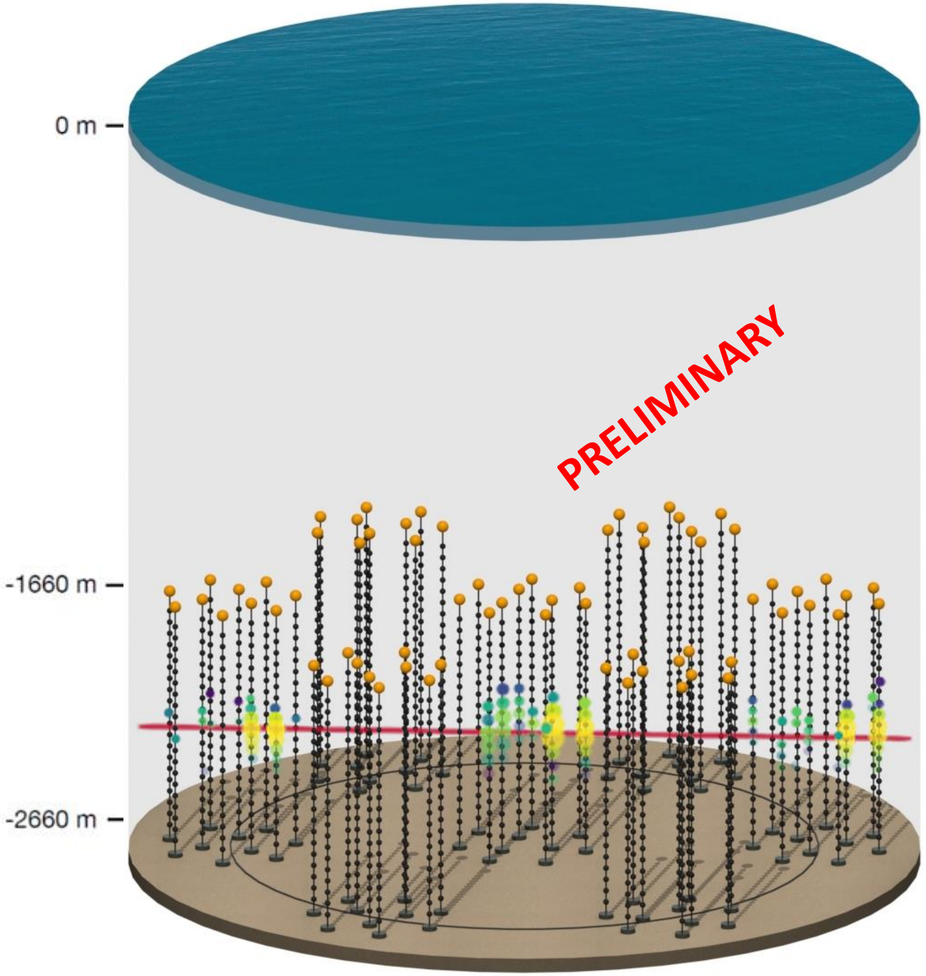
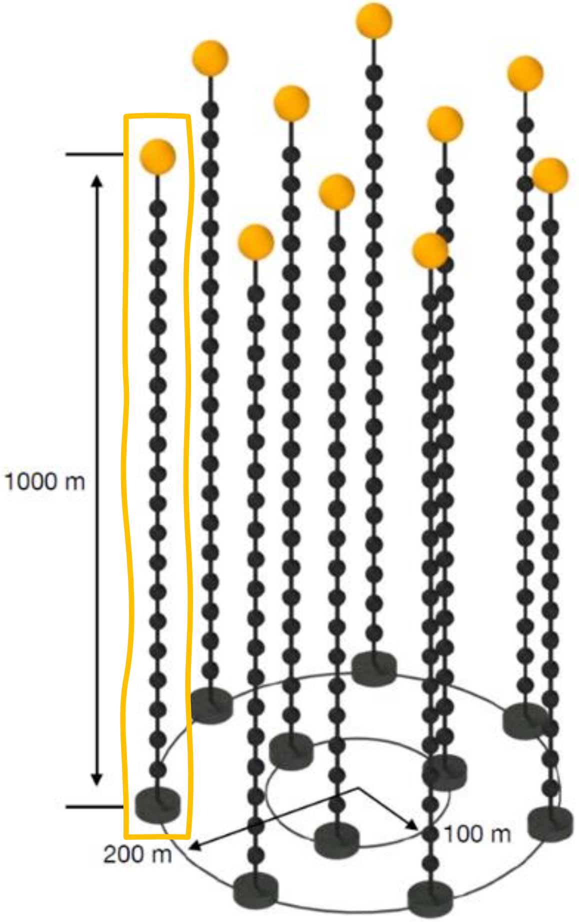
# Machine-learning aided experimental design for **P-ONE**

J. Prottung, C. Haack & A. Llorente Anaya for P-ONE collaboration

**TUM – Experimental Physics with Cosmic Particles**

# P-ONE – detector overview




- P-ONE detector concept:
  - 7 clusters, 10 mooring lines each
  - 1000 m long mooring lines

- **Please note:** Illustrations are preliminary studies!

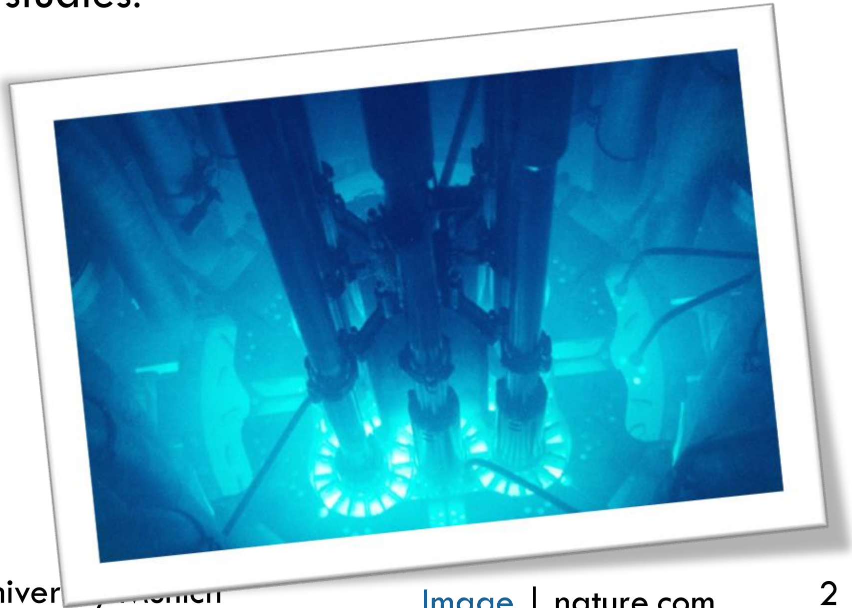
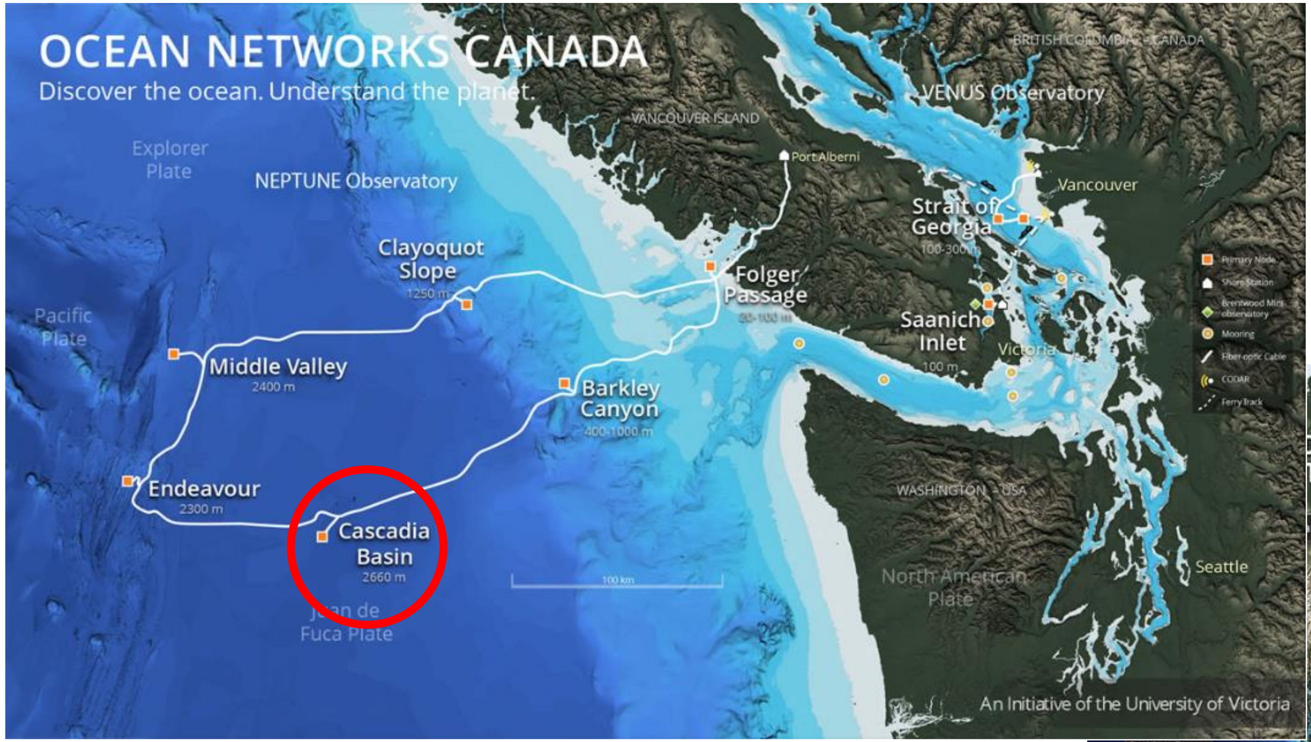


Image | nature.com

# NEPTUNE observatory

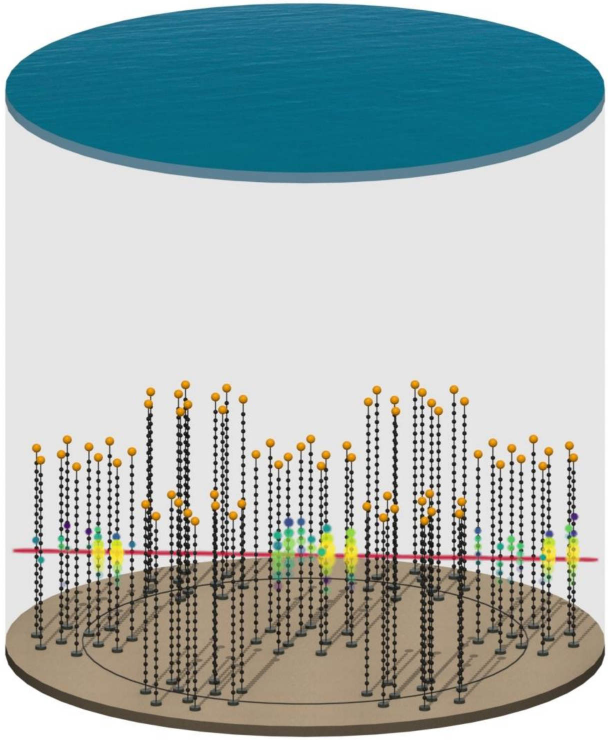
- Cabled ocean observatory (completed 2009)
- Annual budget ~$27M (CDN)
- 800km loop of fiber optical cable (4GB/s, 8kW/node)



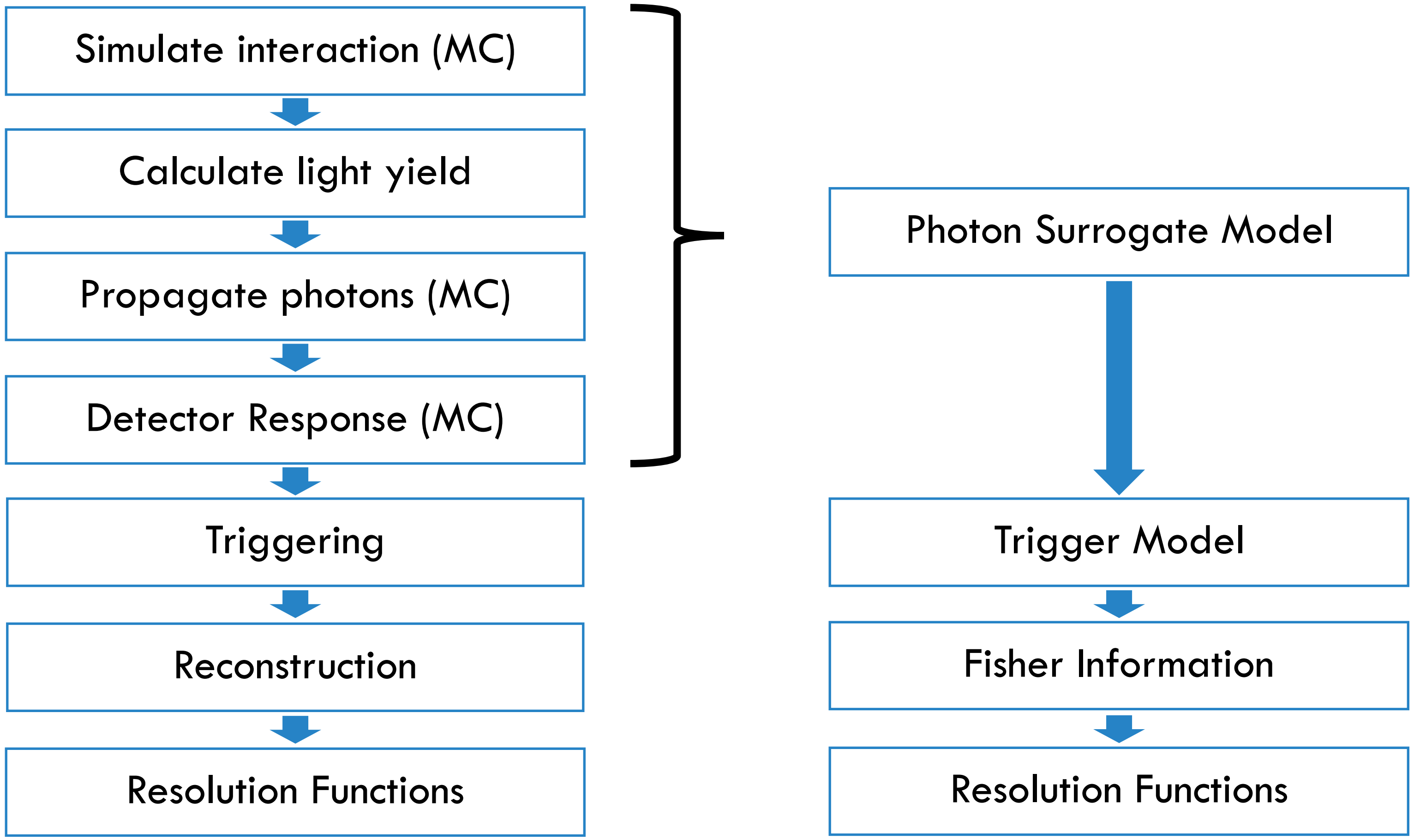

# Motivation – Machine Learning

Raw Signal → Preprocessing → **Trigger** → **Reconstruction** → Analysis

- Huge parameter space coverable with ML
- Searching for possibilities to apply ML like triggering, reconstruction, simulation or analysis
- Great success of NNs within IceCube Analysis



# Optimization Workflow




One MC campaign to train model, exploration of parameter space is cheap.

The differentiable surrogate model gives access to continuous likelihood functions. Use FI to calc. resolutions.

**No need to develop reconstruction algorithms.**

**Gradient-based optimisation algorithms**

# Detector Optimization

Detector resolution & Effective Area

## Hardware

- PMT properties
- Calibration devices

## Trigger Algorithms

- Efficiency
- Throughput

## Geometry

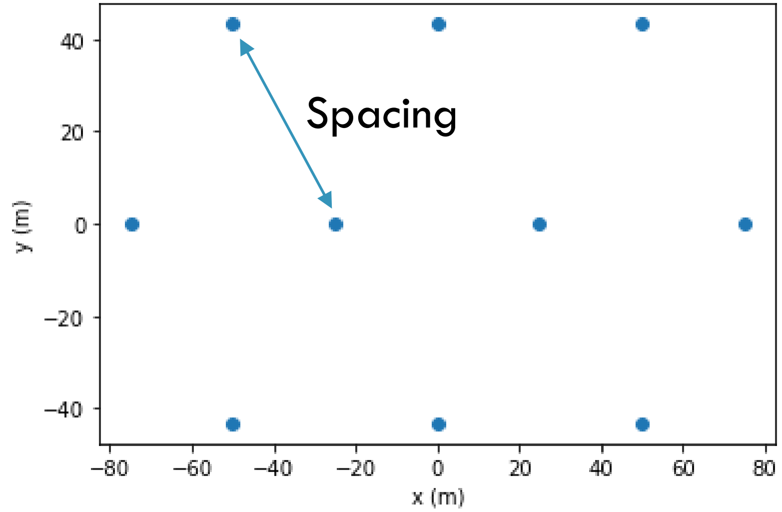
- Hexagonal, Triangular, etc.
- Module spacing on line

## Cost

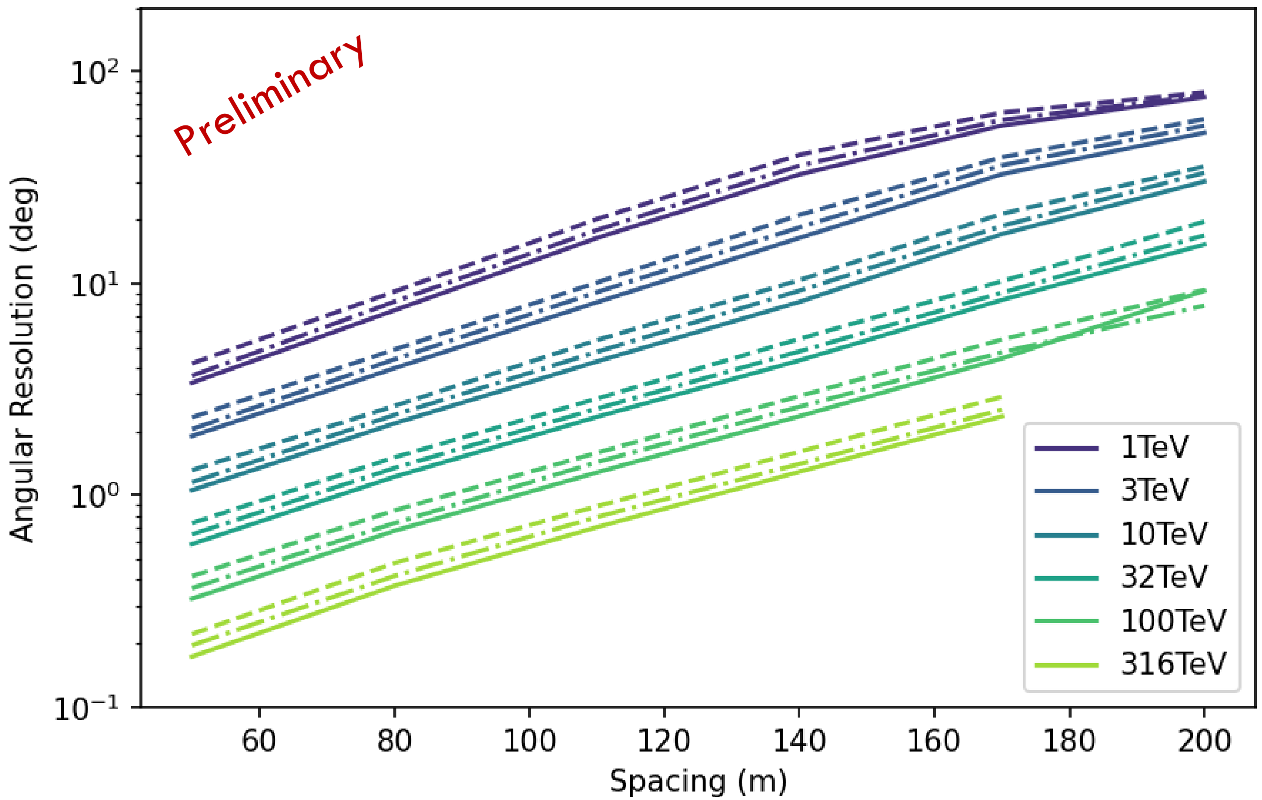
- Number of Modules, Lines, etc.
- Deployment complexity

# Detector Optimization - Resolution

The angular resolution of electromagnetic cascades based on energy and string spacing




Used 10 string detector geometry

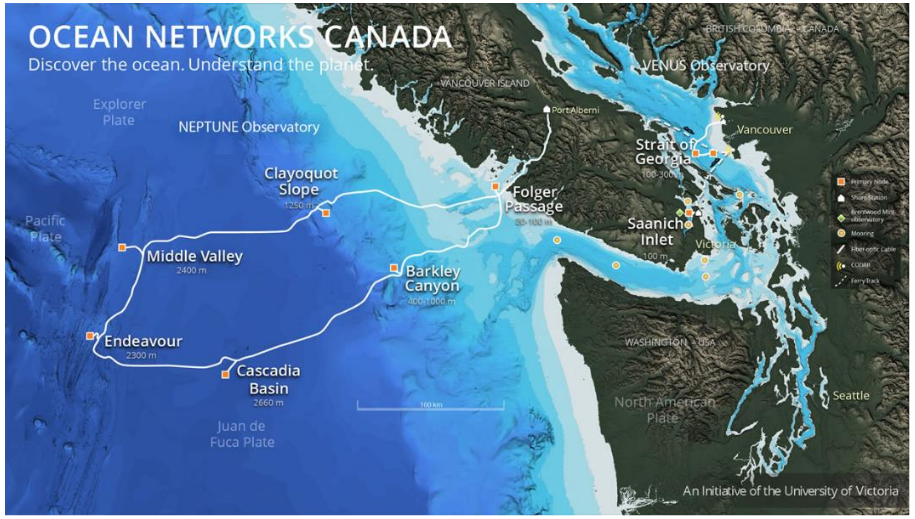



Note: Parameters are interdependent. Improvements in one often negatively impact others like cost and/or effective area

# Motivation – ML aided Triggering

- Several sources of background: k40 decays, bioluminescence, atmospheric muons → several orders of magnitude
- Limited Bandwidth of ~1 GB/s
- Limited Power Availability: 5 kW/ node
- Estimated event rate 2,5 kHz

→ Apply the power of Machine Learning



# Motivation – ML based Triggers on FPGAs

- Easy deployment in Module, String or Junction Box
- Improved performance due to tailored application
- Very power efficient
- Promising applications at particle detectors like Belle II

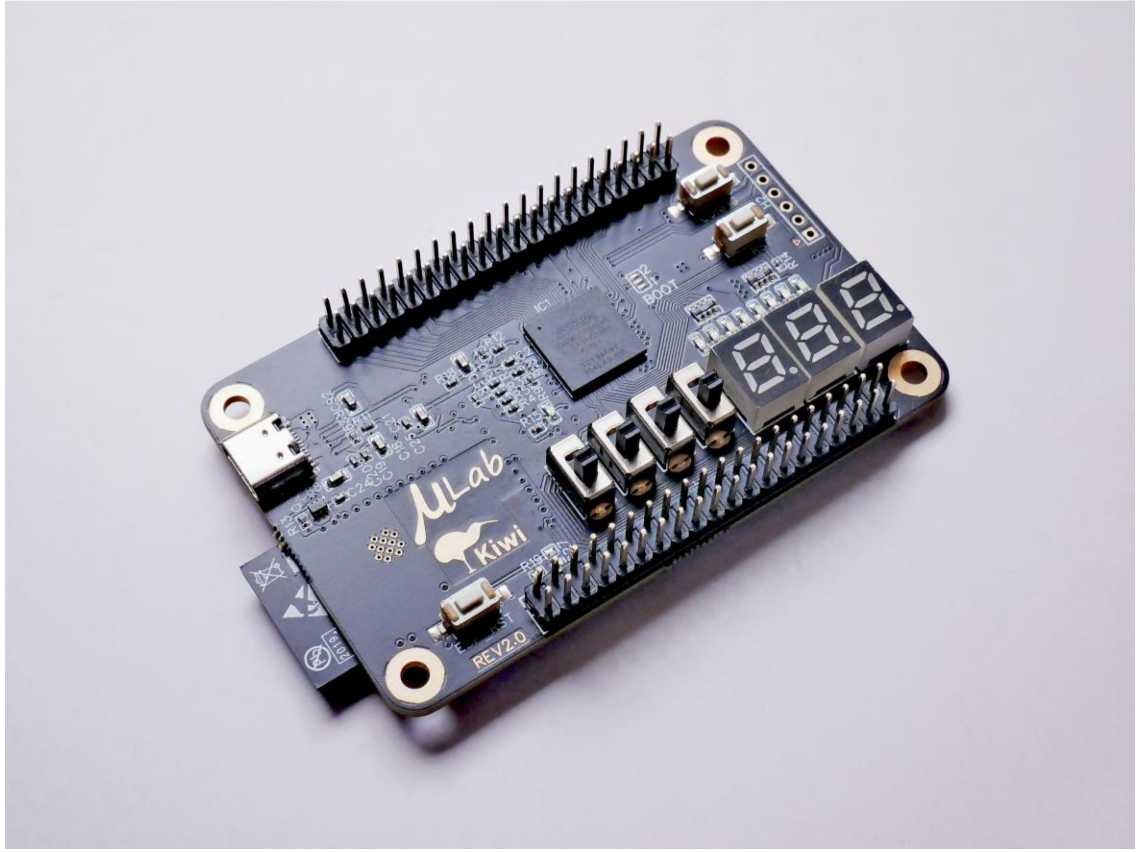
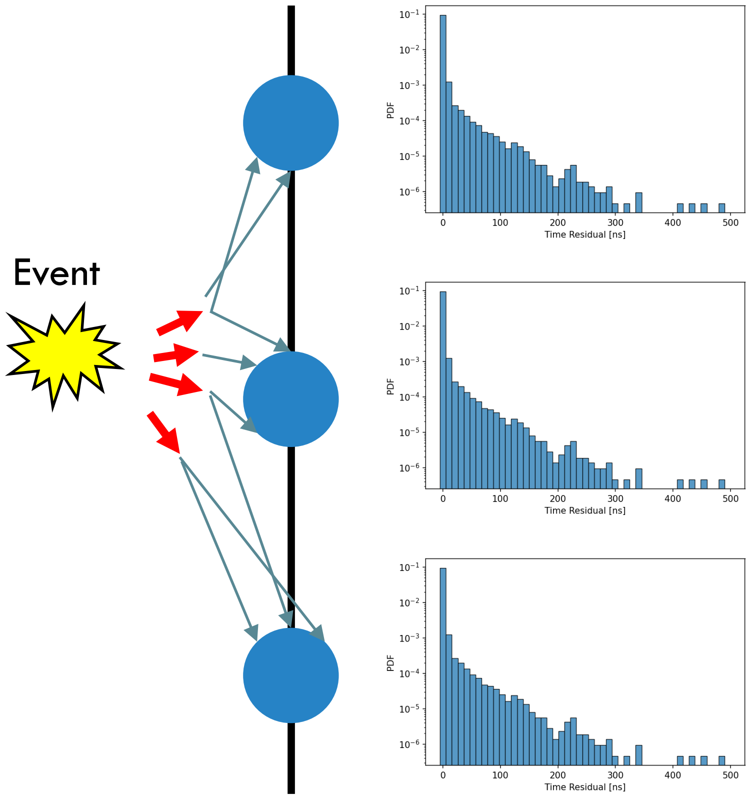



Photo by V. Mohanan: uLab FPGA

Technical University of Munich | P-ONE

# Triggering Principle




Preprocessing

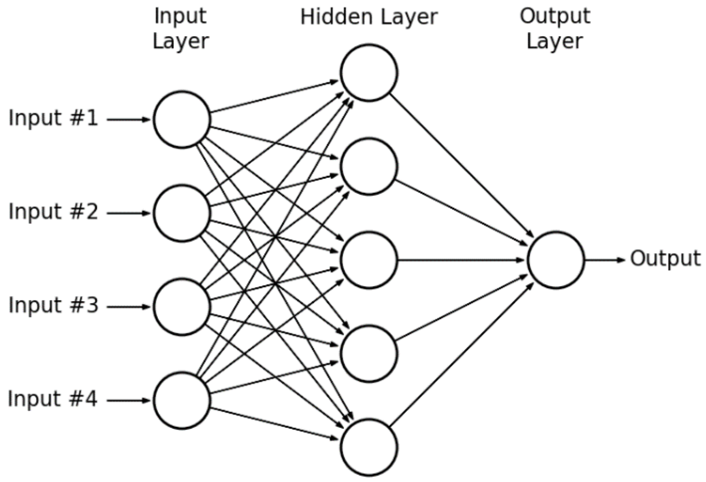



Figure: Mohamed Zahran

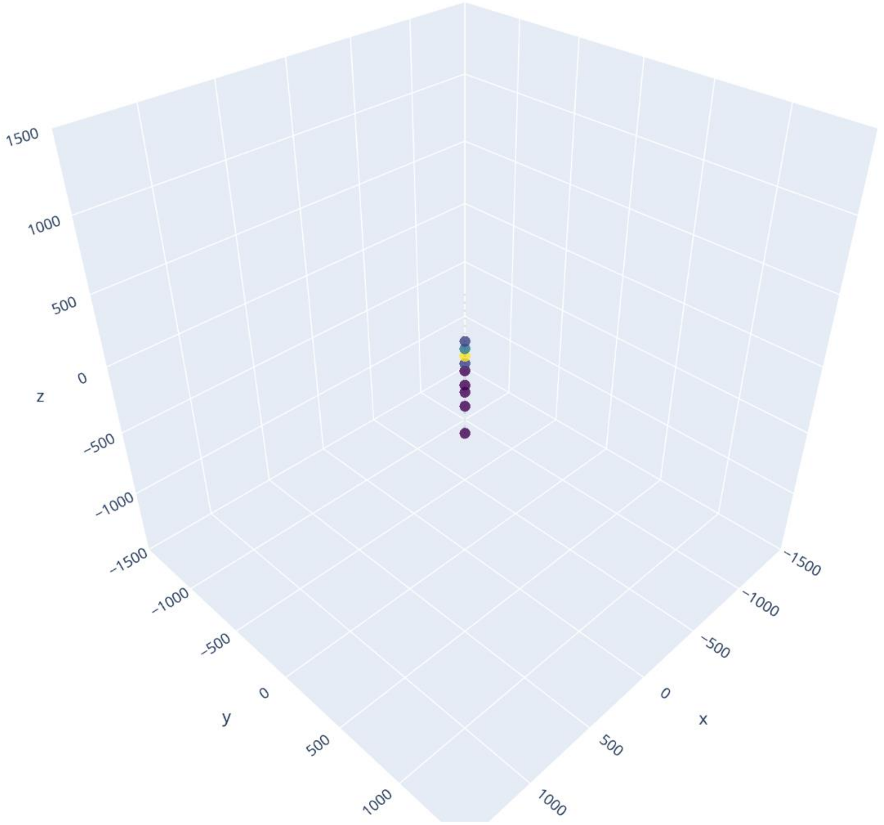
Cascade, track, background, noise, etc.

| Type |
| --- |
| Keep (yes, no) |
| Direction |
| Energy |
| … |
| … |
| … |
| … |

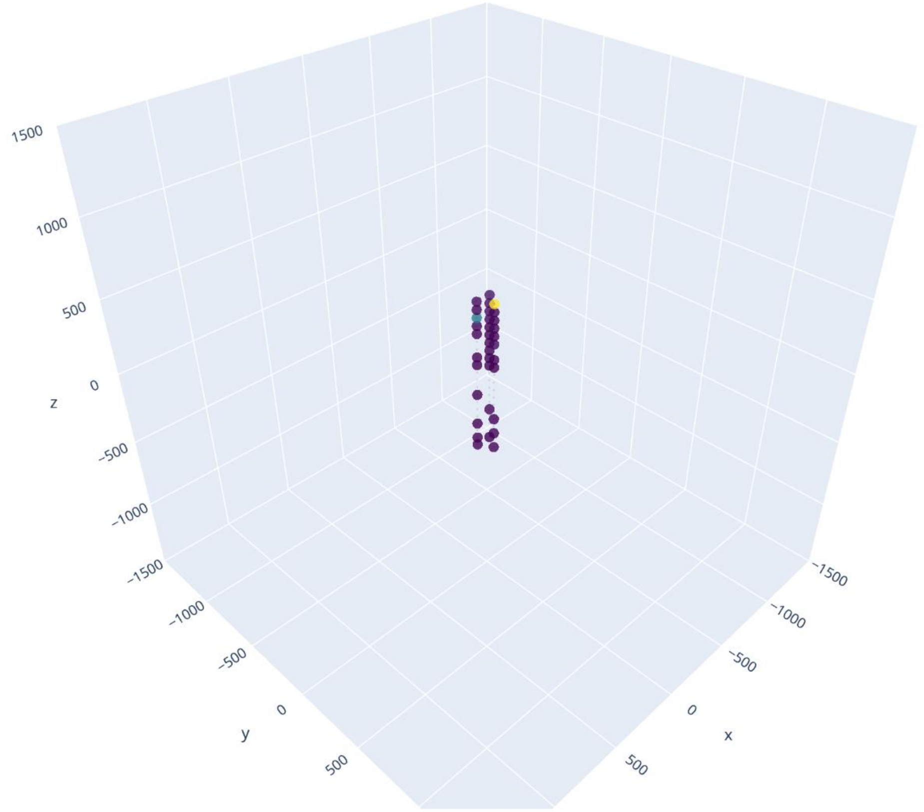
Reconstructed properties

# Digital Twin

A realistic virtual model of detectors behavior in time

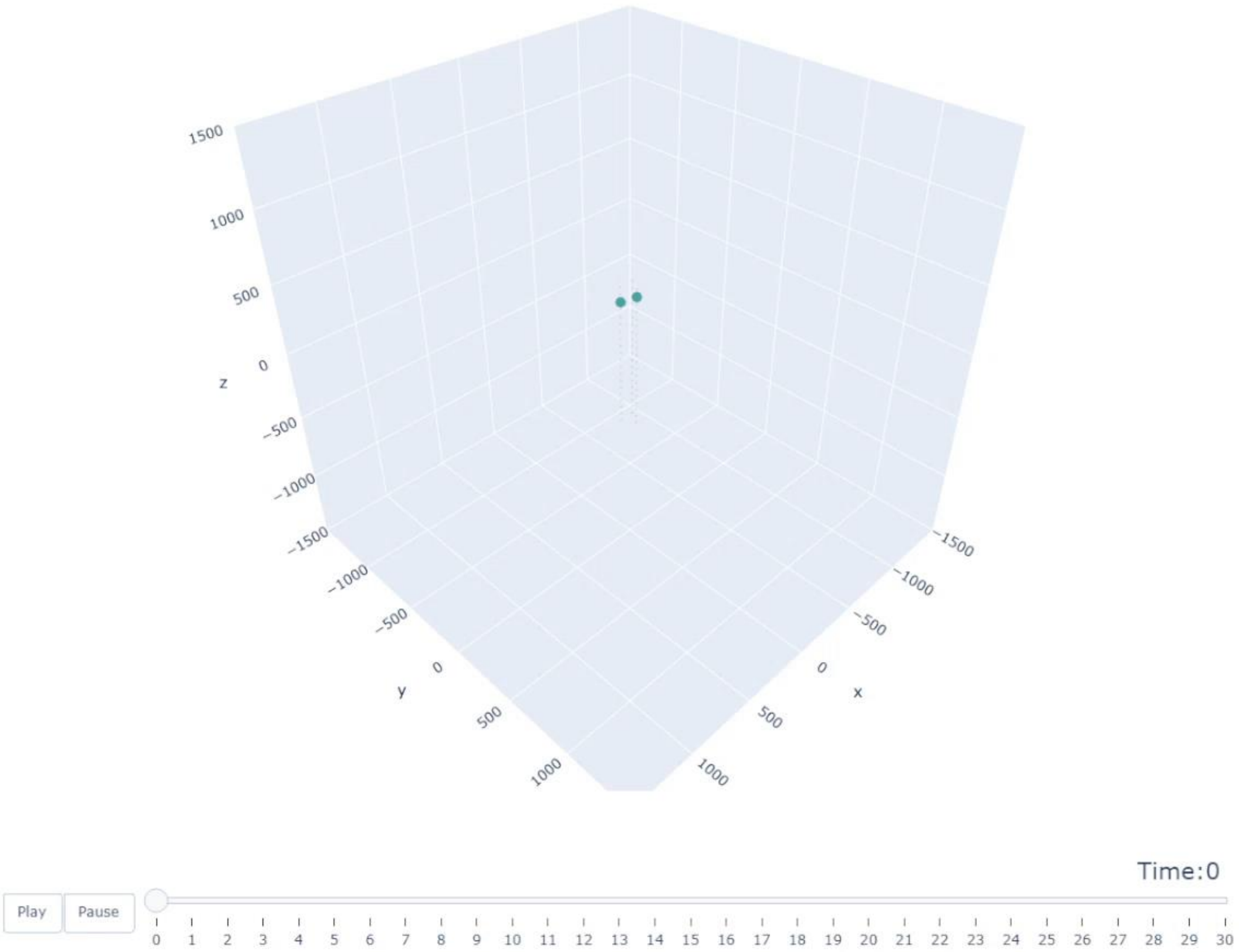



One String detector




Three String Detector

# Digital Twin



# Conclusion & Next Steps

Above's machine learning model facilitates the detector design

- ➢Geometry, Cost, Hardware and Trigger Algorithm affect performance
- ➢Multiple architectures can be created using the digital twin

Investigating machine learning-based trigger for P-One

- ➢Could improve effective area
- ➢Possibility to use FPGAs as efficient on-site computing units

Up next: The creation of a real-time machine learning-based trigger algorithm

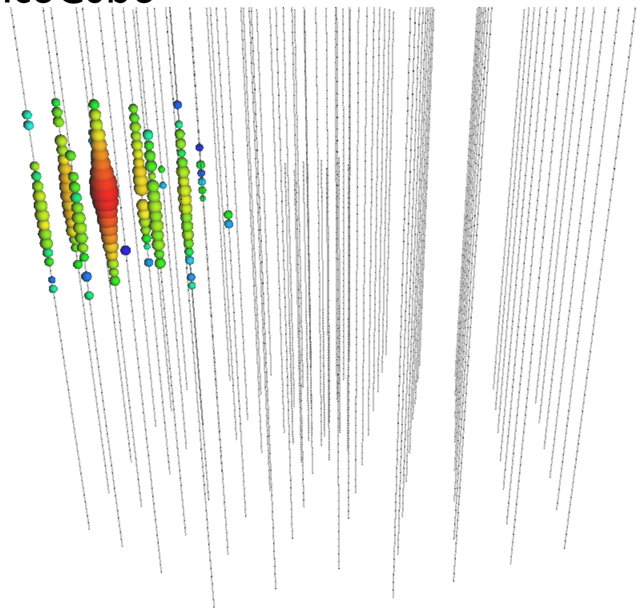
- ➢Further optimize detector design
- ➢Proof of concept: FPGA implementation of the algorithm

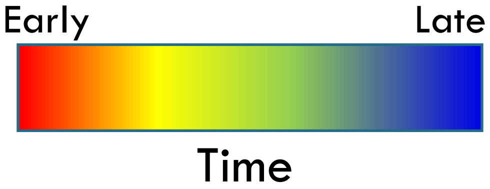
Thank you for the attention!

# Backup

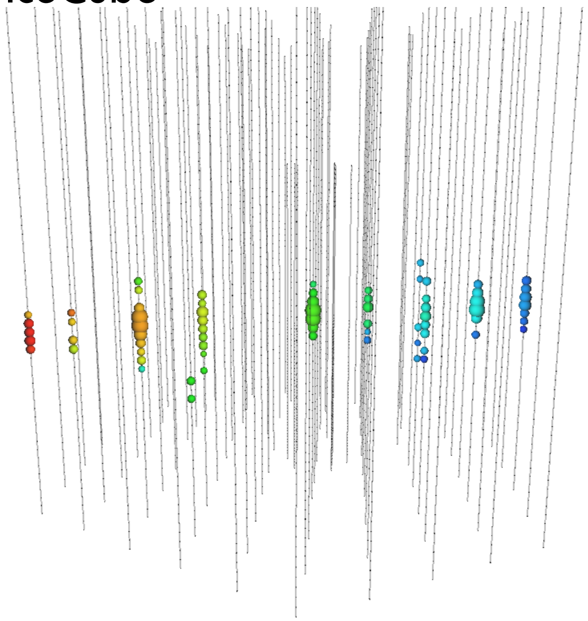
# Why build a new Neutrino Detector?

IceCube






IceCube



**(EM / Hadronic) Cascades**

Neutral Current (NC) & $\nu_e$ ($\nu_\tau$) Charged Current (CC)

Typically good energy resolution

Good for spectral measurements

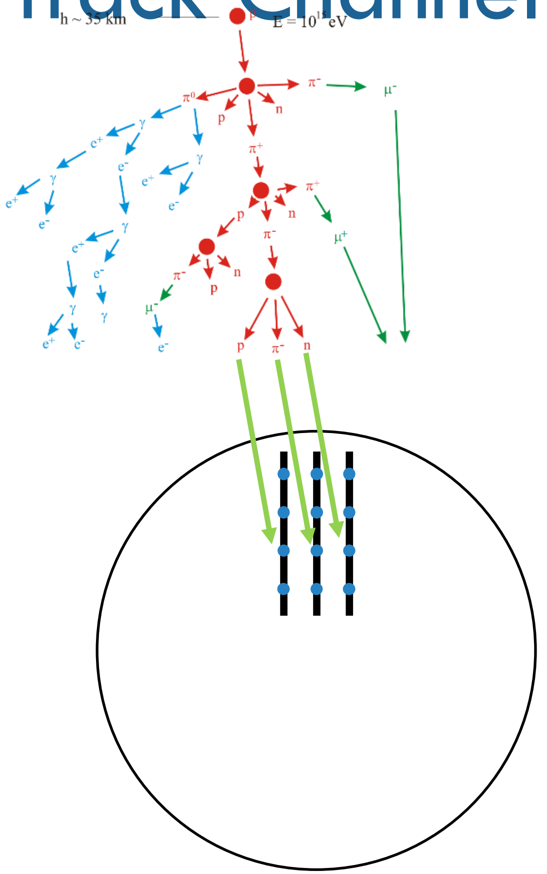
**Throughgoing Tracks (muons)**

E.g. from $\nu_\mu$ CC, but also atmospheric

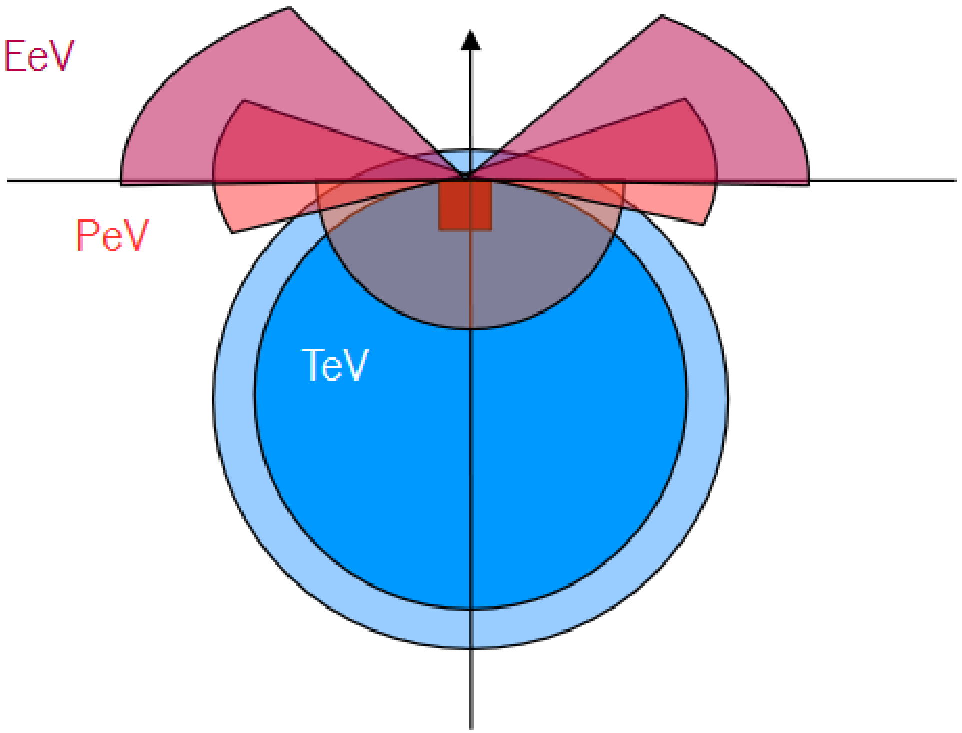
Typically good angular resolution

Good for finding pointsources

# The Track Channel




Sketch by Antoine Kouchner



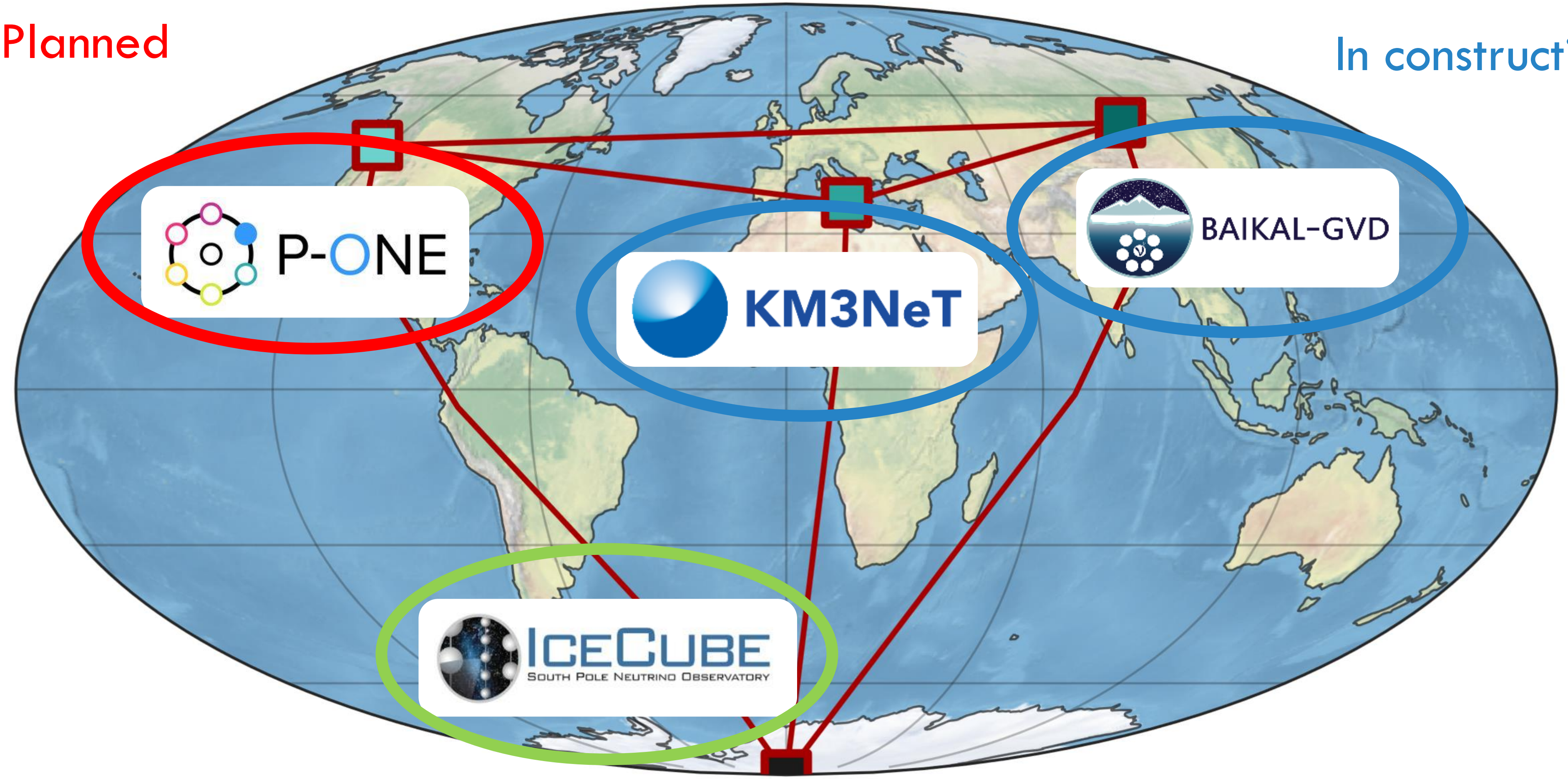

Downgoing region is dominated by atmo. muon background.
High-energy upgoing neutrinos are absorbed by Earth

Horizontal region is optimal for observing high-energy tracks

# High Energy Neutrino Telescopes

Planned

In construction

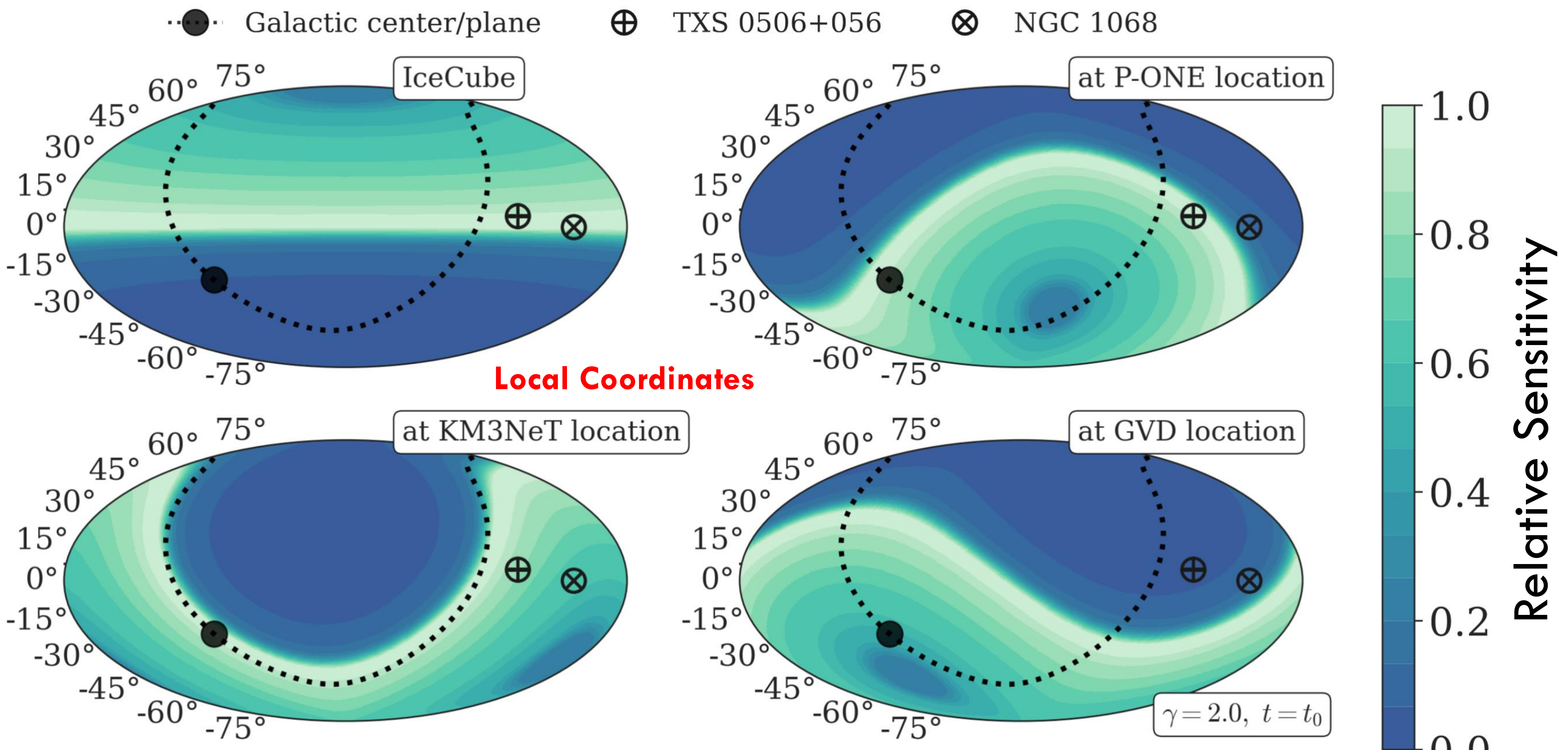



Taking data for 10+ years



Image | nature.com

# Relative Sensitivities

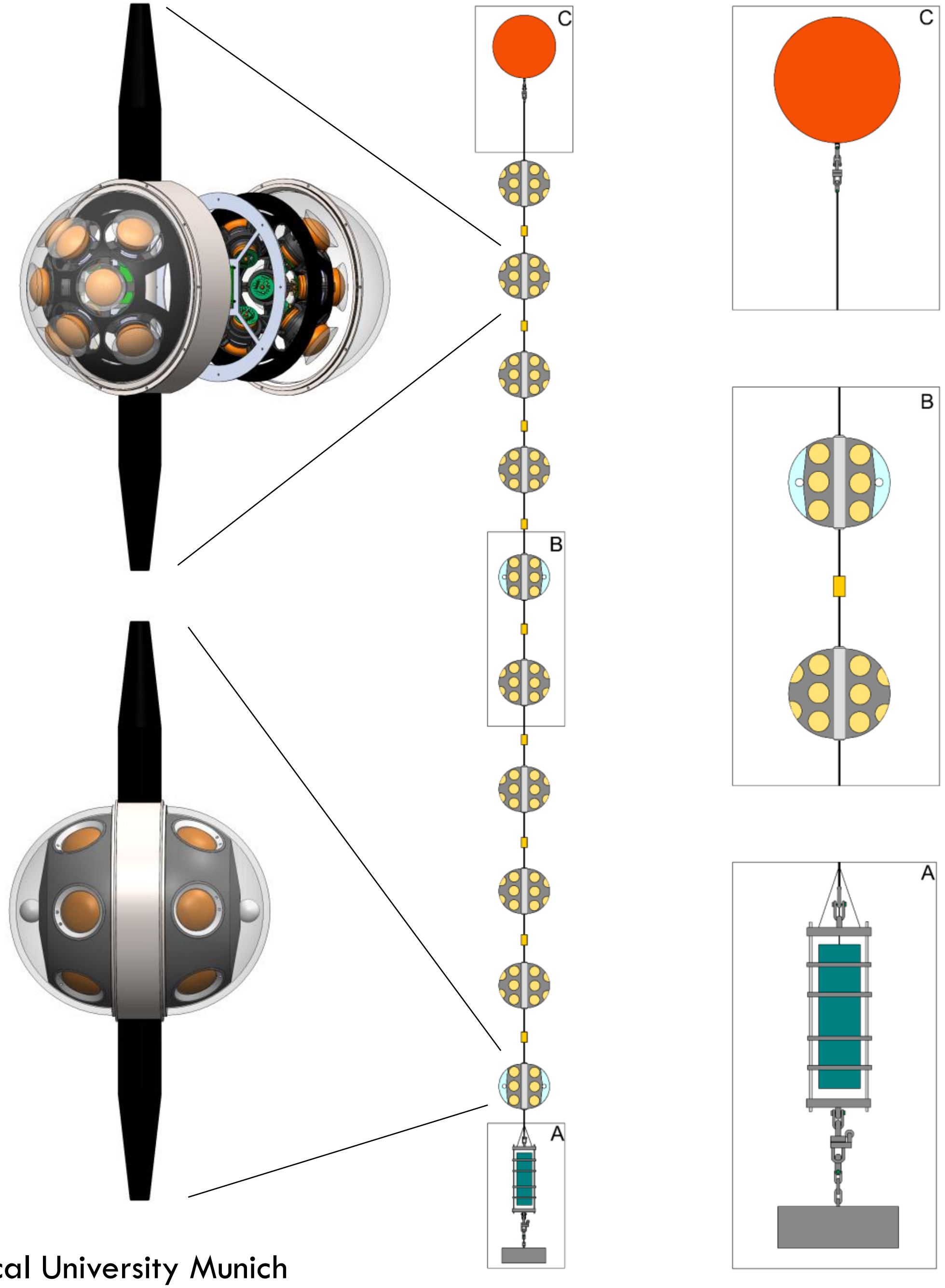



Lisa Schumacher, https://pos.sissa.it/395/1185/

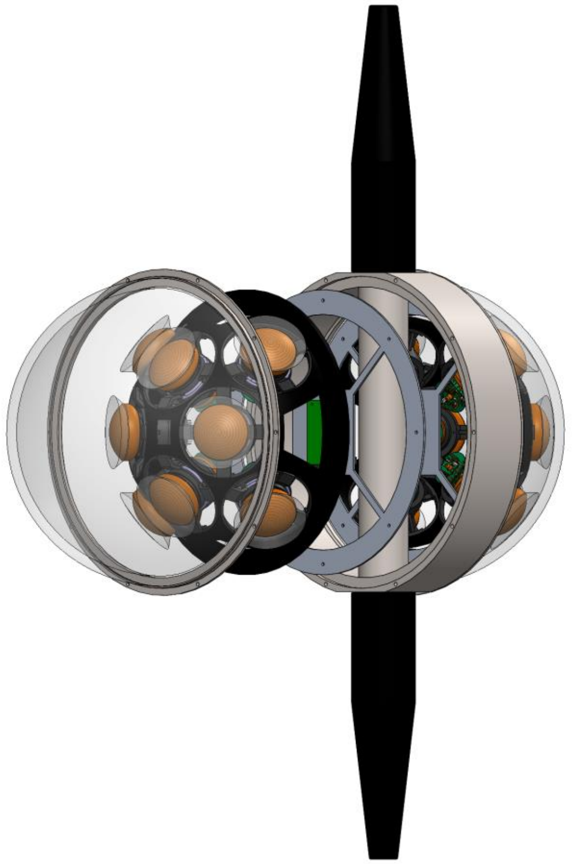
# P-ONE-1 overview

- **Project target:** Construction and deployment of a P-ONE mooring line as first installation of the final P-ONE detector. The prototype line shall verify the working principle, deployment technique, and be the blue print for the following mooring lines.

- **List of objectives:**
  1) 1st line of P-ONE
  2) Proof of deployment concept (scalability)
  3) Optical and calibration module development
  4) Time synchronisation for mooring line (and full P-ONE)
  5) Collect as much data as possible (understand data stream)

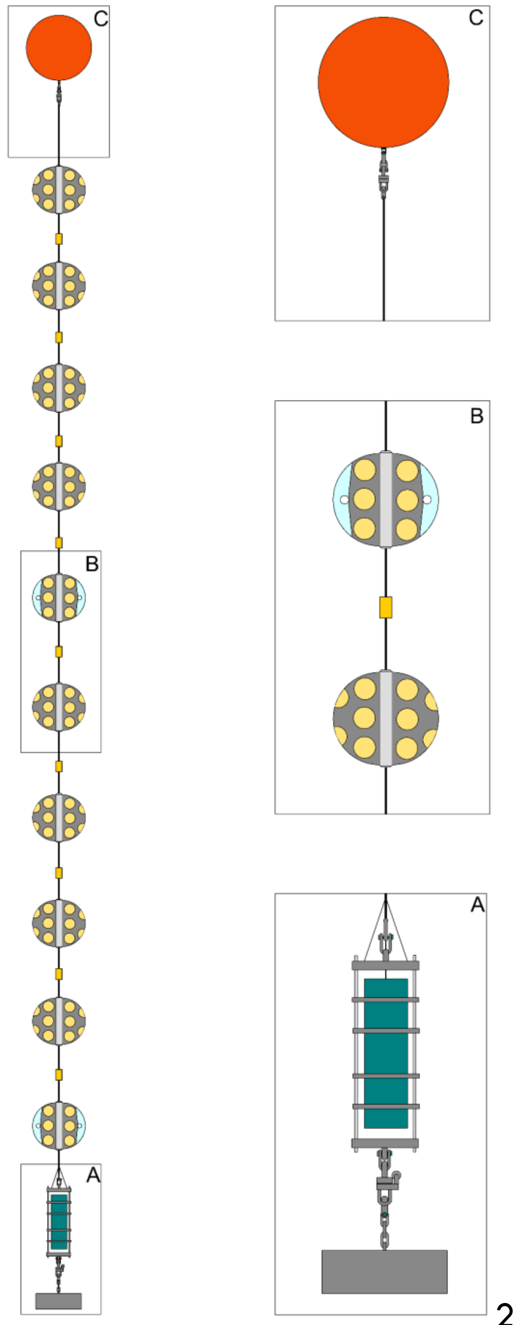


# P-ONE-1 overview



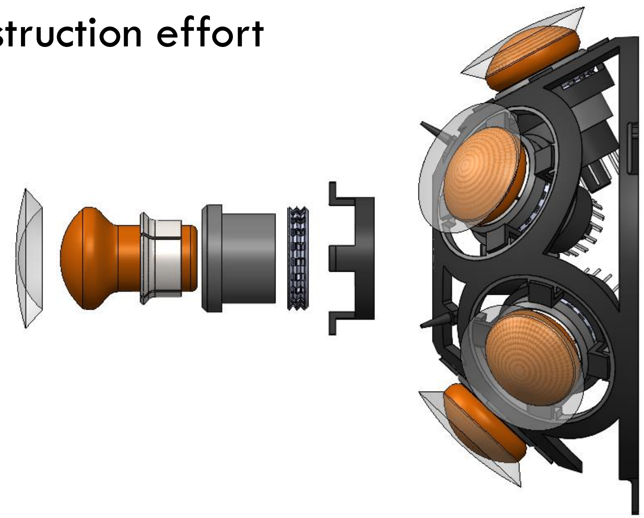
Optical Module | around 16 PMTs | 16 pcs

Calibration Module | hybrid module | 4 pcs

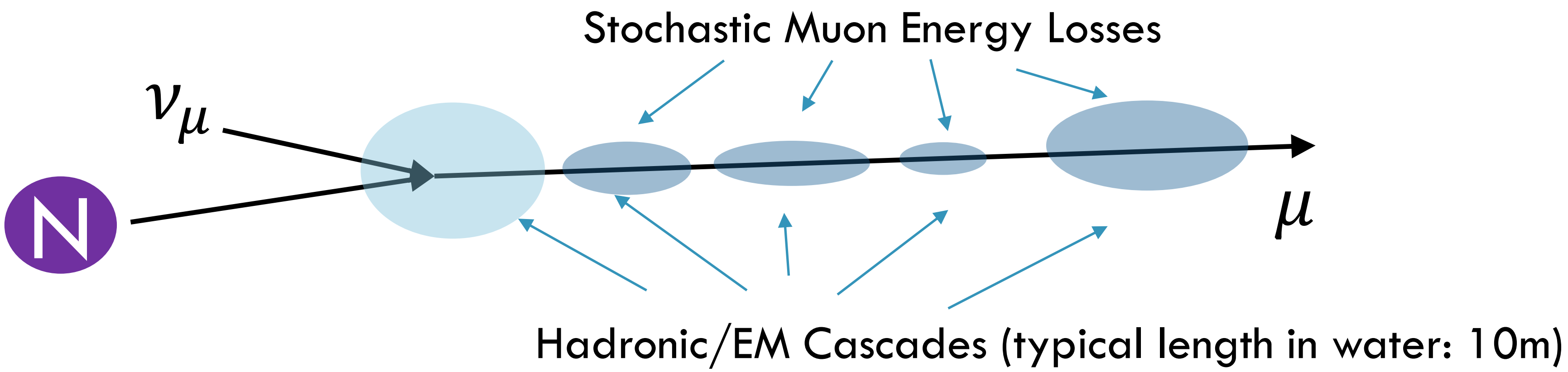


# P-ONE – optical module

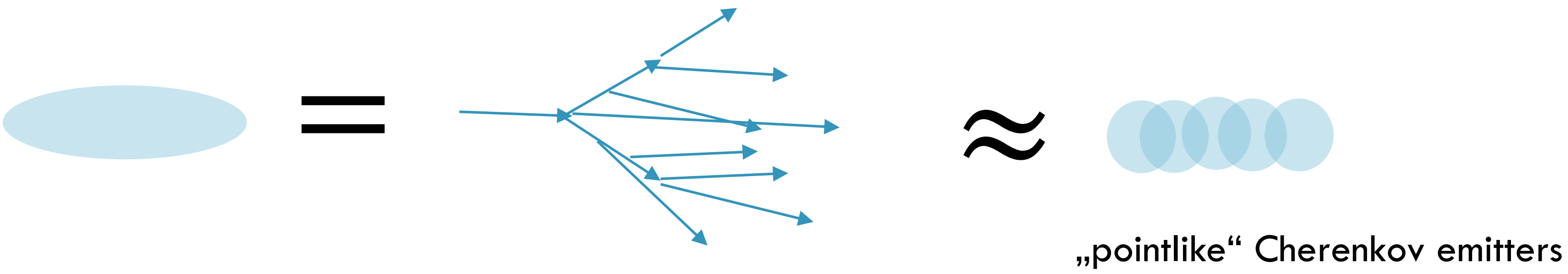
- Photomultiplier tubes (PMT) used as photosensors
- Multi-PMT approach
  - Biological processes are slow(er)
  - Suppression of background by requiring coincidence hits on PMTs (ns scale)
- Modular mounting structure to ease construction effort
- Electronics are currently developed



# Photon Surrogate Model




Approximate EM/Hadronic showers and muons with linear combination of „pointlike“ emitters



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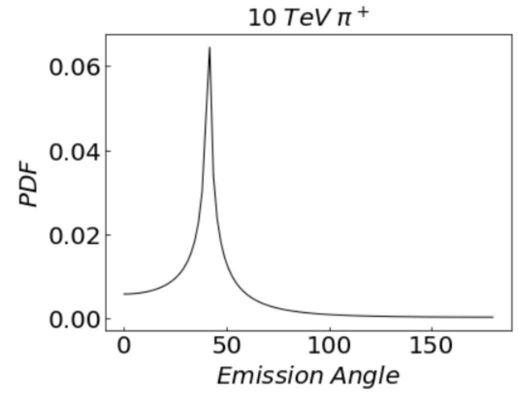
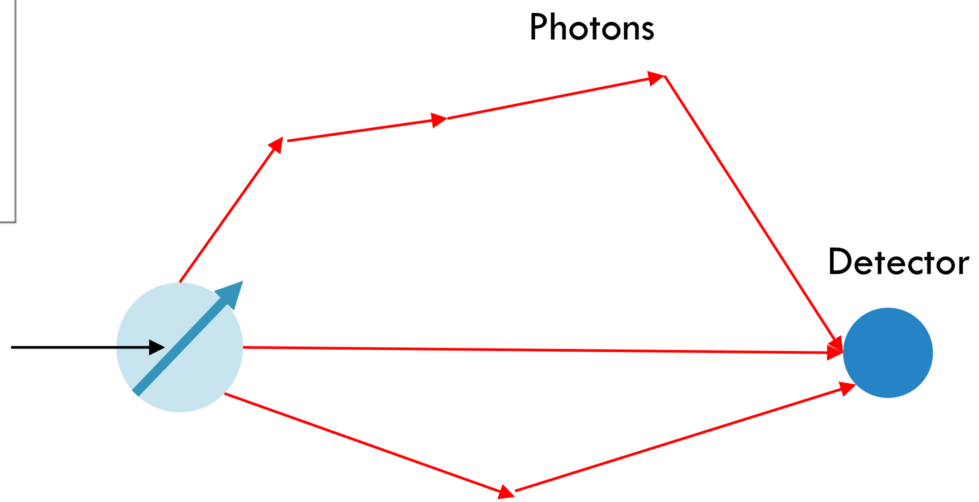
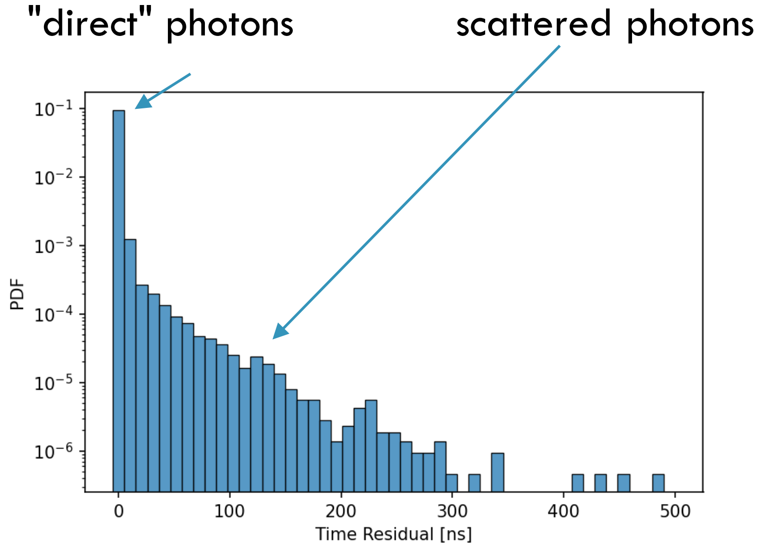


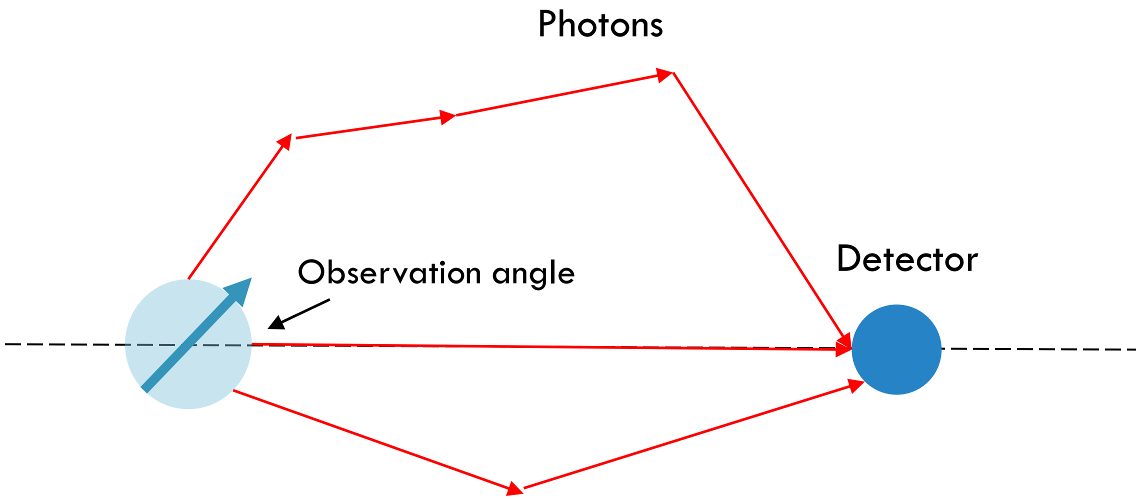



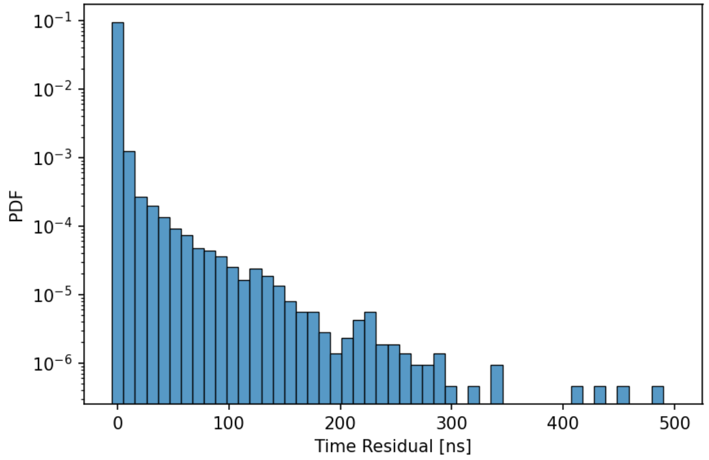

Arrival time relative to direct propagation time

*Hyperion* photon propagation code. Implemented in jax

https://github.com/pone-software/hyperion

# Photon Surrogate Model



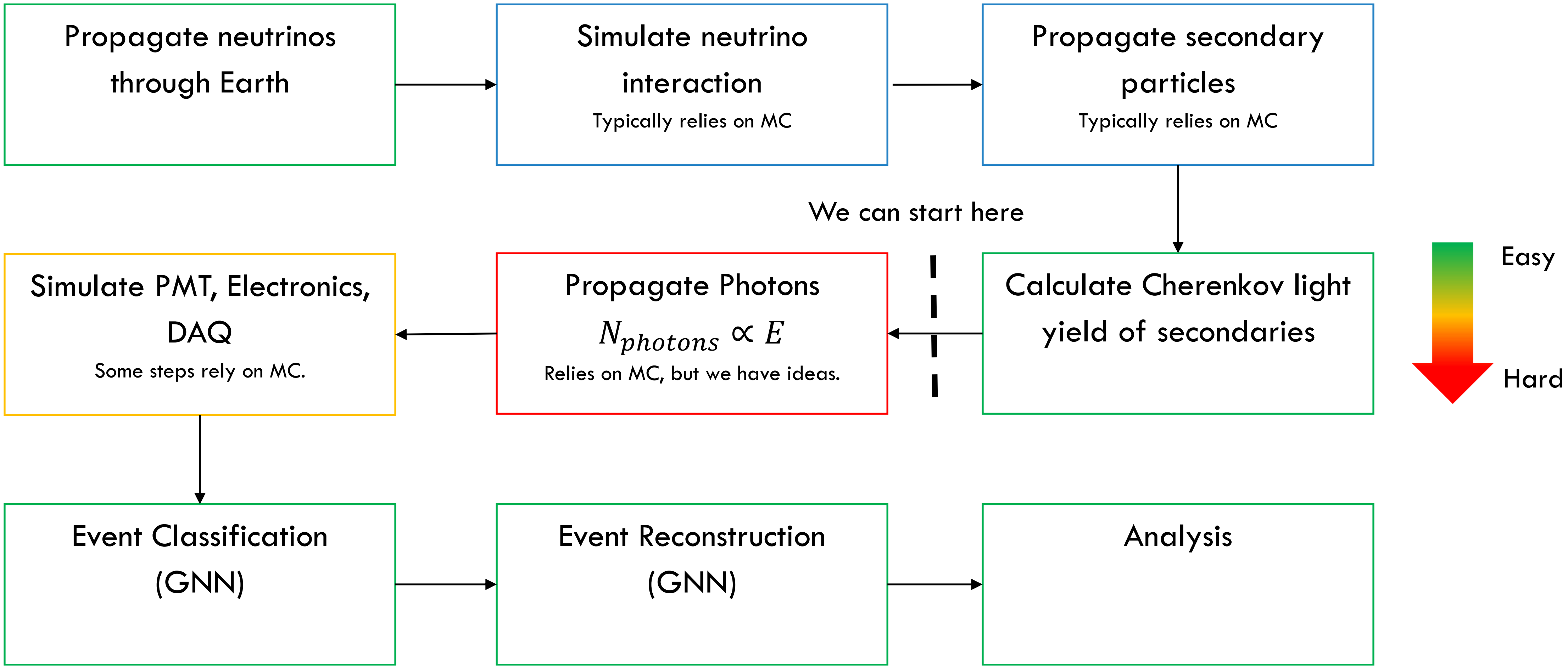

**Symmetries:** Time residual PDF depends only on distance and observation angle.

Use normalizing flow to fit conditional $f(t_{res}; \theta, d)$, where the flow parameters are parametrized by an MLP.

Using distrax + haiku

# Simulating a Neutrino Telescope

How difficult is to achieve differentiability for each step?



# Detector Optimization

**Spacing** → smaller distance: ↗ angular resolution, ↘ detector volume

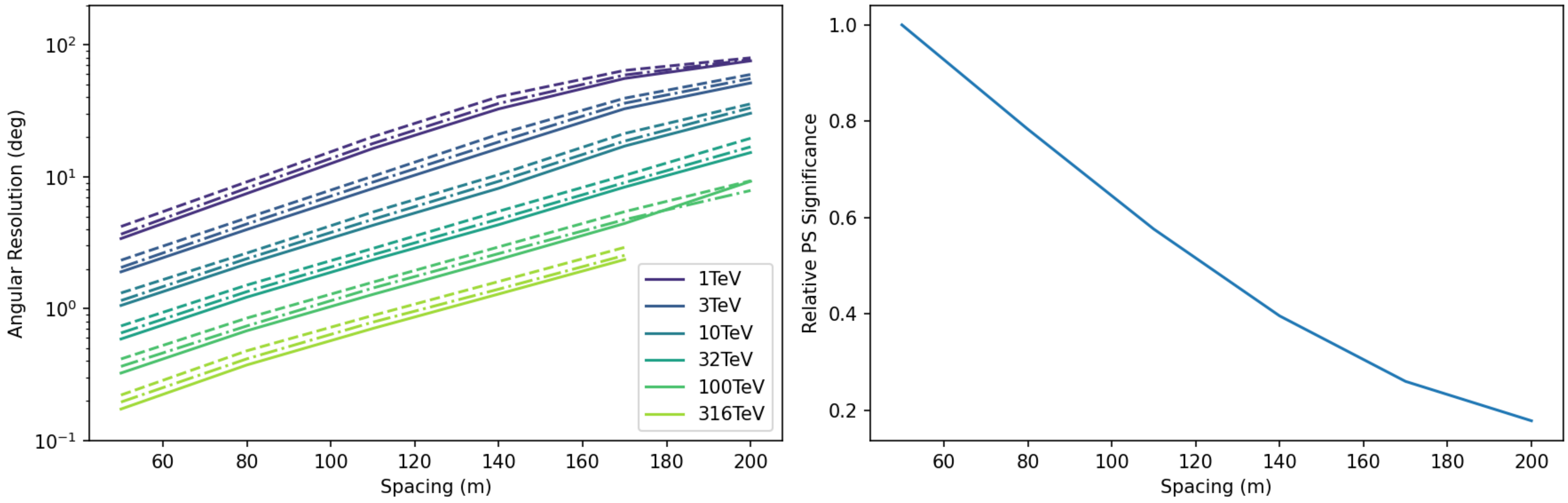



Figure: Preliminary angular resolution and point source significance of cascades for three strings by C. Haack