Probing EeV neutrinos with the IceCube-Gen2 in-ice radio array

Christian Glaser for the IceCube-Gen2 collaboration

Uppsala University and TU Dortmund

ICECUBE GEN2

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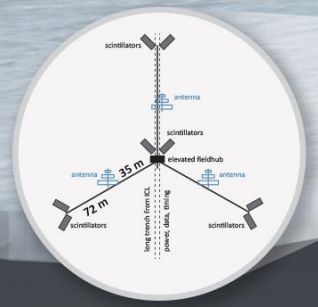
IceCube GEN2 | DETECTORS

SURFACE • RADIO • OPTICAL

Comprehensive documentation:
[IceCube-Gen2 Technical Design Report]



Cosmic Ray Surface Array

An air shower array that sits on top of the optical array

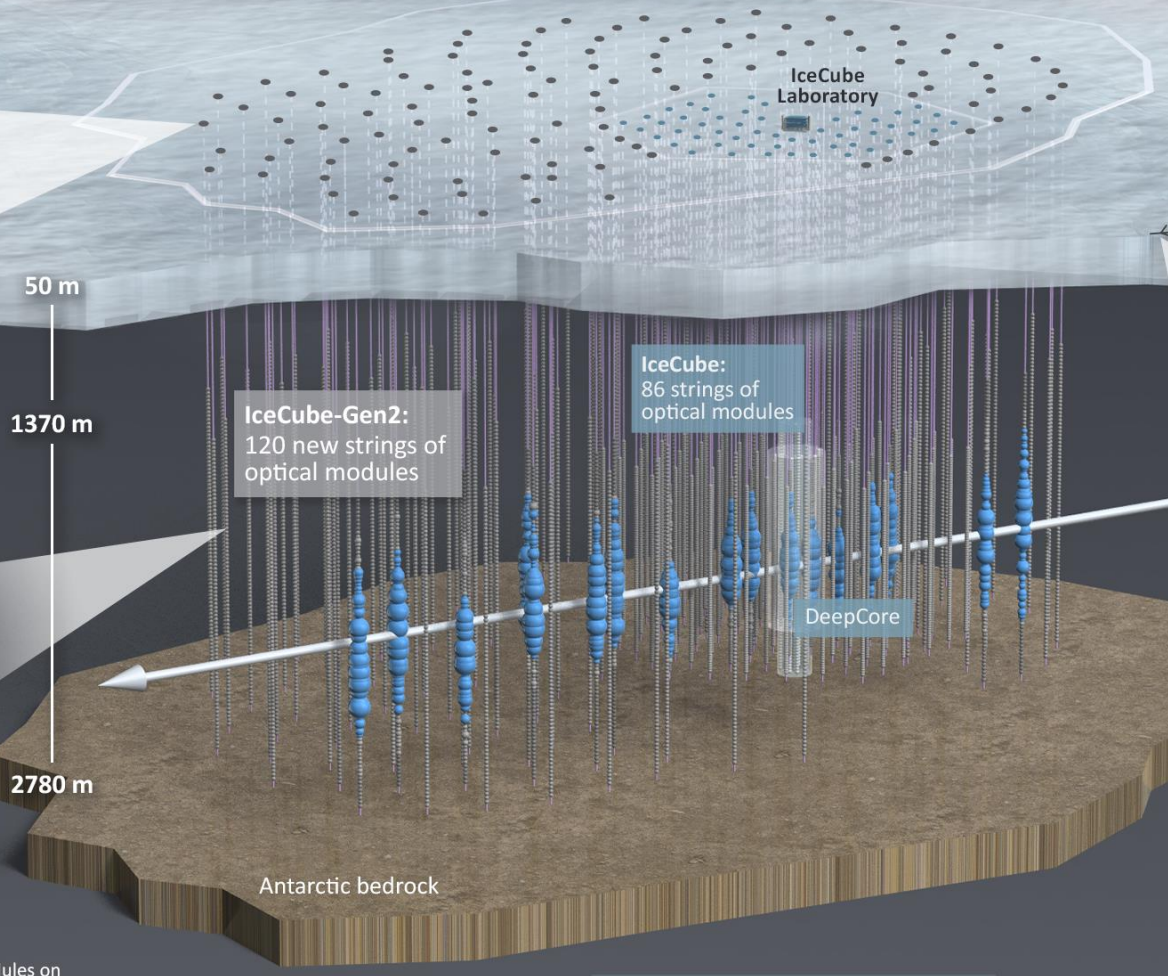
One surface station installed above each optical string

IceCube-Gen2 Optical Module

4x the sensitivity of IceCube's modules

9,600 new optical modules in total to be deployed in the ice

80 modules on each string, spaced 17 meters apart

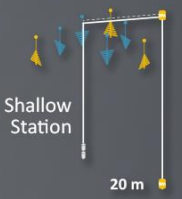


IceCube (1 km)

IceCube-Gen2 (5 km)

Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

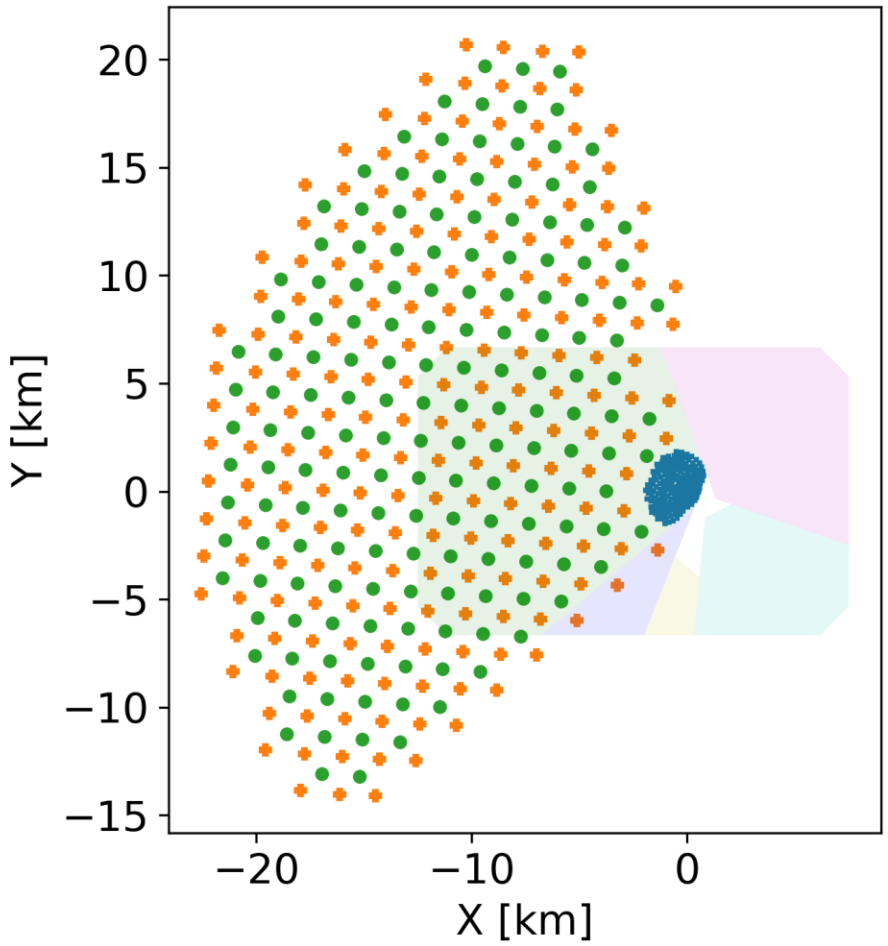


Below-Ice Radio Array

361 detector stations spread over an area of 500 km²

IceCube-Gen2 radio

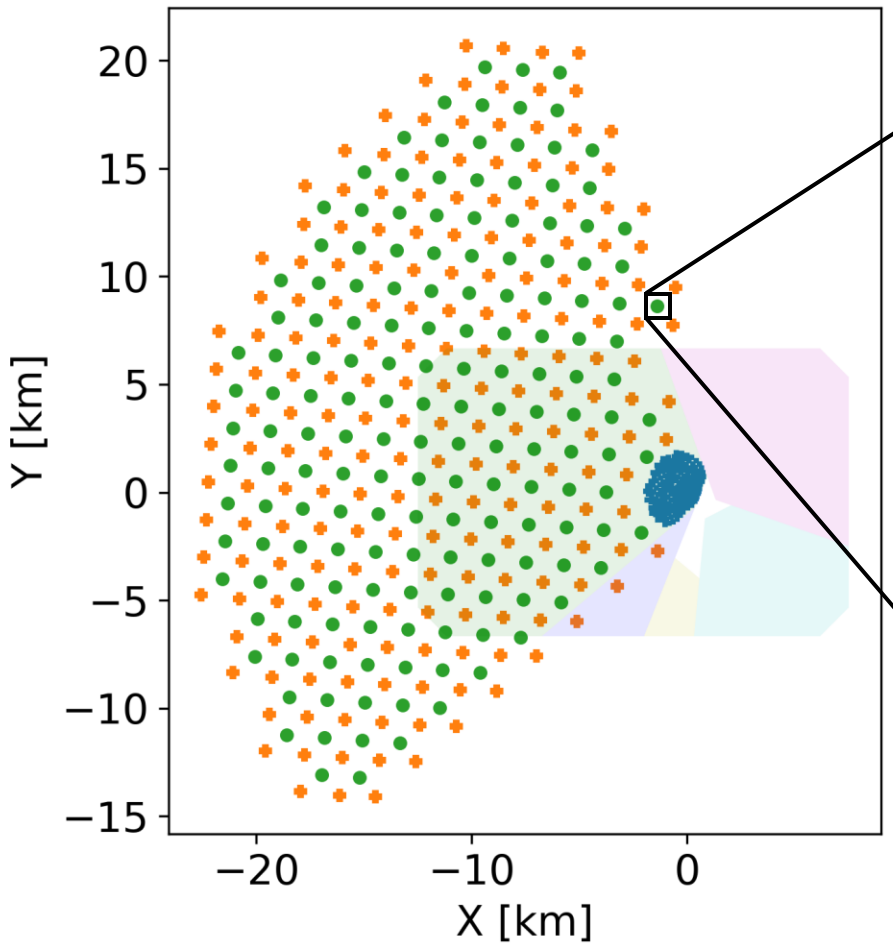
unprecedented sensitivity to UHE neutrinos

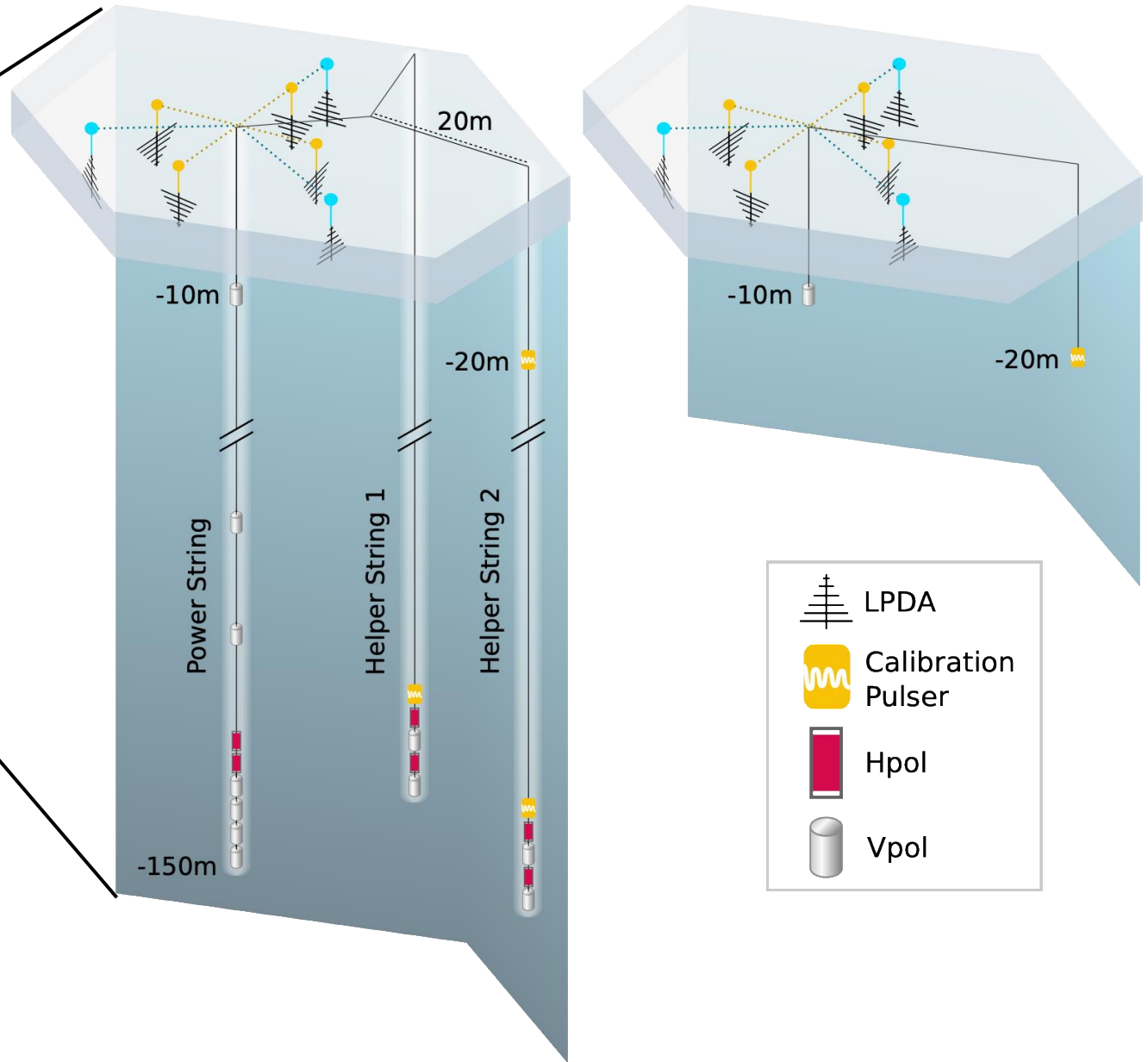


IceCube-Gen2 radio

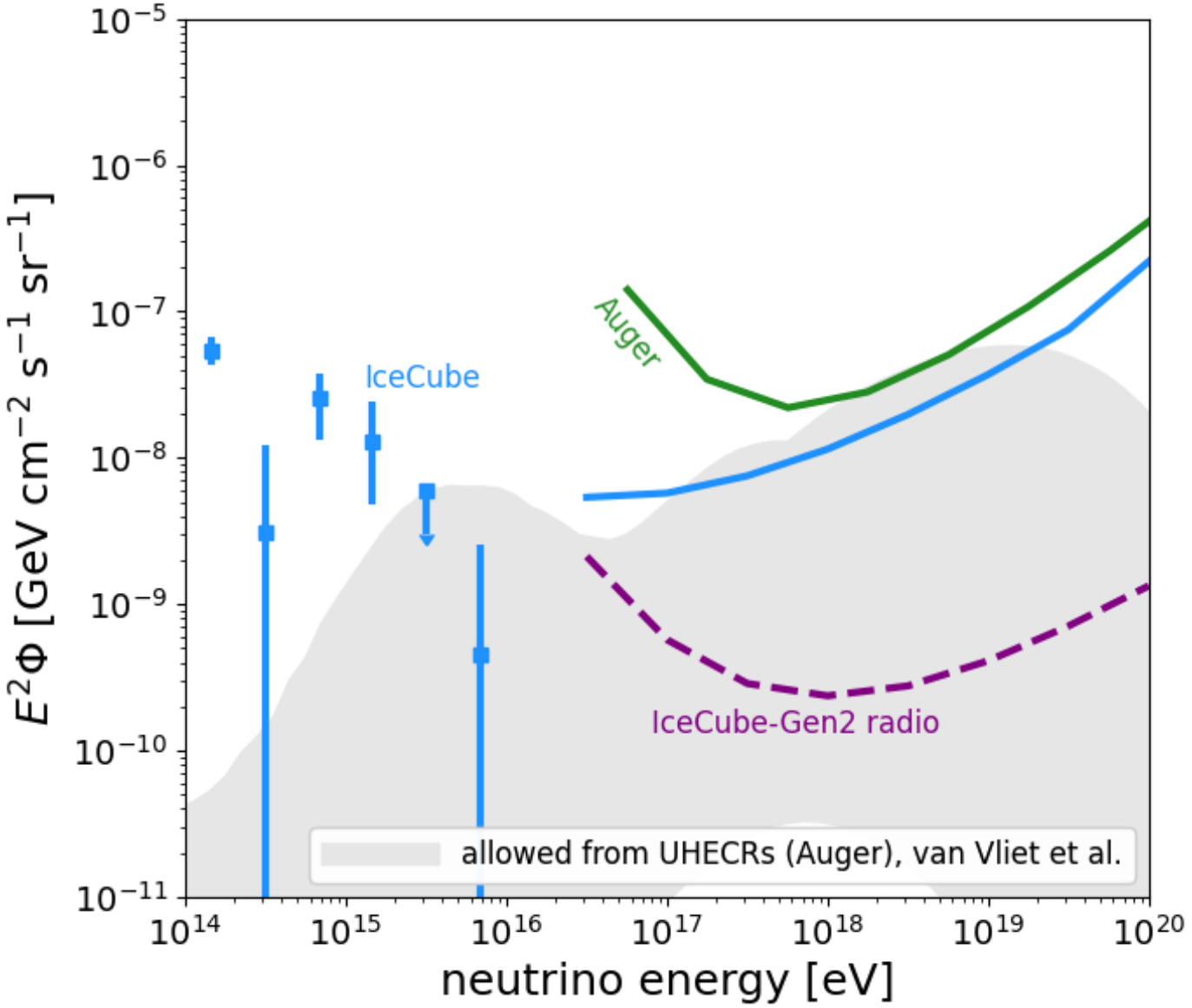
unprecedented sensitivity to UHE neutrinos

Hybrid array design with *shallow* and *deep* detector components to minimize syst. uncertainties, deployment risk, and cross-validate neutrino detection and reconstruction





UHE Neutrino Sensitivity



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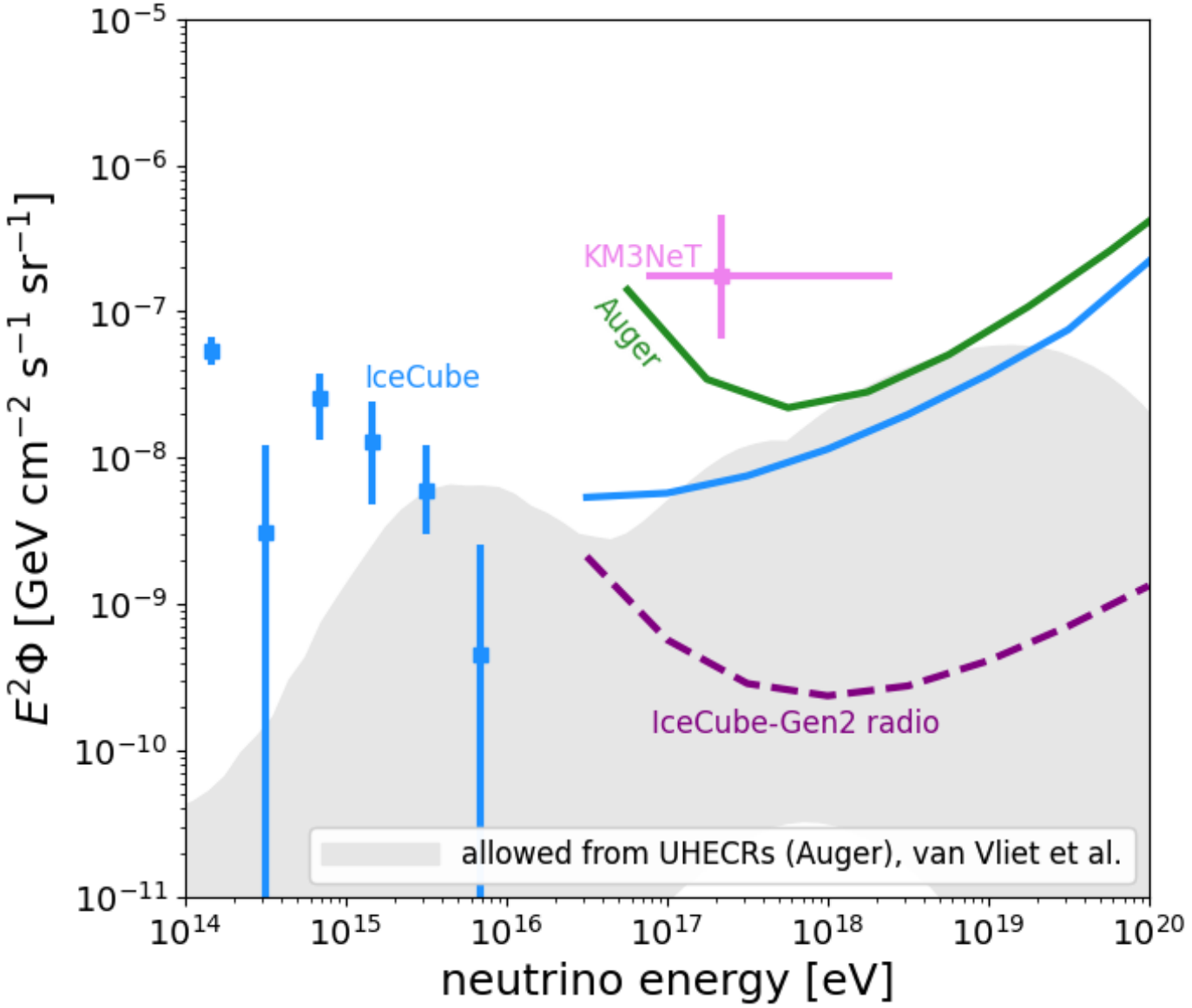

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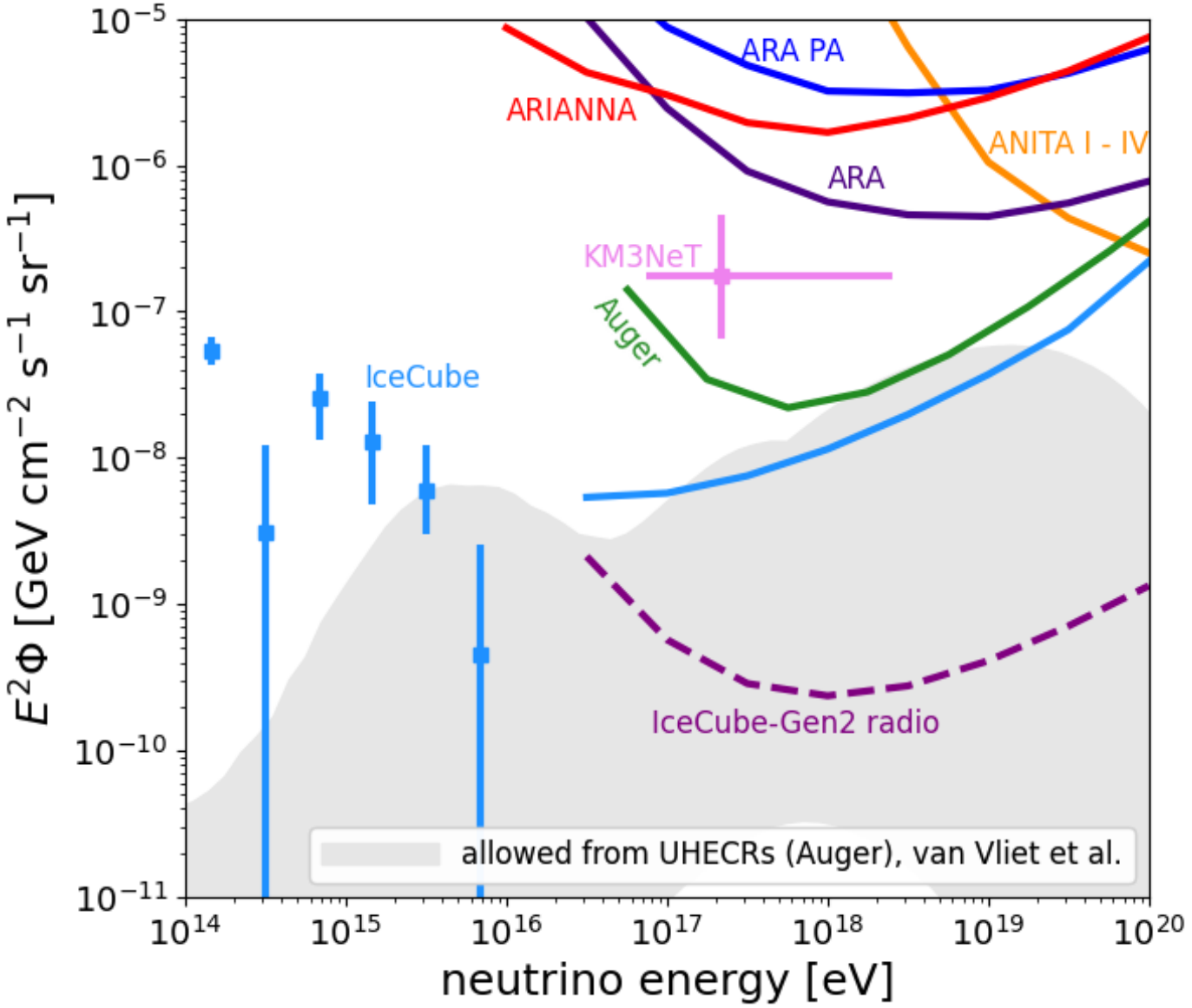
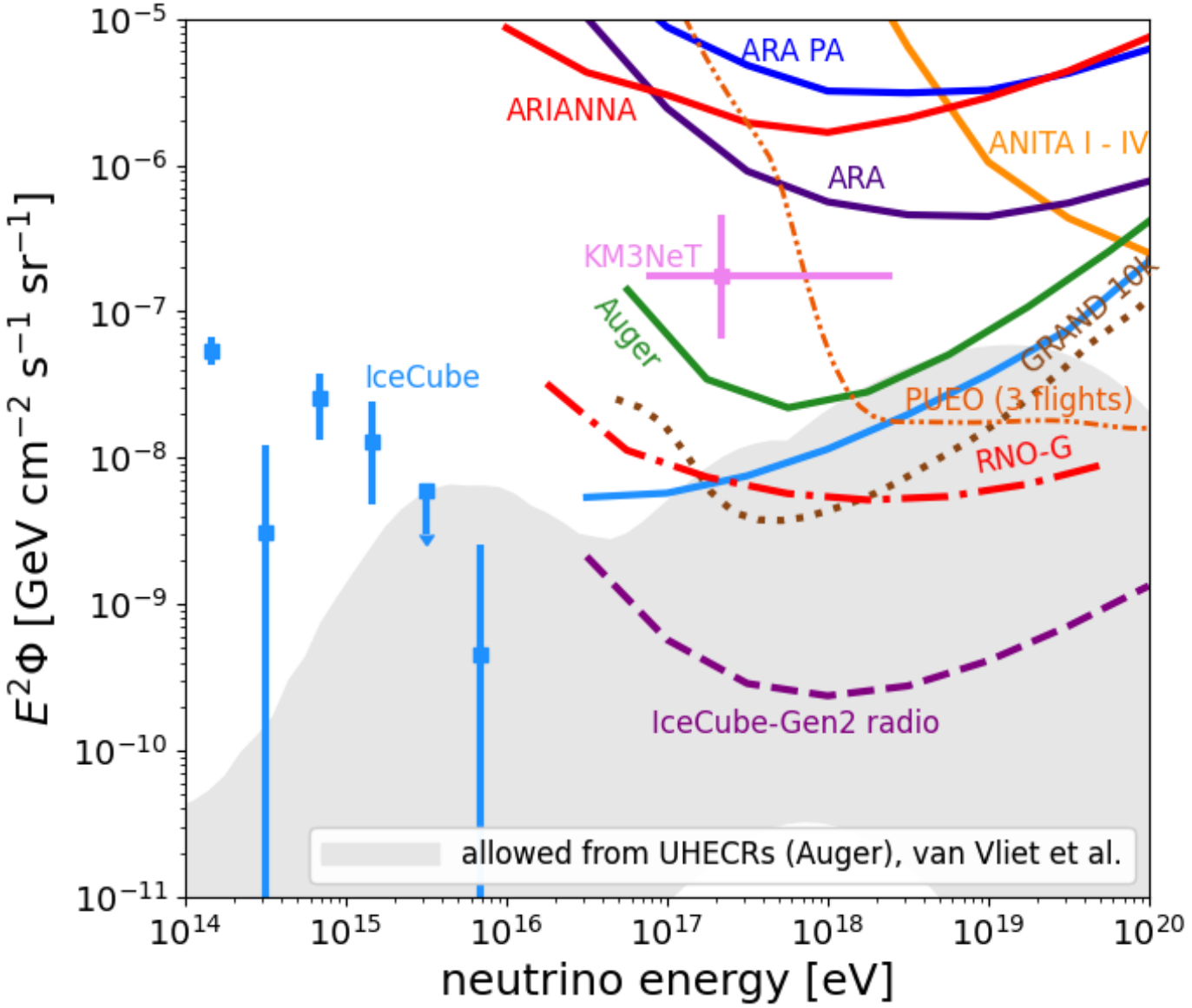


Pilot in-ice radio arrays demonstrated experimental feasibility

UHE Neutrino Sensitivity



Pilot in-ice radio arrays demonstrated experimental feasibility

Mid-scale arrays under construction/planning

RNO-G is already operating with 8 stations
→ testbed for Gen2-radio

Experimental Feasibility Demostrated

- End-to-end neutrino search with ARA and ARIANNA
  → limits of neutrino flux published

ARA collaboration, Phys. Rev. D 102, 043021
ARIANNA collaboration, JCAP 03(2020)053
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  - Signal direction (incl. correction for ice bending) with <1deg resolution *ARIANNA collaboration, JINST 15 (2020) P09039*
  - Cosmic-ray identification at expected rates ARIANNA collaboration, Astropart. 90 (2017) 50-68
  - Polarization from air-showers with <2deg resolution ARIANNA collaboration, JCAP 04(2022)022
  - Radio emission from air-shower cores *A. Coleman et al., Astropart. 172 (2025) 103136*
    ARA collaboration, PoS(ICRC2025)1213 -> talk P. Windischhofer Tue 17:50
  - + many, many simulation studies…

    → see also new results from RNO-G: *Overview A. Nelles PoS(ICRC2025)1129*

For RNO-G see e.g.
- *RNO-G Hardware PoS(ICRC2025)1168; F.Schlüter*
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- Efficient and reliable deployment procedures established with RNO-G
  - Ongoing construction of RNO-G tests all deployment aspects
  - Deep drilling performance much improved this season
    - World's largest mechanical drill with speeds up to 100 m in 12 hours
  - Detailed calibration plans

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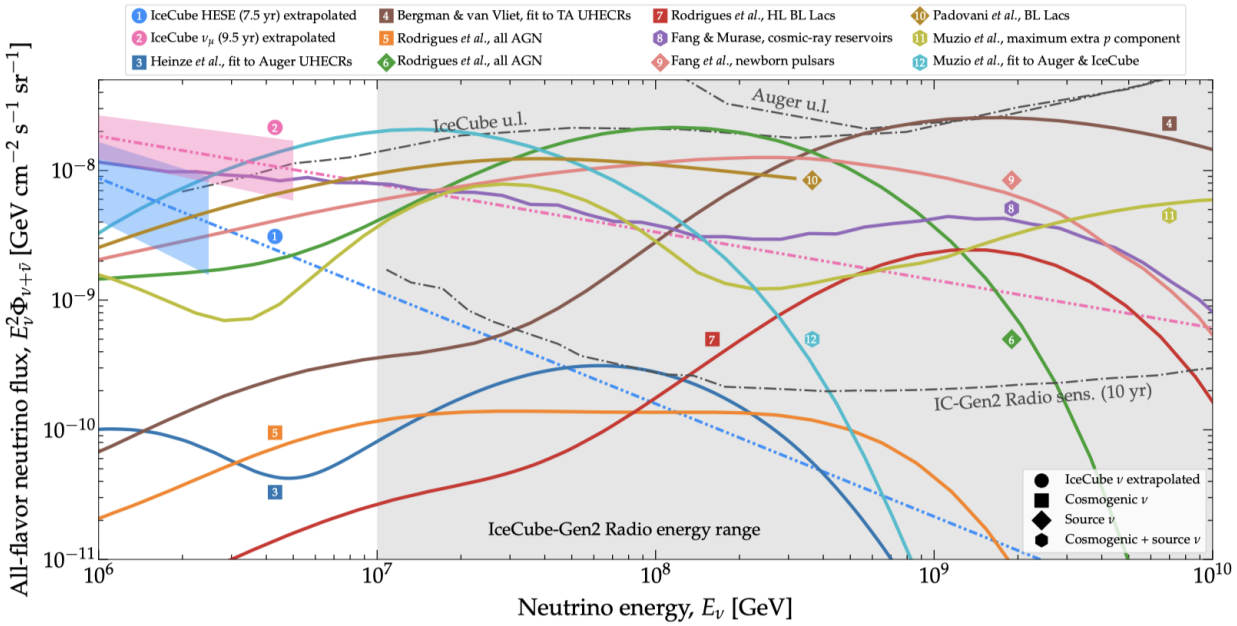
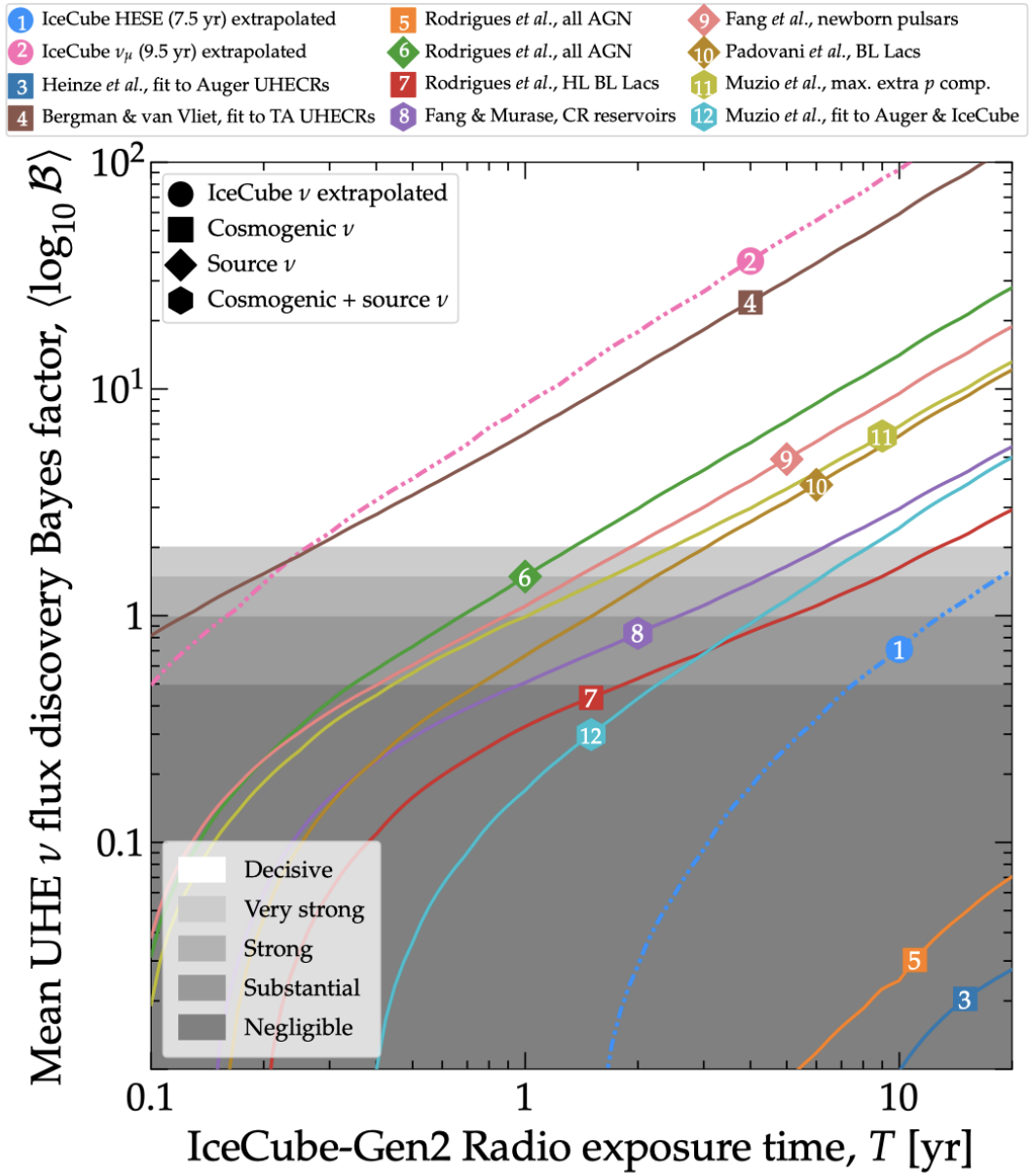
Science Overview: Diffuse Flux Discovery

- **Most models can be probed within 10 years**

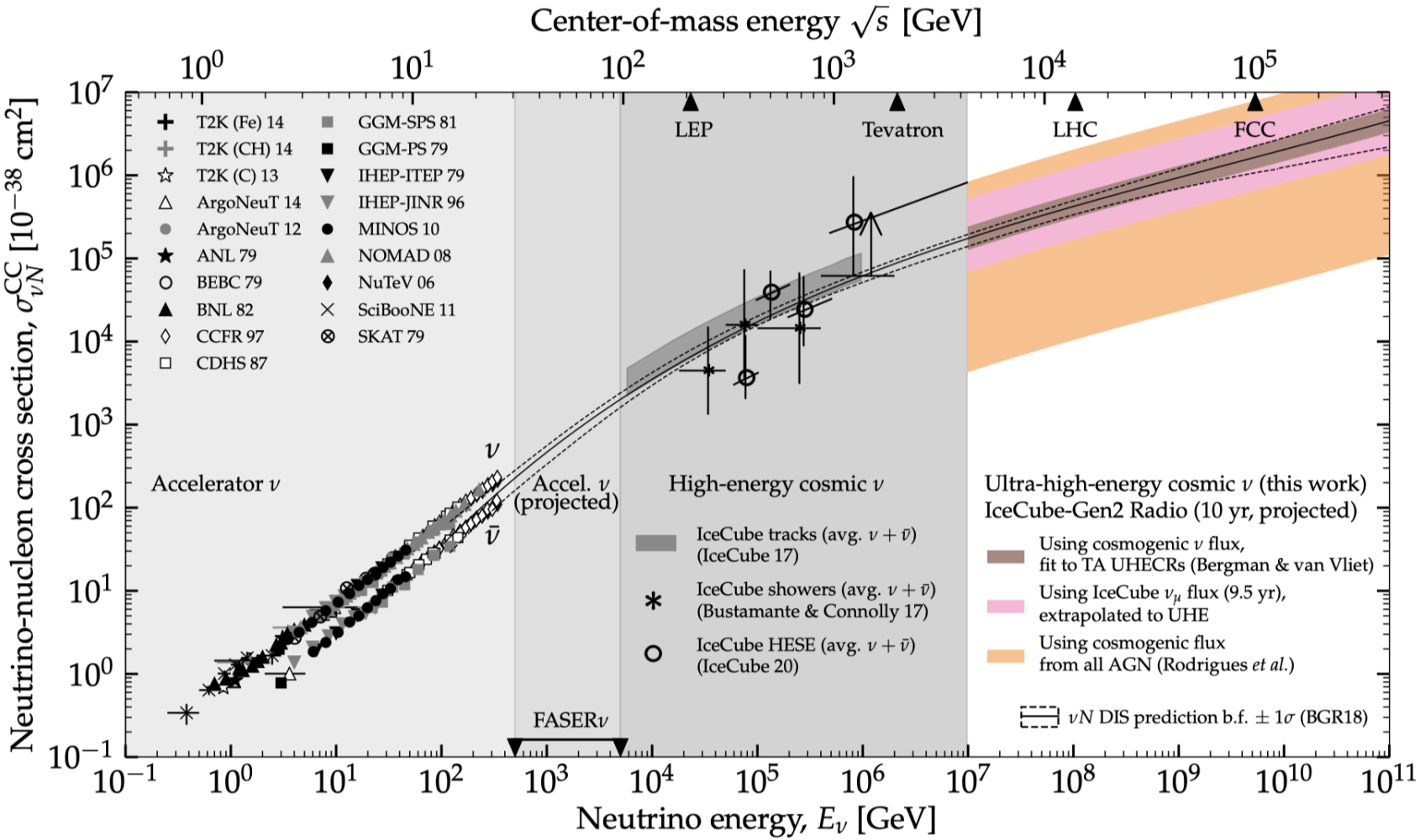




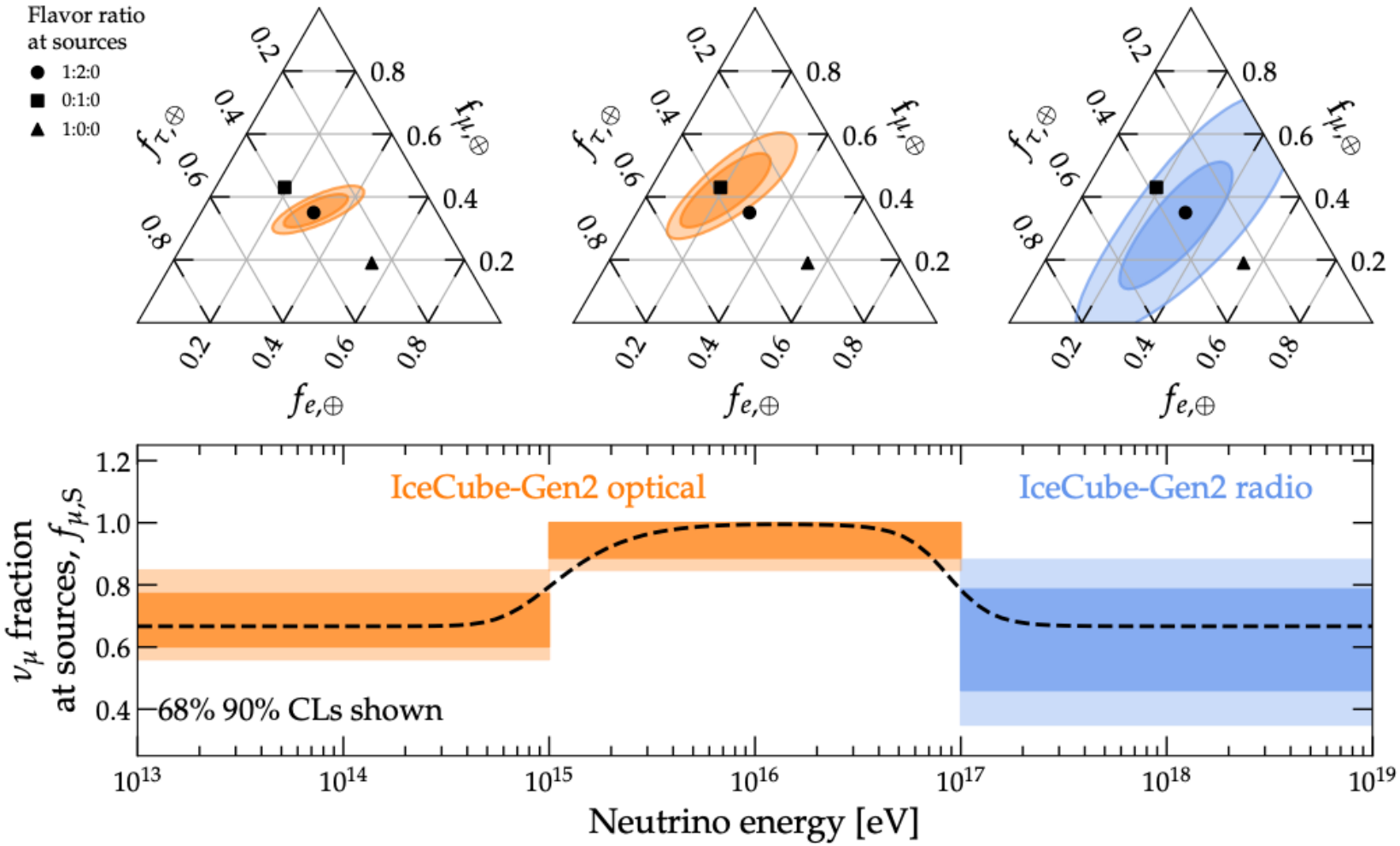
Science Overview: Cross Section

- Sensitivity comes from Earth attenuation
  - Angular resolution important
  - Horizontal events important

$$N_\nu(E_\nu, \theta_z) \propto \Phi_\nu(E_\nu)\sigma(E_\nu)e^{-L(\theta_z)/L_{\nu N}(E_\nu,\theta_z)}$$
$$L_{\nu N} \equiv (\sigma n_N)^{-1}$$



IceCube-Gen2 Flavor Sensitivity



source neutrinos
(transition from pion decay to muon-damped production)

GZK neutrinos

Outlook: Further Improvement of Gen2-radio (*NuRadioOpt*)

Two key factors impact the science output

detection rate of UHE neutrinos

→ **Deep-Learning-Based Trigger**

precision to determine the neutrino's direction and energy

→ **End-to-End Optimization**
Deep Learning Reconstruction

How:
Using Deep Learning and Differential Programming

European Research Council
Established by the European Commission

Main science objectives of UHE neutrino astronomy:

Impact of NuRadioOpt

Neutrino-Nucleon Cross Section

→ 3x more precise measurement

V. Valera, M. Bustamante, 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. Bustamante, 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. Bustamante, JCAP03(2023)026

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

Summary

- In-ice radio detector of IceCube-Gen2
  → unprecedented sensitivity to UHE neutrinos
- Detailed forecasts of main science objectives
  - diffuse flux, cross-section, point sources, flavor
- Technical feasibility demonstrated in pilot arrays (ARA, ARIANNA)
- Large-scale deployment under demonstration with RNO-G
- Comprehensive documentation: IceCube-Gen2 Technical Design Report
- Outlook: Further improvements possible using advances in deep learning and differential programming

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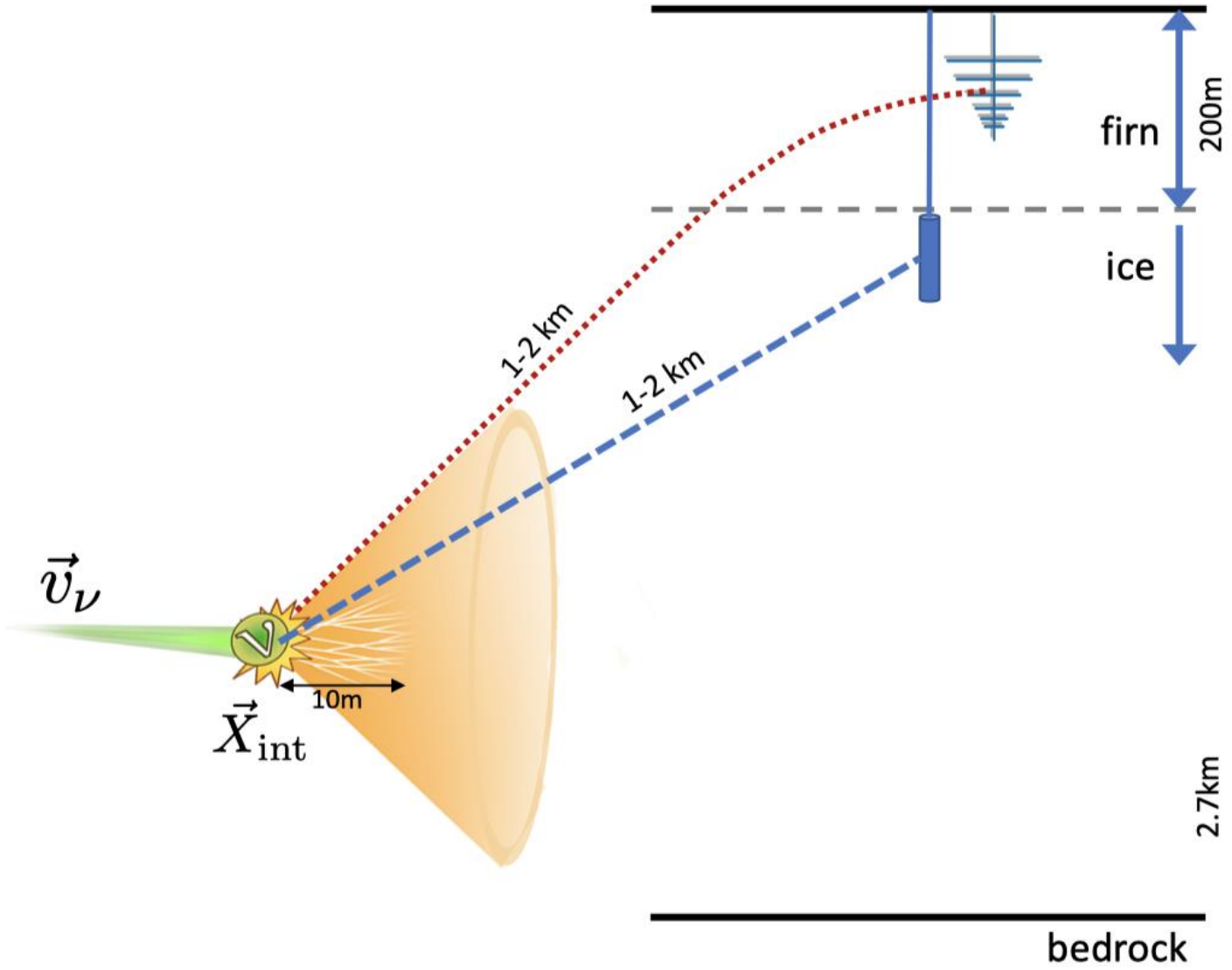
Bonus Slides

In-Ice Radio Detection in a Nutshell

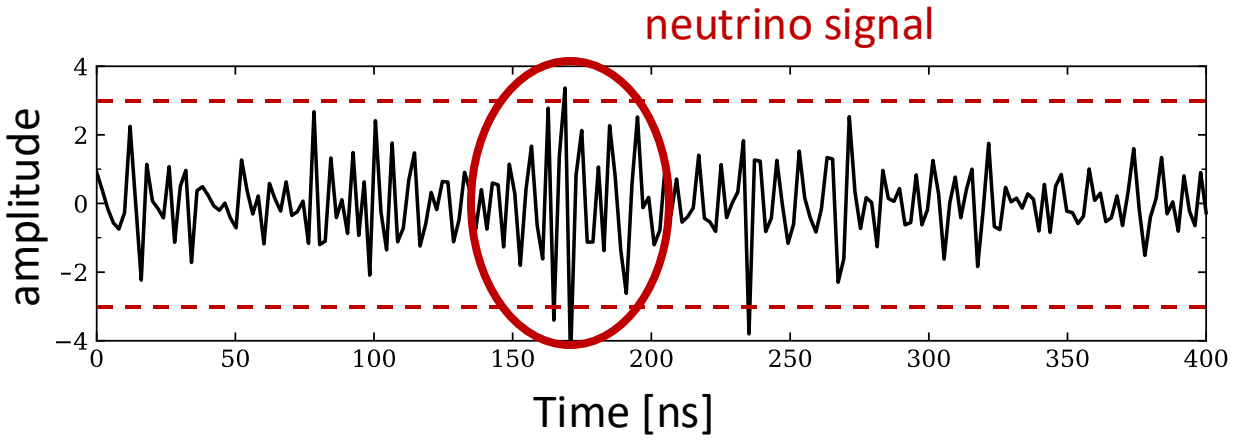


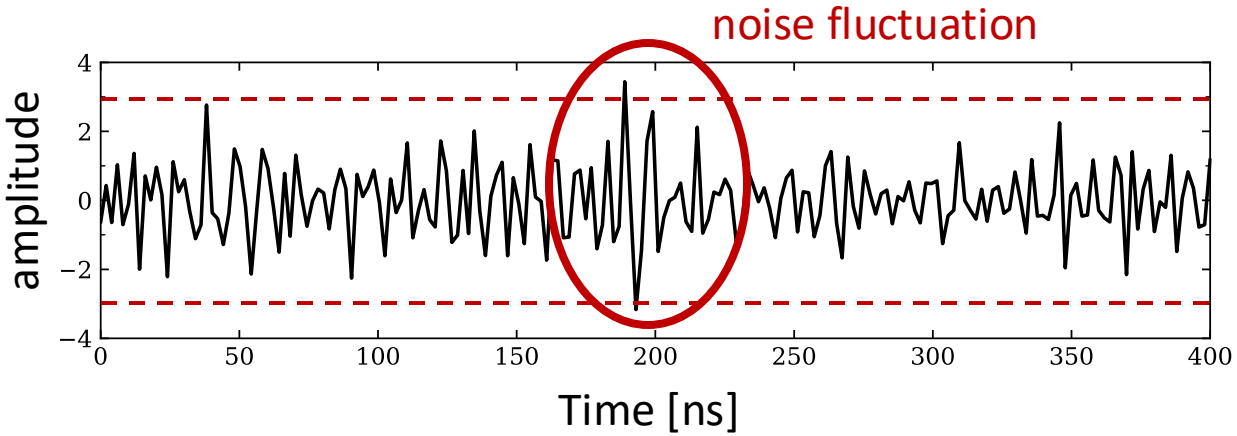
more infos: Book Chapter *In-Ice Radio Detection* arXiv:2208.04971

Deep-Learning-Based Trigger

- Data can't be stored continuously
- Current state of the art: Threshold-based trigger
  - Unavoidable thermal noise fluctuations dominate trigger
  - Thresholds need to be high enough to limit trigger rate on thermal noise

- **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., JINST 17 P03007 (2022)





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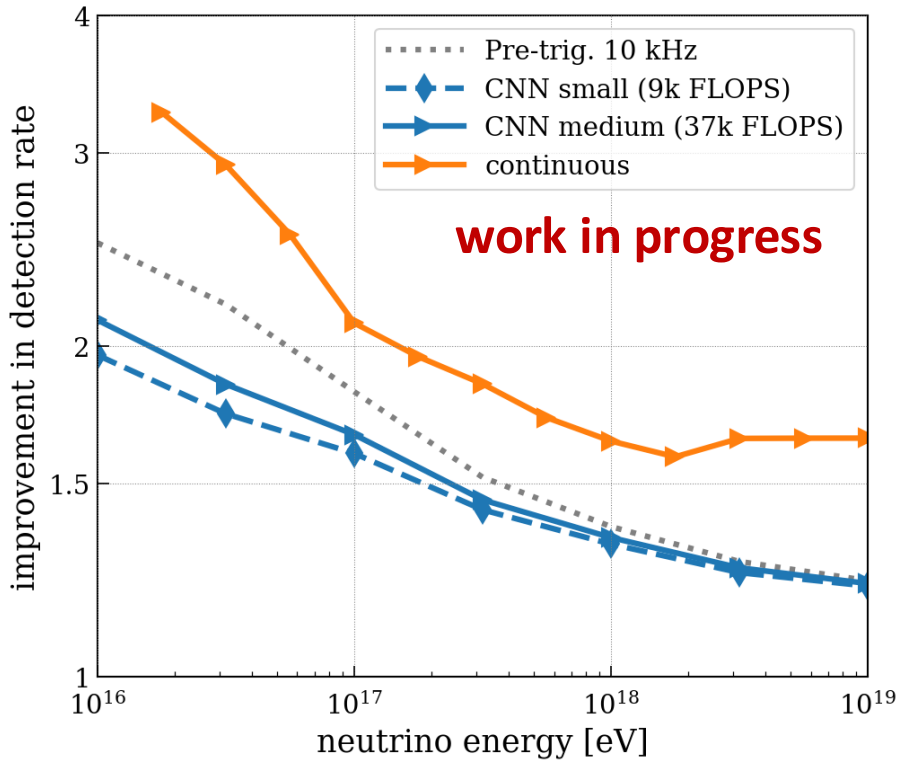
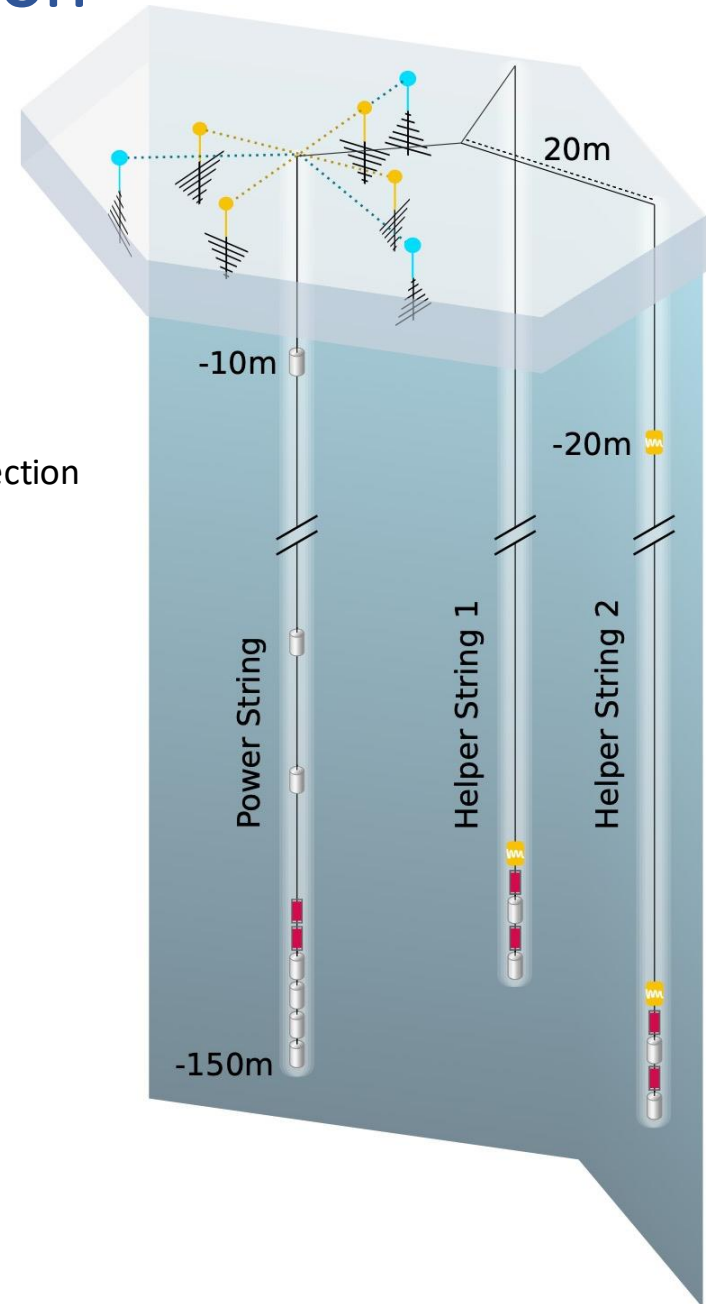


Projected improvements:
doubling neutrino detection rate in IceCube-Gen2

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

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

automatic differentiation

Θ → MC simulation x reconstruction x analysis → f(Θ)

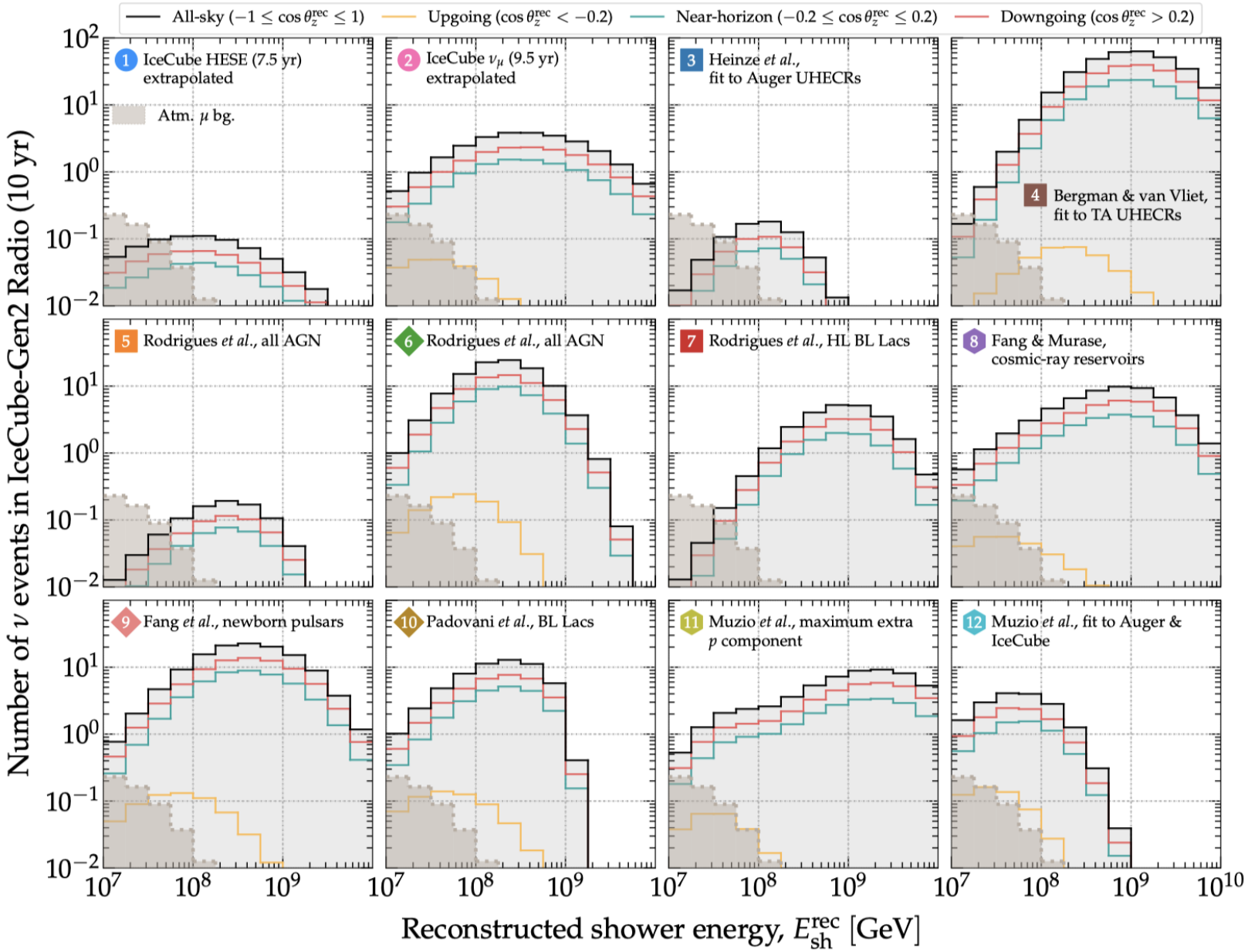
costs, engineering constraints

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

Promising first results: *M. Ravn et al, MODE workshop 2025*

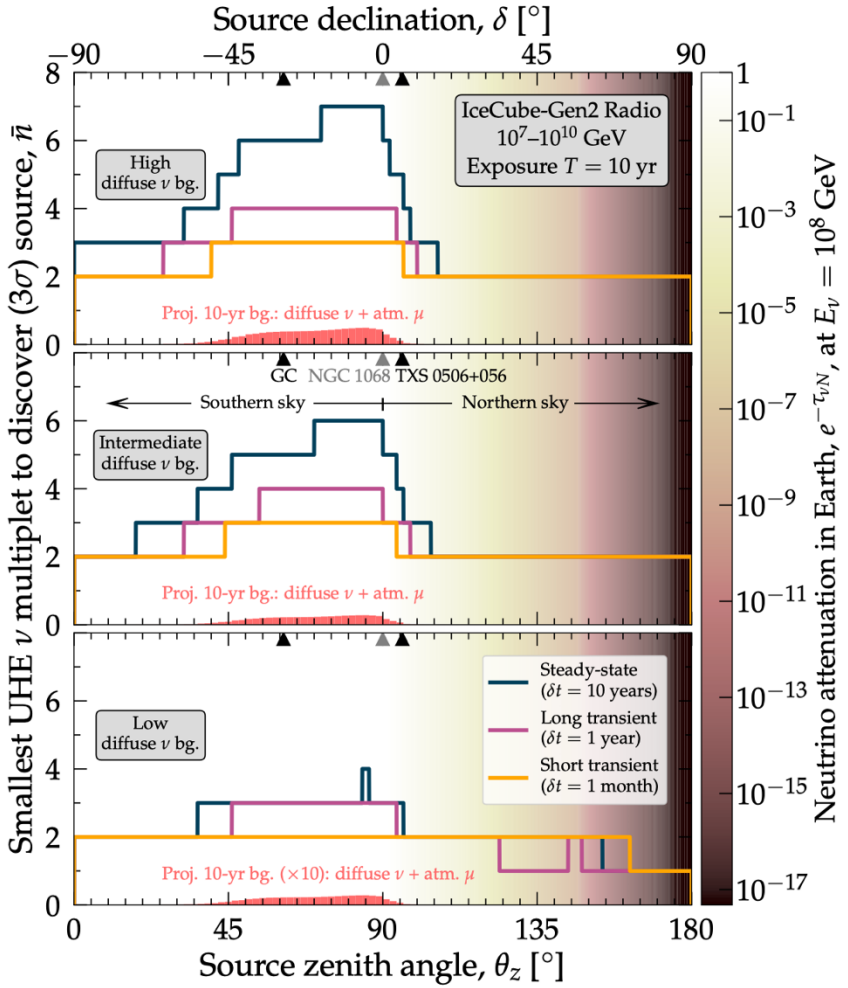
Science Overview: Neutrino Detection Rate

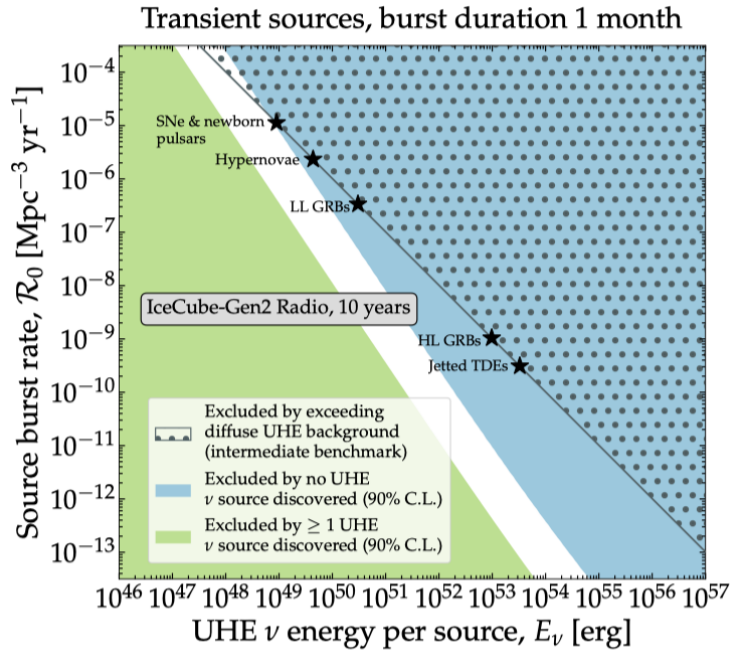
- Large variety in model predictions from both
  - GZK (cosmogenic)
  - source (astrophysical)
- 30 – 300 neutrinos in 10 years

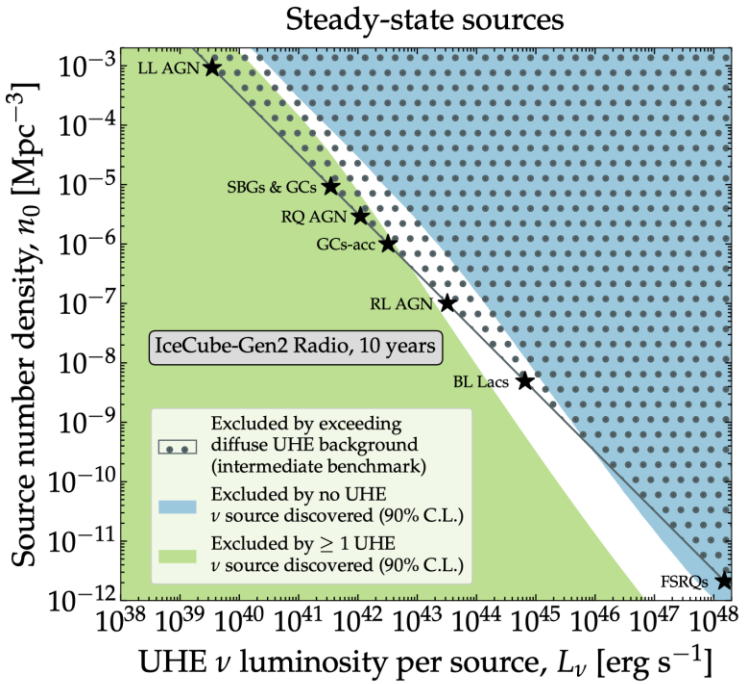


Science Overview: Point Sources

- Multiplet analysis assuming 3deg angular resolution
- Good constraints on single dominant source classes

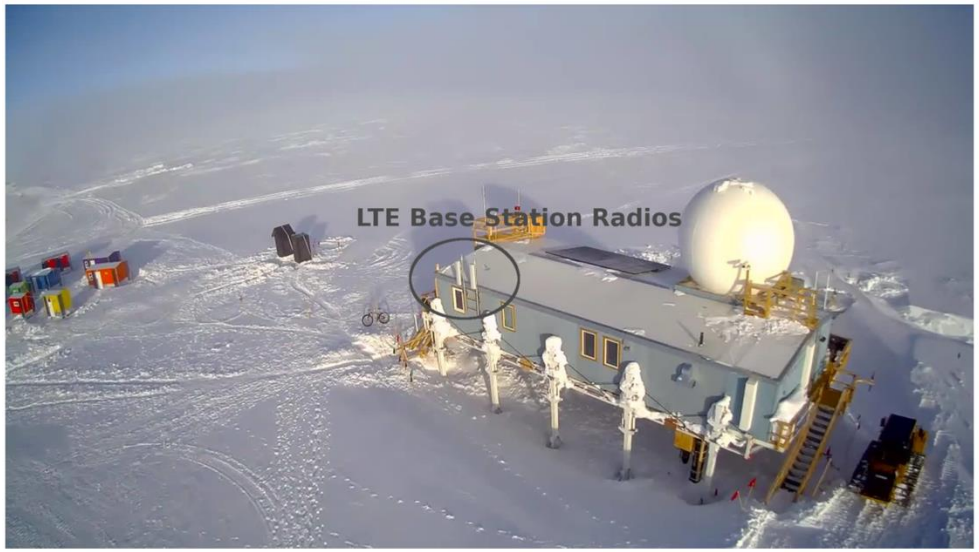


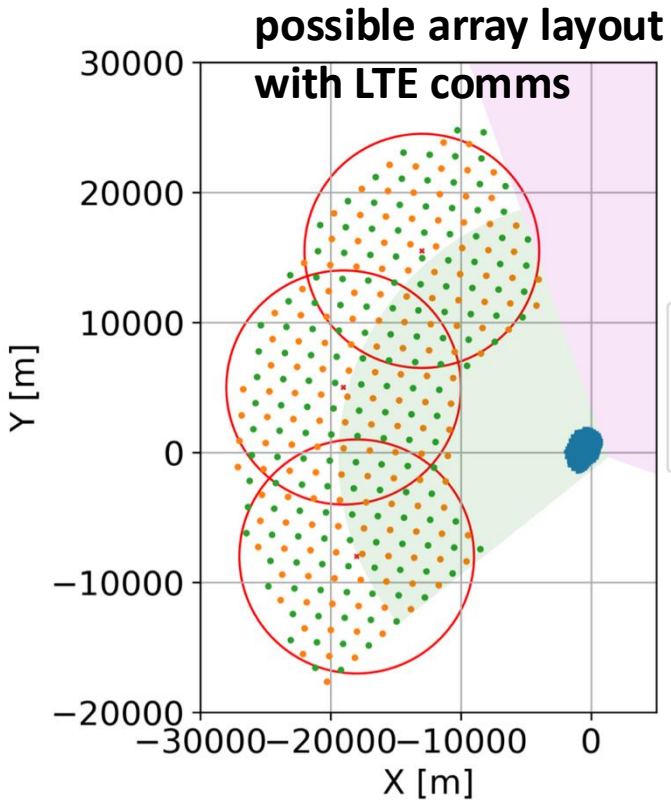




Power and Communication

- Baseline plan: Cabled array for power and comms
- Alternatives:
  - Autonomous power:
    - Solar panels in summer
    - Wind power + batteries during winter
      - under development, tests in Greenland and South Pole, not yet working reliably
  - Communication via LTE and LoraWAN
    - successfully used in RNO-G
    - **but** potential background for CMB telescopes, problem for dark sector



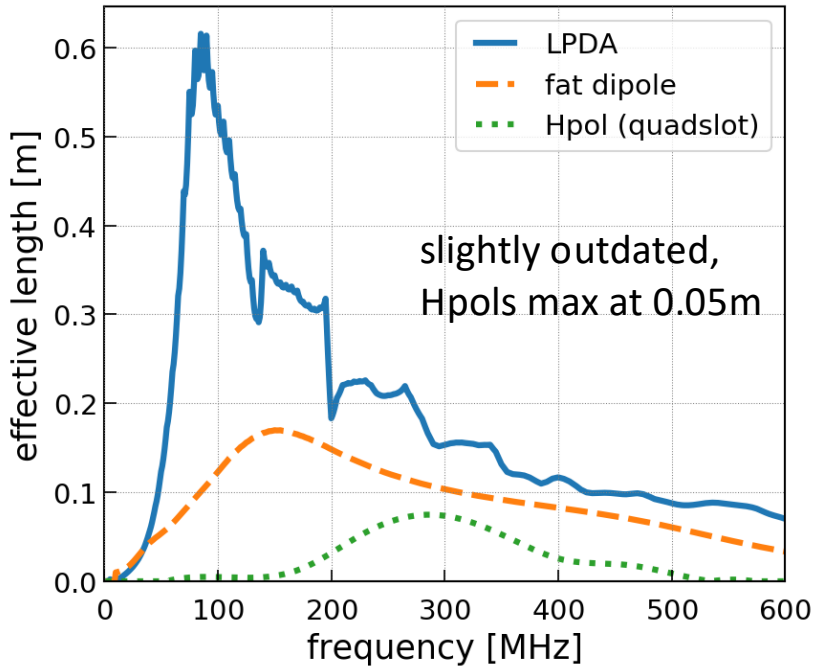


Christian

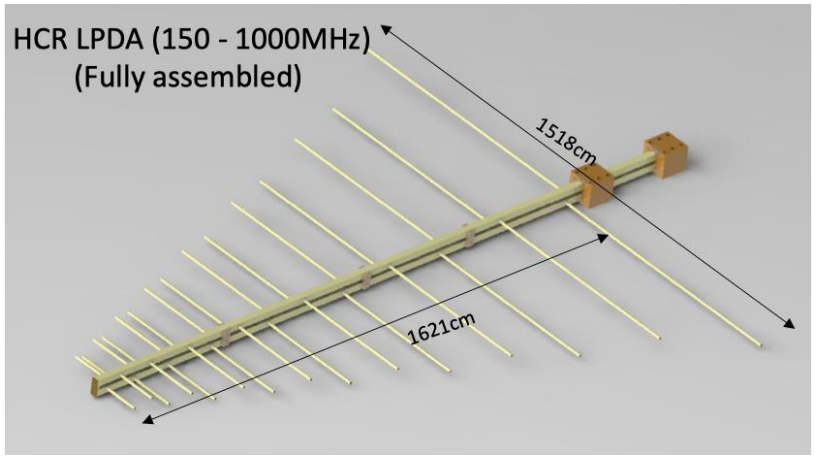
Antennas and Signal Chain

- Antennas
  - LPDAs
  - Vpols (fat dipoles)
  - Hpols (quad slot)
- Signal Chain (developed and tested in RNO-G)
  - Downhole: LNA + RFoF + Amplifier
  - Shallow: Coax + Amplifier

Chain	Median Gain	Bandwidth [-3dB]	Noise Temp [<400MHz]	Pwr/ch
Downhole	61dB	80-620 MHz	<140 K	0.24 W
Shallow	62dB	80-650 MHz	<110 K	0.26 W

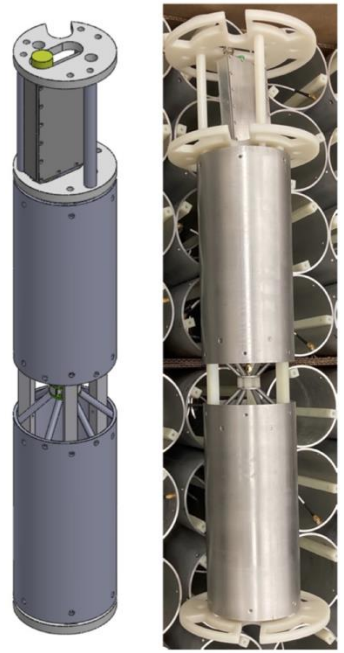


LPDA



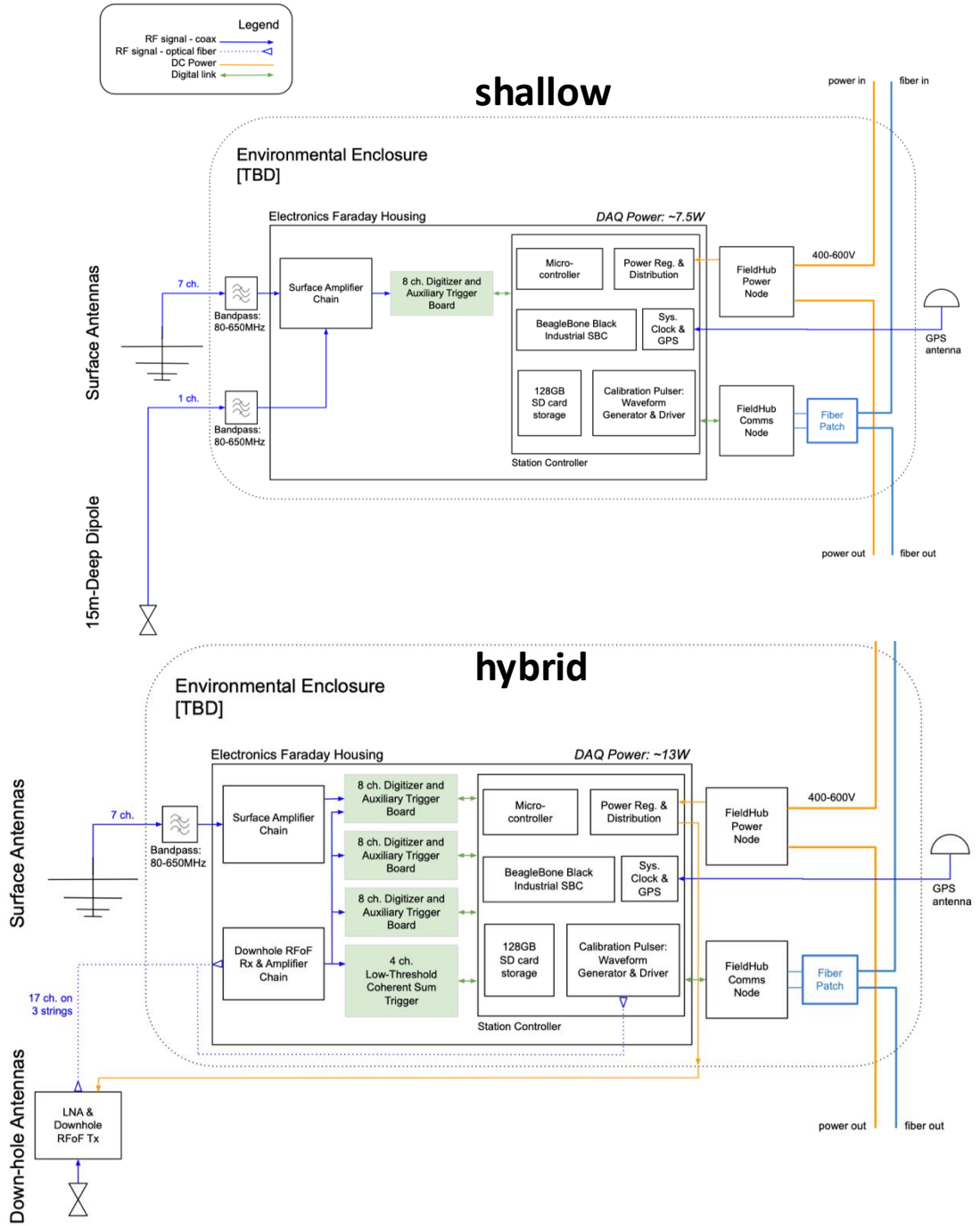
Hpol

Vpol



DAQ System

- Flexible data acquisition system of full baseband-radio waveforms that can be used in multiple contexts
  - Surface-only
  - Deep-only
  - Surface & Deep coincidences
- Requires long (~1 microsec) and/or multiple readout buffers
- Existing hardware not ideal
  - SST chip (ARIANNA) works well but only 256 samples
  - LAB4D (RNO-G) only single channel and with issues
- **Plan A: Develop modular 8-channel digitizer with new 4-channel ASIC (12 bits)**
  - + separate trigger board (using RNO-G design)
- Plan B: Use LAB4D/RADIANT design from RNO-G

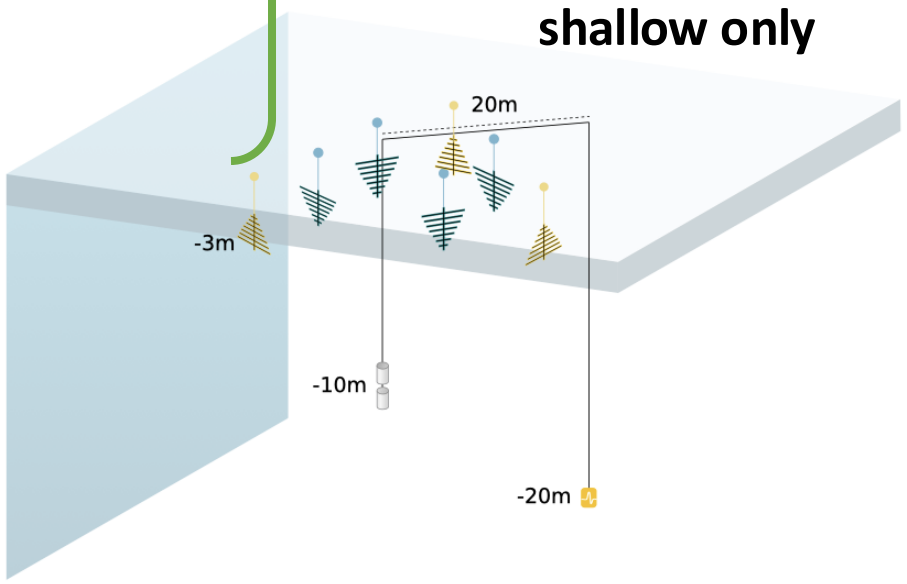


Station Types

- *Shallow* and *Deep* detector components
- Both components have same sensitivity (Veff) at trigger level per $
- Complementary uncertainties
  - triggering
  - signal identification
  - reconstruction
- Complementary risks
  - deep drilling
  - ice effects
  - backgrounds

-> ideal for discovery instrument

shallow only



hybrid