ECAP – Neutrino research

Thesis topics – status: April 2022

Neutrino astronomy: ANTARES, IceCube, KM3NeT-ARCA
Neutrino oscillations: KM3NeT-ORCA
Radio-detection of neutrinos: RNO-G
Cosmic rays: LOFAR, SKA
Lightning: LOFAR

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Phone: 09131 – 85 – 2xxxx (cf. list above)
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IceCube

Software / Data analysis
Contact: Thorsten Glüsenkamp (thorsten.gluesenkamp@fau.de)

• Comparing normalizing flows on spheres (MSc):
  Normalizing flows are a novel kind of artificial neural networks that model probability
distribution functions. In this work such flows will be compared for distributions on spherical
surfaces with the aim to apply them to direction reconstruction.

• Unsupervised classification (MSc):
  This work will investigate if variational autoencoders with hierarchical structure are suited to
classify general IceCube data. In particular, if this method can distinguish between neutrinos
and cosmic rays despite the large differences in rate.

• Unsupervised visualization (BSc):
  IceCube data of various types should be visualized with U-MAP to gain some insight into
  separation behaviour.

Hardware
Contact: Jonas Reubelt (jonas.reujon.reubelt@fau.de)

• IceCube optical modules:
  For the indirect measurement of neutrinos novel optical modules are being developed for the
next generation IceCube detector (mDOMs, LOMs). In Erlangen, photomultiplier tube (PMT)
candidates and their electronics are characterized regarding their usability as photo sensors in
the optical modules. In addition, an optical final acceptance test setup (FAT) for mDOMs will be
developed. The following thesis topics are available:

  • Measurement of the absolute detection efficiency of different PMT models
  • Investigation of temperature dependent PMT parameters
  • Characterization and calibration measurements of optical components used for the FAT
Fermi Bubbles (MSc)
The so-called Fermi Bubbles are two large gamma ray lobes located above and below the centre of our galaxy. They were detected by the Fermi-LAT experiment in 2010, and although their origin is still unknown there are a few hypotheses both for the astrophysical source and for the mechanisms leading to gamma ray emission from the source. Some of these hypotheses also predict the emission of neutrinos. Based on these hypotheses, phenomenological models can be used to relate the observed gamma ray flux to a flux of high energy neutrinos which could be detected by neutrino telescopes like ANTARES. The challenge for such an instrument is to discriminate the high energy neutrinos of astrophysical origin from background neutrinos produced by the interaction of cosmic rays in the atmosphere.

In this research project, more than 12 years of data from the Antares neutrino telescope will be used to search for neutrinos originating from the Fermi Bubbles. The proposed search method exploits the characteristic morphology of the source in order to identify an excess of neutrino events within the Fermi Bubble region. The detection of a significant excess would be an important discovery. The non-detection of a significant excess would be used to constrain the existing neutrino emission models by means of Monte-Carlo simulations.
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KM3NeT-ARCA

Data analysis and simulation

Contact: Kay Graf (kay.graf@fau.de)
Rodrigo Gracia-Ruiz (rgracia@km3net.de)
Jutta Schnabel (jutta.schnabel@fau.de)

• Combined neutrino and gamma-ray analysis for astrophysical sources (MSc):
The observation of neutrinos correlated with the emission of very high energy gamma rays will contribute valuable information about the gamma-ray production in astrophysical sources. KM3NeT will provide neutrino data sets to facilitate multi-messenger analyses in an open science environment. This study will aim at a combined sensitivity estimate with information from gamma-ray instruments towards extended galactic gamma-ray sources in order to develop a publication-ready data format for instrument response functions (IRFs) for the KM3NeT telescope.
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Radio-detection of neutrinos

Contact: Anna Nelles (anna.nelles@fau.de)
         Robert Lahmann (robert.lahmann@fau.de)

The Radio Neutrino Observatory (RNO-G) currently under construction will detect radio emission from neutrino-induced showers. Deployment has started at Summit Station in Greenland in 2021 and will continue until 2024. The experiment targets energies beyond $10^{15}$ eV, i.e. the highest energies in the Universe.

The group is involved in simulations, analysis, and hardware developments for RNO-G and there are various topics. Below we outline some concrete examples to provide an idea of the projects. Additional topics will be available and can be discussed. I am also open to ideas.

At the same time, development for IceCube-Gen2 is taking place. IceCube-Gen2 is planned with a large radio array that builds on RNO-G experience. Simulation studies and hardware projects are available.

Literature:

- Ice measurements: https://arxiv.org/abs/2201.07846

Data analysis / simulations:

- Analyze first data from RNO-G (BSc / MSc)

  The Radio Neutrino Observatory Greenland has been taking data since 2020. First data is on disk and searches for neutrinos, cosmic rays, as well as searches for air plane signals, wind related backgrounds and other signals have started and will need to be intensified. Several topics are available depending on the preference. Each will be together with a PhD student working on a broader topic.
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Radio-detection of neutrinos

Contact: Anna Nelles (anna.nelles@fau.de)
Robert Lahmann (robert.lahmann@fau.de)

Data analysis / simulations:

• Separate electro-magnetic from hadronic neutrino radio signals (BSc / MSc)
  Electromagnetic (charge current) and hadronic showers create different signals, which will have impact on the energy reconstruction. The thesis would use/test various tools (machine learning, template searching, … ) on simulations to develop a separation of these two types of showers.

• Study the arrival direction of neutrinos (BSc / MSc)
  The sources of astrophysical neutrinos are still unknown. RNO-G and IceCube-Gen2 will have a sub-set of events with superior angular resolution, called coincidence events. This thesis will estimate the angular resolution obtainable with such coincidence events and study how the can contribute to multi-messenger astronomy.

• Signal propagation in the ice (MSc)
  The polar ice is an interesting fabric that still evades our understanding. This thesis will combine (existing) measurements with modelling to understand more about the polar ice and how neutrino radio signals propagate in it. Also, new measurements can be designed that will be carried out at Summit Station.
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Contact: Anna Nelles (anna.nelles@fau.de)
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Hardware:

- **Construct and operate a test station for RNO-G (BSc / MSc)**
  The first stations of RNO-G have been installed in the field. We plan to build a RNO-G station in the lab to test the performance and to develop new software, as well as future generations of the DAQ board, LTE modem, solar panels, wind-turbine etc. Various thesis topics are available in designing testing procedures, learning about modern detector design.

- **Testing amplifiers for the Radio Neutrino Observatory Greenland (RNO-G) (BSc / MSc)**
  ECAP is responsible for the construction of the amplifying system in the signal chain. An automated test-set-up is supposed to be constructed to simplify mass-production. Special attention is needed for temperature testing of components. This will be combined with analysis the systematic uncertainties.
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Cosmic rays

Contact: Anna Nelles (anna.nelles@fau.de)

We use the LOFAR radio telescope to record cosmic-rays. Many interesting features in the cosmic ray composition have been found and the data-set is constantly increasing. LOFAR is currently the instrument with which you can most precisely image cosmic-ray induced air showers.

In addition, we prepare for the detection of air showers with the Square Kilometer Array (SKA). SKA will be the world's largest radio telescope and will deliver ultimate precision measurements.

Literature:
https://www.nature.com/articles/nature16976
https://www.skatelescope.org/ska-magazine/

• Hardware work on a LOFAR station (BSc / MSc)
LOFAR is a distributed telescope, with a station in Unterweilenbach being co-operated by the FAU. The thesis will require field-work in understanding the antenna responses, looking at weather data and other environmental conditions.

• Information Field Theory for cosmic-ray signals in SKA (MSc)
Many techniques used in LOFAR have to be improved for the ultimate challenges (amount of data and precision) for SKA. We have developed a new, machine learning based method for radio data (using radio neutrino experiments) and would like to test its applicability to LOFAR data. Information Field Theory, a machine learning method, is an important aspect and the thesis work would build on already existing software to better identify and reconstruct the relevant signals.
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Lightning

Contact: Anna Nelles (anna.nelles@fau.de)

We use the LOFAR radio telescope to make images of lightning strikes. These images are the most detailed radio images ever made of lightning strikes and have helped us to find many new features. Ultimately, we hope to be able to explain how lightning is initiated, how it propagates and how it connects to the ground. Surprisingly, there are very fundamental questions that we still are unable to answer concretely.

Various projects are available to work in collaboration with the University of Groningen.

Literature:
https://www.nature.com/articles/s41586-019-1086-6
https://www.youtube.com/watch?v=UcKQSG_3MUk

• Time calibration of LOFAR antennas (BSc / MSc)
  We typically use only the central core of the distributed radio telescope to image lightning strikes. Using antennas further out would enhance the imaging capabilities, but additional timing calibration of the antennas is needed. This is done manually at the moment and quite cumbersome. This thesis would involve checking the quality of the current LOFAR timing calibration and developing new methods.

• Judging the lightning image quality (MSc)
  Many lightning images have been recorded, but there is no statistically sound approach to judging the image quality. The thesis would involve looking at the pulse finding algorithm and adapting it to provide a quality statement together with the pulse finding for the images.