Реконструкция ШАЛ, зарегистрированных флуоресцентными телескопами, с помощью нейронных сетей

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[a]Моделирование и анализ для EUSO-TA поддержаны грантом РНФ 22-62-00010;
разработка нейронных сетей для EUSO-SPB2 была выполнена при поддержке гранта РНФ 22-22-0367.

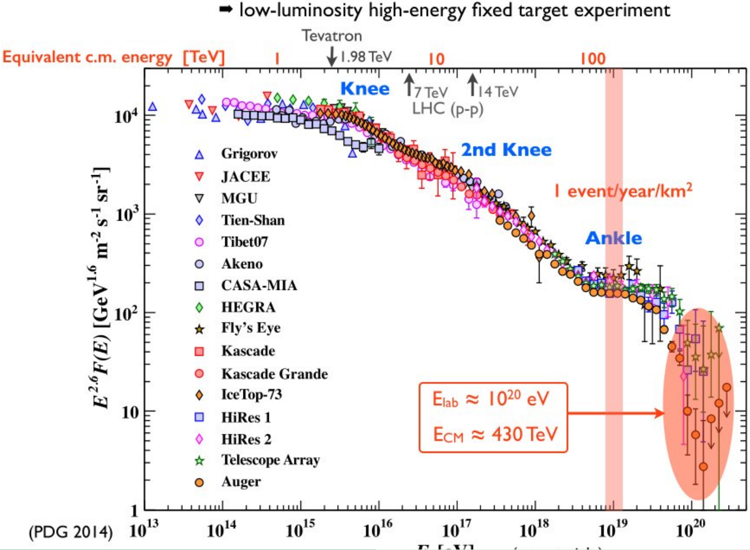
Глобальный предмет исследований: космические лучи предельно высоких энергий

КЛ ПВЭ: $E \gtrsim 5 \times 10^{19}$ эВ (начиная с предела ГЗК)

1961: **50 ЭэВ** (Volcano Ranch)
1962: **100 ЭэВ** (Volcano Ranch)
1991: **320 ЭэВ** (Fly's Eye)
1993: **213 ЭэВ** (Agasa)
2021: **244 ЭэВ** (Telescope Array)

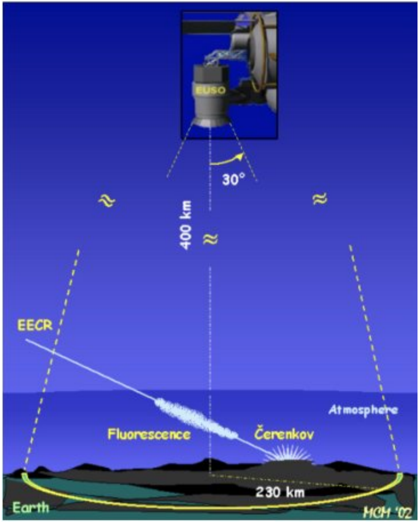
Природа и происхождение КЛ ПВЭ остаются загадкой!

Одна из ключевых проблем: крайне низкий поток



Изучение КЛ ПВЭ из космоса и с земли

1980: Linsley, Benson:



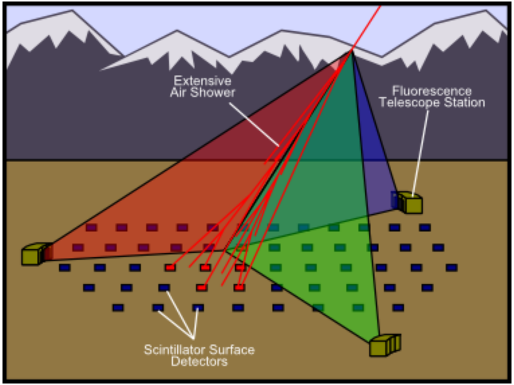
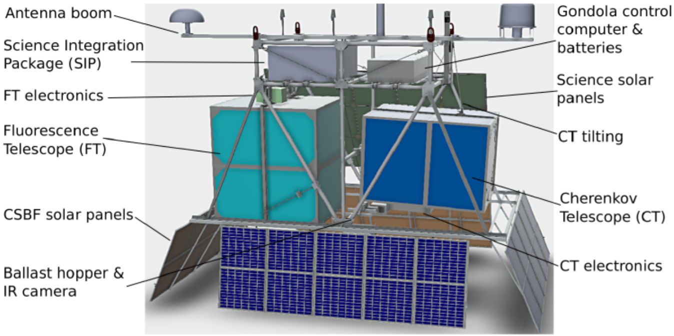


Figure: Telescope Array

EUSO-SPB2 (2023)



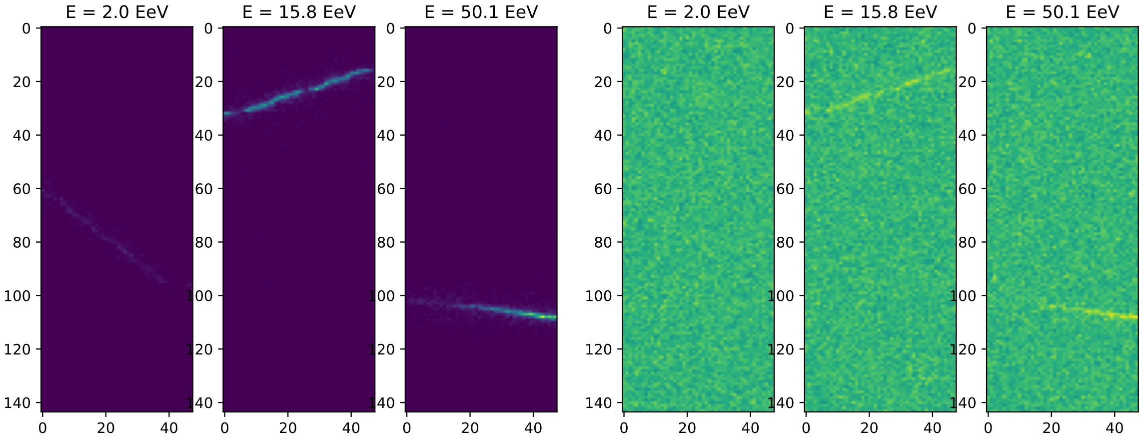
Стратосферный эксперимент: черенковский и флуоресцентный телескопы.

FT: входное окно $\varnothing 1$ м, поле зрения $12^\circ \times 36^\circ$, фокальная поверхность 48×144.

The datasets, integral tracks w/o & with background

Two datasets simulated with $\overline{\text{Off}}\underline{\text{line}}$: energies $10^{18.1}$ eV, $10^{18.2}$ eV,...,$10^{19.7}$ eV (1.26...50.12 EeV)

1. Set created with Geant4-based optics: 8,123 tracks; 5,527 of them with $E \geq 10^{19}$ eV
2. Set created with parametric optics: 141,425 tracks; 102,086 of them with $E \geq 10^{19}$ eV



1. 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.

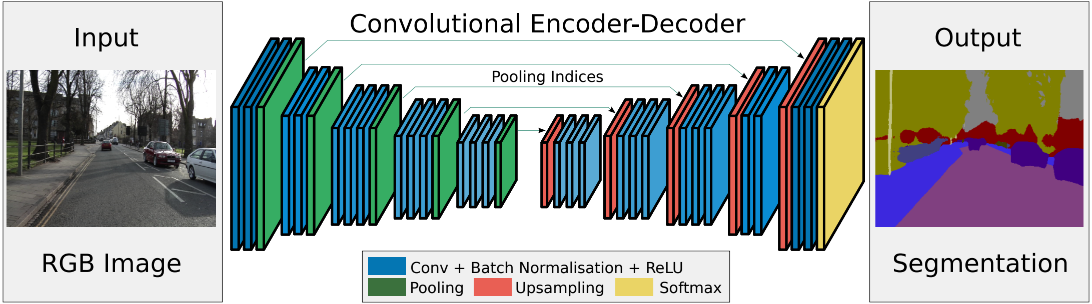
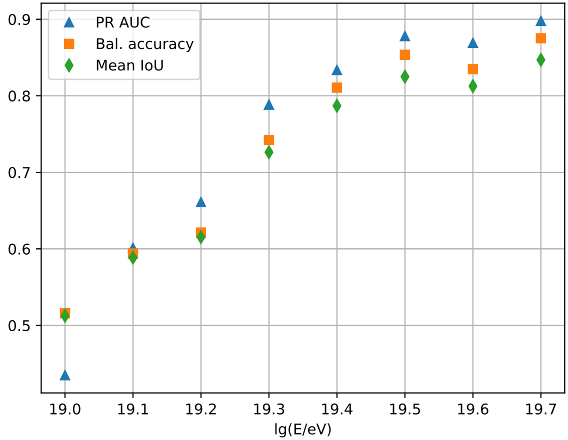
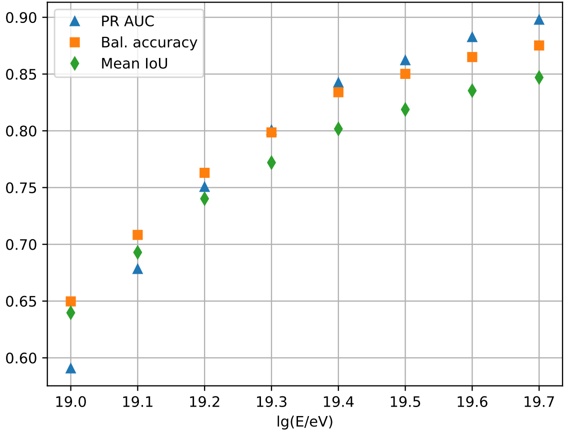


Figure: https://arxiv.org/abs/1511.00561

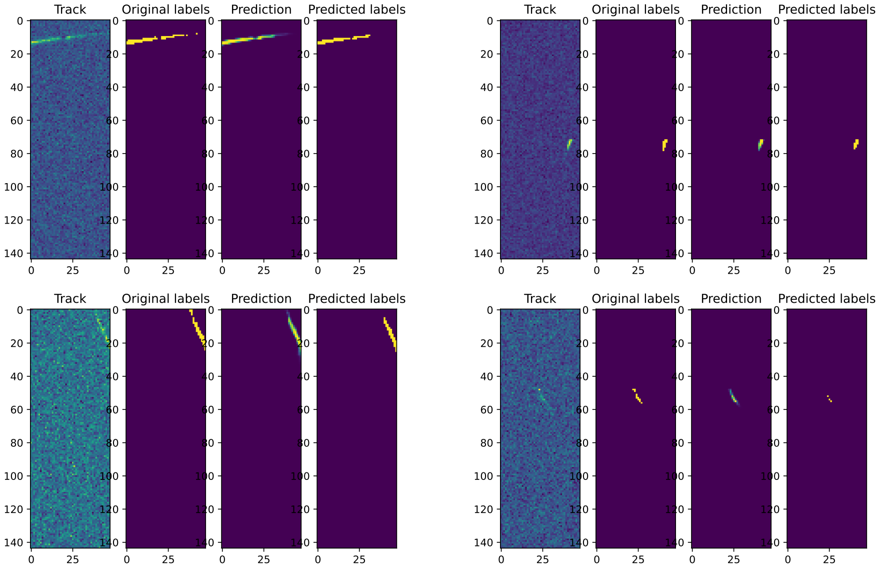
Performance metrics for tests (integral tracks)





Left: each test was run on samples with the same energy as used for training.
Right: ANN trained on $E = 10^{19.7}$ eV samples.

Track recognition for photon count sums, $E = 10^{19.7}$ eV



Another approach: Image Filtering

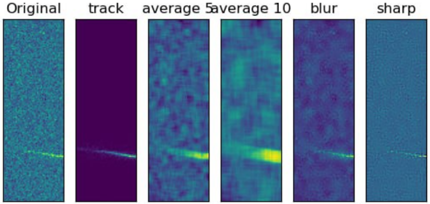
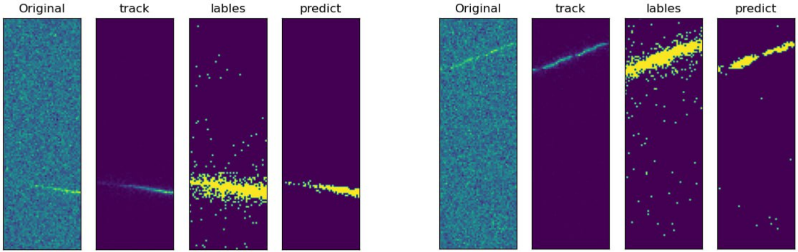
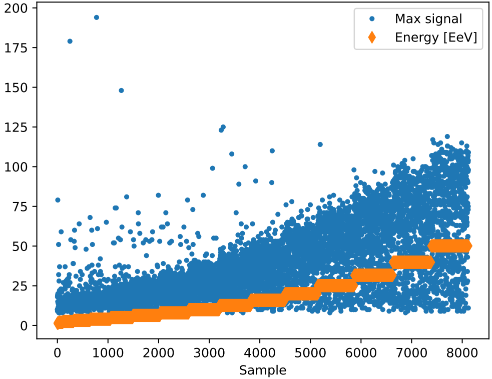


Image filtering (opencv library) and gradient boosting classifier.



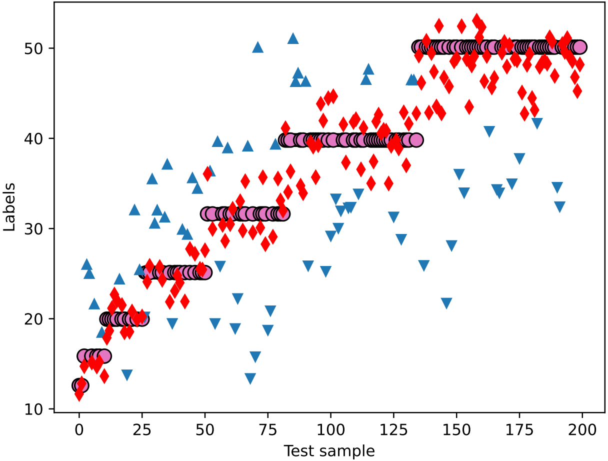
Left: training sample. Right: test sample.

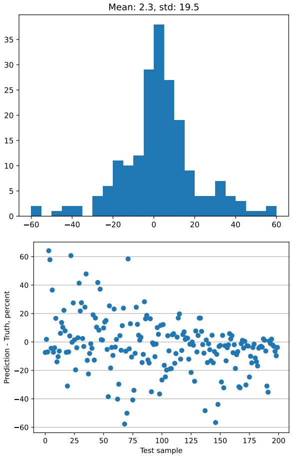


Dependence of the maximum photon count vs. energy in samples in dataset 1.

One can employ a CNN similar to those used for image classification with the linear activation function in the final FC layer instead of sigmoid. Currently: 6 convolutional and 3 FC layers.

Data set 2 (parametric optics) with “realistic” track recognition





$E \geq 10$ EeV, tracks recognized with Mean IoU ≥ 0.89. MAPE $\approx 14\%$. MAPE $\sim 16\%$ for MIoU ≥ 0.8

EUSO-TA: наземный ФТ на сайте эксперимента Telescope Array (USA)

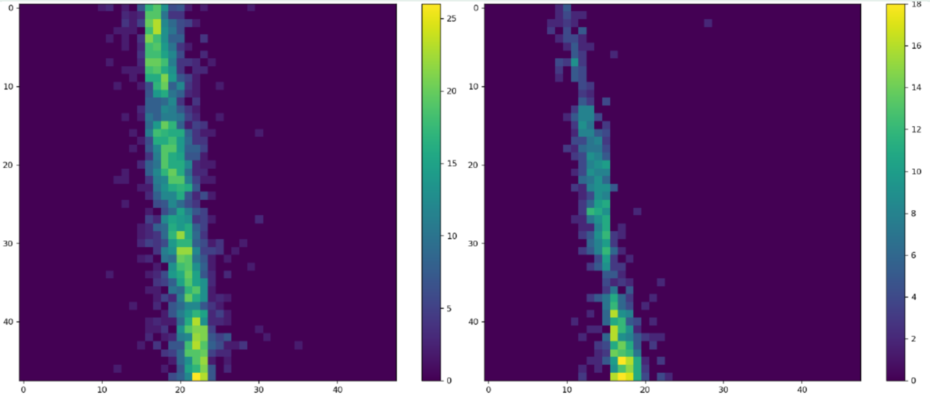
Телескоп-рефрактор: две линзы Френеля ø1 м, фокальная поверхность 48×48.

Ingredients

- CONEX (QGSJet-II)
- $\overline{\text{Off}}\underline{\text{line}}$ (`eyeCentric`).
  The core of EASs is within the projection of the EUSO-TA FoV on the ground.
- Two sets of events with energies in the range 5...100 EeV (one log-uniform, another quasi uniform)
- Elevation angle 10°.
- Data selection:
  - `HasTrigger = True`
  - In the pure signal, the number of GTUs with non-zero signal is > 1.
  - In `IntTrack`, the distance between pixels with > 2 photon counts is ≥ 24 (to exclude dim "clouds")
- The number of events used for training: 40–50 thousand. Test: 200 events.
- The convolutional network is almost the same as used for EUSO-SPB2.
- The background was simulated but not used yet.

At the moment, I omit the stage of track recognition because it is clear how to implement it, and work only with pure signals. According to the SPB2 experience, this isn't crucial.

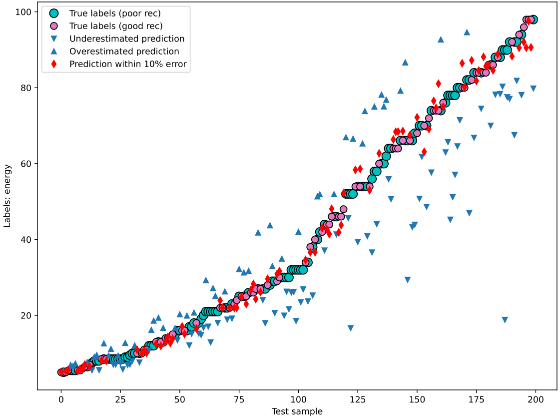
Наземный телескоп: сигнал зависит от расстояния до оси ливня

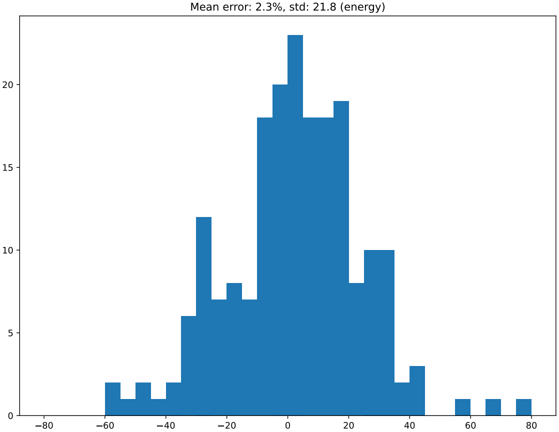


Пример интегральных треков
Слева: E = 38 EeV (D = 10.6 km), $\theta = 33^\circ$, $\phi = 173^\circ$
Справа: E = 92 EeV (D = 18 km), $\theta = 42^\circ$, $\phi = 15^\circ$

Маленькое поле зрения $10.5^\circ \times 10.5^\circ$. Практически нет полных треков.

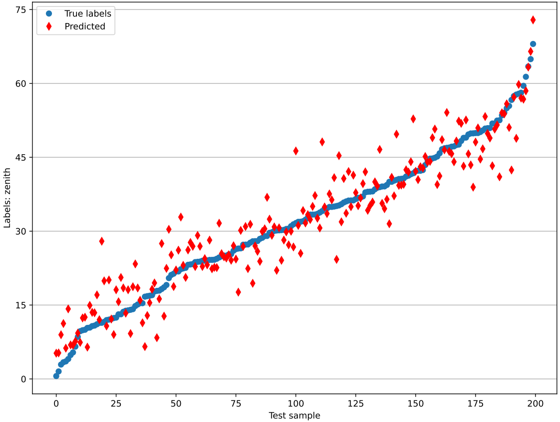
Reconstruction of energy. Metric: MAPE = 17%

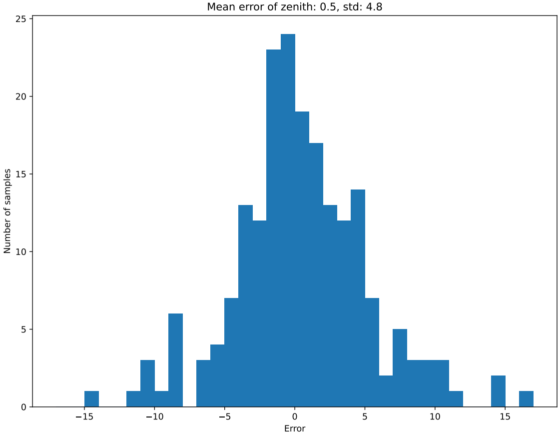




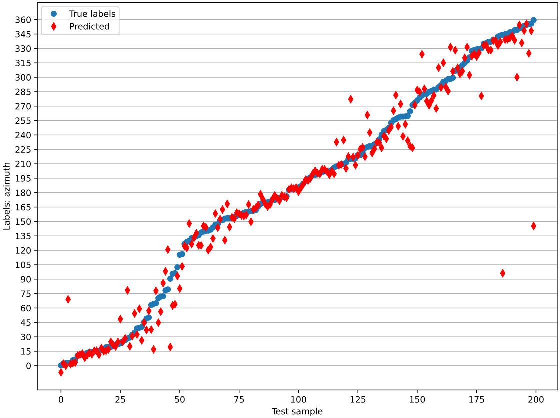
Left: true labels vs. predicted ones (units: EeV).
Right: histogram for percentage error 100(true-predicted)/true

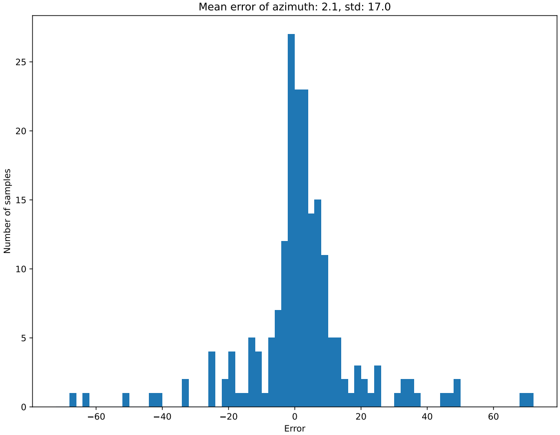
Reconstruction of zenith angles



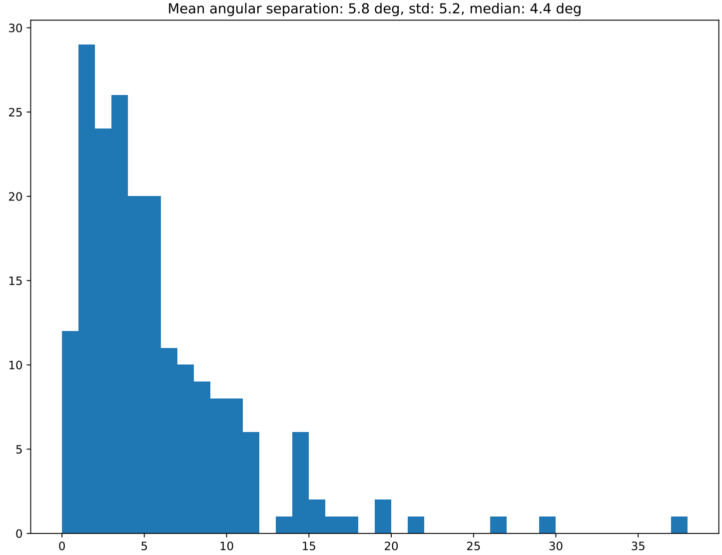


Reconstruction of azimuth angles



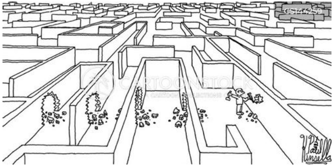


Angular separation between true and predicted arrival directions



Резюме

- We have developed a pair of simple ANNs aimed at recognition of EAS tracks and reconstruction of CR energy and arrival directions using simulated data for the EUSO-SPB2 and EUSO-TA fluorescence telescopes. (Very) preliminary results for EUSO-SPB2 are available in the ICRC-2023 proceedings.
- To the best of our knowledge, this is the first work of this kind for FTs.
  Neither TA, nor Auger have published works on ML-based energy/AD reconstruction with FT data.
- The approach is generic and can be applied to other FTs, both in space and on the ground.
- The first results aren't groundbreaking but... Work in progress...



Backup slides

Performance Metrics (intrinsically imbalanced data!)

PR AUC: area under the precision-recall curve

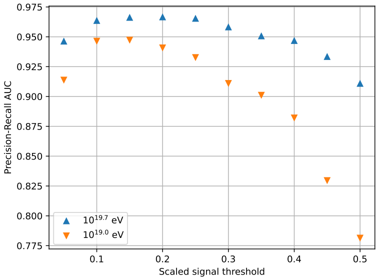
$$\text{Precision} = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}}, \qquad \text{Recall} = \text{TPR} = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}}$$

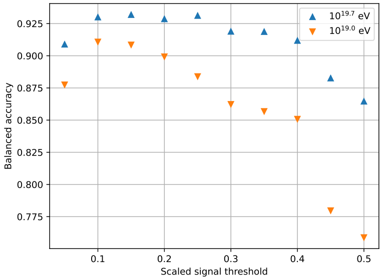
Mean IoU (a common evaluation metric for semantic image segmentation):

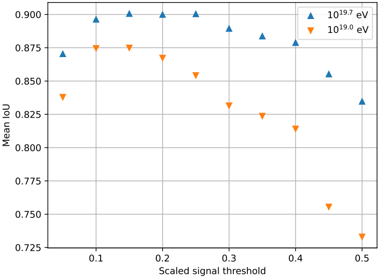
$$\text{Intersection-Over-Union} = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}+\mathrm{FN}}$$

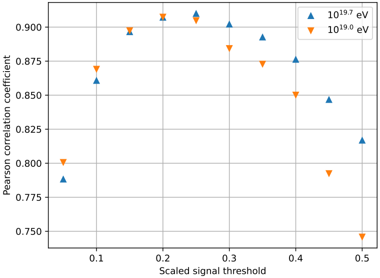
Balanced accuracy (useful when # positives $\ll$ # negatives): $(\text{TPR} + \text{TNR})/2$

Train/test with `IntTracks`: Test metrics for different cuts at two energies

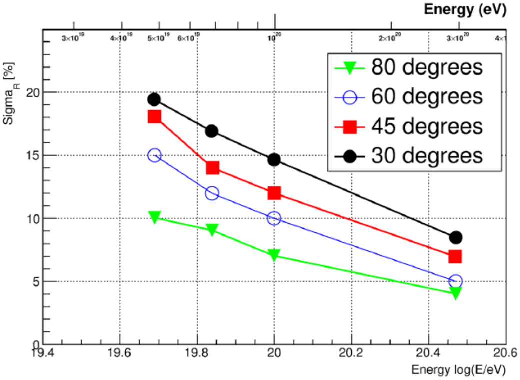


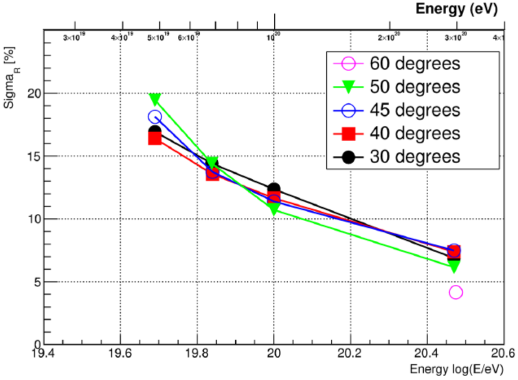






Реконструкция энергии для орбитального телескопа JEM-EUSO





Два метода реконструкции энергии КЛ ПВЭ, см. Exp. Astronomy (2015) 40:153.