UPPSALA
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Advancing Ultra-High Energy Neutrino Astronomy through Deep Learning and Differential Programming

Christian Glaser

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credit: Nils Heyer

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European Research Council
Established by the European Commission

Swedish Research Council

CARL TRYGGERS STIFTELSE
FÖR VETENSKAPLIG FORSKNING

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

The need to detect UHE (E_ν>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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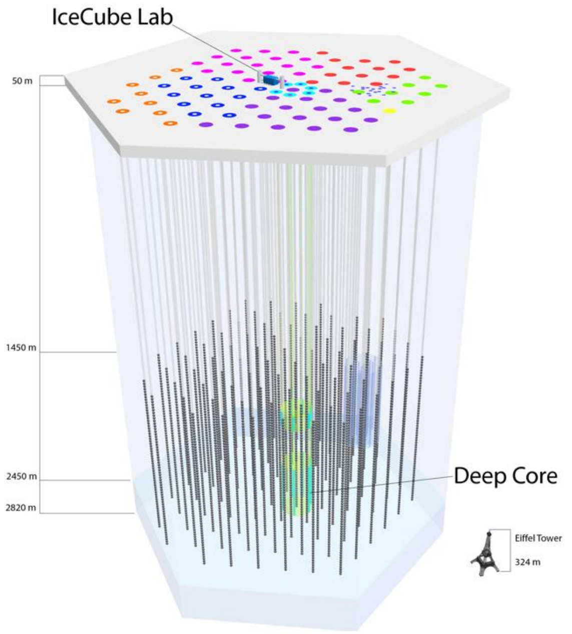
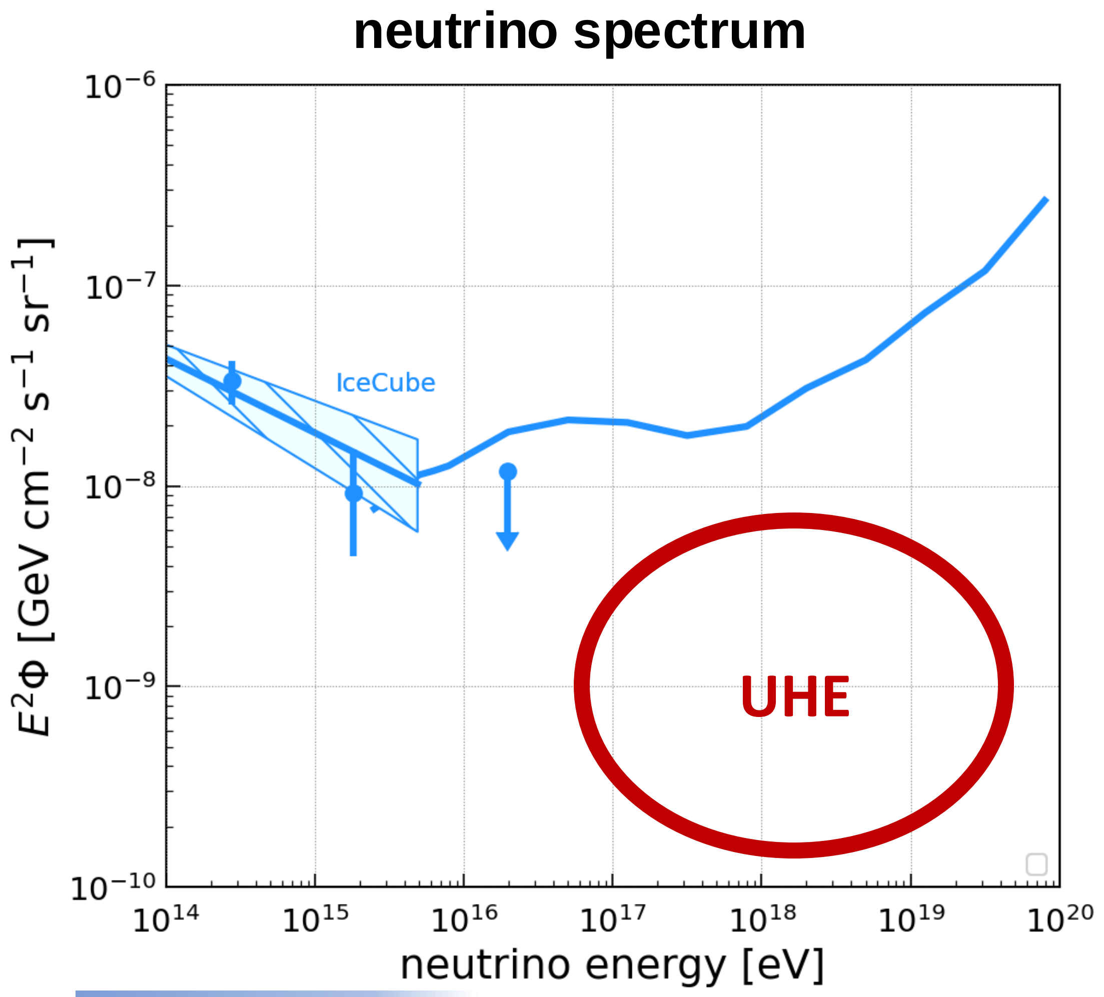
TeV – PeV energies

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





optical/IceCube

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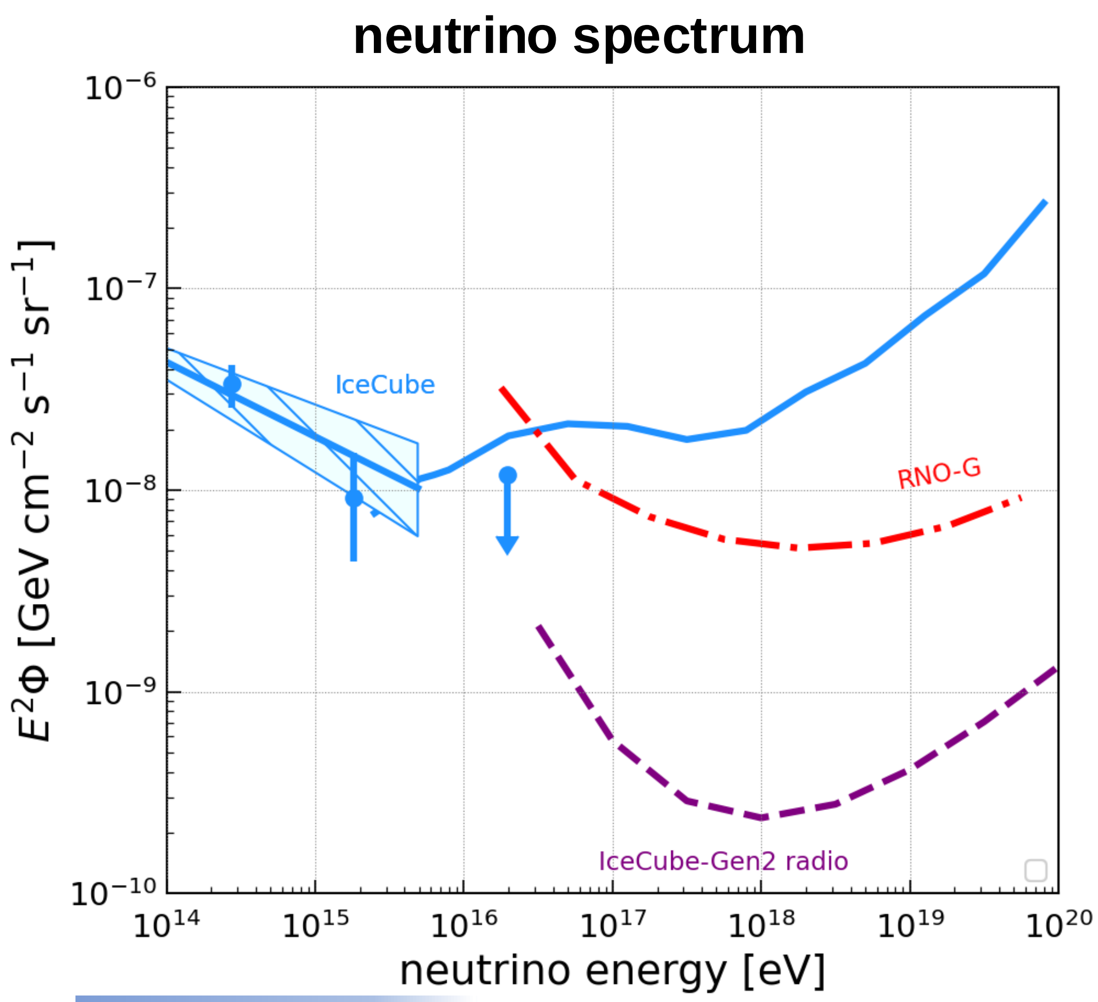
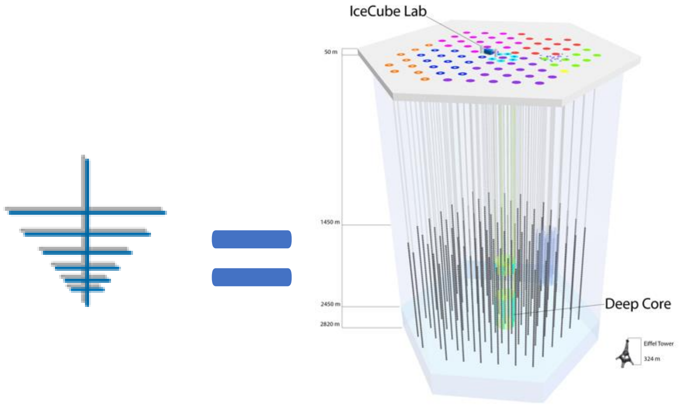
EeV

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



optical/IceCube

radio



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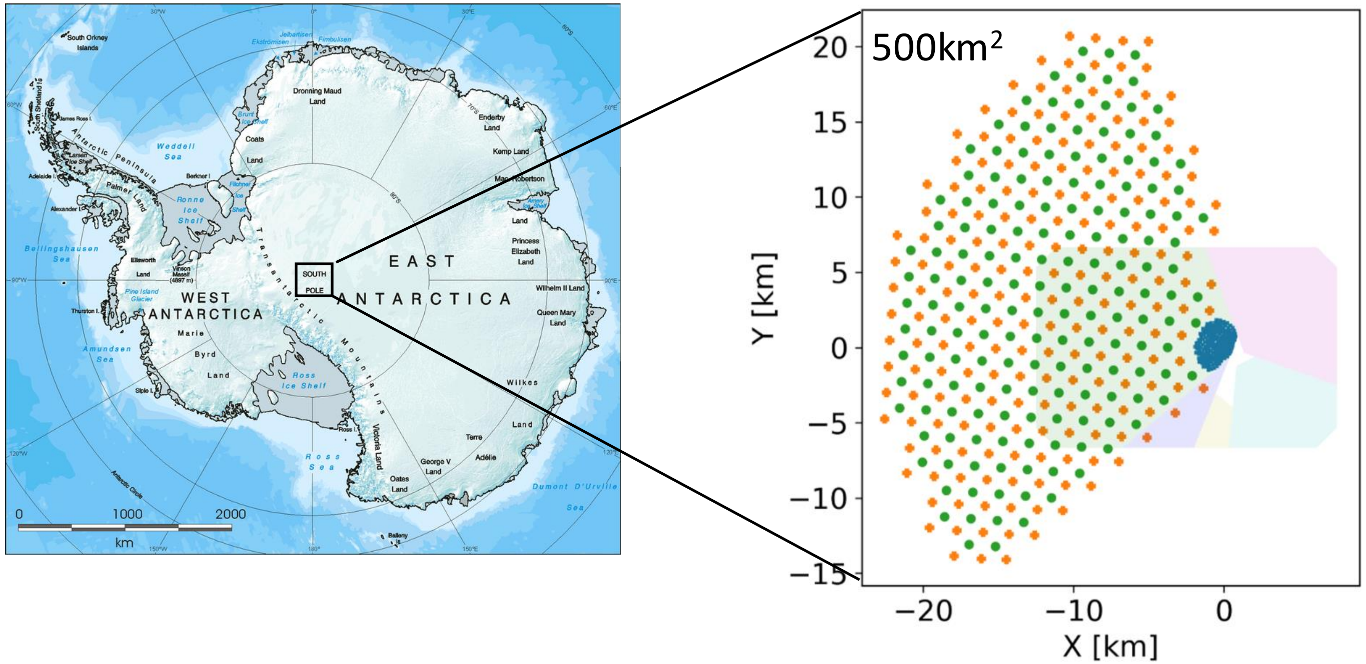
IceCube-Gen2 radio



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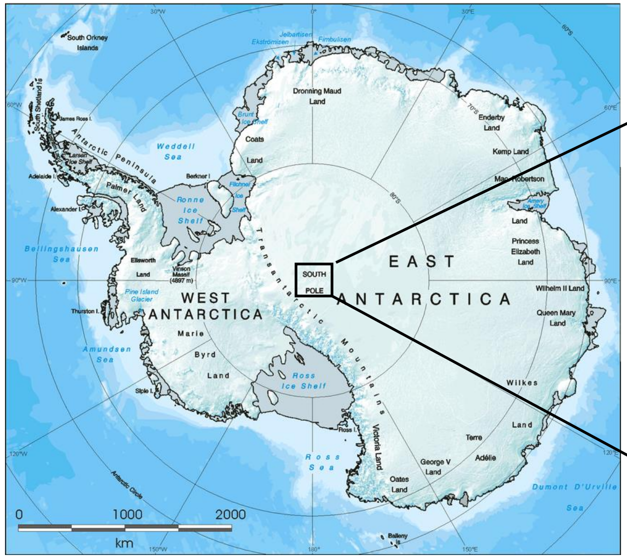

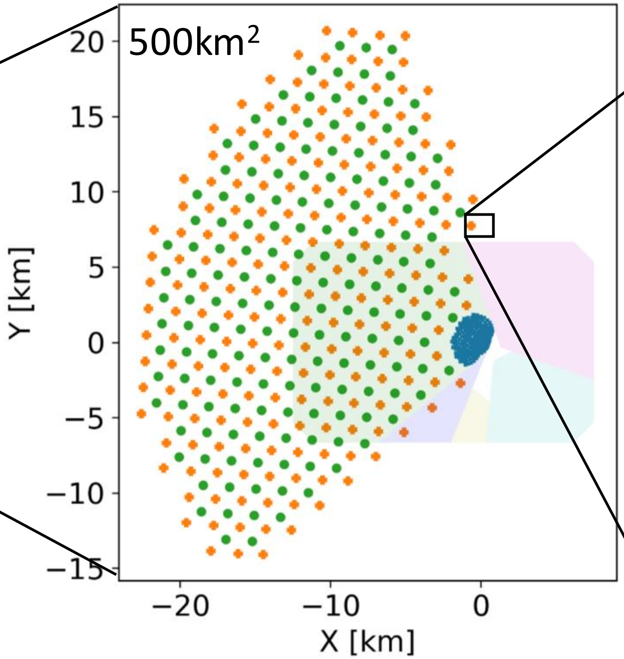

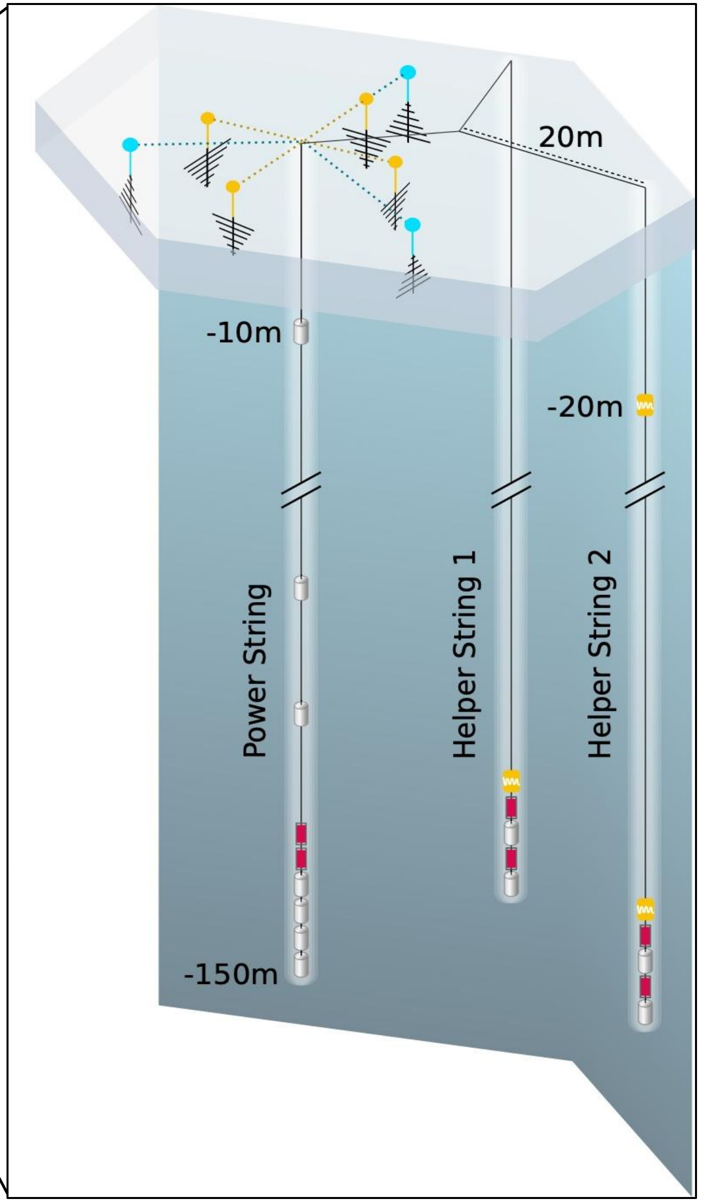

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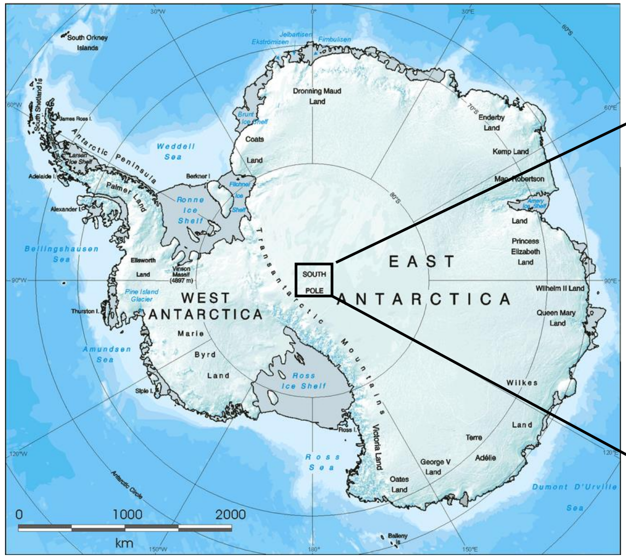
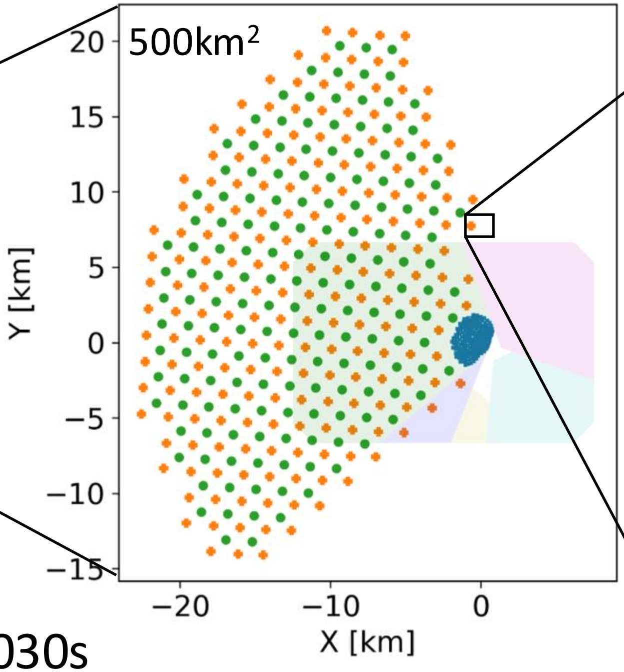
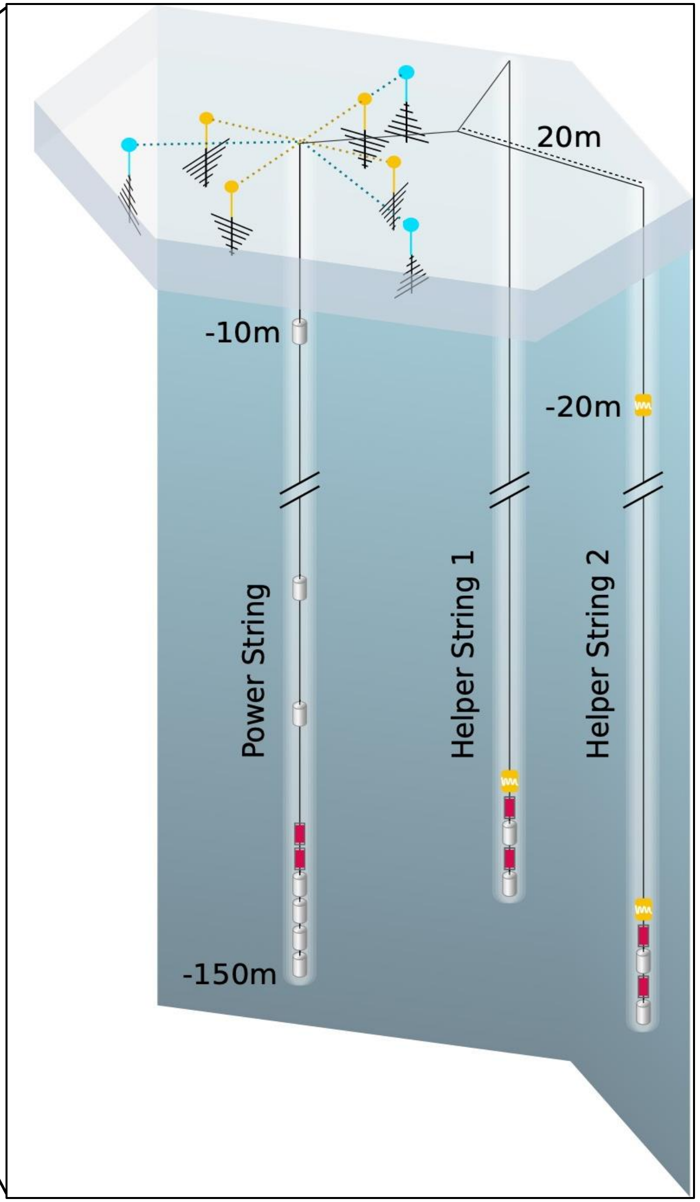
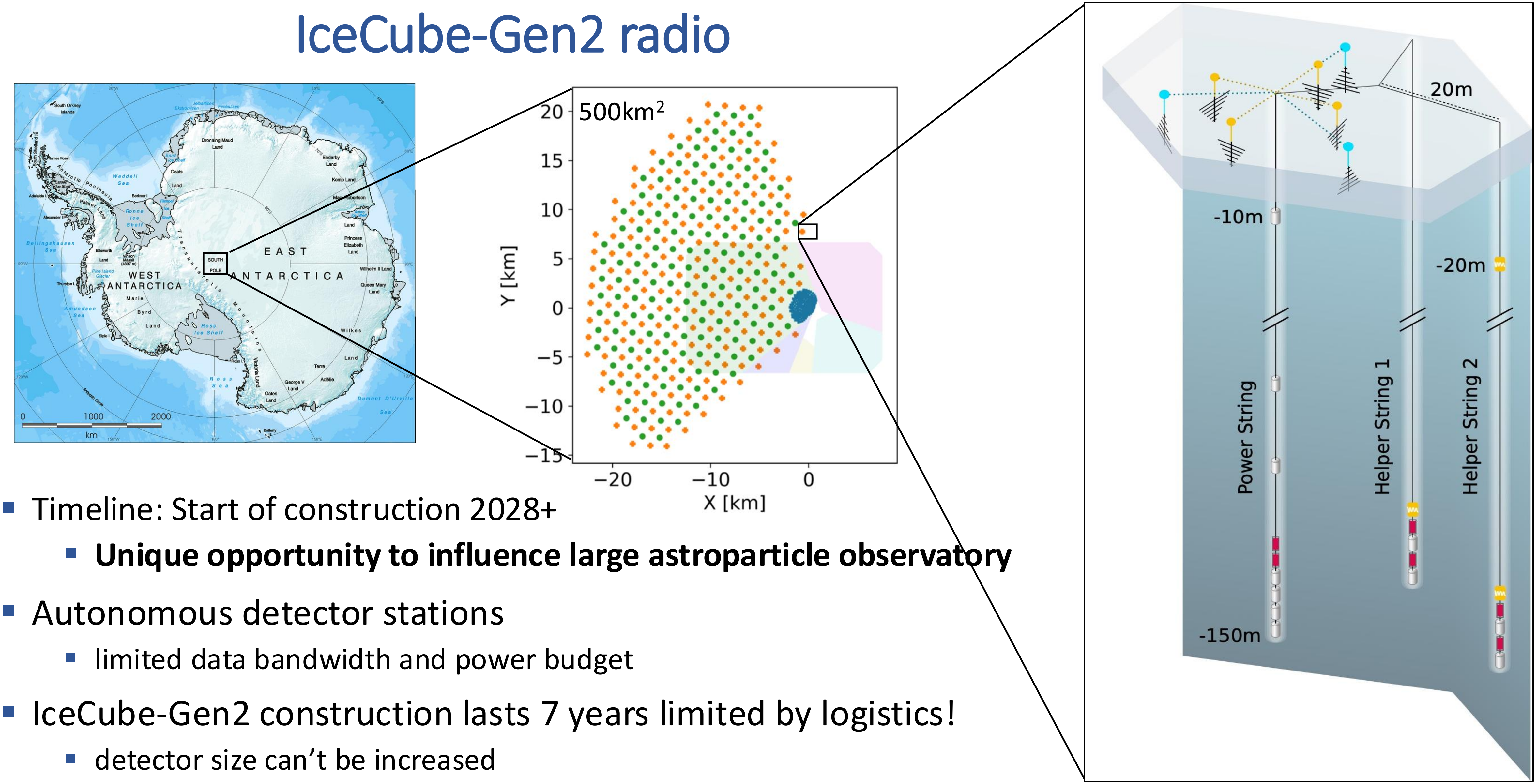






- Timeline: Start of construction 2030s
  - **Unique opportunity to influence large astroparticle observatory**

IceCube-Gen2 radio

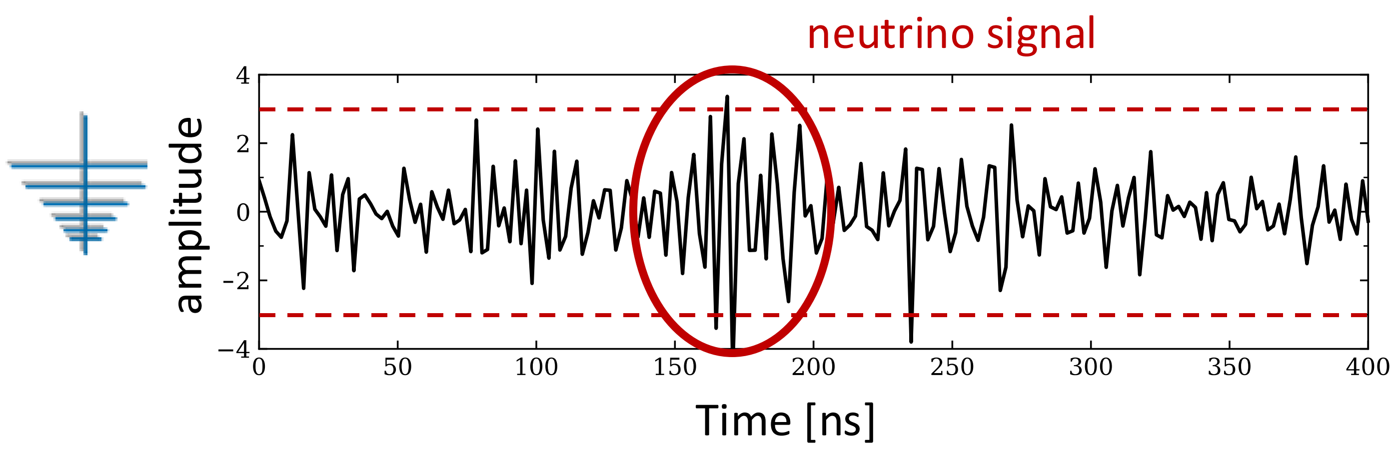


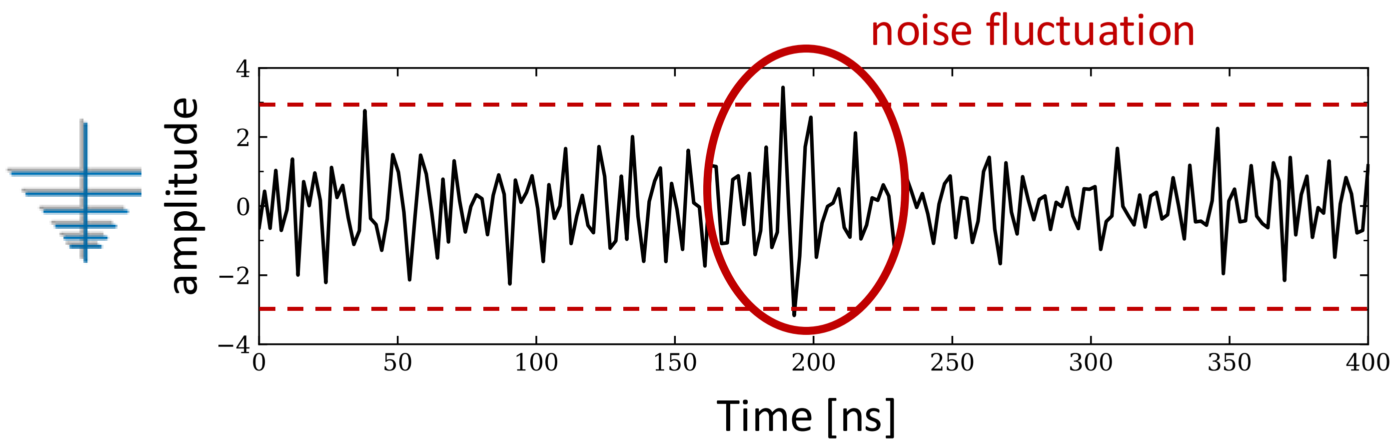
- Timeline: Start of construction 2028+
  - **Unique opportunity to influence large astroparticle observatory**
- Autonomous detector stations
  - limited data bandwidth and power budget
- IceCube-Gen2 construction lasts 7 years limited by logistics!
  - detector size can't be increased

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

Deep-Learning-Based Trigger

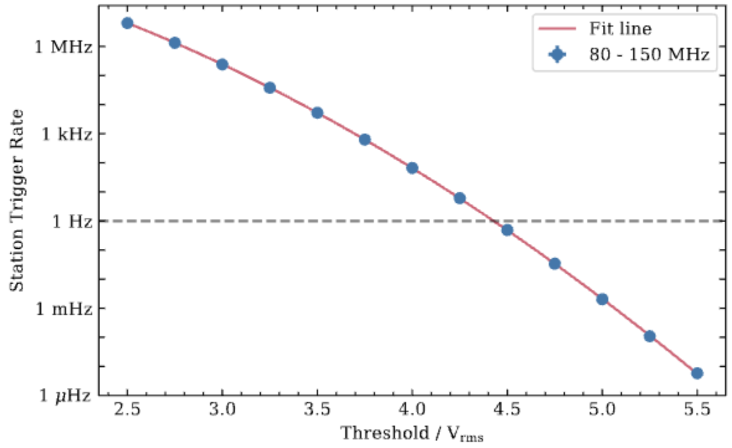
- Data can't be stored continuously
- Current state of the art: Threshold-based trigger
  - Unavoidable thermal noise fluctuations dominate trigger
  - Thresholds need to be high enough to limit trigger rate on thermal noise



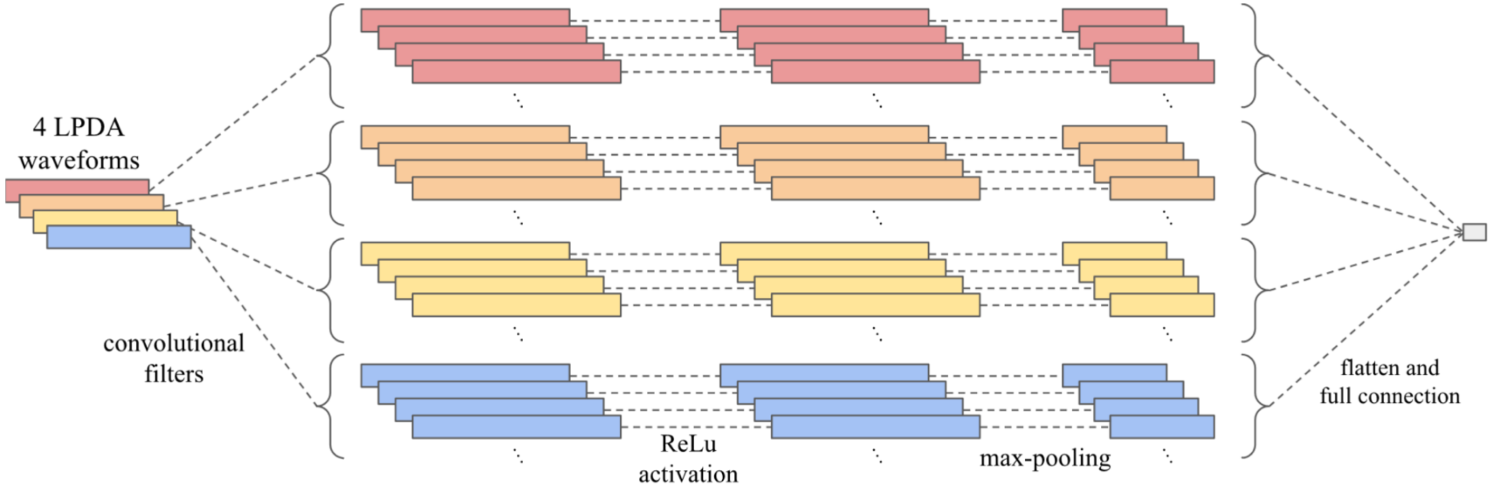


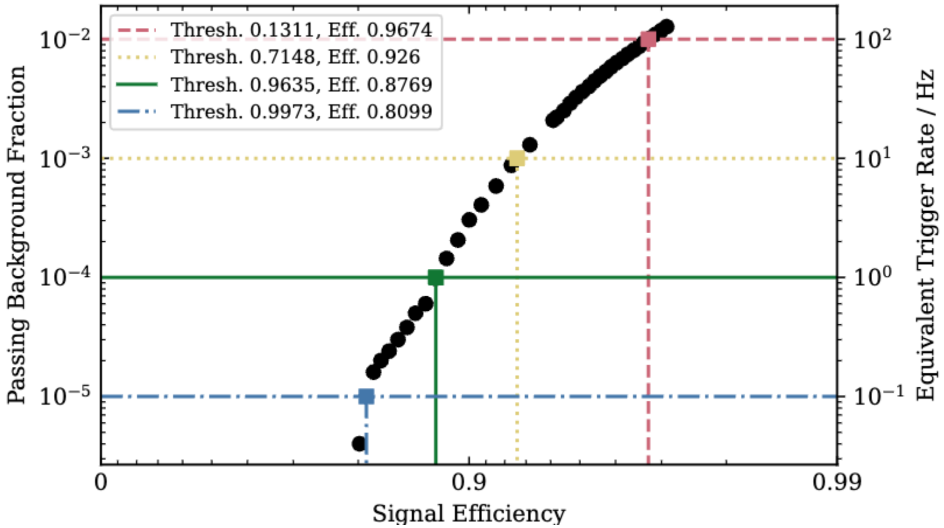
- **Huge potential of improvement:**
  - offline analysis: thermal noise can be rejected with high efficiency
  - Neural networks are very good at classification tasks
  - Proof-of-concept study
    ARIANNA collab. (… C. Glaser, …) , JINST 2022

Option 1: Second Stage Filter



Suitable network: Single CNN layer



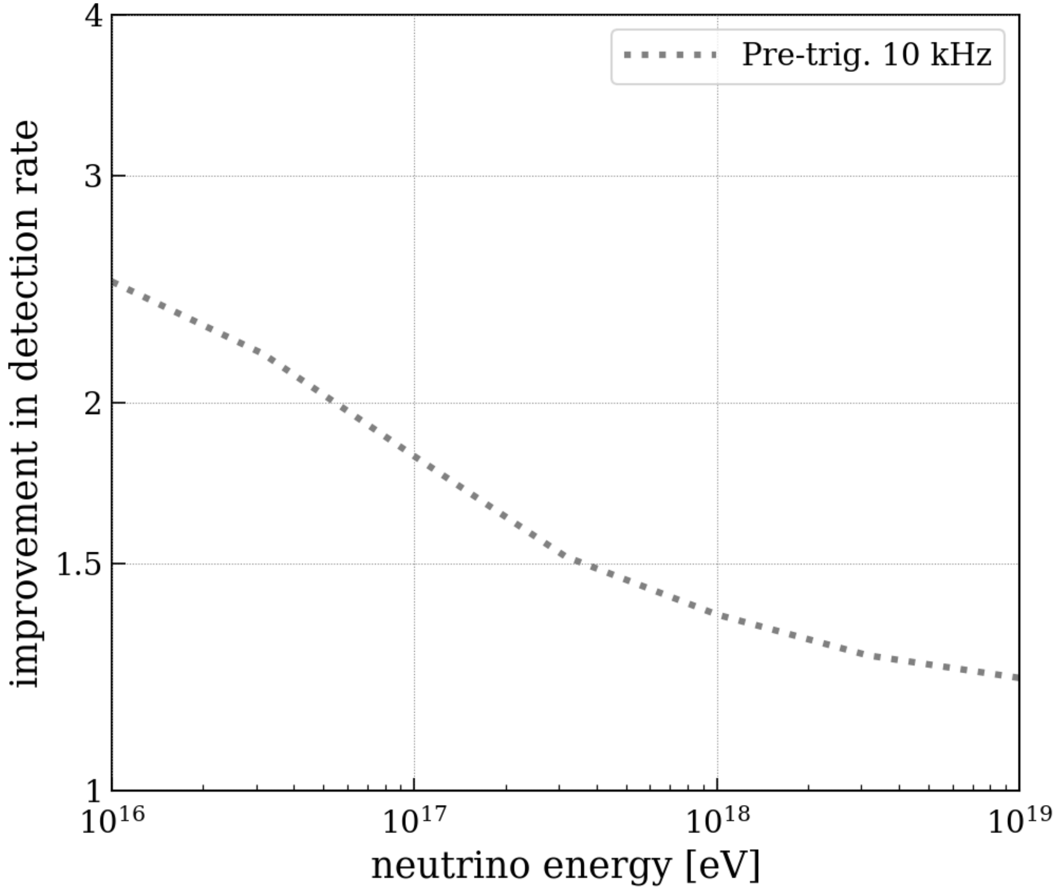


Fits easily on an “old” Cyclone V FPGA

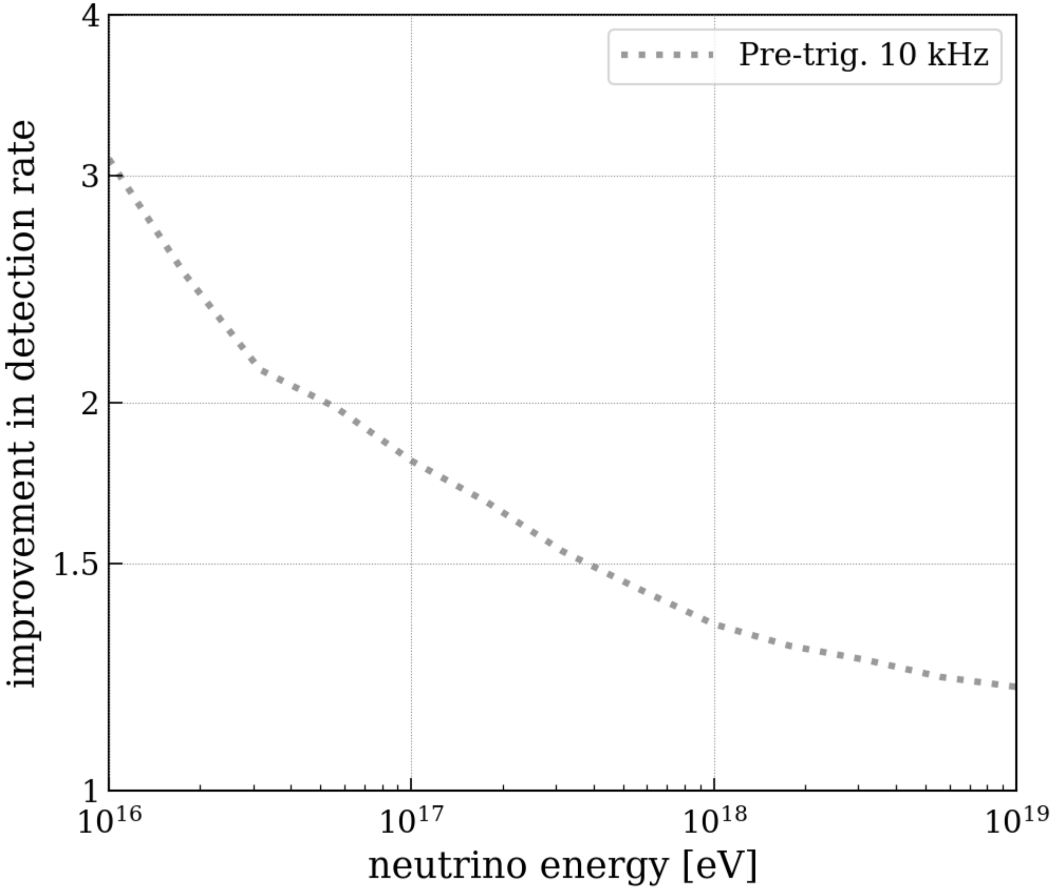
CNN rejects 99.99% of noise at ~90% signal efficiency

Option 1: Second Stage Filter - Performance

shallow



deep



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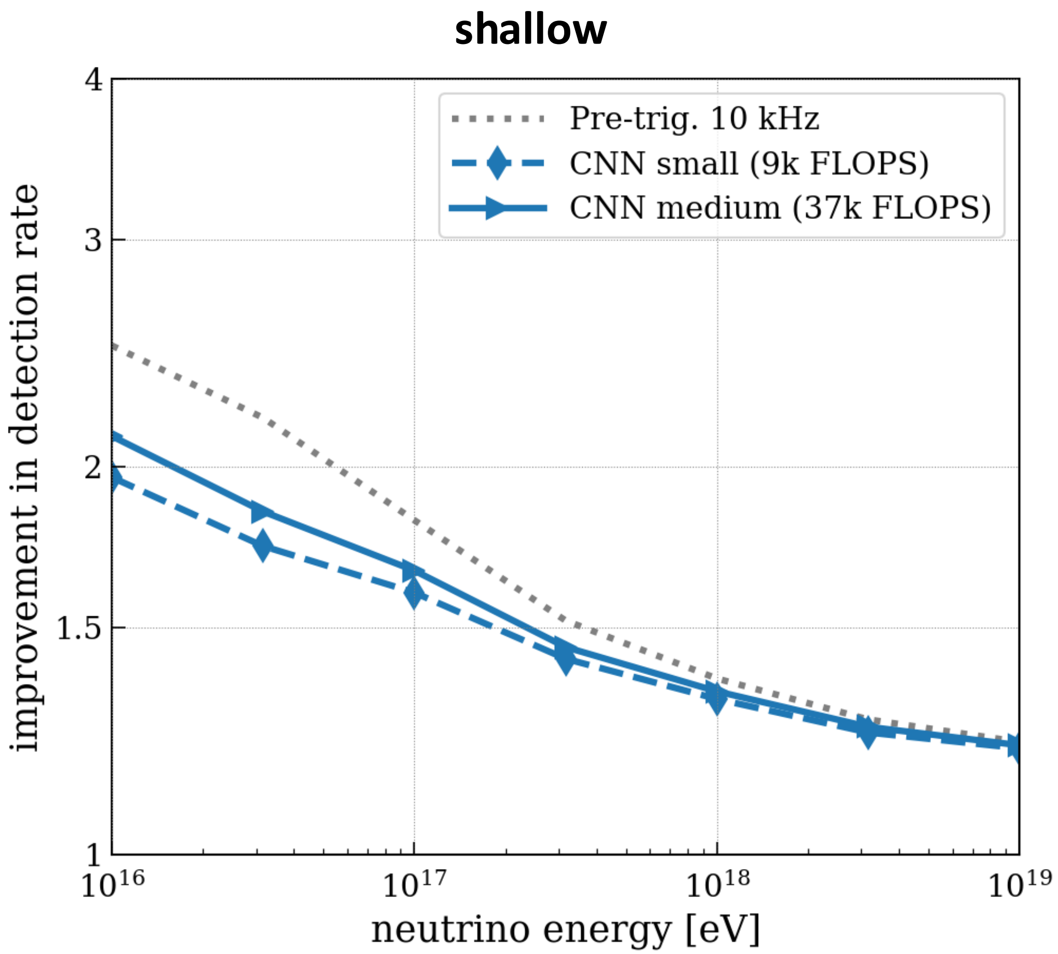
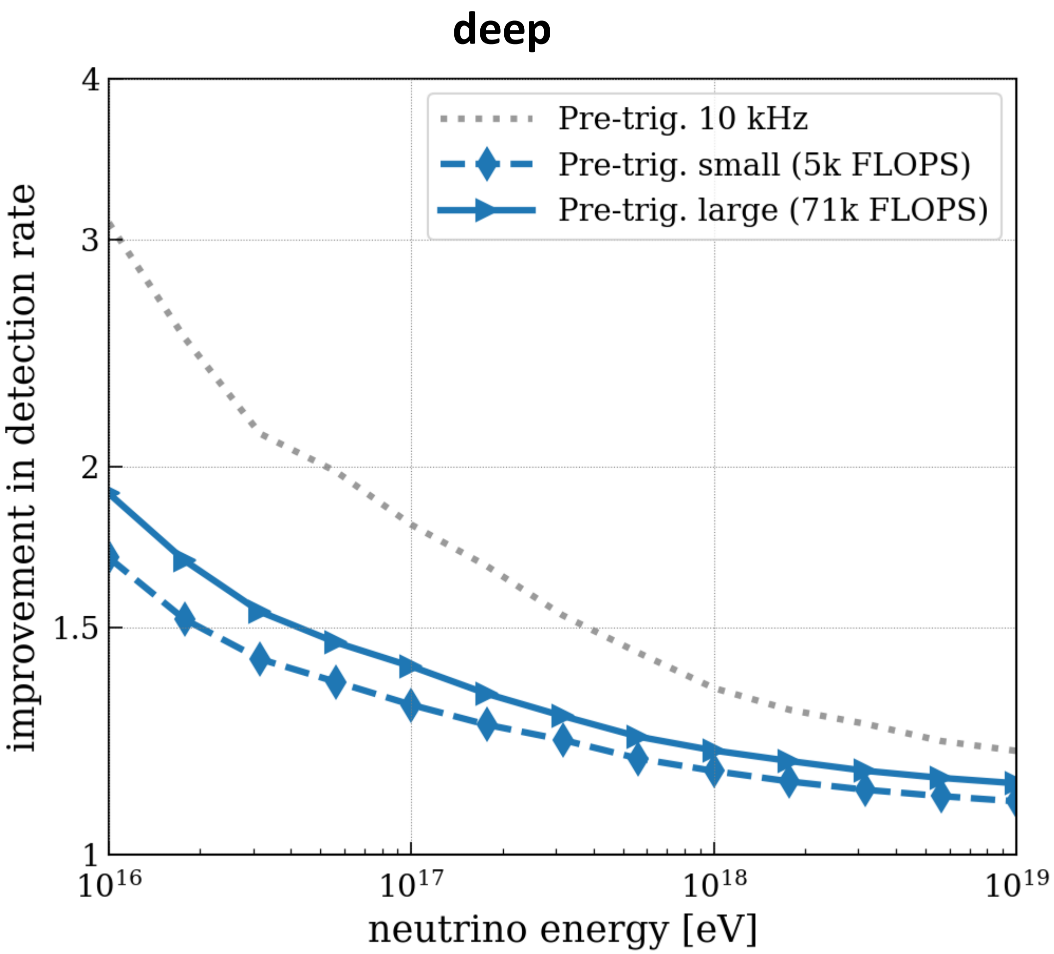
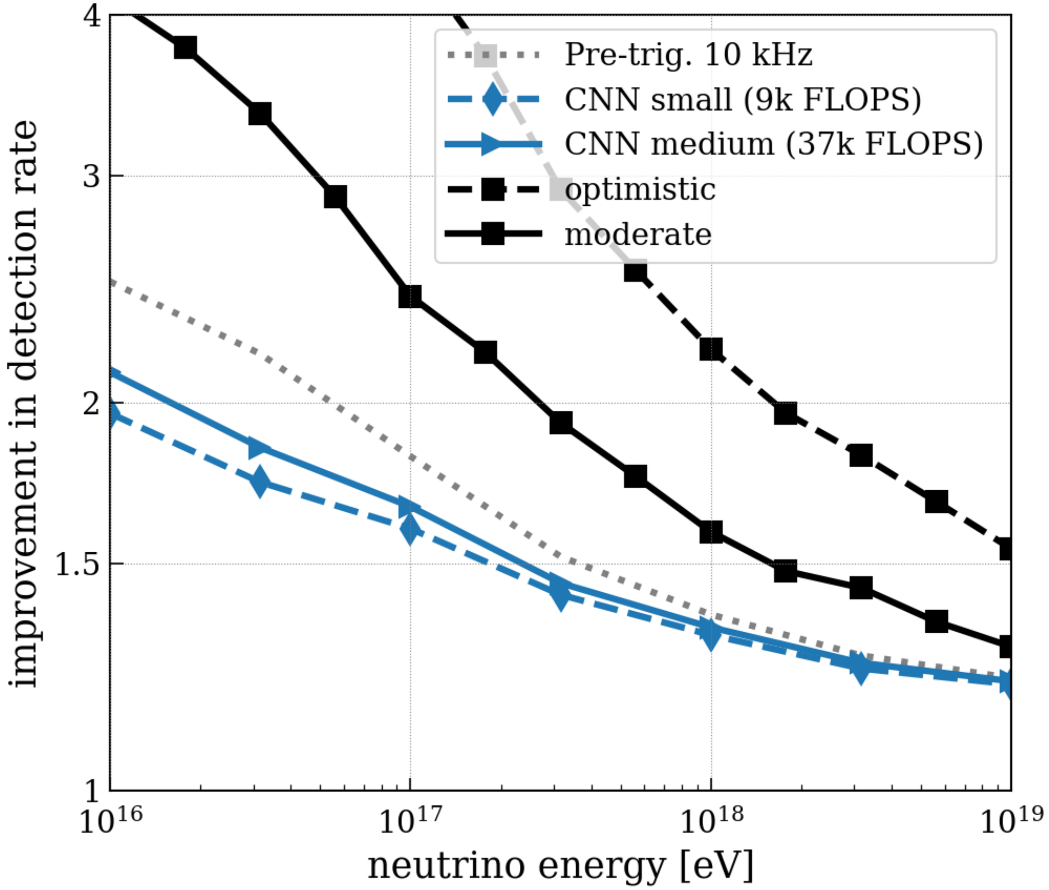




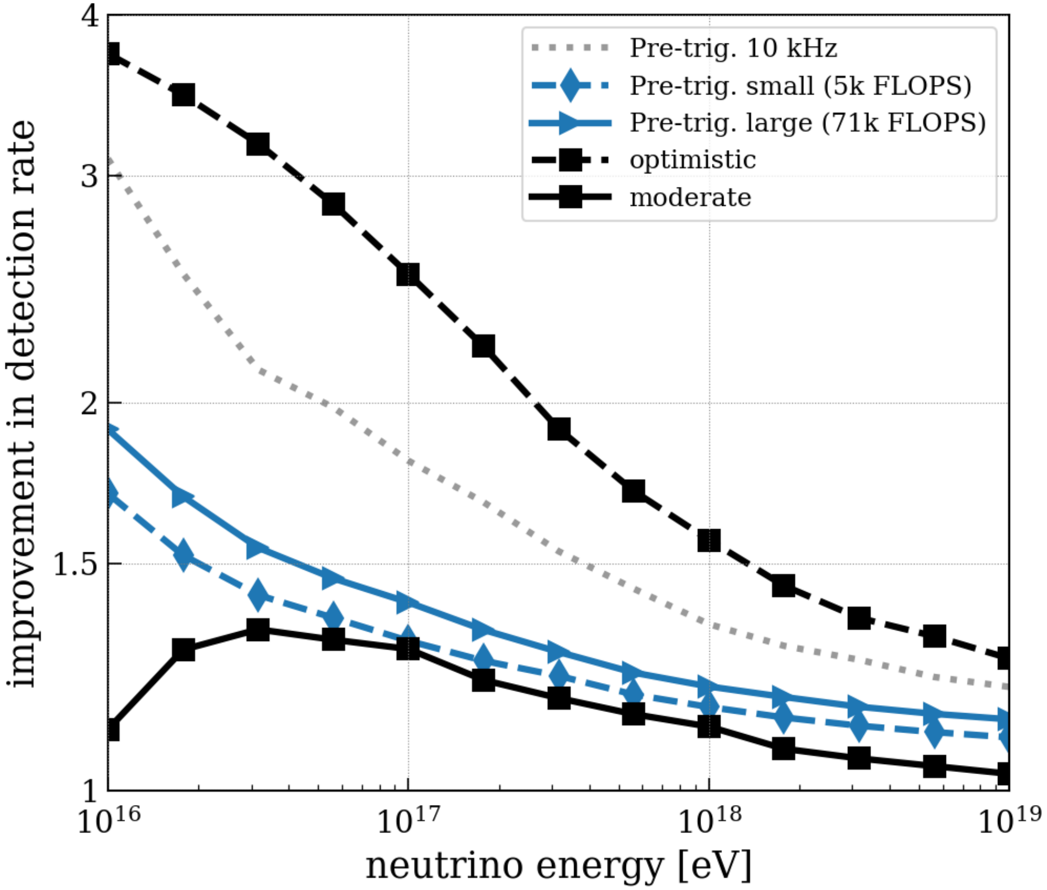
Option 2: Continuous analysis of data stream

work in progress

shallow



deep



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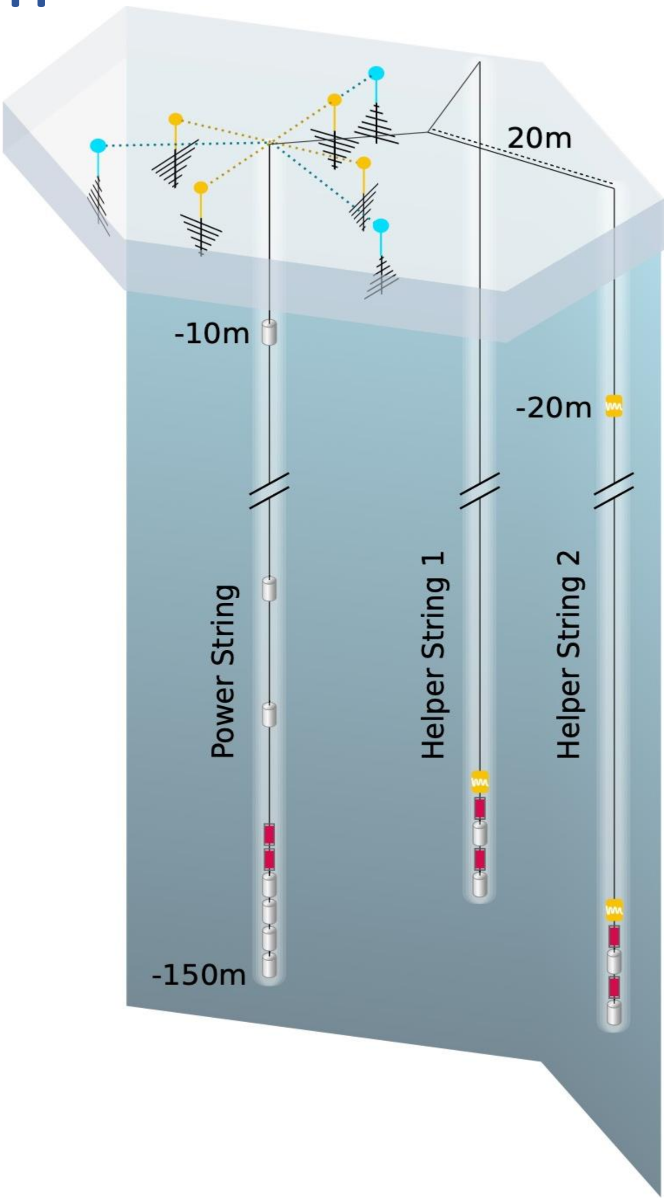
Objective 2: End-To-End Optimization

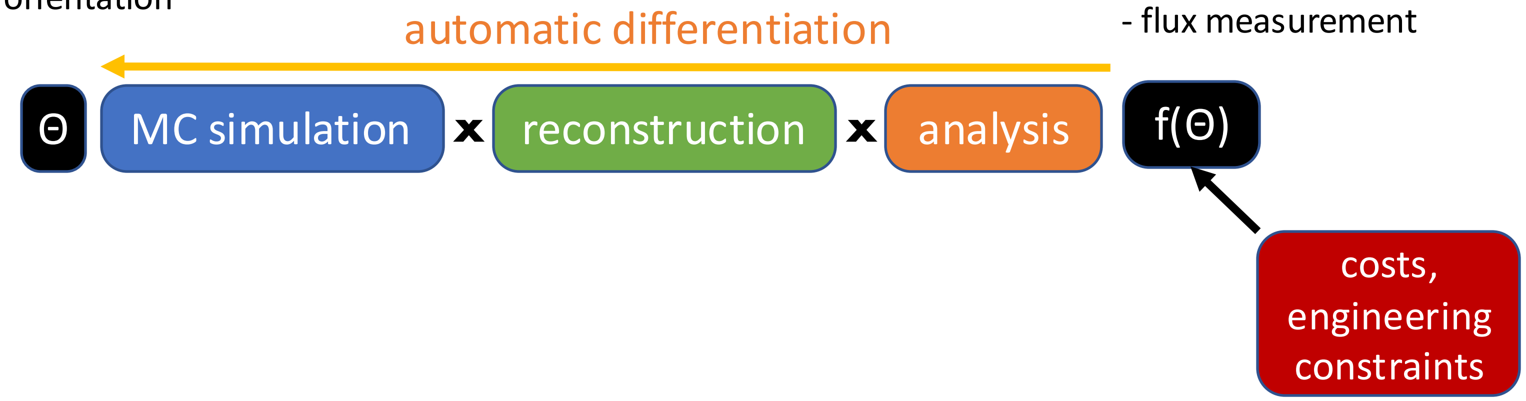


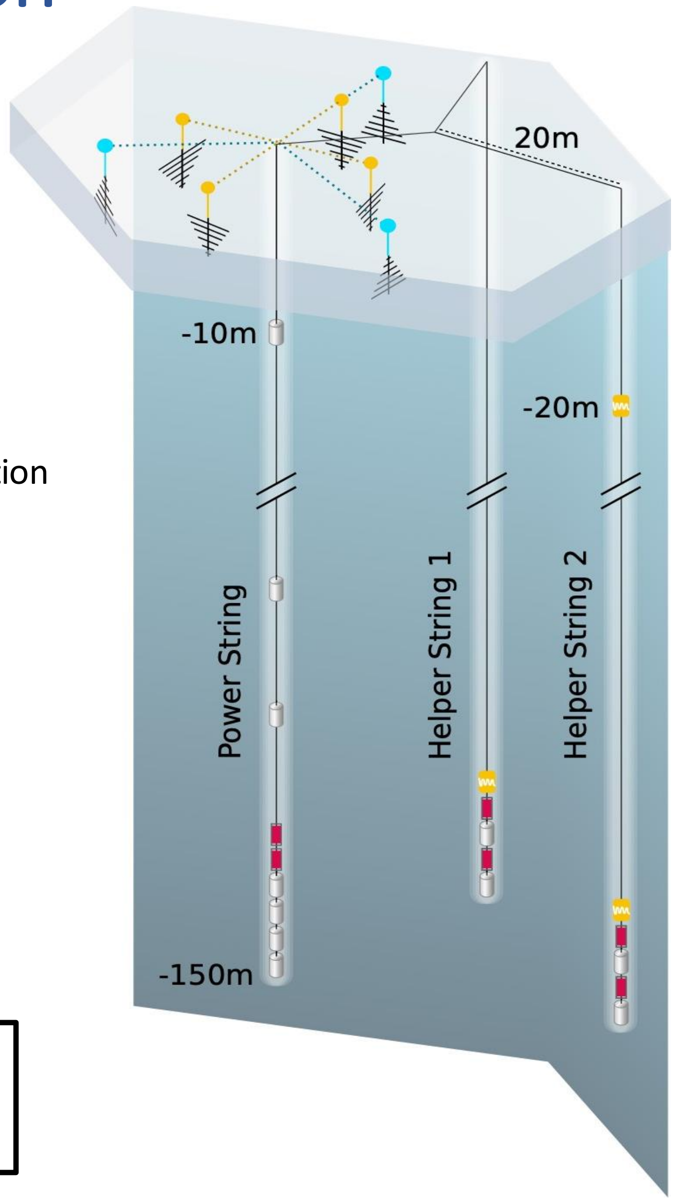
Objective 2: End-To-End Optimization

- 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

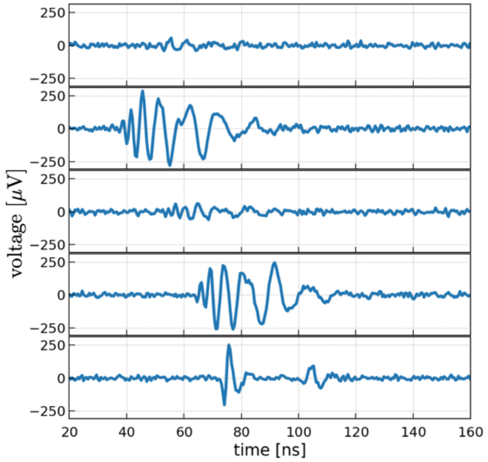




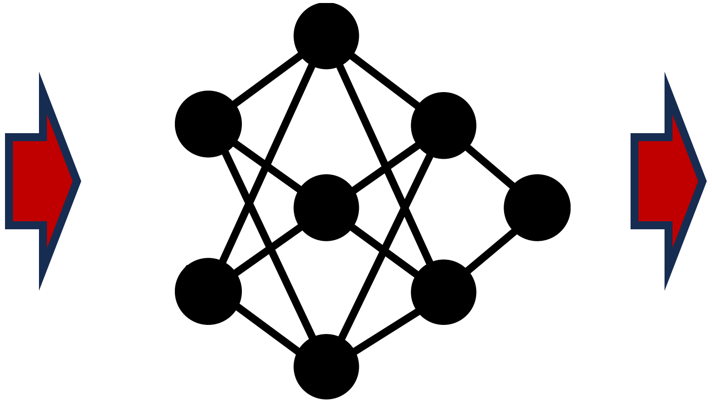
→ Expected improvements: up to three times more precise measurement of neutrino direction and energy

Deep-Learning Reconstruction using Normaling Flows (Simulation-Based Inference)

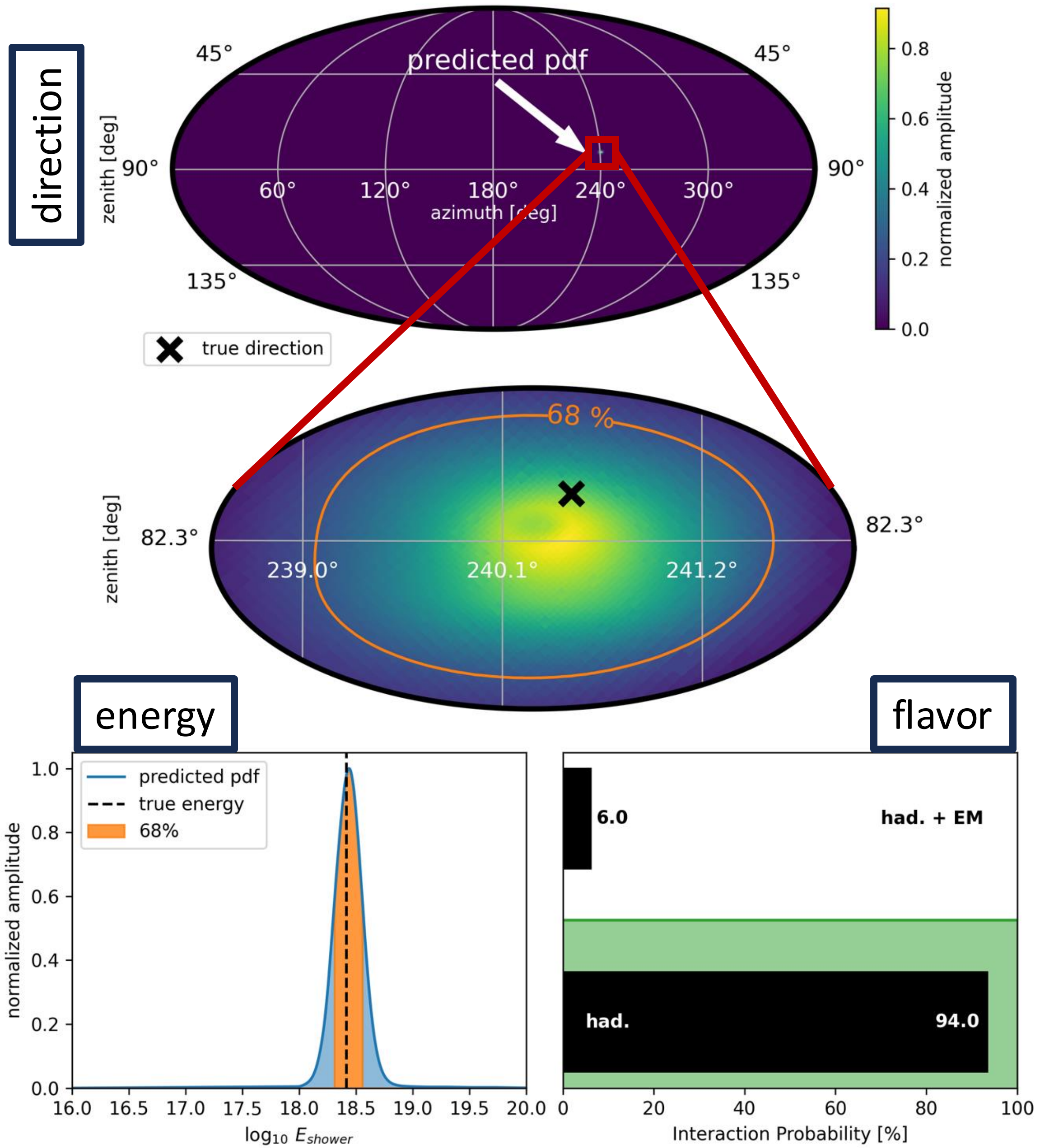
raw traces



reconstruction algorithm



Single Event Reconstruction



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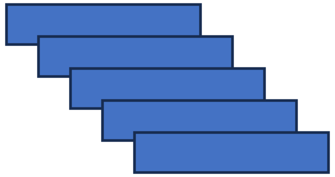
Model architecture

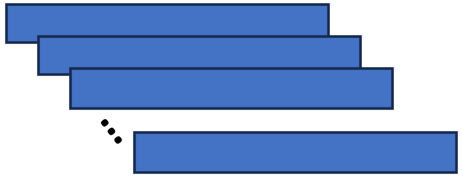
<u>Model Shallow</u>:

1 x 5 x 512



<u>Model Deep</u>:

1 x 16 x 2046

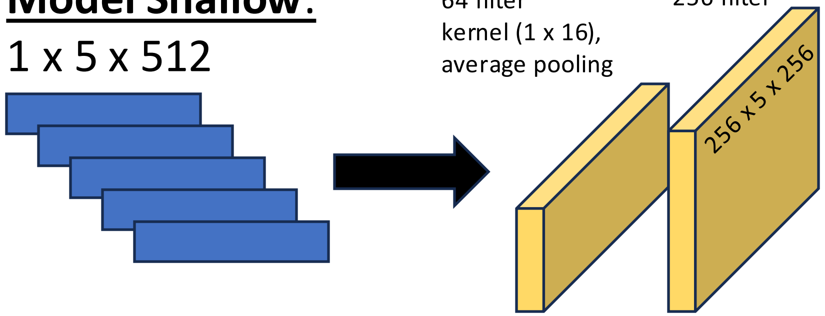


Model architecture

CNN1
4x 1d-conv
64 filter
kernel (1 x 16),
average pooling

CNN2
4x 1d-conv
kernel (1 x 16),
256 filter

Model Shallow:
1 x 5 x 512



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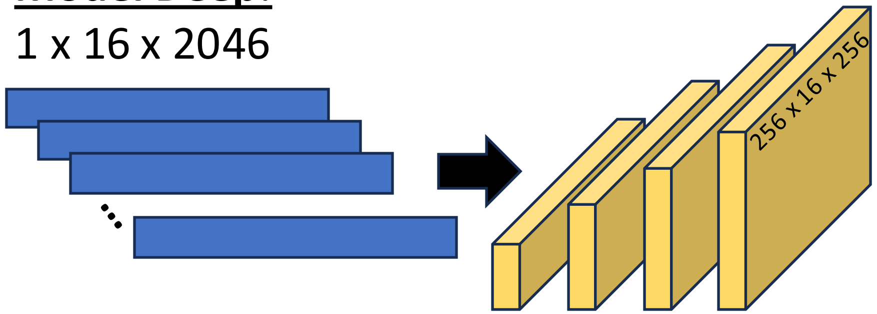
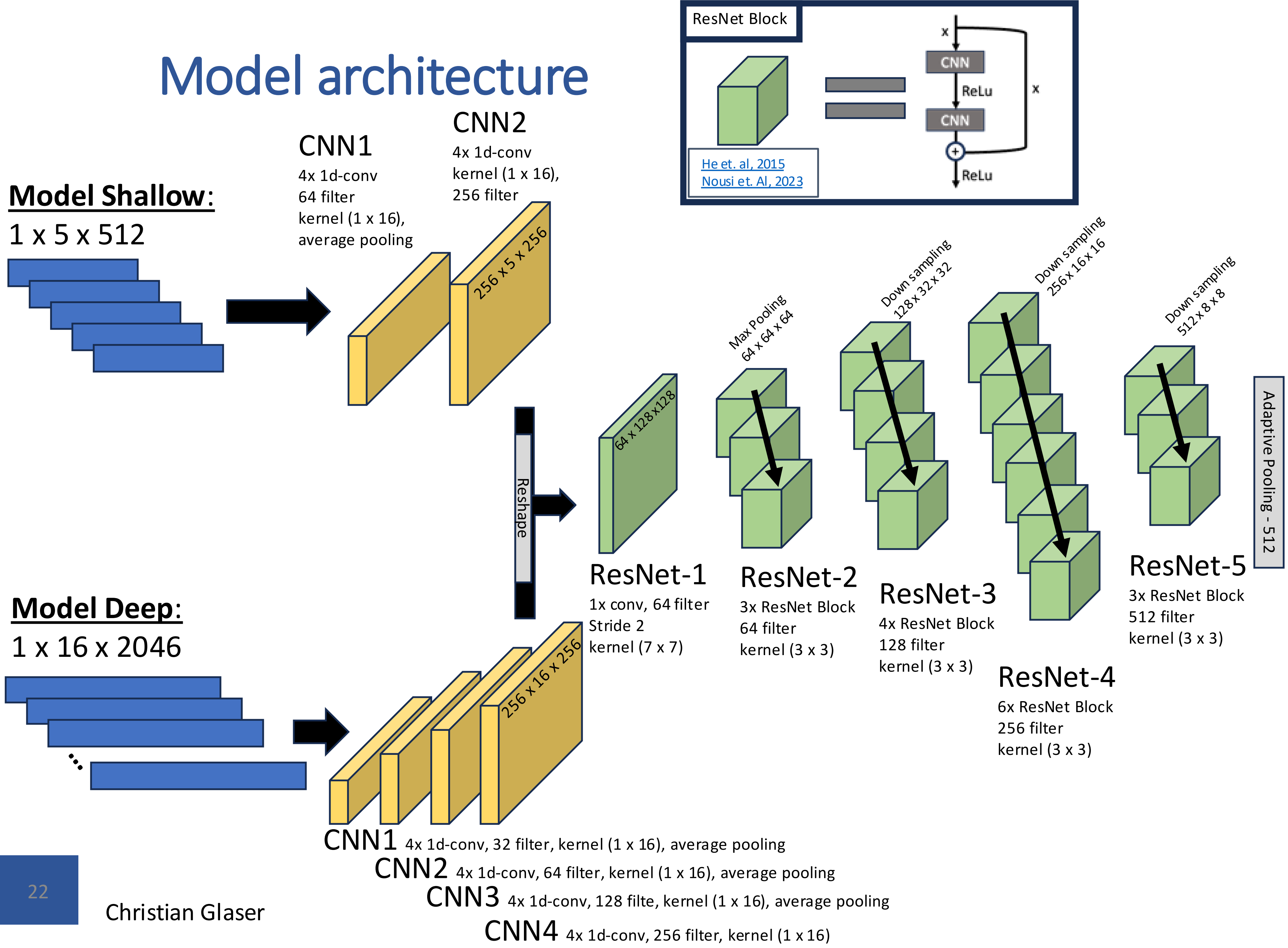


CNN1 4x 1d-conv, 32 filter, kernel (1 x 16), average pooling
CNN2 4x 1d-conv, 64 filter, kernel (1 x 16), average pooling
CNN3 4x 1d-conv, 128 filte, kernel (1 x 16), average pooling
CNN4 4x 1d-conv, 256 filter, kernel (1 x 16)

Model architecture



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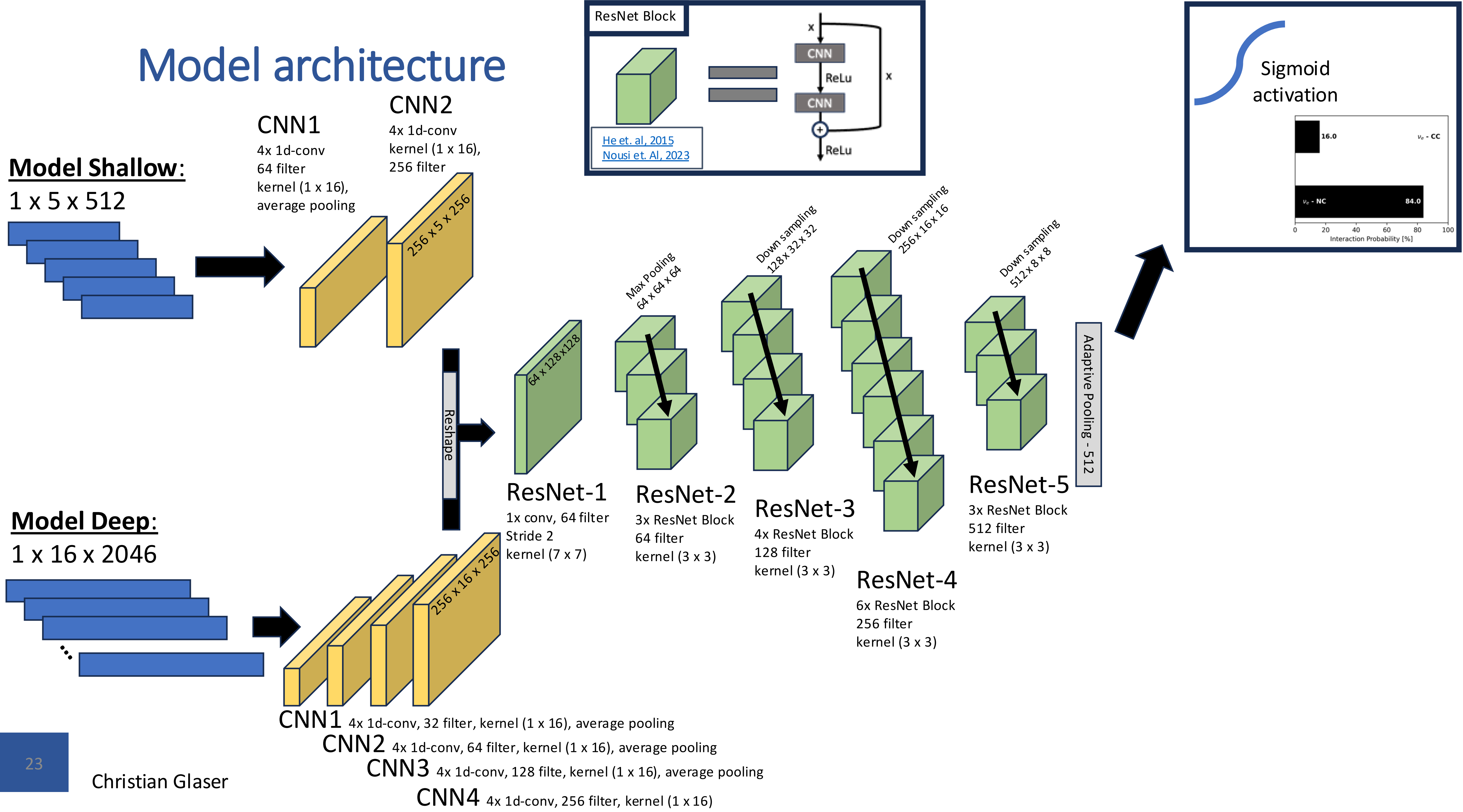

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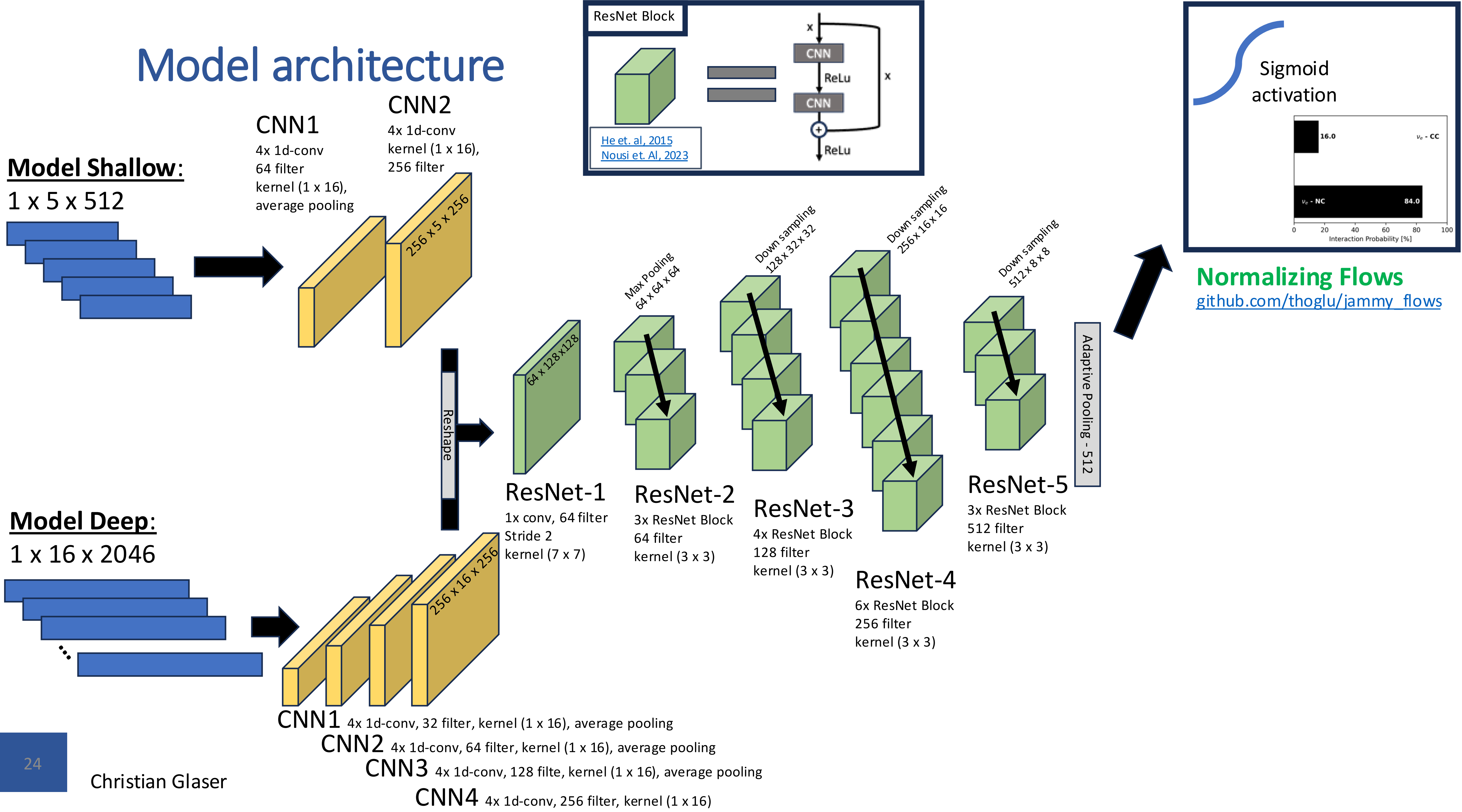

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CNN2

ResNet Block

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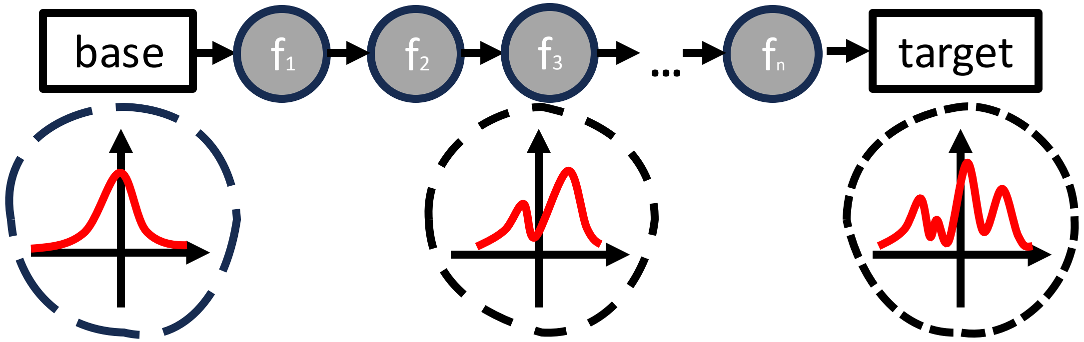
Adaptive Pooling - 512

Sigmoid activation

Normalizing Flows
github.com/thoglu/jammy_flows

Normalizing Flow

- A **function that maps** a gaussian PDF to a non-gaussian target PDF
- Parameters of the flow can be learned by a **neural network**
- Can model **complex PDF shapes**



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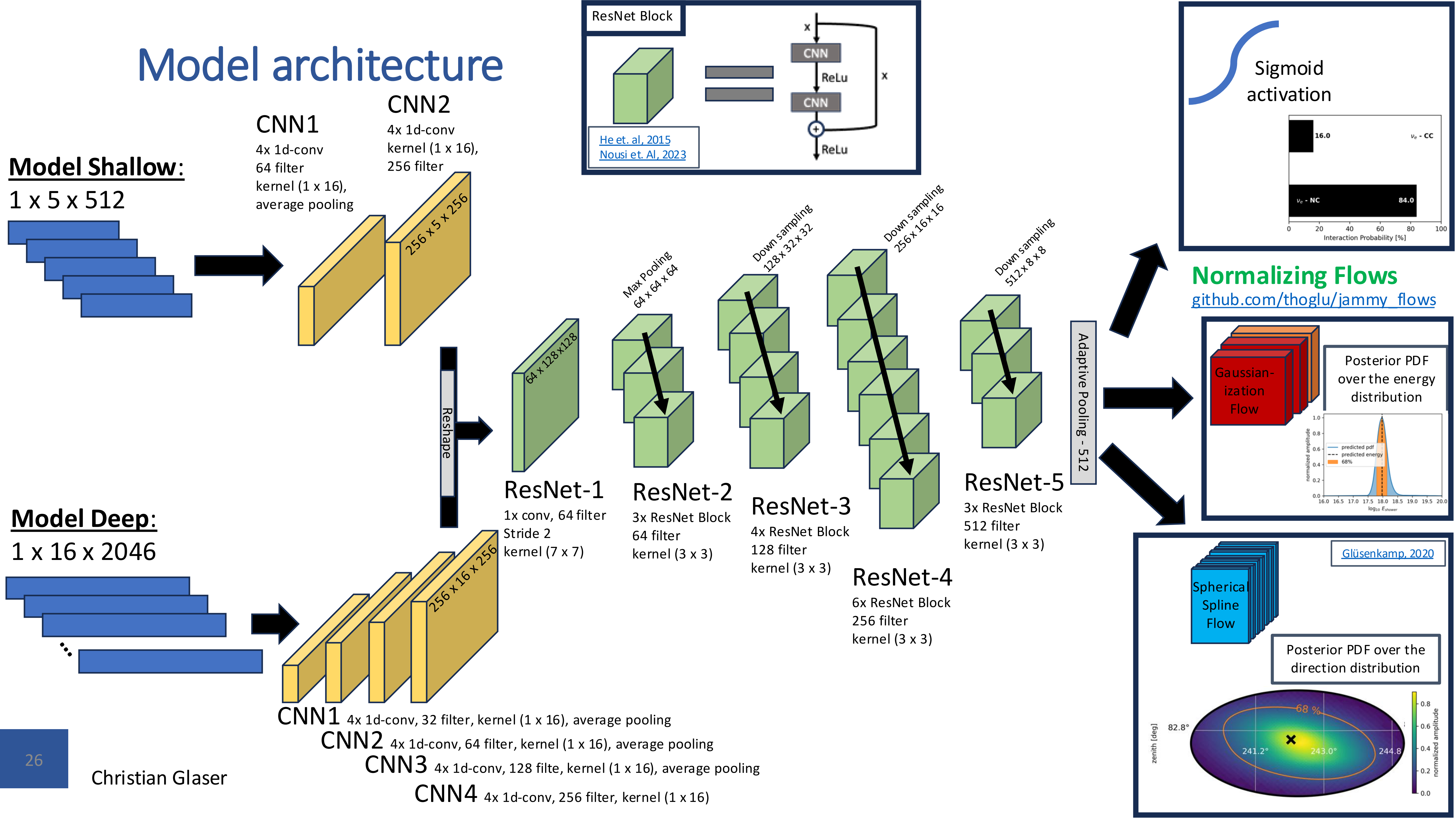

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Model Deep:
1 x 16 x 2046

ResNet Block

Sigmoid activation

Improvements to previous reconstructions:

1. Normalizing flows return full posterior PDFs allowing for event-by-event uncertainties (Glüsenkamp, EPJ-C, 2024)
2. Factor 10x improvement in angular resolution (compared to previous best reconstruction of deep stations)
3. No analysis cuts are needed – all neutrino events can be used
4. One model (per station type) to predict all parameters

Posterior PDF over the energy distribution

Glüsenkamp, 2020

Posterior PDF over the direction distribution

CNN1 4x 1d-conv, 32 filter, kernel (1 x 16), average pooling
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Main science objectives of UHE neutrino astronomy:

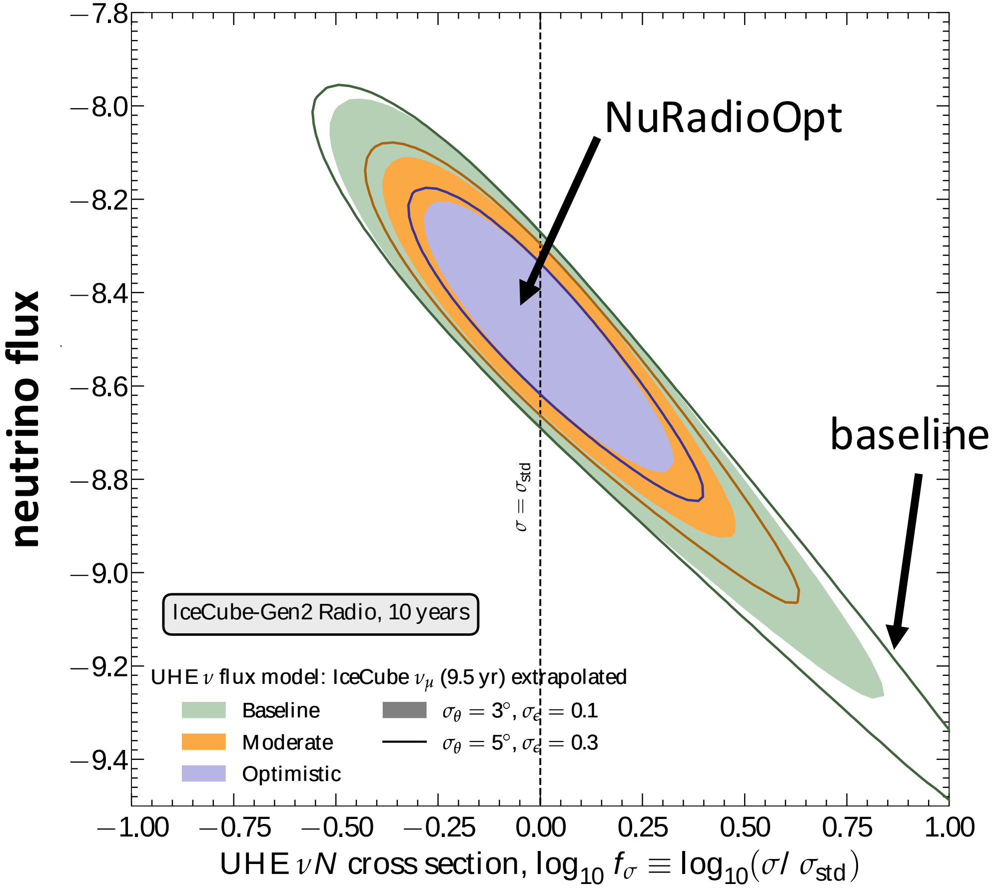
Impact of NuRadioOpt

Neutrino-Nucleon Cross Section

Diffuse Flux

Point Sources

→ 3x more precise measurement



cross section at 10^{18}eV

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

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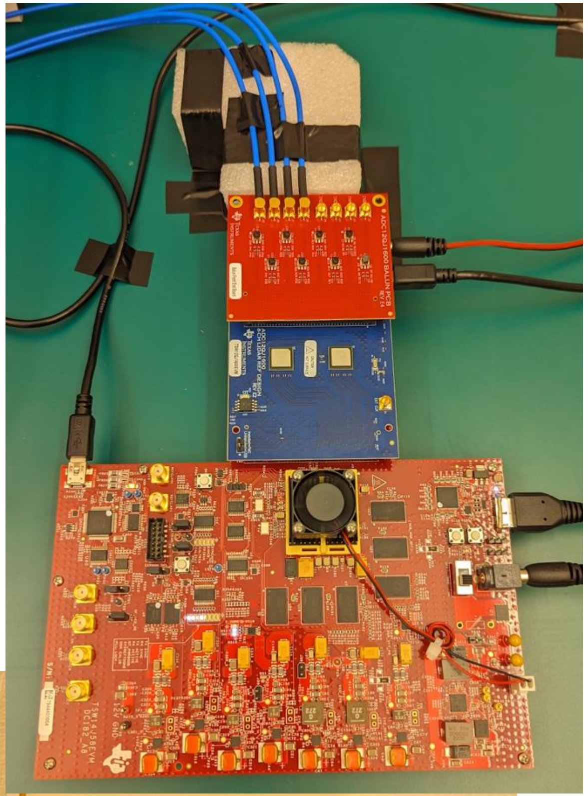
D. F. G. Fiorillo, V. Valera, M. Bustamente, JCAP03(2023)026

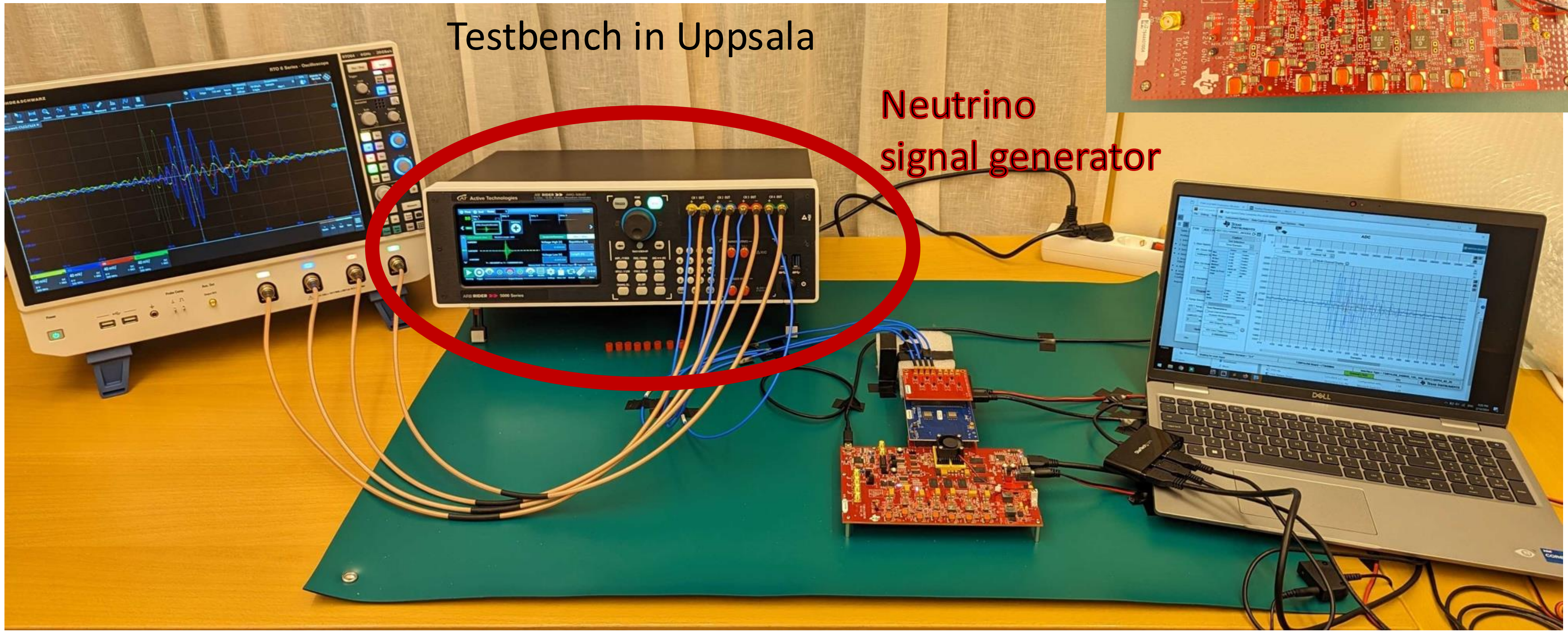
- **Improvements equivalent to building a more than three times larger detector** at essentially no additional costs
- because we are already at the limit of logistical resources at the South Pole, **NuRadioOpt is the only option to accelerate UHE neutrino science in the next decade**
- **Deep Learning and Differential Programming will Accelerate Science** (reanalysis of existing data, better trigger, better detector design)

Bonus slides

New DAQ Development

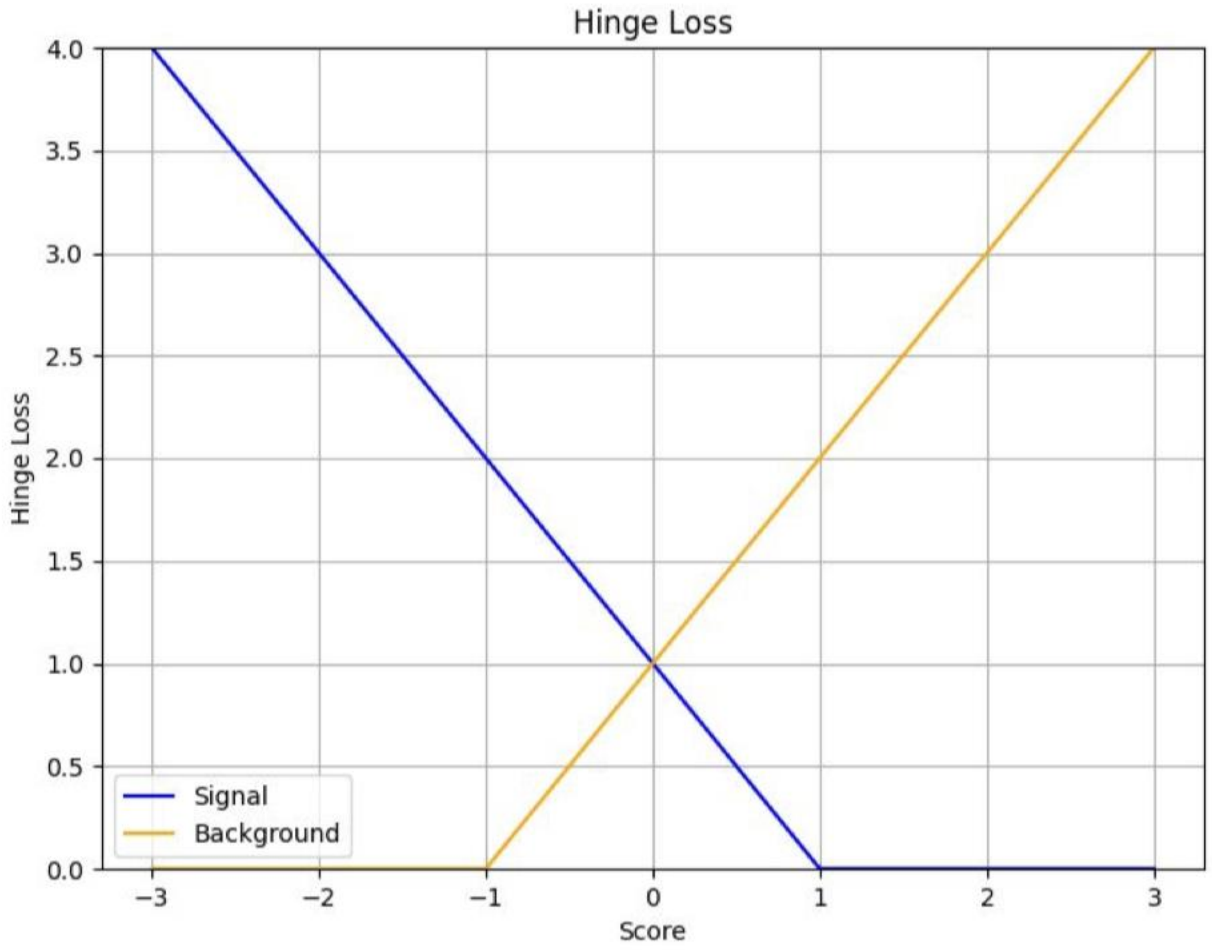
- New ADC generation (JESD204B interface)
  - High speed and low power (~1GHz, 12bit at 0.5W/channel)
  - Simpler compared to custom ASICS of previous hardware
  - Better data quality and opportunities for advanced triggers
- Also looking into Neuromorphic Computing
  (with Tommaso Dorigo + Fredrik Sandin)





Hinge Loss

- No sigmoid activation
- Penalize (only) wrong predictions

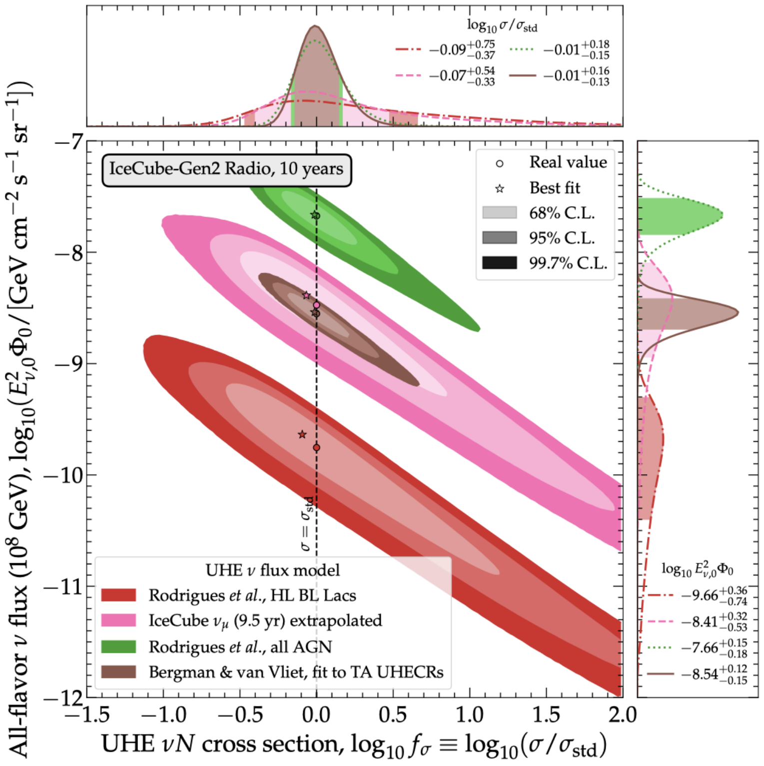


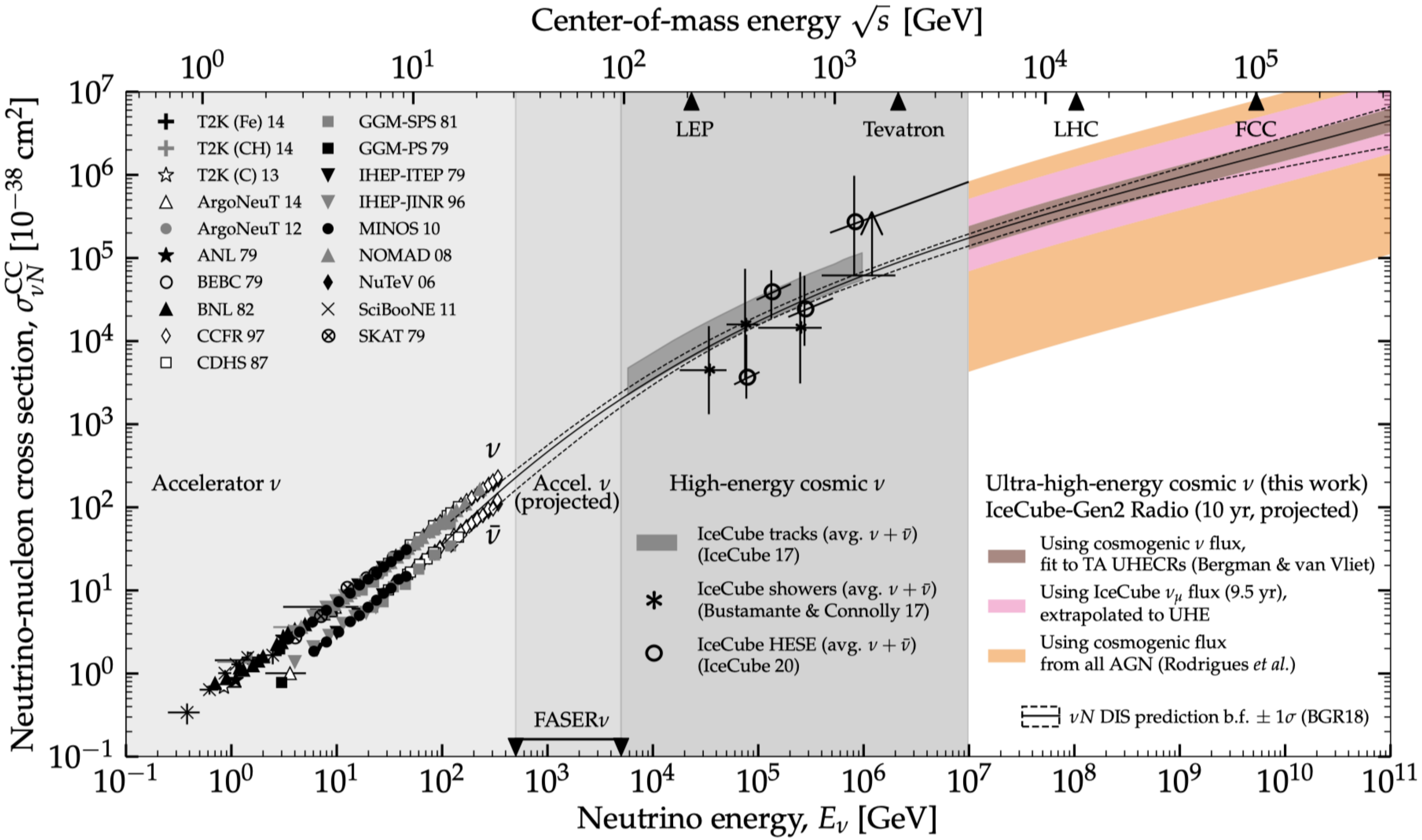
Science Overview: Cross Section

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

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

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





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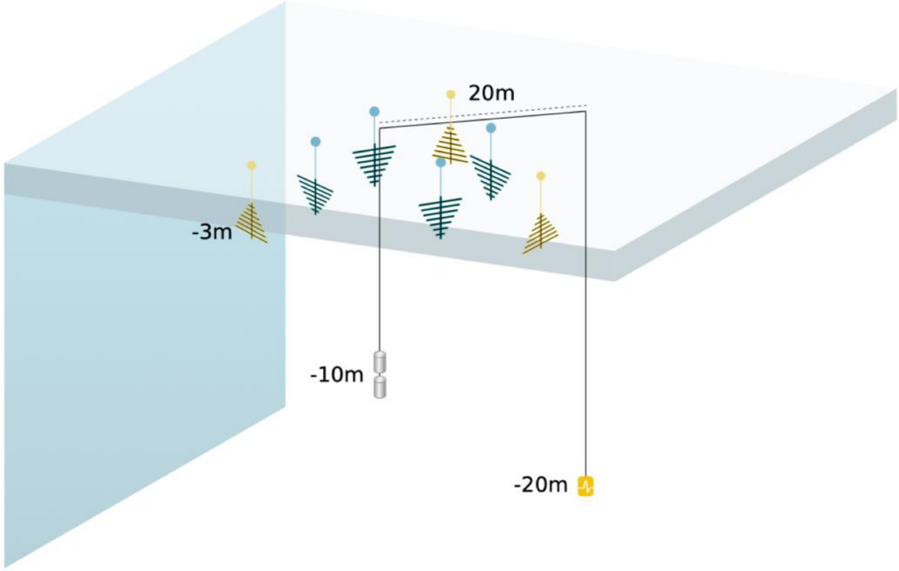
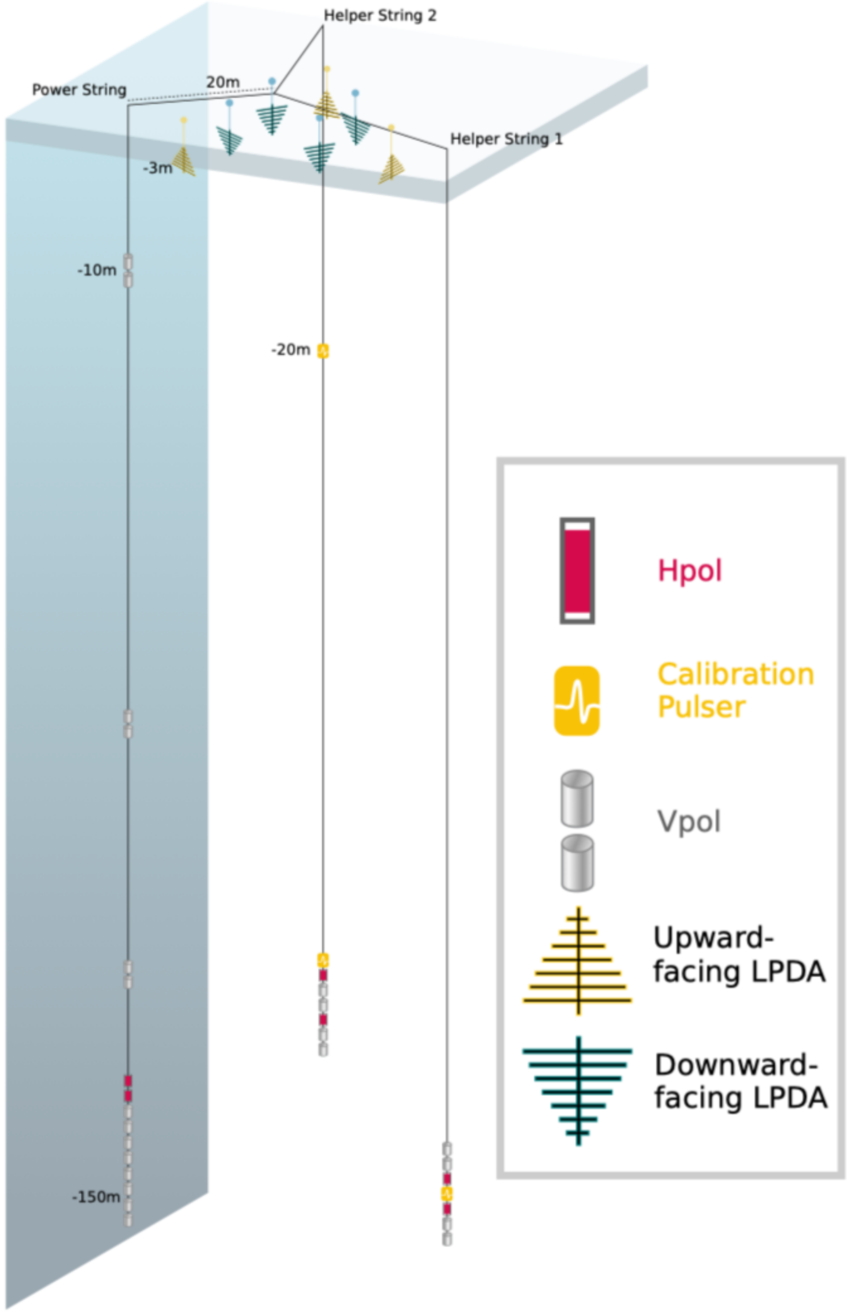
Current Trigger

- 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