Overview of in-ice radio simulations for neutrino detection

Christian Glaser

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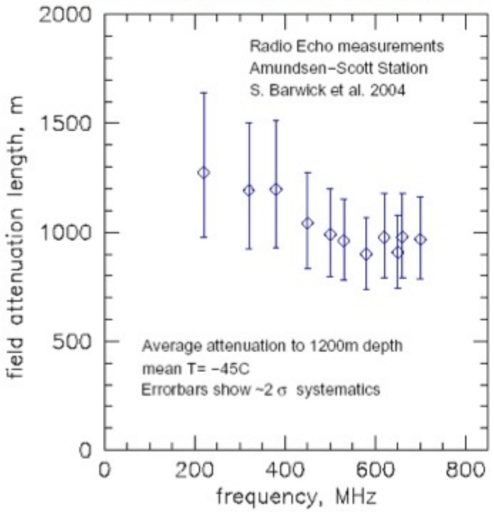
UPPSALA
UNIVERSITET

Going to ultra-high energies

- Low interaction cross section of neutrinos
- Very low neutrino flux

→ Very large volumes needed for reasonable rates

- **Solution: radio technique**
  - Large volumes at no cost: Antarctic ice
  - Ice transparent to radio waves (L ~ 1km)
  - A single radio station has 1km³ effective volume (comparable to IceCube)



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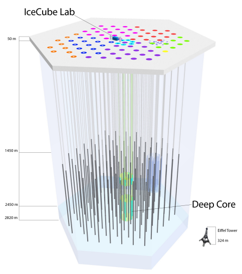
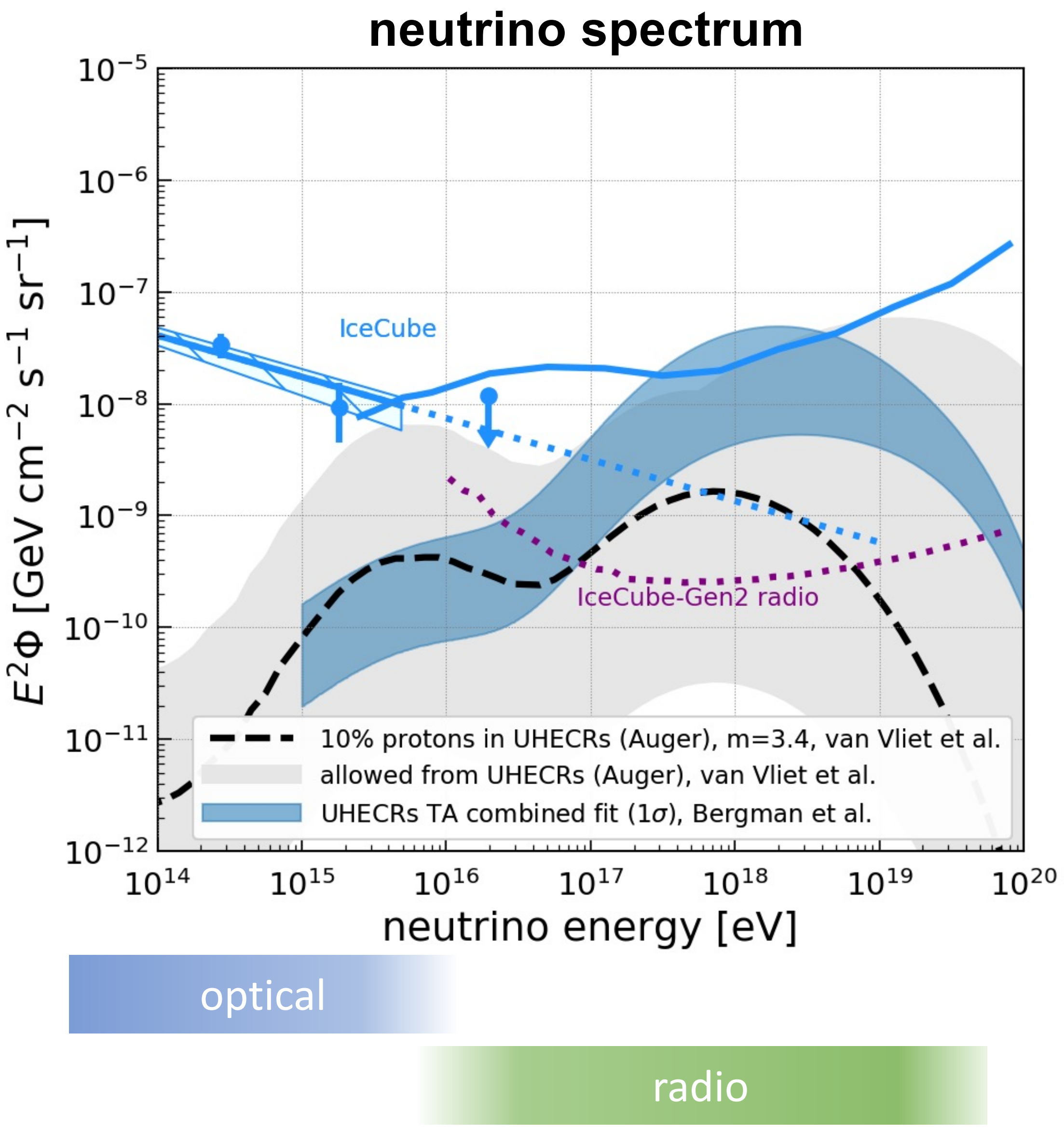
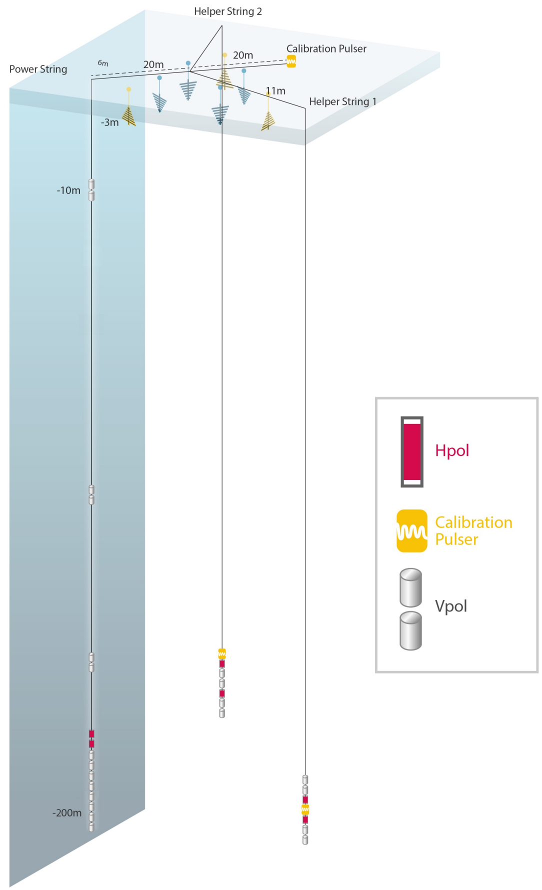




Experimental Landscape



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

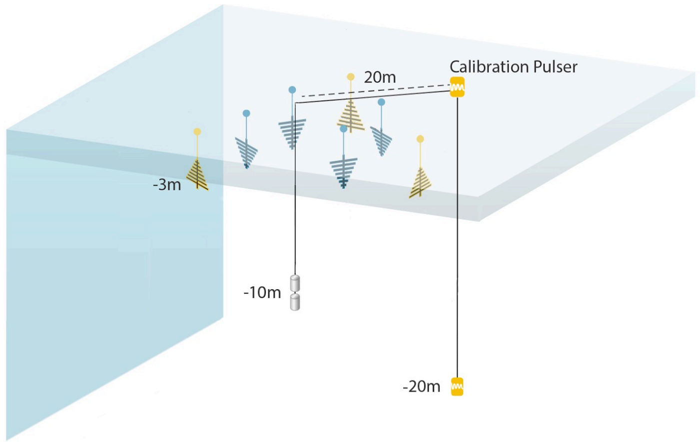
RNO-G

- 35 detector stations in Greenland
- first deployment summer 2021

past

now

future



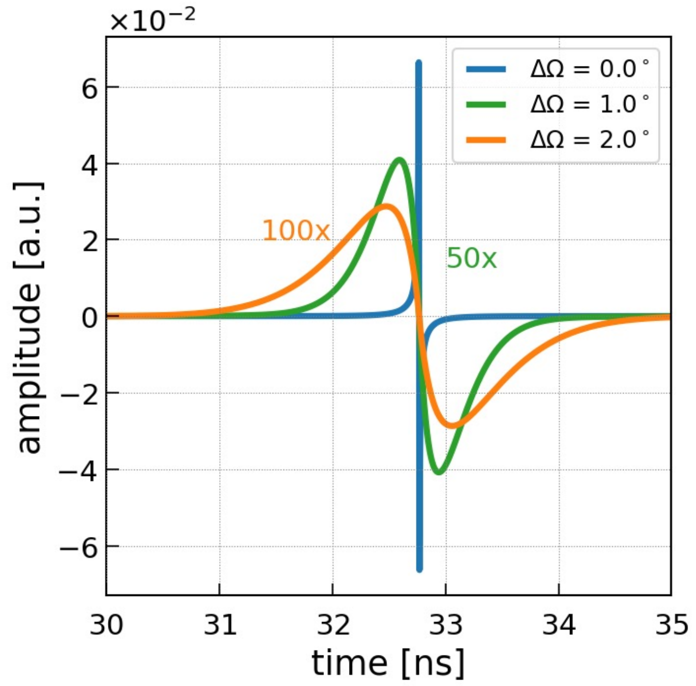
IceCube-Gen2

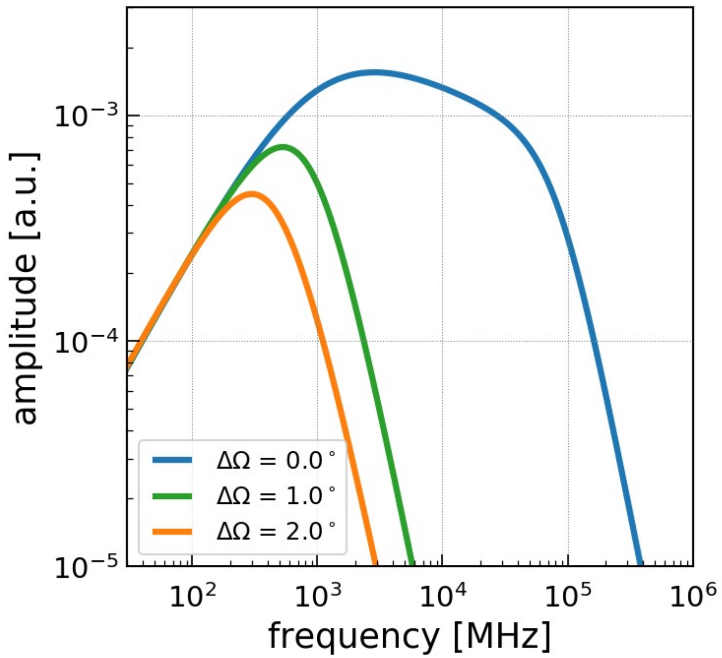
- 300+ detector stations at South Pole
- hybrid array of deep and shallow stations

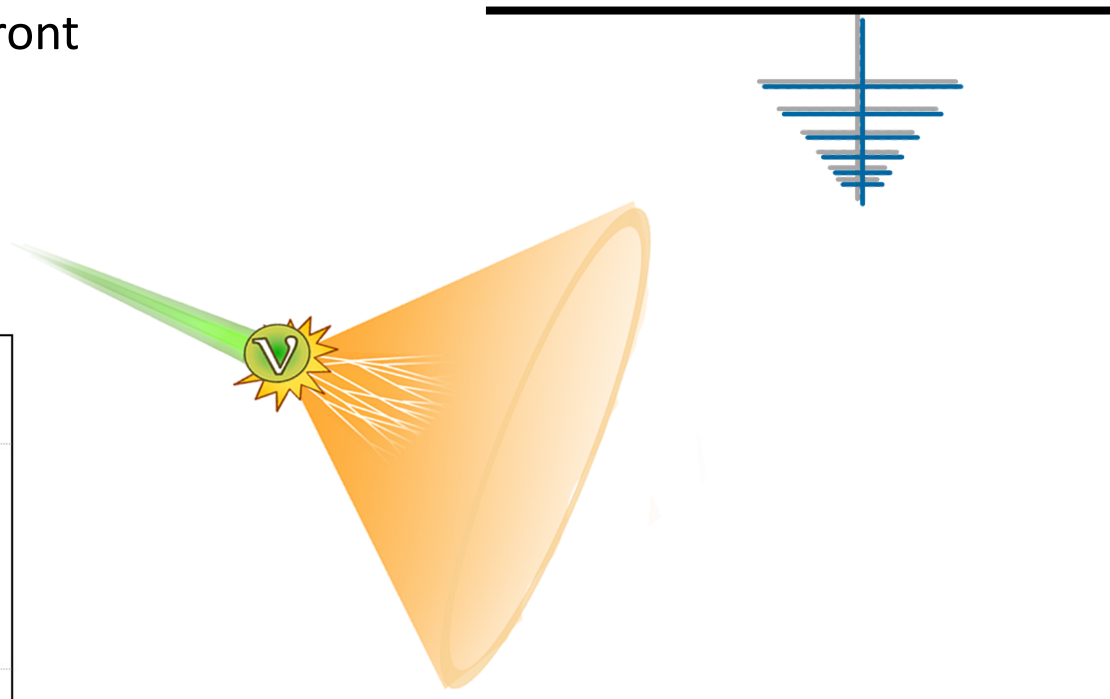
[S. Hallmann et al., PoS(ICRC2021)1183](#)

Radio Emission of Particle Showers

- Askaryan effect: Negative charge excess in the shower front







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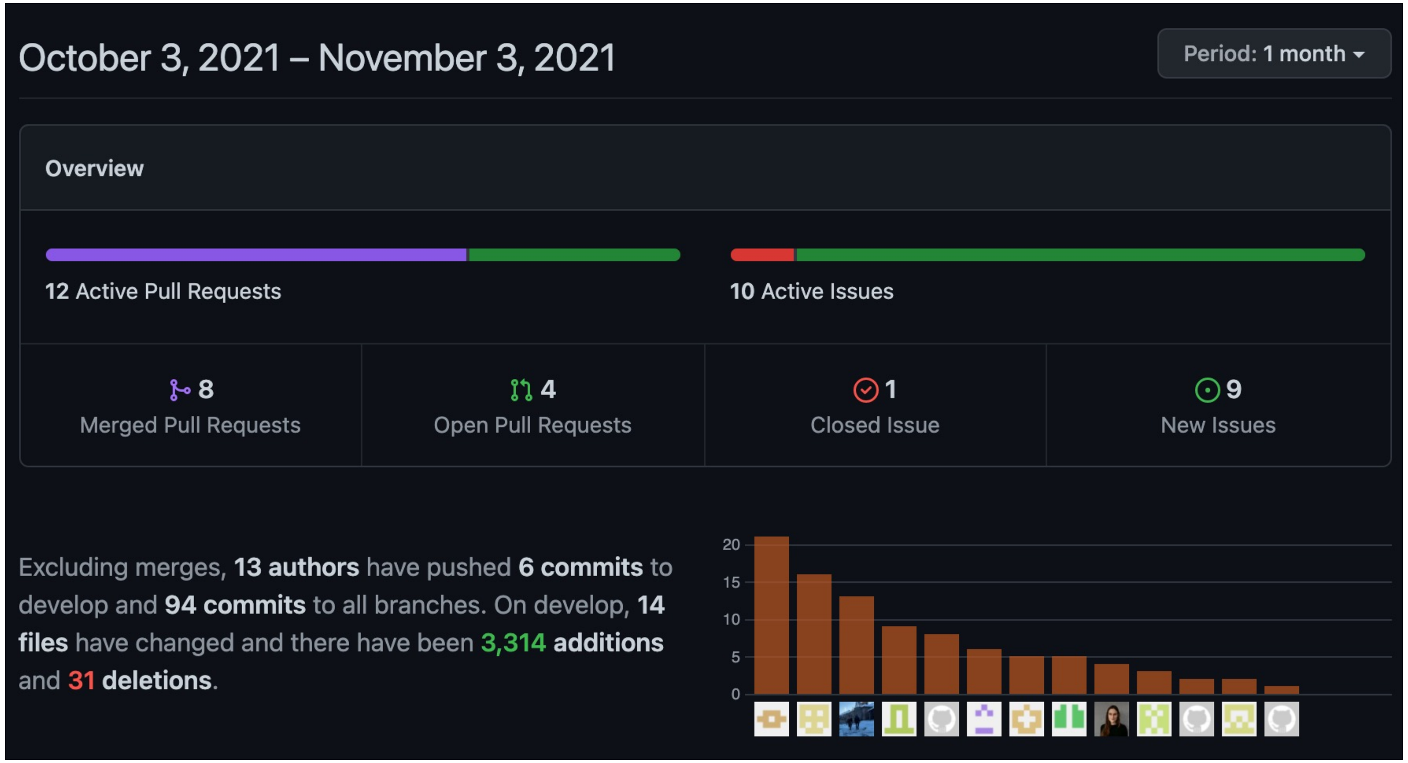
C. Glaser et al., EPJ-C 79: 464 (2019)
C. Glaser et al., EPC-C 80, 77 (2020)
D. Garcia et al, Rev. D **102** 083011 (2020)

NuRadioMC Overview

- From neutrino interaction to detector output
- Modular python code (C++ modules for time critical operations)
- Open source: *github.com/nu-radio/NuRadioMC*
- Community wide effort, started in 2018, now 20+ contributors
- More flexible, faster, more precise modelling of physics



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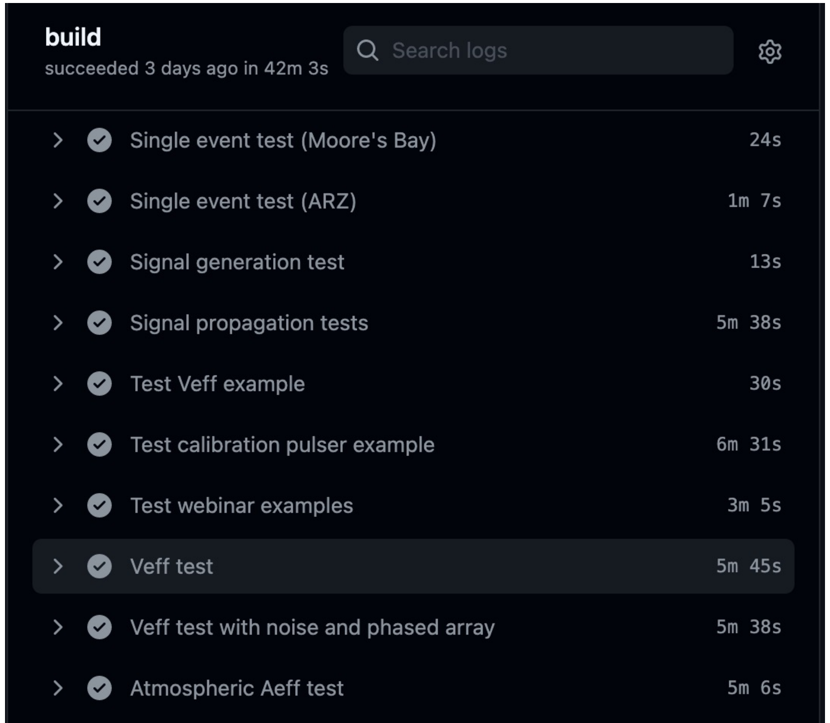
- Open source: *github.com/nu-radio/NuRadioMC*
- Community wide effort, started in 2018, now 20+ contributors
- More flexible, faster, more precise modelling of physics
- Accuracy:
  - Extensive comparison with existing codes: agreement within 10% for the same physics settings
  - automatic testing of relevant components
  - review of every code addition



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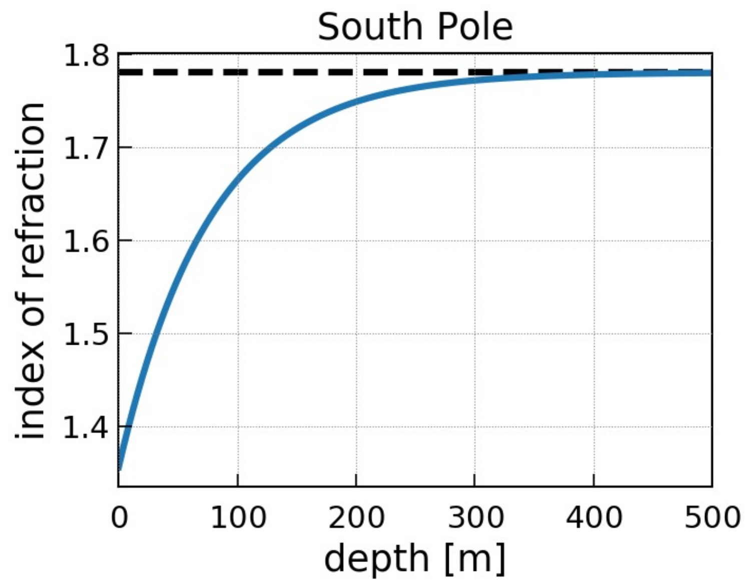
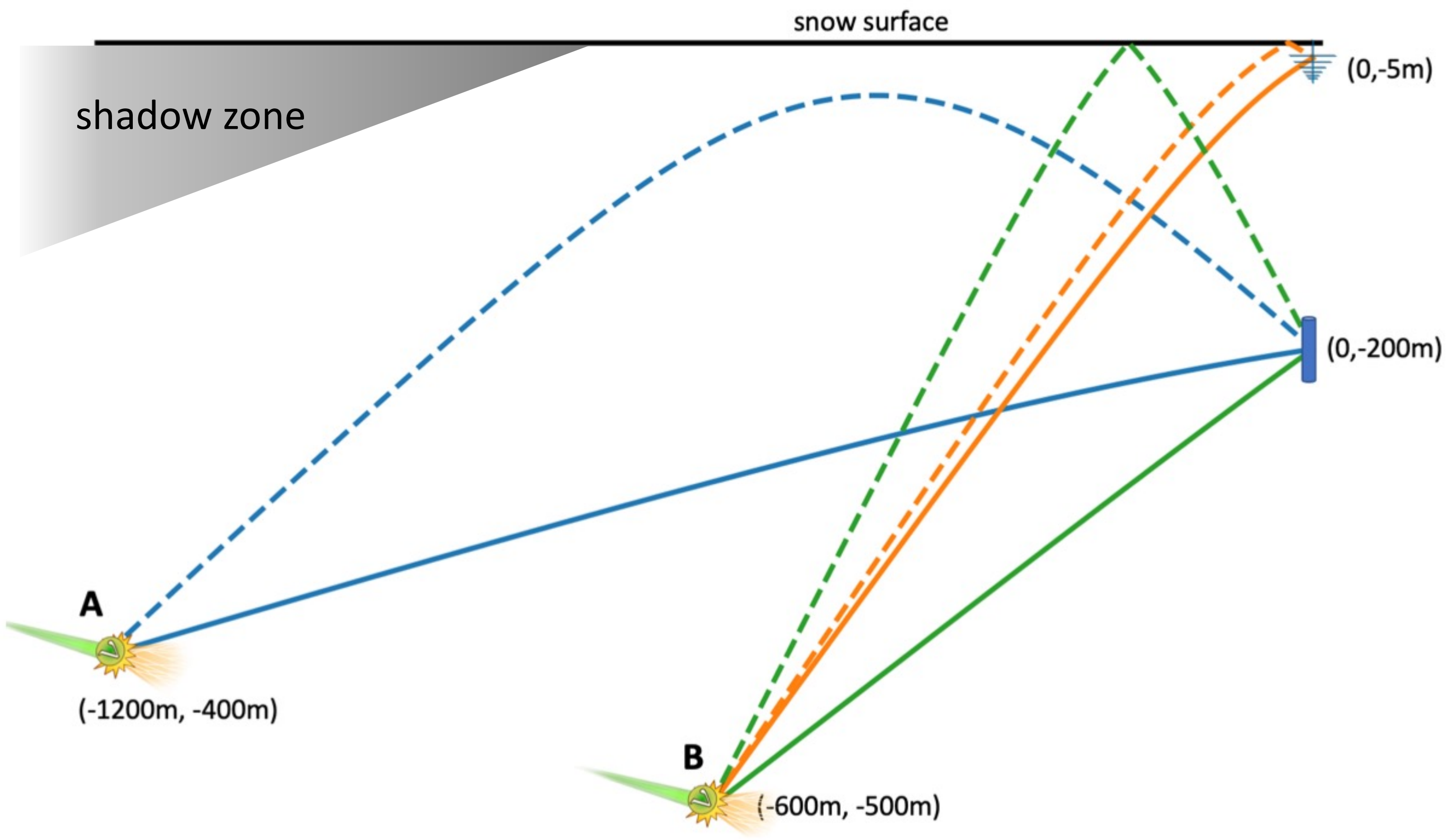
Signal Propagation





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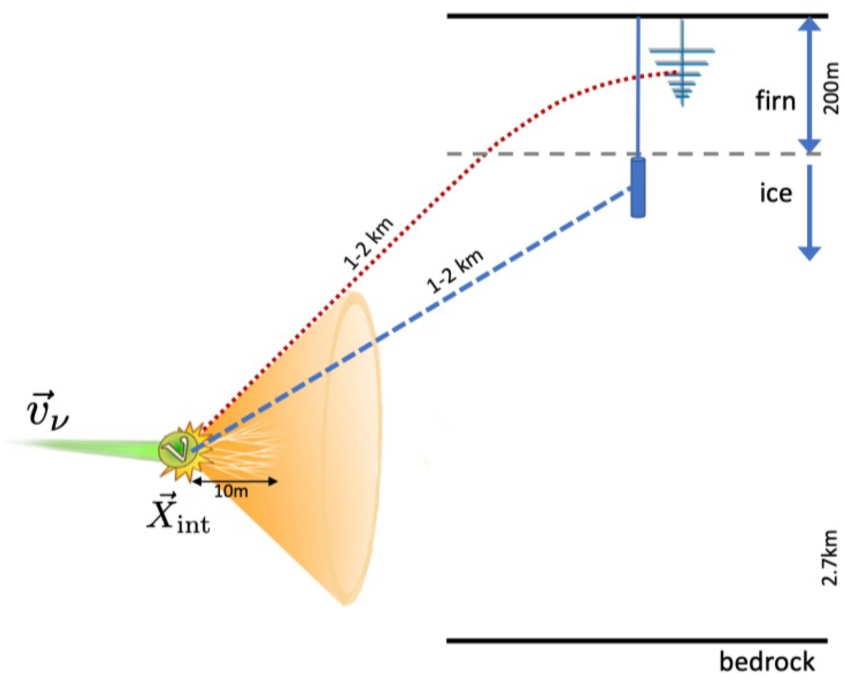
Overview: Radio detection of neutrinos

Neutrino interaction → Askaryan emission → Signal Propagation → Detection



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CORSIKA 8

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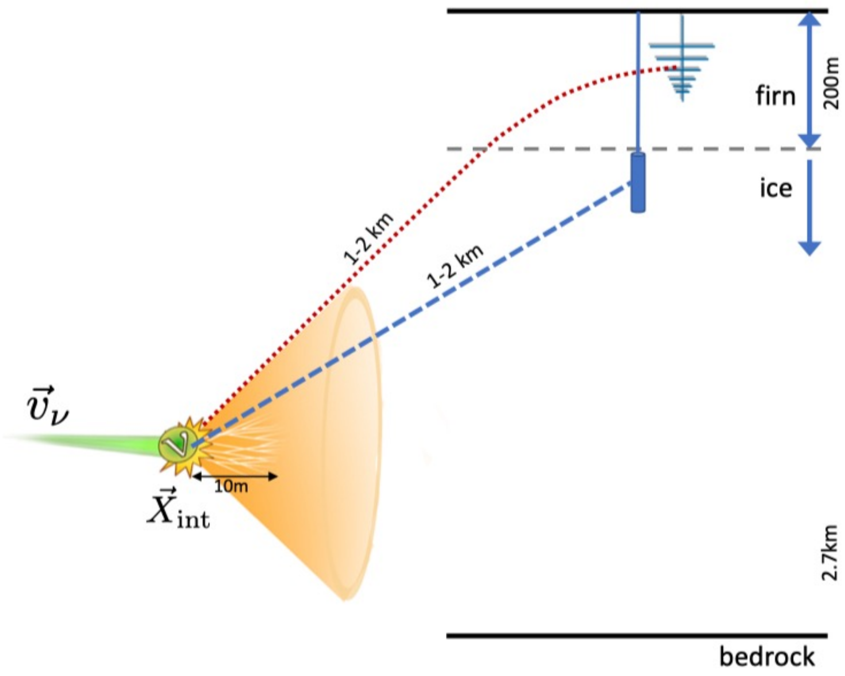

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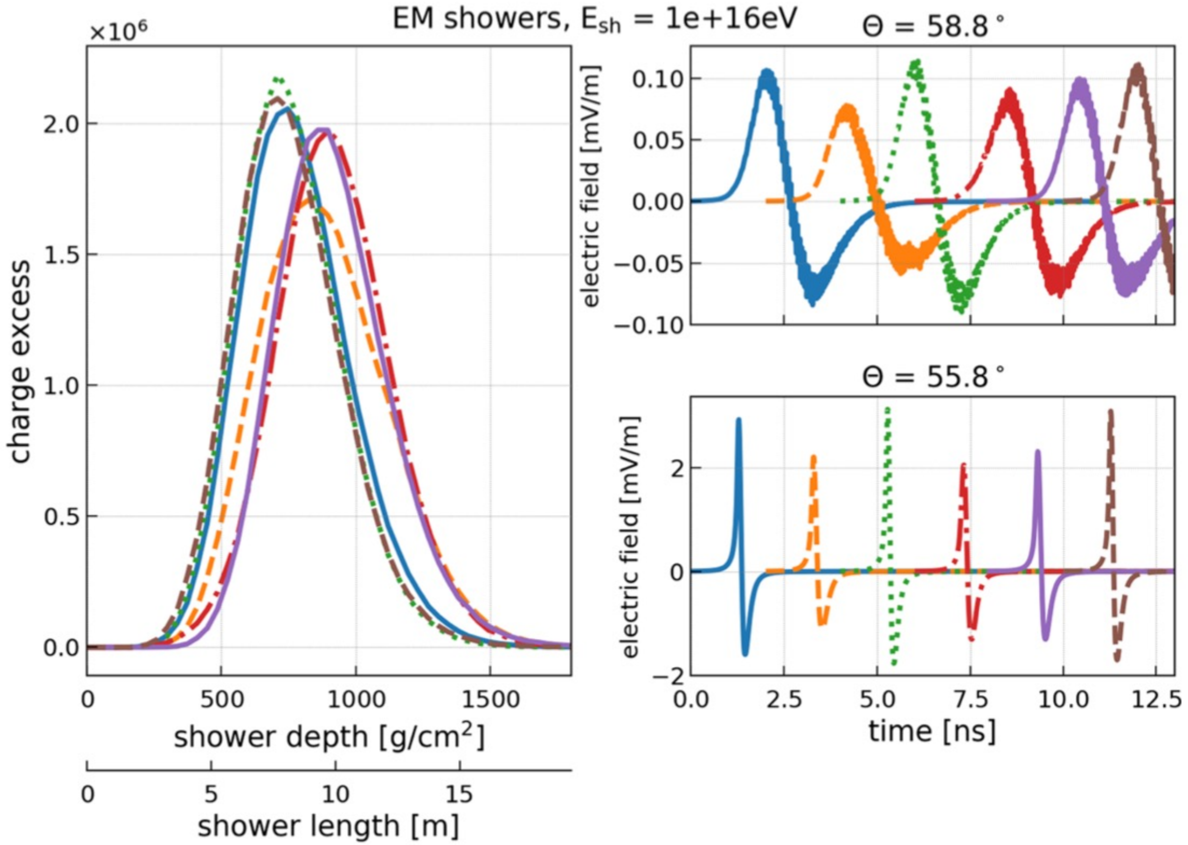
Current state-of-the-art in calculating radio emission

- Microscopic shower simulations in **homogeneous ice** (using ZHAireS)
- Semi-analytic formalism to calculate emission for arbitrary charge-excess profiles
  - Agrees within 3% with full MC simulation

*Alvarez-Muñiz et al., Phys. Rev. D **101**, 083005*



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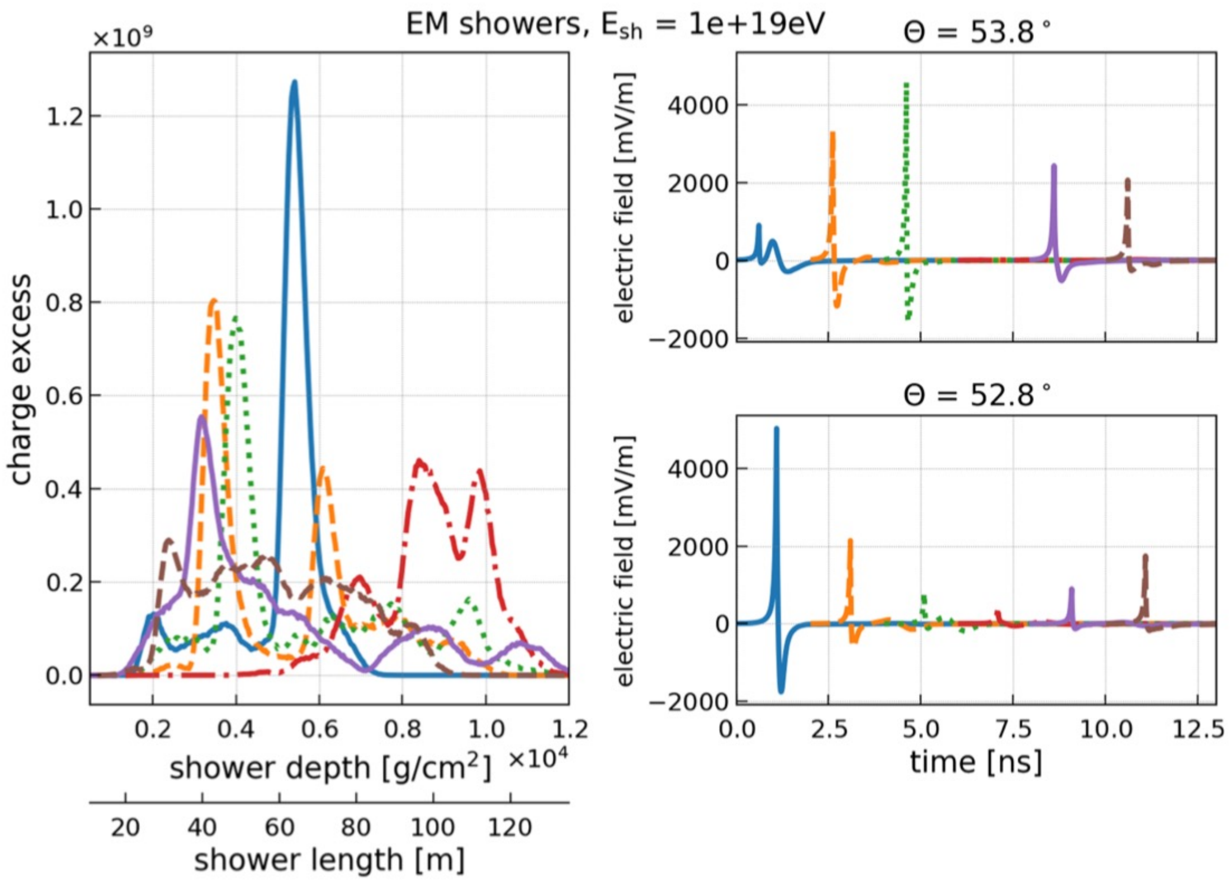
- Semi-analytic formalism to calculate emission for arbitrary charge-excess profiles
  - Agrees within 3% with full MC simulation
    Alvarez-Muñiz et al., Phys. Rev. D ***101****, 083005*
  - Precise calculation of LPM showers
- Full end-to-end (from neutrino interaction to detector) simulation codes exist
  - e.g. NuRadioMC
    C. Glaser et al., Eur. Phys. J. C (2020) 80:77
- **So far: Calculations assumed medium with constant index of refraction**



Goal 1: Microscopic simulation in inhomogeneous medium

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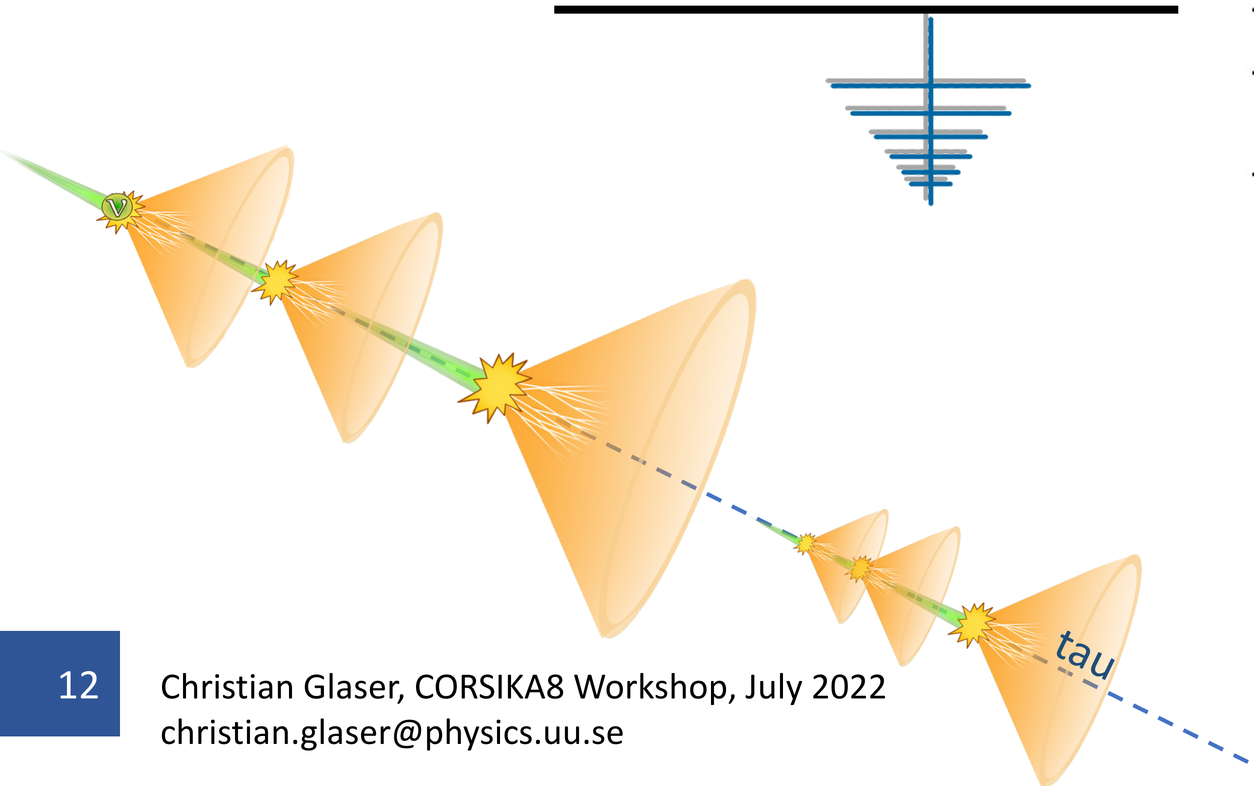
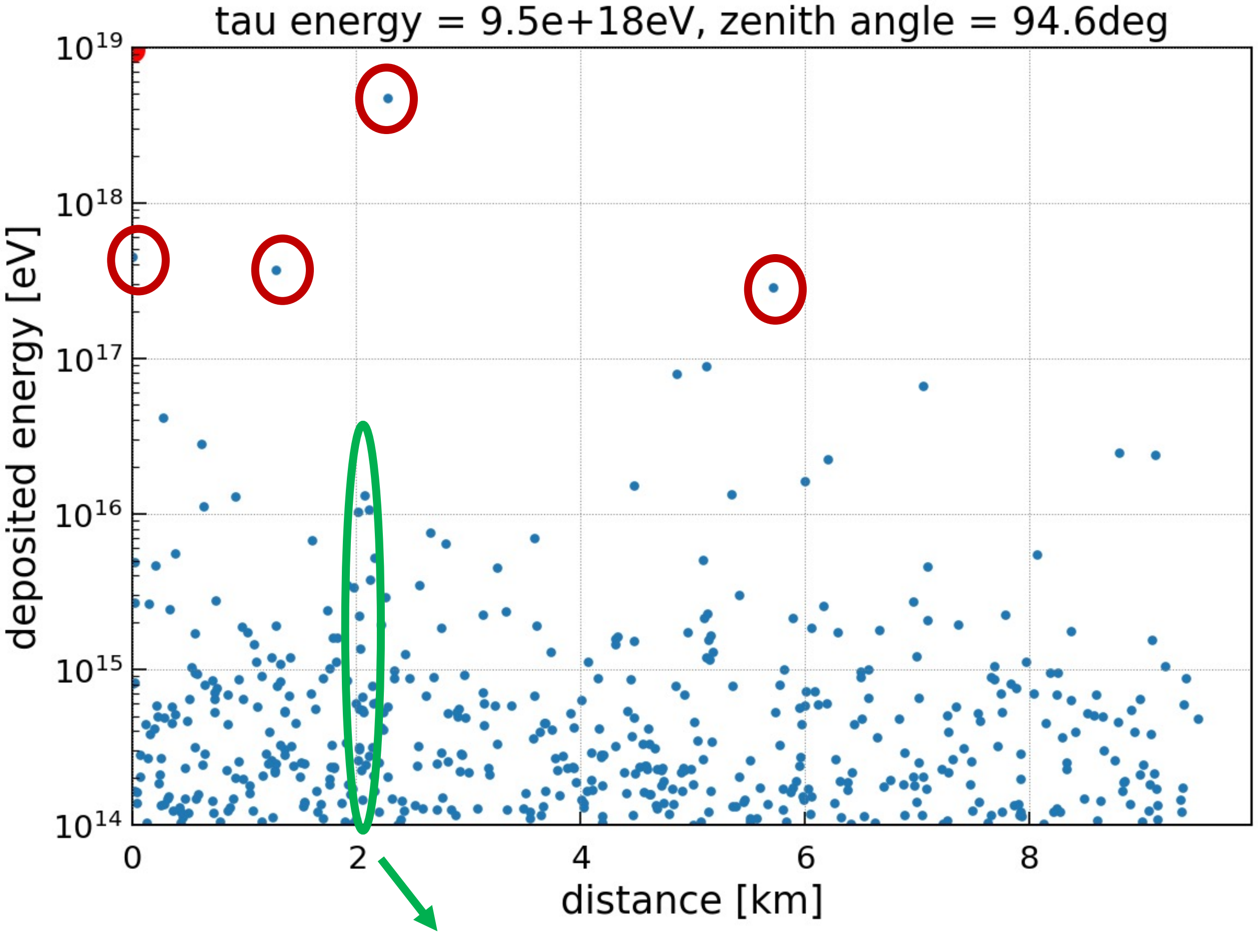
D. Garcia et al, Rev. D **102** 083011 (2020)

Energy losses of high-energy muon/tau

- 1 EeV tau propagating through ice
- Simulated using *PROPOSAL*
- Stochastic energy losses > 10^{14} eV shown





many low energy showers might interfere constructively

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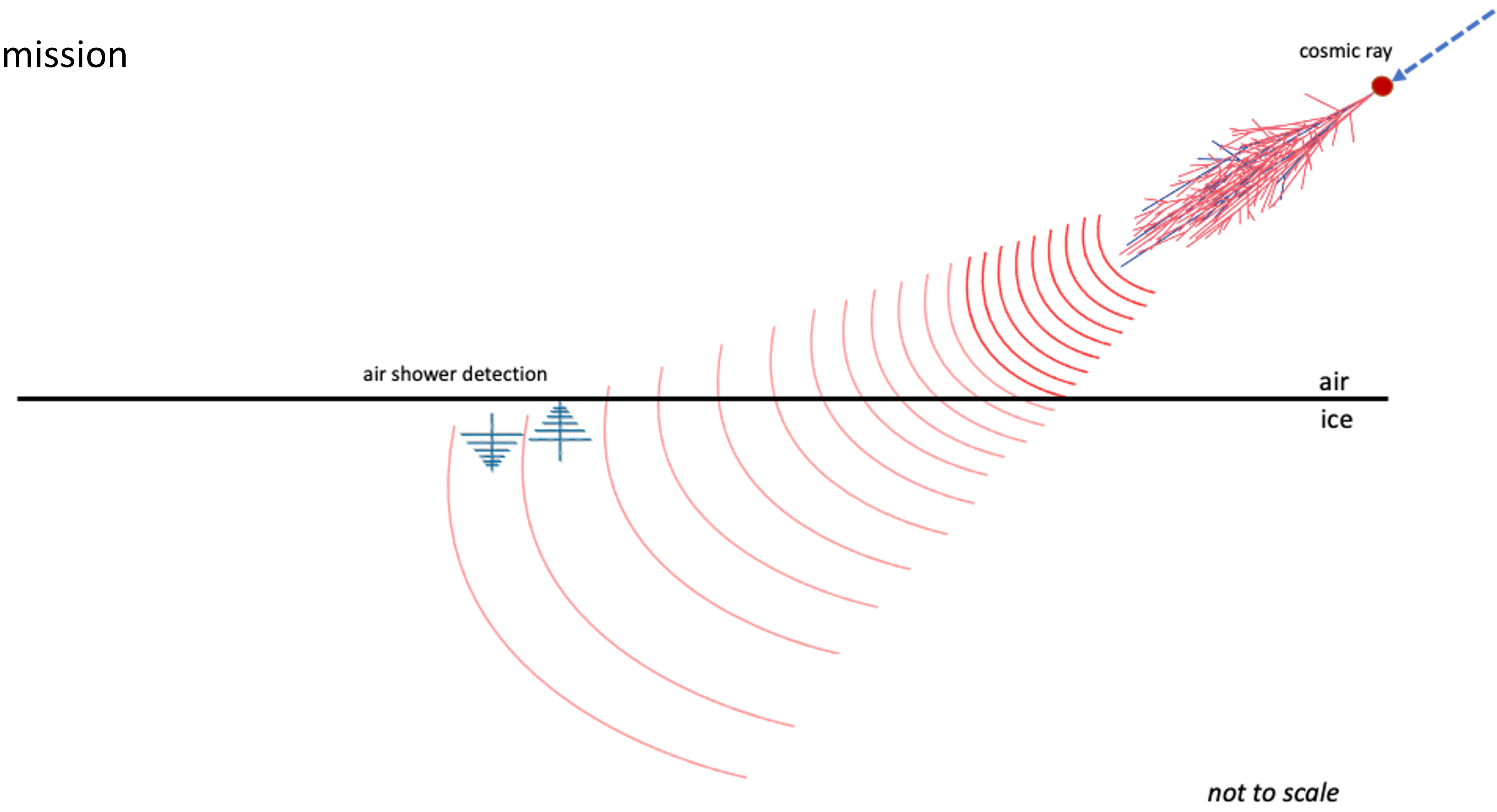
Additional Geometries

1. Air shower radio emission



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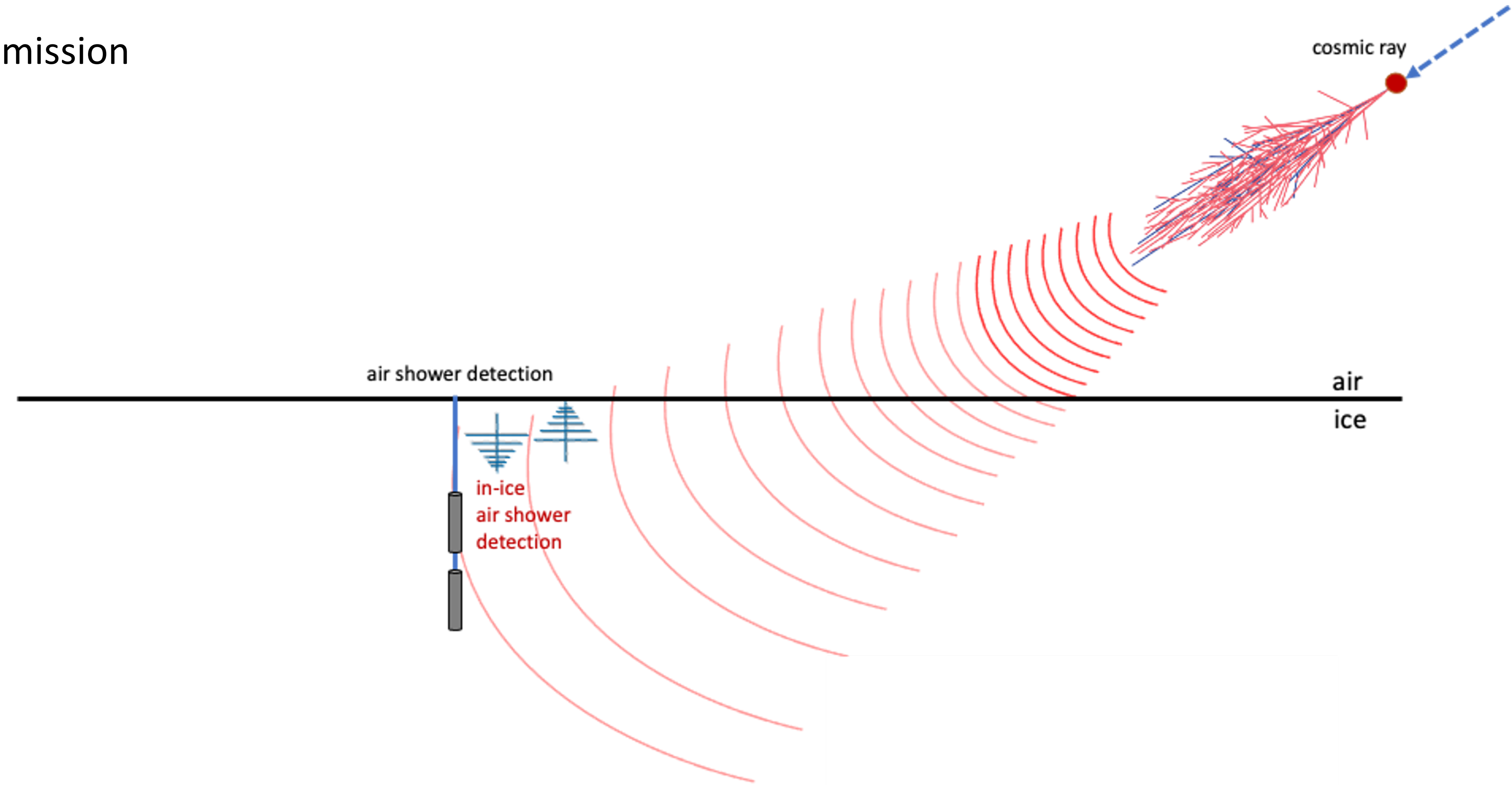

-> see Uzairs talk

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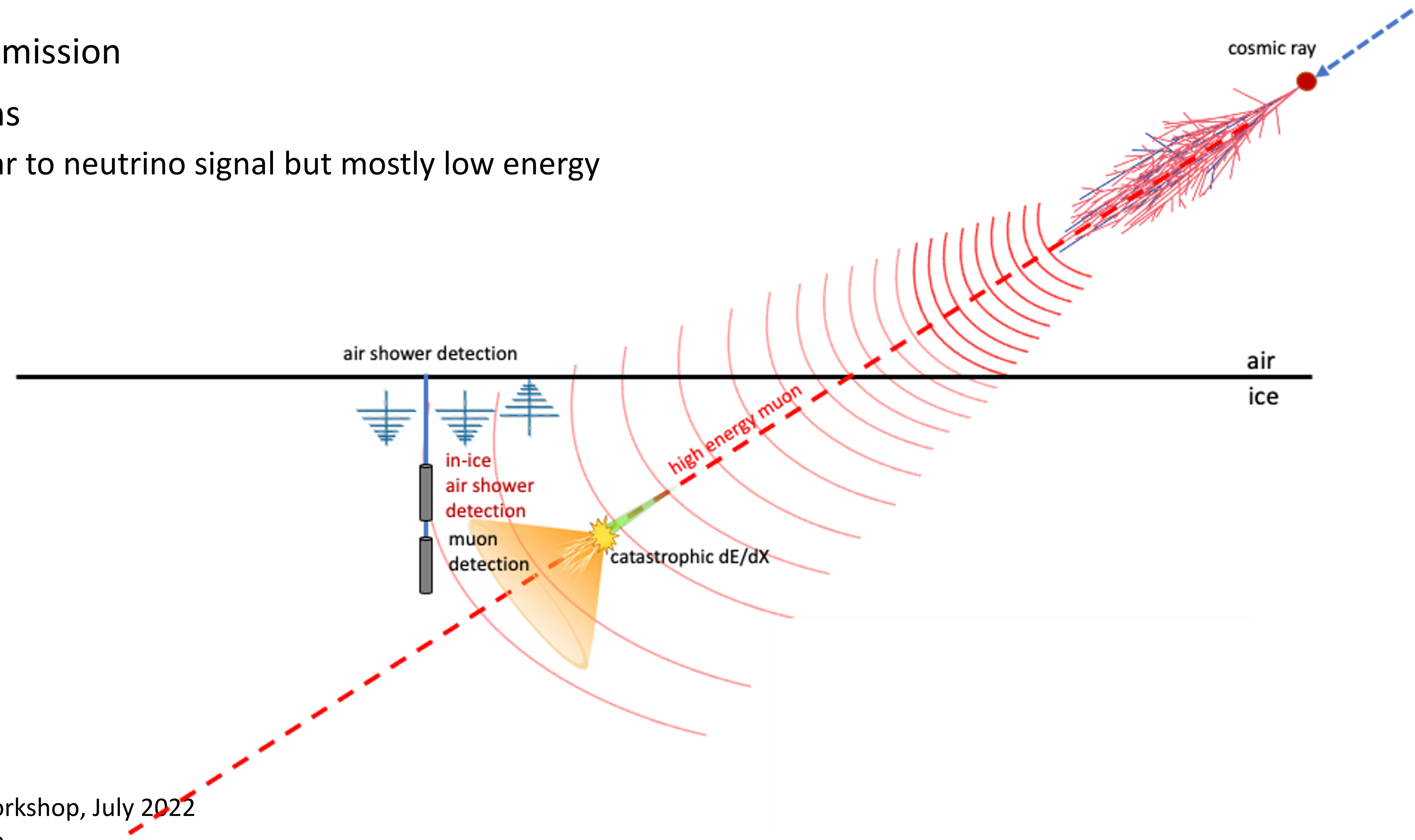
Additional Geometries

1. Air shower radio emission
2. High-energy muons
   a. signature similar to neutrino signal but mostly low energy



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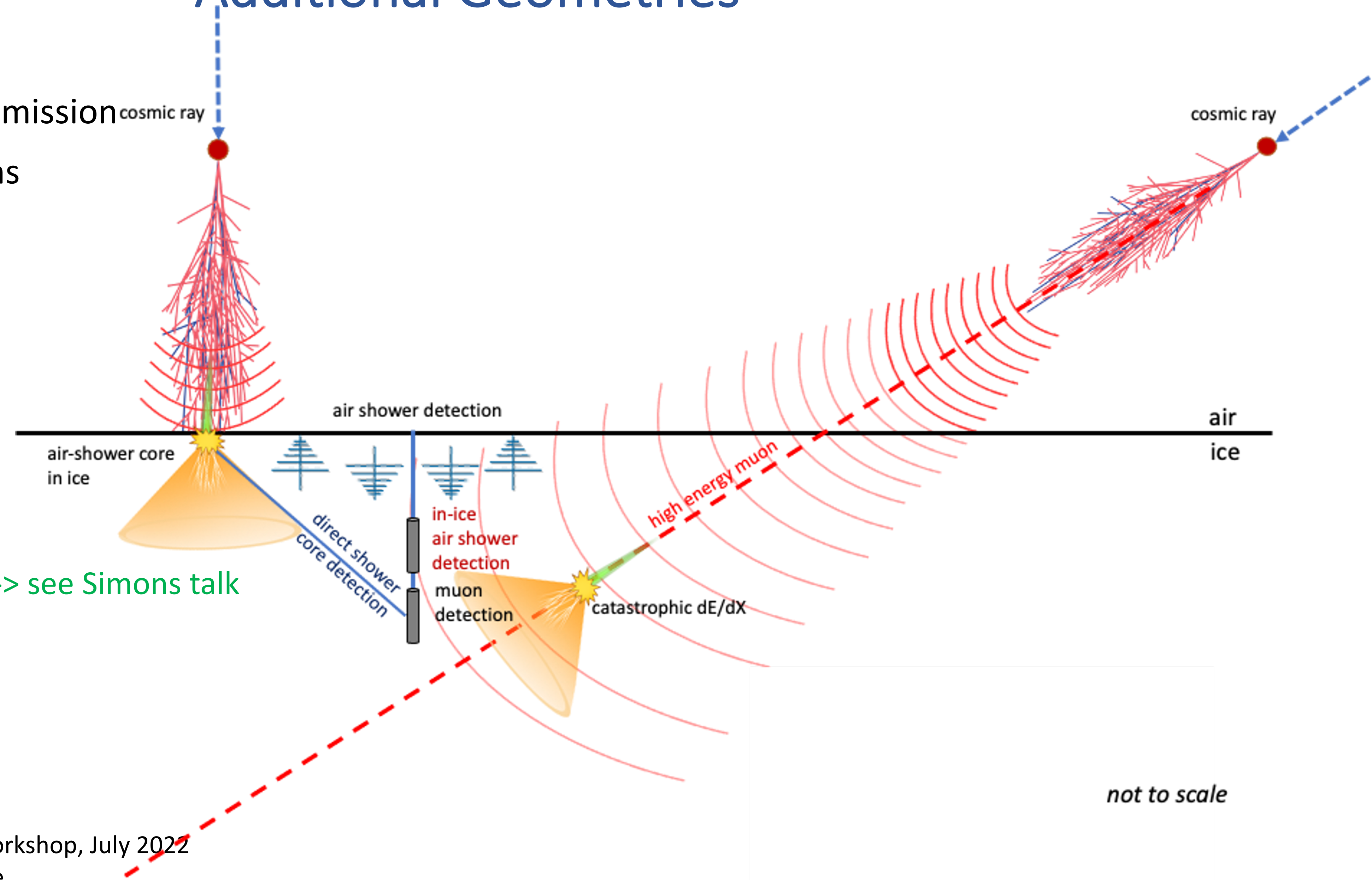
Additional Geometries

1. Air shower radio emission
2. High-energy muons
3. Shower cores



-> see Simons talk

not to scale

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Additional Geometries

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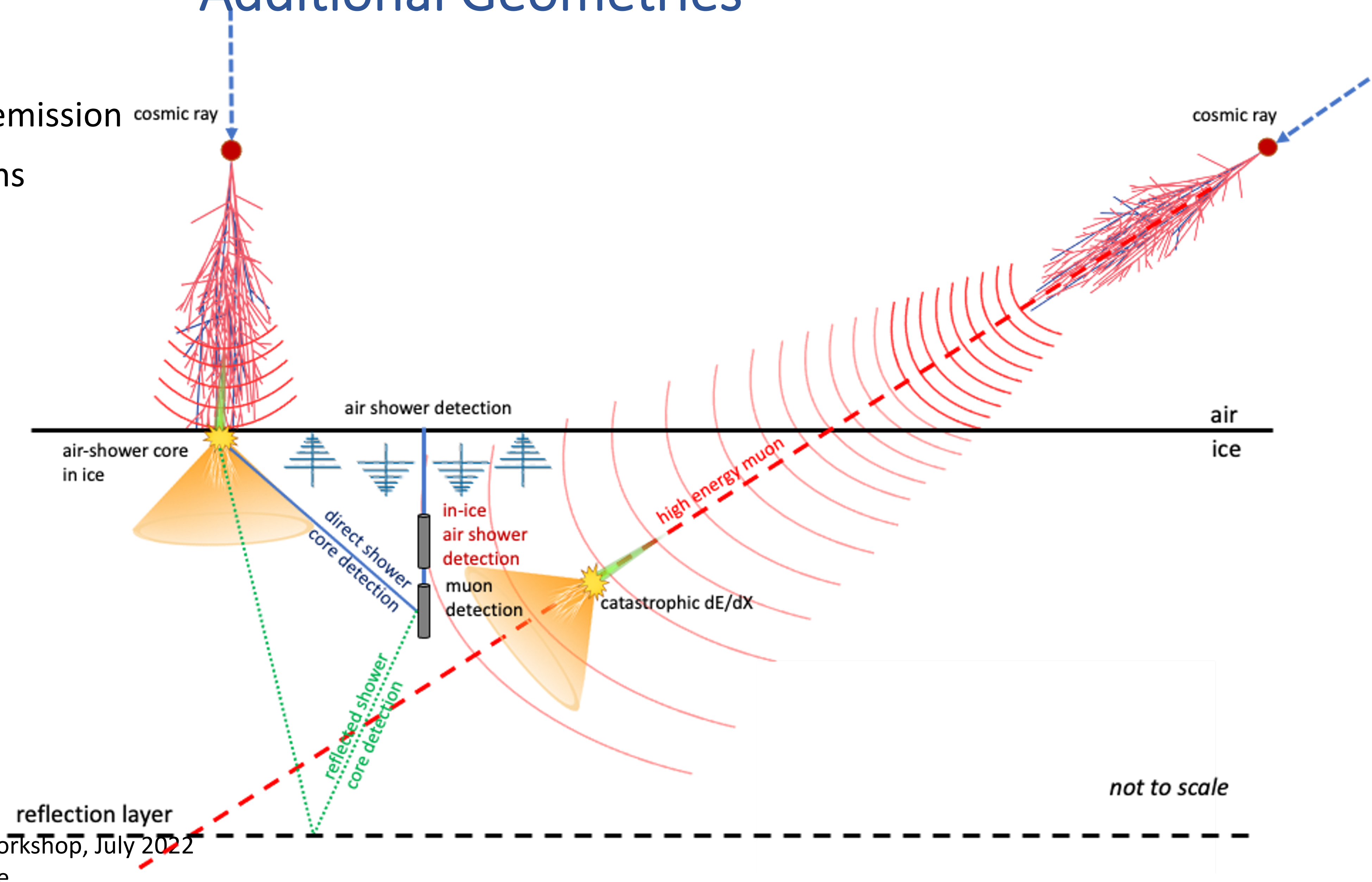

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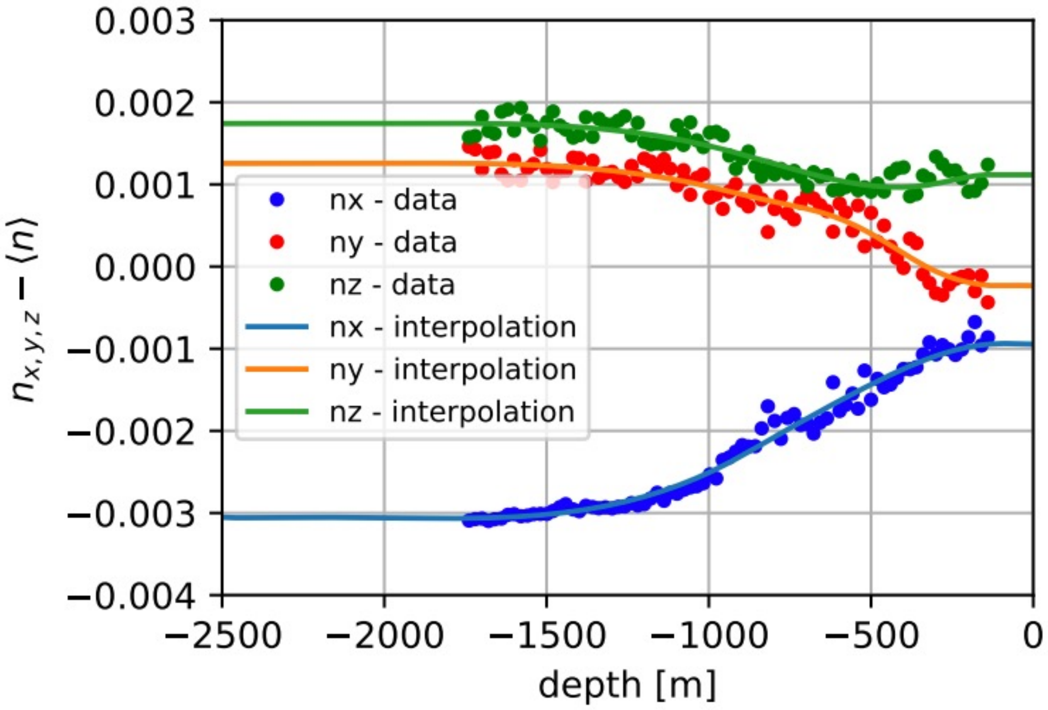
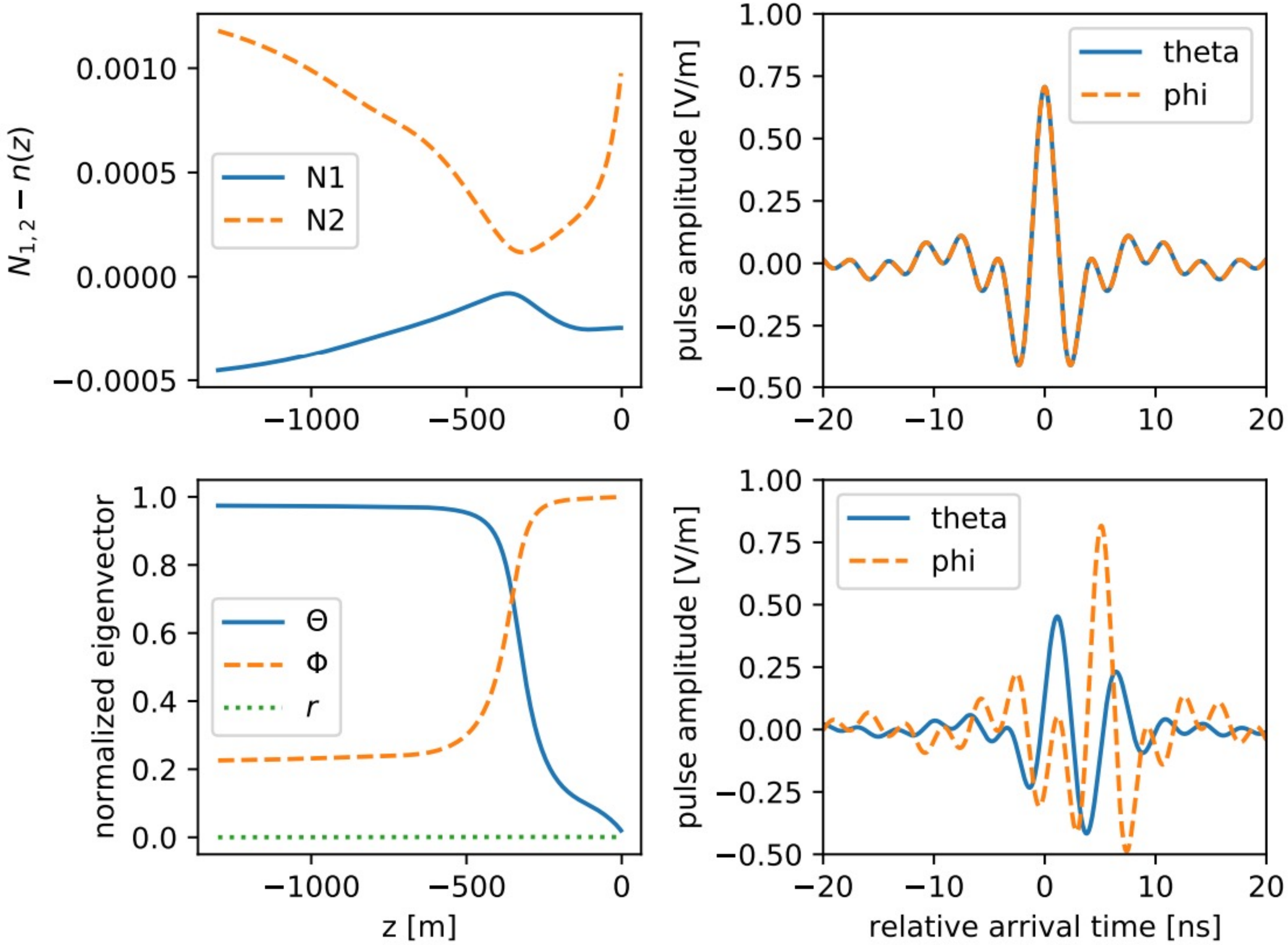
N. Heyer, C. Glaser arXiv:2205.06169

Additional Propagation Effects: Birefringence

- Index–of-refraction different for different signal polarizations
- Complex interference after propagation





-> propagation time between *shower track* and *receiver* not sufficient

any ideas how to model this effect time efficient?

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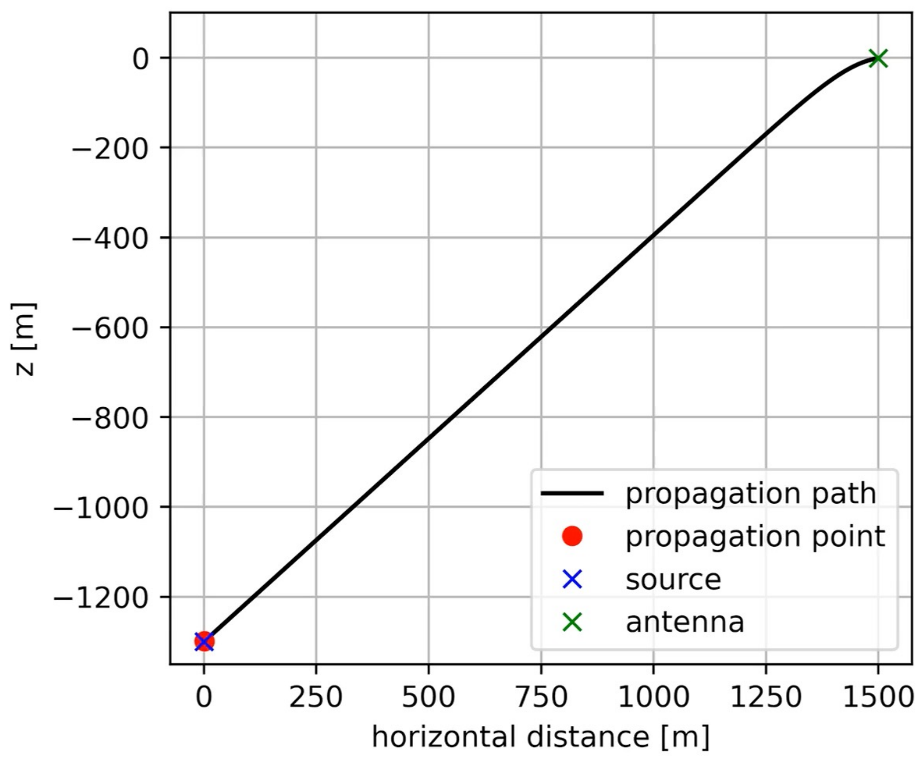
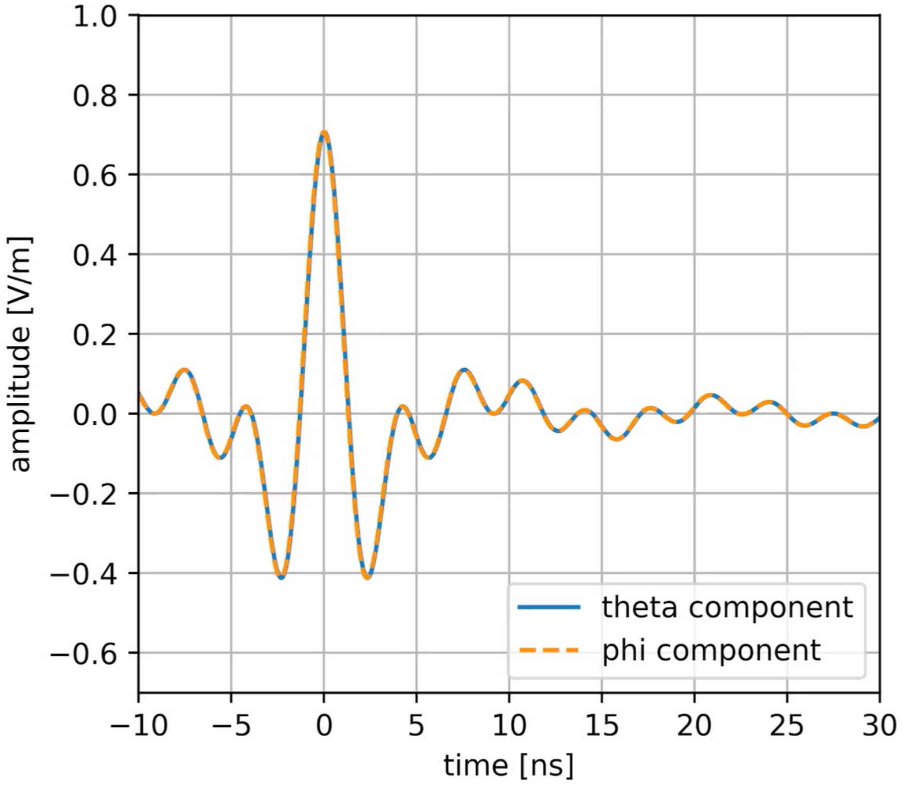
Pulse Propagation (⊥)





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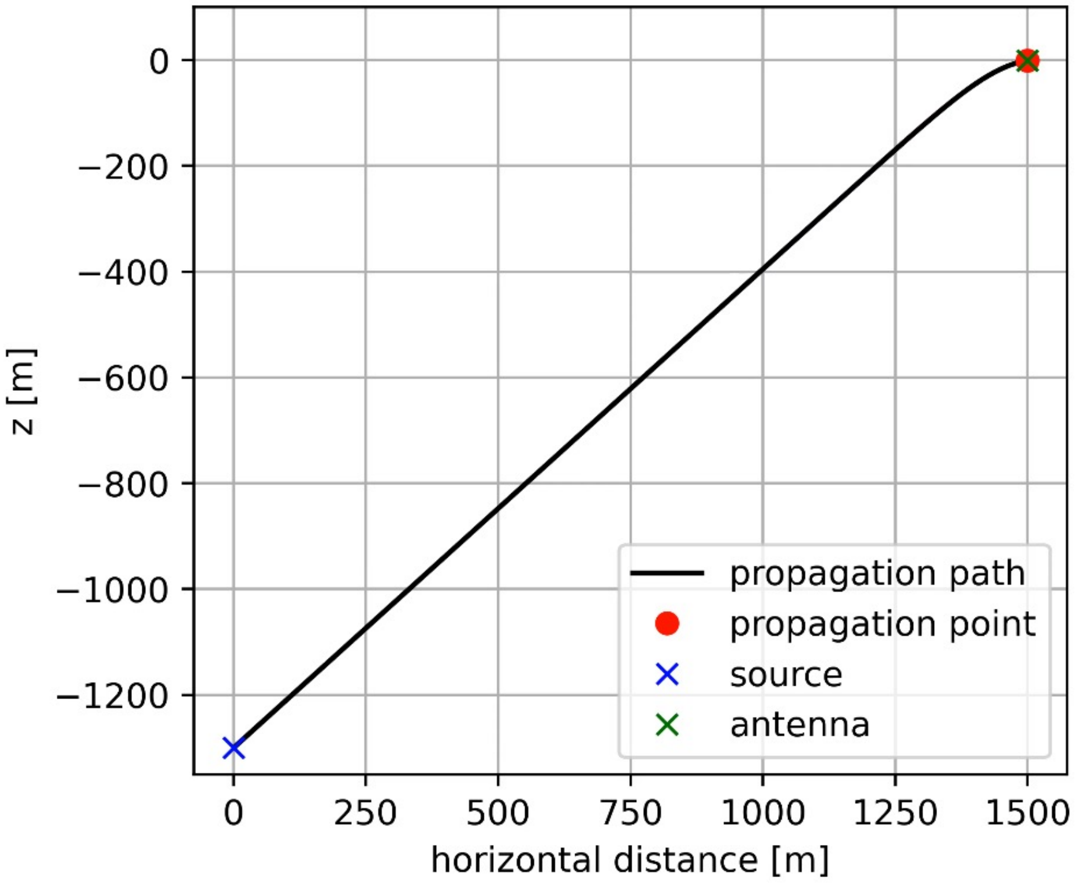
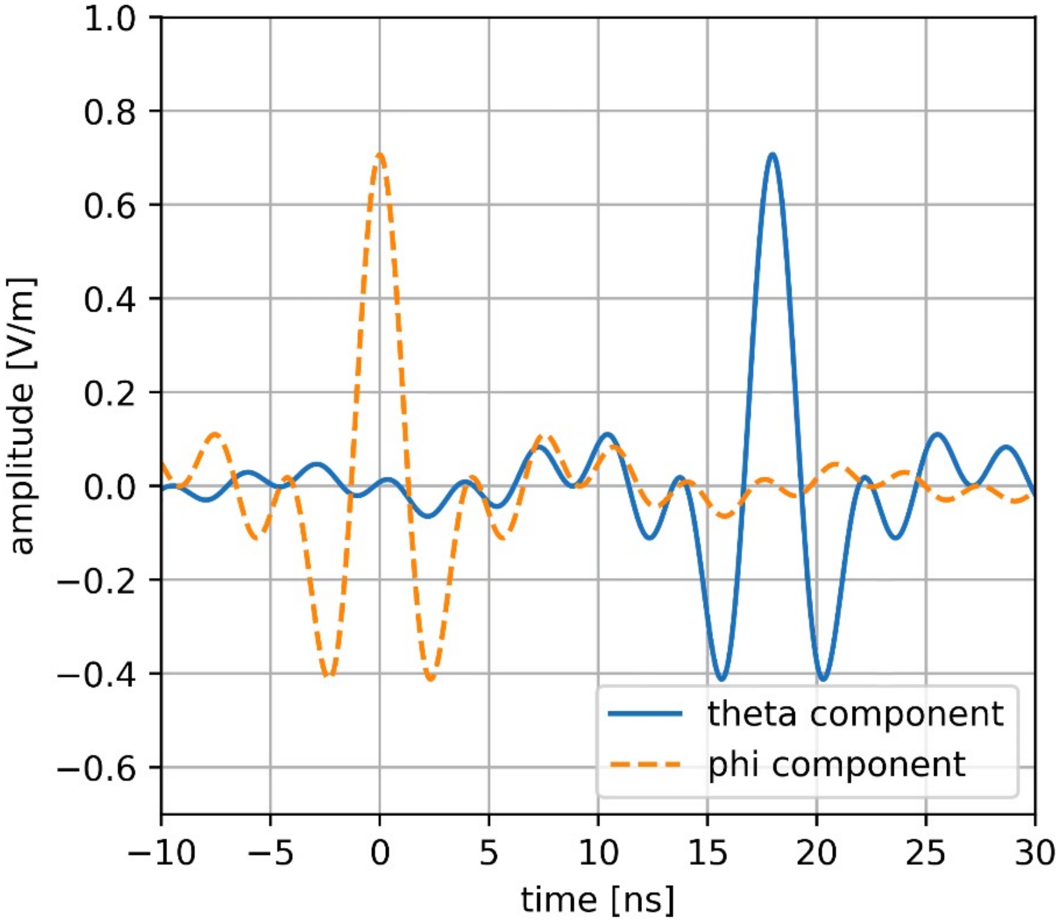
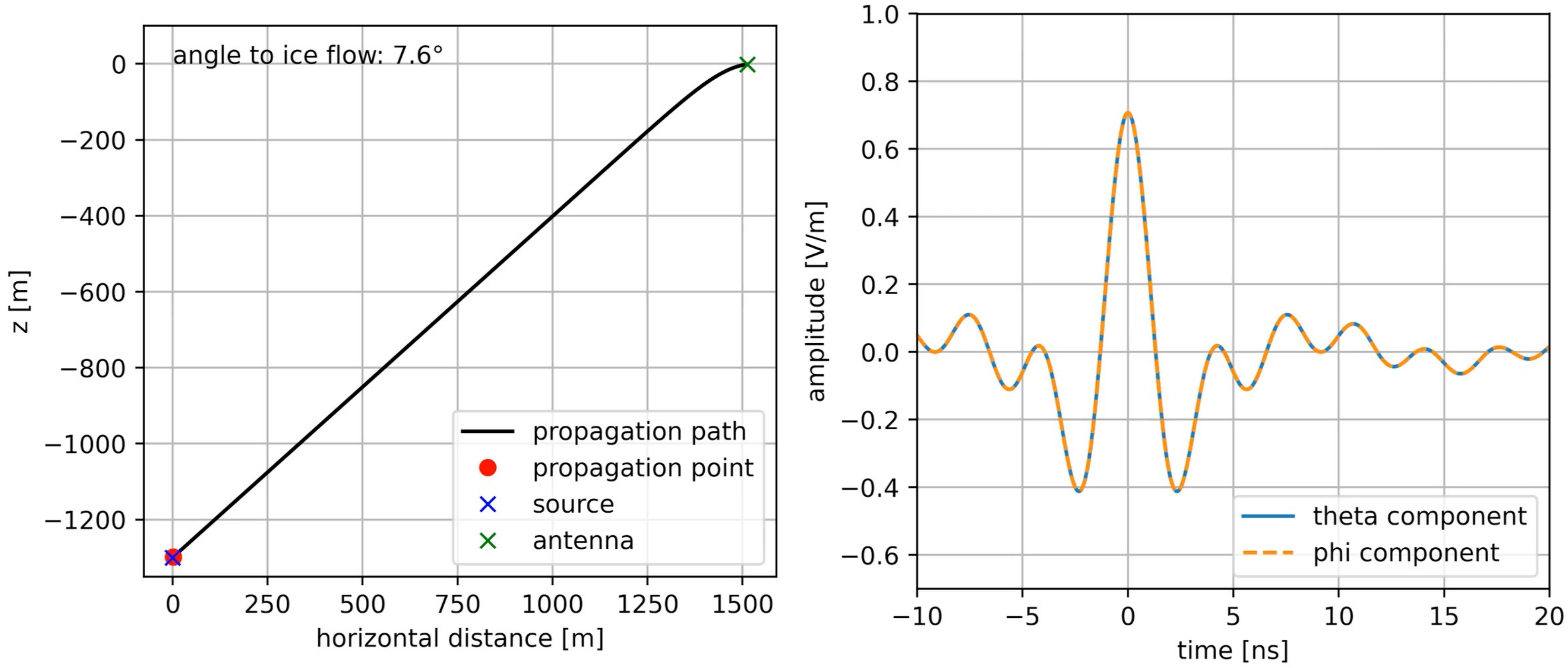
Pulse Propagation (⊥, final state)



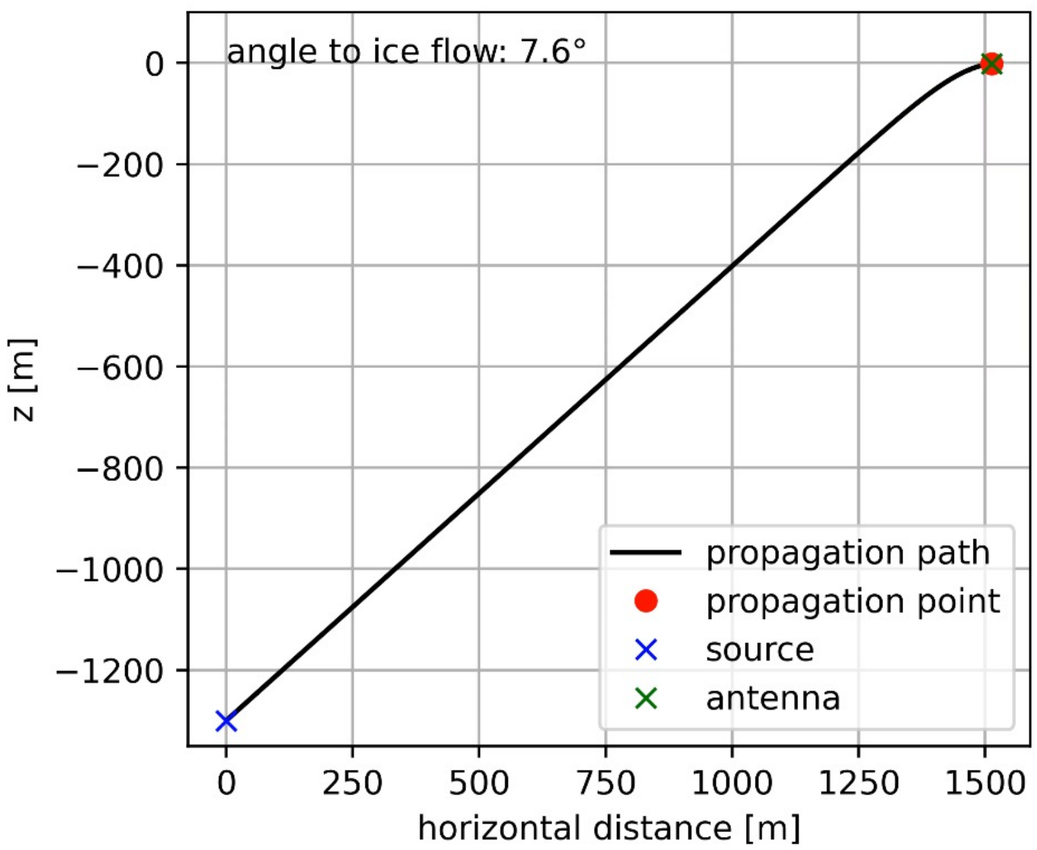


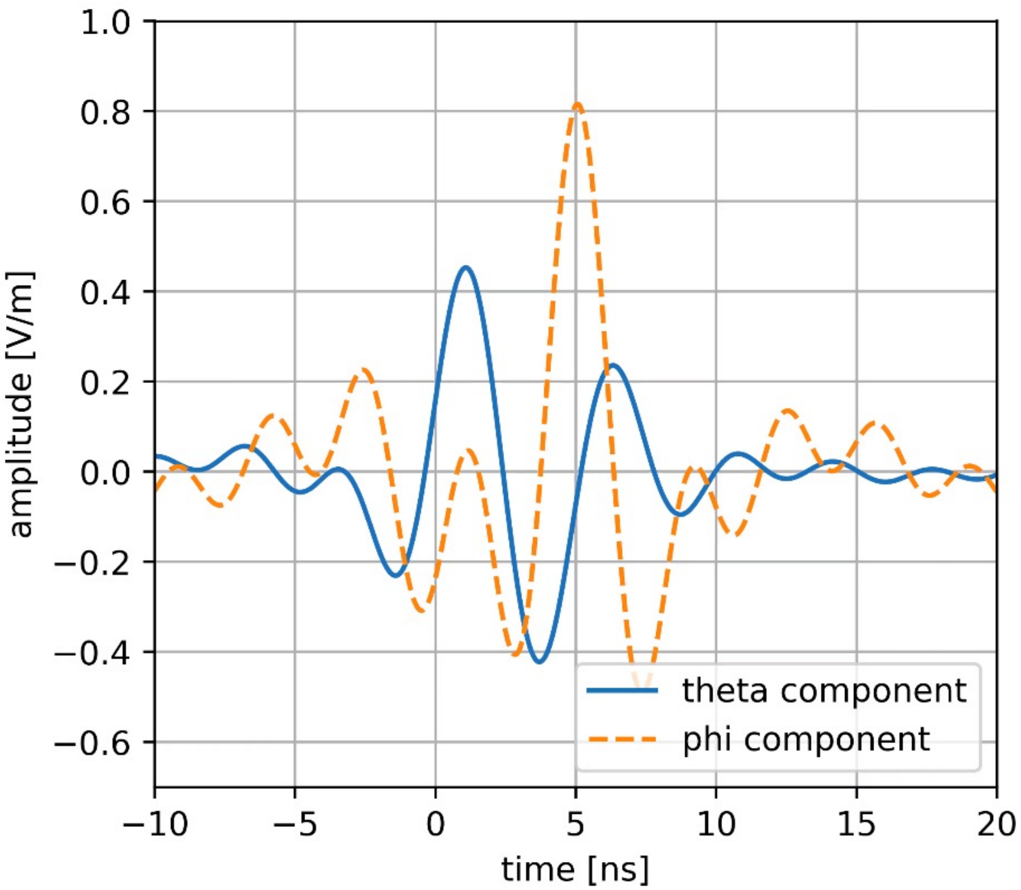
Pulse Propagation (∡)



N. Heyer, C. Glaser arXiv:[2205.06169](https://arxiv.org/abs/2205.06169)

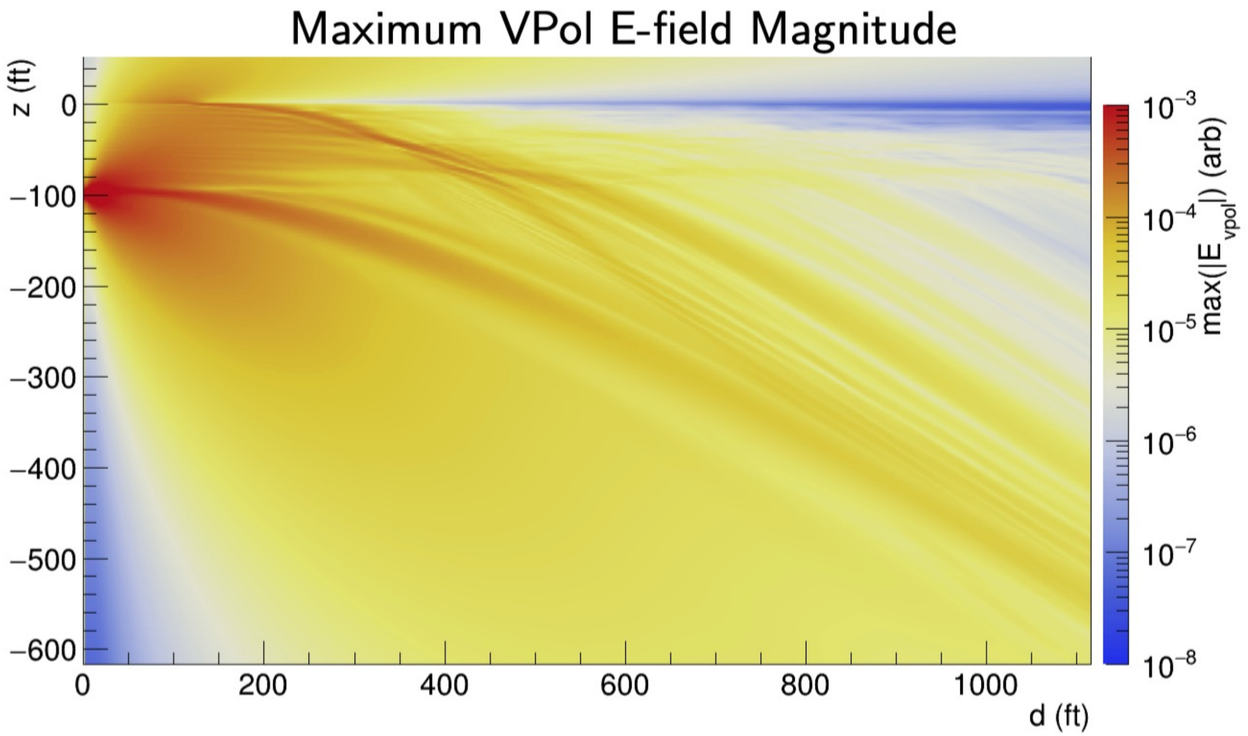
Pulse Propagation (∡, final state)





Additional Propagation Effects: Everything

- Complex ice properties can lead to propagation effects beyond ray tracing
- Solvable via Finite-difference time-domain (FDTD)
  - solves Maxwell's equation with discretized space / time
  - BUT very time consuming (100k core hours for single geometry)
  - feasible once for every antenna position/depth
    - **use reciprocity approach**



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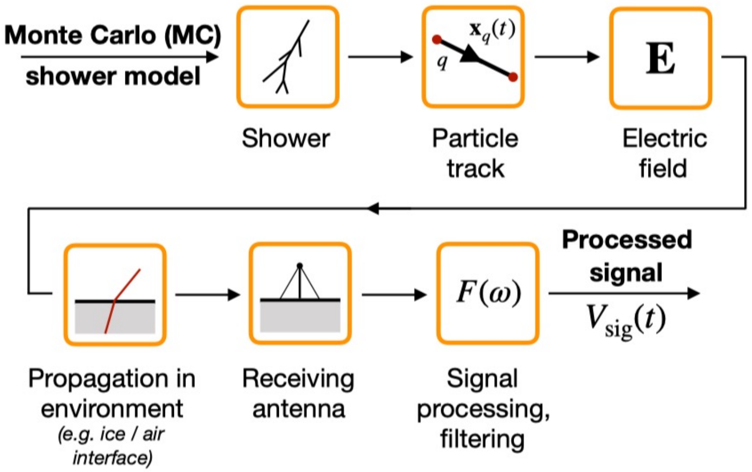
see e.g. C. Deaconu arXiv:1805.12576

Calculation of Propagation Effects via Reciprocity

current approach

“Particle-centric” solution: moving particle represents a current, use as source term in Maxwell’s equations, compute field & signal



Incur overhead if the same detector geometry is exposed to many different particle trajectories!

Repeat (unnecessarily!) the propagation of the radiation through the environment

using reciprocity

In the time-domain, this is

$$V^{\mathrm{ind}}(t) = -\frac{q}{Q_w}\int_{-\infty}^{\infty}\mathbf{E}_w(\mathbf{x}_q(t'), t-t')\dot{\mathbf{x}}_q(t')dt'$$

Normalising constant

Weighting field

Particle trajectory

only calculated once per medium and antenna

“Weighting field”: Green’s function for detector signal

Encodes information about detector geometry & environment; reciprocity defines concrete algorithm to compute it

Fully general, no approximations

holds exactly for all linear, anisotropic materials; approximately for nonlinear, anisotropic materials

slides by Philipp Windischhofer

more info: W. Riegler, P. Windischhofer, NIM-A 980 164471 (2020)

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Summary: Simulation of InIce Radio Emission

- What we already have:
  - microscopic simulation of radio emission in dense **homogeneous** media
  - End-to-end MC code (NuRadioMC) for fast simulation
- What we need:
  1. Simulation in inhomogeneous media *(first step n(z) gradient)*
     - can be solved by adding ray tracing to radio module
  2. Complex geometries (transition of boundaries)
  3. Second-order propagation effects, e.g. birefringence
     - propagation time between *shower track* and *receiver* is not sufficient
     - can potentially be solved using an reciprocity approach

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Backup

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Hard requirements

from ARENA2018 brain storming meeting

- Support of dense media such as ice, water, lunar regolith, ...
  - Do we need to implement additional interactions that are only relevant for dense media? E.g. tau propagation, dE/dX for muons, LPM effect?
  - Does the medium need to couple back to simulation parameters such as low-energy cutoffs?
- Support of arbitrary medium configurations, including transitions from air to dense media or dense media to vacuum (at least medium properties as a function of height, better arbitrary 3D medium configurations)
- Medium model including refractive index profile, and possibility to do ray-tracing on the basis of this in both air and dense media
  - Additional properties needed? Humidity? Temperature?
- Direct interface to the tracking of each particle in the shower simulation with bi-directional communication
  - E.g. readjust step size in particle tracking
  - E.g. readjust thinning level of important/unimportant particles or even throw away particles that are not relevant for radio emission
  - E.g. modify particle properties due to atmospheric electric fields
- Simple interface to inject arbitrary particles (including their energy, momentum) and possibly specify their interactions to start a shower (“the world’s dumbest event generator”)
- Global coordinate system that supports curvature of Earth (anyway planned, adaption from Offline)

Very useful features

from ARENA2018 brain storming meeting

- Inspect particle cascade at arbitrary observation planes, e.g. to calculate drift velocities on the fly, ...
- In general a very flexible adjustment of thinning
  - First interactions are very important -> low thinning
  - Medium energy interactions are less important -> high thinning
  - Low energy interactions are important to correctly model coherence -> low thinning
- Possibility to simulate air showers induced by upgoing neutrinos (from the Earth, mountains, …)

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Wishlist

from ARENA2018 brain storming meeting

- Retain information on particles at rest -> ionization in medium (relevant for RADAR reflections, low-frequency radio emission)
- Simulate ‘very’ low energy particles (keV scale) and interaction with atmospheric electric fields relevant for thunderstorm studies - in general allow interfacing of additional interaction models for particles/energy ranges not treated by existing models
- Simulate particle oscillation (e.g. neutrino oscillation or strong oscillations such as K-short -> K-long). I.e., in general provide the possibility to change the type of the particle during propagation; this could be implemented in form of a propagation modules.
- Save state of simulation at any stage (e.g. a specific height/atmospheric depth). Then be able to resume simulation with e.g. modified density profile or just with different random seeds

Implementation of Radio Modules

from ARENA2018 brain storming meeting

- Radio part should be modular in itself, i.e. decouple
  - Emission calculation (e.g. ZHS vs. endpoints)
  - Signal propagation
    - Straight lines (for air showers/constant density)
    - Ray tracing
    - Full FDTD propagation?
  - Receive module
    - Add emission from all particle tracks (as right now in CoREAS)
    - Keep track of incoming direction of signal -> efield in angular bins
    - On-the-fly convolving with directional antenna response

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