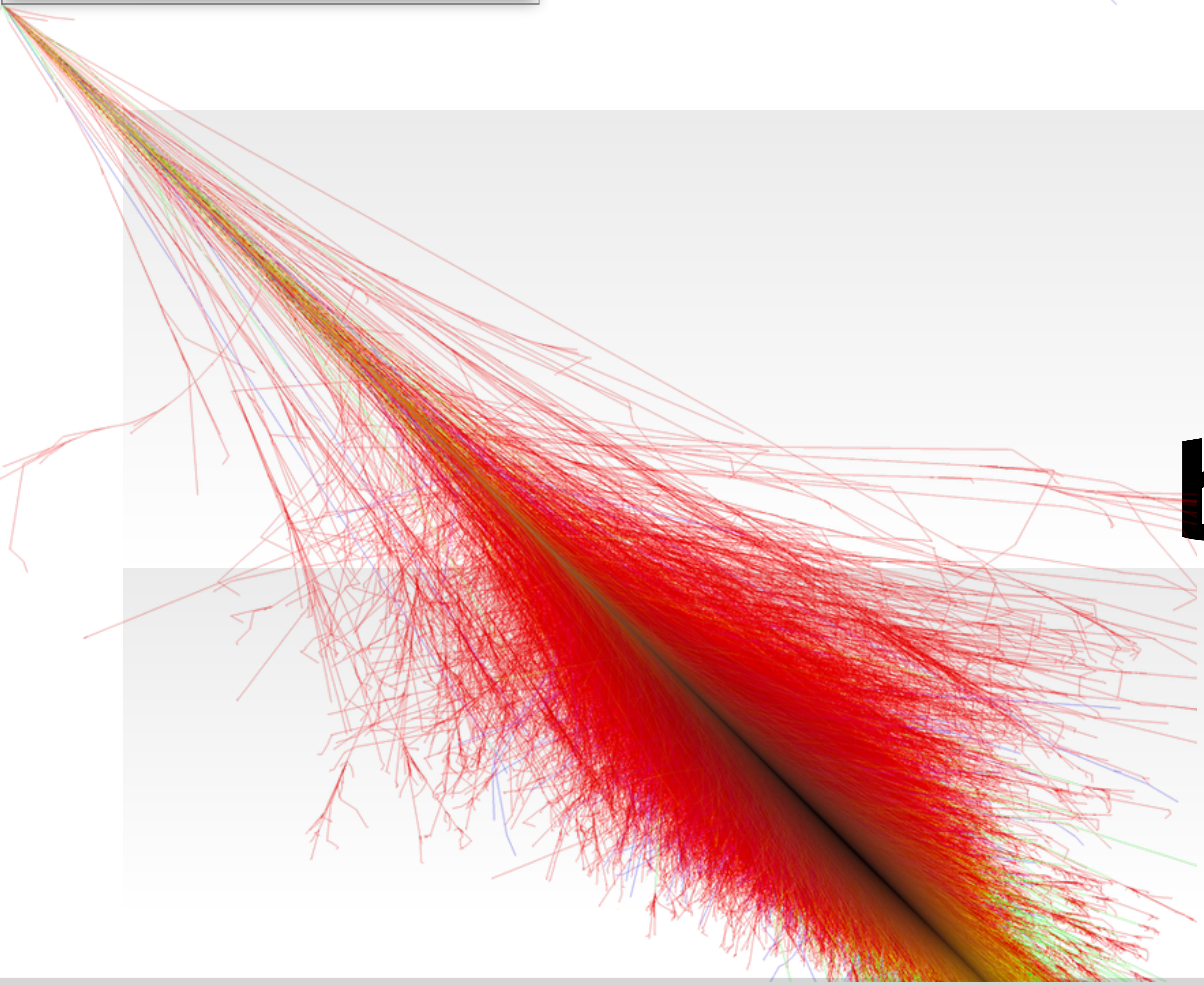

CORSIKA 8: particle cascades beyond air showers

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Supported by PAPIIT IN114924

Standard tool for Air Shower Simulation: CORSIKA 7

- Written in FORTRAN (various dialects)
  - Started over 30 years ago
  - Hand optimized
  - Code options through conditional compilation
  - Design limitation hard to overcome
  - Key developers retired, skills limited in new generation of developers
    - Python or C++

- Some problems require complicated pipelines

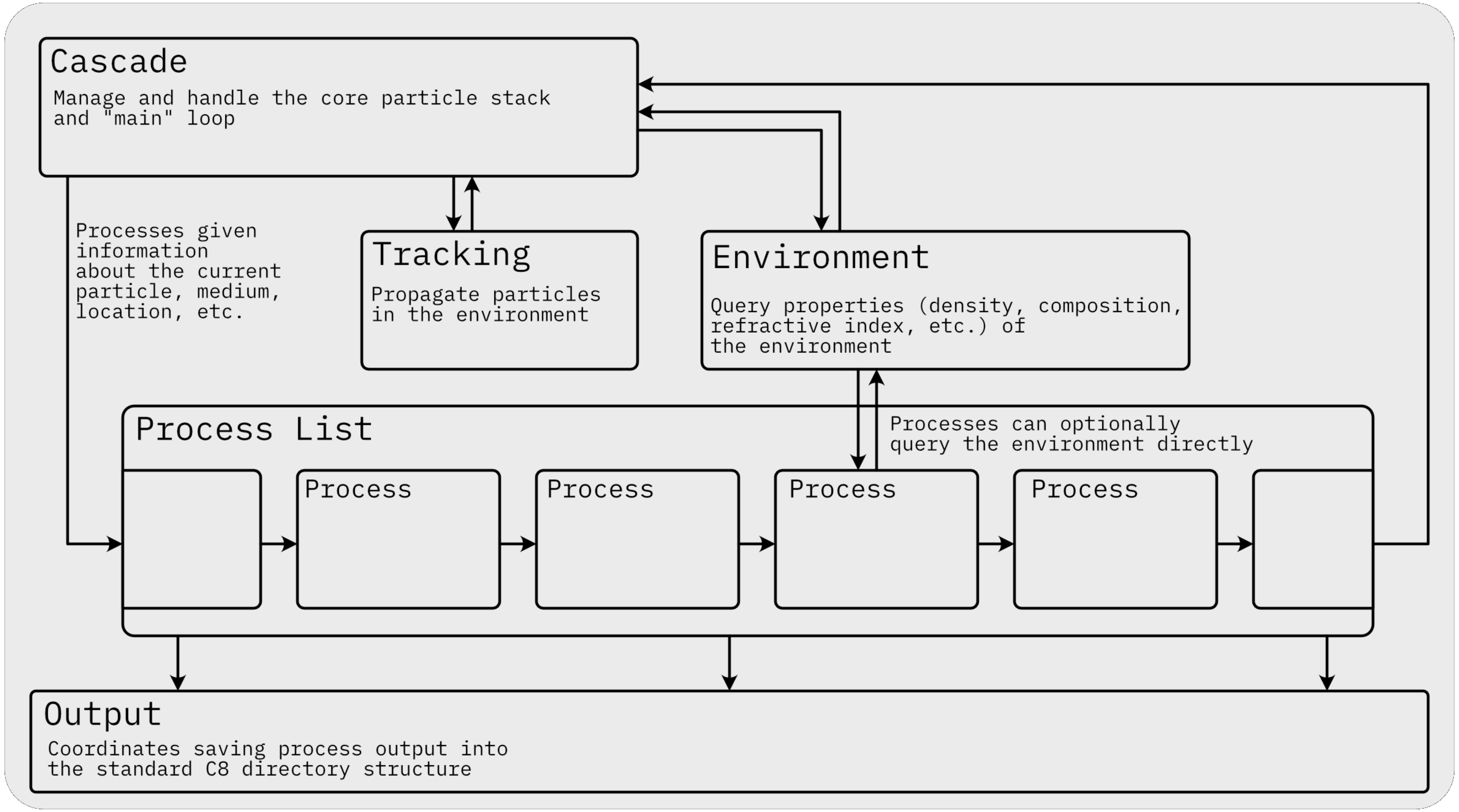
- Successor needed

The importance of a well designed, standard tool

- Focus on discussion of science
  - Avoid war about tools
- Well designed tool avoids "accidents"
- Documentation and community experience help everybody

CORSIKA 8

- Project started in 2018
- Designed as framework
  - Simplify extension
  - Specialize on large geometries (Atmosphere!)
- Use modern C++
- Anticipate use on modern High-performance computers
  - Parallelism (MPI) and multi-threading
- Development is community effort



Project Status

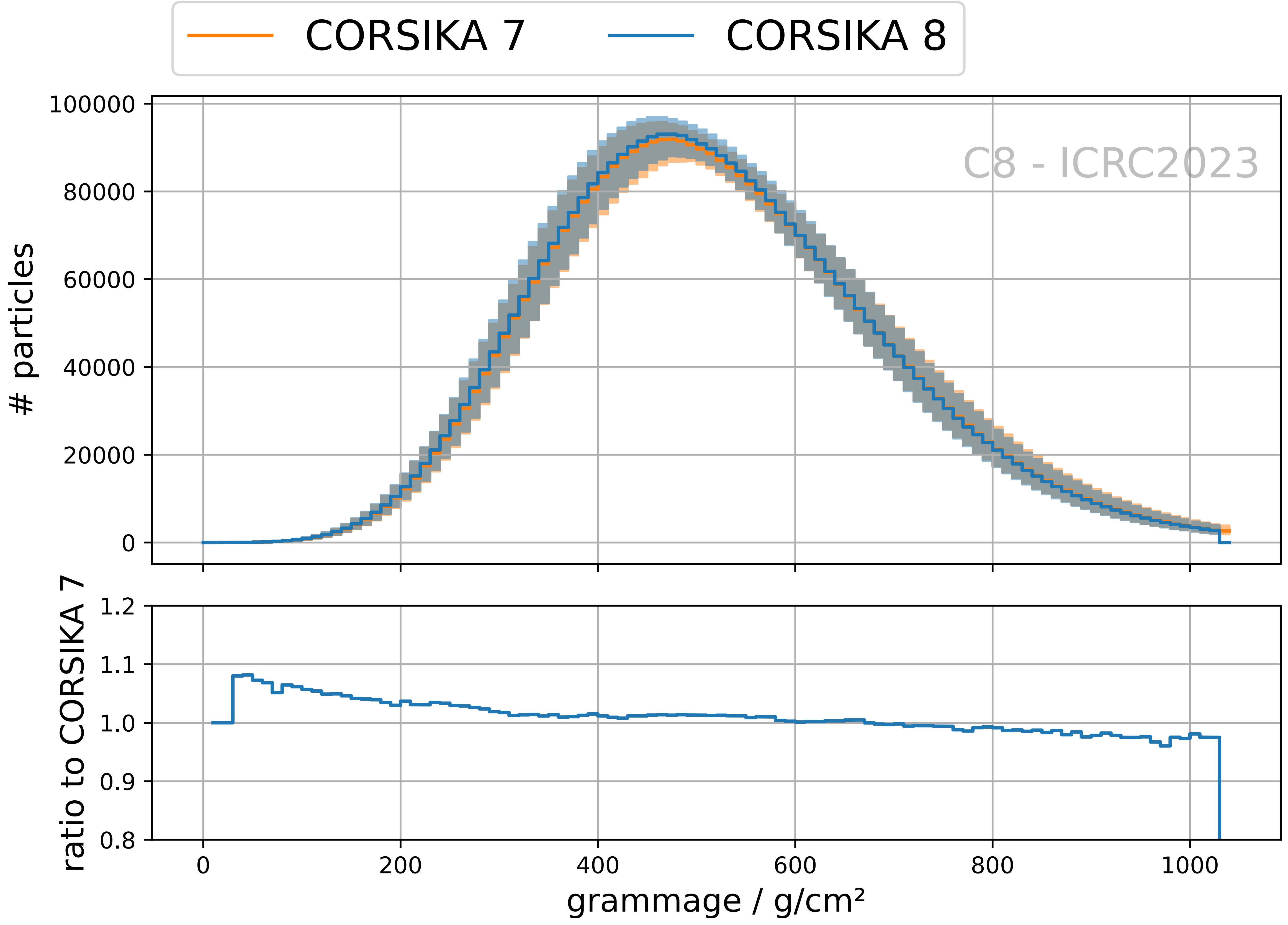
- Physics complete:
  - Can simulate EM and hadronic air showers
  - Radio, Cherenkov and Fluorescence emission
- Important or new features
  - High energy models: EPOS, QGSJet, Sibyll, Pythia 8.3 (testing)
  - Low Energy model: FLUKA
  - PROPOSAL for EM interactions
    - Photohadronic interactions, LPM Effect
  - Particle Thinning
  - Cherenkov light emissions
  - Radio Emissions
  - Demonstrator: parallelized computation of Radio Emission
  - Simulation steering
- Validation against CORSIKA 7

Development activities

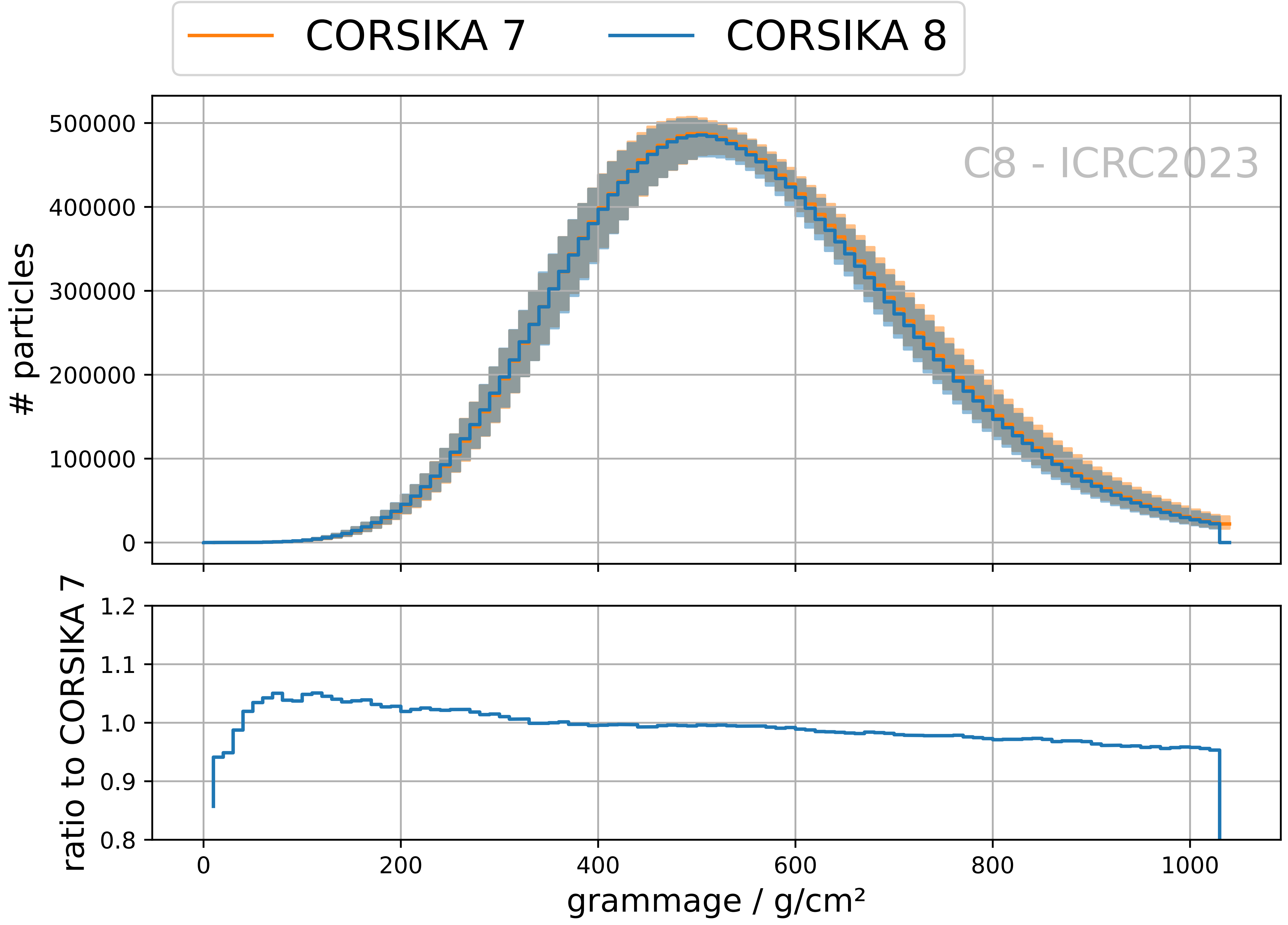
- Regular developer calls
- Developer workshops
  - June 2023
  - September 2024
- Focussing on first beta release
  - Physics complete
  - Applications beyond CORSIKA 7
  - Still slow
- New collaborators welcome

KIT, June 2023

- ◉ PROPOSAL 7.6.2 (CORSIKA 7 uses modified EGS)



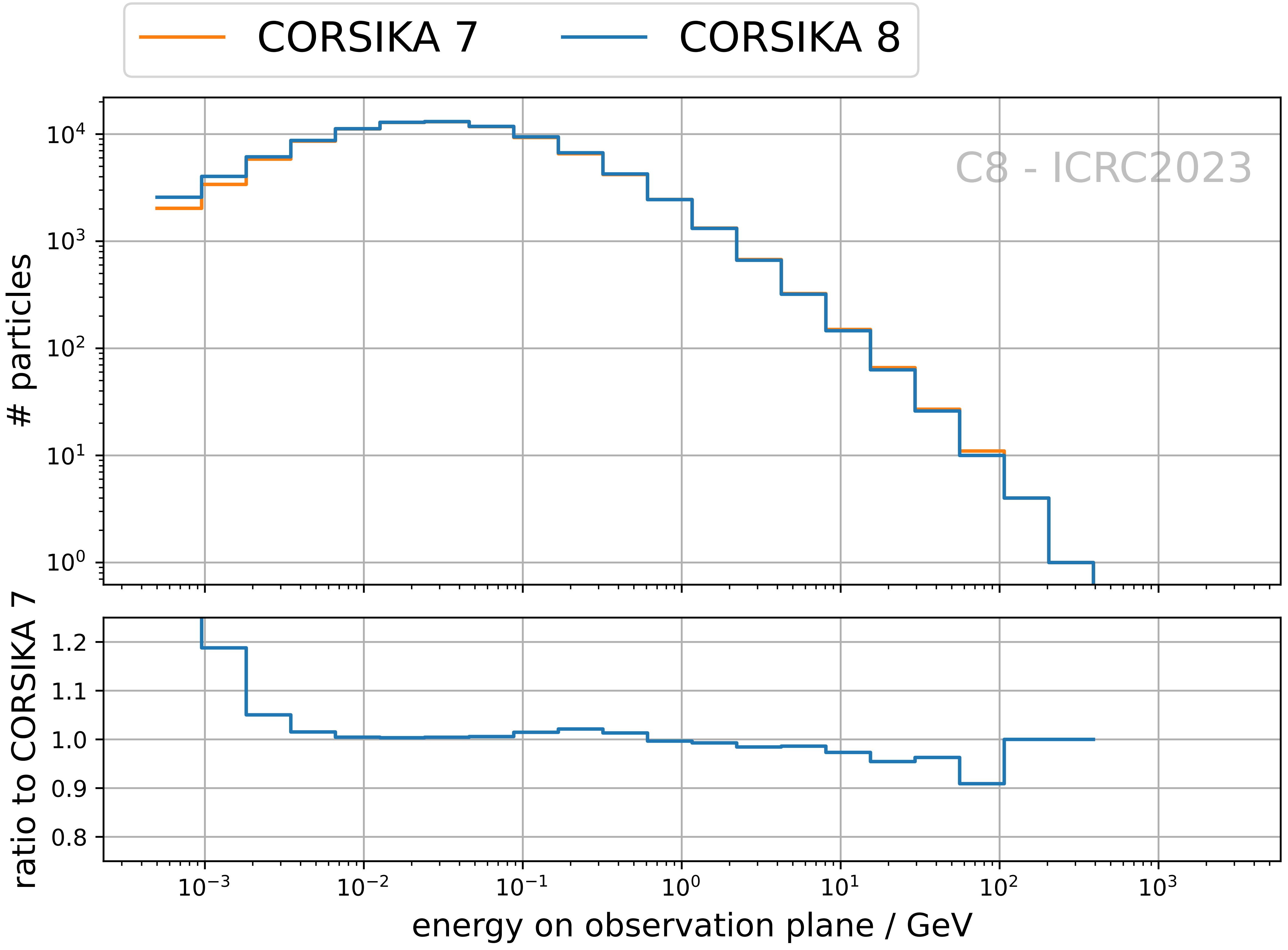
Longitudinal Profile (charged particles)



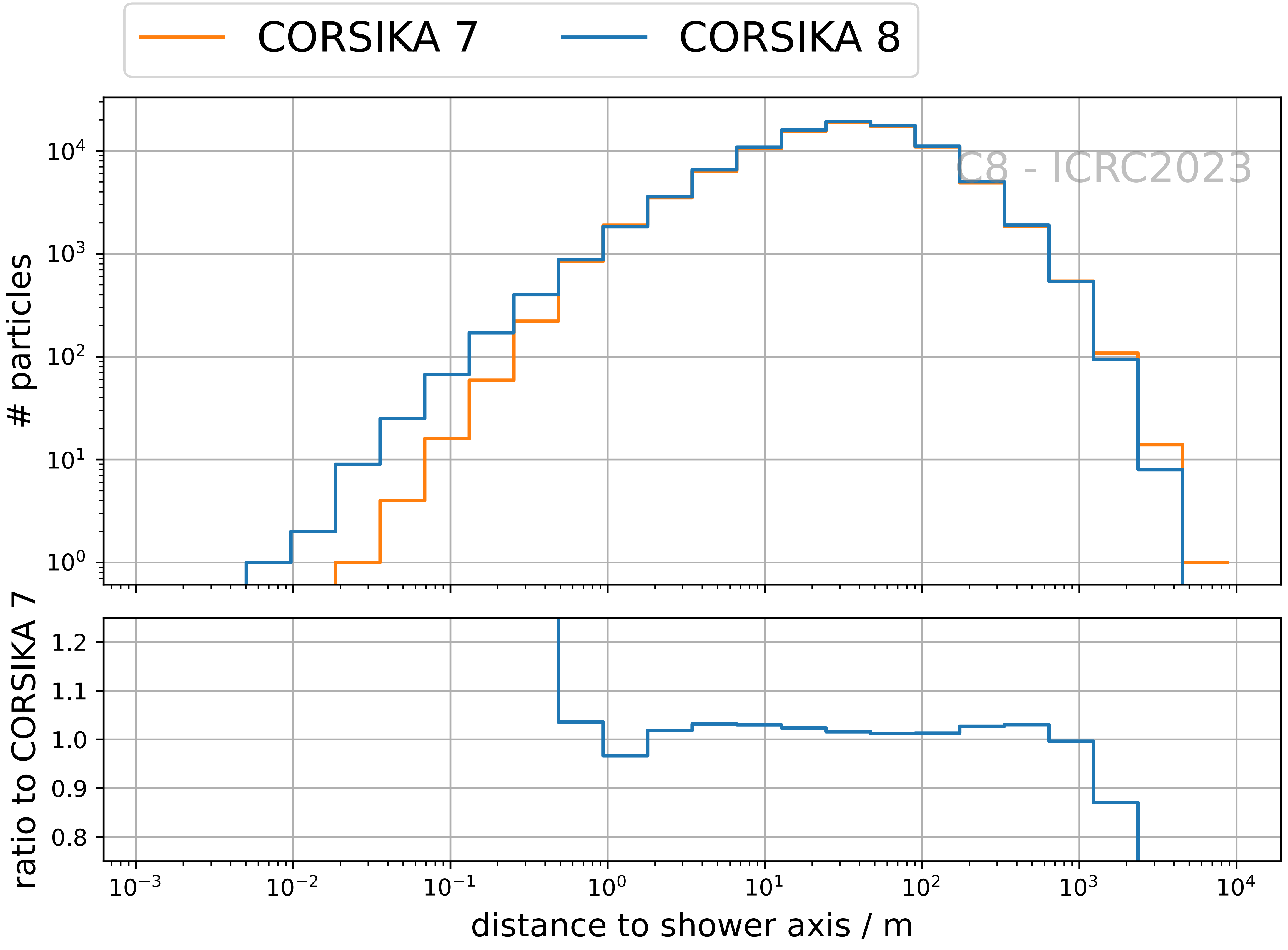
Longitudinal Profile (photons)

EM cascade

- PROPOSAL 7.6.2 (CORSIKA 7 uses modified EGS)



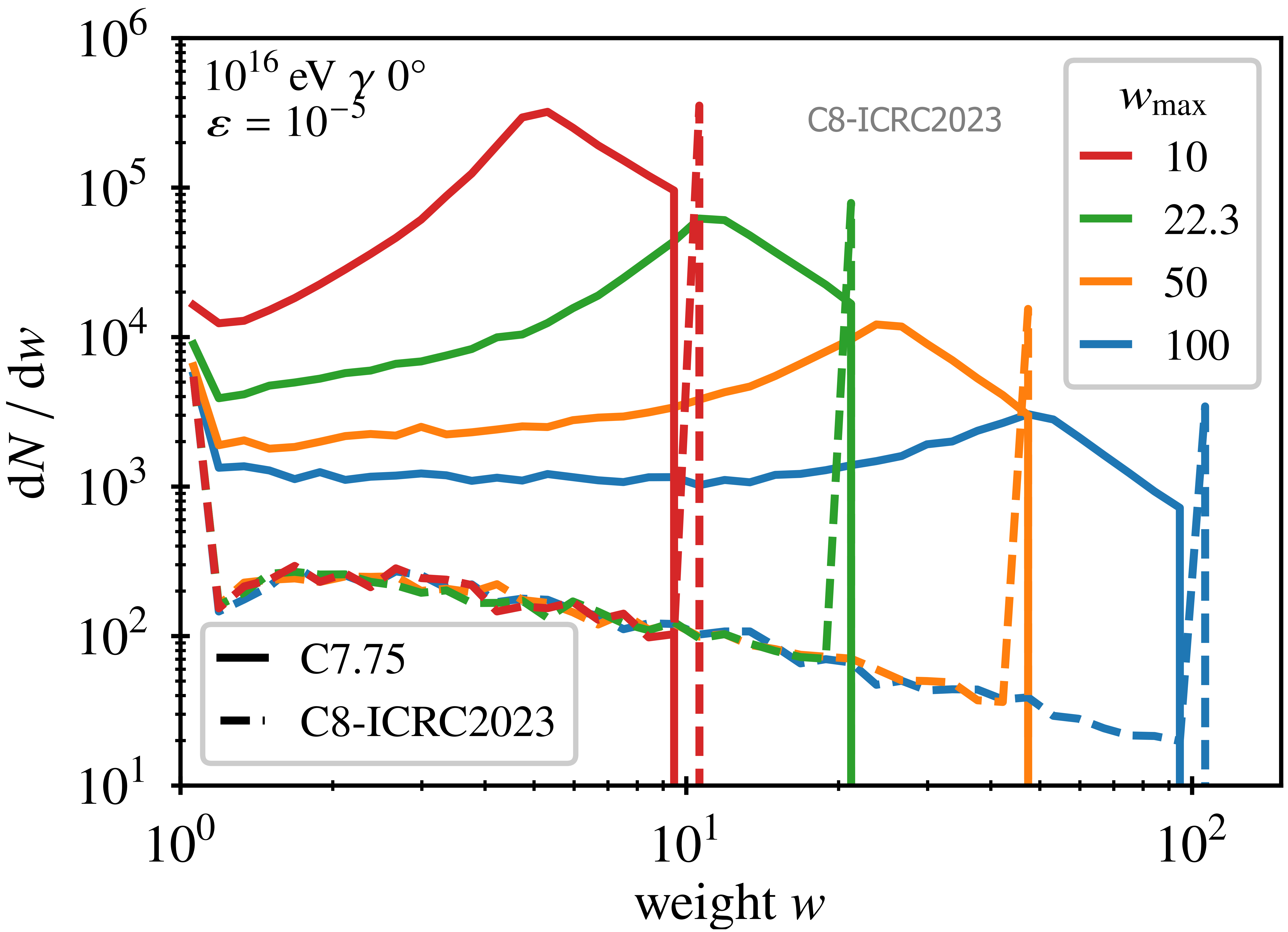
Charged Particles: Energy Spectrum



Charged Particles: Lateral Distribution

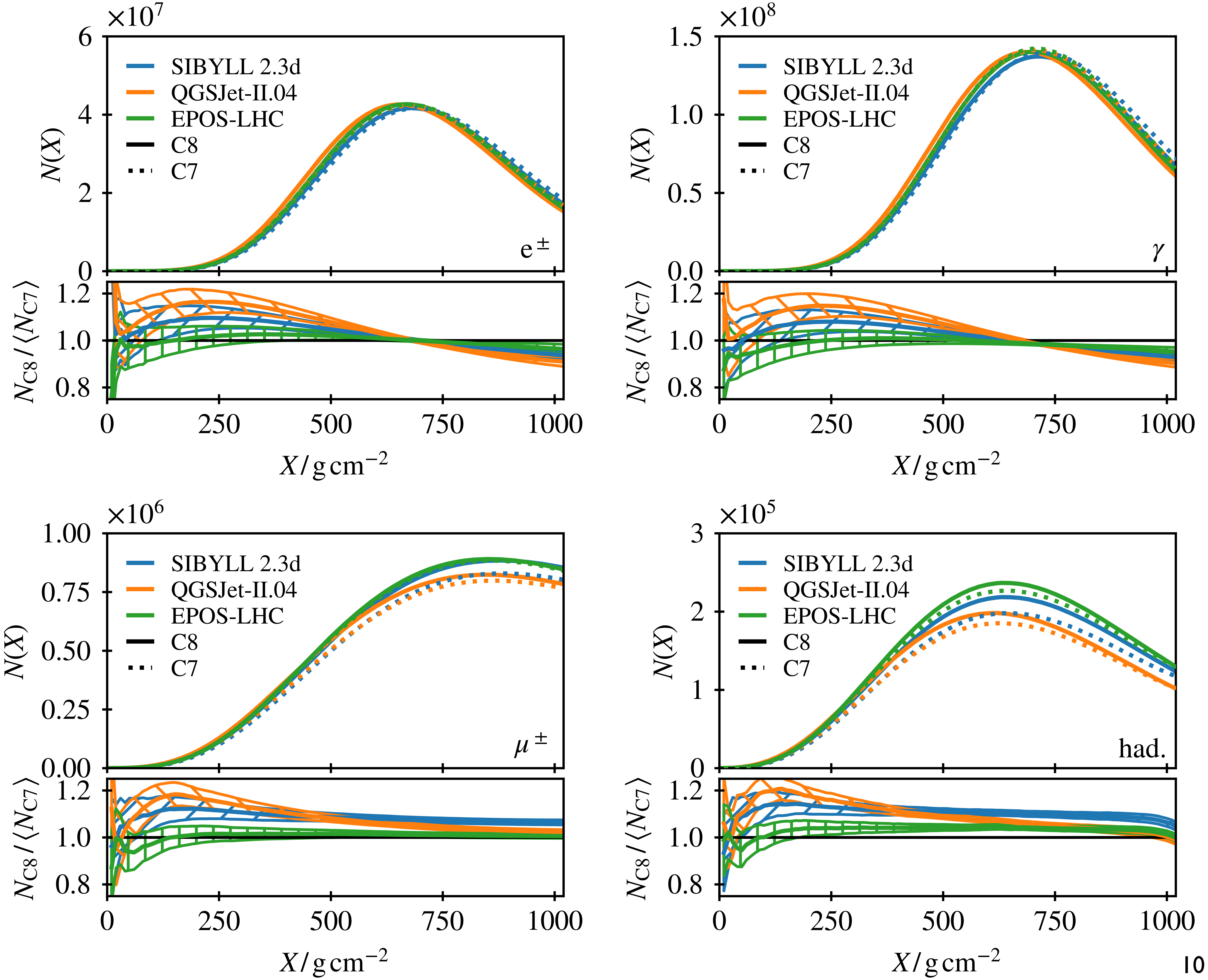
Thinning (EM Cascade)

- New algorithm, mixes
  - Hillas Thinning (C7)
  - Statistical Thinning
- Narrower weight distributions
  - Most weights close to maximum allowed
  - Reduced artificial fluctuations



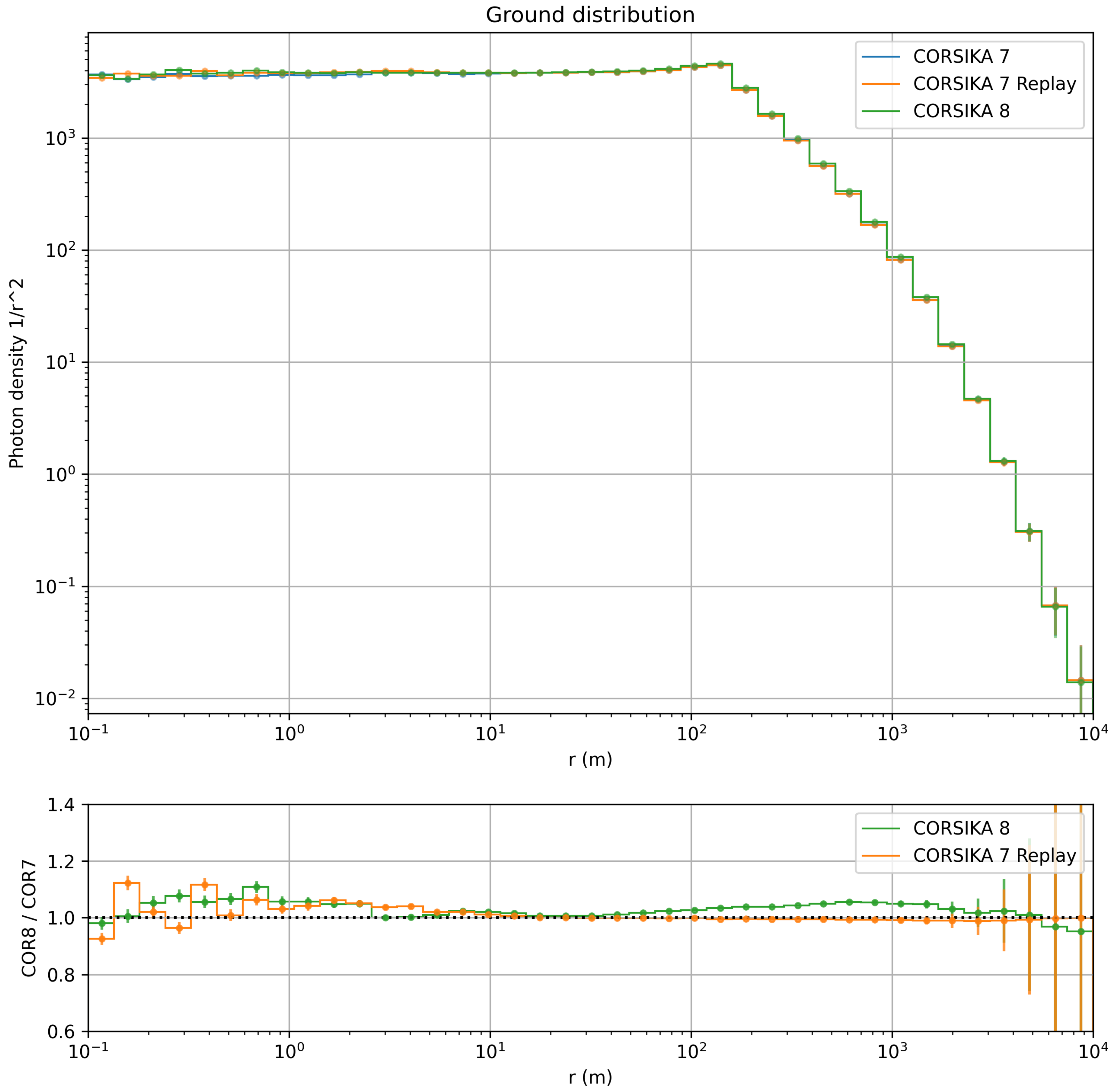
Hadronic showers

- Agreement C7 vs C8 ~ 10%
- Depends on interaction model
- More tests ongoing

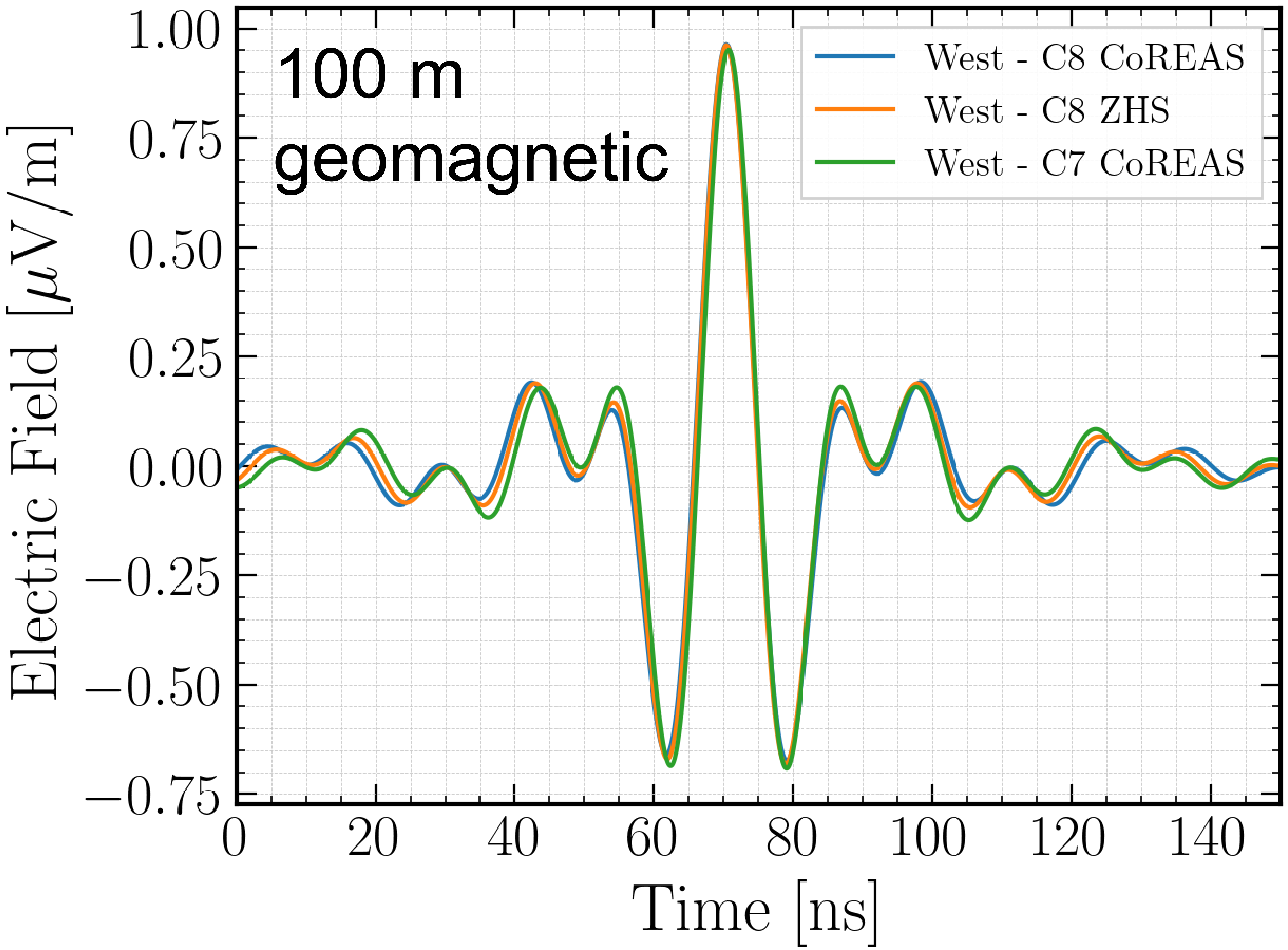


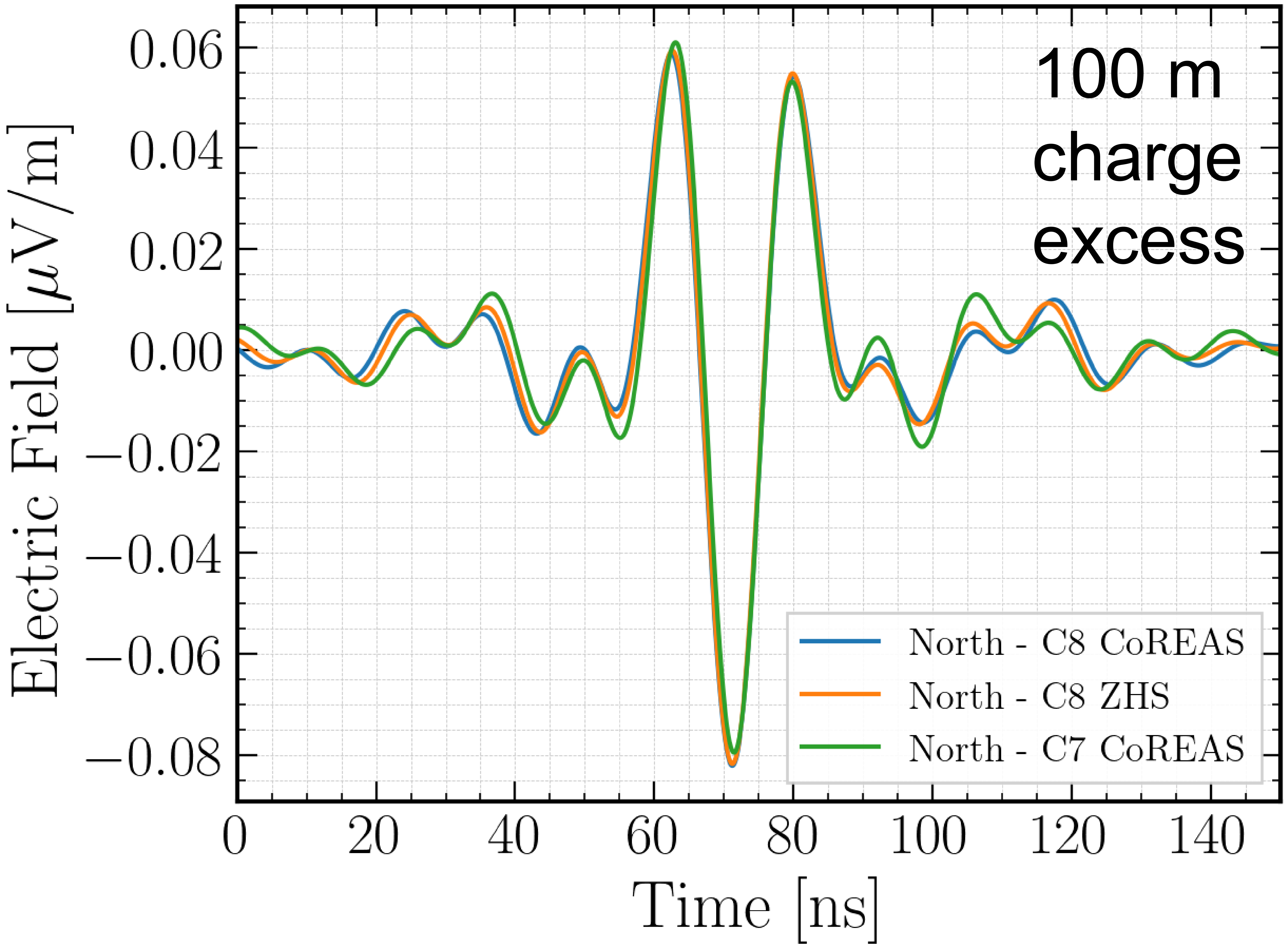
GPU accelerated light emission

- Fluorescence
  - Simplified, for testing and optimization
- Cherenkov
  - Optimizing phase space considered
  - Validated against C7
- Fully GPU-parallelized photon propagation available
  - Not yet integrated into CORSIKA 8



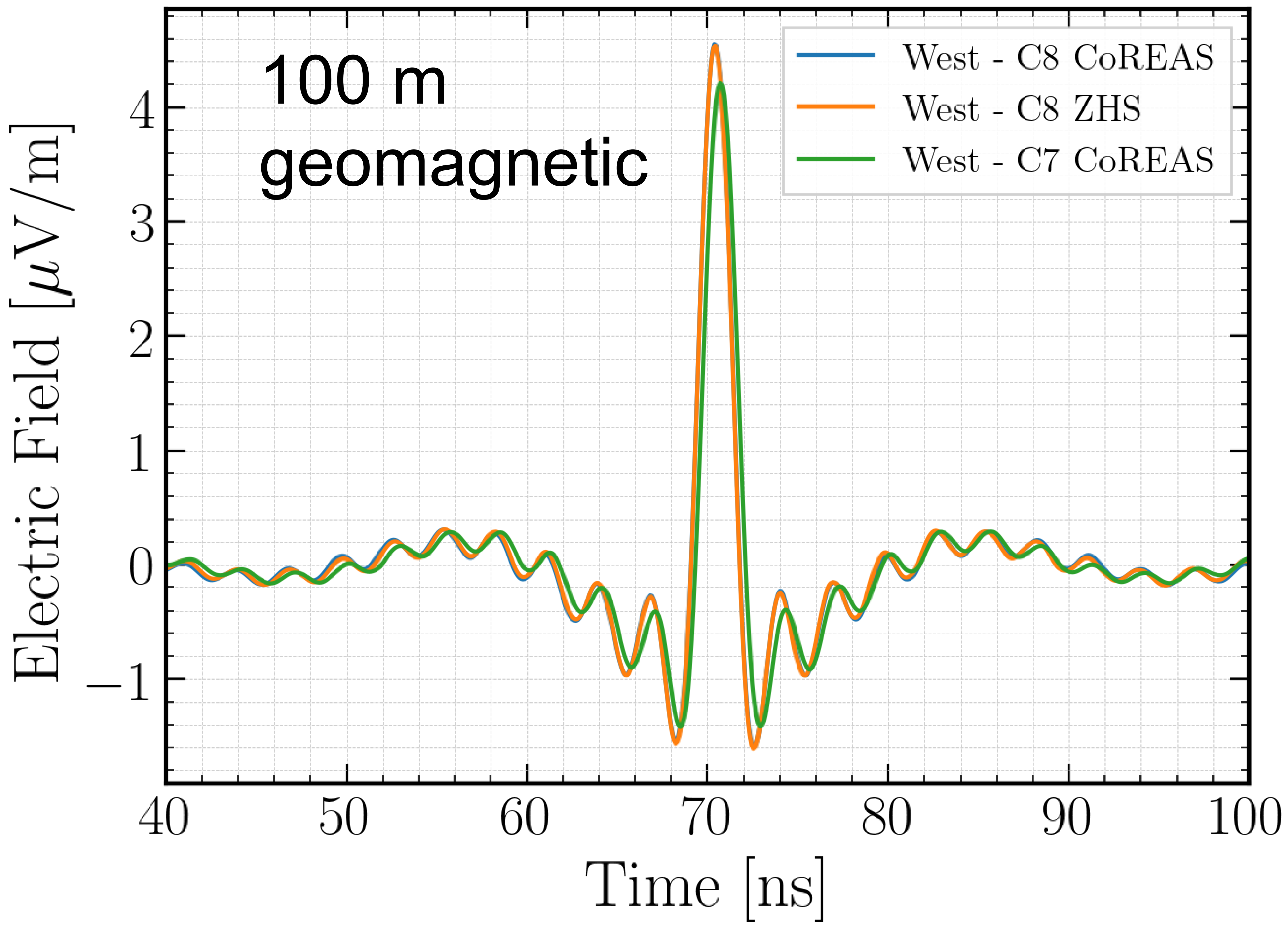
Pulses C8 vs C7, small steps, 30-80 MHz

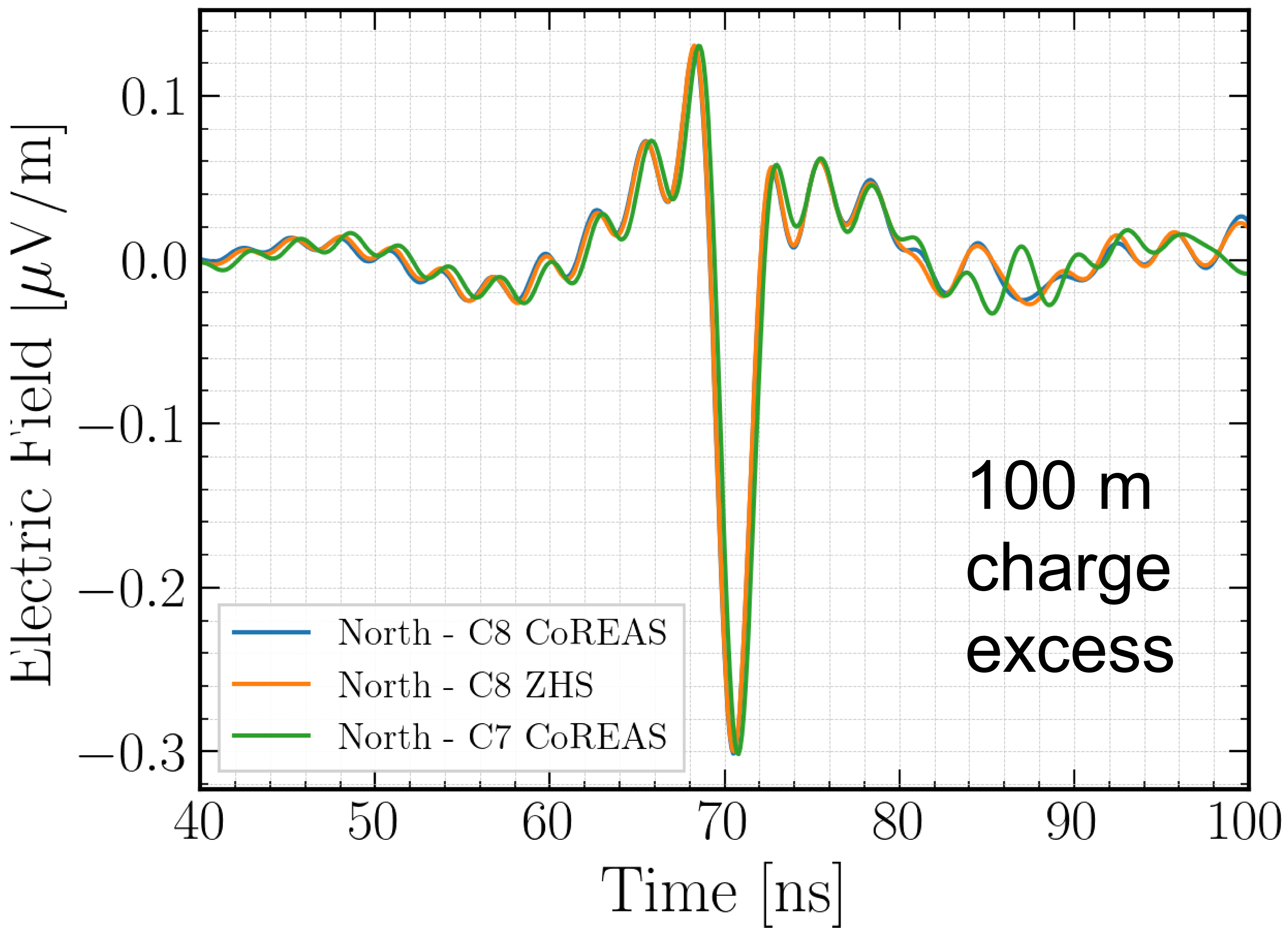




- 1PeV vertical shower, pulses agree well for small steps

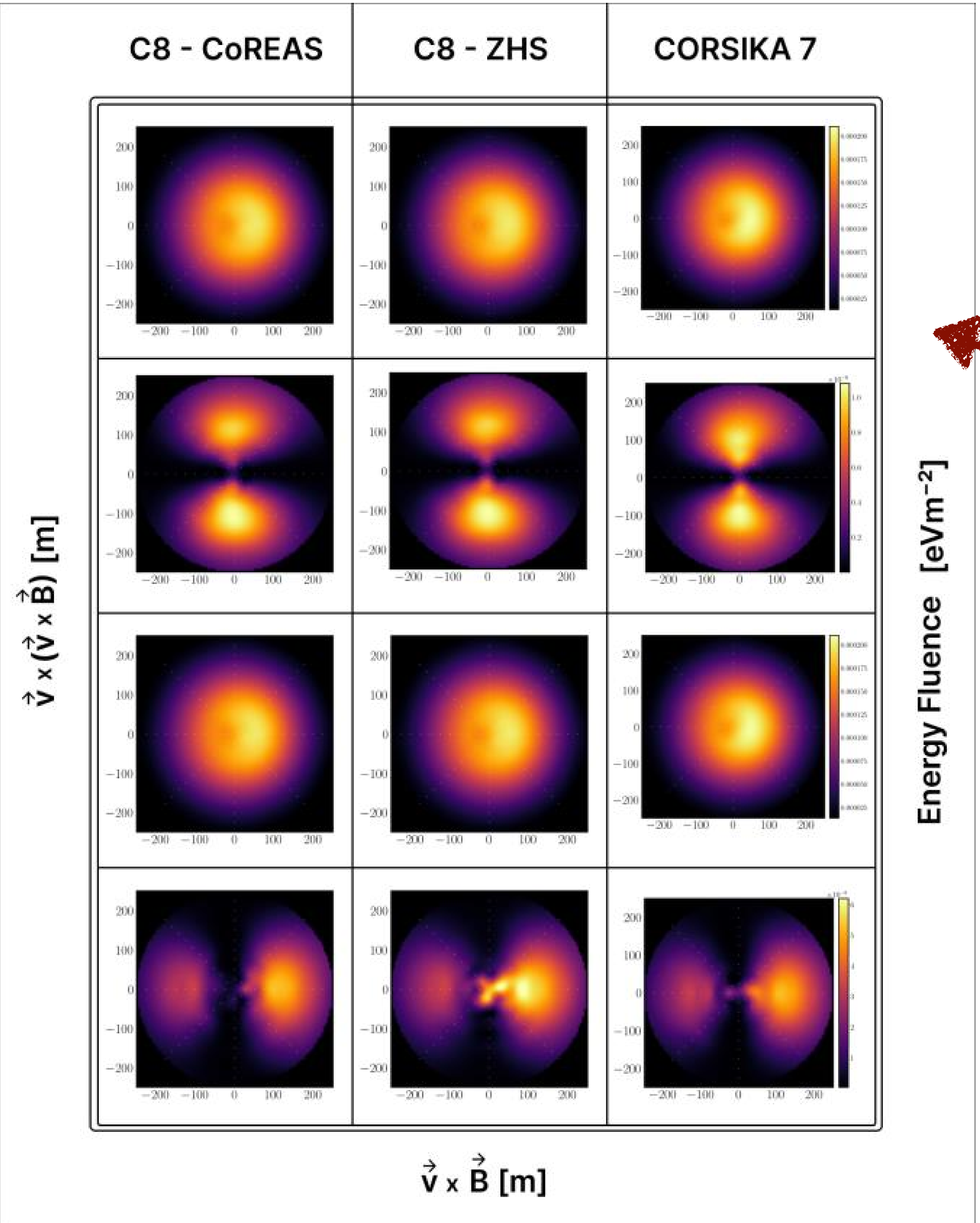
Pulses C8 vs C7, small steps, 50-350 MHz





- 1PeV vertical shower, pulses agree well for small steps

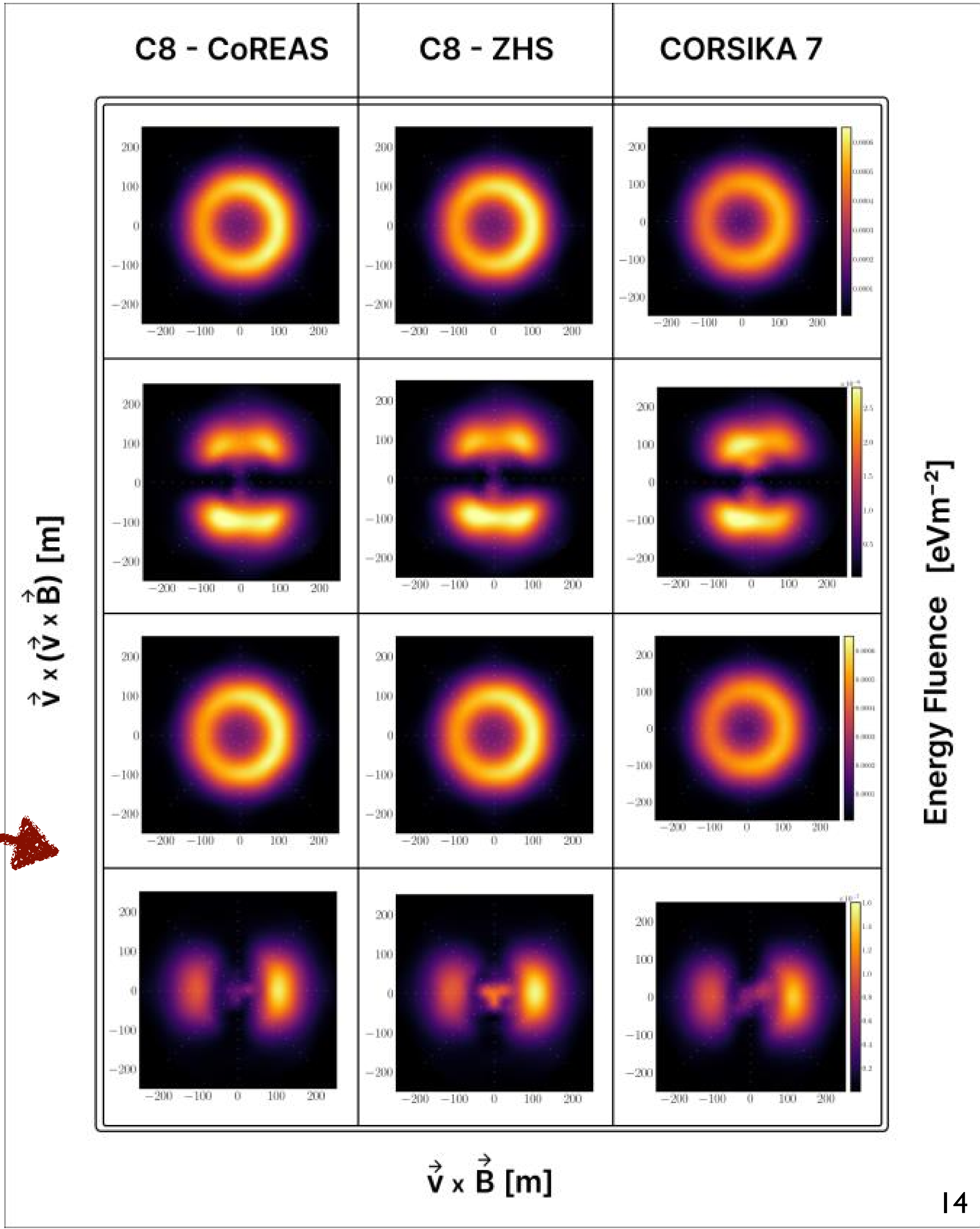
Fluence map comparison (small steps)



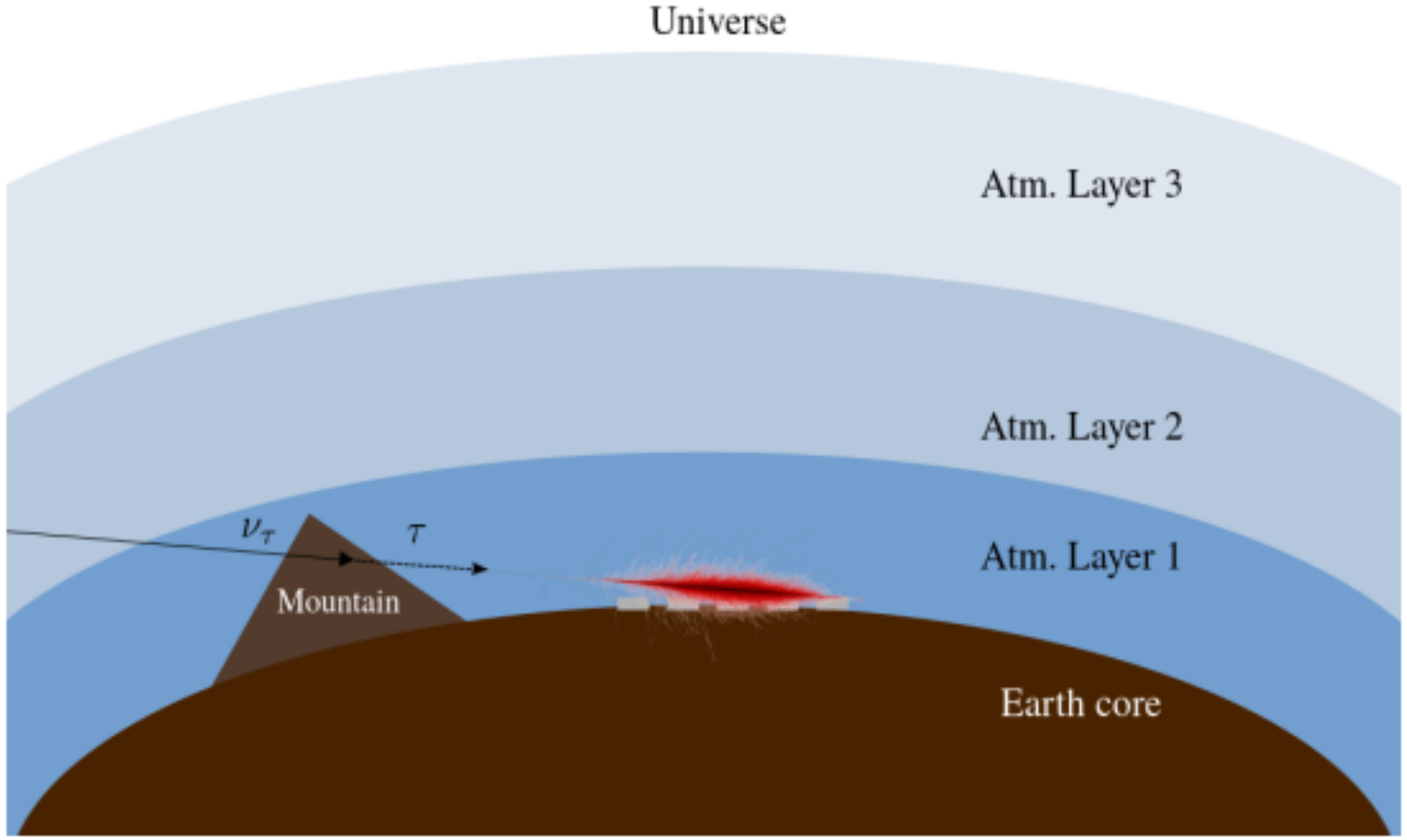
Improved agreement on absolute scale

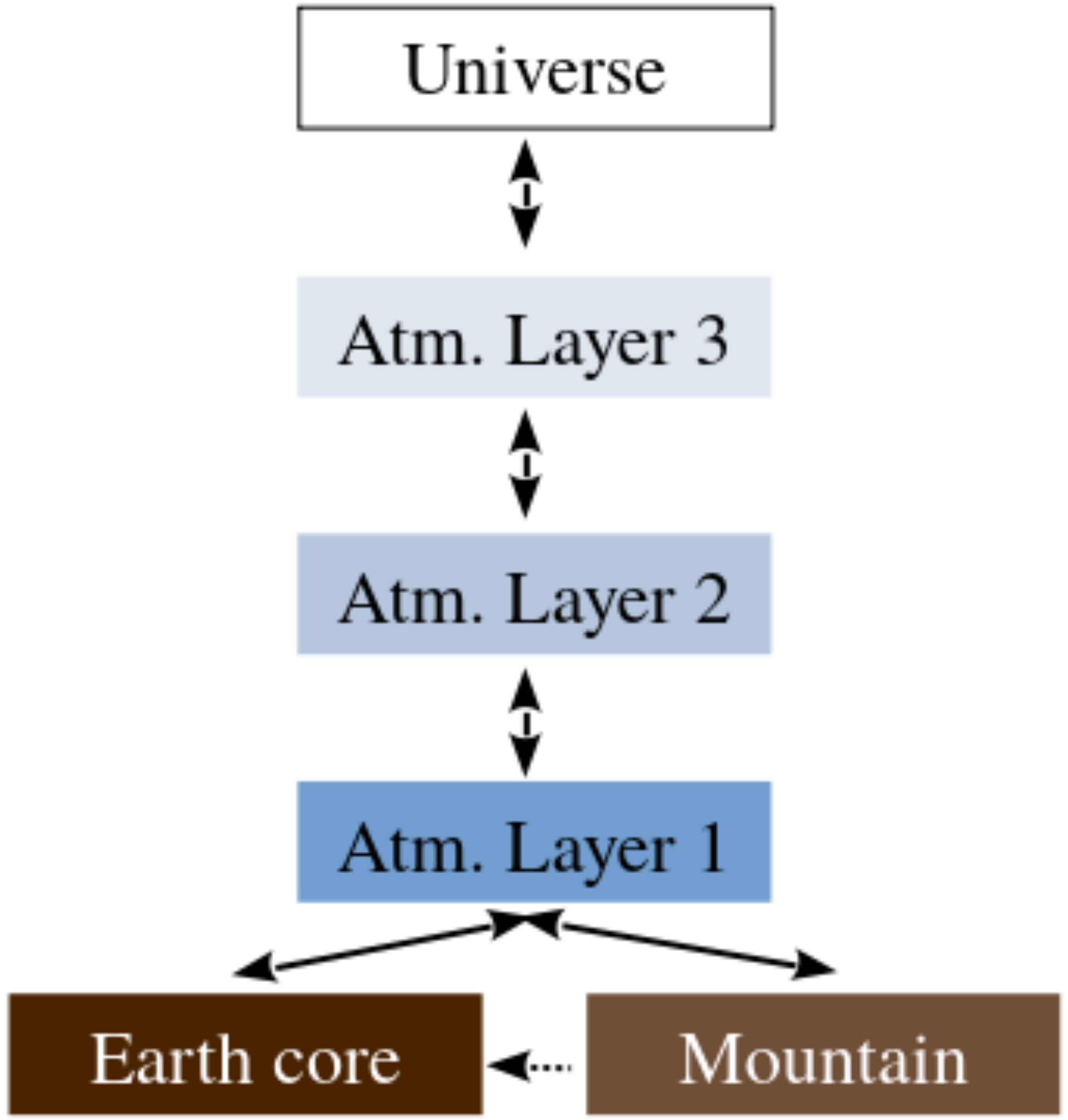
30-80 MHz

50-350 MHz



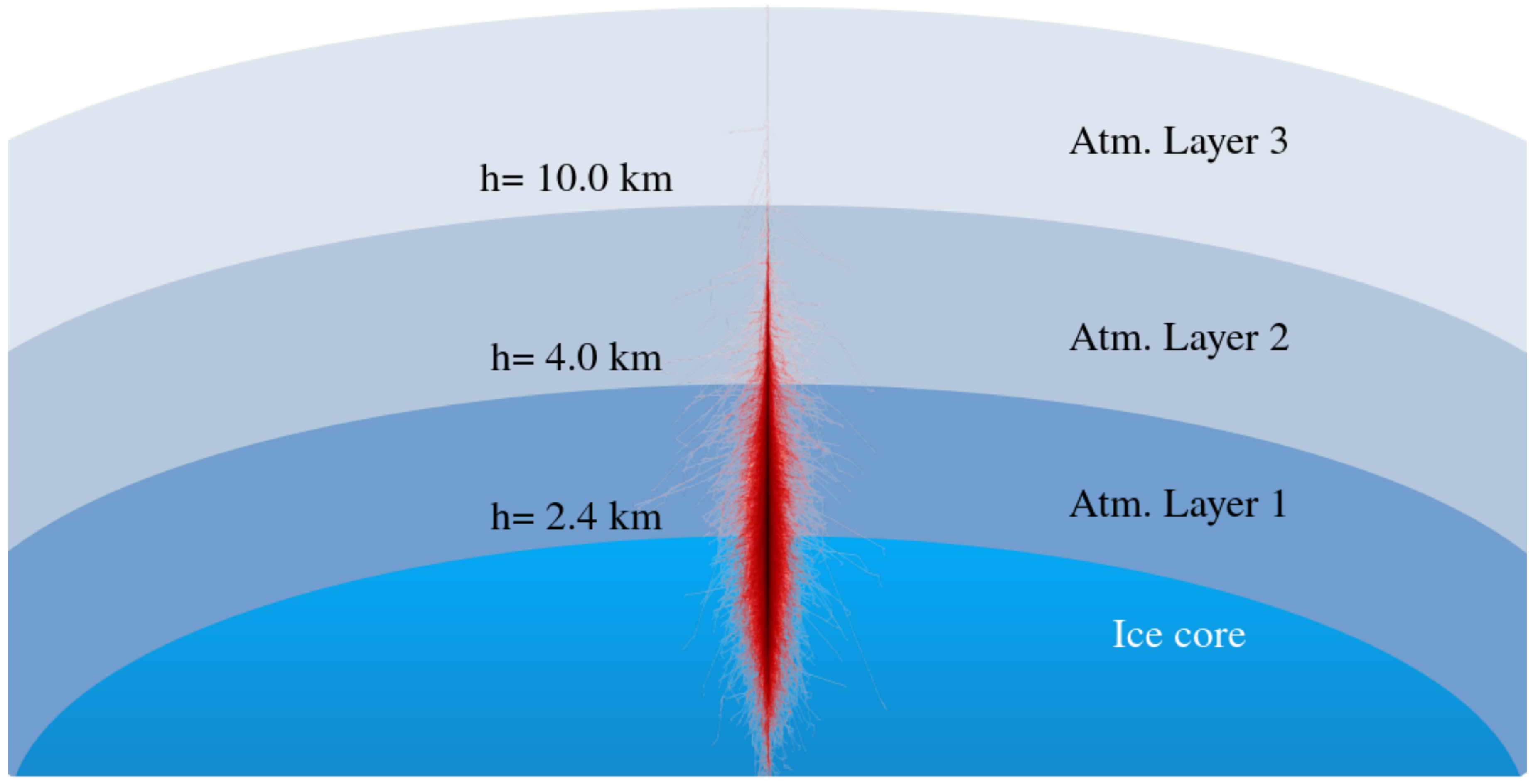
Cross-media showers

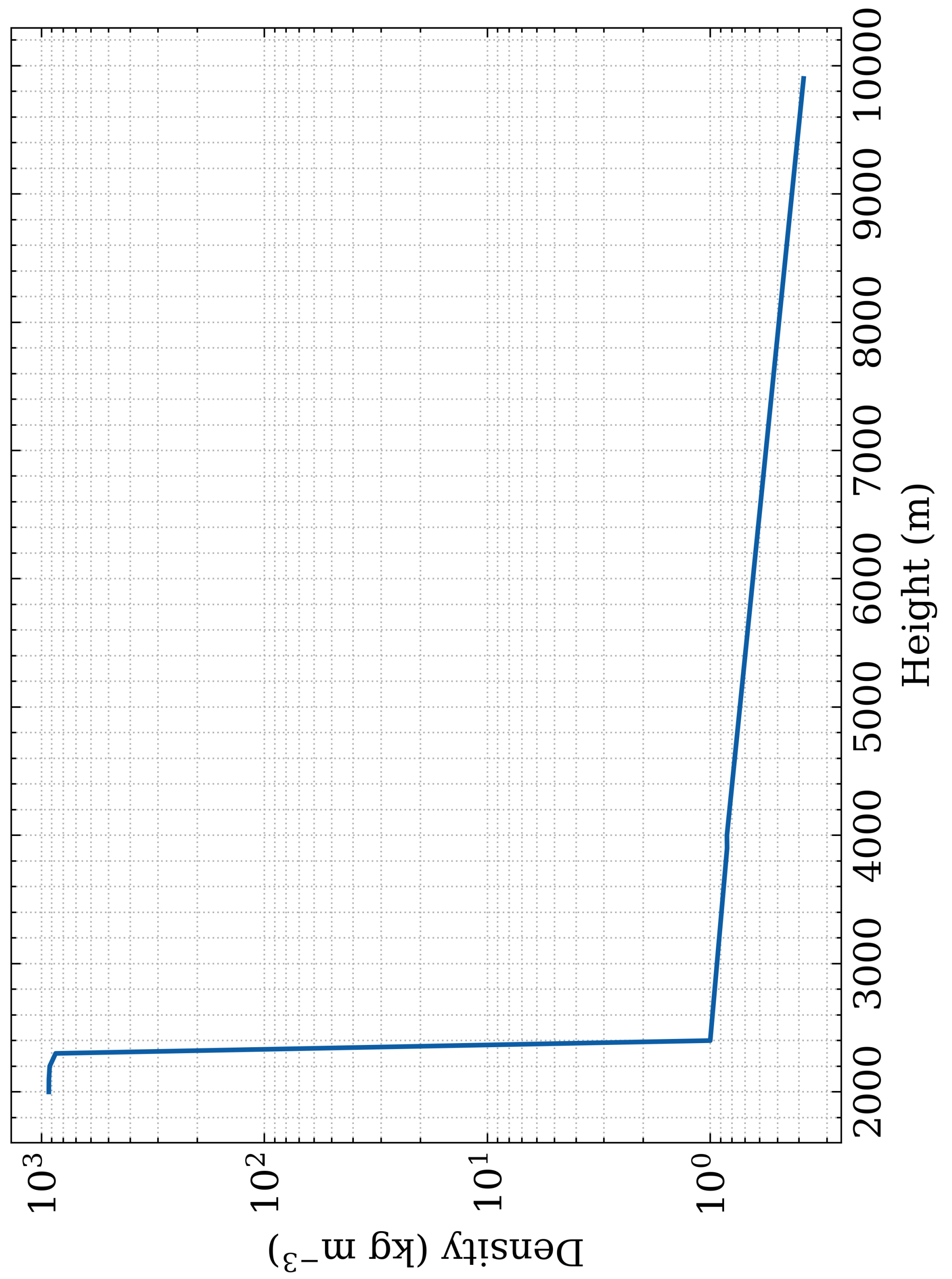


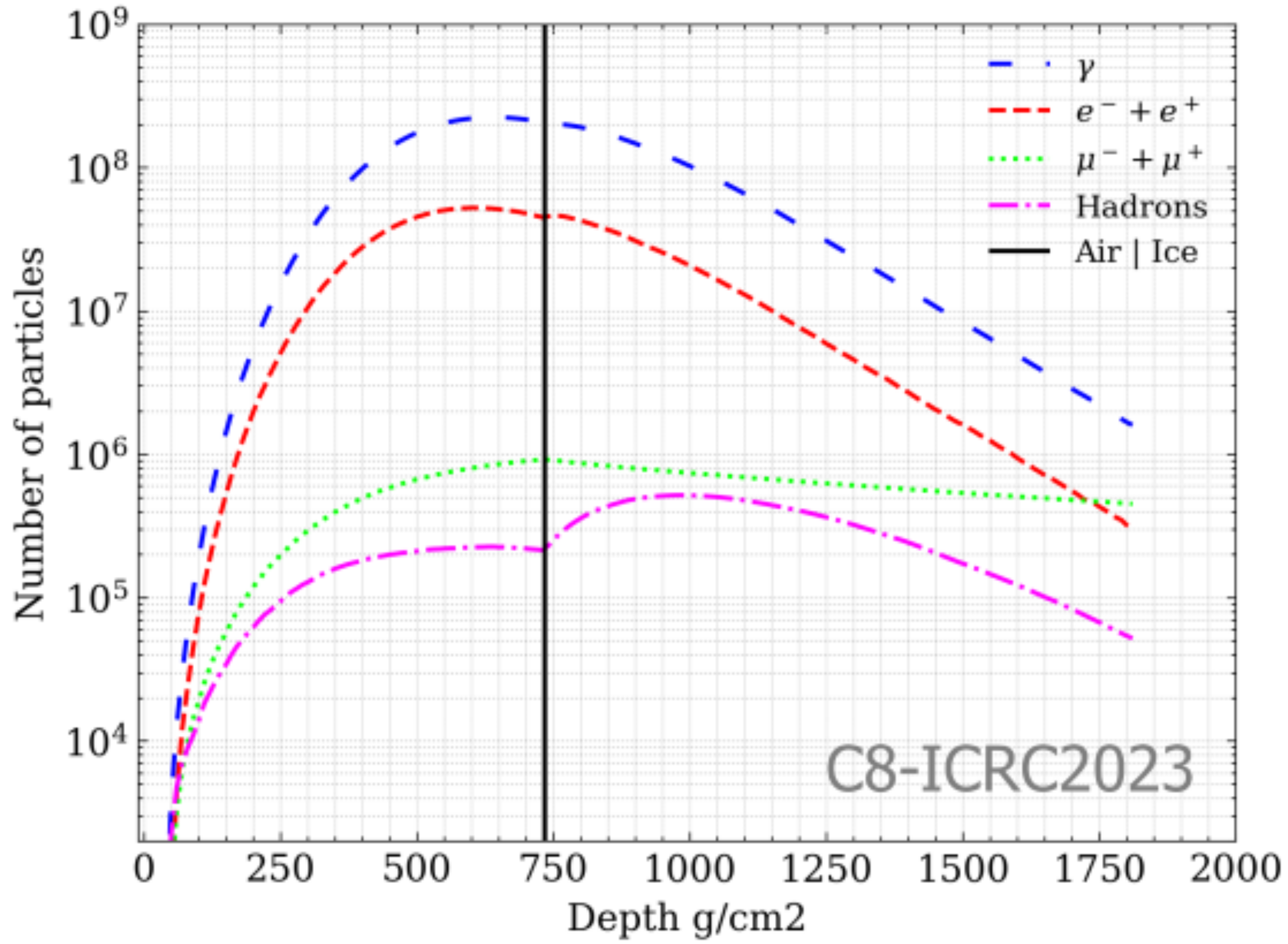


- Geometry for horizontal shower
  - Earth skimming or mountain crossing

Cross-media showers



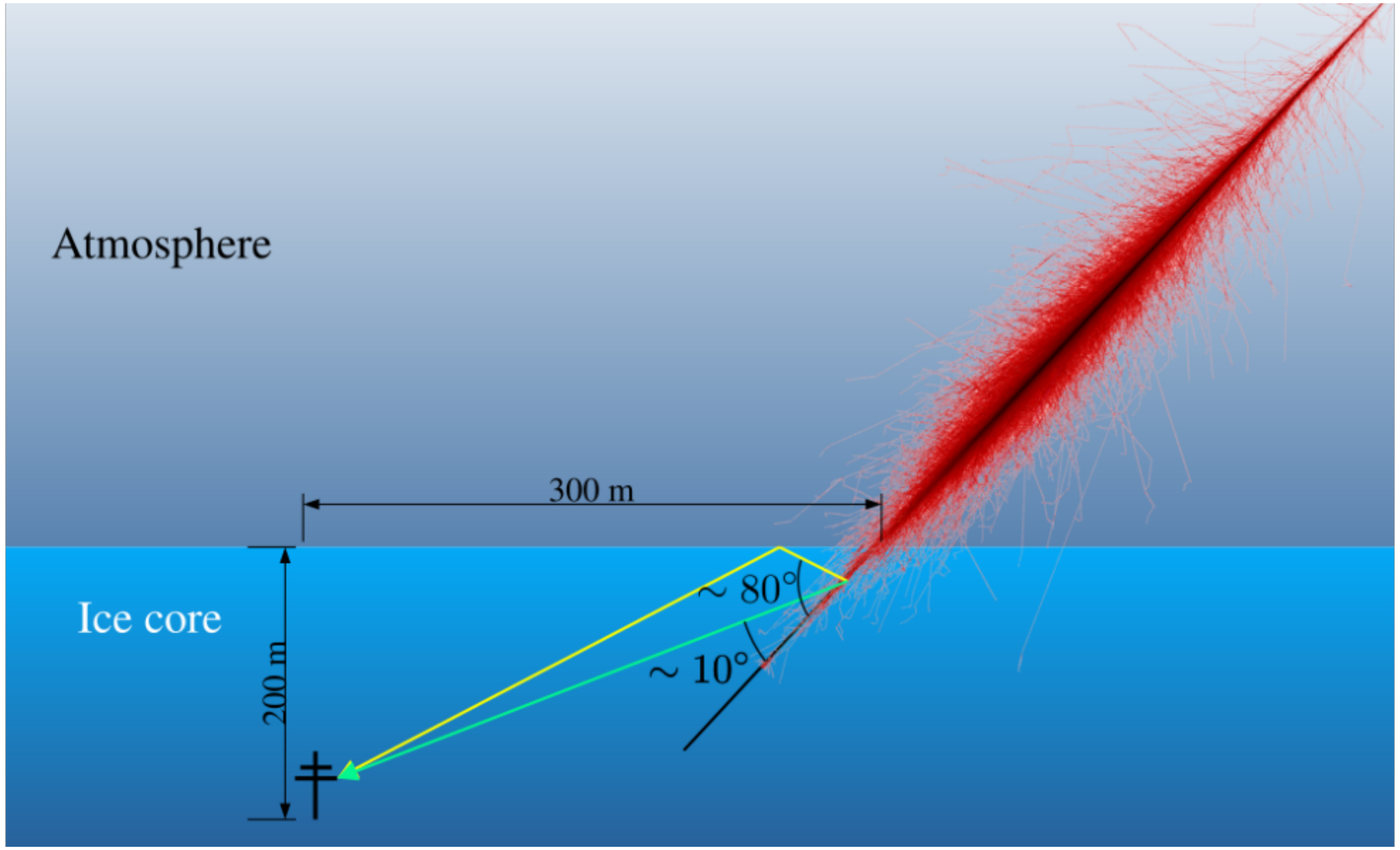




- Vertical shower
  - From Atmosphere to ice
    - High density in ice
    - Exponential profile in air

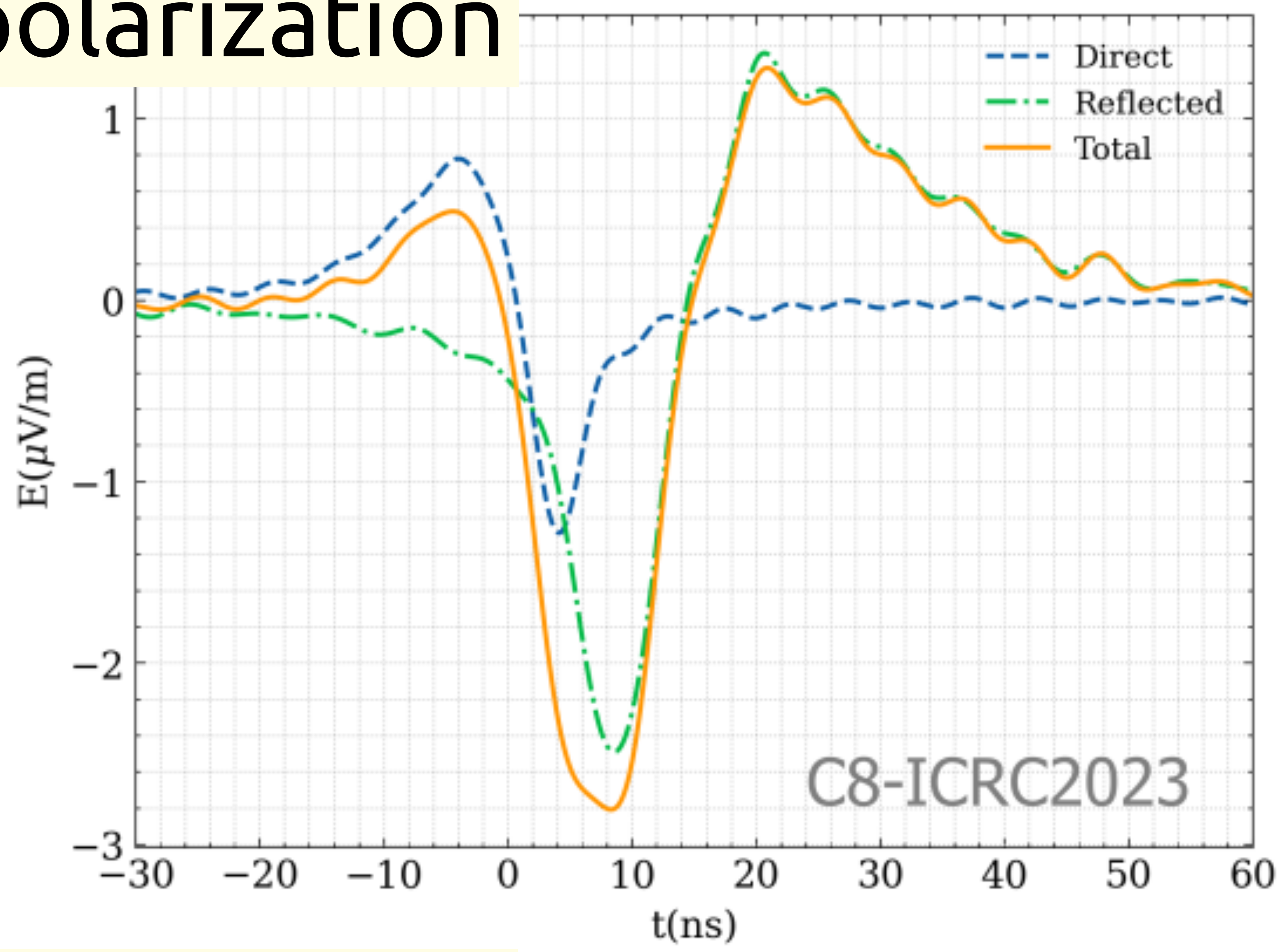
- Discontinuity on border
  - Hadron regeneration
    Higher density
    ⇒ More interaction ∴ more hadrons

Cross-media shower: in-ice radio production

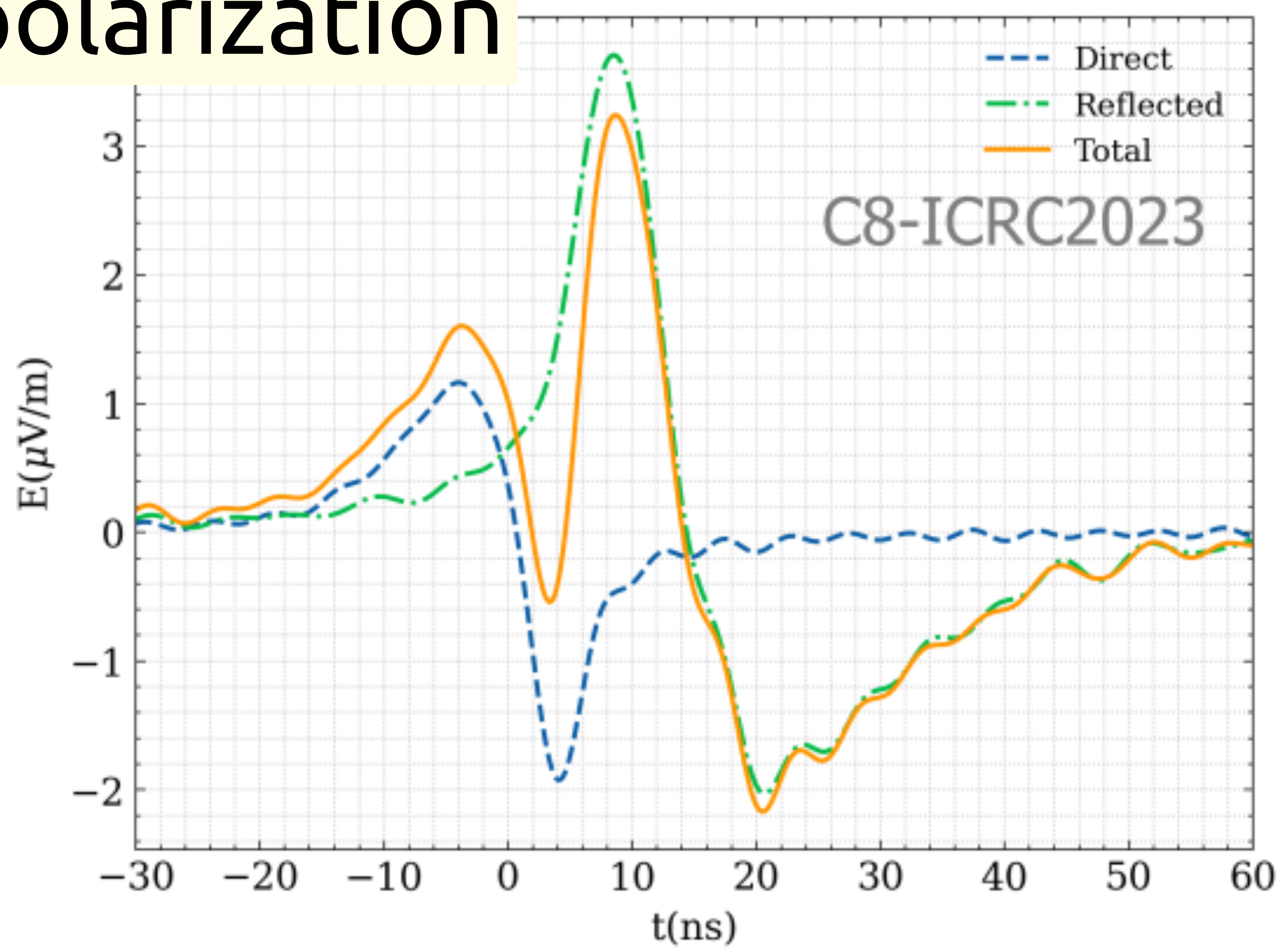


- CORSIKA 8
  flexible environment
- Many applications for cross-media showers

x polarization



z polarization



In-ice Showers and Verification of NuRadioMC

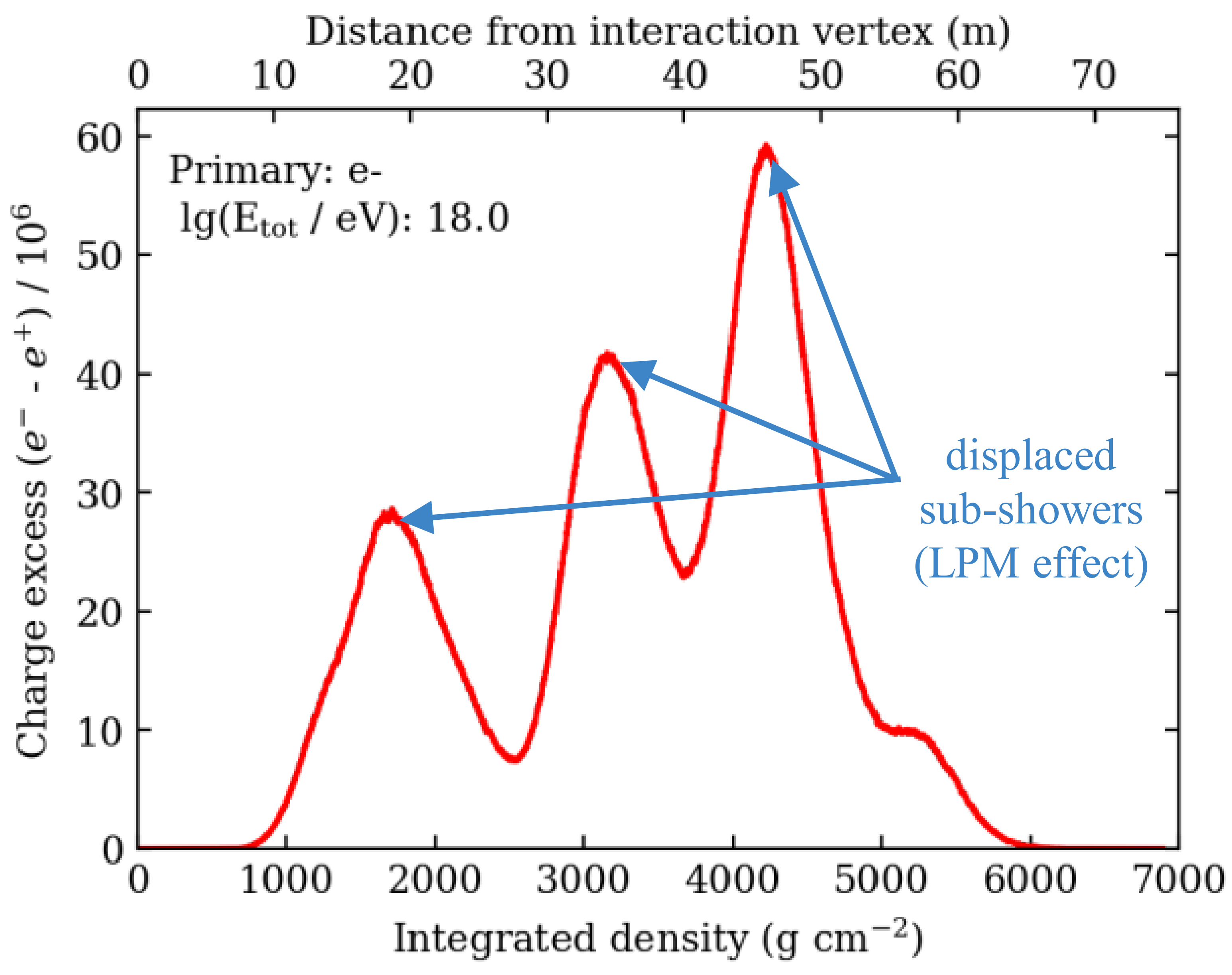
work by Alan Coleman, Maria Duran, Christian Glaser (Uppsala University)

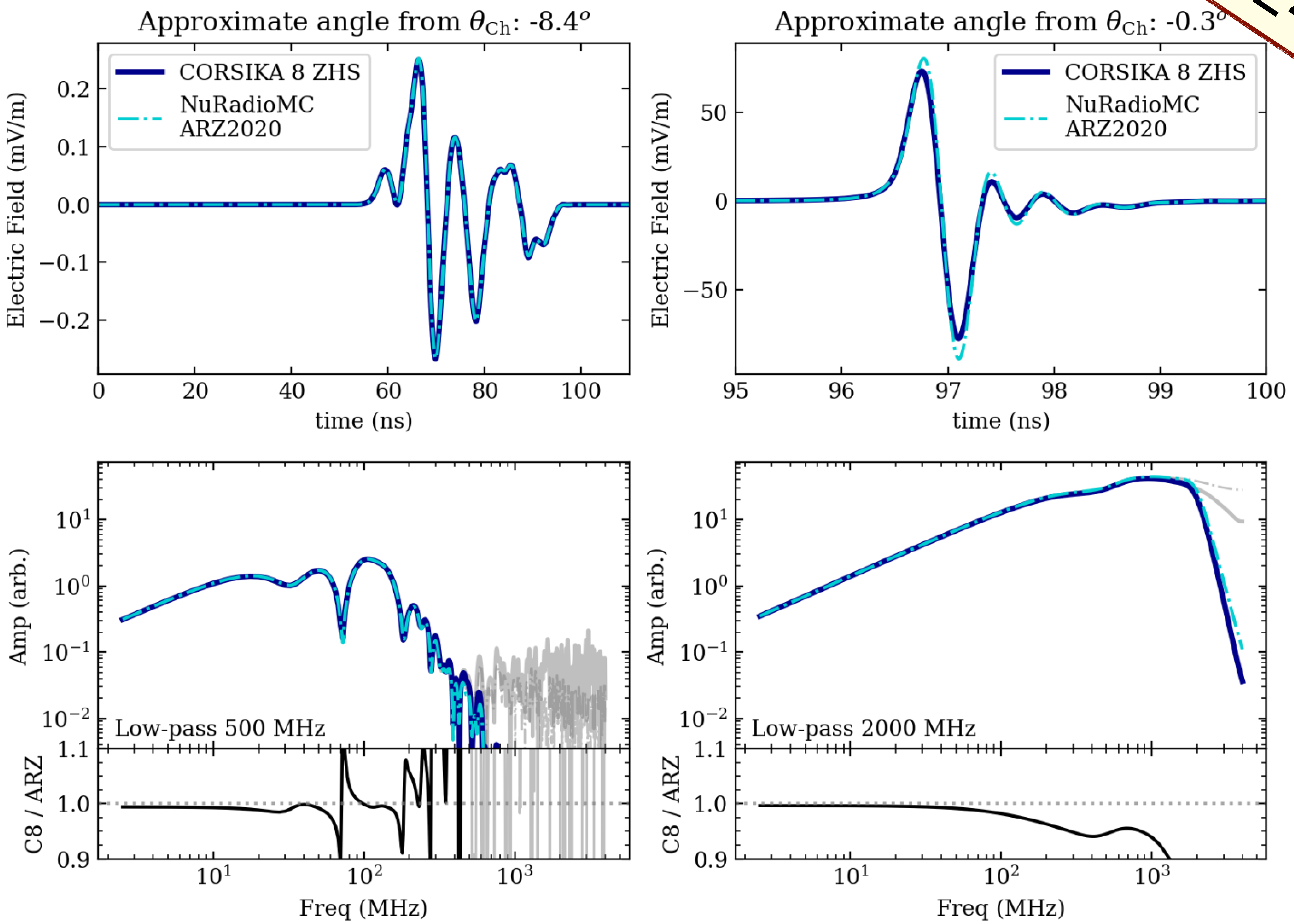
ARENA 2024

CORSIKA 8 can be used in dense media (ice)
Here: homogeneous ice with n=1.78 with antennas 1km from interaction vertex

CORSIKA 8 prediction reproduces previous results (ARZ model parameterized from ZHAireS simulations)

Next step: Study effect of inhomogeneous media (now enabled by CORSIKA8)

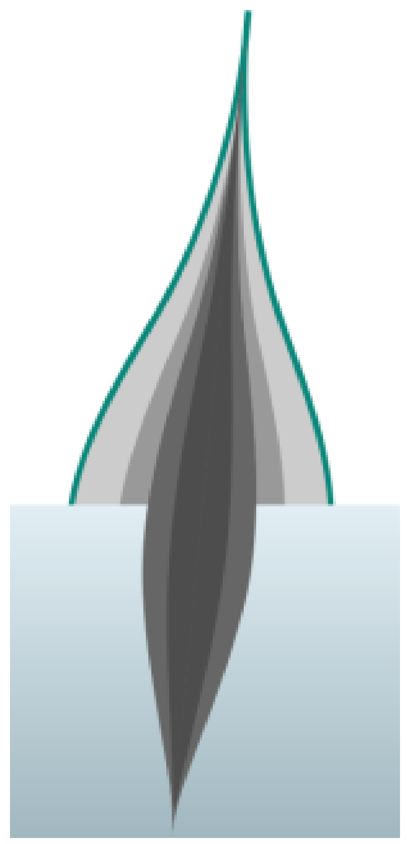




Cross-media Showers (Air-Shower Core impacting Ice)

ARENA 2024

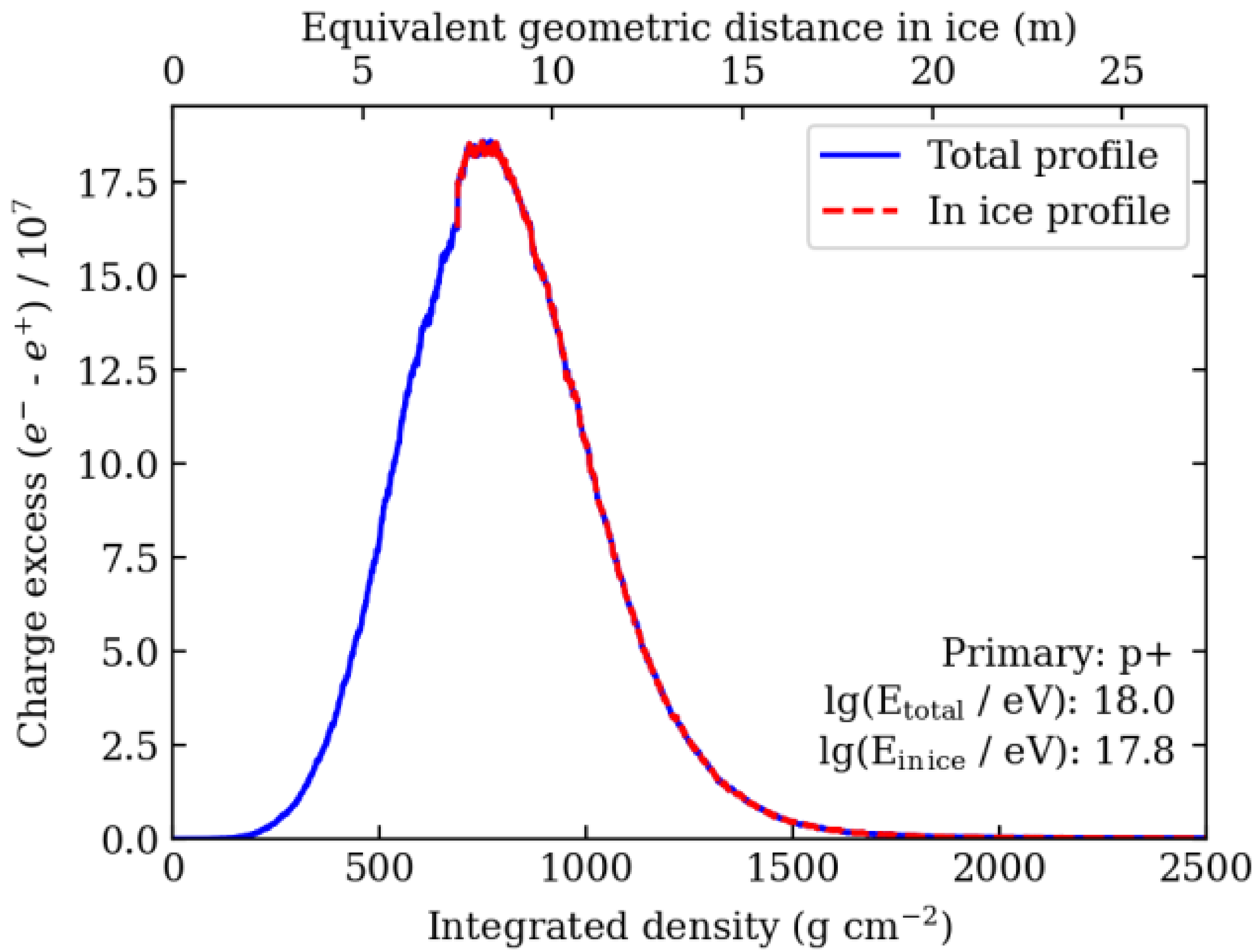
work by Alan Coleman, Maria Duran, Christian Glaser (Uppsala University)



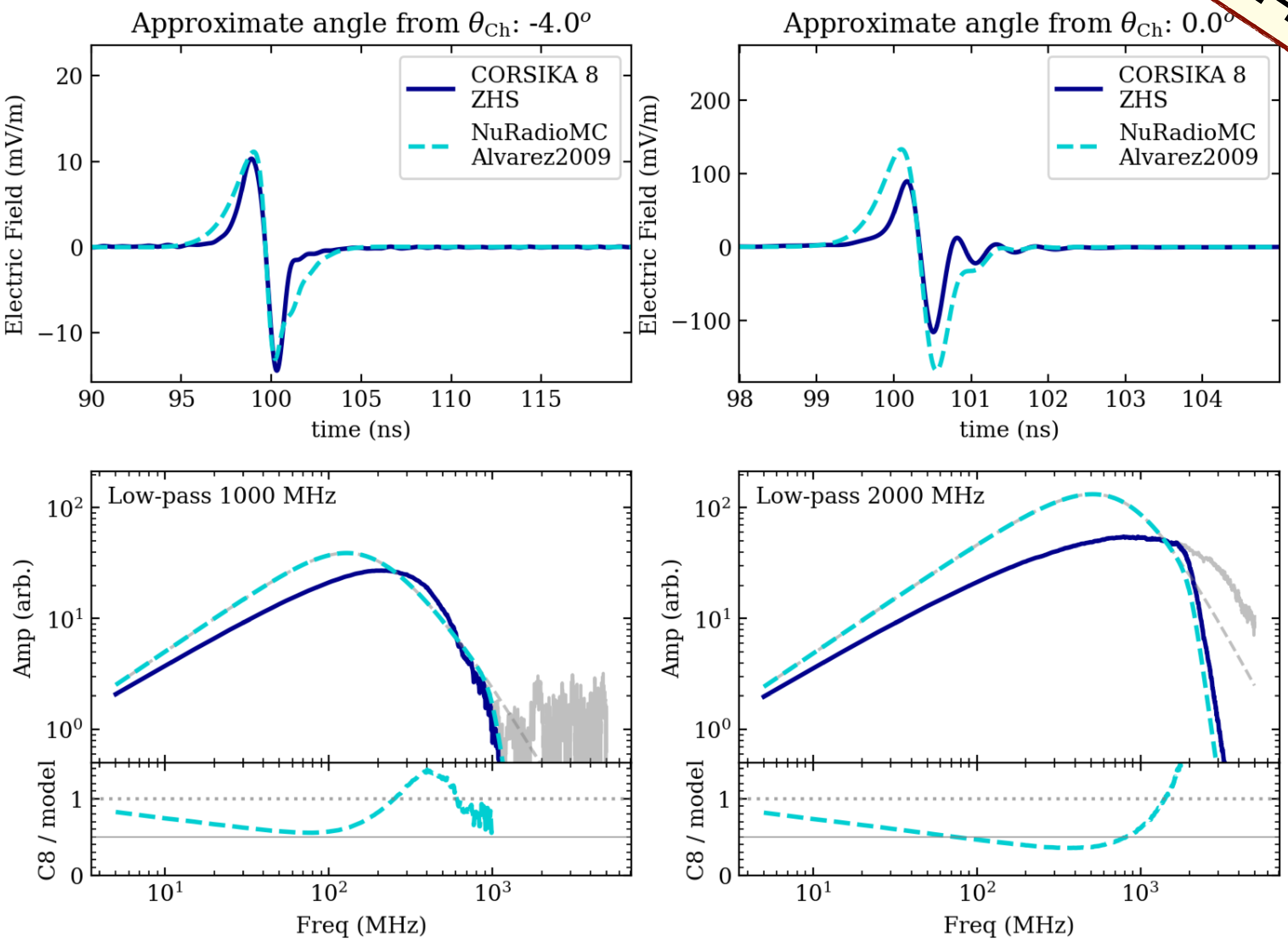
Plots show in-ice Askaryan emission only

Comparison with Askaryan emission models of neutrino-induced showers show (very) coherent emission
(Askaryan model evaluated for deposited in-ice energy as shower energy)

Next step: create a fast emission model of shower cores hitting the ice based on C8 simulations!

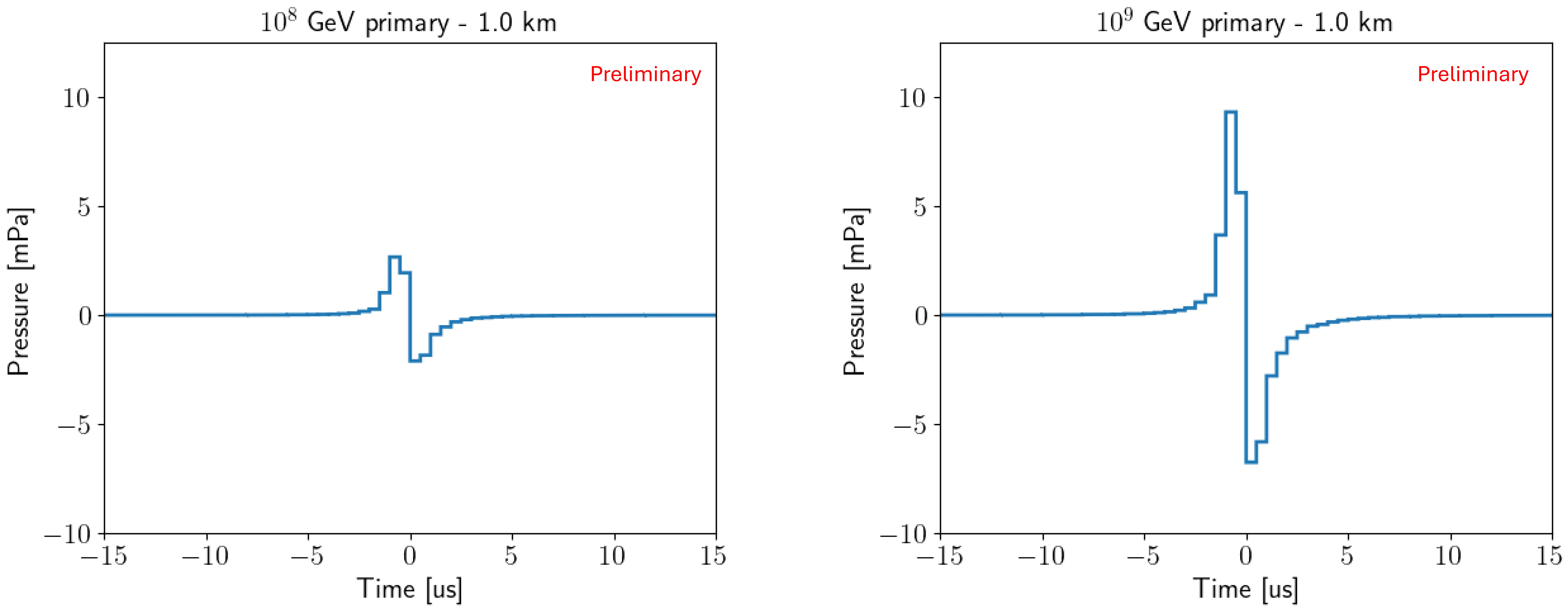


1EeV vertical Air Shower at South Pole



Acoustic neutrino signatures

Simulation



No seawater correction applied.

Acoustic neutrino signatures

SFU

Summary

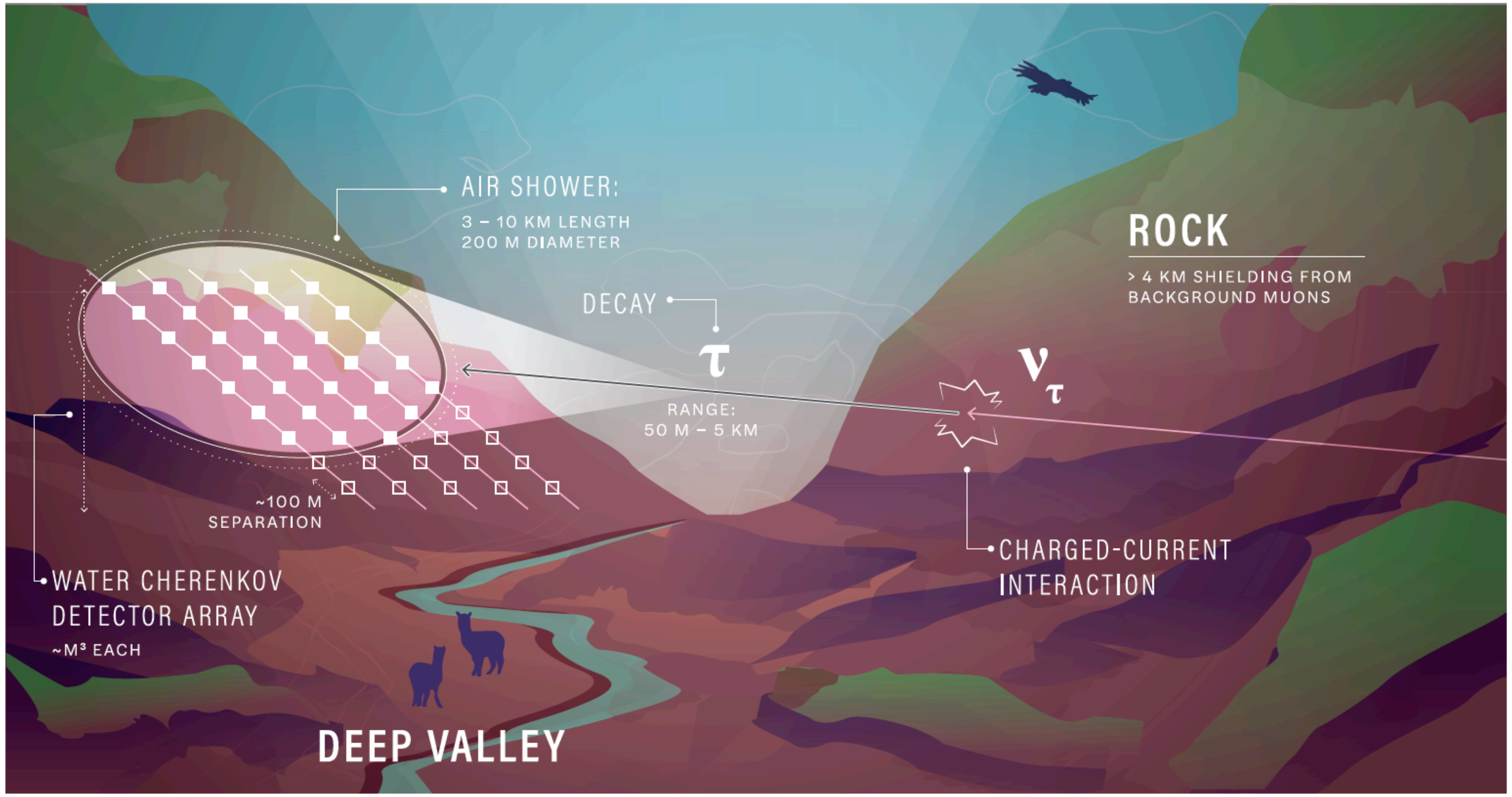
Successful generation of acoustic neutrino signatures in water based on CORSIKA 8 shower simulations

- More effort needed to verify results against existing work
- Systematic study of acoustic signatures (~ energy, observation angle) needed
- Intention to eventually develop an acoustic module for CORSIKA 8

Interest in application of new features

- Air showers in gas giants

- TAMBO project
  - neutrino detection in Colca Canyon, Peru



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

Before (beta) release

- User documentation
- Reference paper(s)
- Physics validation
- User distribution tooling
  - Standard CORSIKA 8 binary for typical applications
  - Framework build-kit for experts or tuning
- C++ package manager for externals
  - Control versions of external packages for predictable validation
  - Avoid the pain of hand-installing packages
  - Options: conan 2, spack, vcpk, …
- containerized distribution
  - "static" binary
  - ready-to-use build environment
  - use apptainer (https://apptainer.org/)

CORSIKA 8 collaboration

The CORSIKA 8 project is coordinated by the **steering committee** consisting of the following members (deputies):

- Tim Huege <tim.huege@kit.edu>: project coordination
- Dominik Baack (Alexander Sandrock): electromagnetic interactions
- Tanguy Pierog (Felix Riehn): hadronic interactions
- Alan Coleman (Max Reininghaus): software development
- Augusto Alves jr.: performance, parallelization
- Lukas Nellen: deployment, continuous integration

Collaborators

Jean-Marco Alameddine, Johannes Albrecht, Jaime Alvarez-Muniz, Juan Ammerman-Yebra, Luisa Arrabito, Jannik Augscheller, Antonio Augusto Alves Jr, Dominik Baack, Konrad Bernlöhr, Marcus Bleicher, Alan Coleman, Hans Dembinski, Dominik Elsässer, Ralph Engel, Alfredo Ferrari, Chloé Gaudu, Christian Glaser, Marvin Gottowik, Dieter Heck, Fan Hu, Tim Huege, Karl-Heinz Kampert, Nikolaos Karastathis, Uzair Abdul Latif, Hualin Mei, Lukas Nellen, Tanguy Pierog, Remy Prechelt, Maximilian Reininghaus, Wolfgang Rhode, Felix Riehn, Maximilian Sackel, Paola Sala, Pranav Sampathkumar, Alexander Sandrock, Jan Soedingrekso, Ralf Ulrich, Donglian Xu, Enrique Zas

Conclusion

- CORSIKA 8 is physics complete
  - Can simulate electro-magnetic and hadronic showers
  - Commonly used hadronic interaction models available
- Radio emission is first class citizen
- Applications beyond CORSIKA 7
  - Transition into ice or ground
  - Upwards-going neutrinos (including meson propagation in earth)
- Link from CORSIKA page https://www.iap.kit.edu/corsika/
  - Code available: https://gitlab.iap.kit.edu/AirShowerPhysics/corsika
    - Might change
- Working towards first public (beta) release (expert oriented)
- Speed-up in progress