Future facilities for high-energy neutrinos

A personal selection

Anna Nelles

Neutrino Telescopes, 2021, Online

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

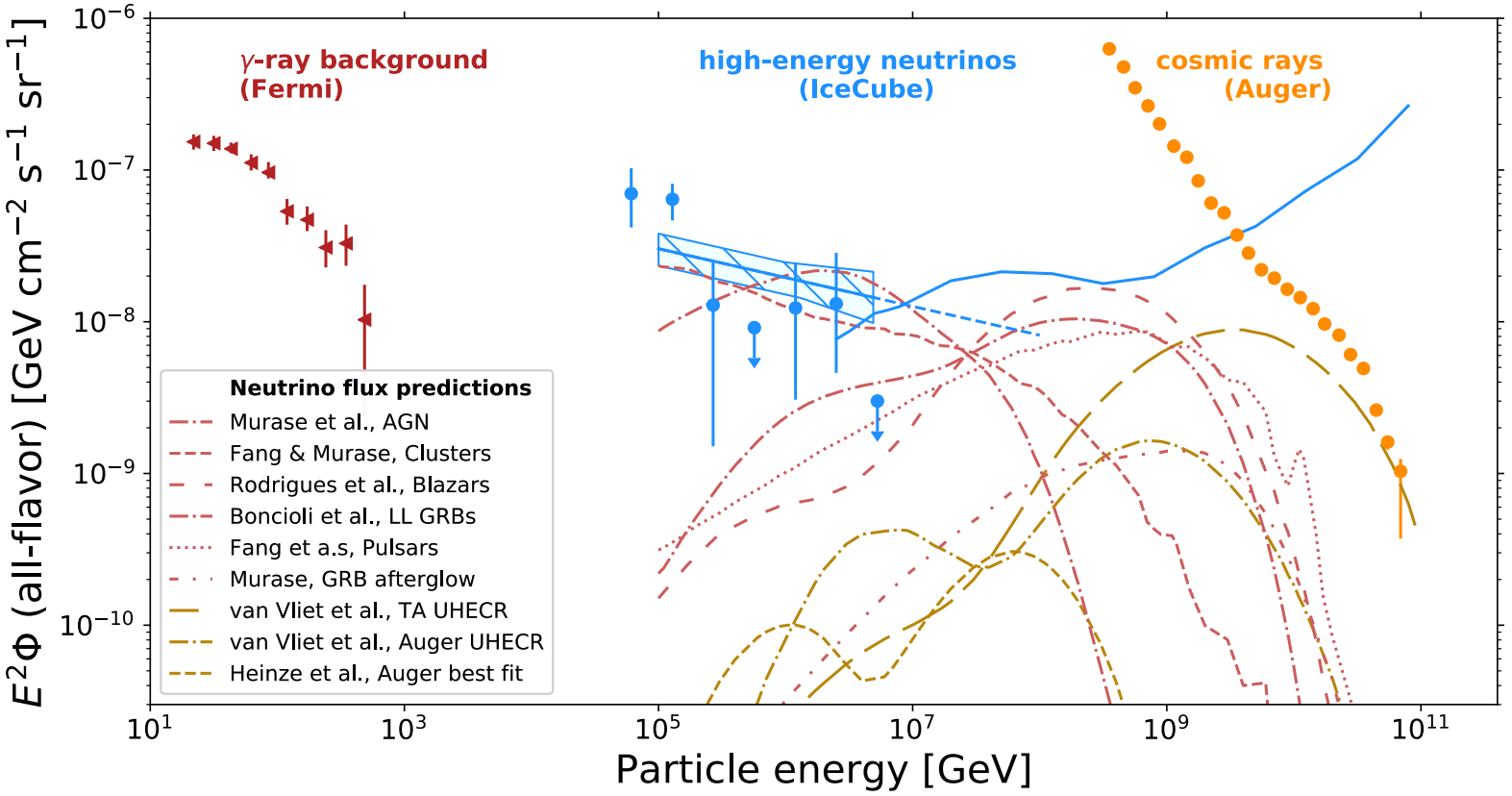
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

ECAP ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

DESY.

Scientific motivation

We have several contributions during this conference



Scientific objectives

See also: arXiv:2008.04323

What should future experiments deliver?

- Resolving the high-energy neutrino sky from TeV to EeV energies: **What are the sources of high-energy neutrinos detected by IceCube?**
- Understanding cosmic particle acceleration through **multi-messenger observations**: Combining neutrino telescopes through alerts systems and common analyses with other observatories
- Revealing the **sources and propagation of the highest-energy particles** in the universe
- Probing **fundamental physics** with high-energy neutrinos
- This means:
  - Improved neutrino point source sensitivity
  - Reconstruction of individual high-energy neutrinos in near real-time
  - Higher collection rate than the current arrays for neutrinos of all flavors in the energy range 100 TeV to 10 PeV
  - Expansion of the energy range beyond 10 PeV to EeV energies

Highlighting some future detection options

A bias towards > EeV energies = radio detection of neutrinos

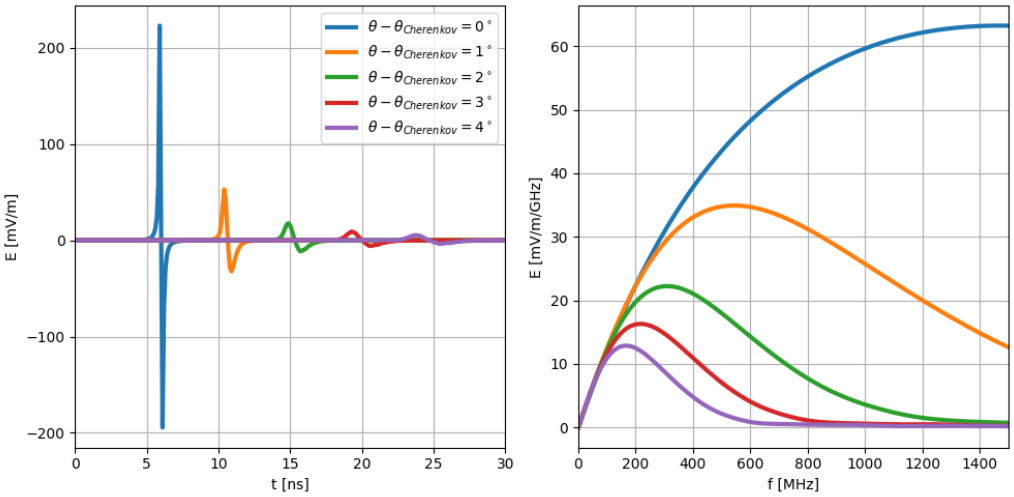
- At the highest energies > 30 PeV, current optical detectors are too small
- Detectors of O(100) km^3 needed
- Optical detectors limited by the attenuation length of light and the required spacing of light sensors
- Next generation optical detectors can build on the successes of past detectors and improve in their energy range to provide a better handle of the known flux (Outlook later in this talk)
- A different technology needed to target higher energies: **Radio detection**
  - Polar ice has a radio attenuation length of kilometre scale
  - Very sparse instrumentation can be built to cover large areas
  - Emission confirmed by air showers and dedicated accelerator experiments

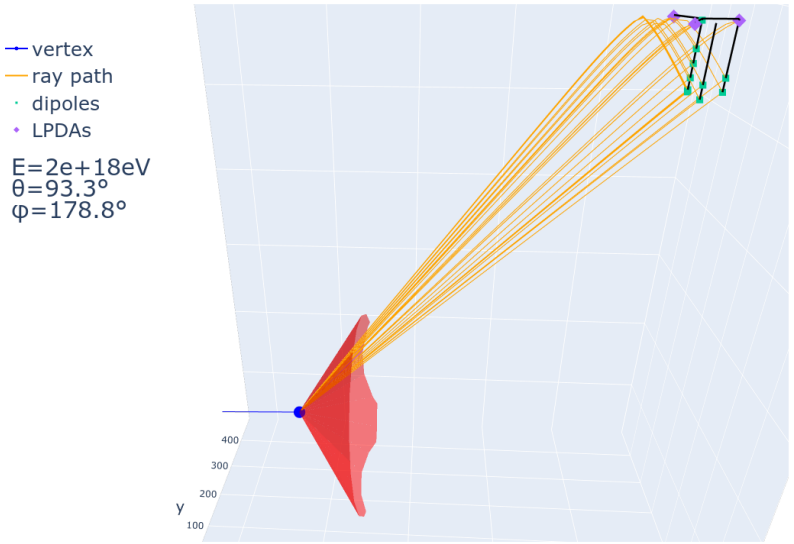
Radio emission of showers in dense media

What are we looking for?

https://github.com/nu-radio/NuRadioMC

- **Askaryan effect**: Charge accumulation in the shower front gives rise to a changing current, which gives rise to radio emission
- Emission is coherent at frequencies corresponding to the size of the shower
- Index of refraction >> 1, emission strong on the Cherenkov cone, travel on non-straight lines with changing n
- Signals contain information in amplitude, frequency and polarisation

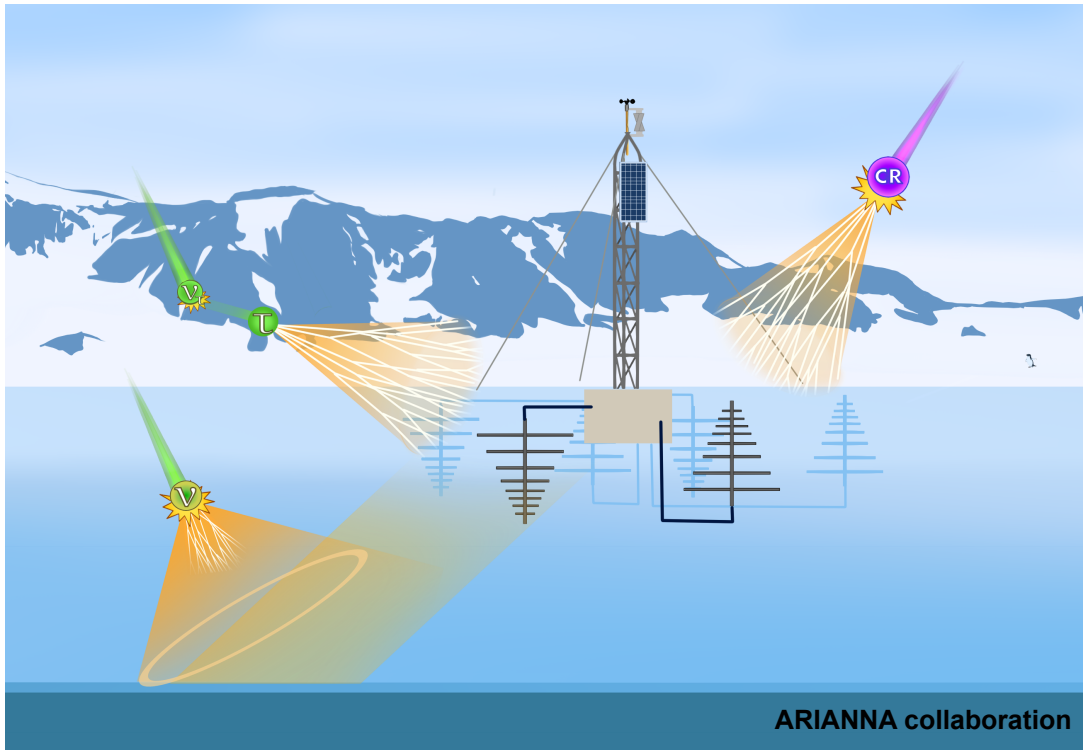




Radio detection of other particles

Why it is interesting for neutrinos?

- Any shower containing an electro-magnetic cascade creates radio emission
- A similar experimental approach for:
  - air showers from cosmic rays
  - air showers from neutrino induces tau decays
  - in ice showers following a neutrino interaction



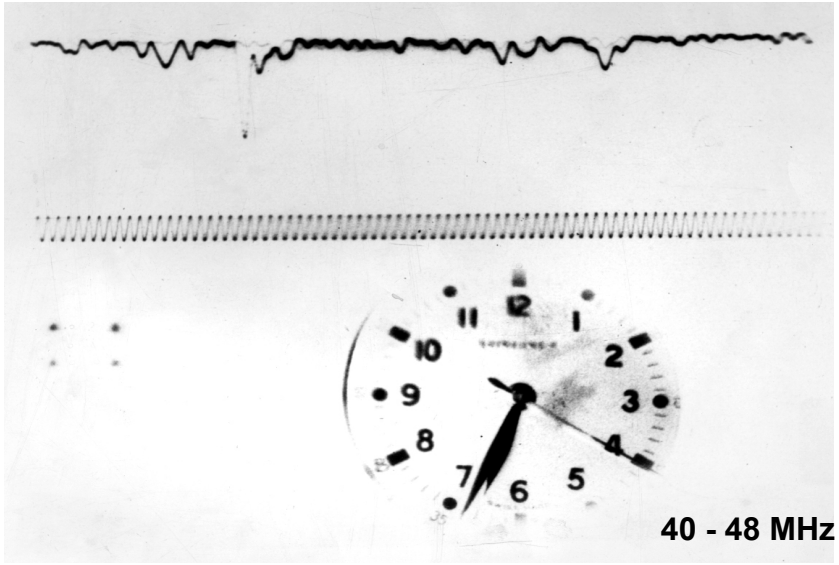
- All experiments utilize negligible radio attenuation in air and kilometer-scale attenuation length in ice

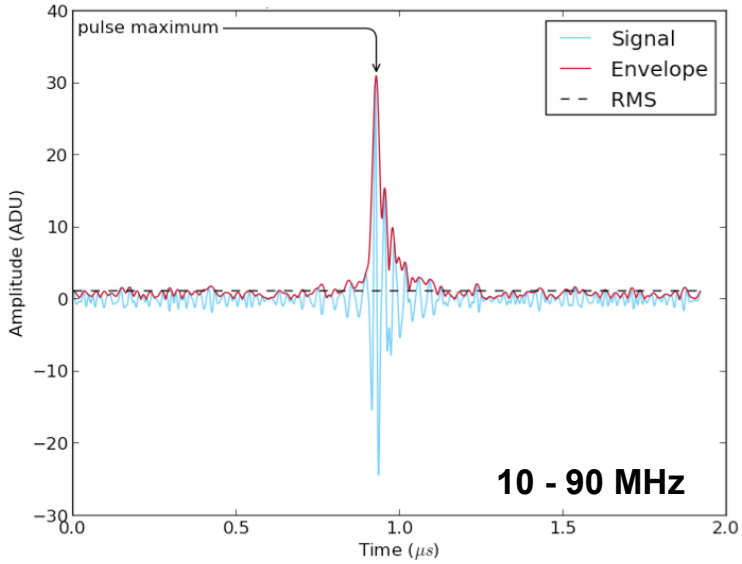
Detecting radio emission of air showers

Experimental challenges and opportunities

- Search for a very broad-band nanosecond scale pulse
- Detectable typically at shower energies > 10^{15} eV, i.e. rare signal
- Sampling speeds of at least 200 MHz
- Needs full waveform sampling for frequency content and polarization
- Preferably stations run independently at very low power
- Duty-cycle (almost) independent of weather

Jelley et al, Nature 1965

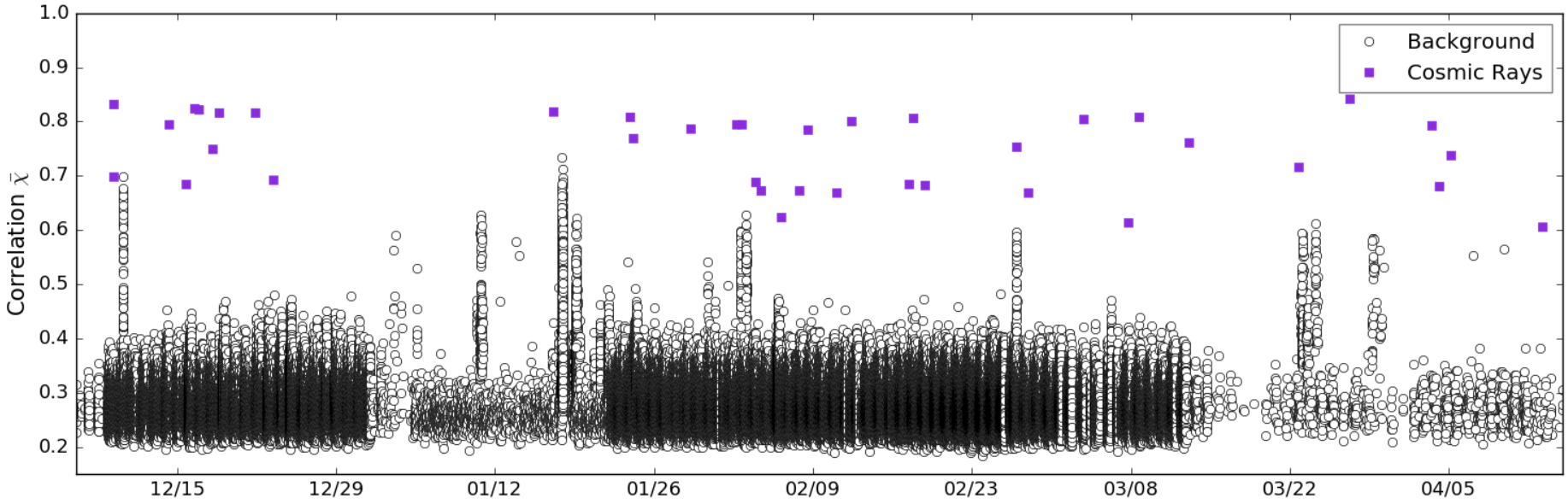


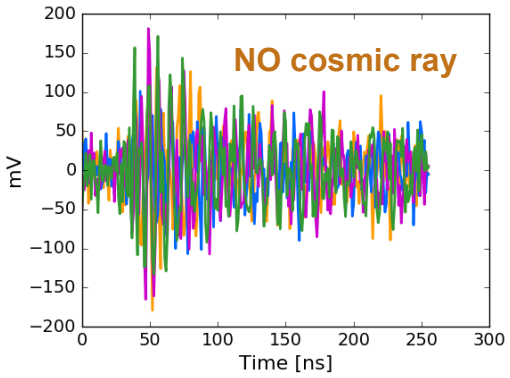


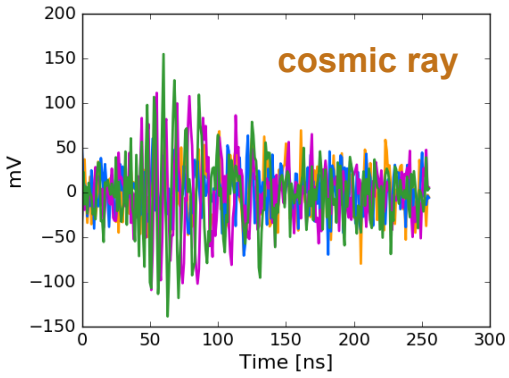
Detecting radio emission of air showers

Experimental challenges and opportunities

ARIANNA Coll., Astropart. Phys. 90 (2017) 50





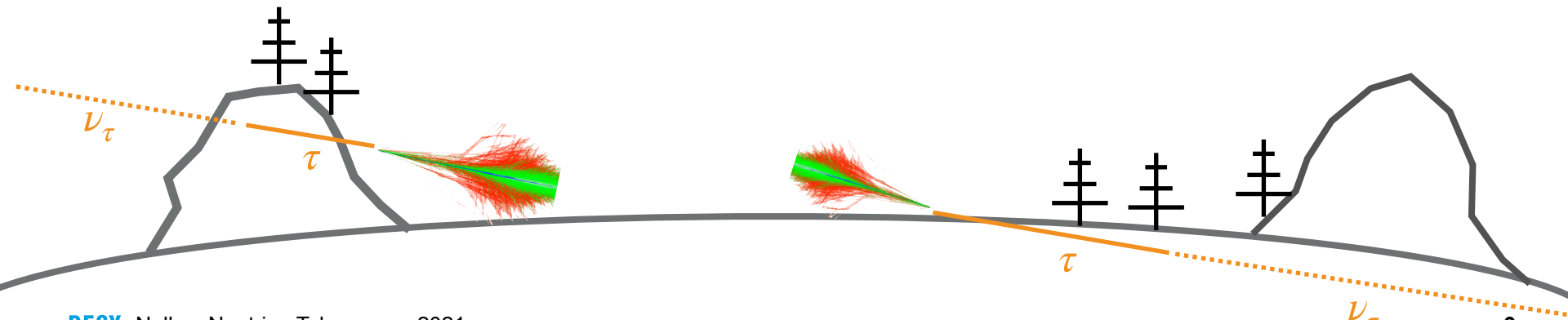


- Unfortunately, a lot of things make radio pulses
- Self-triggering and event identification remain a challenge
- Site quality important
- New opportunities in modern data analysis methods

Radio detection of neutrinos

Tau neutrinos emerging from the Earth

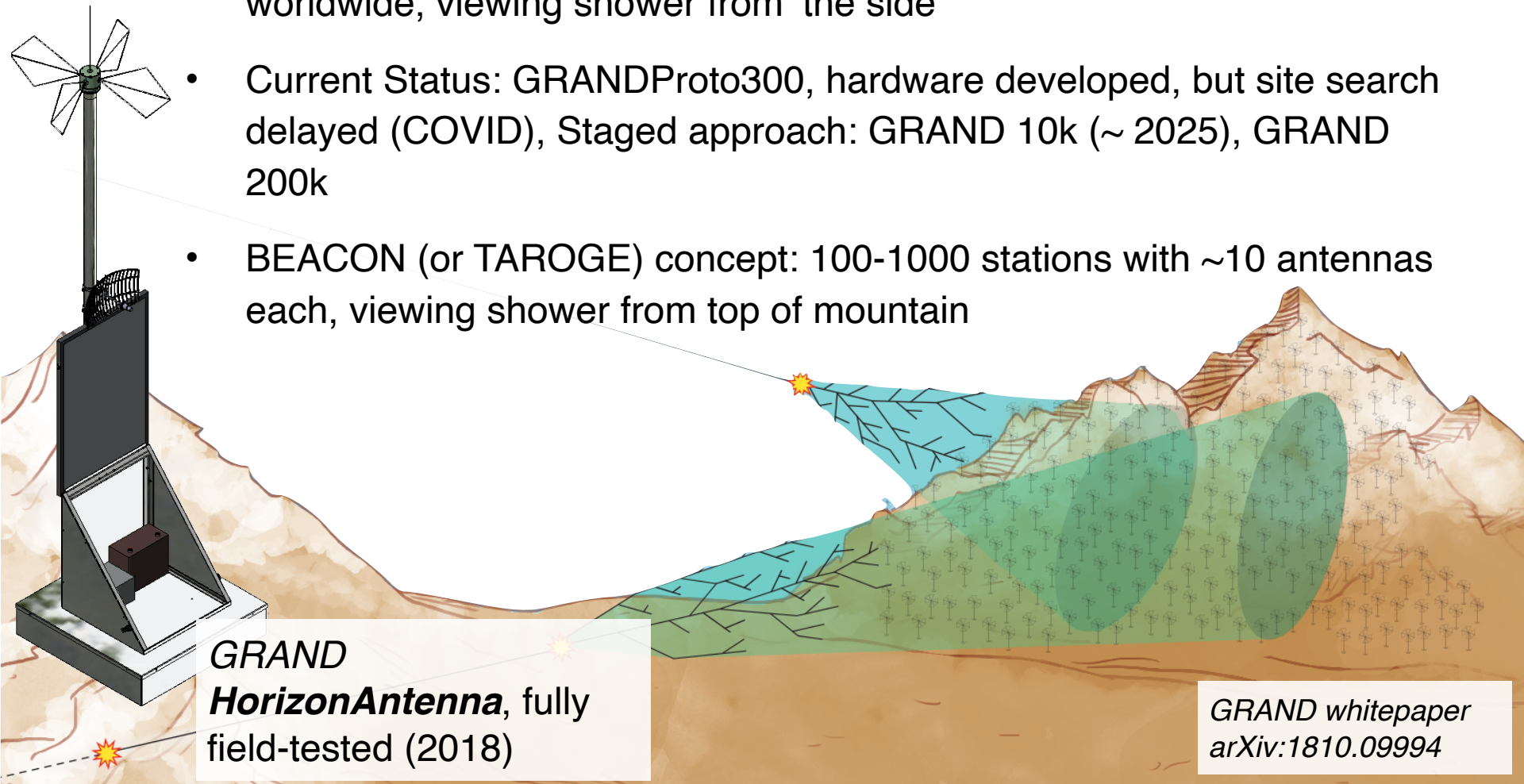
- Looking at tau's emerging from the Earth, creates large effective volumes for neutrinos, radio emission is (almost) not attenuated in air
- Radio detectors probably most effective, when they use mountainous terrain
- Have to exploit economies of scale for very cheap antenna stations
- Largest challenge: suppress (human-made) background close to the horizon
- A couple of projects on-going or proposed,
  e.g. GRAND, BEACON, TARGOE (radio),
  TAMBO (water-Cherenkov), TRINITY (air-Cherenkov), …



Radio detection of (tau)-neutrinos

Looking for air showers but stemming from neutrinos

- GRAND: concept: 200'000 radio antennas over 200'000 km^{2,} i.e.~ 20 hotspots of 10'000 antennas over favorable sites in China and worldwide, viewing shower from 'the side'
- Current Status: GRANDProto300, hardware developed, but site search delayed (COVID), Staged approach: GRAND 10k (~ 2025), GRAND 200k
- BEACON (or TAROGE) concept: 100-1000 stations with ~10 antennas each, viewing shower from top of mountain



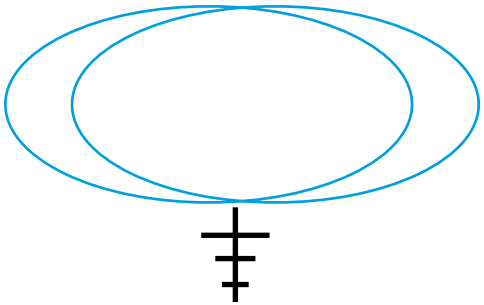
GRAND ***HorizonAntenna***, fully field-tested (2018)

GRAND whitepaper arXiv:1810.09994

Radio detection of neutrinos

Neutrino interactions in ice

- Cold polar ice has attenuation length in the order of kilometers
- One radio station can typically monitor 1 km^3 of ice (= the size of IceCube)
- Detection threshold around 10 PeV shower energy, determined not by array spacing but pulse height above thermal noise
- > 100 km^3 needed to obtain sensitivity for cosmogenic neutrinos, neutrinos from UHECR with CMB, if very few protons at highest energies
- Human-made background typically smaller in polar regions, event identification and self-trigger less challenging
- Many early experiments:
  RICE, ARA, ARIANNA, …



and of course, ANITA

Radio detection of neutrinos

Results so far

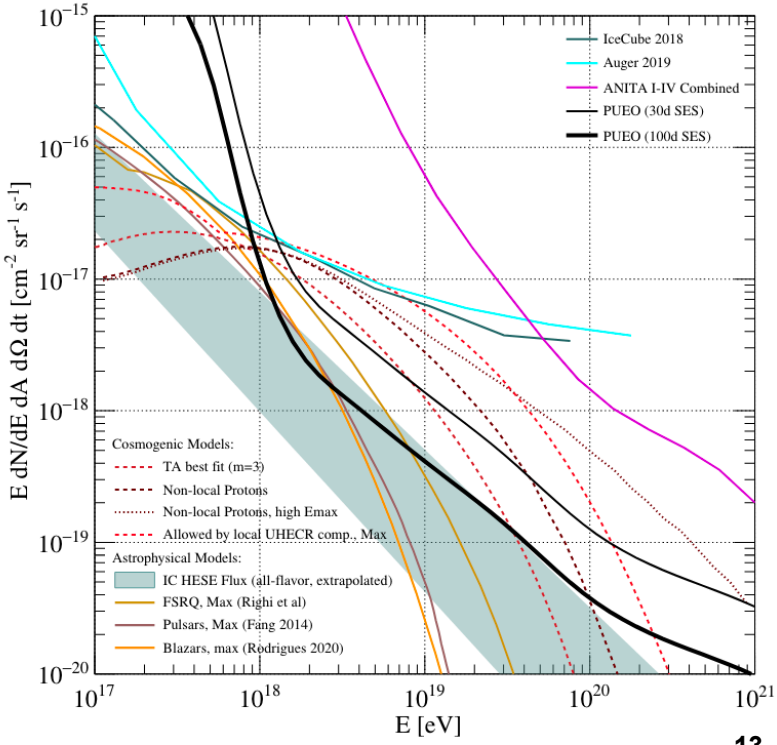
- Neutrino limits from radio detection of neutrinos towards high energies, not competitive to IceCube below 10^{10} GeV
- So far: experiments focussed on proof-of-concept, reconstruction and performance
- Exception: ANITA I-III: Mystery events — behave like cosmic ray signals, but show signal polarization/polarity like neutrino from deep trough Earth
  - If truly neutrino: disagreement with IceCube limits, difficult to reconcile with Standard Model
  - Other explanations offered: ice, background, etc.
  - ANITA IV: again 4 events with inconsistent polarity, but near horizon, nothing ‘mysteriously’ steep arXiv:2008.05690

Radio detection of neutrinos

PUEO: The Payload for Ultrahigh Energy Observations

- Much lower threshold than ANITA (x10 more sensitive across energies), takes over from IceCube at 10^{18} eV
- Especially large instantaneous effective volume, for transient, point source, and multi-messenger searches
- Order-of-magnitude improvement enabled by:
  - interferometric phased array trigger
  - real-time digital filtering
  - x2 more antenna collecting area above 300 MHz
  - Improved pointing resolution

Whitepaper:
arXiv:2010.02892

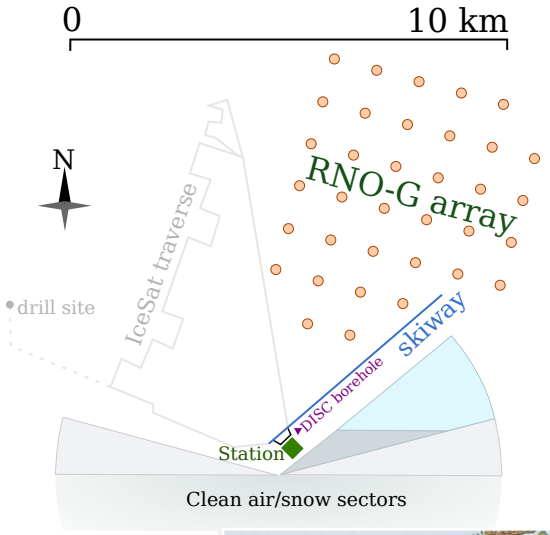


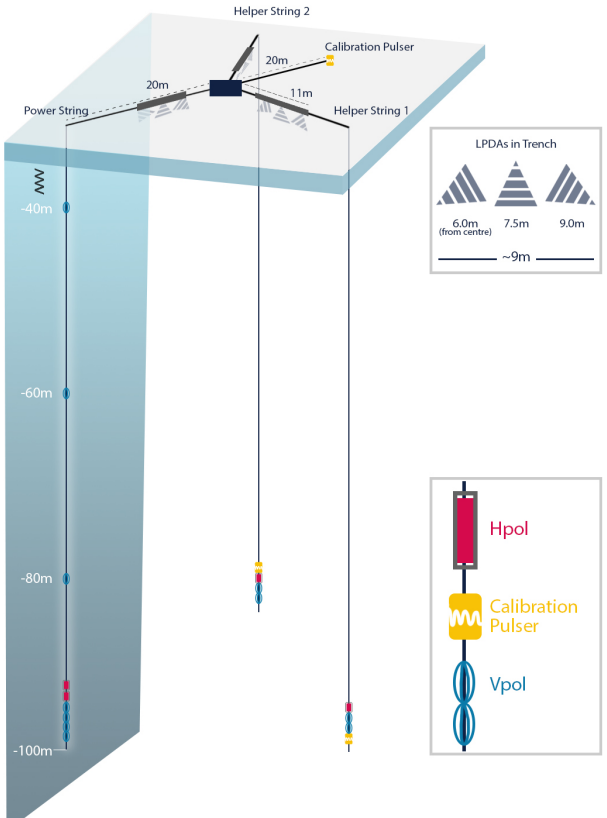
Selected for Pioneers Mission by NASA
Scheduled to fly in December 2024

Radio detection of neutrinos

Radio Neutrino Observatory Greenland

- RNO-G: Start construction in 2021
- 35 stations as first production scale implementation for neutrino detection
- Deployment in Greenland allows for fast development turn-around
- Europe-led experiment with members from all previous in-ice experiments
- Largest yearly neutrino sensitivity > 10 PeV
- Concept and design paper: arXiv:2010.12279



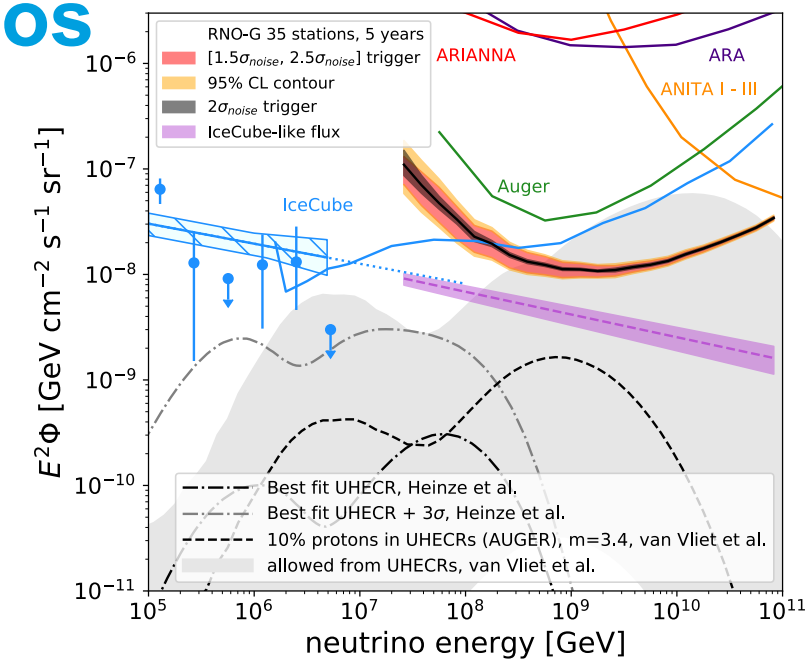


Radio detection of neutrinos

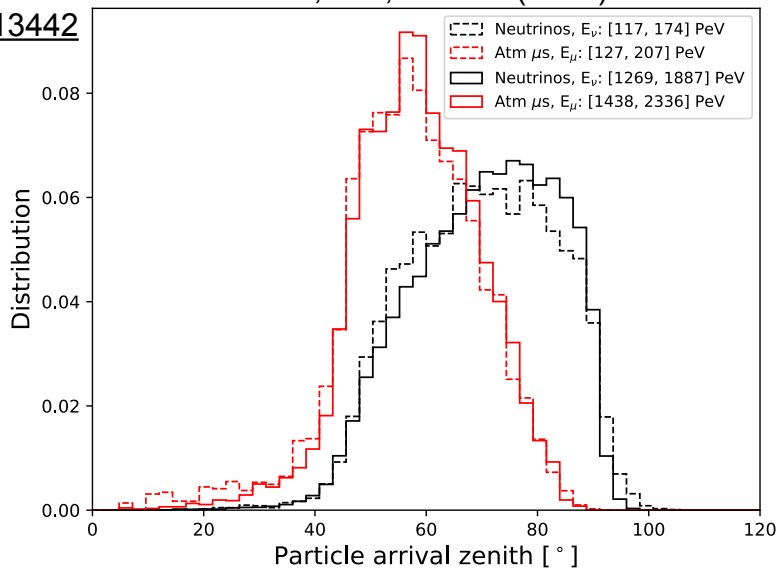
Radio Neutrino Observatory Greenland

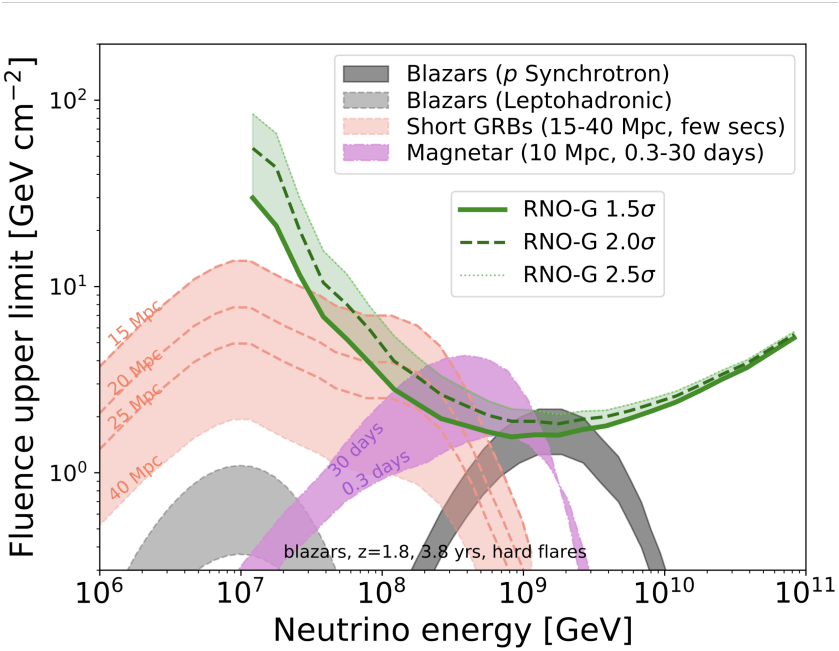
- RNO-G interesting sensitivities to transients and diffuse flux above 10 PeV
- Sensitive to all 3 flavors (NC and CC) with flavor-sensitivity under study
- Muon background may become interesting depending on hadronic interaction models

arXiv:2010.12279



Garcia-Fernandez et al. PRD, 102, 083011 (2020)
2003.13442

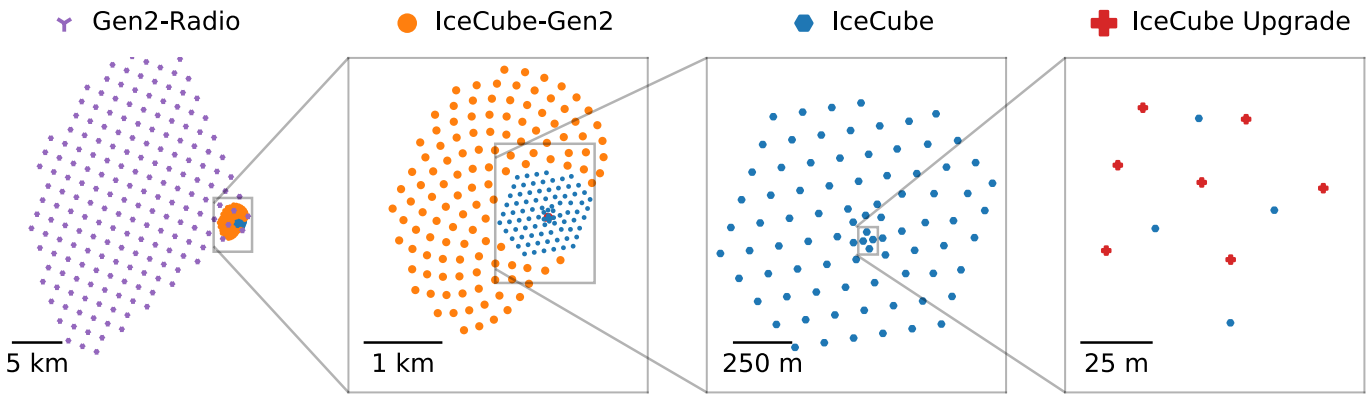




IceCube-Gen2

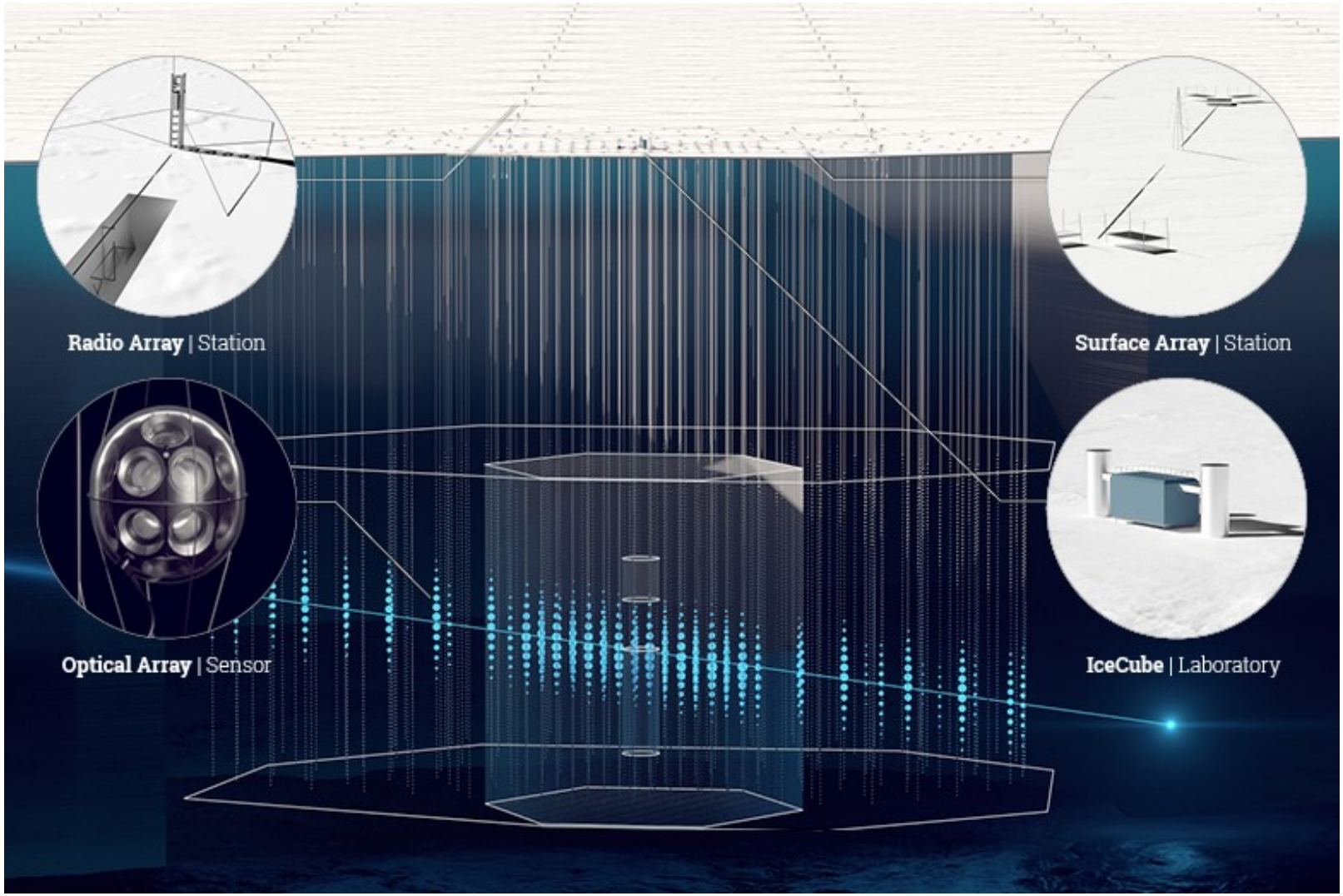
The foreseeable future: a facility using optical and radio

- IceCube Collaboration has put forward a baseline design for IceCube-Gen2 arXiv:2008.04323
- Significant extension of the optical array with improved optical sensors
- Addition of large radio array, at least a factor 5 improvement over RNO-G, however with nice complimentary in sky coverage
- Preliminary Design Review for IceCube-Gen2 expected for fall 2021



IceCube-Gen2

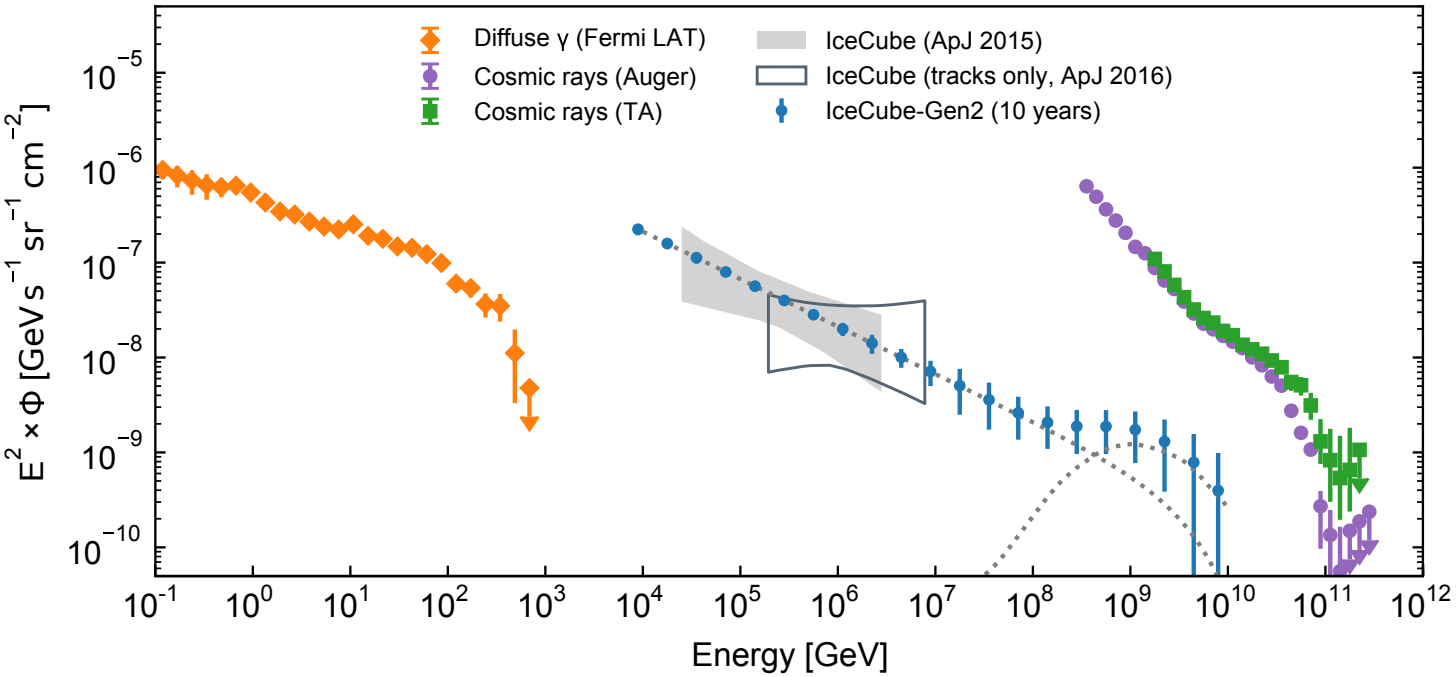
A 3D Idea



IceCube-Gen2

Lots of science in the white paper

"IceCube-Gen2 will play an essential role in shaping the new era of multi-messenger astronomy, fundamentally advancing our knowledge of the high-energy universe."



IceCube-Gen2: The Window to the Extreme Universe , https://arxiv.org/abs/2008.04323, Journal of Physics G, in press

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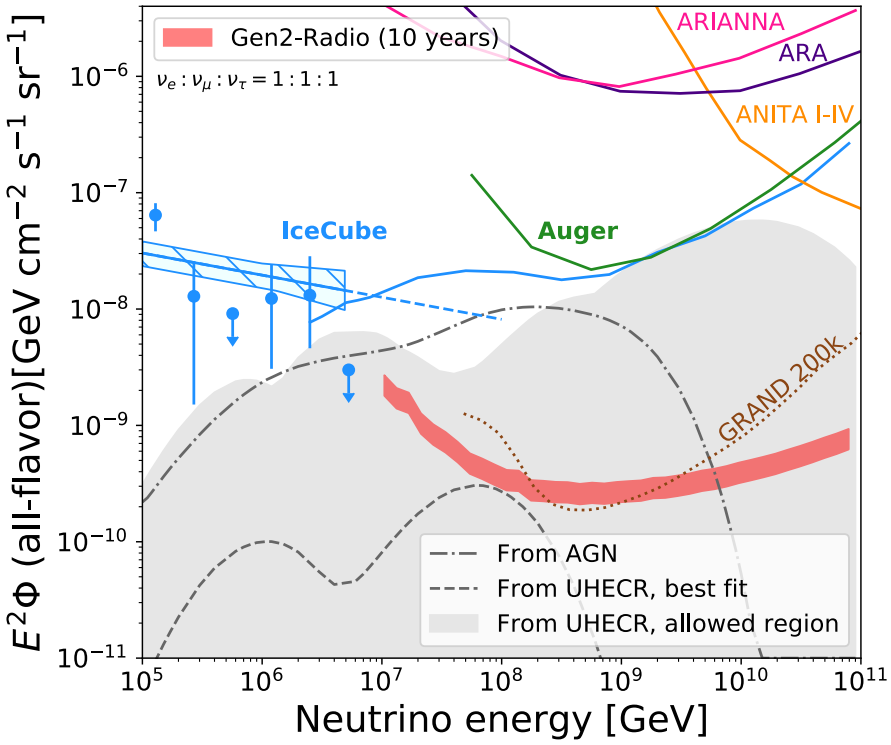

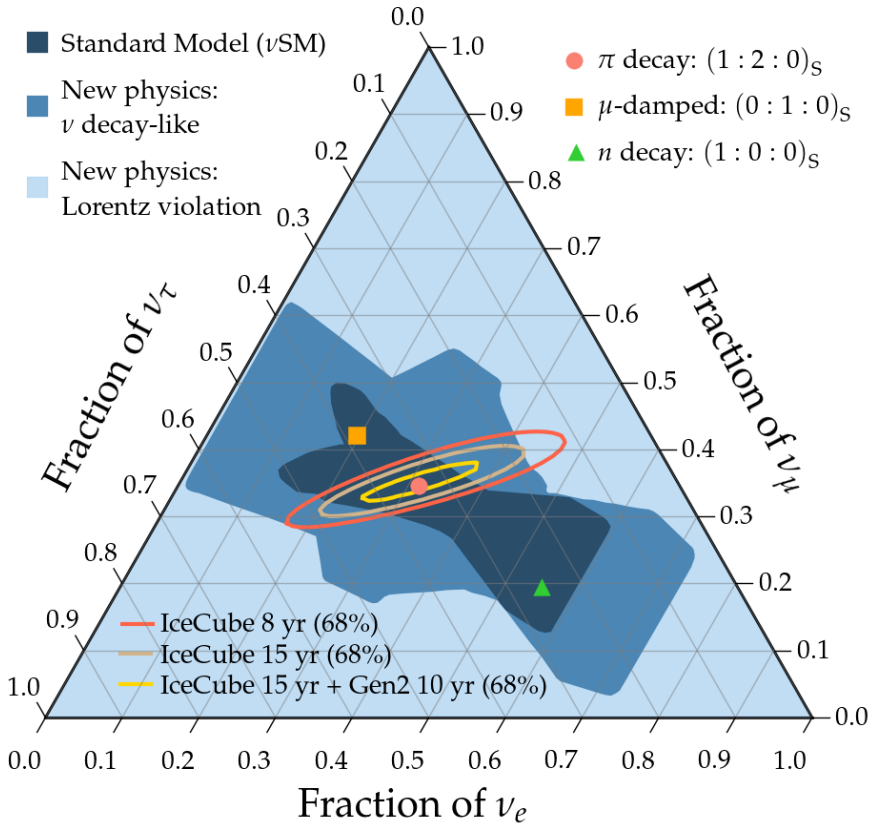

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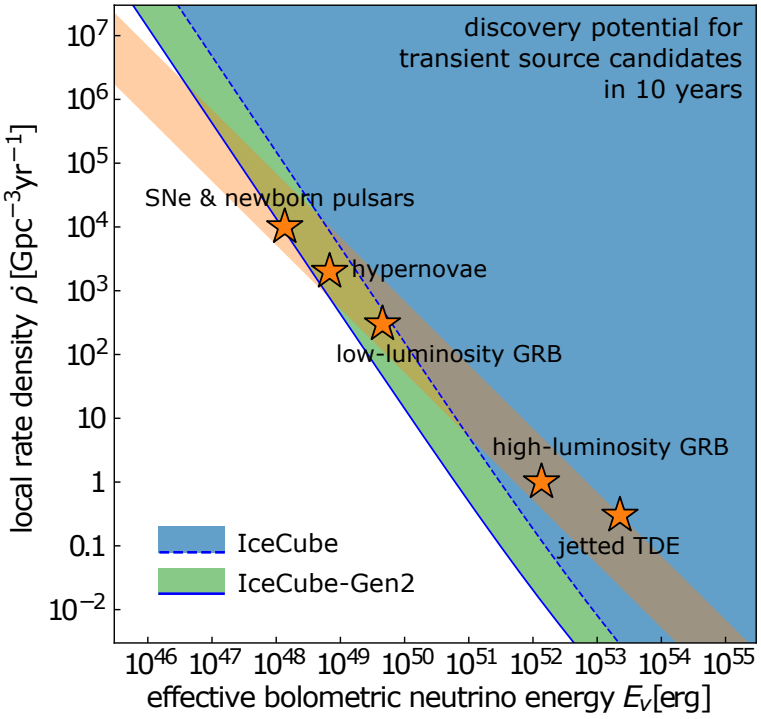

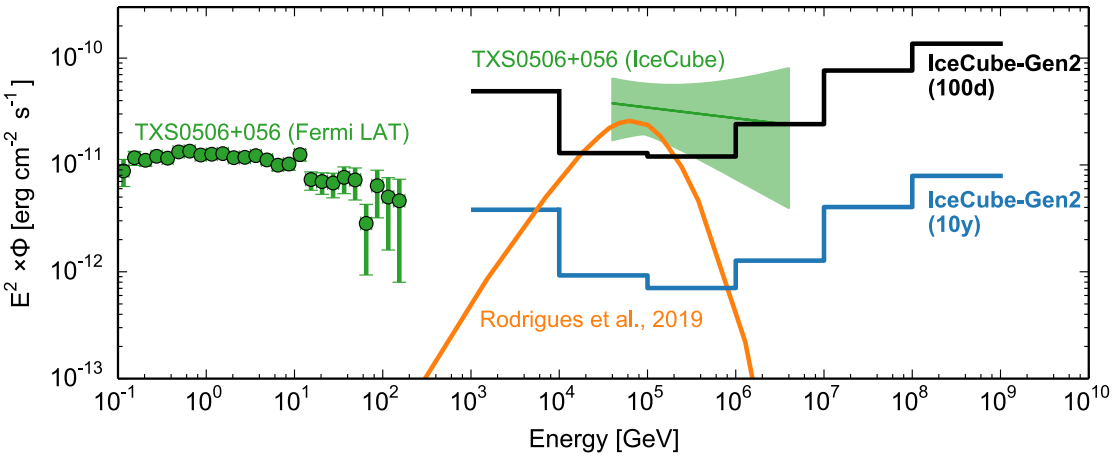

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https://arxiv.org/abs/2008.04323, Journal of Physics G, in press

Conclusions

Future facilities for high-energy neutrinos

- The energy range beyond 30 PeV can only be tackled by radio detectors
- Several upcoming experiments in the radio regime with unprecedented sensitivity
- IceCube is proposing to continue its success with IceCube-Gen2
- IceCube-Gen2 will combine optical and radio and improve on several frontiers