# Methods to measure the cosmic-ray composition with the Auger Engineering Radio Array

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for the Pierre Auger Collaboration

ARENA 2018

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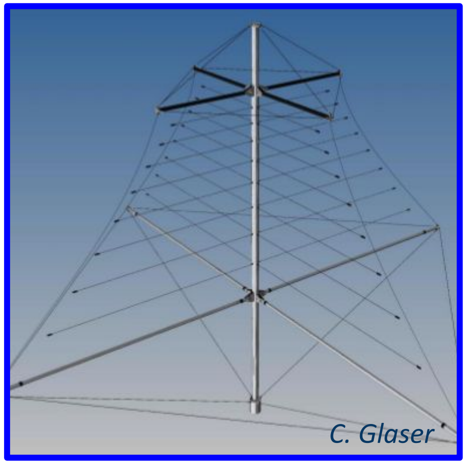
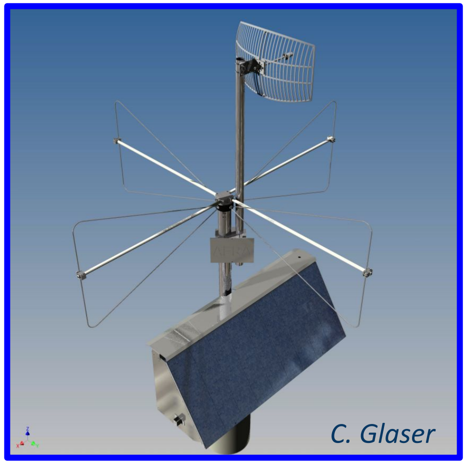
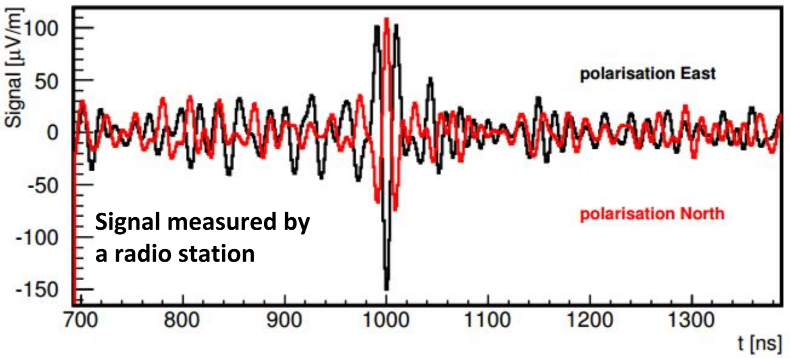
PIERRE AUGER OBSERVATORY
AERA Auger Engineering Radio Array

# The Auger Engineering Radio Array

- **153** radio **antenna stations** spread over **17 km²** in the Argentinean pampa
- Sensitive to the frequency range of **30 to 80 MHz**
- Located within the **particle detector array** and in the field of view of **fluorescence telescopes** of the Pierre Auger Observatory

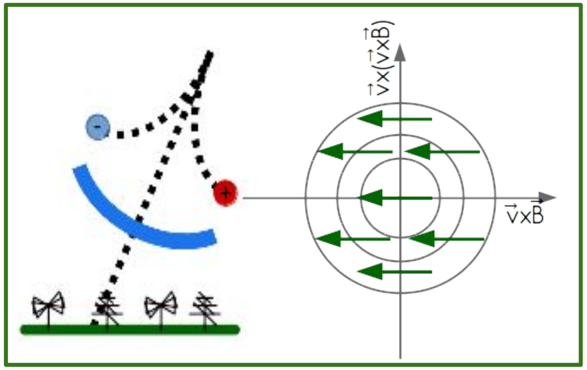


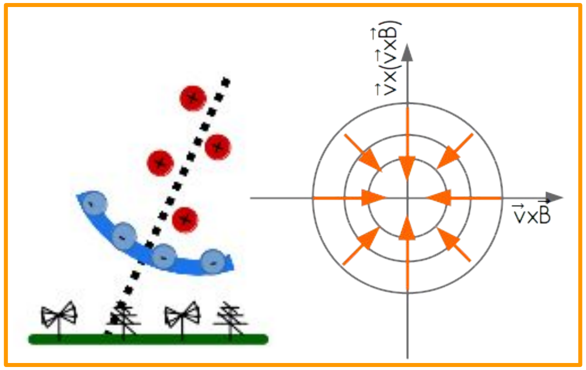



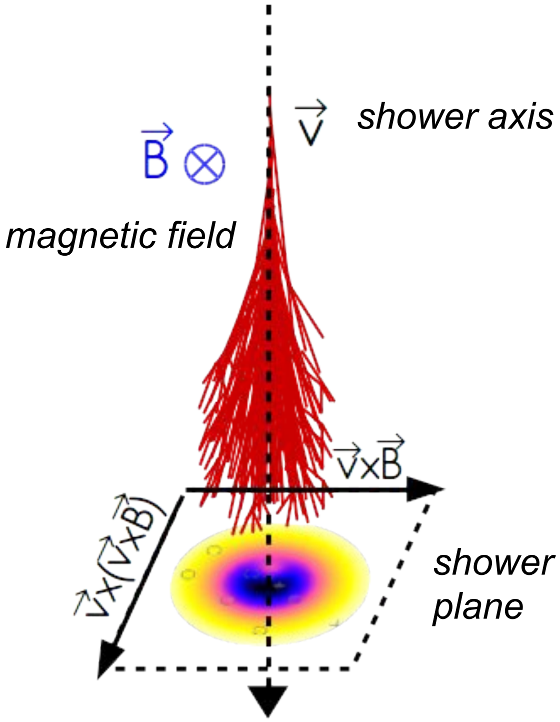
# Radio emission from extensive air showers

- **Geomagnetic:**
  - $e^+$ and $e^-$ separation in the Earth magnetic field
  - radiation linearly polarized in the direction of the Lorentz force




- **Charge excess:**
  - longitudinal charge imbalance
  - radiation radially polarized towards the shower axis



# Radio emission from extensive air showers

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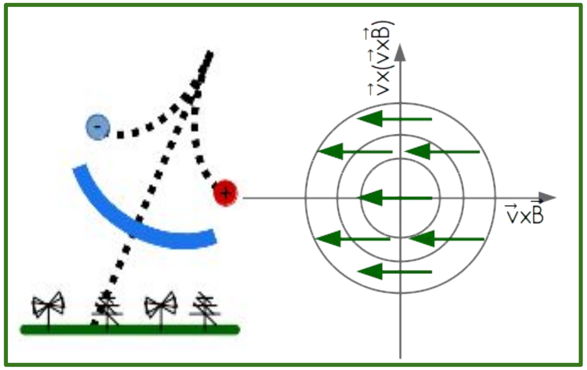


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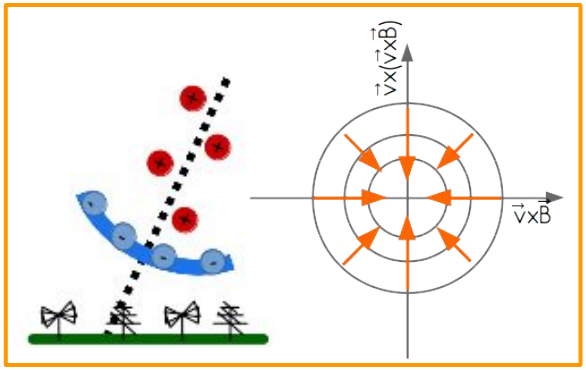
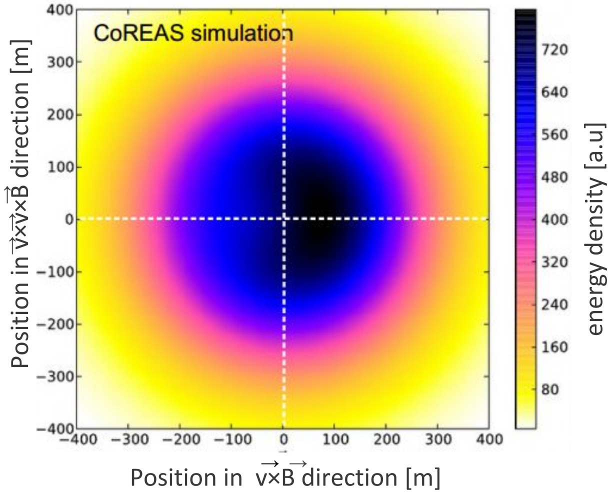
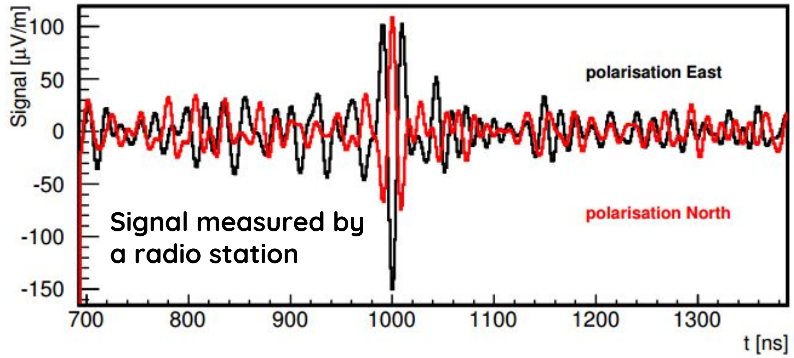



## Asymmetric footprint



# Mass composition techniques

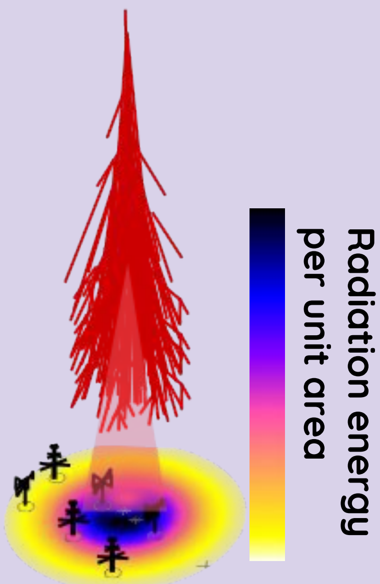



Peak of the Hilbert envelope

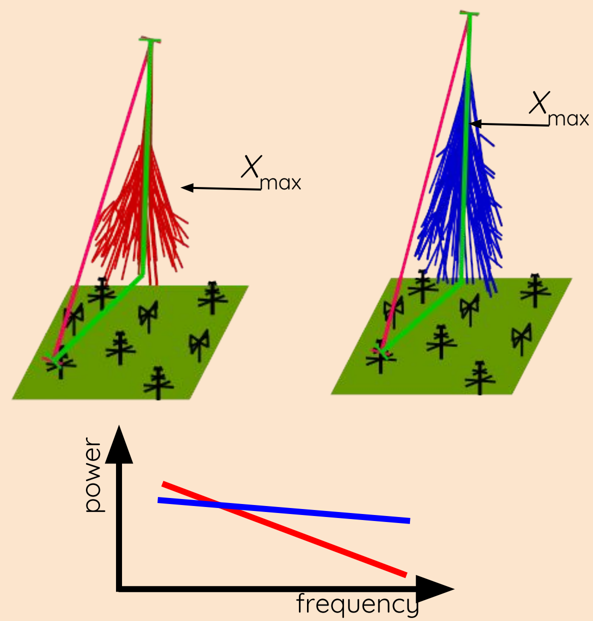
Fourier Transformation

Signal arrival time

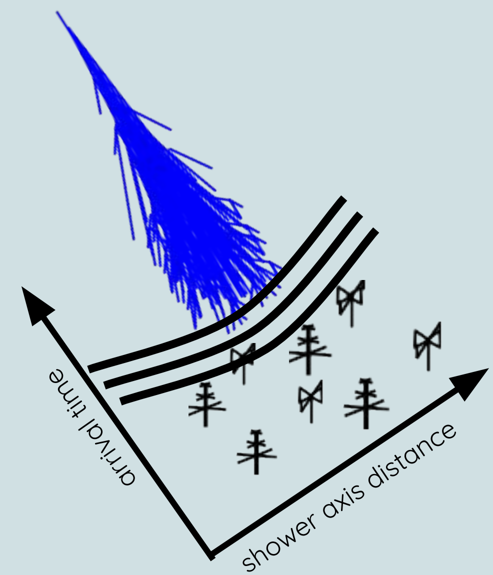
1. $X_{max}$ from the energy density footprint




2. $X_{max}$ from spectral information




3. $X_{max}$ from the arrival time fit

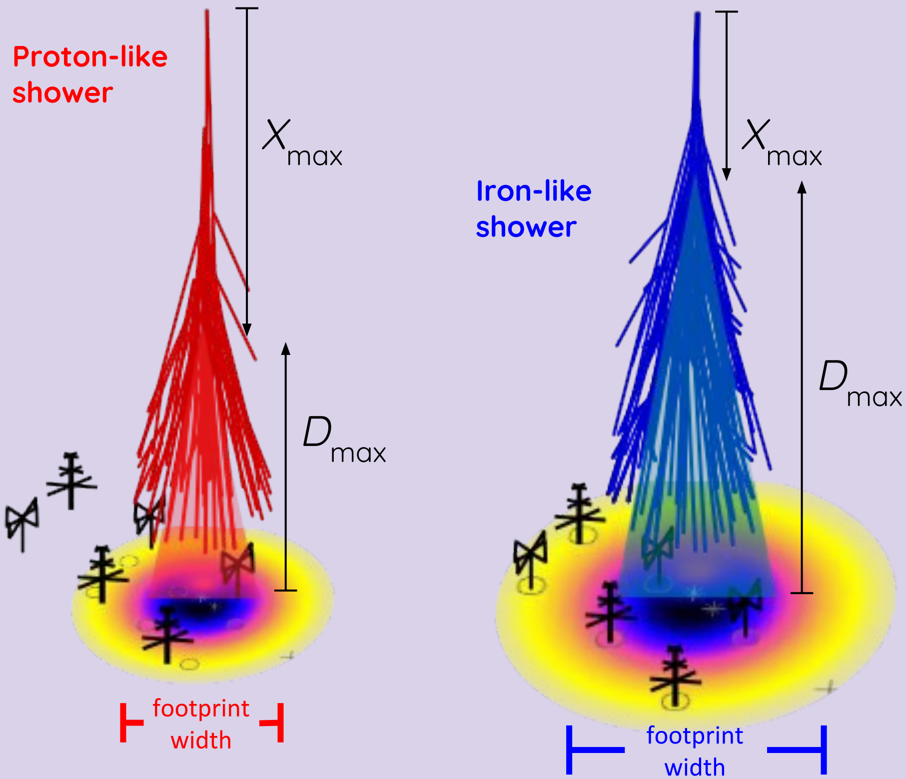


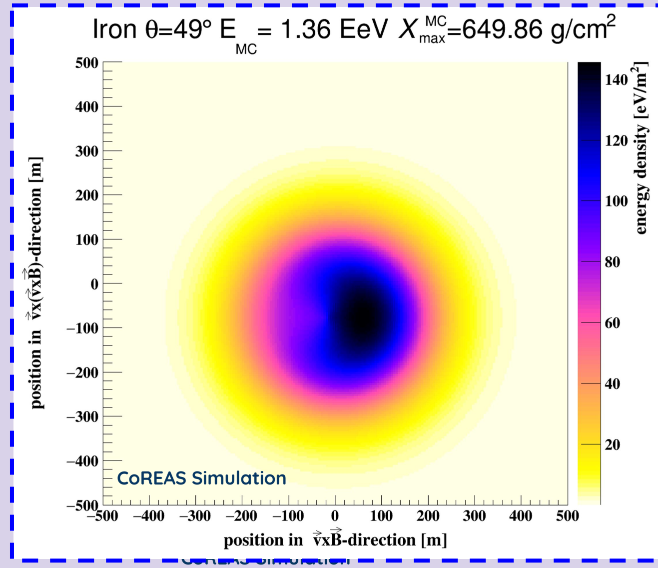
# Xmax from the energy density footprint

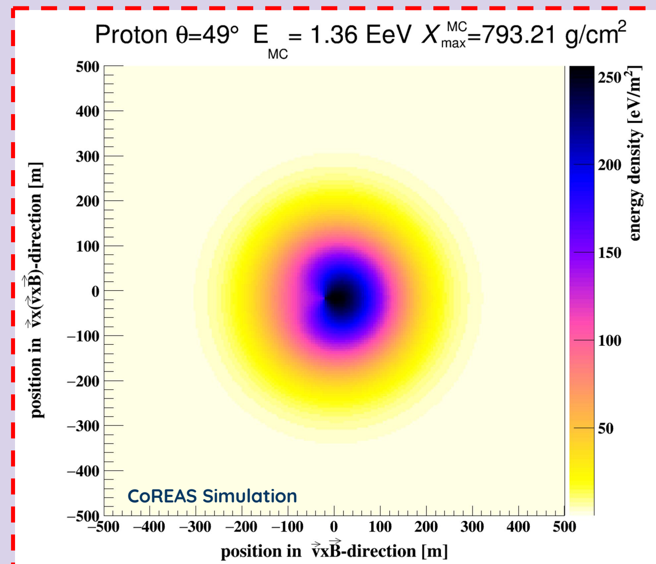
**1.** **Parametrizations of the energy density distribution:**

a. subtraction of two gaussians

b. description of the geomagnetic and charge excess mechanisms



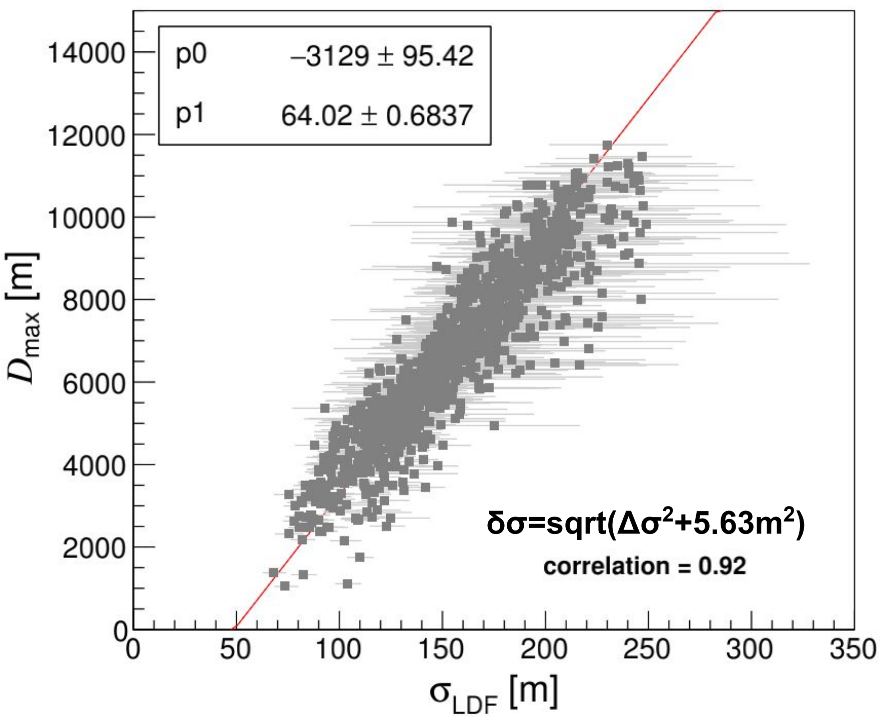
# $X_{max}$ from the energy density footprint

## 1.a

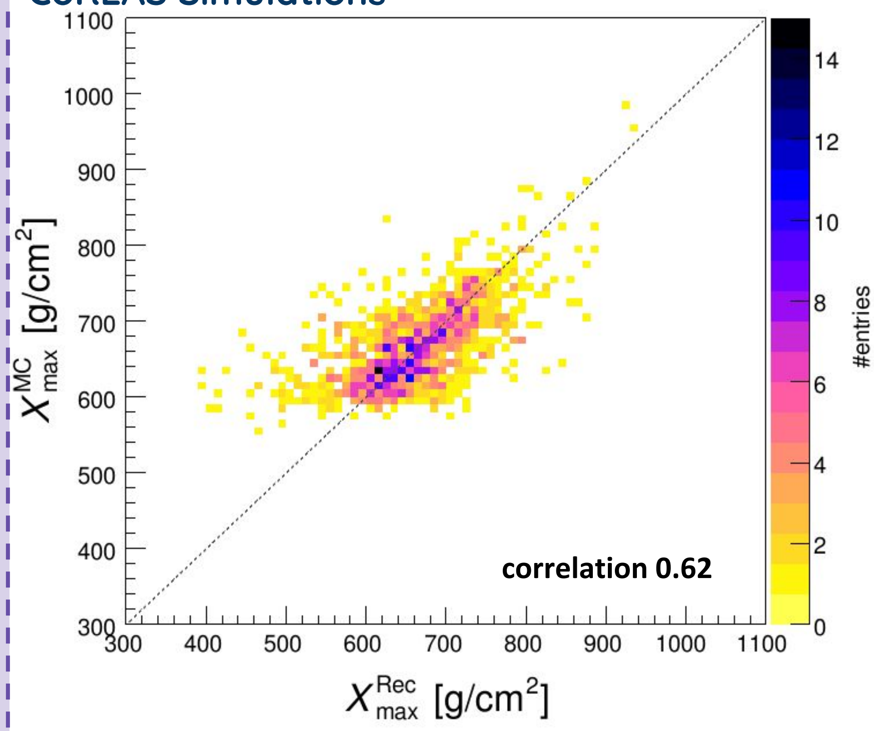
**Parametrization of the energy density distribution:**

a. subtraction of two gaussians

**CoREAS Simulations**




**CoREAS Simulations**




**The width of the footprint is linearly correlated to the distance to $X_{max}$**

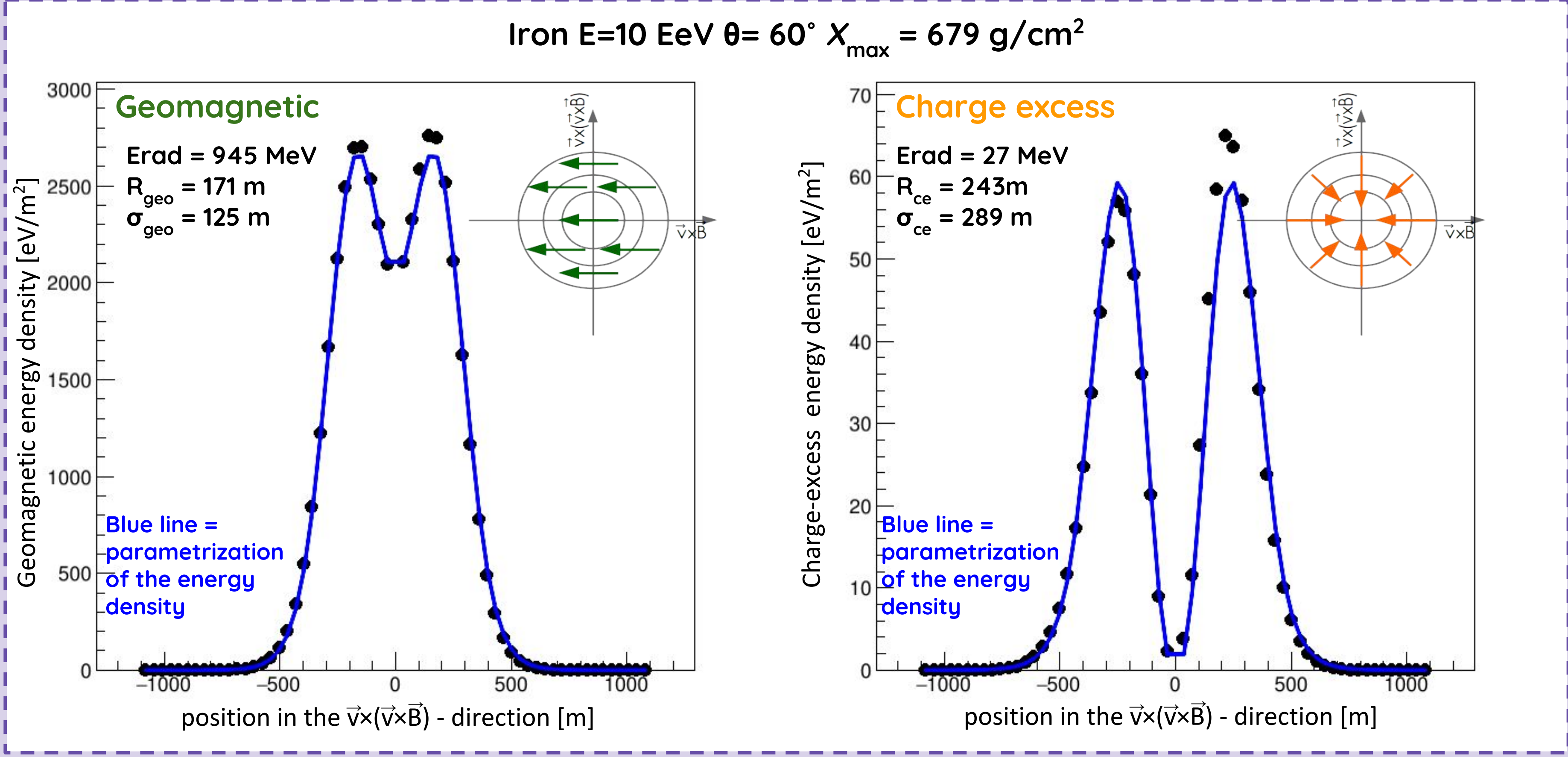
**Reconstruction uncertainty ~ 51 g/cm²**

# Xmax from the energy density footprint

1.b

## Parametrization of the energy density distribution:

b. description of the geomagnetic and charge excess mechanisms




CoREAS simulation with a star-shaped antenna alignment in the shower plane $\vec{v}\times\vec{B}$-$\vec{v}\times\vec{v}\times\vec{B}$

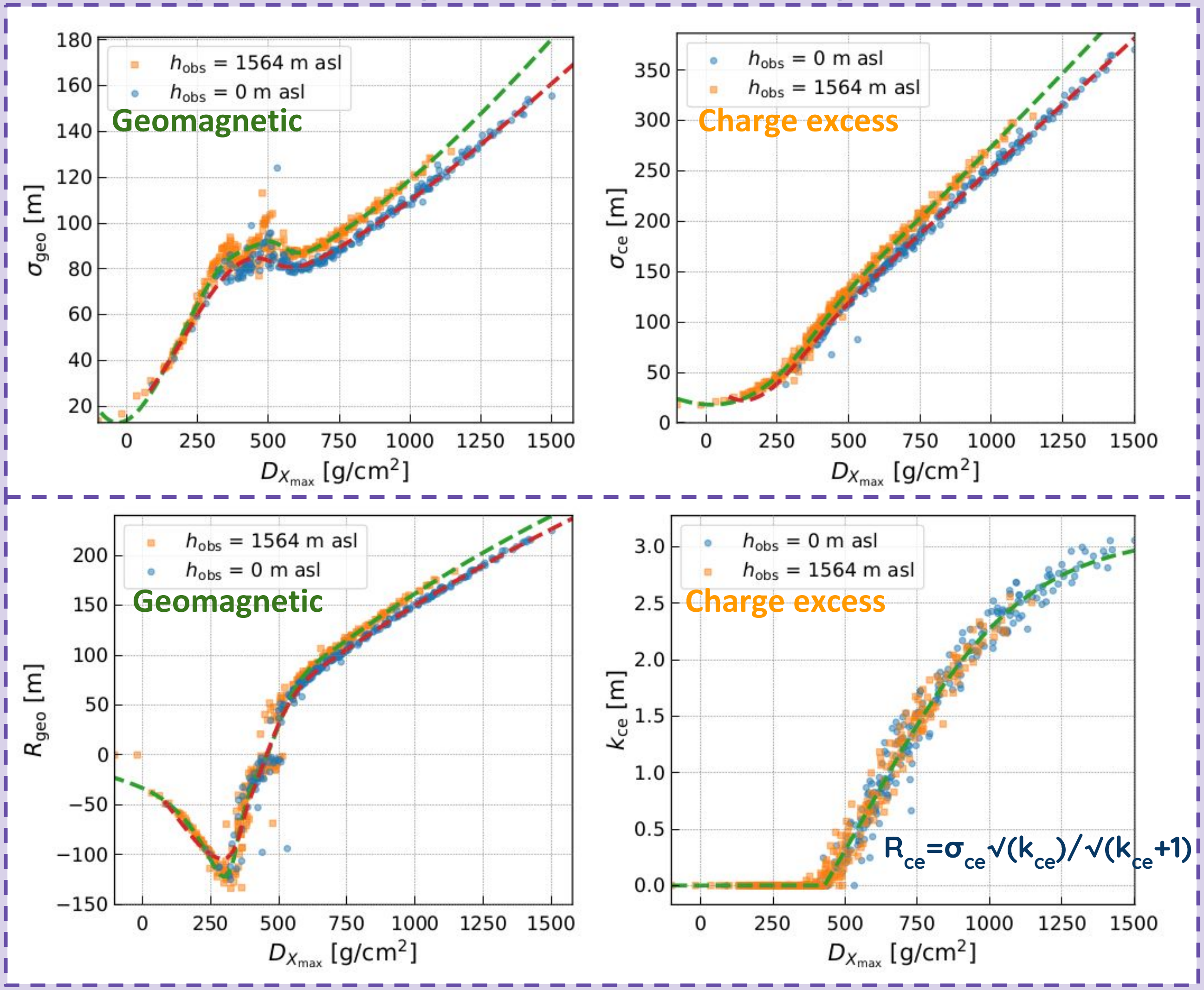
**More details→ talks C.Glaser**

# Xmax from the energy density footprint

## 1.a

**Parametrization of the energy density distribution:**

b. description of the geomagnetic and charge excess mechanisms



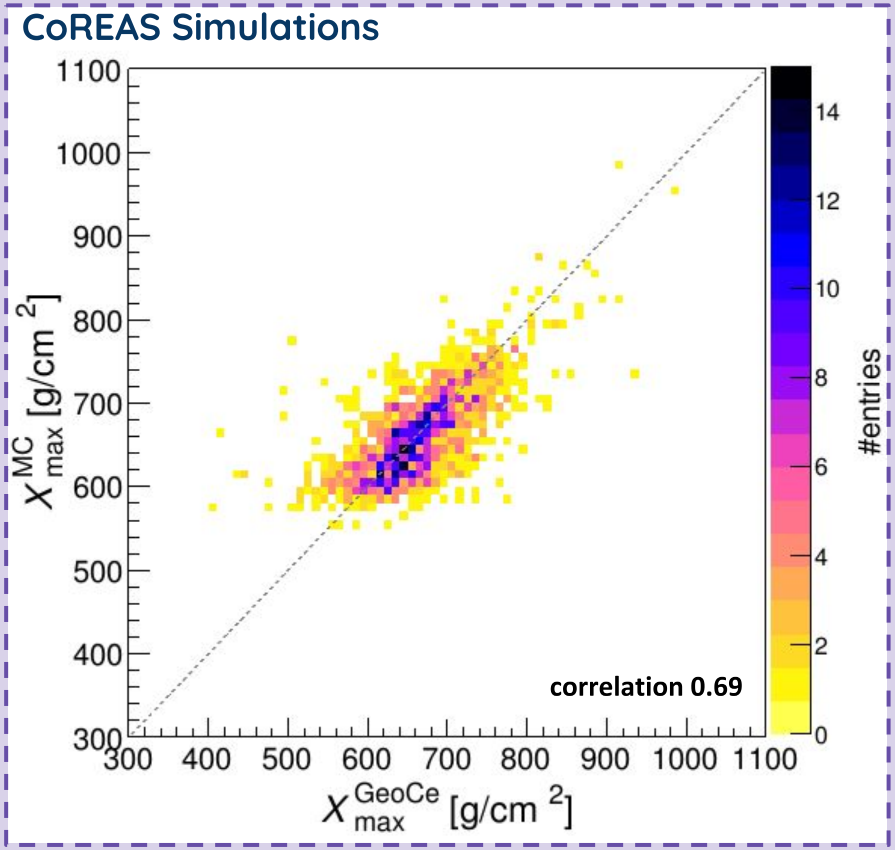

*C. Glaser*
arXiv:1806.03620 [astro_ph.HE]

# $X_{max}$ from the energy density footprint

## 1.b

**Parametrization of the energy density distribution:**

b. description of the geomagnetic and charge excess mechanisms



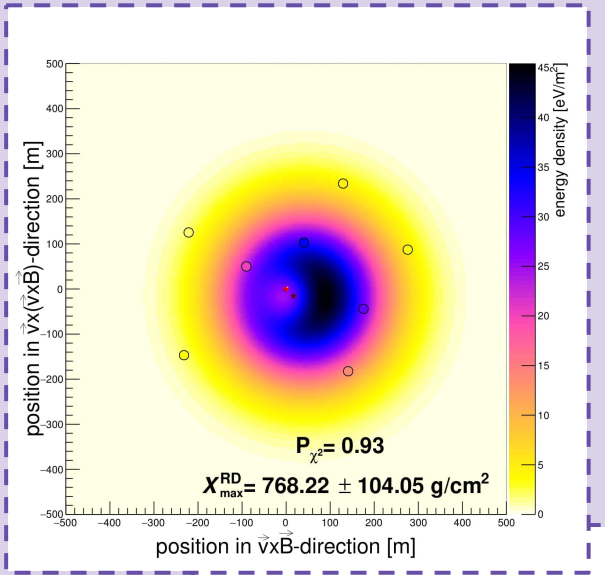

**Reconstruction uncertainty ~ 41 g/cm$^2$**

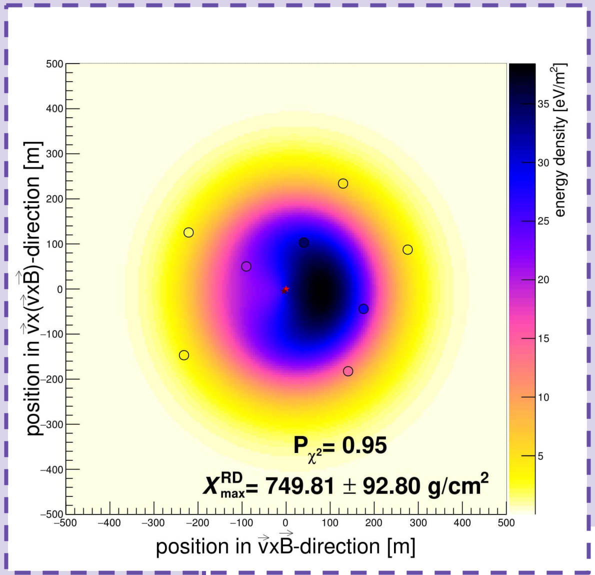
# $X_{max}$ from the energy density footprint

## 1. Auger Fd-Rd hybrid data

a. subtraction of two gaussians

b. geomagnetic and charge excess mechanisms

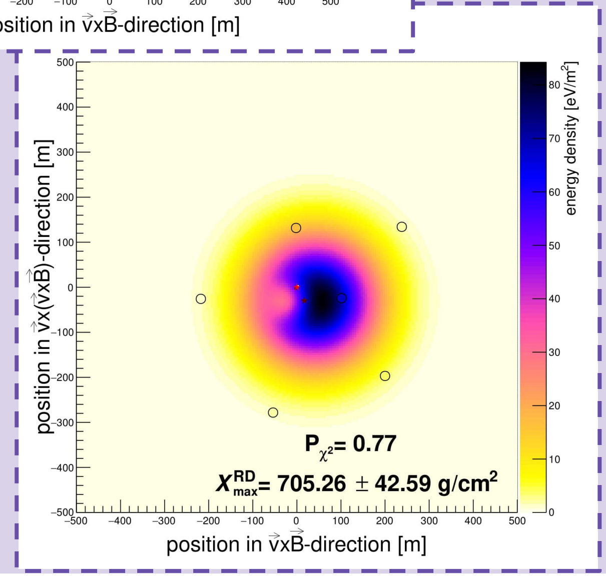


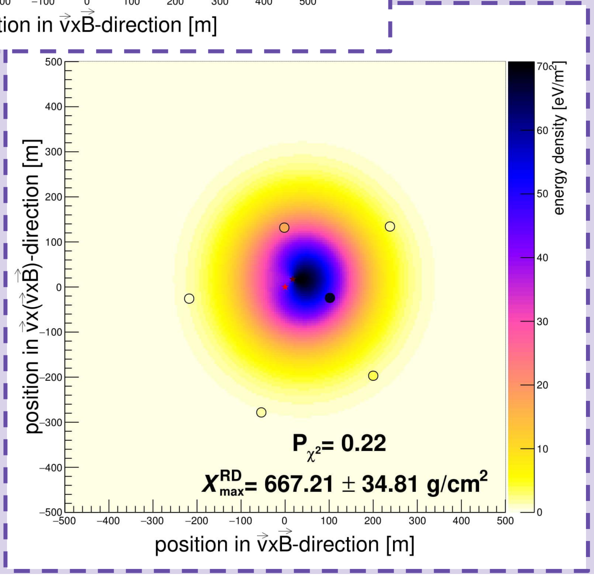




$E_{FD}$=(5.45±0.24)·10$^{17}$eV

$\theta_{FD}$=(50.7±0.2)°

$X^{FD}_{max}$=(700.10±16.56)g/cm$^2$



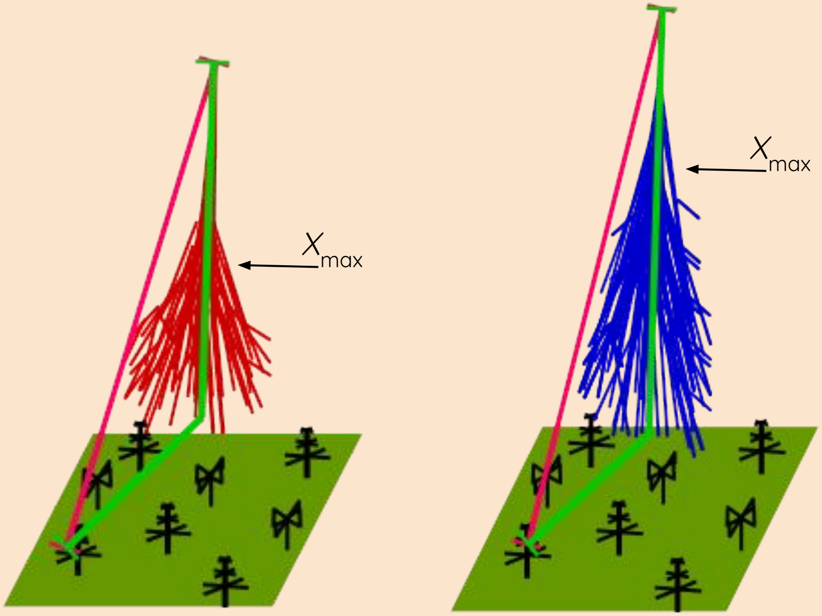

$E_{FD}$=(4.78±0.18)·10$^{17}$eV

$\theta_{FD}$=(41.0±0.2)°

$X^{FD}_{max}$=(701.66±12.54)g/cm$^2$

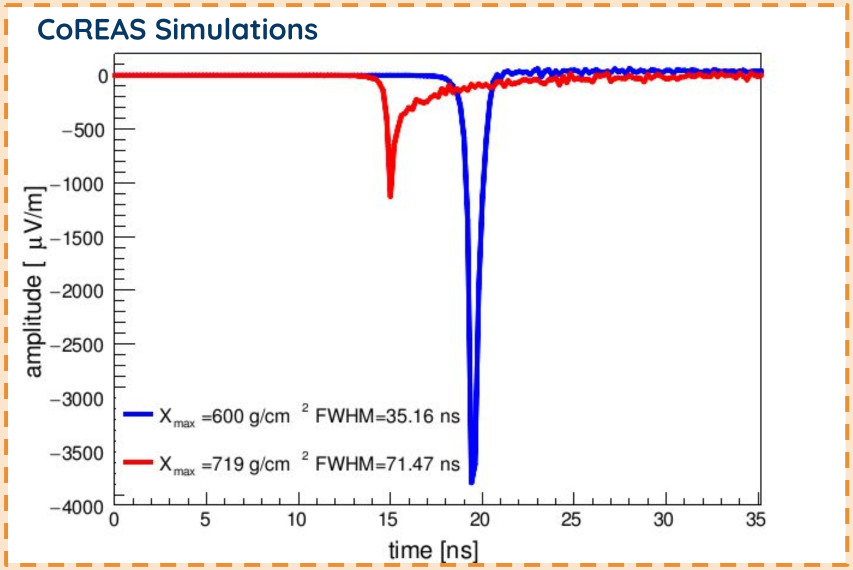
# Xmax from the spectral information

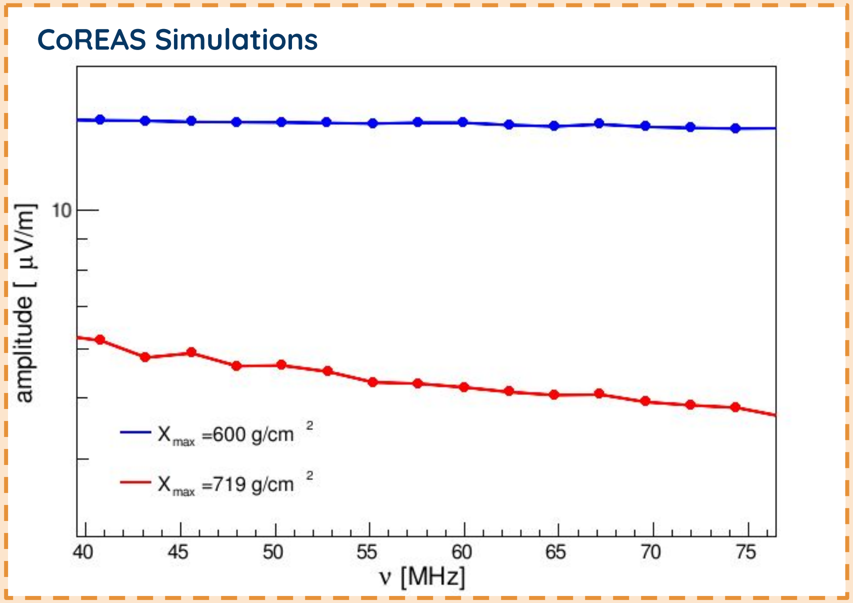
**2.**




**The spectral slope b depends on $X_{max}$**

**b** parametrization as function of
- distance to $X_{max}$
- distance antenna shower axis
- angle between the antenna and the $\vec{v}\times\vec{B}$ axis



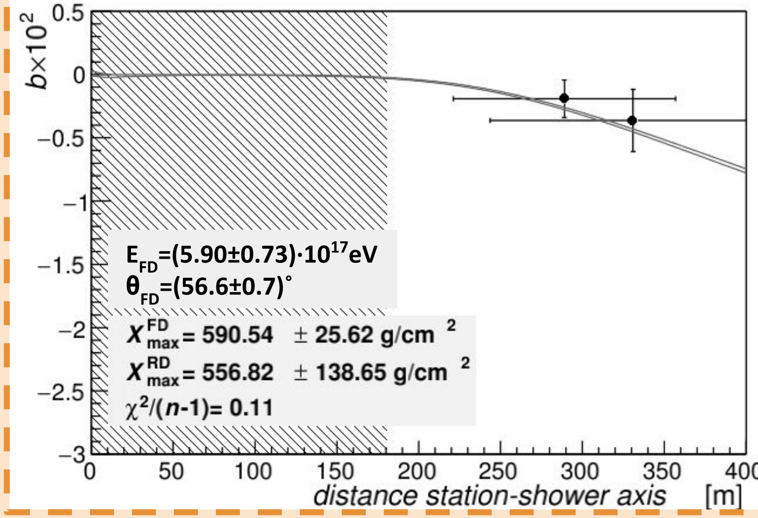
# Xmax from the spectral information

**2.**

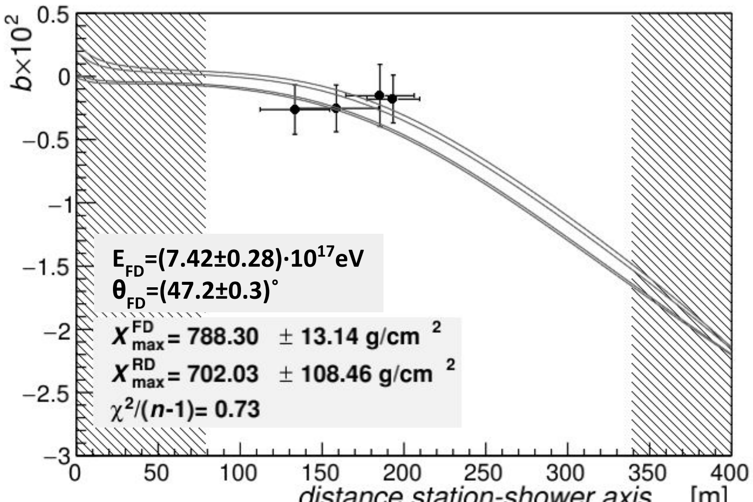
### FD-RD $X_{max}$ comparison for 3 events

Spectral index ***b*** as function of the the distance to the shower maximum
The **grey** line is the best prediction line obtained using $X_{max}^{FD}$

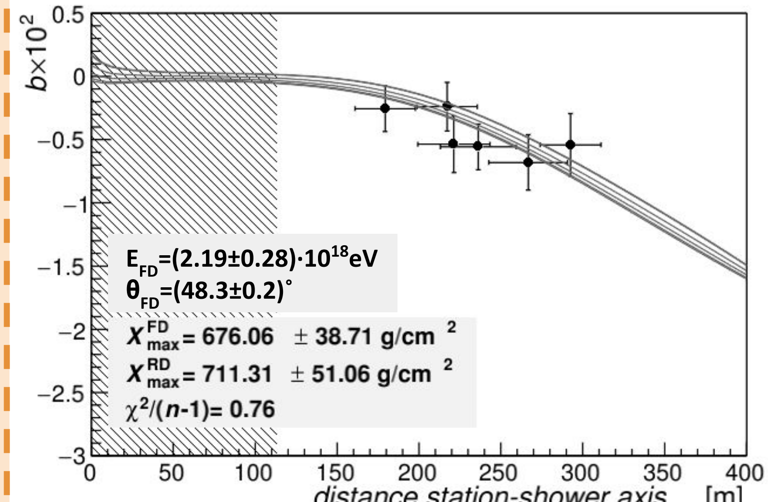
2 stations




4 stations



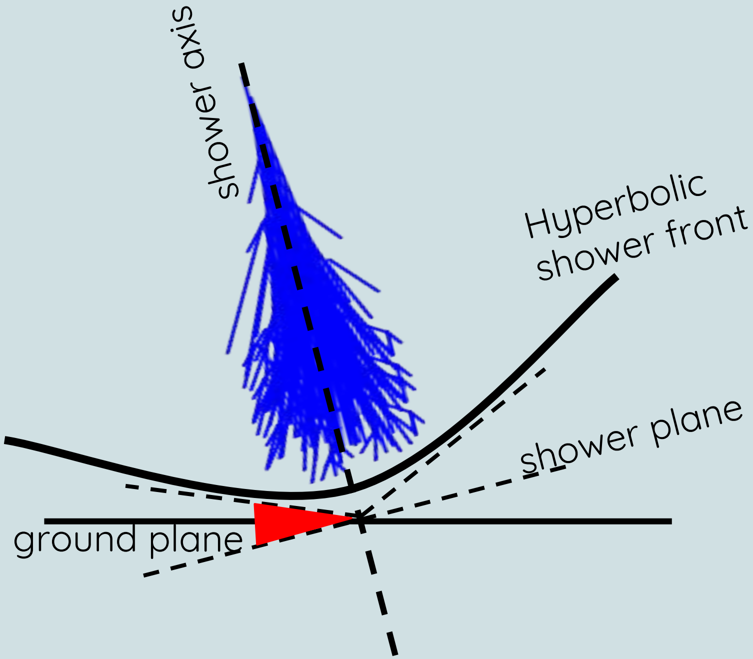

6 stations



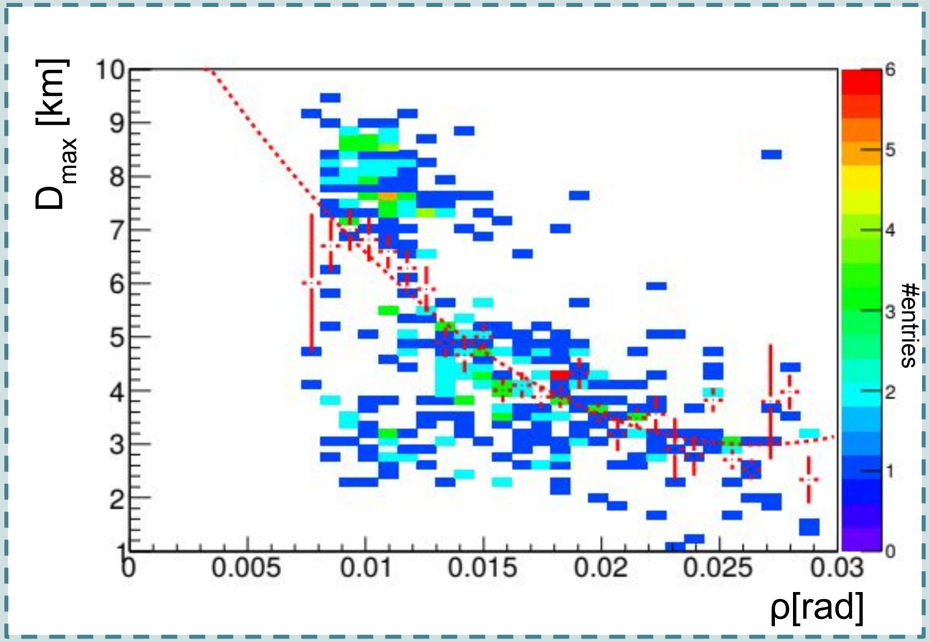
# Xmax from the arrival time fit

## 3.

**The arrival time distribution of the radio signal can be well described by a hyperbola**




**The angle ρ of the asymptotic cone of the hyperbola depends on $X_{max}$**




**Distance to shower maximum as a function of the cone opening angle ρ for the MC dataset**

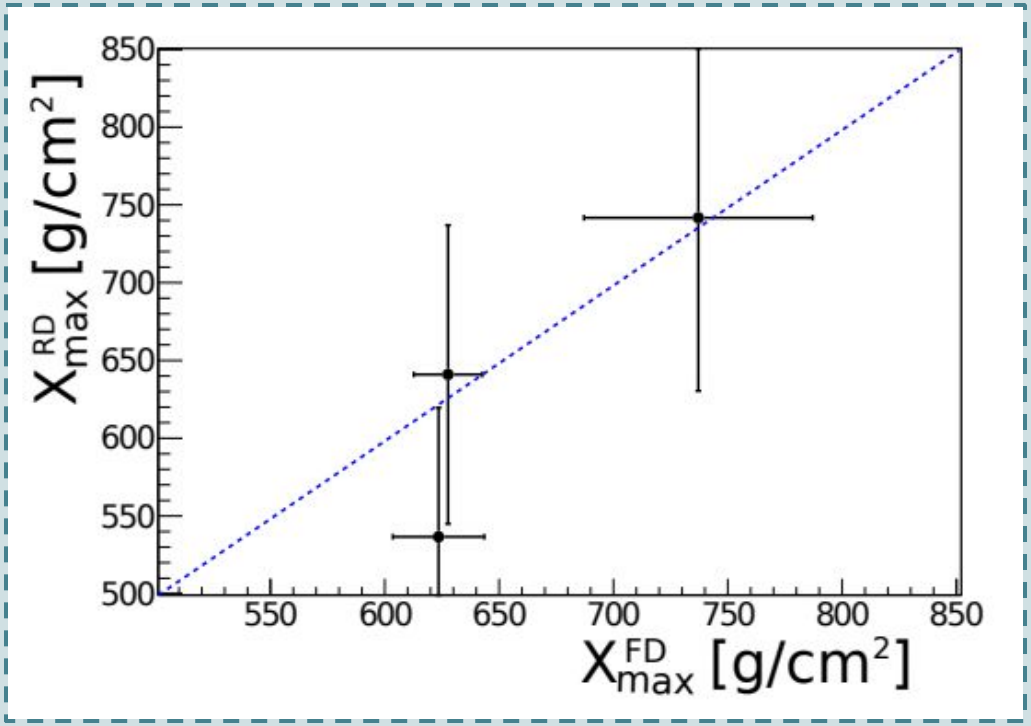
The dashed line shows the polynomial function fitted on the profile distribution

Q.Dorosti arXiv:1705.06230

# $X_{max}$ from the arrival time fit

**3.**

**FD-RD $X_{max}$ comparison for 3 events**




The dashed line shows the bisection line

Q.Dorosti arXiv:1705.06230

# Summary

**Three independent methods under investigations**

**1. $X_{max}$ from the energy density footprint**

The width of the footprint is correlated to the distance to $X_{max}$.

Footprint parametrizations:

a. subtraction of two gaussians

b. geomagnetic and charge excess mechanisms

**2. $X_{max}$ from spectral information**

The spectral slope of radio signals depends on $X_{max}$.

Cosmic rays that interact high in the atmosphere have a shorter pulse and a lower spectral slope.

**3. $X_{max}$ from the arrival time fit**

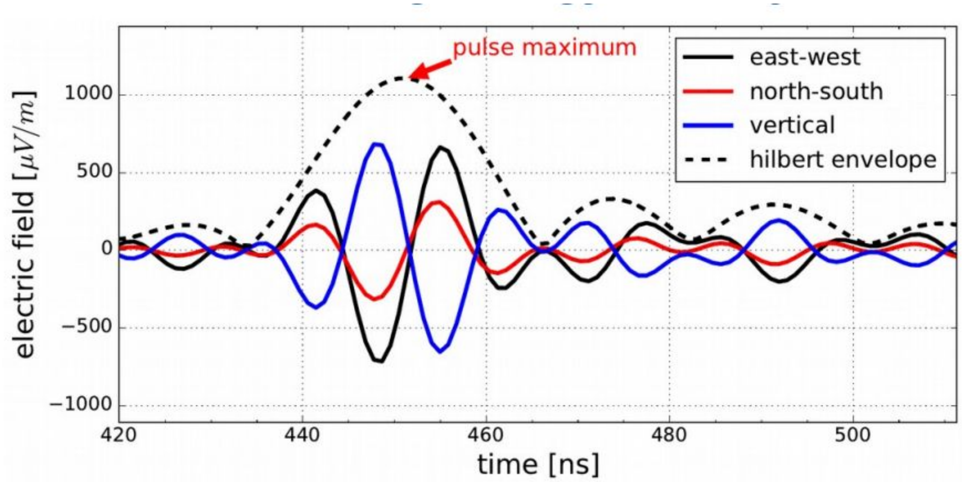
Arrival time measurements can be used to study the longitudinal shower development.

The opening angle of the hyperbolic wavefront is sensitive to $X_{max}$ .

**The results of these analysis can be combined to obtain a mass composition reconstruction that uses all the information in the detected radio signal**

# Backup

# Energy density




**Energy density in eV/m²**

Time integral of Poynting vector

$$u = \varepsilon_0 c \left( \Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

Window [$t_1$-$t_2$] around the maximum of the Hilbert envelope

Noise subtraction

# Energy density parametrization - two Gaussians

**1.a**

**Parametrization of the energy density distribution:**

a. subtraction of two gaussians

$$u(\vec{r}) = A \cdot \left[ \exp\left( \frac{-(\vec{r} + C_1 \cdot \vec{e}_{\vec{v} \times \vec{B}} - \vec{r}_{core})^2}{\sigma^2} \right) - C_0 \cdot \exp\left( \frac{-(\vec{r} + C_2 \cdot \vec{e}_{\vec{v} \times \vec{B}} - \vec{r}_{core})^2}{(C_3 \cdot \exp(C_4 \cdot \sigma))^2} \right) \right]$$

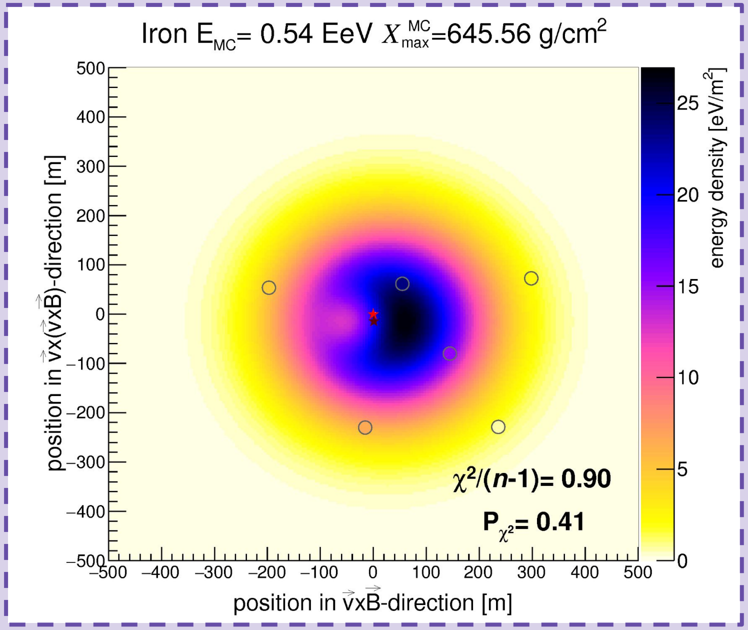
Nelles et al., Astropart. Phys. 60, 13 (2015)

***A*** amplitude

***σ*** width of the footprint

$\vec{r}_{core}$ coordinate of the shower core

$C_{0-4}$ simulation-based constants



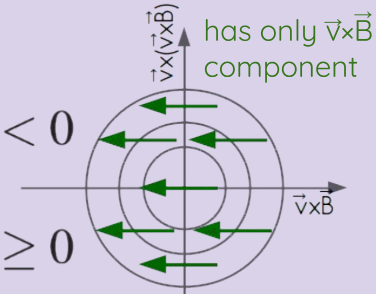
## 1.b

**Parametrization of the energy density distribution:**

b. description of the geomagnetic and charge excess mechanisms

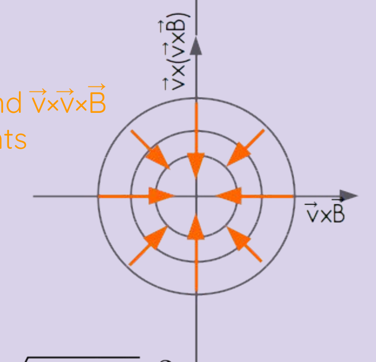
### Geomagnetic

$$f_{\text{geo}} = \begin{cases} \frac{1}{N_{R_-}} E'_{\text{geo}} \exp\left(-\left(\frac{r-R_{\text{geo}}}{\sqrt{2}\sigma_{\text{geo}}}\right)^{p(r)}\right) & \text{if } R_{\text{geo}} < 0 \\ \frac{1}{N_{R_+}} E'_{\text{geo}} \left[\exp\left(-\left(\frac{r-R_{\text{geo}}}{\sqrt{2}\sigma_{\text{geo}}}\right)^{p(r)}\right) + \exp\left(-\left(\frac{r+R_{\text{geo}}}{\sqrt{2}\sigma_{\text{geo}}}\right)^{p(r)}\right)\right] & \text{if } R_{\text{geo}} \geq 0 \end{cases}$$




### Charge excess

$$f_{\text{ce}}(r) = \frac{1}{N_{\text{ce}}} E'_{\text{ce}}\, r^k \exp\left(\frac{-r^{p(r)}(k+1)}{p(r)\,\sigma_{\text{ce}}^{p(r)}}\right)$$




**Total energy density**

$$f = f_{(\vec{v}\times\vec{B})} + f_{\vec{v}\times(\vec{v}\times\vec{B})} \begin{cases} f_{\vec{v}\times\vec{B}} = \left(\sqrt{f_{geo}(r)} + \cos\phi\,\sqrt{f_{ce}(r)}\right)^2 \\ f_{\vec{v}\times(\vec{v}\times\vec{B})} = \sin^2\phi\, f_{ce}(r) \\ \phi = \arctan 2(y, x) \end{cases}$$

# Xmax from the energy density footprint

**1.b**

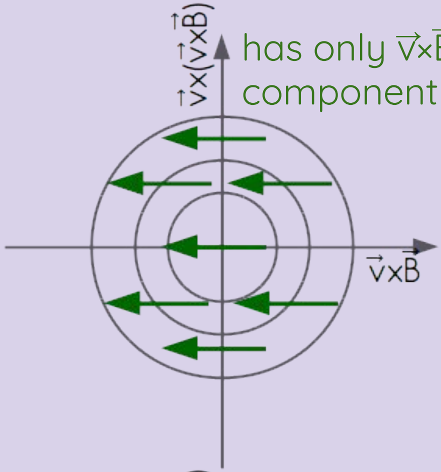
## Parametrization of the energy density distribution:

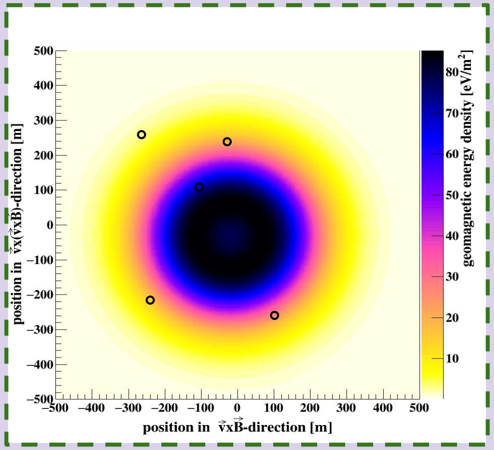
b. description of the geomagnetic and charge excess mechanisms

### Polarization

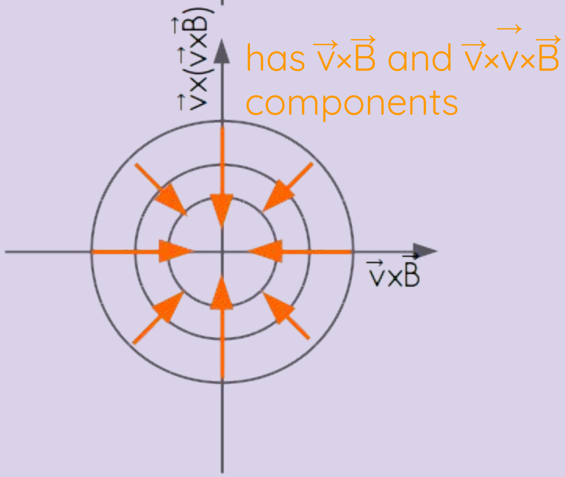
### Energy density distribution

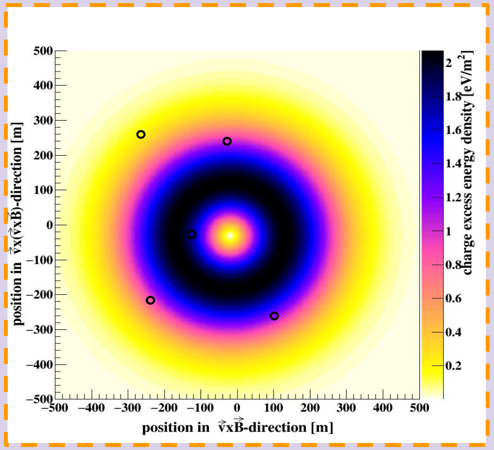
Geomagnetic



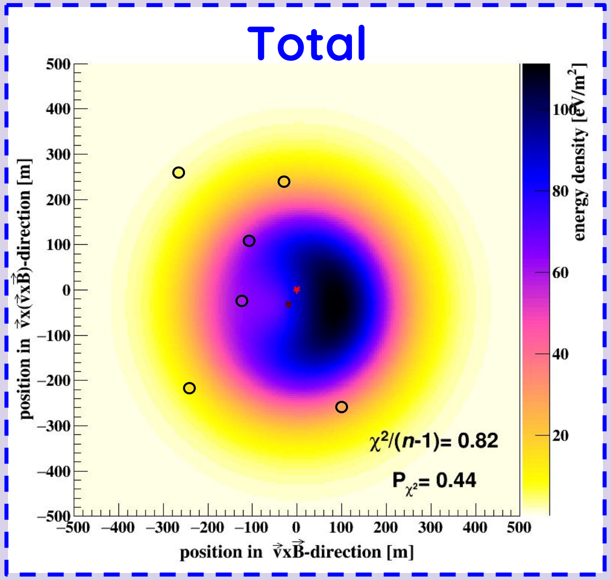




Charge excess




CoREAS Simulations
Iron
E= 1.24 EeV $X_{max}$=679.03 g/cm$^2$



# Shape of the energy density distribution

## 1.b

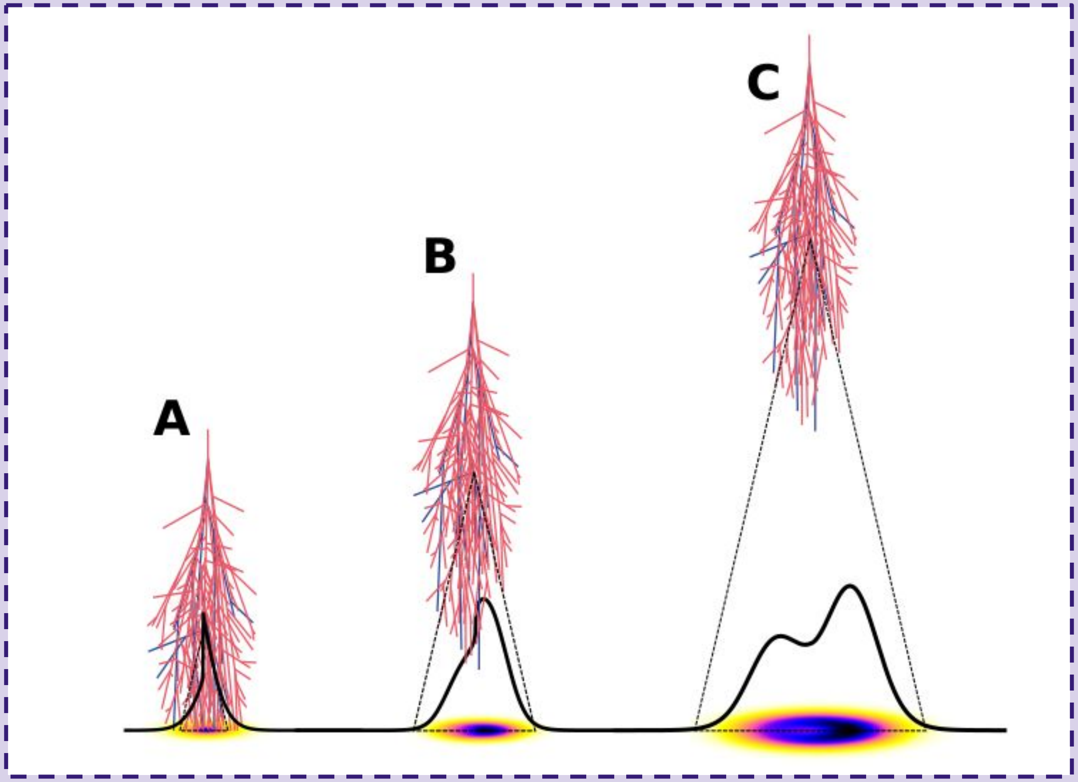
**Parametrization of the energy density distribution:**

b. description of the geomagnetic and charge excess mechanisms

(A) that hit ground before emitting most radiation energy

(B) that hit ground shortly after emitting all radiation energy

(C) that have large distances between the ground and the air-shower development

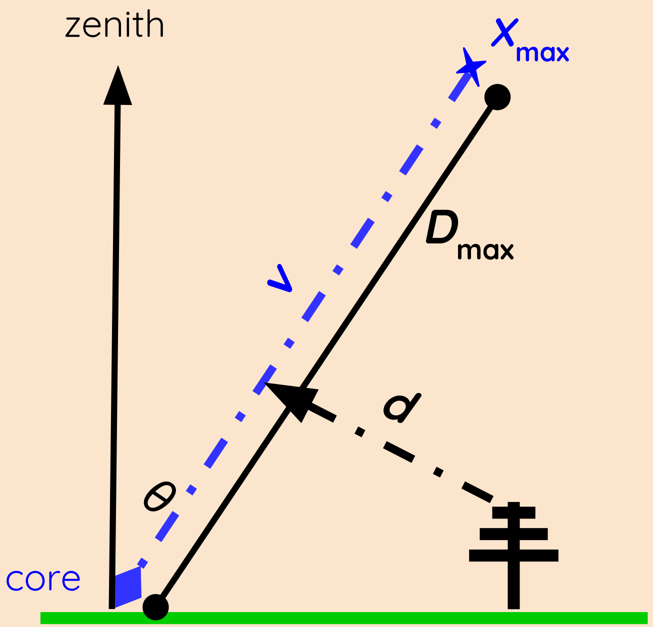



*C. Glaser*
arXiv:1806.03620
[astro_ph.HE]

# Spectral index parametrization

**2.**

$$b_T = \frac{1}{\nu_+ - \nu_-} \log_{10}\left[\frac{10^{b_G(\nu_+ - \nu_0)} + f(\Phi_{obs})R \cdot 10^{b_C(\nu_+ - \nu_0)}}{10^{b_G(\nu_- - \nu_0)} + f(\Phi_{obs})R \cdot 10^{b_C(\nu_- - \nu_0)}}\right]$$




where $\boldsymbol{b_G}$ and $\boldsymbol{b_C}$:

$$b \times 10^2 = \frac{\beta}{1 + \exp(-\gamma \cdot D_{max}/1\mathrm{km})} - \beta$$

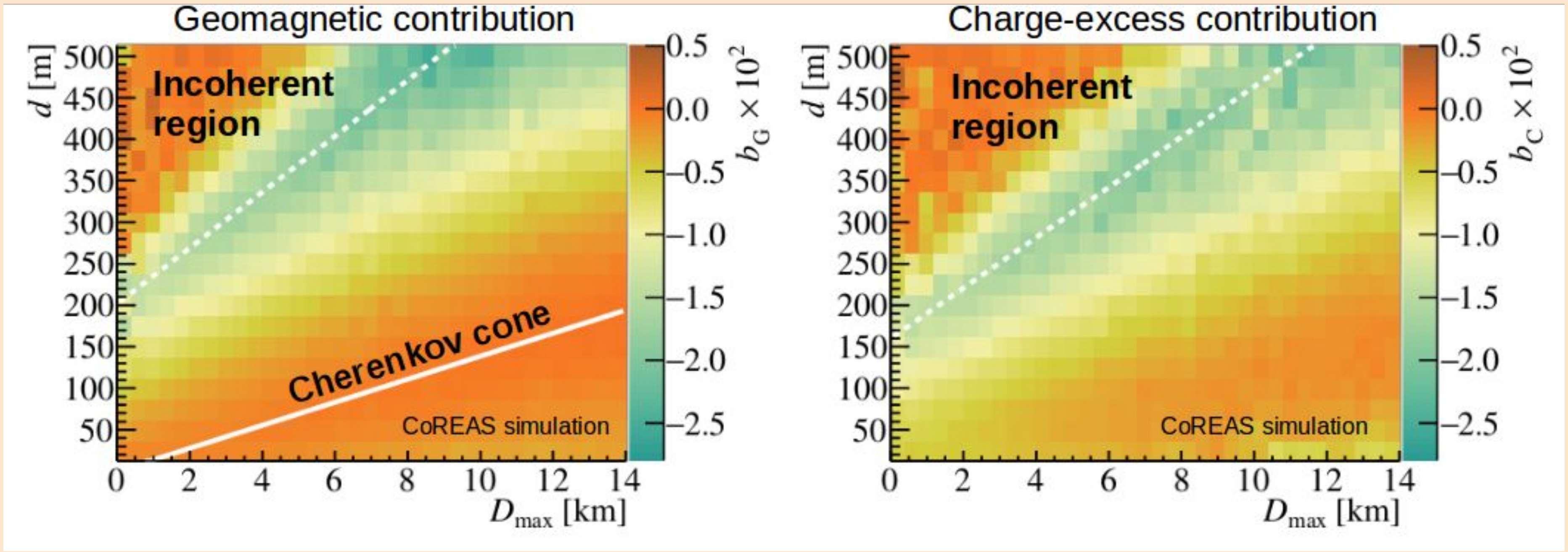
***β*** and ***γ*** are functions of the distance to the shower axis d

***R*** is the ratio between the scale parameter $A_C/A_G$

$\boldsymbol{f(\Phi_{obs}) = \cos\Phi_{obs}}$ in the $\vec{v}\times\vec{B}$ direction

# Spectral index parametrization

**2.**




S. Jansen PhD thesis (2016)