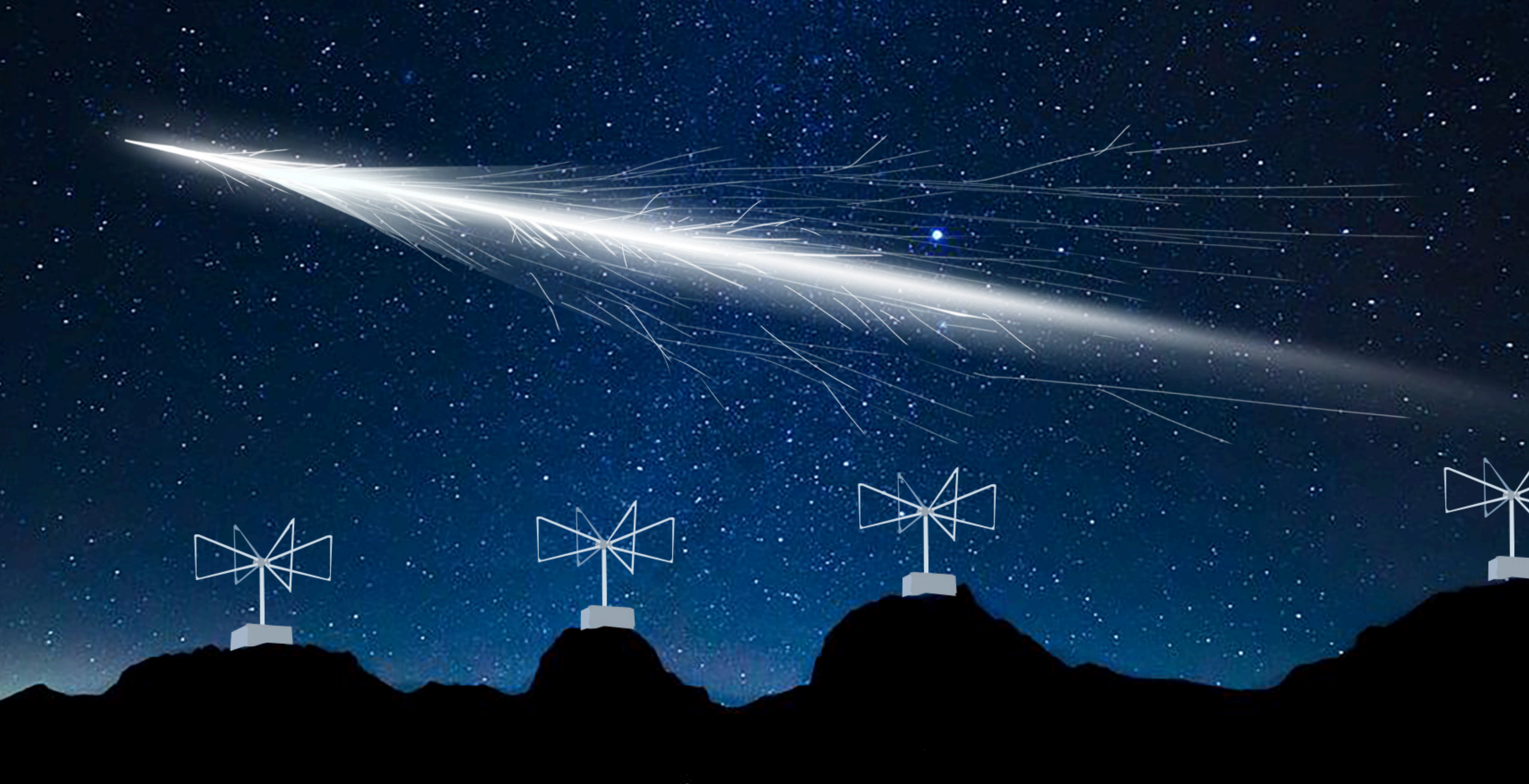
Looking for ultra-high-energy astroparticles in a radio haystack with GRAND

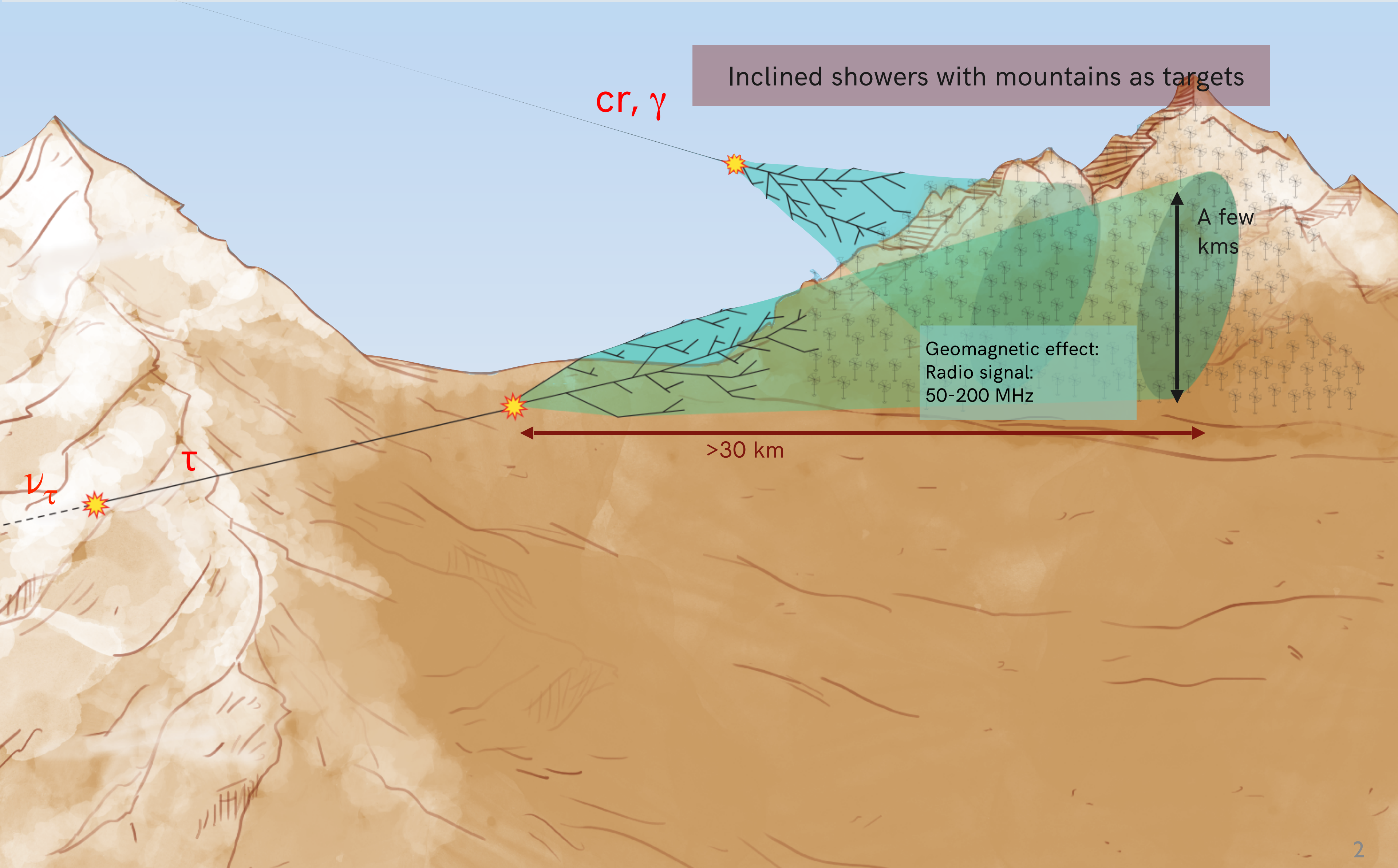


Simon Chiche

iihe BRUXELLES BRUSSEL

The Giant Radio Array for Neutrino Detection

GRAND: Giant radio array of 200 000 radio antennas over 200 000 km^2



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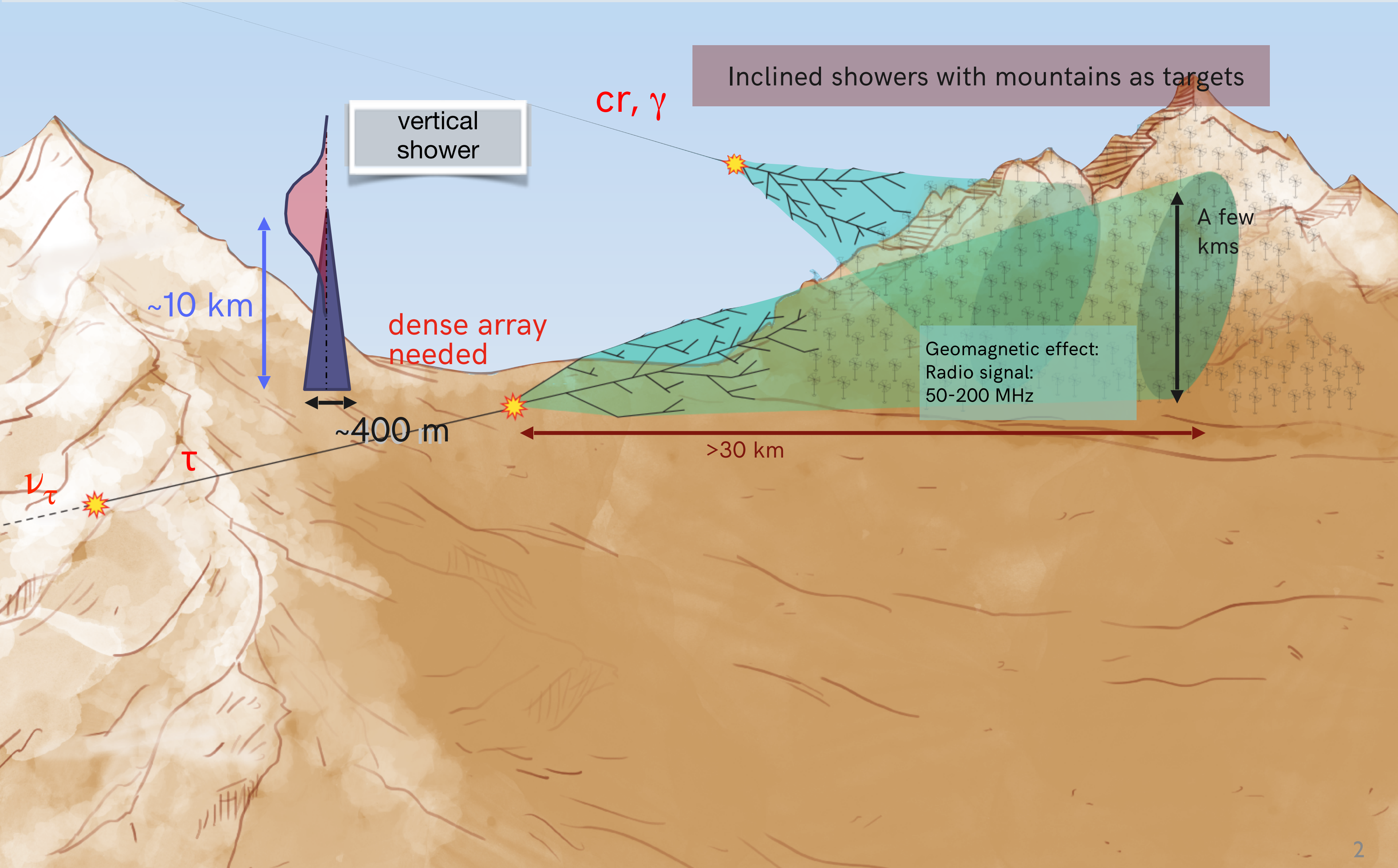

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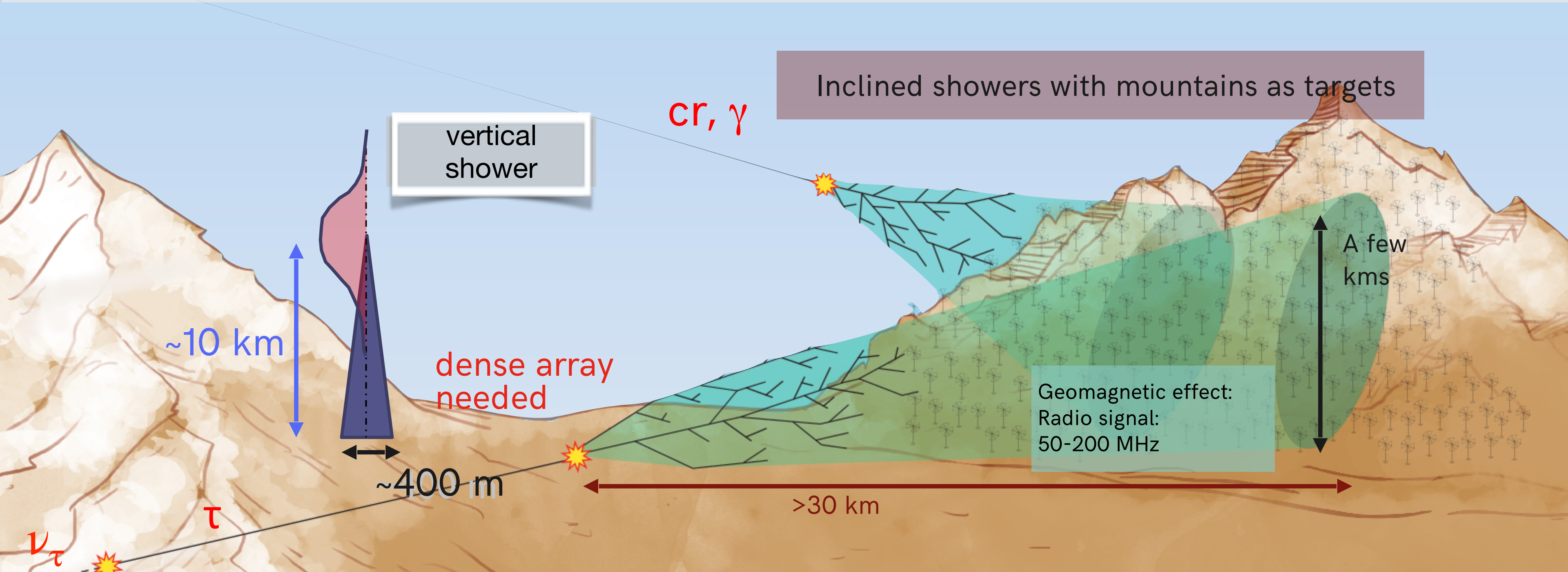


GRANDProto300	GRAND10k	GRAND200k
2024	2028	203X
• Prototype of 300 antennas over 200km² • Cosmic-ray detection: $E_{\mathrm{range}} = 10^{16.5} - 10^{18}\,\mathrm{eV}$	• 10,000 radio antennas over 10,000 km² • discovery of EeV neutrinos for optimistic fluxes	• 200,000 antennas over 200,000 km² • 1st EeV neutrino detection and/or neutrino astronomy!

Prototyping phase

GRAND @ Nançay

4 antennas
(Nançay, France)
Autumn 2022

Test bench for triggering and hardware

GRAND @ Auger

10 antennas
(Malargüe, Argentina)
March 2023

Calibration by comparison with Auger data

GRANDProto300

13 antennas
(Xinjiang, China)
February 2023

- Seed of GRANDProto300
- Test of reconstruction methods

A rich science case

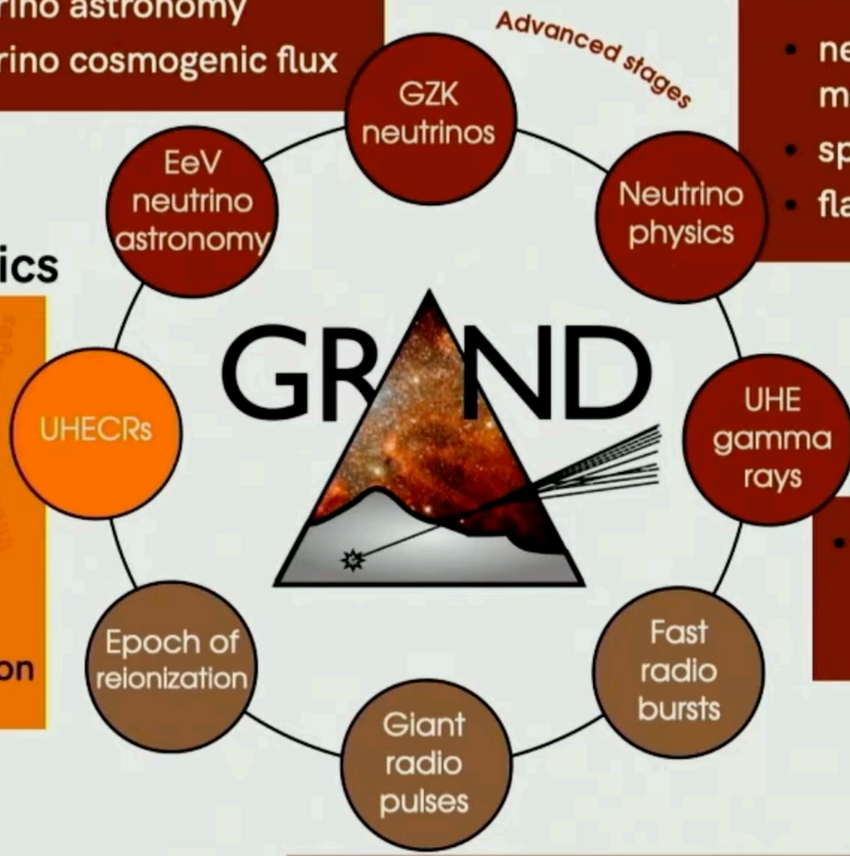
Aim: Detect the first EeV neutrinos and beginning of EeV multi-messenger astronomy

UHE neutrinos

- UHE neutrino astronomy
- UHE neutrino cosmogenic flux

neutrino physics

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



UHECR, hadronic physics

- 20-80 times the exposure of Auger!
- GRANDProto300: transition from Galactic/ extragalactic
- hadronic physics: muon discrepancy, UHECR mass composition, p-air cross-section

UHE gamma rays

- could be competitive with Auger at GRANDProto300 stage

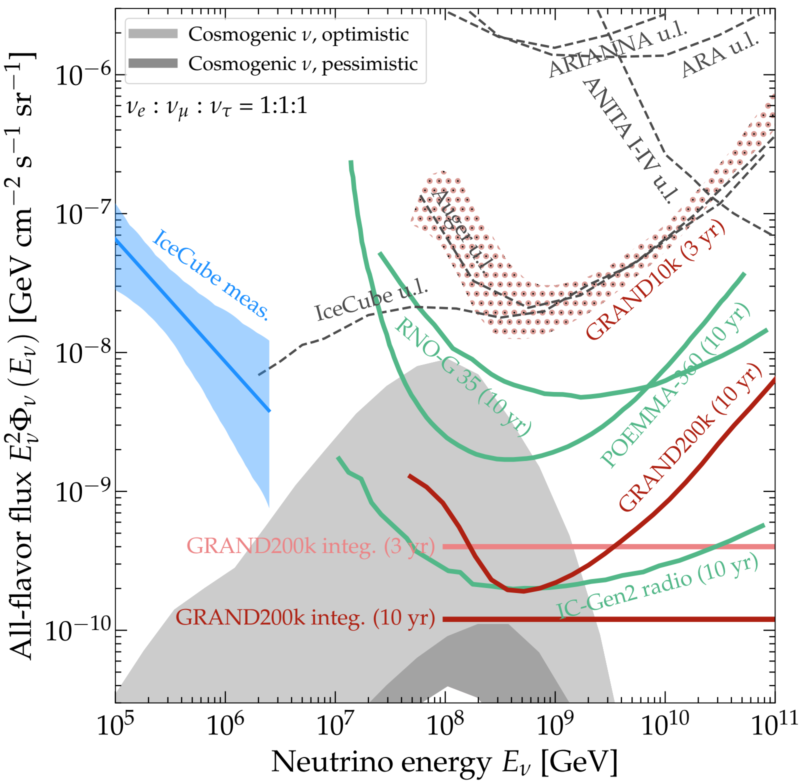
radio-astronomy in a novel way

Early stages

- 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

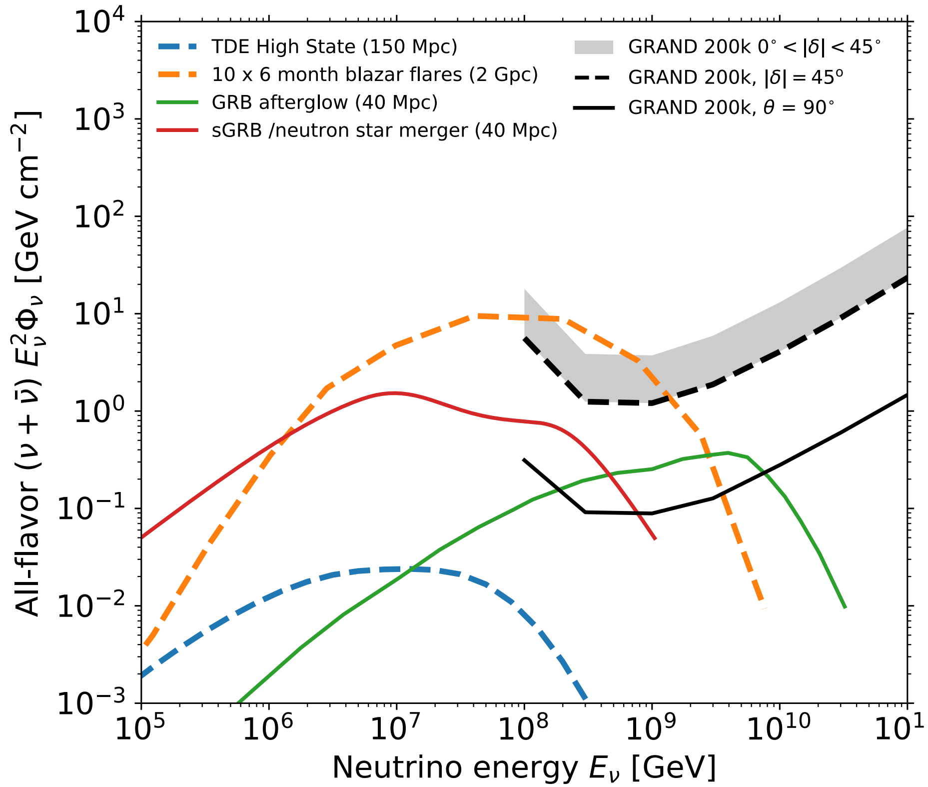
Ultra-high-energy neutrino sensitivity

Cosmogenic neutrinos



(Alvarez-Muniz 2020)

Neutrinos from transients

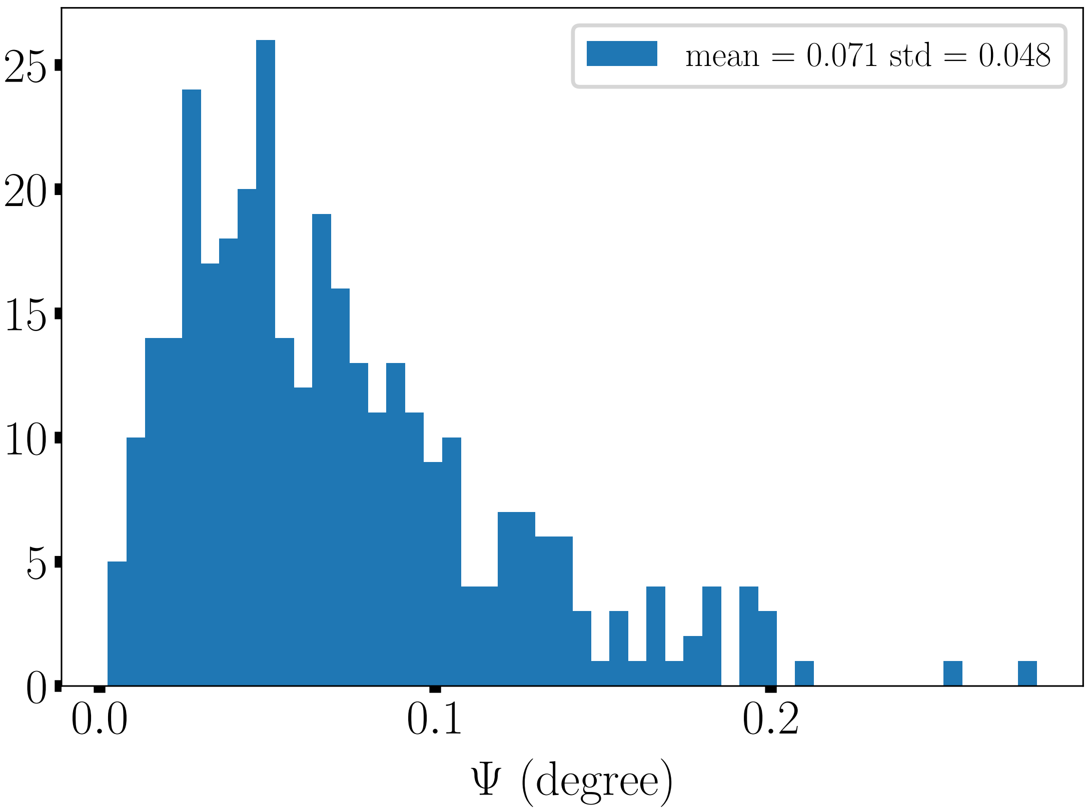


(Alvarez-Muniz 2020)

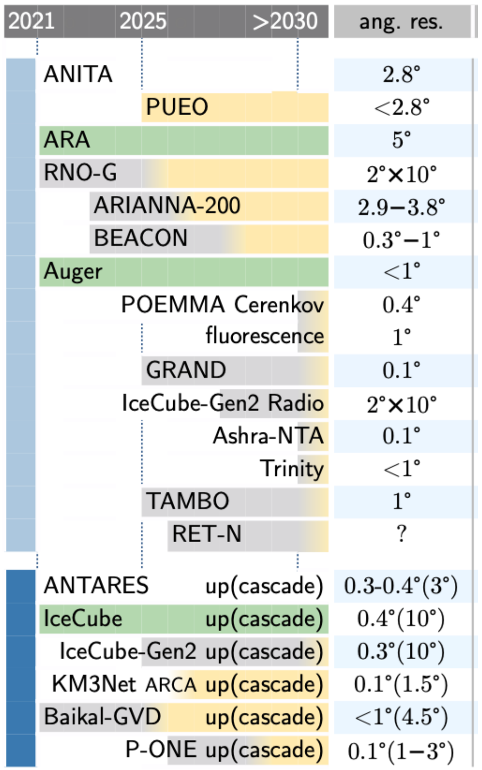
GRAND will be the most sensitive ultra-high-energy neutrino detector

GRAND will reach an angular resolution below 0.1°

(Decoene 2021)



(Guépin et al., 2022)



Will be decisive to identify the first ultra-high-energy neutrino point sources

GRAND and the challenges of radio-detection

- Find the radio signal in the noise

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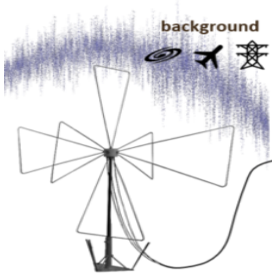
GRAND: Radio detection of astroparticles



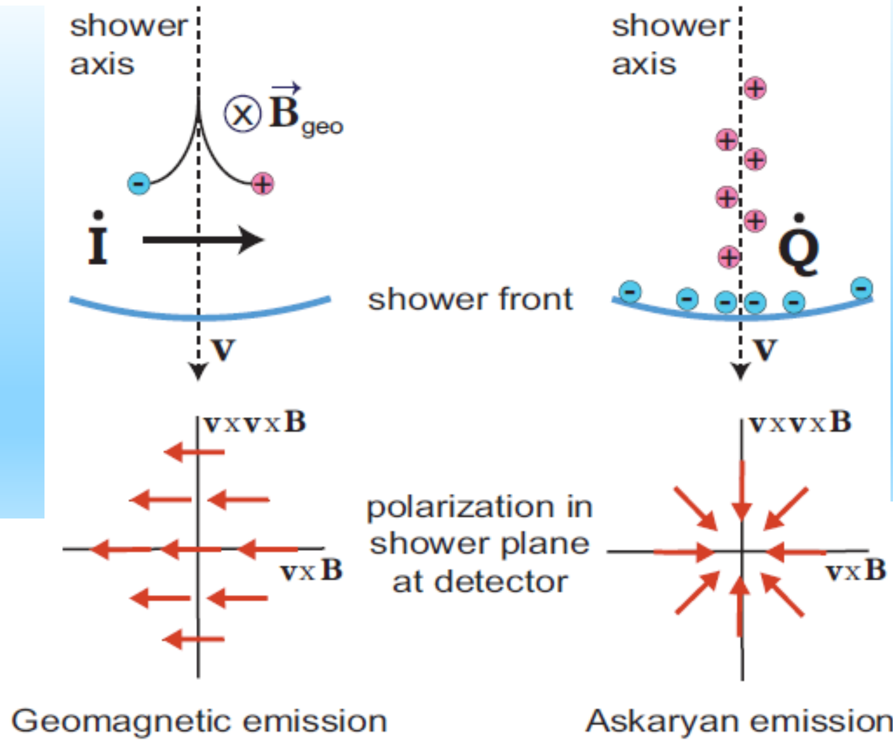
Overwhelming noise from human emissions

Radio signal from extensive air-showers - CLASSICAL picture

2 main sources for the radio emission

Geomagnetic emission

- Induced current with $\vec{\mathbf{B}}_{geo}$
- Polarisation along -$\boldsymbol{v} \times \boldsymbol{B}$
- Main contribution to the radio signal



Schröder (2017)

Charge excess emission

- Accumulation of negative charges close to the shower core
- Radial polarisation
- ≈ 10% of the amplitude of the total emission for vertical air showers

vertical air-showers: well known, mature and verified

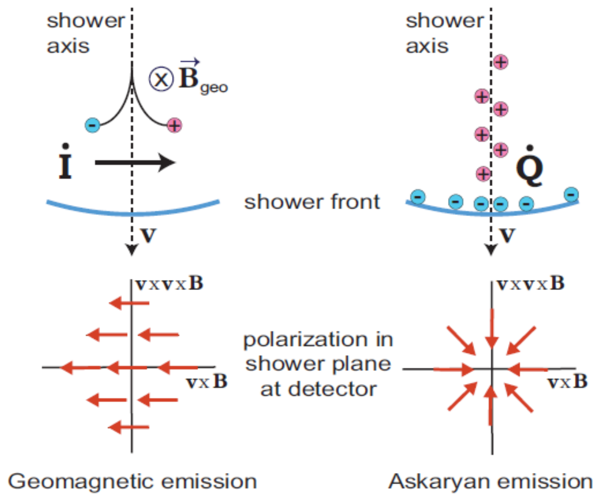
Inclined air showers: still several challenges, trending topic

(Schlüter et al. 2022, Chiche et al. 2022)

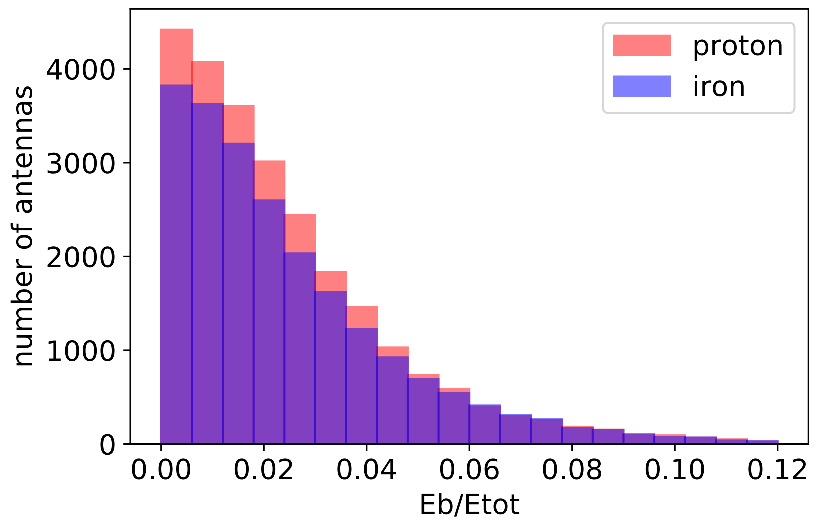
Identification principle with radio signal polarization

$E_b = E_{tot} \bullet u_B$: projection along the direction of the magnetic field

For each antenna we can compute E_b/E_{tot}



(SC, el al. (2022), accepted in Astroparticle Physics)



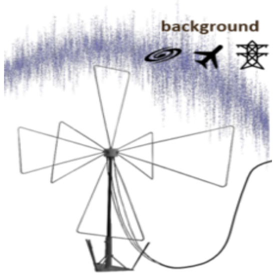
99% of antennas have E_b/E_{tot} <0.07 -> we can reject any signal with E_b/E_{tot} > 0.07

Allow to reject 93% of noise induced events at the DAQ level!

GRAND and the challenges of radio-detection

- Find the radio signal in the noise

GRAND: Radio detection of astroparticles



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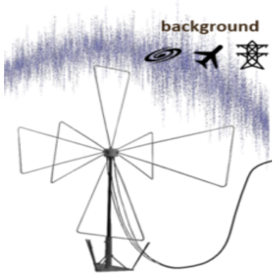

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Polarization

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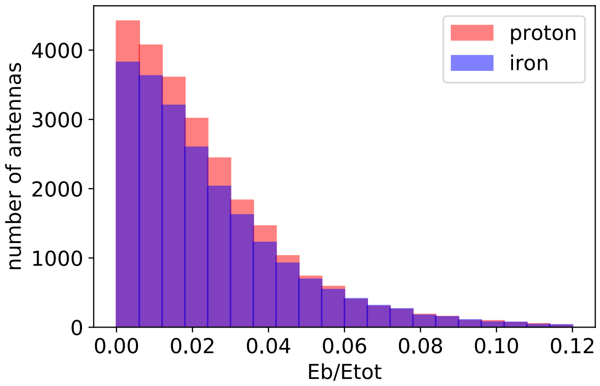

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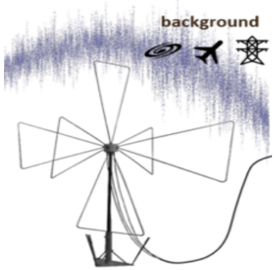

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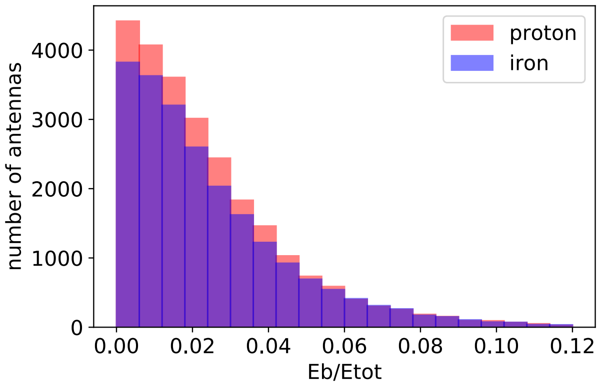

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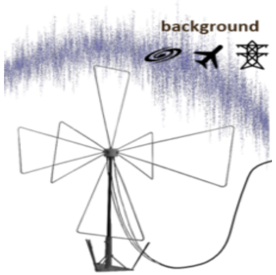

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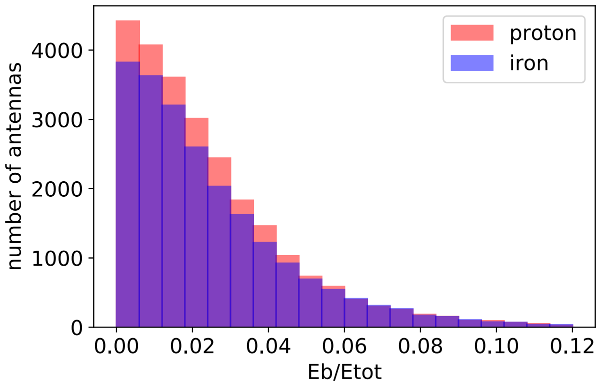

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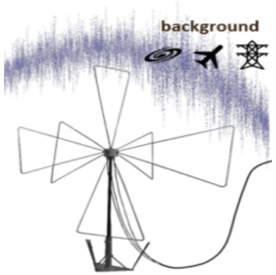

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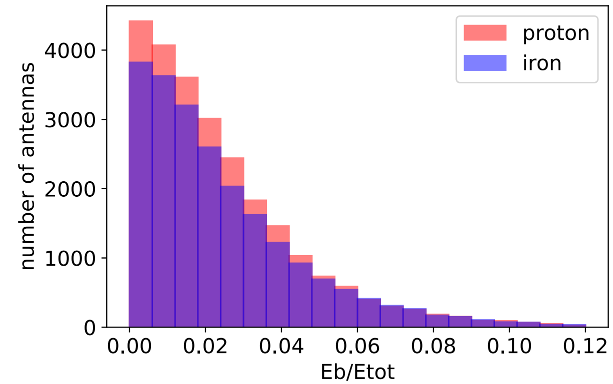

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Monte-Carlo simulations are computationally demanding

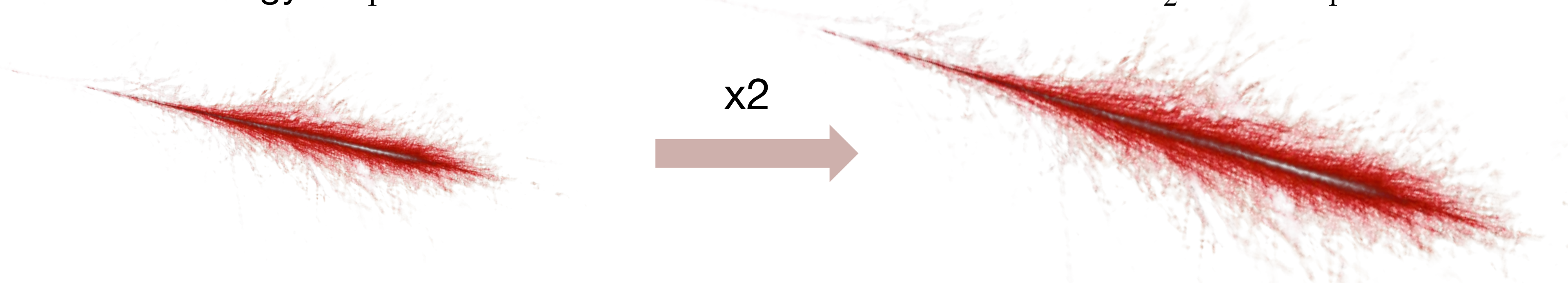
We need a fast and efficient simulation tool!

Simulating air shower radio signals: Radio Morphing

Idea: We can use one single Monte Carlo simulation as a reference shower to derive the electric field from any other shower

Energy: $\mathscr{E}_1$

$\mathscr{E}_2 = 2 \times \mathscr{E}_1$



before

MC simulation

shower 1 $(\mathscr{E}_1, \theta_1, \varphi_1)$

MC simulation

shower 2 $(\mathscr{E}_2, \theta_2, \varphi_2)$

computation time: $N \times t_{MC}$

now

MC simulation

Radio Morphing

shower 1 $(\mathscr{E}_1, \theta_1, \varphi_1)$

shower 2 $(\mathscr{E}_2, \theta_2, \varphi_2)$

shower 3 $(\mathscr{E}_3, \theta_3, \varphi_3)$

⋮

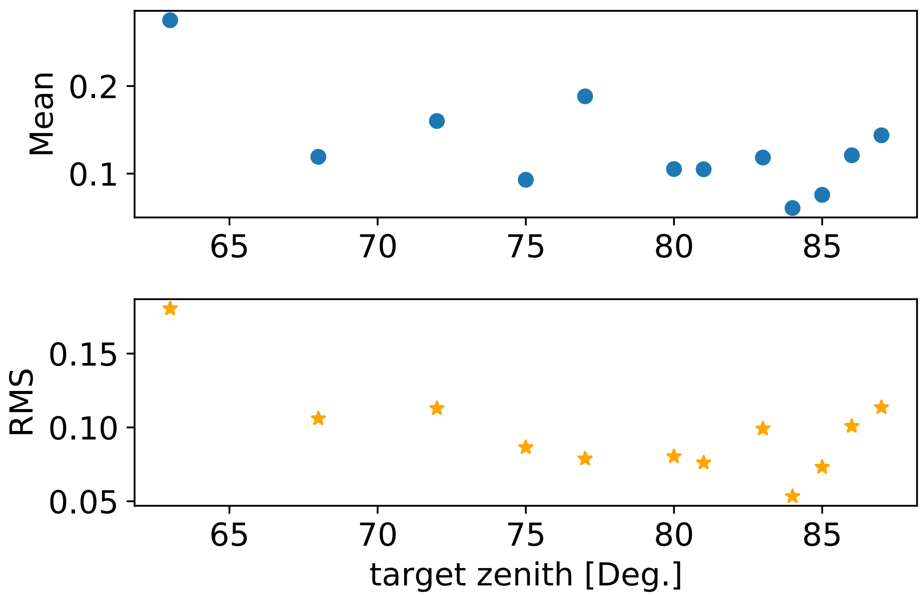
computation time: $t_{MC} + (N-1)t_{RM}$

Radio Morphing results

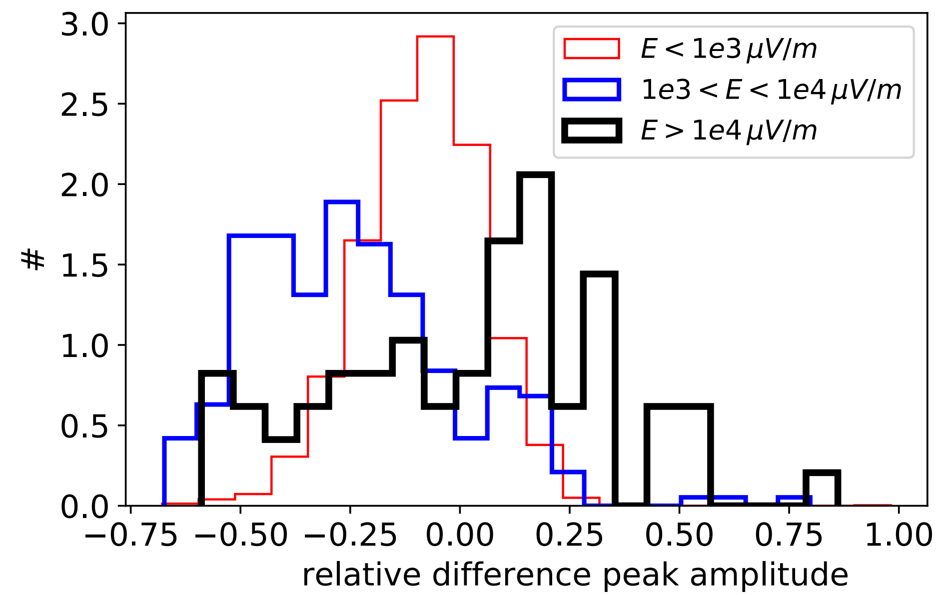
(SC, Kotera, Martineau, Tueros, De Vries, proceeding ICRC (2022) ; Chiche et al. in prep.)

Test of the Radio Morphing by comparison with Monte-Carlo simulations

Mean and RMS of relative differences with ZHAireS simulations on the peak amplitude



Distribution of errors on the peak amplitude at the antenna level



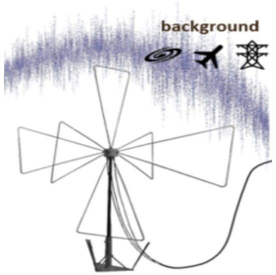
Mean relative differences on the peak amplitude between ≈10% to 20%

91% of antennas with relative differences < 10%

GRAND and the challenges of radio-detection

- ## Find the radio signal in the noise

GRAND: Radio detection of astroparticles



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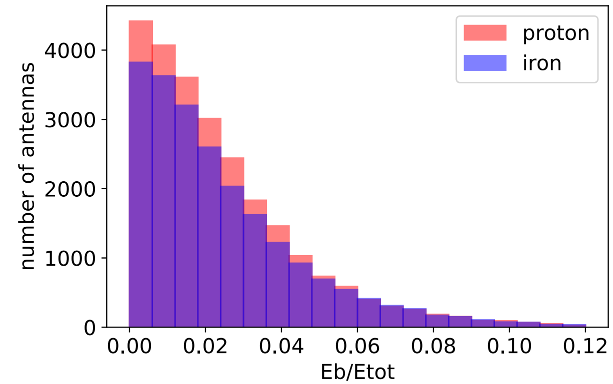

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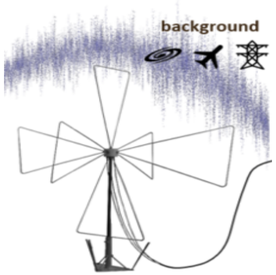

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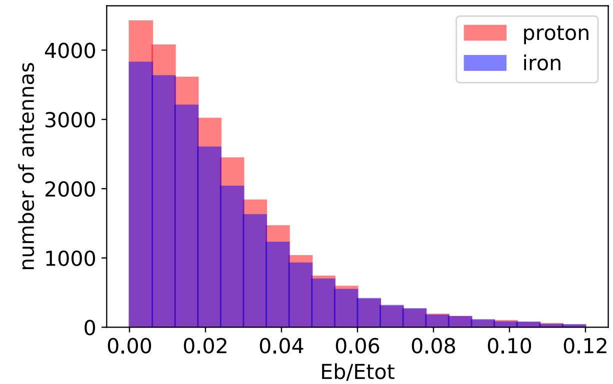

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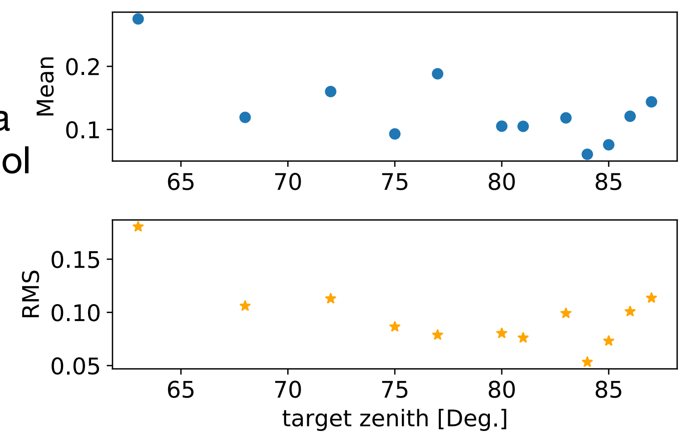

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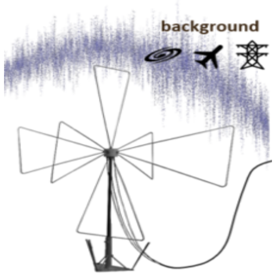

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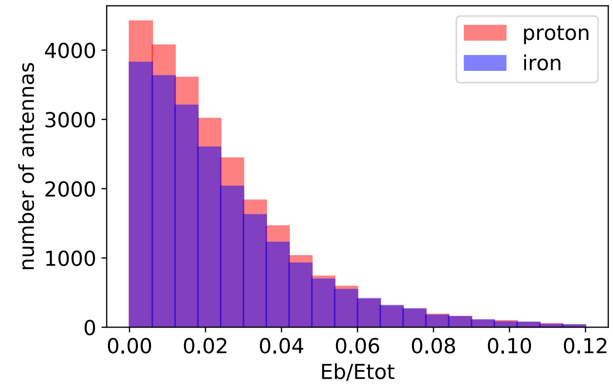

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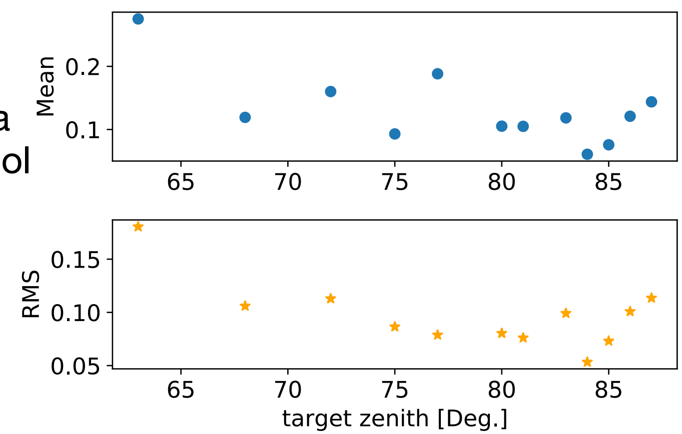
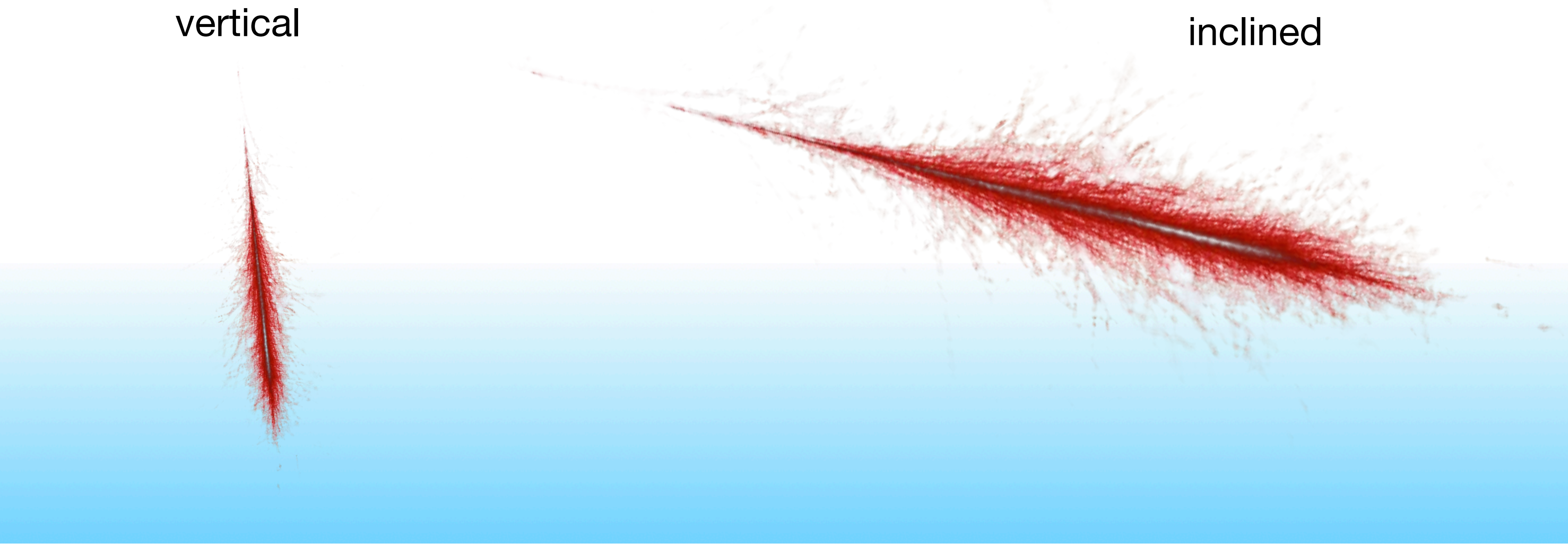


We need a fast and efficient simulation tool!

- Physical modeling of radio emission signals for very inclined showers

Characteristics of inclined air-showers

- development at **lower air density**
- development over **longer trajectories**



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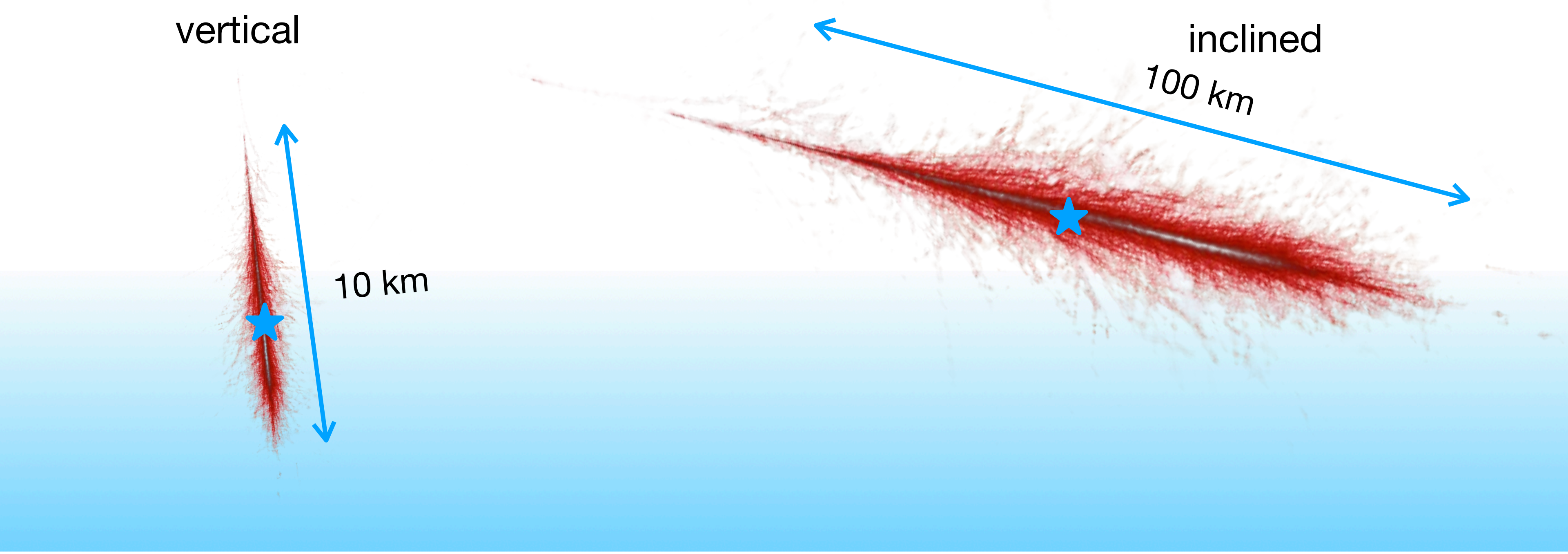

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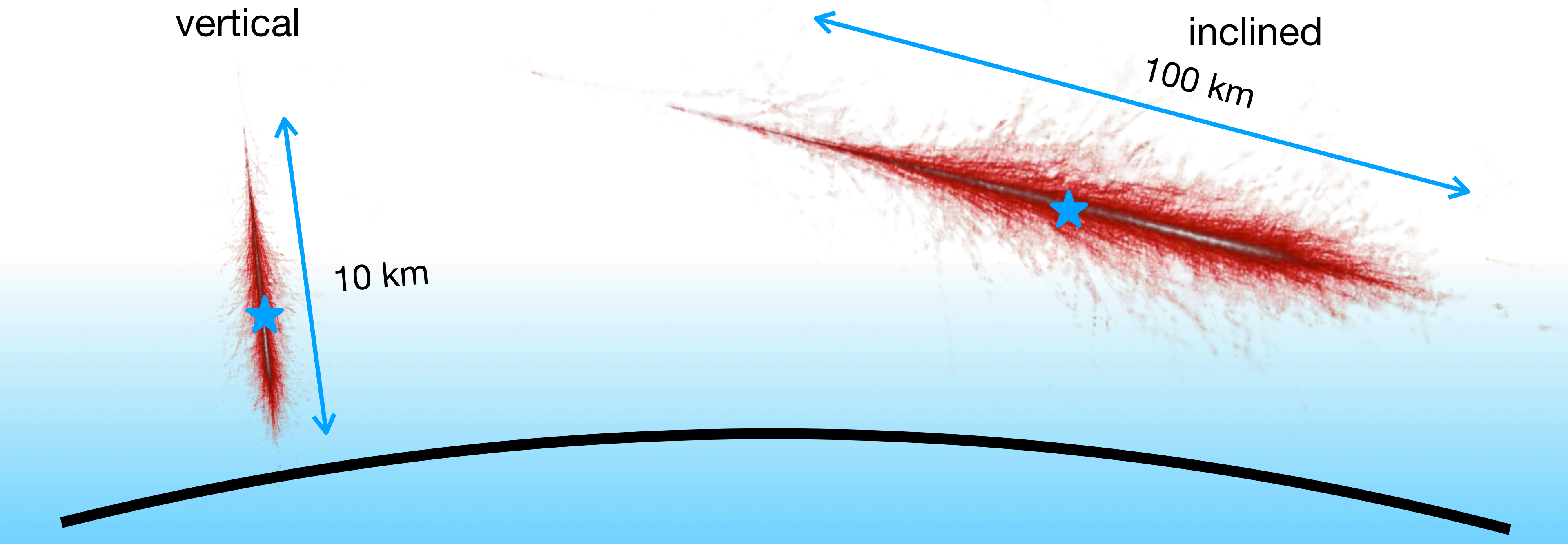

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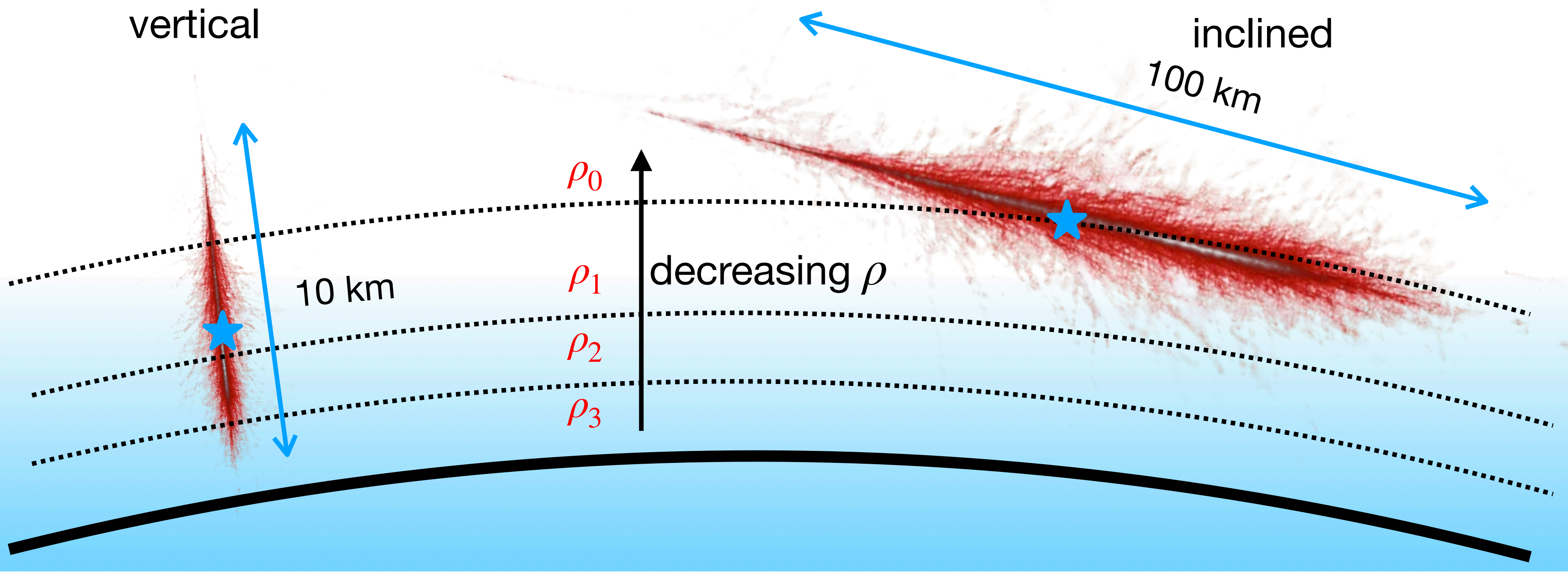

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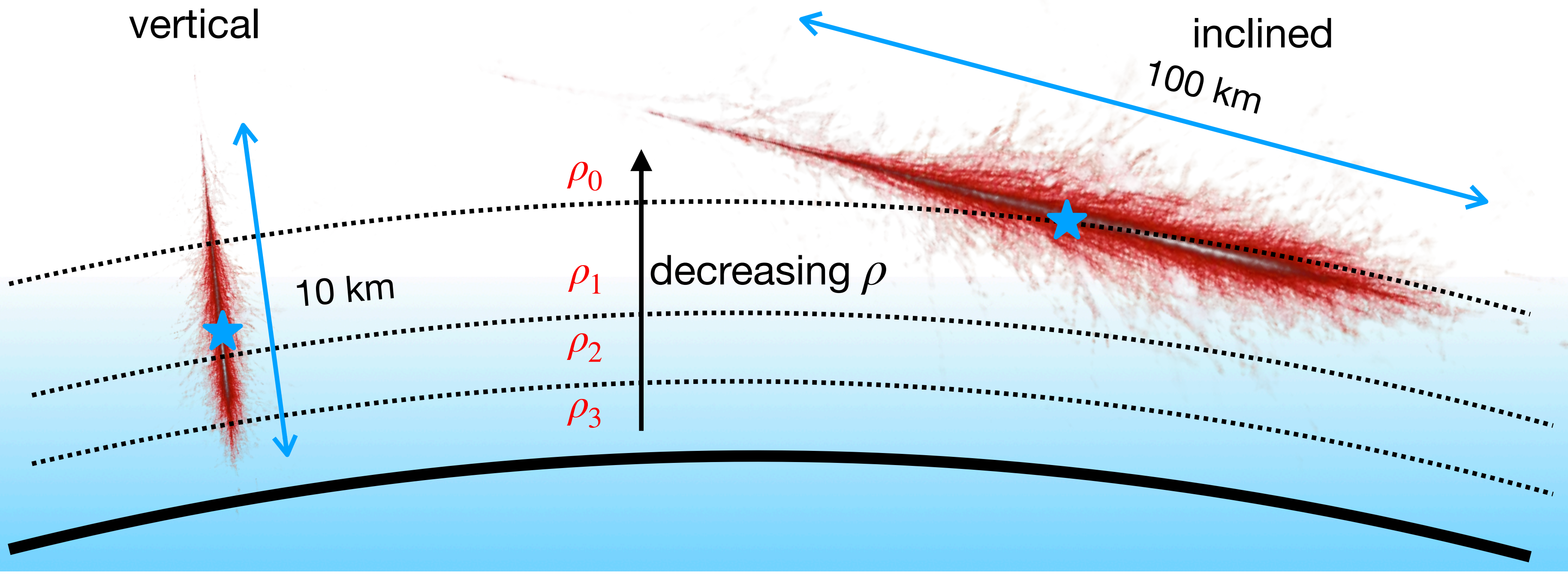

How do all these characteristics affect the radio emission?

Enhanced effect of B!

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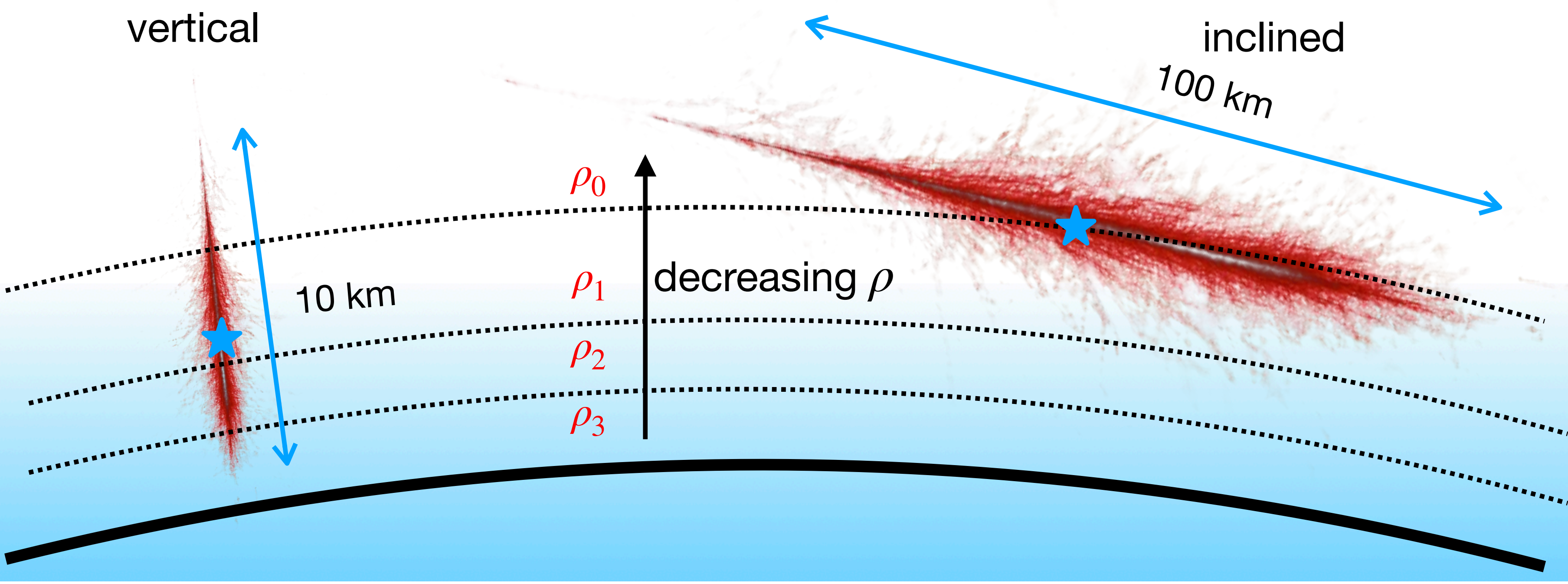


How do all these characteristics affect the radio emission?

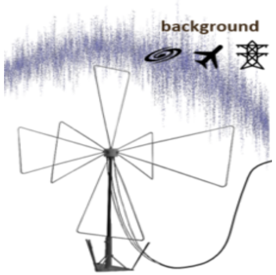
Enhanced effect of B!

- particles more deflected —> **synchrotron like emission?**
- particles more deflected —> larger lateral shower extension —> **coherence loss?**

GRAND and the challenges of radio-detection

- Find the radio signal in the noise

GRAND: Radio detection of astroparticles



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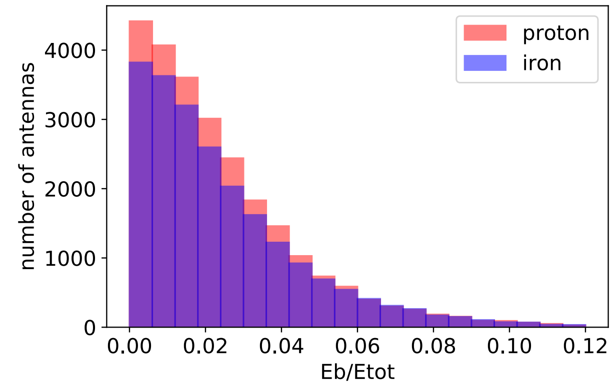

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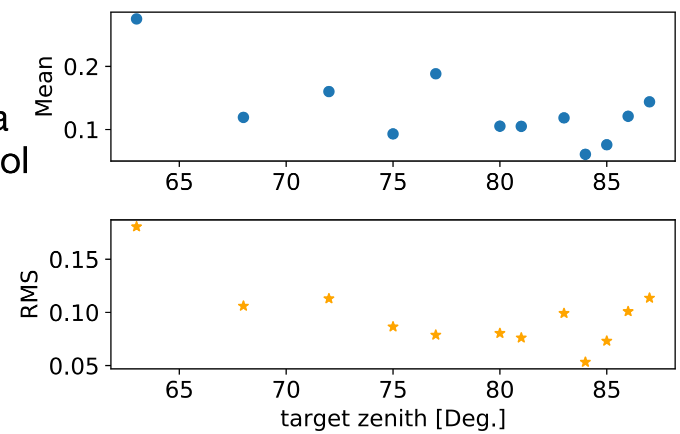

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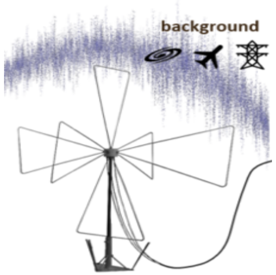

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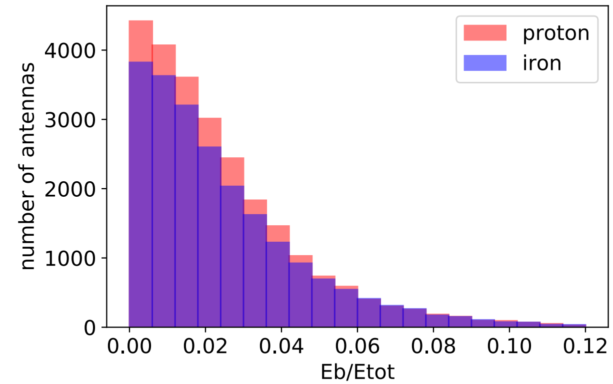

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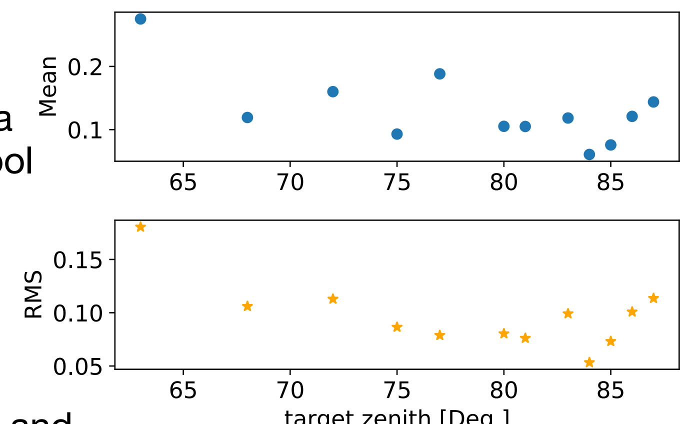

- ## Physical modeling of radio emission signals for very inclined showers

synchrotron and coherence model

(Chiche et al., submitted to PRL)

Summary

slide from Kumiko Kotera

References:

Website: http://grand-observatory.org

GRAND White Paper: https://arxiv.org/abs/1810.09994

GRAND ICRC 2023: https://arxiv.org/abs/2308.00120

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

GRAND Carbon Footprint & Life Cycle Analysis Studies:
https://arxiv.org/abs/2101.02049, https://arxiv.org/abs/2309.12282

Documentary by Jean Mouette *The Road to the Neutrino*:
https://www.youtube.com/watch?v=8tDnwq8gAe4