Reconstruction of energy and arrival directions of UHECRs registered by fluorescence telescopes with neural networks

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Workshop on Machine Learning for Analysis of High-Energy Cosmic Particles
University of Delaware, January 27–31, 2024

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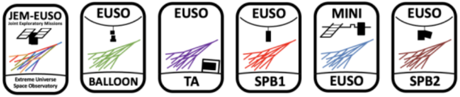
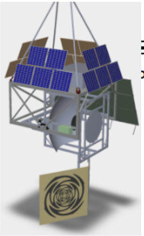
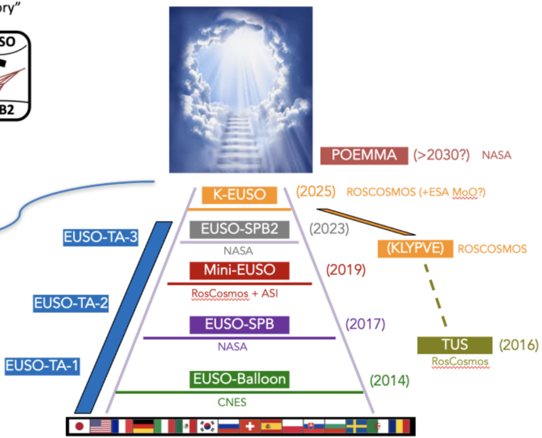




~~EUSO-SPB3 aka~~ PBR

POEMMA Balloon with Radio

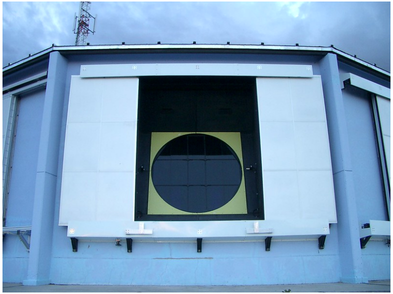
Stairway to heaven!



The stairway by Etienne Parizot

Fluorescence telescopes for registering UHECRs

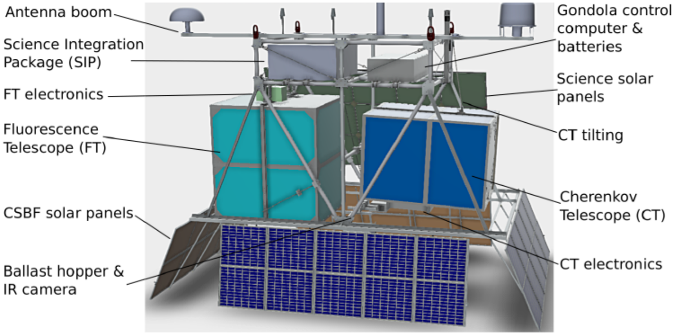
Deep-Learning based Reconstruction of the Shower Maximum Xmax using the Water-Cherenkov Detectors of the Pierre Auger Observatory, The Pierre Auger Collaboration, JINST 16 P07019 (2021)



Source: Auger

Can we reconstruct energy and arrival directions of UHECRs registered by FTs with neural networks?

EUSO-SPB2 (2023)



Stratospheric experiment: fluorescence and Cherenkov telescopes of the Schmidt type

FT: input aperture ∅1.1 m, field of view $12^\circ \times 36^\circ$, concave focal surface 48×144 (3 parts 48×48); time resolution 1 μs.

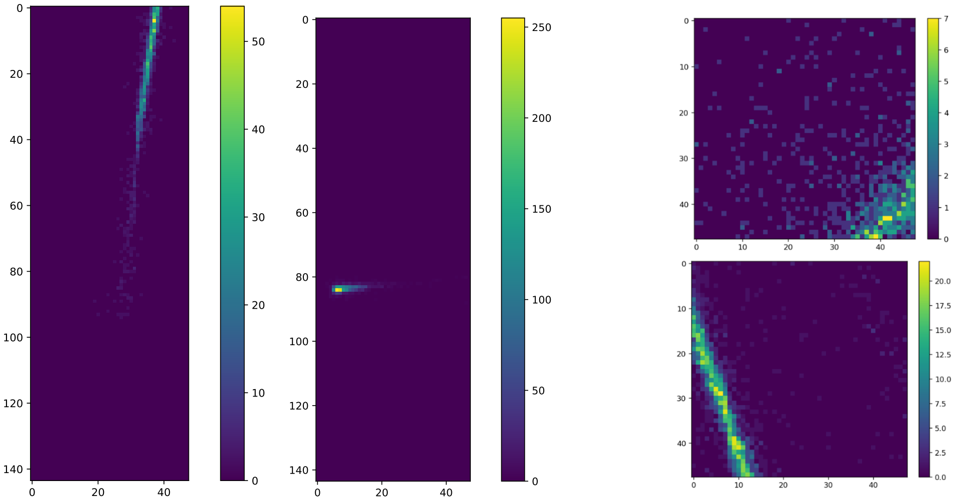
Details: Eser et al., PoS(ICRC2021) 395 (2021) 404; Eser et al., PoS(ICRC2023) 444 (2023) 397.

EUSO-TA: ground-based FT at the Telescope Array site (Utah, USA)

Refractor telescope with two Fresnel lenses ⌀1 m, focal surface 48×48.
Field of view $10.6^\circ \times 10.6^\circ$

Details: Adams et al., Exp. Astronomy 40 (2015) 301; Abdellaoui et al., ApP 102 (2018) 98

What do we need to recognize? Examples of integrated tracks (w/o bg)



Left two panels: EUSO-SPB2, tracks from proton showers: 26 EeV, $\theta = 63^\circ$; 96 EeV, $\theta = 19^\circ$
Right: EUSO-TA, tracks from proton-generated showers 10 EeV (top) and 68 EeV (bottom)

Track recognition via semantic segmentation

For Mini-EUSO, we developed a 2-step method of meteor track recognition employing a CNN for the signal localization in a 3D chunk of data and an MLP identifying hit pixels within the chunk [Algorithms, 2023]. It can be applied here, too.

Completely different approaches are possible. One of them is **semantic segmentation**, which means predicting, for each pixel of an image, the class of the object to which it belongs.

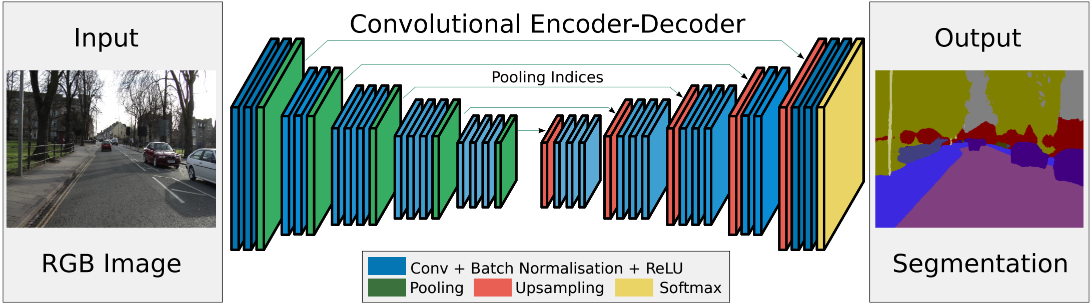
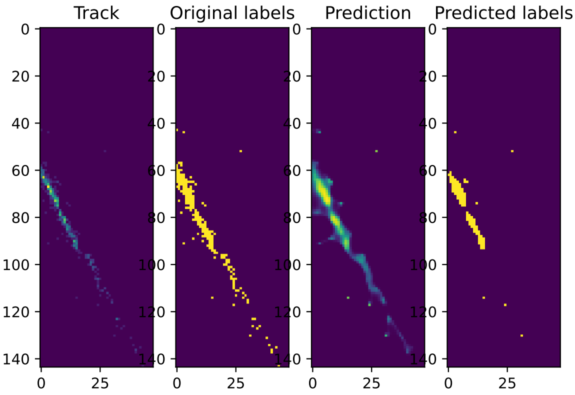
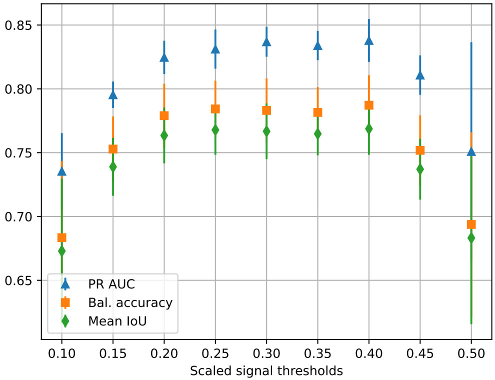


Figure: https://arxiv.org/abs/1511.00561

How should we label hit pixels for training the ANN?

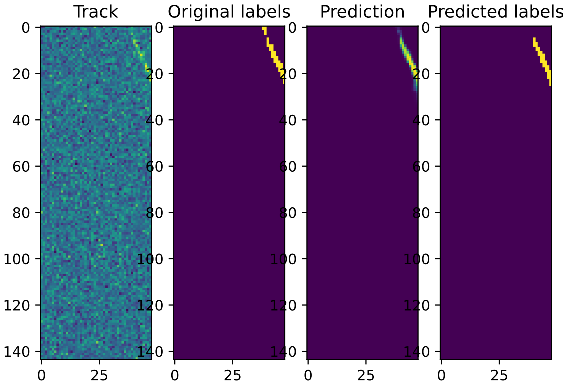


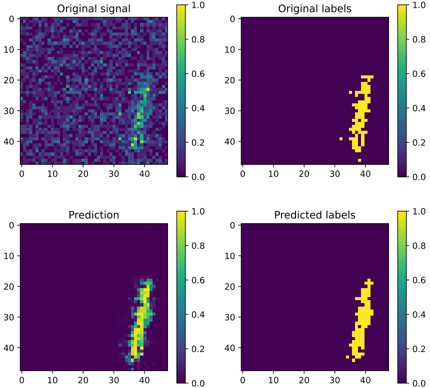


Left: Scaled integrated track with a threshold 0.05. With a low threshold, predicted tracks look blurred.

Right: Performance metrics (at 50 EeV). Optimal thresholds for labelling are around 0.25–0.35.

Track recognition: examples for EUSO-SPB2 and EUSO-TA





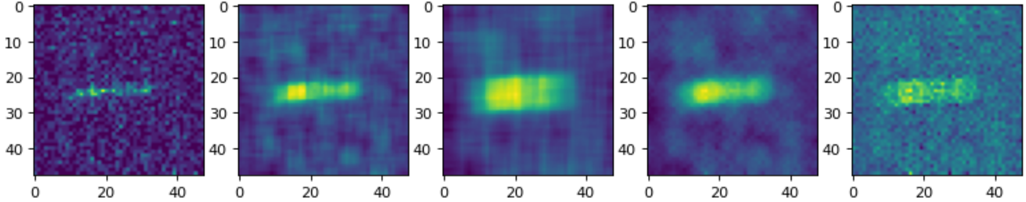
The training sample for EUSO-TA: 32k events, 12 frames each, 384k images in total.

The testing sample: 500 events, each consisting of 12 frames (some of which w/o tracks).

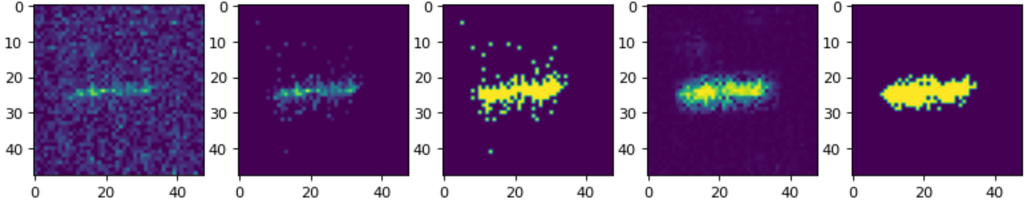
PR AUC, balanced accuracy, and mean IoU metrics were equal to 0.941, 0.934, and 0.882 respectively.

Similar results for EUSO-SPB2.

Track recognition with gradient boosting and OpenCV library



Visual representation of the generated features. From left to right: the initial signal with background illumination, 5-neighbor average, 10-neighbor average, a bilateral filter, and an inverse bilateral filter.

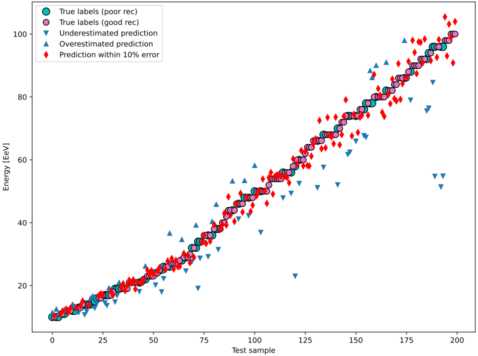


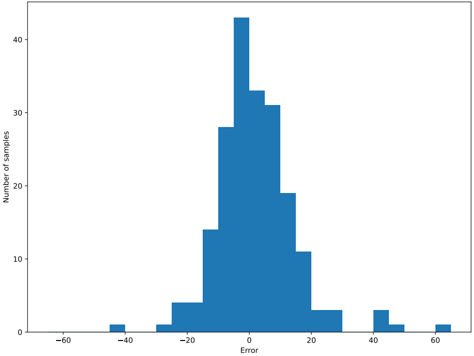
From left to right: the initial signal with background illumination, the same signal with the background removed, the focal surface with hit pixels (yellow), predicted probabilities for the pixels to belong to the track, recognized hit pixels. **Pixel-level sampling!** [See details in arXiv:2501.02311]

Performance metrics are slightly lower than for the CED but large training data sets are not required.

Energy reconstruction for EUSO-SPB2 (w/o track recognition)

Tool: simple 6-layer CNN implemented in Python with TensorFlow. Data: integrated tracks

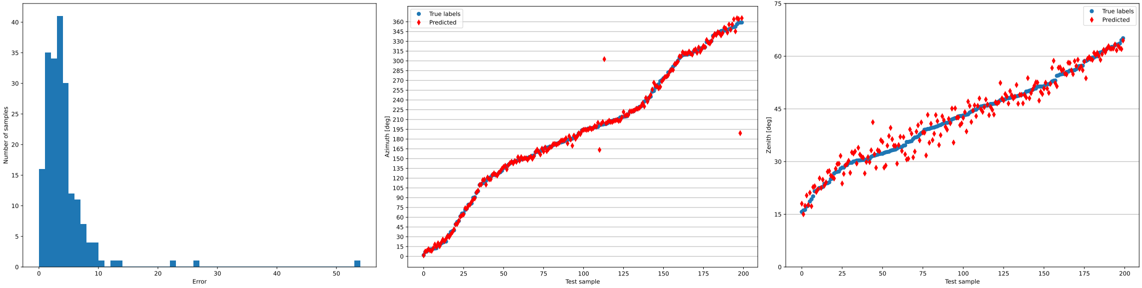




Left: energy reconstruction for SPB2 using integrated tracks. MAPE=9.1%, maximum error 60.2%

Right: histogram of errors expressed in %%. The mean equals 2%, the standard deviation equals 12.6%.

Arrival direction reconstruction for EUSO-SPB2



Left: angular separation between true and predicted directions. Median$= 3.3^\circ$

Center: reconstruction of azimuth angles

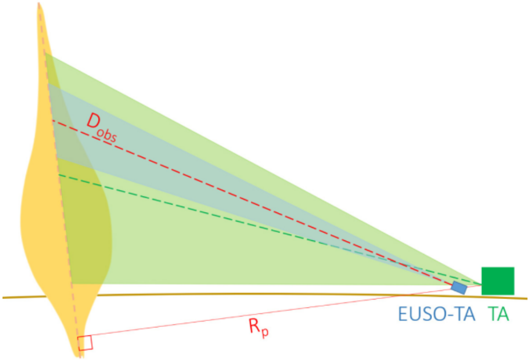
Right: reconstruction of zenith angles (reconstructed separately); mean error 0.1°, std 2.4°

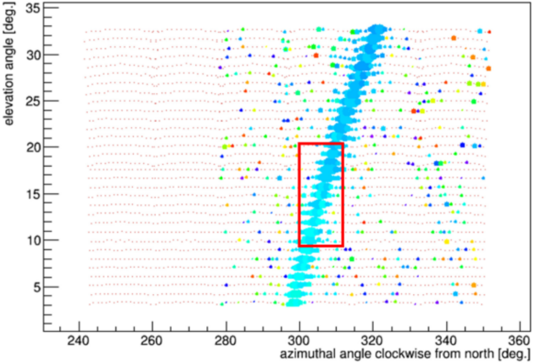
Loss functions: MSE, MAE, angular separation

Largest errors in arrival directions are mostly due to poorly reconstructed *azimuth*: the opposite direction[1] or a nearly vertical shower with the track just too short to reconstruct azimuth properly.

[1]Only when using integrated tracks instead of full signals

EUSO-TA: difficulties of reconstruction





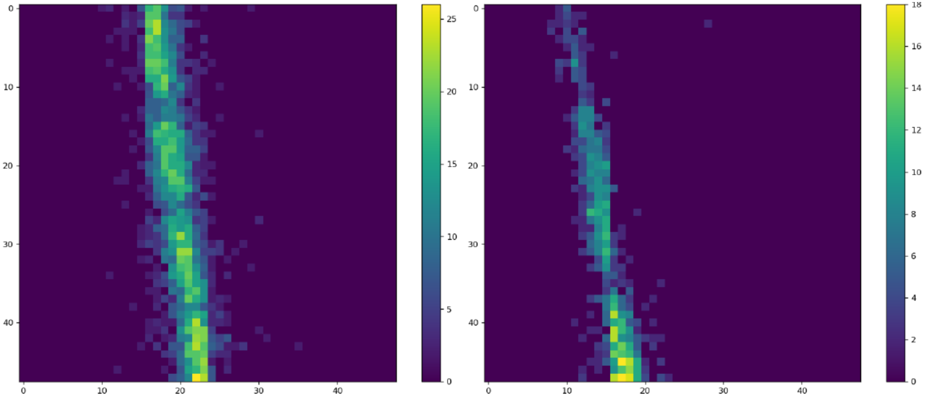
Left: small field of view of EUSO-TA vs. that of a FT of Telescope Array $\longrightarrow$ **no complete tracks**[2]

Right: UHECR detected on May 13, 2015 as seen by a TA Black Rock Mesa telescope. The red frame: FoV of EUSO-TA [both plots: Adams et al., ApP 163 (2024) 103007]

Another problem: time resolution 2.5 μs in comparison with 100 ns at TA and Auger $\Rightarrow$ just a few images for an event (maybe 1) $\Rightarrow$ difficult to reconstruct the arrival direction

[2] Unless a shower is directed towards the telescope "eye"

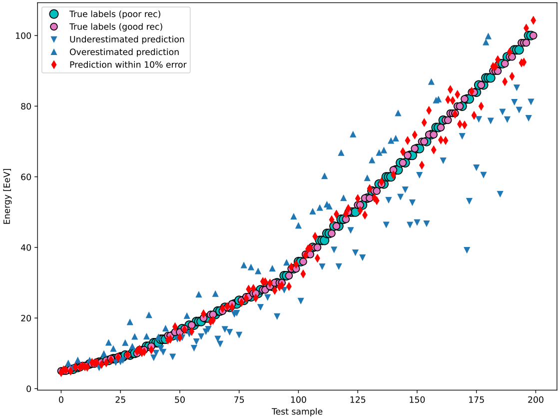
Signal depends on the distance from the telescope to the shower

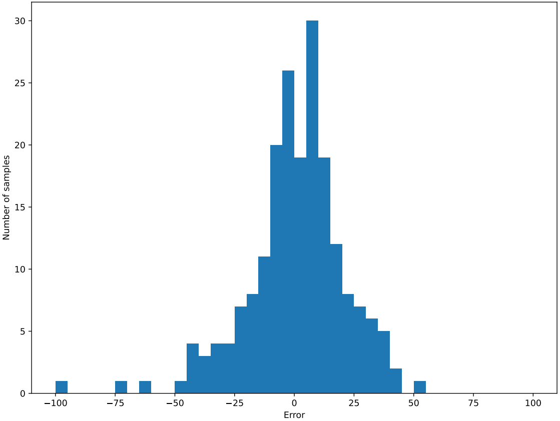


Example: integrated tracks
Left: E = 38 EeV (D = 10.6 km), $\theta = 33^\circ$, $\phi = 173^\circ$
Right: E = 92 EeV (D = 18 km), $\theta = 42^\circ$, $\phi = 15^\circ$

Integrated tracks are not enough, we need stacks of images

EUSO-TA: energy reconstruction (protons, telescope elevation angle 10°)

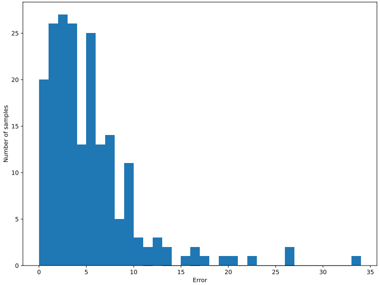


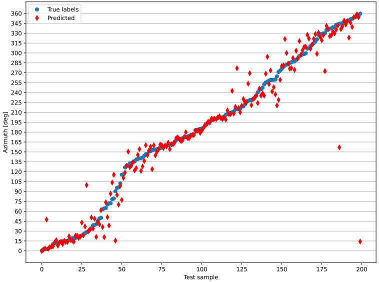


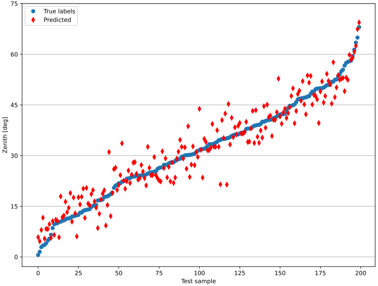
Left: true labels vs. predicted ones (units: EeV). MAPE=15.2% for $E = 5 \ldots 100$ EeV

Right: histogram for percentage error. Mean=0.8%, std=20.7%

EUSO-TA: reconstruction of arrival directions







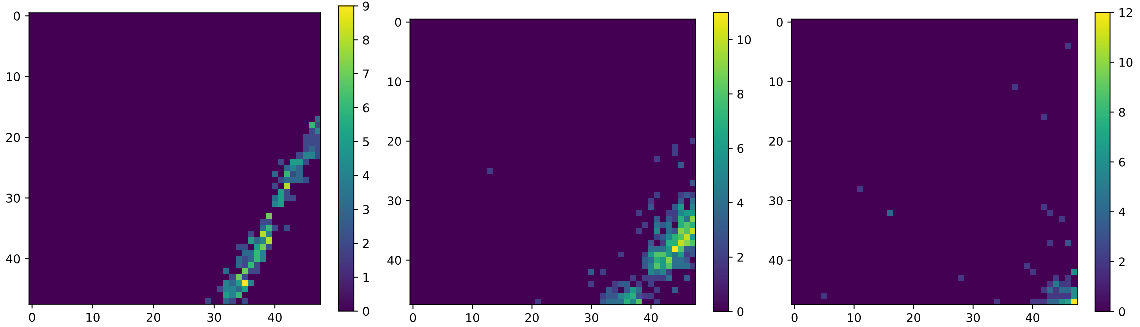
Left: angular separation between true and predicted directions. Median$= 4.1^\circ$

Center: reconstruction of azimuth angles (the axis is $0^\circ - 180^\circ$)

Right: reconstruction of zenith angles

The largest errors of reconstruction are for events with just a few hit pixels and 1–2 “active” frames

Examples of EUSO-TA events difficult to reconstruct

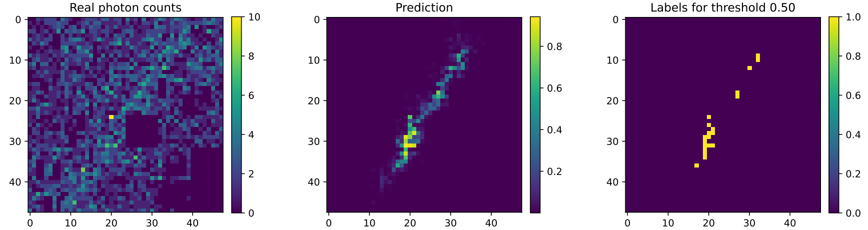


Left: integrated track of an event with the largest error in energy reconstruction (98%).
Only two active frames.
A similar event with another AD had 7 active frames, the energy was reconstructed with the error $\sim 1\%$

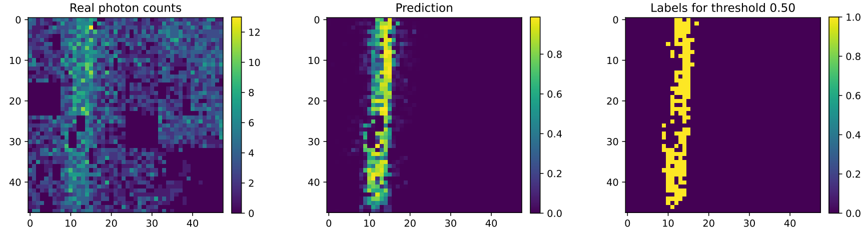
Center: error in arrival direction 26.5°. Only two active frames

Right: error in arrival direction 33.6°

EUSO-TA, real data. VERY PRELIMINARY RESULTS!!!



May 13, 2015. Energy by TA: 1.15 EeV. Our best estimates (lower, upper): 1.05 EeV, 1.16 EeV



Nov. 7, 2015: Energy by TA: 2.63 EeV. Our best estimates (lower, upper): 2.08 EeV, 4.80 EeV

Both events have a single active frame; they were registered with the elevation angle 15°

Summary

- Tracks of extensive air showers registered with a fluorescence telescope can be recognized by convolutional encoder-decoders and by classical ML methods
- A proof-of concept 6-layer CNN for reconstruction of energy and arrival directions of UHECRs was tested on simulated data for the EUSO-SPB2 and EUSO-TA fluorescence telescopes and demonstrated reasonable efficacy.

  The same CNN works for both telescopes with just different input data representations.
- There are a few ways to improve the performance of the CNN
- It would be interesting to apply the approach to the FTs of the Telescope Array experiment and the Pierre Auger Observatory

Full details can be found in arXiv:2408.02440 and arXiv:2501.02311

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Thank you for your attention!

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