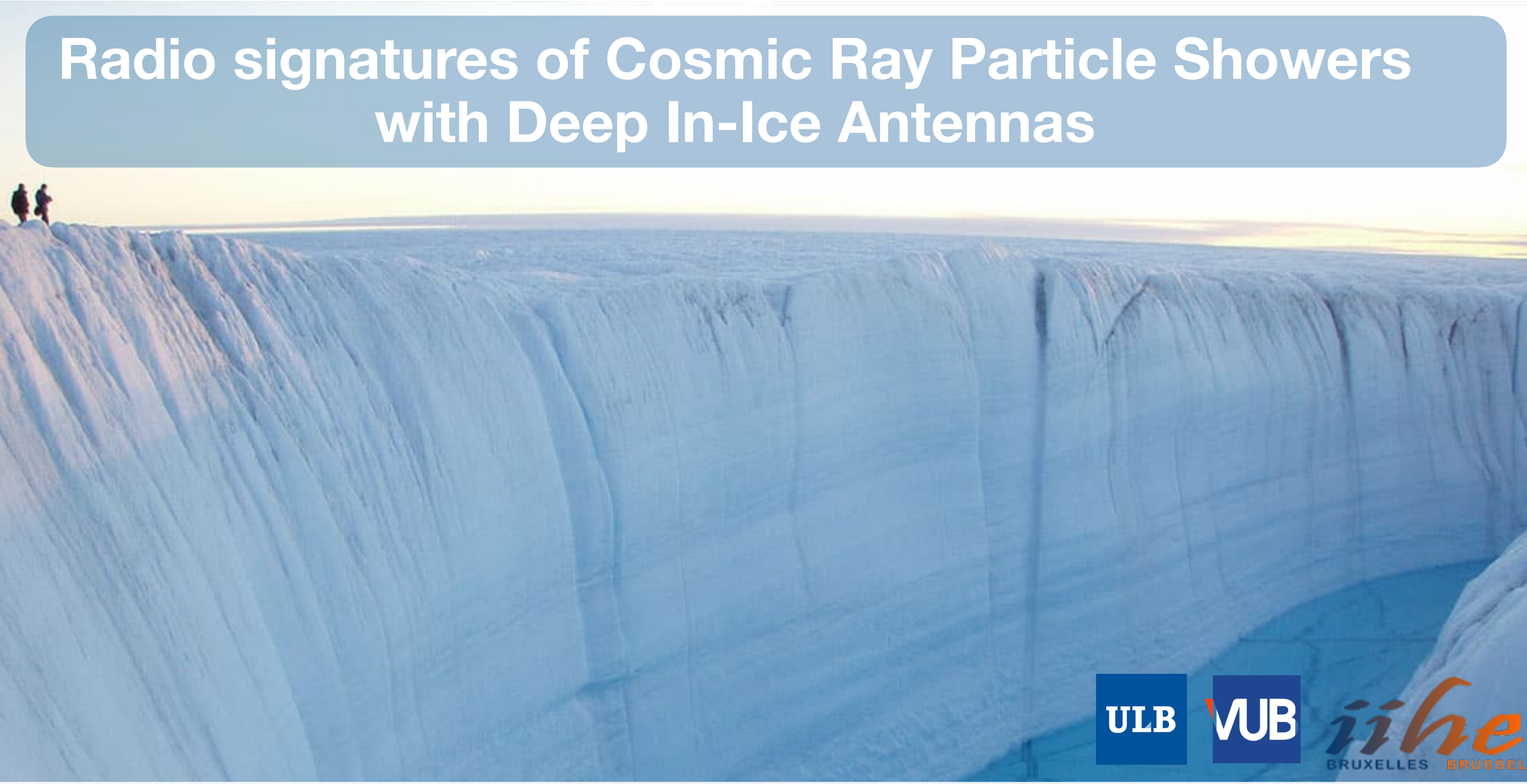
Radio signatures of Cosmic Ray Particle Showers with Deep In-Ice Antennas



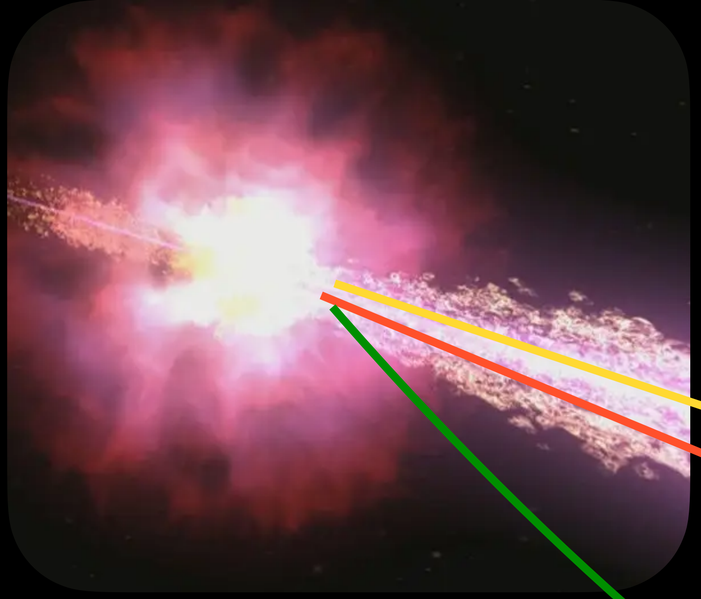
Simon Chiche, *Krijn de Vries, Simona Toscano*

Ultra-high energy (UHE) neutrinos

Cf. talk by S. Toscano

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

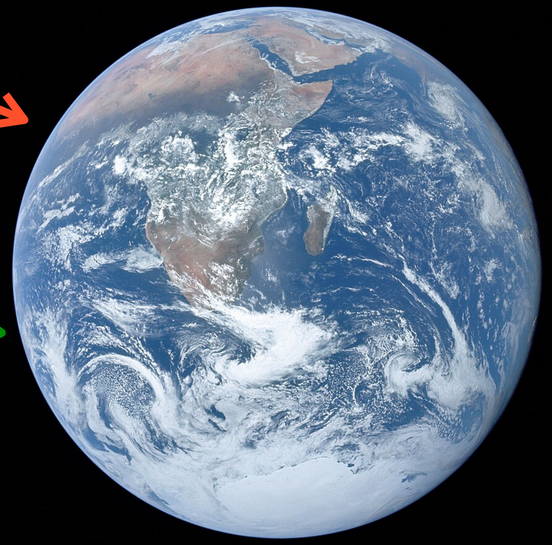
- ✓ probe the most powerful sources in the Universe
- ✓ understand the origin of ultra-high energy cosmic rays



γ

ν

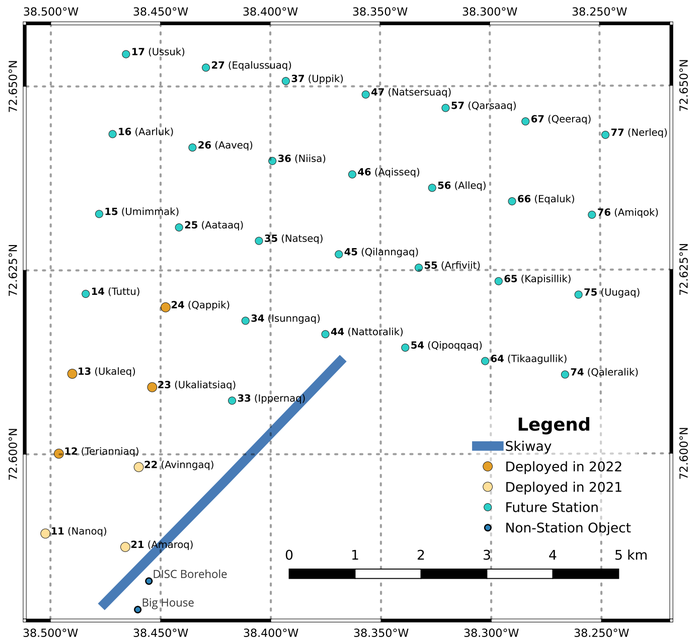
CR



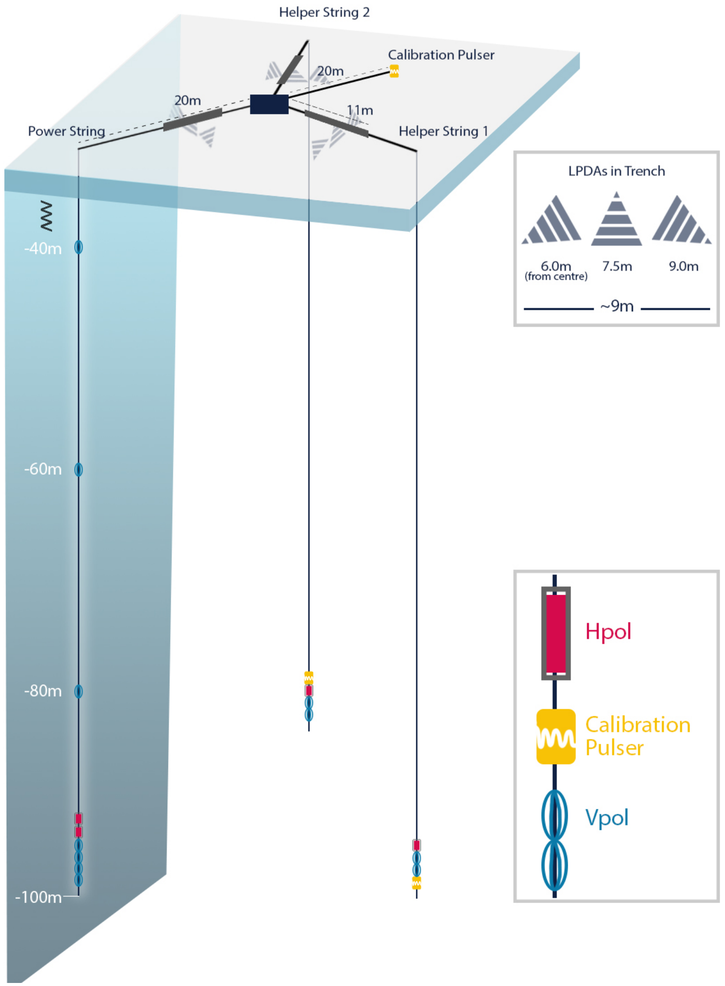
RNO-G: The Radio Neutrino Observatory in Greenland

Simon Chiche (IIHE)

35 autonomous stations at Summit Station (Greenland)

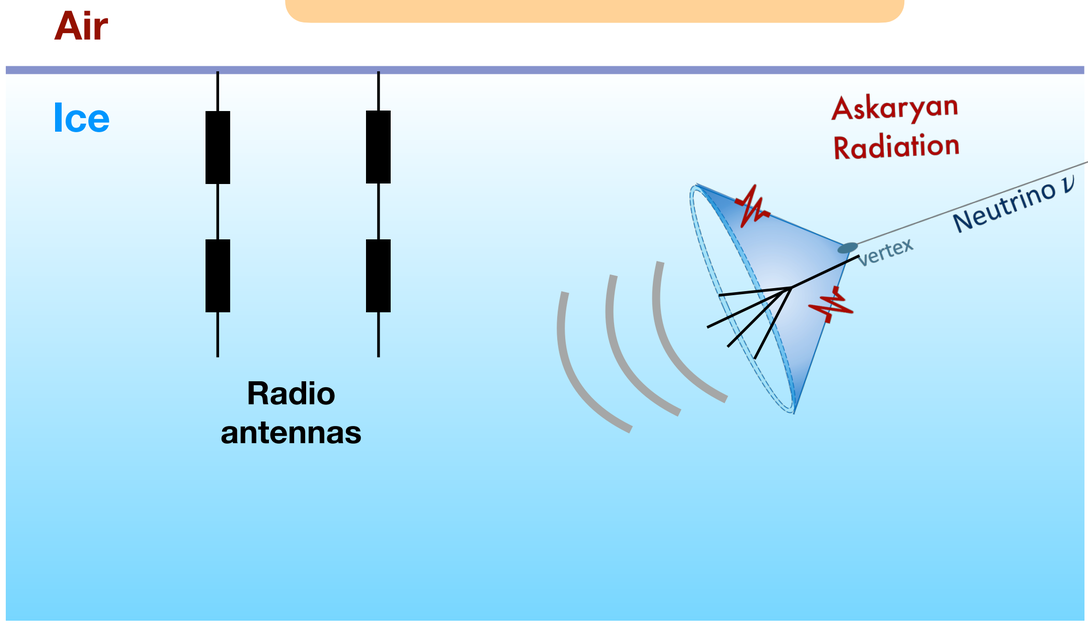


1 station: 24 radio antennas



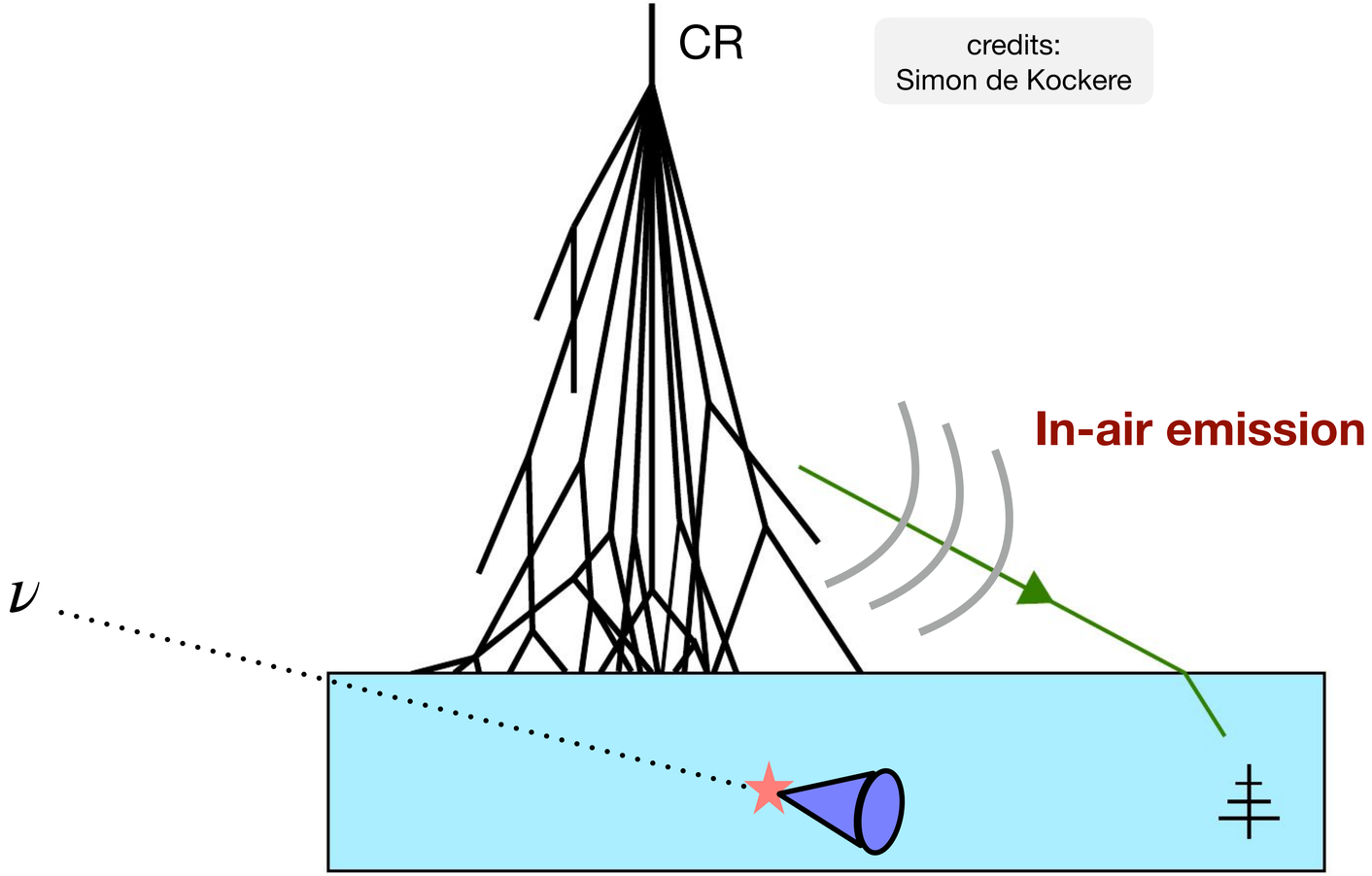
Cf. talk by E. Huesca Santiago

Radio detection of ultra-high energy neutrinos

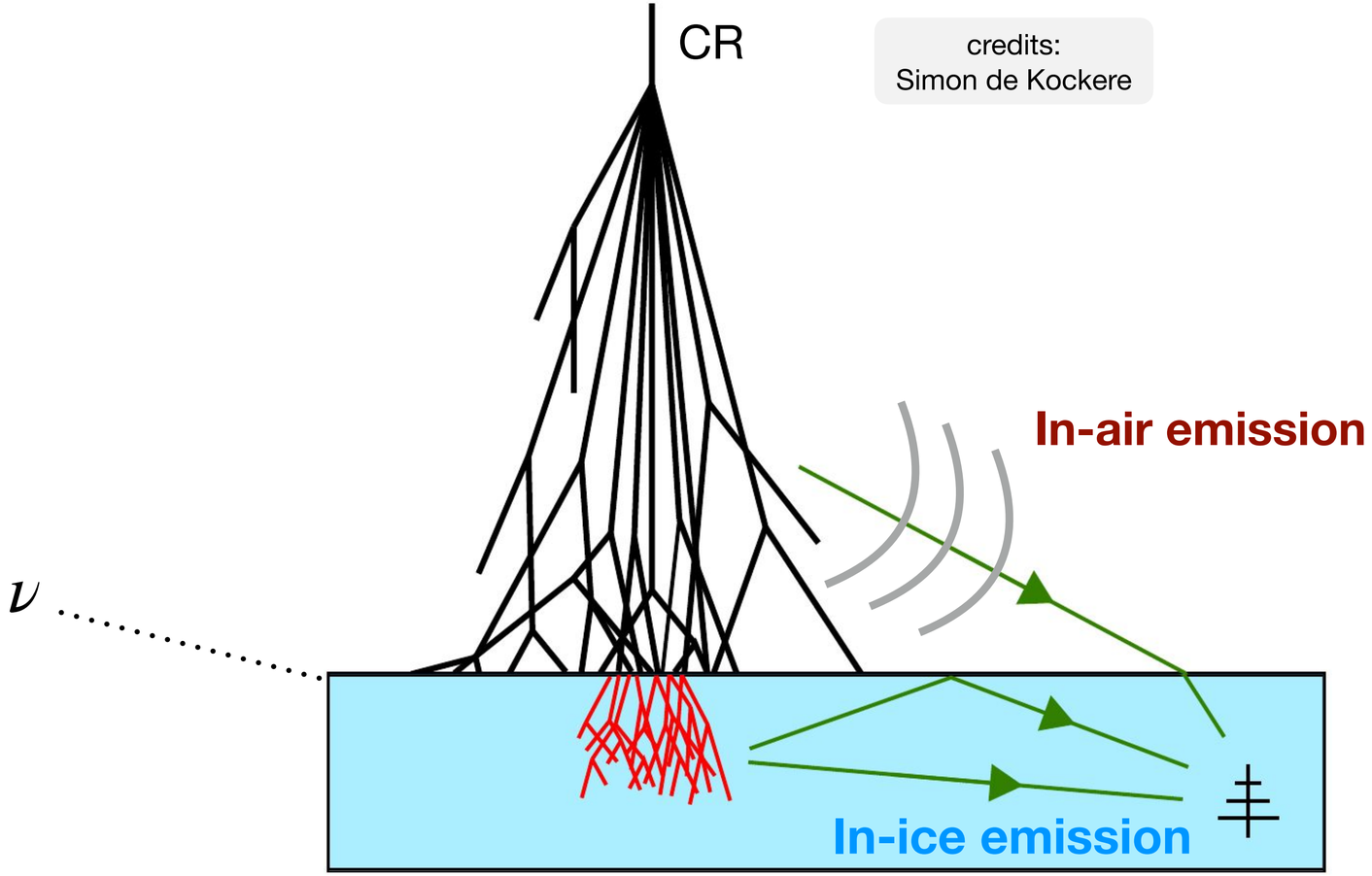


In-ice radio detection: promising technique to detect ultra-high energy neutrinos

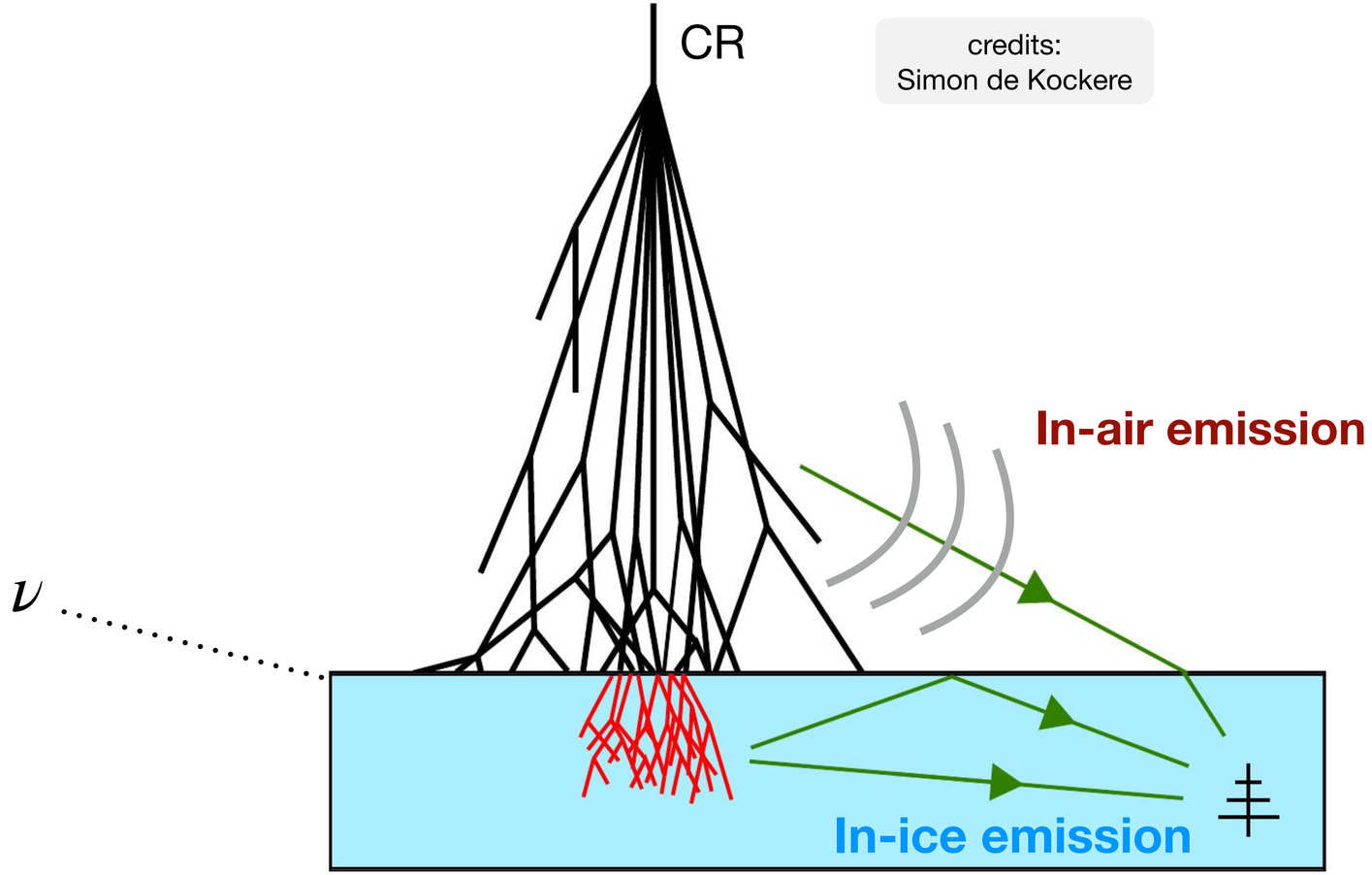
Radio emission of cosmic-ray air showers can also reach the deep antennas



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



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

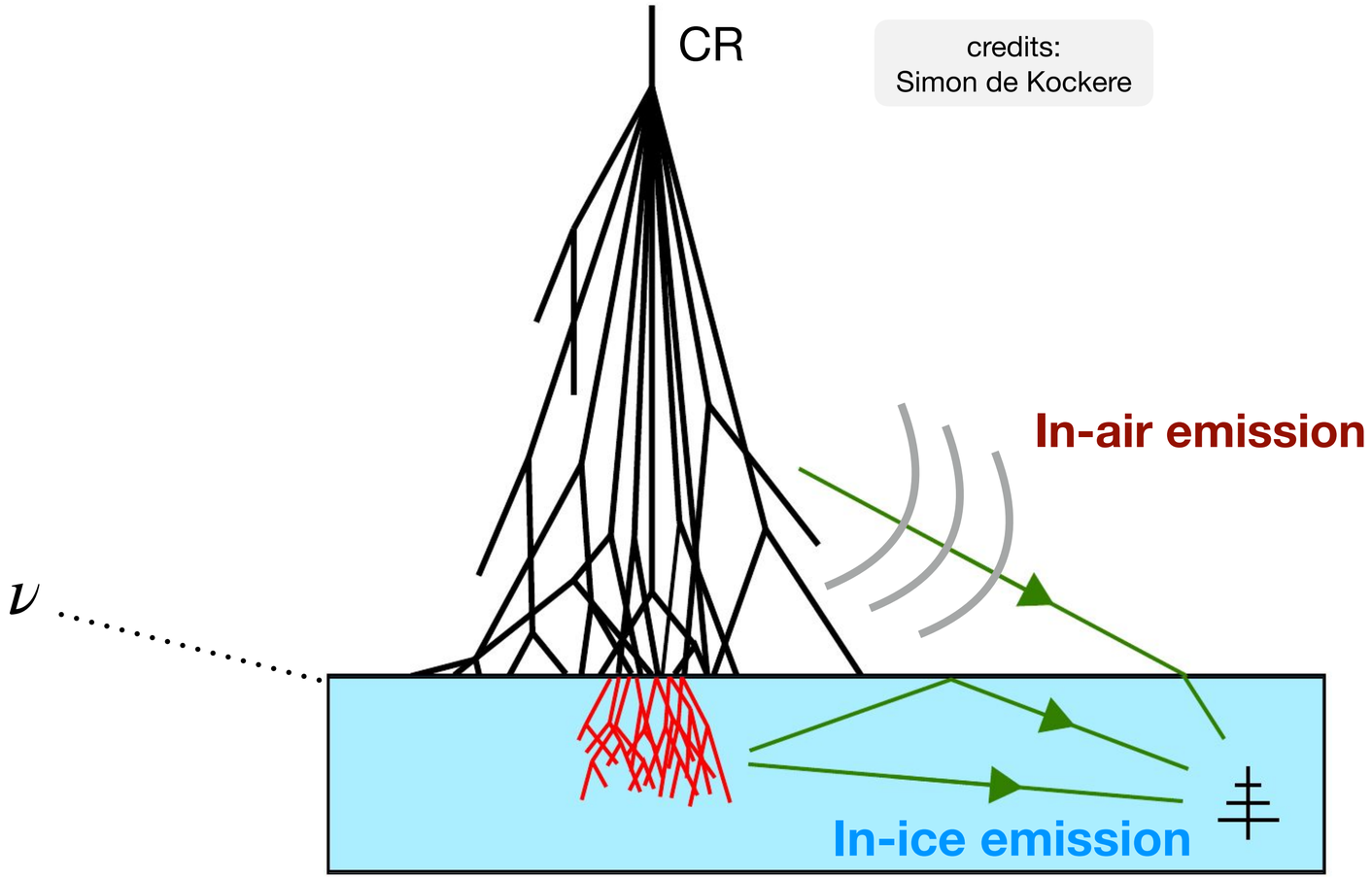


The cosmic-ray flux should be much larger than the neutrino flux:

Simon Chiche (IIHE)

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

cf. talk by N. Alden



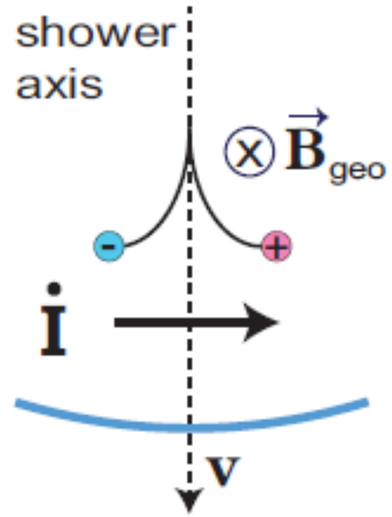
The cosmic-ray flux should be much larger than the neutrino flux:

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

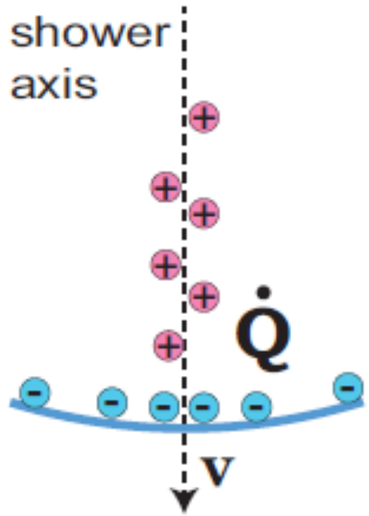
Simon Chiche (IIHE)

2 main sources for the radio emission of cosmic rays

Geomagnetic emission



Askaryan emission



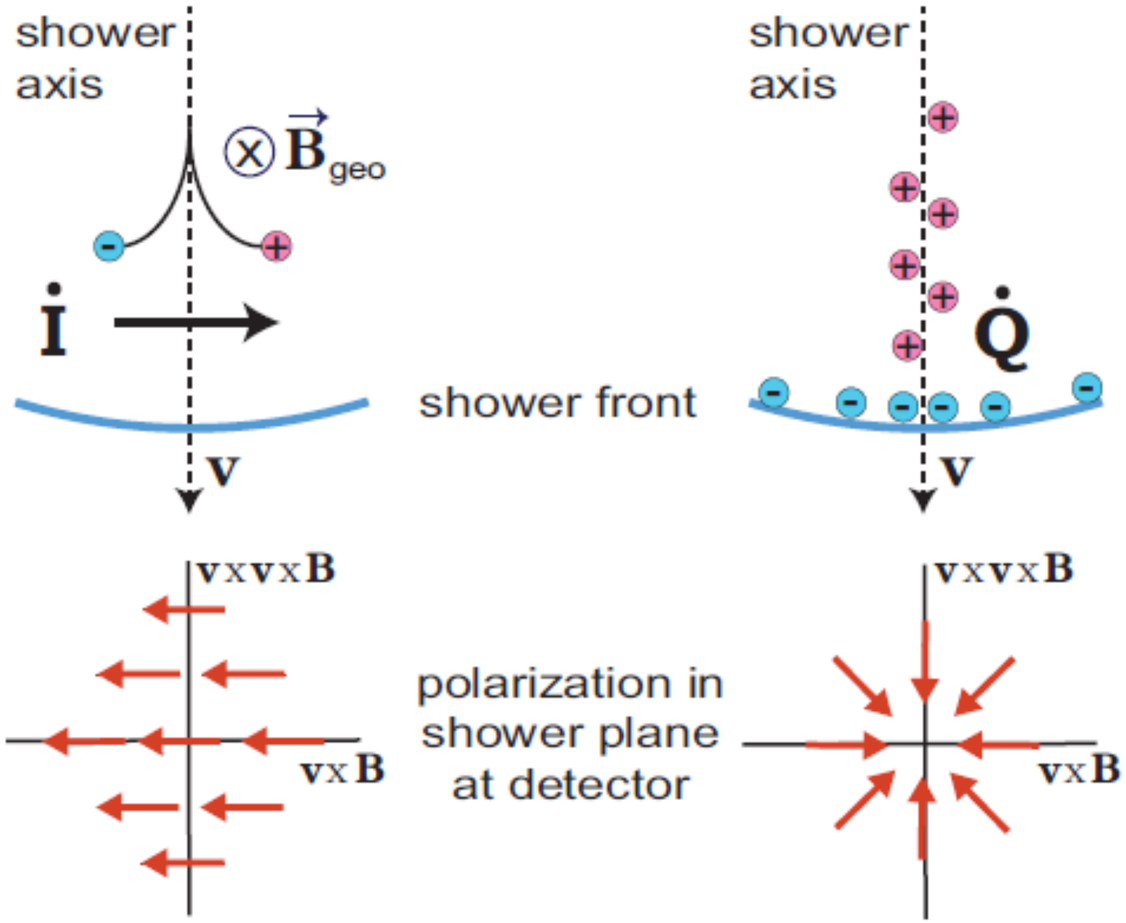
shower front

polarization in shower plane at detector

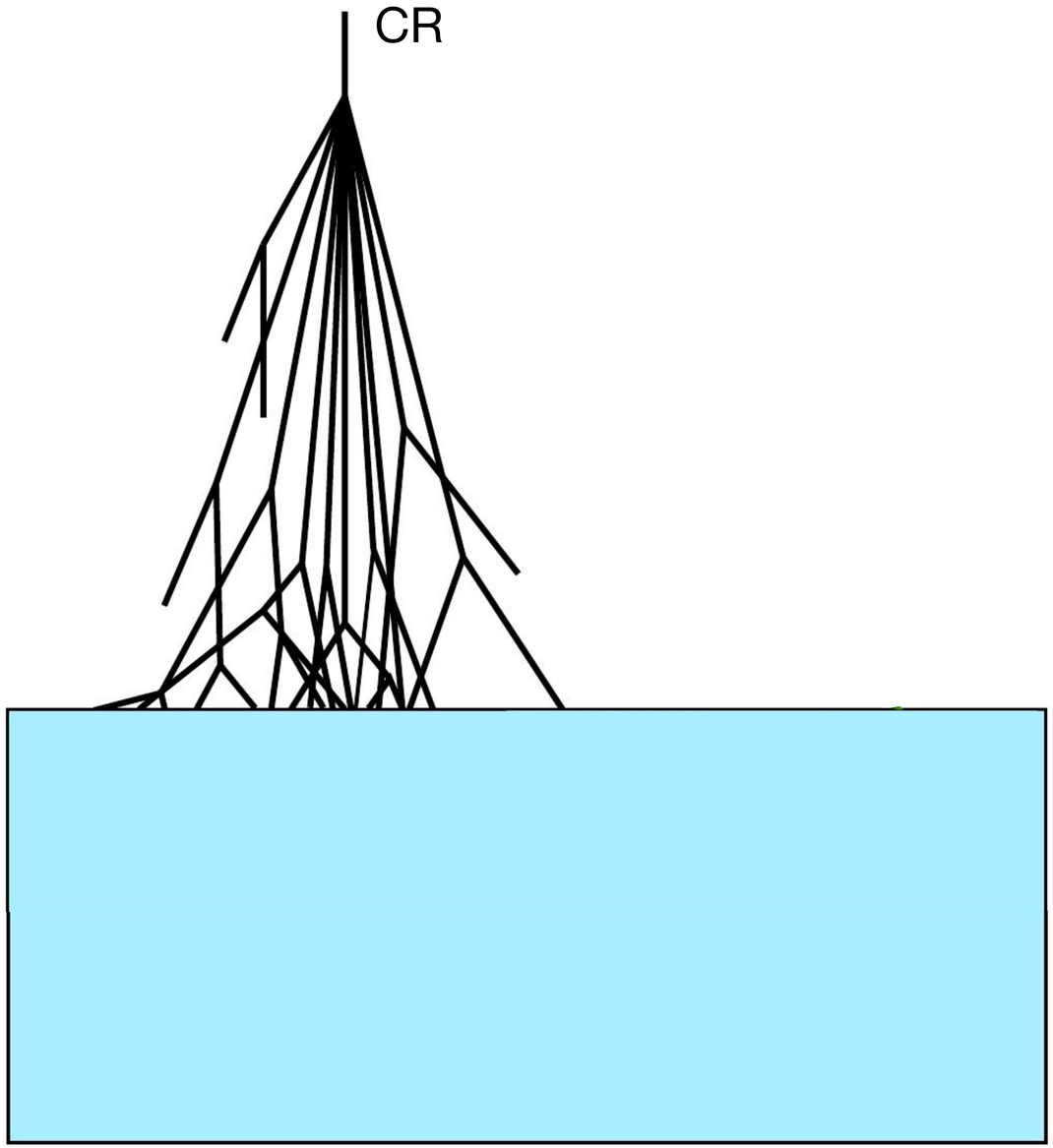
Simon Chiche (IIHE)

2 main sources for the radio emission of cosmic rays

Geomagnetic emission

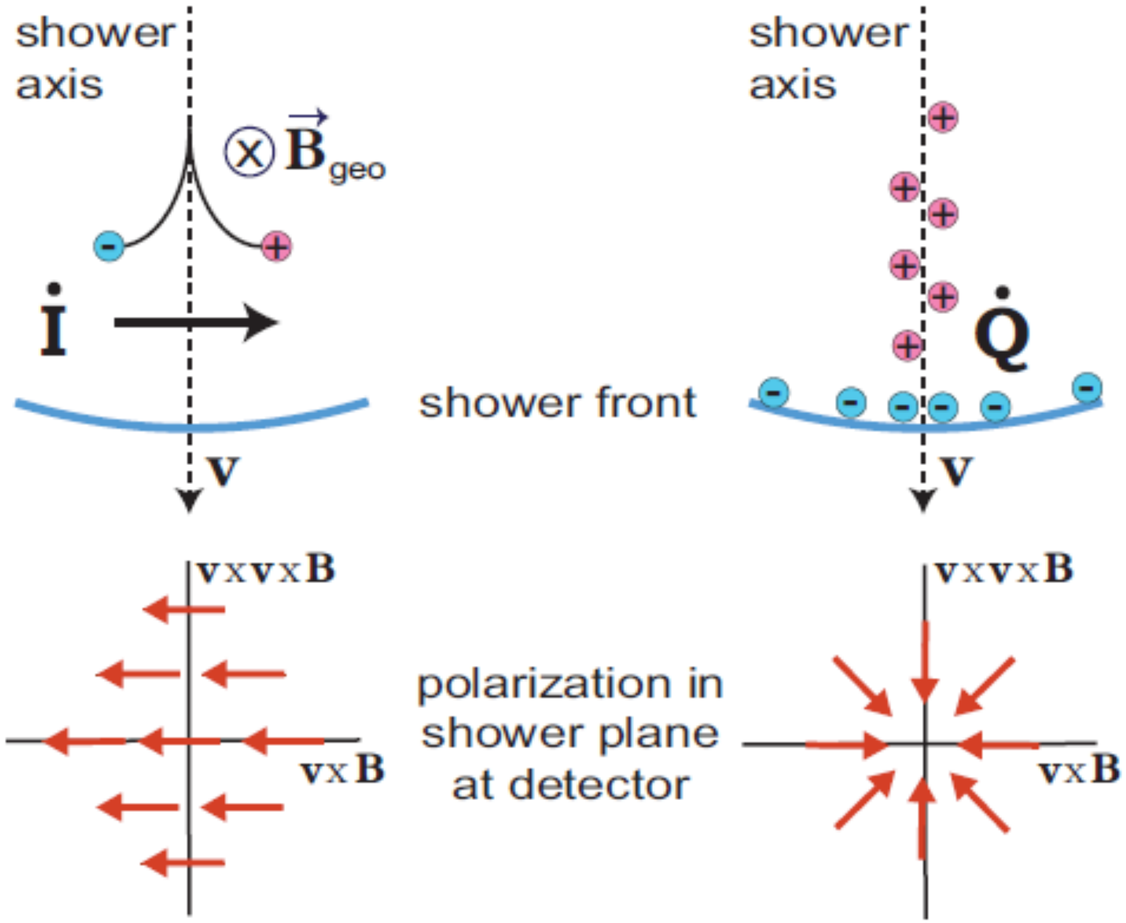


Askaryan emission

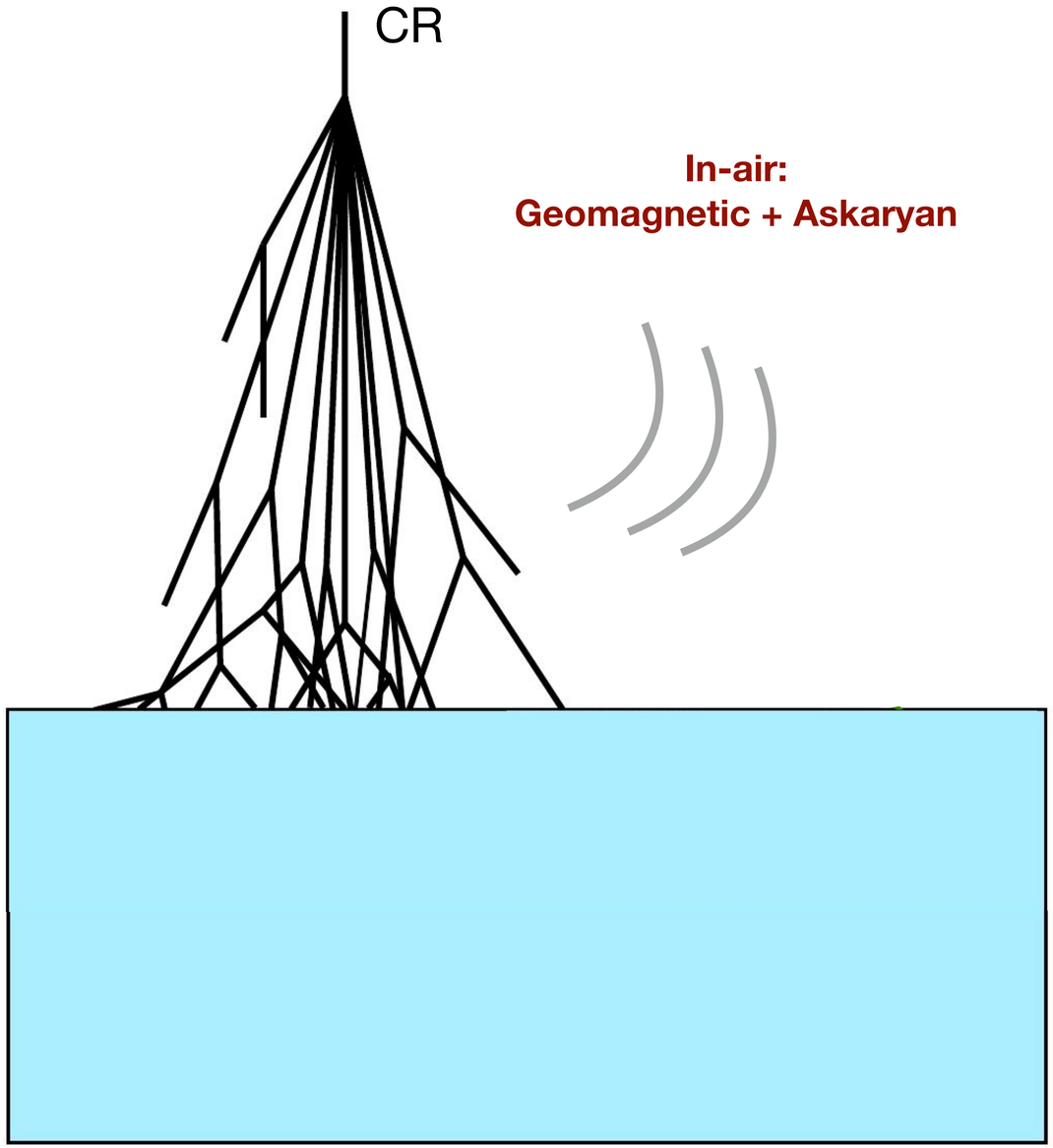


2 main sources for the radio emission of cosmic rays

Geomagnetic emission



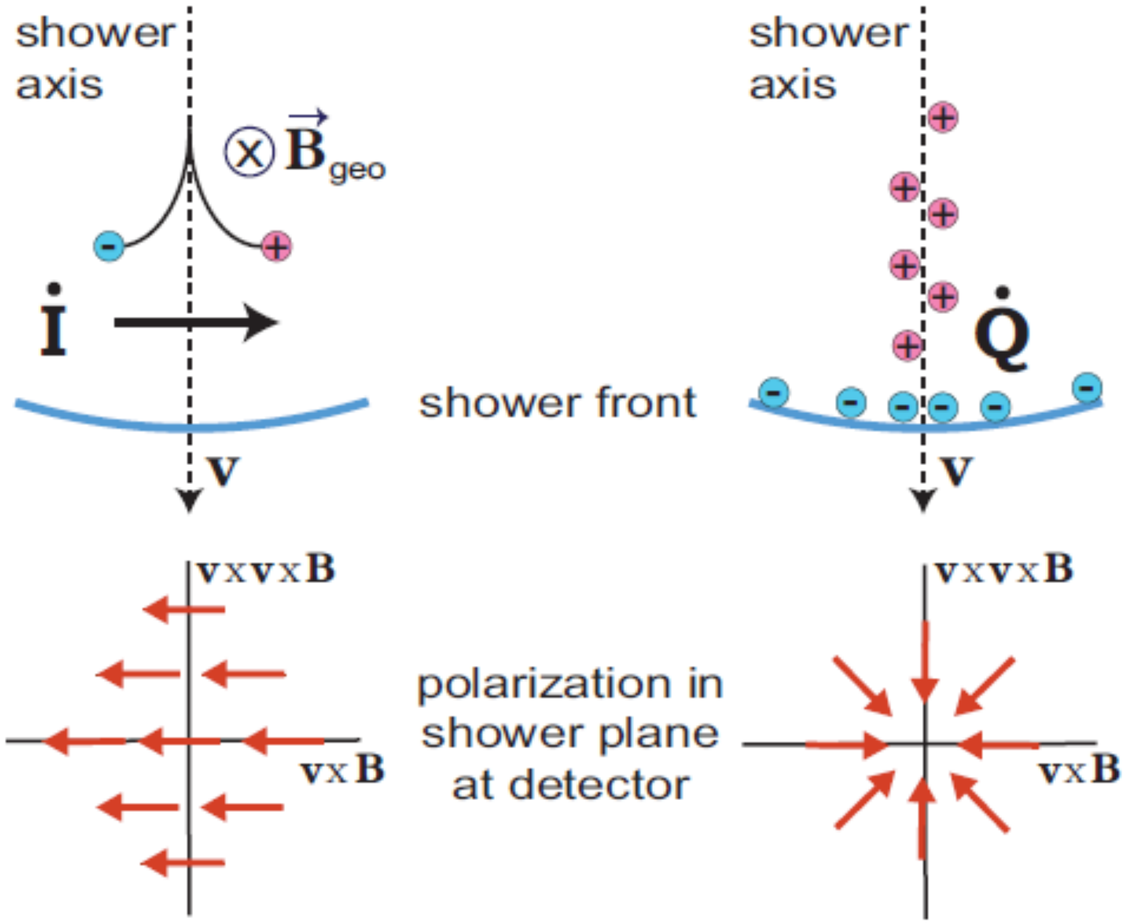
Askaryan emission



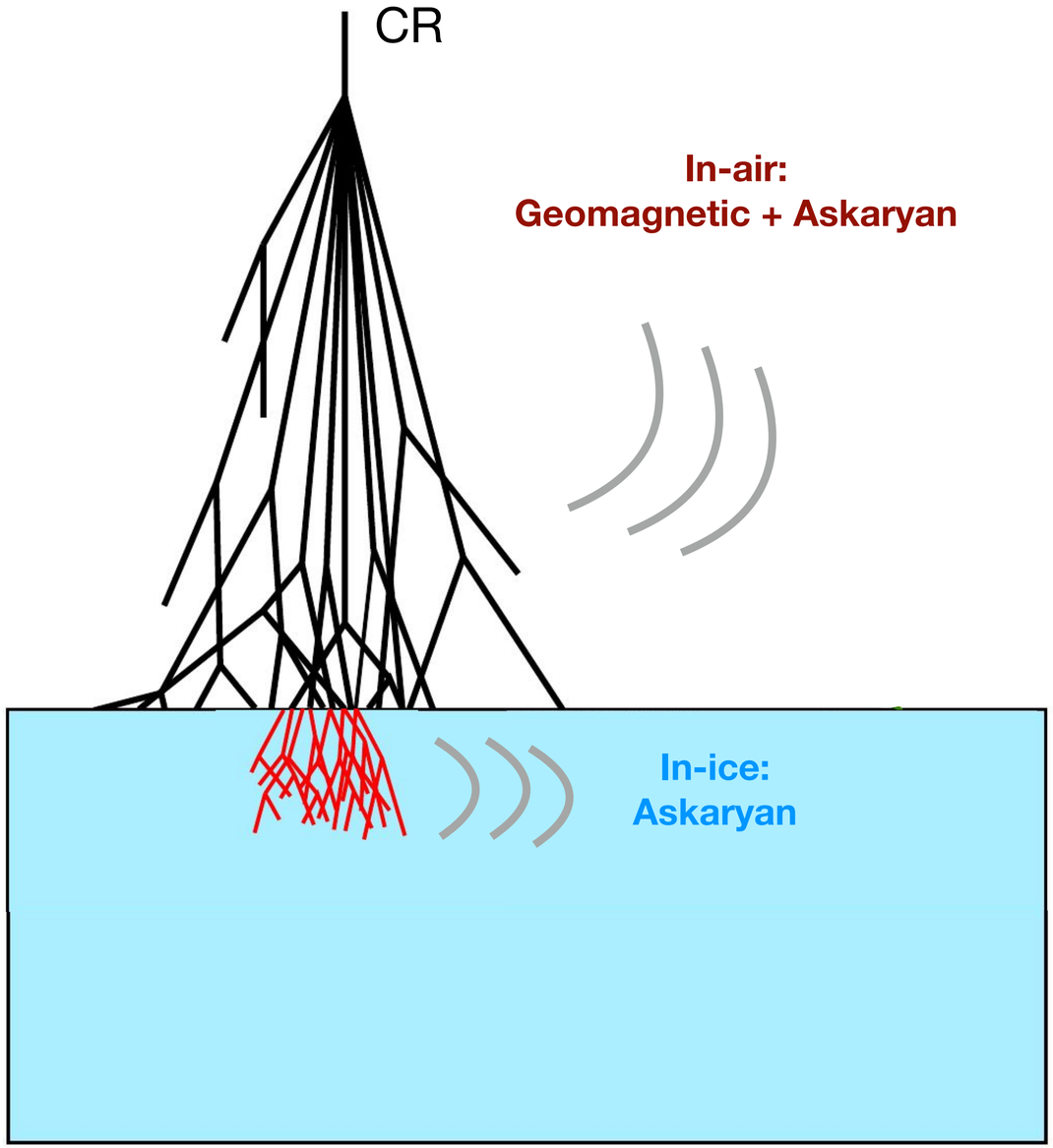
Simon Chiche (IIHE)

2 main sources for the radio emission of cosmic rays

Geomagnetic emission

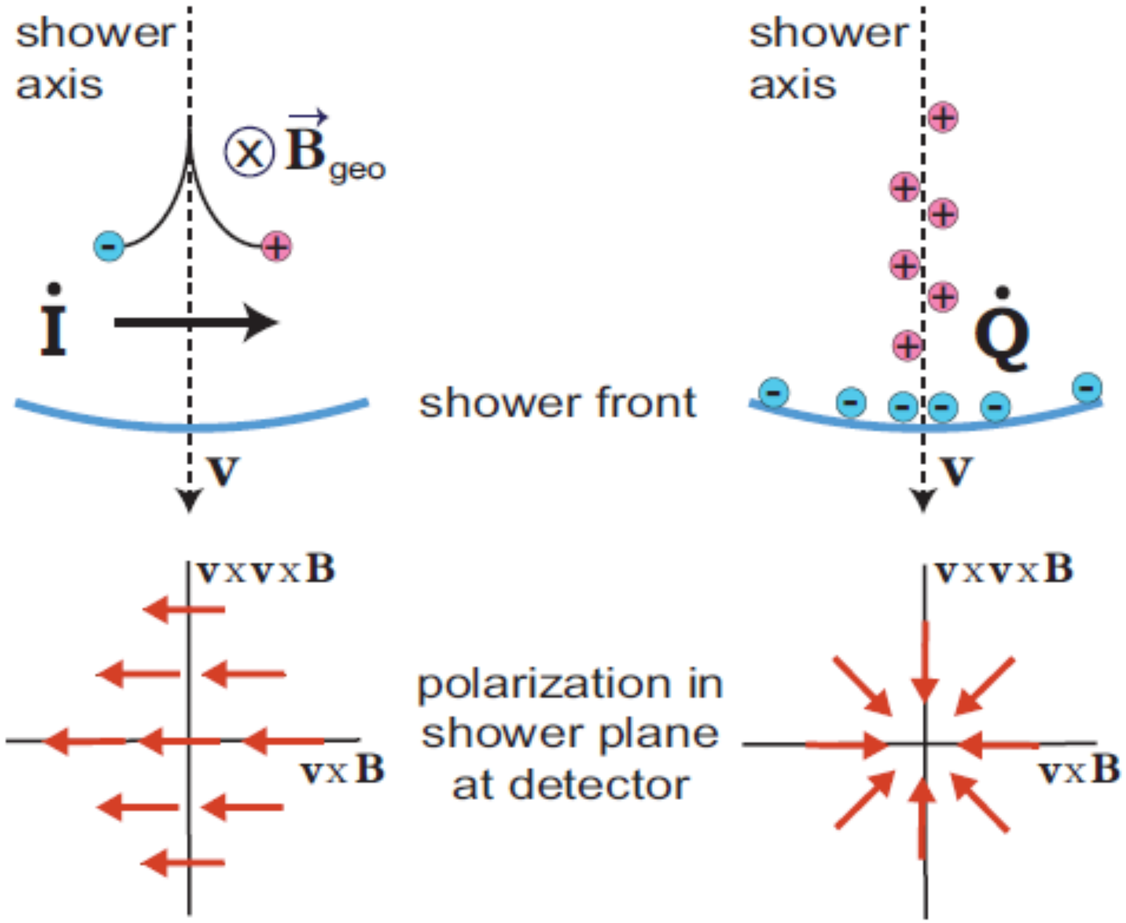


Askaryan emission

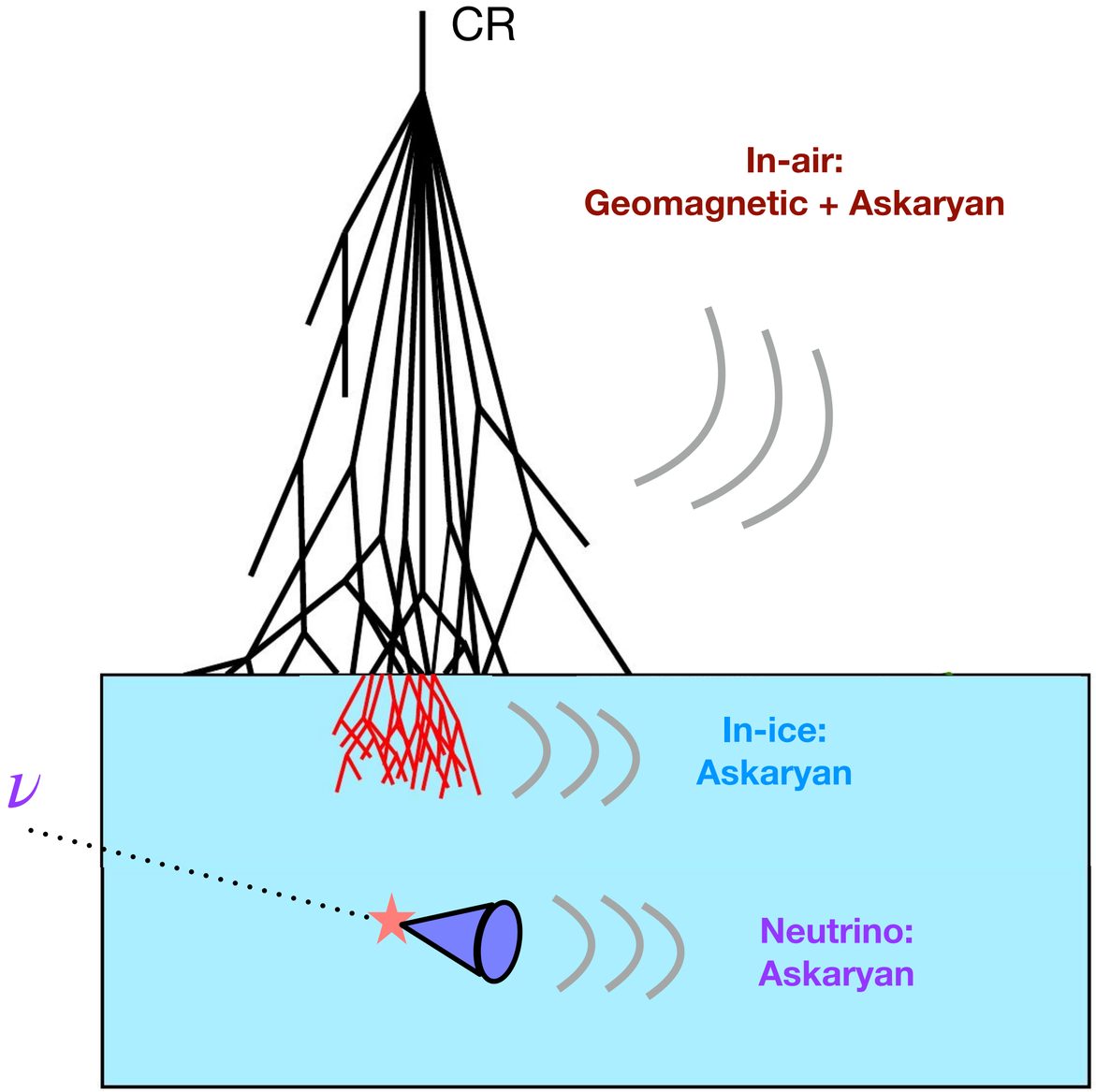


2 main sources for the radio emission of cosmic rays

Geomagnetic emission



Askaryan emission



Simulation setup

Simon Chiche (IIHE)

We aim to characterize cosmic-ray radio emission using the Monte-Carlo tool FAERIE

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

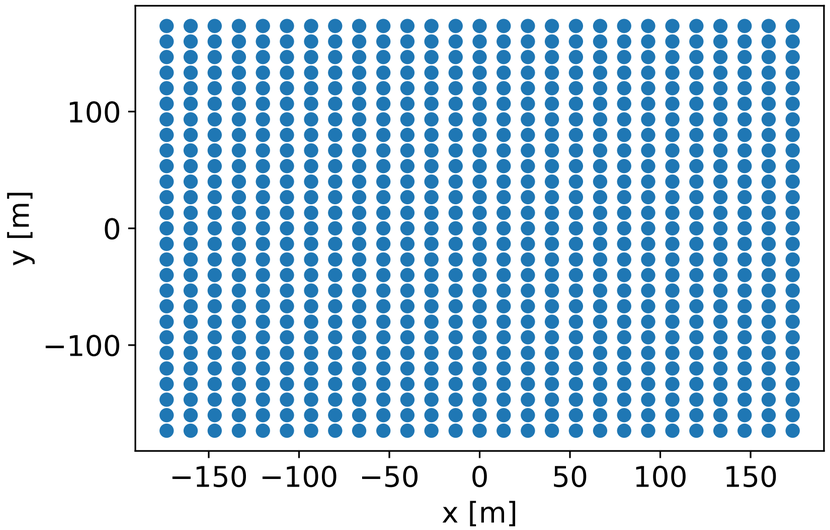
Simulation setup

Simon Chiche (IIHE)

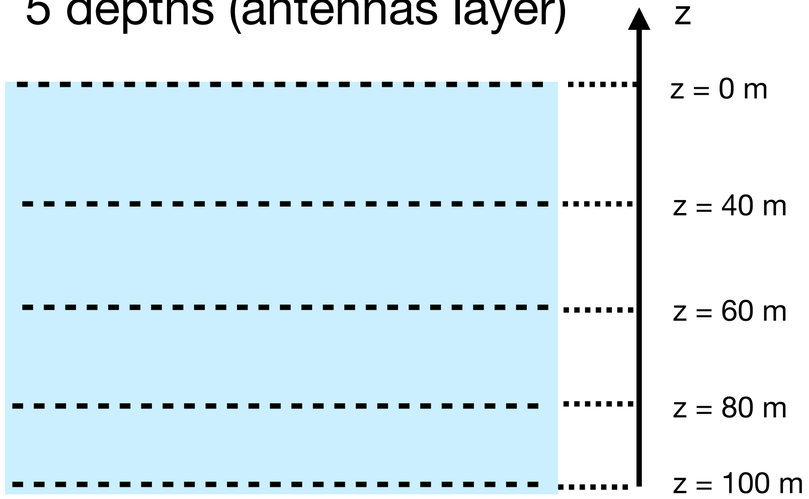
We aim to characterize cosmic-ray radio emission using the Monte-Carlo tool FAERIE

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

Rectangular antennas grid



5 depths (antennas layer)



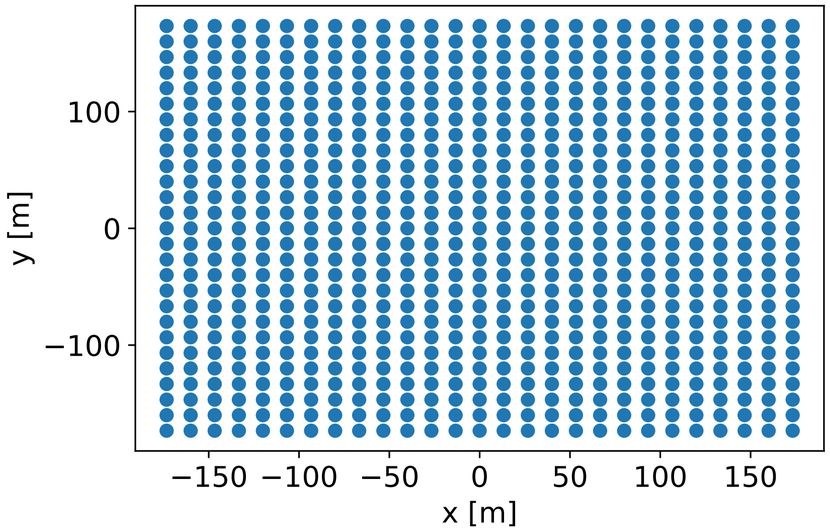
Simulation setup

Simon Chiche
(IIHE)

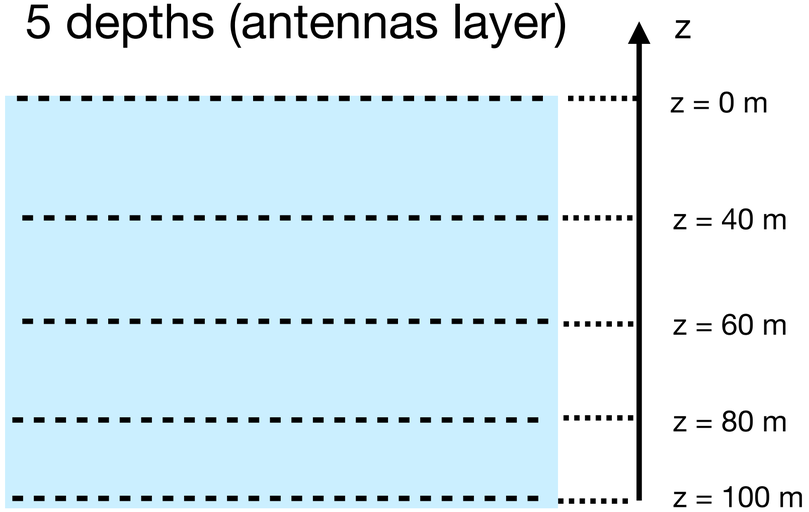
We aim to characterize cosmic-ray radio emission using the Monte-Carlo tool FAERIE

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

Rectangular antennas grid



5 depths (antennas layer)



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

(Deaconu et al., 2018)

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

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

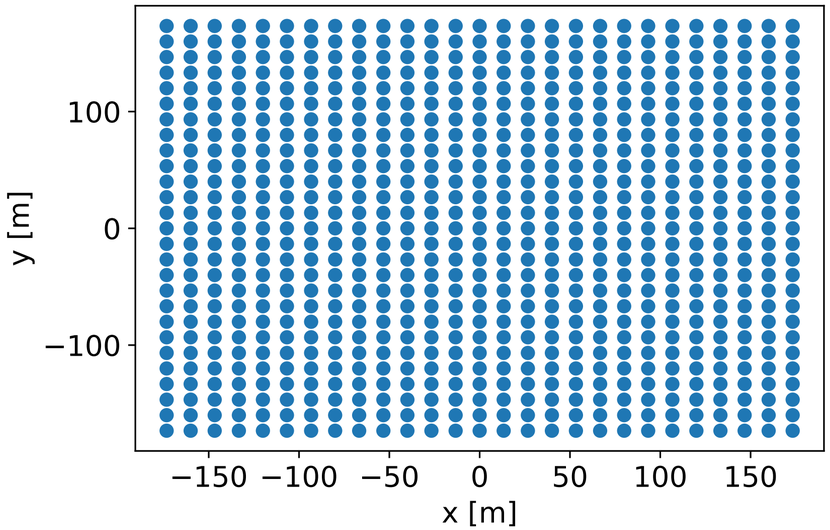
Simulation setup

Simon Chiche
(IIHE)

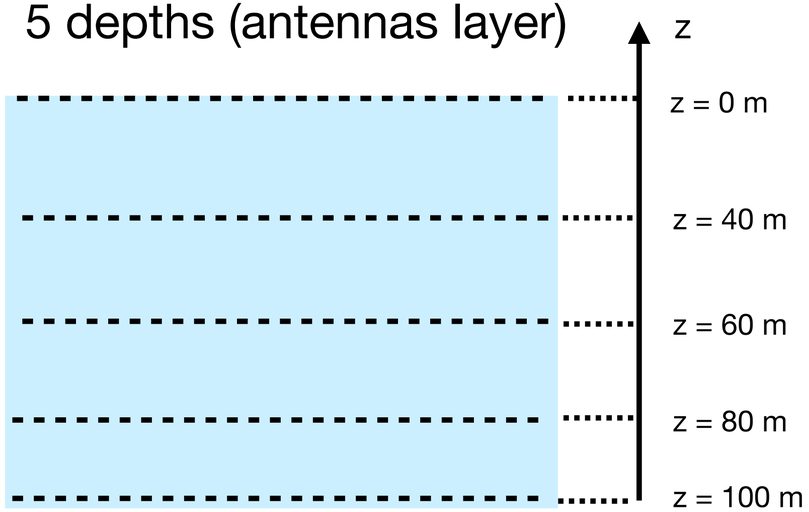
We aim to characterize cosmic-ray radio emission using the Monte-Carlo tool FAERIE

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

Rectangular antennas grid



5 depths (antennas layer)



Ice profile: $n(z) = A - B\exp^{-C|z|}$ (Deaconu et al., 2018)

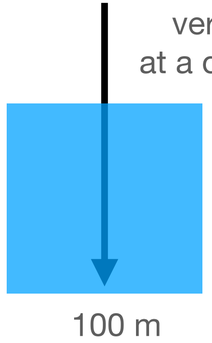
$|z| < 14.9\,\mathrm{m}$ $A = 1.775,\ B = 0.5019,\ C = 0.03247$

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

⟶ **Simulation library to investigate cosmic ray signatures**

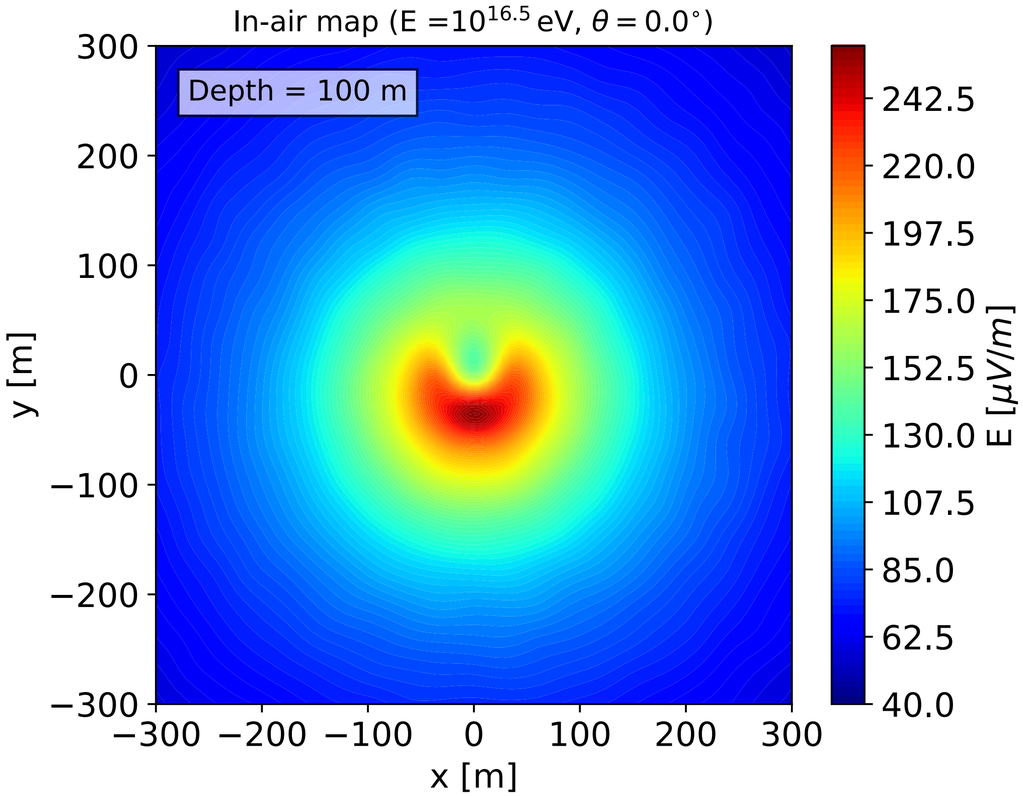
Proton primaries; $\mathrm{E} = [10^{16.5} - 10^{17.5}]\,\mathrm{eV};\ \theta = [0^\circ - 50^\circ];\ \varphi = 0^\circ;\ \mathbf{B} = \mathbf{B}^{\mathrm{summit}}$

Simon Chiche (IIHE)

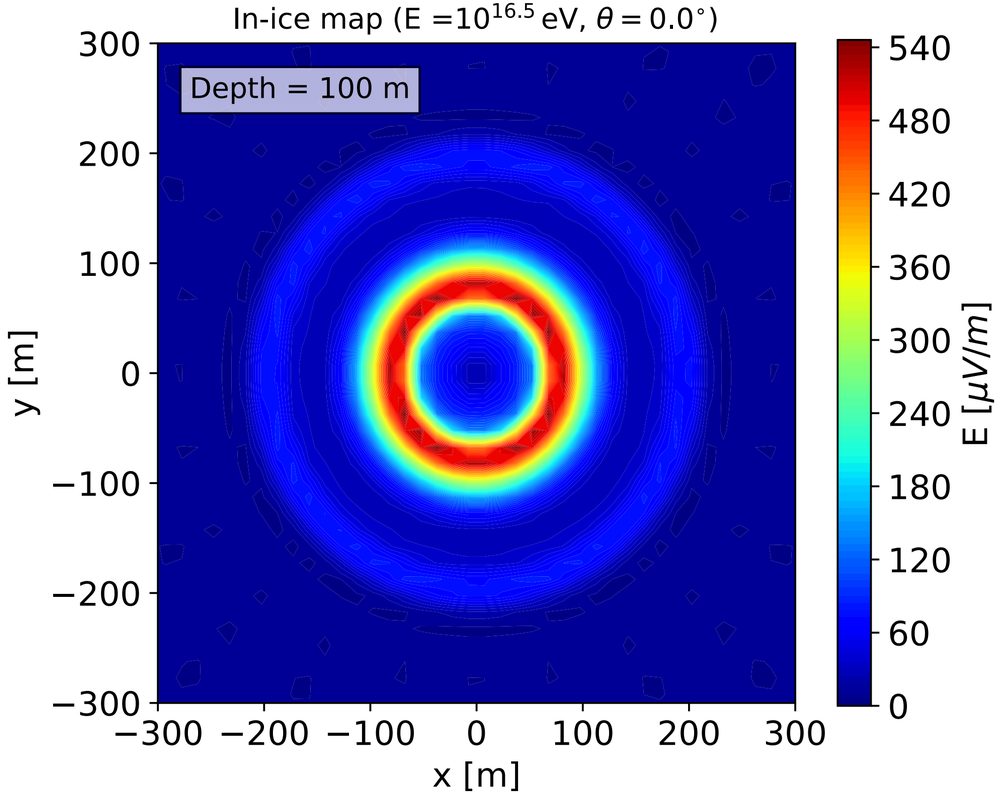


Simulated electric field maps at the antenna level

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

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

Radiation energy
(Glaser et al., 2016)

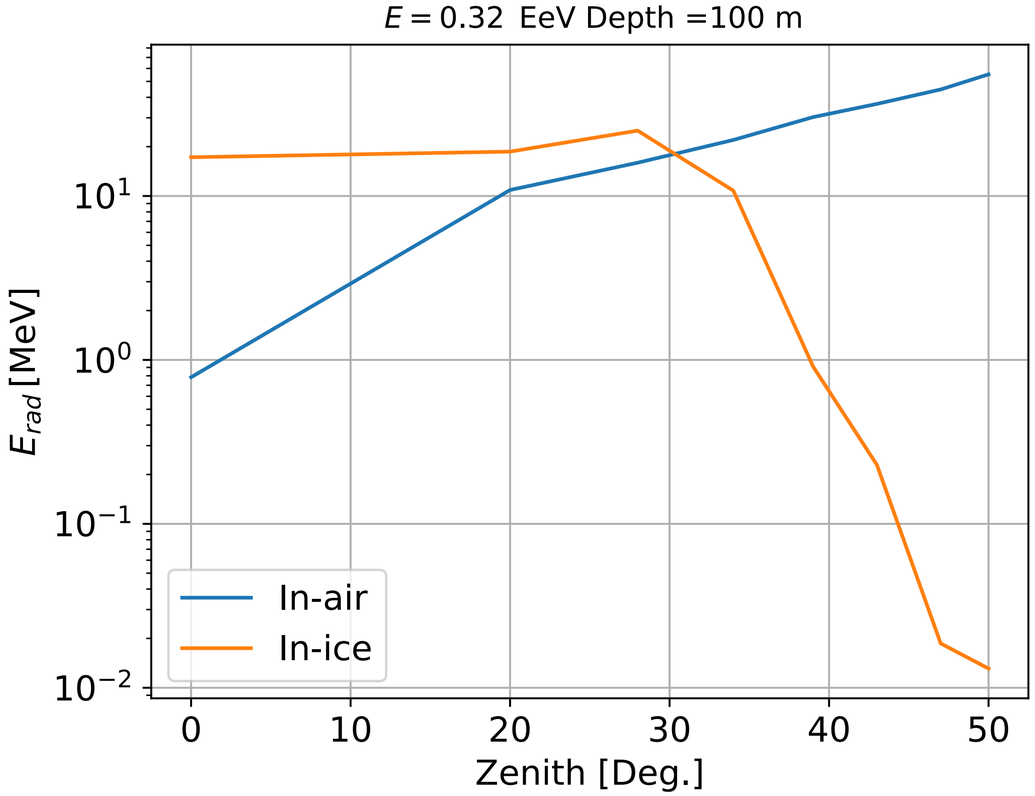
Simon Chiche (IIHE)

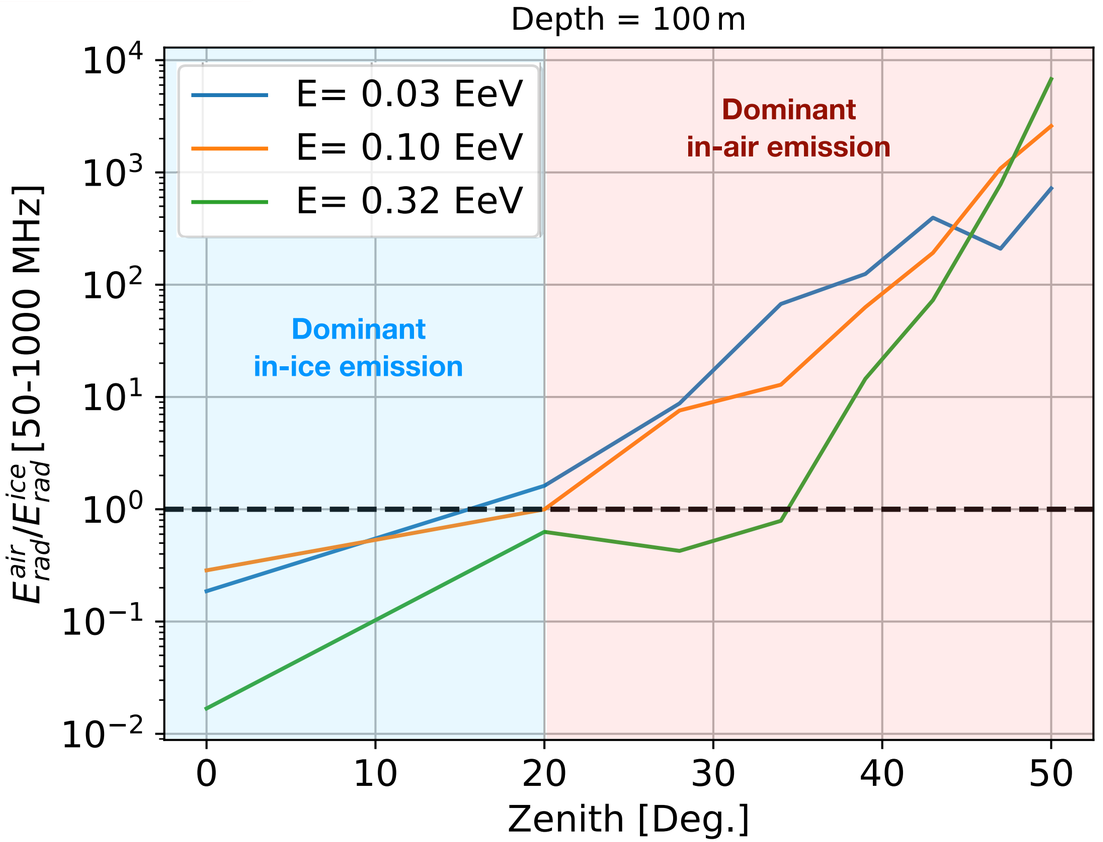
We want to evaluate the relative contribution of the air/ice component

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

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

Radiation energy
(Glaser et al., 2016)





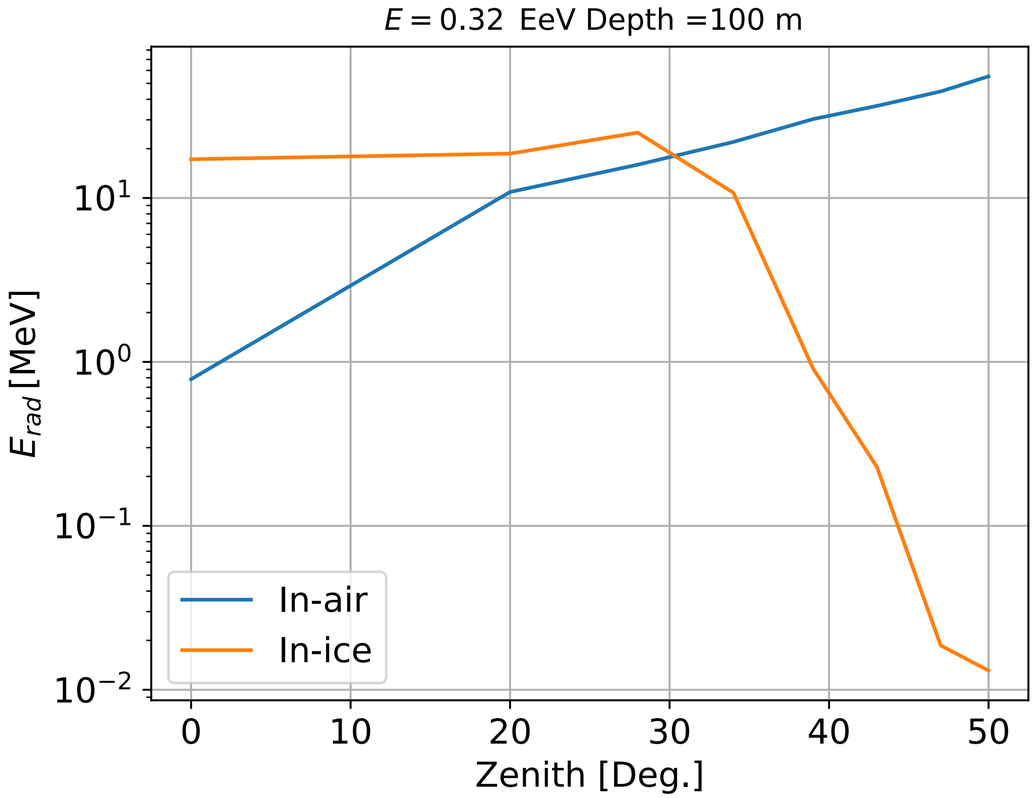
Simon Chiche (IIHE)

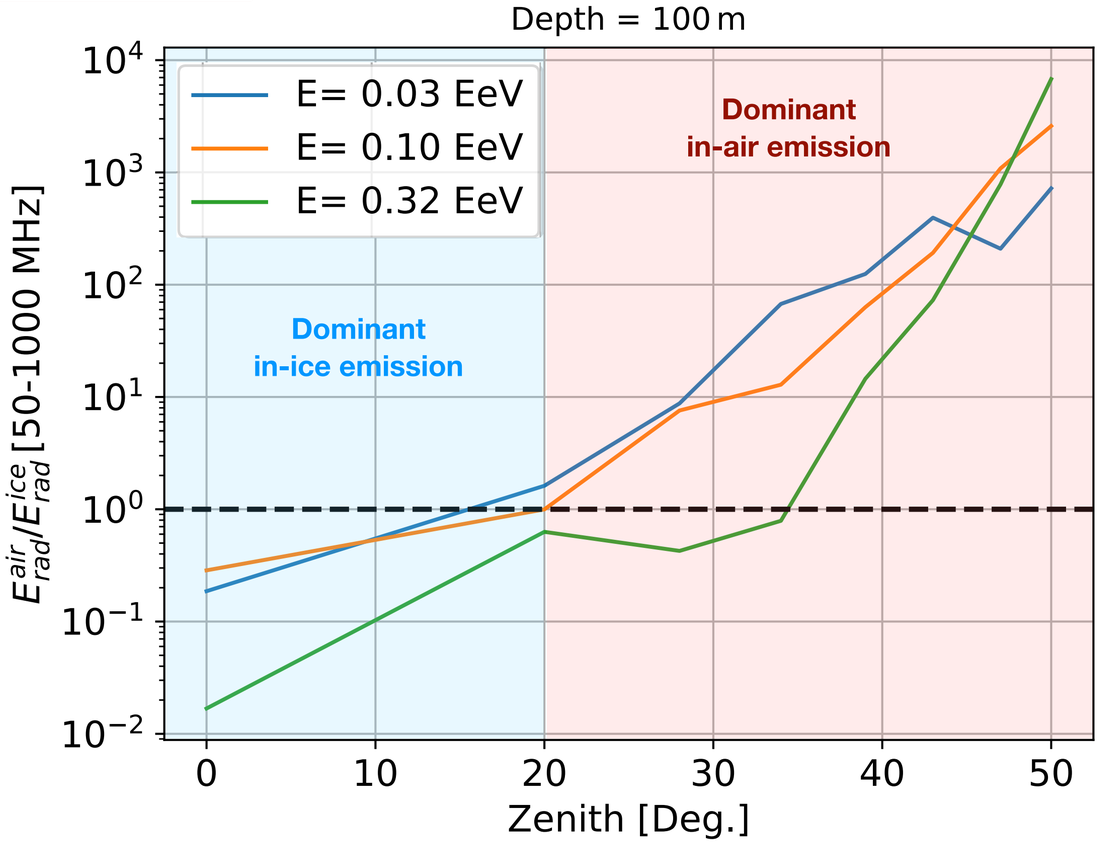
We want to evaluate the relative contribution of the air/ice component

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

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

Radiation energy
(Glaser et al., 2016)





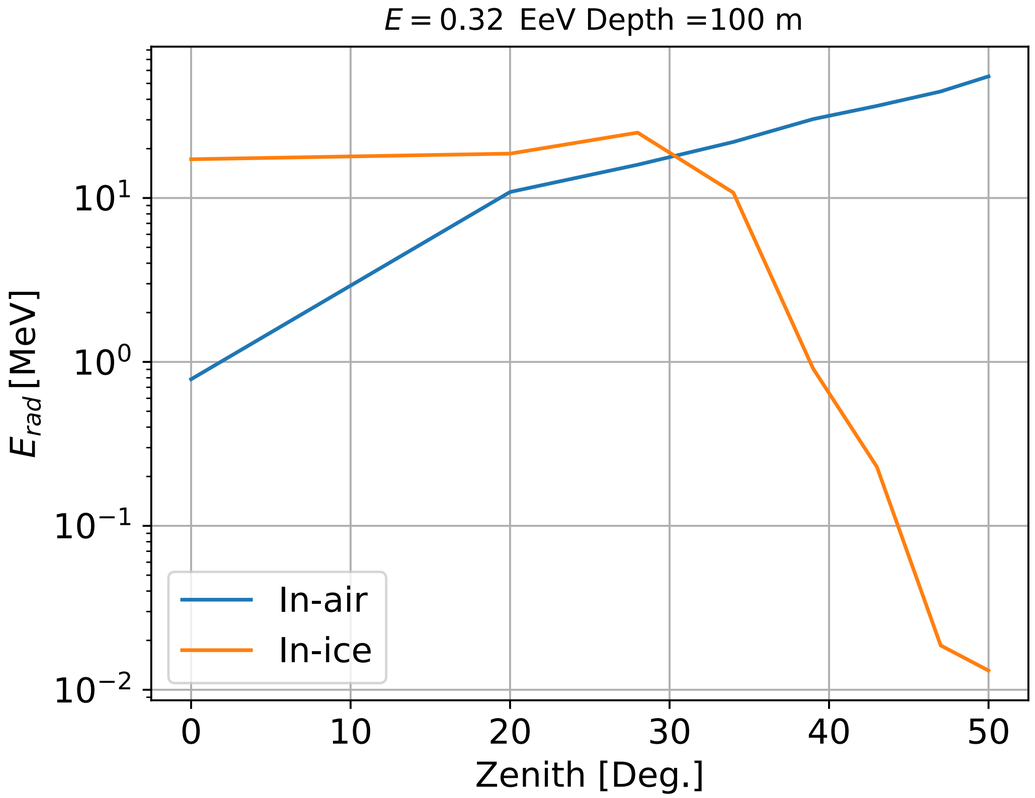
→ Decreasing in-ice contribution with increasing zenith angle

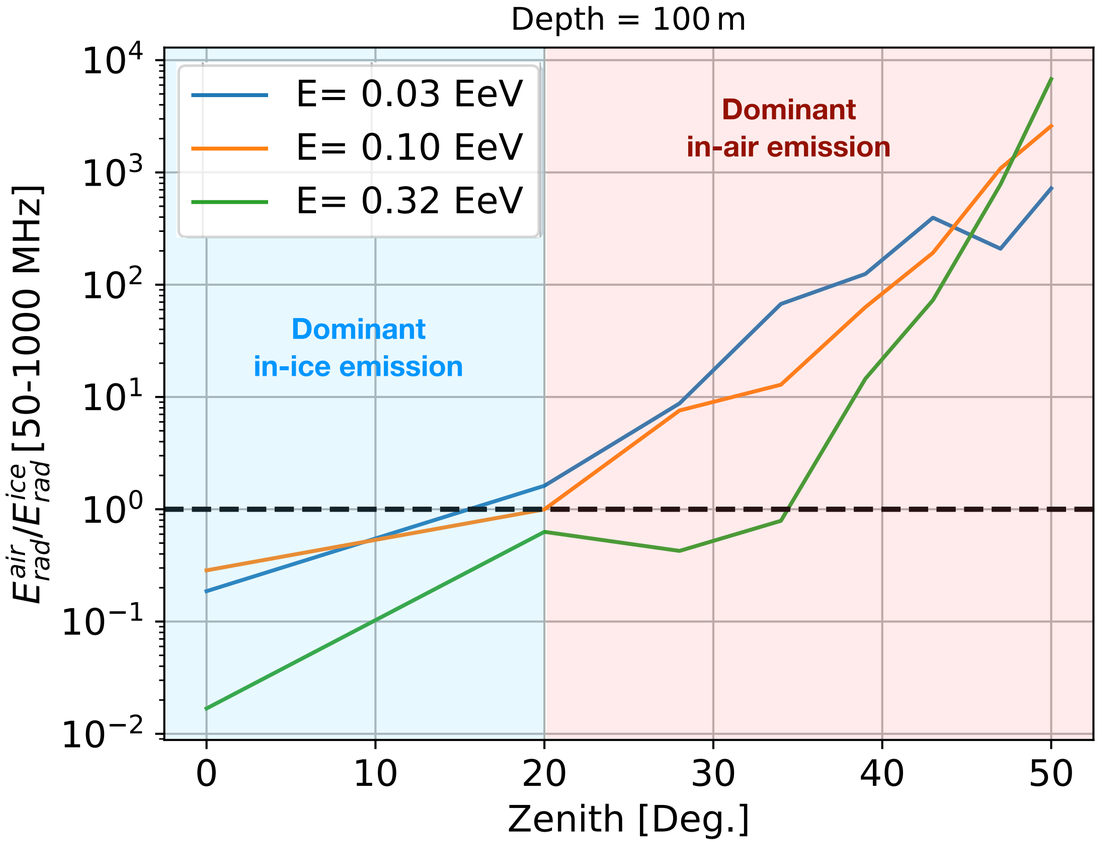
We want to evaluate the relative contribution of the air/ice component

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

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

Radiation energy
(Glaser et al., 2016)





→ Decreasing in-ice contribution with increasing zenith angle

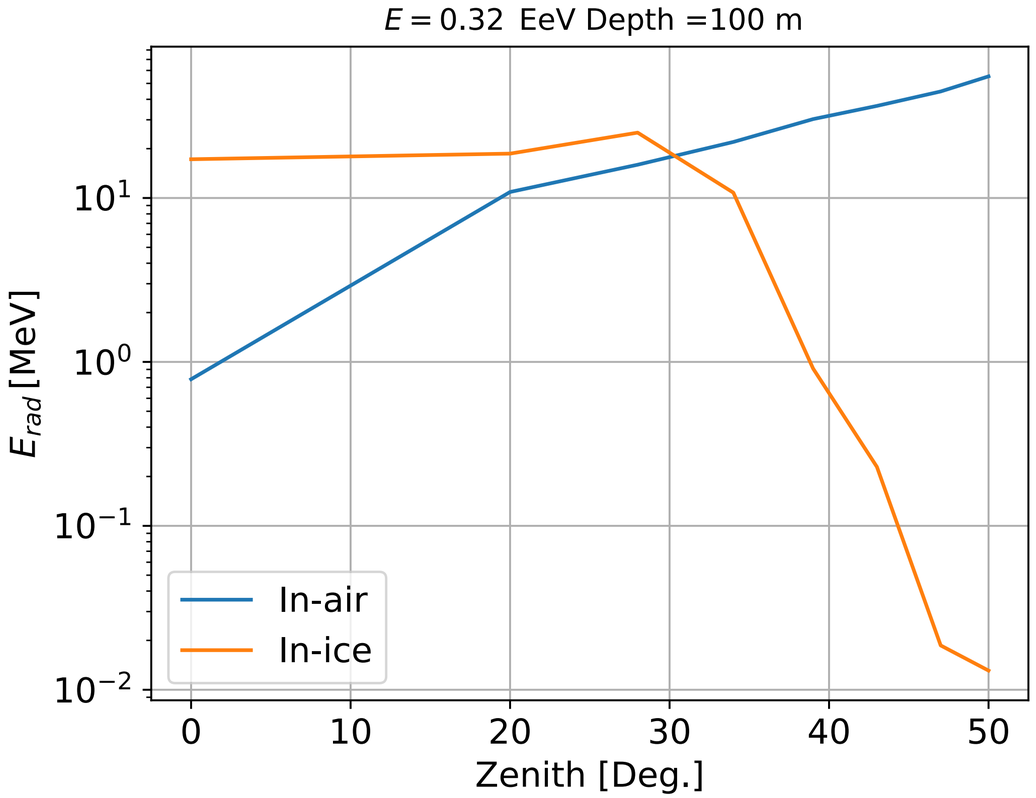
→ Dominant in-air contribution for showers with zenith angle $\theta \gtrsim 20°$

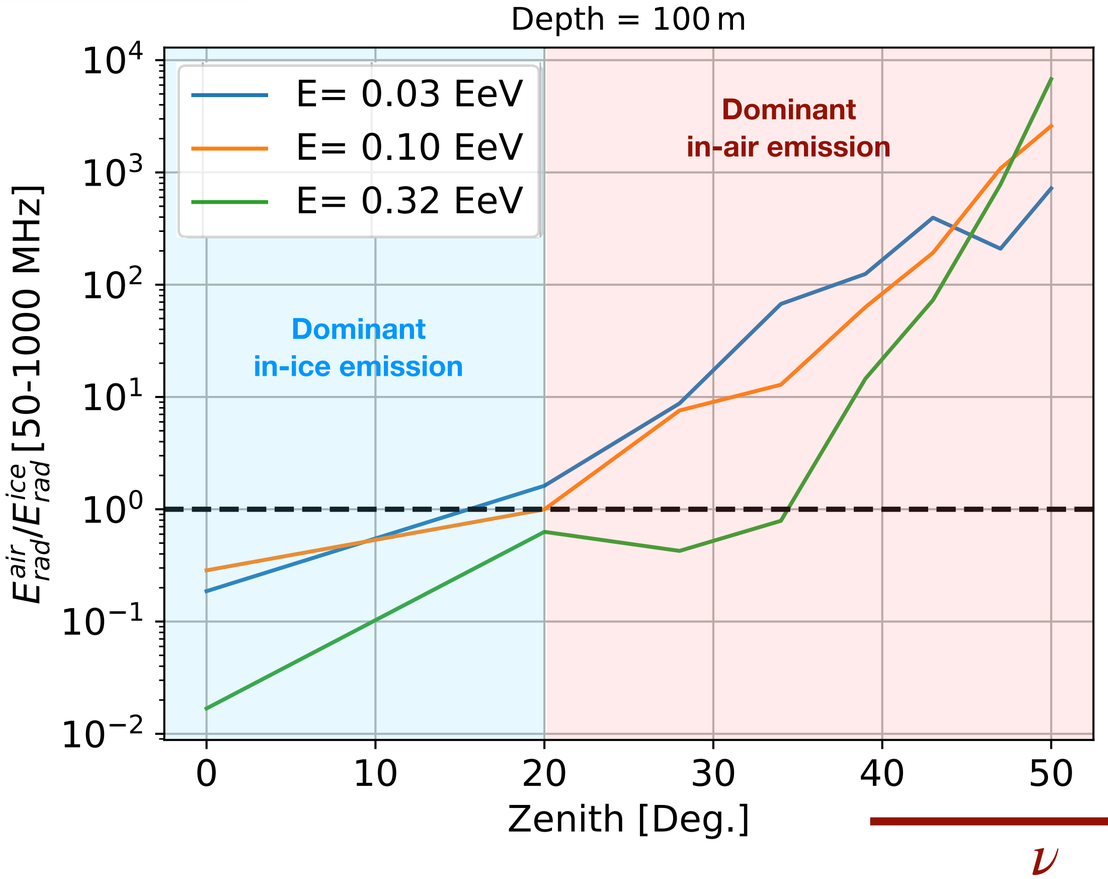
We want to evaluate the relative contribution of the air/ice component

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

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

Radiation energy
(Glaser et al., 2016)



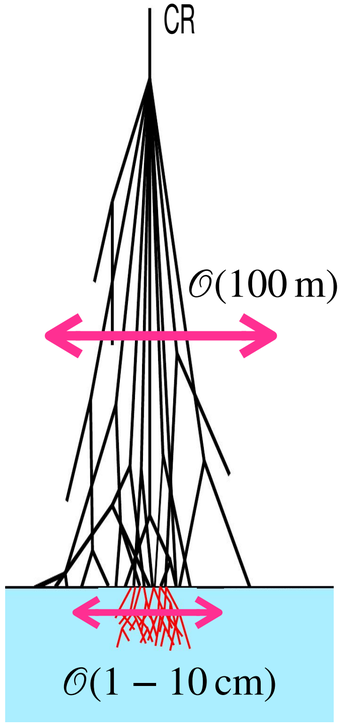


→ Decreasing in-ice contribution with increasing zenith angle

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

Simon Chiche (IIHE)

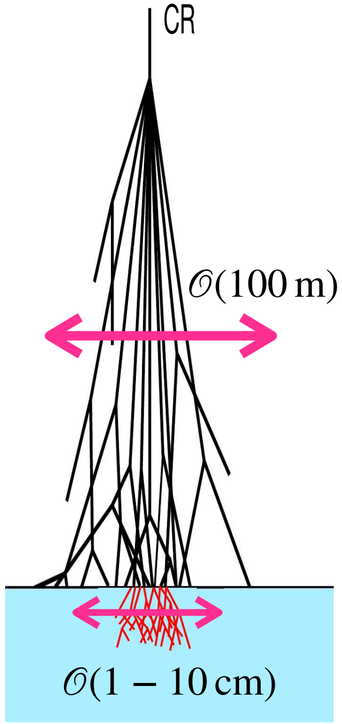
In-ice emission should be more coherent than the in-air component



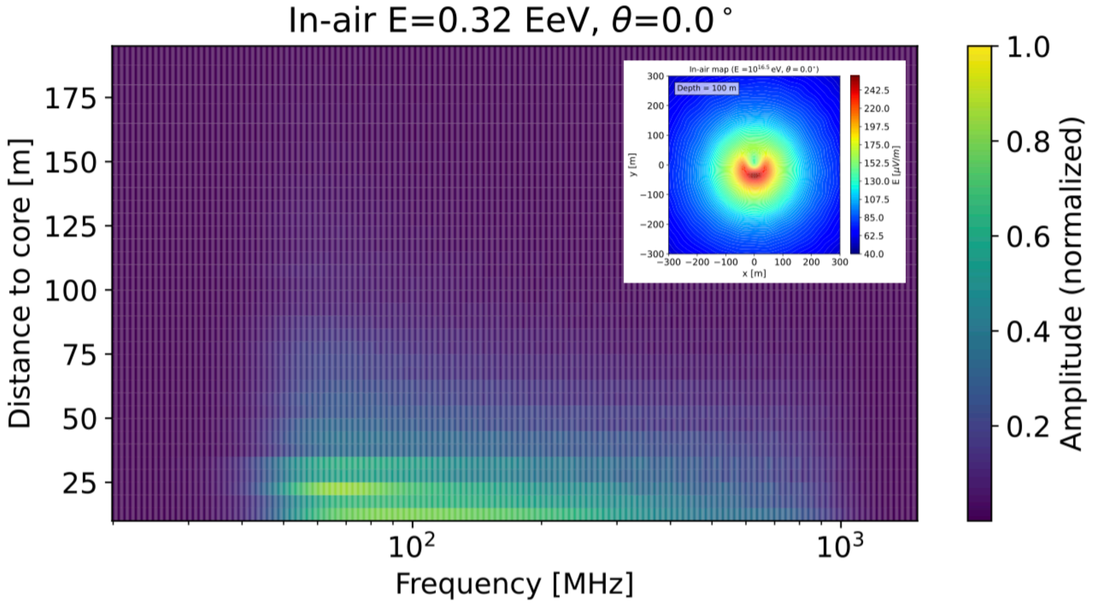
Frequency signatures

Simon Chiche (IIHE)

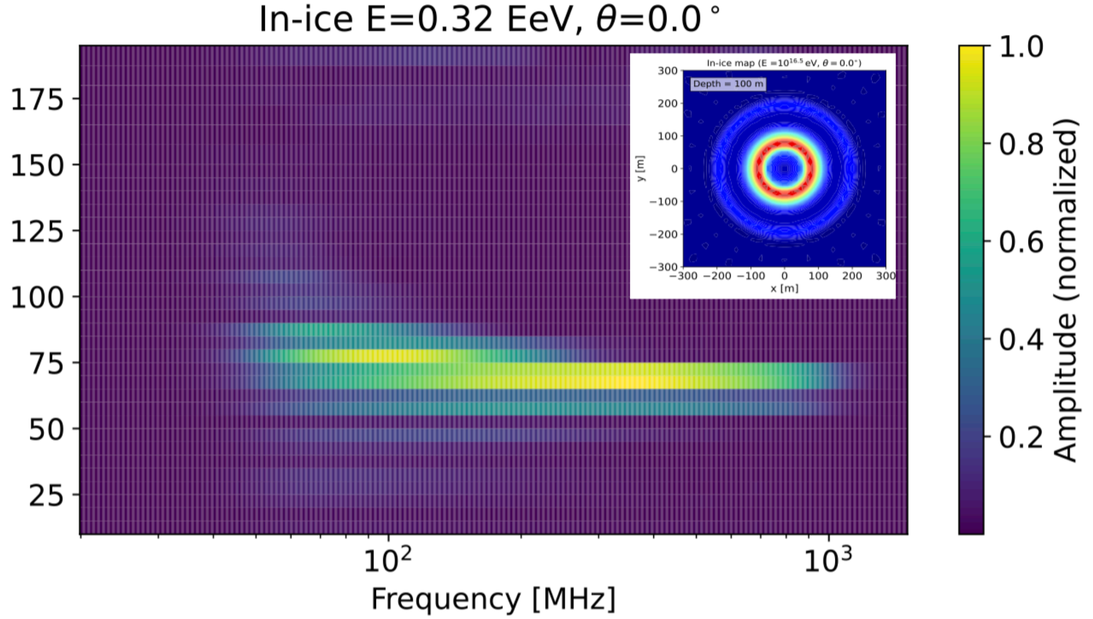
In-ice emission should be more coherent than the in-air component



In-air



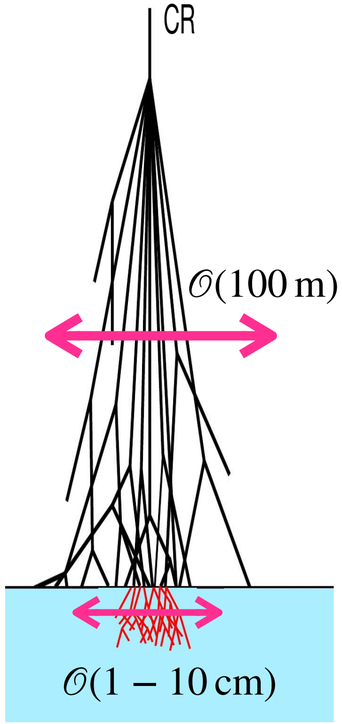
In-ice



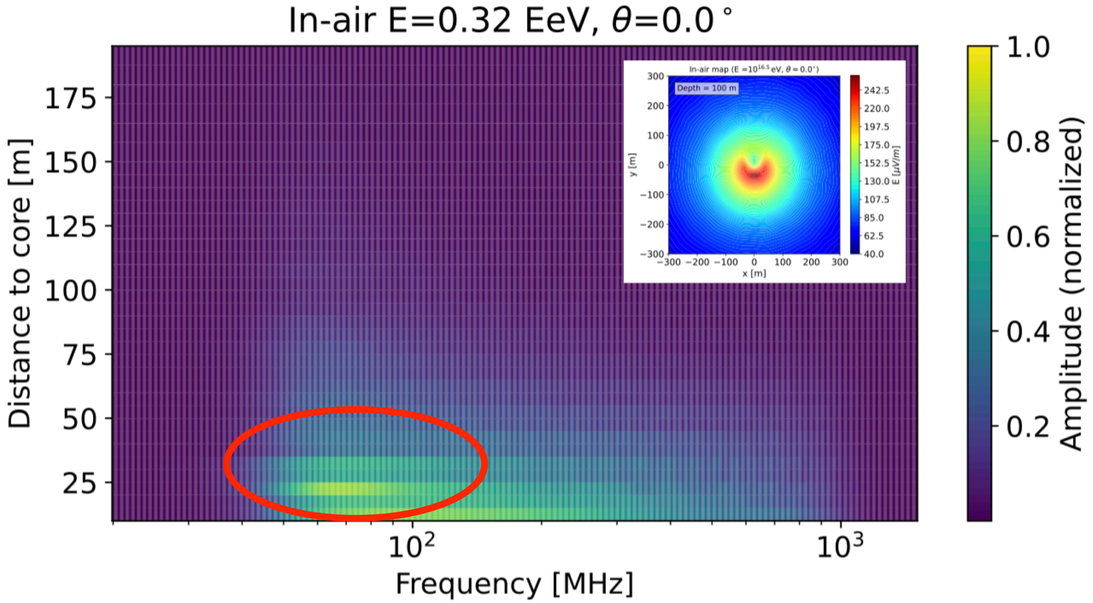
Frequency signatures

Simon Chiche (IIHE)

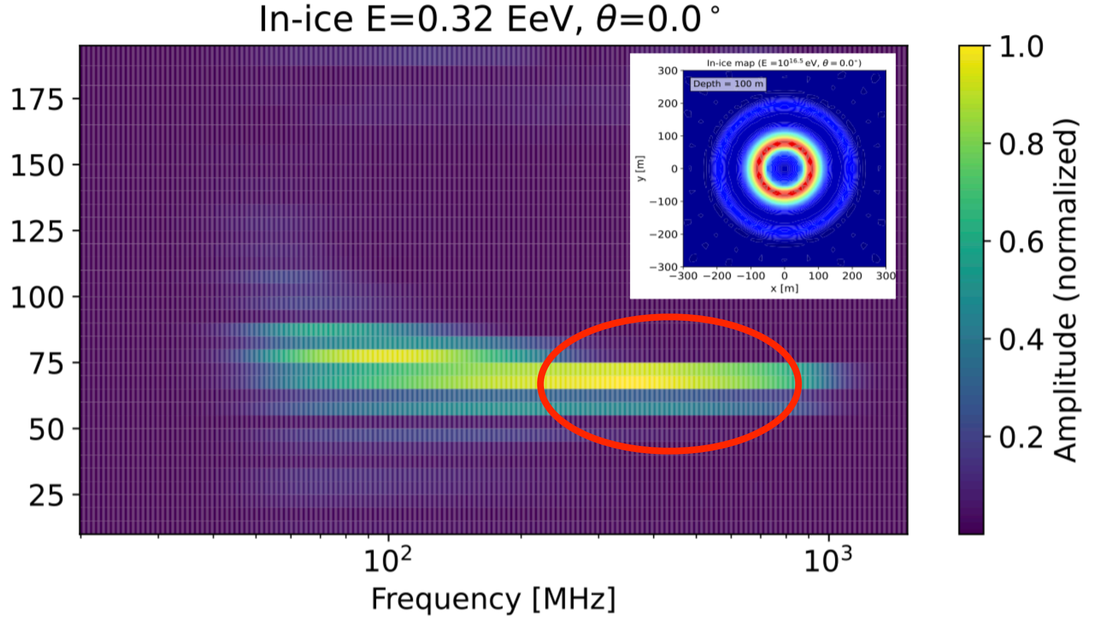
In-ice emission should be more coherent than the in-air component



In-air

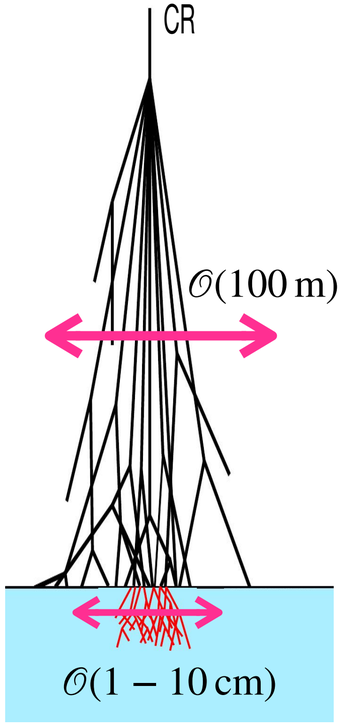


In-ice

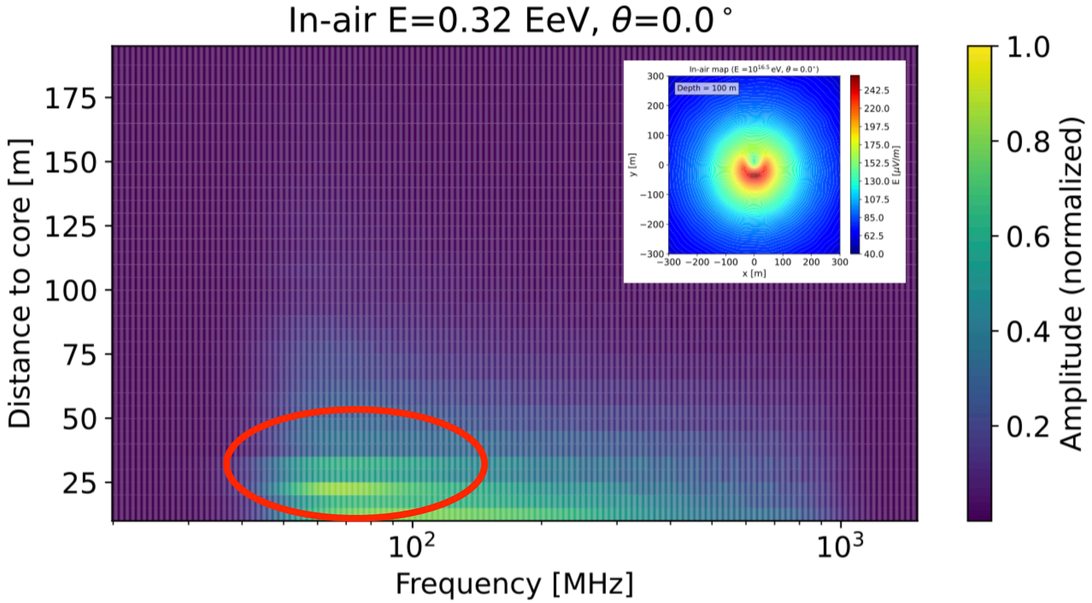


Simon Chiche (IIHE)

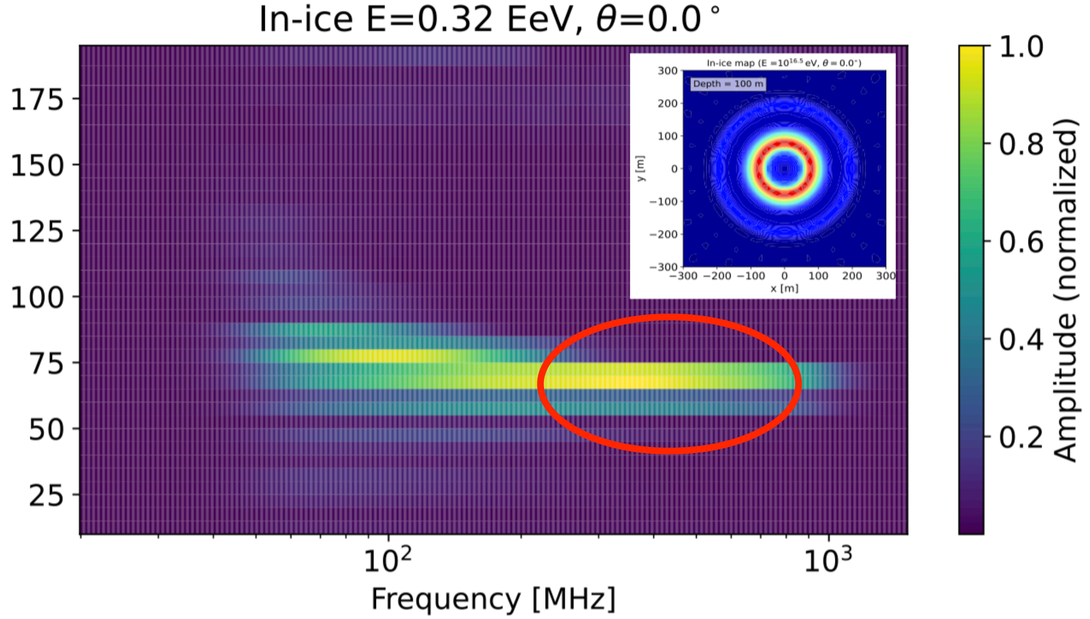
In-ice emission should be more coherent than the in-air component



In-air



In-ice



→ Frequency content can help identify and discriminate each mechanism at the single antenna level

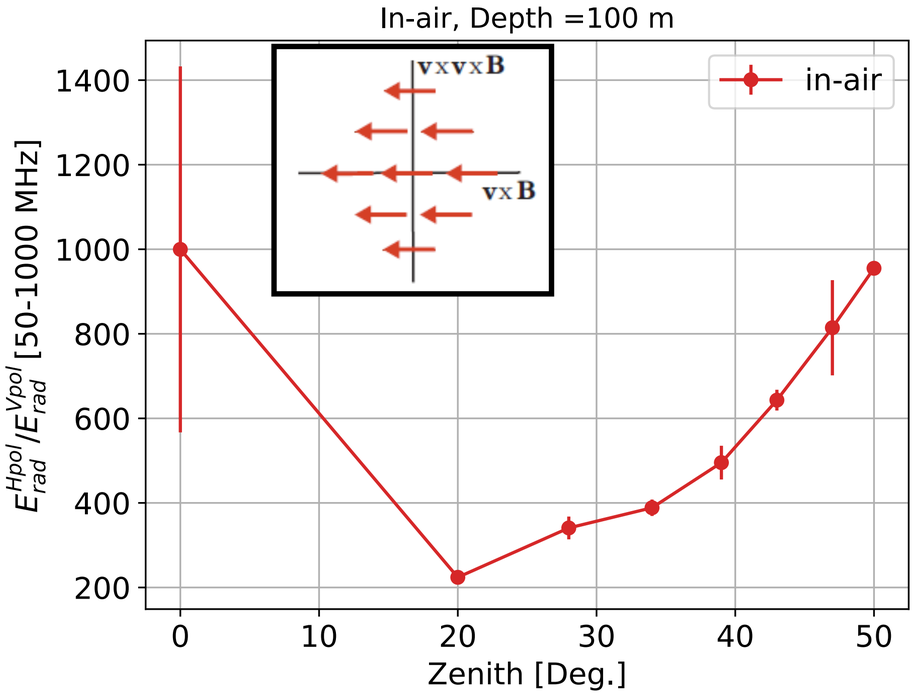
→ Spatial variations of the frequency content bring further constraints on the emission

Simon Chiche (IIHE)

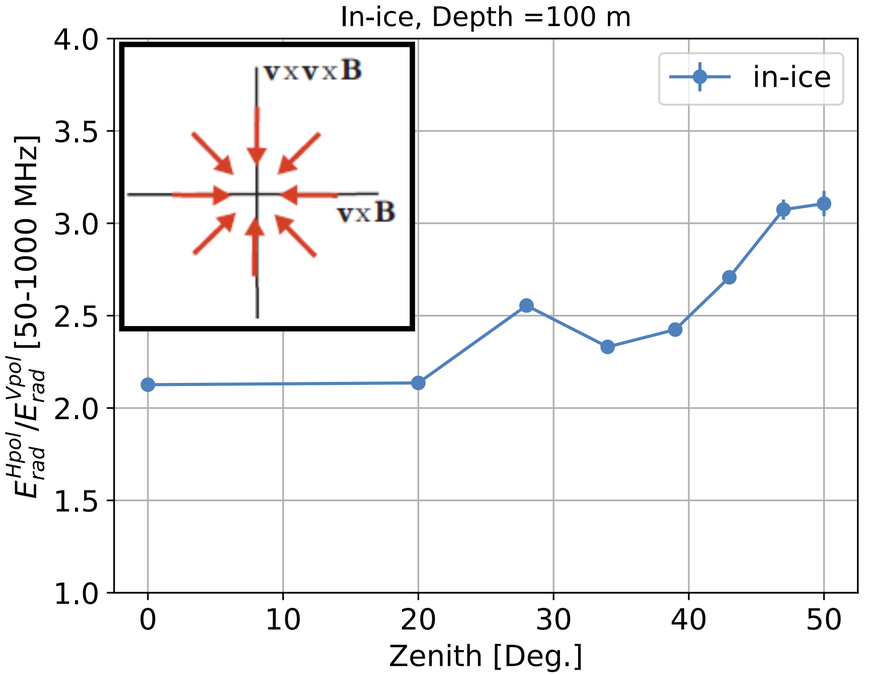
We evaluate the horizontal to vertical polarization ratio for both in-air and in-ice emissions

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

In-air



In-ice

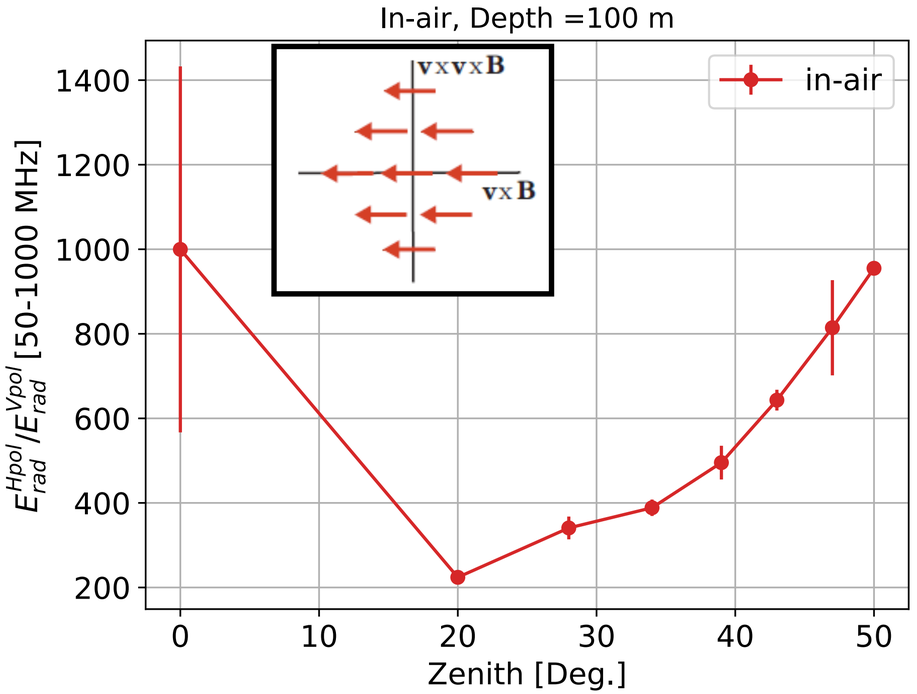


Simon Chiche (IIHE)

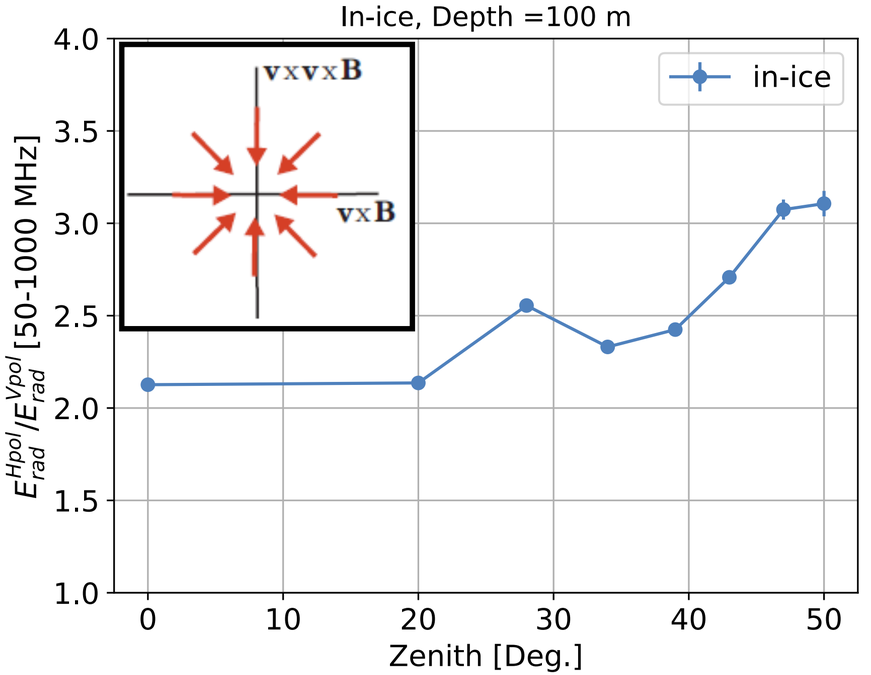
We evaluate the horizontal to vertical polarization ratio for both in-air and in-ice emissions

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

In-air



In-ice

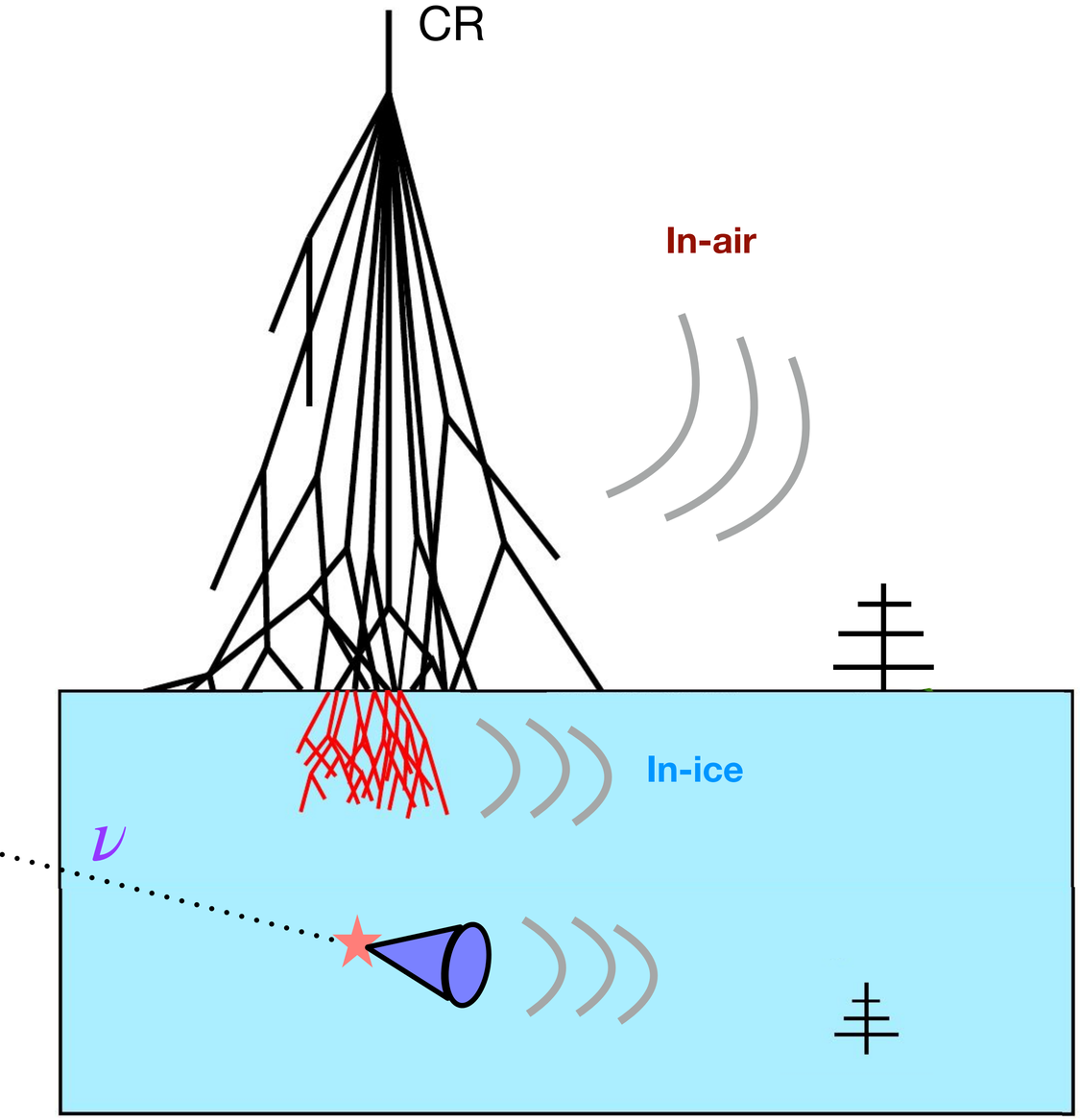


Two orders of magnitude between the in-air and the in-ice component

→ Efficient observable for cosmic ray/neutrino discrimination

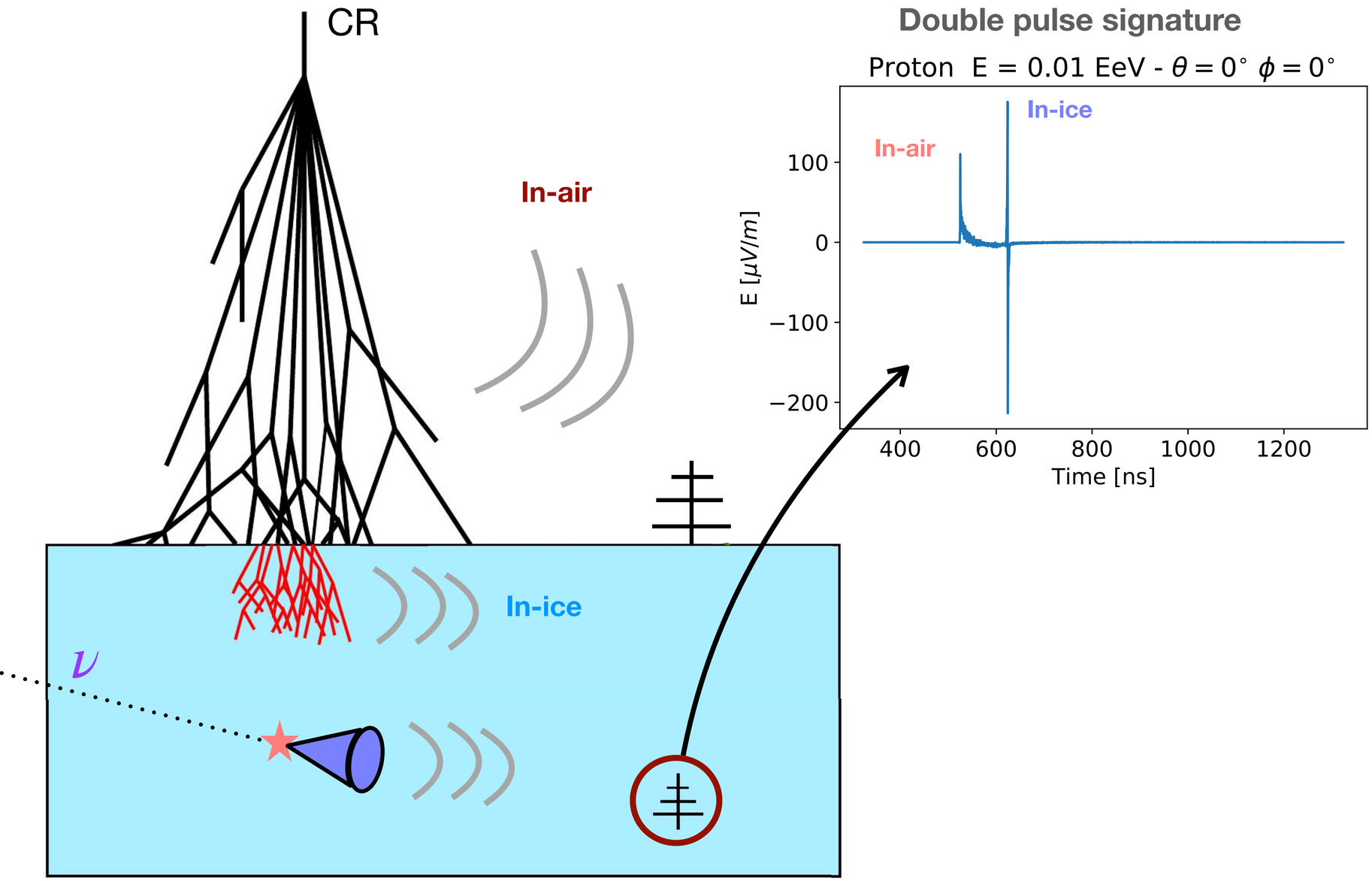
Identifying cosmic rays

Simon Chiche (IIHE)



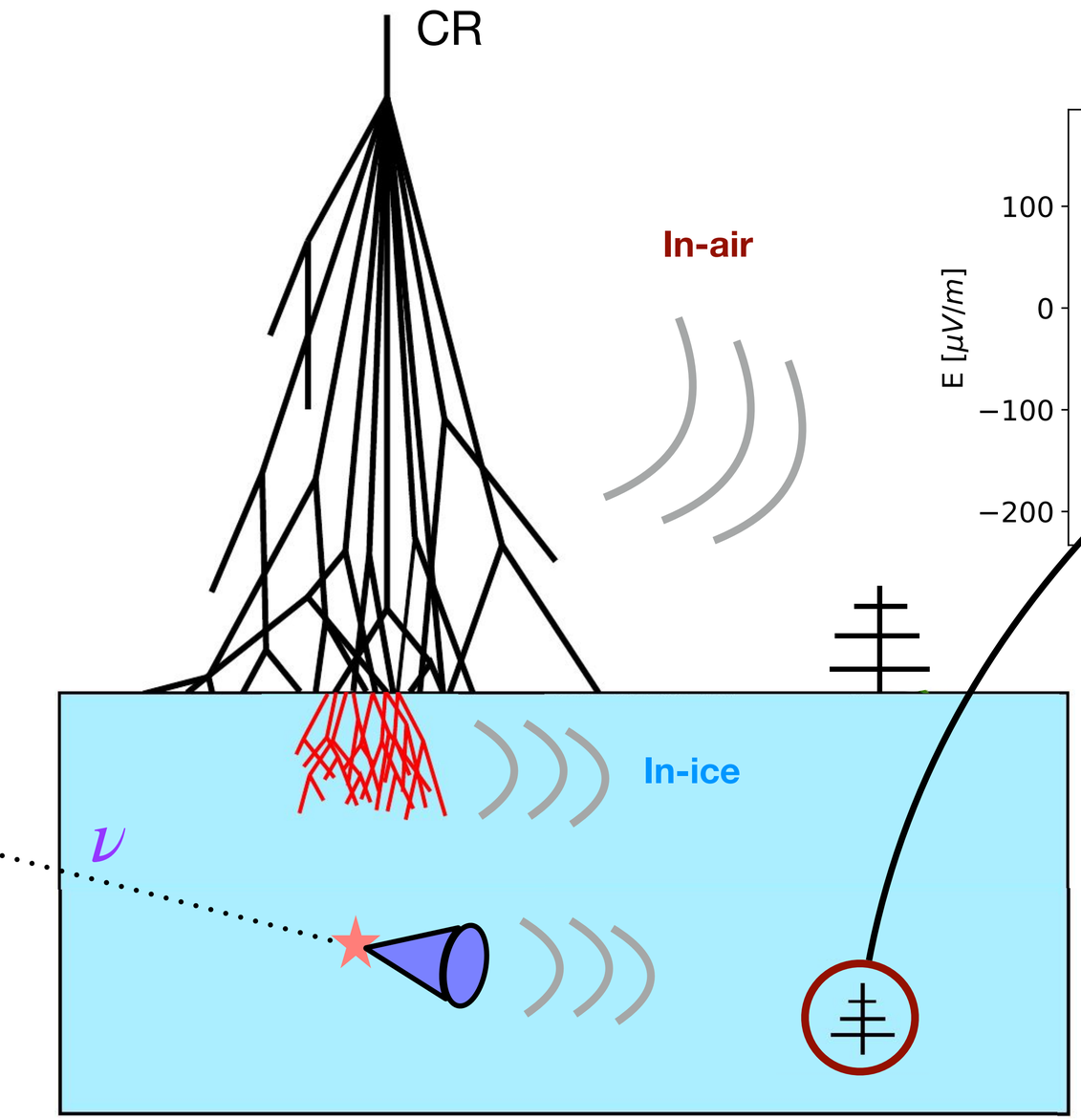
Identifying cosmic rays

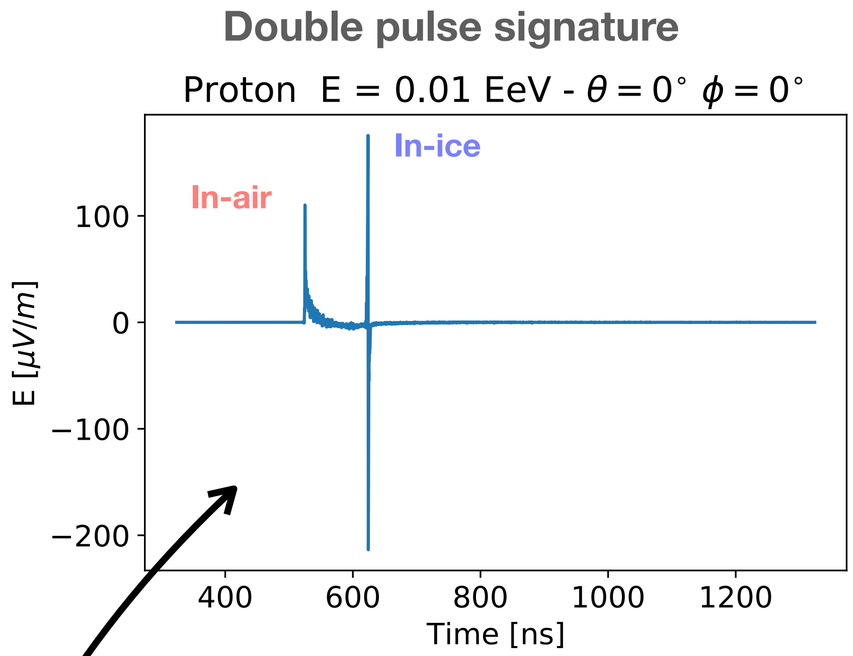
Simon Chiche (IIHE)

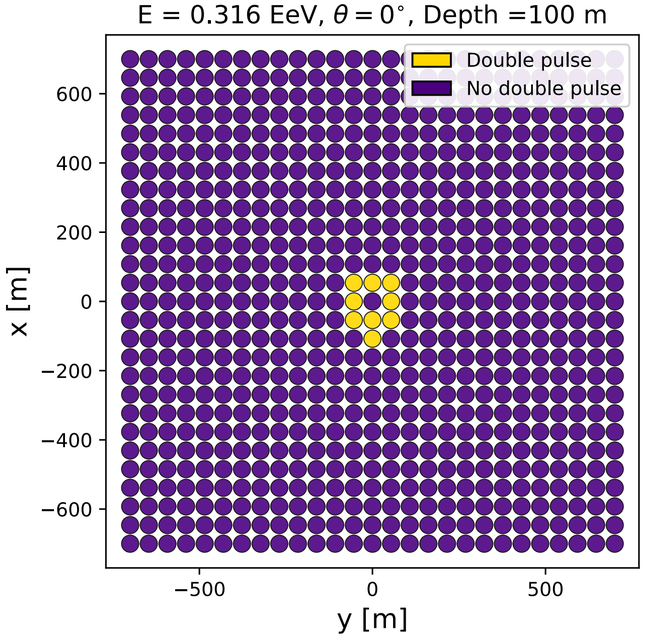


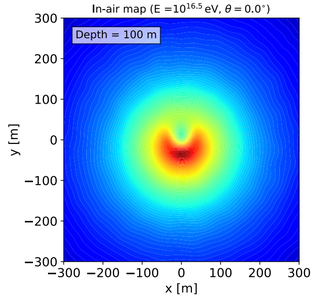
Identifying cosmic rays

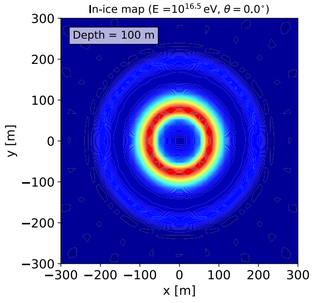
Simon Chiche (IIHE)





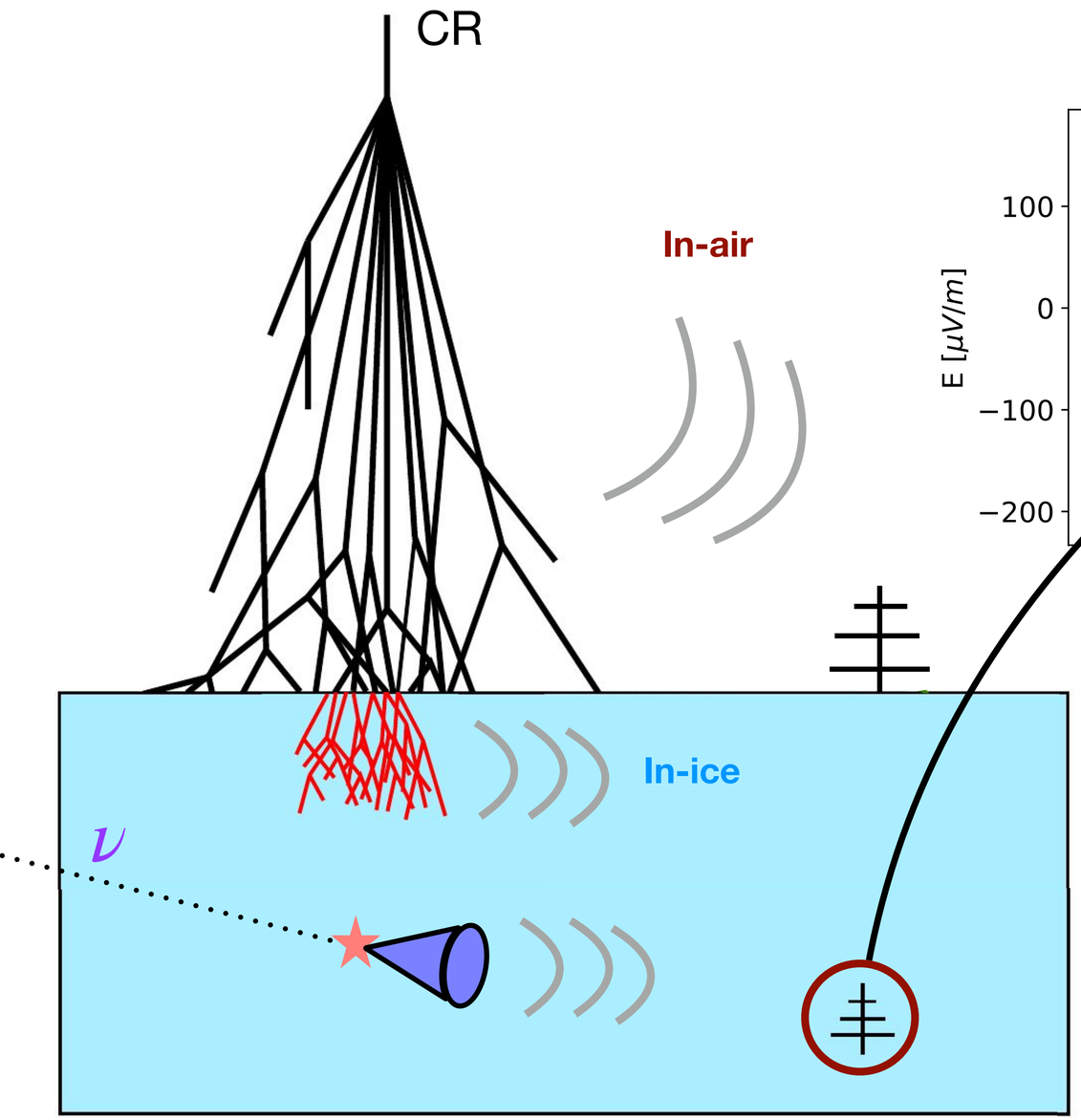


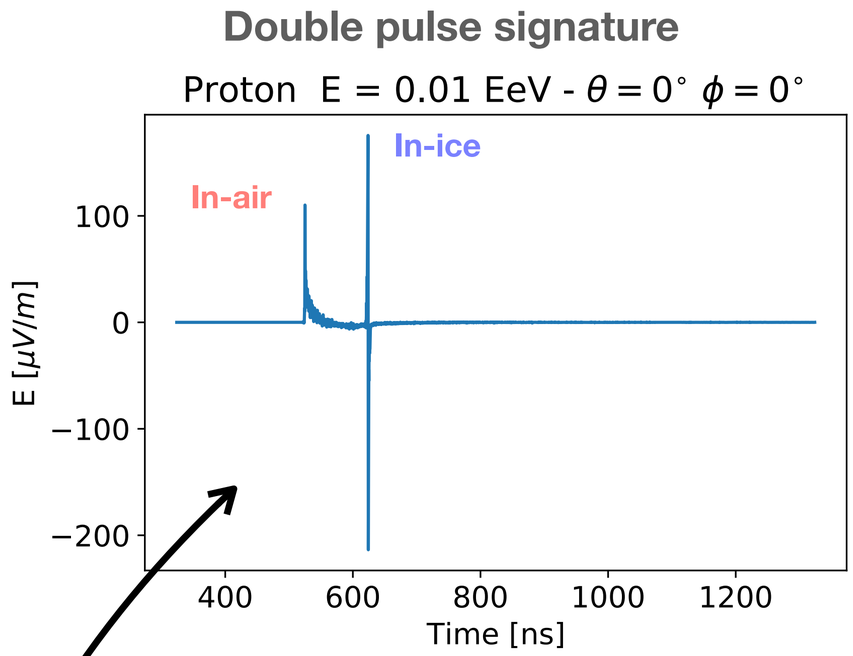


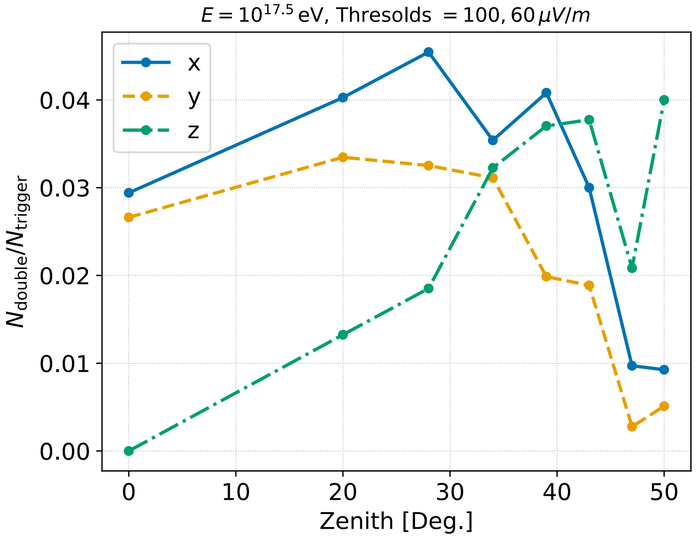


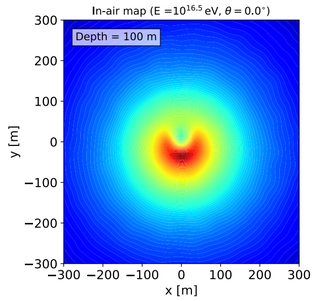
Identifying cosmic rays

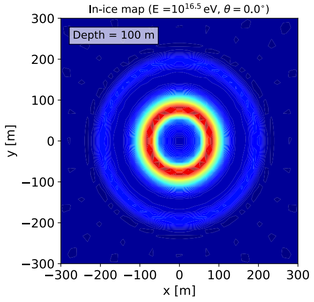
Simon Chiche (IIHE)





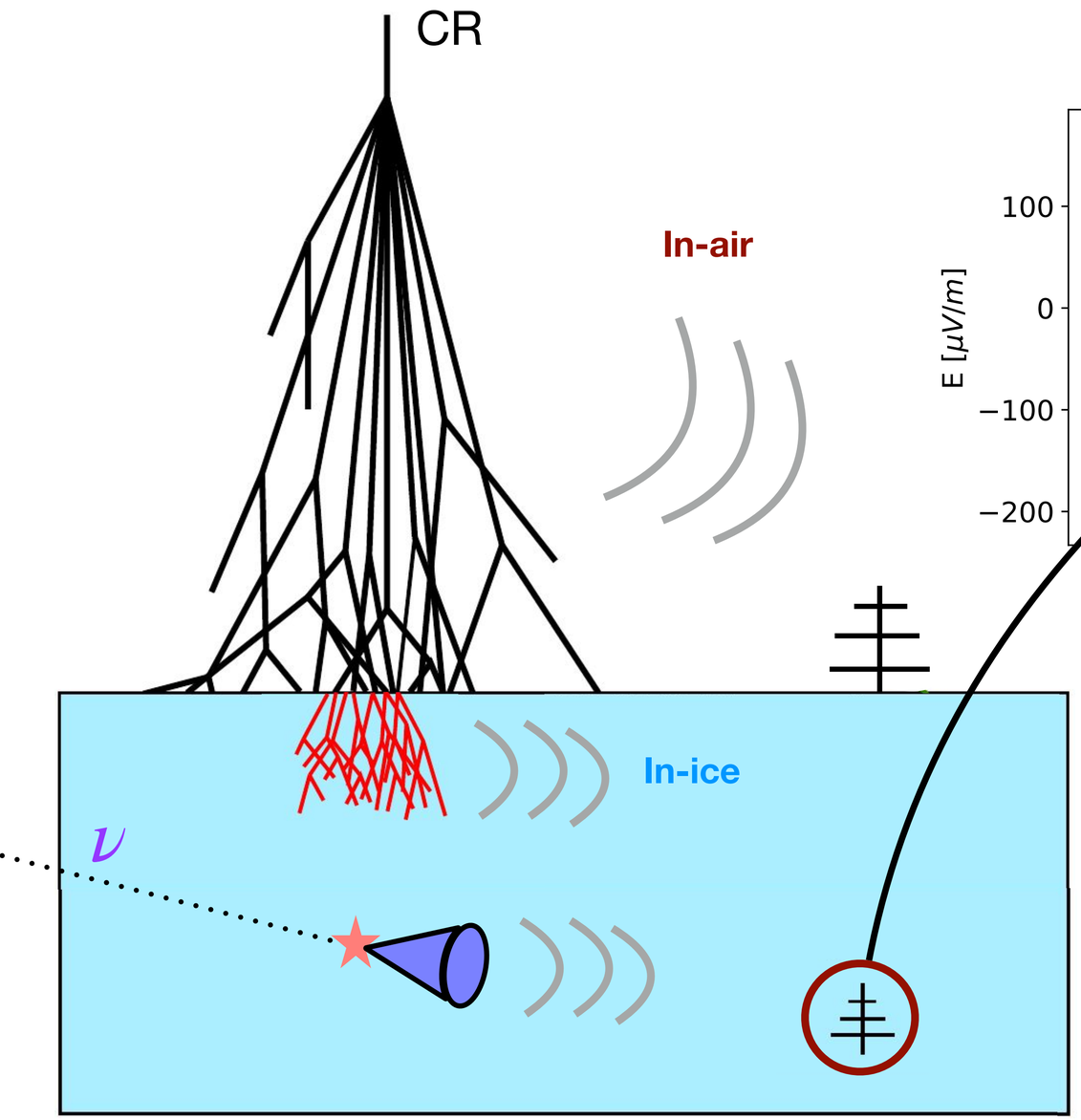




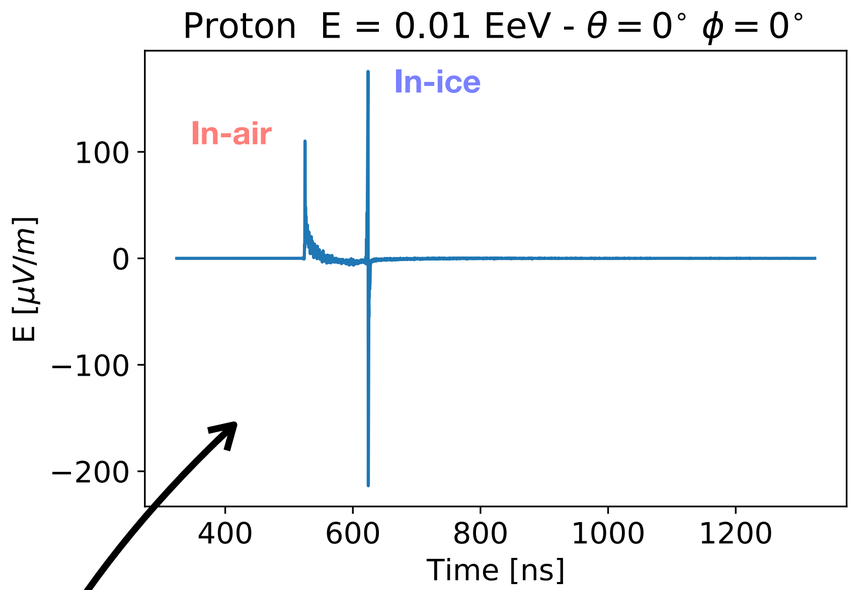


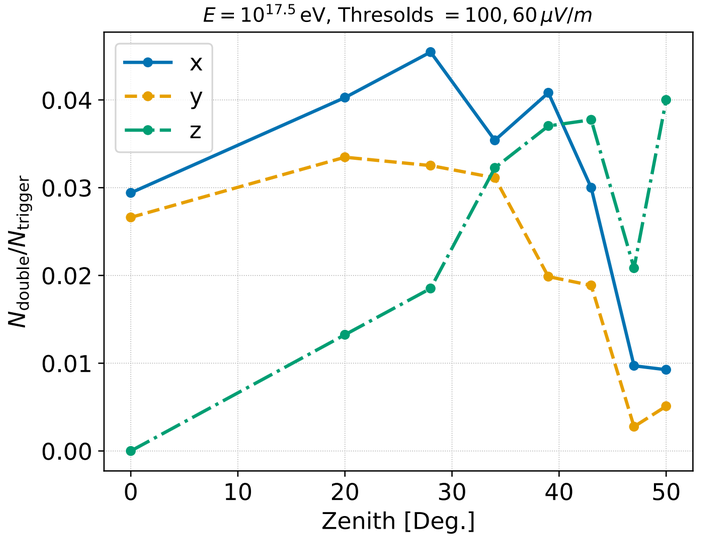
Identifying cosmic rays

Simon Chiche (IIHE)

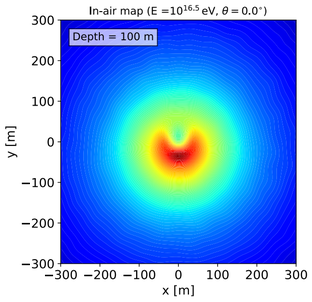


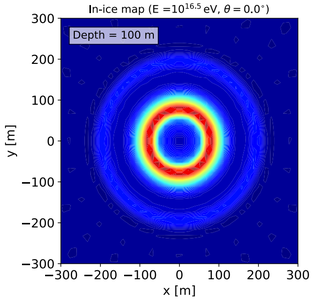
Double pulse signature





In-air	In-ice
• Dominates at large zenith angles	• Dominates at low zenith angles
• linear polarization	• radial polarization
• peaks at low frequencies	• peaks at high frequencies

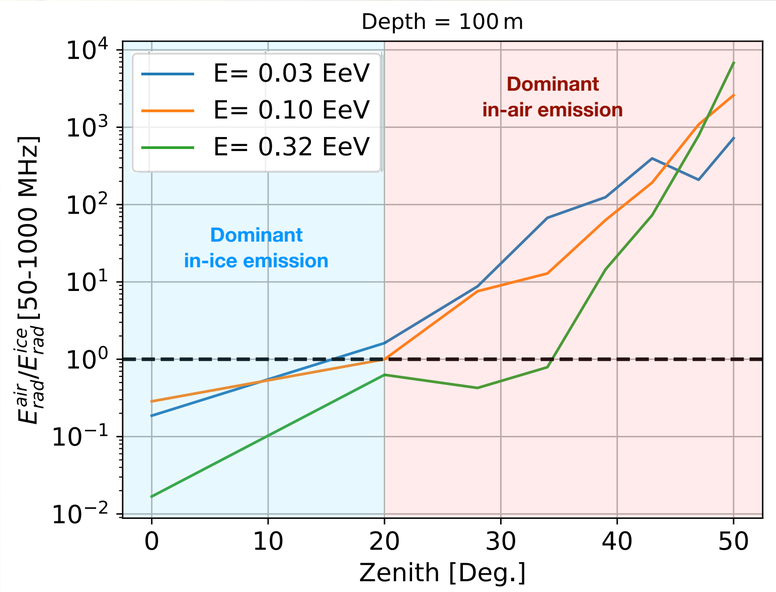




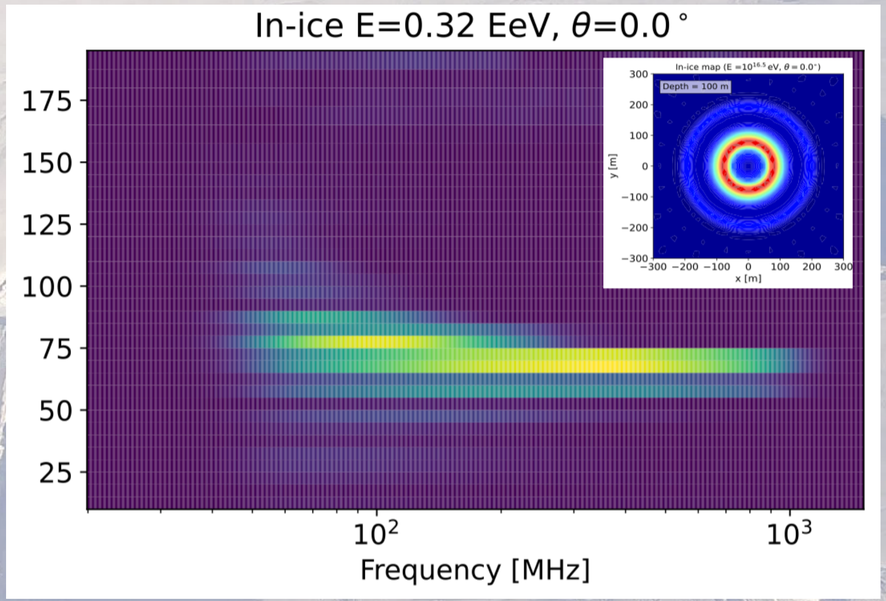
Simon Chiche (IIHE)

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

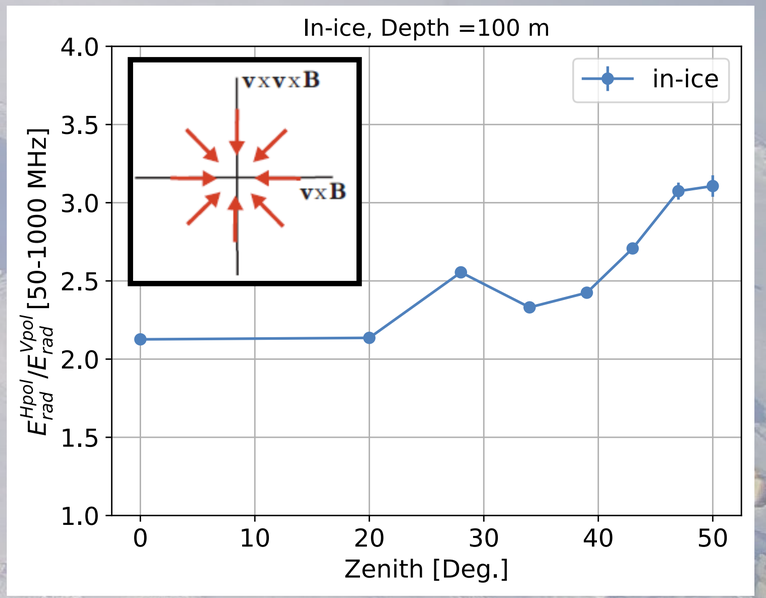
Radiation energy



Frequency content



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