Looking for ultra-high energy astroparticles in a radio haystack

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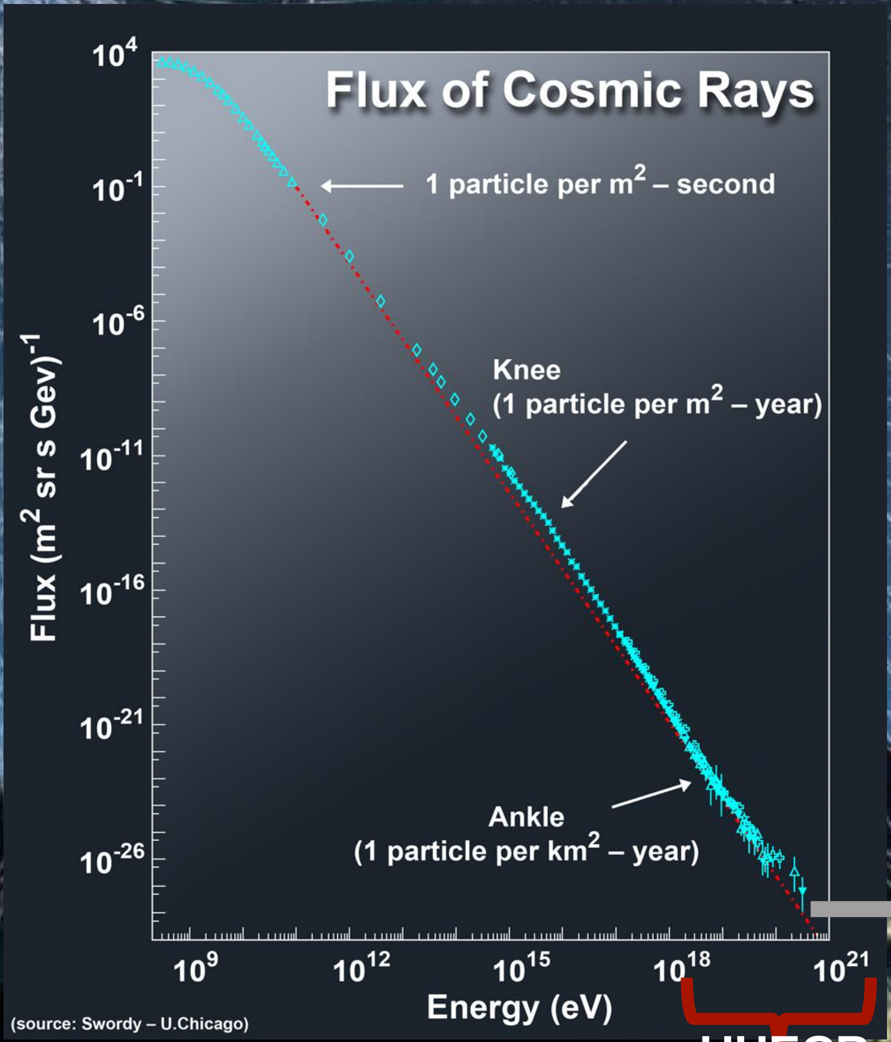
The mystery of ultra-high energy cosmic rays (UHECRs)

- Cosmic rays: high energy atomic nuclei (protons, iron nuclei, etc)
- Most energetic particles in the universe
- **Where do they come from?**



UHECRs

- At the lowest energy: Solar origin
- Intermediate energy: SNR (galactical origin)
- **Ultra-high energy : ?**

We don't know the exact nature of these particles

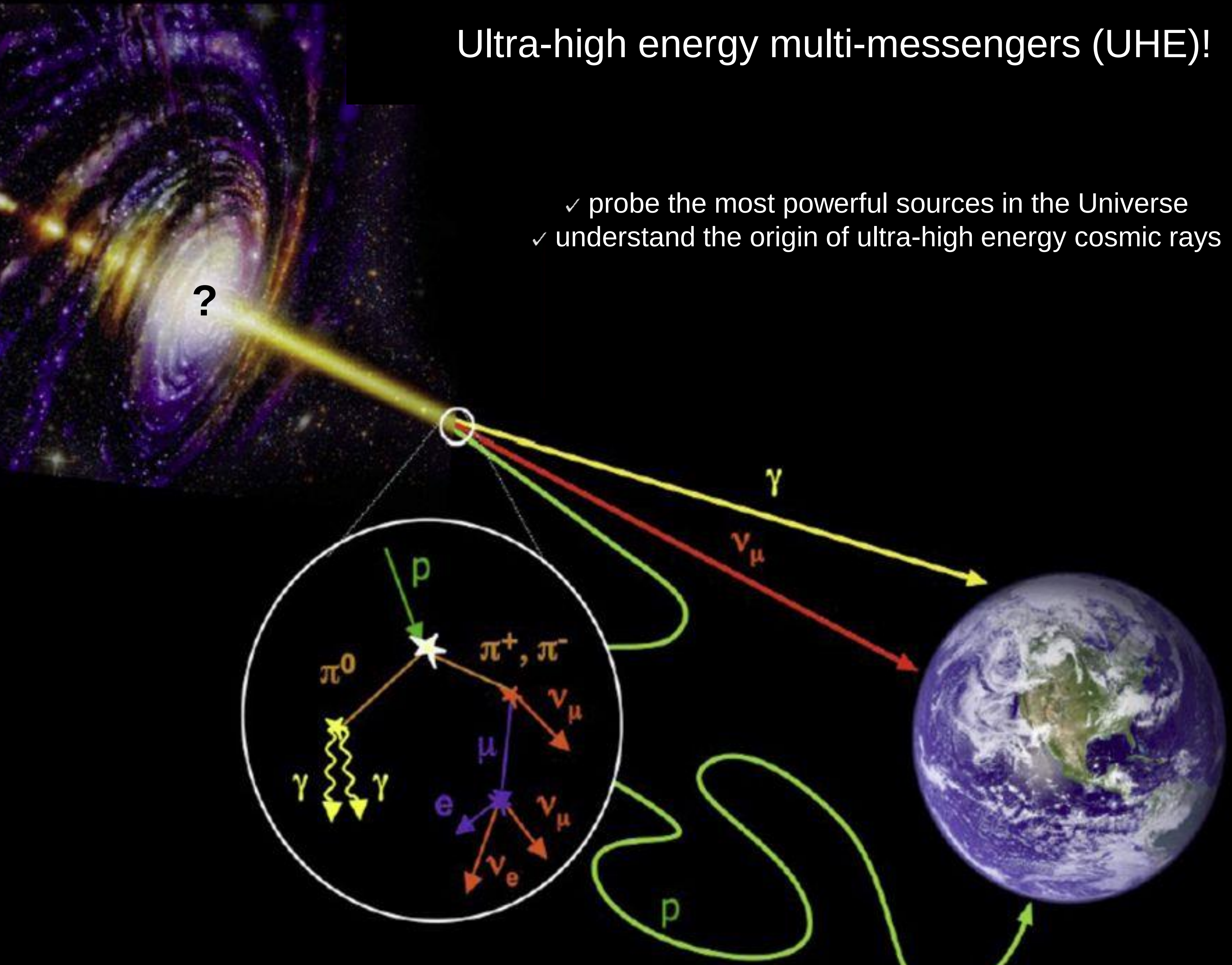
We don't know the sources

We don't the mechanisms responsible for the acceleration

Very low flux:
$$10^{-2}.km^{-2}.yr^{-1}$$

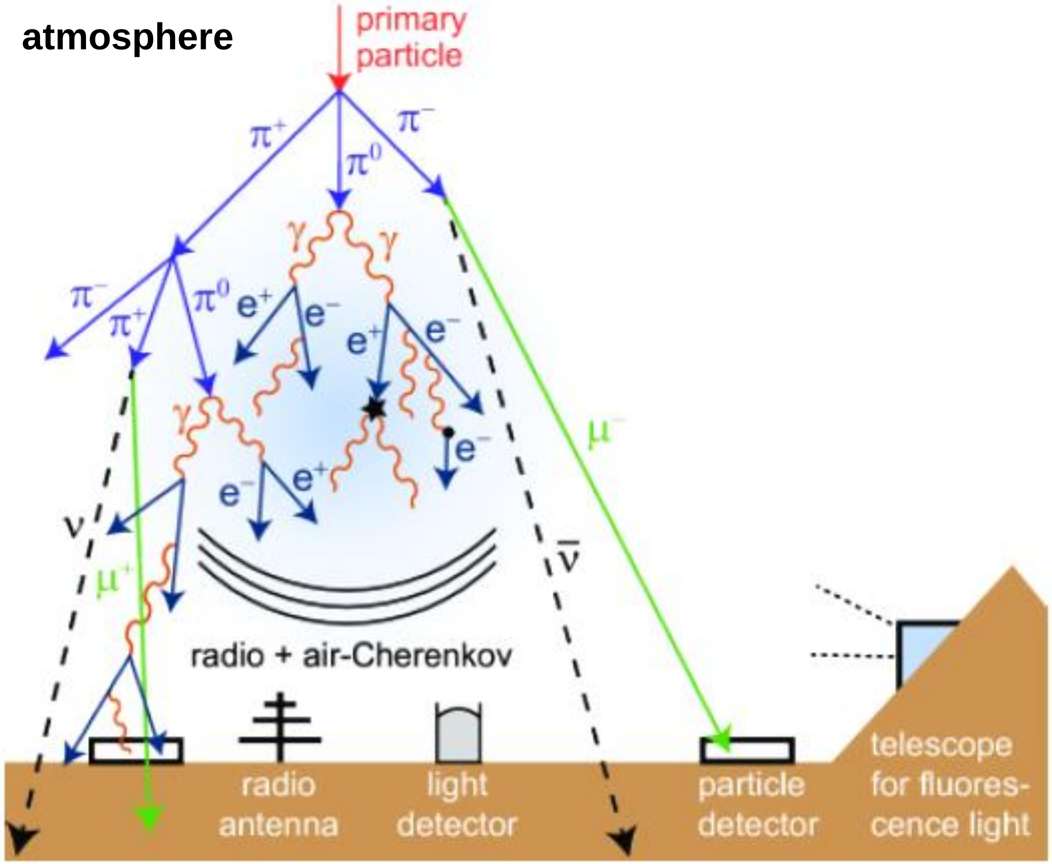
Ultra-high energy multi-messengers (UHE)!

✓ probe the most powerful sources in the Universe
✓ understand the origin of ultra-high energy cosmic rays



Extensive air showers (EAS)

Interaction of high enrgy astroparticles with the atmosphere: shower/cascade of secondary particles!



- Hadronic part: mainly π decaying into μ and ν
- Electromagnetic part: e^+, e^-, γ

Main emissions:

- Cherenkov light
- Fluorescence light
- Radio emission

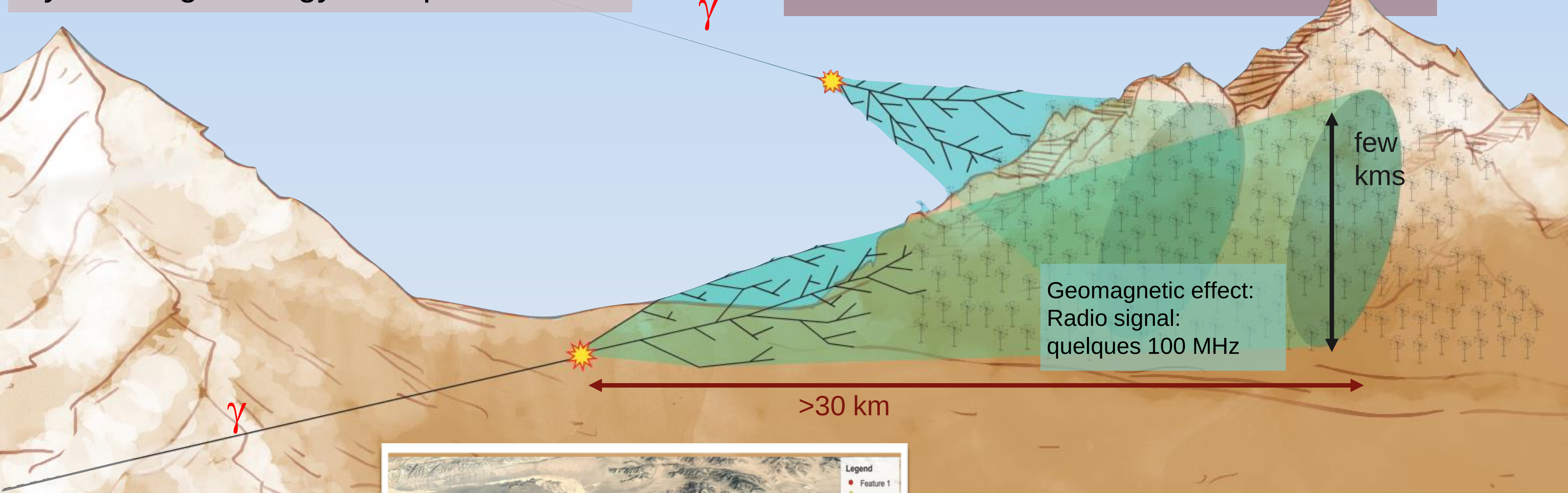
We can detect the signal originating from the electromagnetic part with radio antennas!

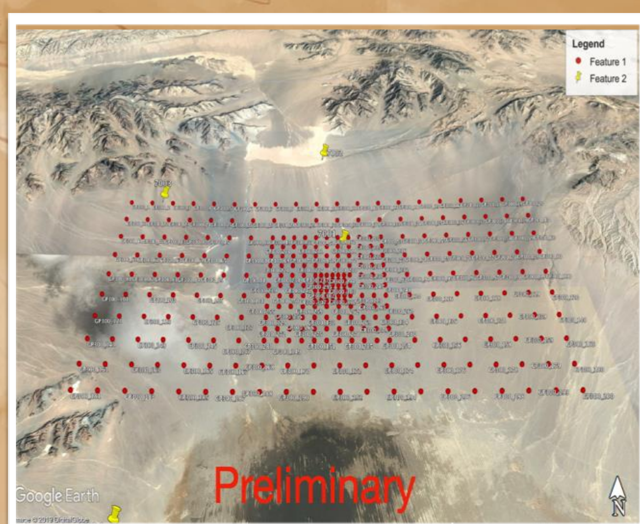
GRAND and GRANDproto300

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

Détection of particle showers induced by ultra-high energy astroparticles

Inclined showers with mountains as targets





Prototype of 300 antennas, 200km²

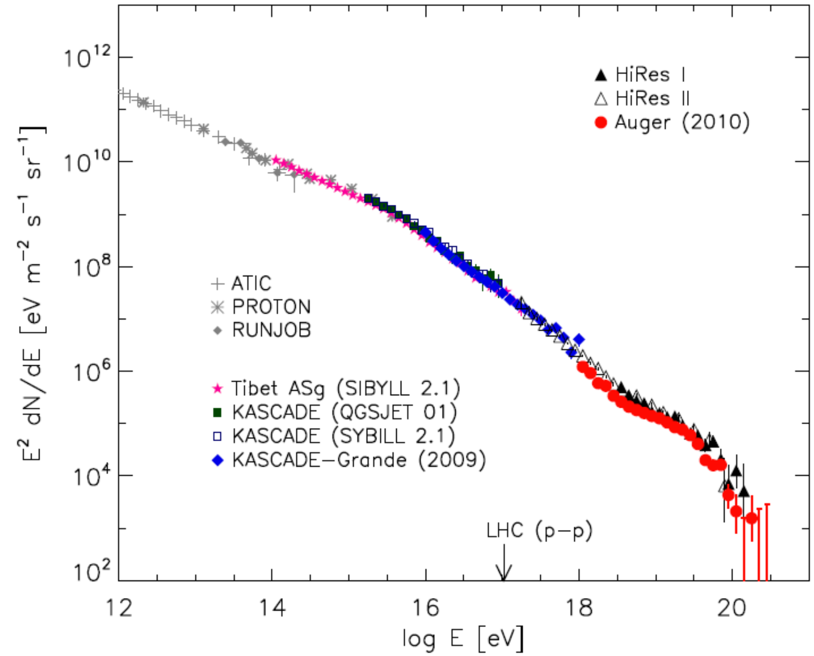
Détection of astroparticules with $E_{range} = 10^{16.5}$-10^{18} eV

GRANDProto300 first prototype in 2021!

Science case of GRANDproto300

Galactical to extragalctical transition

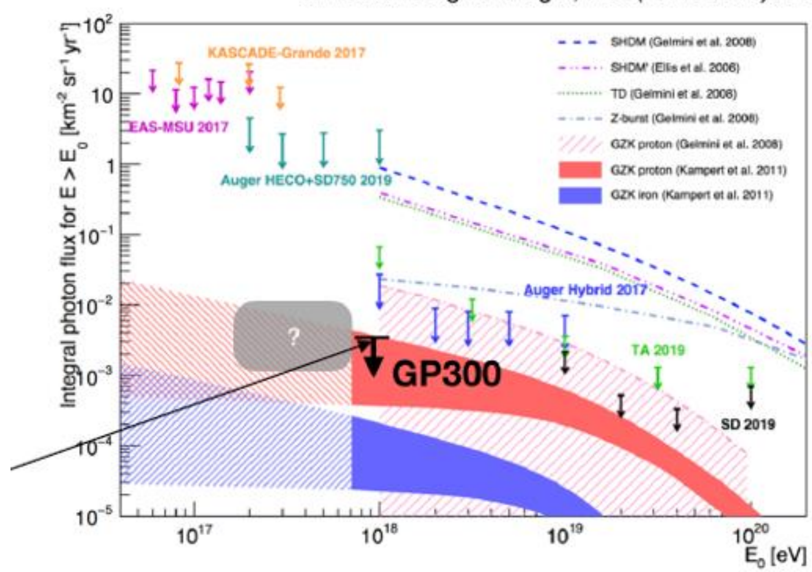
- GRANDProto 300: $E_{range} = 10^{16.5}$-10^{18} eV
- We expect a galactical to extragalctical transition in this region
- GRANDProto 300 could provide precious informations about the transition!



J. Rautenberg for Auger, PoS(ICRC2019)398

Constraints on the gamma flux

- Unprecedented sensibility to diffuse UHE gamma rays with GRANDProto300
- Could allow the detection of UHE gamma rays or constrains the limits on the flux

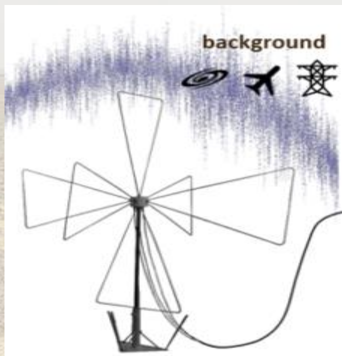


GRANDProto300 : Défis de la radiodétection

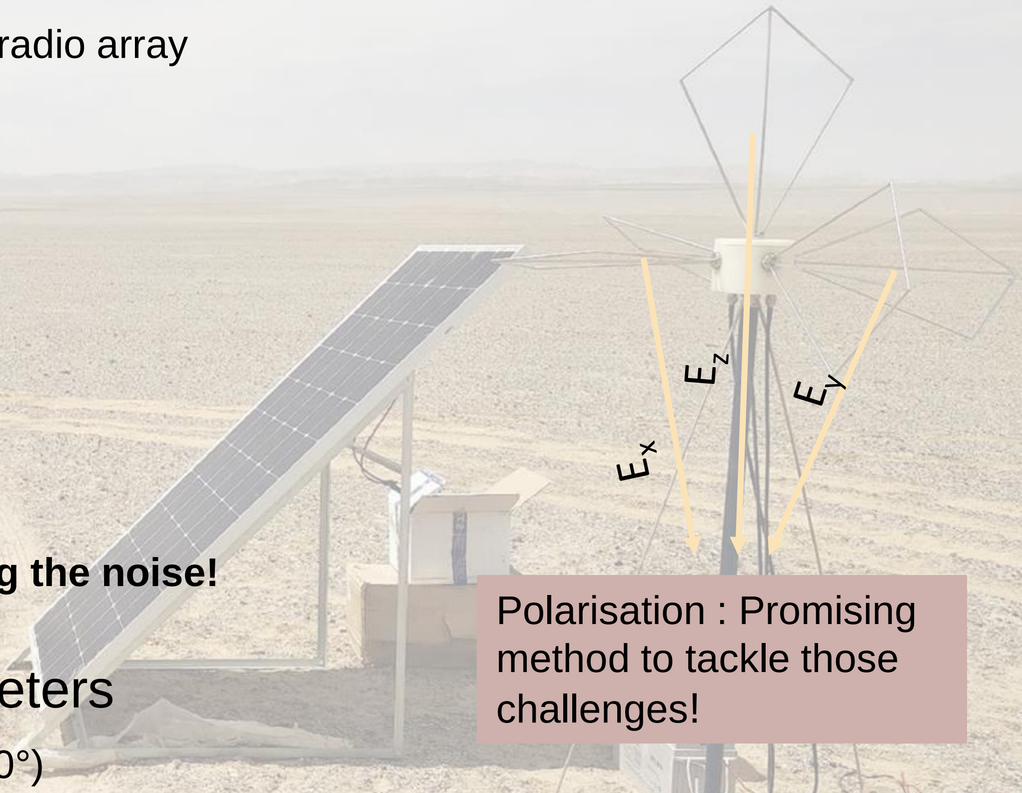
- Autonomous detection of astroparticles → Graal of radiodétection!

Current experiences: external triggers (Cerenkov cuves, scintillators)

GRAND: radio antennas only because giant radio array



Overwhelming noise from human emissions



We have to identify the radio signal among the noise!

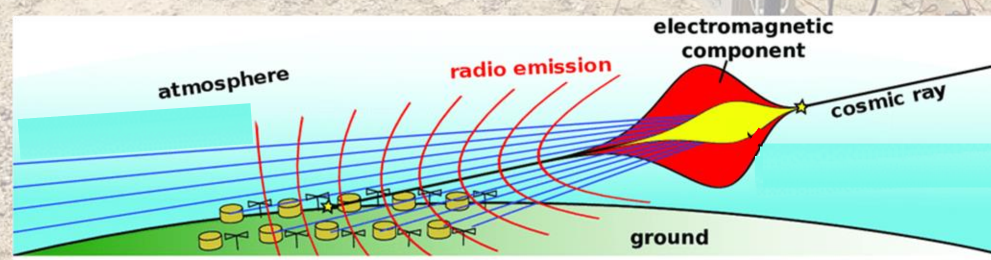
Polarisation : Promising method to tackle those challenges!

- Reconstruction of shower parameters

Current experiences: vertical showers (θ < 70°)

GRAND détection of inclined showers (θ > 70°)

Asymmetries, ground reflexion effects



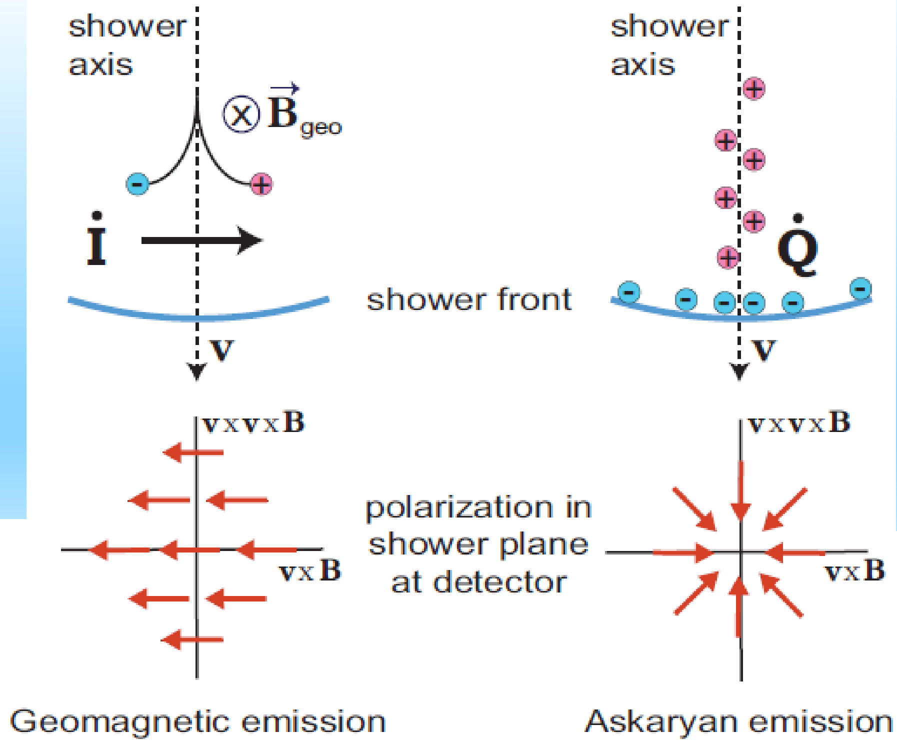
Schröder (2019)

Polarisation of the radio signal

2 main contributions to the polarisation

Geomagnetic emission

- Induced dipole with $\overrightarrow{\mathbf{B}_{geo}}$
- 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

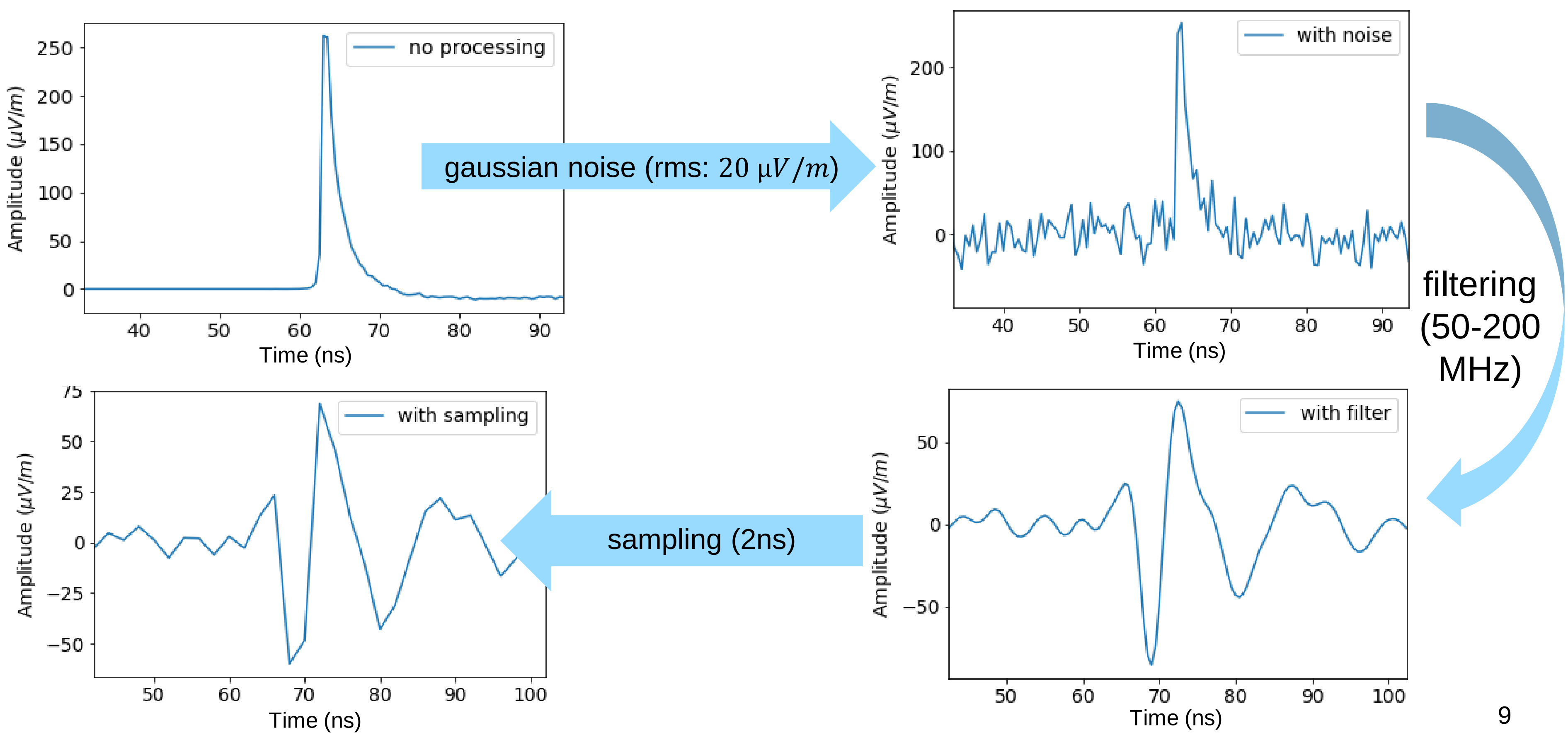
- Complex signature in polarisation: allow to discriminate the signal from the noise
- Charge excess signature: gives insights about the core position

Traces processing

ZHAireS Simulations (Alvarez-Muñiz et al. 2011)

Outputs: Traces Ex(t), Ey(t), Ez(t) at each antenna

Account for experimental detection effects



Shower plane

- Outputs of the simulations: Ex(t), Ey(t), Ez(t)
- We want to derive Ev(t), Evxb(t), Evxvxb(t)

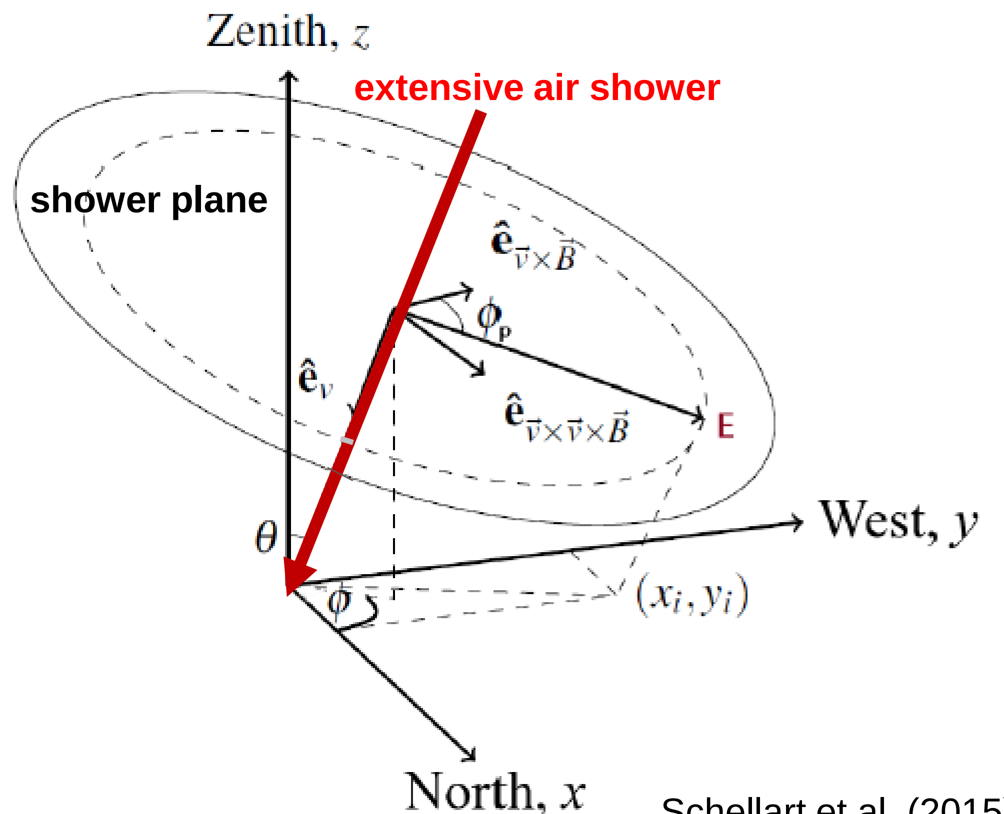
i: inclination of the magnetic field

θ: zenith angle

ϕ: azimuth of the shower

$$\boldsymbol{u_B} = \cos i \, \boldsymbol{u_x} - \sin i \, \boldsymbol{u_z}$$

$$\boldsymbol{u_v} = \sin\theta \cos\phi \, \boldsymbol{u_x} + \sin\theta \sin\phi \, \boldsymbol{u_y} + \cos\theta \, \boldsymbol{u_z}$$



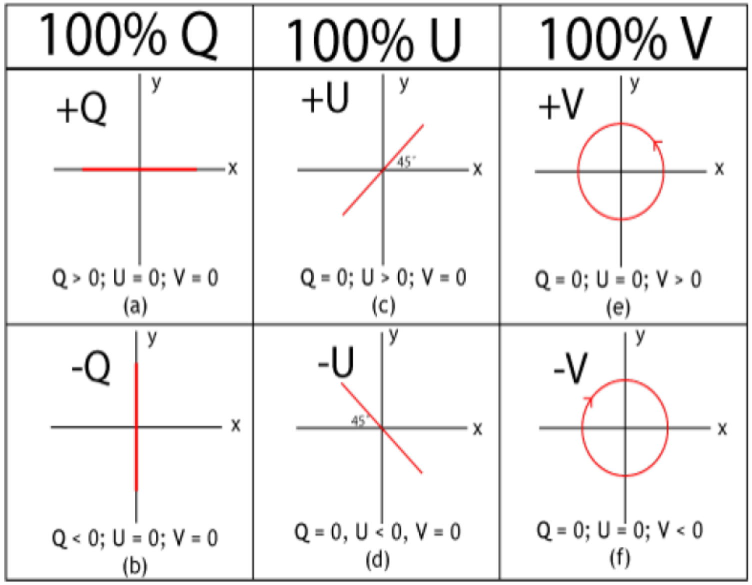
Schellart et al. (2015)

We can derive $\boldsymbol{u}_{v\times B}$ and $\boldsymbol{u}_{v\times v\times B}$ from $\boldsymbol{u}_v$ and $\boldsymbol{u}_B$ and thus $E_v(t)$, $E_{v\times B}(t)$ and $E_{v\times v\times B}(t)$

Stokes parameters

- Stokes parameters I,Q, U, V: standard method to reconstruct the polarisation (Schoorlemmer 2012)
- $x_i = E_{v\times B}(t_i),\ y_i = E_{v\times v\times B}(t_i),$
- $\hat{x}_i,\ \hat{y}_i,$ Hilbert transform of x_i, y_i, i.e., extension of the traces in the complex domain

Stokes parameters



$$I = \frac{1}{n}\sum_{i=1}^{n}\left(x_i{}^2 + \hat{x}_i{}^2 + y_i{}^2 + \hat{y}_i{}^2\right) = |E_{v\times B}|^2 + |E_{v\times v\times B}|^2$$

$$Q = \frac{1}{n}\sum_{i=1}^{n}\left(x_i{}^2 + \hat{x}_i{}^2 - y_i{}^2 - \hat{y}_i{}^2\right) = |E_{v\times B}|^2 - |E_{v\times v\times B}|^2$$

$$U = \frac{2}{n}\sum_{i=1}^{n}\left(x_i y_i + \hat{x}_i\hat{y}_i\right)$$

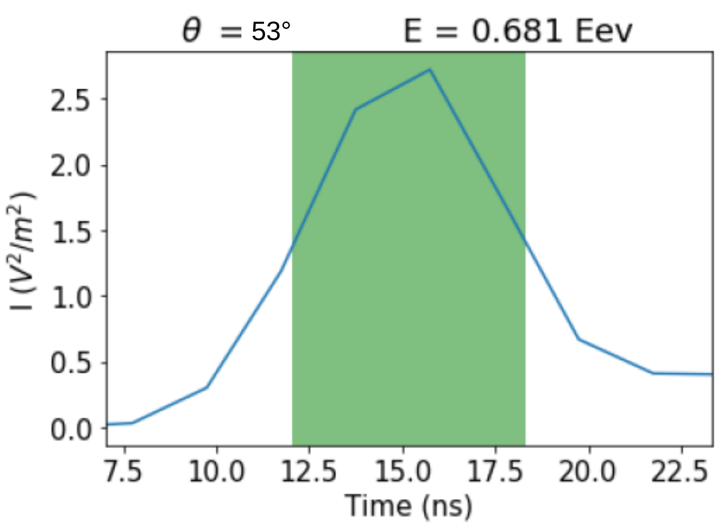
$$V = \frac{2}{n}\sum_{i=1}^{n}\left(\hat{x}_i y_i - x_i\hat{y}_i\right)$$

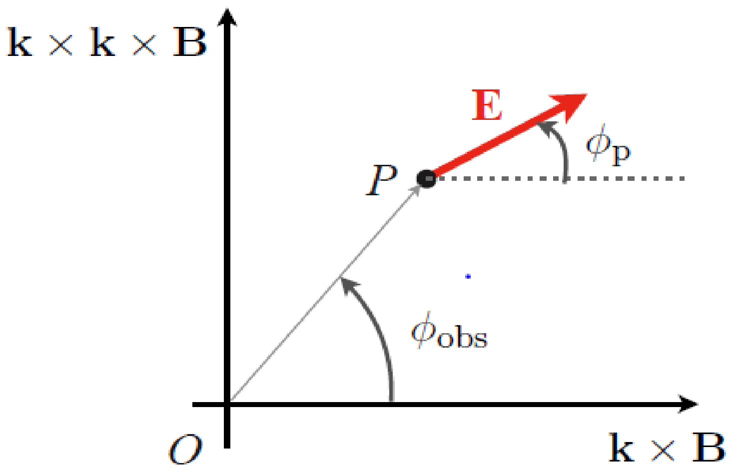
Reconstruction of the polarisation

- We have to define a time window over which we average the traces
- Stokes parameters I: Related to the total intensity of the traces

Time window: Fwhm of the I parameter

ϕ_p: angle between the polarisation and the $v \times B$ direction



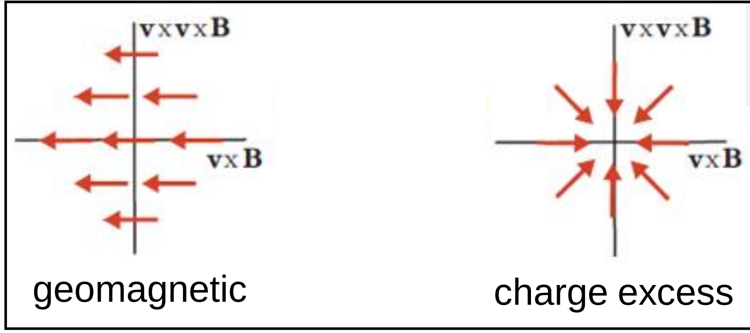


$$\phi_p = 0.5 \tan^{-1} \frac{U}{Q}$$

$$E_{v\times B} = \sqrt{< I >} \cos \phi_p$$

$$E_{v\times v\times B} = \sqrt{< I >} \sin \phi_p$$

Reconstruction of the polarisation

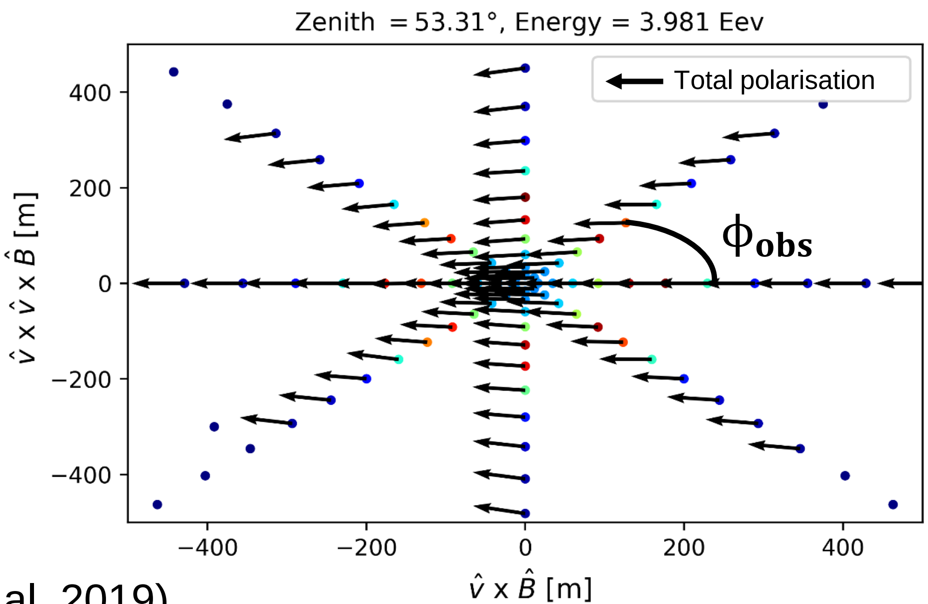


Total polarisation

Various methods to reconstruct the polarisation: absolute value, max value, Stokes parameters…

Total polarisation essentially along $-\mathrm{v} \times B$

Dominant geomagnetic emission



Separation of each mechanism: (Huege et al. 2019)

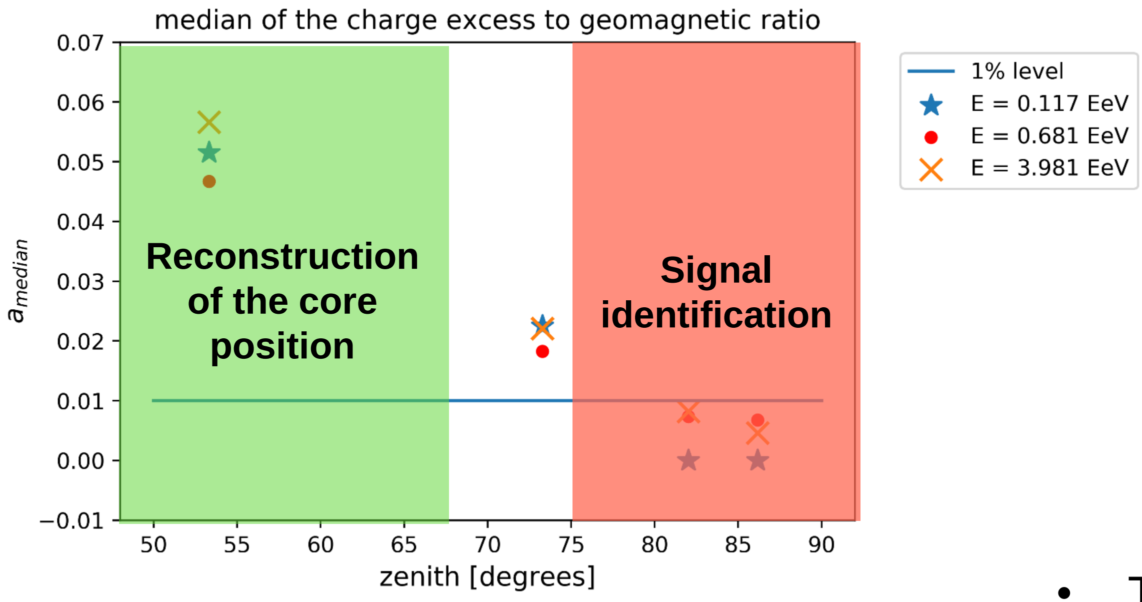
$$E_{ce} = \frac{E_{\mathrm{v}\times\mathrm{v}\times\mathrm{B}}}{|\sin\phi_{obs}|} \qquad E_{geo} = E_{\mathrm{v}\times\mathrm{B}} - E_{\mathrm{v}\times\mathrm{v}\times\mathrm{B}}\frac{\cos\phi_{obs}}{|\sin\phi_{obs}|}$$

→ Signatures to identify the radio signal
→ Reconstruction of the air shower core position

Signal identification

Ratio of the amplitude of each mechanism

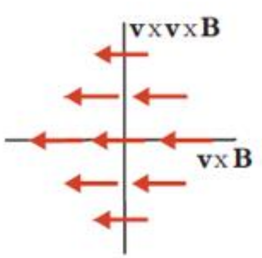
For different simulations



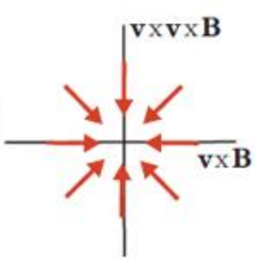
$$a = \sin\alpha \frac{E_{\text{charge excess}}}{E_{\text{geomagnetic}}}$$

Ratio below 1% for inclined air showers

Dominant contribution of the geomagnetic emission for inclined showers



geomagnetic

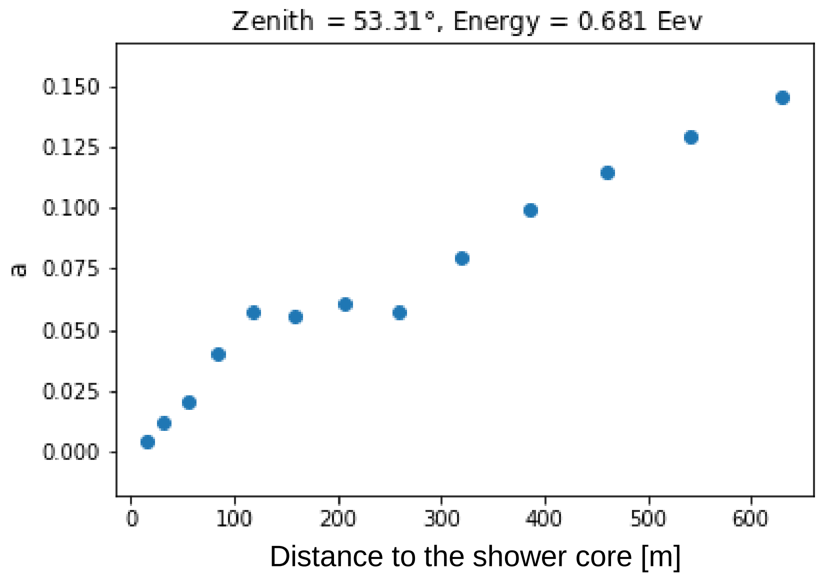


charge excess

- Total field orthogonal to B
- Strong signature of the radio signal visible directly at the antenna level
- Could be implemented in the trigger hardware of GRAND antennas

Shower core Reconstruction

$$a = \sin\alpha \frac{E_{\text{charge excess}}}{E_{\text{geomagnetic}}}$$



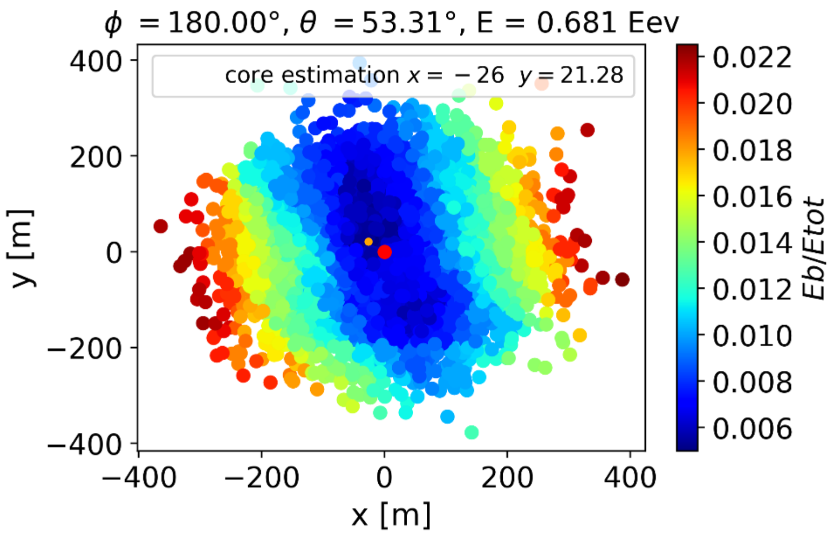
The ratio drops to 0 at the core

Increase with the distance to the core

Estimation of the shower core as the position that minimizes the ratio

Method

- For several positions we compute the mean ratio measured by the 20 closest antennas
- Core estimation: position with the lowest measurement



Still a preliminary work, but promising for showers with $z \leq 65°$

Conclusion

Aim: Understanding the origin of ultra-high energy cosmic rays

- Multi-messengers approach to tackle this challenge
- Detection of the radio signal from extensive air showers induced by UHE astroparticles

GRANDProto300: Prototype of 300 antennas for the detection of UHE astroparticles

- Identification of the radio signal among the noise
- Reconstruction of the shower parameters

Results:

- Electric field orthogonal to **B** for inclined showers

➡ Strong criteria to identify the radio signal!

- The charge excess to geomagnetic ratio increases with distance to the core

➡ Allow for reconstruction of the core position for showers with low inclination!