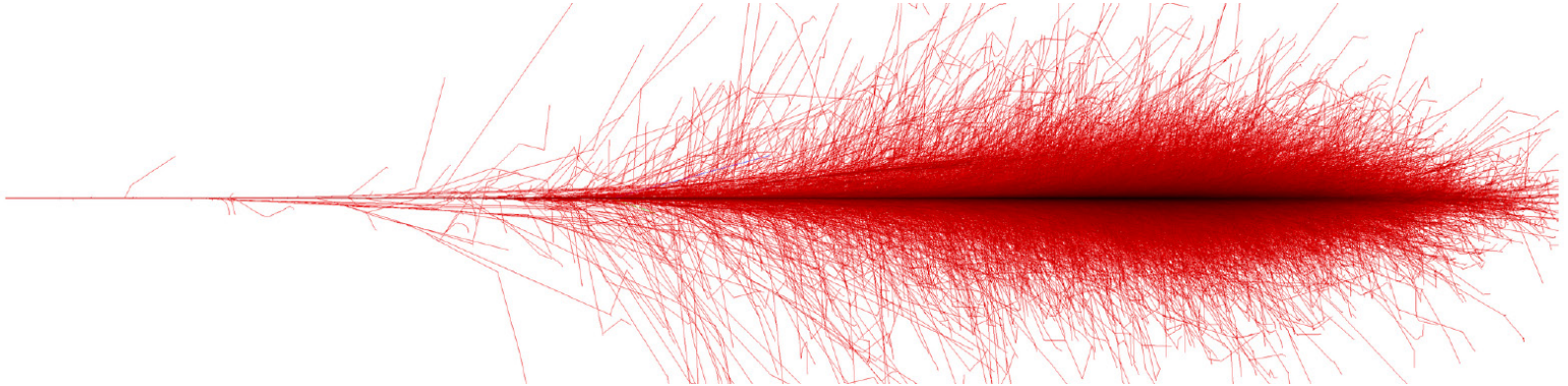
Karlsruhe Institute of Technology

VRIJE UNIVERSITEIT BRUSSEL

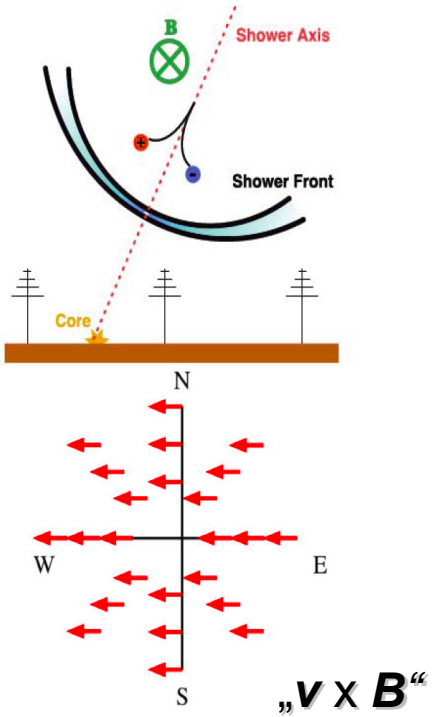
Air-Shower Radio Simulations – where we stand and where we go

Tim Huege (KIT & VUB)

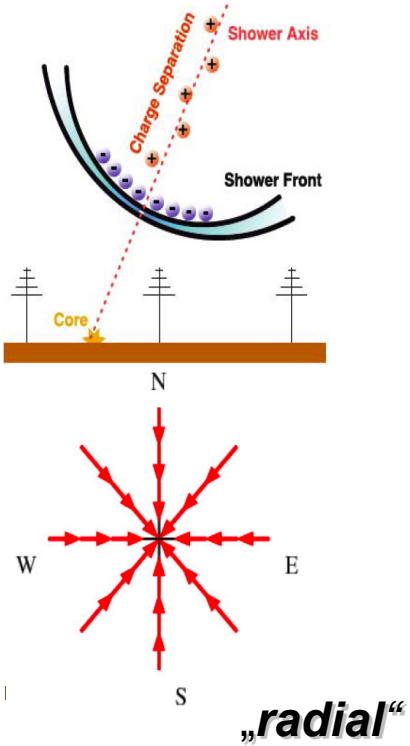


Air-shower radio simulations

- have been a success story – fundamentally important for the field
- two types of approaches were followed
  - macroscopic (net charge, currents, …): MGMR, MGMR3D
  - microscopic (emission from particle tracks): CoREAS, ZHAireS, (SELFAS)



„$v \times B$“



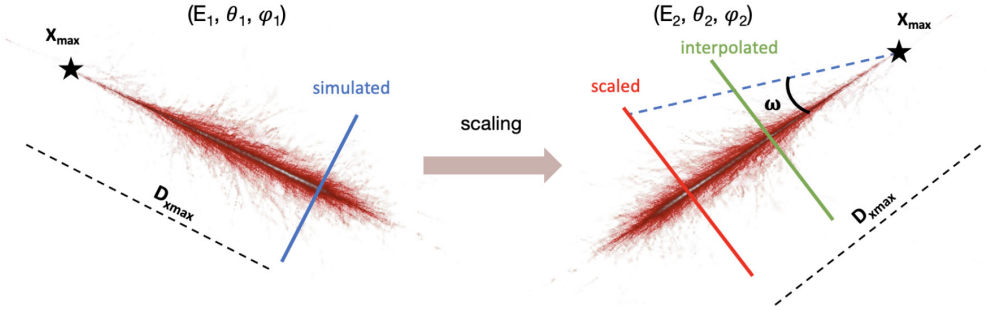
„*radial*“

Diagrams by H. Schoorlemmer & K.D. de Vries

Under development: hybrid approaches

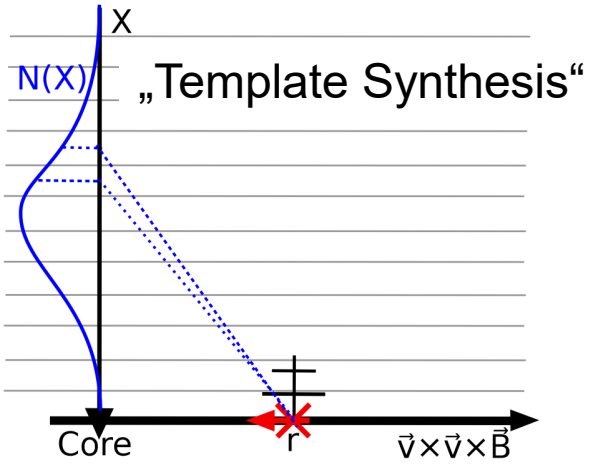
- microscopic: accurate but compute-intensive
- macroscopic: fast but approximative
- hybrid: combine best of both worlds, „re-scale“ microscopic simulations

„Radio Morphing“



Chiche et al., arXiv:2202.05886

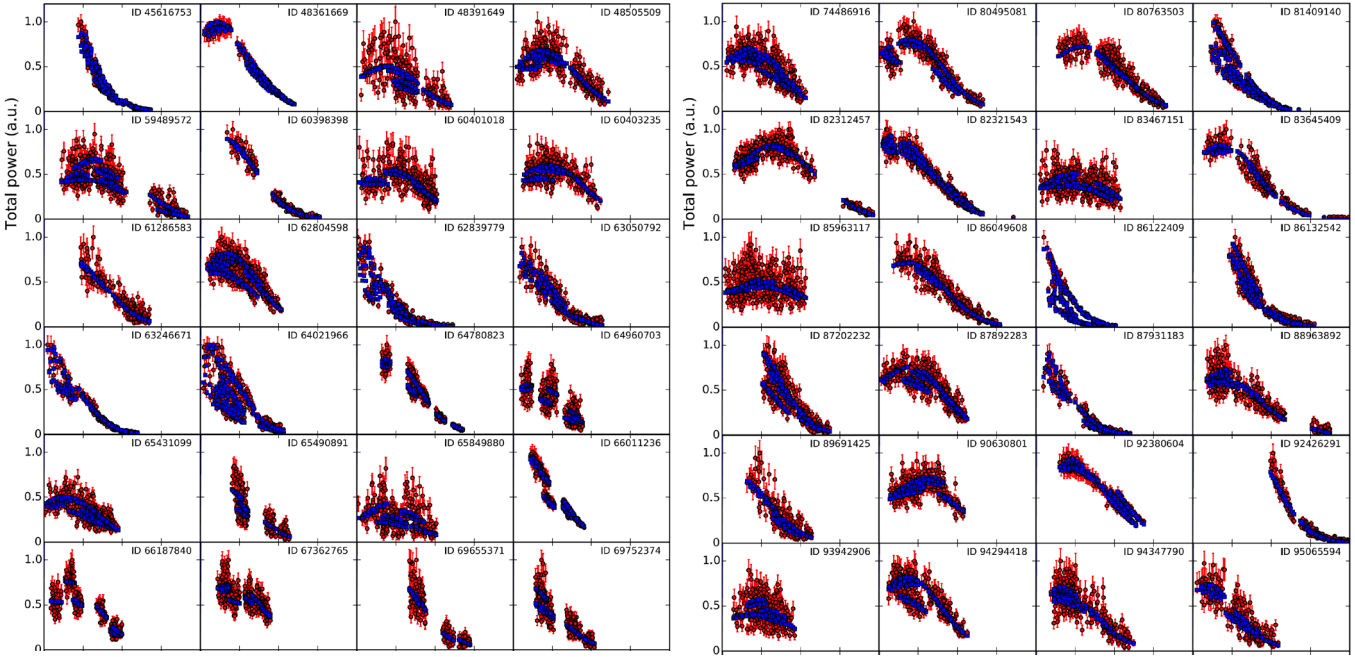
„Template Synthesis“



Butler et al., arXiv:1908.09543 – see talk Desmet

Vertical Air Showers
(30-80 MHz)

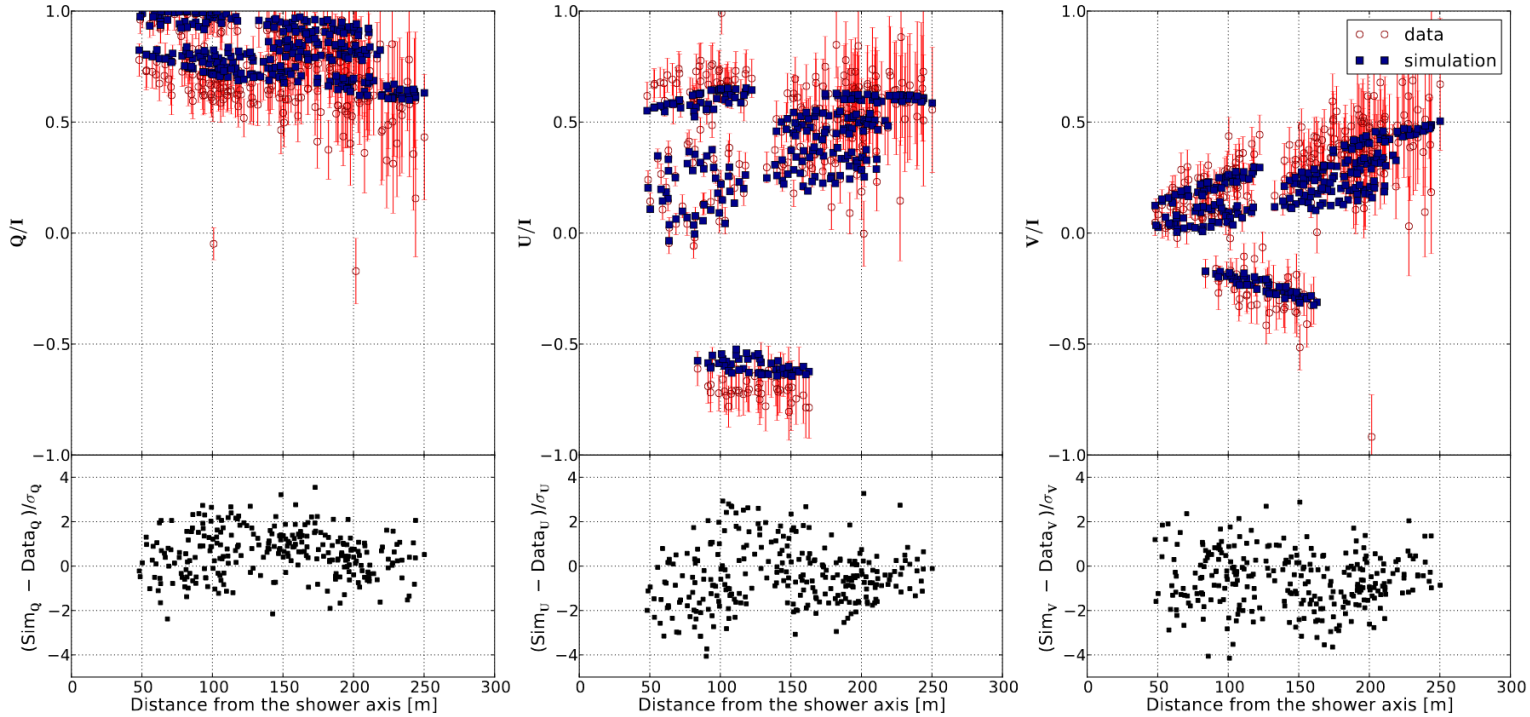
Microscopic sims against air-shower data



- LOFAR has compared hundreds of showers with hundreds of antennas each to CoREAS sims: excellent agreement in 30-80 MHz band

Buitink et al., Nature 531 (2016) 70–73

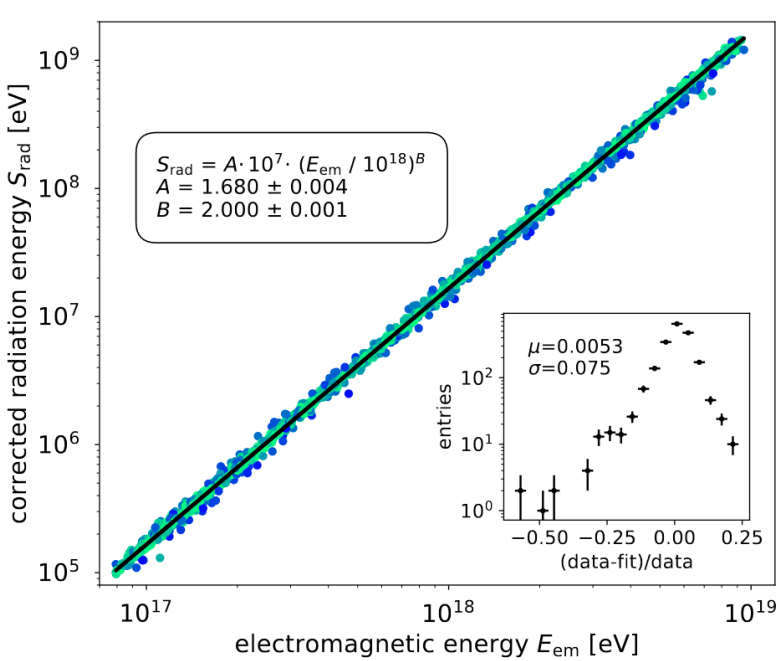
Microscopic sims against air-shower data II

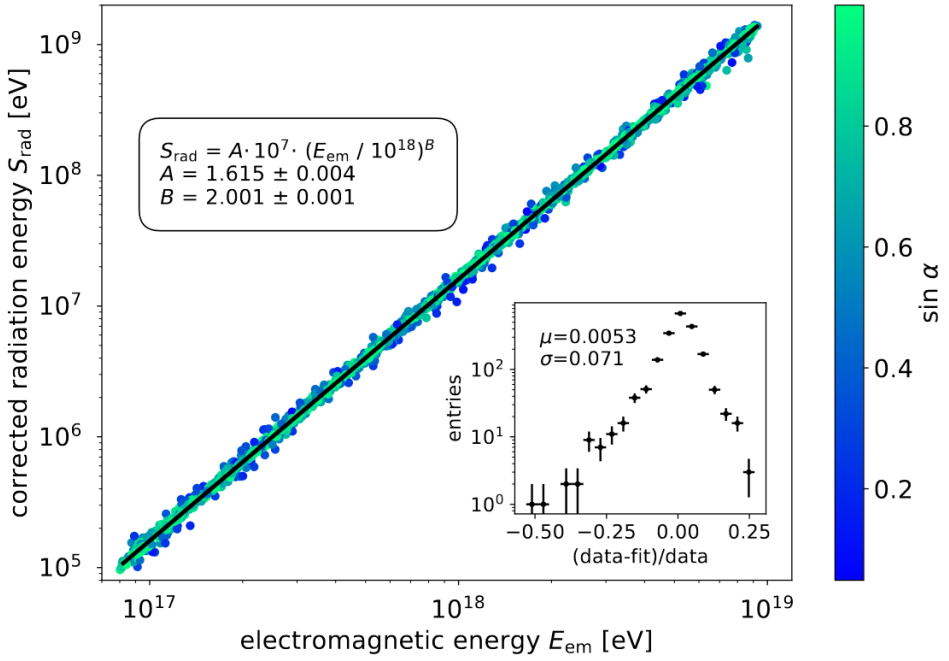


Scholten et al., arXiv:1611.00758

- LOFAR showed that even circular polarization matches with CoREAS

Comparison of microscopic simulations





- radiation energy predicted by CoREAS & ZHAireS matches within 5.2%
- caveat: agreement of footprints *not* investigated

Gottowik et al., arXiv:1712.07442

Caveat: electromagnetic cascade details

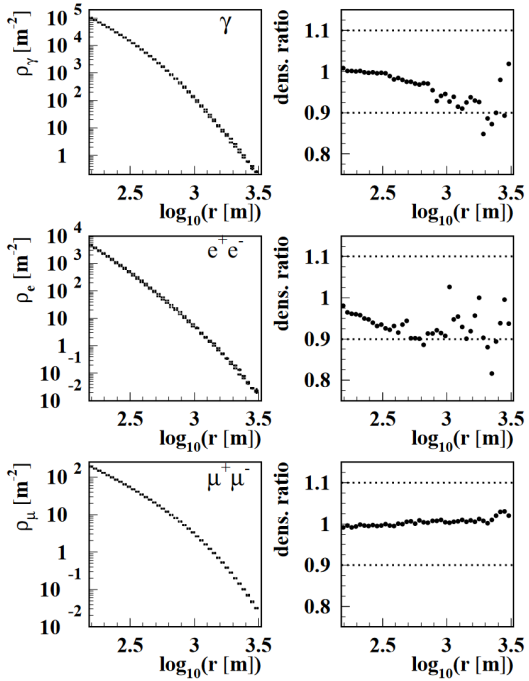
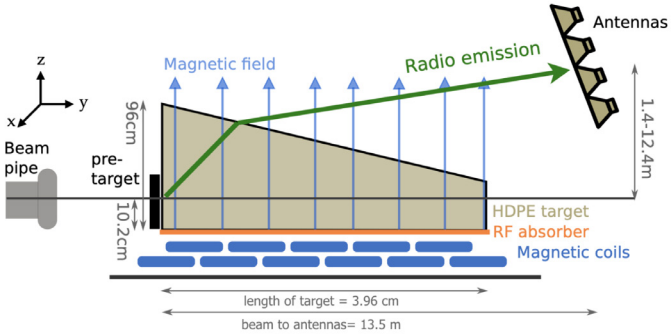


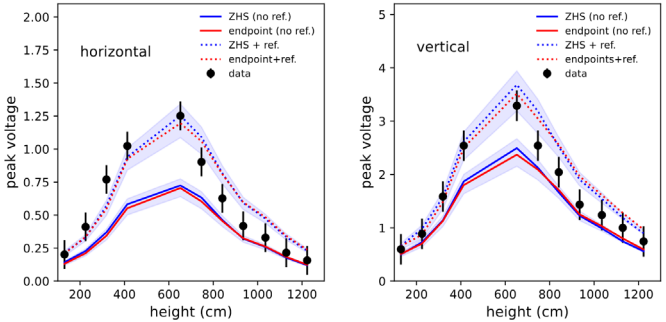
Fig. 3. Lateral particle densities for photons, electrons and muons. Left: particle densities. Right: relative difference between AIRES and CORSIKA as function of core distance.

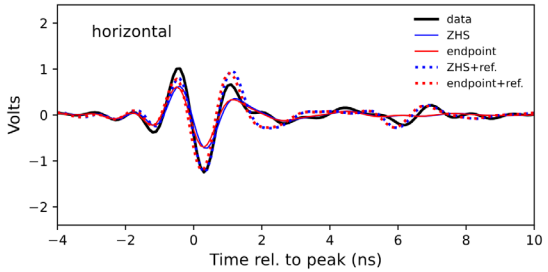
Sciutto, Knapp, Heck, ICRC2001, 526

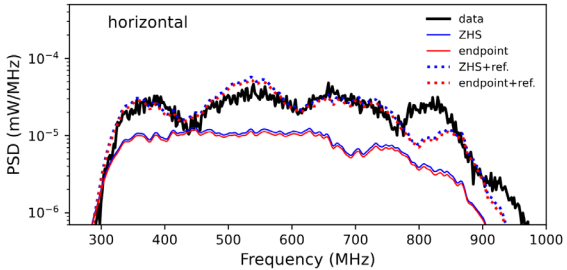
- CORSIKA and Aires use different treatments of the electromagnetic interaction: CORSIKA uses EGS4, Aires somewhat simplified (faster) treatment
  - some differences in the electromagnetic particle distributions are documented
- both might neglect some (minor) effects
- a detailed comparison of CoREAS and ZHAireS footprints, or better ZHAireS against high-fidelity data like LOFAR would be beneficial

Microscopic sims against lab data









- Recently published final results, after taking into account reflections, absolute (!) agreement is excellent

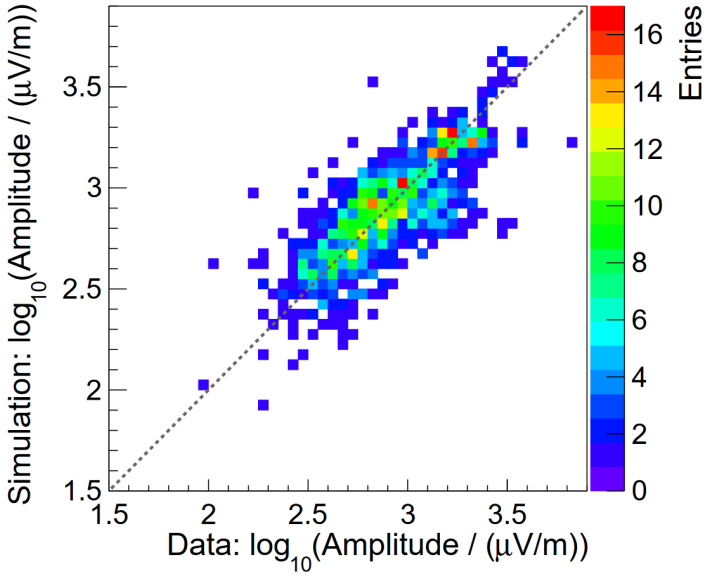
Bechtol et al., arXiv:2111.04334

Summary vertical air showers

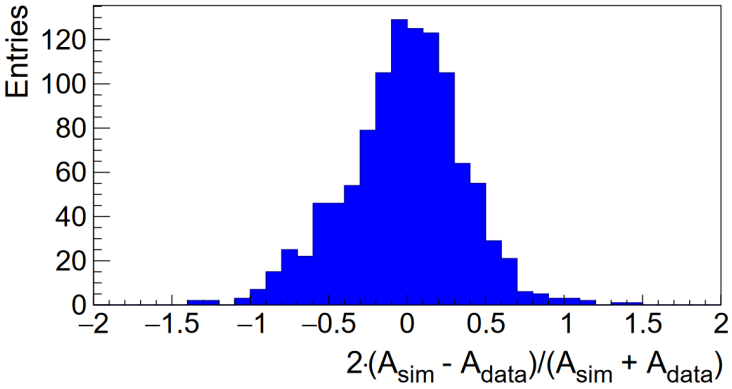
- emission from vertical EAS in 30-80 MHz band tested in detail
- atmospheric modelling with GDAS is excellent
- higher frequencies not tested well, but do not really expect surprises

Inclined Air Showers

Comparison against AERA data



(a) Each of the 1078 entries characterizes one individual antenna station. The color scale denotes the number of entries in each bin.

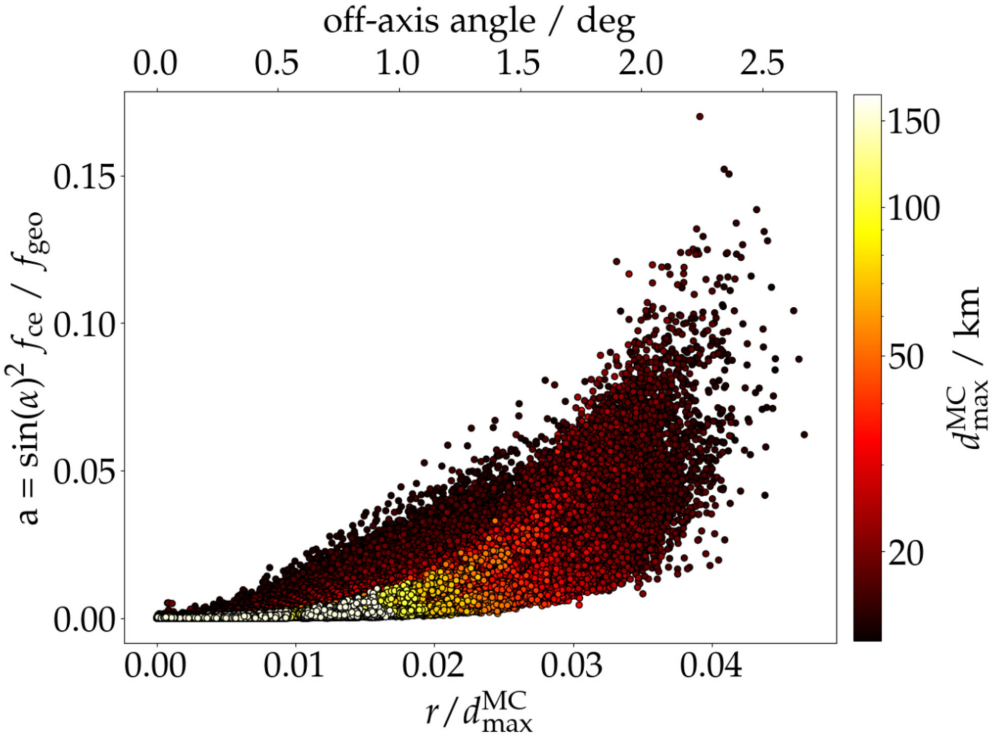


(b) Histogram of the deviations of the simulated and measured electric field amplitudes in each individual radio-detector station. The mean deviation amounts to −2%, the spread as measured by the standard deviation is 38%.

Aab et al., arXiv:1806.05386

- 30-80 MHz signal matches between AERA and CoREAS up to ~80°

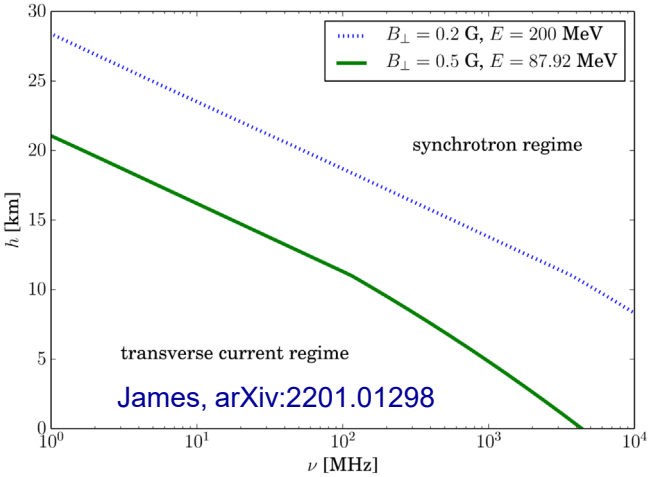
Charge excess diminishes



- note that charge excess loses its relevance for very inclined showers (>~75° zenith angle)
- the source is then very far away
- both sort of make situation „easier“
- but …

Schlüter & Huege, arXiv:2203.04364

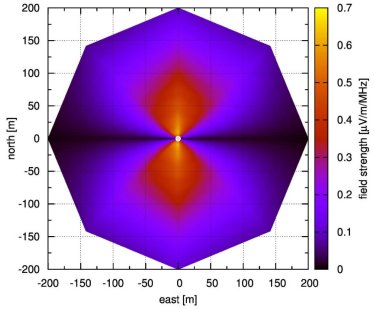
Transition to synchrotron radiation?



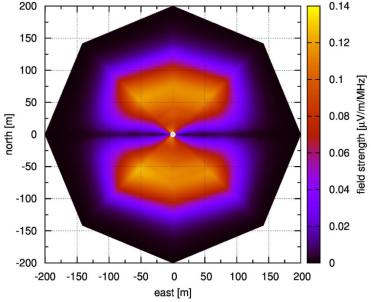
James, arXiv:2201.01298

- excellent paper by Clancy James
- predicts transition from transverse currents to synchrotron emission for low air density/high frequencies
- for high frequencies seen in CoREAS simulations in 2013, hint in CROME data!

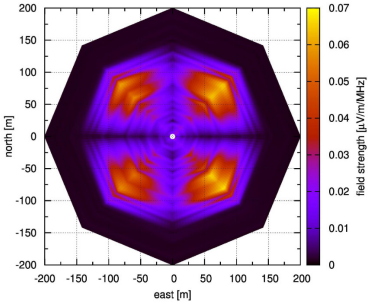
40-80 MHz



300-1200 MHz



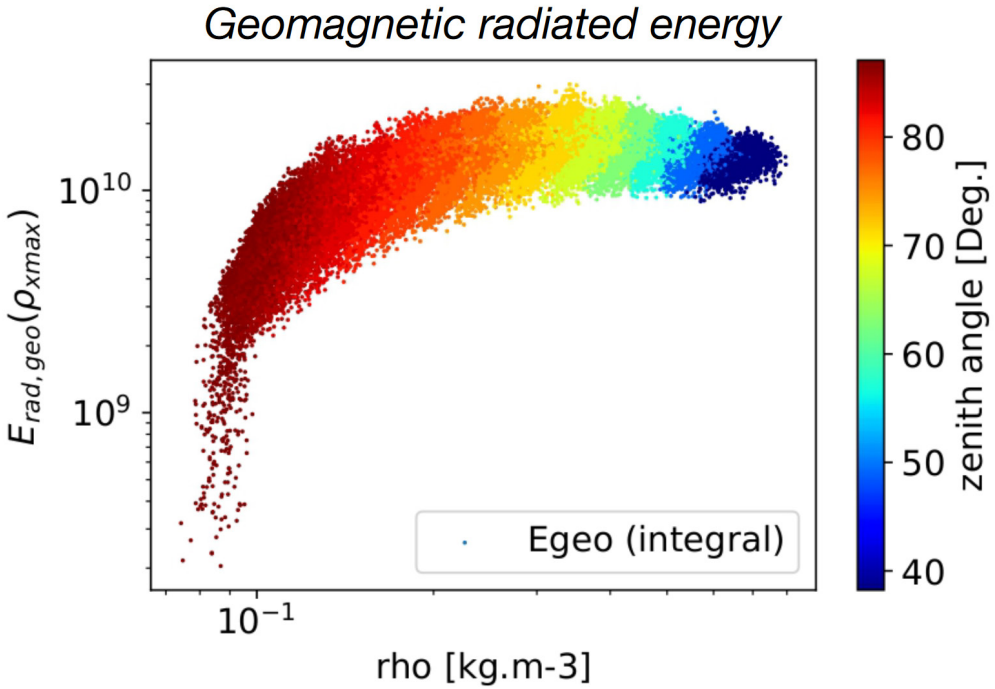
3.4-4.2 GHz

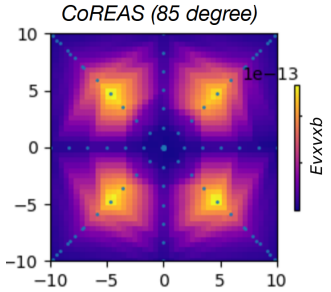


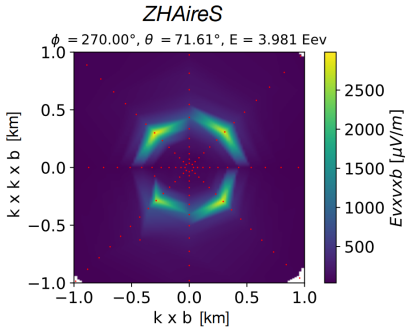
„***v*** x (v x ***B***)“

Huege & James, arXiv:1307.7566

Loss of coherence and change in polarization!



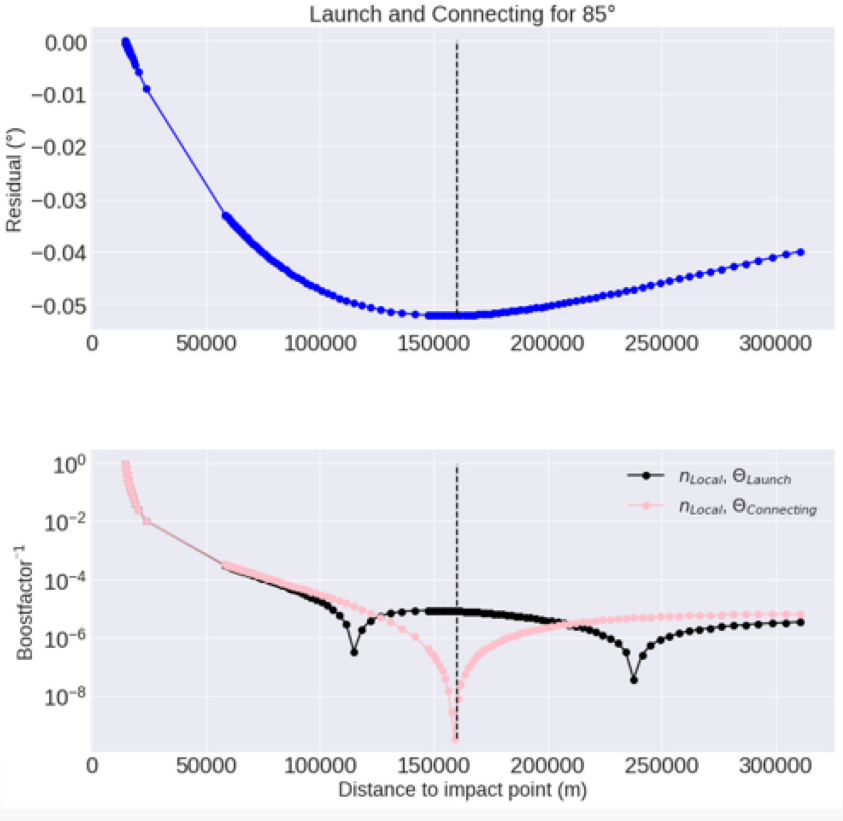




- plausible and „expected“ – but needs experimental confirmation
- to be accounted for in signal modelling efforts

see talk Simon Chiche

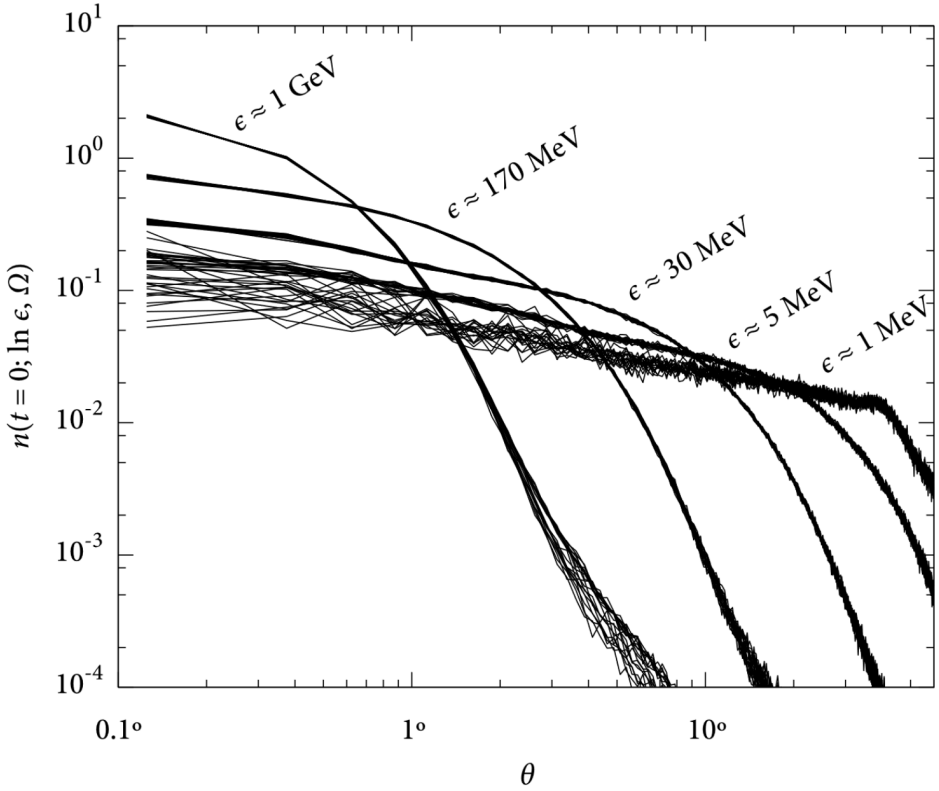
Approximations in code breaking down?



- good (non-trivial) result: 1-nβcos(θ) correctly describes the boost when using proper launch angle
- but CoREAS and ZHAireS use straight ray propagation, so wrong launch angle
- might significantly affect the „Cherenkov boost“, esp. at high frequencies?

see talk Dieder van den Broeck

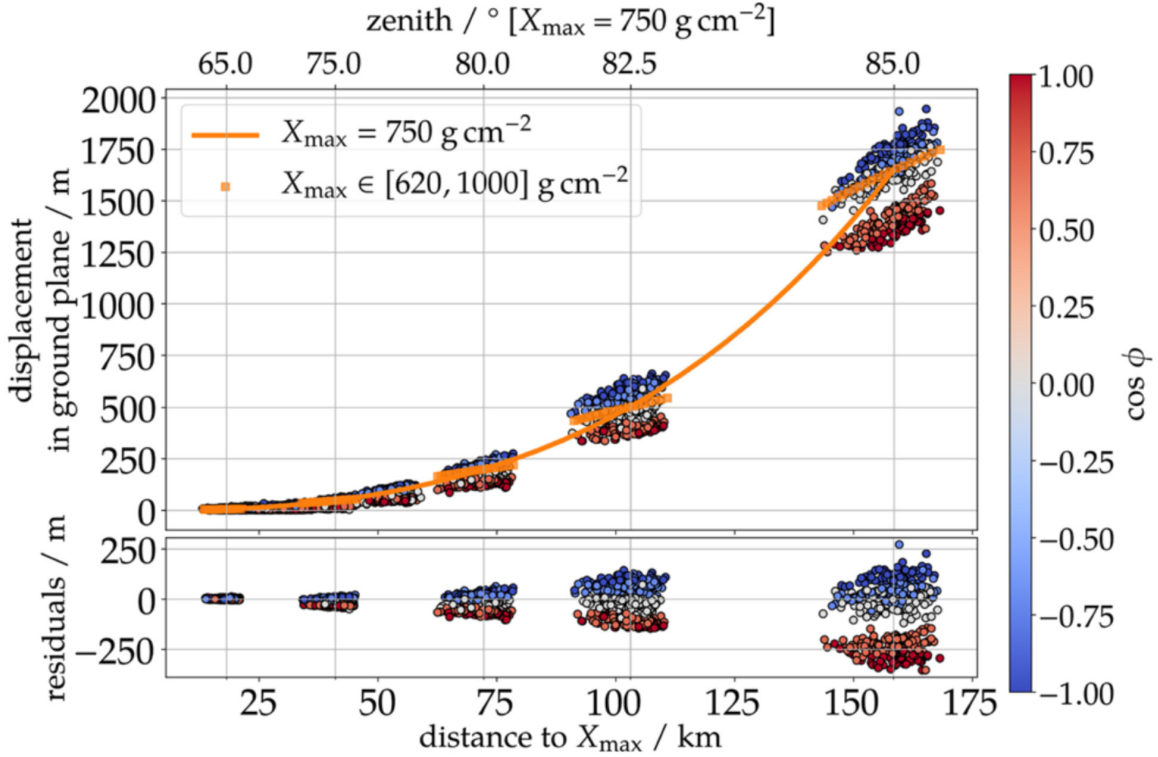
But particle momentum distributions are broad



- particle momentum distributions are much broader, O(°) as compared with O(1/100°) deviation between launch versus connecting angle
- my intuition: will wash out
- but beware angular resolution limitations

Lafebre et al., arXiv:0902.0548

Refractive displacement



- predicted – and mostly understood – in CoREAS simulations, but yet to be checked with data!

Schlüter, Gottowik, Huege, Rautenberg, arXiv:2005.06775

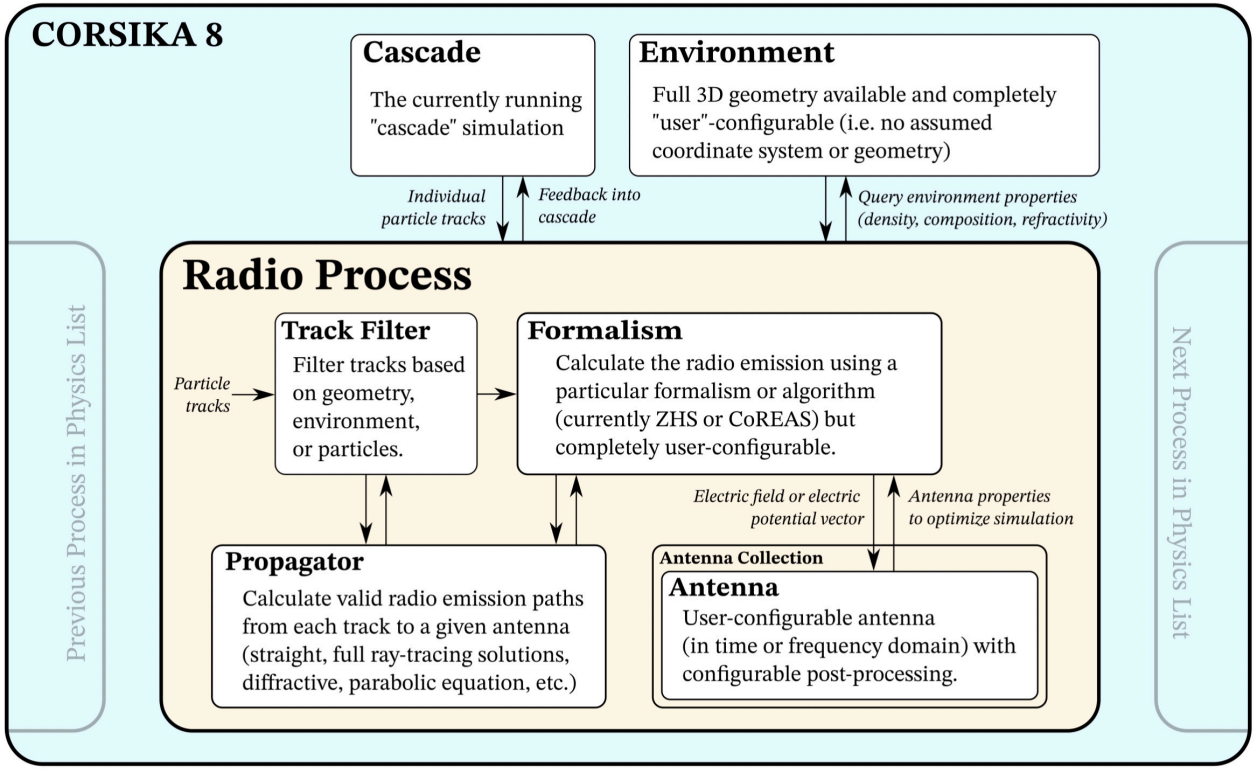
Summary inclined air showers

- very little data so far!
- agreement on average between AERA data and CoREAS simulations
- proper verification on simulation accuracy yet to be done
  - absolute signal strength
  - refractive core shift
  - appearance of synchrotron emission
  - coherence loss in strong magnetic fields
- possibly „unknown unknowns“, e.g. near-surface propagation effects

Future – CORSIKA 8

Radio-emission simulations

- radio emission from particle cascade fully implemented
- two time-domain formalisms ready: „CoREAS“ and „ZHS“
- *made* to include more complex cases (e.g., cross-media)



Radio-emission maps

- field strength & polarization match expectations
- some slight deviations
- a great tool to study details in emission calculations and EM cascade

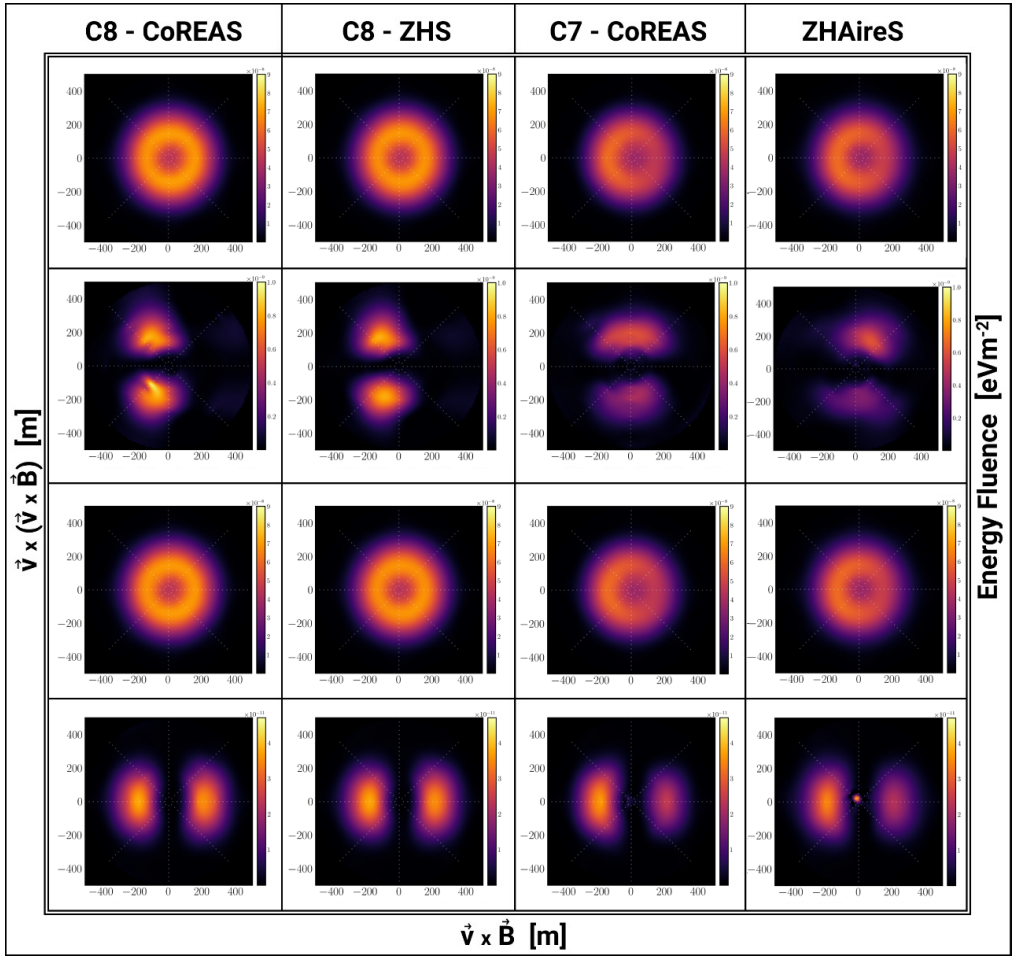
see talk Nikolaos Karastathis

modulus

$$\vec{v} \times \left(\vec{v} \times \vec{B}\right)$$

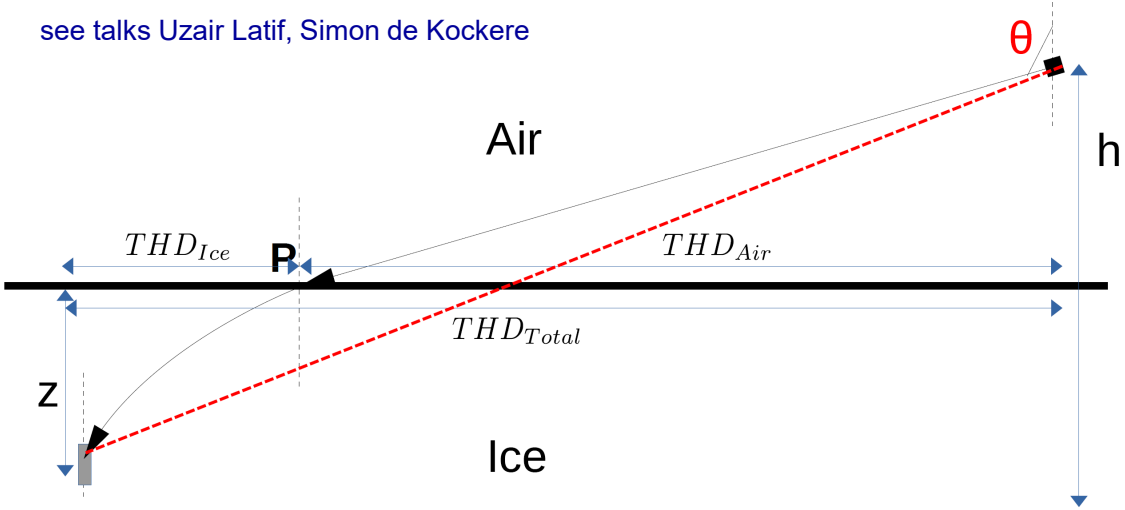
$$\vec{v} \times \vec{B}$$

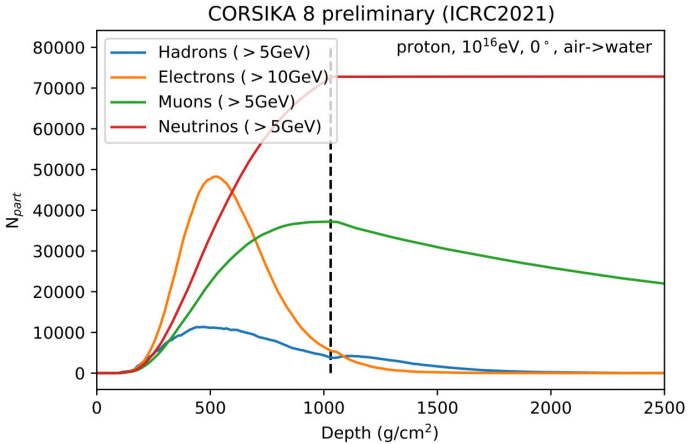
$$\vec{v}$$



Cross-media showers

see talks Uzair Latif, Simon de Kockere





R. Ulrich et al., arXiv:2112.11761

- very relevant for in-ice radio detection activities (background, calibration)
- so far piecing together modified CoREAS and modified GEANT4 sims
- in the future, natural to implement in CORSIKA 8

Conclusions

- air-shower radio simulations are in very good shape
- vertical air showers tested very thoroughly
  - CoREAS sims and LOFAR data agree very well at 30-80 MHz
  - SLAC T-510 data agree very well with sims, absolute scale matches
  - ZHAireS and CoREAS absolute radiation energies agree, but should check ZHAireS signal distributions against precision data
  - higher frequencies than 80 MHz not checked against precision data
- (very) inclined air showers less tested
  - potential breakdown of „straight ray“ approximation? I think unlikely
  - transition from transverse currents to synchrotron, loss of coherence!?
  - refractive displacement in data?
  - near-surface propagation effects?
- In the future, use CORSIKA 8 for complex scenarios and comparisons