# NuRadioOpt

## Doubling the Detection Rate of Ultra-High Energy Neutrinos through a Neural Network Trigger

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CARL TRYGGERS STIFTELSE FÖR VETENSKAPLIG FORSKNING
Swedish Research Council
European Research Council
Established by the European Commission
UPPSALA UNIVERSITET

# Executive Summary

NuRadioOpt will improve both key factors that impact the science output

detection rate of UHE neutrinos

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

precision to determine the neutrino’s direction and energy

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

How:
Using Deep Learning and Differential Programming

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How:
Using Deep Learning and Differential Programming

MODE collaboration https://mode-collaboration.github.io/
4th MODE workshop, Valencia, 23.-25. Sept https://indico.cern.ch/event/1380163/
EuCAIF working group 2, Tuesday afternoon

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# The need to detect UHE ($E_\nu$>$10^{17}$eV) neutrinos

- Breakthrough in astroparticle physics
- New Window to the Universe
- Excellent probes of astroparticle and high-energy physics

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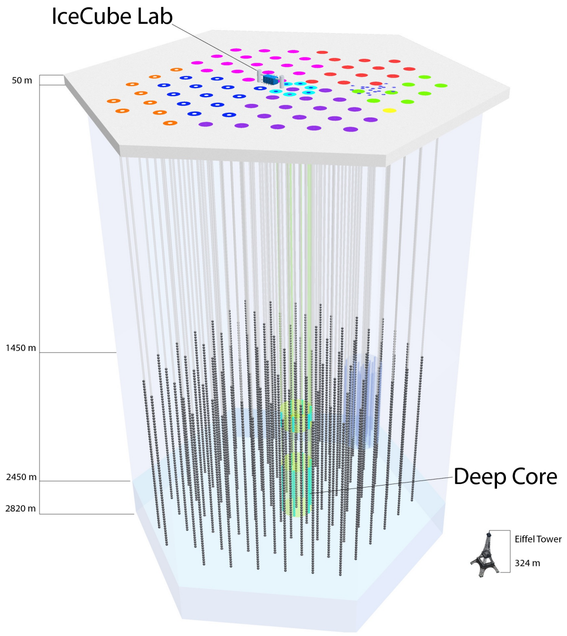
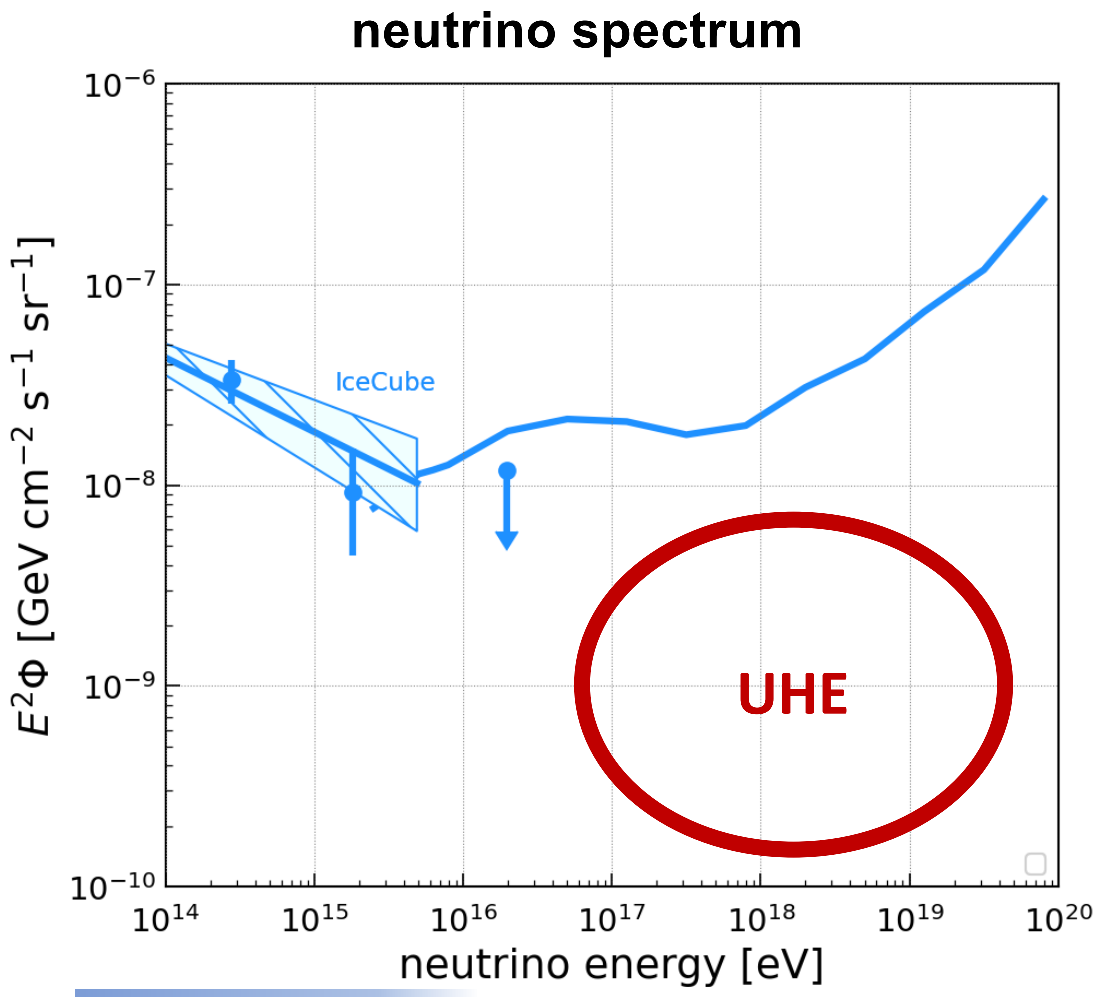
**TeV – PeV energies**

- IceCube: Currently world's largest neutrino telescope
- Breakthrough discoveries




optical/IceCube

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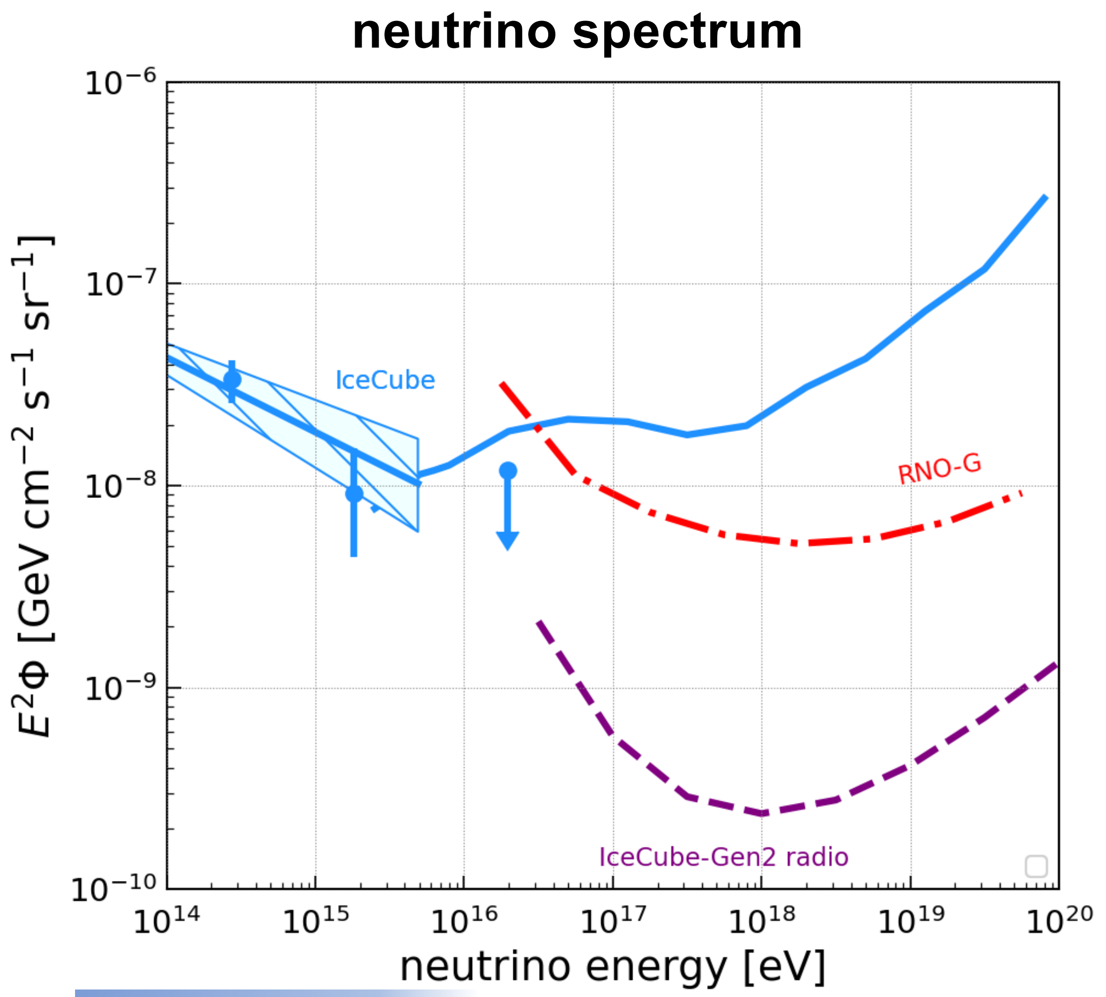
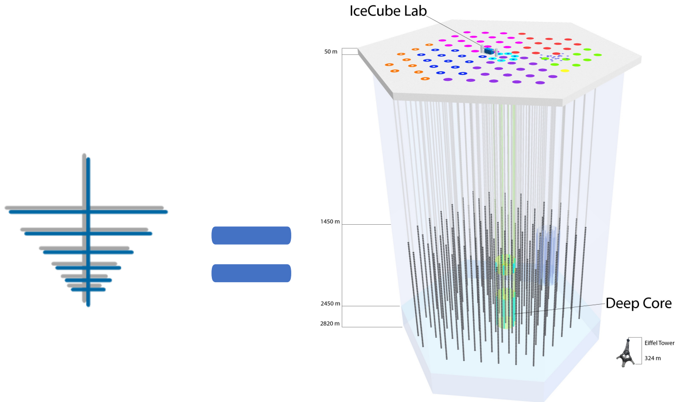
**EeV**

- **Solution: radio technique**
  - Large attenuation length in ice (>1km)

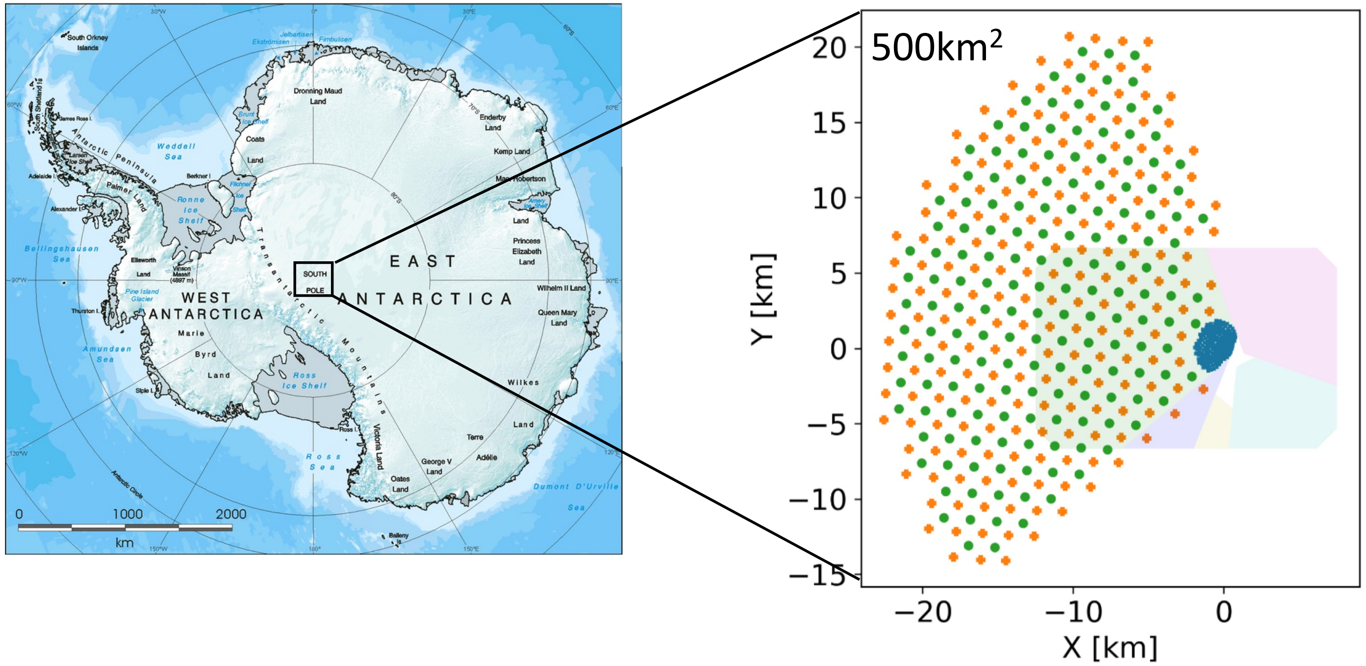



optical/IceCube

radio



# IceCube-Gen2 radio



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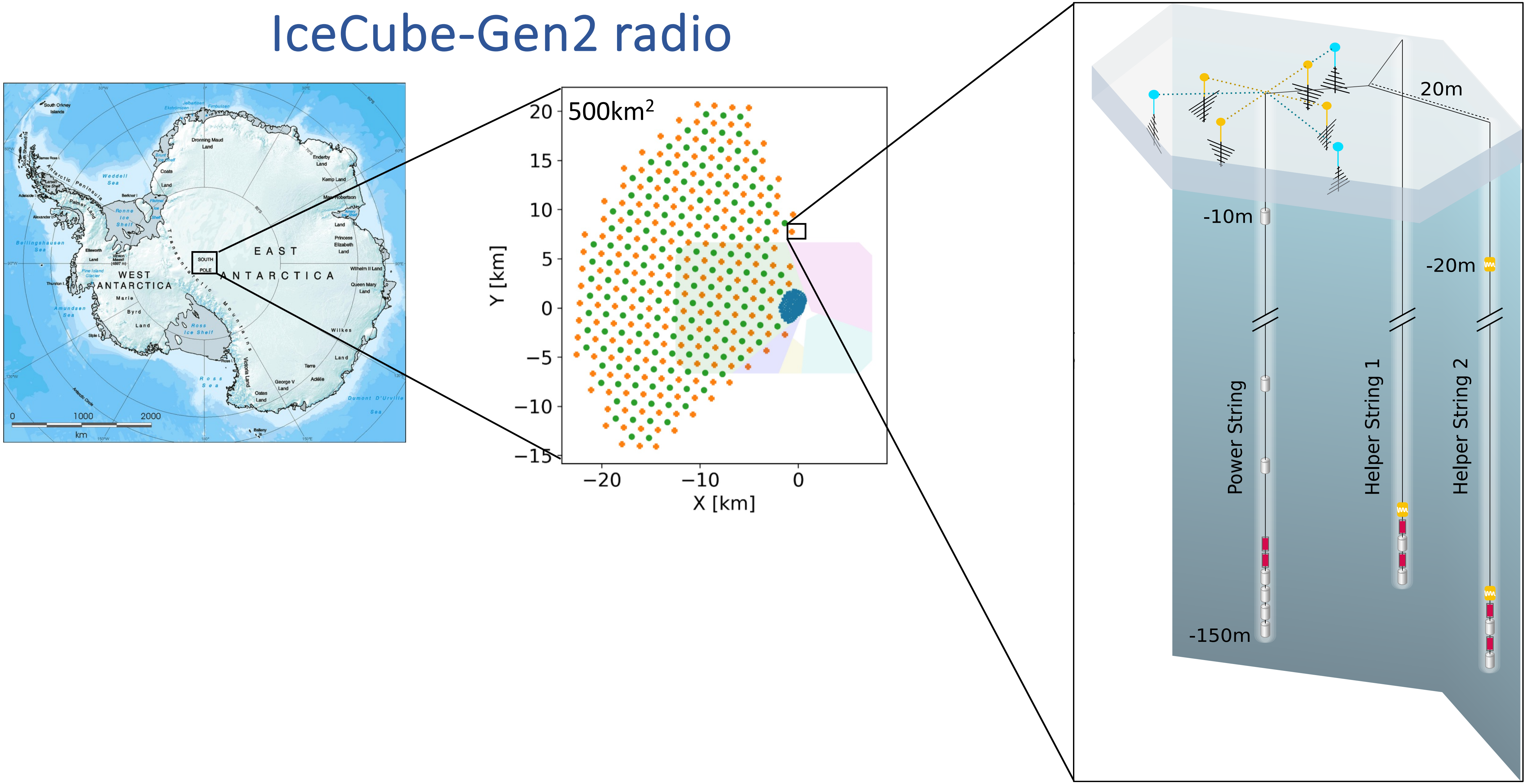




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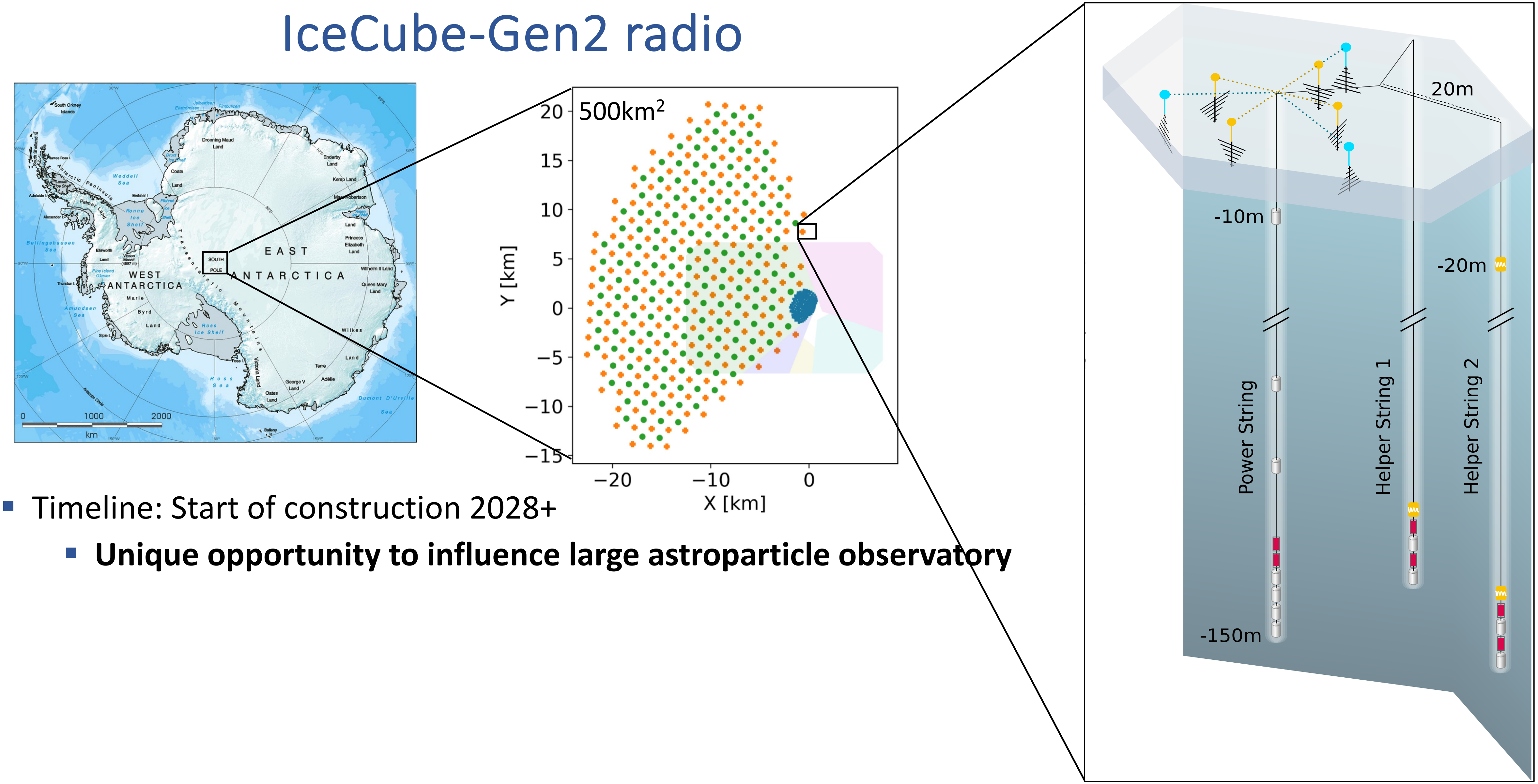


- Timeline: Start of construction 2028+
  - **Unique opportunity to influence large astroparticle observatory**


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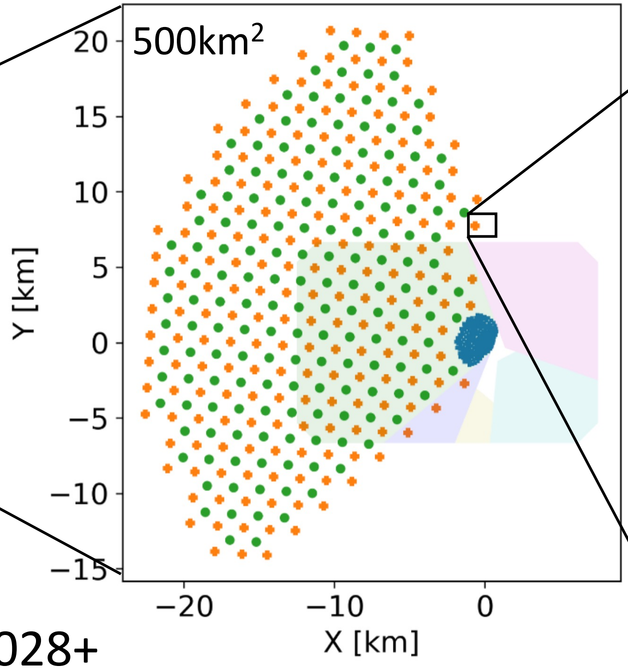
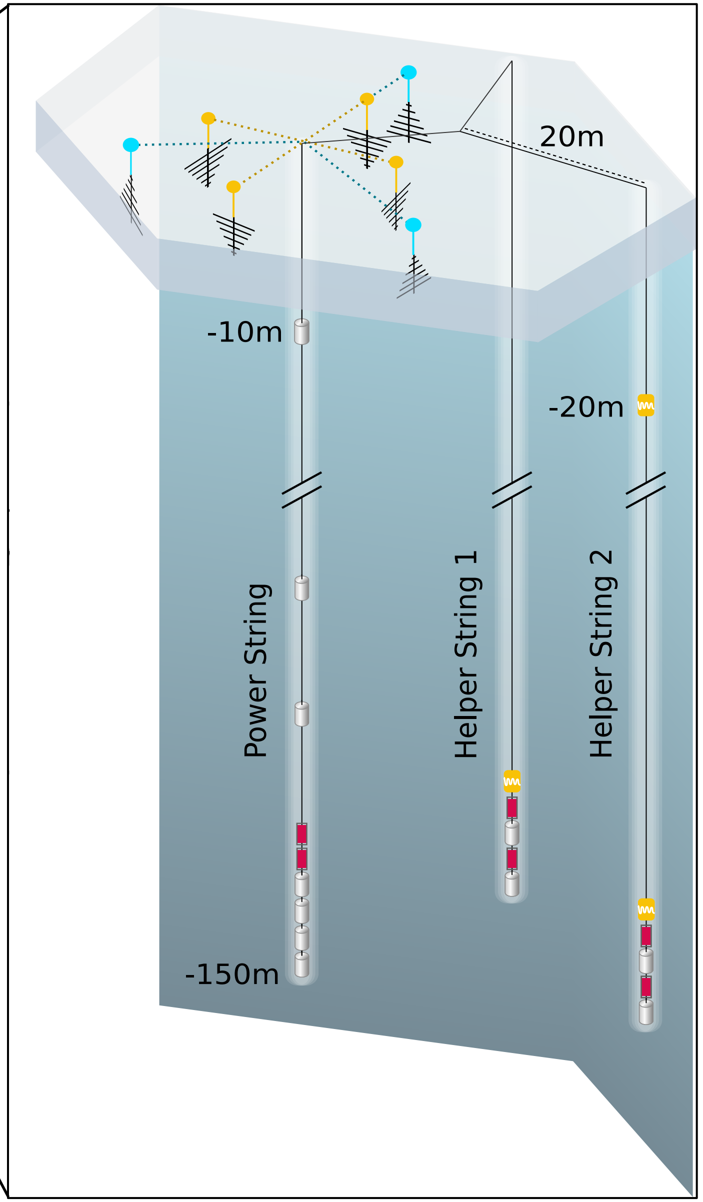


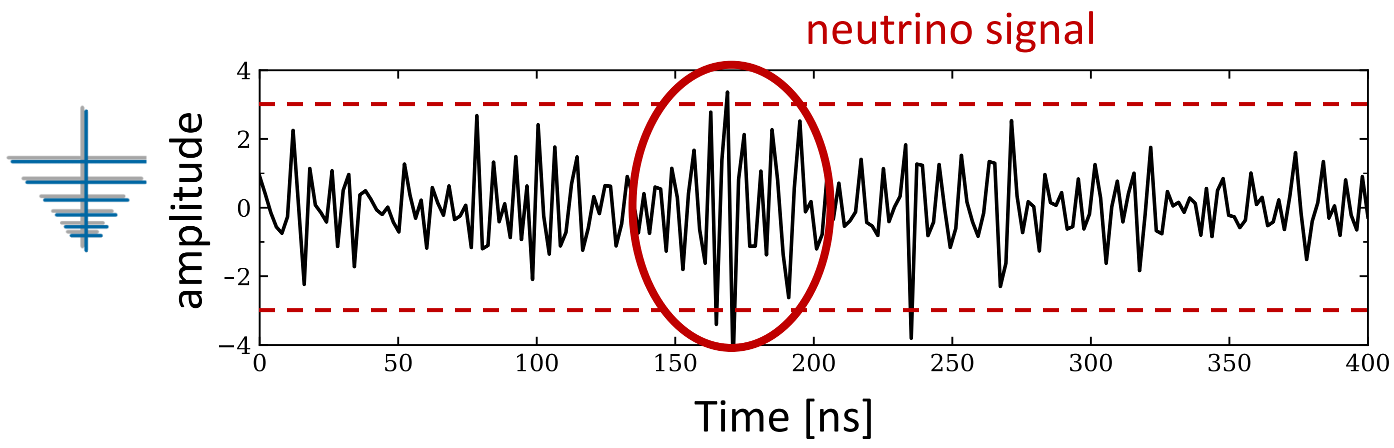



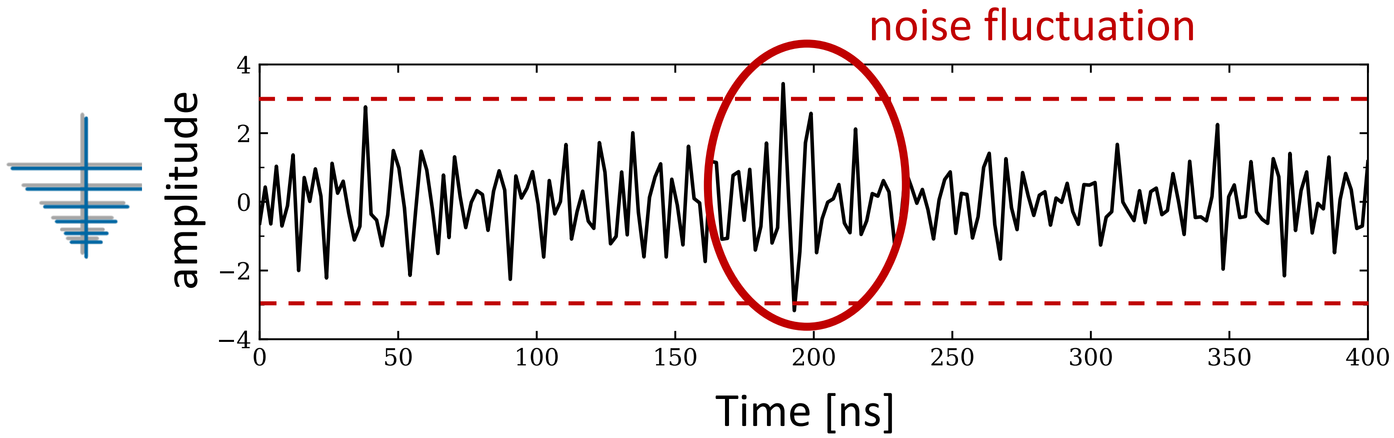

- Timeline: Start of construction 2028+
  - **Unique opportunity to influence large astroparticle observatory**
- Autonomous detector stations
  - limited data bandwidth and power budget
- IceCube-Gen2 construction lasts 7 years limited by logistics!
  - detector size can’t be increased

**→ Only option to accelerate the research field: better detector (this project)**

# Deep-Learning-Based Trigger

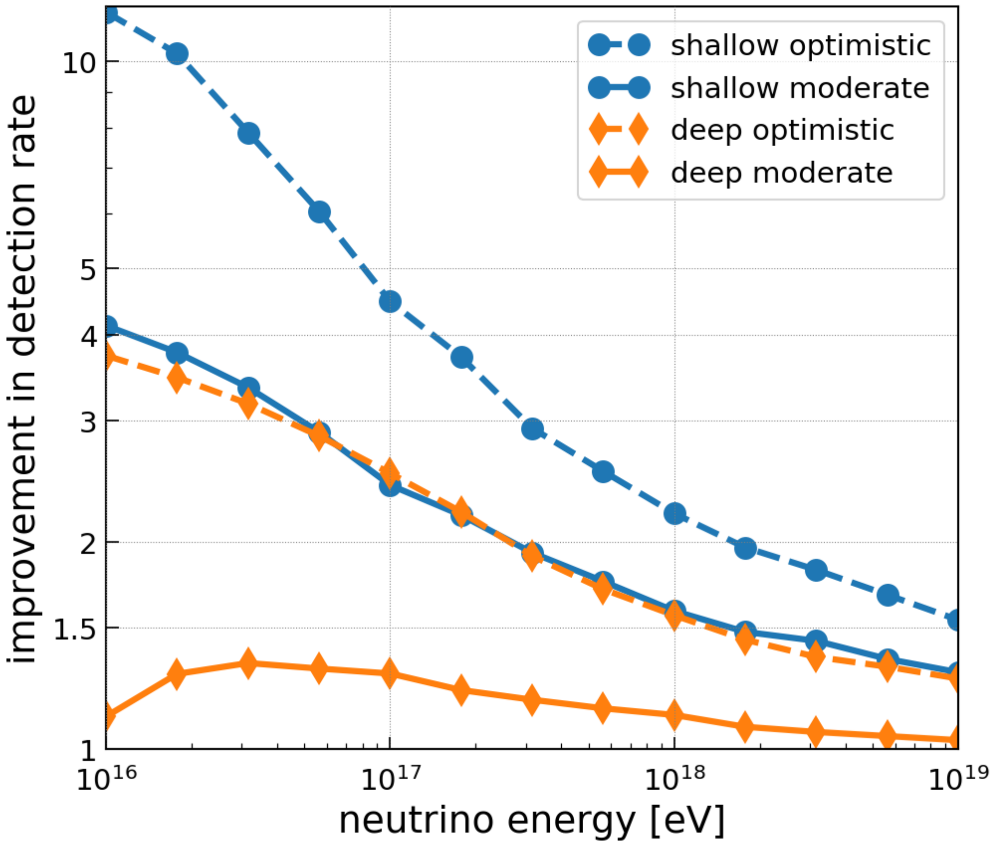
- Data can't be stored continuously
- Current state of the art: Threshold-based trigger
  - Unavoidable thermal noise fluctuations dominate trigger
  - Thresholds need to be high enough to limit trigger rate on thermal noise




- **Huge potential of improvement:**
  - offline analysis: thermal noise can be rejected with high efficiency
  - Neural networks are very good at classification tasks
  - Proof-of-concept study
    *ARIANNA collab. (… C. Glaser, …) , JINST 2022*

# Expected Improvements



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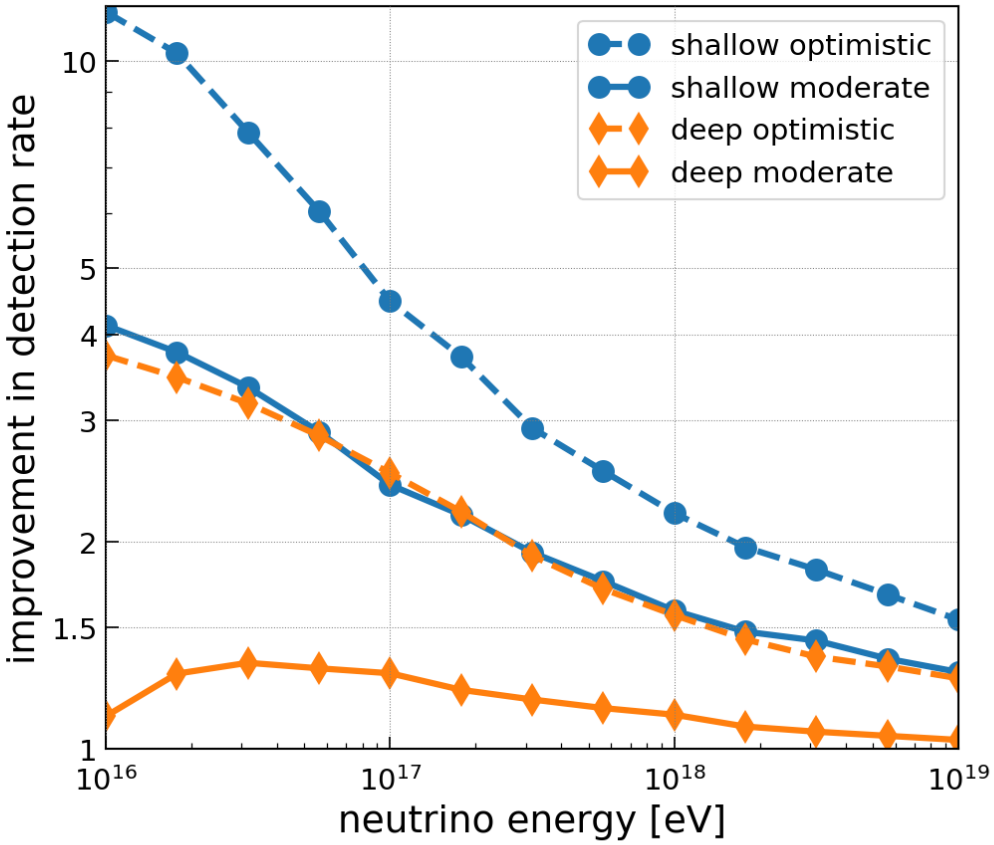
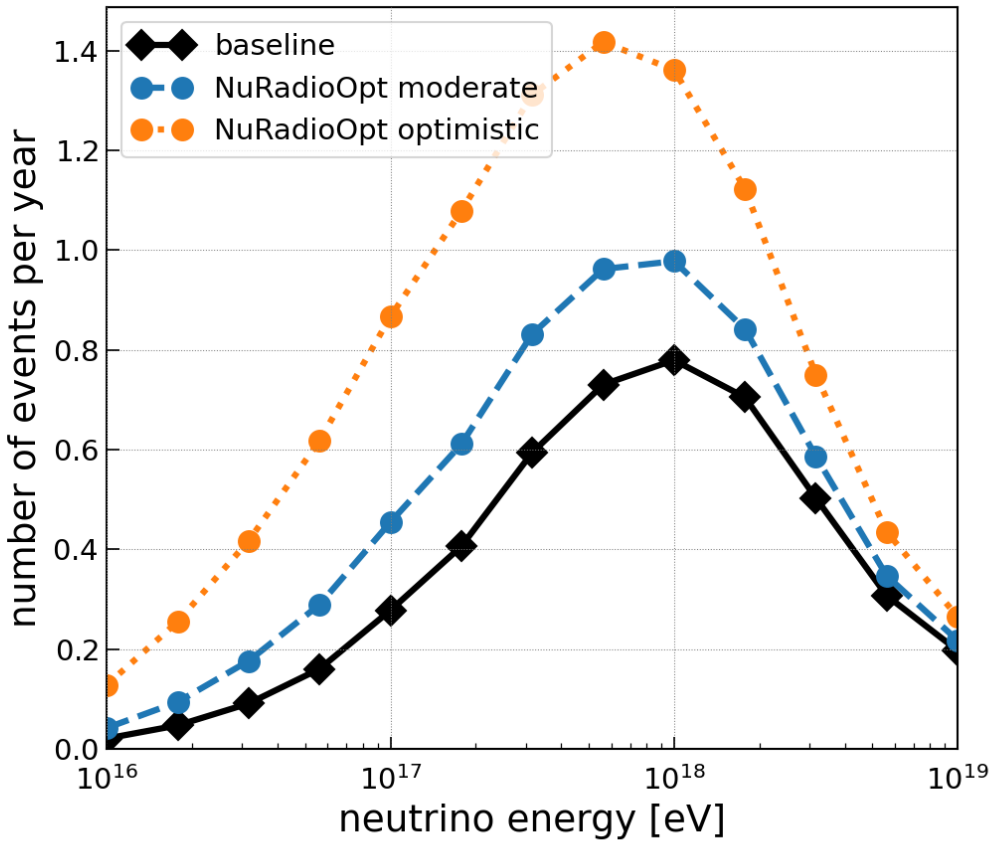
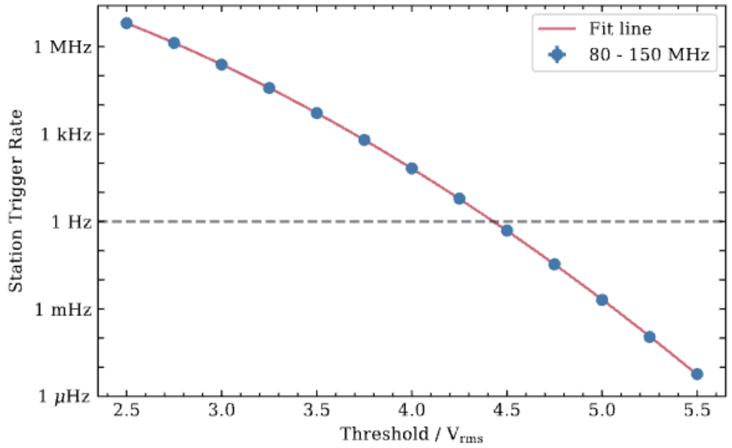


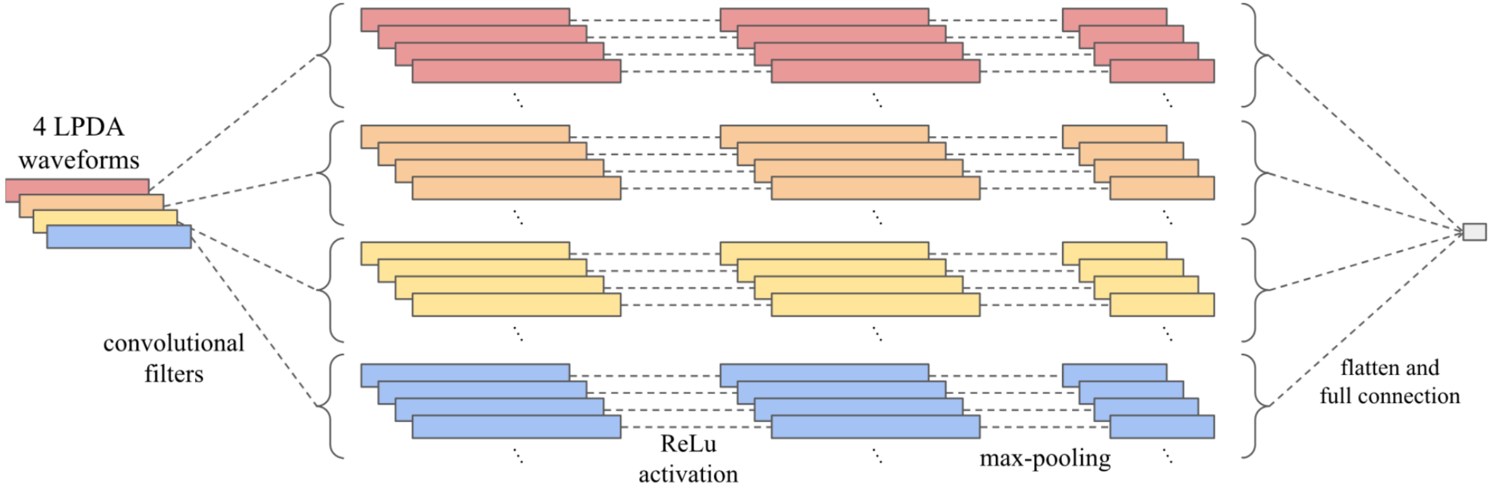



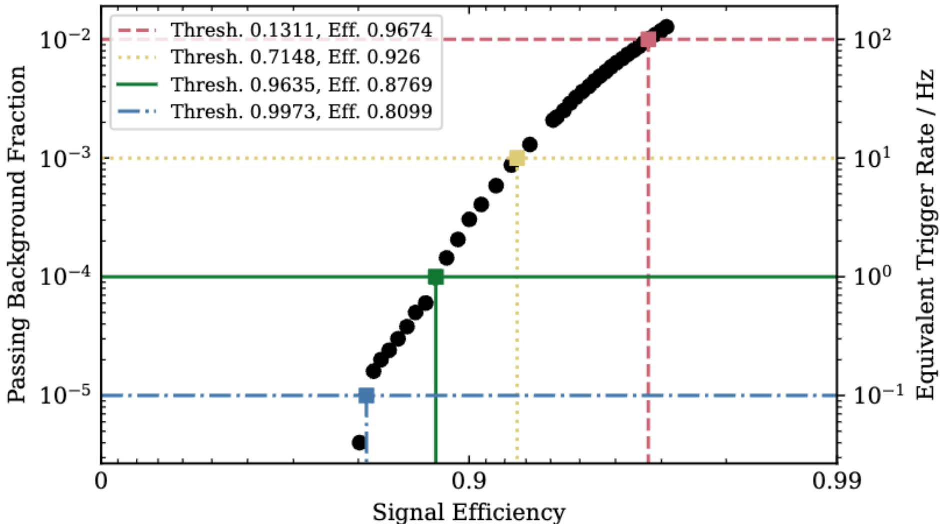

**doubling neutrino detection rate in IceCube-Gen2**

# Option 1: Second Stage Filter


Suitable network: Single CNN layer




Fits easily on an “old” Cyclone V FPGA


**CNN rejects 99.99% of noise at ~90% signal efficiency**

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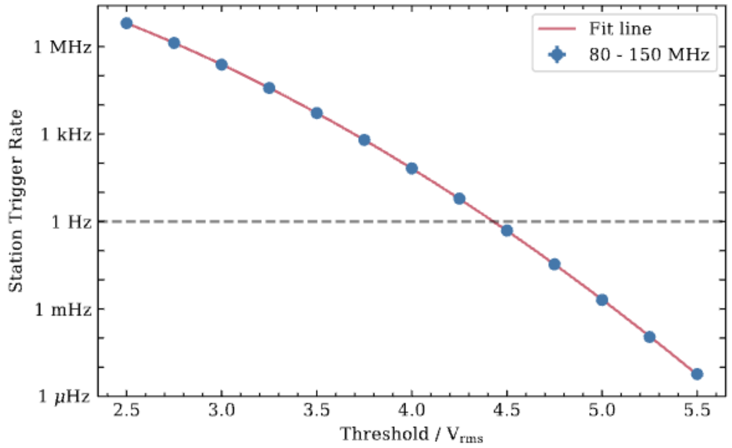


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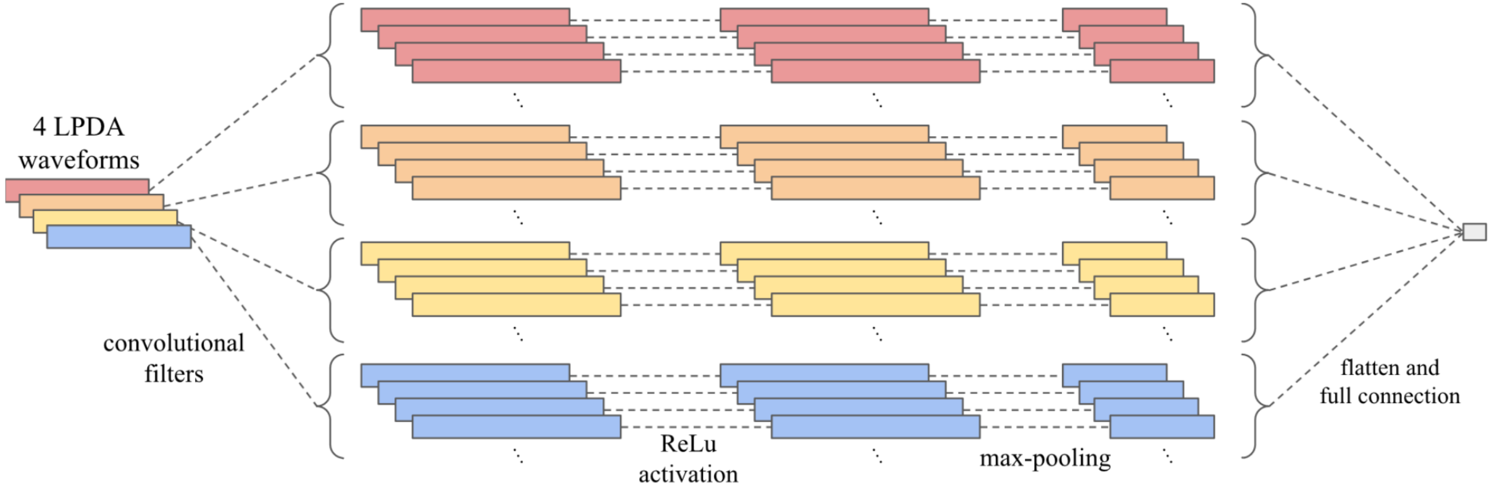


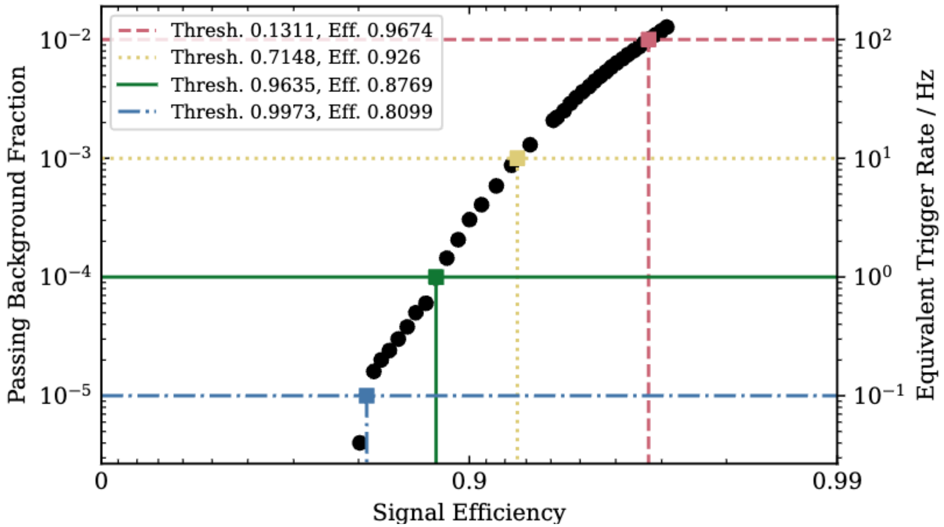


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**-> 1st FPGA Developers' Forum (FDF)**
**11-13 June at CERN cern.ch/fdf**

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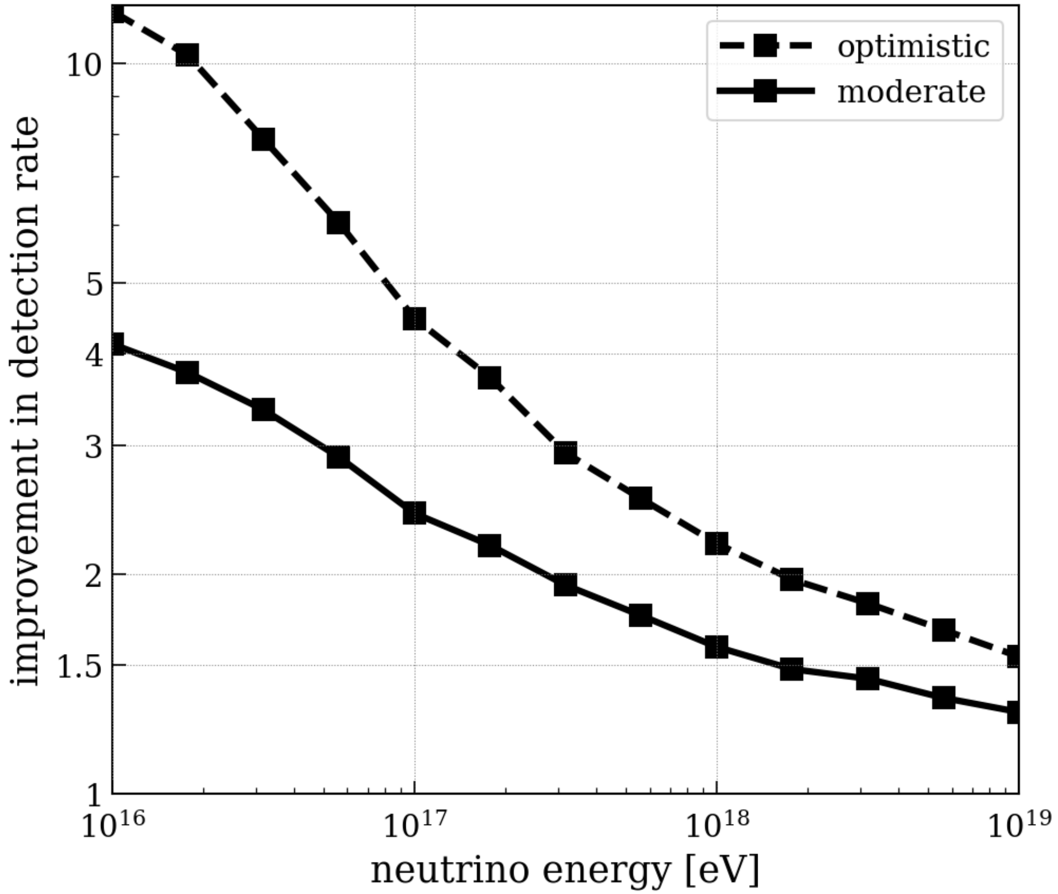
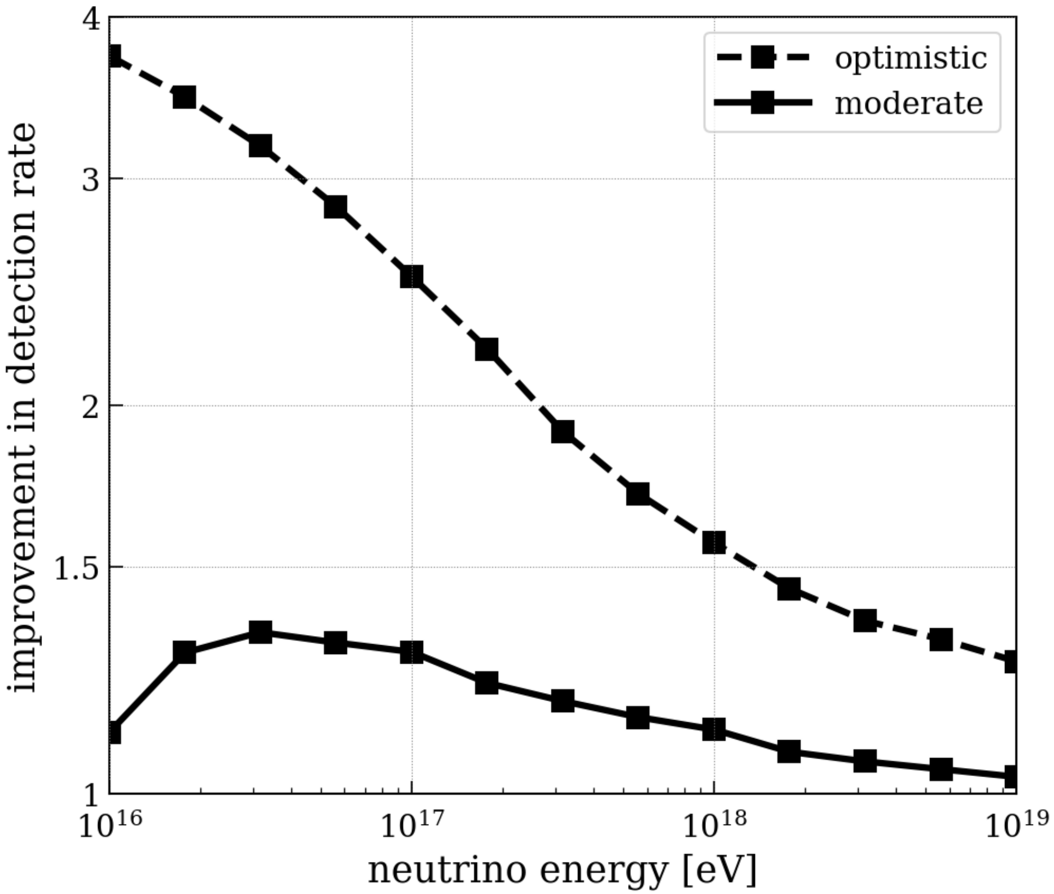
# Option 1: Second Stage Filter - Performance

**shallow**




**deep**



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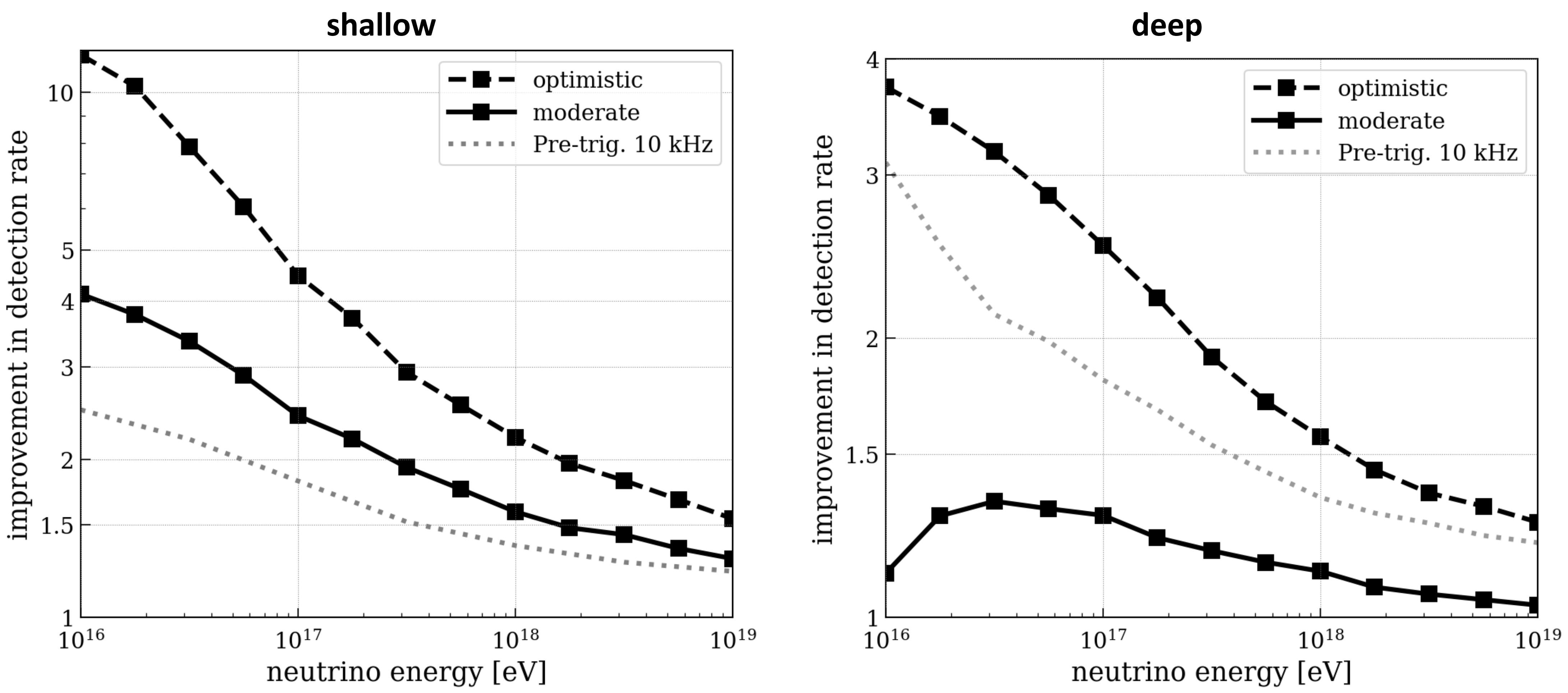




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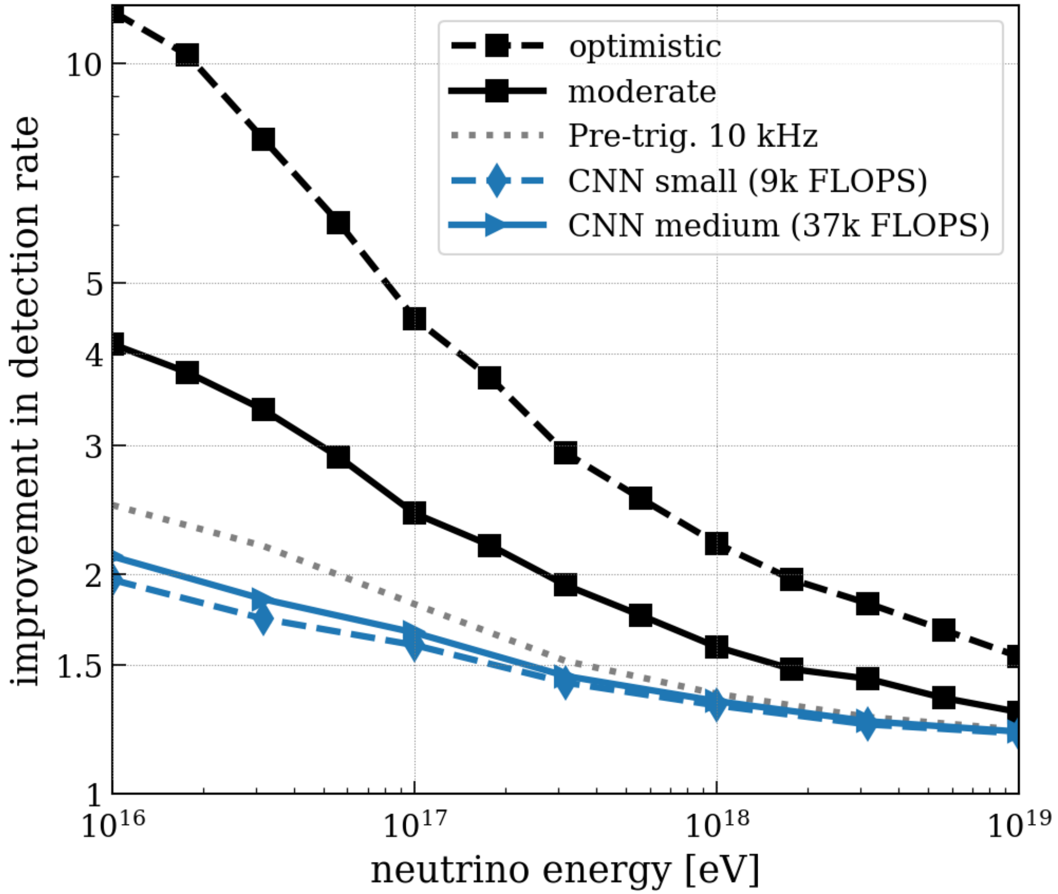


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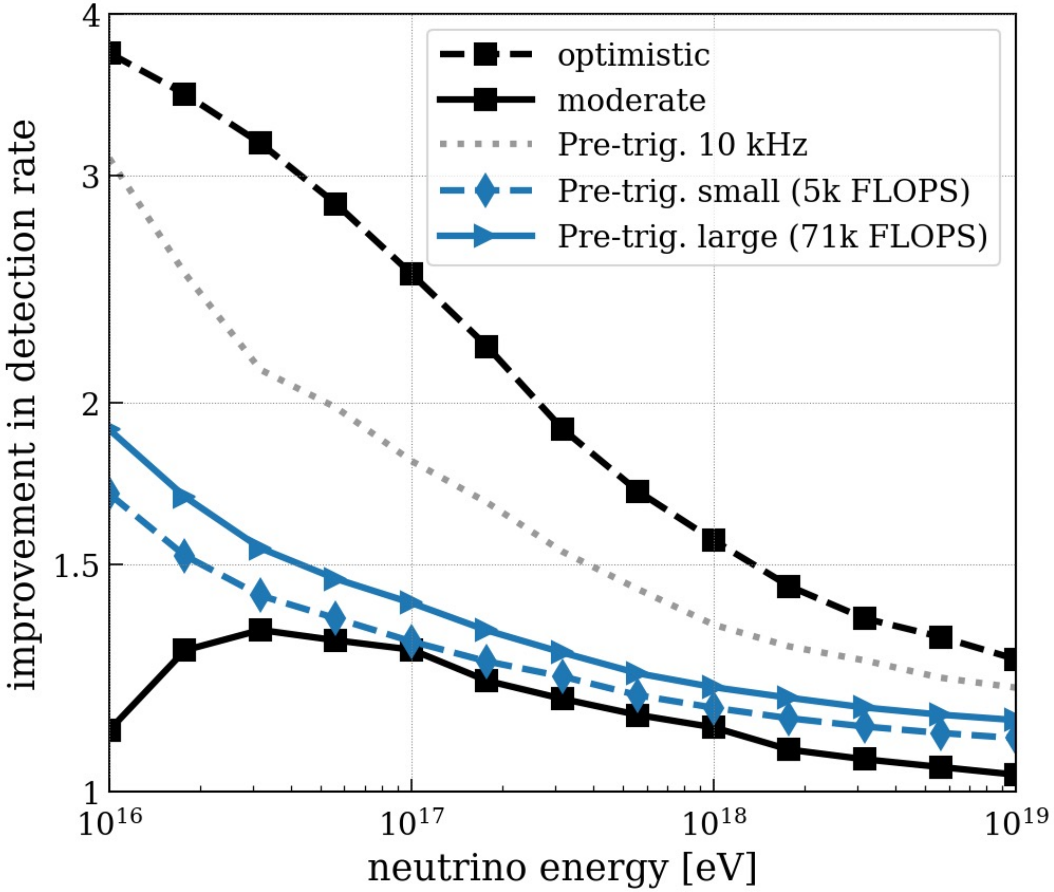
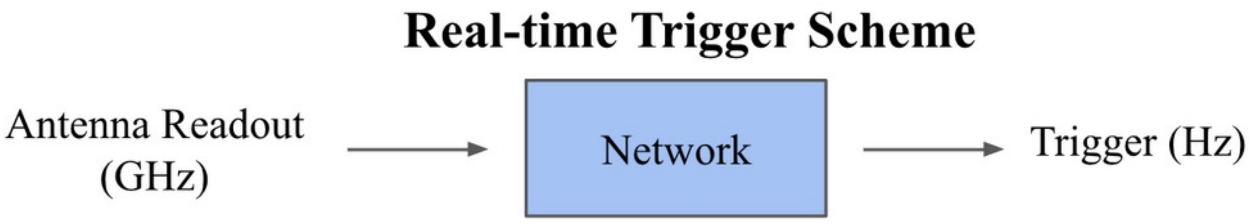
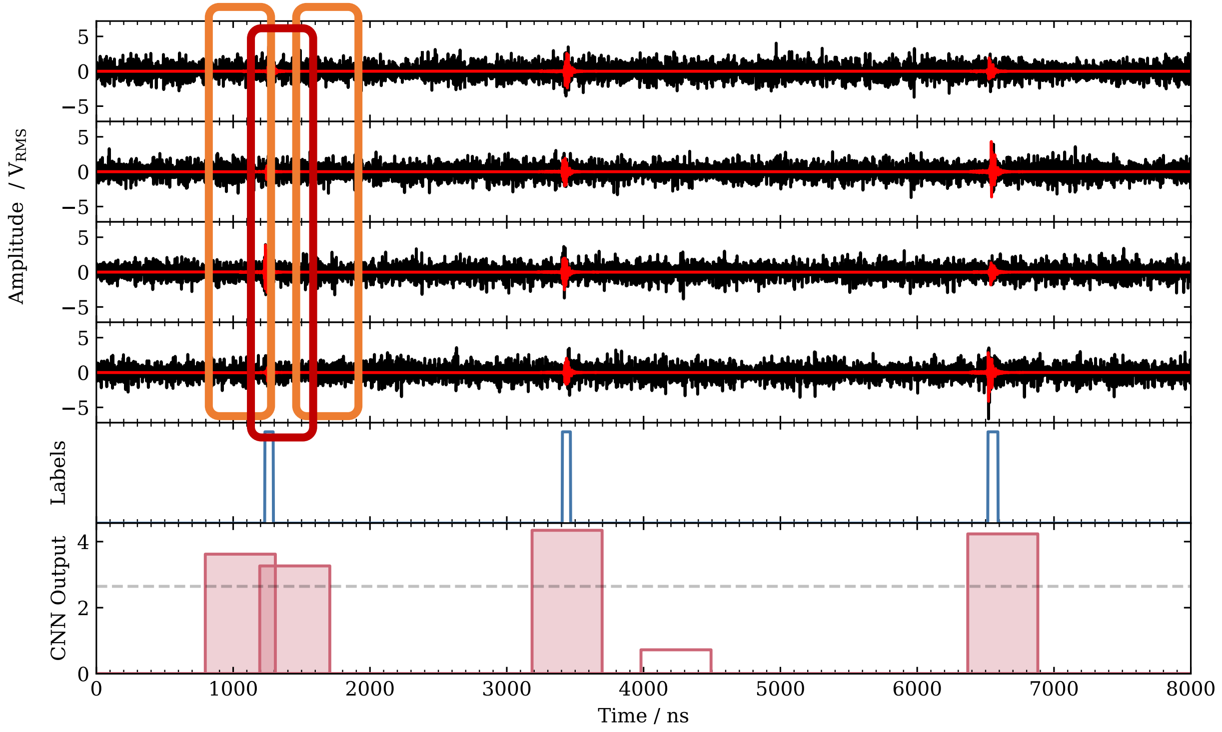


# Option 2: Continuous analysis of data stream




- Simplest option: Run CNN on overlapping chunks of data
- Trigger on CNN output
- Efficient FPGA implementation by calculating overlap only on last network layer





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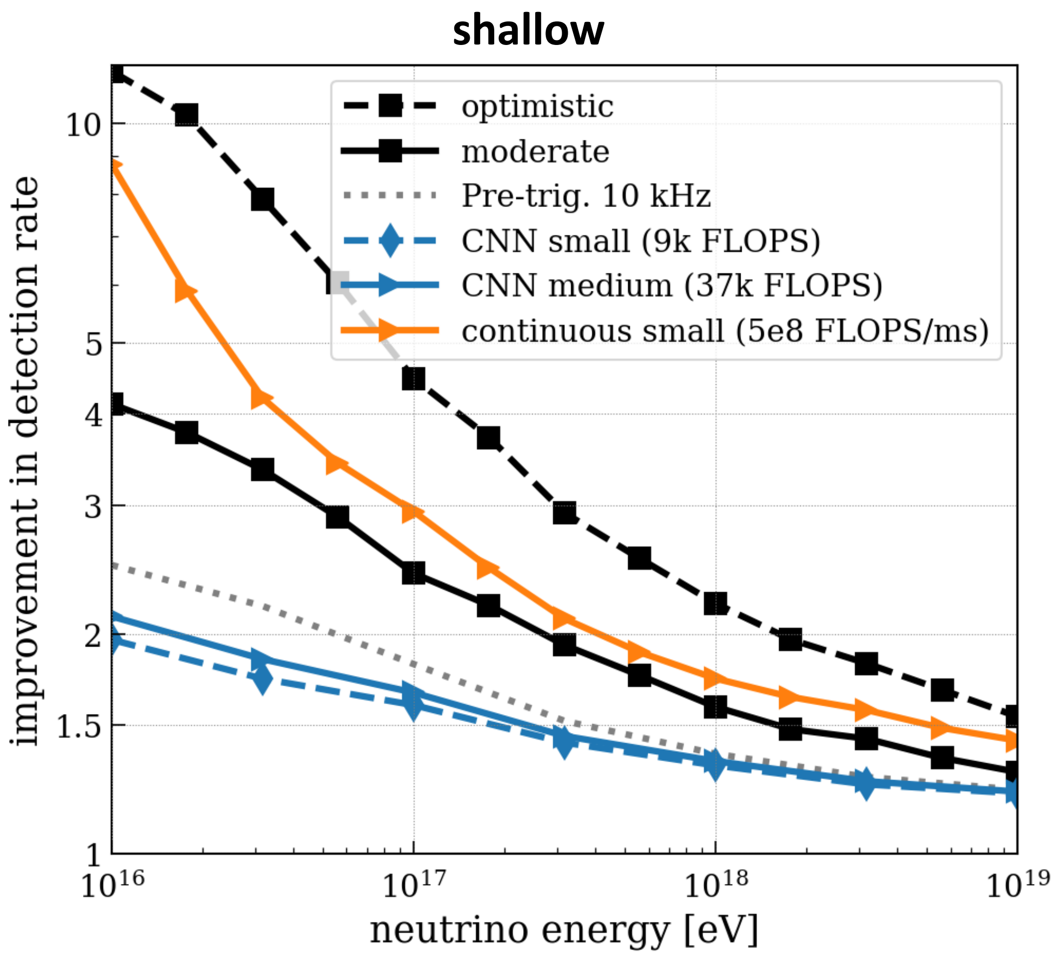
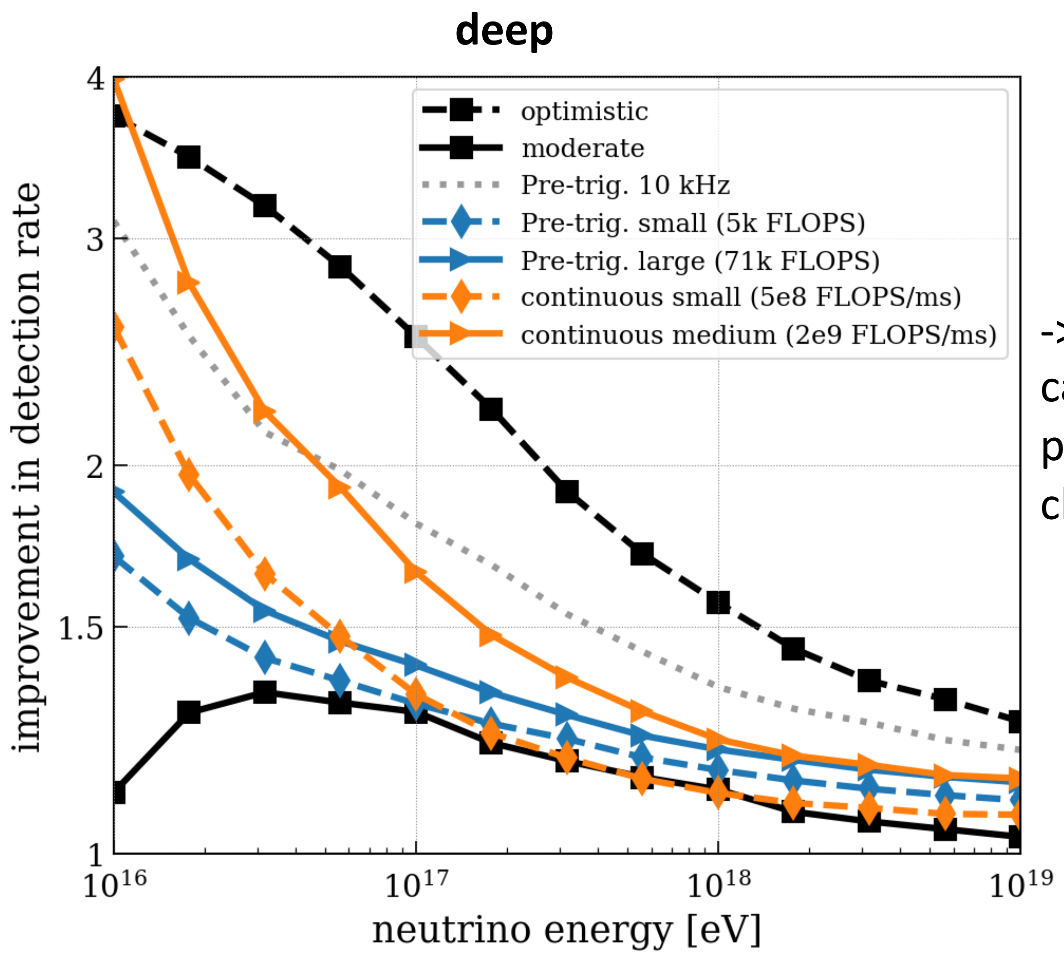


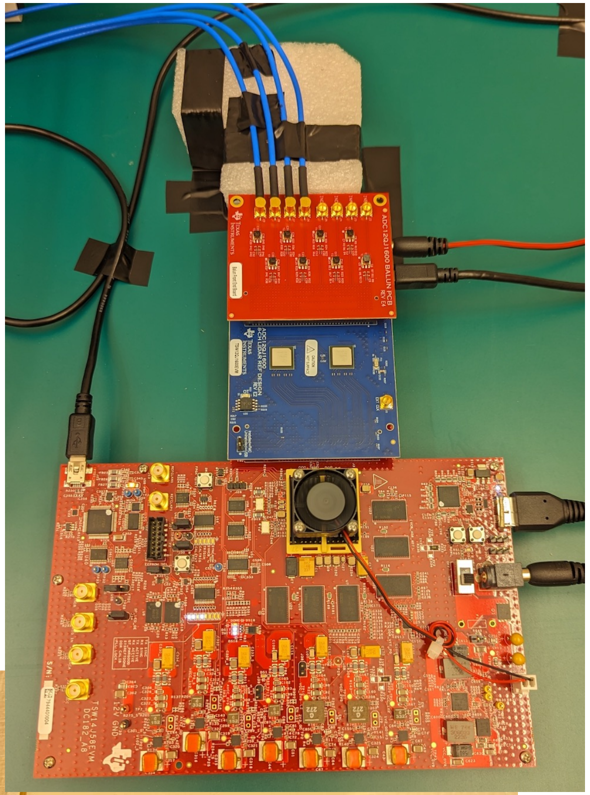



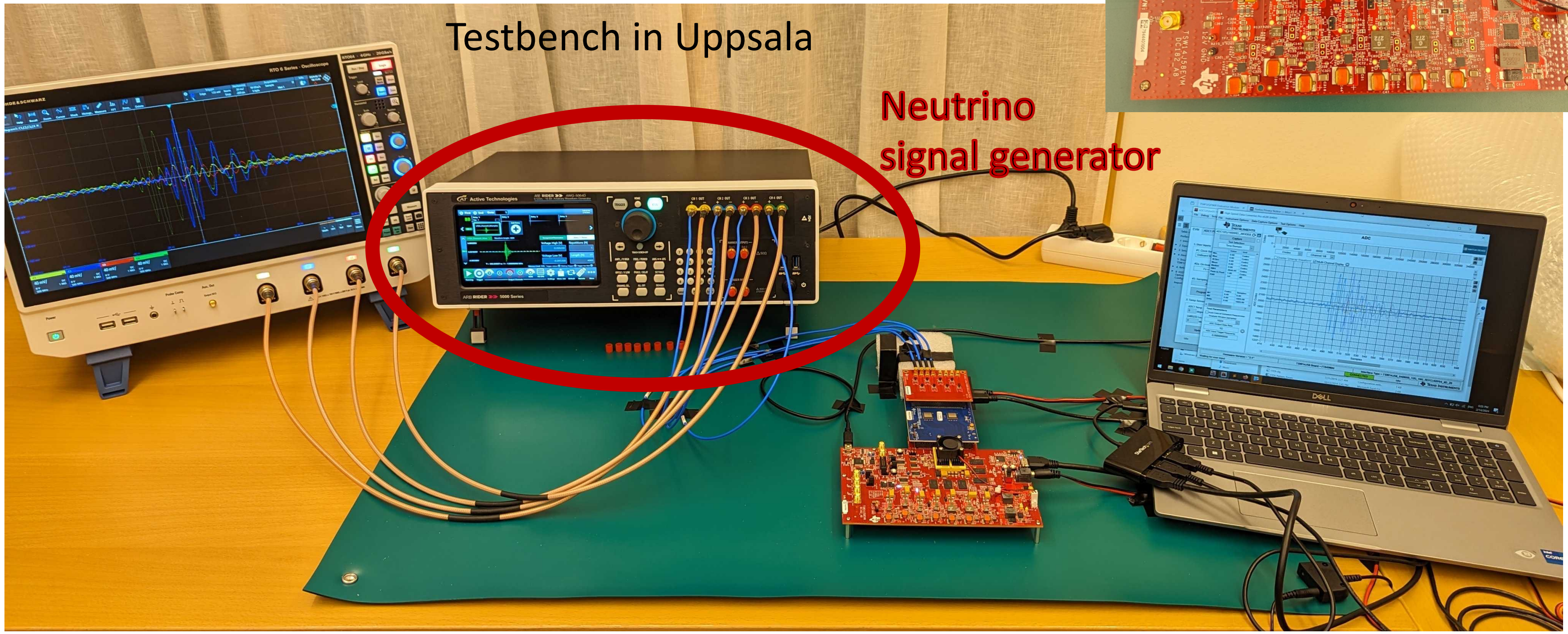

-> 1,000 calculations per FPGA clock cycle

**Performance already halfway between moderate and optimistic benchmark**

# New DAQ Development

- New ADC generation (JESD204B interface)
  - High speed and low power (~1GHz, 12bit at 0.5W/channel)
  - Simpler compared to custom ASICS of previous hardware
  - Better data quality and opportunities for advanced triggers
- Also looking into Neuromorphic Computing
  (with Tommaso Dorigo + Fredrik Sandin)





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**Main science objectives of UHE neutrino astronomy:**

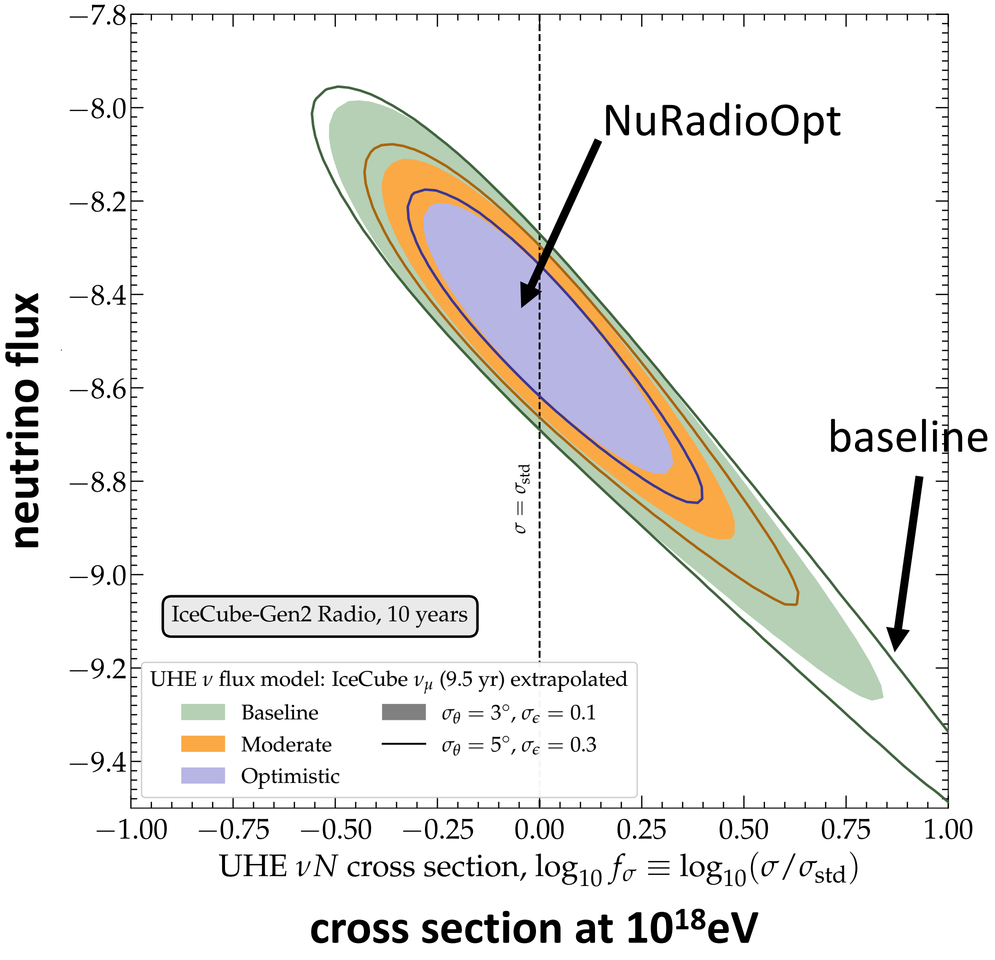
# Impact of NuRadioOpt

Neutrino-Nucleon Cross Section

Diffuse Flux

Point Sources

→ 3x more precise measurement




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

**Main science objectives of UHE neutrino astronomy:**

# Impact of NuRadioOpt

**Neutrino-Nucleon Cross Section** → 3x 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*

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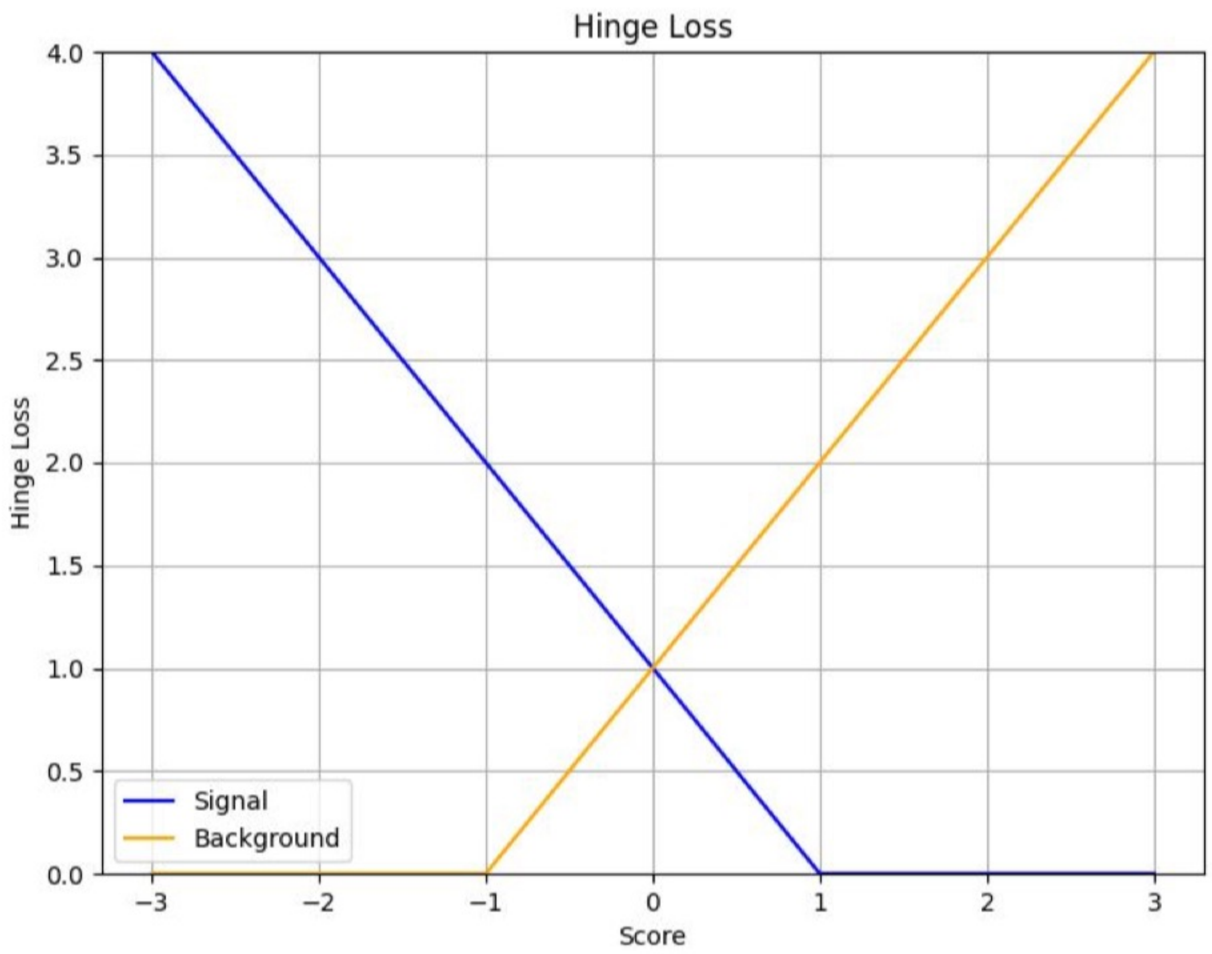
*D. F. G. Fiorillo, V. Valera, M. Bustamente, JCAP03(2023)026*

- **Improvements equivalent to building a more than three times larger detector** at essentially no additional costs
- NuRadioOpt timeline perfect for influencing IceCube-Gen2
- because we are already at the limit of logistical resources at the South Pole, **NuRadioOpt is the only option to accelerate UHE neutrino science in the next decade**

# Bonus slides

# Hinge Loss

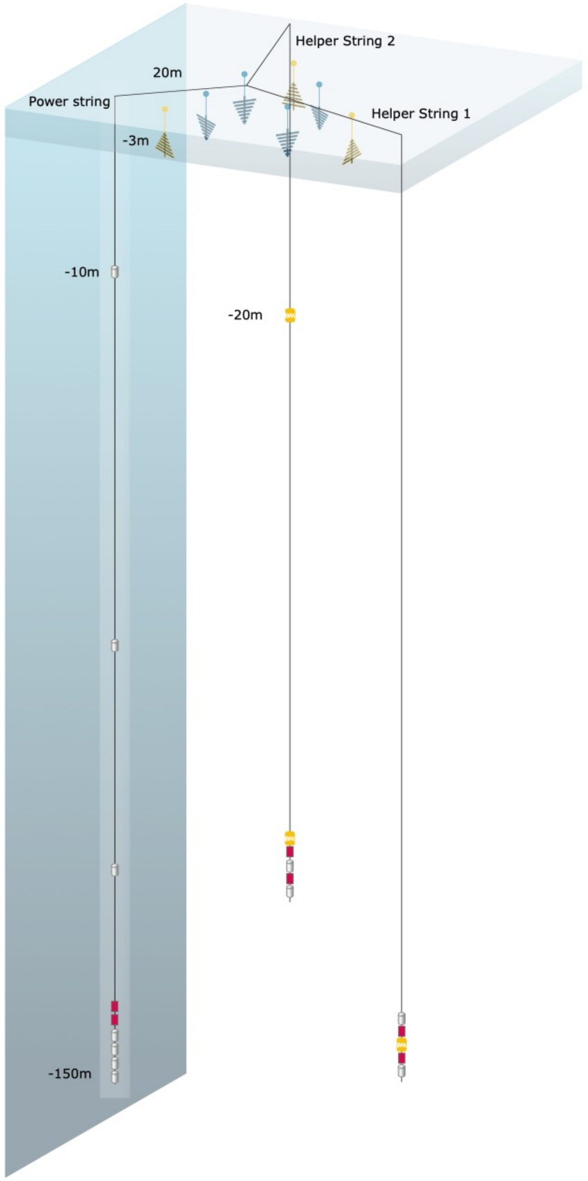
- No sigmoid activation
- Penalize (only) wrong predictions



# Objective 2: End-To-End Optimization

- Current status: Station layout has not been thoroughly optimized
  - because MC tools and reco algorithms were not available
  - because turnaround times are too large
  - scaling relations are insufficient

*-> changed with NuRadioMC/Reco*



# Objective 2: End-To-End Optimization

- Deep learning and differential programming can build an end-to-end optimization pipeline
- Direct optimization of science objective

detector parameters, e.g.,
- antenna positions
- antenna orientation

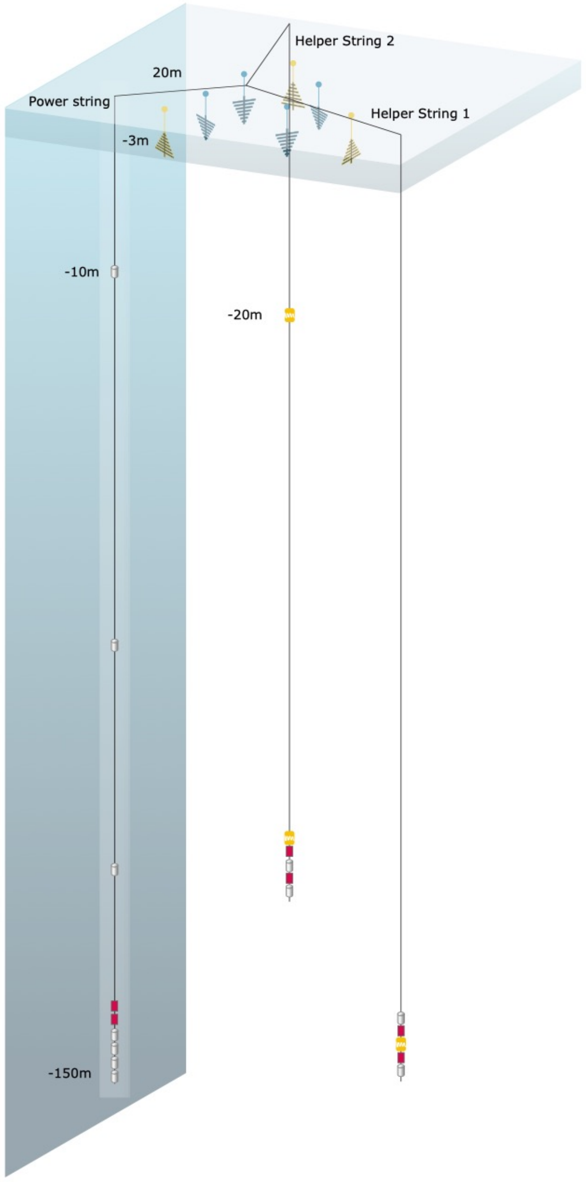
science output, e.g.,
- neutrino-nucleon cross-section
- source discovery
- flux measurement

automatic differentiation

Θ | MC simulation x reconstruction x analysis | f(Θ)

costs, engineering constraints

**→ Expected improvements: up to three times more precise measurement of neutrino direction and energy**



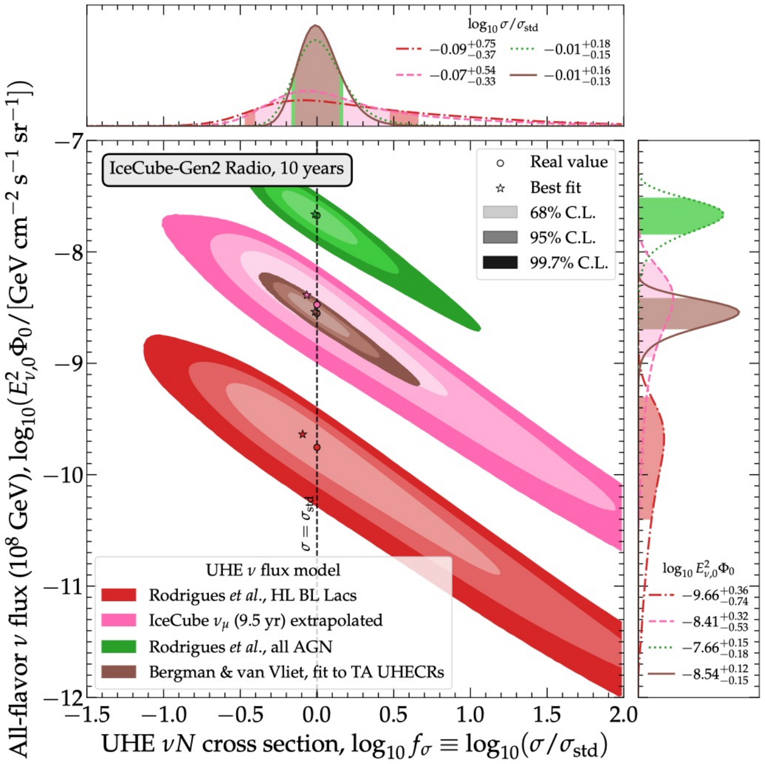
V. B. Valera, M. Bustamante and C. Glaser, JHEP 06 (2022) 105
also I. Esteban, S. Prohira, J. Beacom, Phys. Rev. D 106, 023021

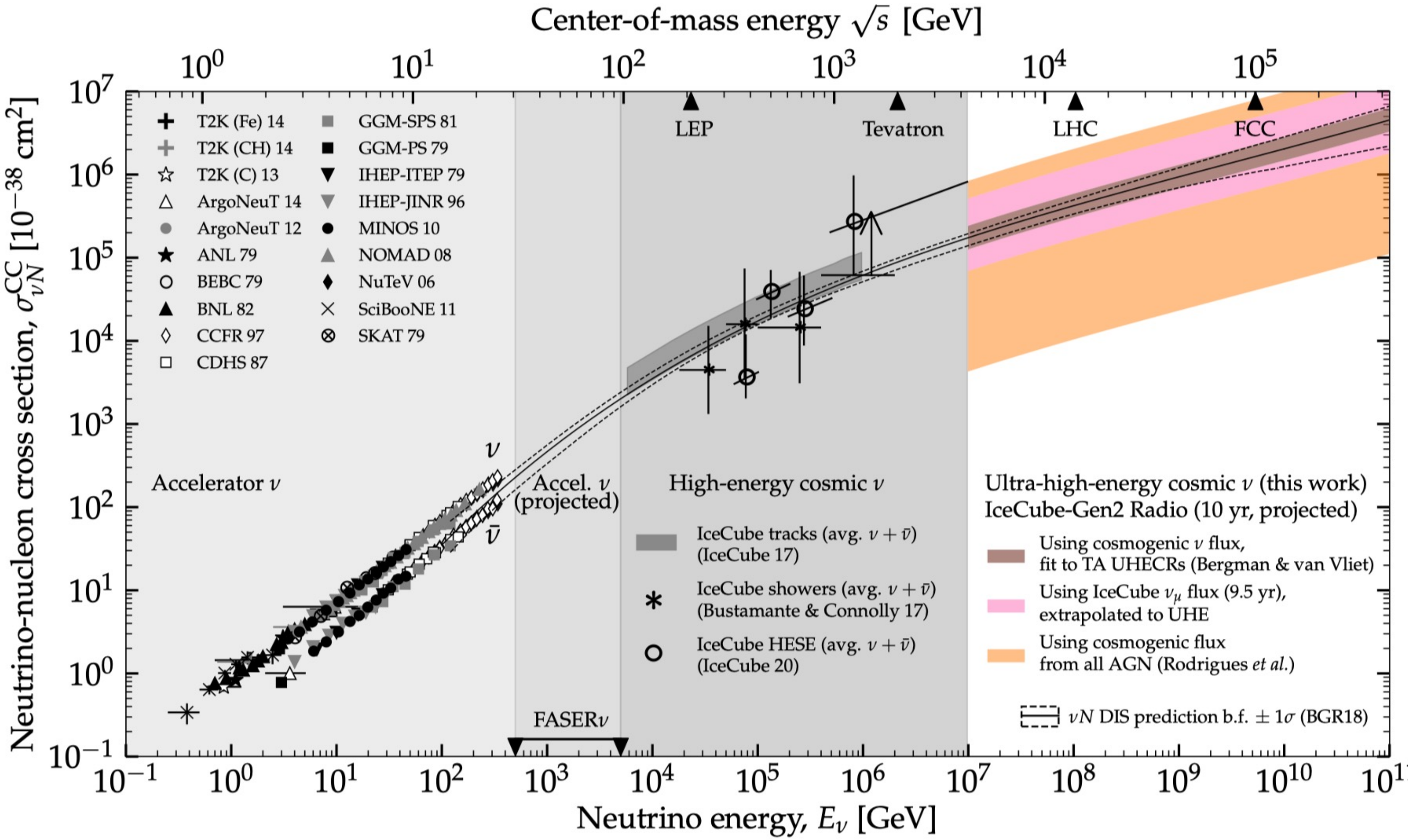
# Science Overview: Cross Section

- Sensitivity comes from Earth attenuation
  - Angular resolution important
  - Horizontal events important

$$N_\nu(E_\nu, \theta_z) \propto \Phi_\nu(E_\nu)\sigma(E_\nu)e^{-L(\theta_z)/L_{\nu N}(E_\nu,\theta_z)}$$

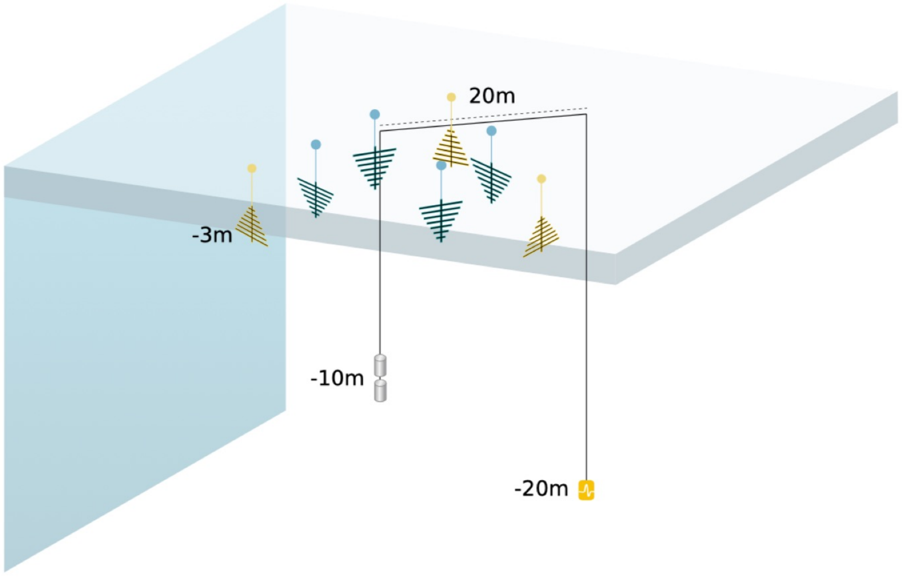
$$L_{\nu N} \equiv (\sigma n_N)^{-1}$$

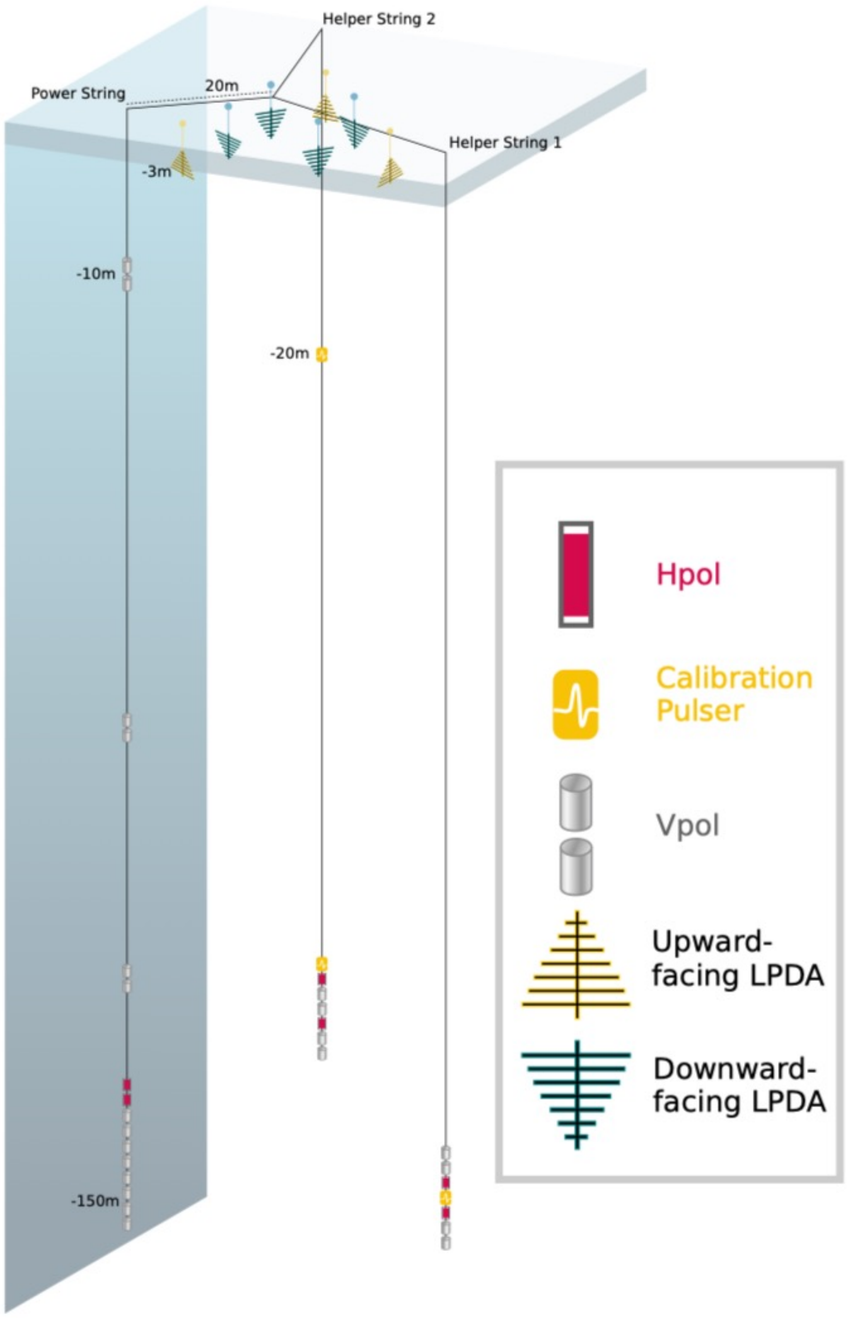


# Current Trigger

- Shallow:
  - high/low threshold crossing trigger for each LPDA
  - additional 2/4 time coincidence required
  - effective threshold ~4x Vrms
- Deep: Phased array
  - coherently summed waveforms to increase SNR by sqrt(n_antennas)
  - power integration trigger
  - effective threshold ~2-3* x Vrms




*: not a useful metric because dependent on bandwidth and group delay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