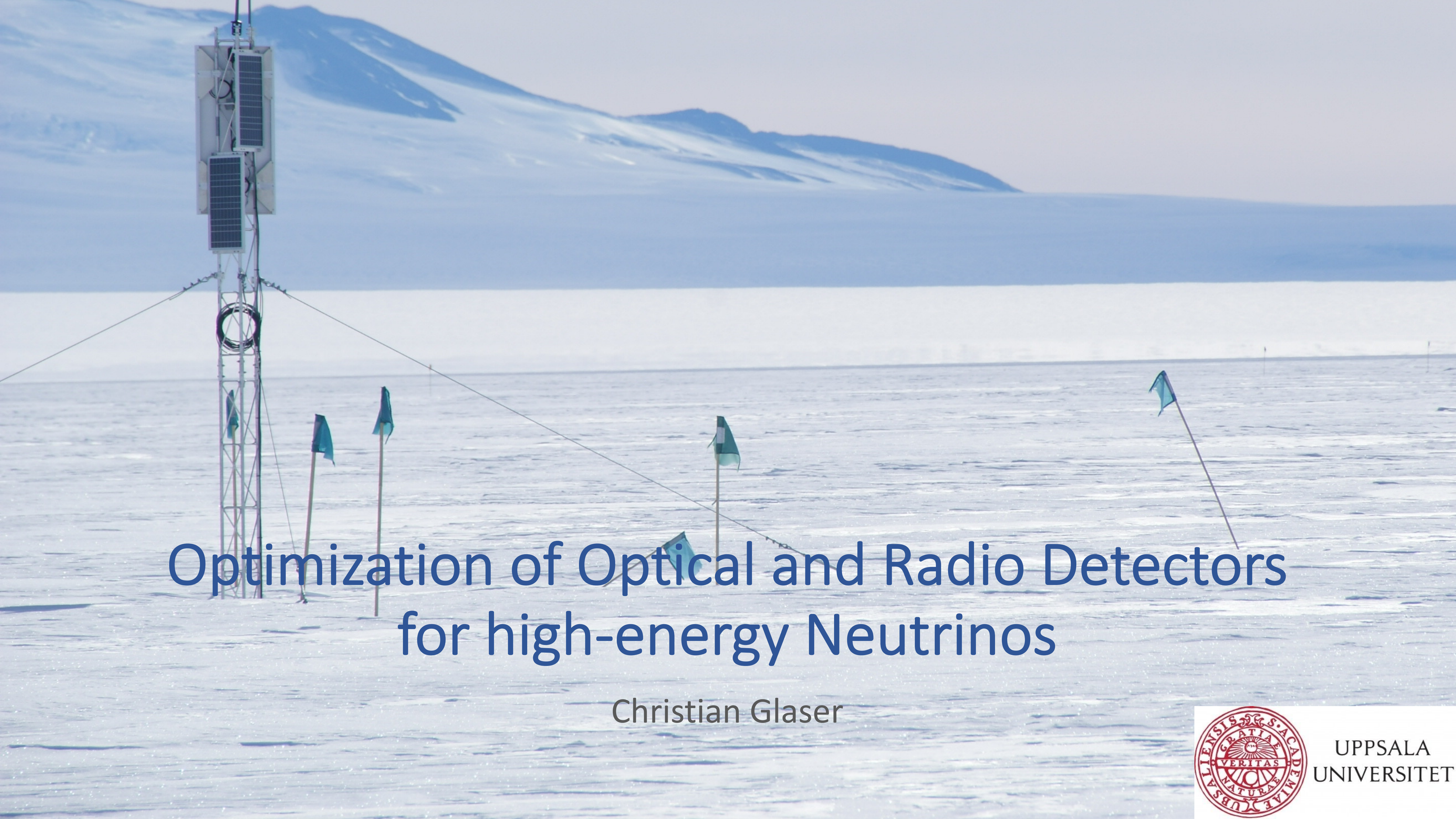


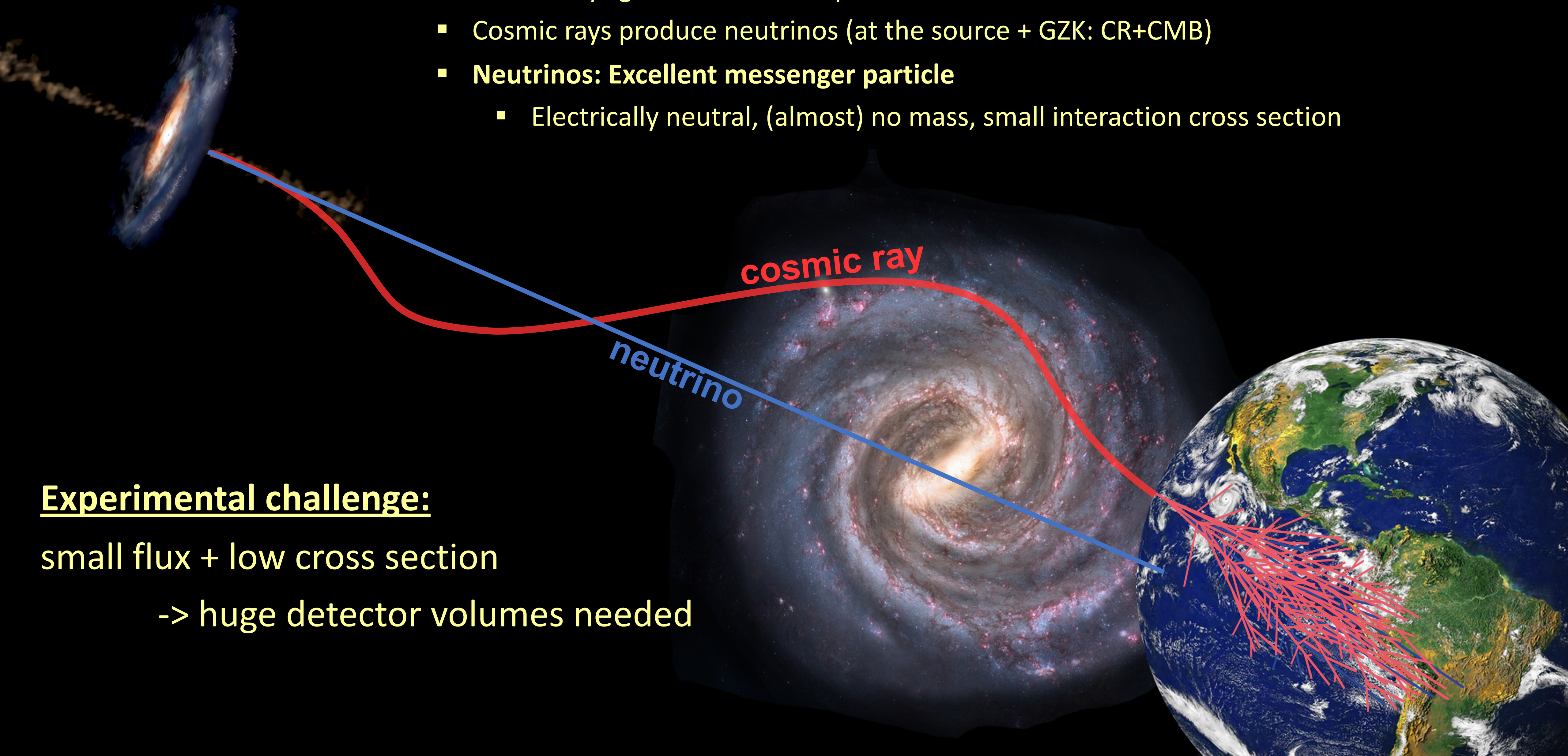
# Optimization of Optical and Radio Detectors for high-energy Neutrinos

Christian Glaser

UPPSALA UNIVERSITET

# The High Energy Universe

- Cosmic rays gets accelerated up to $10^{20}$eV
- Cosmic rays produce neutrinos (at the source + GZK: CR+CMB)
- **Neutrinos: Excellent messenger particle**
  - Electrically neutral, (almost) no mass, small interaction cross section



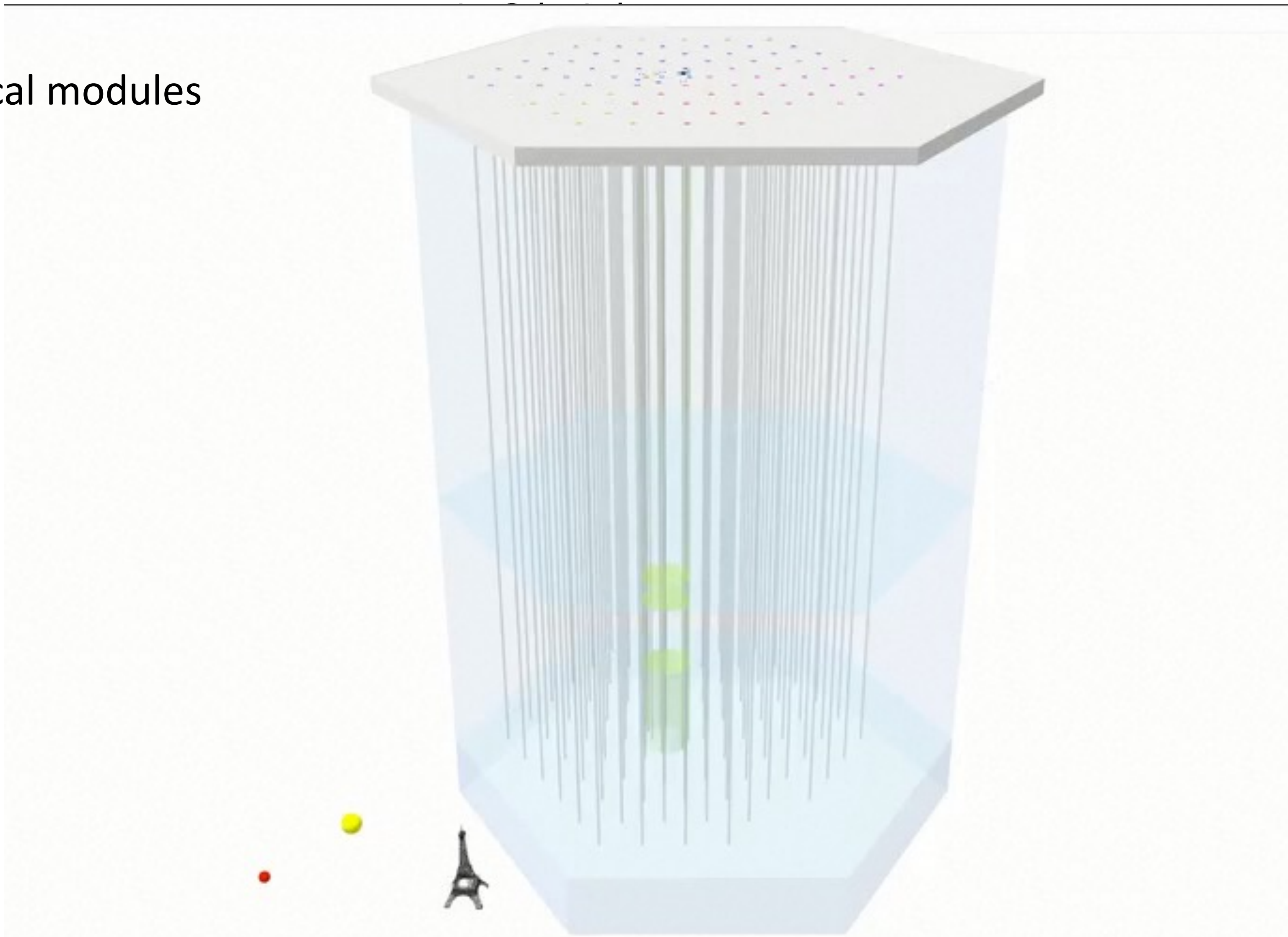

**Experimental challenge:**

small flux + low cross section

-> huge detector volumes needed

# IceCube Neutrino Observatory

- 1 km$^3$ of ice instrumented with optical modules

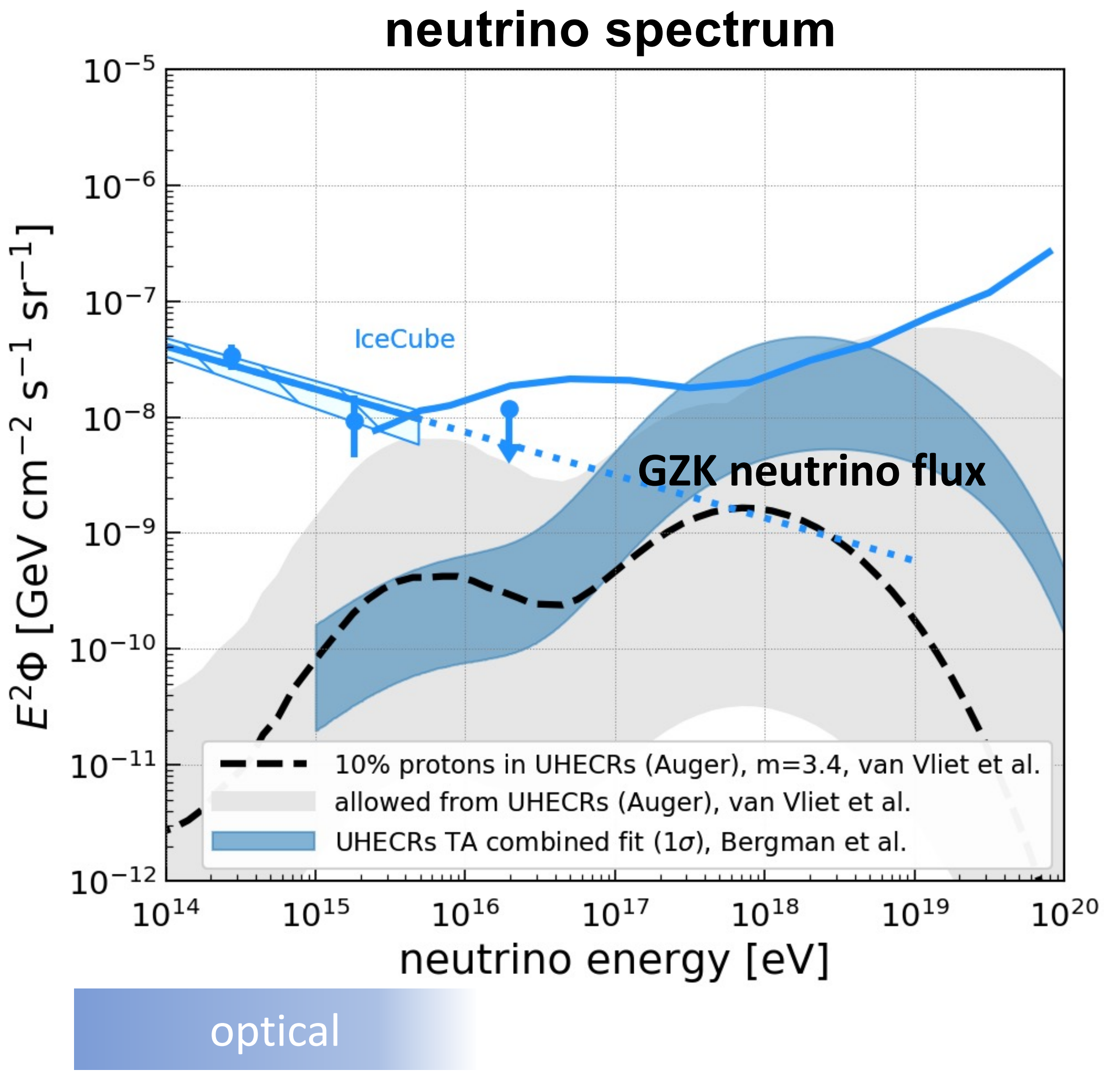


*also other detectors coming online, see talk by P-ONE*

# IceCube Neutrino Observatory

- 1 $km^3$ of ice instrumented with optical modules
- Major breakthroughs
  - discovery of astrophysical neutrino flux
  - indication for sources of neutrinos
  - observation of Glashow resonance
- Goals for a next generation instrument:
  - Statistically significant observations over a broad energy range
  - Better pointing for point source localization and multi-messenger observations → improved angular resolution

**→ IceCube-Gen2**



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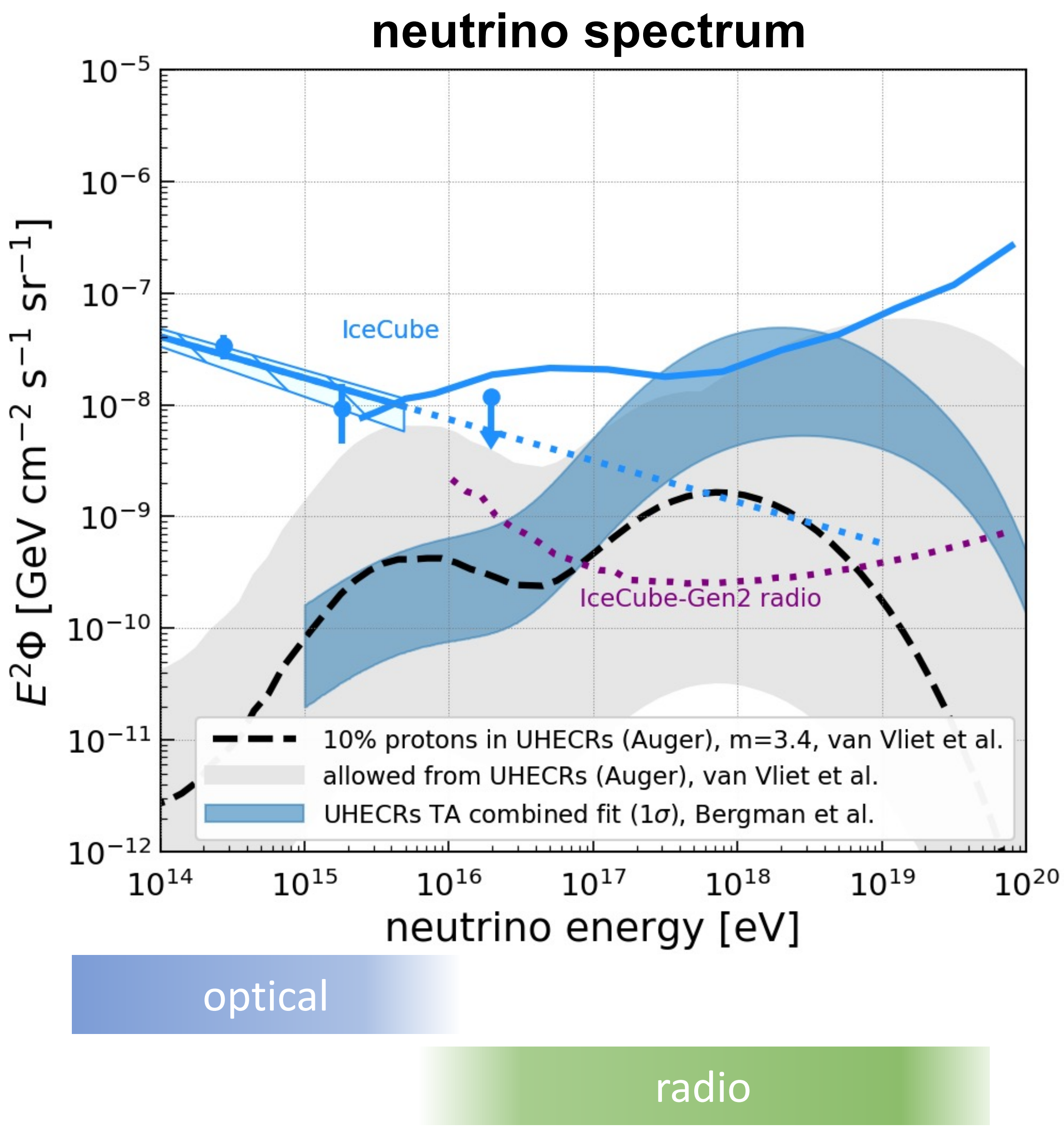
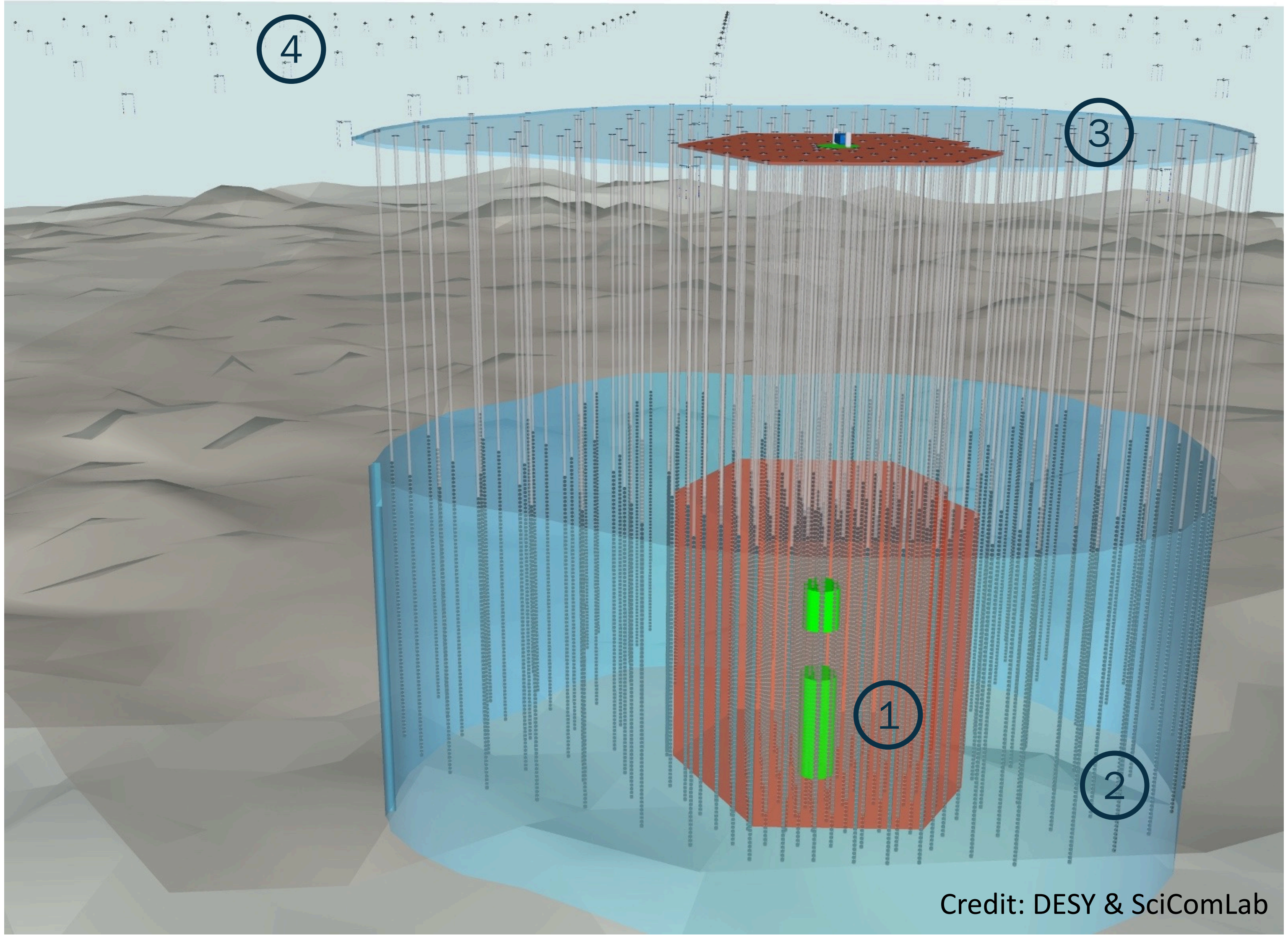


Gen2 White Paper: 2008.04323

# IceCube-Gen2

Four new elements, leveraging complimentary technologies, to achieve sensitivity to MeV-EeV neutrinos

1. IceCube Upgrade
2. **Enlarged deep optical array**
3. Surface Array
4. **Shallow radio array**
   - expands energy reach to EeV energies








*Slides from Brian Clark, ICRC2021*

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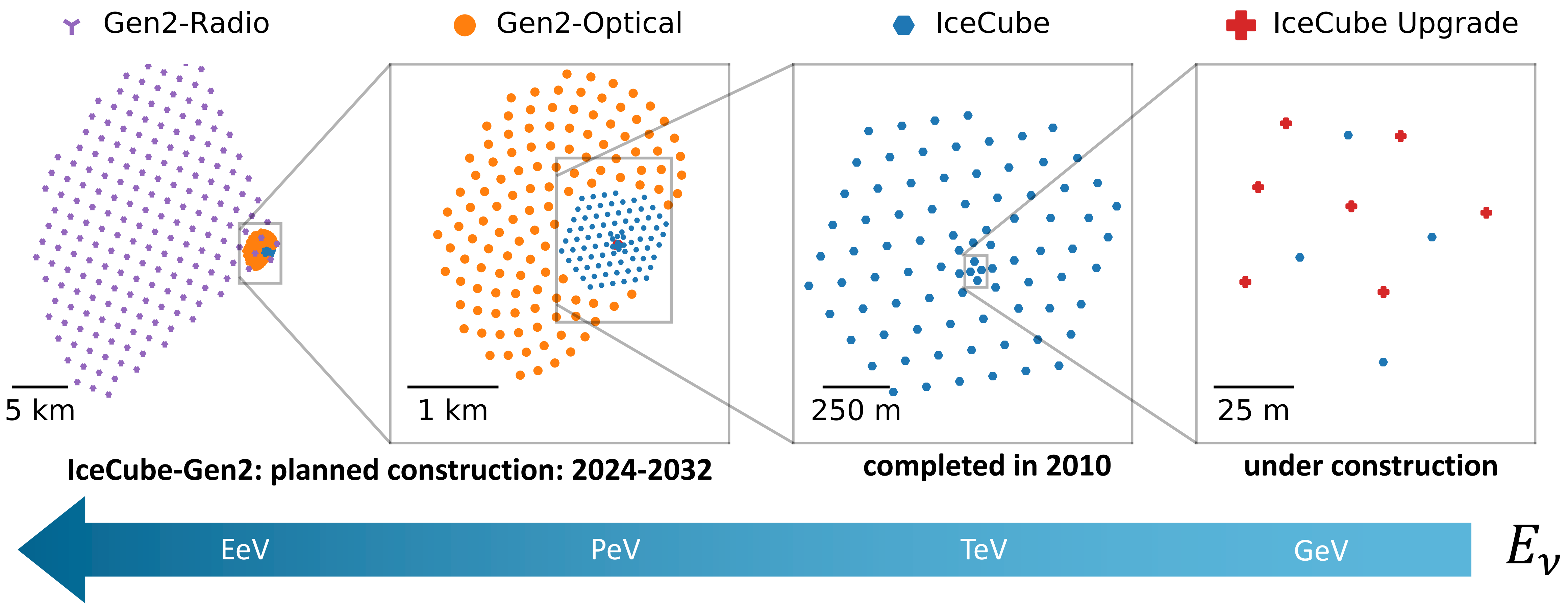
# IceCube-Gen2




**What is the optimal detector for the next decade?**




*Slides from Brian Clark, ICRC2021*

# Optimization of Optical Detector

## Parameters to optimize

- String locations
  - String spacing
  - Layout (grid, sunflower, other?)
- Optical modules on a string
  - Vertical spacing
  - How many modules
  - Number of PMTs per module
  - PMT orientations
  - …
- Trigger

## Objective

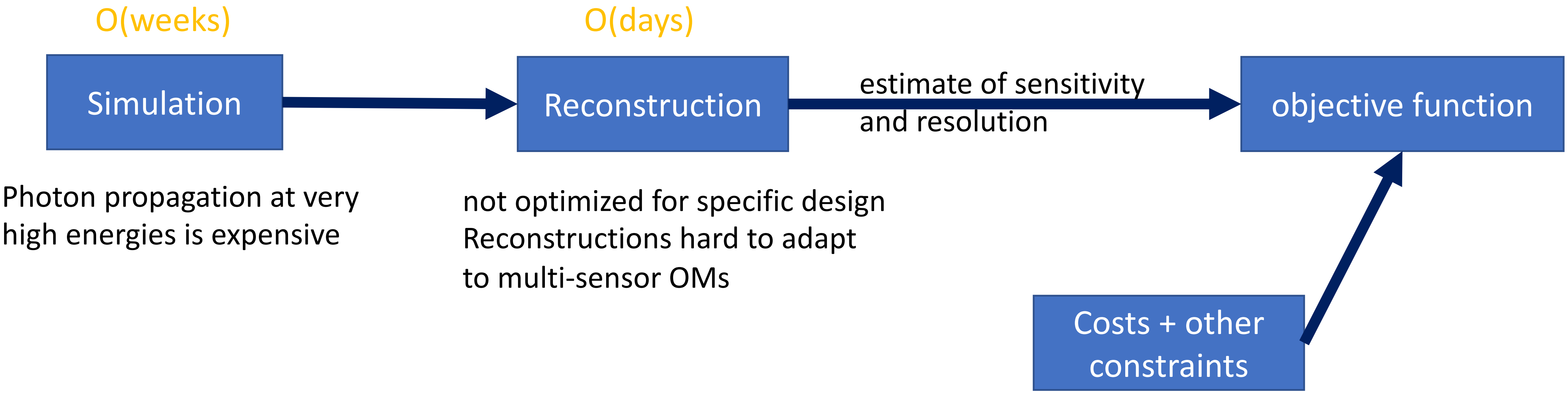
- Neutrino sensitivity (i.e. effective area)
- Resolution
  - Energy, Direction, Flavor
- Turns into
  - Diffuse neutrino flux sensitivity
  - Point source sensitivity (steady and transient, etc.)
  - …

diverse science program
different optima for
different science cases

**+ costs,**
**deployment constraints,**
**engineering constraints**

# Automated Optimization Setup

For each detector design:

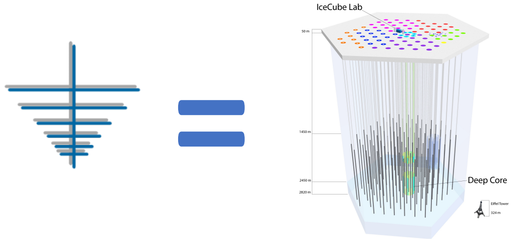


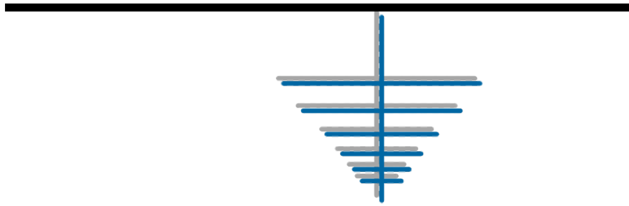


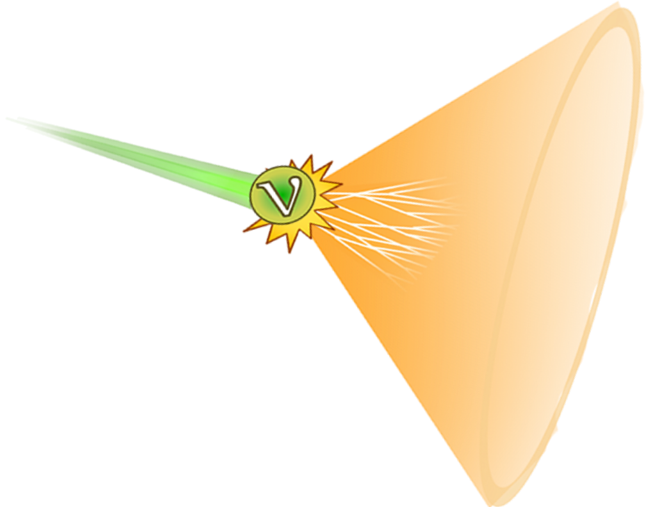
Christian Glaser

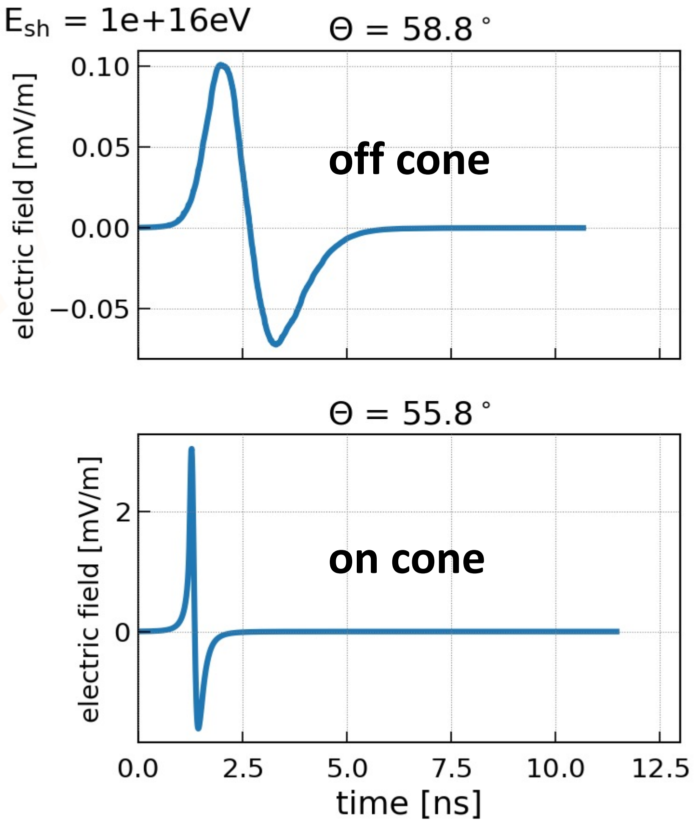
# Radio Detection of Neutrinos

- Particle showers generate radio flashes through Askaryan effect
- Attenuation length in ice: O(1km)



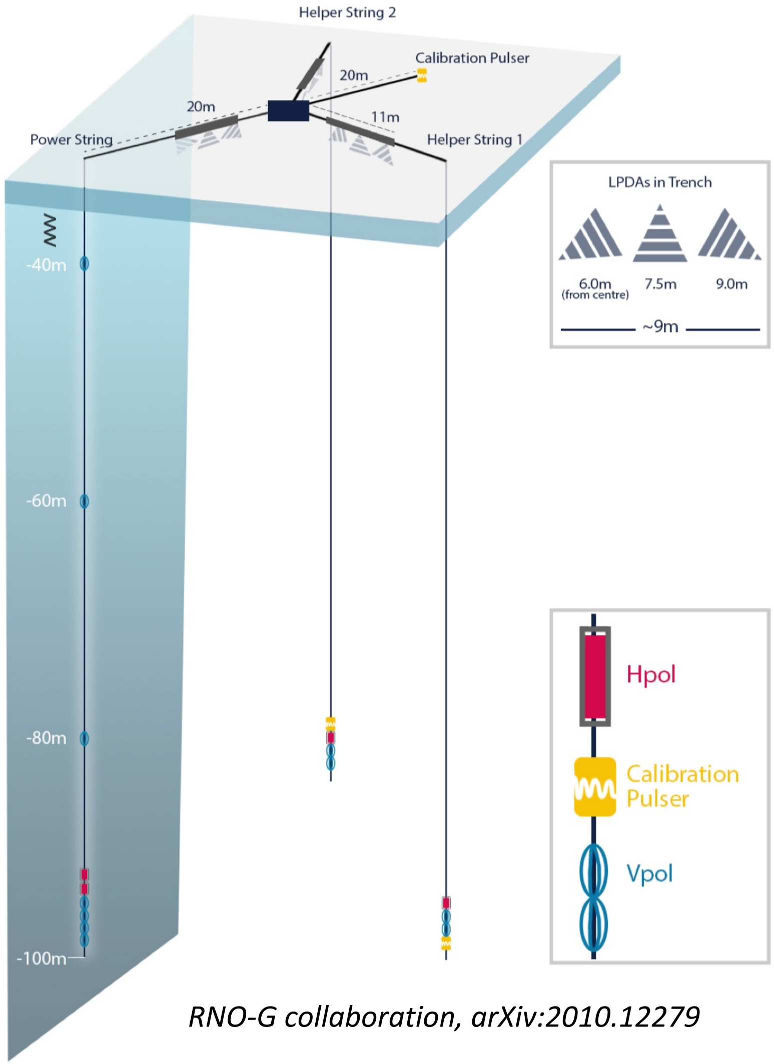





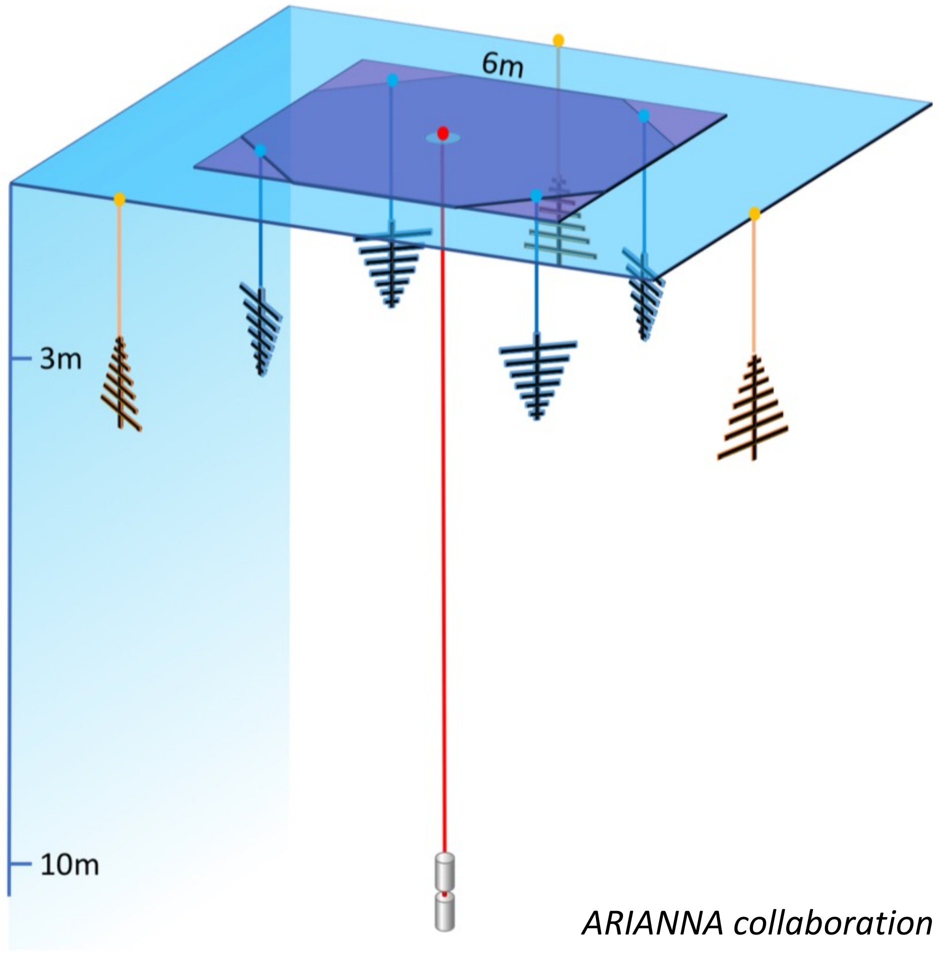


# Radio Detector Examples

# Radio Detector Examples




*RNO-G collaboration, arXiv:2010.12279*




*ARIANNA collaboration*

# Optimization of Radio Detector

## Parameters to optimize

- Station spacing and layout
- Station layout
  - number of antennas
  - position of antennas
  - type of antennas
  - orientation of antennas
- Trigger

## Objective

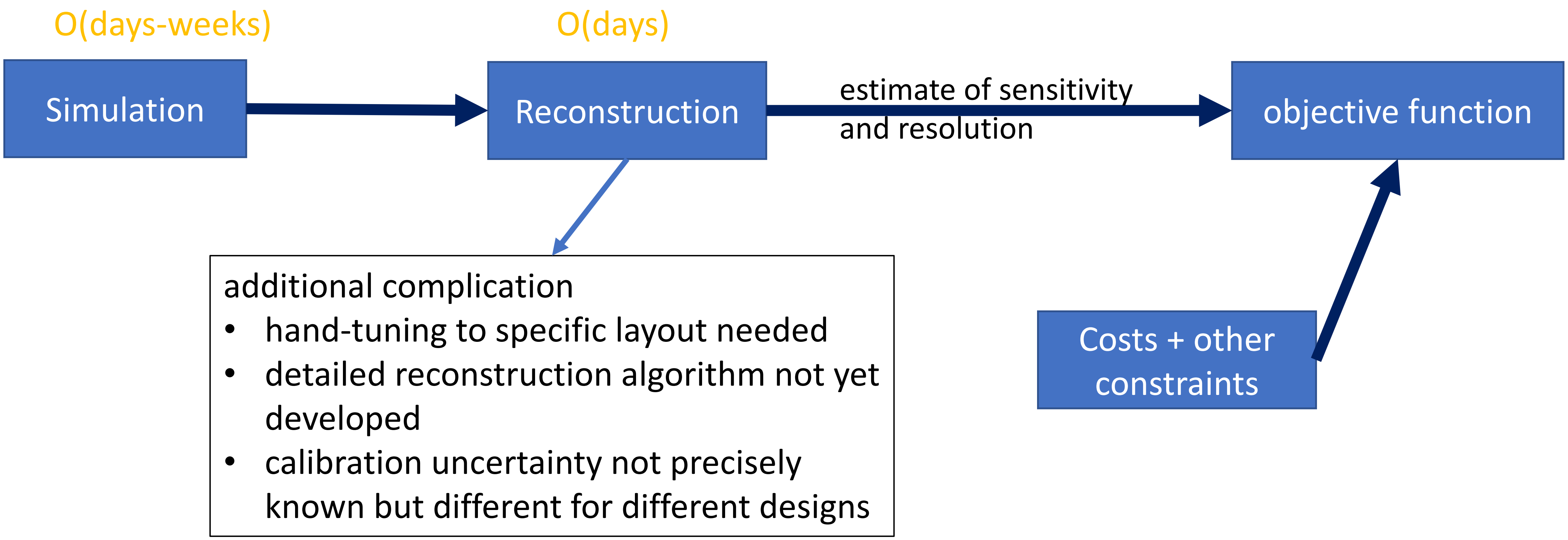
- Neutrino sensitivity (i.e. effective area)
- Resolution
  - Energy, Direction, Flavor
- But also: Robustness against systematic uncertainties
  - Redundancy in measurments
- Also: Ability to reject rare background

**+ costs,**
**deployment constraints,**
**engineering constraints,**

**diverse science program**
**different optima for different science cases**

# Optimization of Radio Detector

For each detector design:



# What we do at the moment

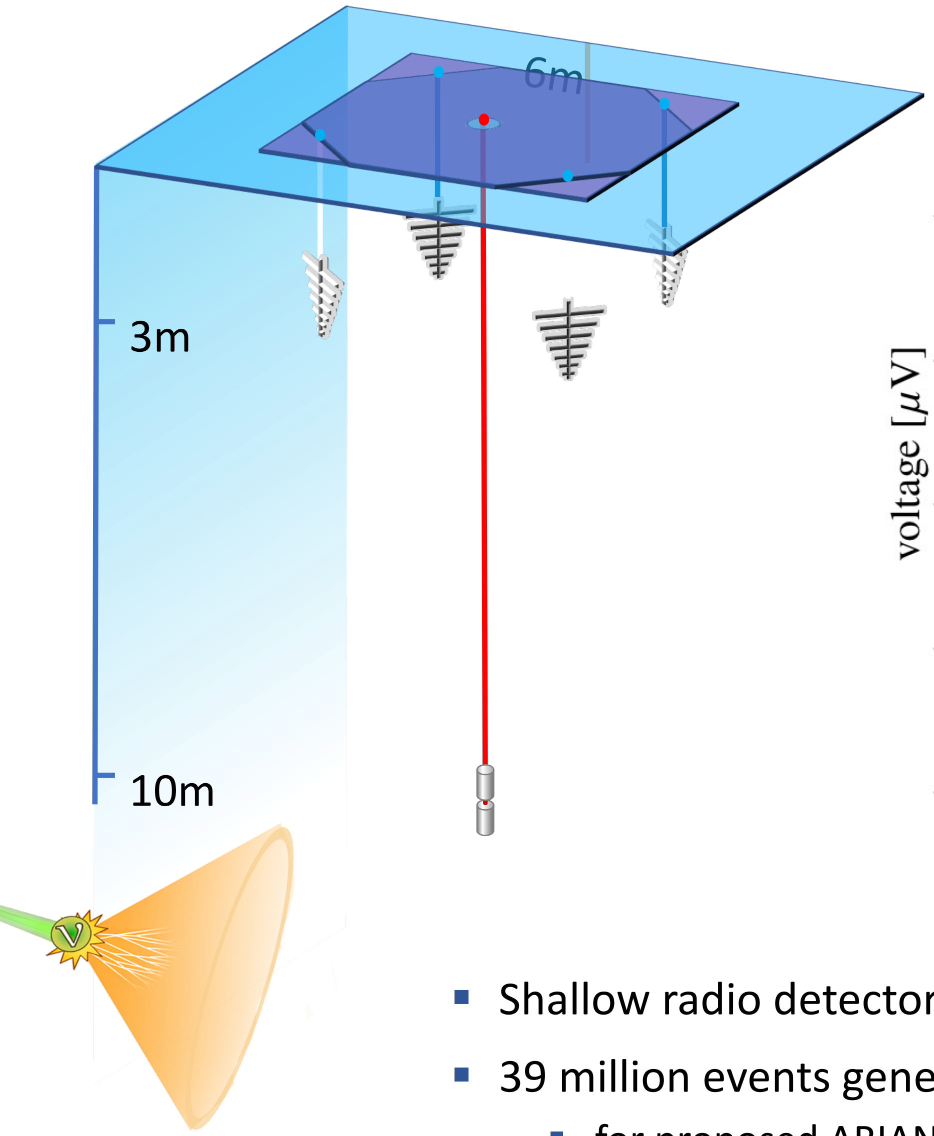
- Extrapolation from previous experiments
  - especially in harsh antarctic environment, reliability and technical feasibility important
- Usage of scaling relations
  - Using a multi-PMT optical module increases angular resolution by X% compare to a single PMT
  - Station spacing between radio stations vs. coincidence rate
  - Increase of sensitivity with deployment depth of radio antennas
- Individual studies:
  - Background rejection vs. station spacing and station layout
  - Antenna design *(see GENETIS talk)*
  - Trigger Optimization (*e.g. phased array arXiv:1809.04573, neural network filter doi:10.22323/1.395.1074)*
  - Detector resolution for specific layouts
    - *e.g. CNN reconstruction of (optical) IceCube data arXiv:2101.11589*
    - *e.g. DNN reconstruction of radio data (doi:10.22323/1.395.1055, doi:10.22323/1.395.1051)*

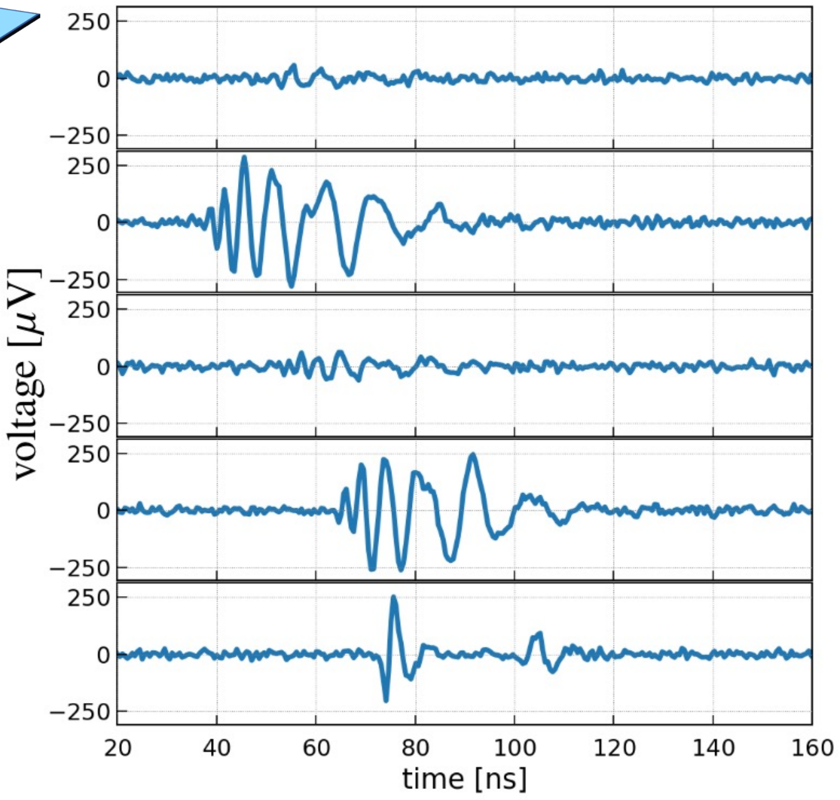
# Deep Learning Estimation of Reconstruction Resolution

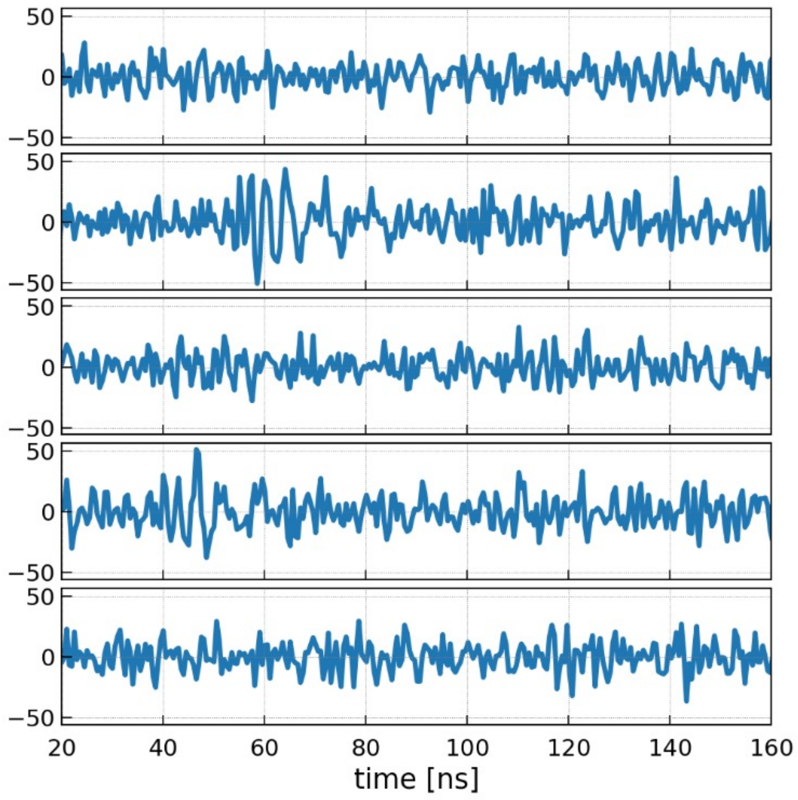
1. Create MC data set for design X
   - >10k core hours
2. Train a deep neural network (DNN) to predict neutrino energy, direction and flavor
   - < day on a single GPU
3. Use DNN resolution as a proxy for the performance of X


Christian Glaser

# Deep Learning Event Reconstruction



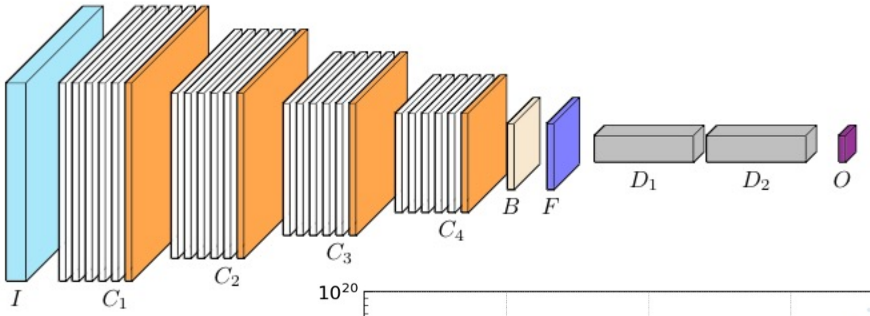

- Shallow radio detector (ARIANNA, RNO-G, IceCube-Gen2)
- 39 million events generated with NuRadioMC
  - for proposed ARIANNA-200 at Ross Ice Shelf
  - so far only hadronic showers

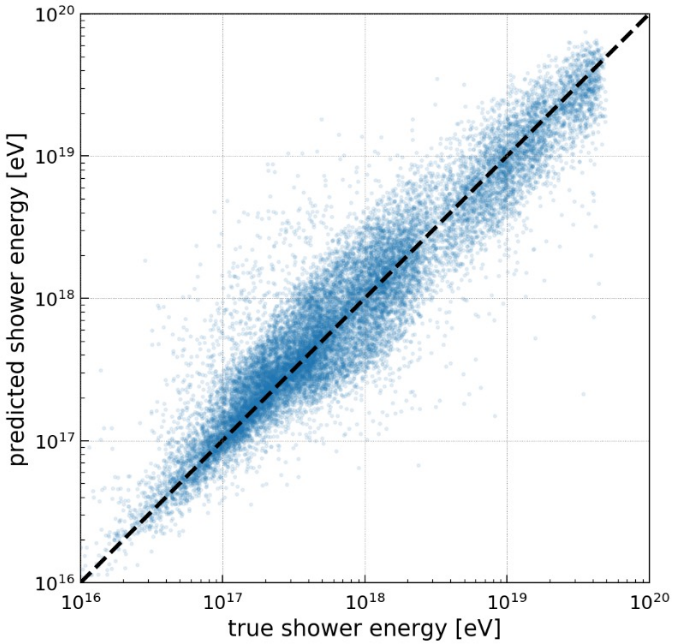
PoS(ICRC2021)1051

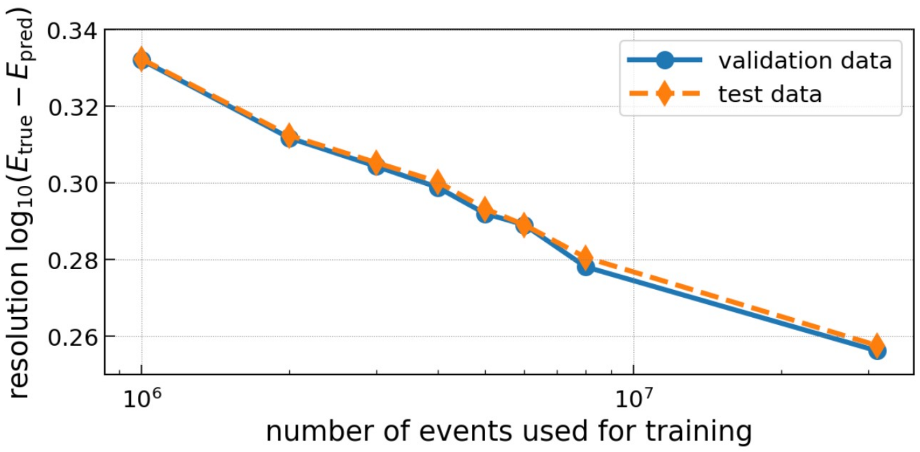
# Energy Resolution*

*: similar results also obtained for direction and flavor

- Deep convolutional neural network with 39 million free parameters
- Predicts shower energy based on raw waveforms
- Energy resolution: 80%
  - better than irreducible uncertainty from unknown inelasticity
- Further improvement with more training data expected



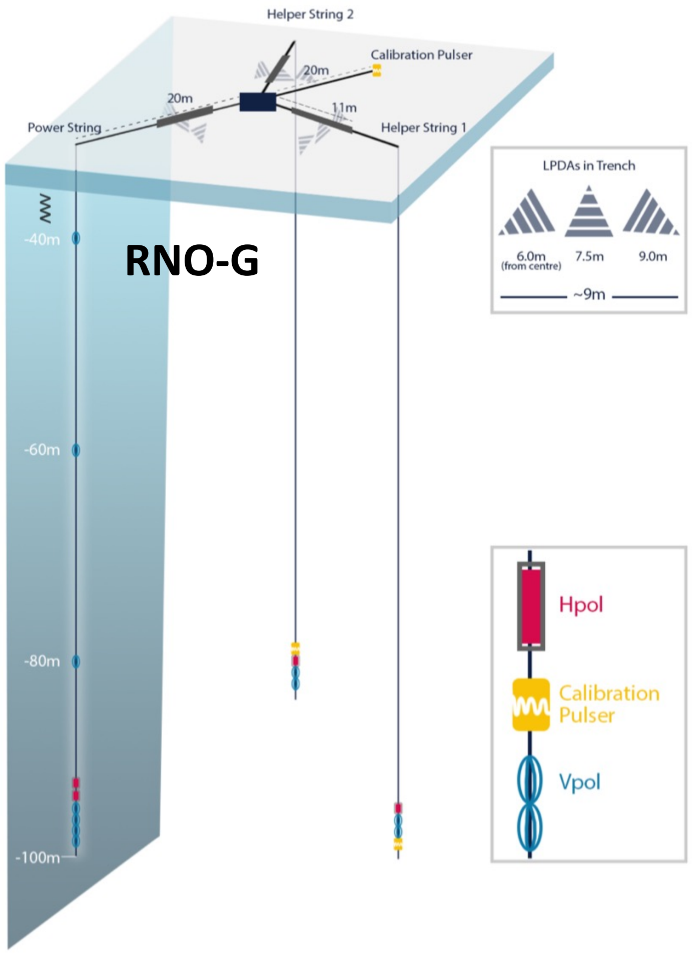

Challenge: resolution dependent on input data and network size
- > could be kept constant, but what if input size changes (e.g. more antennas)?

# Conclusions

- Optimization problem of optical and radio detector of IceCube-Gen2 is highly dimensional
  - Large parameter space
  - Detector simulation slow
  - Detector resolution difficult to quantify quickly
  - Additional contraints (costs, technical feasibility, deployment contraints …) difficult to quanitify
- Deep neural networks successfully used for event reconstruction
- In the future:
  - use NN for automated estimation of detector abilities?
  - use NN to speed up simulation?
  - MODE tools?

# backup

# Experimental Landscape

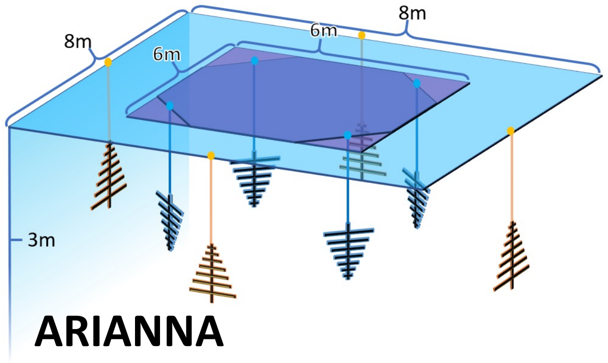



**ARIANNA test bed**
- 12 shallow stations at Moore's Bay + South Pole

**ARA**
- 5x 200m deep stations at South Pole

Radio technology developed and verified; hardware proven reliable

past




now

**RNO-G**
- 35 detector stations in Greenland
- first deployment summer 2021

**ARIANNA-200**
- 200 shallow detector stations at Moore's Bay
- funding decision pending

future

**IceCube-Gen2**
- 300+ detector stations at South Pole
- hybrid array of deep and shallow stations