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Deep Learning based Algorithms in Astroparticle Physics

Martin Erdmann, Michael Dohmen, ***Jonas Glombitza,*** *Maximilian Vieweg, Marcus Wirtz*

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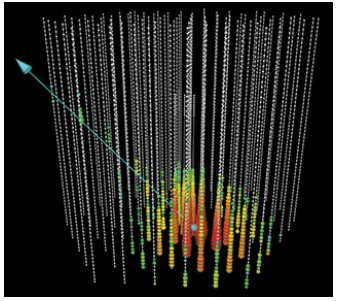

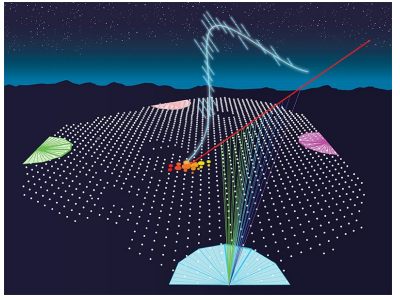

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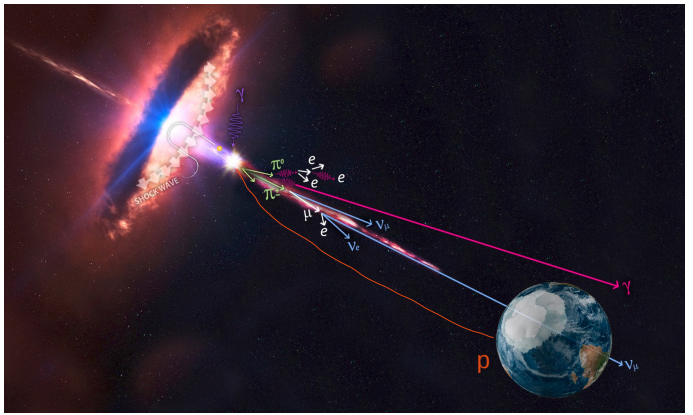
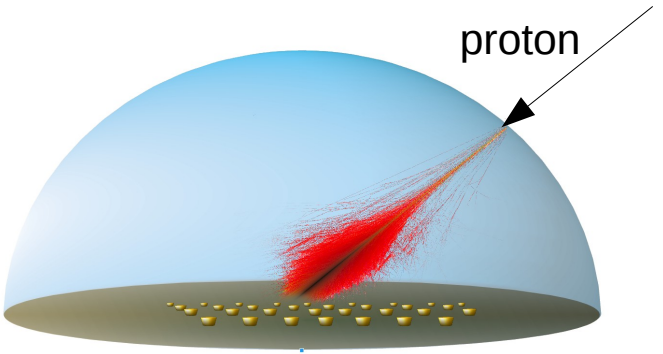
Astroparticle Physics

- Observation of particles with astronomical origin
- Measuring energy spectrum and composition
- Find, identify and understand sources
  - Multi-messenger astronomy
- Feature **very** large detector volumes
  - Ice, water, atmosphere → indirect detection
  - Relatively sparse read out
  - Limited computational resources at site



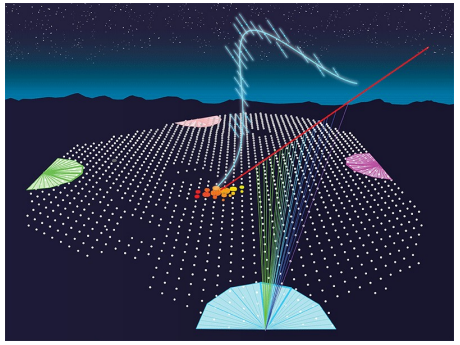
Example
Cosmic Ray Observatory

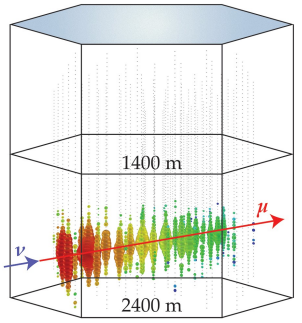
Atmosphere = calorimeter
detector = single readout layer



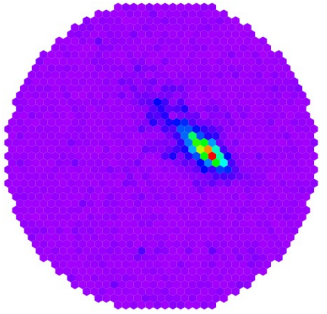
Measured Data

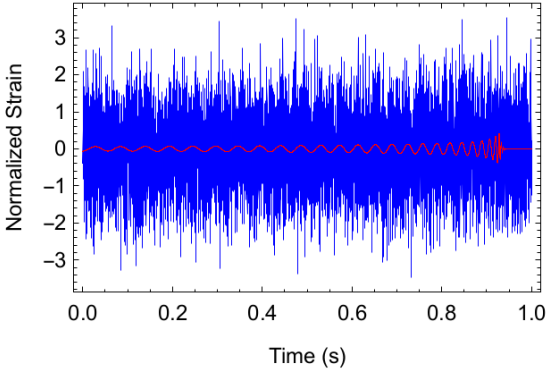
- Widely distributed sensors / telescopes
- Most experiments feature Hexagonal or Cartesian sensor grids
  - 2 and 3 dimensional **structured** footprints / signal patterns
- Many sensors provide time trace of signals
- Structured multi-dimensional data
- Motivates convolutional and recurrent architectures





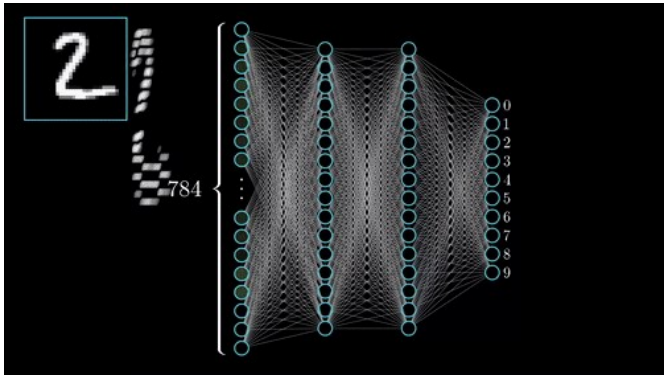
APS/Joan Tycko





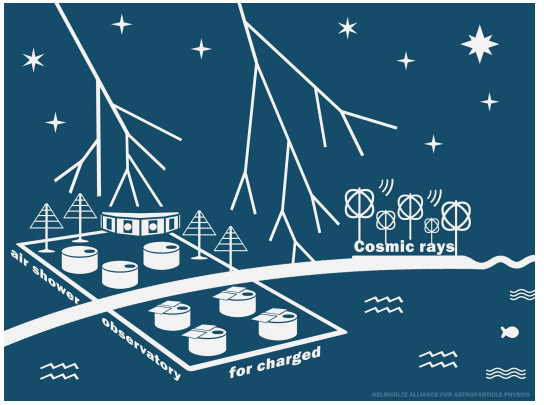
Supervised Learning

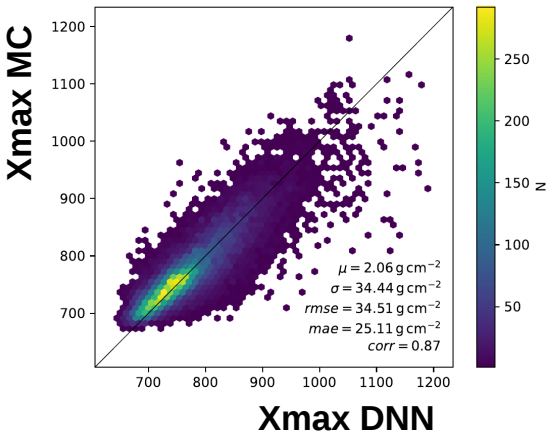
- Convolutional Neural Networks
- Recurrent Networks
- Classification, Regression, Denoising
- Segmentation

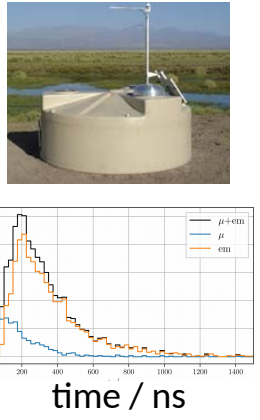


Cosmic Ray Observatory

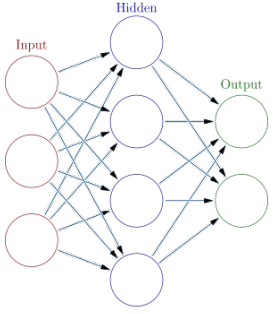
- Measurement of Ultra-high energy cosmic rays
- Reconstruction of Air Showers
  - Geometry (shower axis, shower core)
  - Inferring primary mass very challenging
- Use Deep Convolutional Network
- Results are very promising







+ time offset map



Deep Convolutional Neural Network

Erdmann, Glombitza, Walz - 10.1016/j.astropartphys.2017.10.006

Ice Cube: Neutrino Reconstruction

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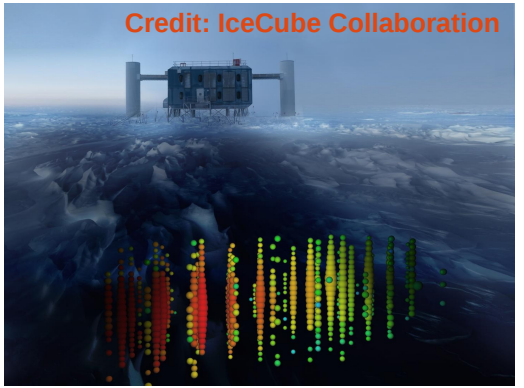
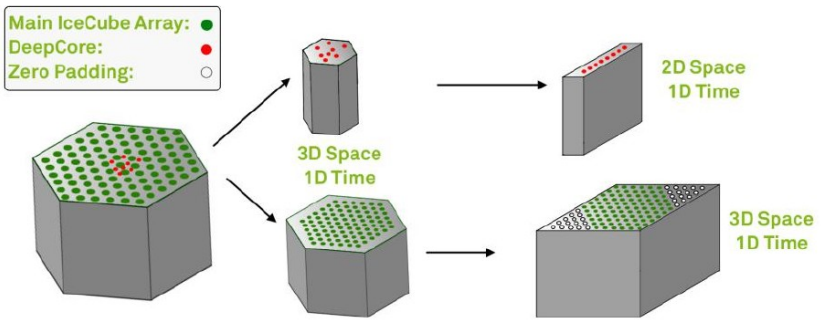
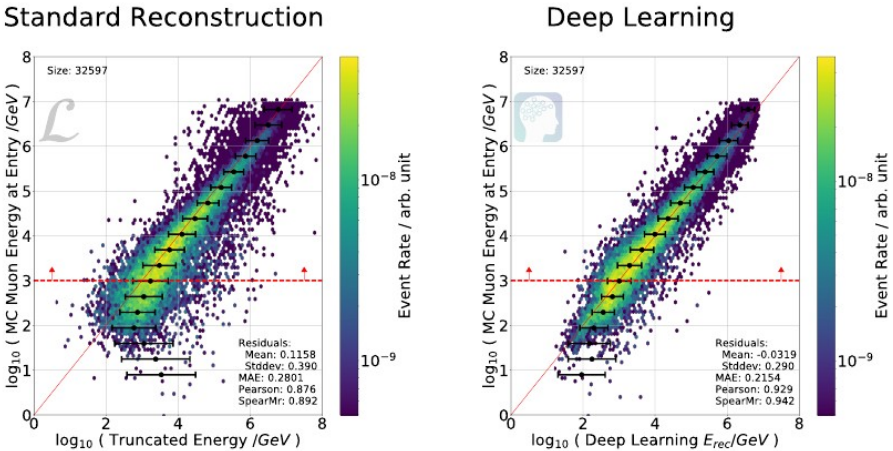
- Neutrino Observatory placed at the south pole
  Use 3D Convolutional Neural Network
  - Reconstruction of muon neutrino: energy, direction
- DNN shows improved runtime and performance
- On-site reconstruction: Deep Learning close to sensors
  - Real-time alerts → Multi-messenger astronomy



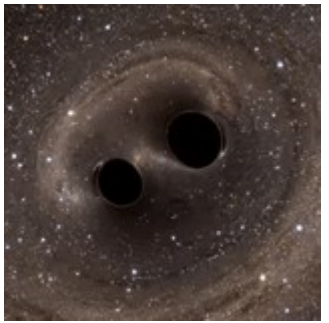


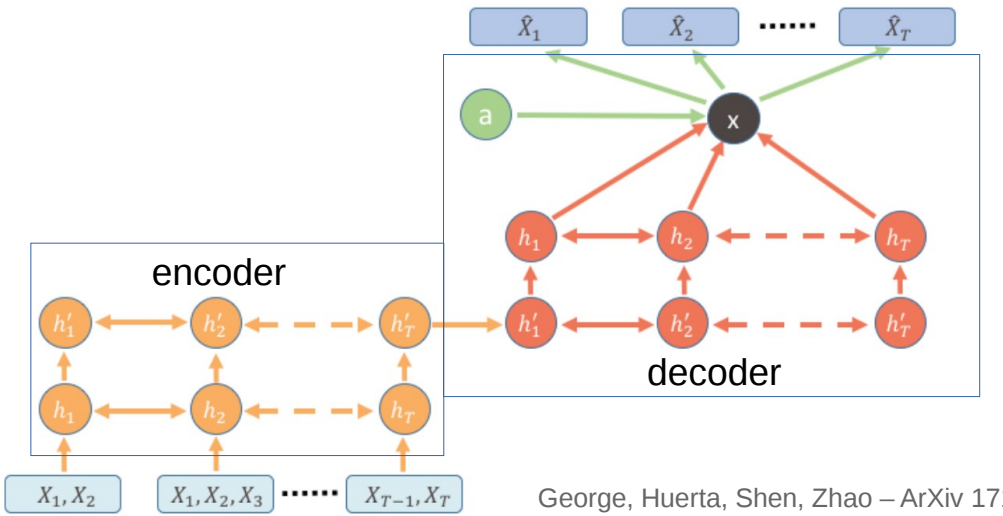
Hünnefeld, ICRC17 - 10.22323/1.301.1057



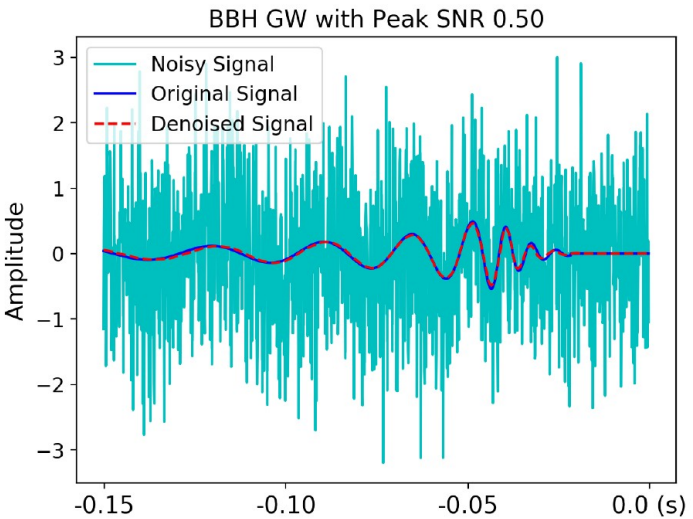
Recurrent Autoencoders

- Measured data of binary black hole mergers contain noise
- Denoising Autoencoder: remove noise and reconstruct signal
- Use Recurrent LSTM layers
- Excellent recovery of original signal



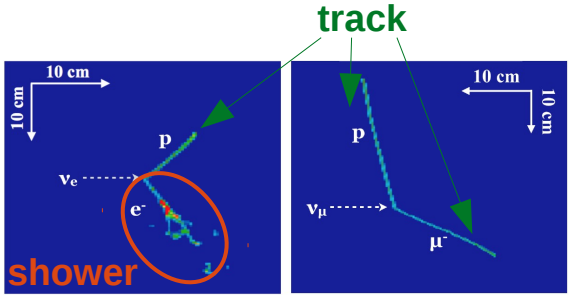


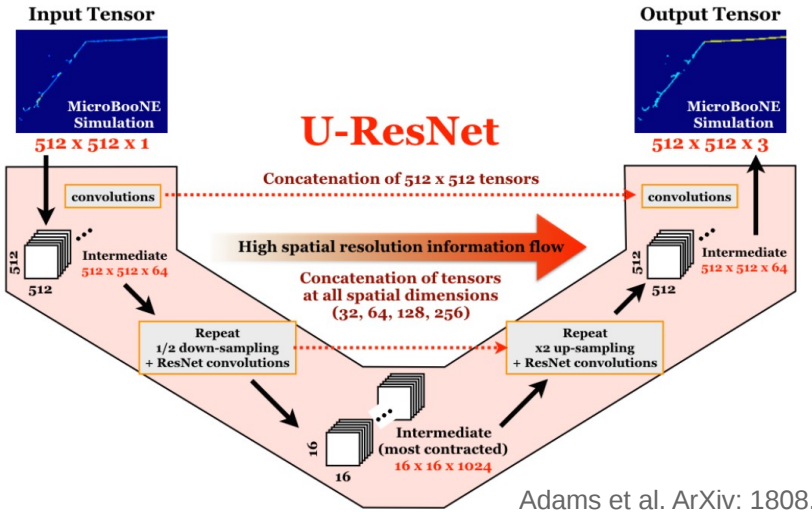
George, Huerta, Shen, Zhao – ArXiv 1711.09919



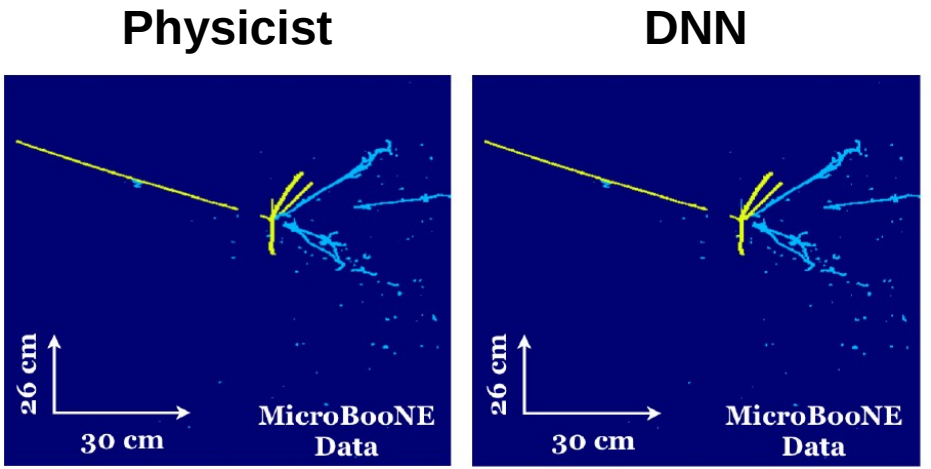
Segmentation - MircroBooNE

- Liquid Argon TPC for neutrino detection
- Pixel-wise segmentation into tracks and EM-showers
  - Architecture: Combination of ResNet and U-Net
- Evaluation on simulations and data (vs. physicist)
- Incorrectly classified pixel fraction per image ~ few percent





Adams et al. ArXiv: 1808.07269

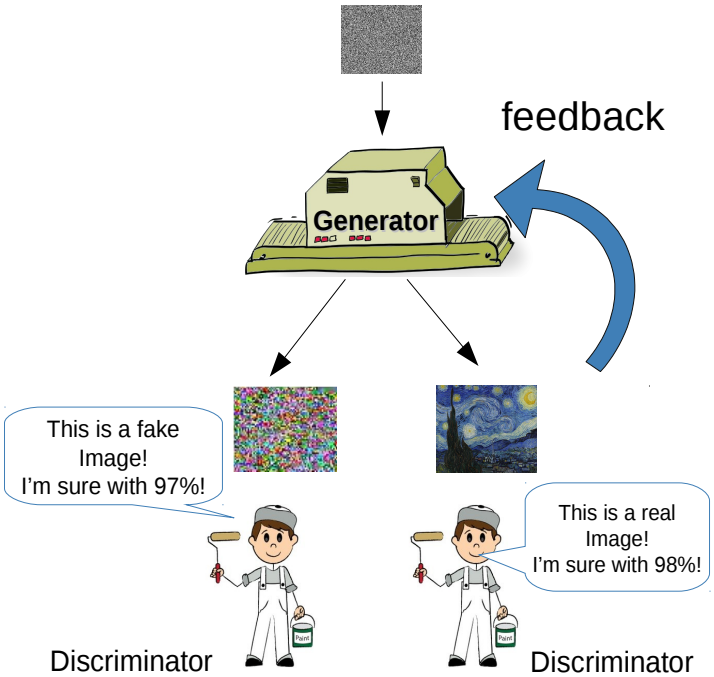


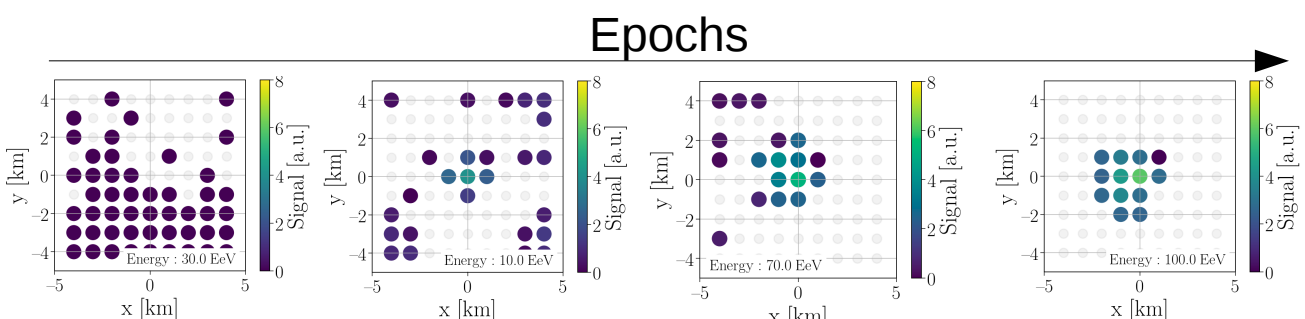
Unsupervised Learning

- Generative Models
- Simulation Refinement

Generative Adversarial Networks

- Use Generative Adversarial Networks (GANs) for simulations
- Generator network generates new events
  - Discriminator rates quality of generated events
  - Discriminator feedback is used to train generator
- Conditioning of generator to physics parameters
- Speed up physics simulations ~10^3 – 10^5
- First application shows promising results





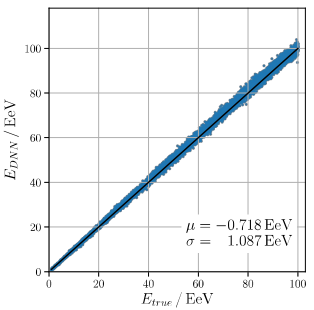
Erdmann, Geiger, Glombitza, Schmidt - 10.1007/s41781-018-0008-x

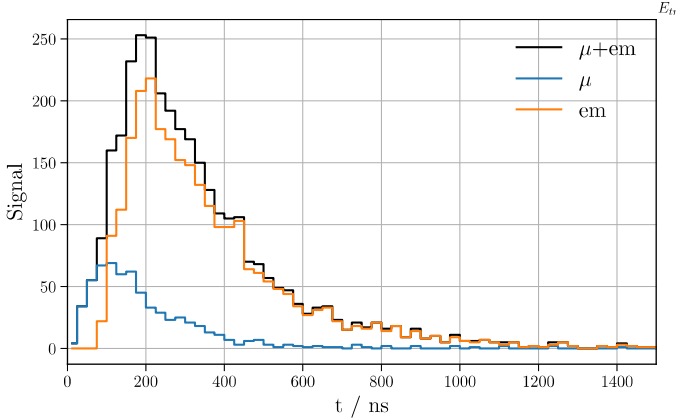
Simulation Refinement

- Models trained on **simulations** but application on '**data**' (simulated)
  - Model can be sensitive to artifacts / mismatches existing in simulation

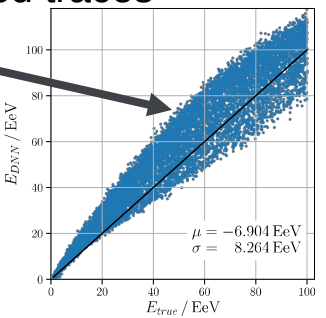
Neural network can not handle modified traces

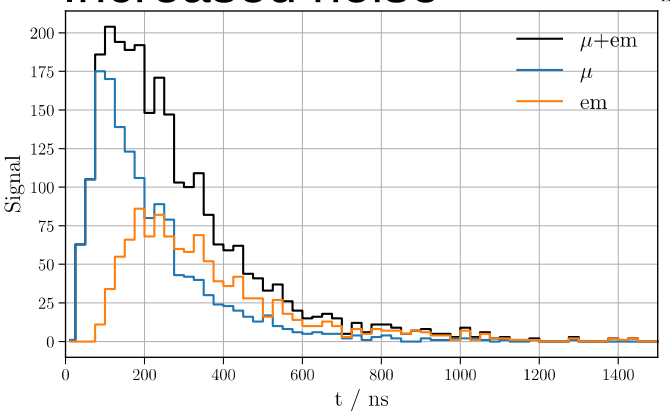
Simulation
70% electromagnetic
30% muonic



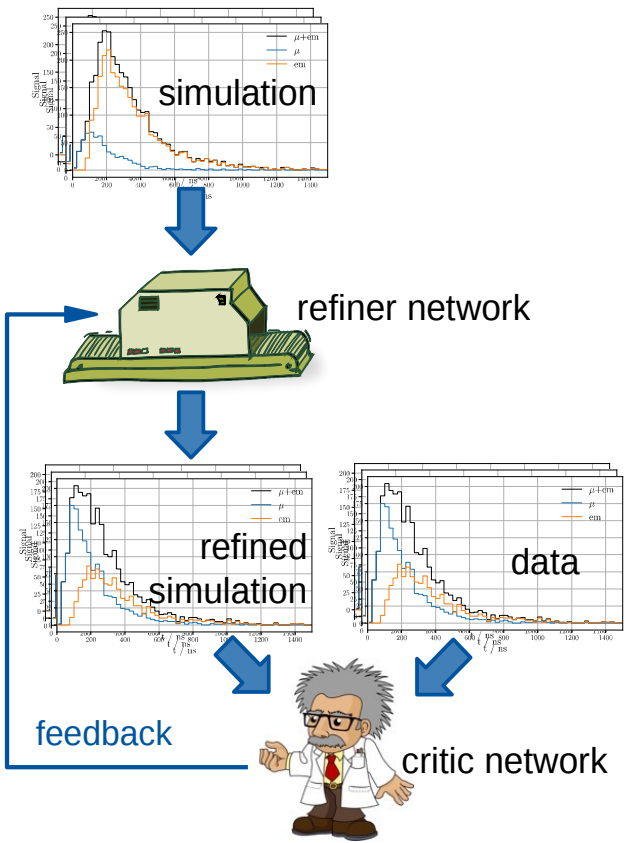


'Data'
30% electromagnetic
70% muonic
+ Increased noise





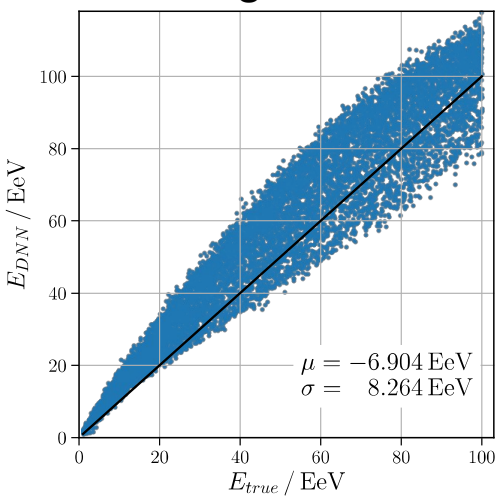
Simulation Refinement



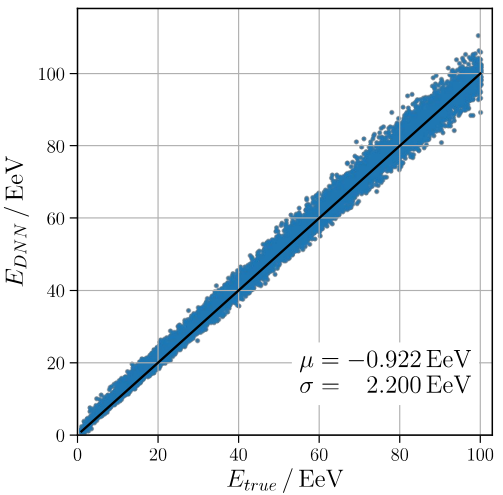
Erdmann, Geiger, Glombitza, Schmidt - 10.1007/s41781-018-0008-x

- Refiner network ‘refine’ simulation using feedback of critic network
- Evaluate network performance on **data**
  (simulation, with different component scalings)

Trained on **original simulation**



Trained on **refined simulation**



- **Training on refined simulations is able to improve reconstruction**

Visualization of Deep Networks

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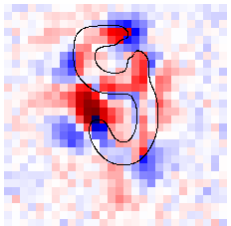
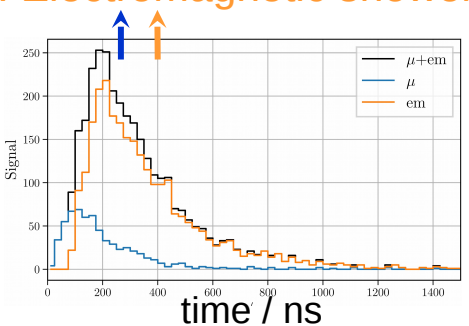
Erdmann, Eich, Glombitza

What makes a “9” a “9” for DNNs?

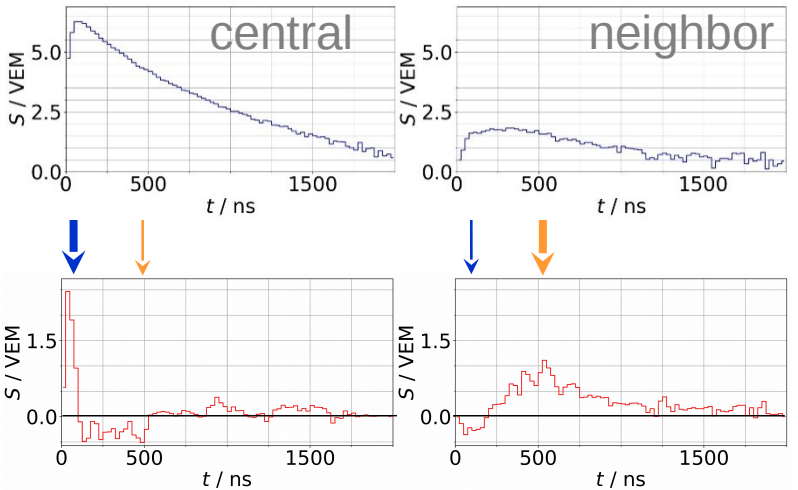


- Find patterns important for the reconstruction

  1. Muons arrive first, then
  2. Electromagnetic shower particles



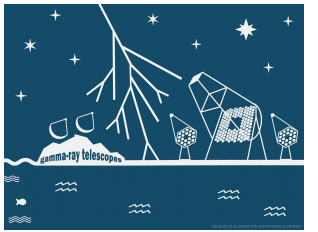
1 event: raw signal traces of 2 detectors

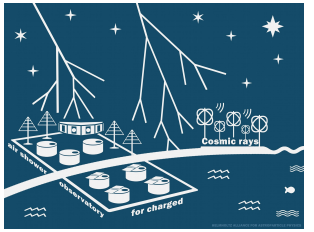


Network learns physics aspects from data in 3h

Summary

Deep Learning arrived in all fields of astroparticle physics!



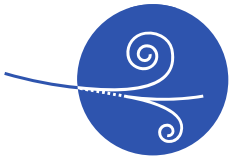


Supervised Applications

- Segmentation and Denoising
- Improved object reconstruction
- Deep Learning close to sensors
  - online reconstruction → real-time analysis
- First steps towards understanding physics networks

Unsupervised Applications

- Generative models for simulation acceleration
- Promising results on simulation refinement



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Backup

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Denoising of Air Shower Radio Signals

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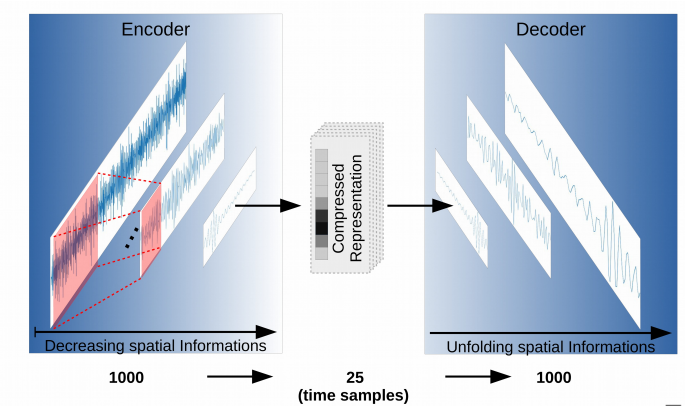
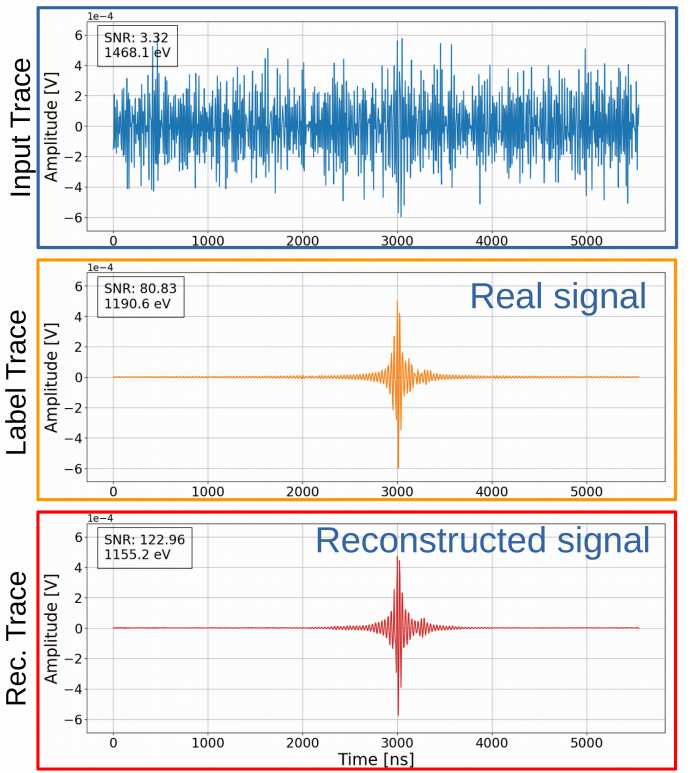
- Supervised trained Autoencoder
  - Network encodes only relevant information
- Remove noise of radio signals from cosmic ray induced air showers
- Signal energy and frequency spectrum approx. conserved

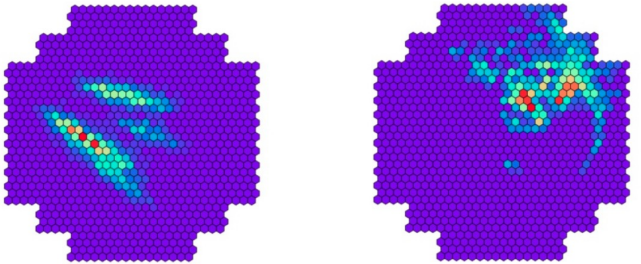


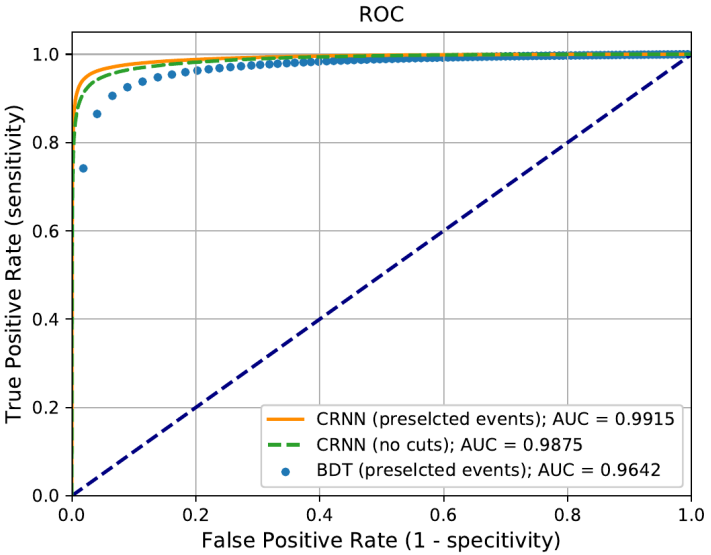


Erdmann, Schlüter, Smida - https://arxiv.org/pdf/1901.04079.pdf

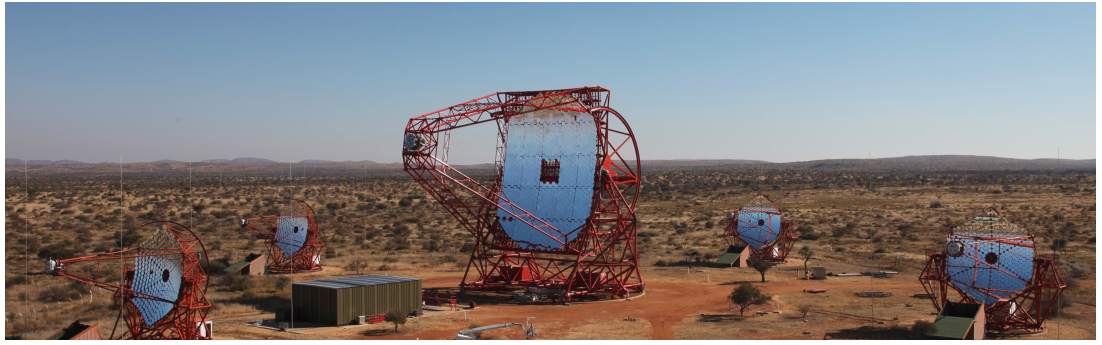
Classification: H.E.S.S.

- Imaging Atmospheric Cherenkov Telescopes
- Background rejection using Convolutional Neural Network
- Classification between:
  - Hadronic showers
  - Photon showers
- ➢ Network outperforms BDT

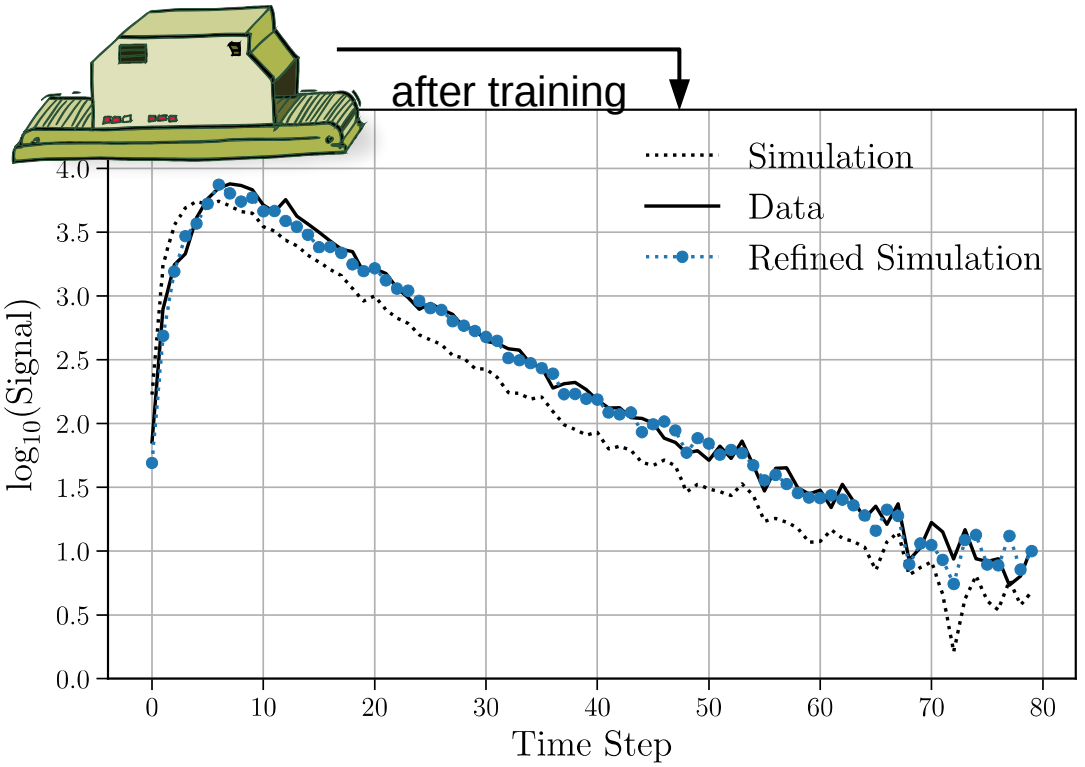




Shilon et al. - 10.1016/j.astropartphys.2018.10.003



Simulation Refinement



- ResNet like architecture
- WGAN-GP loss
- Refined trace more data like