Energy reconstruction in analysis of Cherenkov telescopes images in TAIGA experiment using Deep Learning methods

Gres Elizaveta[1,2], Kryukov A.[2]

[1] Research Institute of Applied Physics, Irkutsk State University, Irkutsk

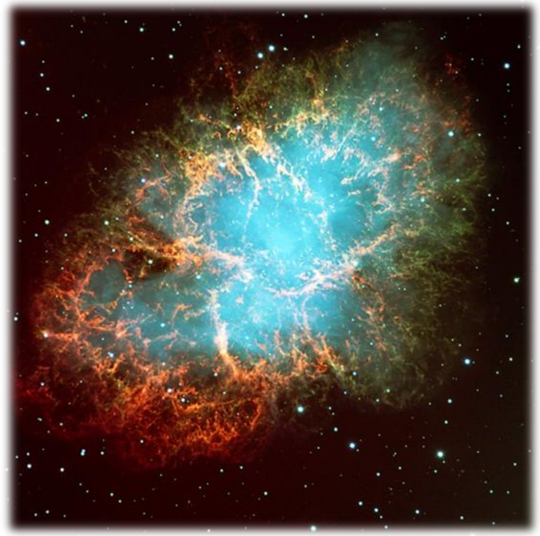
[2] Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow

6th International Workshop on Deep Learning in Computational Physics, Jule 6-8, 2022

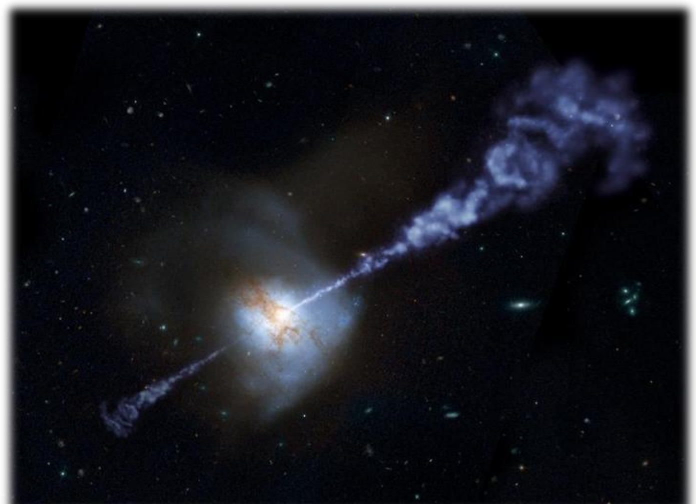
Scientific research in gamma astronomy

- Scientific problem: determination and study of sources of high-energy (energy of the order of tens of TeV) gamma radiation.

- Measurement of the flux, energy spectrum, direction of arrival of gamma rays helps to understand the mechanisms of generation of high energy gamma radiation and the morphology of these sources.



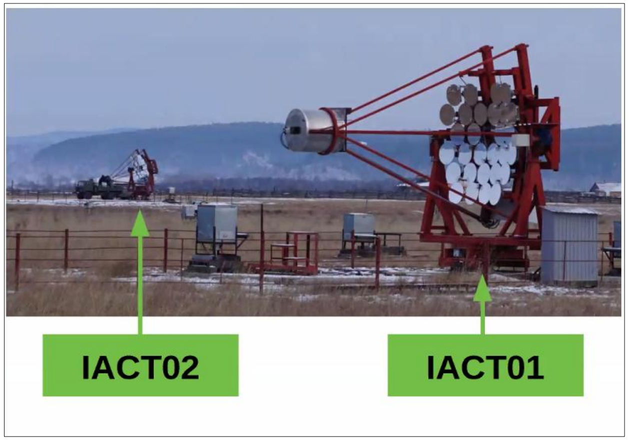
Supernova Remnant (Crab Nebula)



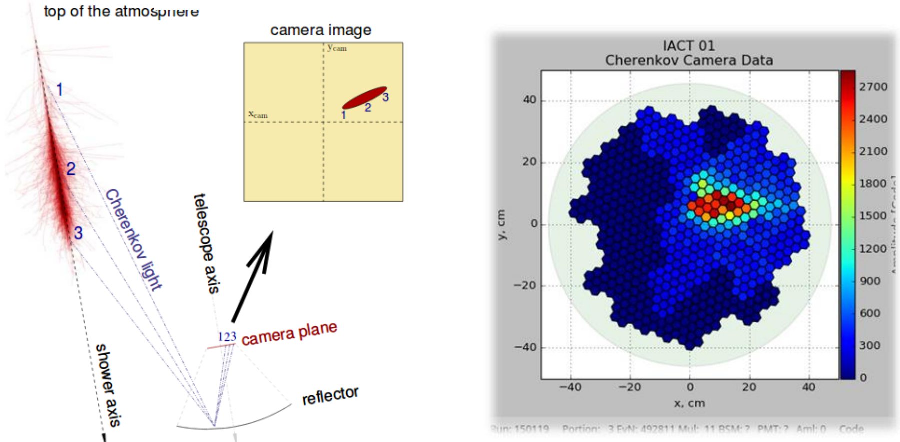
Active nucleus of galaxies

TAIGA-IACT

- TAIGA-IACTs are located in The Tunka valley of the republic Buryatia. Three telescopes have been installed and are operating.
- Telescopes detect Cherenkov radiation created by the Extensive Air Shower (EAS).
- EAS is an avalanche-like cascade of secondary particles formed as a result of the interaction of a primary particle of cosmic radiation with atmospheric atoms.



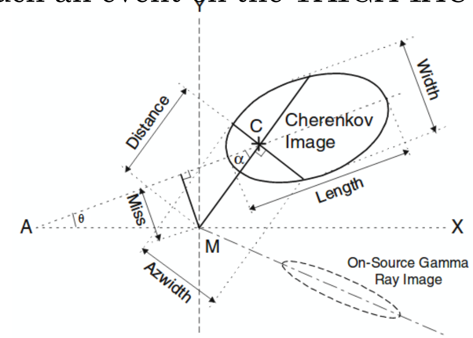
TAIGA-IACT



The principle of registration of Cherenkov light SHAL (left) and an example of such an event on the TAIGA-IACT camera (right)

Traditional image processing method:

- Hillas parameters – description of the image by an ellipse with certain parameters.



Schematic representation of the Hillas parameters

Model data

The data description:

- Monte Carlo events simulated with CORSIKA (provided by the TAIGA collaboration).

Set	Total events (gamma/proton)	Train / validation separation	Energies
Mono-mode	200 000 (100 000 / 100 000)	160 000 / 40 000	Protons: 5-100 TeV Gammas: 2-50 TeV
Stereo-mode	Only gamma: 30 000 – mono 14 800 – stereo-2 7 700 – stereo-3	Separation 3:1 in each case	1-50 TeV

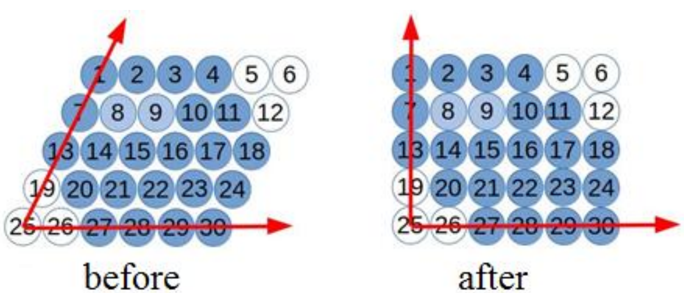
- In stereo mode the training set was expanded by 2 times in "stereo-2" and 6 times in "stereo-3" by mixing the channel inputs: for example, for "stereo-2" a pair of images of one event (1,2) were also fed into the CNN as pair (2,1).

MODEL DATA

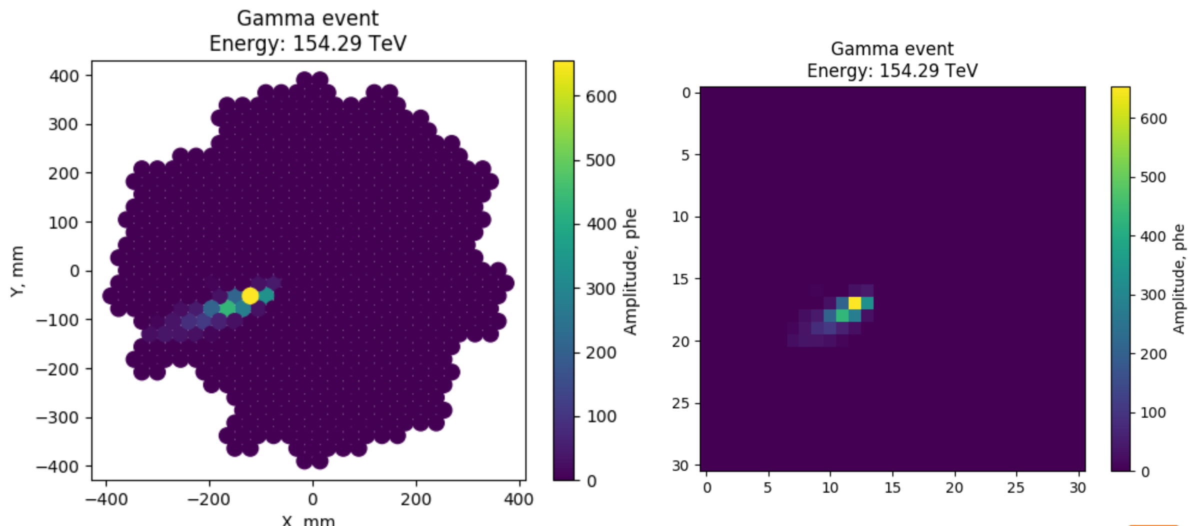
<u>*Image Preprocessing*</u>:

- *Cleaning:* zeroing out negative pixel values and single noise pixels;
- *Pixelation:* converting a hexagonal image to a rectangular shape;
- *Scaling:* logarithmic transformation of pixel amplitudes (x_i):

$$\tilde{x}_i = \frac{1}{9} ln(1 + x_i)$$



The principle of image pixelation

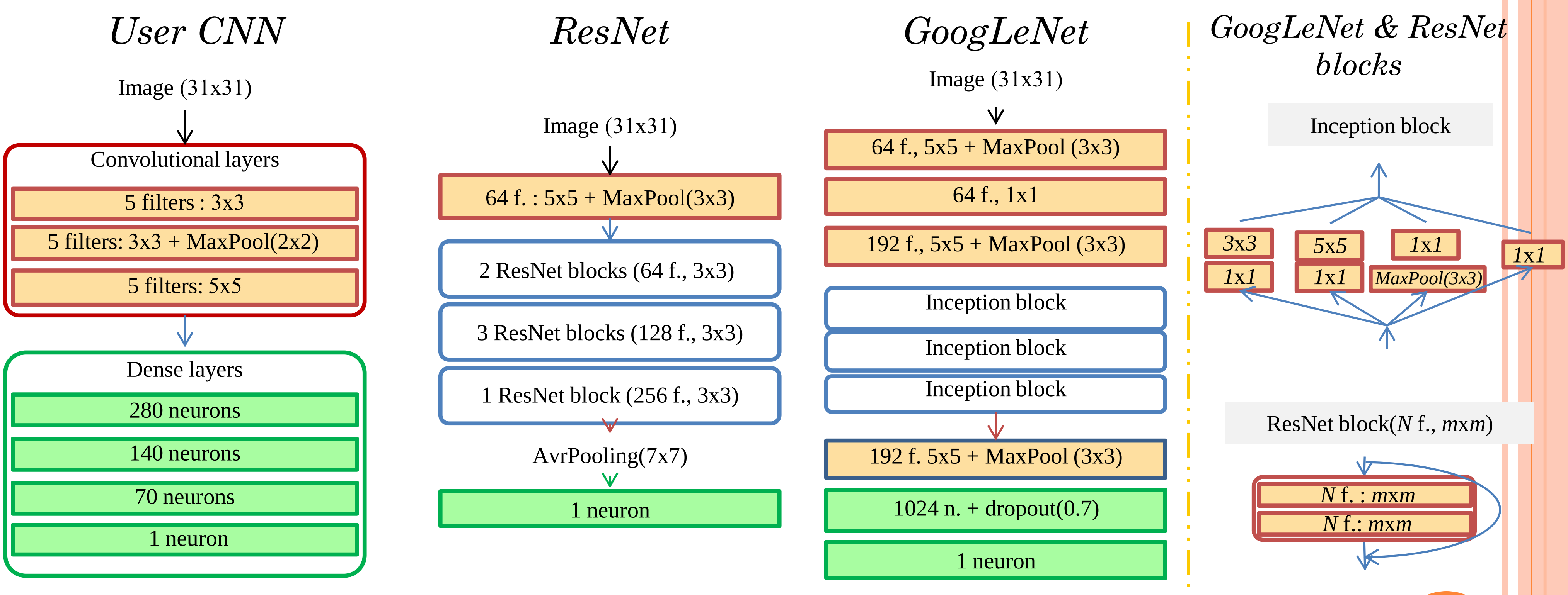


Example of image pixelation

MONO-MODE: USED CNN ARCHITECTURES

Regression task: energy reconstruction of primary particle.

- For an adequate comparison, ResNet and GoogLeNet were simplified in such a way that the number of weight coefficients for CNN networks approximately coincided. In this case, their number is ~2 millions.



Loss function: MSE;
Output activation function: linear.

O. Russakovsky et al., ImageNet Large Scale Visual Recognition Challenge: https://arxiv.org/abs/1409.0575

Mono-mode: results

- ***Criteria for estimation of energy reconstruction of events and energy spectra:***

$$Rel\_err = \frac{\left|E_{pred} - E_{true}\right|}{E_{true}}$$

$$\chi^2 = \sum_{i=1}^{k} \frac{\left((c_{rec})_i - (c_{MC})_i\right)^2}{(c_{MC})_i}$$

E_{pred} – the energy predicted by CNN;

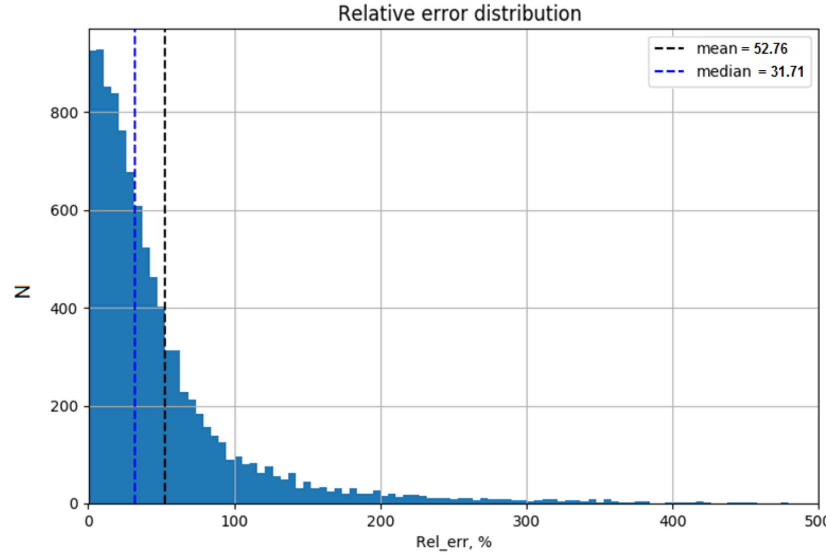
E_{true} – the true value of energy;

k – the number of bins in the histogram of the spectrum;

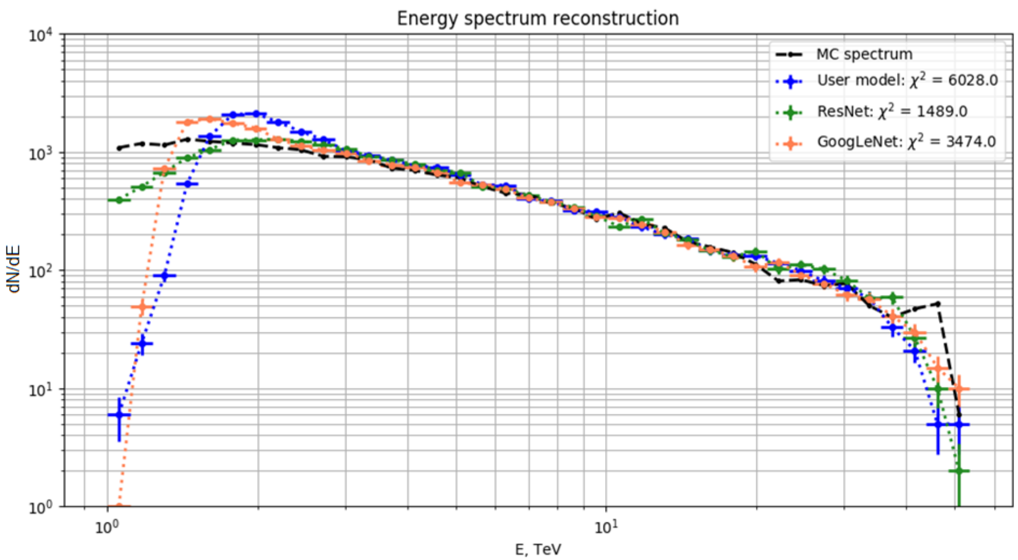
c_{rec} – the number of events in bins in the case of the reconstructed spectrum;

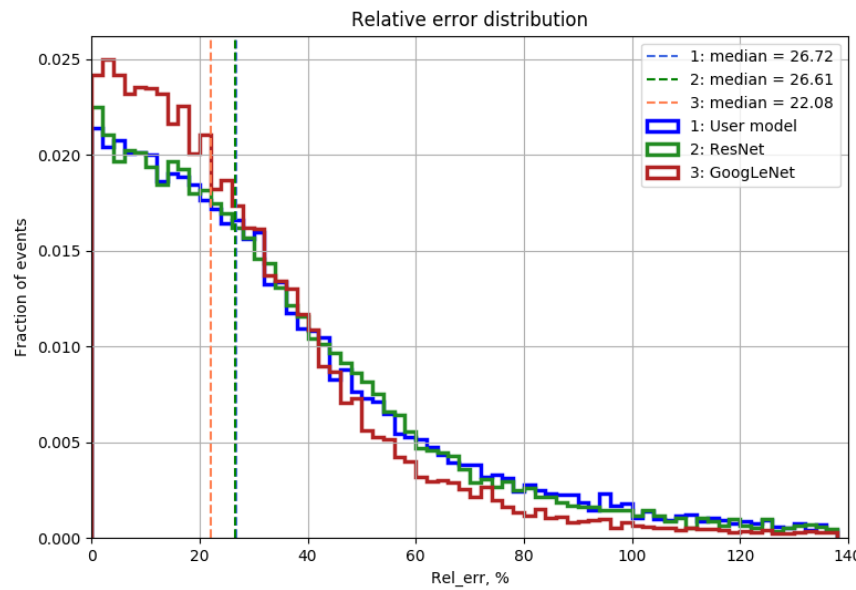
c_{MC} – he number of events in bins of the model spectrum.

Energy reconstruction estimation of gamma quanta and proton events:



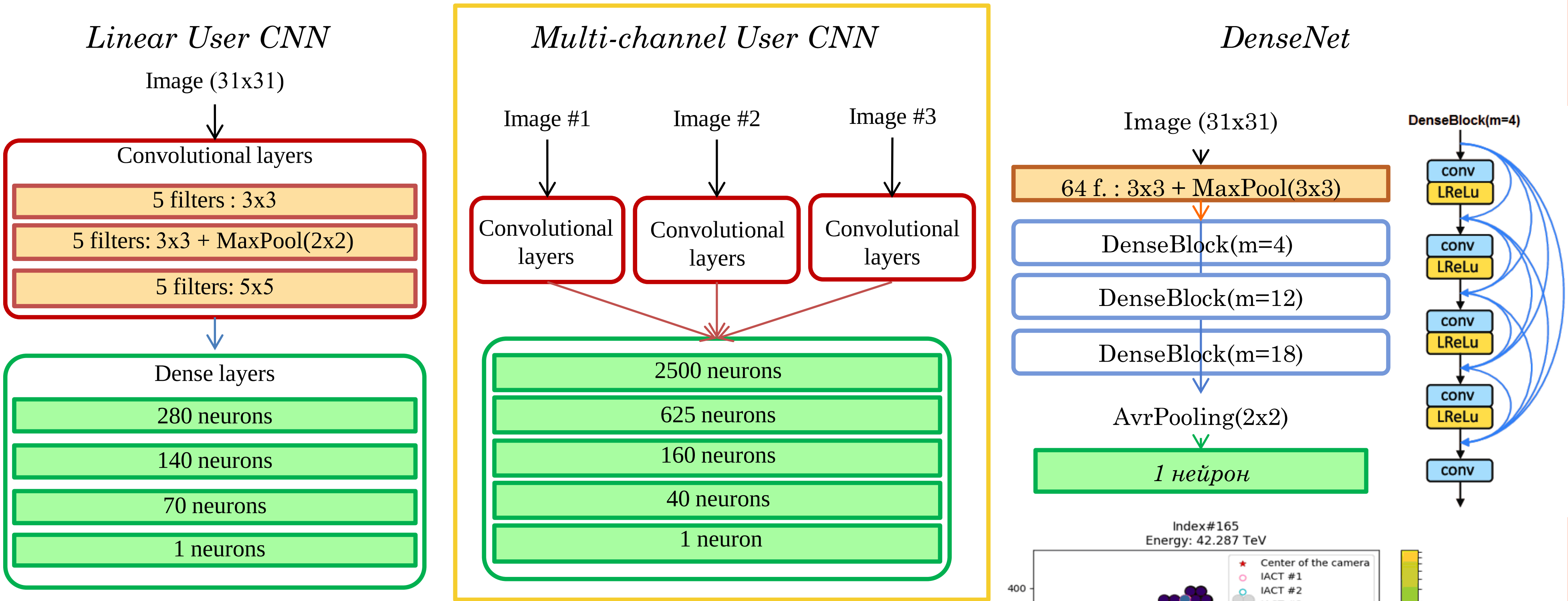
Energy reconstruction of only gamma quanta events with different CNNs:



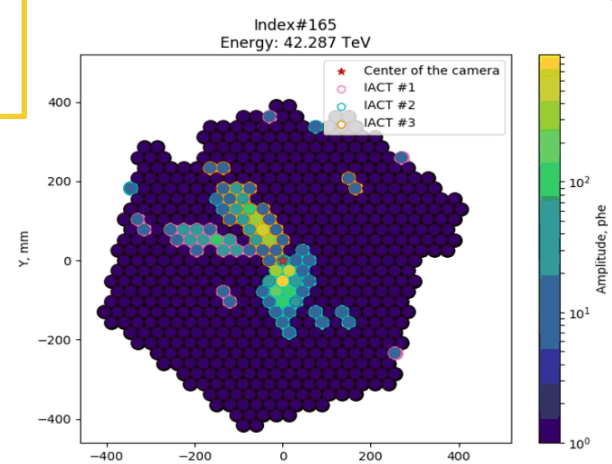


STEREO-MODE: USED CNN ARCHITECTURES

- A multi-channel User CNN was used for energy reconstruction and comparison mono- and stereo-modes (two and three telescopes). Also the following linear structures for "stereo-3" mode were also compared:

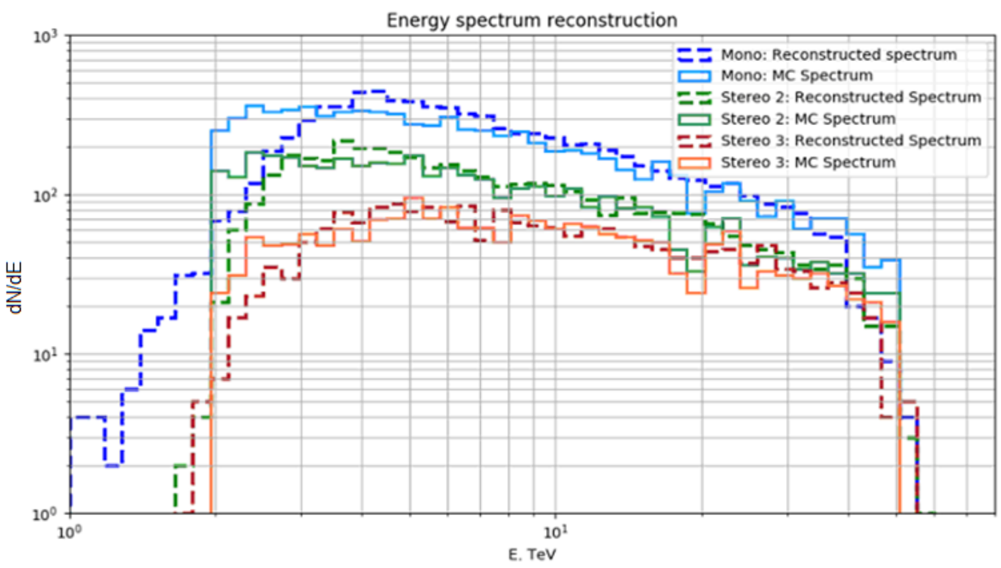


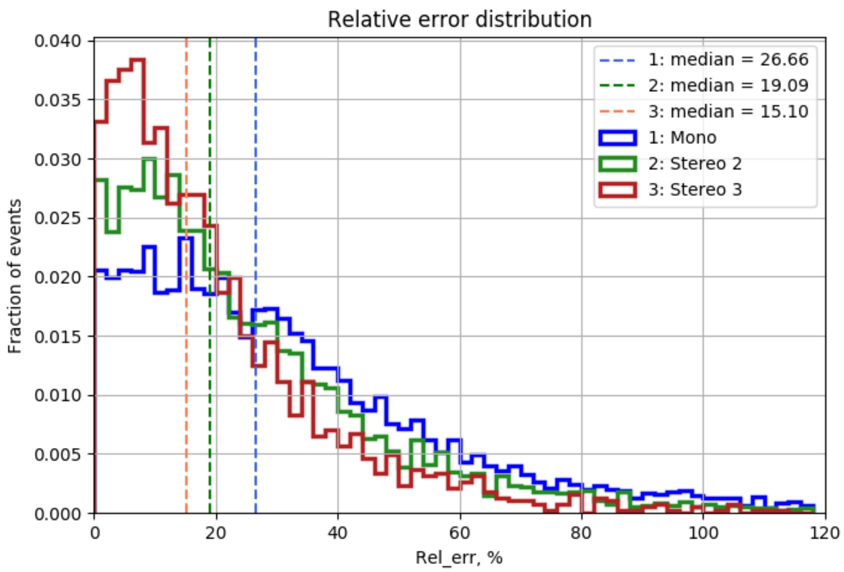
- Telescopes images were overlaid on each other forming one image before being fed into the linear CNNs:



Comparison mono- and stereo-modes: results

- Reconstruction of the event energy and the energy spectrum was carried out by a multi-channel user CNN.
- The χ^2 values in mono mode are 1 546, in the case of "stereo-2" – 495, in "stereo-3" – 156. The relative error decreased from 26% to 15%.

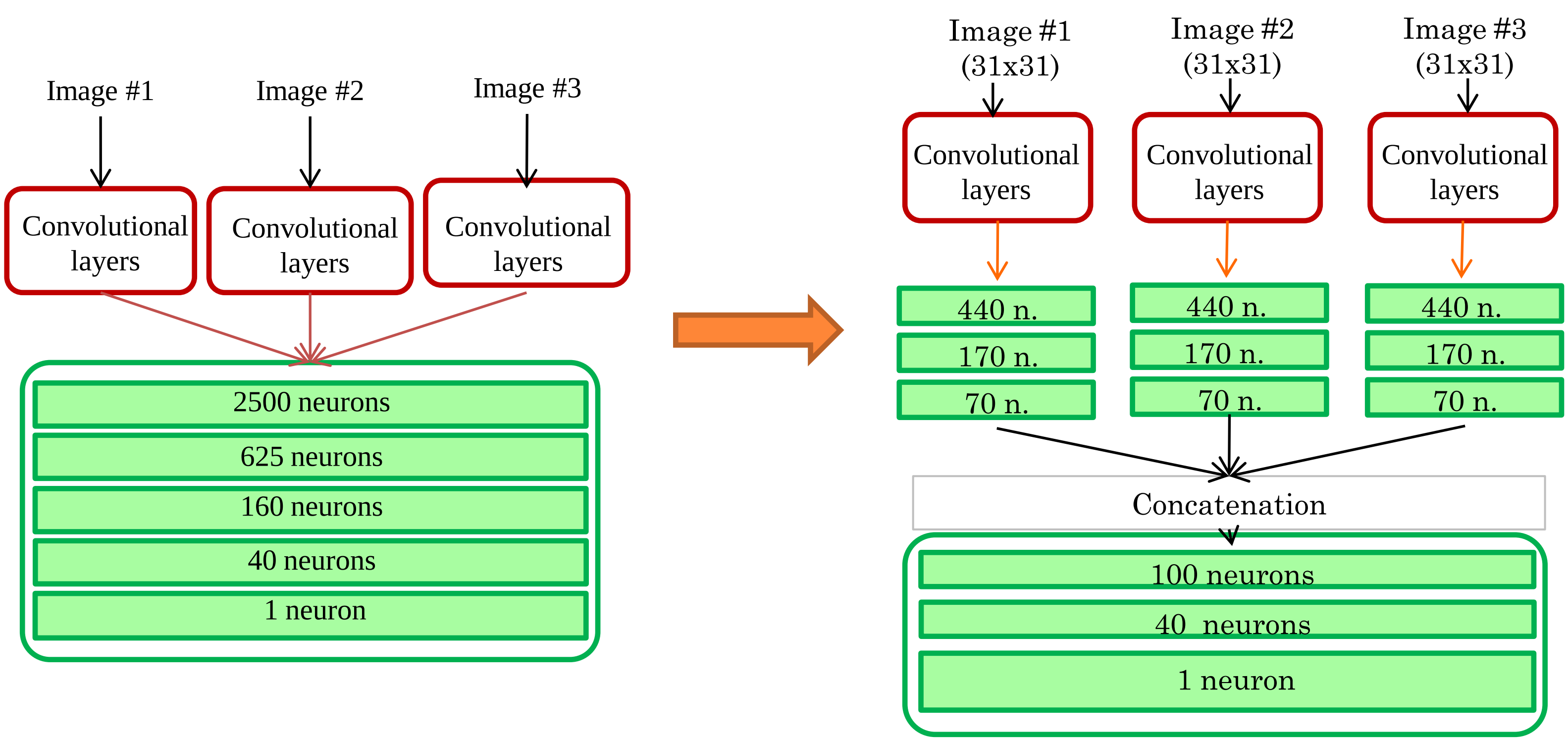




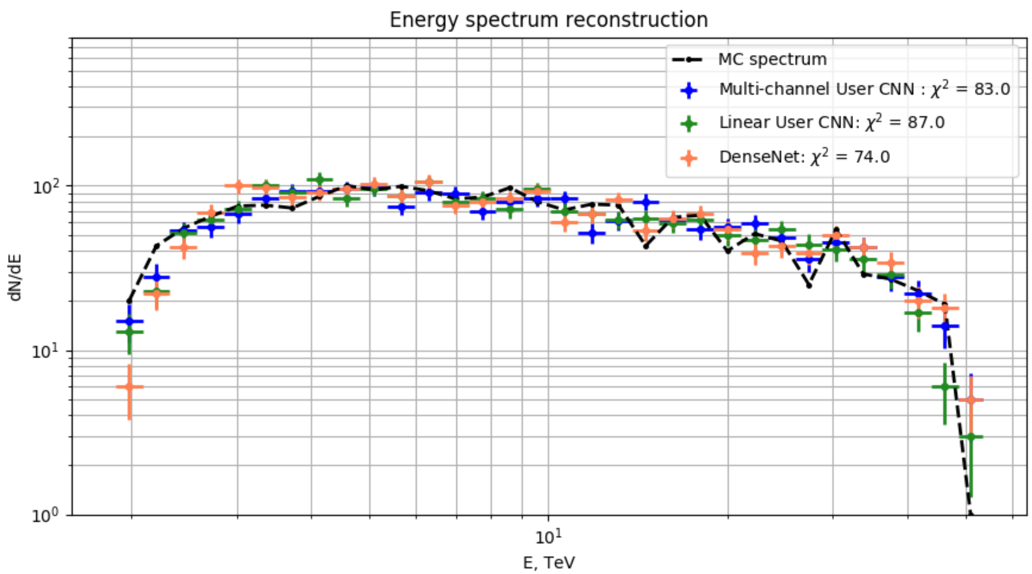
«Stereo-3» comparison : used CNN architectures

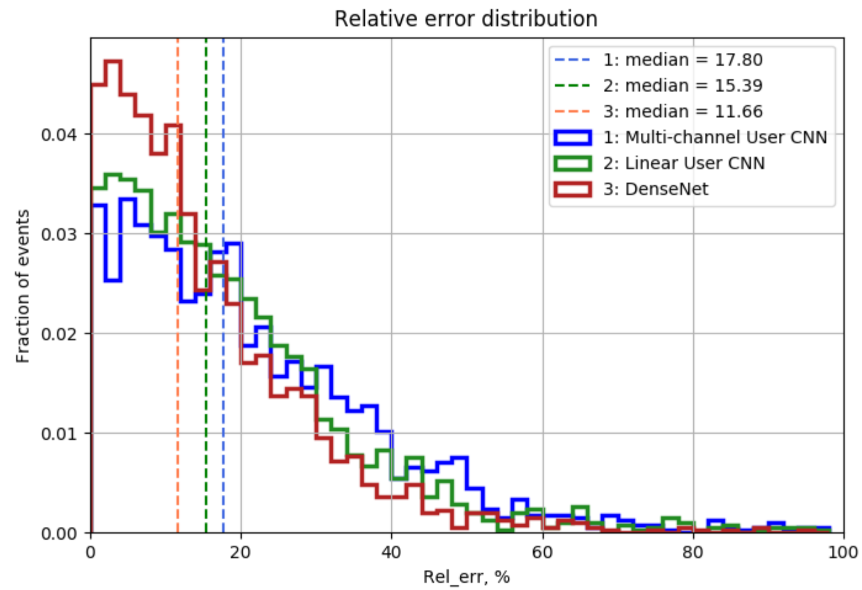
- The linear User CNN model and DenseNet were used for comparison.
- The number of weights for a three-channel CNN is *10 million*. The number of weights for a linear CNN and DenseNet is *1.7 million*. To adequately compare all three structures the three-channel network was modified as follows:

Multi-channel User CNN *Modified Multi-channel User CNN*



«STEREO-3» COMPARISON : RESULTS

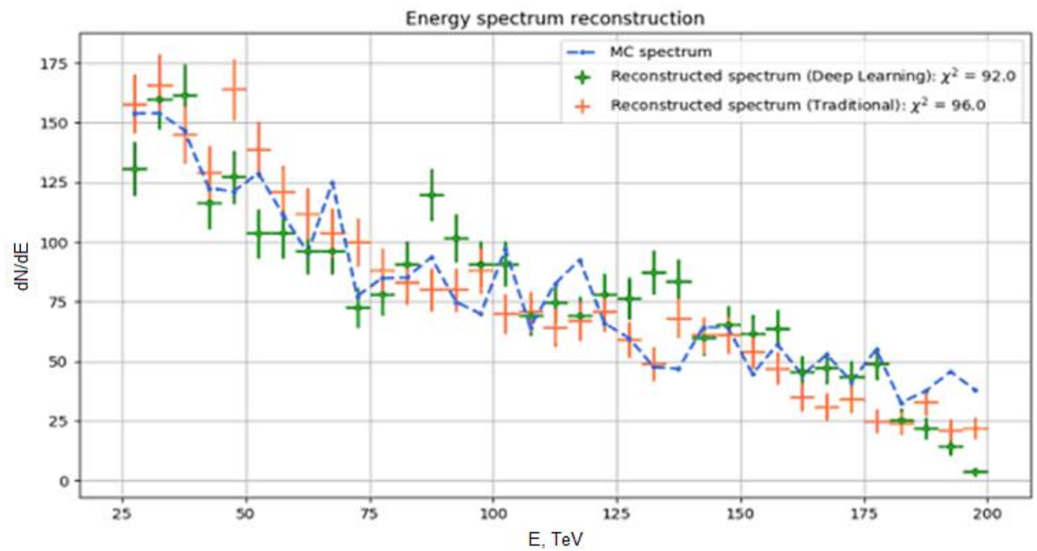




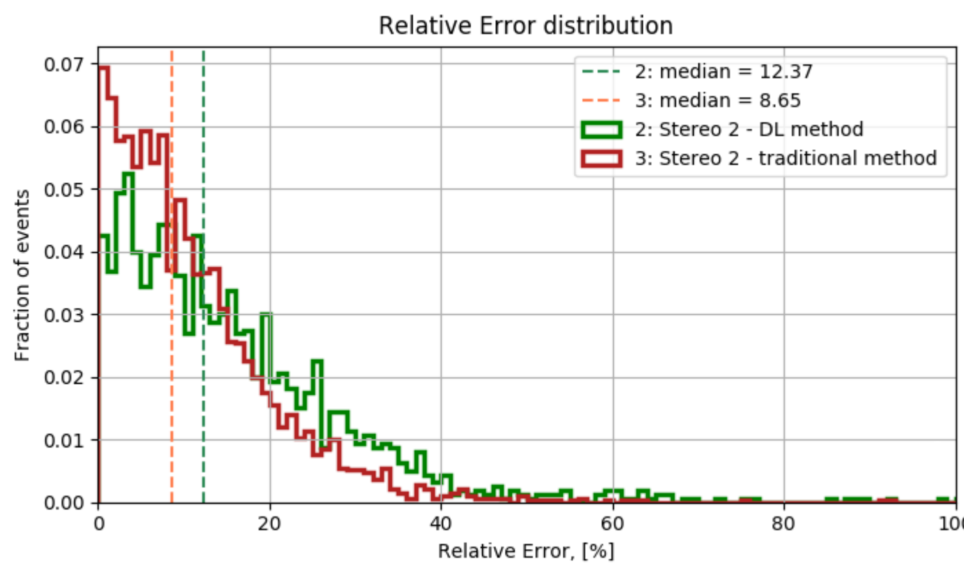
- It can be seen from the results that each of the CNNs gives small differences in the reconstruction of the spectrum shape, while in determining the errors in the reconstruction of each event DenseNet significantly reduces the error: the error has become 12%.
- The form of data submission gives a slight improvement in the result in user networks: an improvement in spectrum reconstruction is seen (the χ^2 criterion has decreased from 156 to 87), but the error does not decreased (also 15%).

Comparison of deep learning method and traditional energy reconstruction method

- Model data:
  - Only gamma;
  - Energies: 25-200 TeV;
  - ~5 000 joint events for 2 telescopes;
  - 3:1 train/valid separation;
  - Expanding the training sample by shuffling the channels and adding data from another pair of telescopes.



- *Traditional energy reconstruction method*: approximation for each telescope by a function depending on some Hillas parameters (spot brightness *Size*, *Distance*) and EAS characteristics (EAS maximum height).
- *Deep learning method*: Multi-channel User CNN.



Conclusion

- Many Deep Learning methods were considered to solve the problem of energy recovery in the processing and analysis of data from TAIGA-IACT telescopes in the work.
- It was demonstrated that a good result is achieved in energy reconstruction in the case of stereoscopic observations.
- Reconstruction of the energy spectrum by neural networks showed good agreement with the traditional method based on the Hillas parameters.
- In the future results obtained can be improved by more subtle settings of neural networks.

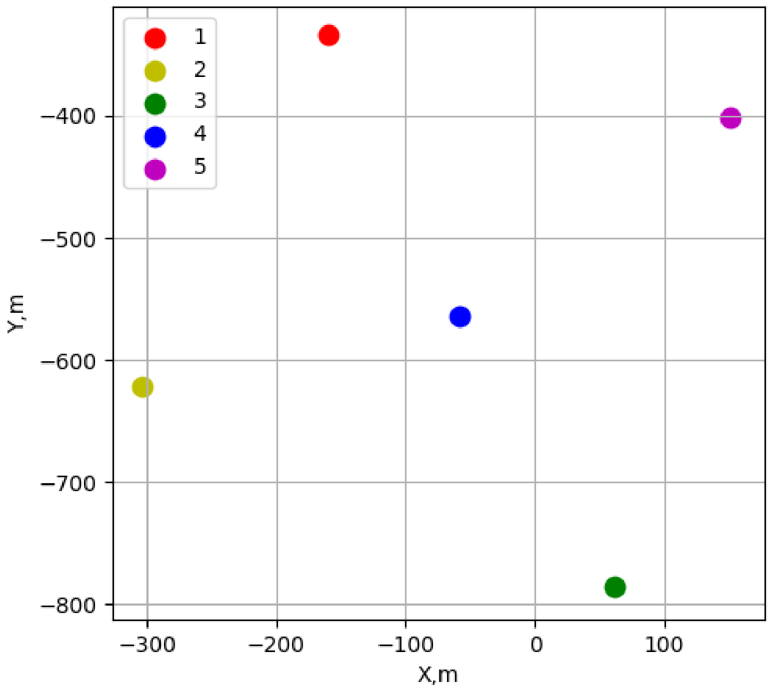
Acknowledgments

Authors would like to thank the staff of the TAIGA collaboration for their help in the work, and also express special gratitude to Volchugov P.A. for the provided data of traditional energy reconstruction method.

Thank you for attention!

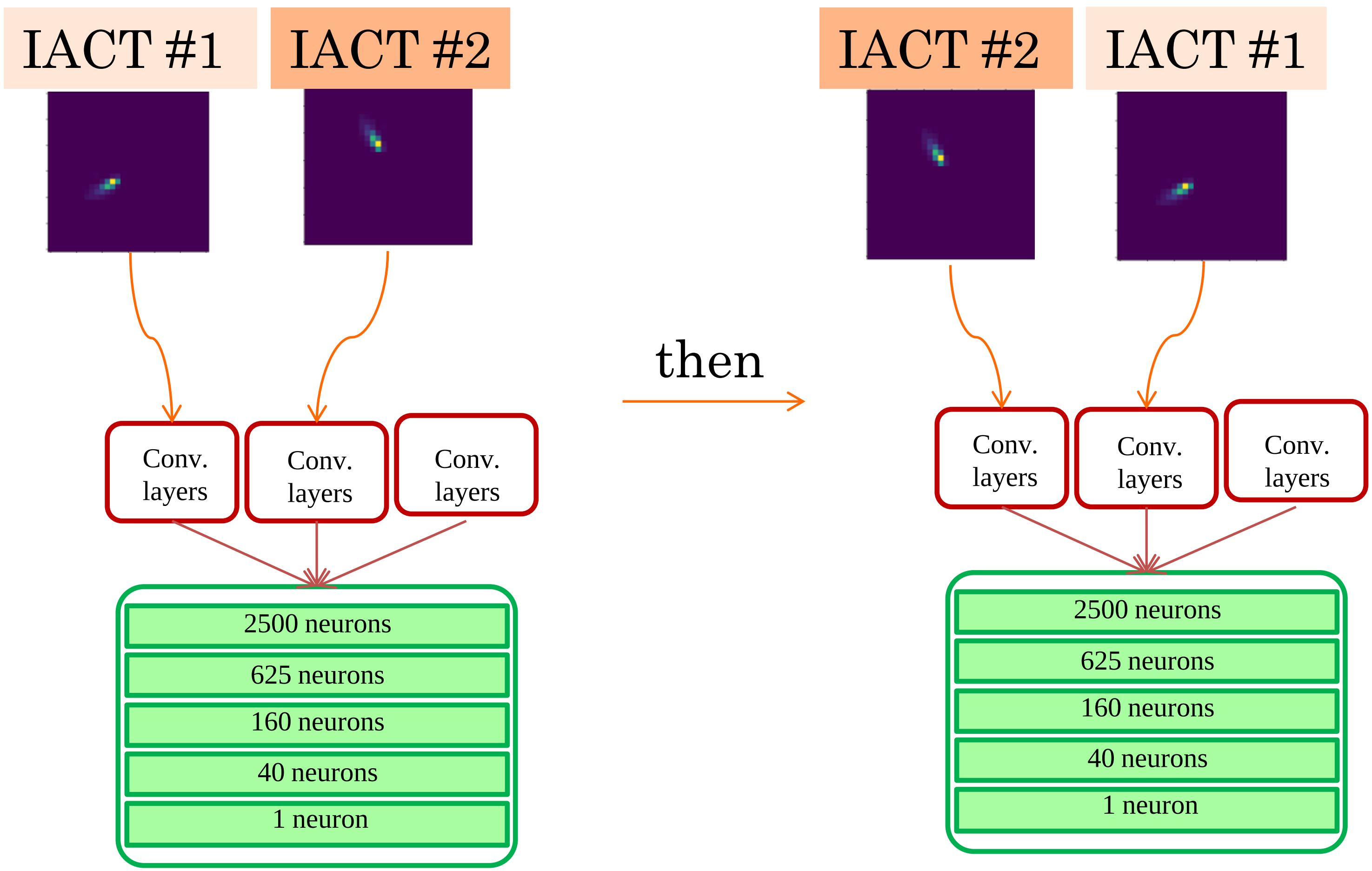
Comparison of deep learning method and traditional energy reconstruction method

- Model data includes joint events from 5 telescopes. Images of the pair (IACT1,IACT2) were processed by traditional method. The number of joint "stereo-2"events is 5 thousands.
- For expanding training set images from (IACT1,IACT2) and (IACT1,IACT5) was taken because of equal distance between telescopes (~320 m).
- Thus training set included 16 thousand events.



Relative position of IACTs

SAMPLE EXPANSION METHOD FOR STEREO-MODE



Dependence relative error from energy