Simulation of the propagation of cosmic ray air shower cores in ice

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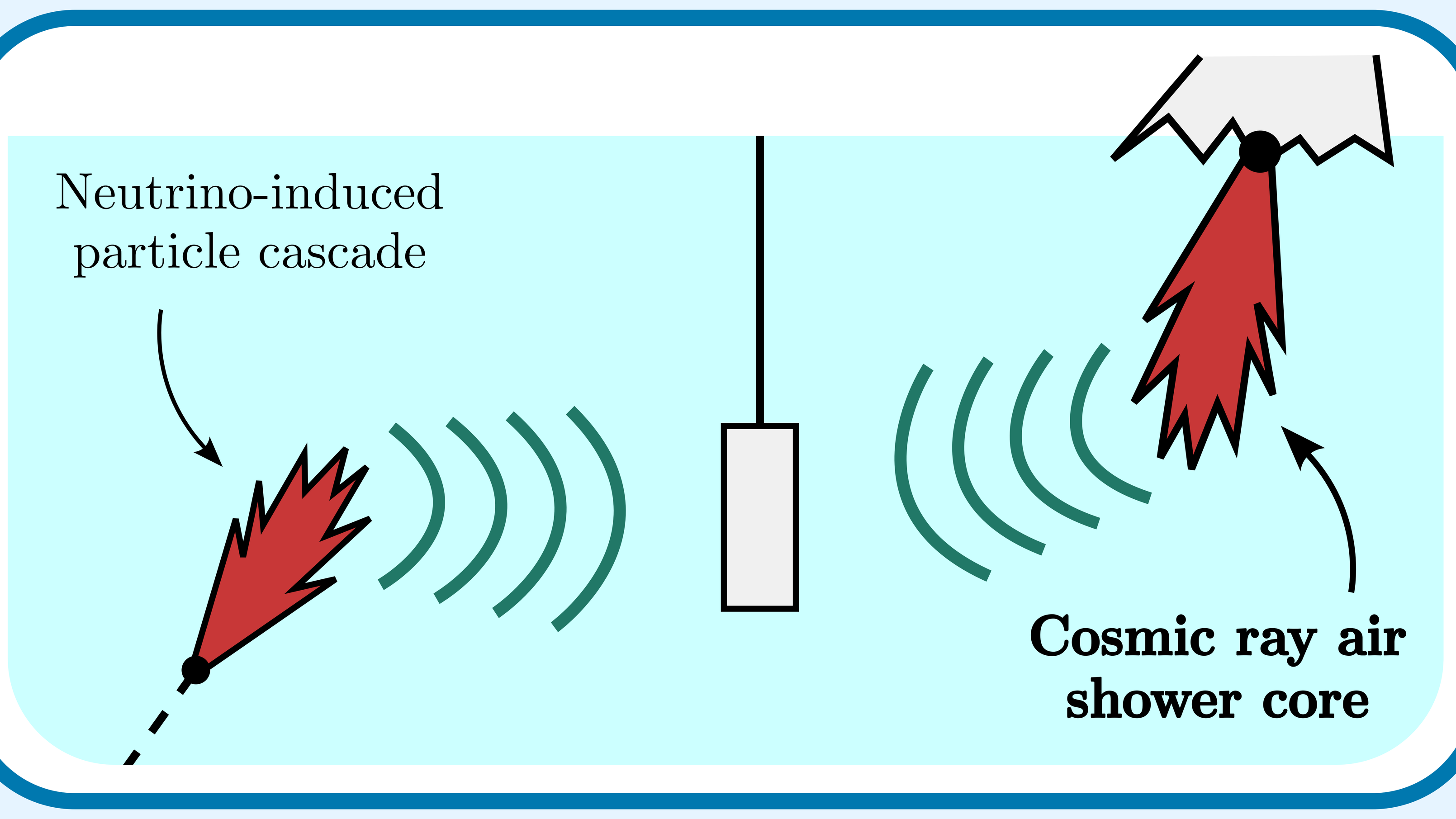
Motivation

- Sensitivity of current **neutrino** observatories limited to PeV scale, but can be extended using **radio detection technique**
- **Neutrino**-induced particle cascade in ice are detected through **coherent Askaryan radio emission**
- **Cosmic ray air shower cores** penetrating high-altitude ice form an important **background** as well as in-situ **calibration**



Simulation setup

In air:

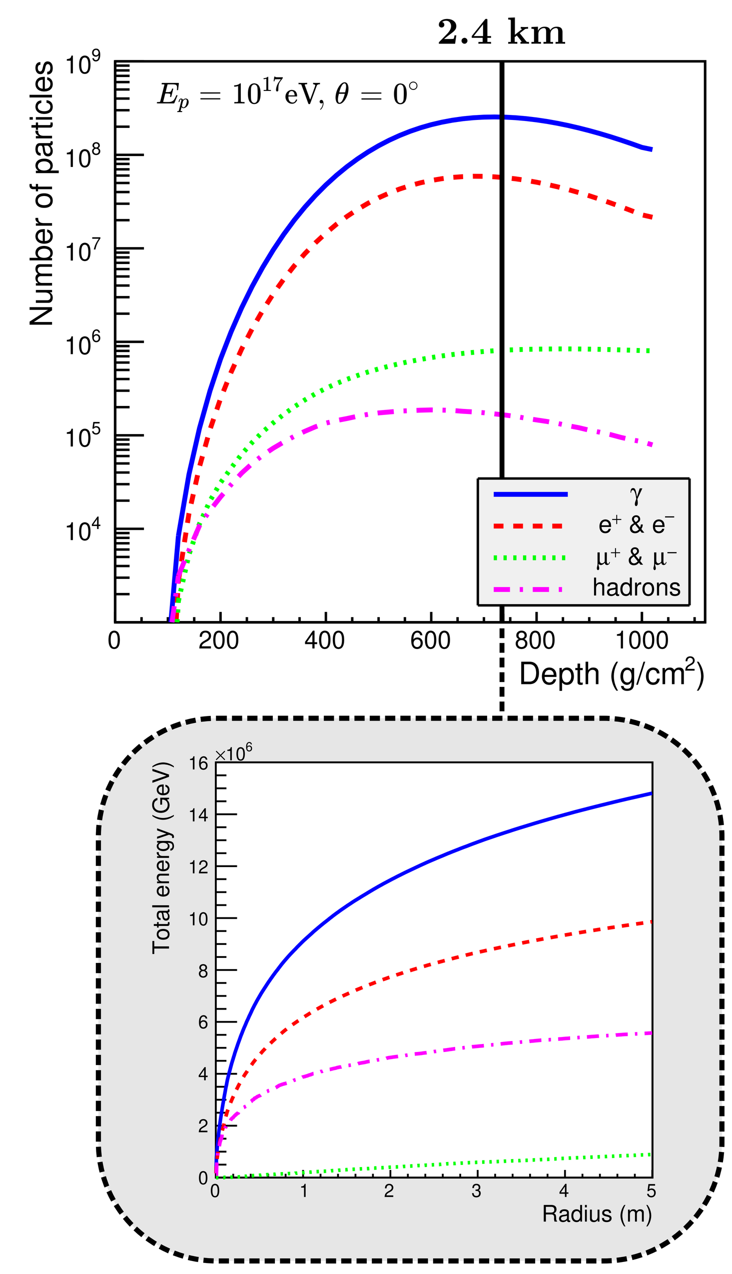
- *CORSIKA 7.7100*
- High-energy proton primaries ($E_p \geq 10^{16}$ eV)
- Small zenith angles ($\theta \leq 40^\circ$)

Read out all particles at 2.4 km altitude within 5 m radius ($\vec{p}$, $\vec{r}$, t, w)

In ice:

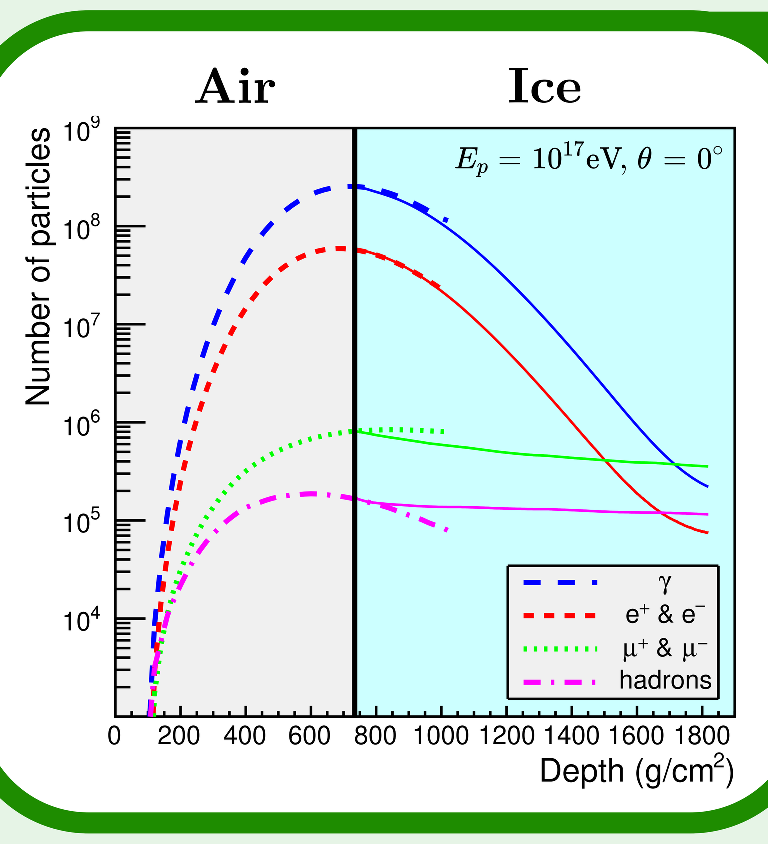
- *Geant4 10.5*
- Block of ice, following the ice density gradient measured at Taylor Dome (Antarctica)

Expect high-energy air showers to hit ice surface close to shower maximum, with very energy dense cores



In-ice cascade properties

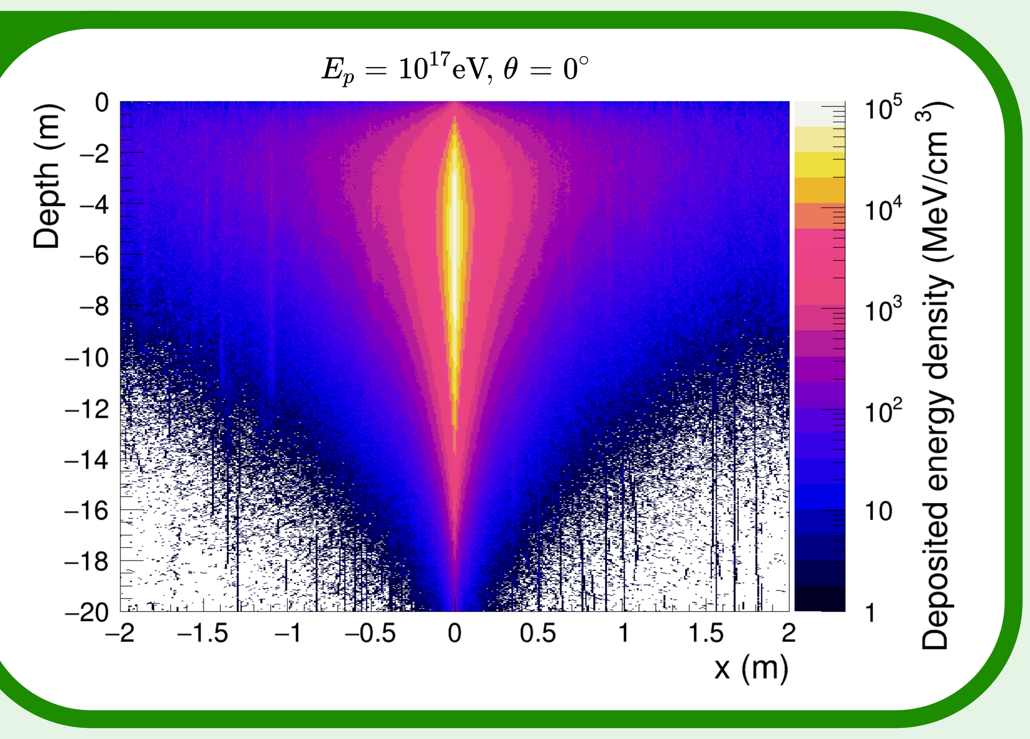
Shower development



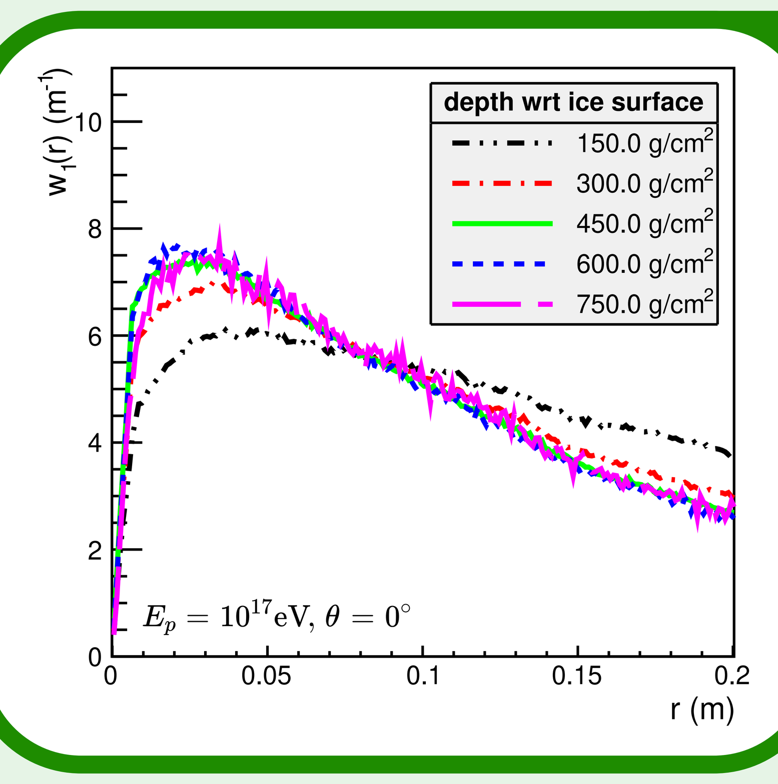
- Propagation through ice does not influence longitudinal development of electromagnetic part
- Standard air shower parameterizations can be used, e.g. Gaisser-Hillas

Deposited energy in ice

- Energy highly concentrated around core, resembling neutrino induced particle cascade
- Shower core is still developing



Charge distribution

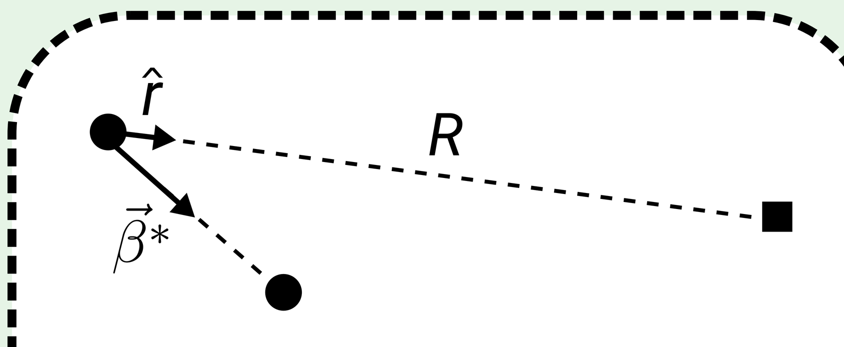


- Lateral dimension is most relevant
- $w_1(r)dr$ = number of charges in $[r, r+dr[$ (normalized)
- Parameterization in function of X_{max}

$$W(r) = \frac{1}{A}\sqrt{r}e^{-(r/b)^c}$$

Radio emission

- Calculate radio emission using the **end-point** formalism
- Constant index of refraction n



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

C. W. James et al., Physical Review E 84, 056602 (2011), arXiv:1007.4146
Also used in CoREAS (arXiv:1402.2872)
and T-510 slack experiment (arXiv:2111.04334).