Differentiable End-to-End Optimization of In-Ice Radio Neutrino Detectors

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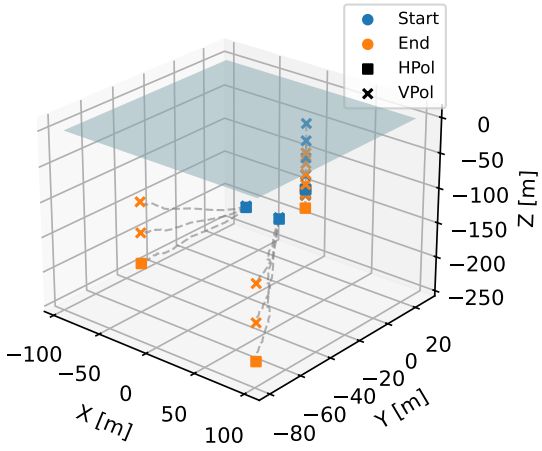
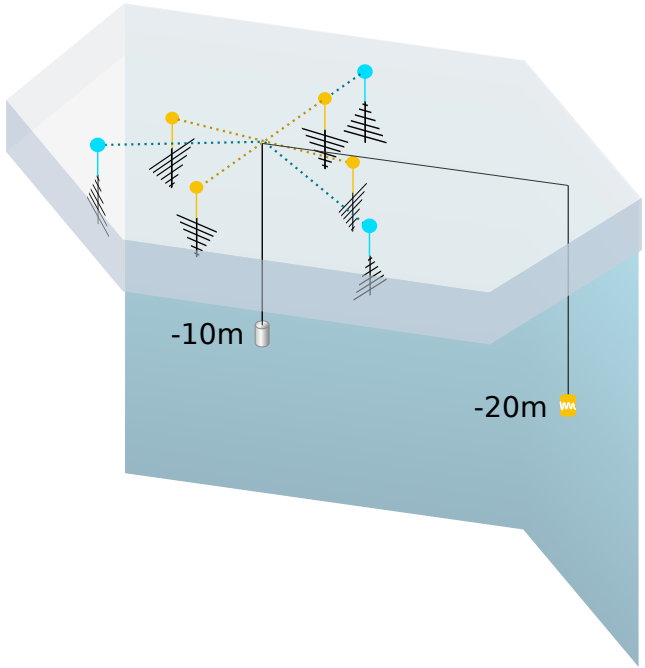
ARENA 2026, Karlsruhe

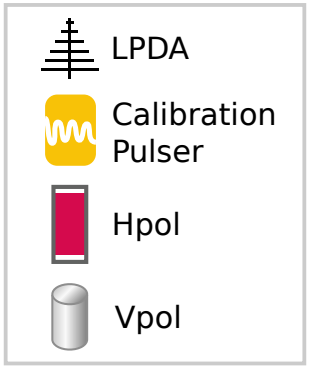


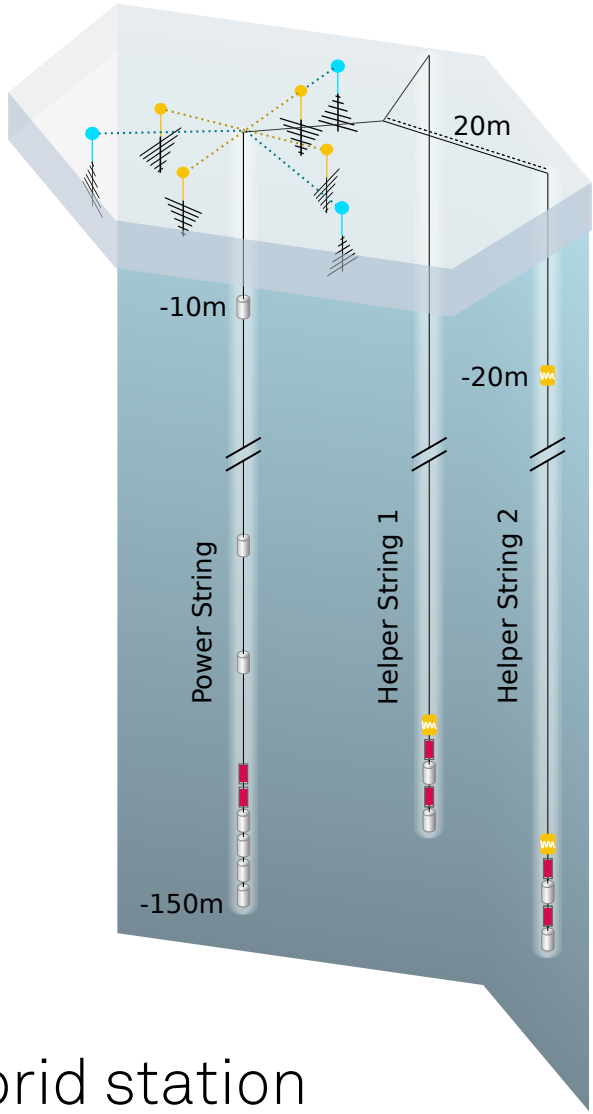
IceCube-Gen2 radio station layouts

- Shallow and hybrid (shallow + deep) station layouts



shallow station



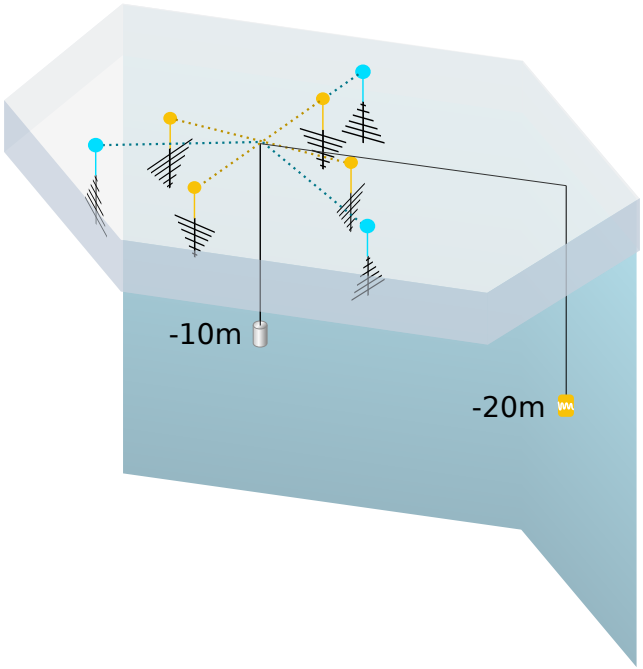


hybrid station

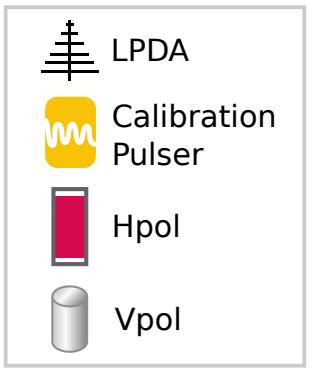
IceCube-Gen2 radio station layouts

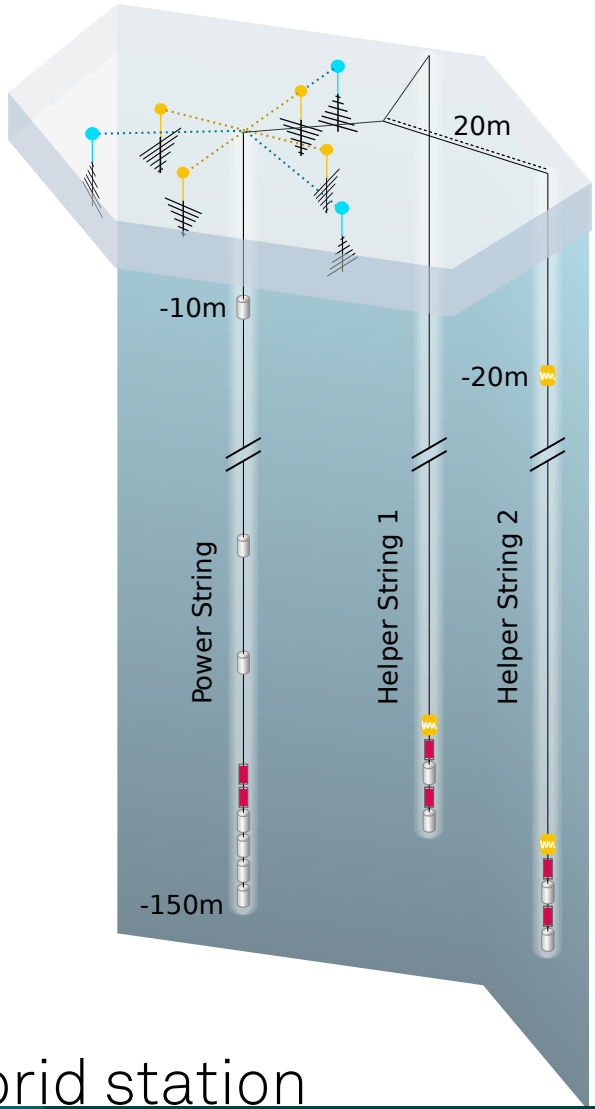
- Shallow and hybrid (shallow + deep) station layouts
- Current design guided by experience and intuition

  → Can we do better?



shallow station

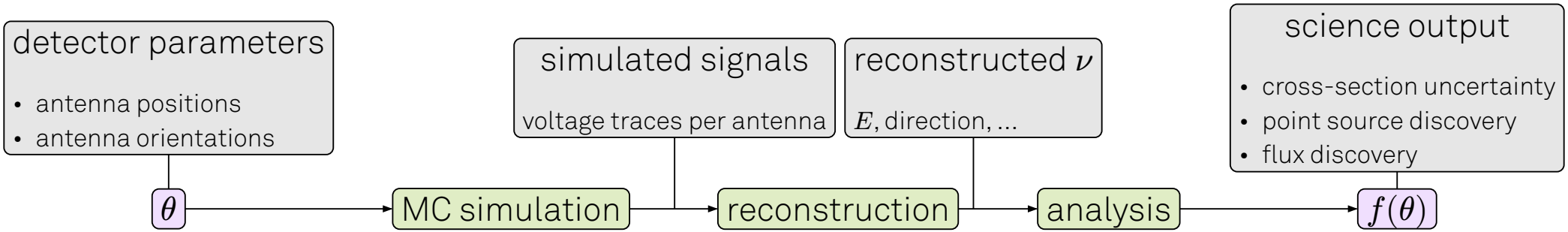




hybrid station

In-ice radio detector optimization

- Traditional, fully MC-based detector optimization is unfeasible



In-ice radio detector optimization

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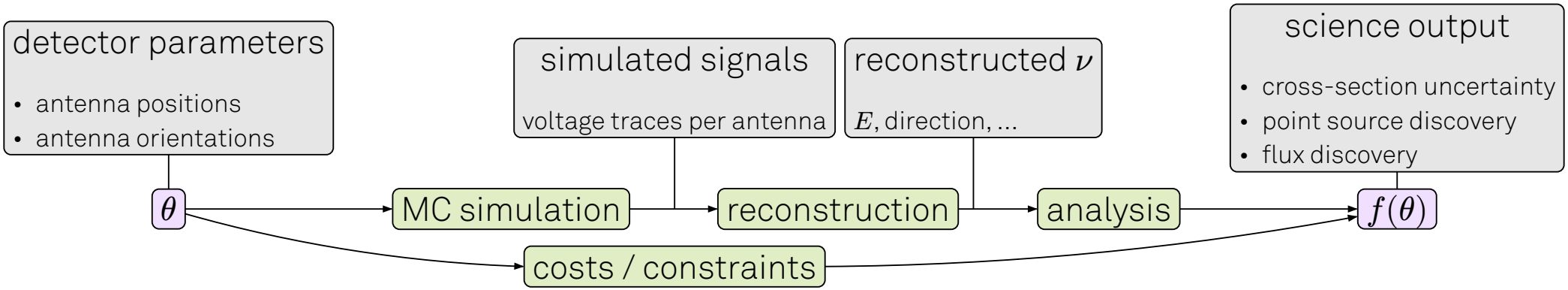
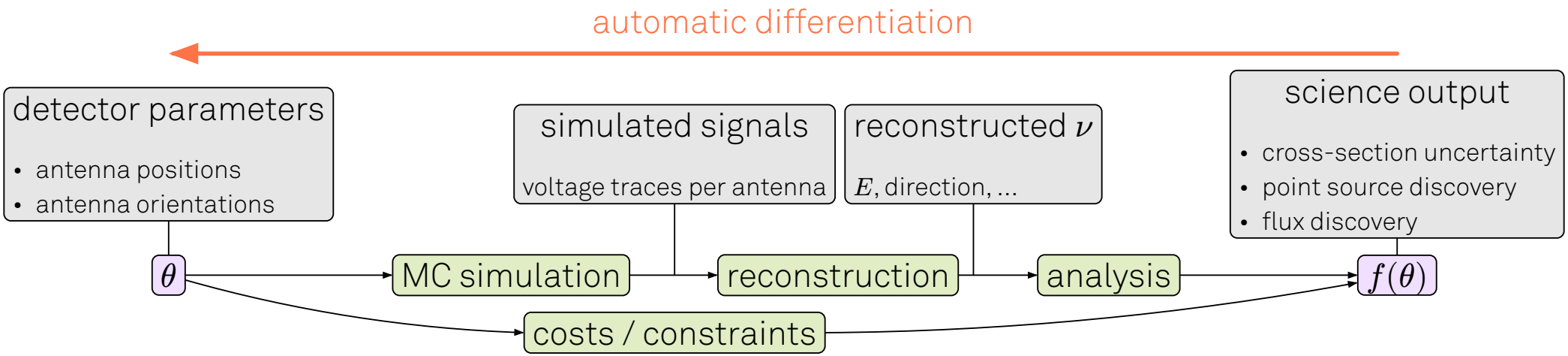


In-ice radio detector optimization

- Traditional, fully MC-based detector optimization is unfeasible
- Solution: Make pipeline differentiable
  - Compute gradient → move antennas accordingly → repeat



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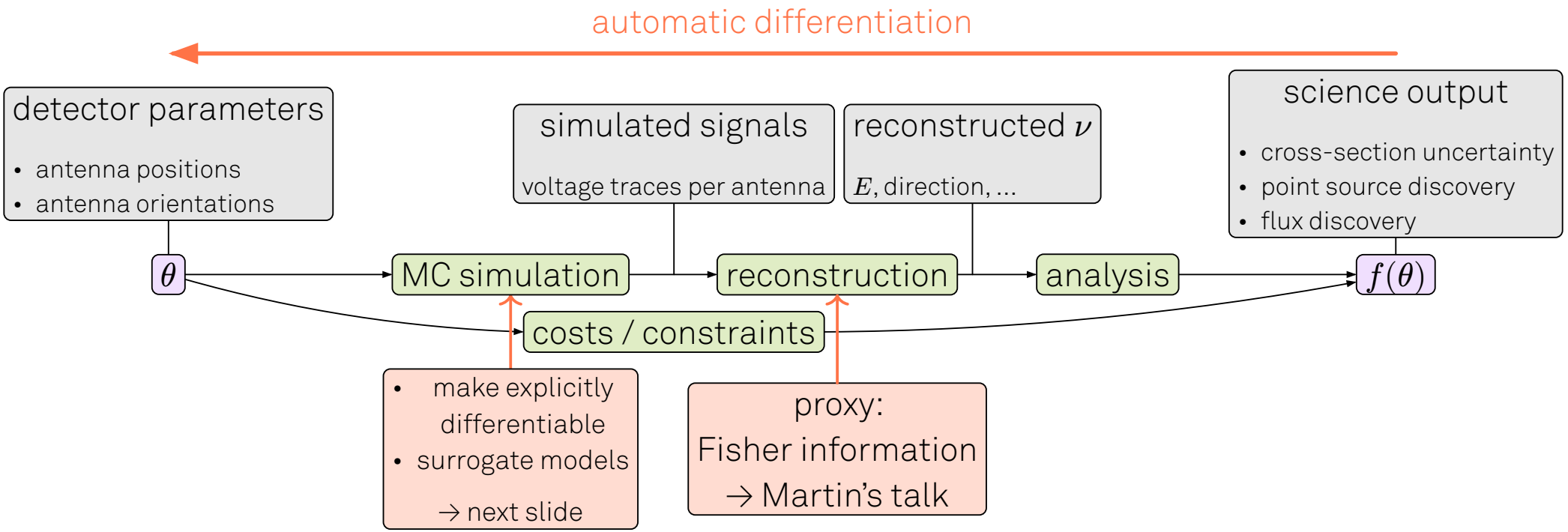
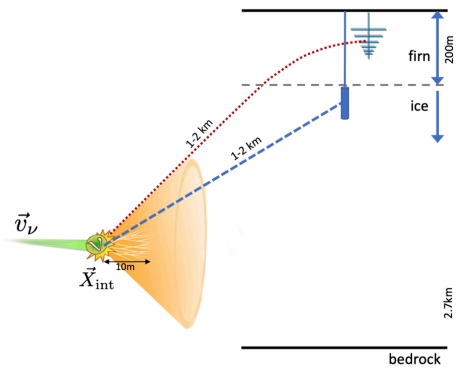


Differentiable simulation pipeline

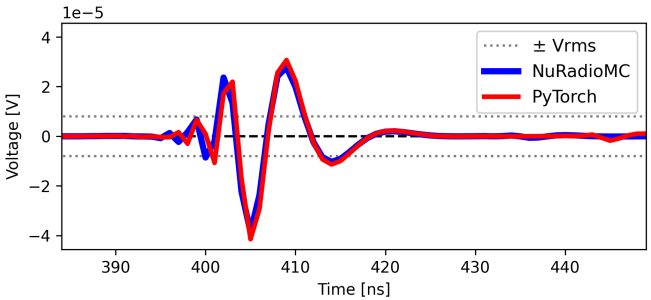
M. Ravn et al., 2025, PoS:491/031

Input: Neutrino and detector parameters:

$$E_{\text{shower}}, \theta_\nu, \phi_\nu, x_\nu, y_\nu, z_\nu, t_0$$
$$x_{\text{ant.}}, y_{\text{ant.}}, z_{\text{ant.}}, \theta_{\text{ant.}}, \phi_{\text{ant.}}, \psi_{\text{ant.}}$$



Output: Voltage trace(s)



Traditional simulation pipeline

ported to PyTorch

Differentiable simulation pipeline

Event generation

Fixed list of triggered events

Askaryan emission

- Alvarez2009
- Diffusion model by P. Pilar et al., 2026 Mach. Learn. Sci. Technol. 7 025017

Propagation

Neural network ray-tracing surrogate

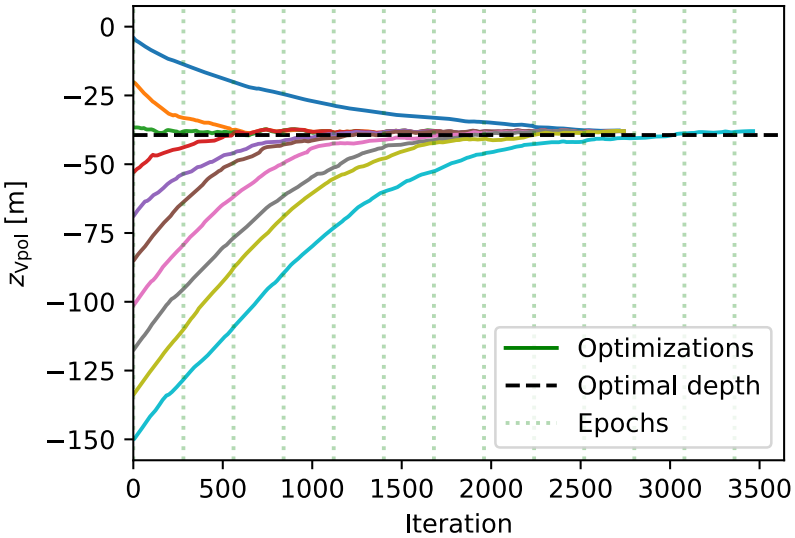
Detection

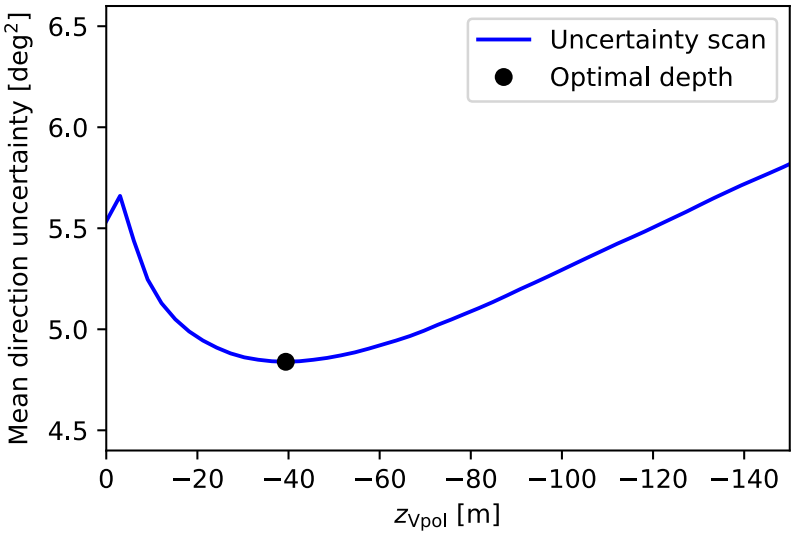
Analytic approx. of LPDA, VPol, HPol

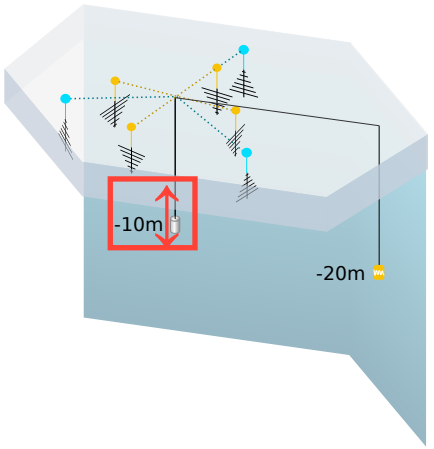
Proof of concept optimization 1: VPol depth

- Goal: demonstrate stable convergence
- Loss: Neutrino direction uncertainty

- 100k triggered events (fully hadronic)
- Evt.gen.: NuRadioMC; $10^{16.5}$ eV – $10^{17.5}$ eV
- Emission: Alvarez2009 (diff.able impl.)
- Propagation: NN ray tracing surrogate
- Batch: 512 events
- Loss: angular uncertainty



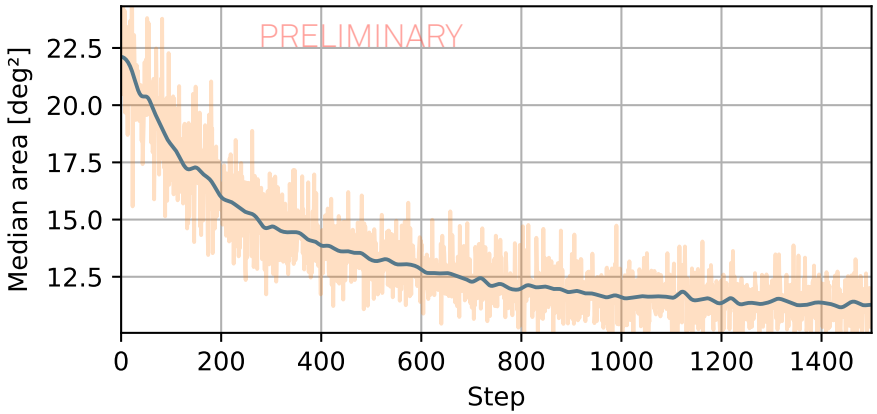


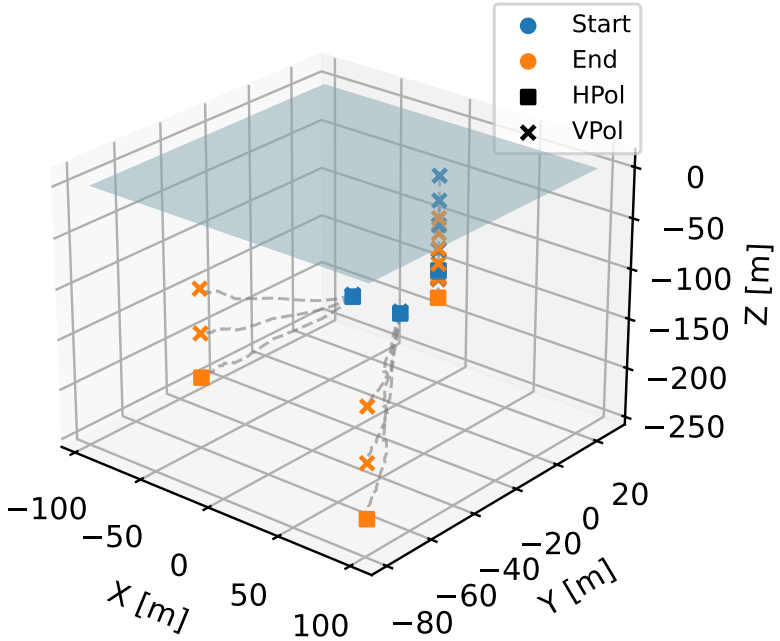


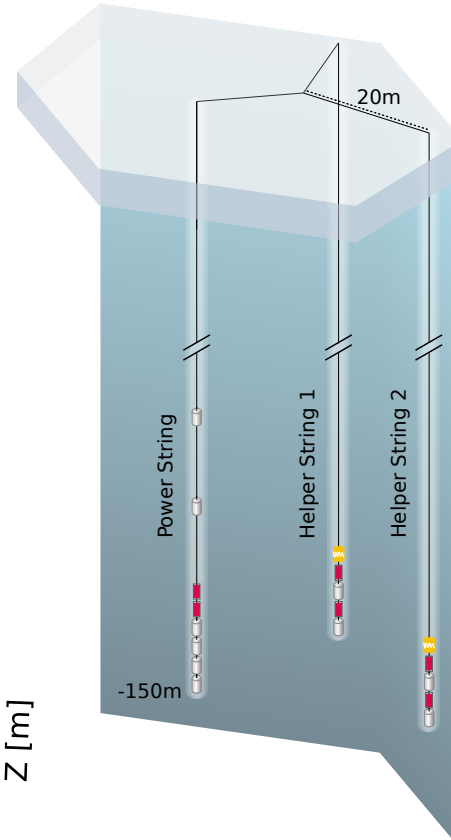
Proof of concept optimization 2: Deep station

Simultaneous optimization of 16 antennas

- Larger detector
- Directional uncertainties reduced by a factor of 2





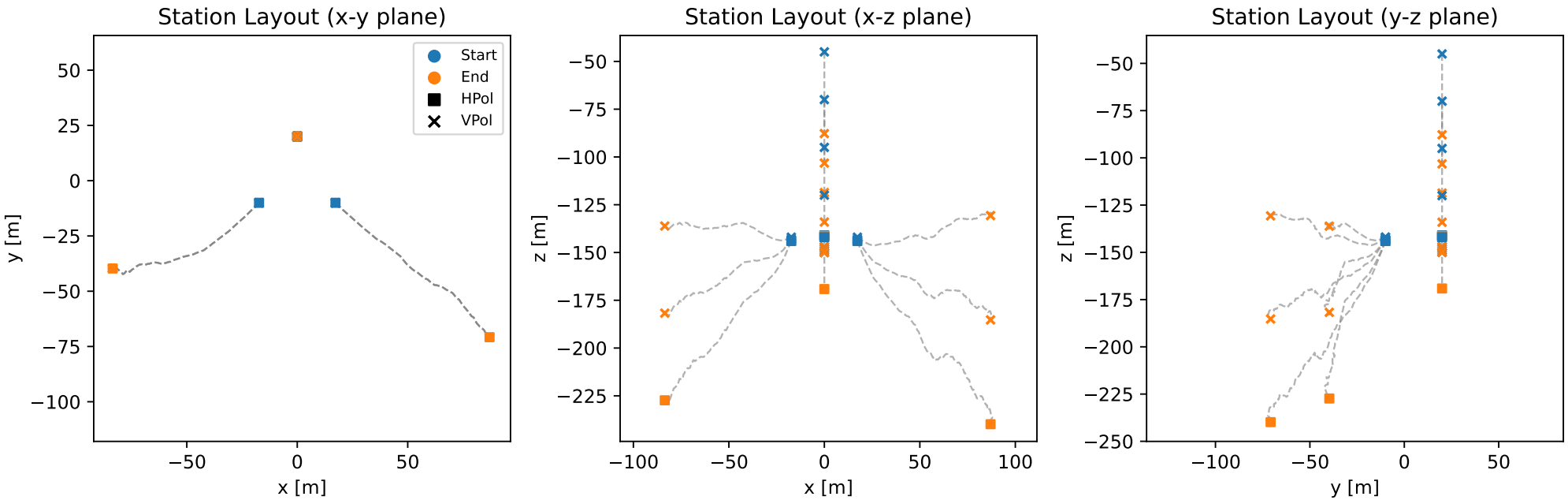


Proof of concept optimization 2: Deep station

Simultaneous optimization of 16 antennas

- Larger xy footprint
- Antennas go deeper
- $z < -200\,\mathrm{m}$ is not feasible

PRELIMINARY

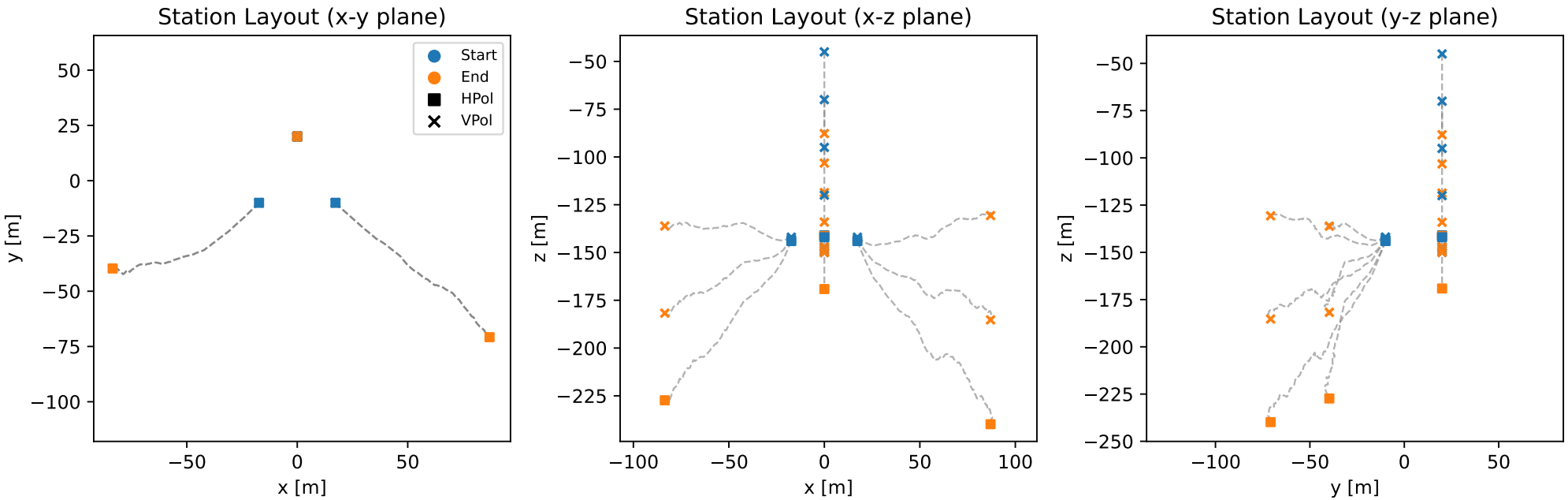


Proof of concept optimization 2: Deep station

Simultaneous optimization of 16 antennas

- Larger xy footprint
- Antennas go deeper
- $z < -200\,\mathrm{m}$ is not feasible → add a constraint

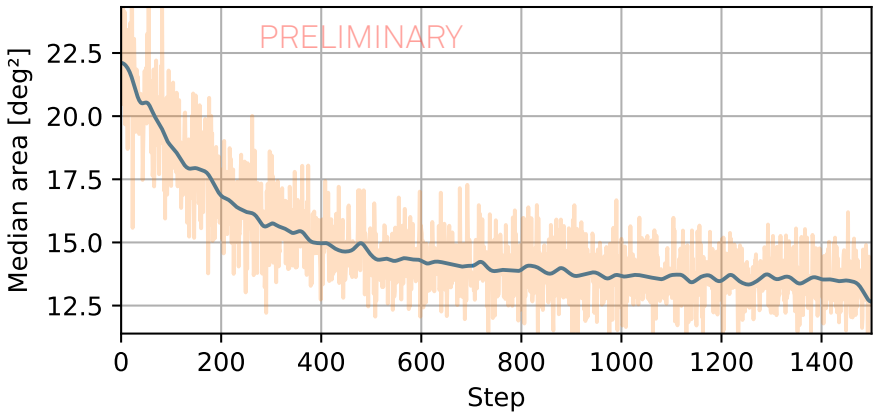
PRELIMINARY

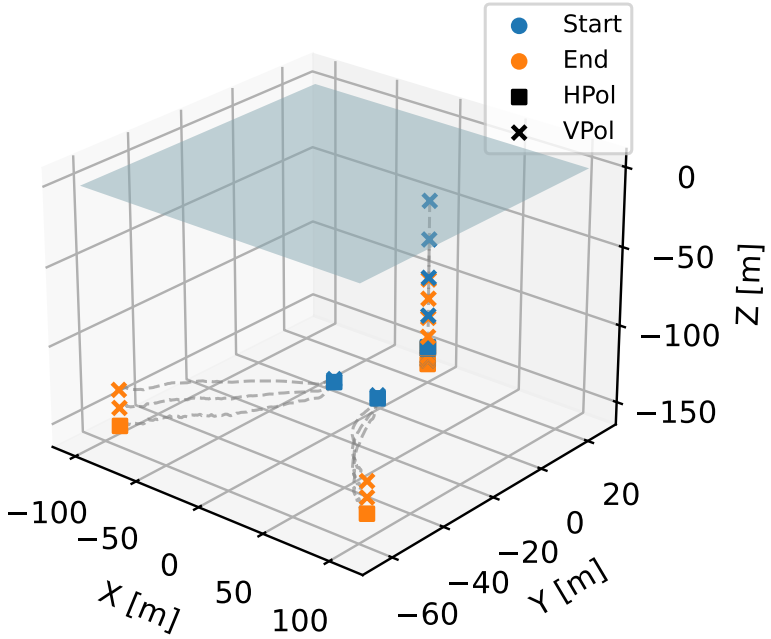


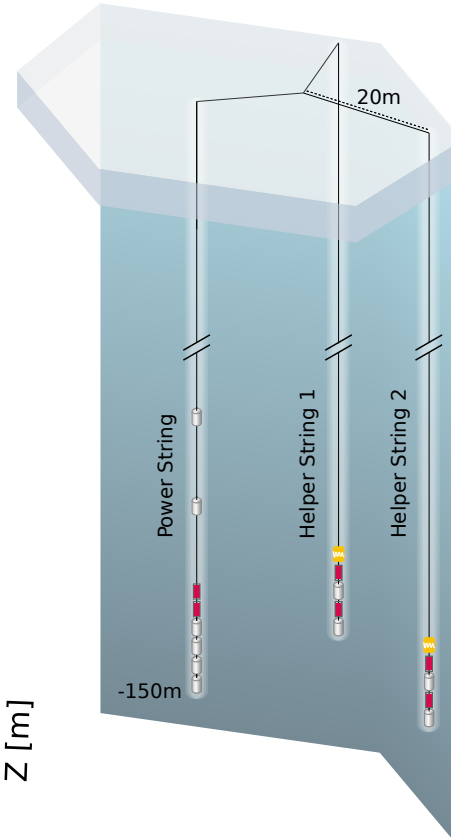
Proof of concept optimization 2: Deep station

IceCube-Gen2 default, with cost for $z < -150\,\mathrm{m}$

- Add cost term to the loss function
  - $\propto \sum_{\text{ant.}} \mathbf{ReLU}(z_{\text{thresh}} - z)$
- Directional uncertainties still reduced by a factor of 1.8





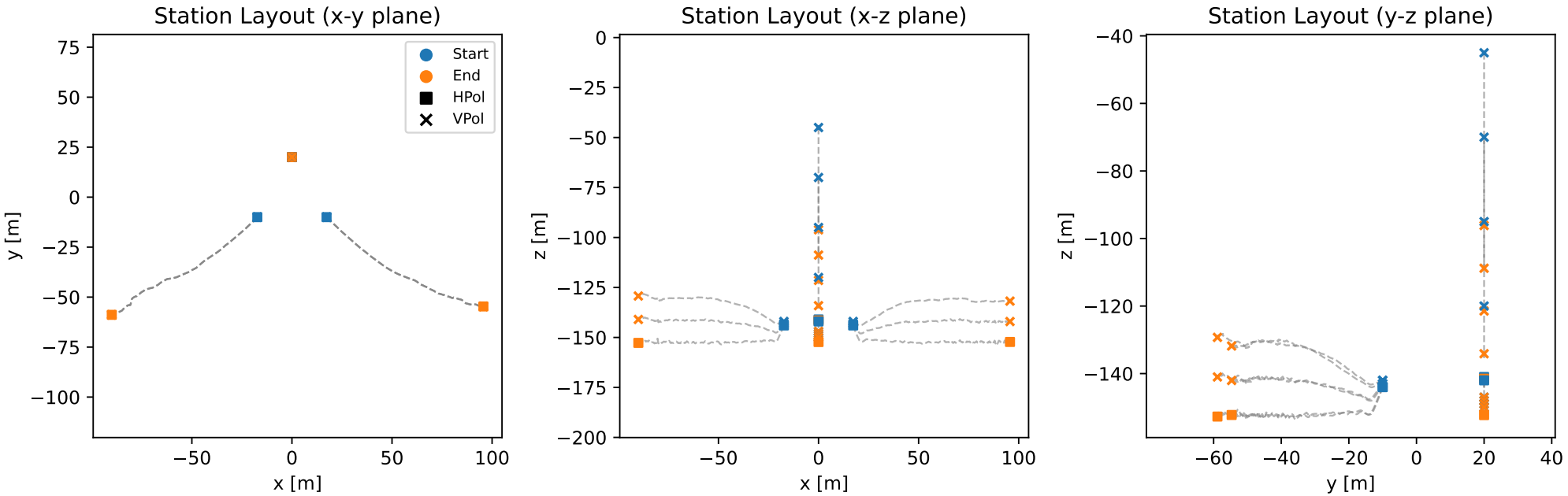


Proof of concept optimization 2: Deep station

IceCube-Gen2 default, with cost for $z < -150\,\mathrm{m}$

- Cost term pushes antennas above the $-150\,\mathrm{m}$ line
- Antenna spacing on helper strings increases

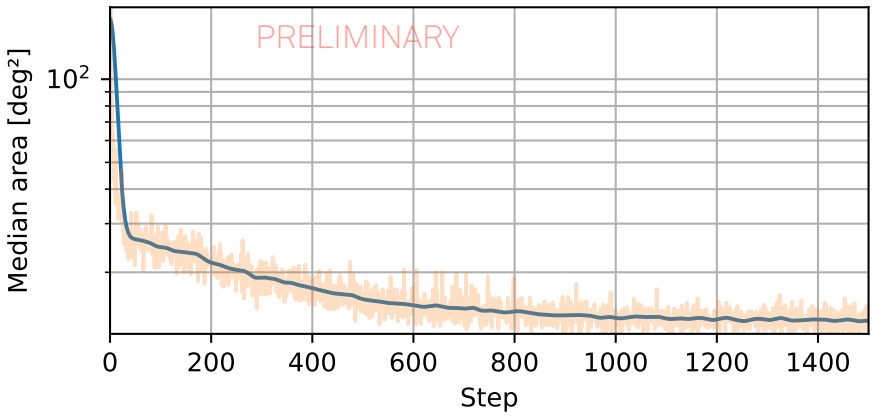
PRELIMINARY

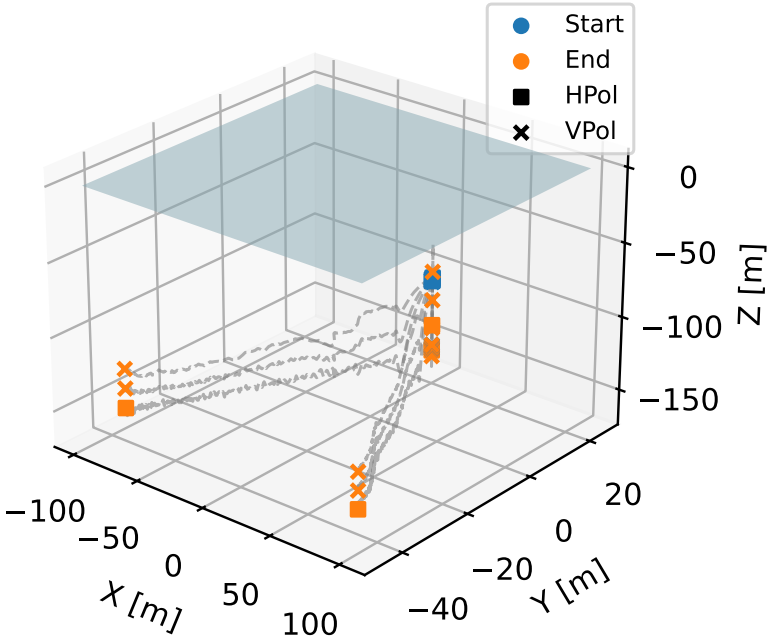


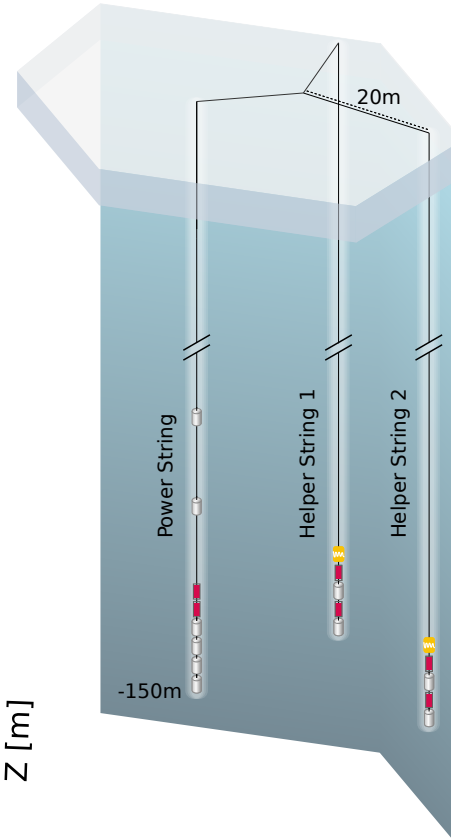
Proof of concept optimization 2: Deep station

Starting from the “worst case”

- All antennas initialized at the ~same position
- Results in similar layout and uncertainties



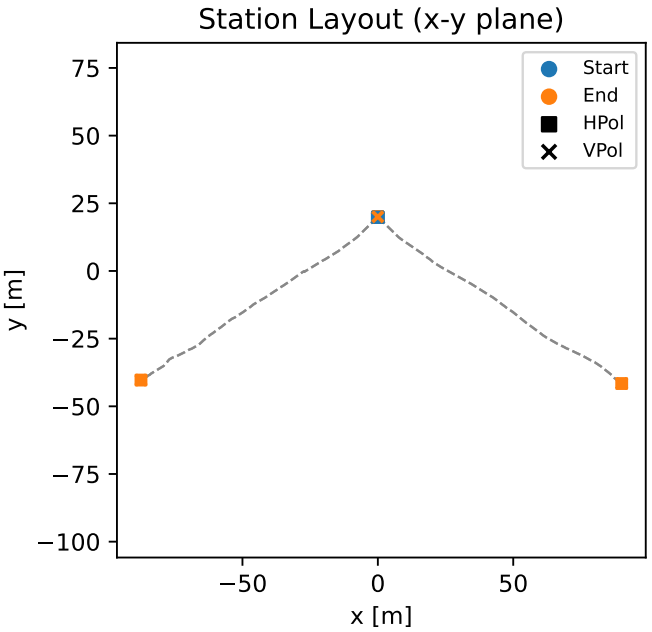


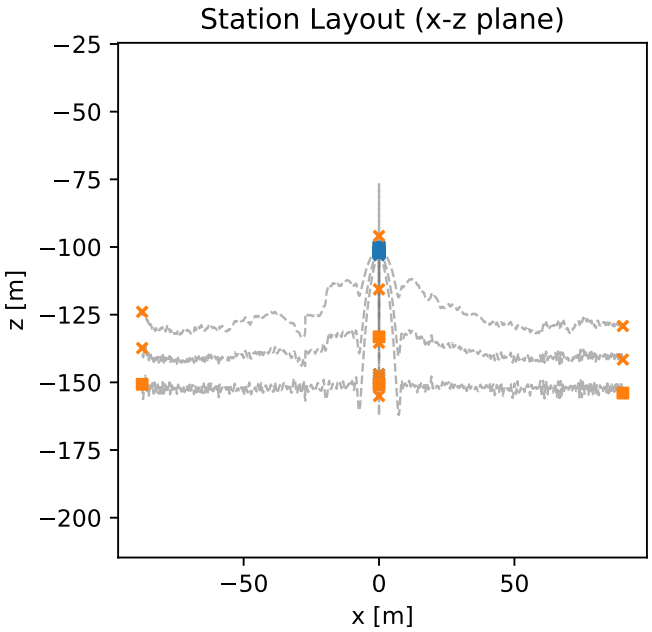


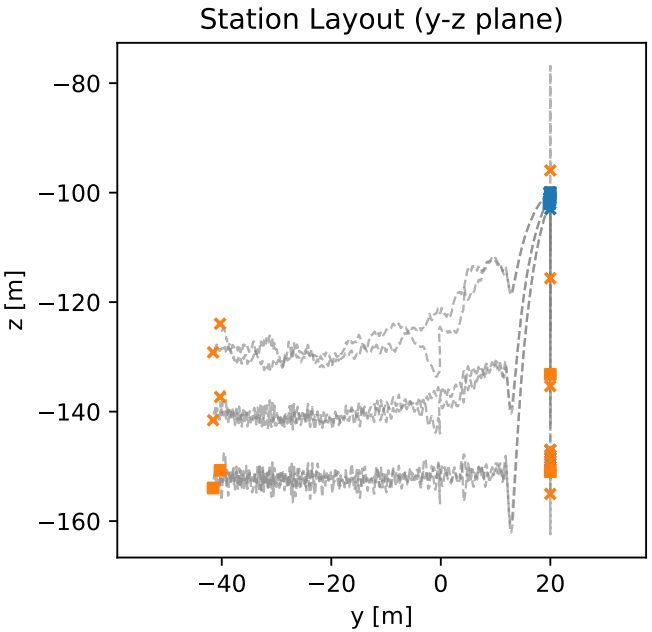
Proof of concept optimization 2: Deep station

Starting from the “worst case”

PRELIMINARY

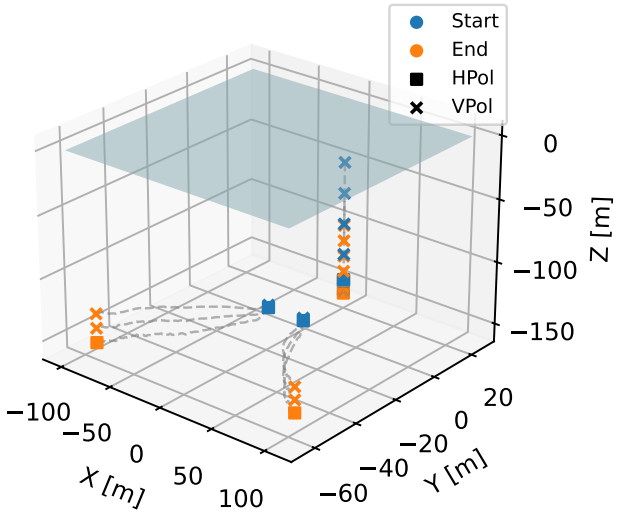


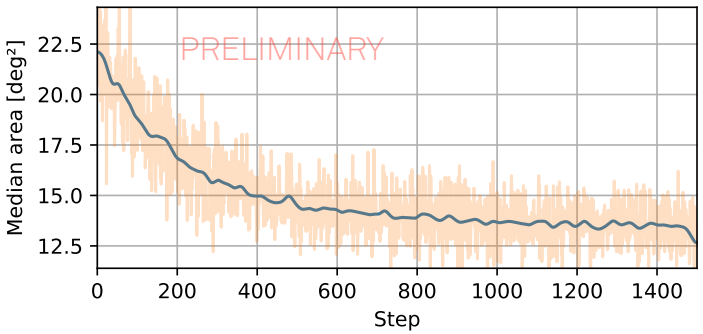




Conclusion

- Differentiable simulation and reconstruction pipeline developed
- Proof-of-concept: IceCube-Gen2 station layout
- Future work:
  - More realistic costs and engineering constraints
  - Systematic studies of optimization landscape
  - Optimize for specific science analyses





Thank you for your attention!

Setup

- Dataset: 10000 triggered events (fully hadronic)
- Event generation: NuRadioMC; $10^{16.5}\ \mathrm{eV} < E_{\mathrm{shower}} < 10^{17.5}\ \mathrm{eV}$
- Askaryan emission: differentiable implementation of Alvarez2009
- Ray tracing: neural network surrogate
- Loss: Neutrino direction uncertainty
  (area of ellipse)
  - $\sum_{\mathrm{evt}} \ln(A/°)$ (simplified)
- Optimize with Adam like a neural network
- Runtime until convergence: $\mathcal{O}(30\,\mathrm{min})$ on RTX 6000 Blackwell

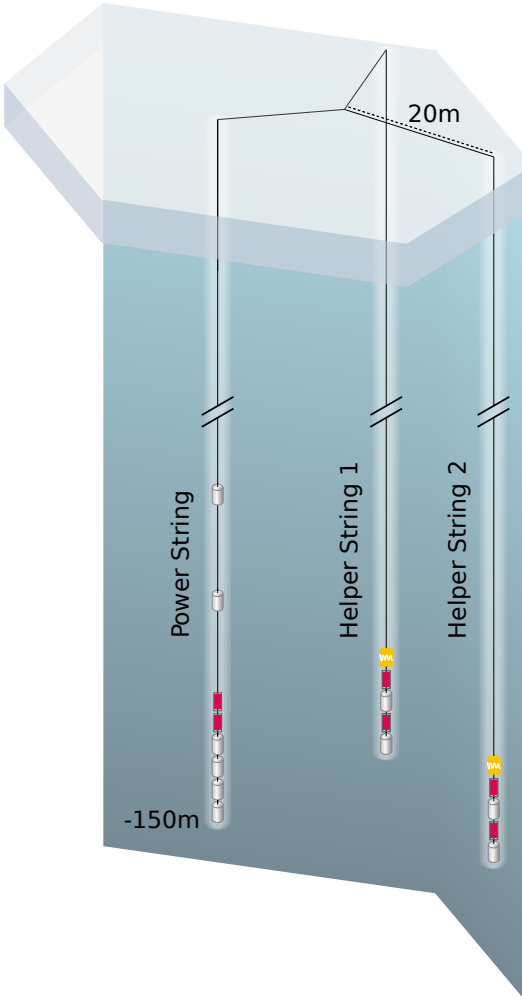
Costs implemented now

- antennas above the ice surface
- antennas below $-150\,\mathrm{m}$
- currently inactive:
  - minimum distance between antennas
  - distance between strings (xy)

Adapting to deep stations

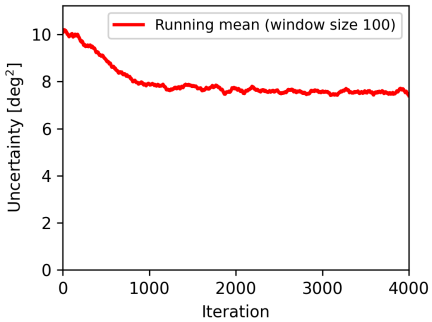
- Add support for HPol antennas
- Different MC dataset
- Reparametrization for interpretability, efficiency, constraints
  - From $16 \cdot 3 = 48$ to 12 parameters
  - Orientations now fixed

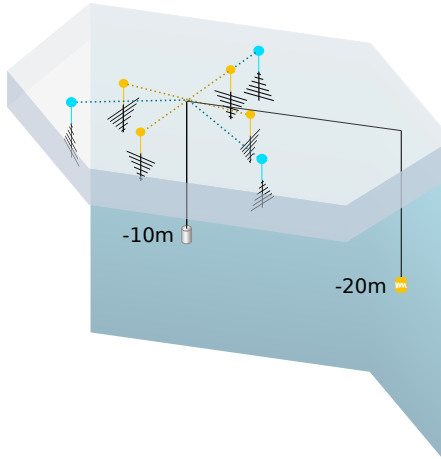
$$\begin{matrix} x_{\text{ant1}}\ y_{\text{ant1}}\ z_{\text{ant1}} \\ x_{\text{ant2}}\ y_{\text{ant2}}\ z_{\text{ant2}} \\ x_{\text{ant3}}\ y_{\text{ant3}}\ z_{\text{ant3}} \\ \dots \end{matrix} \rightarrow \begin{matrix} x_{\text{string1}}\ y_{\text{string1}} \\ z_{\text{ant1}}\ \Delta z_{\text{ant i/i+1}} \\ \dots \end{matrix}$$

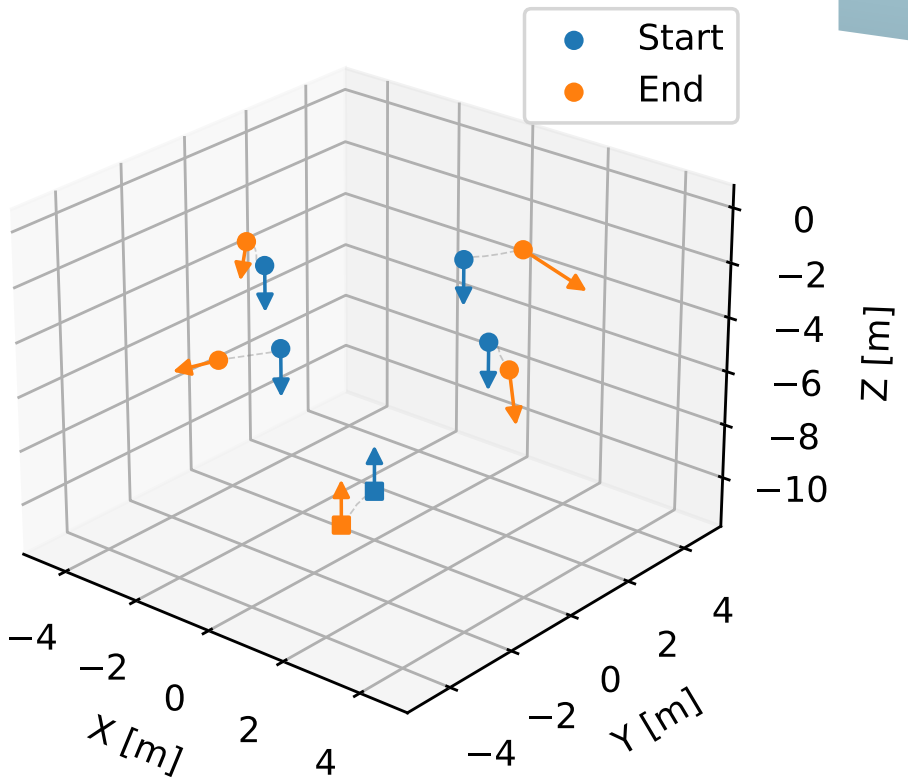


Optimizing a complete shallow station

- Goal: demonstrate high-dimensional optimization
- Optimize all antenna positions and orientations
- Result:
  - Outward-facing antennas
  - Larger detector
- Physically motivated results!



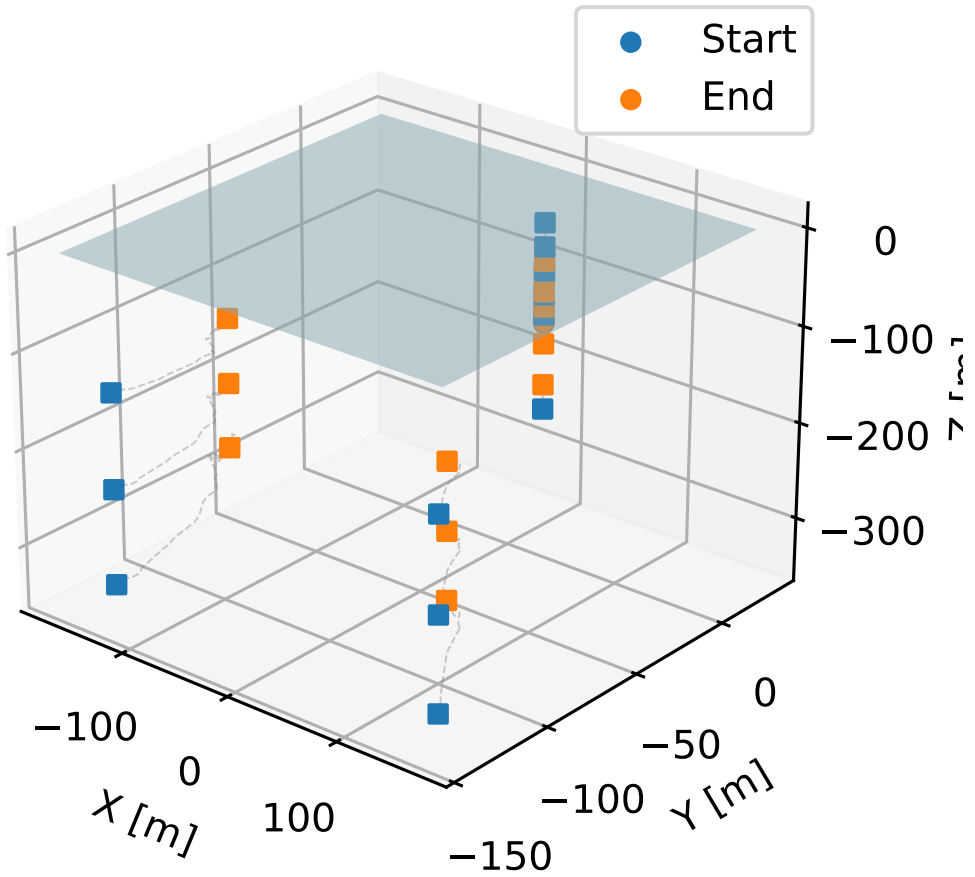




More deep station optimization runs

Very spread-out

- Footprint shrinks → we found an optimum!
- Relies on modeling of the shadow zone



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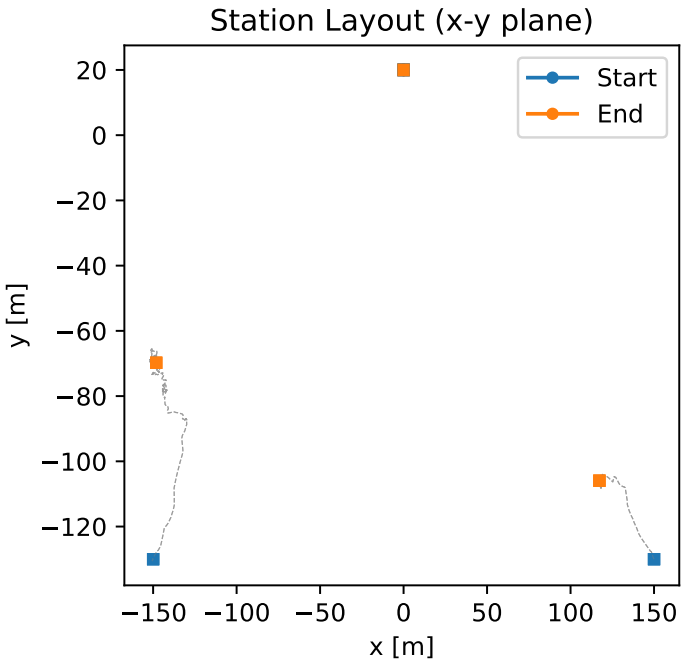

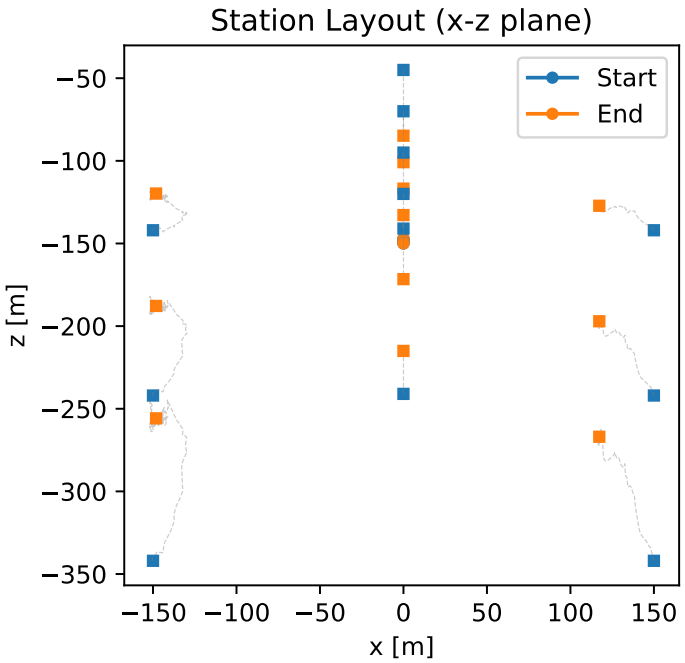

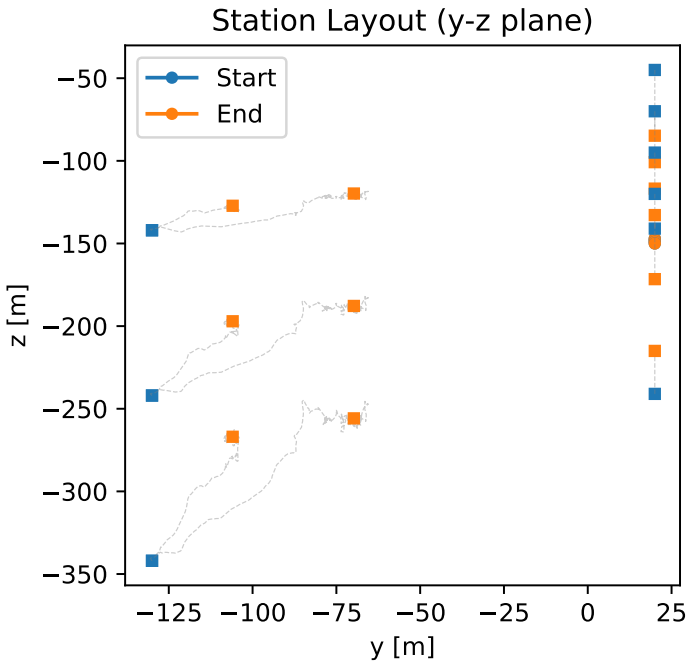

Impact of NuRadioOpt

Neutrino-Nucleon Cross Section 3x more precise measurement

Diffuse Flux Expedite the detection of UHE neutrino fluxes by up to a factor of five

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

- Improvements equivalent to building a more than three times larger detector at essentially no additional cost
- 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 parameters
- 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