Giant Radio Array for Neutrino Detection

A reconstruction procedure for near horizon extensive air showers based on radio signals

Valentin Decoene (PSU-IAP)
in collaboration with
Olivier Martineau (LPNHE-IAP), Matias Tueros (IFLP) and Simon Chiche (IAP)

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Motivations

why are we looking at near horizon extensive-air-shower (EAS) ?

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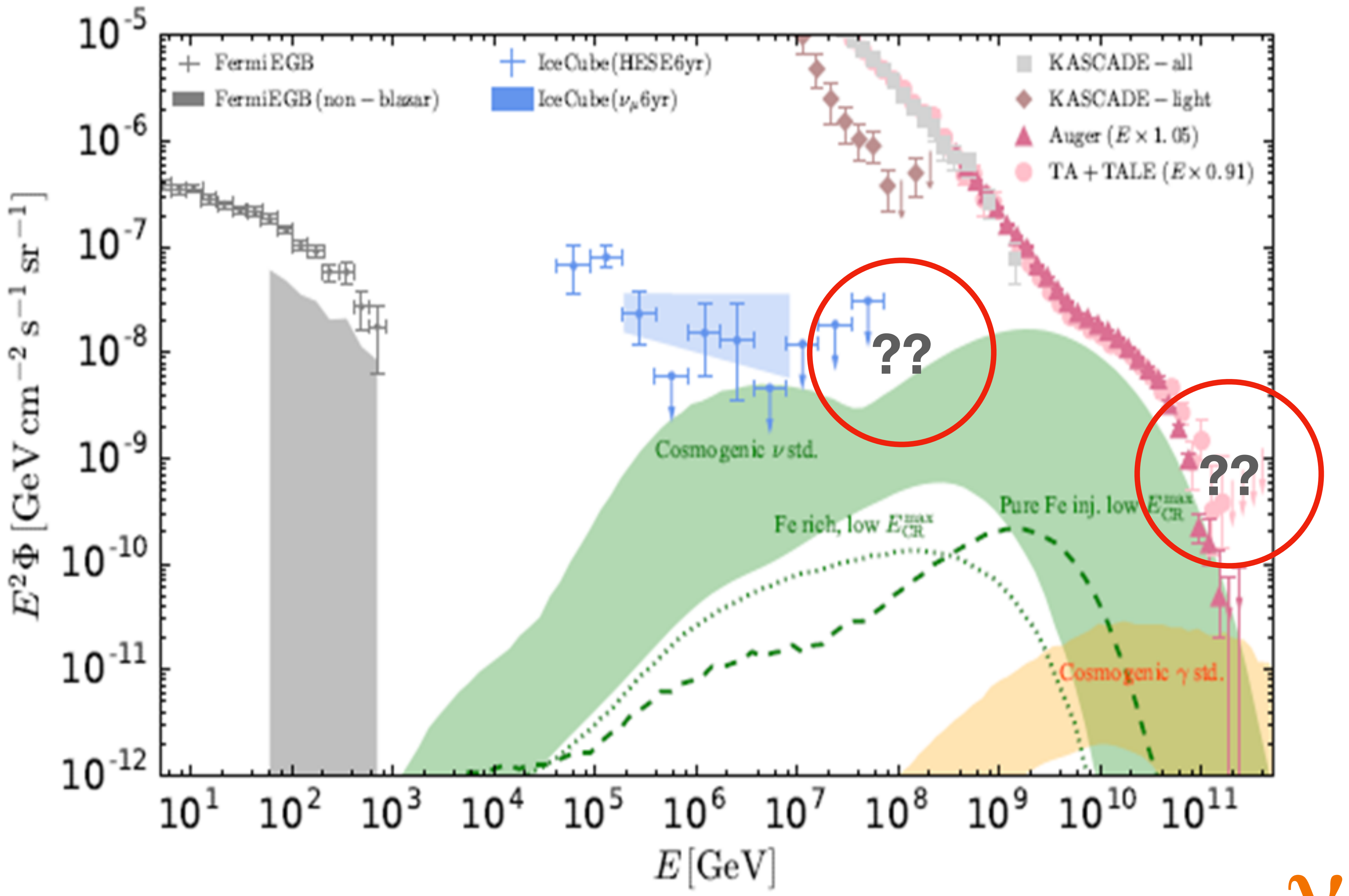
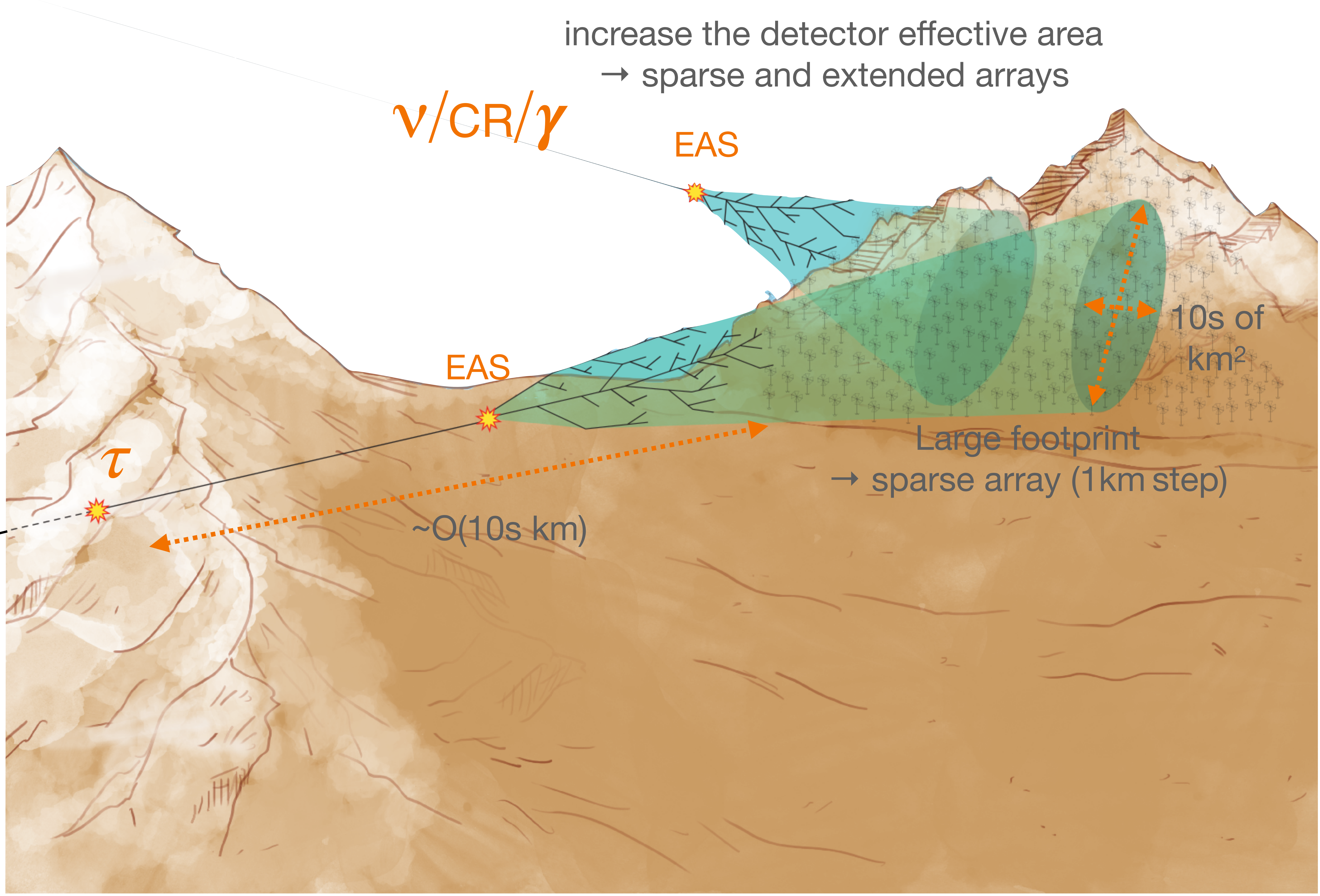


ν_e

ν_μ

ν

Use the Earth as a target
→Earth skimming neutrinos trajectories



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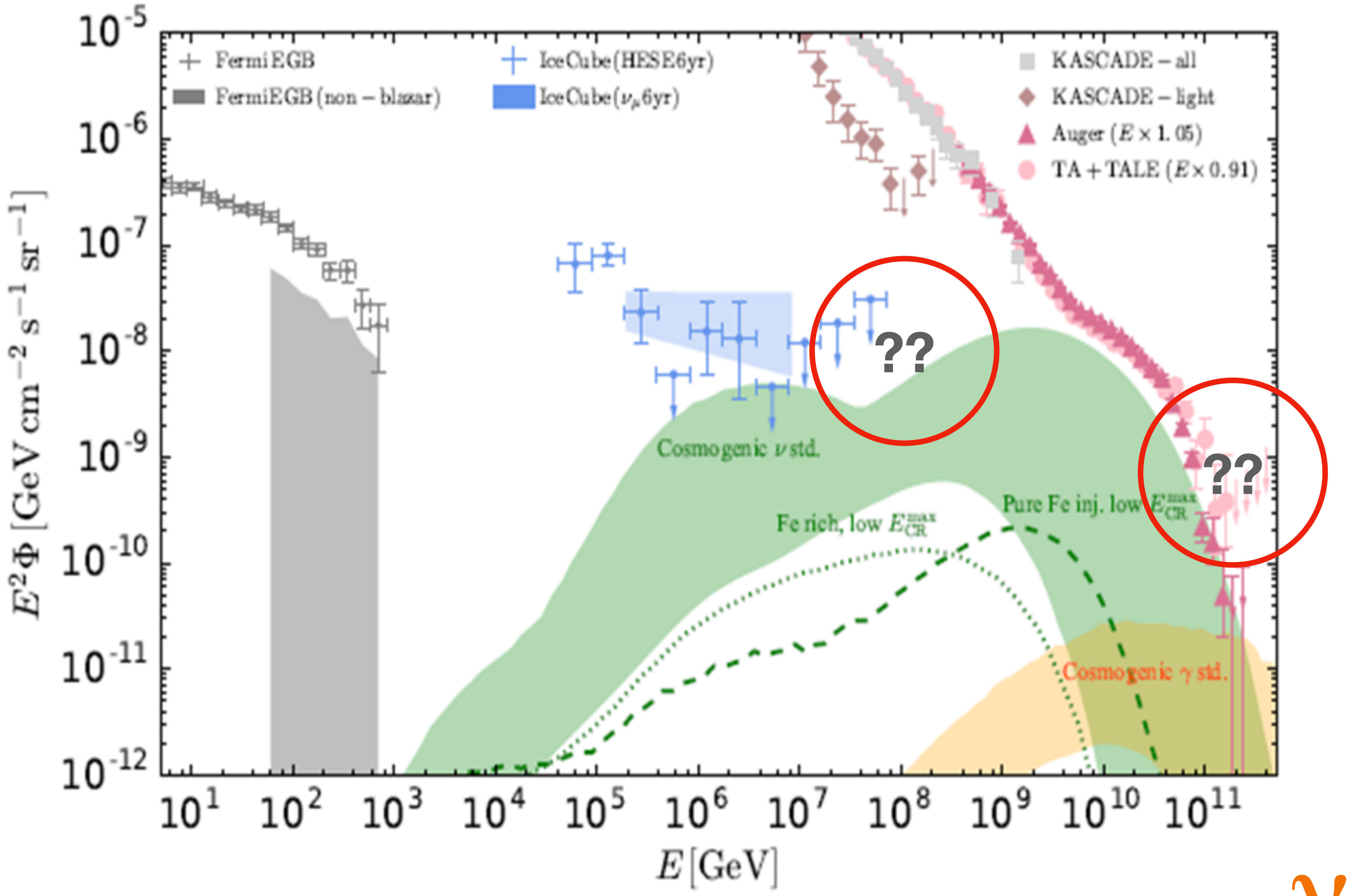
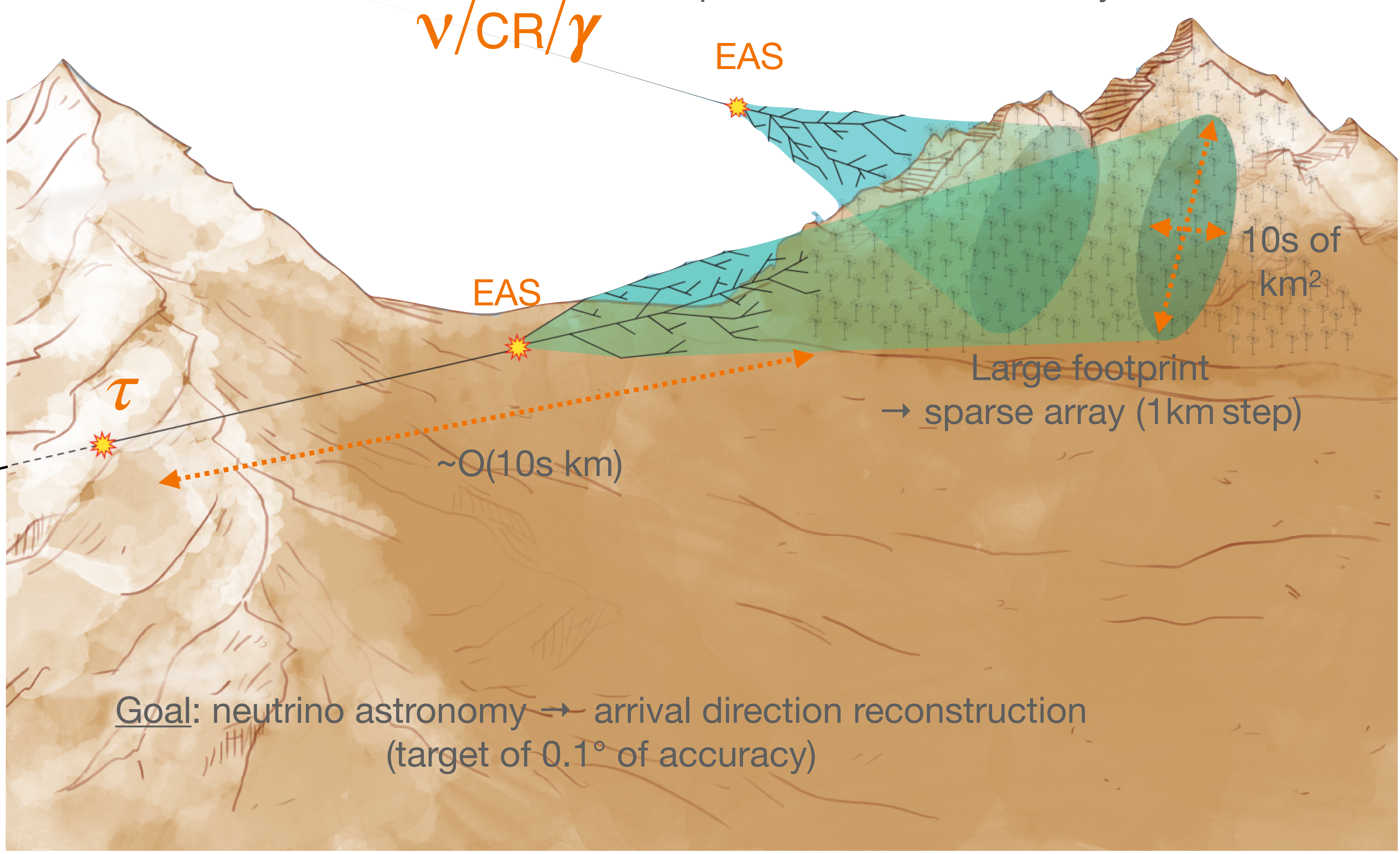


Goals: energy and primary identification

increase the detector effective area
→ sparse and extended arrays



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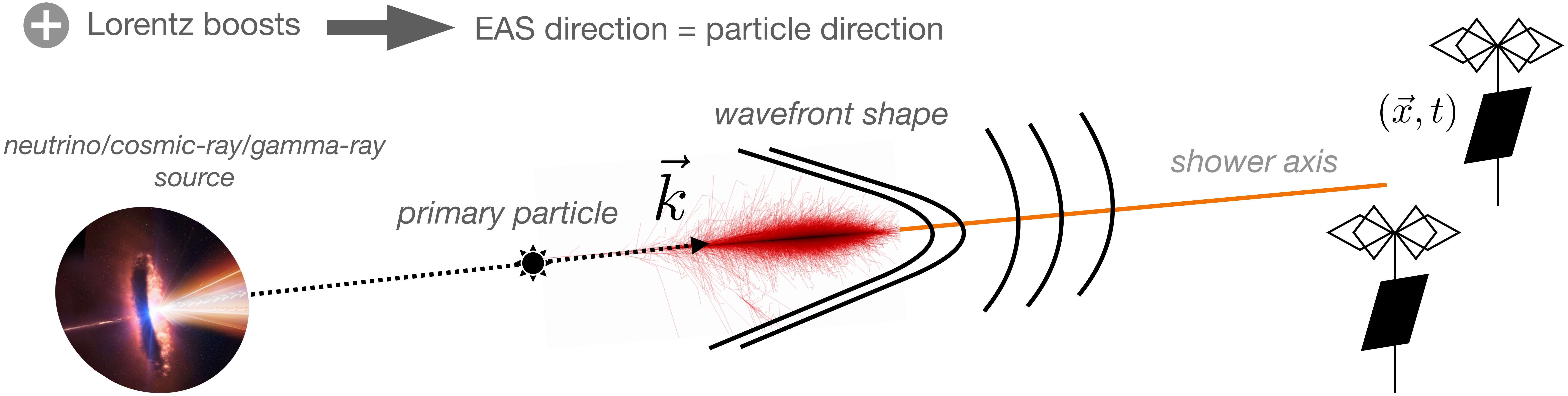
Study of the wavefront shape

The radio wavefront should provide a good signature of the EAS direction

➕ Lorentz boosts ➡ EAS direction = particle direction



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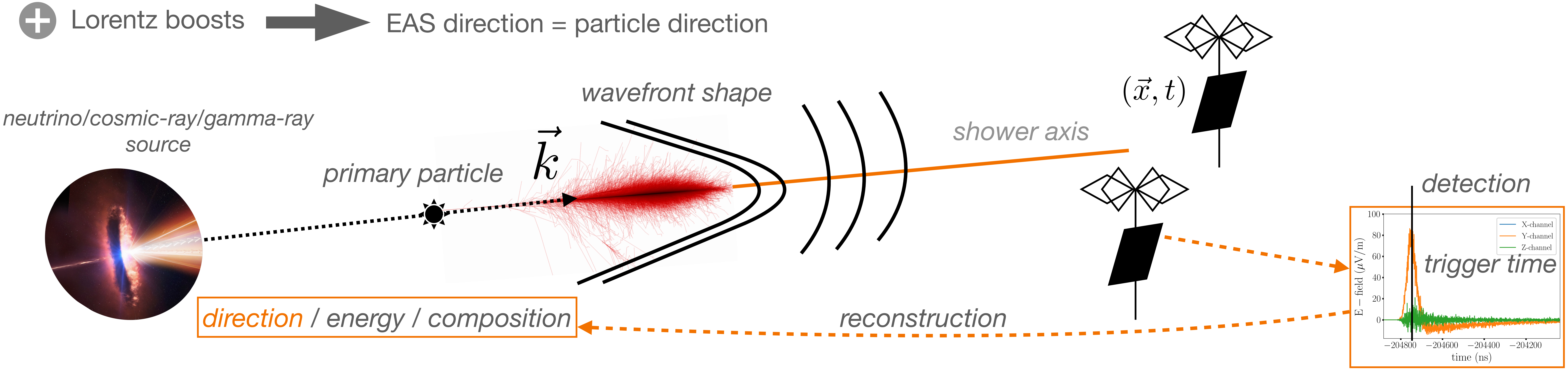

Method: adjust the wavefront model to the trigger times ➡ **direction accuracy = wavefront shape correctness**

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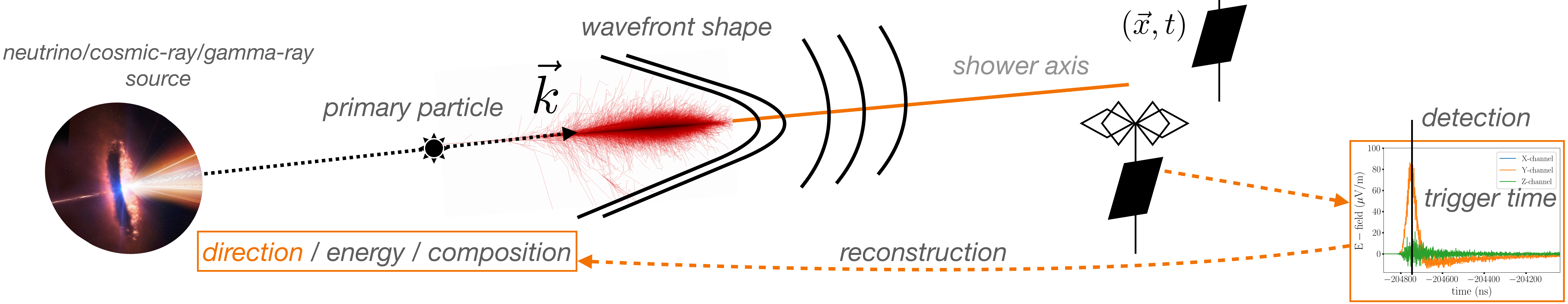

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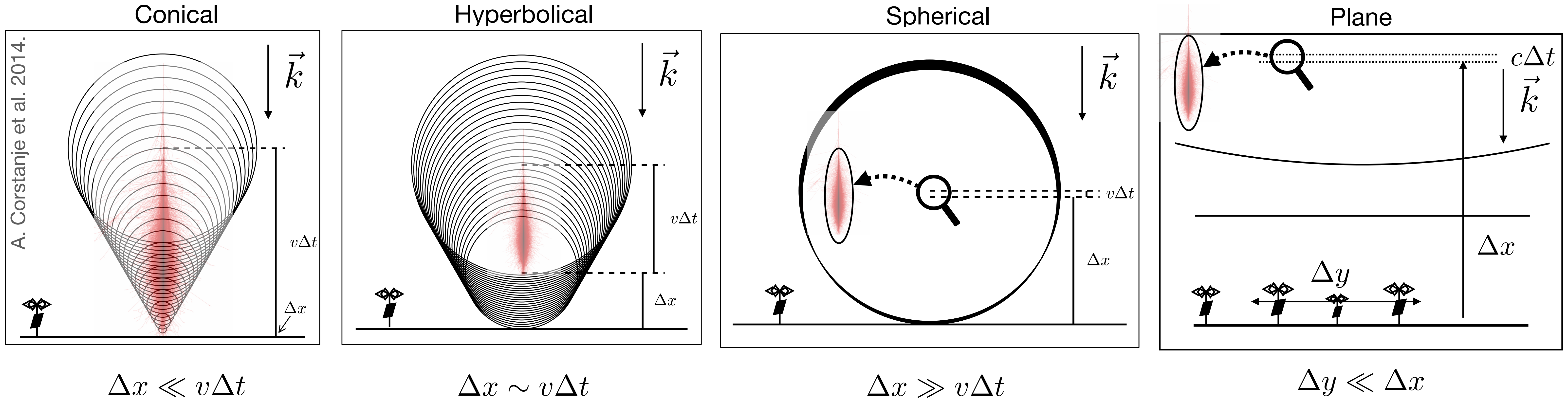
Previous works: LOPES and LOFAR
→ hyperbolic shape

F.G. Schröder et al, 2014.

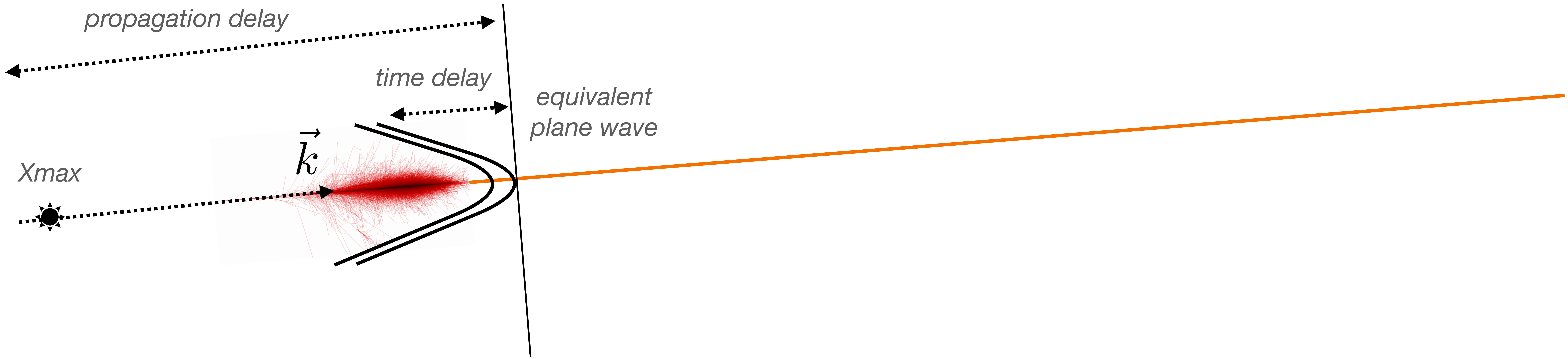
A. Corstanje et al. 2014.



What shape for near horizon EAS seen by sparse and extended arrays ?

Study of the wavefront shape

What time delays tell us about the curvature of the wavefront ?



Wavefront shape modelling:

$$\text{wavefront} = \text{propagation} + \text{curvature}$$

propagation delay = plane wave propagation at speed c/n

time delay = intrinsic curvature of the wavefront

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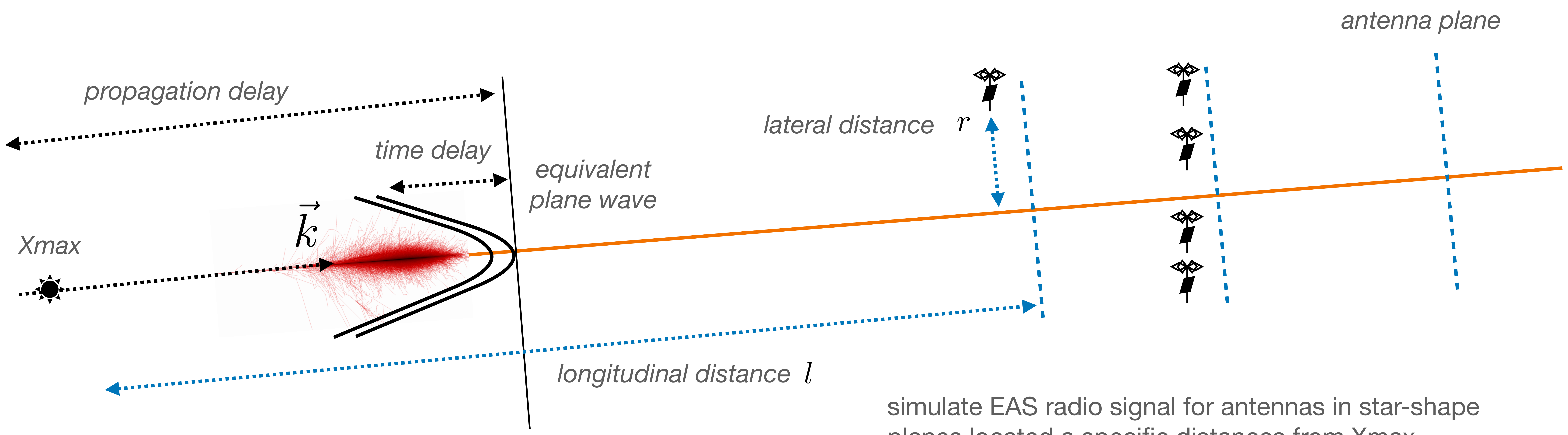

simulate EAS radio signal for antennas in star-shape planes located a specific distances from Xmax

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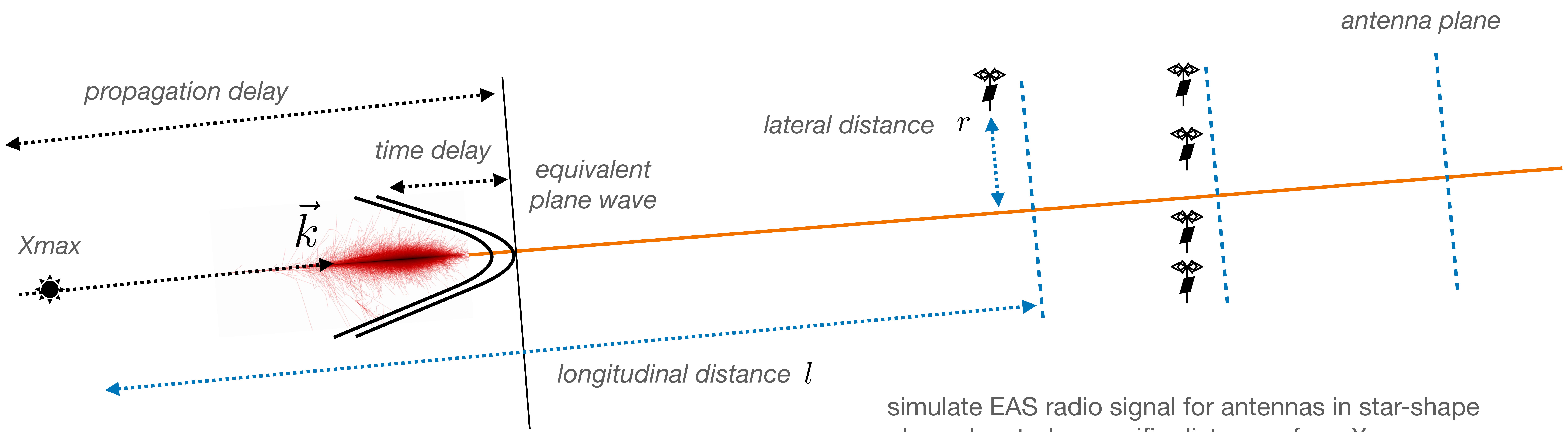

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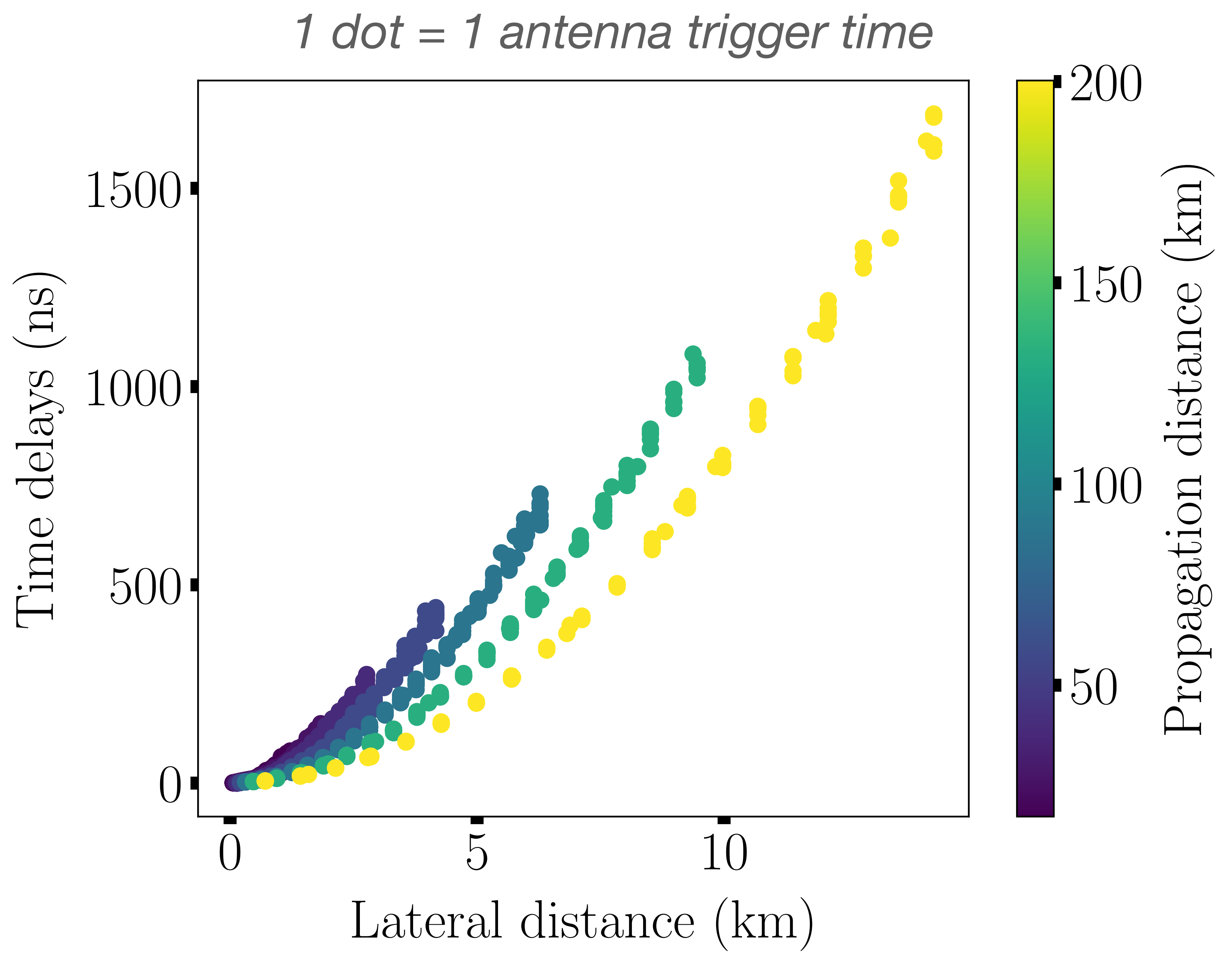
ZHAireS simulation:
- 7 planes from 17km to 200km
- zenith between 63° and 88°
- energies between 0.02EeV and 4EeV
- azimuth values = 0°, 180° and 270° w.r.t. magnetic North

→ sample the wavefront along radial and longitudinal distances

Study of the wavefront shape

Results



- time delays increase with lateral distance
- curvature reduces with propagation distance

what model describes best this curvature ?

Study of the wavefront shape

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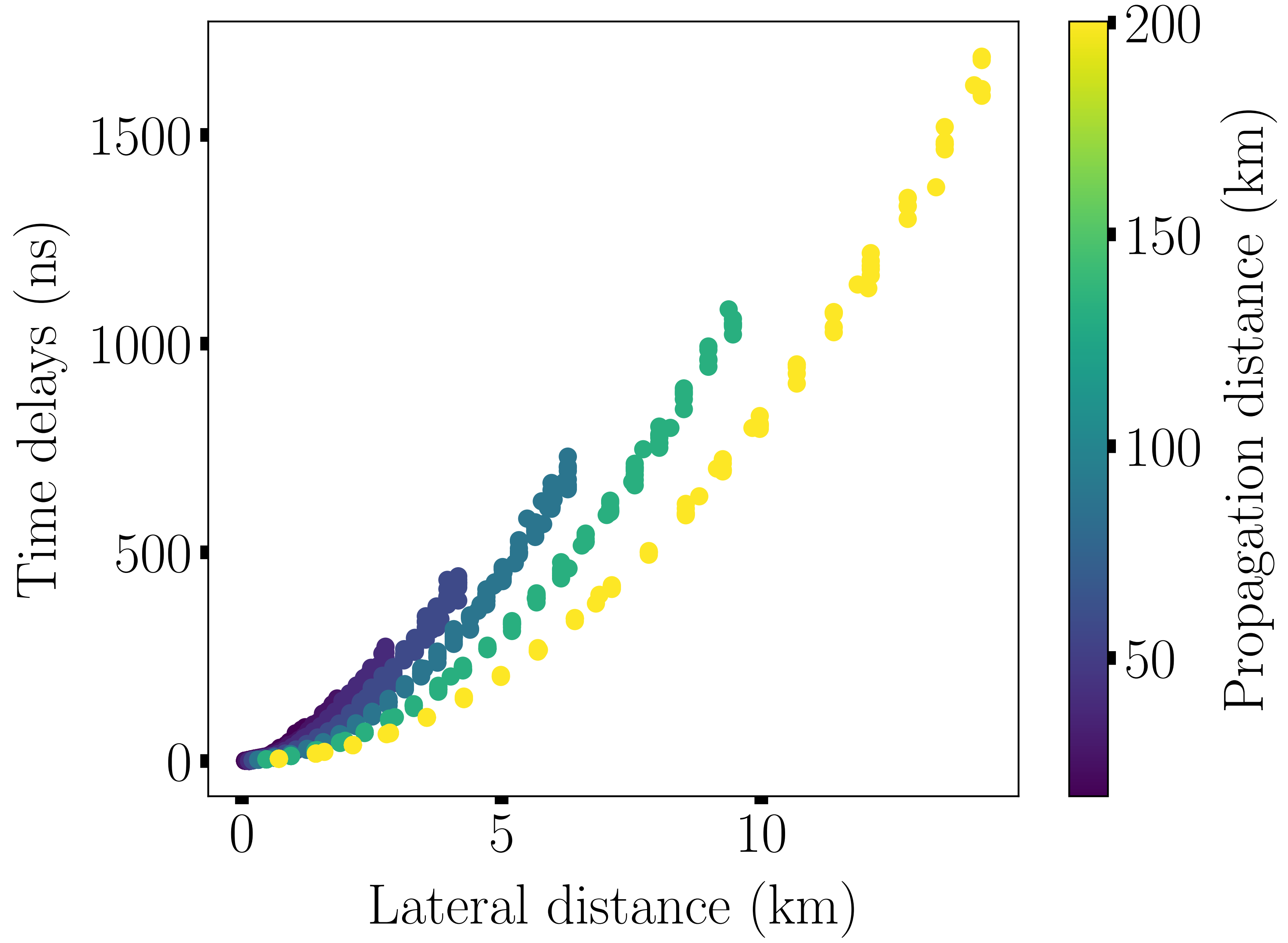
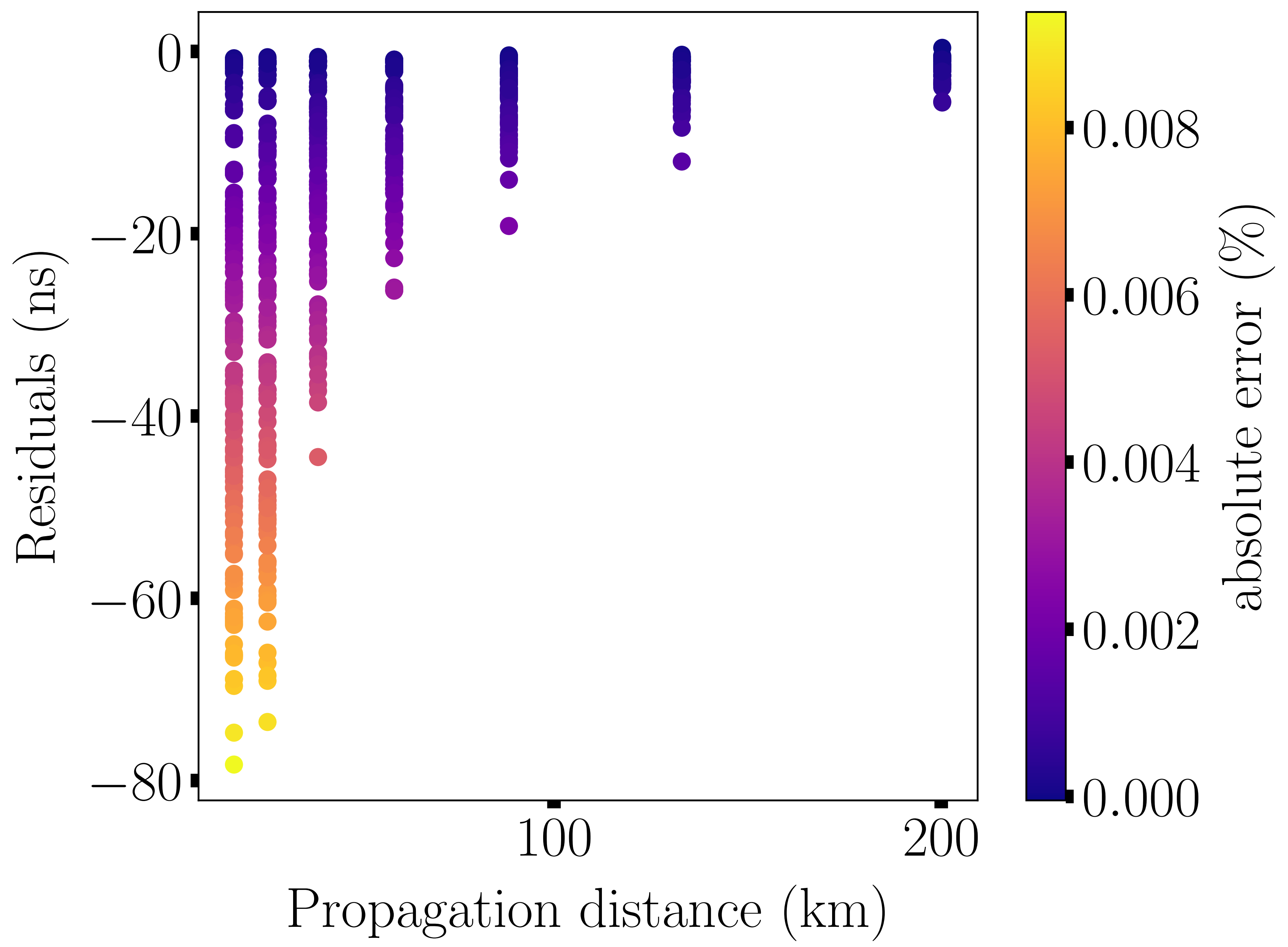
1 dot = 1 antenna trigger time



spherical wavefront model

$$c\,t^{\mathrm{sph}} = n\sqrt{l^2 + r^2}$$

residuals = trigger time - wave front model



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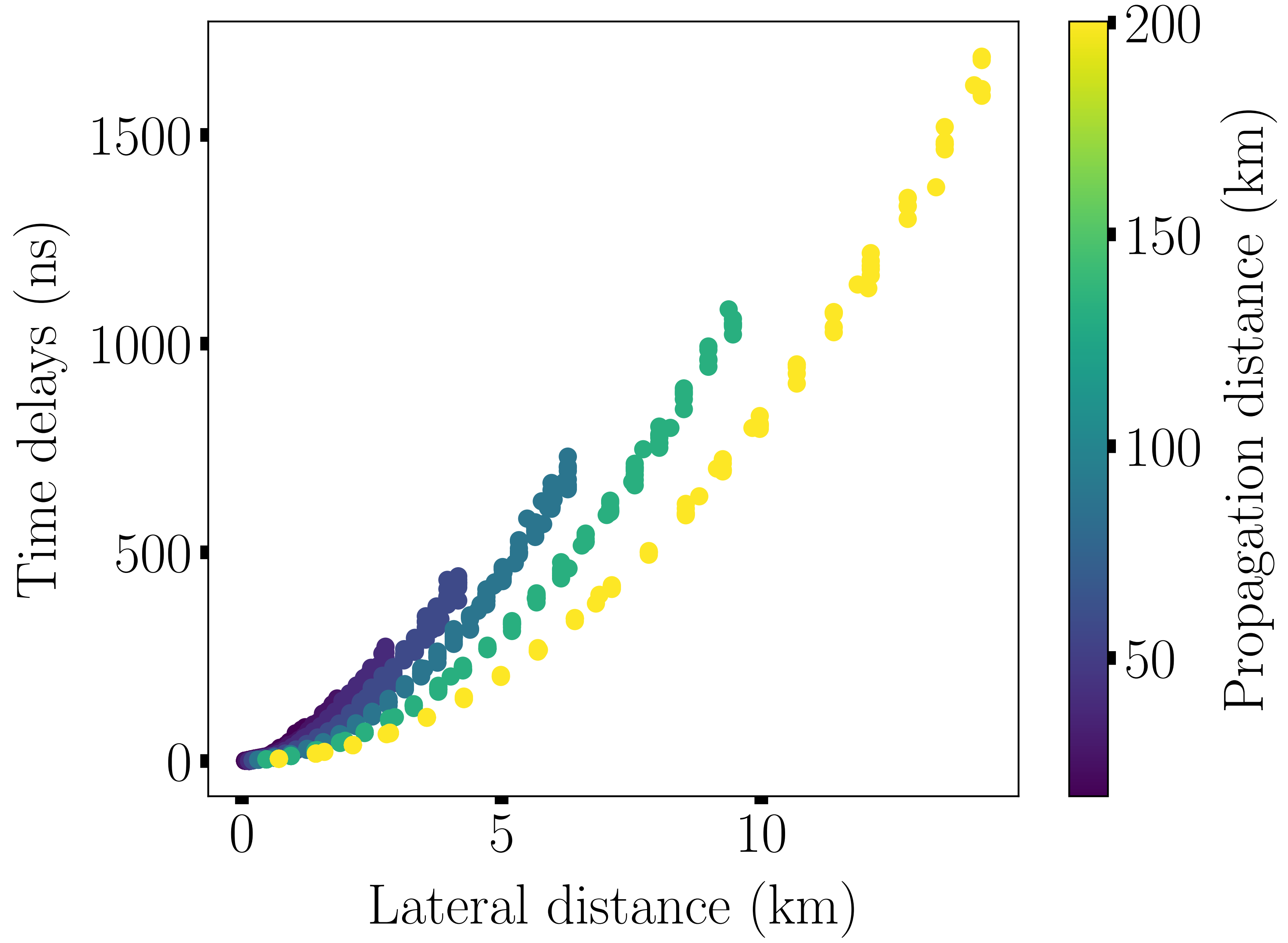

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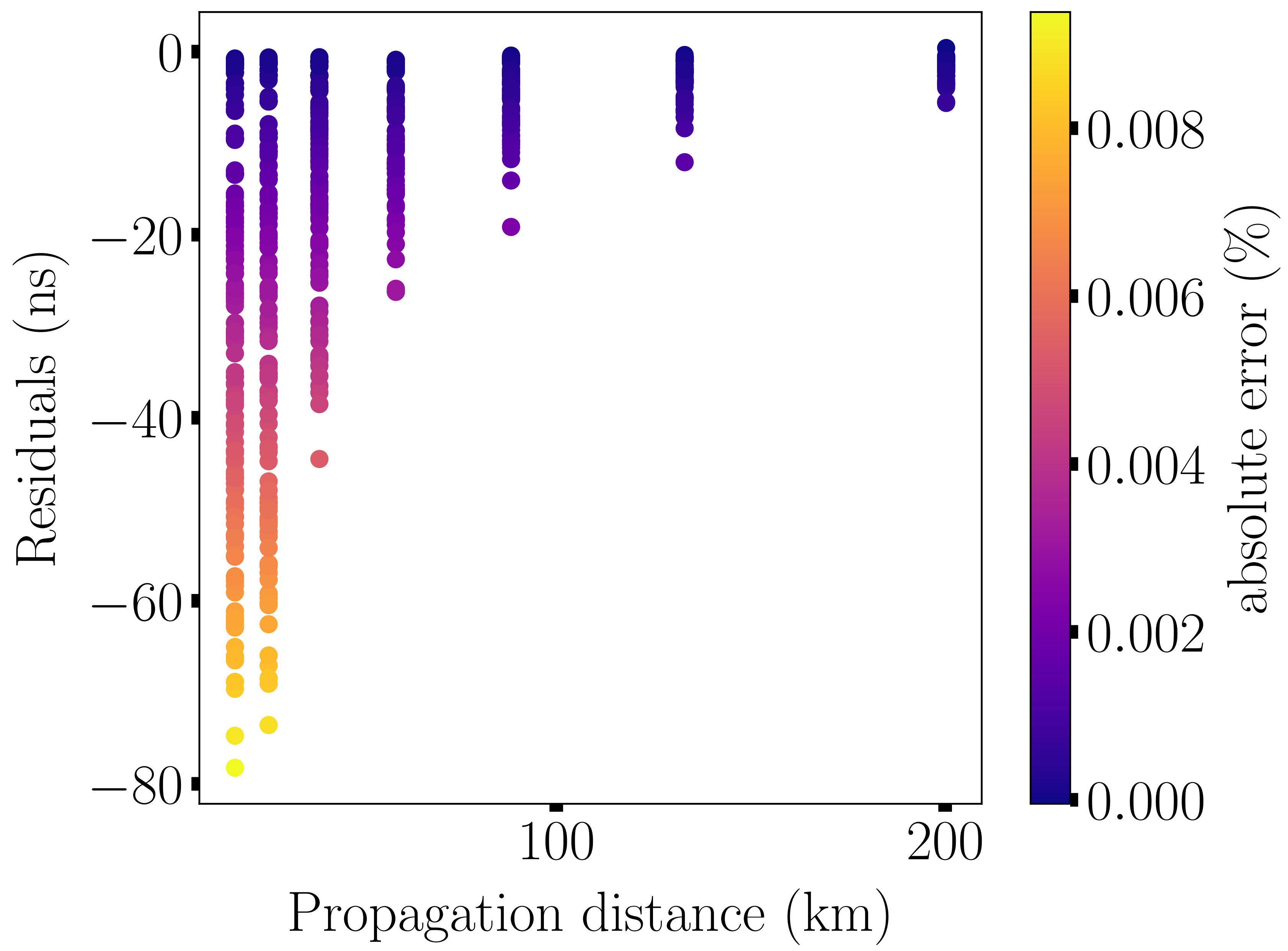


Consequences:

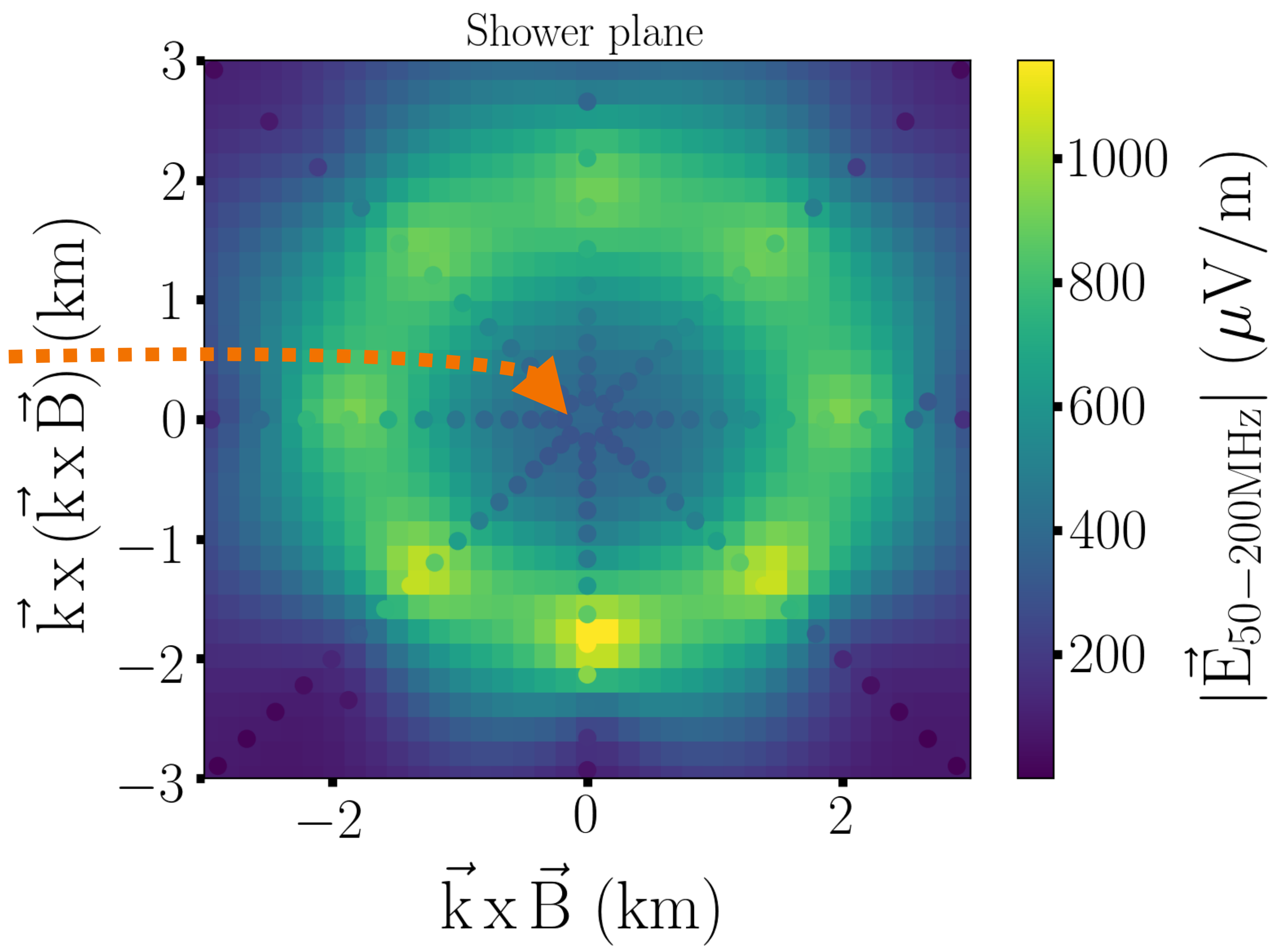
- residuals < experimental time resolution
- arrival times undistinguishable between spherical model and more complex model
- no direction signature → isotropic model
- identification of an emission point possible :
  - composition identification ?
  - axis reconstruction ?

The Angular Distribution Function (ADF)

Describe the signal amplitude pattern for near horizon EAS

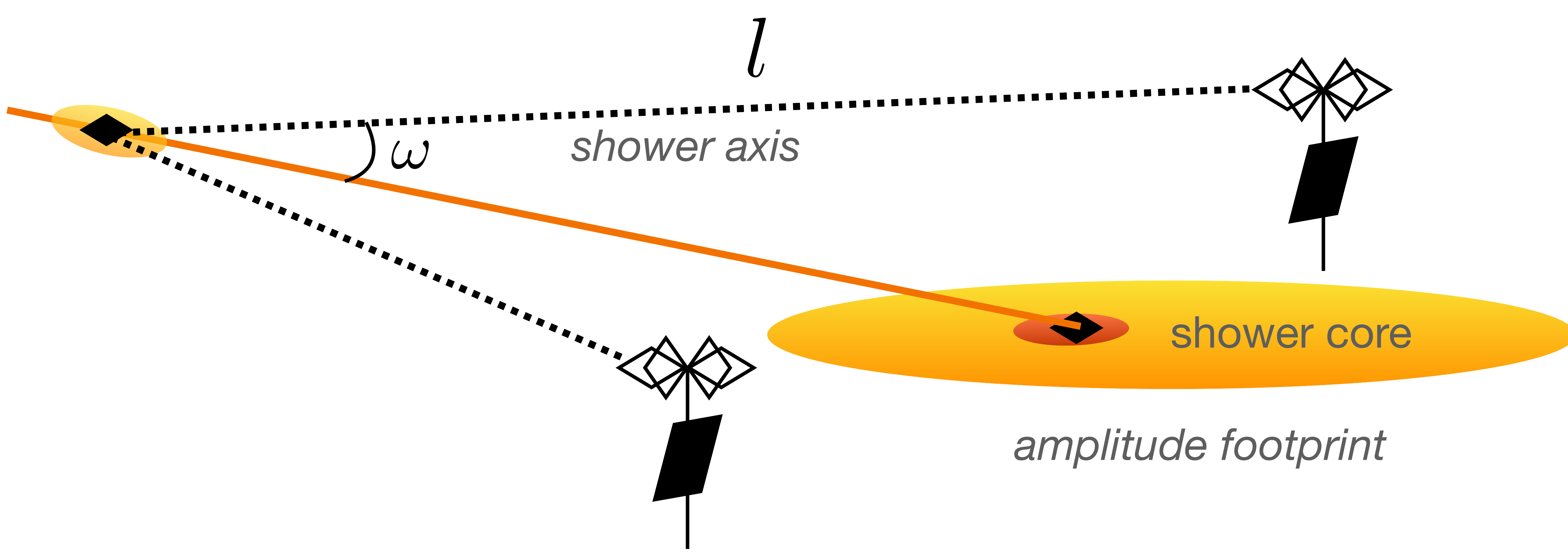
straightforward handle on the core position (hence direction!)

→ beaming effect + Cerenkov effect + asymmetry features (Geomagnetic/Askaryan emissions)



$$f^{\mathrm{ADF}}(\omega, \eta, \alpha, l; \delta\omega, \mathcal{A}) = \frac{\mathcal{A}}{l} f^{\mathrm{GeoM}}(\alpha, \eta, \mathcal{B})\ f^{\mathrm{Cerenkov}}(\omega, \delta\omega)$$

empirical model!



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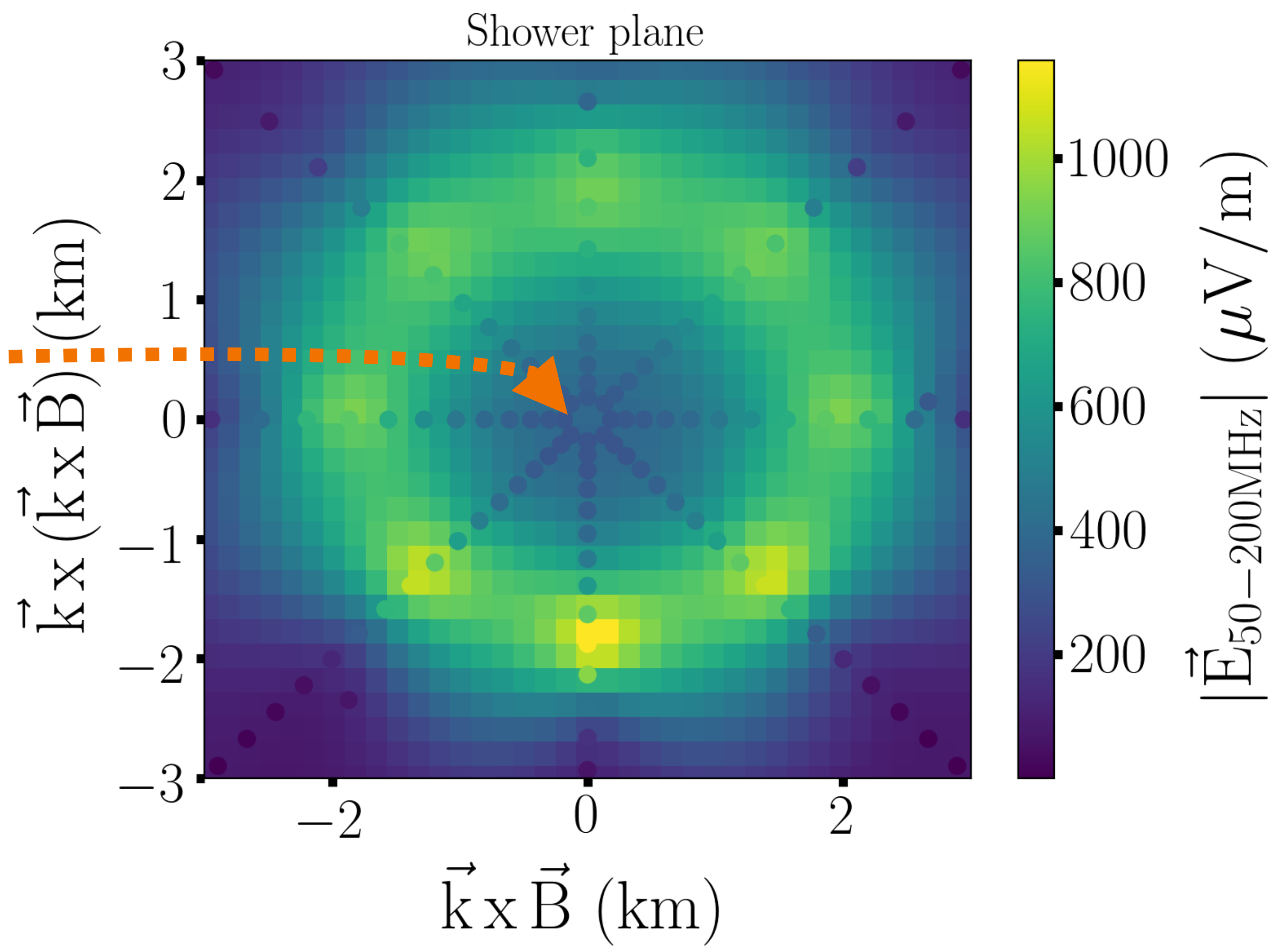

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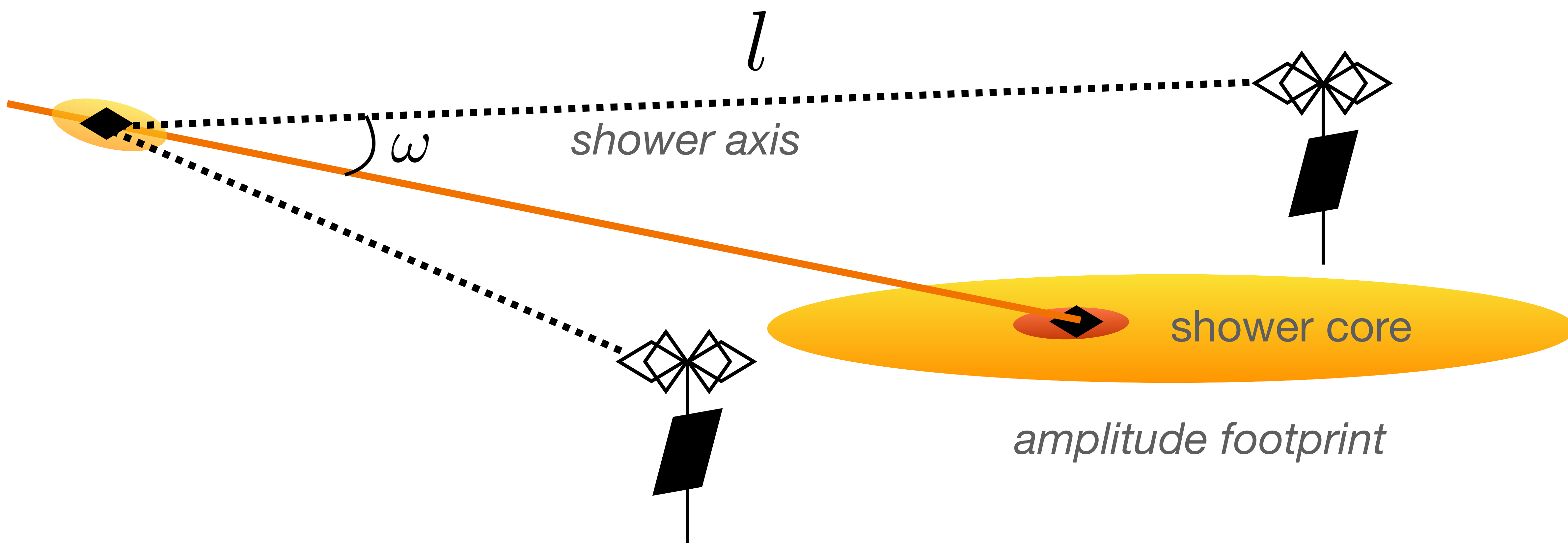
α magnetic field inclination $\mathcal{B}$ geomagnetic strength η polarisation angle

→ interplay between emission mechanisms
→ signal excess along the Lorentz force direction



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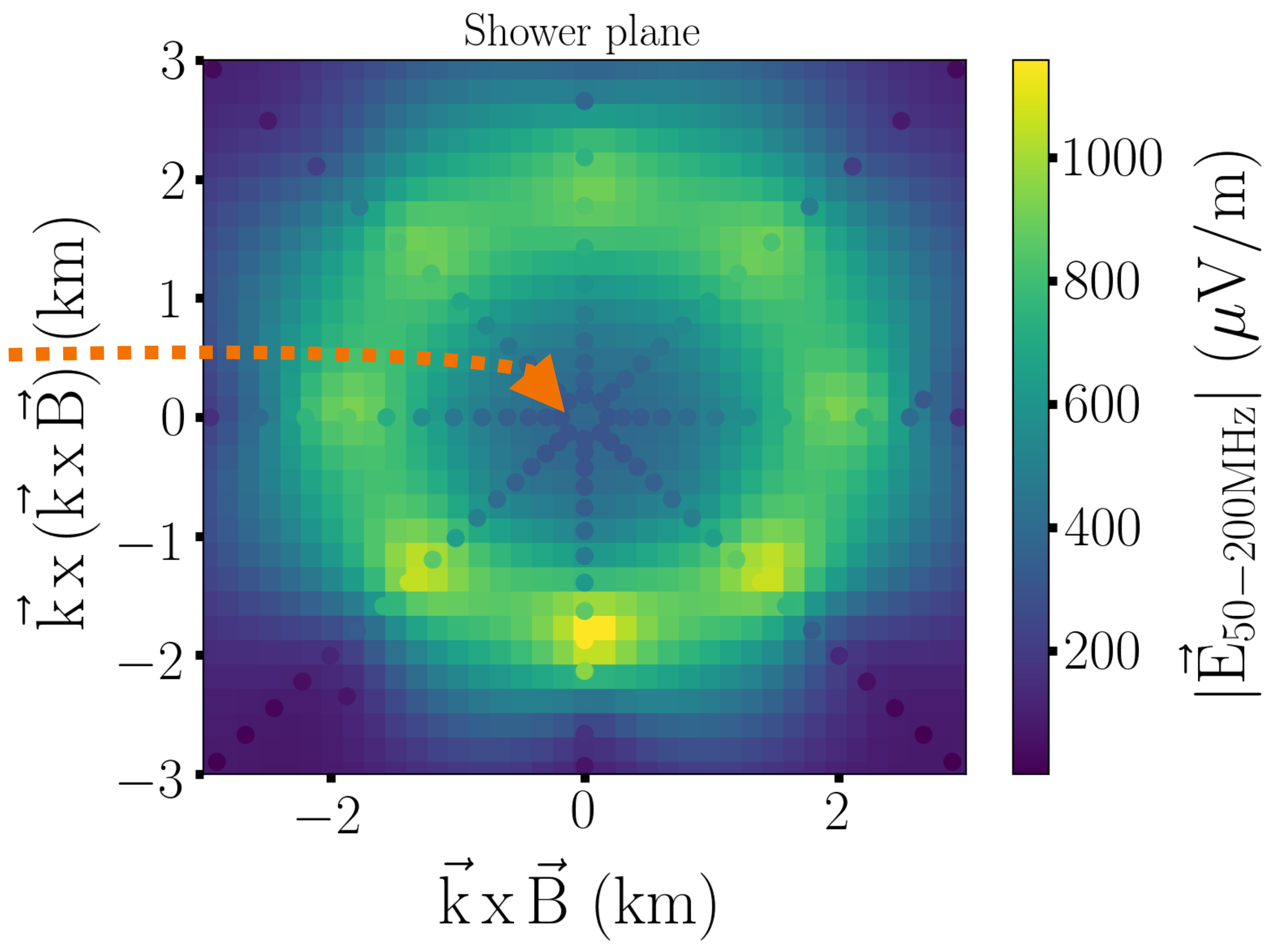

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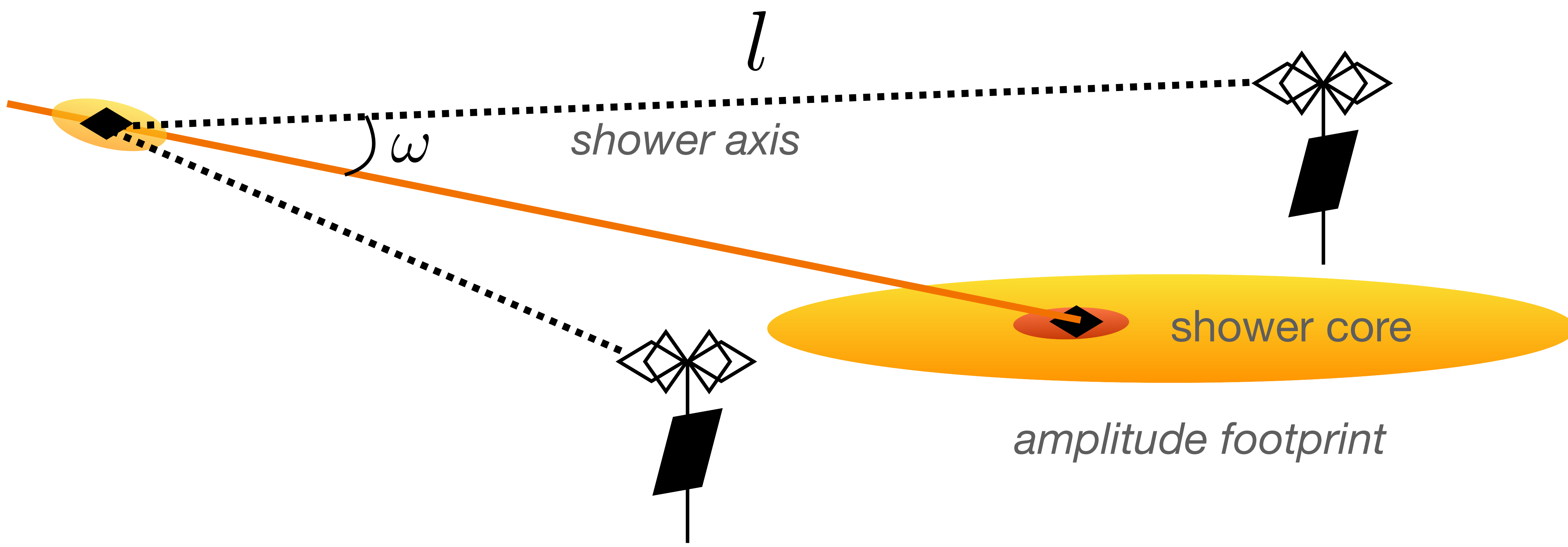

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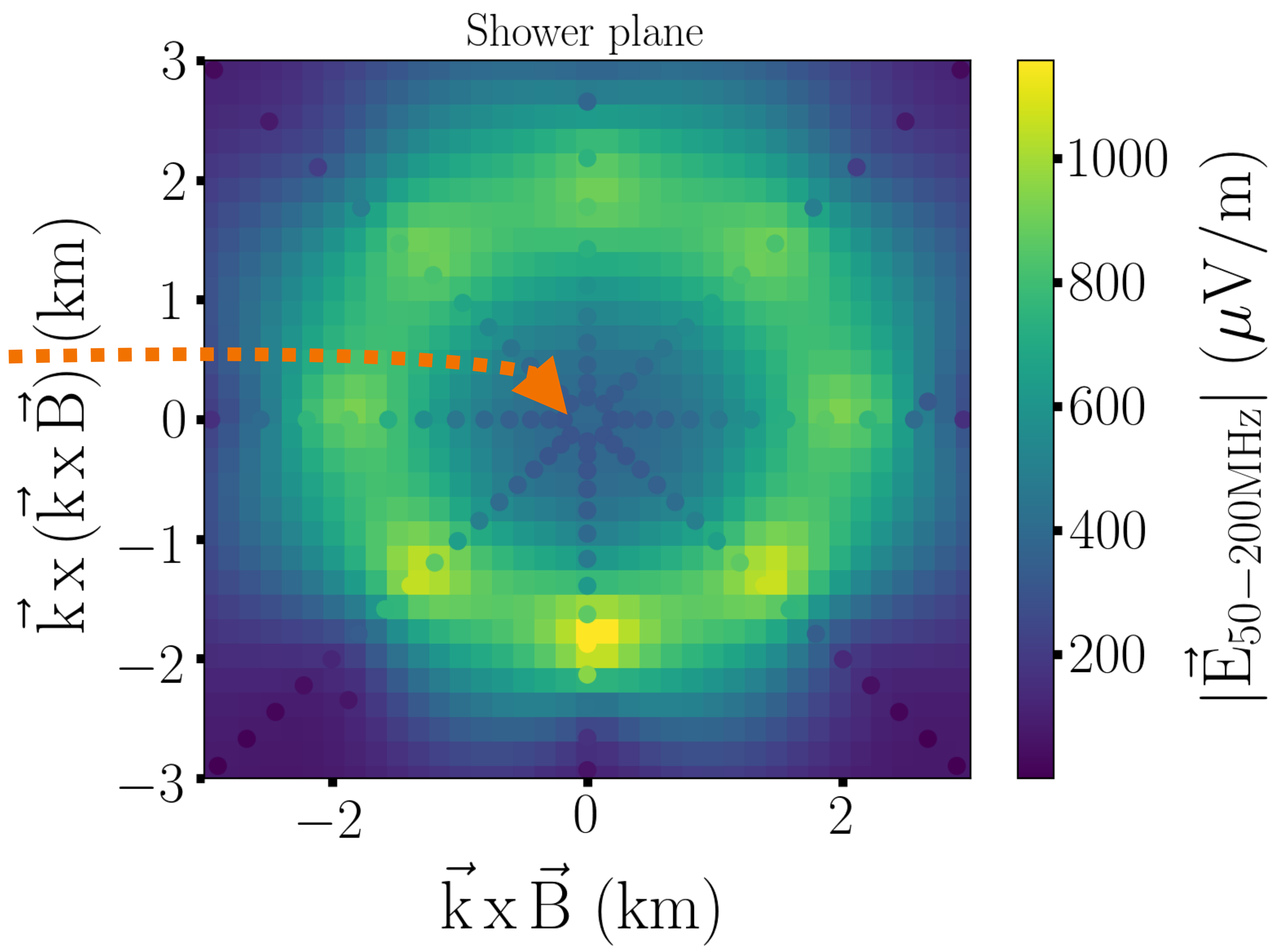

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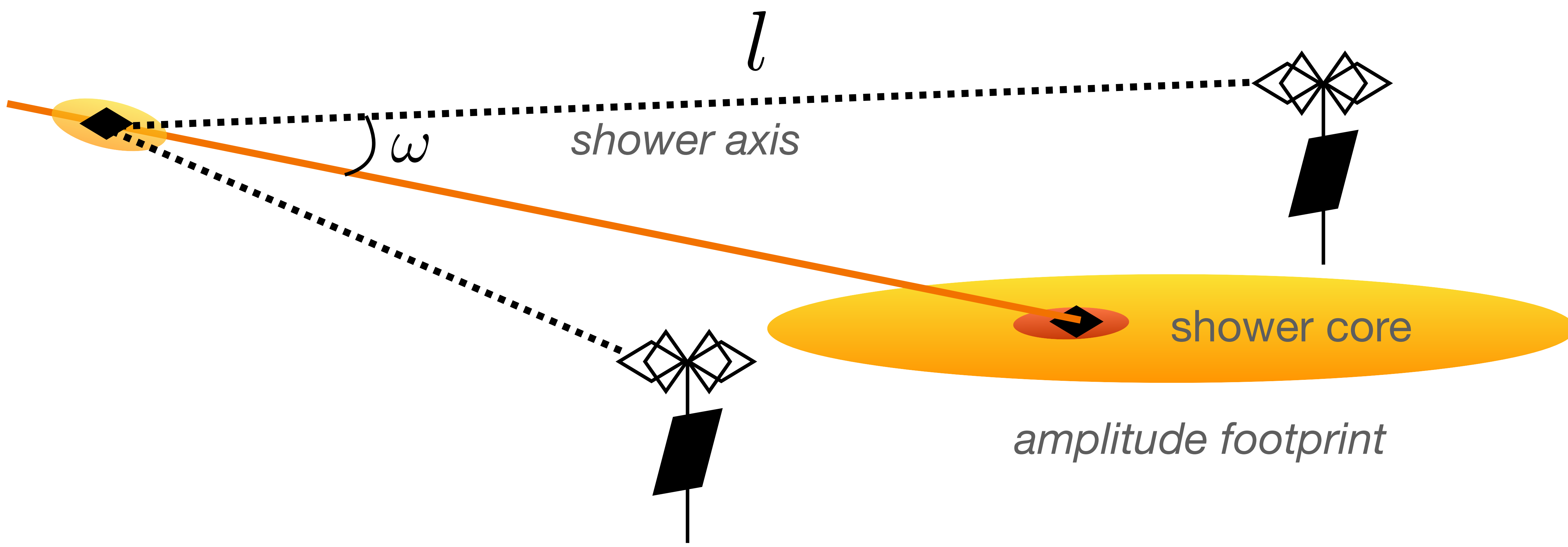
→ geometrical Cerenkov effect description

→ ω_C



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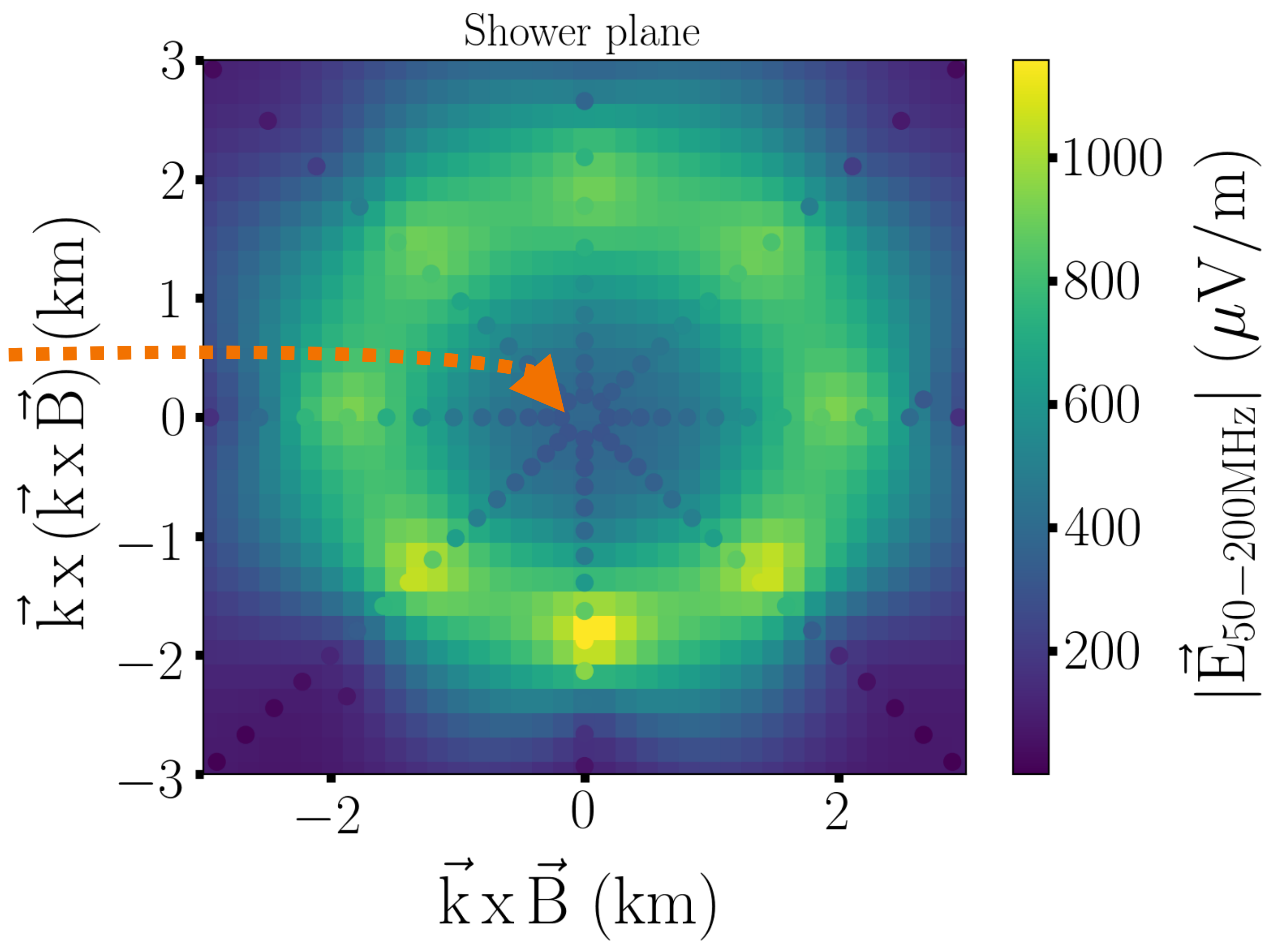

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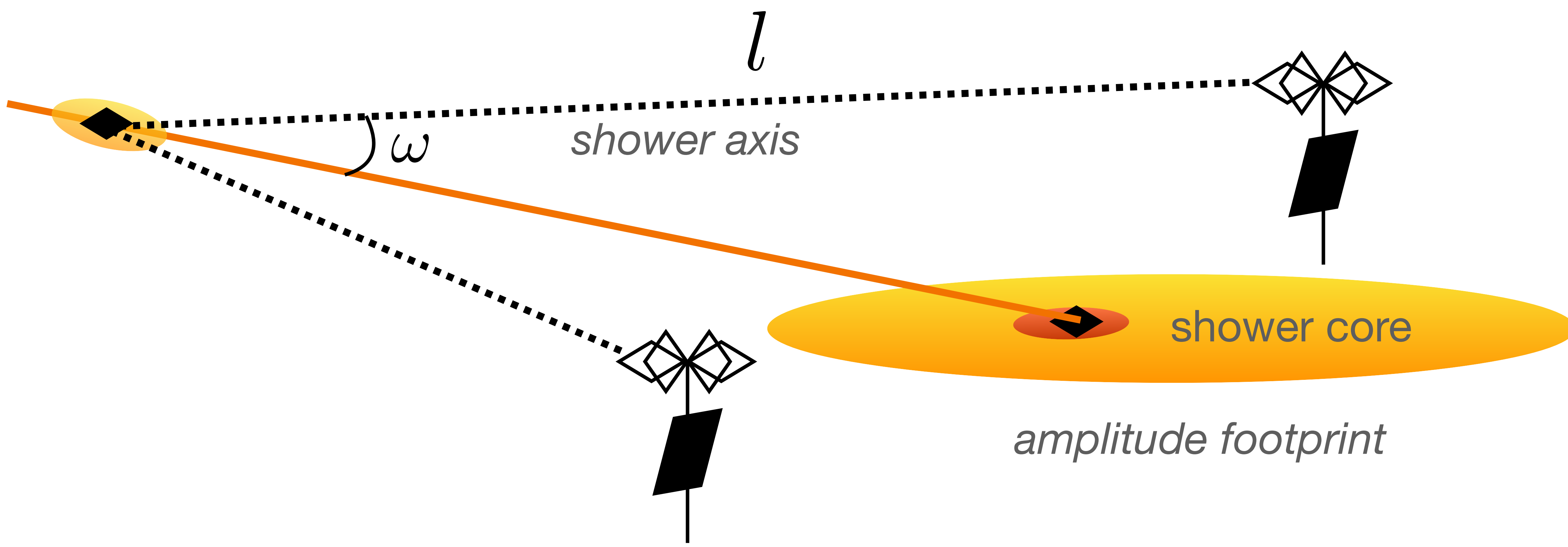


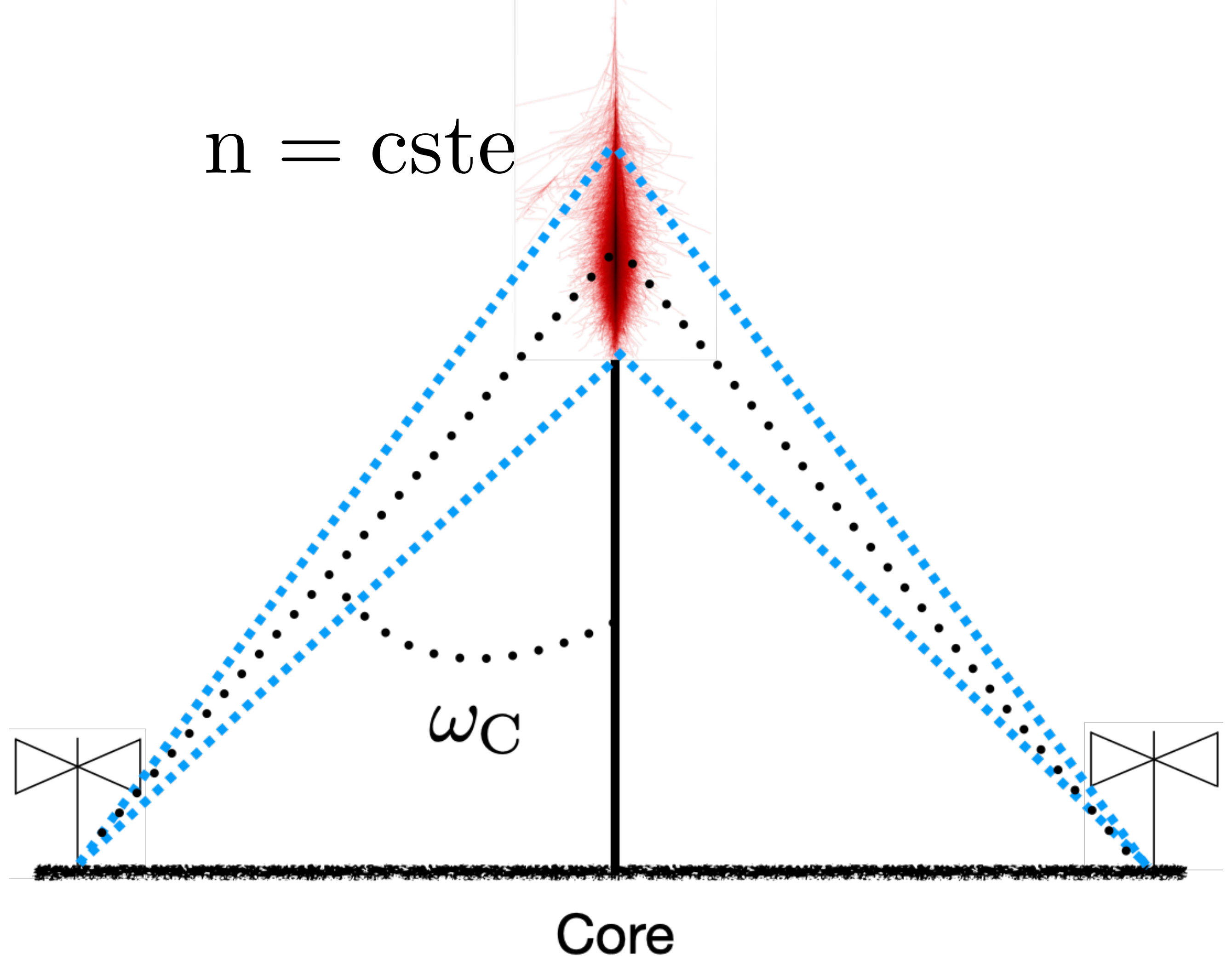
4 fitting parameters only: $\{\theta,\phi,\mathcal{A},\delta\omega\}$

The Angular Distribution Function (ADF)

Cerenkov asymmetry

Cerenkov cone:

- geometrical effect → angle where all emissions arrive at same time
- signal compression → high amplitudes
- standard computation: $\omega_C = \mathrm{acos}(1/\mathrm{n})$ (equal optical paths = constant n)



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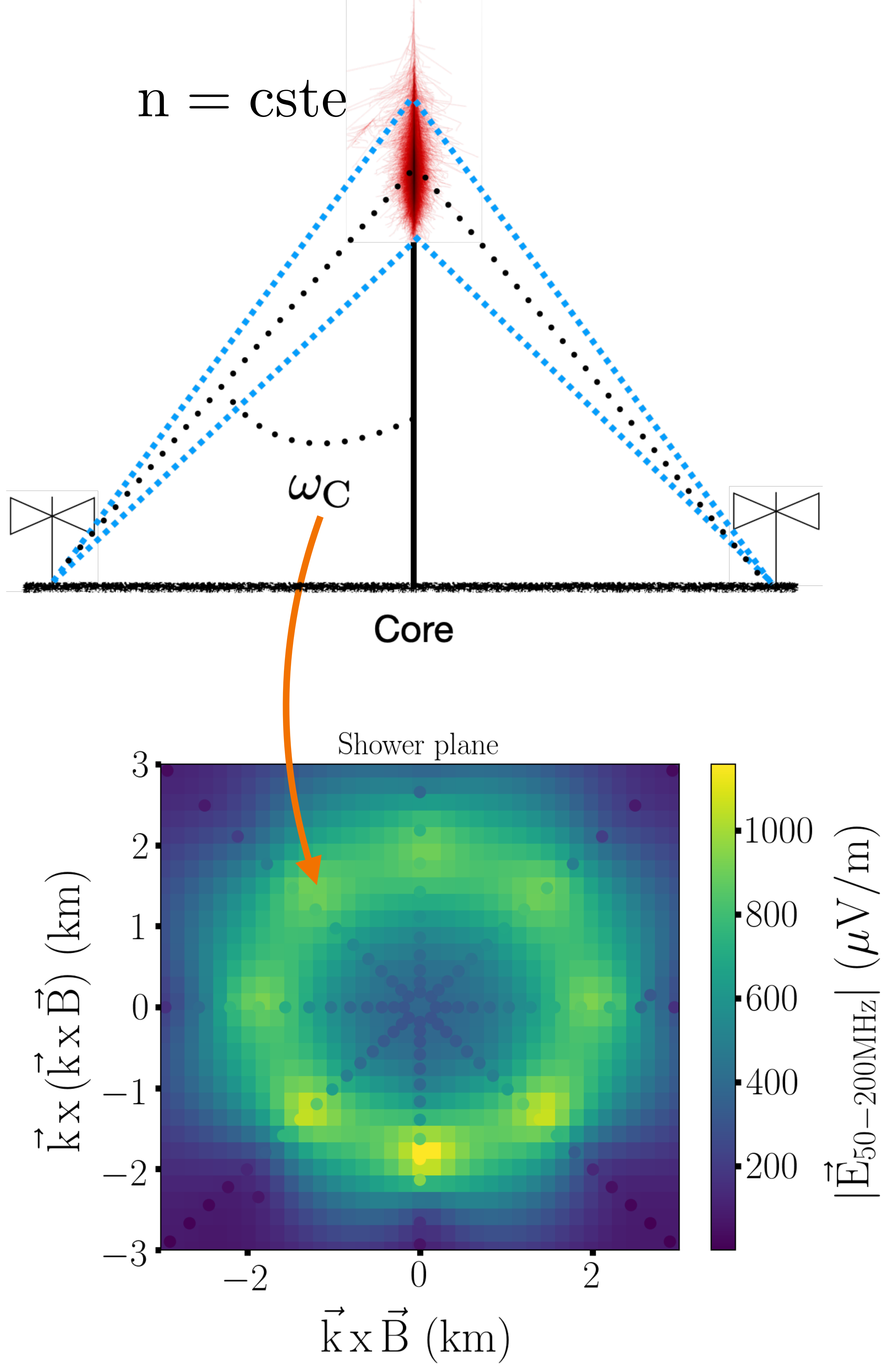

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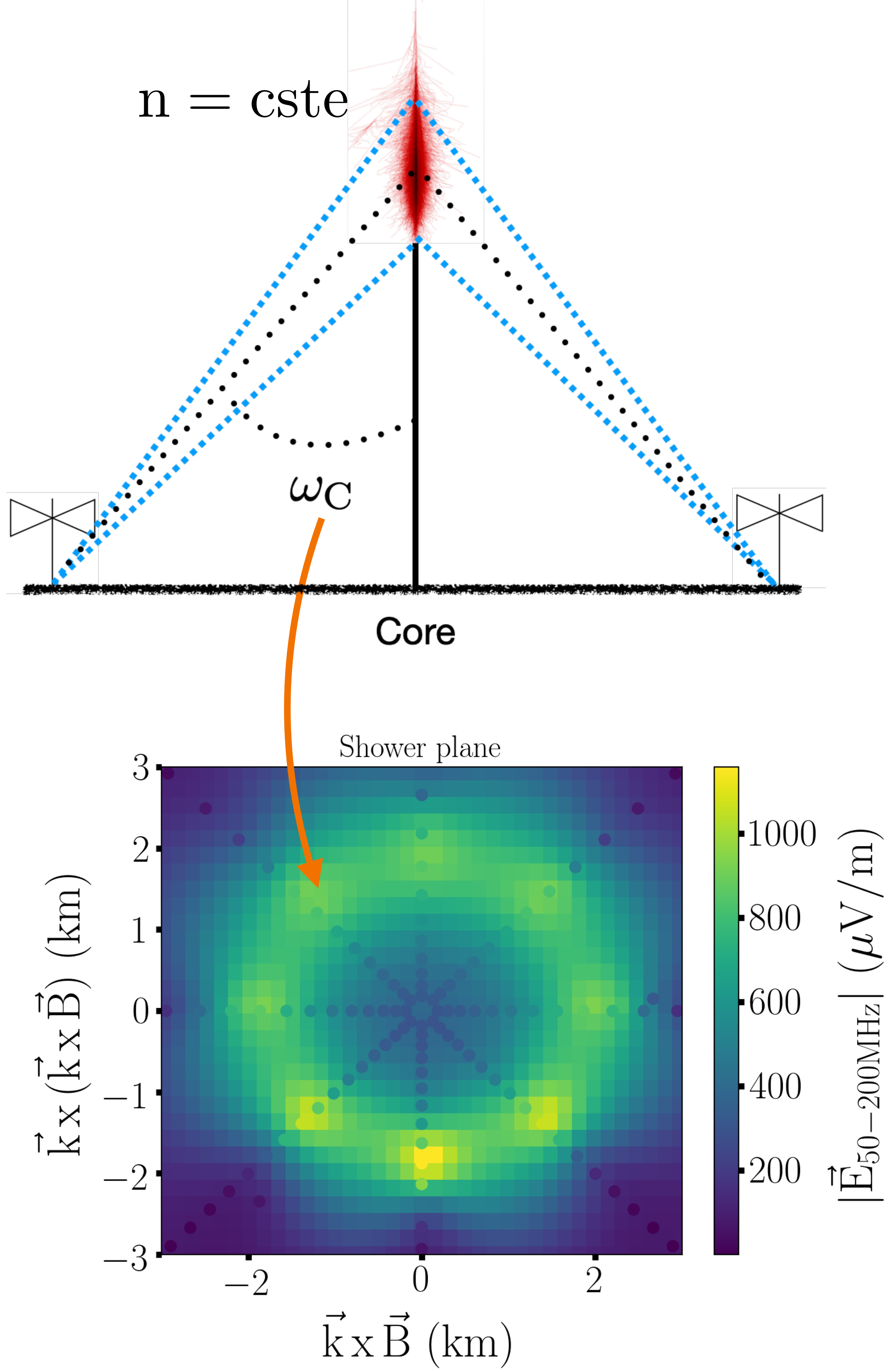
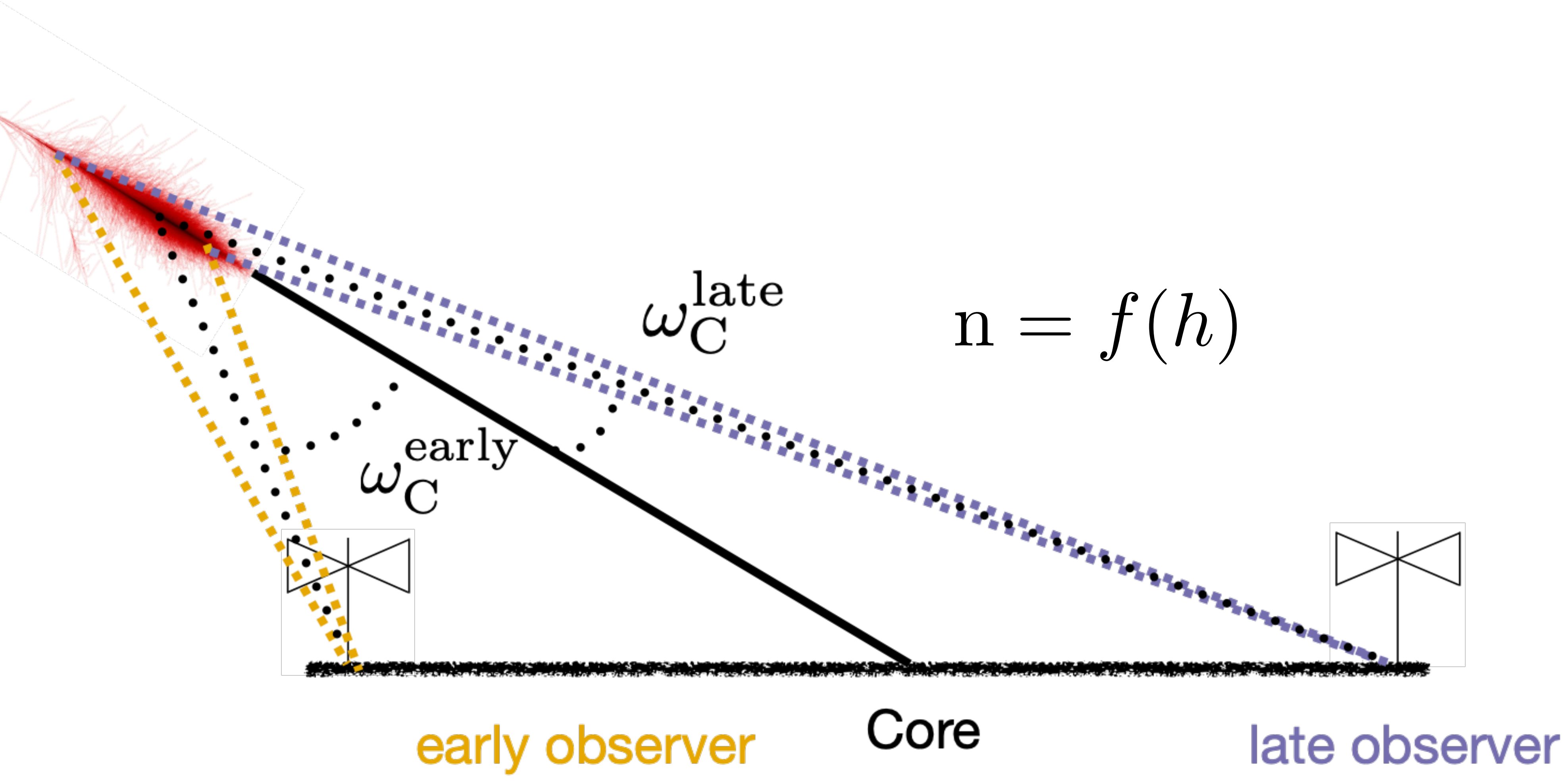
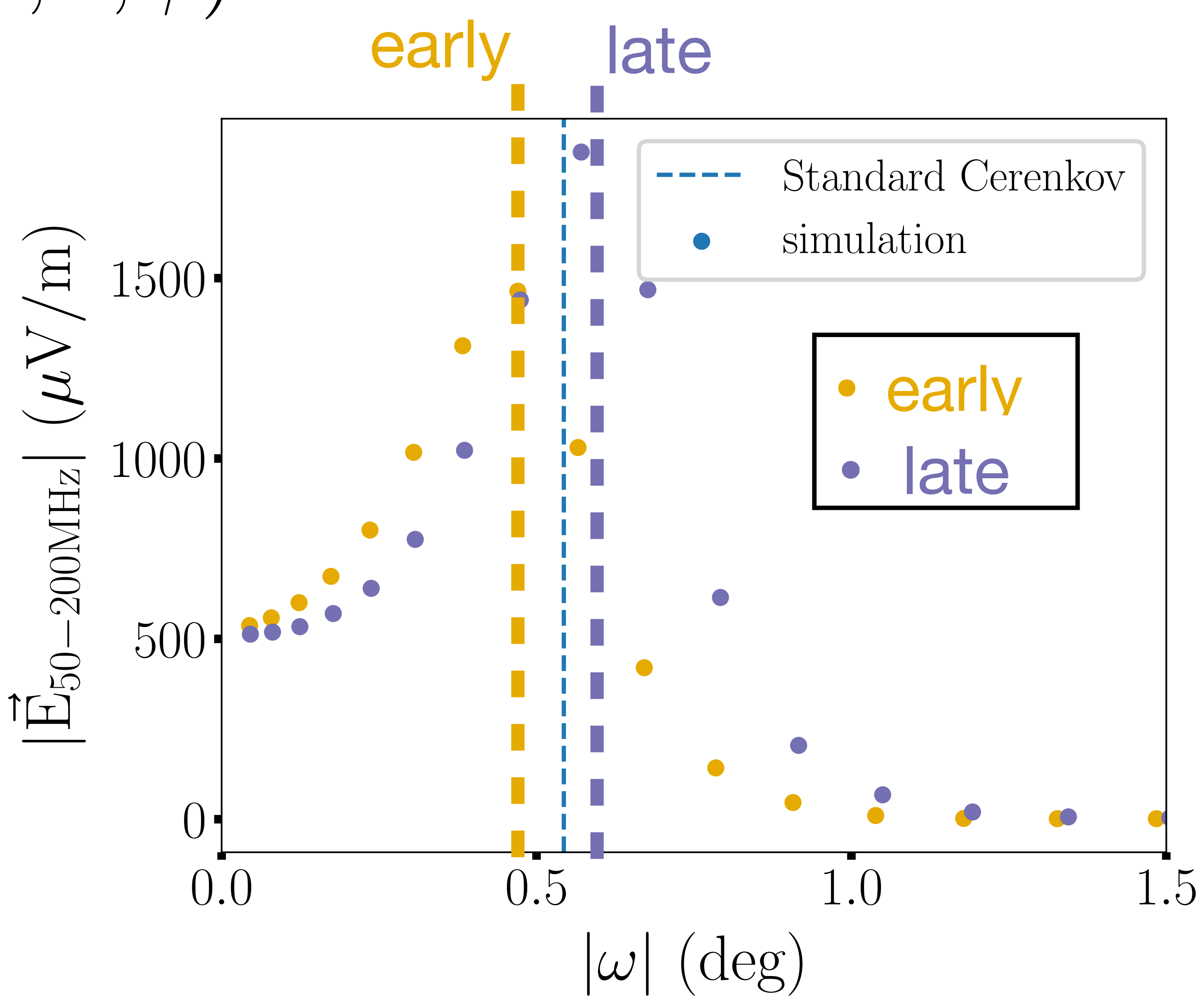


But if optical paths are different (varying n) $\omega_C = f(\vec{x}, \theta, \phi)$





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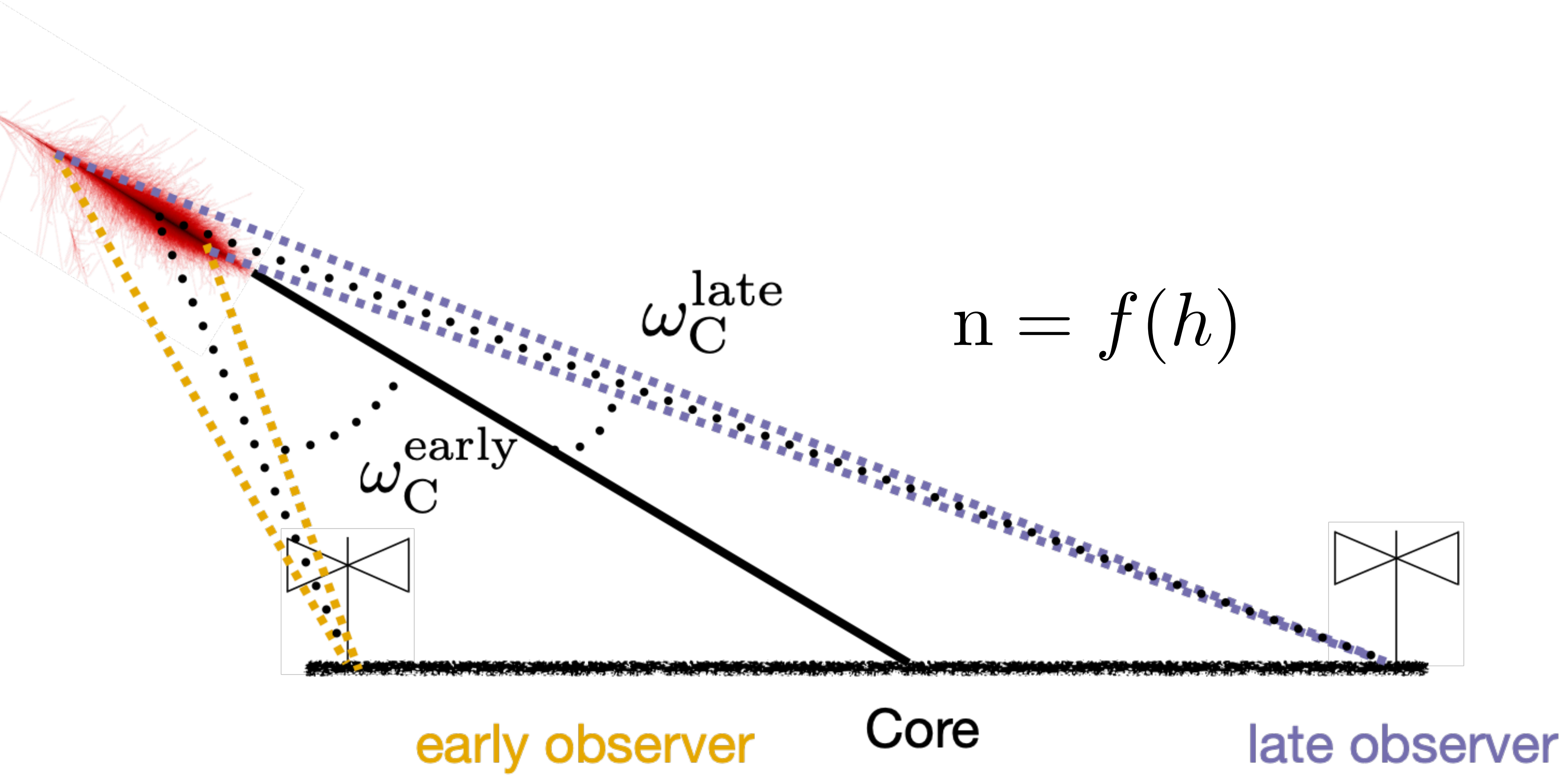
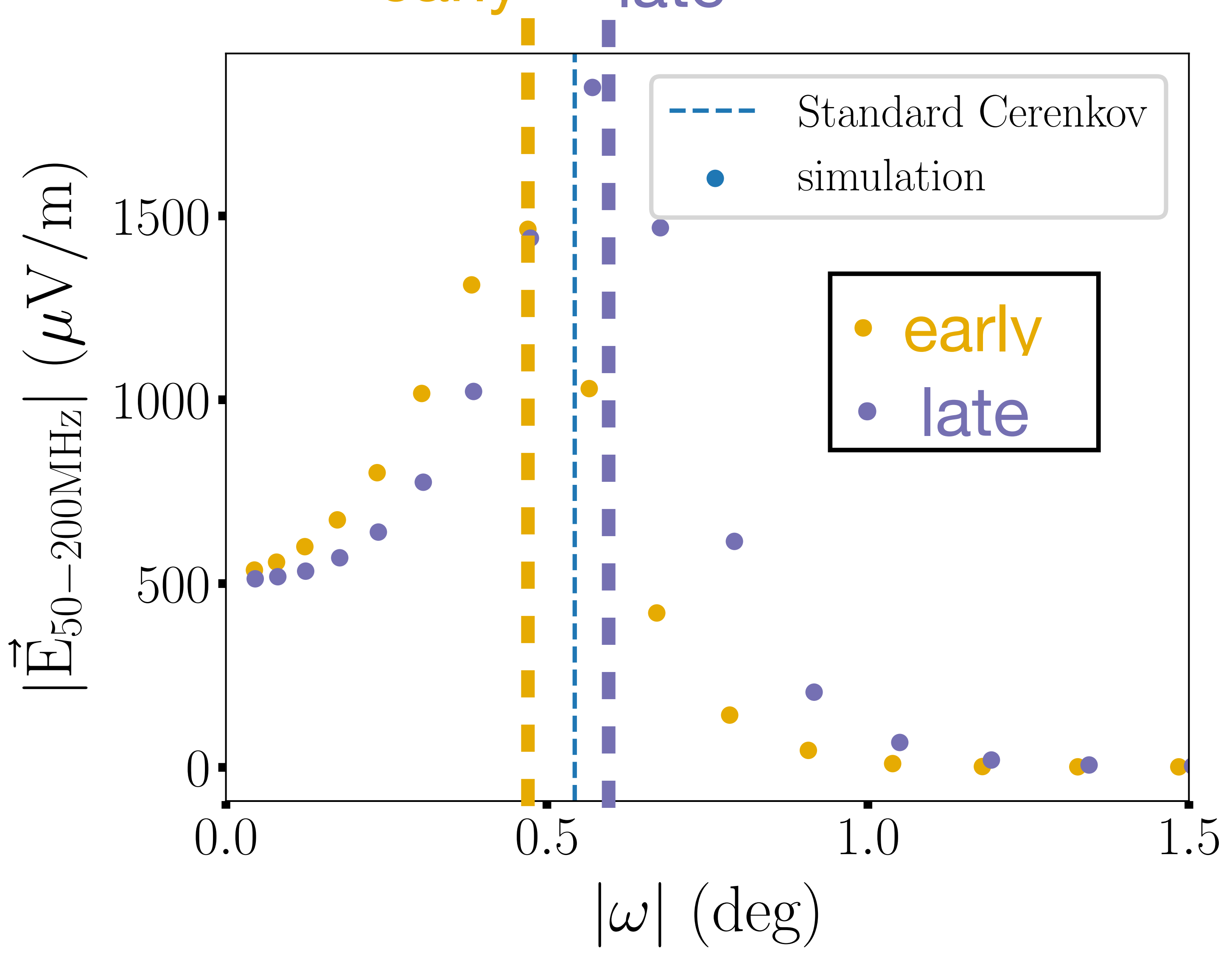
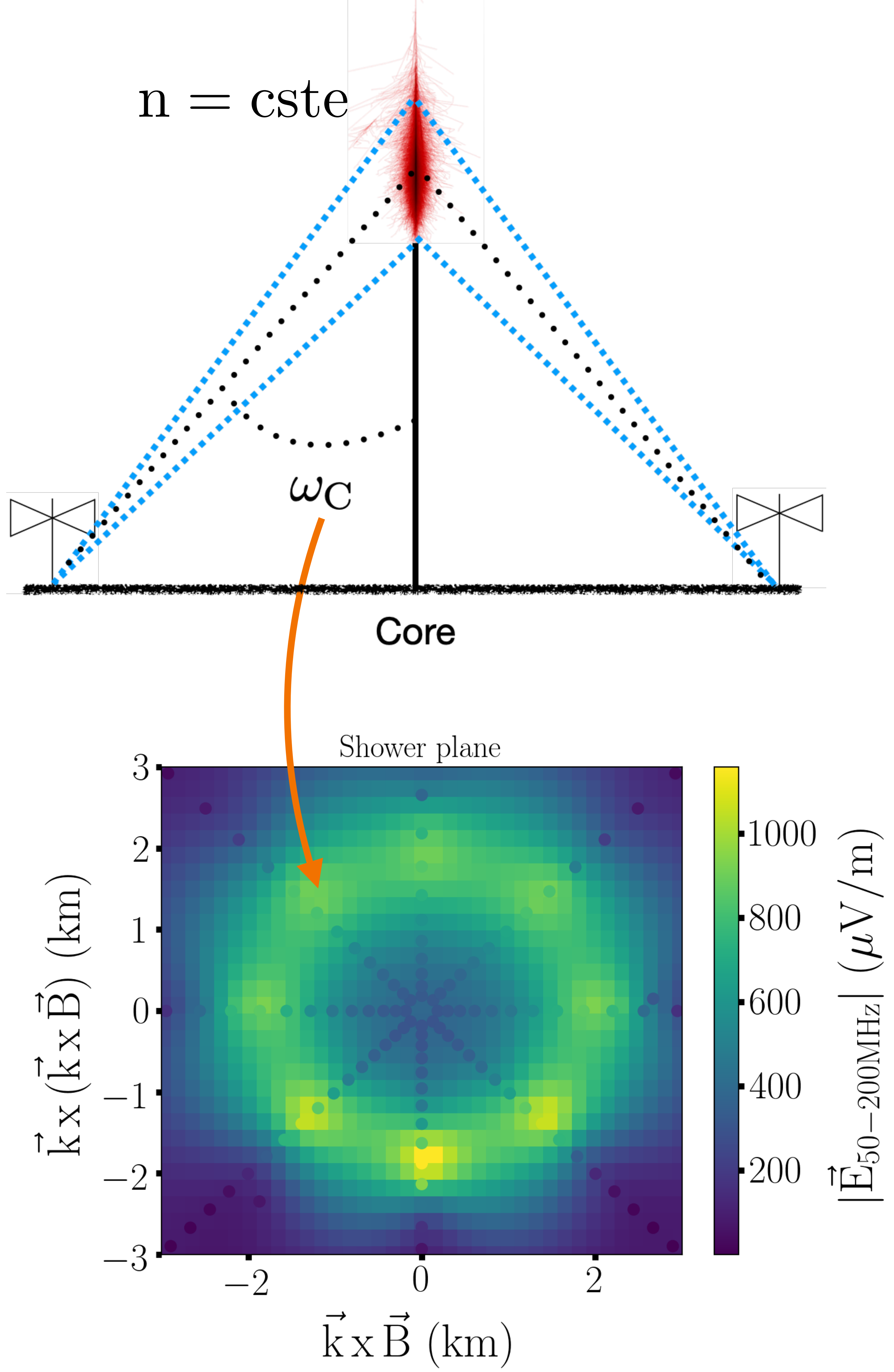






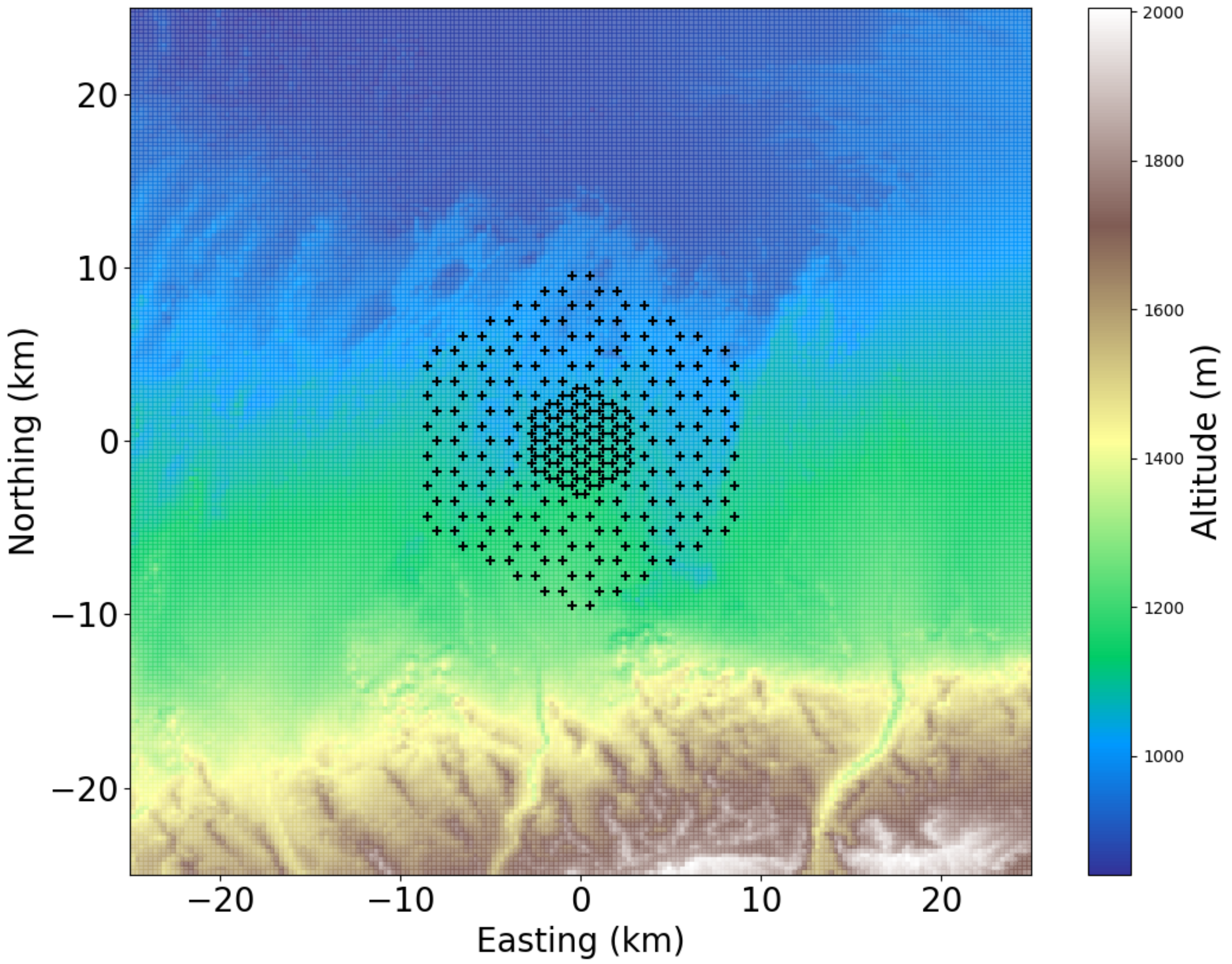
analytical description of $\omega_C = f(\vec{x}, \theta, \phi)$

used into the amplitude model: each antenna "sees" a different Cerenkov cone

The analytical description of the Cerenkov asymmetry matches the simulated data

Reconstruction Performances

For a GRAND Proto 300 (GP300) layout



GP300 layout:
- ~300 antennas over ~200 km^2
- detection of cosmic rays and gamma rays

GP300 simulations:
- real topography
- primaries: proton, iron and gamma

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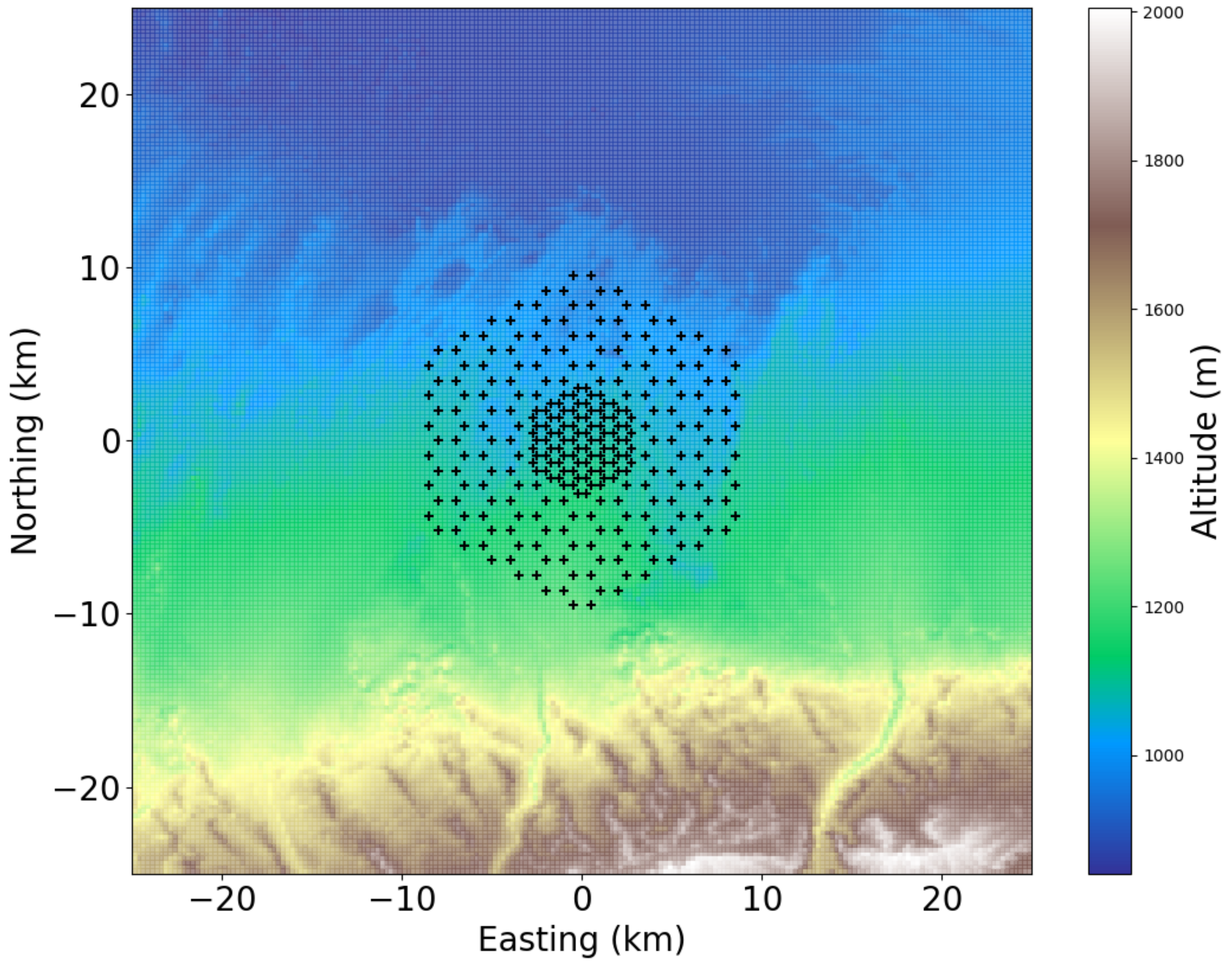

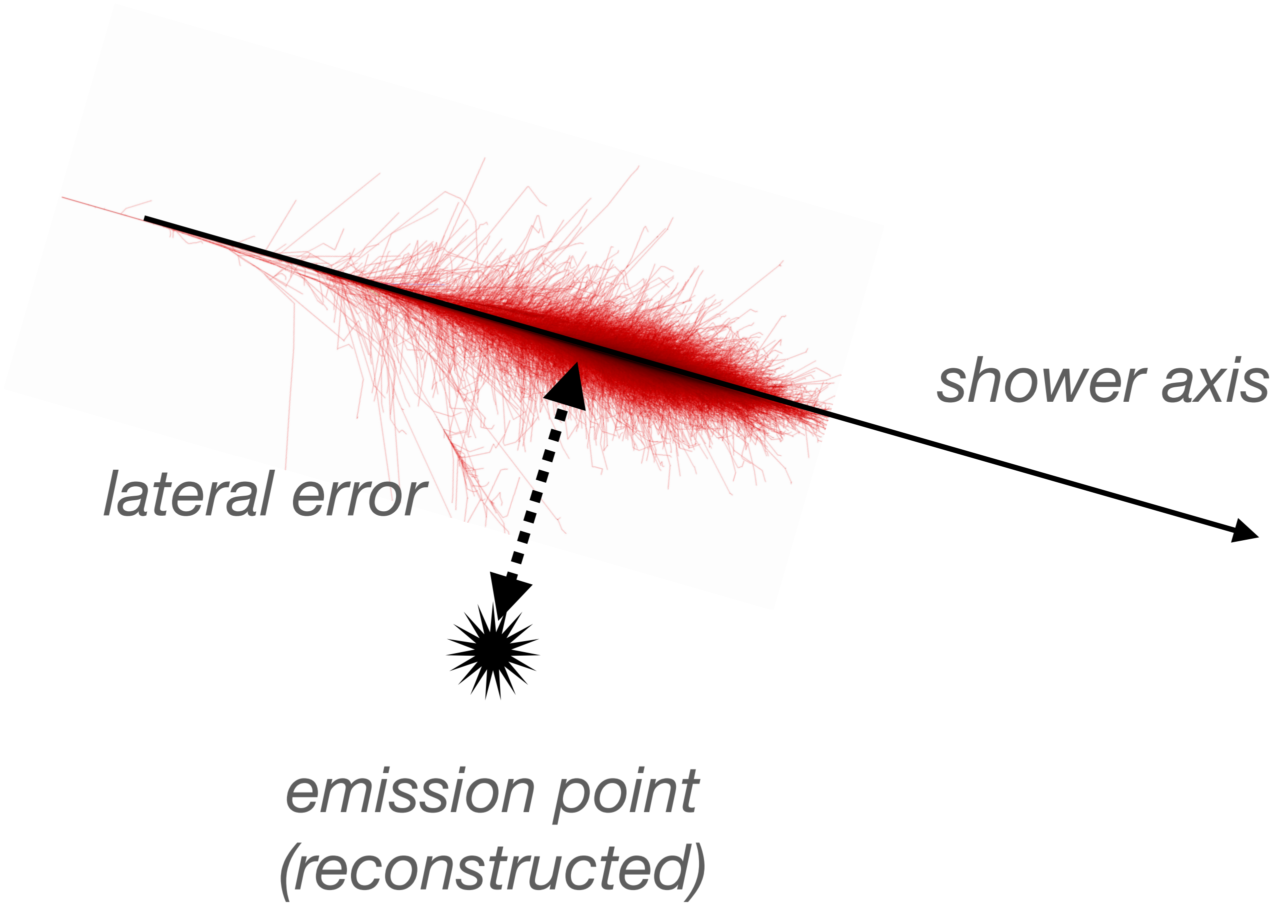

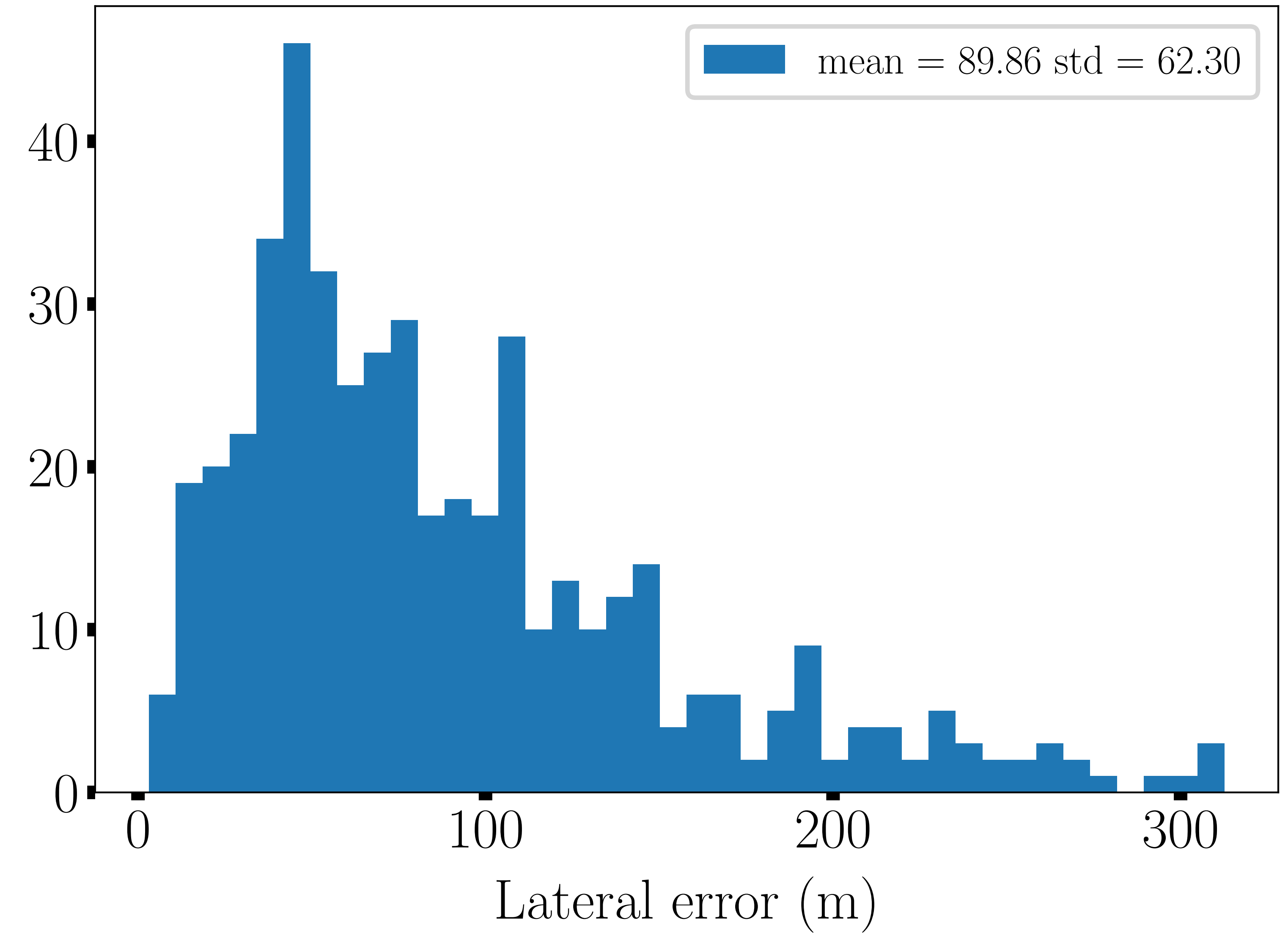

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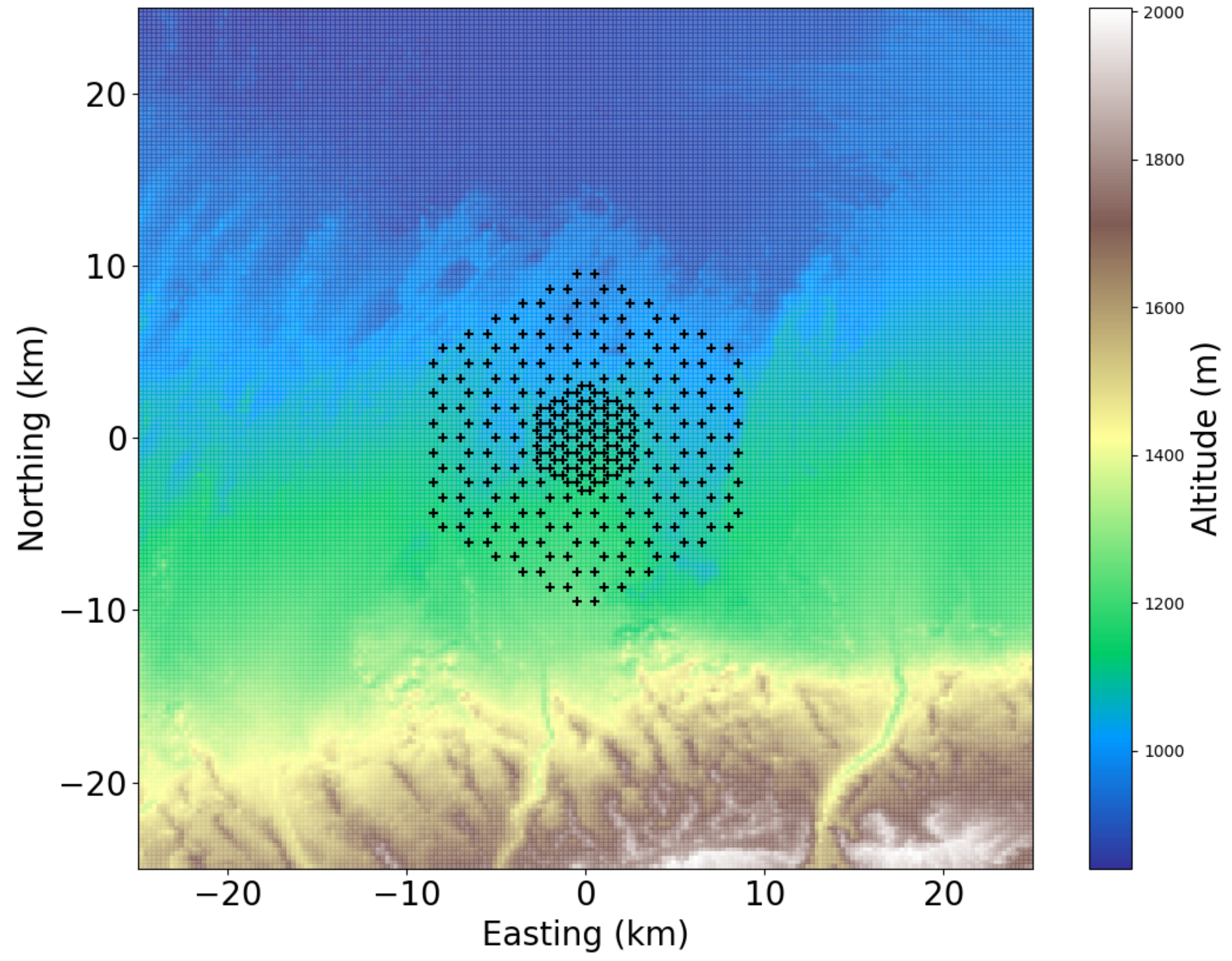

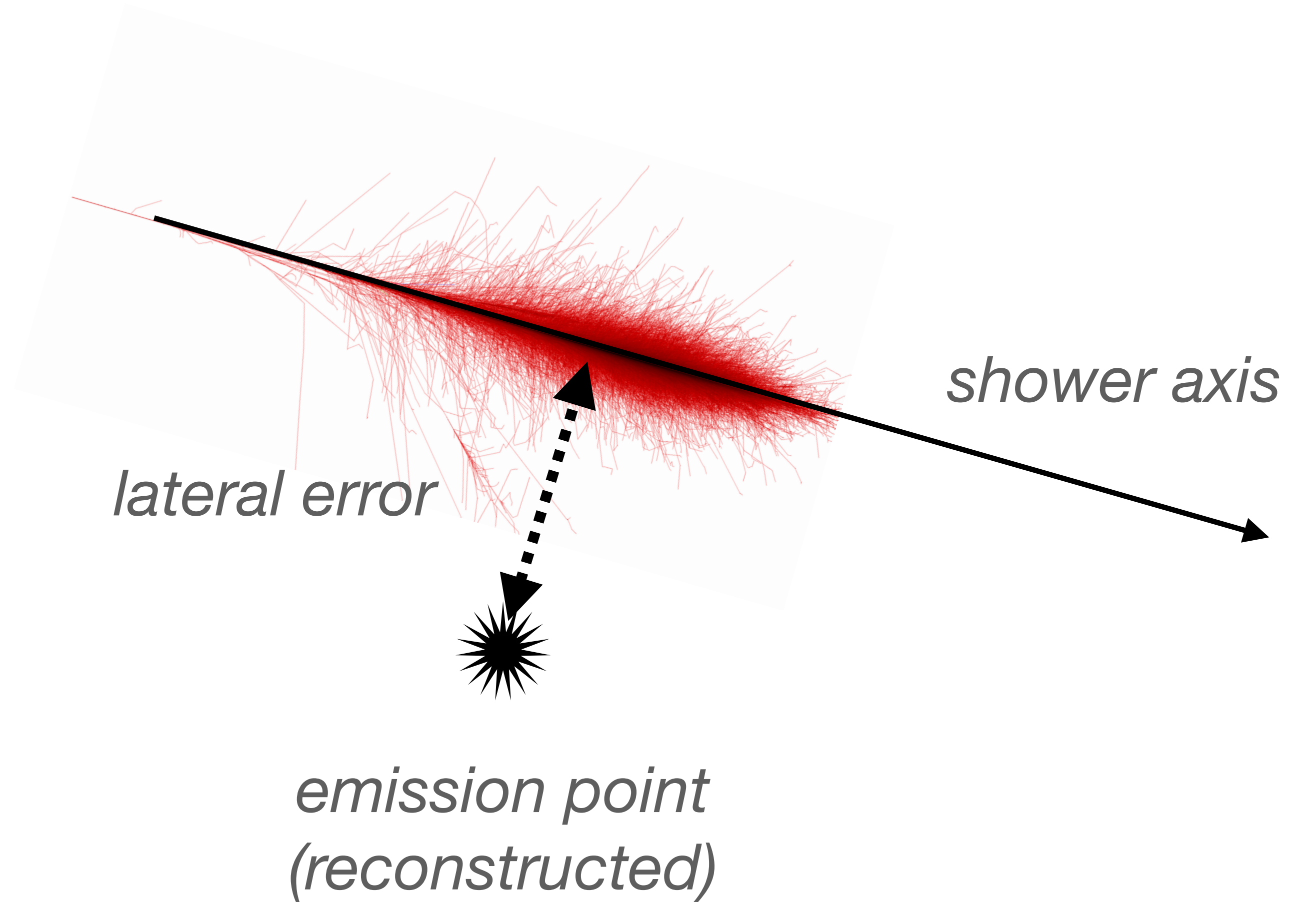

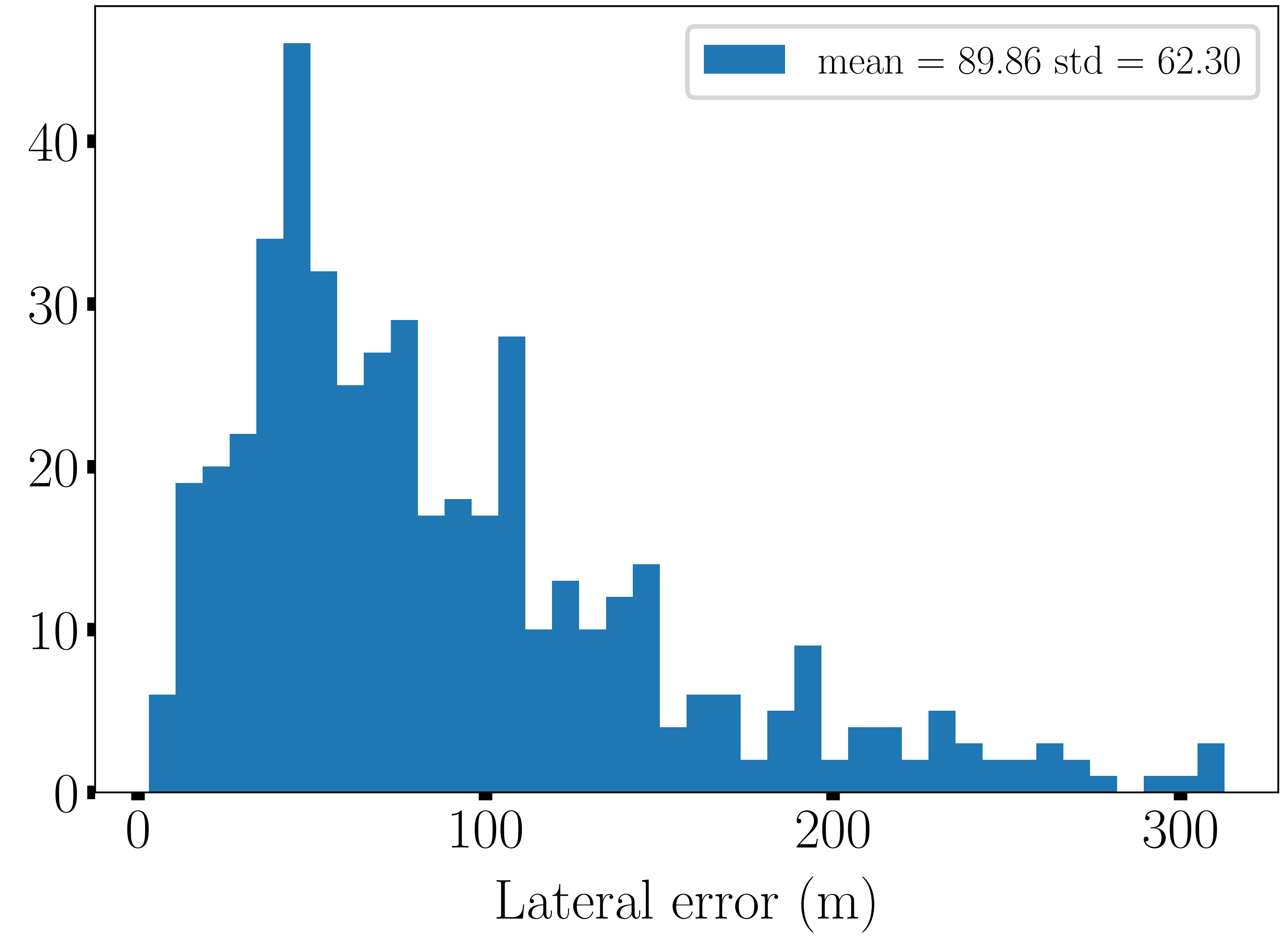

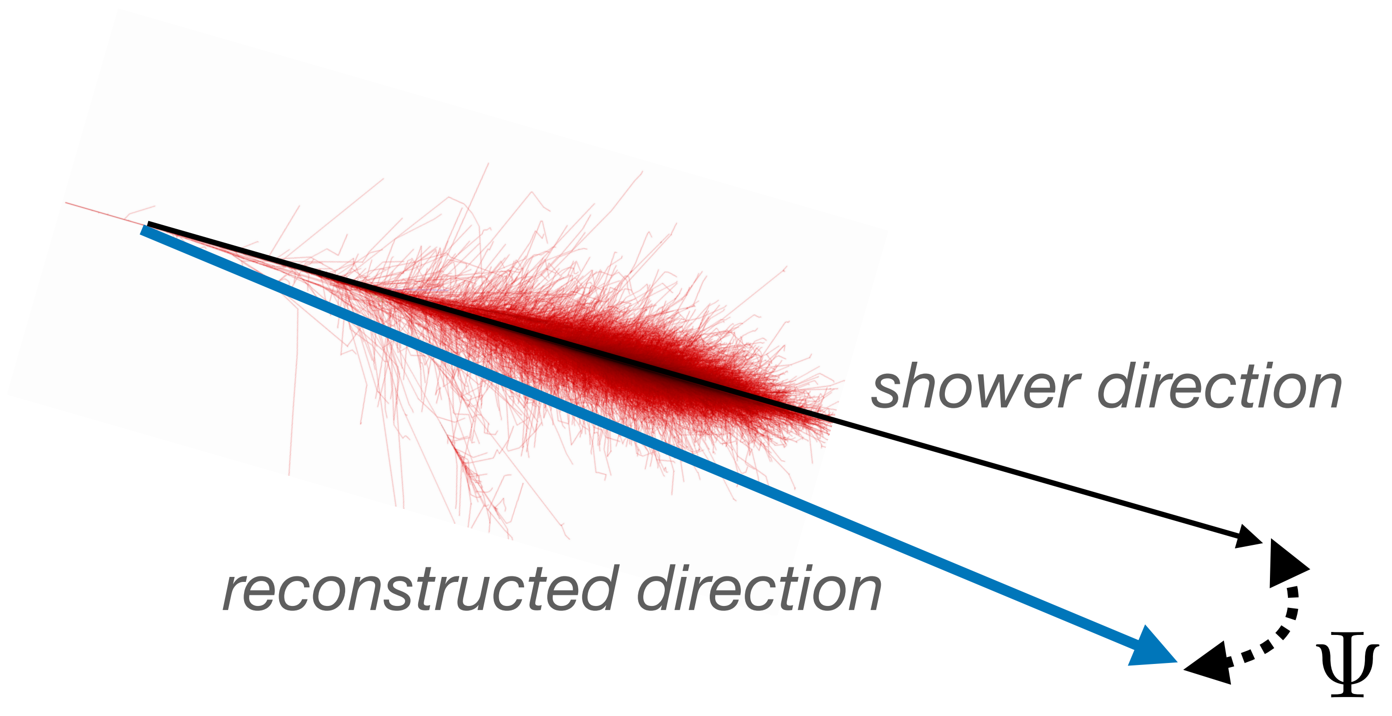

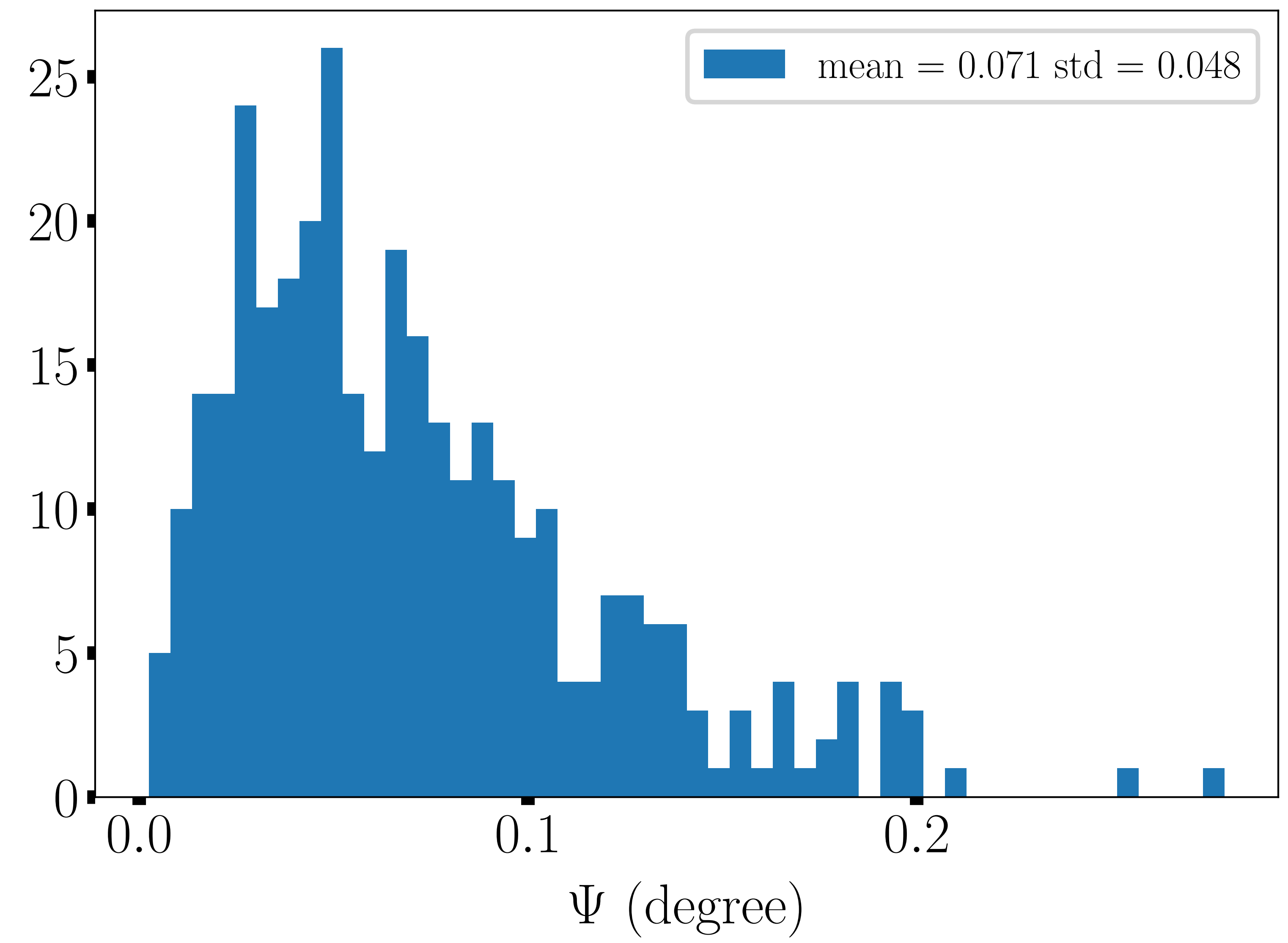

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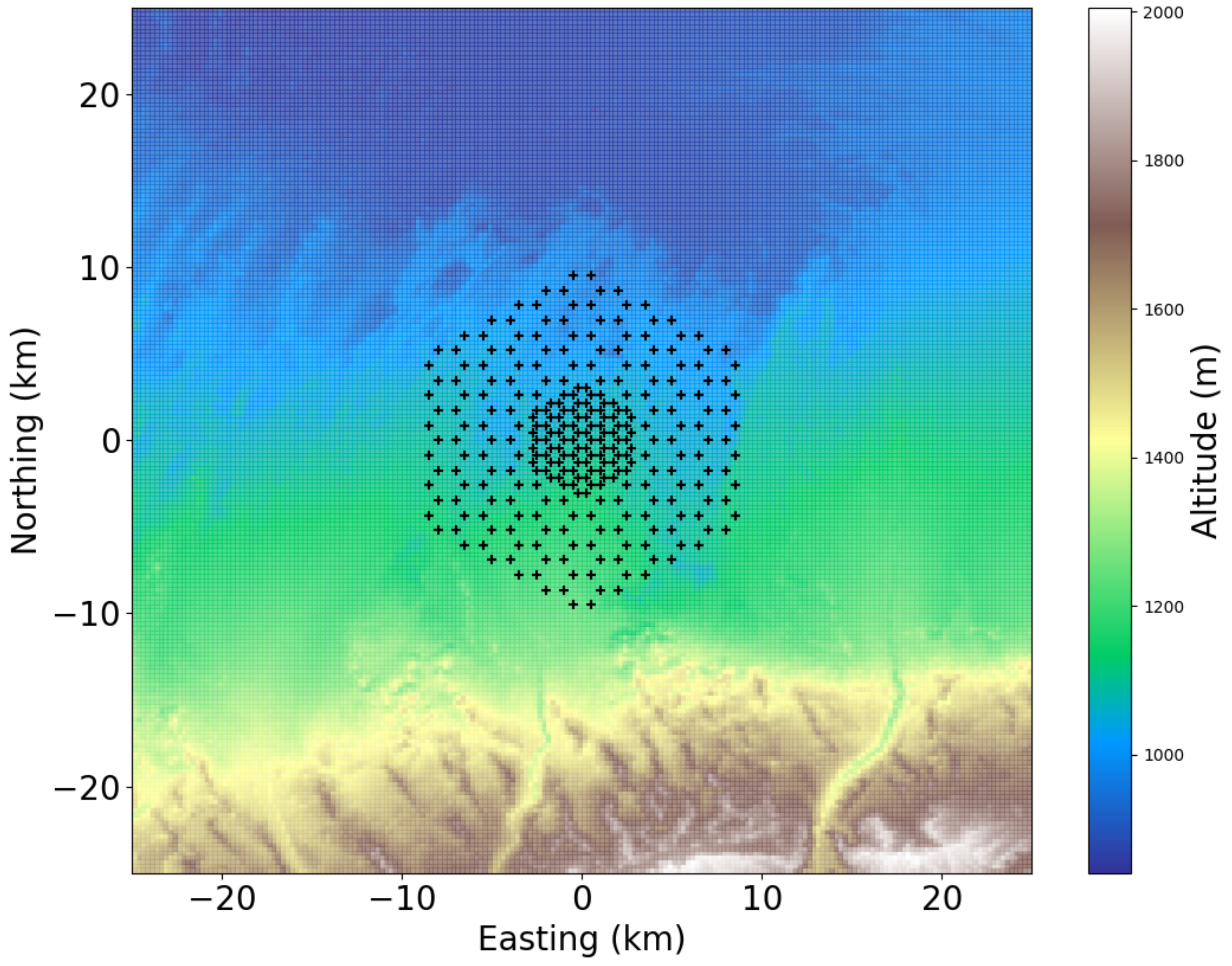

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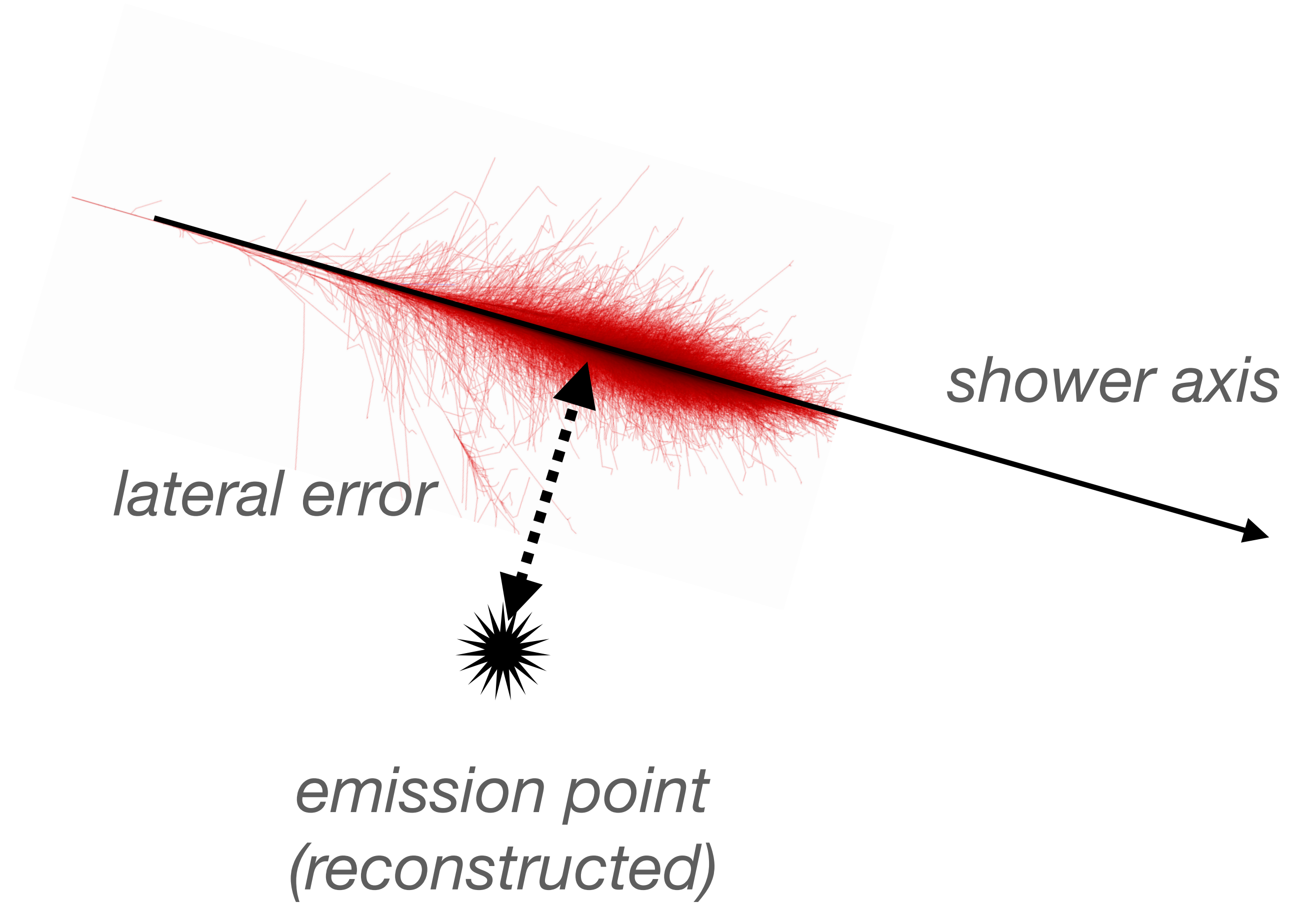
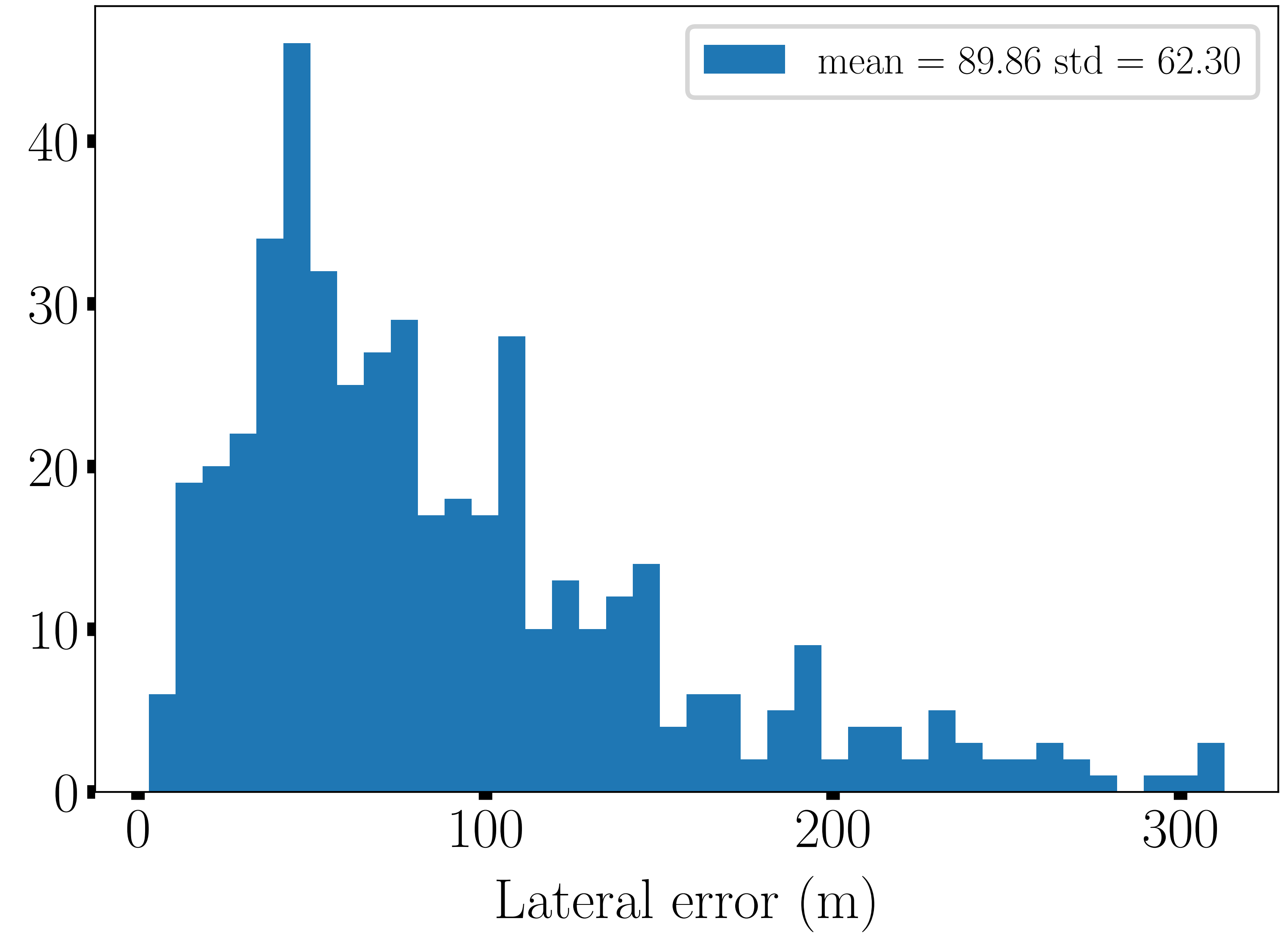
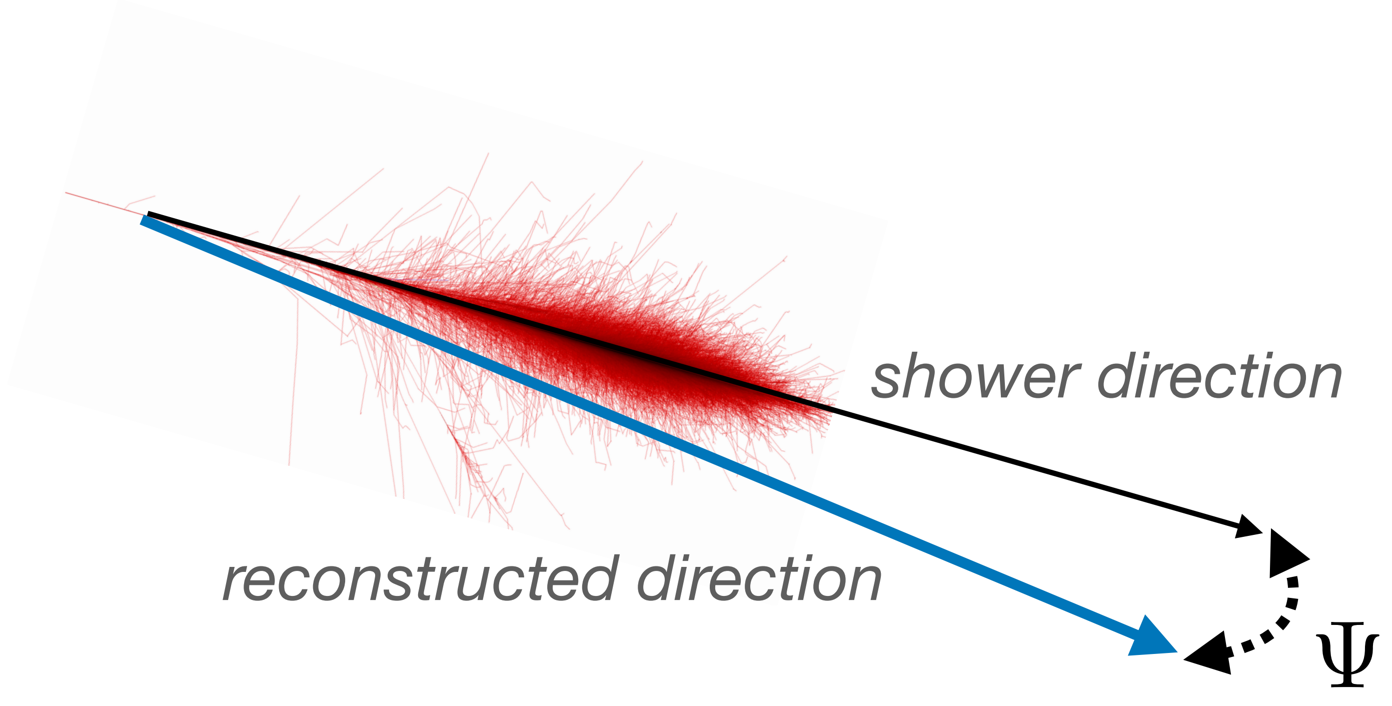
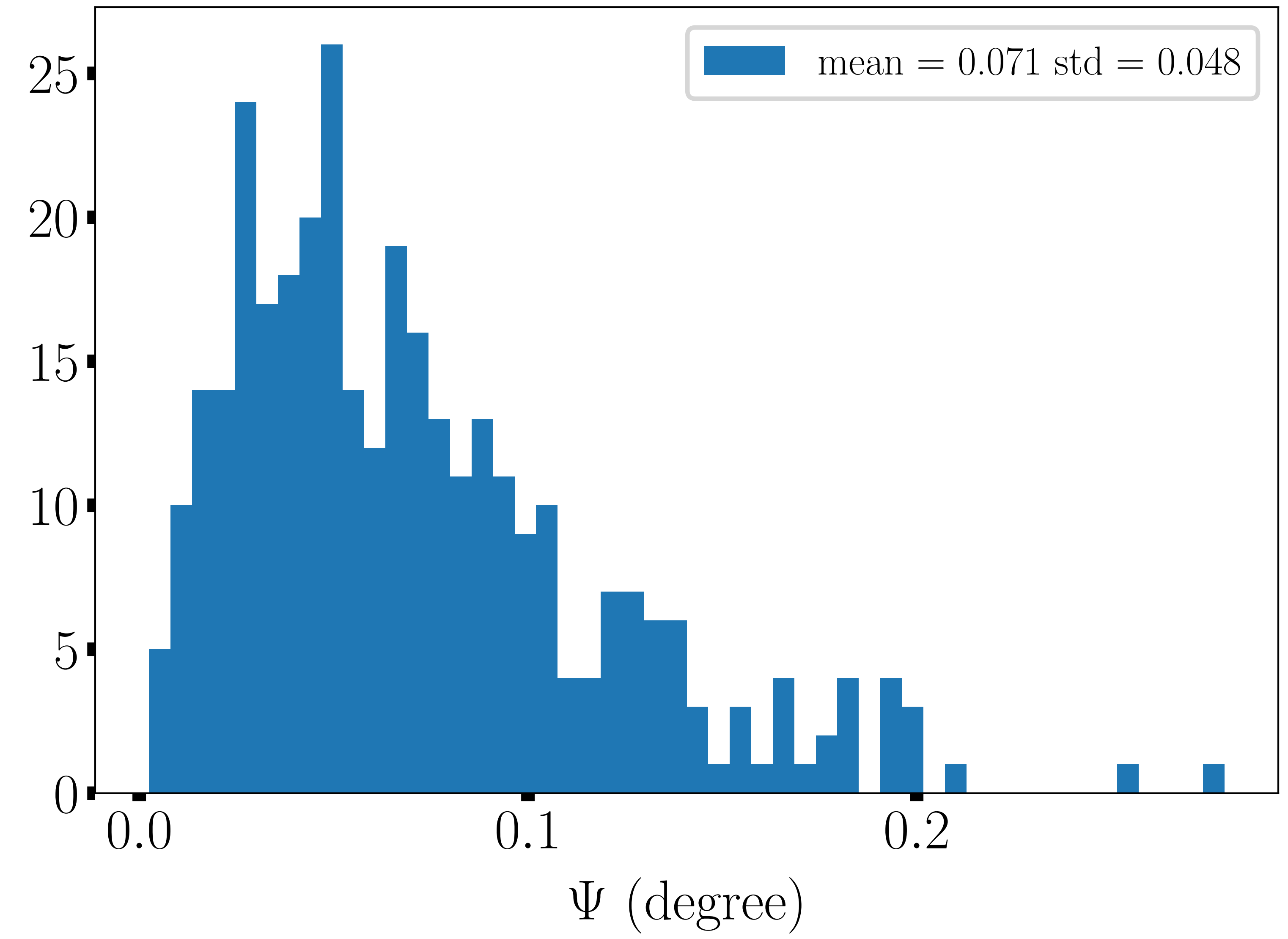




Constraint on the lateral position ~90 m
Angular resolution ~0.07°



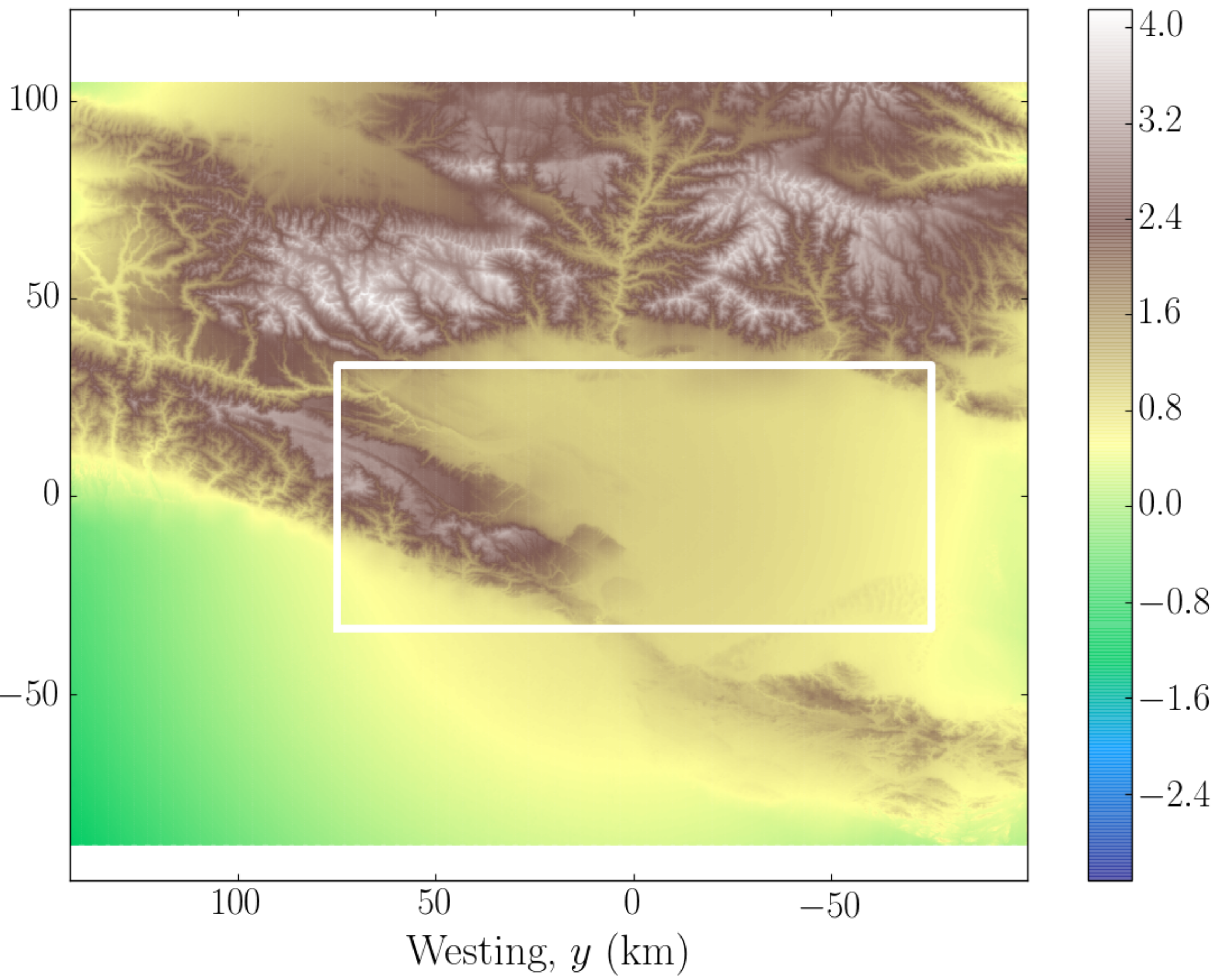


quality cuts:
- convergence cuts
- parameter space cuts

Stationary noise model:
- gaussian time GPS jitter of rms=5ns
- gaussian amplitude errors of 20% (conservative)

Reconstruction Performances

For a GRAND-like hot spot layout



HS1 layout:

- 10 000 antennas over a 10 000 km^2
- square grid array with a 1 km spacing
- neutrino induced EAS from realistic isotropic flux

HS1 simulations:

- real topography
- primaries: neutrino

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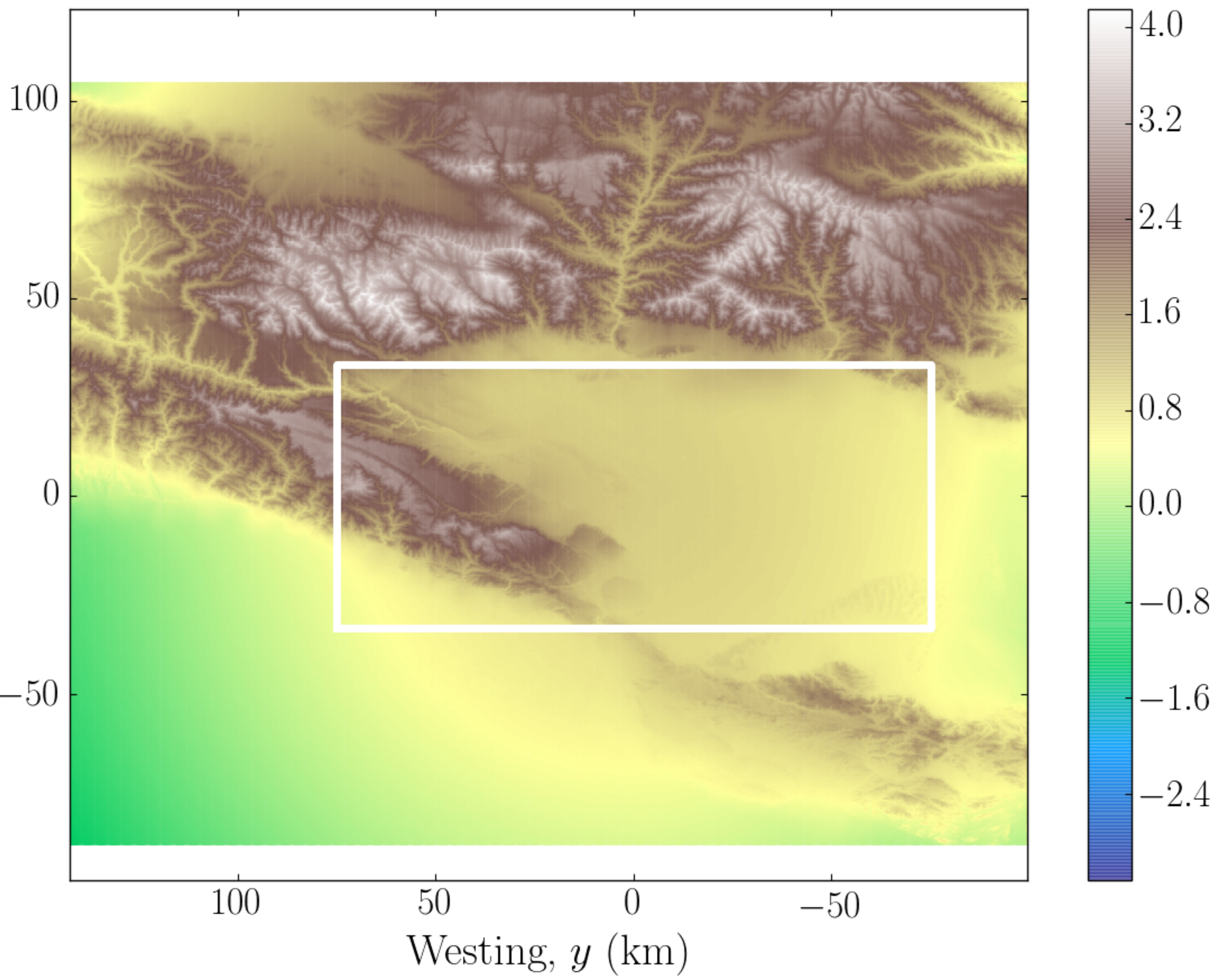

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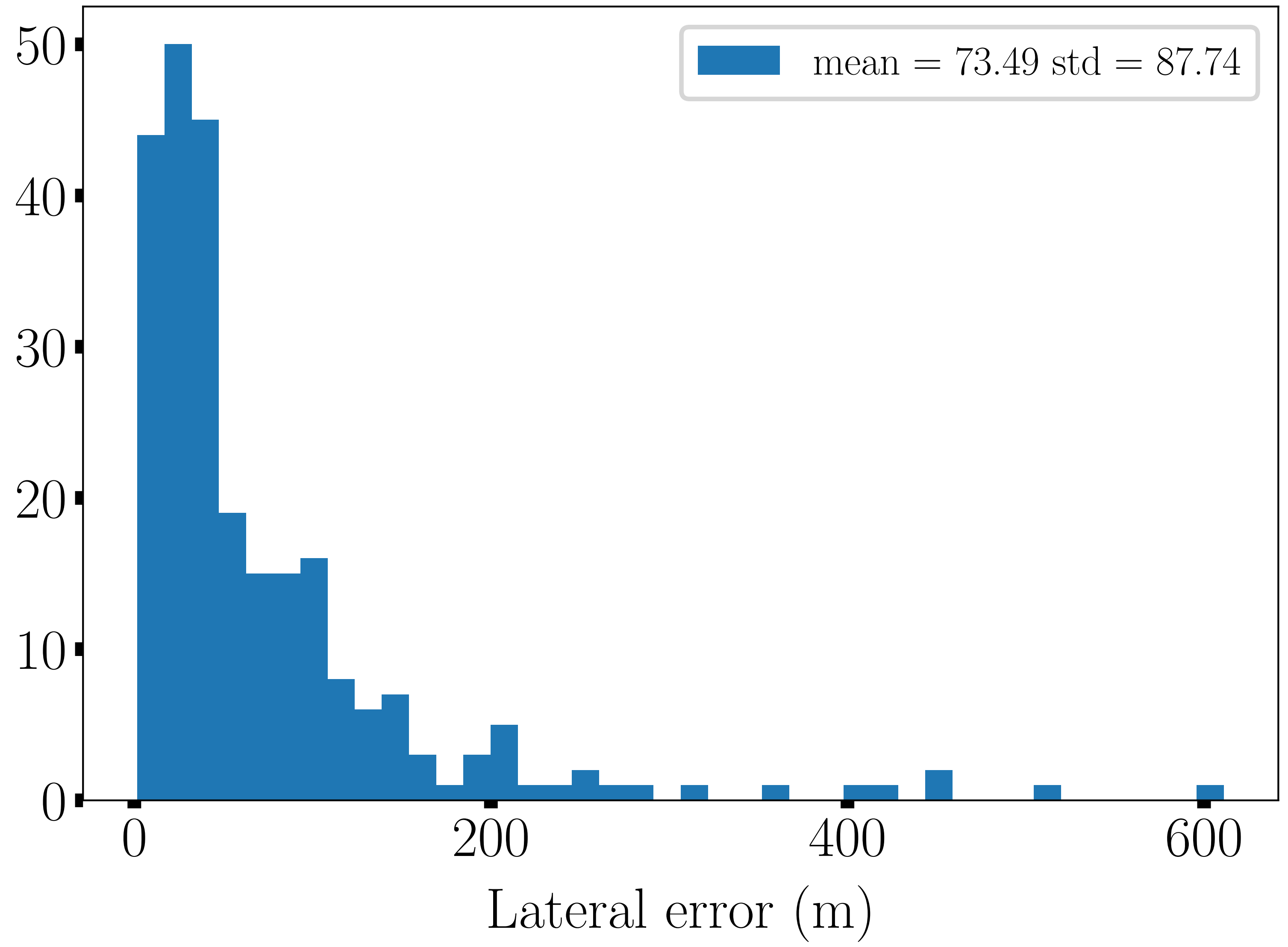

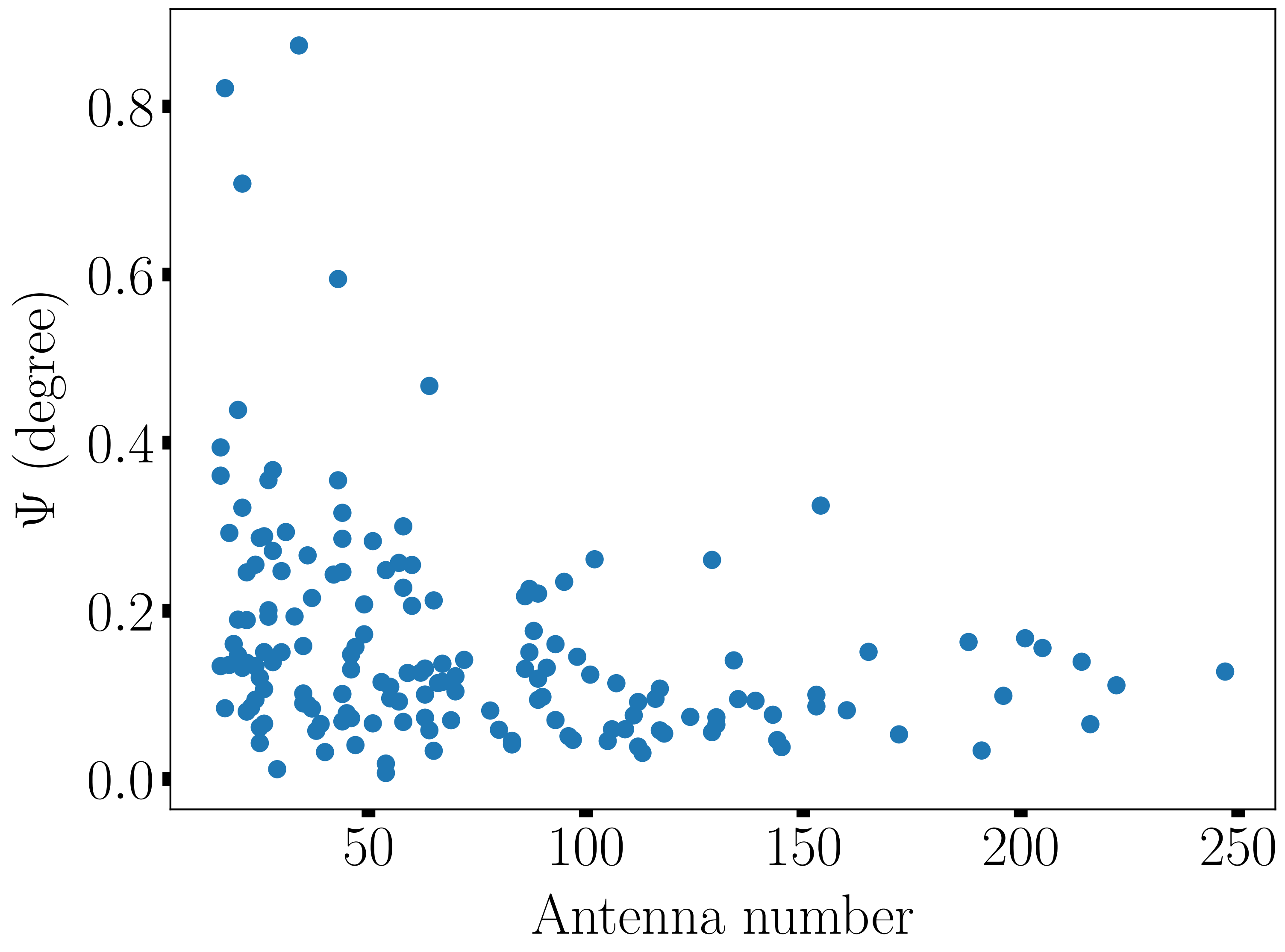

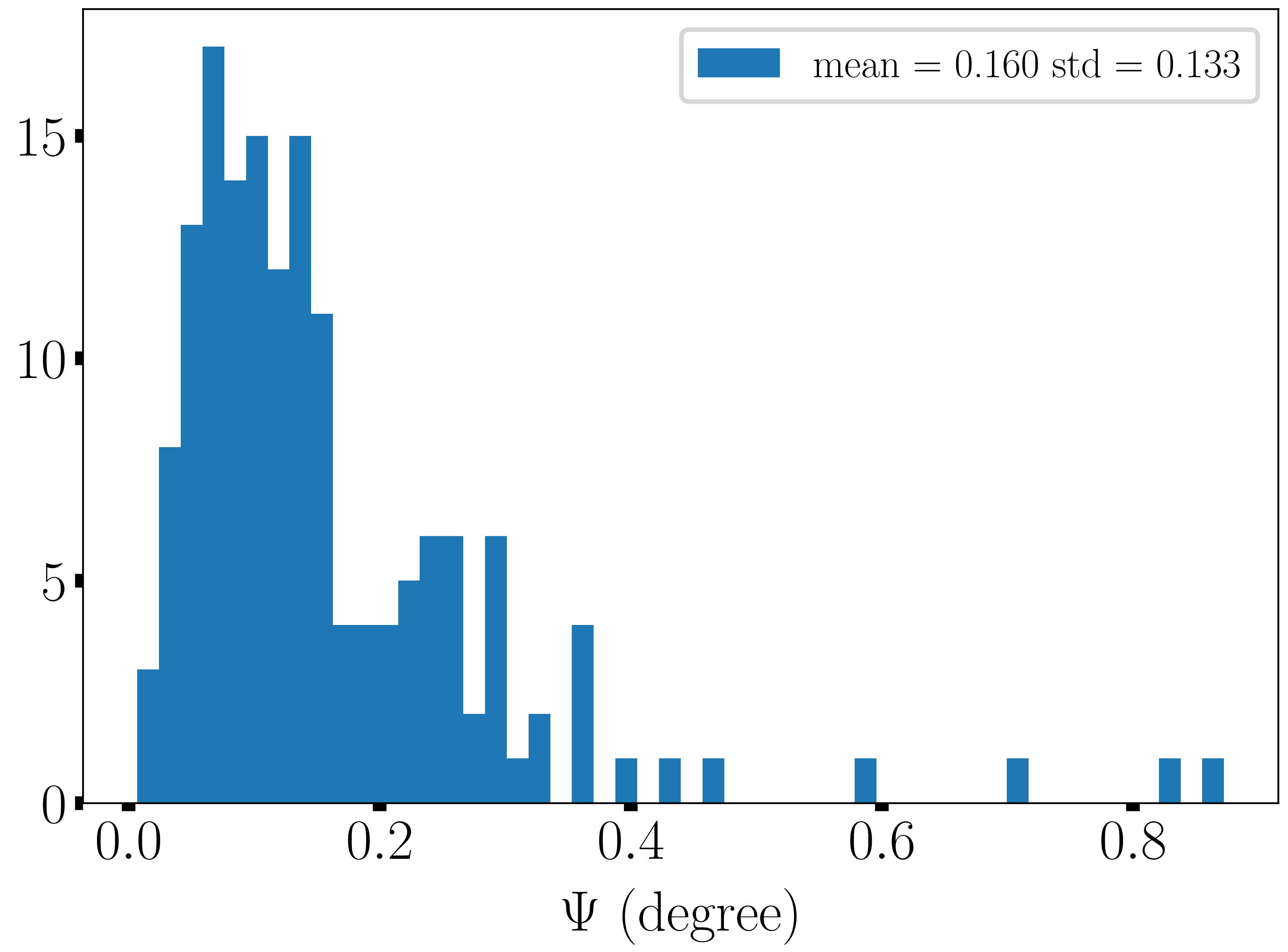

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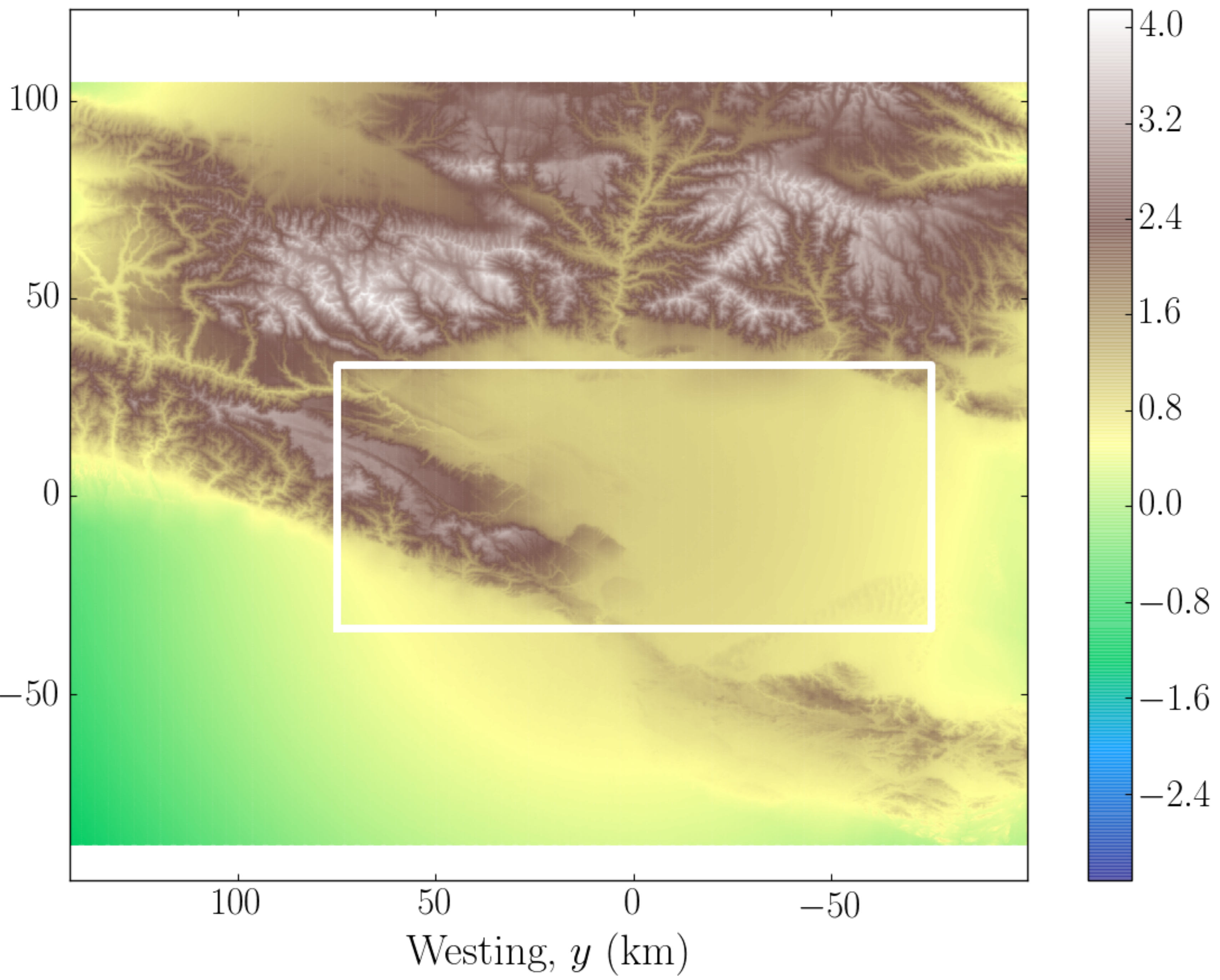

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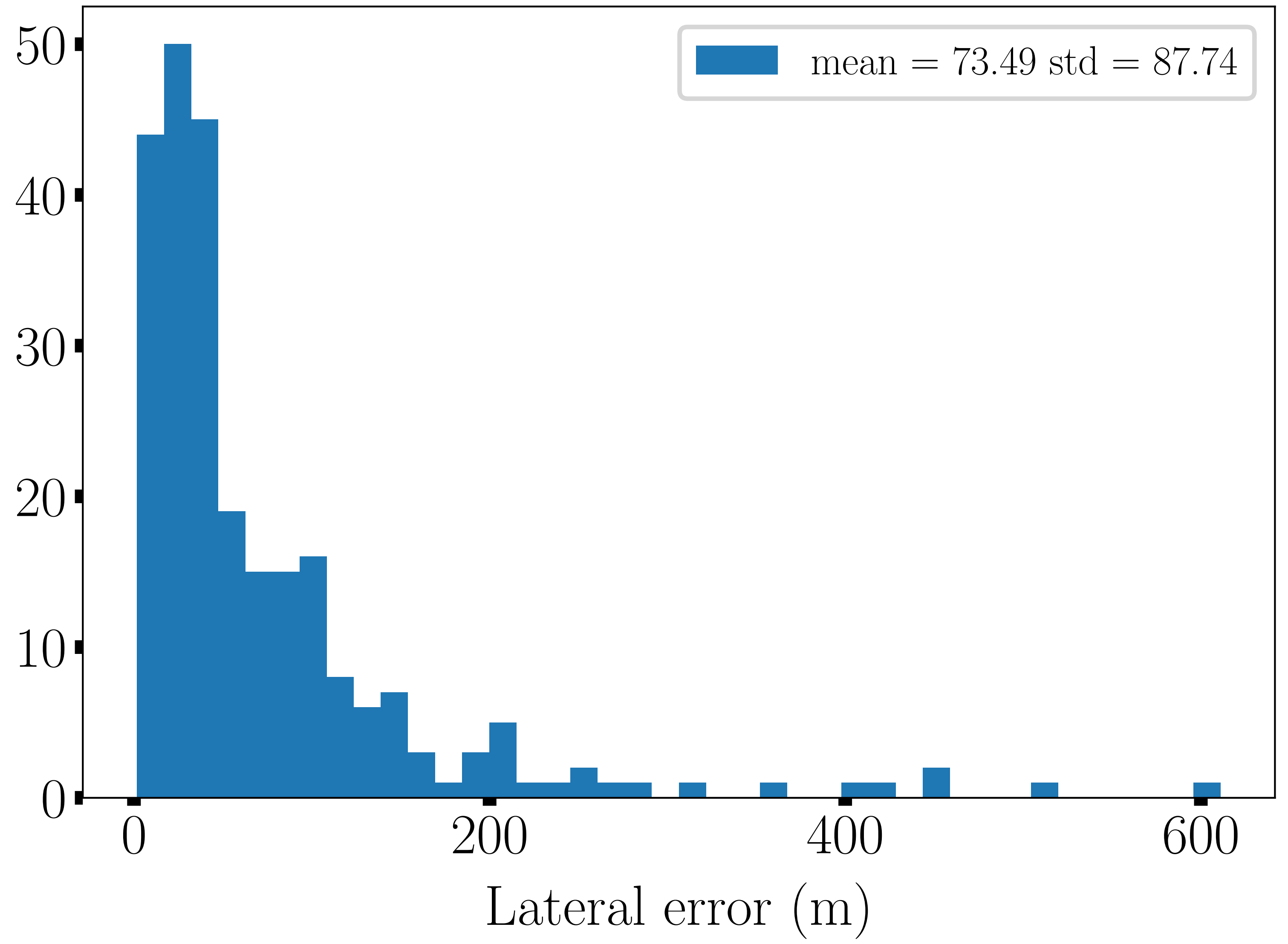

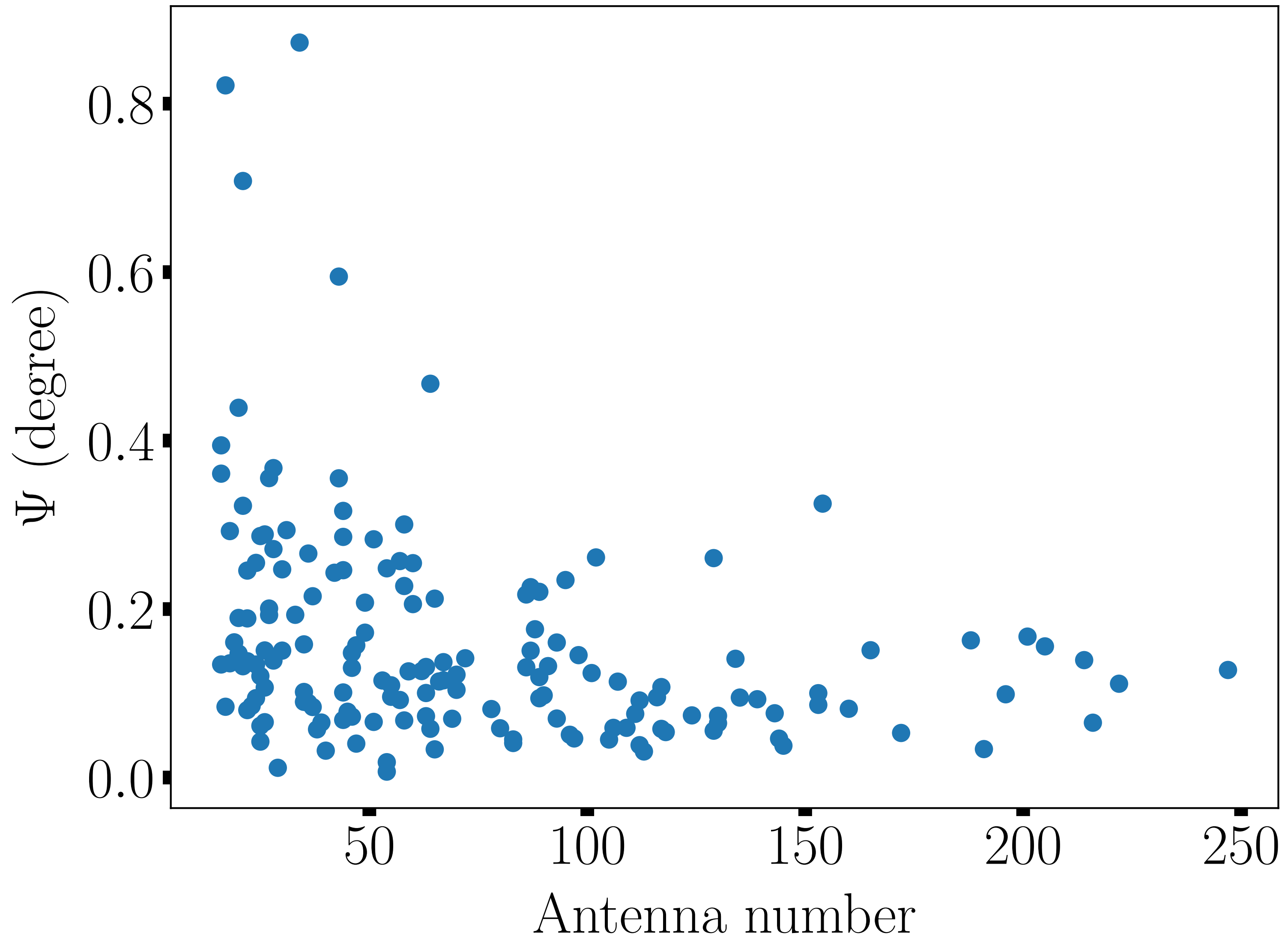

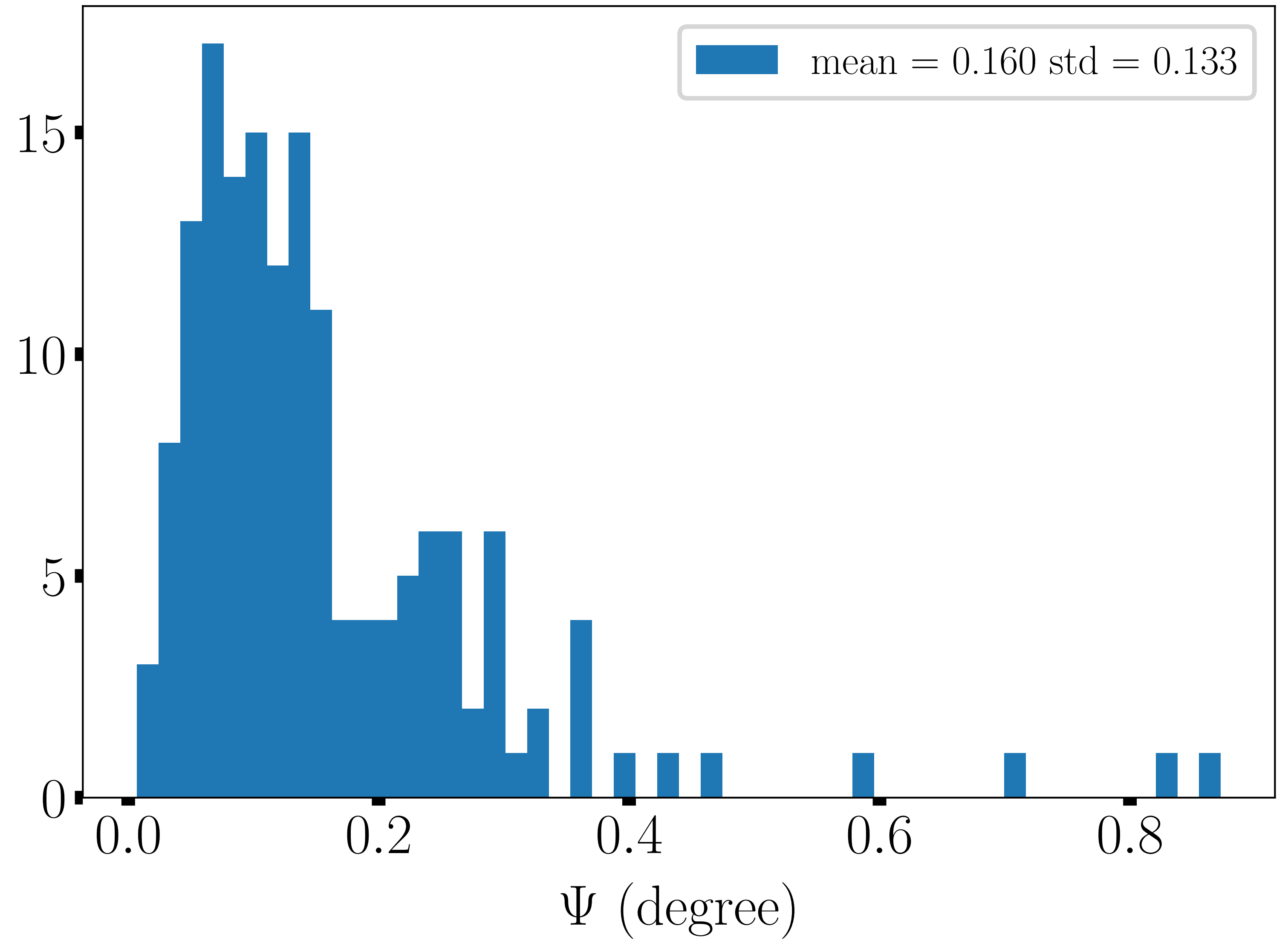

quality cuts:
- convergence cuts
- parameter space cuts

Stationary noise model:
- gaussian time GPS jitter of rms=5ns
- gaussian amplitude errors of 20% (conservative)

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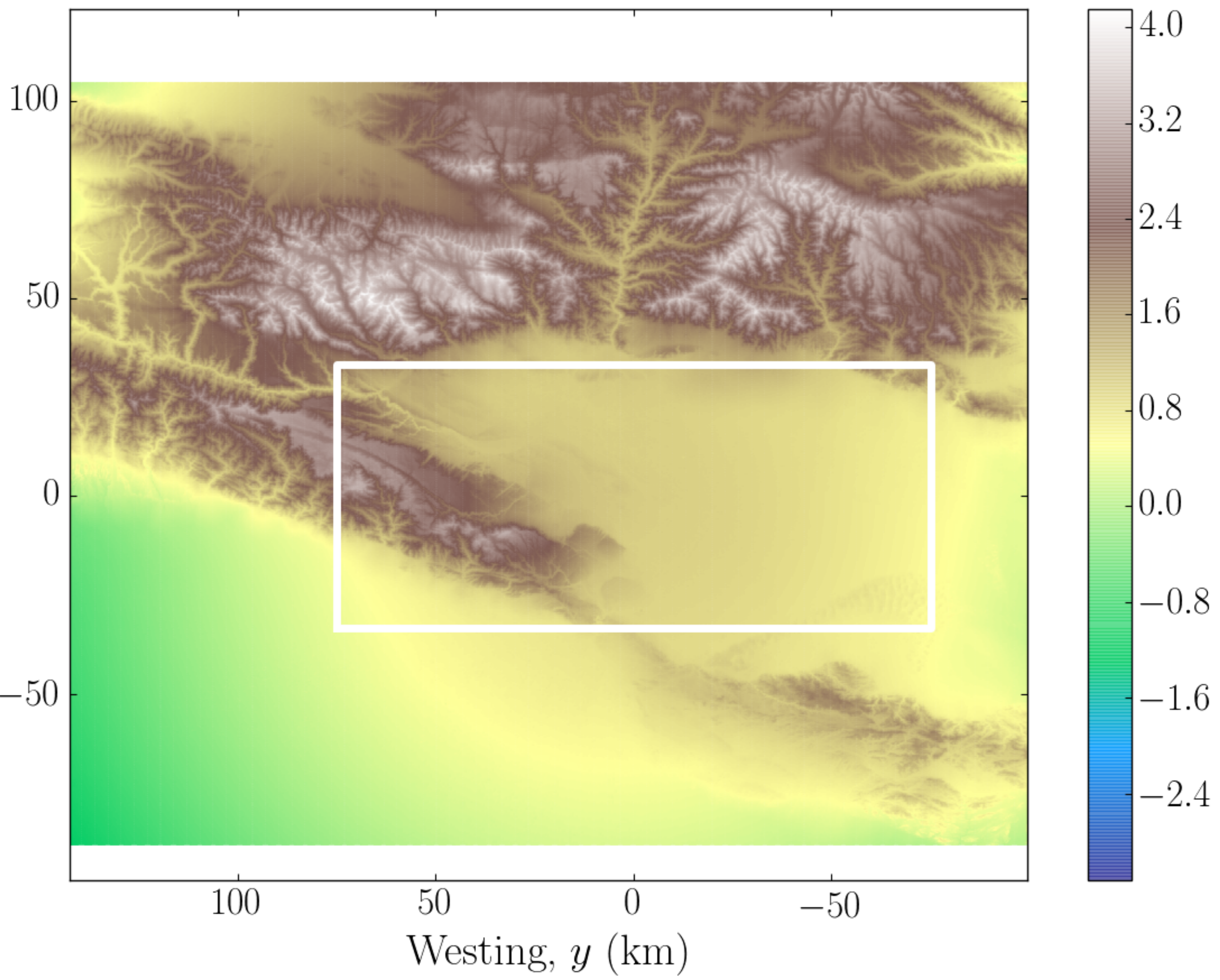
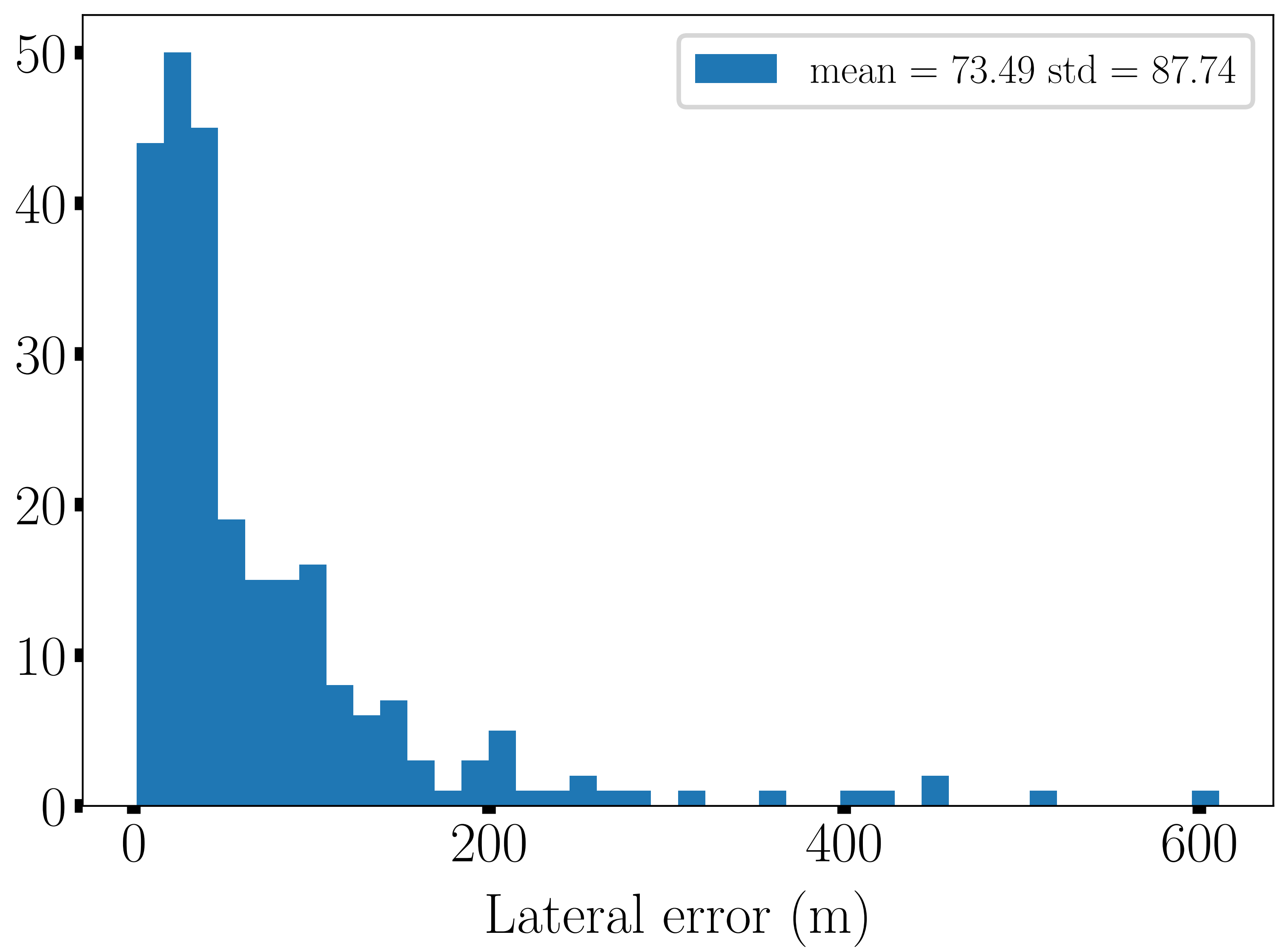
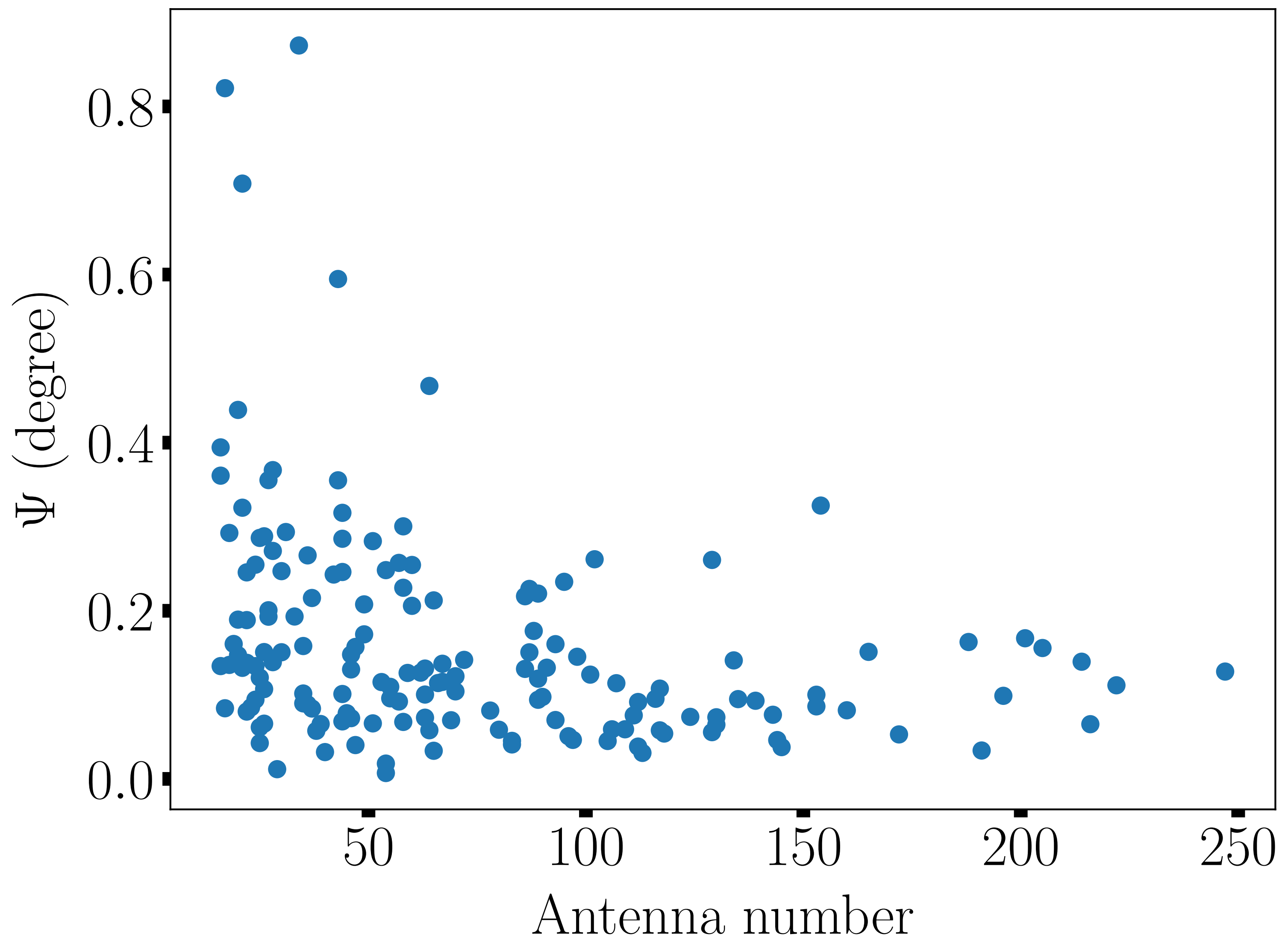
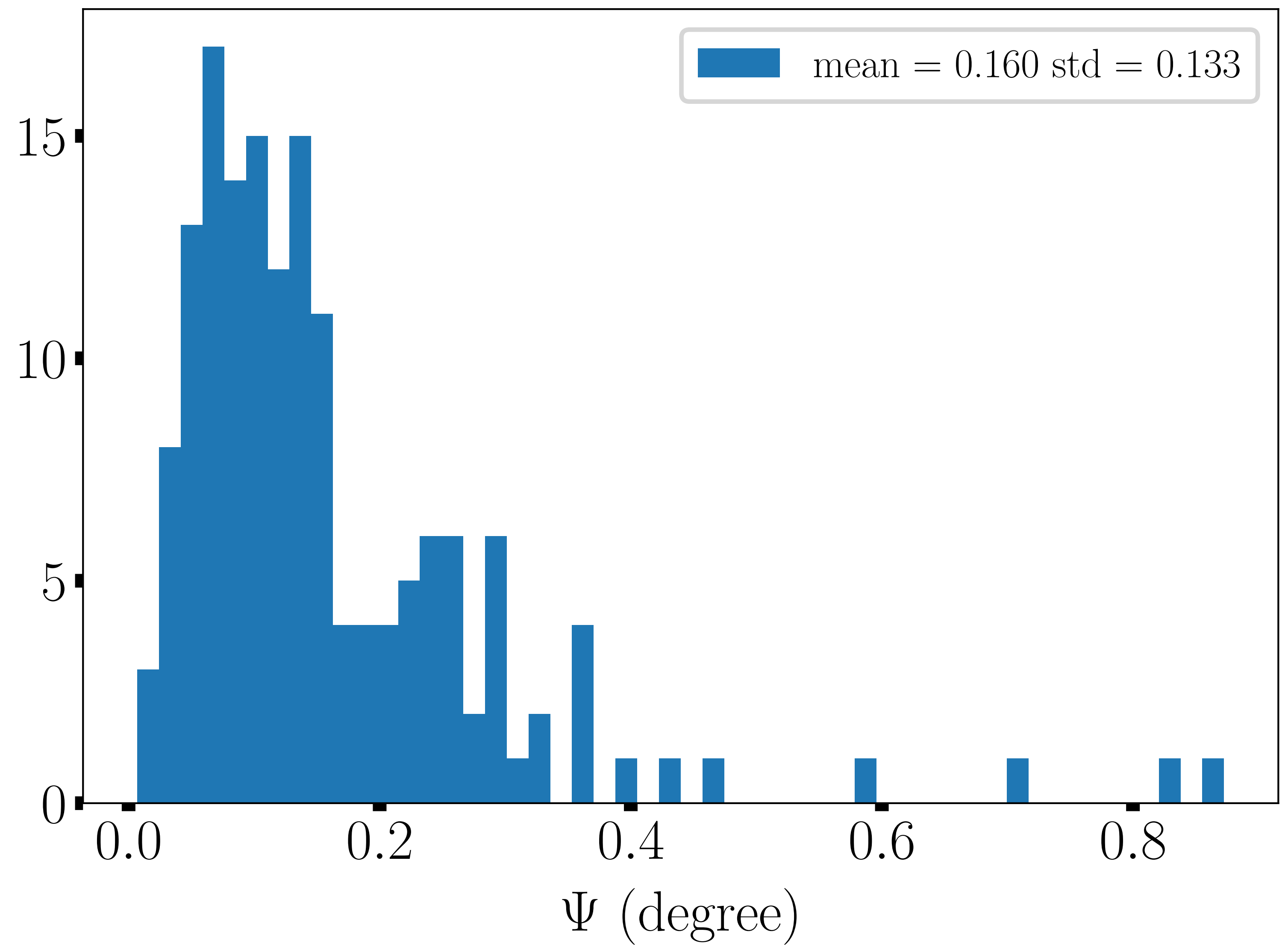


Constraint on the lateral position ~70 m
Angular resolution ~0.1°







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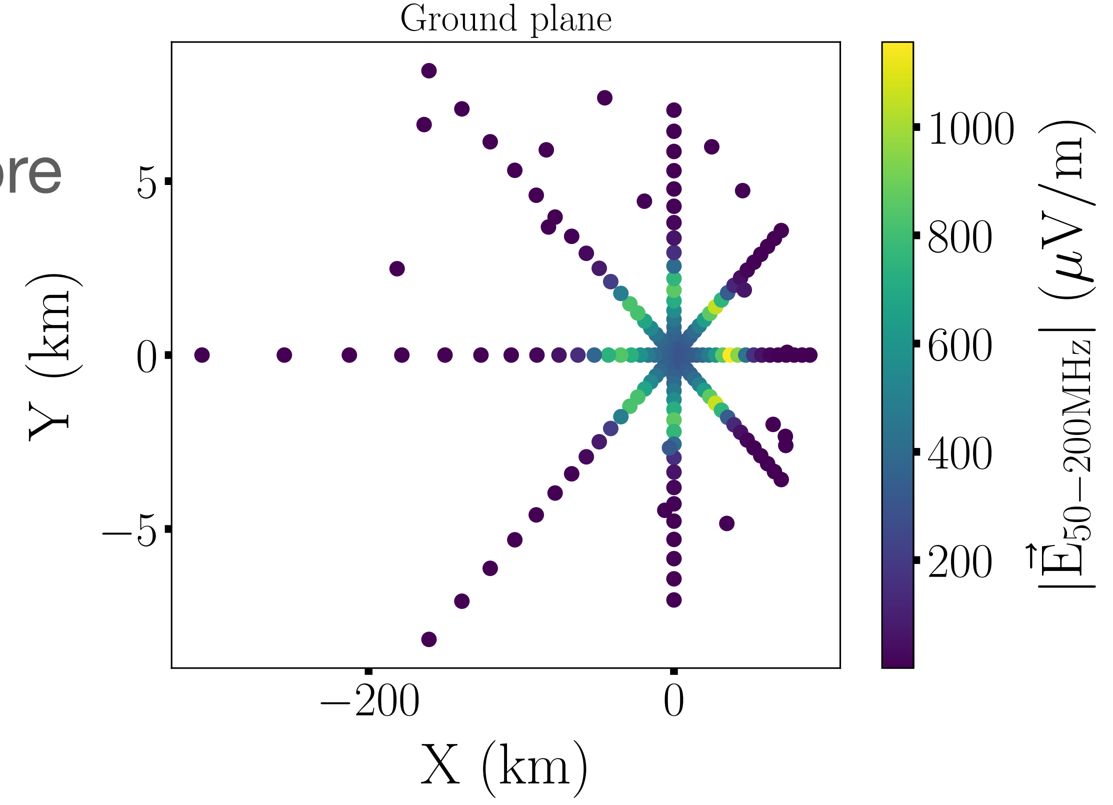
Preliminary results on energy and mass reconstruction

<u>"star-shape" simulation set</u>:

- centered on the shower core
- "star" shaped on ground



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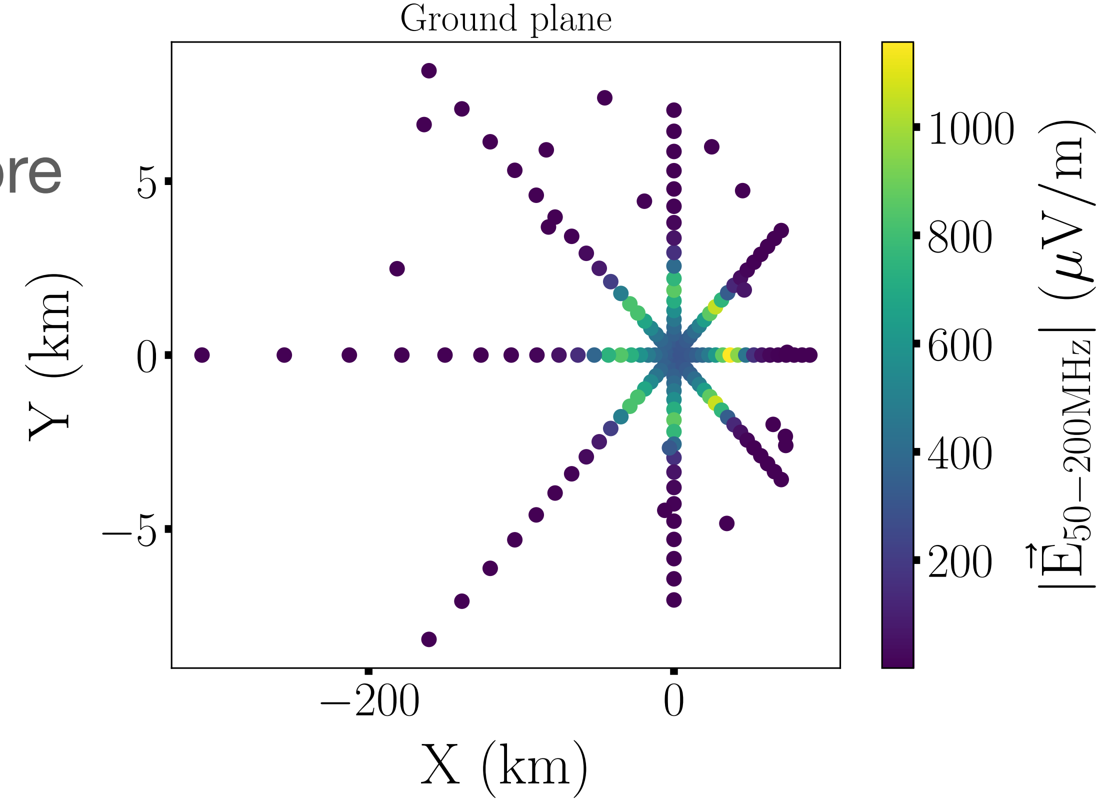

From the ADF fit we directly obtain:

$$f^{\mathrm{ADF}}(\omega, \eta, \alpha, l; \delta\omega, \mathcal{A}) = \frac{\mathcal{A}}{l} f^{\mathrm{GeoM}}(\alpha, \eta, \mathcal{B}) \; f^{\mathrm{Cerenkov}}(\omega, \delta\omega)$$

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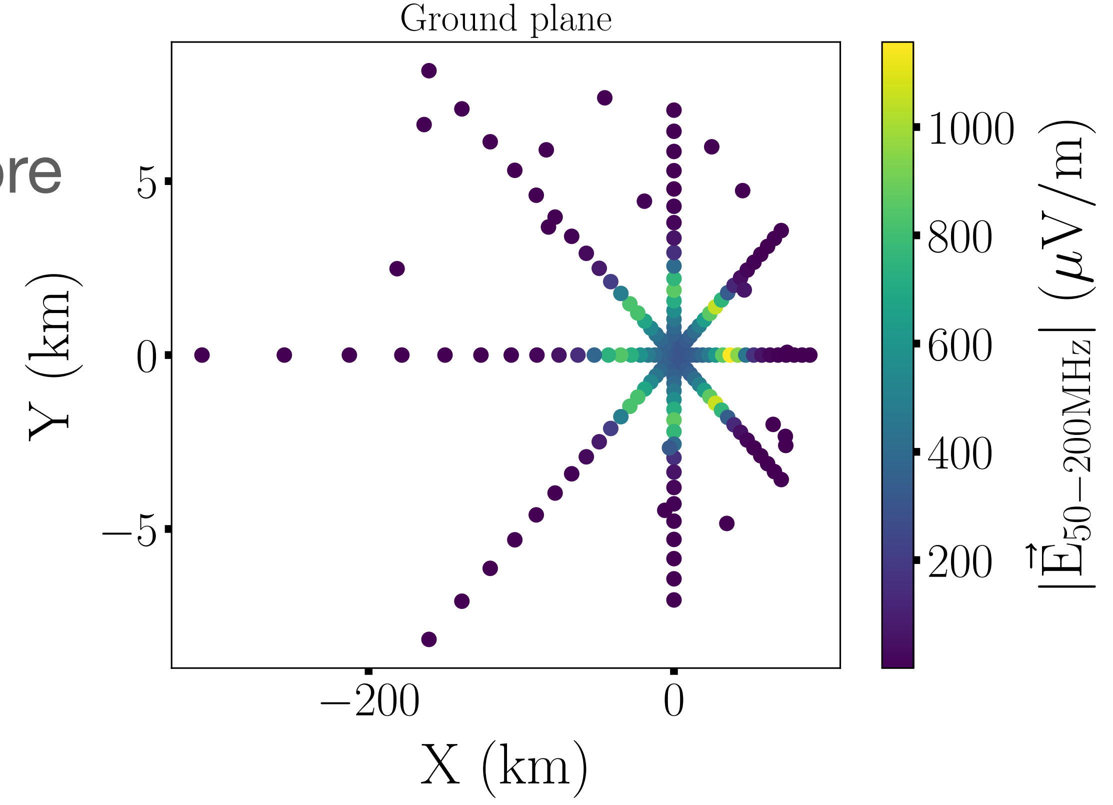

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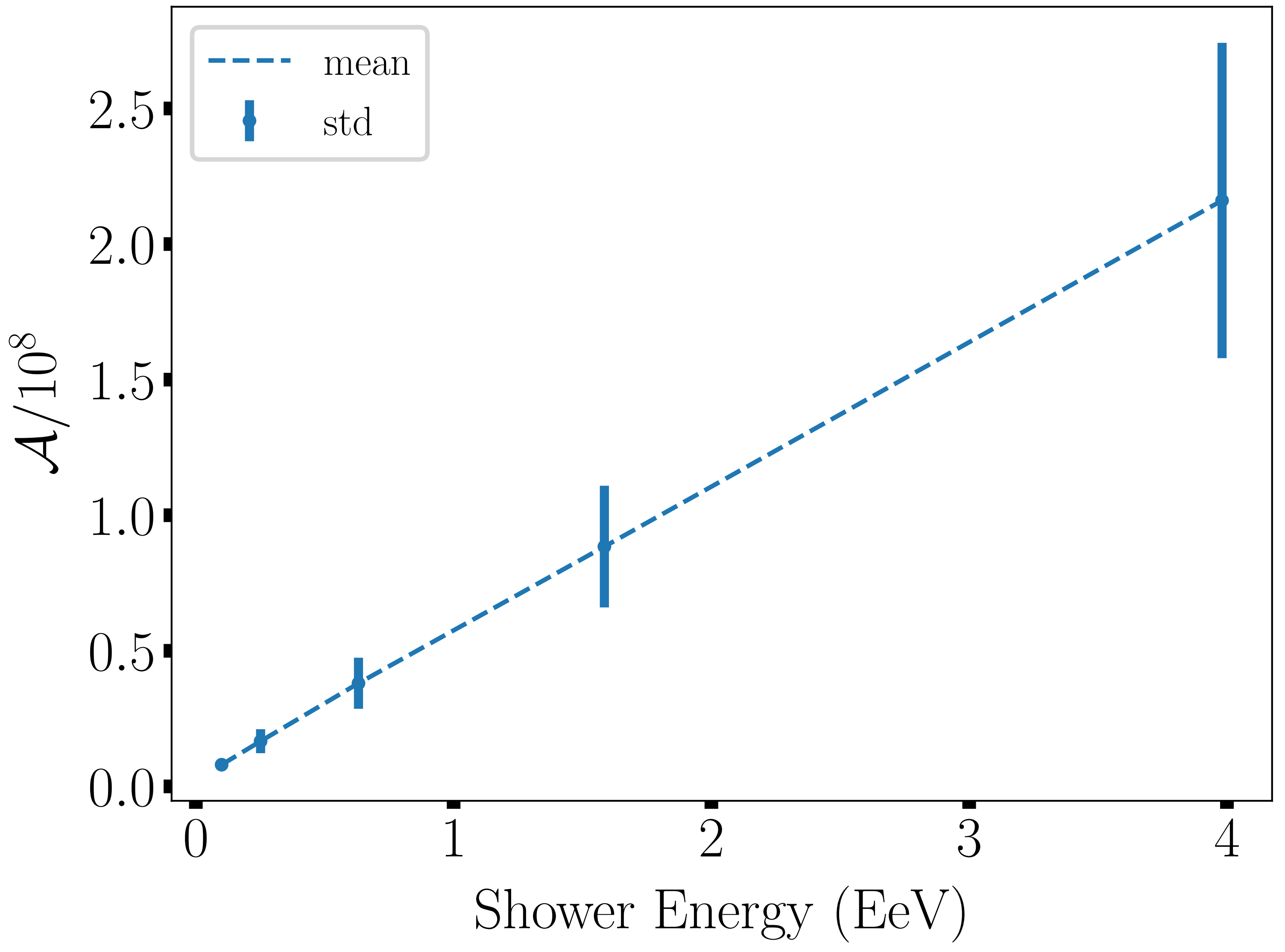

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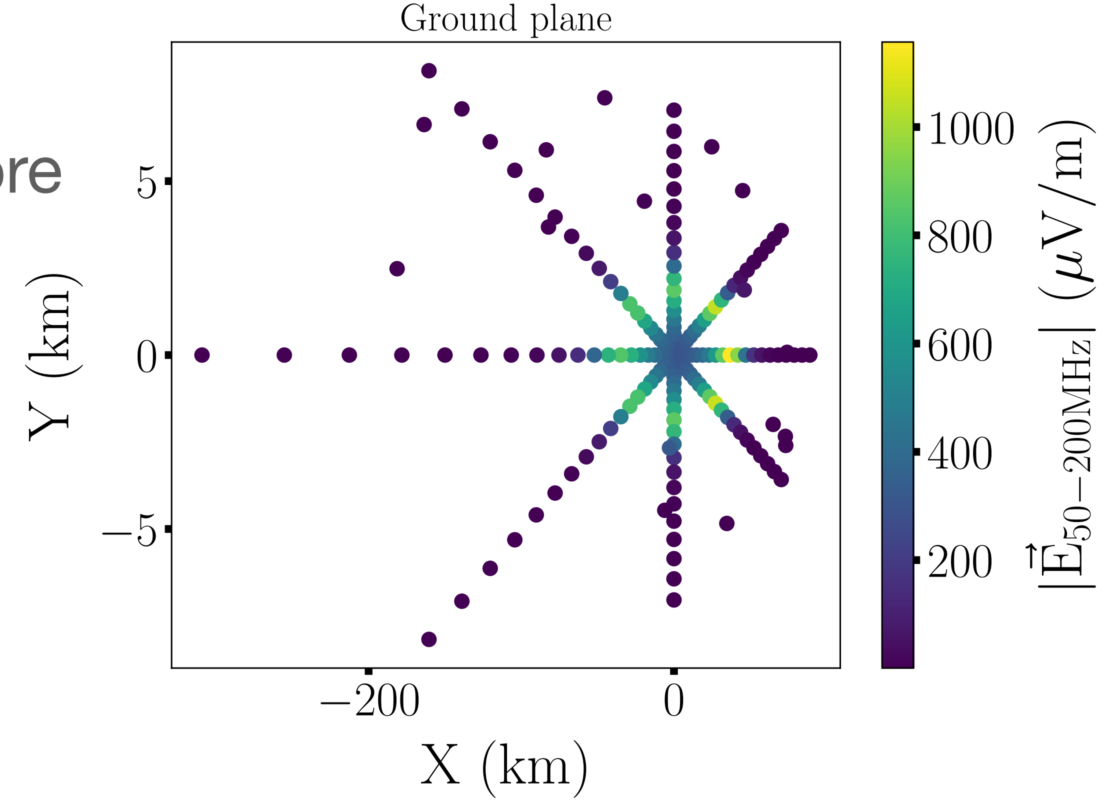

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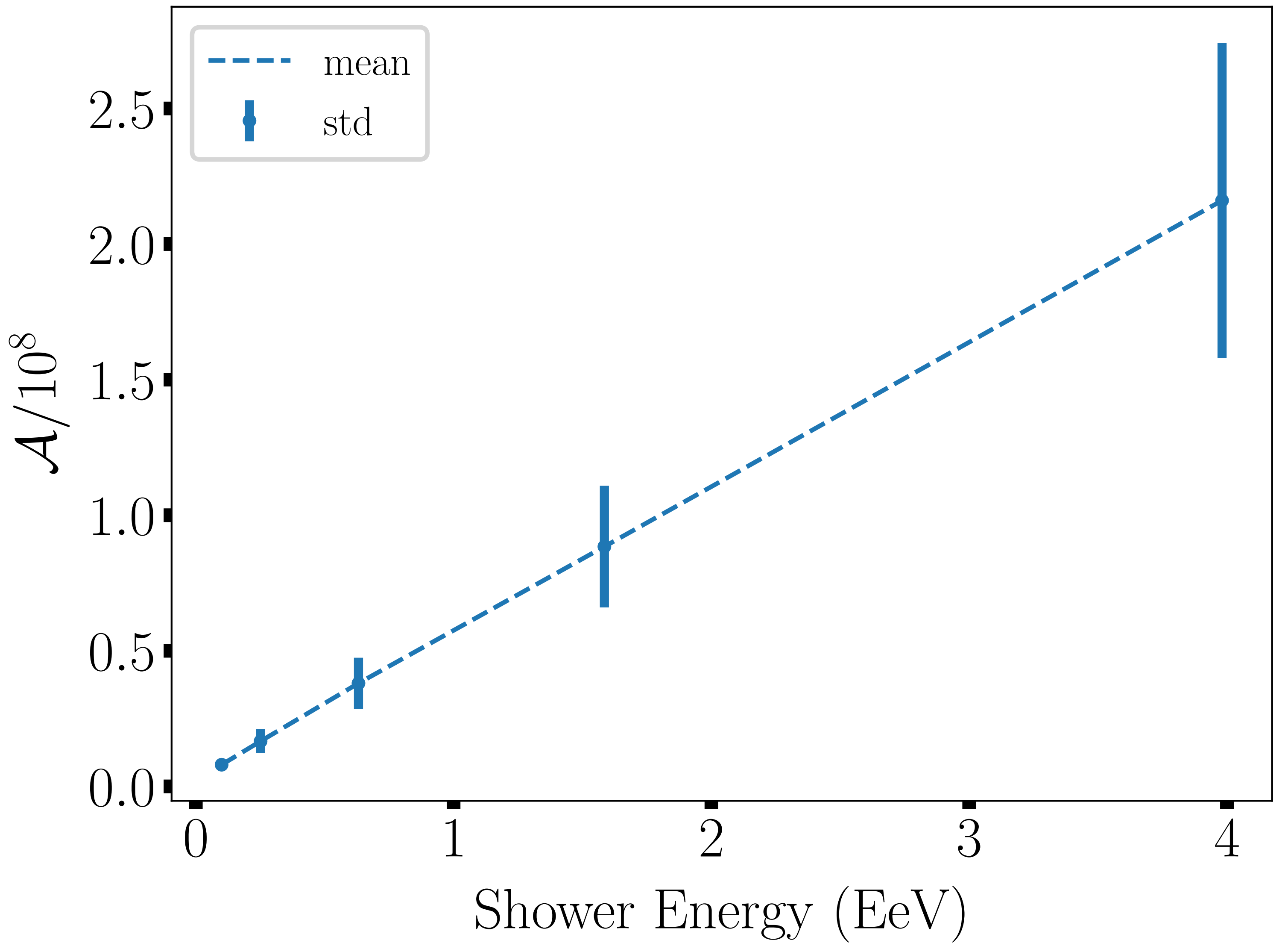

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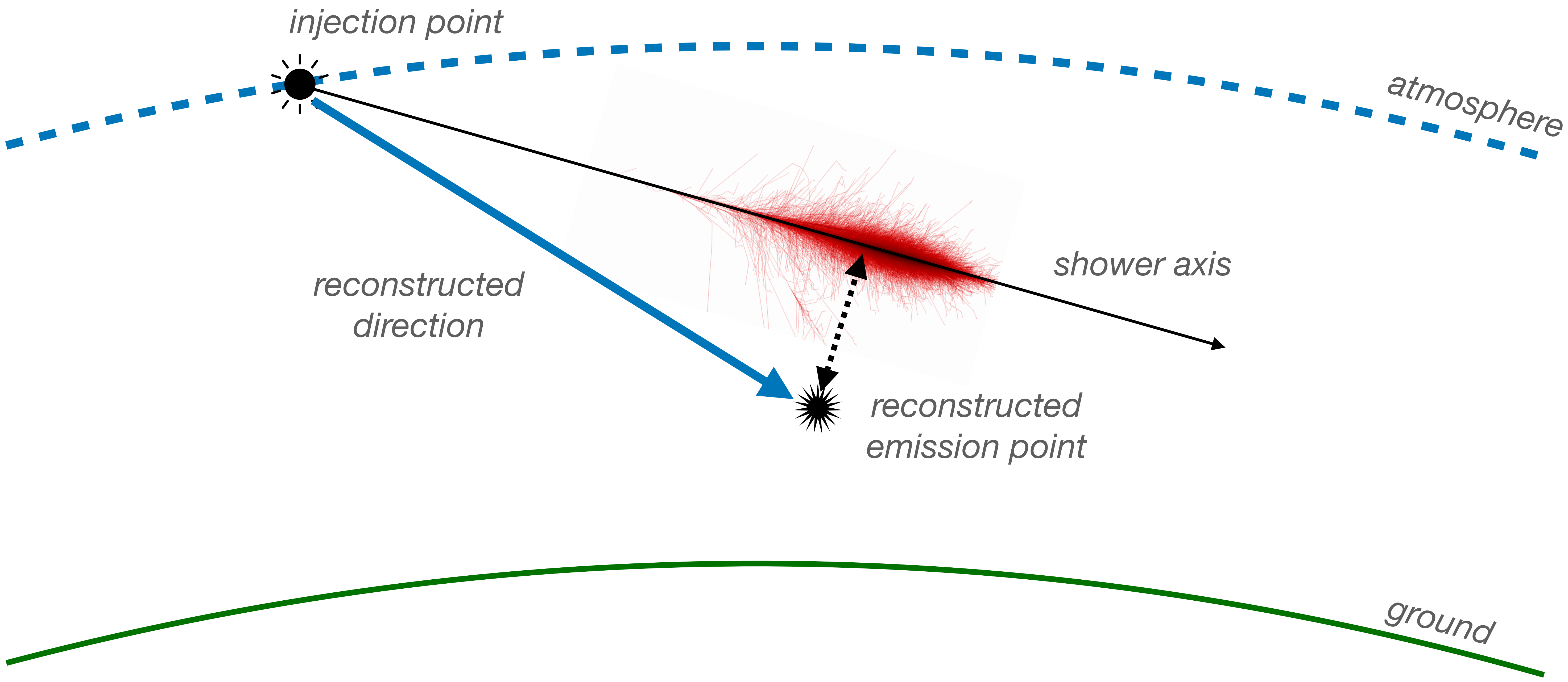
the atmosphere column density integral from injection to reconstructed emission point



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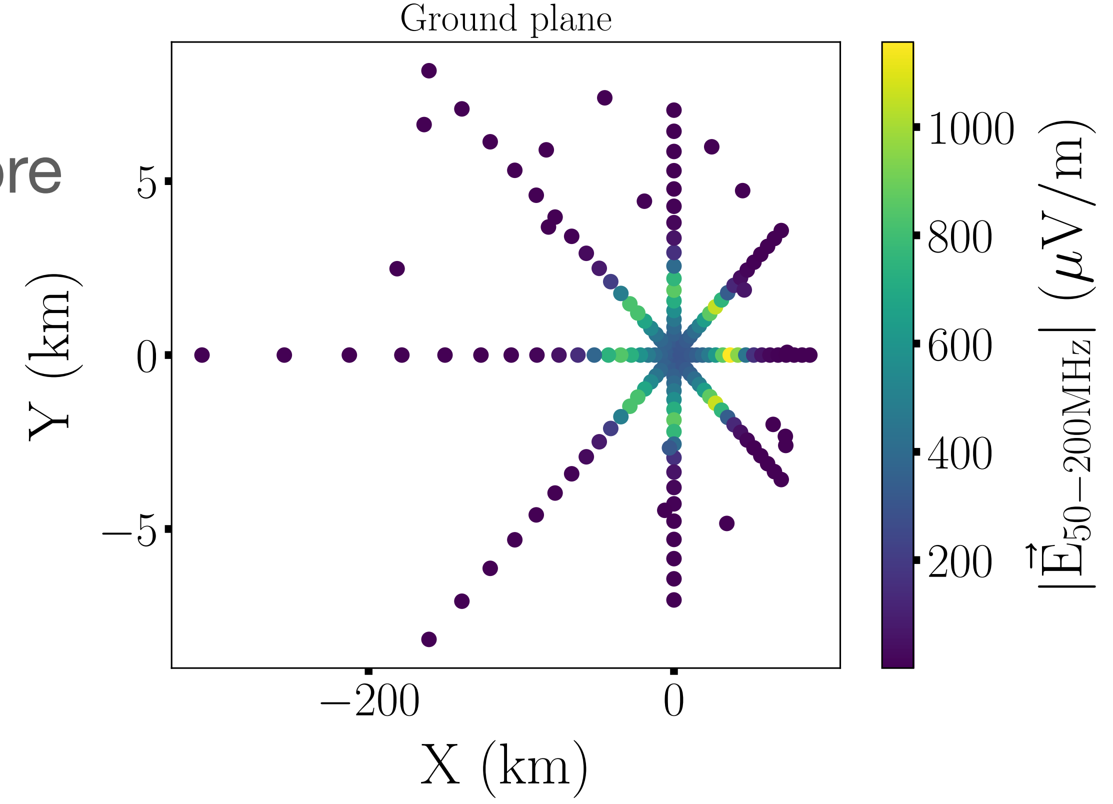

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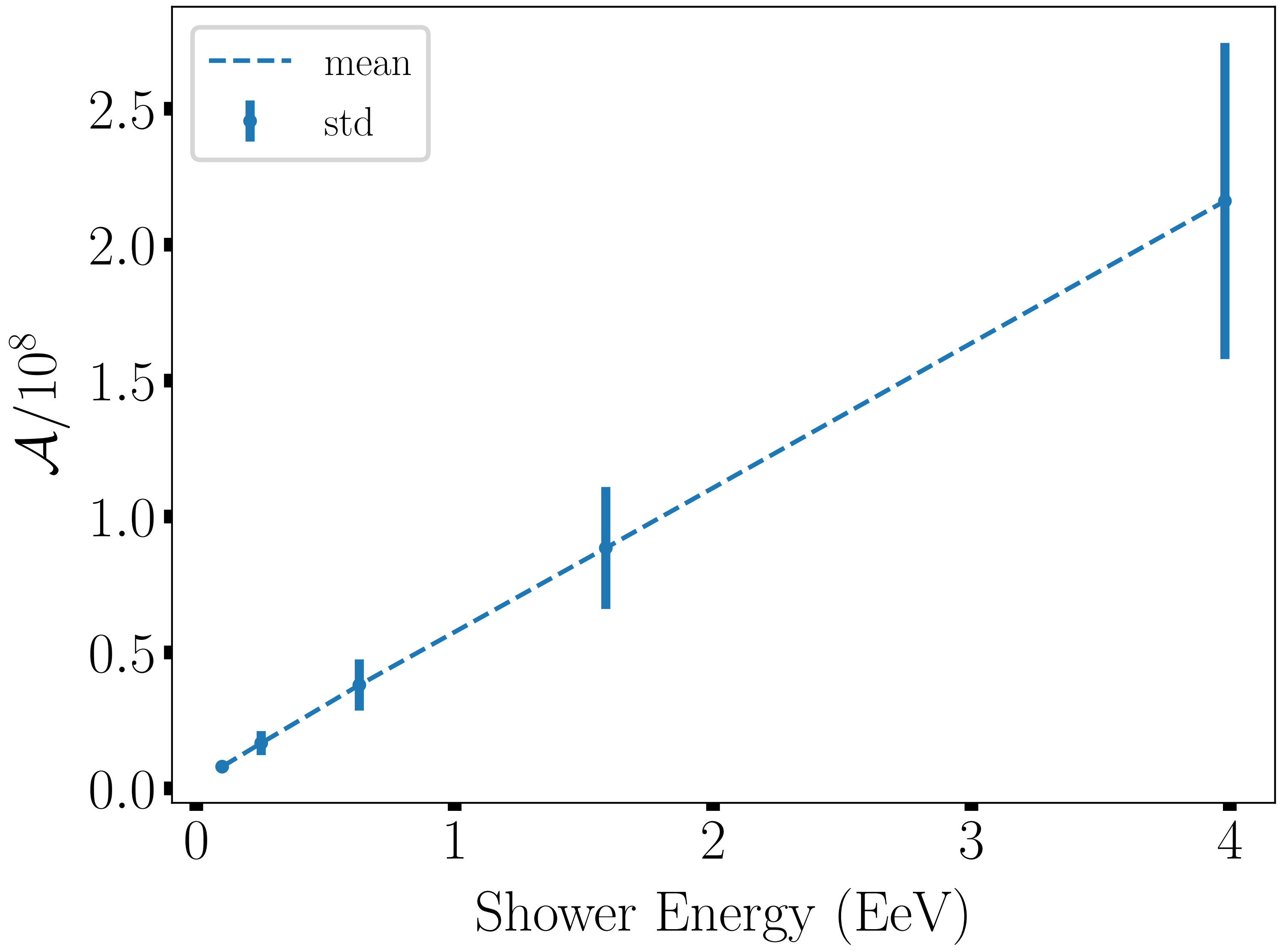

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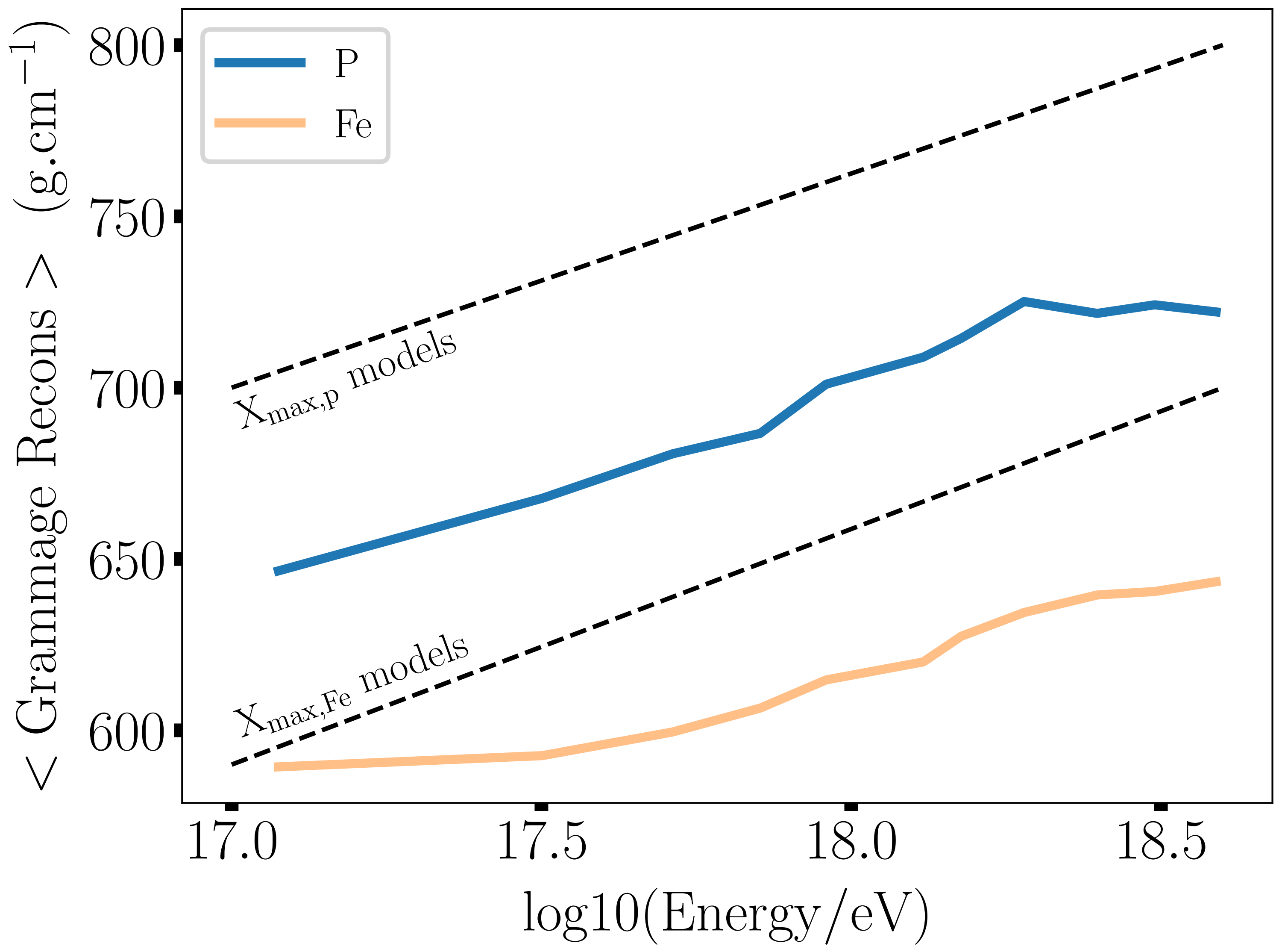

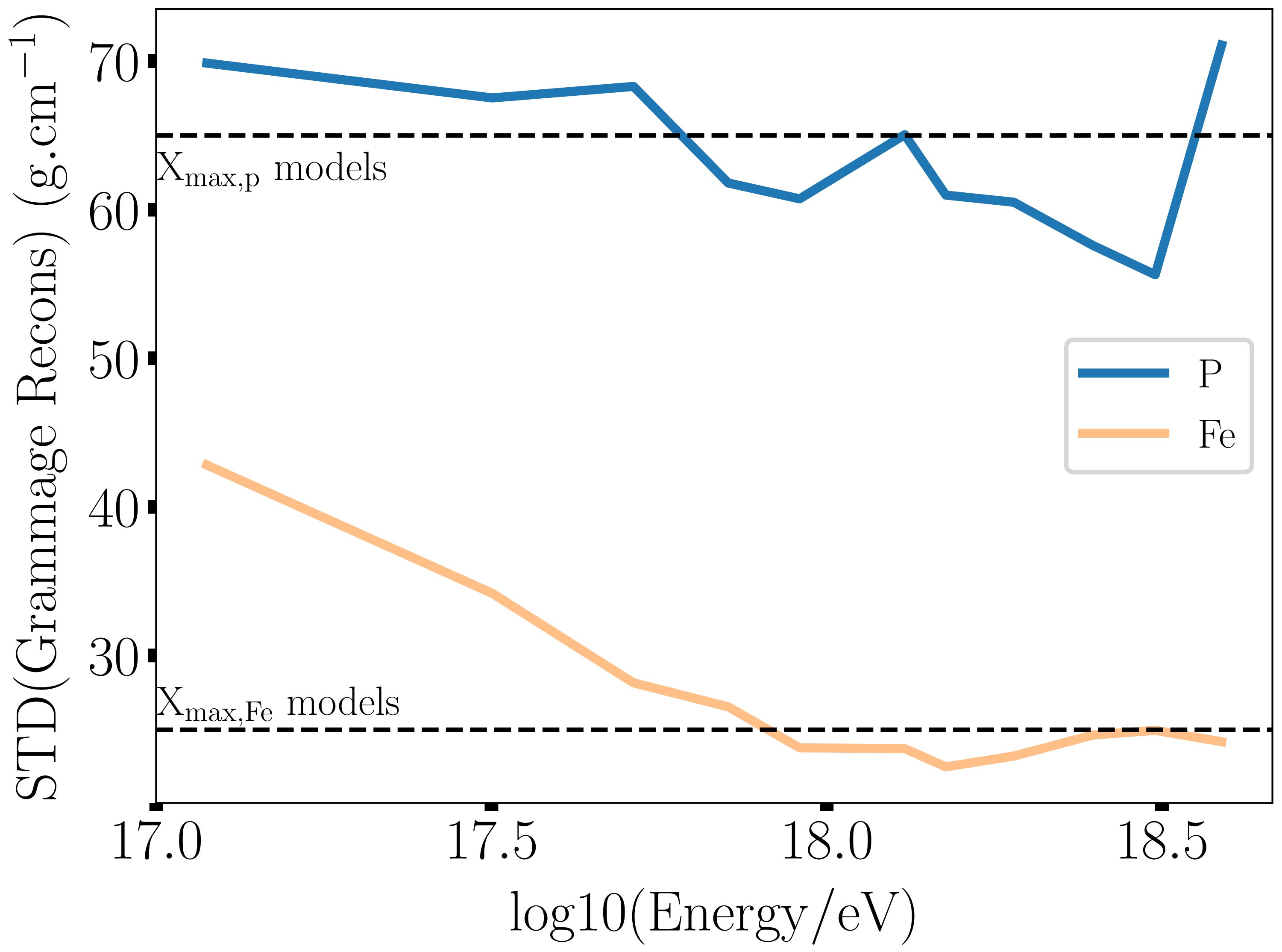

- valid proxy on the mass composition **but** different from Xmax
- nevertheless results are compatible with standard reconstruction of Xmax

Conclusion and Perspectives

Promising results but more work still needed !

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In summary we have:

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