Analysing arrival directions of UHECRs using convolutional neural networks

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Abstract

We show that arrival directions for the deflected ultra-high energy cosmic rays (UHECR) from several nearest active galaxies form specific patterns in the sky, which can be effectively recognized by the convolutional neural networks. We use one of the recently developed convnet implementations for the images defined on sphere to train the classifier which is able to detect the event patterns from particular sources which could be present in the data. We calculate the minimal detectable from-source event fractions for several realistic source candidates and discuss the method limitations in detail.

Motivation

The problem of UHECR sources identification is greatly complicated by the fact that even highest energy cosmic rays may be deflected by tens of degrees in the galactic magnetic fields. To test a hypothesis of the cosmic ray origin one has to invent the proper test statistics.

Method Summary

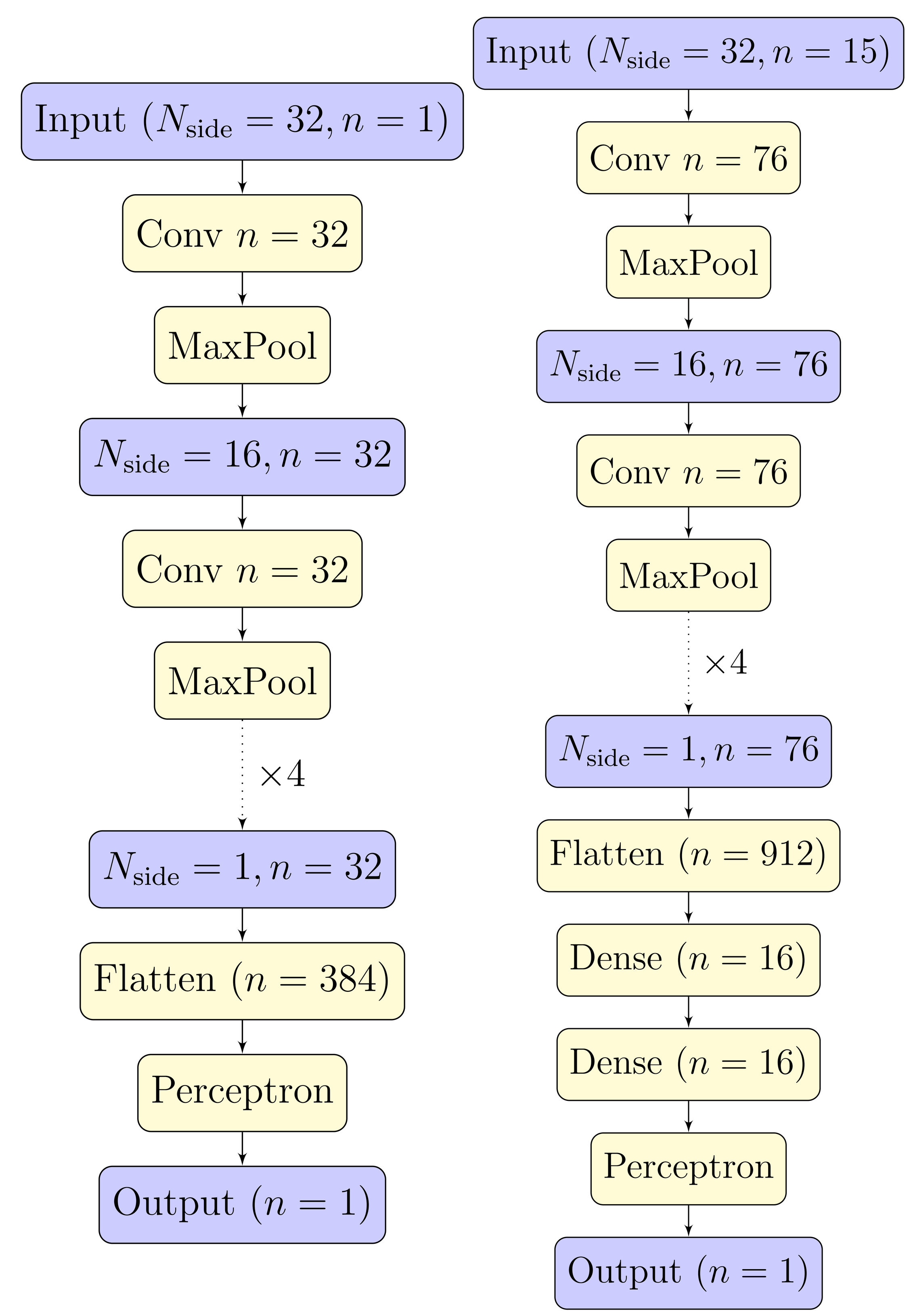
- Define null and alternative hypothesis. Calculate arrival direction maps
- Train classifier model based on convolutional neural network (CNN) to discriminate maps simulated assuming null and alternative hypothesis
- Use output of the classifier as test statistics for the hypothesis verification

Building the Test Statistics

1. Using angular power spectrum

$$D(\text{sample}) = \frac{1}{l_{max}} \sum_{\ell=1}^{l_{max}} \frac{C_{\ell,\text{sample}} - \langle C_{\ell,\text{iso}} \rangle}{\sigma_{\ell,\text{iso}}}, \quad (1)$$

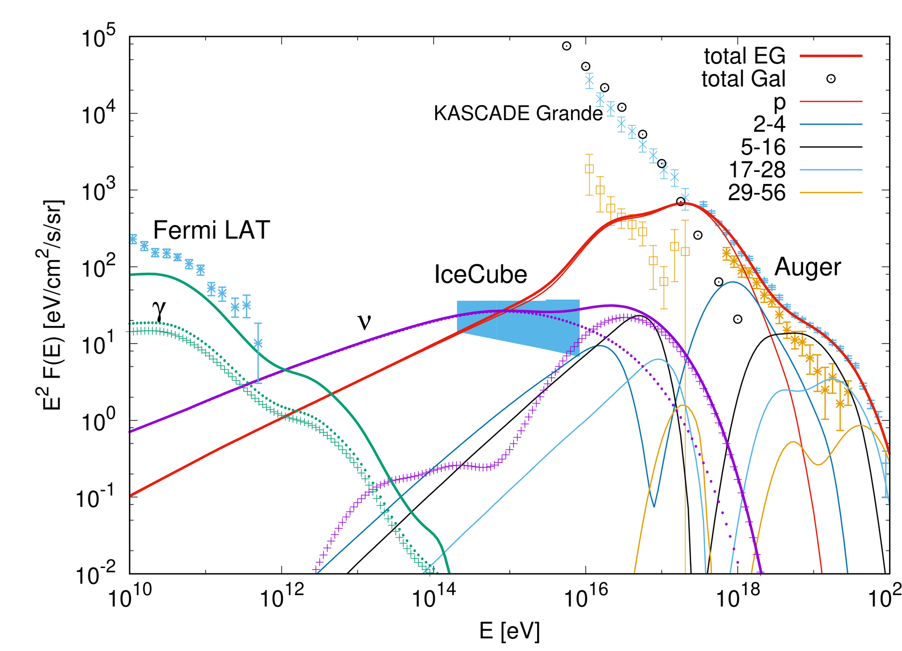
2. Using classifier based on convolutional neural network defined on HEALPix grid [Krachmalnicoff and Tomasi 2019]



- Left: CNN counting all events above $E_{cut} = 57$EeV (single energy bin)
- Right: binned CNN using multiple maps for a number of energy bins, also taking into account energy resolution by counting contribution of every simulated event with given energy to the neighbor energy bins

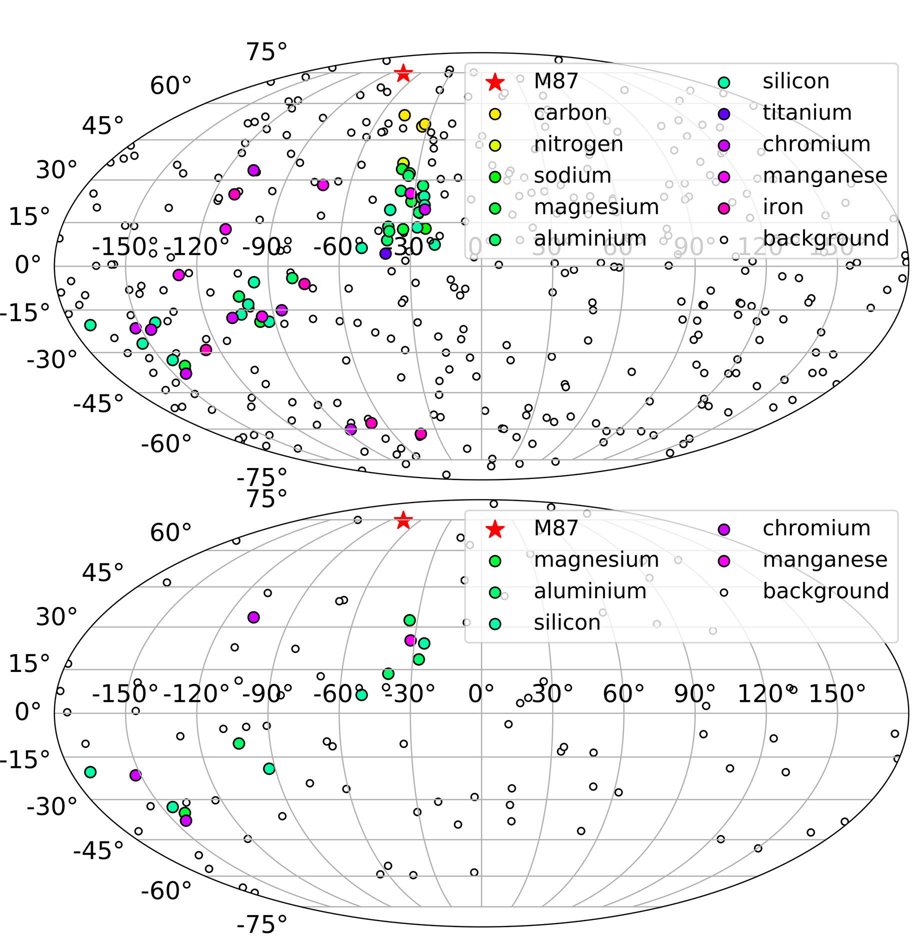
Example Problem

- null-hypothesis: isotropic source distribution
- alternative hypothesis: fraction η of events are coming from a nearby AGN (candidates: CenA, NGC 253, Fornax A, M87, M87)
- energy spectrum and mass composition according to scenario by M. Kachelrieß et al 2017



Energy spectrum of different UHECR mass components along with spectra of secondary ν and γ.

Simulated arrival direction maps



Upper: A sample with the14% of total 400 UHECRs events with energies above 57 EeV coming from M 87 that allows testing H_0 in the approach based on the APS. Lower: A sample of 14% of total 100 UHECRs events from the same source which allows testing H_0 with the CNN.

Detectable percentage of from-source events

Source	Method	50	100	200	300	400	500
NGC 253	APS	24	17	12	10	8	7
	CNN	12	7	4.5	3.67	3	2.6
	BCNN	12	8	5	4	3.25	3.2
Cen A	APS	28	21	14	12	10	9
	CNN	16	11	7	5.67	5	4.4
	BCNN	16	10	7	5.67	4.75	4.2
M 82	APS	36	26	18	14	12	11
	CNN	20	12	7	6	4.75	4.2
	BCNN	20	14	8.5	6.67	5	4.4
M 87	APS	38	29	20	16	14	12
	CNN	22	14	9	8	6.25	5.2
	BCNN	22	15	11.5	7	6.25	5.4
Fornax A	APS	28	19	13	11	9	8
	CNN	16	9	6	5	4.5	3.8
	BCNN	16	10	6	5	4.5	3.8

Percentage of UHECRs arriving from the candidate sources in samples of sizes $N = 50, 100, \ldots, 500$ such that the error of the first kind $\alpha \lesssim 0.01$ for the null hypothesis of isotropy H_0 providing the second kind error $\beta = 0.05$, obtained with the traditional approach with test statistics based on the angular power spectrum (APS) and with the ML-based test statistics applied to integral flux above 57 EeV (CNN) or to binned flux assuming energy resolution $\Delta E/E = 0.2$

Conclusions

- The ML-based test statistics allows to improve the efficiency of UHECR source search
- Unlike APS-based technique this method allows to easily include the effect of nonuniform exposure
- BCNN method allows to reach the same efficiency as CNN while also taking into account energy resolution error of up to 20%
- The method is quite robust with respect to the choice of galactic magnetic field model and assumed UHECR composition