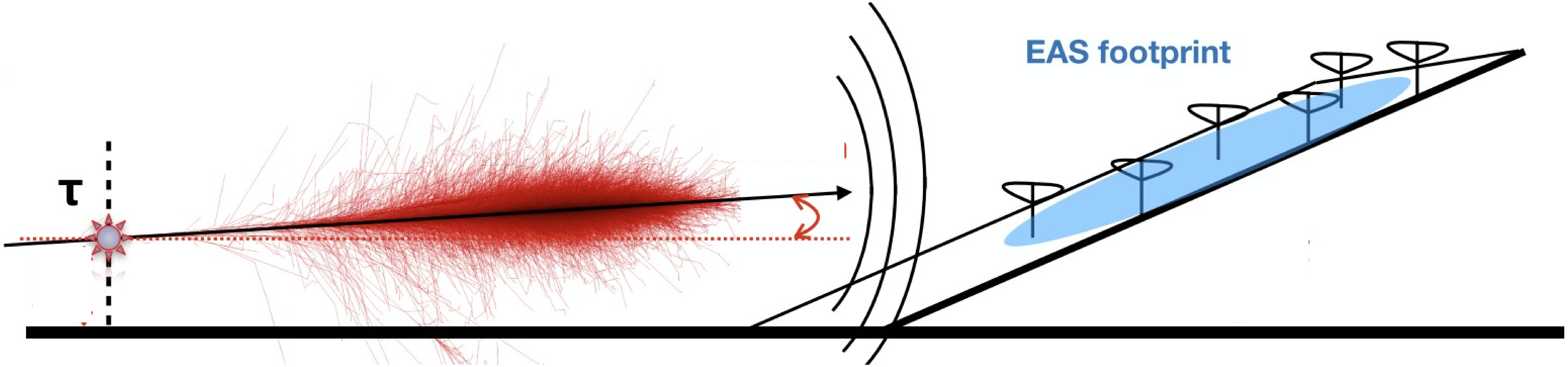
Reconstruction of highly-inclined extensive air showers in GRAND

Oscar Macías
(SFSU)
*On behalf of the **GRAND** Collaboration*

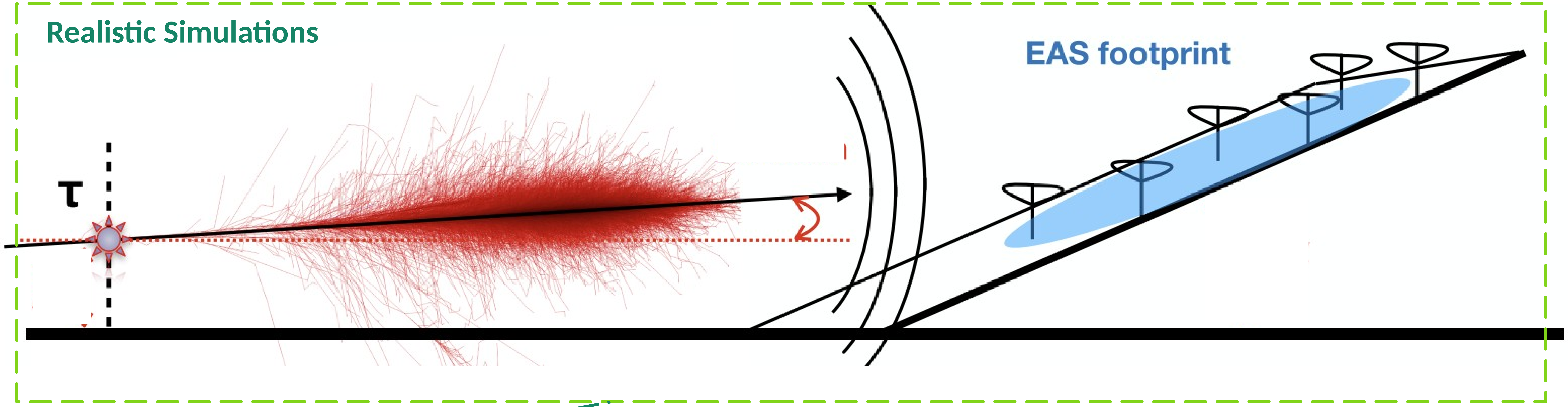
ARENA 2024
KICP, University of Chicago

Reconstruction of highly-inclined Air Showers (conventional + ML methods)



Decoene (2021)

Reconstruction of highly-inclined Air Showers (conventional + ML methods)



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Realistic Data Simulation libraries

✓ Include Galactic noise

✓ Include antenna response + RF chain + GPS jitter

✓ More than 20,000 simulations

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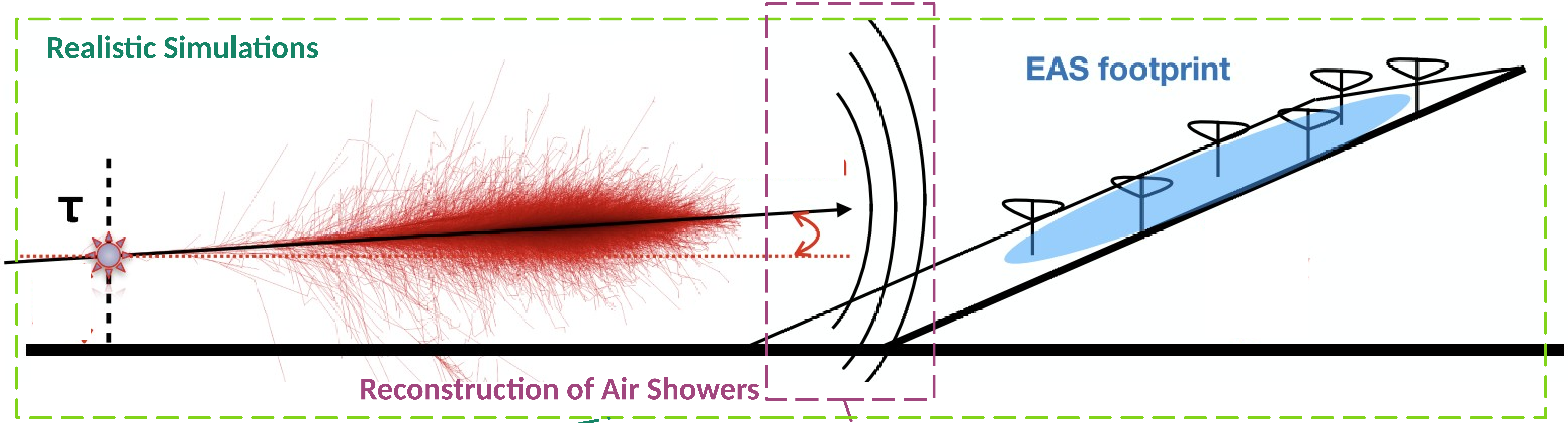

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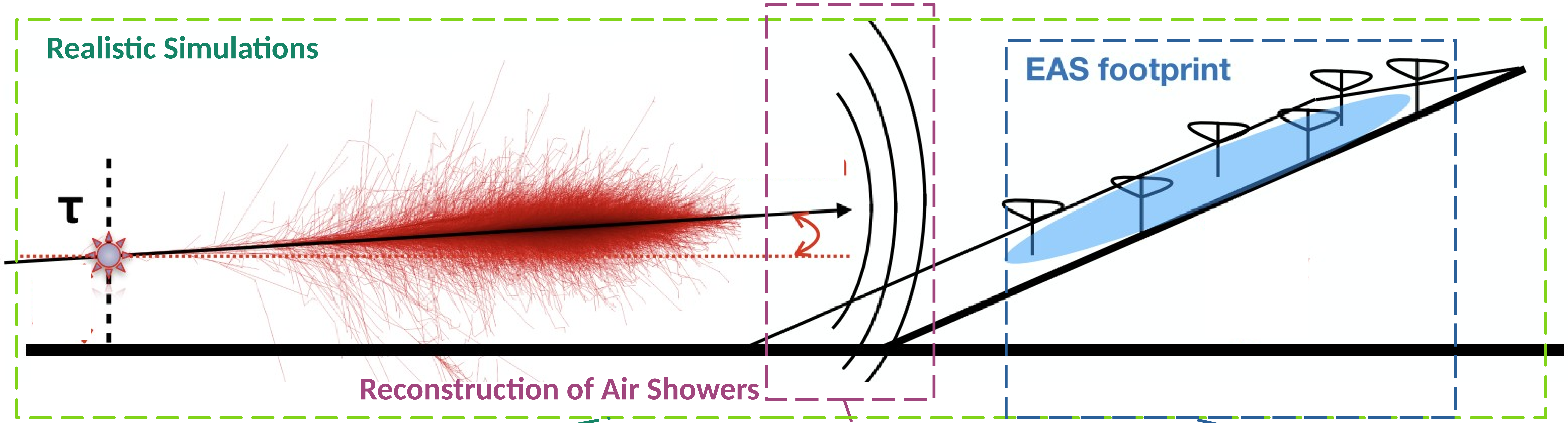
Reconstruction of Air Showers

- ✓ Plane Wave Front (PWF): fast timing & direction reconstruction
- ✓ Fitting (empirical and Physics informed) of Angular Distribution Function: more precise shower parameter reconstruction
- ✓ Empirical fitting of lateral distribution function
- ✓ Graph Neutral Networks for EAS studies

see talks by L. Gülzow & J. Köhler

Reconstruction of highly-inclined Air Showers (conventional + ML methods)



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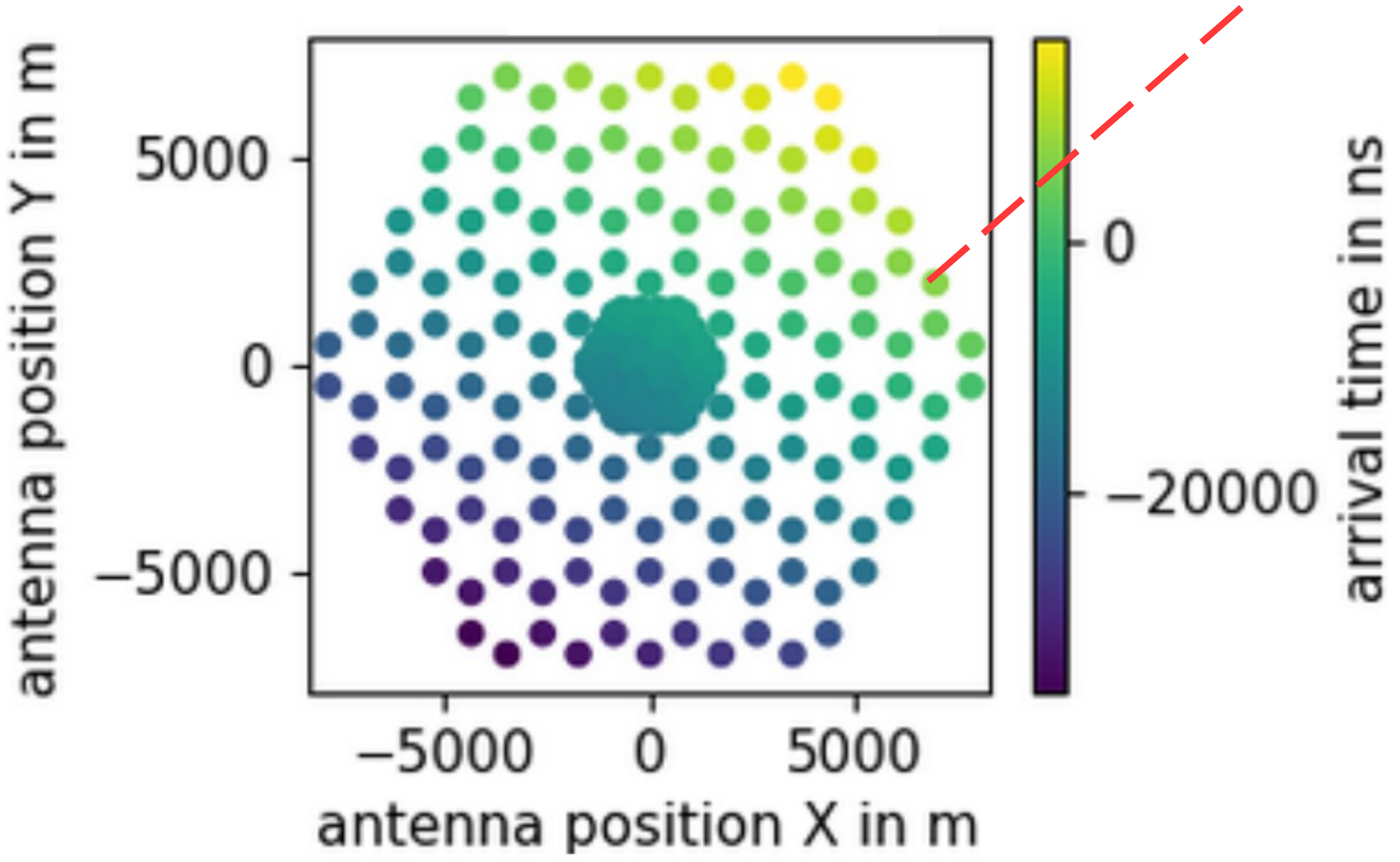
Electric field reconstruction

- ✓ E-field reconstruction with CNN
- ✓ Direction reconstruction based on polarization
- ✓ Denoising of E-field/ADC using ML

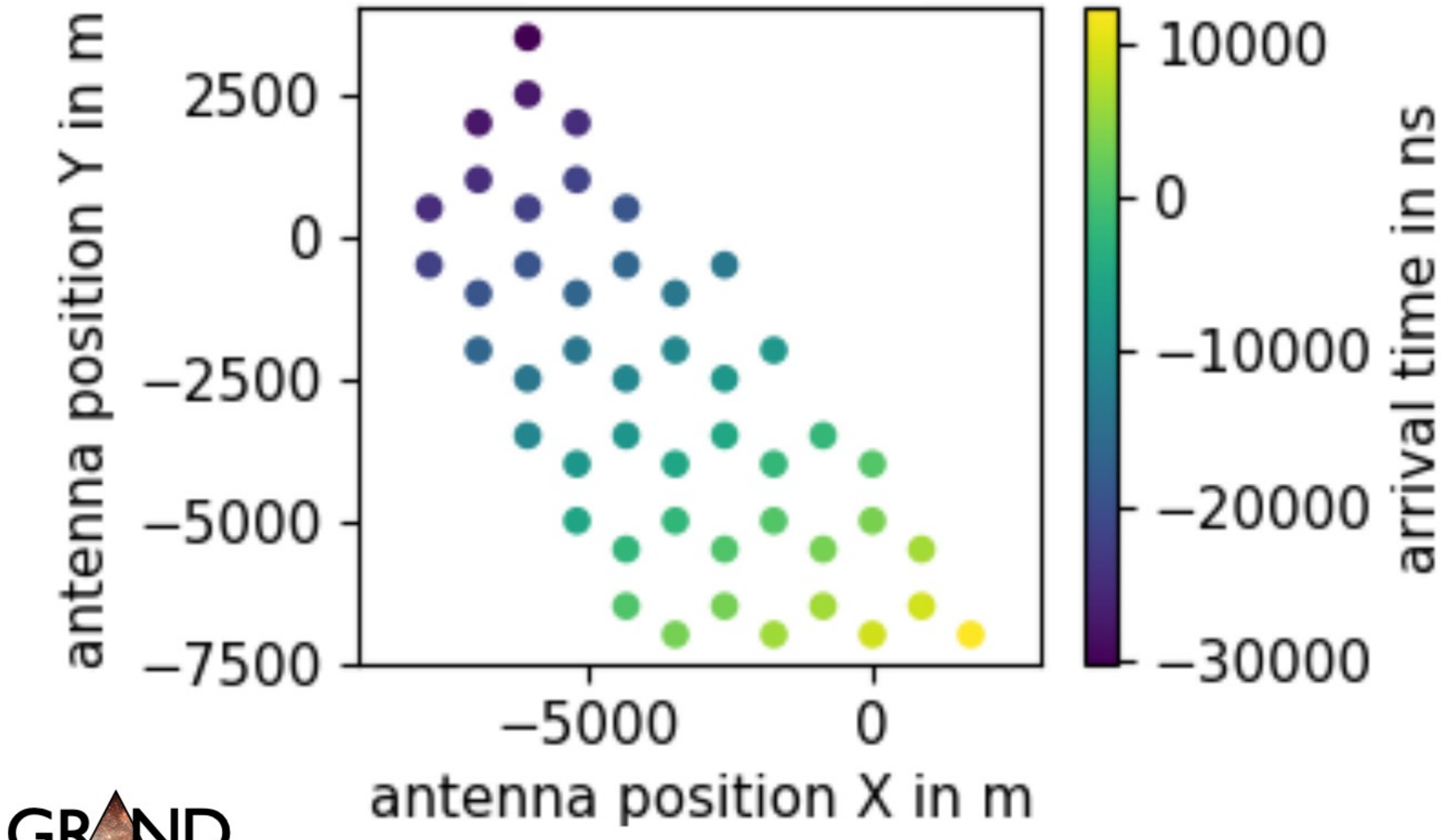
see talks by L. Gülzow & J. Köhler

GRAND Data Challenge 2: a complete realistic simulation library

Zenith=87.1°

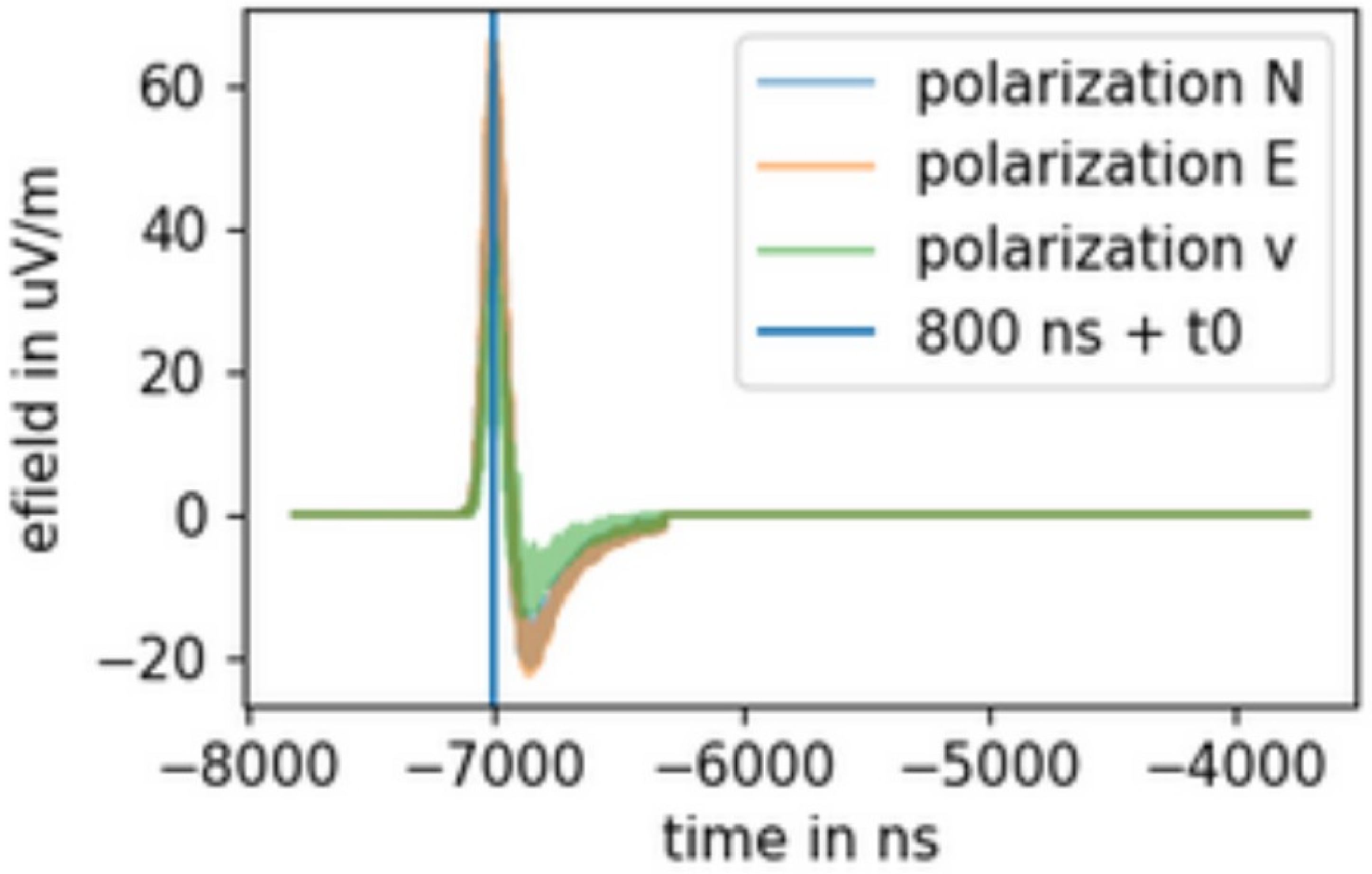


Zenith=77.3°

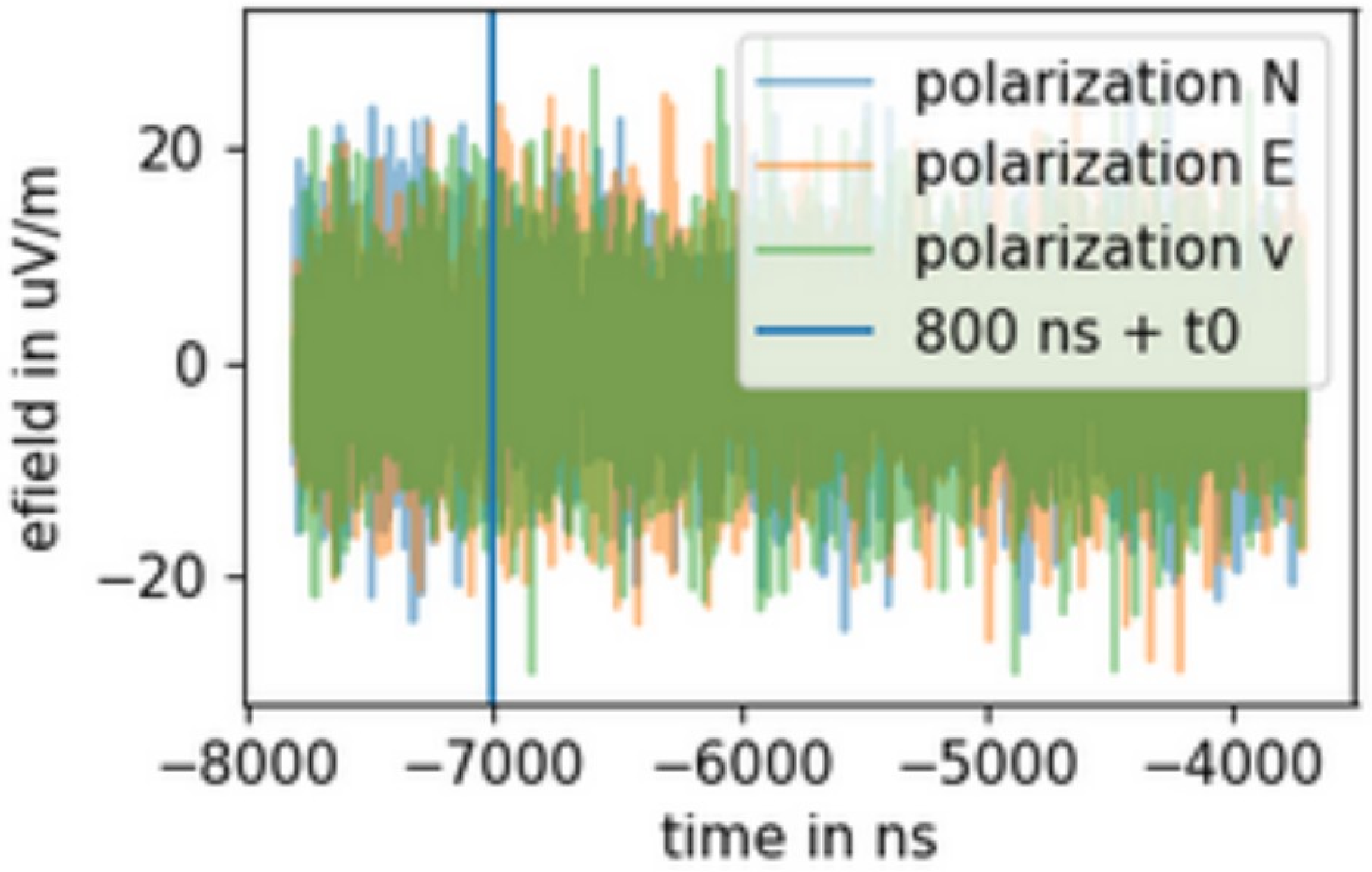


Note: *Only illuminated antennas are simulated*

Pure Signal



Pure Signal + Realistic Noise



DC2 cosmic ray simulation set:

- **ZHAireS and CoREAS** Simulations
- **Pure Signals**: without noise for ML applications
- **Pure Signals + Hardware-like jitter**

(this is going to be the “Data Challenge 2” blind data)

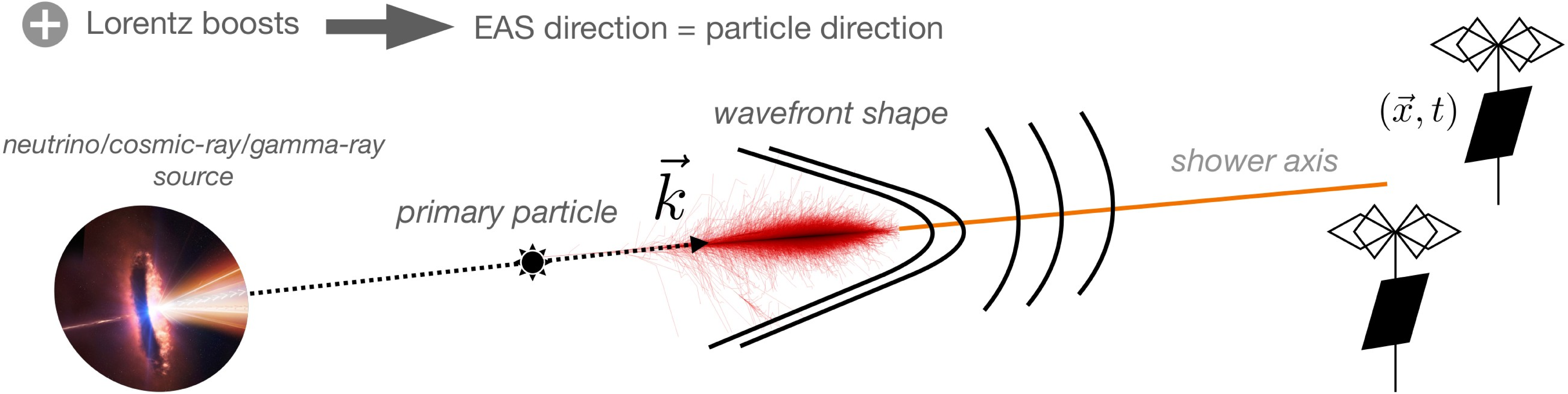
Included in simulations with jitter:

- 5 ns Gaussian smeared "trigger" time (GPS jitter)
- "Amplitude Calibration" Gaussian smeared 7.5%
- Galactic Noise

Study of the wavefront shape

The radio wavefront allows to reconstruct the EAS direction

⊕ Lorentz boosts ➡ EAS direction = particle direction



Credit: Valentin Decoene

Study of the wavefront shape

The radio wavefront allows to reconstruct the EAS direction

➕ Lorentz boosts → EAS direction = particle direction

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

see talk by Kumiko Kotera

Giant Radio Array for Neutrino Detection

Credit: Valentin Decoene

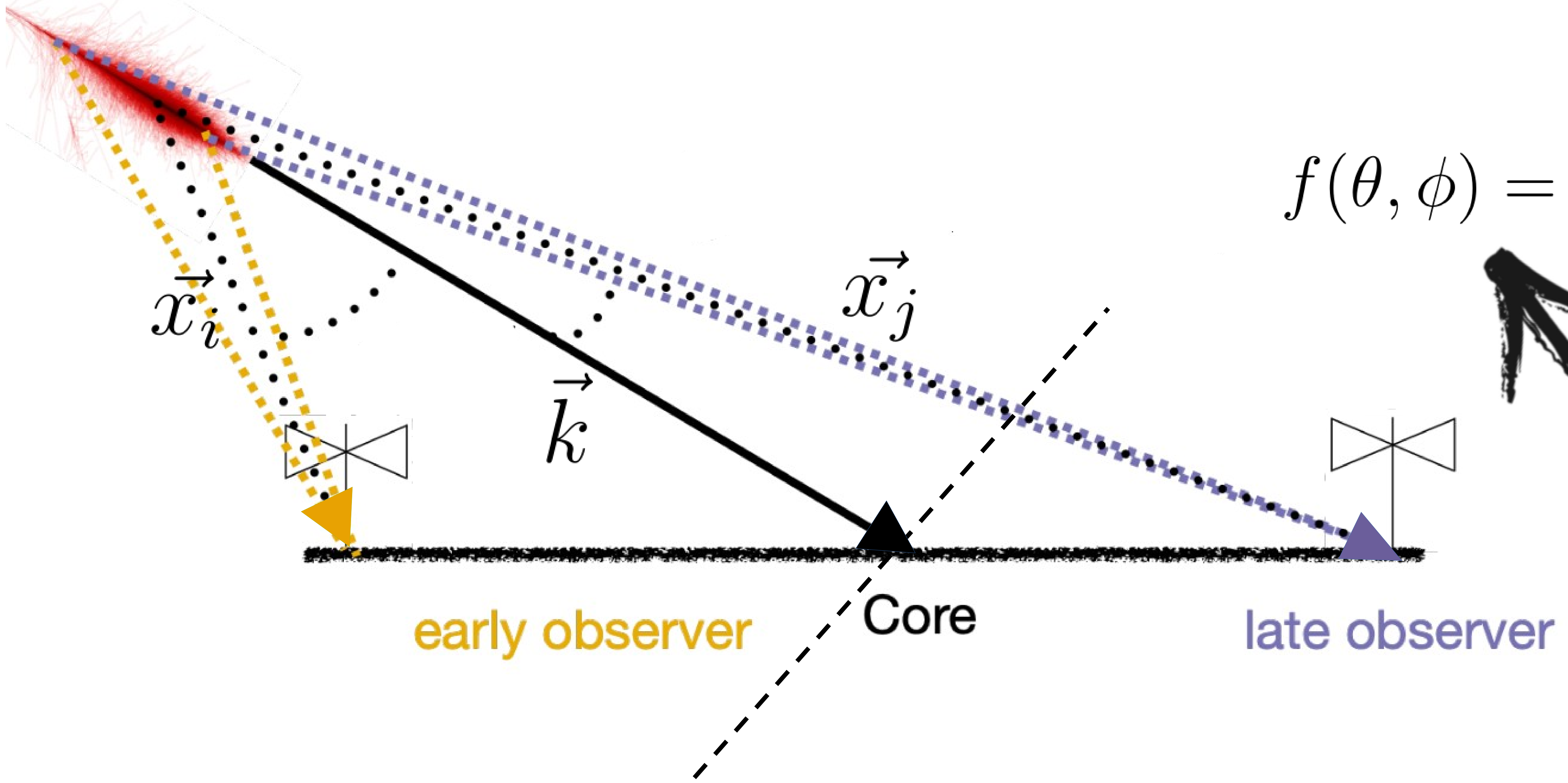
EAS Reconstruction Procedure

Giant Radio Array for Neutrino Detection

EAS Reconstruction Procedure

1) The plane wave reconstruction

The procedure relies on the comparison of the **relative trigger times** from one antenna to another



Decoene+(2021)

$$f(\theta,\phi) = \sum_{i,j}^{N_{\text{antenna}}} \left[\frac{c}{n}(t_i - t_j) - \vec{k}(\theta,\phi)\cdot(\vec{x}_i - \vec{x}_i) \right]^2$$

Minimize residual differences

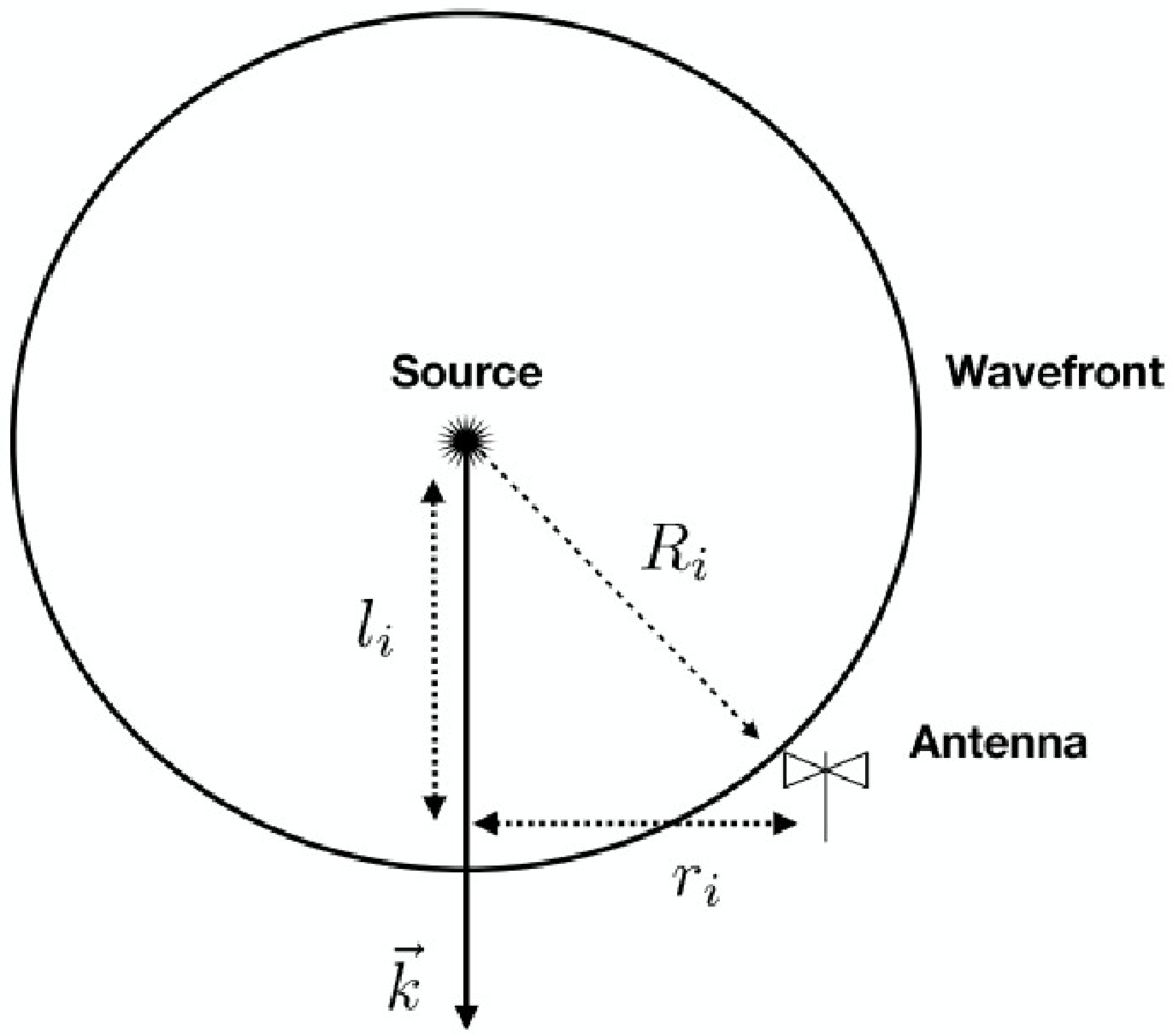
Reduces the parameter space from all the directions down to a cone of a few square degrees

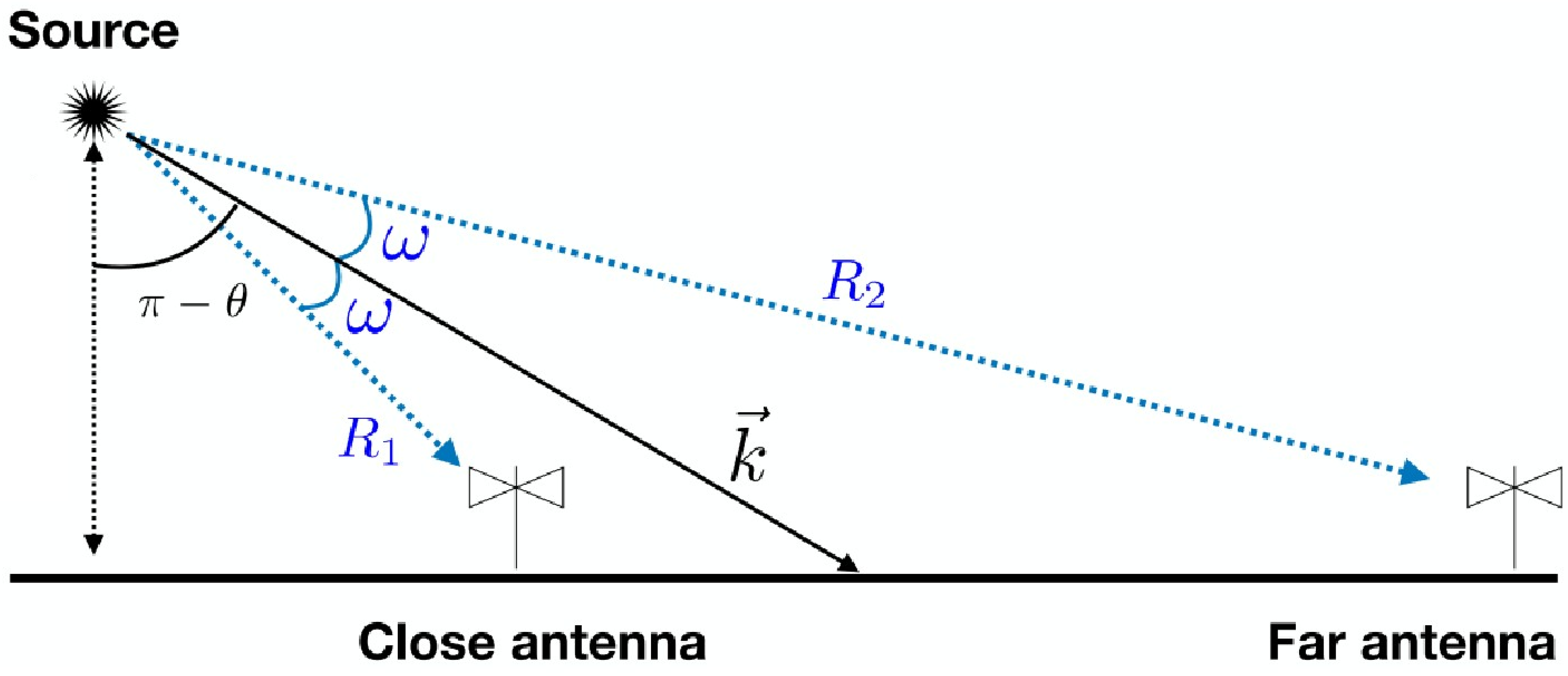
$$\theta_{\text{true}} \in [\theta_{\text{plan}} - 2^\circ, \theta_{\text{plan}} + 2^\circ] \qquad \phi_{\text{true}} \in [\phi_{\text{plan}} - 1^\circ, \phi_{\text{plan}} + 1^\circ]$$

EAS Reconstruction Procedure

2) Spherical wave reconstruction

Determines the best position of the point-source through the minimization of $f(\theta, \phi, \rho, t_{\mathrm{source}})$





Decoene (2021)

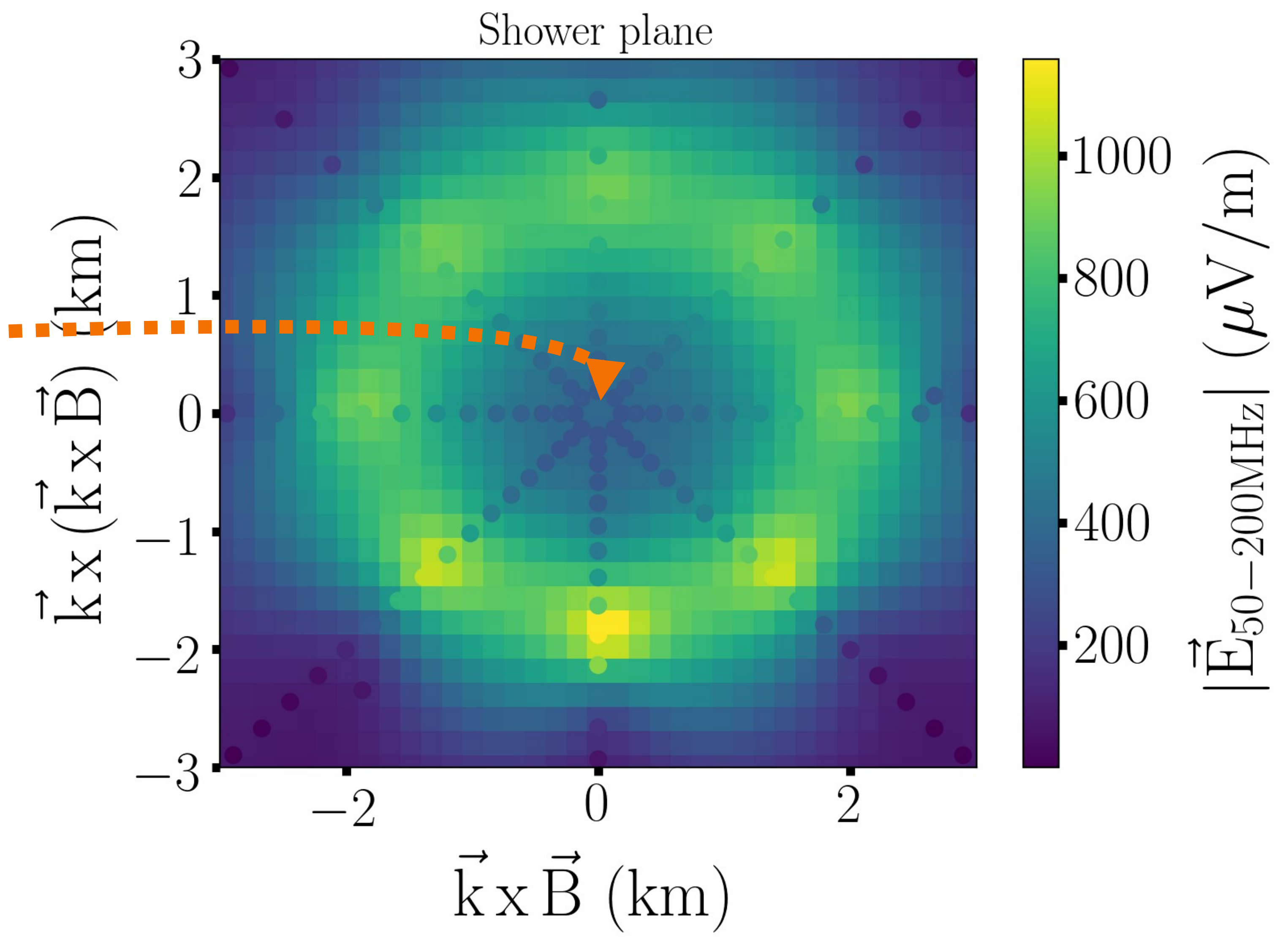
$$f\left(\theta, \phi, \rho, t_{\mathrm{source}}\right)=\sum_{i}^{N_{\mathrm{antenna}}}\left(\frac{c}{n_i}\left(t_i-t_{\mathrm{source}}\right)\right.$$
$$\left.-\sqrt{\left(x_i-x_{\mathrm{source}}\right)^2+\left(y_i-y_{\mathrm{source}}\right)^2+\left(z_i-z_{\mathrm{source}}\right)^2}\right)^2$$

$$\begin{aligned}
x_{\mathrm{source}} &= \rho\cos(\phi)\sin(\theta),\\
y_{\mathrm{source}} &= \rho\sin(\phi)\sin(\theta),\\
z_{\mathrm{source}} &= \rho\cos(\theta),
\end{aligned}$$

EAS Reconstruction Procedure

3) Angular Distribution of the Signal

straightforward handle on the core position (hence direction!)
→ beaming effect + Cerenkov effect + asymmetry features (Geomagnetic/Askaryan emissions)



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

empirical model!

- Geomagnetic asymmetry $\boxed{f^{\mathrm{GeoM}}(\alpha, \eta, \mathcal{B}) = 1 + \mathcal{B} \sin(\alpha)^2 \cos(\eta)}$ → interplay between emission mechanisms → signal excess along the Lorentz force direction

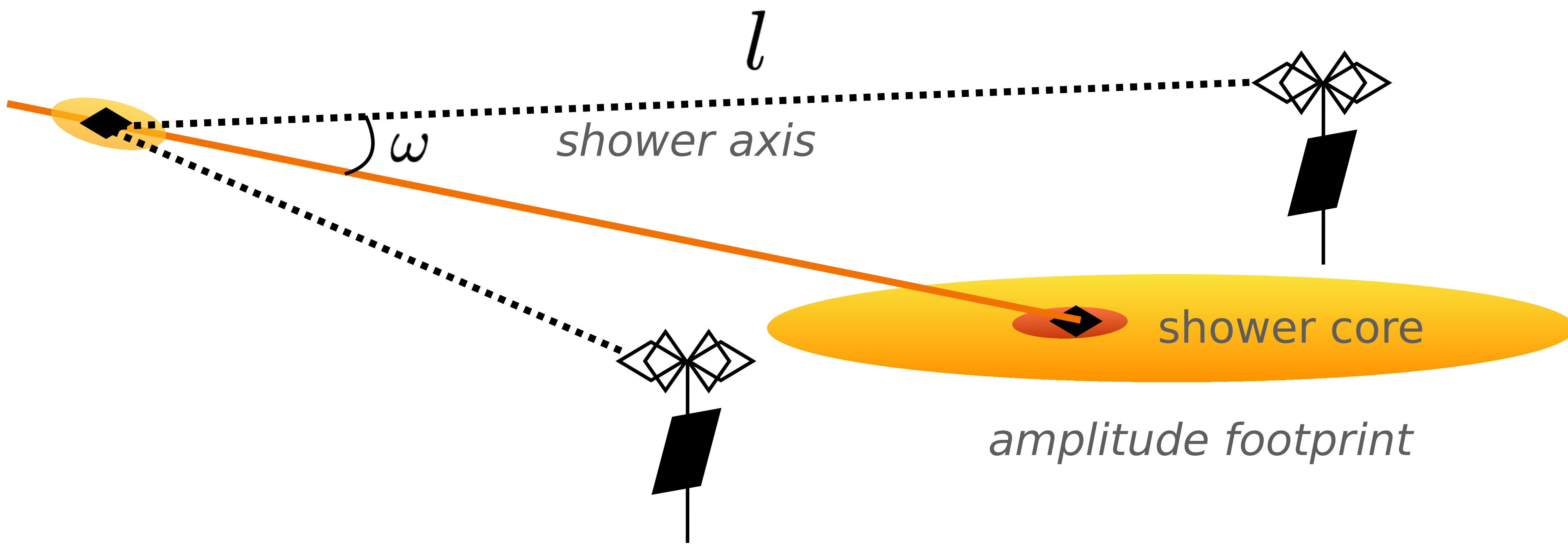
  α magnetic field inclination $\mathcal{B}$ geomagnetic strength η polarisation angle

- Early-late asymmetry $\boxed{\frac{\mathcal{A}}{l}}$ → energy dilution

- Cerenkov cone $\boxed{f^{\mathrm{Cerenkov}}(\omega, \delta\omega) = \frac{1}{1 + 4\left[\frac{(\tan(\omega)/\tan(\omega_C))^2 - 1}{\delta\omega}\right]^2}}$

→ geometrical Cerenkov effect description

→ ω_C



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

Credit: Valentin Decoene

Results I:

Plane Wave Reconstruction On Data Challenge 2 Simulations

EAS Direction Reconstruction on “Data Challenge 2” Simulations (Analytical solution)

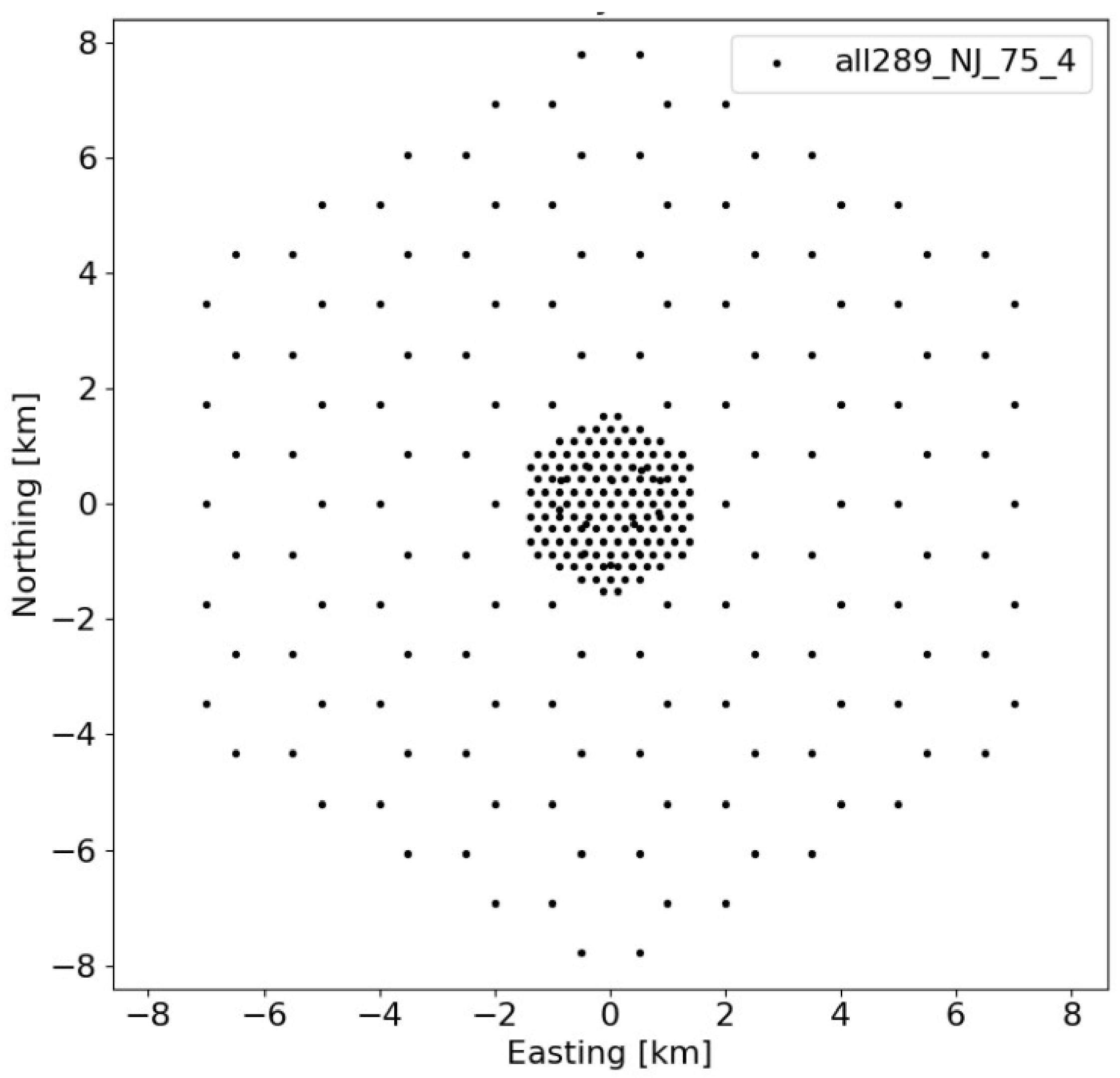
DC2 simulation set:

- **Simulated data including realistic noise**

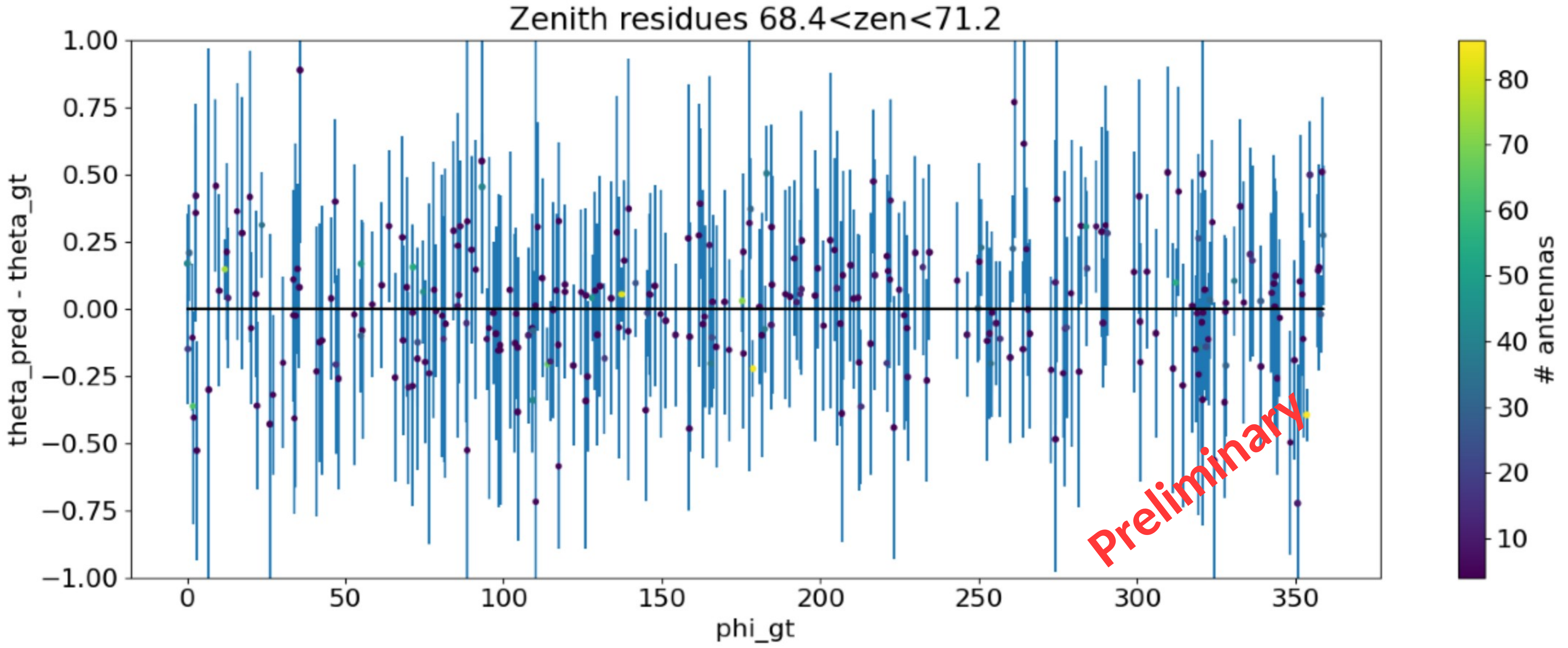
Processing:

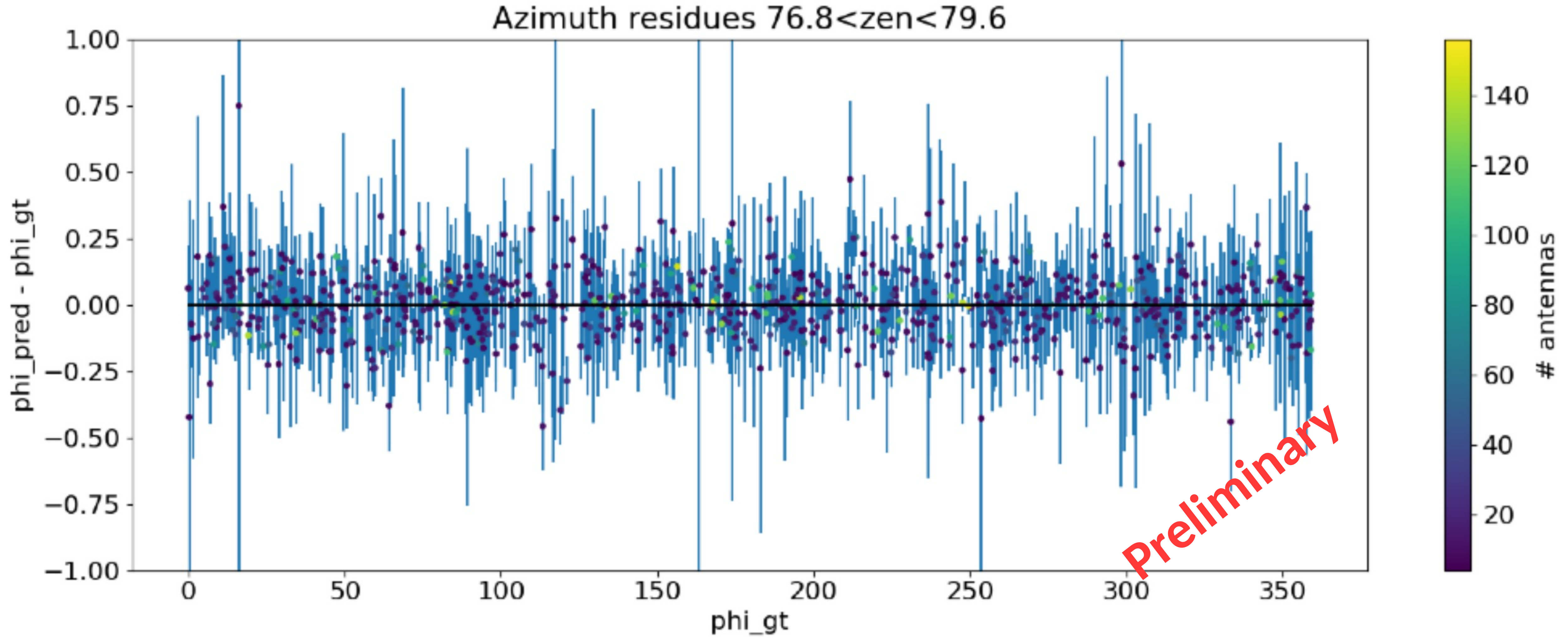
- Filter in the [50, 200] MHz frequency range
- Amplitude: Hilbert peak amplitude/Trigger time read from root files
- Quality cuts:
  - ➔Amplitude threshold = **110**
  - ➔Antenna threshold: **5 antennas**

All 289 antennas



Plane wave reconstruction



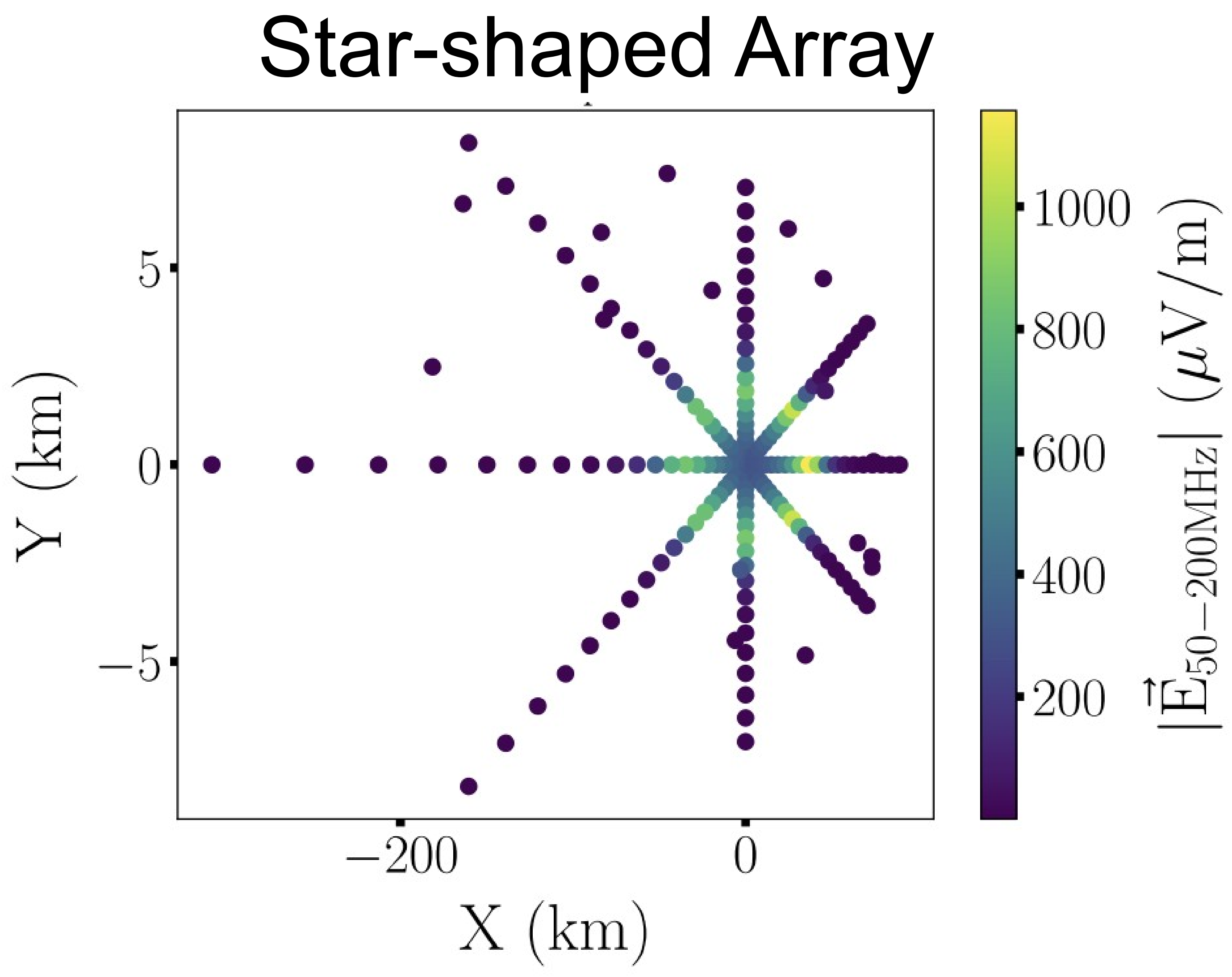


Results II:
Reconstruction on star-shaped simulations

Giant Radio Array for Neutrino Detection

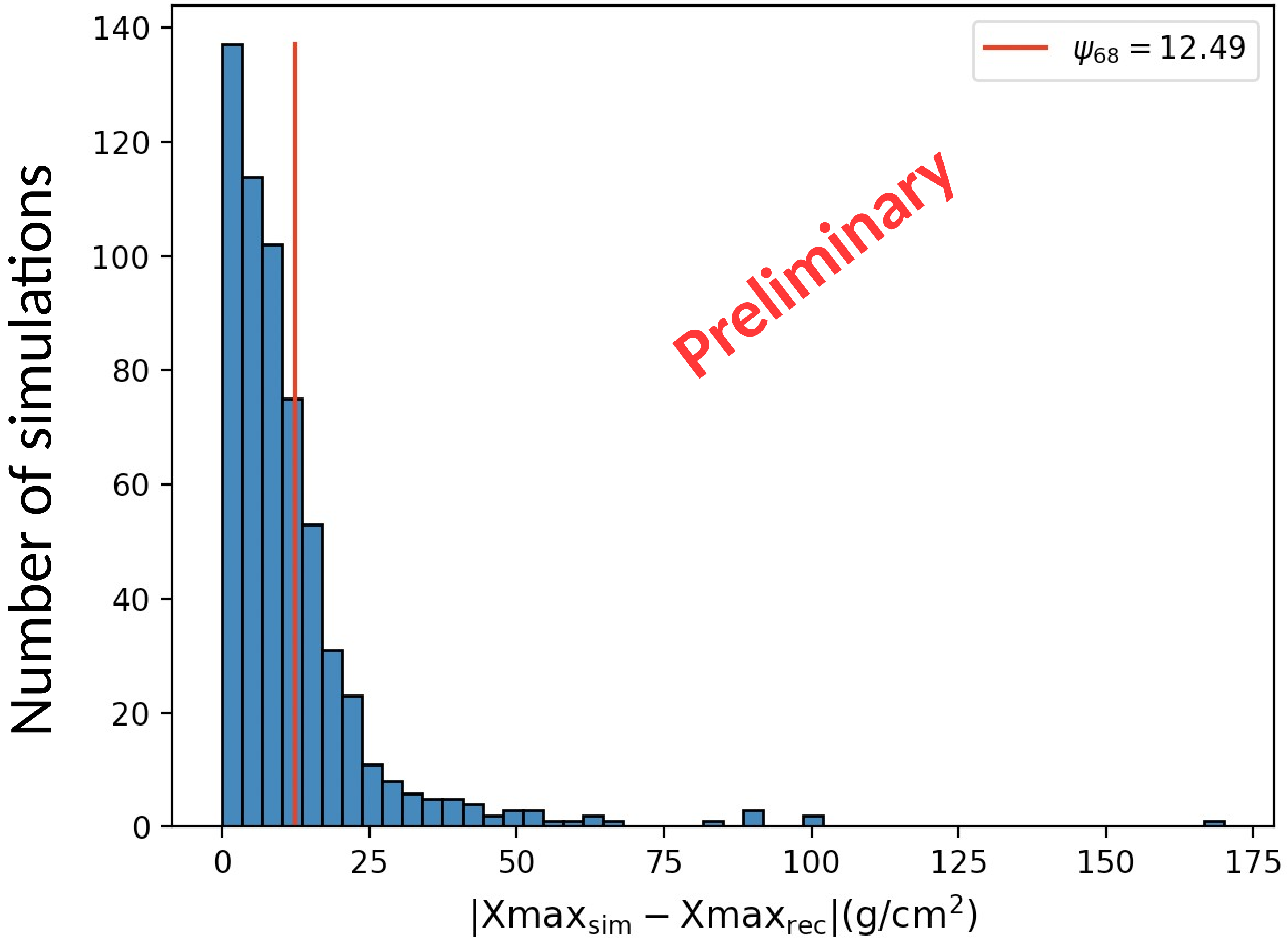
Performance on Star-shaped antenna layout

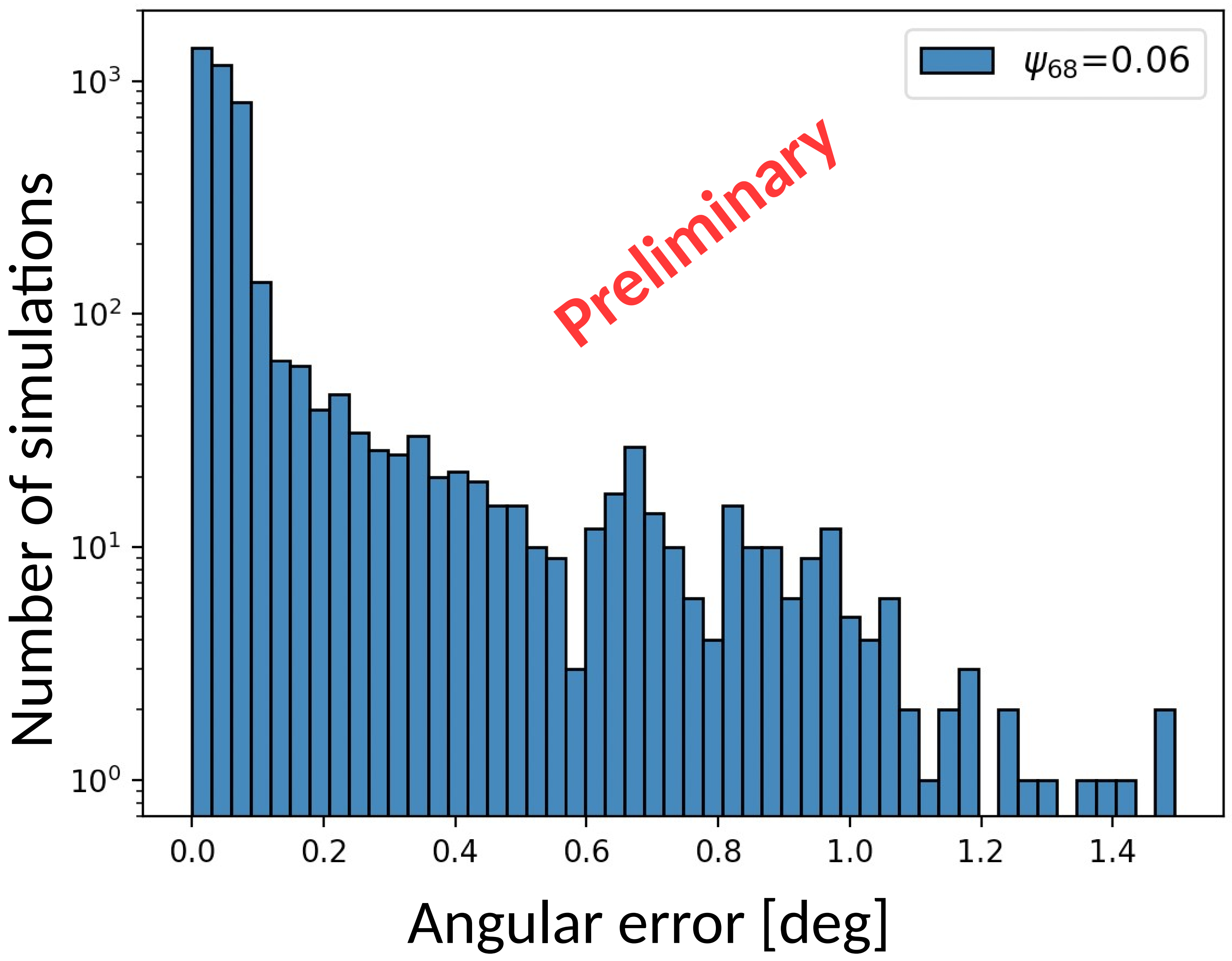
Decoene (2021)



EAS simulations without realistic noise.

Zenith=84.2°





Reconstruction of Xmax and direction of EAS on Star-shaped simulations:

- Xmax reconstruction resolution around 10g/cm^2 for very inclined showers (and 5g/cm^2 for vertical showers)
- Angular reconstruction has a resolution of about ~0.1°

Follows the LOFAR methodology introduced in Buitink et al, 2014

Results III:
Angular Distribution Function

On toy GP300 simulations

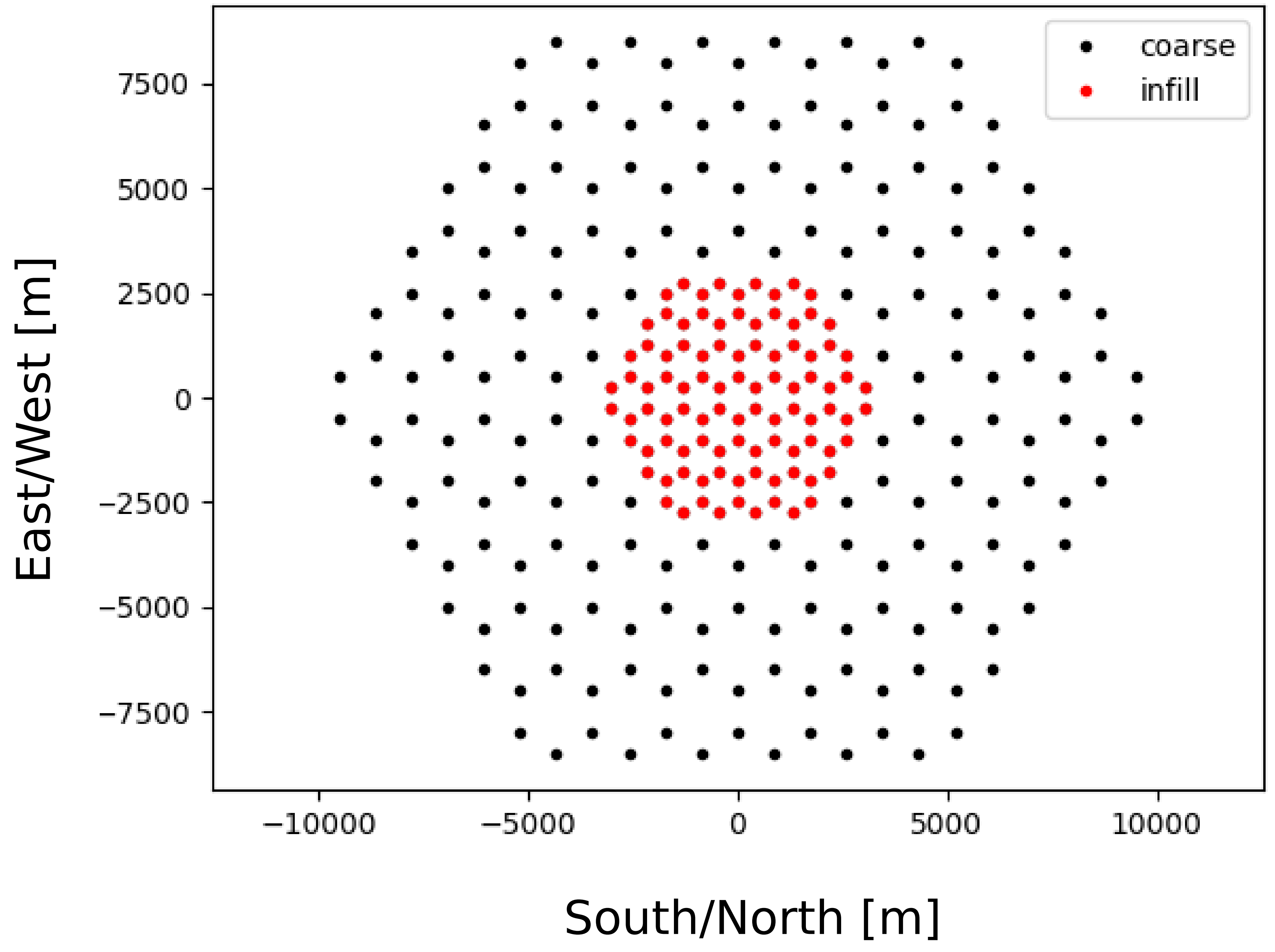
Description of the toy GP300 EAS simulations

ZHAireS Simulations:

- Primaries: Proton, Iron, Gamma
- Energy: 0.251, 0.631, 1.58, 3.98 EeV
- Zenith: [63°,87°]

Toy GP300 layout with infill

- Shower core always contained in the layout
- Raw electric field data without galactic noise
- Random gaussian error = 5 ns on trigger times (GPS)
- Random gaussian error of = 10% on signal amplitudes (calibration)



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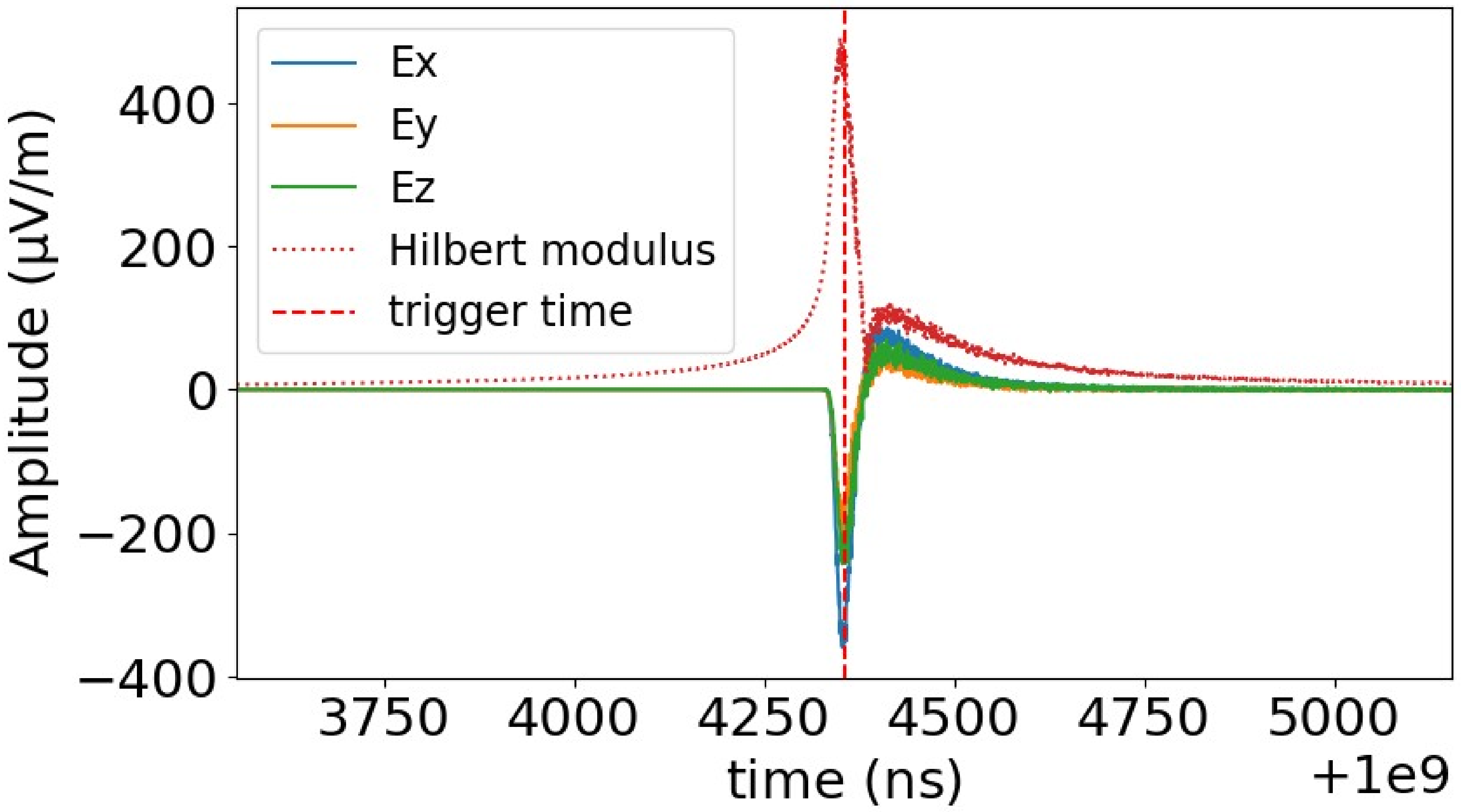


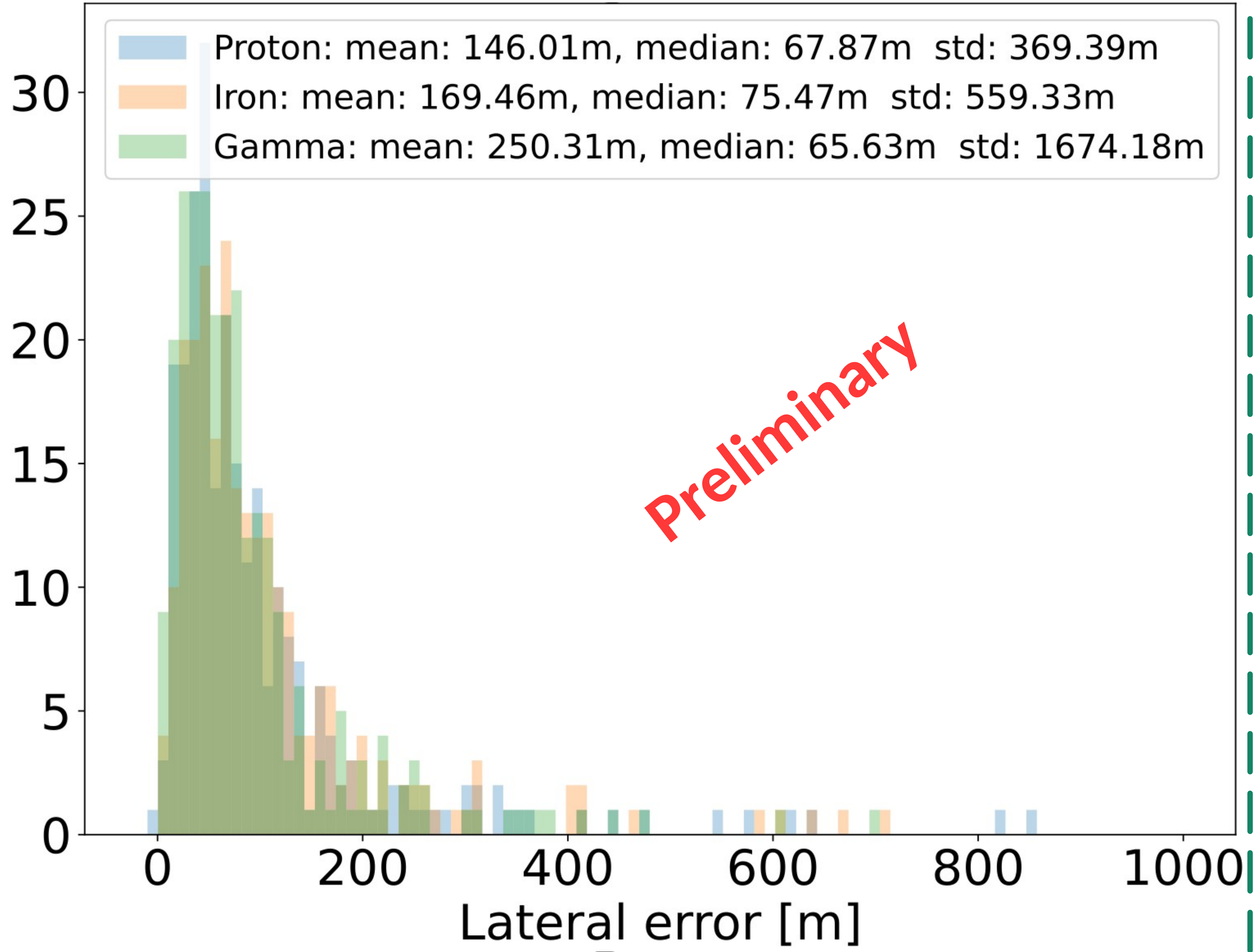
Credit: Marion Guelfand

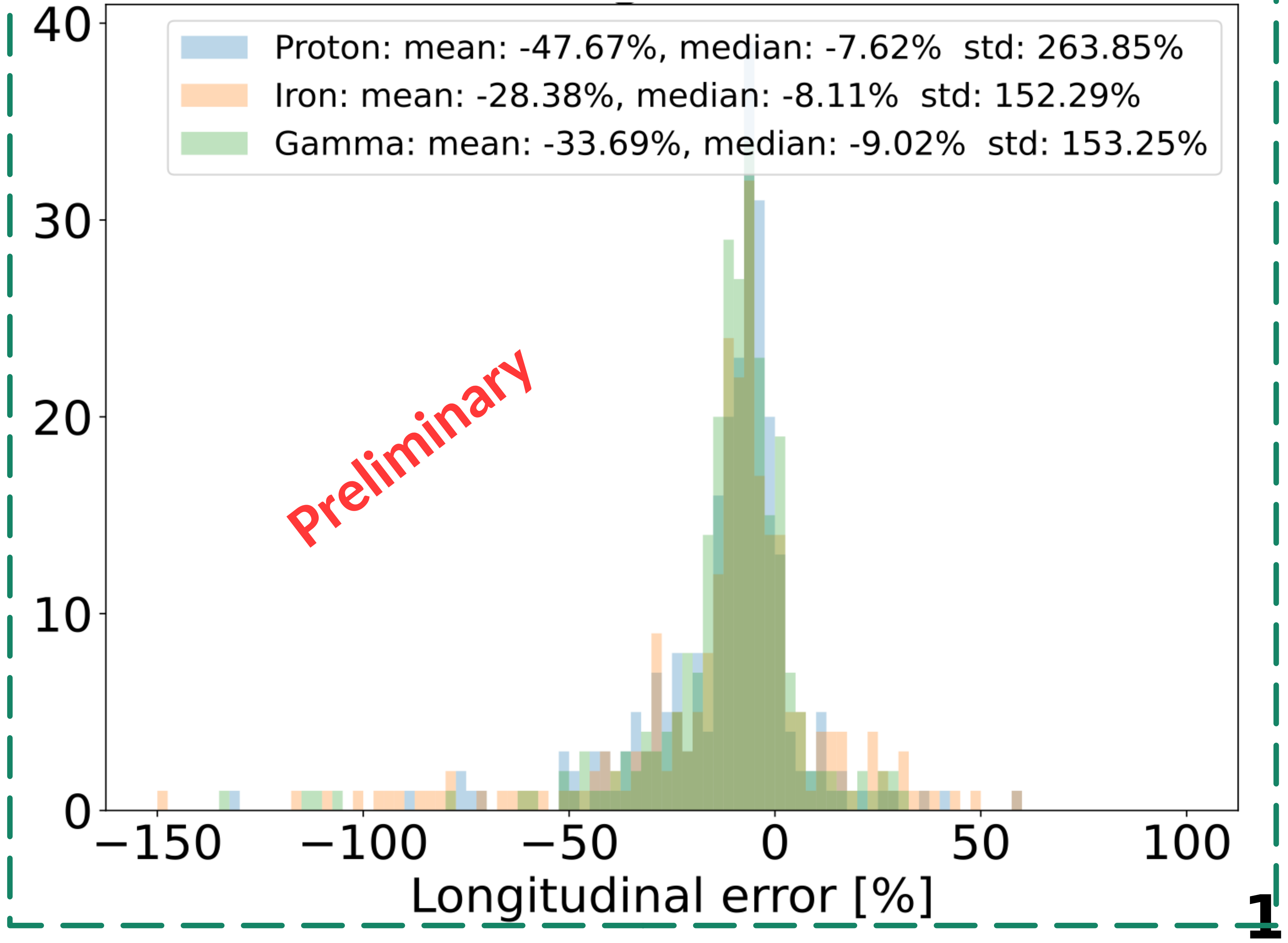
EAS Direction Reconstruction on toy GP300 Simulations

Main Results:

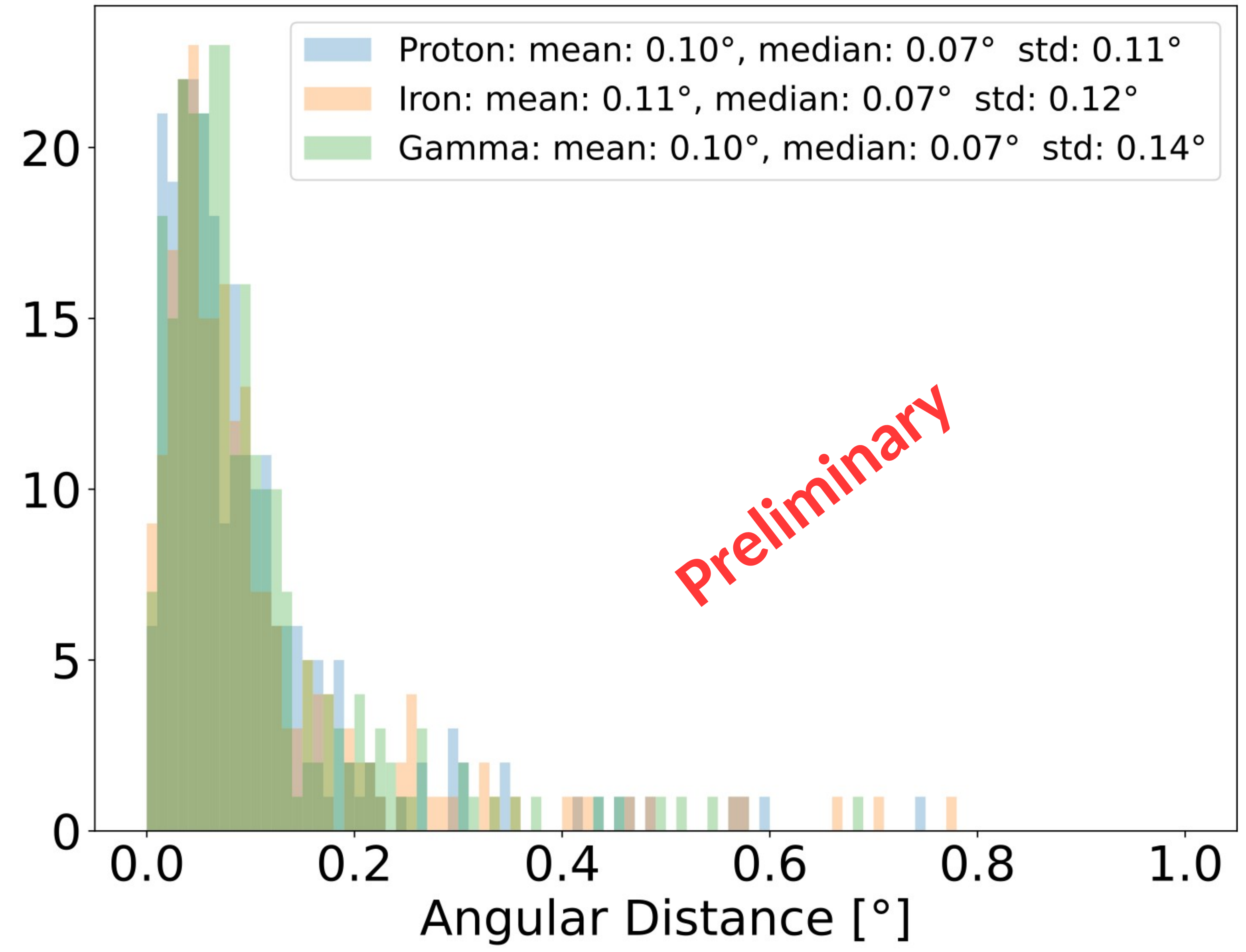
- Reconstruction on GP300 ZHAireS simulations with experimental uncertainties
- Excellent angular reconstruction: approx. ~0.1°
- ADF approx. matches angle and amplitude peak for zenith angles greater than ~70°

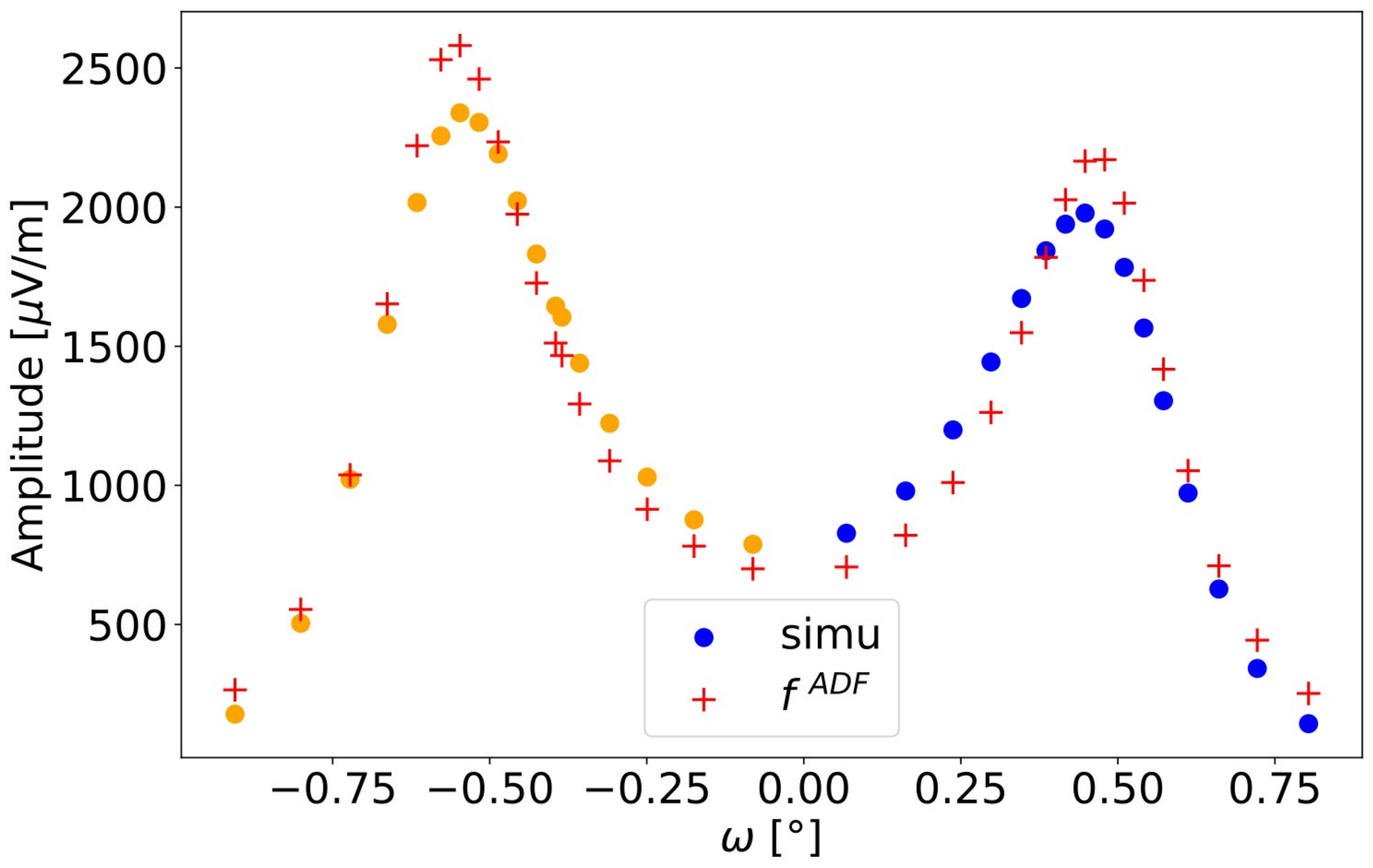
Spherical wave reconstruction

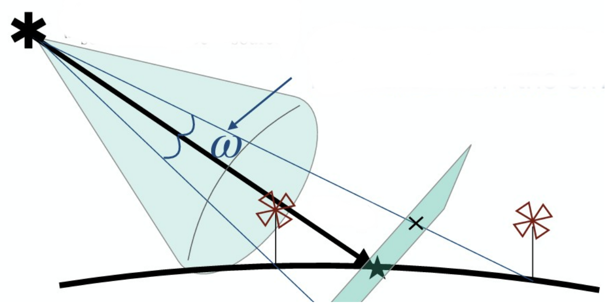




ADF reconstruction





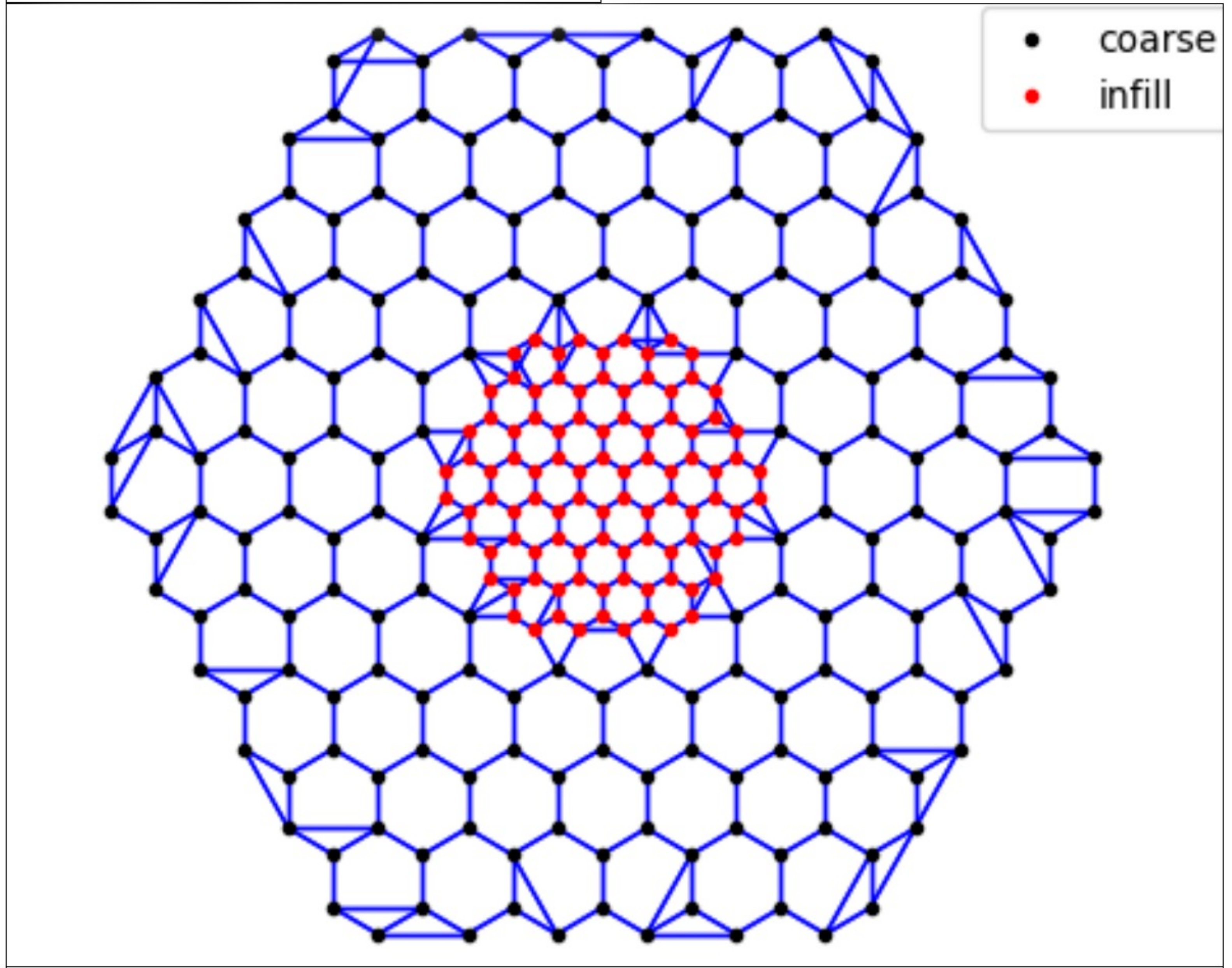


Results IV:
EAS Reconstruction
using Machine Learning methods

Giant Radio Array for Neutrino Detection

Reconstruction of EAS with Graph Neural Networks (GNN)

Graph generation



- Each antenna is linked to at least its three neighbors.
- Some antennas have more neighbors due to being neighbors of neighbors.

Training data:

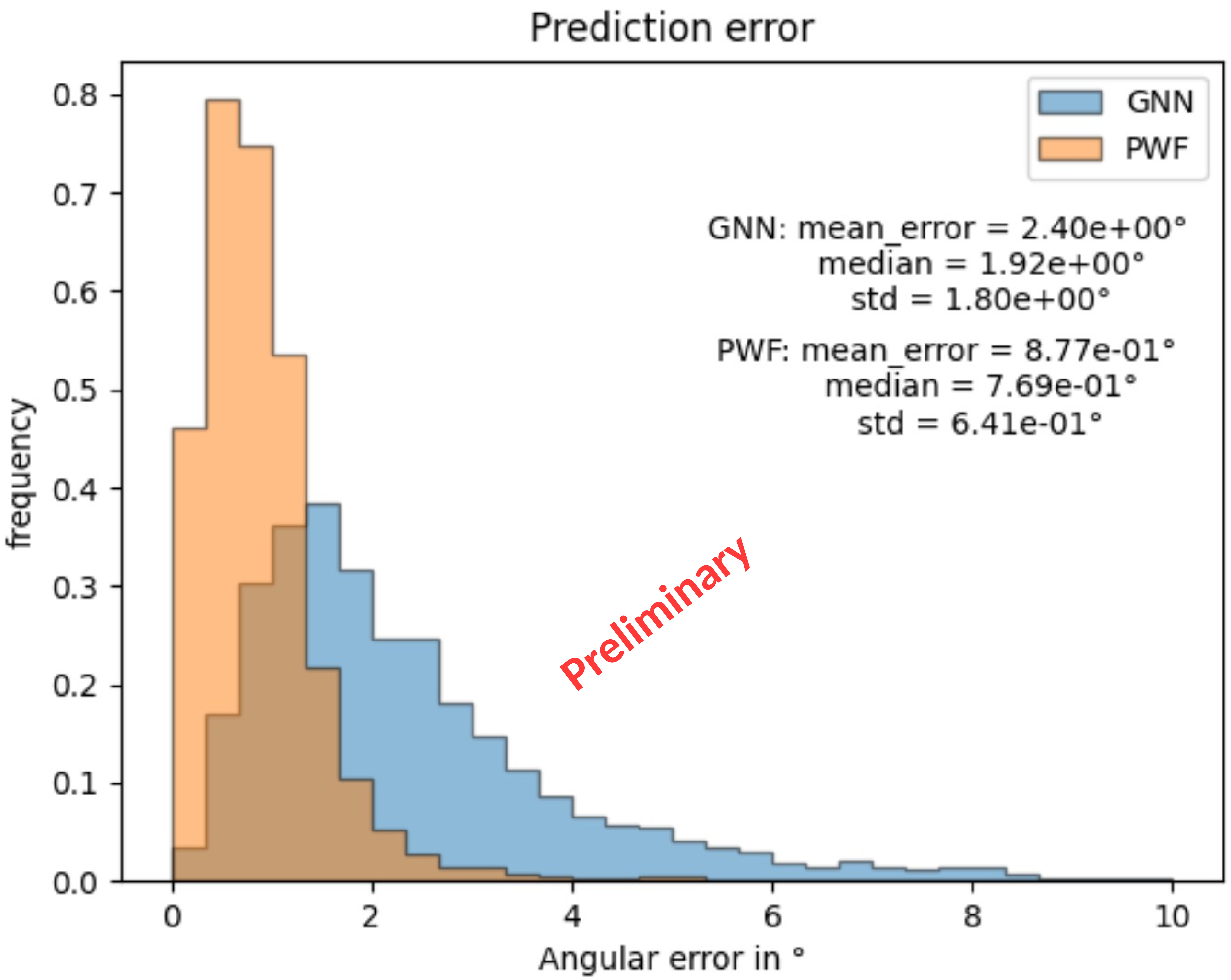
◆ Use only antennas with E-field> 30 μ V/m

◆ Keep only events with >7 triggered antennas

◆ Features:

→Peak time and amplitude

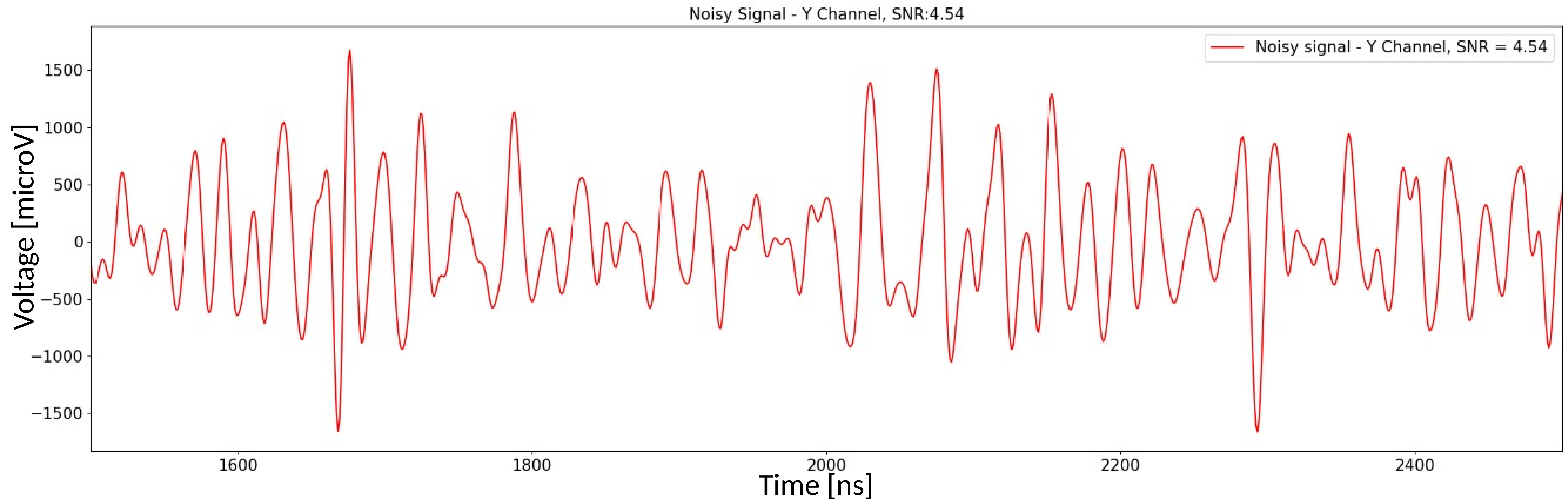
→Antenna position

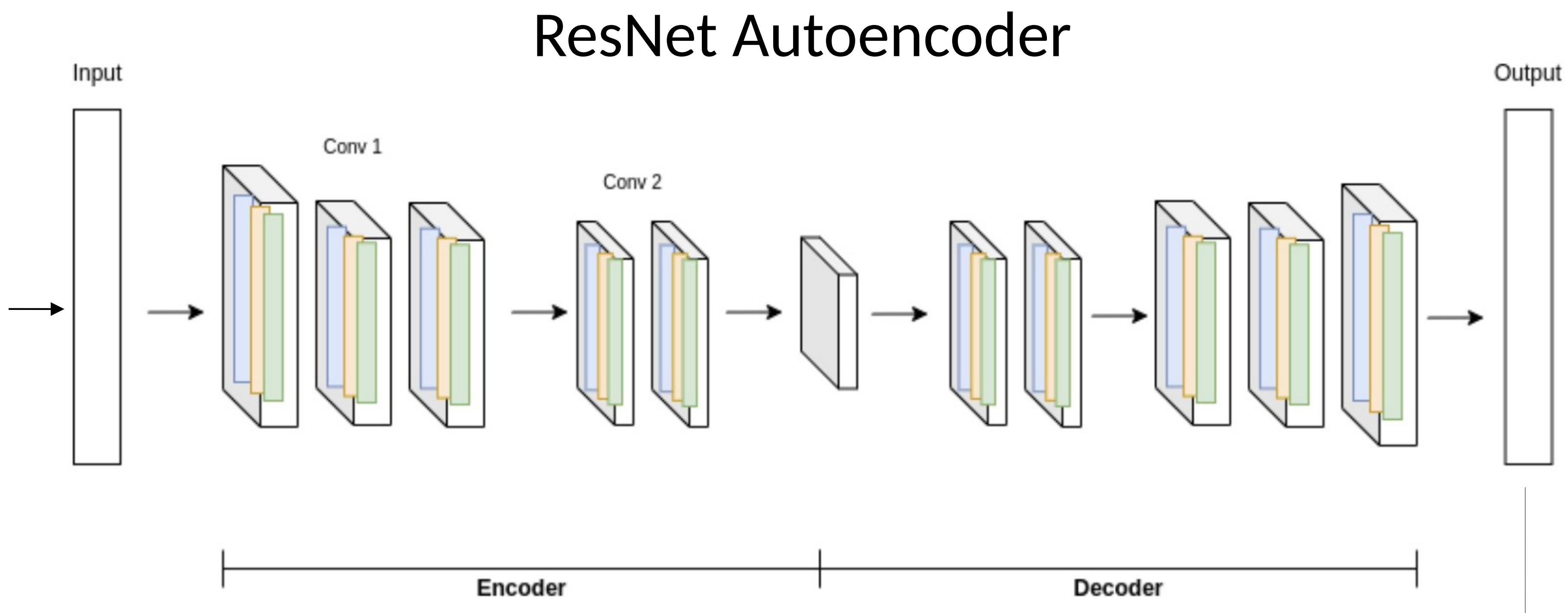


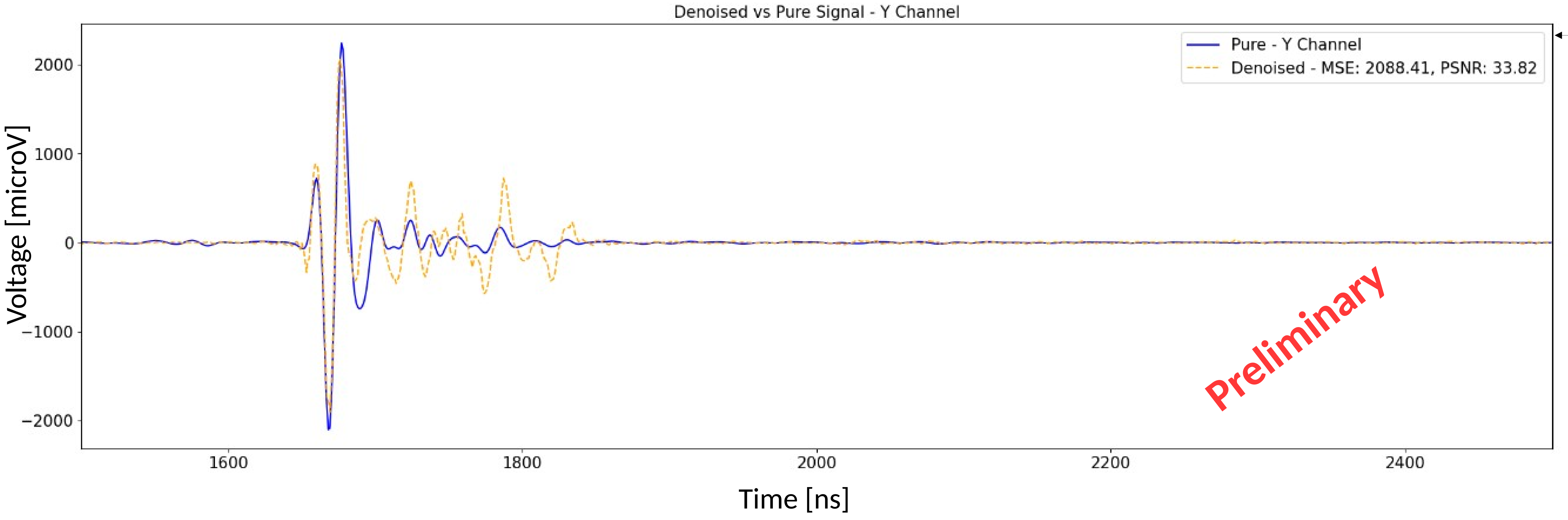
Results V:
Signal Denoising using an Autoencoder

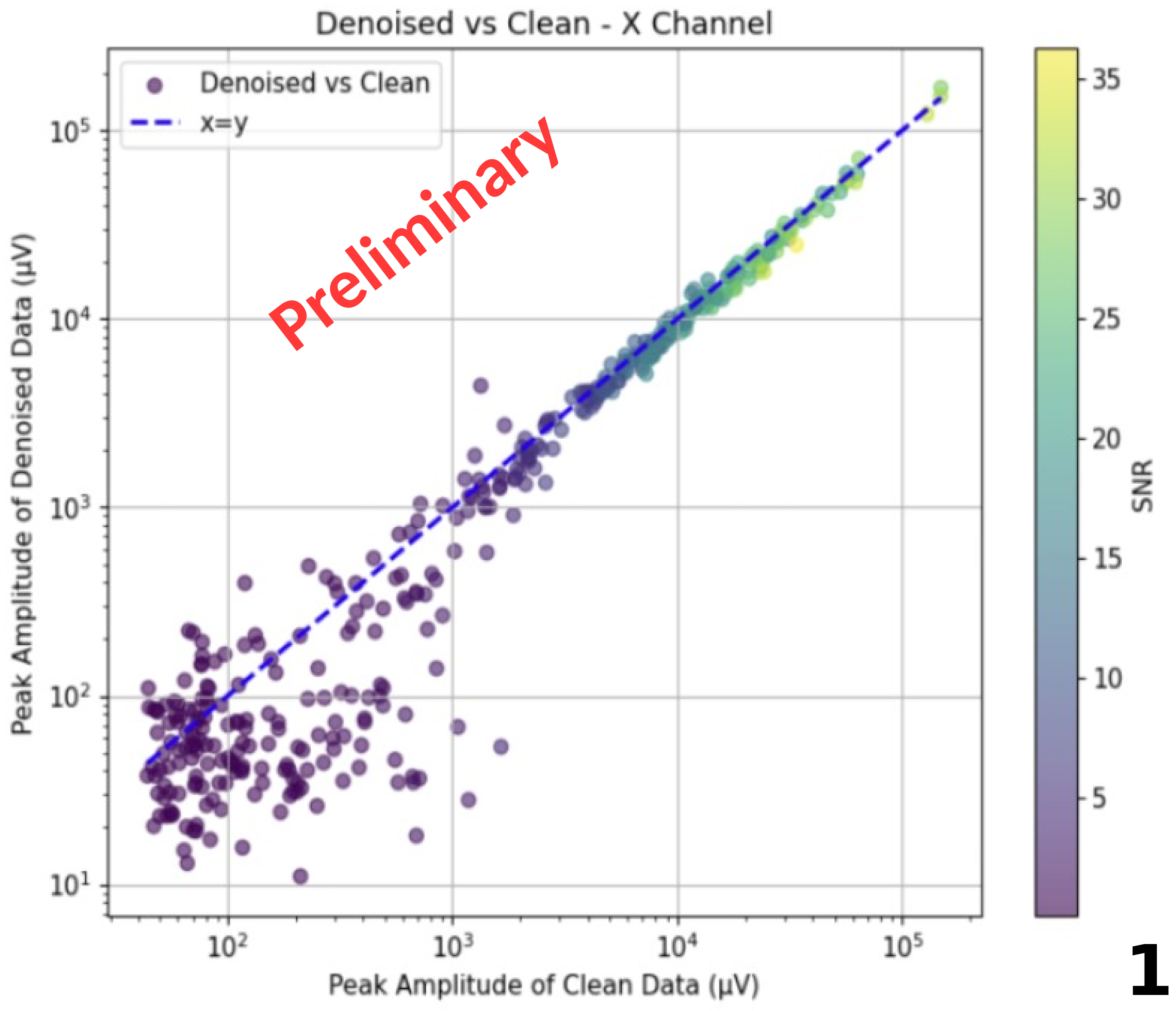
Giant Radio Array for Neutrino Detection

Voltage Denoising with a ResNet Autoendoer




ResNet Autoencoder





Conclusions

✓ Developed and tested direction reconstruction on the new *Data Challenge 2* simulations with and without realistic noise. Preliminary results are promising.

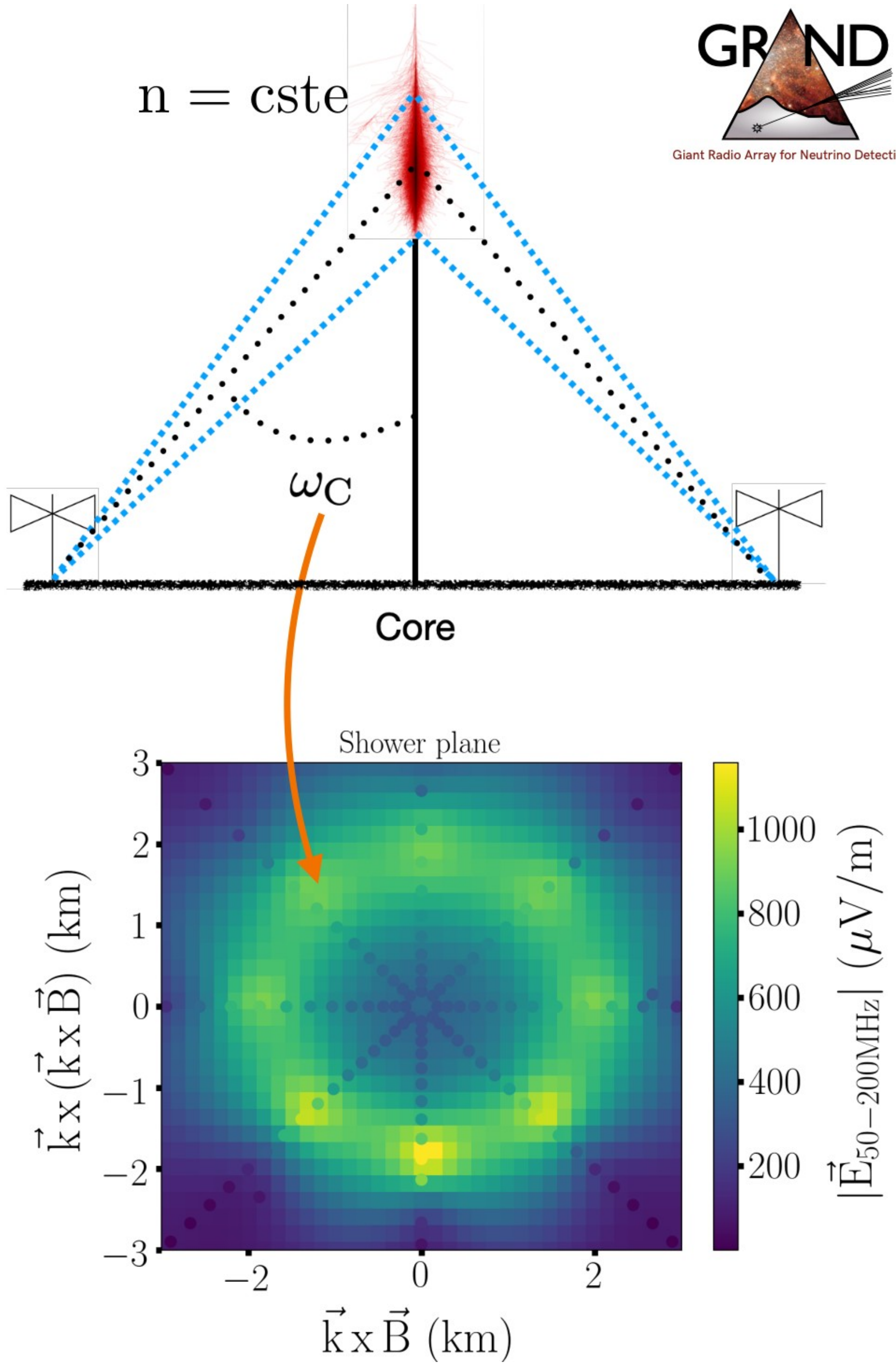
✓ Fitted an empirical Angular Distribution Function (ADF) on various sets of simulations. Early results indicate that the ADF method has the potential to increase the reconstruction sensitivity.

✓ Preliminary results using machine learning methods achieve a sensitivity close to standard methods. Further studies are ongoing to enhance its capabilities.

Backup Slides

The Angular Distribution Function (ADF)

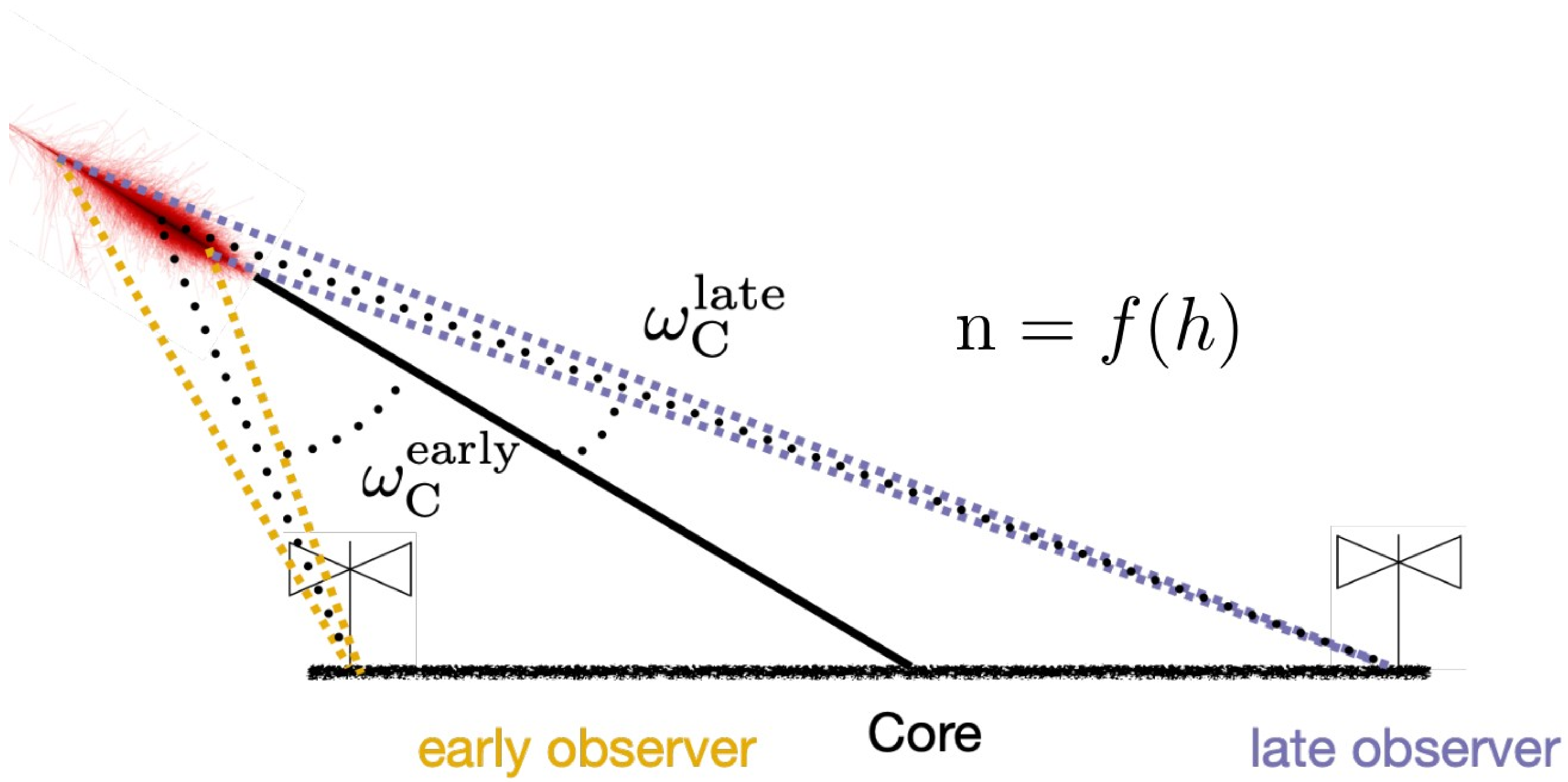
Cerenkov Asymmetry

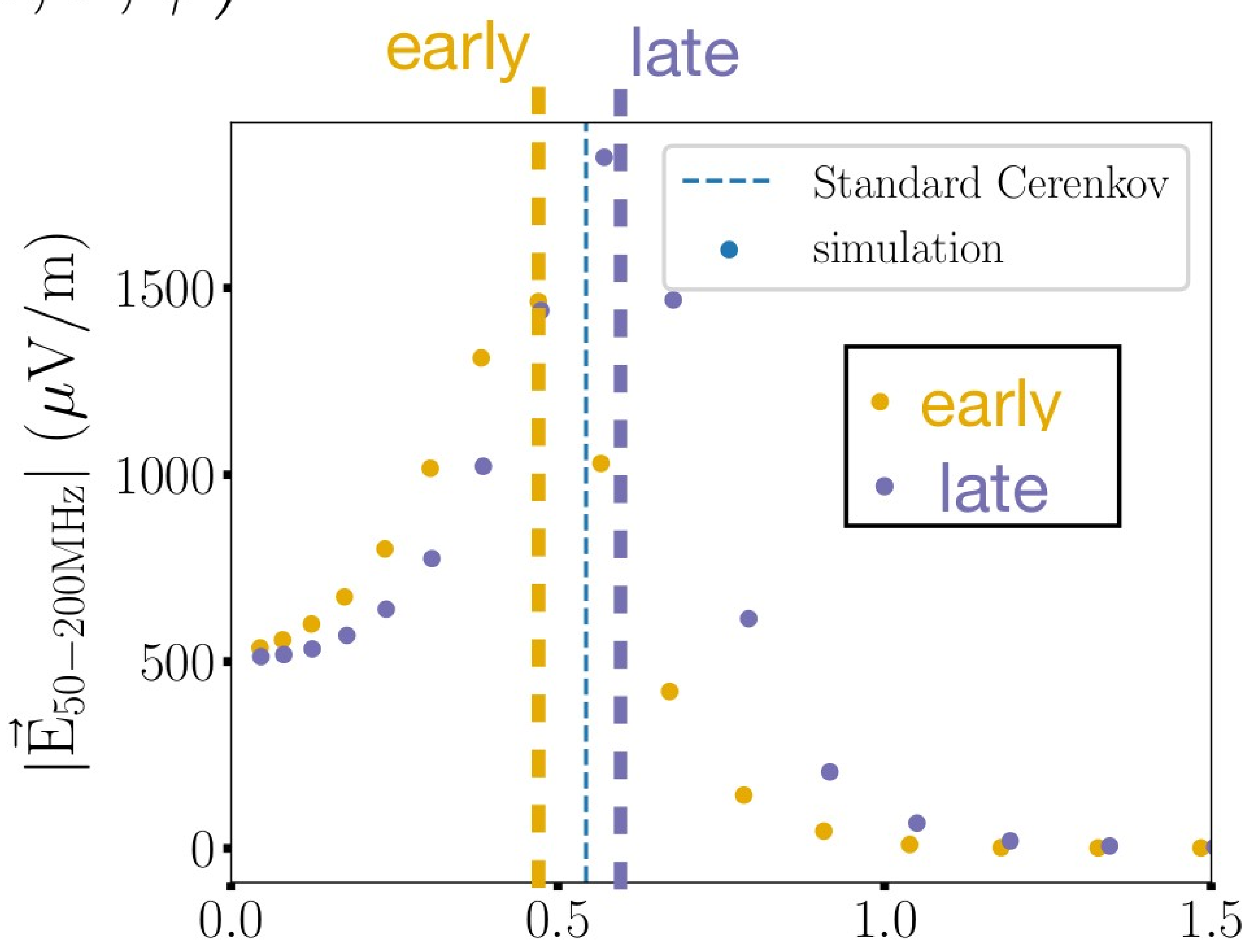


Cerenkov cone:

- 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)

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





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

Credit: Valentin Decoene