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Alliance for Astroparticle Physics

Recognizing patterns in the arrival directions of ultra-high energy cosmic rays using deep neural networks

galactic magnetic field

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Ultra-high energy cosmic rays @ Pierre Auger Observatory





- X Steeply falling energy spectrum
- X Heavier composition
- X Anisotropy? Point Sources?





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Patterns caused by the galactic magnetic field



- Deflection in galactic magnetic field:
 characteristic patterns
- X Variety of shapes (energy, charge, sources)
- ✗ Challenge: find source position by those structures → image recognition



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16

3

Patterns caused by the galactic magnetic field



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3

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3

Image recognition on a sphere

- X Healpy scheme
- X Divide sphere into 12 patches (~planar) size: 100° x 100°





X Run one 2D-CNN on each patch

X Output: Classify as one of 768 possible source regions



```
model = Sequential()
```

model.add(Convolution3D(nfil, 1, nconv, nconv, border_mode='valid', input_shape=(npix_patch, patch_size, patch_size, 1), activation='relu'))
model.add(MaxPooling3D(pool_size=(1, npool, npool)))
model.add(Convolution3D(not_size=(1, npool, npool)))

```
model.add(Convolution3D(nfil, 1, nconv, nconv, activation='relu'))
model.add(MaxPooling3D(pool_size=(1, npool, npool)))
model.add(Convolution3D(nfil, 1, nconv, nconv, activation='relu'))
model.add(MaxPooling3D(pool_size=(1, npool, npool)))
model.add(Convolution3D(nfil, 1, nconv, nconv, activation='relu'))
model.add(MaxPooling3D(pool_size=(1, npool, npool)))
```

```
model.add(Flatten())
model.add(Dropout(dropout))
model.add(Dense(nout, activation='relu'))
model.add(Dropout(dropout))
model.add(Dense(nout, init='normal', activation='softmax'))
```

Network:	Input data:
nfil = 32 nconv = 3 npool = 2 dropout = 0.4	npix_patch = 12 patch_size = 100 nout = 768

 \sim 5.3 million trainable parameters

model.compile(optimizer='adam', loss='categorical_crossentropy', metrics=['accuracy'])



Training

- X Training data is expensive: 1,000 skymaps ~ 1 GB
- ✗ Maximum of 20,000 at once





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Performance: Two source positions at 1% signal



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Full sky at 1% signal

X Averaged over 100 maps for each of the 768 source regions

1) exact accuracy: true classification / total 2) nearby accuracy: (exact + neighboring) / total 3) alpha: $\alpha = \measuredangle(\vec{n}_{\text{source}}, \vec{n}_{\text{rec}})$ $\vec{n}_{\text{rec}} = \sum_{\text{pix}} p(\text{pix}) \cdot \vec{n}_{\text{pix}}$





Smallest detectable signal fraction

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X Performance as a function of the signal fraction



Smallest detectable signal fraction

X Performance as a function of the signal fraction

exact accuracy: true classification / total
 nearby accuracy: (exact + neighboring) / total





Good reconstruction of the faint structures in the arrival directions

Summary & Outlook

- X Successfully trained a 3D convolutional neural network classifying arrival maps as one of 768 source regions including deflection in magnetic fields
- X Can cope with variations in energy spectrum, mass composition, extragalactic spread and signal fraction
- X At 0.5% signal fraction the exact source is identified in 44% of the cases; the reconstructed source is in a nearby pixel in 80% of the cases

Outlook

- X Convolution on sphere
- X Regression (multiple sources, discriminate from isotropy)
- 🗡 Cosmic rays energy



Backup

Galactic magnetic field - parametrizations

X Models tuned to measurements (e.g. rotation measurements, synchrotron radiation)







GMF arrival distributions



Galactic magnetic field lenses

Matrices for each rigidity R = E / Z mapping extragalactic directions to observed arrival directions

- X Based on Healpy framework (divide sphere into 49,152 cells)
- CRPropa simulation: Backtrack 5 million particles (inverting charge) per rigidity-bin to the edge of the galaxy
- \checkmark 175 rigidity bins in the range from 10^{17} eV to $10^{20.5}$ eV
- X Matrices are normalized to the highest arrival probability
 - → rigidity and direction dependent transparency



https://web.physik.rwth-aachen.de/Auger_MagneticFields/PARSEC/downloads.php

Model.summary()

Layer (type) O	utput Shape Param #	¢ Connec	cted to	
convolution3d_1 (Convolu	ution3D) (None, 12, 98, 98	, 32 320	convolution3d_input_1[0][0]	
	ling3D) (None, 12, 49, 49), 32 0	convolution3d_1[0][0]	
convolution3d_2 (Convolu	ution3D) (None, 12, 47, 47	, 32 9248	maxpooling3d_1[0][0]	
maxpooling3d_2 (MaxPoo	ling3D) (None, 12, 23, 23	8, 32 0	convolution3d_2[0][0]	
convolution3d_3 (Convolu	ution3D) (None, 12, 21, 21	, 32 9248	maxpooling3d_2[0][0]	
maxpooling3d_3 (MaxPoo	ling3D) (None, 12, 10, 10), 32 0	convolution3d_3[0][0]	
convolution3d_4 (Convolu	ution3D) (None, 12, 8, 8, 3	2) 9248	maxpooling3d_3[0][0]	
maxpooling3d_4 (MaxPoo	ling3D) (None, 12, 4, 4, 3	32) 0	convolution3d_4[0][0]	
flatten_1 (Flatten)	(None, 6144)	0 r	maxpooling3d_4[0][0]	
dropout_1 (Dropout)	(None, 6144)	0 f	flatten_1[0][0]	
dense_1 (Dense)	(None, 768)	4719360) dropout_1[0][0]	
dropout_2 (Dropout)	(None, 768)	0 d	dense_1[0][0]	
dense_2 (Dense)	(None, 768)	590592	dropout_2[0][0]	
Total params: 5,338,016 Trainable params: 5,338,0 Non-trainable params: 0	16			



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Performance: Examples

- X Testing for 12 different source locations on the sphere
- X Signal fractions: 3% X



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Performance: Examples

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Multiple sources



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Pierre Auger Observatory

- X Worlds largest detector for ultra high energy cosmic rays
- X Situated in Argentina in Pampa Amarilla on an area of 3,000 km²
- X Hybrid detector system:
 - → Surface detector: 1660 water-Cherenkov stations
 - → Fluorescence detector: 4 eyes with
 6 fluorescence telescopes each
- 🗡 Radio antenna array (AERA)
- 🗡 In progress: Auger Prime



