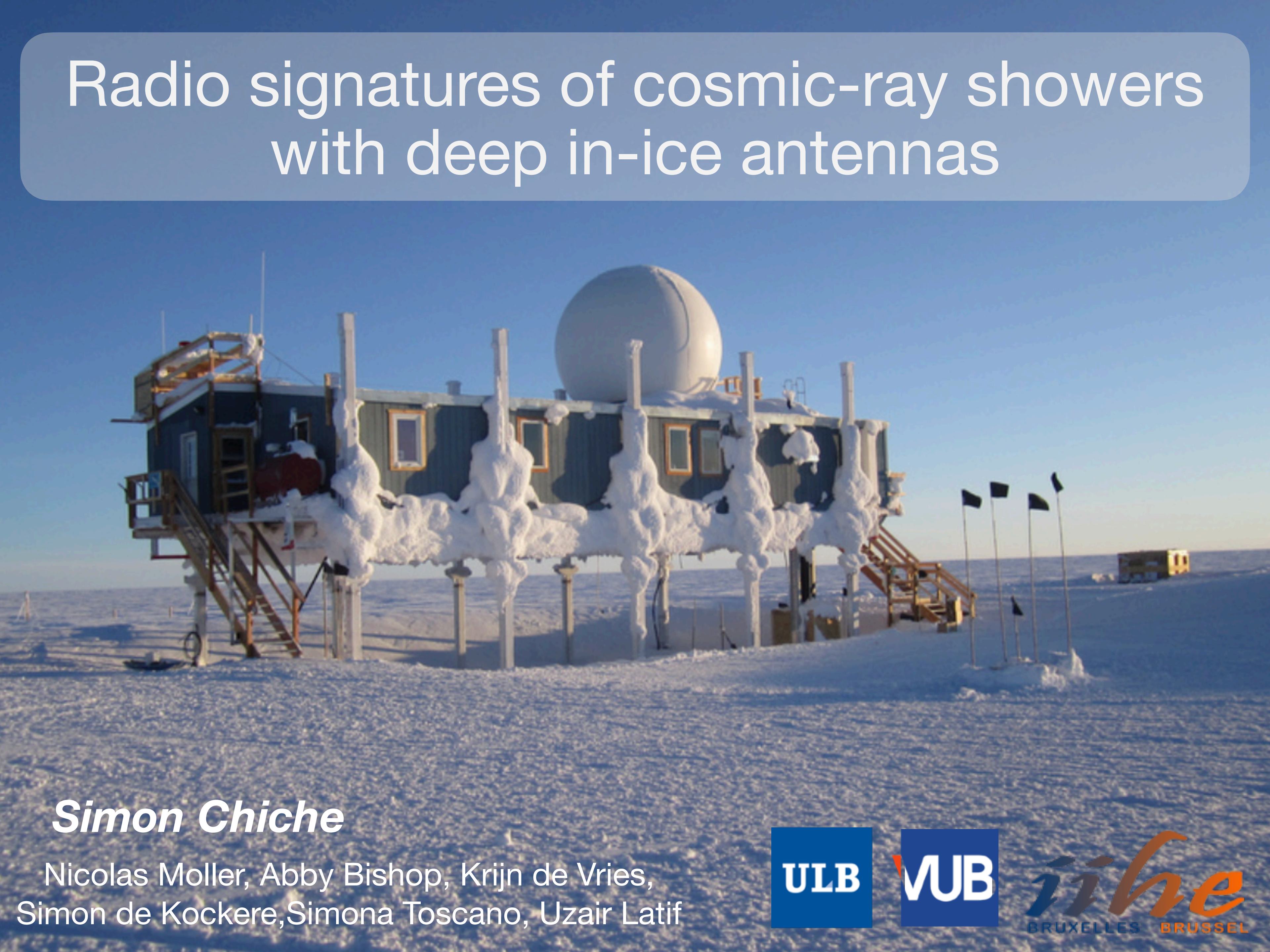
Radio signatures of cosmic-ray showers with deep in-ice antennas



Simon Chiche

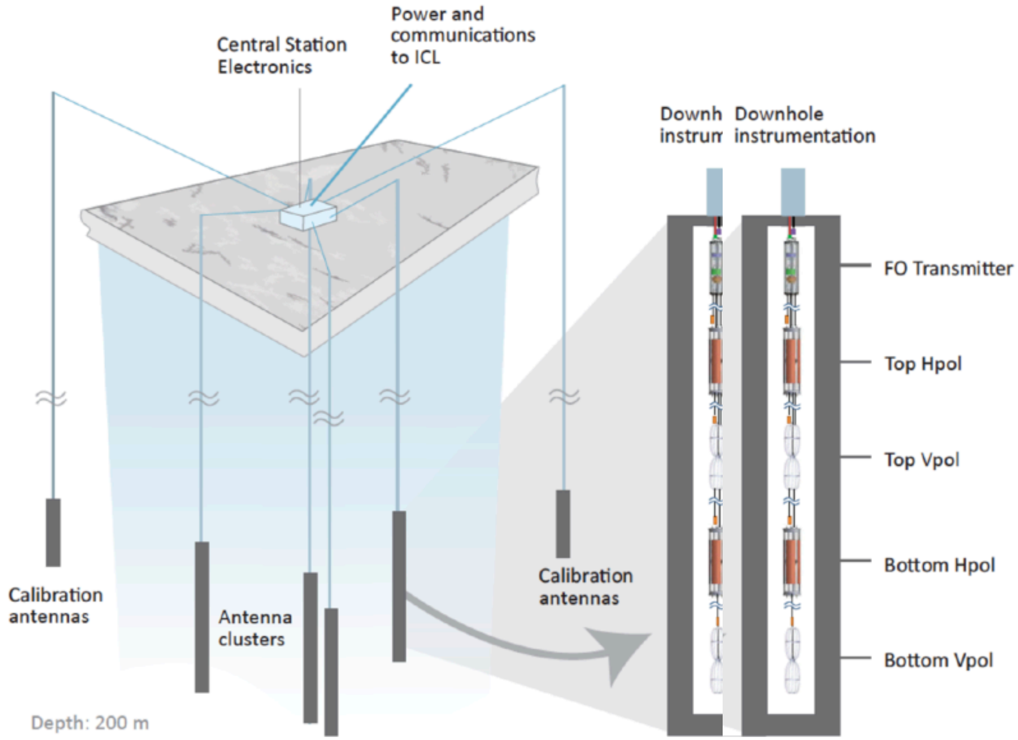
Nicolas Moller, Abby Bishop, Krijn de Vries,
Simon de Kockere,Simona Toscano, Uzair Latif

ULB VUB iihe BRUXELLES BRUSSEL

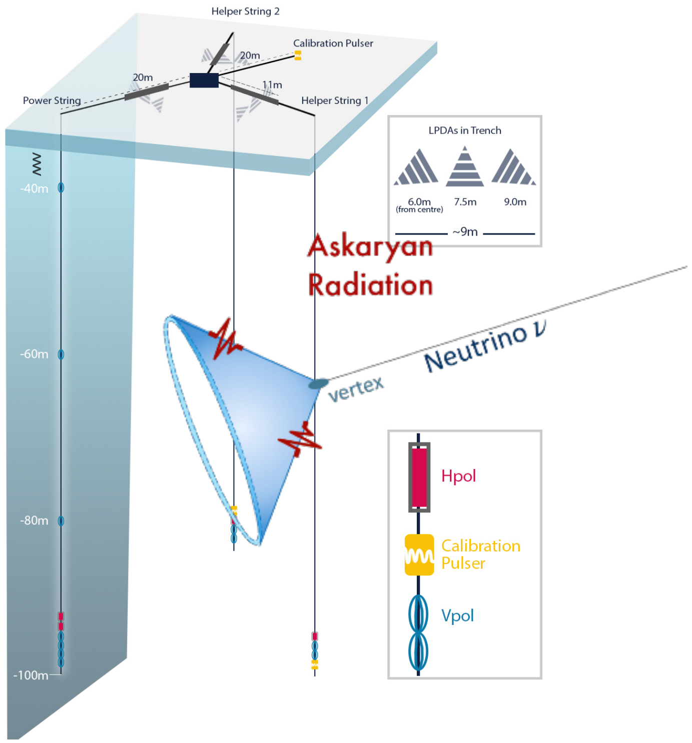
In-ice radio detection of neutrinos

Simon Chiche (IIHE)

ARA (South Pole)



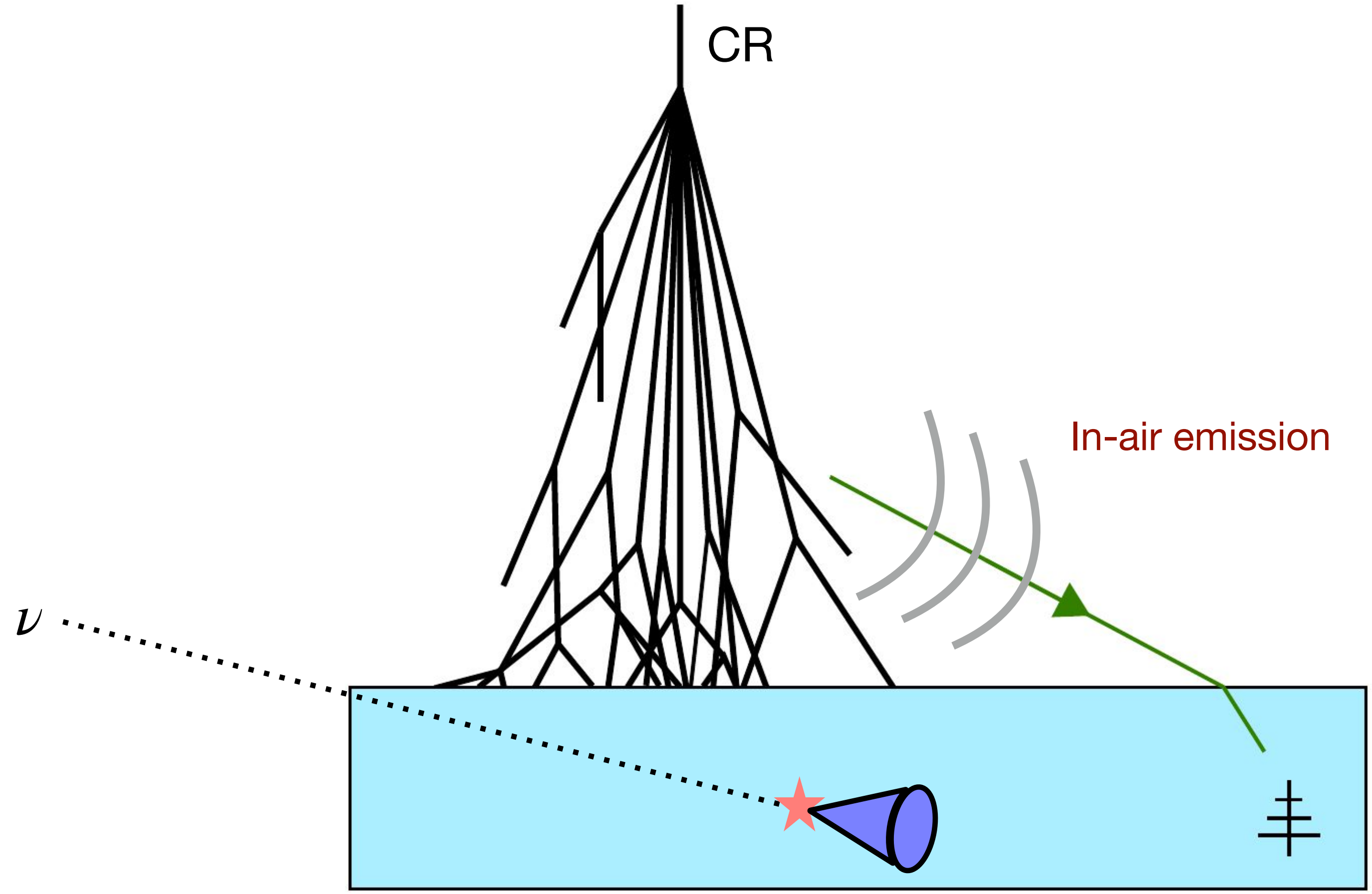
RNO-G (Greenland)



In-ice radio detection: promising technique to detect the first EeV neutrinos

Simon Chiche
(IIHE)

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



credits:
Simon de Kockere

Simon Chiche (IIHE)

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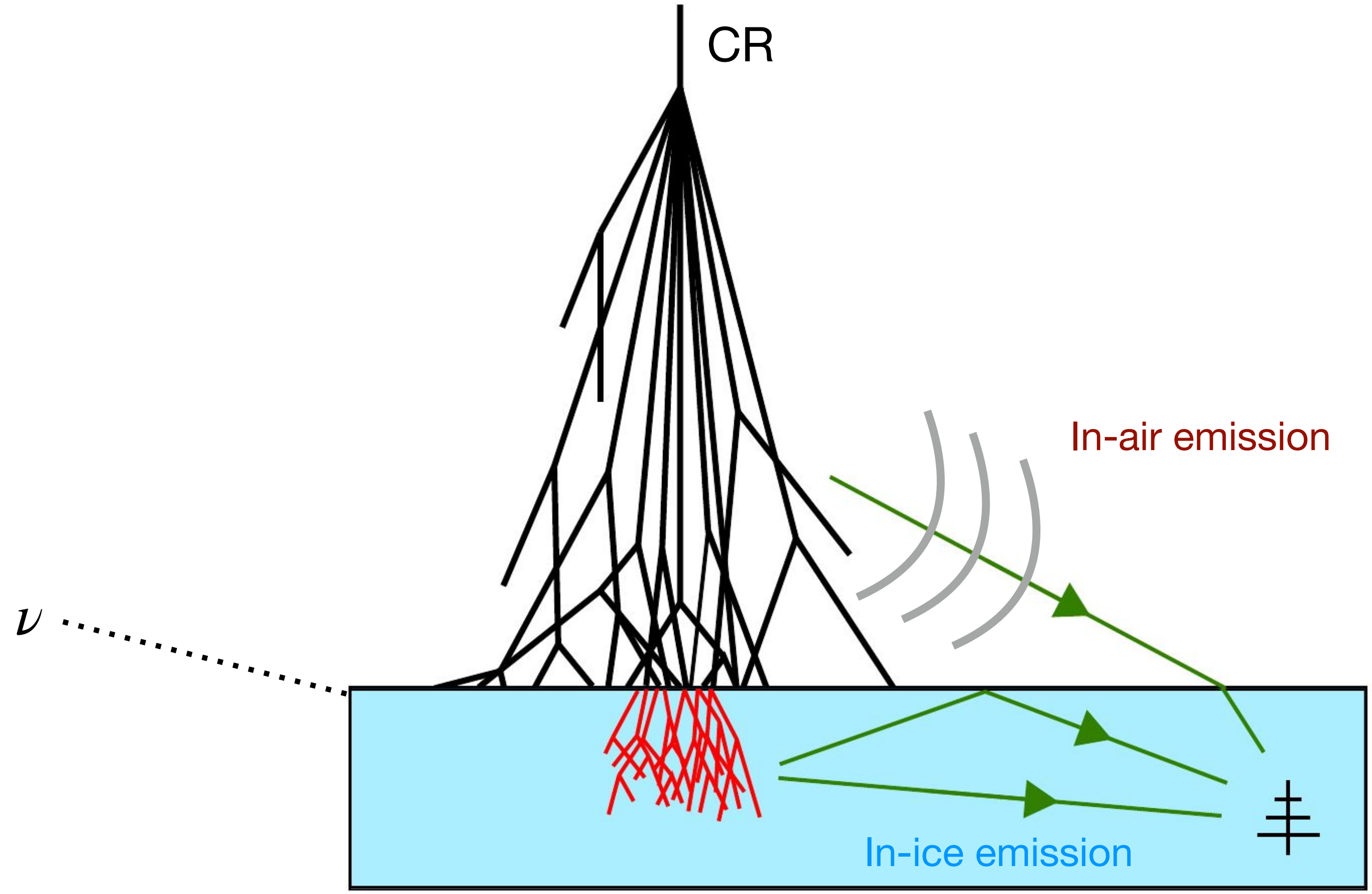

credits: Simon de Kockere

Simon Chiche
(IIHE)

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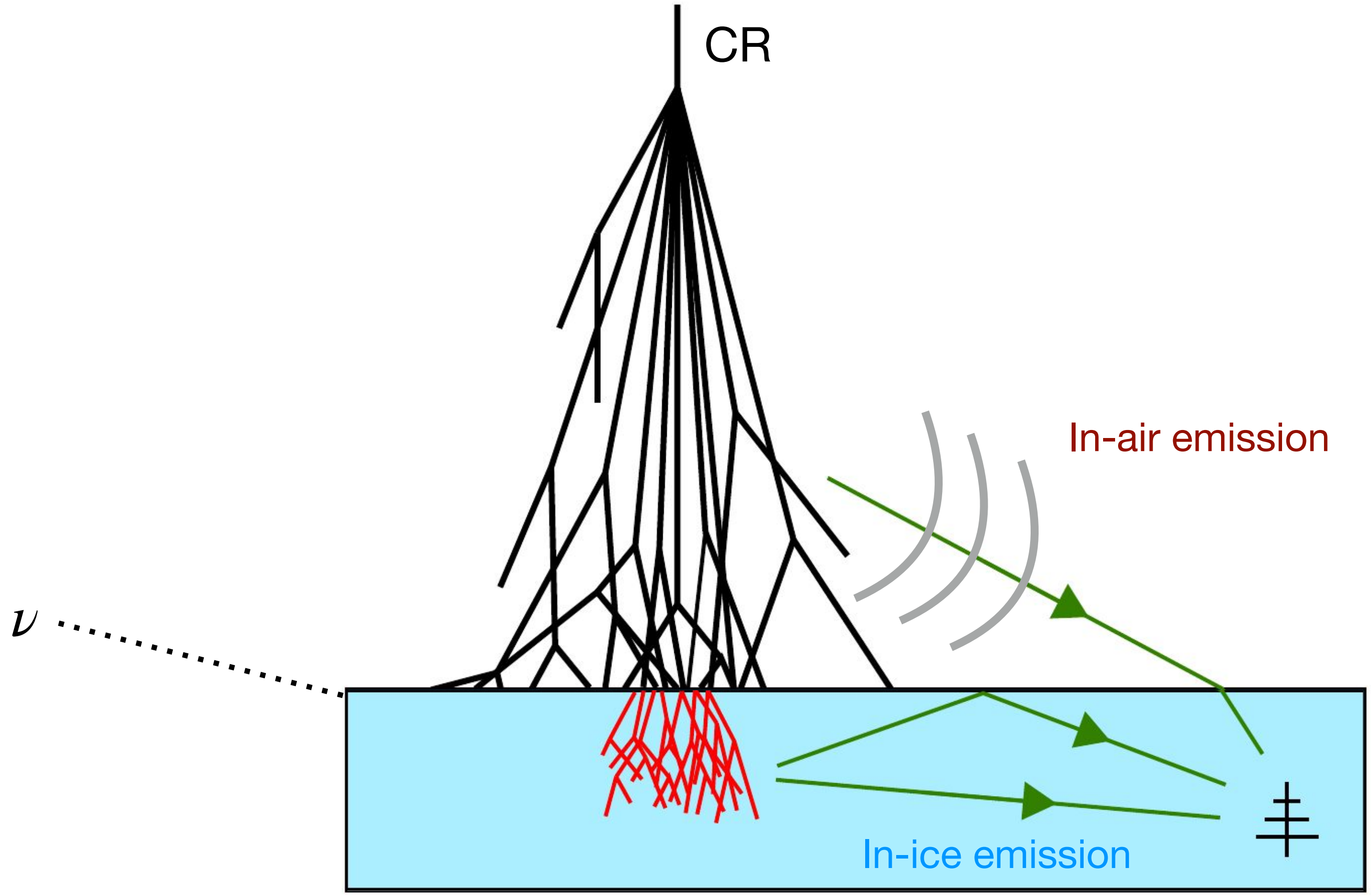

credits:
Simon de Kockere

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

Simon Chiche (IIHE)

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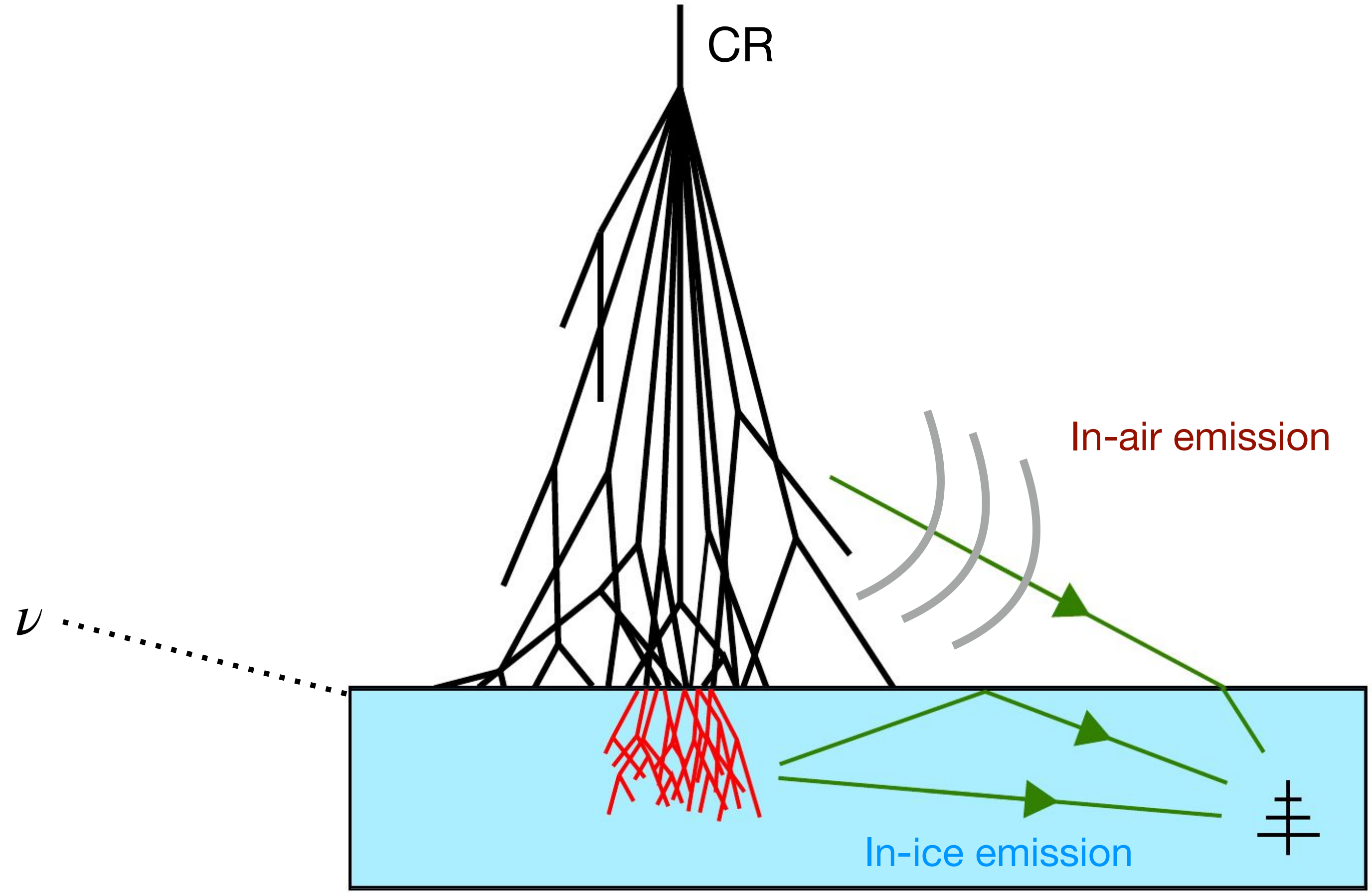


credits: Simon de Kockere

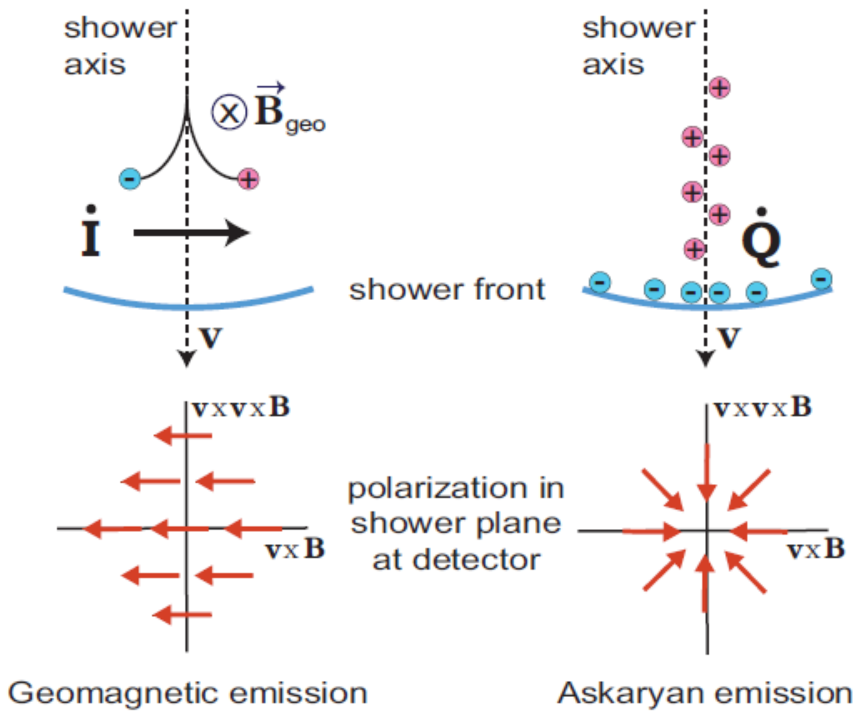
The cosmic-ray flux should be much larger than the neutrino flux:

- 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

Geomagnetic emission

- Induced dipole with $\vec{\mathbf{B}}_{geo}$
- Polarisation along $-\boldsymbol{v} \times \boldsymbol{B}$
- Main contribution to the radio signal



Schröder (2017)

Charge excess emission

- Accumulation of negative charges close to the shower core
- Radial polarisation
- ≈ 10% of the amplitude of the total emission for vertical air showers

In-air cascade: Geomagnetic + Askaryan

In-ice cascade: Askaryan only

Polarisation results from the coherent sum between both emissions

FAERIE: Framework for the simulation of Air shower Emission of Radio for in-Ice Experiment

How to simulate both the in-air and in-ice emission from cosmic-ray showers?

→ FAERIE: Combination of CORSIKA and Geant Monte-Carlo codes
(De Kockere et al., 2024 [2403.15358])

In air

- Particle cascade with CORSIKA 7.7500
- Radio emission with CoREAS

In ice

- Particle cascade with Geant4 10.5
- Radio emission with code from the T-510 experiment (radio detection in dense medium)
  (Belov et al., 2015 [1507.07296])

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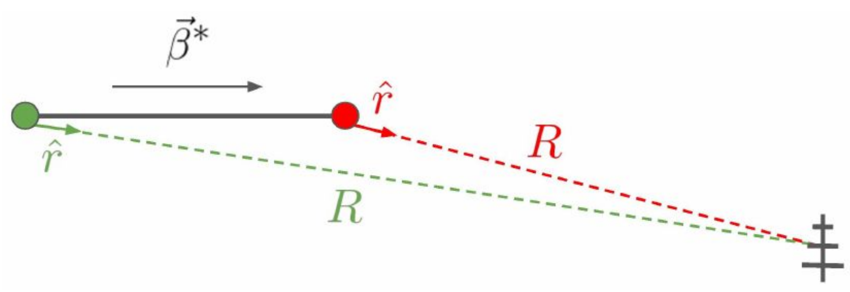
In both cases radio emission computed using **Endpoint formalism**:

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



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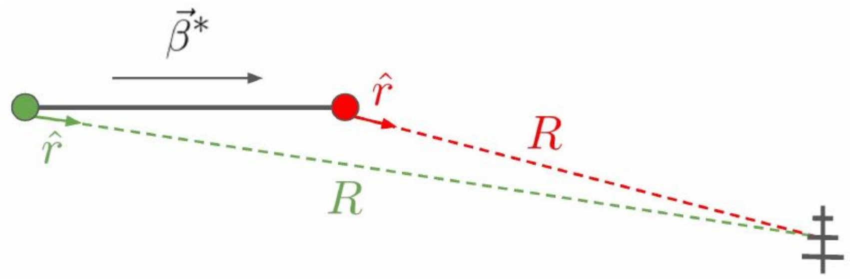


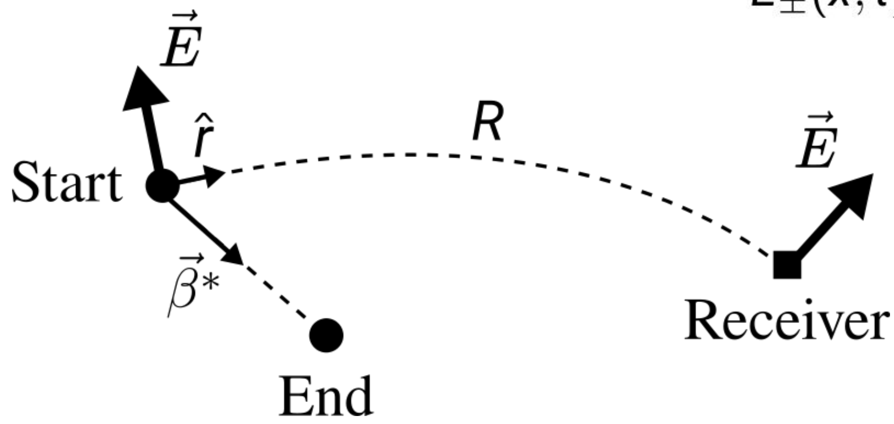
Endpoint formalism must be modified with ray-tracing to account for the varying refractive index in ice

Simon Chiche
(IIHE)

See talk from Dieder

Modified Endpoint formalism due to ray-bending in ice

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



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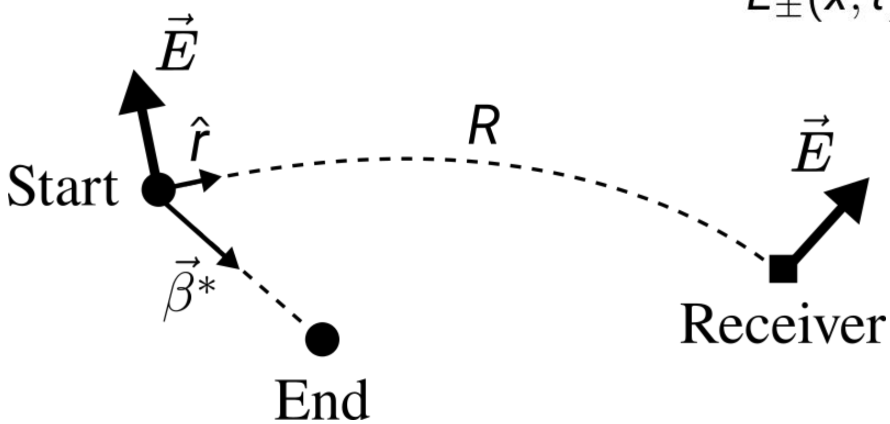
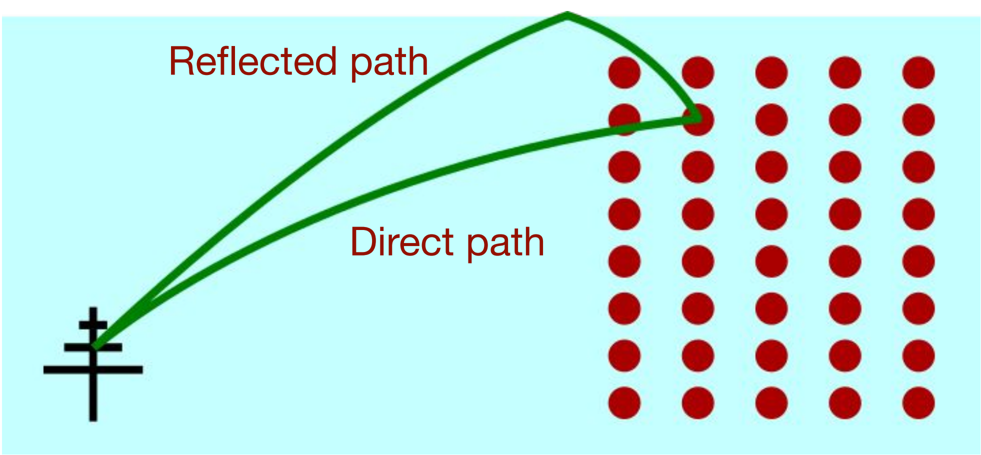


Ray tracing: What are the paths that goes from a given source point to an observer?

Snell-Descartes: $n_1 \sin i_1 = n_2 \sin i_2$

2 solutions:

- Direct path
- Reflected path



Ice refractive index can be modeled using an exponential profile

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

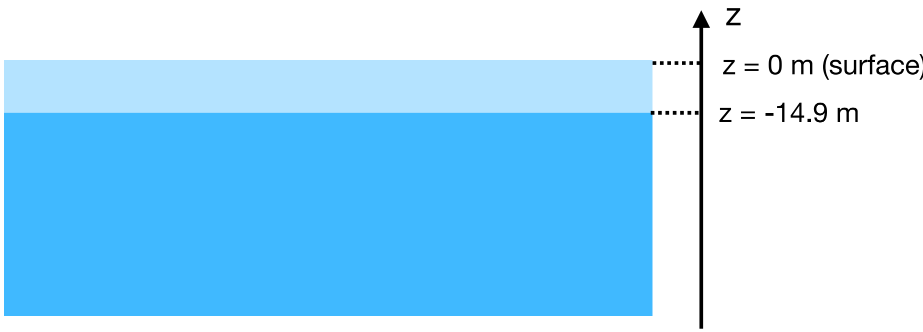
South Pole

Single exponential model:

Kelley et al., 2018 (https://doi.org/10.22323/1.301.1030)

$$A = 1.775,\ B = 0.43,\ C = 0.0132$$

Greenland



Double exponential model:

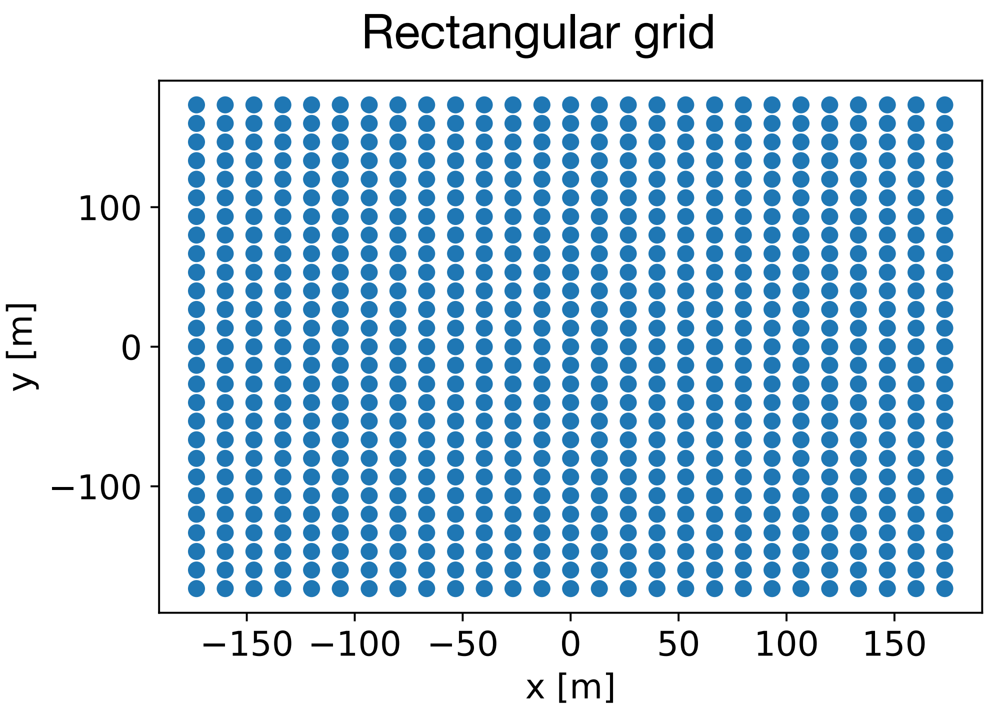
(Deaconu et al., 2018)

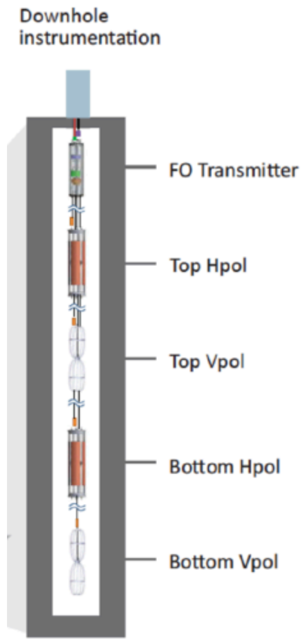
$$|z| < 14.9\,\mathrm{m} \qquad A = 1.775,\ B = 0.5019,\ C = 0.03247$$

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

Library generation

Simon Chiche
(IIHE)





ARA: 12 depths [145-200] m

RNO-G: 5 depths [0, 40, 60, 80,100] m

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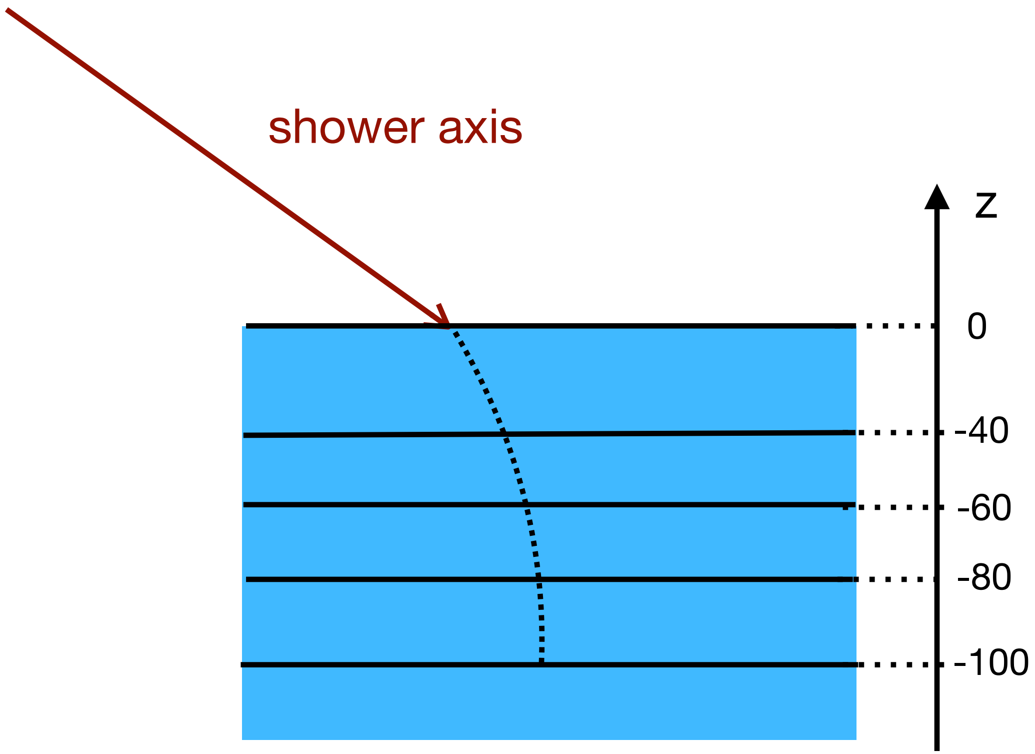
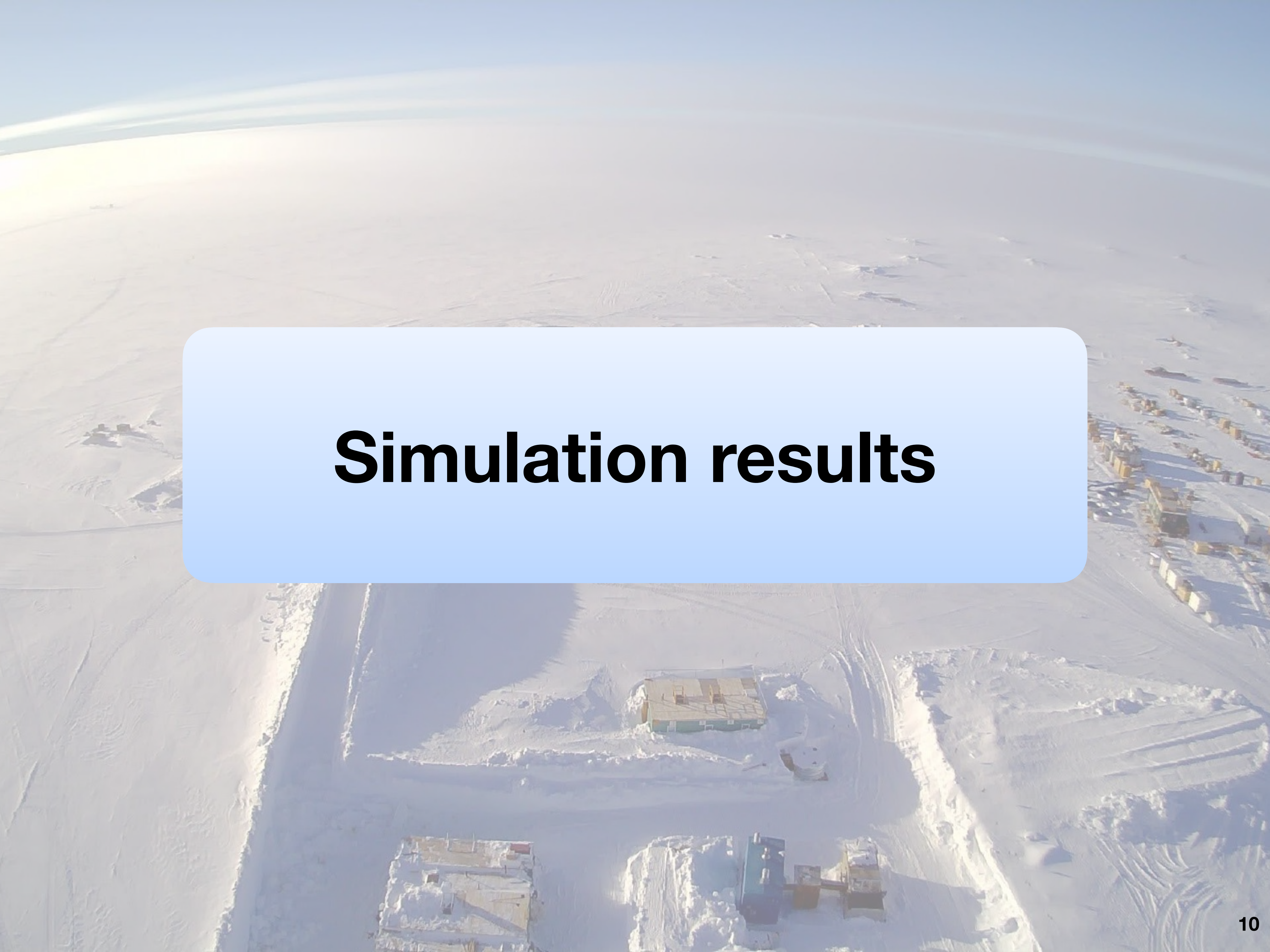
Where to set the antenna positions?

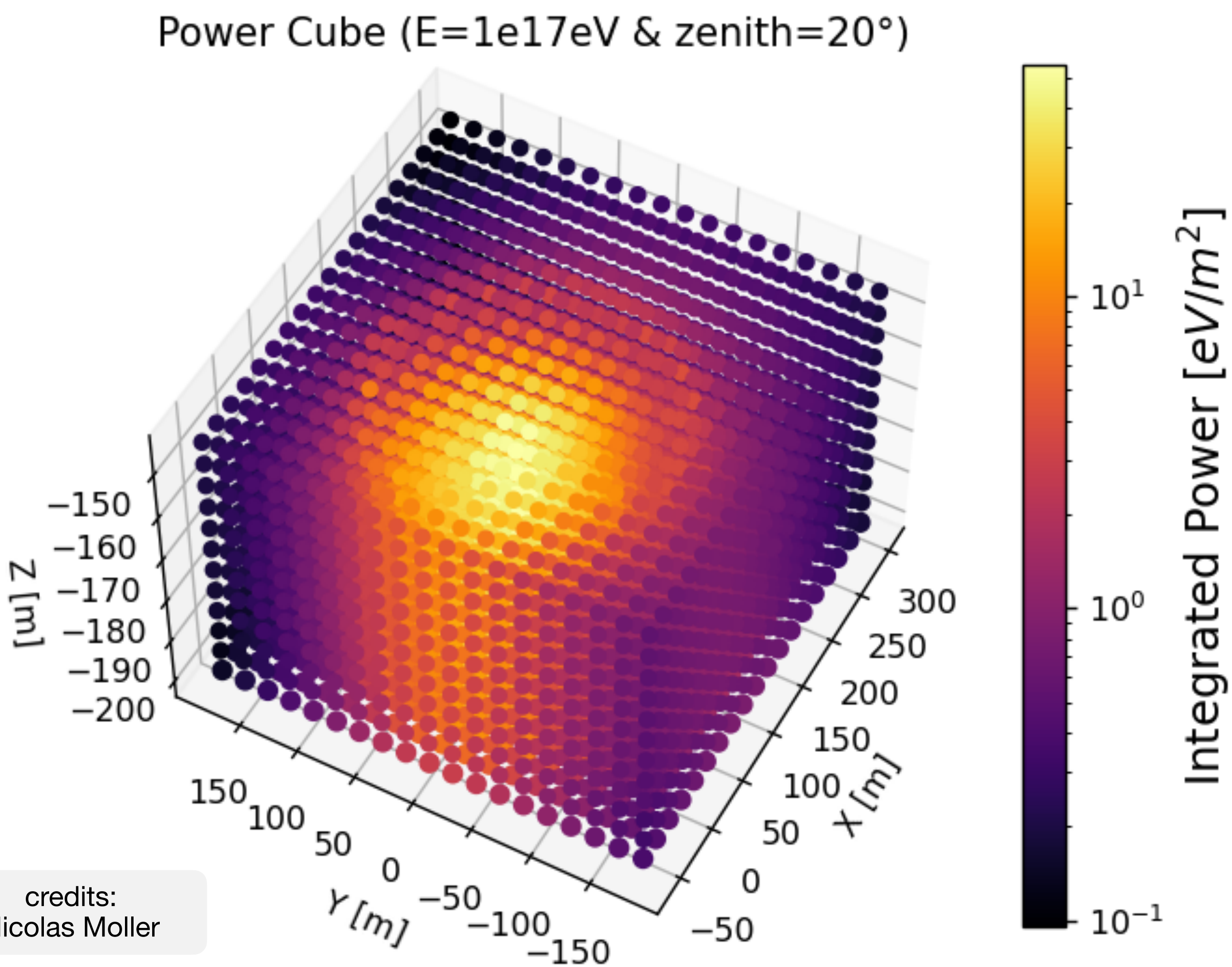


We use ray-tracing so that the « ice-core ray » intersects the center of the layer at |z| =100 m

Simulation results



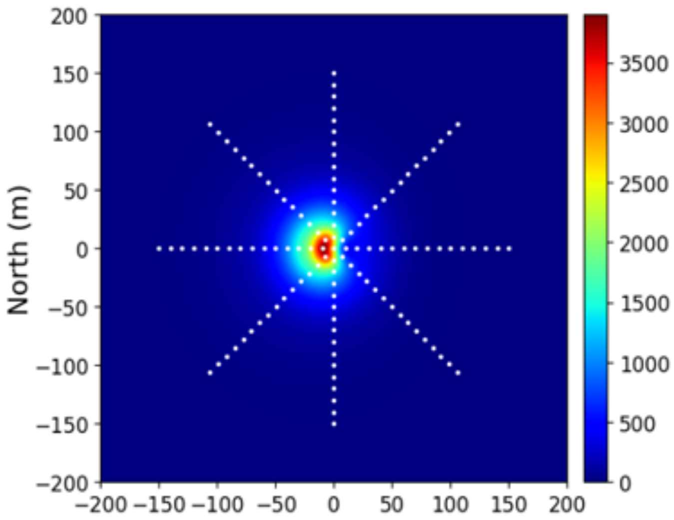
Cubic simulation of a given proton-induced shower at South Pole



credits:
Nicolas Moller

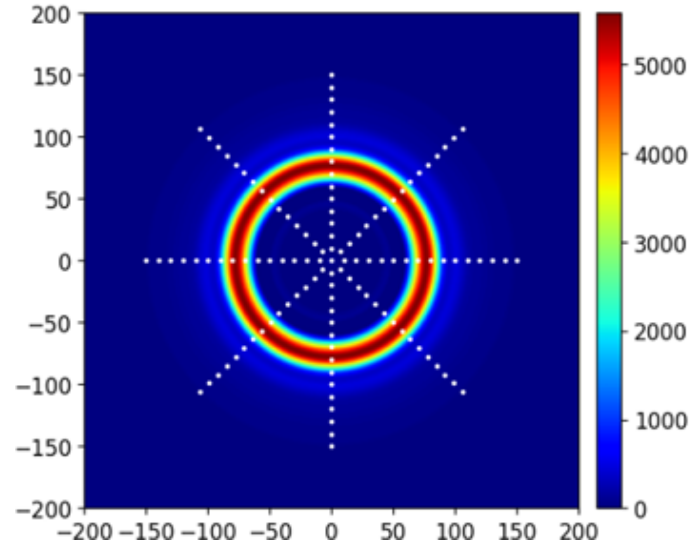
Simon Chiche (IIHE)

In-air emission

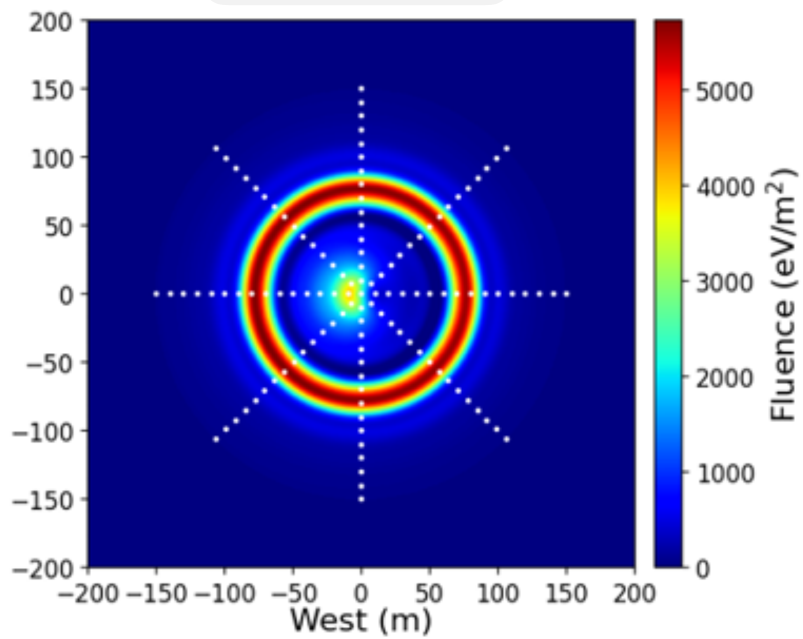


+

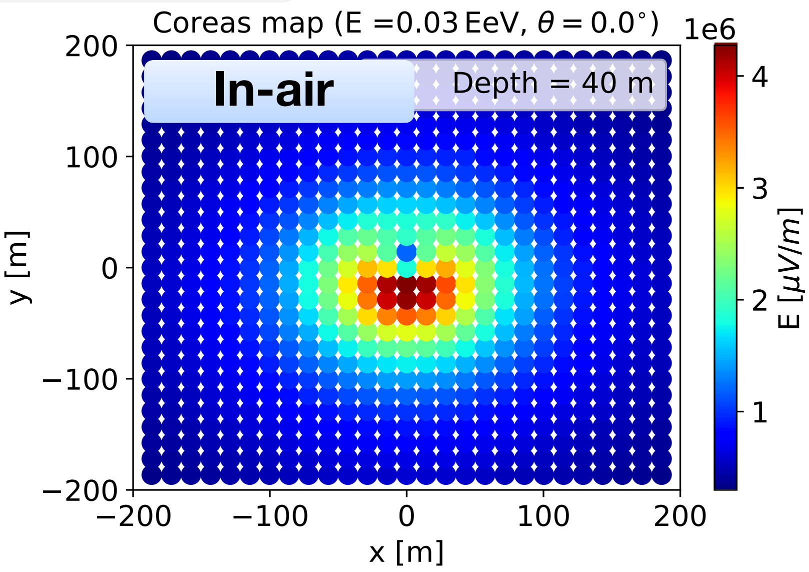
In-ice emission

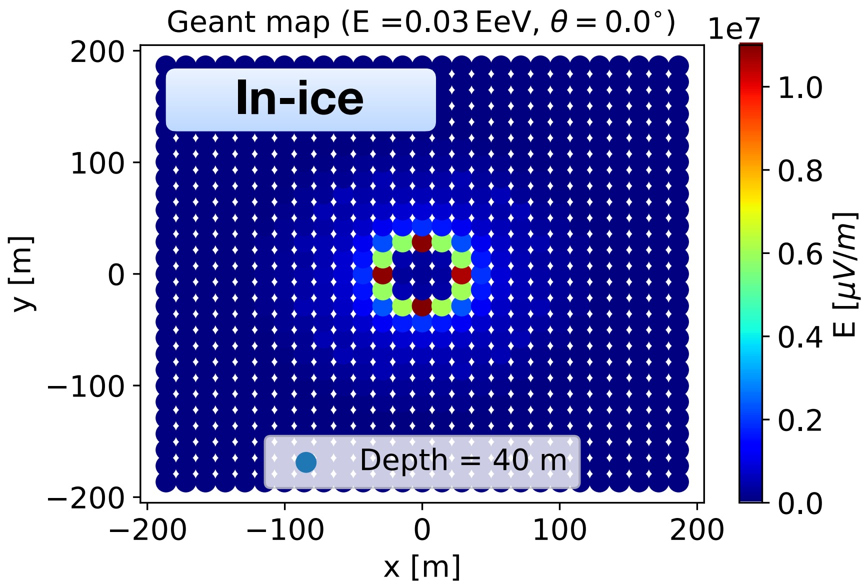


Air + Ice



Depth = 40 m


Coreas map (E =0.03 EeV, $\theta = 0.0^{\circ}$)
In-air
Depth = 40 m
1e6
E [μV/m]
y [m]
x [m]


Geant map (E =0.03 EeV, $\theta = 0.0^{\circ}$)
In-ice
Depth = 40 m
1e7
E [μV/m]
y [m]
x [m]

Dependency of the emission with the depth

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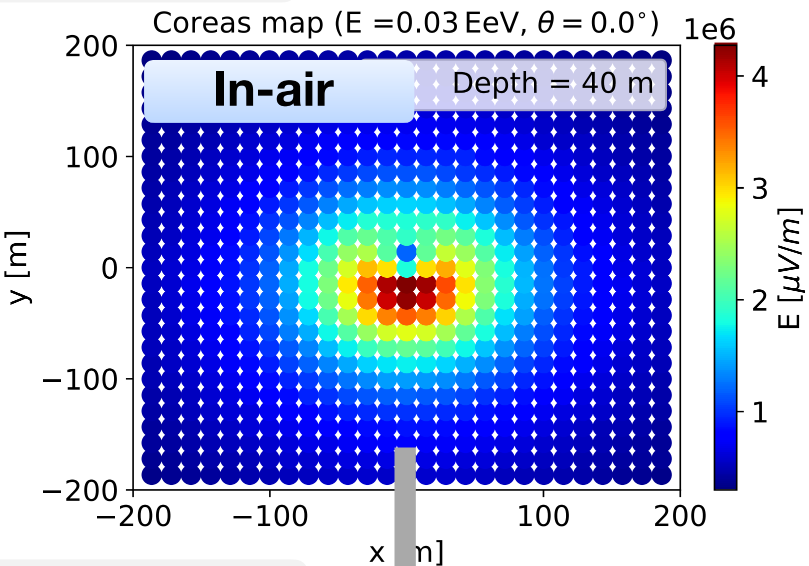
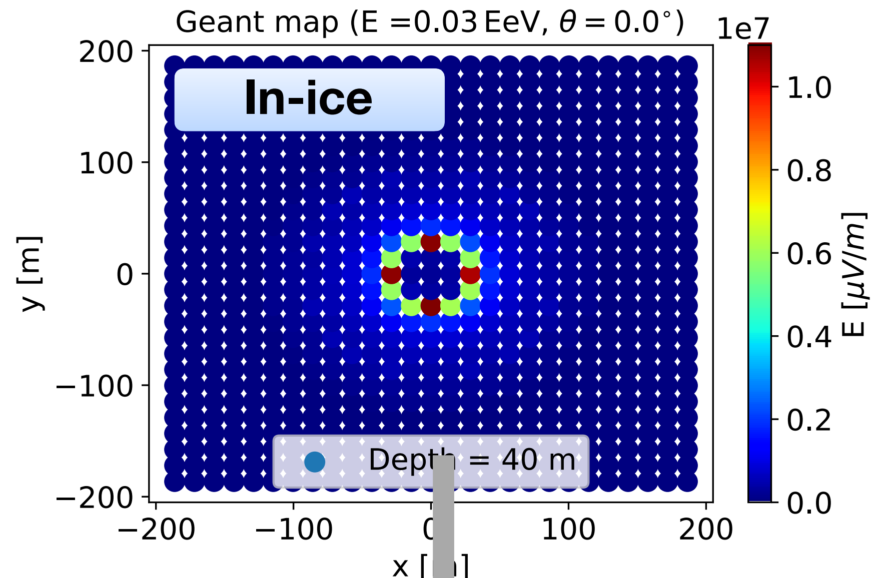
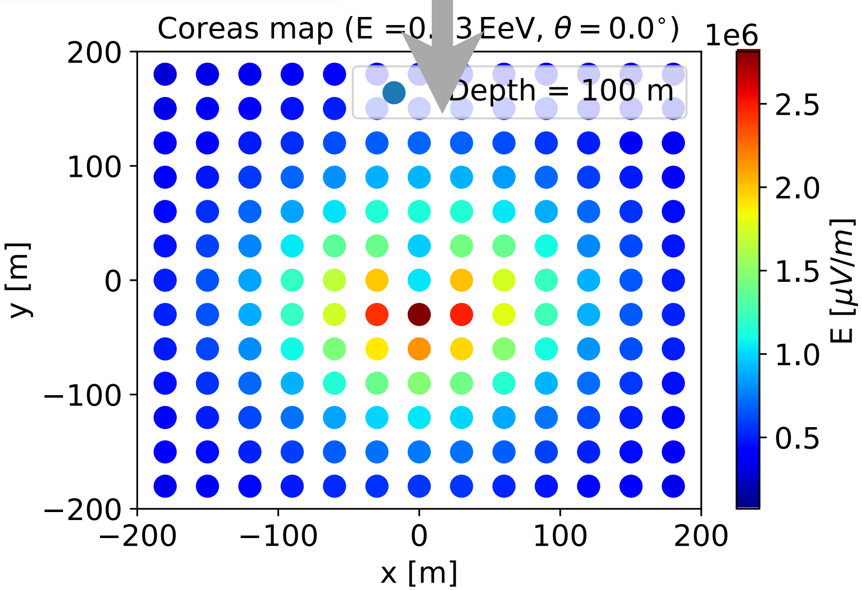
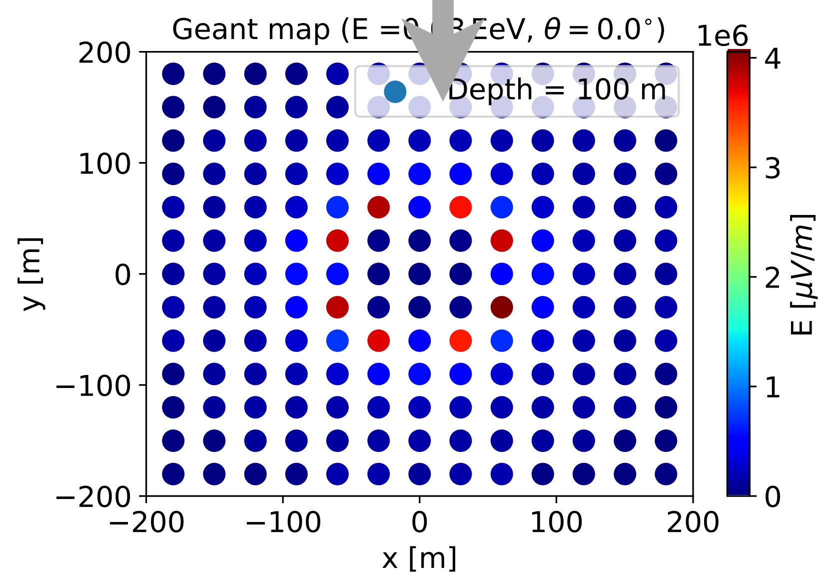
Depth = 40 m



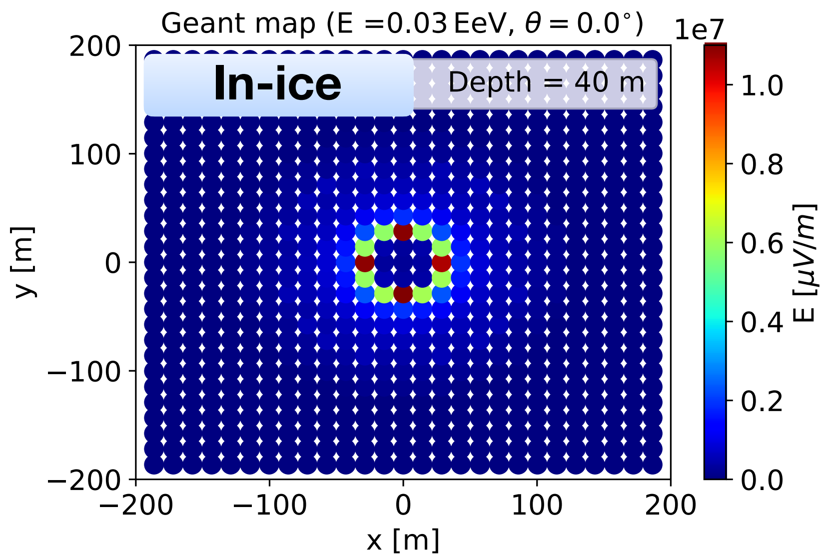


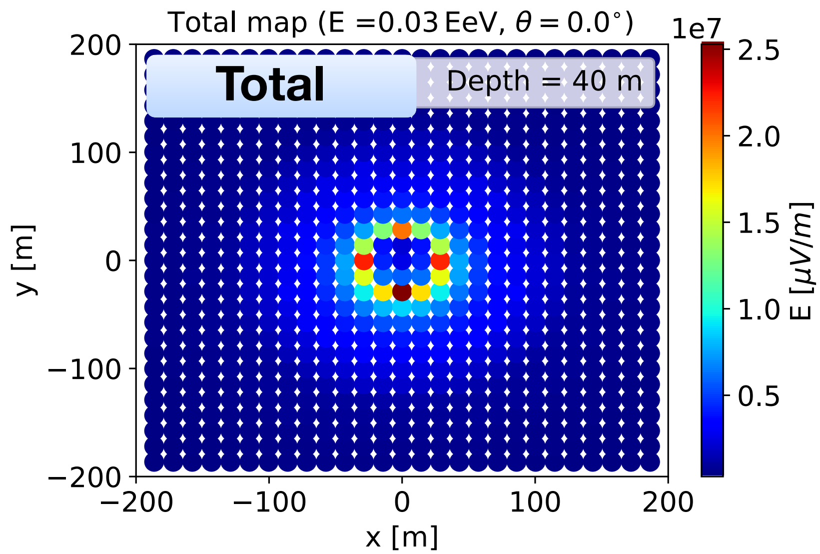
Depth = 100 m





Vertical shower ($\theta = 0°$): signifiant in-ice emission





Zenith angle dependency

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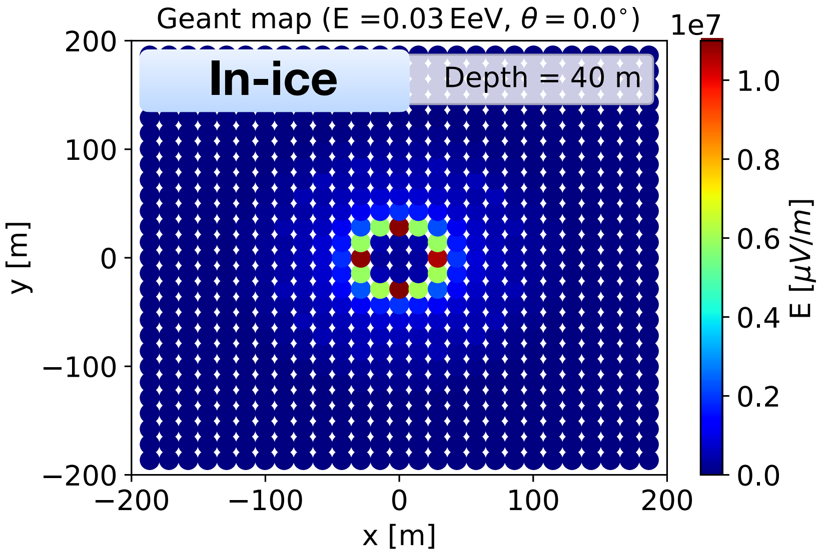
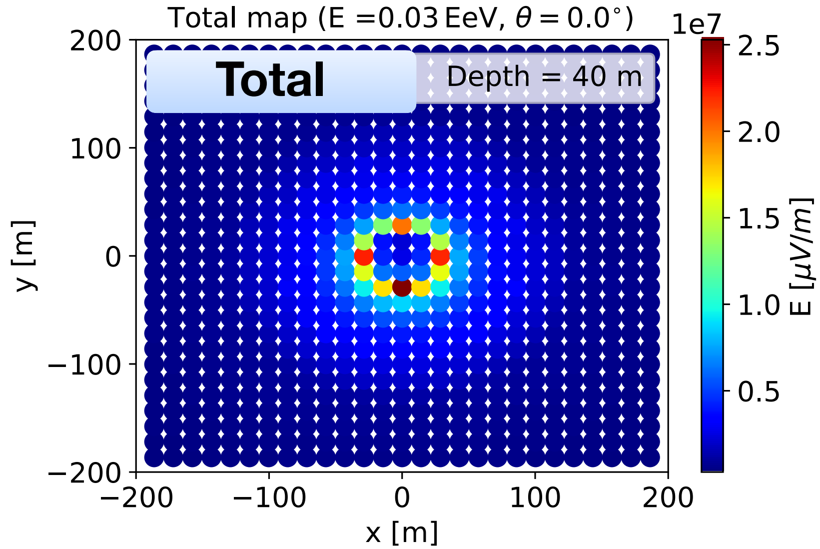
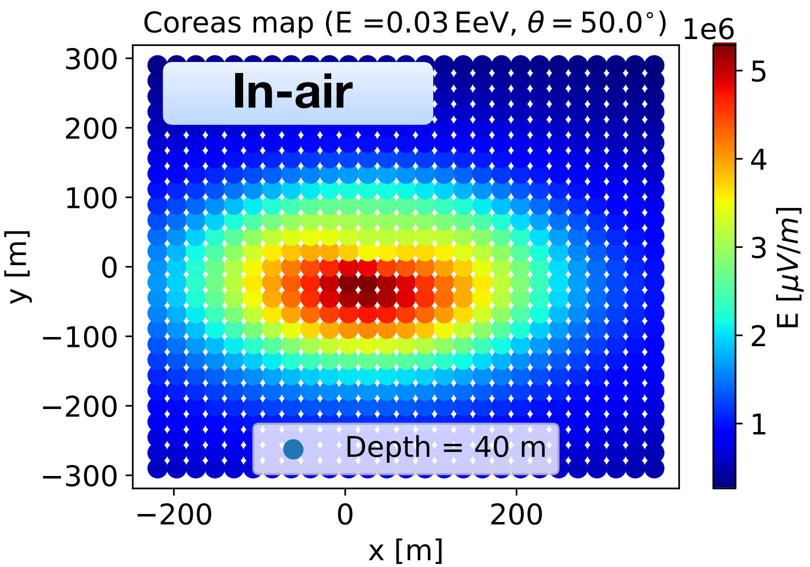
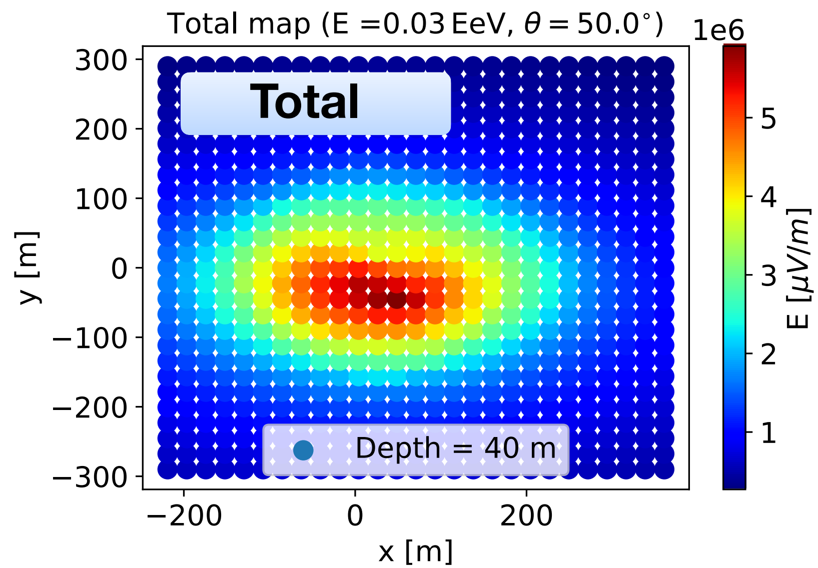
Vertical shower ($\theta = 0°$): signifiant in-ice emission

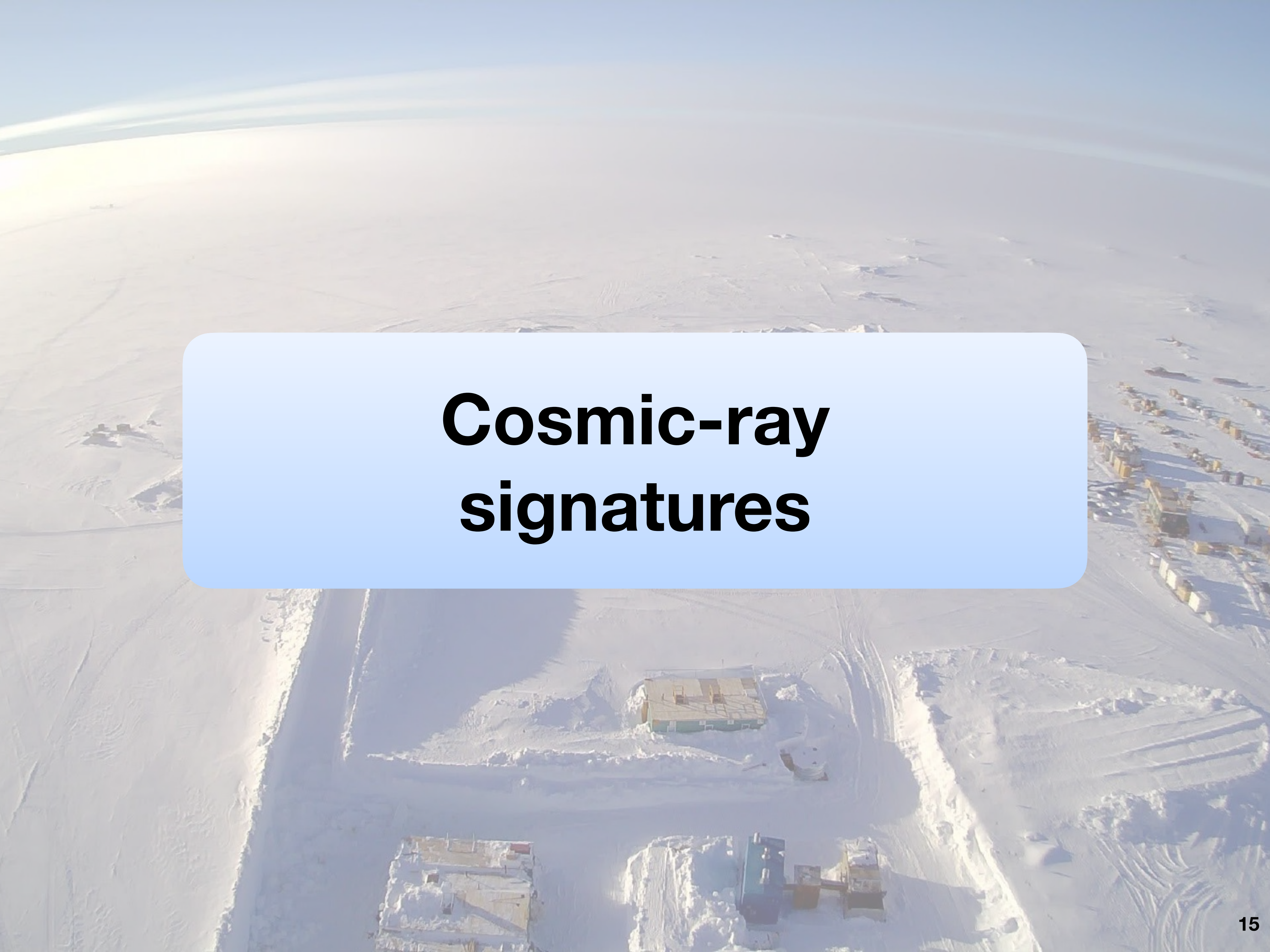




Inclined shower ($\theta = 50°$): dominant in-air emission





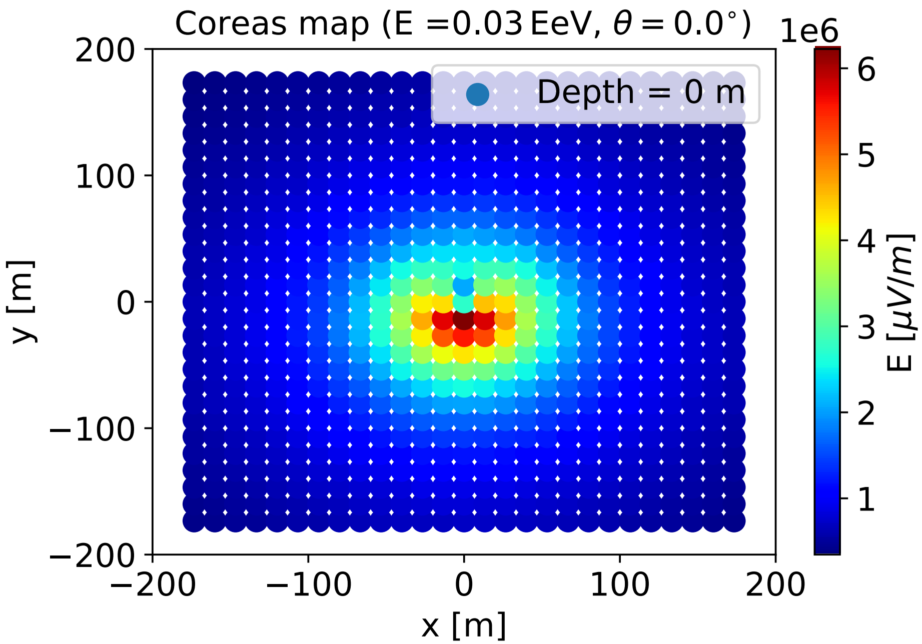


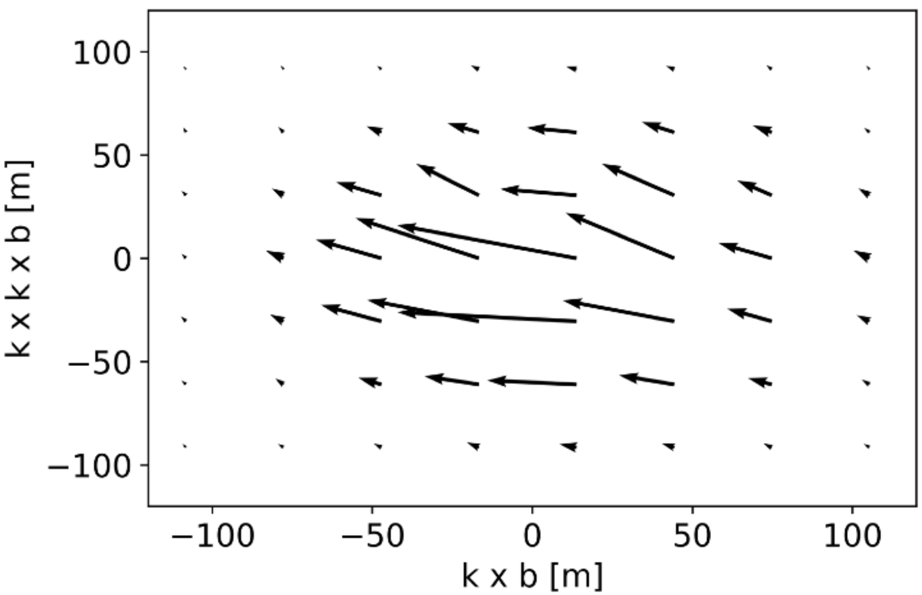
Cosmic-ray signatures

Simon Chiche (IIHE)

Surface antennas: first proxy for cosmic-ray identification and veto

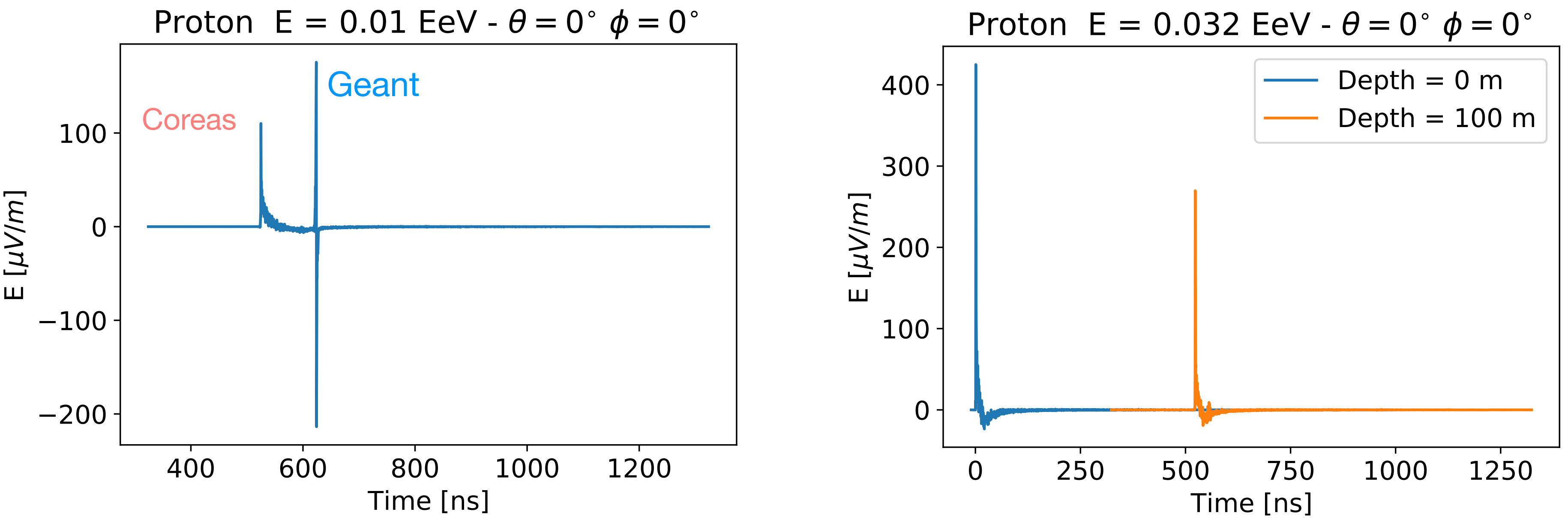
Polarisation: direction of the electric field vector





- Bean-shaped fluence pattern (Geomagnetic/Askaryan interferences)
- Linear and ~unidirectional polarization (dominant geomagnetic emission)

The emission from both the in-air and in-ice cascades can sometimes reach the same antennas



Valuable signatures for cosmic-ray identification!

Event rate computation

We can draw a cosmic-ray event rate from simulations

Strategy:

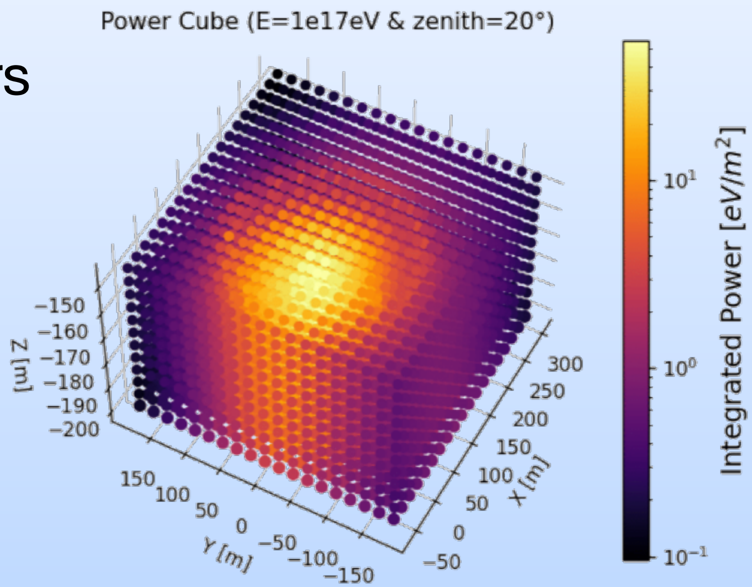
- Run a library of simulations (E, θ, φ)
- Apply scaling factors to interpolate between events
- Generate random events
- Detector response and trigger (AraSim/NuRadioMC)
- Derive the event rate

Simon Chiche
(IIHE)

We can simulate in-ice radio emission from cosmic-ray showers!

Objectives:

- Cosmic-ray event rate for in-ice detectors like ARA and RNO-G
- Identification of cosmic-ray signatures (polarization, fluence pattern, timing…)
- Cosmic-ray/neutrino discrimination



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(IIHE)

FAQ:

Simulations size?: A few gigabytes at $10^{17}\,\mathrm{eV}$

Computation time?:

- In-air emission: $\sim 5 - 10\,\mathrm{h} \times \dfrac{N_{\mathrm{ant}}}{10\,\mathrm{ant}} \times \dfrac{\cos(\theta = 0^{\circ})}{\cos(\theta)} \times \dfrac{E}{10^{16.5}\,\mathrm{eV}}$ on 1 node
- In-ice emission: $\sim 5\,\mathrm{h} \times \dfrac{N_{\mathrm{ant}}}{120\,\mathrm{ant}} \times \dfrac{\cos\theta}{\cos(\theta = 0^{\circ})}$ on $20 \times \dfrac{E}{10^{17}\,\mathrm{eV}}$ nodes