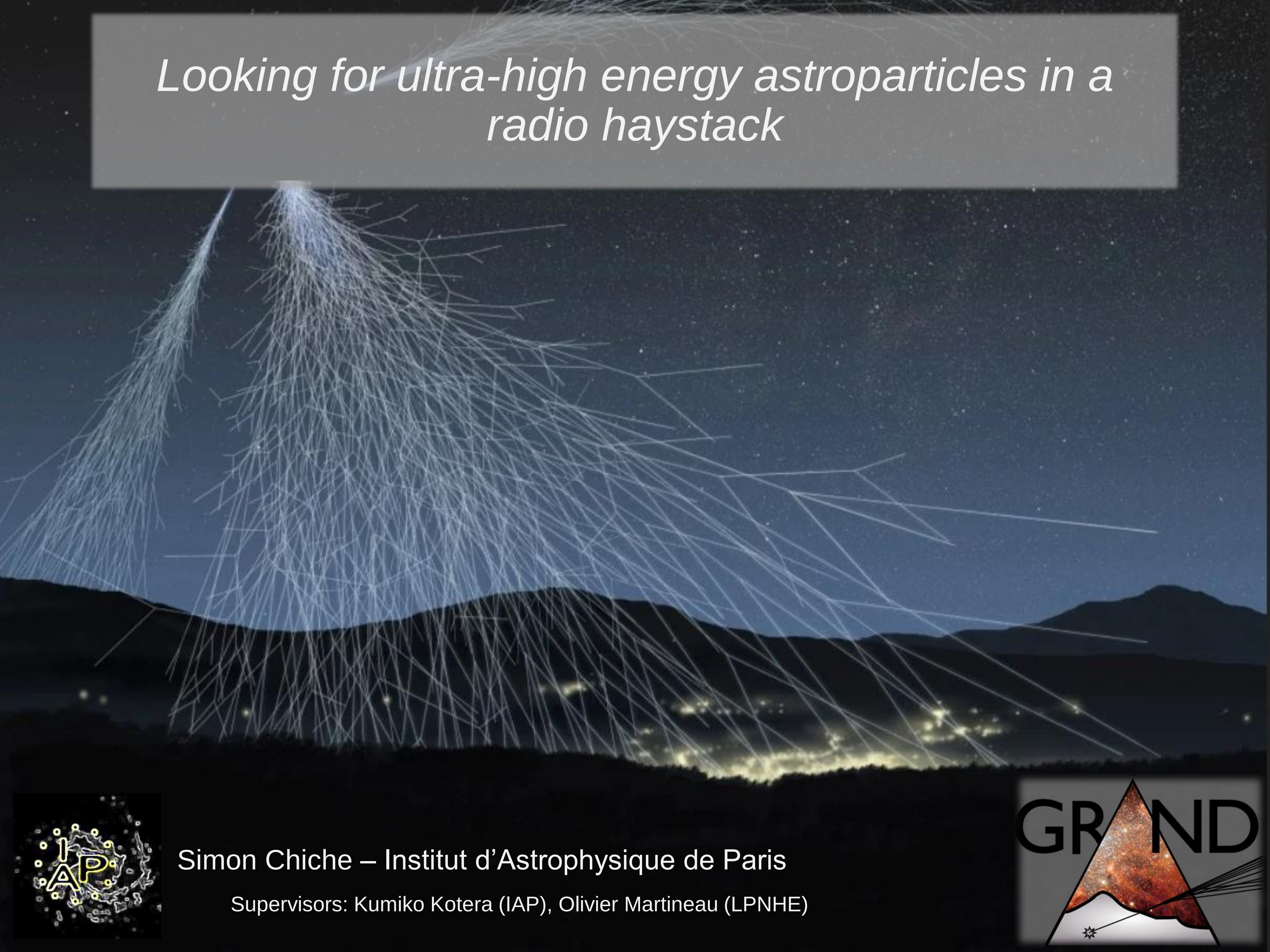
Looking for ultra-high energy astroparticles in a radio haystack



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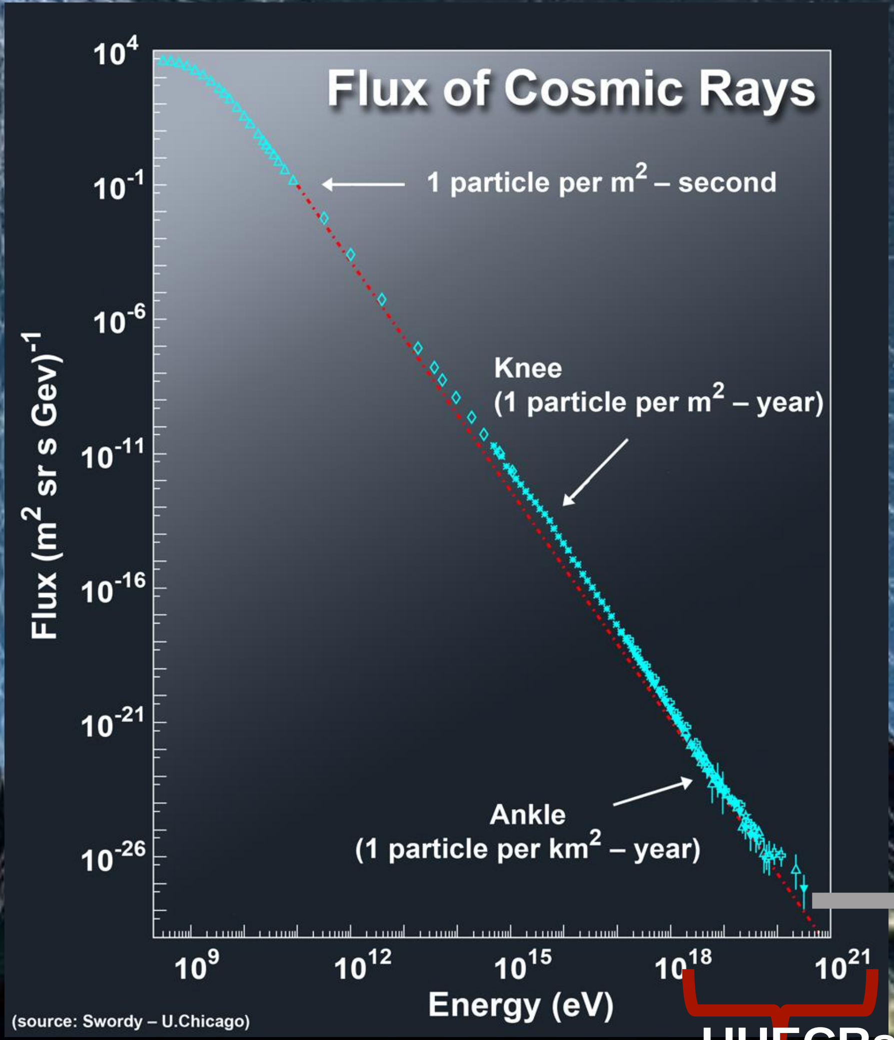
The mystery of ultra-high energy cosmic rays (UHECRs)

- Cosmic rays: high energy atomic nuclei (protons, iron nuclei, etc)
- Most energetic particles in the universe (ultra-high energy cosmic rays: $E > 10^{18} eV$)
- **Where do they come from?**



(source: Swordy – U.Chicago)

UHECRs

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

We don’t know the exact nature of these particles

We don’t know the sources

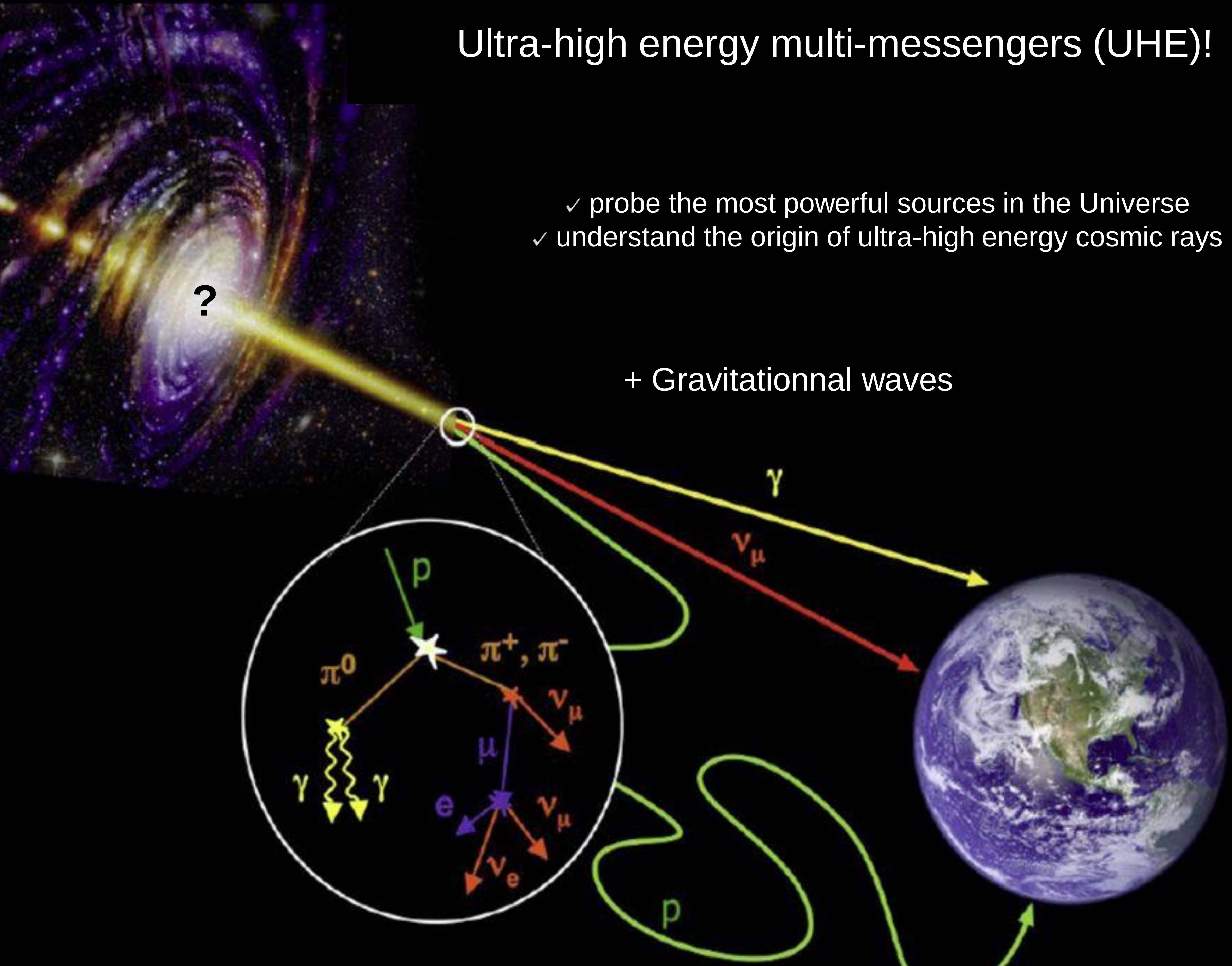
We don’t know the acceleration mechanisms

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

Ultra-high energy multi-messengers (UHE)!

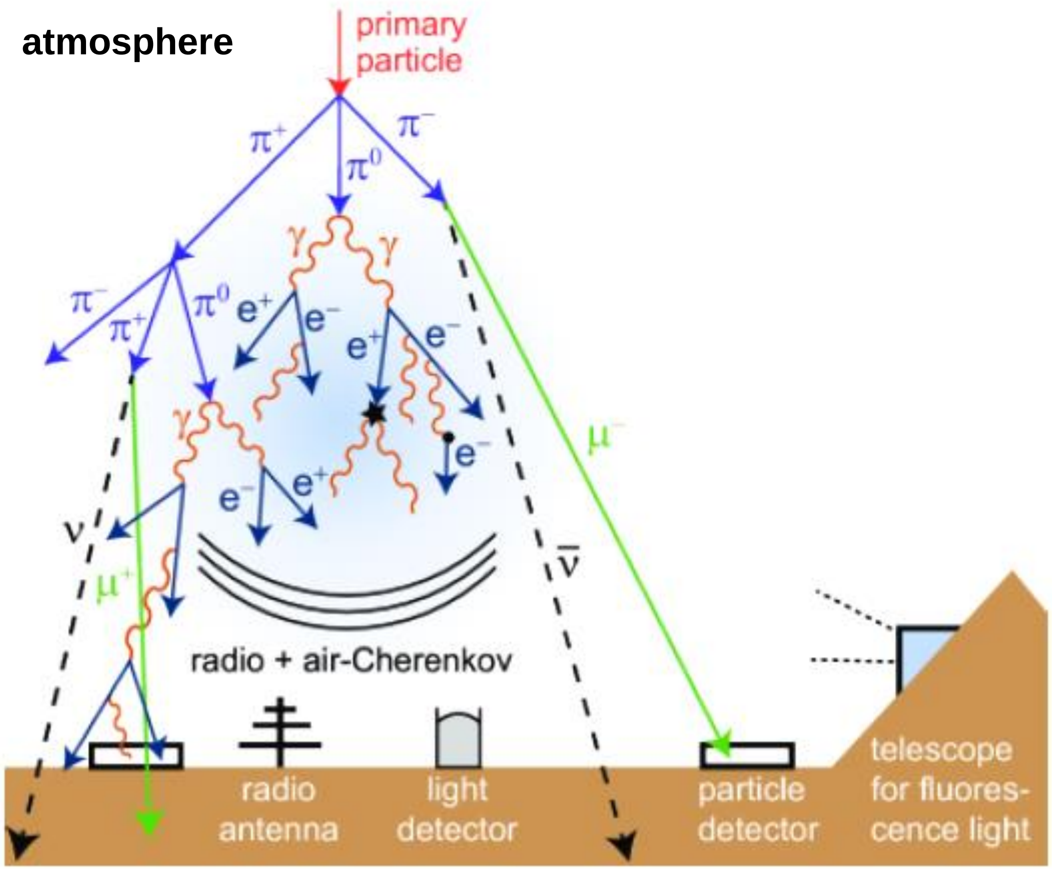
- ✓ probe the most powerful sources in the Universe
- ✓ understand the origin of ultra-high energy cosmic rays

+ Gravitationnal waves



Extensive air showers (EAS)

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



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

Main emissions:

- Cherenkov light
- Fluorescence light
- Radio emission

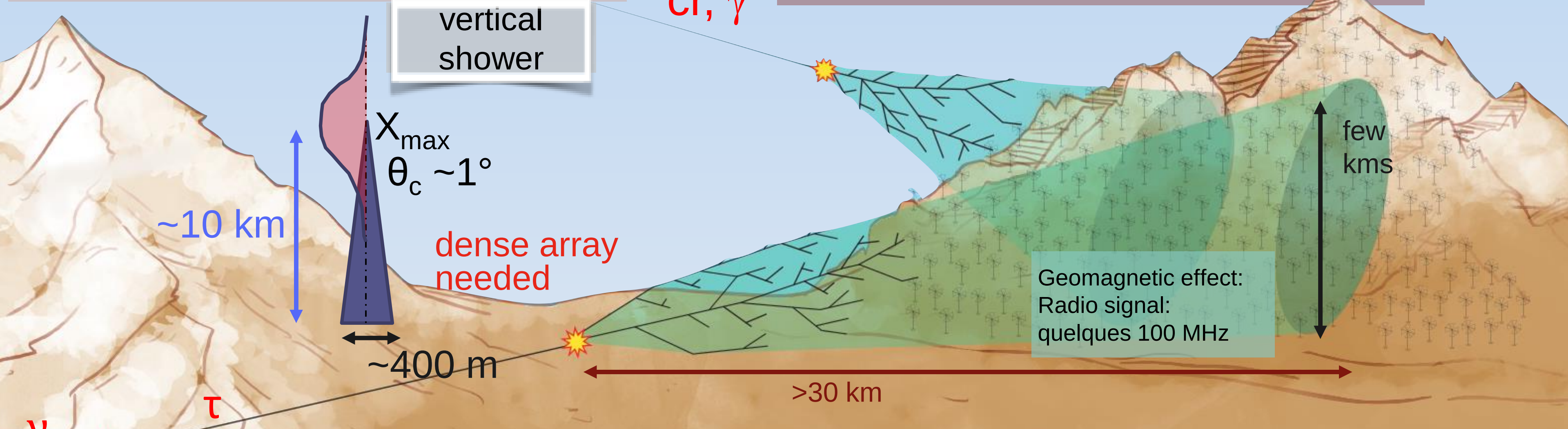
We can detect the signal originating from the electromagnetic part with radio antennas!

GRAND and GRANDproto300

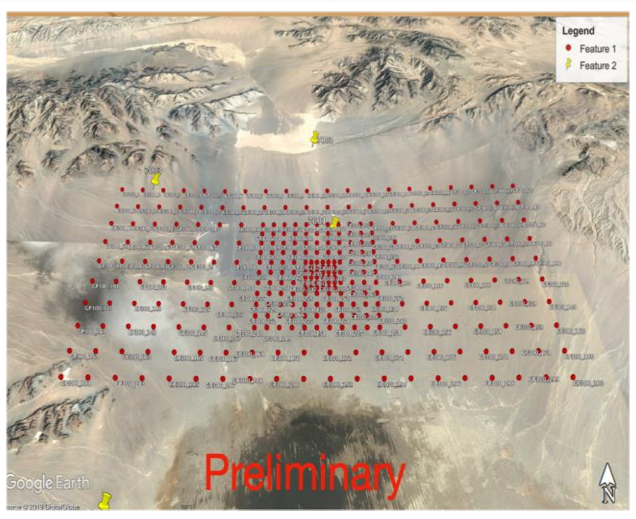
GRAND : Giant radio array of 200 000 radio antennas over 200 000 km^2

Detection of air showers induced by ultra-high energy astroparticles

Inclined showers with mountains as targets



GRANDProto300 first prototype in 2021!



Prototype of 300 antennas, 200km²

Detection of astroparticles with $E_{range} = 10^{16.5}$-10^{18} eV

GRANDProto300: Challenges of radiodetection

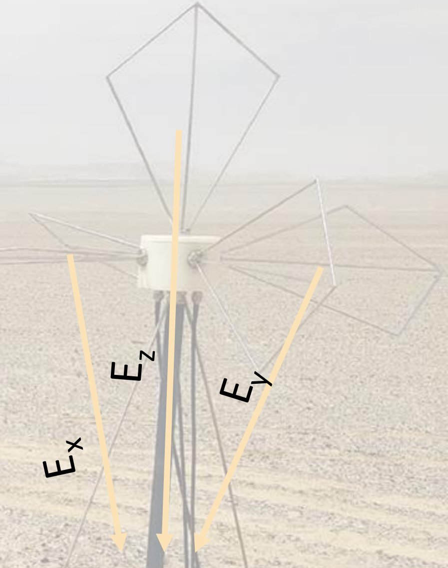
- Autonomous detection of astroparticles → Grail of radiodetection!

Current experiments: external triggers (Cerenkov tanks, scintillators)

GRAND: radio antennas only

Overwhelming noise from human emissions

We have to identify the radio signal among the noise!



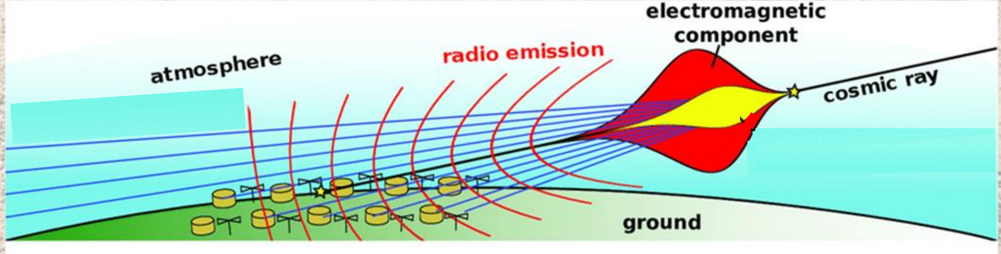
Polarisation : Promising method to tackle those challenges!

- Reconstruction of shower parameters

Current experiments: vertical showers (θ < 70°)

GRAND detection of inclined showers (θ > 70°)

Asymmetries, ground reflections effects



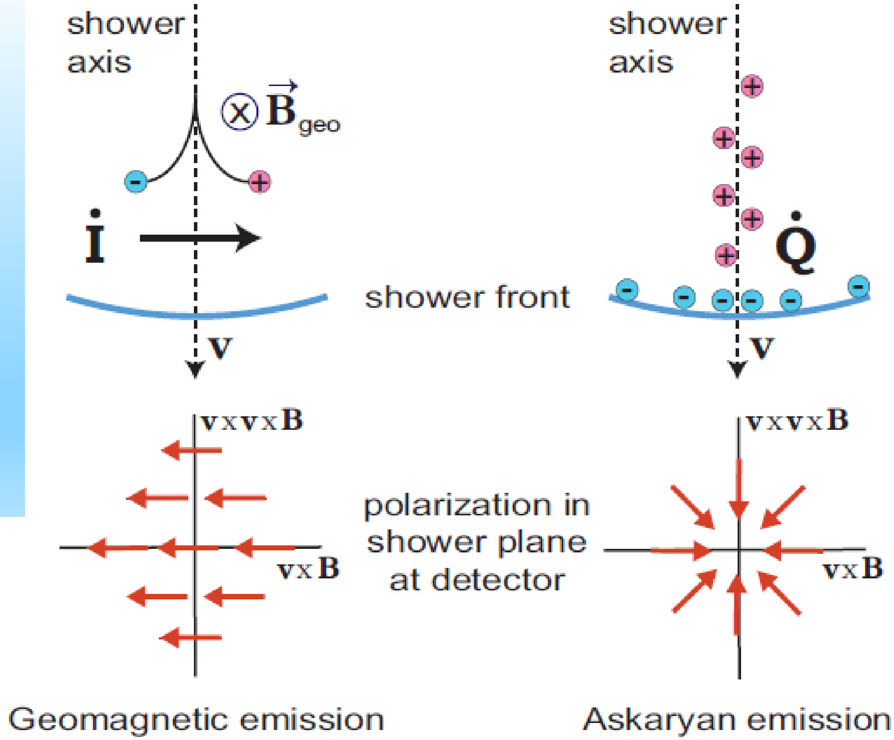
Schröder (2019)

Polarisation of the radio signal

Polarisation: direction of the electric field

Geomagnetic emission

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

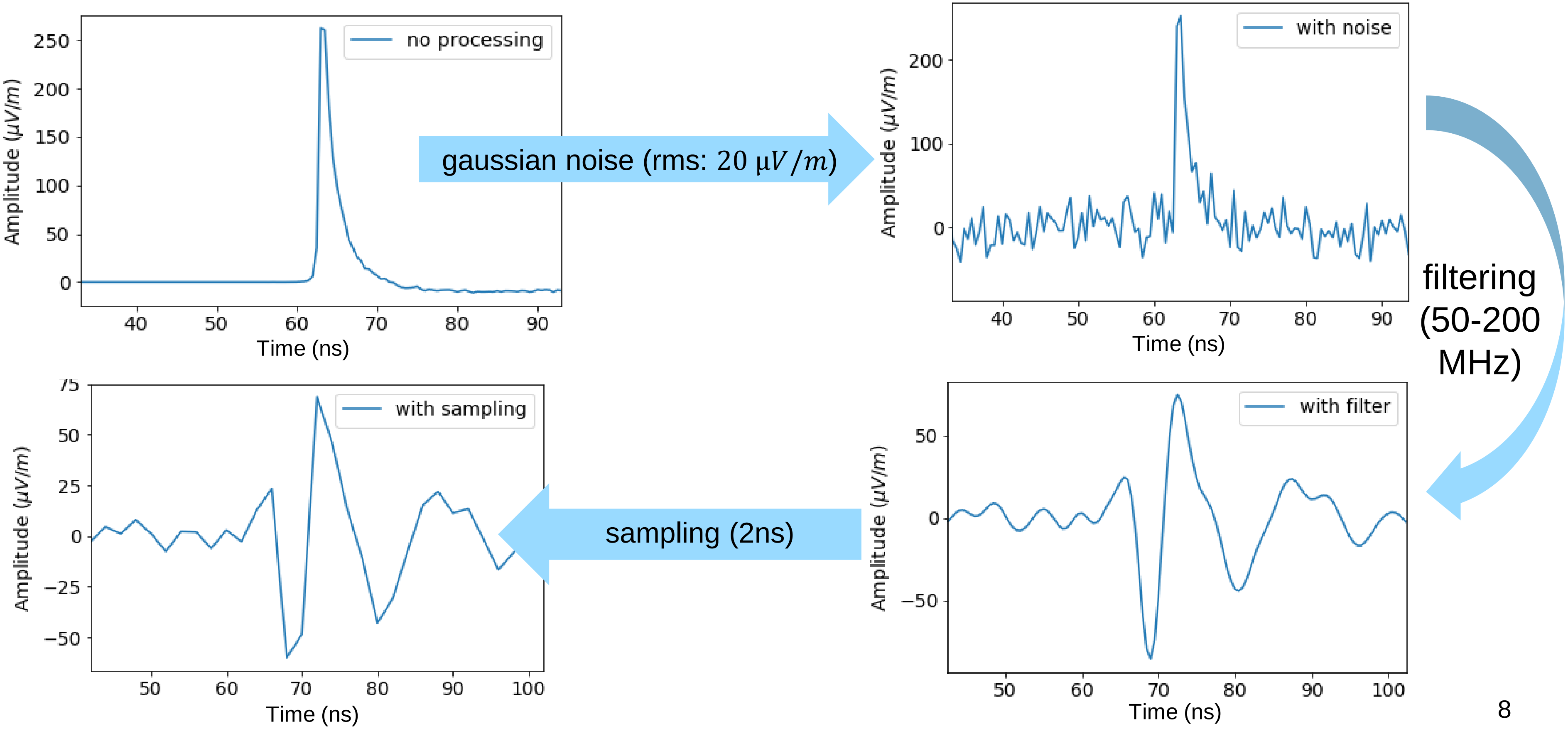
- Complex polarisation signature: allows to discriminate the signal from the noise
- Charge excess signature: gives insights about the core position

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



gaussian noise (rms: 20 $\mu V/m$)

filtering (50-200 MHz)

sampling (2ns)

Shower plane

- Outputs of the simulations: Ex(t), Ey(t), Ez(t)

- We want to derive Ev(t), Evxb(t), Evxvxb(t)

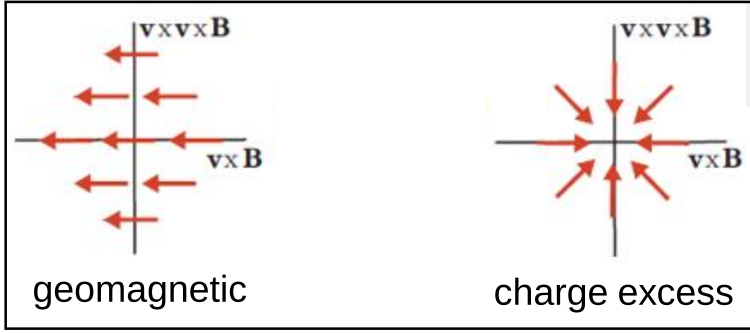
i: inclination of the magnetic field

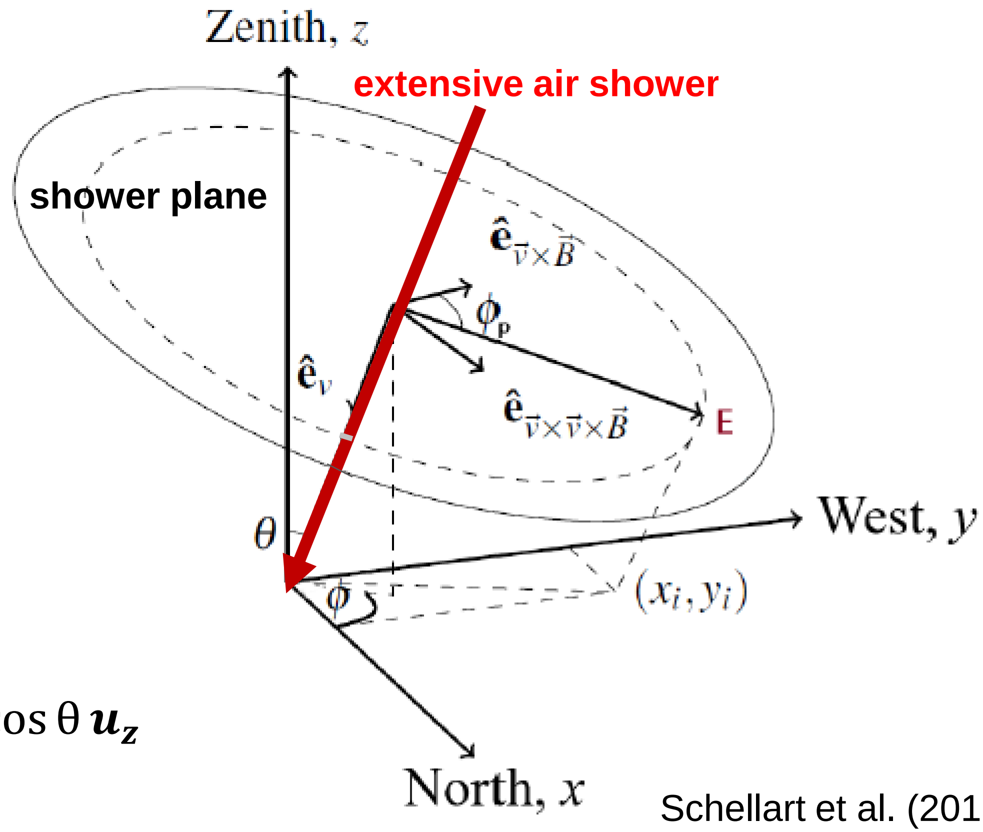
θ: zenith angle

ϕ: azimuth of the shower

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

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





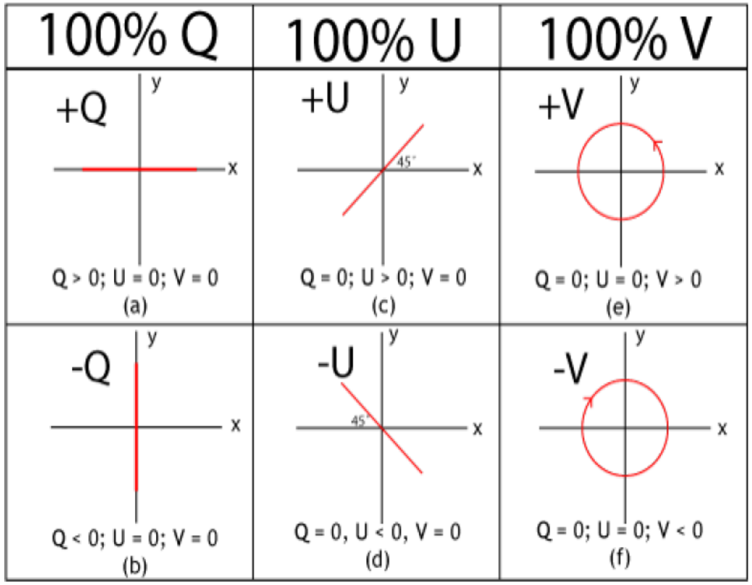
Schellart et al. (2015)

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



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

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

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

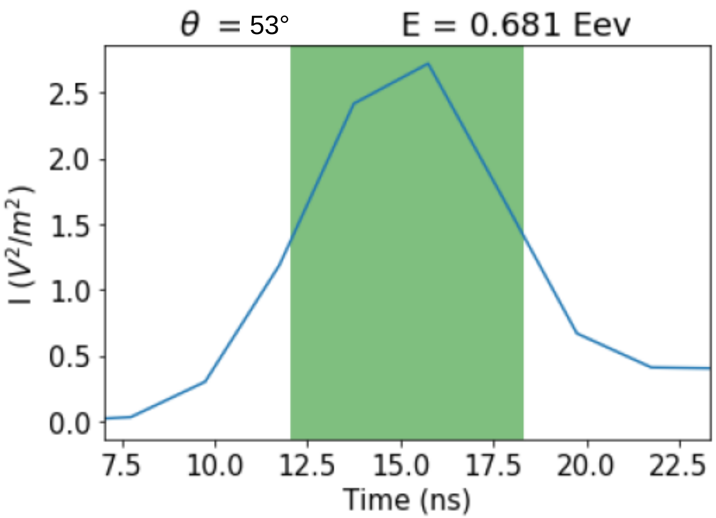
$$\mathrm{V} = \frac{2}{n}\sum_{i=1}^{n}(\hat{x}_i y_i - x_i \hat{y}_i)$$

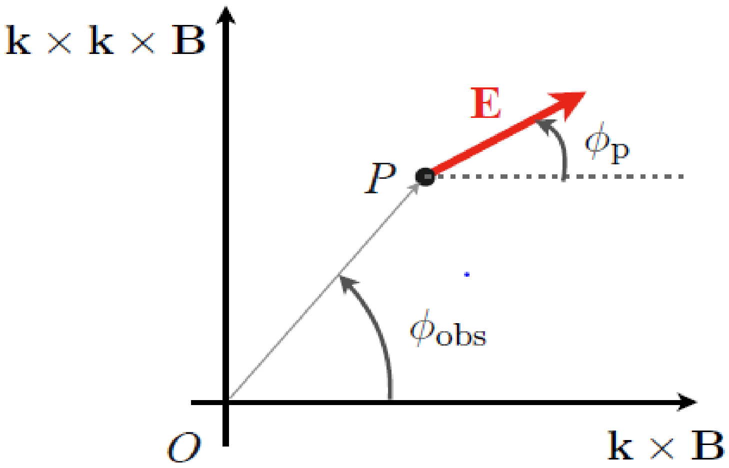
Reconstruction of the polarisation

- We have to define a time window over which we average the traces
- Stokes parameter 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



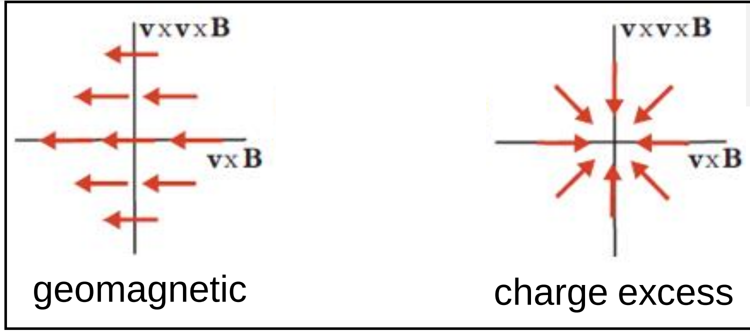


$$\phi_p = 0.5\tan^{-1}\frac{U}{Q}$$

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

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

Reconstruction of the polarisation

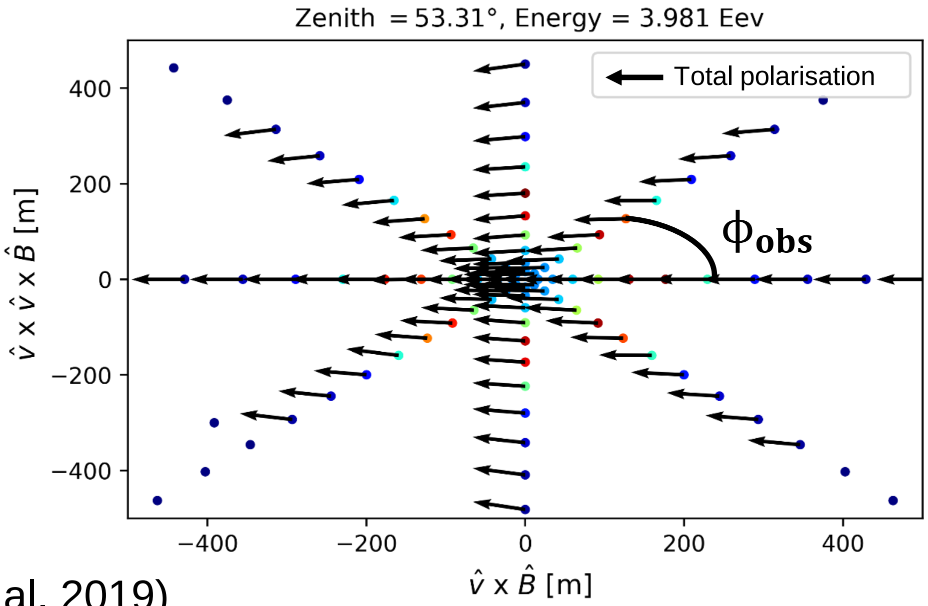


Total polarisation

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)

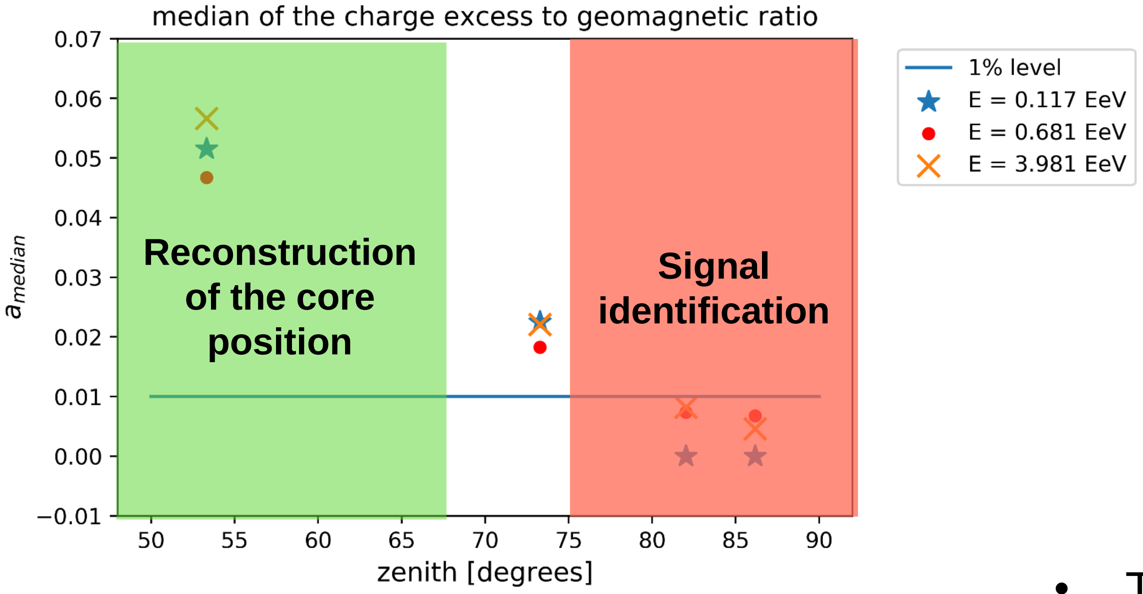
$$E_{\mathrm{ce}} = \frac{E_{\mathrm{v\times v\times B}}}{|\sin\phi_{\mathrm{obs}}|} \qquad E_{\mathrm{geo}} = E_{\mathrm{v\times B}} - E_{\mathrm{v\times v\times B}}\frac{\cos\phi_{\mathrm{obs}}}{|\sin\phi_{\mathrm{obs}}|}$$

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

Signal identification

Ratio of the amplitude of each mechanism

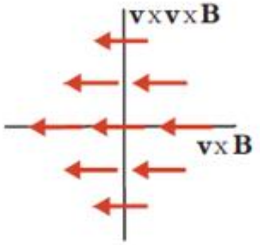
For different simulations



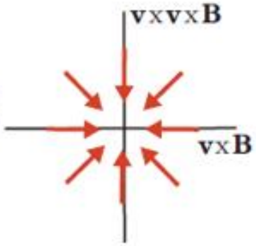
$$a = \sin\alpha \frac{E_{\text{charge excess}}}{E_{\text{geomagnetic}}}$$

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

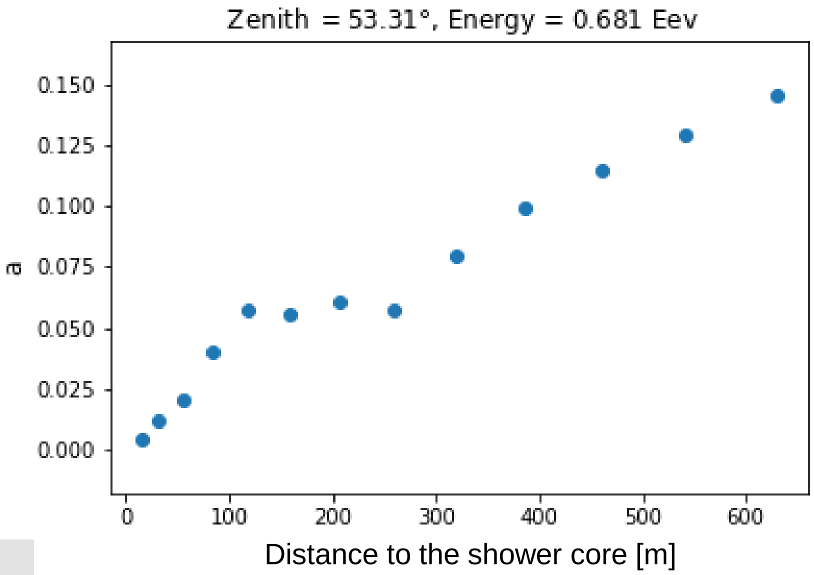
Shower core econstruction

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

The ratio drops to 0 at the core

Increase with the distance to the core

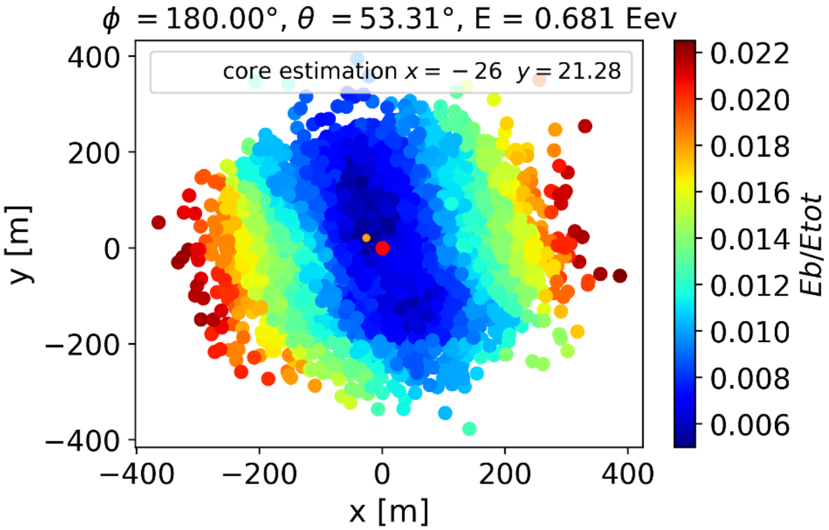
Estimation of the shower core as the position that minimizes the ratio



Method

$$E_b = \boldsymbol{E_{tot}} \cdot \boldsymbol{u_B}$$

- In fact, we used the fraction of the total electric field along **B** (Eb/Etot)
- 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 $\theta \leq 55^\circ$

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