Radio detection of cosmic-ray showers with the Radio Neutrino Observatory in Greenland

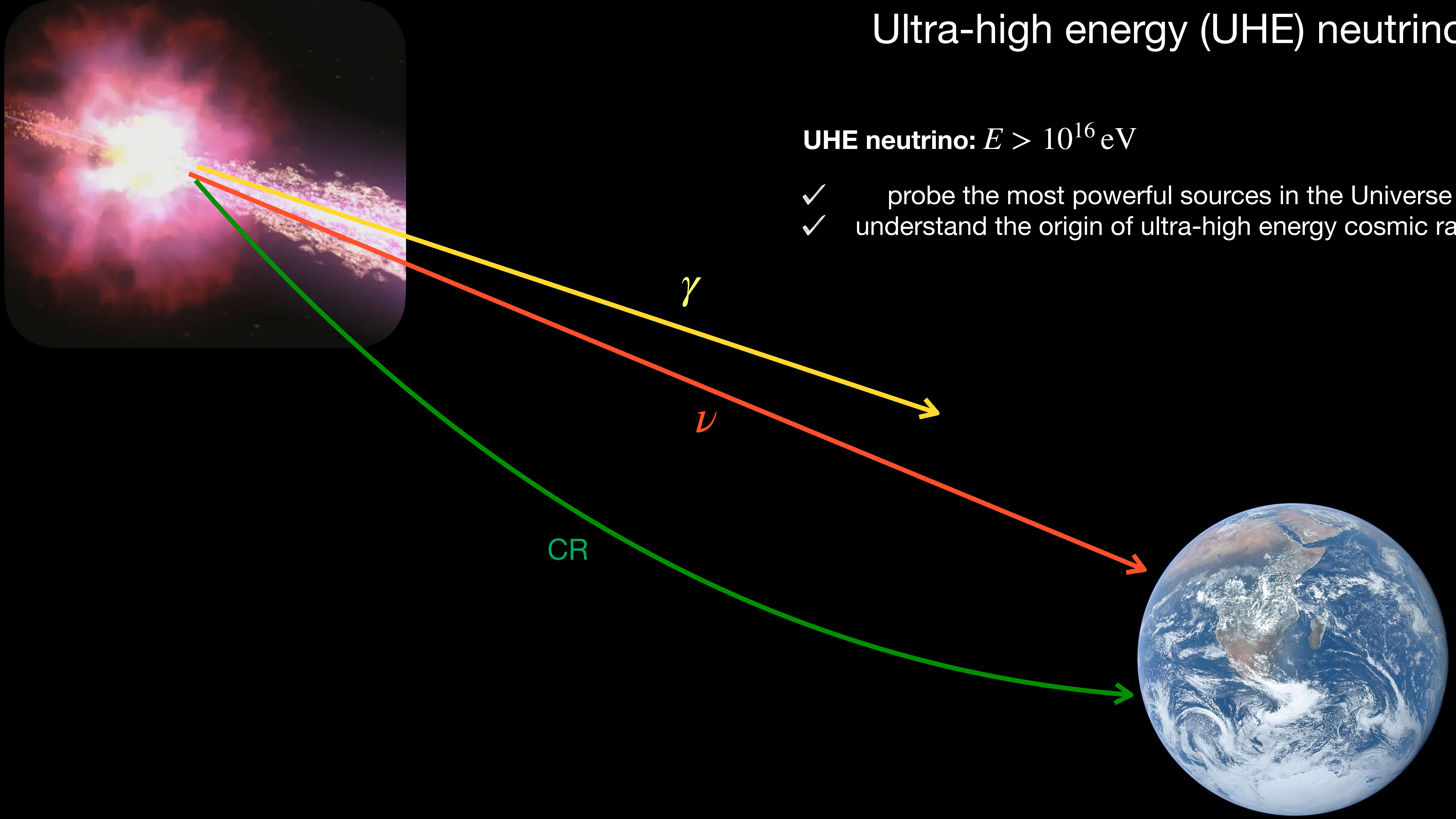
Simon Chiche, *Krijn de Vries, Simona Toscano*

ULB VUB iihe BRUXELLES BRUSSEL

Ultra-high energy (UHE) neutrinos

UHE neutrino: $E > 10^{16}\,\mathrm{eV}$

✓ probe the most powerful sources in the Universe
✓ understand the origin of ultra-high energy cosmic rays



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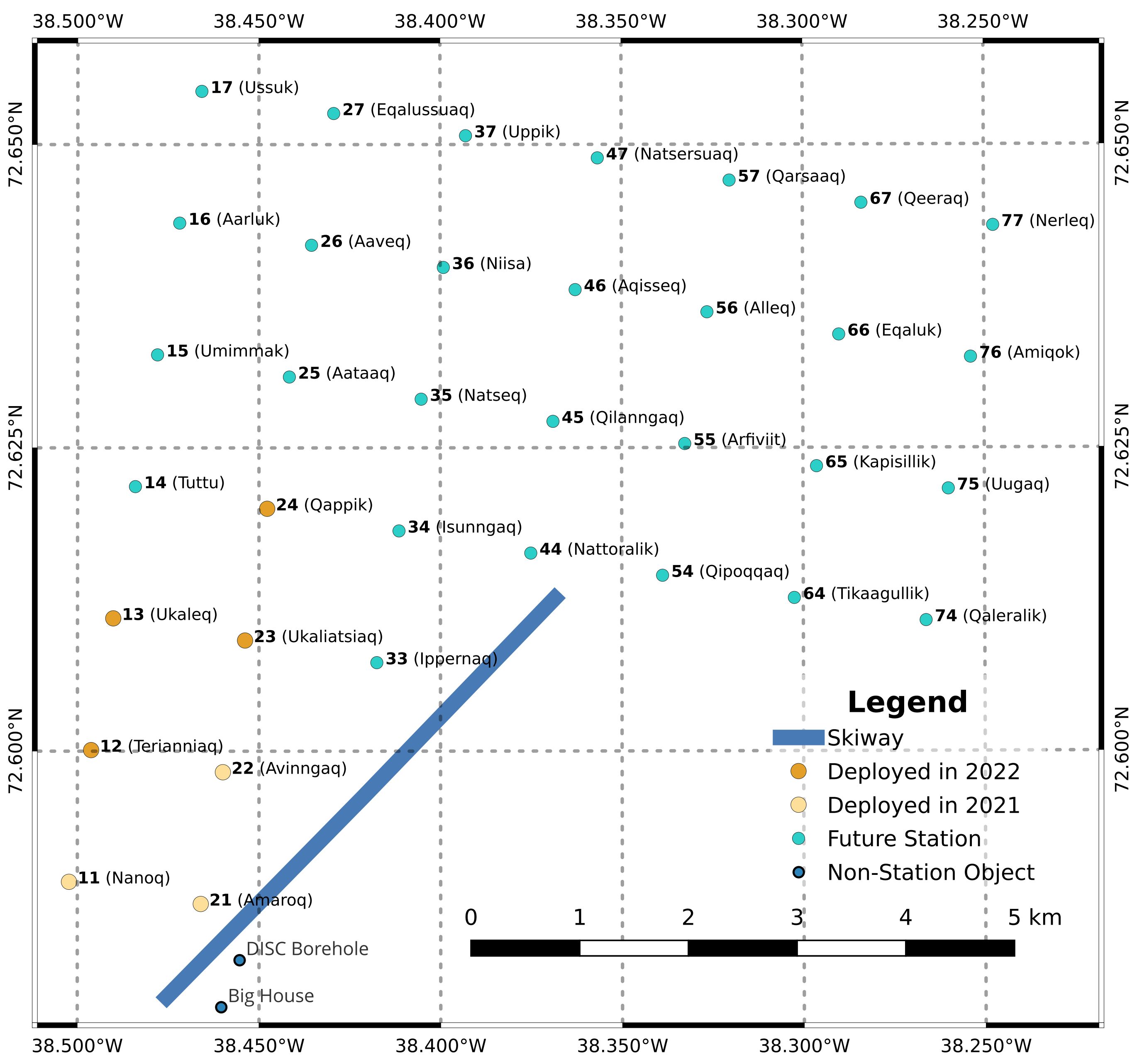
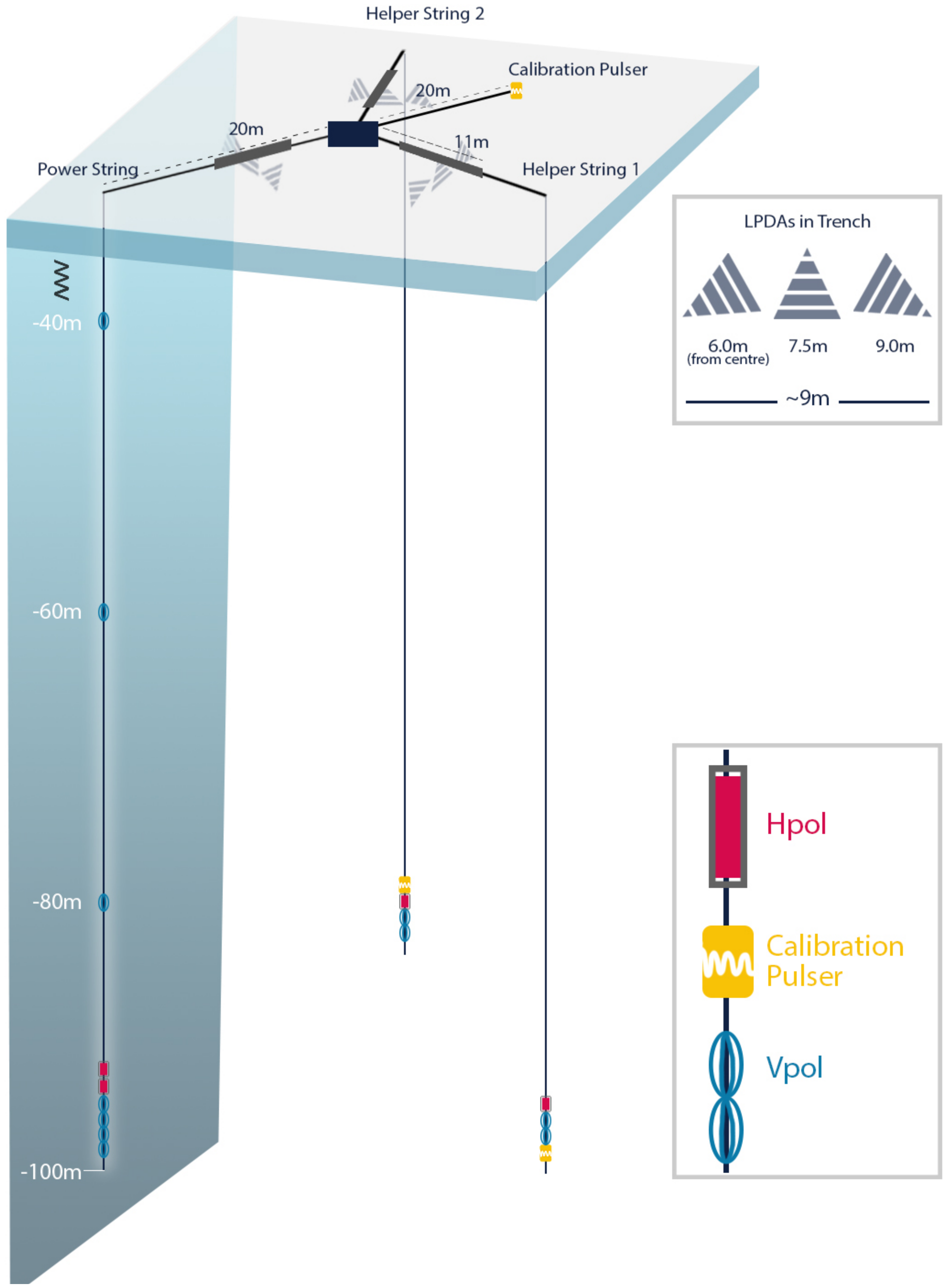
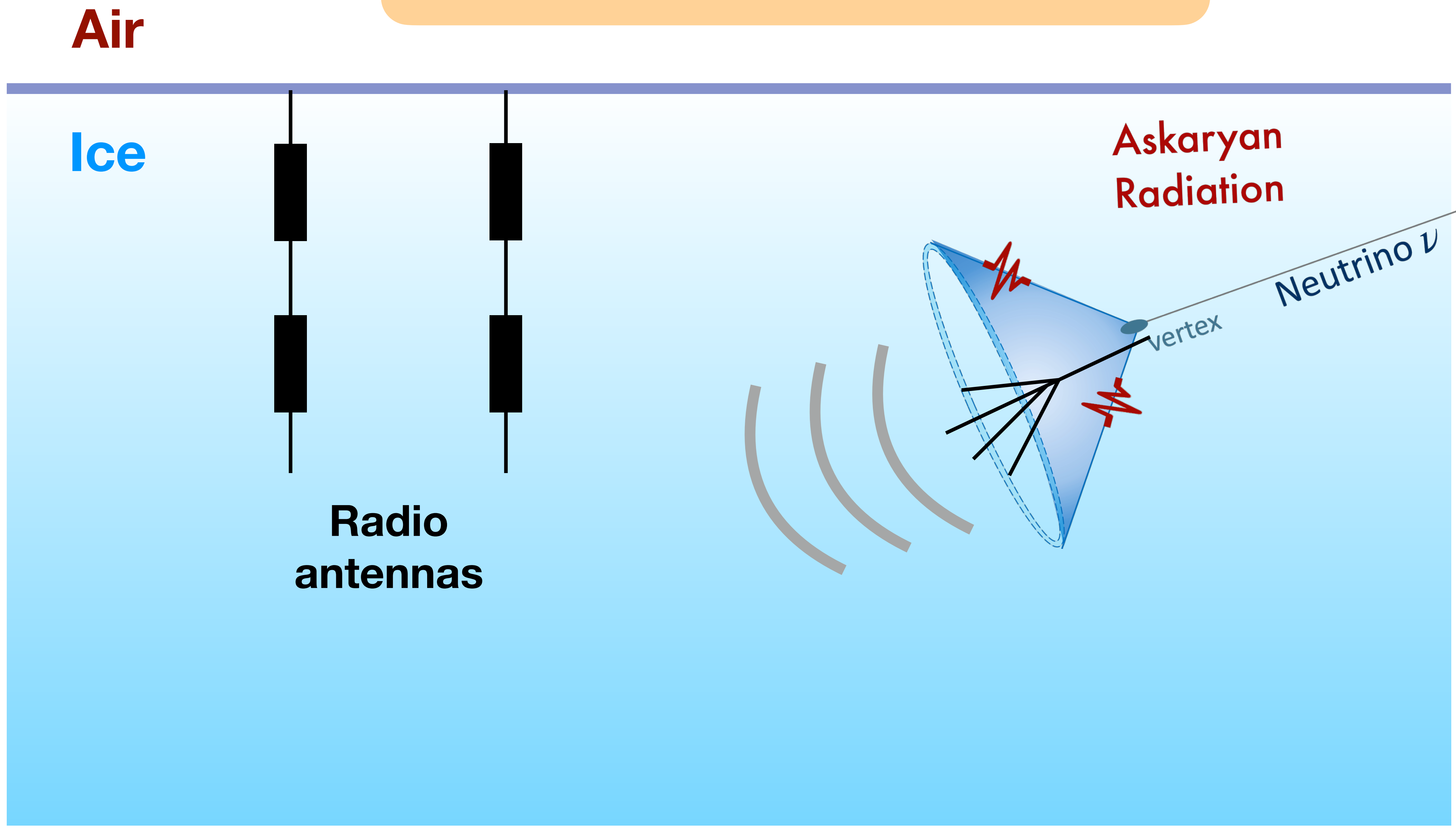
35 autonomous stations at Summit Station (Greenland)



1 station: 24 radio antennas

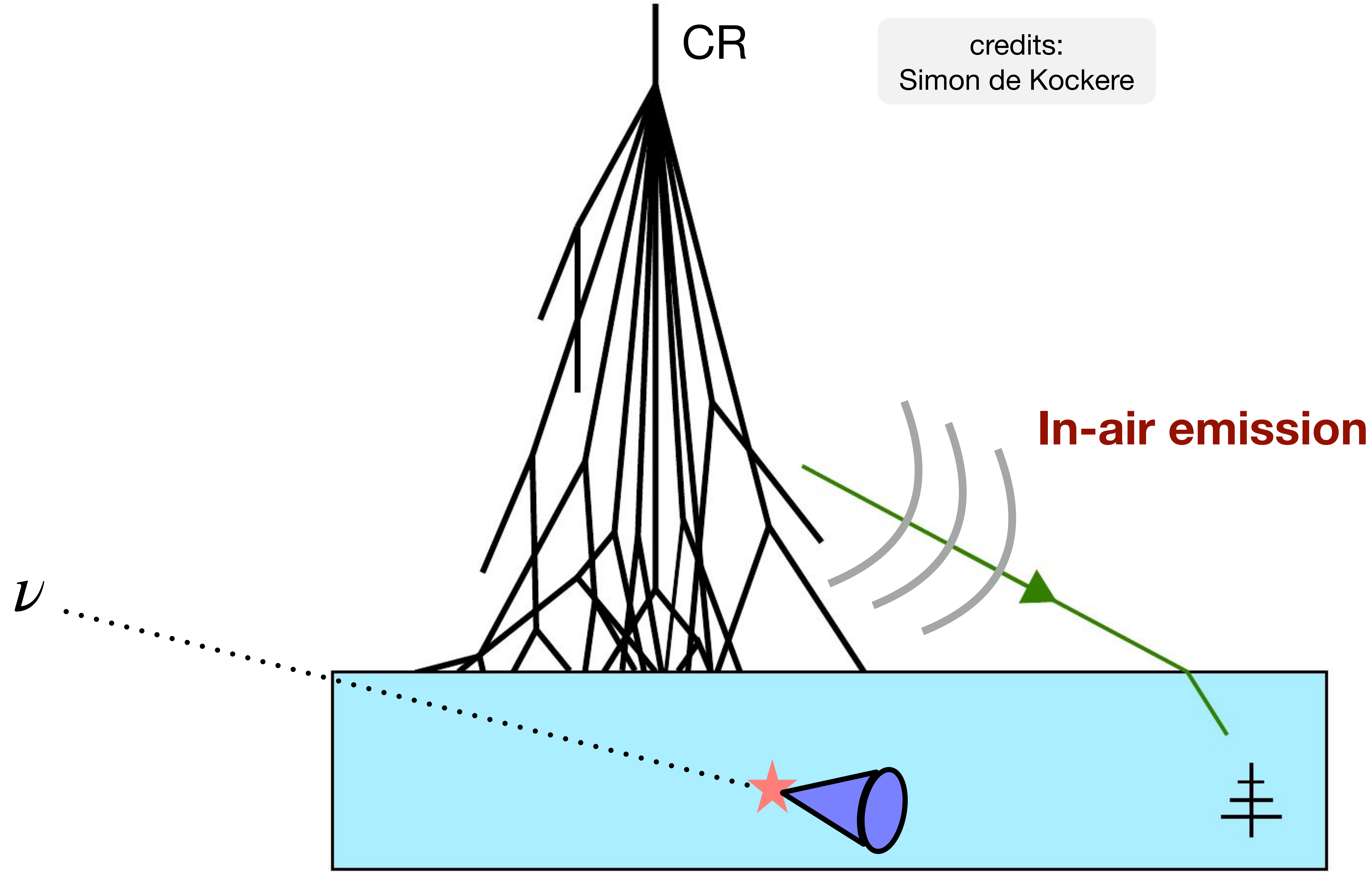


Radio detection of ultra-high energy neutrinos



In-ice radio detection: promising technique to detect ultra-high energy neutrinos

Radio emission of cosmic-ray air showers can also reach the deep antennas



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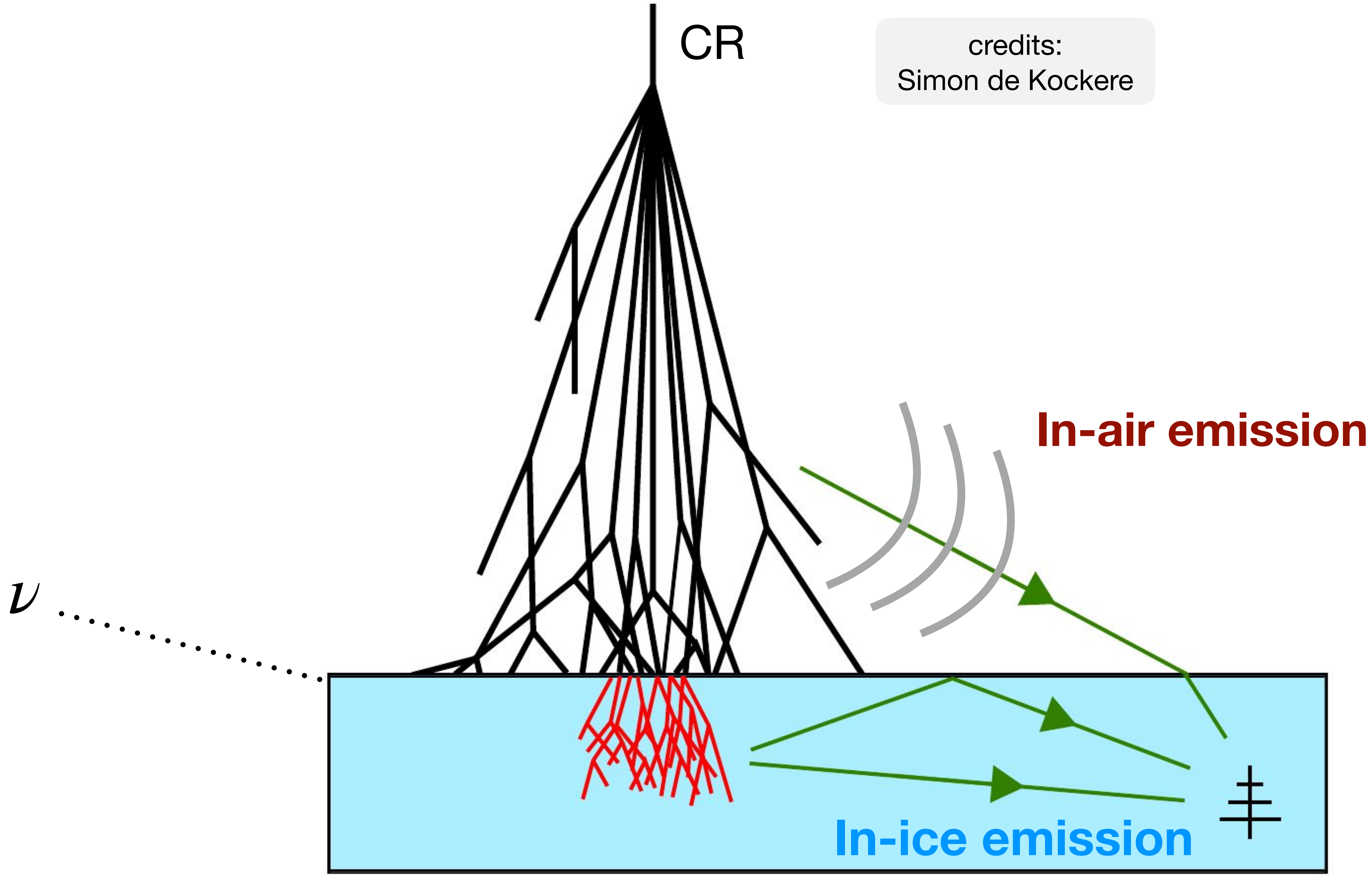

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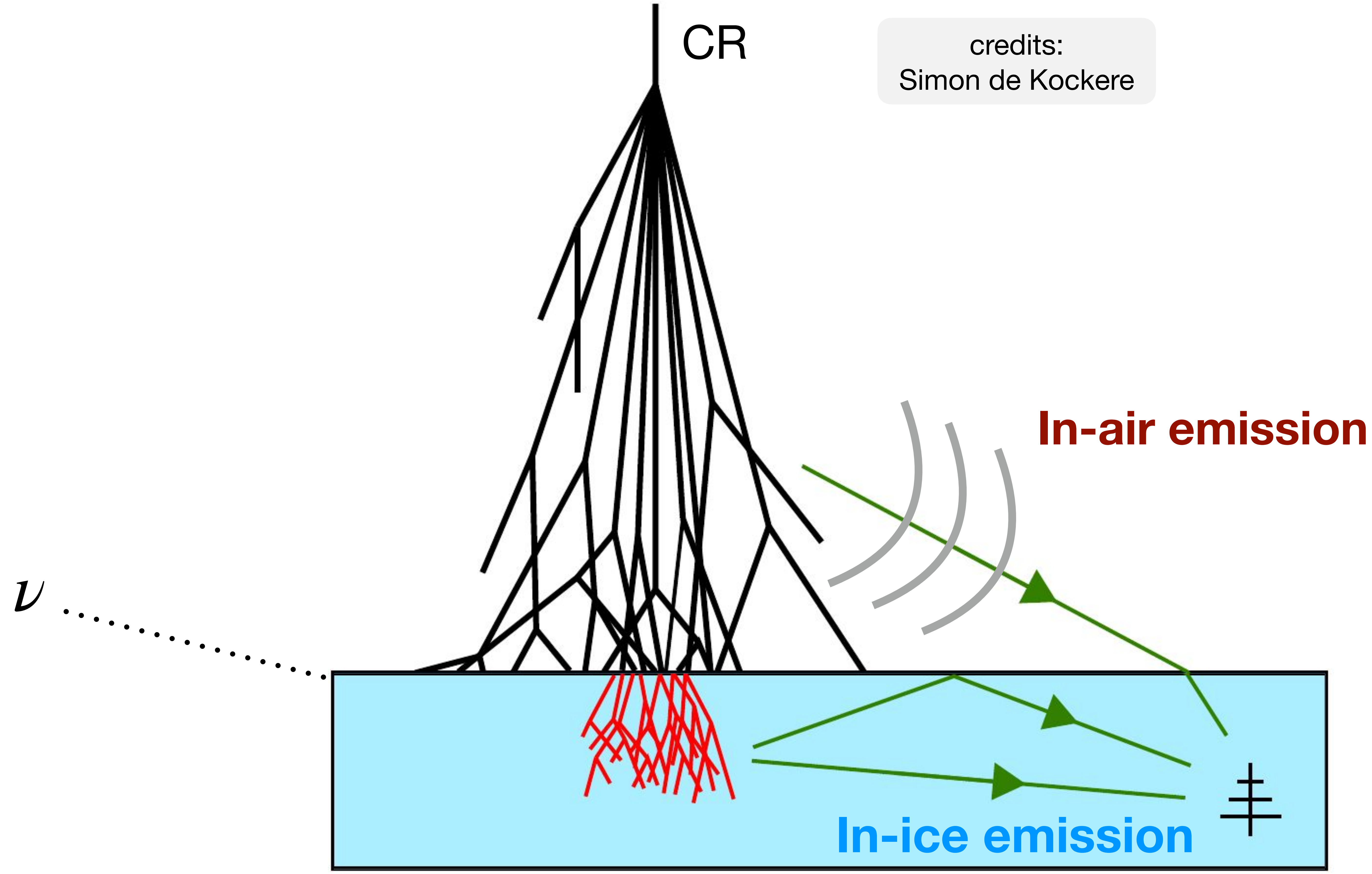
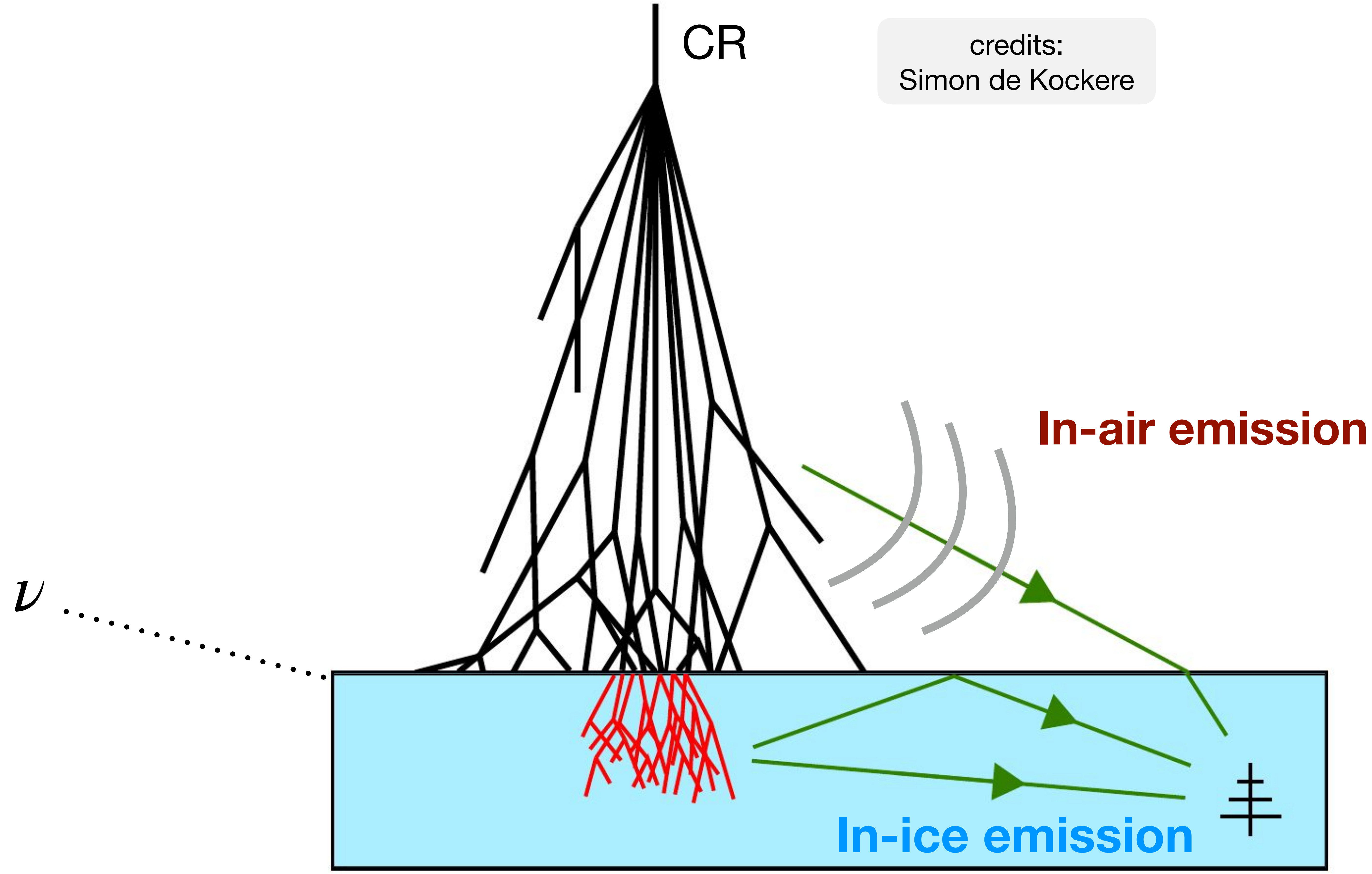


The cosmic-ray flux should be much larger than the neutrino flux:

Radio emission of cosmic-ray air showers can also reach the deep antennas

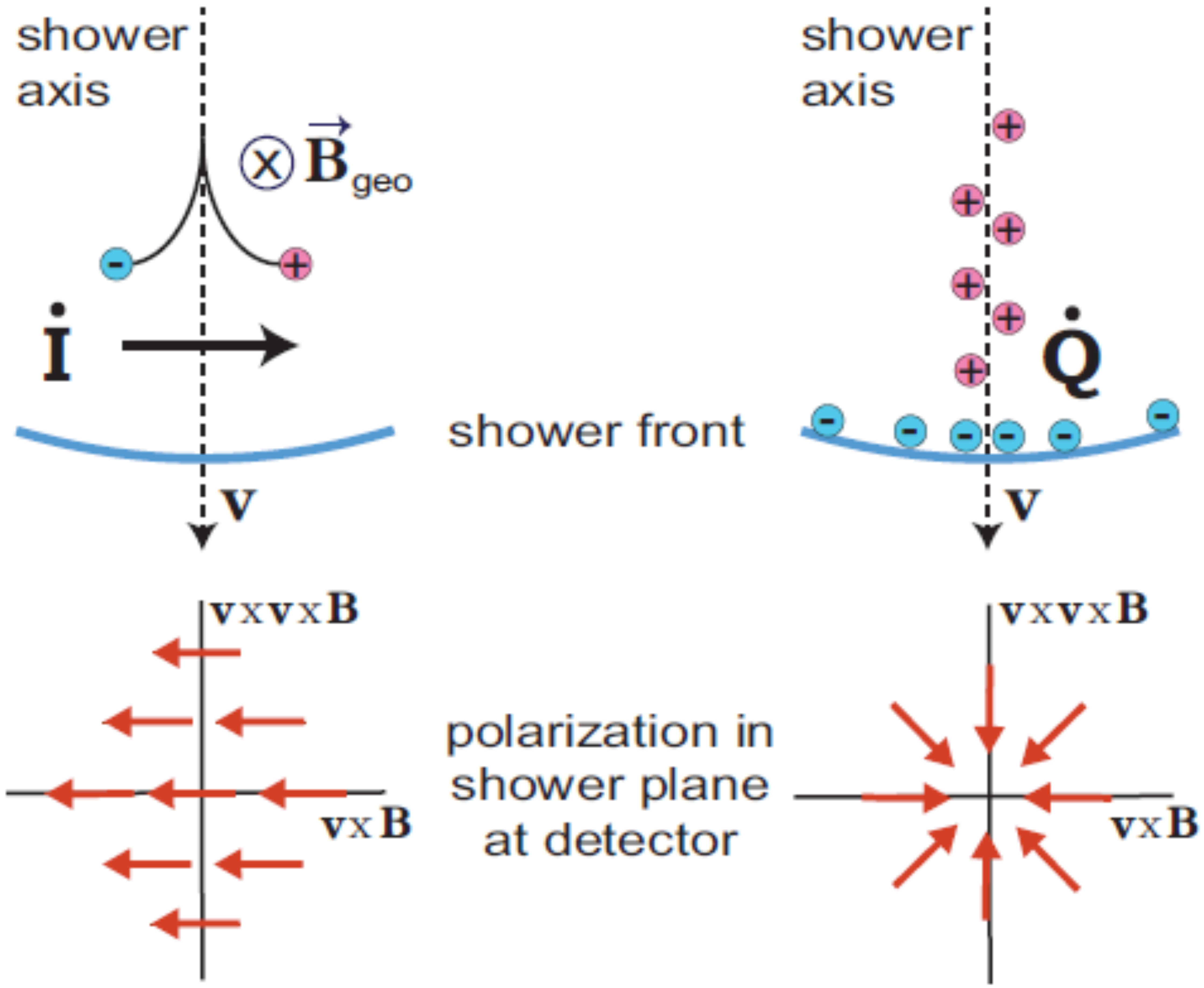


The cosmic-ray flux should be much larger than the neutrino flux:

- Cosmic-ray detection would validate in-ice radio detection principle
- Cosmic-ray/neutrino discrimination is needed to ensure successful neutrino detection

2 main sources for the radio emission of cosmic rays

Geomagnetic emission **Askaryan emission**



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2 main sources for the radio emission of cosmic rays

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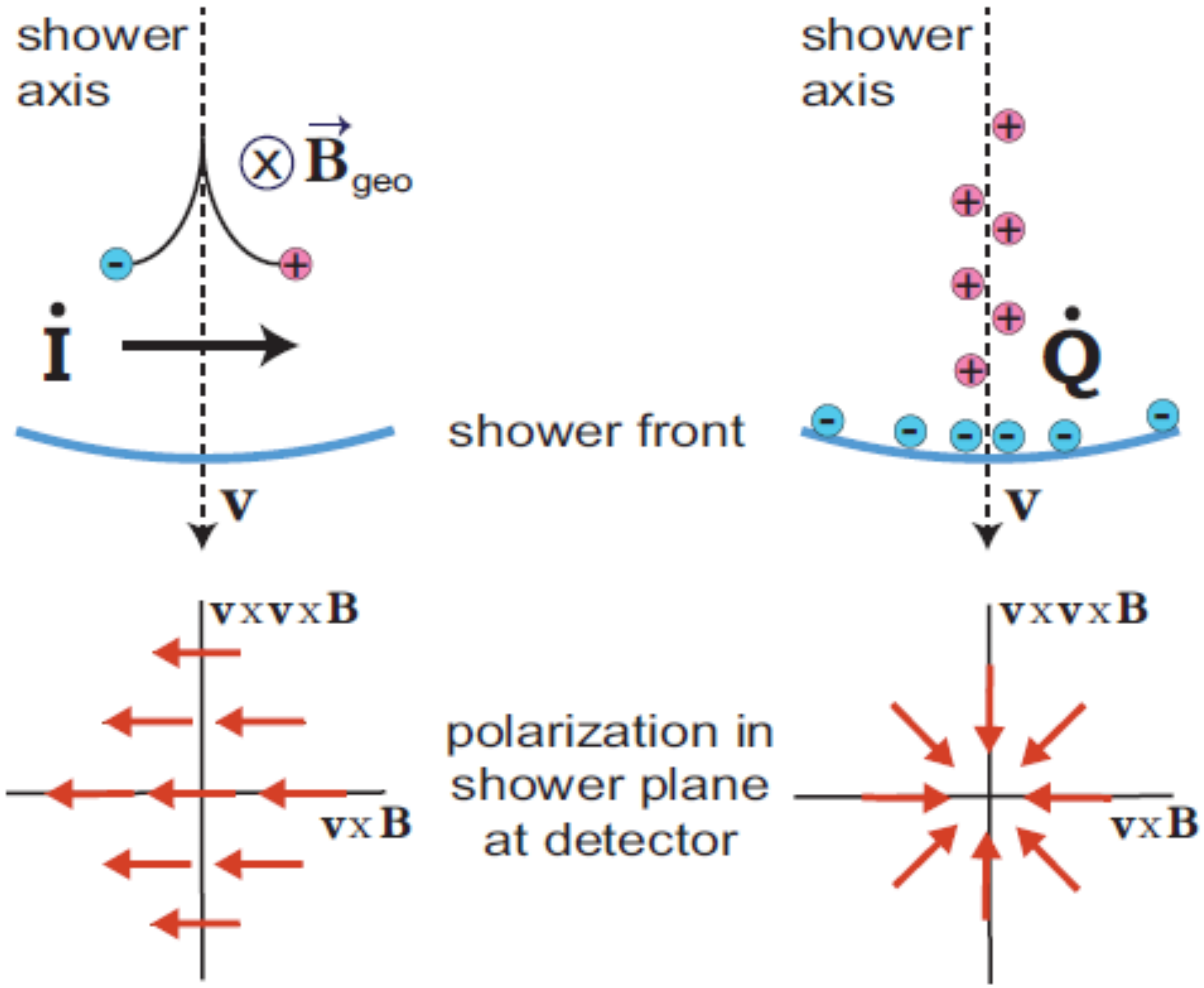

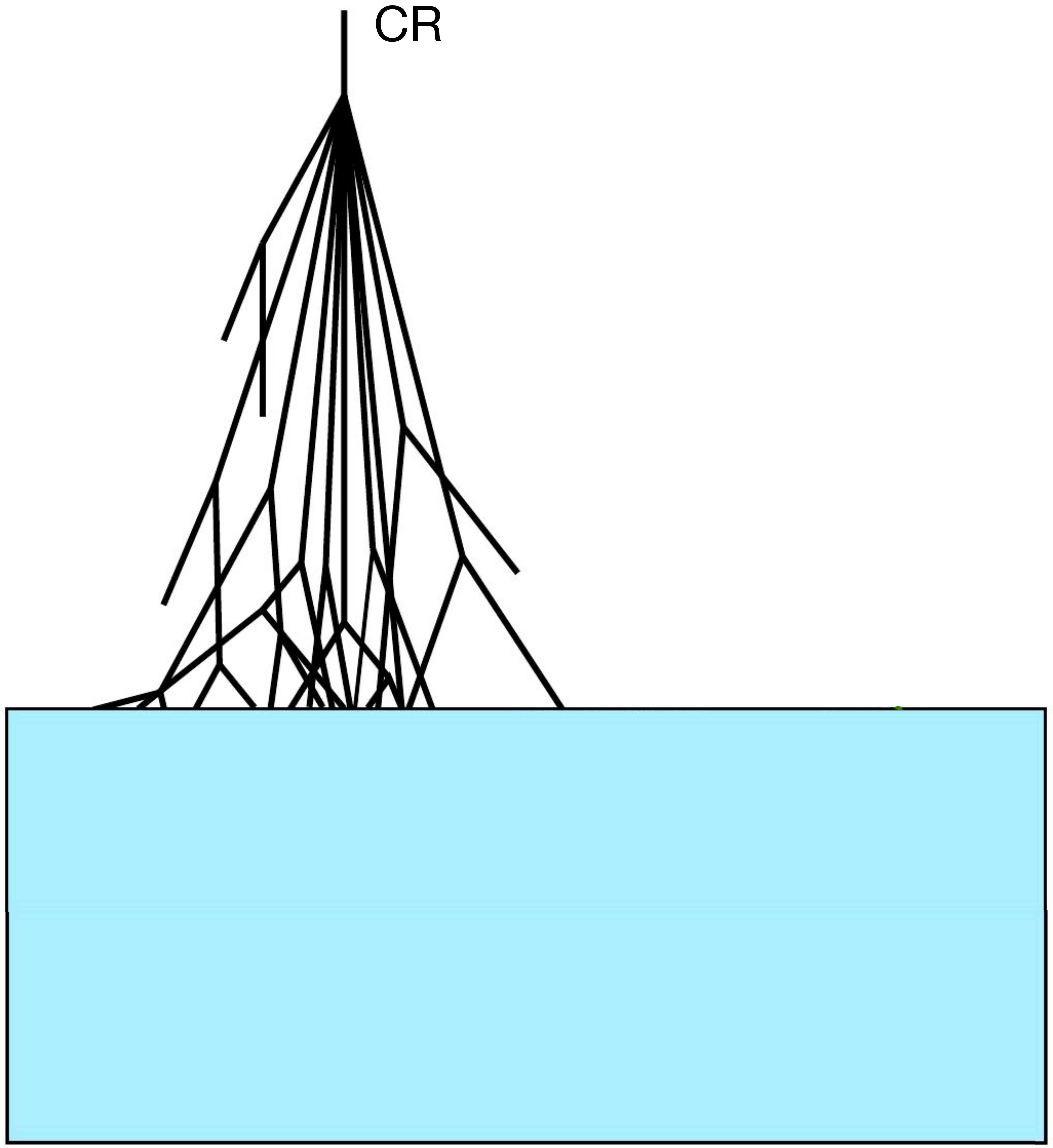

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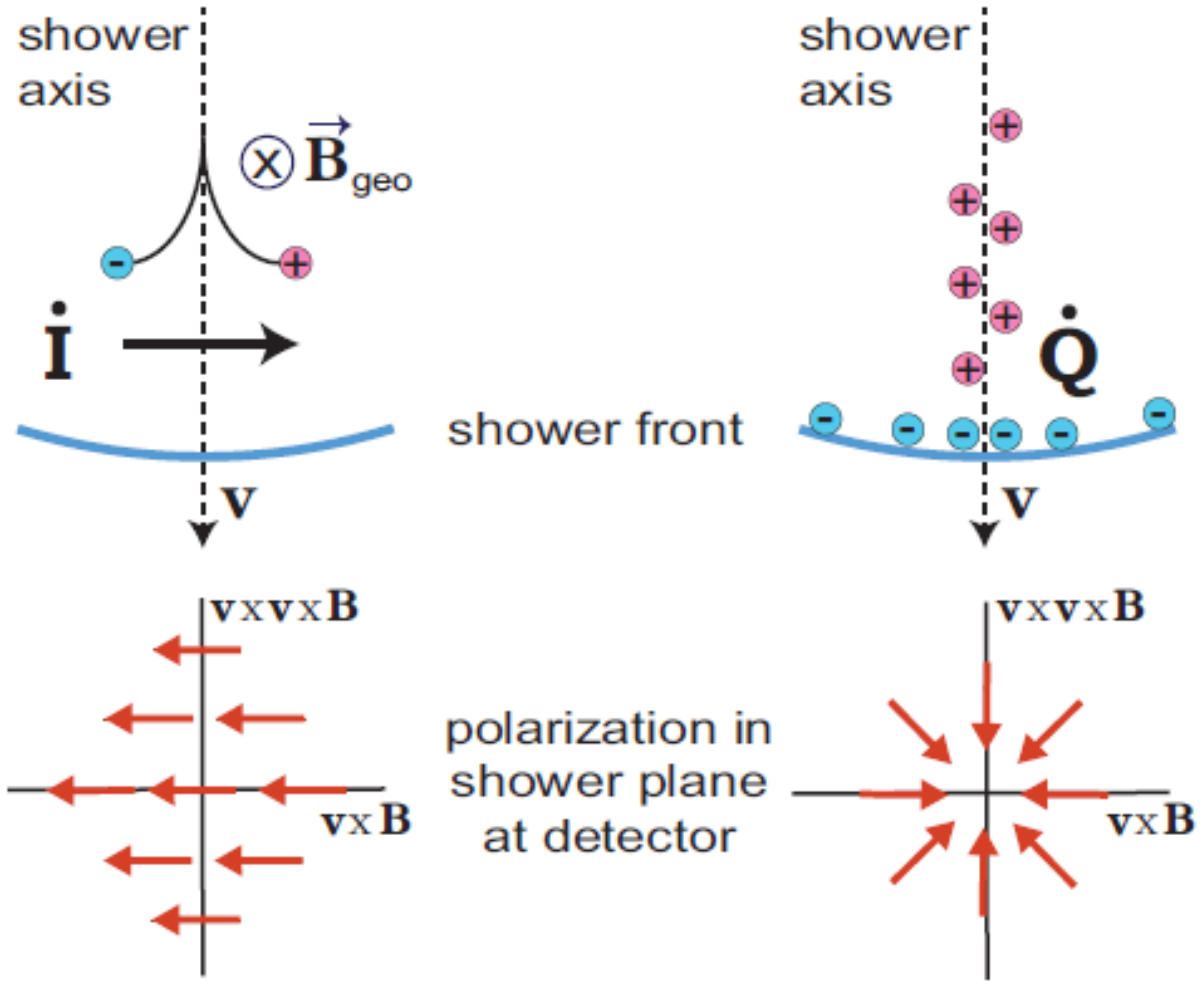

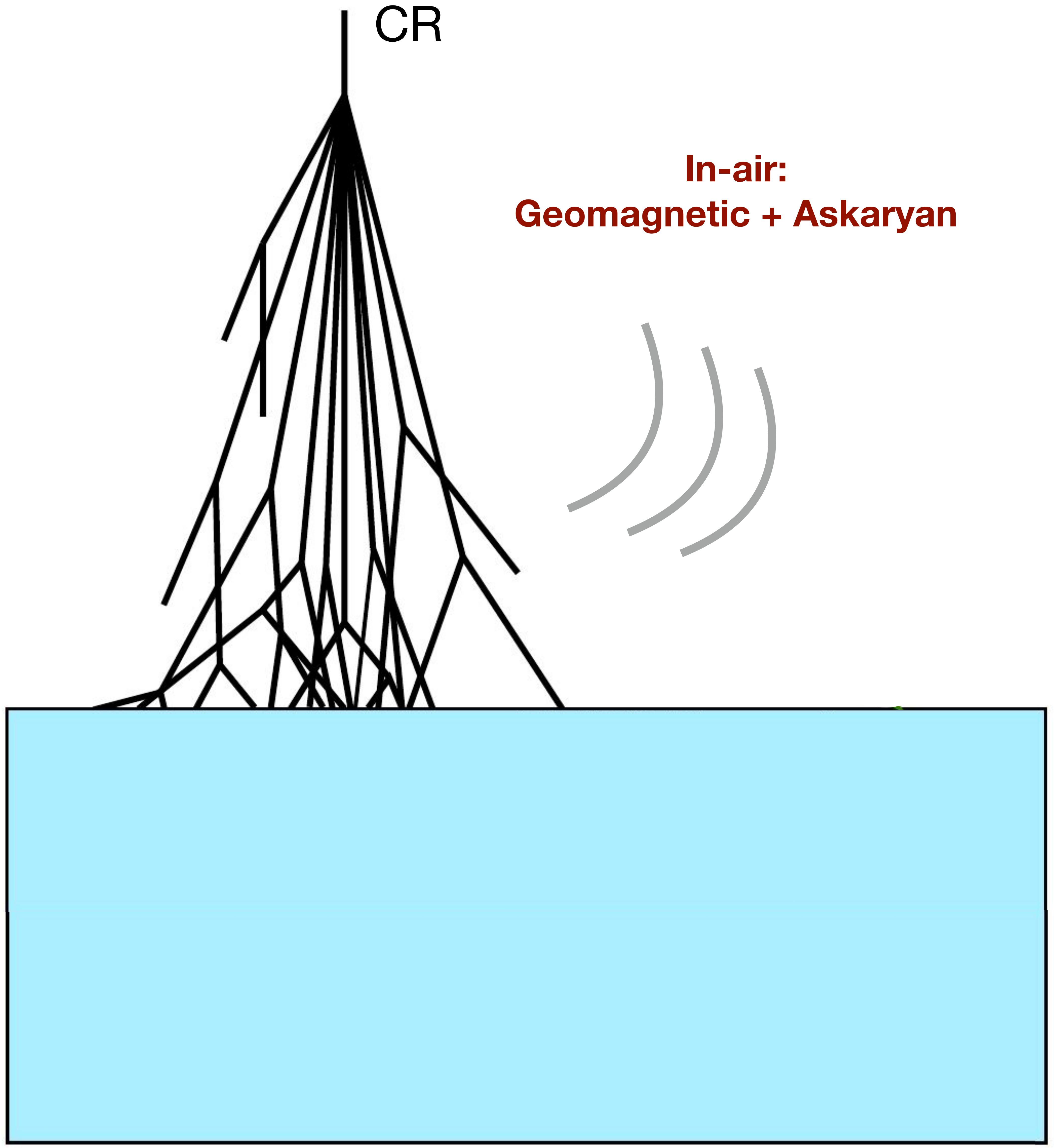

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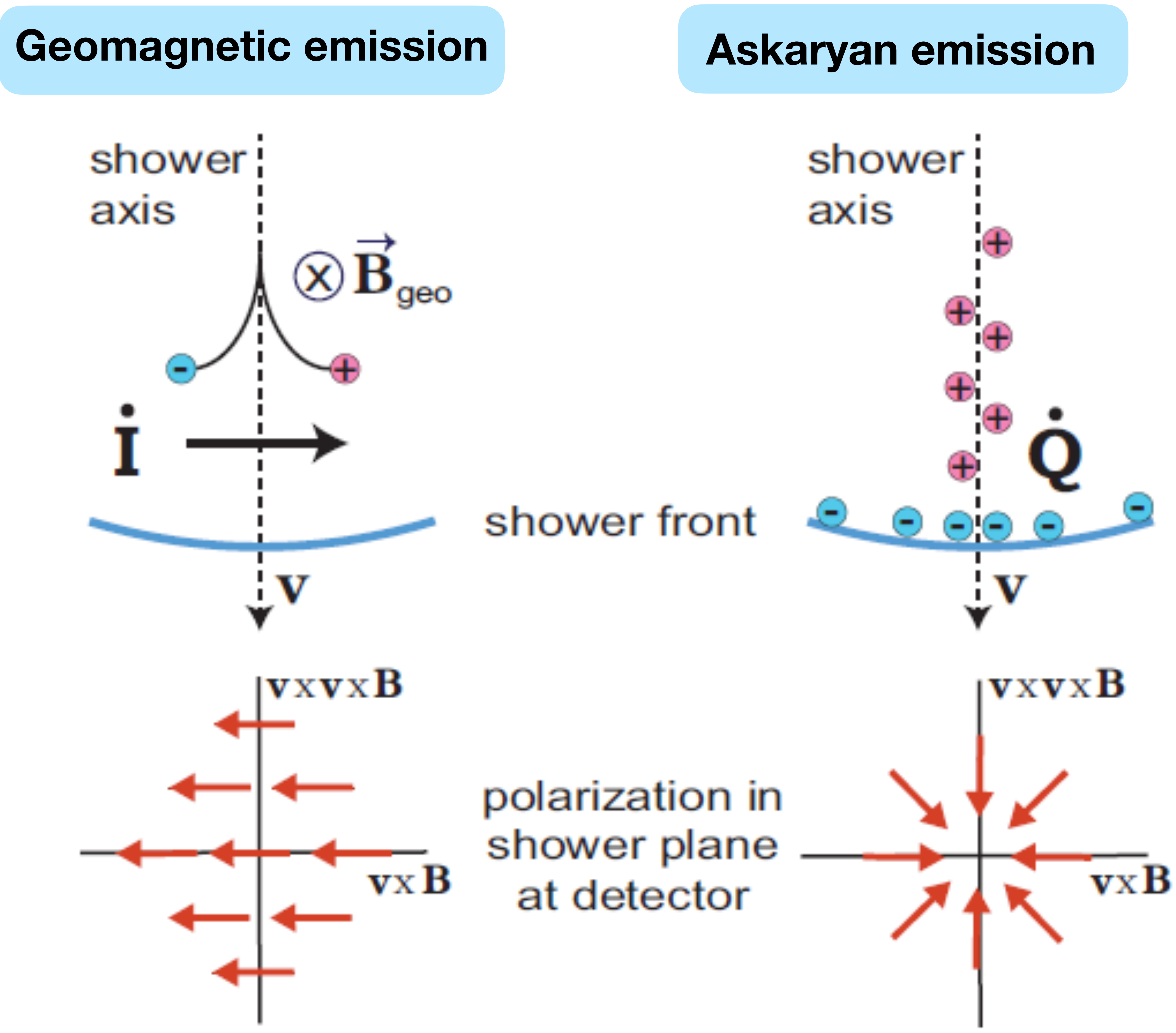

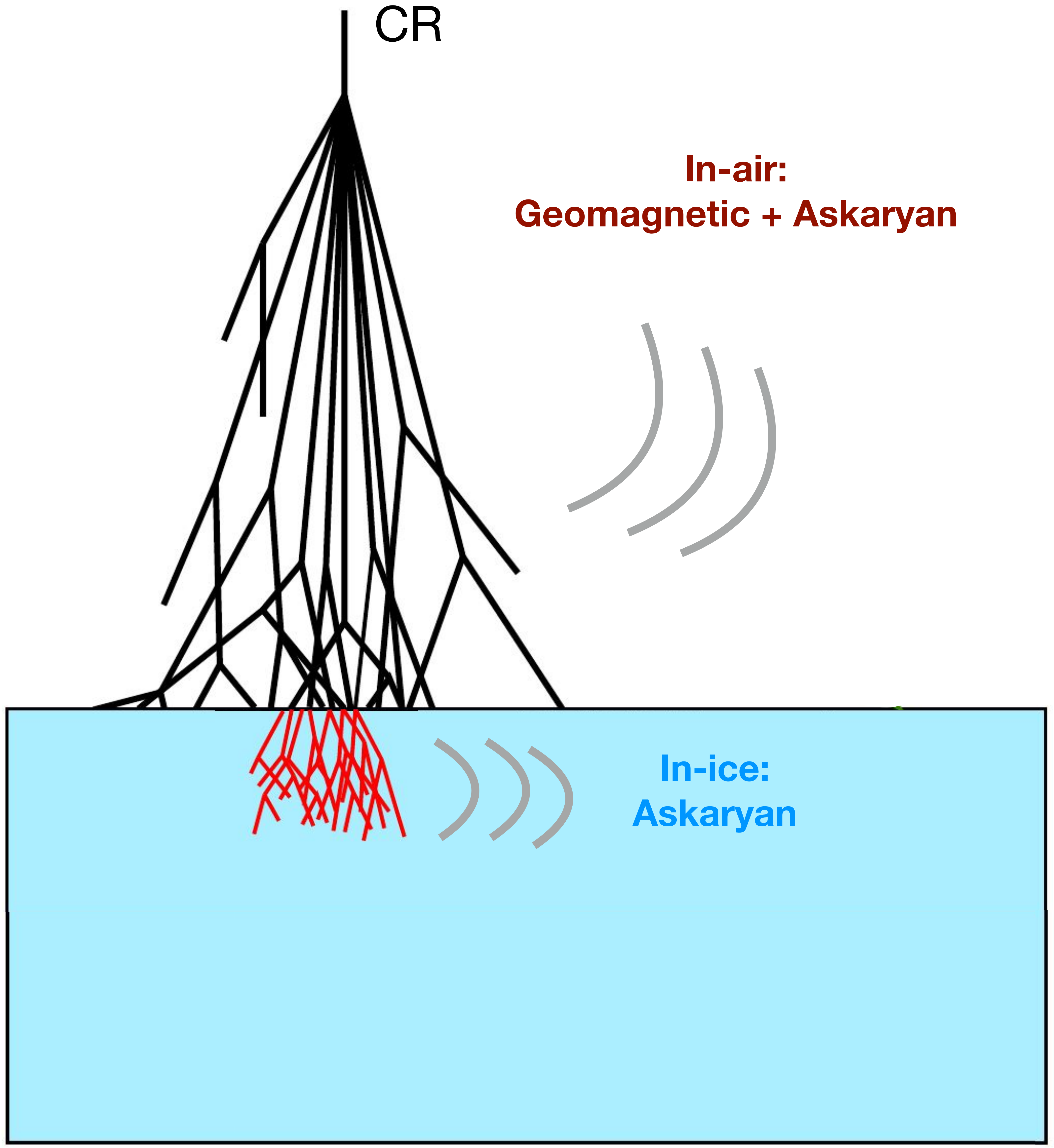

2 main sources for the radio emission of cosmic rays

Geomagnetic emission

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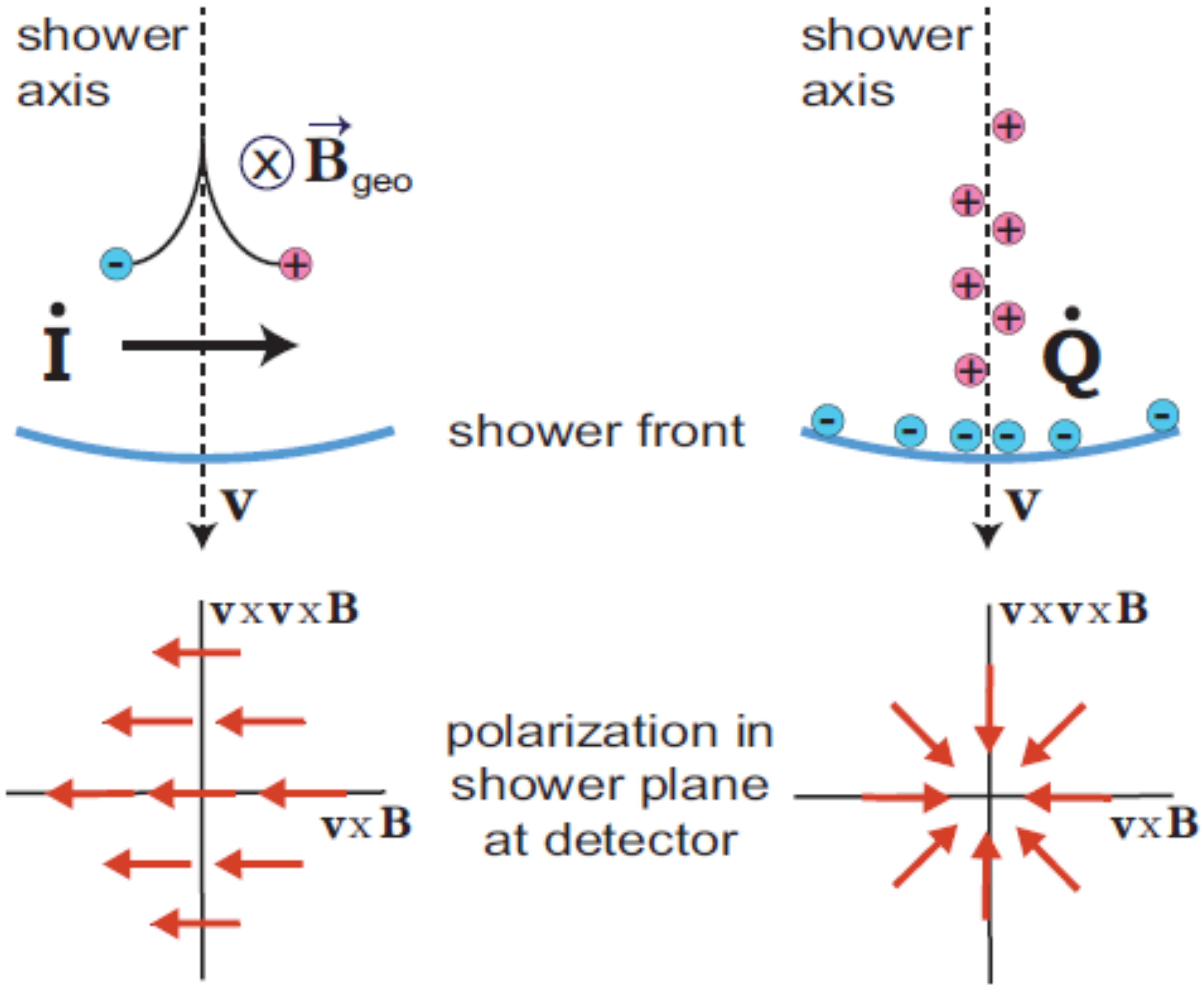

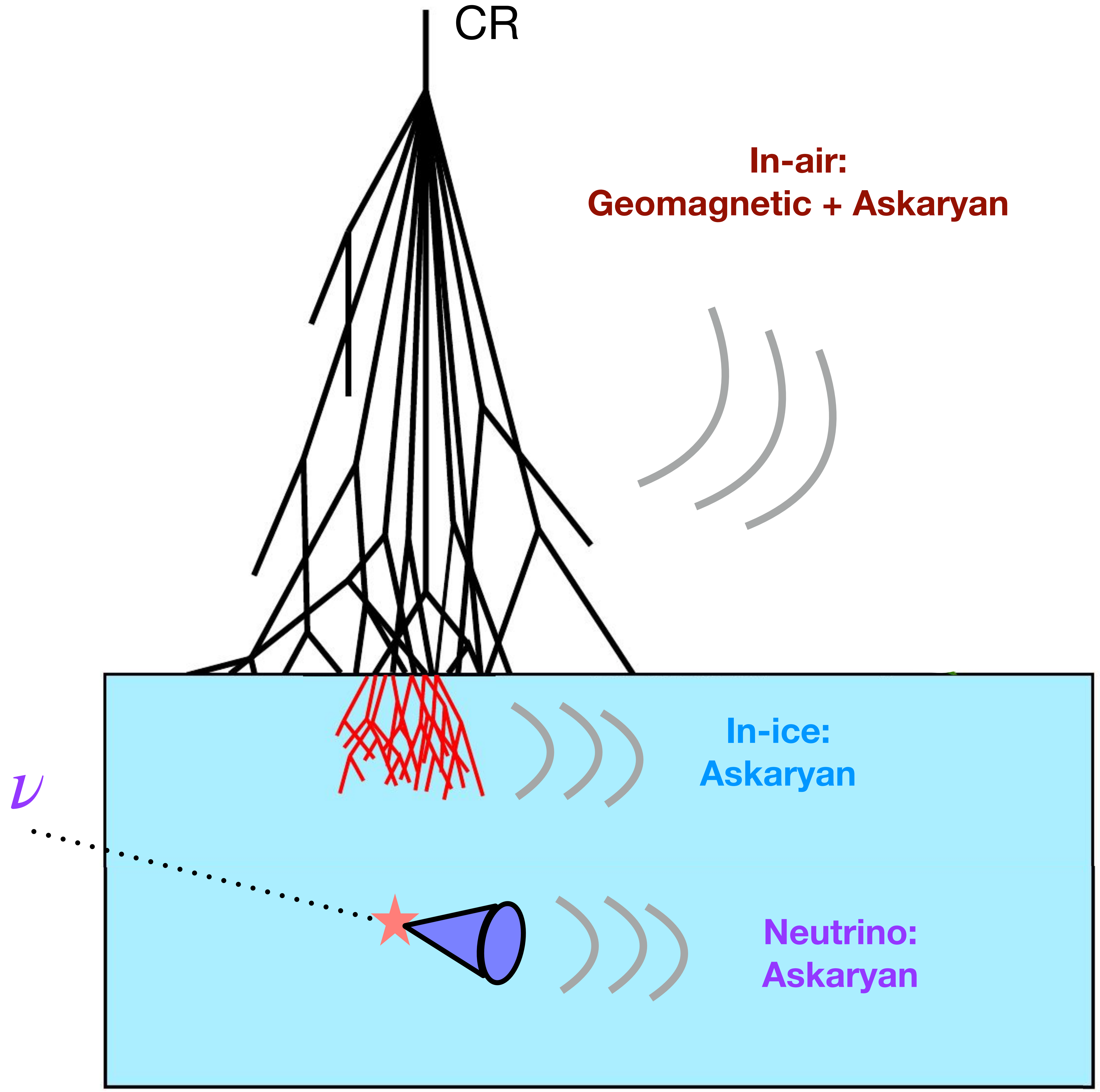

Simulation setup

We simulated cosmic-ray radio emission using the Monte-Carlo tool FAERIE

(De Kockere et al., 2024 [2403.15358])

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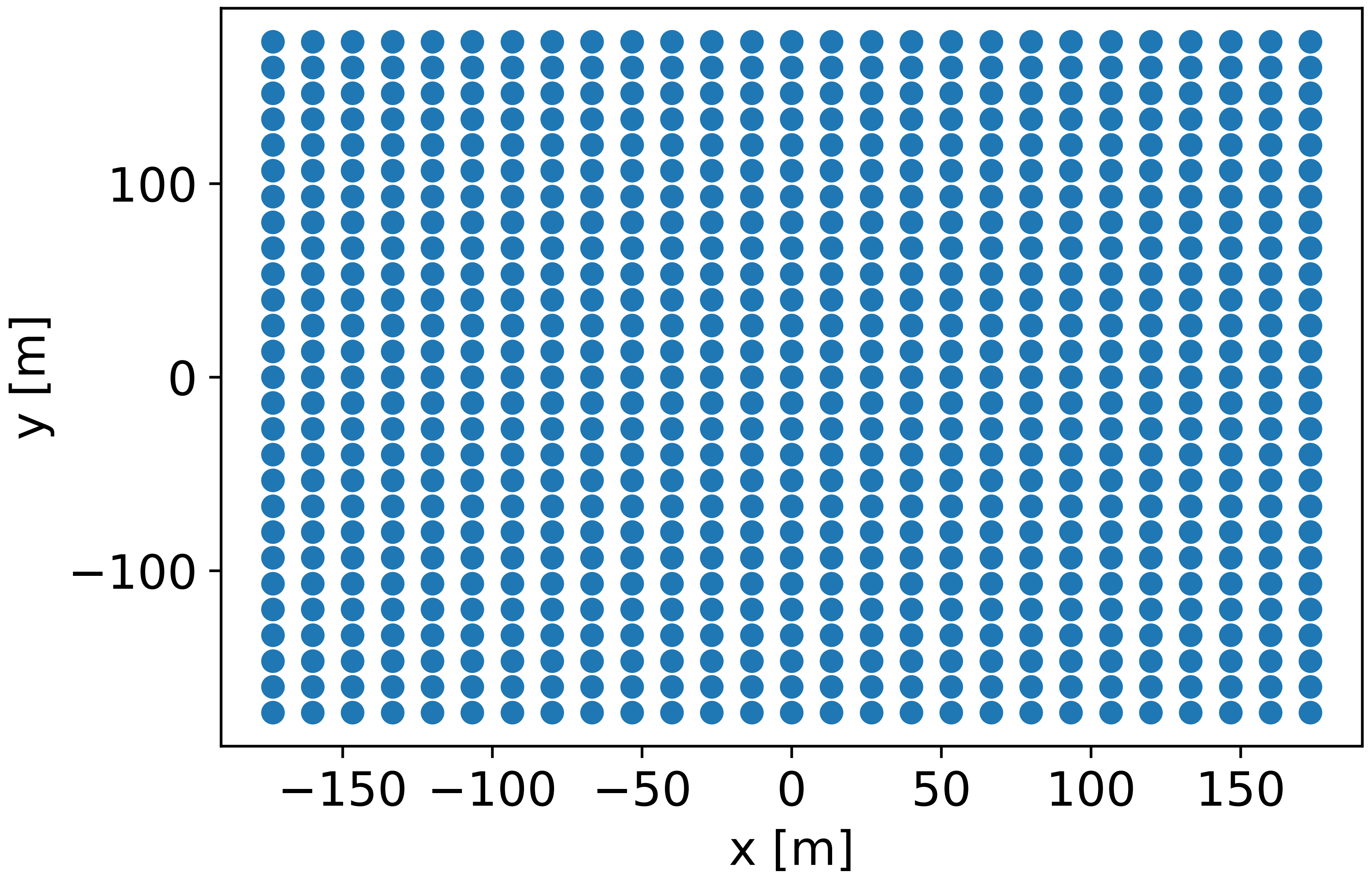
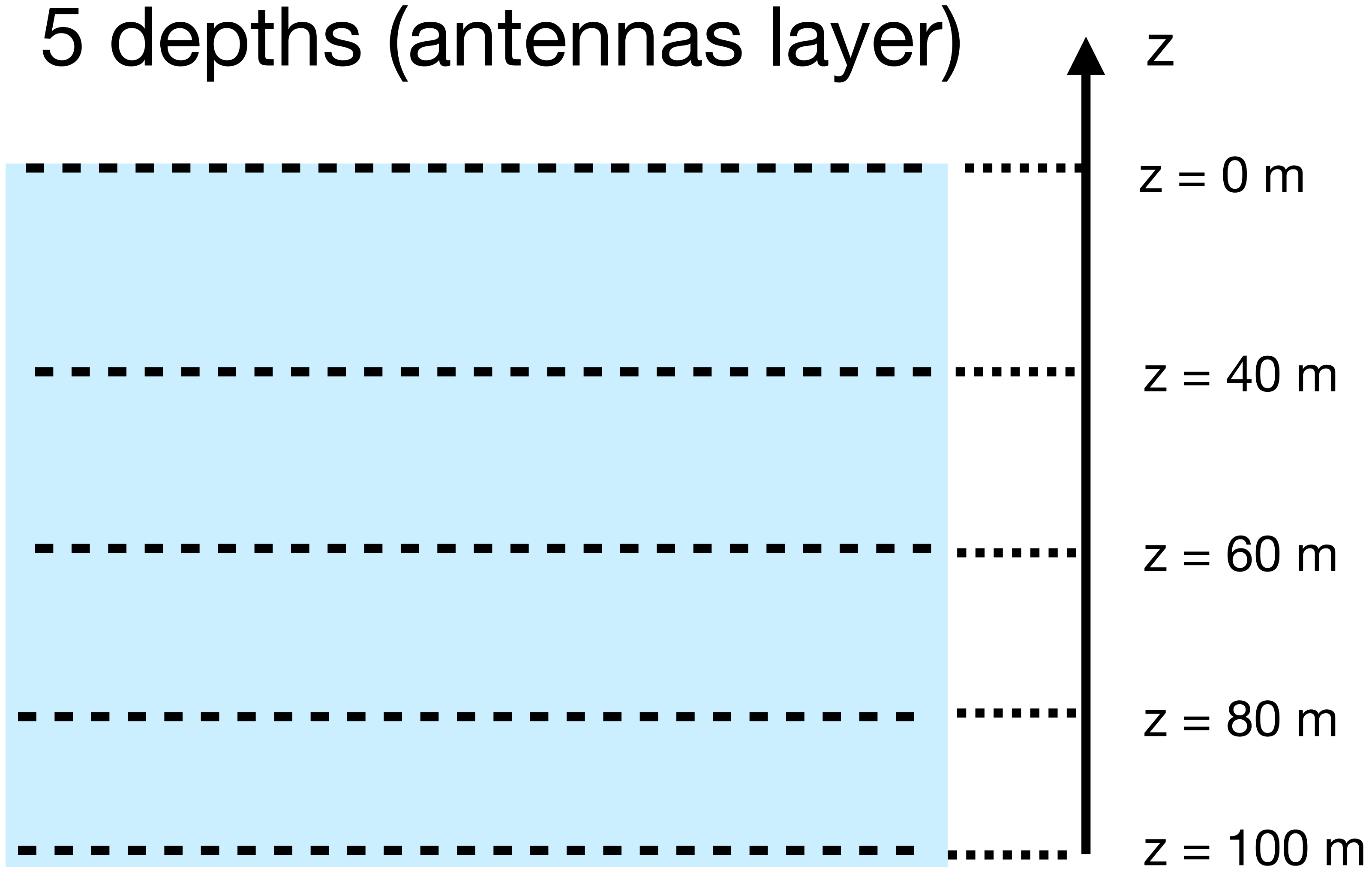
Rectangular antennas grid



5 depths (antennas layer)



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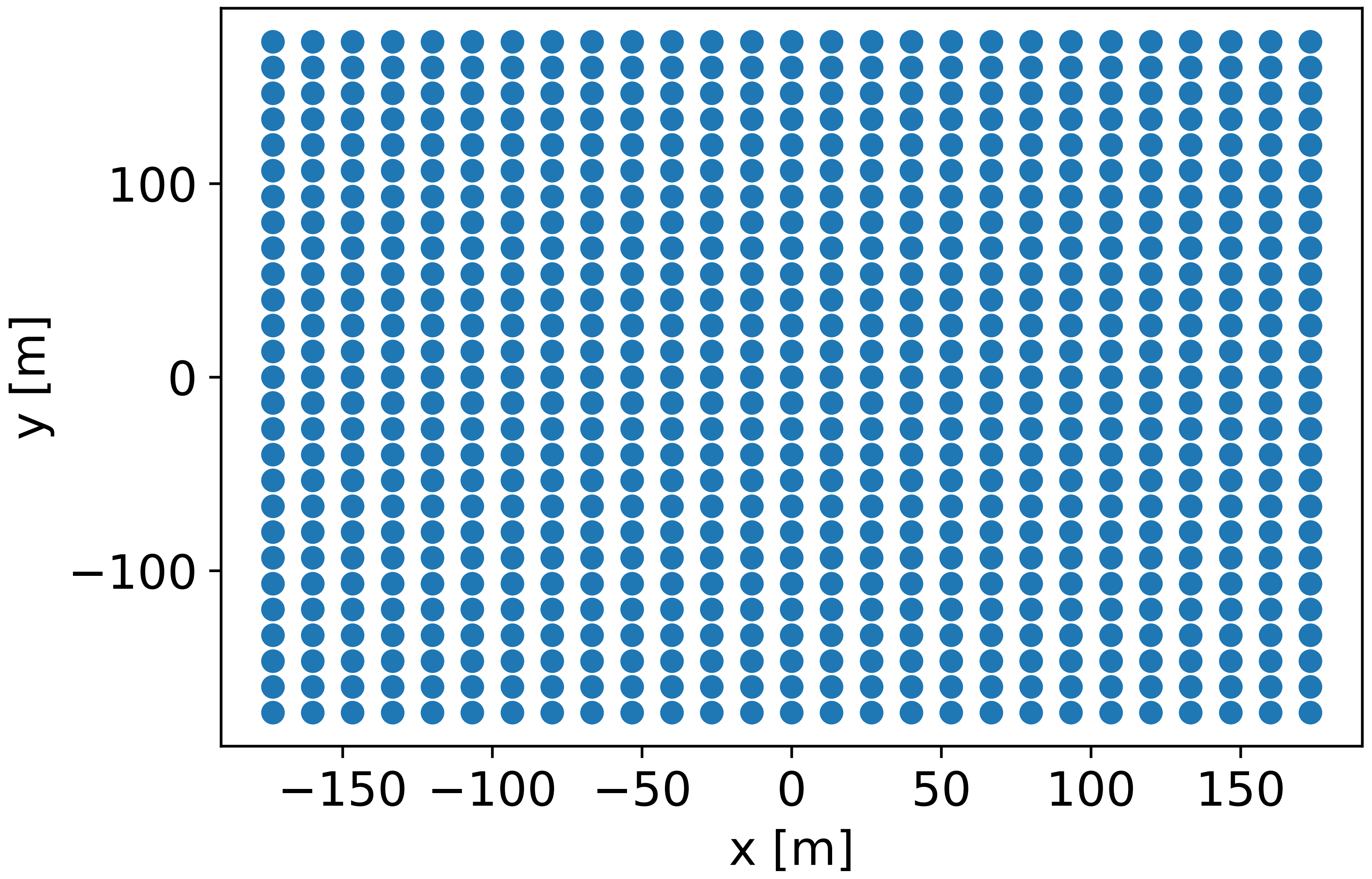

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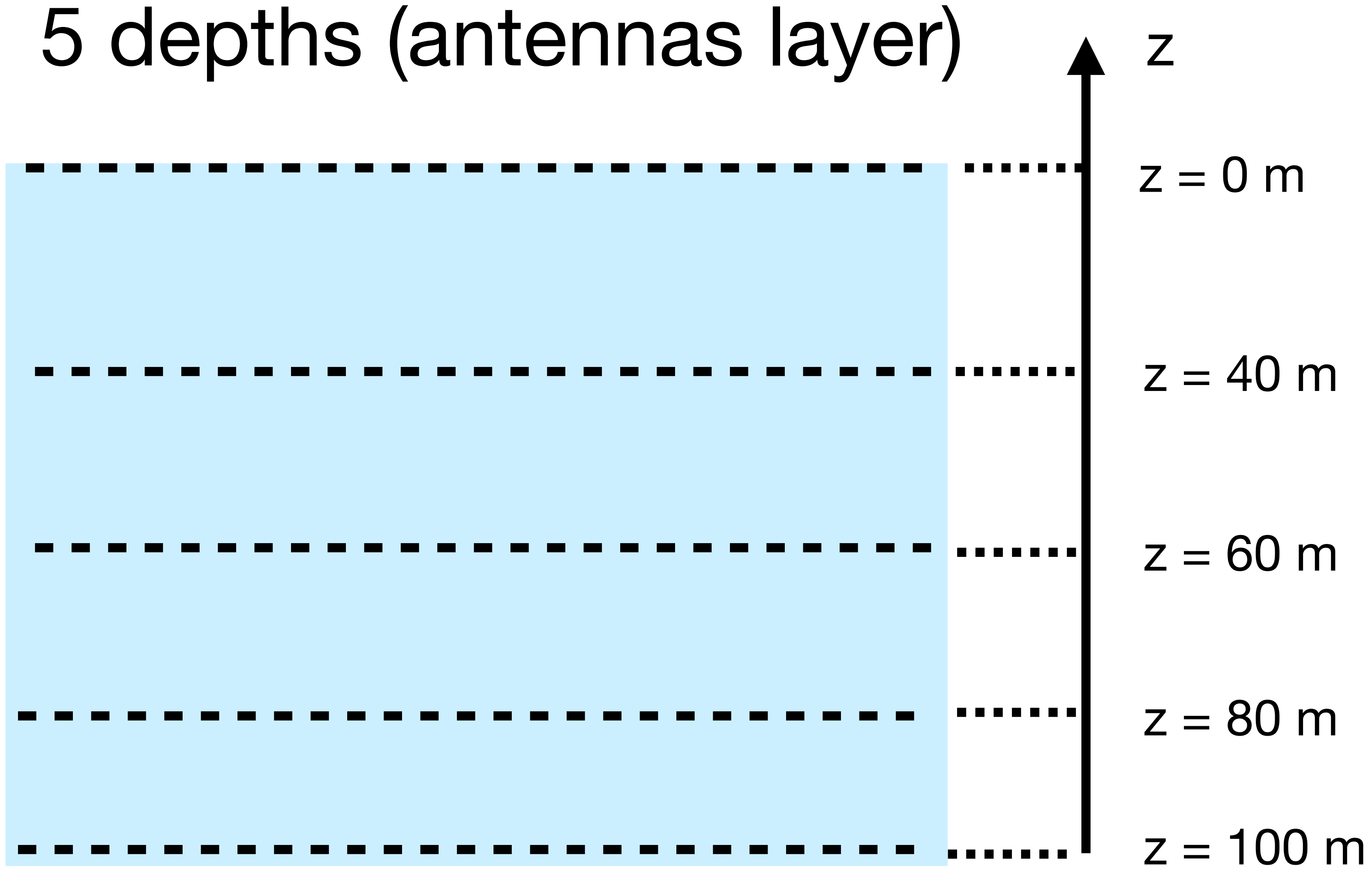

Ice profile: $n(z) = A - B\exp^{-C|z|}$

(Deaconu et al., 2018)

$|z| < 14.9\,\mathrm{m}$ $A = 1.775,\ B = 0.5019,\ C = 0.03247$

$|z| > 14.9\,\mathrm{m}$ $A = 1.775,\ B = 0.448023\ C = 0.02469$

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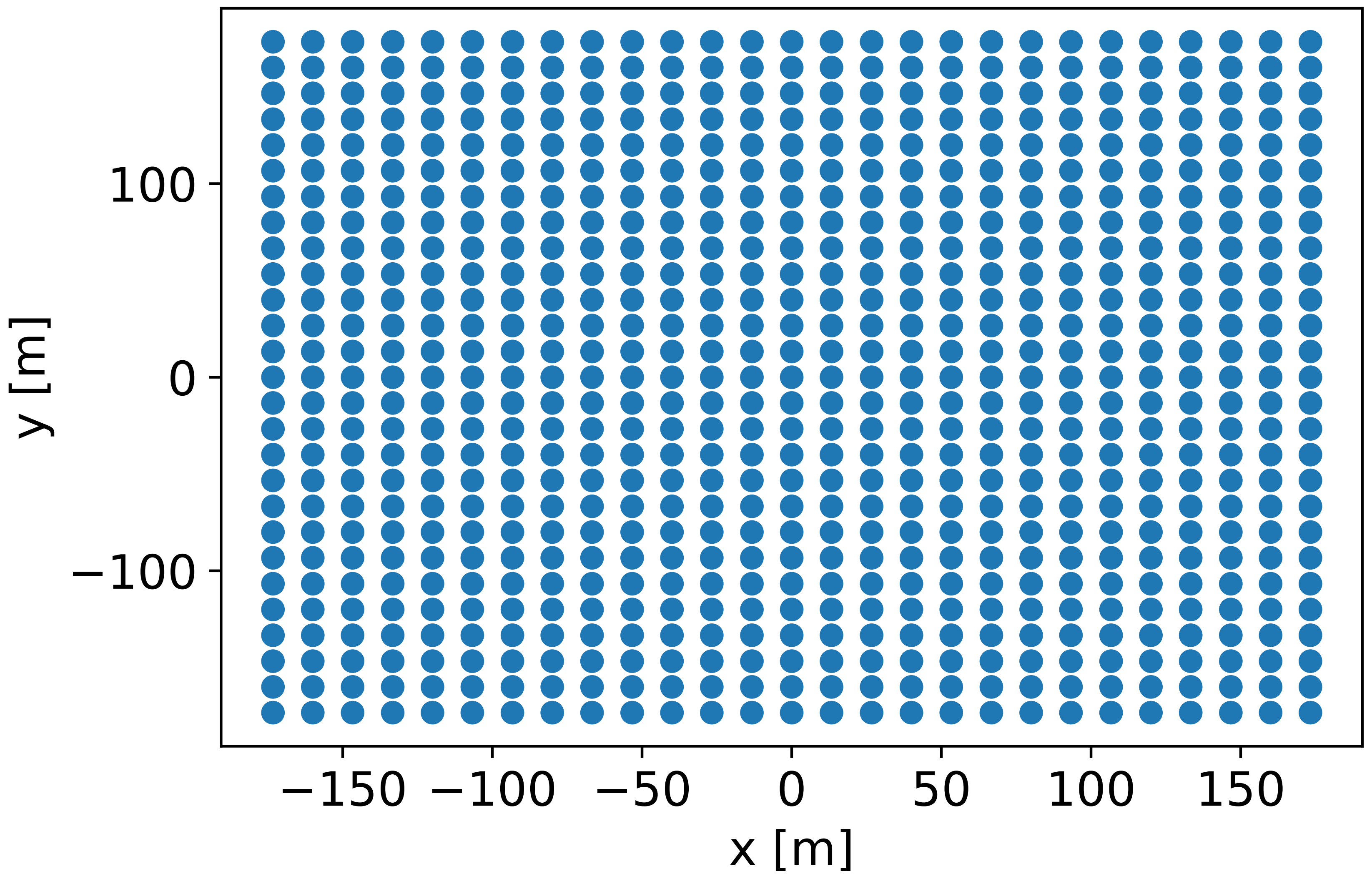

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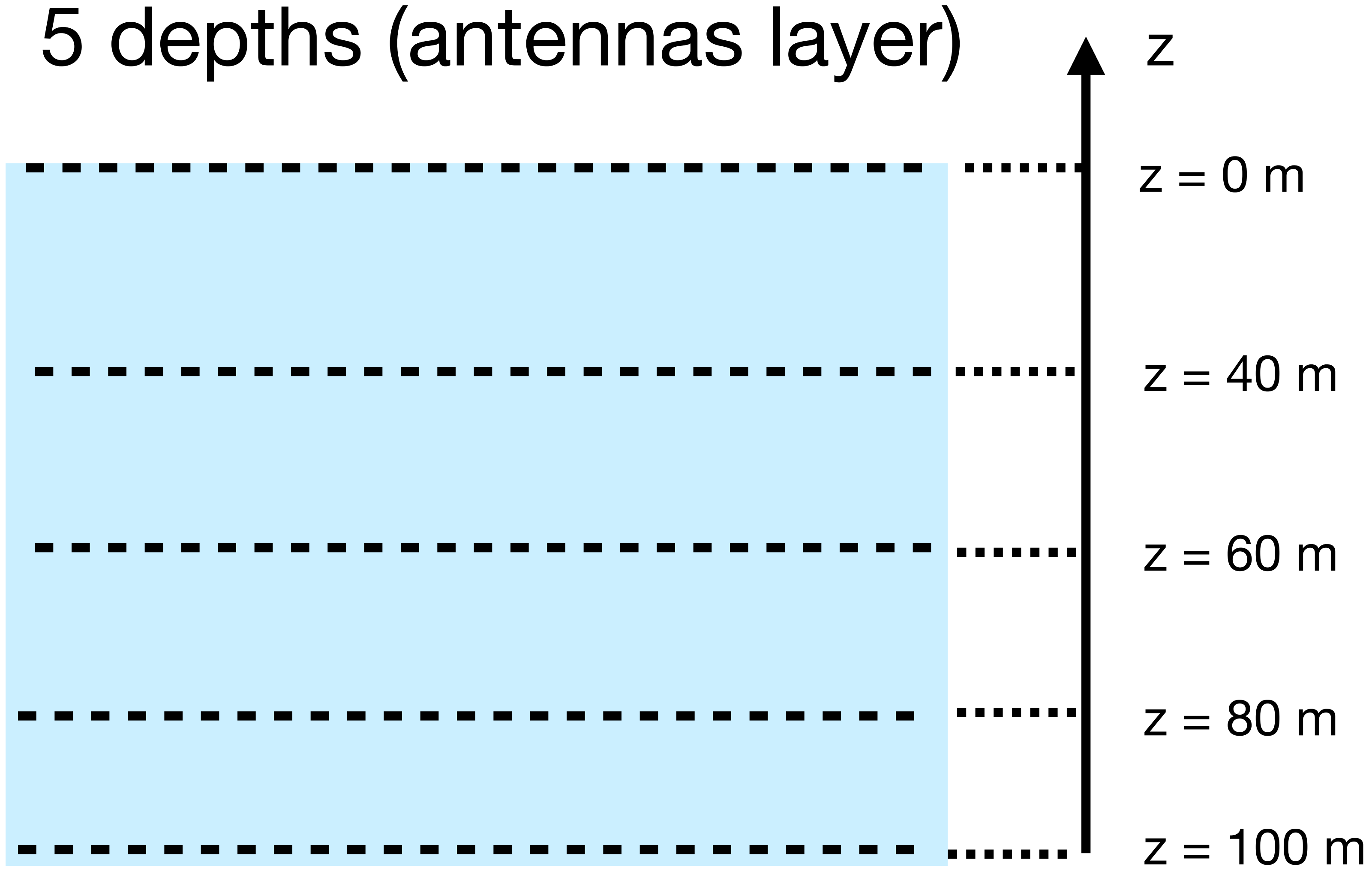

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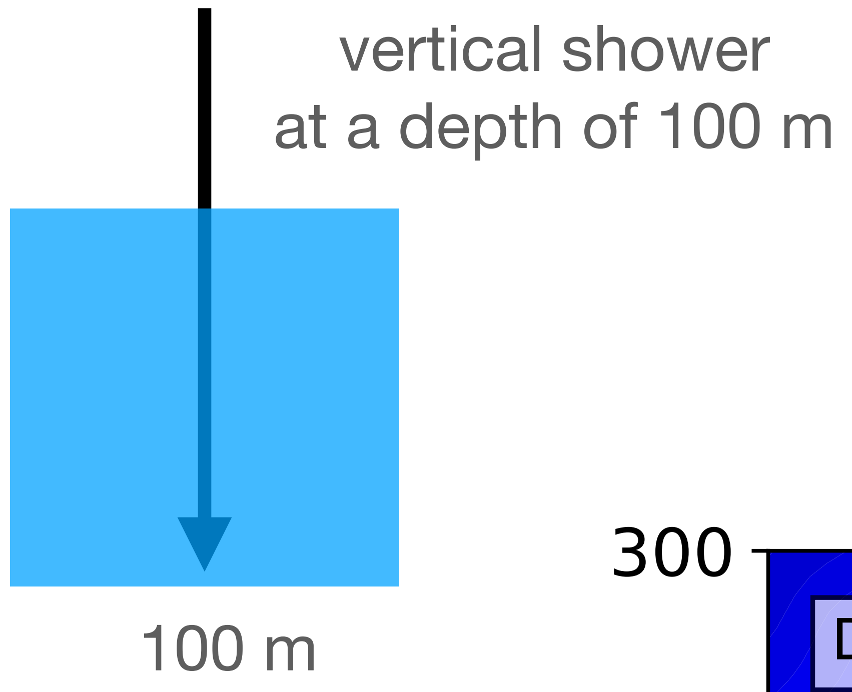
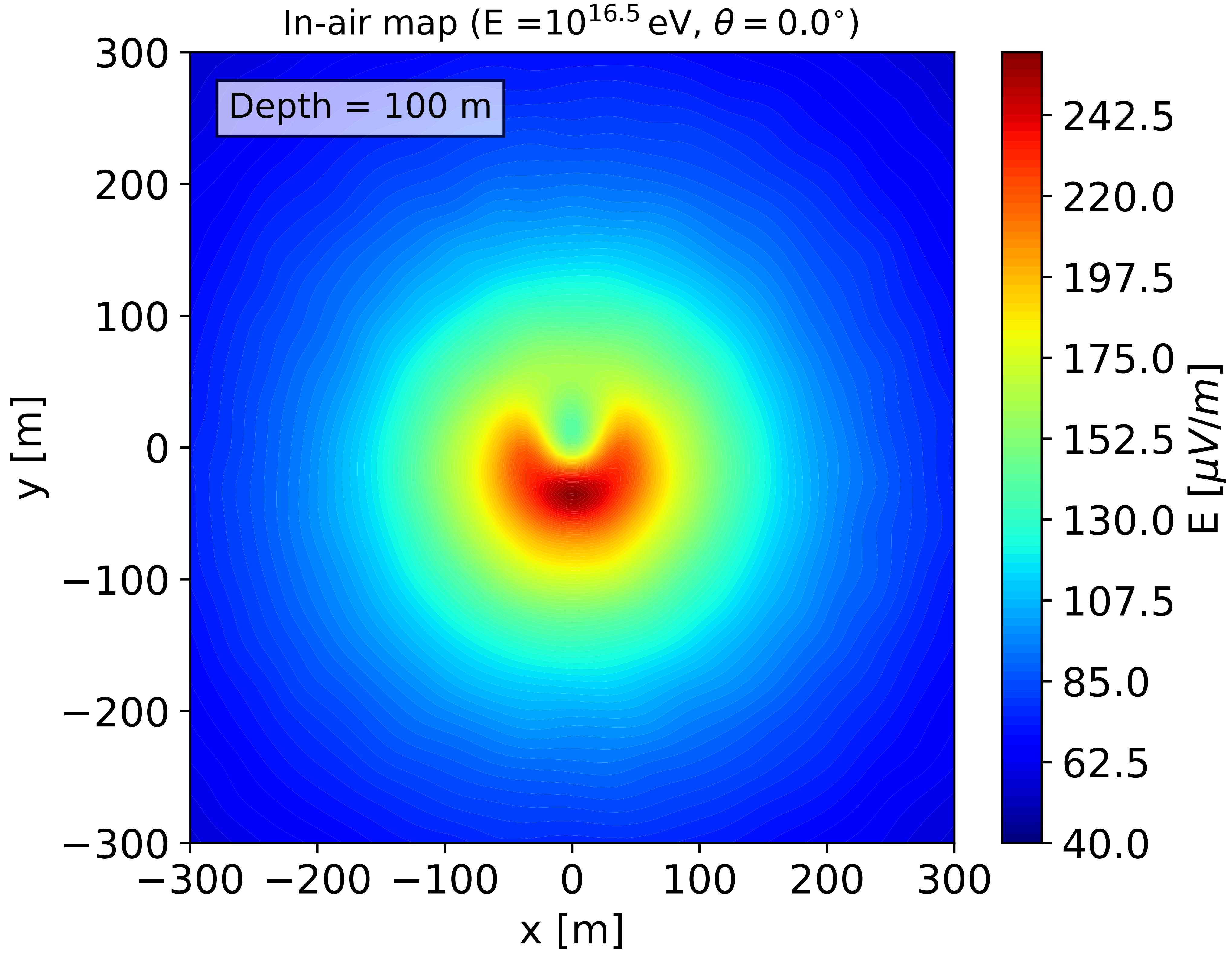
⟶ **We built a simulation library to investigate cosmic ray signatures**

Proton primaries; E $=[10^{16.5} - 10^{17.5}]\,\mathrm{eV}$; $\theta = [0^\circ - 50^\circ]$; $\varphi = 0^\circ$; $\mathbf{B} = \mathbf{B}^{\mathrm{summit}}$

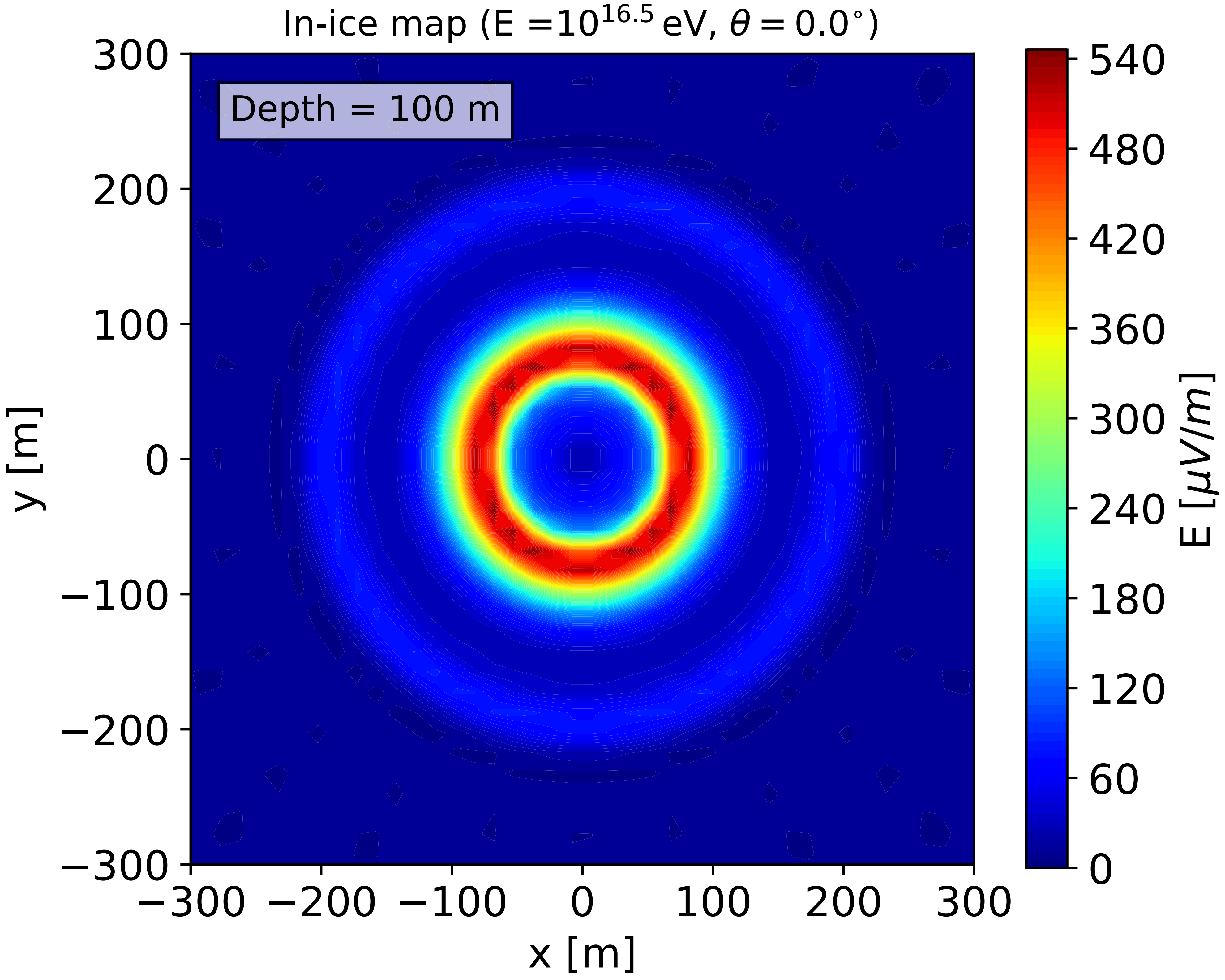


Simulated electric field maps at the antenna level

In-air



In-ice



→ In-air emission: Destructive interferences between geomagnetic and Askaryan

→ In-ice emission: Rotationally symmetric emission pattern

We want to evaluate the relative contribution of the air/ice component

$$E_{\mathrm{rad}} = \int_{x_{\min}}^{x_{\max}} \int_{y_{\min}}^{y_{\max}} f(x, y)\mathrm{d}x\,\mathrm{d}y$$

Radiation energy
(Glaser et al., 2016)

We want to evaluate the relative contribution of the air/ice component

Results from one single shower:
Error-bars (shower-to shower fluctuations) to be included

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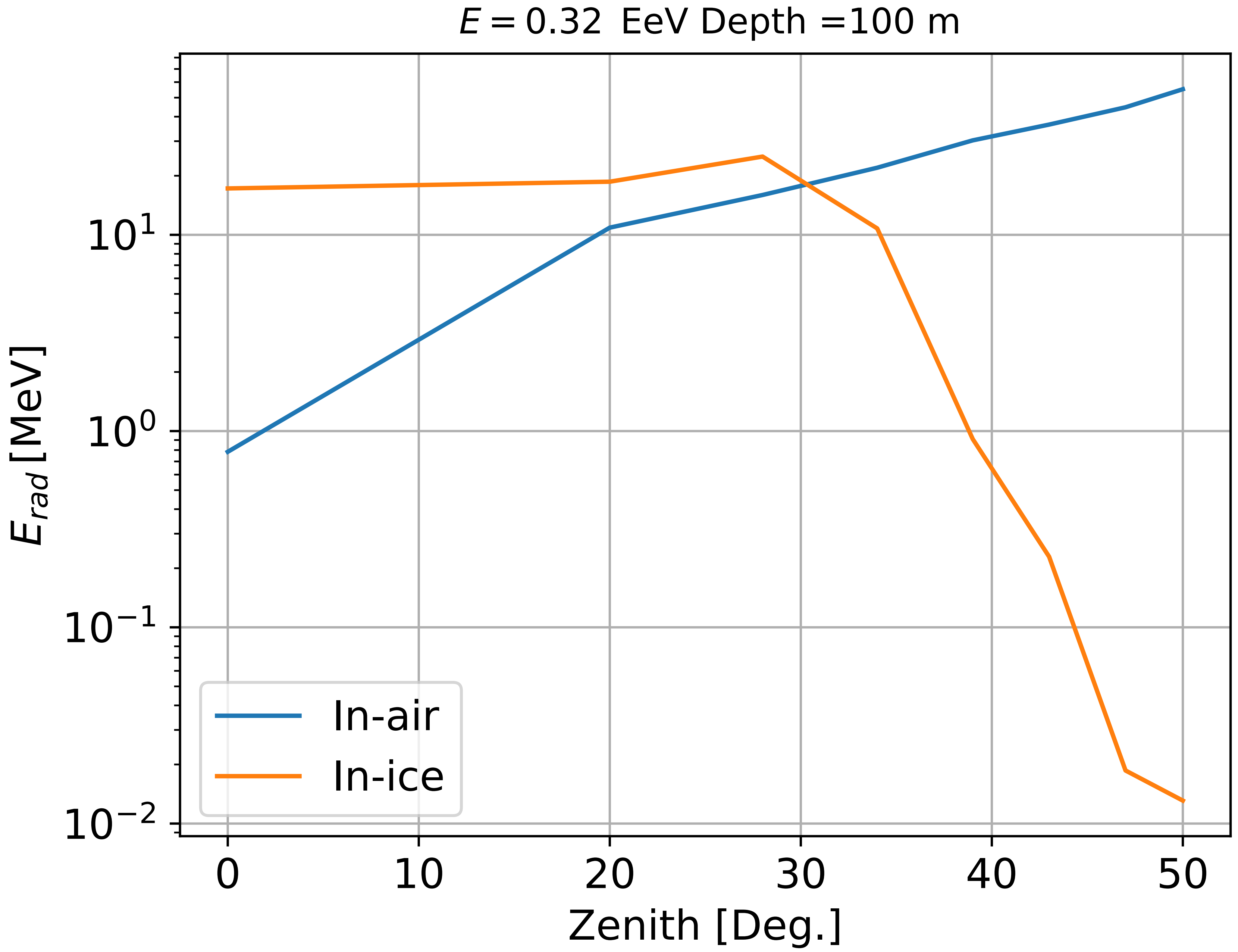

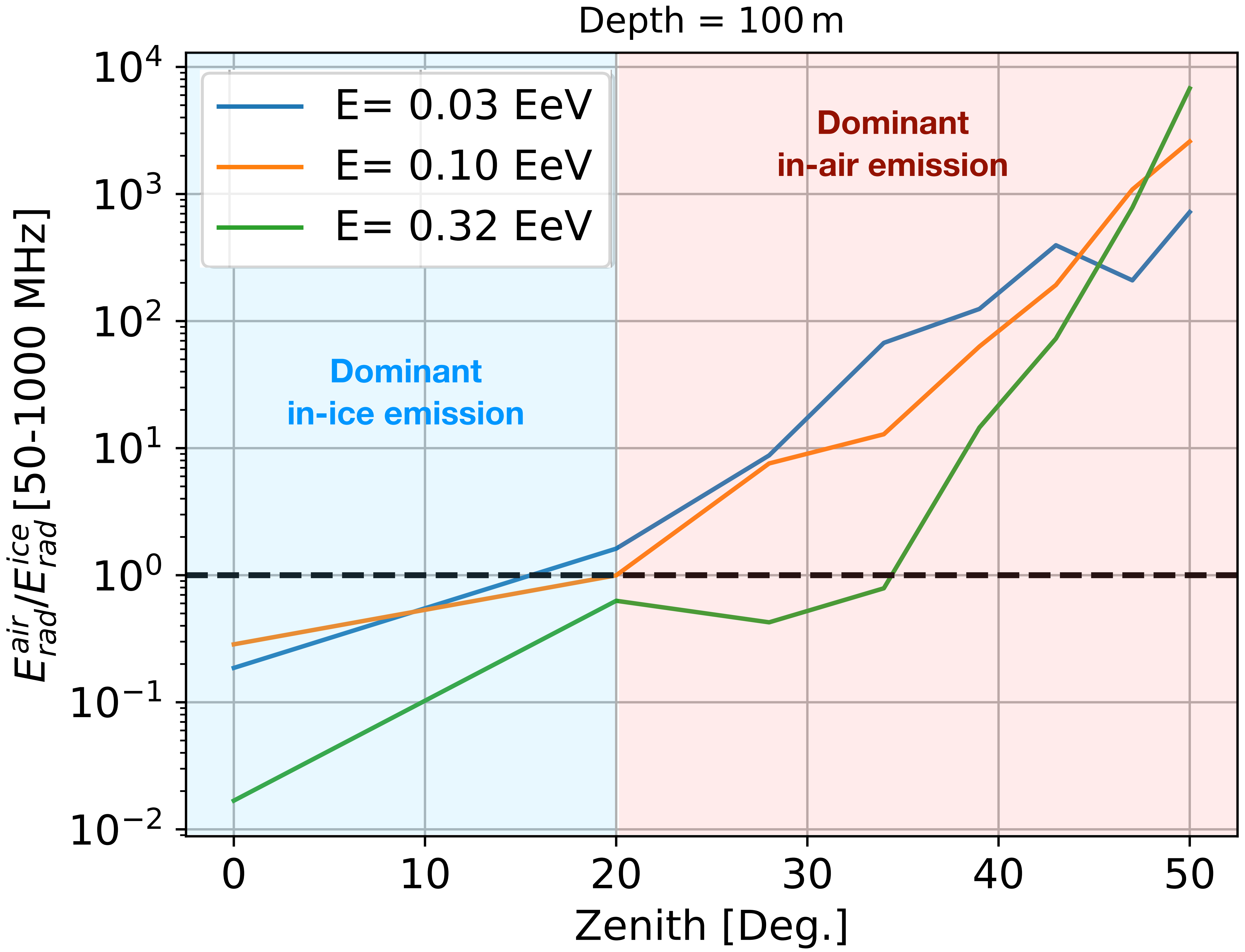

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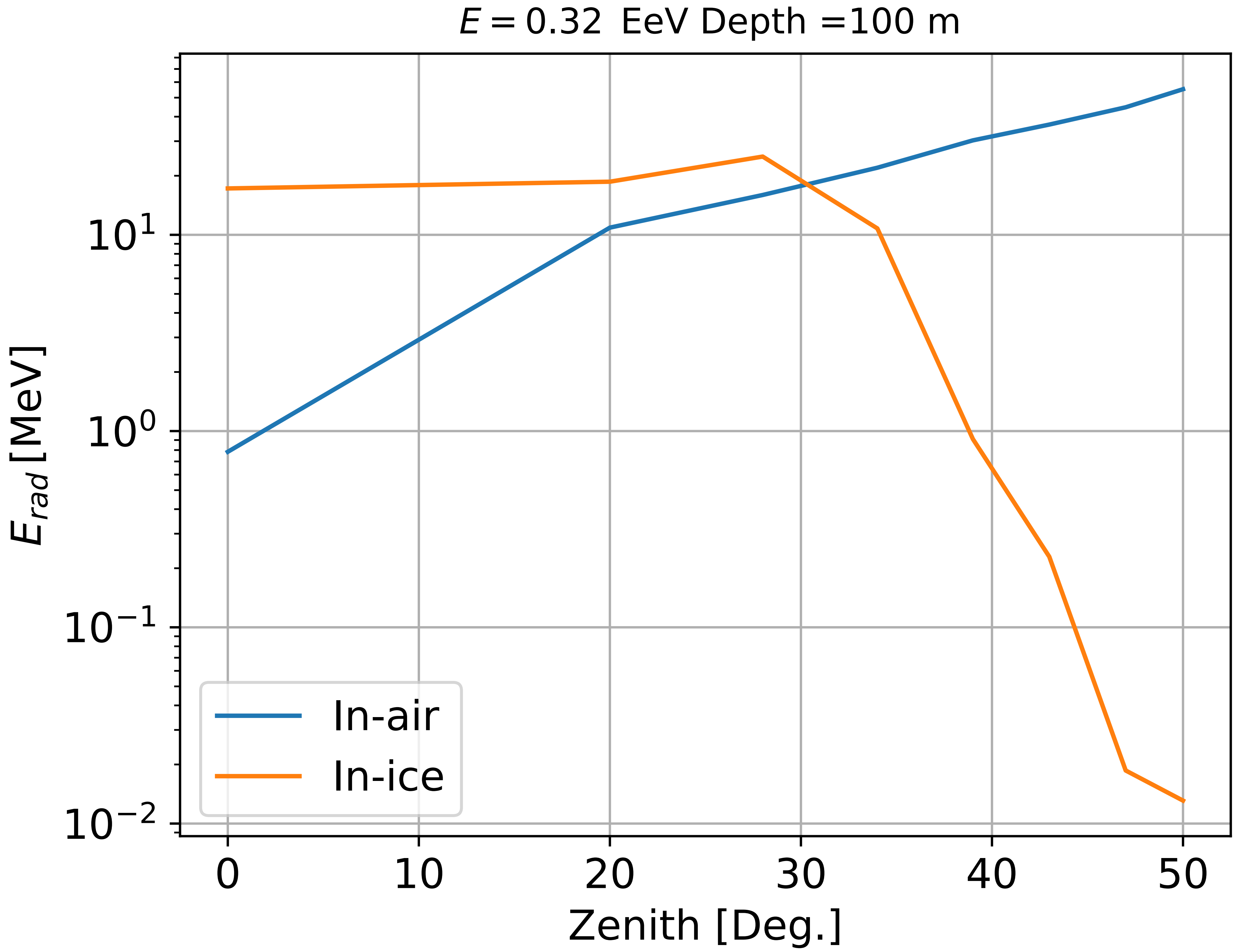

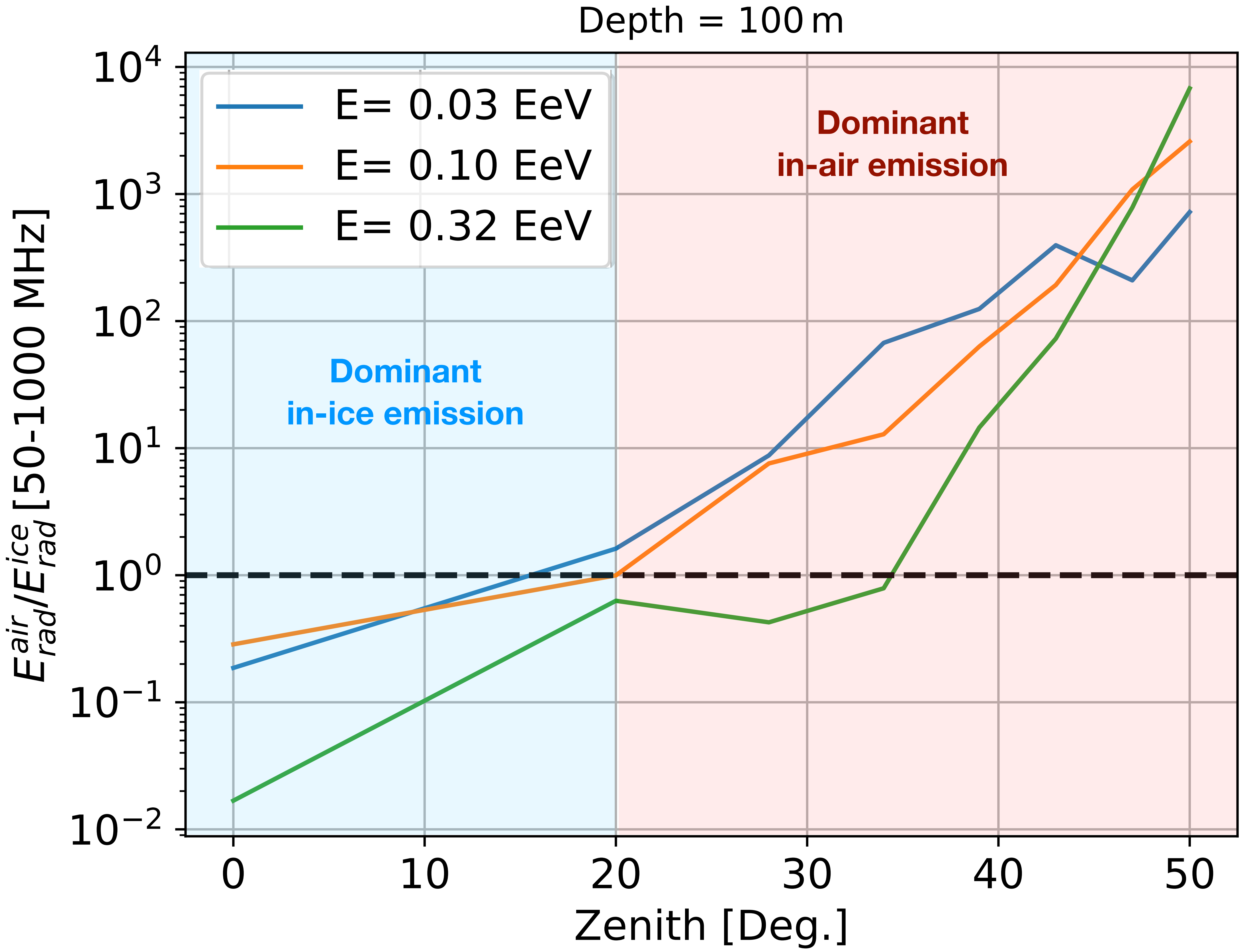

→ Decreasing in-ice contribution with increasing zenith angle

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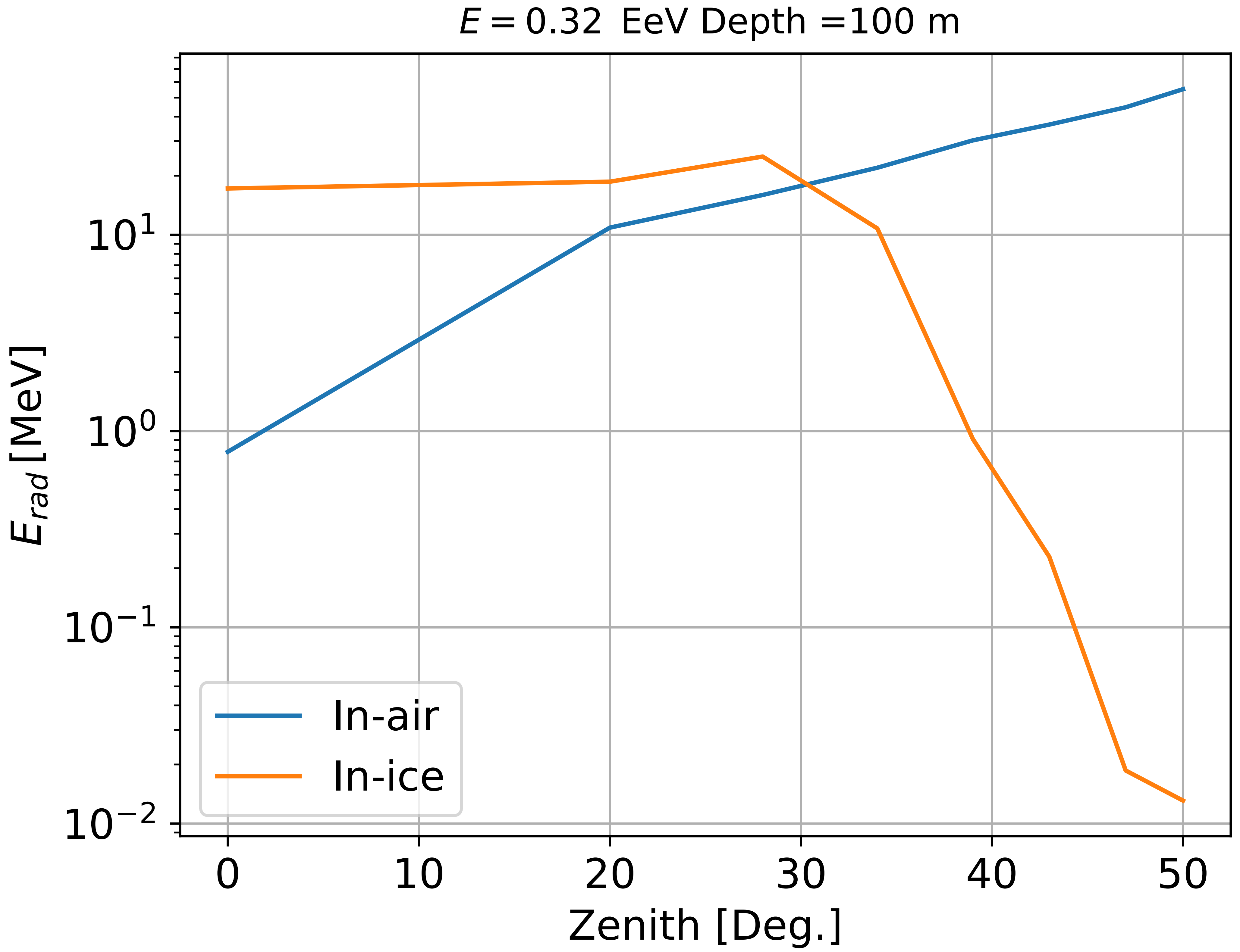

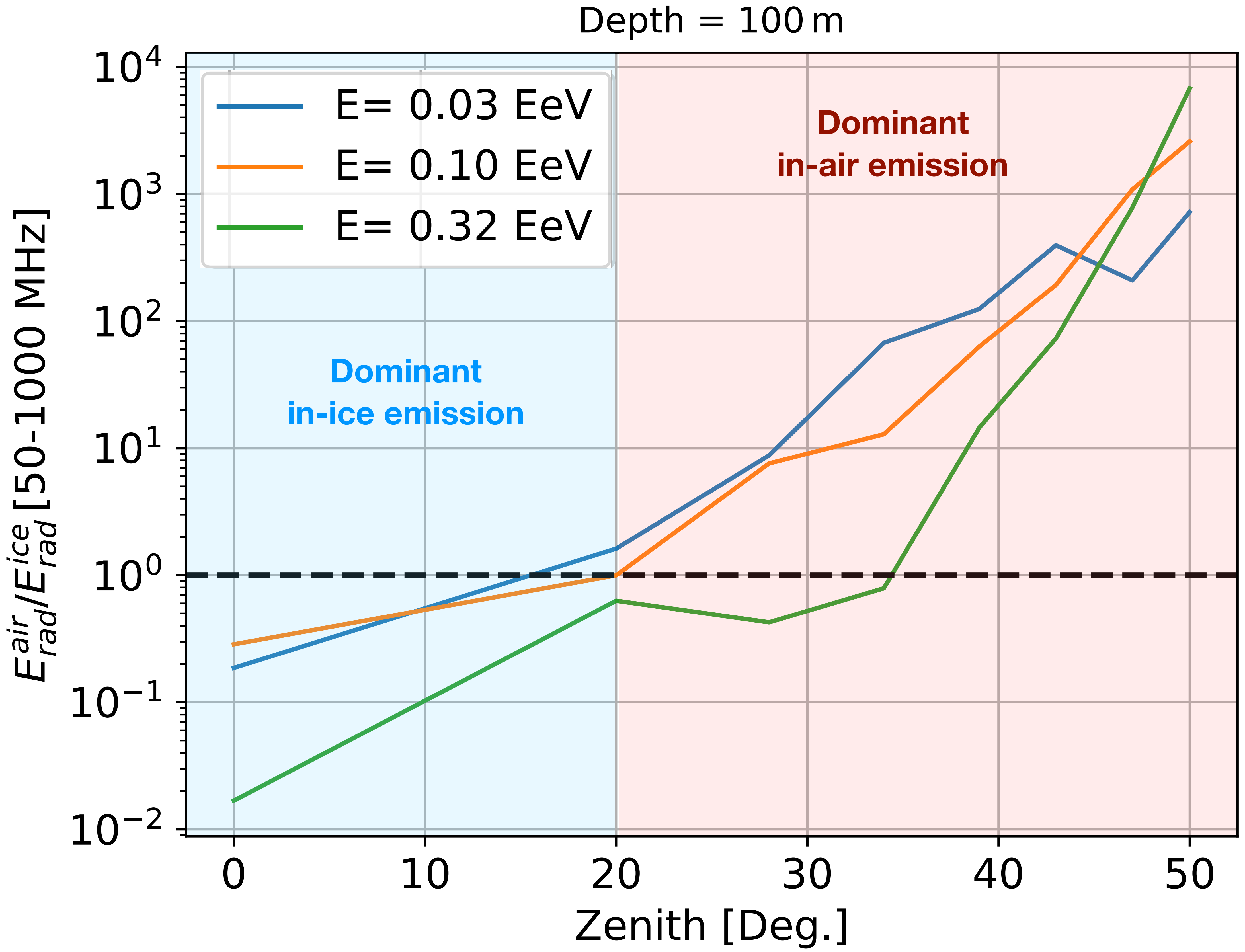

→ Decreasing in-ice contribution with increasing zenith angle

→ Dominant in-air contribution for showers with zenith angle $\theta \gtrsim 20°$

Double pulse signature

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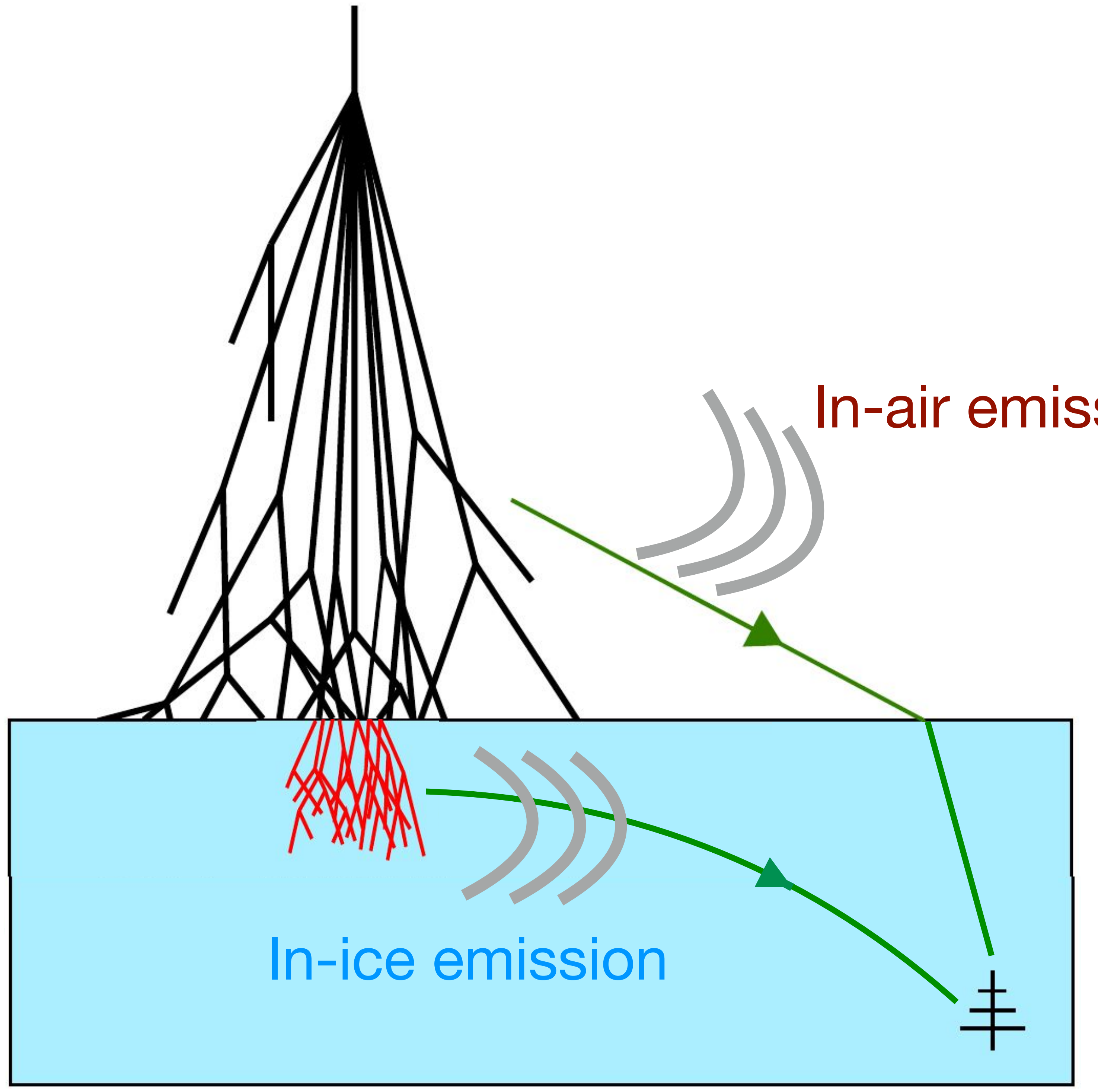
The in-air and the in-ice emissions can sometimes reach both the same antenna



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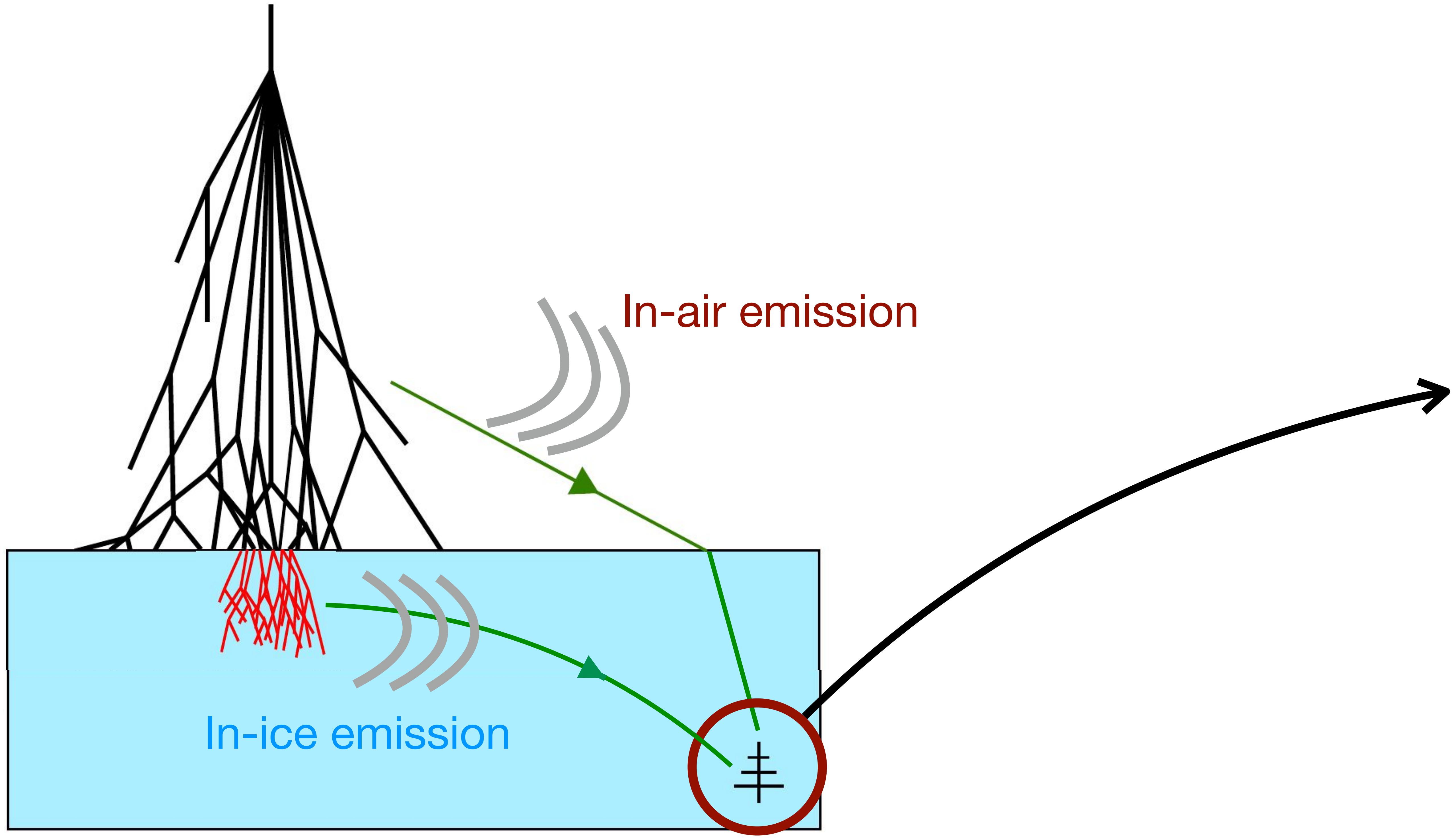

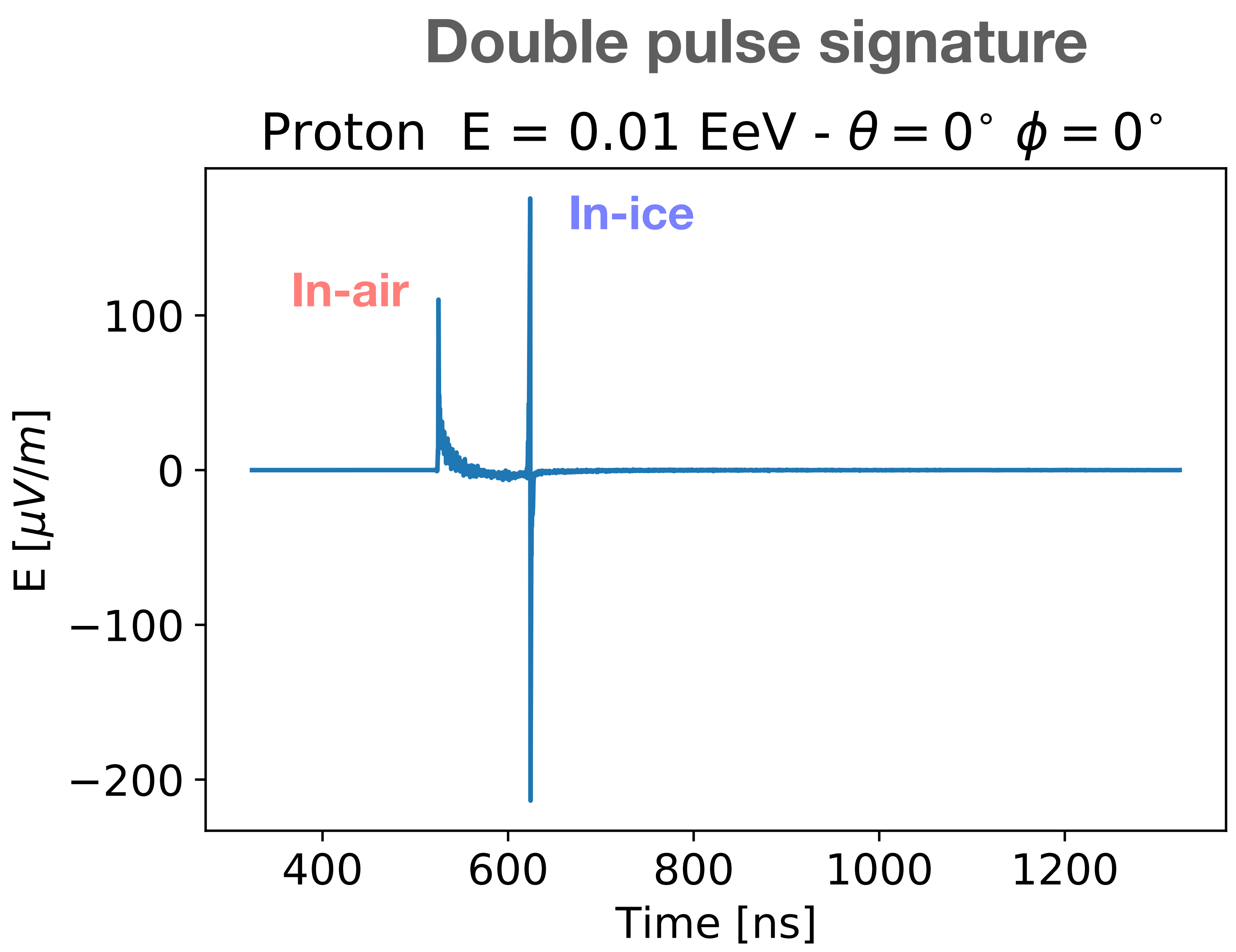

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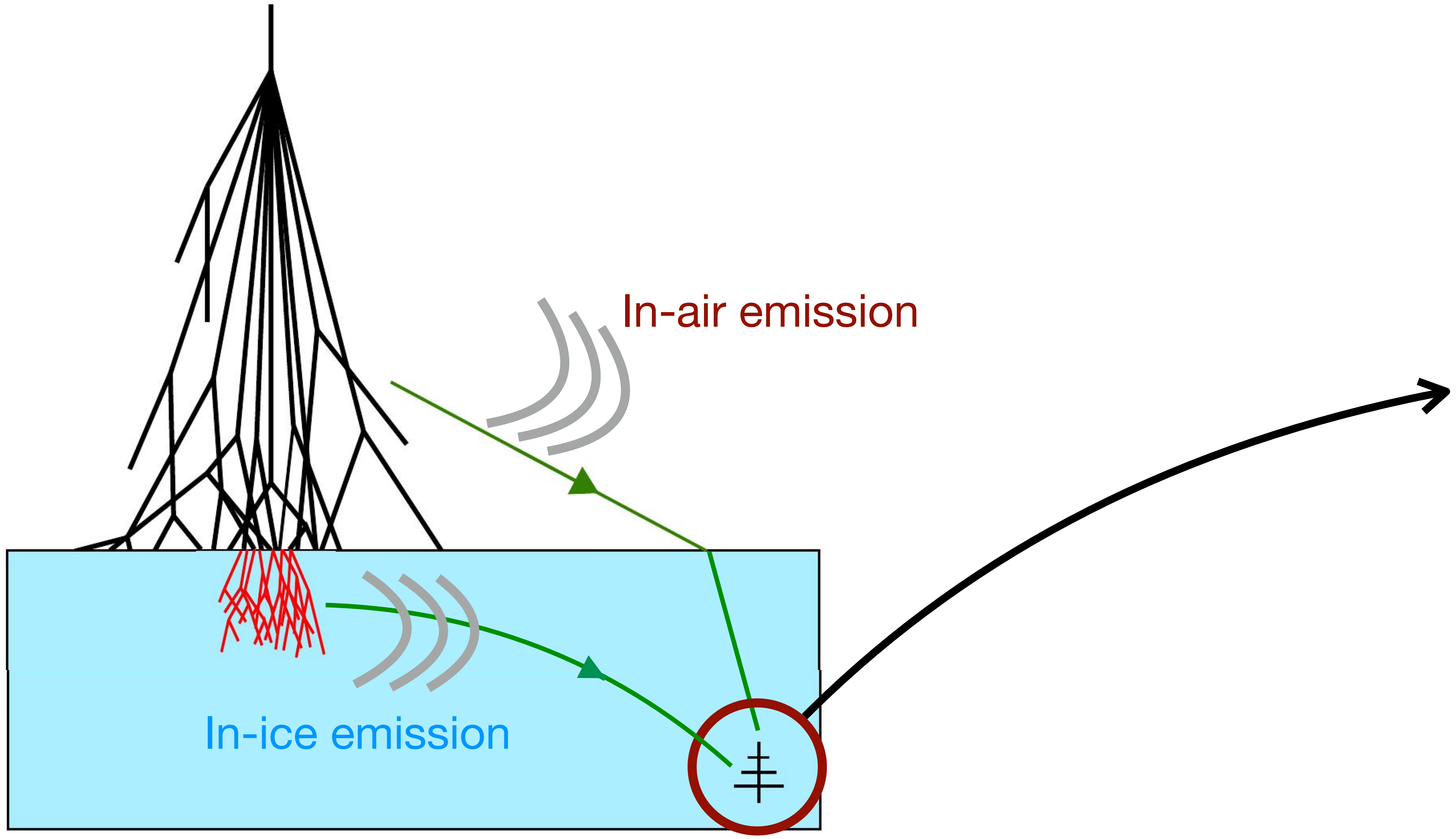
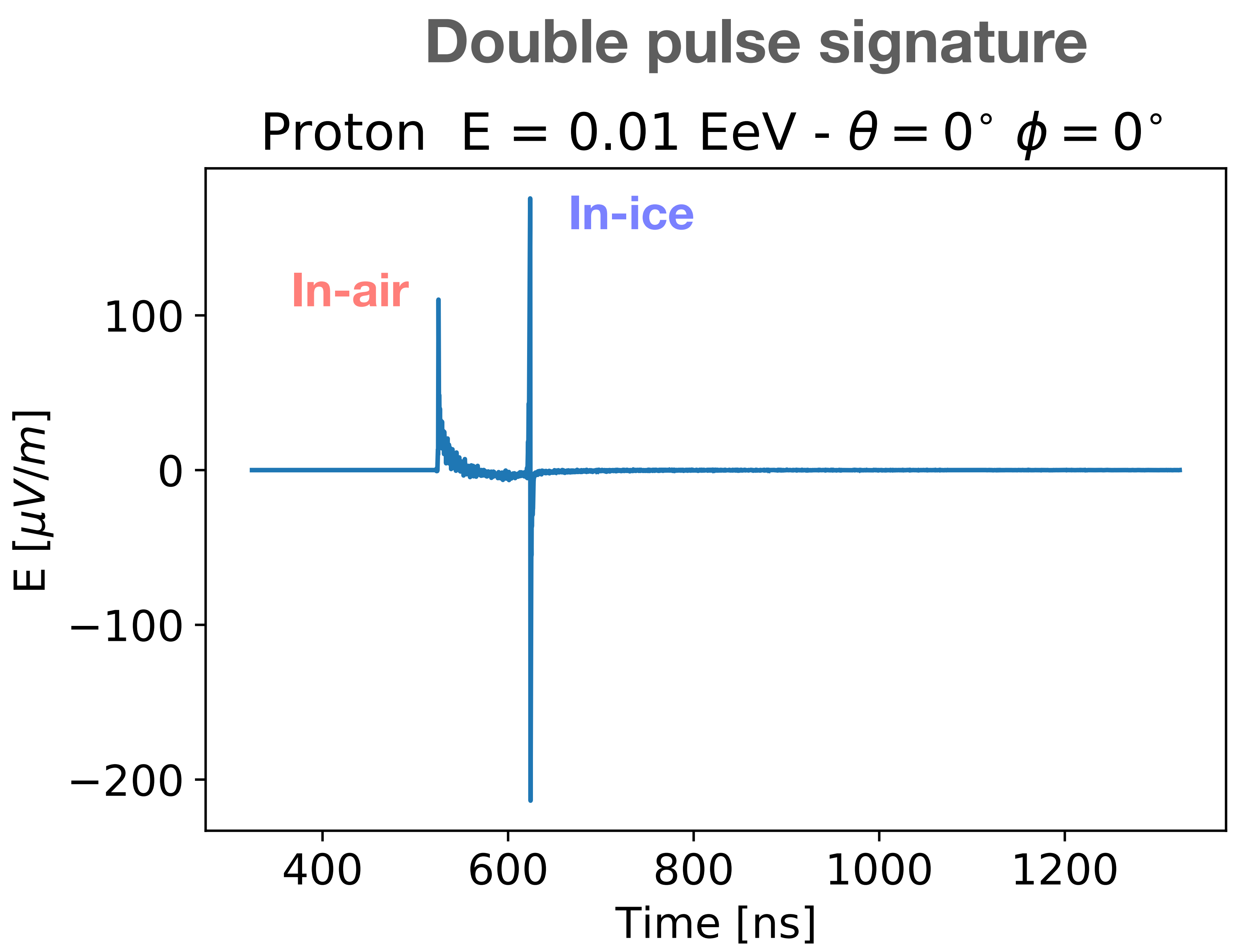




How to identify double pulses?:

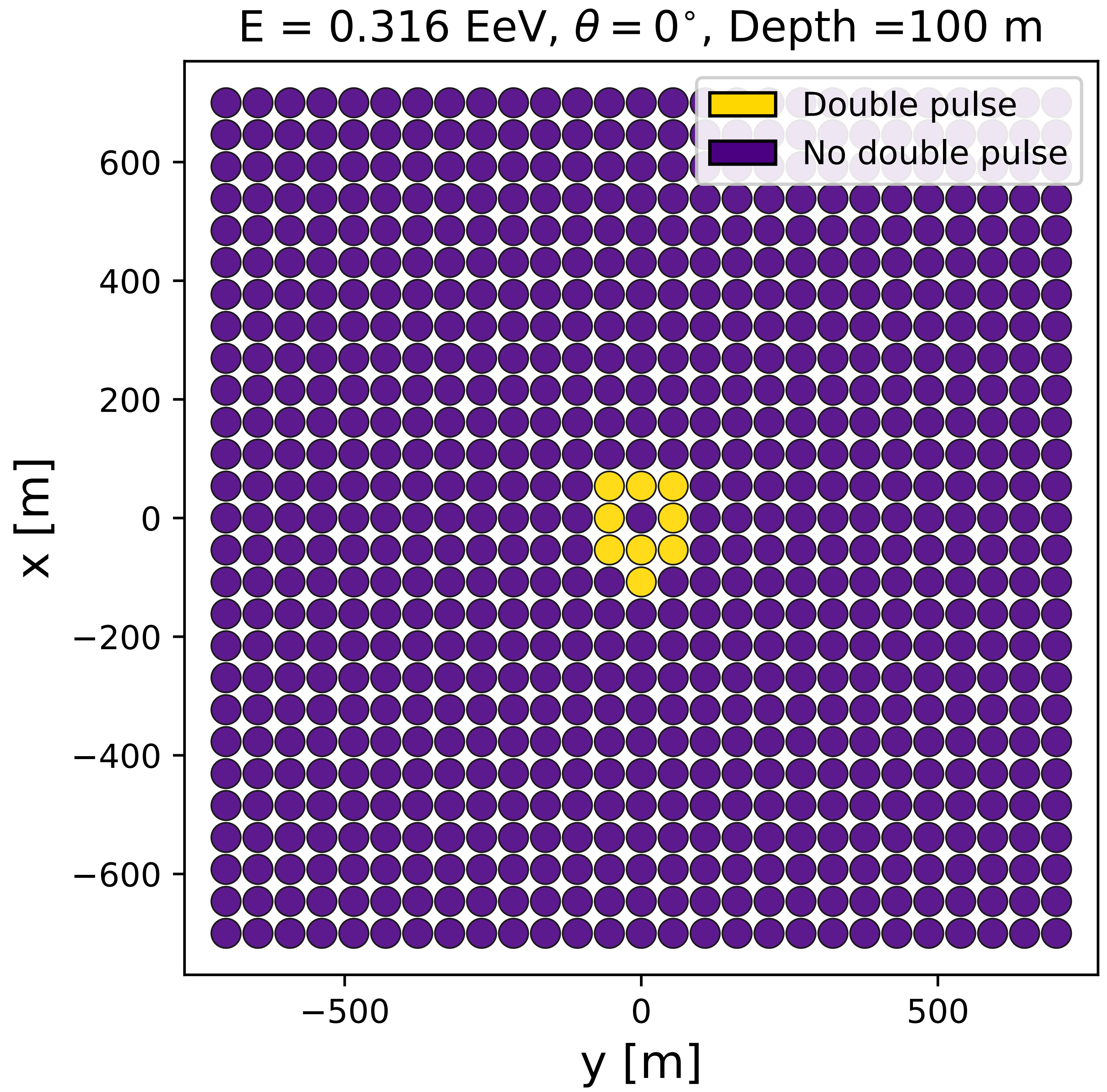
(1) Requires at least one pulse with peak amplitude $E_1^{\mathrm{peak}} > 100\,\mu\mathrm{V/m}$ (trigger at the antenna)

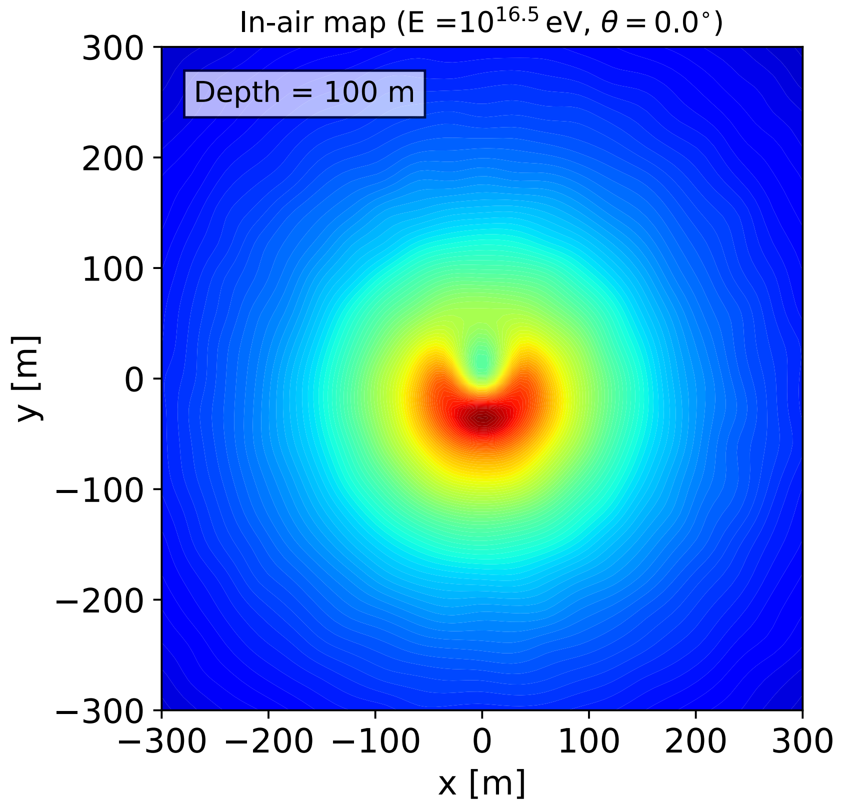
(2) Requires a secondary pulse with peak amplitude $E_2^{\mathrm{peak}} > 60\,\mu\mathrm{V/m}$

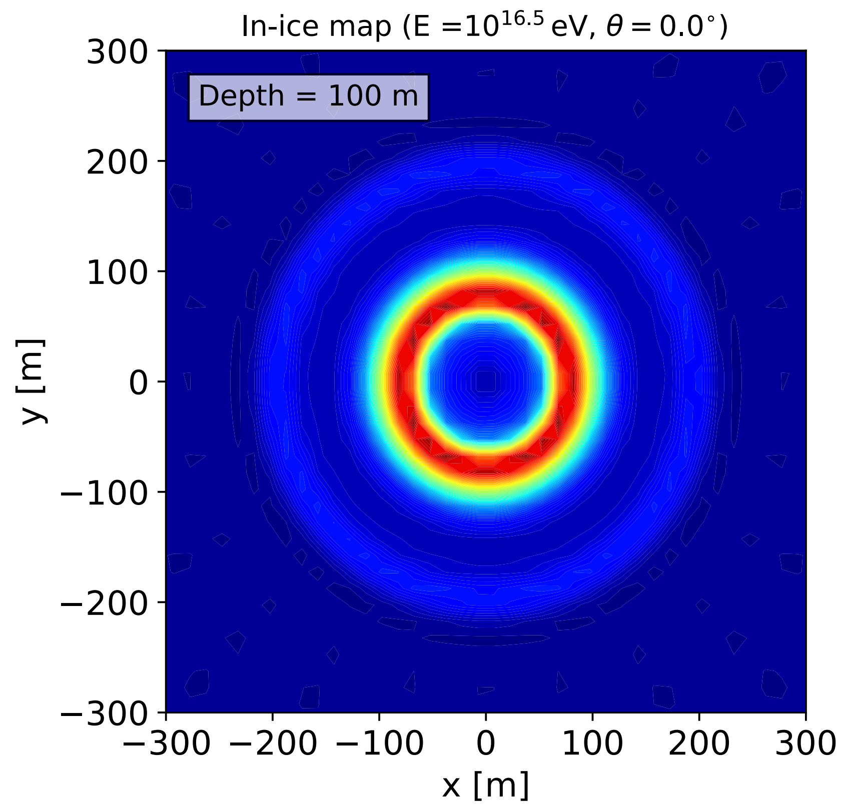
Double pulse map:

- Vertical showers: almost rotationally symmetric distribution
- Inclined showers: distribution elongated towards the shower azimuthal direction (shadowing effects)

Double pulses map







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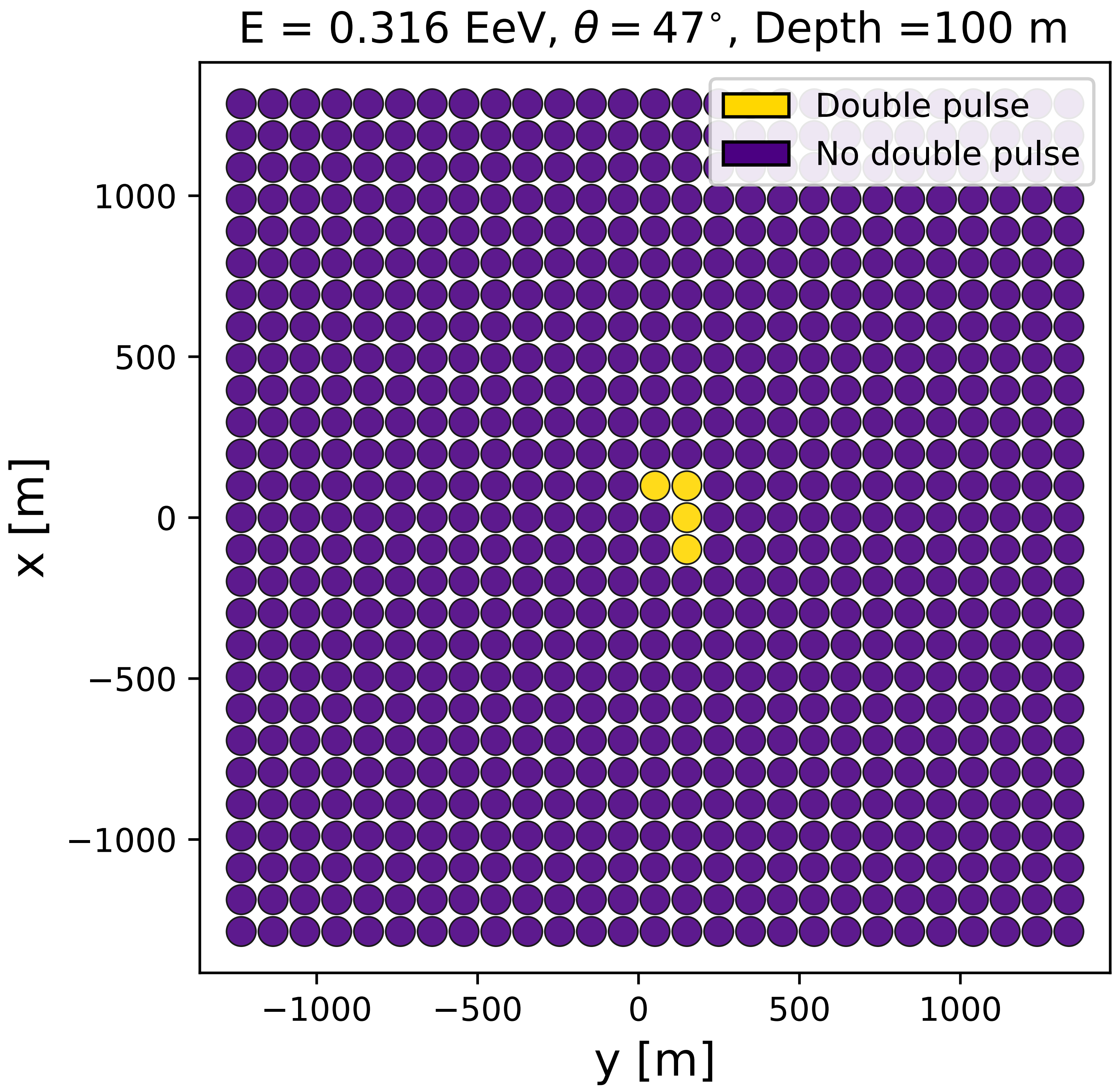
Double pulses map



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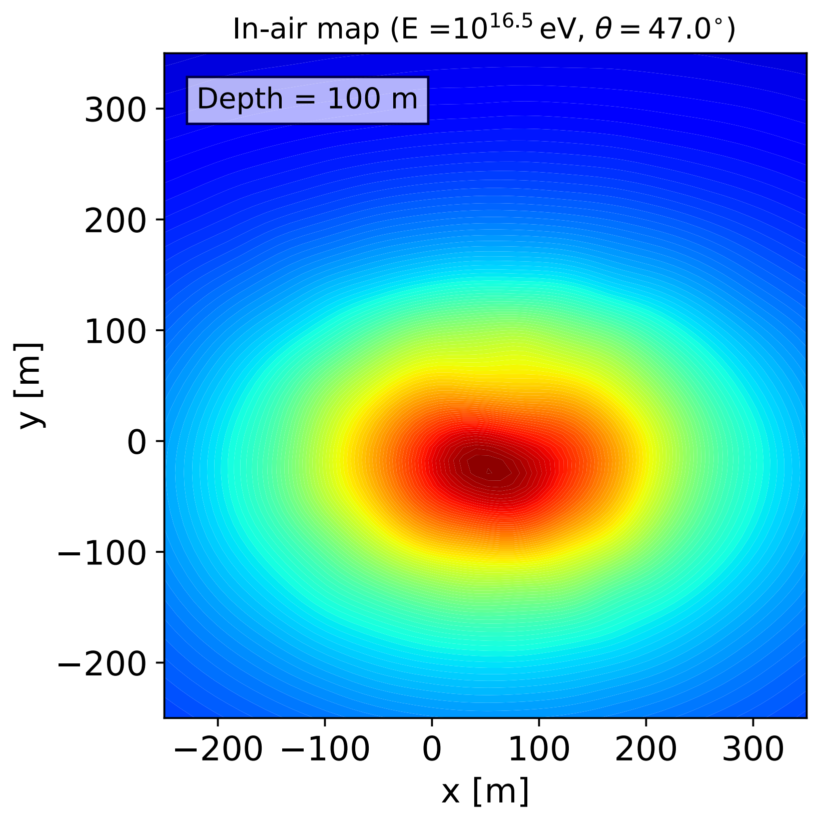

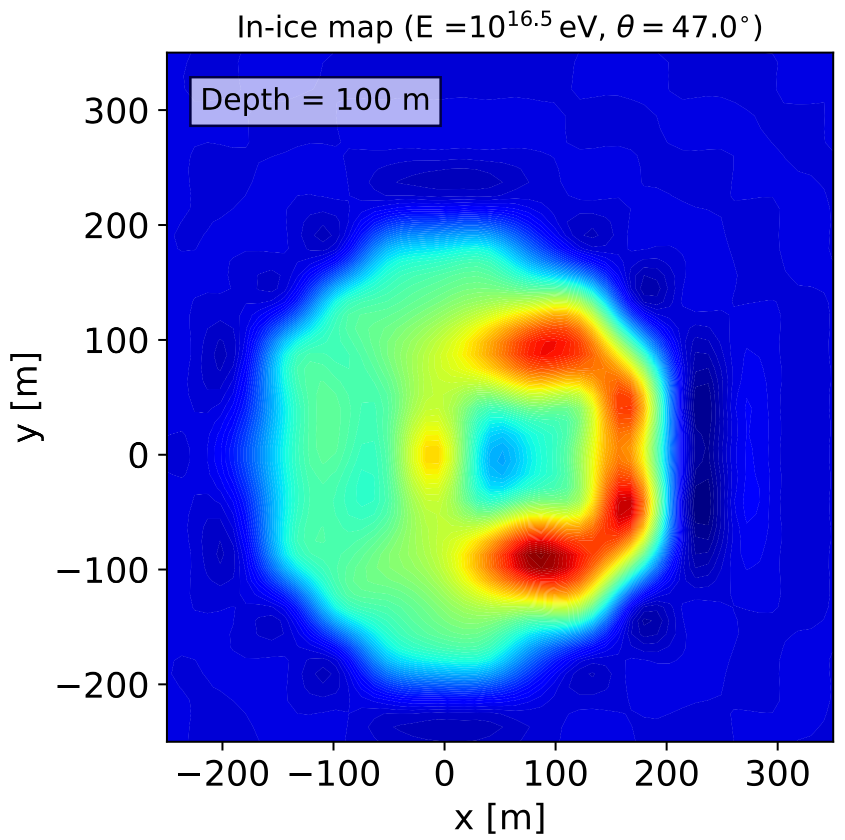

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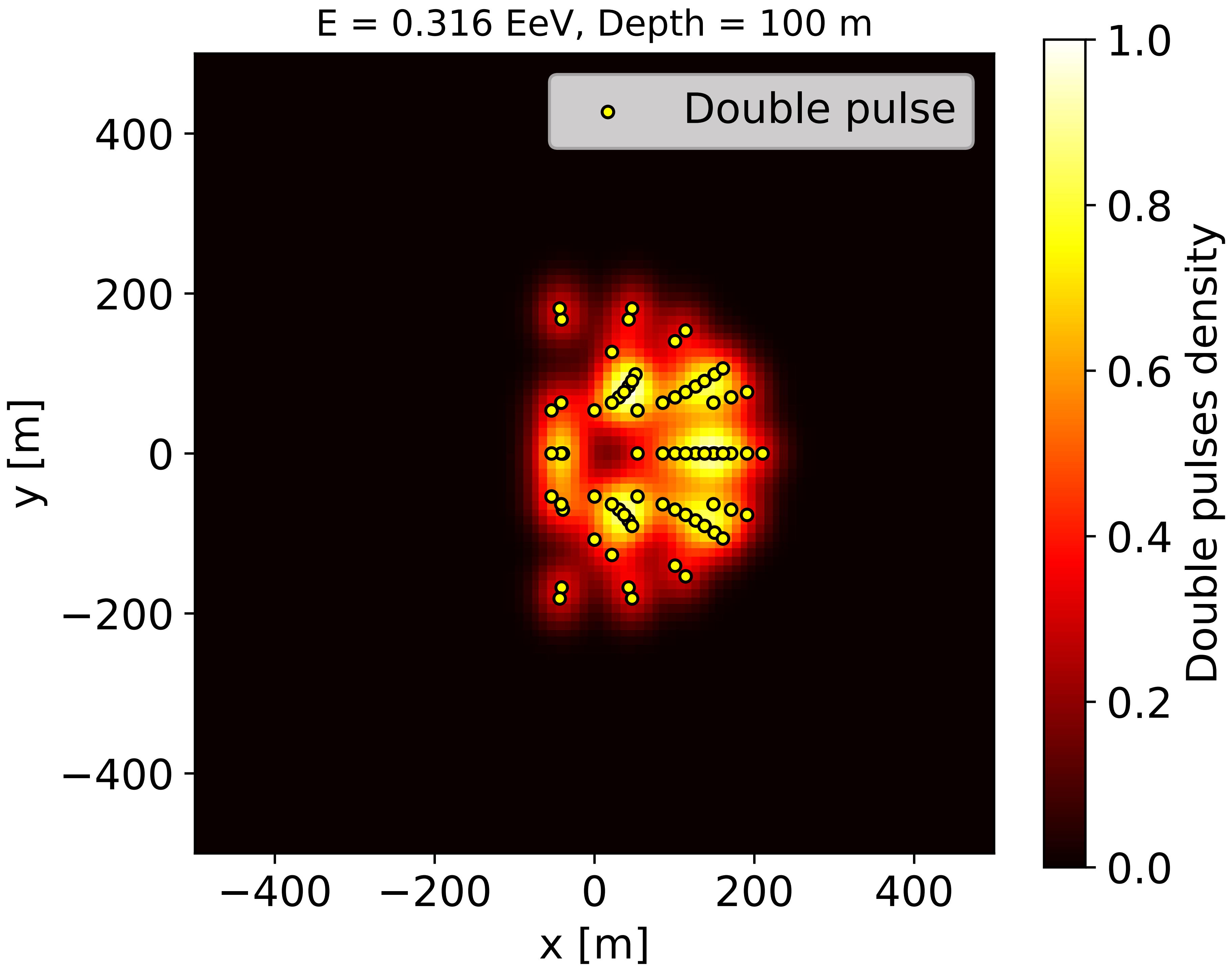
All-zeniths double pulses map



Double pulse signature

Simon Chiche (IIHE)

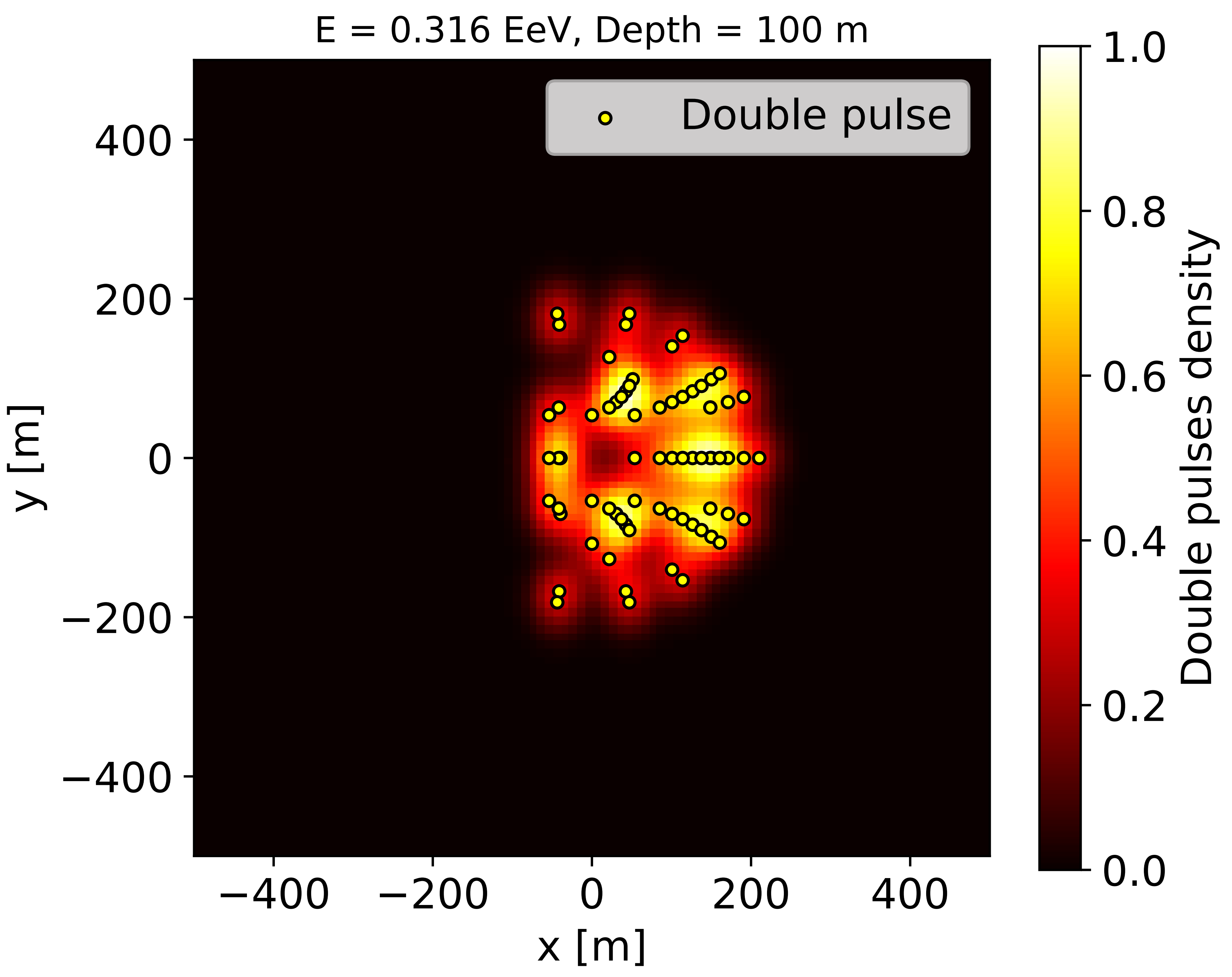
Double pulse map:

- Vertical showers: almost rotationally symmetric distribution
- Inclined showers: distribution elongated towards the shower azimuthal direction (shadowing effects)

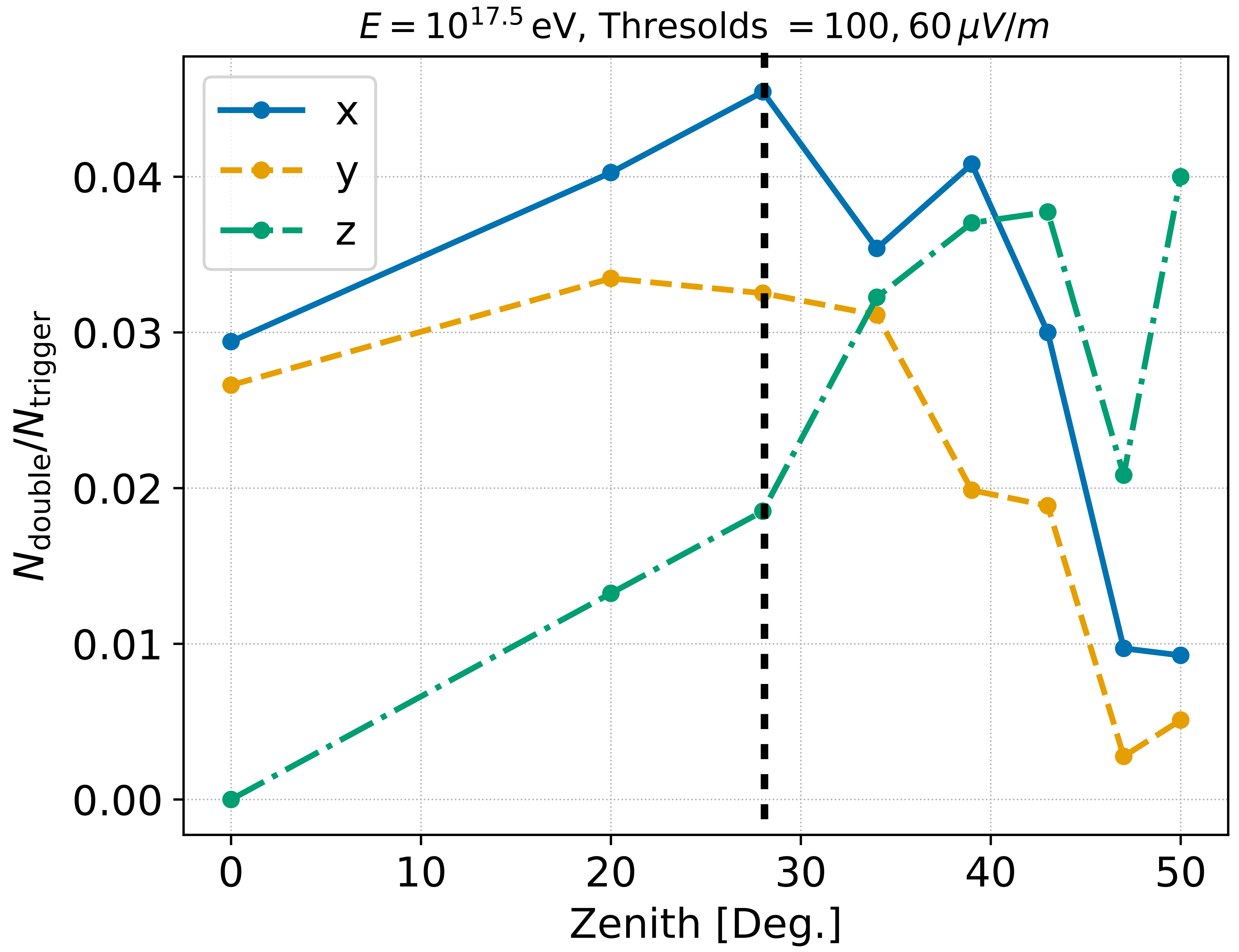
Double pulse fraction:

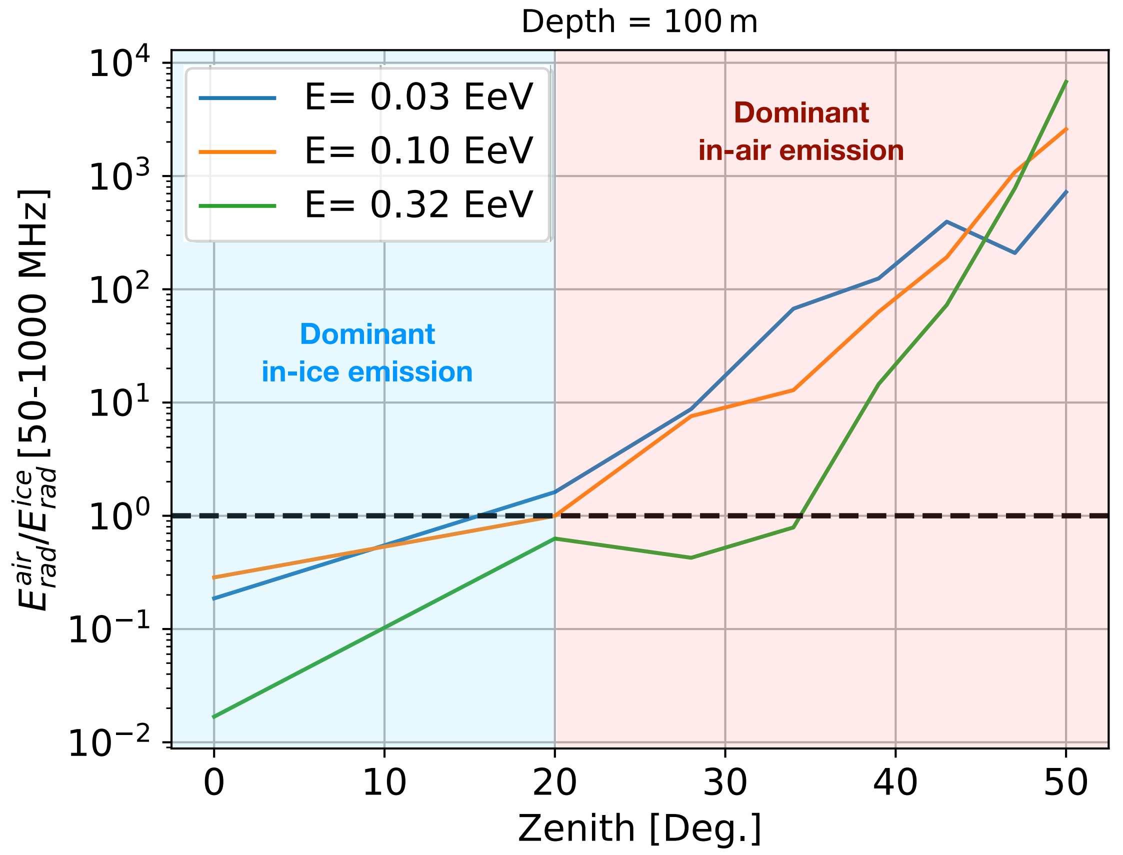
- Trigger if $E_{\mathrm{peak}} > 100\,\mu\mathrm{V/m}$
- Vertical showers: increasing with increasing zenith angle (scaling of the in-air emission with θ)
- Inclined showers: decreasing with increasing zenith angle (scaling of the in-ice emission with θ)

All-zeniths double pulses map



Fraction of double pulses per channel



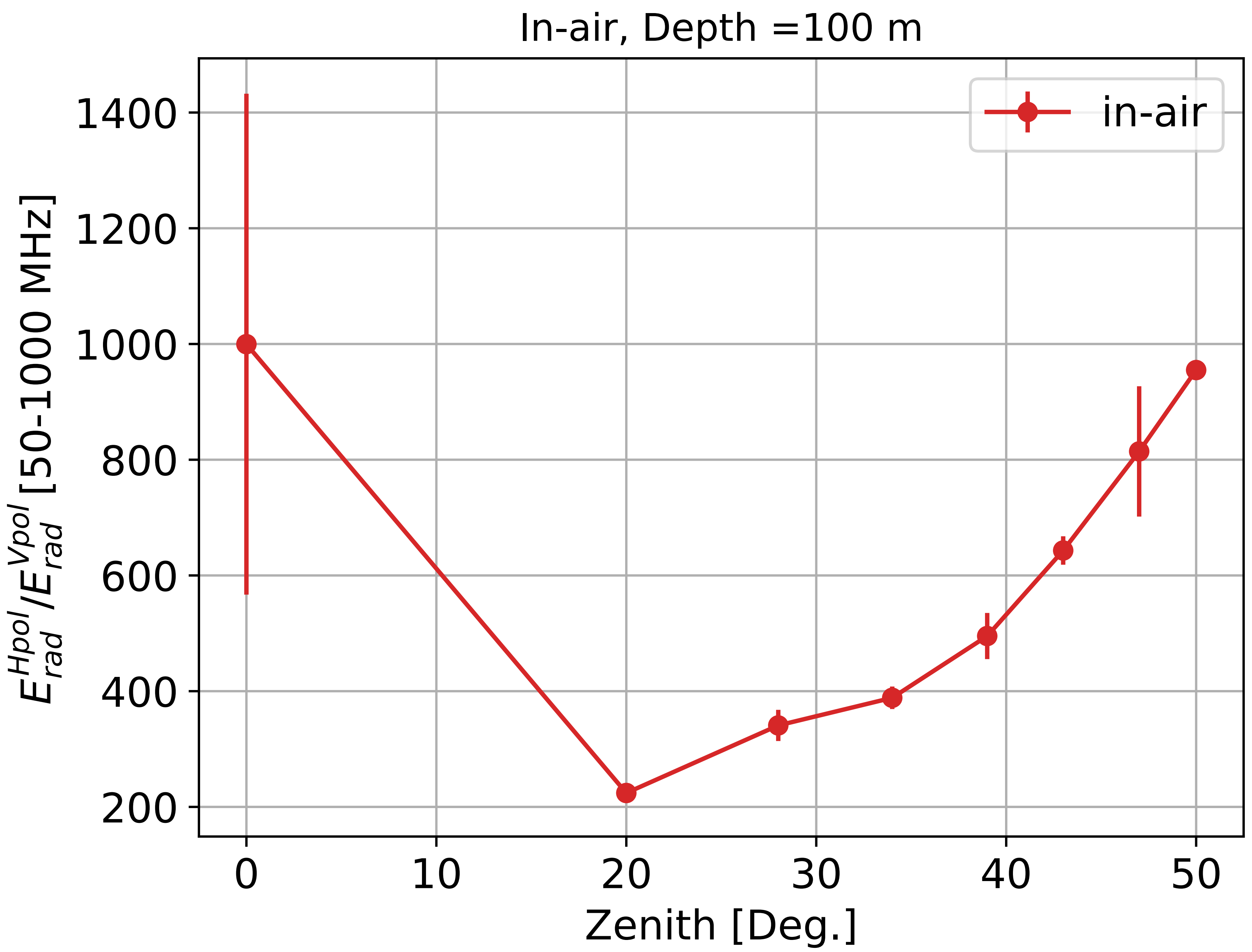


Radio signal polarization

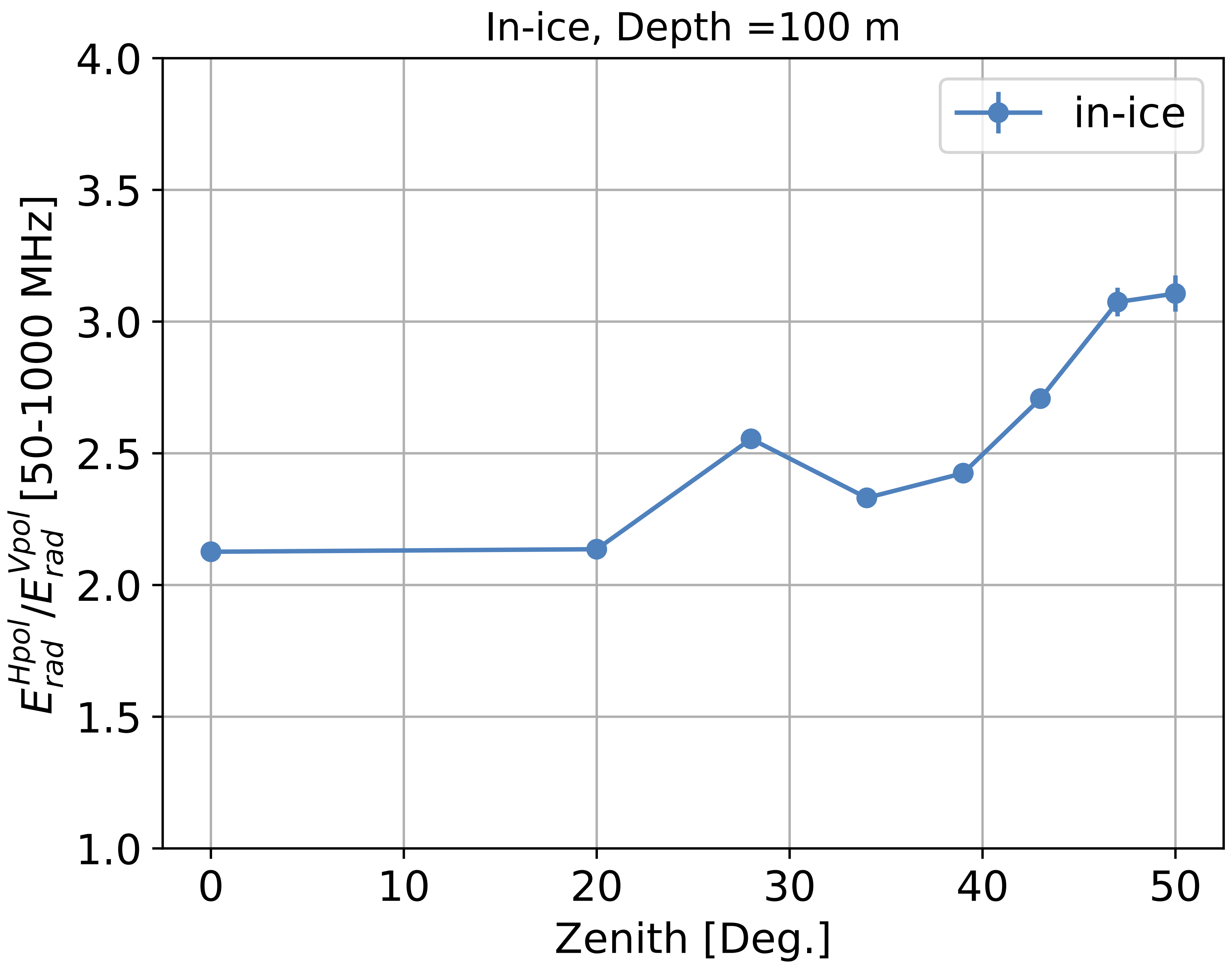
We can evaluate the Hpol/Vpol ratio for the in-air and the in-ice emission

Vertical polarization: $E_{\rm rad}^{\rm Vpol} = E_{\rm rad}^{z}$ Horizontal polarization: $E_{\rm rad}^{\rm Hpol} = \sqrt{(E_{\rm rad}^{x})^2 + (E_{\rm rad}^{y})^2}$

In-air



In-ice



Hpol/Vpol radiation energy ratio

We can evaluate the Hpol/Vpol ratio for the in-air and the in-ice emission

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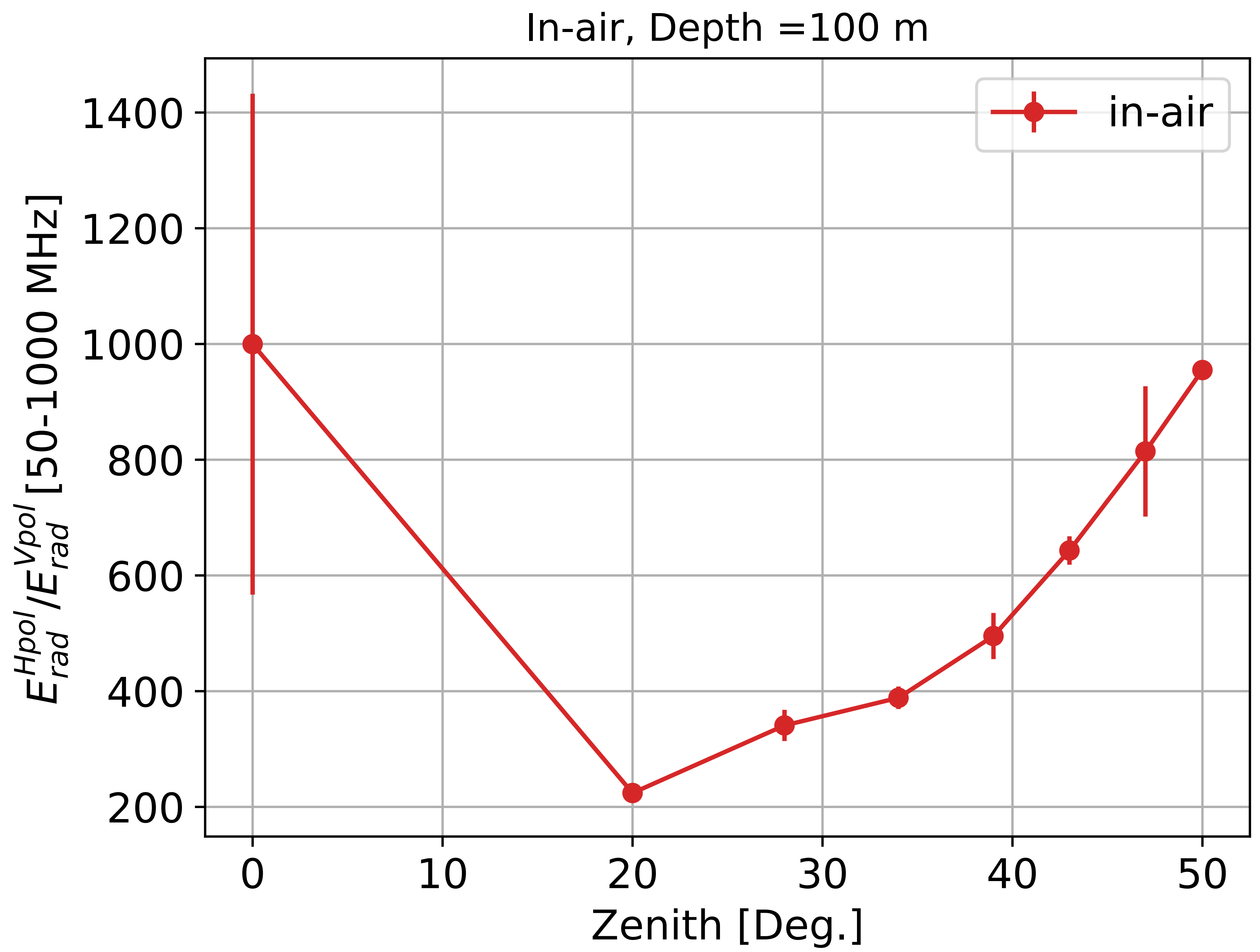
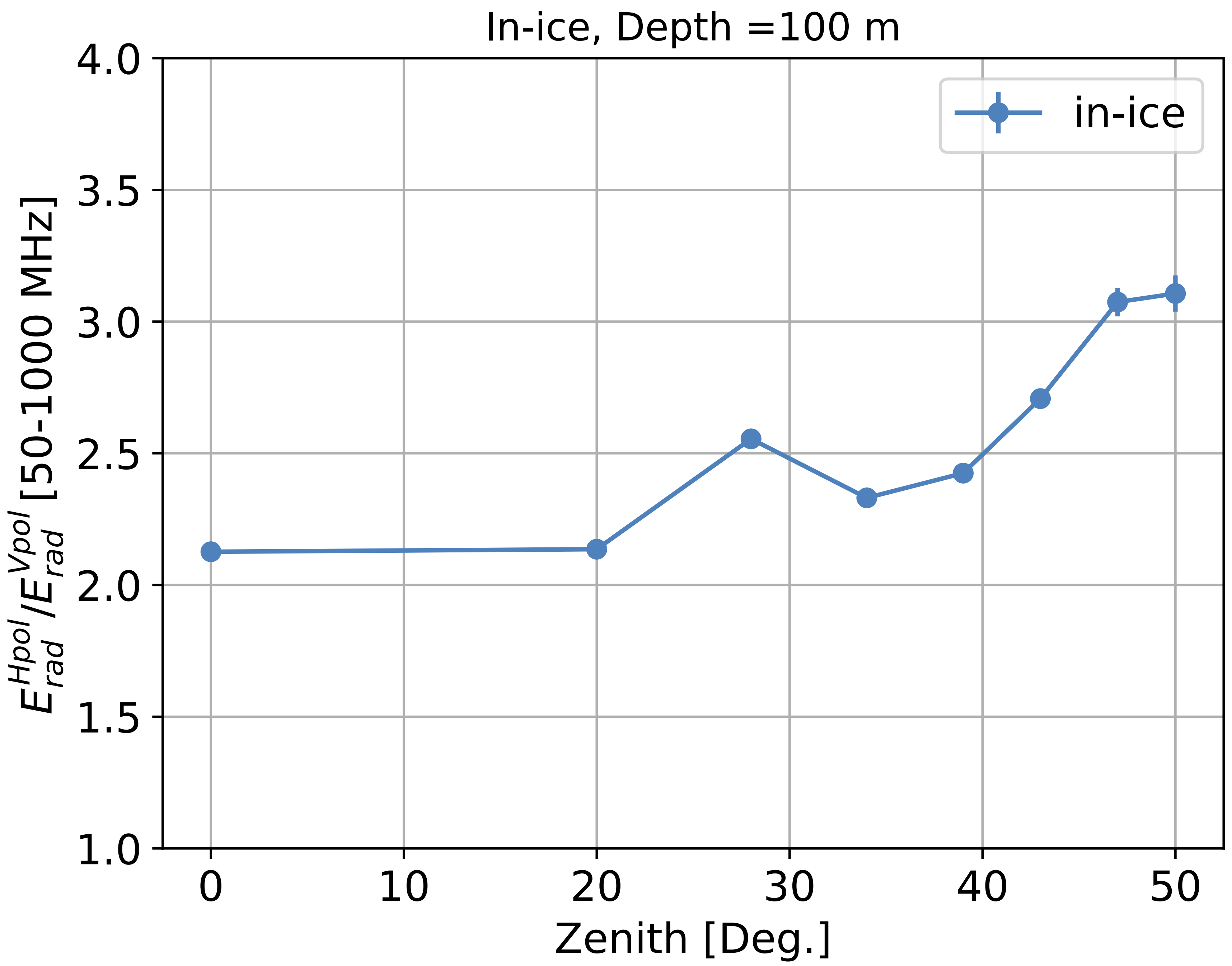
In-air



In-ice

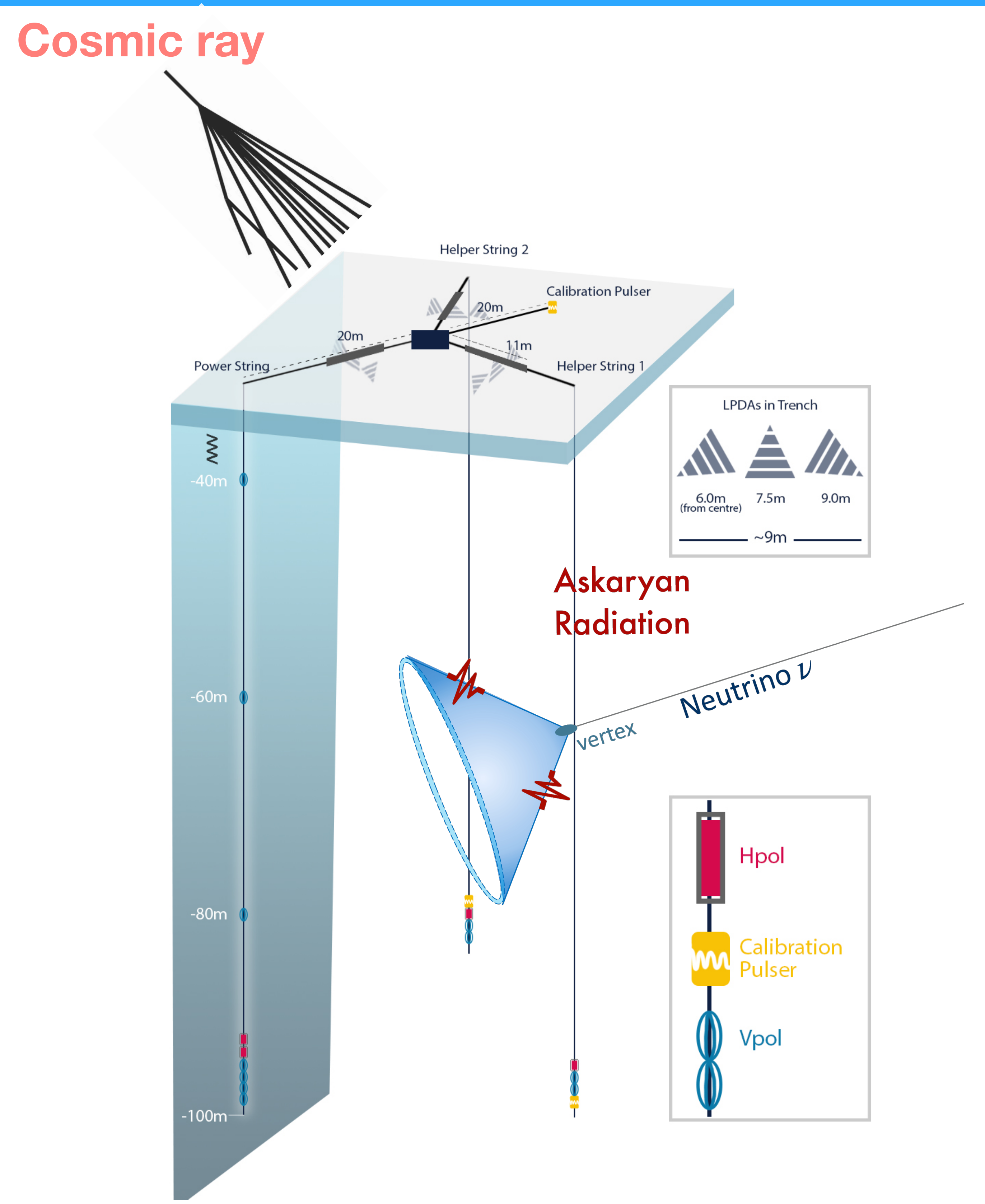


Two orders of magnitude between the in-air and the in-ice component

→ Efficient observable for cosmic ray/neutrino discrimination

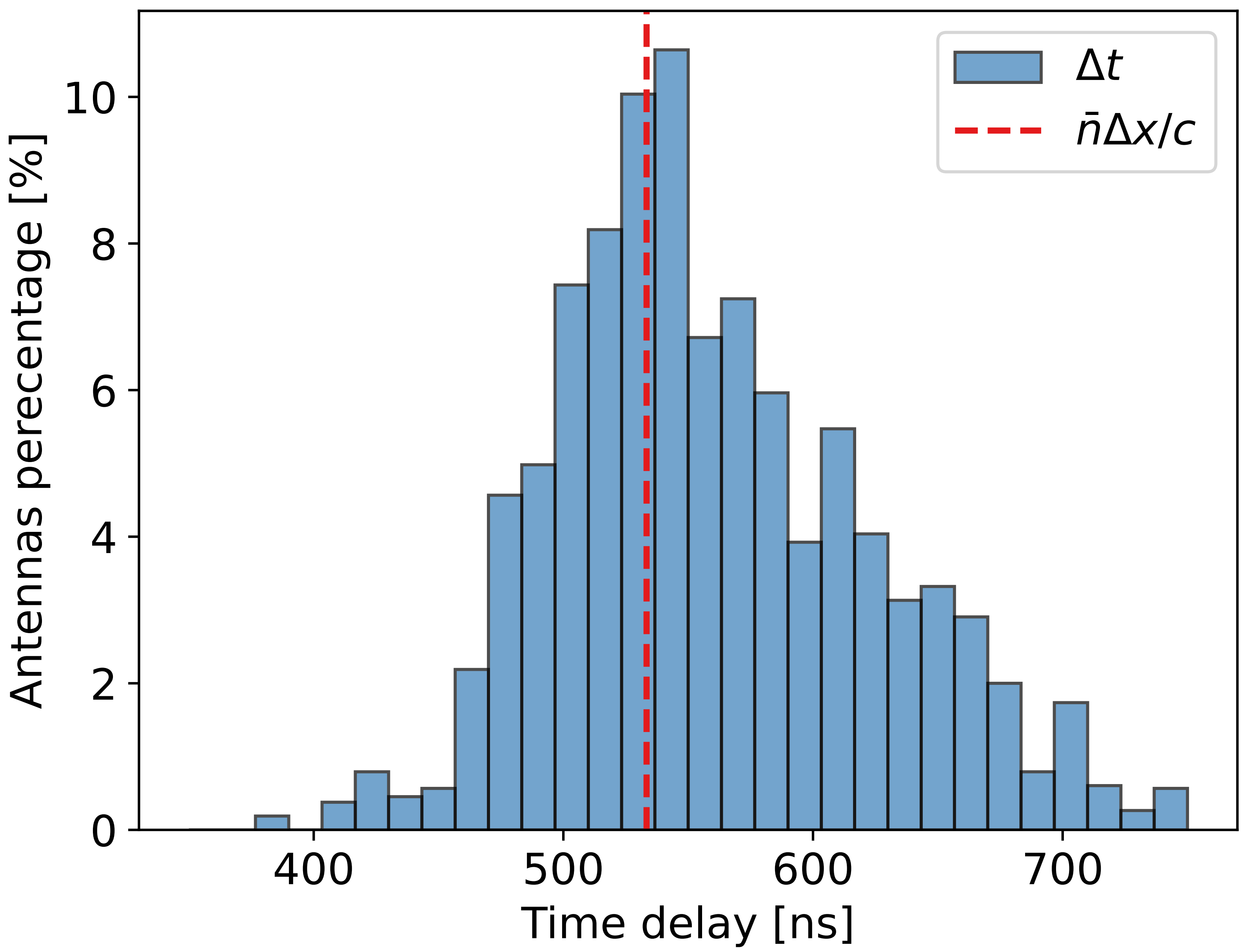
Surface antennas

Cosmic ray detection at different depths

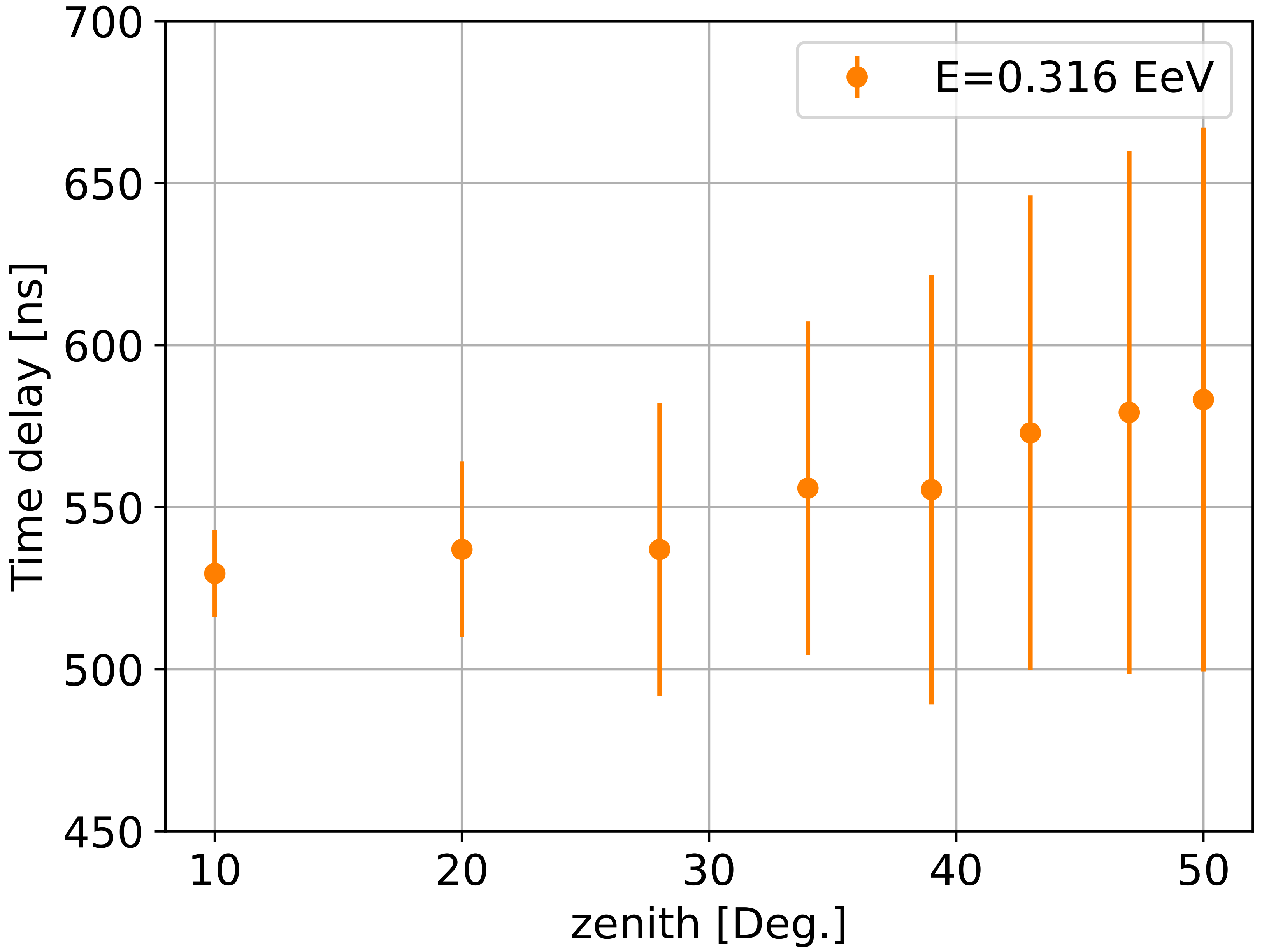


Surface antennas can act as veto for cosmic ray

Time delay distribution between 100m-deep and surface antennas



Mean and RMS of the time delays versus zenith angle



Time delays distributed around $500\,\mathrm{ns} \simeq \bar{n}\Delta x/c$

The mean and the the RMS of the time delays increase with the shower zenith angle (footprint asymmetry)

Summary

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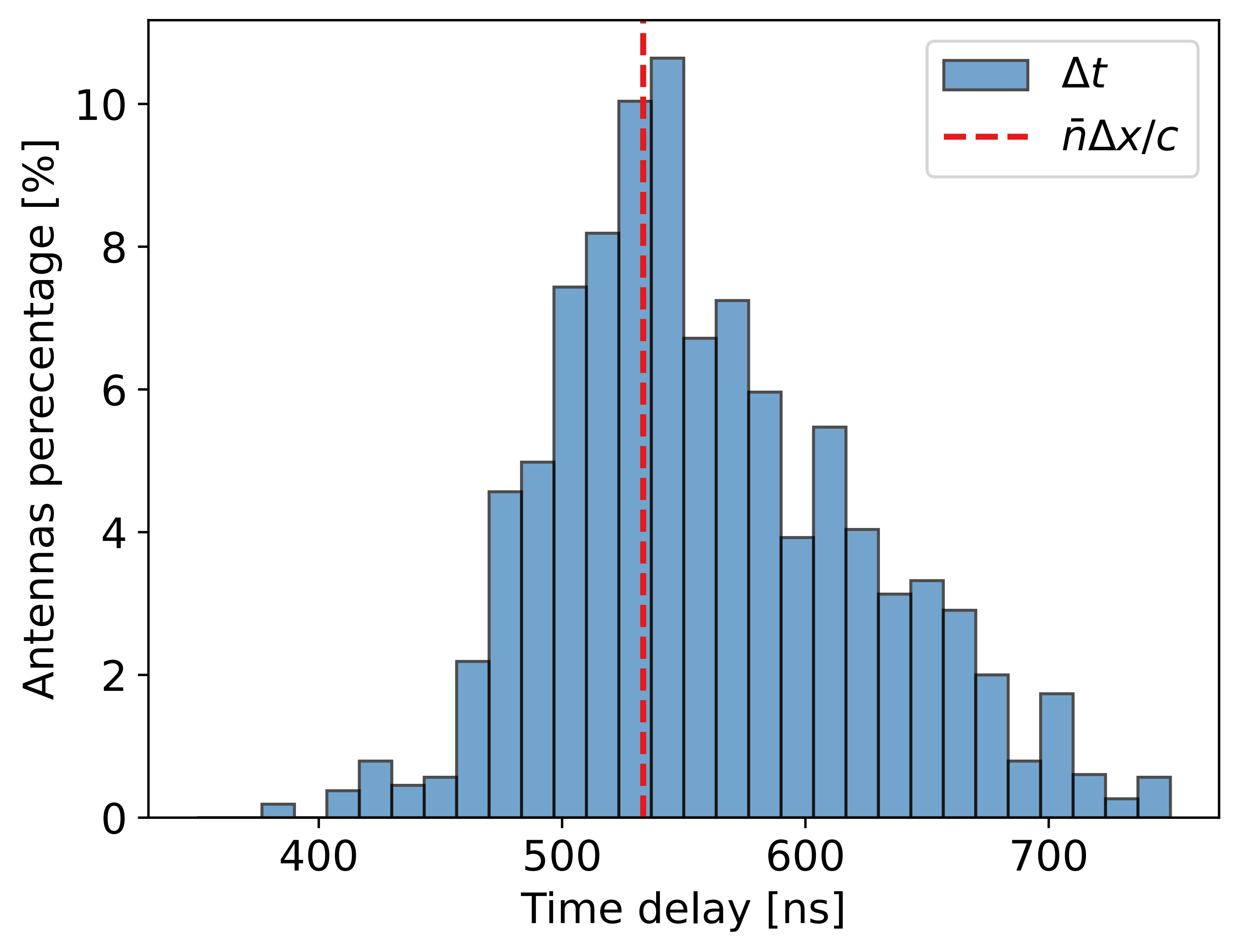
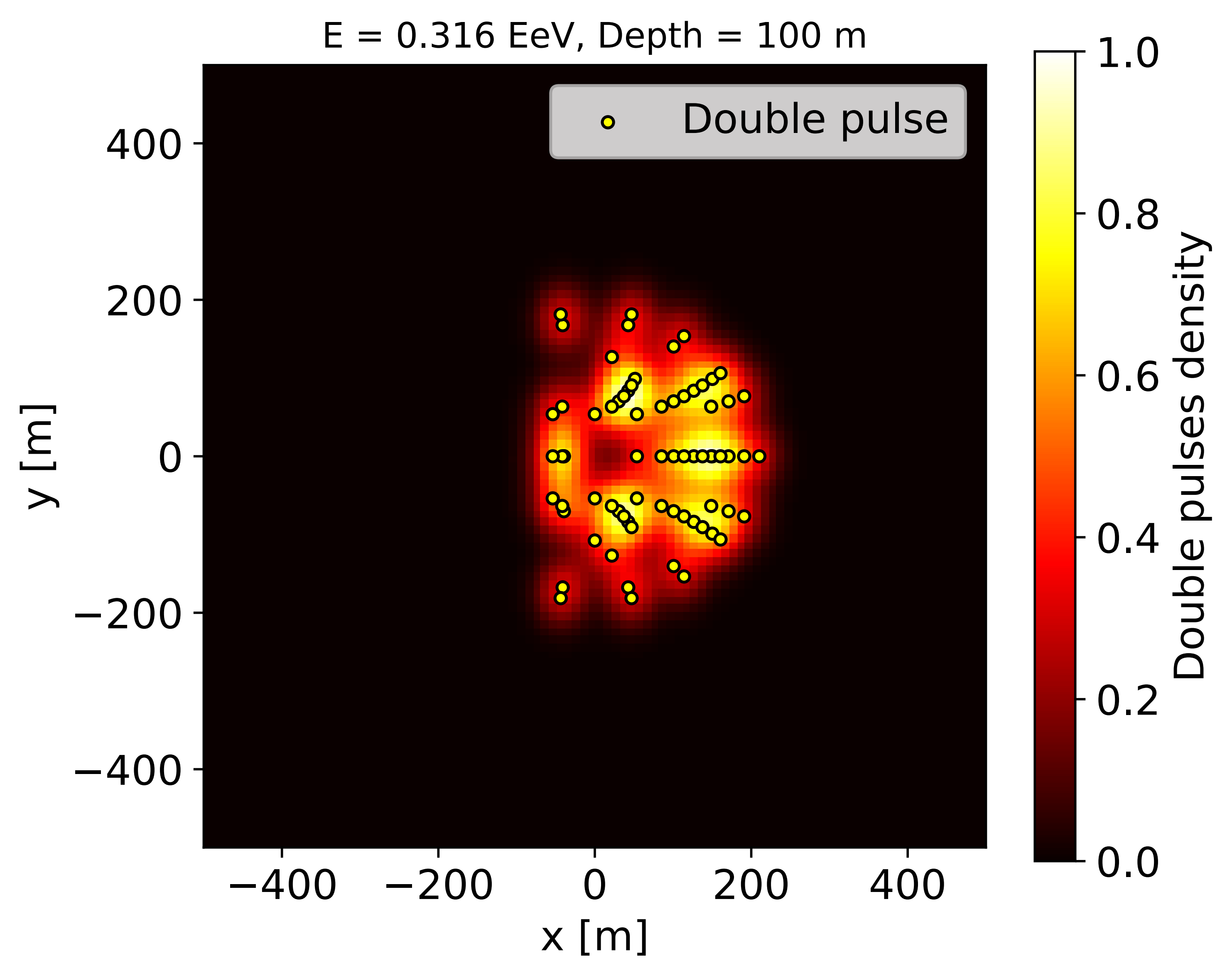
Using FAERIE simulations we characterized radio signatures from cosmic ray showers as seen by deep in-ice observers

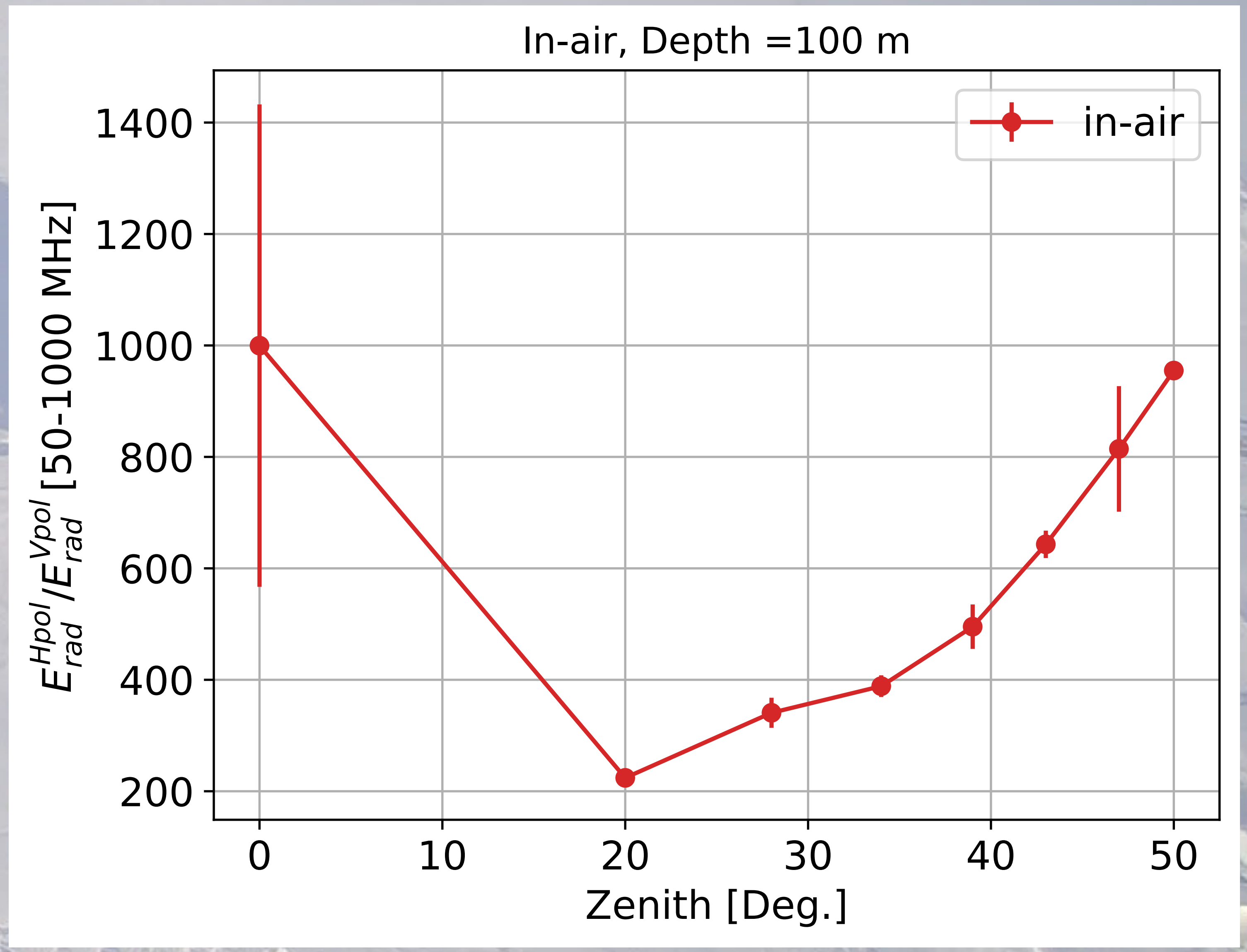
Signal timing



Double pulses



Polarization



These specific features of the radio specific will help identifying the first cosmic ray events

→ Validate detection principle of in-ice experiments and FAERIE simulations

→ Support the calibration of the detectors

→ Provide valuable insights for cosmic ray/neutrino discrimination