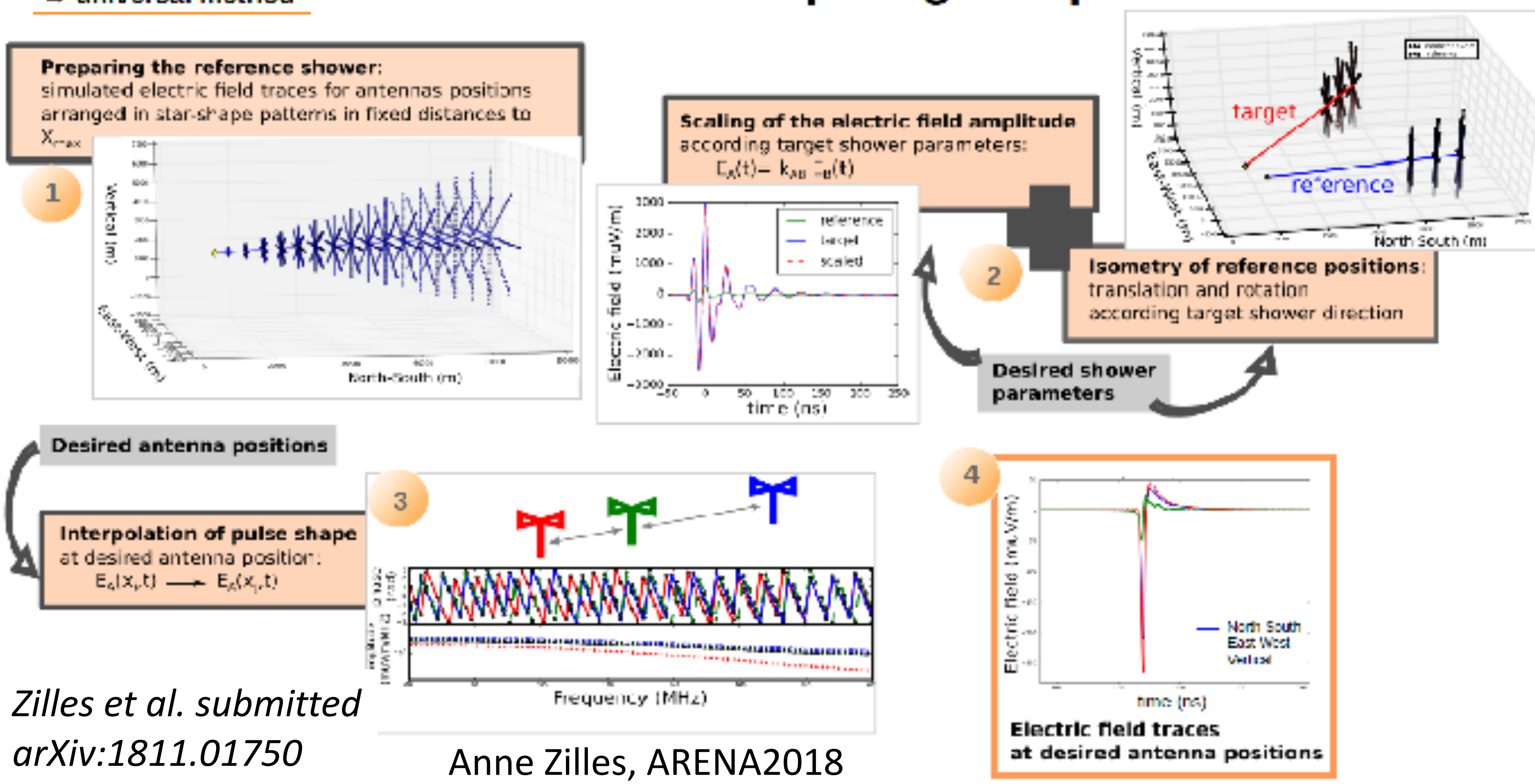
Zilles et al. submitted to Astropart. Phys.

Anne Zilles, ARENA2018

14

The Radio Morphing recipe

Not GRAND specific!
→ universal method



Zilles et al. submitted
arXiv:1811.01750

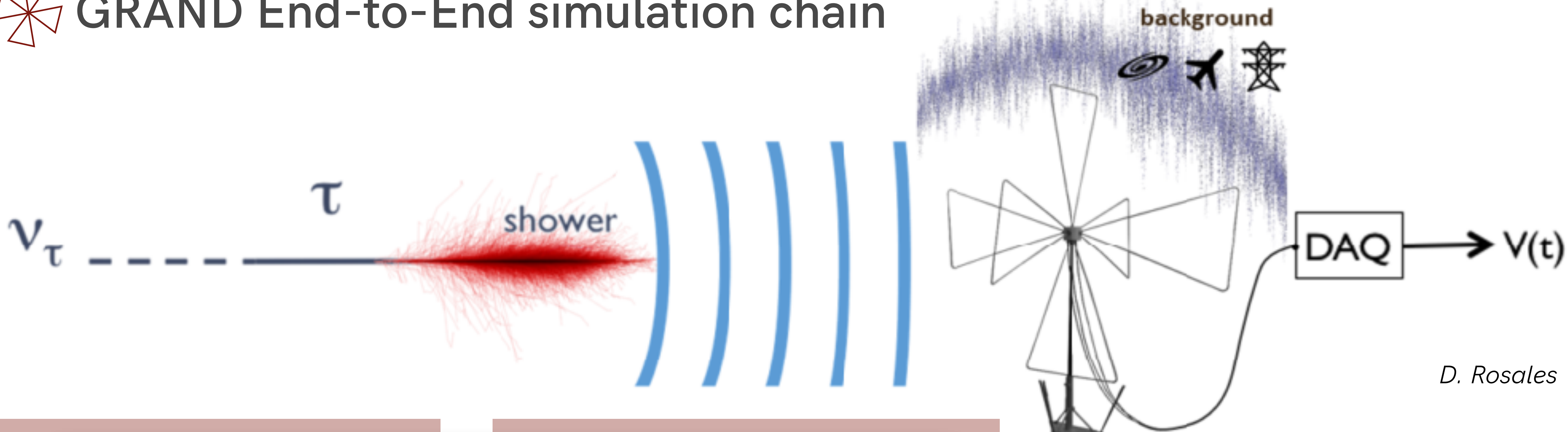
Anne Zilles, ARENA2018

(background noise sim)

→ NEC

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

GRAND End-to-End simulation chain



D. Rosales

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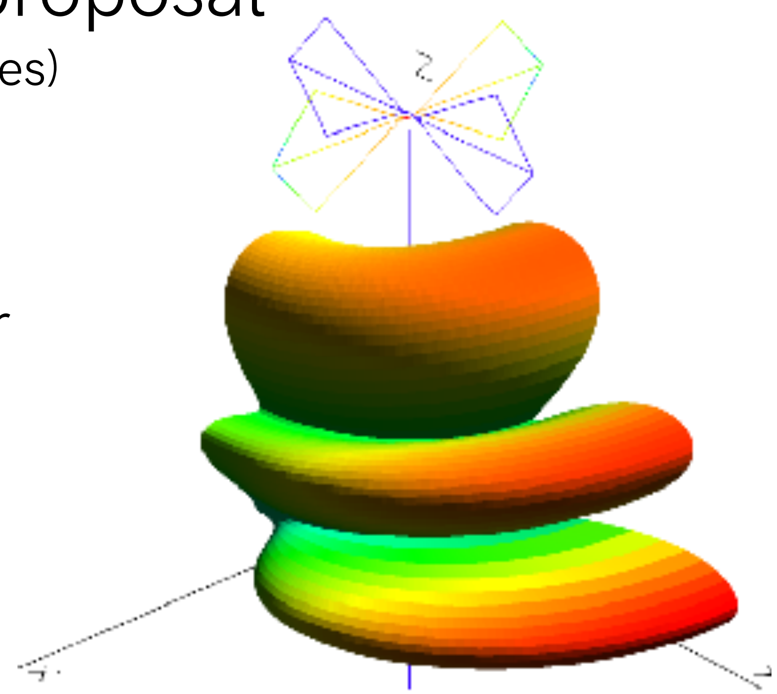
HorizonAntenna proposal

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

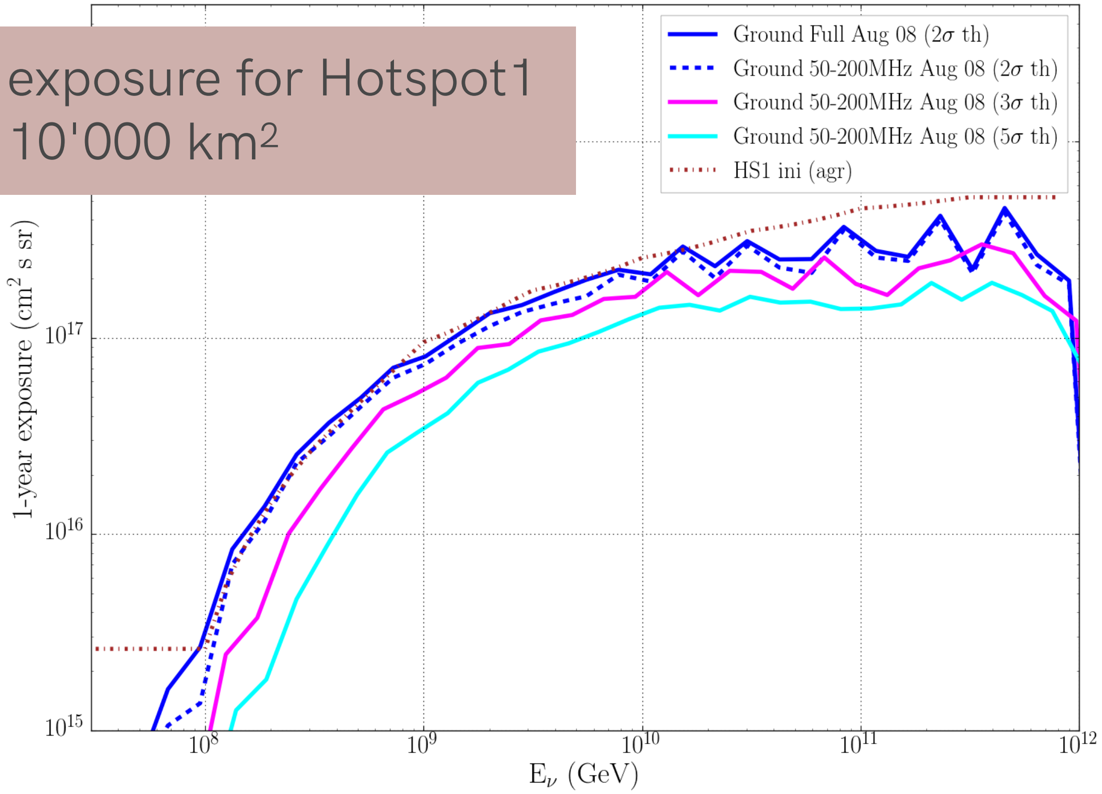
- Antenna response
- Antenna trigger
  (background noise sim)

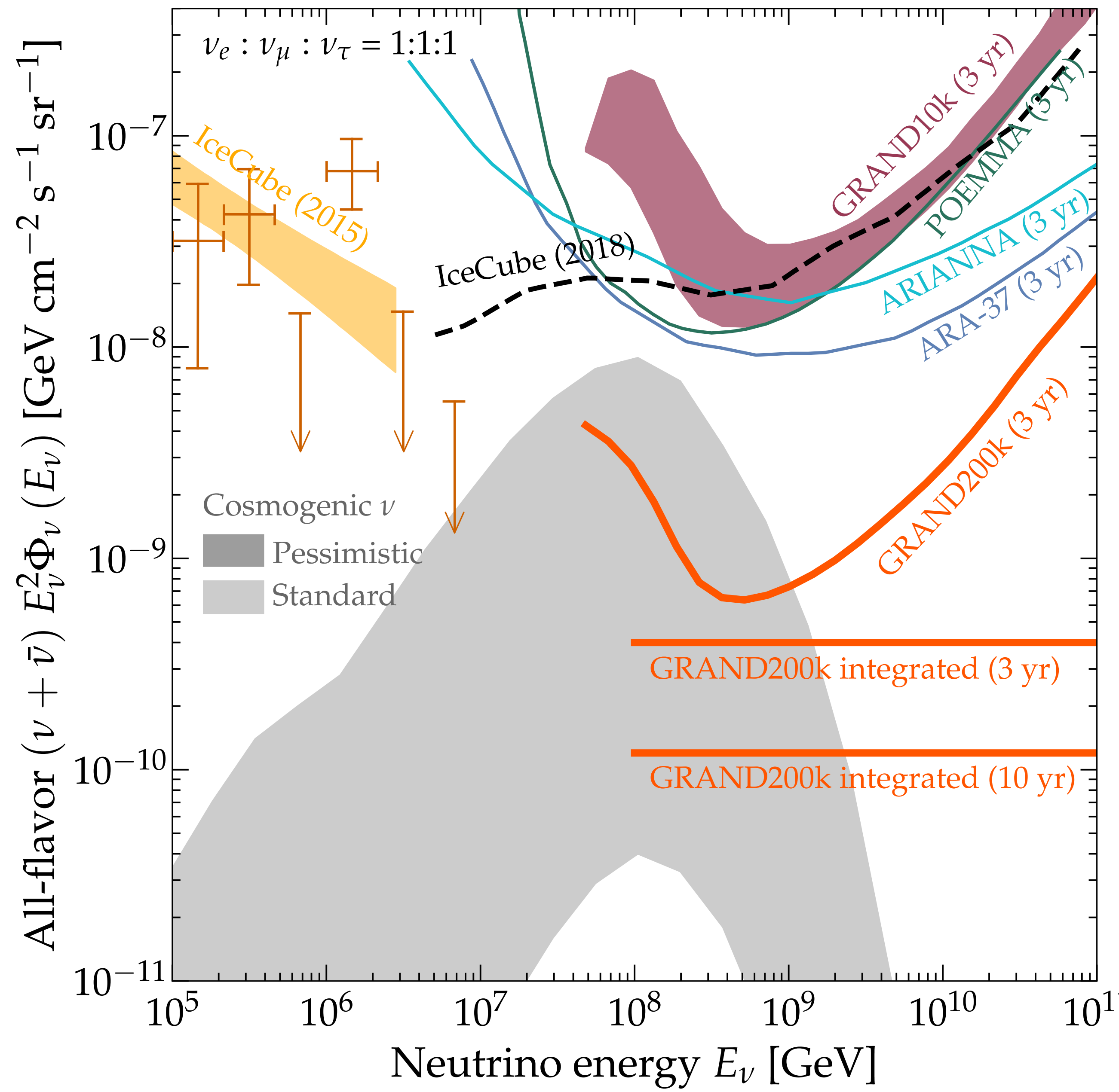
➔ **NEC**

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

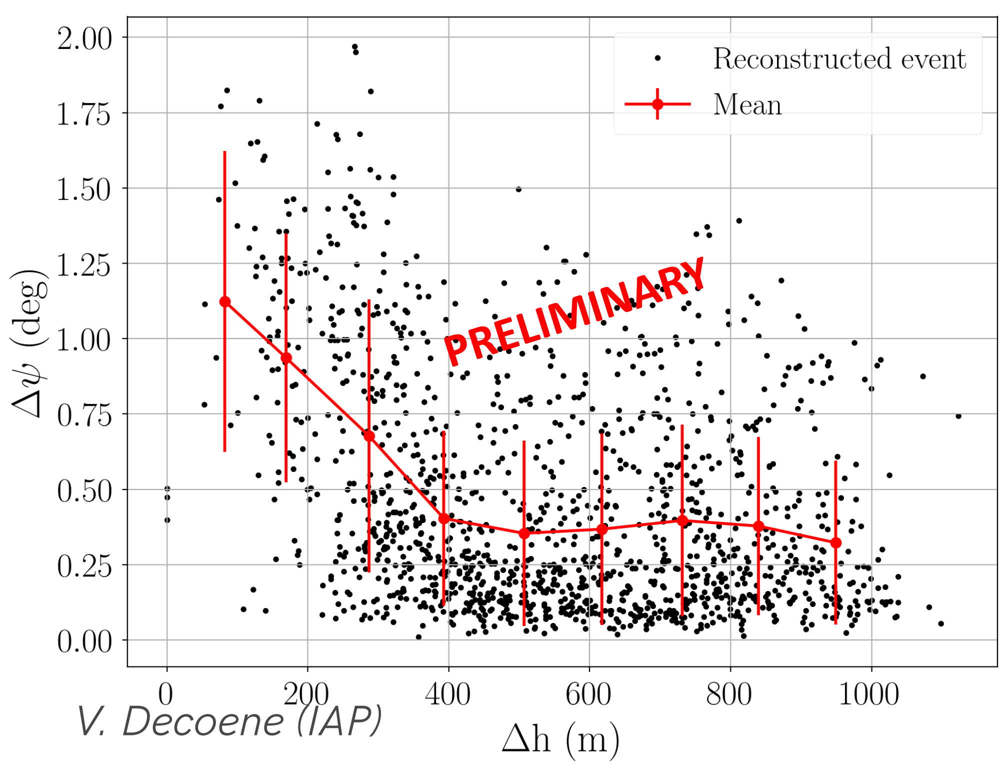
Simulated performances

exposure for Hotspot1
10'000 km²





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



V. Decoene (IAP)

<ψ>< **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/cm² achievable for $E>10^{19}$ eV
with GP300 & further stages

A. Zilles, C. Guépin (IAP)

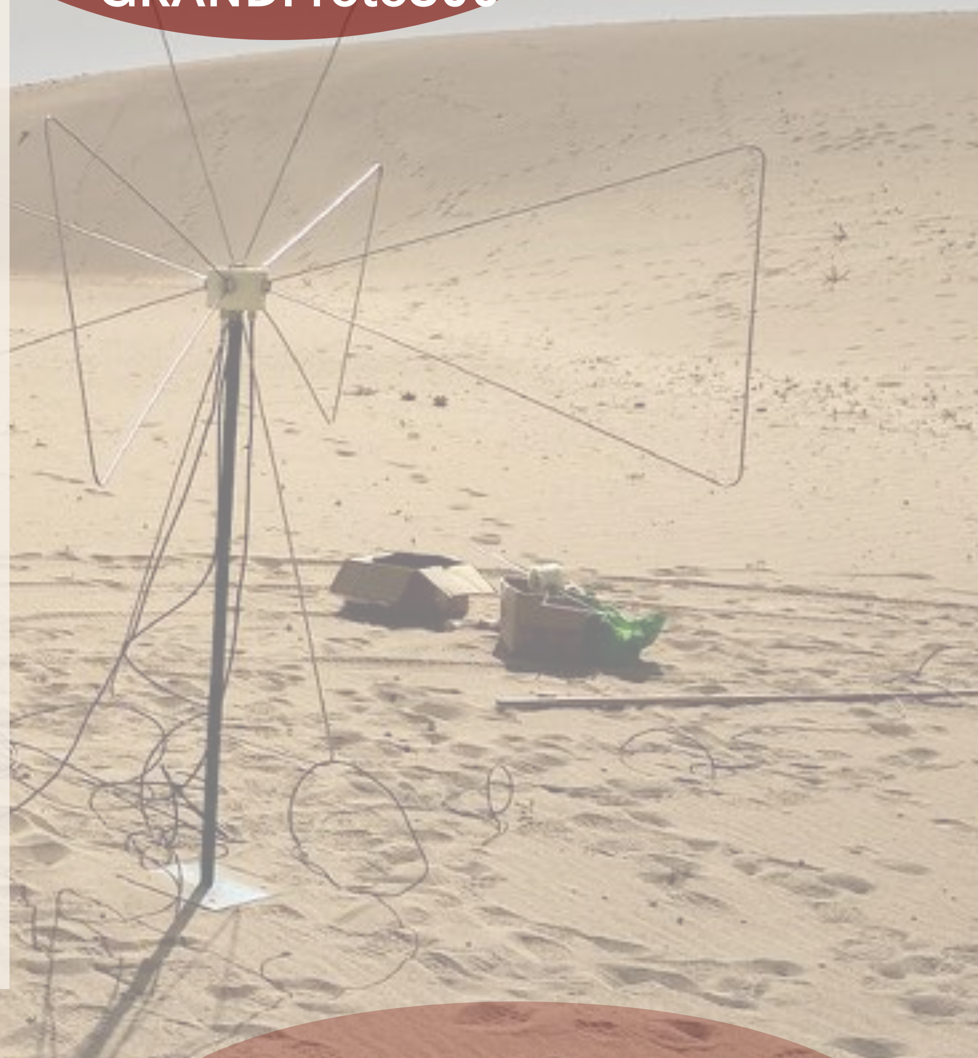
GRAND Technical Challenges

- 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 200,000km^2?
- 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 (2018)	2020	GRAND10k (2025)	GRAND200k (203X)
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 km² • Fast DAQ (AERA+ GRANDproto35 analog stage) • Solar panels + WiFi data transfer • Ground array (a la HAWC/Auger)	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	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
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

GRANDProto300: a self-standing pathfinder

- **Autonomous** detection of **very inclined cosmic rays** $E = 10^{16.5}$-10^{18} eV
  reconstructing spectrum, arrival direction & composition
  ➔ validation via comparison to known results
  ➔ test bench for further GRAND stages

- **Beautiful physics instrument** if complemented by **array of particle detector**
  Galactic/extragalactic transition
  hadronic physics (muon content in EAS)
  UHE gamma-rays
  Giant Radio Pulses from Crab pulsar
  Fast Radio Bursts

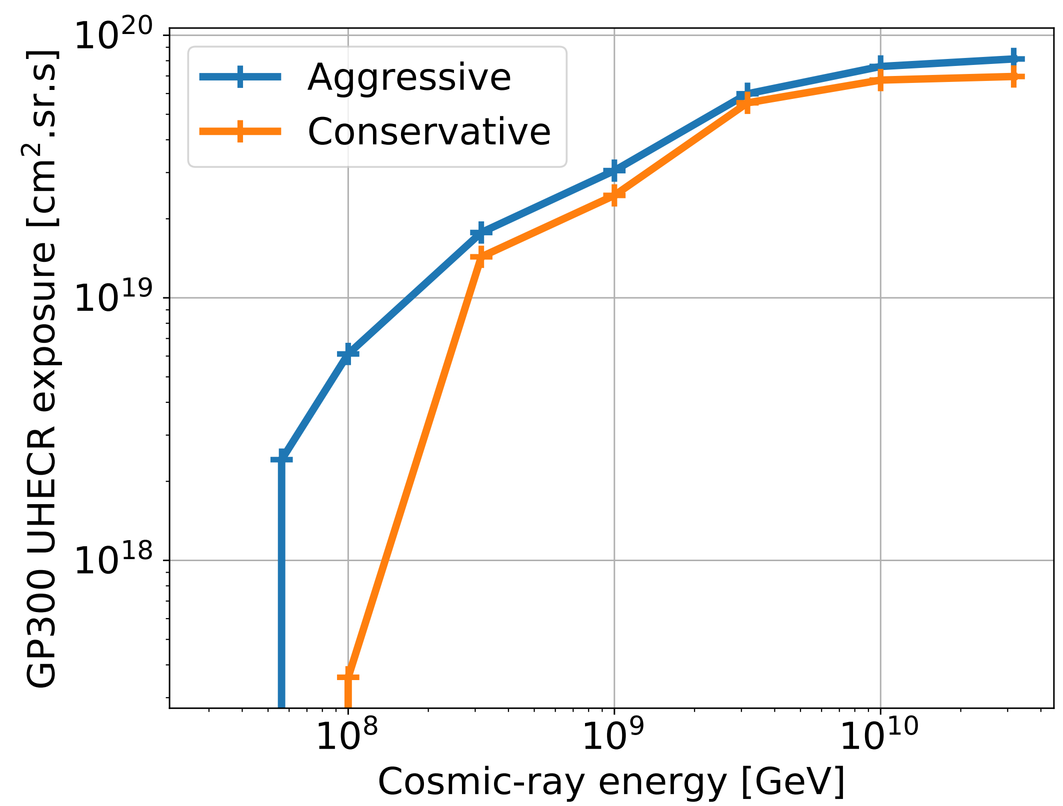
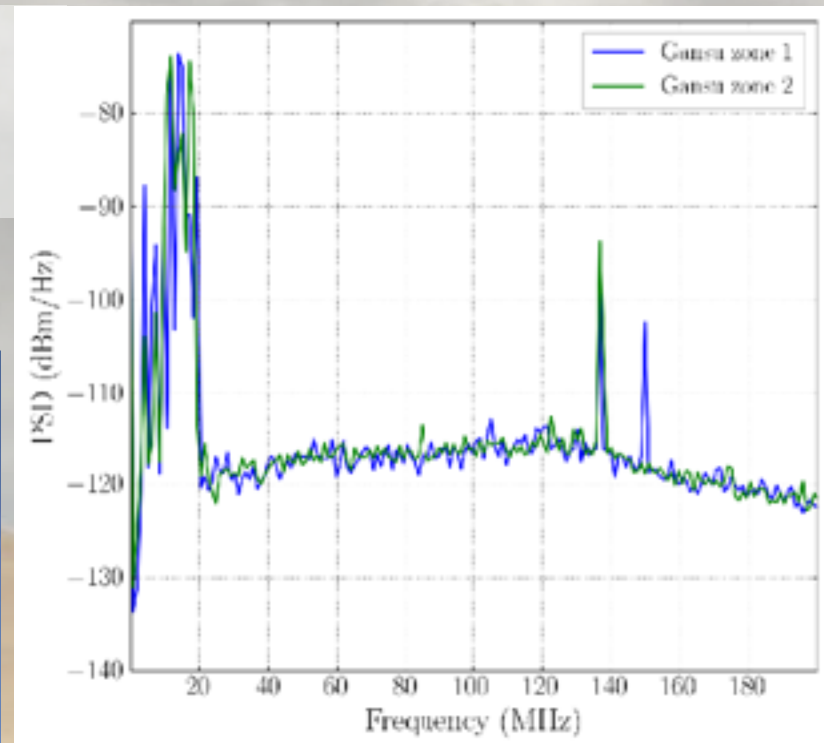


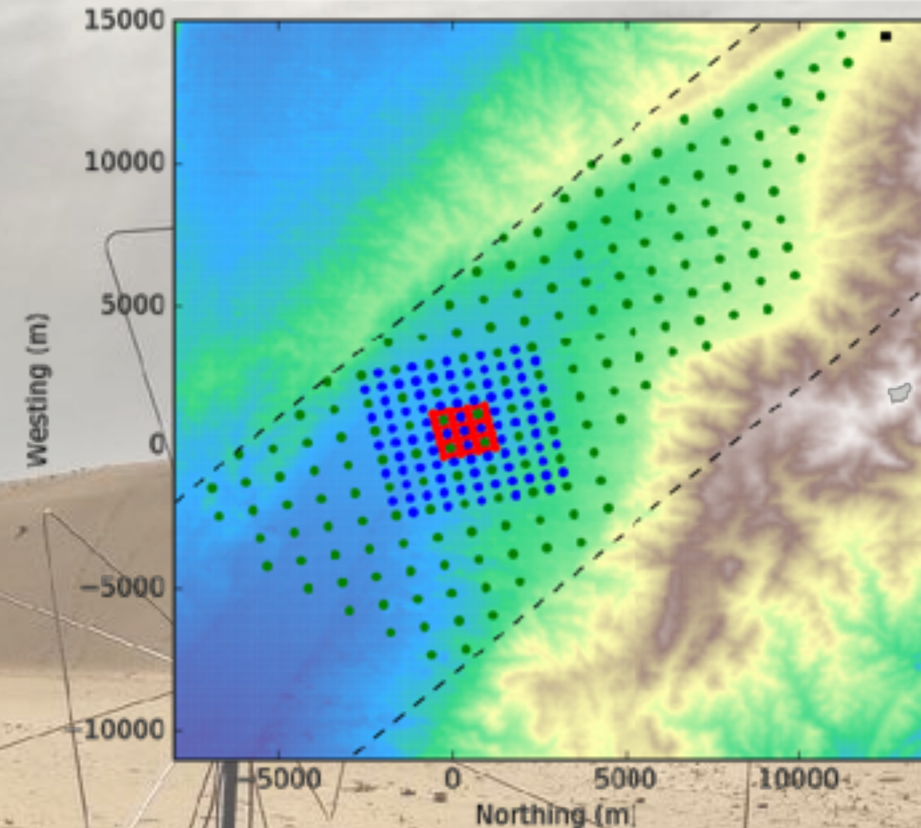
FIG. 34. Simulated 1-year UHECR exposure for the GRAND-Proto300 array, assuming the layout in Fig. 32. The aggressive and conservative thresholds correspond to a minimum peak-to-peak amplitude of 30 and 75 μV, respectively, simultaneously measured in at least five units; see Section IV E 1. Event rates are, respectively, $1.2 \cdot 10^6$ and $2.5 \cdot 10^6$ events per year.

GRANDProto300: a self-standing pathfinder

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

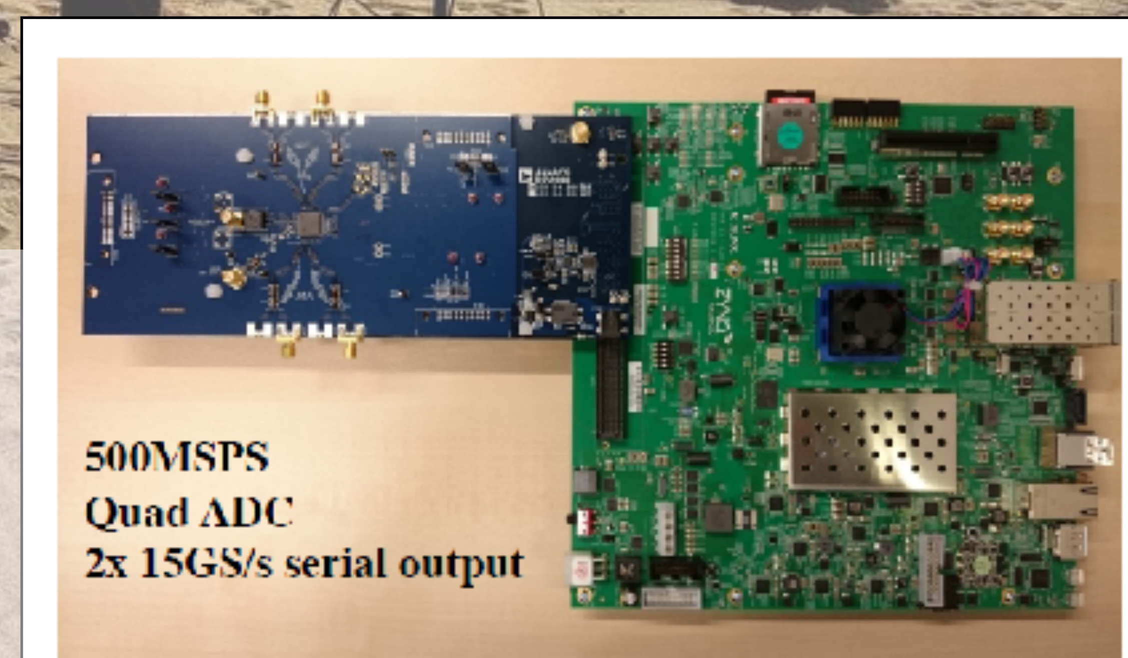
Site: 9 sites surveyed in China, 7 with excellent electromagnetic conditions



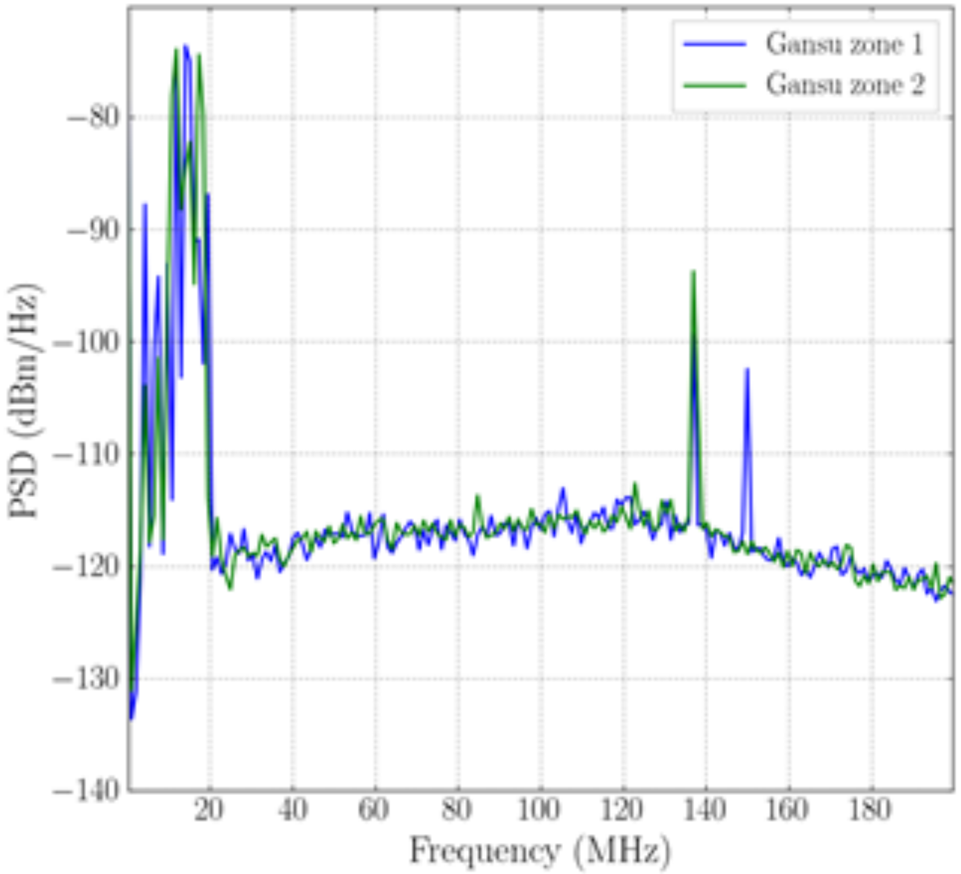


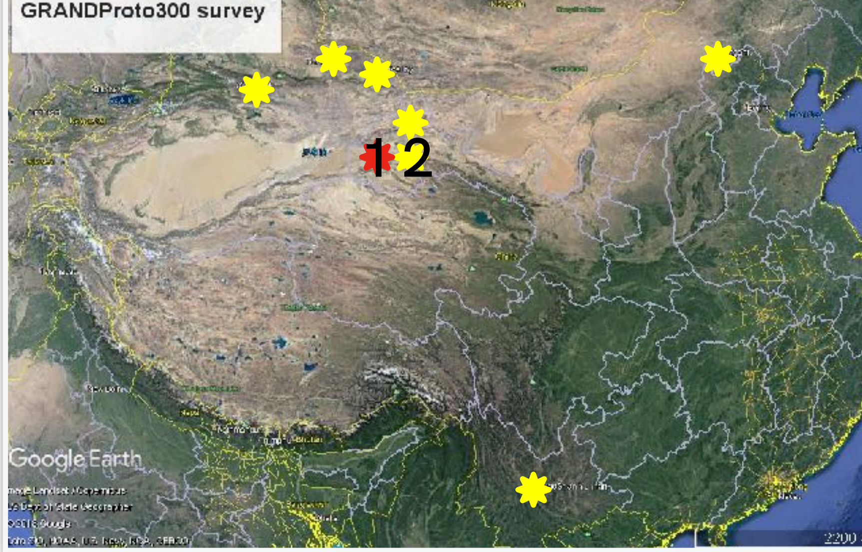
HorizonAntenna, successfully tested in the field (August, December 2018)

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



Radio environment measurements in China

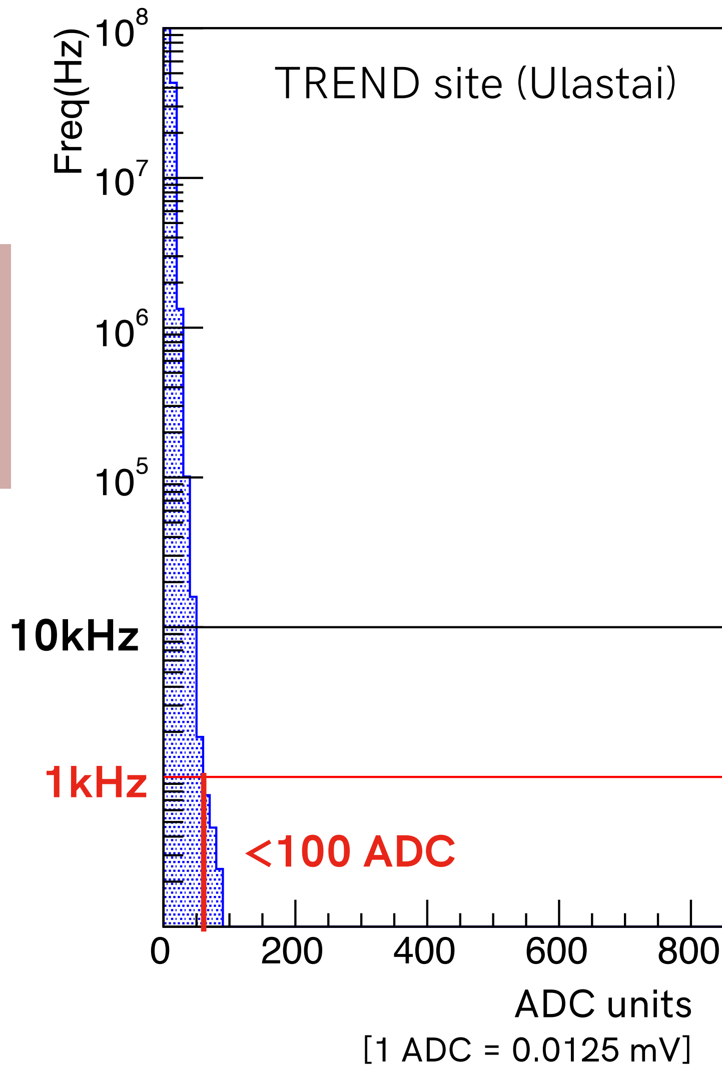




Transient measurements 50-200MHz:

- 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

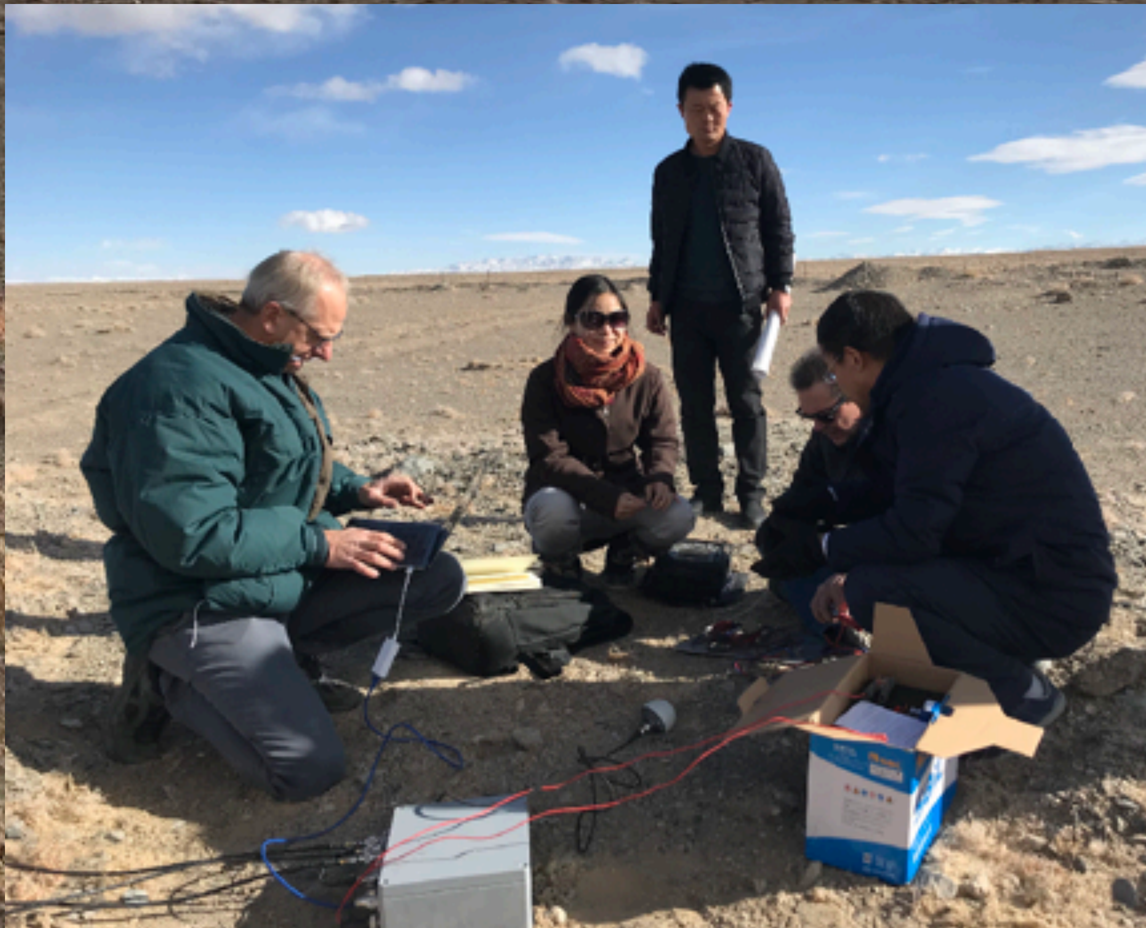


- ~50 measurements in 50-200 MHz range (April 2017-August 2018)
- **10/12 tested sites are very good candidates for 10k-antenna hotspots**
- deployment of several antennas next spring in Gansu Province

- How to deal with the huge transient event rate ⇔ self-triggering?
  - ➔ Surveyed sites: stationary noise within factor 2 of (irreductible) Galactic radiation and <1kHz antenna transient rate in 30-80MHz
  - ➔ Include this constraint in **DAQ design** (**100% livetime up to 1kHz transient rate**)
  - ➔ machine learning techniques (*Führer et al. arXiv:1809.01934*)

GRANDProto300 test bench

Local authorities in China supporting GRANDProto300



GRAND Today

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

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,*], Sandra Le Coz[25], Jean-Philippe Lenain[5], Guoliang Lü[26], Olivier Martineau-Huynh[5,25,*], Miguel Mostafá[27,28,29], Fabrice Mottez[30], Kohta Murase[27,28,29], Valentin Niess[31], Foteini Oikonomou[32,27,28,29], Tanguy Pierog[17], Xiangli Qian[33], Bo Qin[25], Duan Ran[25], Nicolas Renault-Tinacci[13], Markus Roth[17], Frank G. Schröder[34,17], Fabian Schüssler[35], Cyril Tasse[36], Charles Timmermans[14,15], Matías Tueros[37], Xiangping Wu[38,25,*], Philippe Zarka[39], Andreas Zech[30], B. Theodore Zhang[40,41], Jianli Zhang[25], Yi Zhang[24], Qian Zheng[42,24], Anne Zilles[13]

~50 collaborators from 10 countries

France (15), China (7), USA (6), Netherlands (2), Germany (2), Copenhagen (2), Spain (2), Brazil (2), Belgium, Argentina, Sweden

GRAND Workshop, IAP, August 2018

electronics: Nikhef/Radboud U.
antenna design: Subatech (design), Electronics University of XiAn (production)
simulations: IAP, VUB
particle detectors: Penn State U.
computing resources: KIT

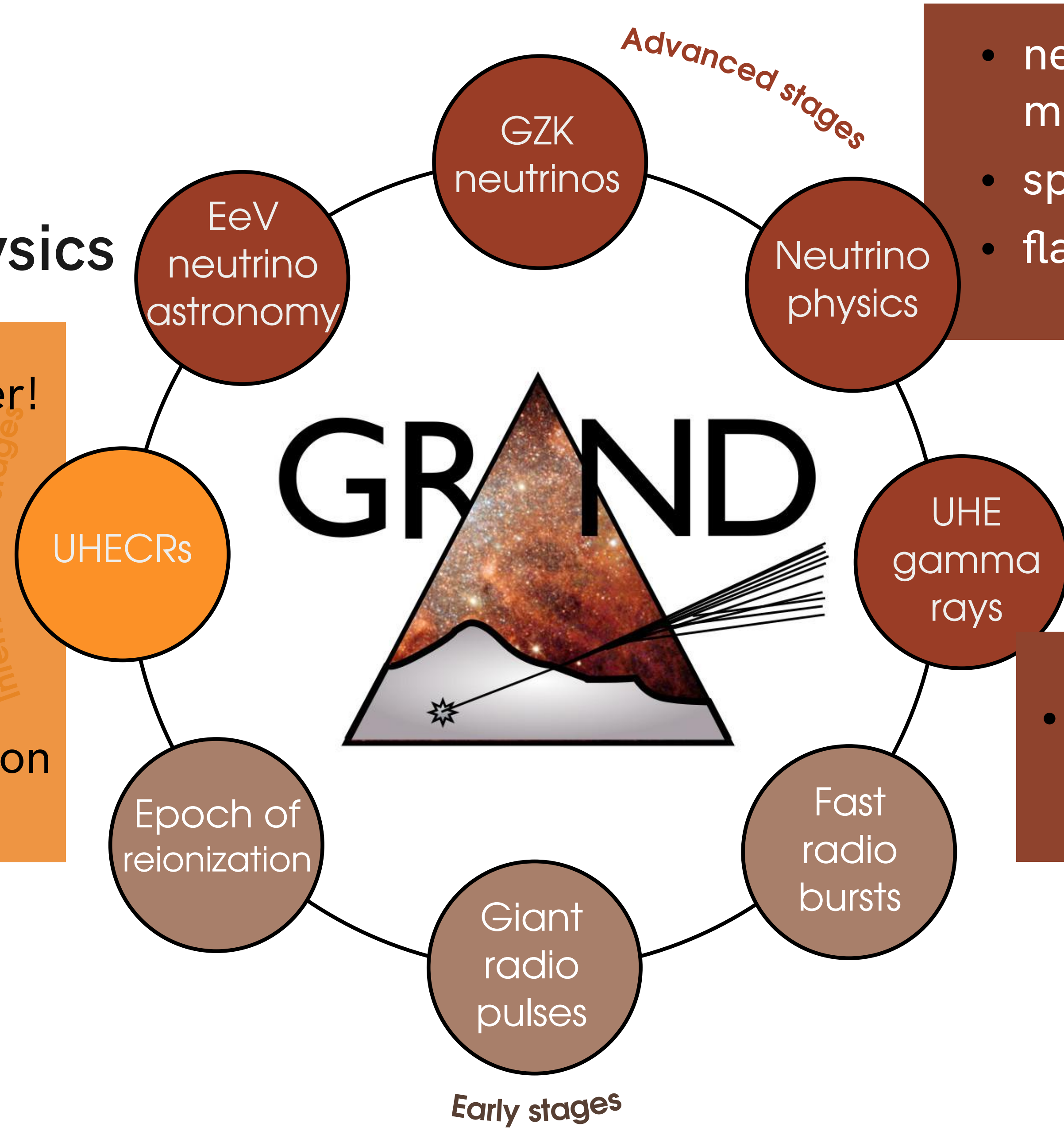
A rich science case

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

3/ 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/