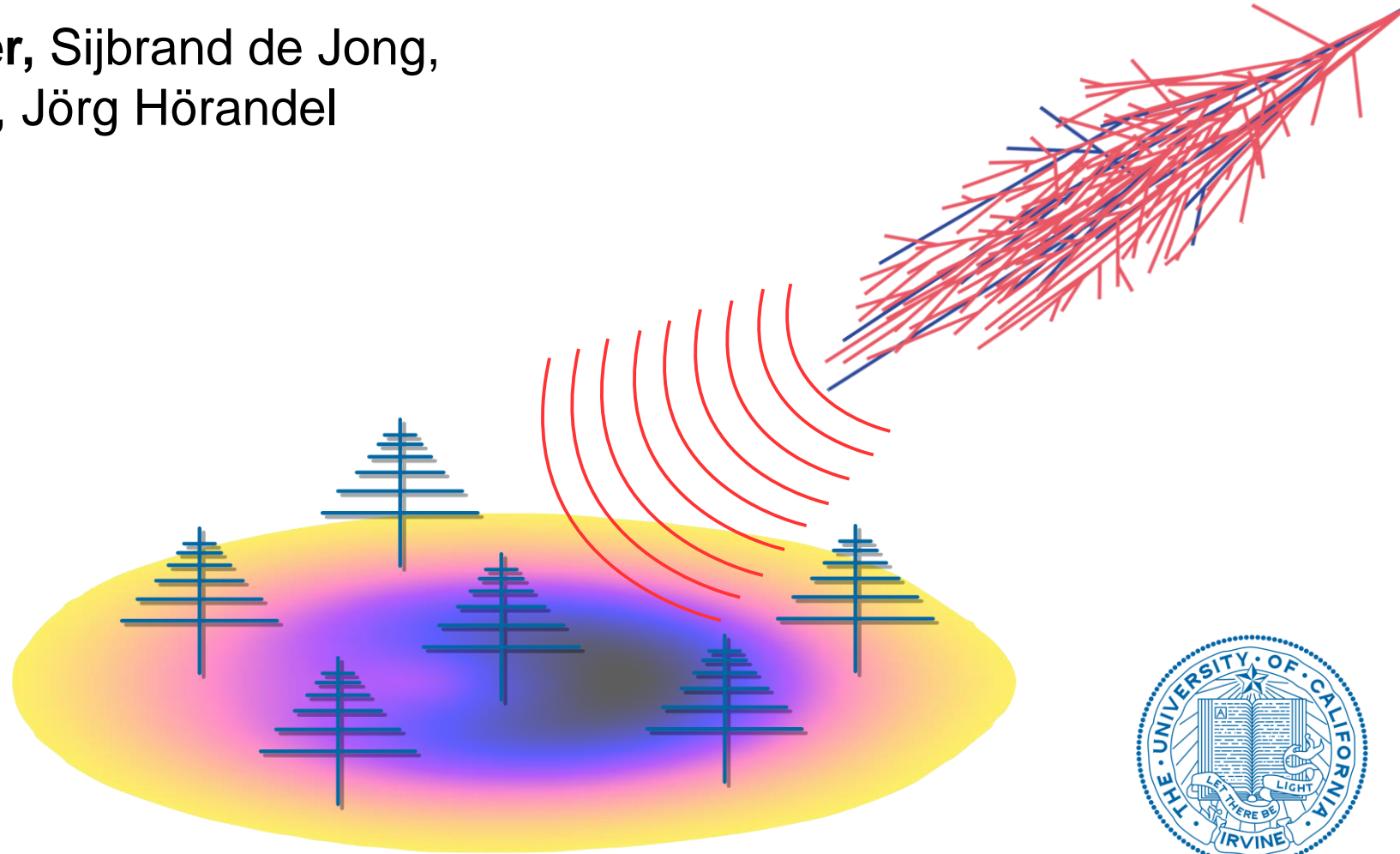


Analytic description of the radio emission of air showers based on its emission mechanisms

Christian Glaser, Sijbrand de Jong,
Martin Erdmann, Jörg Hörandel



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Analytic description of the radio emission of air showers based on its emission mechanisms

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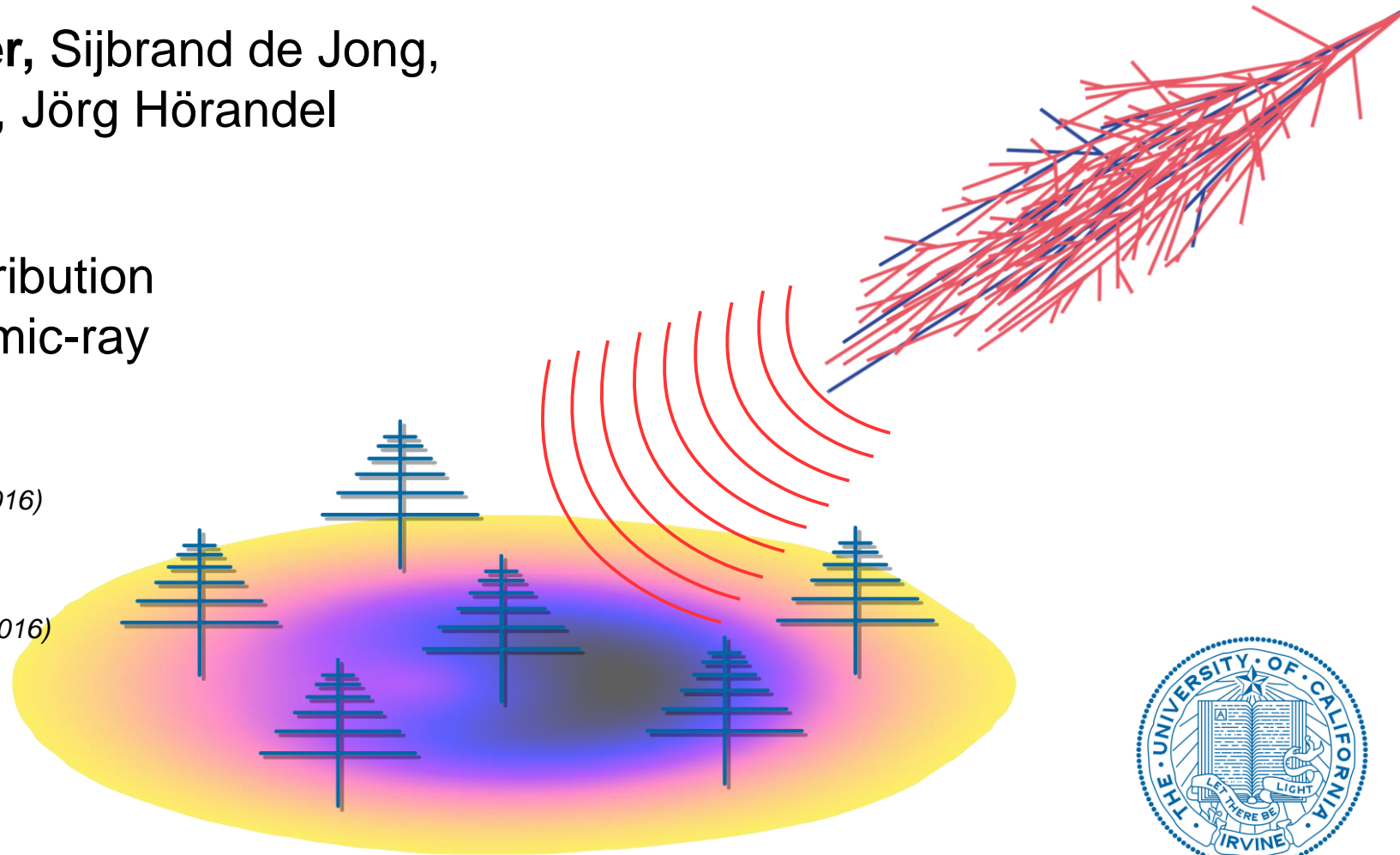
radio signal distribution
sensitive to cosmic-ray

→ **energy**

e.g. Aab et al.,
PRL **116** 241101 (2016)

→ **mass**

e.g. Buitink et al.,
Nature **531** 70-73 (2016)



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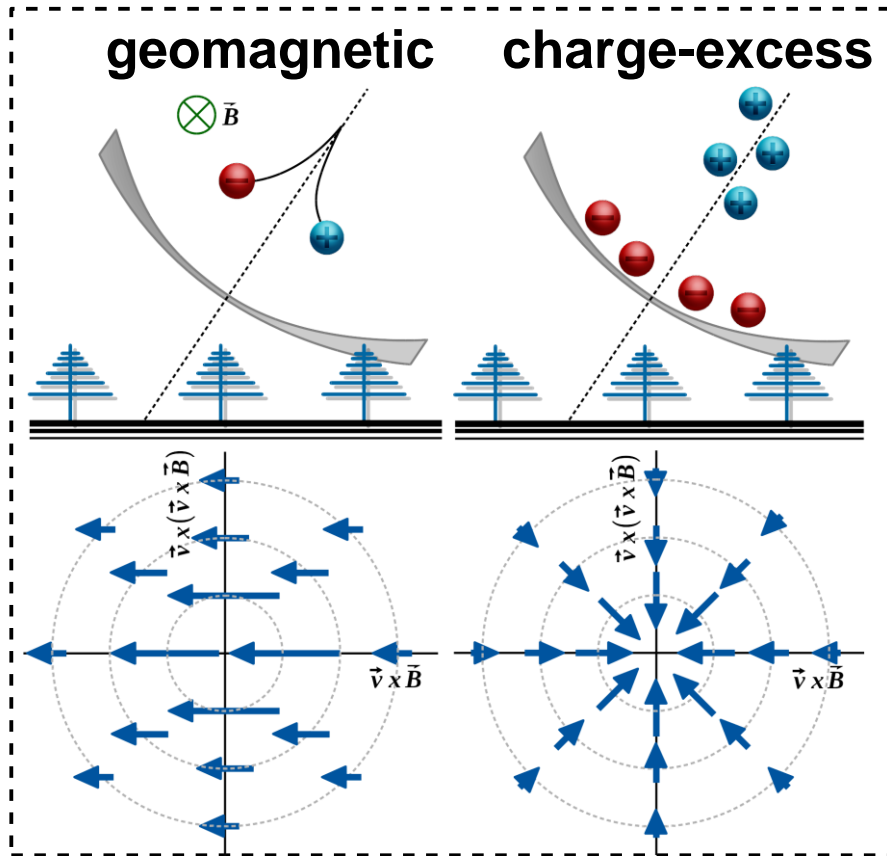


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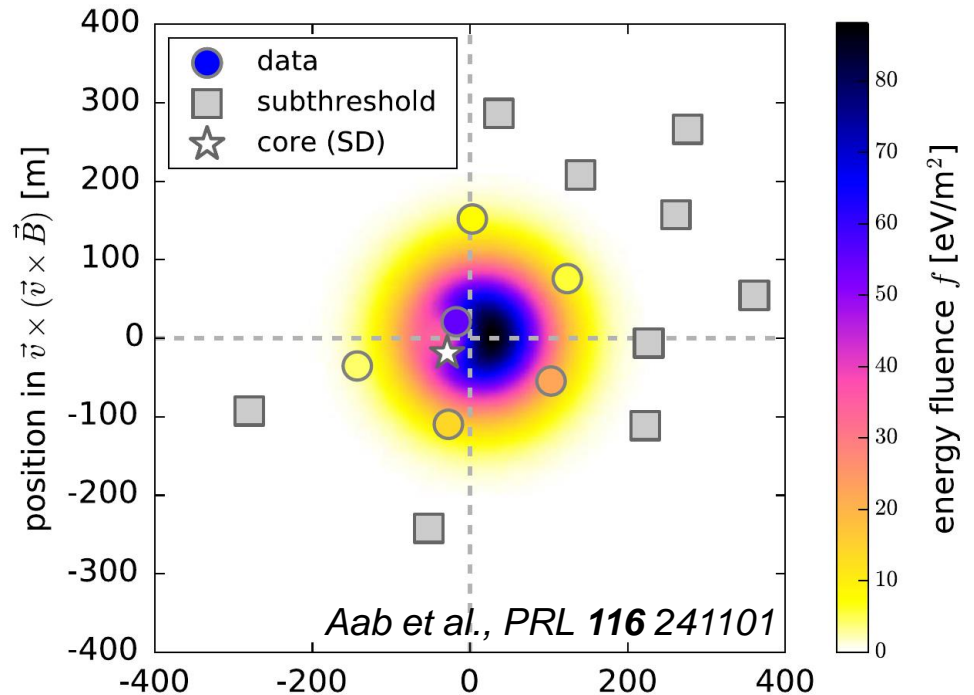
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Radio Emission from Extensive Air Showers



Challenge: Access information with sparse grid of antennas



- **so far:** described with empirical function (2 Gaussian's)

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

- successfully used to reconstruct radiation energy

- determination of cosmic-ray energy

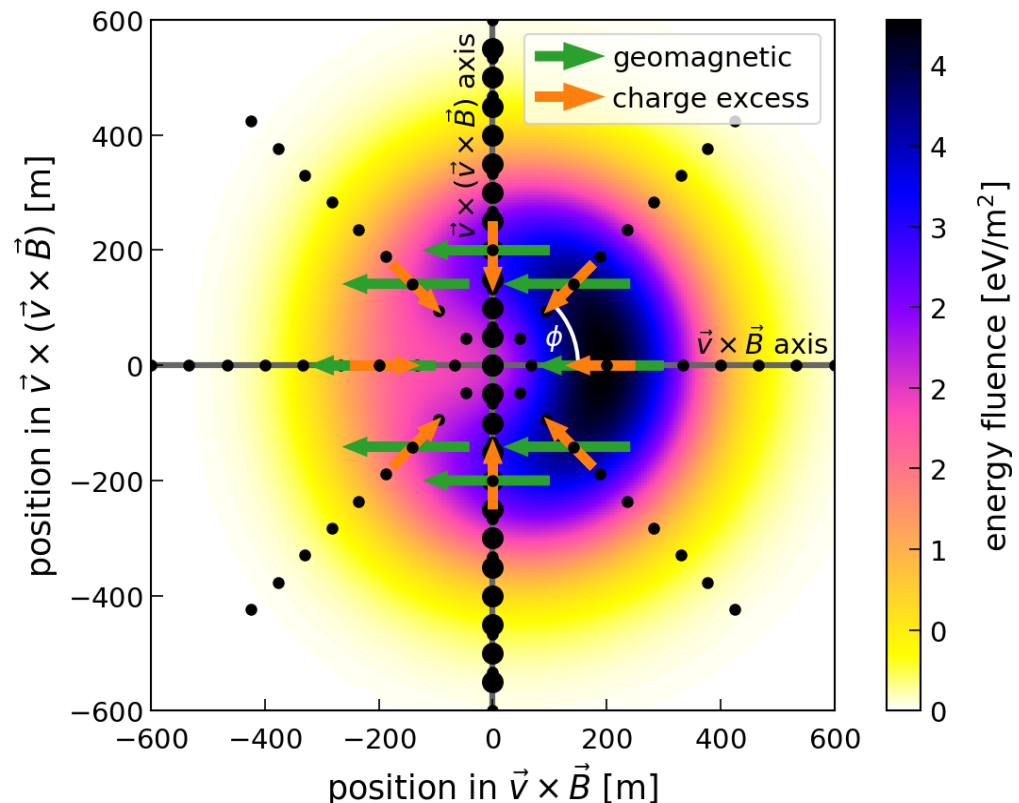
Pierre Auger Collaboration, PRL 116 241101 & PRD 93 122005 (2016)

- no use of polarization information

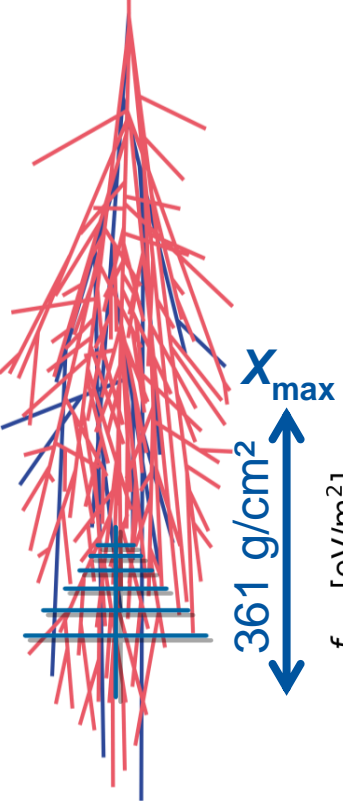
- no direct physical interpretation of fit parameters

New Model of Radio Signal Distribution

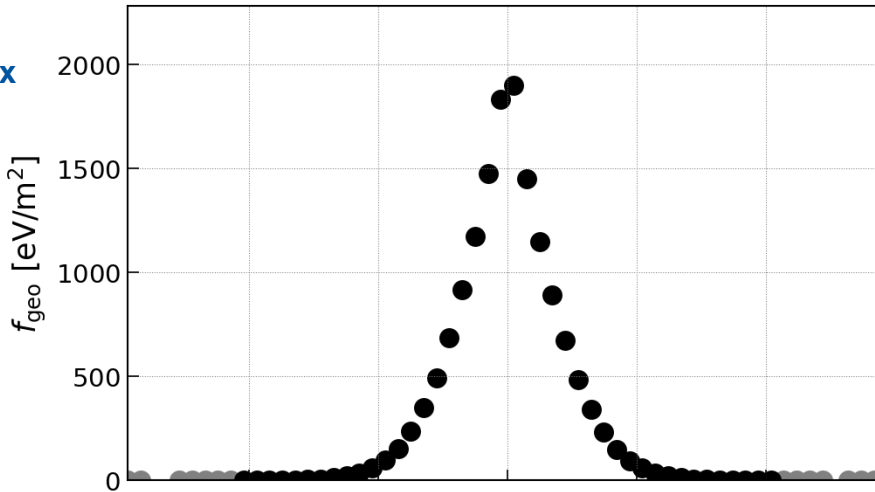
- **now:** describe the two emission mechanisms separately
- explicitly use polarization of radio signal
 - doubles usable information per station
- **goal:** analytic model with minimal number of parameters
- develop model with full Monte-Carlo air-shower simulation (CoREAS)
 - radio emission calculated via first-principles from particle movement
 - excellent agreement btw. data and simulation
 - no explicit modelling of geomagnetic and charge-excess
 - Trick: use $\vec{v} \times (\vec{v} \times \vec{B})$ axis



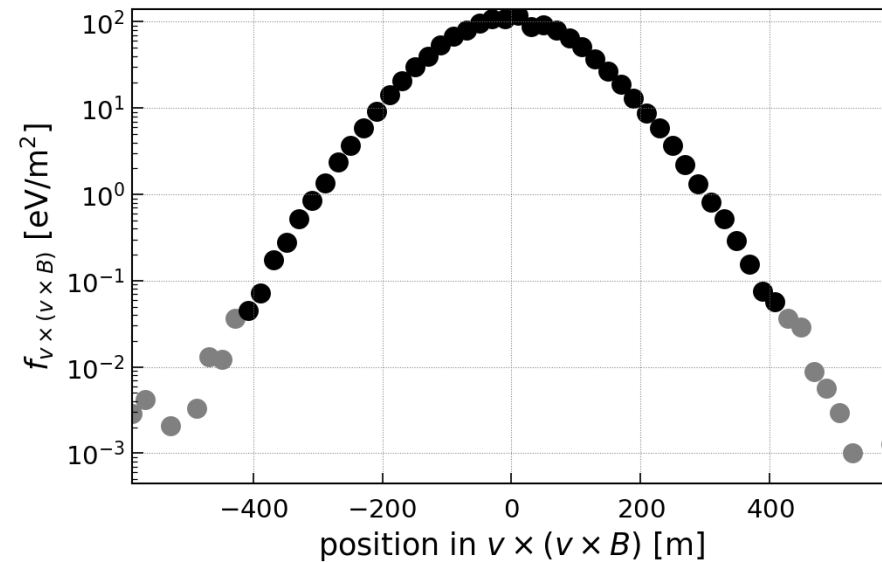
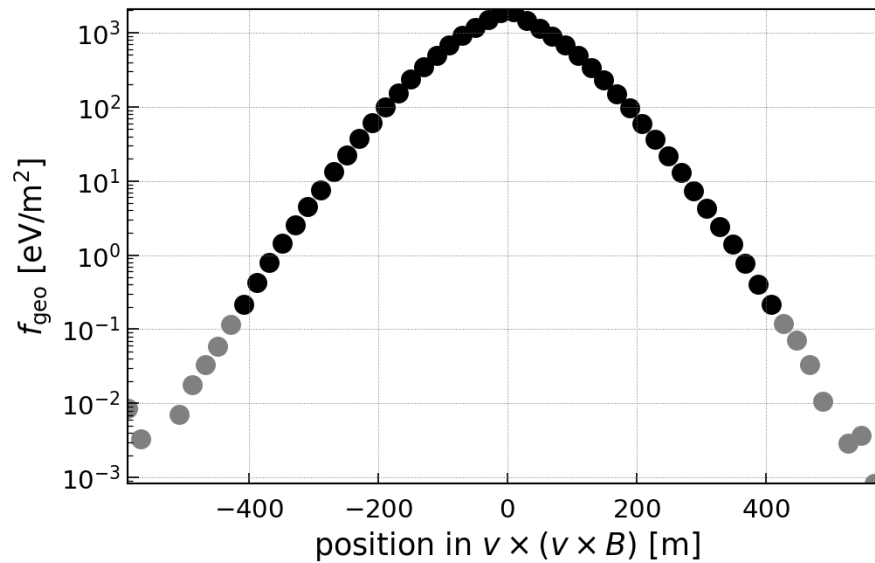
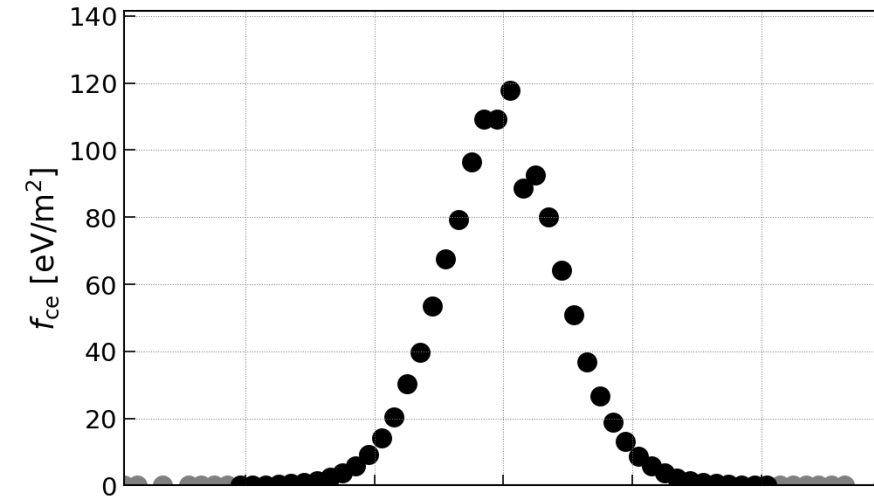
Decomposition: Geomagnetic – Charge-Excess



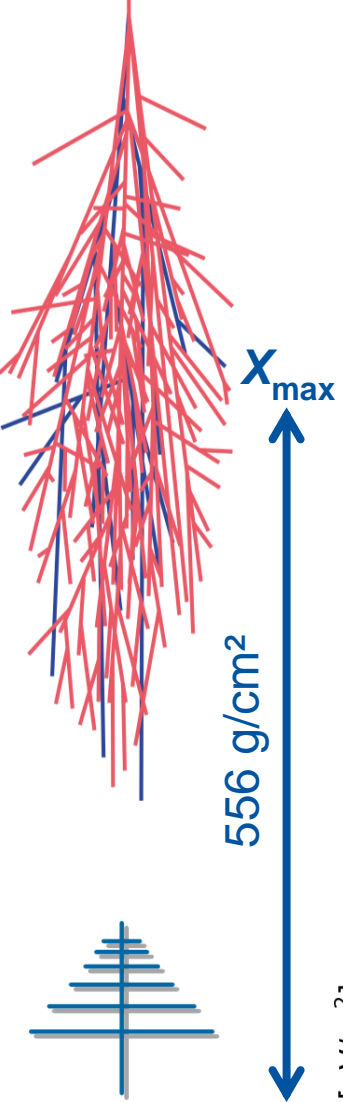
geomagnetic



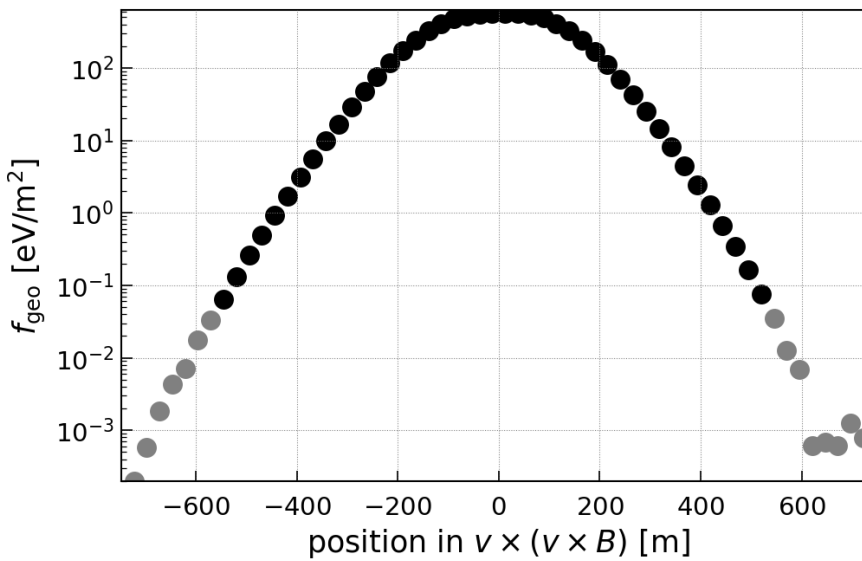
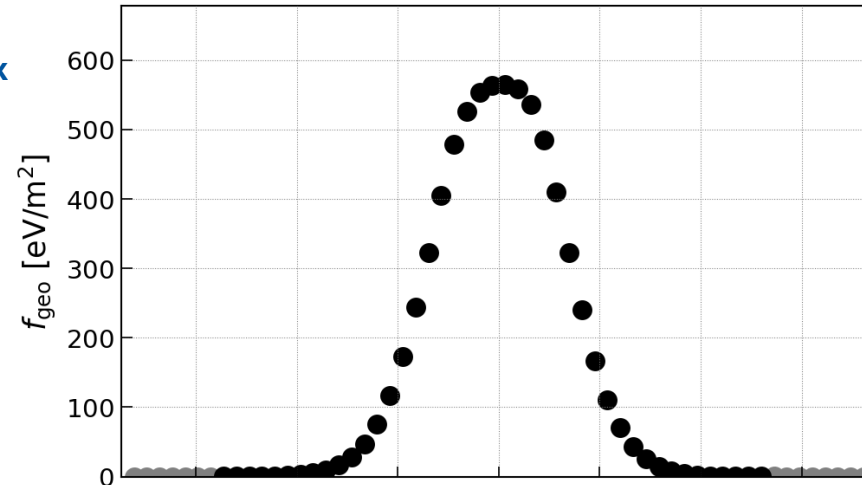
charge-excess



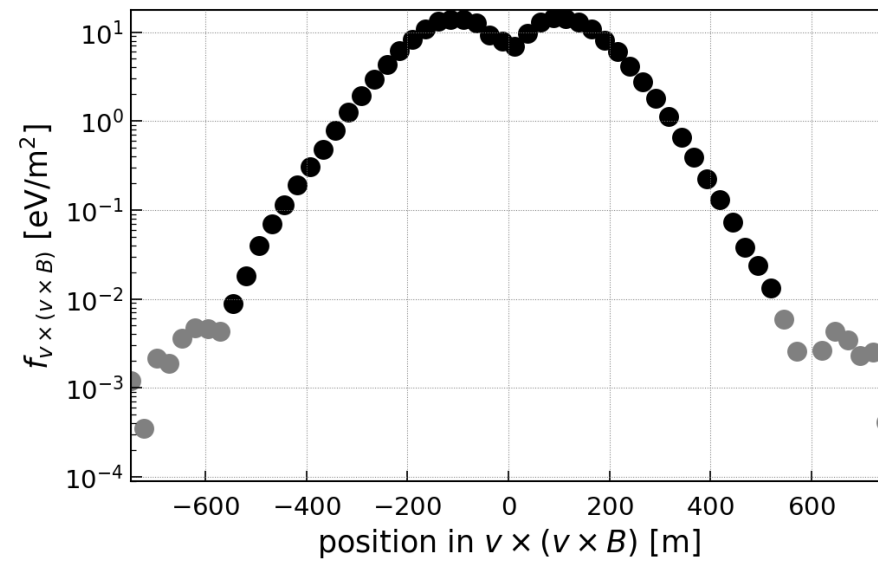
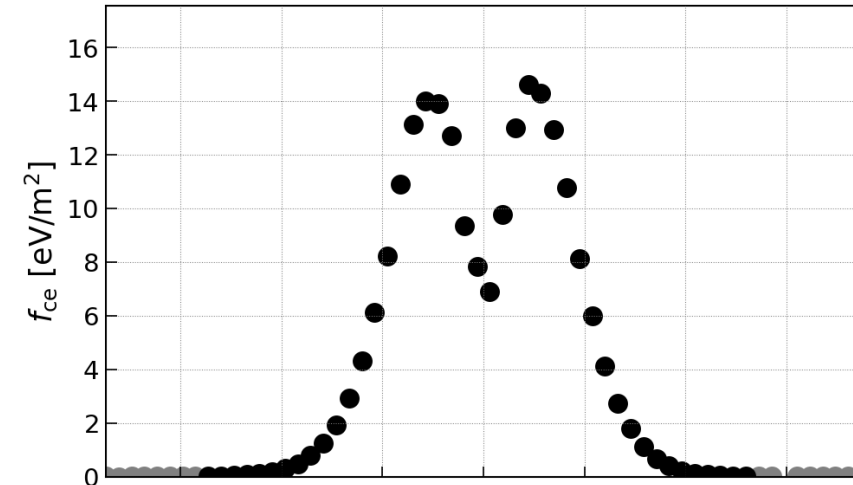
Decomposition: Geomagnetic – Charge-Excess



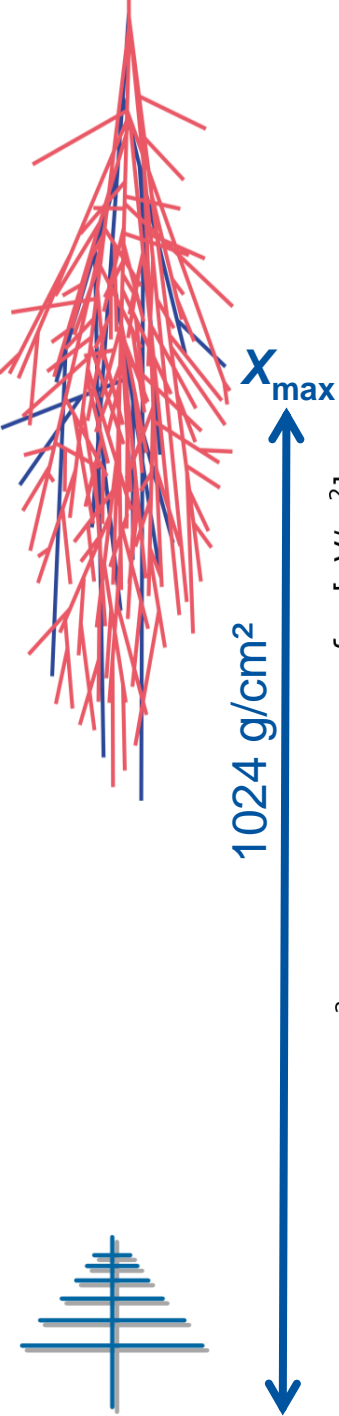
geomagnetic



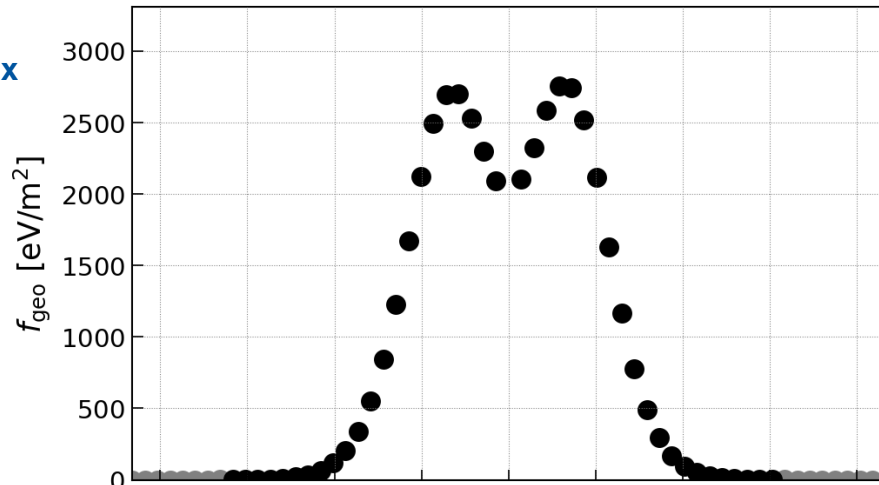
charge-excess



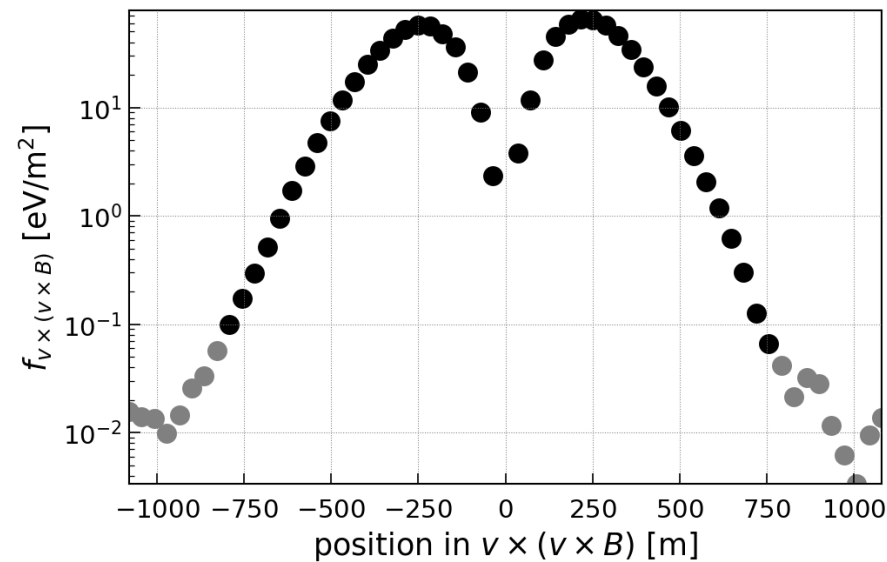
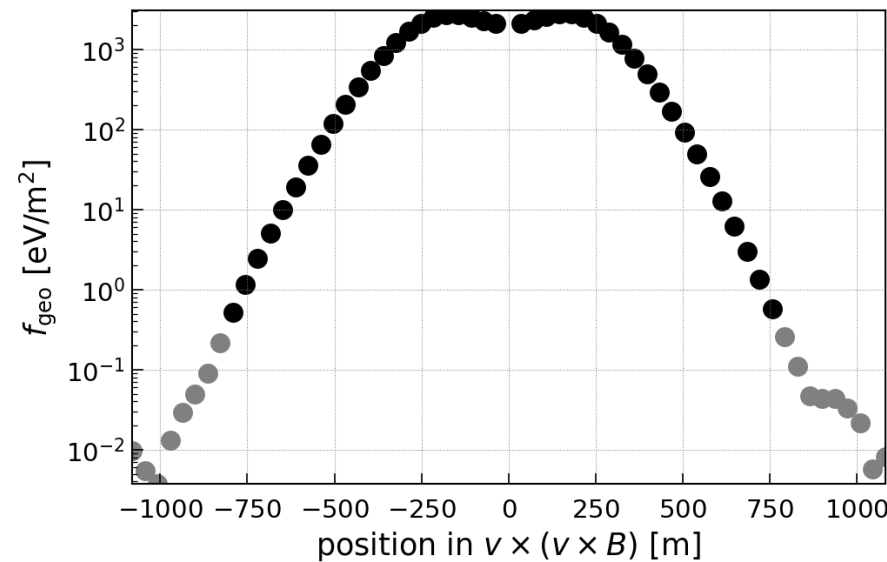
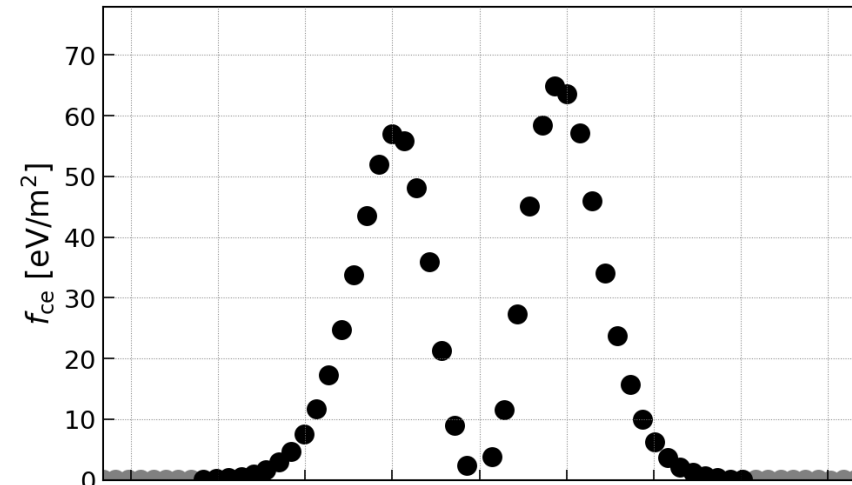
Decomposition: Geomagnetic – Charge-Excess



geomagnetic



charge-excess

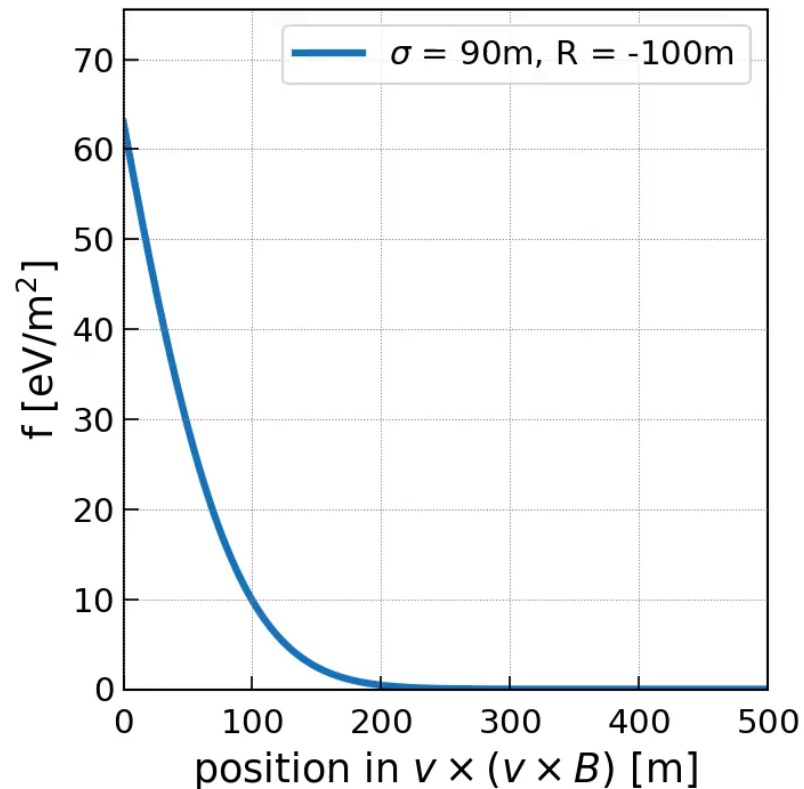


Geomagnetic

Parameters

- radiation energy E'_{geo} → cosmic-ray energy
- width σ_{geo}
- Cherenkov ring R_{geo} } distance to X_{max} → cosmic-ray mass

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

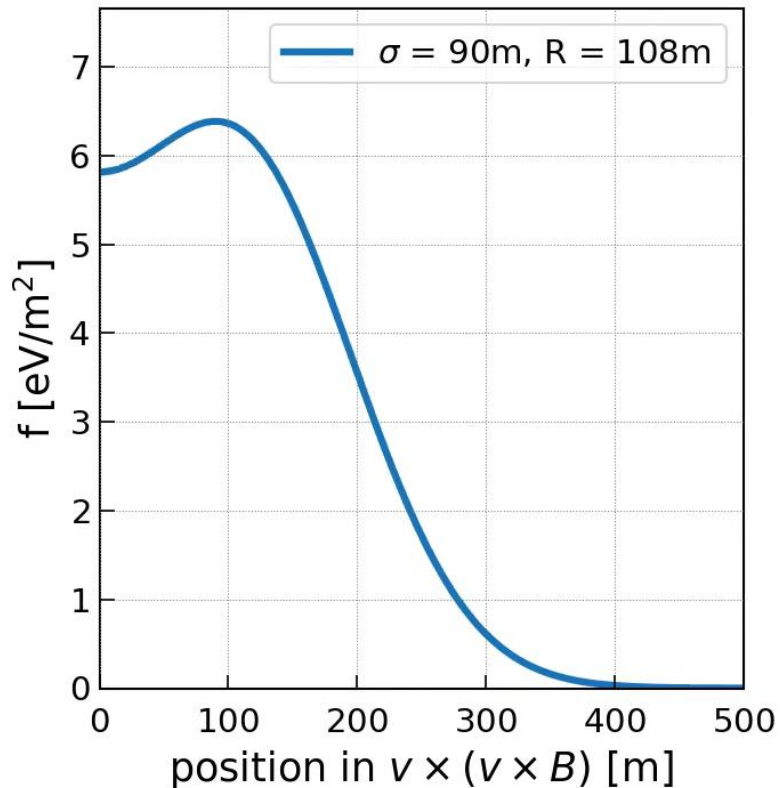


Geomagnetic

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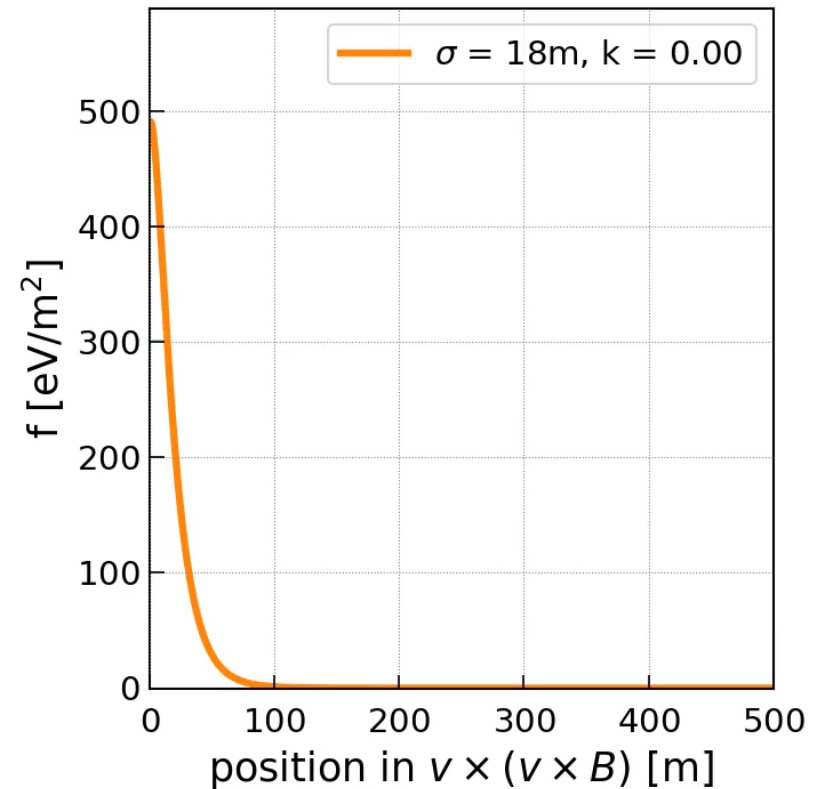


Charge-Excess

Parameters

- radiation energy E'_{ce} → cr energy
- width σ_{ce}
- shape k } distance to X_{max}

$$f_{ce}(r) = \frac{1}{N_{ce}} E'_{ce} r^k \exp\left(\frac{-r^2(k+1)}{2\sigma_{ce}^2}\right)$$

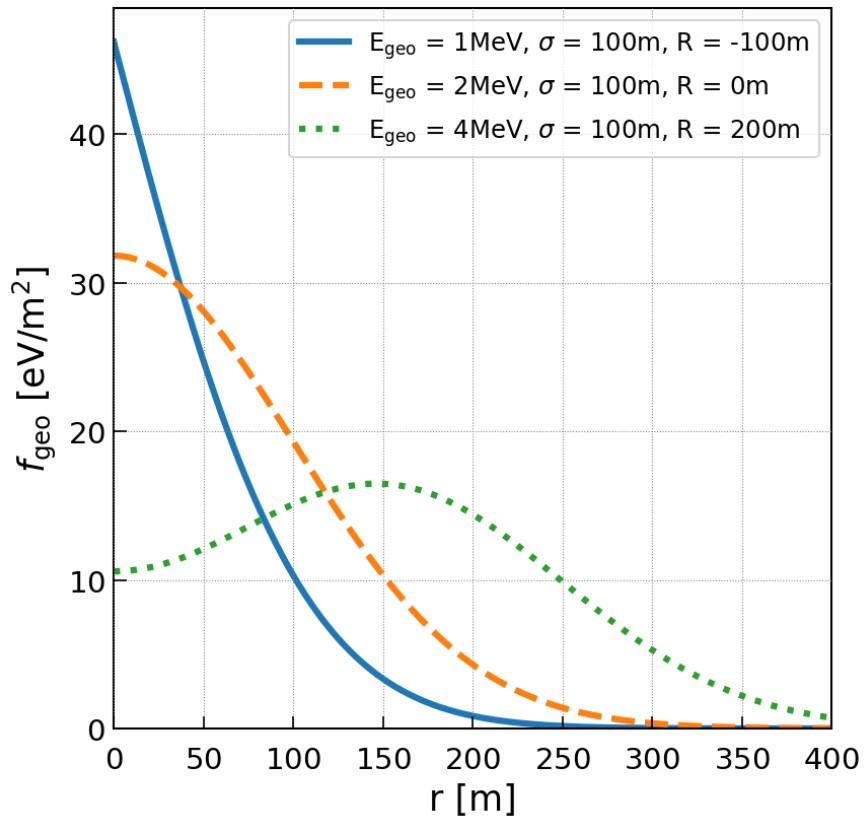


Geomagnetic

Parameters

- radiation energy E'_{geo}
- width σ_{geo}
- Cherenkov ring R_{geo}

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

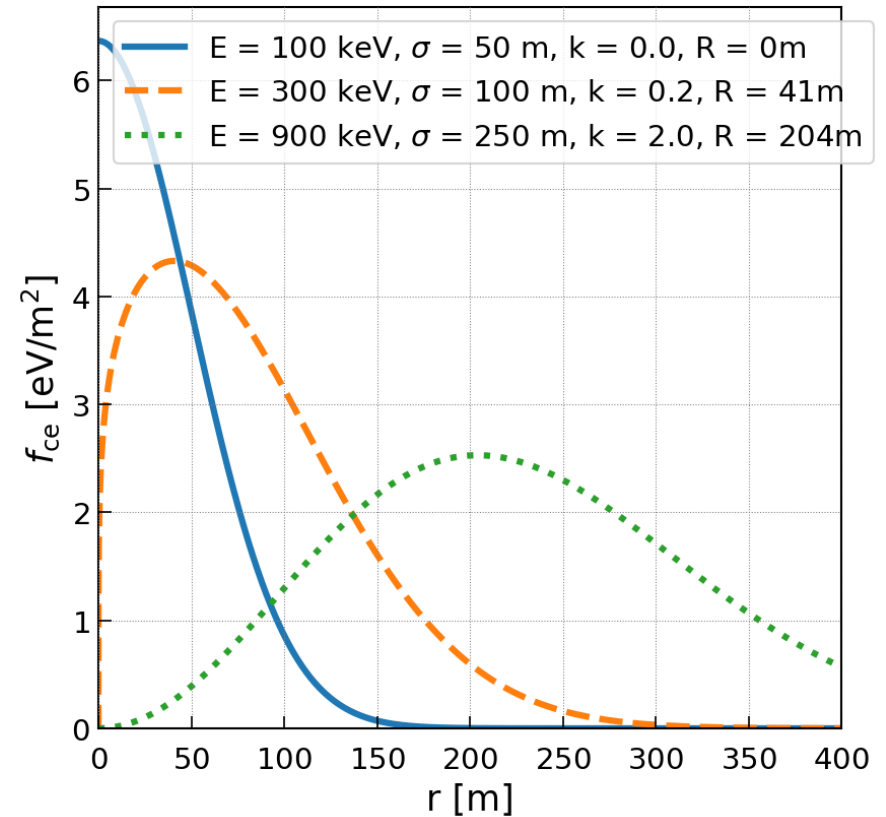


Charge-Excess

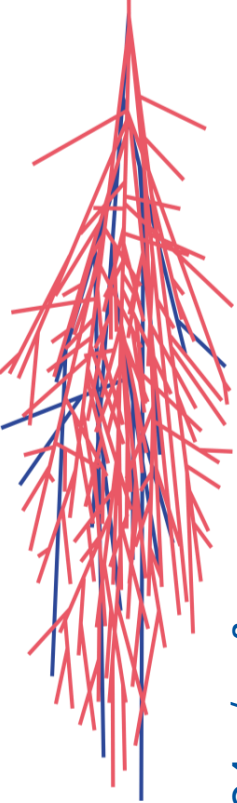
Parameters

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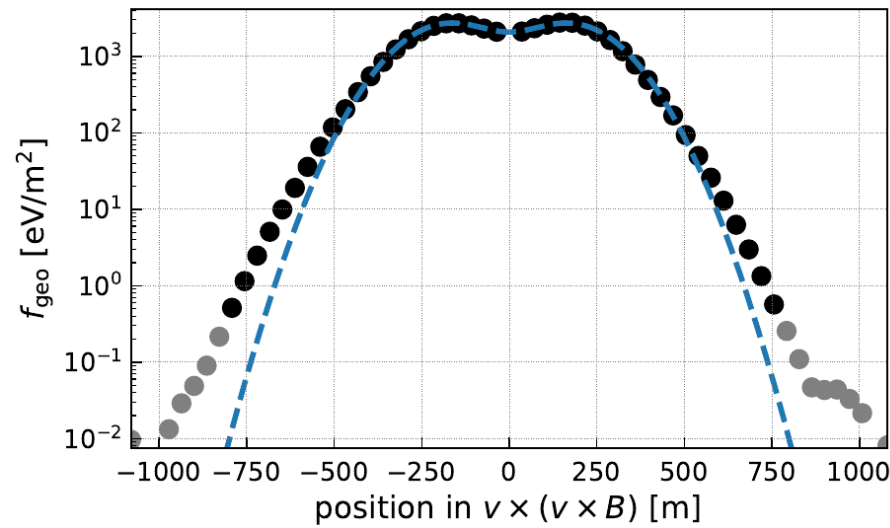
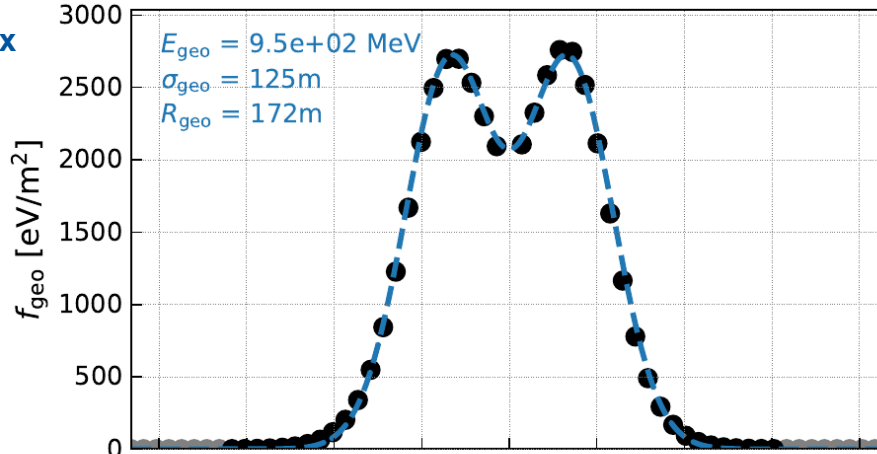


Behaviour at Large Distances



X_{\max}
 1024 g/cm^2

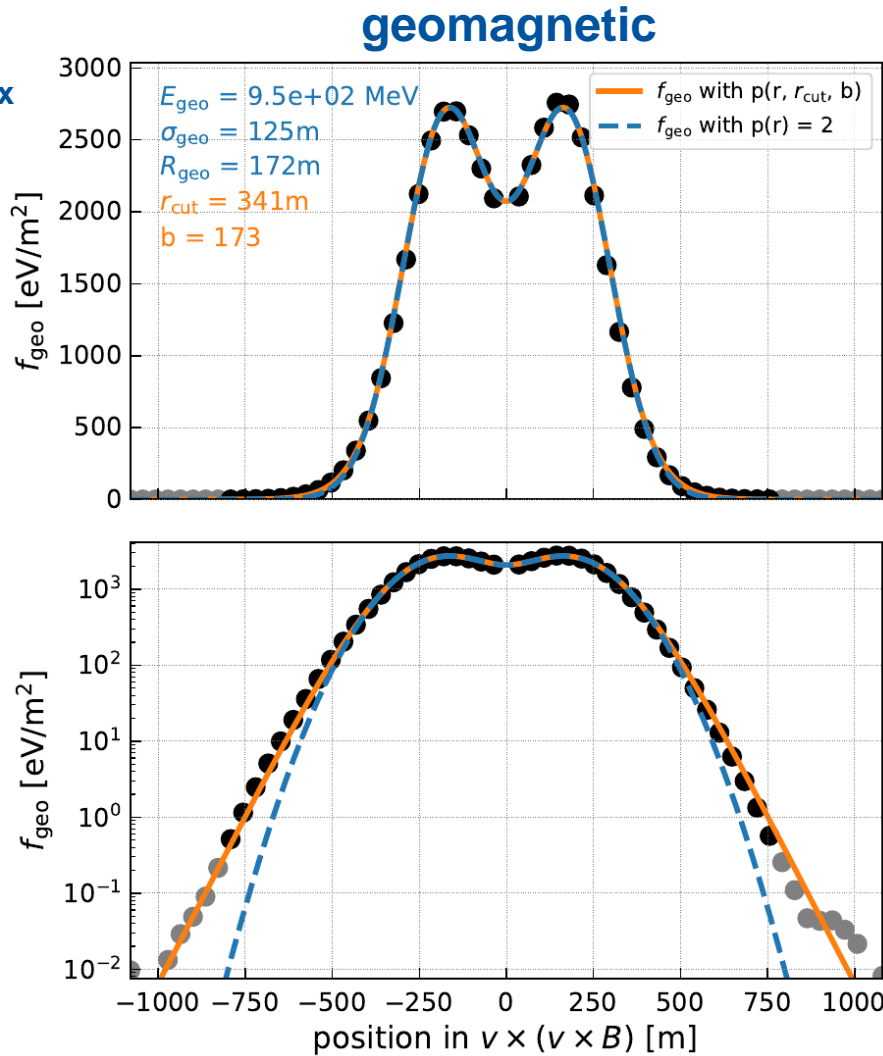
geomagnetic



Behaviour at Large Distances



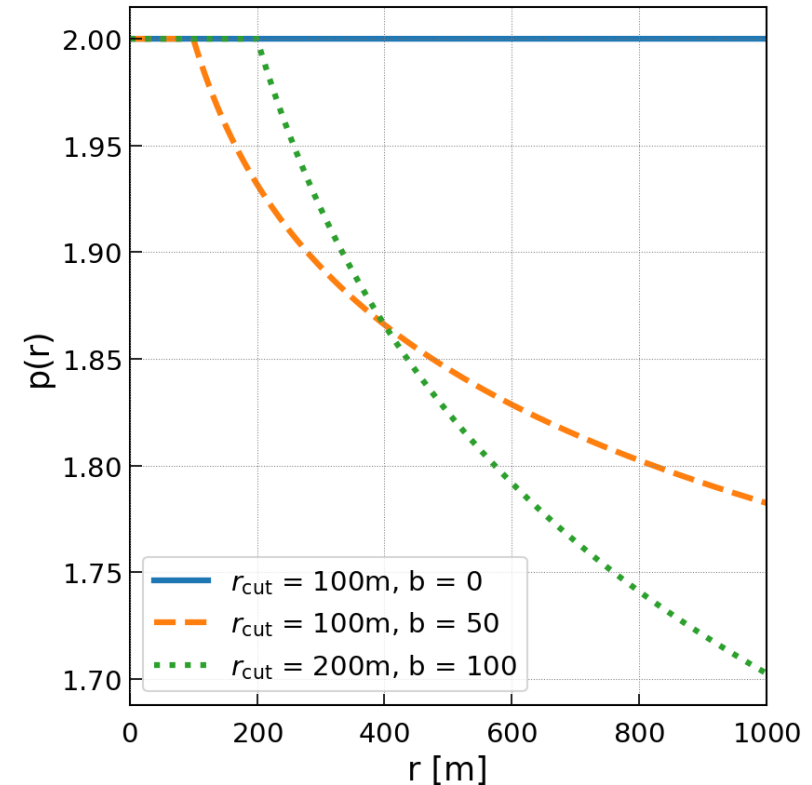
X_{\max}
1024 g/cm²



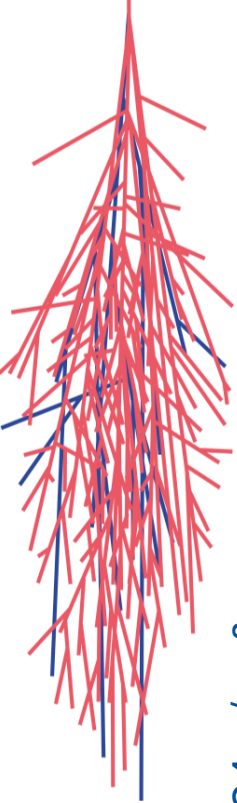
- signal falloff of function too strong
- modelled via modification of exponent

$$\rightarrow \exp\left(-\left(\frac{r+R_{\text{geo}}}{\sqrt{2}\sigma_{\text{geo}}}\right)^{p(r)}\right)$$

$$p(r) = \begin{cases} 2 & \text{if } r \leq r_{\text{cut}} \\ 2 \left(\frac{r}{r_{\text{cut}}}\right)^{-b/1000} & \text{if } r > r_{\text{cut}} \end{cases}$$

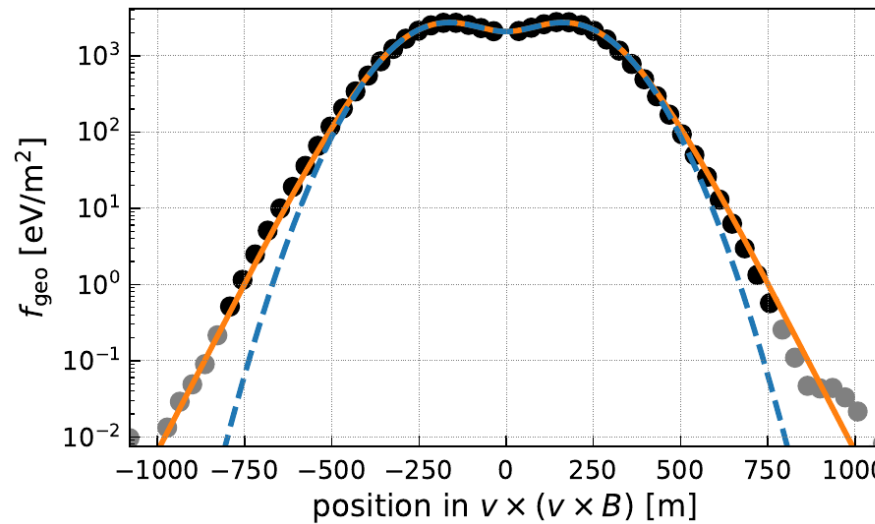
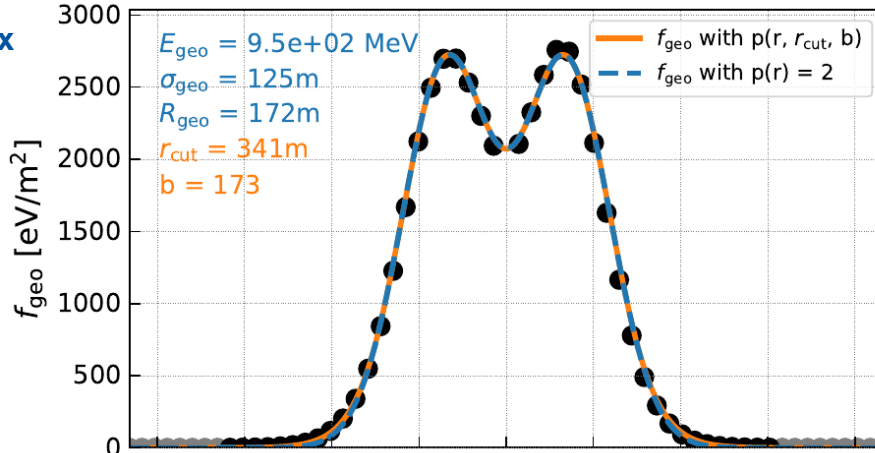


Example 3

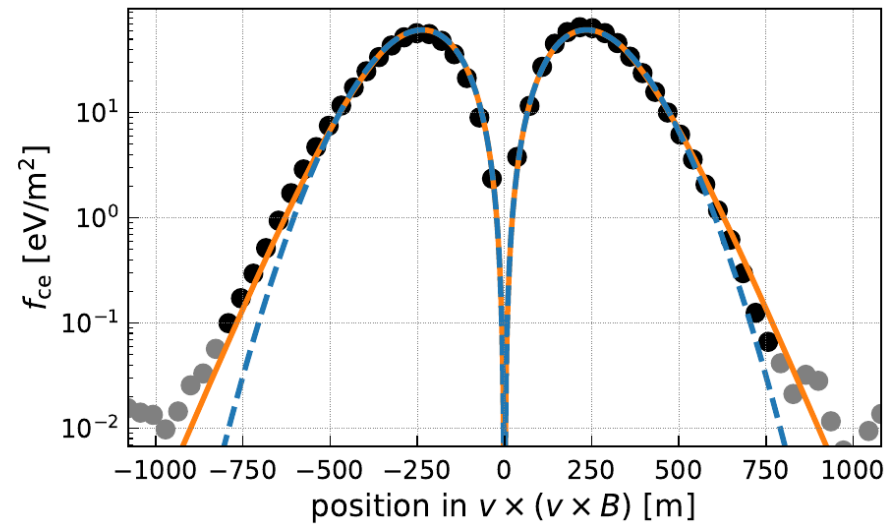
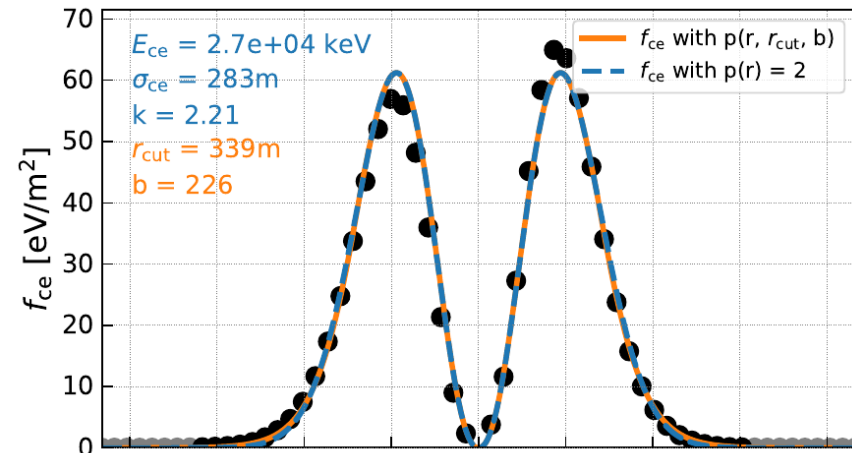


X_{\max}
1024 g/cm²

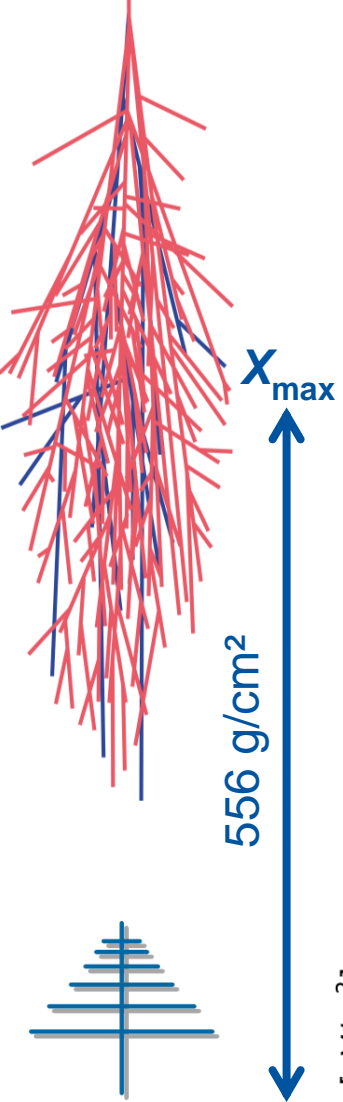
geomagnetic



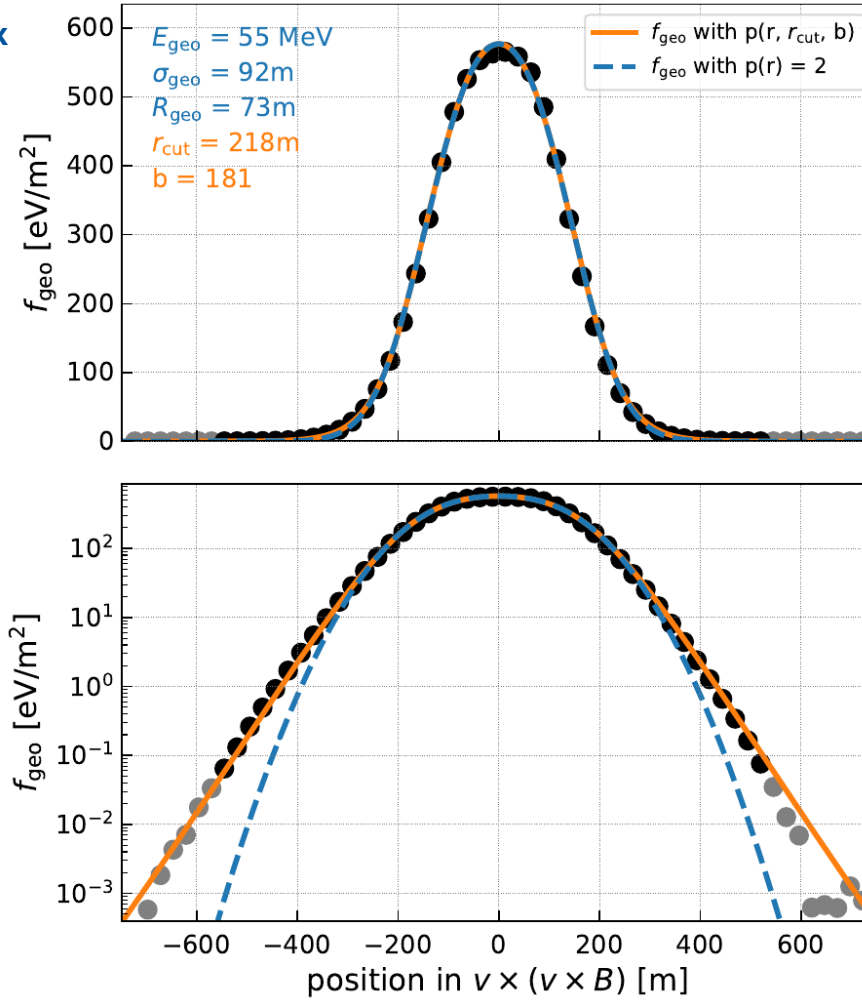
charge-excess



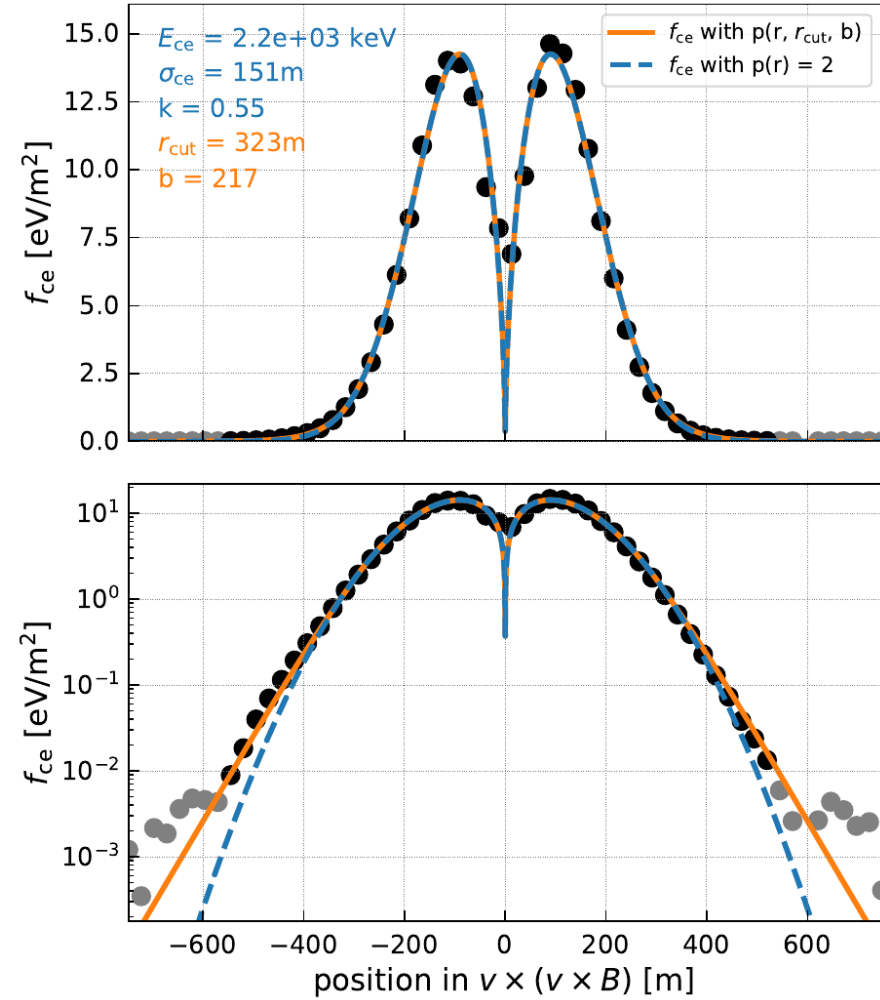
Example 2



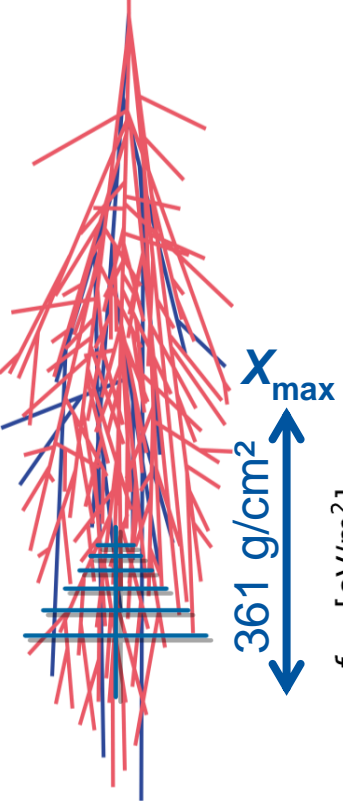
geomagnetic



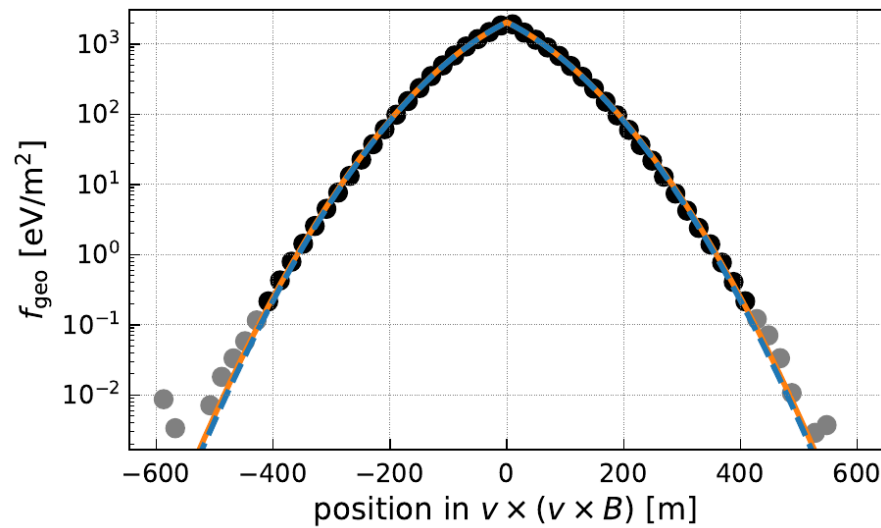
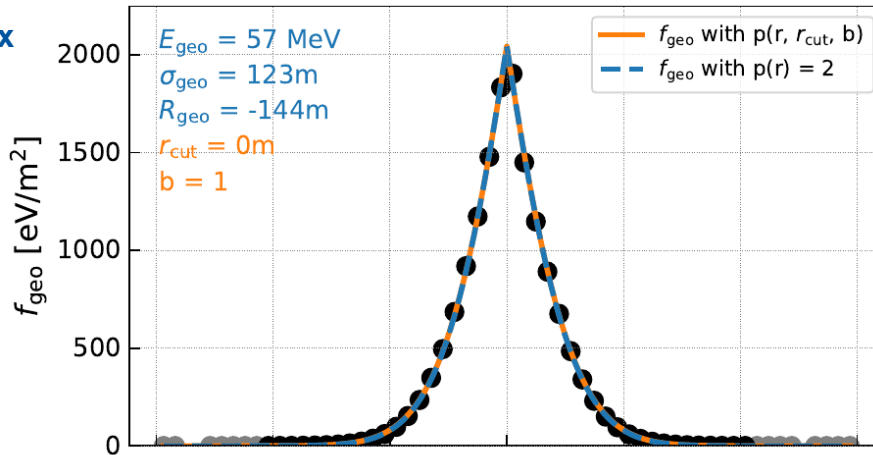
charge-excess



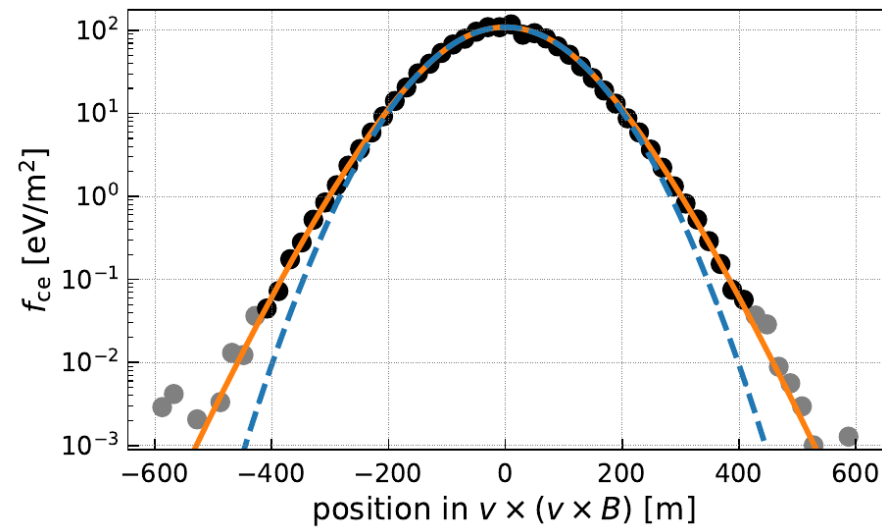
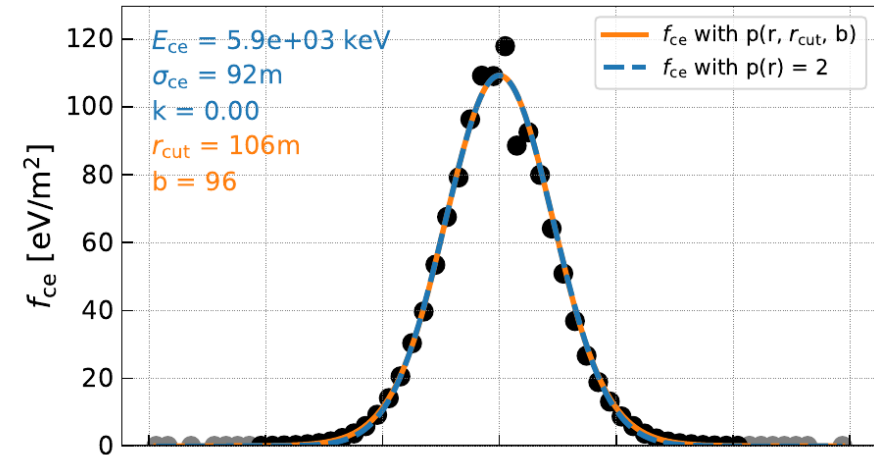
Example 1



geomagnetic



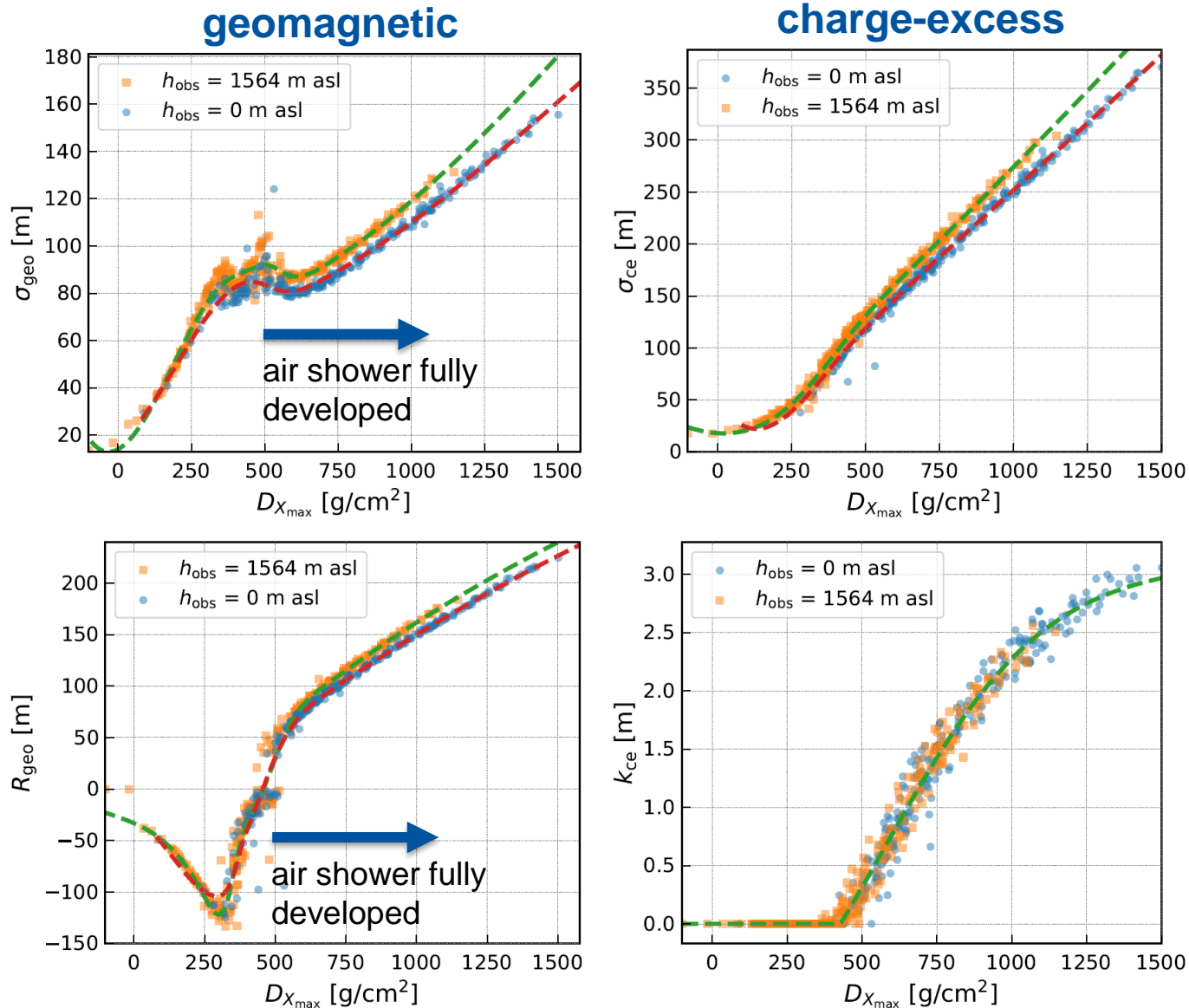
charge-excess



Dependence on Air-Shower Parameters

- radiation energy scales with cosmic-ray energy
- all other parameters depends on D_{Xmax}
 - only **two free parameters**: radiation energy and D_{Xmax} (+ core position)

Glaser et al. JCAP 09(2016)024



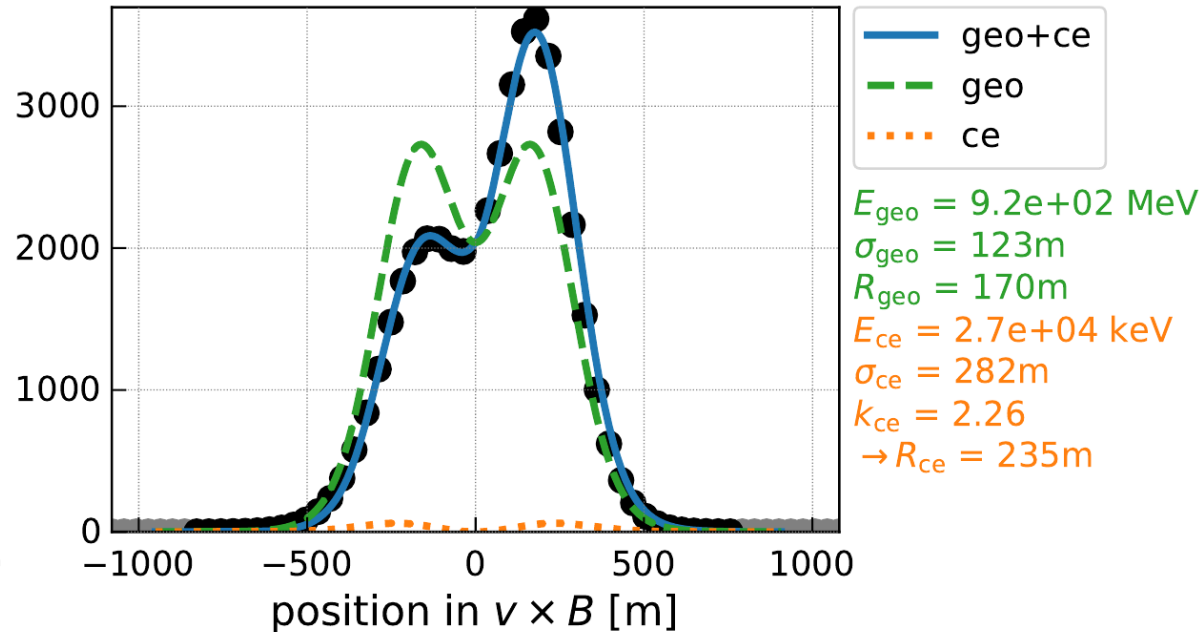
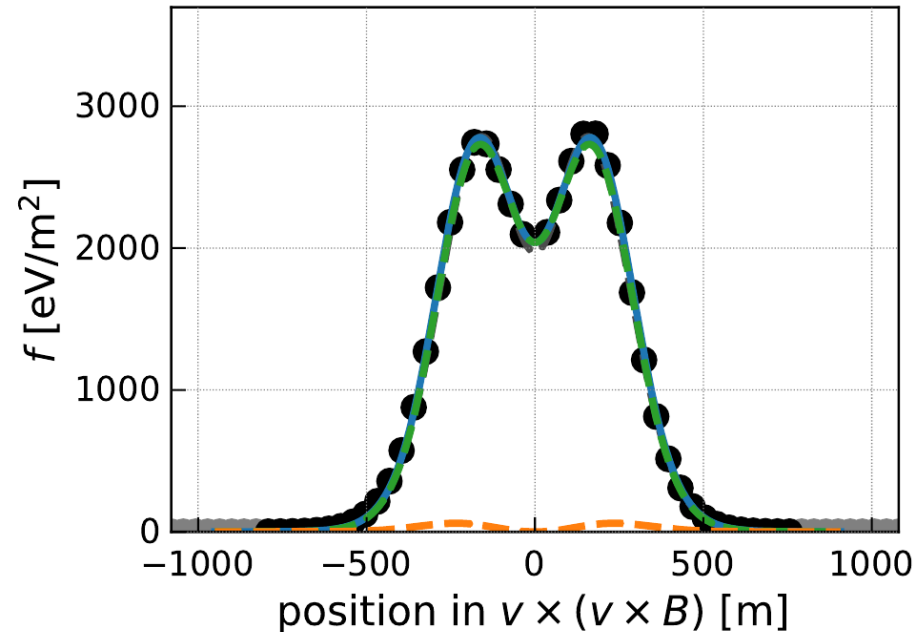
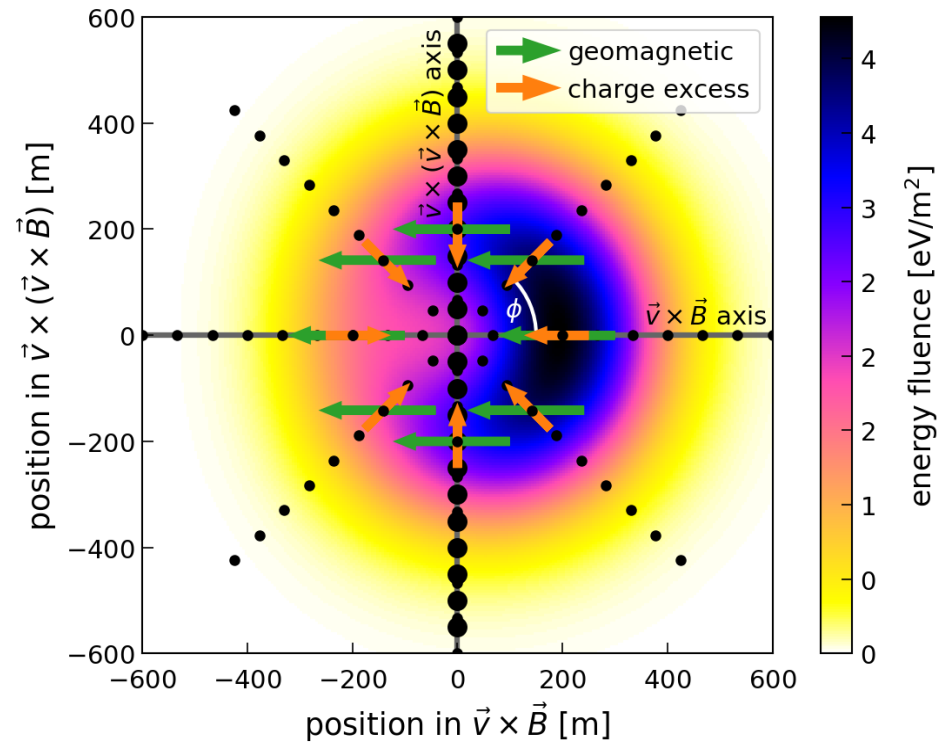
Combination to full 2D LDF

- Interference results in asymmetry

$$f_{\vec{v} \times \vec{B}}(\vec{r}) = \left(\sqrt{f_{\text{geo}}(\vec{r})} + \cos \phi \sqrt{f_{\text{ce}}(\vec{r})} \right)^2$$

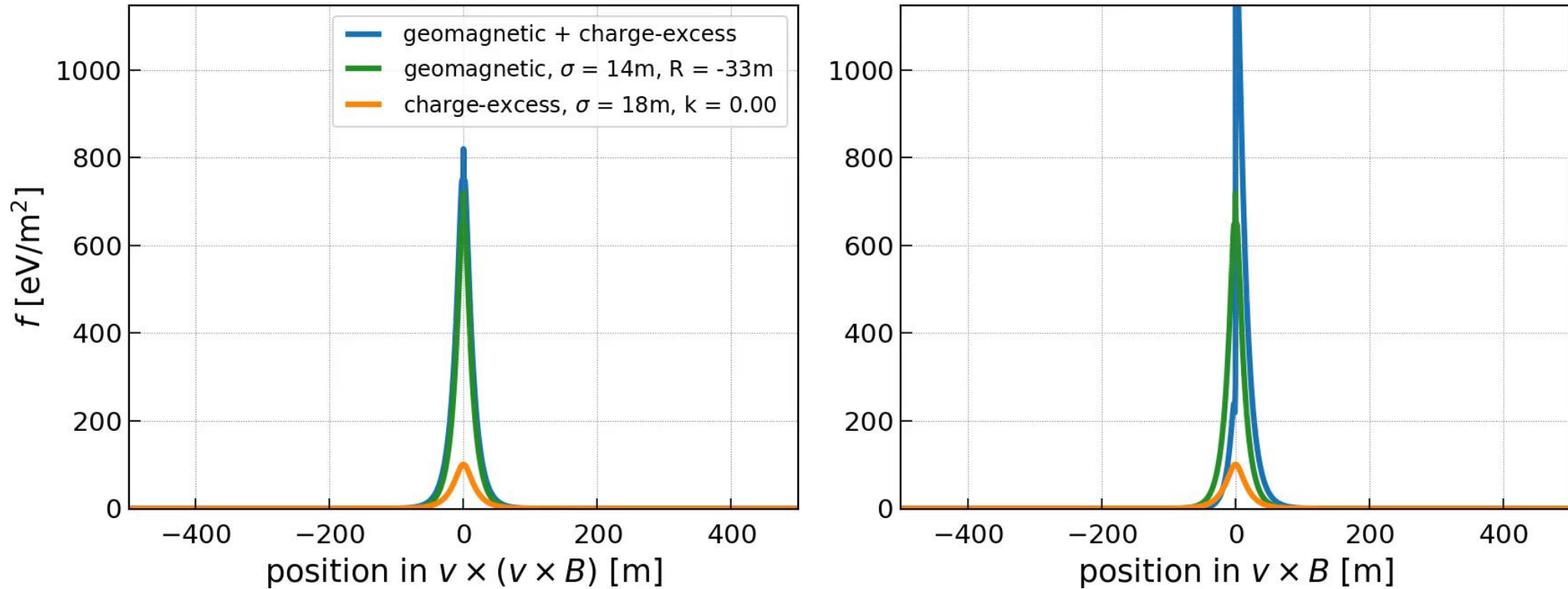
$$f_{\vec{v} \times (\vec{v} \times \vec{B})}(\vec{r}) = \sin^2 \phi f_{\text{ce}}(\vec{r})$$

Glaser et al. JCAP 09(2016)024



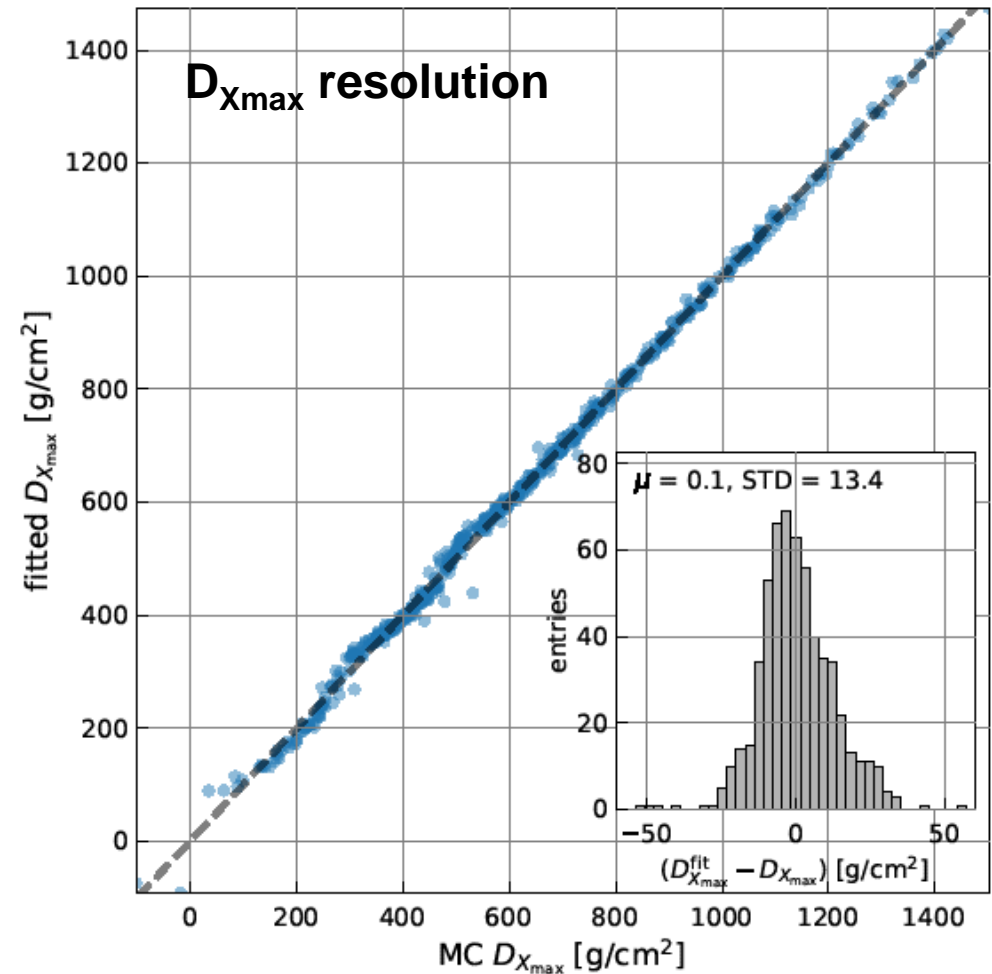
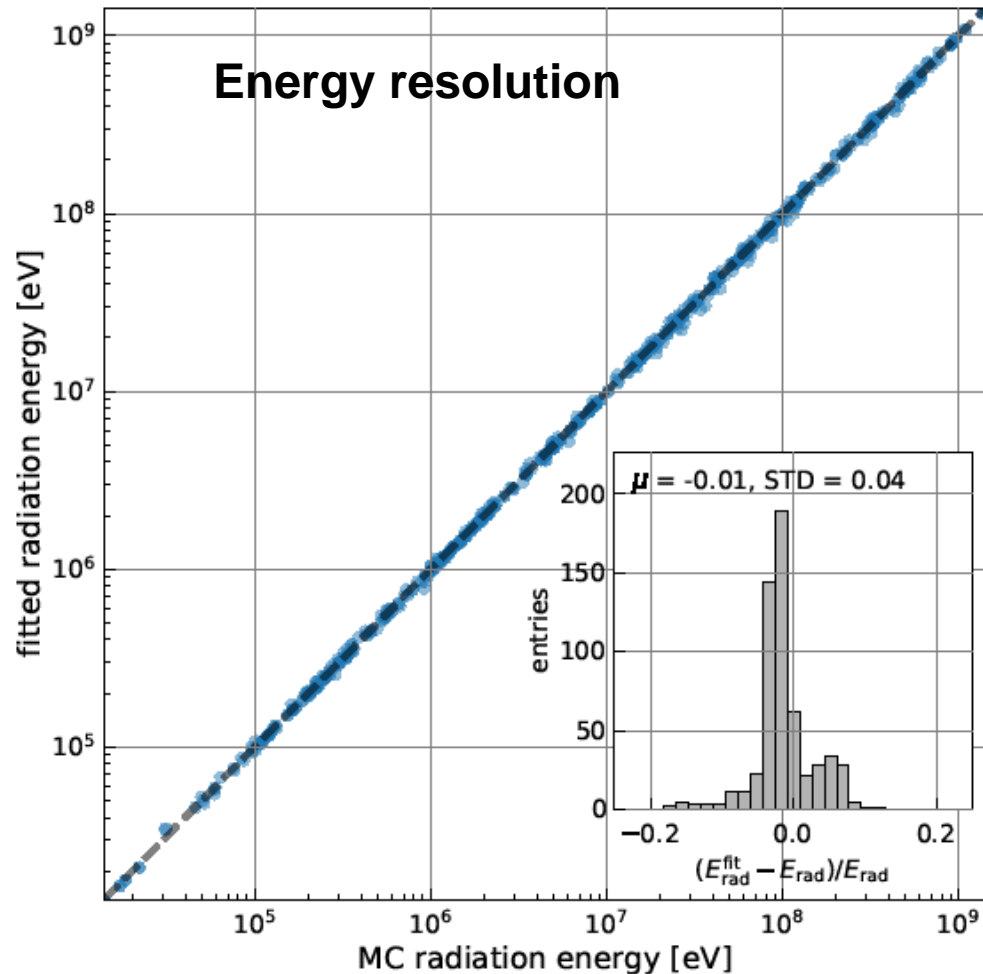
Combination to full 2D LDF

distance to $X_{\max} = 0$ [g/cm²], $\theta = 0^\circ$, $h = 1564$ m asl



Energy and X_{\max} Resolution

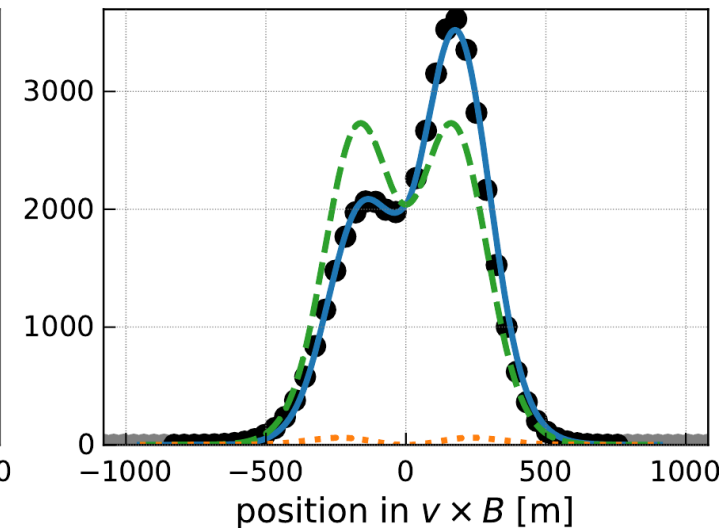
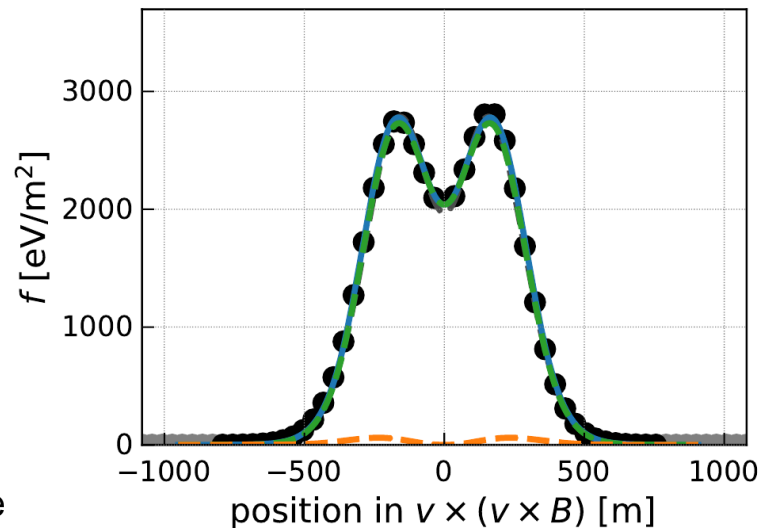
- Accuracy of model quantified via resolution to air-shower parameters
- Model uncertainties negligible compared to experimental uncertainties
 - 2% energy resolution
 - 13 g/cm² $D_{X_{\max}}$ resolution



Summary

- New model of spatial radio signal distribution that
 - models **geomagnetic** and **charge-excess** emission separately
 - uses polarization information → uses full information per station
- Fit parameters with direct physical meaning
 - **radiation energy**
 - scales with **cosmic-ray energy**
 - **width** and **radius** of Cherenkov ring
 - scales with X_{\max} → **cosmic-ray mass**
- Accuracy of model:
 - 2% energy resolution, $13 \text{ g/cm}^2 D_{X_{\max}}$ resolution
- Reference implementation at github.com/cg-laser/geoceLDF (and in Offline)

More details
arXiv:1806.03620



backup

$p(r)$ dependence on $D_{X_{\max}}$

