Transition radiation from particle showers

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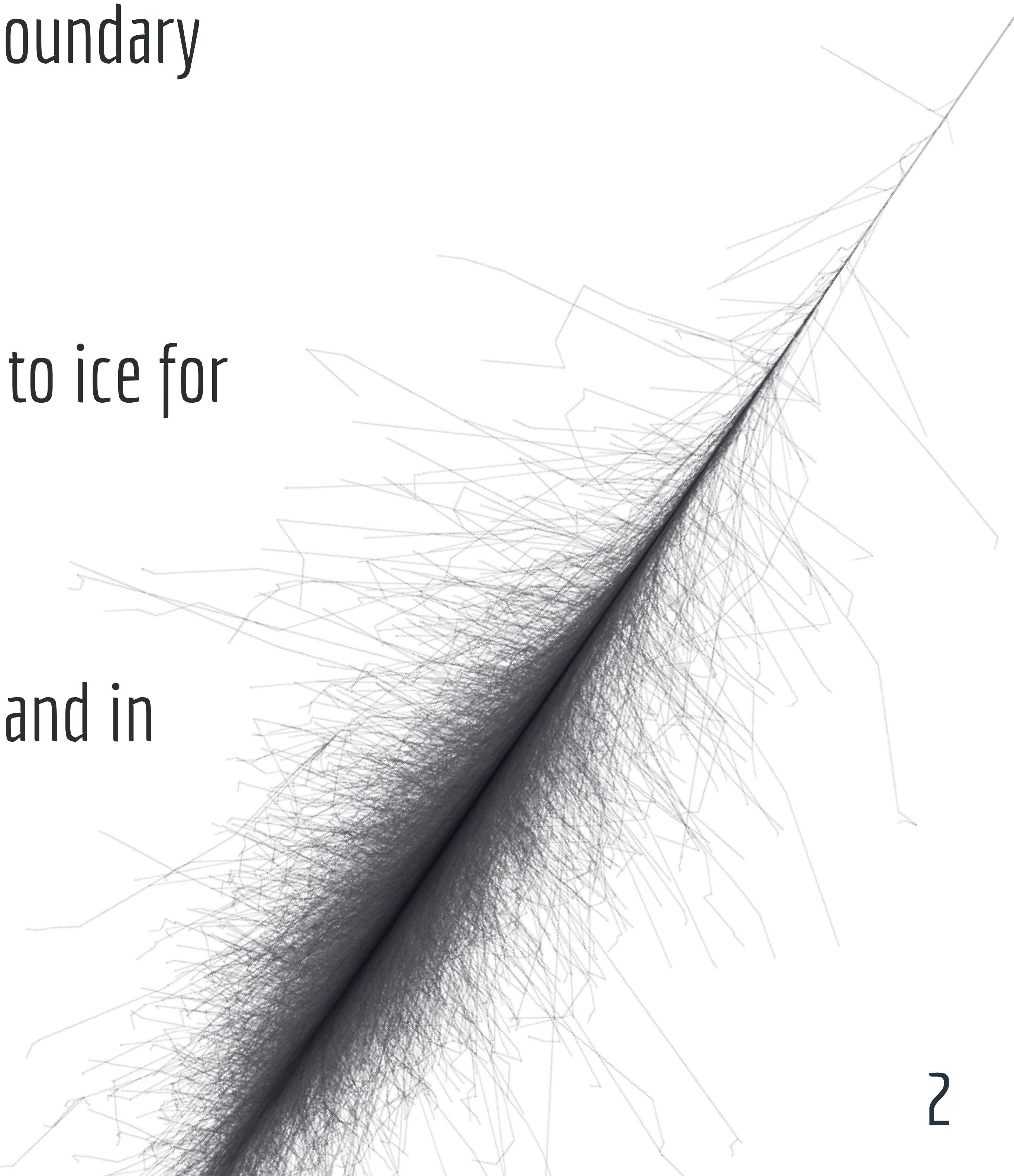
Introduction

- Transition Radiation (TR) is emitted when a particle crosses the boundary between two media with different dielectric properties.

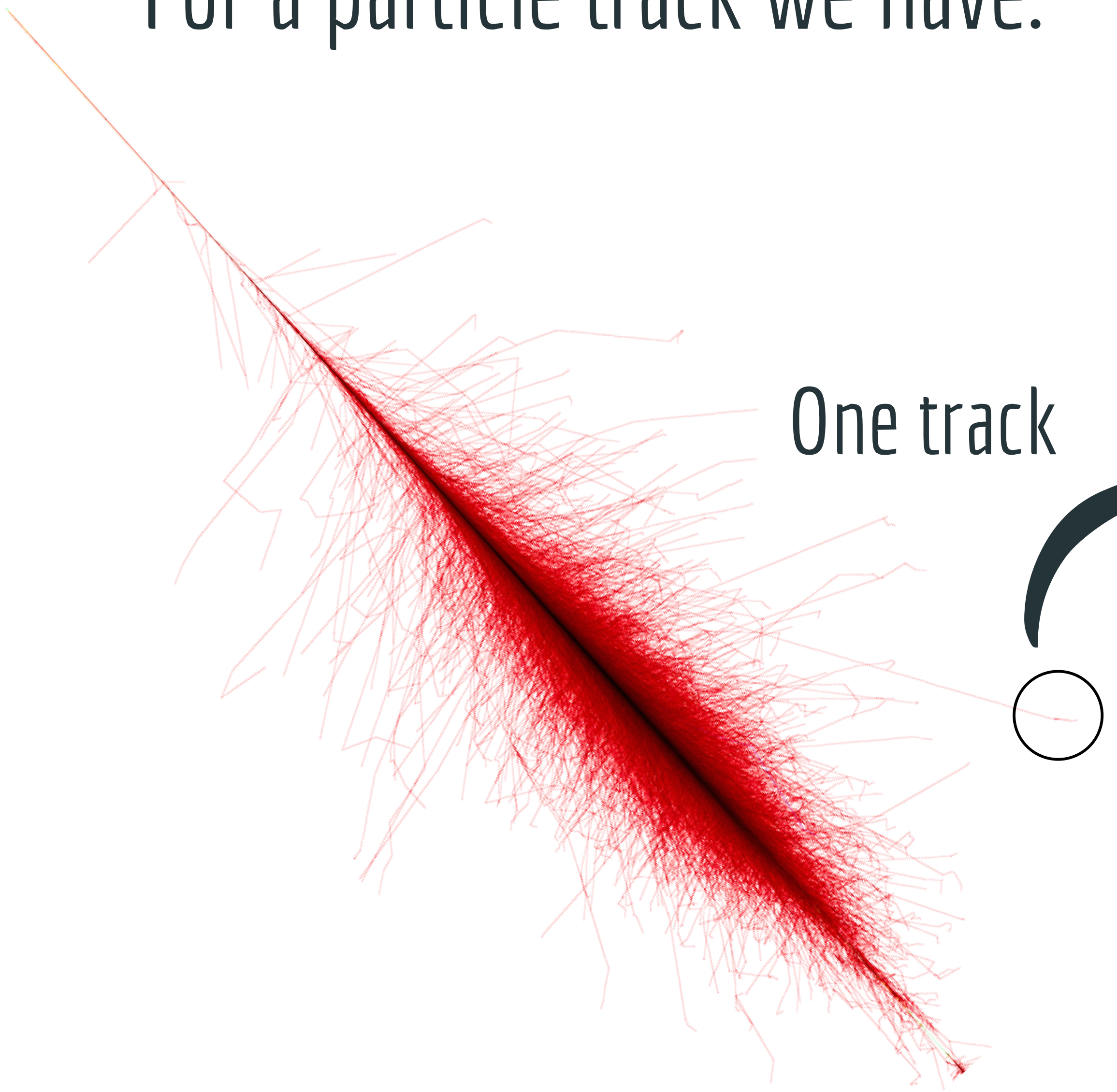
- This can happen when a particle shower traverses two media (air to ice for example).

- The radio emission strongly depends on the density of the media and in what media the observer is located.



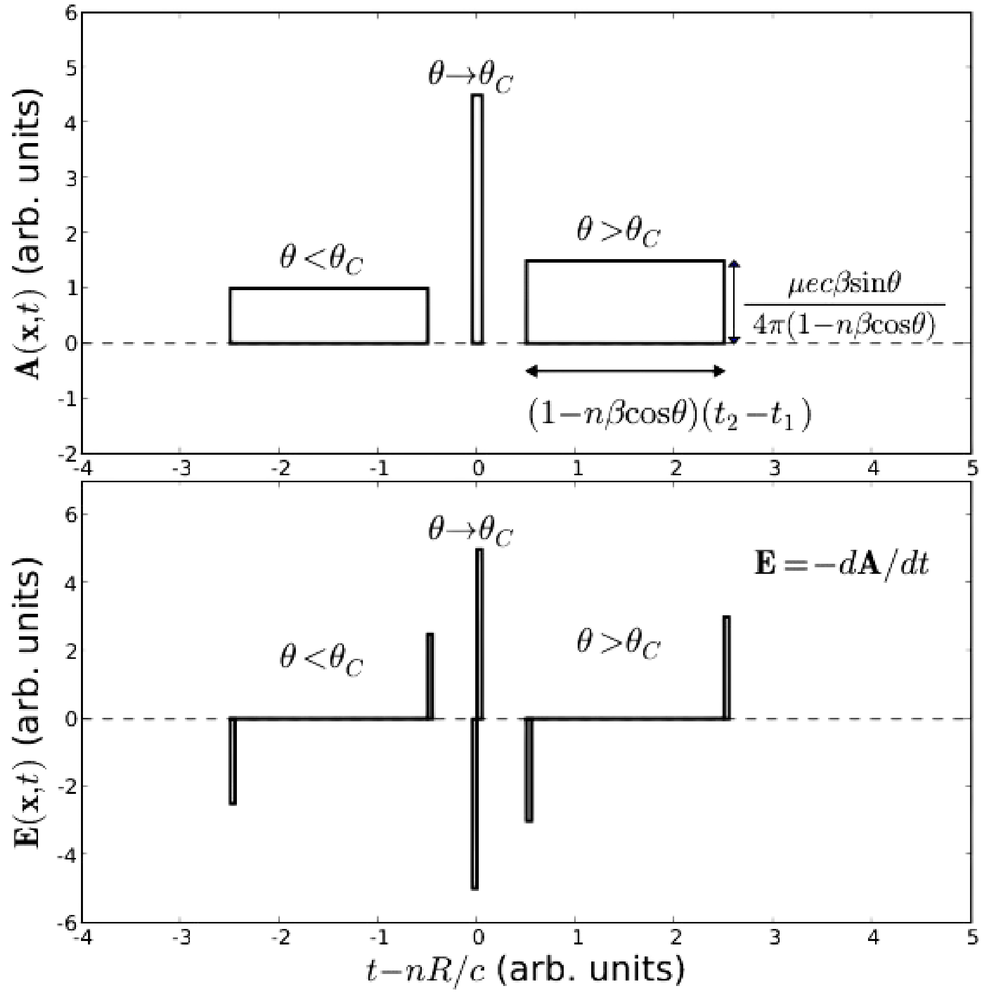
How can we study it with MC simulations?

- The electric field is calculated from the vector potential as E=-dA/dt .
- For a particle track we have:



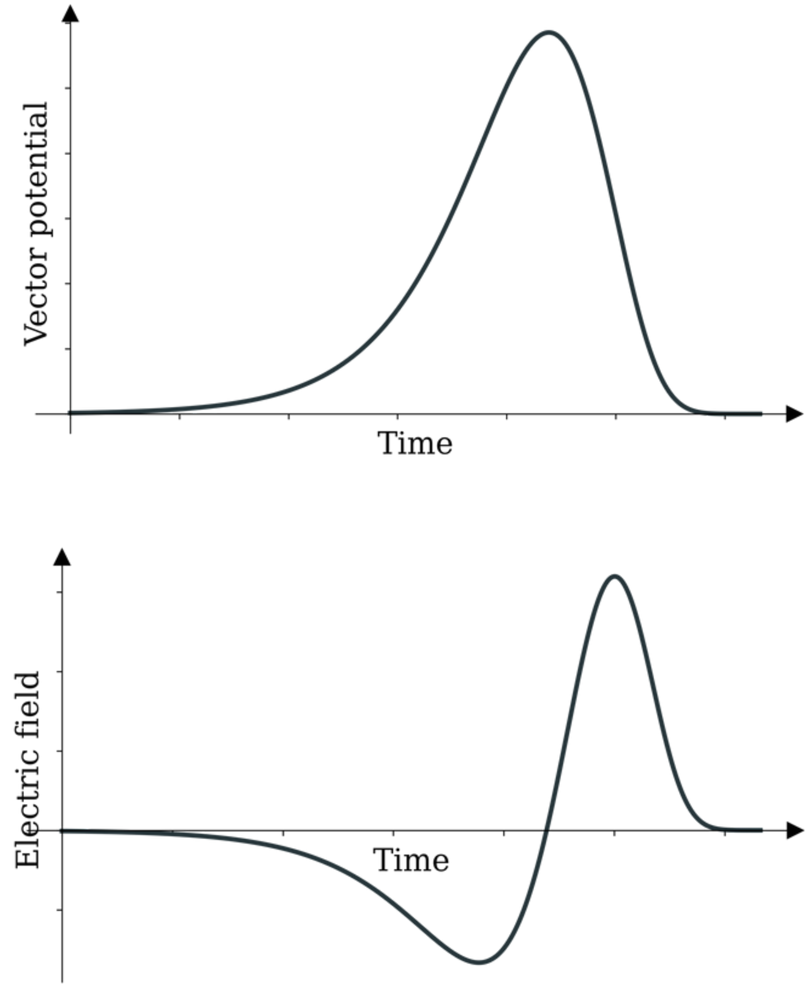
One track

ZHS algorithm



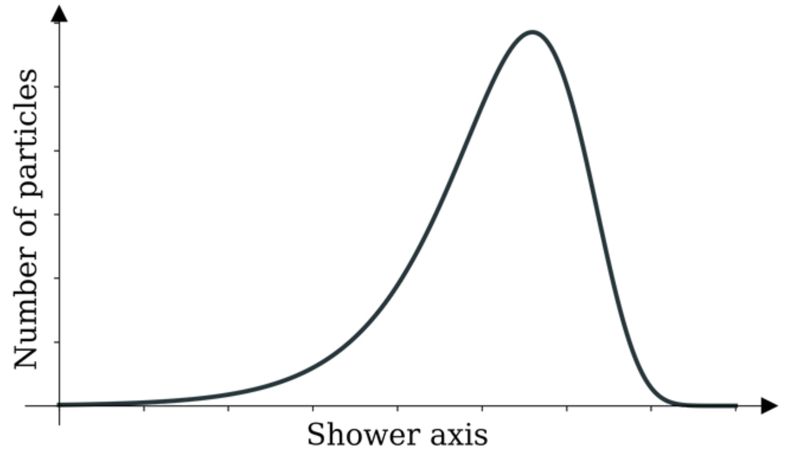
[J. Alvarez-Muniz, et al Phys. Rev. D 81, 123009 (2010).]

All tracks

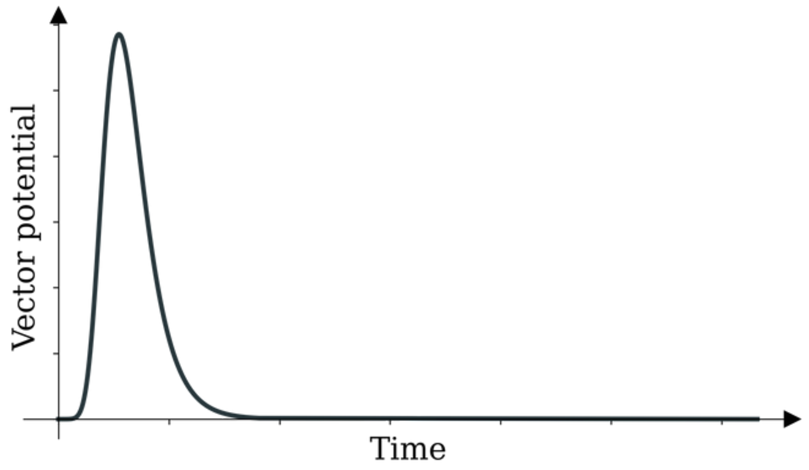


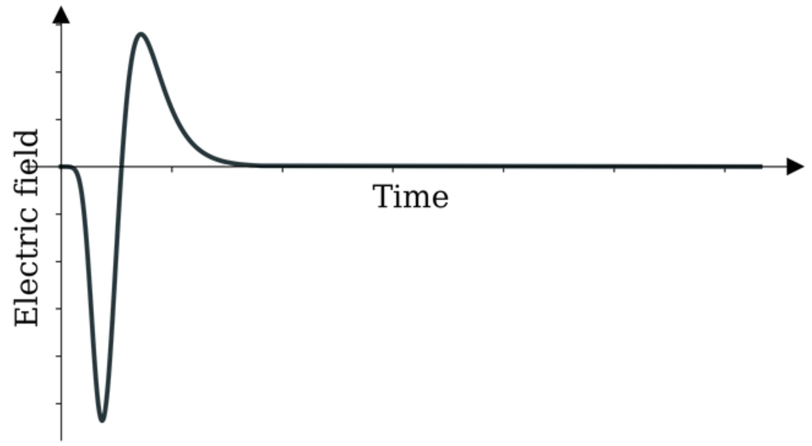
How can we study it with MC simulations?

- The position of the observer determines the shape of the Vp/EF:

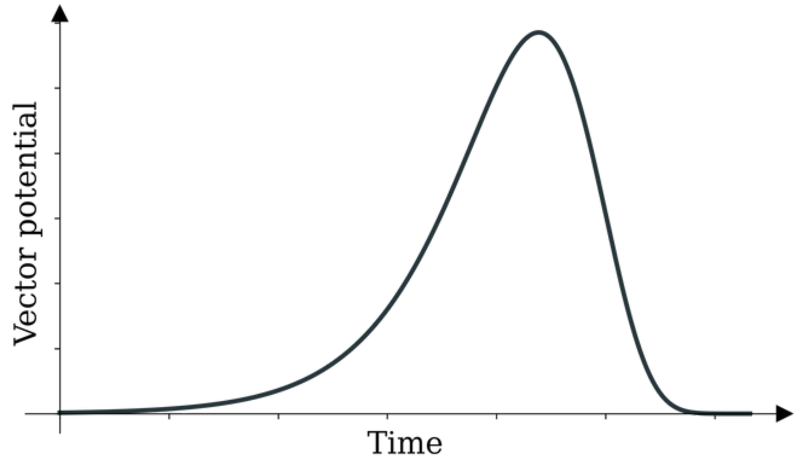


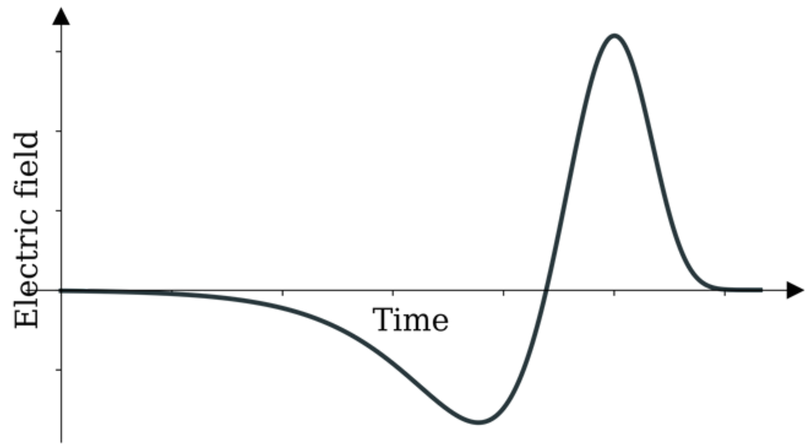
Inside Cerenkov cone





Outside Cerenkov cone



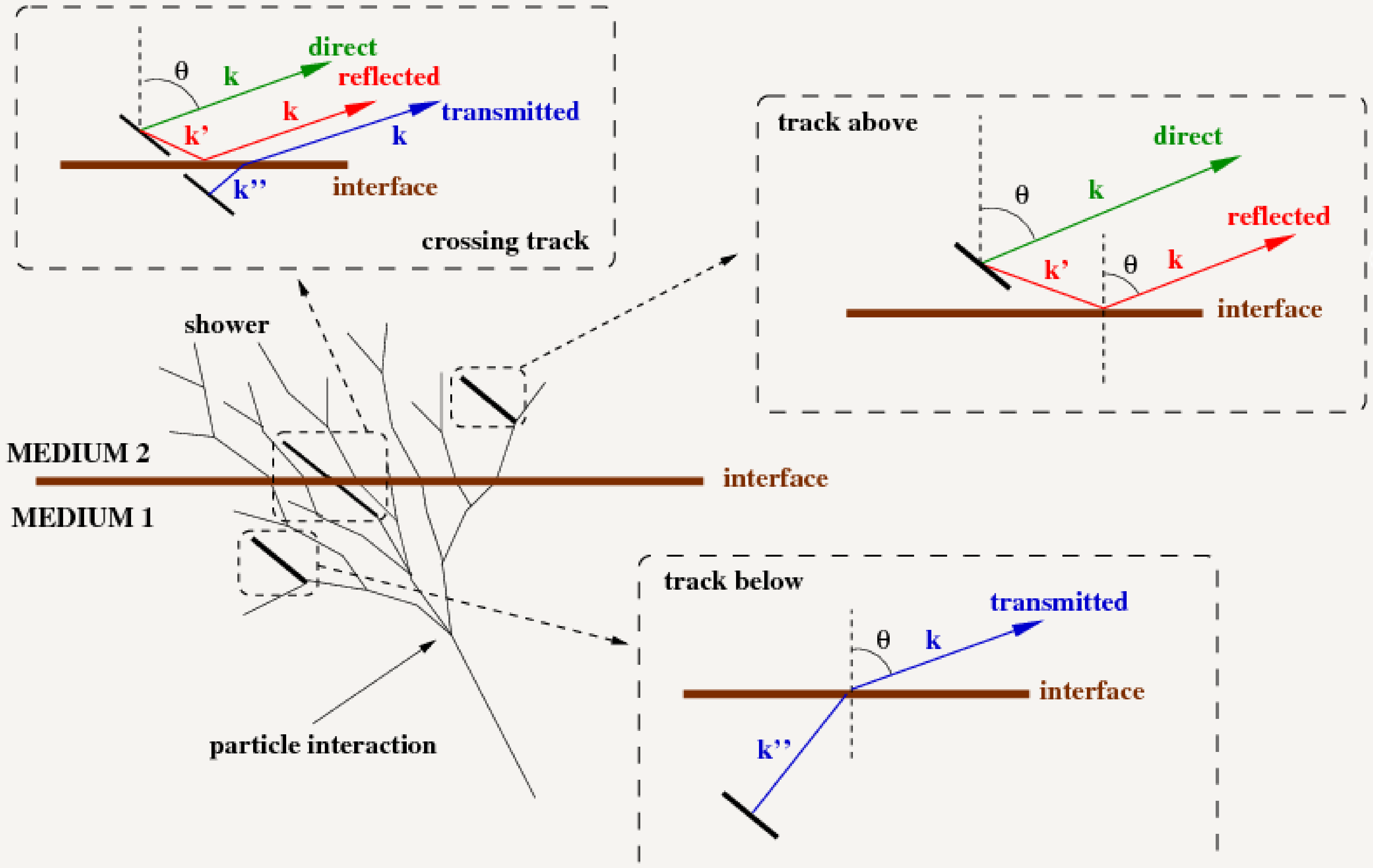


***One dimensional shower**

How do we deal with TR?

- We split the shower in two:
  1. **Direct** emission
  2. **Reflected** emission } Air tracks
  3. **Transmitted** emission ⟶ Ice tracks

[C. W. James, et al. PRE 84.5 (2011): 056602.]

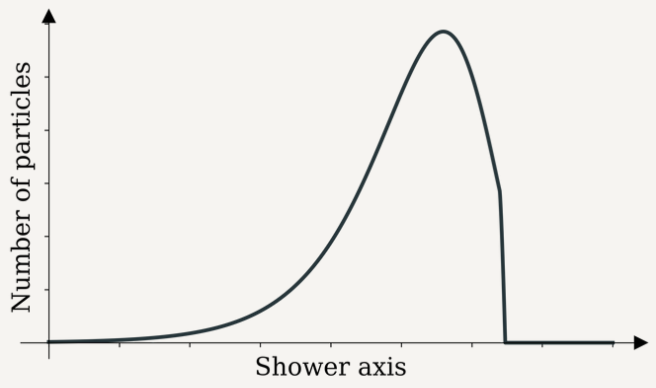


- TR arises from the non cancelling endpoints at the interface.

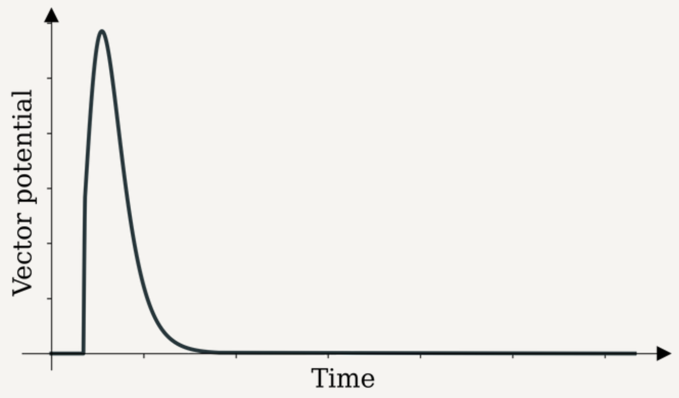
- The formalism makes the **separation of TR** from the shower **impossible.**

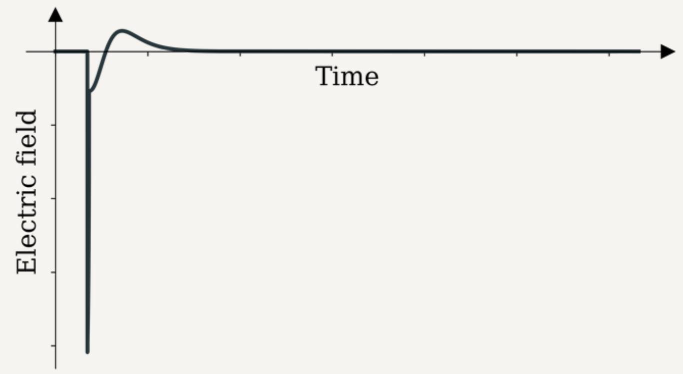
A simple view of TR from a particle shower

- Depending on the observer position, there is usually only one contribution from one media that is coherent.



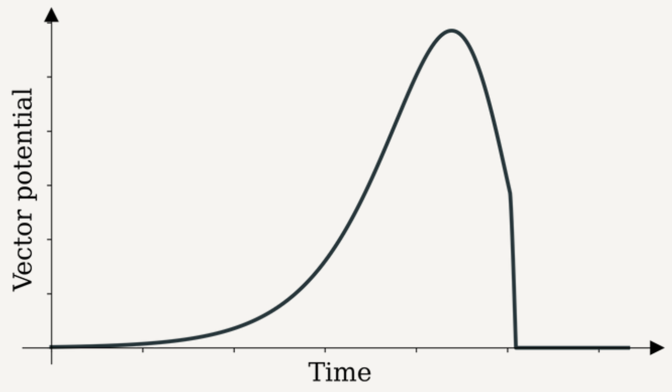
Inside Cerenkov cone

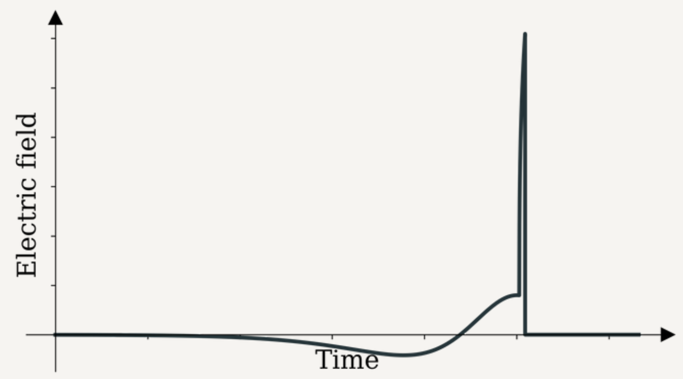




TR amplifies one of the peaks

Outside Cerenkov cone



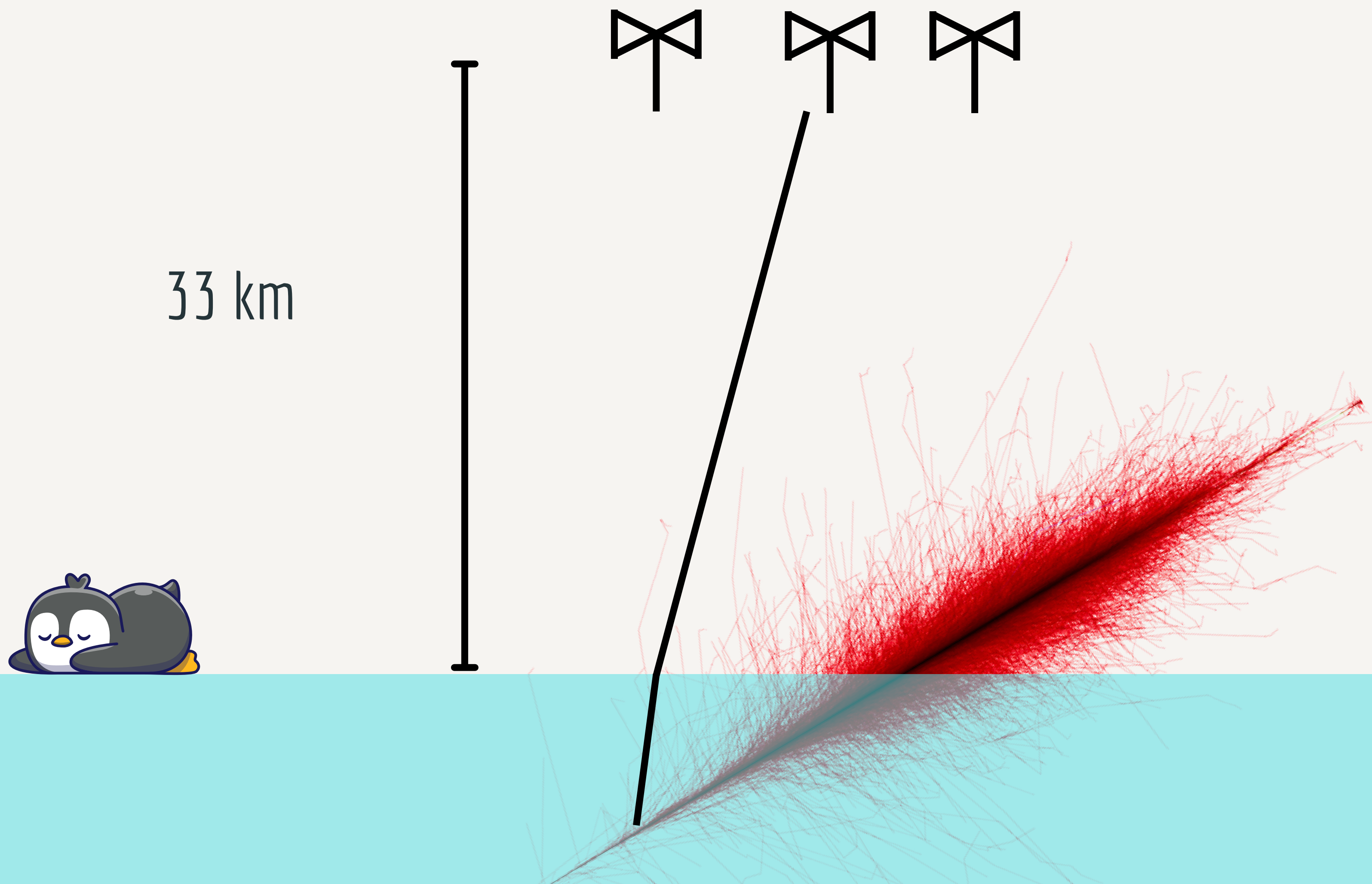


- Idea behind Krijn D. de Vries and Steven Prohira's paper Phys. Rev. Lett. 123, 091102.

Simulation set-up: ZHS-TR

- Modification of the ZHS MC: MC for coherent radio pulses from EM showers (homogeneous media).
  [E. Zas, et al., PRD 1992, 45, 362-376.]

- Splits the shower in two and has magnetic field deflections. [P. Motloch, et al. PRD 2016, 93, 043010.] [J. Ammerman-Yebra, *et al* JCAP08(2023)015.]



- 1 PeV e- at 60º with no thinning intersecting at Xmax, from ice to air.

- We will check positions inside and outside the refracted Cherenkov cone.

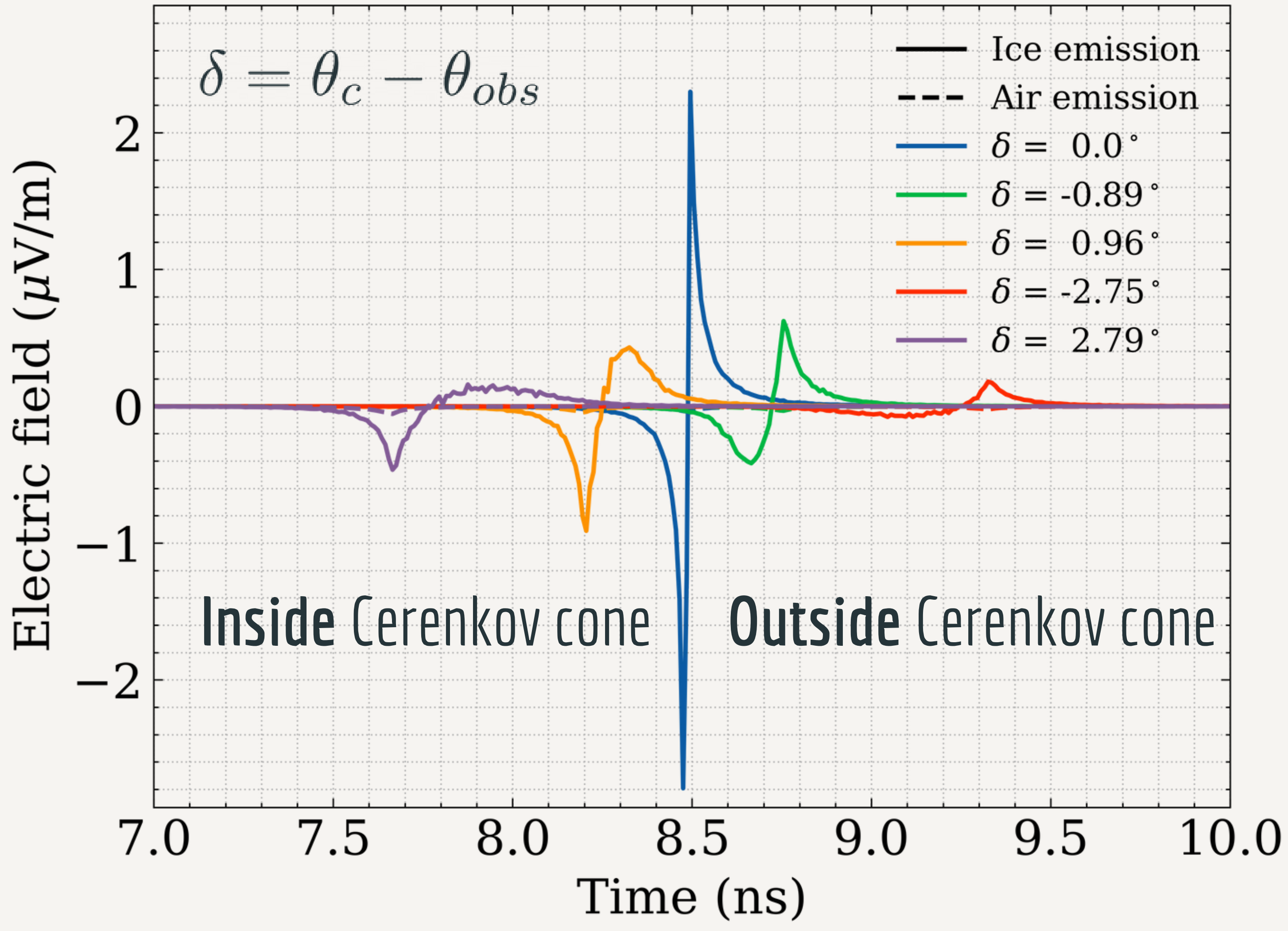
Results ice to air: near refracted Cherenkov cone

- Observer in Cherenkov angle ($\delta = 0$) sees the usual symmetric bipolar pulse from ice.

- As the observer moves away from the Cherenkov angle, the shape turns asymmetric.

- The asymmetry in the pulse reflects the asymmetric longitudinal profile in the ice.

Z polarization (vertical)

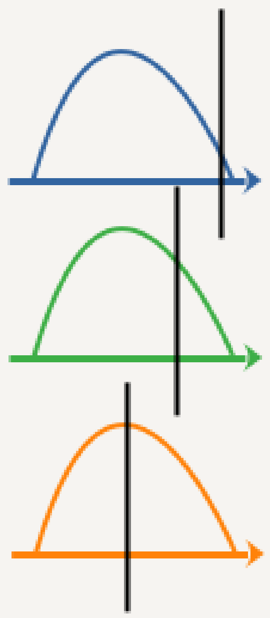


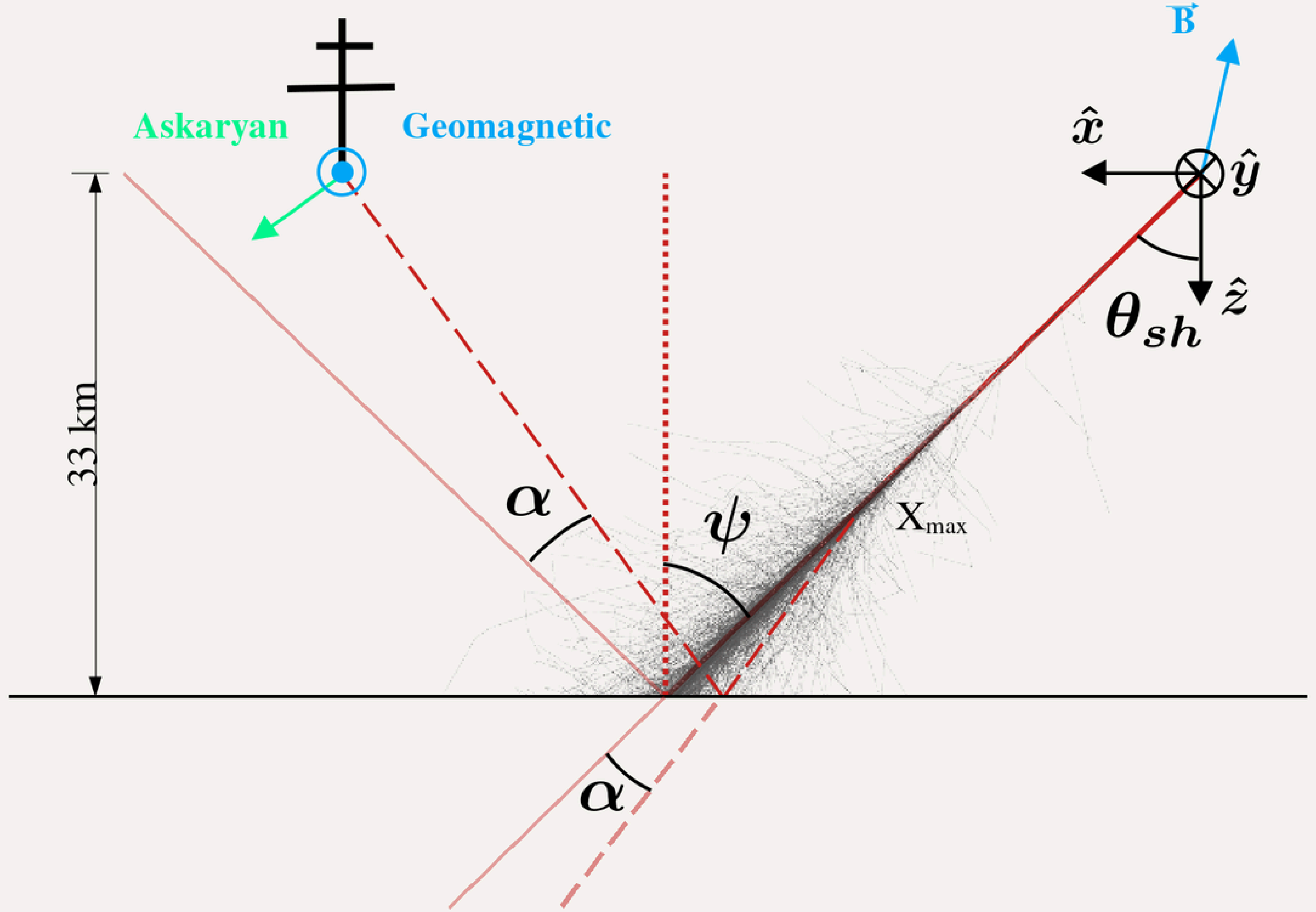
Transition radiation from air to ice

- 55º 1 PeV electron shower (35º elevation).
- Only contribution from the air tracks.

- X polarization -> Askaryan
- Y polarization -> Geomagnetic

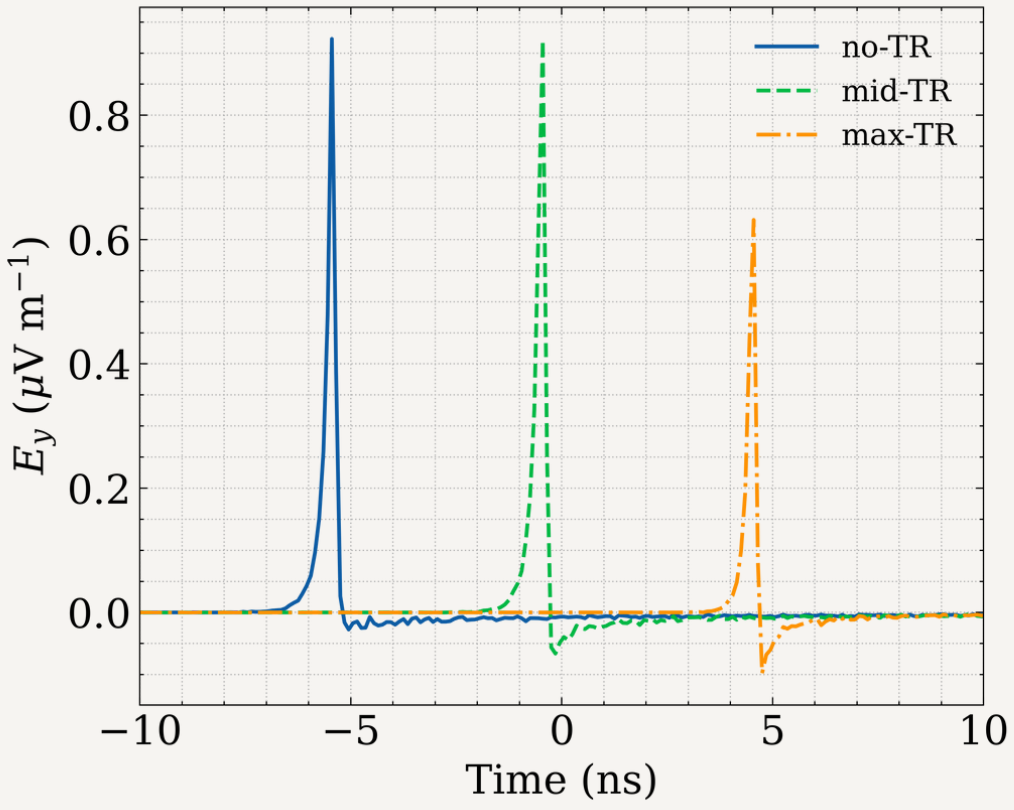
- Three cases:
  - No TR
  - Mid TR
  - Max TR



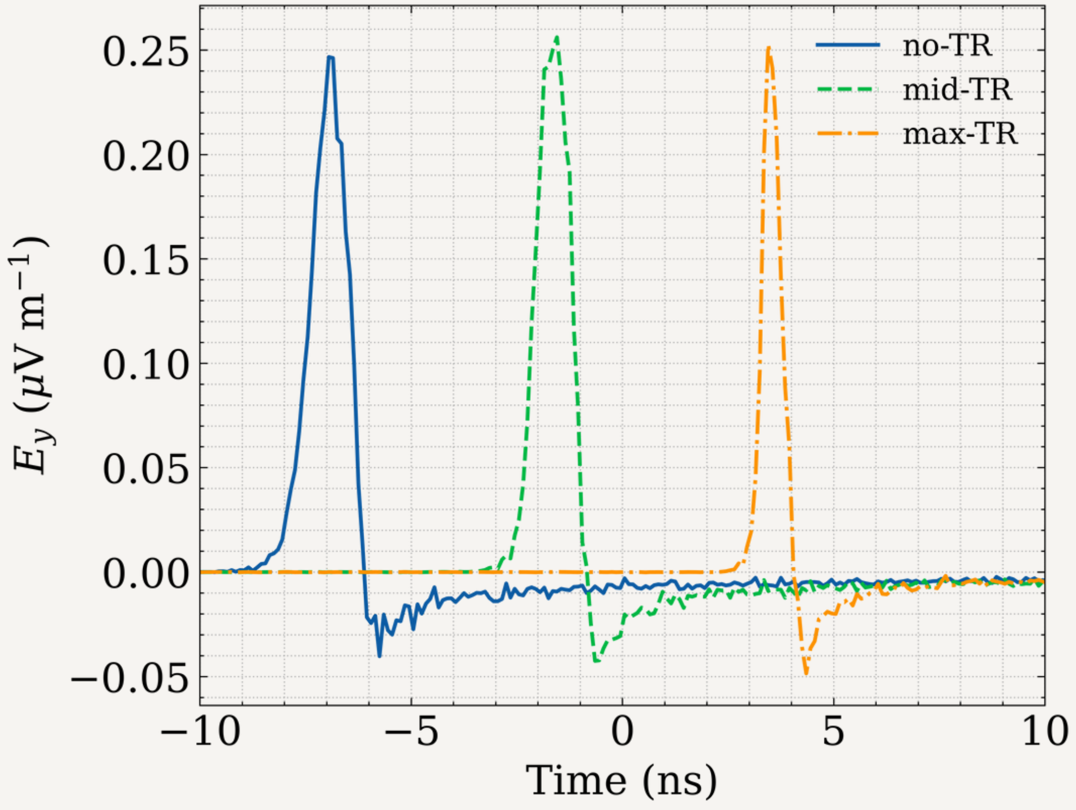


Results: TR at different positions

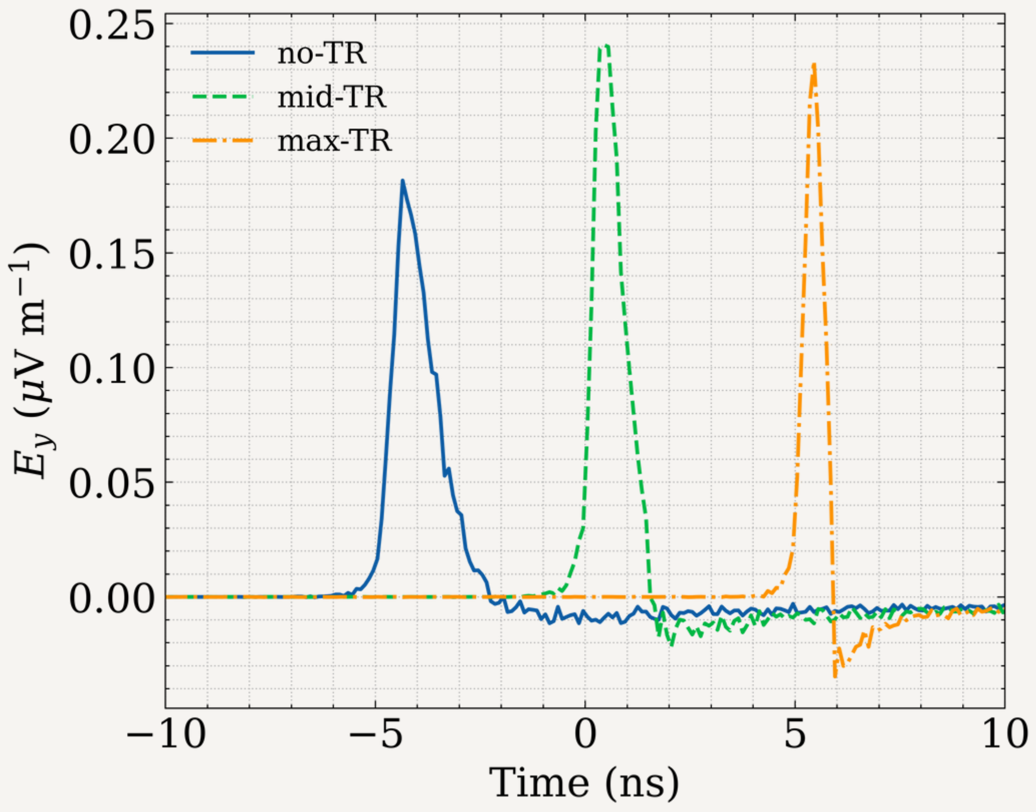
- All radio pulses are quite similar and with same the same polarity.
- Intercepting the ice surface causes a sudden change in vector potential resulting in narrower pulses than showers with no TR.



Cerenkov cone (1.22º)



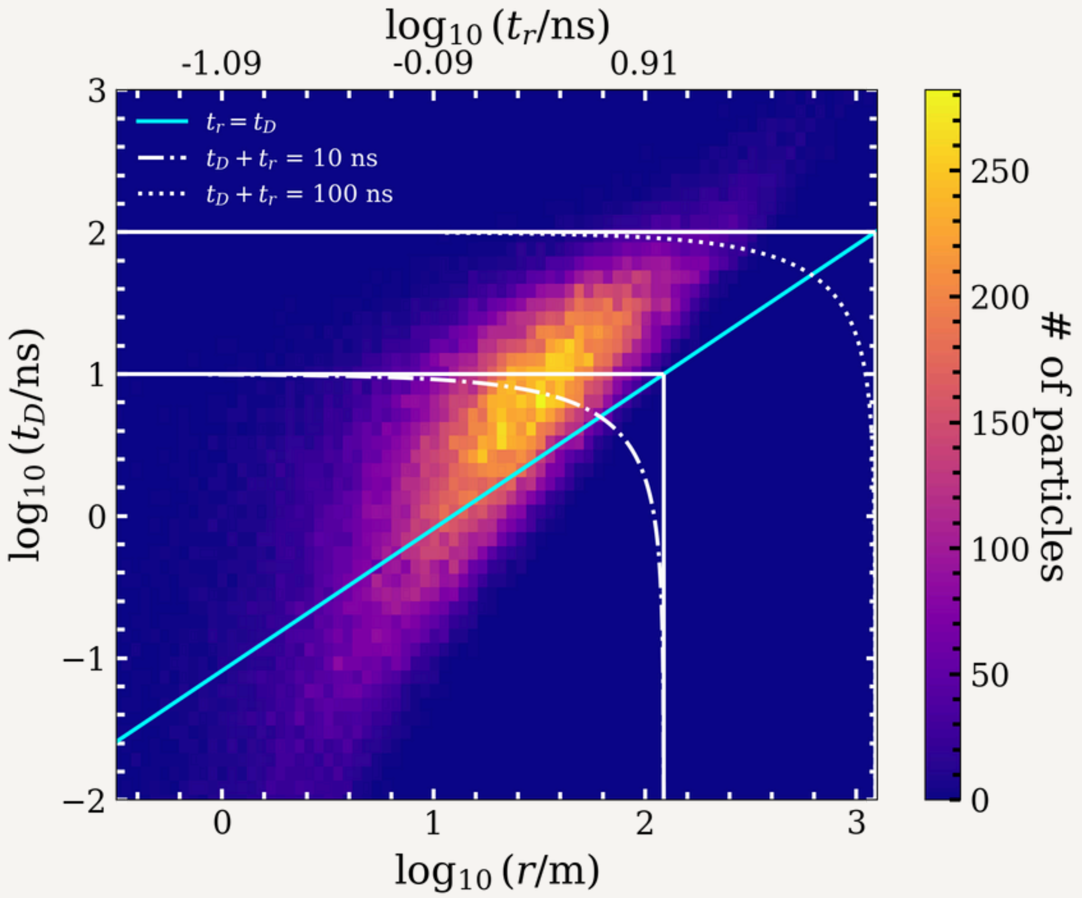
Inside Cerenkov cone (1.02º)



Outside Cerenkov cone (1.42º)

What is going with the polarity?

Time delays of the shower front prevent the time inversion of the Vp from happening.



Typical particle time delays at shower max for an air shower

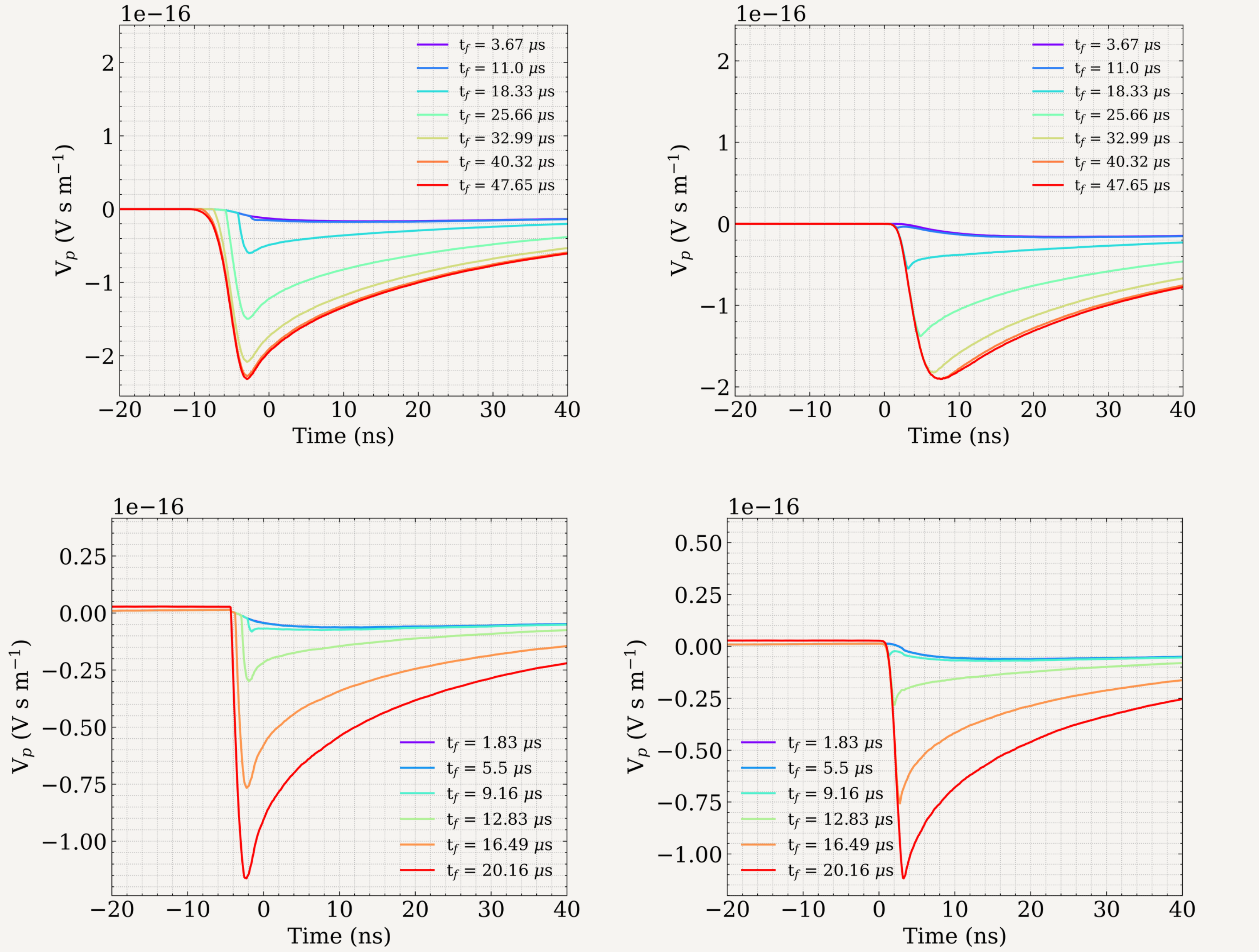
[J. Ammerman-Yebra, *et al* JCAP08(2023)015.]

Time evolution of the vector potential

Inside Cerenkov cone (0°) | Outside Cerenkov cone (1.7°)

No TR

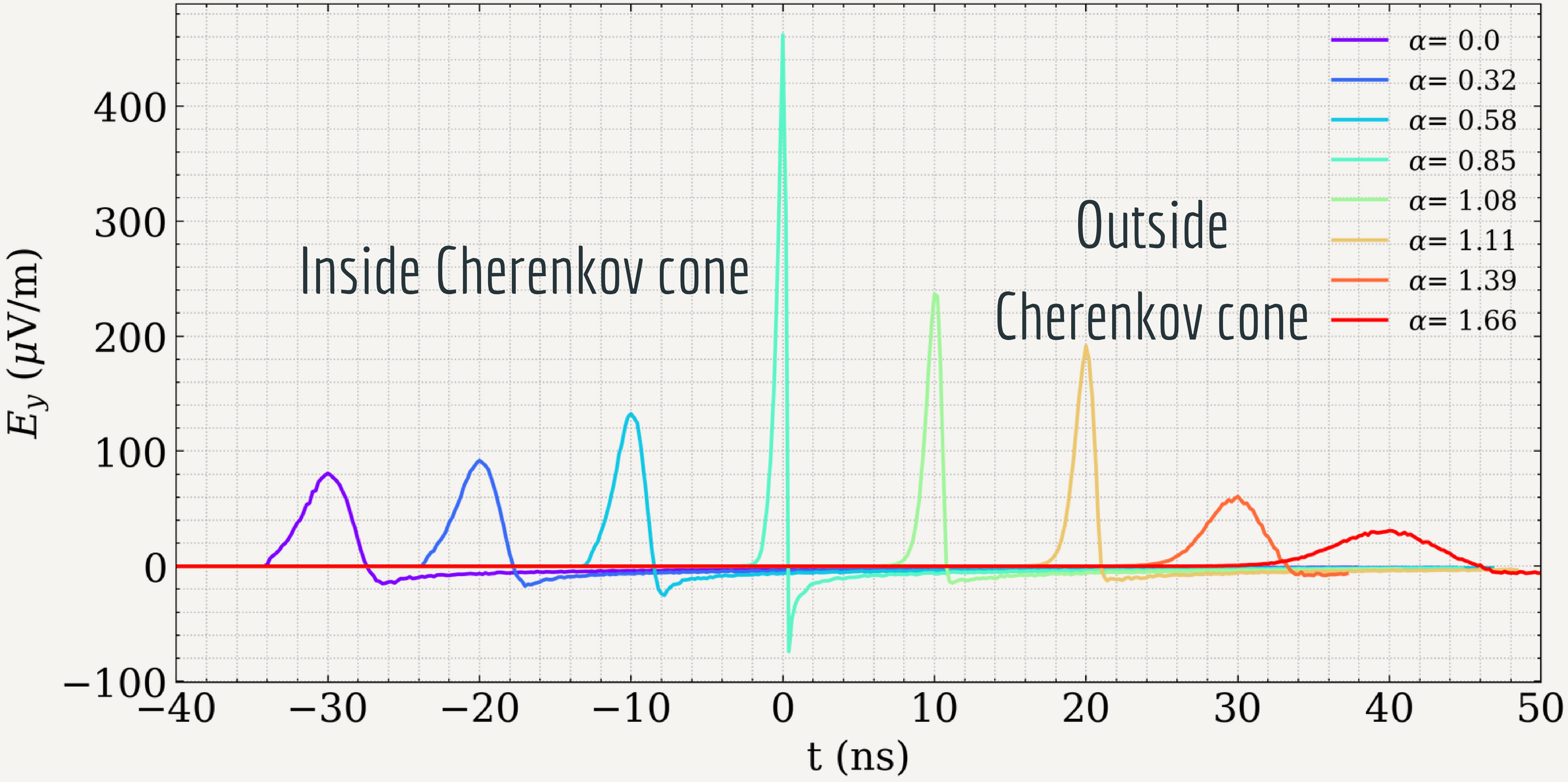
With TR (max TR)



1 PeV e- shower at 55°

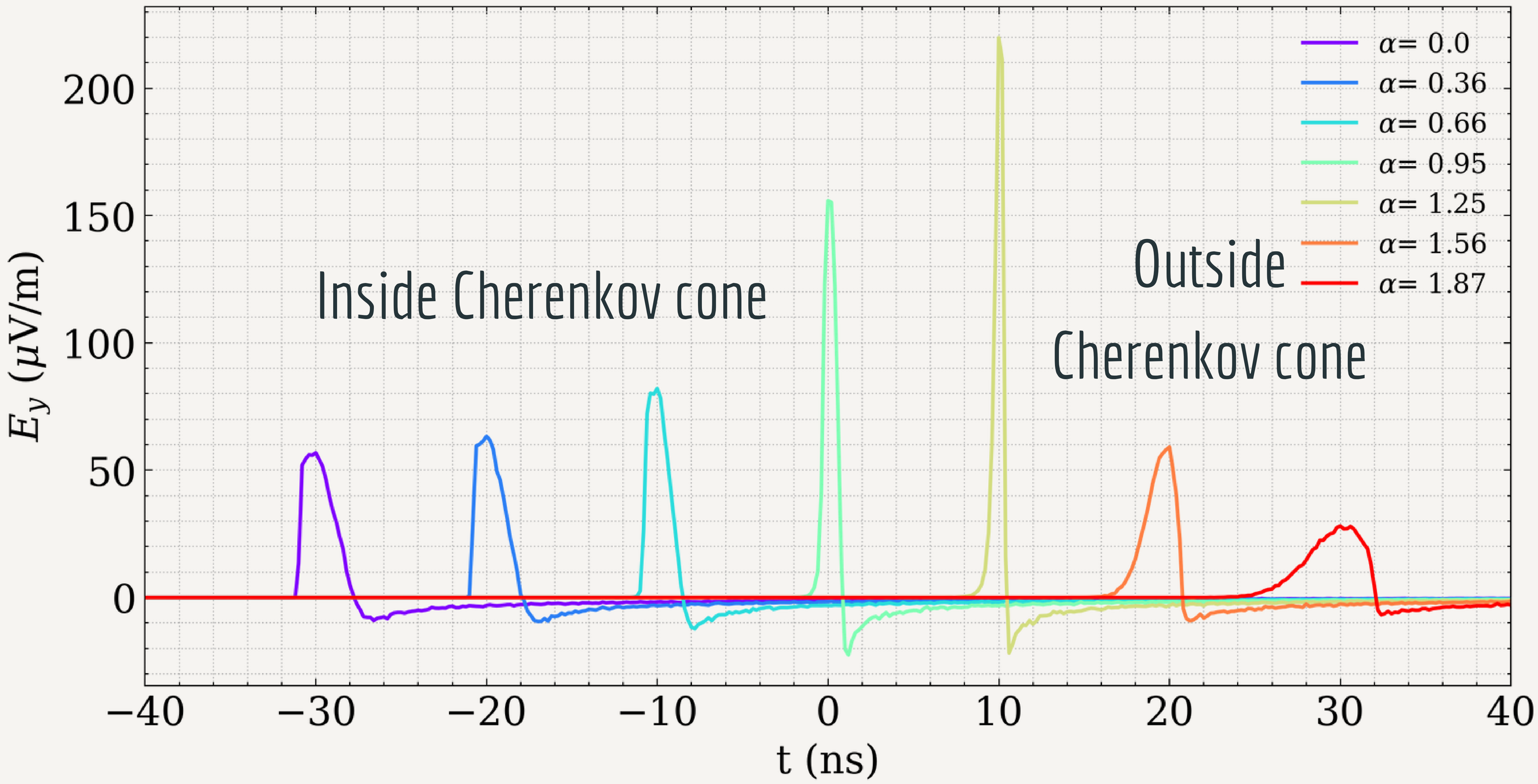
Results: Realistic scenario, ZHAireS reflex

- Modified version of ZHAireS to calculate the reflected emission.
- 55°, 1 EeV proton in realistic atmosphere. Injection altitude: 100 km.



Results: Max-TR with ZHAireS reflex

- 55º, 1 EeV proton. Injection altitude: 10 km (not a realistic interaction point but we get max TR).
- Intercepts the ice surface at approximately shower maximum.



Results summary

- TR in showers ice->air and air->ice have been studied with detailed MC simulations.

- The coherence of the transition radiation emitted by a particle shower depends greatly on the medium's density.

- Even with TR, the radio emission is beamed near the Cerenkov angle, as in a normal shower.

- For a shower from ice to air there is an inversion of the highest peak of the pulse between an observer inside and outside the refracted Cherenkov cone.

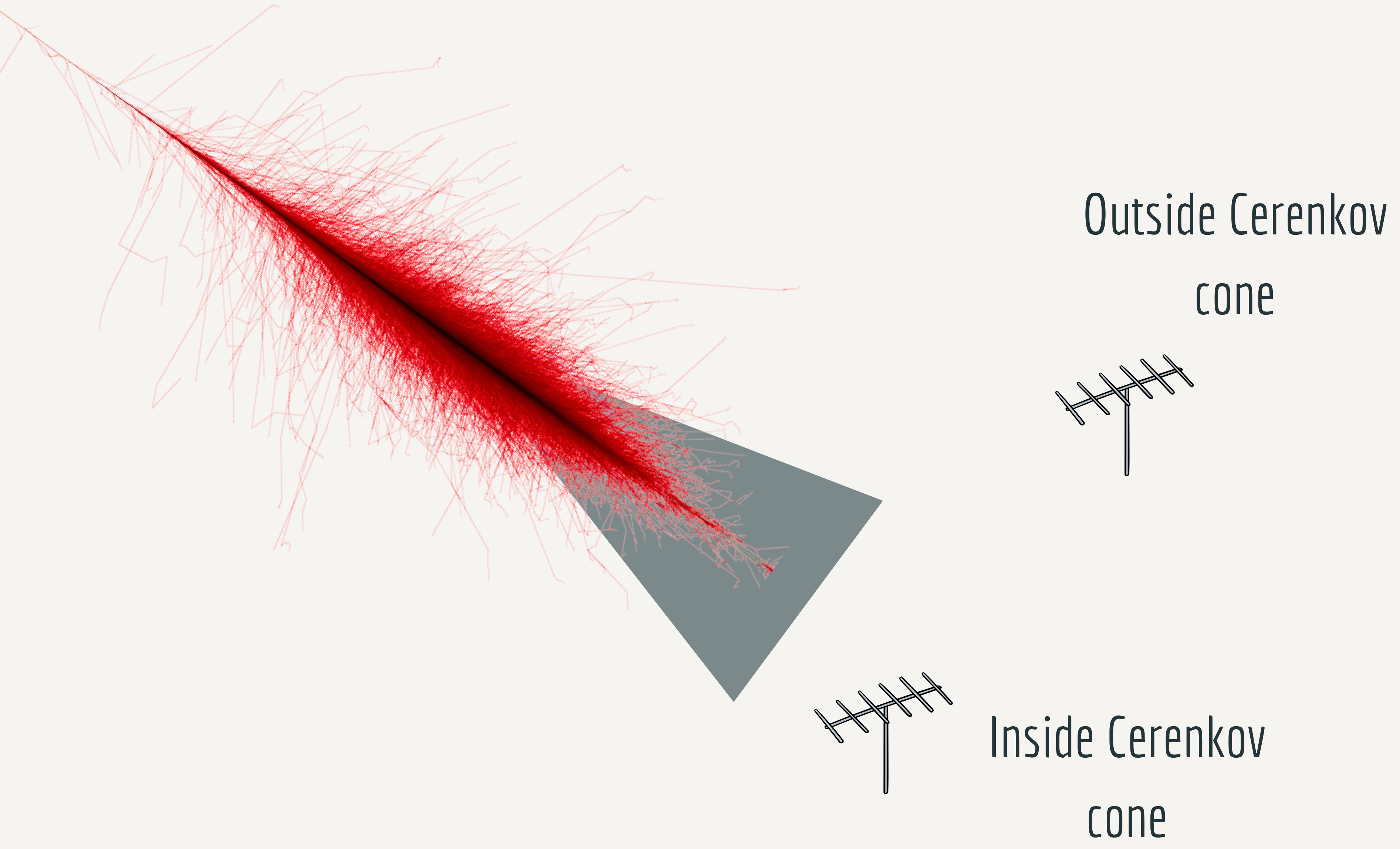
- A detailed simulation shows no polarity inversion in TR for an observer inside or outside the Cherenkov cone for a shower from air to ice with the observer in the air.

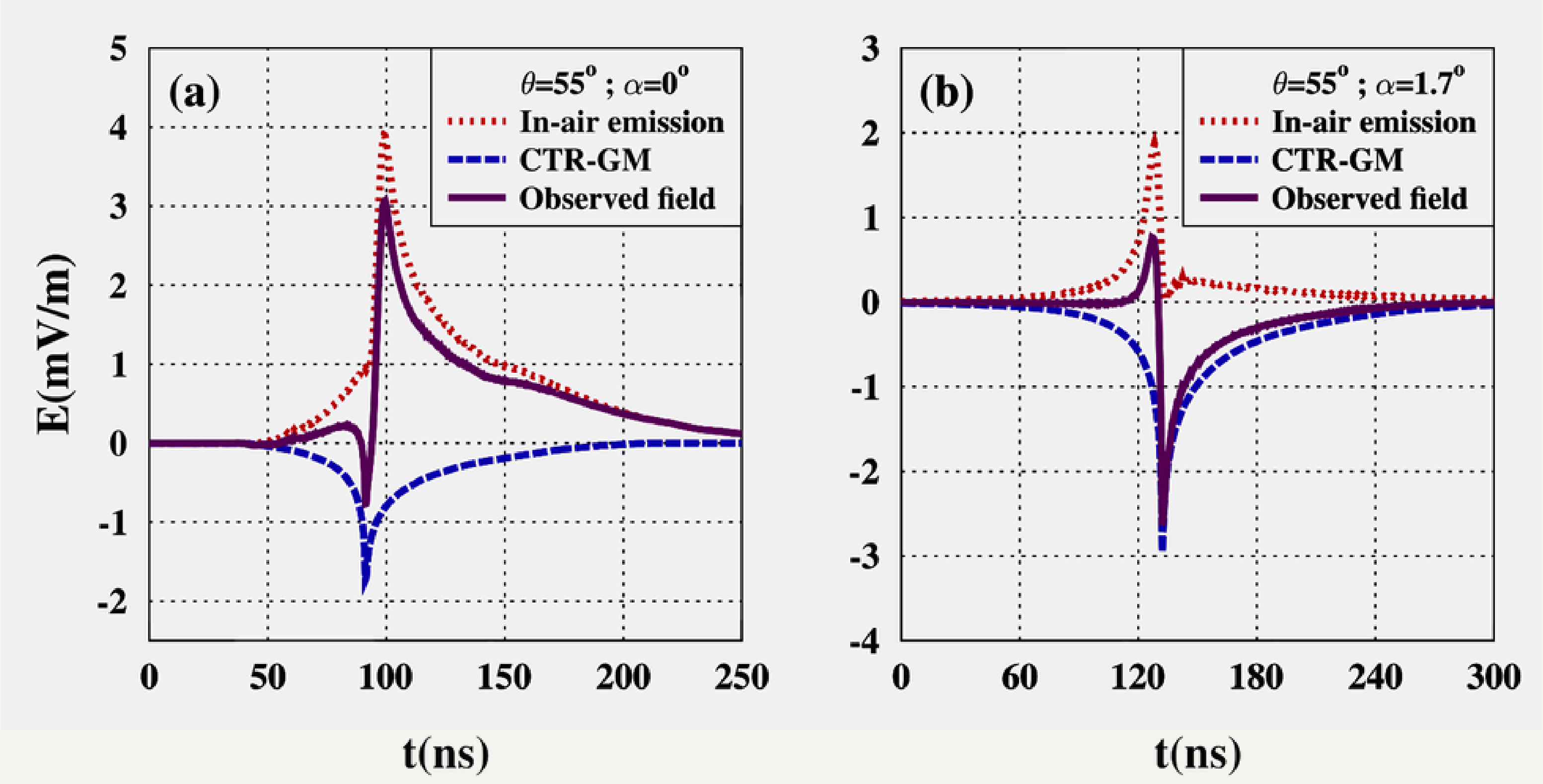
Back-up slides

TR from air to ice

Semi-analytical calculation. [de Vries, K. & Prohira, S., Phys. Rev. Lett. 2019, 123, 091102.]

Results suggest a **polarity reversal** between observers **inside** and **outside** the **Cerenkov cone**.





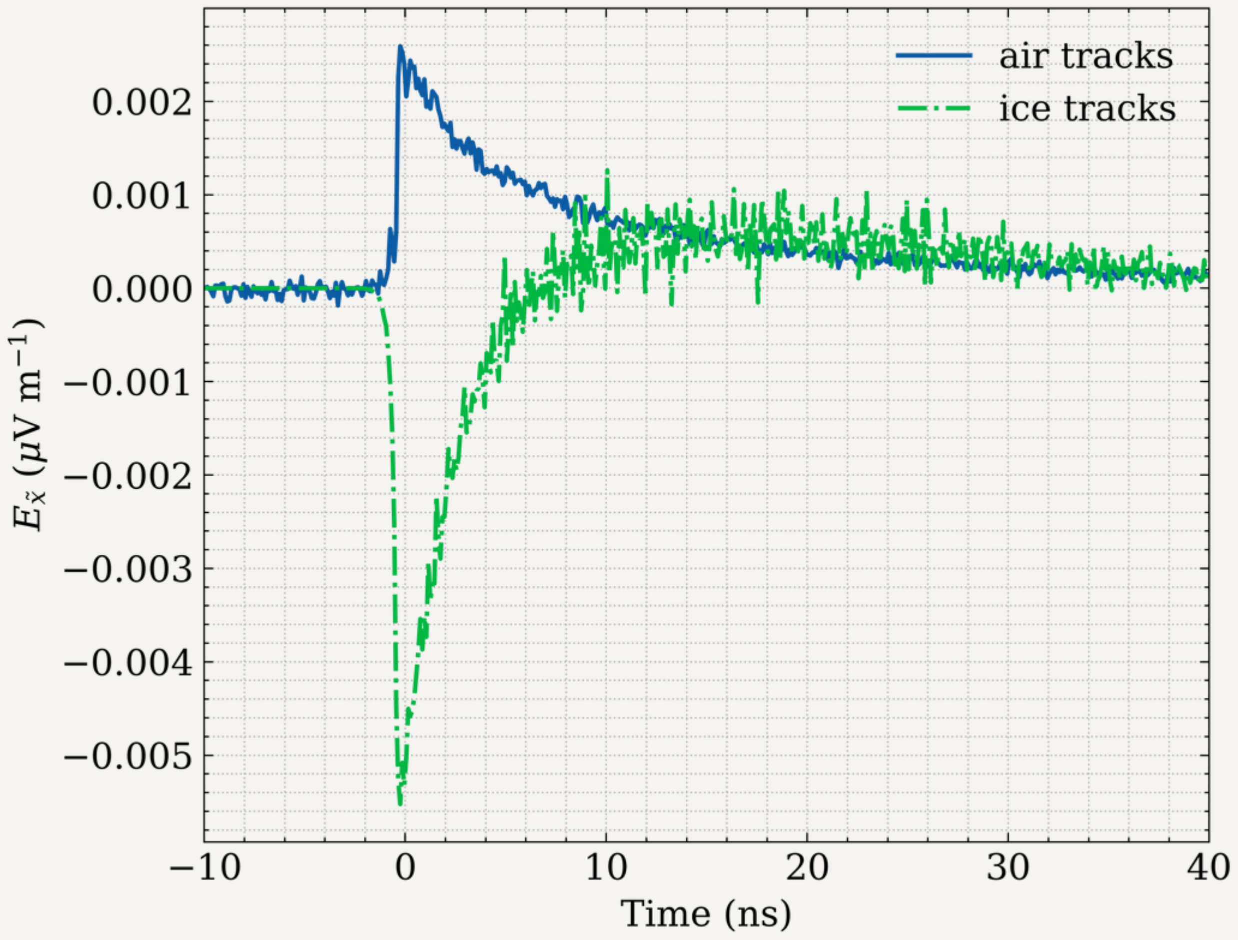
Inside Cerenkov cone

Outside Cerenkov cone

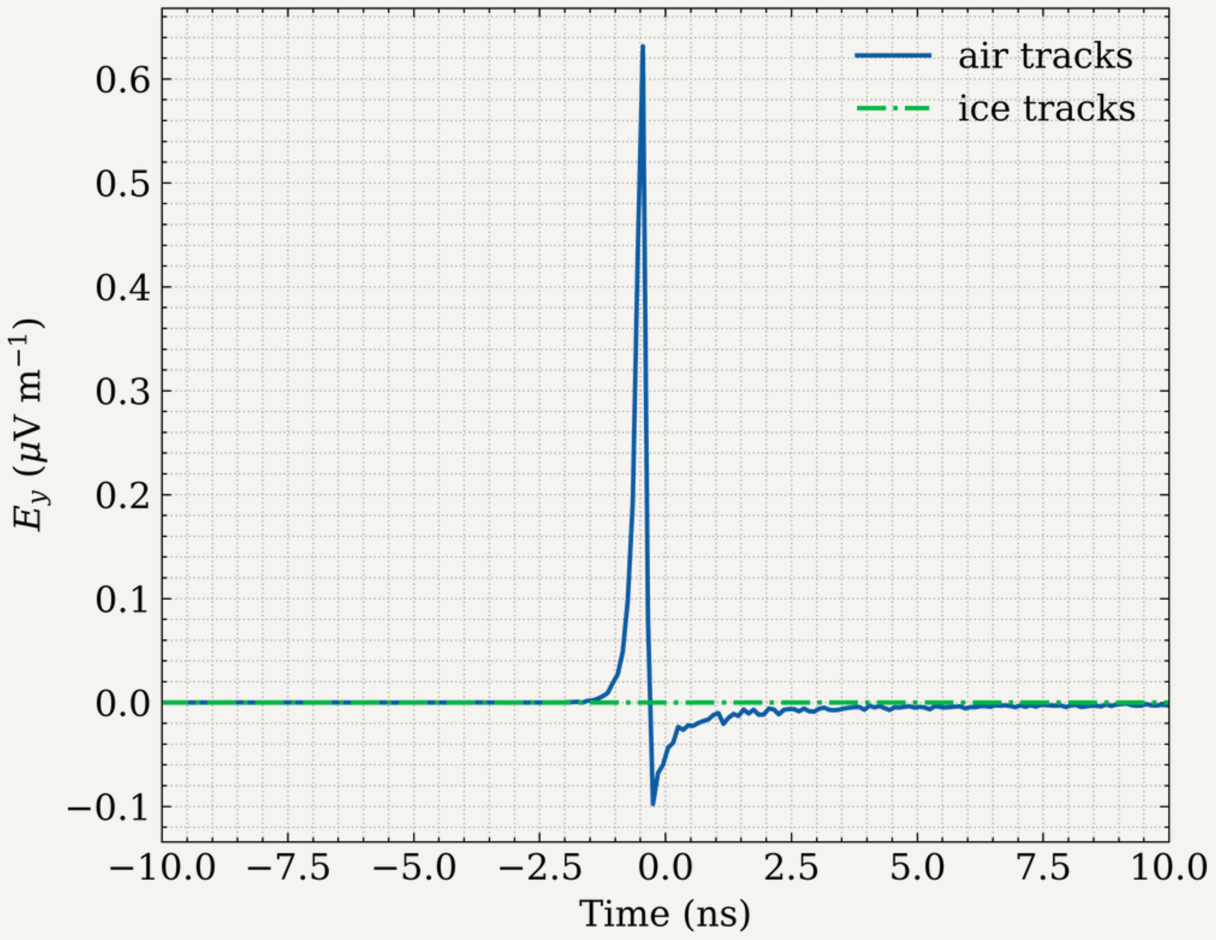
Results: the reflected approximation

Observer placed in the Cherenkov cone.

Shower intersecting interface at Xmax.



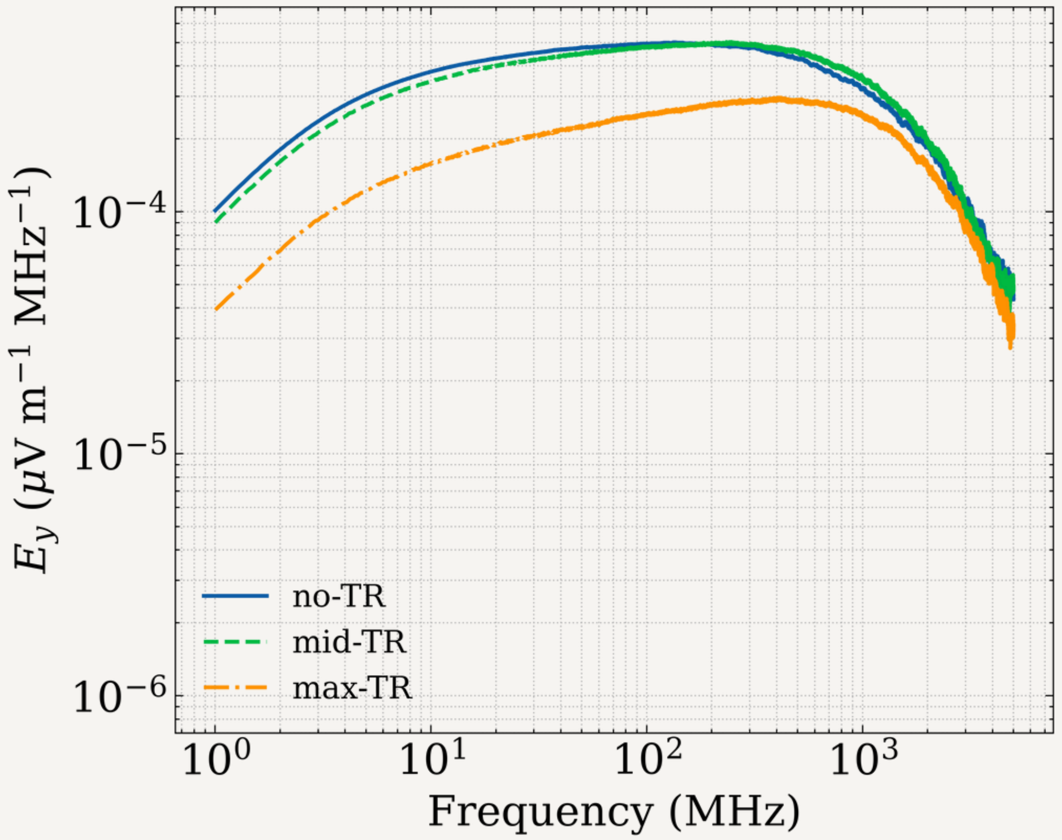
Askaryan effect



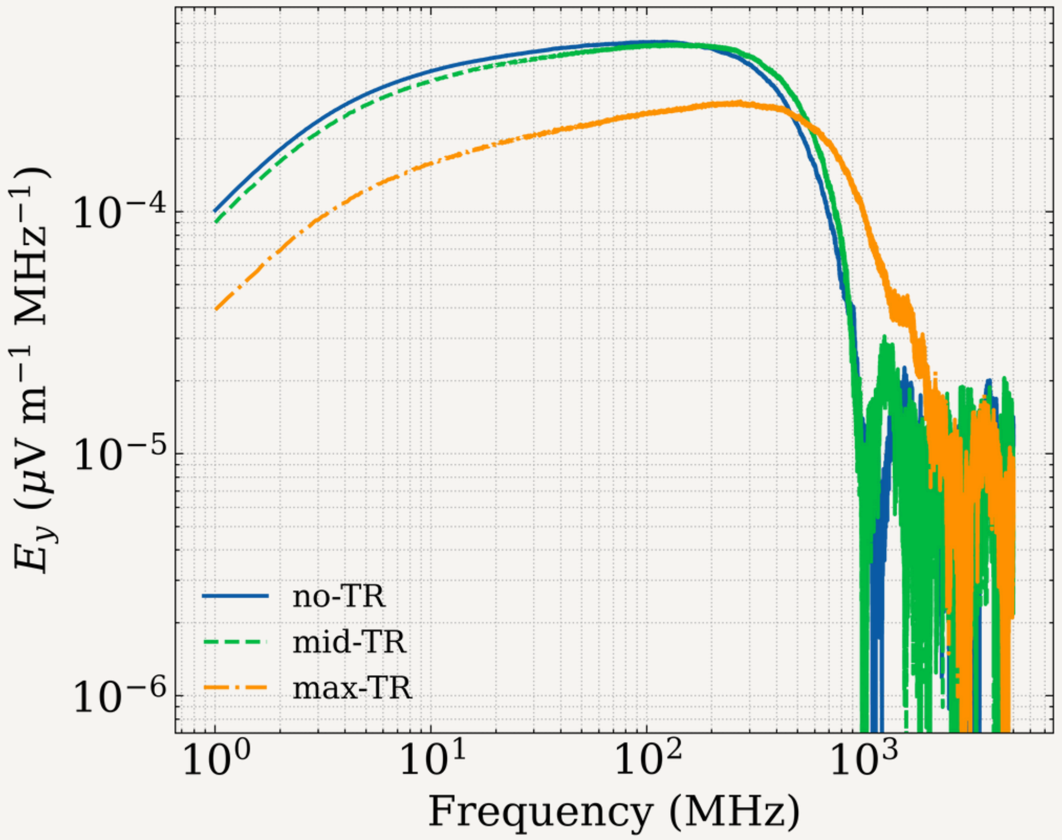
Geomagnetic effect

Results: TR at different positions

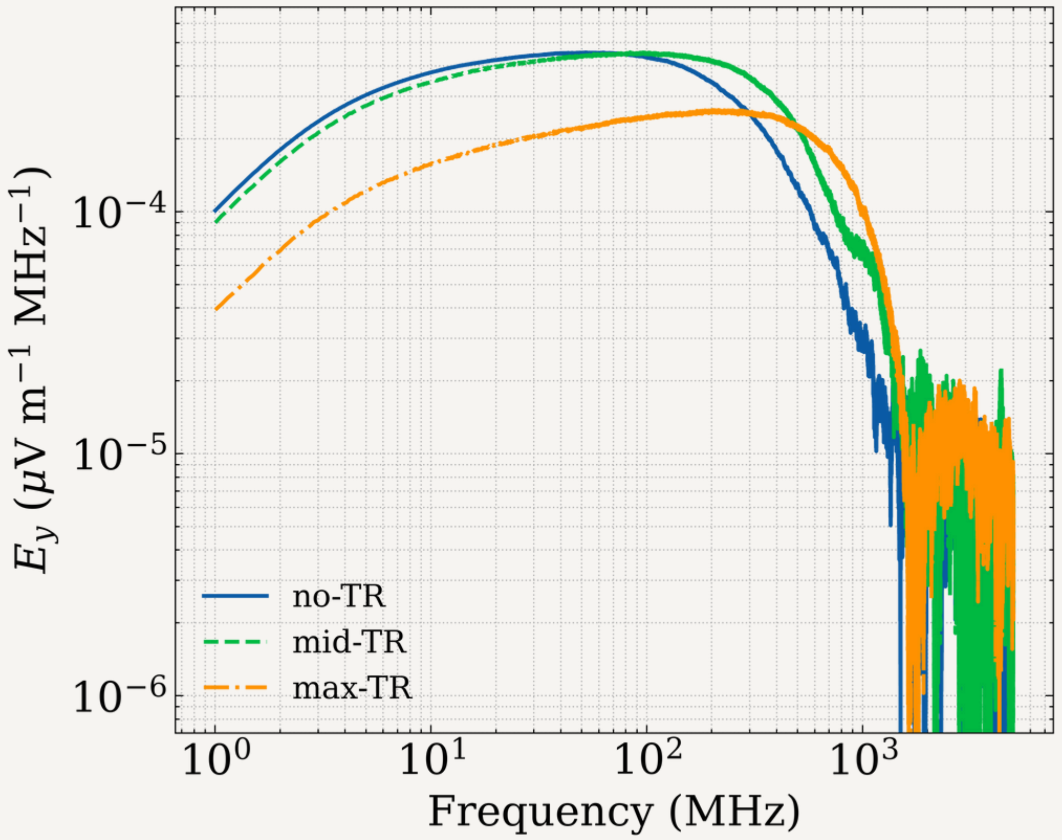
The frequency spectra clearly shows a higher frequency content.



Cerenkov cone (1.22°)



Inside Cerenkov cone (1.02°)

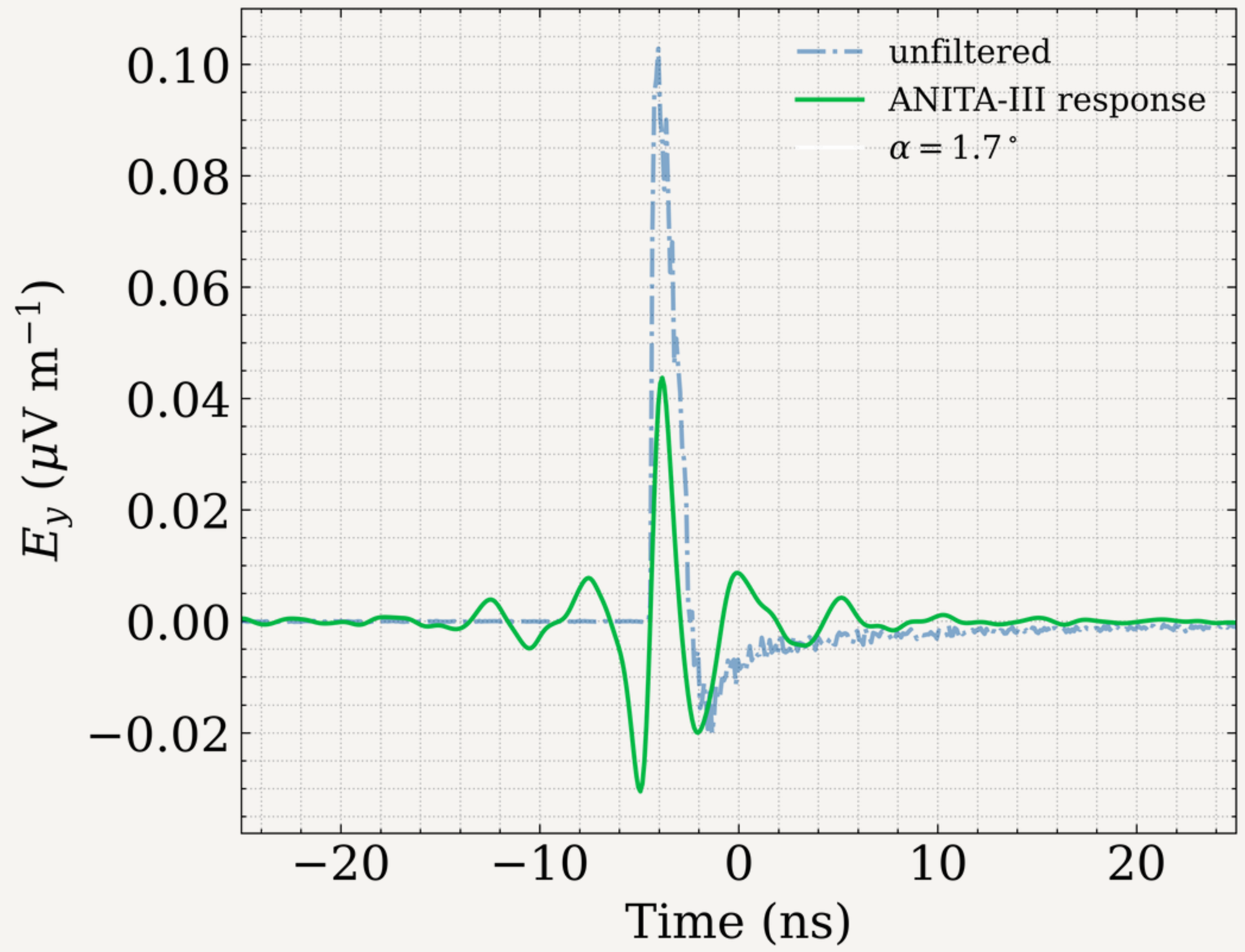


Outside Cerenkov cone (1.42°)

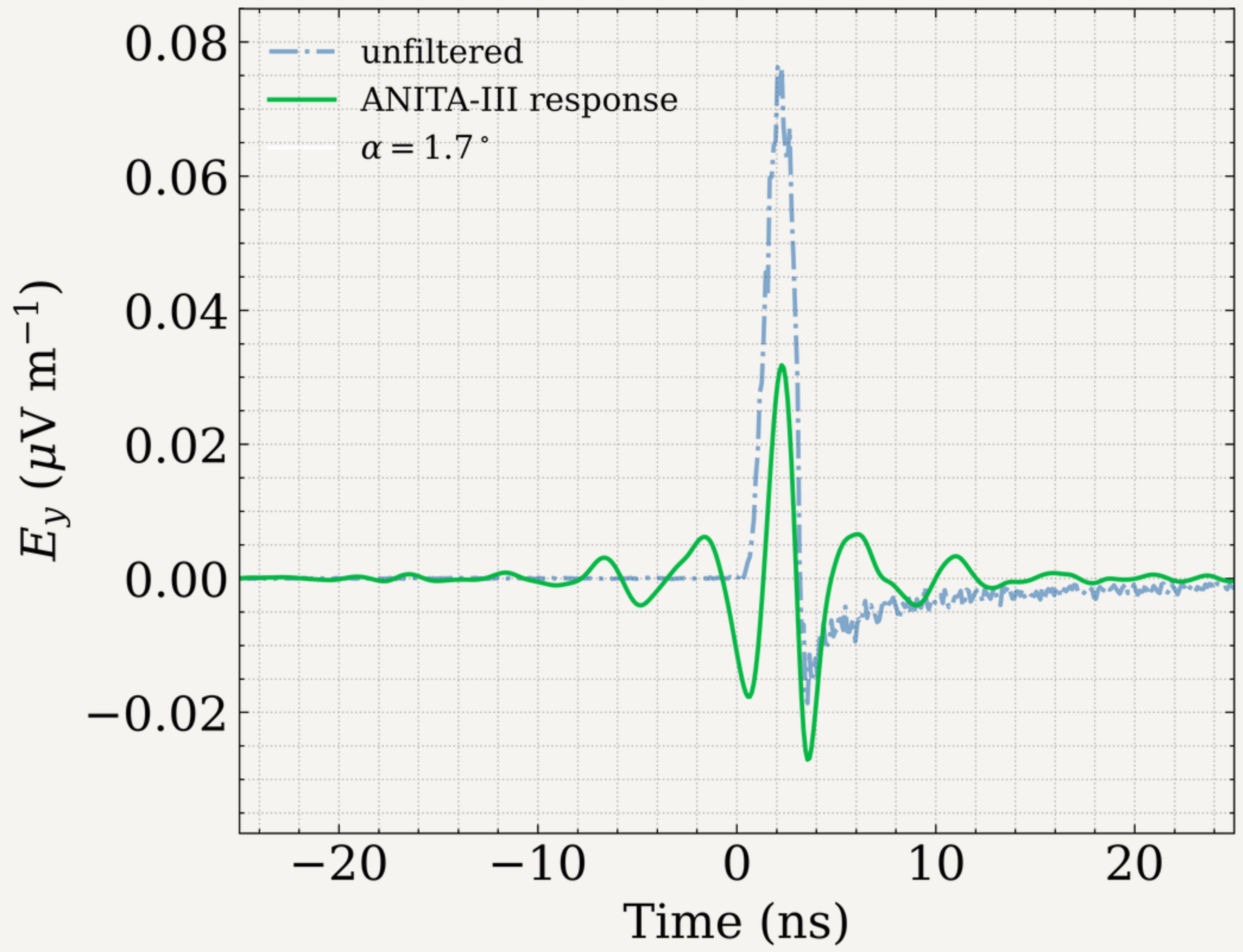
Results: TR as an explanation of the AAE

Shower intersecting interface at Xmax.

Signal convoluted with the impulse response of the ANITA-III instrument.



Inside Cerenkov cone (0°)



Outside Cerenkov cone (1.7°)