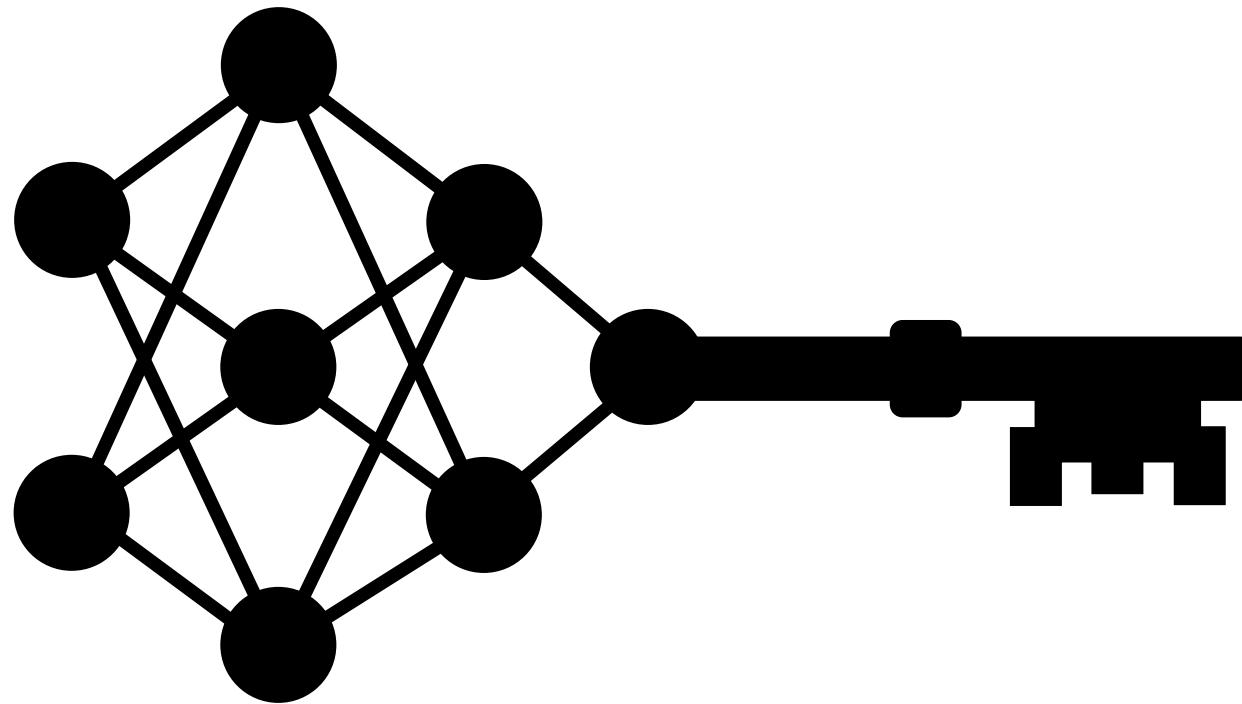




UPPSALA
UNIVERSITET

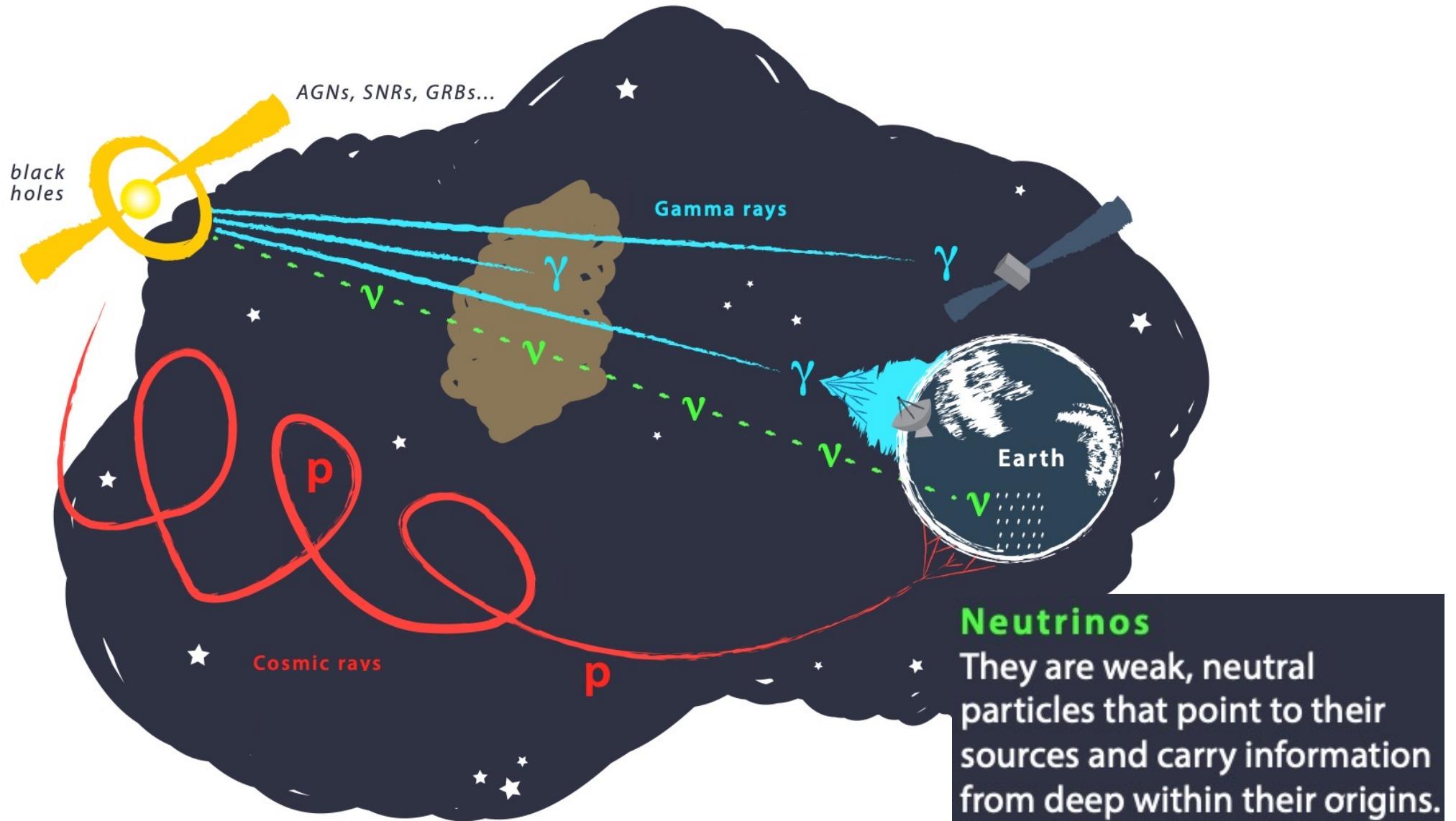
Optimization of Radio Detectors for Ultra-High Energy Neutrinos

Nils Heyer*, Christian Glaser, Thorsten Glüsenkamp,
Alan Coleman, Arnau Serra Garet
Uppsala University, Sweden



CARL TRYGGETS
STIFTELSE
FÖR VETENSKAPLIG FORSKNING

Why care about cosmic neutrinos?



Neutrinos

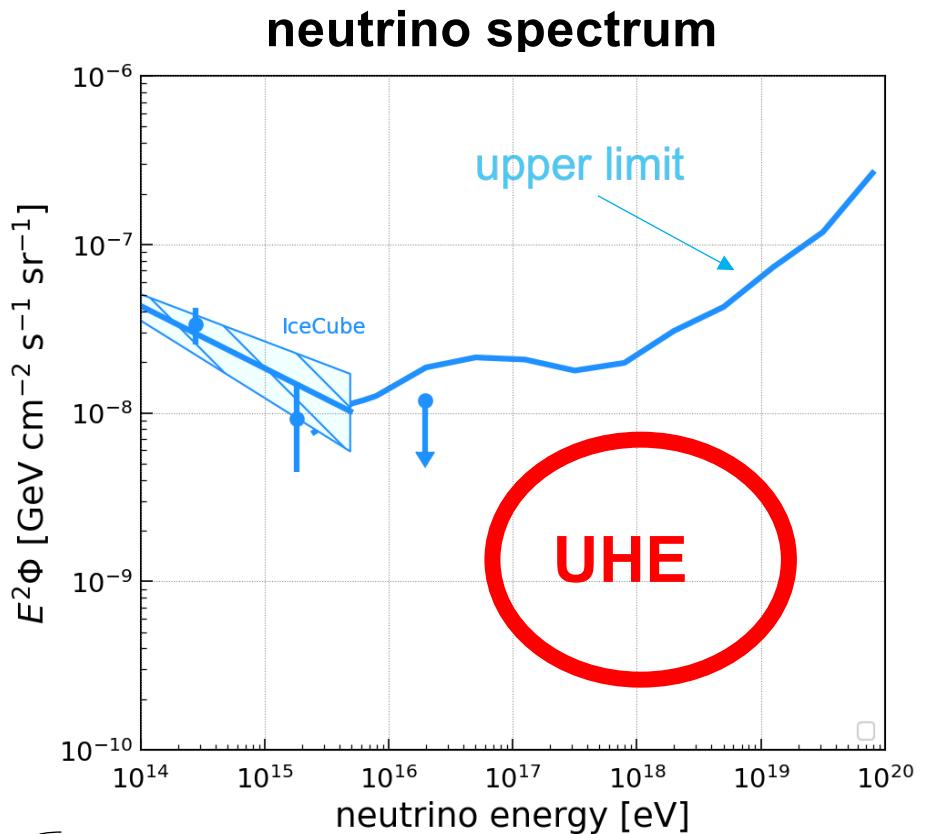
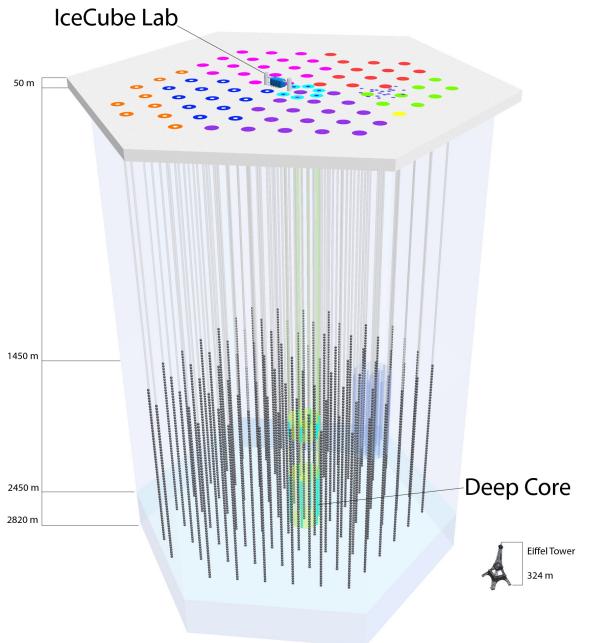
They are weak, neutral particles that point to their sources and carry information from deep within their origins.



IceCube – currently the worlds largest neutrino telescope

- Instruments a **gigatonne** of ice
- Successfully measured the cosmic neutrino flux in the **TeV-PeV range**
- Detected point sources of neutrinos (**NGC1068, TXS 0506+056**)
- Not sensitive above 10 PeV

Radio detection can go further ...



Mode of detection

optical

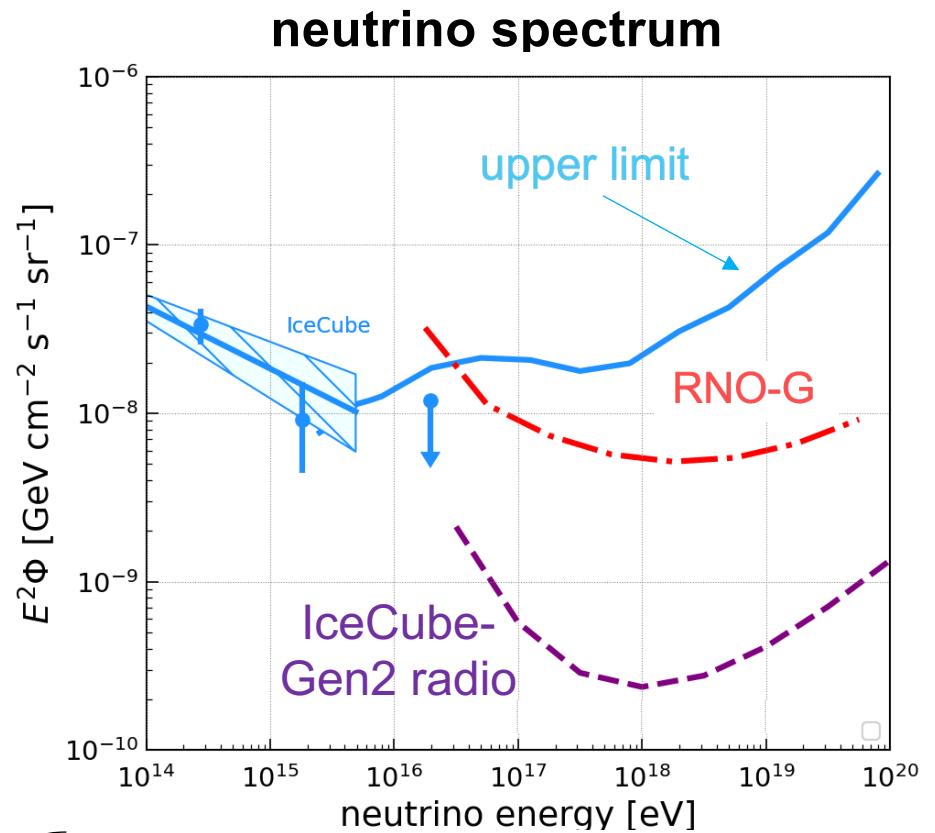
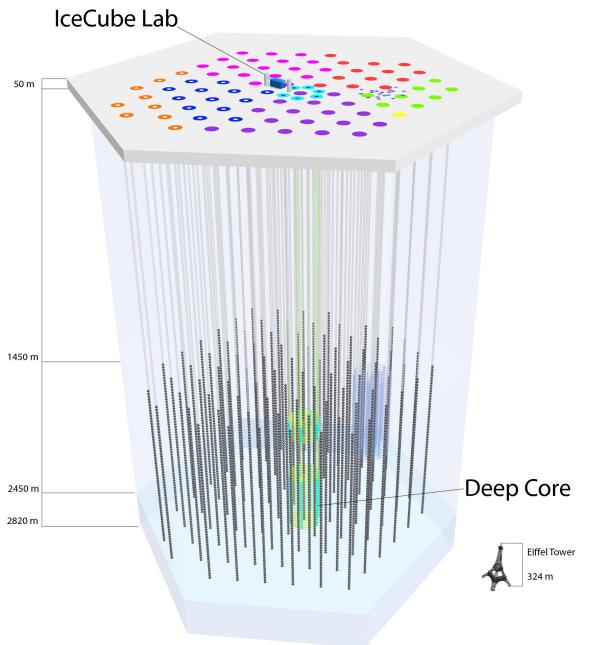


IceCube – currently the worlds largest neutrino telescope

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- Not sensitive above 10 PeV

Radio detection can go further ...

- It extends the reach into the **EeV range**
- Can cost effectively instrument **over a teratonne** of ice
- **Feasibility demonstrated** in pilot arrays

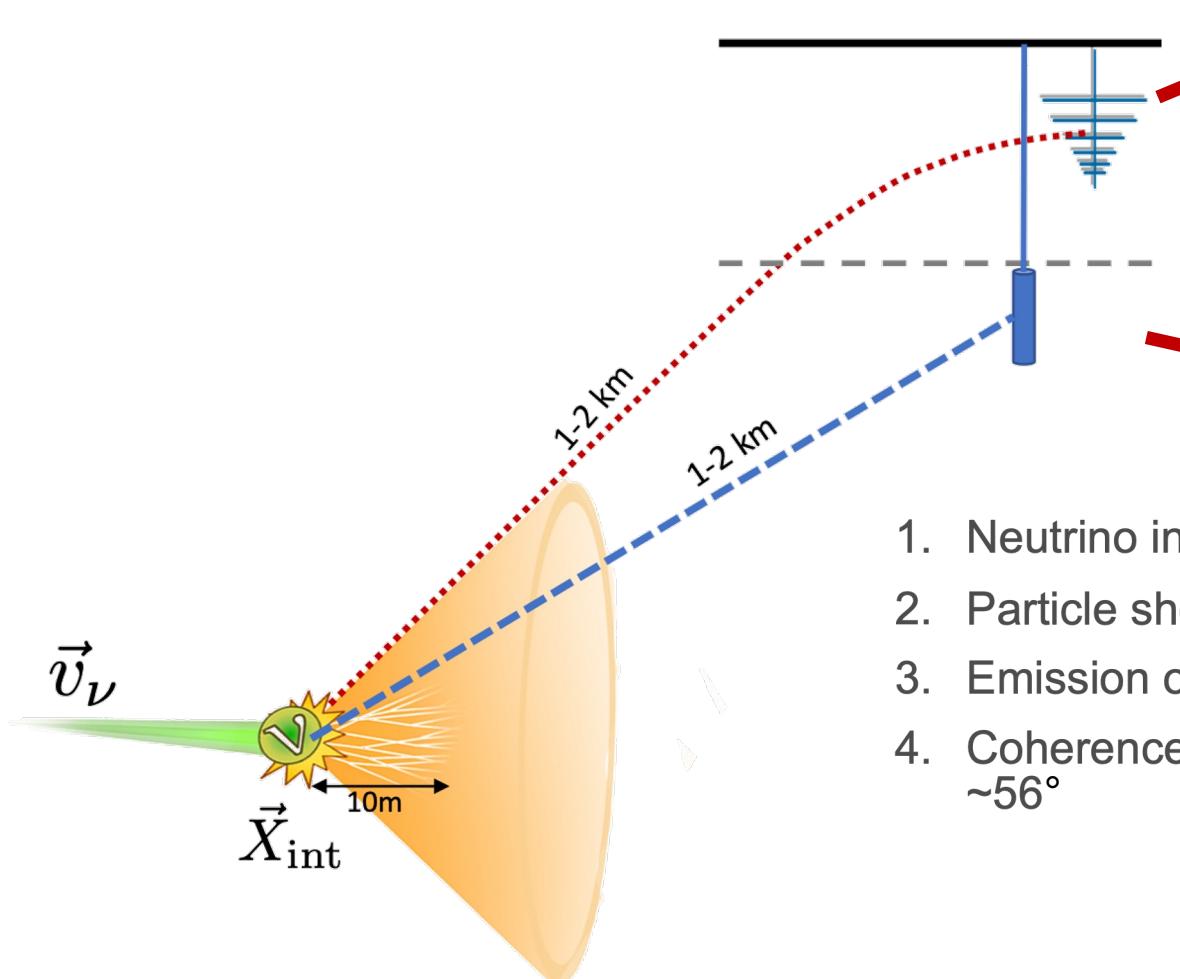


Mode of detection

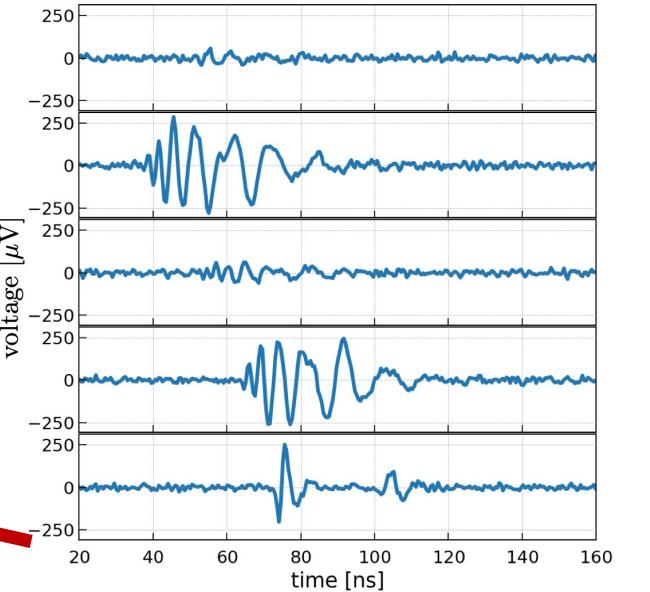
optical

radio

Detection via Askaryan Radiation



1. Neutrino interaction in the ice
2. Particle shower
3. Emission of EM radiation
4. Coherence at the Cherenkov angle
 $\sim 56^\circ$





Current in-ice Radio Experiments

Under construction:

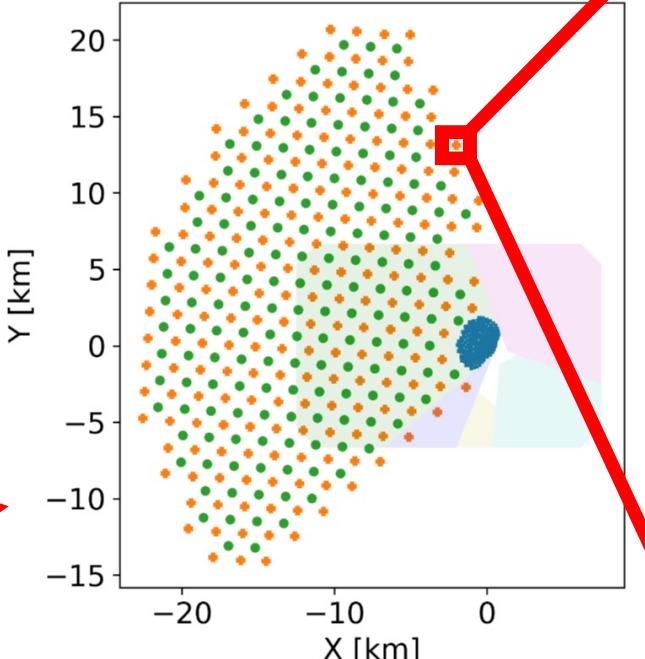
RNO-G



Pilot Arrays:

ANITA
ARIANNA
ARA

Construction is planned to start 2028:
IceCube-Gen2 Radio



Detector design not fully optimized yet!





Opportunities for Optimization

detection rate of UHE neutrinos

→ **objective 1: Deep-Learning-Based Trigger**

precision to determine the
neutrino's properties

→ **objective 2: End-to-End Optimization +
Deep Learning Reconstruction**

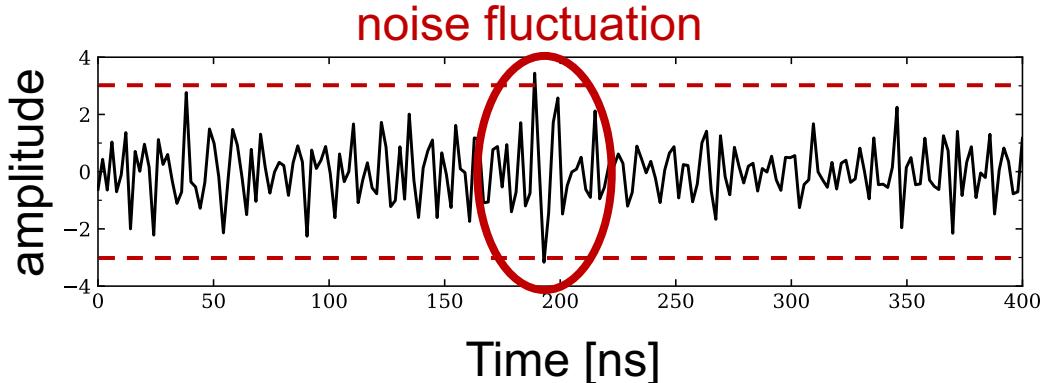
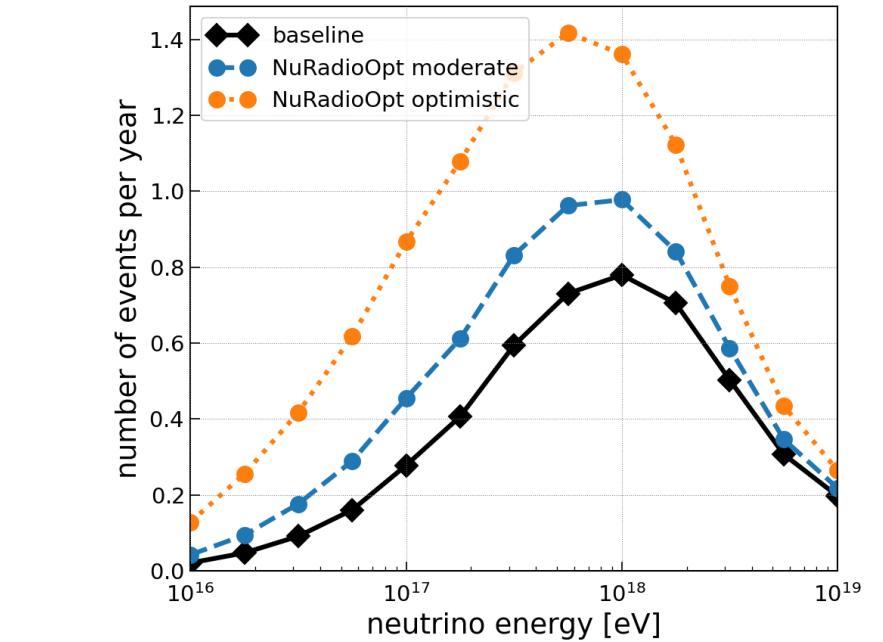
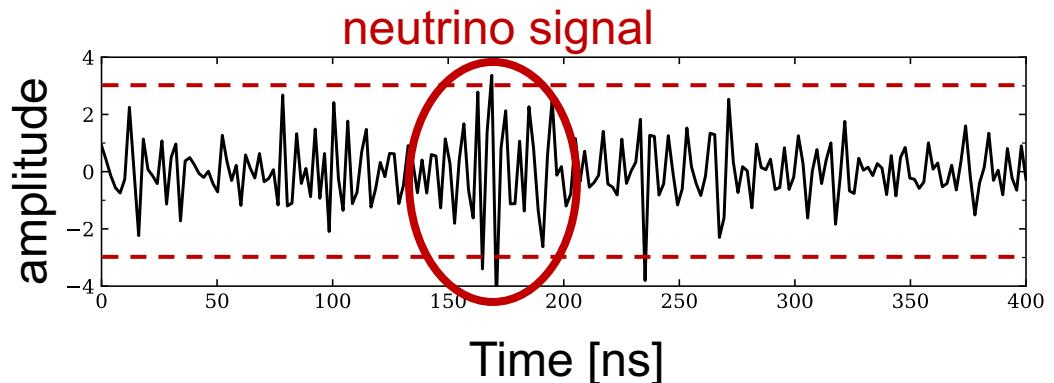
Impact: Substantial improvement of science output



I.) Deep-Learning-Based Trigger

Huge potential of improvement:

- Current: threshold and power integrated trigger
- Future: Deep-learning based trigger
- Neural networks are very good at classification tasks
- Proof-of-concept studies:
 - *ARIANNA collaboration, JINST 2022*
 - *A. Coleman, PoS(ICRC 2023)1100*
- Improvements limited by computational recourses at the station
 - A few watts for the full station
-> Neuromorphic computing
- Potential to doubling the neutrino detection rate in IceCube-Gen2

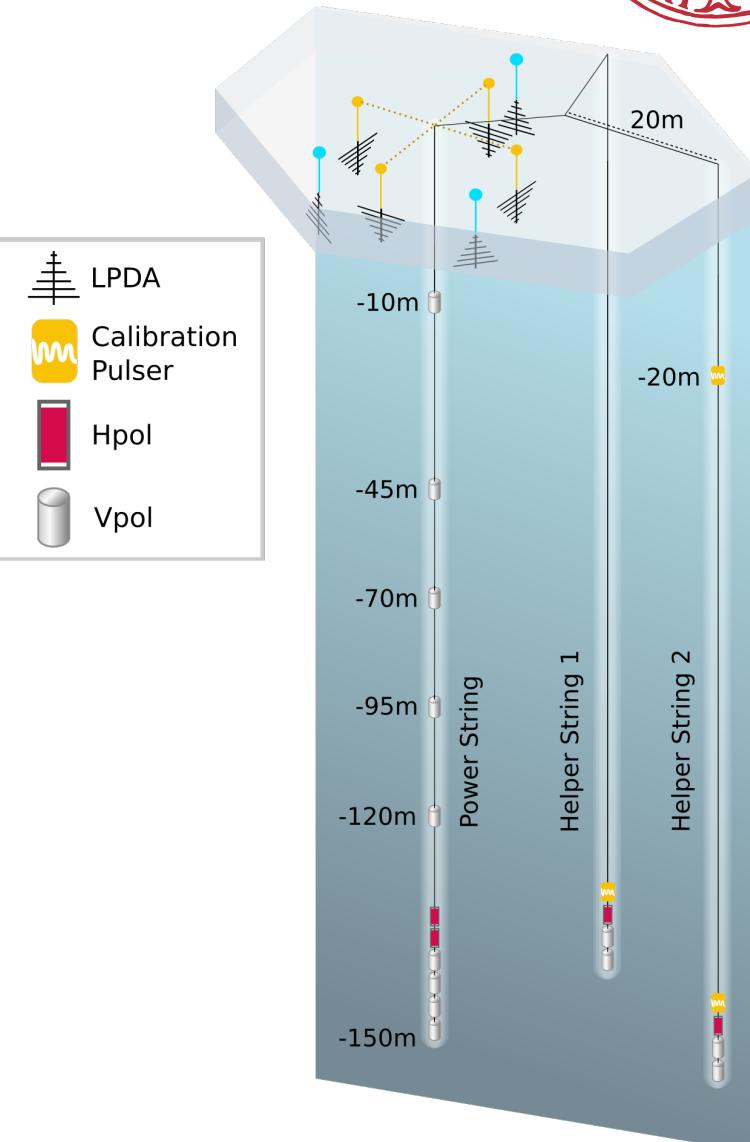
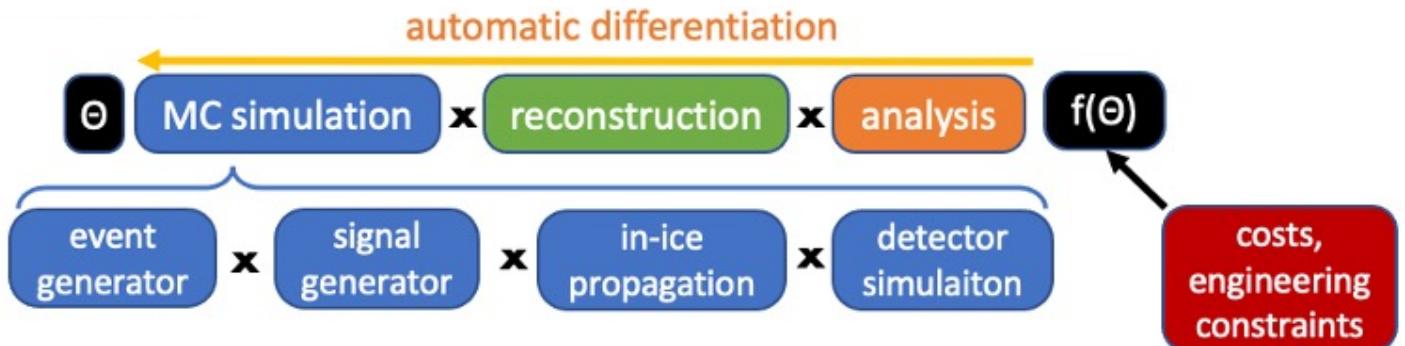




II.) End-to-End Optimization

- Deep learning and differential programming can build an end-to-end optimization pipeline
- Optimization of detector parameters:
 - antenna positions/orientations
 - number/type of station
- Direct optimization of science objectives:
 - neutrino-nucleon cross-section
 - source discovery
 - flux measurement

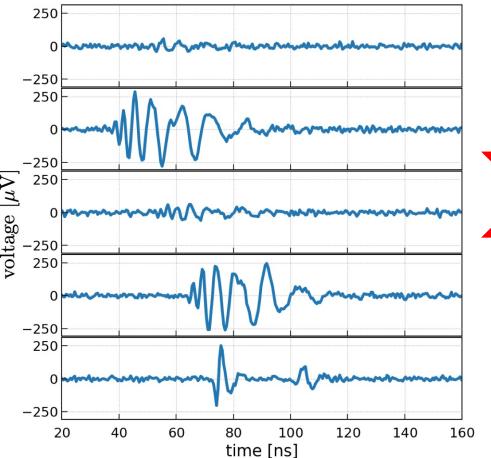
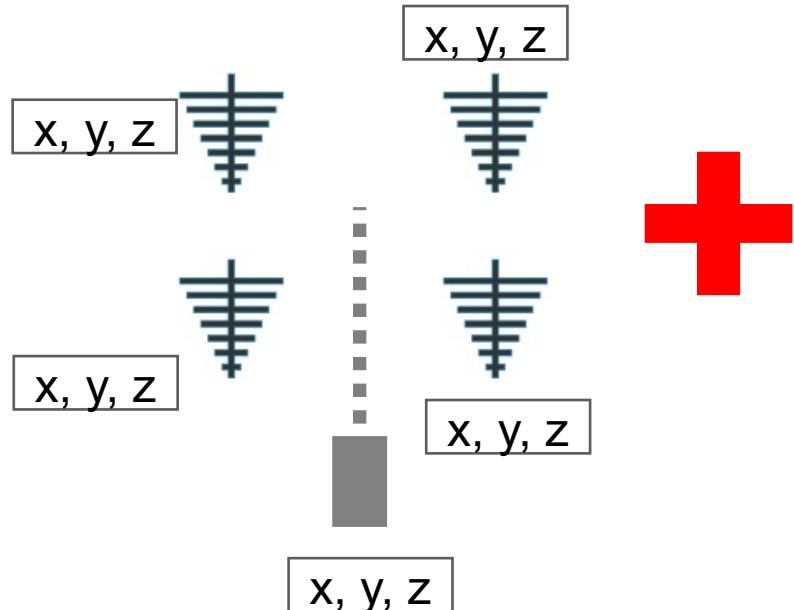
The detector parameters Θ will be optimized to maximize the science output $f(\Theta)$.



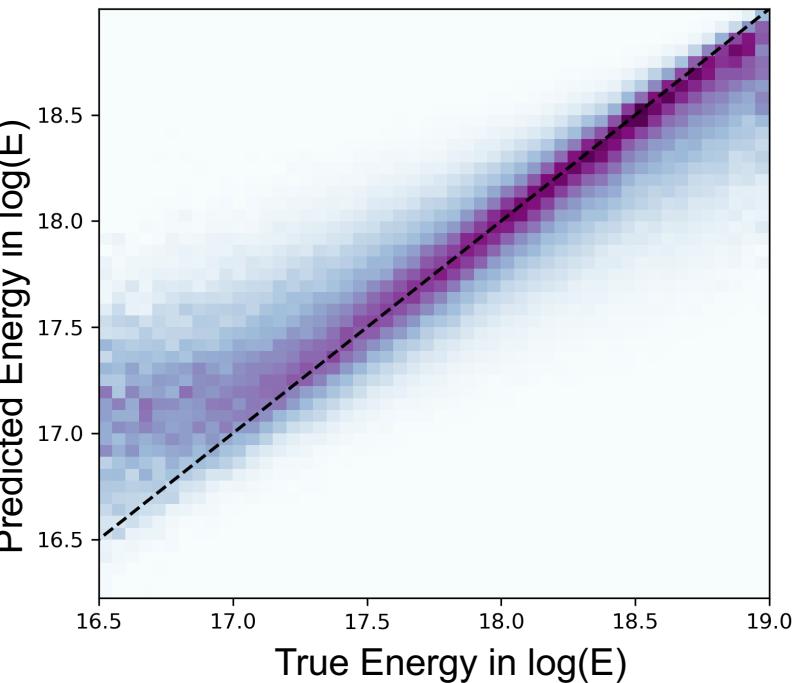


Reconstruction using GNNs

- Problem: Simulating MC data for a single geometry takes ~500k core hours
 - Time and resource intensive!
 - Has to be repeated for every detector layout
- Solution: Antenna position-aware neural network
 - Train a graph-neural-network on randomized antenna positions
 - Allows for a fast optimization loop
- First results for energy reconstruction using GNNs



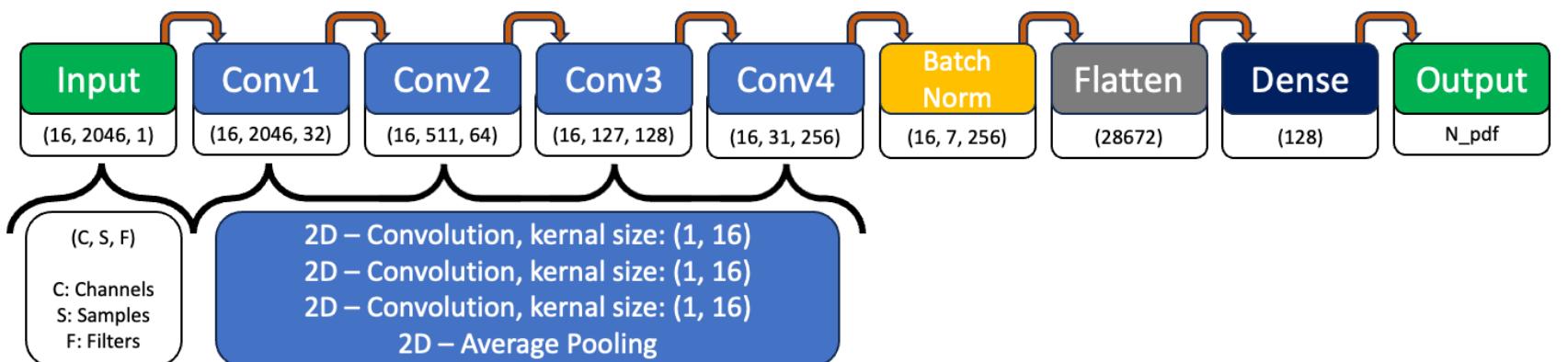
GNN





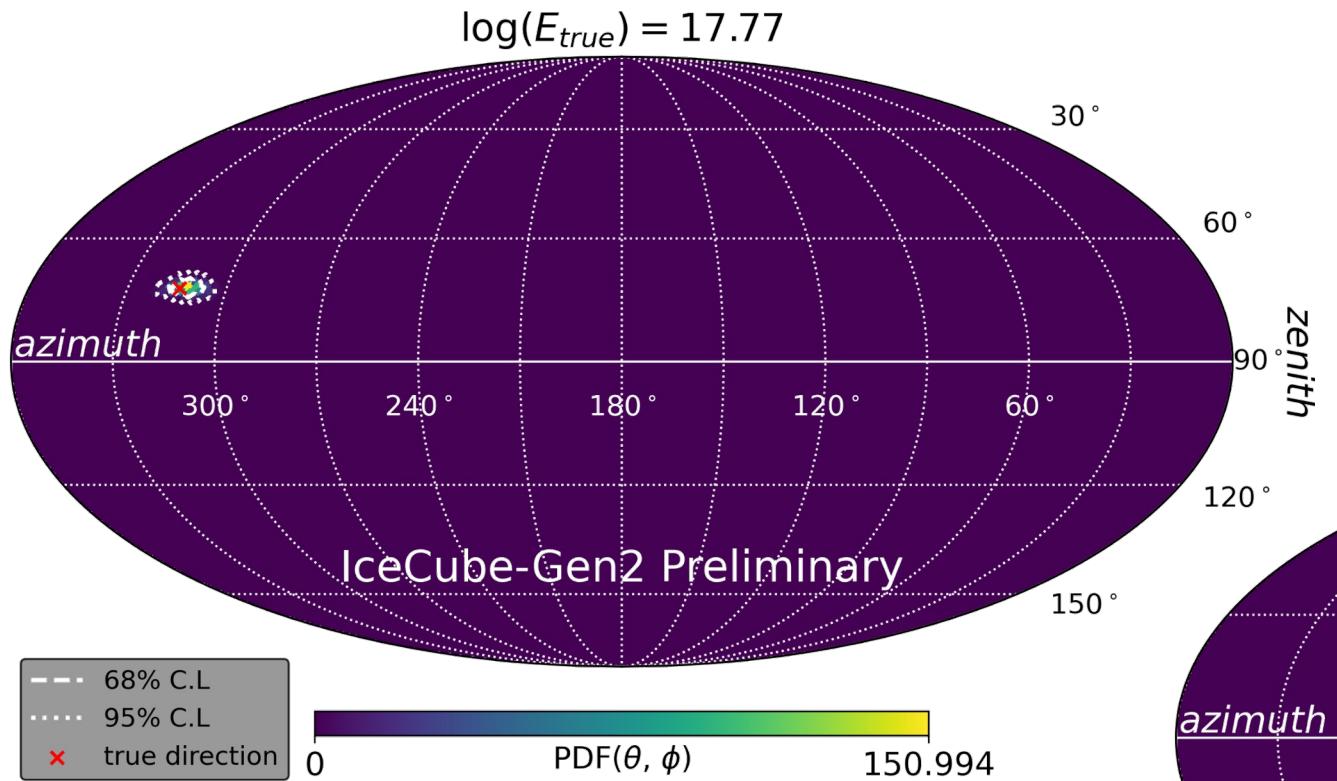
Reconstruction using Normalizing Flows

- Conditional normalizing flows offer an opportunity to predict **arbitrarily shaped uncertainty contours**
- Network predicts the parameters of a function instead of a single value
- Using open-source toolkit pytorch and **jammy_flows**
- Network input:
 - Raw voltage traces simulated for every antenna
- Network output:
 - 1D PDF from conditional Normalizing Flows for **energy reconstruction**
 - 2D PDF from conditional Normalizing Flows for **direction reconstruction**
 - Sampling from the predicted PDF allows for the calculation of a mean and a standard deviation

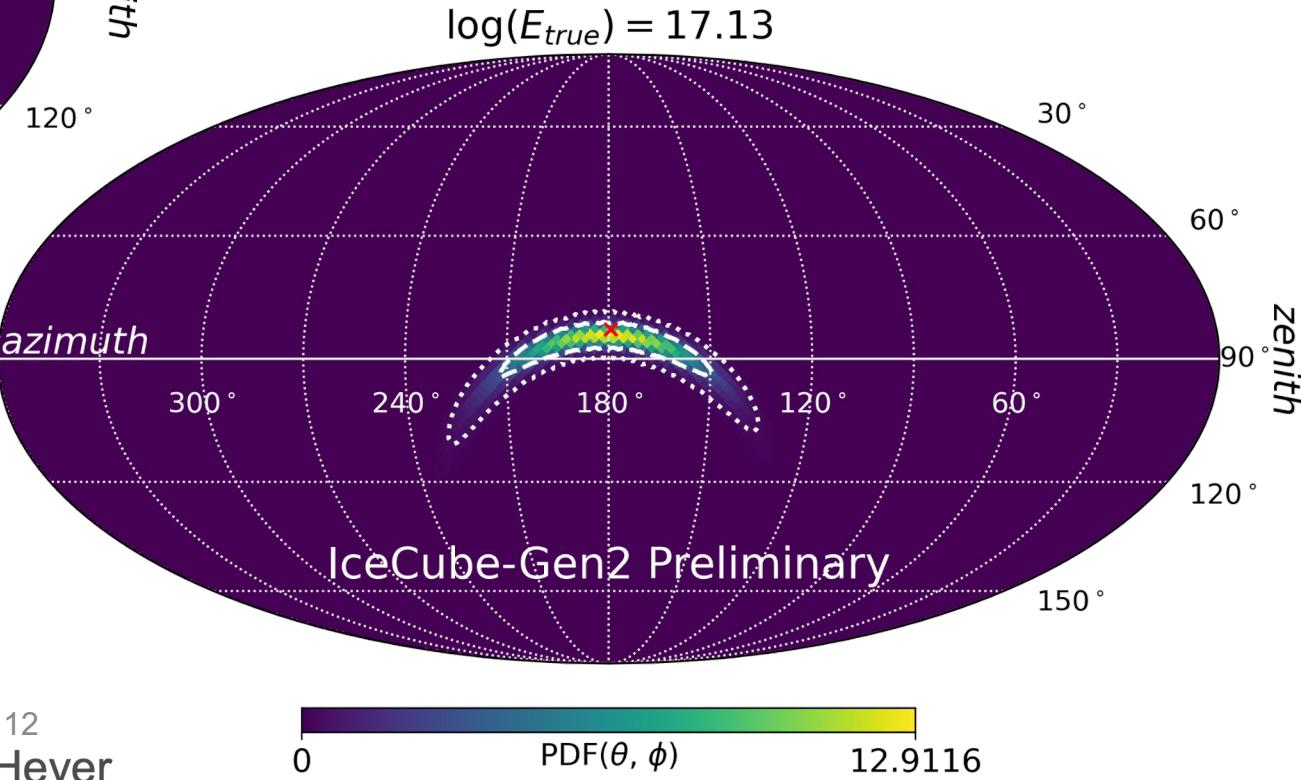




Reconstruction Results - Direction

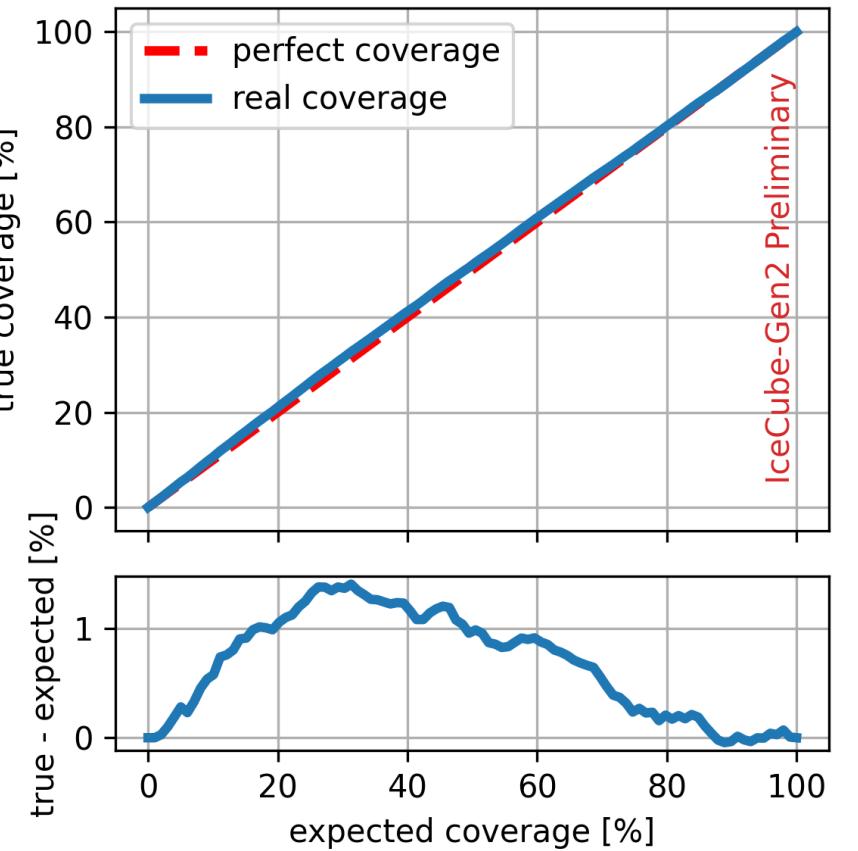
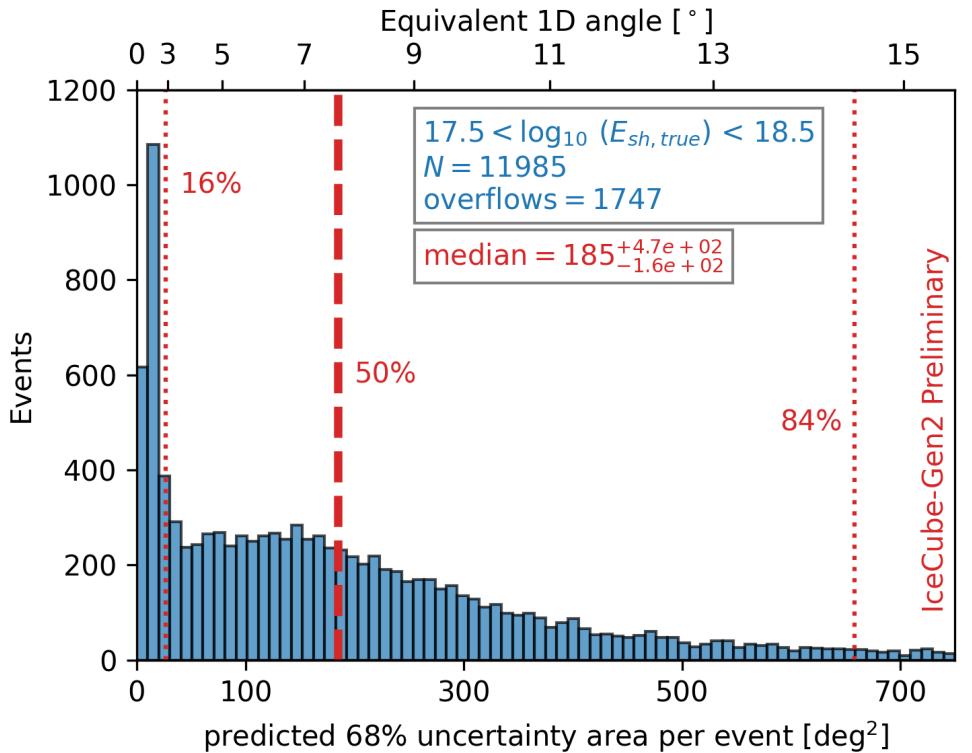


- First event-by-event uncertainty predictions
- ‘Banana’-like shapes are expected from physics-based calculations and previous reconstructions
- The size/entropy can be used as a quality cut



Reconstruction Results - Direction

- About 16% of events could be reconstructed extremely well
- About 15% of events could not be reconstructed well
- **Excellent coverage** with a deviation of only ~1%





Impact of the Optimization

Main science objectives of UHE neutrino astronomy:

Neutrino-Nucleon
Cross Section

→ factor three more
precise measurement

V. Valera, M. Bustamente, C. Glaser, JHEP 06 105 (2022)

Diffuse Flux

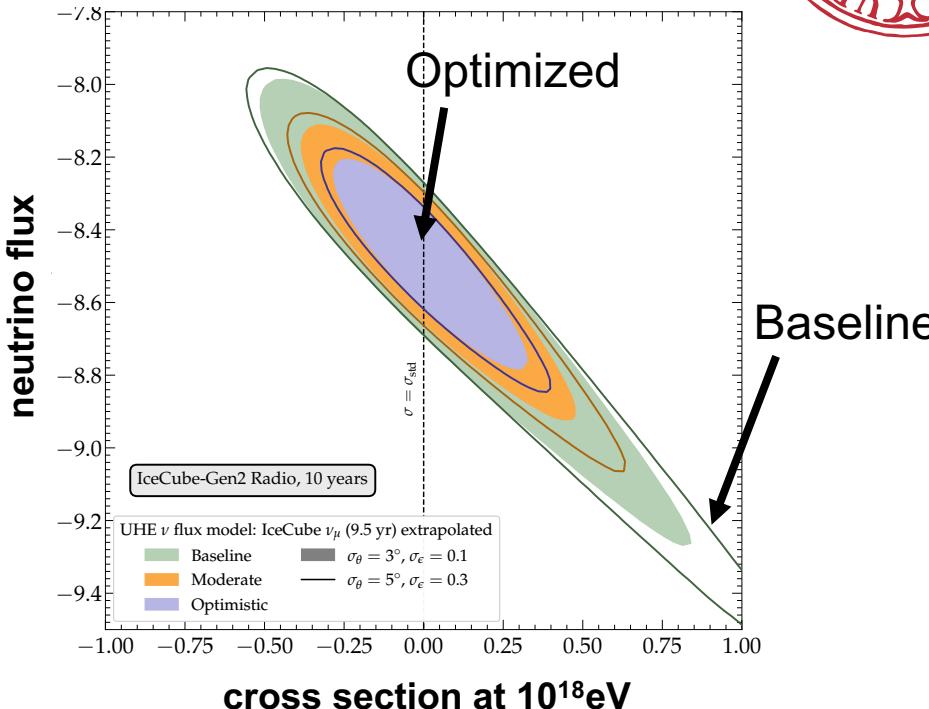
→ expedite the detection of UHE
neutrino fluxes by up to a factor of five

V. Valera, M. Bustamente, C. Glaser, PRD 107, 043019 (2023)

Point Sources

→ identify sources from deeper in our Universe,
increasing the observable volume by a factor of three

D. F. G. Fiorillo, V. Valera, M. Bustamente, JCAP03(2023)026

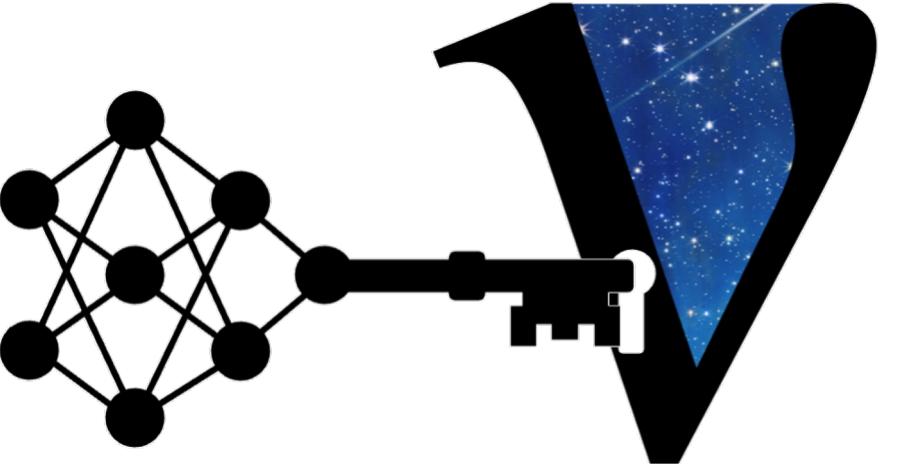


Improvements similar to building a more than three times larger detector
- at essentially no additional costs!



Summary

- Many topics are still open to optimization for UHE neutrino detection
 - Trigger development - A. Coleman, PoS(ICRC 2023)1100
 - Event reconstruction – energy, direction, flavor - N. Heyer, C. Glaser, T. Glüsenkamp, PoS(ICRC 2023)1102, A. Serra Garet, Master Thesis (2023)
 - Detector optimization - C. Glaser, A. Coleman and T. Glüsenkamp, PoS(ICRC 2023)1114
 - Replacing sections of the Monte Carlo tools by neural networks - Anton Holmberg, Master thesis, (2022)
 - Noise classification - T. Glüsenkamp PoS(ICRC 2023)1056
- The timeline is perfect for influencing IceCube-Gen2
- Improvements similar to building a more than three times larger detector
 - at essentially no additional costs
- Unique opportunity to accelerate UHE neutrino science in the next decade



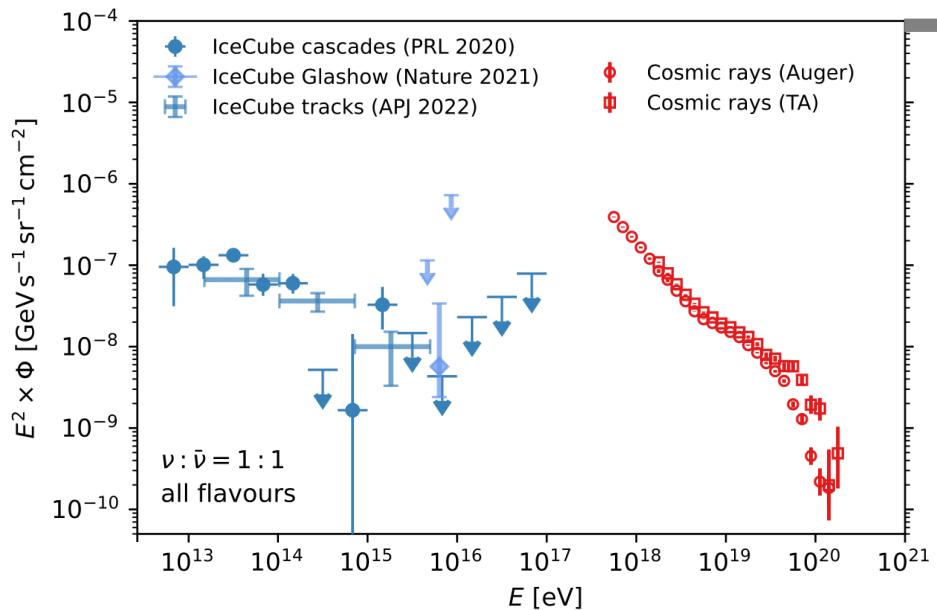


EXTRA SLIDES



High-Energy Cosmic Neutrinos

- These neutrinos originate at the **most violent events** in the universe
 - active galactic nuclei (NGC 1068), blazars (TXS 0506+056)
- The most energetic neutrino was reported at **~6PeV** in 2021
- Neutrinos have started the field of **multimessenger astronomy**

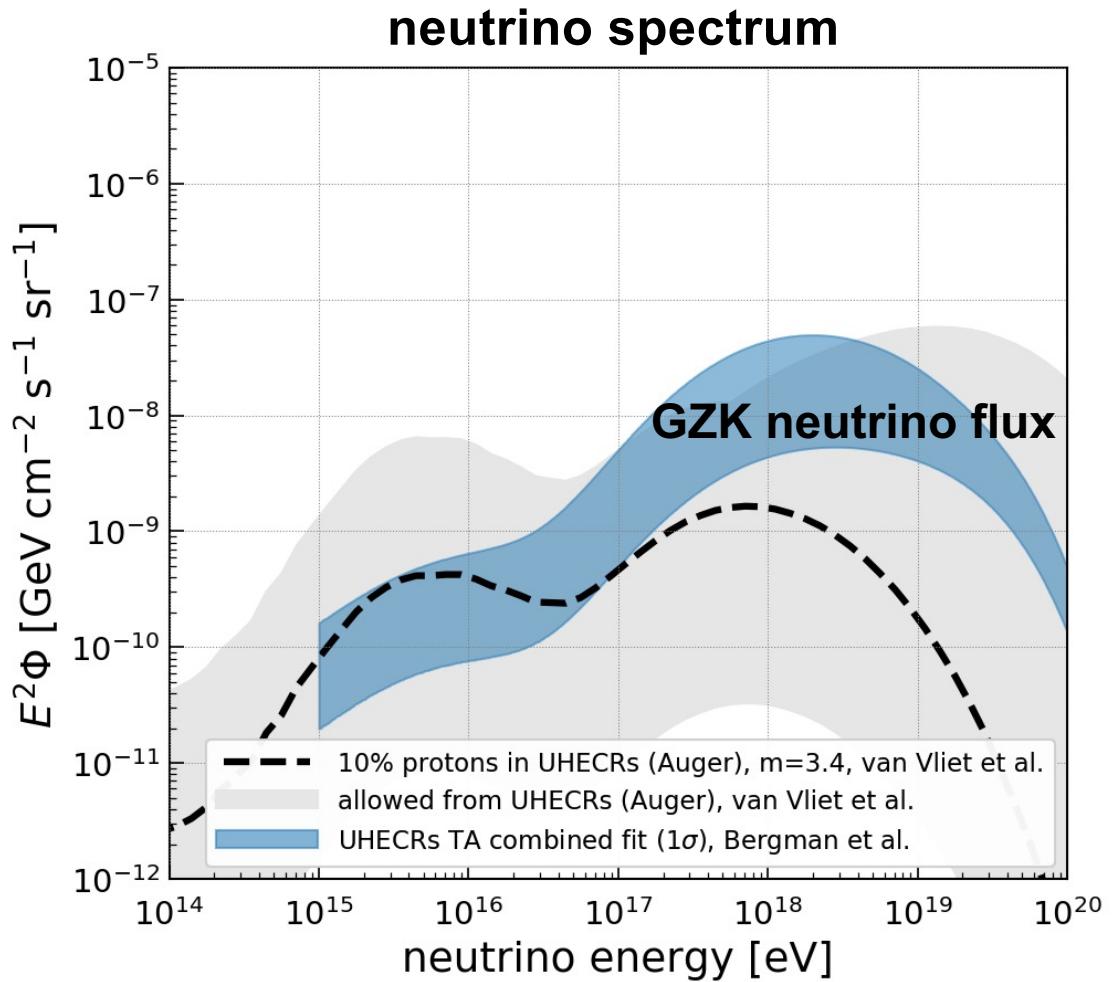


The measured neutrino and cosmic ray flux.
(Ackermann et al., 2022)





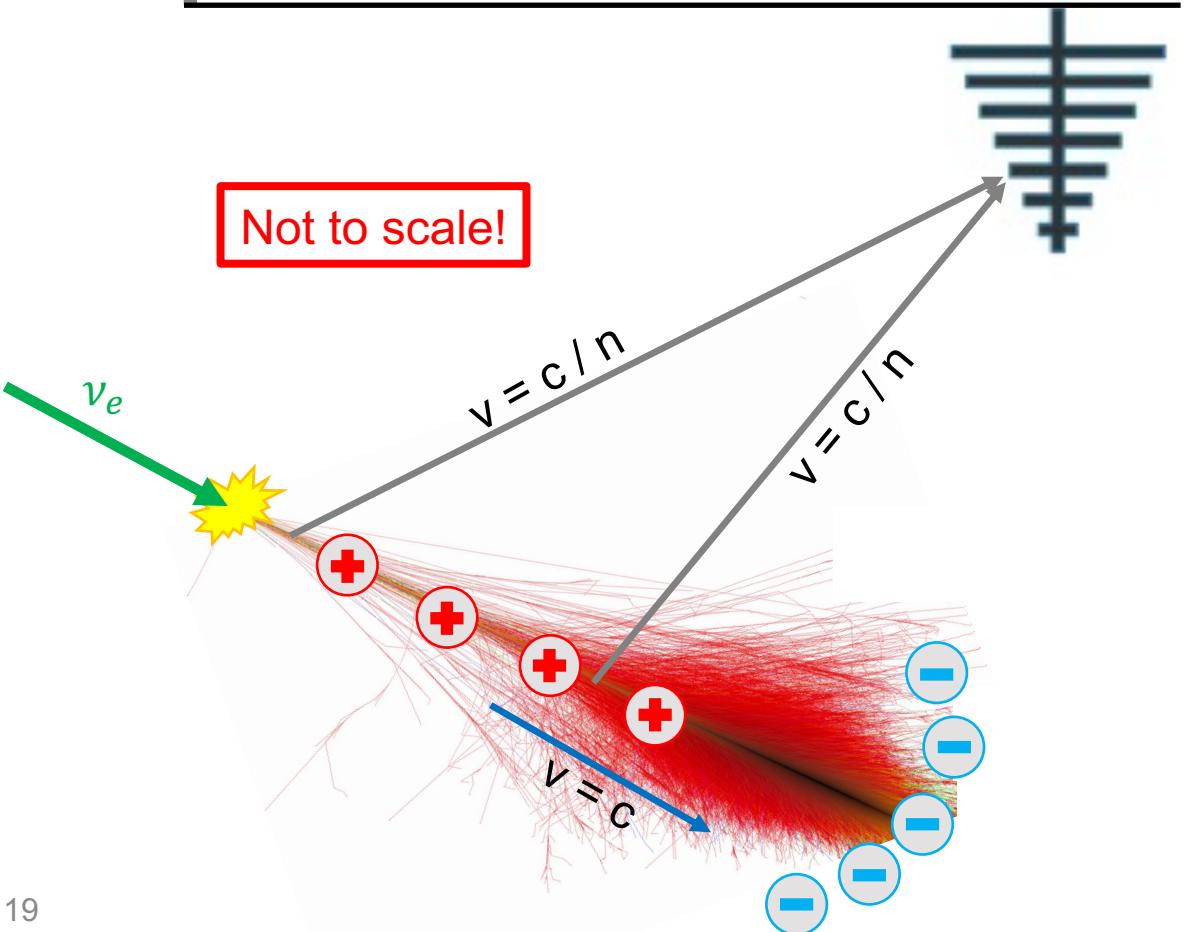
Expected neutrino flux



Askaryan Radiation

1. Neutrino interaction in ice
2. Particle shower
3. Electrons from the medium collect at the shower front
4. Positron annihilation
5. Time-dependent charge imbalance
6. Emission of EM radiation
7. Coherence at the Cherenkov angle ($\sim 56^\circ$)

Schematic drawing of the neutrino interaction, the shower development and the emission of radiation.

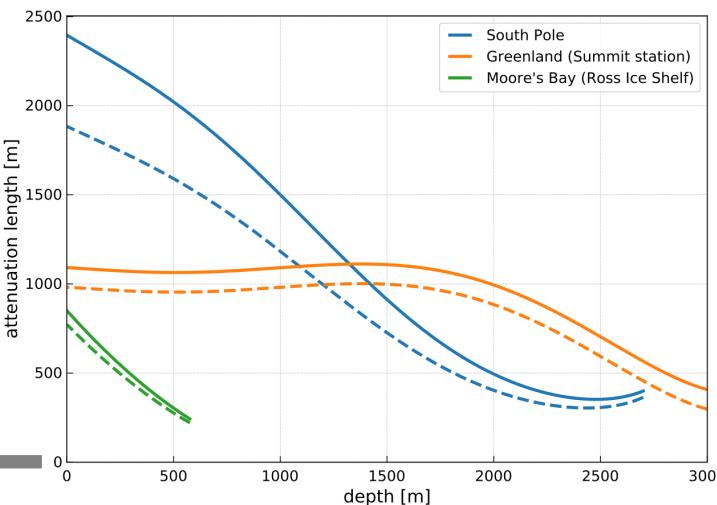




Important Effects to consider

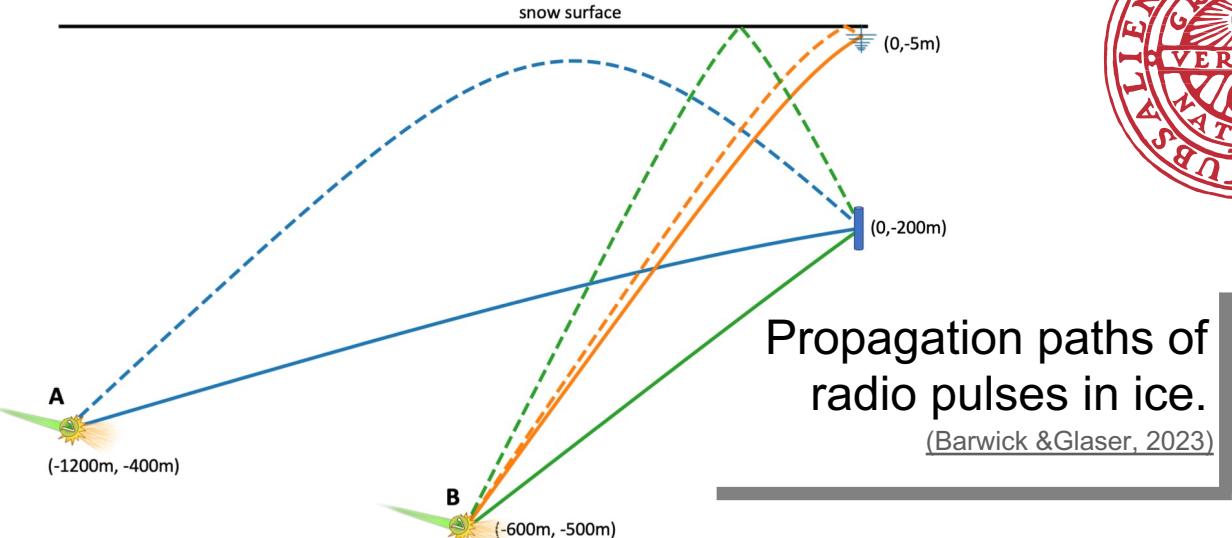
Many effects change the pulses on their path from the interaction to the antenna

- Refracted ray trajectories
- Off-cone emission
- Attenuation in ice
- Birefringence → later more

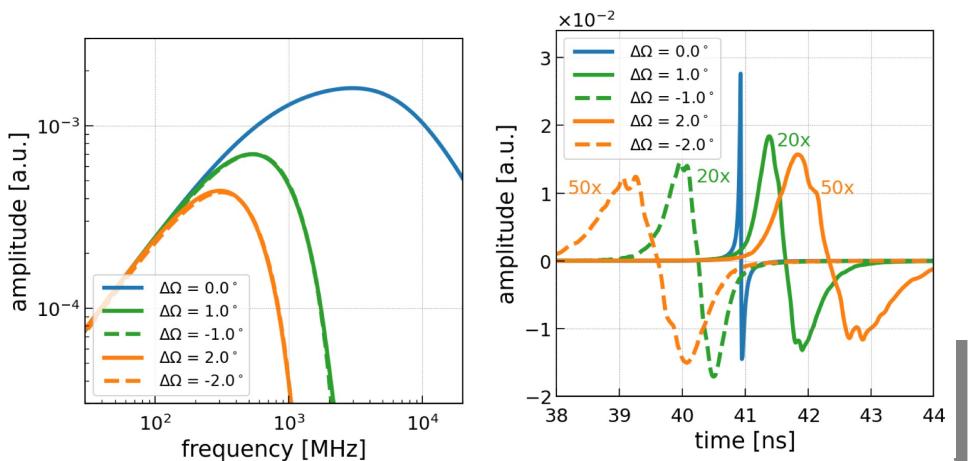


Attenuation length in ice.

(Barwick & Glaser, 2023)



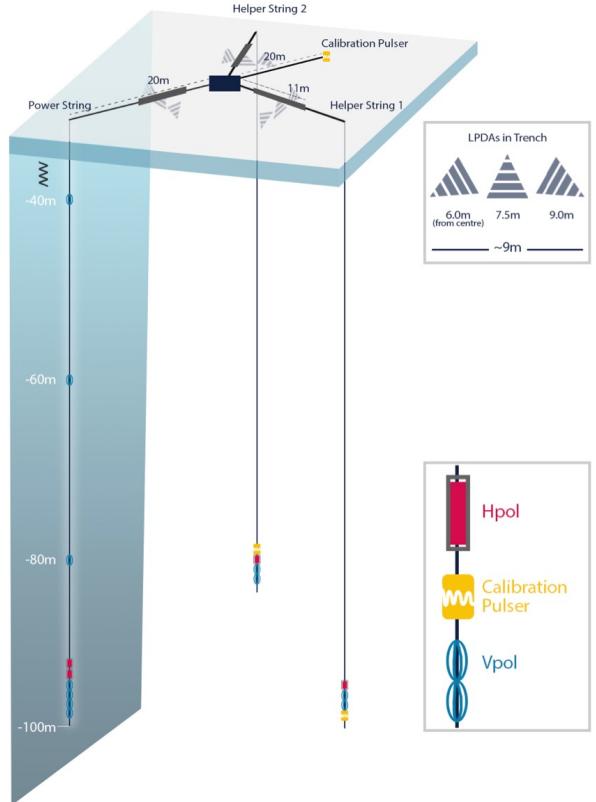
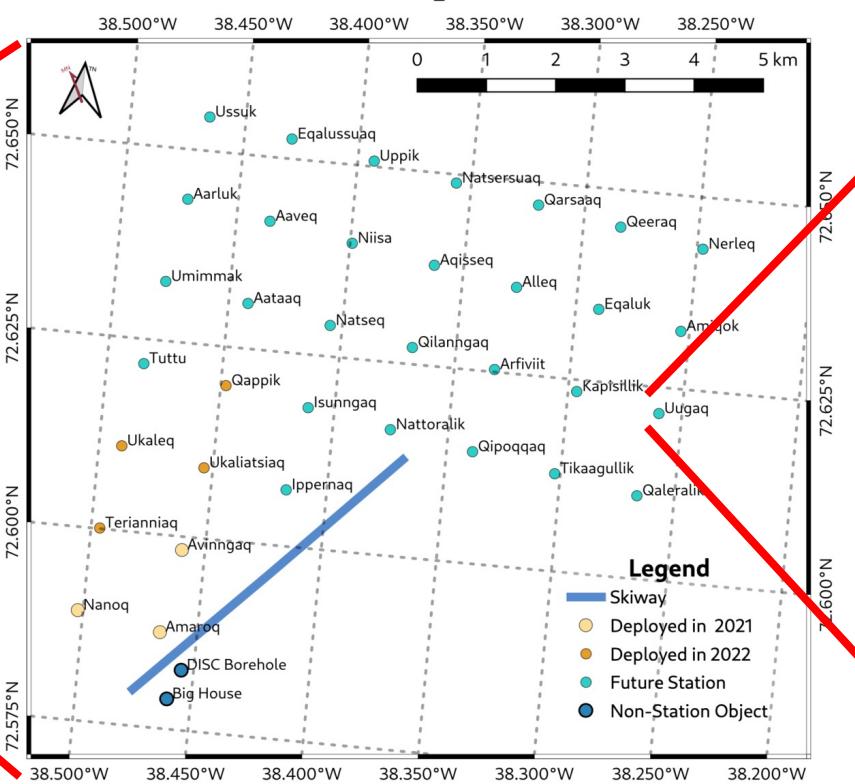
Propagation paths of radio pulses in ice.
(Barwick & Glaser, 2023)



Changing pulse shape with changing viewing angle.
(Barwick & Glaser, 2023)



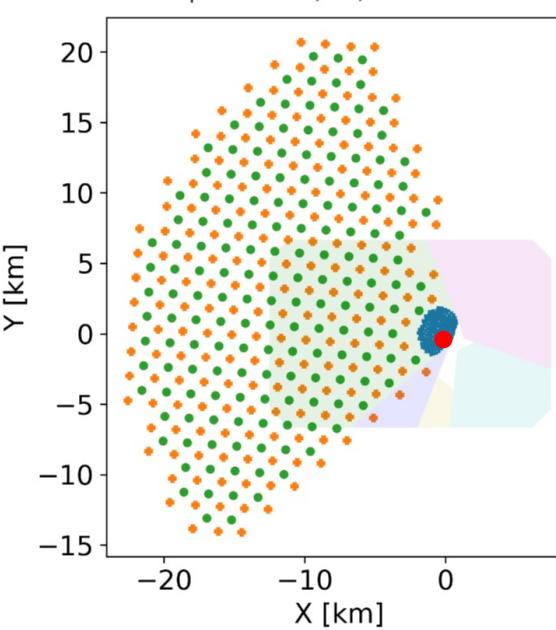
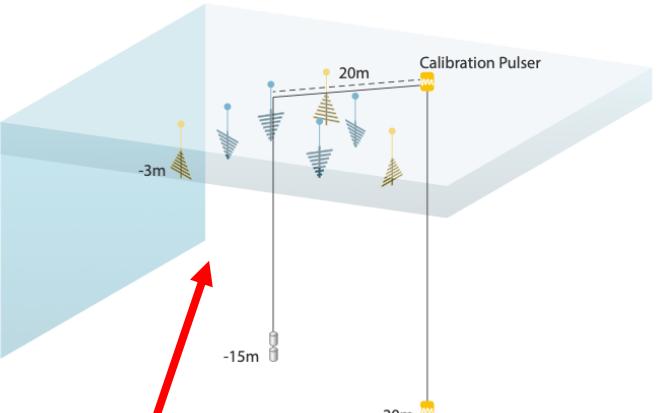
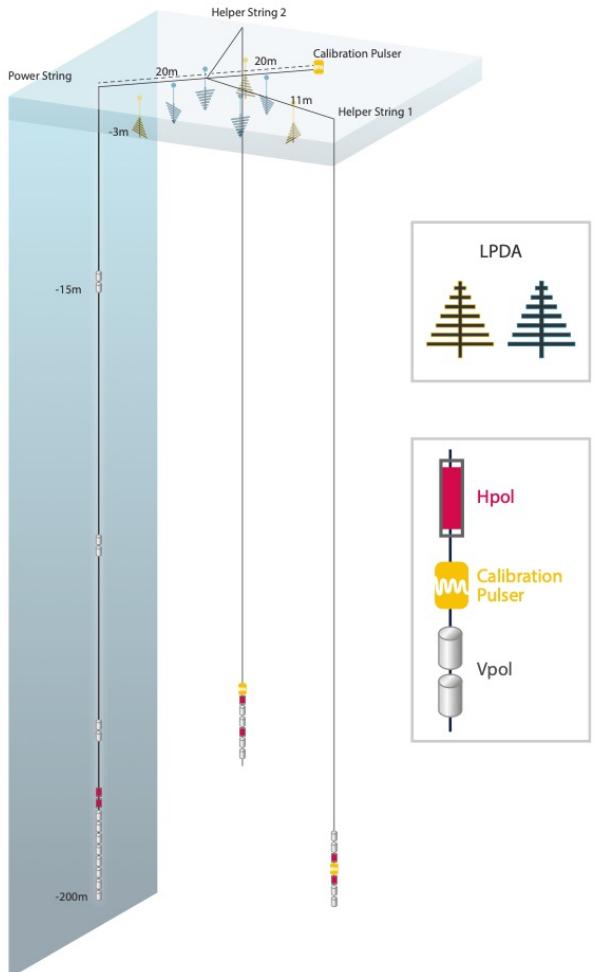
Radio Neutrino Observatory – Greenland (RNO-G)



The layout of the RNO-G experiment. [\(NSF, 2022\)](#), [\(RNO-G, 2022\)](#), [\(RNO-G, 2021\)](#)



IceCube-Gen2 Radio



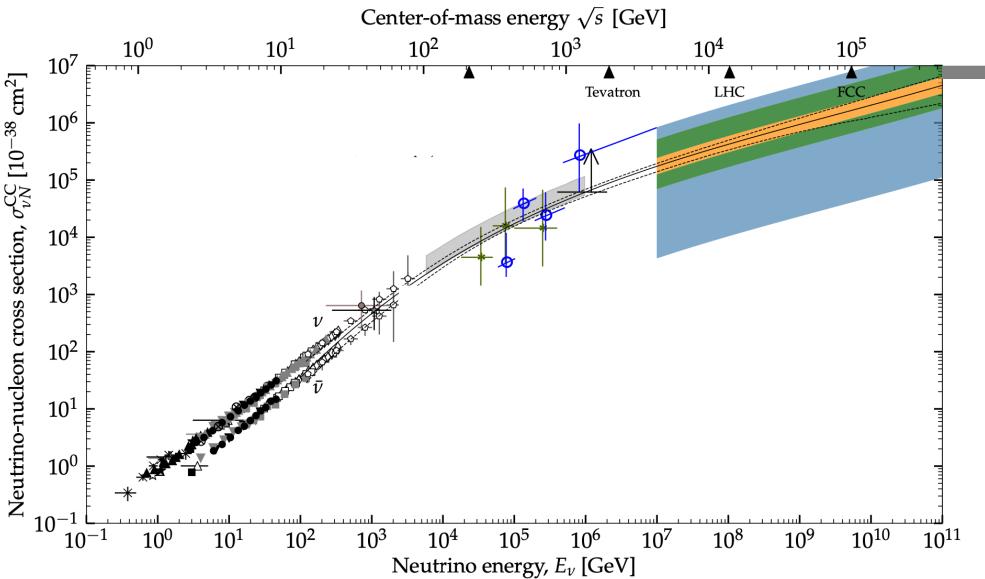
The layout of the IceCube-Gen2 Radio experiment.

(IceCube-Gen2 Collaboration, 2022)

(BBC, 2016)

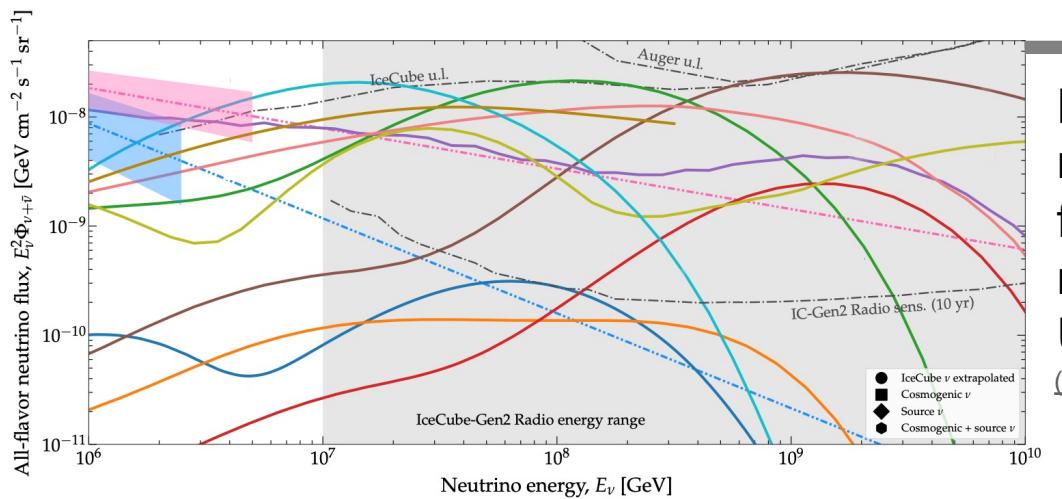
Science case for Ultra-High Energy Neutrino Detection

- Theoretical predictions for neutrinos with energies into the EeV range
- Particle Physics:
 - What is the neutrino cross section at these energies?
 - What is the flavor composition?
 - Test the Standard Model predictions!
- Astro Physics:
 - What sources emit UHE neutrinos?
- Astro particle physics:
 - What is the UHE neutrino flux?
 - How are cosmic messengers accelerated?
- UHE multimessenger astrophysics
 - Neutron star mergers



Measured and predicted neutrino cross-section.

(Ackermann et al., 2022)

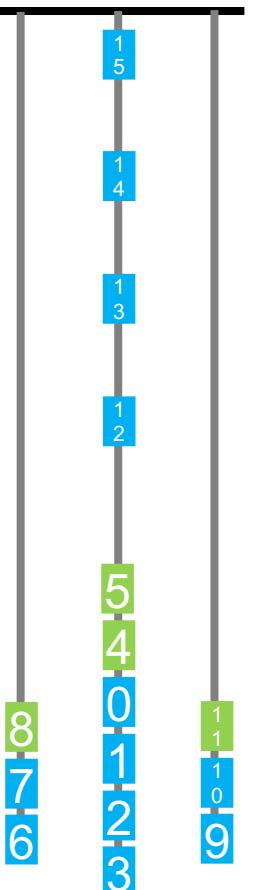
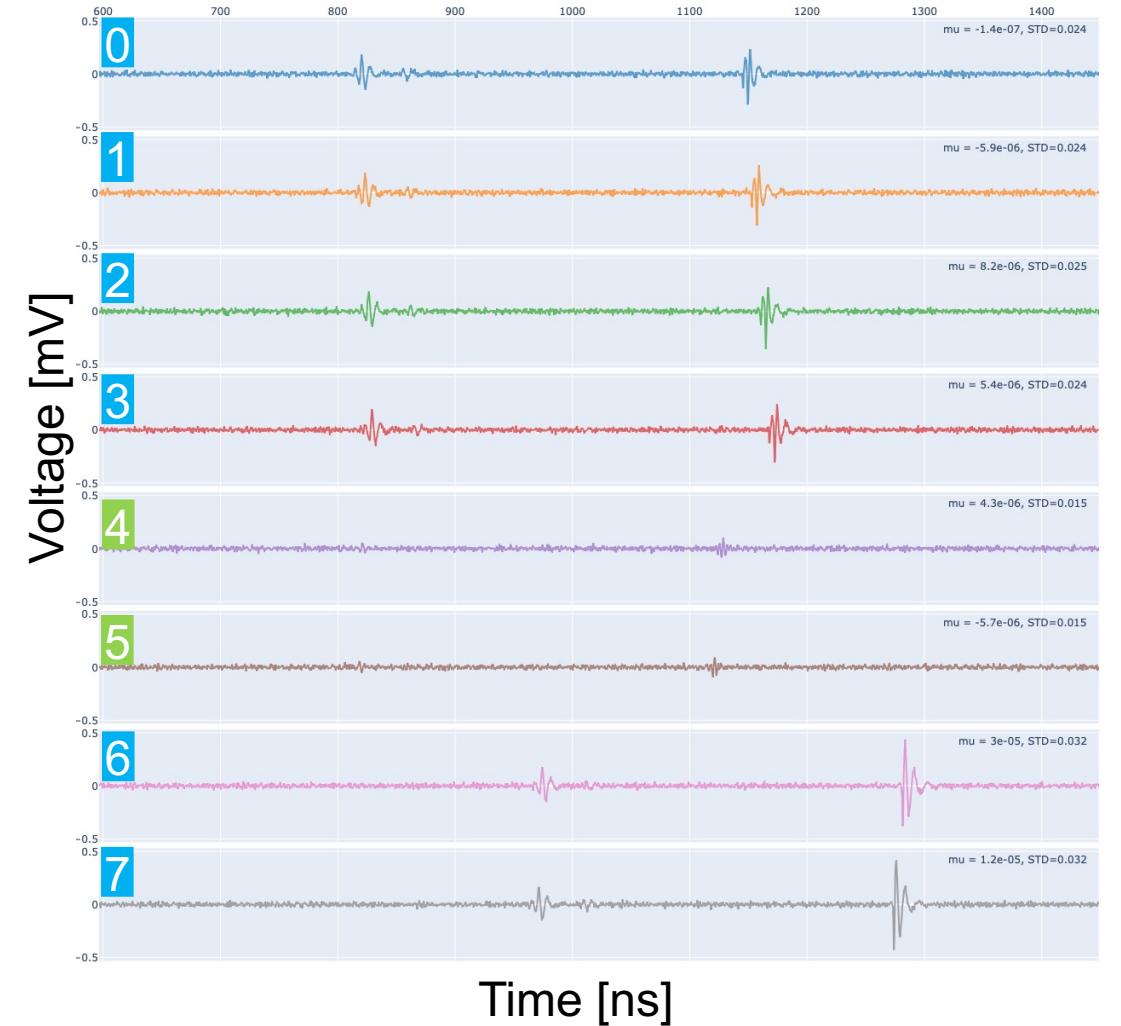


Predicted neutrino flux from different models at UHE.

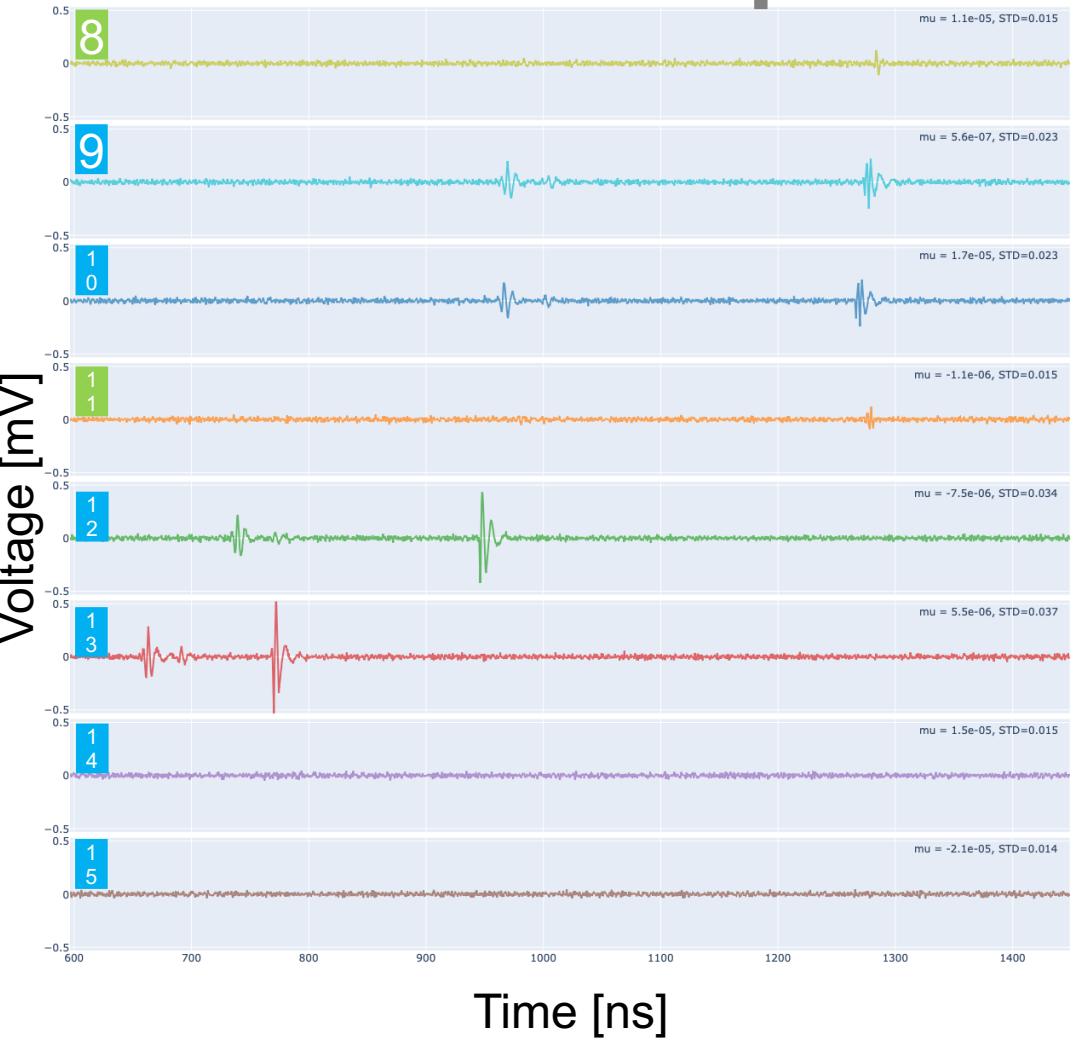
(Valera et al., 2022)



Simulating Training Data

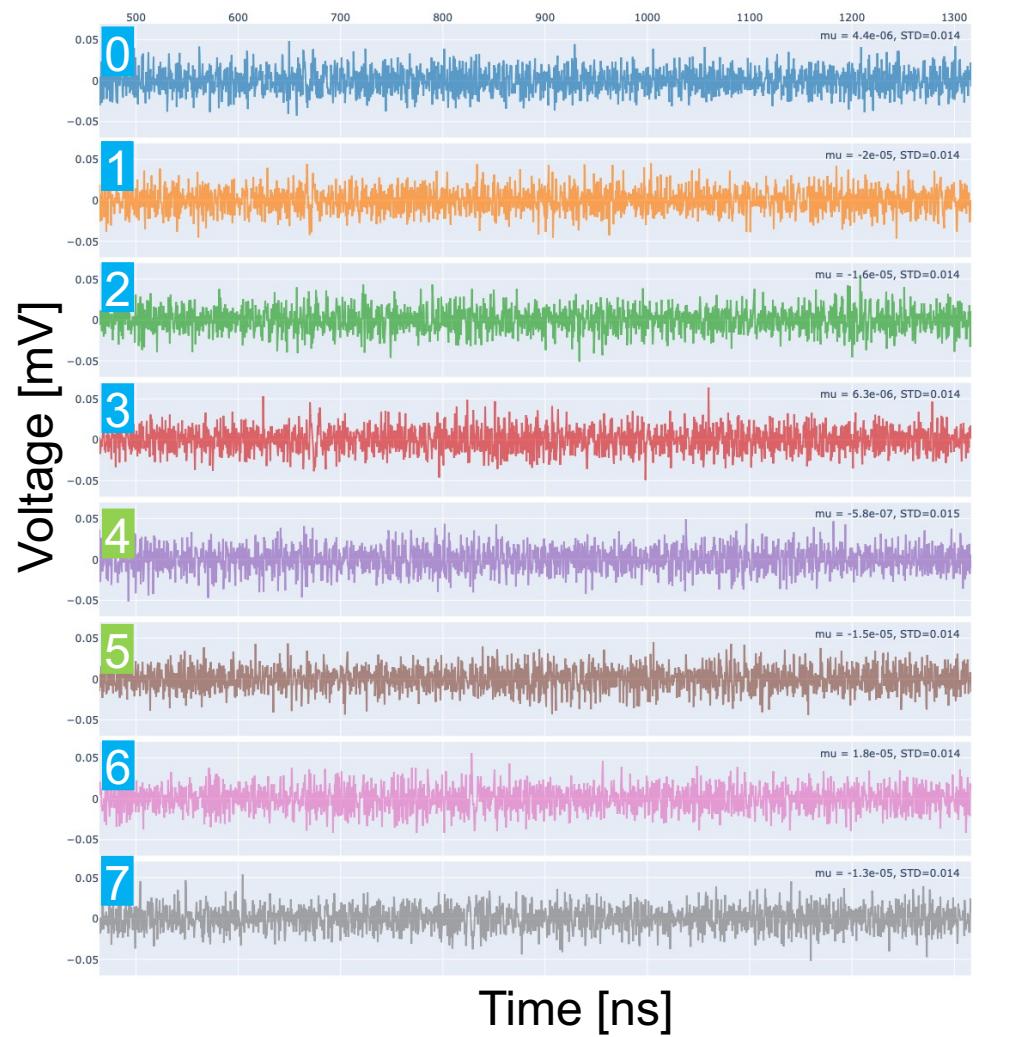


My work: MC simulated signals for deep radio stations.

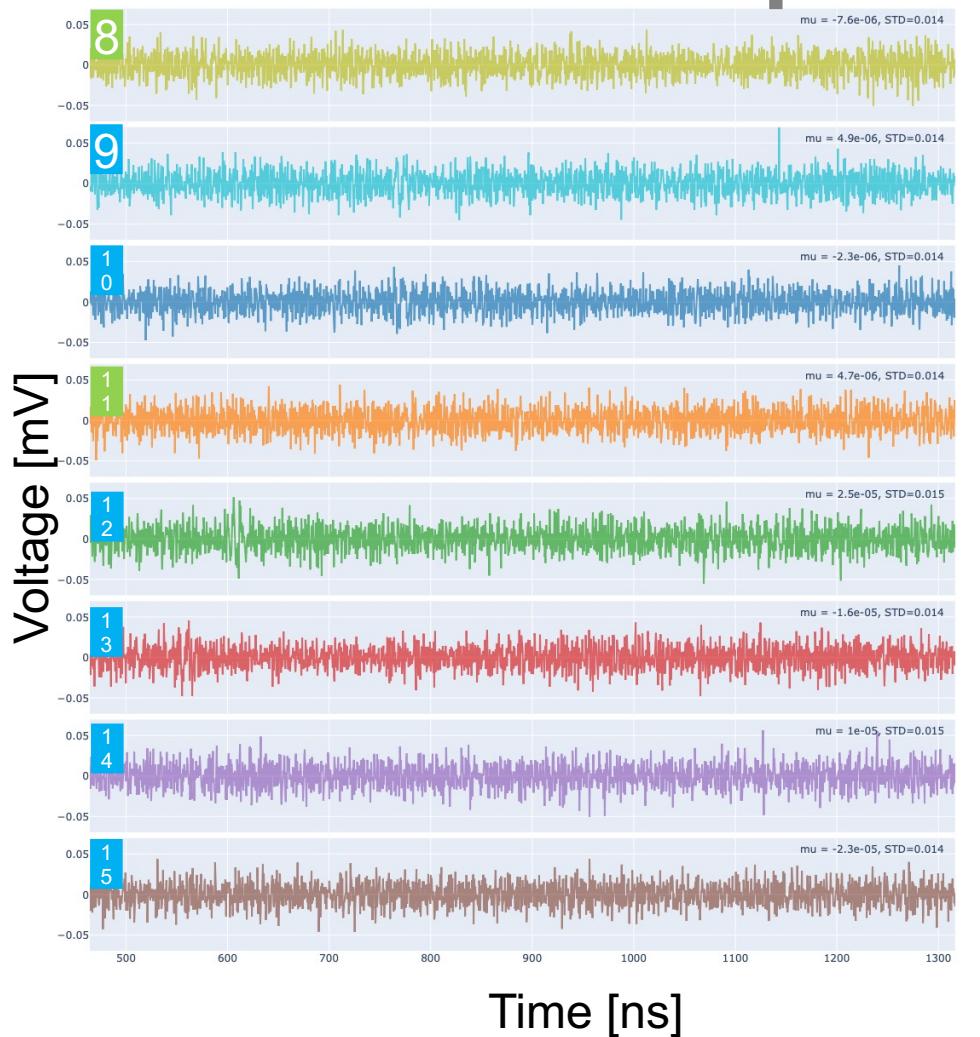




Simulating Training Data

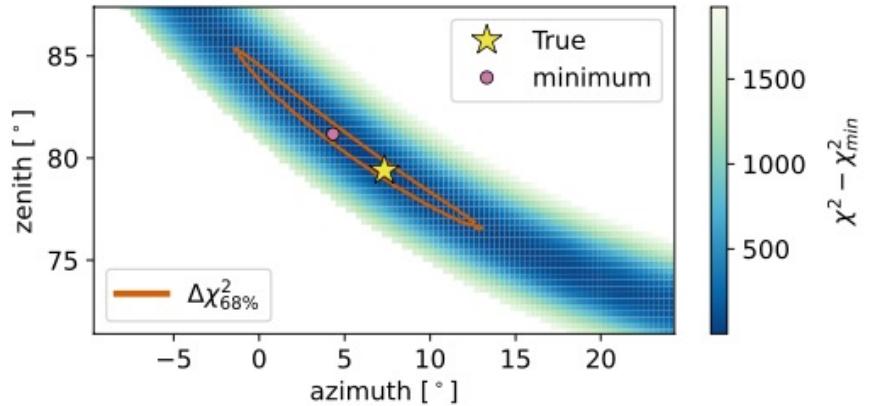
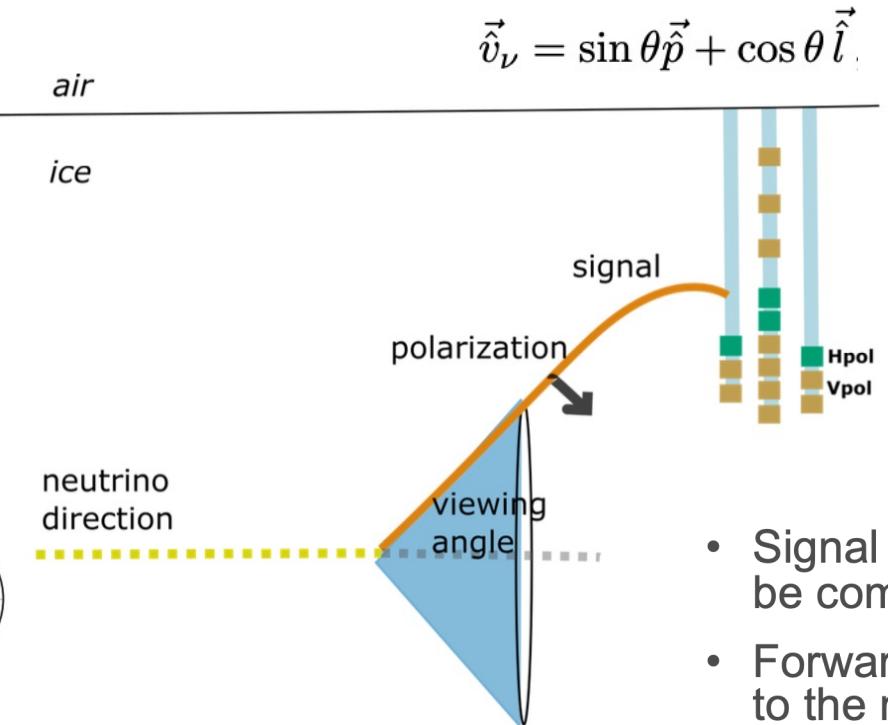
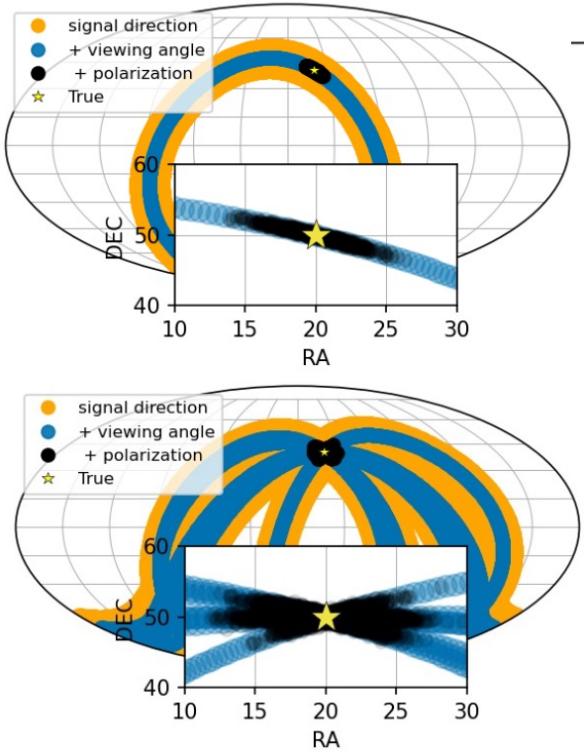


My work: MC simulated signals for deep radio stations.



Conventional Reconstruction of Neutrino Properties

- Direction



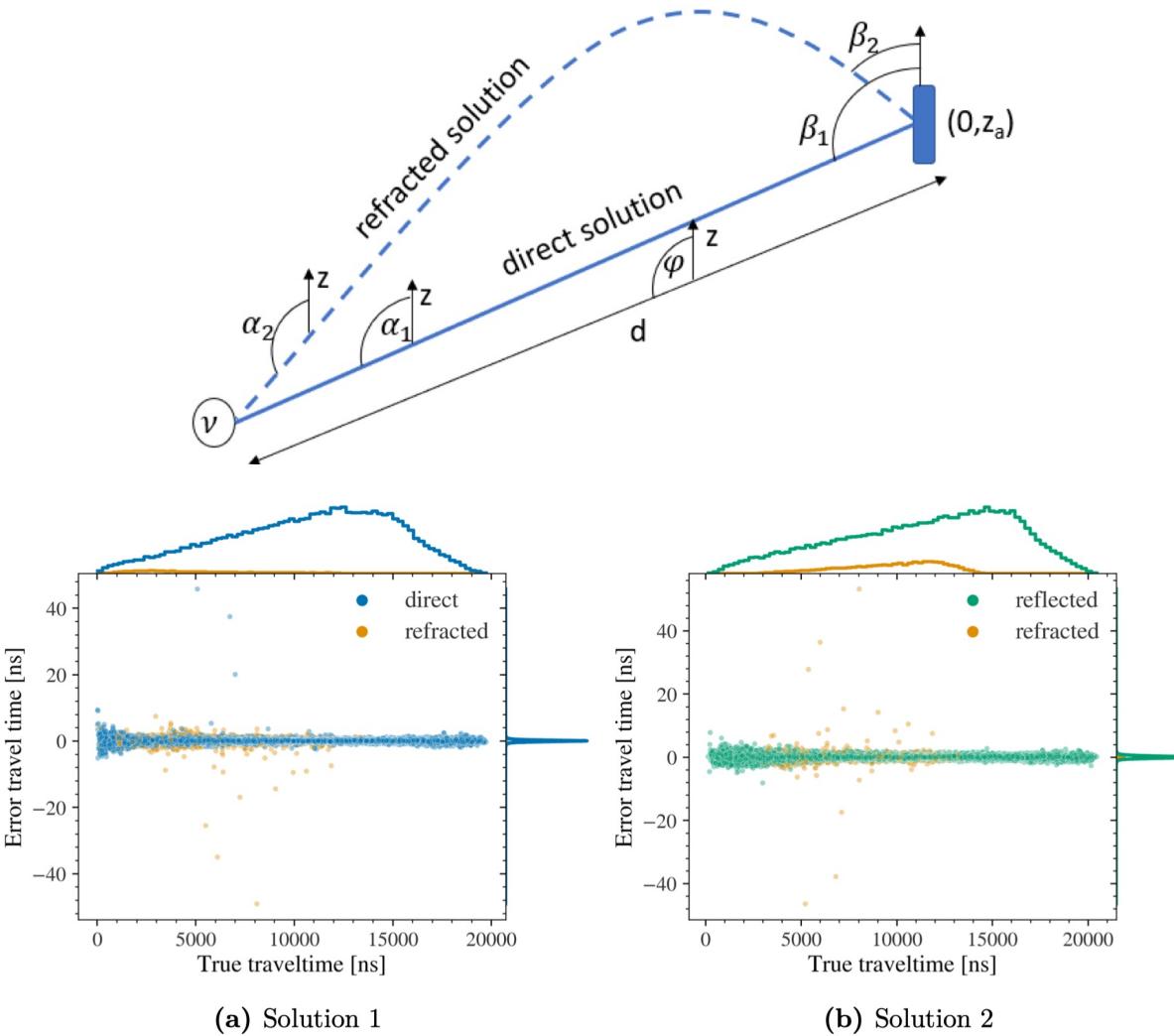
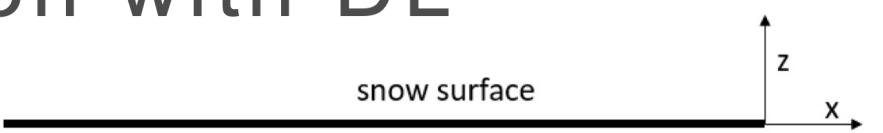
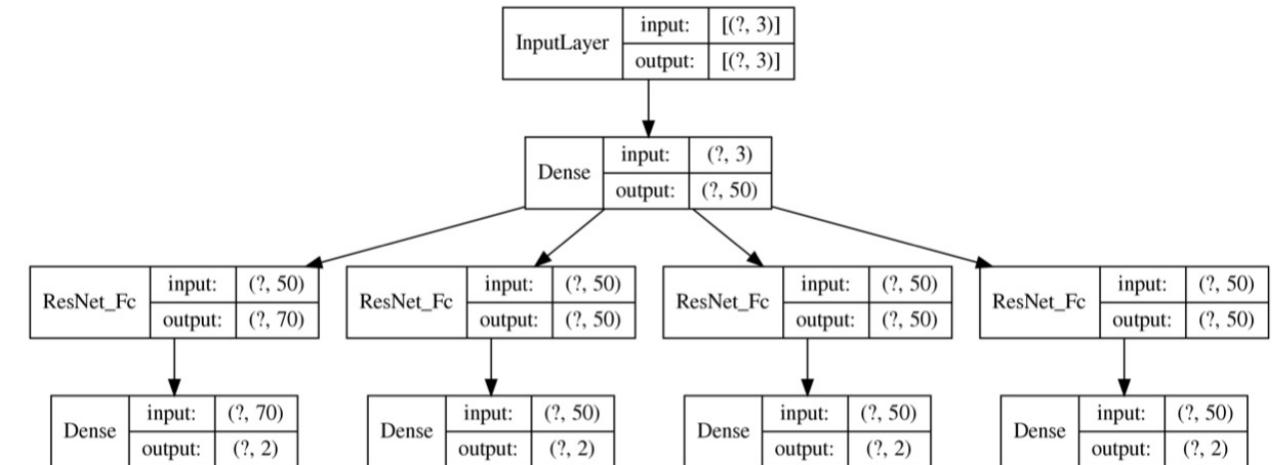
- Signal direction, viewing angle and polarization can be combined to reconstruct the neutrino direction
- Forward folding of simulated signals are compared to the measured signal
- Polarization is the main source of uncertainty, especially for the deep stations
- Non gaussian uncertainty contours can be constructed with a banana like shape

[\(Plaisier et al., 2023\)](#)



Step 1: Replace MC simulation with DL surrogate model

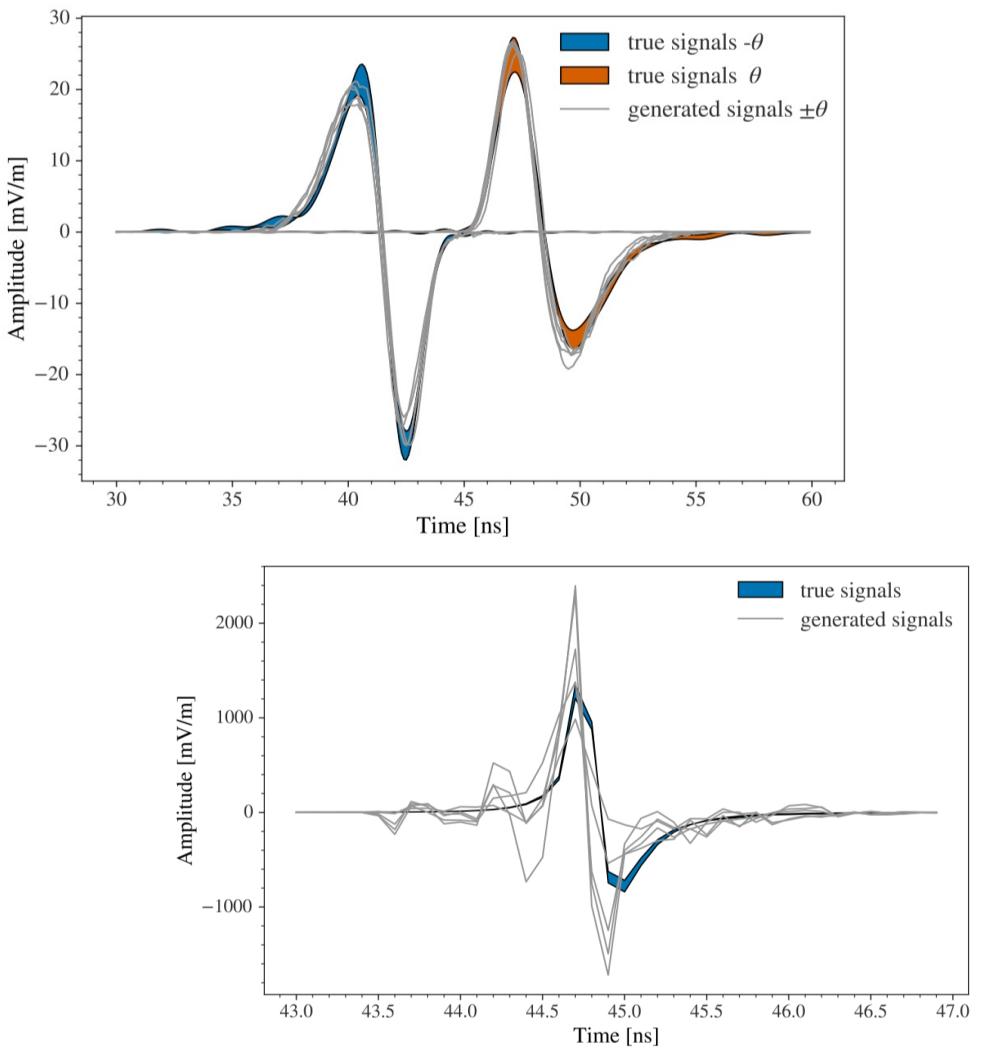
- 4 modular steps:
 - event generation
 - signal generation
 - **signal propagation**
 - detector response + trigger
- Promising first results
 - fully connected network
 - precision already close to target resolution



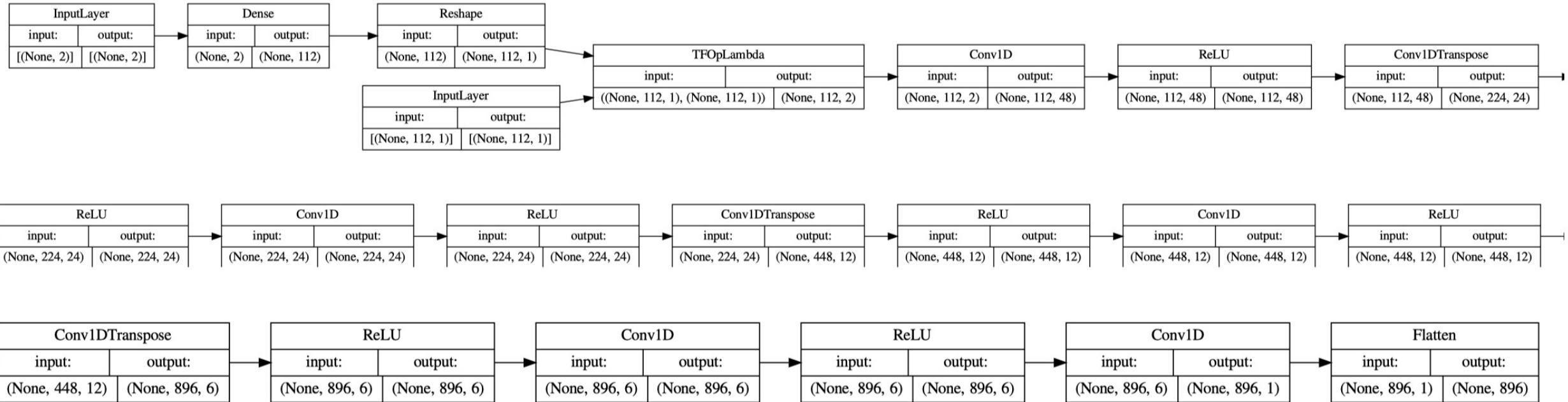


Step 1: Replace MC simulation with DL surrogate model

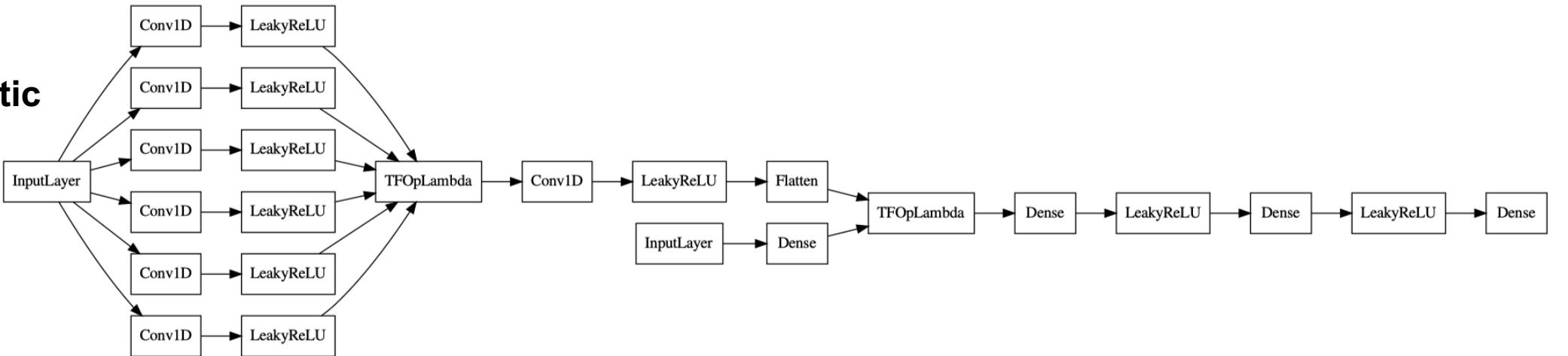
- 4 modular steps:
 - event generation
 - **signal generation**
 - signal propagation
 - detector response + trigger
- Signal depends on
 - shower energy
 - geometry
- Stochasticity due to shower development
- Using WGAN with two conditions

(a) E=10EeV, $\theta = 0^\circ$

Generator



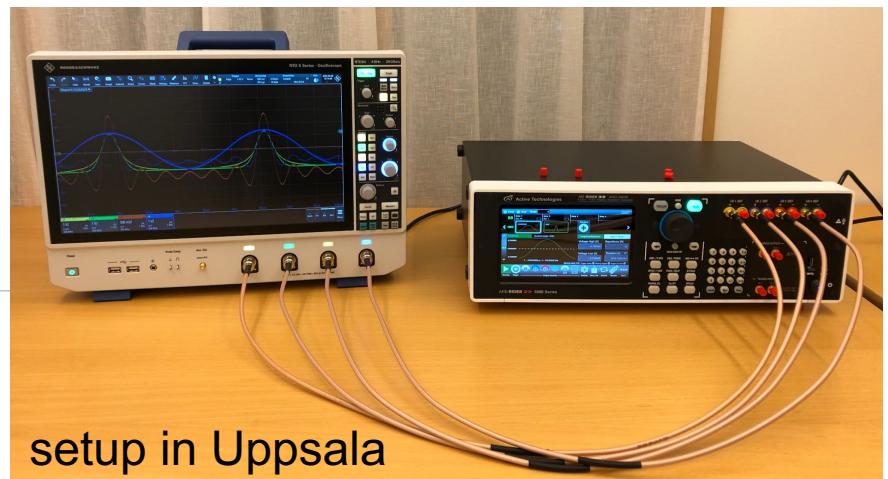
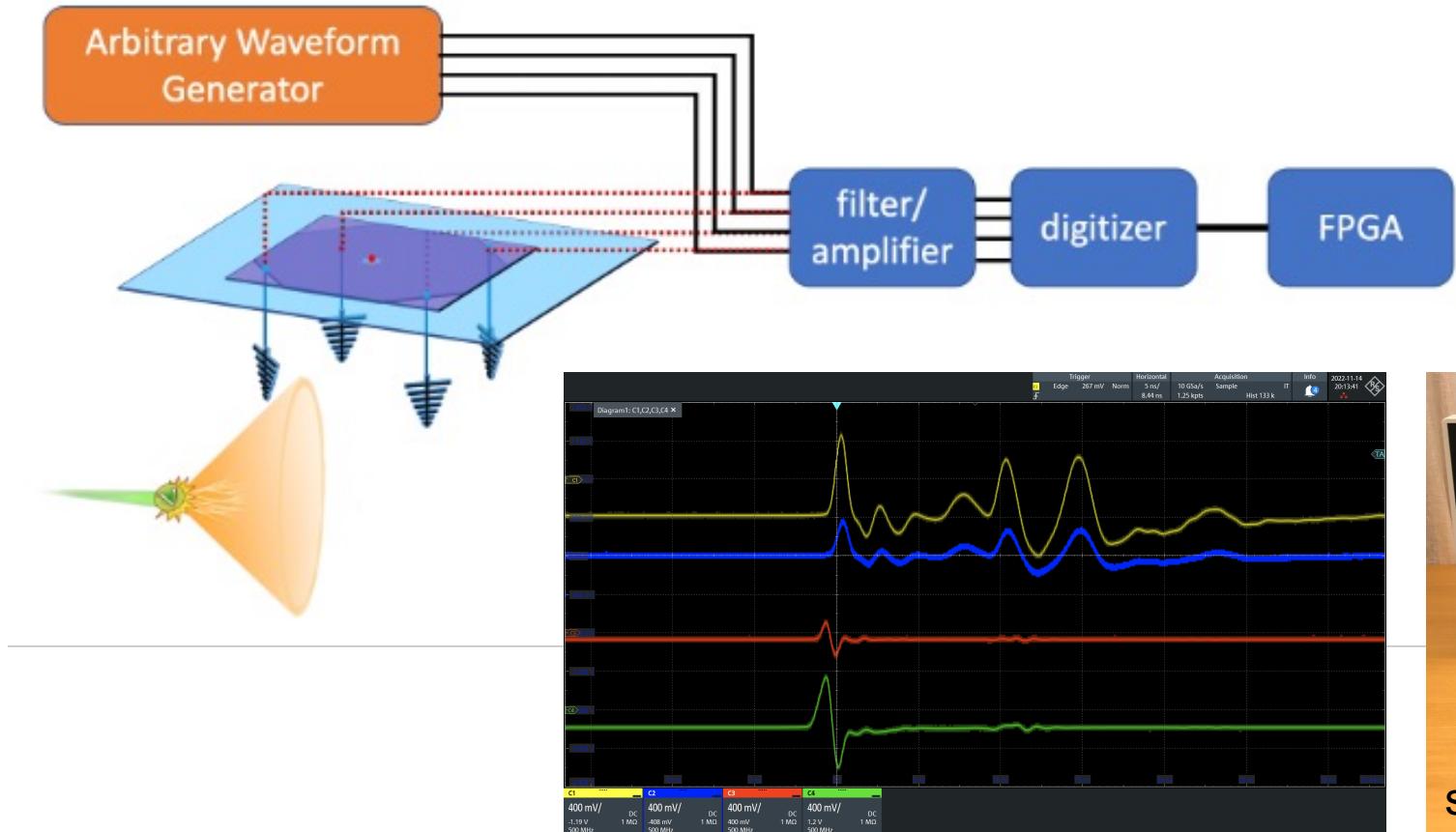
Critic





Lab Verification

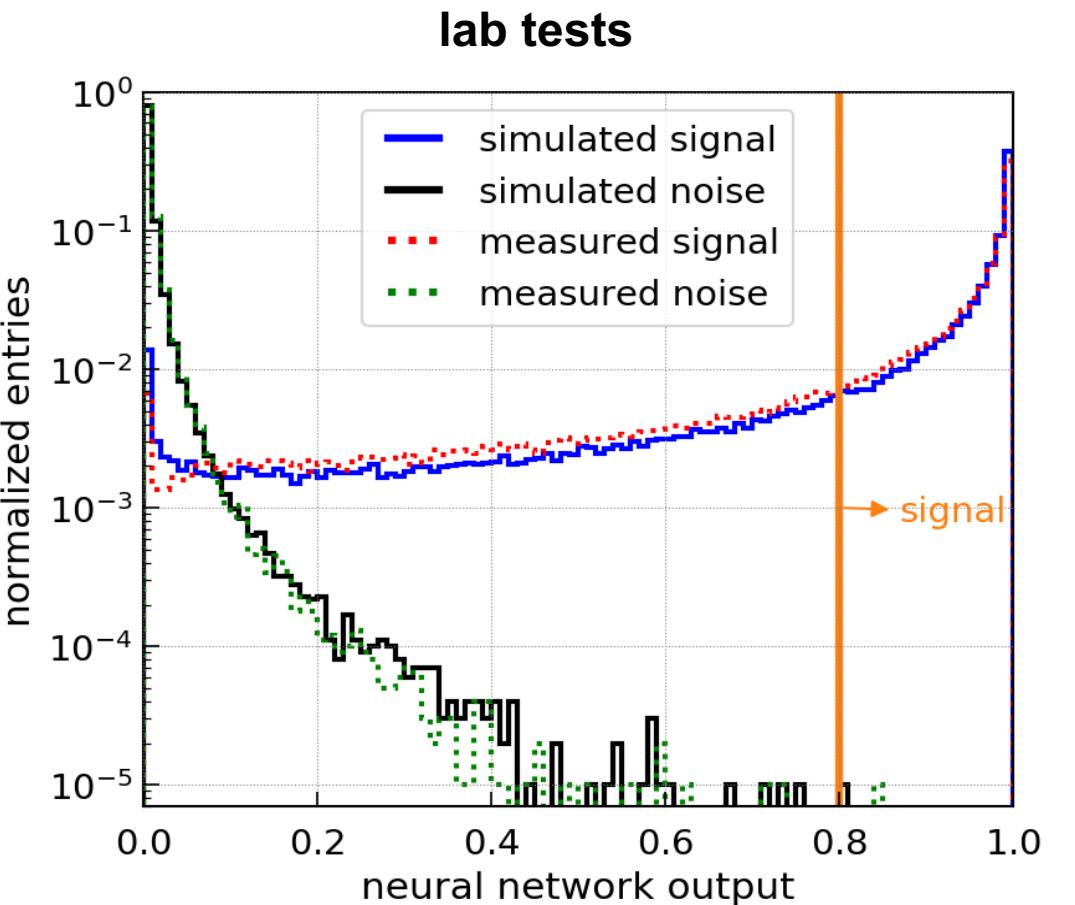
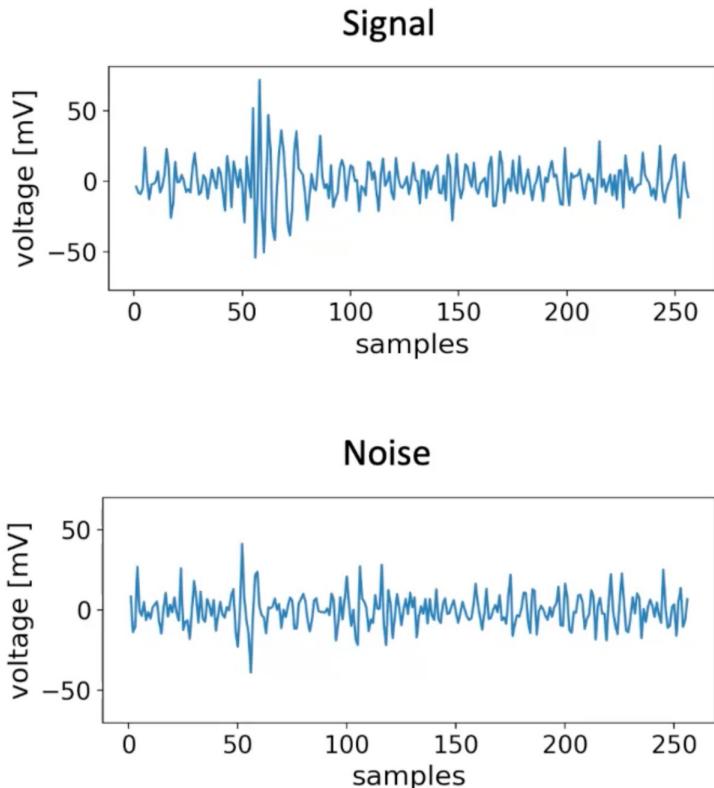
“Neutrino signal generator in the lab”





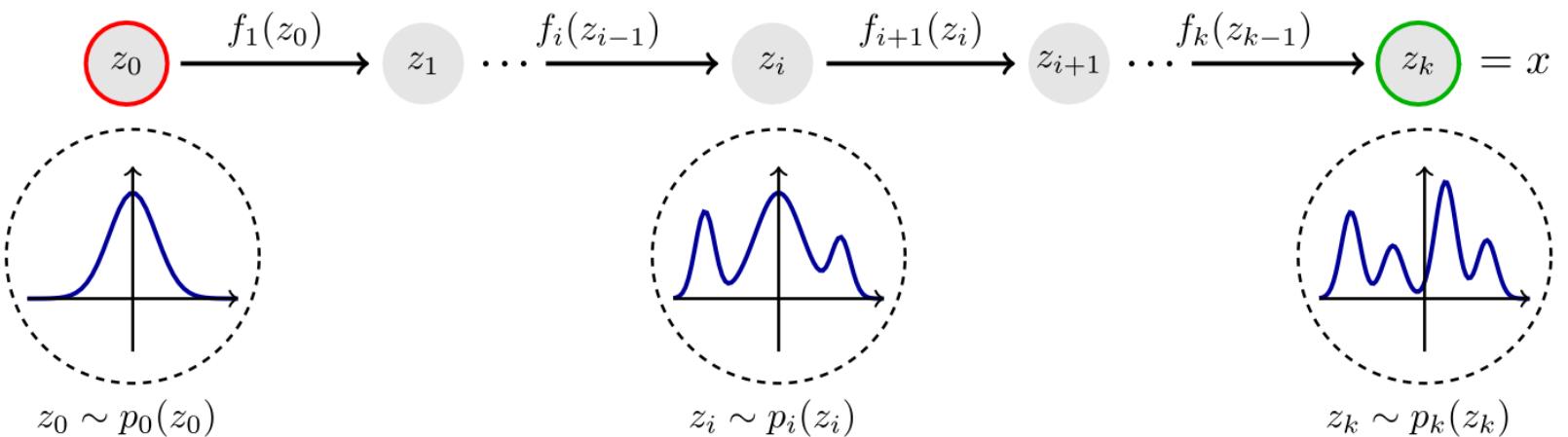
Deep Learning Trigger

- Current trigger based on simple thresholds
- Huge gain expected by replacing trigger with neural network that analyzes data stream in real time



Normalizing Flows - Theory

- Goal: Modelling an arbitrarily complex non-gaußian PDF ($p_x(\mathbf{x})$) by sampling from a simpler PDF ($p_z(\mathbf{z})$)
- The two are connected via the change of variable formula $p_x(\mathbf{x}) = p_z(\mathbf{z}) |\det J_f(\mathbf{z})|^{-1}$
- The function \mathbf{f} is a diffeomorphism that can be found by a deep neural network
- Diffeomorphism can be stacked to create more complex distributions



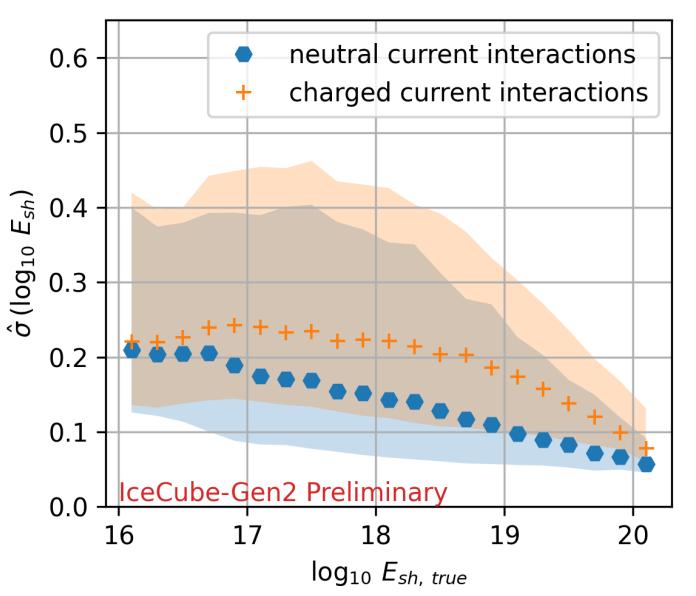
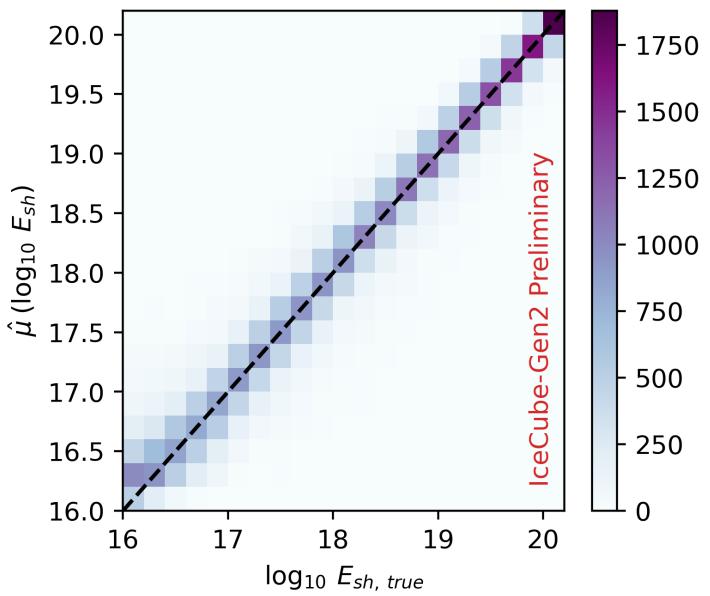
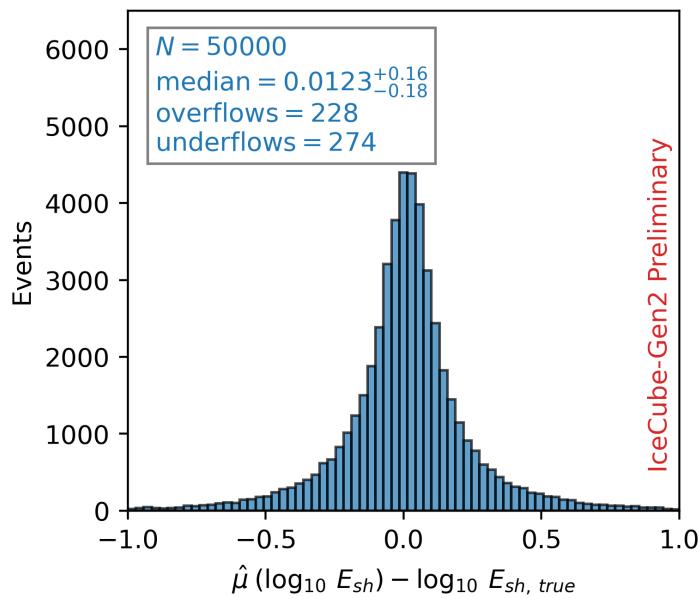
Normalizing flow estimating
a complex 1-d PDF from a
gaußian base distribution.

[\(Riebesell, 2023\)](#)



Reconstruction Results - Energy

- Excellent resolution: $\Delta \log(E_{shower}) = 0.2$
Within the inelasticity uncertainty of the neutrino interaction
- Event-by event uncertainties possible
Coverage can be further improved (10% deviation)

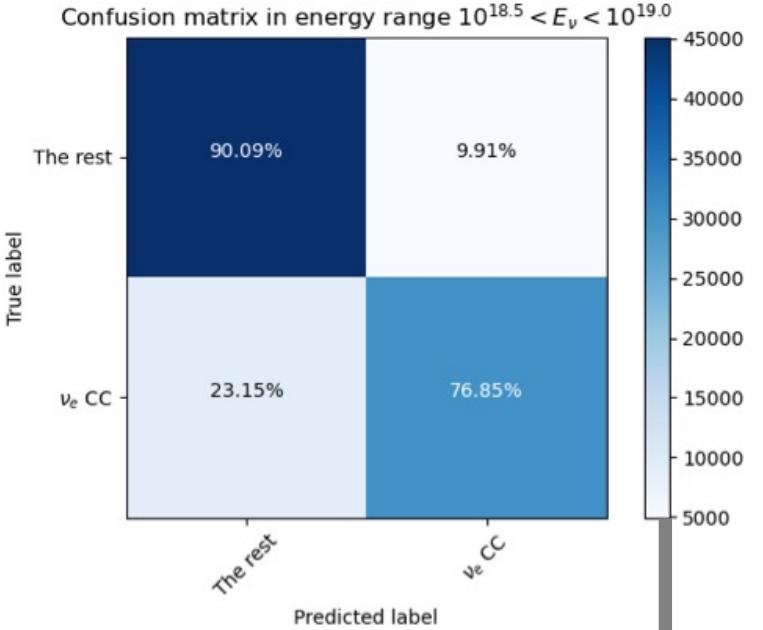
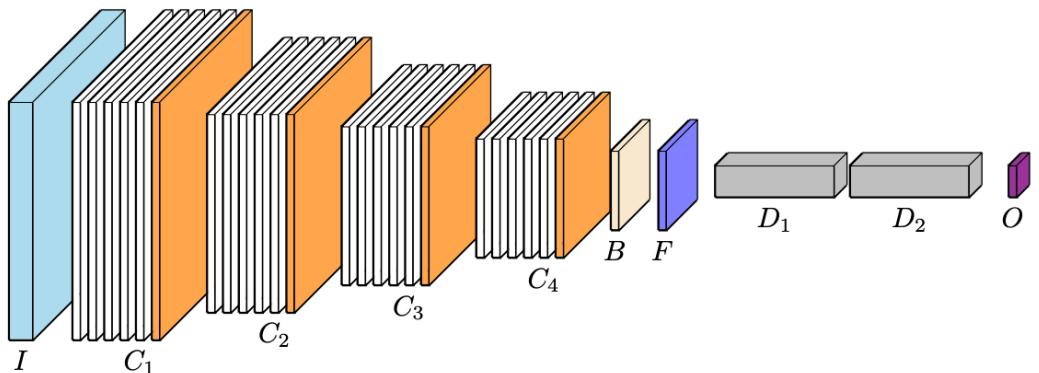




Event Reconstruction using Deep Learning

- Flavor

- There is no ‘conventional’ way of reconstructing the neutrino flavor
- NC interaction result in detectable hadronic showers
- mu or a tau particle created by CC interactions leave the interaction and are practically undetectable with radio antennas
- CC interactions creating an electron result in a hadronic and an electromagnetic shower
- The only handle for flavour distinction is the LPM effect at high energies



Previous results using neural networks for flavor classification for shallow stations.

(Ericsson, 2021)