UPPSALA UNIVERSITET

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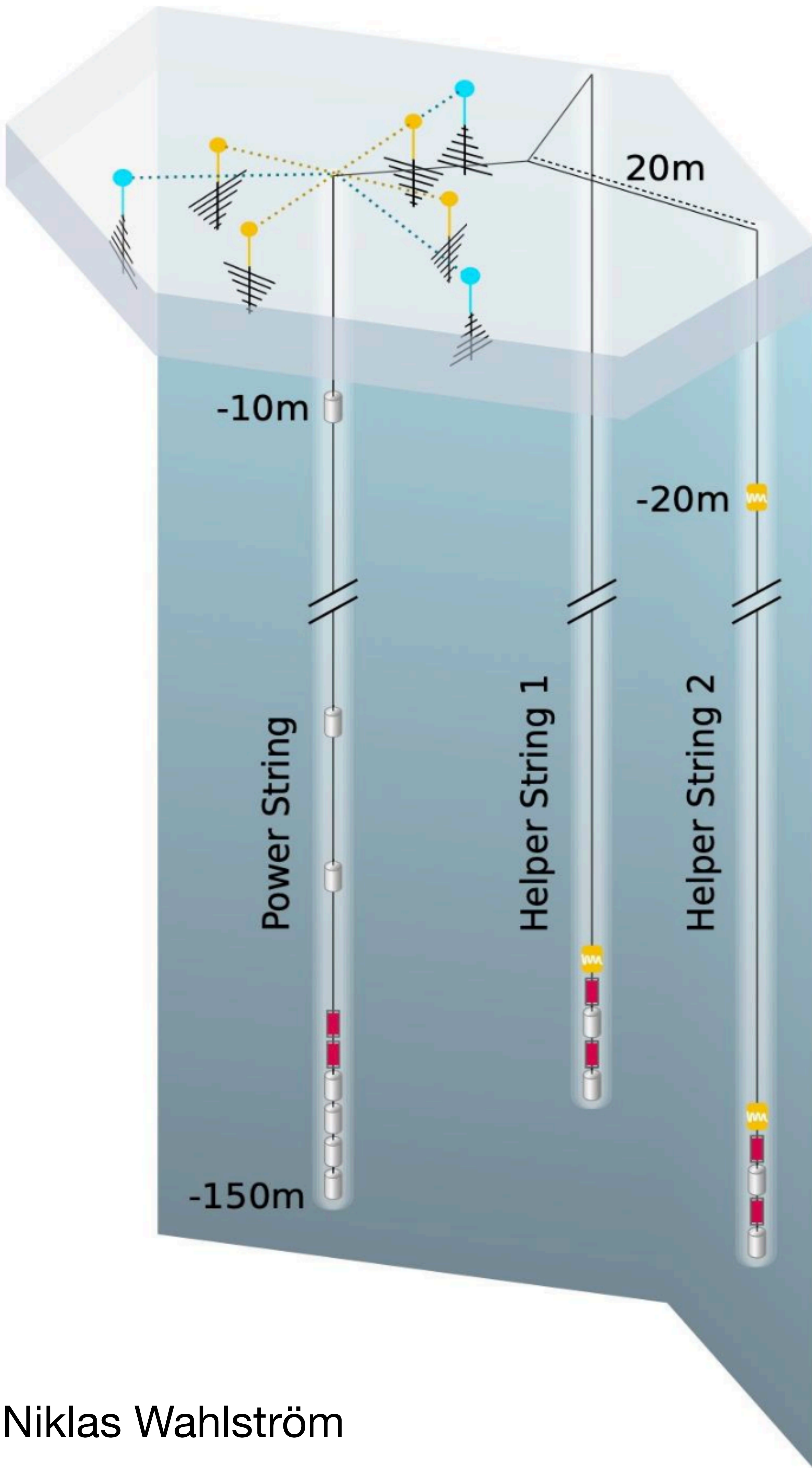
erc European Research Council
Established by the European Commission

Swedish Research Council

Differentiable end-to-end optimization for in-ice radio neutrino detectors

NBI Neutrino Summer School

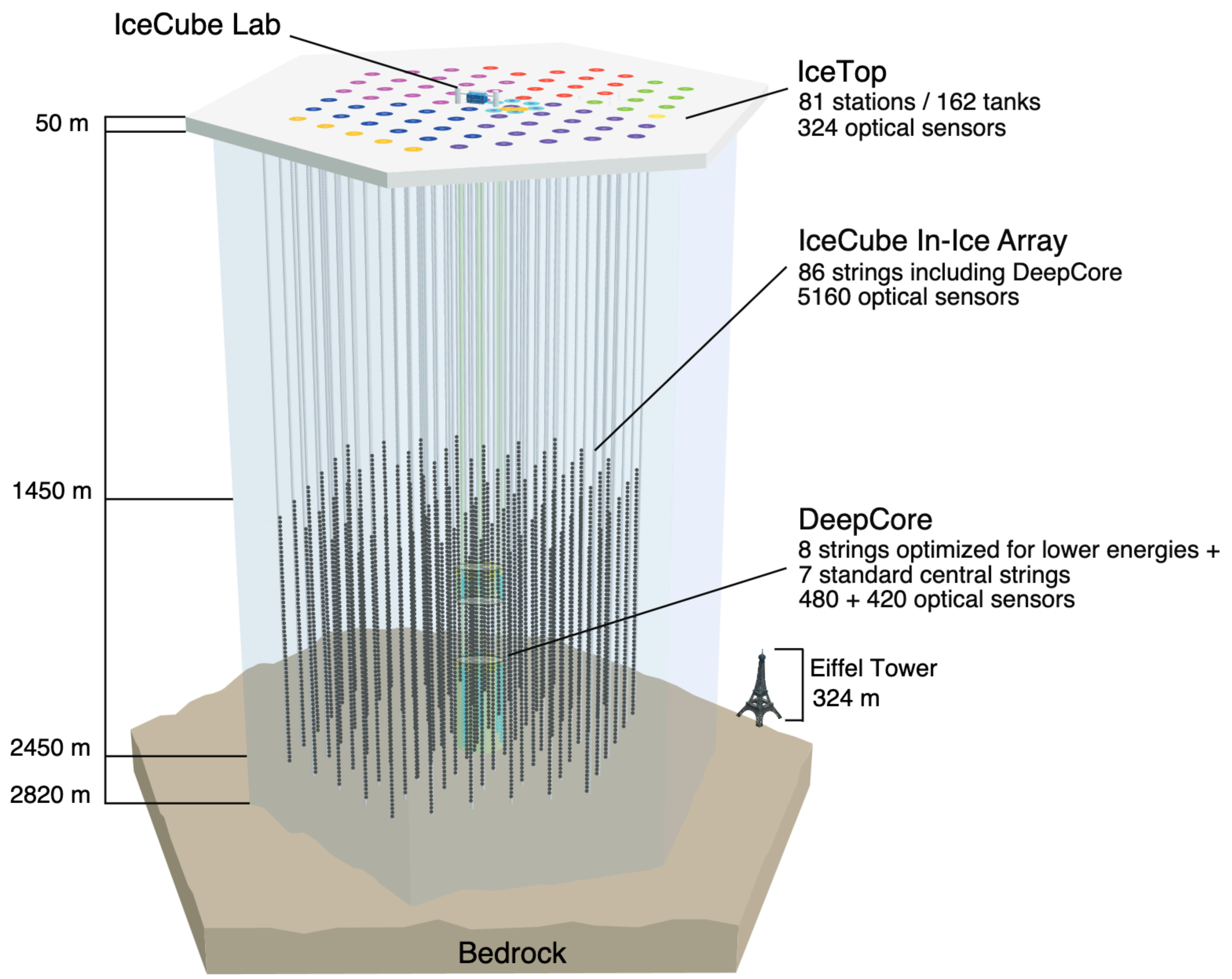
2025-07-10

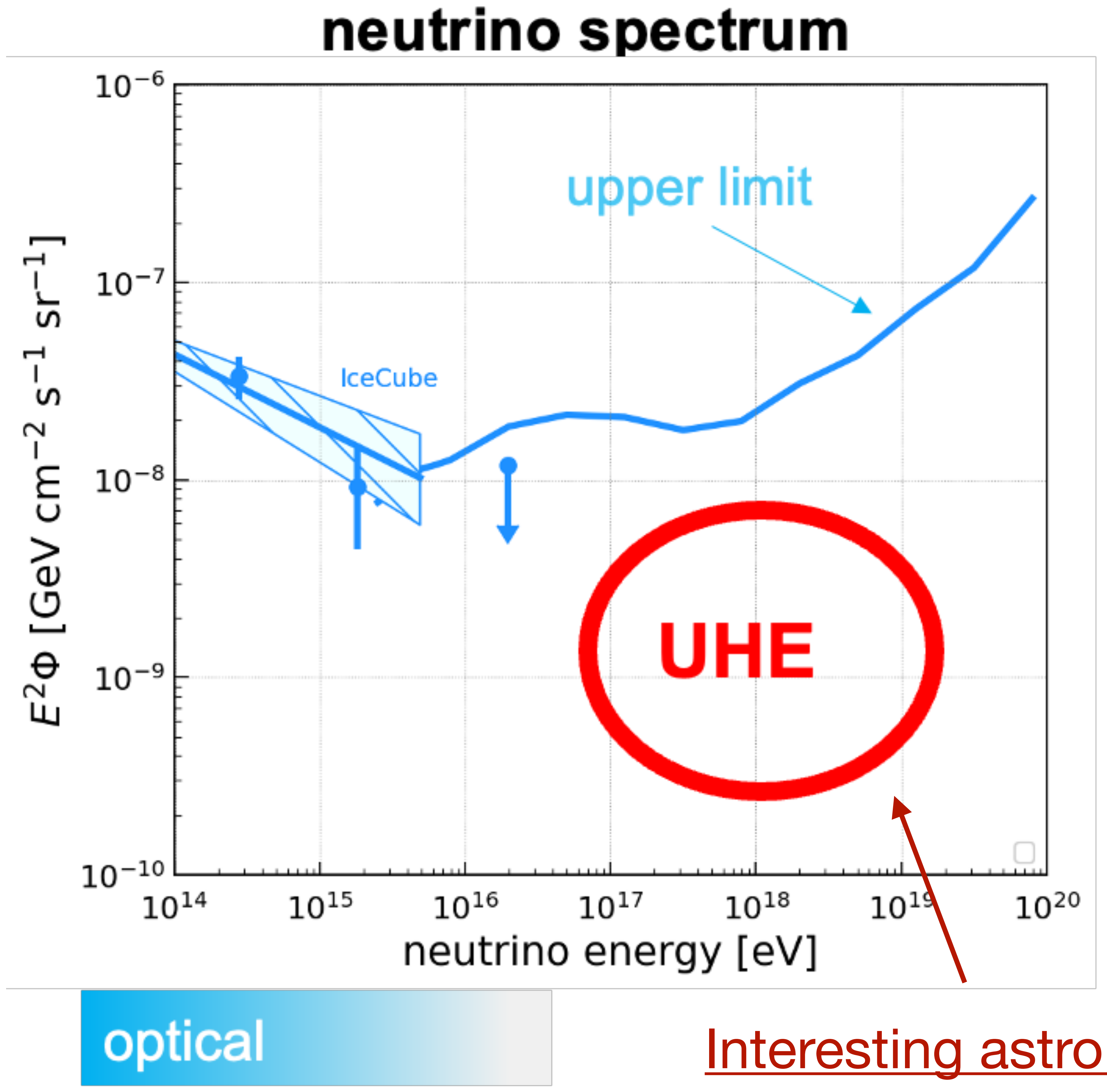


Martin Langgård Ravn, Philipp Pilar, Christian Glaser, Thorsten Glüsenkamp, Niklas Wahlström

Ultra-high energy neutrino detection

- Ultra-high energy (>PeV) neutrino flux is too low for IceCube to measure
- 100 times the effective volume is needed

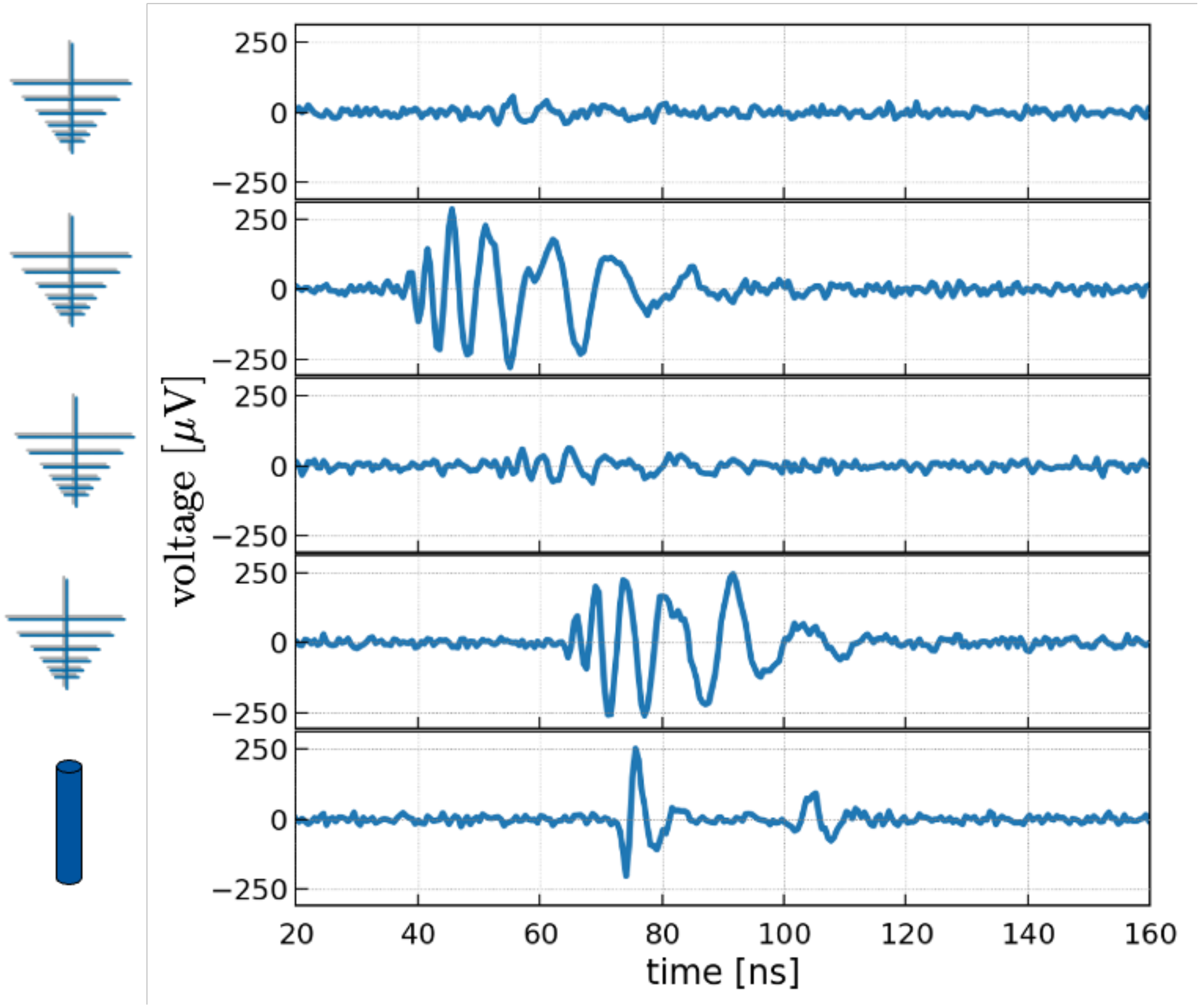


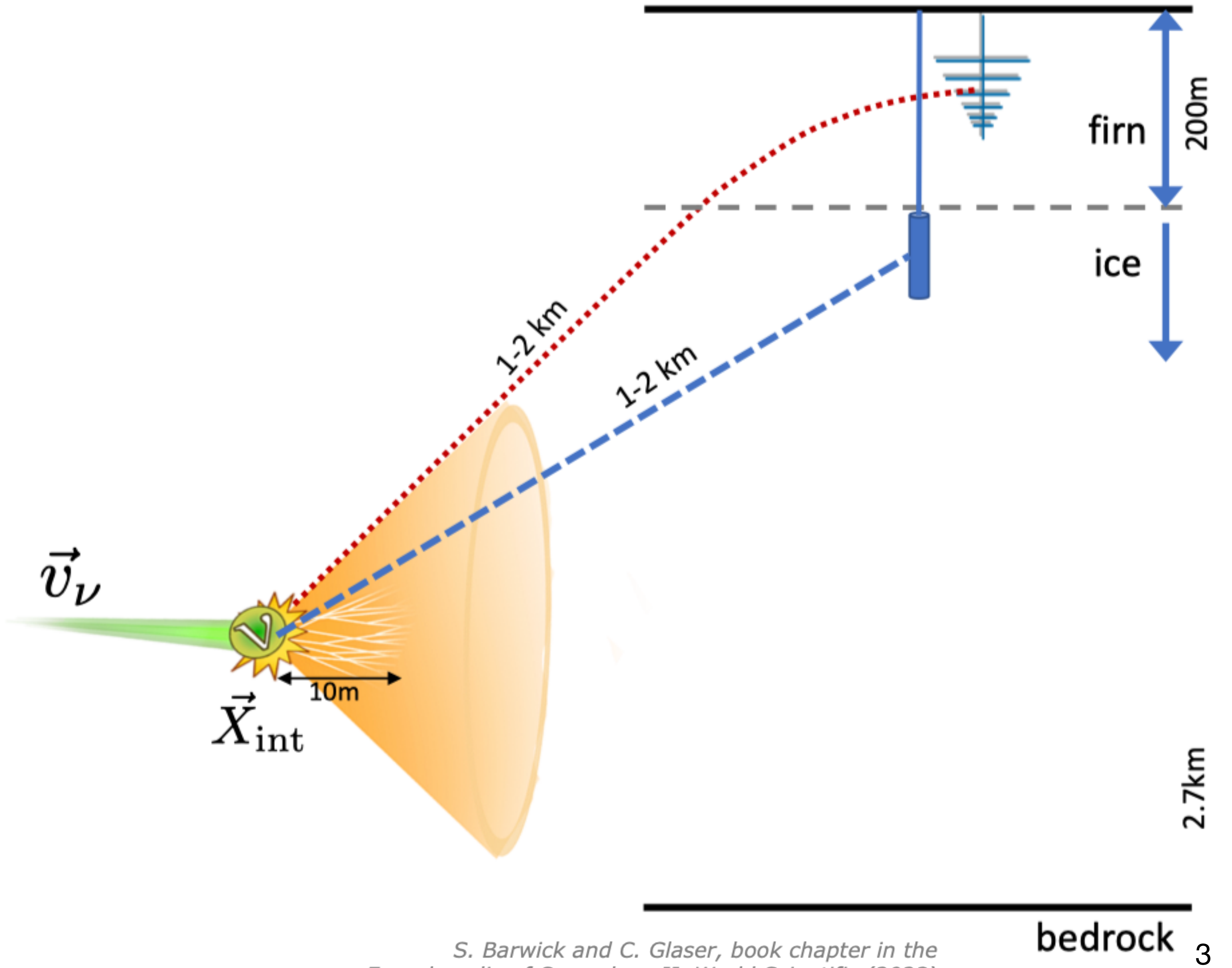


<u>Interesting astrophysics:</u>
Active galactic nuclei, gamma ray bursts, pulsars, blazars, cosmogenic neutrinos, etc.

Radio detection of neutrinos

- Askaryan effect produces radio emission at $E_\nu > 10^{15}$ eV
- Attenuation length of radio signals in ice is 1-2 km



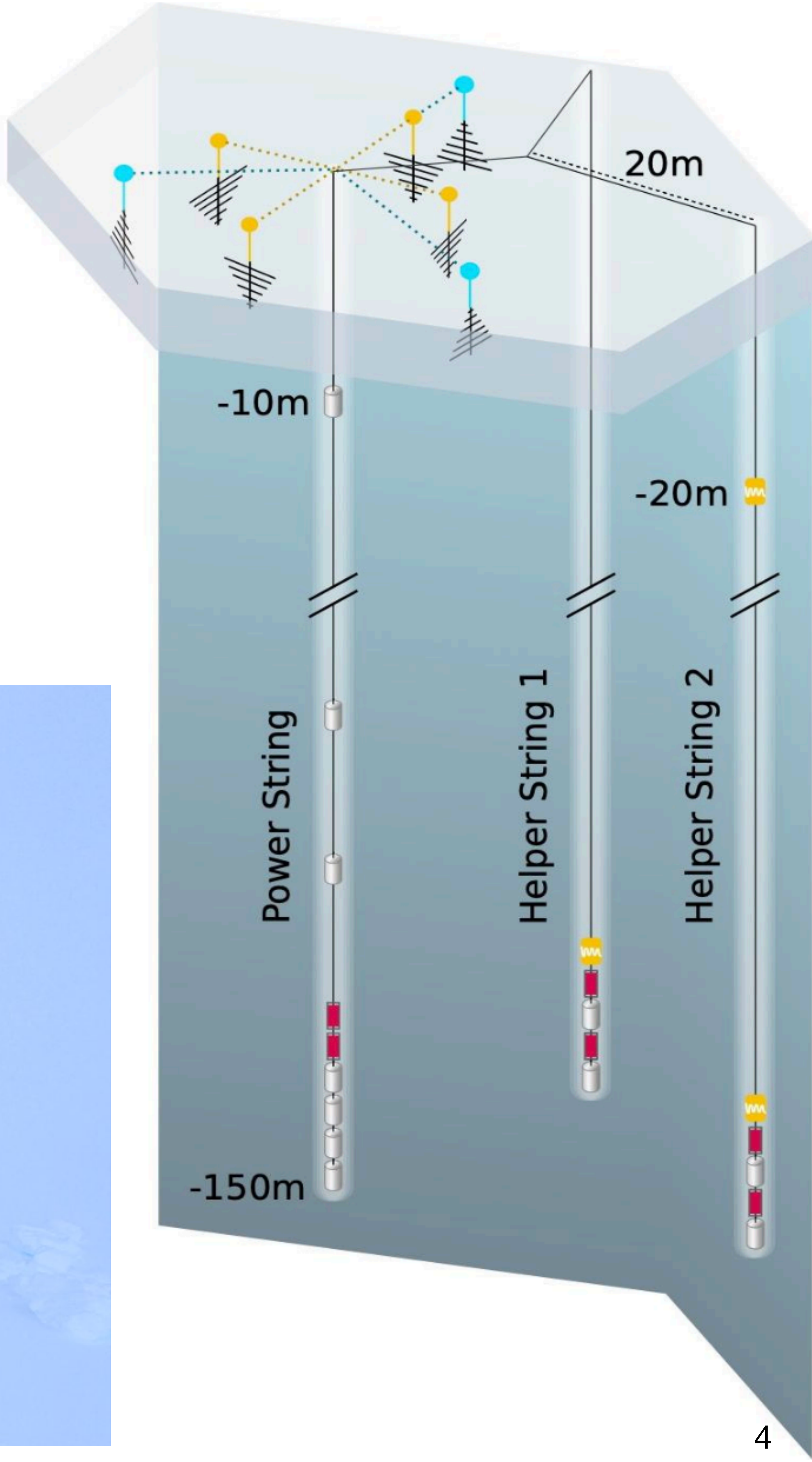


S. Barwick and C. Glaser, book chapter in the Encyclopedia of Cosmology II, World Scientific (2023)

Experimental landscape

- In-ice radio detection:
  - ARIANNA
  - ARA
  - **RNO-G** (8 out of 35 stations deployed)
  - Future: IceCube-Gen2 Radio (~350 stations)

In-ice radio station:



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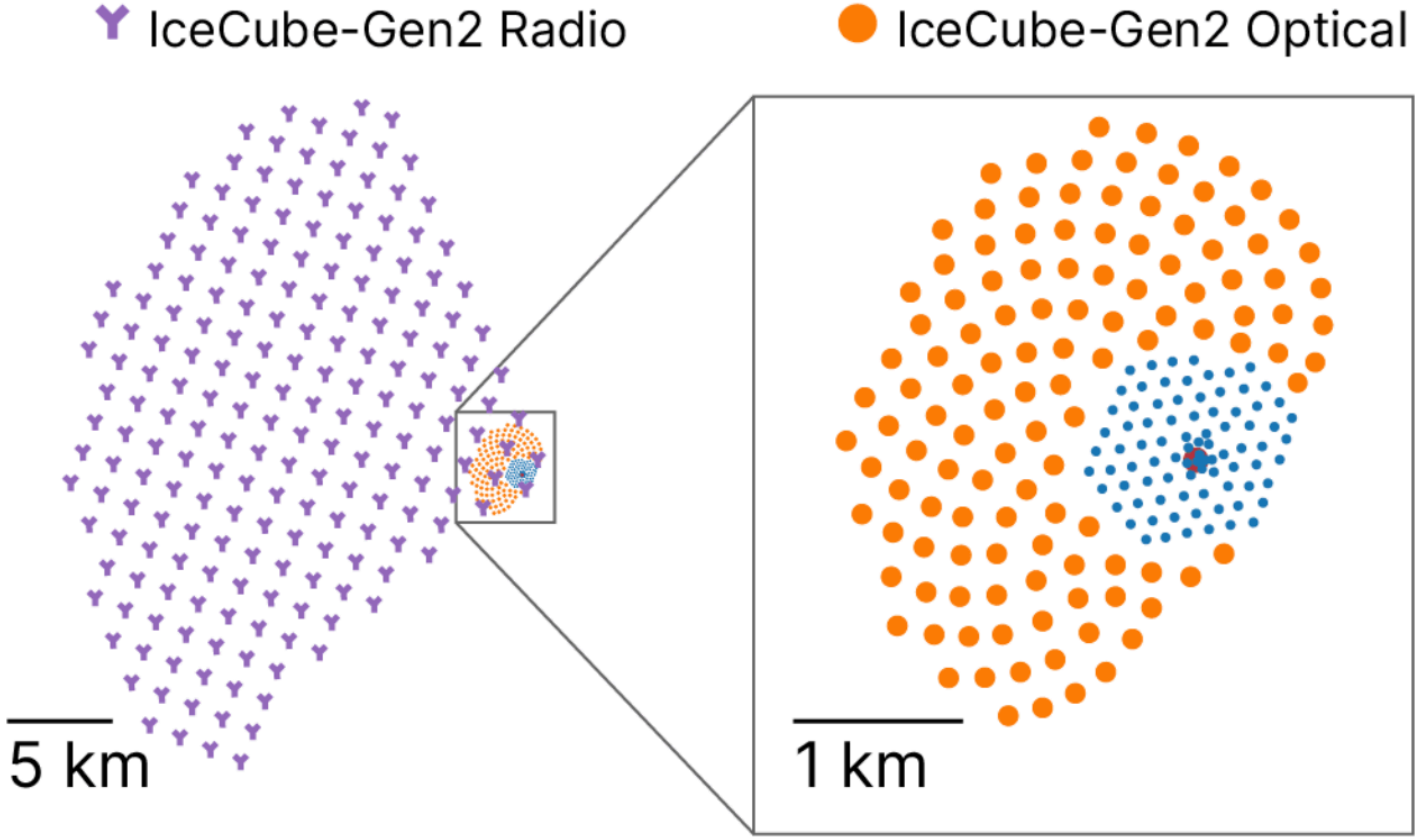

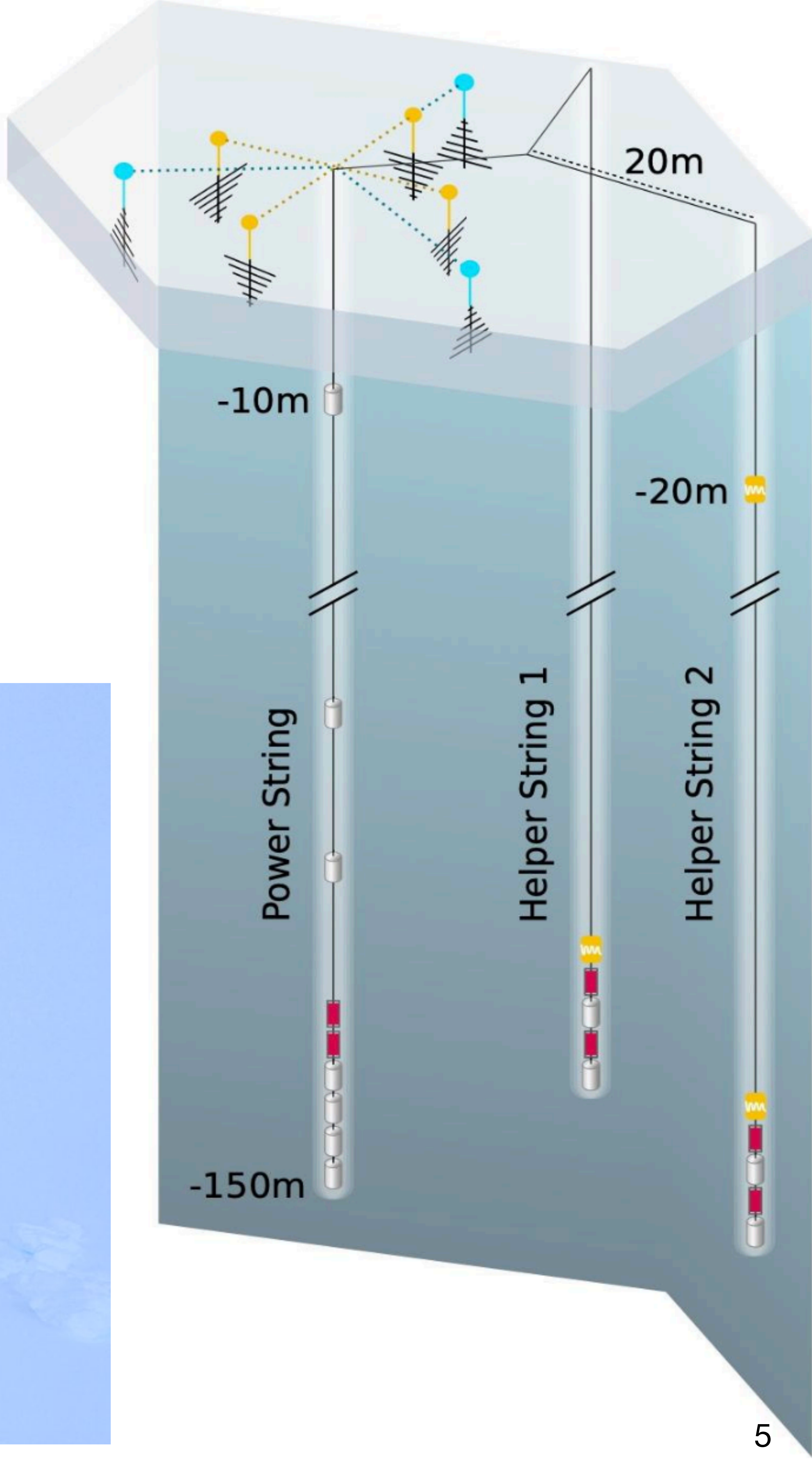

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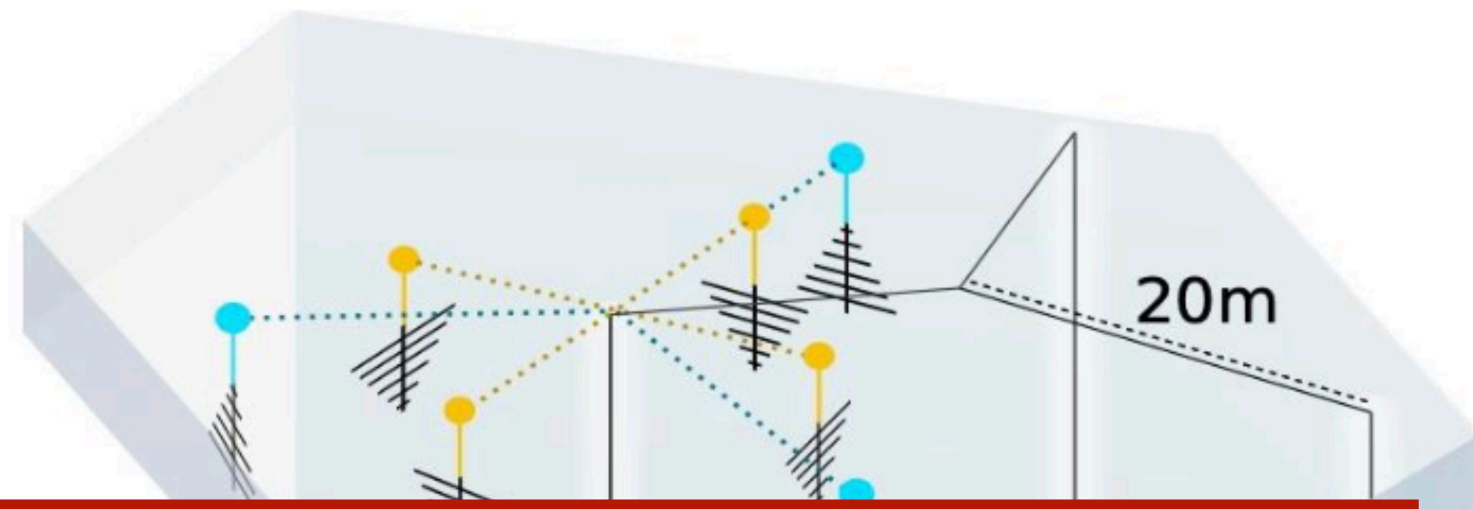
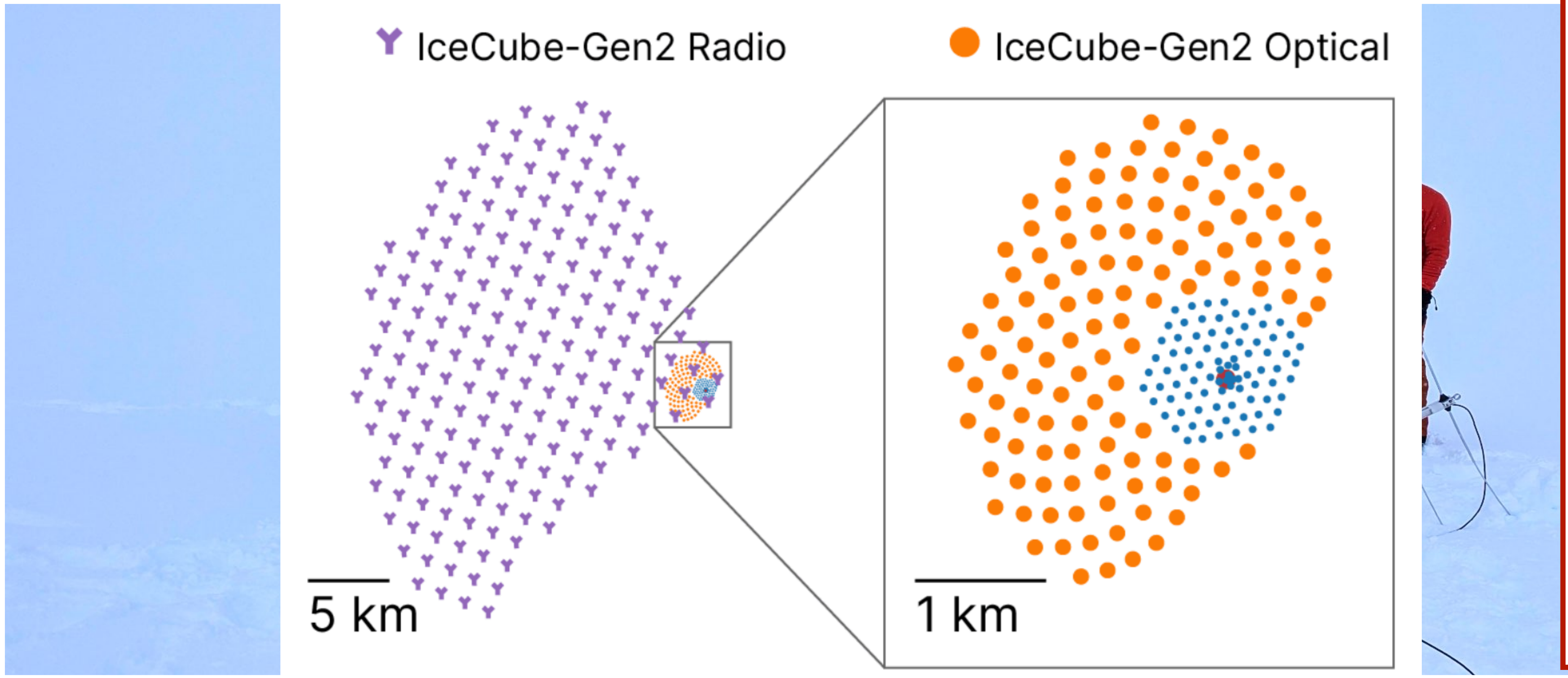
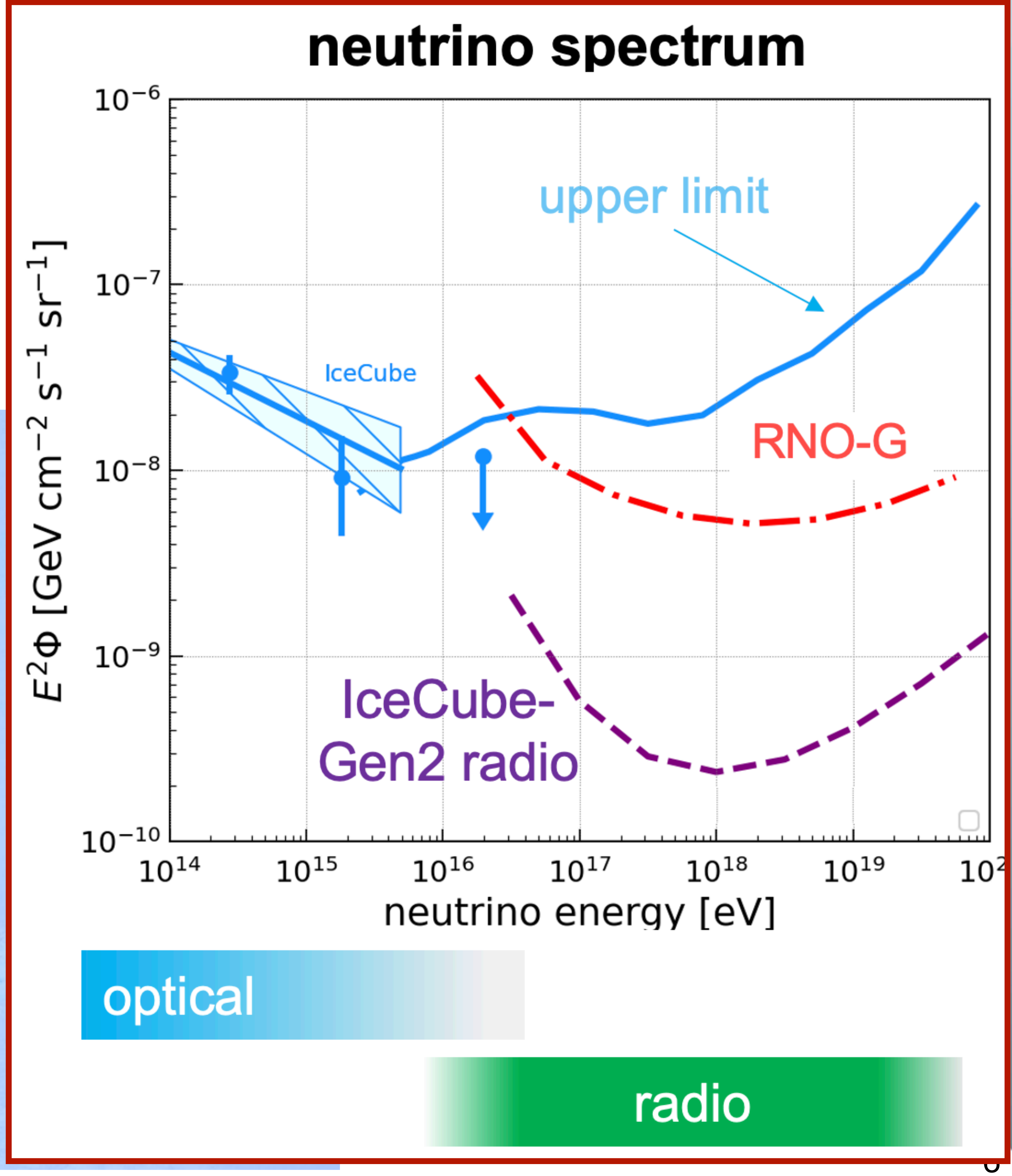






IceCube-Gen2 Radio detector design

- Traditional **detector optimization** is slow
- Make pipeline **differentiable** using PyTorch

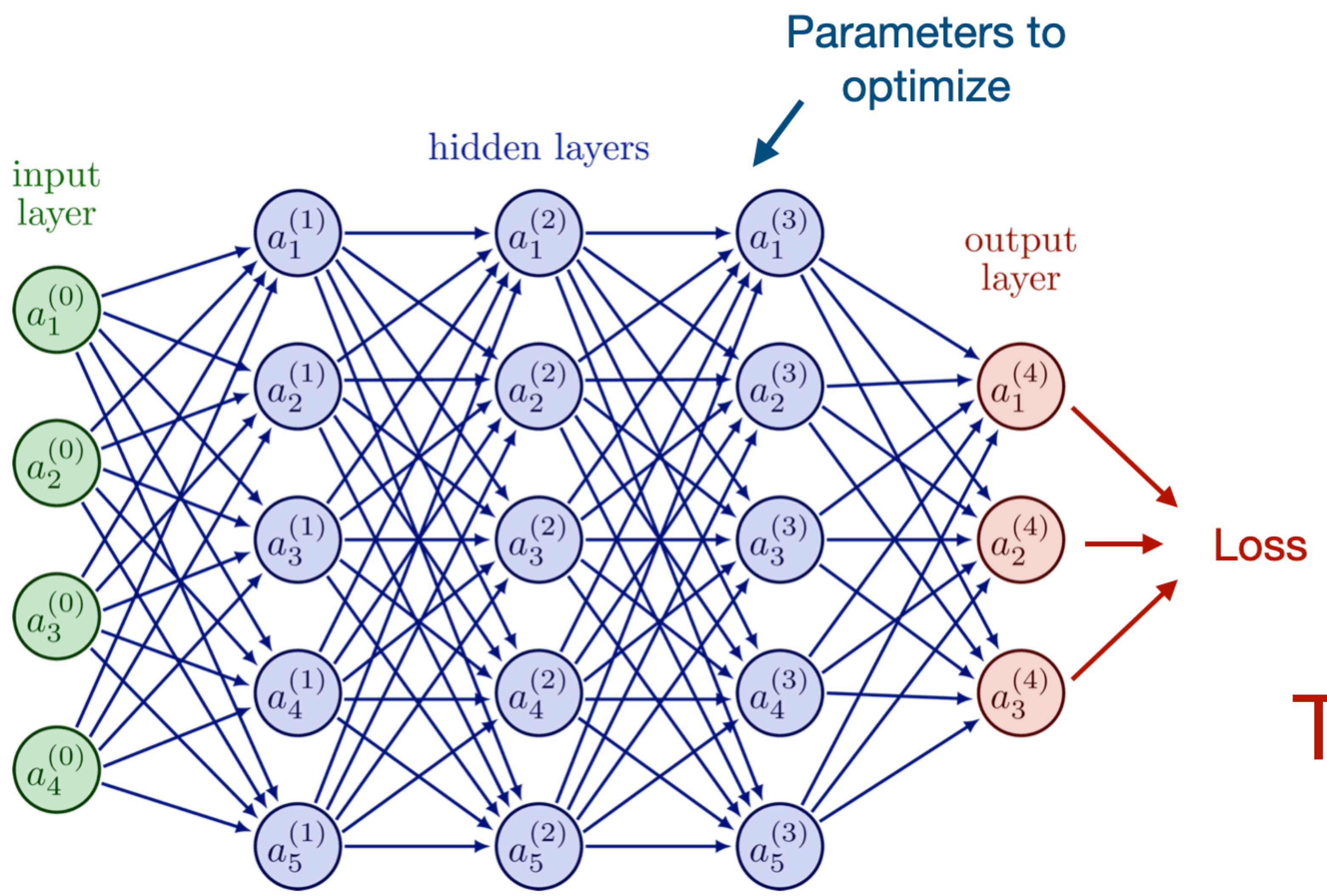
detector parameters, e.g.,
- antenna positions
- antenna orientation

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

automatic differentiation

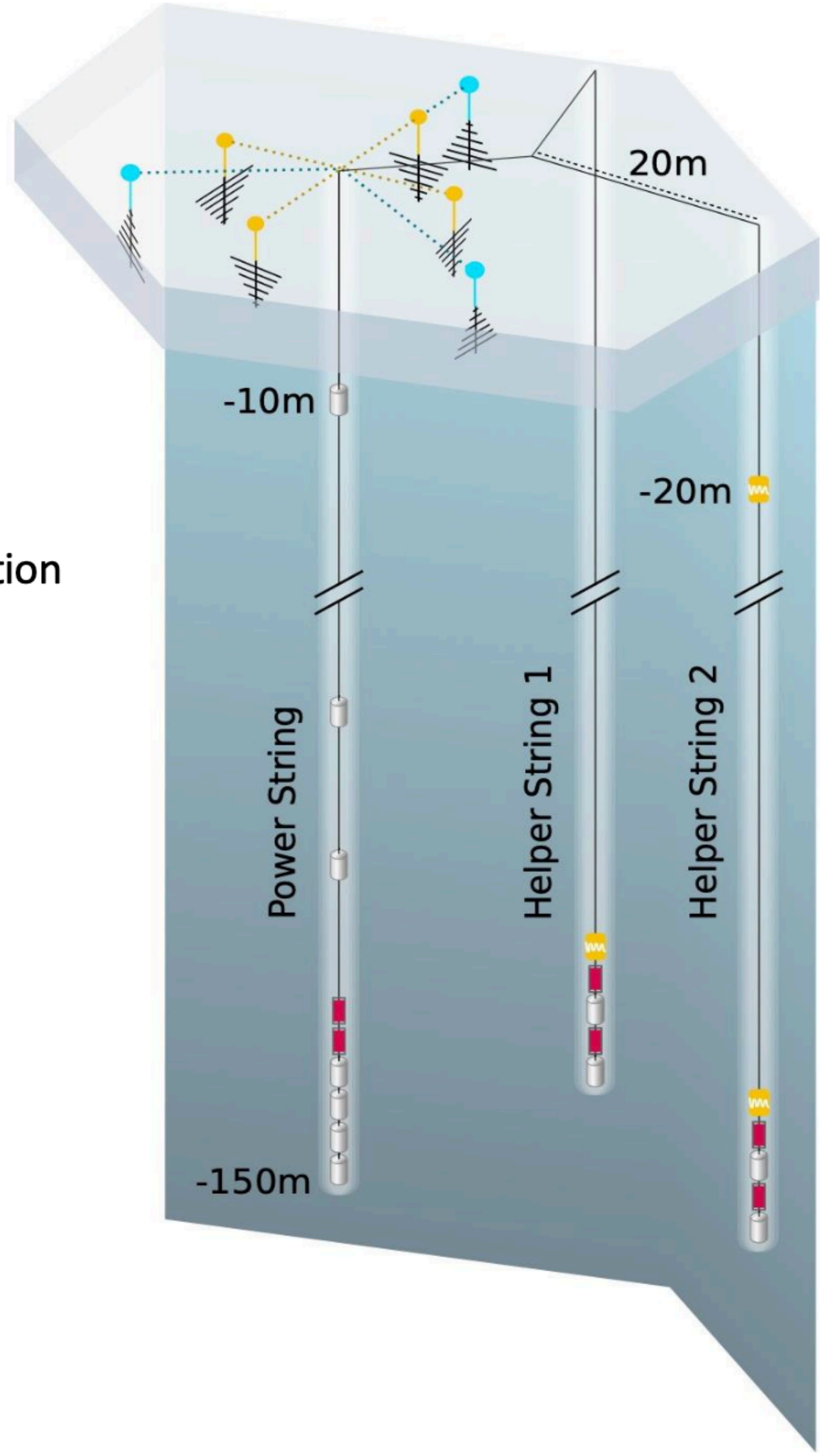
Θ | MC simulation x reconstruction x analysis | f(Θ)

costs, engineering constraints



Train detector like neural network

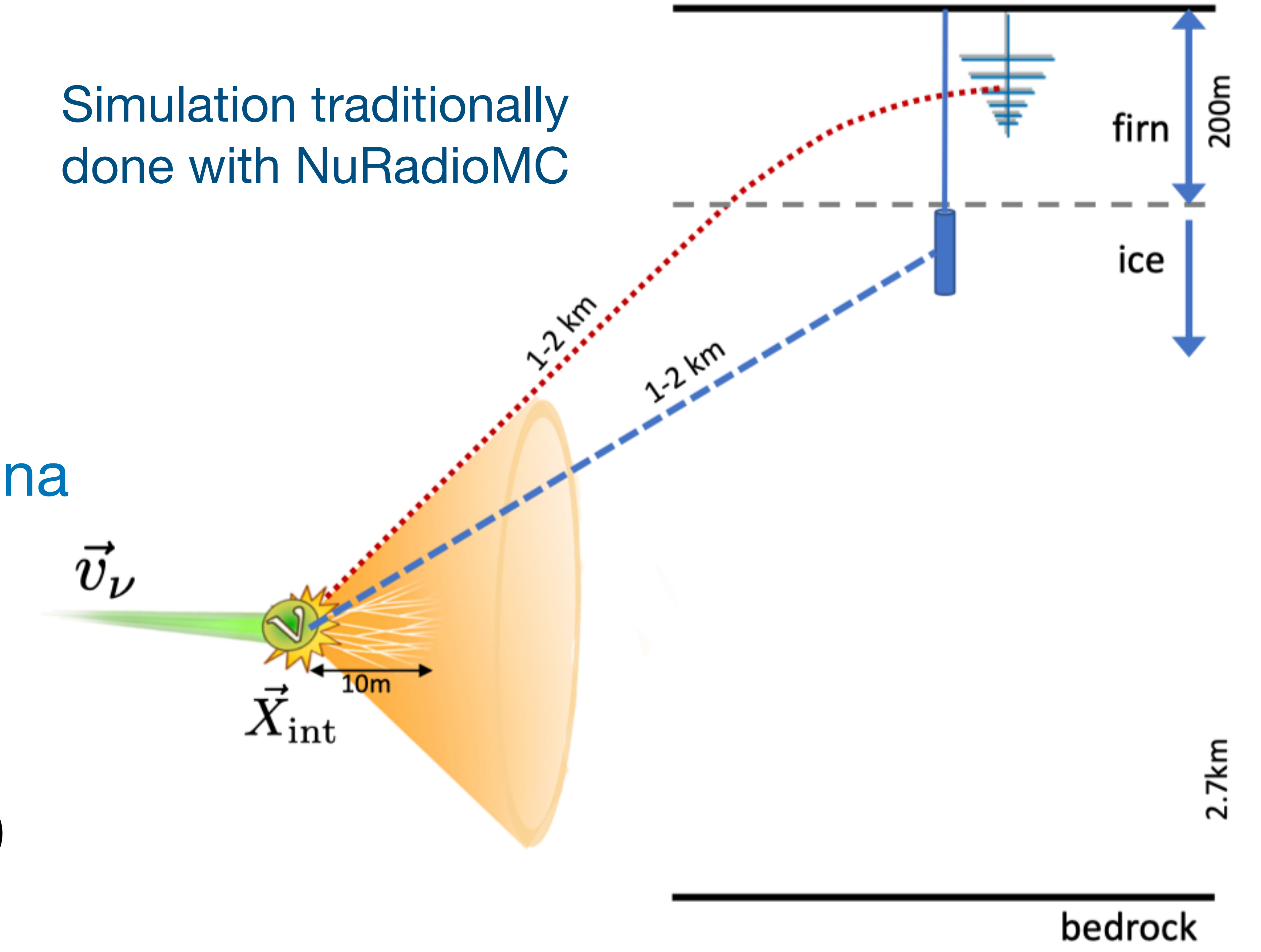
:ion



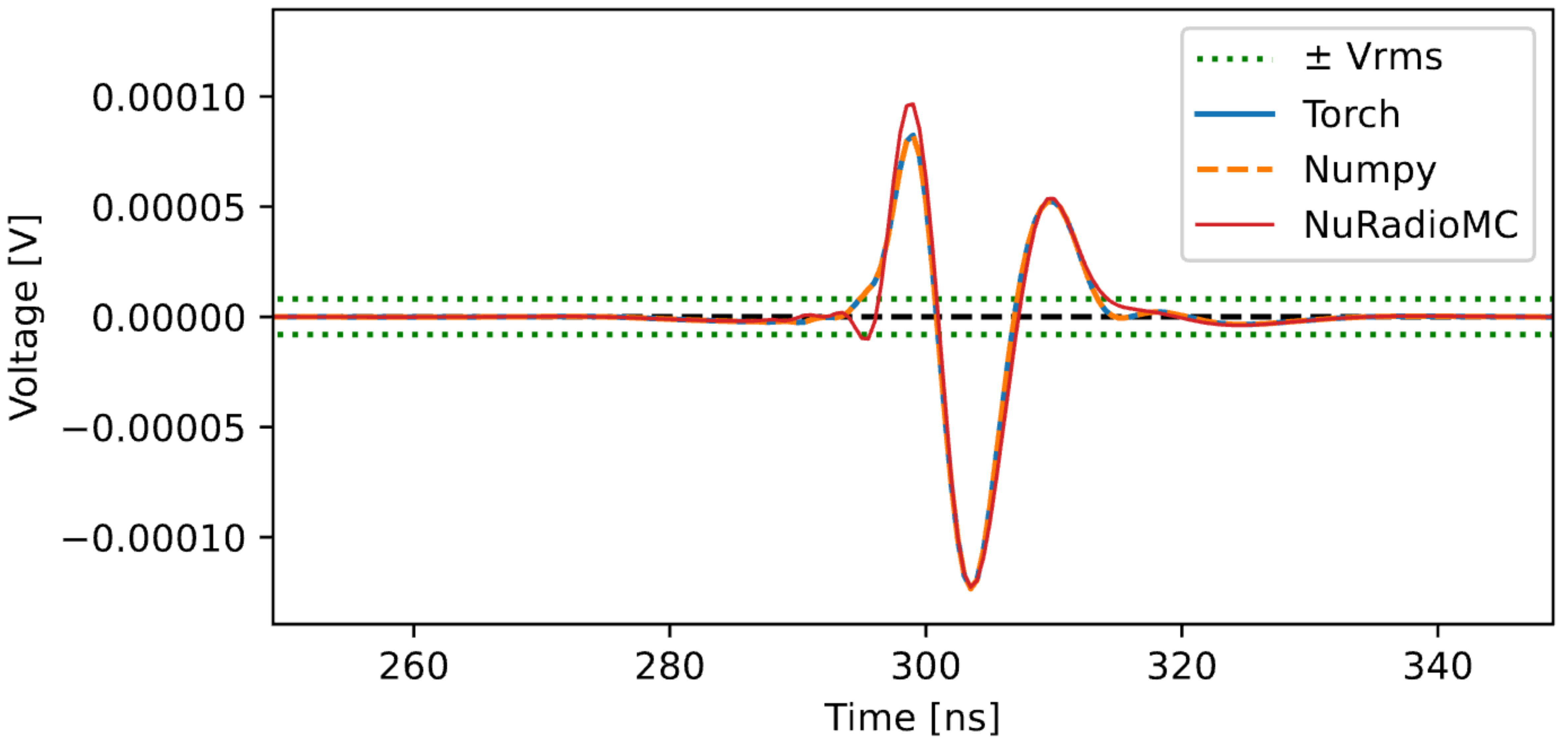
Differentiable simulation pipeline

- Input: Neutrino and detector parameters:
  - E_{shower}, θ_ν, ϕ_ν, x_ν, y_ν, z_ν, t_0, xyz_antenna, ori._antenna
- Simulation implemented in PyTorch:
  - Event geometry
  - Askaryan emission (Diffusion model by Philipp Pilar)
  - Propagation (straight line - constant n)
  - Detection (LPDAs)
- Output:
  - **Voltage traces**

Simulation traditionally done with NuRadioMC

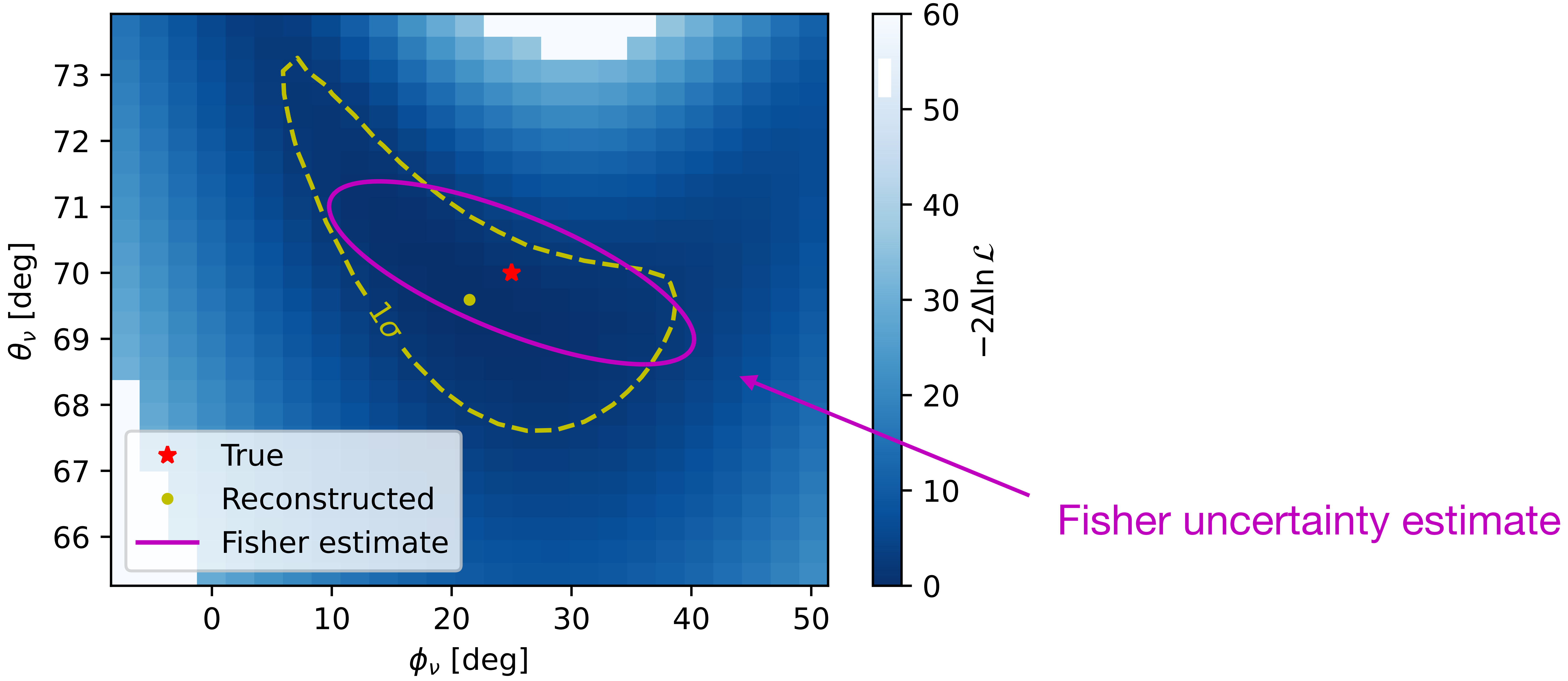


Example simulation:



Reconstruction uncertainty estimation

- Reconstruction of MC **neutrino arrival direction** in in-ice radio detector:



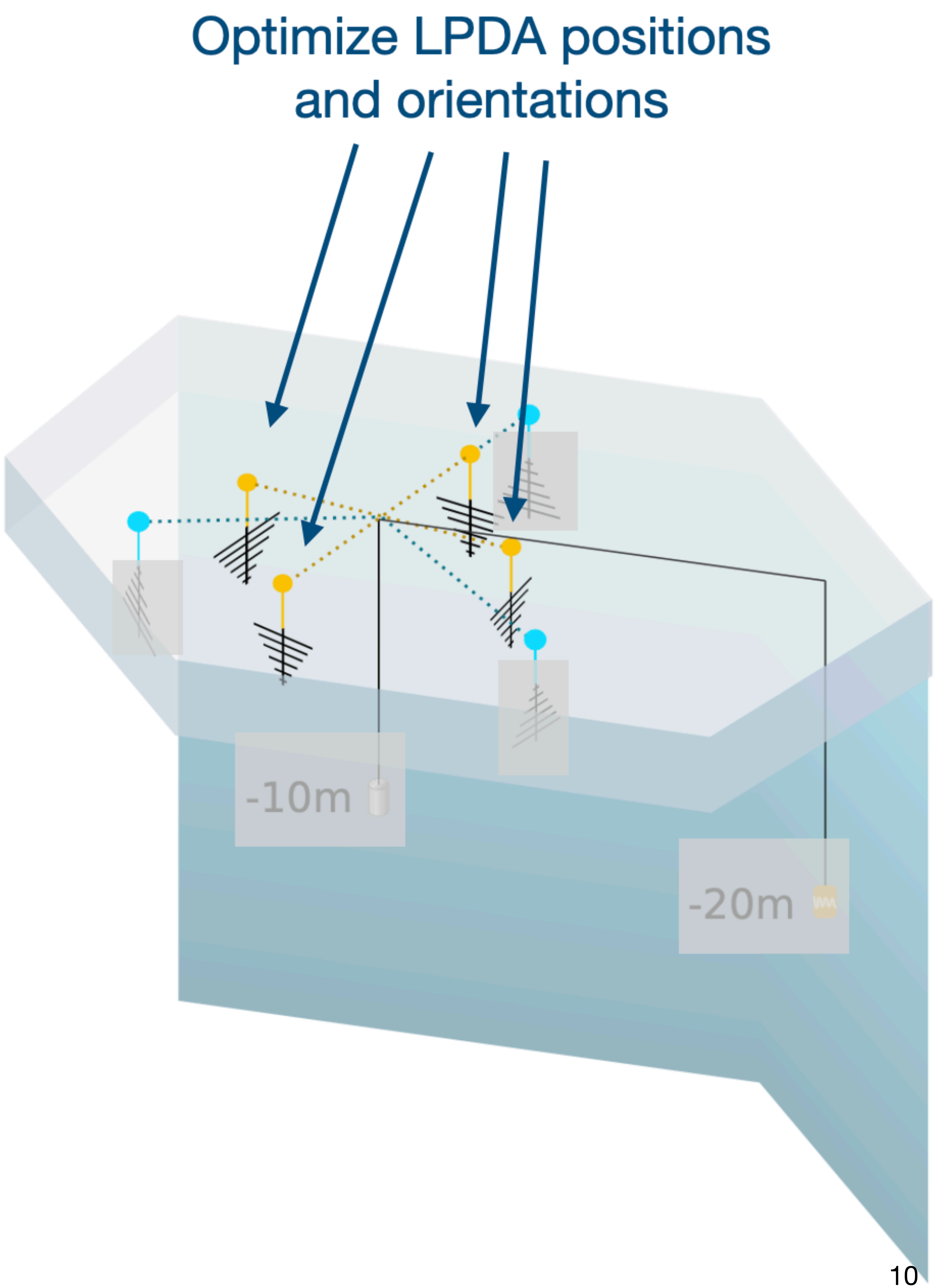
- Uncertainty can be estimated with **Fisher information**
- Orders of magnitude faster than full reconstruction
- Implemented in PyTorch

$$\mathcal{I}_{m,n} = \sum_{ant.} \frac{\partial \boldsymbol{\mu}^{\mathrm{T}}}{\partial \theta_m} \boldsymbol{\Sigma}^{-1} \frac{\partial \boldsymbol{\mu}}{\partial \theta_n}$$

$$\sigma^2 = \left(\mathcal{I} \right)^{-1}$$

Proof of concept optimization

- Optimize antenna **positions and orientations**
- **Batch**: 28 random neutrino events
- **Loss**: log(reconstructed direction **uncertainty** area)



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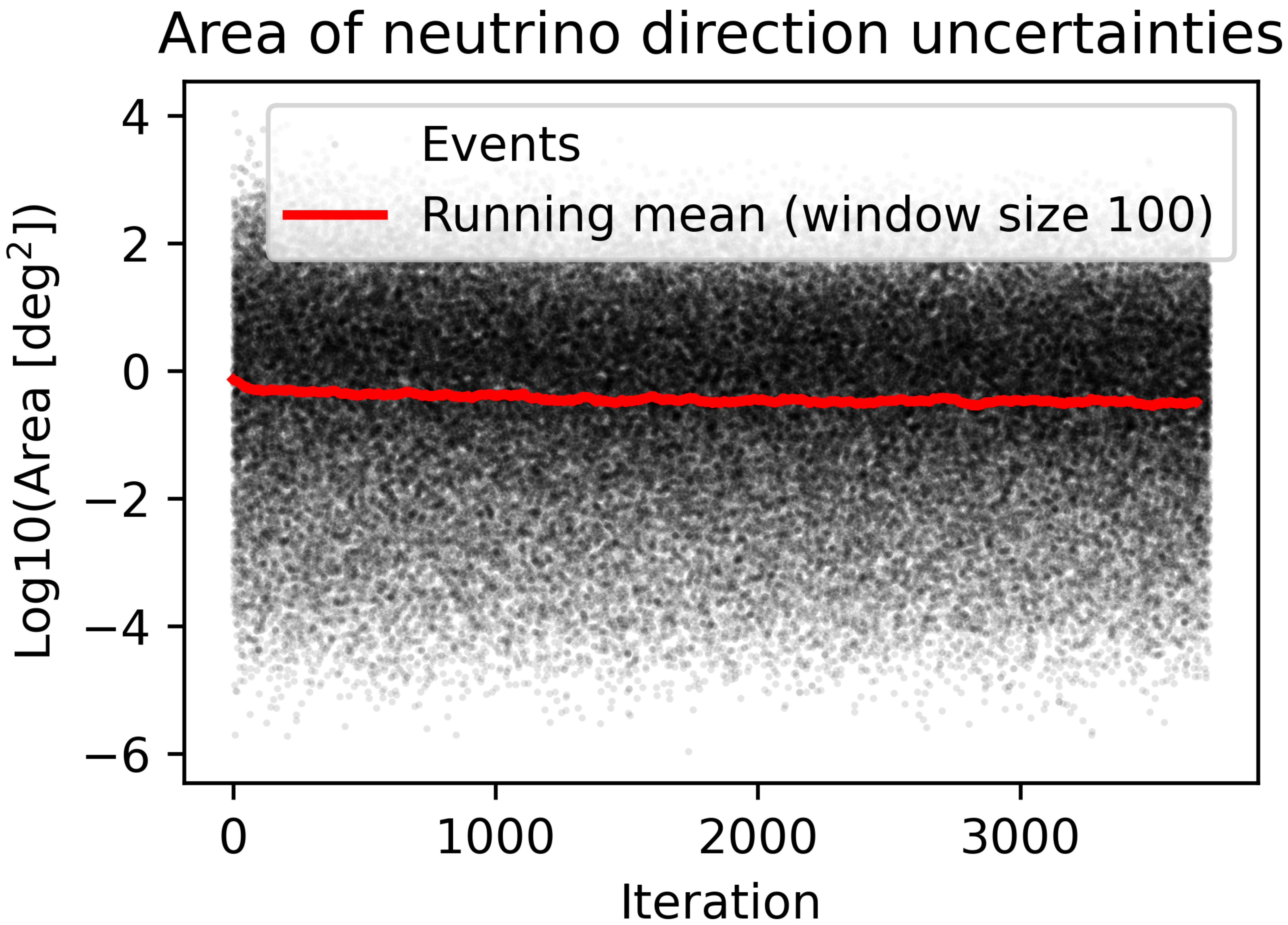

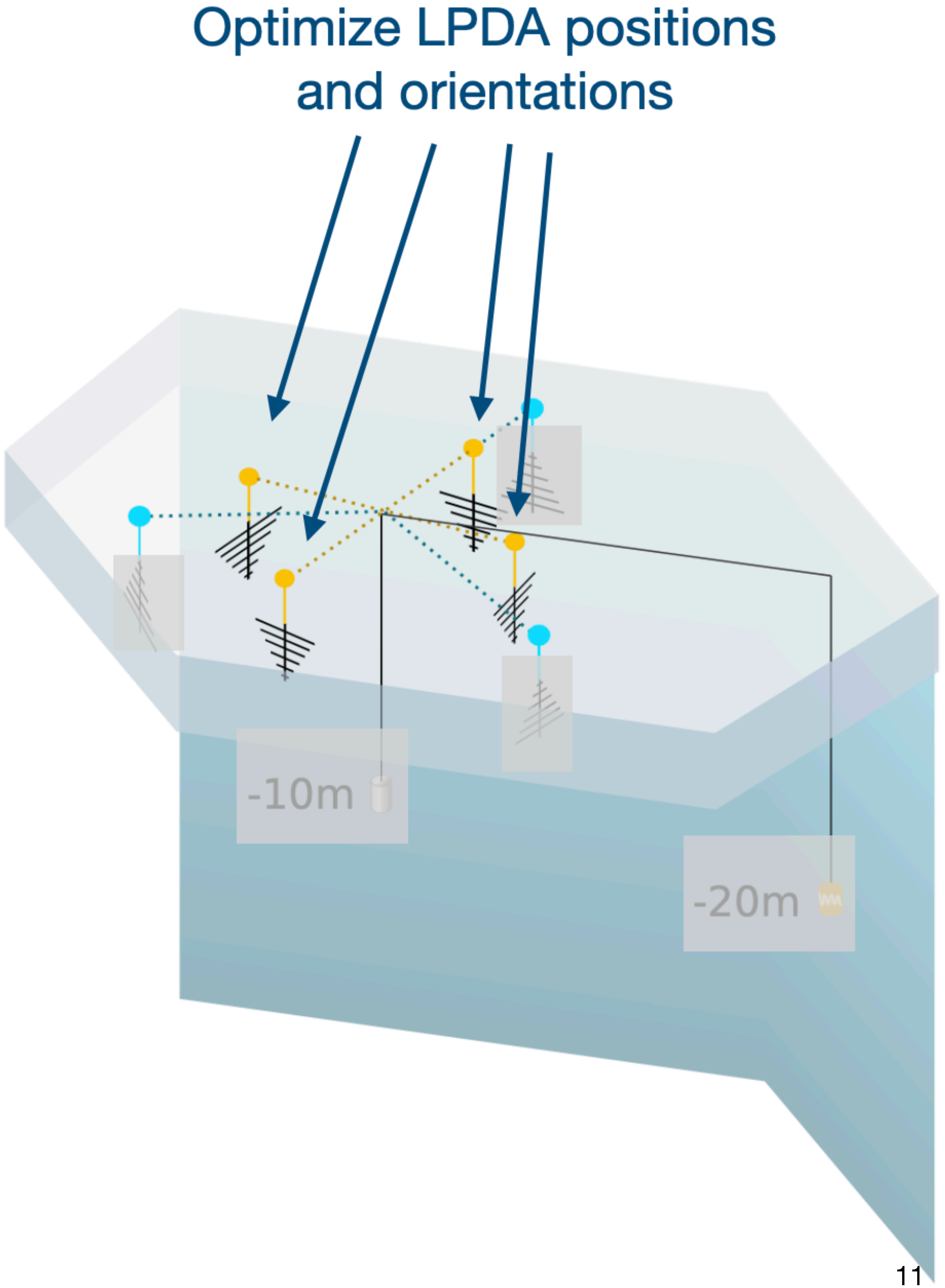

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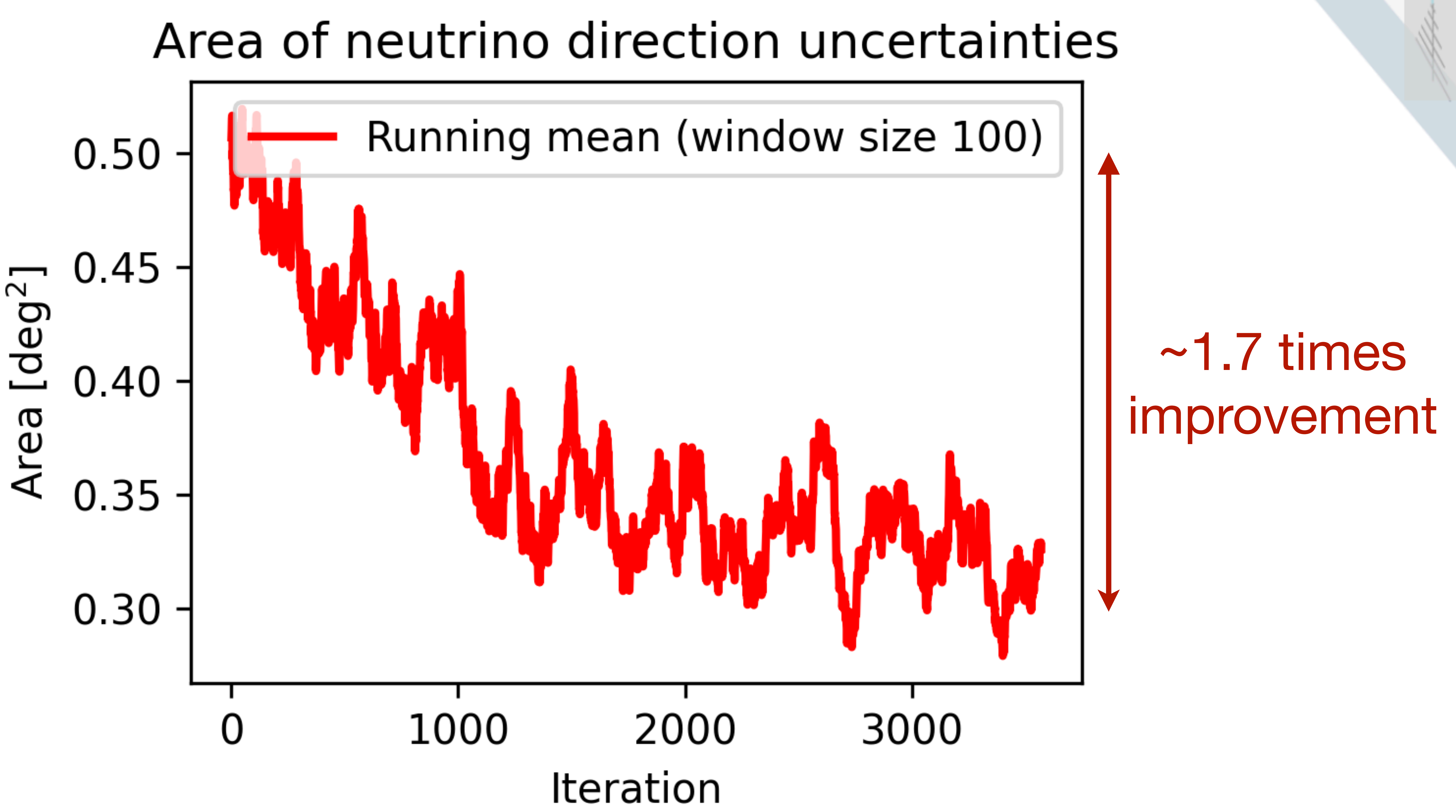

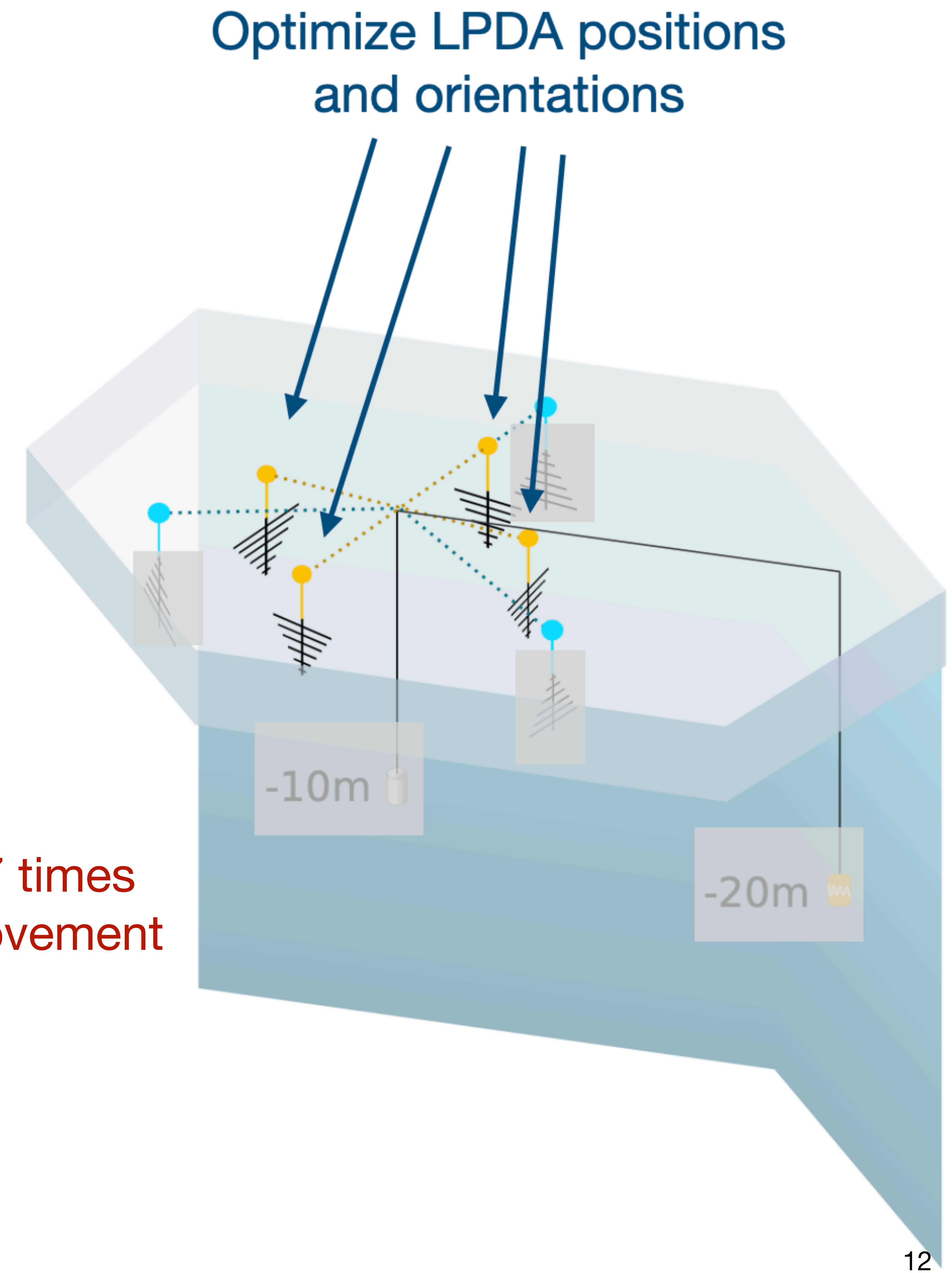

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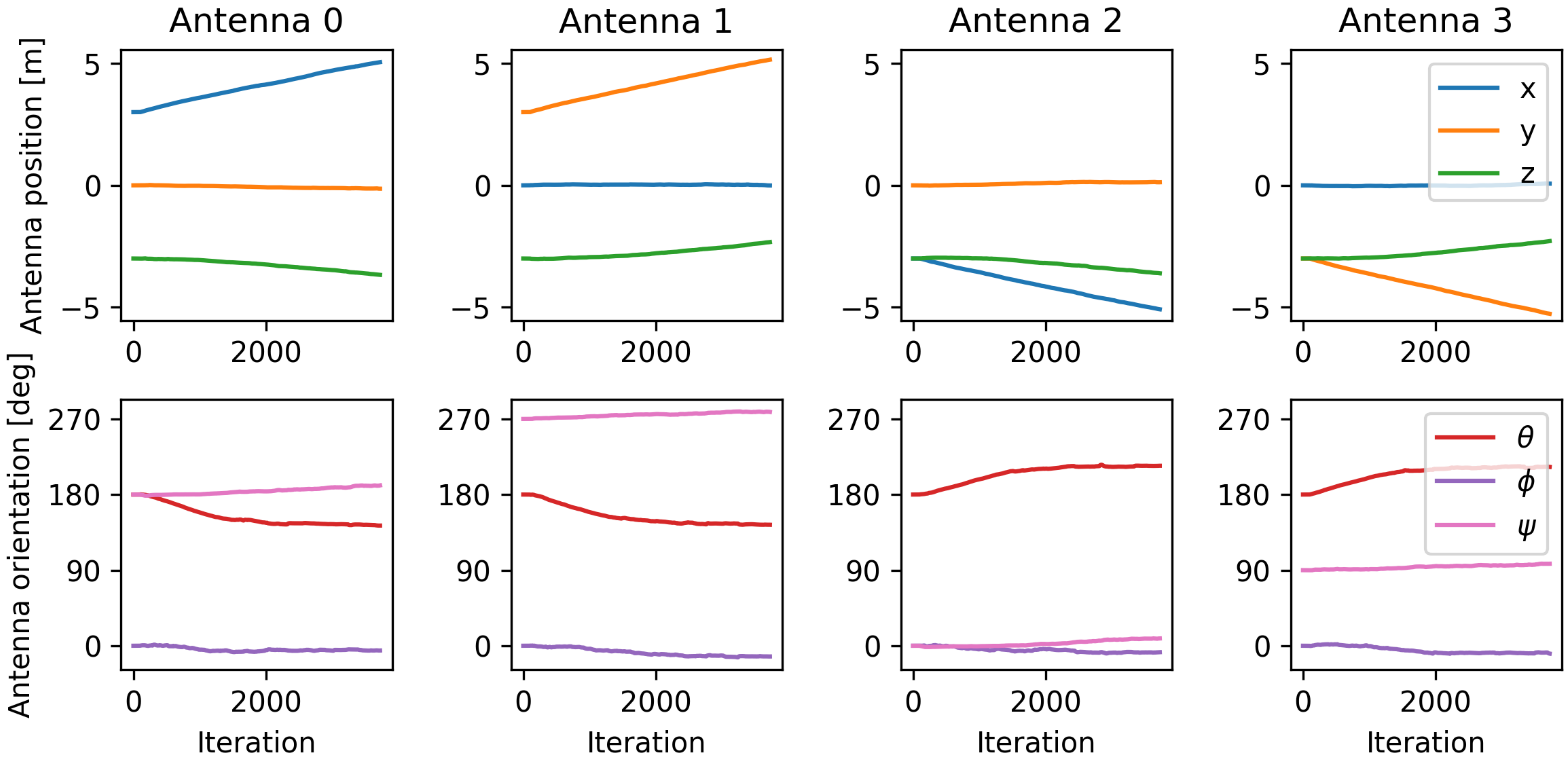
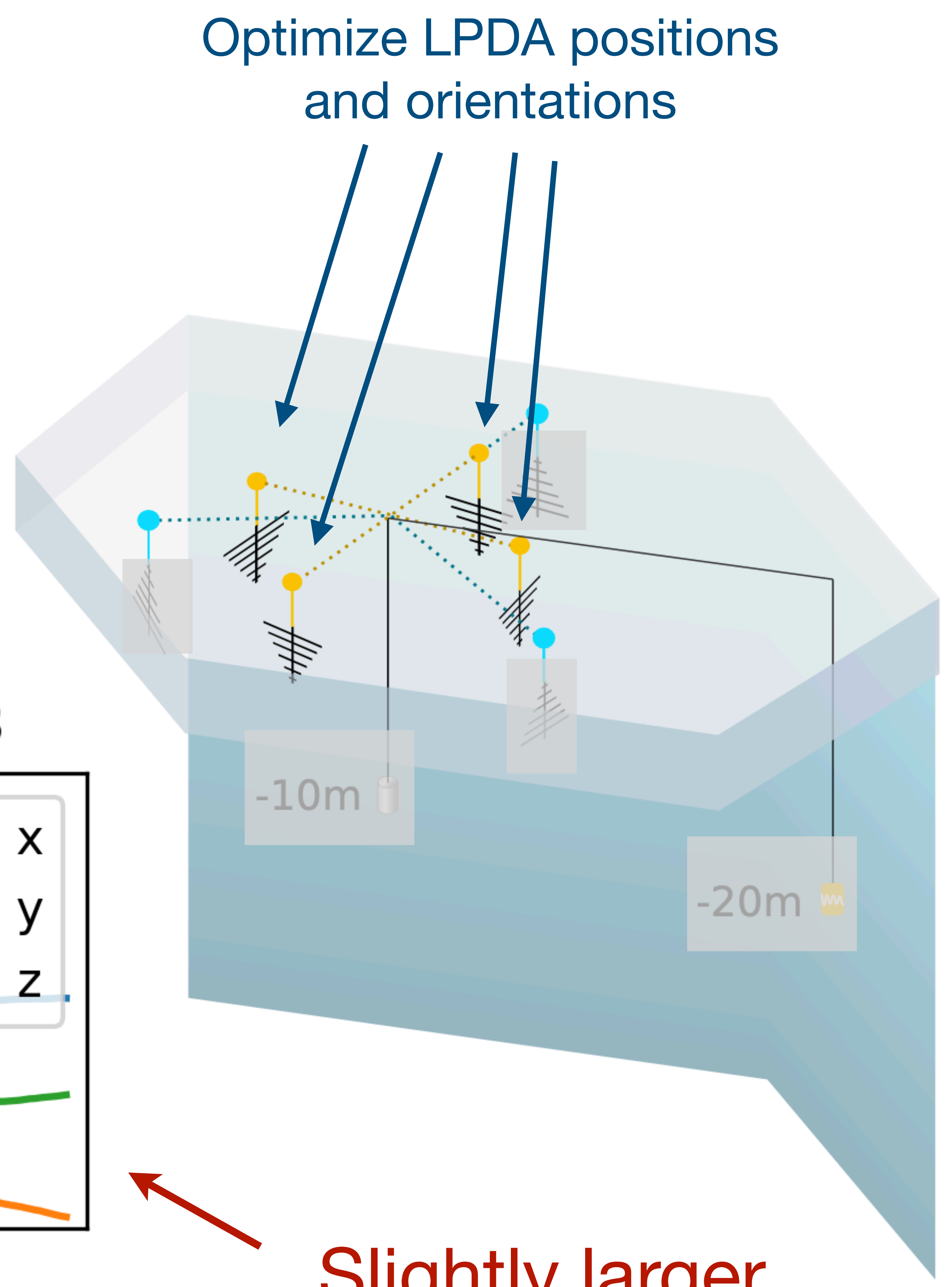




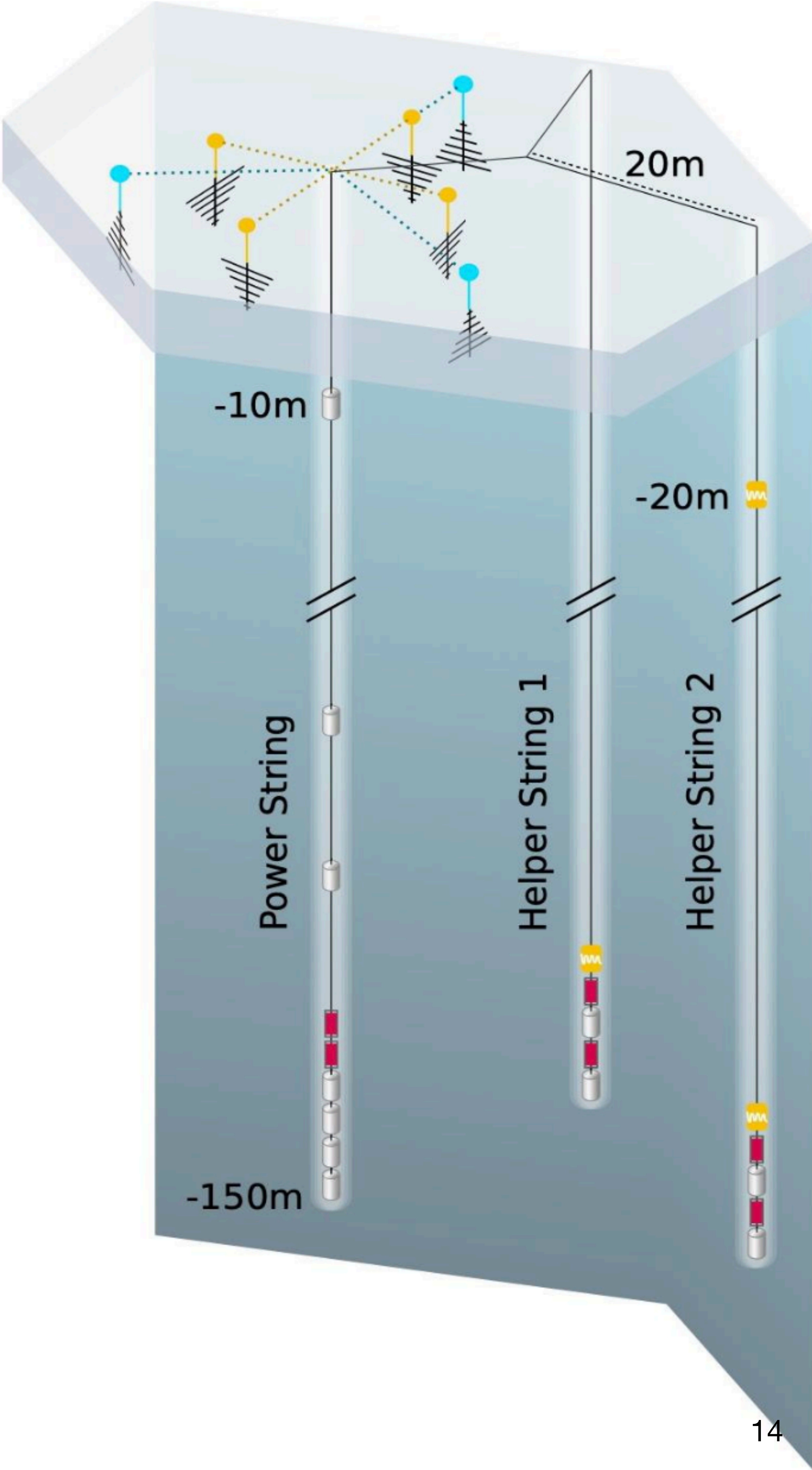
Slightly larger detector

Slightly less downward-facing

Sensible results!

Conclusions

- (Slightly simplified) differential radio neutrino simulation and reconstruction pipeline in PyTorch is ready
- Proof of concept: differentiable end-to-end optimization works
- Next steps:
  - Increase realism of the differentiable signal model (in particular in-ice ray-tracing with surrogate model)
  - Use large event sample with realistic neutrino distrubutions
  - Optimize more complex stations with more antennas
  - Full end-to-end optimization of the RNO-G and Gen2 radio stations



Extra slides

NuRadioOpt

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

This talk

Main science objectives of UHE neutrino astronomy:

Impact of NuRadioOpt

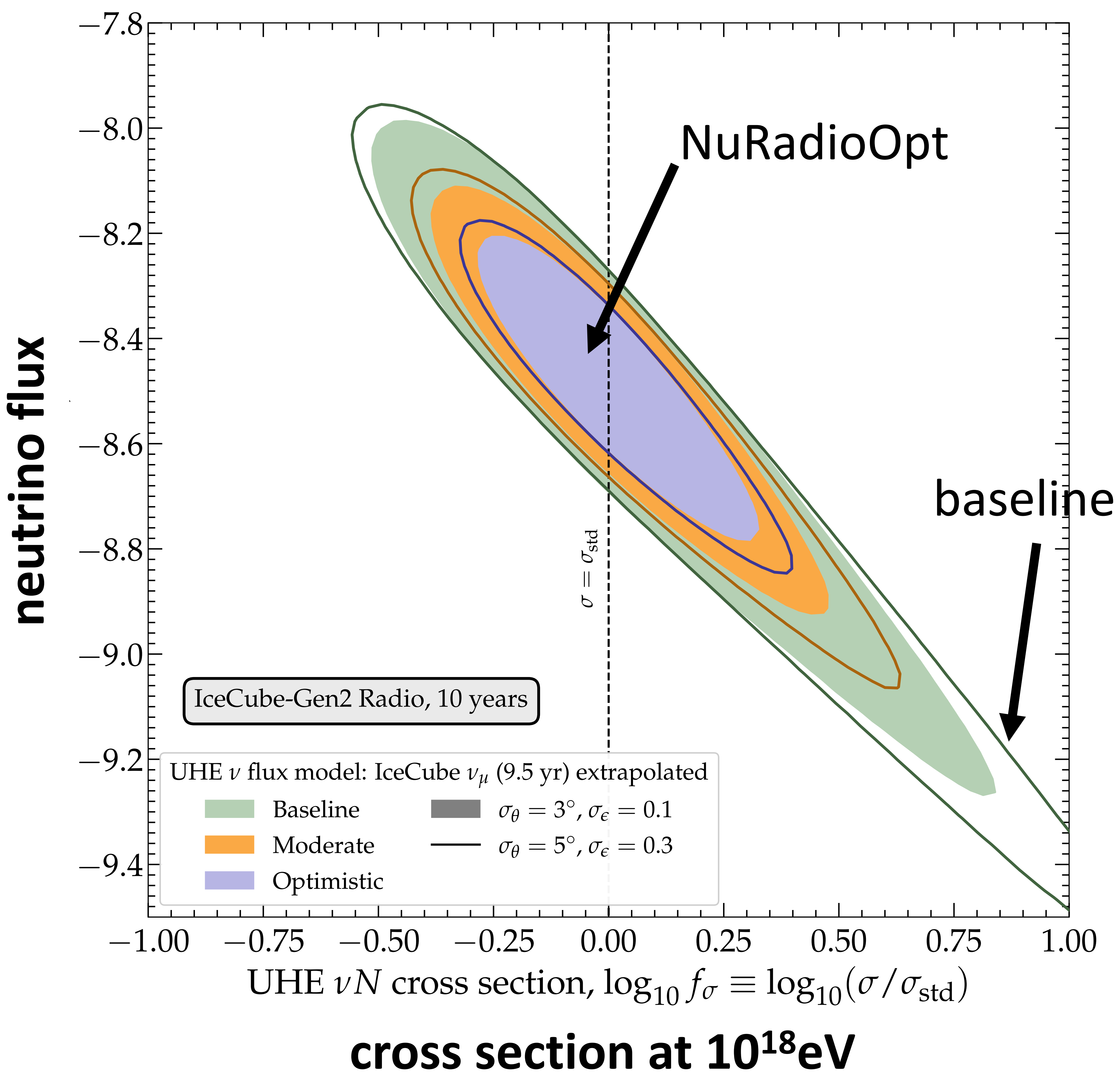
Neutrino-Nucleon Cross Section

Diffuse Flux

Point Sources

→ 3x more precise measurement

*V. Valera, M. Bustamante, **C. Glaser**, JHEP 06 105 (2022)*



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

Main science objectives of UHE neutrino astronomy:

Impact of NuRadioOpt

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→ 3x more precise measurement

*V. Valera, M. Bustamante, **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. Bustamante, **C. Glaser,** PRD 107, 043019 (2023)*

Point Sources

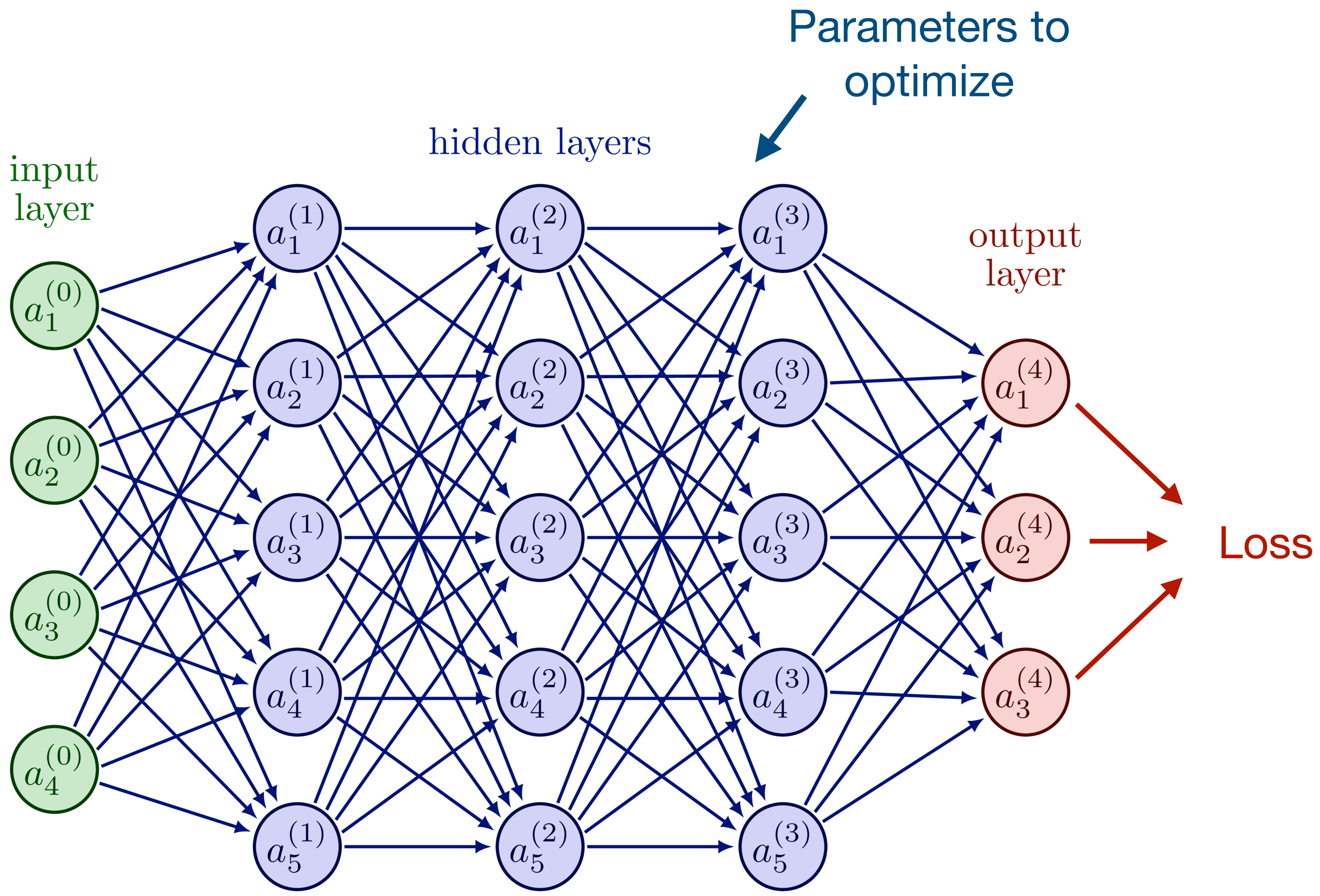
→ identify sources from deeper in our Universe, increasing the observable volume by a factor of three

D. F. G. Fiorillo, V. Valera, M. Bustamante, 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**

Differentiable programming

- Central concept in machine learning
- Automatically calculate and save derivatives of output w.r.t. parameters in forward pass
- Calculate gradient of loss w.r.t. parameters in backpropagation (chain rule)
- Take step opposite gradient to optimize network
- Use for detector optimization:
    - Network is simulation pipeline
    - Input is neutrino parameters
    - Parameters are detector parameters
    - Loss is neutrino reconstruction uncertainty
- We can utilize differential programming frameworks to optimize detector layouts



IceCube-Gen2 Radio detector design

- Traditional detector optimization is slow
- 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

automatic differentiation

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

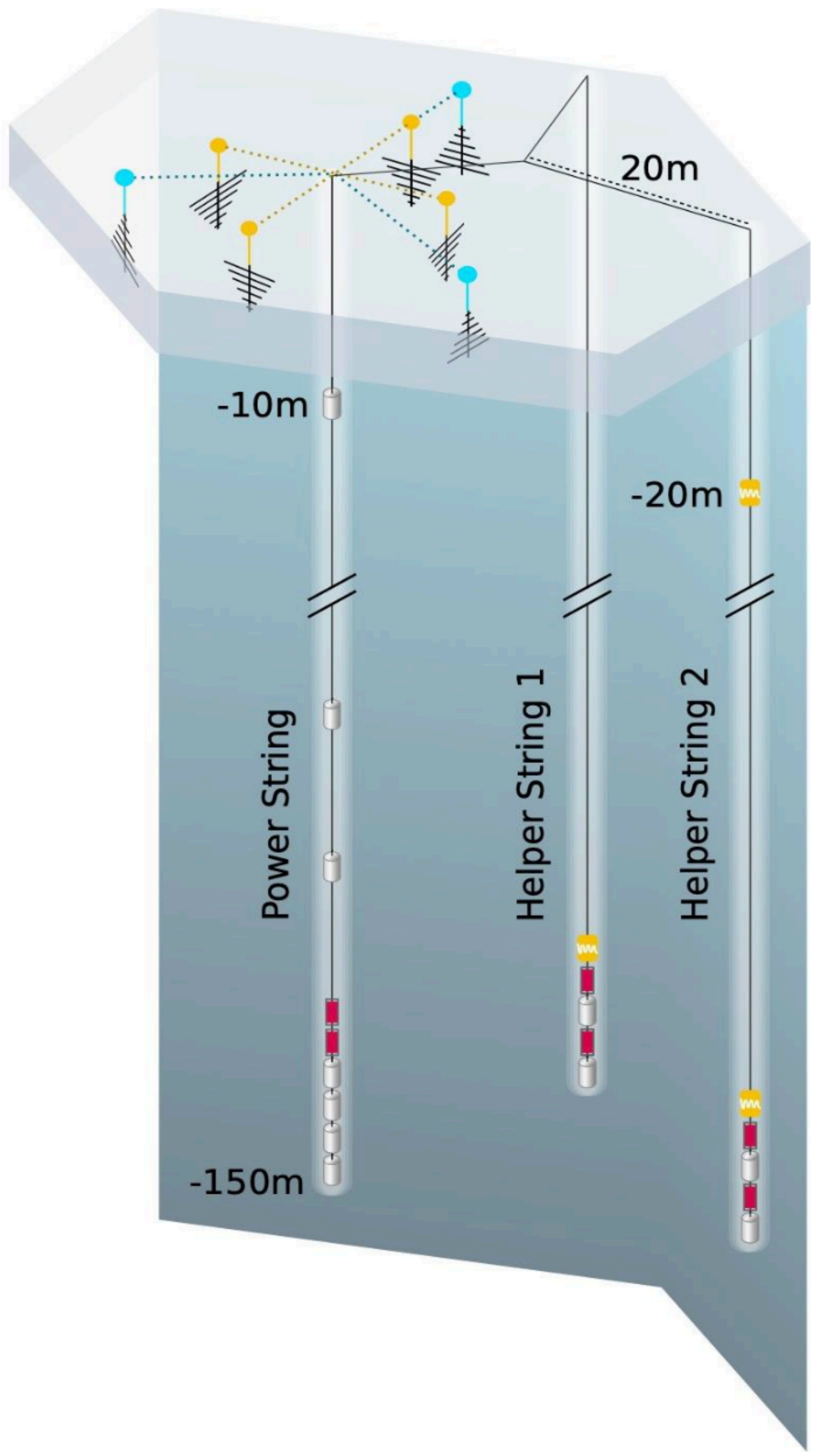
science output, e.g.,
- neutrino-nucleon cross-section
- source discovery
- flux measurement

costs, engineering constraints

Port NuRadioMC to PyTorch

Proxy: Fisher information matrix

Objective: Neutrino direction uncertainty



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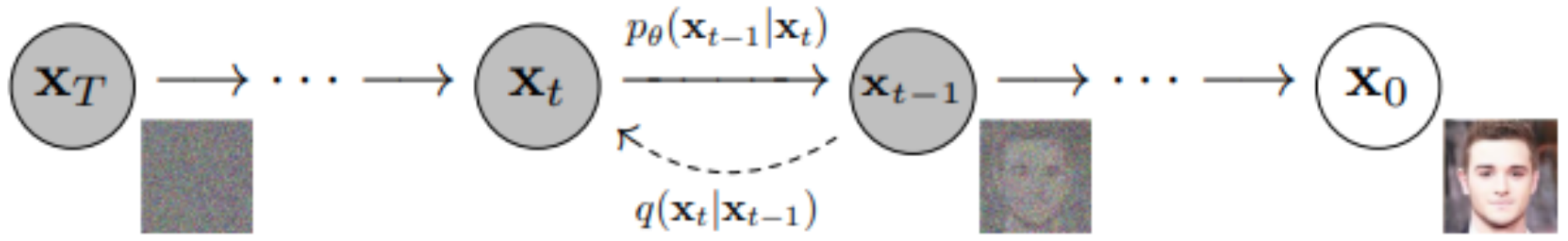
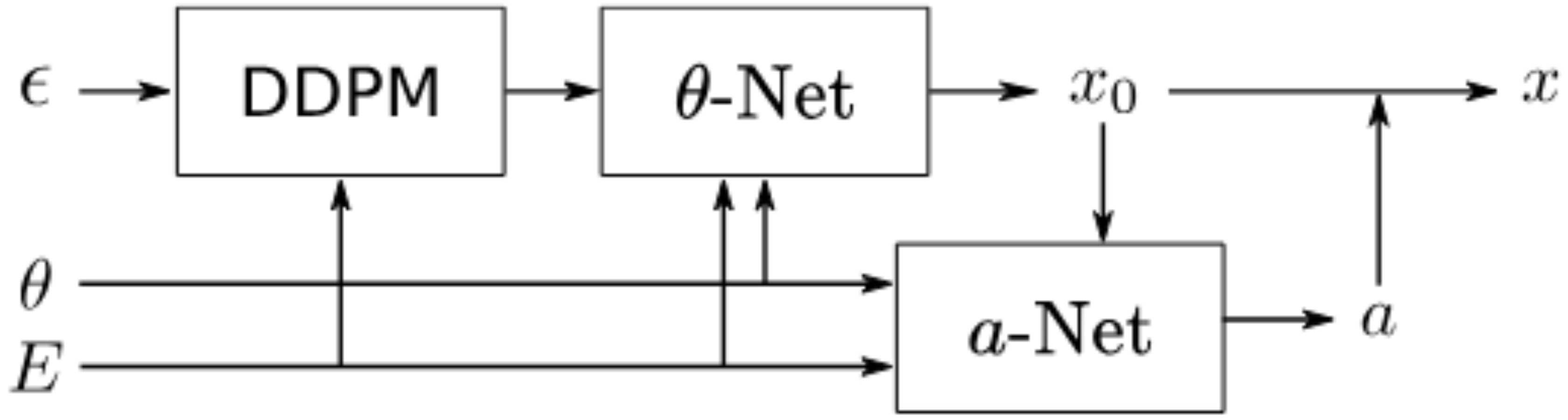
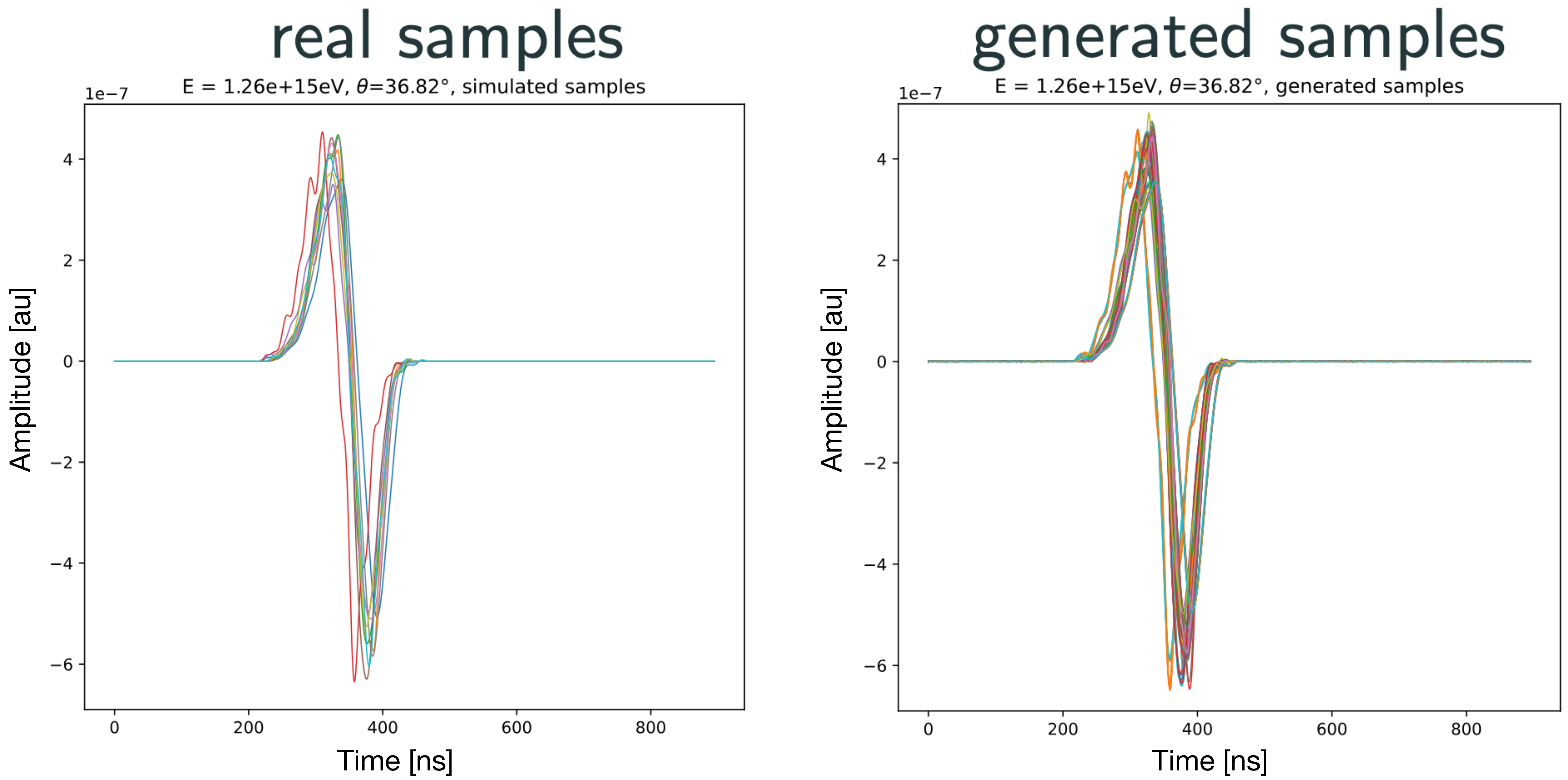
  - Voltage traces

Shown at last year's MODE Workshop:



Diffusion model trained to generate Askaryan emission (surrogate model):





Likelihood Reconstruction

- Likelihood for Radio Neutrino Detectors:

Signal

$$p(\boldsymbol{x};\boldsymbol{\mu}(\theta),\boldsymbol{\Sigma}) = \frac{1}{\sqrt{(2\pi)^{n_t}|\boldsymbol{\Sigma}|}} \exp\left(-\frac{1}{2}(\boldsymbol{x}-\boldsymbol{\mu}(\theta))^{\mathsf{T}}\boldsymbol{\Sigma}^{-1}(\boldsymbol{x}-\boldsymbol{\mu}(\theta))\right)$$

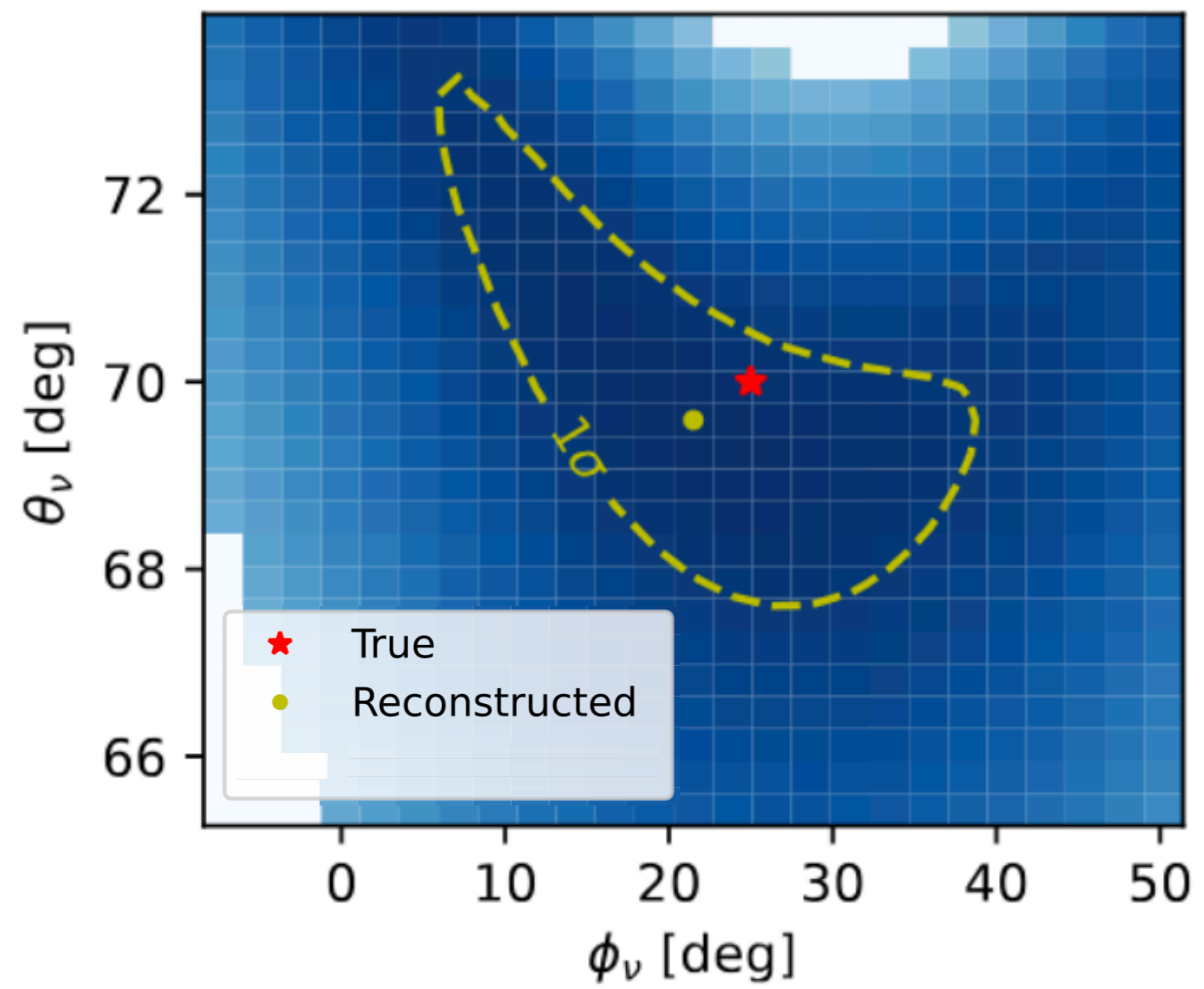
Trace Noise

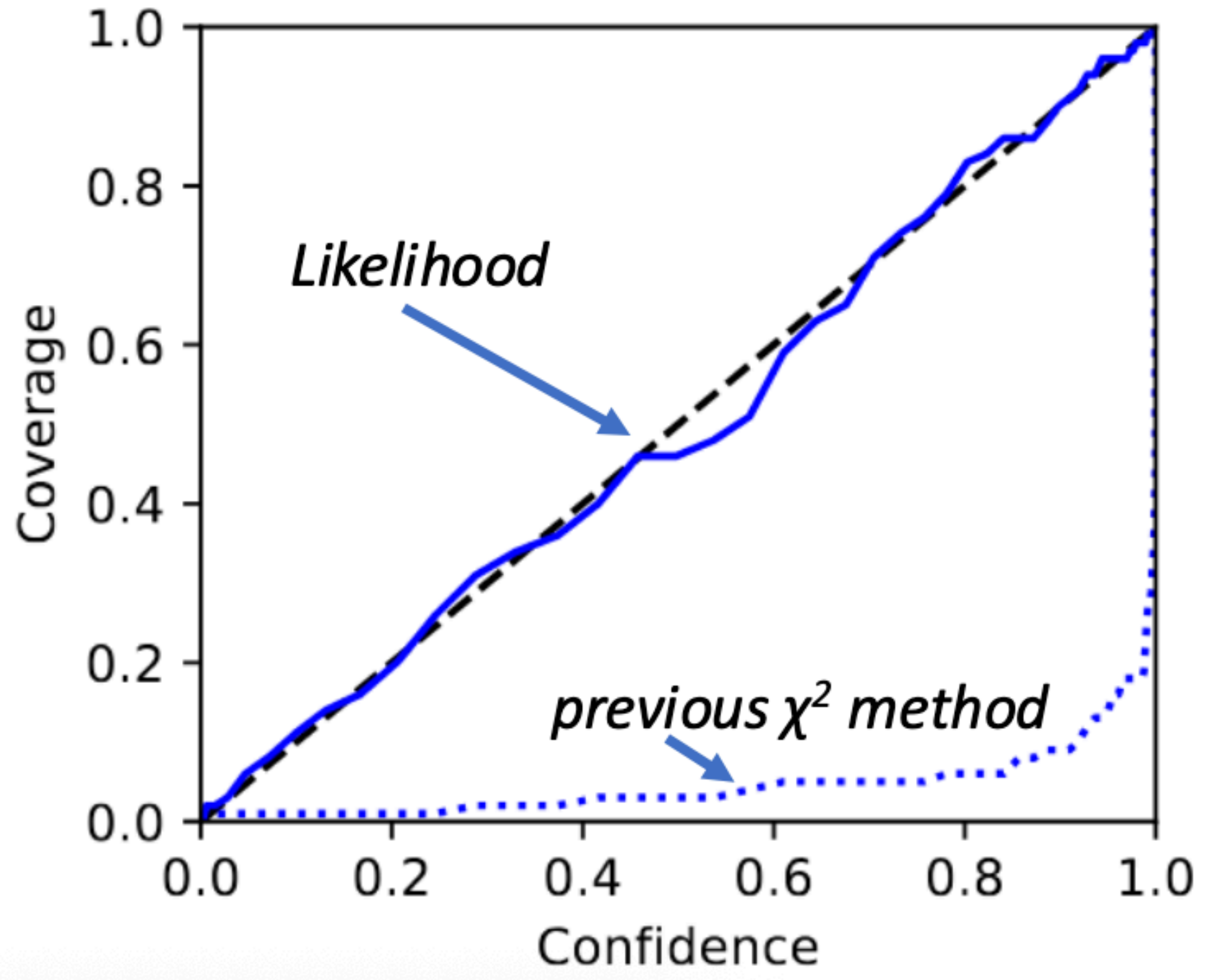
- Key ingredient: Bandwidth-limited noise can be modeled as multi-variate Gaussian

- Minimize to get best-fit parameters and uncertainties

$$-2\ln\mathscr{L}(\boldsymbol{\mu}(\theta);\boldsymbol{x},\boldsymbol{\Sigma}) = \sum_{\text{ant.}} (\boldsymbol{x}-\boldsymbol{\mu}(\theta))^{\mathsf{T}}\boldsymbol{\Sigma}^{-1}(\boldsymbol{x}-\boldsymbol{\mu}(\theta)) + const$$

arxiv: 2409.11888





Uncertainty estimation with Fisher information matrix

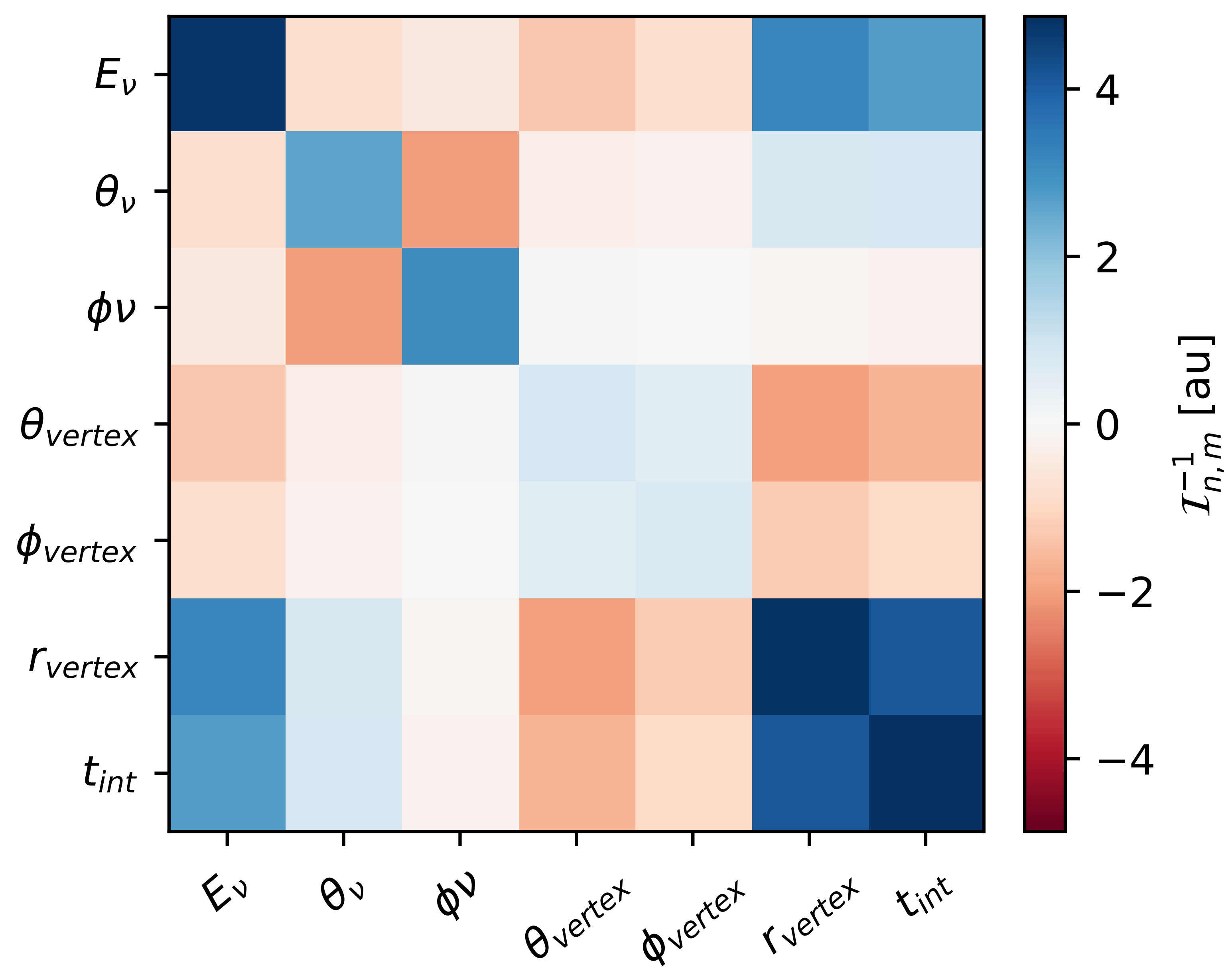
- Fisher Information Matrix can be calculated directly from signal model:

$$\mathcal{I}_{m,n} = \sum_{ant.} \frac{\partial \boldsymbol{\mu}}{\partial \theta_m}^{\mathrm{T}} \boldsymbol{\Sigma}^{-1} \frac{\partial \boldsymbol{\mu}}{\partial \theta_n} \qquad \sigma^2 = \left(\mathcal{I} \right)^{-1}$$

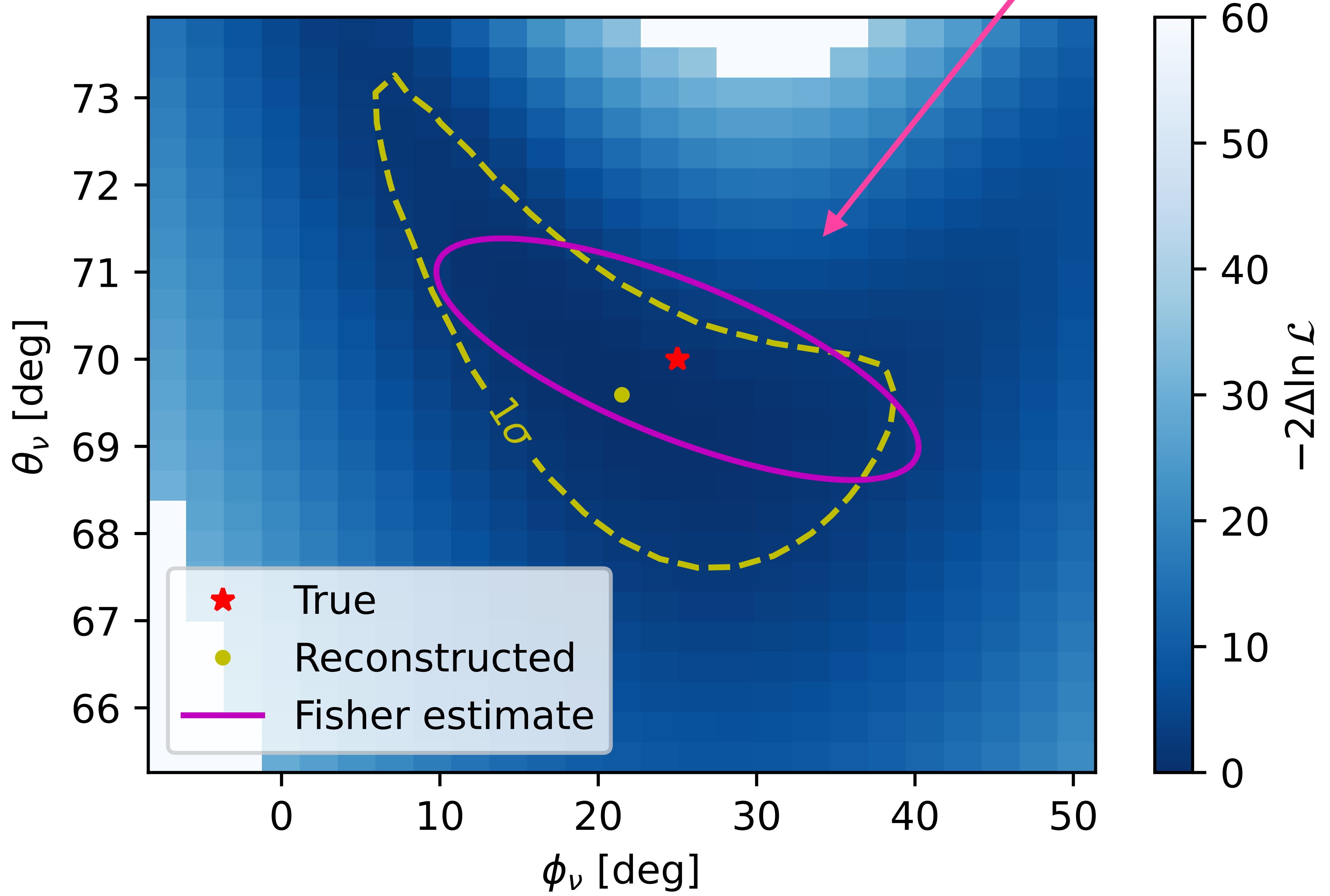
Implemented in PyTorch:
Autodiff (in forward mode) or
Finite difference (shown here)

- Inverse gives uncertainty estimate through Cramer-Rao bound

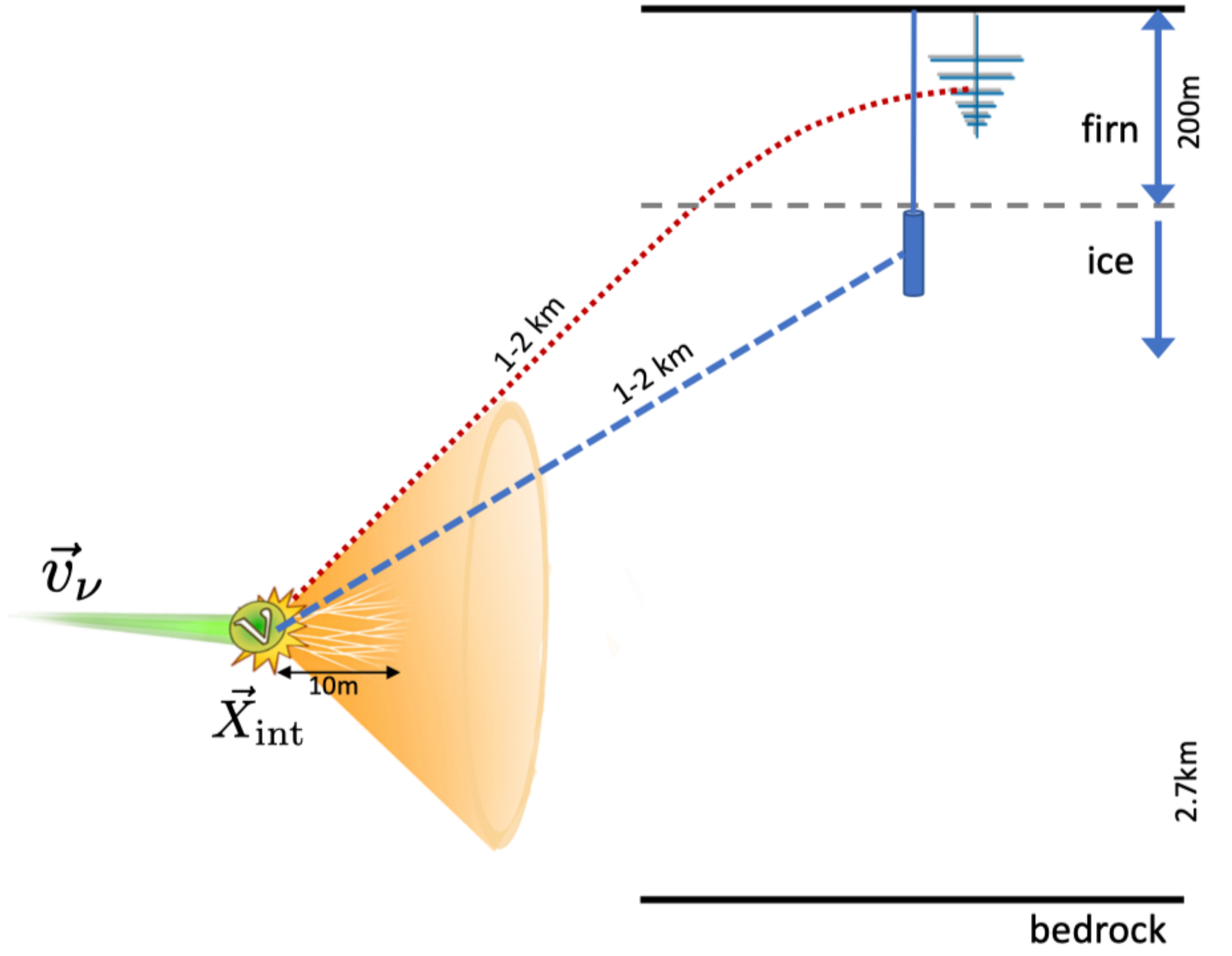
- Depends only on neutrino and detector parameters → fast uncertainty estimation

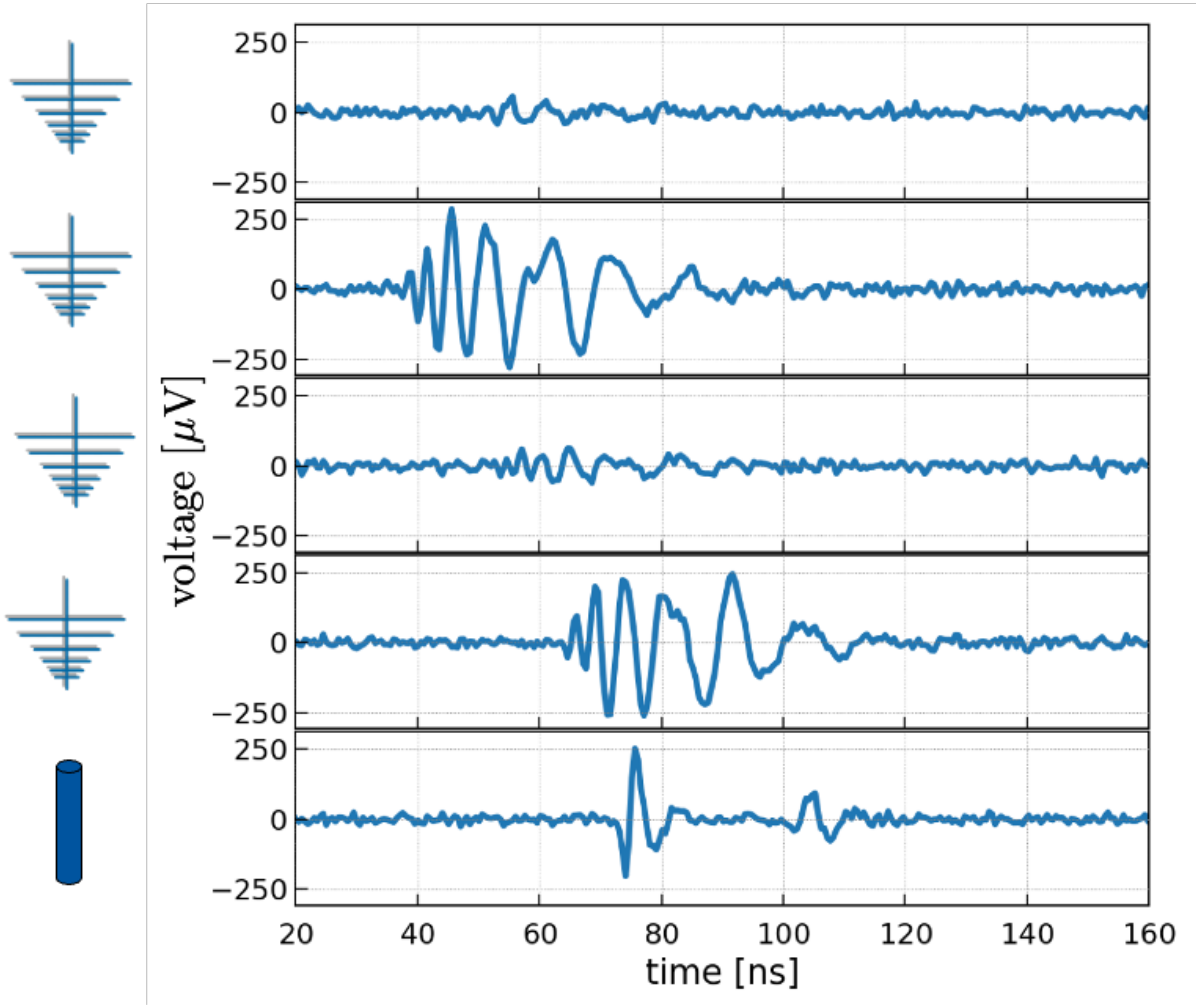


Fisher uncertainty estimate



Radio neutrino simulation and reconstruction





Neutrino parameters:

E_ν

θ_ν, ϕ_ν

x_ν, y_ν, z_ν

t_0

Simulation with NuRadioMC

Reconstruction

$V(t)$

Probabilistic noise model

- Covariance matrix:

$$\boldsymbol{\Sigma} = \begin{pmatrix} \mathrm{Var}(t_0, t_0) & \dots & \mathrm{Cov}(t_n, t_0) \\ \vdots & \ddots & \vdots \\ \mathrm{Cov}(t_0, t_n) & \dots & \mathrm{Var}(t_n, t_n) \end{pmatrix}$$

- Calculate from traces:

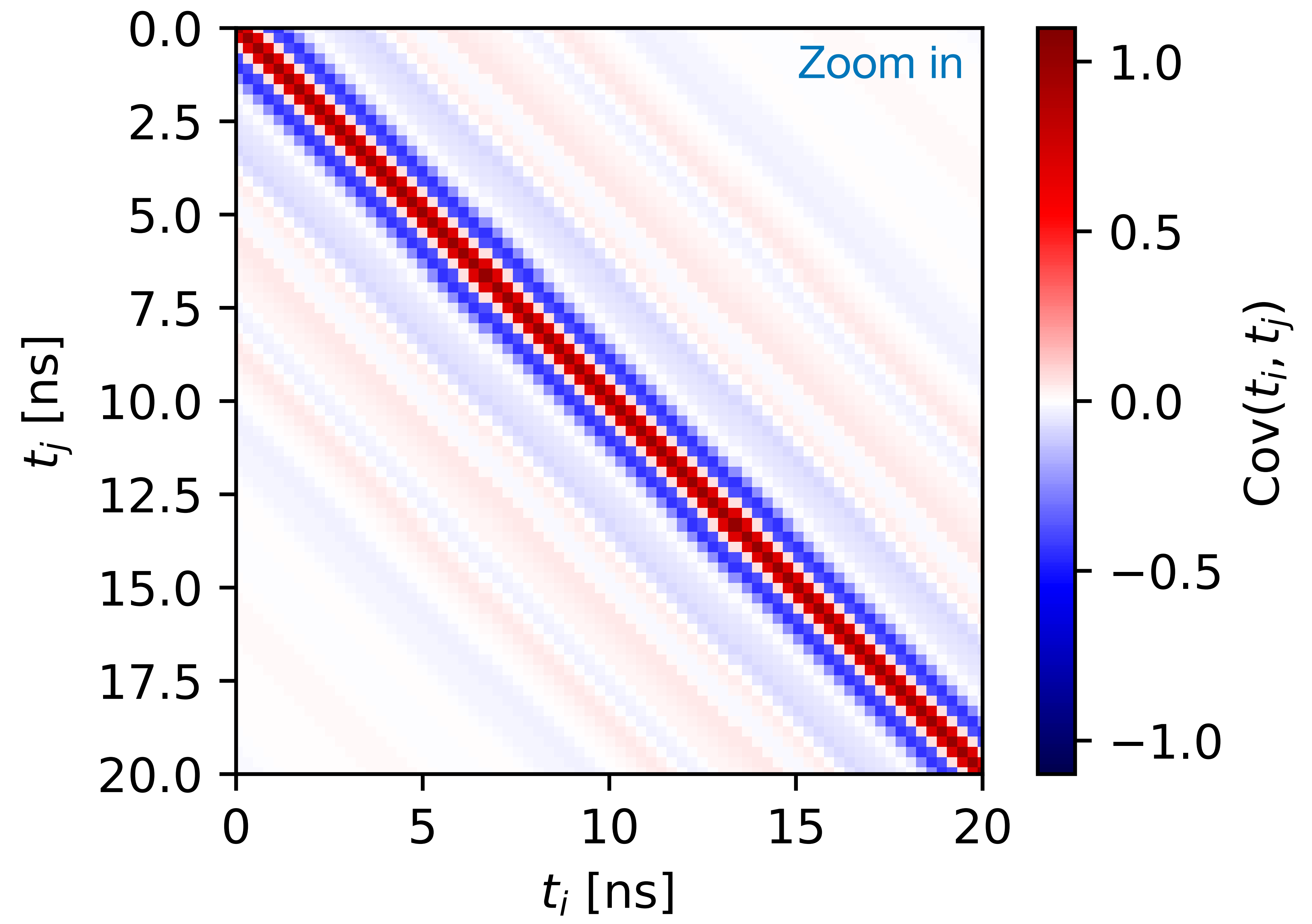
$$\mathrm{Cov}(t_i, t_j) = \frac{1}{N} \sum_{n=1}^{N} (x_{n,i} - \mu_i)(x_{n,j} - \mu_j),$$

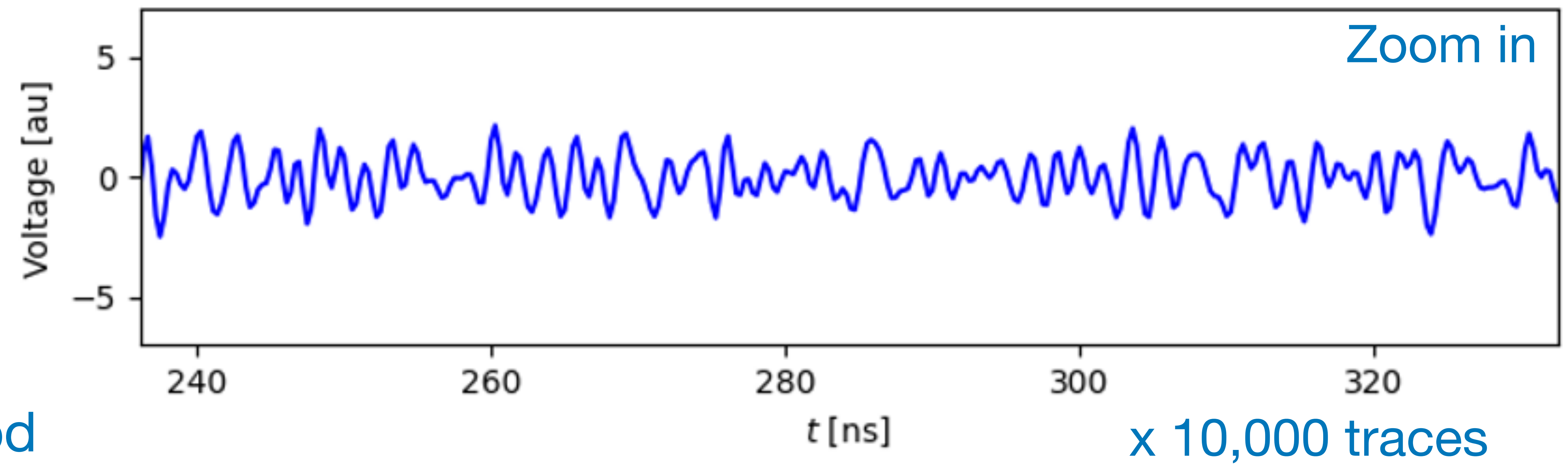
- Has been verified against data

- Probability is likelihood:

$$p(\boldsymbol{x}; \boldsymbol{\mu}(\theta), \boldsymbol{\Sigma}) = \mathscr{L}(\boldsymbol{\mu}(\theta); \boldsymbol{x}, \boldsymbol{\Sigma})$$

Likelihood

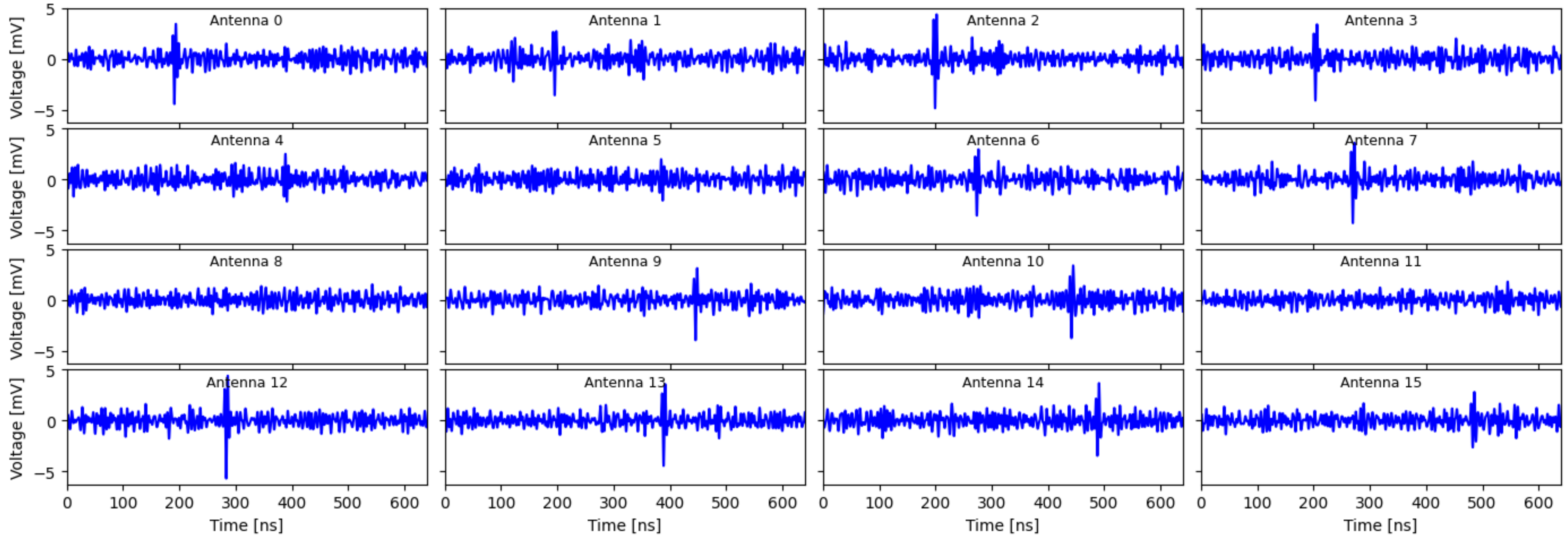




x 10,000 traces

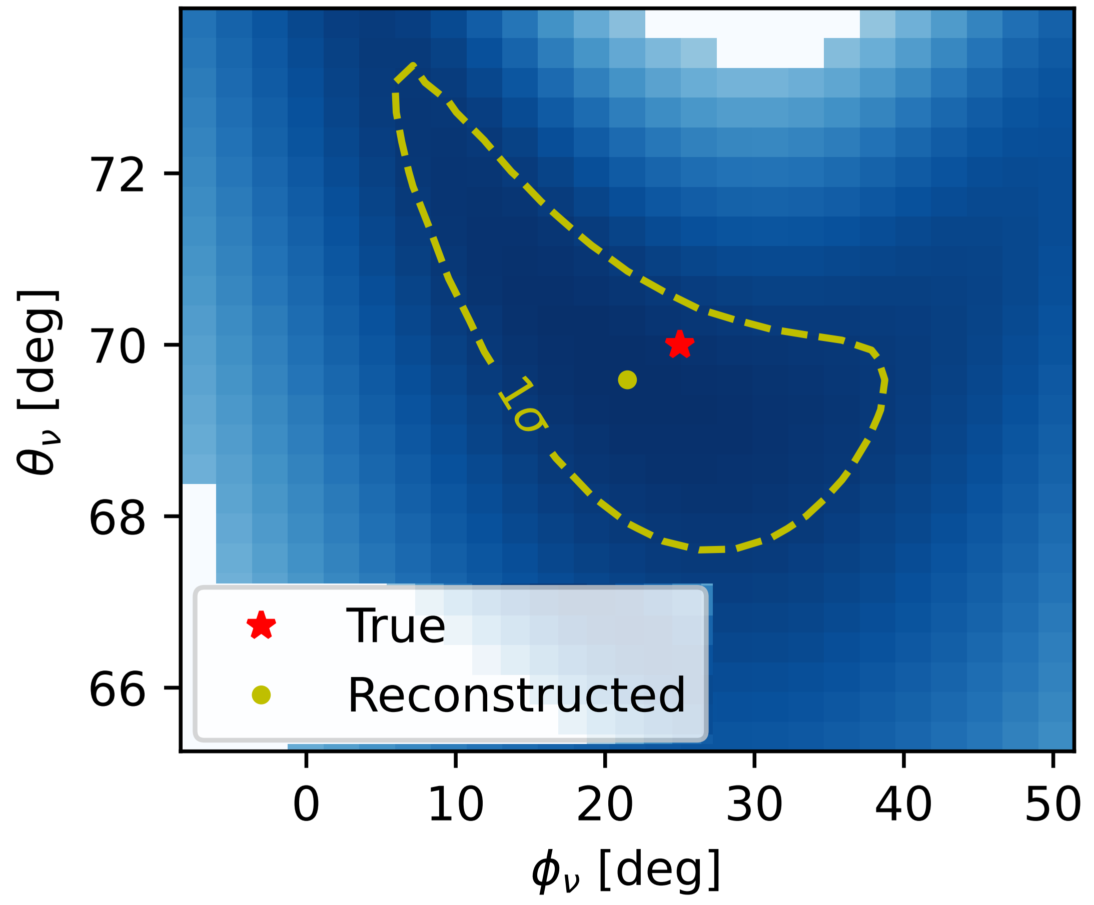
RNO-G reconstruction

- Example event in deep detector simulated with NuRadioMC:

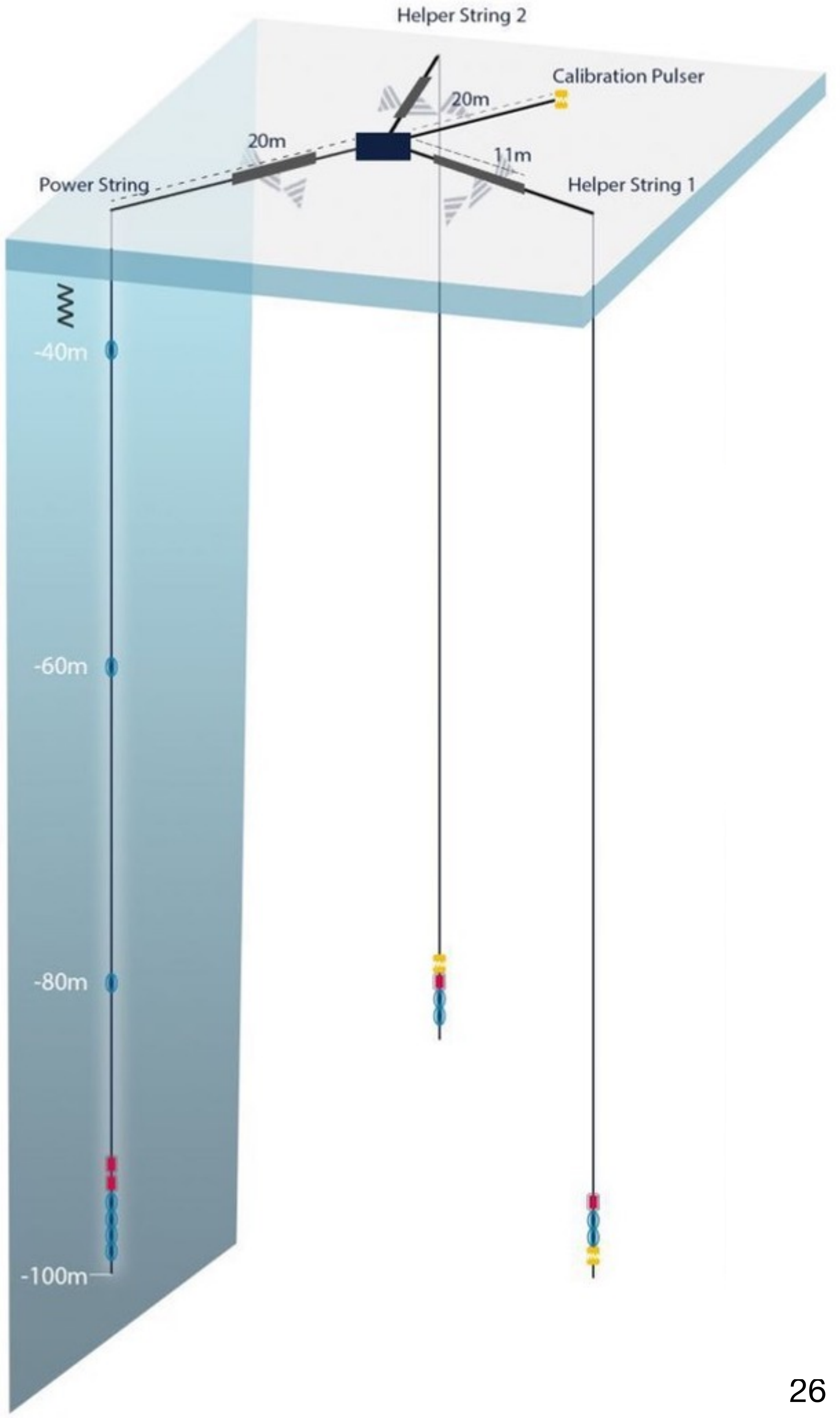


Likelihood reconstruction

Neutrino arrival direction



RNO-G station:



Fisher information matrix contour

- Four different ways of estimating uncertainties