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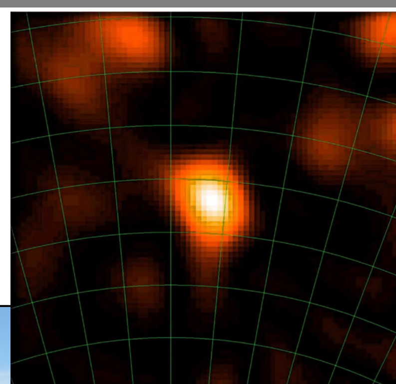
Next-generation CORSIKA and radio simulations

Tim Huege (Karlsruhe Institute of Technology & Vrije Universiteit Brussel) for the radio community

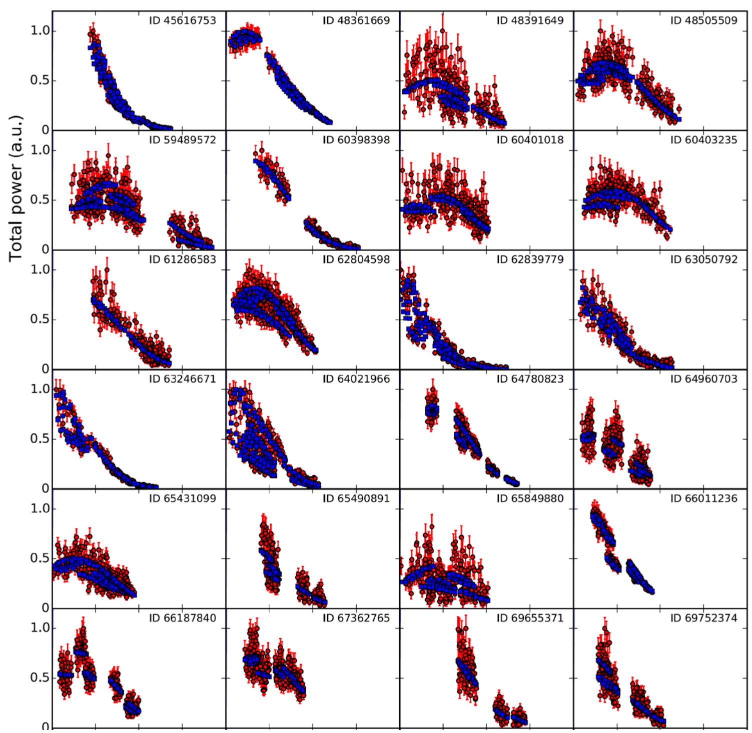



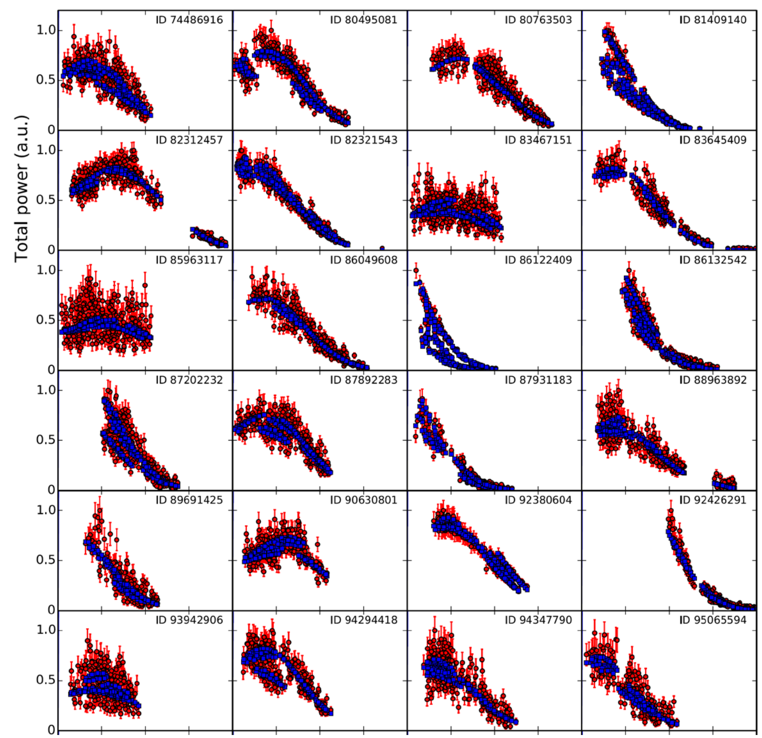



Radio in CORSIKA: CoREAS

- full Monte Carlo of the radio emission
- used by LOPES, CROME, Tunka-Rex, Auger, LOFAR, ARIANNA, …
- fully parallelized with MPI
- predictions in agreement with all measurements made so far

TH al., arXiv:1301.2132





Buitink et al., Nature

CoREAS: Shower sim plus endpoint formalism

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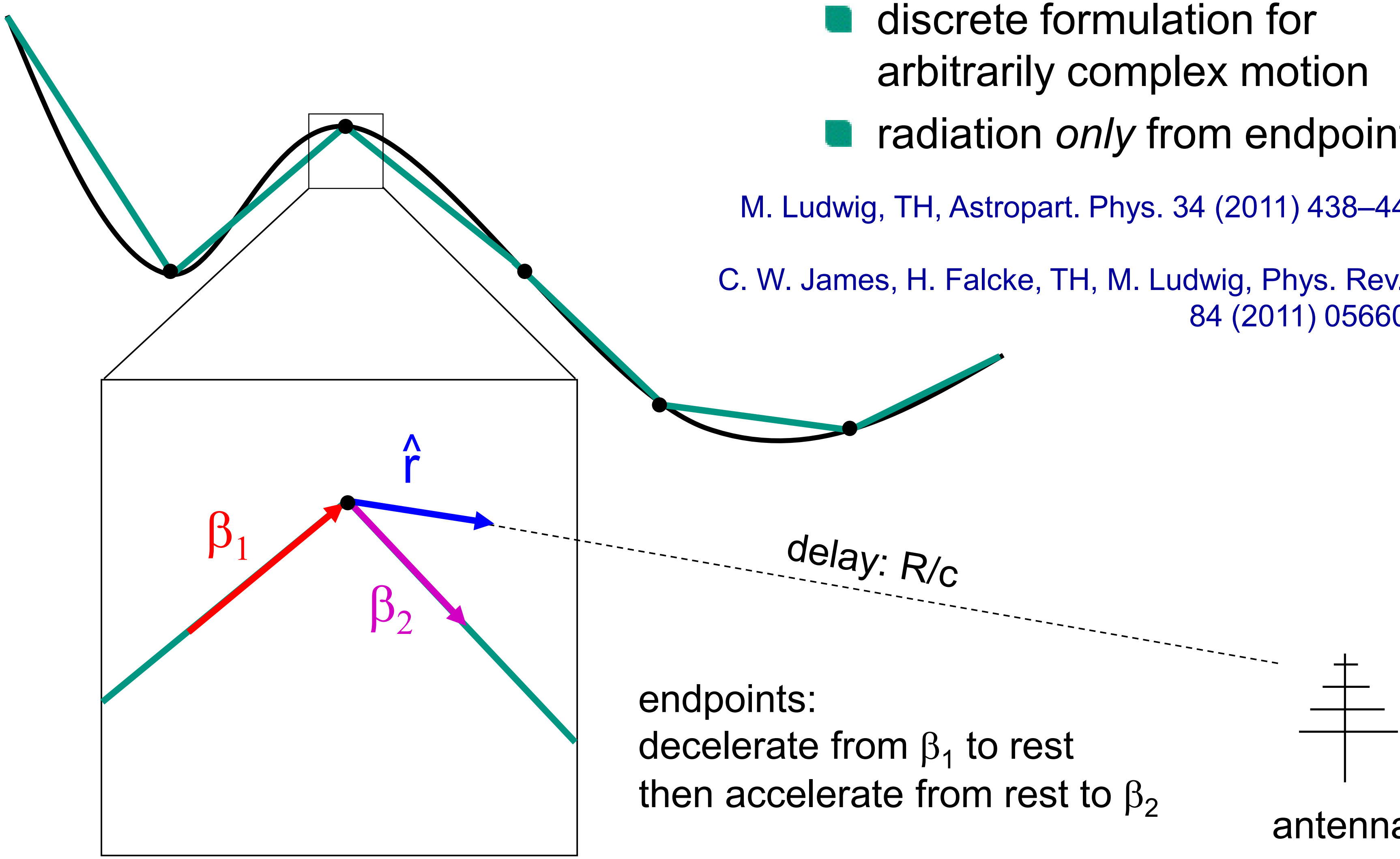
- discrete formulation for arbitrarily complex motion
- radiation *only* from endpoints

M. Ludwig, TH, Astropart. Phys. 34 (2011) 438–446.

C. W. James, H. Falcke, TH, M. Ludwig, Phys. Rev. E 84 (2011) 056602.



endpoints:
decelerate from β_1 to rest
then accelerate from rest to β_2

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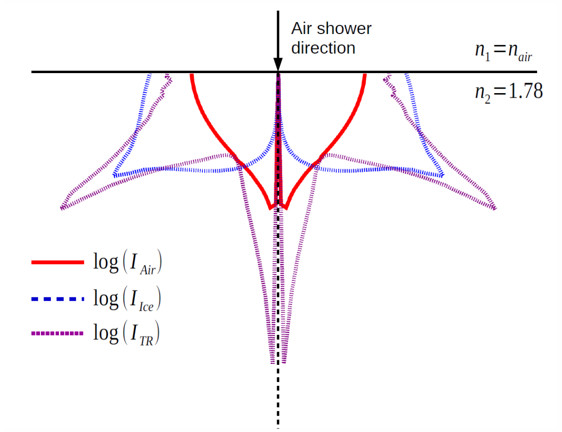
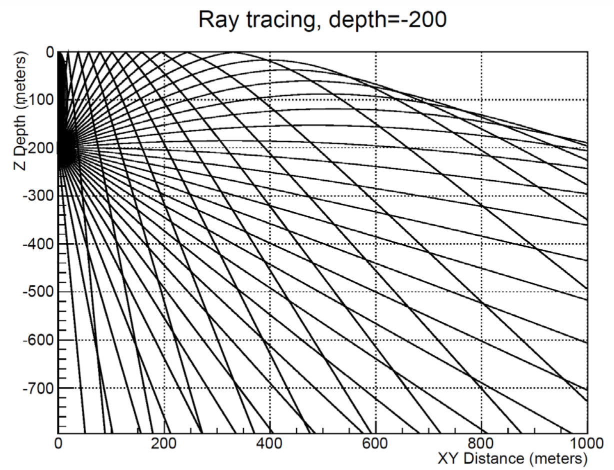
Limitations of current radio simulations

- the atmosphere is too limited, need transition to dense media
  - in particular for in-ice radio detection of neutrinos



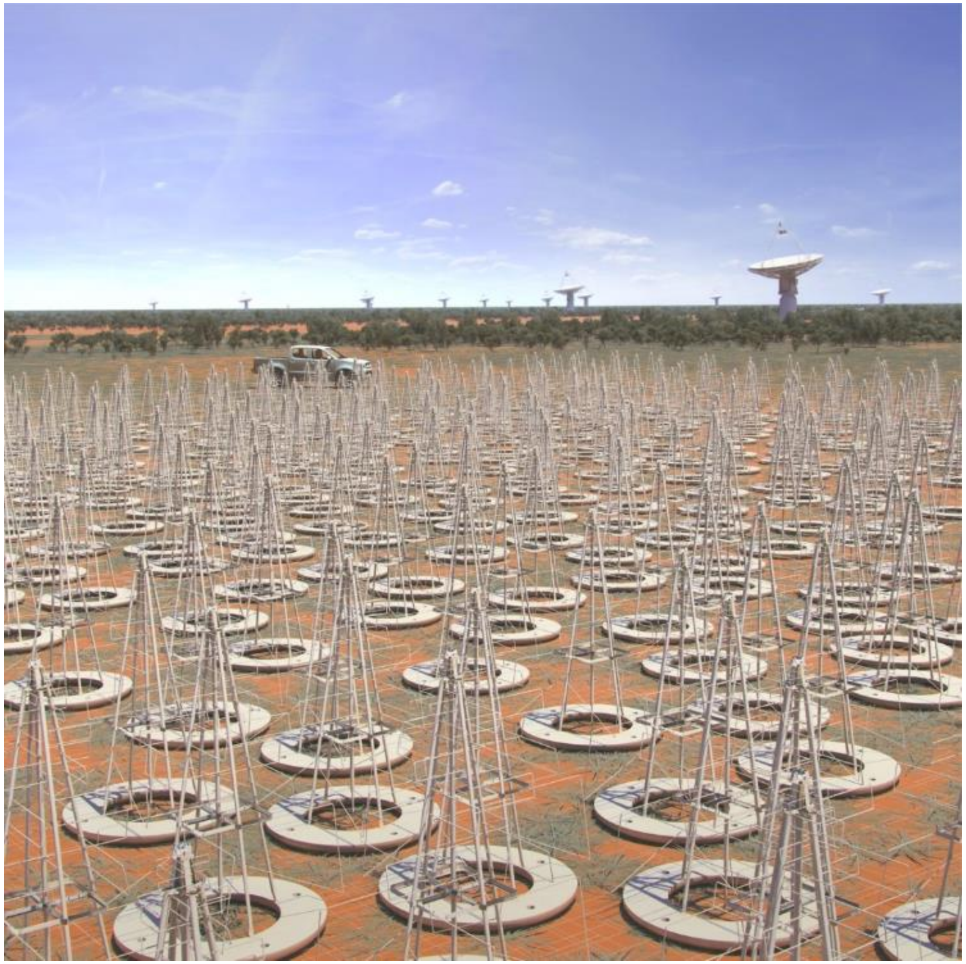
K. de Vries et al., arXiv:1503.02808



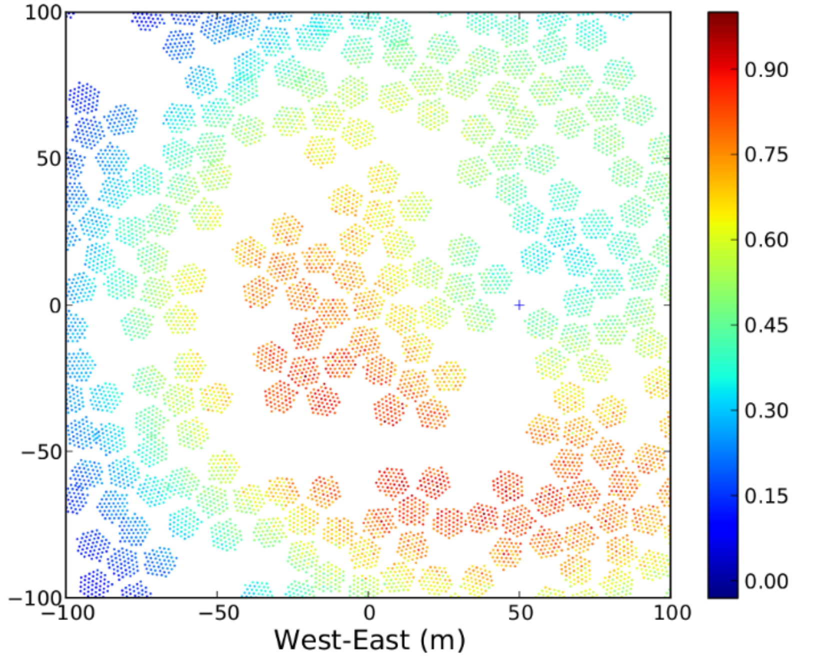
S. Barwick et al., arXiv:1804.10430

- in general, the geometry needs to be more flexible
- need refraction during wave propagation in refractive index gradients
- computation times can be very long (many antennas)
  - could be overcome by GPU parallelisation

Simulations for very dense antenna arrays



- ~70,000 dual-polarized antennas within 750 m diameter



TH et al., ARENA2016 conference, arXiv:1608.08869

Discussion within radio – Requirements 1

- 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?

Discussion within radio – Requirements 2

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- 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)

Discussion within radio – Useful features

- 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, …)

Discussion within radio – Wishlist

- 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

Envisioned implementation of radio

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- 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

Synergies with existing software

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- Several ideas/solutions might be portable from CRPropa3 to CORSIKA next gen.
  - Well written modular C++ code
  - Arbitrary modules act on particles
  - supports 3D density fields
  - Shared memory (implemented) as well as MPI (possible in user space) parallelization
  - https://github.com/CRPropa/CRPropa3
- GEANT4/5/6
  - So far GEANT supports only energies below 1PeV

Peer-reviewing of code

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- Define a scheme of how reliable a certain functionality is
  - Core functionality implemented by maintainers
  - Contributed functionality that has been peer-reviewed in the community
  - Non-peer-reviewed contributed functionality

Summary

- the radio community heavily relies on simulations
- the next-generation experiments run into limitations of CORSIKA
  - in-ice neutrino detection: atmosphere too limited
  - dense arrays: computing times too long
- radio should be part of next-generation CORSIKA from the start, and will directly benefit from the added flexibility and modularity