Application of the radio detection technique in neutrino astronomy

Christian Glaser

CARL TRYGGERS STIFTELSE
FÖR VETENSKAPLIG FORSKNING
Swedish Research Council
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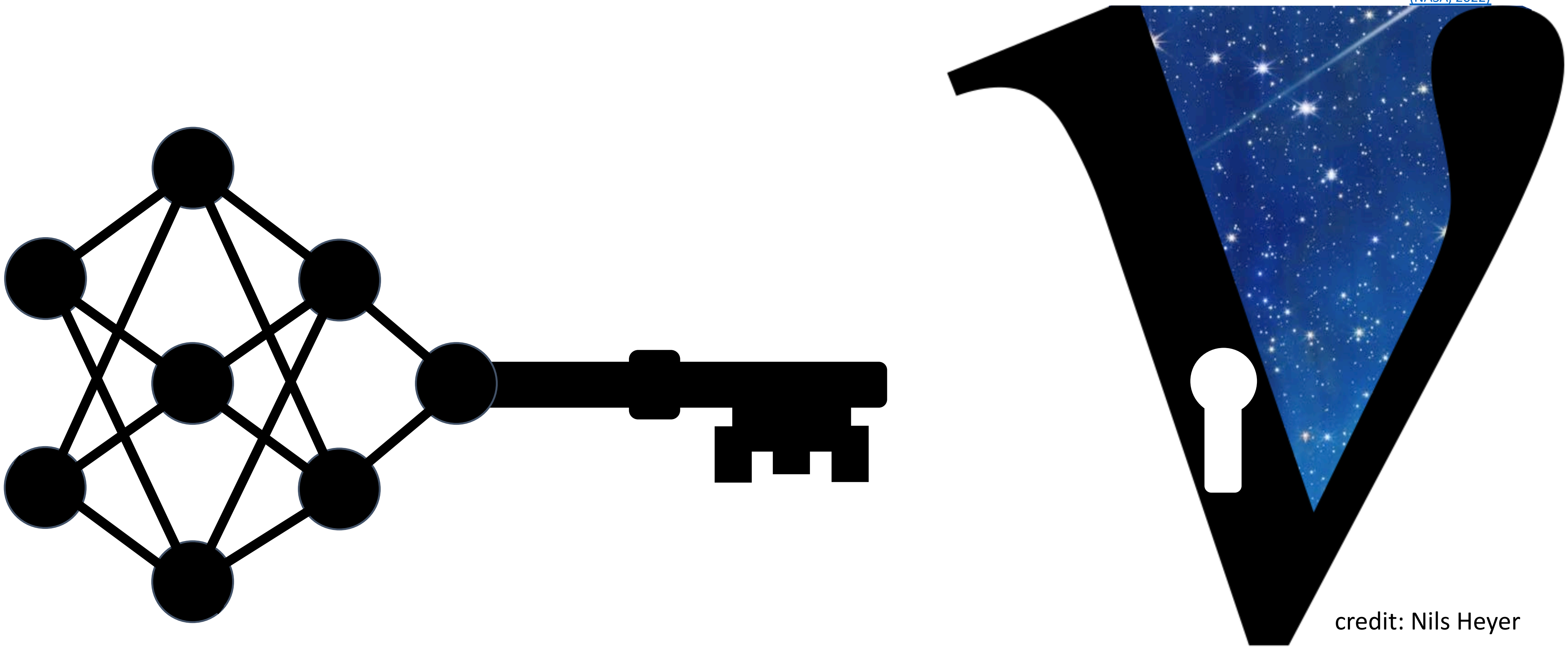
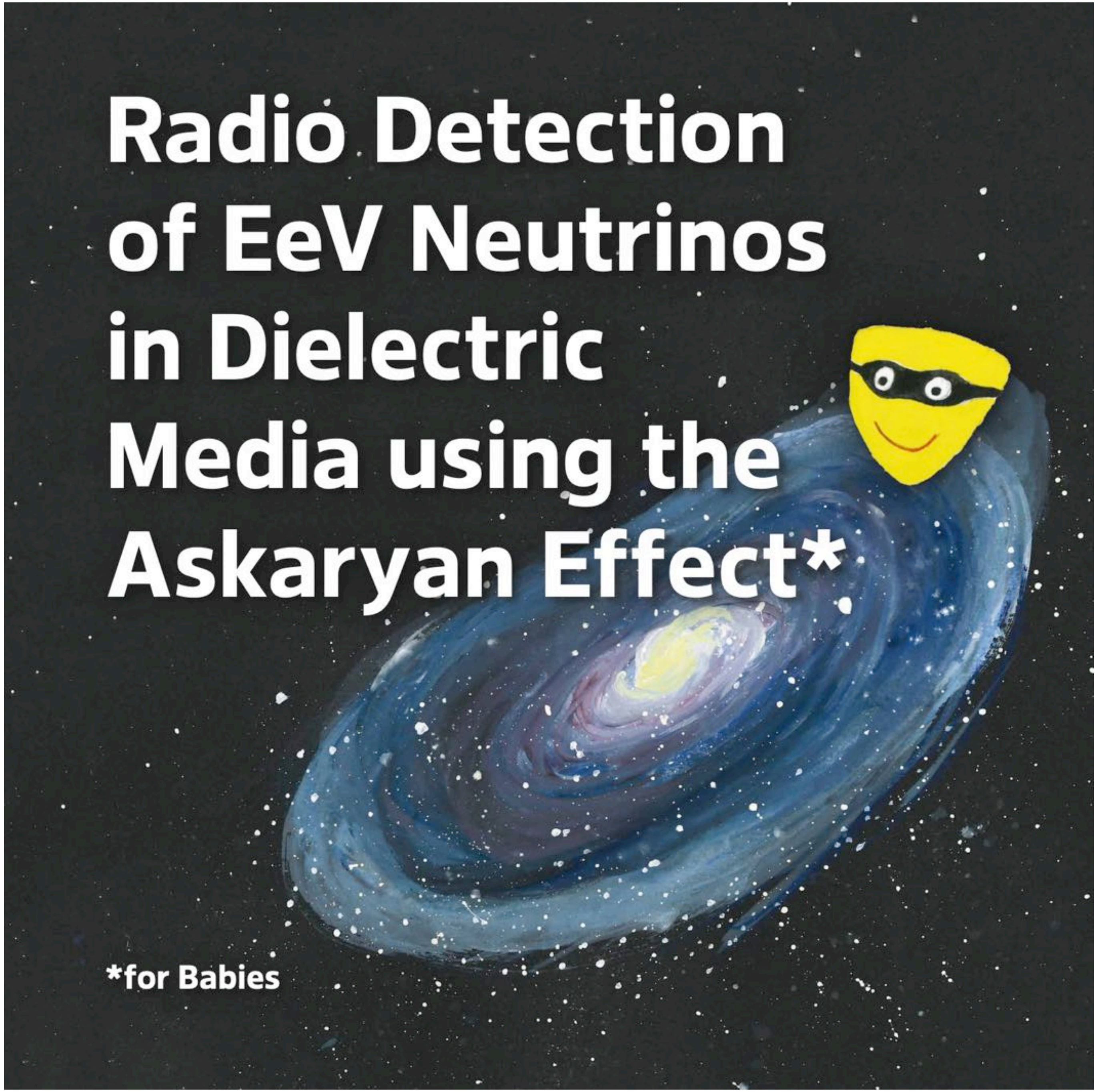
European Research Council
Established by the European Commission
Co-funded by the European Union
UPPSALA UNIVERSITET



(NASA, 2022)

credit: Nils Heyer



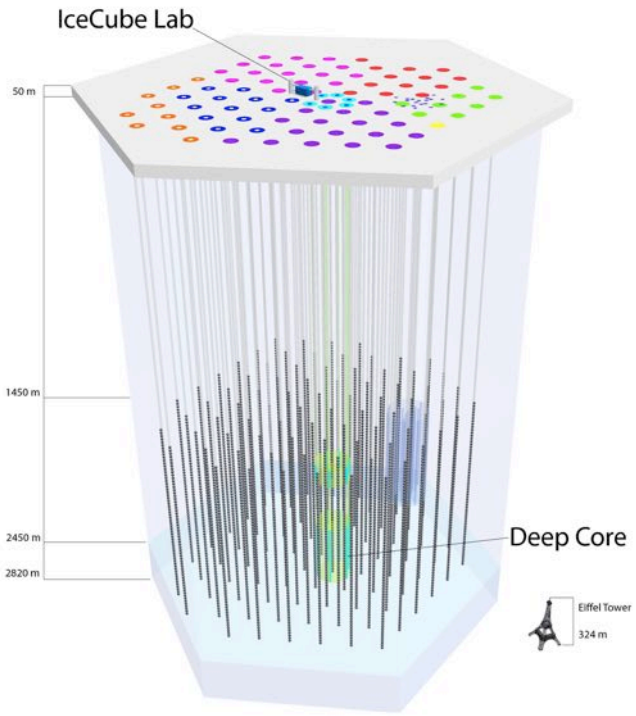
Link to Book

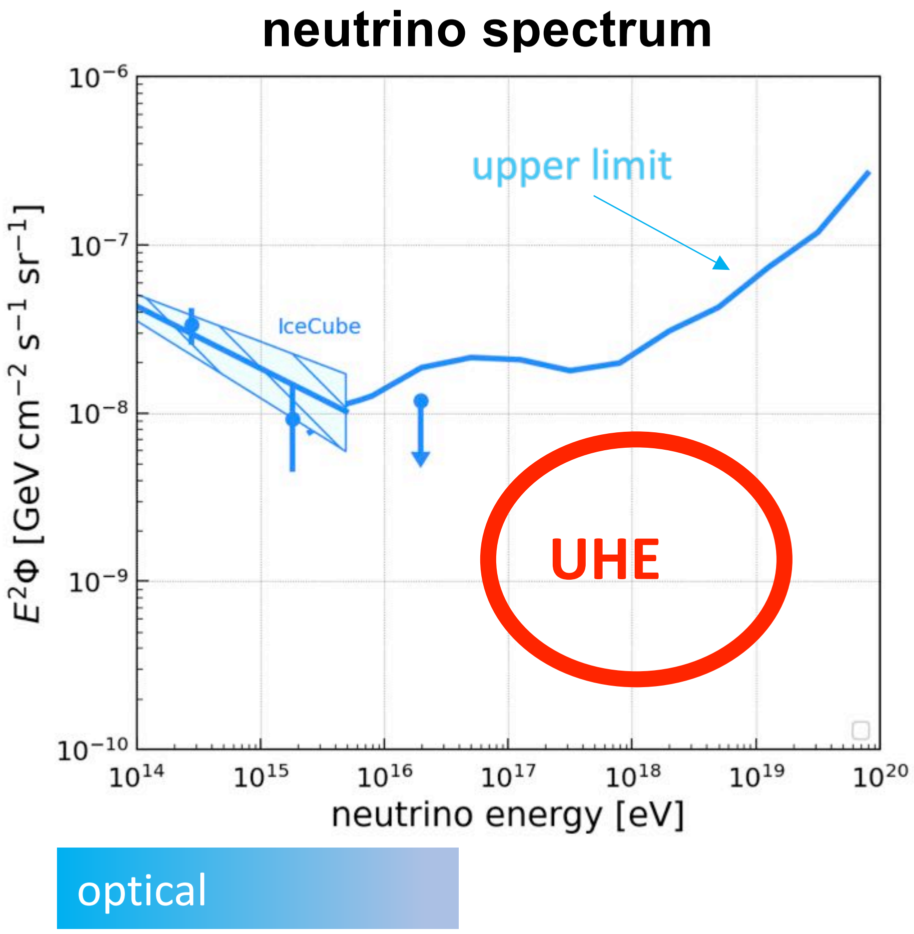
doi:10.3204/PUBDB-2021-03021

Experimental Challenges

- Low interaction cross section of neutrinos
- Very low neutrino flux

→Very large volumes needed for reasonable rates



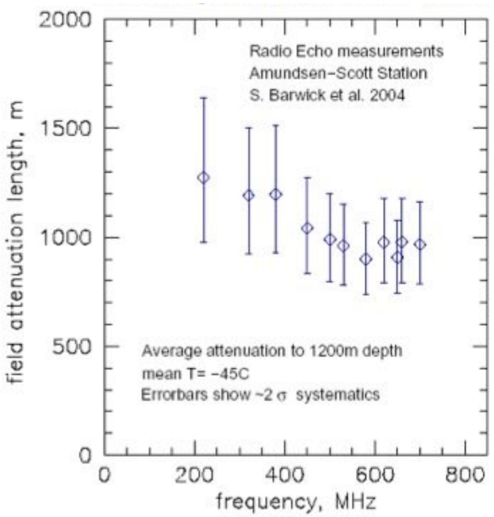


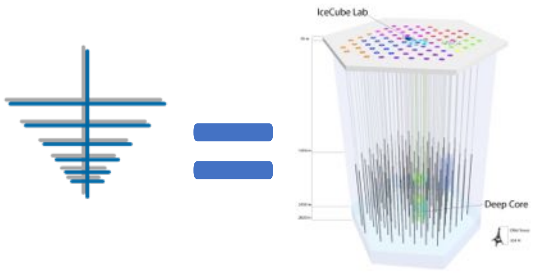
Experimental Challenges

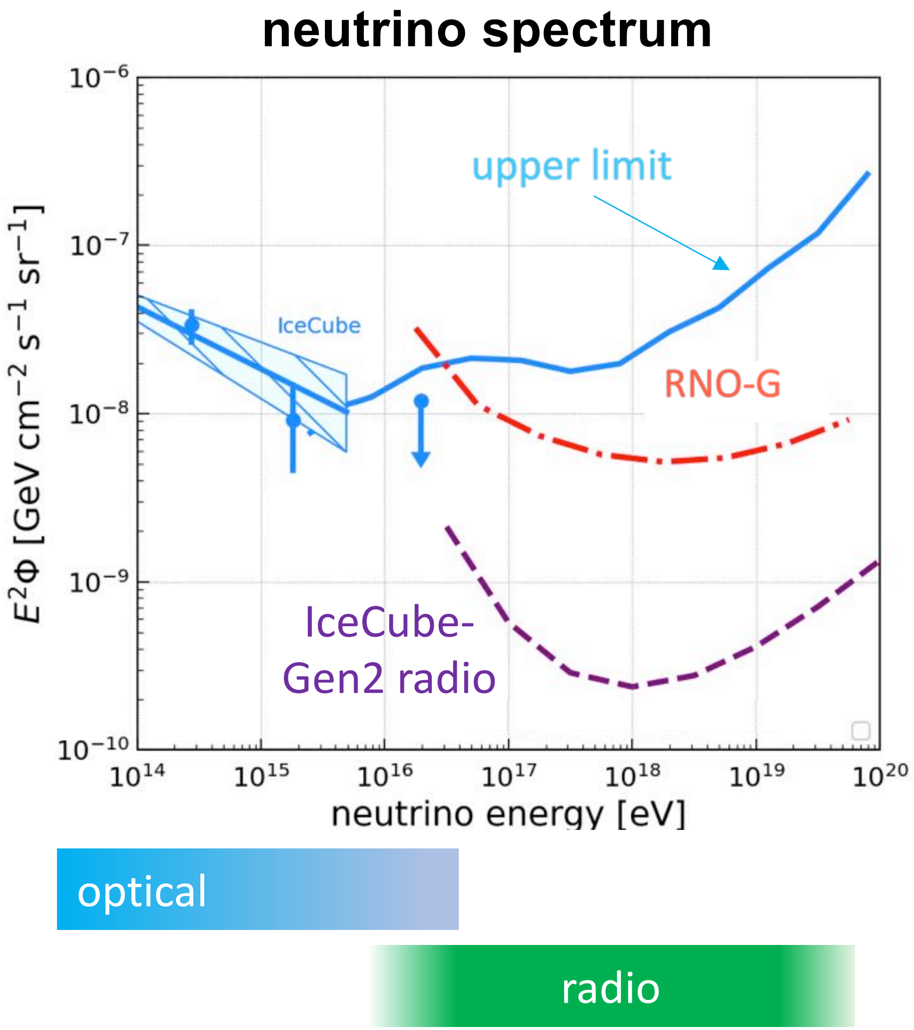
- Low interaction cross section of neutrinos
- Very low neutrino flux

→Very large volumes needed for reasonable rates

- **Solution: radio technique**
  - Large volumes at no cost: Antarctic ice
  - Ice transparent to radio waves (L ~ 1km)
  - A single radio station has 1km³ effective volume (comparable to IceCube)



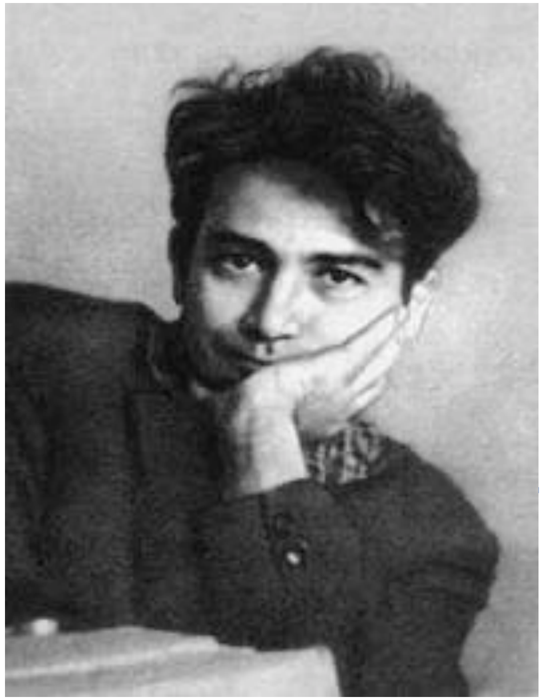


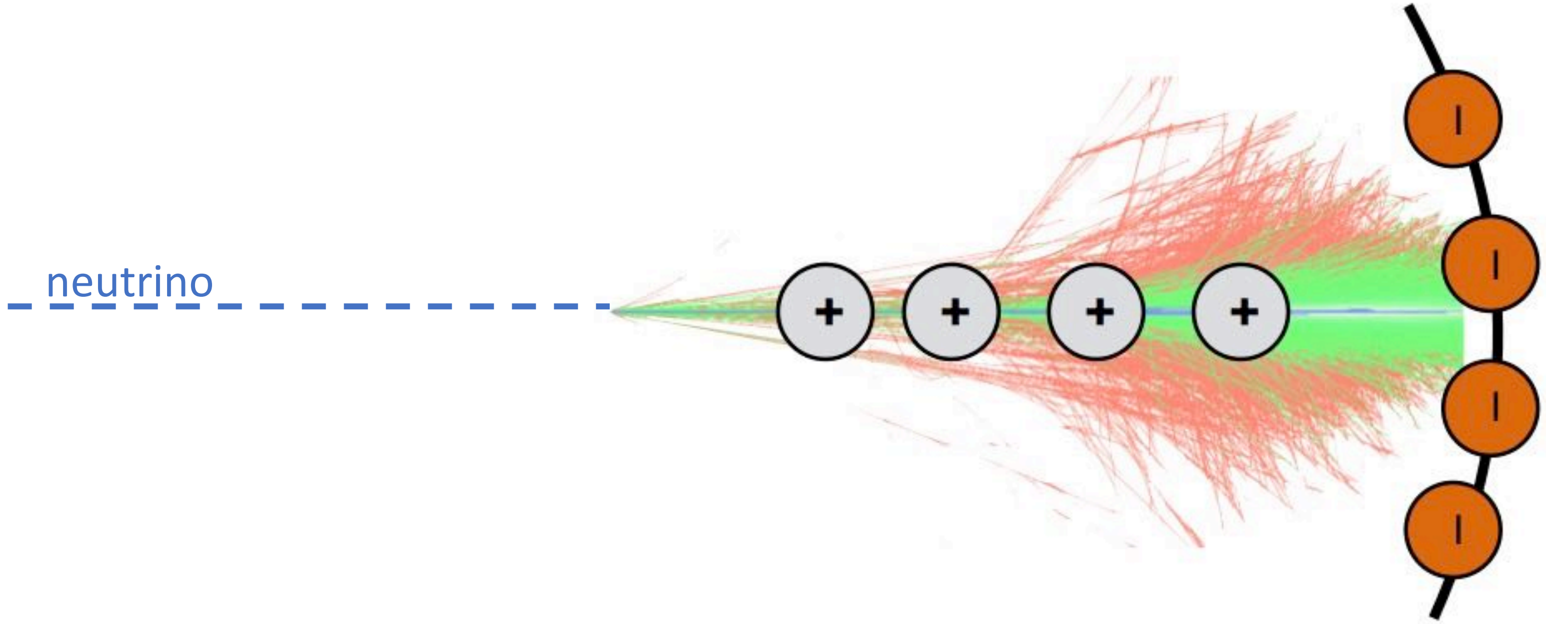


Expected event rate: a few per year but background free

Radio Emission of Particle Showers

- Askaryan effect: Time varying negative charge excess in the shower front
- Macroscopic: Longitudinal current





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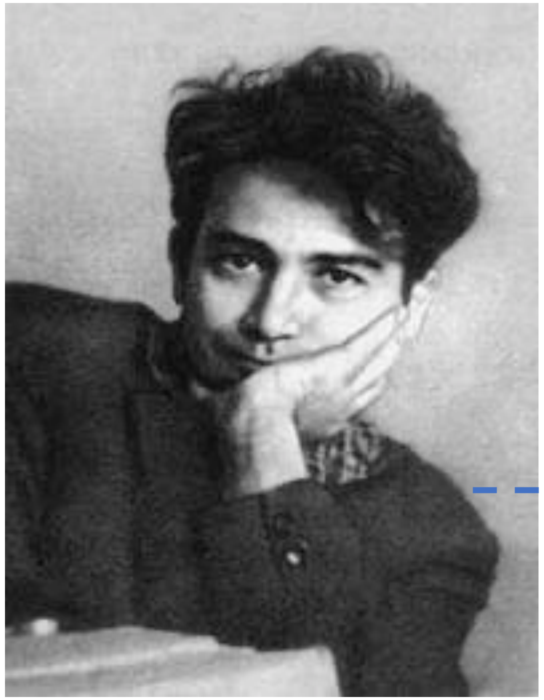

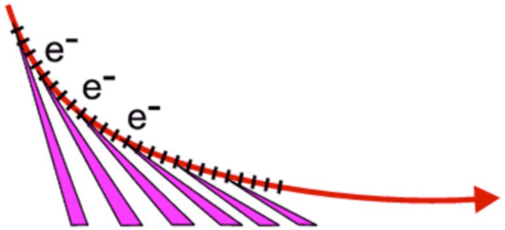

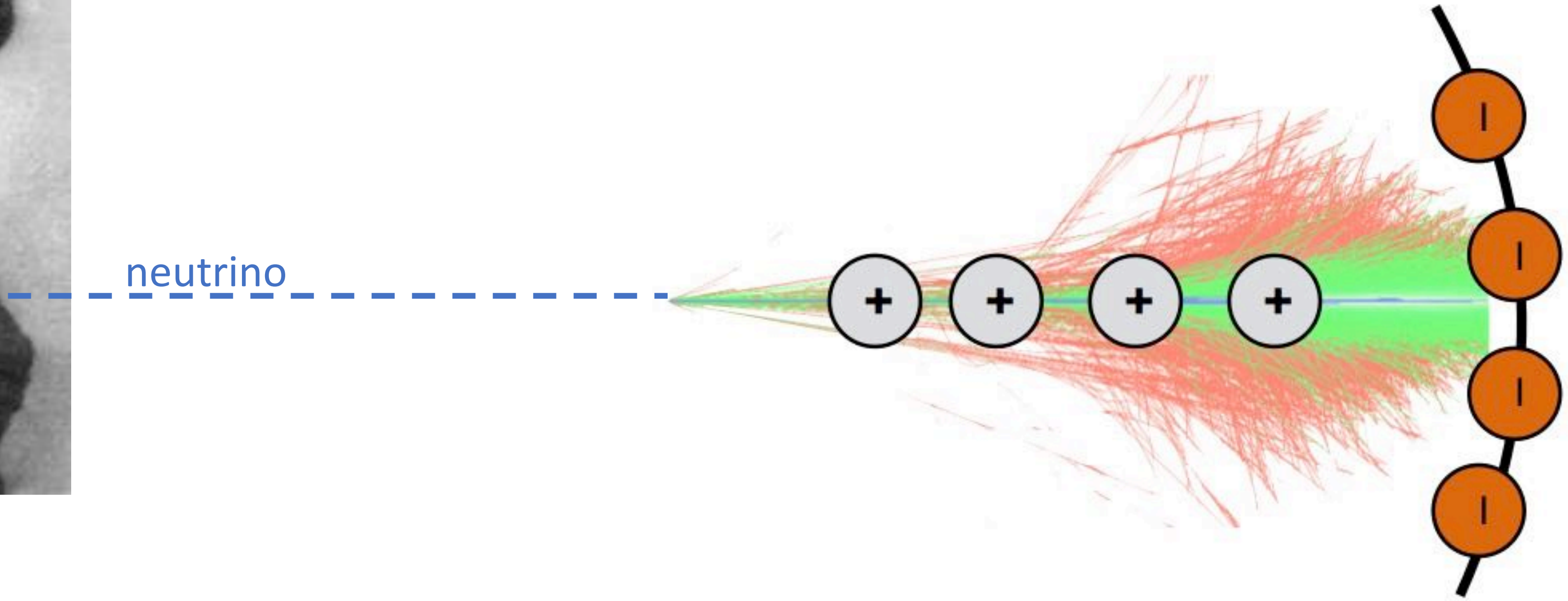

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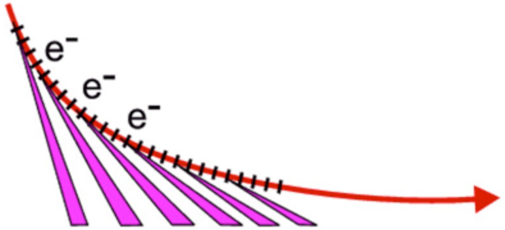
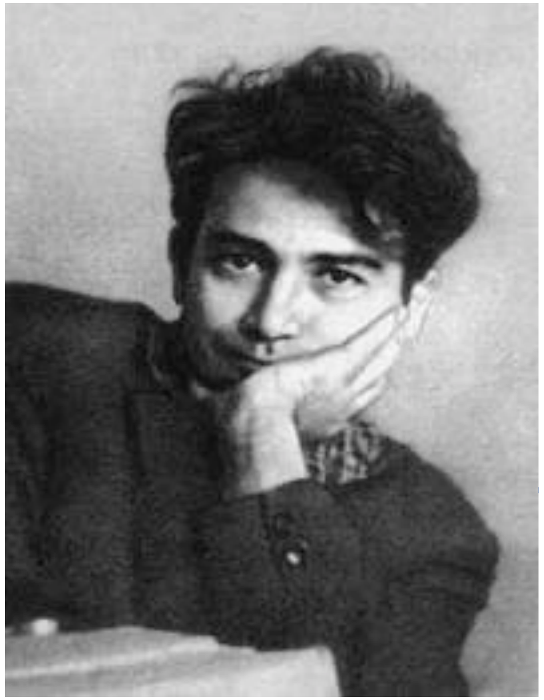
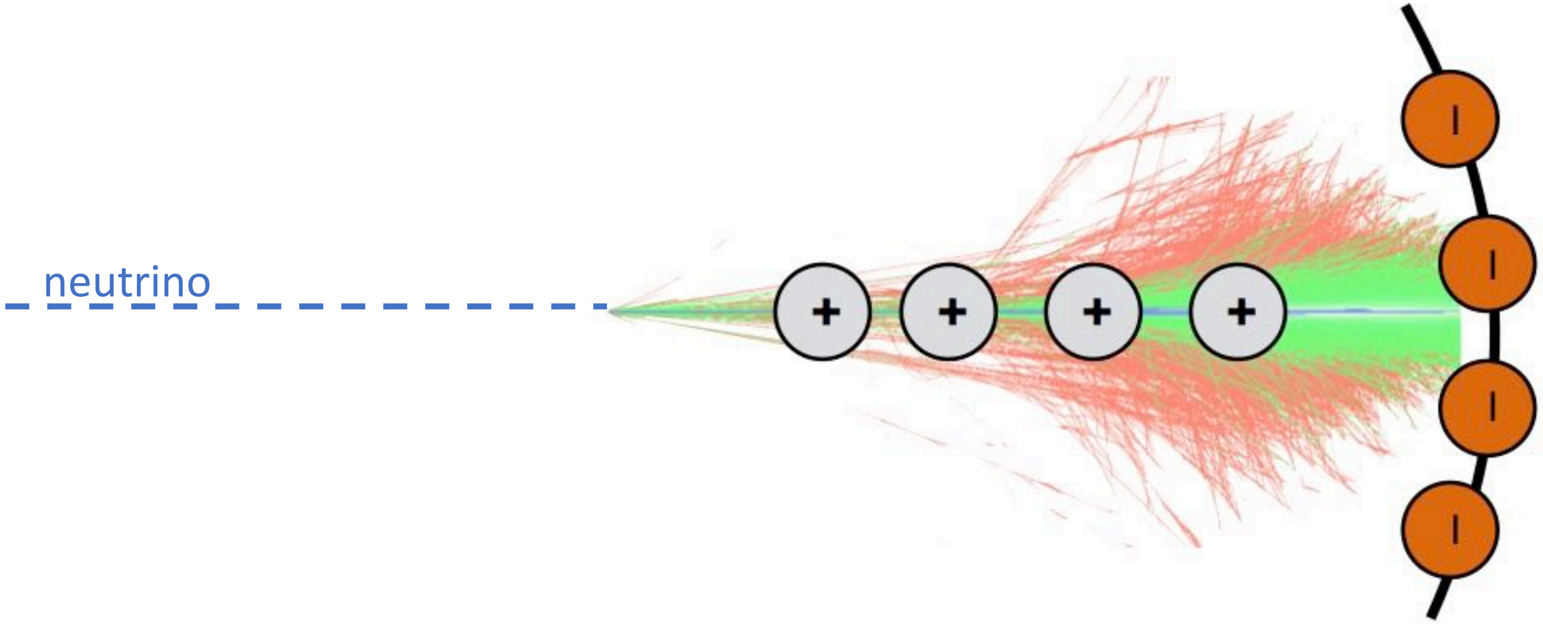




ice n=1.78



Christian Glaser

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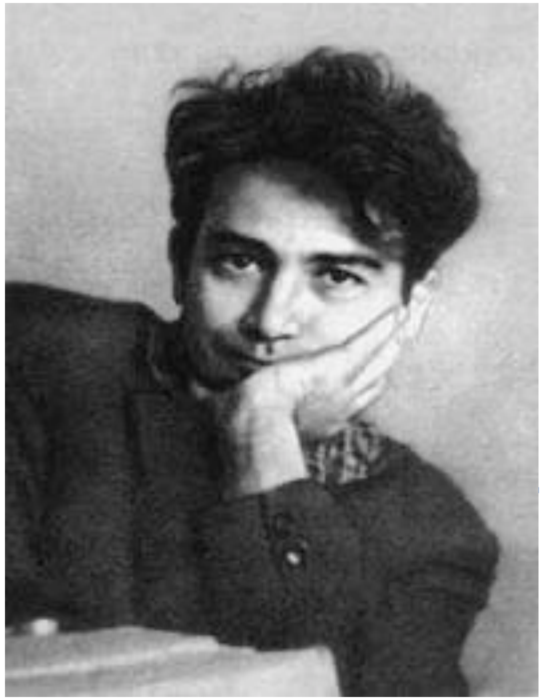
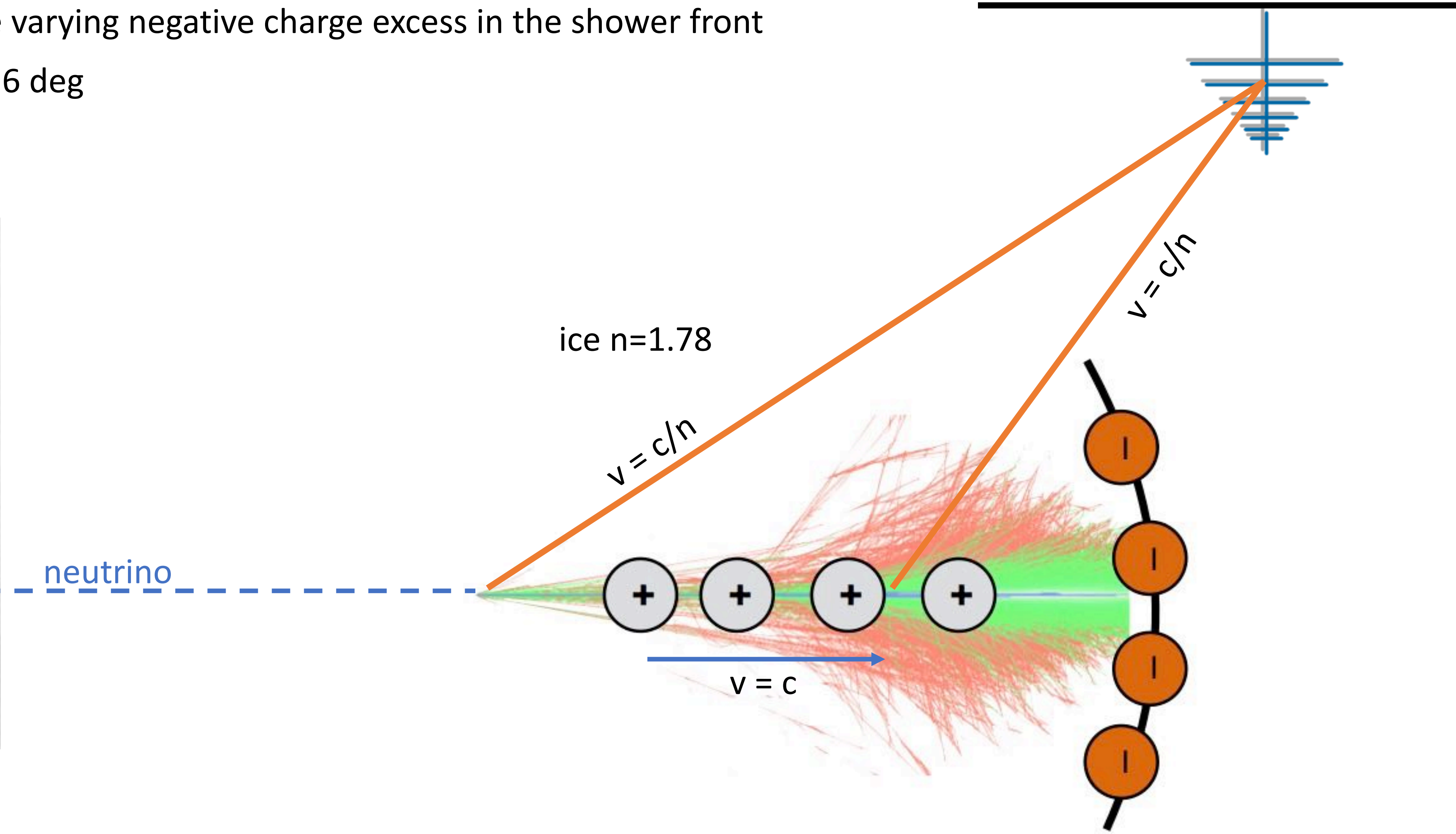
- In ice: arccos(1/n) = 56 deg





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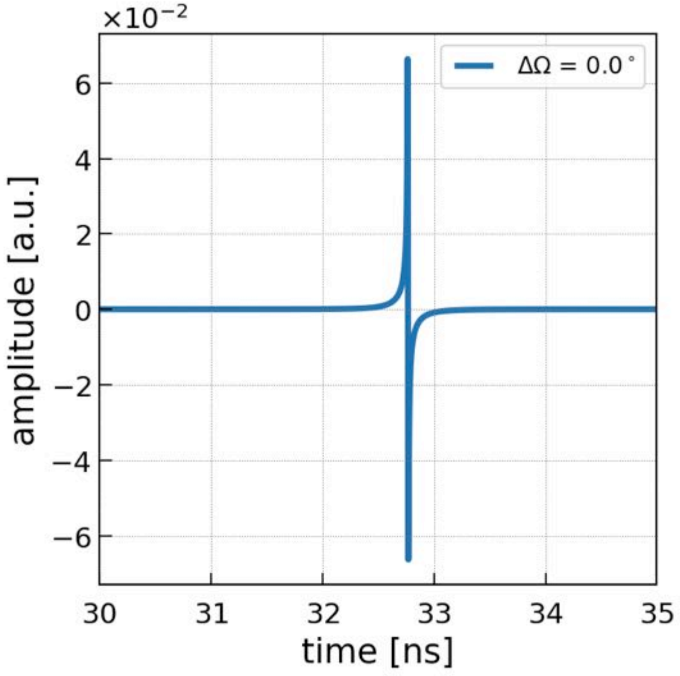

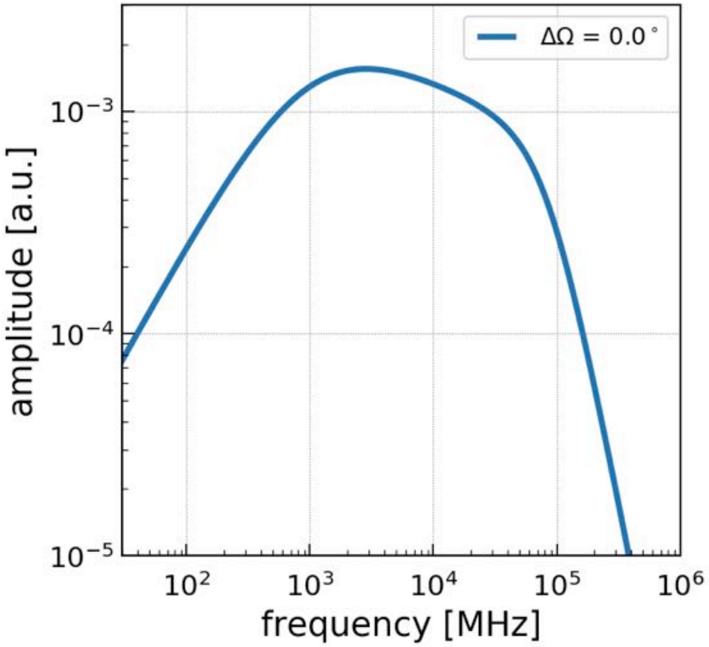

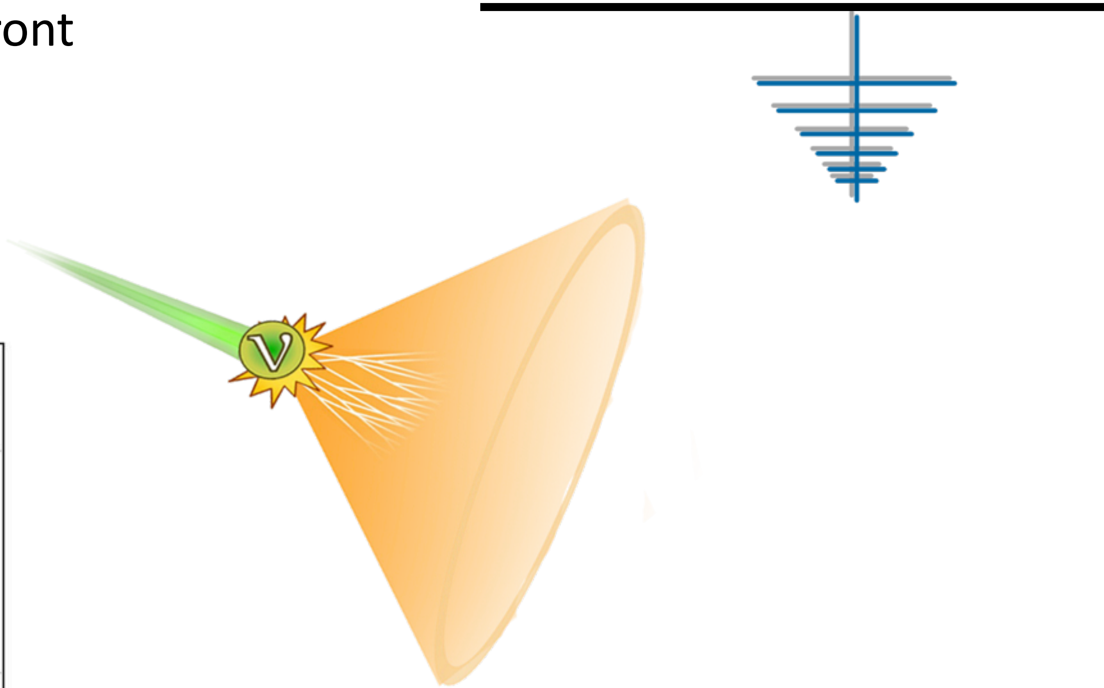

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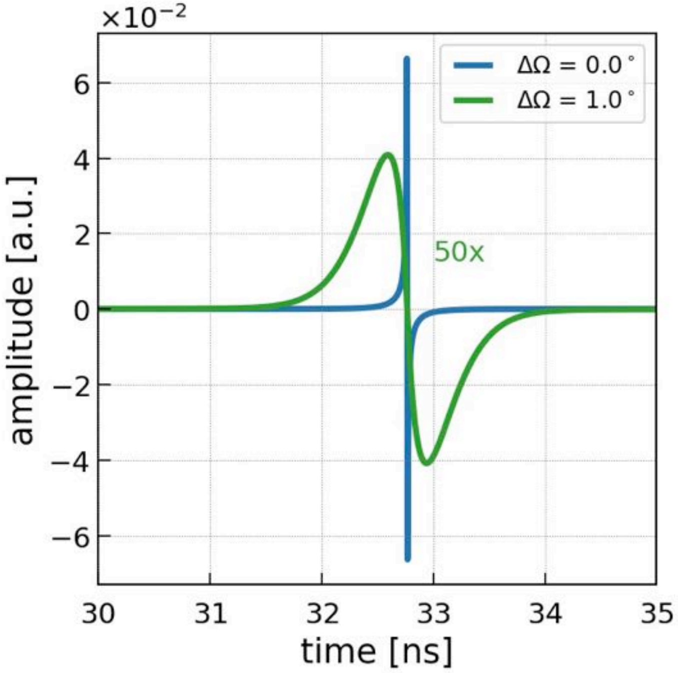

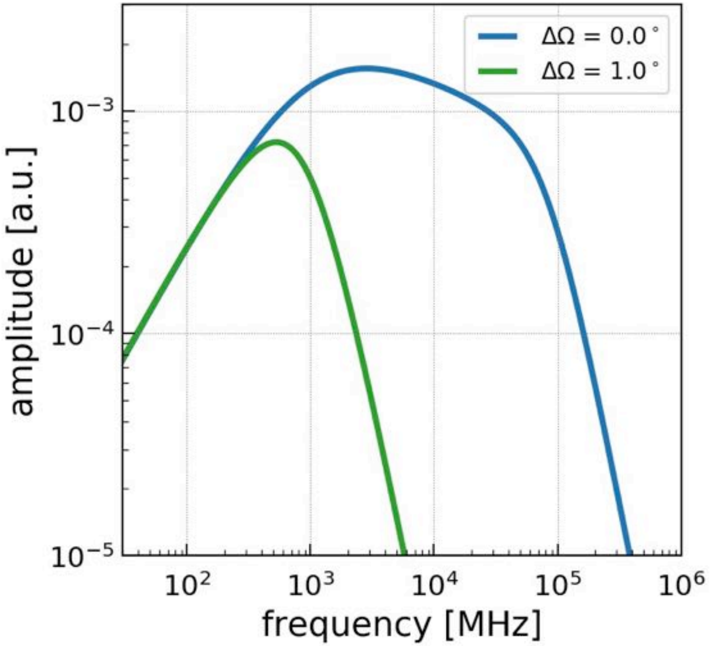

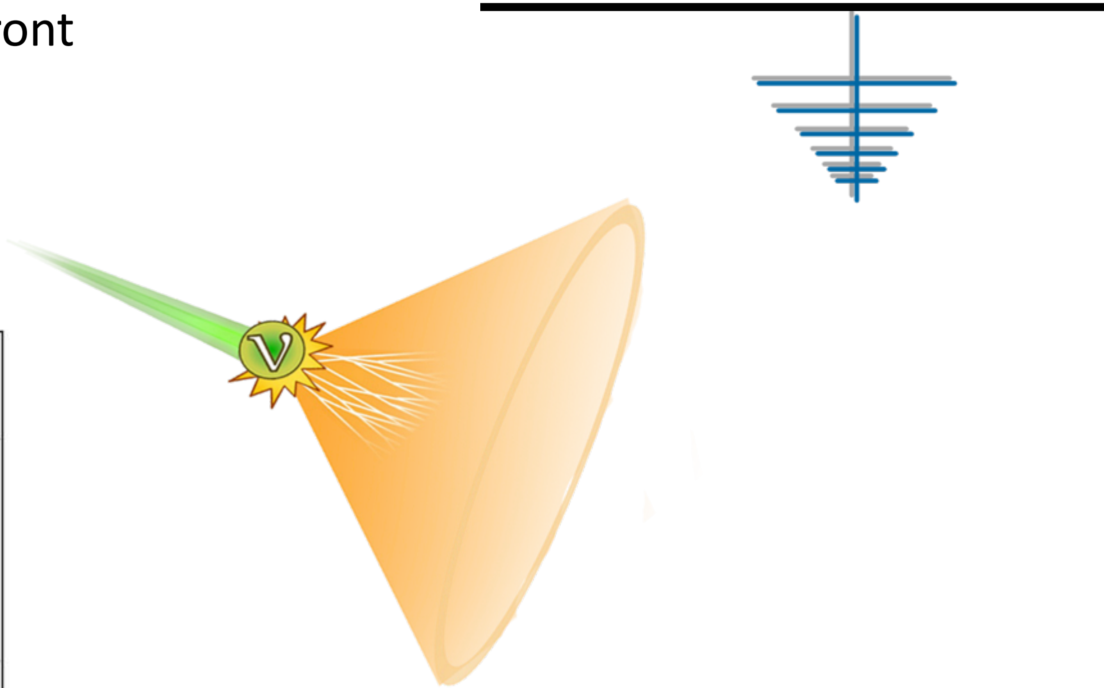

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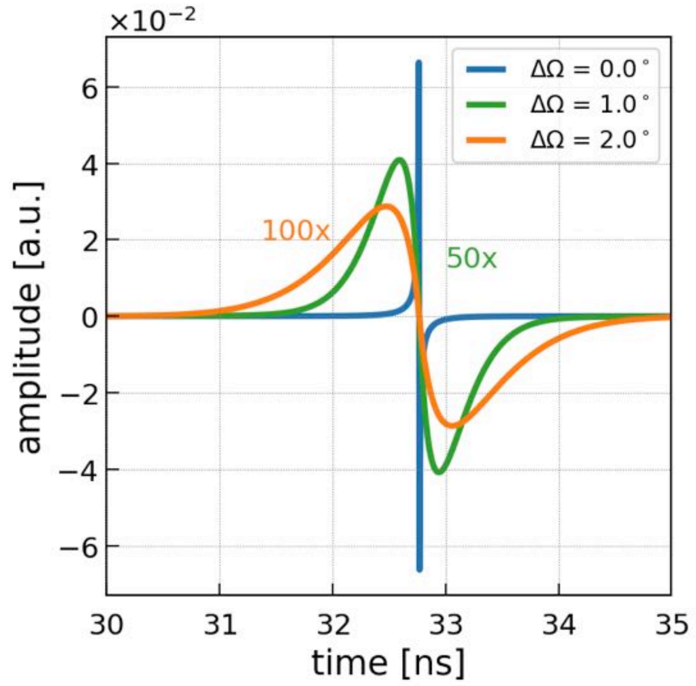
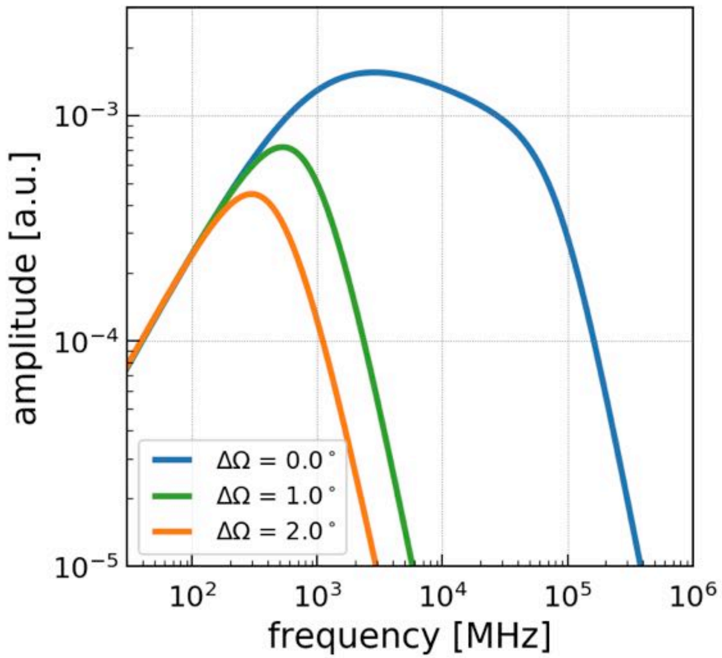
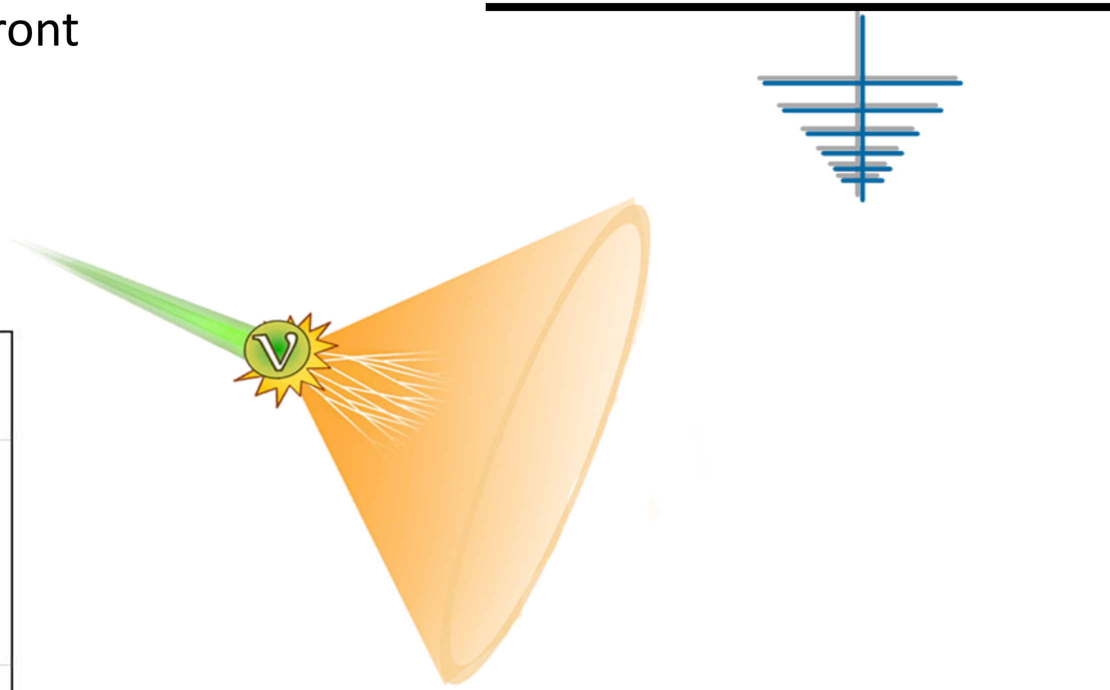
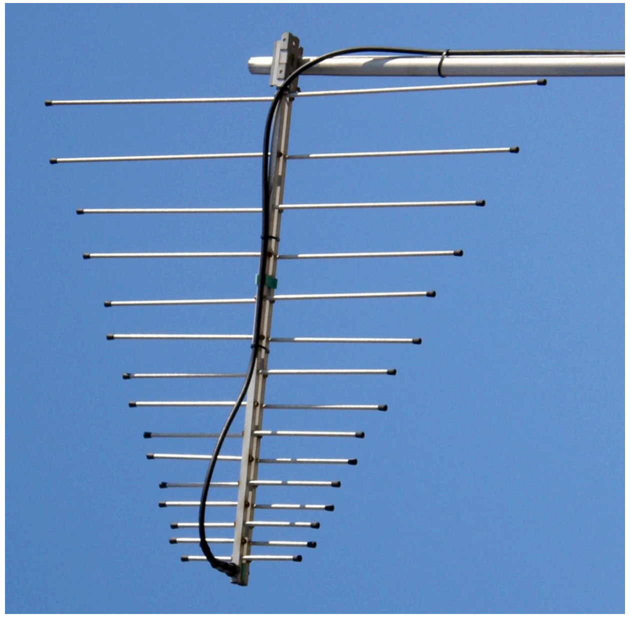






Askaryan Radiation Verified in the Lab and through Air-Shower Meausrements

Antennas

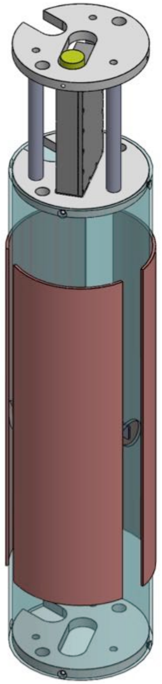


LPDA

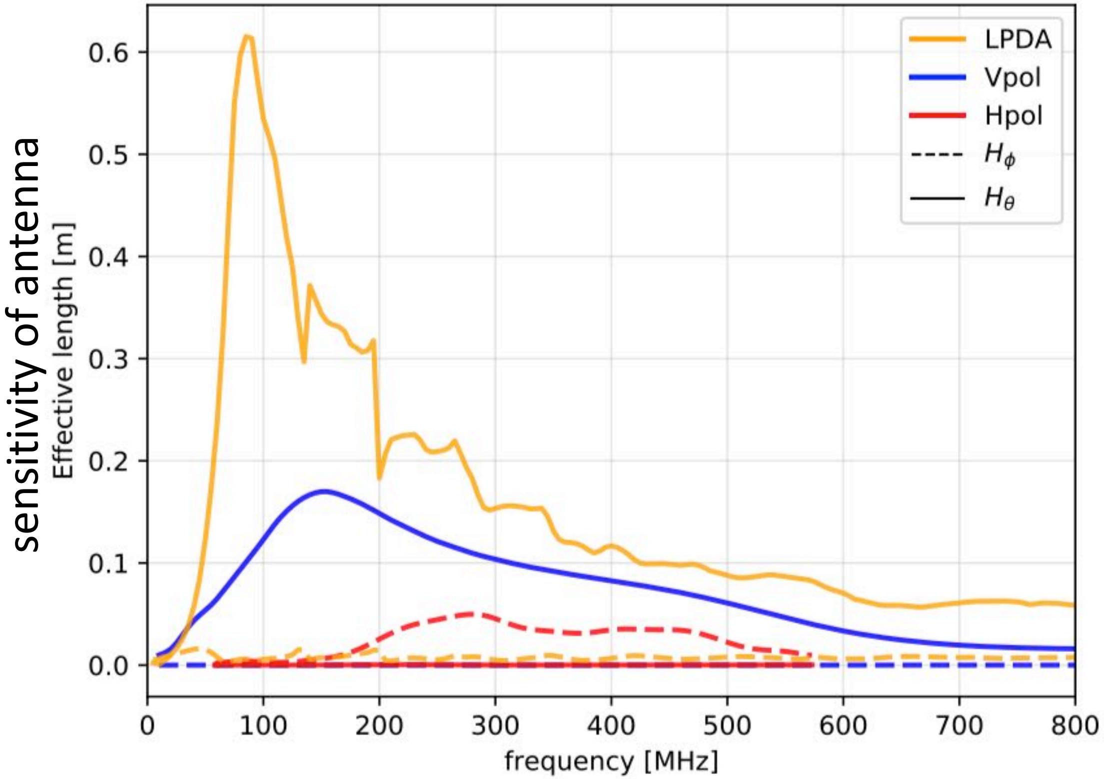
can only be deployed
at the surface

dipole antenna

slot antenna



fit into a borehole



S. Barwick and C. Glaser, book chapter in the Encyclopedia of Cosmology II, World Scientific (2023) arXiv:2208.04971

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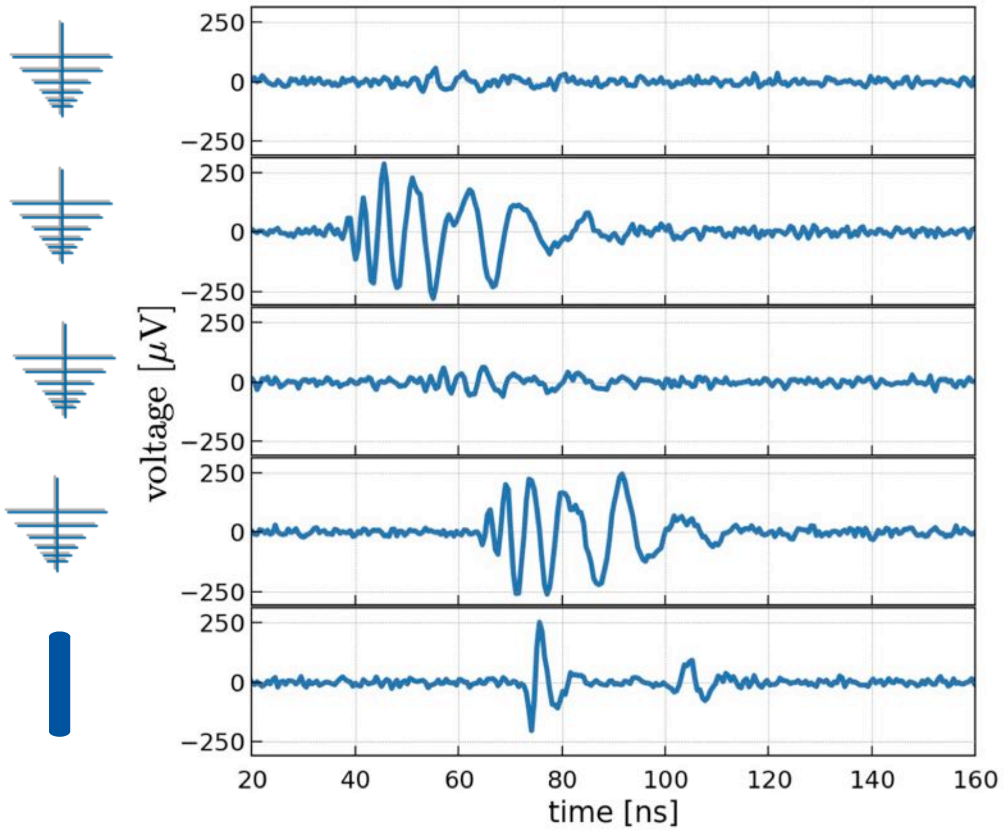
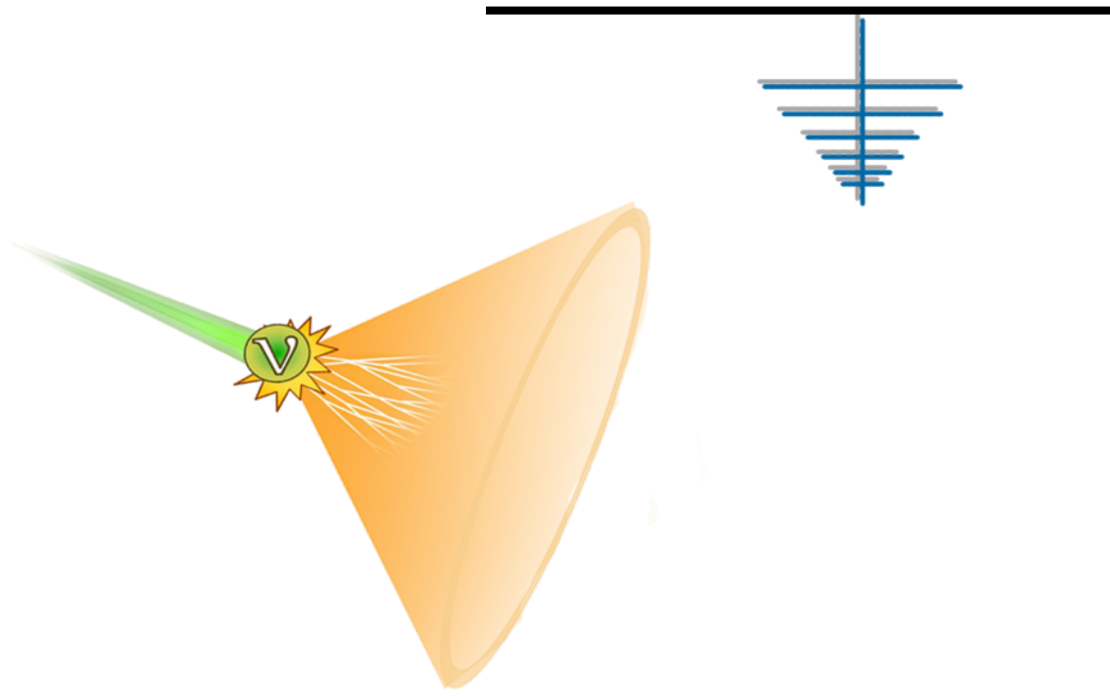
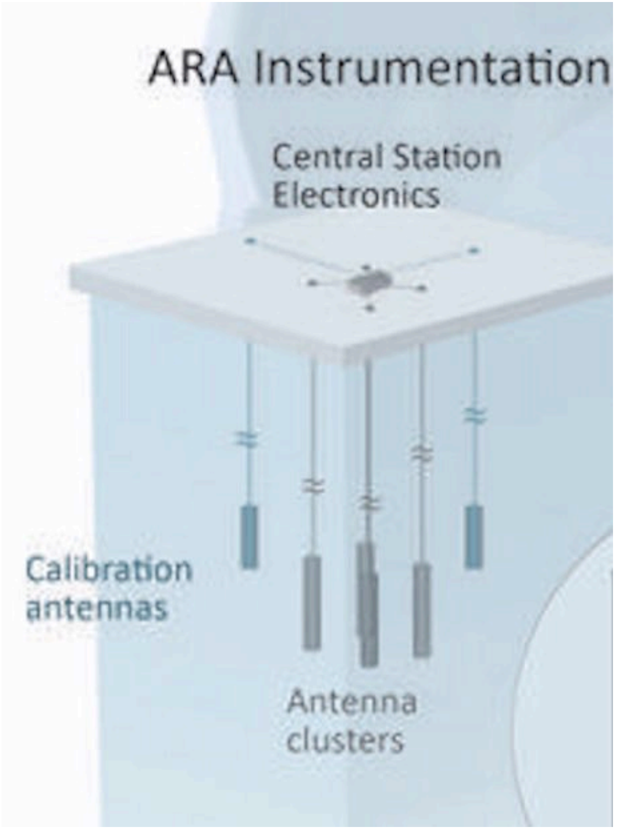




→ Synergies with Gravitational Waves data analysis/Einstein Telescope

In-Ice Radio Neutrino Detection Experiment Landscape



ARIANNA test bed

- 12 shallow stations at Moore's Bay + South Pole

C. Glaser for the ARIANNA collaboration, ARENA2022

ARA

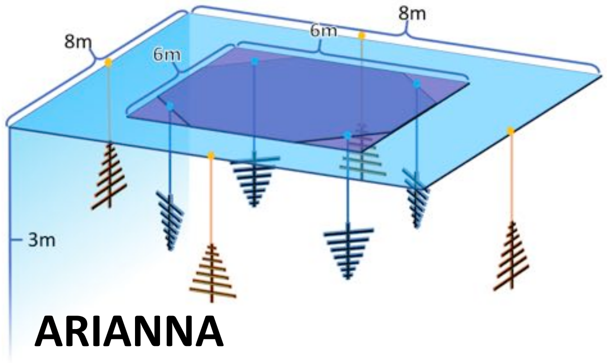
- 5x 200m deep stations at South Pole

Radio technology developed and verified; hardware proven reliable

past

now

future



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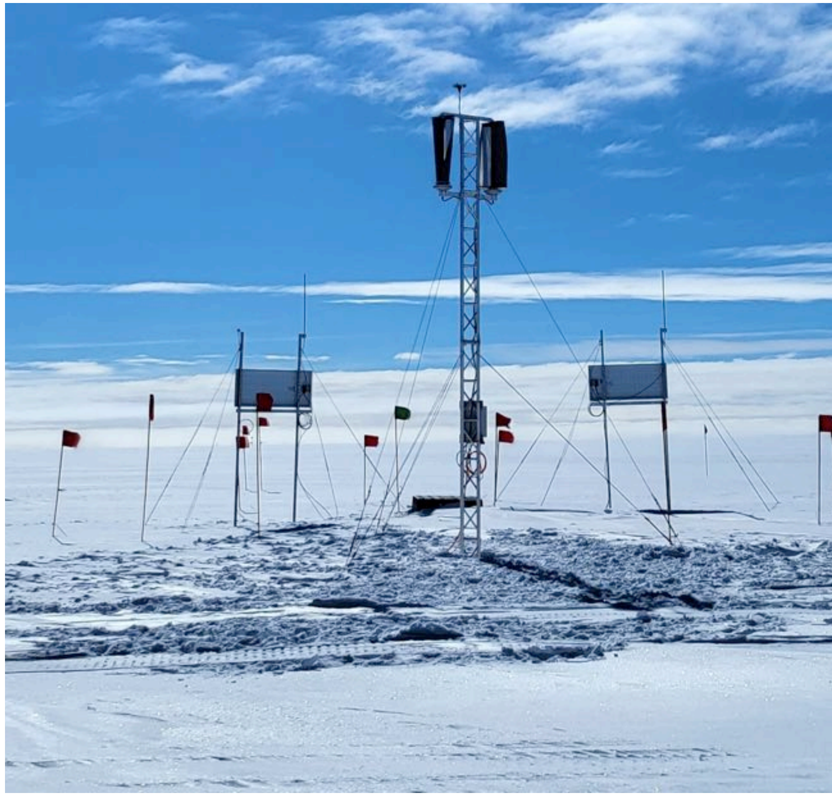
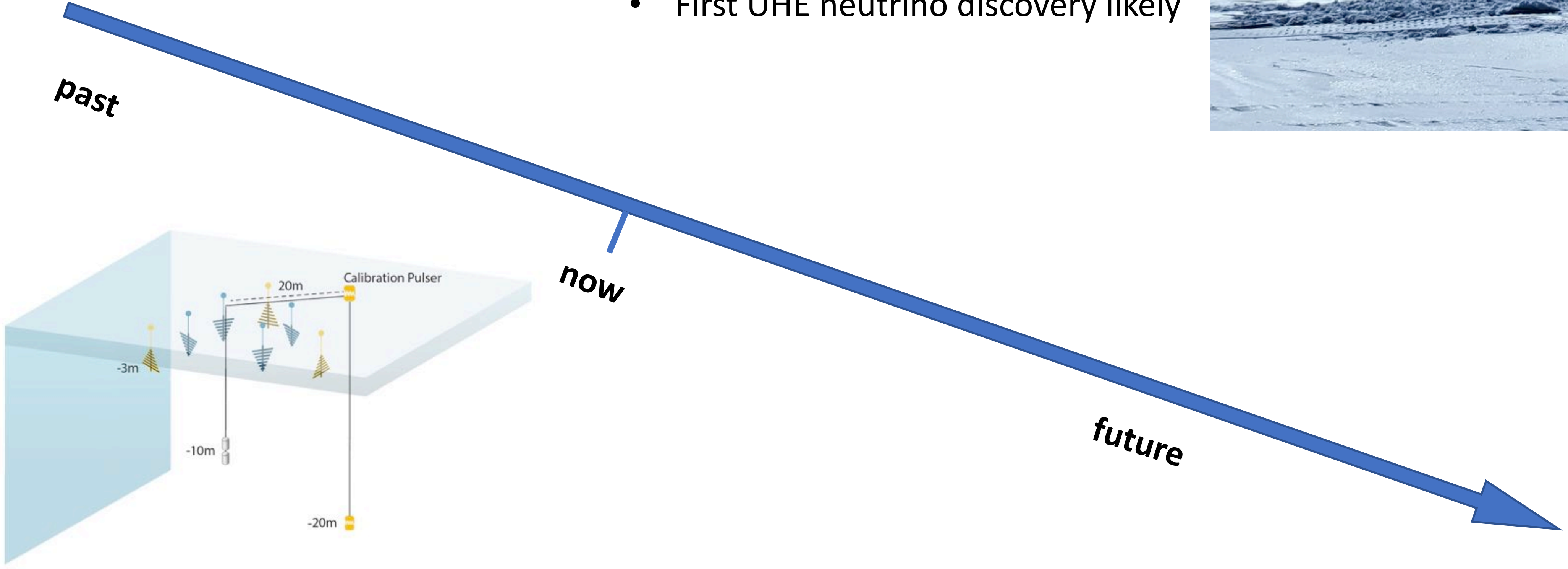
RNO-G

- 35+ detector stations in Greenland
- first deployment summer 2021
- First UHE neutrino discovery likely






PLASTIC BOTTLES
SOREL

RNO-G collaboration, Penn State, Sept. 2023

I'm organizing the next collaboration meeting in Fall 2024 in Uppsala

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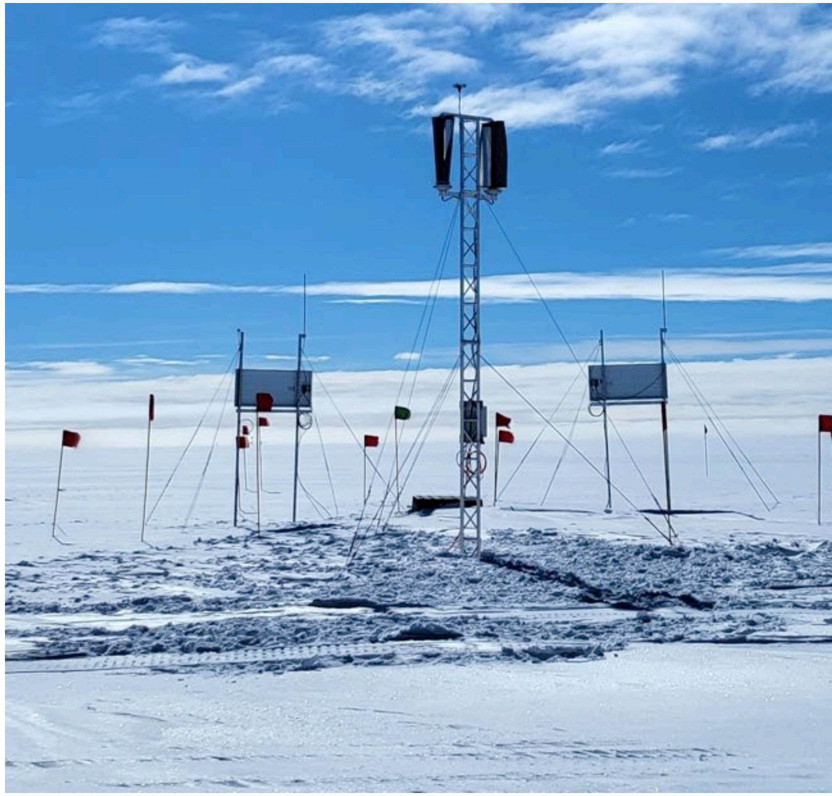

Radio technology developed and verified; hardware proven reliable

past

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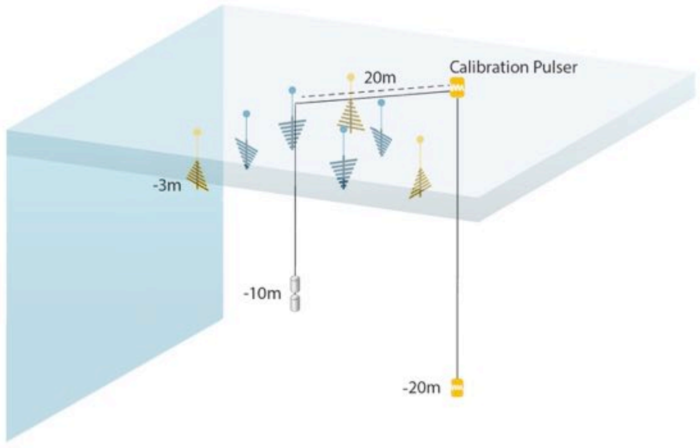
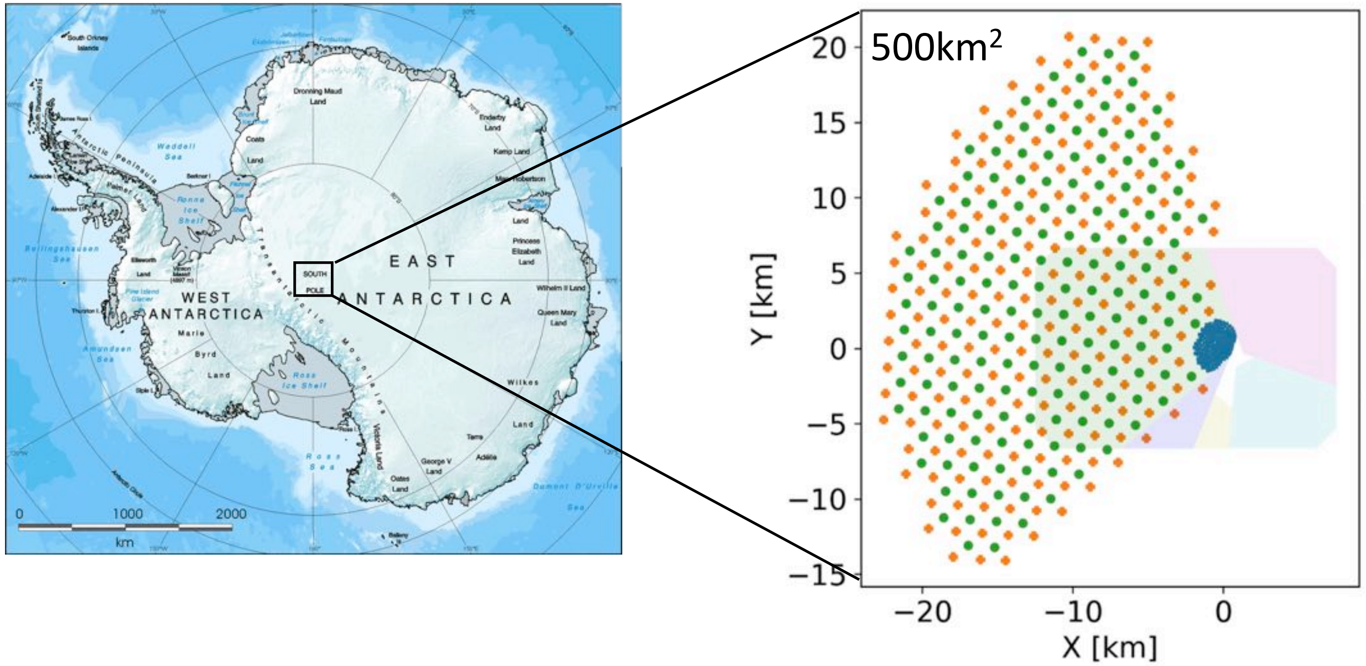
IceCube-Gen2

- 300+ detector stations at South Pole



IceCube-Gen2 radio



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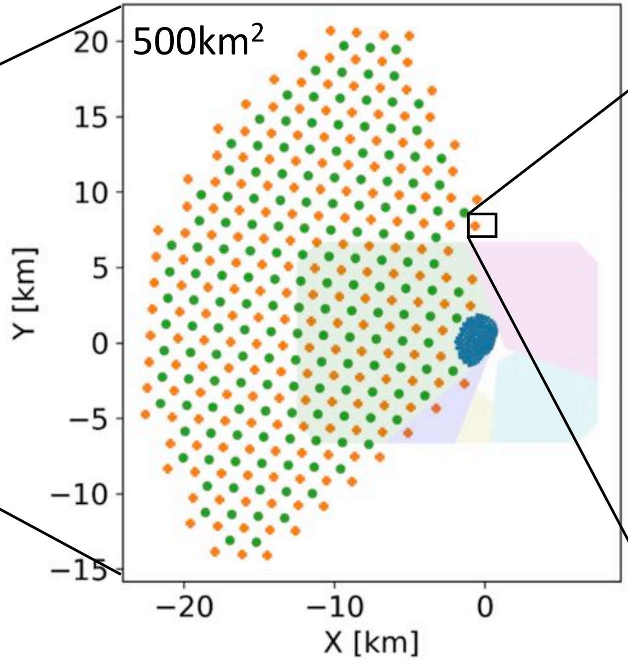
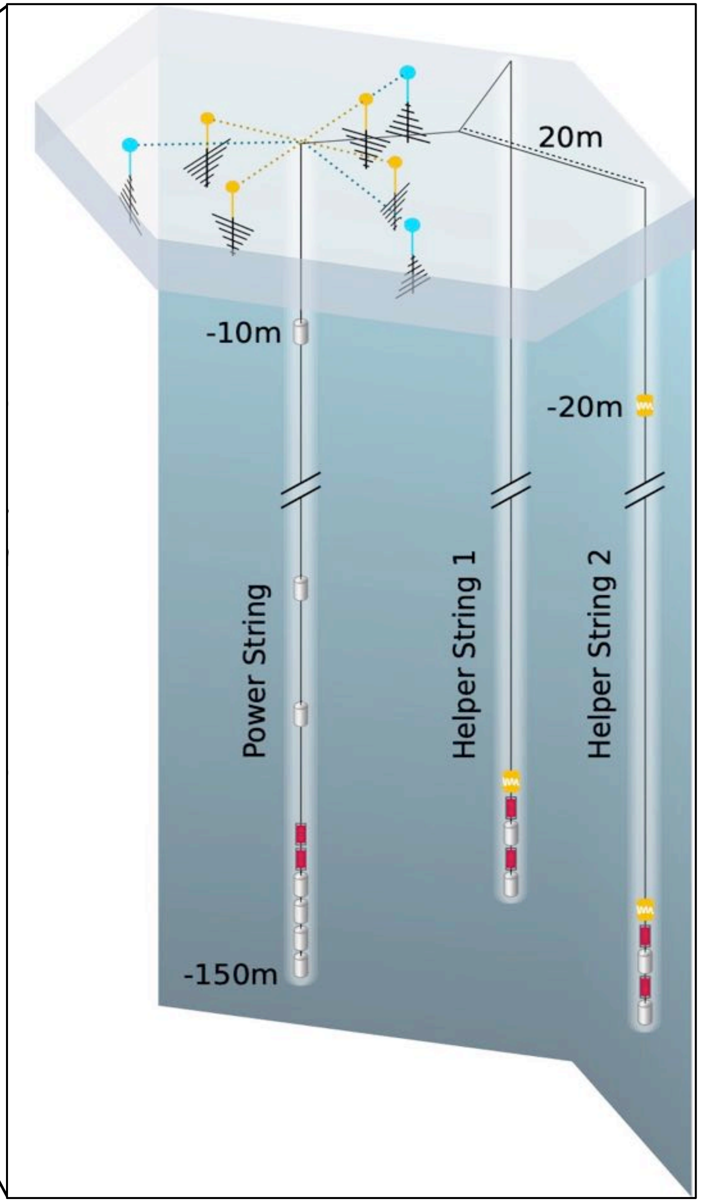
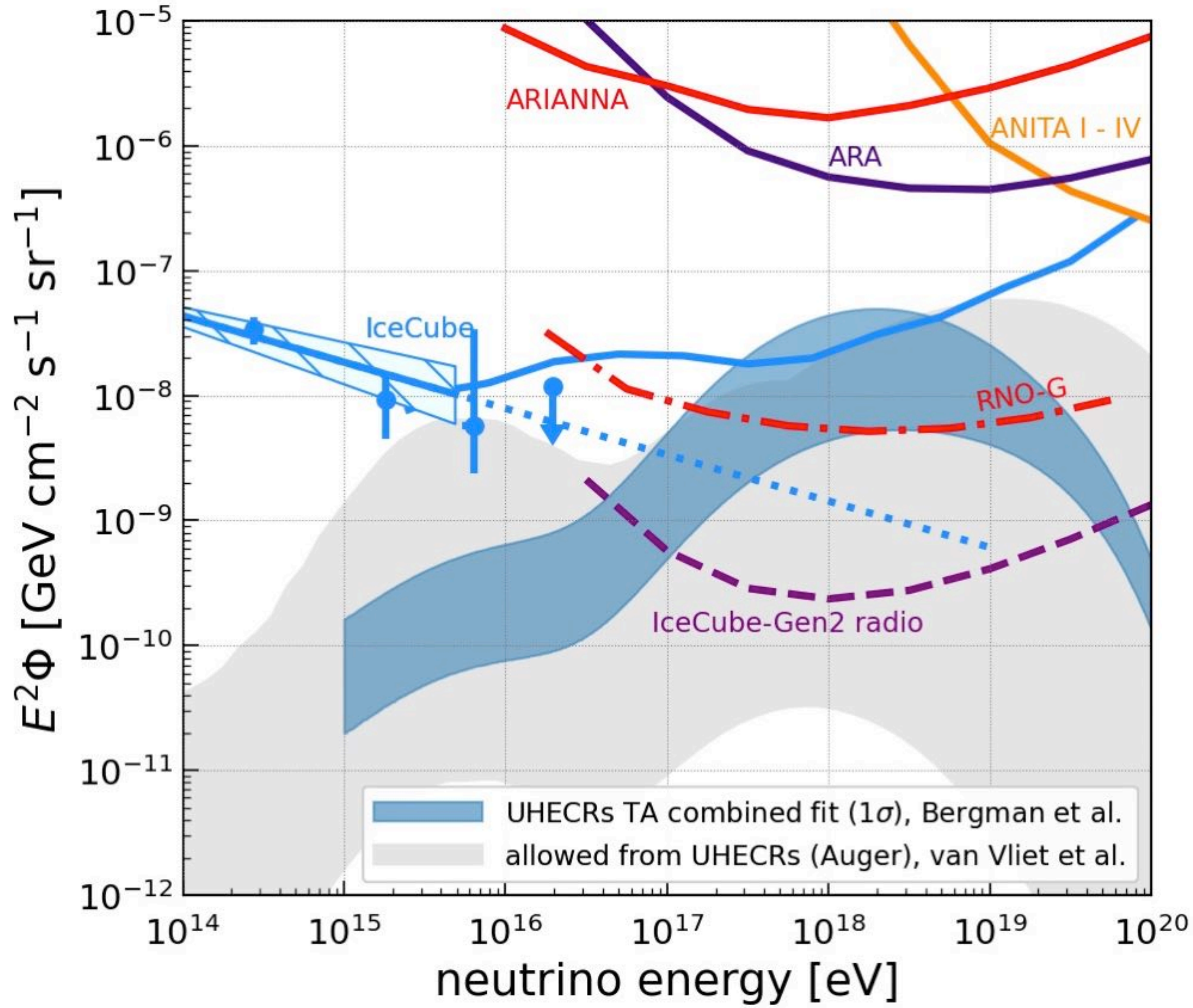
IceCube-Gen2 radio





- Hybrid array of shallow and deep detector component
  - complementary systematic uncertainties
  - different angular resolution



10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
ARIANNA
ARA
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UHECRs TA combined fit (1σ), Bergman et al.
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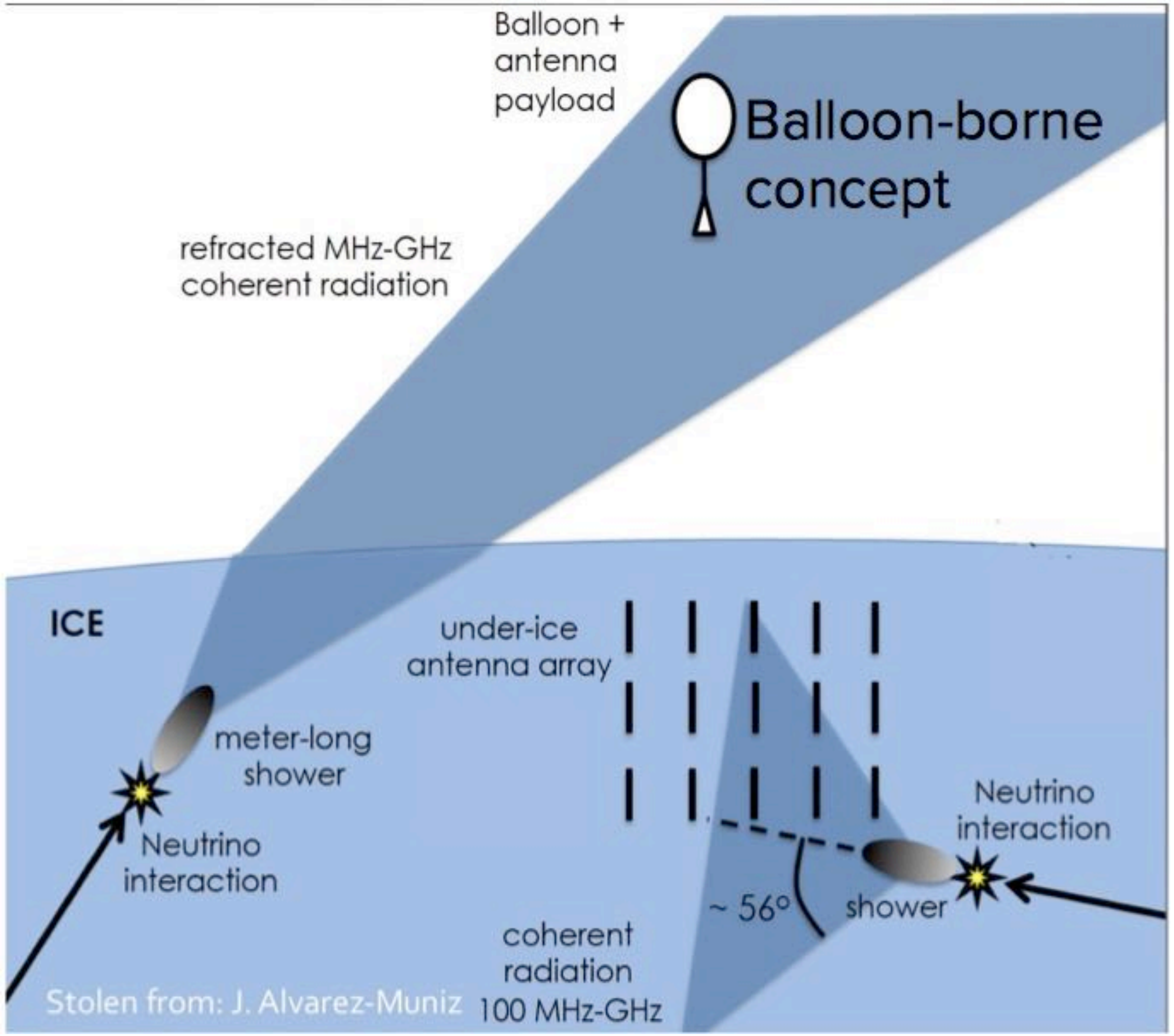
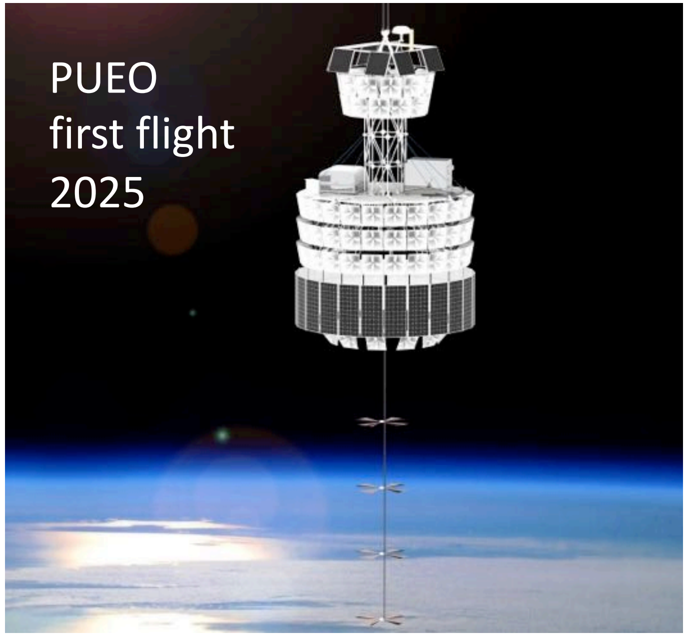
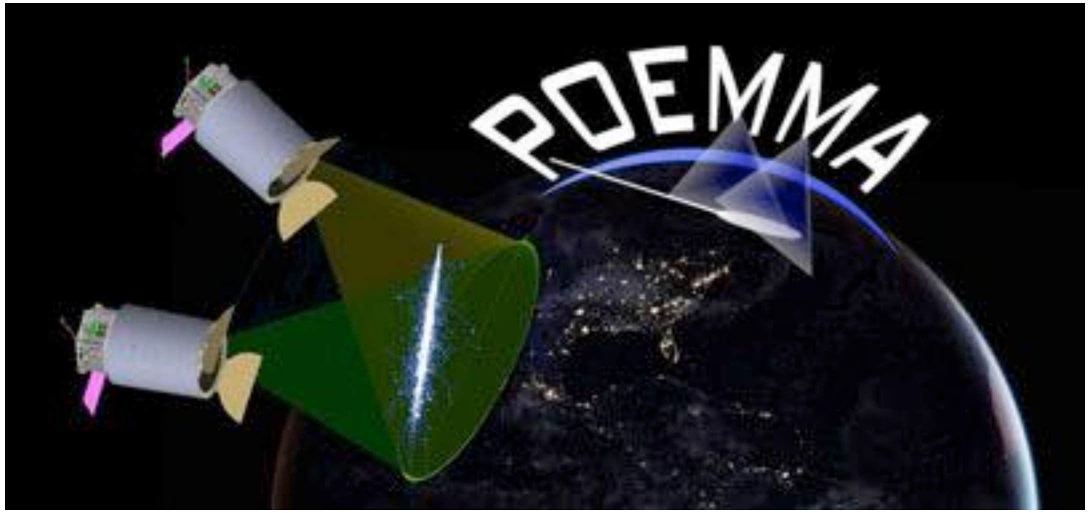
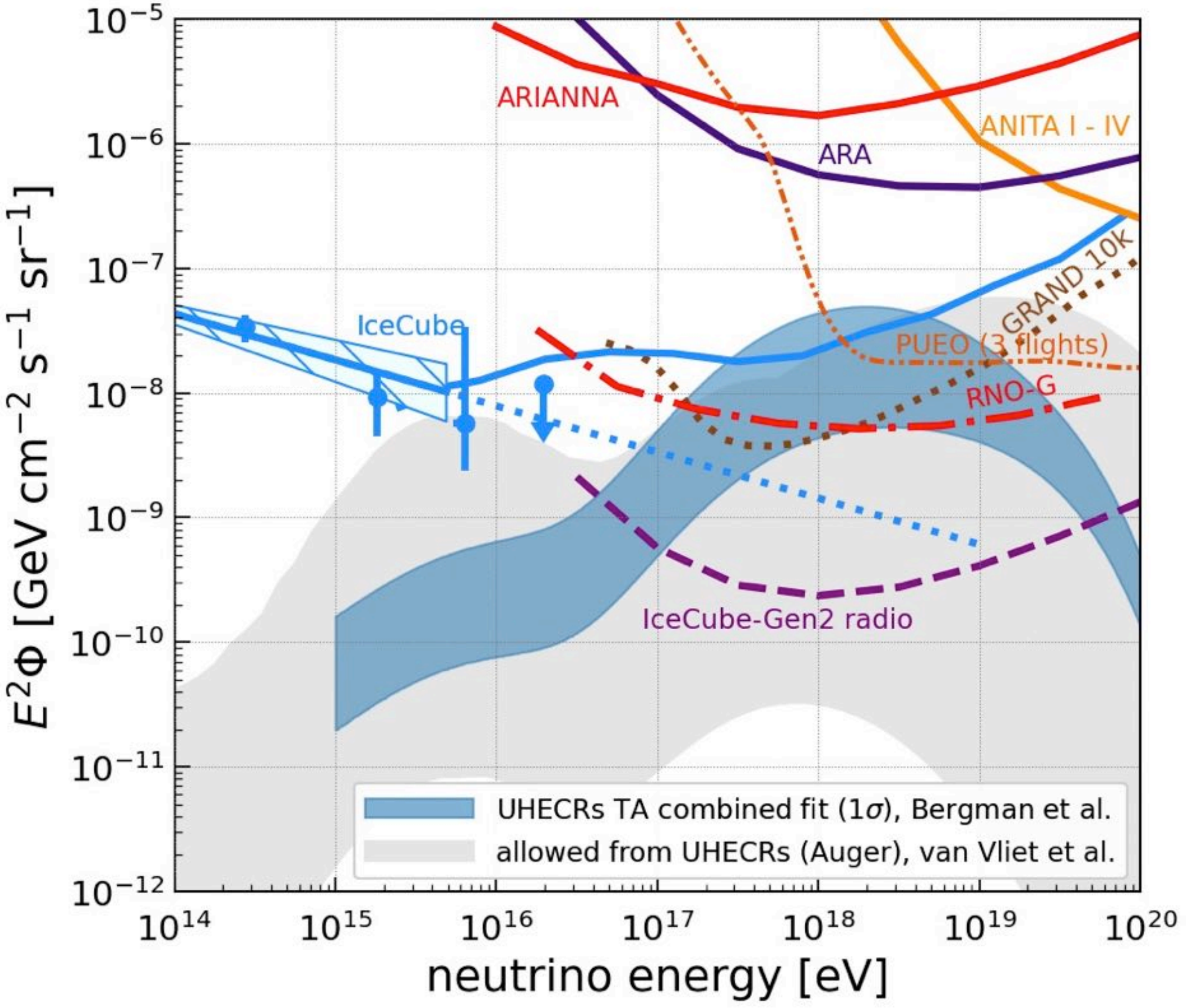
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
neutrino energy [eV]

Alternative concepts: Detection in Atmosphere





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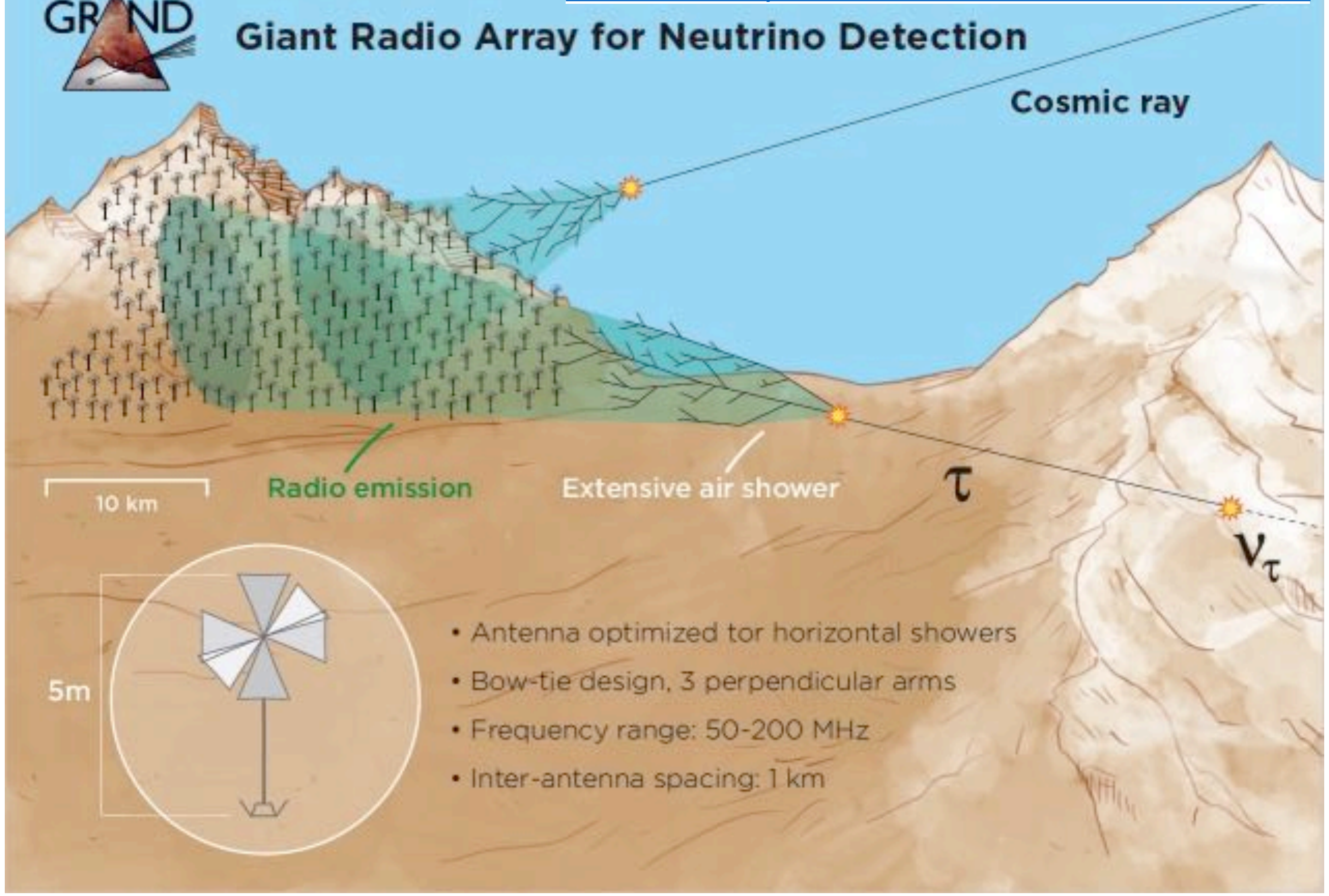
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

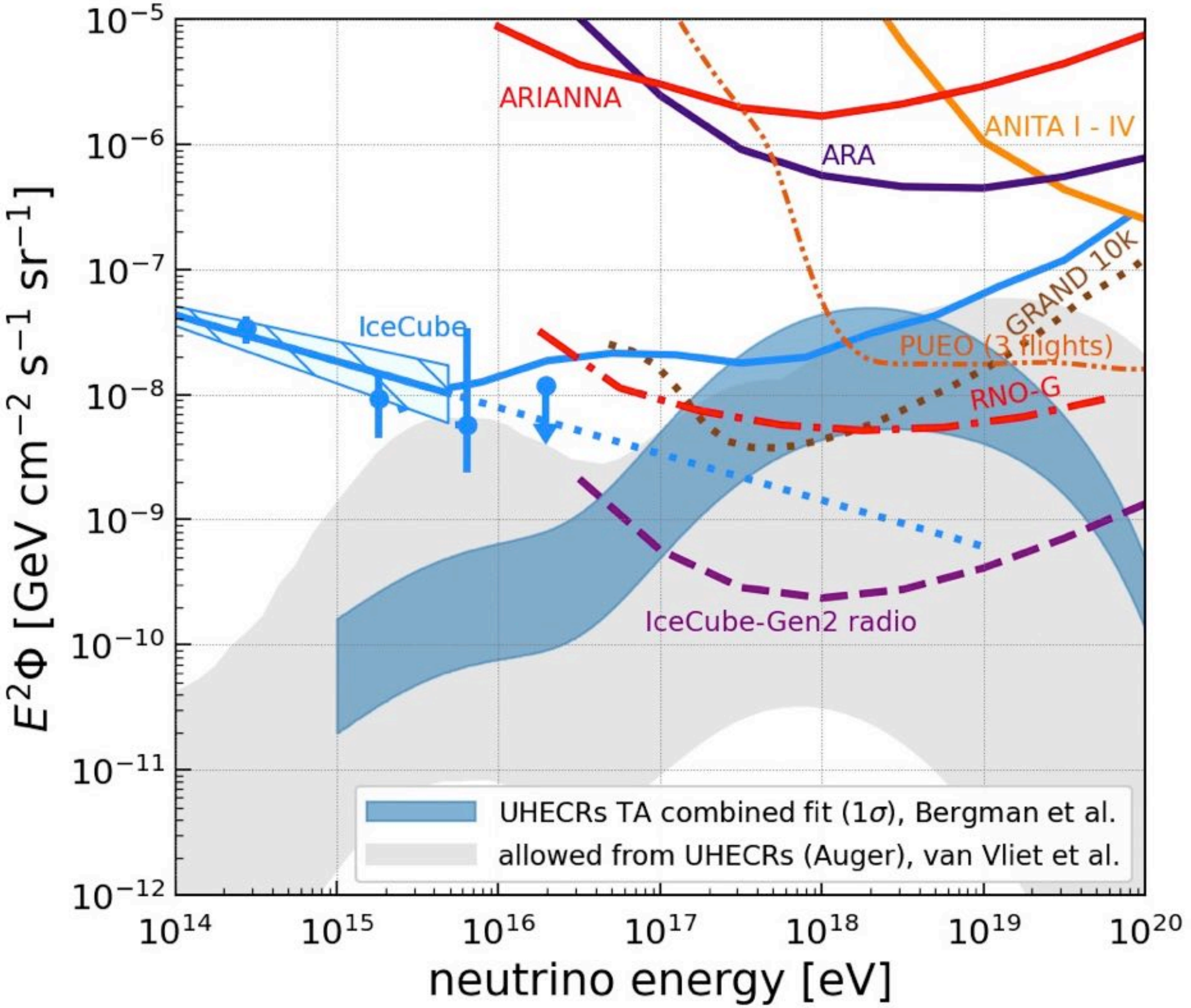
Alternative concepts: Air-Shower Detection

Sci. China–Phys. Mech. Astron. 63, 219501 (2020)



- Advantage: Better sub-degree angular resolution (because radio signal direction = neutrino direction)
- However:
  - Much larger background
  - Trigger efficiency and neutrino identification not yet demonstrated
  - Much larger instrumentation for same neutrino sensitivity
    (only sensitive to nu_tau CC and few-degree aperture for Earth-skimming neutrinos)
    - In-ice: 840 antennas (RNO-G)
    - In-air: 30,000 antennas (Grand-10k)
    - Can be partly mitigated by beam-forming trigger: BEACON + TAROGE-M

S. Wissel et al JCAP11(2020)065
S.-H. Wang et al JCAP11(2022)022



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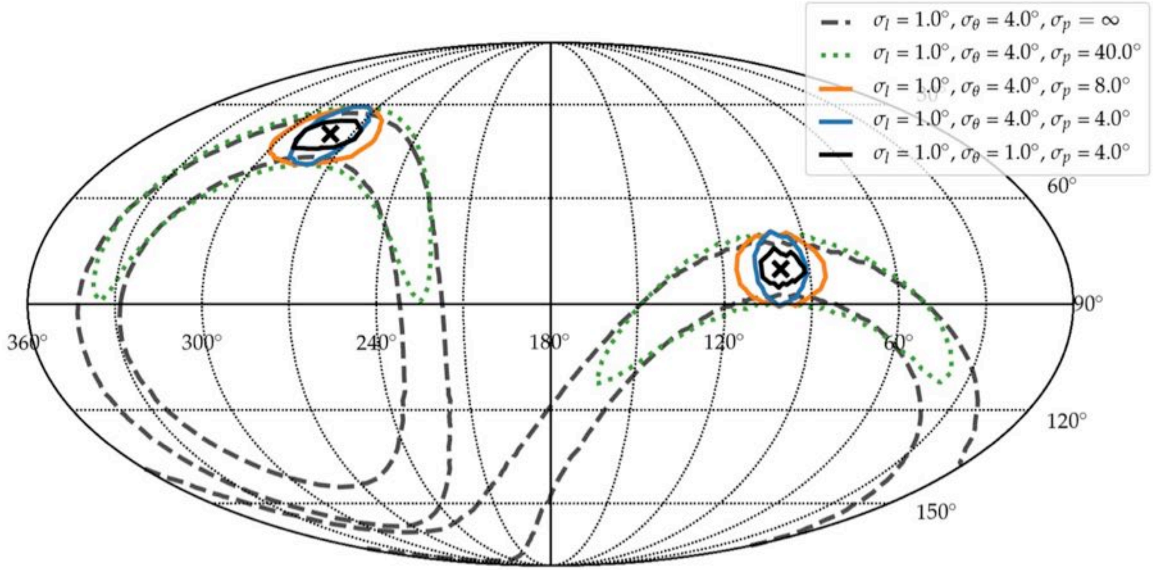
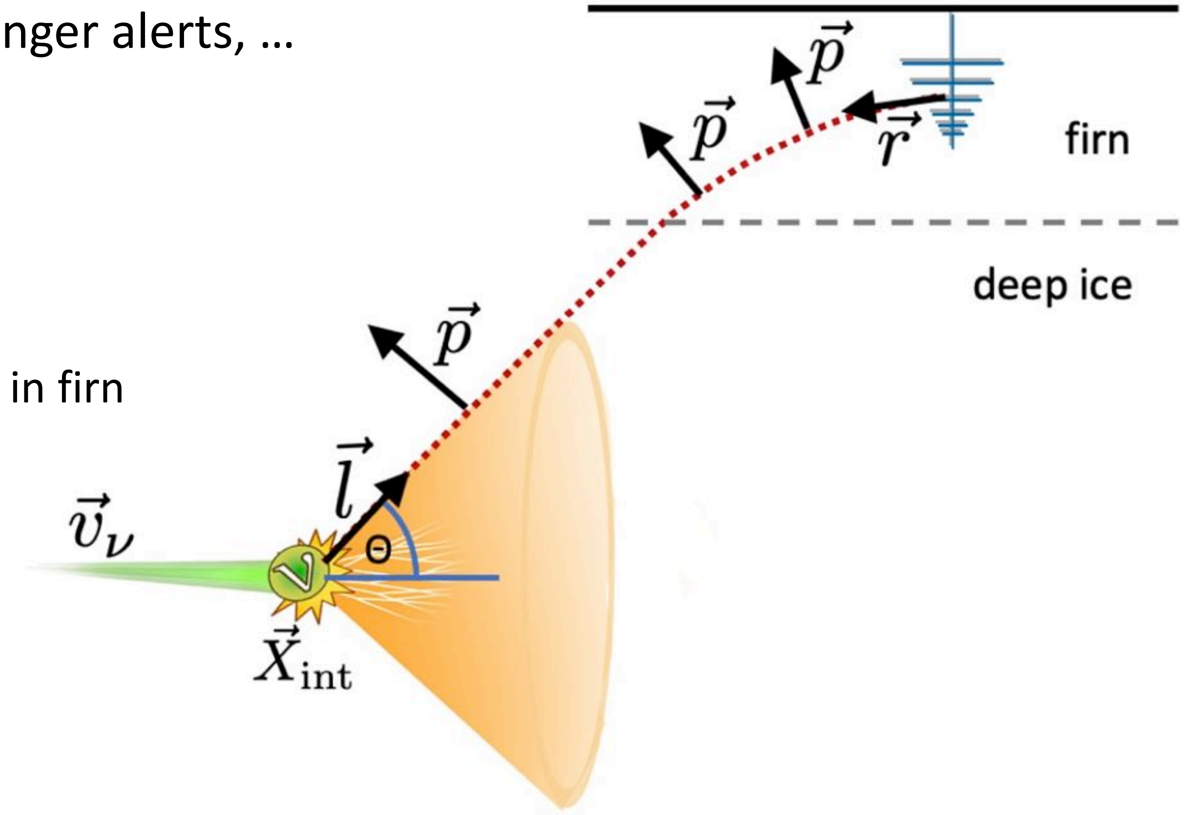
S. Barwick and C. Glaser, book chapter in the Encyclopedia of Cosmology II, World Scientific (2023)
arXiv:2208.04971

How to Reconstruct the Neutrino Direction and Energy?

- Direction important for source searches, multi-messenger alerts, …
- The neutrino direction depends on the
  - signal arrival direction $\vec{l}$
  - signal polarization $\vec{p}$
  - viewing angle Θ
  - distance to neutrino interaction to correct for bending in firn
  - knowledge of ice properties

$$\hat{\vec{v}}_\nu = \sin\theta \hat{\vec{p}} + \cos\theta\, \hat{\vec{l}}$$





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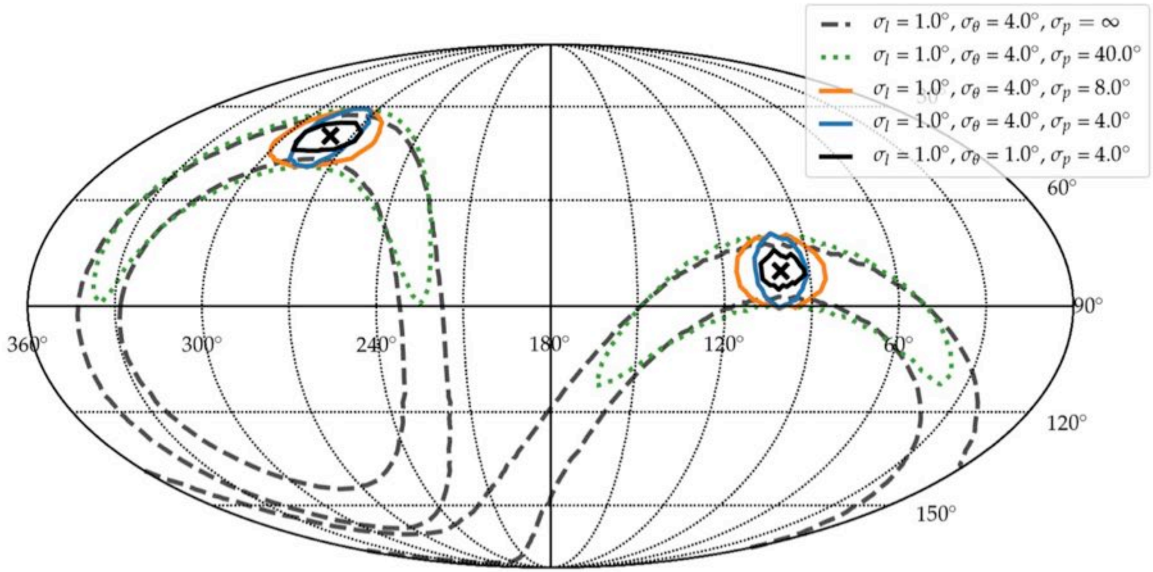

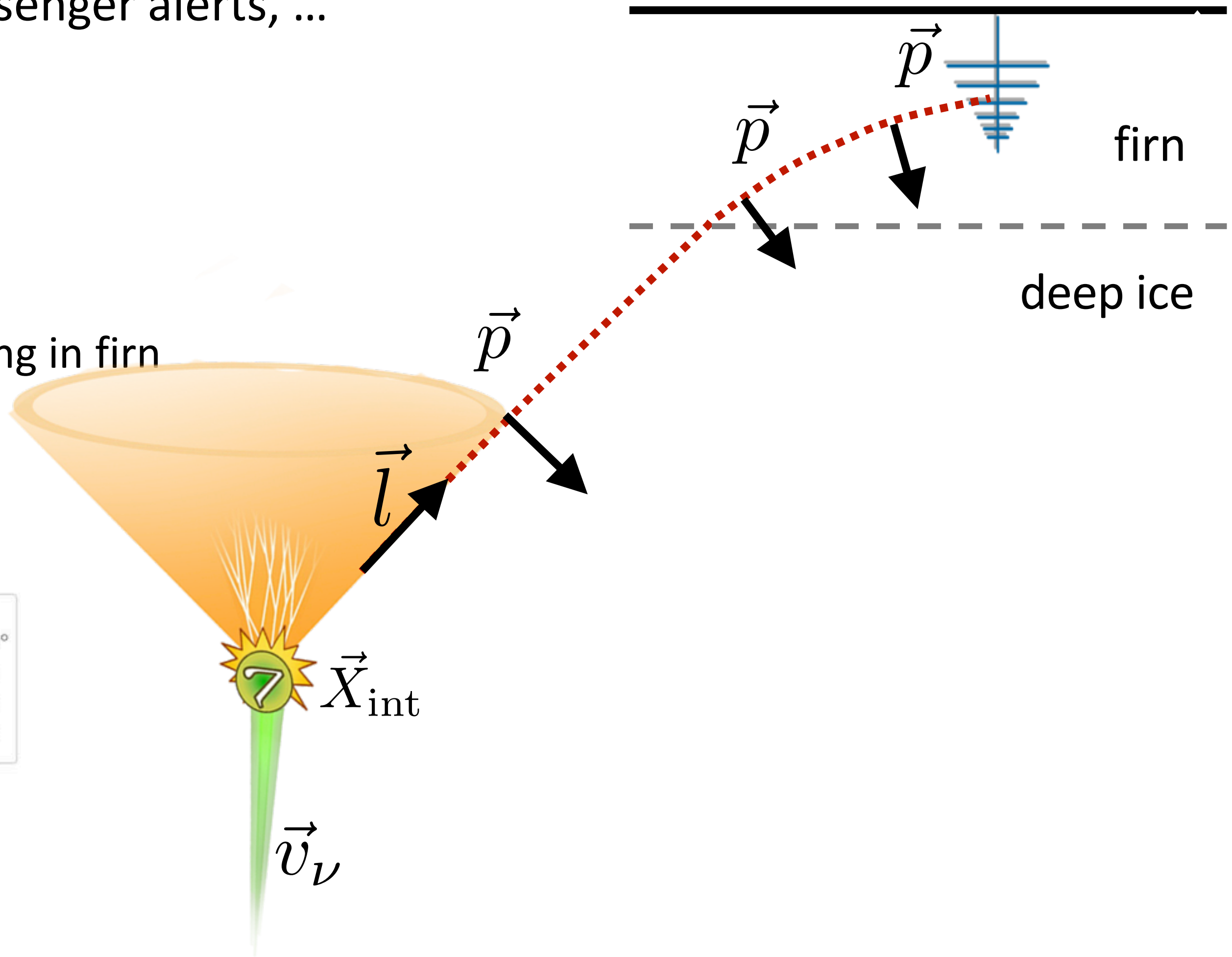

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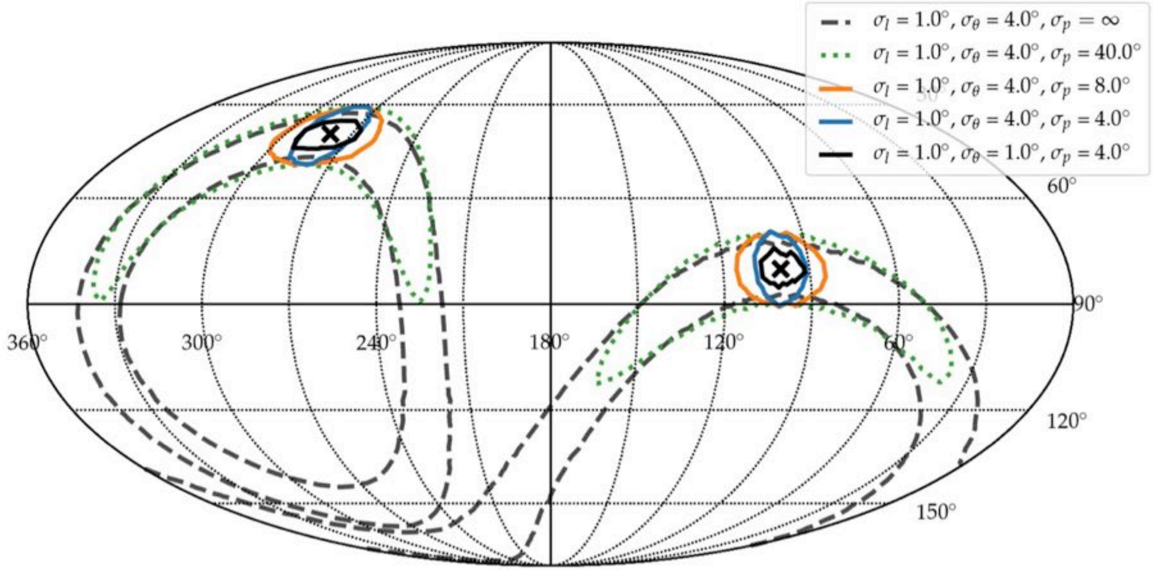
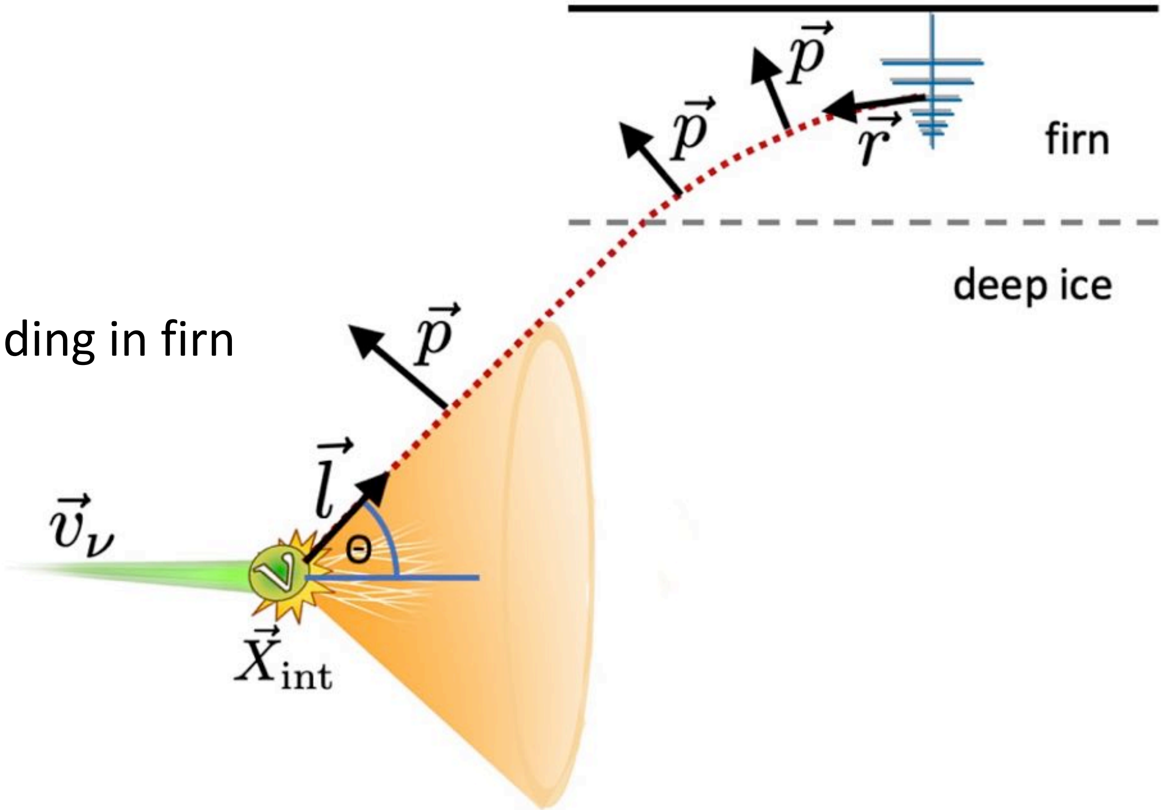




Tested in-situ with ARIANNA station at South Pole and with cosmic rays at Moore's Bay

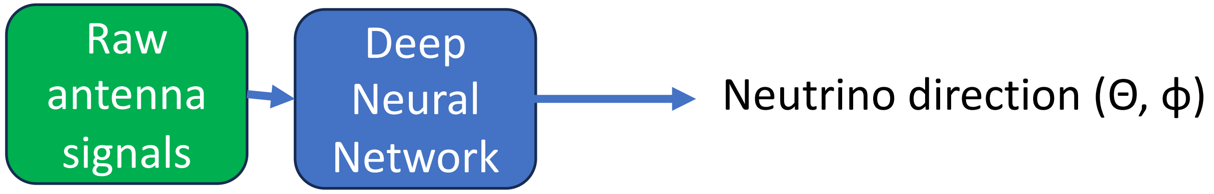
ARIANNA collaboration, JCAP 11(2019)030
ARIANNA collaboration, JINST 15 (2020) P09039
ARIANNA collaboration, JCAP 04(2022)022.
Glaser & Barwick, JINST 16 T05001 (2021)
ARIANNA collaboration, JINST 17 P03007 (2022)

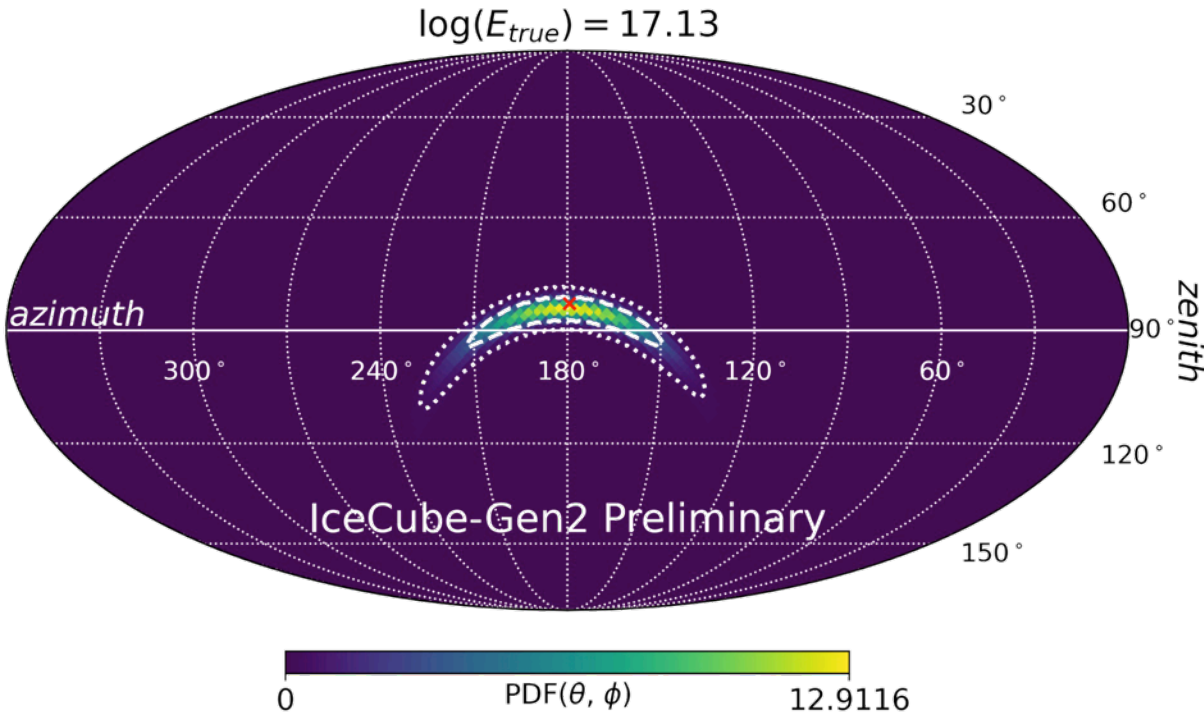
Deep-Learning Reconstruction using Normaling Flows (Simulation-Based Inference)

- Conditional normalizing flows offer an opportunity to predict arbitrarily shaped uncertainty contours
- Network predicts the parameters of a function instead of a single value
- Using open-source toolkit pytorch and jammy_flows: github.com/thoglu/jammy_flows

T Glüsenkamp, Eur. Phys. J. C 84, 163 (2024)

- First event-by-event uncertainty predictions
- The size/entropy can be used as a quality cut





Deep-Learning Reconstruction using Normaling Flows (Simulation-Based Inference)

- Conditional normalizing flows offer an opportunity to predict arbitrarily shaped uncertainty contours
- Network predicts the parameters of a function instead of a single value
- Using open-source toolkit pytorch and jammy_flows: github.com/thoglu/jammy_flows

T Glüsenkamp, Eur. Phys. J. C 84, 163 (2024)

- First event-by-event uncertainty predictions
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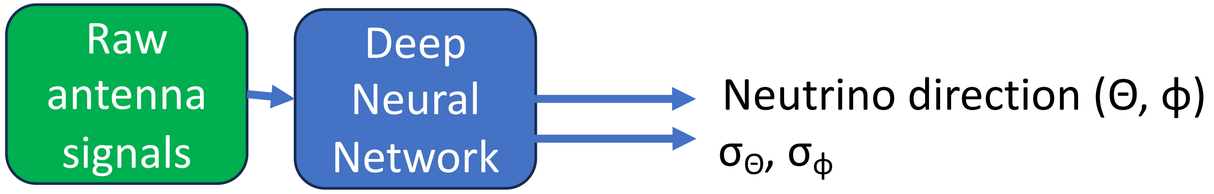

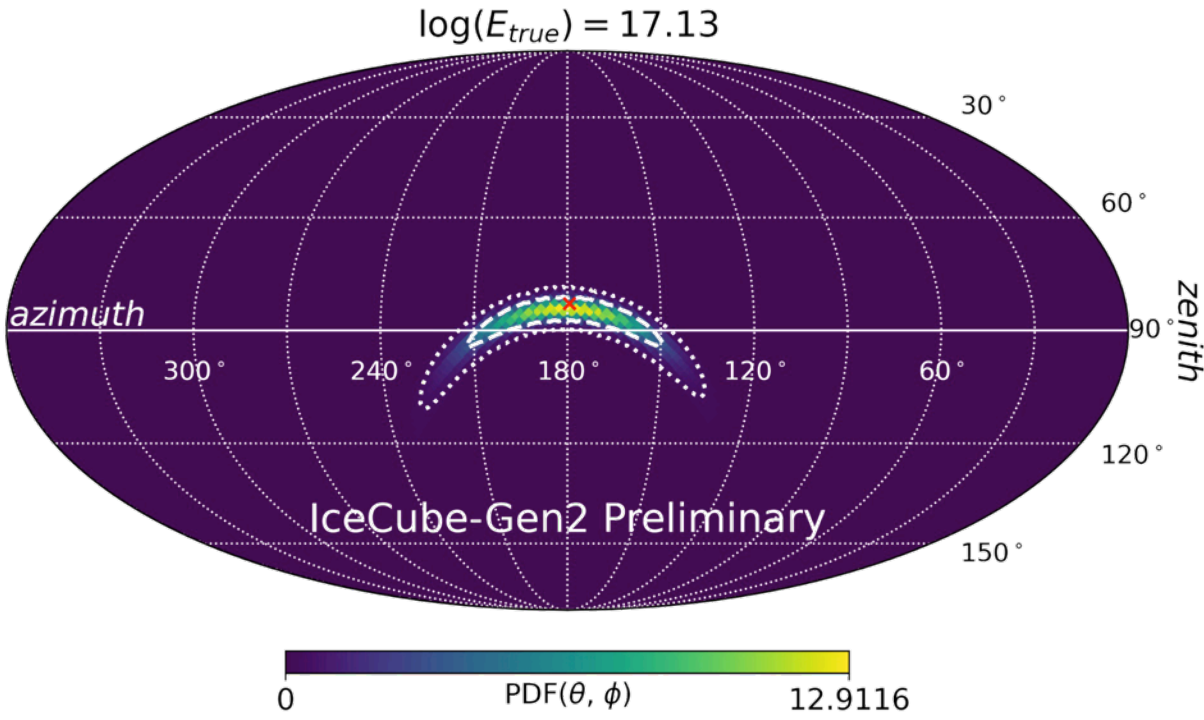

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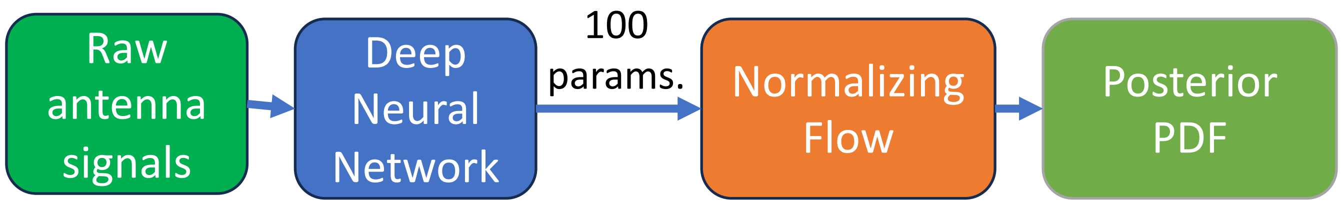
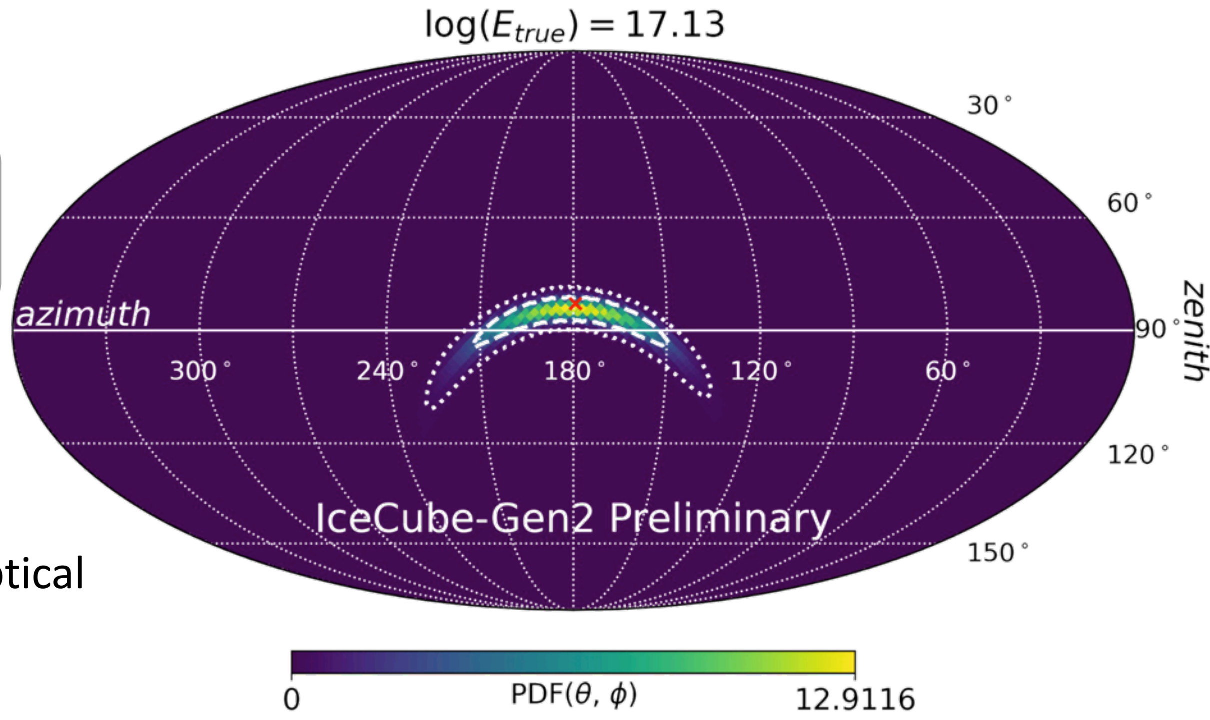


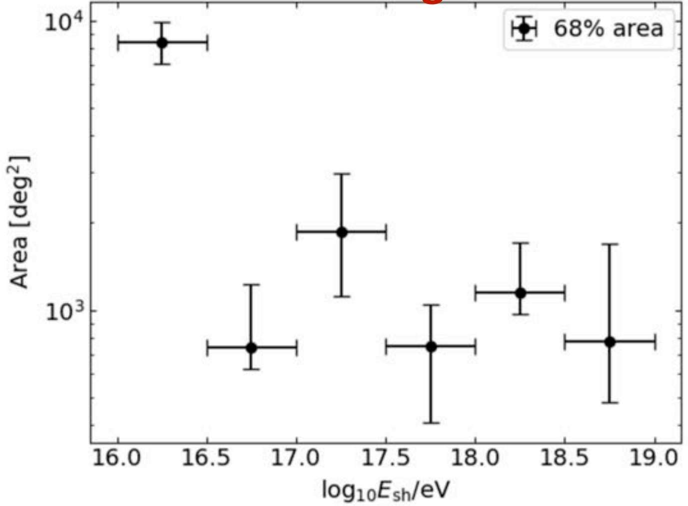


→ see also T. Glüsenkamp, PoS(ICRC23)1003 for IceCube optical

Angular Resolution

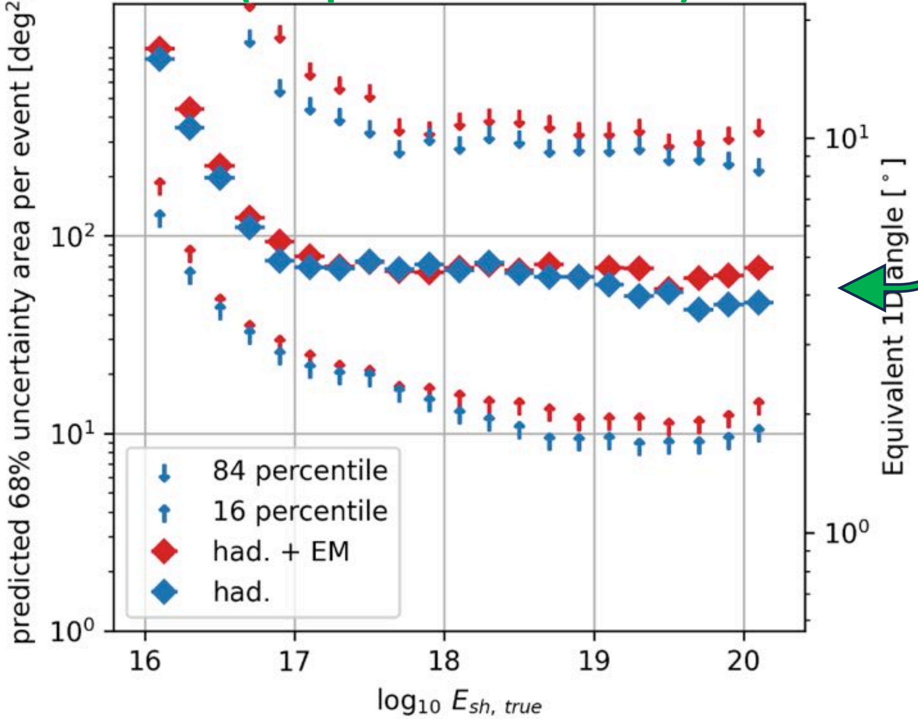
Nils Heyer, UU, work in progress

Old Forward Folding Reconstruction

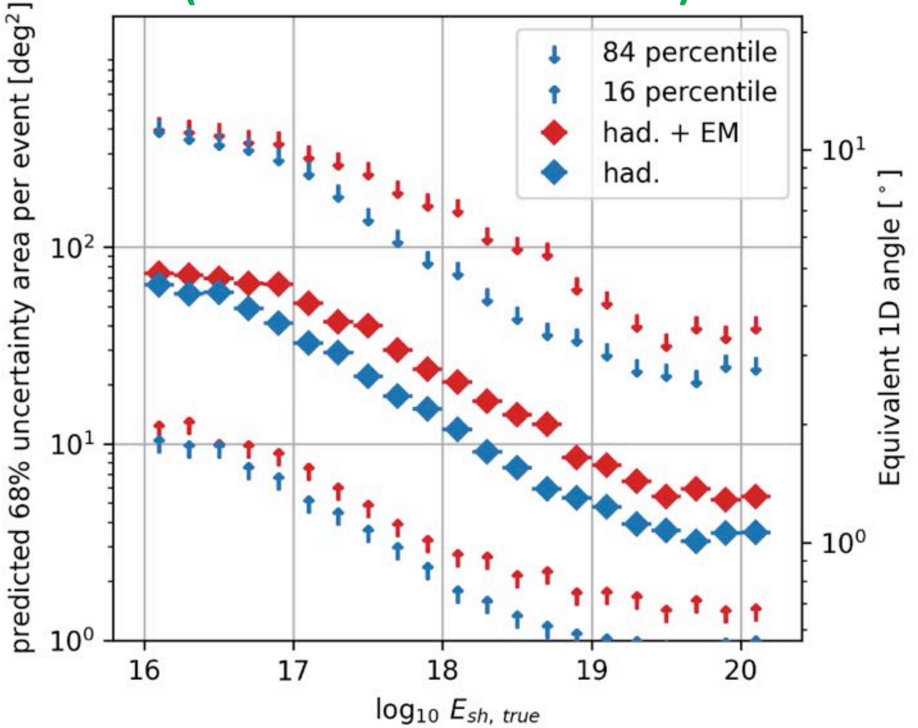


Factor 10 improvement(!)

New Deep Learning Reconstruction (deep detector station)

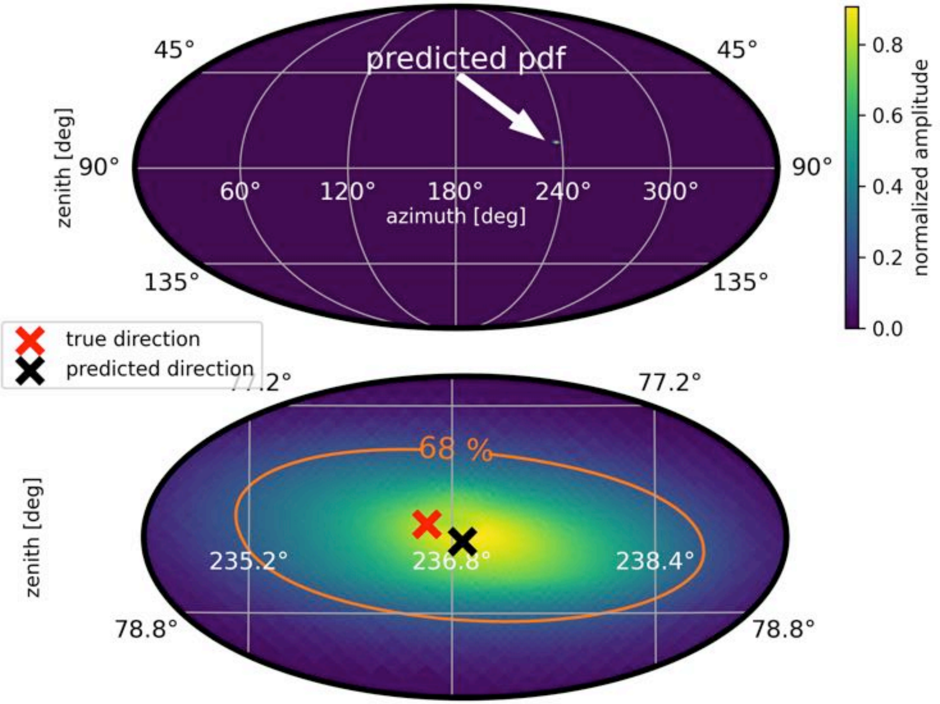


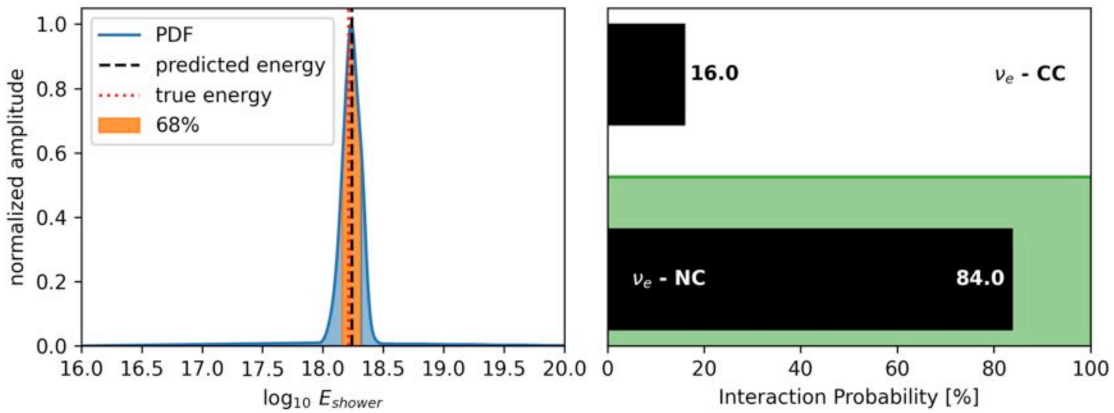
New Deep Learning Reconstruction (shallow detector station)



Nils Heyer, UU, work in progress

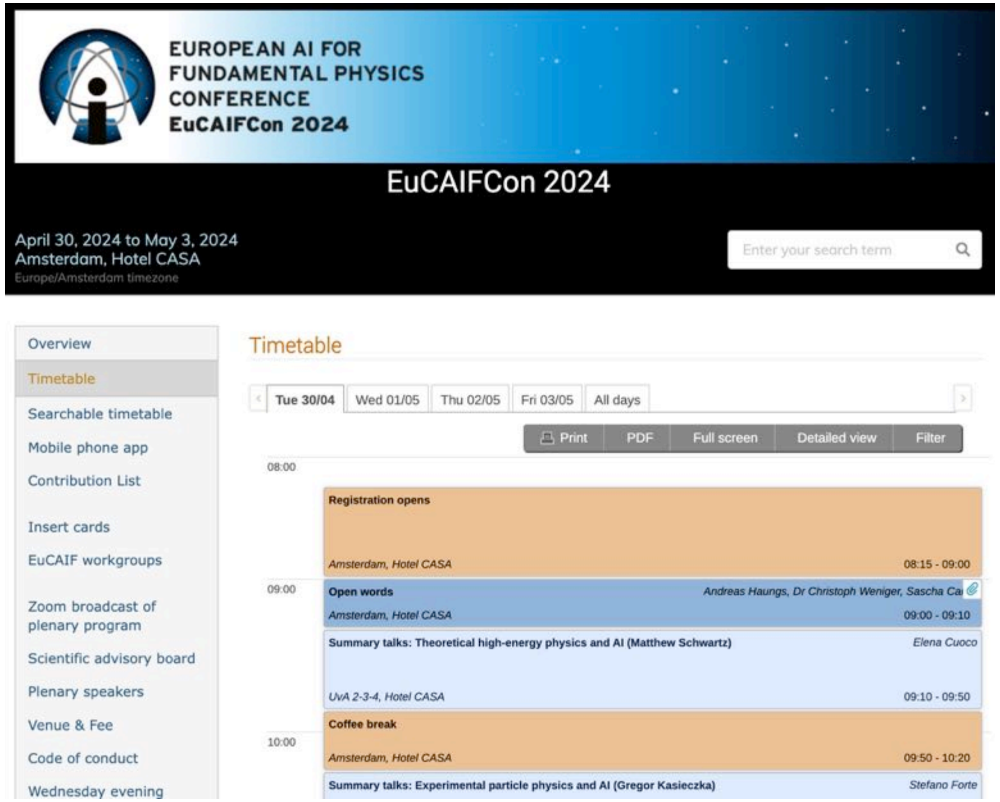
High-Quality Event





	Flavor [ν_e CC – %]	Energy$_{log}$ [eV]	Zenith [deg]	Azimuth [deg]	Area [deg^2]
predicted	16.09	18.24±0.07	78.25	236.87	3.78
true	0.0	18.21	78.12	236.59	-

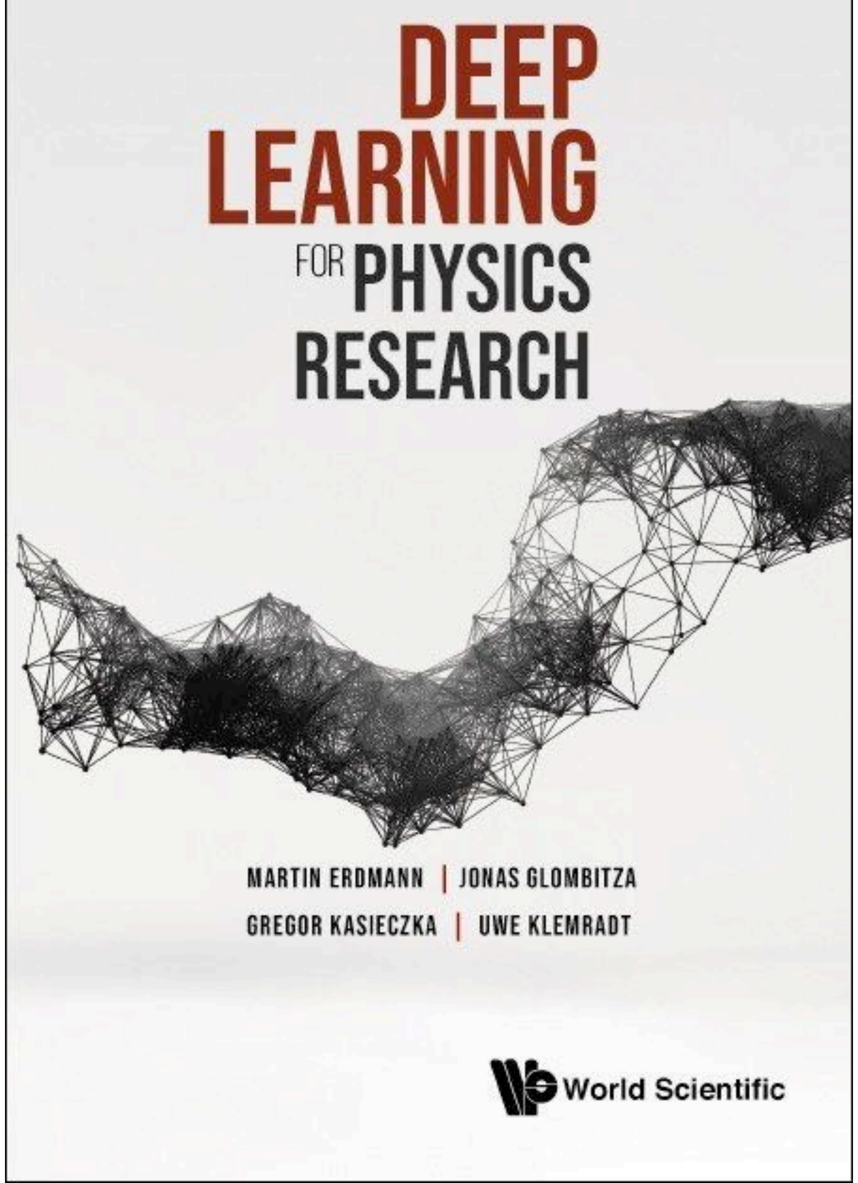
Interested in Deep Learning?



Remote PhD course at Uppsala University

https://www.uu.se/en/staff/faculty/science-and-technology/education-and-teaching/doctoral-studies/doctoral-student/courses/faculty-courses/applied-deep-learning-5-credits

Great introduction for physicists:



NuRadioOpt:
Optimization of Radio Detectors of Ultra-High Energy Neutrinos through Deep Learning and Differential Programming

European Research Council
Established by the European Commission

NuRadioOpt will improve both key factors that impact the science output

detection rate of UHE neutrinos

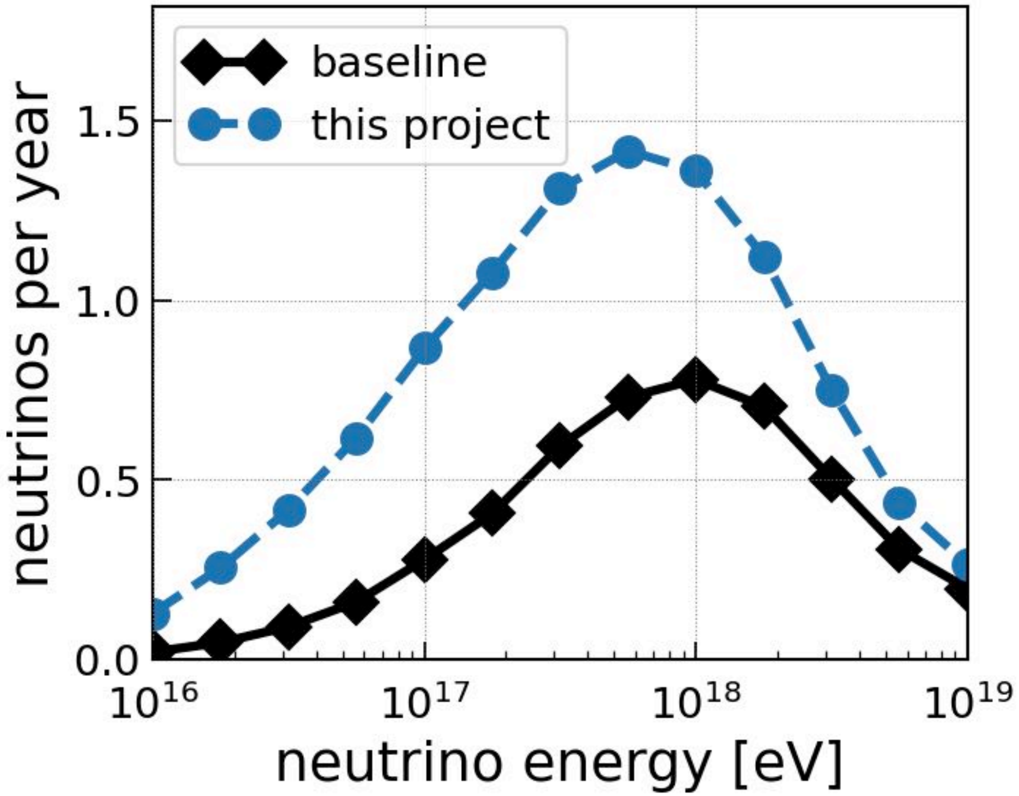
→ **objective 1: Deep-Learning-Based Trigger**

precision to determine the neutrino's direction and energy

→ **objective 2: End-to-End Optimization + Deep Learning Reconstruction**

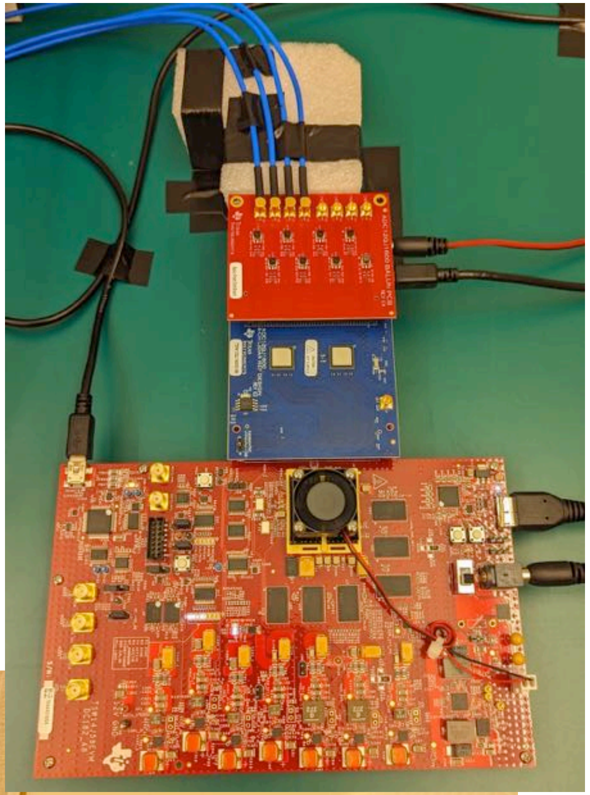
Objective 1: Deep-Learning-Based Trigger

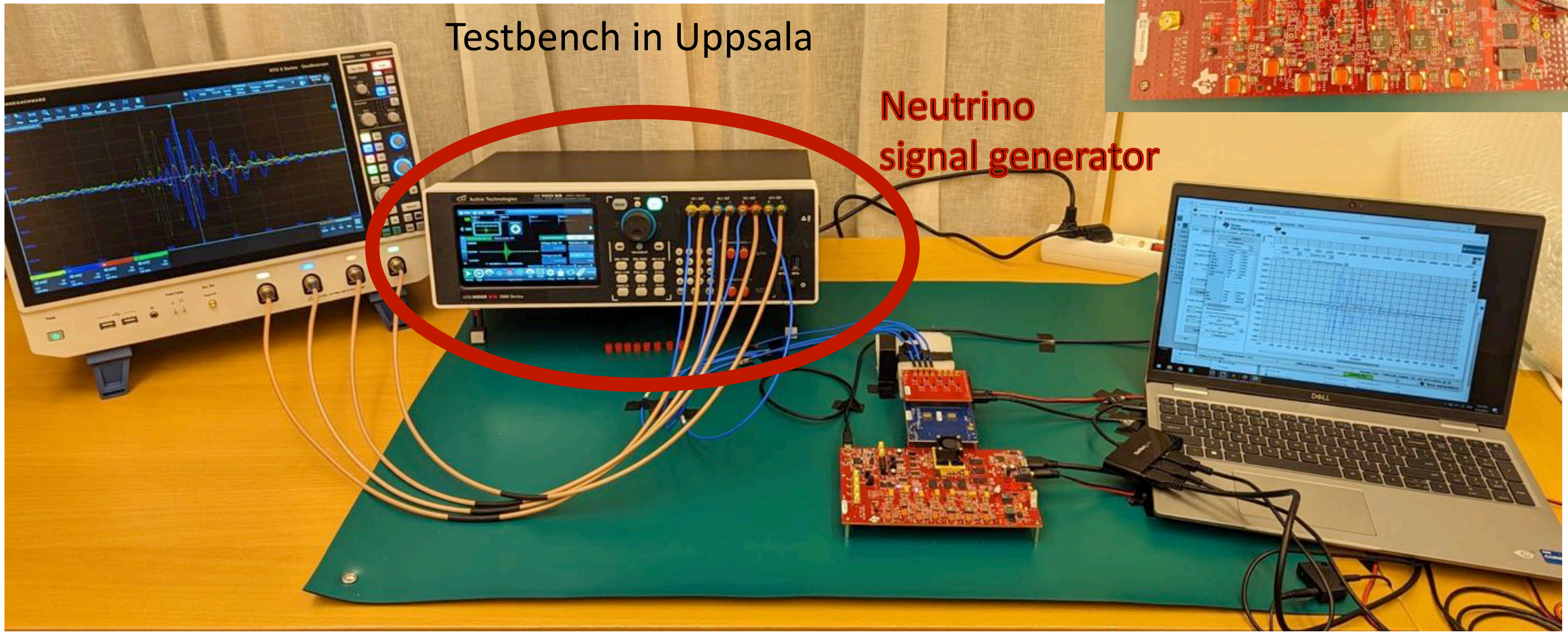
- **Huge potential of improvement:**
  - offline analysis: thermal noise can be rejected with high efficiency
  - Neural networks are very good at classification tasks
  - Proof-of-concept study: *ARIANNA collab. (… C. Glaser, …) , JINST 2022*
- Projected improvements:
  - **doubling neutrino detection rate in IceCube-Gen2**



New DAQ Development

- New ADC generation (JESD204B interface)
  - High speed and low power (~1GHz, 12bit at 0.5W/channel)
  - Simpler compared to custom ASICS of previous hardware
  - Better data quality and opportunities for advanced triggers
- Also looking into Neuromorphic Computing
  (with Tommaso Dorigo + Fredrik Sandin)



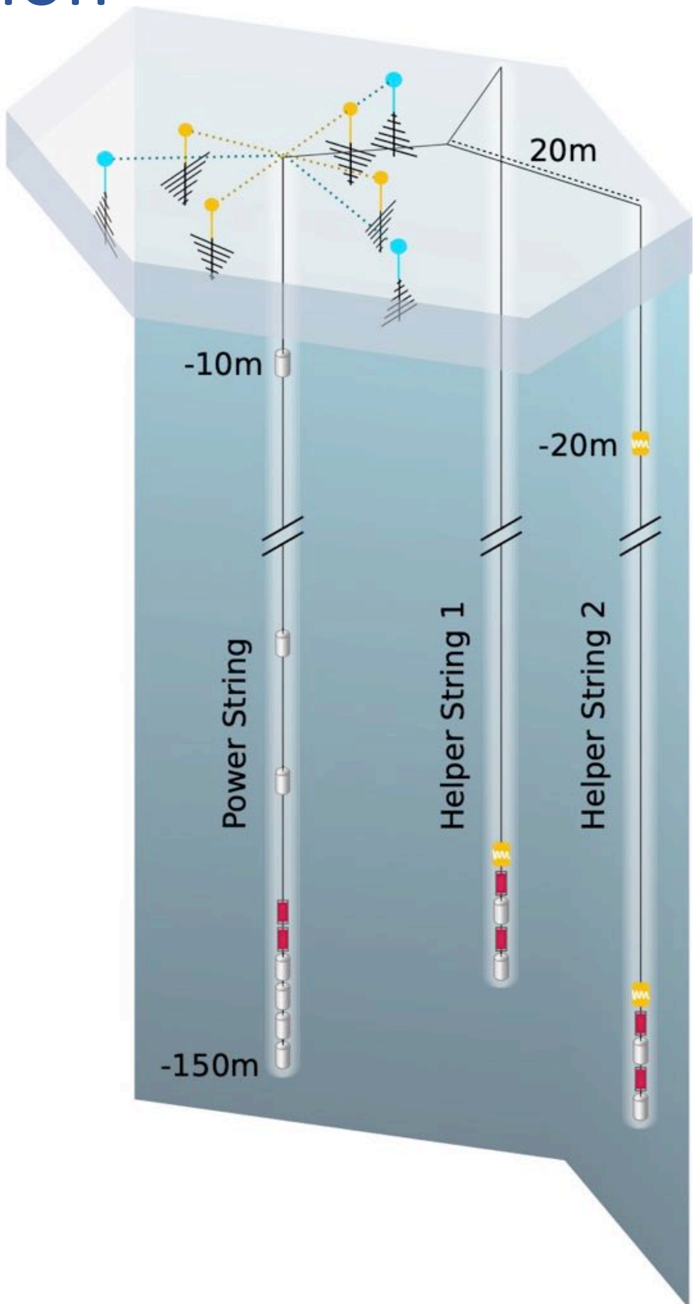


Christian Glaser


FDF 2024
FPGA Developers' Forum
an open space to discuss FPGA design
1st meeting
CERN, 11-13 June 2024
Organising Committee:
Nicolò Vladi Biesuz - INFN, IT
Filiberto Bonini - CERN, CH
Andrea Borga - Oliscience, NL
Davide Cieri (co-chair) - Max-Planck-Institute for Physics, DE
Christian Glaser - Uppsala University, SE
Francesco Gonnella (co-chair) - University of Birmingham, UK
Evangelia Gousiou - CERN, CH
Christian Krieg - TU Wien, AT
Mathieu Saccani - CERN, CH
Paschalis Vichoudis - CERN, CH
Tom Williams - RAL, UK
Rui Zou - Cornell University, US
cern.ch/fdf
fdf@cern.ch

Objective 2: End-To-End Optimization

- Current status: Station layout has not been thoroughly optimized
  - because MC tools and reco algorithms were not available
  - because turnaround times are too large *-> changed with NuRadioMC/Reco*
  - scaling relations are insufficient



Objective 2: End-To-End Optimization

- Deep learning and differential programming can build an end-to-end optimization pipeline
- Direct optimization of science objective

detector parameters, e.g.,
- antenna positions
- antenna orientation

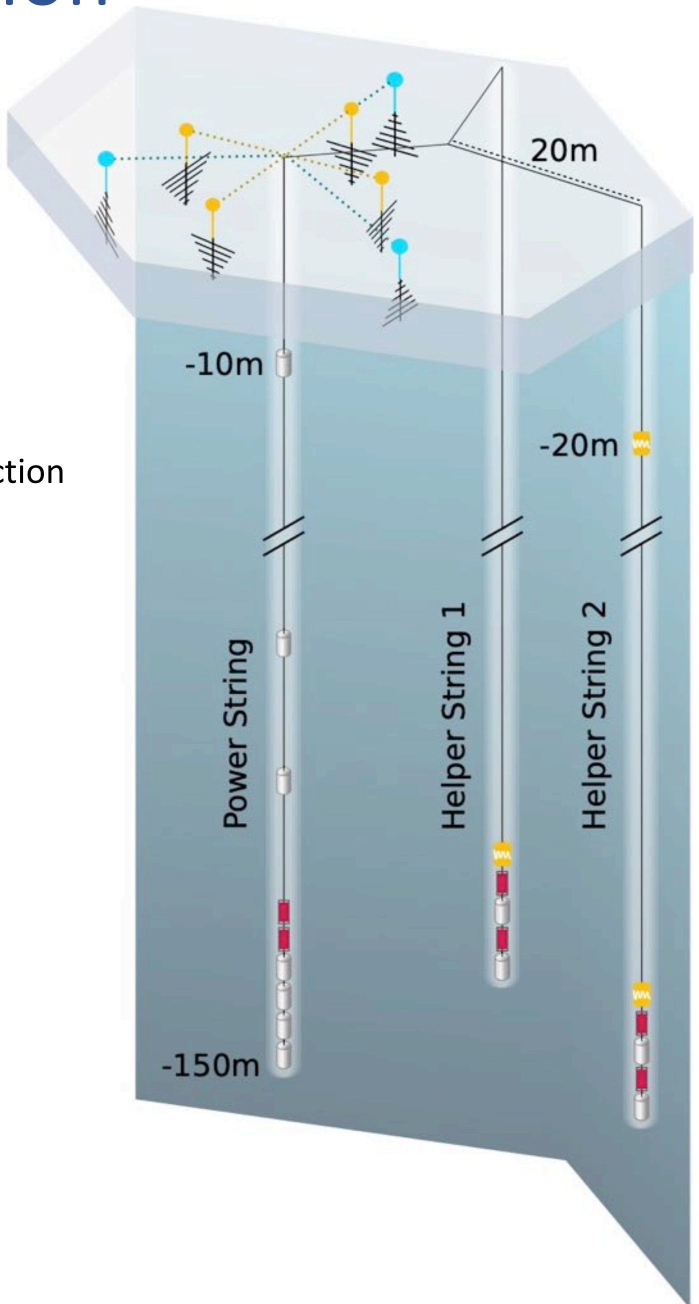
automatic differentiation

Θ | MC simulation × reconstruction × analysis | f(Θ)

science output, e.g.,
- neutrino-nucleon cross-section
- source discovery
- flux measurement

costs, engineering constraints

→ Expected improvements: up to three times more precise measurement of neutrino direction and energy



Main science objectives of UHE neutrino astronomy:

Impact of NuRadioOpt

Neutrino-Nucleon Cross Section

→ 3x more precise measurement

*V. Valera, M. Bustamente, **C. Glaser**, JHEP 06 105 (2022)*

Diffuse Flux

→ expedite the detection of UHE neutrino fluxes by up to a factor of five

*V. Valera, M. Bustamente, **C. Glaser,** PRD 107, 043019 (2023)*

Point Sources

→ identify sources from deeper in our Universe, increasing the observable volume by a factor of three

D. F. G. Fiorillo, V. Valera, M. Bustamente, JCAP03(2023)026

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D. F. G. Fiorillo, V. Valera, M. Bustamente, JCAP03(2023)026

- **Improvements equivalent to building a more than three times larger detector** at essentially no additional costs
- NuRadioOpt timeline perfect for influencing IceCube-Gen2
- because we are already at the limit of logistical resources at the South Pole, **NuRadioOpt is the only option to accelerate UHE neutrino science in the next decade**

Abstract submission open until June 1st
https://indico.cern.ch/event/1380163/

MODE collaboration https://mode-collaboration.github.io/

MODE collaboration, Reviews in Physics ***10*** *100085 (2023)*

Summary

- Sensitivity to UHE neutrinos can be obtained with in-ice radio detection
- Frequency band: 80-500 MHz
- Mature technology, discovery scale experiment under construction
  - RNO-G (construction 2021 – 2026)
- Angular resolution:
  - Average ~a few degrees
  - High quality neutrinos can have sub-degree resolution
- Best way forward?: Multimessenger astronomy
  - Spatial and temporal correlation with other messengers (Gravitational Waves, Gamma Rays, Optical/Radio observations)