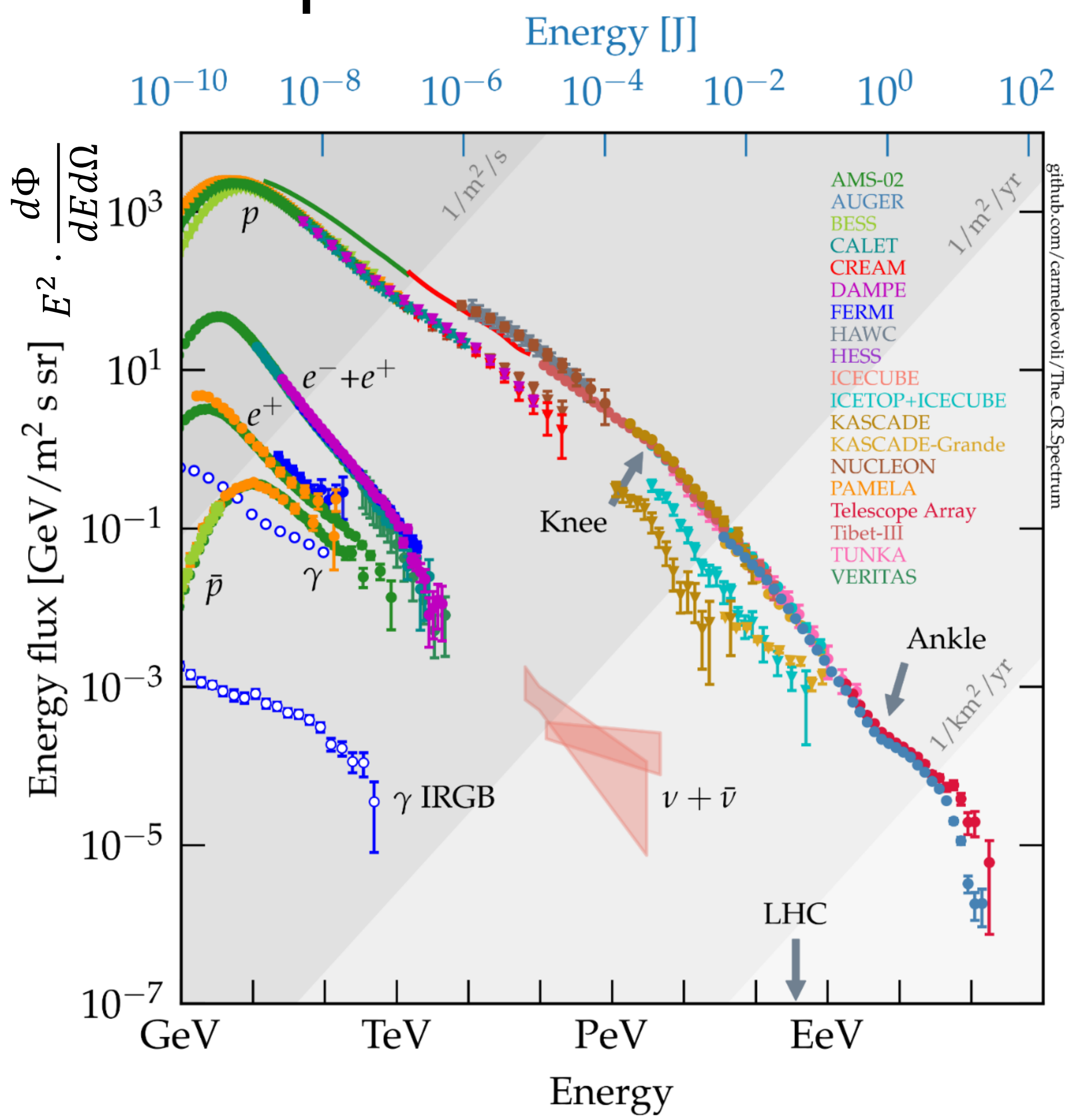
# P-ONE: Test Case for ML Based Detector Design

Christian Haack, Technical University of Munich
MODE Workshop, 07.09.2021

# Outline

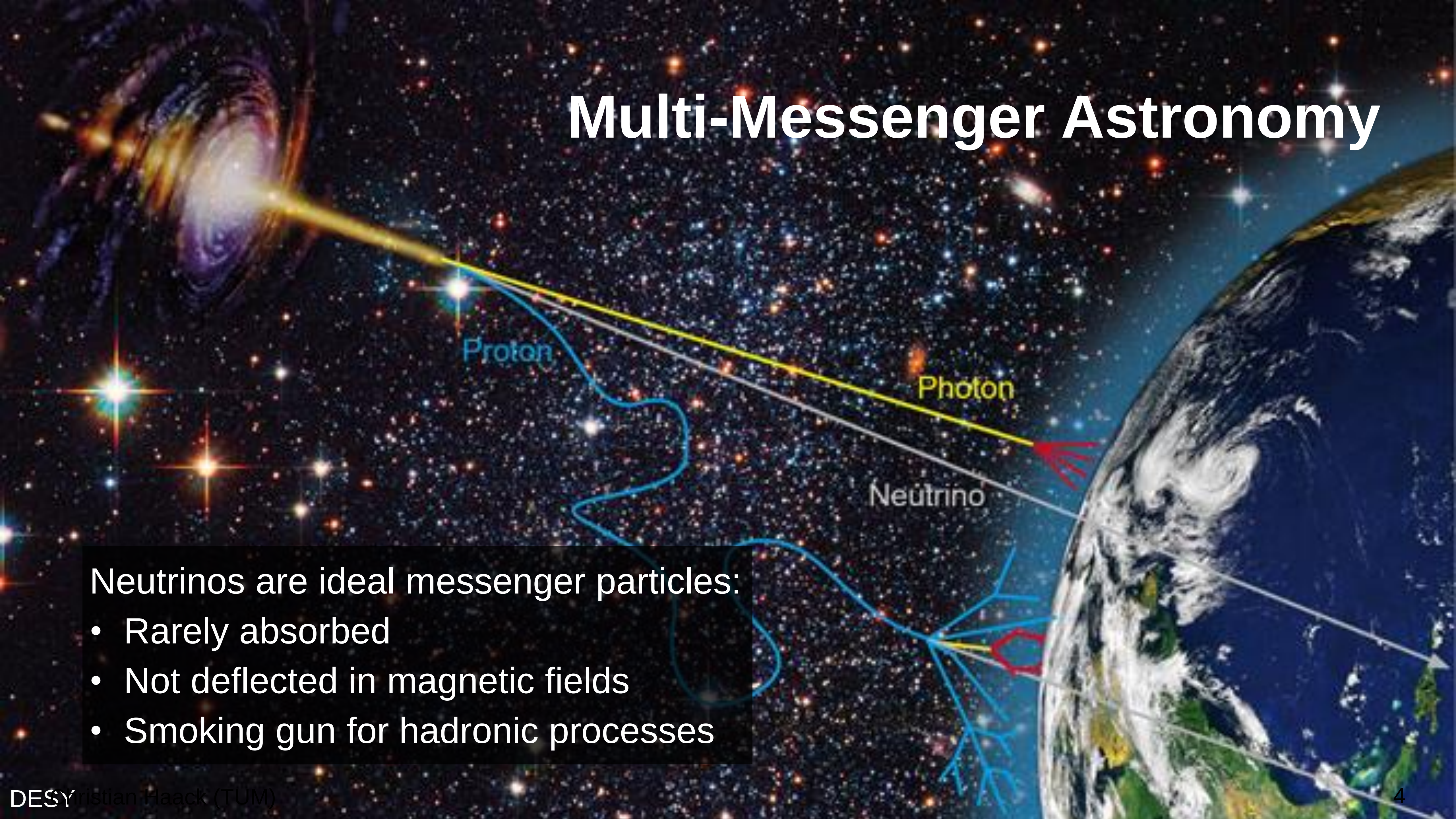
1. Introduction: Multi-Messenger Astronomy
2. Neutrino Telescopes
3. Pacific Ocean Neutrino Experiment (P-ONE)
4. P-ONE as Test-Case for Machine-learning Optimized Design of Experiments

# The Spectrum of Cosmic Rays



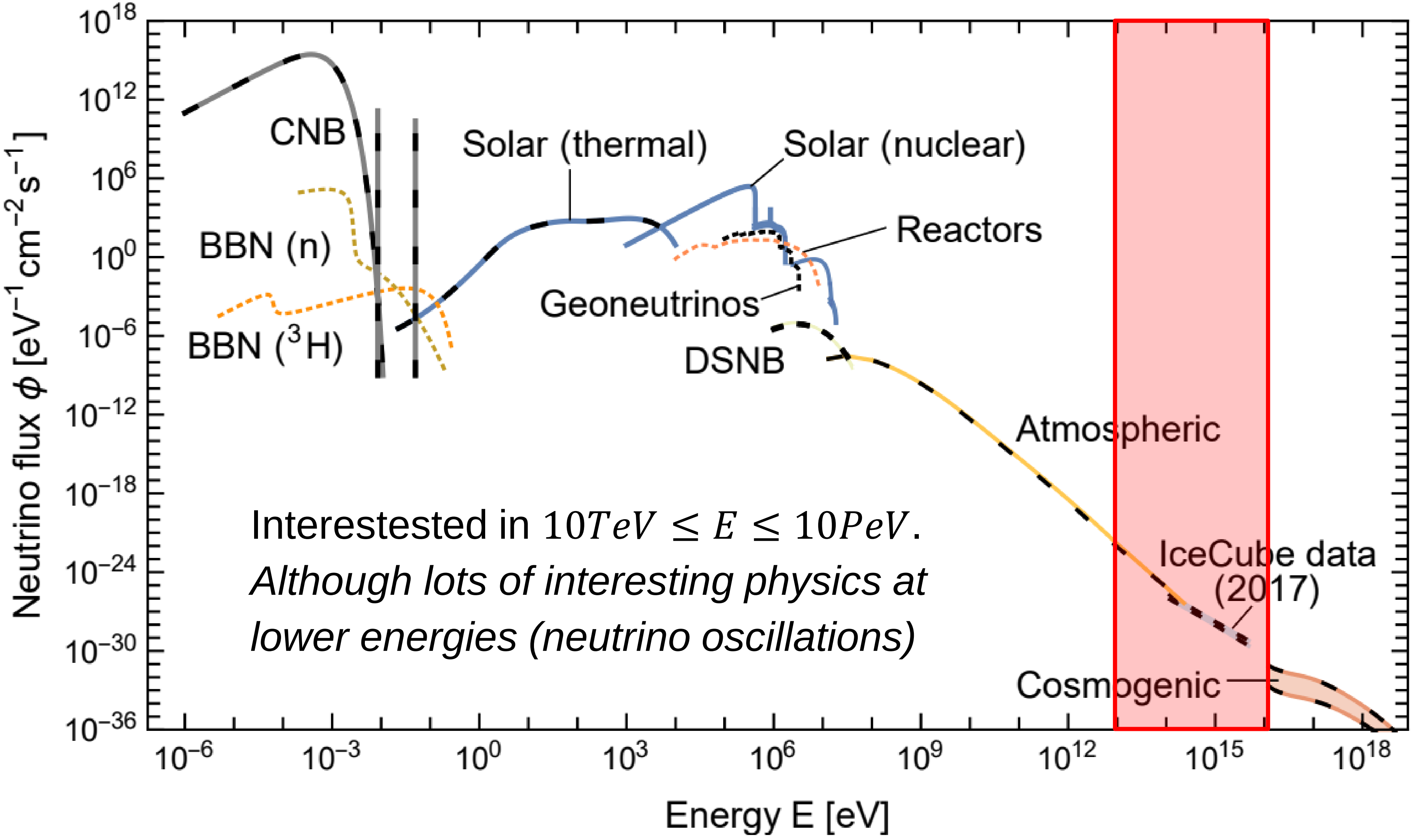

- Where do the highest energy CR come from?
- How are they accelerated?

# Multi-Messenger Astronomy




Neutrinos are ideal messenger particles:
- Rarely absorbed
- Not deflected in magnetic fields
- Smoking gun for hadronic processes

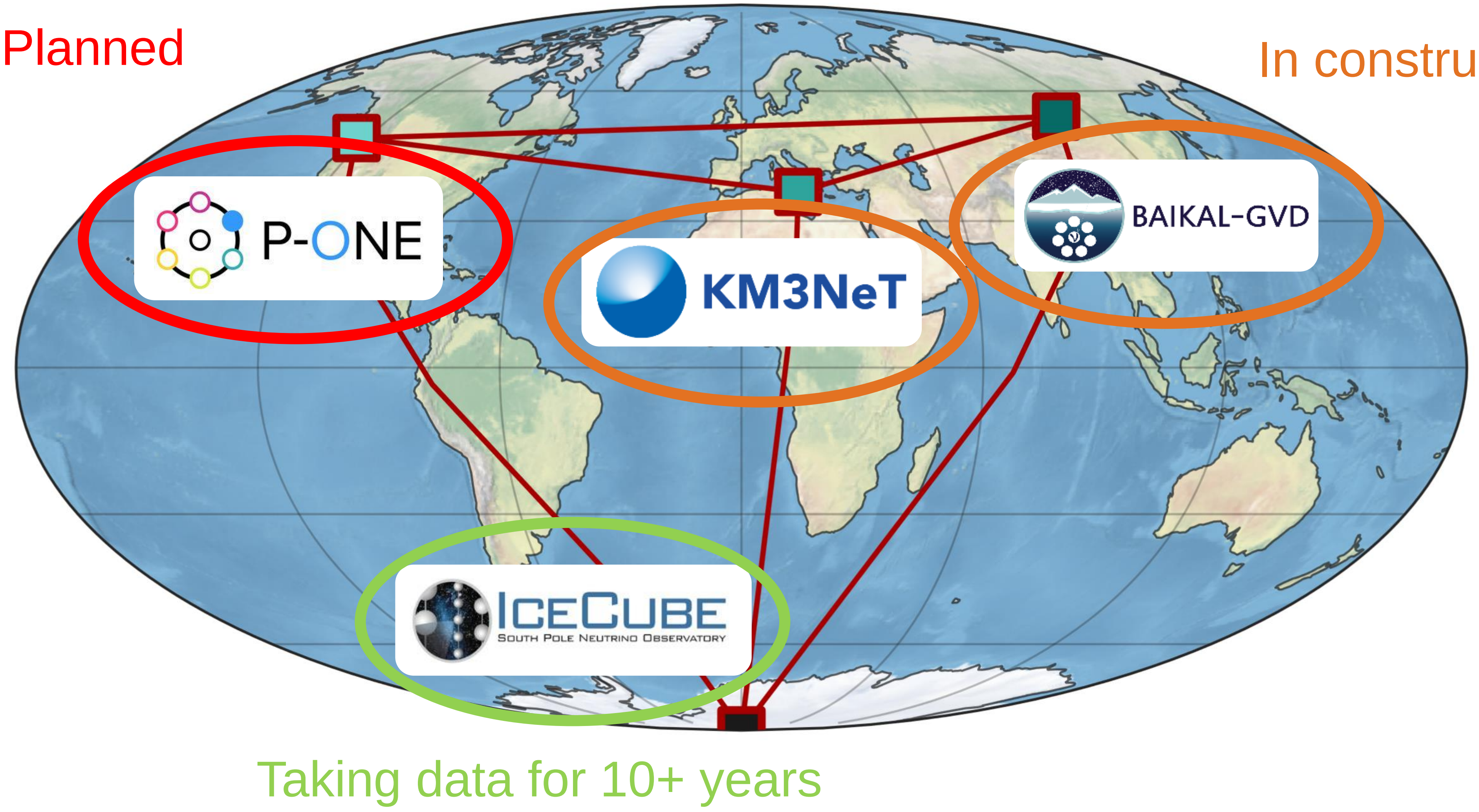
# Neutrino Fluxes at Earth




Interestested in $10TeV \leq E \leq 10PeV$.

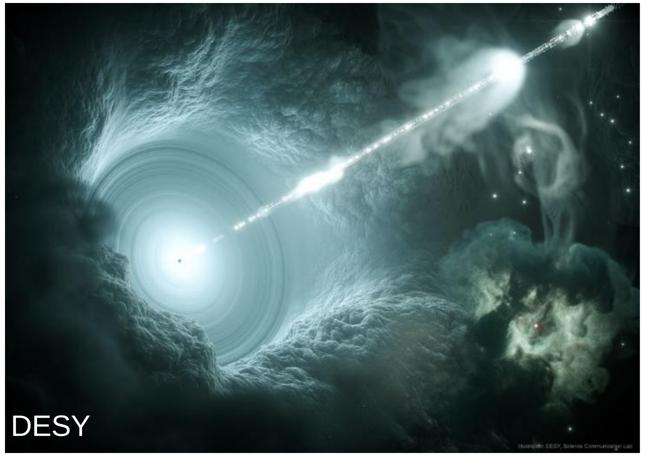
*Although lots of interesting physics at lower energies (neutrino oscillations)*

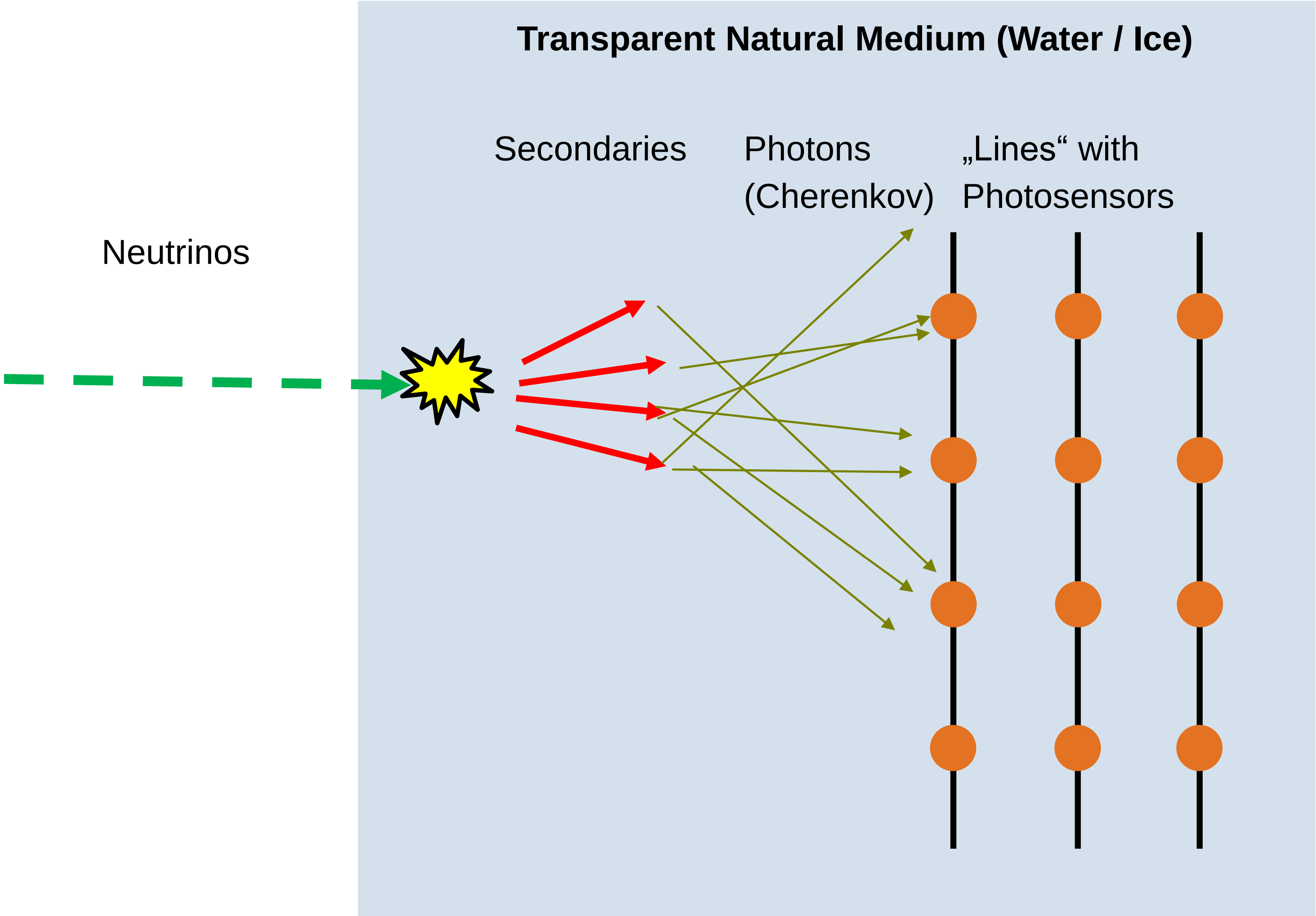
# High-Energy Neutrino Telescopes



# Detection Principle of Neutrino Telescopes

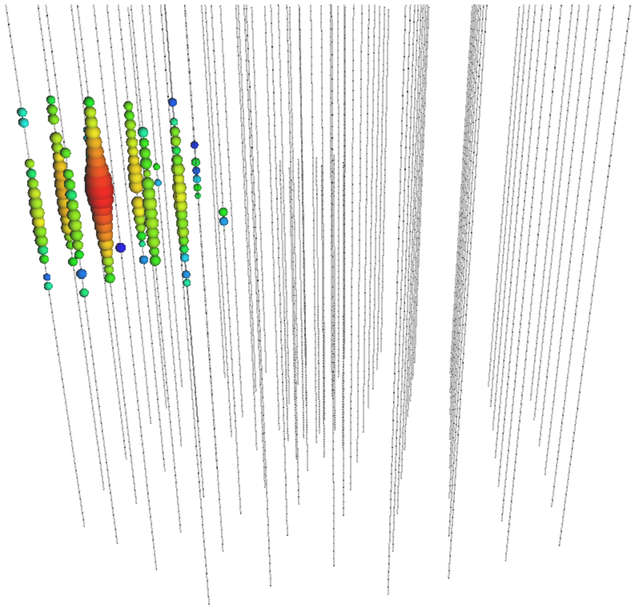
**Astrophysical Accelerator**

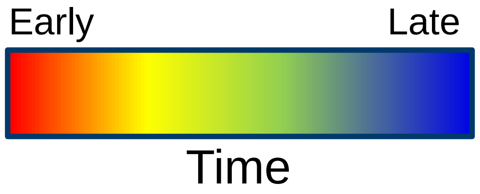


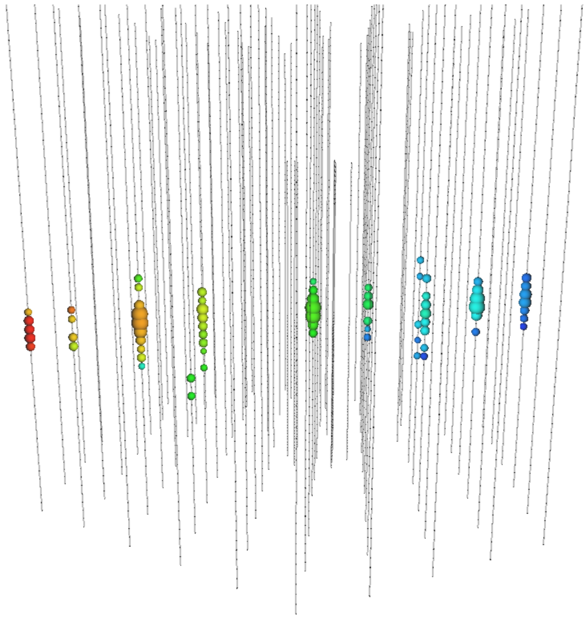
# Event Topologies in Nu-Telescopes

IceCube






IceCube



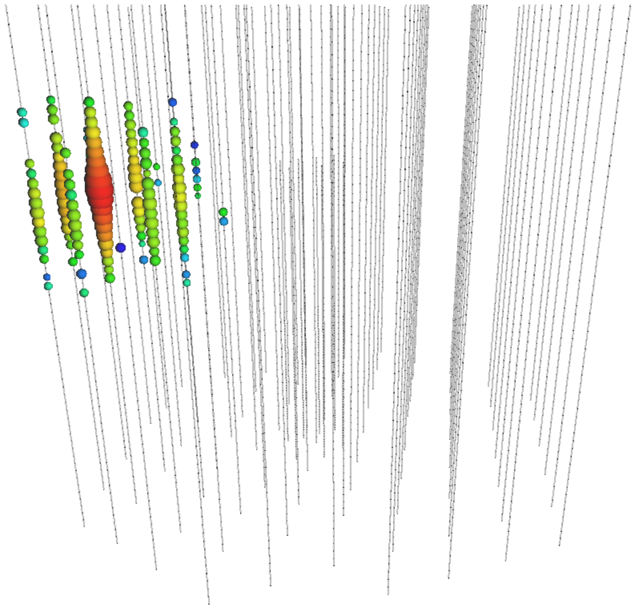
**(EM / Hadronic) Cascades**
Neutral Current (NC) & $\nu_e$ ($\nu_\tau$) Charged Current (CC)
Typically good energy resolution
Good for spectral measurements

**Throughgoing Tracks (muons)**
E.g. from $\nu_\mu$ CC, but also atmospheric
Typically good angular resolution
Good for finding pointsources

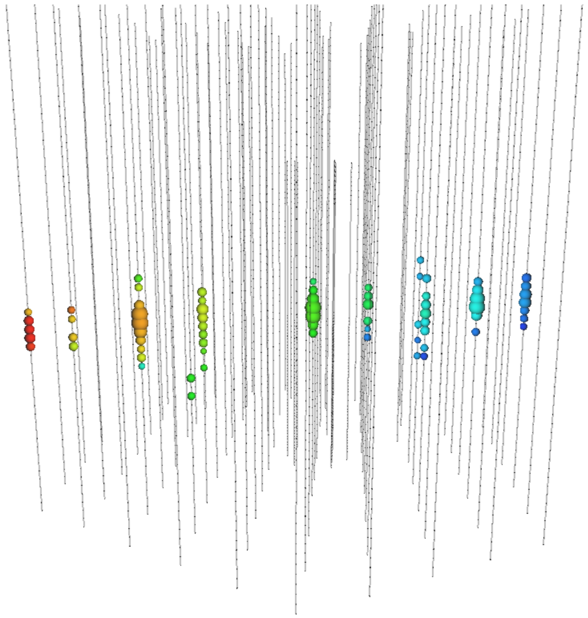
# Why do we need another neutrino telescope?

# Event Topologies in Nu-Telescopes

IceCube



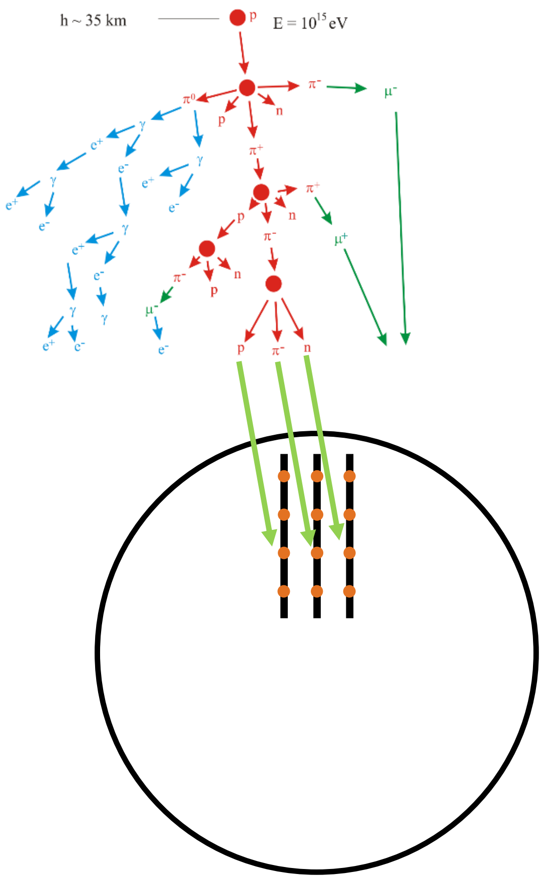

IceCube



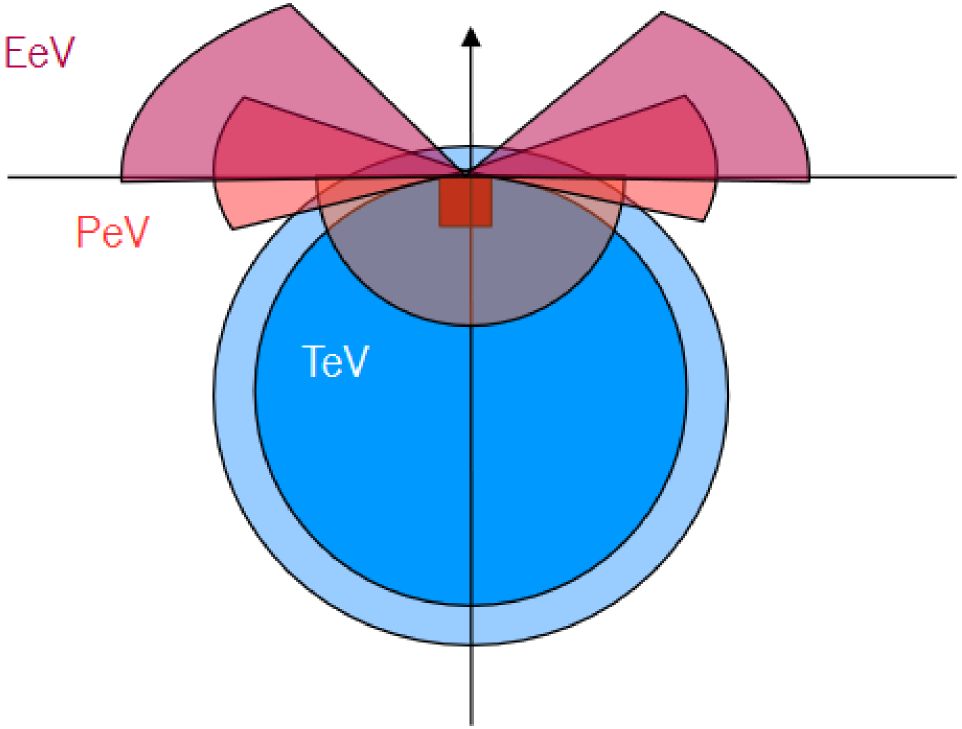
**(EM / Hadronic) Cascades**
Neutral Current (NC) & $\nu_e$ ($\nu_\tau$) Charged Current (CC)
Typically good energy resolution
Good for spectral measurements

**Throughgoing Tracks (muons)**
E.g. from $\nu_\mu$ CC, but also atmospheric
Typically good angular resolution
Good for finding pointsources

# The Track Channel



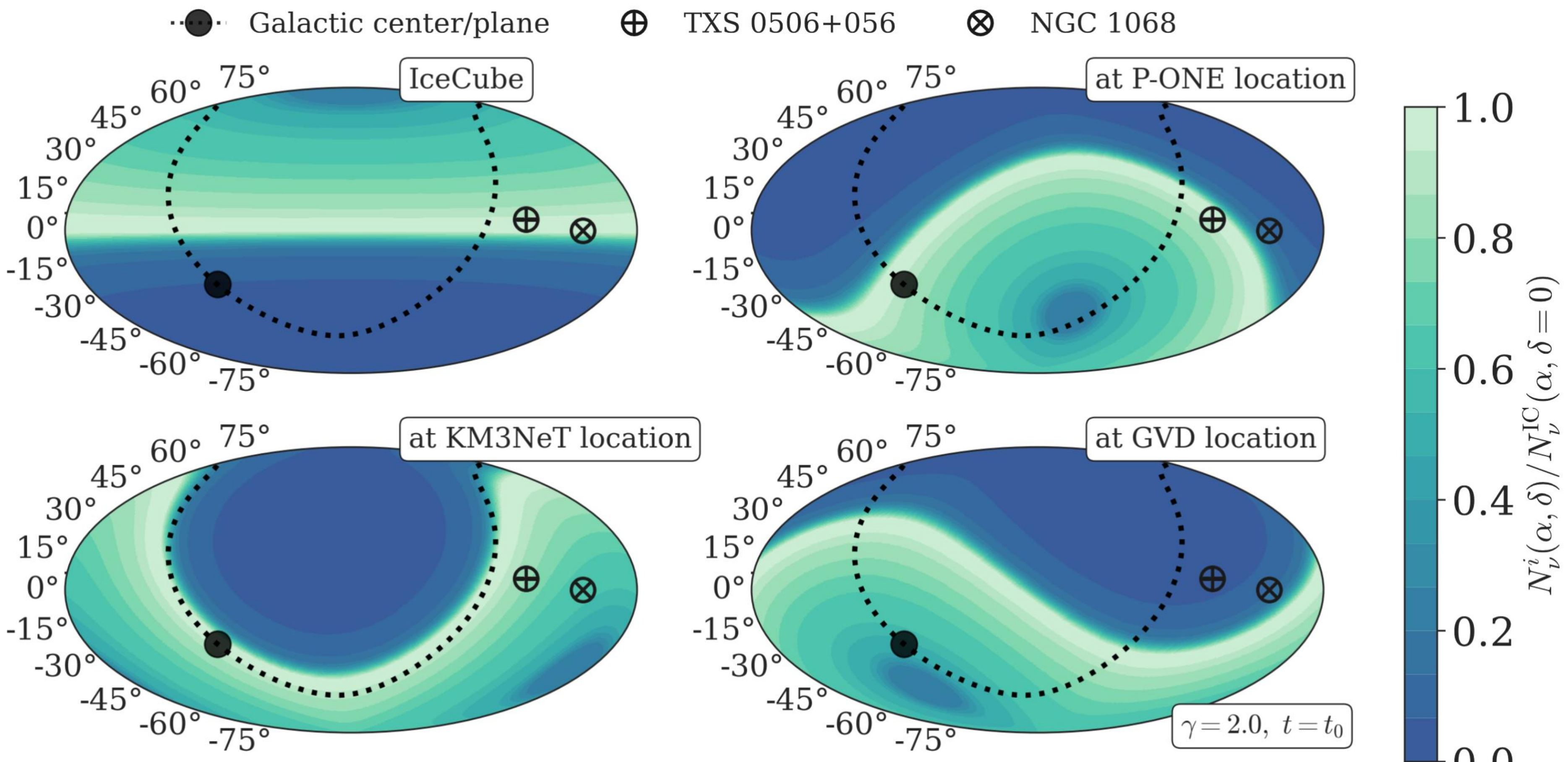

Sketch by Antoine Kouchner




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

Horizontal region optimal for observing high-energy tracks

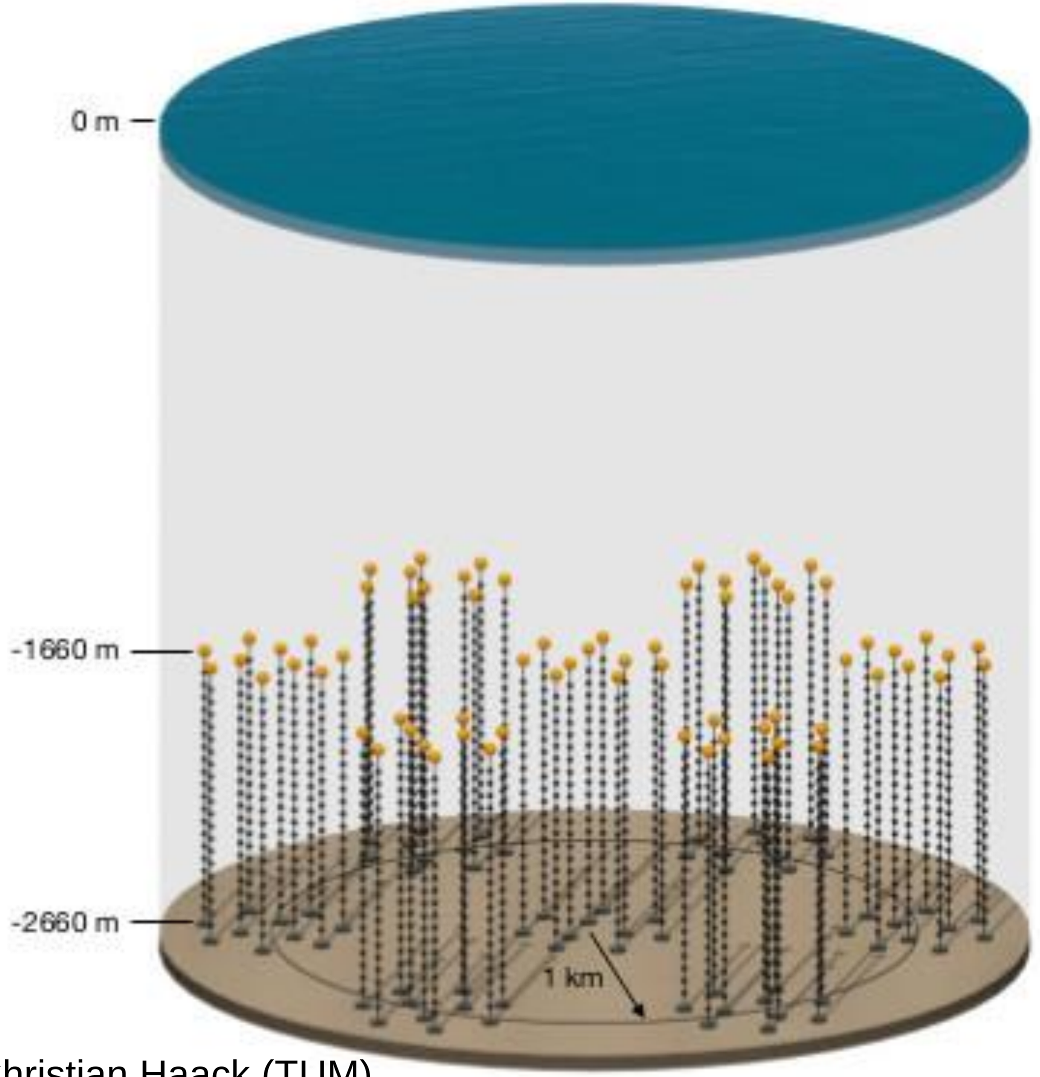
# Relative Sensitivies



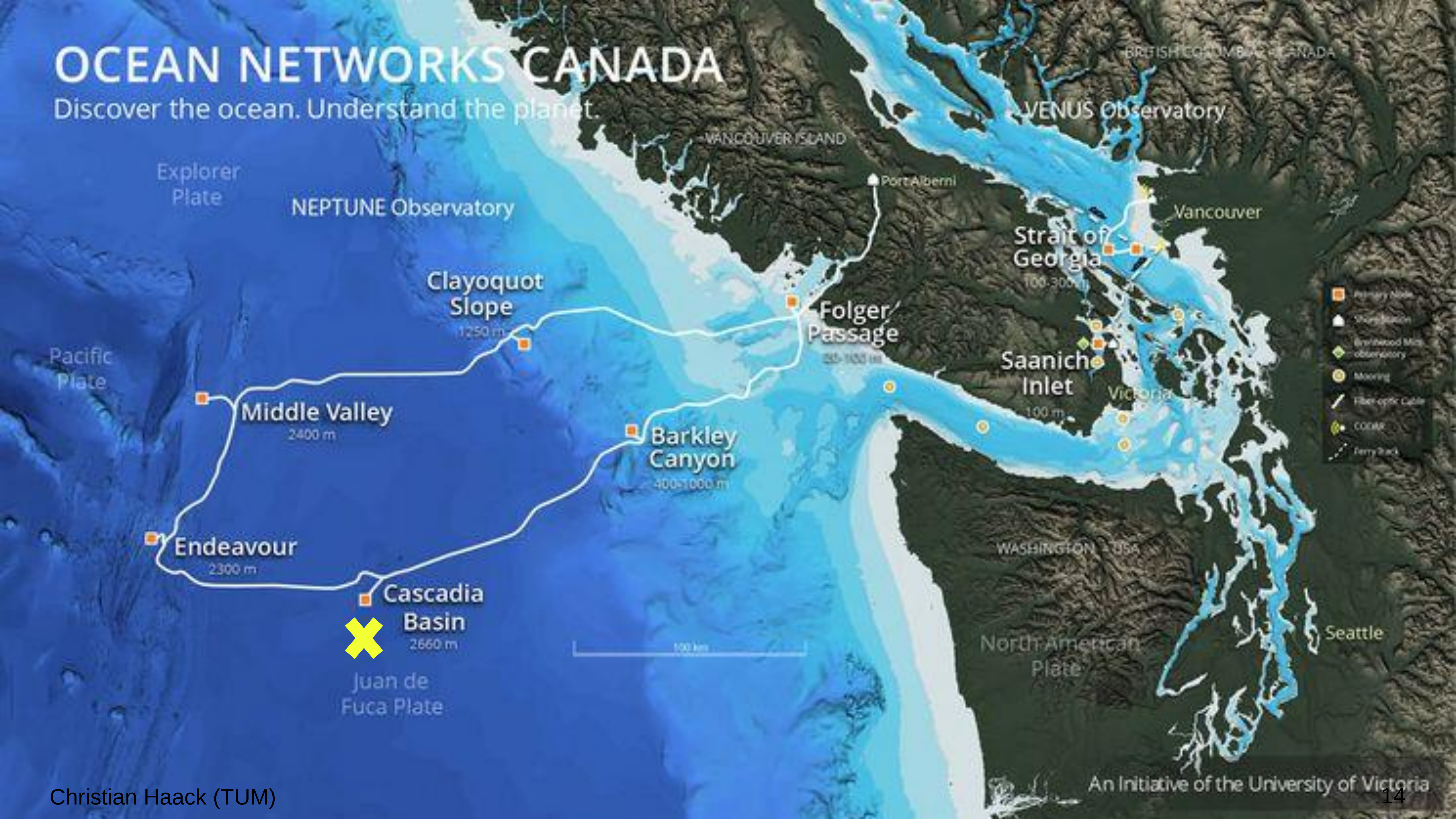

Lisa Schumacher, https://pos.sissa.it/395/1185/

# The Pacific Ocean Neutrino Experiment

## First Vision

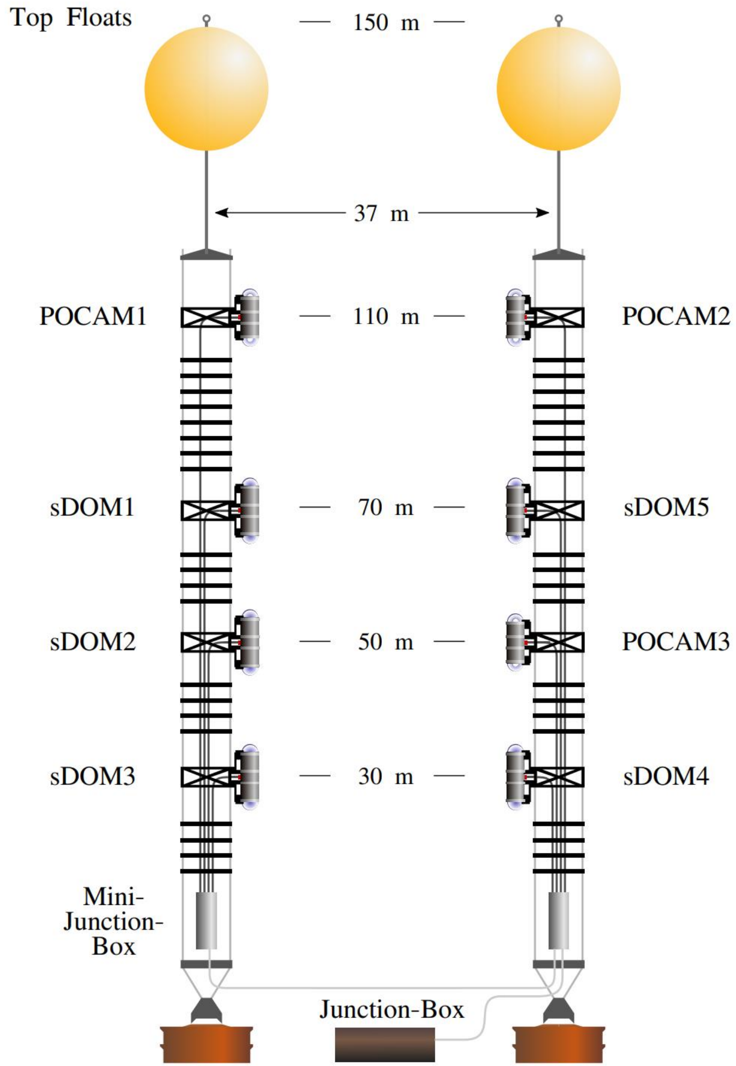


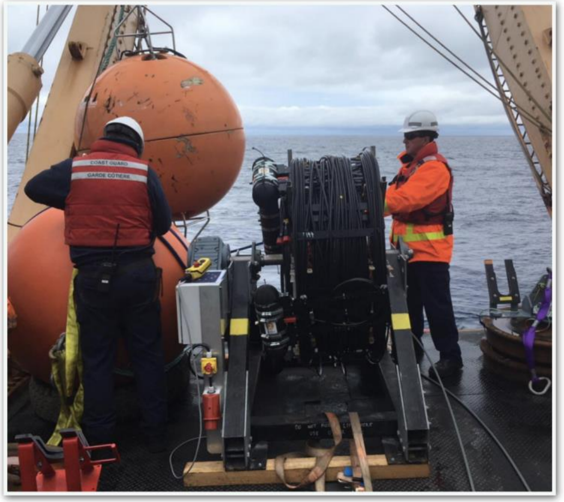

First Neutrino Telescope hosted by an existing large scale oceanographic infrastructure: *Ocean Networks Canada*

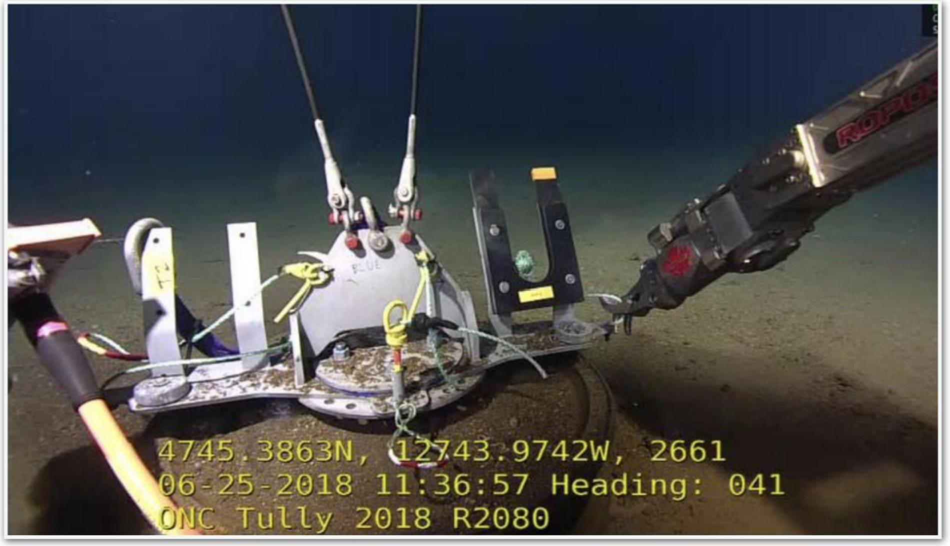


OCEAN NETWORKS CANADA
Discover the ocean. Understand the planet.
BRITISH COLUMBIA, CANADA
VENUS Observatory
VANCOUVER ISLAND
Port Alberni
Explorer Plate
NEPTUNE Observatory
Vancouver
Strait of Georgia
Clayoquot Slope
1250 m
Folger Passage
Pacific Plate
Saanich Inlet
100 m
Victoria
Middle Valley
2400 m
Barkley Canyon
400-1000 m
Endeavour
2300 m
WASHINGTON – USA
Cascadia Basin
2660 m
Seattle
North American Plate
Juan de Fuca Plate
An Initiative of the University of Victoria

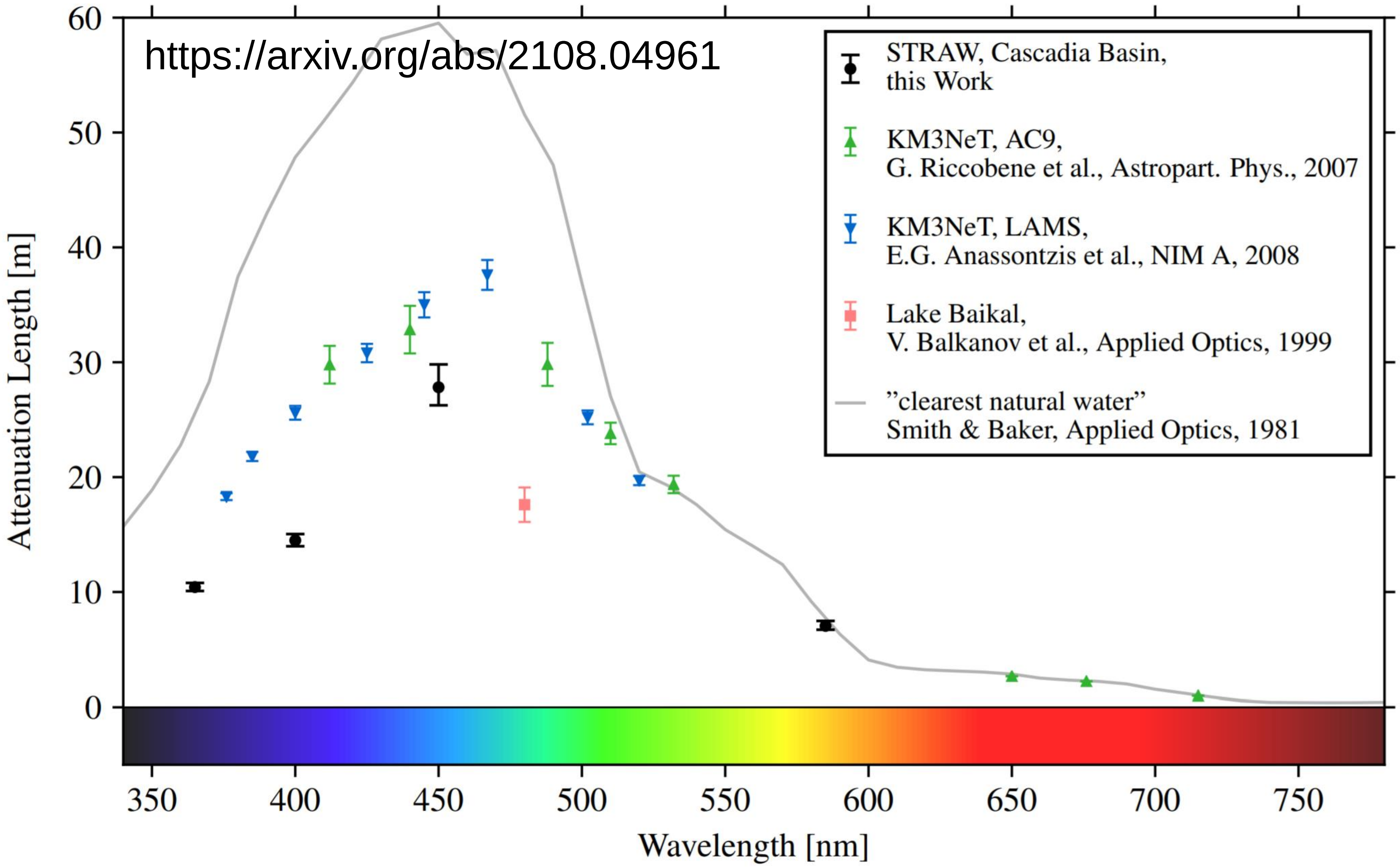
# Two Pathfinder Missions (2018, 2020)





# Optical Properties @ Cascadia Basin

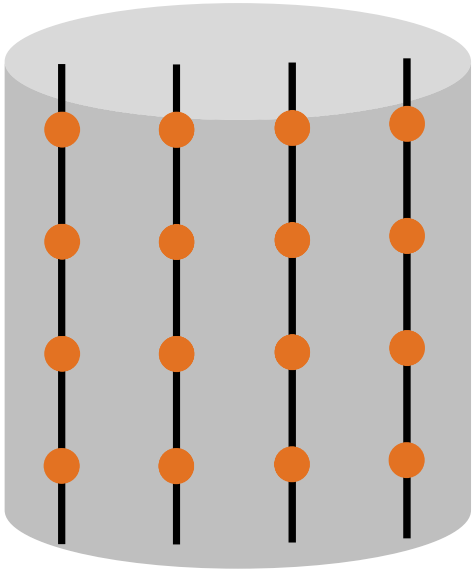


What is the best detector geometry to achieve our science goals?

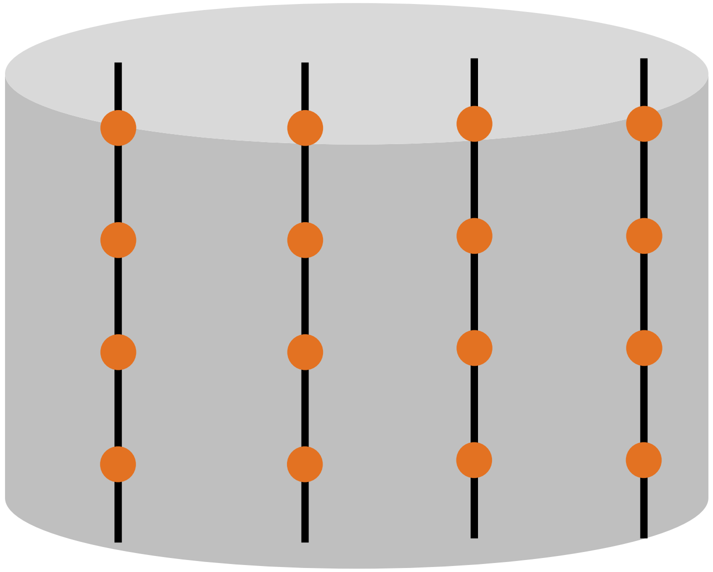
# Key Geometry Parameters for Tracks

## Acceptance

Above detection threshold, acceptance is proportional to the detector cross section relative to the track direction



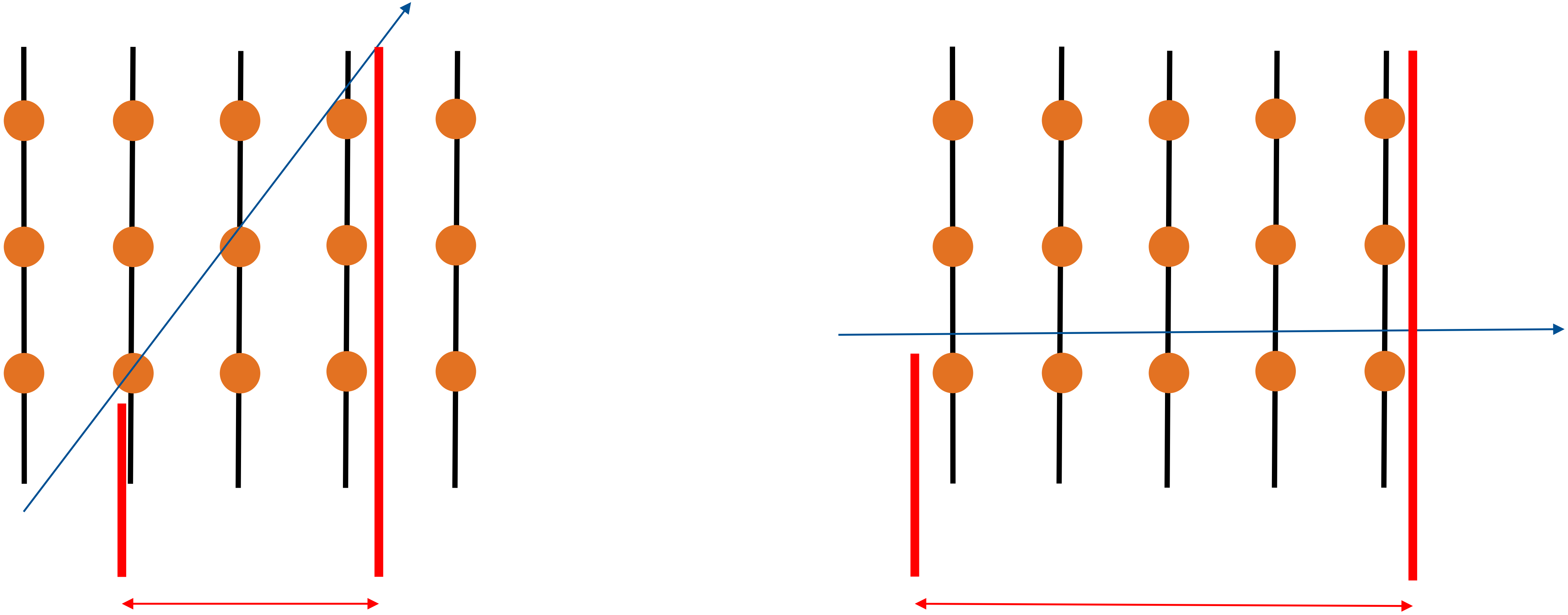
Small acceptance for horizontal track



Large acceptance for horizontal tracks

# Key Geometry Parameters for Tracks

## Angular Resolution



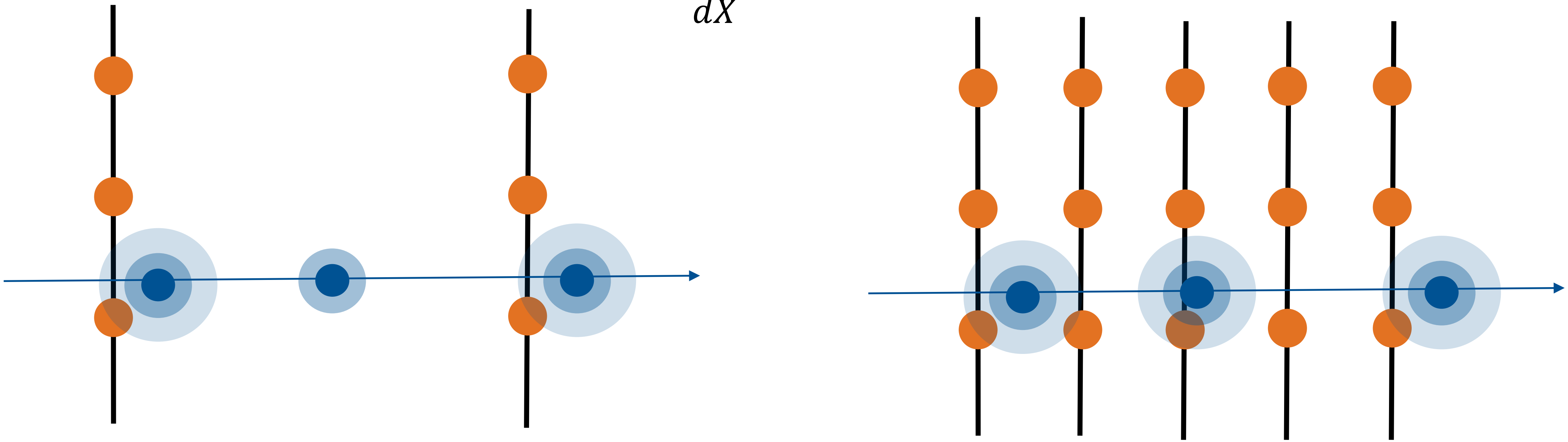
„Lever arm“

Angular resolution improves for larger lever arm

# Key Geometry Parameters for Tracks

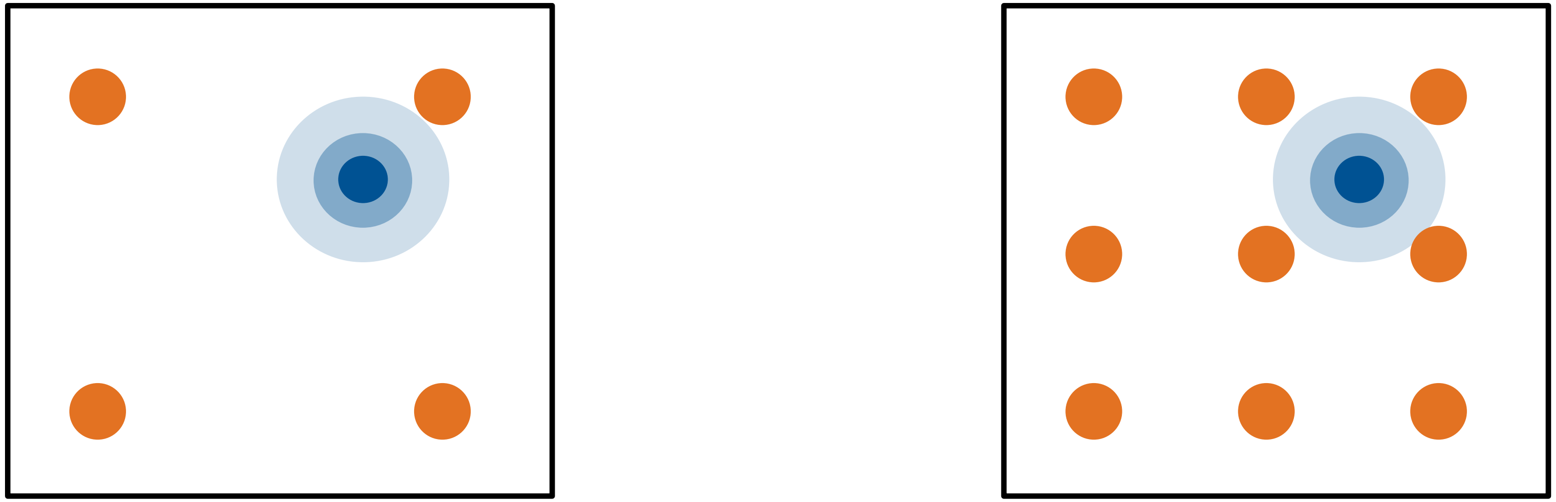
## Energy Resolution

$$\frac{dE}{dX} = a + bE$$



Energy resolution (dE/dX) improves with higher sensor density

# Key Geometry Parameters for Cascades



Energy & directional resolution improves with higher sensor density.
Acceptance proportional to instrumented volume.

# The „Perfect“ Neutrino Telescope

**Constraints**

- Photosensors need to be vertically aligned on lines (deployment)
- Each line adds significant overhead (cable cost) -> number of lines is limited by money

**Minimal**

IceCube as reference:

- *All flavor* acceptance (poor $\nu_\tau$ id)
- 100 GeV energy threshold
- $1km^3$ volume
- 0.3° track ang. resolution
- 5-10° cascade ang. resolution
- 10% cascade energy resolution

**Optimal?**

- Result of optimization of sensitivity wrt. cost
- Depends on volume and photosensor distribution

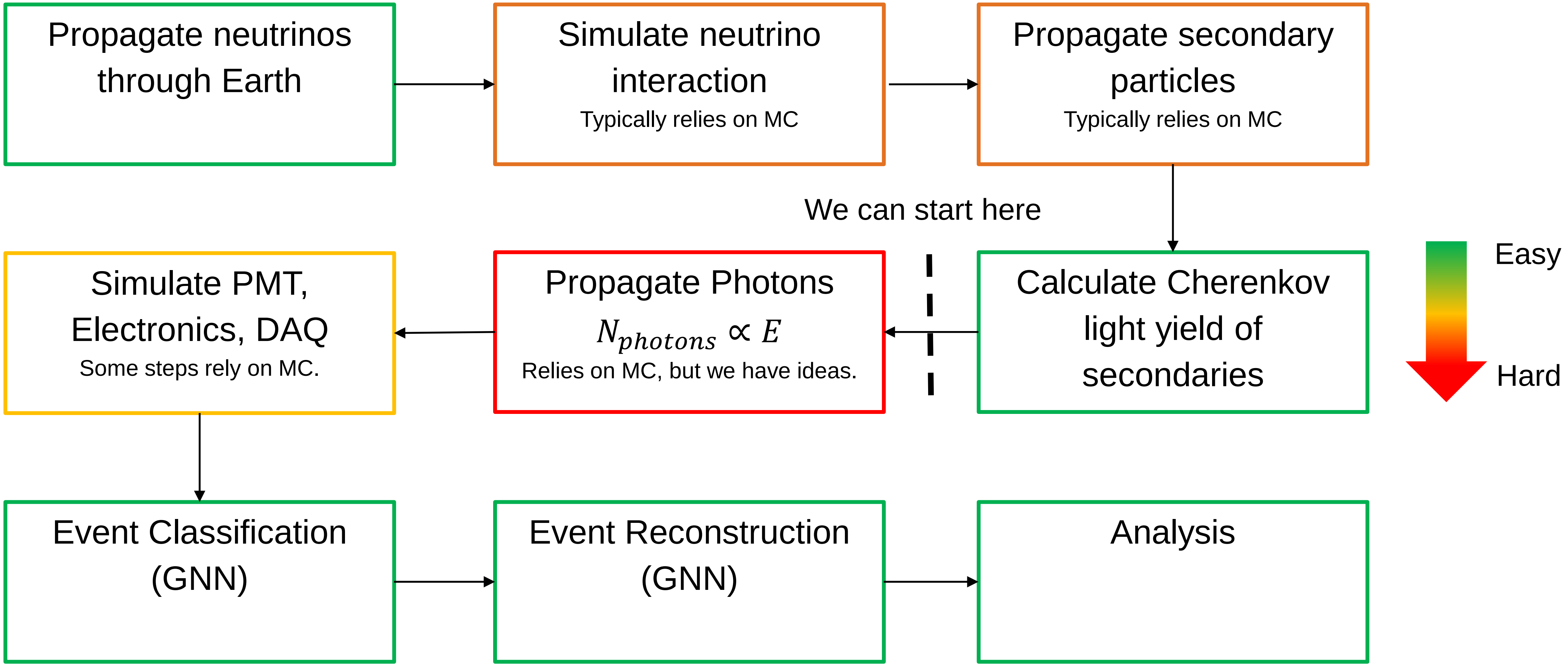
**Perfect**

∞ €

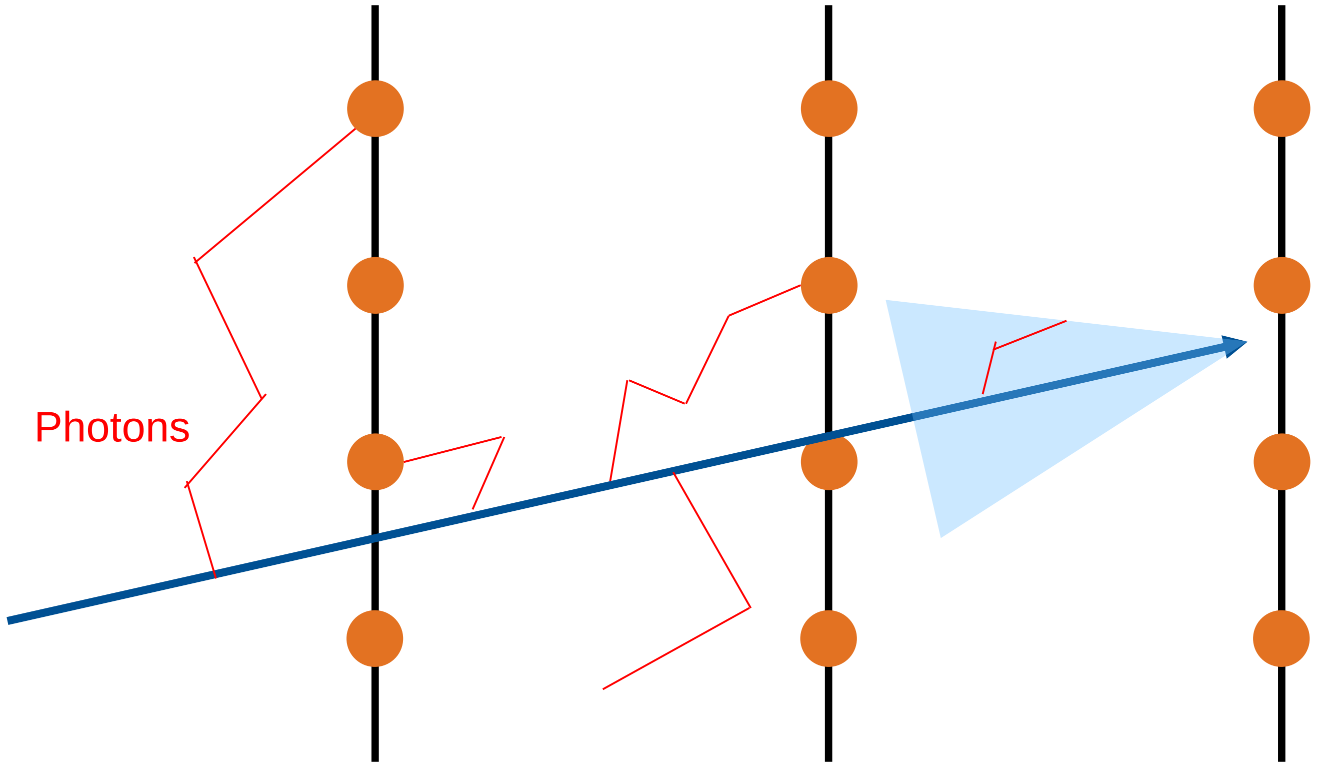
- 99.9% efficient flavor id
- 100 GeV energy threshold
- $100km^3$ volume
- <0.1° track ang. resolution
- 1° cascade ang. resolution
- 1% cascade energy resolution

# Simulating a Neutrino Telescope

How difficult is to achieve differentiability for each step?



# Photon Propagation




MC Photon propagation
absorption / scattering

~ 1E5 photons / GeV
⇒ 1E11 photons for PeV energy deposits

On modern GPU‘s ~ ns / photon

Can precalculate LUT for emitter / receiver pairs => Ideal for neural networks!

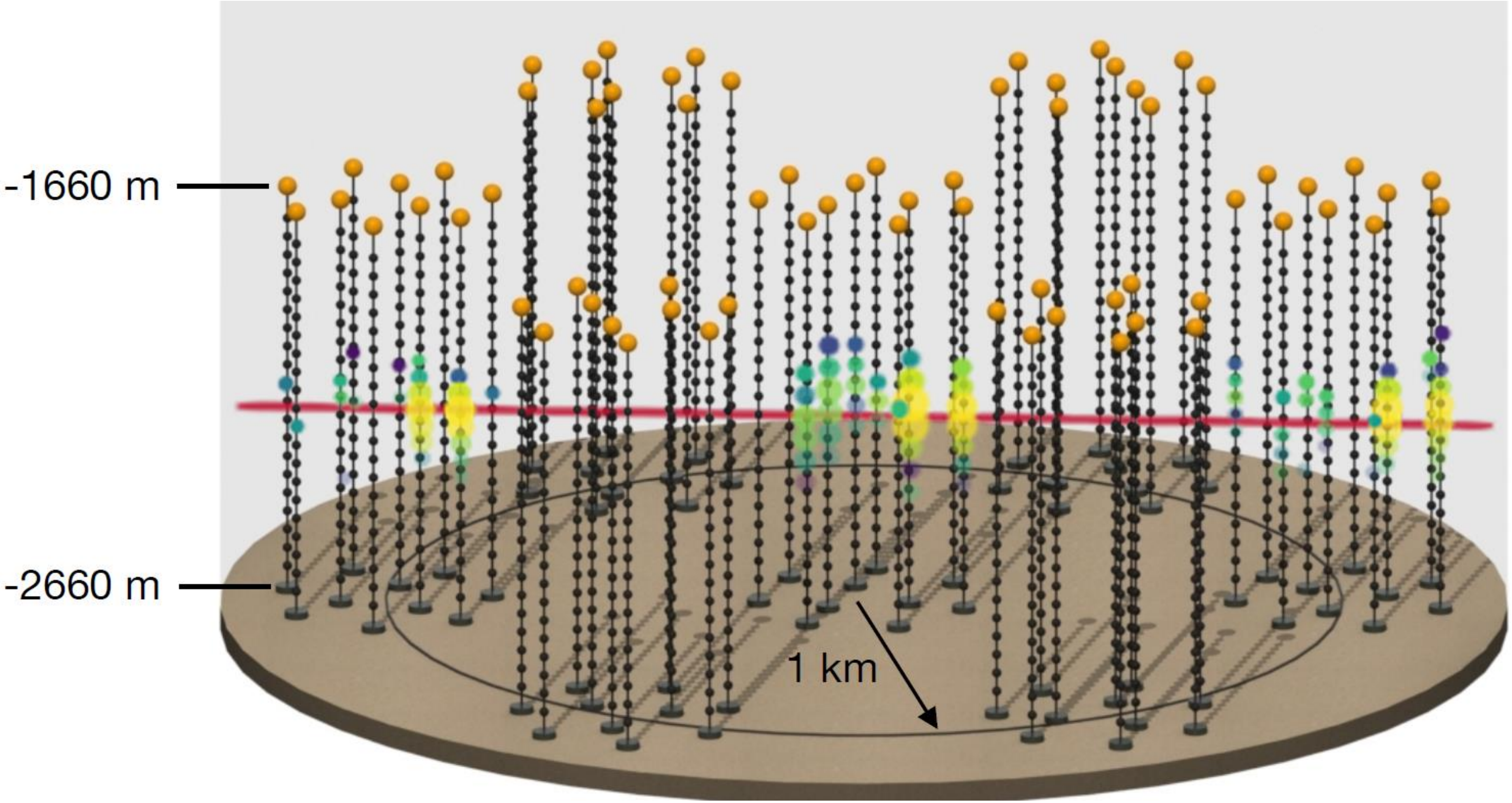
Maybe differentiable programming?

# Summary

- Neutrino telescopes are an integral part to further our understanding of the high-energy Universe
- Need to have multiple telescopes across the globe to achieve good all-sky performance
- P-ONE is a planned neutrino telescope to be hosted in an existing oceanographic infrastructure
- Due to its (relatively) simple detector design, P-ONE could be an ideal test-case for machine-learning based detector design.
- No real showstoppers for making the entire detector simulation differentiable, but quite some development required.

# Backup

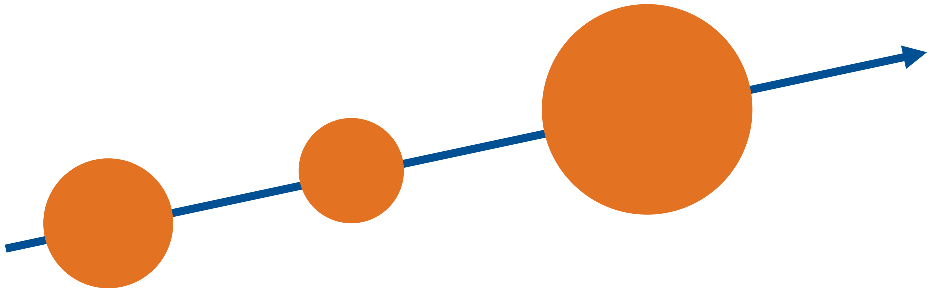
# Muon in P-ONE



# Track Reconstruction

$$\frac{dE}{dX} = a + bE$$

continuous — stochastic



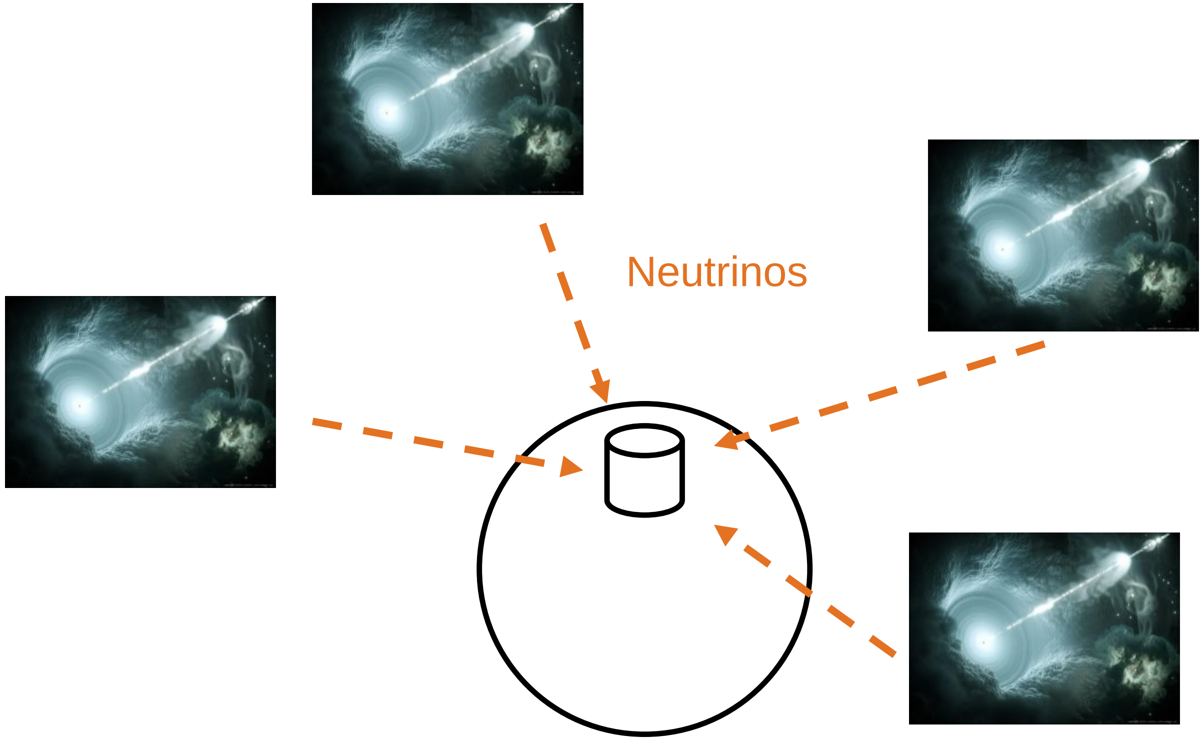
Above ~ 1TeV, the main light yield comes from stochastic energy losses.

Muon appears like a series of particle cascades.

For reconstructing energy and direction, need to model stochastic losses.
Traditional method: LUT of photon yield and arrival time PDF at detector modules.
Maximum likelihood to fit muon energy / direction.

# Science Goals of Neutrino Telescopes

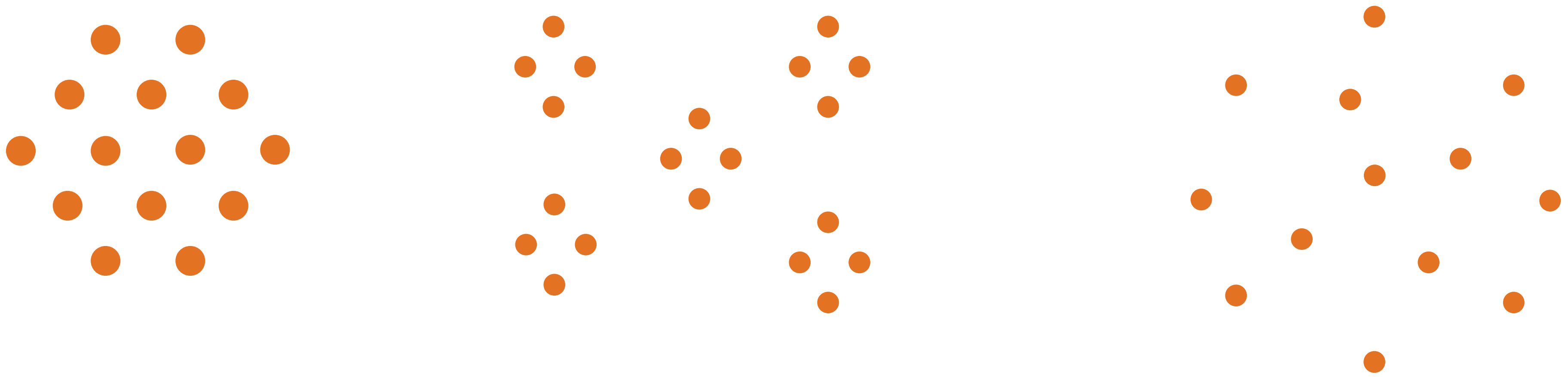

**Detecting neutrino point sources**
Gives insight into highest energy phenomena in the Universe (e.g. GRB's, AGN's, Super-Novae)




**Characterize the total spectrum of all sources**
Gives insight into the population of the accelerators of cosmic rays

# Possible Detector Geometries

Top views

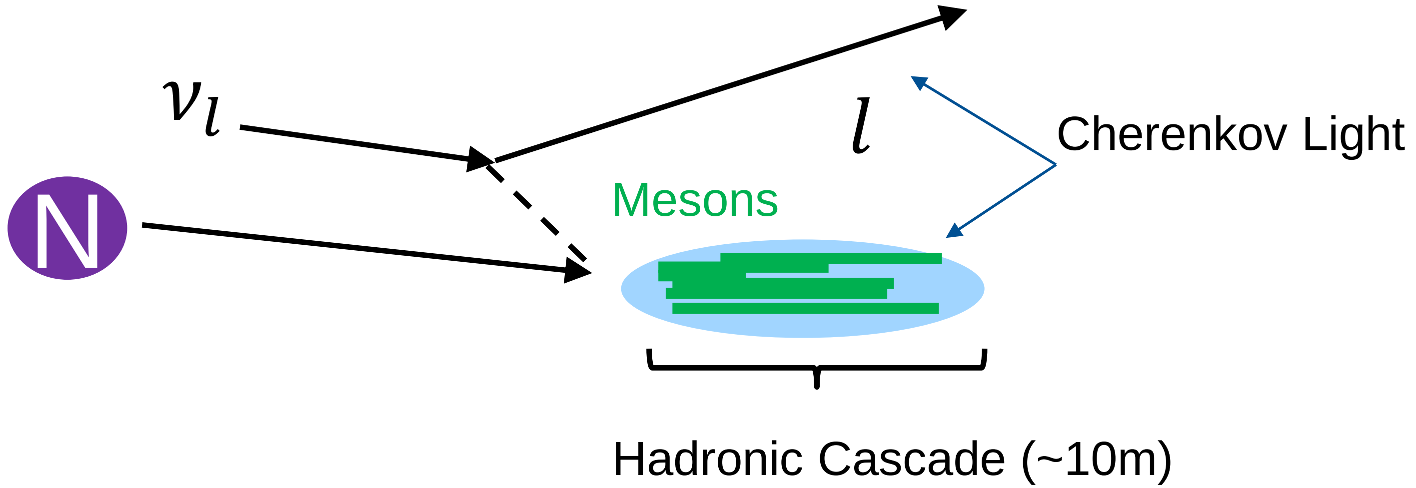


Which geometry is best for our physics goals, given the constraint of limited money?
Overall detector is „simple“: 3D array of (identical) photo-sensors.

Ideal test-case for machine-learning based detector design!

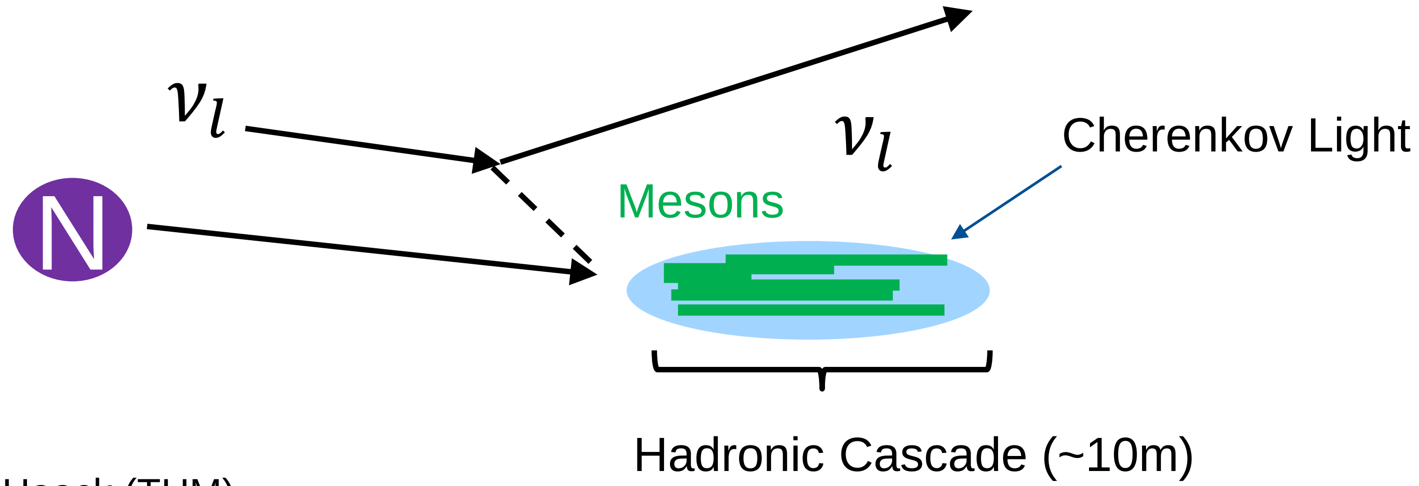
# High-Energy Neutrino Interactions

In case of $\nu_\mu$ CC, outgoing muon can propagate multiple km




**CC Deep Inelastic Scattering**

$$\nu_l + X \rightarrow l + X'$$




**NC Deep Inelastic Scattering**

$$\nu_l + X \rightarrow \nu_l + X'$$

# The „Perfect“ Neutrino Telescope

**Constraints**

- Photosensors need to be vertically aligned on lines (deployment)
- Each line adds significant overhead (cable cost) -> number of lines is limited by money

**Perfect:**
Large cross section for every direction (muon acceptance)
Large volume (cascade acceptance)
Homogeneous photosensor coverage (resolutions)
Average sensor distance smaller than absorption length (low energy threshold)

**Optimal?**

**Minimal:**
Large cross section for horizontal tracks
Large track lever arm
Average sensor distance not much larger than scattering length (resolution)

Which geometry is best for our physics goals, given the constraints?
Overall detector is „simple“: 3D array of (identical) photo-sensors.
Ideal test-case for machine-learning based detector design!