The cosmic-ray air shower signal in Askaryan radio detectors

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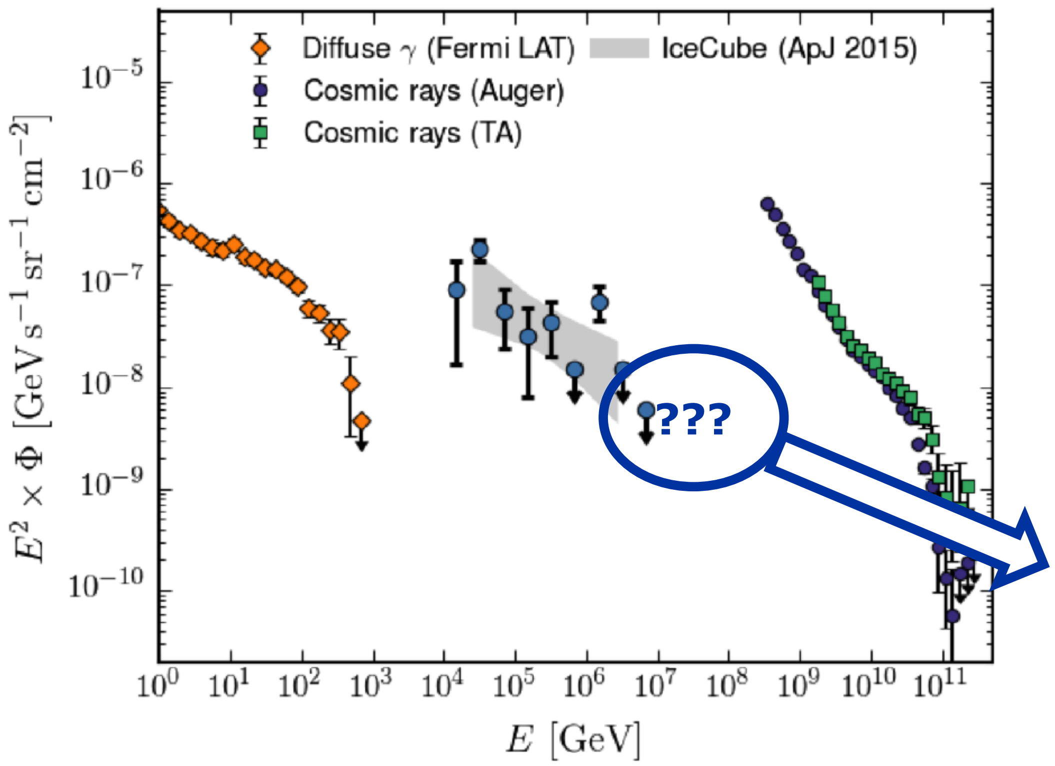
Tim Huege

HIGH-ENERGY PARTICLE CASCADE

COSMIC PARTICLES INTERACTING IN OUR ATMOSPHERE OR EARTH



L. B. Mohrmann. PhD thesis, Humboldt U., Berlin, 2015-11-11

Earth is constantly bombarded by high-energy particles, charged nuclei, photons and neutrinos.

Typically the induced particle cascade is the way to detect the cosmic particle.

Flux drops rapidly toward higher energies. Large detection volumes needed.

Need to cover large volumes at low cost → **Radio!!**

RADAR AND ASKARYAN RADIO DETECTION OF COSMIC NEUTRINOS

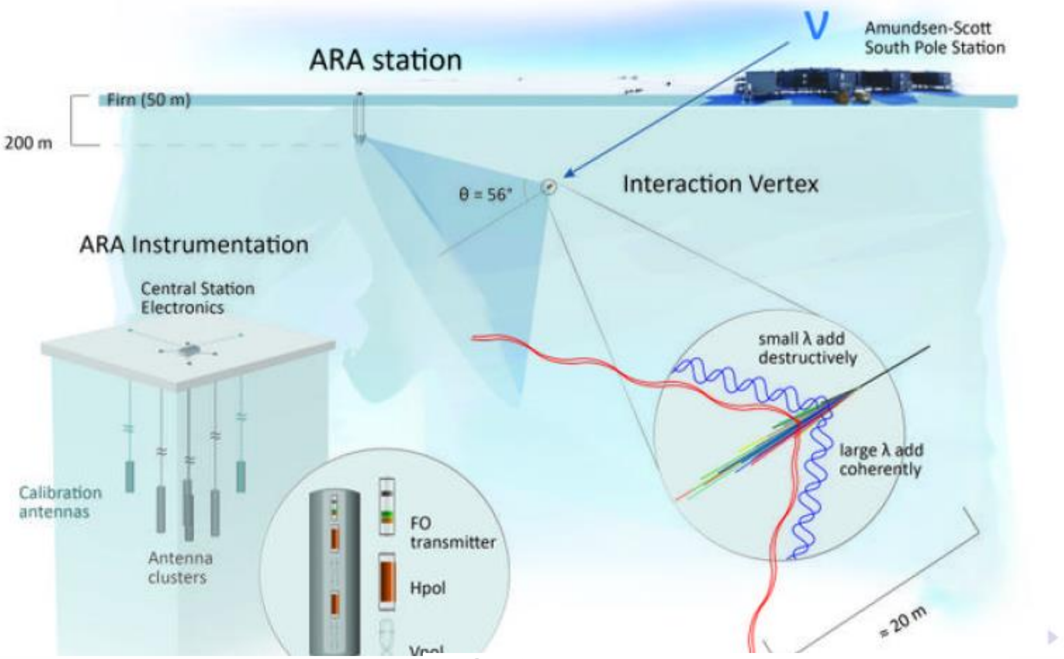
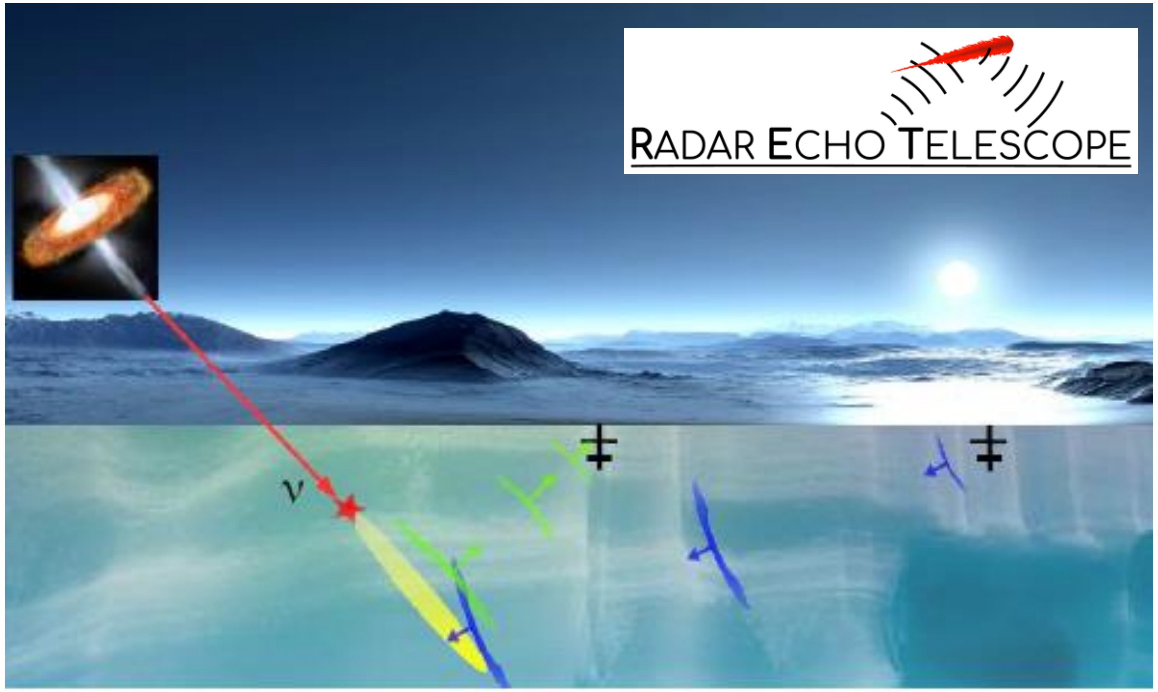
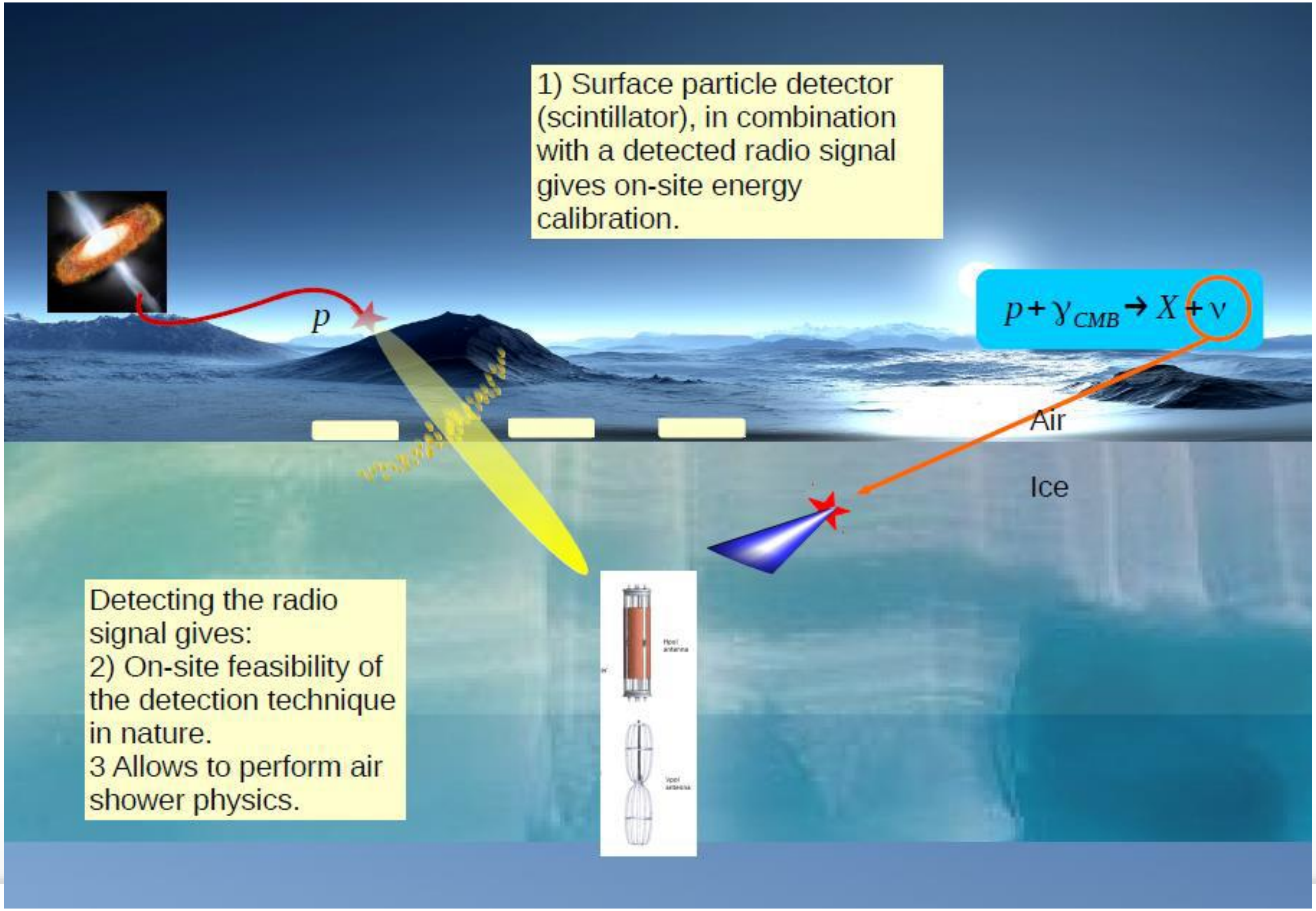


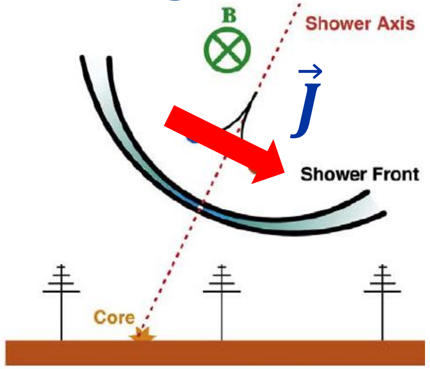
Fig. credit: ASKARYAN RADIO ARRAY



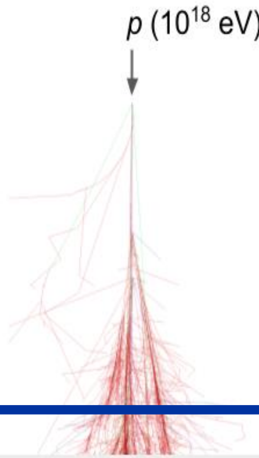
ASKARYAN NEUTRINO DETECTION: THE AIR SHOWER BACKGROUND (SIGNAL)



Geomagnetic



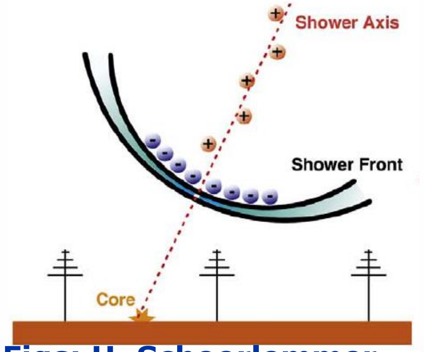
FROM AIR TO ICE



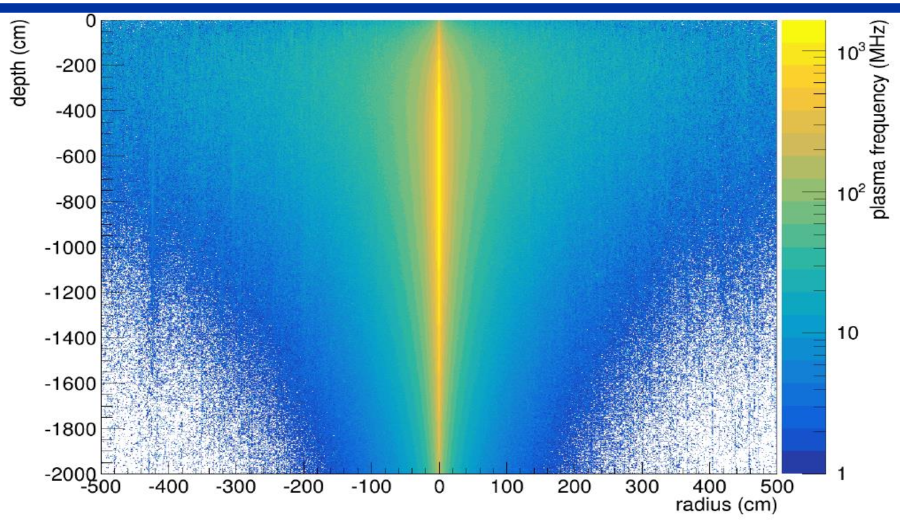
Air EM profile:
10 km length
100 m width

Transition Radiation

Askaryan



Figs: H. Schoorlemmer



Ice EM profile:
10 m length
10 cm width

TOWARDS CORSIKA 8: THE PERFECT SCENARIO

To calculate the full radio emission process from air showers penetrating the ice:

Cascade calculation / propagation

- The shower propagates from air into the ice (Earth?)
- At user specified ice/Earth heights
- With user specified density (refractive index) profiles
- Earth composition (water, ice, salt, ….?)

Radio emission

- The antenna (observer) can be located in the ice (Askaryan radio detectors) or air at ground or large altitude (ANITA)
- Ray tracing has to be performed from emission point to antenna (tables)
- Transition radiation has to be included (CoREAS)

THE AIR SHOWER SIGNAL IN ICE: CURRENT STATUS

CoREAS modification (Uzair Latif, Tim Huege):

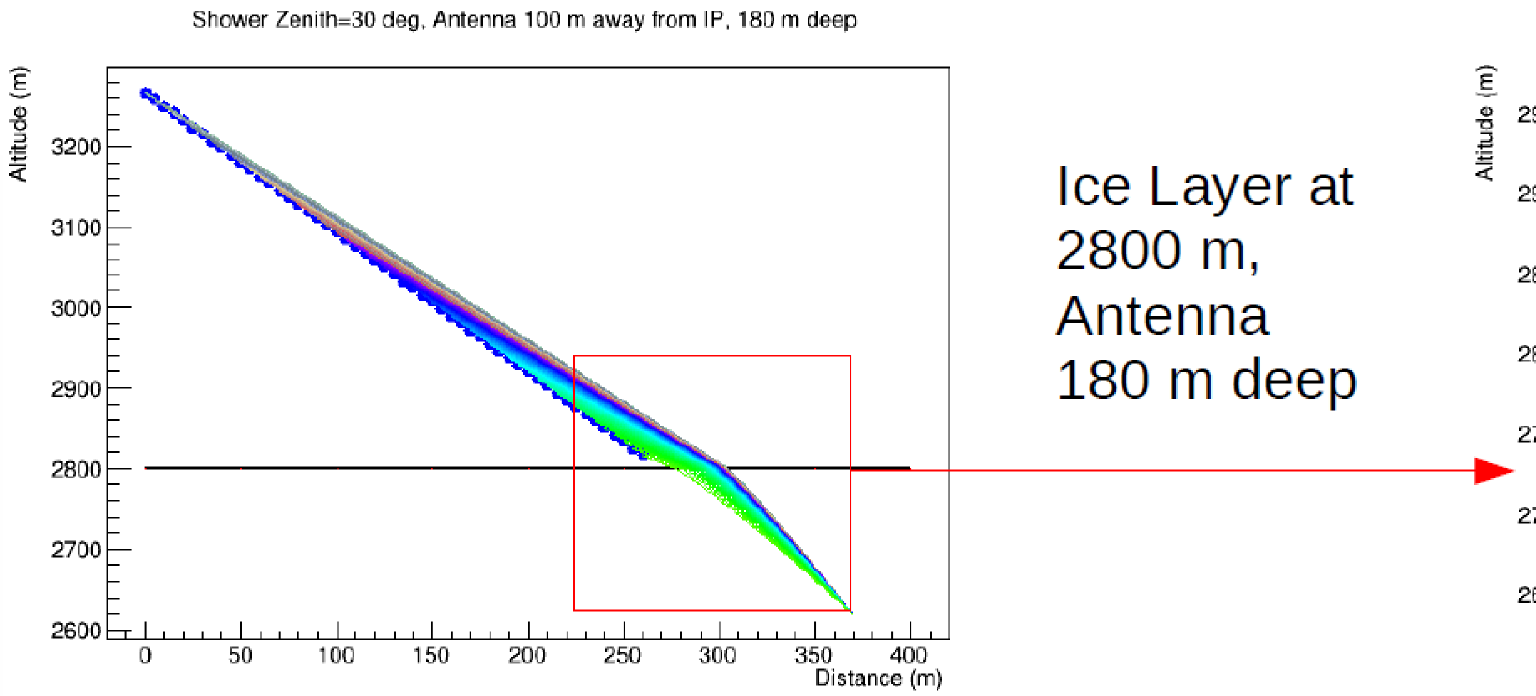
- Generate tables with ray-tracing solutions on start of simulation O(1 min) (Analytic ray-tracing inside CoREAS not feasible due to calculation time)
- Exponential density profile needed
- Interpolate signal travel times from tables for each particle track segment → Large increase in calculation time
- Calculate radio signal using CoREAS

Under investigation:

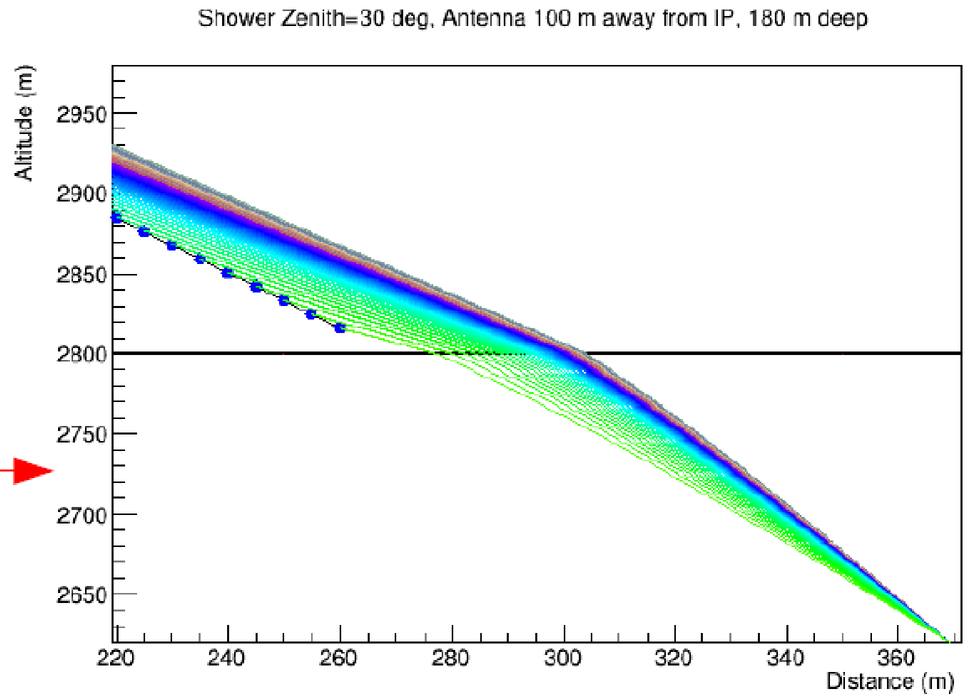
- Modify electric field calculation? $R(1 - n\beta\cos(\theta)) =? R\frac{dt}{dt'}$
- Include transition radiation

THE AIR SHOWER SIGNAL IN ICE: CURRENT STATUS

Ray-tracing implemented

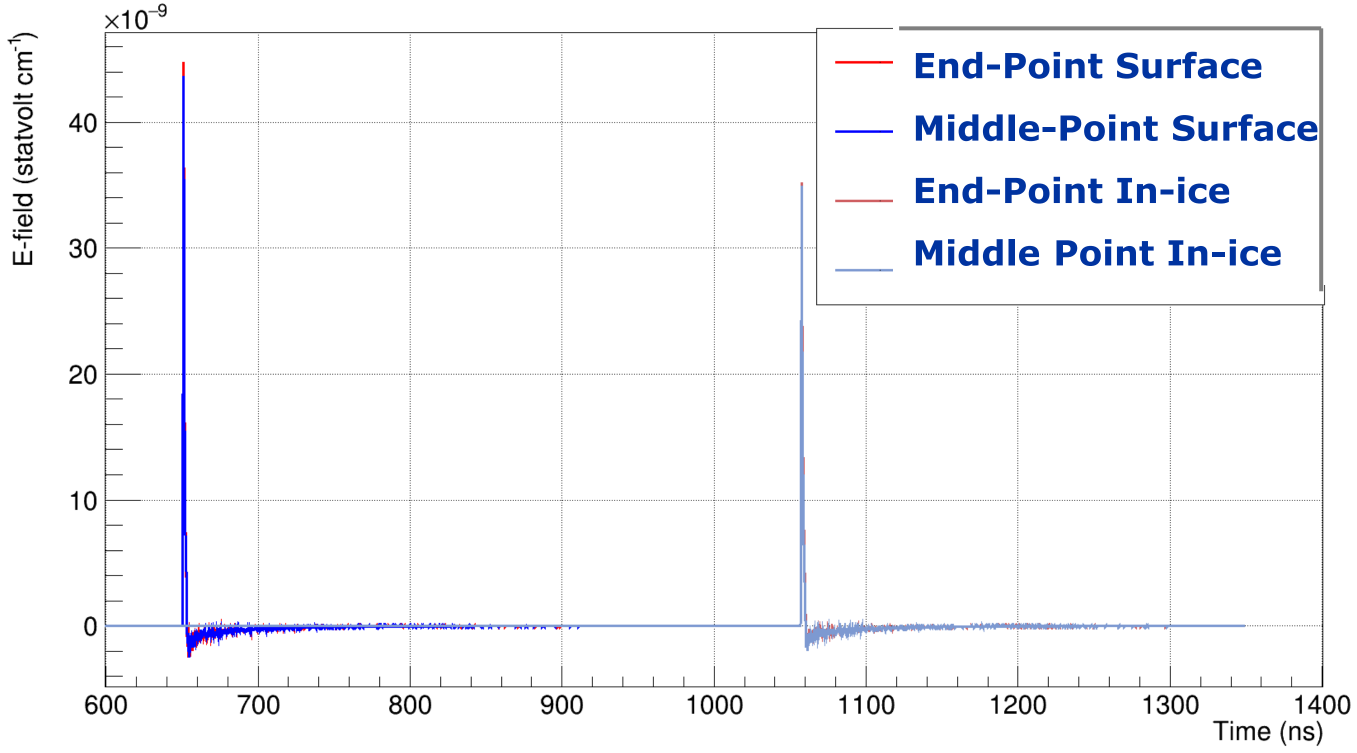


Ice Layer at 2800 m, Antenna 180 m deep



THE AIR SHOWER SIGNAL IN ICE: CURRENT STATUS

Cross-checks show good results



WHAT DOES THE IN-ICE CASCADE LOOK LIKE?

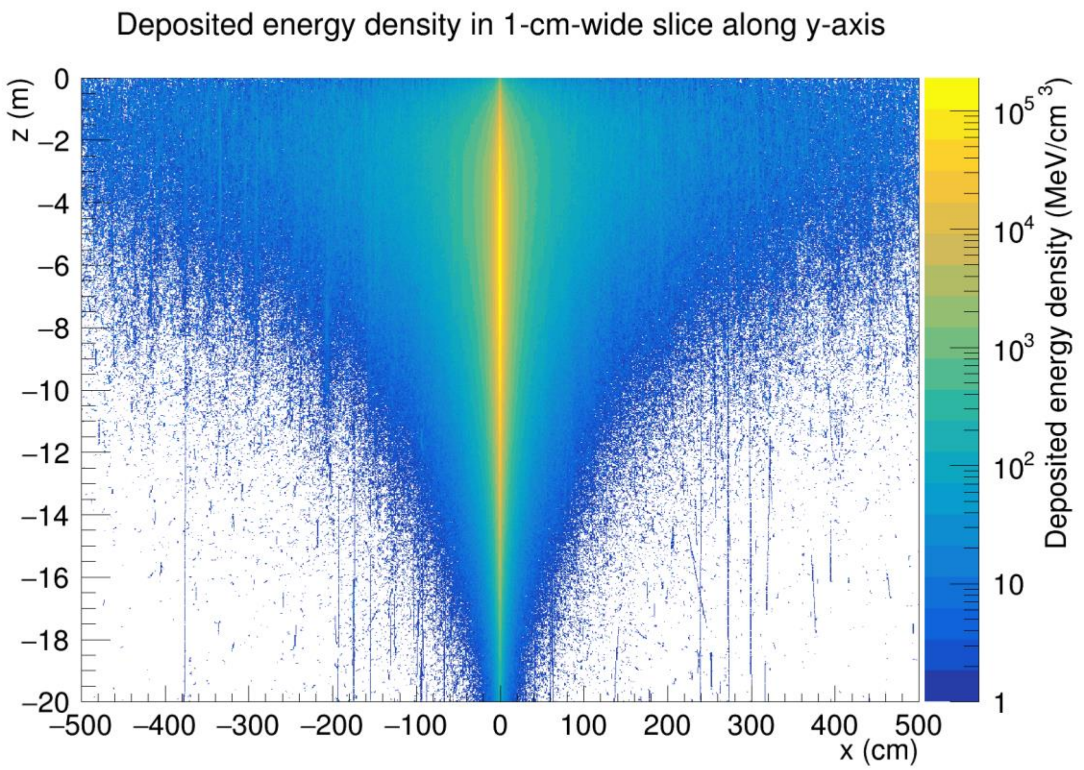
Method

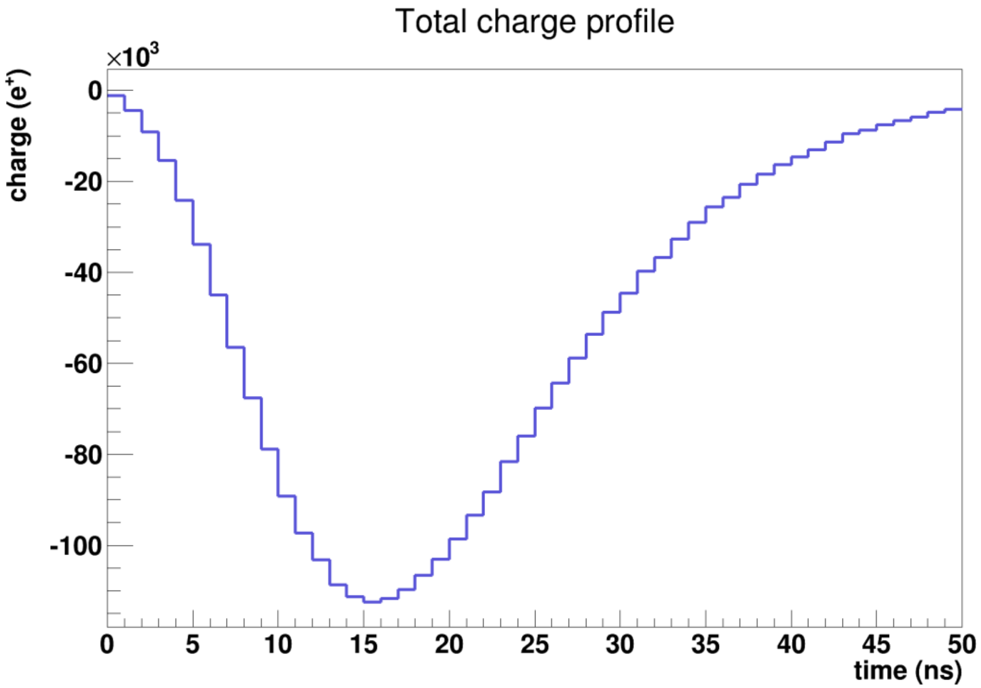
- Use Corsika to simulate air shower:
  - QGSJET-04
  - Primary particle: proton
  - $E = 10^{18}$ eV
  - $\theta = 0$, $\phi = 0$ (perpendicular to surface)
  - observation level: 2500 m
  - energy cuts: 0.3 GeV (hadrons, without π^0's), 0.3 GeV (muons), 0.003 GeV (electrons), 0.003 GeV (photons, including π^0's)
  - thinning enabled: $\epsilon_{th} = 10^{-5}$, $w_{max_{em}} = 10^4$, $w_{max_{hadr}} = 10^2$

- Take CORSIKA particle output and propagate in GEANT4
- Set-up block of ice (10m x 10m x 20m) with gradient ice density

Slide from Simon de Kockere

WHAT DOES THE IN-ICE CASCADE LOOK LIKE?

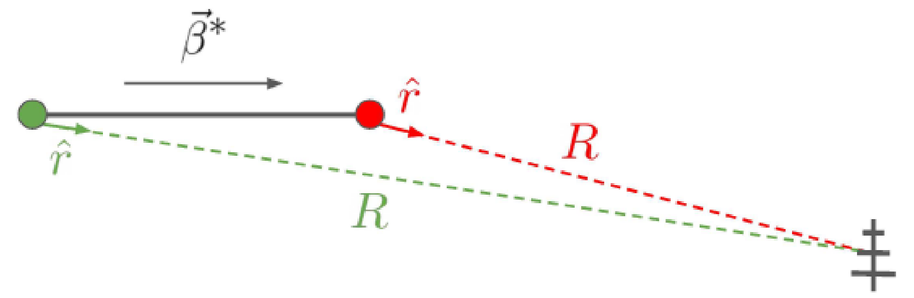




Figs.: Simon de Kockere

FROM CASCADE TO RADIO SIGNAL

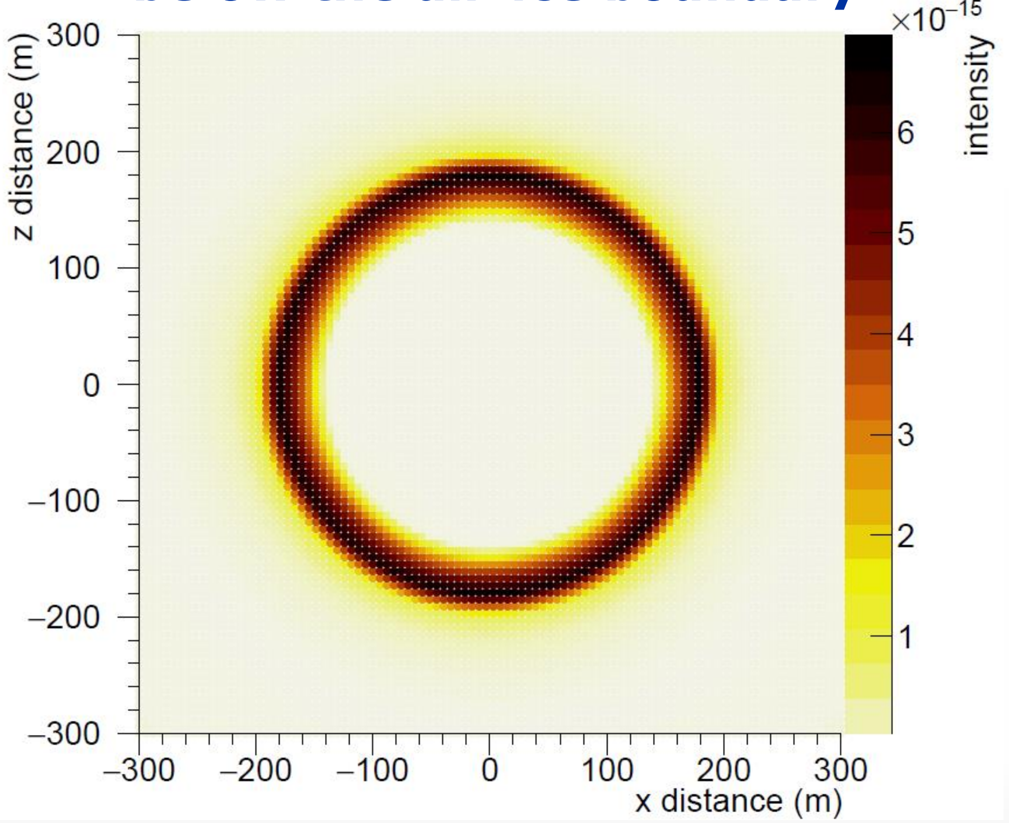
Apply CoREAS formalism on particle tracks from GEANT4



Contribution to the electric field in the antenna at $t = R/(c/n)$ for starting point (+) and end point (-):

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

Radio intensity 150 m below the air-ice boundary



Figs.: Simon de Kockere

SUMMARY AND TO DO

Close, but not yet there:

- Modify electric field calculation? $R(1 - n\beta\cos(\theta)) =? R\frac{dt}{dt'}$
- Include transition radiation
- Include ray-tracing for in-ice emission

- Merge in-air and in-ice simulation. Initially this will need to run both CORSIKA and GEANT4

→ CORSIKA8

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To be continued!!!!

VRIJE UNIVERSITEIT BRUSSEL

THE UNIVERSITY OF KANSAS

Karlsruher Institut für Technologie

European Research Council
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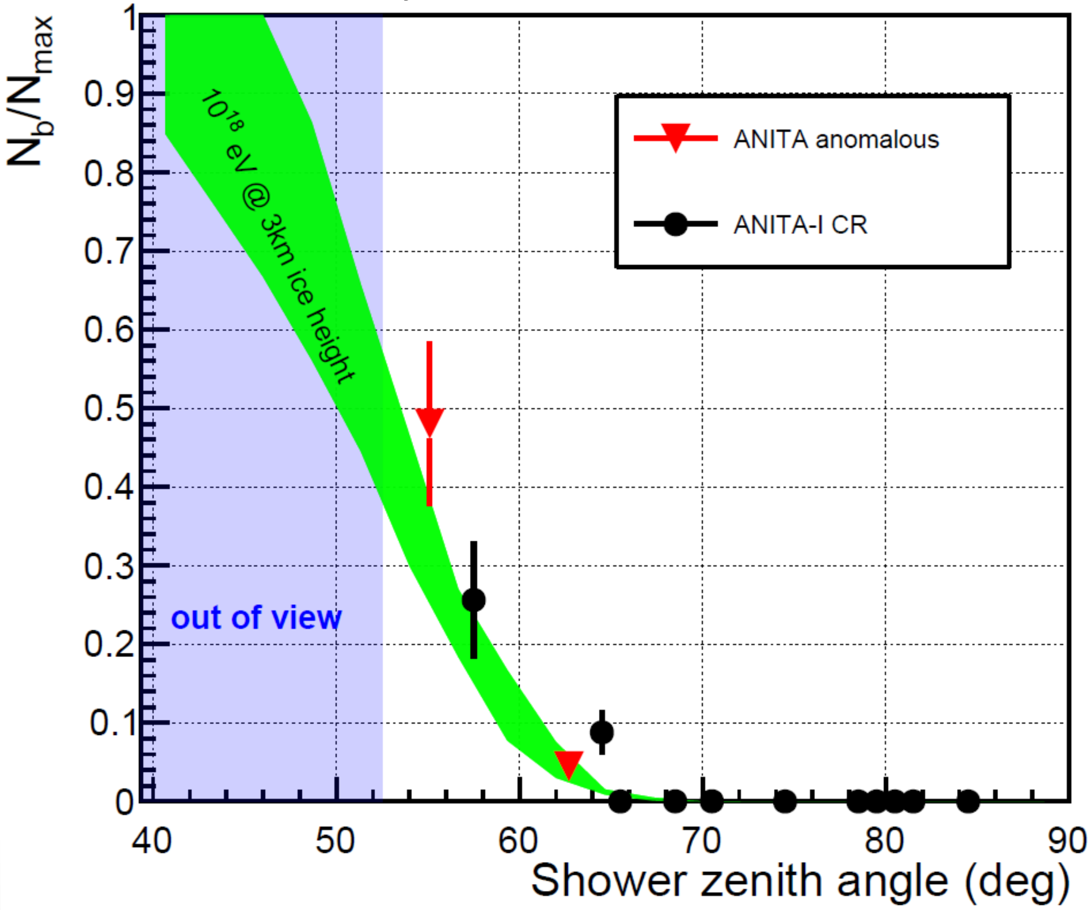
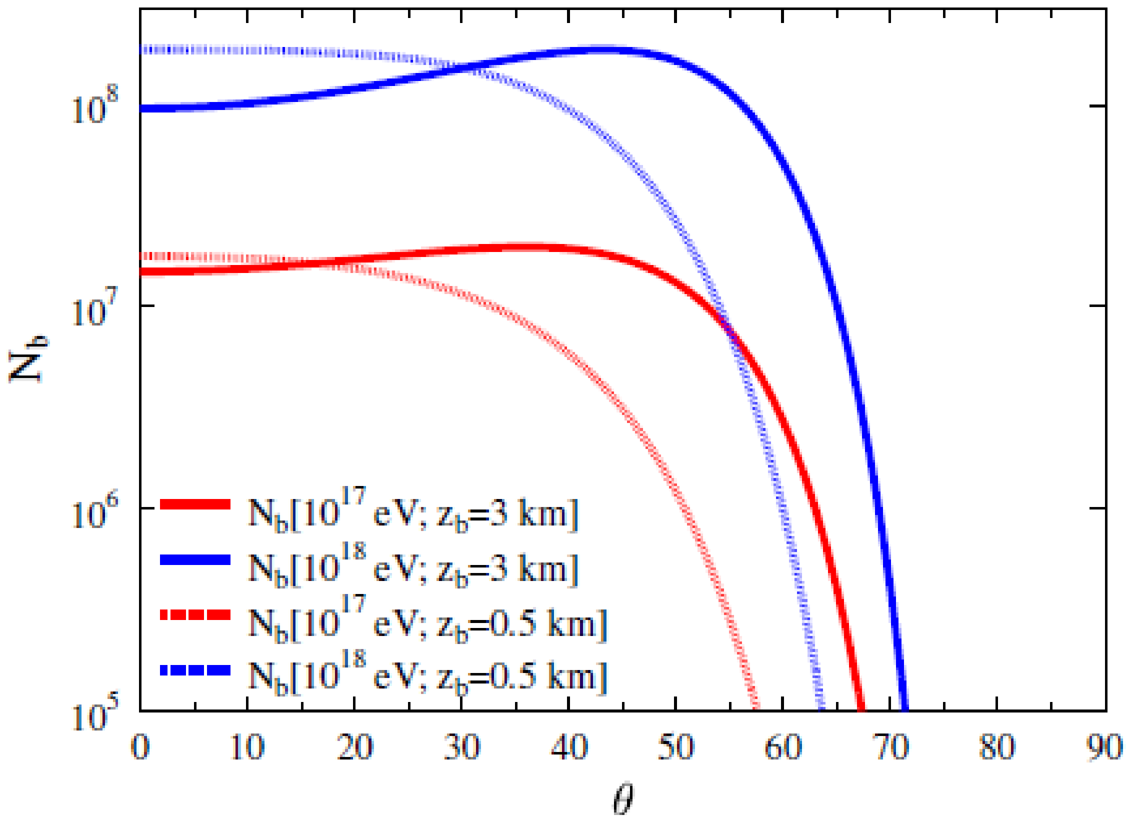
THE AIR SHOWER CORE IN ICE: CURRENT STATUS AND WHY CORSIKA 8

DOES A SIGNIFICANT AMOUNT OF PARTICLES HIT EARTH? YES!!

KdV, SP, Phys. Rev. Lett. 123, 091102 (2019)



KdV, et. al., Astropart.Phys. 74 (2016) 96-104



SOURCE AND GEOMETRY

$$A^{\mu}(\vec{x},t) = \left.\frac{J^{\mu}(\vec{x},t')}{|D|}\right|_{t'=t_r}$$

Geometry:

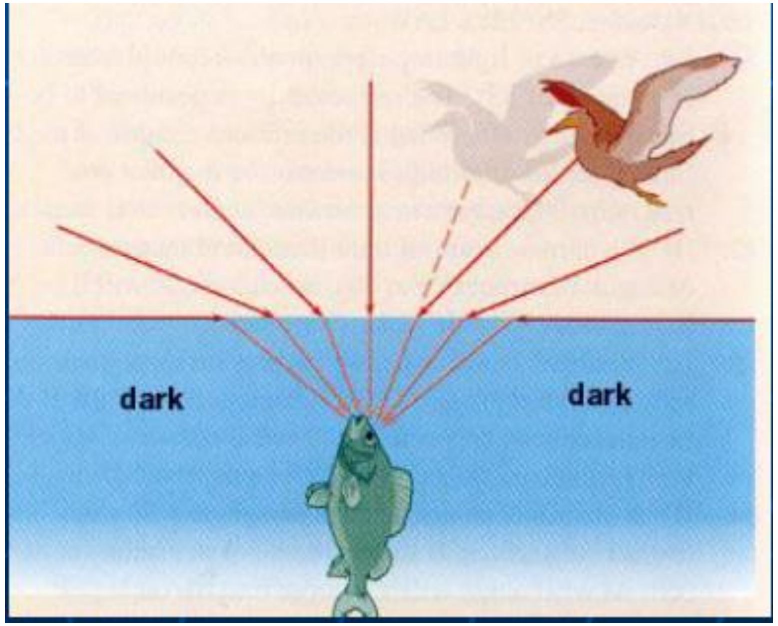
$$\frac{1}{D} = \frac{1}{L}\frac{dt'}{dt}$$

What matters is how the observer sees the emission source (charge or current)!!

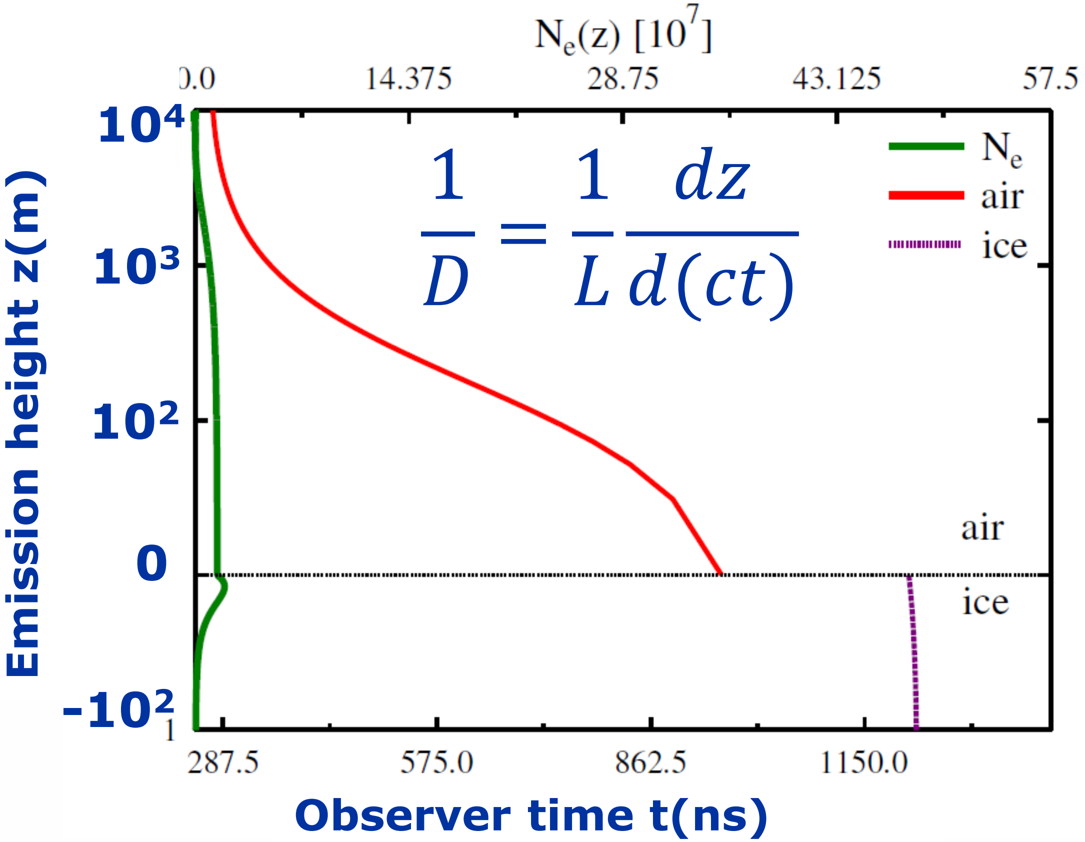
t': Emission time (retarded time when signal was emitted)
t : Observer time

Signals emitted over a time dt' arrive within a time dt.

<u>**It is crucial to know the full path from emission point to observer!! → Ray-tracing needed**</u>

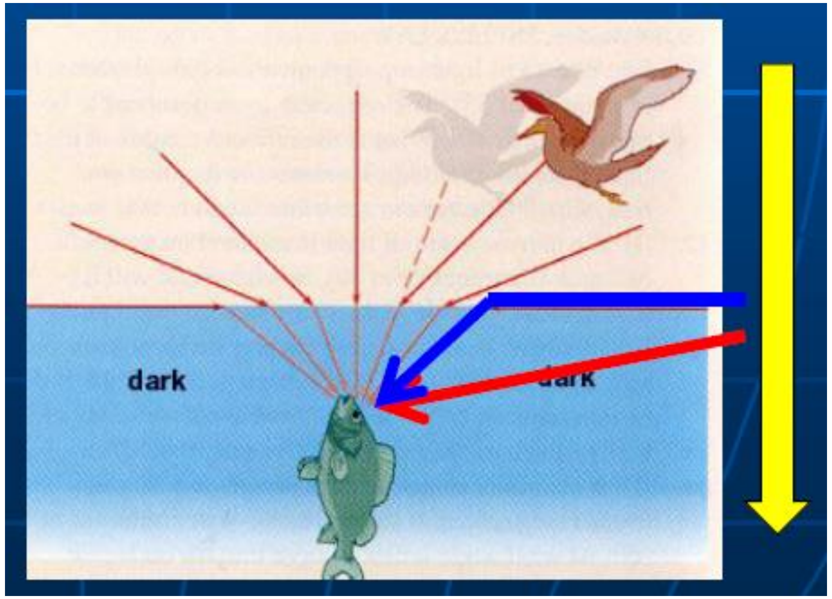


EXAMPLE: FROM CHERENKOV EFFECTS TO TRANSITION RADIATION



$$\frac{1}{D} = \frac{1}{L}\frac{dz}{d(ct)}$$

Travel paths and thus arrival times are completely different for signals emitted in air compared to those in ice!!!!!



It is crucial to know the full path from emission point to observer!!
→ Ray-tracing needed

RADIO EMISSION FROM A HIGH-ENERGY PARTICLE CASCADE

CLASSICAL ELECTRODYNAMICS

So what about the geometry? Cherenkov effects etc...?

$$A^{\mu}{}_{PL}(\vec{x},t) = \frac{J^{\mu}{}_{PL}(t')}{|D(\vec{x},t)|}$$

$$D = R(1 - n\beta\cos(\theta))$$

$$= R\frac{dt}{dt'}$$

$$\vec{E}(\vec{x},t) = -\frac{d}{dt}\vec{A}(\vec{x},t) - \frac{d}{d\vec{x}}A^{0}(\vec{x},t)$$

$$\vec{E}(\vec{x},t) \propto \frac{1}{D^2}$$