Karlsruher Institut für Technologie

ICECUBE NEUTRINO OBSERVATORY

New approaches for gamma-hadron separation at the IceCube Neutrino Observatory

RICAP-22 Roma International Conference on AstroParticle Physics

September 06-09, 2022

Bontempo, Federico
for the IceCube collaboration

PhD student
Institut für Astroteilchenphysik (IAP)
Karlsruher Institut für Technologie (KIT)
Telefon: +49-721-608-22426
Email: federico.bontempo@kit.edu

European Research Council
Established by the European Commission

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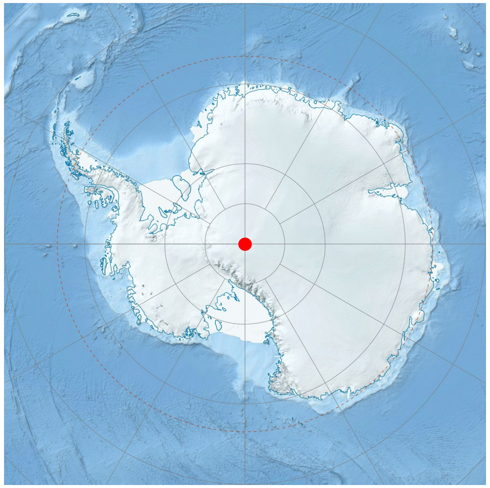
IceCube Neutrino Observatory

- IceCube Neutrino Observatory is a neutrino observatory constructed at the Amundsen–Scott South Pole Station in Antarctica
- The successor of Antarctic Muon And Neutrino Detector Array (AMANDA)



Source: https://icecube.wisc.edu/

Bontempo, Federico - *federico.bontempo@kit.edu*

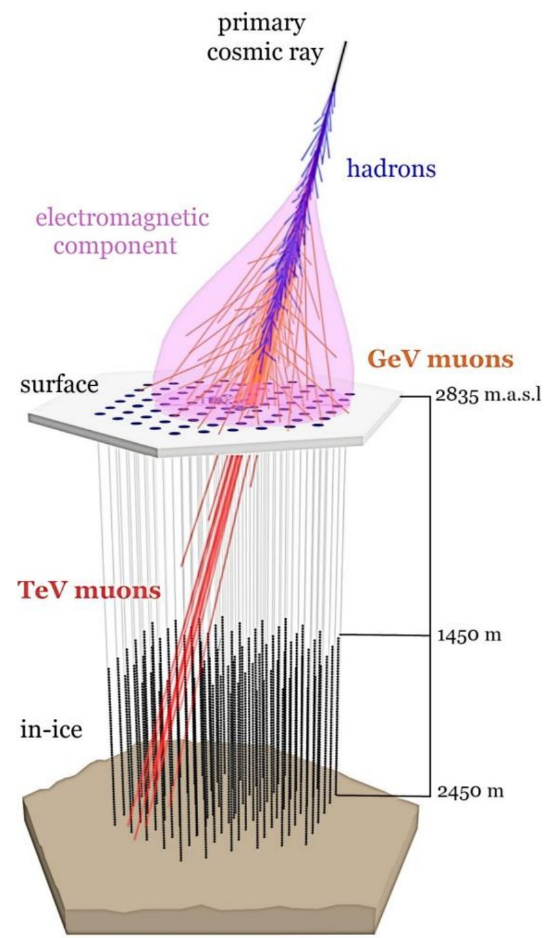
Karlsruher Institut für Technologie (KIT)
Institut für Astroteilchenphysik (IAP)

IceCube Neutrino Observatory

A three-dimensional cosmic ray detector:

- IceTop is a 1 km^2 array of ice-Cherenkov detectors on the surface that serve as:
  - partial veto for the down-going background of penetrating muons created by cosmic-ray interactions in the atmosphere
  - to detect cosmic ray air showers generated by interactions of high-energy cosmic rays in the atmosphere
  - Cosmic ray detection
  - Measure electromagnetic and muonic components of air shower
  - Shower reconstruction (energy and direction)

- IceCube 1 km^3 in-ice array
  - Measure high energy muon (E > 400 GeV)
  - Detection of high energy muons generated by:
    - high energy cosmic rays interacting with the atmosphere
    - neutrino in-ice interaction



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Bontempo, Federico - federico.bontempo@kit.edu

Karlsruher Institut für Technologie (KIT)
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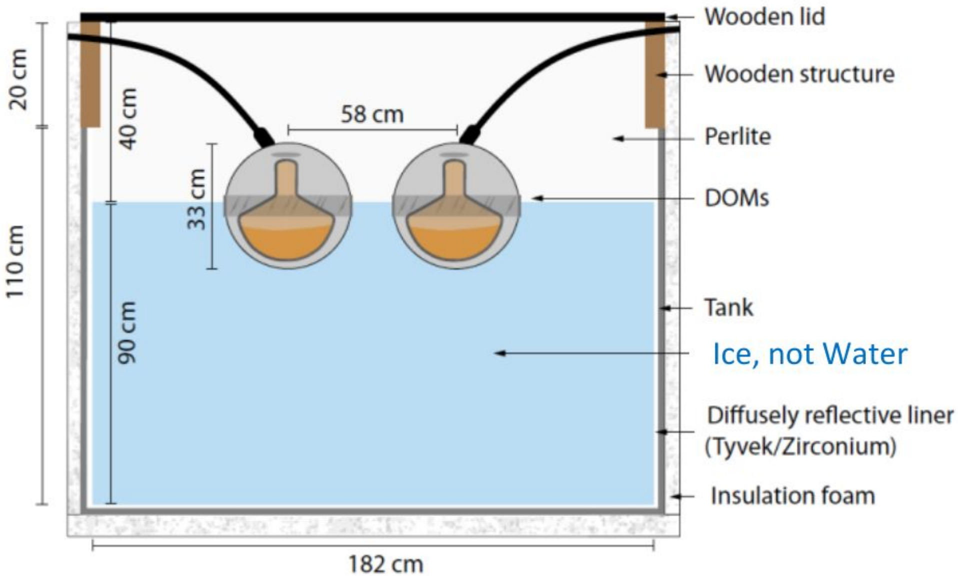
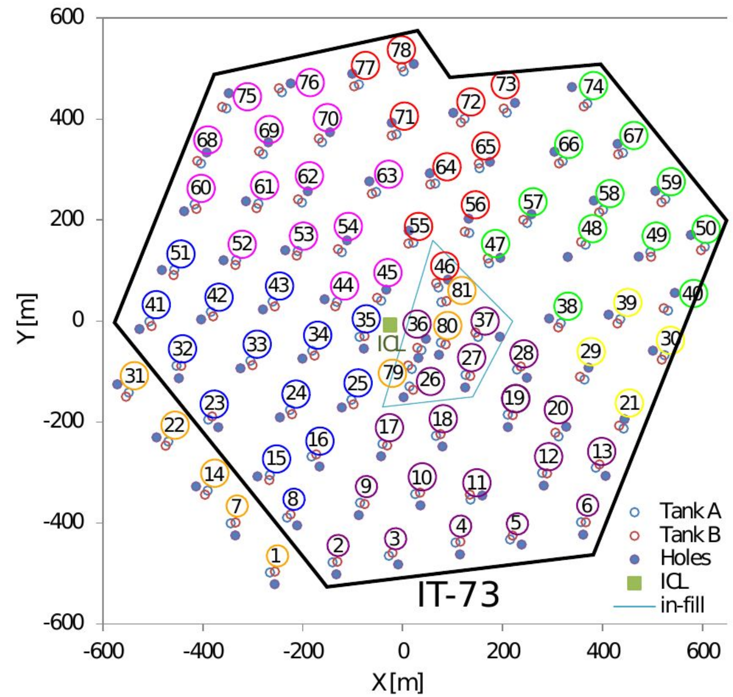
IceTop: Surface array

- Cosmic ray energies 1 PeV to 1 EeV
- 2835 m a.s.l. 680 g/cm2
- 81 stations with 2 tanks each (2 DOMs per tank)
- Angular resolution ~ 1 degree (energy and zenith dependend)
- Timing resolution 3ns
- Energy resolution 0.1 in $\log_{10}(E/GeV)$





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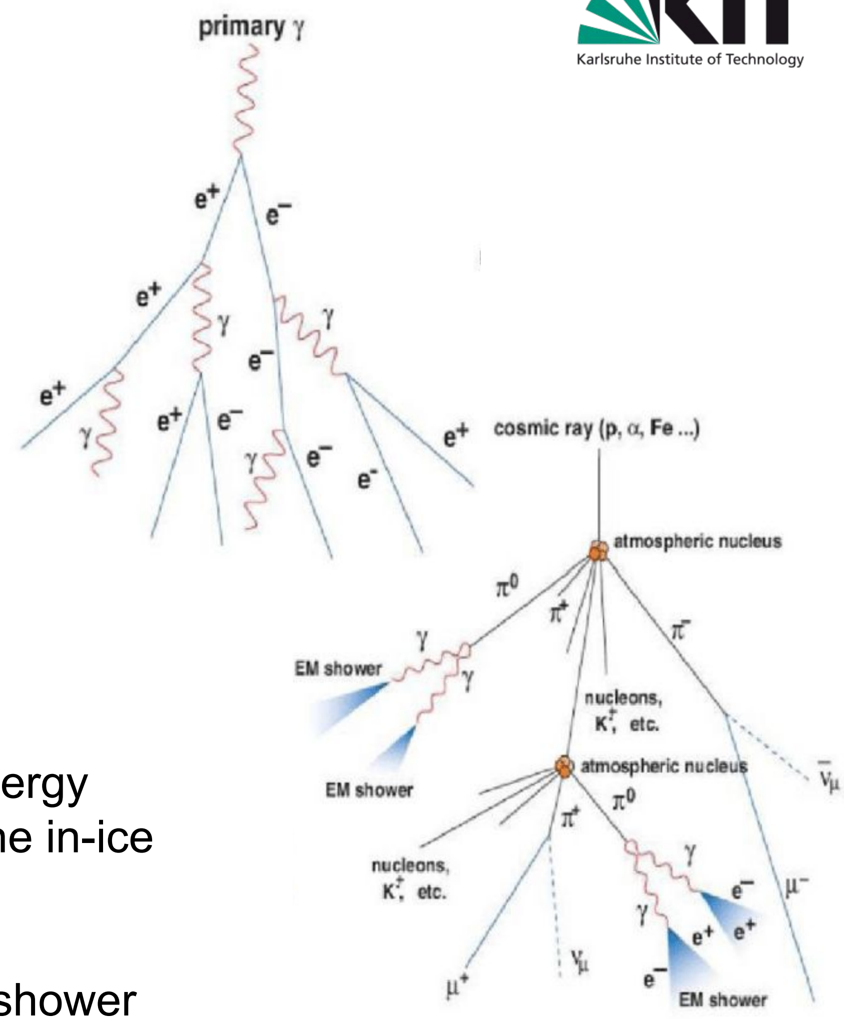
Gamma hadron separation

- Gamma-ray induced air showers:
  - fewer muons
  - less shower fluctuations
  - narrower lateral spread
- Hadronic air showers:
  - richer in muon content
  - more shower fluctuations
  - wider lateral spread
- How to discriminate them:
  - Calculating the total charge of high energy muon via the total in-ice charge and the in-ice containment
  - Reconstructed energy of the primary
  - Reconstructed zenith angle of the air shower



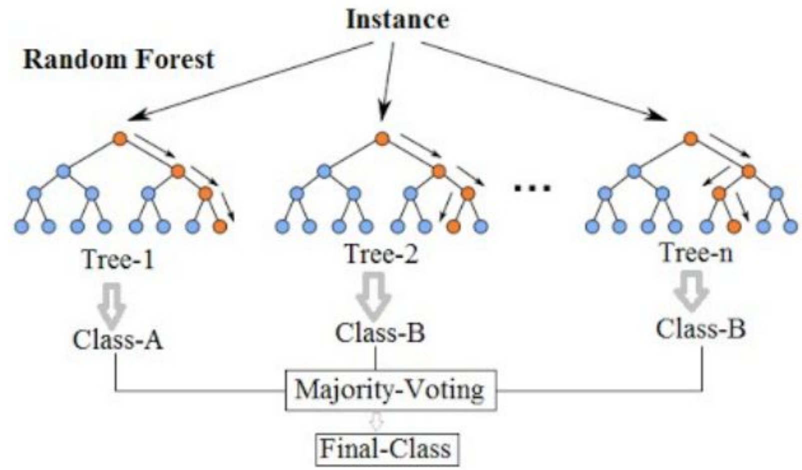
Images source: doi: 10.13140/RG.2.1.4140.4969

Bontempo, Federico - federico.bontempo@kit.edu

Karlsruher Institut für Technologie (KIT)
Institut für Astroteilchenphysik (IAP)

Machine Learning: Random Forest

A Random Forest classifier consists of
a combination of many simple decision trees



Each tree acquires its n events from the training sample, such that each tree trains on a different set of events every time

The splitting condition: minimization of the Gini impurity in the child nodes

$$I_G = 1 - \frac{w_S^2 + w_B^2}{(w_S + w_B)^2}$$

w_S and w_B are the total weights in a node for the signal and background classes

“probability of misclassification”:
all of the weight in the node is in one class IG = 0
an even split in the node results in IG = 0.5.

Input features:

- total in-ice charge
- In-ice fraction containment
- $\log_{10}(S_{125})$: Energy related parameter
- sin of declination angle
- log-likelihood parameter

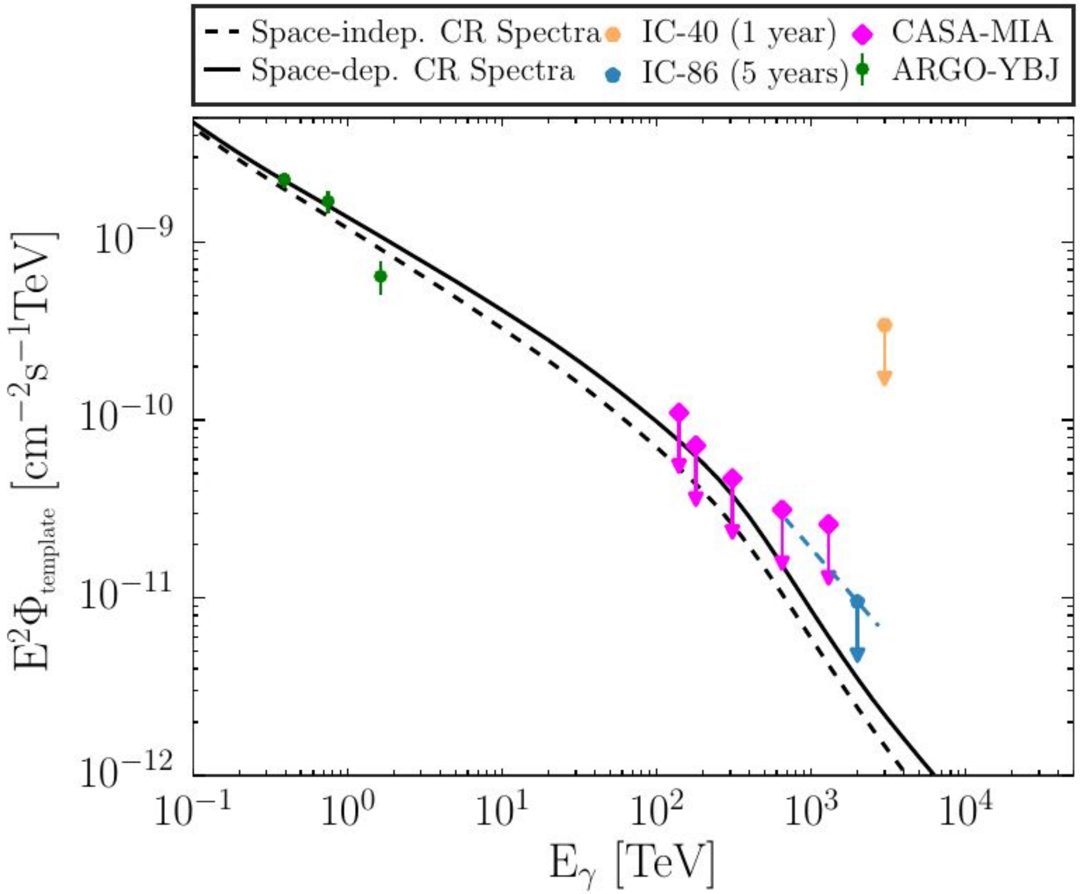
Source: https://scikit-learn.org/stable/

Bontempo, Federico - federico.bontempo@kit.edu

Previous work: diffuse Galactic plane flux

- The IceCube 90% confidence level upper limit on the flux from the Galactic plane in IceCube field of view

- A spatial distribution of emission given by the π_0 decay component of the Fermi-LAT Galactic plane diffuse emission model



https://arxiv.org/abs/1908.09918: Search for PeV Gamma-Ray Emission from the Southern Hemisphere with 5 Years of Data from the IceCube Observatory

Bontempo, Federico - *federico.bontempo@kit.edu*

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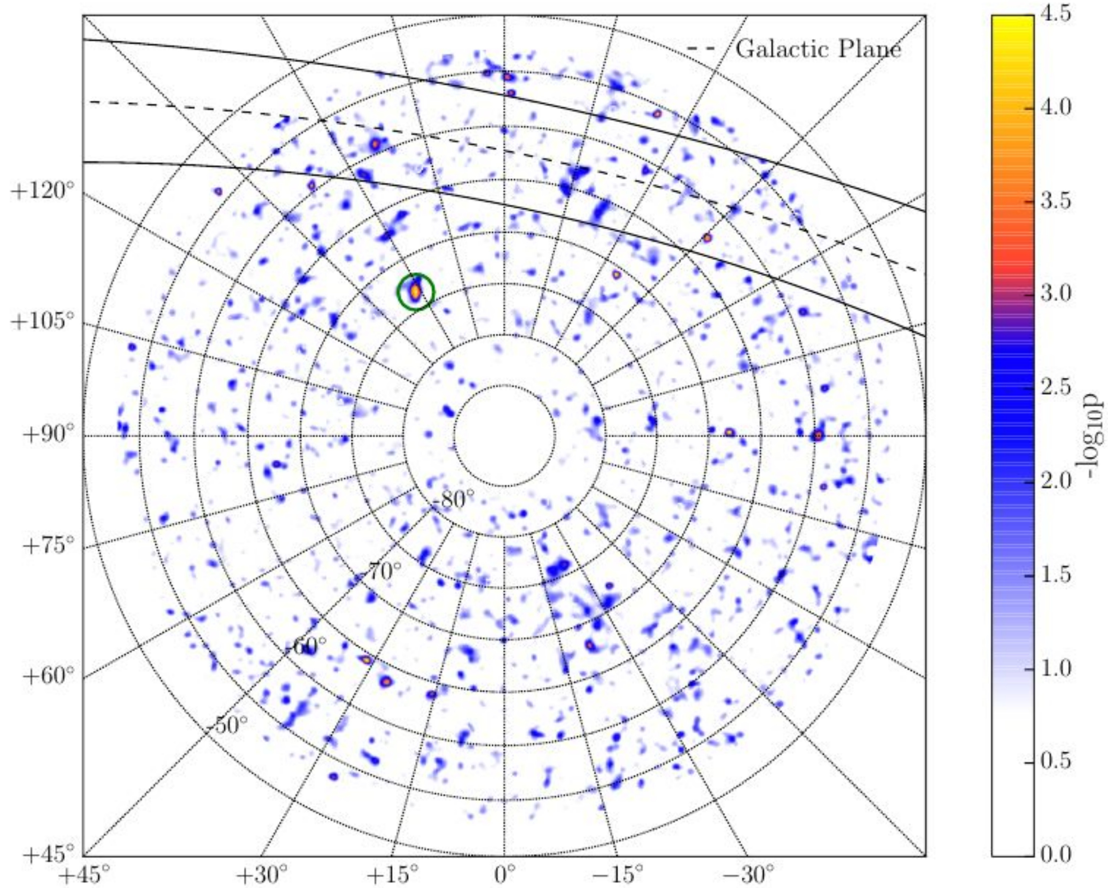
Previous work: point source sky search

- The gamma-hadron discrimination was performed using Random Forest Clssifier
- After the photon selection, a sky search for gamma ray point sources was performed
- The hottest spot in the sky: pre-trial p-value of $4{\times}10^{-5}$
- The post-trial p-value is consistent with background expectation



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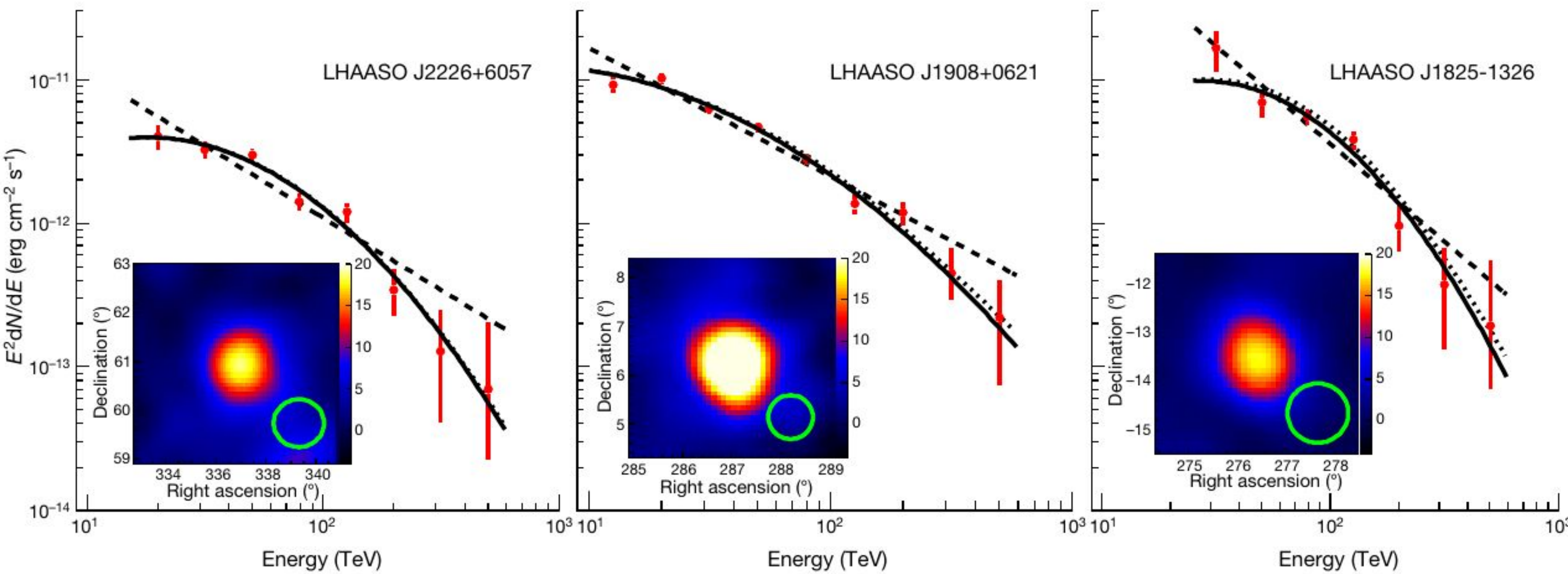
LHAASO sources

- Spring 2021: LHAASO collaboration published in Nature
  - the first observation of a PeV photon
  - multiple UHE gamma ray sources

- Can IceCube detect a LHAASO like source in the south hemisphere?



https://doi.org/10.1038/s41586-021-03498-z: Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources. *Nature*

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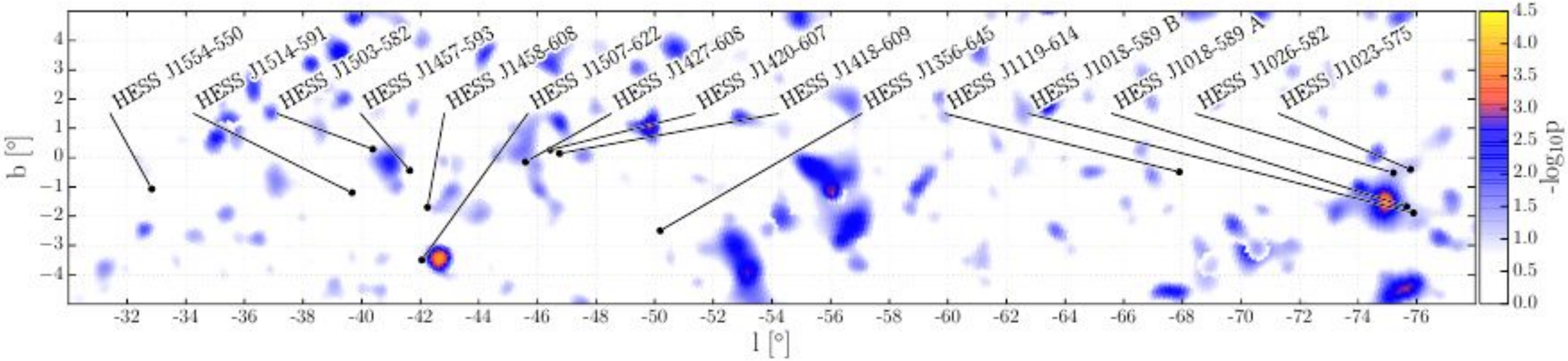
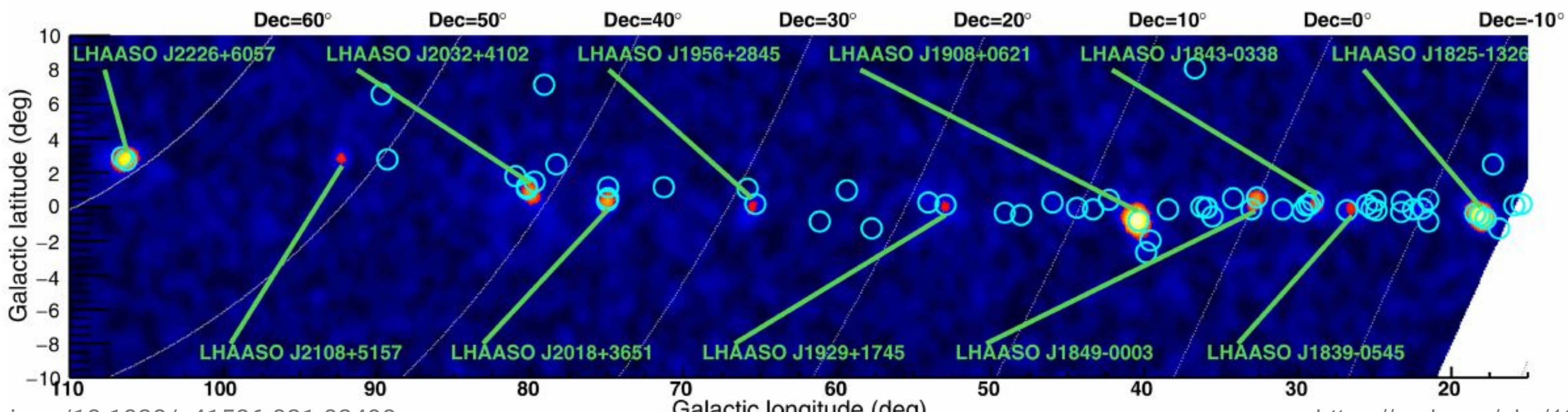
Institut für Astroteilchenphysik (IAP)

Previous work on the Galactic plane search

- LHAASO and IceCube look at 2 different portions of the Galactic Plane
- LHAASO shows that the Galactic Plane is dense with UHE Gamma rays sources





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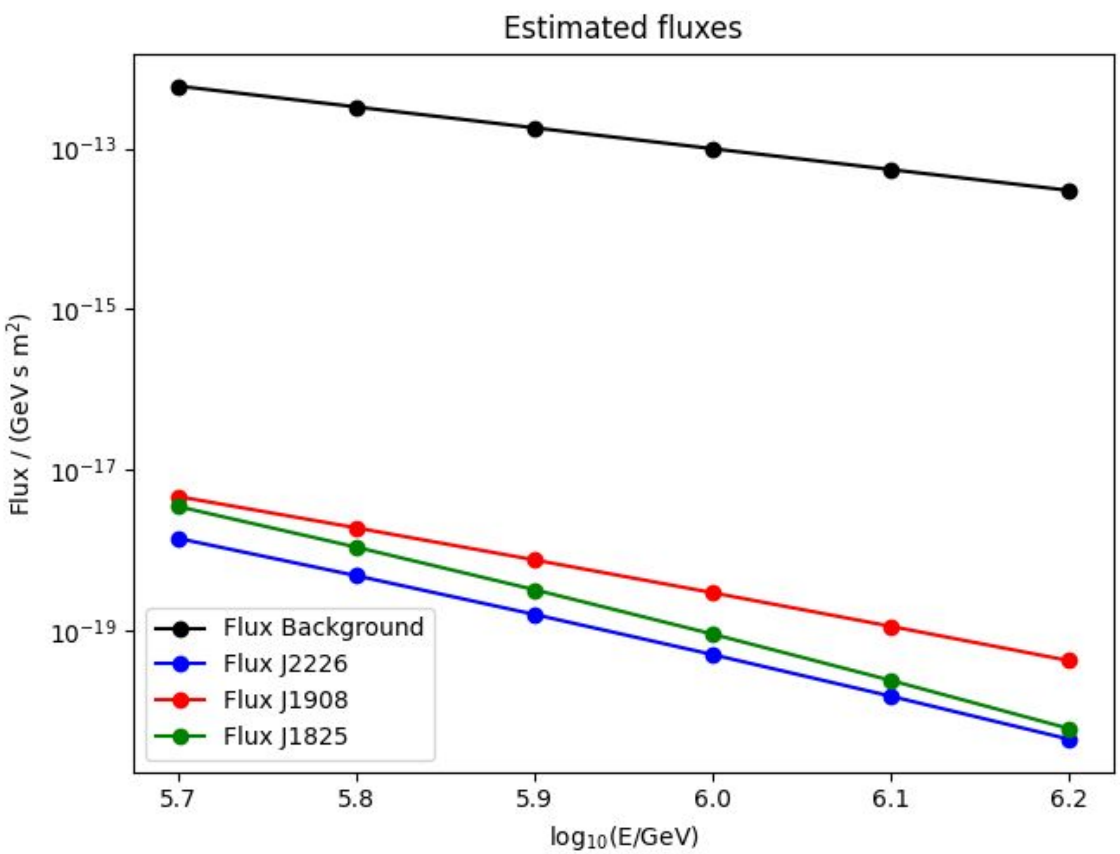
A back of the envelope calculation

- Assuming:
  - energy range $5.7 < \log_{10}(E/\mathrm{GeV}) < 6.3$
  - 4 degree angular resolution (circular region)
- Background events expected per bin: 4 Millions

- Photons expected in IceCube for a LHAASO like source are between 10 and 50 events per year (depending on the flux assumptions and source)



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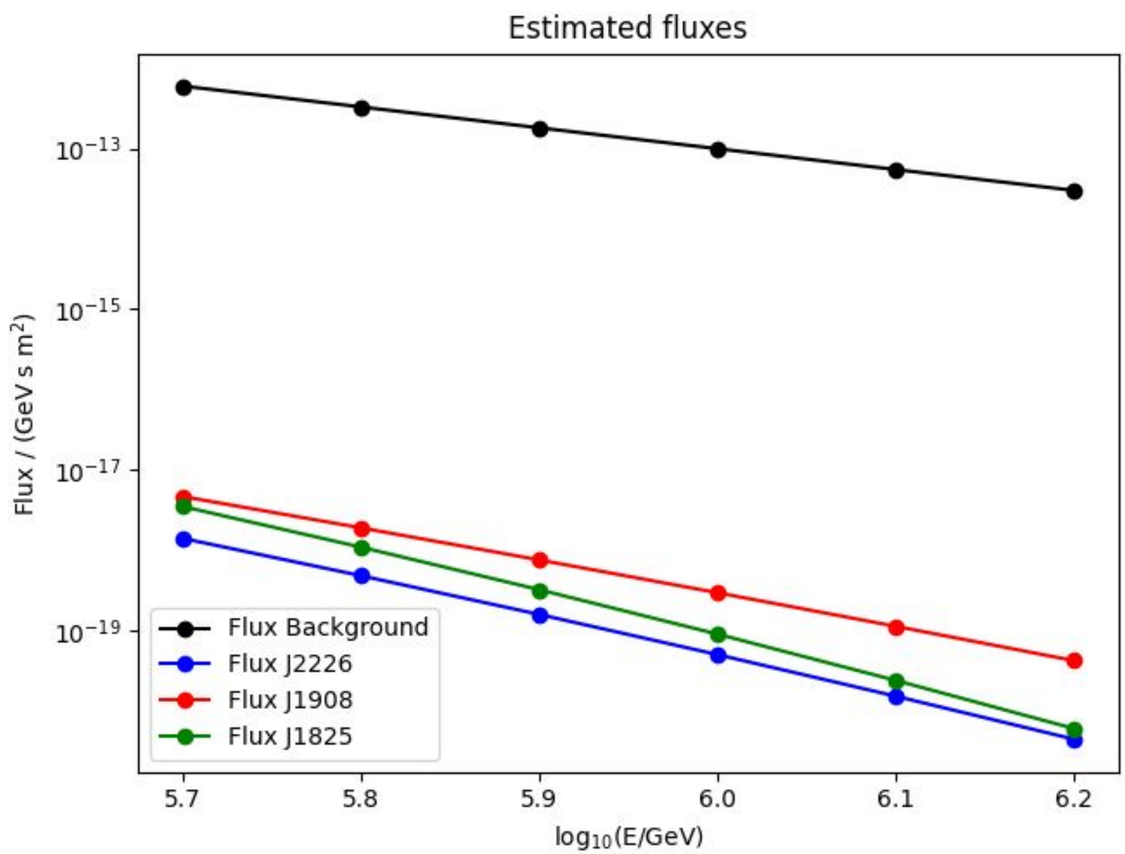
CR and Point sources expected fluxes

- The expected LHAASO like sources fluxes are 5 order of magnitude lower than the cosmic ray background flux

- Between 5 and 7 order of magnitude separation for the optimal separation



Bontempo, Federico - *federico.bontempo@kit.edu*

Random Forest and Deep Learning

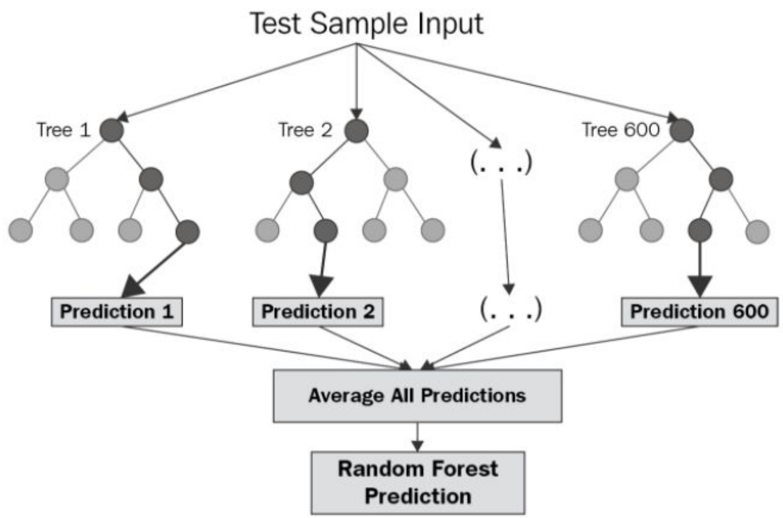
Using machine learning and deep learning methods for the discrimination between signal (Gammas) and Background (hadrons)

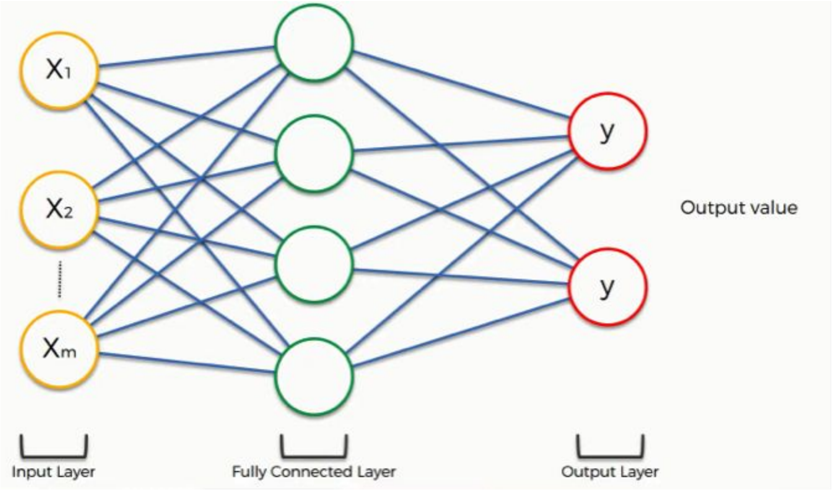
A Random Forest consists of a combination of many simple decision trees with a binary splitting.

Deep Learning uses weights and nonlinear functions for the analysis

Input features:

- total in-ice charge
- In-ice fraction containment
- $\log_{10}(S_{125})$: Energy related parameter
- sin of declination angle
- log-likelihood parameter





Bontempo, Federico - *federico.bontempo@kit.edu*

Karlsruher Institut für Technologie (KIT)
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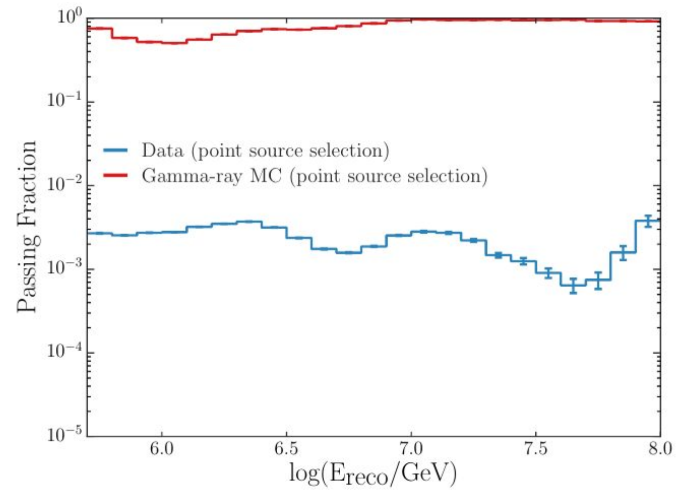
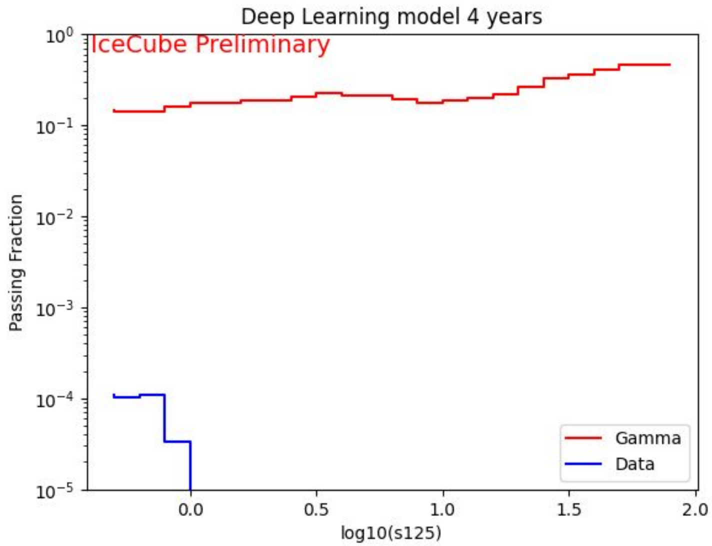
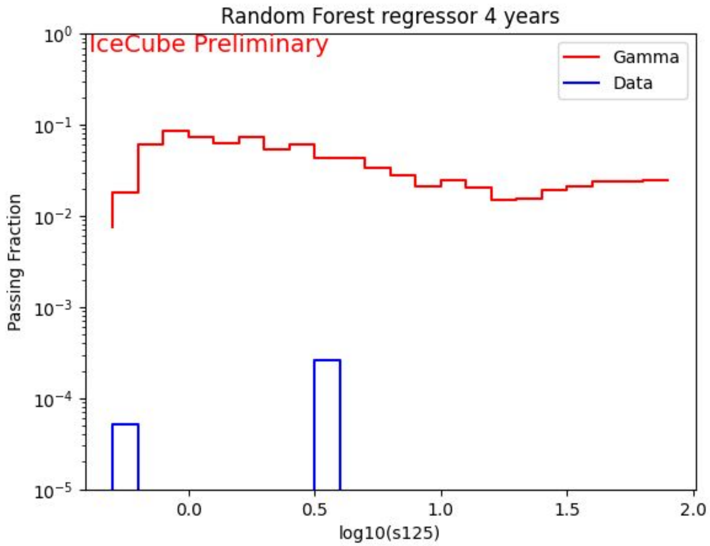
Comparison of recent and published results

- The background suppression depends on the network used
- The higher the suppression of the background the higher the loss in signal
- Thus, high statistic is required by each source to avoid high loss in signal







https://ui.adsabs.harvard.edu/abs/2019PhDT........37G: SEARCH FOR PEV GAMMA RAYS WITH THE ICECUBE OBSERVATORY (Upper plot)

Bontempo, Federico - federico.bontempo@kit.edu

Karlsruher Institut für Technologie (KIT)
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Current status of point source search

- Working on different models using:
  - Random Forest Regressor and Classifier
  - Deep Learning Fully Connectected Neural Network

- More parameters and methods are investigated for the discrimination (e.g. Convolutional Neural Networks)

- Developing a new reconstruction method:
  - lower energies study
  - improved angular resolution

- New simulations are currently running:
  - For the lower energy study
  - IceCube-Gen2

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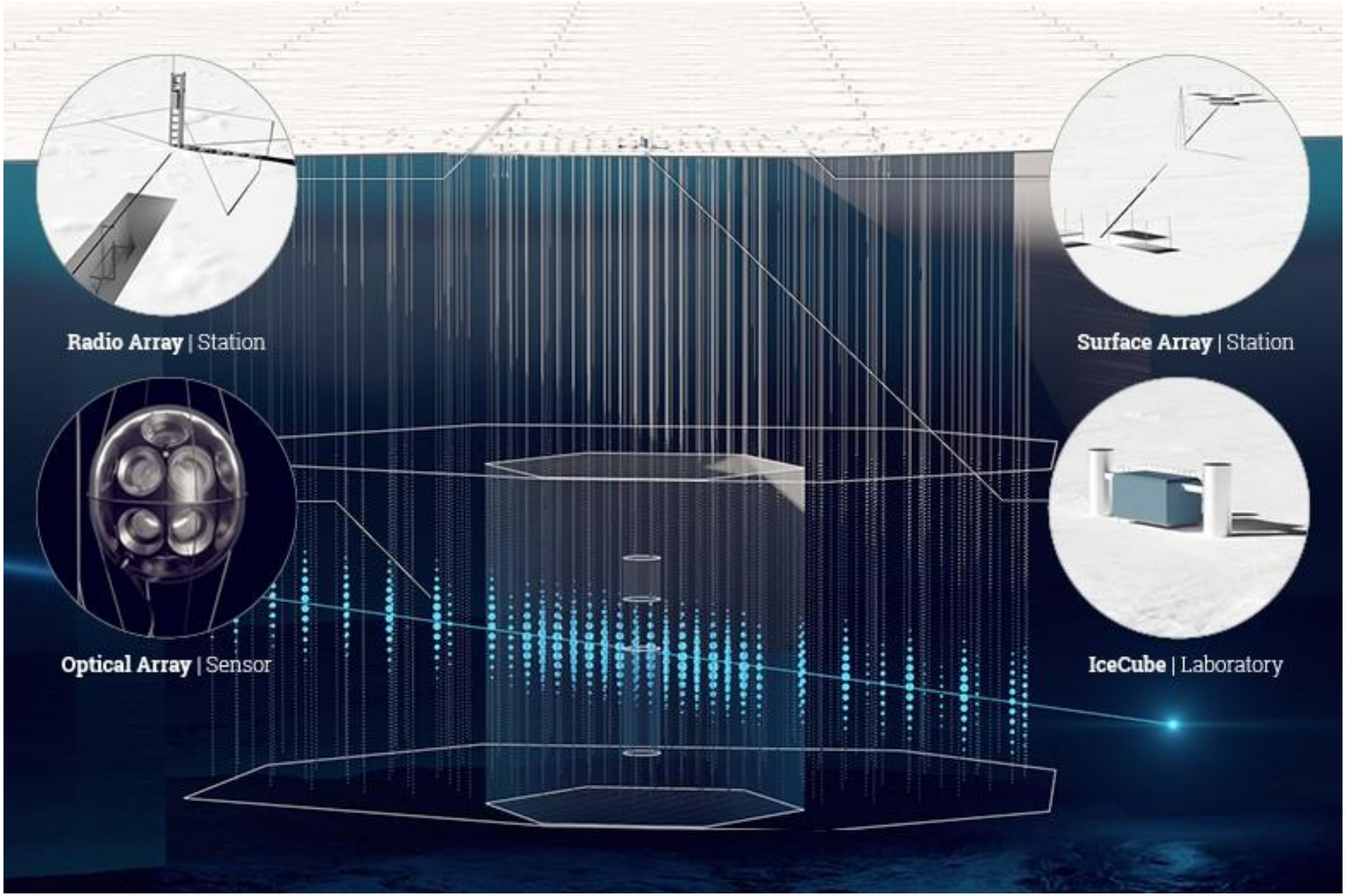
IceCube-Gen2



https://arxiv.org/pdf/2203.08096.pdf: High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

Source: https://www.icecube-gen2.de

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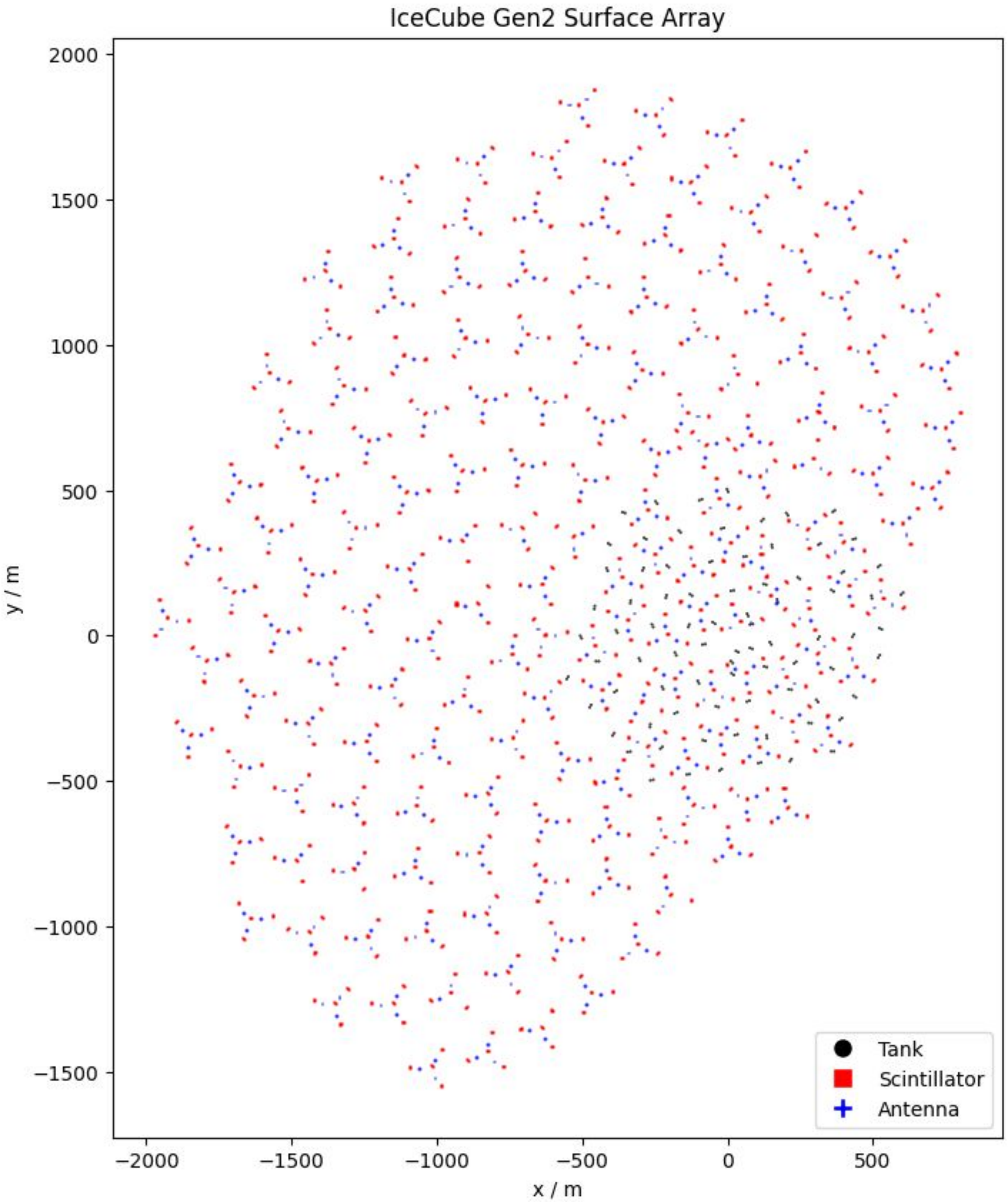

IceCube-Gen2 Surface array

- ~6.5 km^2 surface
- 162 stations
- Each composed by
  - 8 scintillator panels
  - 3 antennas

- x10 improvement in suppression of background
- 8x more statistic

- IceTop surface will improve the gamma-hadron separation via:
  - ice cherenkov tanks
  - scintillator panels
  - antennas

https://arxiv.org/pdf/2203.08096.pdf: High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

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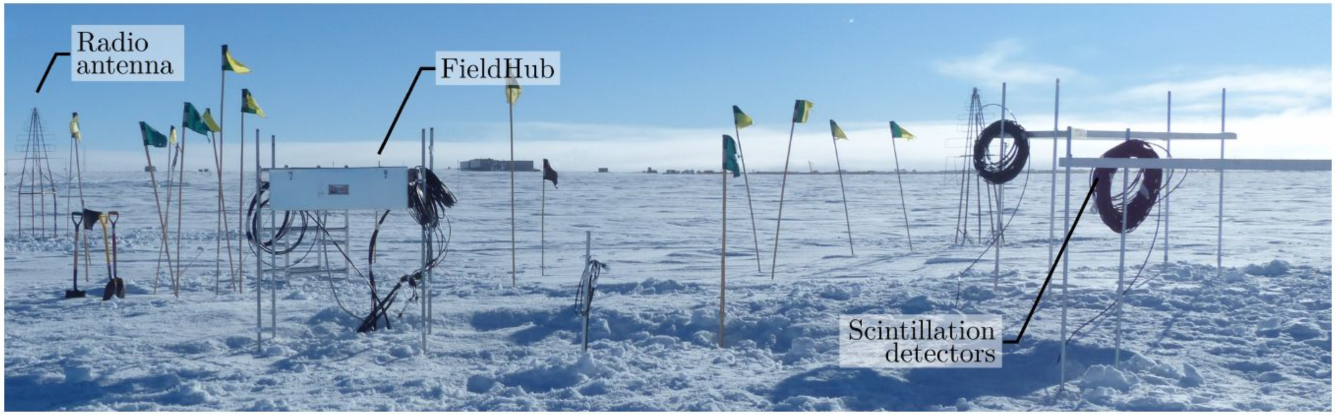
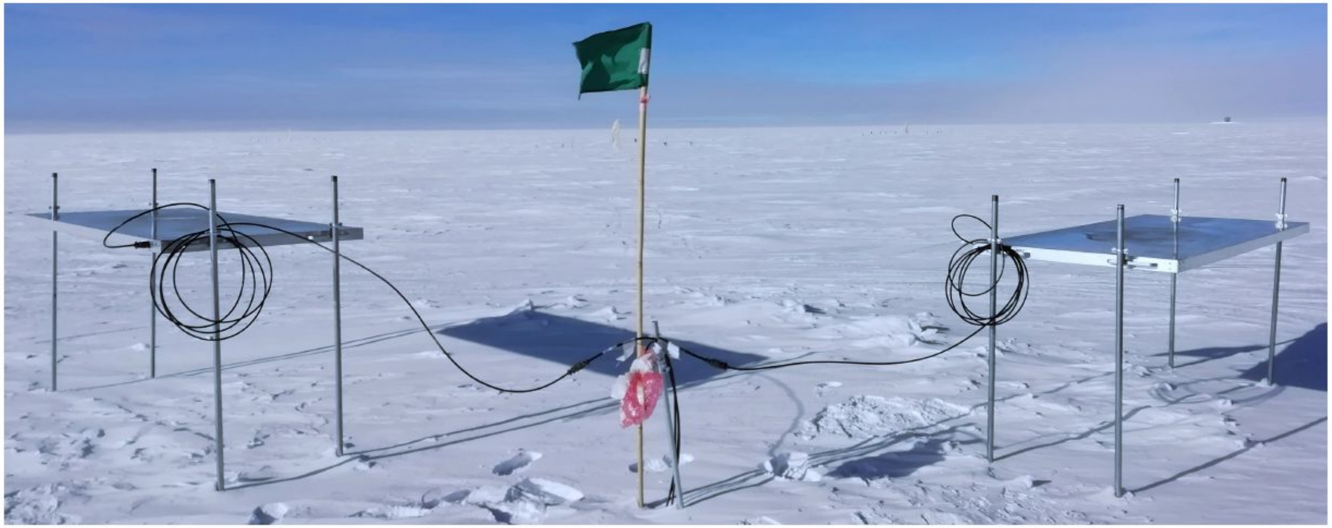
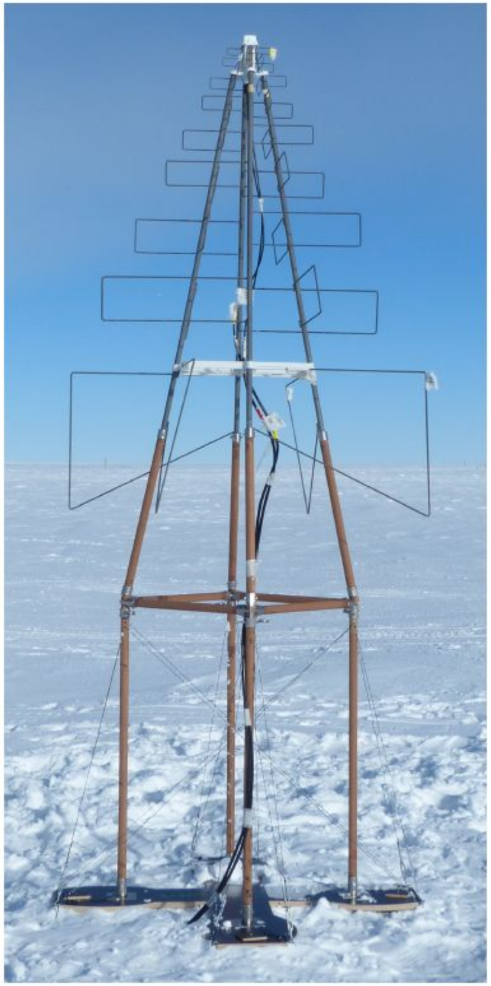
IceTop enhancement prototype-station







https://publikationen.bibliothek.kit.edu/1000142813: The Prototype Station for the IceCube Surface Array Enhancement, Marie Johanna Oehler

Bontempo, Federico - federico.bontempo@kit.edu

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Summary & Outlook

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- The combination of the in-ice and IceTop detectors of the IceCube Neutrino observatory is successfully used for the study of cosmic rays

- Gamma-hadron separation can be performed using machine learning and deep learning methods

- Via the combination of:
  - the total charge of high energy muon detected in-ice
  - Reconstructed air shower parameters (e.g. energy and direction of the primary)
  - Simulation based method: log likelihood function

Coming next:

- IceCube-Gen2 will also increase the field of view and statistic
- The combination of all three detectors will give a better estimation of the muon content of air showers

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