Software for Large Astroparticle Physics Projects

The Example of Radio Detection of Neutrinos

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DESY.

Software in Multi-Messenger Astronomy

There is no science without it

Software in Multi-Messenger Astronomy

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- All research in multi-messenger astronomy relies on software
    - Software to run the experiments
    - Software to transmit the data
    - Software to simulate the instruments performance
    - Software to reconstruct the data
    - …
- However, only a (small) fraction of the software is written and developed by people who have an explicit training for these tasks
- And that is where the 'fun' begins

Software in Science

What the realty looks like

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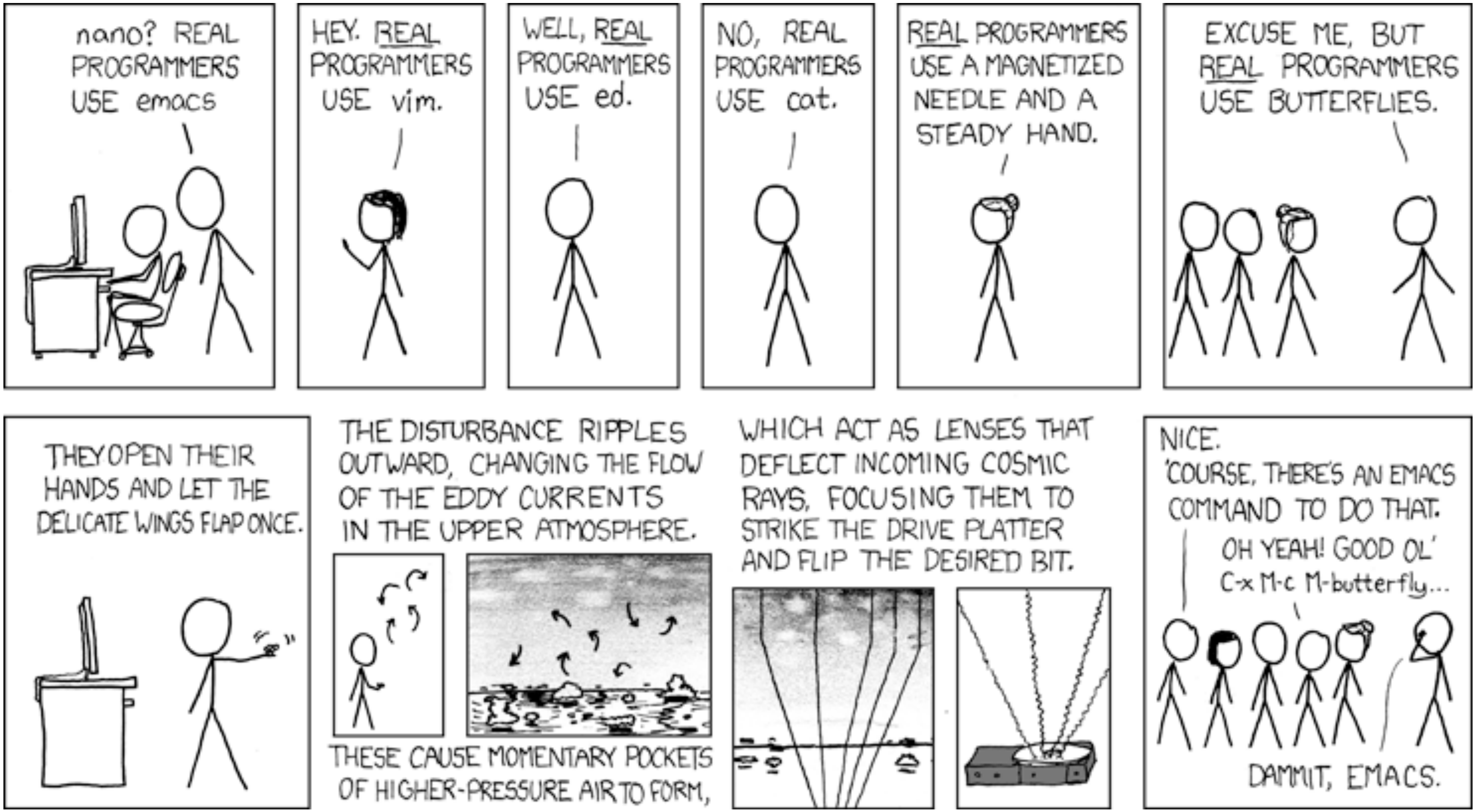
  - Advisor to PhD student: “Fortran77 is not a problem for you, right?”
  - Expert PhD student to young PhD student: “*Llga &%$CTRL gcpaiugrhg zrg (Lots of complicated computing words).* This will fix your problem, super efficiently.”

Software in Science

Some of you may find this funny … others not all



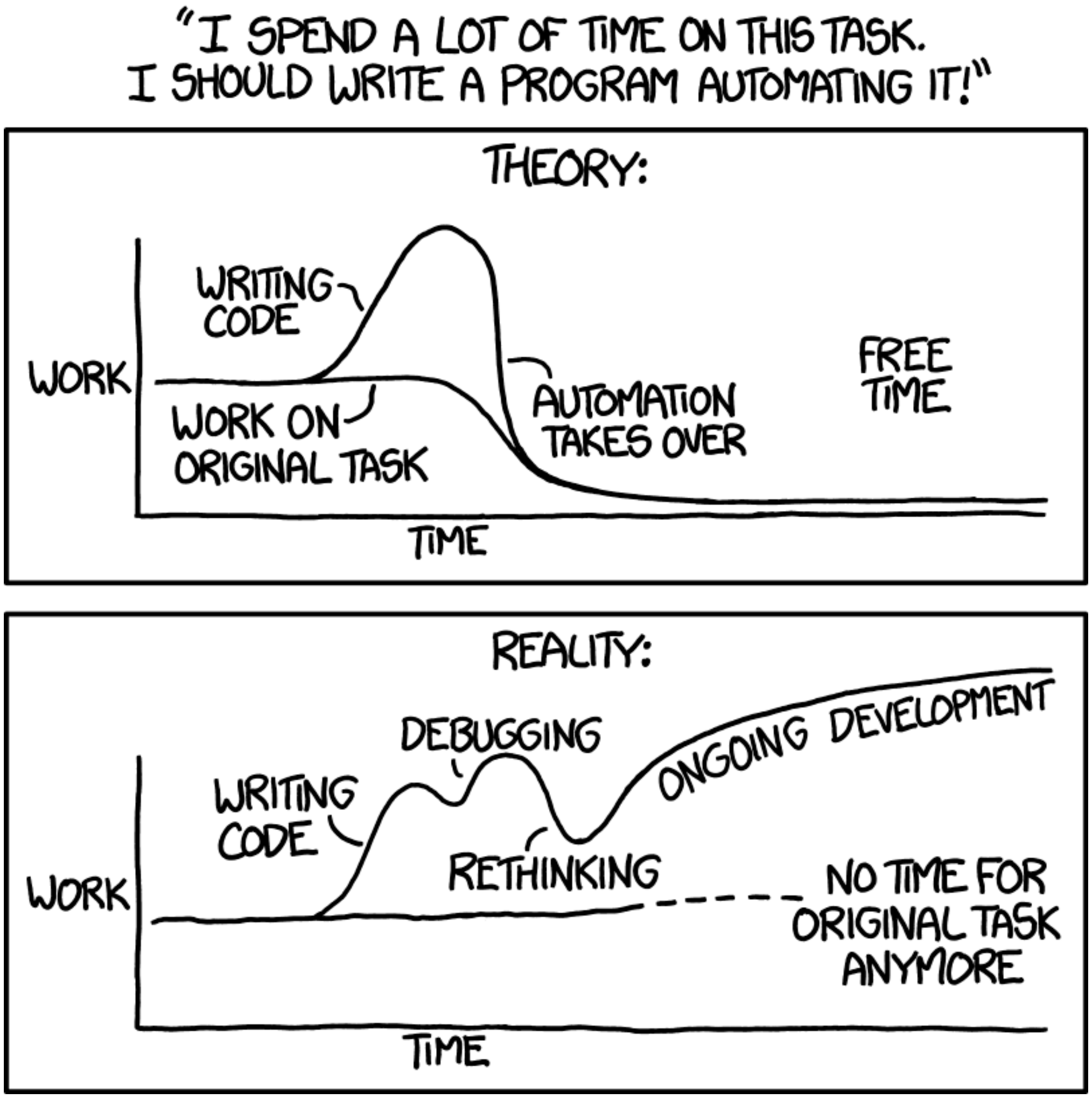
https://xkcd.com

Software in Science

What are the underlying problems?

- Having professional software, e.g. user-friendly, sustainable, flexible, well-documented, well-maintained, is not (yet) a high priority in many research projects
  - Priority: Software development is considered a ‘service task’ that doesn’t give you the papers you need for the scientific career, i.e. waste of time
  - Hierarchy: The PhD students and post-docs carry most of the load and their complaints tend to not reach the senior staff, i.e. “we also always complained during our PhD, how bad can it be? I don’t understand what this is about anyway.”
  - Money: Professional software developers ask for more money than TVL-13, so we simply cannot afford them. It is really hard to get dedicated money for such tasks in research grants, especially for a permanent role.
  - Science: When you start developing a project, you tend to not know what the problems will be ahead.

Software in Science

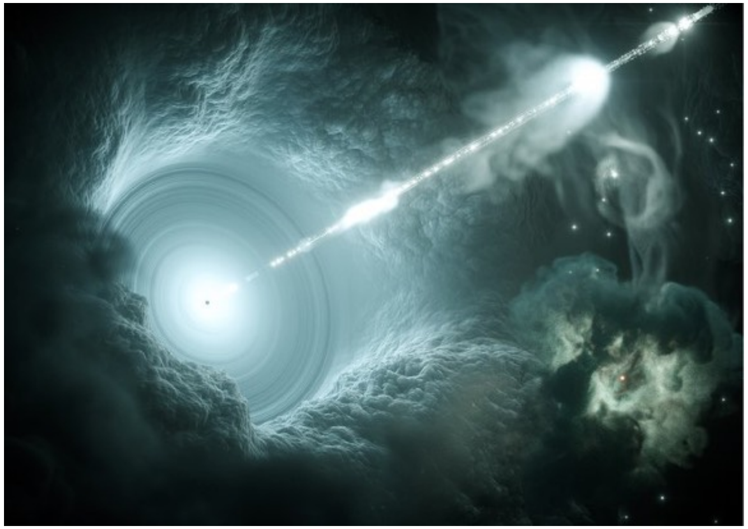


https://xkcd.com

The example of radio detection of neutrinos

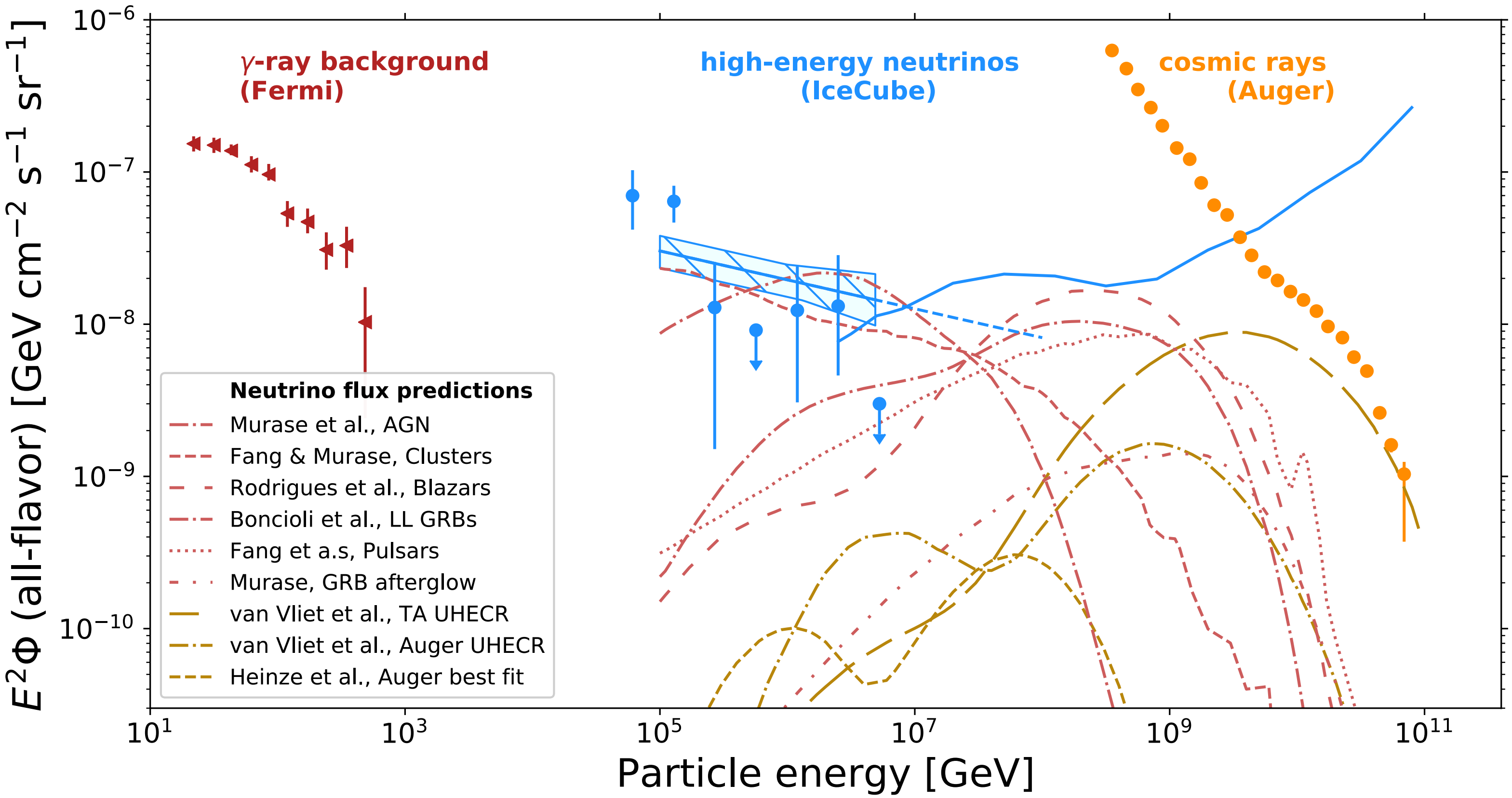
A story that really happened

- Outline
  - Scientific motivation of radio detection of particle showers
  - Underlying physics of radio emission
  - Different software to tackle the problem(s)
  - Current software
  - Outlook



Multi-messenger Universe

Where are we at, at the moment?



Radio detection of particle showers

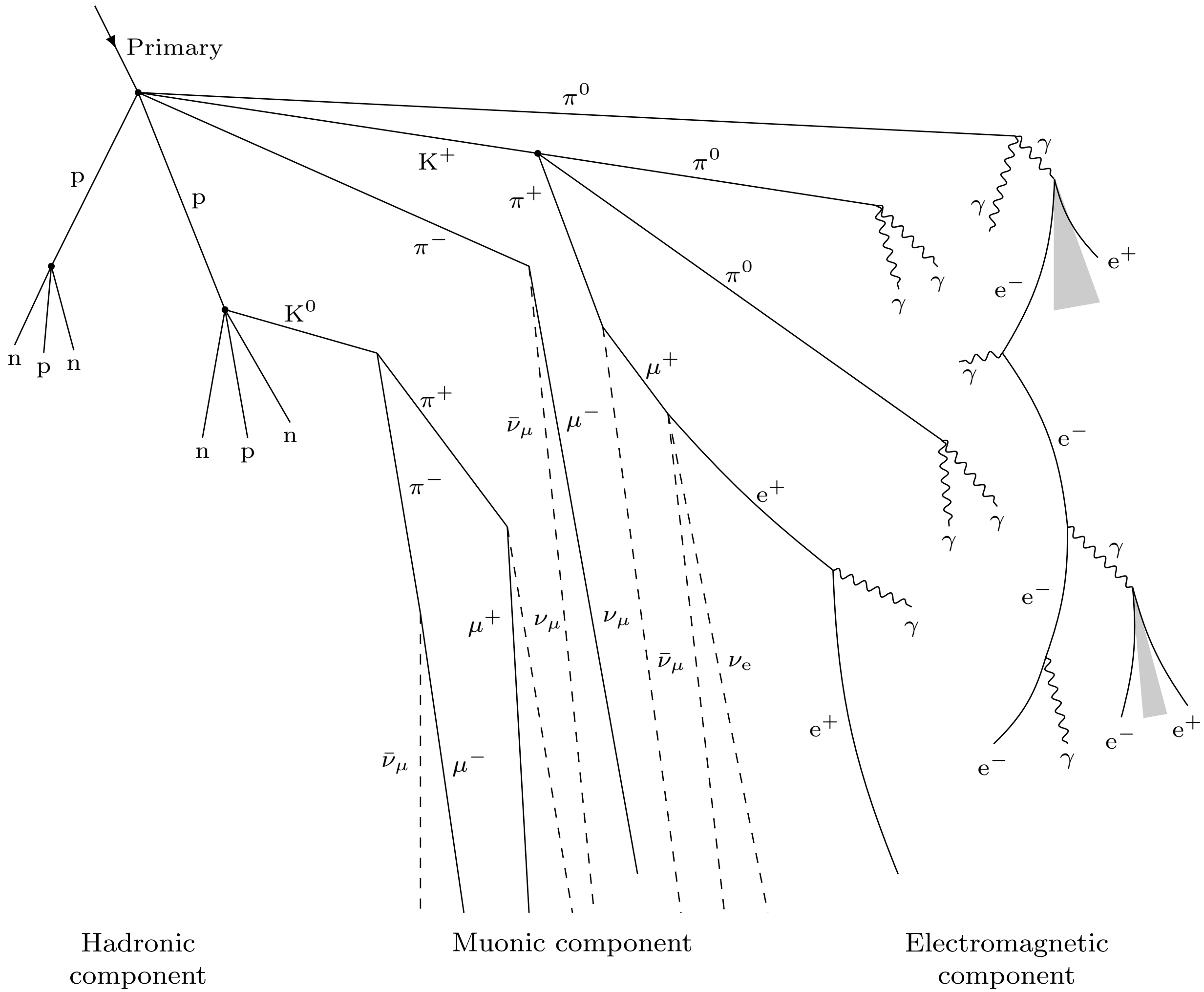
Basic idea, suggested already in the 1960s

- Particle showers create radio emission (see next slides)
- Radio waves are not attenuated in air/ice like light
- Radio antennas are cheap(er) than particle detectors
- One needs huge instrumented volumes to detect the low flux at the highest energies
- So measuring the radio emission of a shower sounds like a useful idea to instrument large volumes to detect air showers or neutrino induced showers

Radio signals

A theoretical introduction

- Highly energetic particles interact with medium and create shower of secondary particles
- Generally one distinguishes hadronic and electromagnetic showers
- Hadronic showers always have a electromagnetic component



Radio emission of particle showers

A theoretical introduction

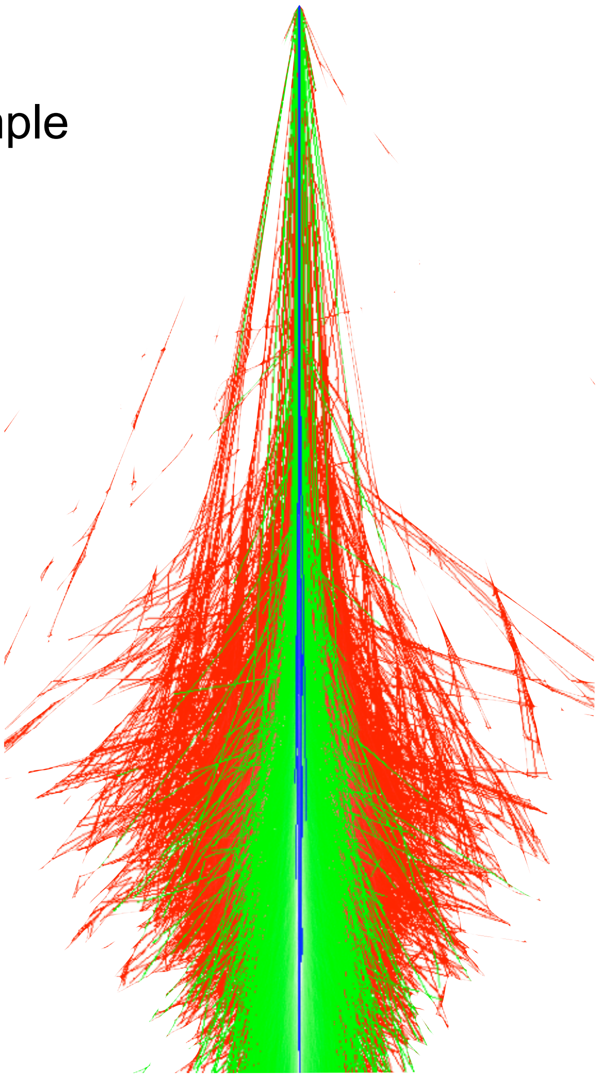
- Radio emission of showers can be explained from simple first principles

- Three ingredients:

    - **Magnetic field**
      (*Geomagnetic field, Lorentz-force*)

    - **Charge imbalance**
      (*Particle Physics processes*)

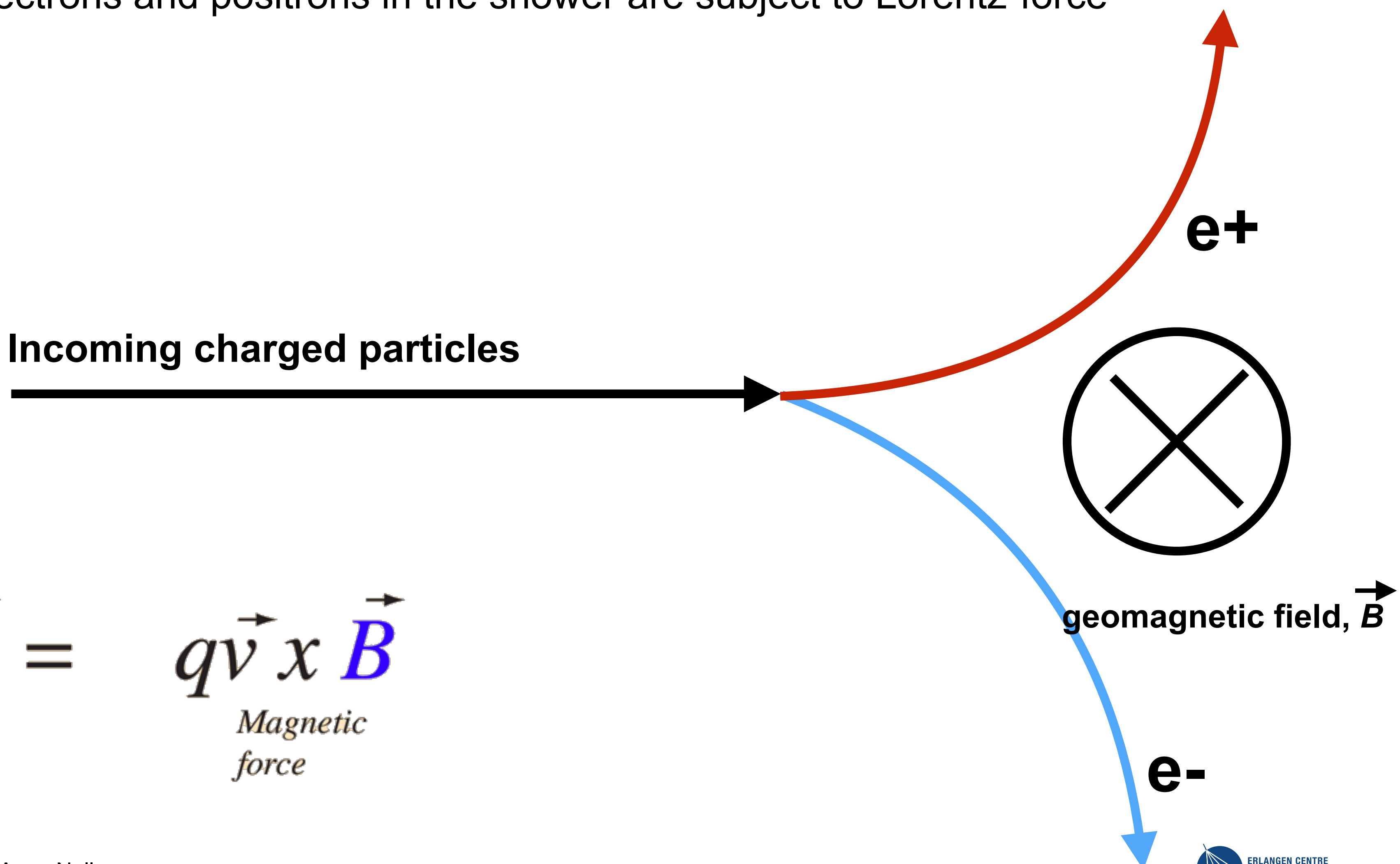
    - **Relativistic compression**
      (*Ray optics and relativity*)



Radio

Geomagnetic effect

- Electrons and positrons in the shower are subject to Lorentz-force



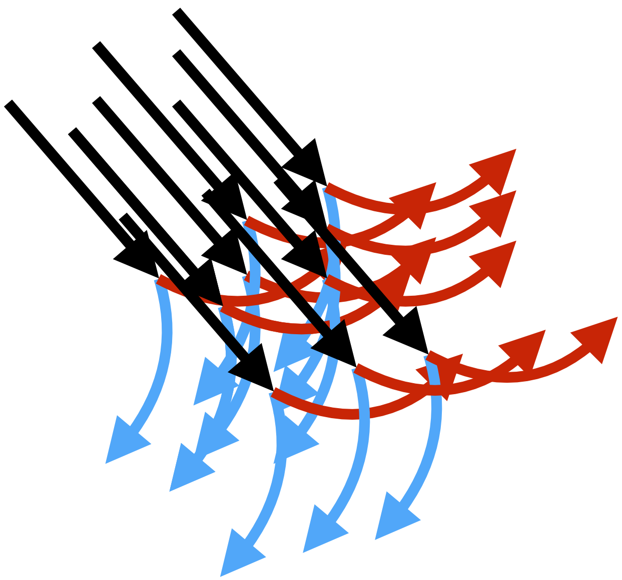
$$\vec{F} = q\vec{v} \times \vec{B}$$

Magnetic force

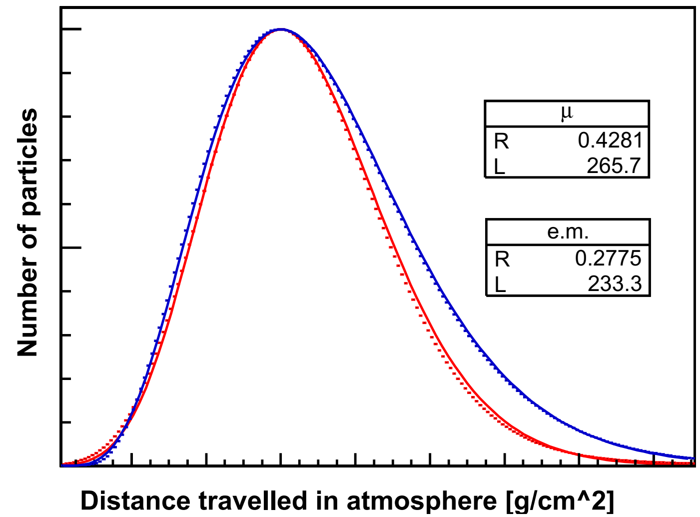
Radio

Geomagnetic effect

- In a shower: many particles
- Charge separation produces a current



- Number of particles is a function of height above ground



Radio

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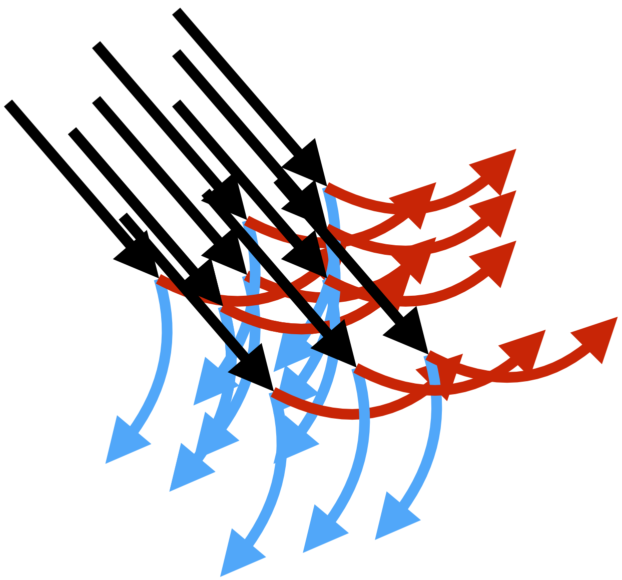

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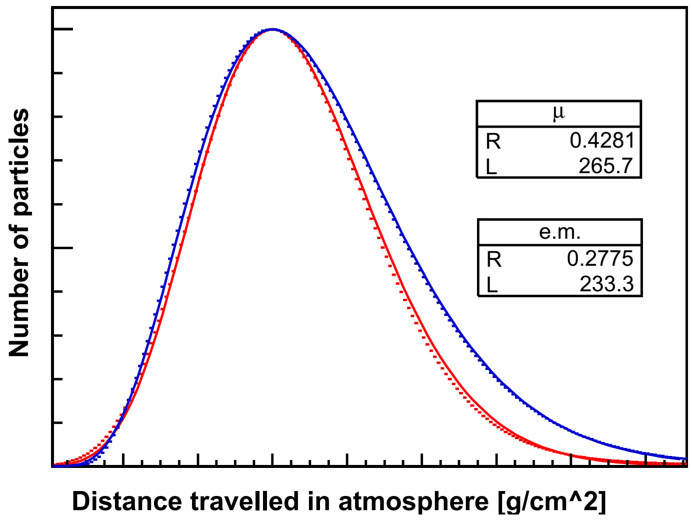
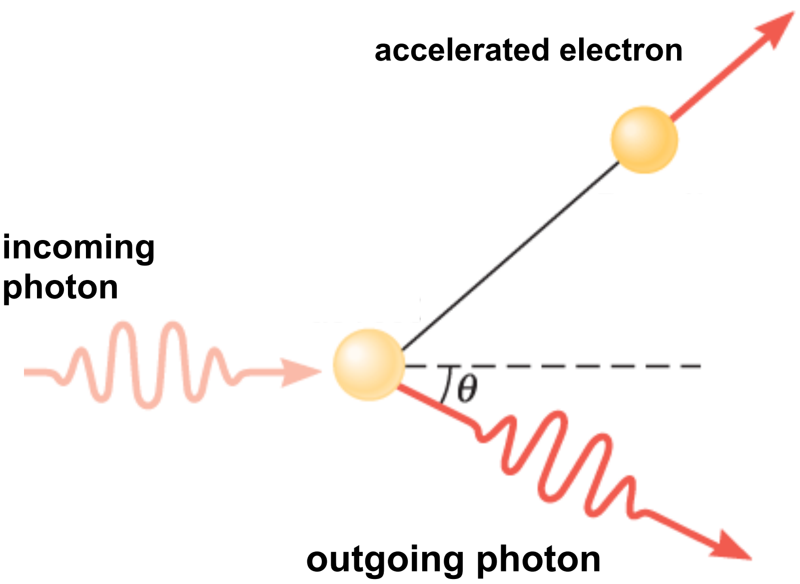


- The current changes as function of time/height
- A changing current causes electromagnetic emission

Radio emission of particle showers

Askaryan effect

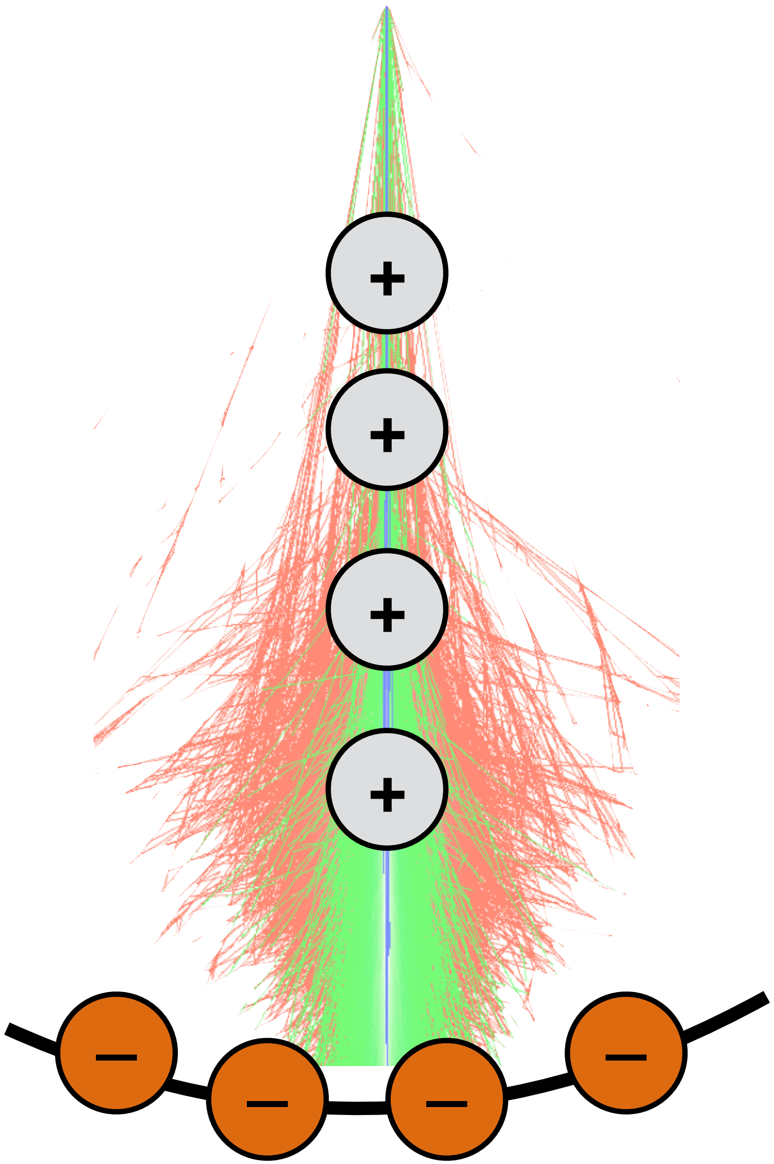
- Remember: numerous high energy photons, positrons electrons in shower
- In atmosphere: only electrons, no positrons
- Shower particles interact with particles in the atmosphere



Radio emission of particle showers

Askaryan effect

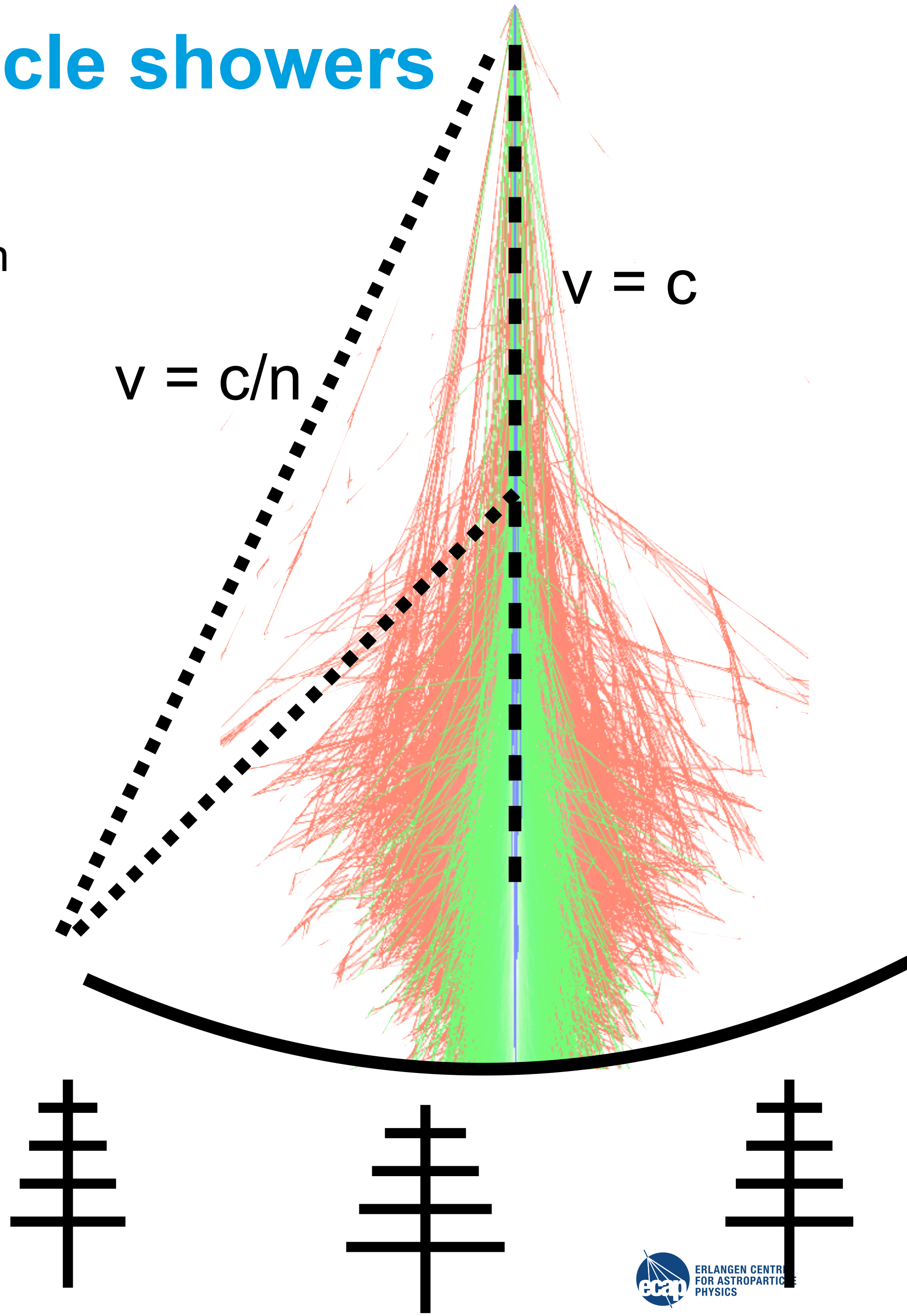
- Charge separation along axis
- Shower front is negative, axis positively charged
- Current along axis, changing as function of time/height
- Also here: changing current induces electric emission



Radio emission of particle showers

Cherenkov-like effects

- Shower is faster than its emission at n = 1.003



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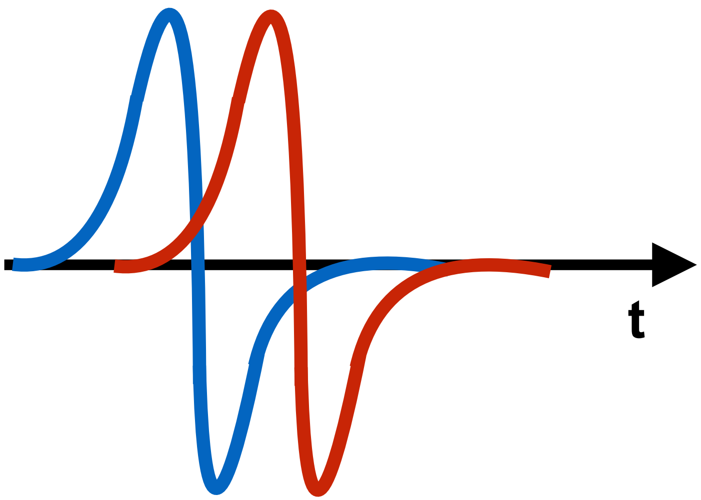
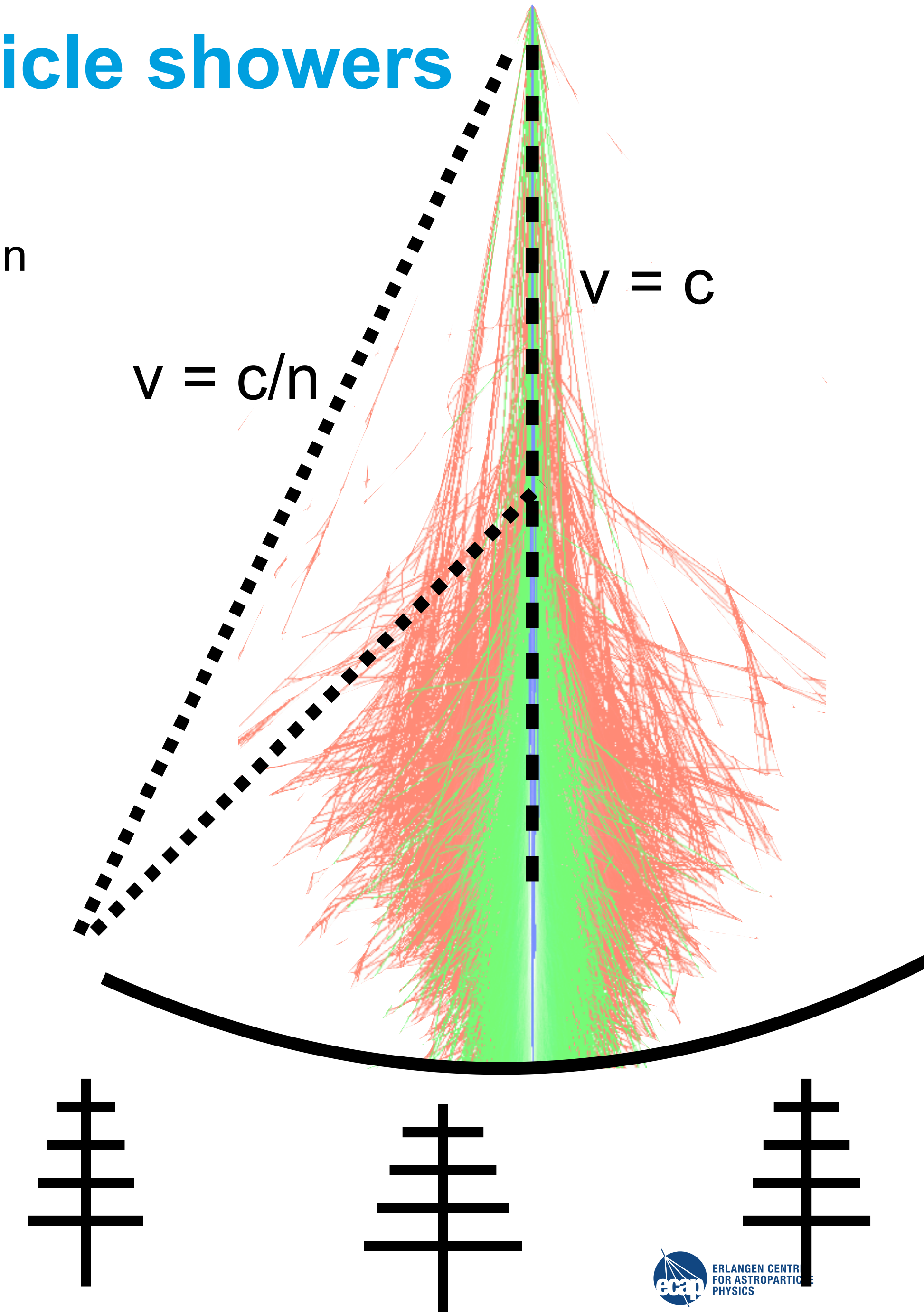


- Signal gets enhanced when it arrives in phase = coherence

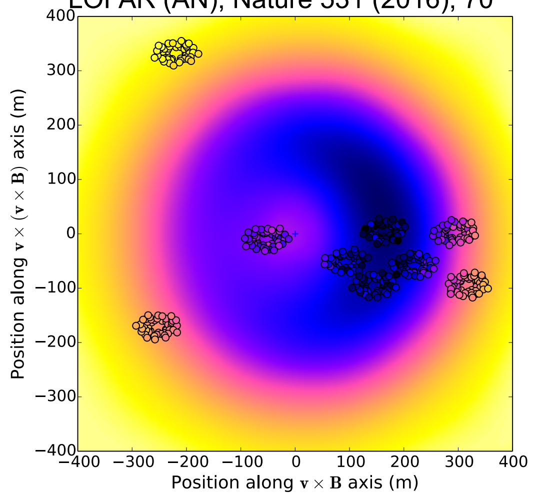
- Enhancement at the Cherenkov angle



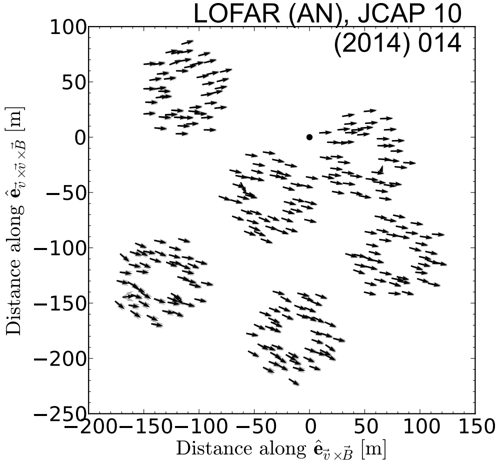
Radio emission of particle showers

We know this now, but not when we started

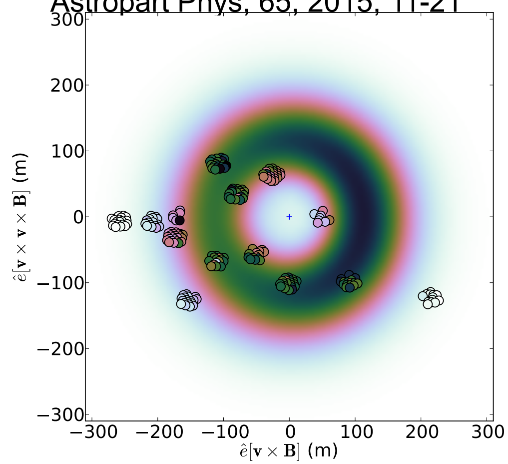
- Signal distribution ✅
- Signal amplitude ✅
- Signal polarization ✅
- Signal frequency spectrum ✅
- Dependence on magnetic field ✅
- Propagation effects ✅
- Detector characterization ✅



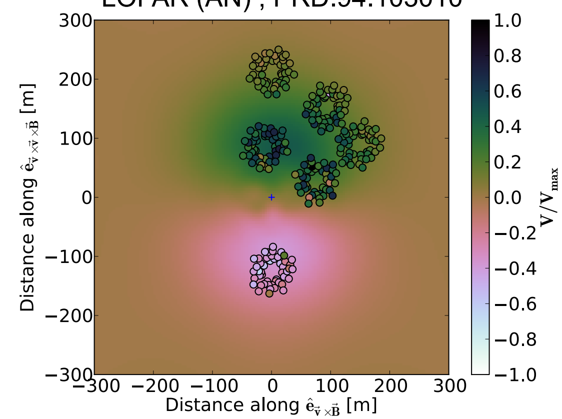
LOFAR (AN), Nature 531 (2016), 70



LOFAR (AN), JCAP 10 (2014) 014



AN et al. (LOFAR) Astropart Phys, 65, 2015, 11-21



LOFAR (AN) , PRD.94.103010

Science and the software

Status roughly 2010

- Radio detection was revisited for air shower detection
- Digital radio telescopes were coming up (like LOFAR) — additional use
- Calculations existed that indicated what an air shower signal would look like
- Software existed that was used for ‘regular’ air showers, i.e. CORSIKA or reconstruction framework of Pierre Auger Observatory
    - A couple of full-time maintainers and mostly user based software development — heritage of particle physics experiments
    - If the software doesn’t do what you want it to do, you have to write it
- Software of radio telescopes existed
    - Software maintained by observatories, users only used complete ‘pipelines’ for producing astronomical images — “the magic black box”
    - If the software doesn’t do what you want it to do, it is likely impossible

Science and the software

Structural decisions

- The format the data comes in, determines half your software set-up, for example:
- Pierre Auger Observatory:
  - originally some binary that the data acquisition spits out, it routinely converted to ROOT (CERN data and analysis framework) using a reader library (different for every detector system)
  - ROOT (used to be) fully C++ based = convenient programming language
  - main Auger software is ROOT and C++ based, with many external dependencies to read all data-formats
- LOFAR:
  - some custom version of HDF5, with a particular data access library embedded in a larger framework of analysis pipeline
  - C++ and Python in principle possible, but framework of analysis pipeline needs to be installed

Science and the software

Structural decisions

- Factors that weren’t thought about **when devising** software:
- Pierre Auger Observatory:
  - Calibration data is stored in XML files and is assumed to be (relatively) constant in time and the same for the whole array
  - Whole software was built around this idea of the detector being stable and identical — good for particle detectors
  - Poor choice for an R&D radio detector with calibration curves for every single electronics item including cables
- LOFAR:
  - LOFAR data was split in half, by polarization of antenna (same orientation of dipoles) and processed separately — good for astronomical images
  - Poor choice for air showers, where one needs to combine all data per antenna to obtain full electric field

Science and the software

Likely consequences

- "One cannot do certain analyses"
  - Not an option, physics needs to advance
- Students and post-docs hack existing software to make the analysis work
  - error-prone, lots of work, complicated (ugly) code, only works until the next problem arises
- Throw out the old software, start again from scratch to write software that actually suits the problem at hand
  - Significant time investment, risk of not finishing on time for a PhD
  - Without decent knowledge of software design, the new solution may just be as bad as the former one
  - Typically no time for documentation, user-friendliness
  - How can one be sure that the new results are correct?

Scientific software development

Some things that would be nice to consider

- “Refactor early and often” (Book: The Pragmatic Programmer)
    - for all software development, one should throw out the old stuff and start fresh — I think this is the most violated rule in scientific software development
- Requirement for refactoring: Testing the results
    - If you have an automated testing system in place, you can always ensure that the results are reproducible
- Requirement for refactoring: Modularized code
    - It is typically impossible for a small group of people to re-write the entire code, it is much more doable to refactor a smaller sub-module
- Requirement for refactoring: Patience of advisors
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INVOLVES RISK

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Scientific software development

Some things that would be nice to consider

- Who do you need for the task in an ideal world?
  - The right group of people, sometimes you have to be lucky:
  - Someone with excellent programming and computing skills
  - Someone who is willing to look at existing solutions and finds the right industry standard for this project
  - Someone with the oversight of the whole problem and project management skills
  - Someone who is willing to make the hard decisions
  - Someone with attention to detail and cleaning up after others

Scientific software development

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Very few projects have it all

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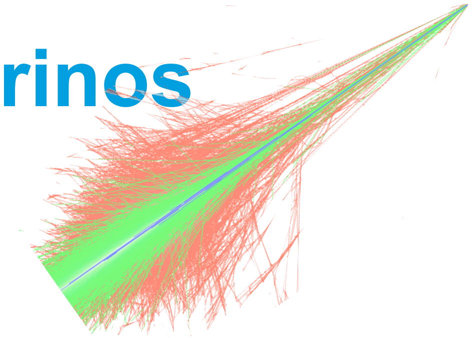
The story of radio detection of neutrinos

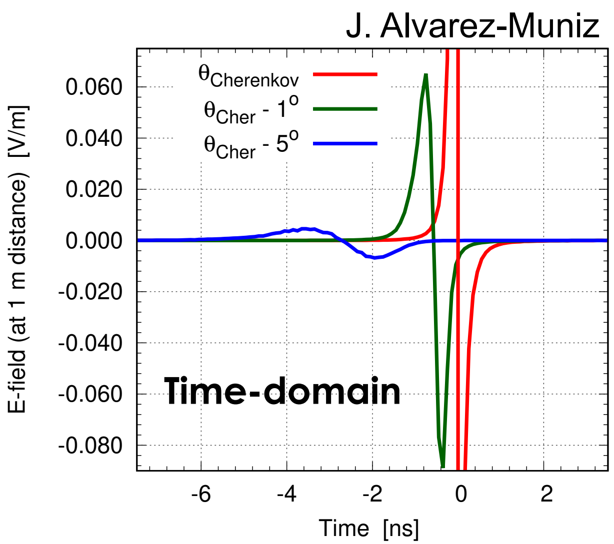
How a piece of code developed and still hindered progress

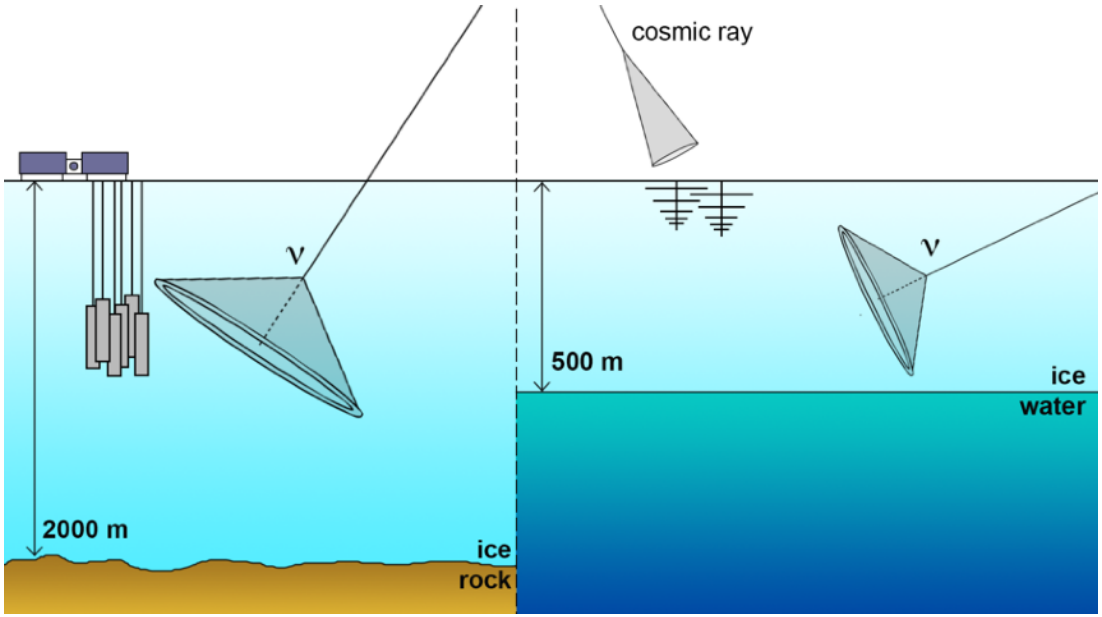


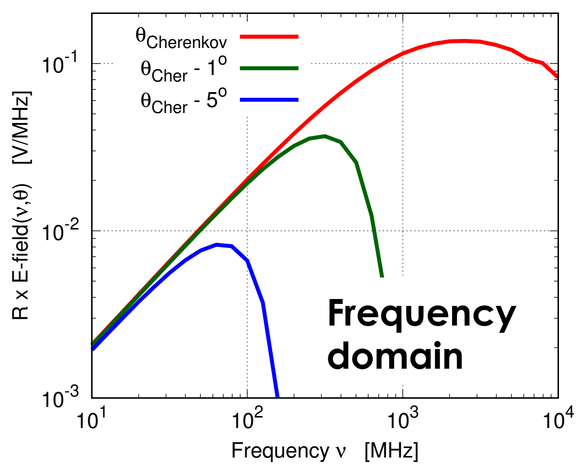
- **Starting conditions:**
  - A paper from 2000 described a theoretical parameterization of the amplitude of the radio signal of neutrinos
  - A student took this parameterization and developed a simple calculation
- **More concrete experimental ideas were developed:**
  - Piece of code was duplicated and extended
    - for a balloon to fly over Antarctica (IceMC) — assuming all emission in the far-field and a single point of detection
    - for a shallow-array of antennas on a reflective surface (ShelfMC) — assuming a regularly spaced grid of stations at the surface
    - for an array of antennas deep in the ice (ARAsim) — assuming deep stations with a regular symmetry

The story of radio detection of neutrinos

Different concepts for the same problem







- Short nano-second scale broad-band pulse
- Amplitude scales with energy of neutrino

The story of radio detection of neutrinos

The code developed (away from each other)

- **Open question: What is the most efficient detector to built?**
  - Some codes used more advanced emission models, some codes used further developed signal propagation, others better treatment of the antenna responses
  - no apples-to-apples comparison using the same code for all designs
- No code had s serious version control, with releases and automated testing (results changed with time)
- Most of the code was uselessly documented and very hard to read
- No code was fully public and installable for anyone outside the collaboration (dependencies of non-public libraries, non-public documentation)
- **Two people with really bad experiences concerning unsuitable software in the past, decided to take the risk and start from scratch**

NuRadioMC

Let's try to build software according to 'industry standards'

- Avoid custom-made solutions at any costs, use only **standard (python) libraries**
- Follow software development routines using **git**
  - Branching, pull-requests, review, commit to master, continous integration, code linting … (see next slide)
- Modularize the code
  - Every step should be exchangeable
- Make code public from Day 1
  - Including issue tracking, discussion and feature requests
- Test the results
  - Standard module sequences are automatically tested for consistency between versions

NuRadioMC

We want a community tool — but it needs rules, not anything goes

- As senior, I have the ‘best’ job now:
  - Review code
  - Complain about missing documentation
  - Ending discussions about which of the 100 options we should choose
  - Being allowed to be convinced to do things differently

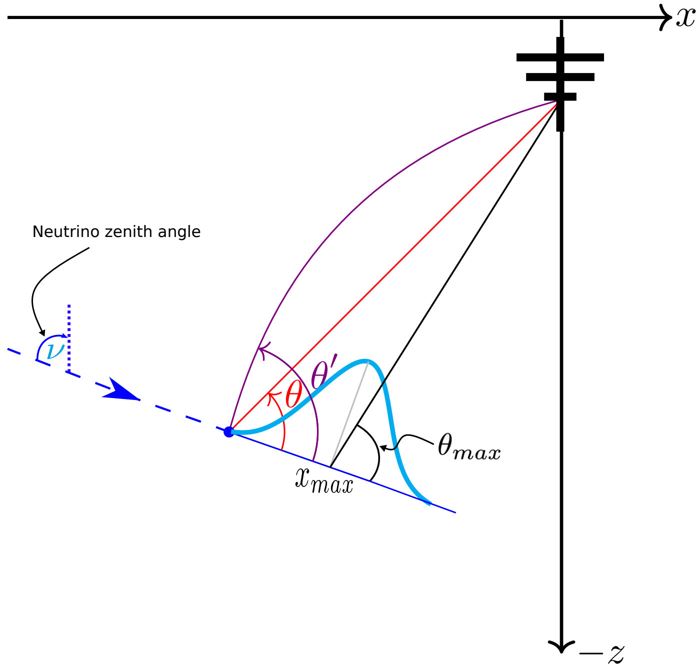
- https://nu-radio.github.io/NuRadioMC/Introduction/pages/contributing.html
- https://github.com/nu-radio/NuRadioMC

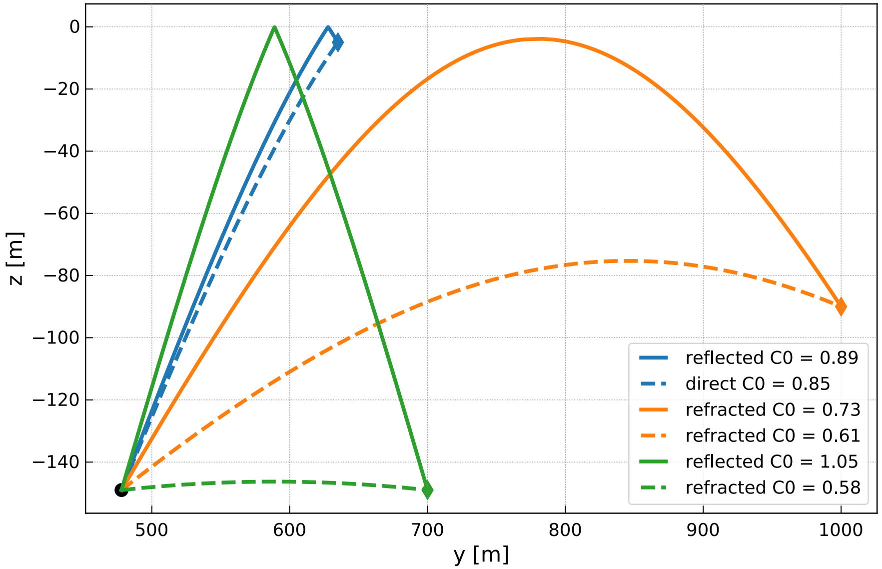
NuRadioMC

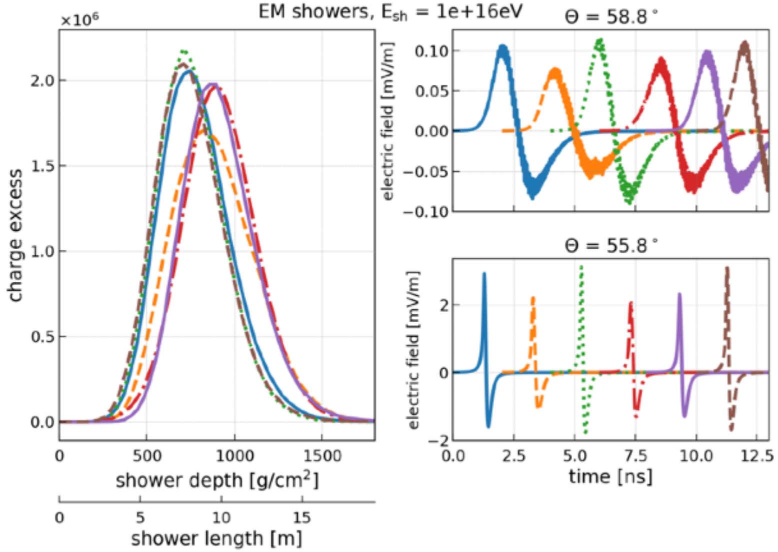
Simulation of neutrino signals

Glaser et al., European Physics Journal C 80, 77 (2020)

- https://github.com/nu-radio/NuRadioMC
- This is our current solution, my personal guess: In 5 years from now, we will start throwing it out







NuRadioMC

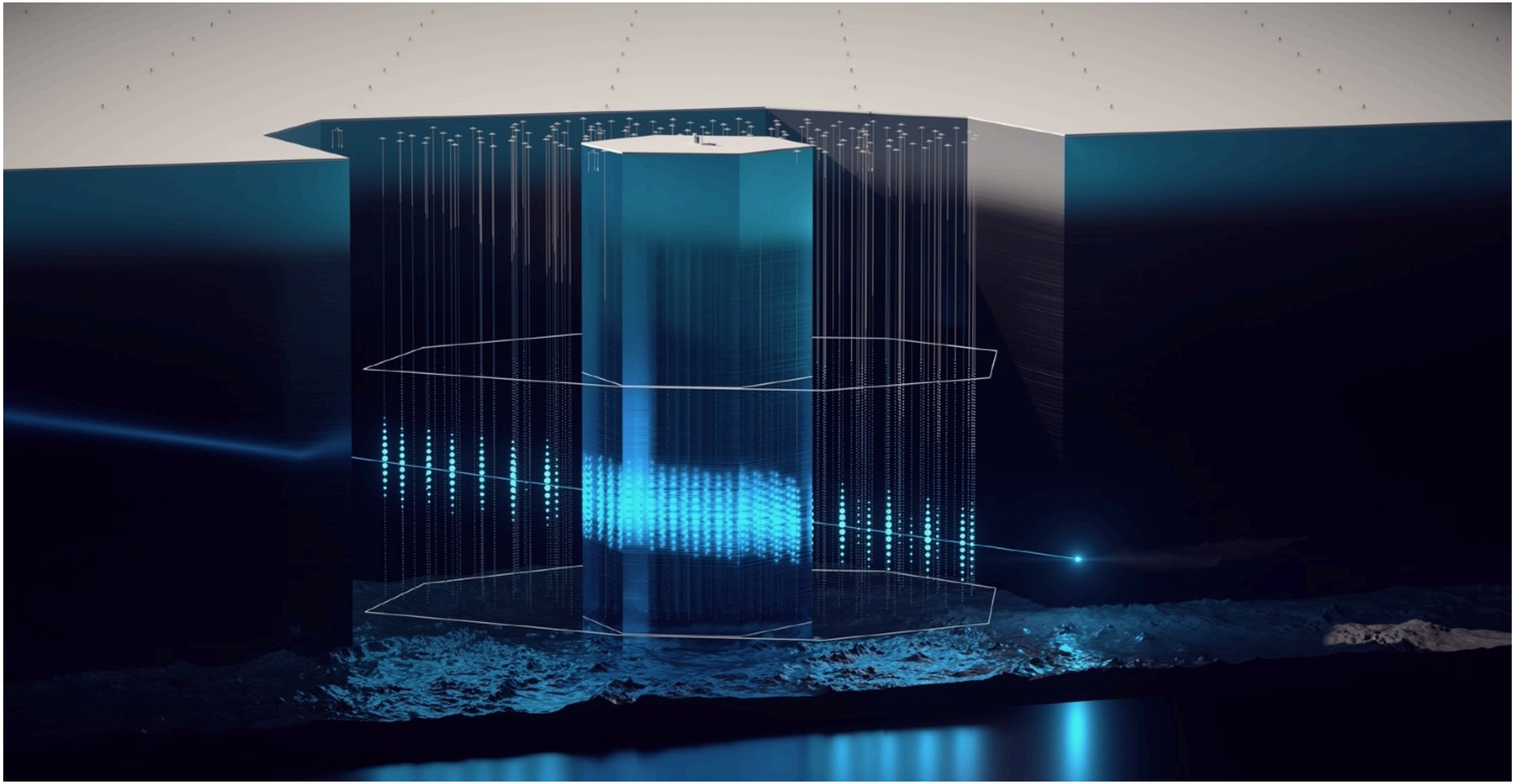
Let’s try to build software according to ‘industry standards’

- Side note:
  Core developers took a risk, but were ‘lucky’ to be in positions where freedom to do so was allowed
  - Positions funded on scholarships with scientific freedom
  - Choice paid off in the end — not necessarily the case
  - Always had ‘other projects’ on the side, i.e. a fall-back option for papers and results
- It is not like there were no hurdles to overcome
  - “Why should we trust the new software?”
  - Developers change positions in the course of writing, load fell temporarily on fewer people
  - Lucky to find students with good software development skills to support project

Why are we doing this?

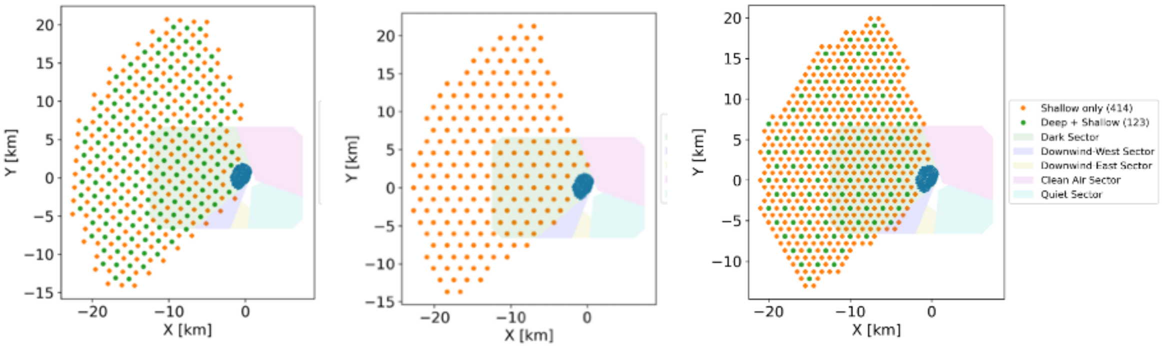
Software should follow a purpose

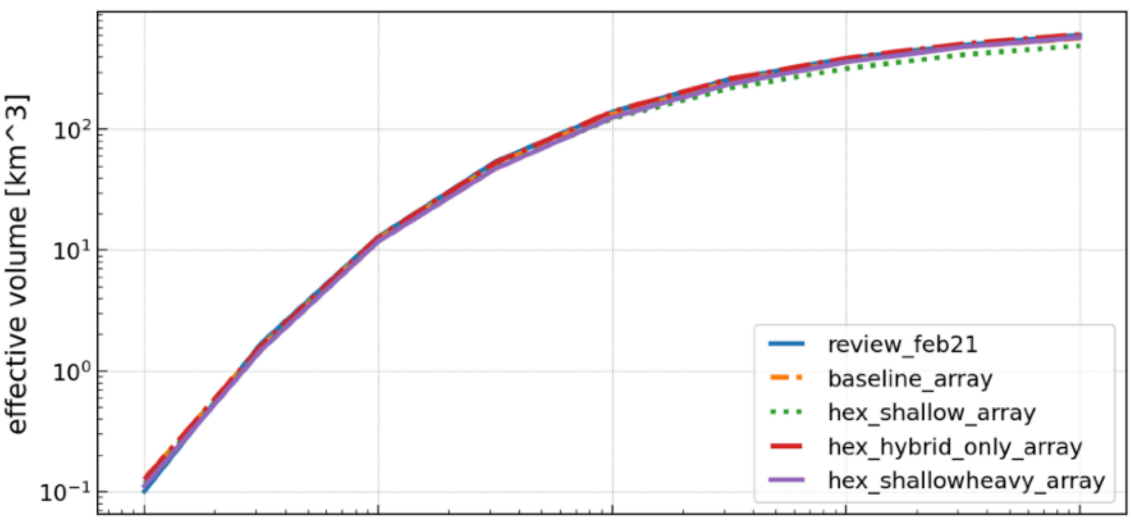
- We can now finally do all the comparisons that we had wanted to do

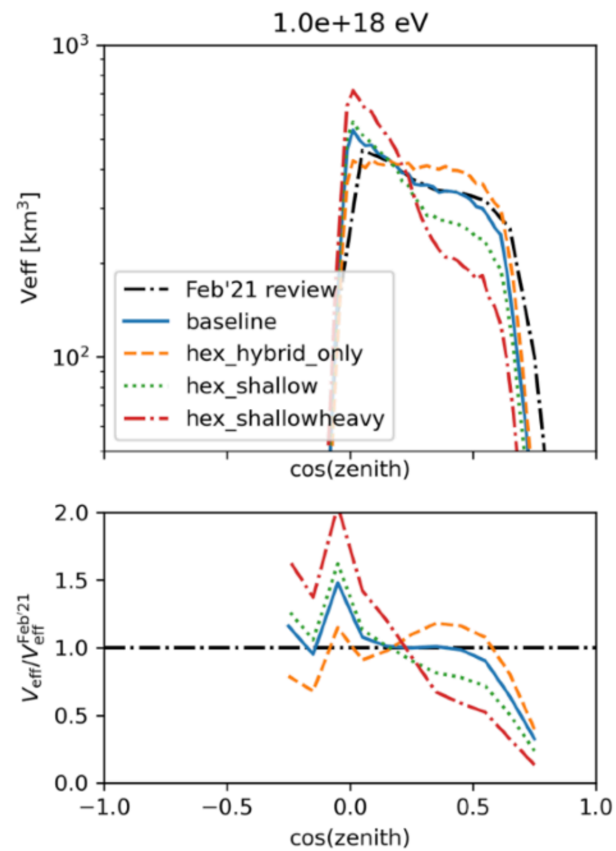


IceCube-Gen2

The reference design to move forward





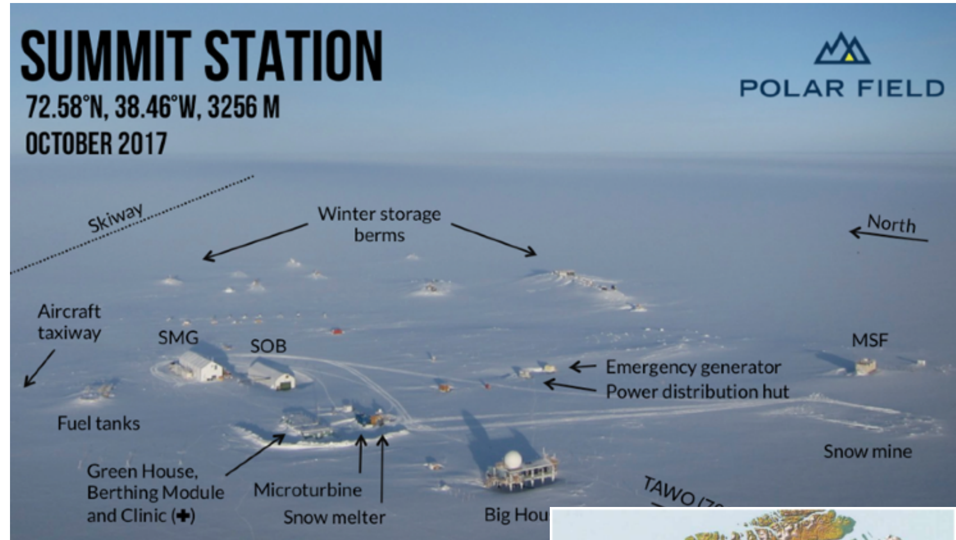


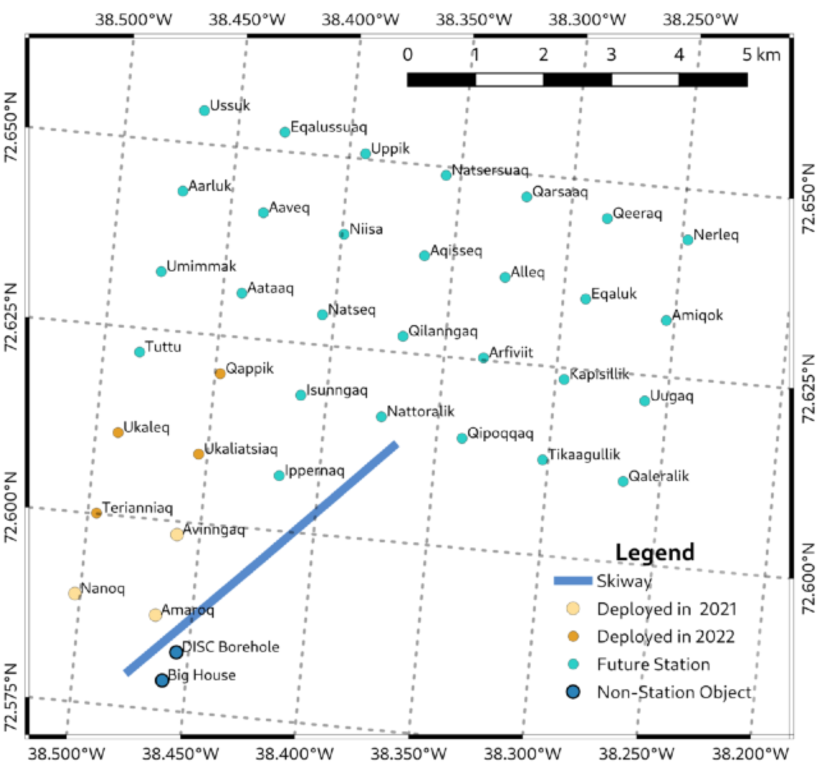
Punchline: After A LOT of CPU hours, it seems that our back-of-the-enevelope calculations weren't so bad after all — only now everyone feels better about them!

So what are we doing for now?

Getting data for all this software

Radio Neutrino Observatory

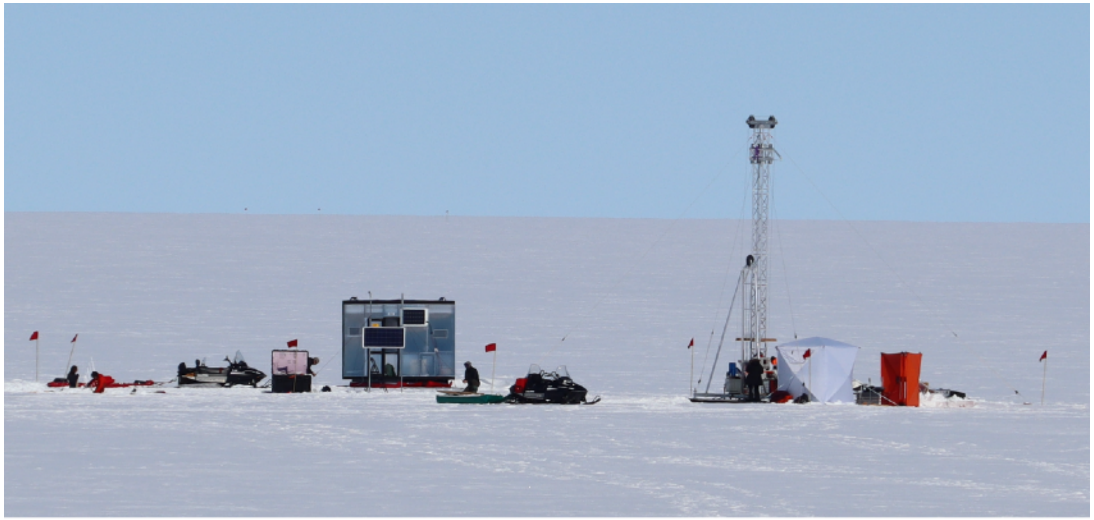


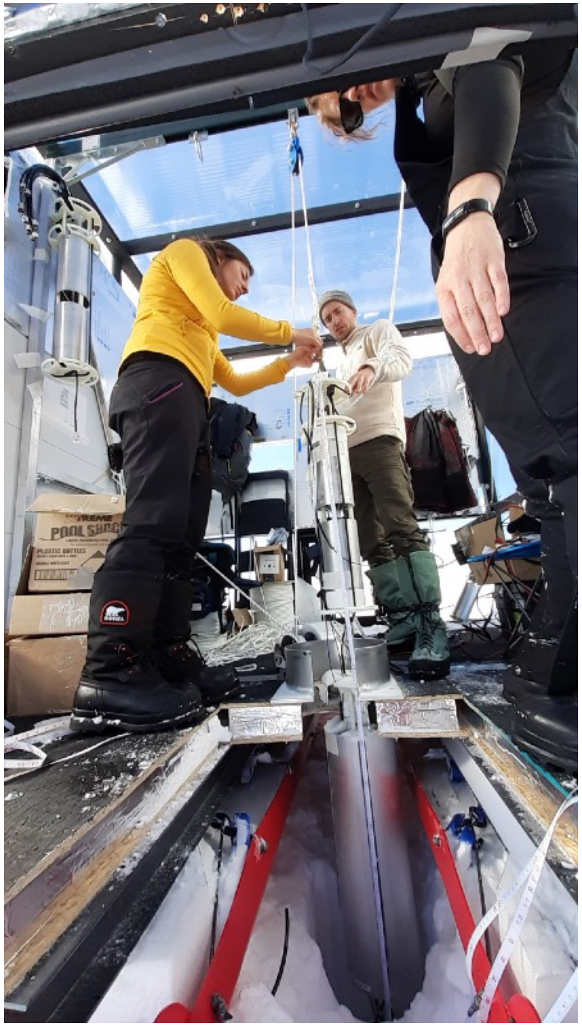


- After lots of proof-of principle experiments: first scale-up to large array

The RNO-G approach

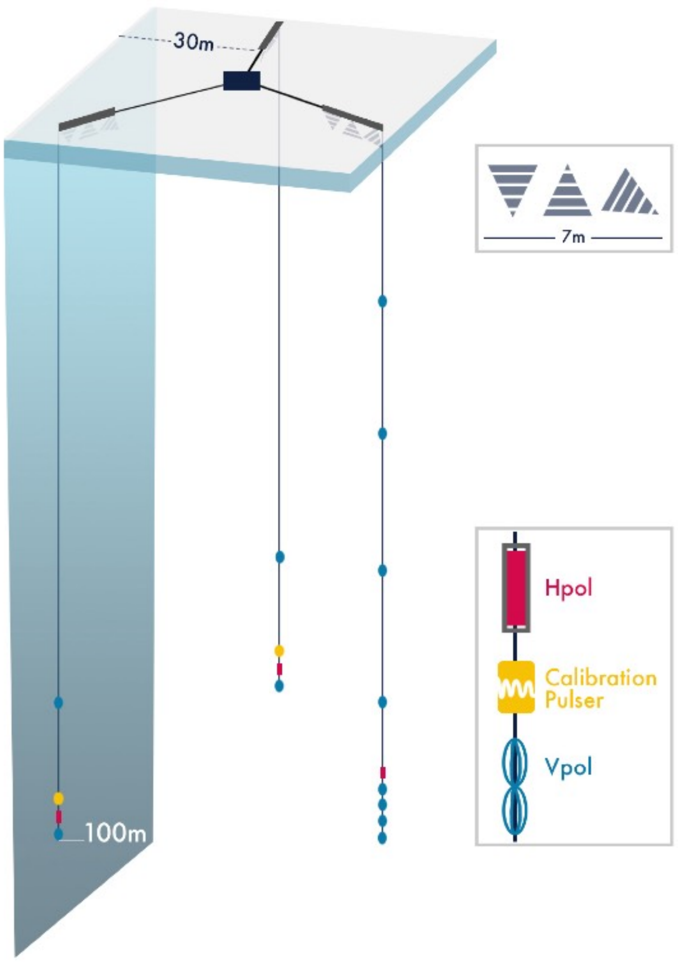
What we are building





The RNO-G approach

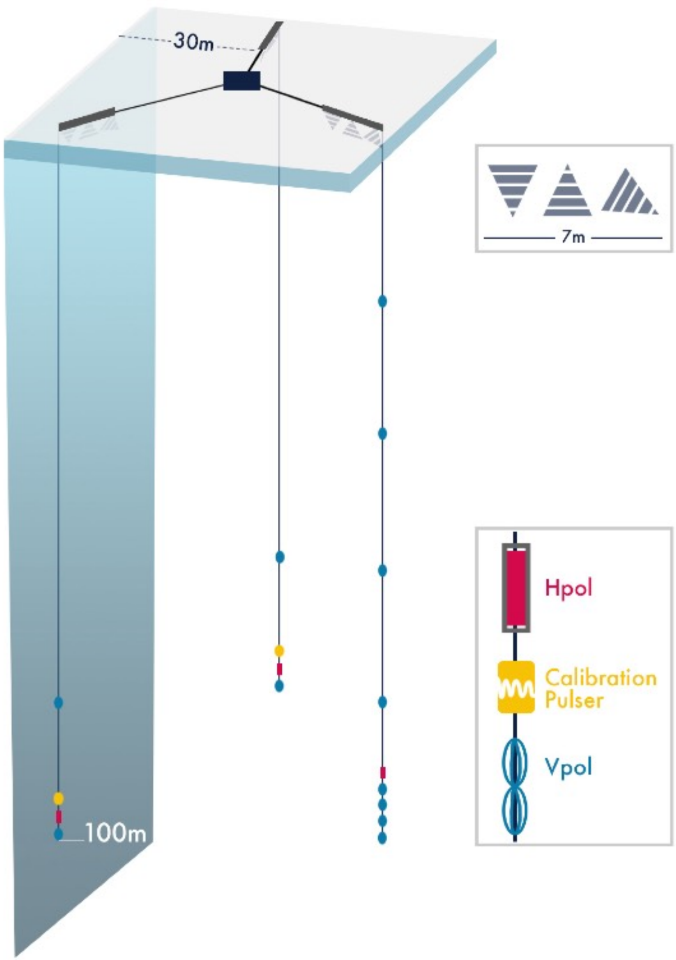
The single components



- Log-periodic dipole antennas (**LPDA**) at the surface:
- High-gain antennas with very good response to neutrino signals, but too big to fit in a hole
- At the surface subject to ray-bending = not all trajectories reach these antennas
- Antennas at the surface also act as cosmic ray veto
- 3x3 antennas to detect all arrival directions and polarizations

The RNO-G approach

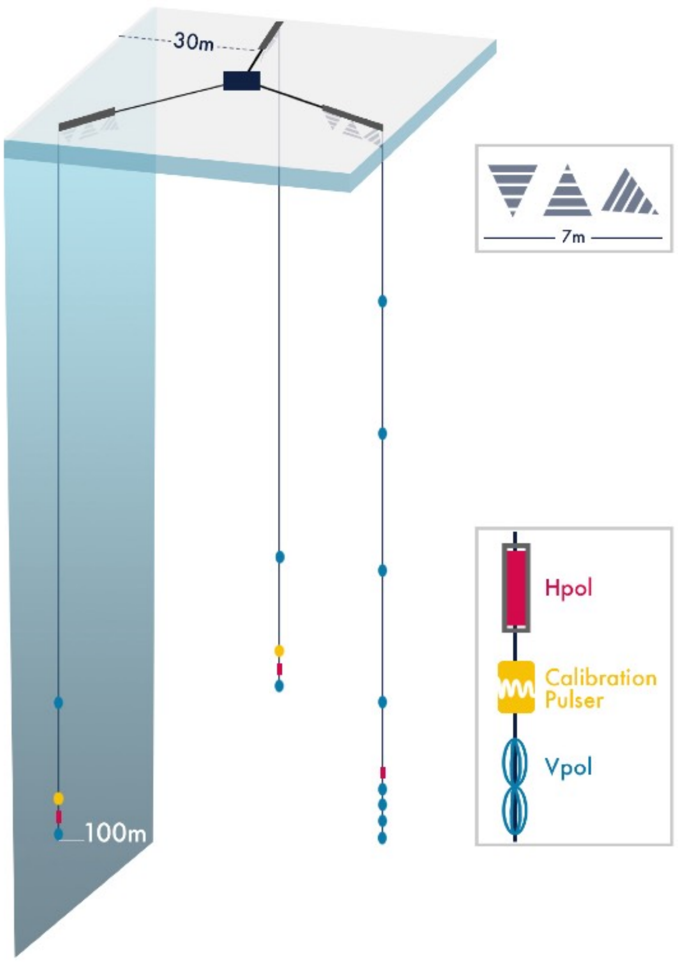
The single components



- Bicone antennas and quad-slot antennas in 100 meter deep holes
- the deeper the better (ray shadowing)
- 100 meters achievable with a fast mechanical drill (cheap)
- two different types of antennas to cover all polarizations
- small antennas have less gain and are typically less broad-band

The RNO-G approach

The single components

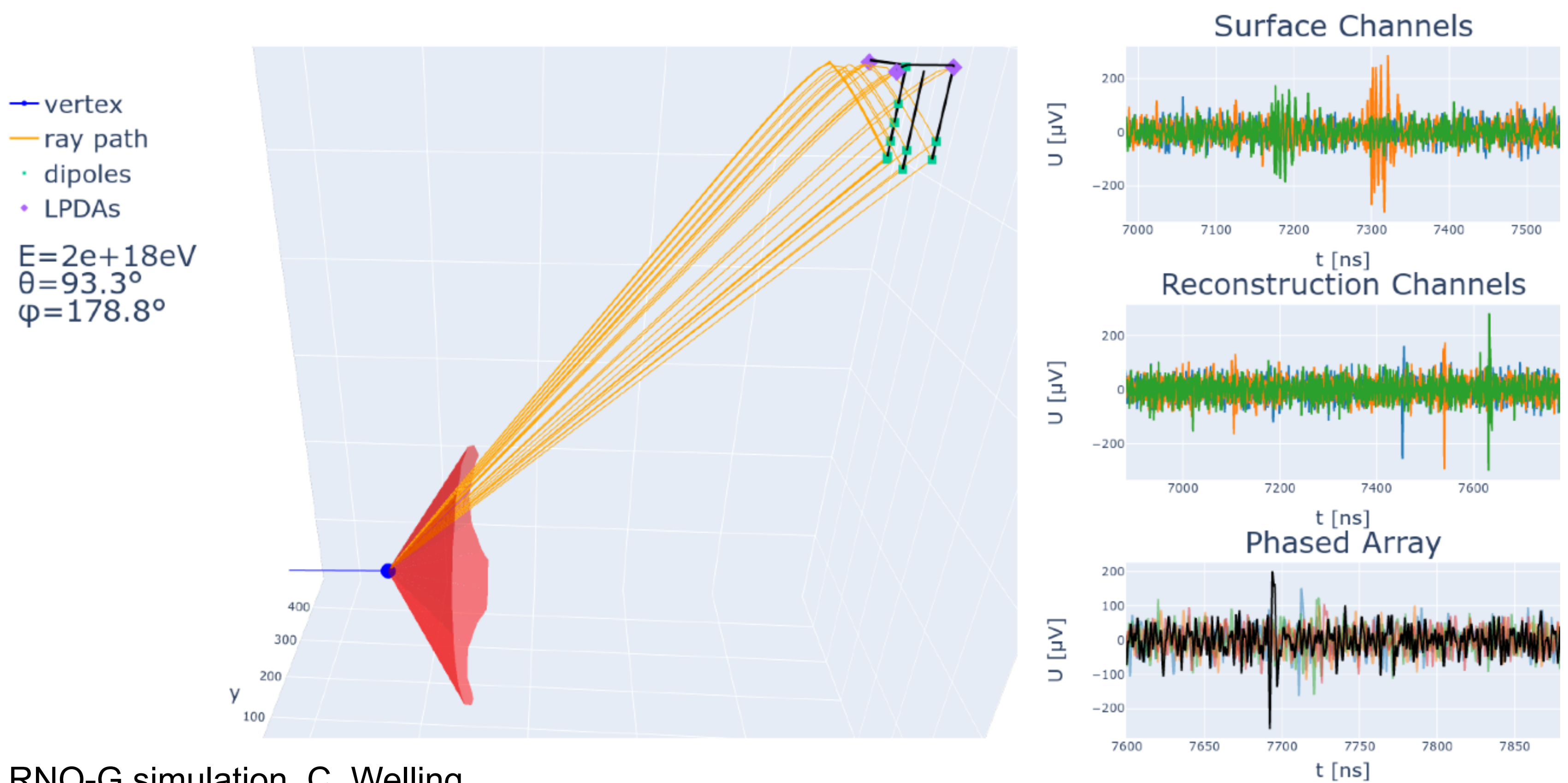


- Station geometry:
- Three strings to reconstruct arrival direction
- One string with many antennas to make the reconstruction of the vertex distance a one-dimensional problem
- String also hosts the phased array trigger
- The lower the threshold the better the sensitivity

The RNO-G approach

More on Friday!

What do the signals look like



Full RNO-G simulation, C. Welling

Software development:
Always make nice visualization tools, increases the number of users

Conclusions

Scientific Software development

- It is not that different from industry software development, but we are all not trained for that
- Additional hurdle: we don’t know what science will be important later and a first iteration always makes assumptions
- Bad software should no longer be acceptable: it is a time sink and precludes scientific results