Using FDTD simulations to study propagation effects

European Research Council

VRIJE UNIVERSITEIT BRUSSEL

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ARENA - Acoustic and Radio EeV Neutrino Detection Activities

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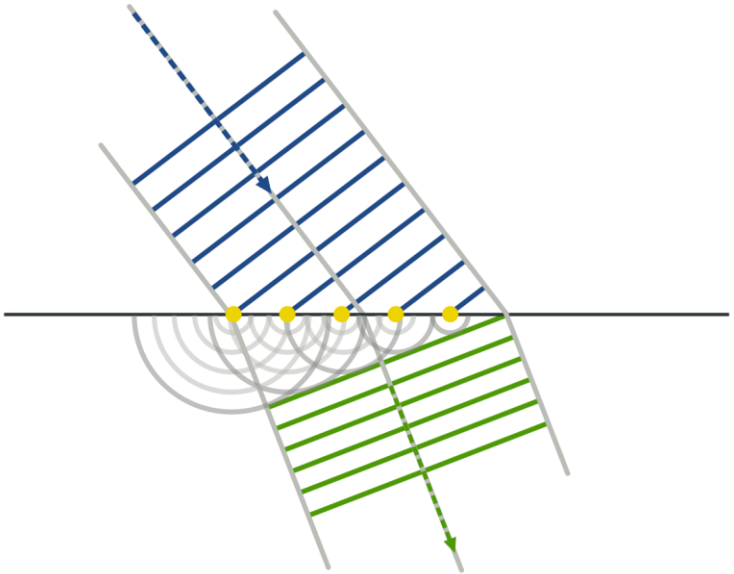
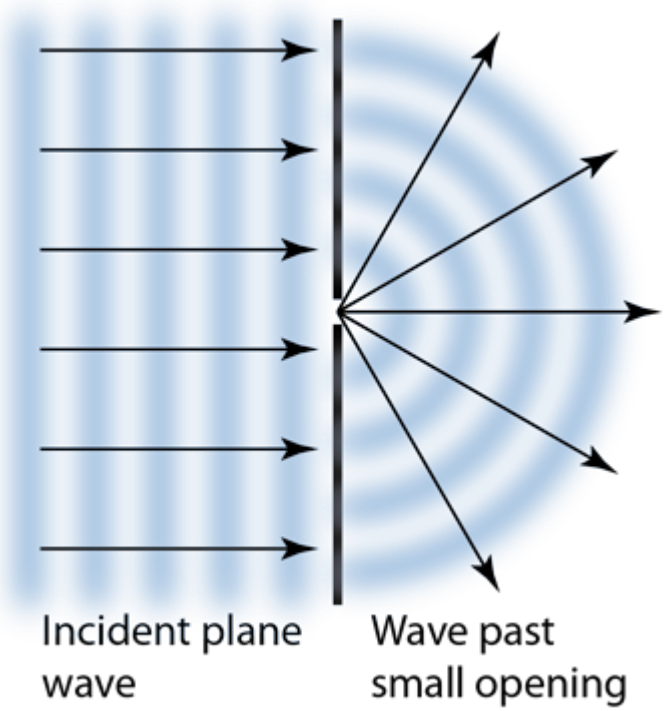
Limits of ray tracing



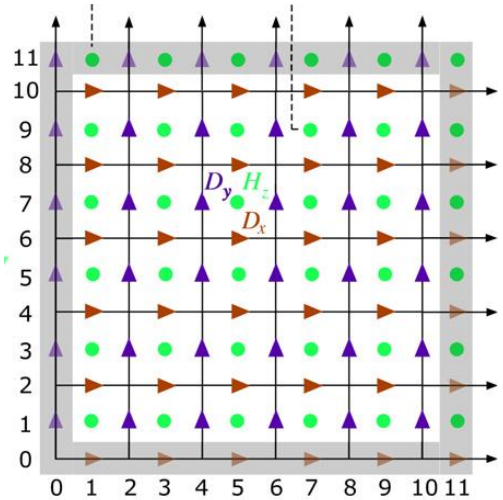
Huygens principle - refraction



Ray tracing fails…

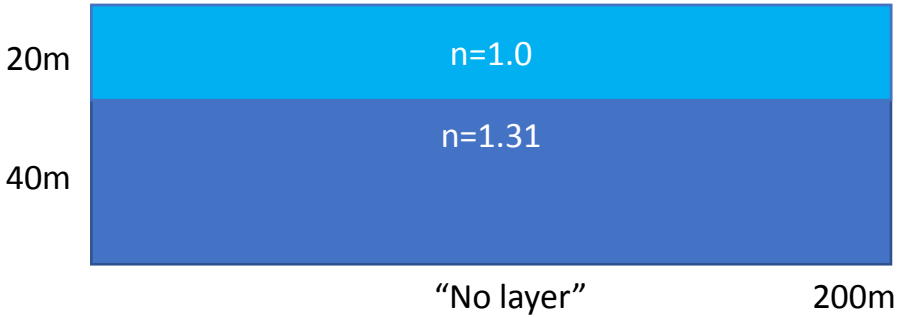
Finite Difference Time Domain codes

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} - \mathbf{J}_B,$$
$$\frac{\partial \mathbf{D}}{\partial t} = +\nabla \times \mathbf{H} - \mathbf{J},$$



- Solve Maxwell equations on a Yee Grid (=displaced B & D grids)
- MEEP (MIT Electromagnetic Equation Propagation) Free & open-source FDTD code)
- Also used by Deaconu et al. (propagation at Summit Station – surface/horizontal modes)
  arxiv: https://arxiv.org/pdf/1805.12576.pdf

Simulation setup

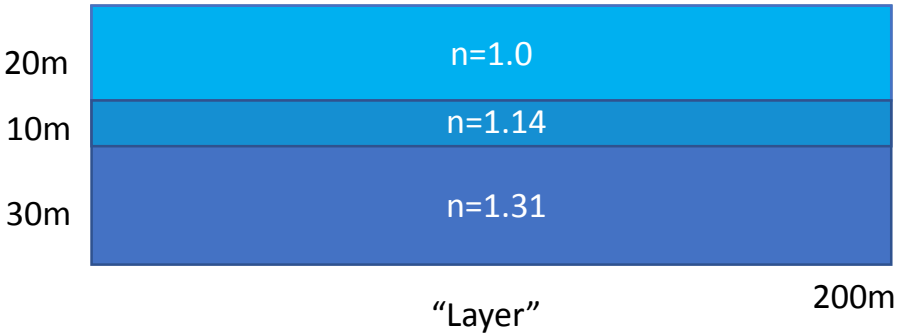


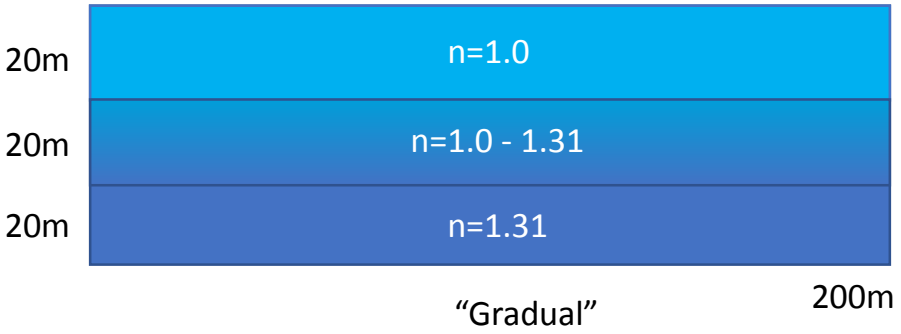
Resolution 5cm
Shortest allowed wavelength > ~8 x 5 = 40 cm

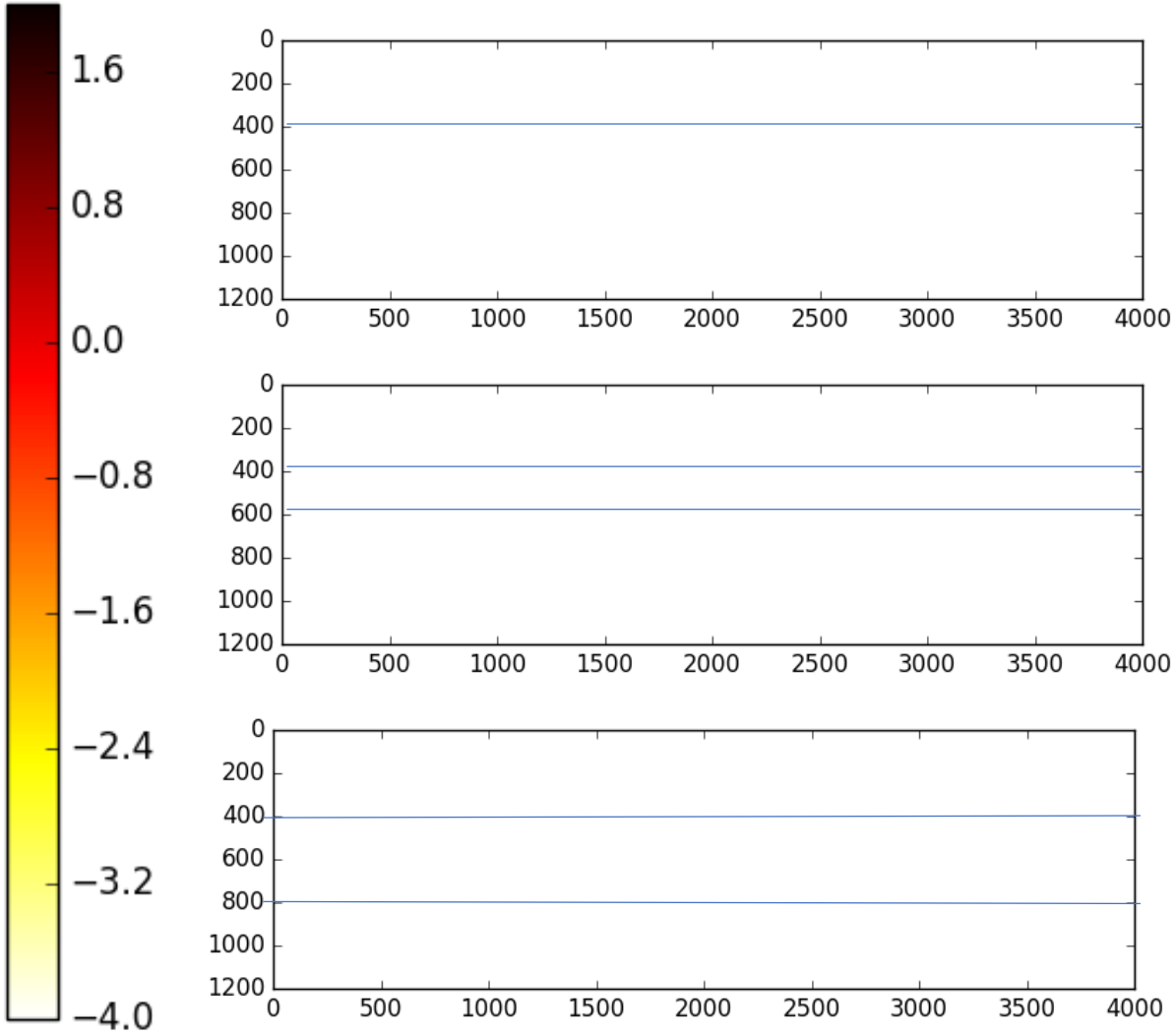
Absorbing layers at edges
(PML – perfectly matched layers)

No absorption

Three variations







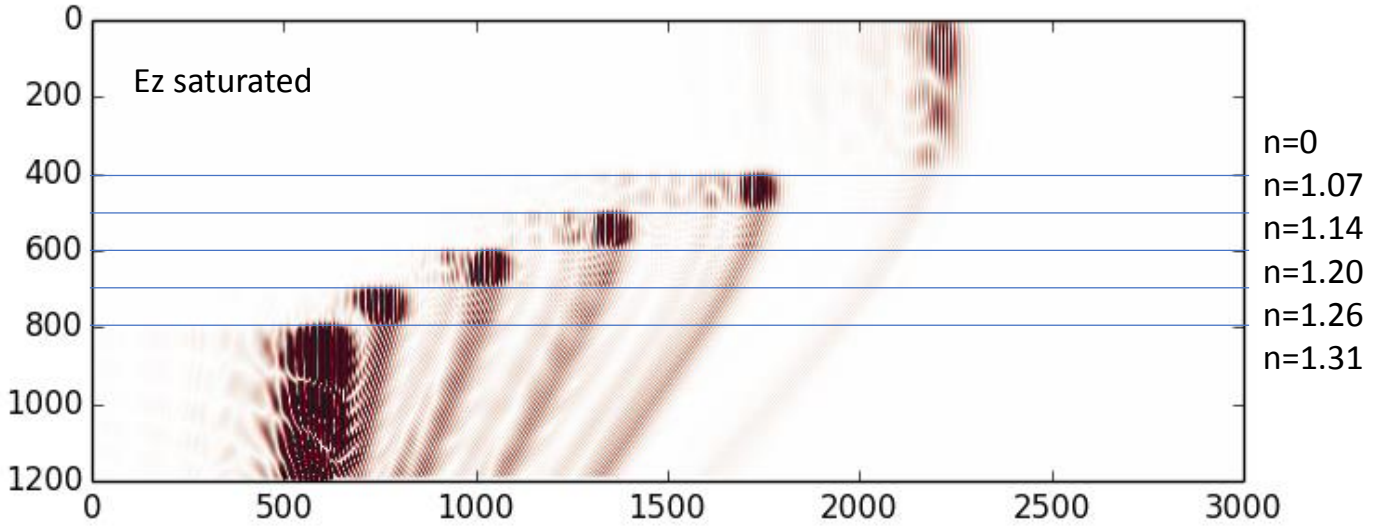
Plotted: energy density on log scale

No layer

Layer

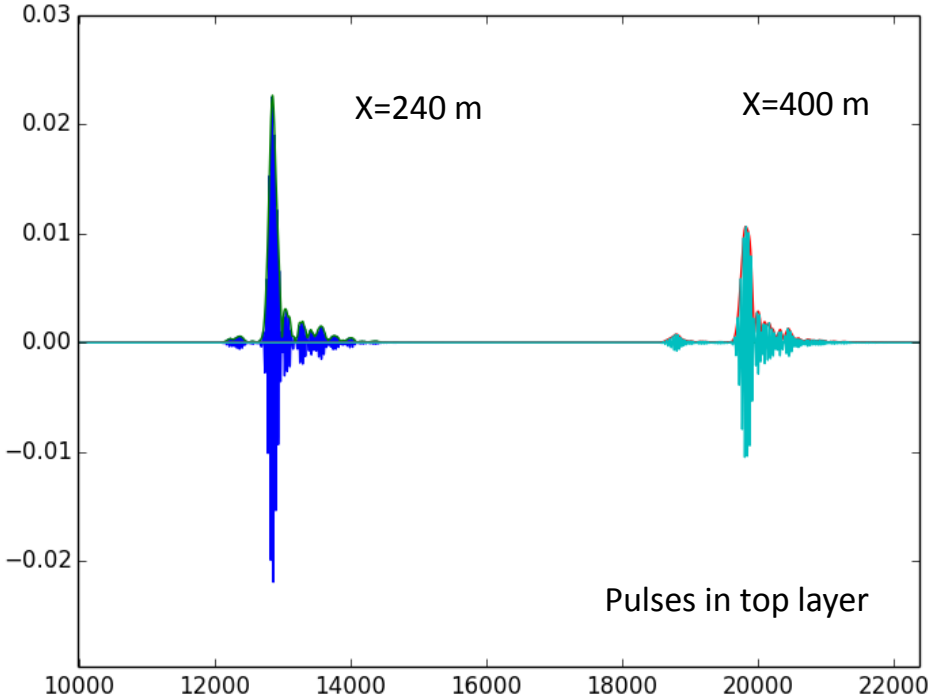
Gradual transition

Horizontal mode – 5 layer simulation



Zoomed in

Waveforms



Through-the-air-signal
Velocity = c/1.02

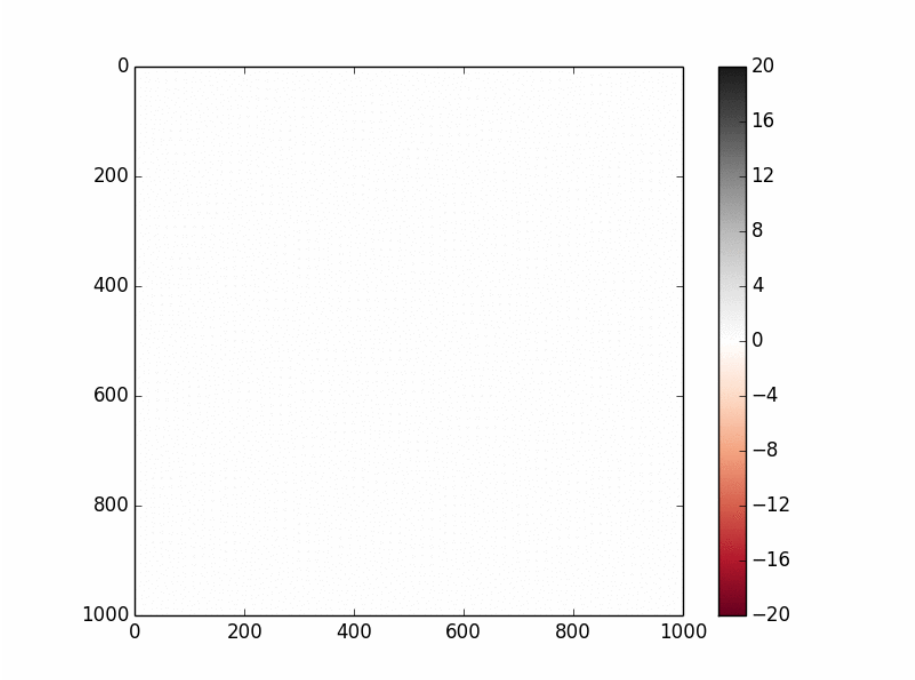
Velocity in layers:

v = c/1.08	(n = 1.07)
v = c/1.15	(n = 1.15)
v = c/1.2	(n = 1.20)
v = c/1.27	(n = 1.26)

Horizontal modes are truly horizontal,
Not bouncing waves

Relative amplitudes will be affected by absorption

Askaryan – naïve attempt

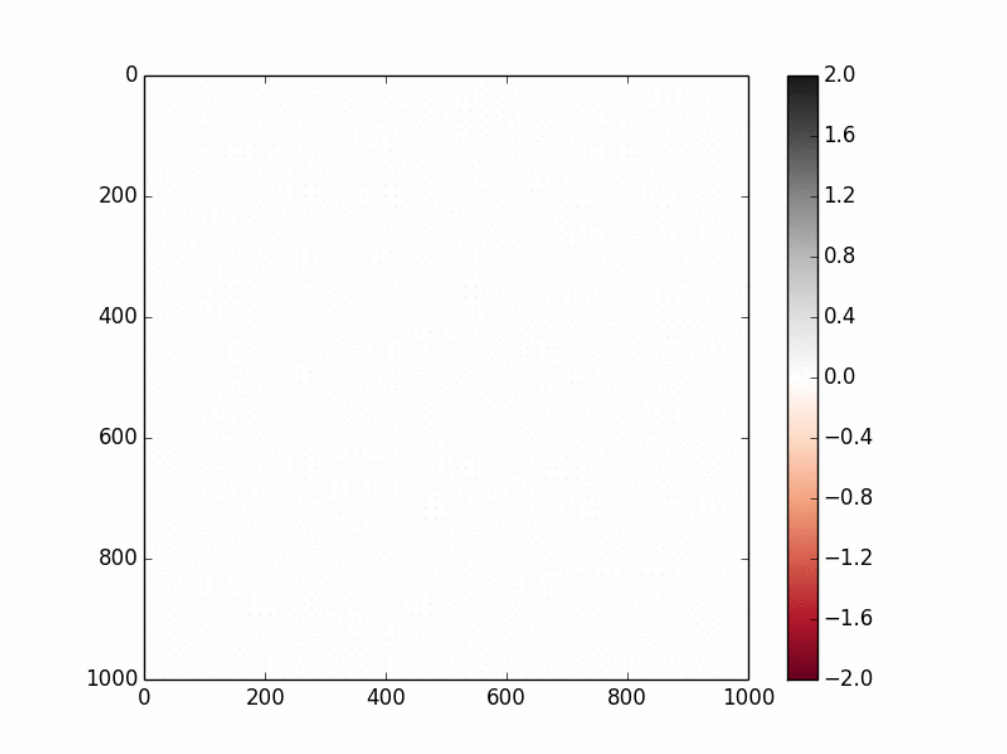


Let a current point source move with velocity *c* (in direction of current)

Modulate the current strength with an envelope that describes shower development

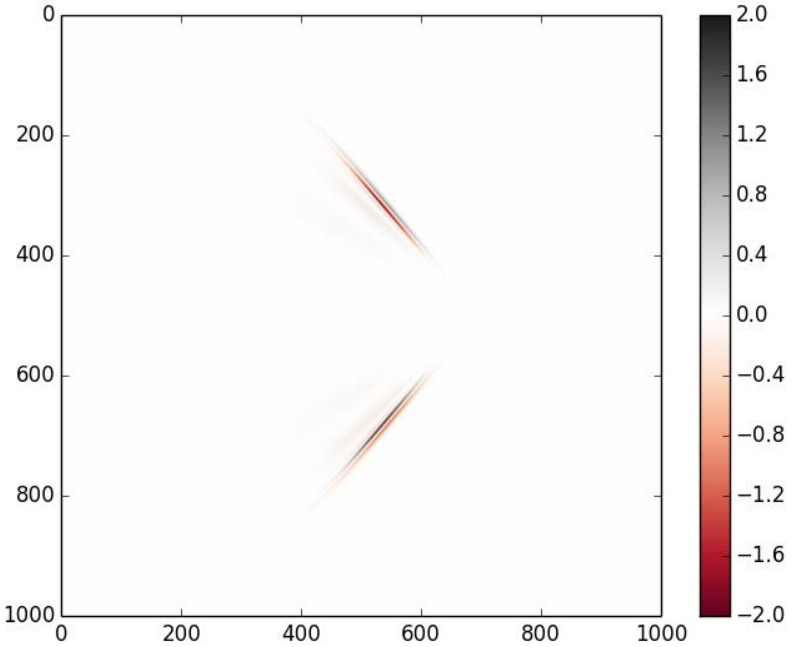
Problem: this incites waves of all frequencies shortest wavelength should be > ~8 bins

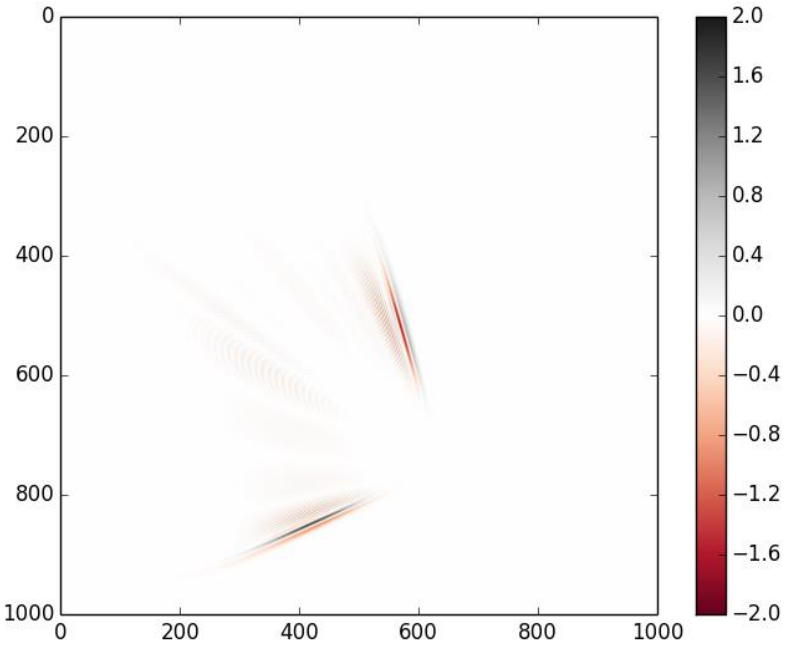
Askaryan – wavefront = 9x9 block

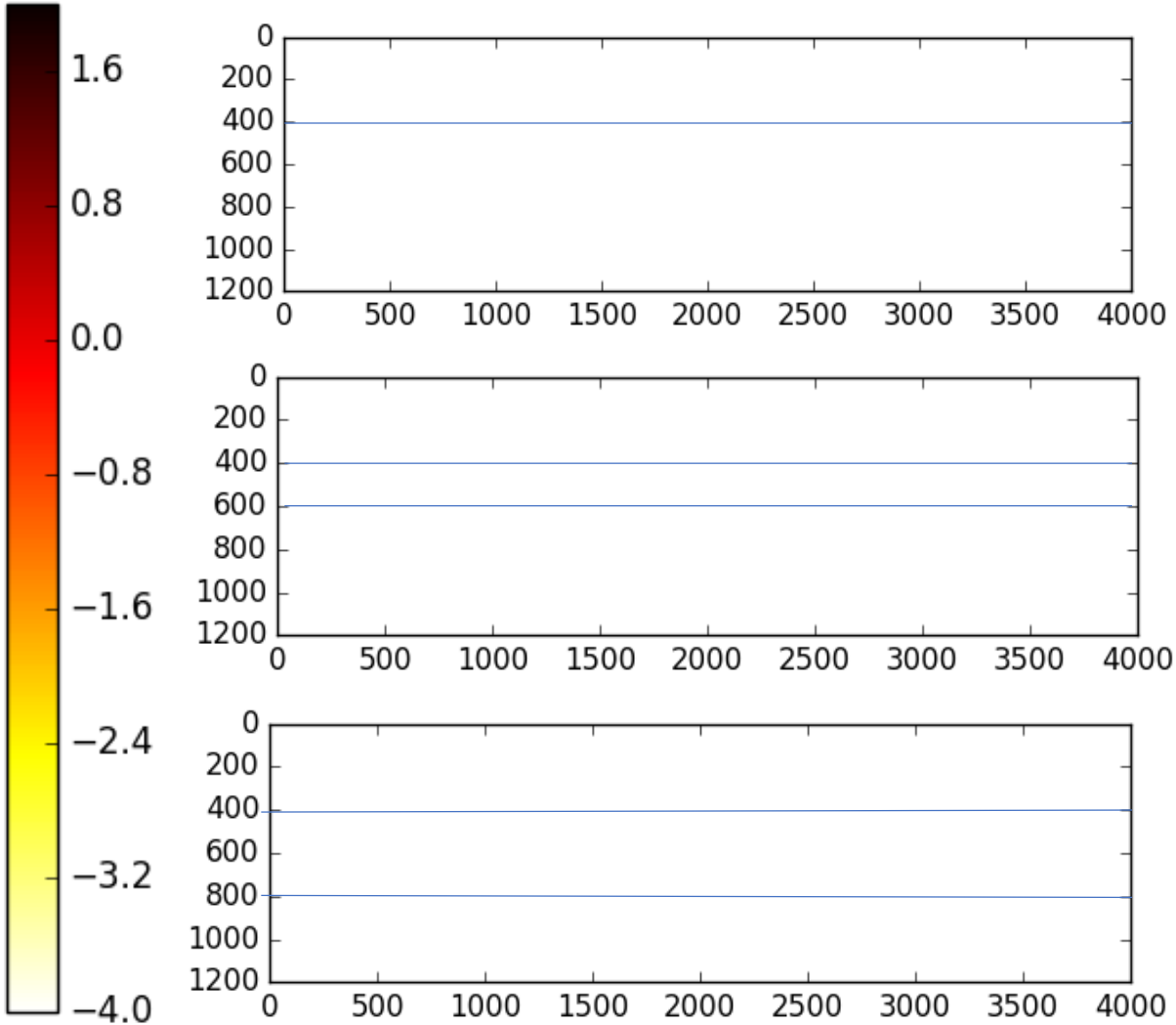


Can be improved to realistic shower front shape as long as the edges are not too sharp

More noise for showers misaligned with grid





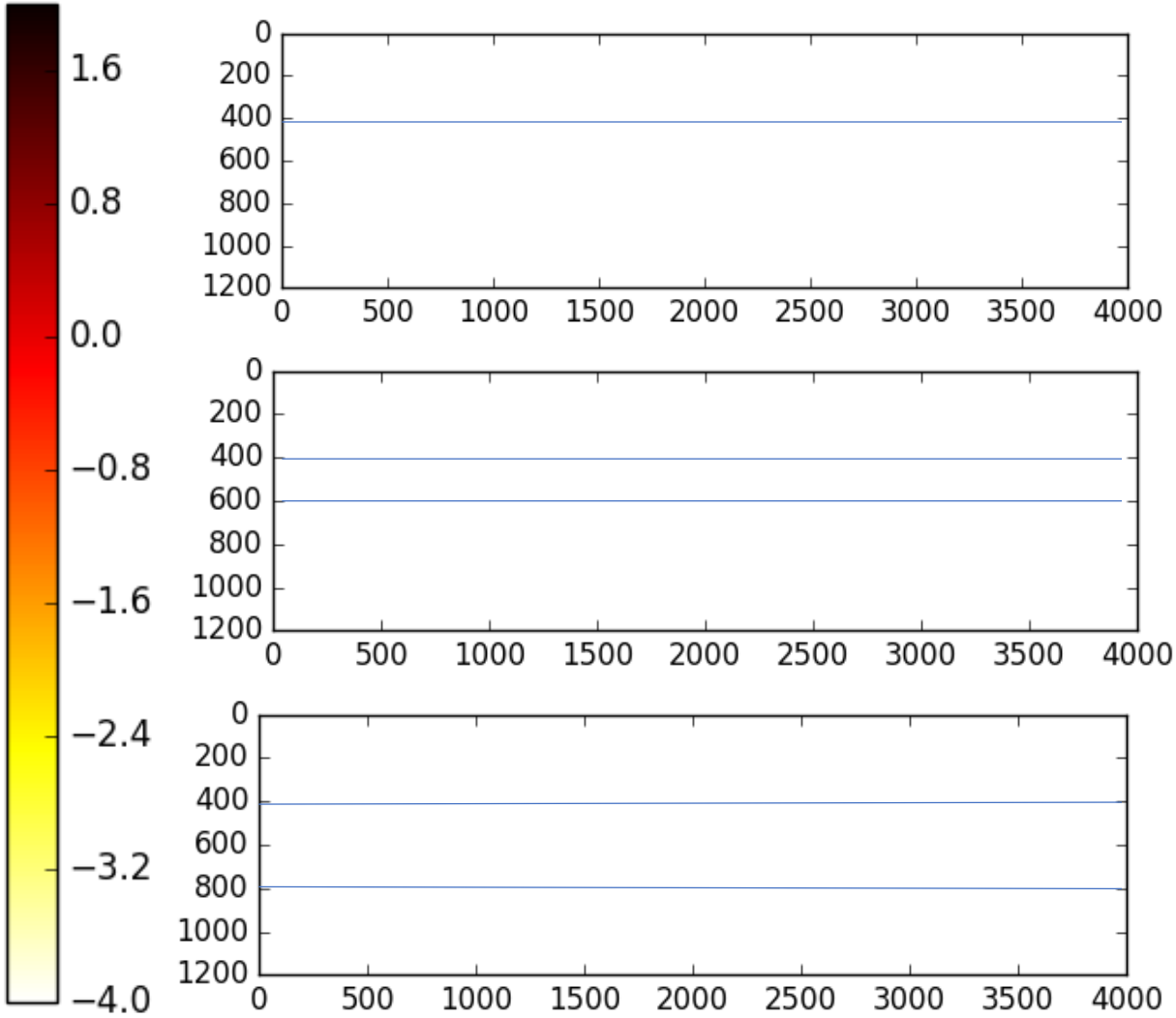


12 m shower
horizontal
Simulation 200x60 m
Resolution 20

No Layer

Layer

Gradual transition



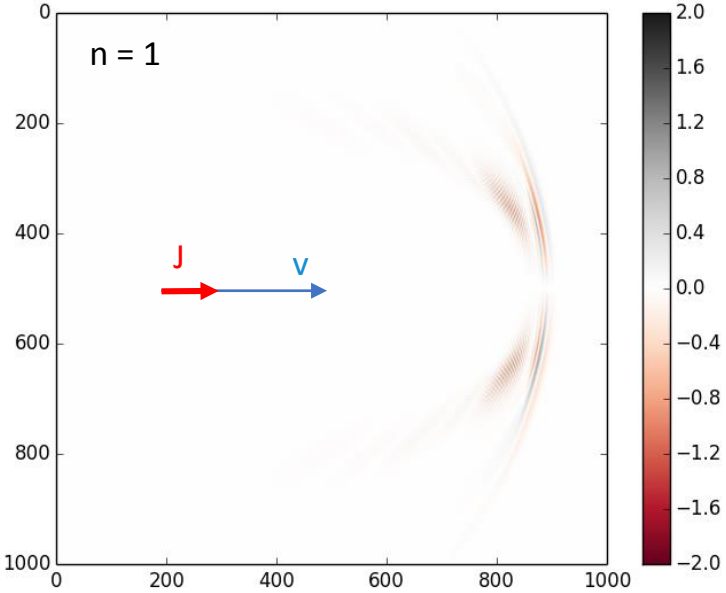
12 m shower
10 degrees inclination
Simulation 200x60 m
Resolution 20

No layer

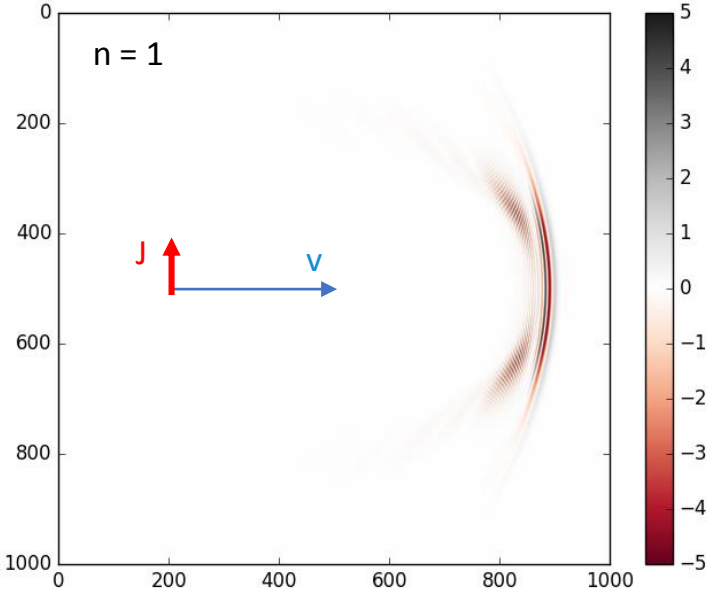
Layer

Gradual transition

Toy air shower (same 12m cascade)

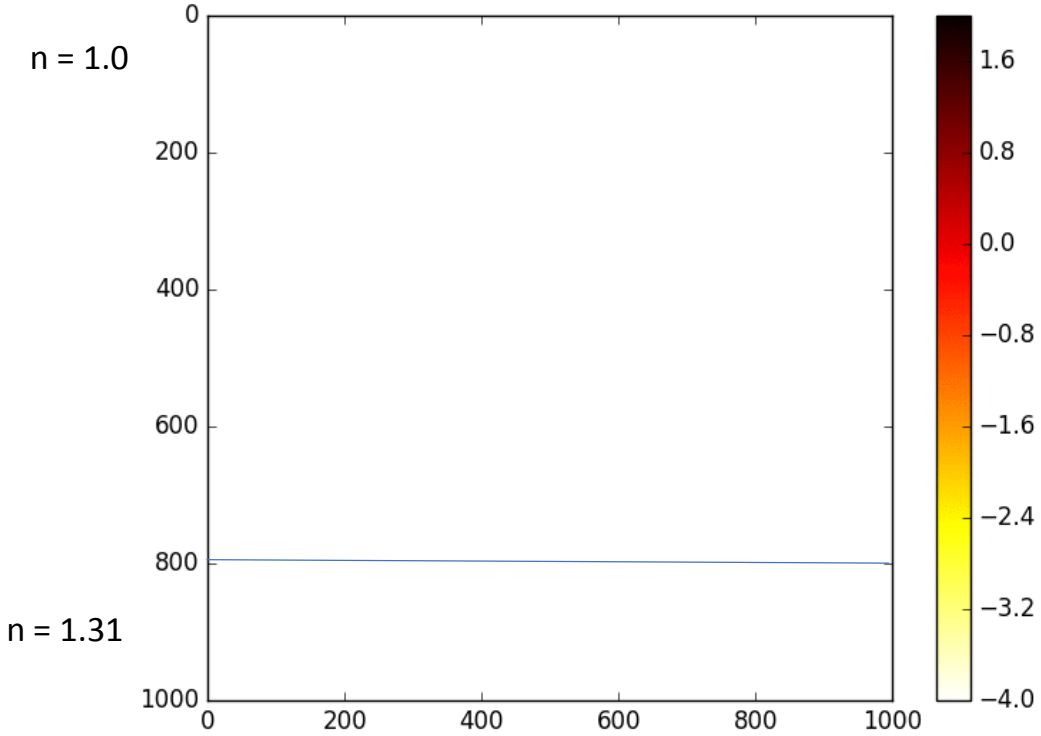


Charge excess emission
“Askaryan in vacuum”



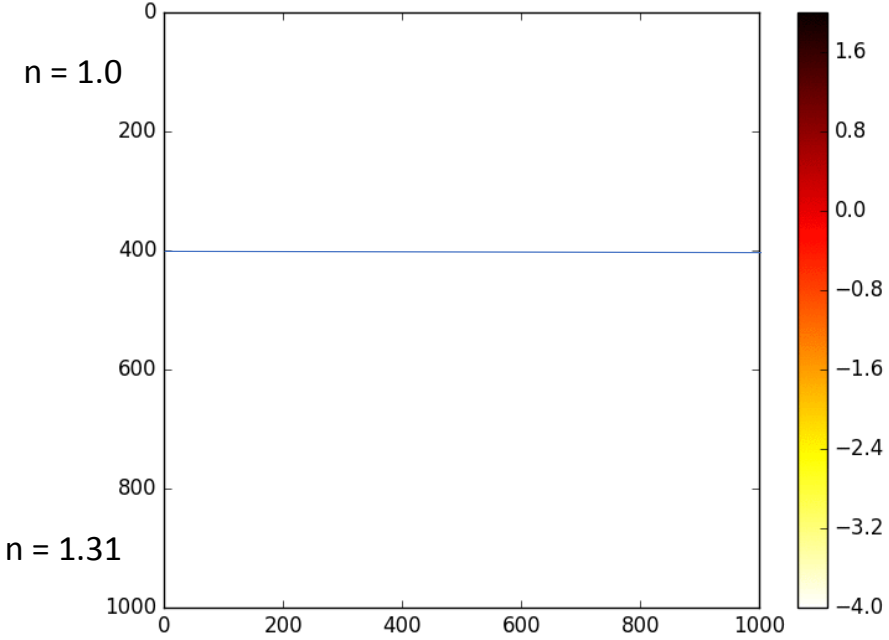
Transverse current

Pure reflection & refraction

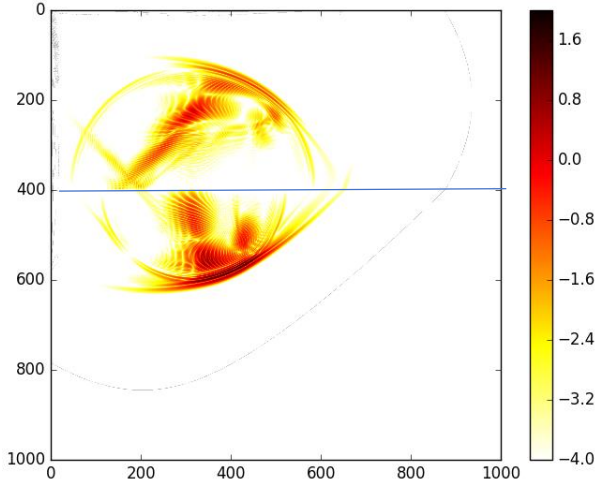


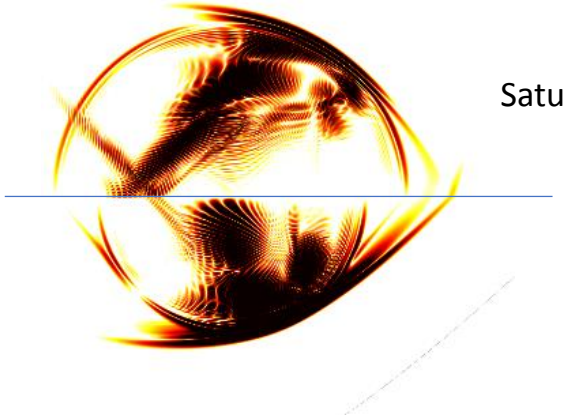
Showers hitting the ice

transverse current only
switches off in ice



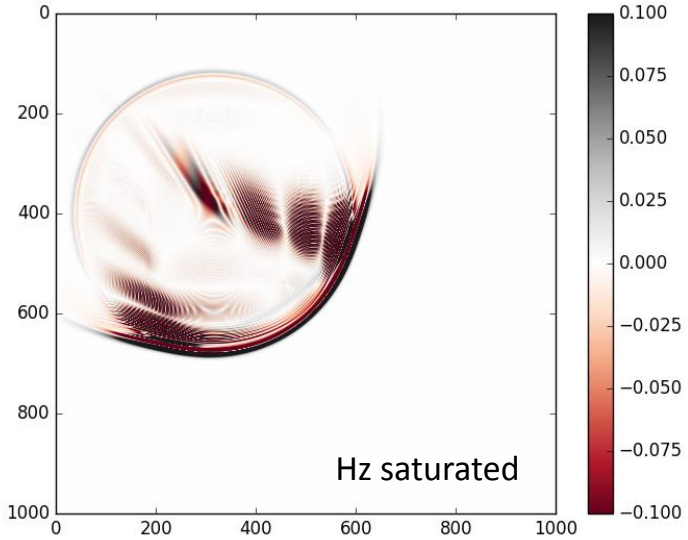
Energy density





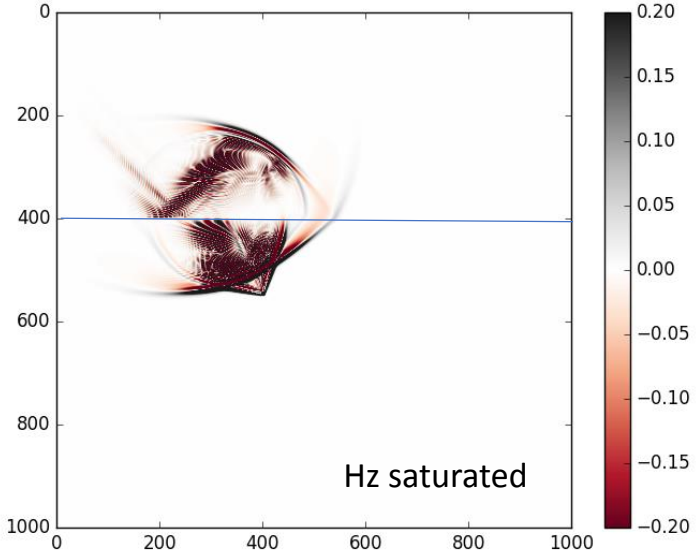
Saturated

Transverse current sudden death



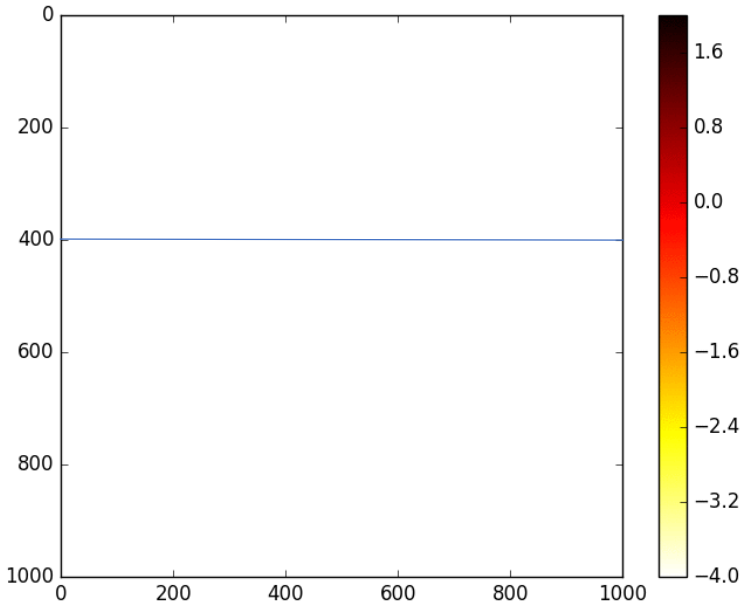
No ice
n = 1 everywhere, but:
transverse current switches off at 400m

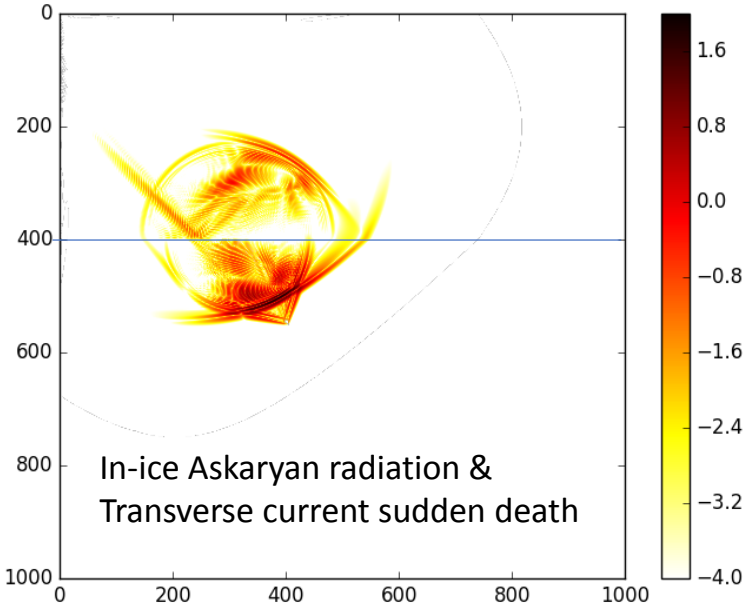
Sudden death signal
~ isotropic /polarization = v x B
Correct properties for ANITA mystery events?



Transverse current continues
no switch-off at 400m - sudden death signal gone
In ice: - refracted atmopsheric signal
- transverse current radiation
- sudden appearance

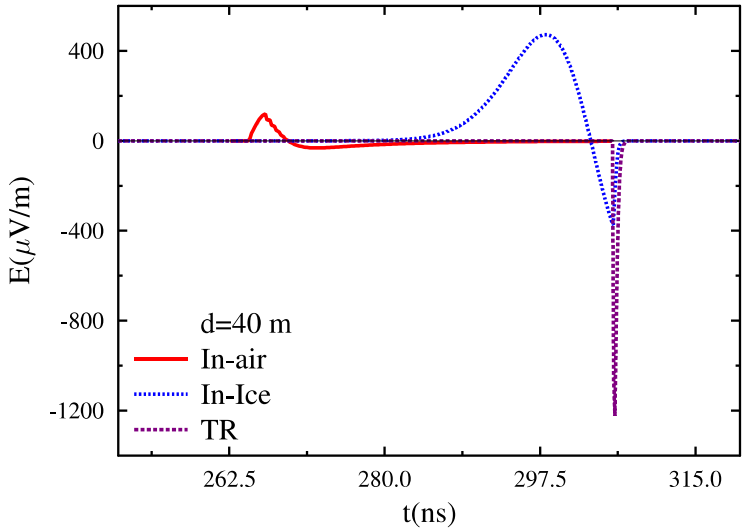
Including charge excess



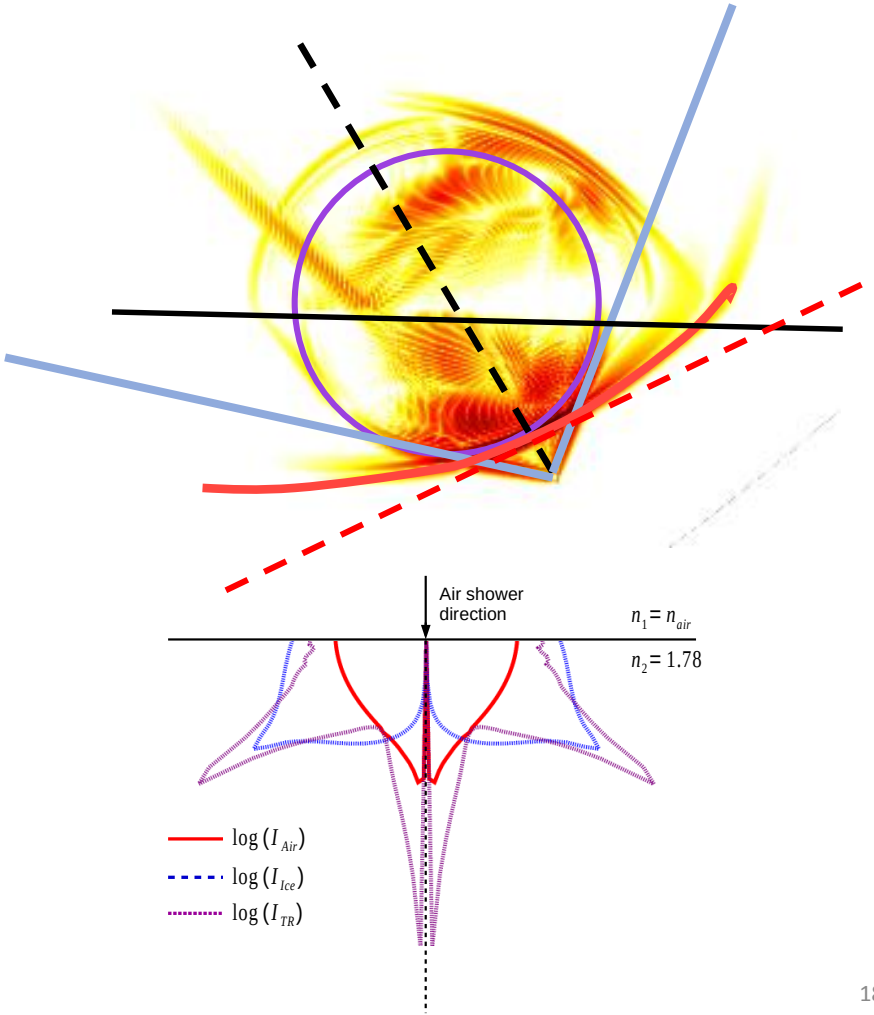


The signal in ice

Air shower signals in Askaryan detectors
K. de Vries et al. Astropart. Phys. 75, 2016



Relative strength and order of contributions depends on observer position



Final thoughts

- Simulations are expensive
  resolution: < ~cm
  macroscopic scales >~ kilometers
  2D: $10^{5\text{-}6}$ x $10^{5\text{-}6}$ bins (no. of time steps also scales with size!)
  …most bins unused… more efficient strategies?

- Reliability – be aware of:
  numerical dispersion/noise
  conservation of charge

- Opportunities
  investigate propagation effects (surface, ice, lunar escape, …)
  investigate radiation mechanisms in non-homogeneous media (where theory becomes too complex)
  visualizations