Radio Morphing: Towards a fast computation of air-shower radio emission

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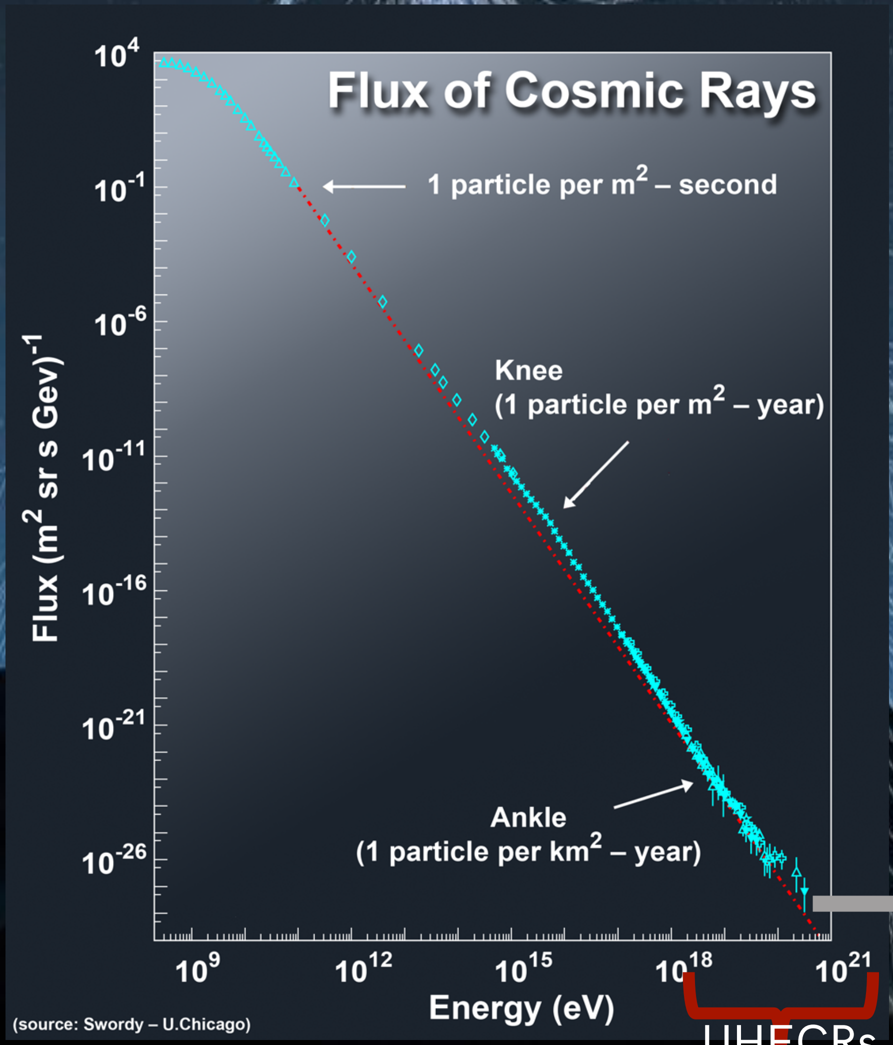
The mystery of ultra-high energy cosmic rays (UHECRs)

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



How huge is 10^{18} eV?

→ A macroscopic energy ($N_a = 10^{23}$) in one given particle

→ 10^5 times higher than the maximal energy reached at LHC

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:
$1 . km^{-2} . century^{-1}$

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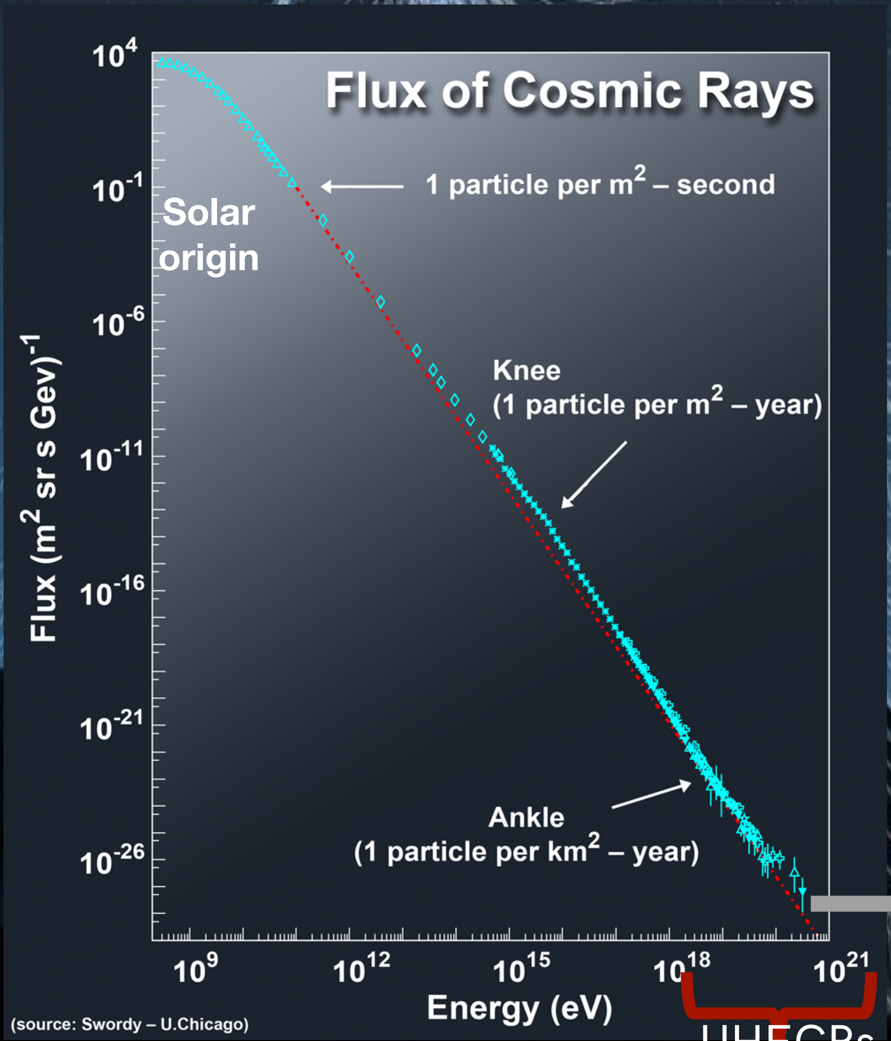

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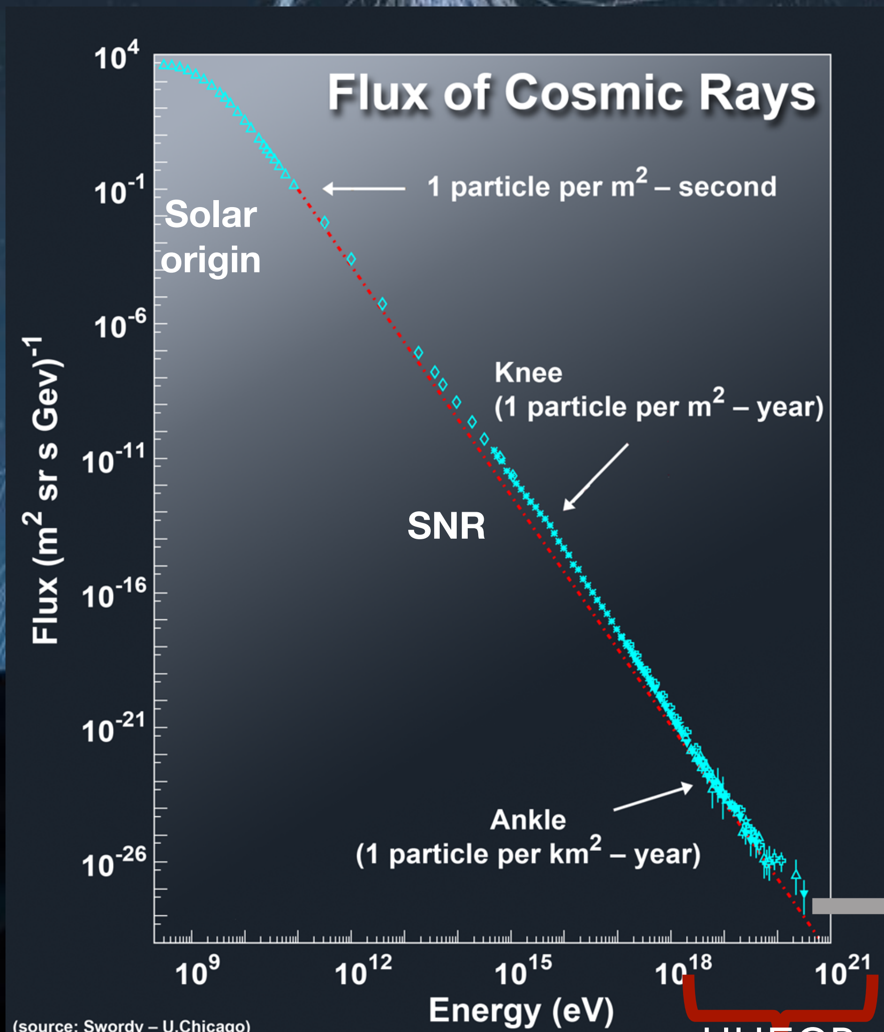

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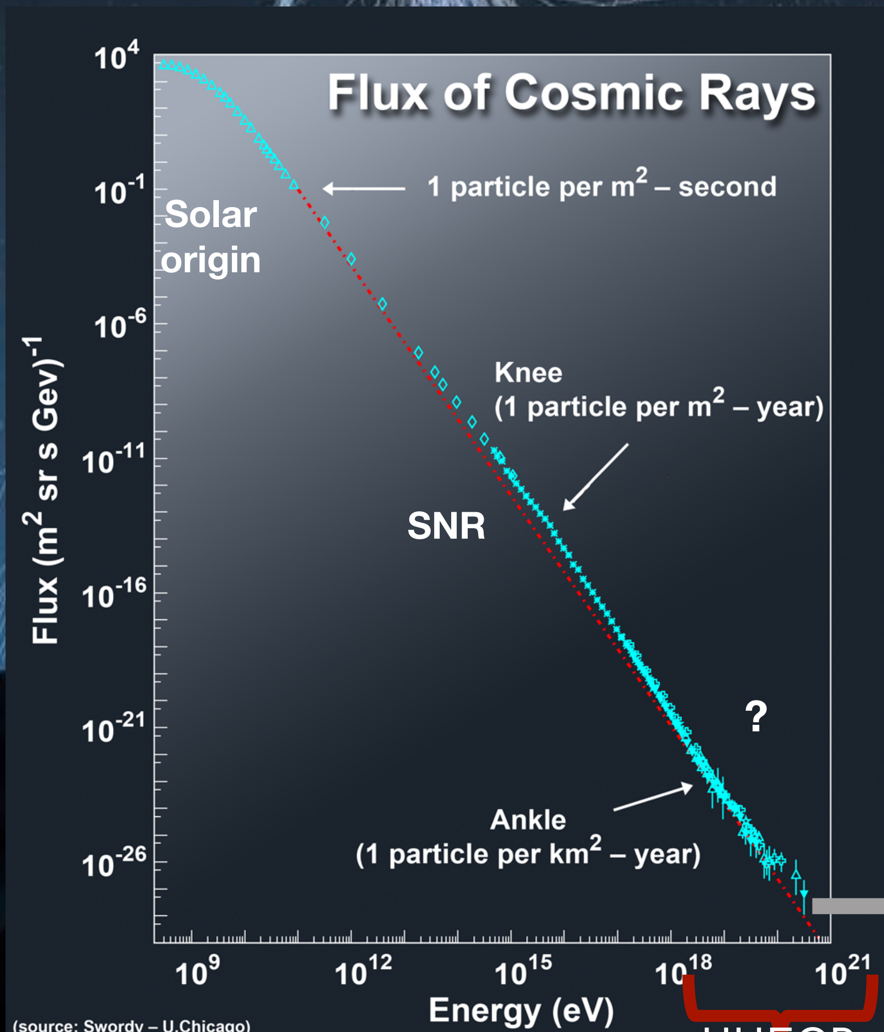

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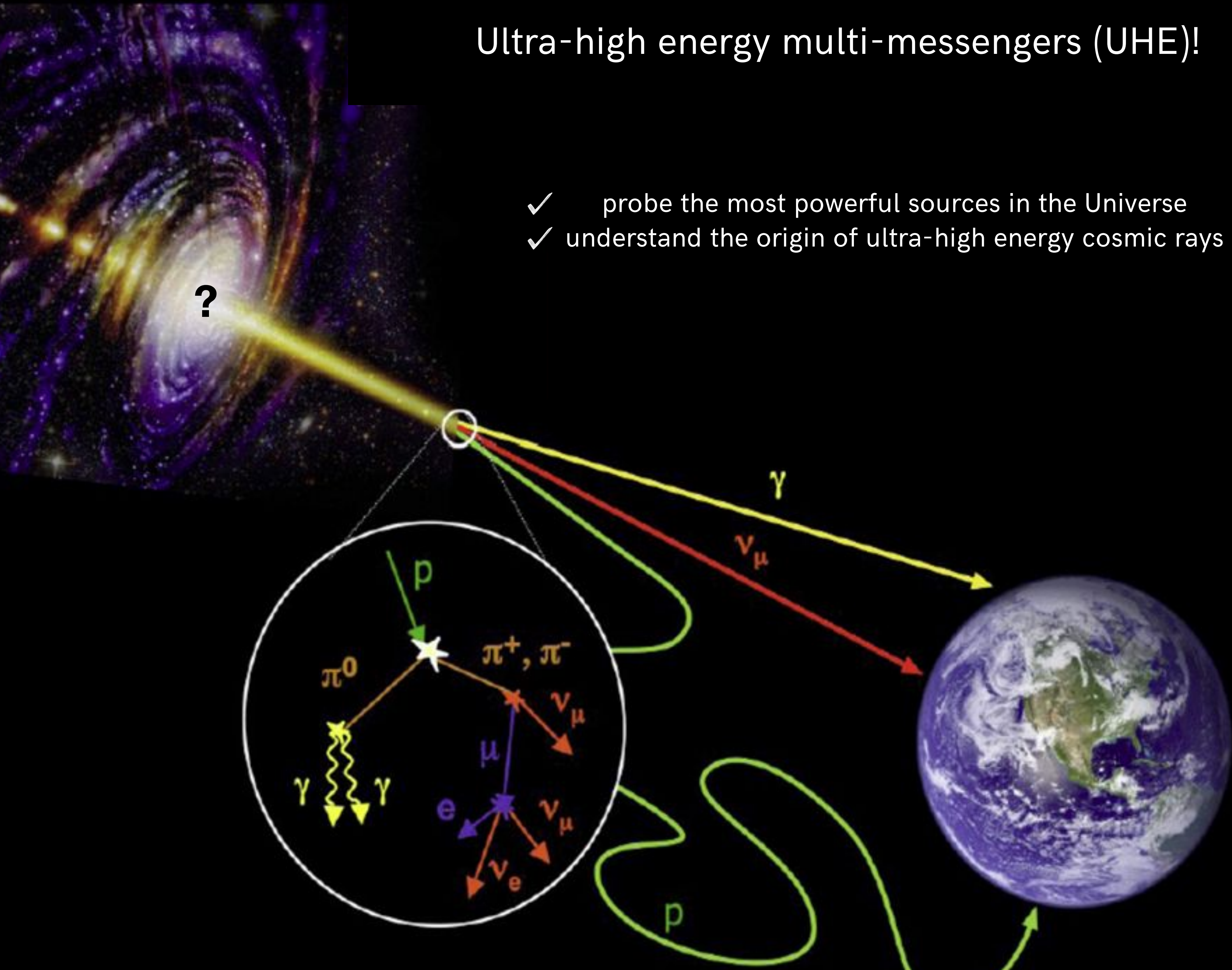
Ultra-high energy multi-messengers (UHE)!

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



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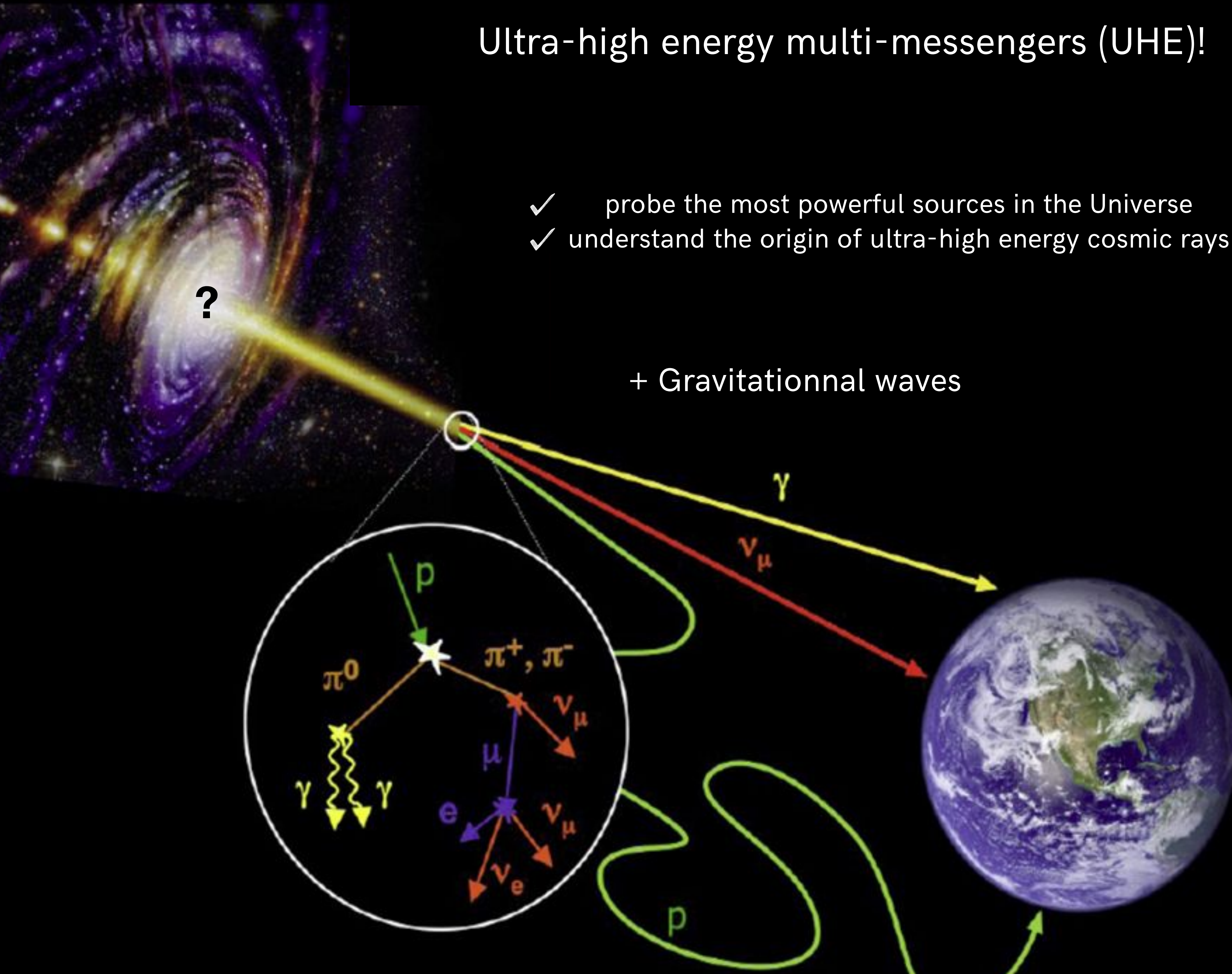
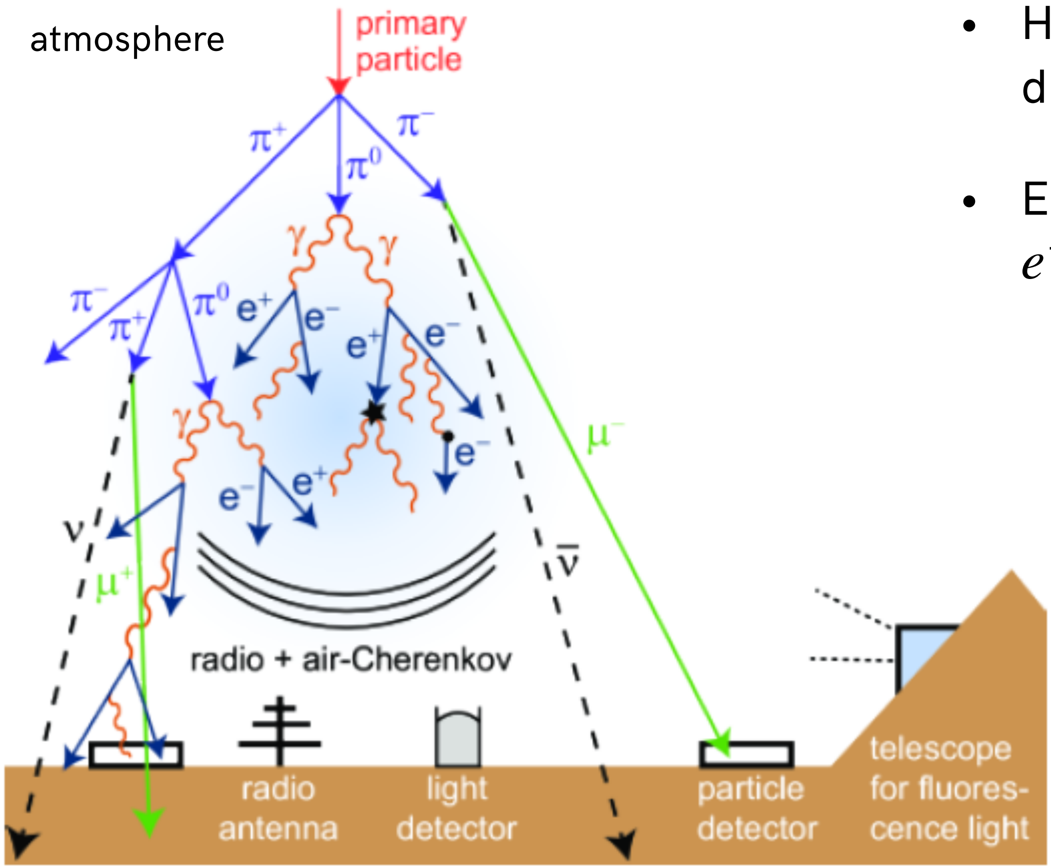
+ Gravitationnal waves



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 component: e^+, e^-, γ

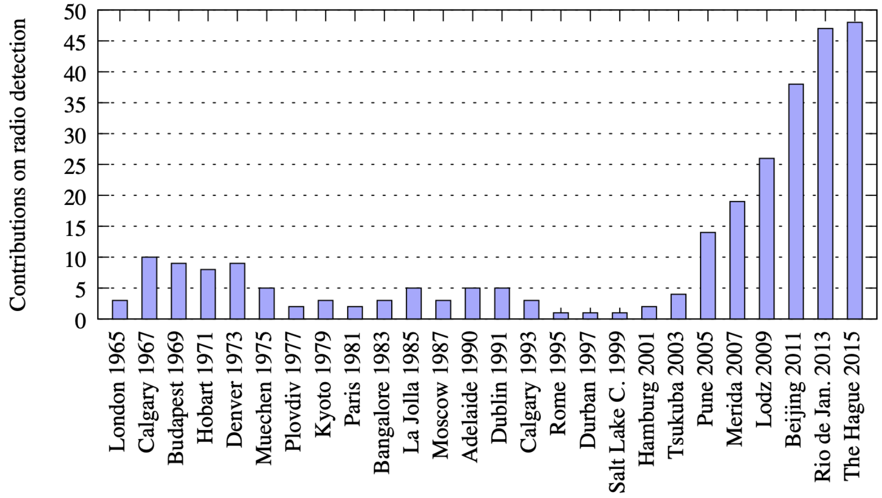
Main emissions:

- Cherenkov light
- Fluorescence light
- Radio emission

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

How to reconstruct shower properties?

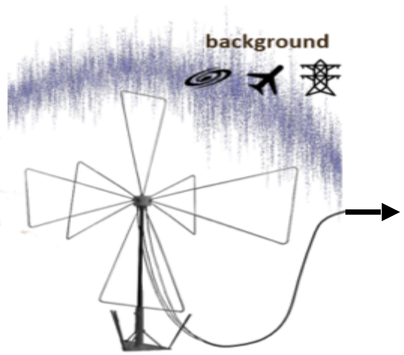
Radio detection of cosmic-rays, a trending and efficient technique:

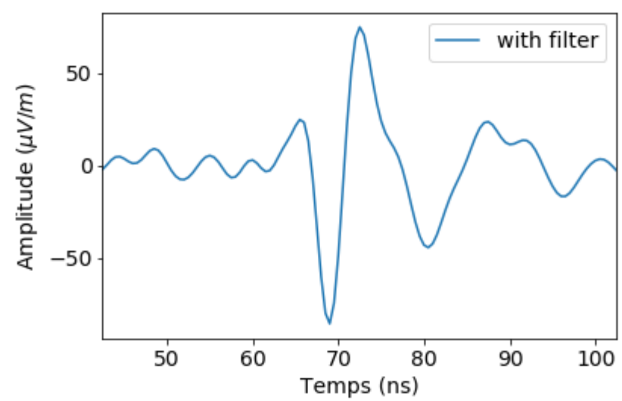


Huege (2016)

cr, γ, ν

E, θ, φ ?





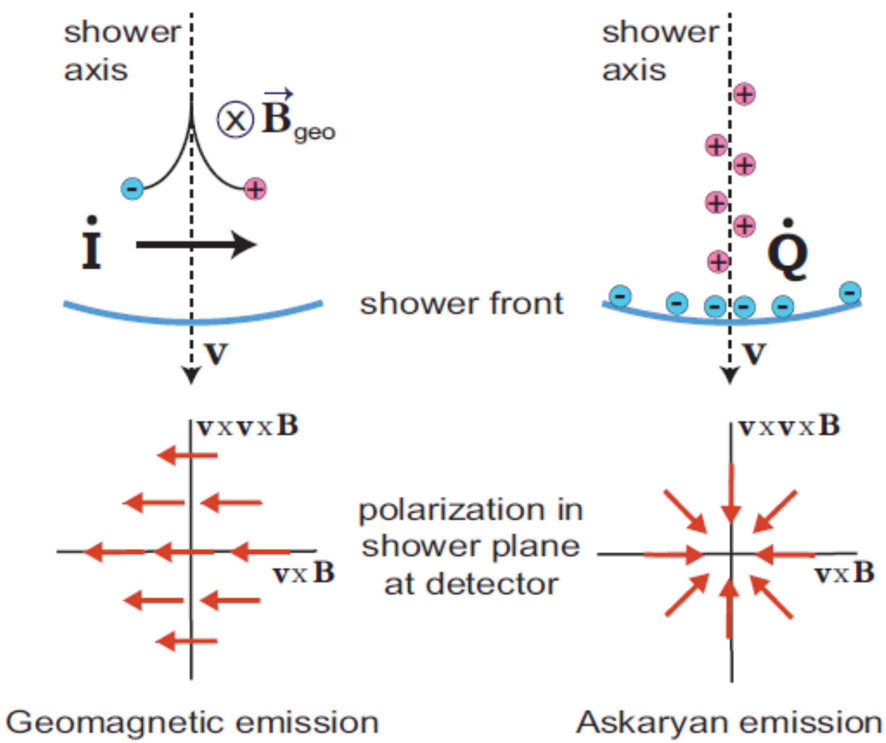
How can we link the experimental measurement of the signal to physical properties of the primary particle?

Fast computation of radio signals from air-showers needed

Radio signal from atmospheric extensive air-showers

Schröder (2017)

2 main sources of emission



Macroscopic approach
(Holt et al., Scholten et al.)

Analytical: **Fast** but many free parameters

Microscopic approach
(Huege et al., Alvarez-Muñiz, et al.)

Monte Carlo simulations: **Accurate** but computationally demanding

Huge number of simulations needed for upcoming large scale radio experiments (GRAND, Auger Prime, RNO-G, Ice Cube Gen2 radio)

We need a **fast** and **accurate** tool to model the radio emission: *Radio Morphing*

Radio Morphing principle

Universality of air-shower (Giller et al., Góra et al.)

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

Reference shower

ZHAireS simulation
$(\mathscr{E}_r, \theta_r, \varphi_r)$

scaling of the electric field

f$(\mathscr{E}_r, \theta_r, \varphi_r, \mathscr{E}_t, \theta_t, \varphi_t)$

Target shower

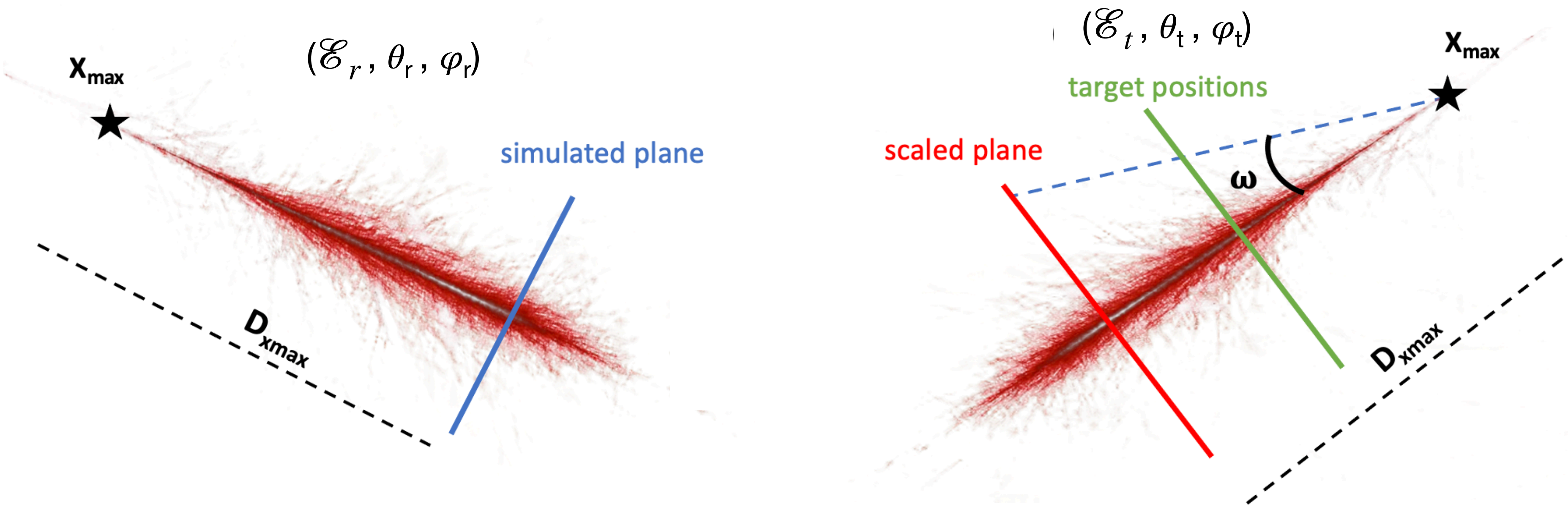
Radio Morphing simulation $(\mathscr{E}_t, \theta_t, \varphi_t)$

- The scaling relies on simple physical principles of electromagnetism
- Hadronic interactions are only computed once (for the reference showers)

Gain in computation time of several orders of magnitude

Radio Morphing principle

Aim: To infer the radio signal from any air-shower at any position



Version 1 (1811.01750, Zilles et al.) with limitations

Improvements: Scaling with **θ**, shower-to-shower fluctuations, time traces interpolation

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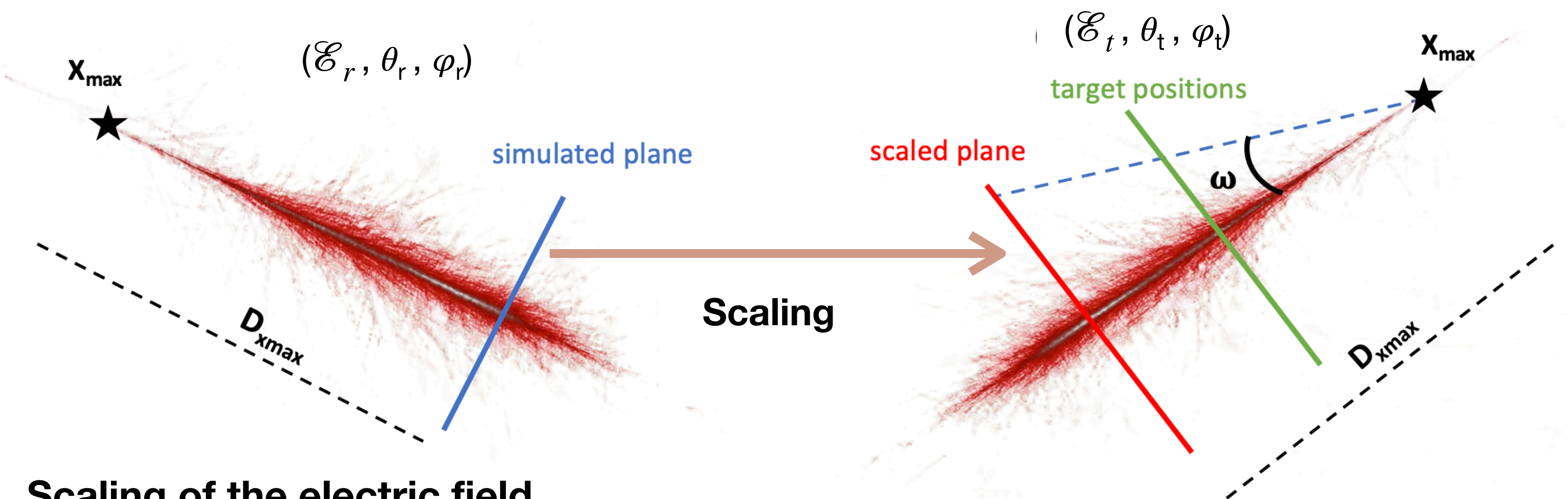

Scaling of the electric field

Scaling with the primary energy $E^t = \dfrac{\mathscr{E}_t}{\mathscr{E}_r} E^r$ Scaling with the azimuth angle $E^t_{v\times B} = \dfrac{\sin\alpha_t}{\sin\alpha_r} E^r_{v\times B}$

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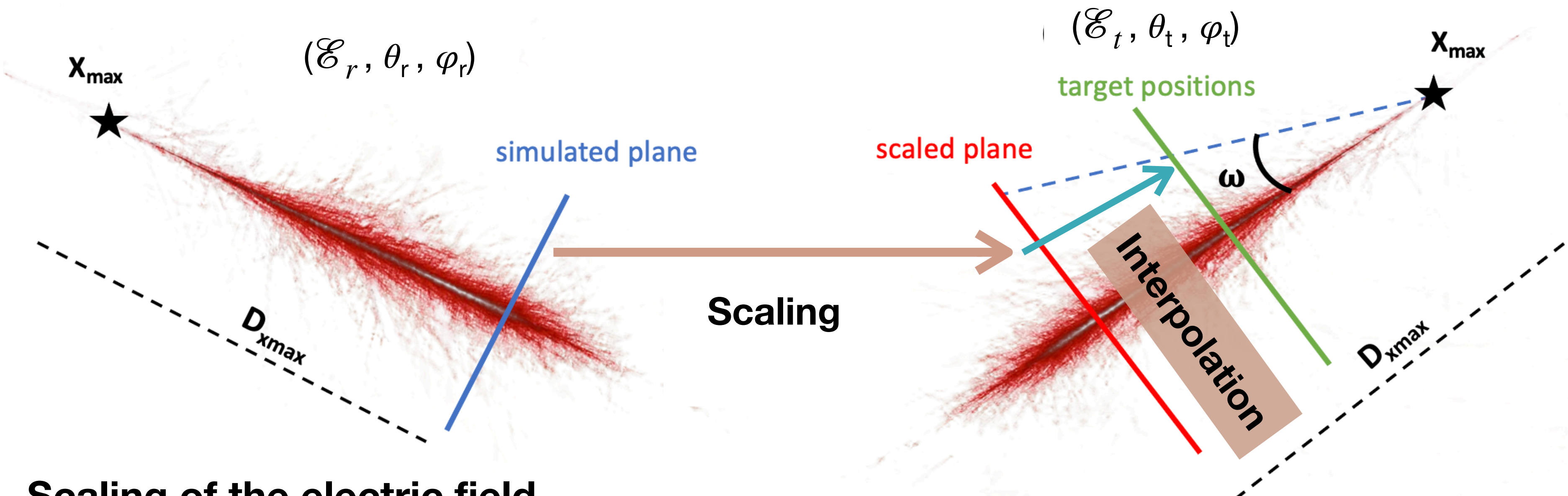

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Interpolation

2D interpolation (in the shower plane) 3D extrapolation (along the propagation axis)

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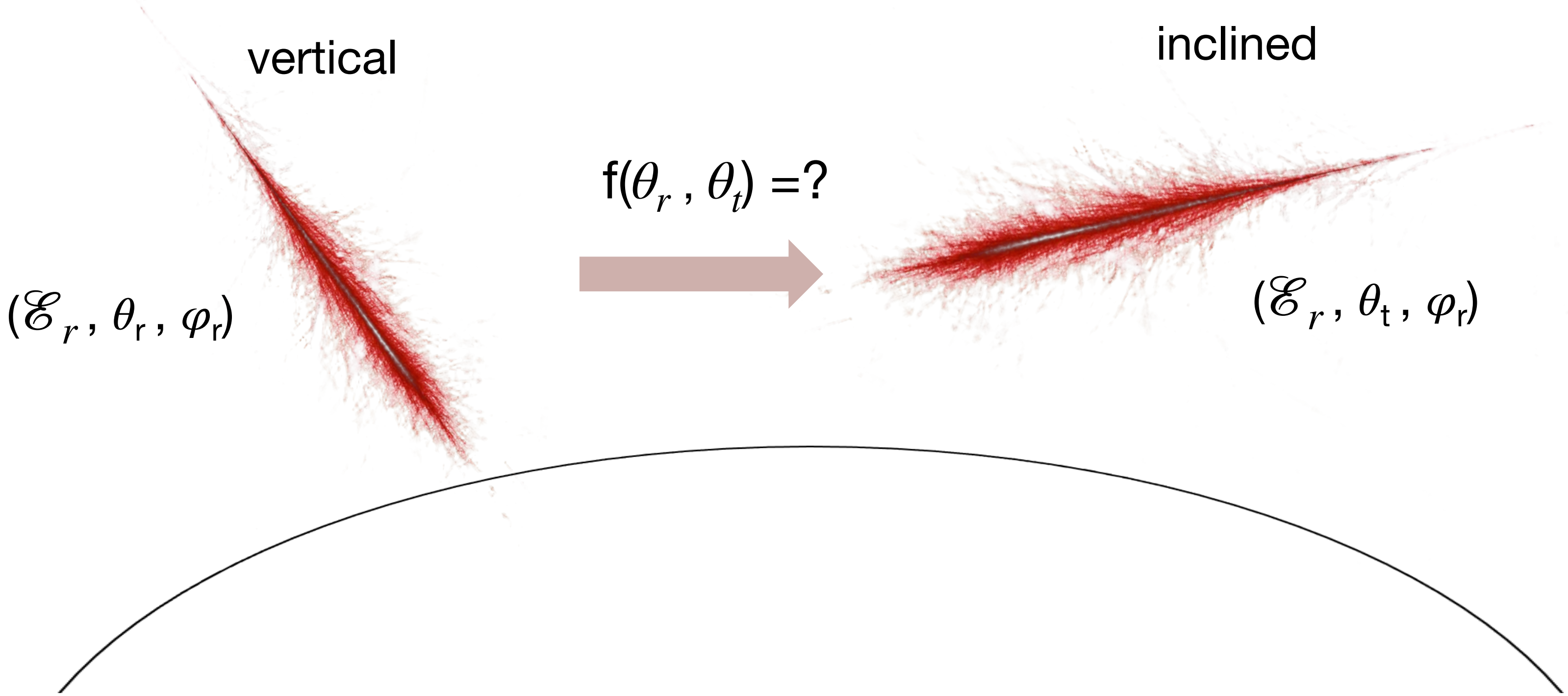
Scaling with the zenith angle

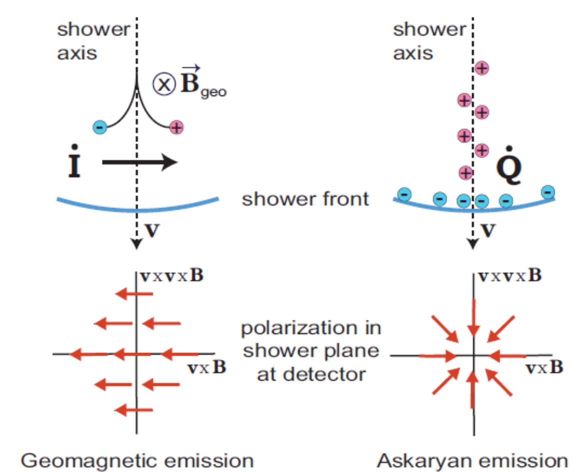


Vertical showers should develop in denser atmosphere than inclined showers

Additionally we have:

$$E_{\mathrm{geo}} = E_{\mathrm{geo}}(\rho) \qquad \text{and} \qquad E_{\mathrm{ce}} = E_{\mathrm{ce}}(\rho)$$

We need $\mathbf{E}_{\mathrm{geo}}$ and $\mathbf{E}_{\mathrm{ce}}$ dependency with air-density!



Geomagnetic and charge excess dependency with air-density

11000 ZHAireS simulations with various energy and arrival directions

Along the $\mathbf{v} \times \mathbf{v} \times \mathbf{B}$ baseline of antennas we have: $E_{\mathrm{geo}} = E_{v\times B}$ and $E_{\mathrm{ce}} = E_{v\times v\times B}$

Reconstruction of the radiated energy $E_{\mathrm{rad}} = \int_0^{2\pi} d\phi \int_0^{\infty} |E|^2 r\mathrm{dr}$ $\rightarrow E_{\mathrm{rad,\,geo}}, E_{\mathrm{rad,\,ce}}$

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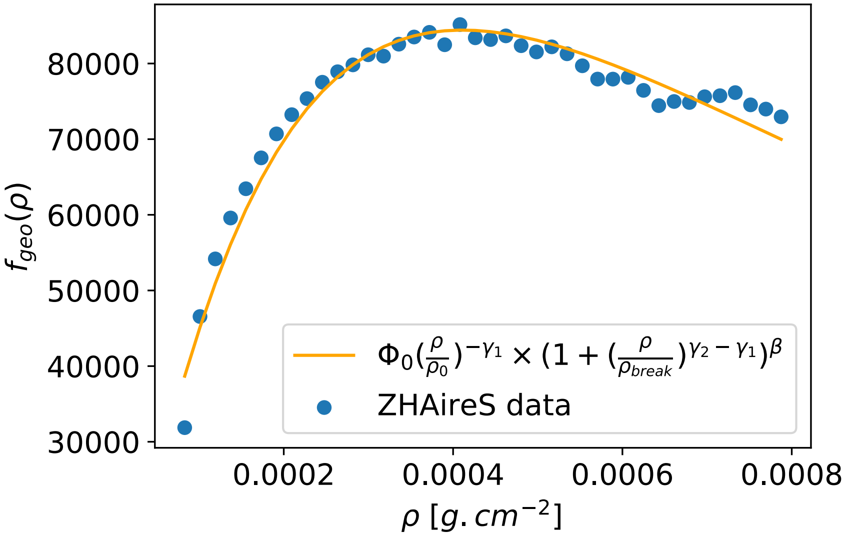
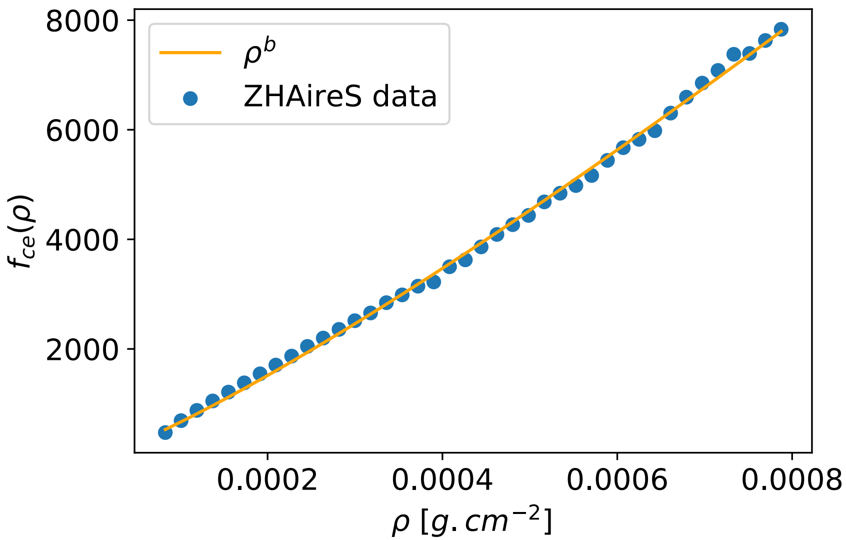
$$f_{\mathrm{geo}}(\rho) = \sqrt{E_{\mathrm{rad,\,geo}}/(\mathscr{E} \times \sin\alpha)^2}$$



$$f_{\mathrm{ce}}(\rho) = \sqrt{E_{\mathrm{rad,\,ce}}/\mathscr{E}^2}$$



Scaling with zenith angle: $E^t_{\mathrm{v\times B}} = \dfrac{f_{\mathrm{geo}}(\rho^t_{\mathrm{xmax}})}{f_{\mathrm{geo}}(\rho^r_{\mathrm{xmax}})} E^r_{\mathrm{v\times B}}$ $\quad E^t_{\mathrm{v\times v\times B}} = \dfrac{f_{\mathrm{ce}}(\rho^t_{\mathrm{xmax}})}{f_{\mathrm{ce}}(\rho^r_{\mathrm{xmax}})} E^r_{\mathrm{v\times v\times B}}$

Test of the scaling procedure

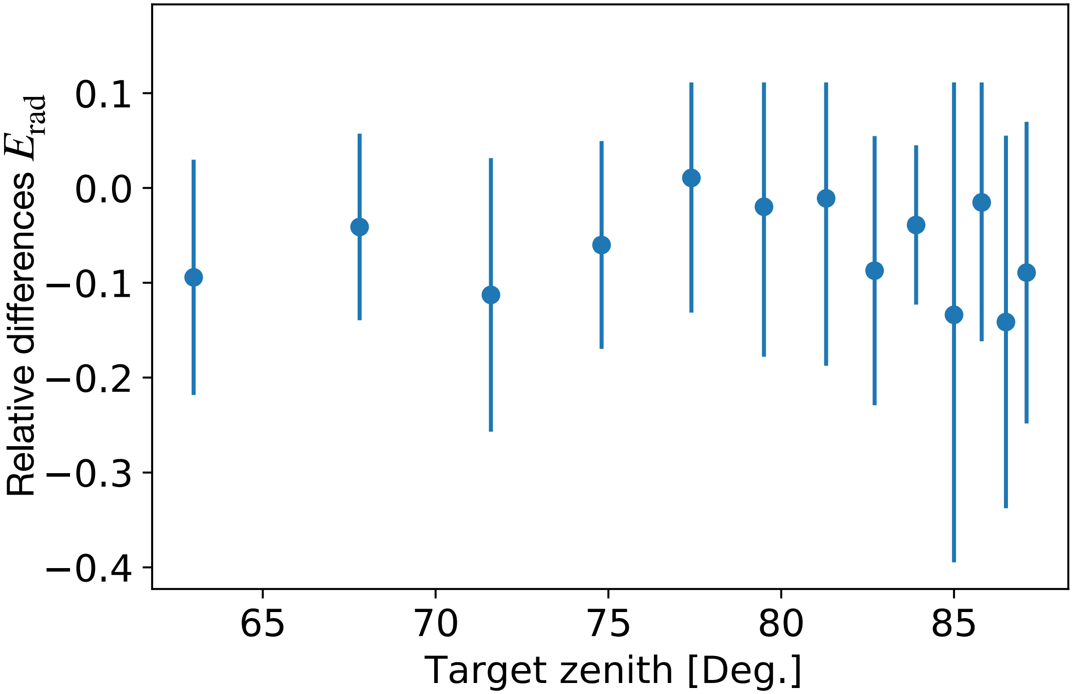
5 showers Reference library: $\mathscr{E}^r = 3.98\,\mathrm{EeV}$, $\phi^r = 90°$ (West), $\theta^r = [67.8, 74.8, 81.3, 83.9, 86.5]$

1200 target showers: $\mathscr{E}^t = [0.1 - 4]\,\mathrm{EeV}$, $\phi^t = [0 - 360]$, $\theta^t = [60 - 90]$

comparison to ZHAireS simulations with corresponding parameters

Relative differences between ZHAireS and Radio Morphing

$$(E_{\mathrm{rad}}^{\mathrm{RM}} - E_{\mathrm{rad}}^{\mathrm{ZHAireS}})/E_{\mathrm{rad}}^{\mathrm{ZHAireS}}$$

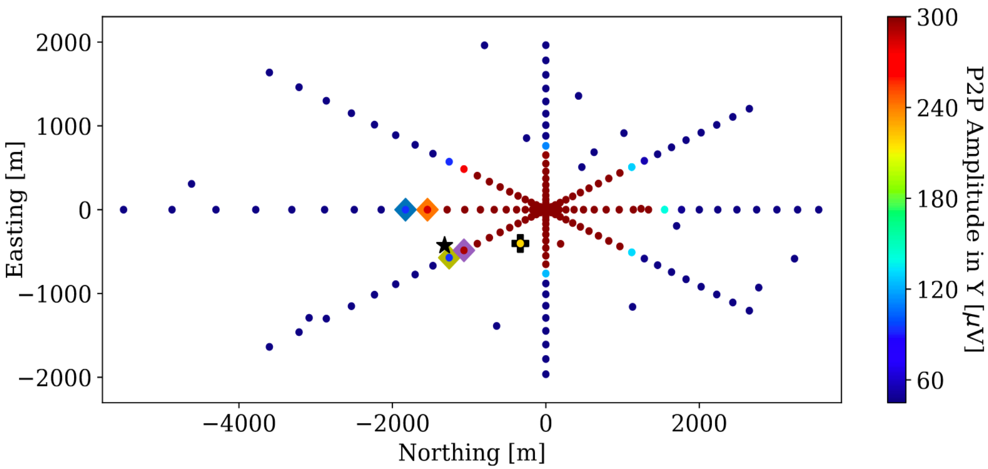


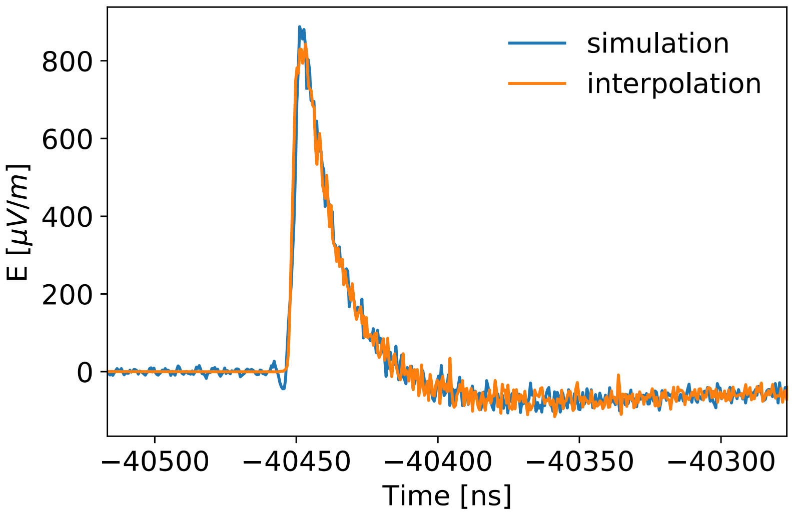
Mean relative differences between radiated energies of ~ 10%!

2D interpolation of the radio signal

We want to infer the radio signal at any position in space

Linear interpolation from https://arxiv.org/pdf/2008.06454.pdf (Tueros, Zilles, 2020)





(Tueros, Zilles, 2020)

Fourier space: Electric field time traces decomposed into a phase φ and an amplitude $\mathscr{A}$ interpolated independently

- Timing accuracy of a fraction of nanosecond
- Relative differences on the peak amplitude of a few percent when outside of the Cerenkov cone

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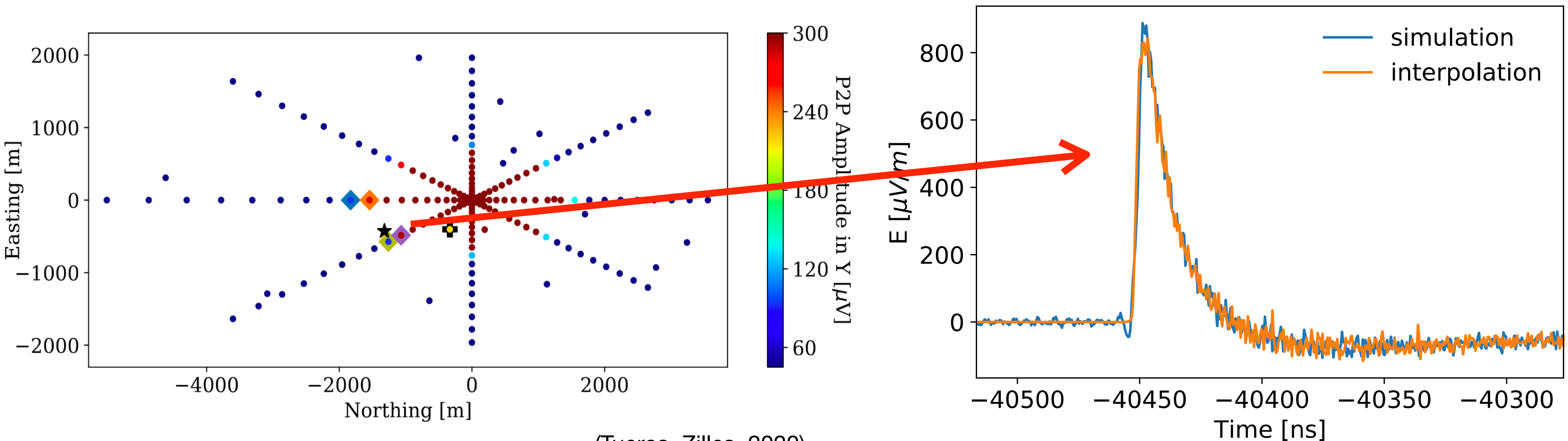

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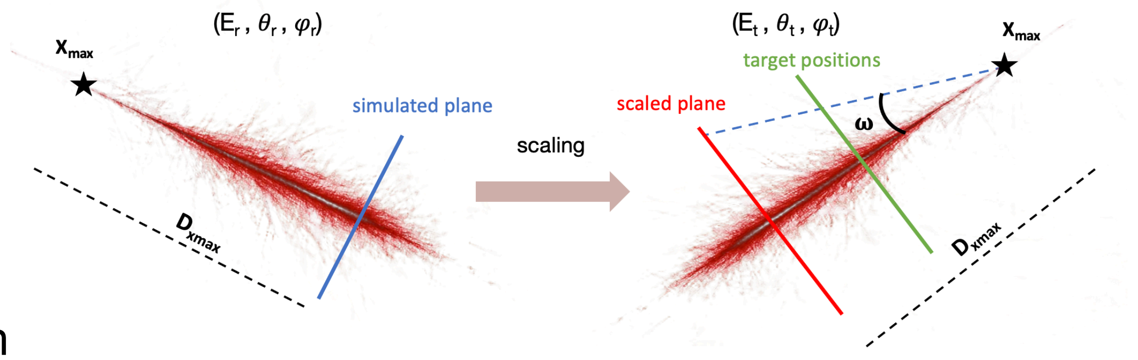
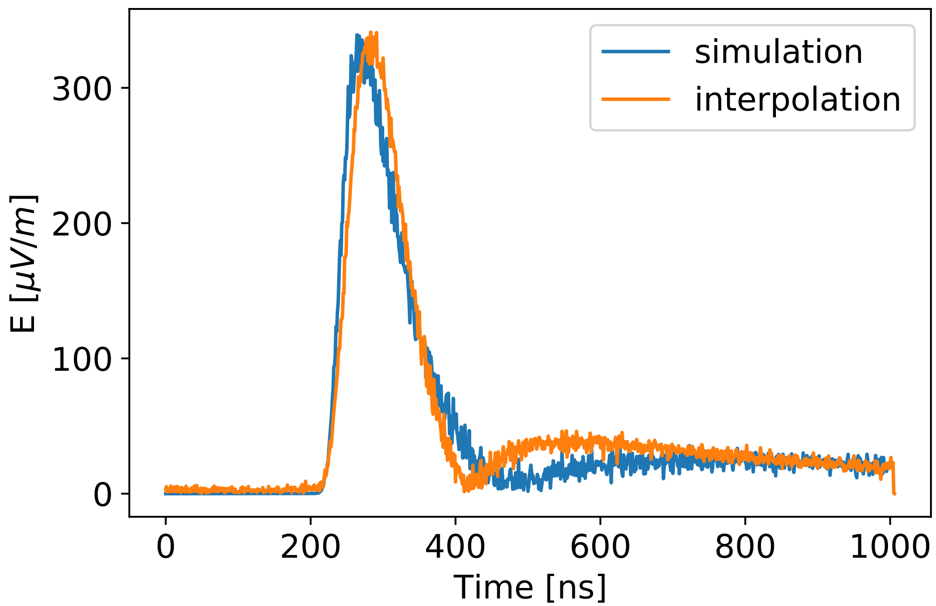
3D extrapolation: correcting for propagation effects

Aim: extrapolate the radio signal at any position along the shower axis



We have to correct for propagation

3D extrapolation after scaling



Relative difference with ZHAireS on the peak amplitude and the integral < 5%

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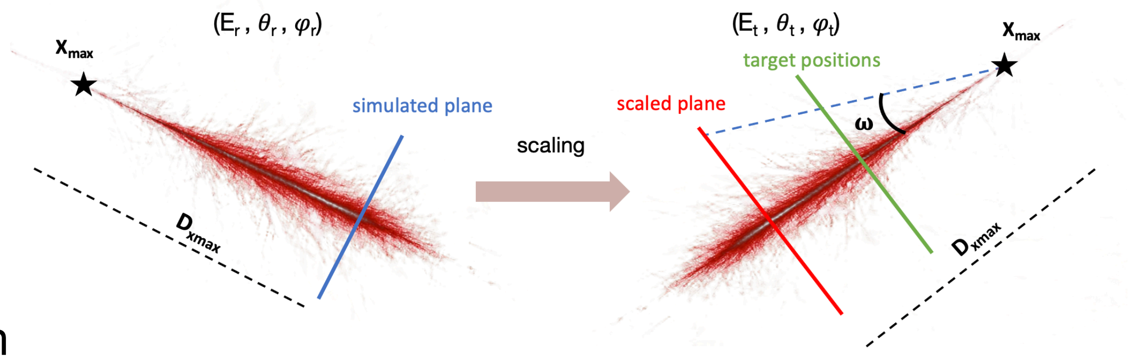

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- **Dilution of the radio signal**

$$E_{\text{target}} = \frac{D_{\text{scaled}}}{D_{\text{target}}} E_{\text{scaled}}$$

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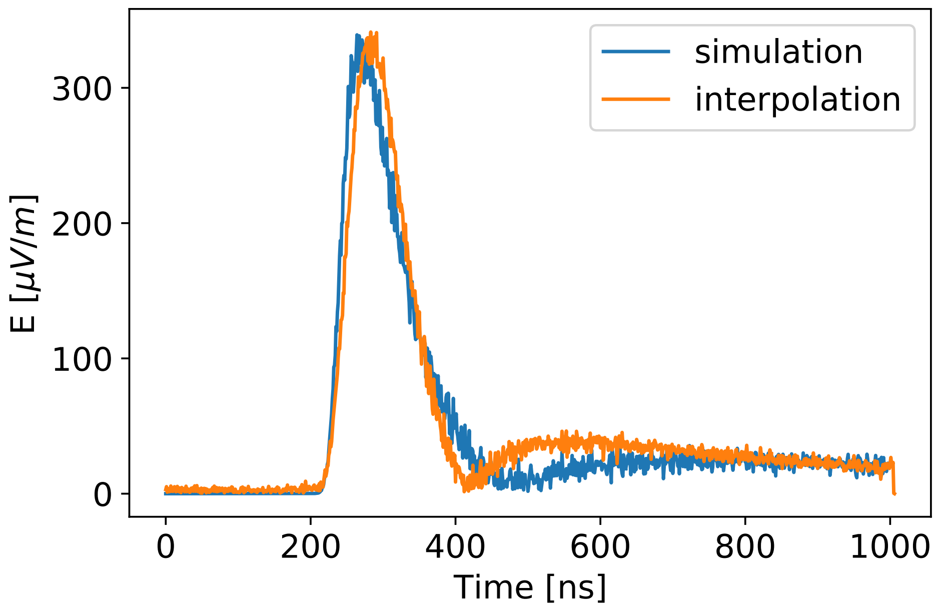

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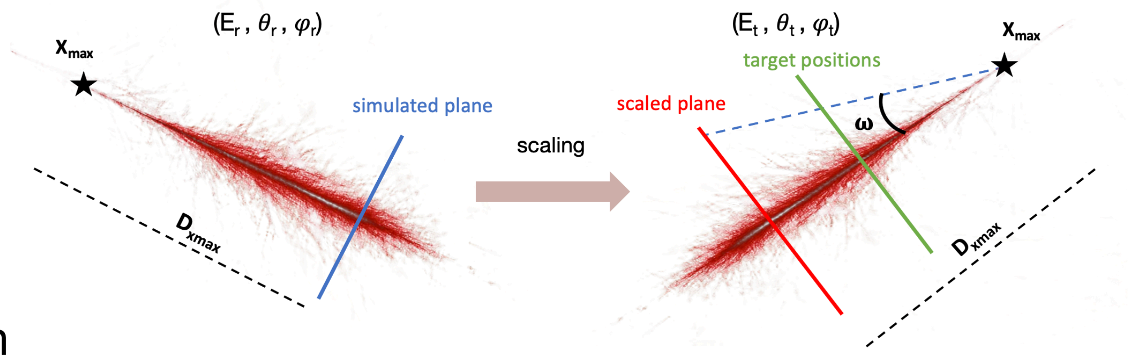

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- **Dilution of the radio signal**

$$E_{\text{target}} = \frac{D_{\text{scaled}}}{D_{\text{target}}} E_{\text{scaled}}$$

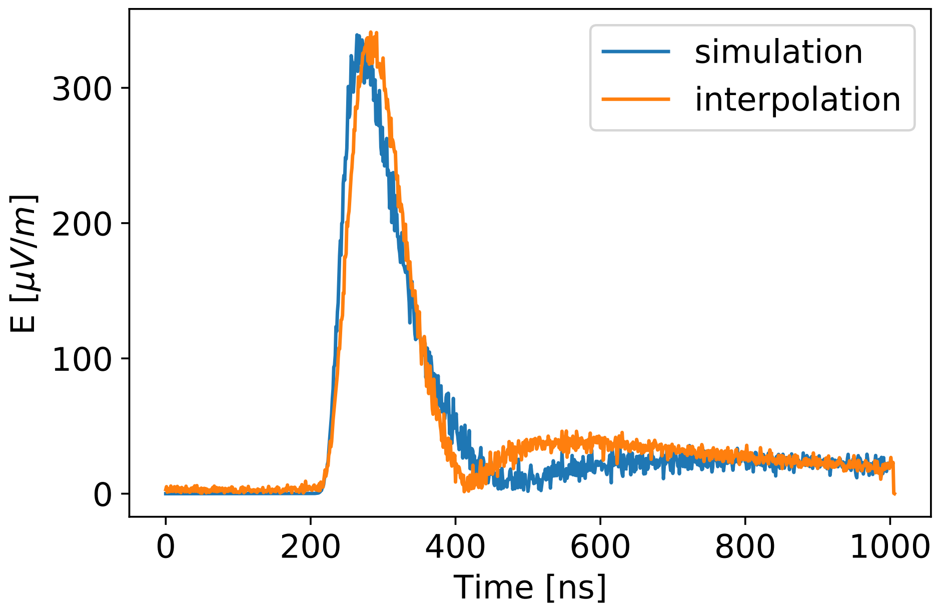
- **Variation of the refractive index $\bar{\mathbf{n}}$**

$$k_{\text{stretch}} = \theta_{\text{cer}}(\bar{n}_{\text{scaled}})/\theta_{\text{cer}}(\bar{n}_{\text{target}})$$

$$E_{\text{target}} = k_{\text{stretch}} E_{\text{scaled}}$$

$$\mathbf{x}_{\text{target}} = \mathbf{x}_{\text{scaled}}/k_{\text{stretch}}$$

3D extrapolation after scaling



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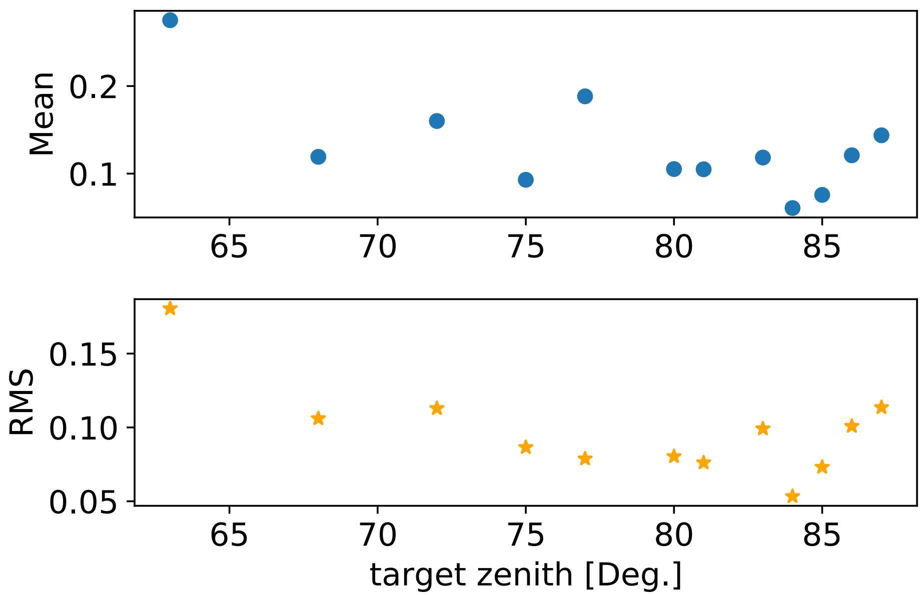
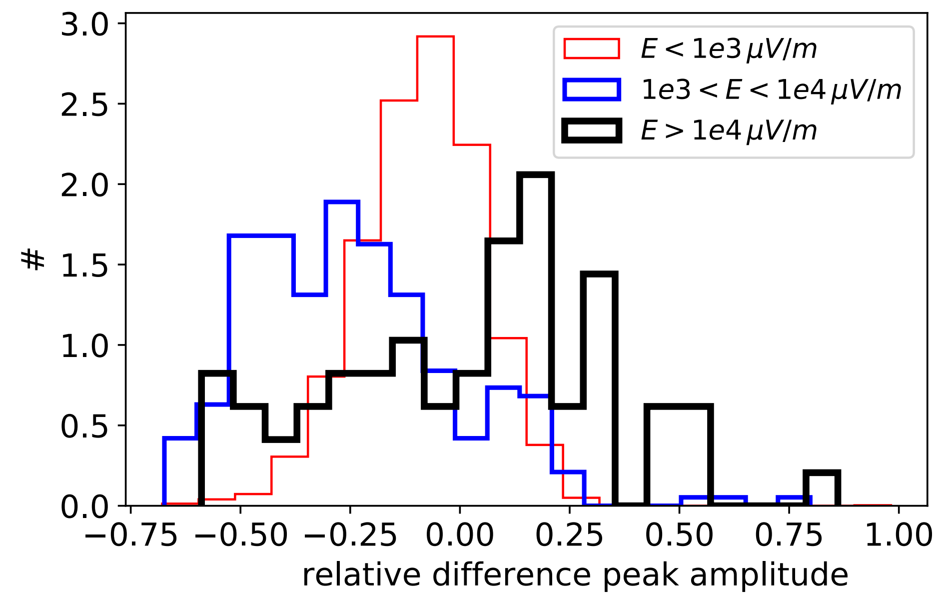
Radio Morphing results

Test of the whole Radio Morphing process (scaling + 3D extrapolation) for 1200 cosmic-ray air-shower 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%

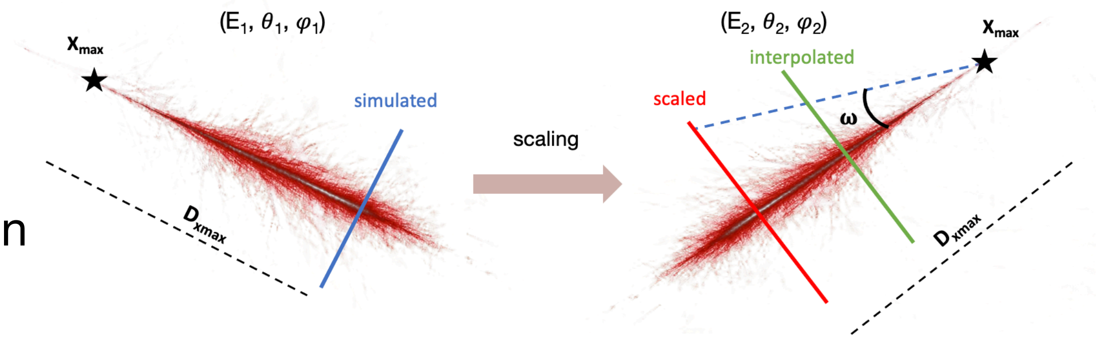
91% of antennas with relative differences < 10%

Conclusion

Radio Morphing: A fast and accurate tool for air-shower radio signals computation

Principle

- Scaling of the electric field
- 2D interpolation and 3D extrapolation



Performances (compared with Monte-Carlo simulations)

- Accuracy: relative differences on the peak amplitude **< 10% for 91% of antennas**
- Computation time: gain of **2 orders of magnitude**

Next steps

- Include Askaryan emission in the scaling with Φ
- Enable to use an input value for Earth magnetic field

Even more accurate and universal method