Simulations for in-ice radio experiments

Christian Glaser for the inice-mc group

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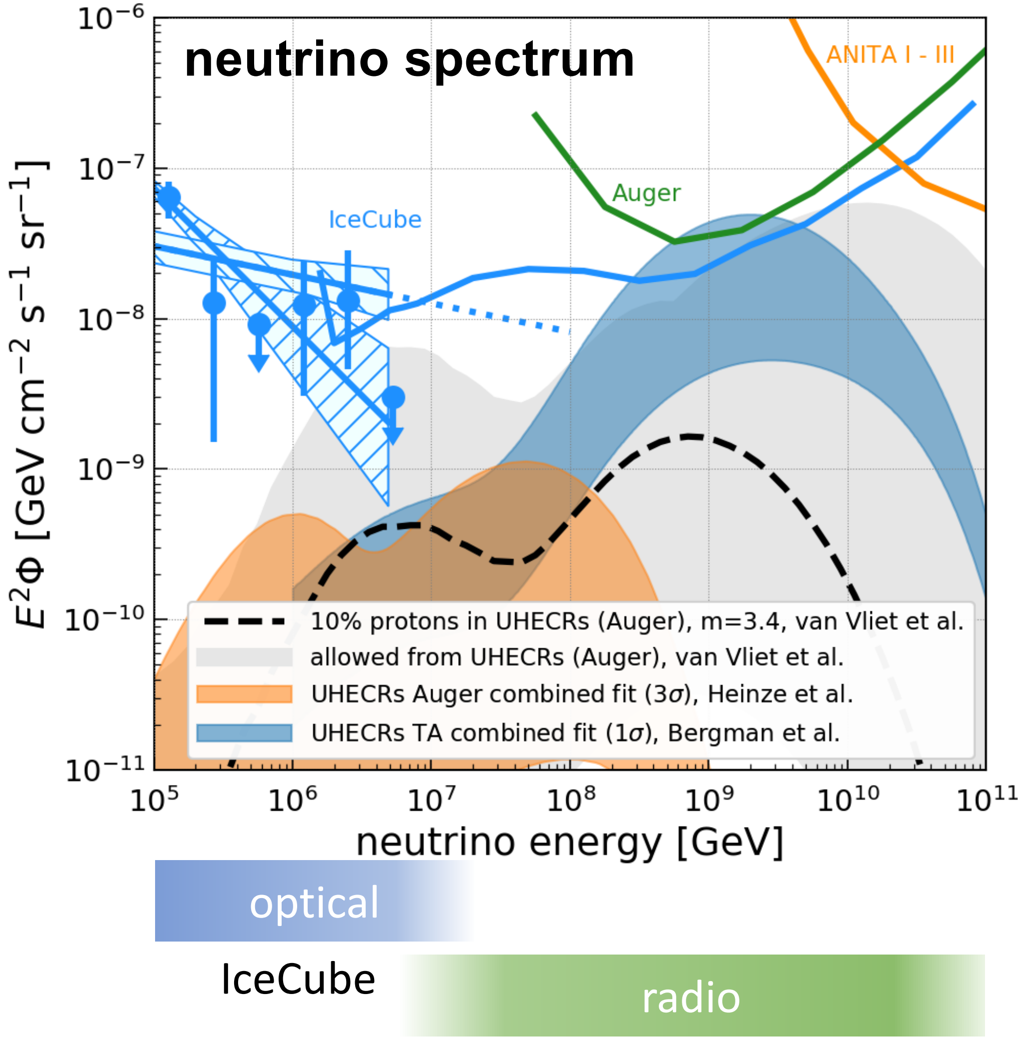
High-energy neutrino detection (>10^{17}eV) only possible through radio detection

- Science case: E.g. GZK neutrinos -> cosmic ray composition and source evolution *see ASTRO2020 white papers 1903.04334 and 1903.04333*
- Low flux and small cross-section of neutrinos require huge instrumented volumes
- Optical techniques (e.g. IceCube) become cost prohibitive
- **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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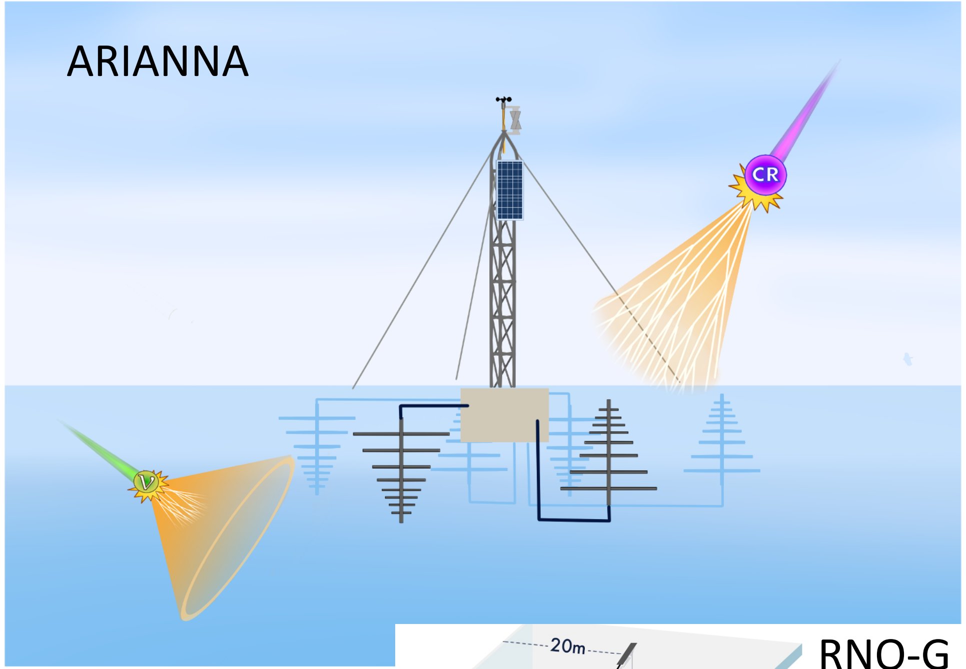
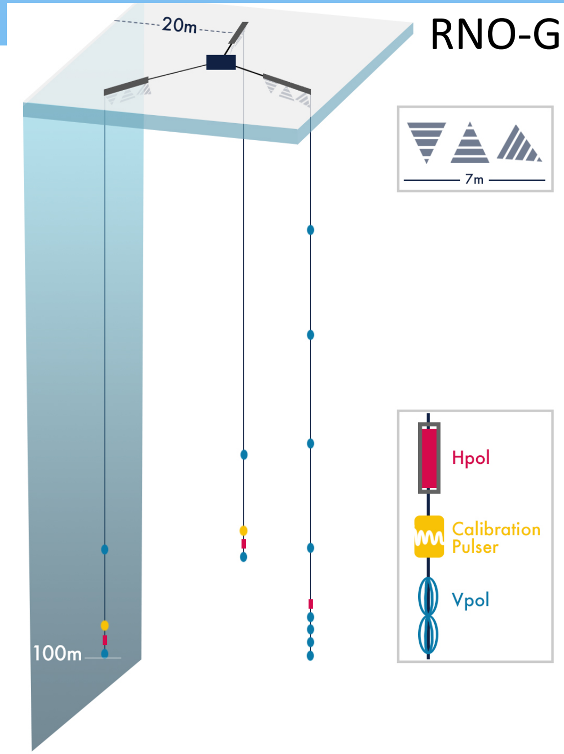
Experimental status

- Proof-of-concept with two pilot arrays (ARA, ARIANNA)
- "Mid scale" (= sensitive enough to potentially measure the first neutrino with radio)
  - RNO-G (Greenland) under construction
  - ARIANNA-200 (Moore's Bay) planned, SOP Nov. 2021
- Large scale
  - Radio detector integral part of IceCube-Gen2 to extend IceCube's sensitivity to higher neutrino energies
  - SOP ~2030





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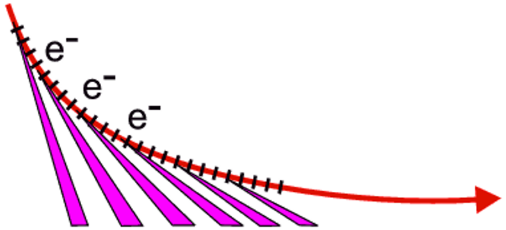
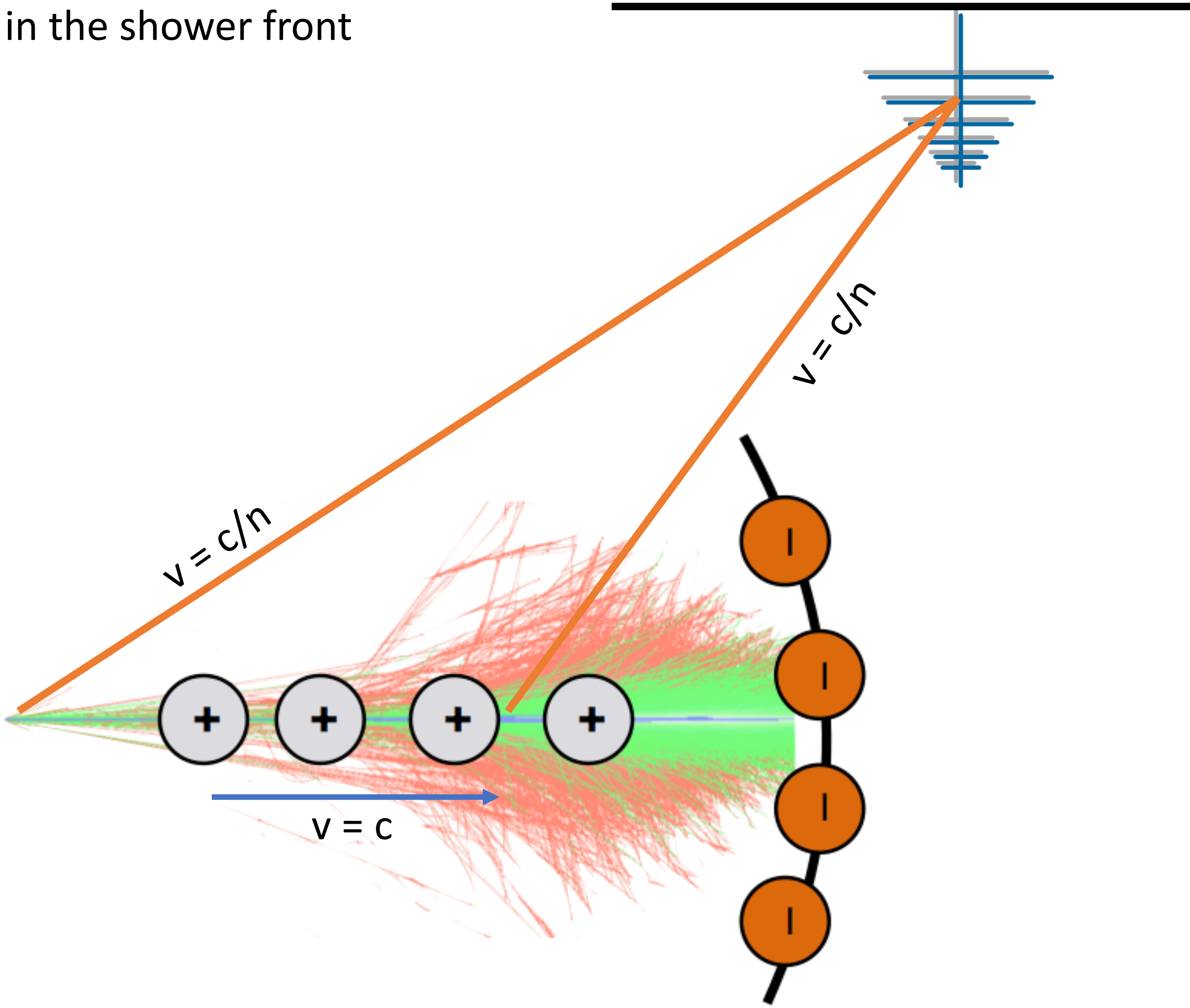
Radio Emission of InIce Particle Showers

- Askaryan effect: Time varying negative charge excess in the shower front
- Macroscopic: Longitudinal current
- Microscopic: Acceleration and creation of charge



- Cherenkov-like time compression effect
- Shower is faster than its emission
- Constructive interference at the Cherenkov angle
- In ice: arccos(1/n) = 56 deg



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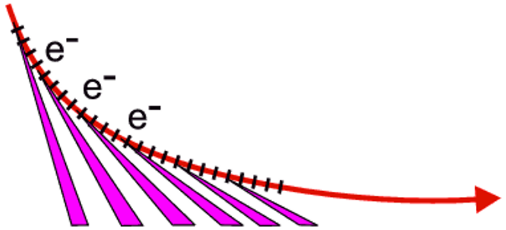

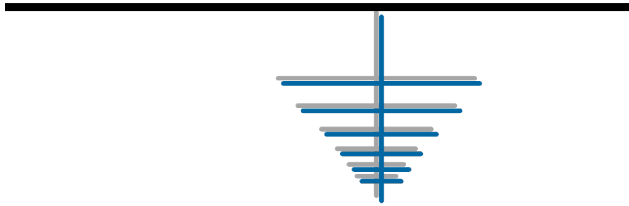

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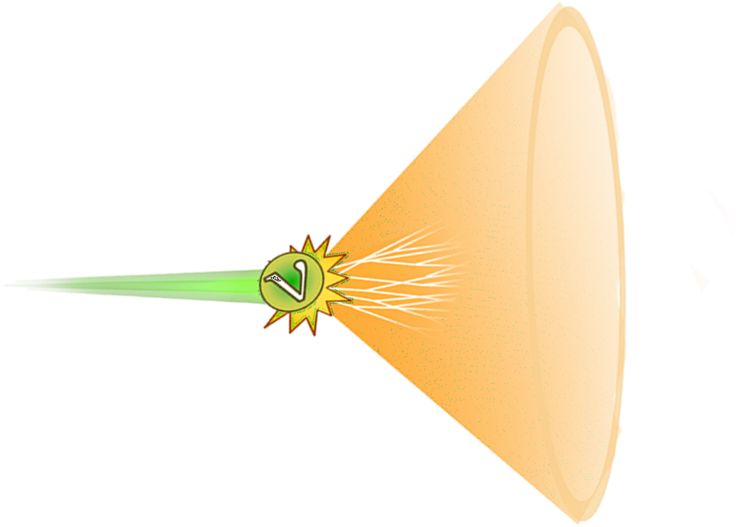

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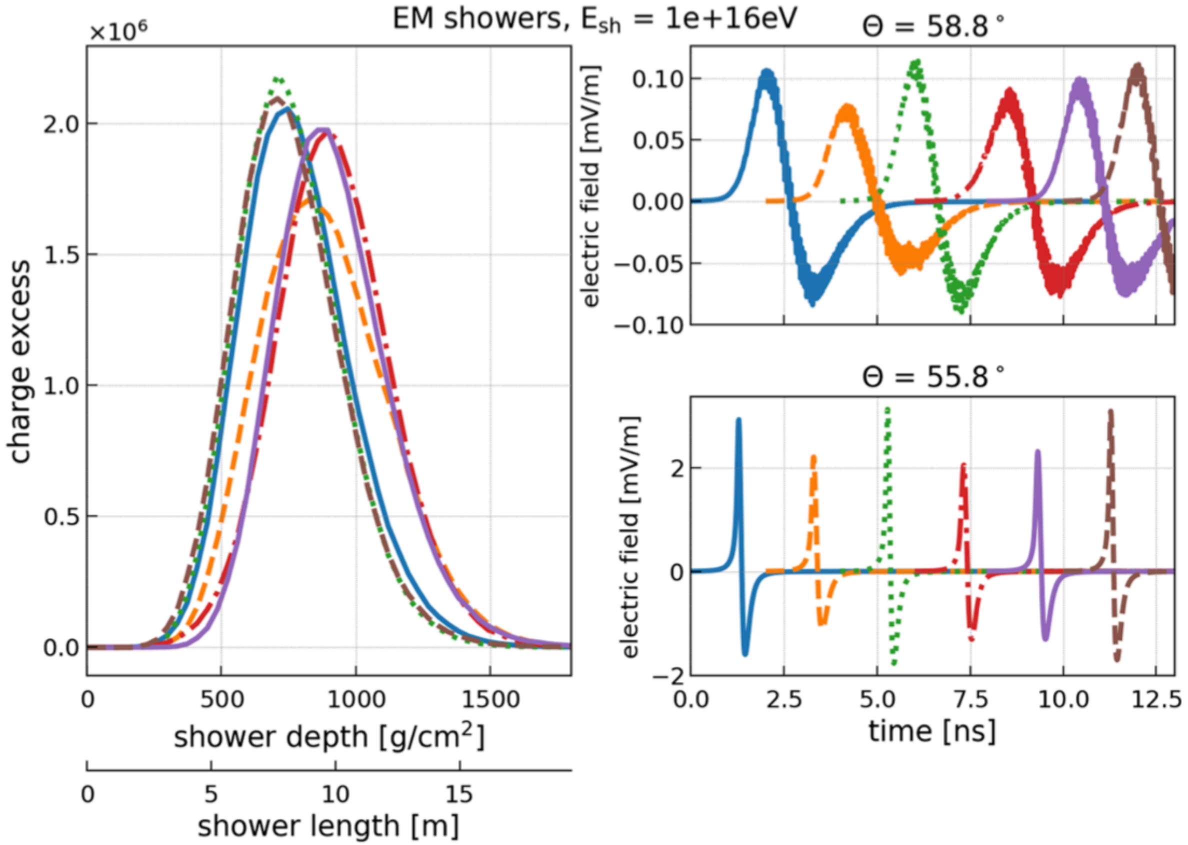
Current state-of-the-art in calculating radio emission

- 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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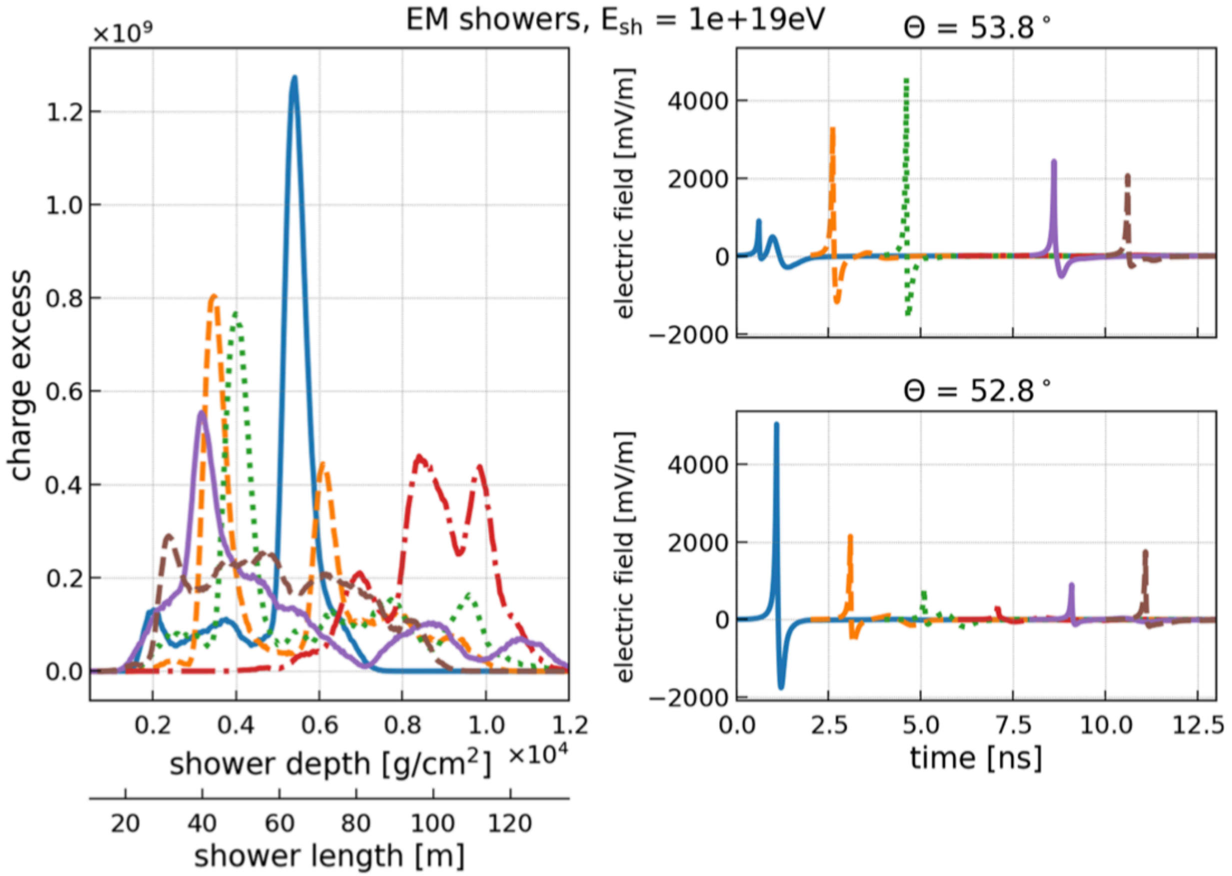
  - Precise calculation of LPM showers
- Full end-to-end (from neutrino interaction to detector) simulation codes exist
  - e.g. NuRadioMC

    C. Glaser et al., Eur. Phys. J. C (2020) 80:77
- **So far: Calculations assumed medium with constant index of refraction**



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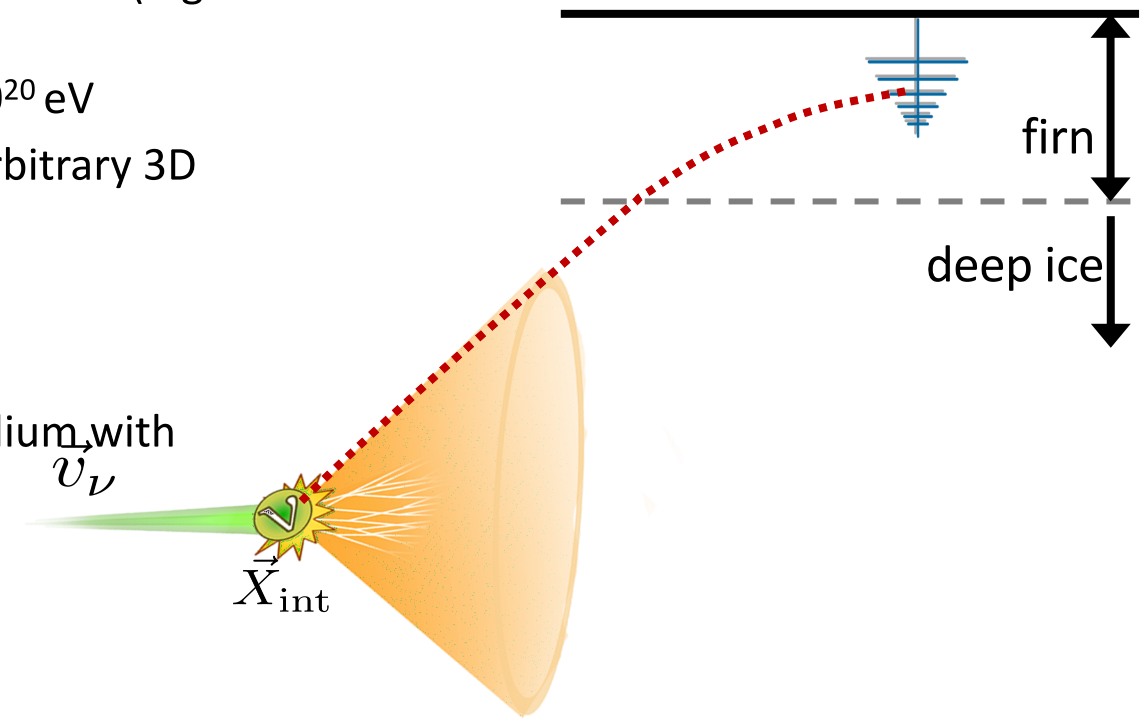
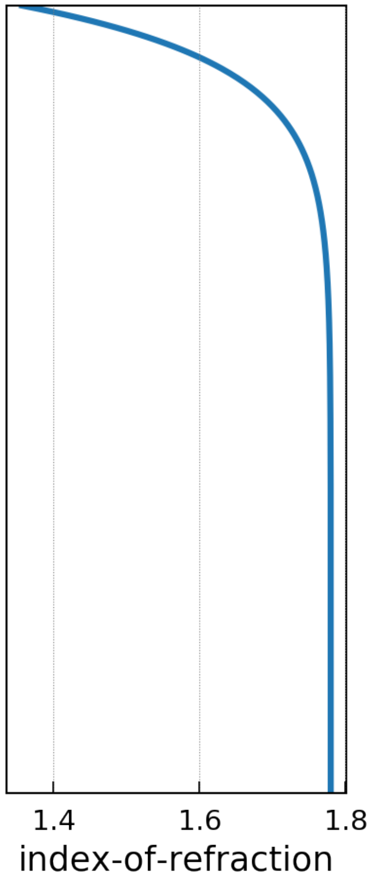
Our Requirements

- Most common event types
  - Shower simulation in homogeneous medium (e.g. ice with n = 1.78)
    - initial neutrino energies up to ~10^{20} eV
  - Propagation of radio signals through arbitrary 3D density/index-of-refraction profiles
    - e.g. n(z) = 1.78 – A exp(-z/B)
- but also
  - Shower development itself also in medium with changing density





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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)

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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

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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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