Reconstruction of GP80 cosmic ray candidates with ADF

Marion Guelfand - Pauline Fritsch - Olivier Martineau

Analysis Session - Warsaw collaboration meeting - 03/06/2025

Reconstruction Procedure: PWF - SWF - ADF

Based on Valentin Decoene's Thesis
See presentation Analysis extended meeting December 2024

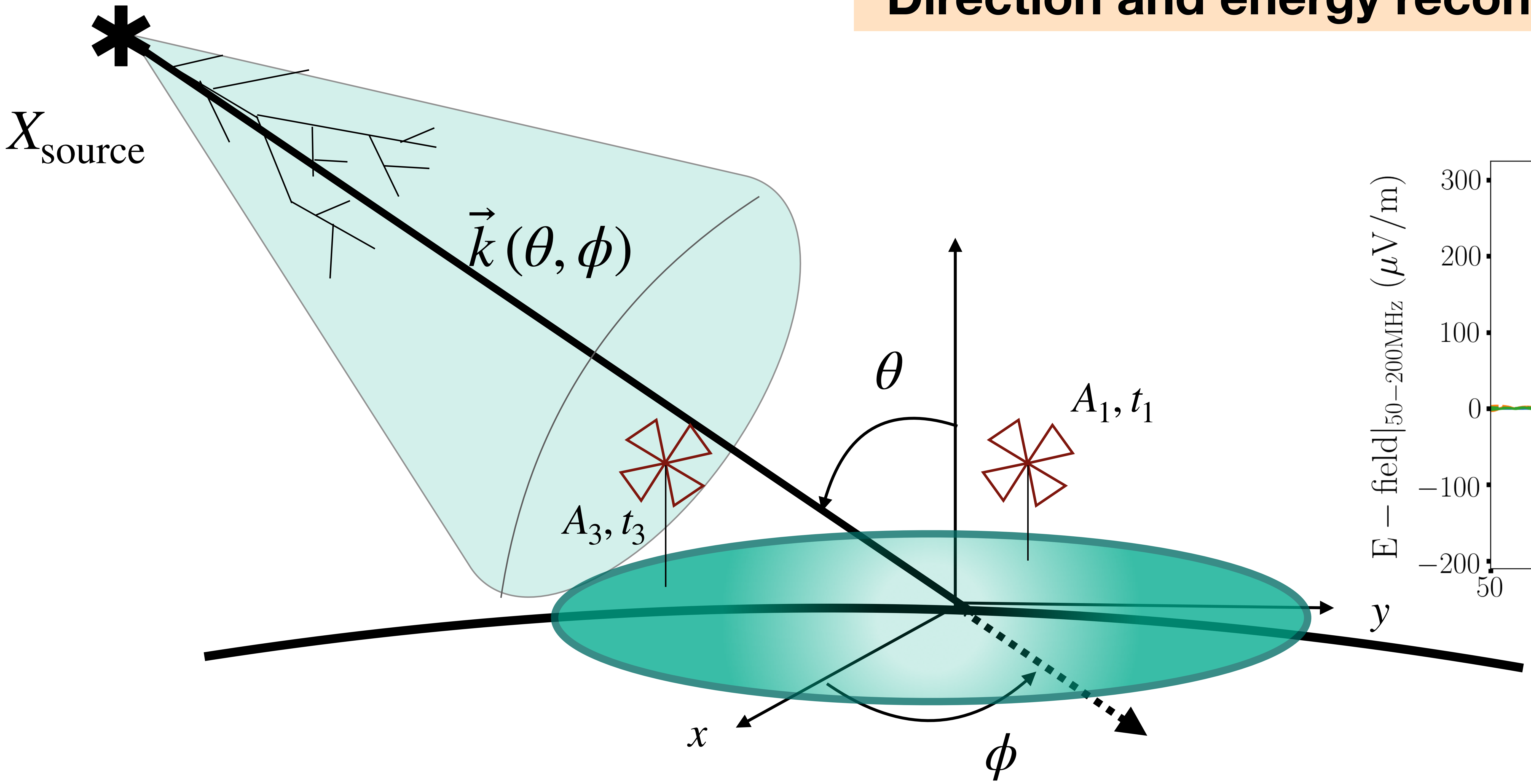
Determine the emission point:
2) Spherical wave function (SWF) to reconstruct X_{source} using trigger times (corresponding time of max amplitude of Hilbert enveloppe)

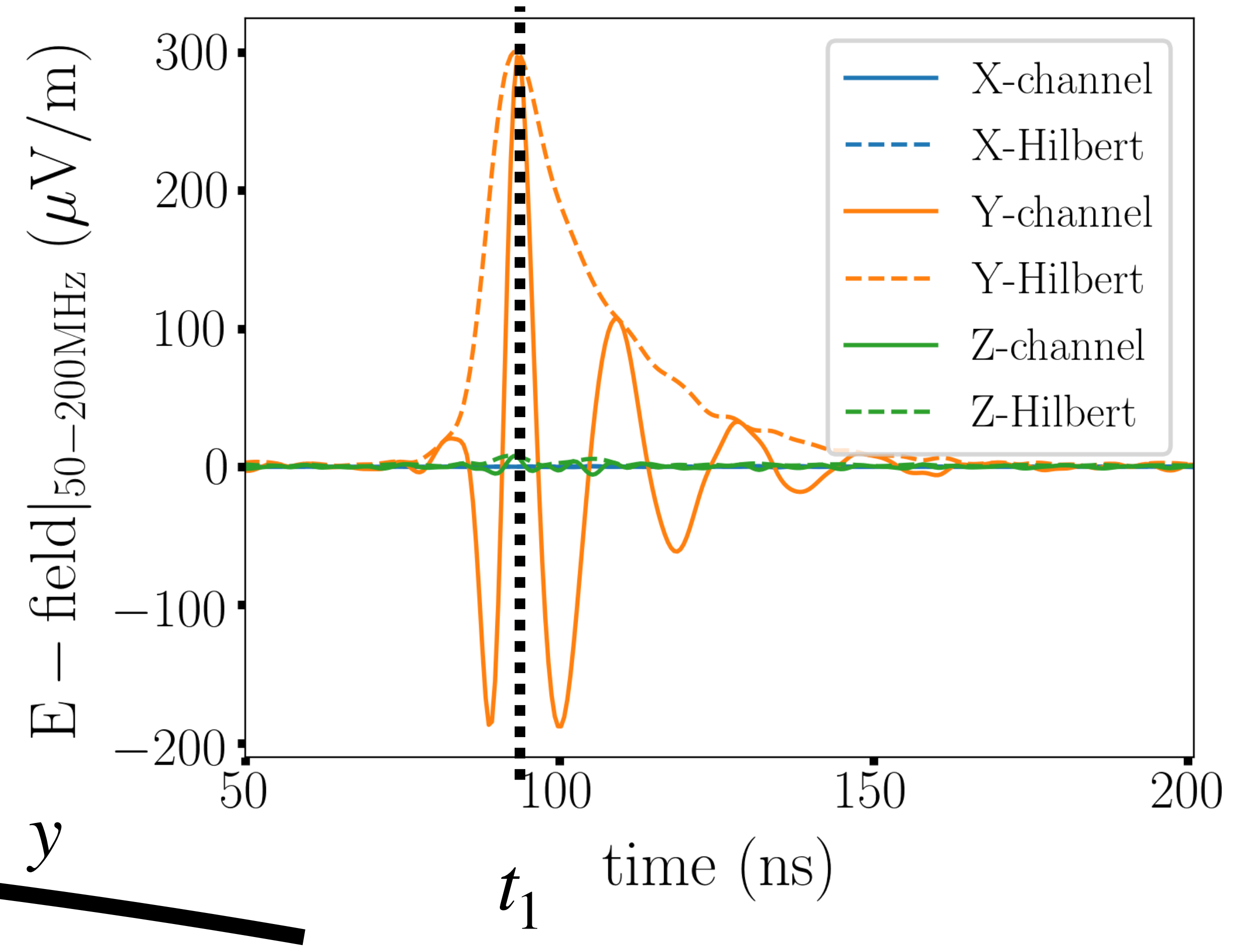
Determine a vector $\mathbf{k}$ which intersects emission point:
1) Plane wave function (PWF): quickly reduced parameter space (θ, ϕ) using trigger times (analytical, with error calc.)
3) Angular Distribution Function (ADF) using peak amplitudes: Fitting the signal amplitude on ground with **ADF model (empirical and Physics informed)**

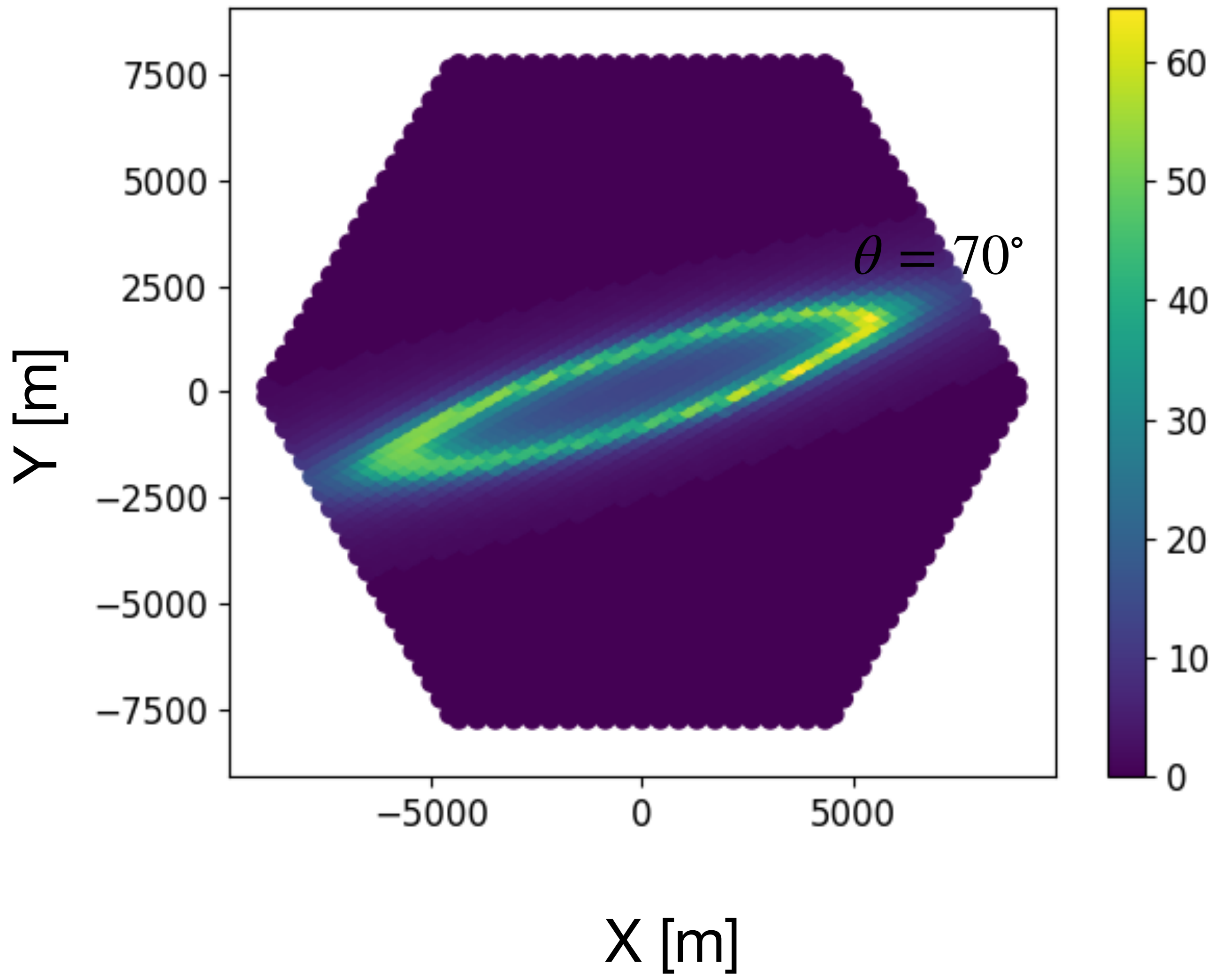
V. Decoene et al.
Astropart. Phys., 102779, 2022
arXiv:2112.07542

Direction and energy reconstruction

***Guelfand**, Decoene, Martineau et al.,*
Astroparticle Physics, 2025, arXiv:2504.18257







The ADF (angular distribution function) model

Based on Valentin Decoene's Thesis

Phenomenological model: describe the **signal amplitude of Efield** of the EAS within the radio footprint.
Adapted for 50-200 MHz frequency range

Signal amplitude of data:
-**Peak amplitude** computed from max of **Hilbert enveloppe**

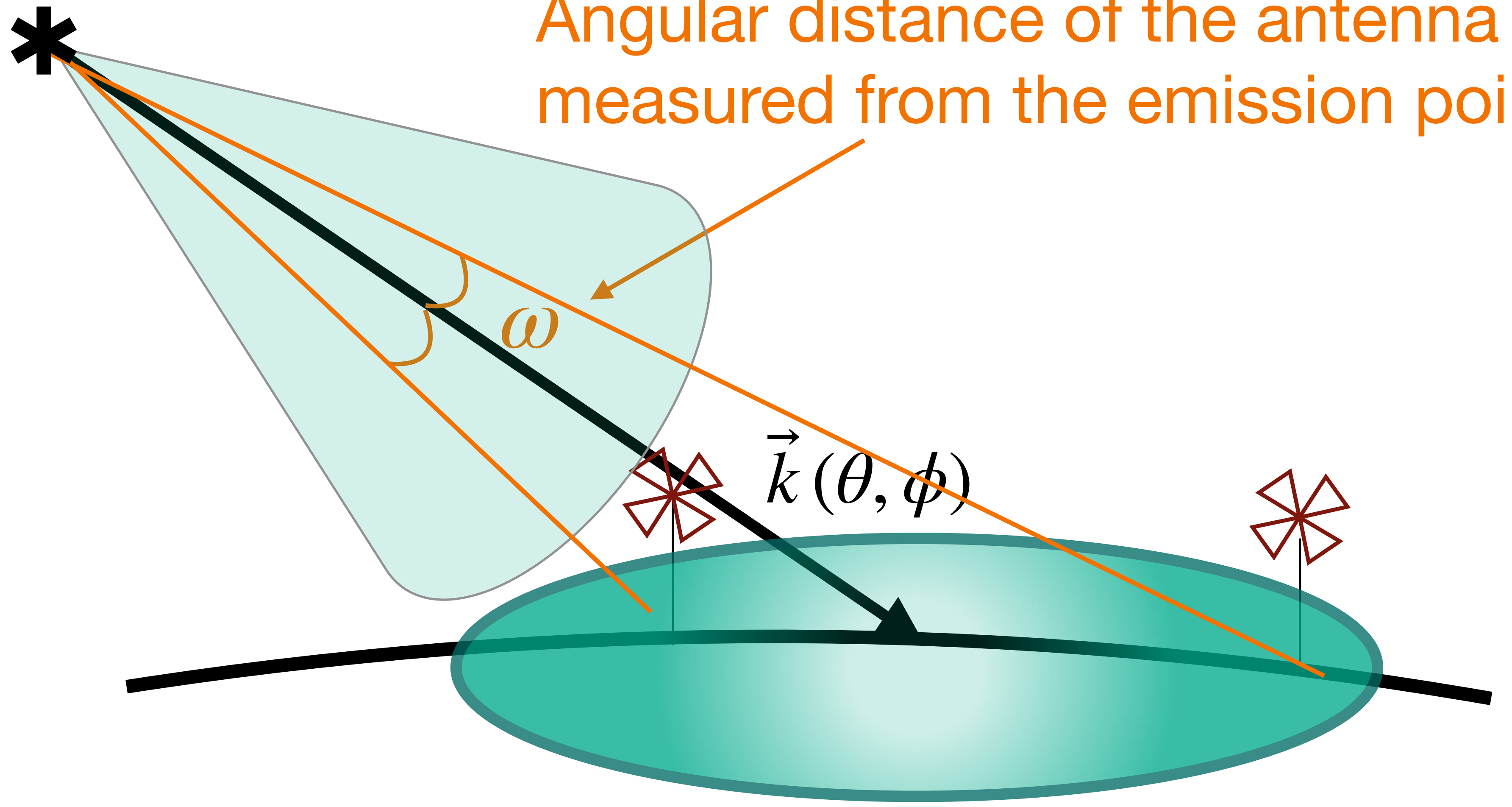
$$f^{\mathrm{ADF}}(\omega, \eta, \alpha, l; \delta\omega, A) = \frac{A}{l} f^{GeoM}(\alpha, \eta, B) f^{\mathrm{Cherenkov}}(\omega, \delta\omega)$$

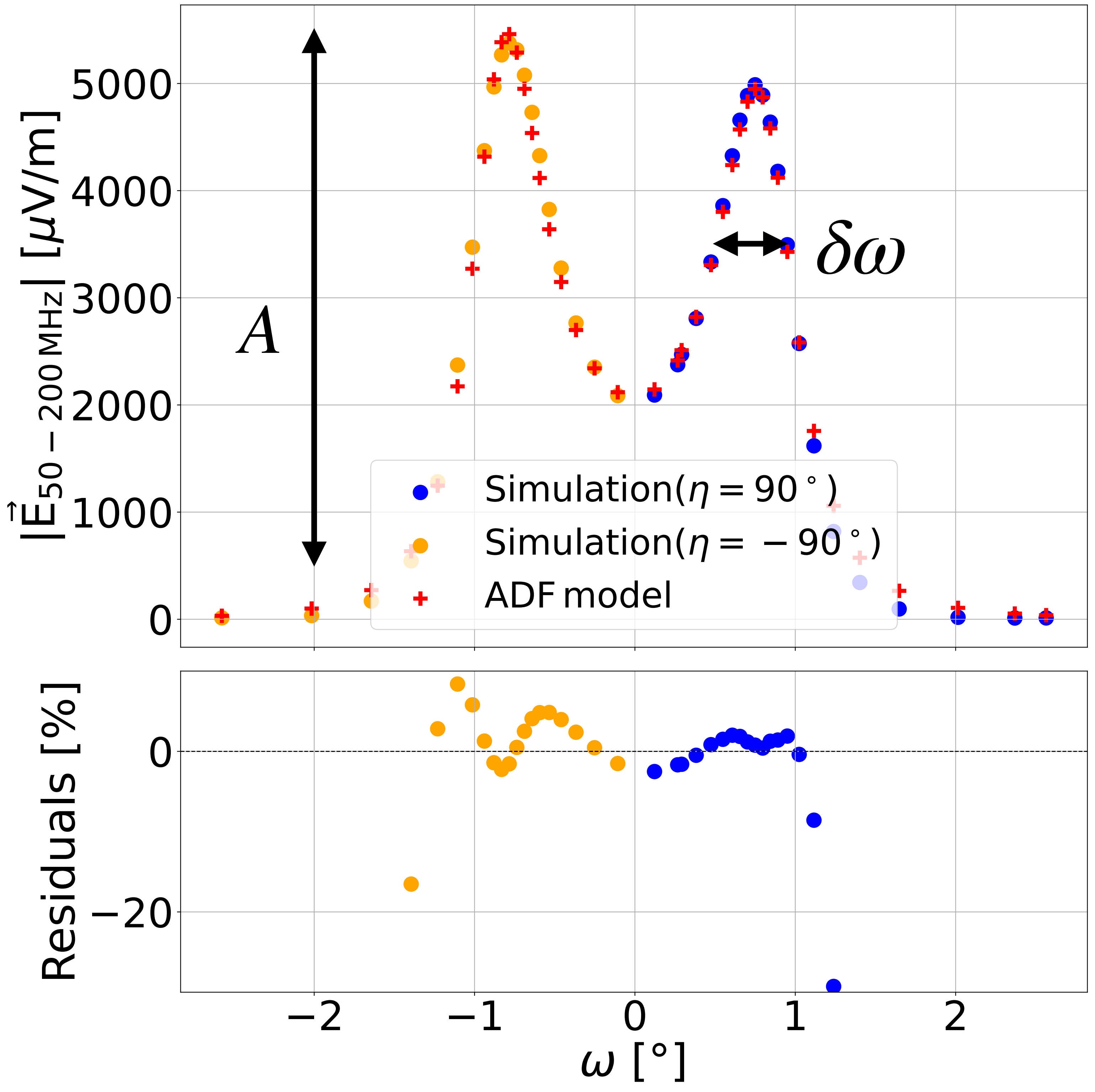
4 free parameters:
- **arrival direction θ, ϕ: direct reconstruction**
- scaling factor A and width $\delta\omega$

- Amplitude of radio signal related to electromagnetic energy E_{em}
- **Scaling factor A to construct energy estimator**

X_{source} from spherical wave reconstruction (SWF)

Angular distance of the antenna to the shower axis measured from the emission point source



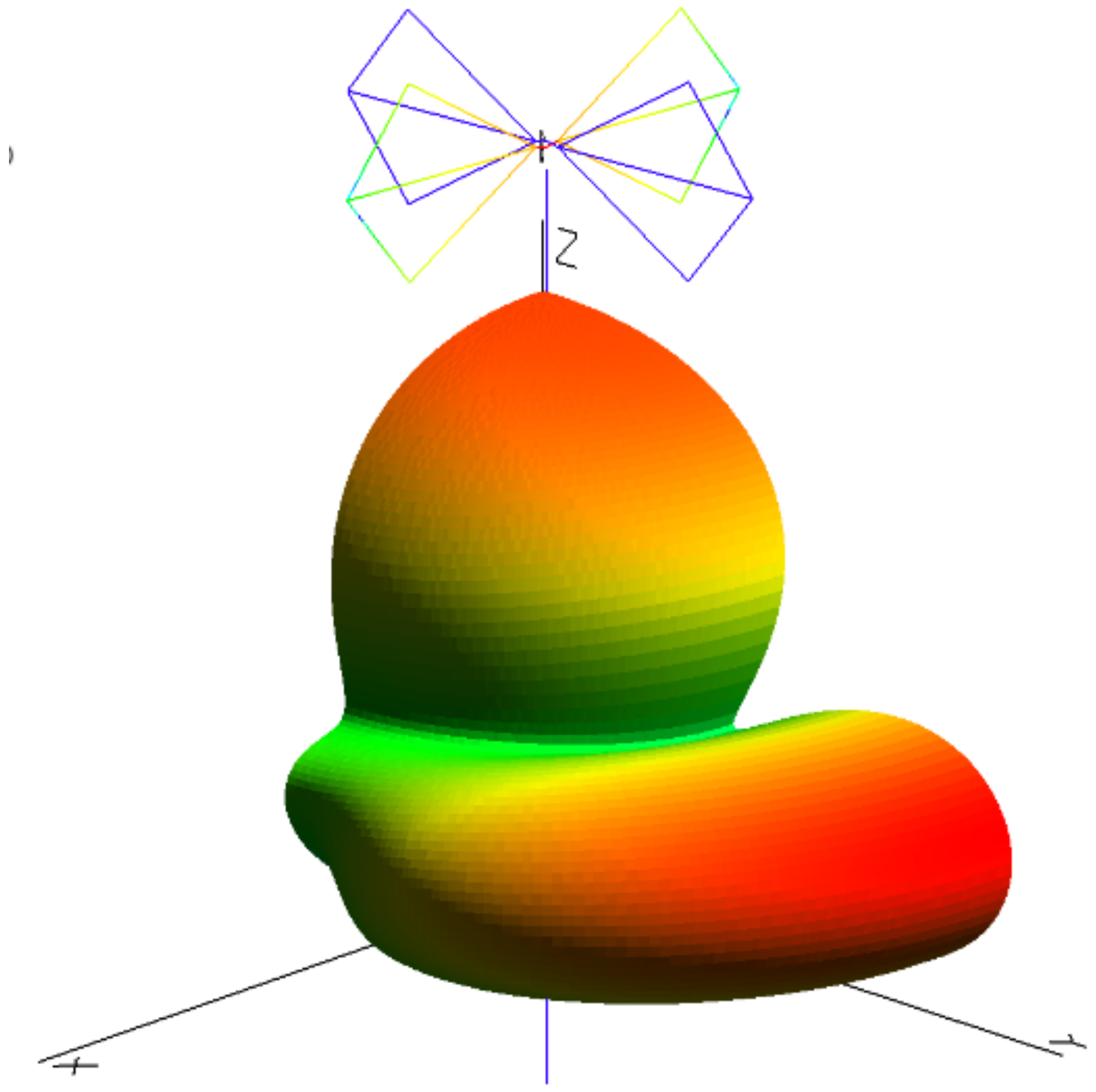


Guelfand, Decoene, Martineau et al., *Astroparticle Physics, 2025, arXiv:2504.18257*

Testing the ADF model on voltage

Work done with Pauline Fritsch, intern @ ICRR, Tokyo and iLance France-Japan lab

Motivation: Identify cosmic ray candidates without going through E-field deconvolution (direct information from the detector)



- Smooth variation of effective length l_{eff} for $\theta \sim$ 70-85°
- Antennas in the array see source from almost same viewing angle
- Amplitude from voltage scales as amplitude from Efield

Testing the ADF model on voltage

Work done with Pauline Fritsch, intern @ ICRR, Tokyo and iLance France-Japan lab

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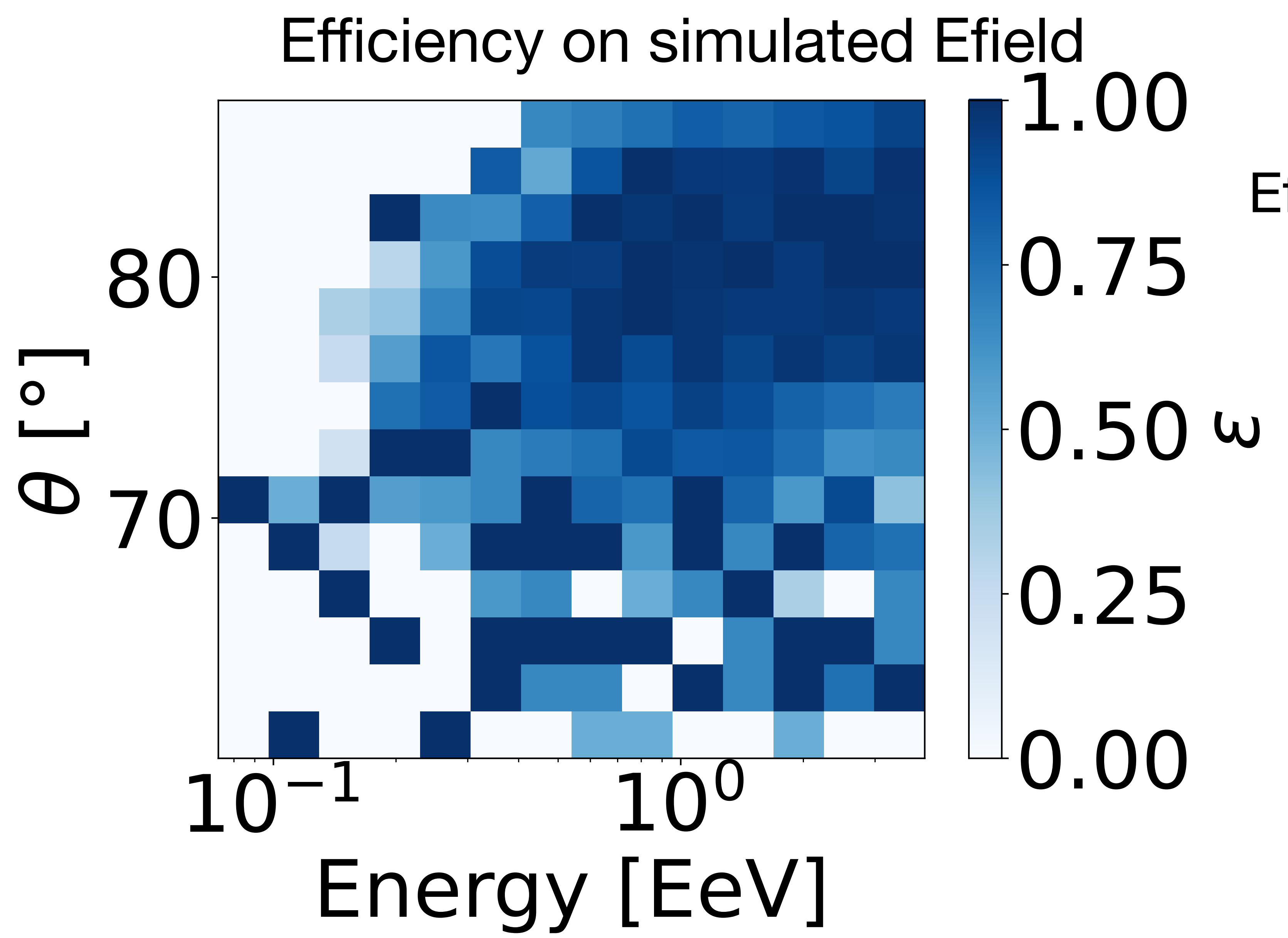
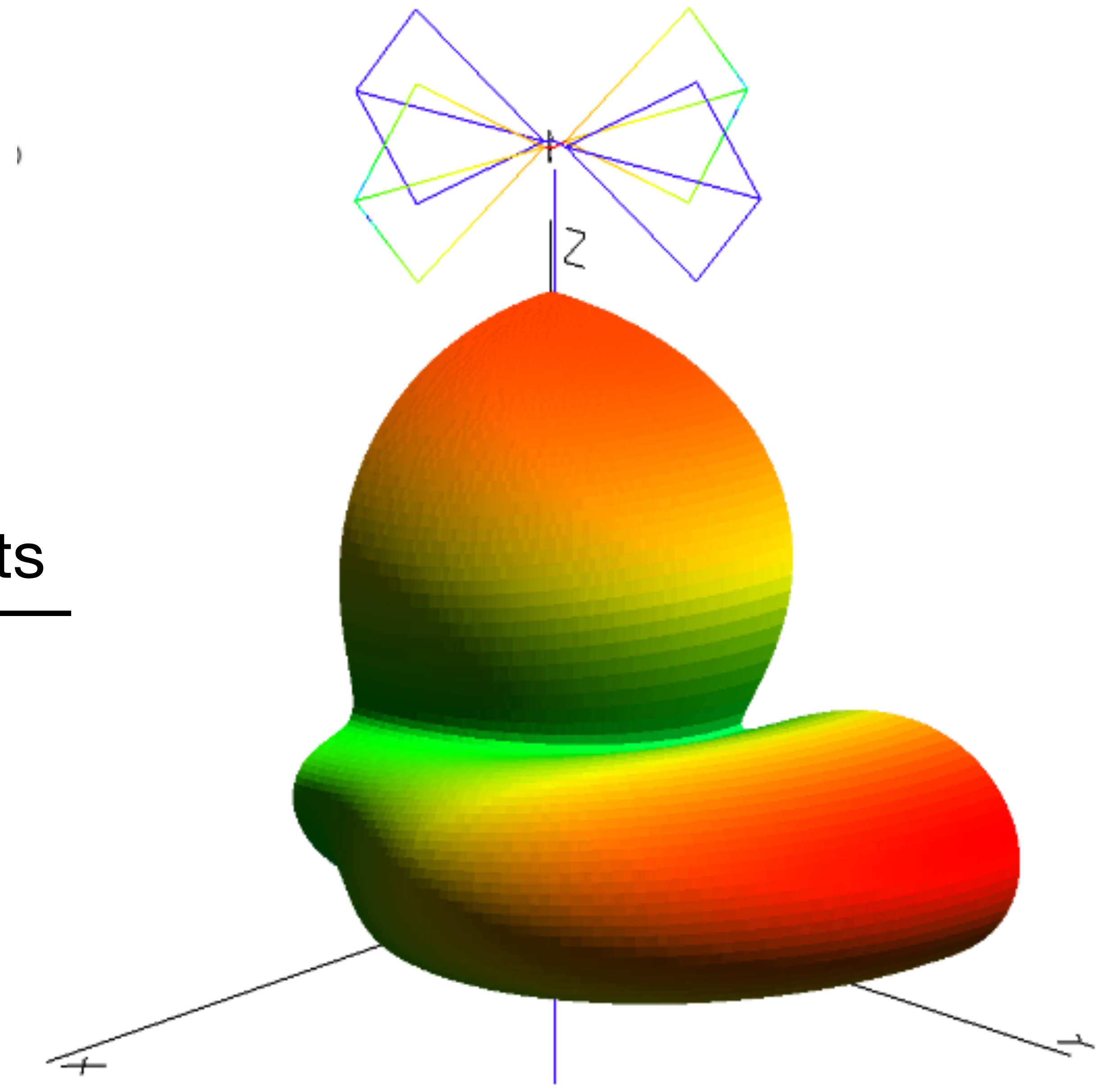
Test on 1000 ZHAireS - AN DC2-RF2 Alpha simulations: experimental noise (from the MD data of GP80) on ADC traces
Trigger conditions: Amplitude threshold $\geq$ 100 ADC and Antenna threshold $\geq$ 5 + select $\theta \geq 60°$

Fit efficiency on simulated Voltage ($\chi^2/\mathrm{ndf} < 25$): 83%



$$\text{Efficiency } \epsilon = \frac{\text{reconstructed events}}{\text{triggered events}}$$



- Smooth variation of effective length l_{eff} for $\theta \sim$ 70-85°
- Antennas in the array see source from almost same viewing angle
- Amplitude from voltage scales as amplitude from Efield

Testing the ADF model on voltage: results

Work done with Pauline Fritsch, intern @ ICRR, Tokyo and iLance France-Japan lab

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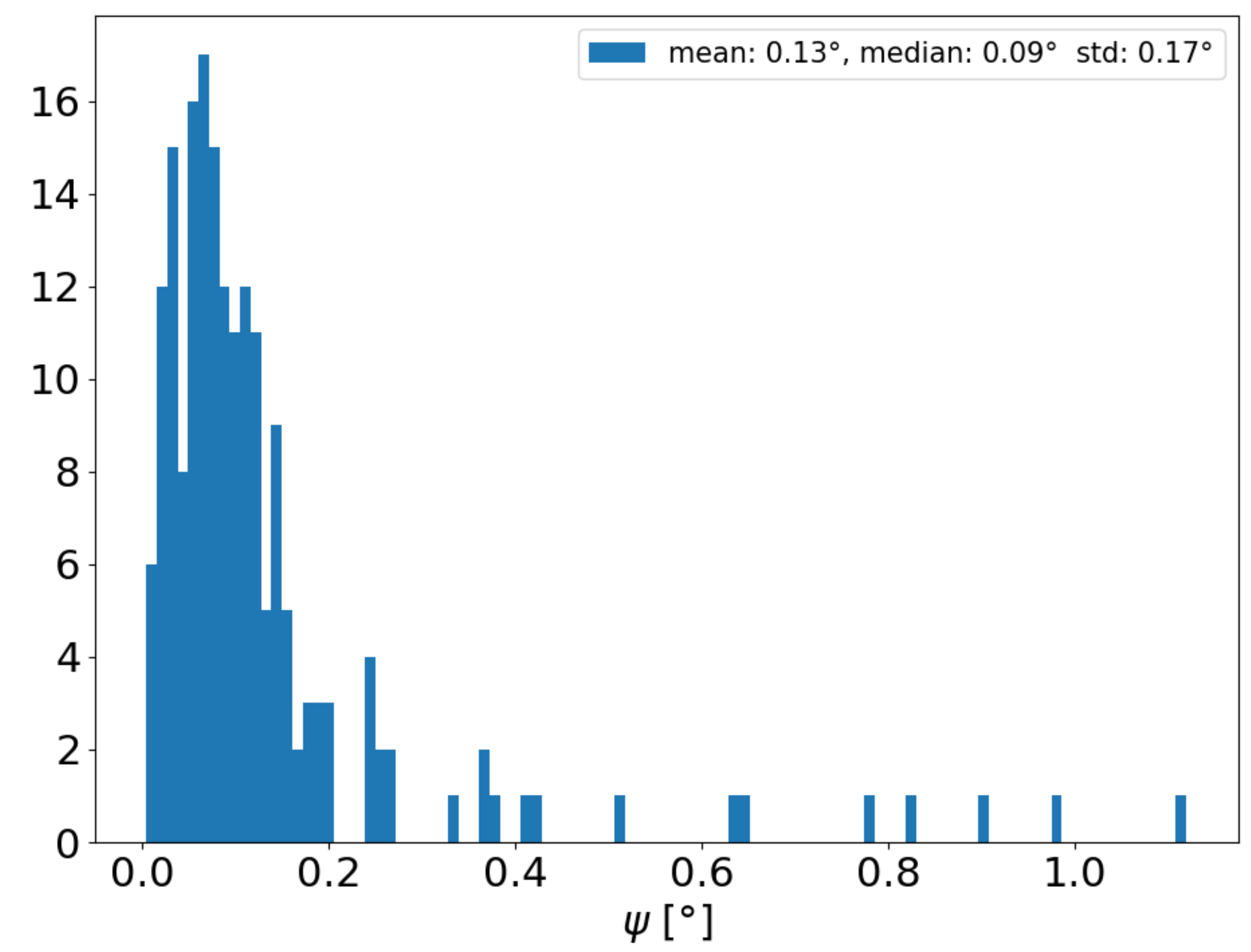
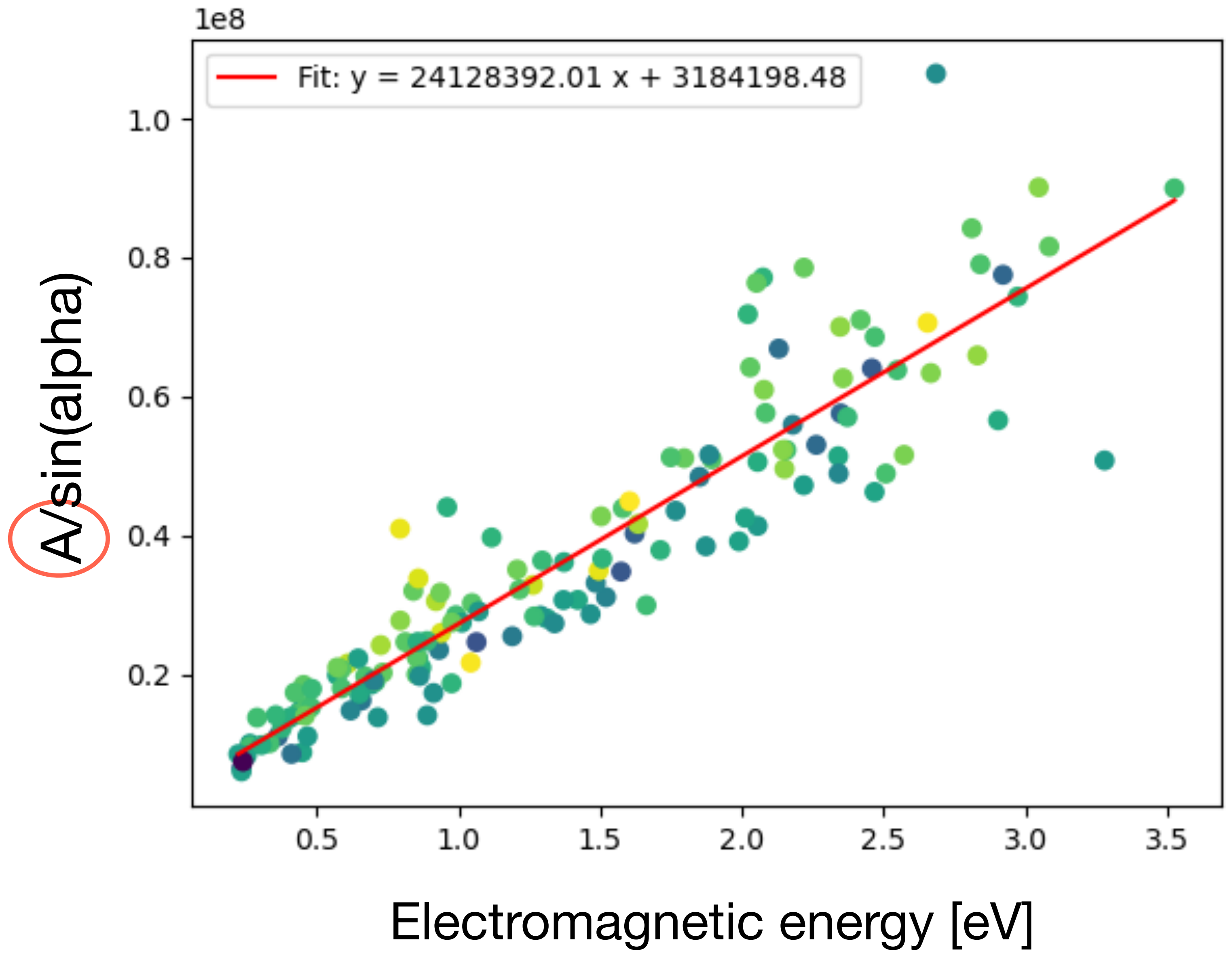


Angular resolution: 0.13°

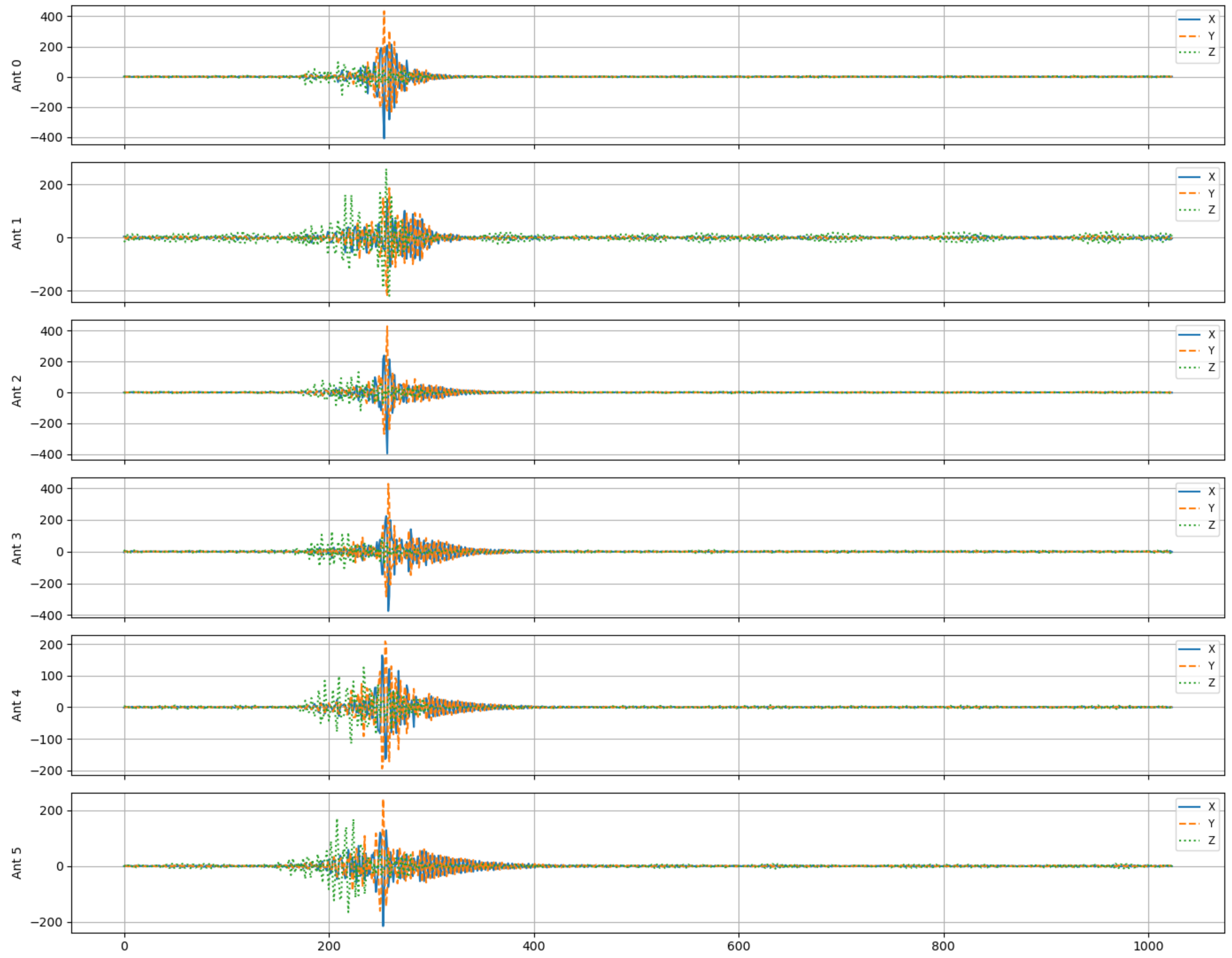


Excellent correlation between electromagnetic energy and scaling factor A/sin(alpha) uses as a proxy for energy

ADF can be used on voltage for **cosmic ray identification** + **direction reconstruction** and **energy estimation**

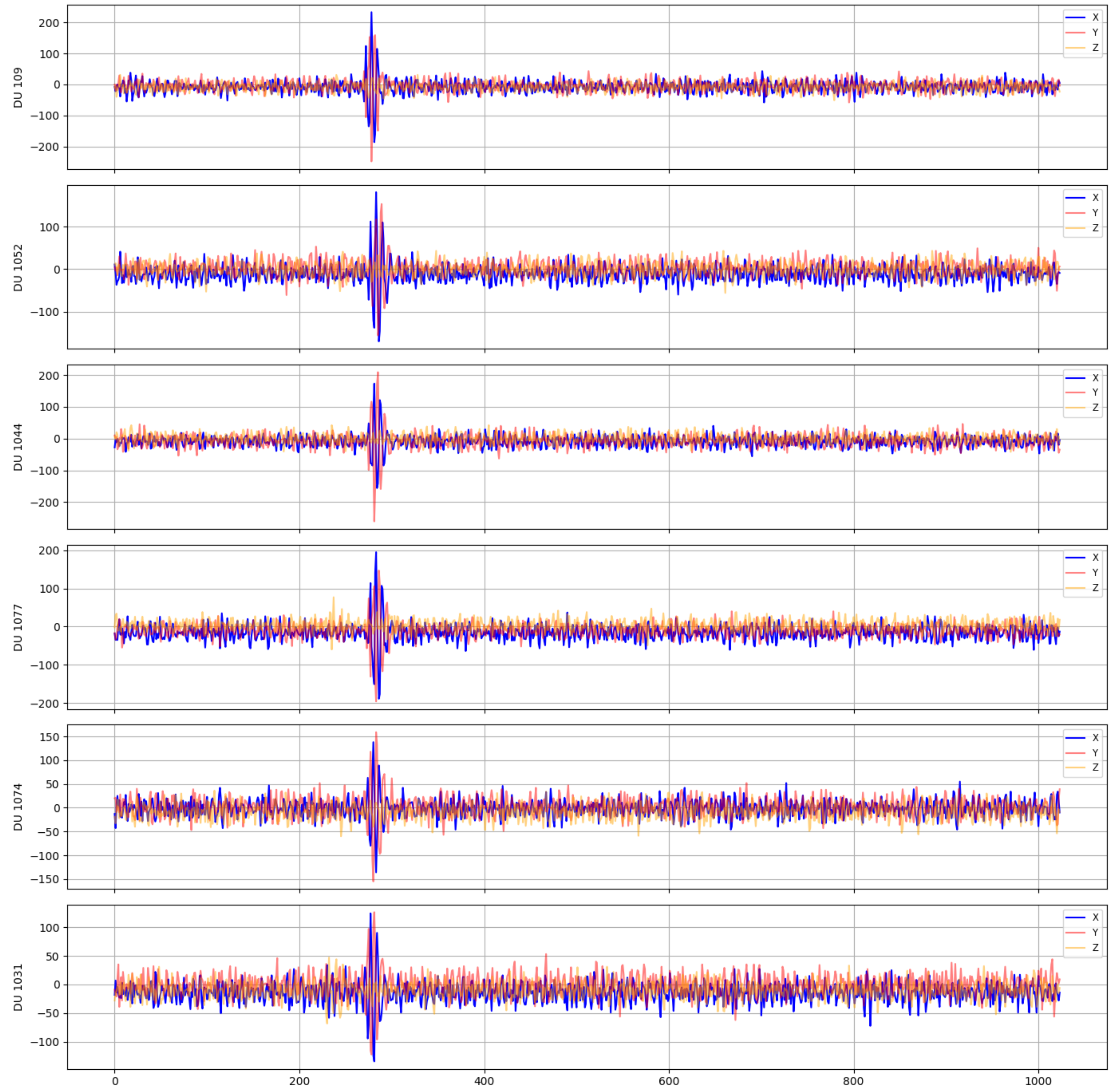
GP80 cosmic ray candidates: Selection on voltage

Reconstructed Efield tracesRun: Run:4666 Event:0



Samples

Voltage traces: Run:4666 Event:0

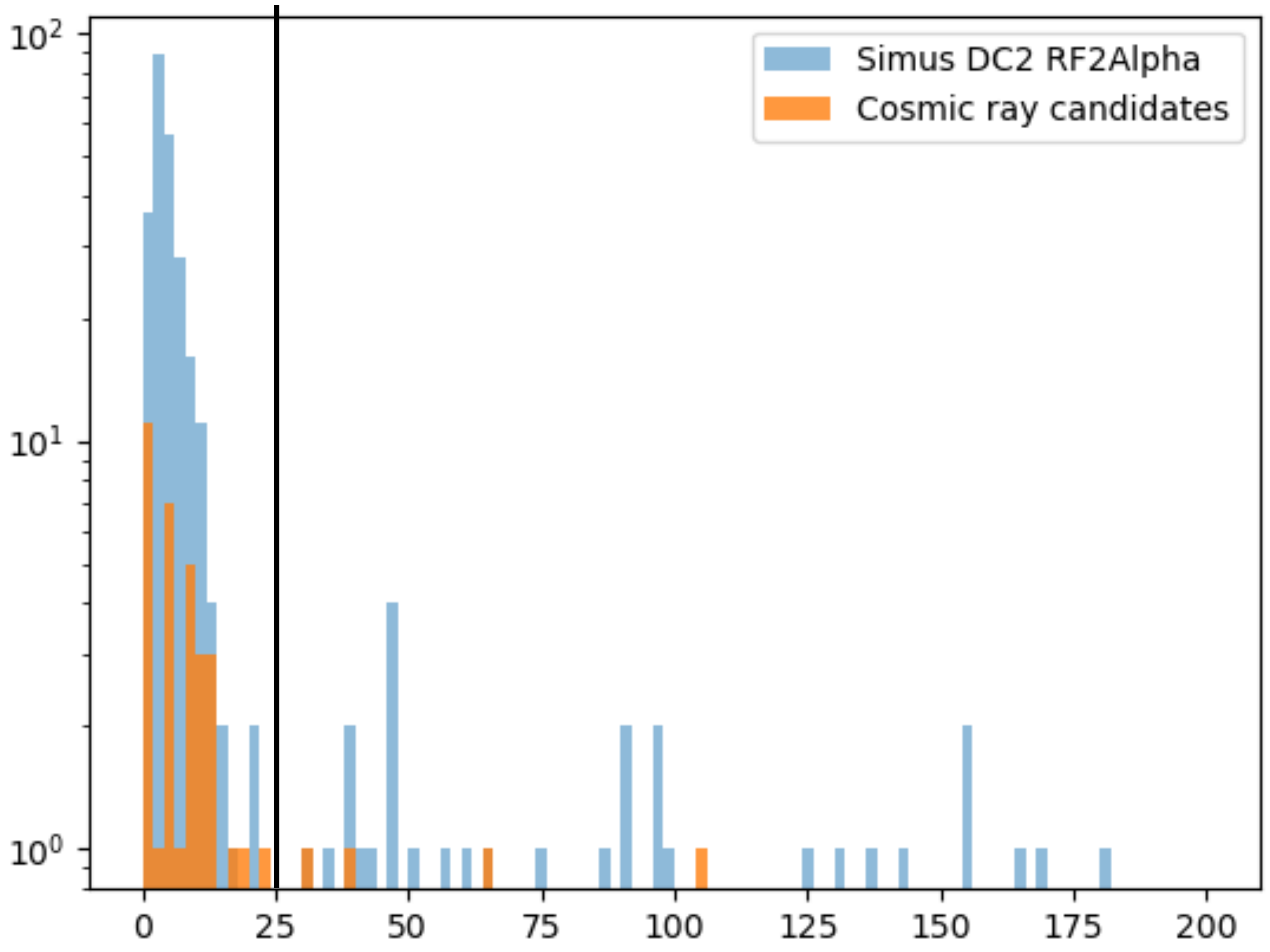


Samples

- Refine cosmic ray candidates selection without going through E-field deconvolution (direct information from the detector)
- Efield deconvolution not convincing for some cosmic ray candidates: baseline too noisy or fluctuating or Efield pulse longer than the ADC one
- Efield reconstruction fails on some antennas (gives multiplicity < 5 for 7 events)

Selection of cosmic ray candidates with voltage

1) Selection on ADF fit on voltage: χ^2/ndf < 25

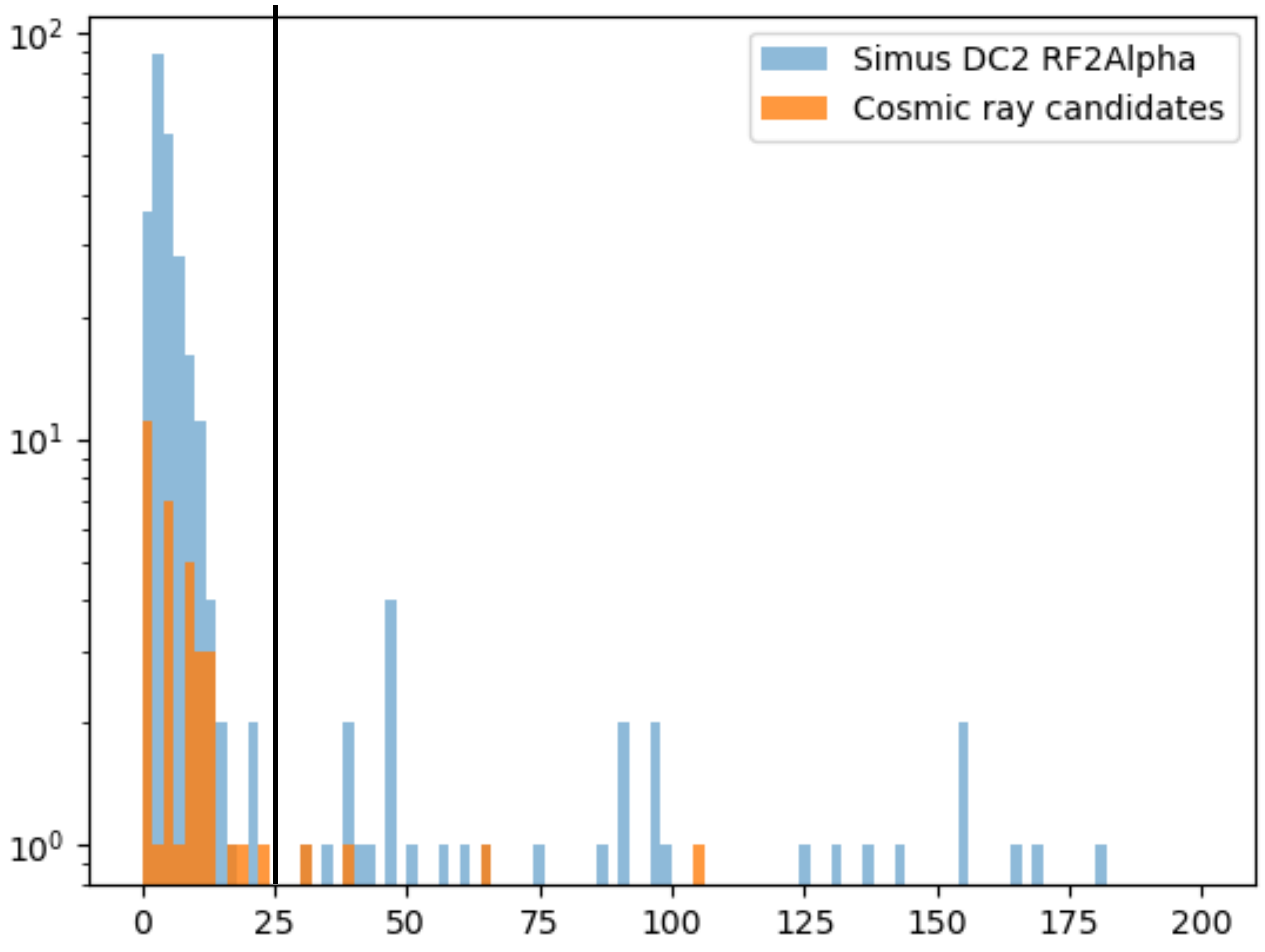


Reduced χ^2 ADF

Ratio of DC2 simulations below the cut: 83%
Ratio of cosmic ray candidates below the cut: 85%

Selection of cosmic ray candidates with voltage

1) Selection on ADF fit on voltage: χ^2/ndf < 25



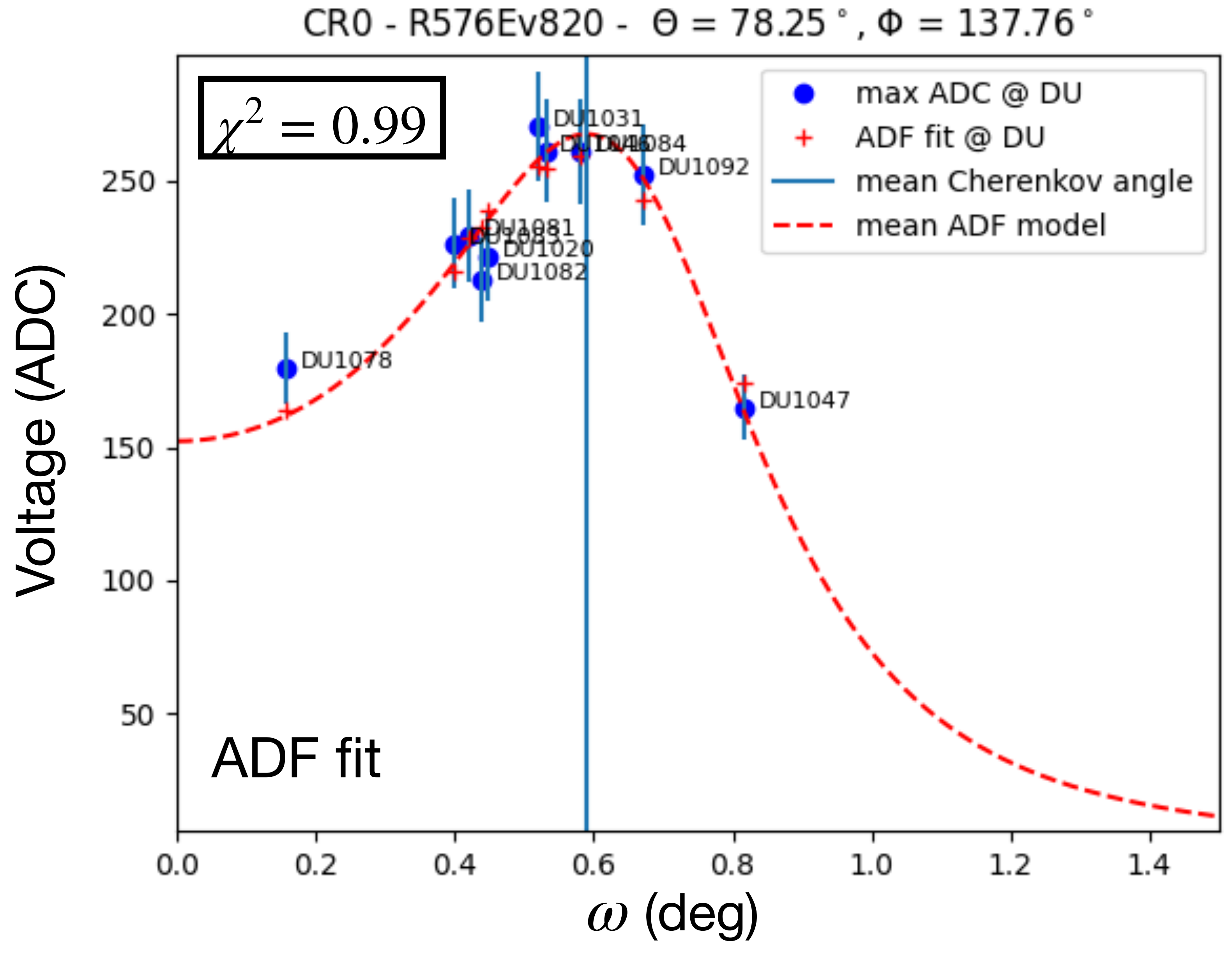
Reduced χ^2 ADF

Ratio of DC2 simulations below the cut: 83%
Ratio of cosmic ray candidates below the cut: 85%

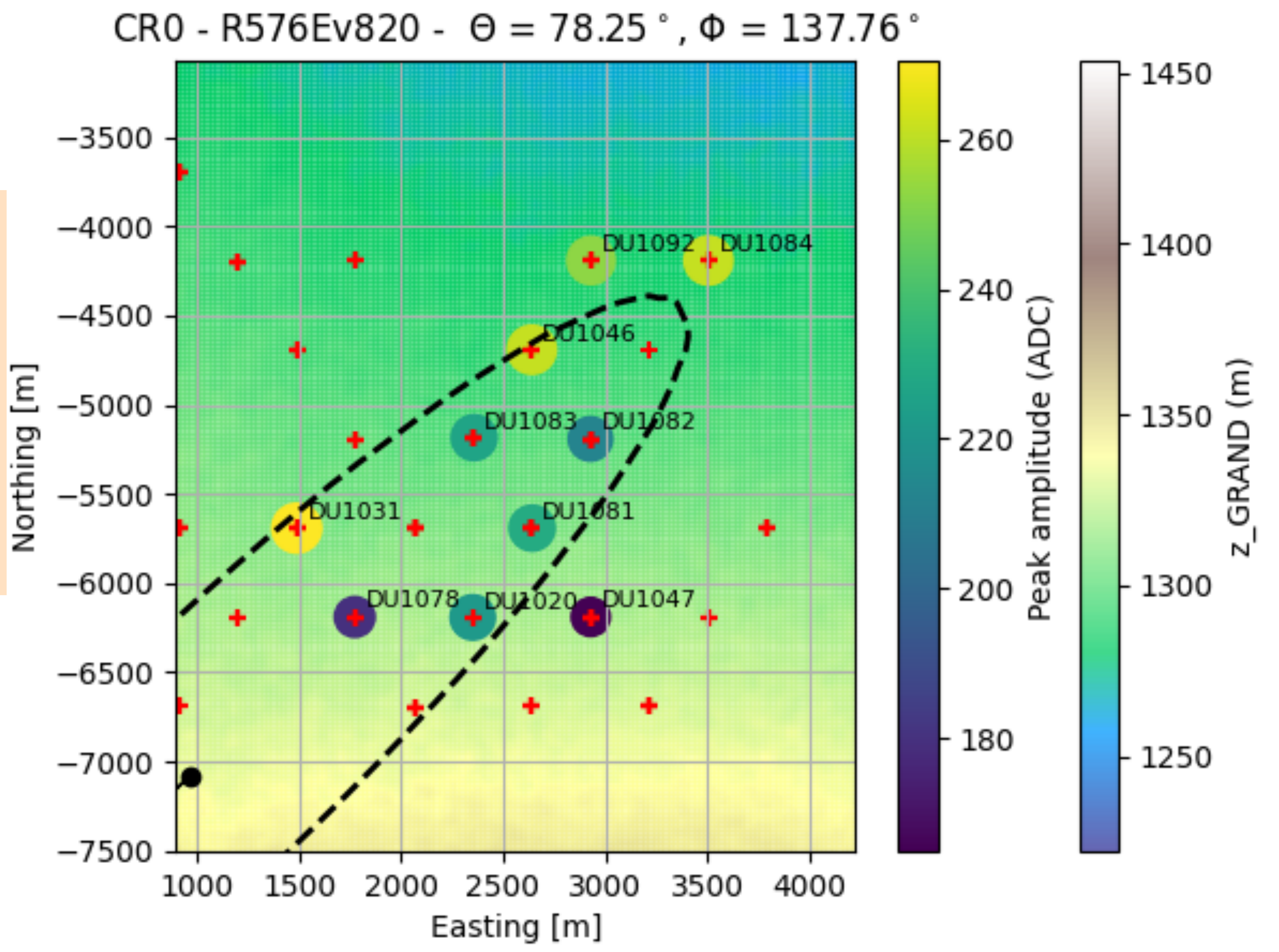
2) Test Background Hypothesis (k/l fit)

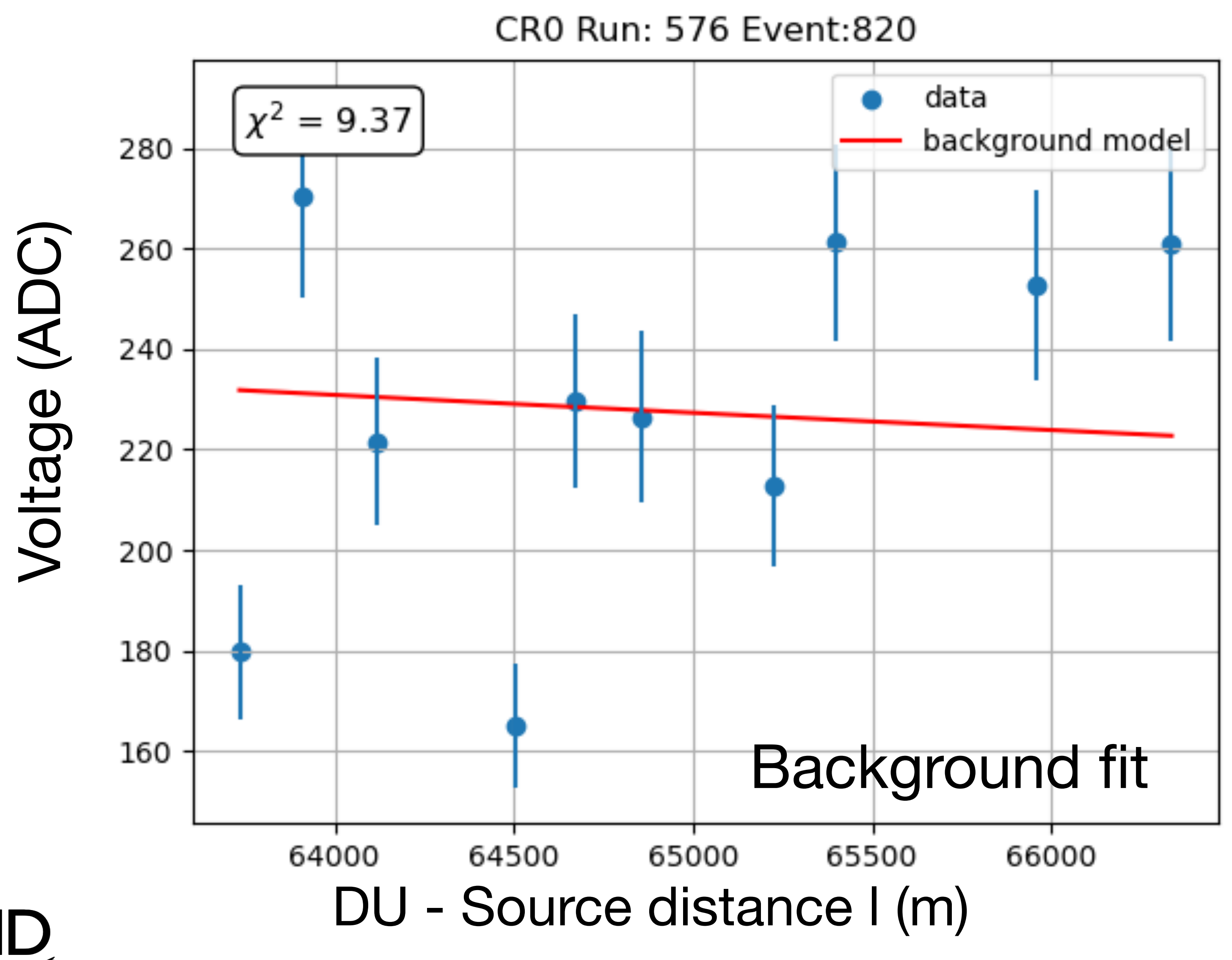
- Fit: Amplitude vs distance l to Xsource (obtained with SWF) for background model: isotropic emission (k/l fit)
- Comparison of χ^2/ndf (k/l) vs. χ^2/ndf (ADF)
- In most cases: χ^2/ndf (k/l) $\gg$ χ^2/ndf (ADF)
- Idea: use fit quality (ADF vs. k/l) to tag true CR candidates

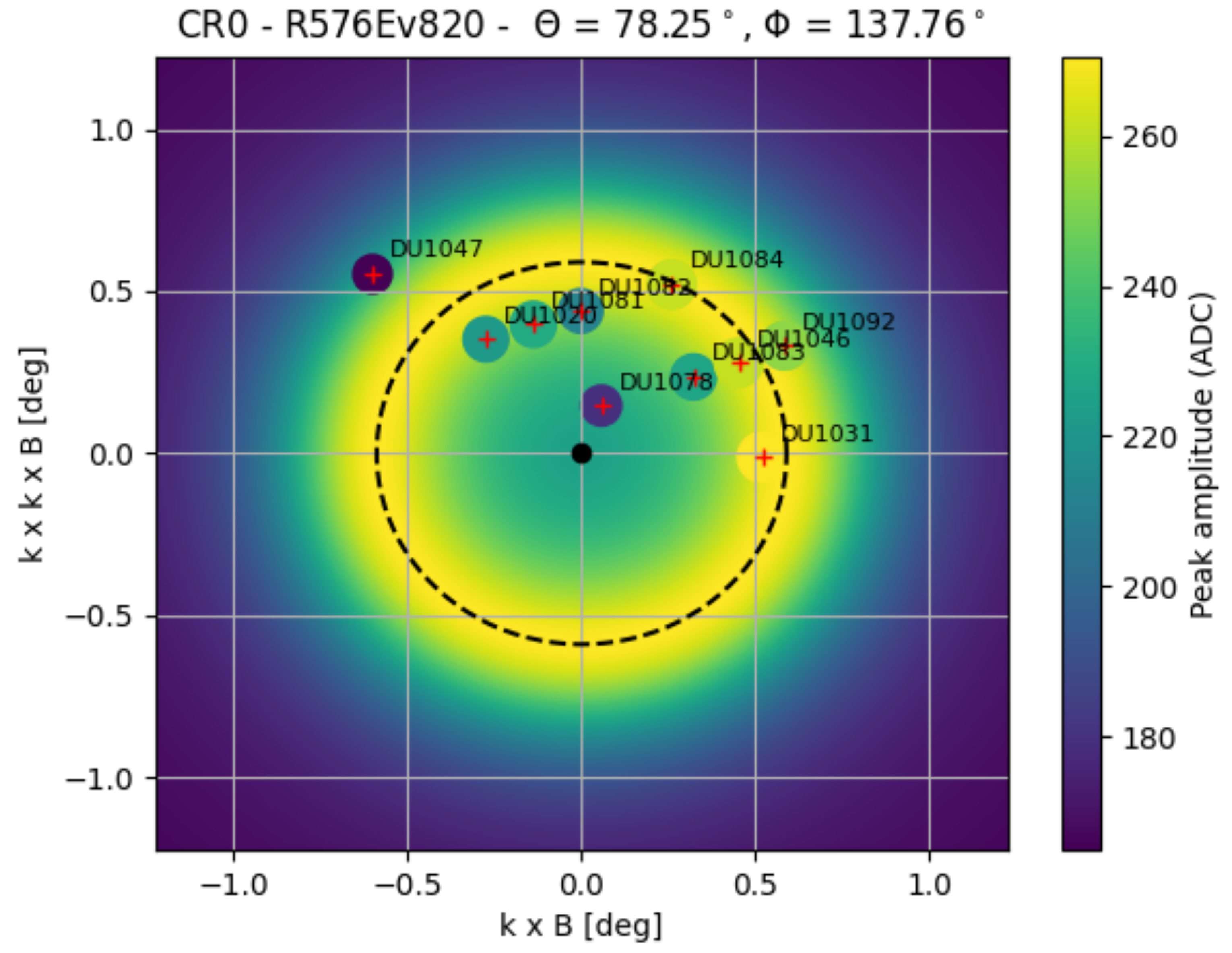
Cosmic ray candidates: some examples



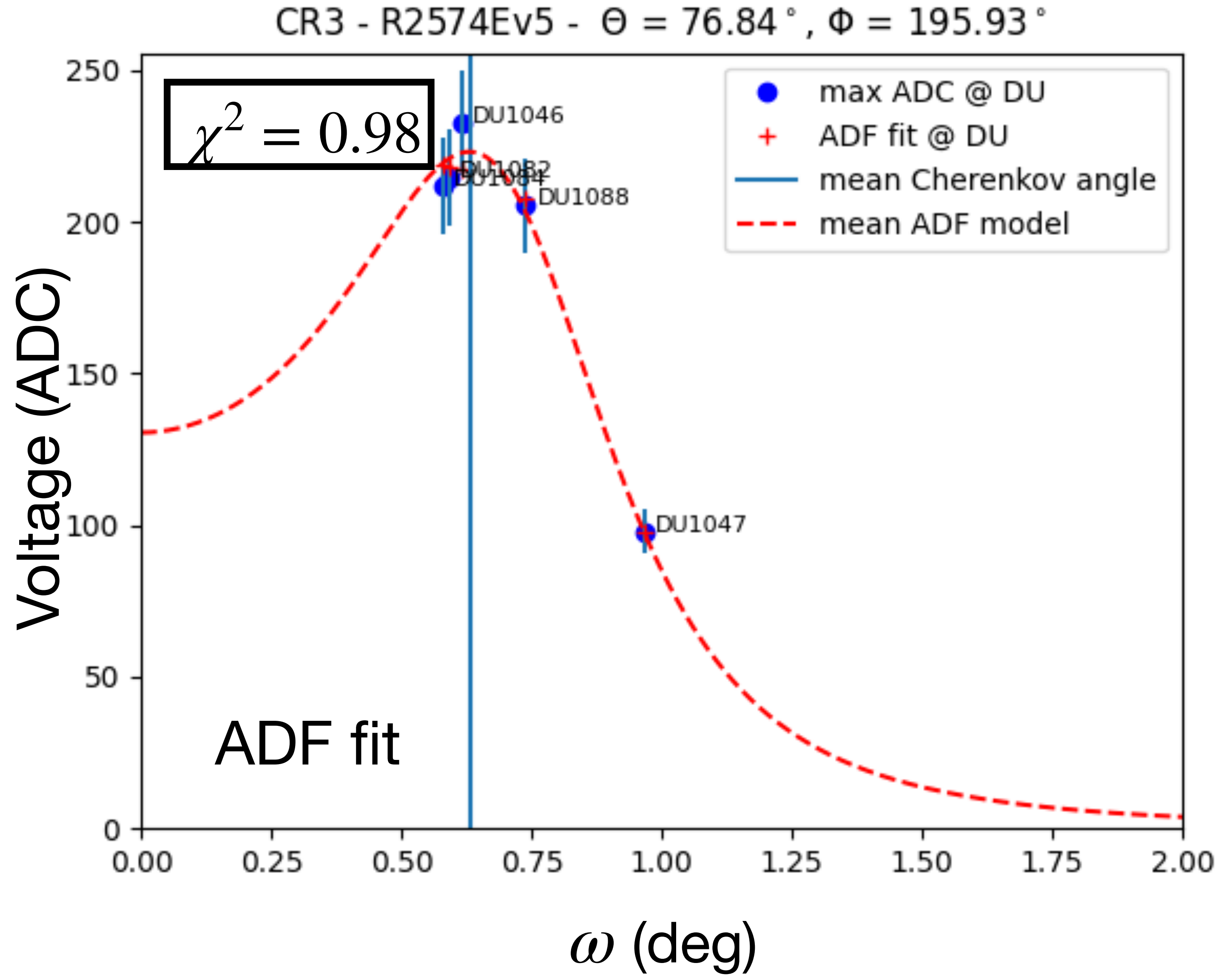
Cherenkov angle:
Fixed parameter of the ADF model computed with semi-analytical toy model (prior to the fit)
Depends on Xsource position and atmosphere model only

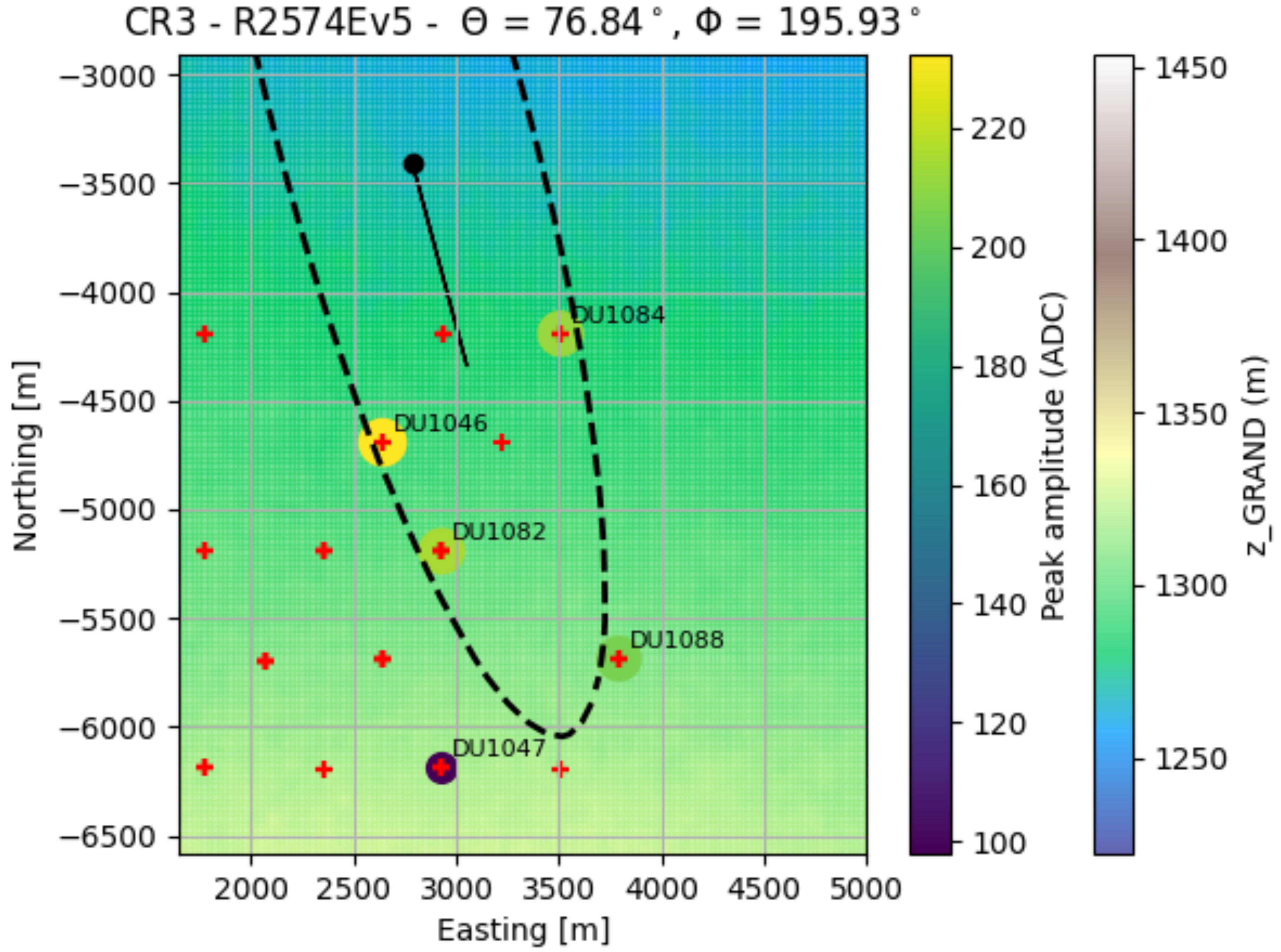


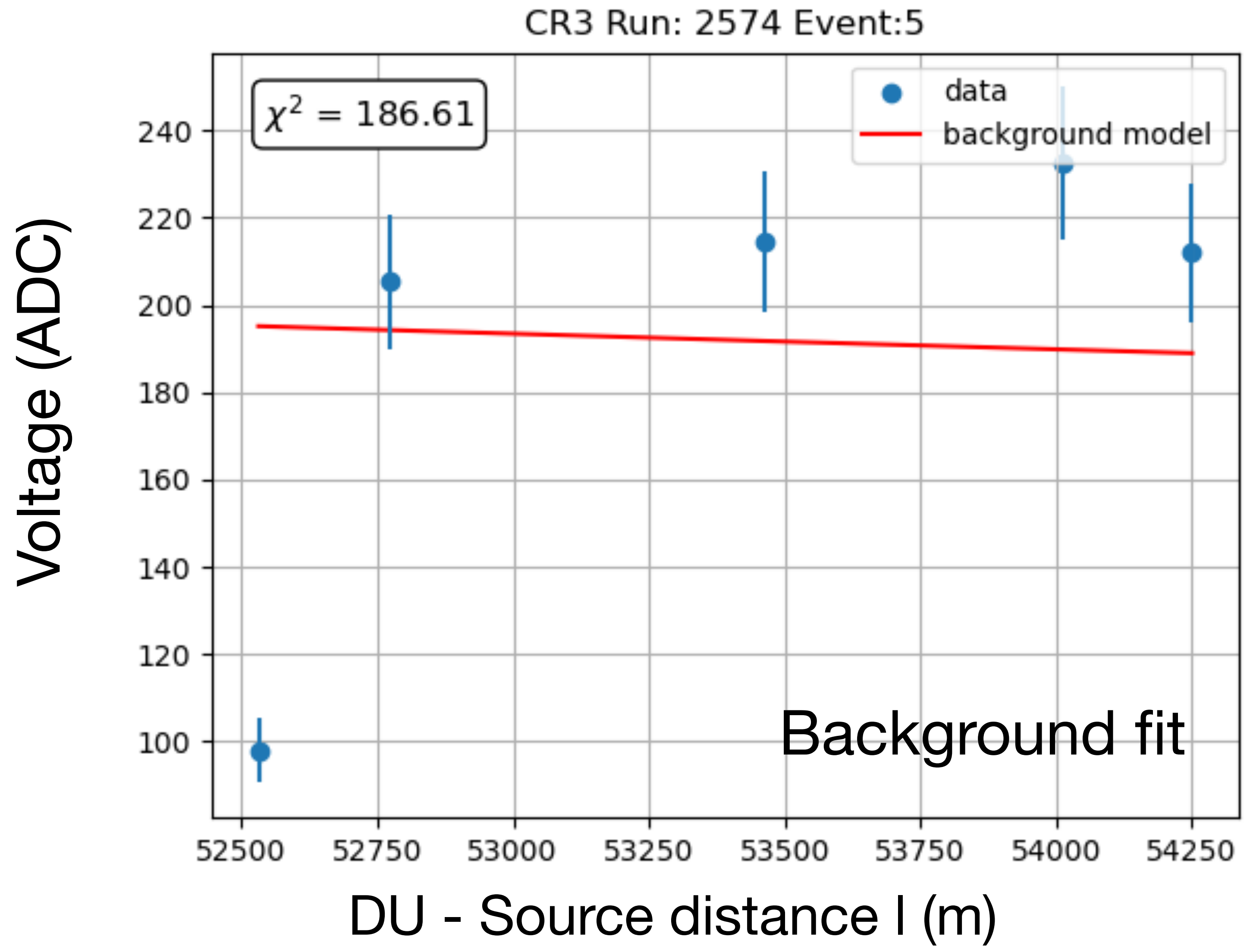


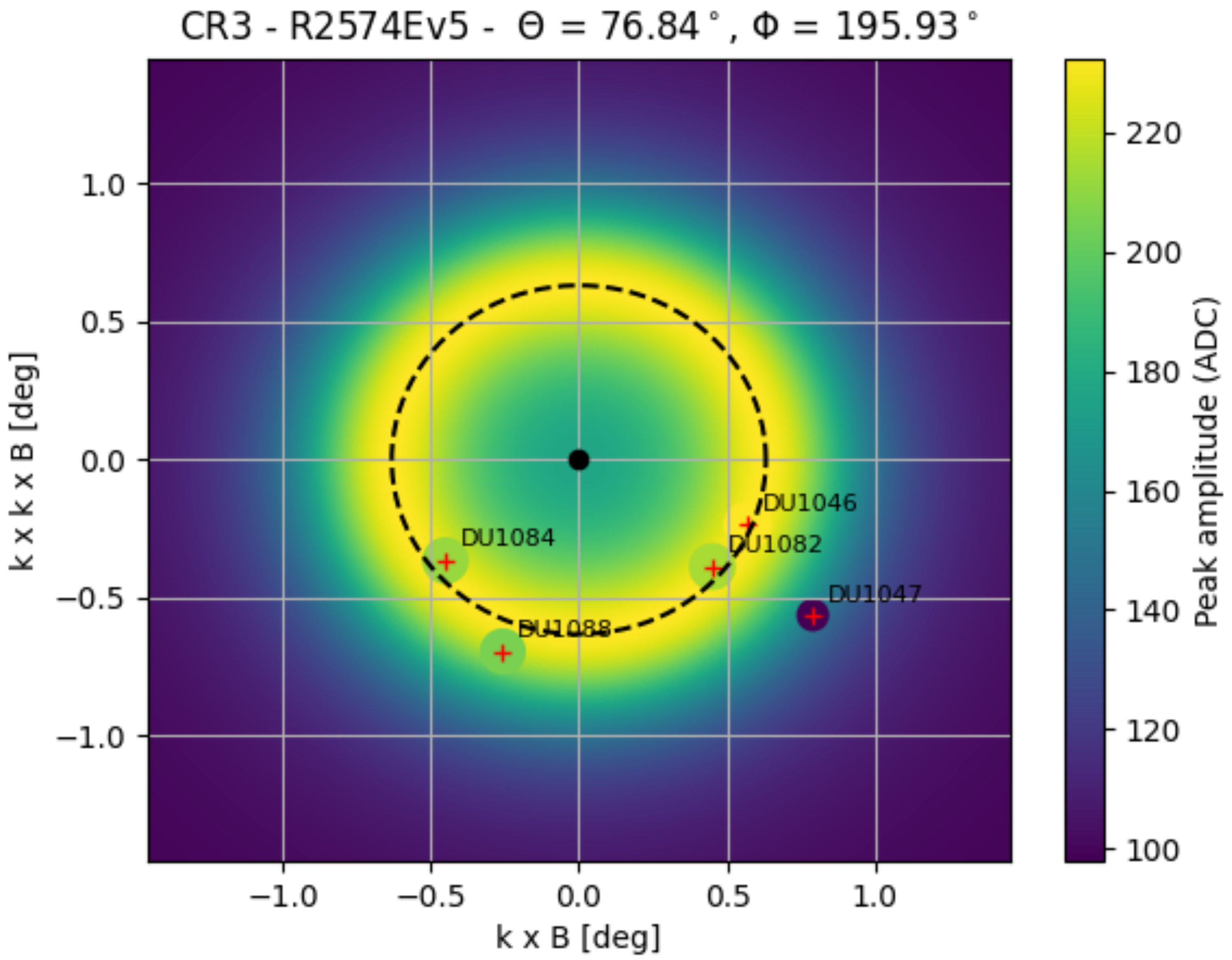


Cosmic ray candidates: some examples

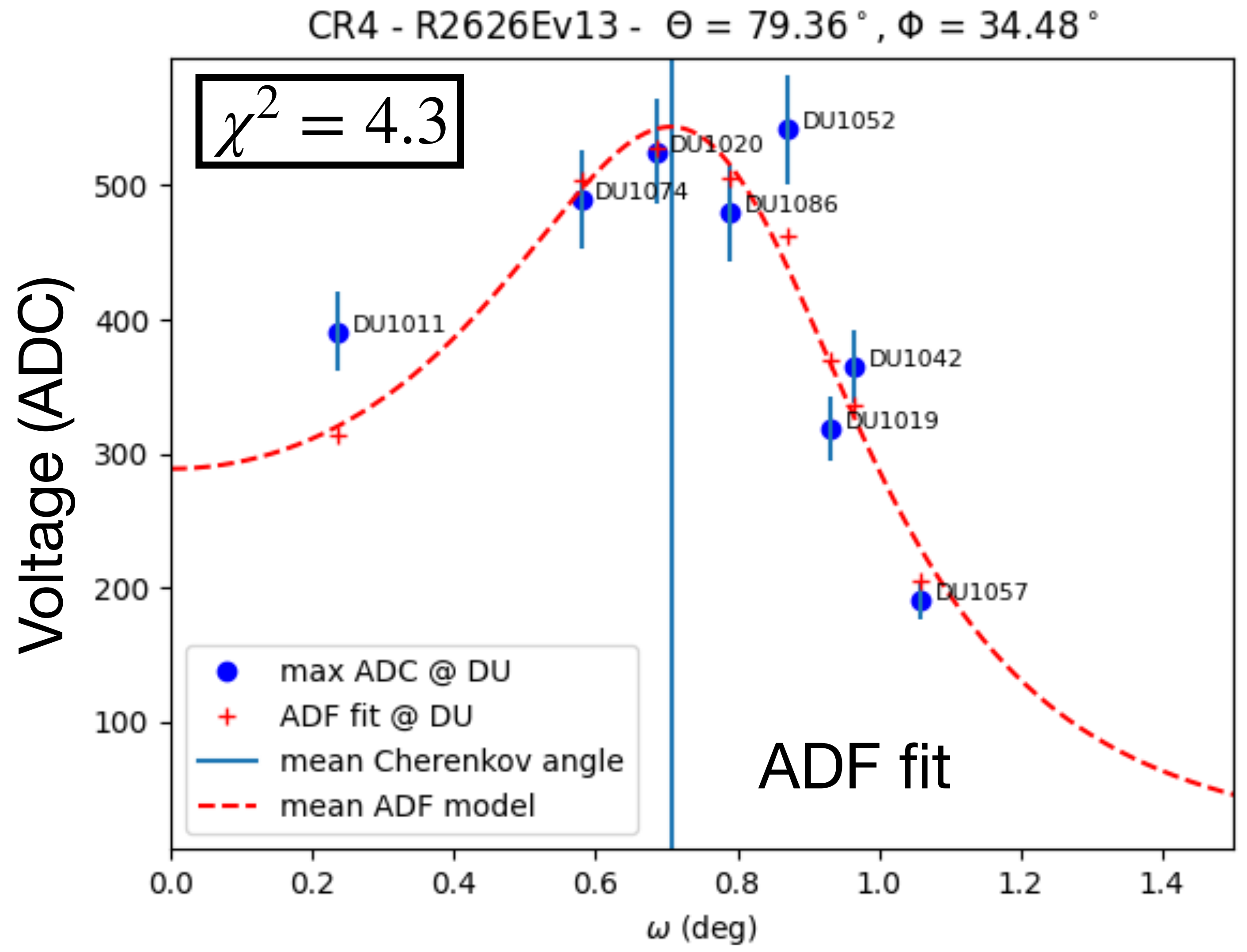


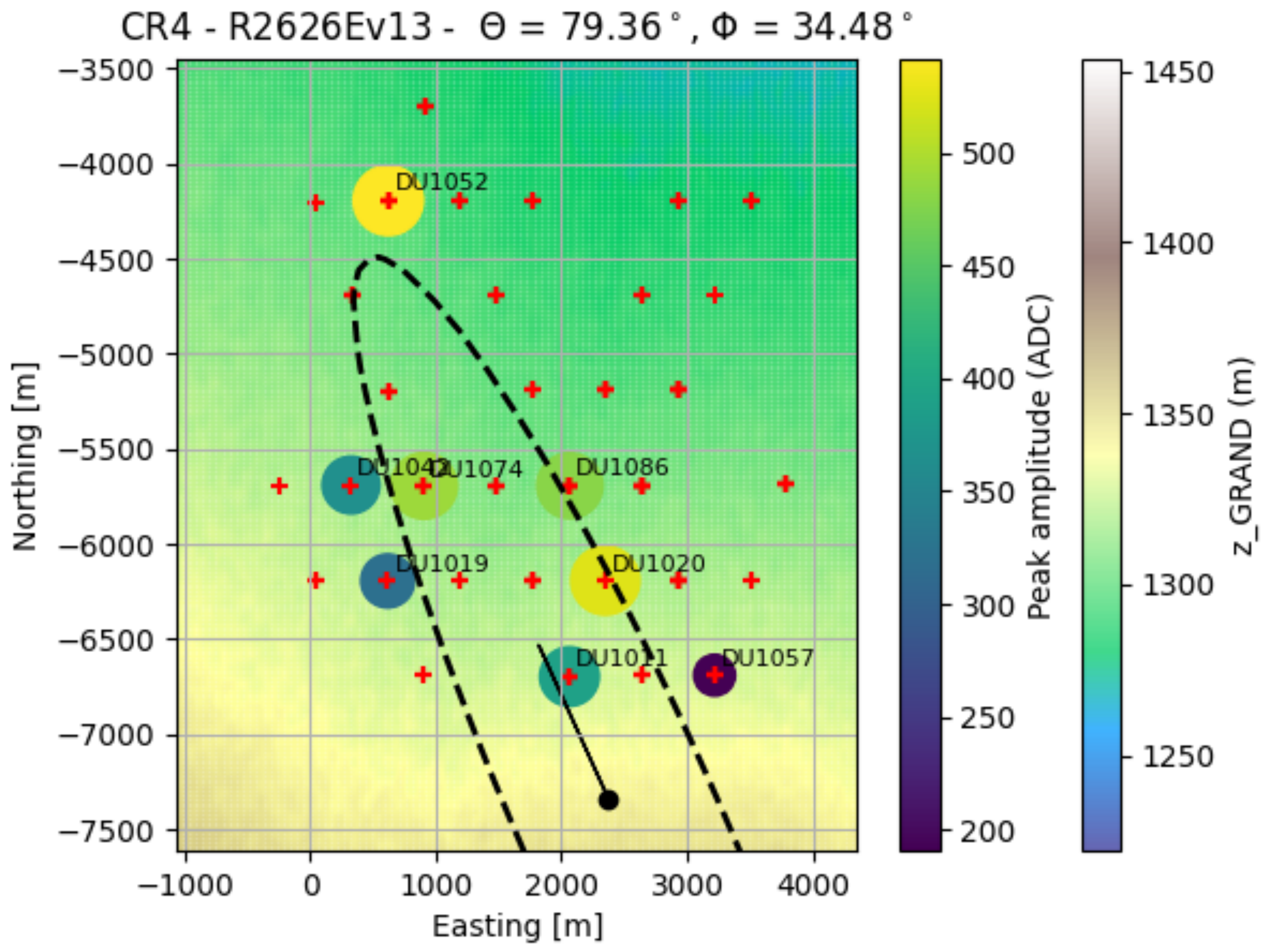


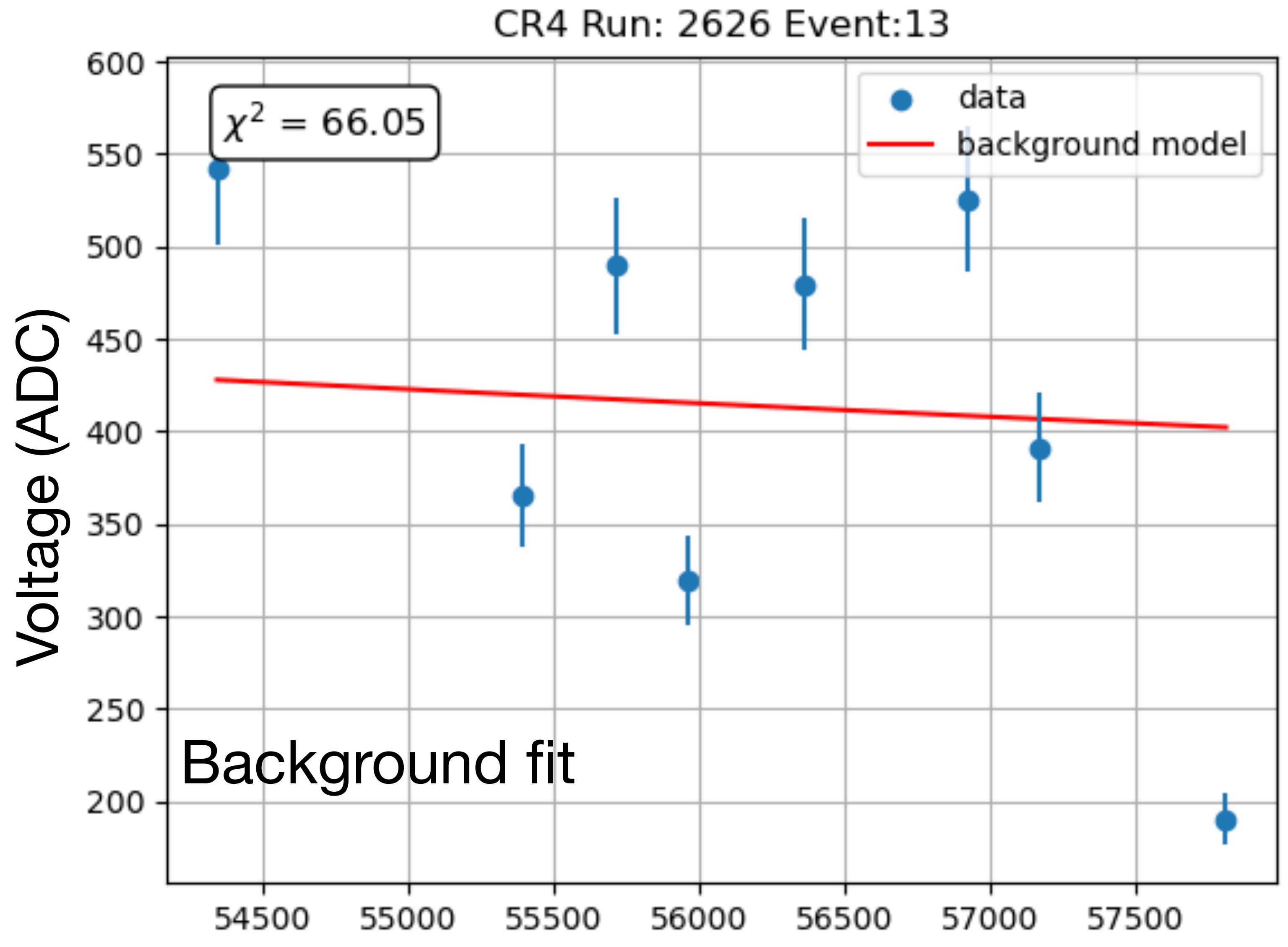


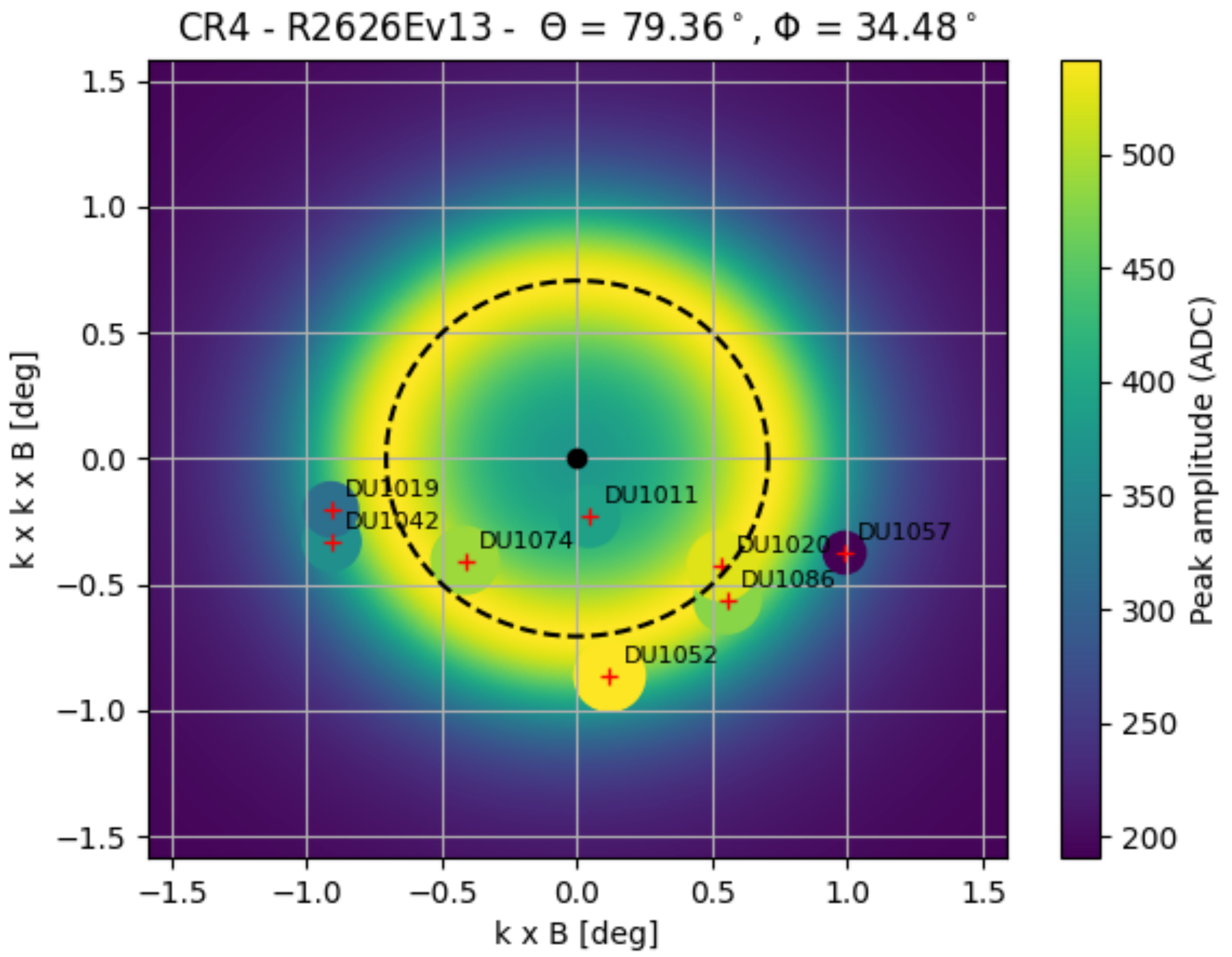


Cosmic ray candidates: some examples



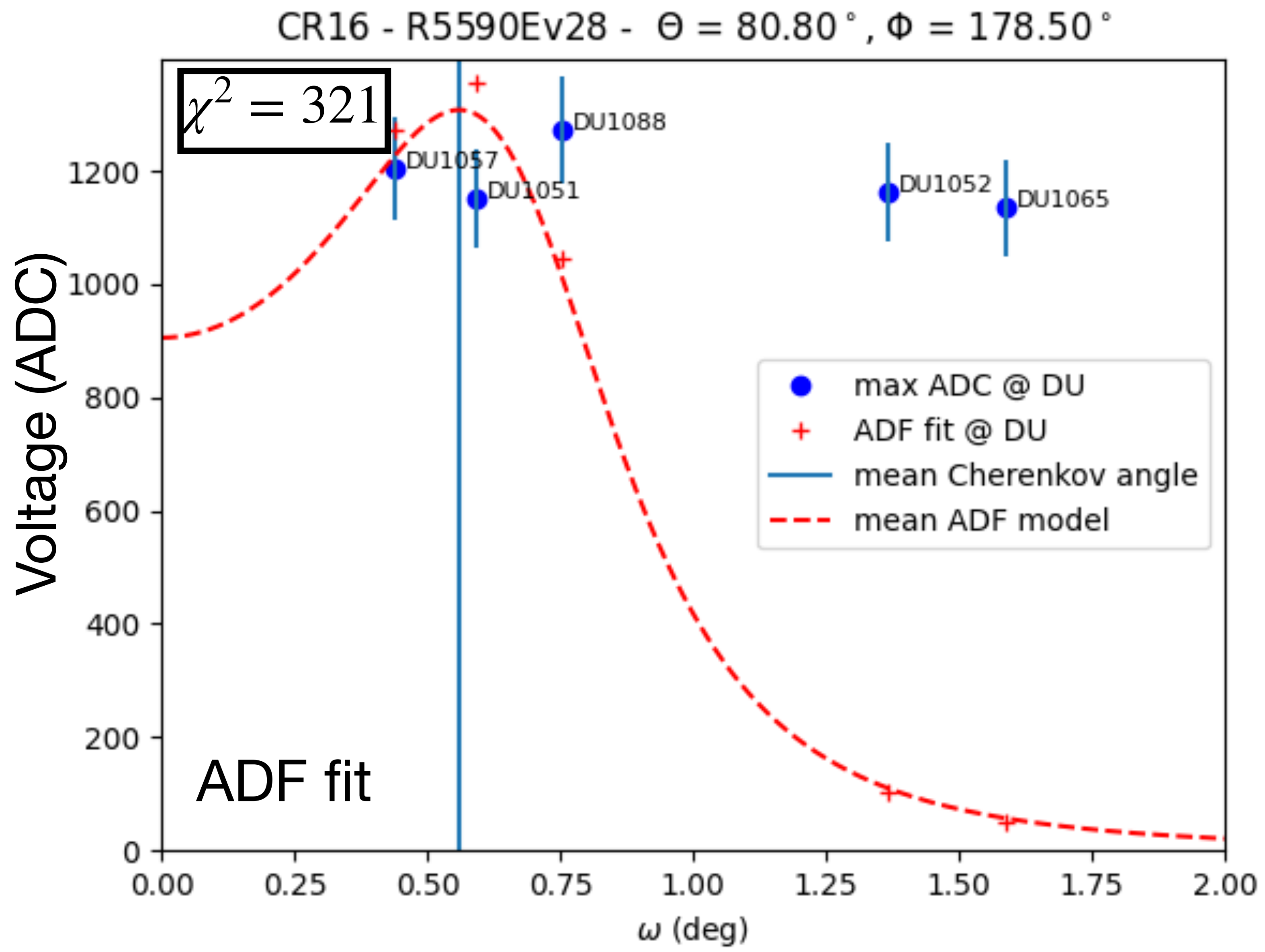


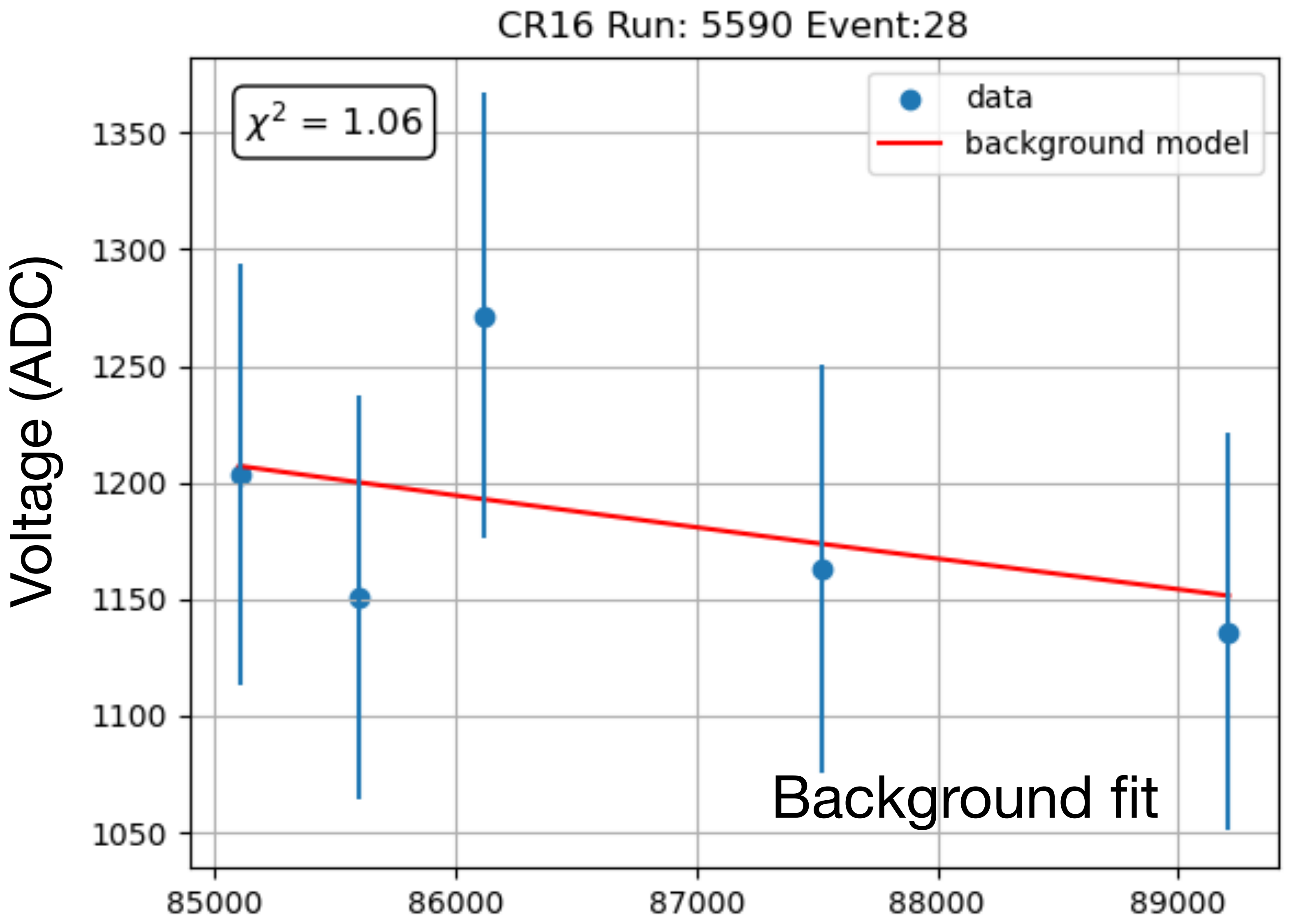


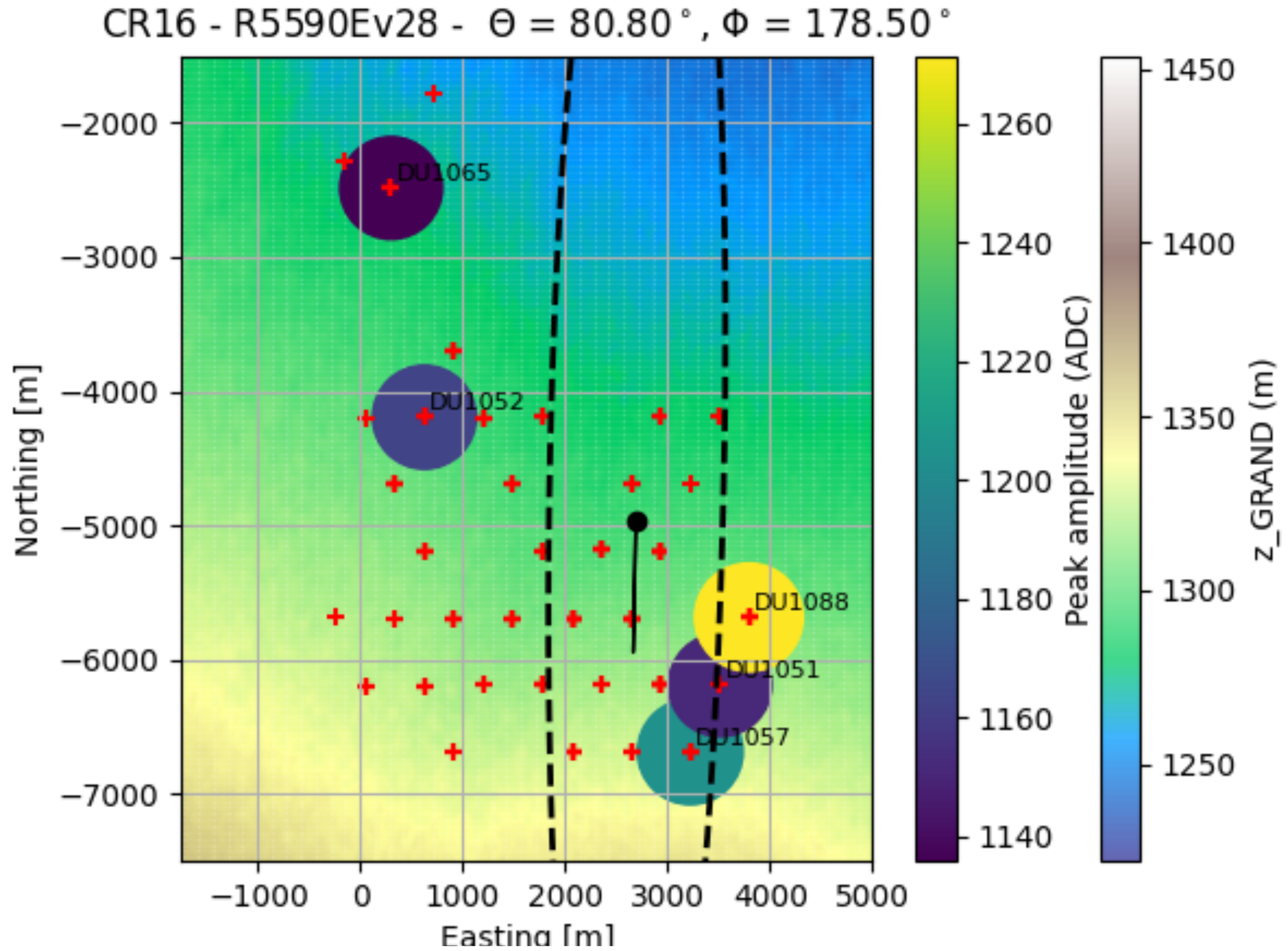


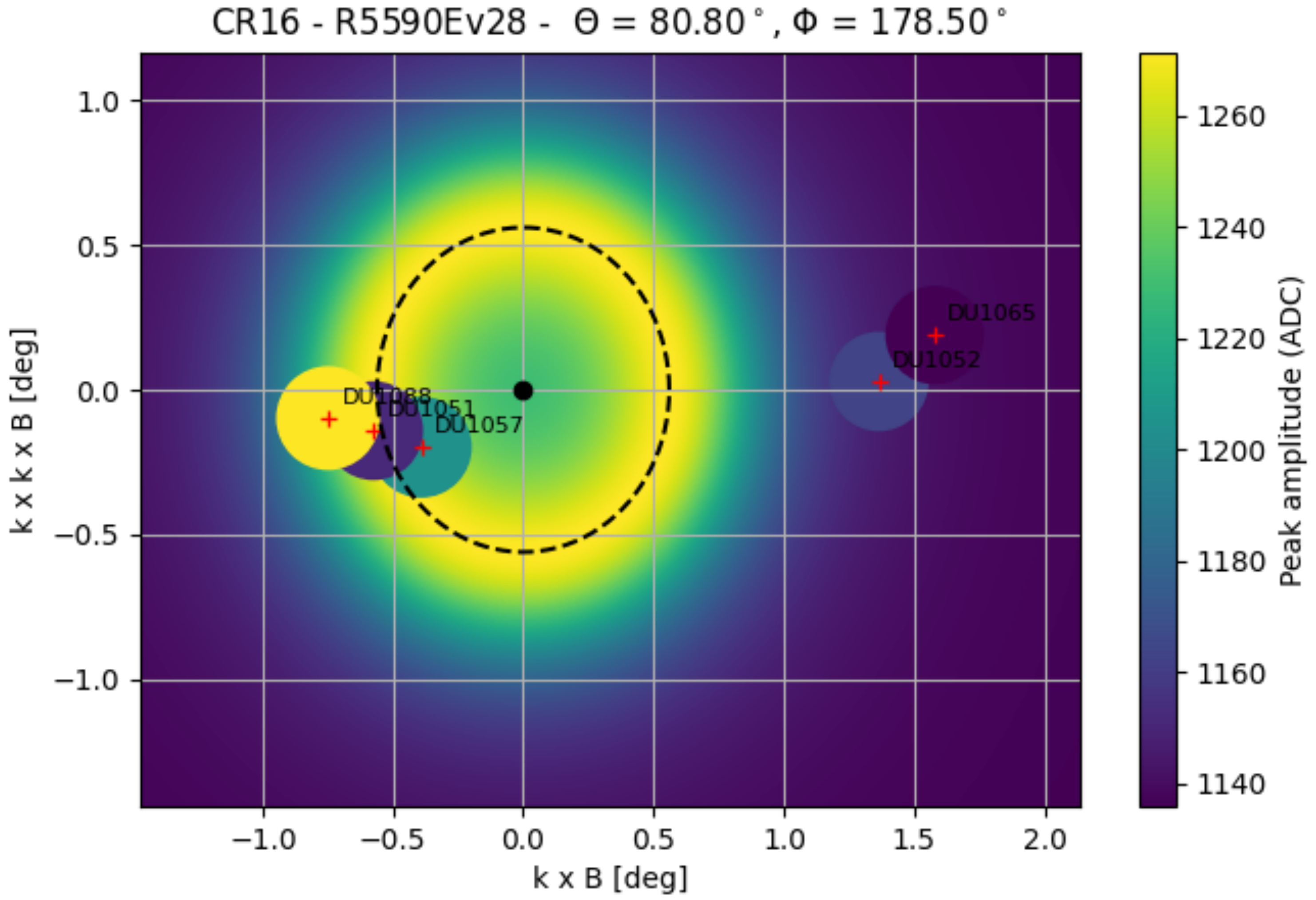
We have some very convincing events

Candidate Not Passing the Selection Criteria





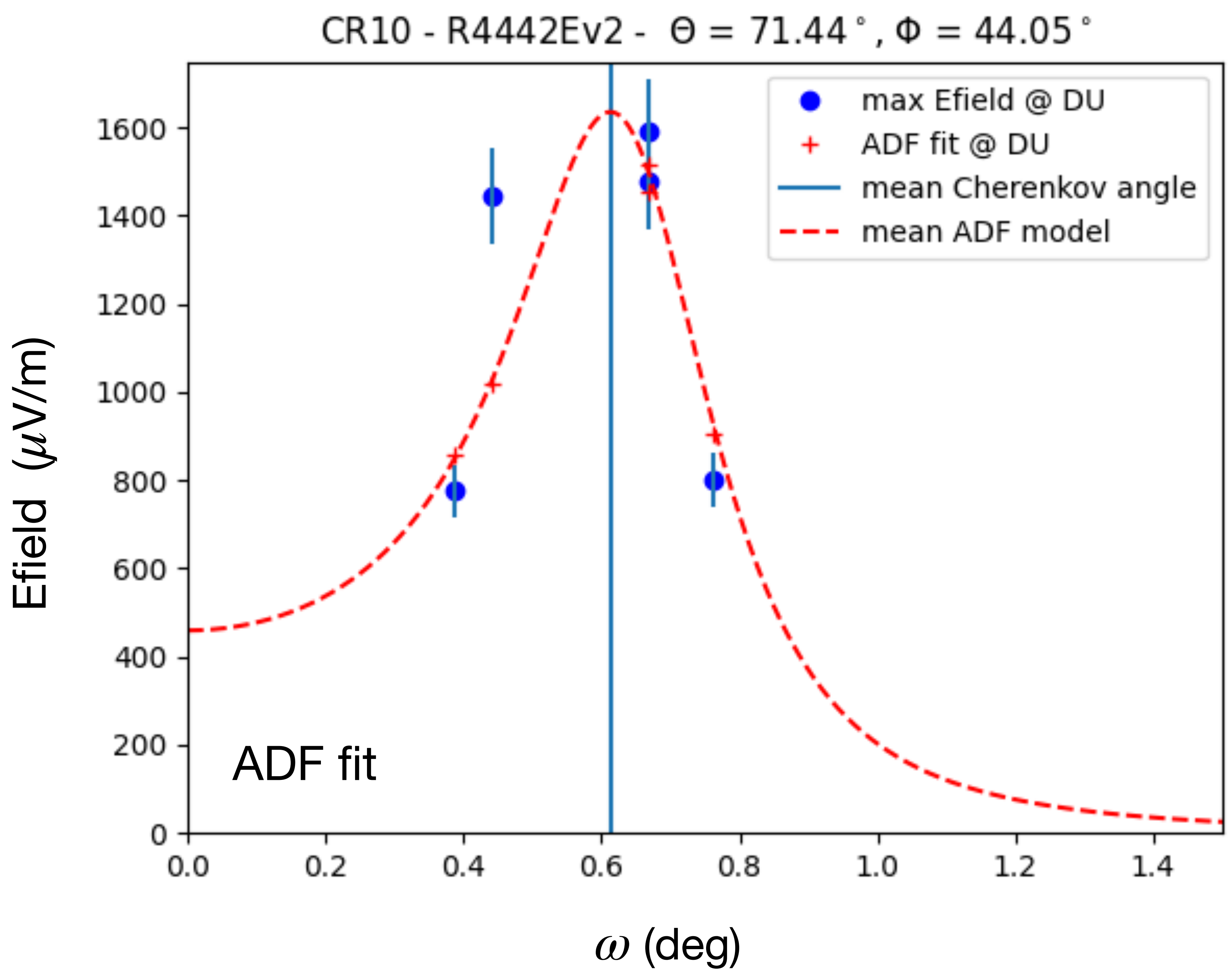




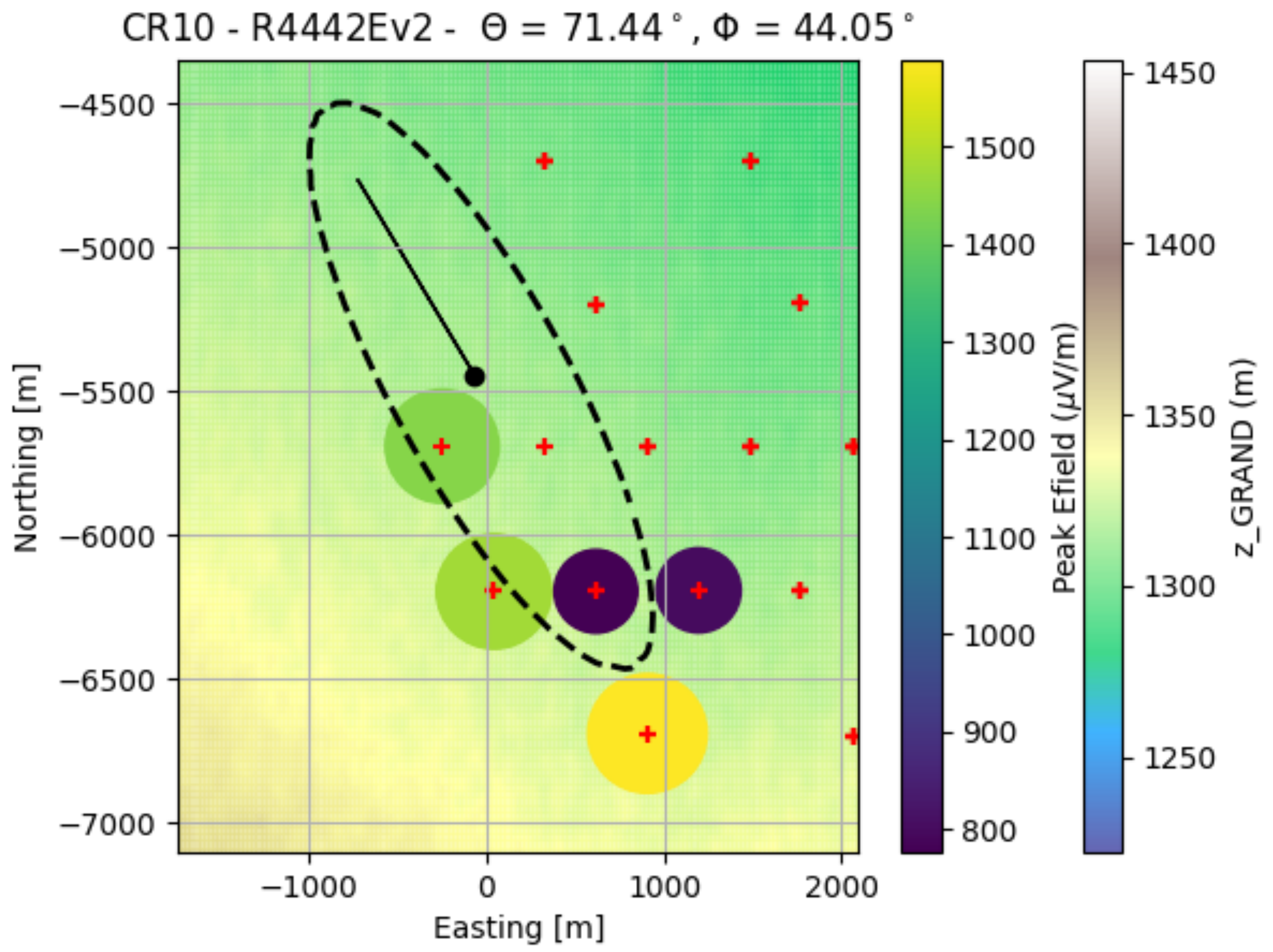
Very possible background event!

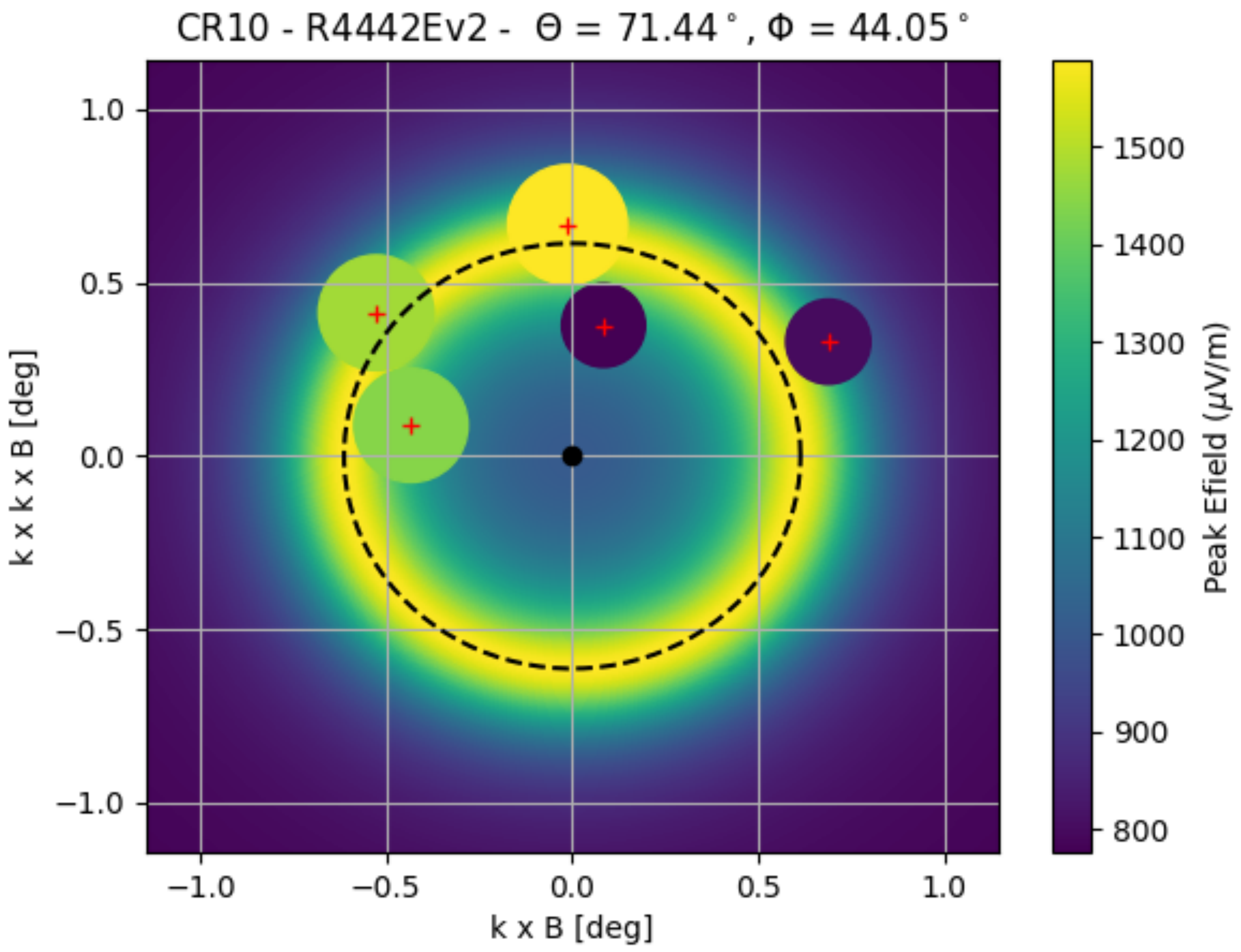
ADF reconstruction applied on reconstructed Efield

Identification of CR candidates with voltage: done
Now, test reconstruction of direction and energy with Efield

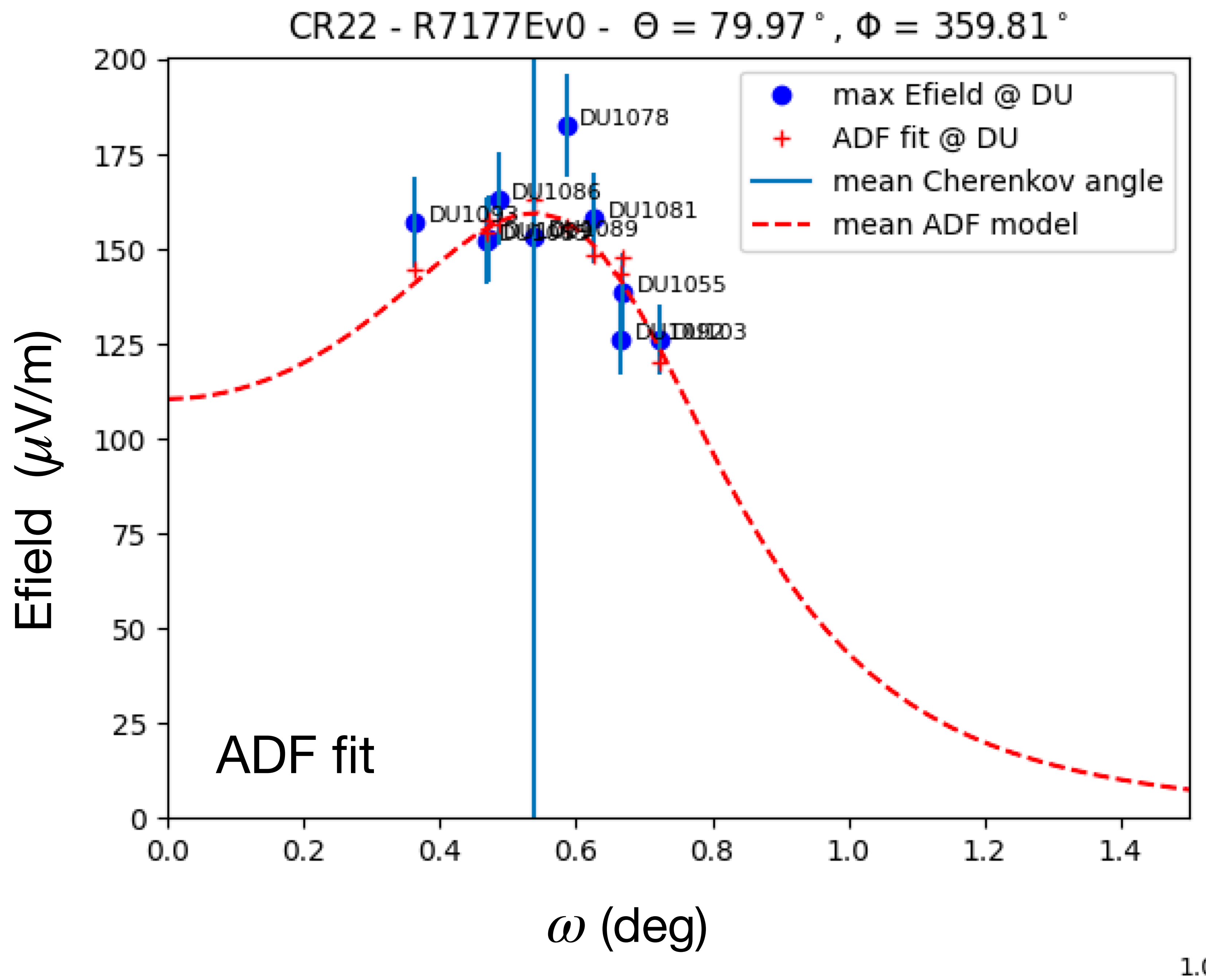


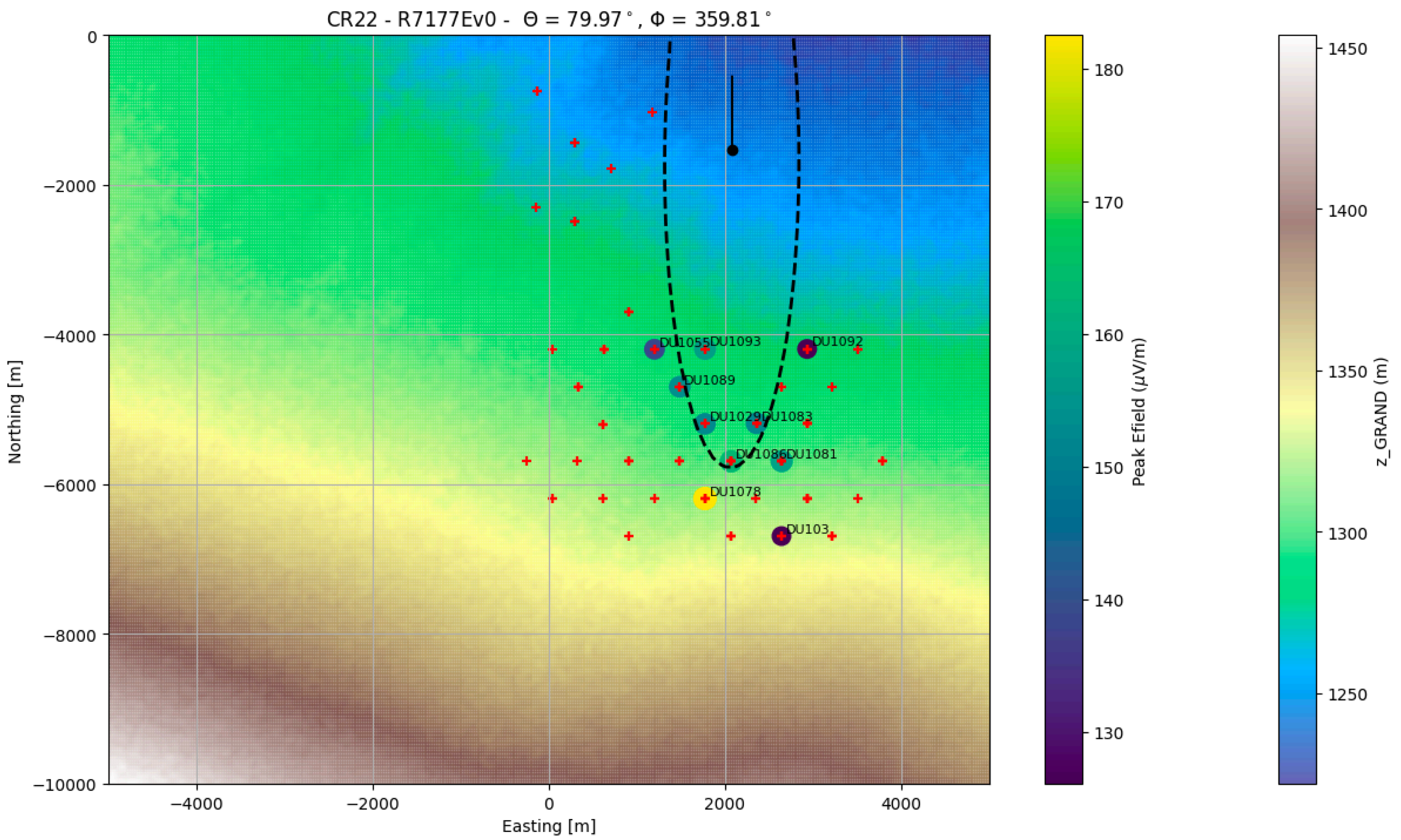
$$E_{\text{em reconstructed}} = 1.1\text{e}18 \text{ eV}$$



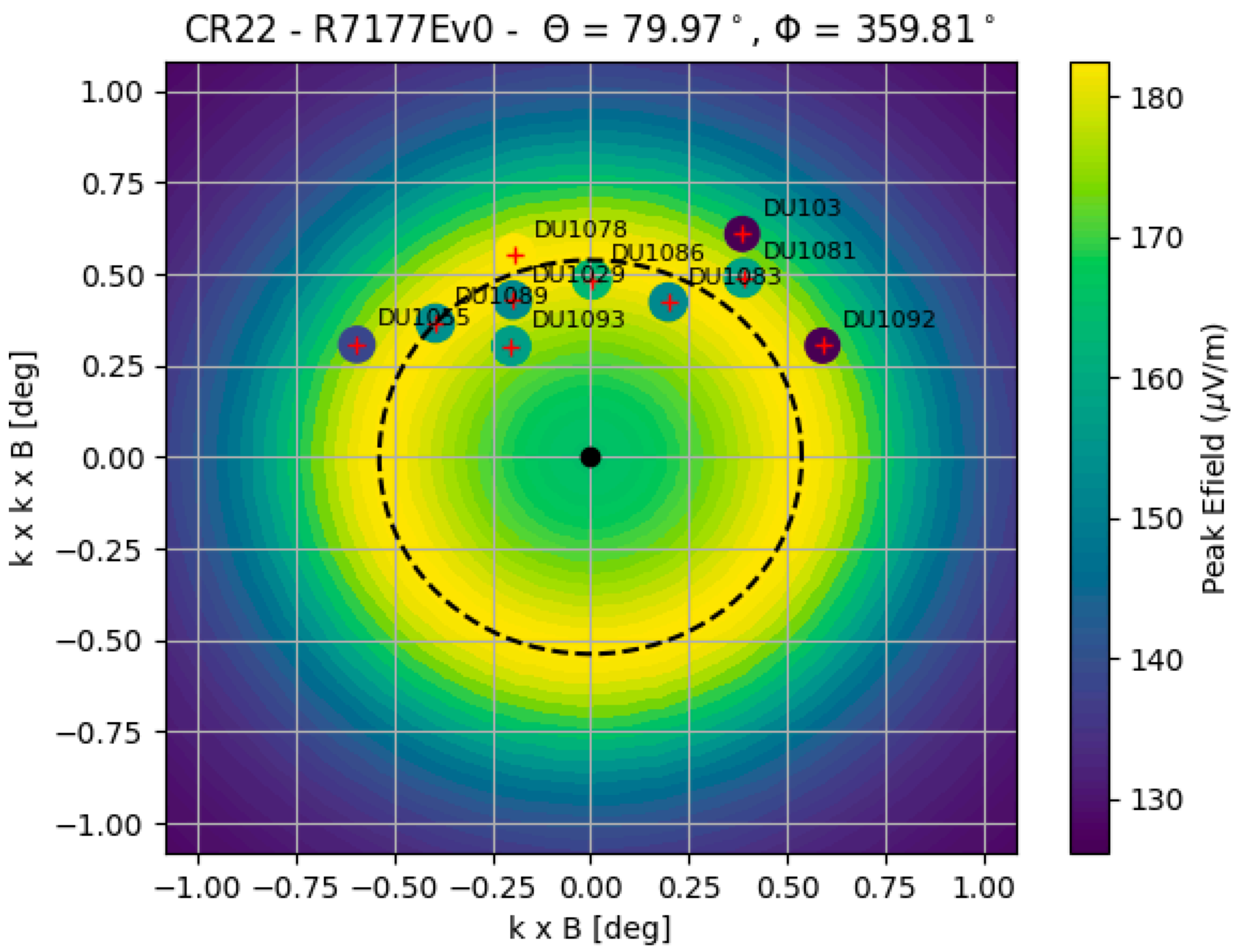


ADF reconstruction applied on reconstructed Efield

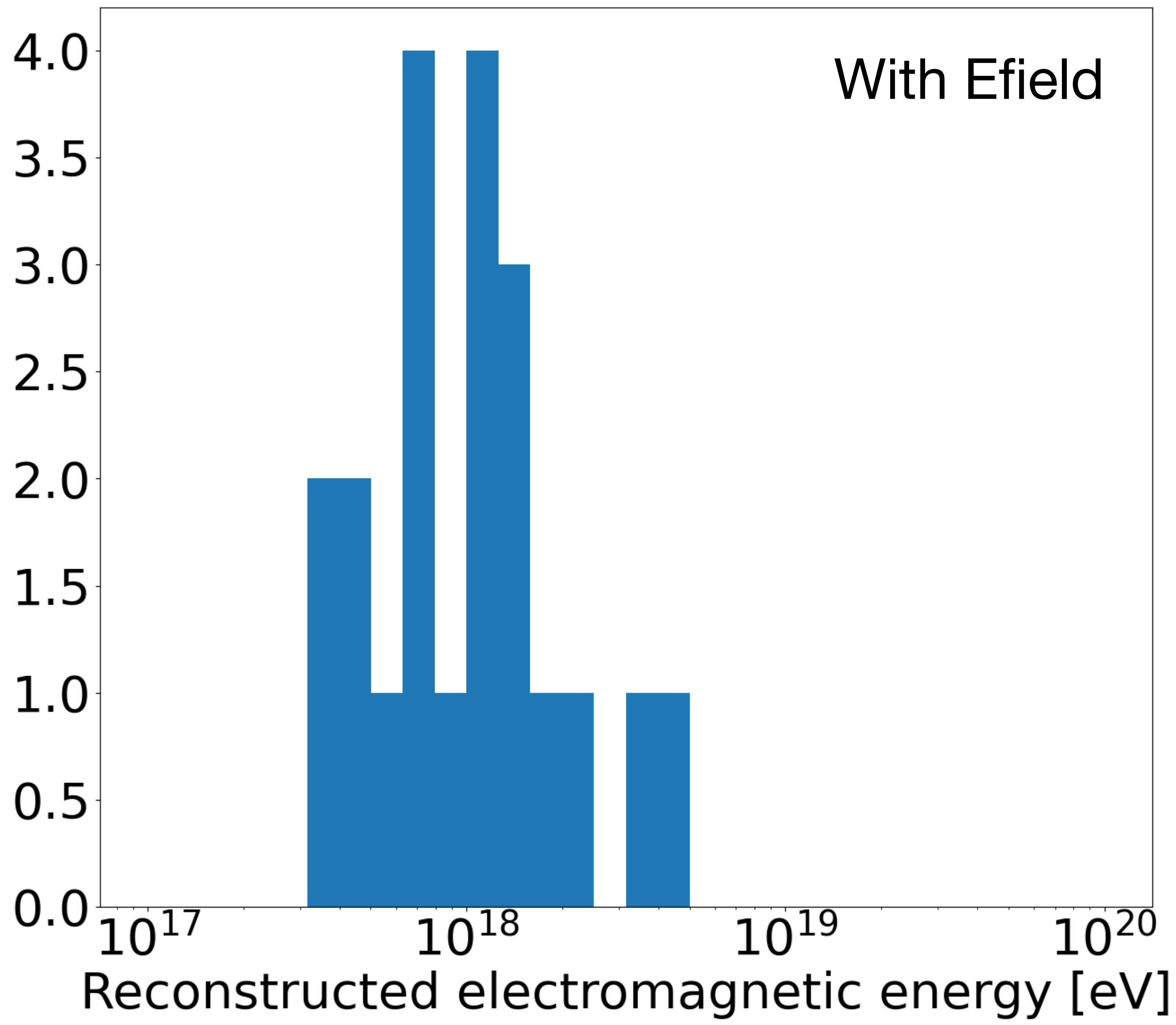




$E_{\text{em reconstructed}} = 6.4\text{e}17$ eV



Direction and energy reconstruction



*See **Guelfand**, Decoene, Martineau et al.,*
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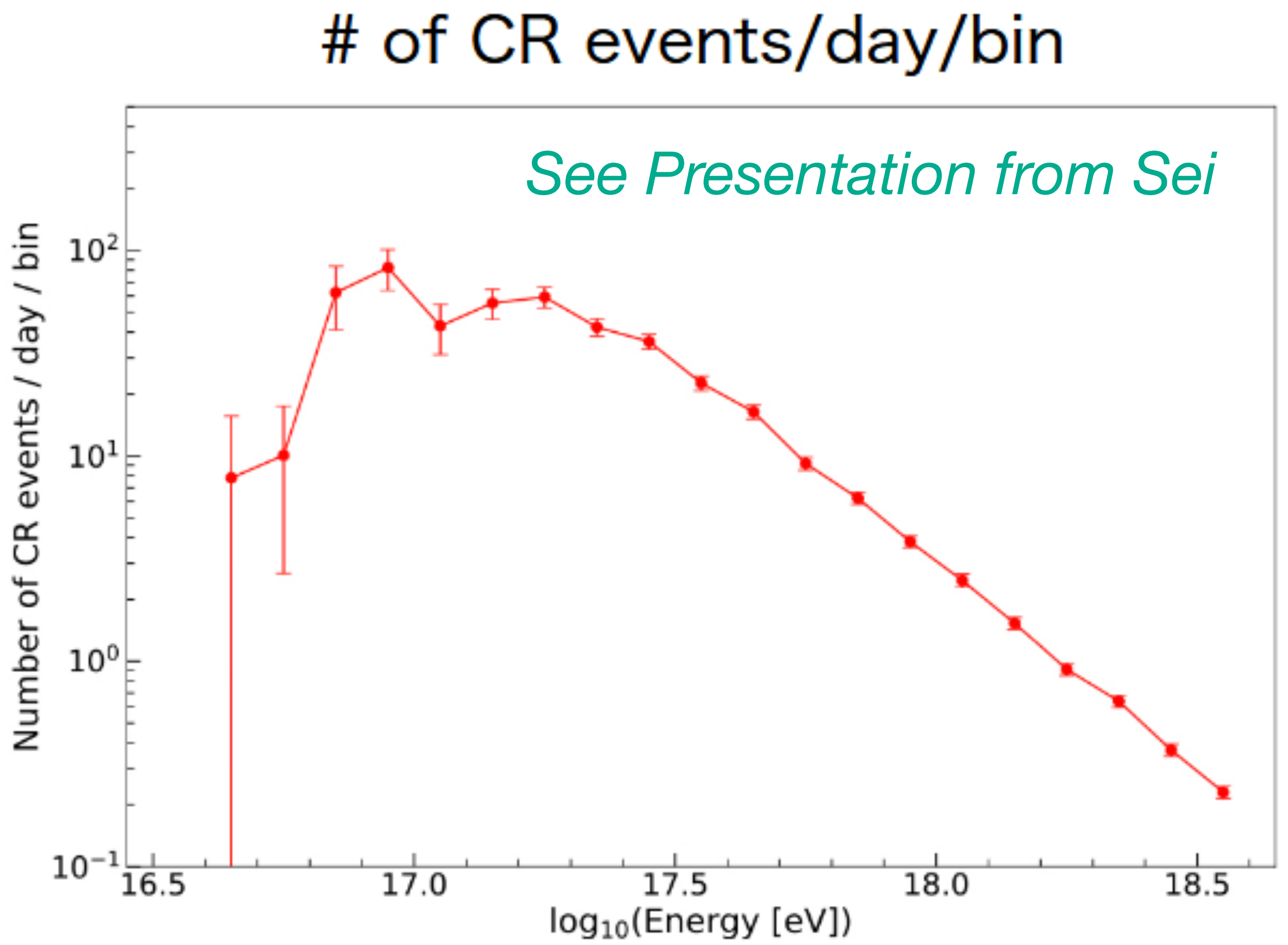
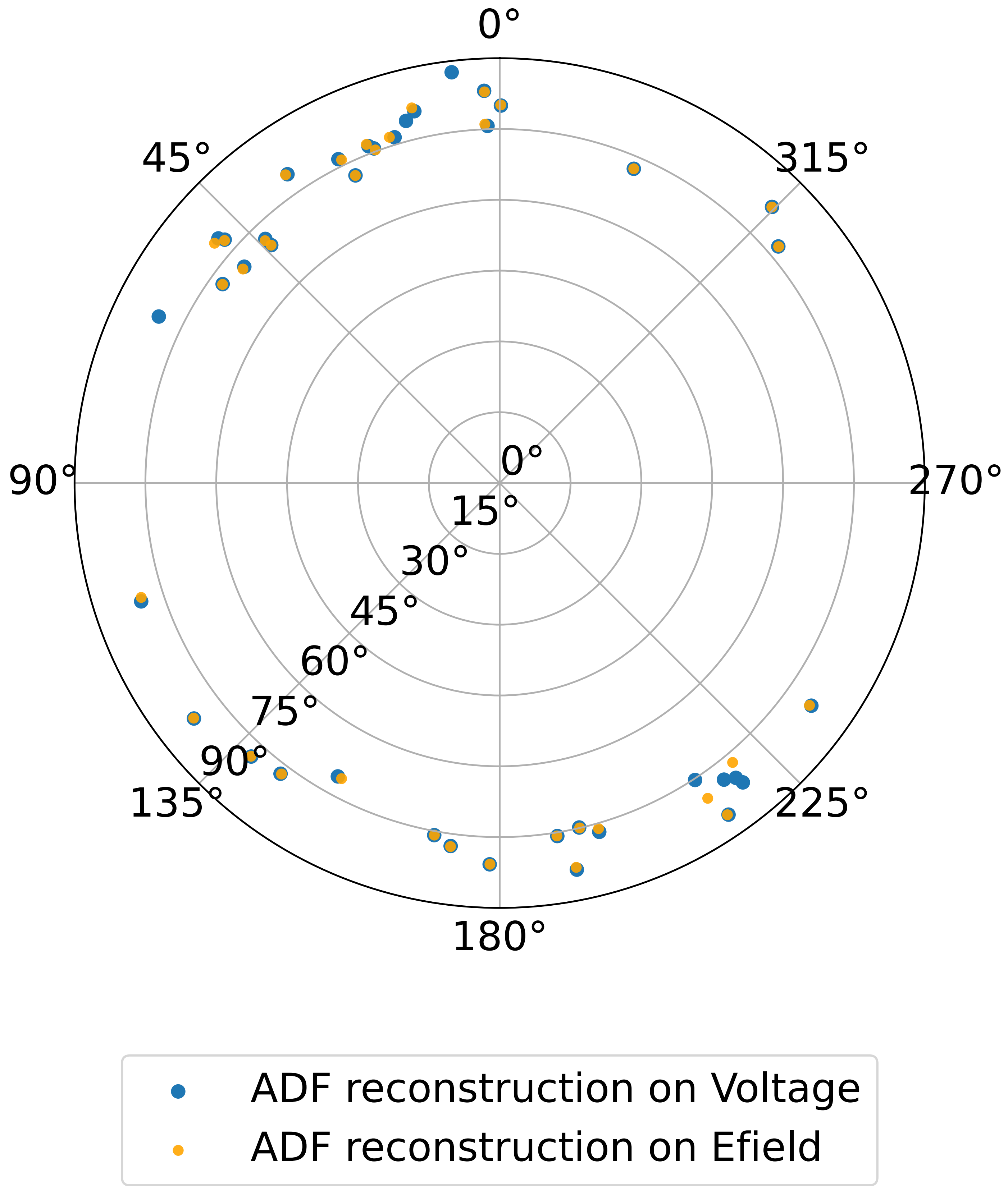
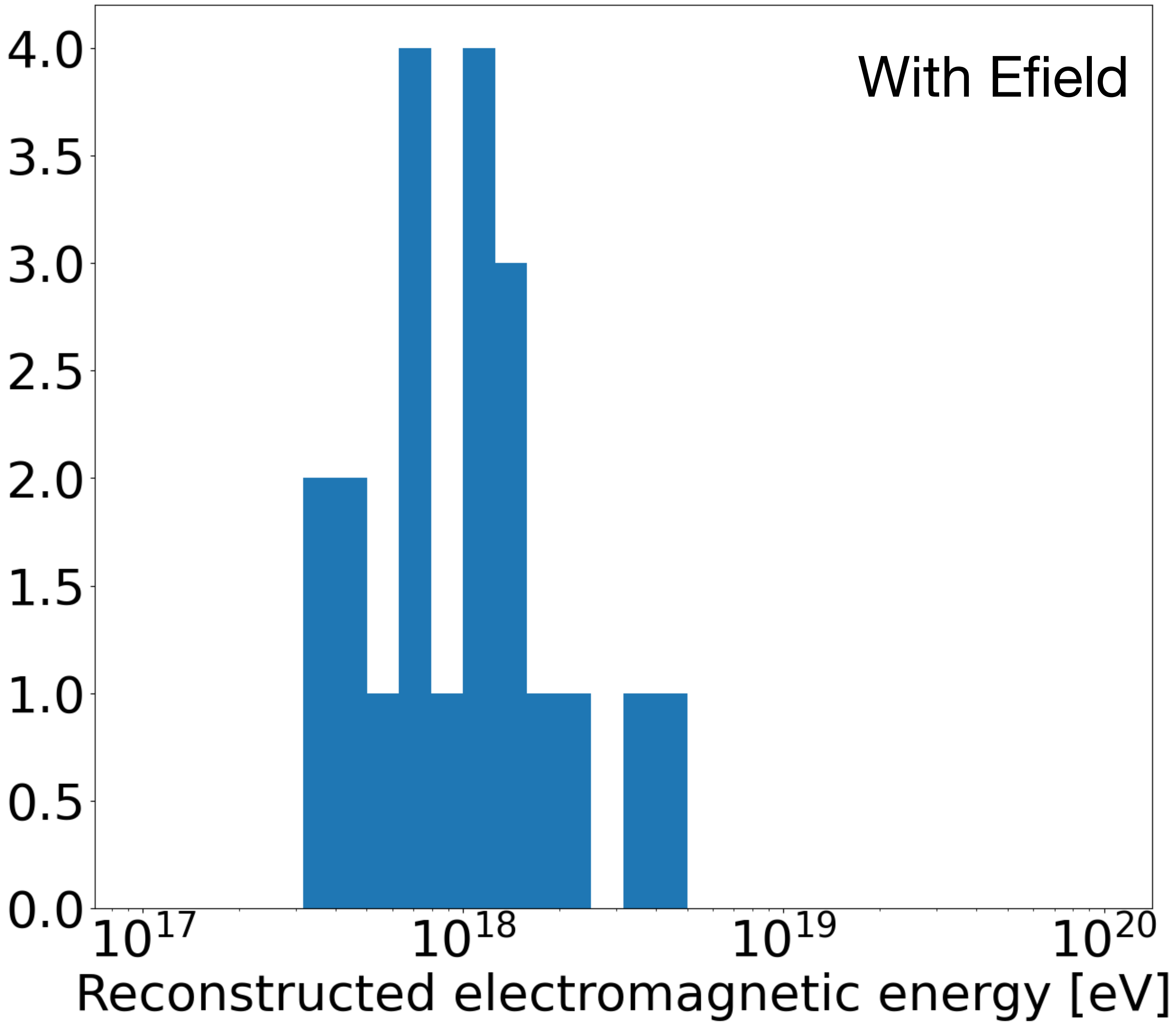
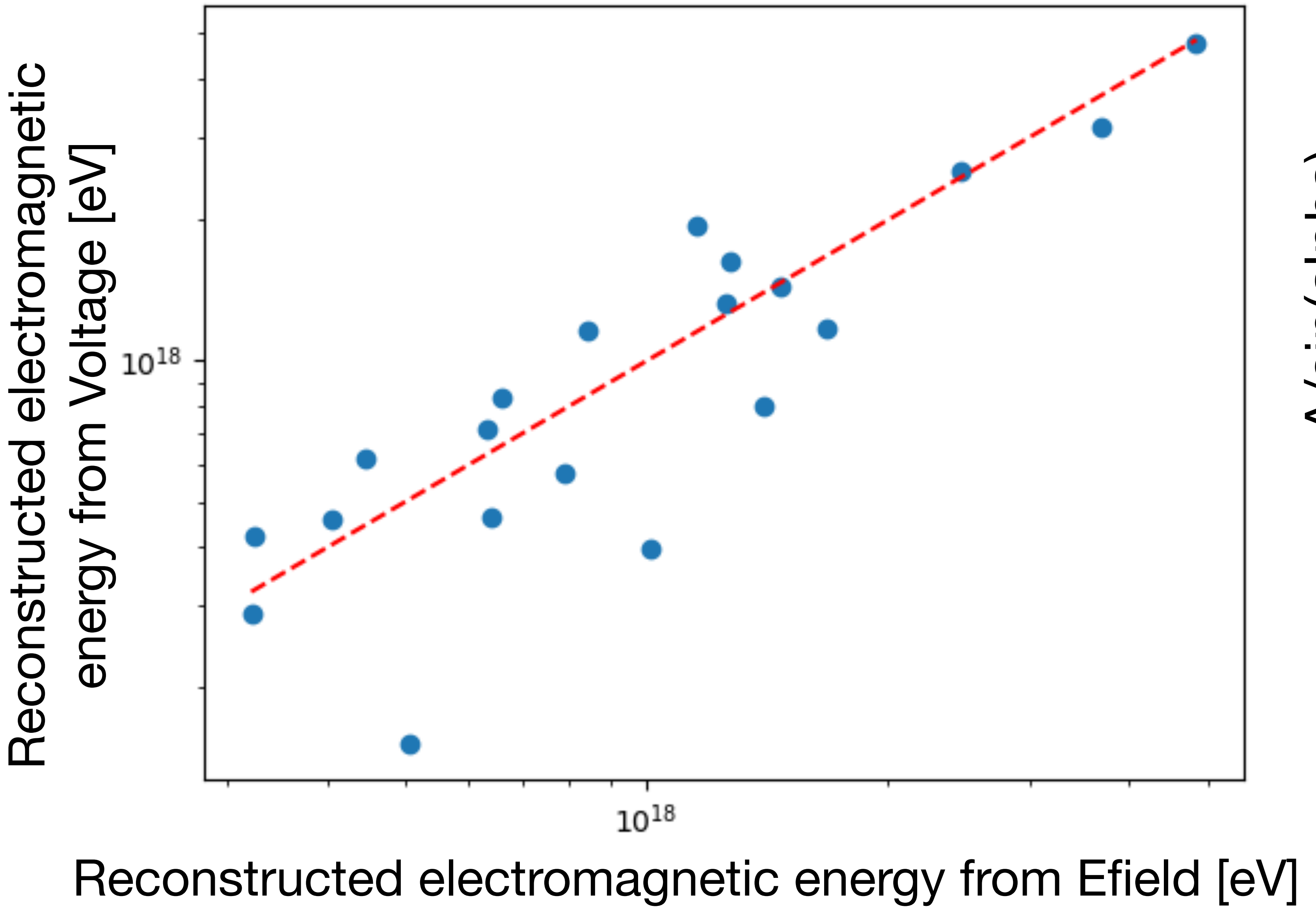




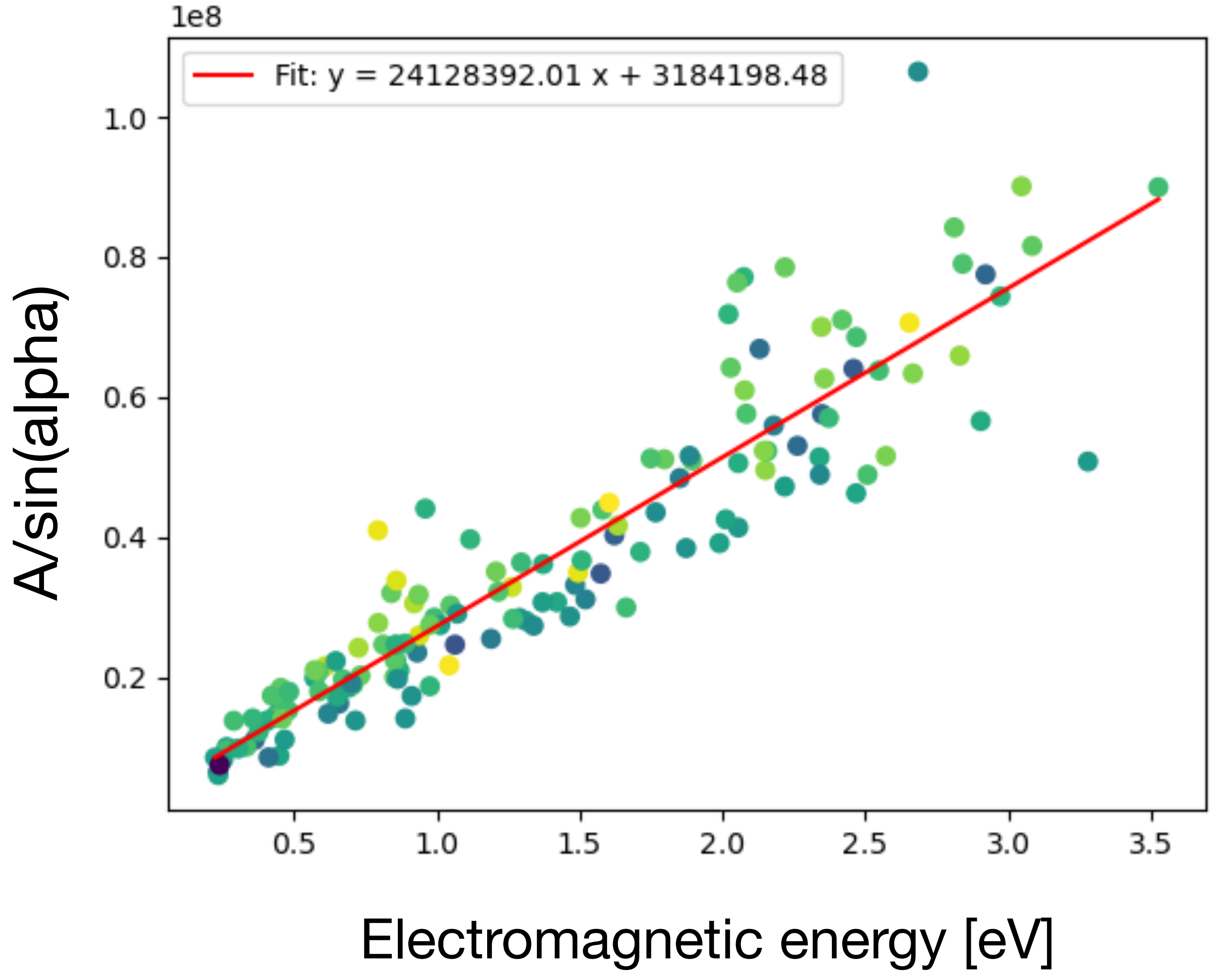
Warning: amplitude calibration not included in
Efield deconvolution and voltage
But energy distribution looks reasonable

Direction and energy reconstruction





With voltage from DC2 simulations



Energy estimator for voltage

$$E^*_{\mathrm{em}} = \frac{A}{\sin(\alpha)}a + b$$

Cross check for energy with ADF voltage:
Use the scaling law derived from simulations to estimate the energy from the ADF voltage fit
Agreement quite good: with a root mean square deviation of only 65%

Conclusion and outlook

- ADF model tested and validated on voltage traces using DC2 simulations (with good efficiency)
- Cosmic ray candidates selected via ADF applied to voltage
- Direction reconstruction performed with both E-field and voltage (results are consistent)
- Energy reconstruction based on E-field, with a cross-check using voltage

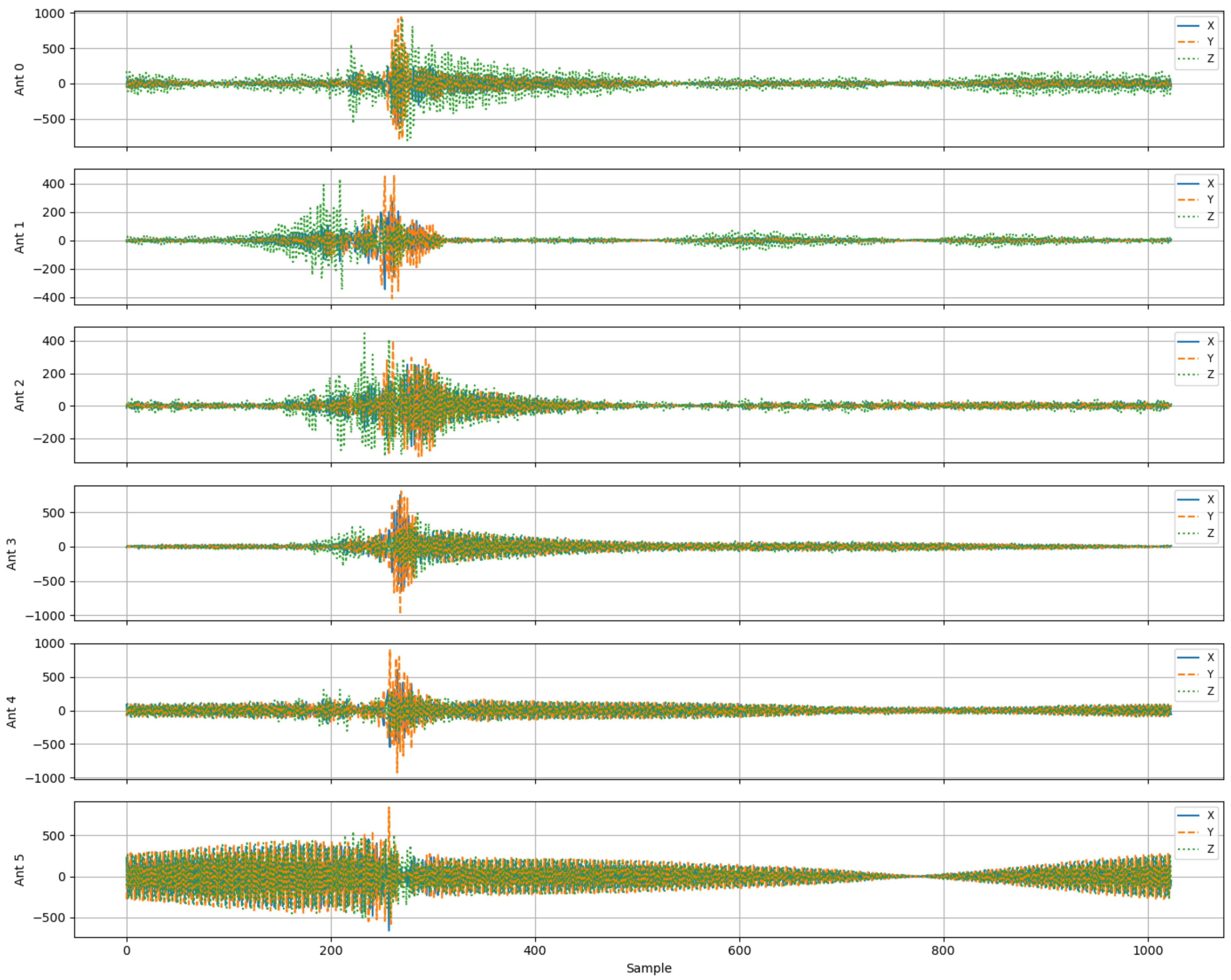
- Test background (k/l) fit + Test ADF fit on coincident data (CD)
- Compute χ^2/ndf distributions and optimize identification
- Include calibration in pipeline
- Compute reconstructed Xsource position (grammage) with SWF

Backup

EventName	Run	Event	AntennasNumber_efield	ZenithRec_efield	AzimuthRec_efield	Energy_em_efield	chi2_reduced_efield	AntennasNumber_voltage	ZenithRec_voltage	AzimuthRec_voltage	Energy_em_voltage	Chi2_reduced_voltage
CR1	1735	0	6	72.1984	54.3489	1.2682235586736768e+18	19.2087	6	72.2236	54.3002	1.6366847960742216e+18	12.62515
CR2	2560	0	5	74.9905	193.048	3.2105102891243494e+17	12.5405	5	74.8852	192.994	2.8885045095367616e+17	4.07641
CR3	2574	5	4					5	76.8379	195.926	5.221480004900508e+17	0.982704
CR10	4442	2	5	71.4409	44.0535	1.1551498880901102e+18	21.8381	5	71.6693	43.8028	1.9345311629224343e+18	1.25685
CR11	4506	2	5	71.9568	25.1197	3.236141153082982e+17	15.2058	5	71.9651	25.0992	4.2334266616285766e+17	5.72735
CR14	4612	1	5	78.9021	49.9141	1.0430881753852512e+18	6.86577	5	78.9404	48.965	1.5307338279132846e+18	105.287
CR31	4666	0	6	69.8616	43.8437	4.052650588376044e+17	19.17815	6	69.8435	43.8186	4.5639179620773824e+17	8.86535
CR18	6222	1	5	70.7786	50.1656	3.045822218388861e+17	88.162	5	70.876	49.7097	3.705429336242009e+17	8.34332
CR19	6606	4	9	77.6707	48.5769	8.440872012662884e+17	5.6224	9	77.771	48.468	1.162860717836544e+18	6.4325
CR32	6826	2	5	75.8414	169.492	4.4493506759343386e+17	16.7502	5	75.8646	169.478	6.209988221767203e+17	16.3703
CR22	7177	0	10	80.0948	359.839	6.398025336500338e+17	5.488816666666666	10	79.9696	359.812	4.612393383447543e+17	1.8952833333333332
CR24	7572	0	5	72.379	336.908	3.638333116741761e+17	69.5022	5	72.3773	336.903	3.888182130956347e+17	65.6279
CR25	7913	0	6	76.0764	2.36484	4.3874521783705126e+17	32.255	7	75.7007	1.95174	4.273614366928888e+17	13.360333333333337
CR27	8372	0	5	81.6231	13.1785	4.849702459650722e+18	1.88781	7	80.8078	12.9149	4.787663773438216e+18	9.187033333333334
CR28	8419	0	5	77.7047	172.301	1.0083011689834225e+18	18.3161	5	77.5891	172.312	3.980367307366609e+17	0.684884
CR34	9139	0						5	87.6108	6.66355	2.1711726399312154e+18	1.12907
CR35	9386	3	5	82.9281	2.22525	1.4004868551270912e+18	2.11718	5	83.1581	2.2662	8.005261602958904e+17	0.160779
CR37	9668	0	3					7	70.9669	151.13	4.3087555389934925e+17	2.674303333333333
CR38	9972	0	6	77.0229	143.156	6.594852103679282e+17	2.805785	6	77.0945	143.005	8.366734400612602e+17	0.709935
CR4	2626	13	6	79.4932	34.7692	1.6710644099438098e+18	1.476615	8	79.3576	34.4779	1.1707325709725092e+18	4.5315
CR7	3709	68	4					5	76.6373	26.4612	2.6255098840037e+17	8.64984
CR8	3711	37	4					5	80.0015	218.689	4.705063307811188e+17	12.6769
CR12	4522	38	3					5	81.1061	234.447	5.452894861440626e+18	22.1316
CR15	5041	78	5	81.7176	127.547	1.257935040077509e+18	0.273576	5	81.7159	127.619	1.328634684171267e+18	0.903116
CR16	5590	28	4					5	80.7974	178.499	5.864552788014391e+18	321.914
CR0	576	820	10	78.2397	137.709	6.32178417645269e+17	14.214233333333333	10	78.2513	137.764	7.173762288183375e+17	0.9901233333333334
CR17	6184	46	5	75.7335	189.208	5.064053671157804e+17	1.41199	5	75.7717	189.269	1.5141684378279914e+17	5.31483
CR20	7003	16	6	77.4381	310.3	7.88418176303038e+17	3.74135	6	77.4113	310.353	5.734040369700268e+17	1.295535
CR21	7137	83	5						78.758	217.086	1.2478679898803651e+17	8.06238
CR26	7961	50	4					5	76.5764	21.2662	4.984012636085028e+17	11.8926
CR29	8602	47	4					5	83.5074	191.282	1.6805323193810842e+18	39.0612
CR30	8716	40	7	82.0854	315.414	2.458263225584772e+18	3.5931	7	82.1343	315.413	2.5528300789588367e+18	5.349466666666667

Backup

Reconstructed Efield tracesRun: Run:2626 Event:13



Reconstructed Efield tracesRun: Run:5590 Event:28