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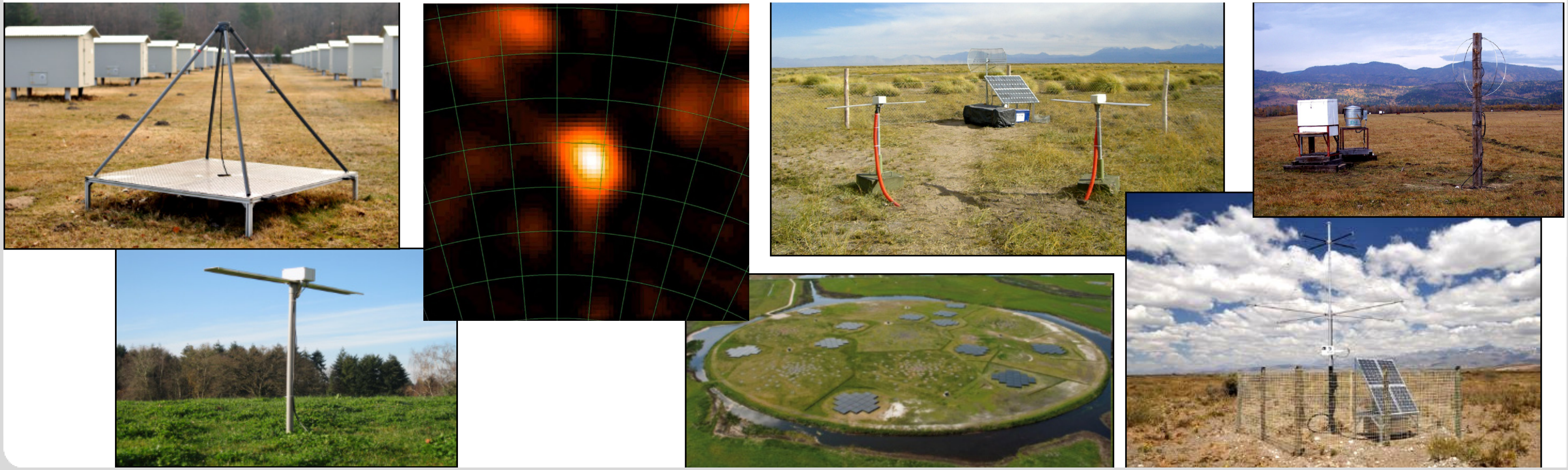
Simulation of radio emission from particle showers in CORSIKA 7 and CORSIKA 8

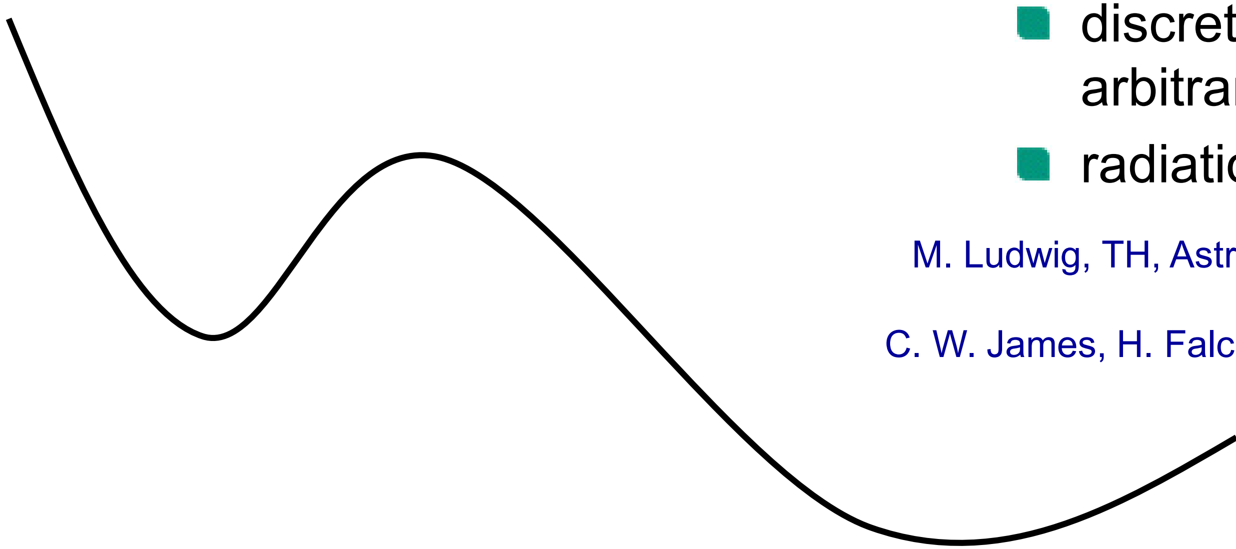
Tim Huege (Karlsruhe Institute of Technology & Vrije Universiteit Brussel) for the radio community



What is CoREAS?

- a C++ plugin to CORSIKA 7 using the COAST interface
  - fully integrated in the build system
- calculation of radio emission from EAS using the „endpoint formalism“

Discretization of particle motion: endpoints



- 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.

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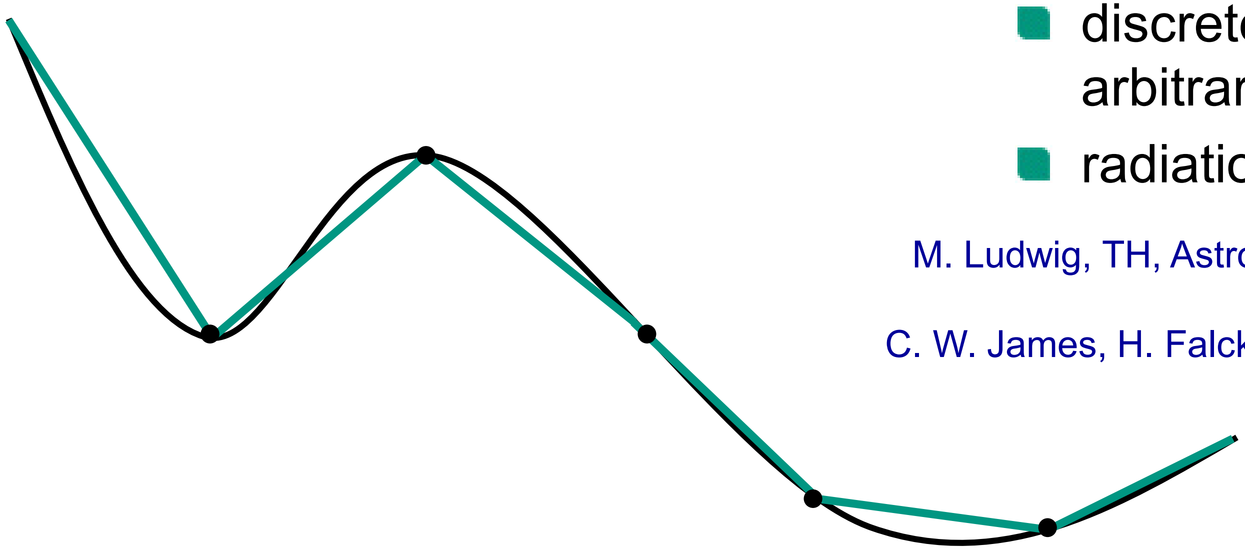

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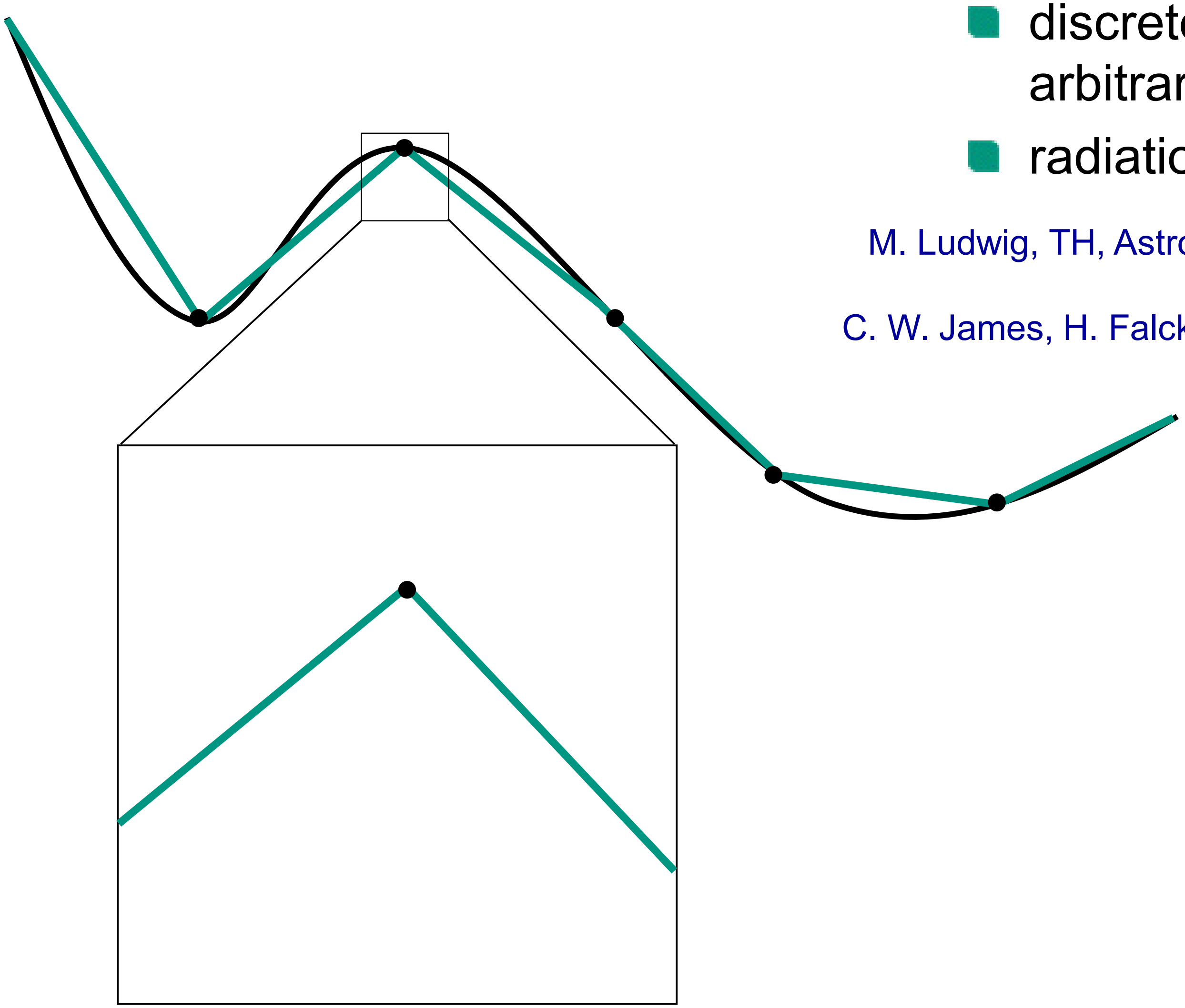

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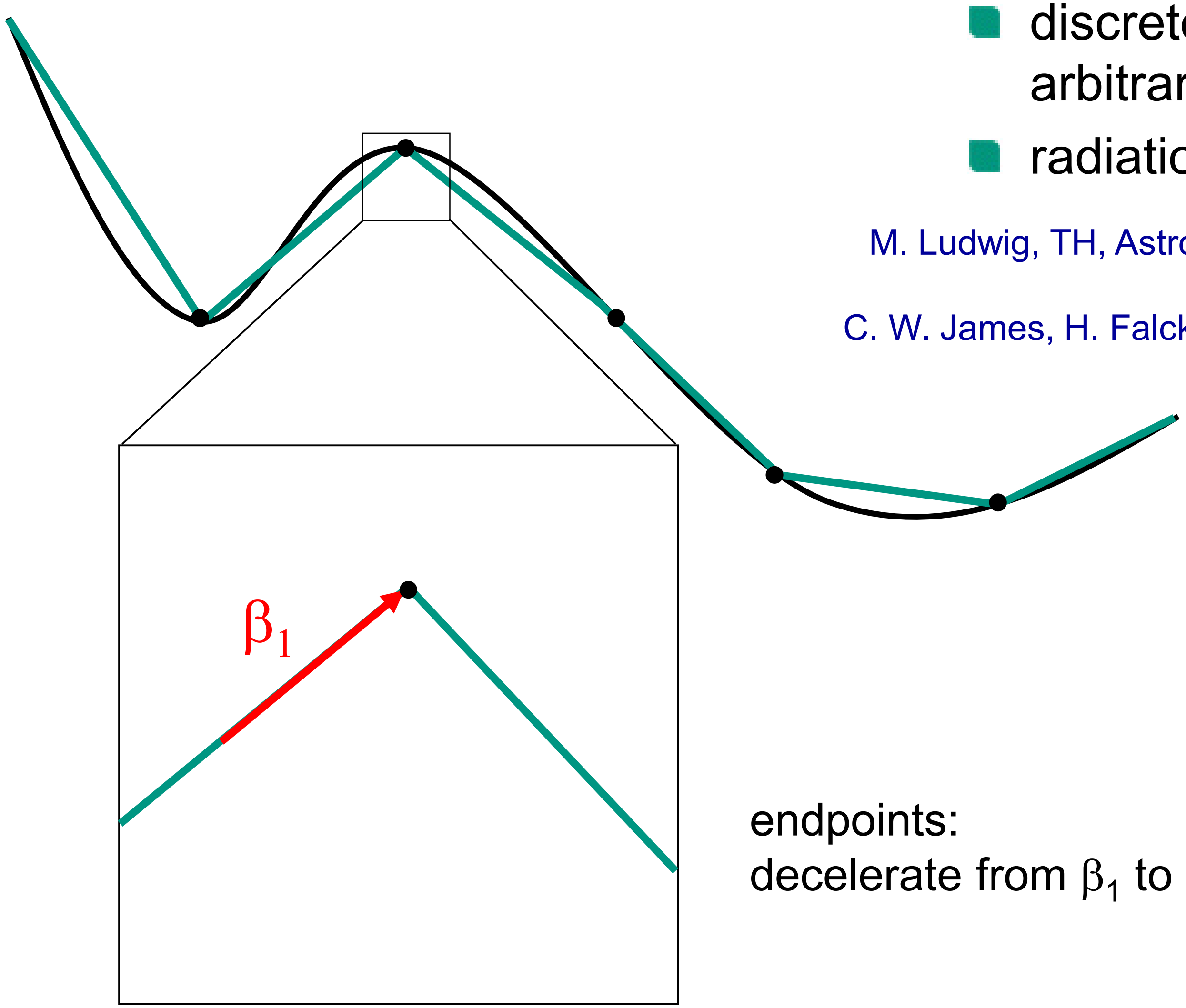

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endpoints:
decelerate from β_1 to rest

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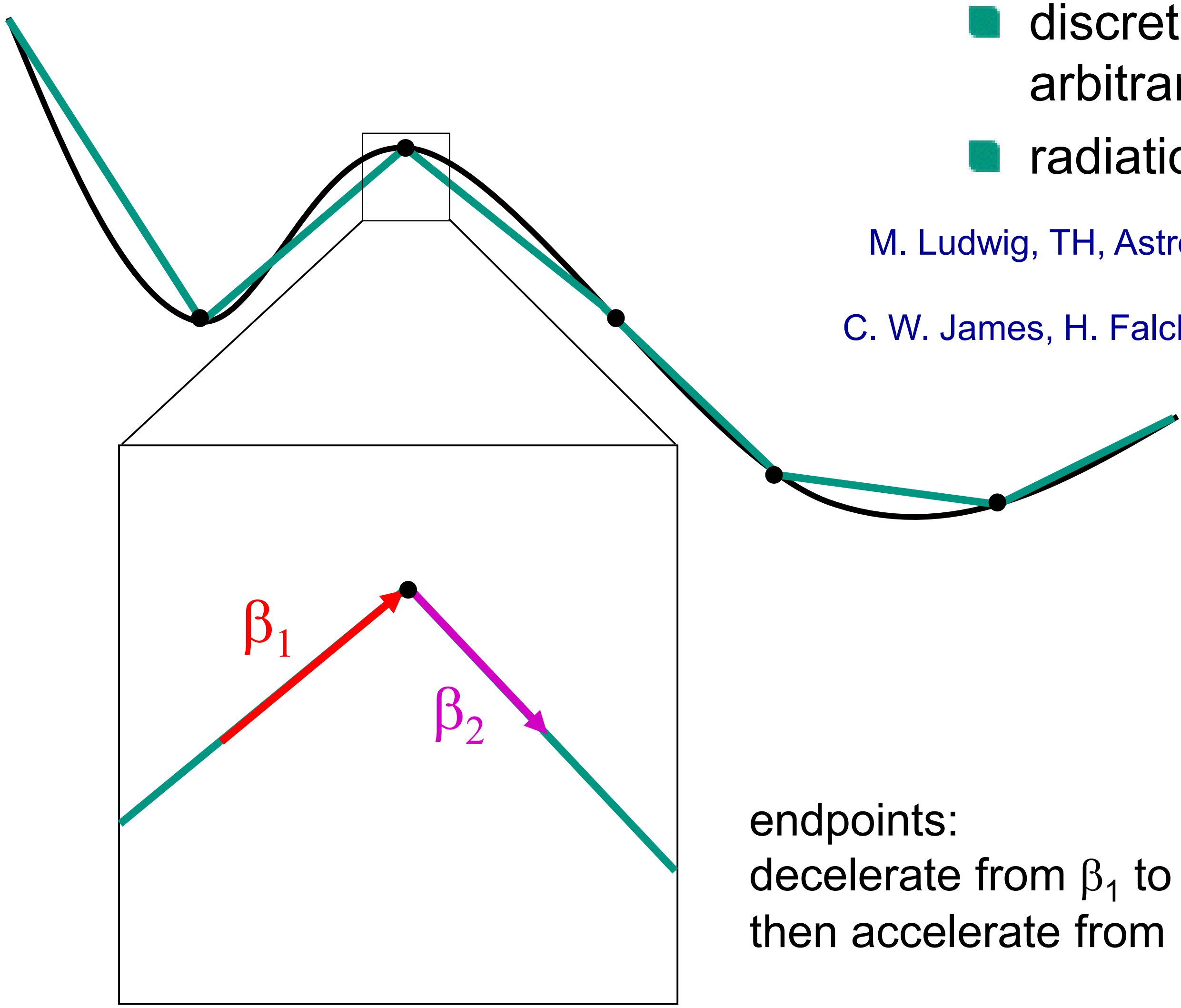

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endpoints:
decelerate from β_1 to rest
then accelerate from rest to β_2

Discretization of particle motion: endpoints

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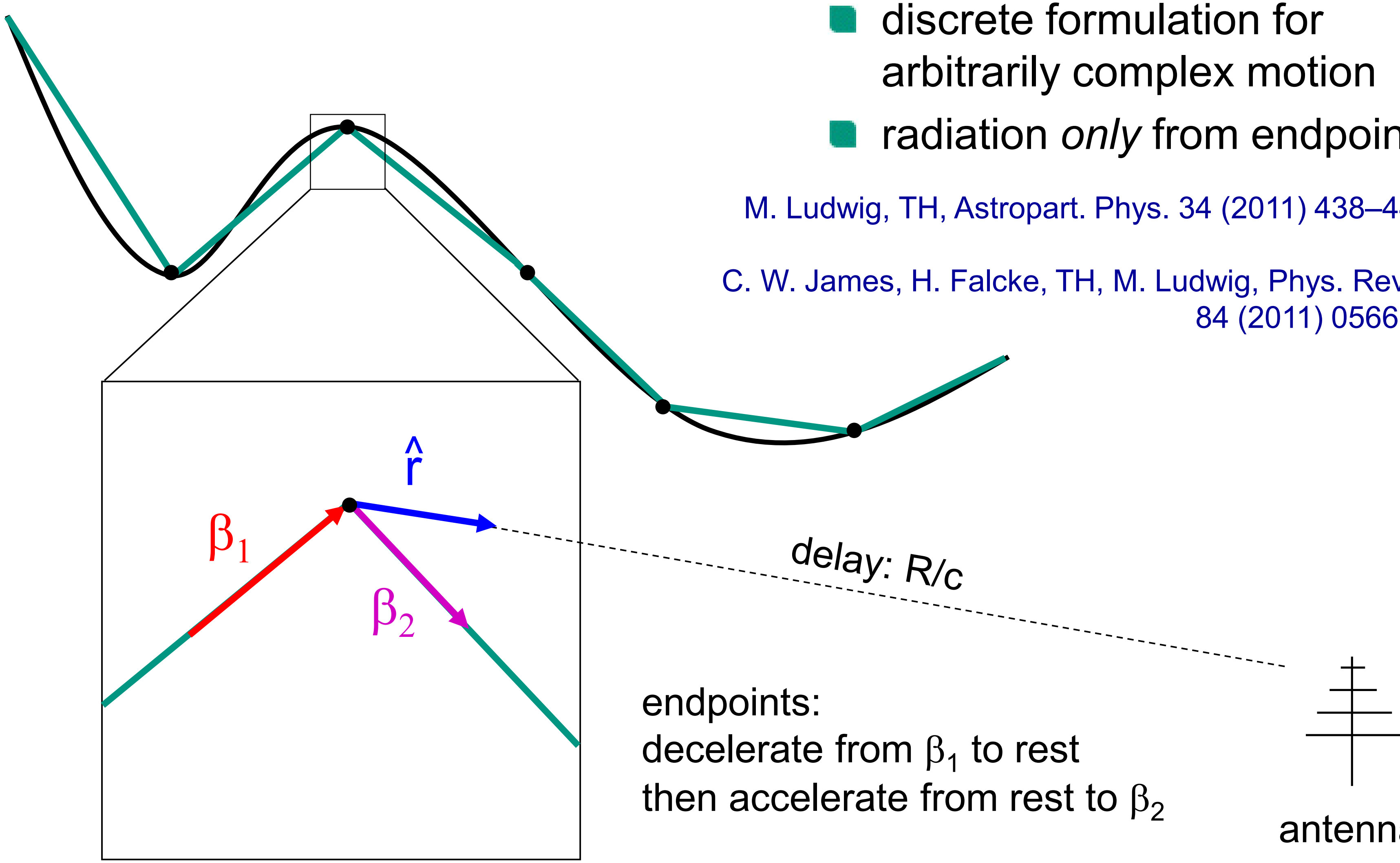

endpoints:
decelerate from β_1 to rest
then accelerate from rest to β_2

Radiation from a single endpoint

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- time domain formulation

$$\vec{E}_{\pm}(\vec{x},t) = \pm \frac{1}{\Delta t} \frac{q}{c} \left(\frac{\hat{r} \times [\hat{r} \times \vec{\beta}^*]}{(1 - n\vec{\beta}^* \cdot \hat{r})R} \right)$$

- frequency domain formulation

$$\vec{E}_{\pm}(\vec{x},\nu) \;=\; \pm \frac{q}{c} \frac{e^{ikR(t_0')}}{R(t_0')} \frac{e^{2\pi i \nu t_0'}}{1 - n\vec{\beta}^* \cdot \hat{r}} \hat{r} \times [\hat{r} \times \vec{\beta}^*]$$

\- for deceleration from β* to rest (stopping point)

\+ for acceleration from rest to β* (starting point)

What is CoREAS?

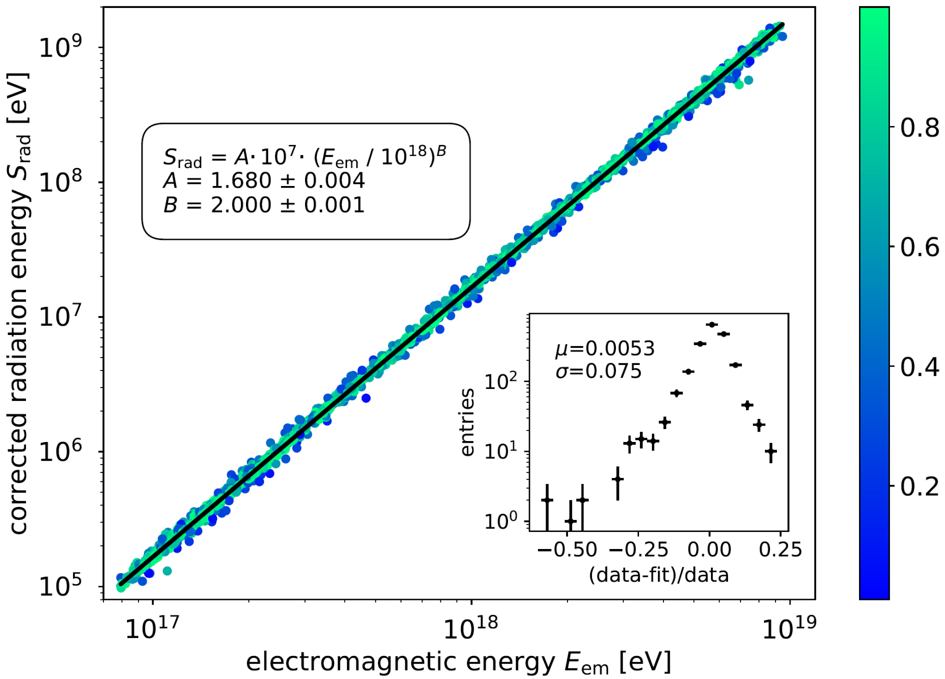
- a C++ plugin to CORSIKA using the COAST interface
  - fully integrated in the build system
- calculation of radio emission from EAS using the „endpoint formalism“
  - downgoing showers in curved and flat geometries fully supported
  - upgoing and skimming geometries untested
- ASCII output of electric field traces per antenna
  - also: HDF5 converter for processed data and better simulation handling
- full MPI parallelization up to thousands of cores
- gdastool: simulate with realistic atmosphere at given time and location, including effects of atmospheric humidity

Tim Huege <tim.huege@kit.edu>

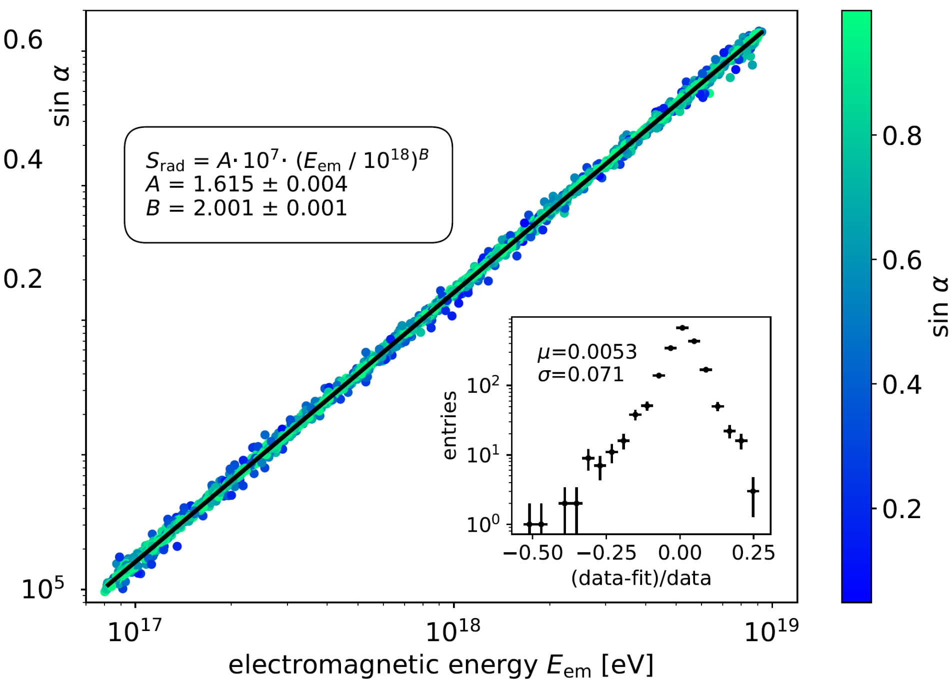
Other codes

- ZHAireS: radio emission calculation in AireS using the ZHS formalism („radio emission from straight track segments“)
- SELFAS: radio emission calculation based on shower universality

Comparison of CoREAS and ZHAireS



CoREAS, **16.8 MeV** radiation
@ 10^{18} eV electromagnetic energy



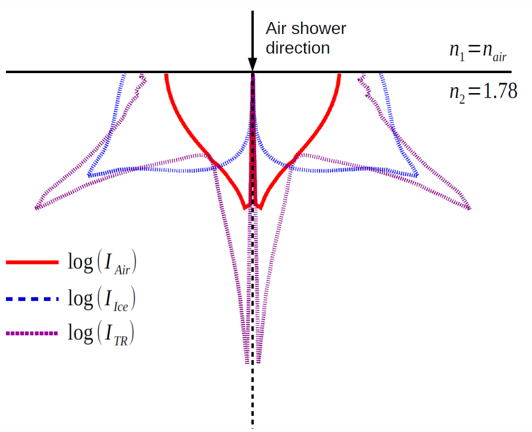
ZHAireS, **16.15 MeV** radiation
@ 10^{18} eV electromagnetic energy

- absolute prediction of radiation energy agrees within 5.2% between two independent full Monte Carlo simulations, use for absolute calibration!

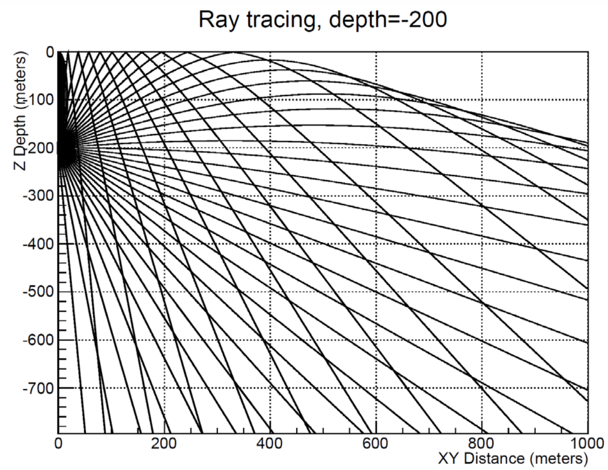
Gottowik, Glaser, Huege, Rautenberg, Astroparticle Physics 103(2018)87

Limitations of CoREAS in CORSIKA 7

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



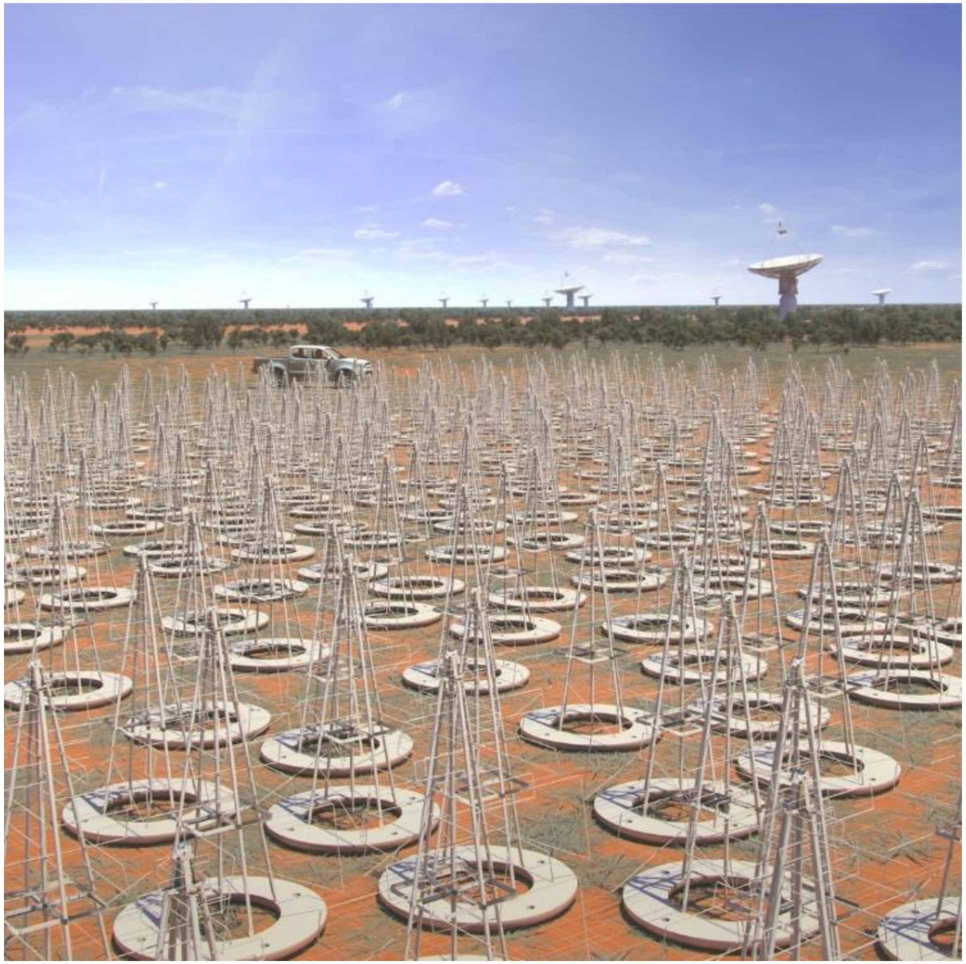
K. de Vries et al., arXiv:1503.02808



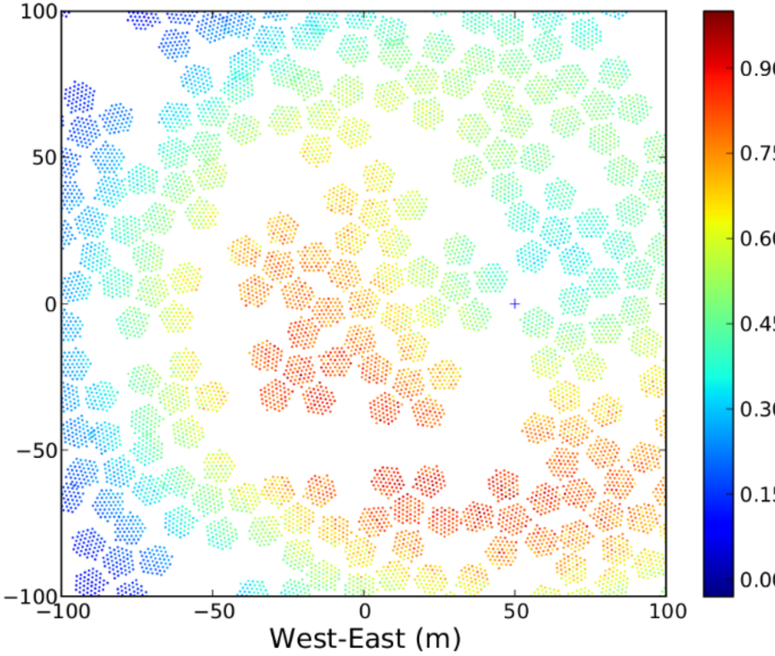
S. Barwick et al., arXiv:1804.10430

- 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

Requirements for radio in CORSIKA 8 (I)

- 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?

Requirements for radio in CORSIKA 8 (II)

- 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

Requirements for radio in CORSIKA 8 (III)

- 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

Wishlist for radio in CORSIKA 8

- 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

(My) plans for radio in CORSIKA 8

- provide same functionality as current CoREAS, but provide flexible basis for adding further capabilites
- port endpoint formalism from CoREAS:
  - simple - as soon as an electromagnetic interaction model is available
- possibly also port ZHS and SELFAS formalisms for direct comparisons and investigation of best suited formalism for GPU parallelisation
- parallelisation
  - work towards including MPI parallelisation early on
  - investigate GPU parallelisation
- foresee plugin of raytracing functionality for in-ice community
- output format based on HDF5, converter for CoREAS already exists

Envisioned implementation of radio

- 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

Summary

- the radio community heavily relies on simulations
- the next-generation experiments run into limitations of CORSIKA 7
  - in-ice neutrino detection: atmosphere too limited
  - dense arrays: computing times too long
- radio will be implemented in CORSIKA 8, and will directly benefit from the added flexibility and modularity

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