Radio Detection of Neutrinos

At energies > 10^{15} eV

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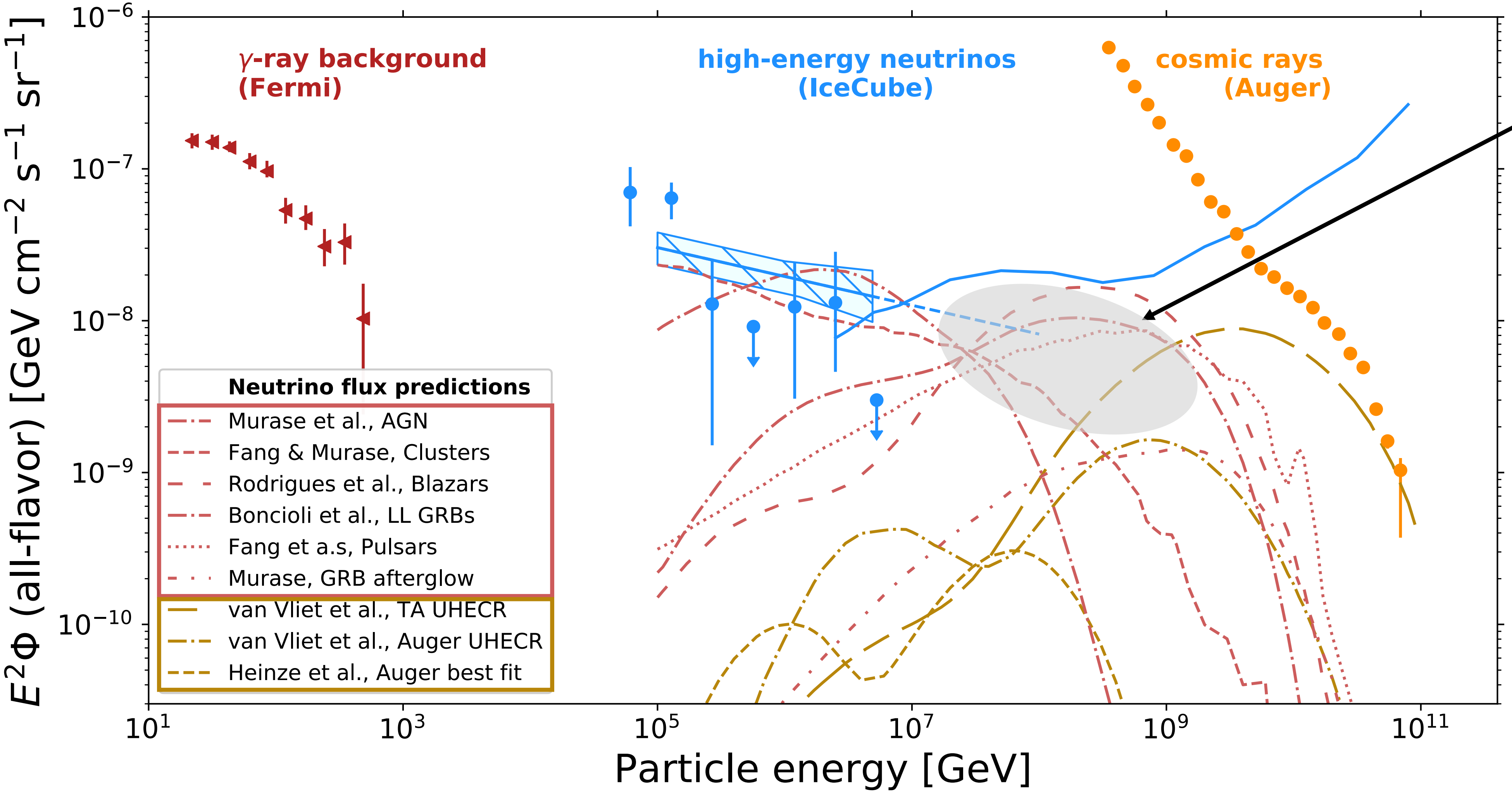
CRIS-MAC

18 June 2024

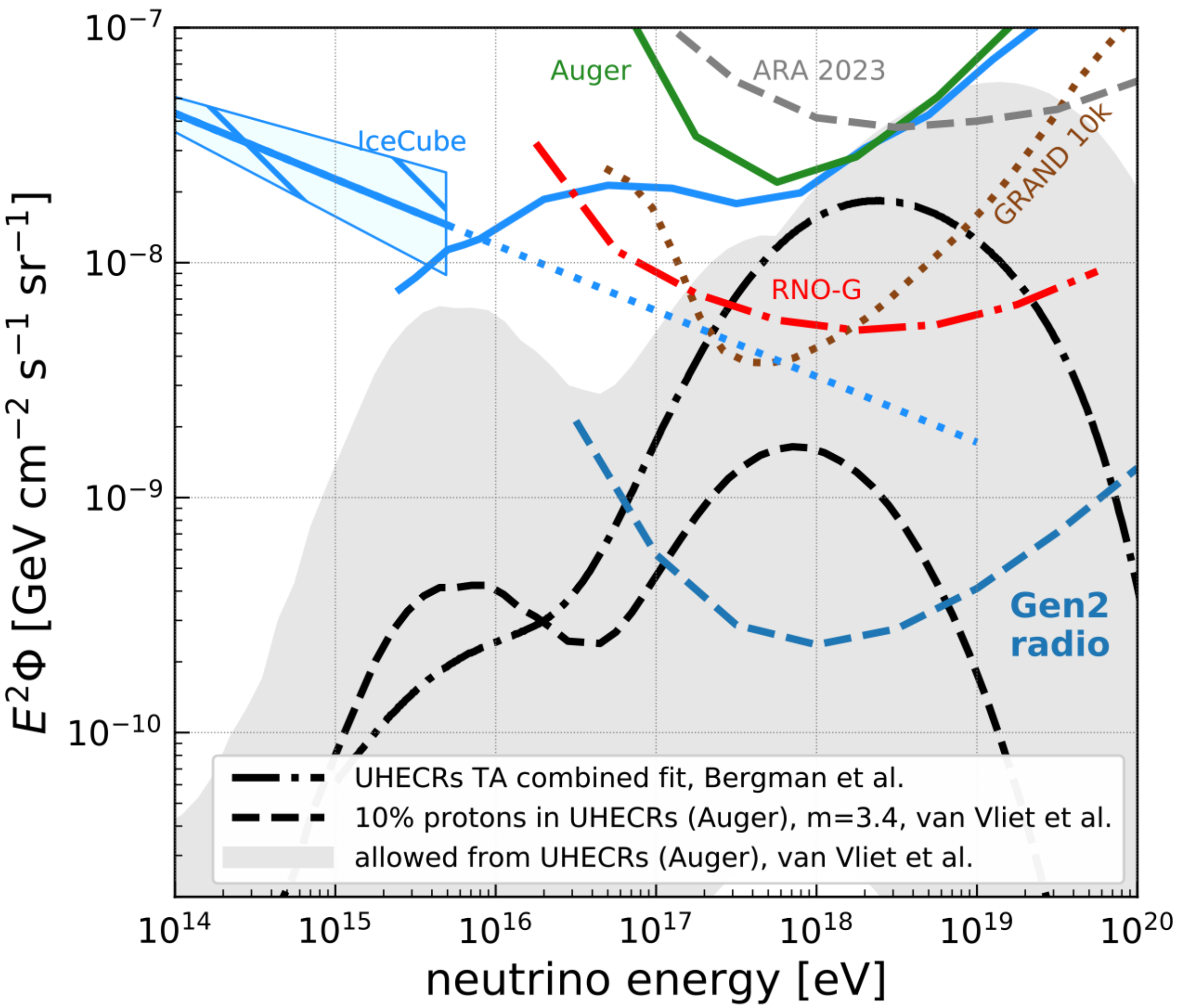
The target: high energy neutrinos



astrophysical:
neutrinos from sources

cosmogenic:
neutrinos from interactions of UHECR with photon background

Radio to the rescue



- ~ 1 UHE neutrino/km^2/year, L_{int} ~ 300 km
- Need a huge (100 km^3) detector
- Detection medium that are free

  e.g. air, water, ice, rock
- Optical technologies: financially not feasible
  - water and ice: optical attenuation length too small (~100m)
  - air not dense enough for neutrinos
- Different technology: Radio detection
  - Large attenuation length in ice and air (~1km)
  - Feasible to instrument a large volume at relatively low cost per detection unit

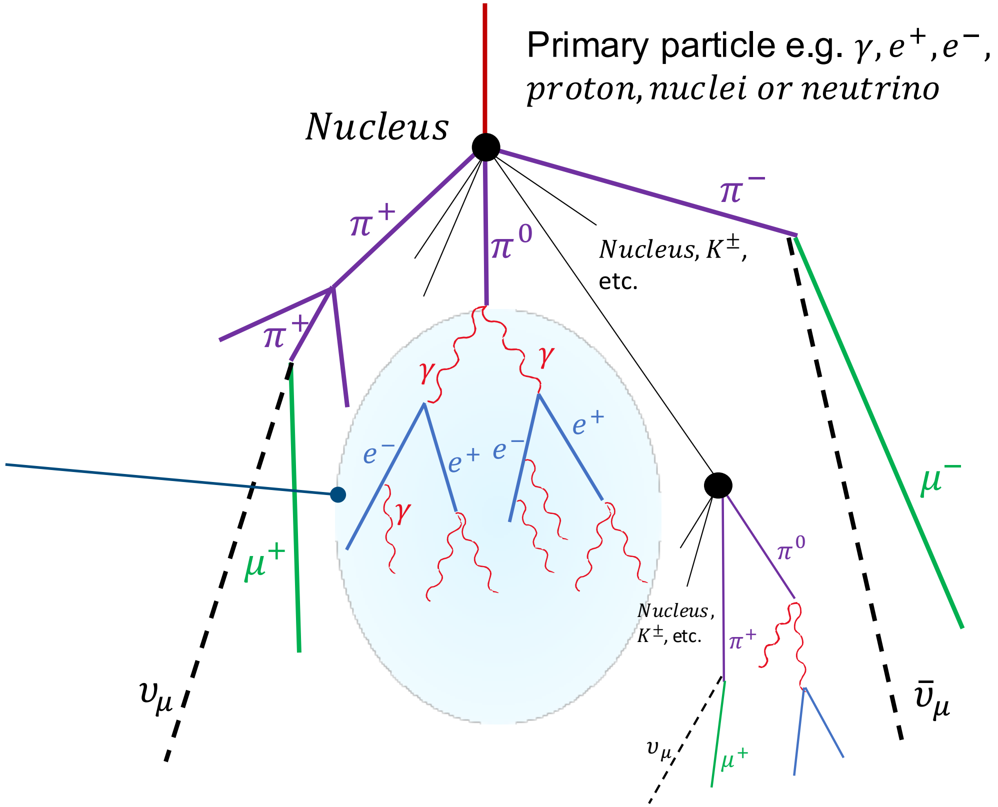
How does radio detection work?

Radio detection

Particle cascades

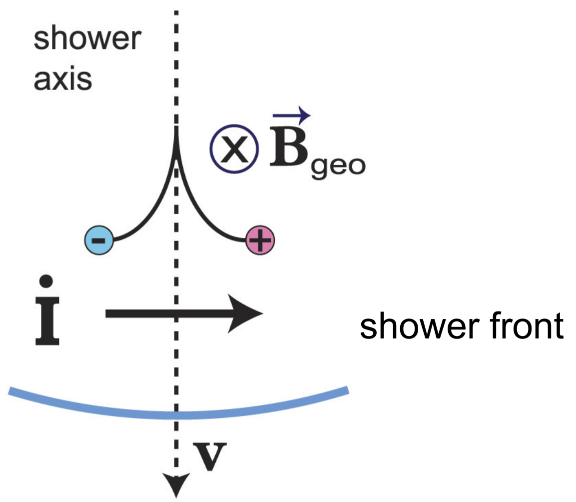
Particle cascades can take place in air or dense media, e.g. ice, rock

Radio emission is mostly generated by the electromagnetic component of the shower

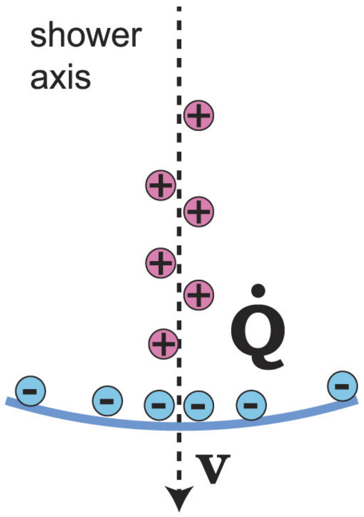


Radio emission of particle cascades

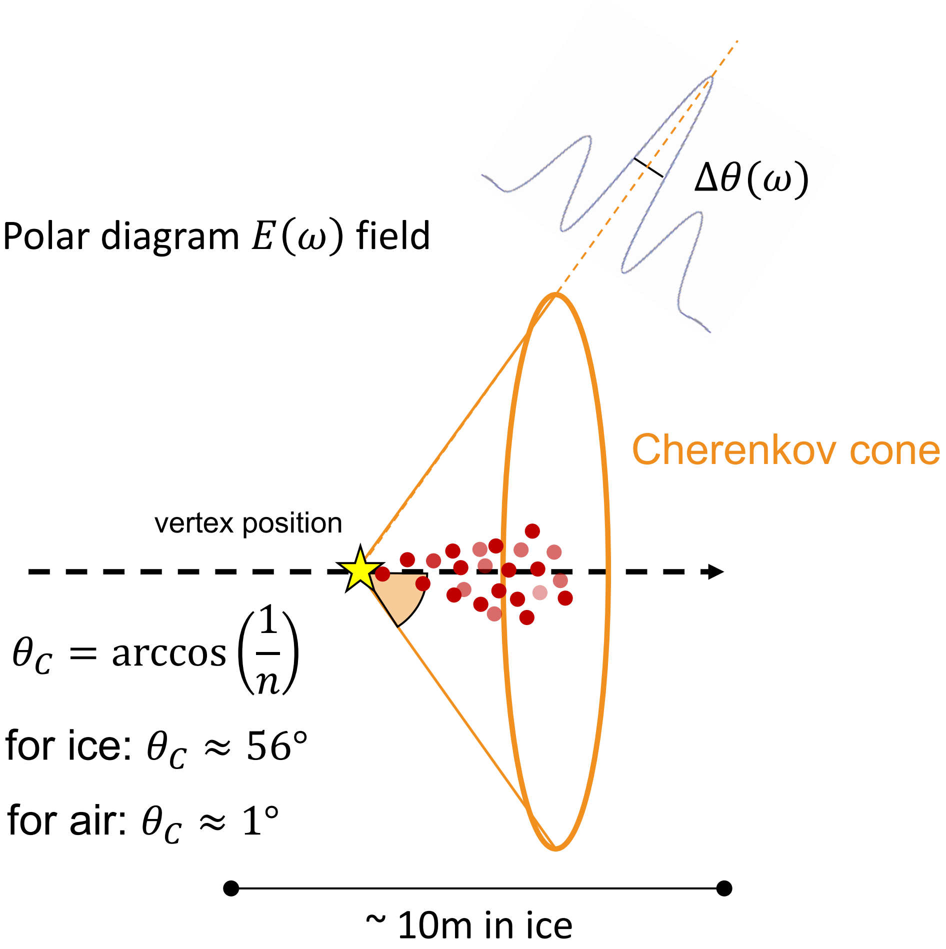
Geomagnetic emission



Askaryan emission



Polar diagram $E(\omega)$ field



$\theta_C = \arccos\left(\frac{1}{n}\right)$

for ice: $\theta_C \approx 56°$

for air: $\theta_C \approx 1°$

1. Geomagnetic deflection of charged particles (e^-, e^+) due to the Lorentz force of the geomagnetic field.

2. Askaryan effect, i.e. radiation due to the time variation of the net charge excess

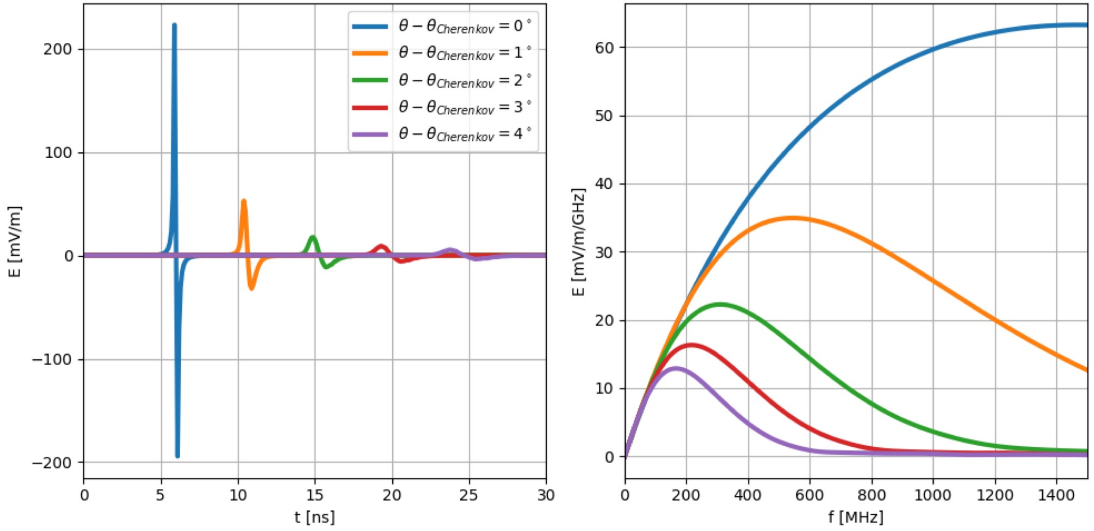
- Superluminal current in a medium
- Emission is added up coherently for all observer angles at which the emission arrives simultaneously:

→ strongest at cherenkov angle

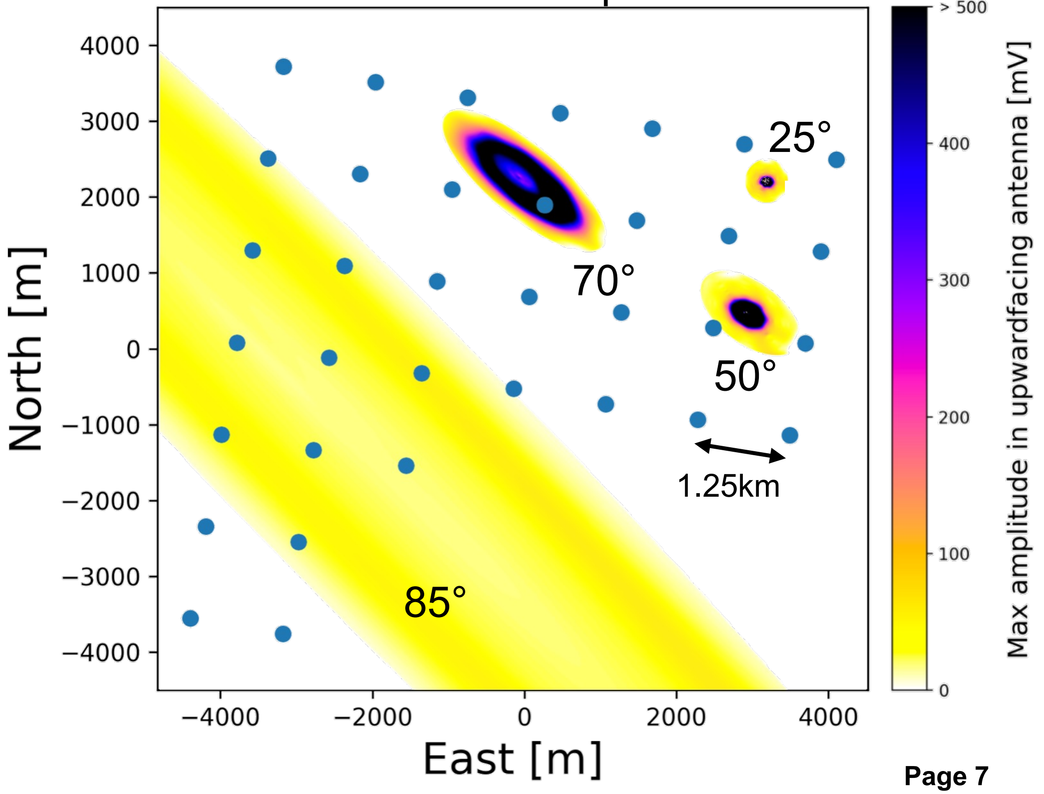
Radio emission

- Radio emission results in non-repeating nanosecond-scale pulses → broad frequency spectrum
- Detection threshold: pulse must be detected above background (thermal noise, Galactic radio emission, human-made radio emission, etc.)
- Pulse amplitude scales linearly with shower energy
- Initial particle energy ~10 PeV → shower energy ~1 PeV

Signal in ice



Air shower footprints



Common challenges for all experiments

- Antennas need to operate **autonomous** and wireless
  → Plan for power supply and (slow) data transfer
- **Low** available **power**
  → Complicates everything: amplifier, digitizing, triggering, data transfer
- Site depended radio **background**

→ **Mostly solved by pilot-arrays**

- Radio **self-trigger** is complicated
  - One approach: using multiple closely spaced antennas for beamforming or phasing
  - For the "plane wave" of a neutrino event, the sum of the signals increase the signal to noise ratio

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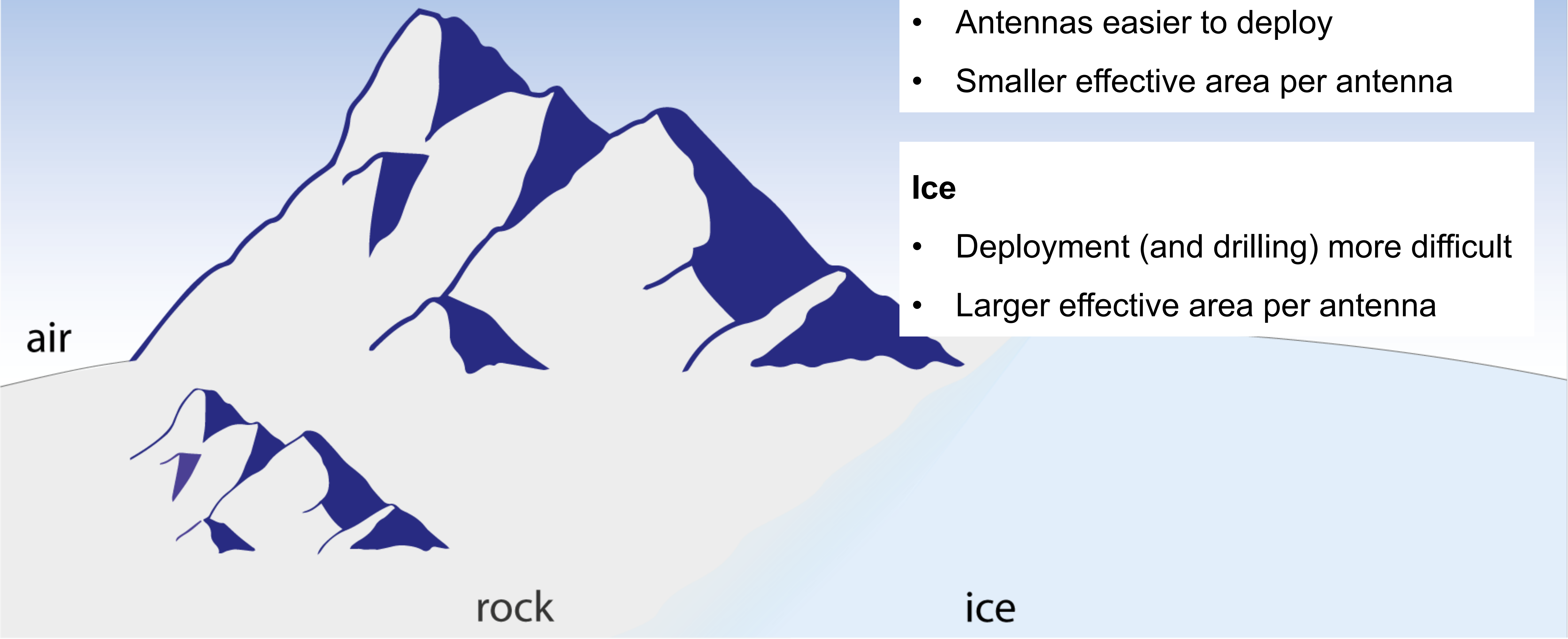
Experimental strategies

Mountain regions

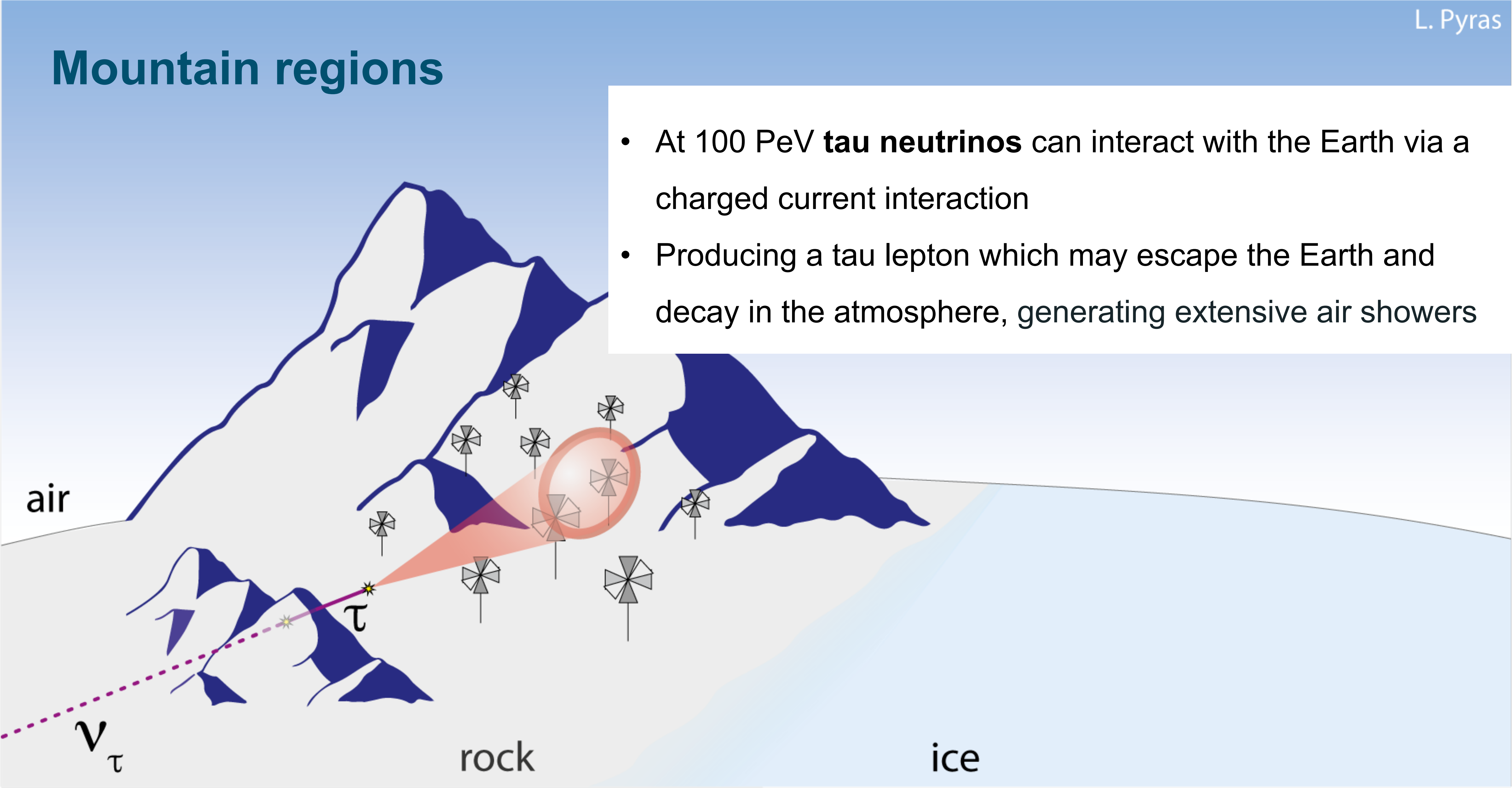
- Antennas easier to deploy
- Smaller effective area per antenna

Ice

- Deployment (and drilling) more difficult
- Larger effective area per antenna



Mountain regions



- At 100 PeV **tau neutrinos** can interact with the Earth via a charged current interaction
- Producing a tau lepton which may escape the Earth and decay in the atmosphere, generating extensive air showers

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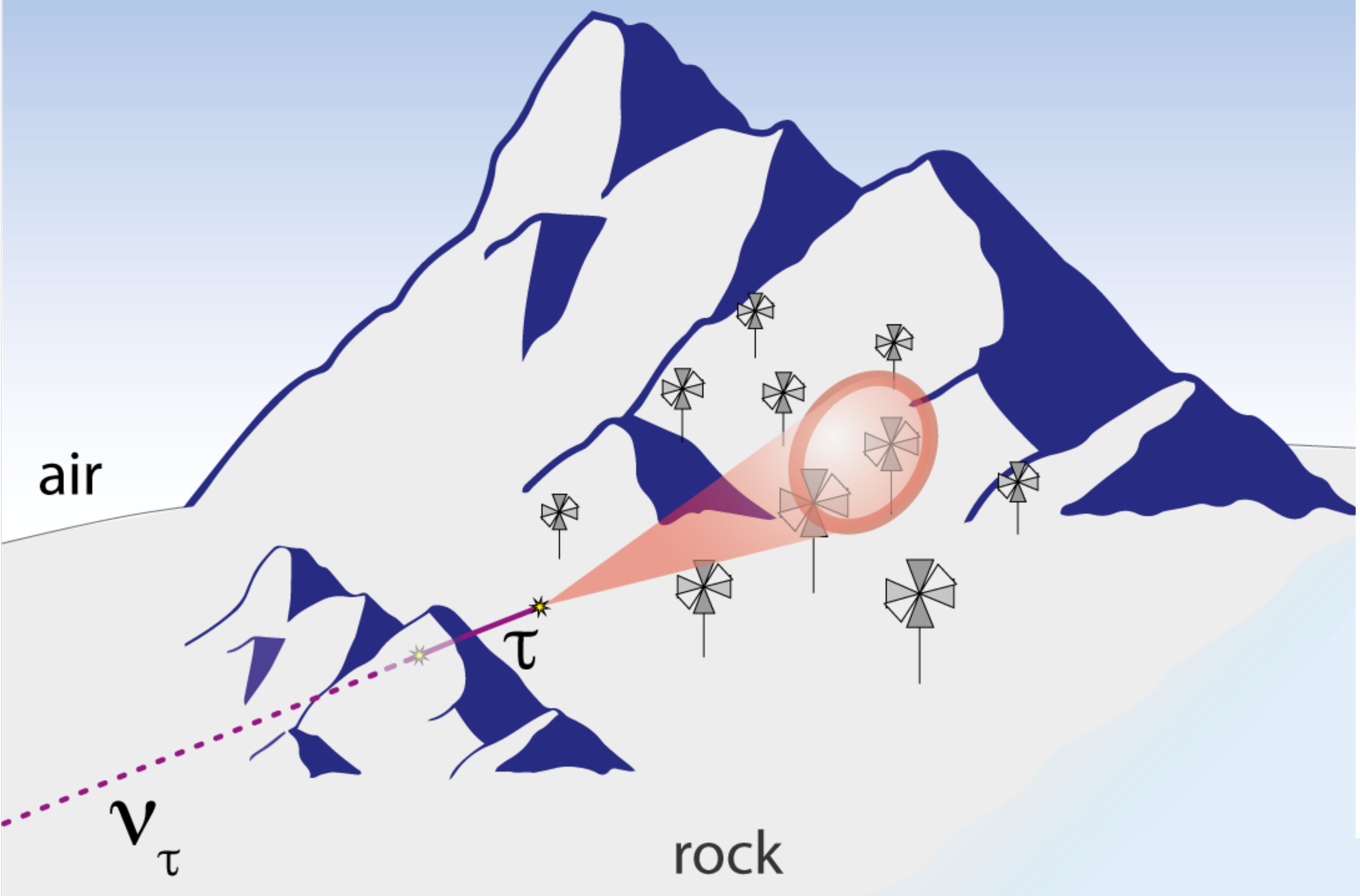
Mountain regions - valley

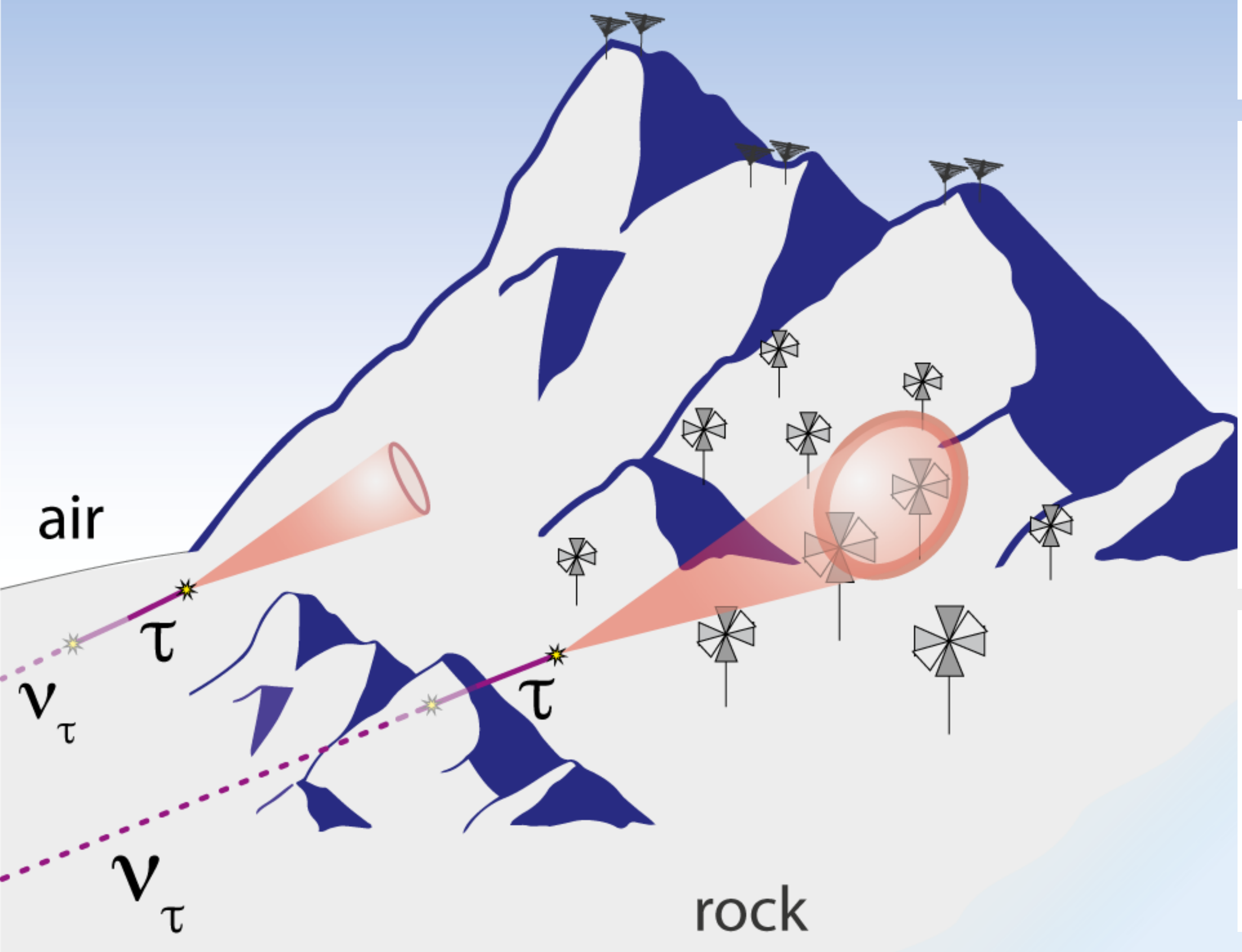


GRAND

- Many single antennas in a valley with 1 km spacing
  → good reconstruction
- Rely on surface roughness
- Sensitive to air showers > 10^{17} eV
- Field of view up to 10° above and below the horizon
- Currently 13 antennas deployed
- Site for another 230 antennas approved

→ More in GRAND talk

Mountain top



Antennas (downward pointing) on mountain top

- Field of view below the horizon
- Increased effective area at high energies
- Sensitive to air showers > 10^{17} eV

BEACON

- Several beamforming antennas → lower threshold
- Prototype with 4 antennas running since 2018 in California
- Cosmic ray candidate in data

TAROGE-M

- Six antennas
- Operated in Antarctica for ~26 days in 2020
- Cosmic ray events

Ballon borne

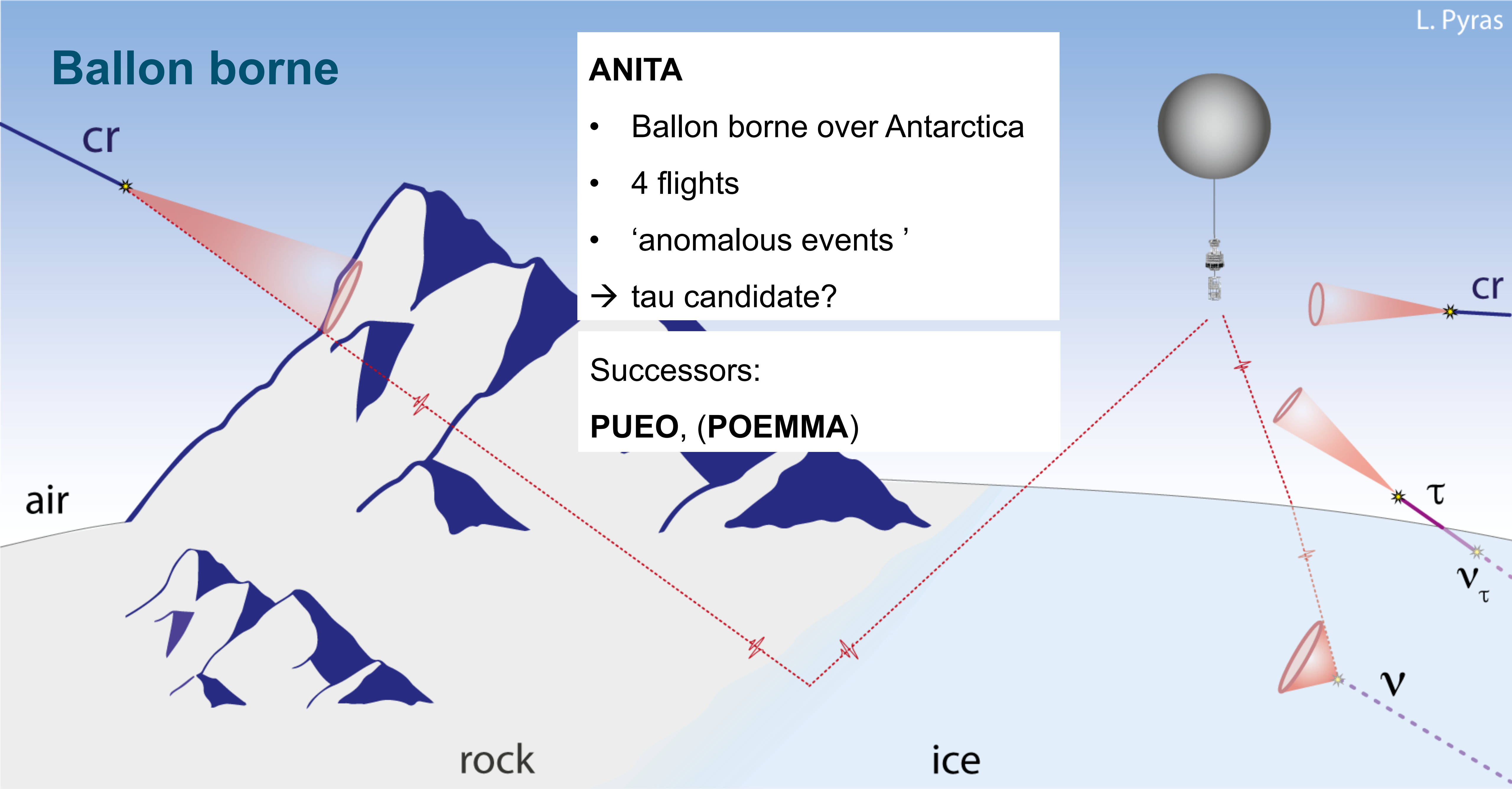
ANITA

- Ballon borne over Antarctica
- 4 flights
- ‘anomalous events ’

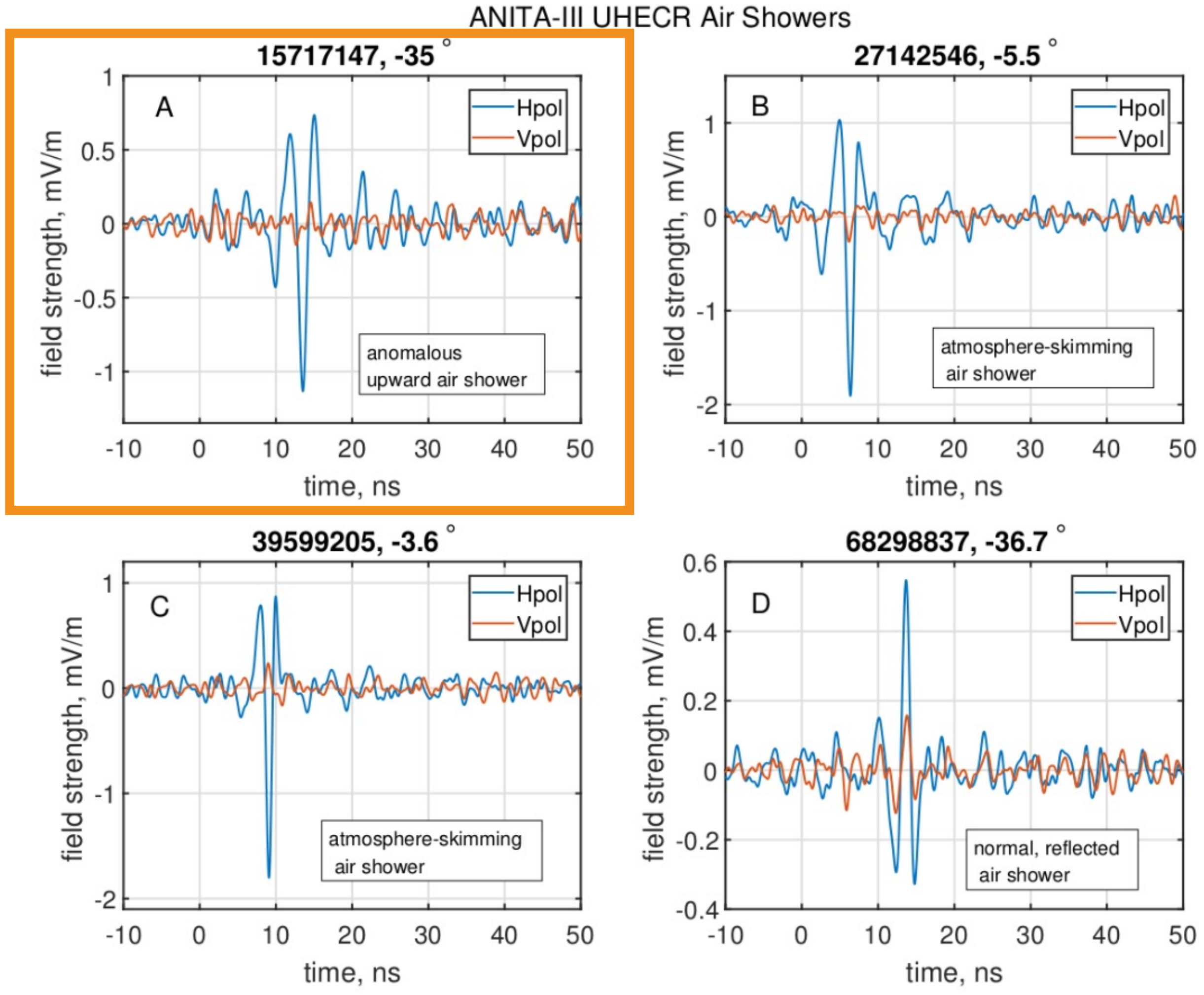
→ tau candidate?

Successors:

PUEO, (**POEMMA**)



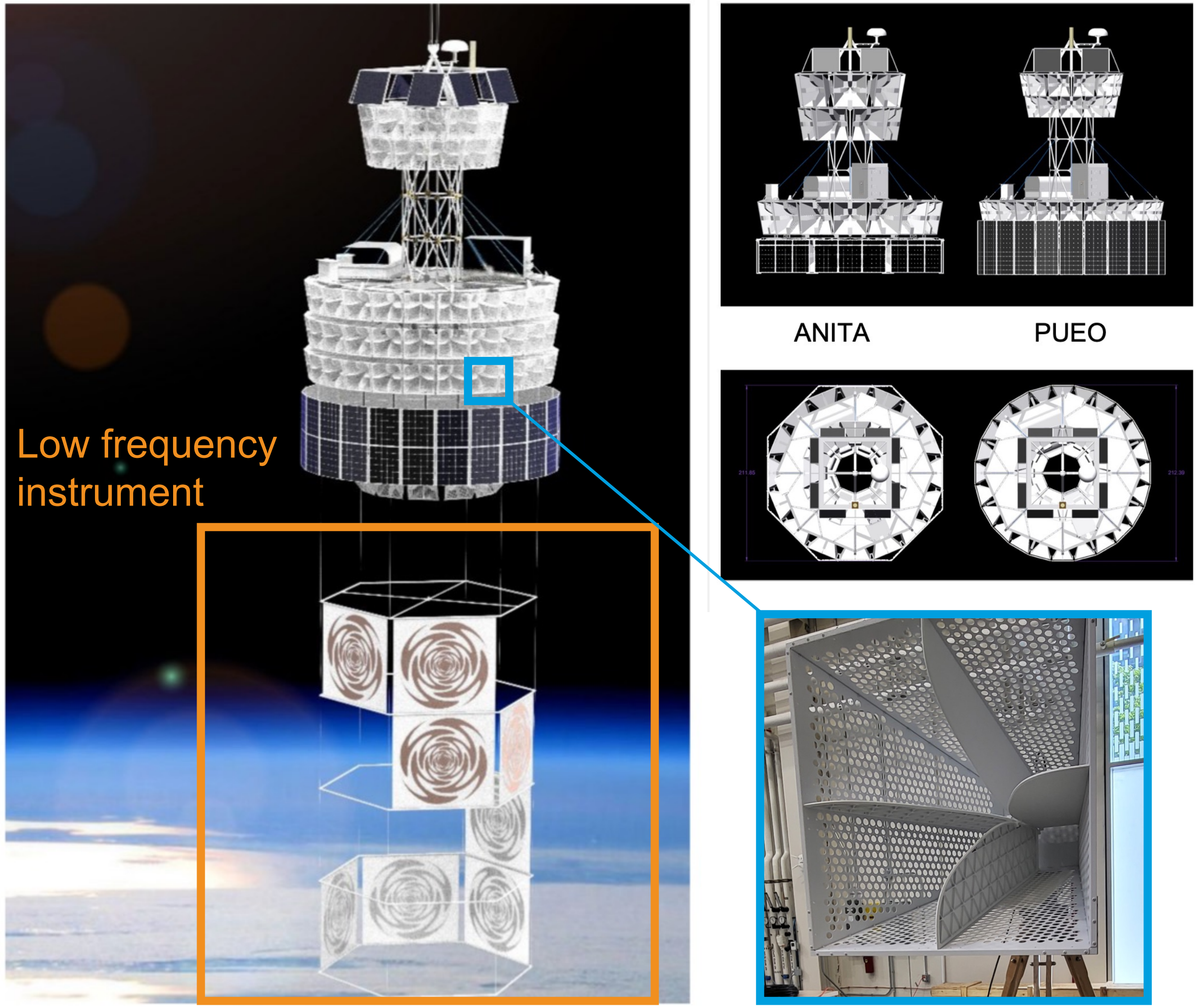
ANITA ‘mystery’ event



- Anomalous events found in ANITA-I and ANITA-III (arXiv:1803.05088)
- Consistent with tau neutrino
- Problem: chord length through Earth in tension with SM cross-section and flux in tension with IceCube and Auger limits
- Flurry of papers: τ candidate or other exotic/new phyics
- No satisfiying interpretation, many explanations besides new physics: particular reflection on ice, man-made background, electric fields in clouds
- PUEO could solve this ‘mystery‘

Payload for Ultrahigh Energy Observations

PUEO



- Successor to ANTIA
- More antennas → higher sensitivity
- Low frequency instrument for air shower
- Interferometric phased array trigger
- Improved pointing resolution
- Best at energies > $10^{18.5}$ eV due to distance to shower
- Complementary to ground based instruments
- Good for transients and point source searches
- Launch planned for Dec. 2026

In ice

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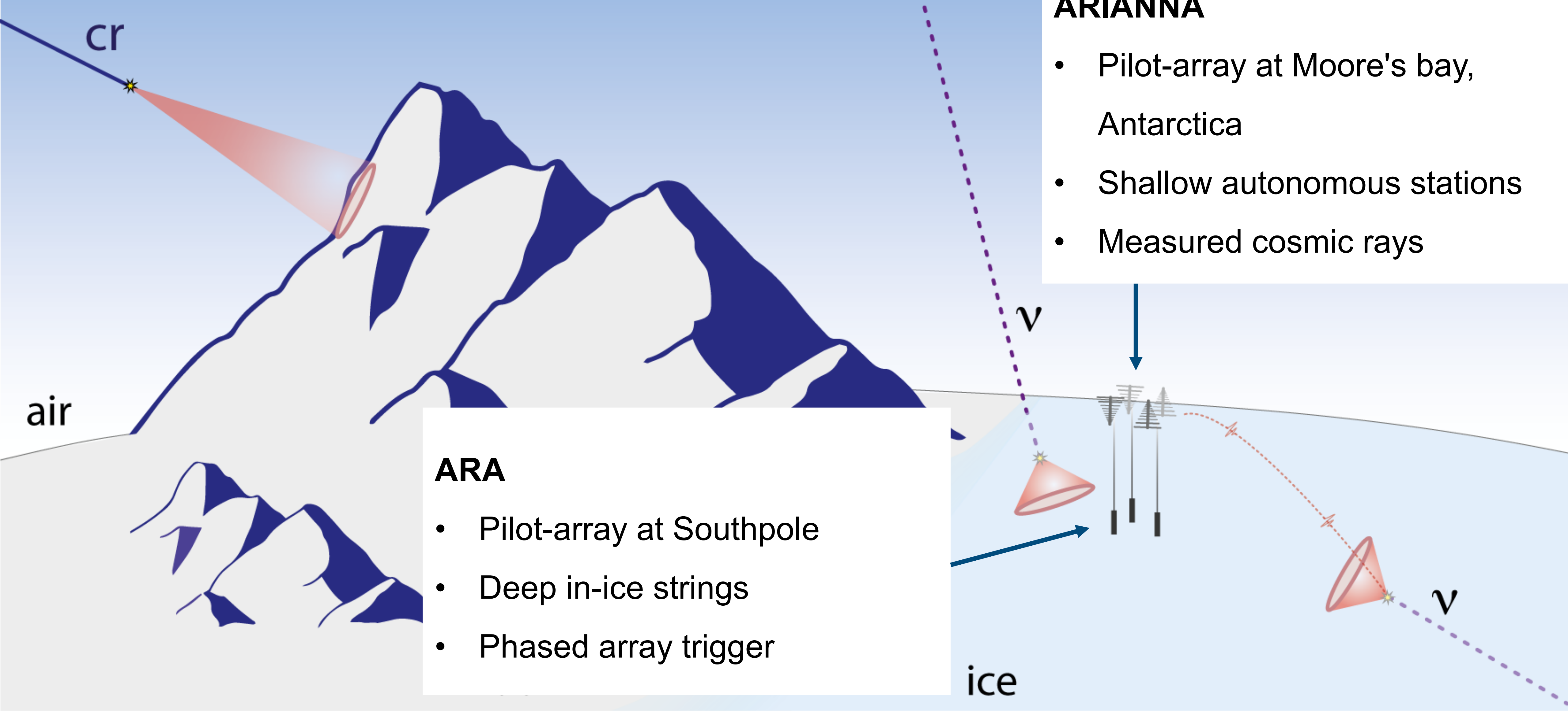
ARIANNA

- Pilot-array at Moore's bay, Antarctica
- Shallow autonomous stations
- Measured cosmic rays



ARA

- Pilot-array at Southpole
- Deep in-ice strings
- Phased array trigger

In ice

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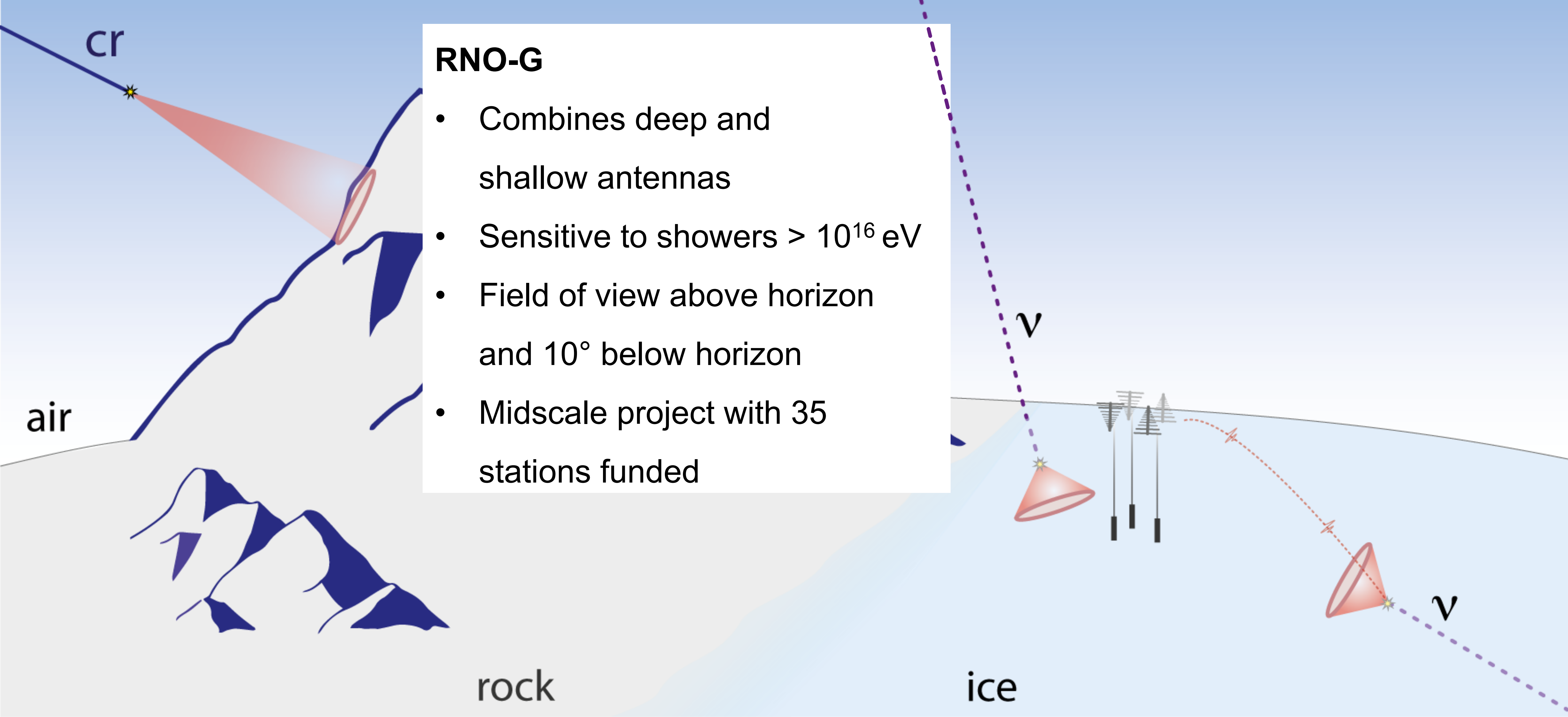


RNO-G

- Combines deep and shallow antennas
- Sensitive to showers > 10^{16} eV
- Field of view above horizon and 10° below horizon
- Midscale project with 35 stations funded

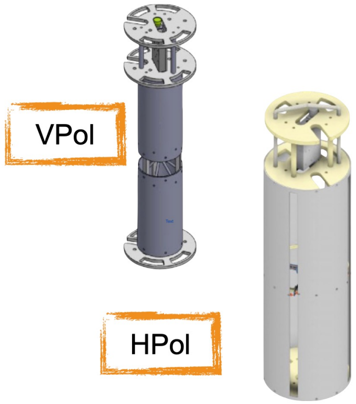
Radio Neutrino Observatory Greenland

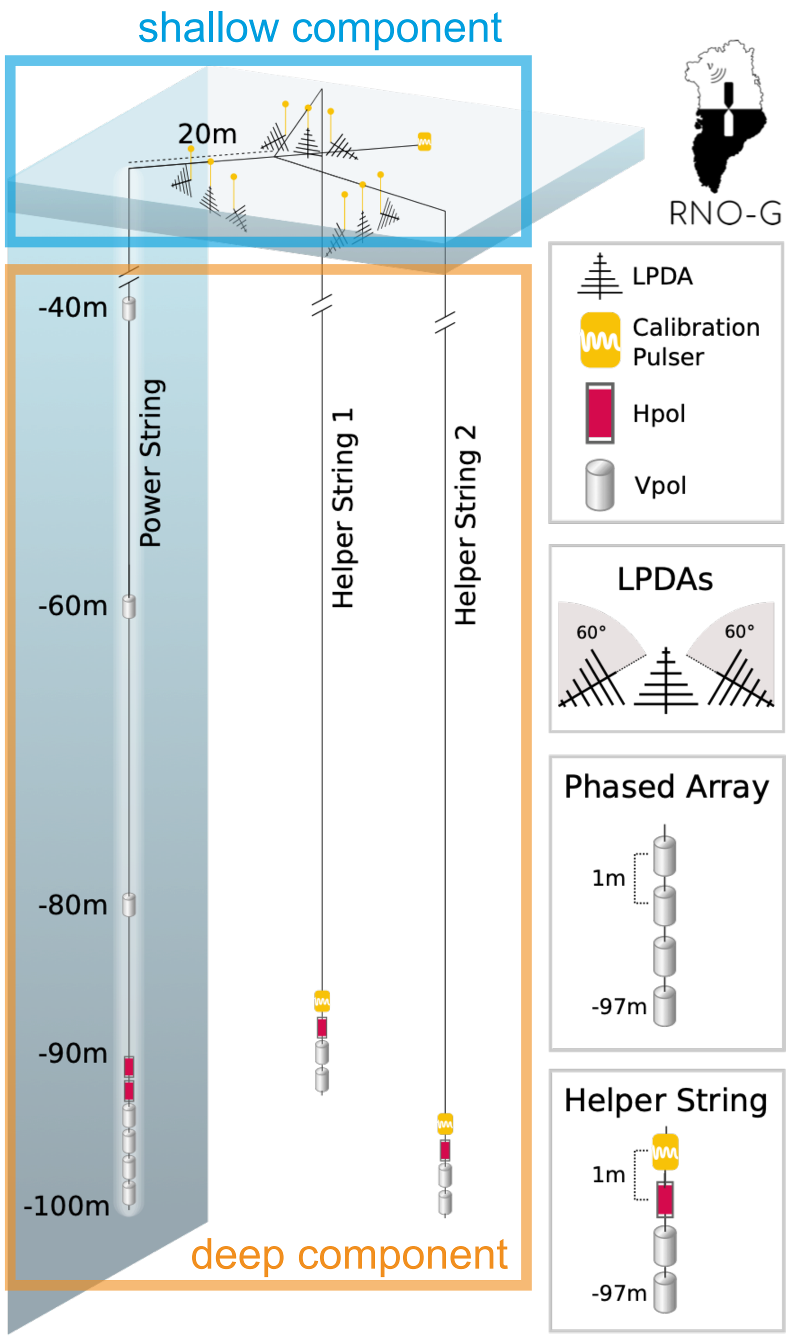
RNO-G

- Builds the expertise gained with ARA (deep in ice strings) and ARIANNA (autonomous stations)
- In-ice interferometric phased array trigger
- Sensitive from 10^{16} eV
- 3 strings for direction reconstruction
- Power via solar panels and wind turbines
- 7 stations are running and taking data
- 35 stations are currently funded and will be deployed until 2026

9 shallow antennas

15 deep antennas



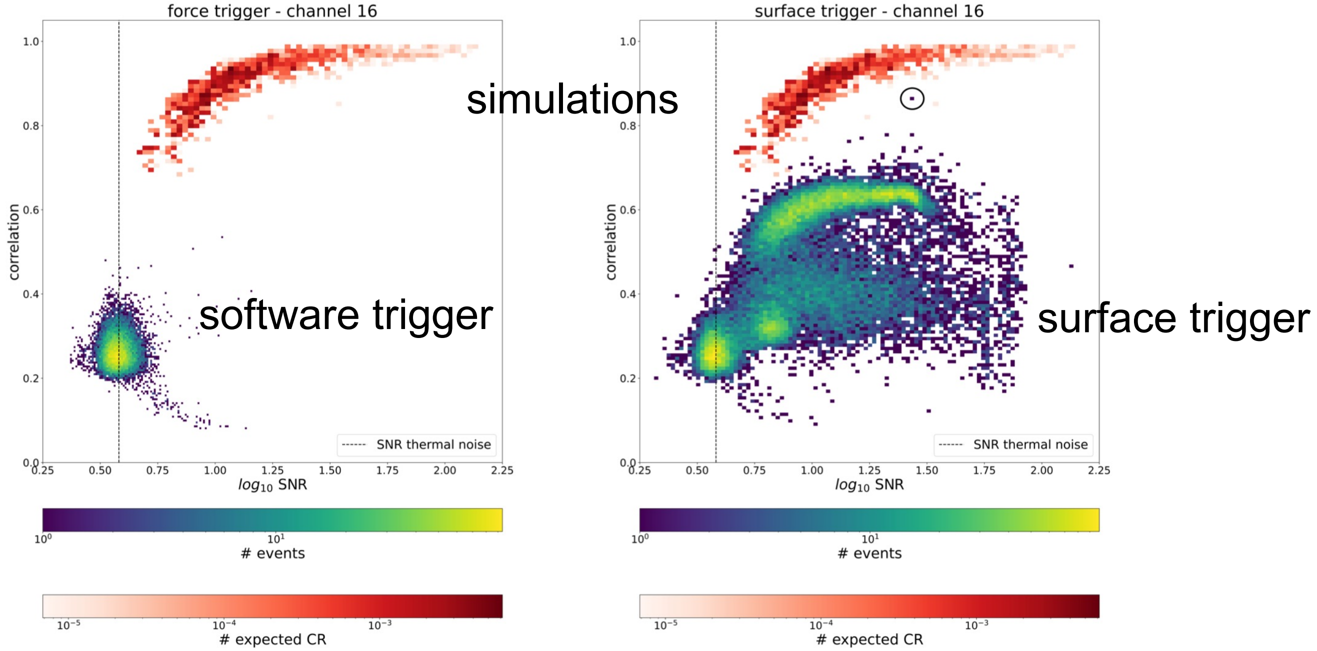


RNO-G Deployment

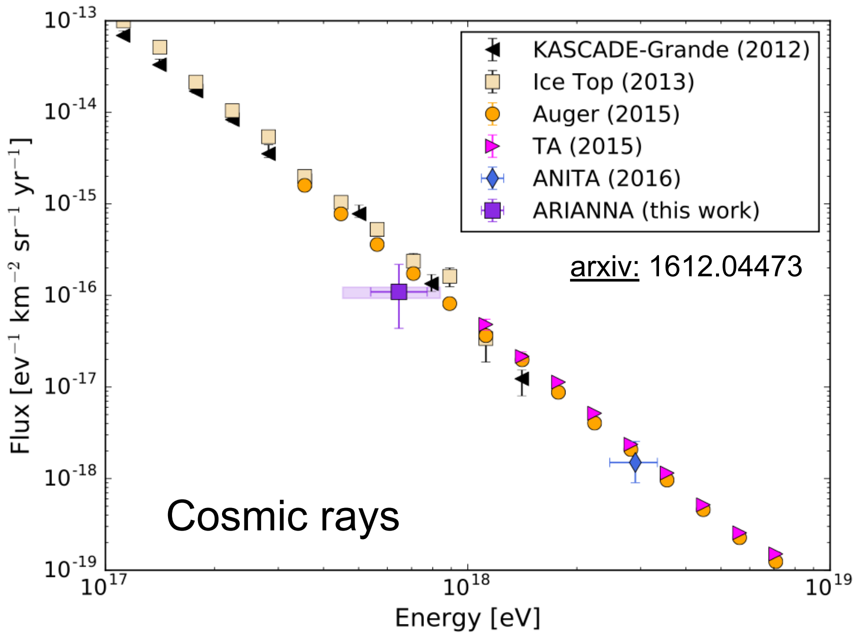
Track-record

Why are we confident that Radio is a good plan

- Pilot-arrays have been running soundly and passed verification tests in calibration, cosmic ray detection, Galactic emission, etc.
- Developed simulation software (e.g. NuRadioMC) and successful analysis strategies
- Reconstruction algorithms tested on air shower

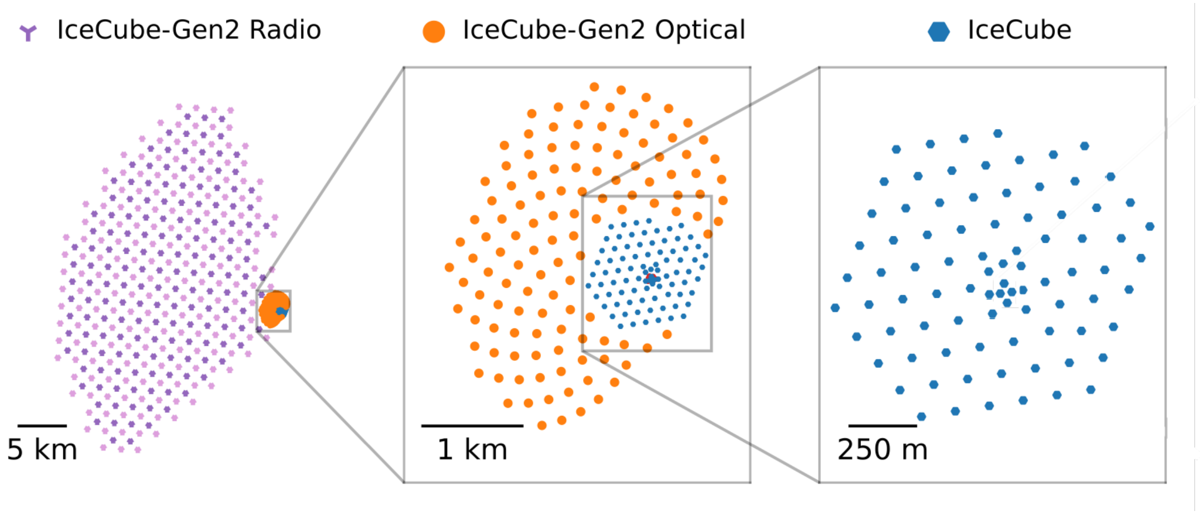


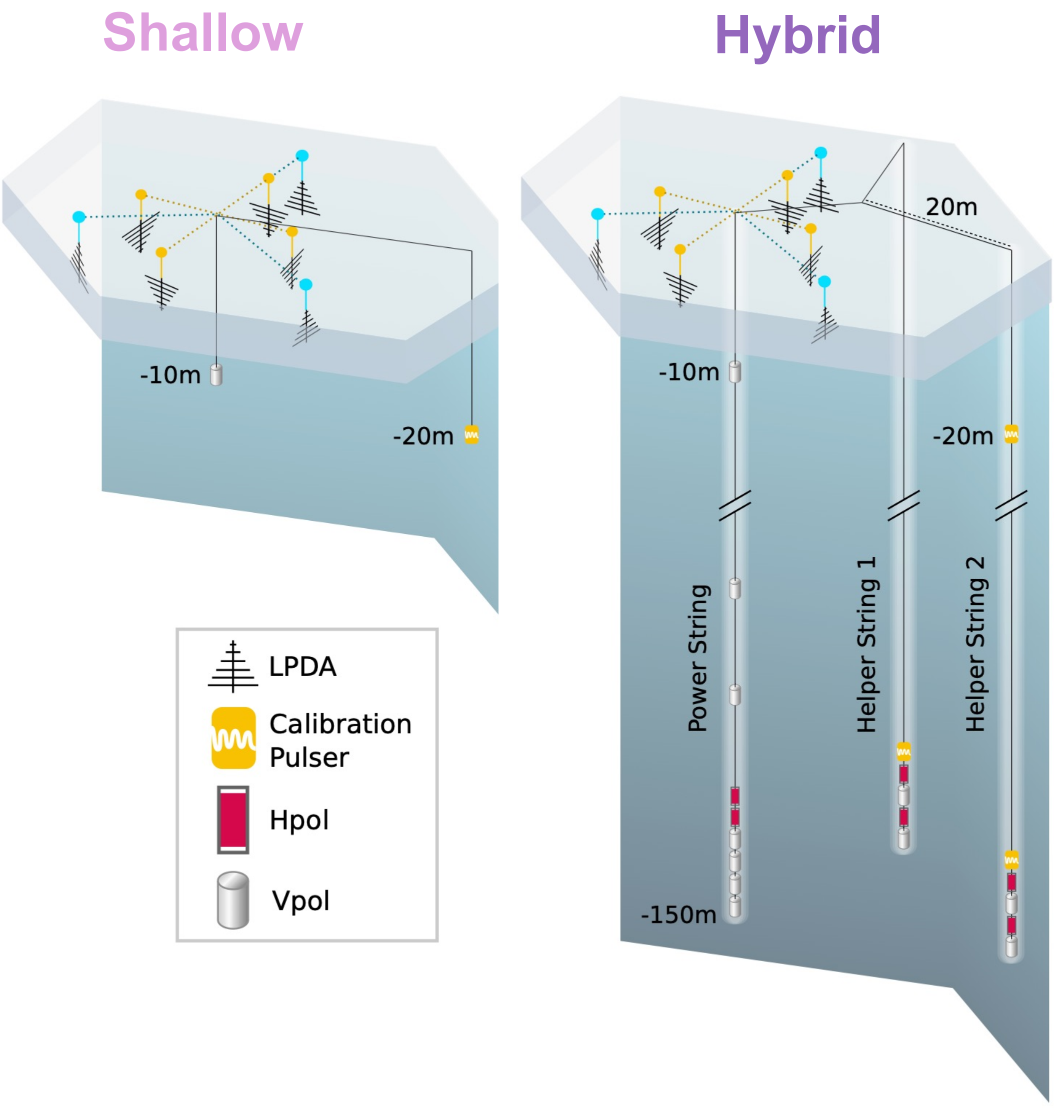
PoS(ICRC2023)259



Radio Array of IceCube-Gen2

- 169 hybrid stations, 1.75km spacing on square
- 192 shallow stations, interspersed in 1.24 km spacing
- Similar to RNO-G design
- Discovery-level array at UHE





IceCube-Gen2 TDR

Radio Array of IceCube-Gen2

Science

- **Astrophysical neutrinos**
  - Resolve the high-energy neutrino sky from TeV to EeV
  - Multi-messenger observations
  - Energy, spectrum, and flavor

D. Fiorillo, V. B. Valera, M. Bustamante JCAP 03 (2023) 026

I. Plaisier, S. Bouma, A. Nelles, EPJ-C 83, 443 (2023)
S. Bouma et al., PoS(ICRC2023)1045
A. Coleman et al. arXiv:2402.02432

- **Cosmogenic neutrinos**
  - Origin of cosmic ray accelerators
  - Targeting discovery at flux level where 10% of the UHECR are protons, with five years of data

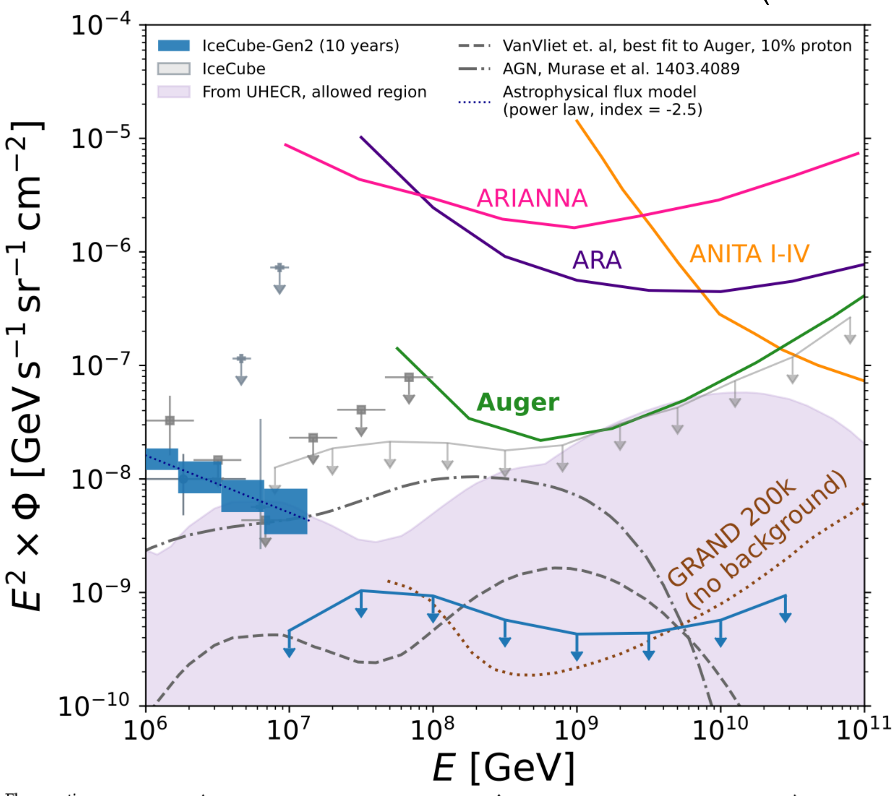
IceCube-Gen2 TDR 2023/2024
M. Muzio, M. Unger, S. Wissel PRD 107, 103030 (2023)
V. B. Valera, M. Bustamante and C. Glaser, Phys. Rev. D 107, 043019 (2023)

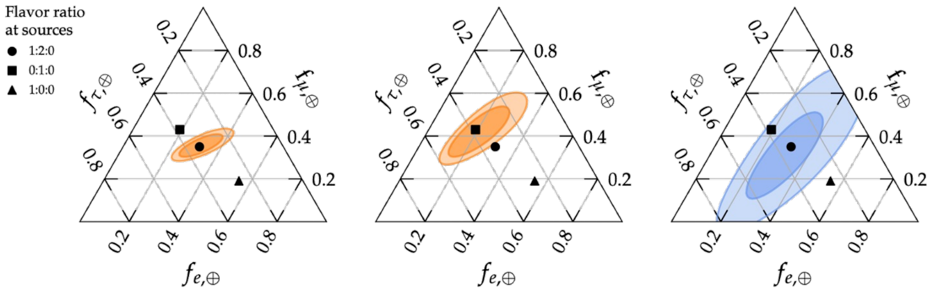
- **Fundamental physics at UHE**

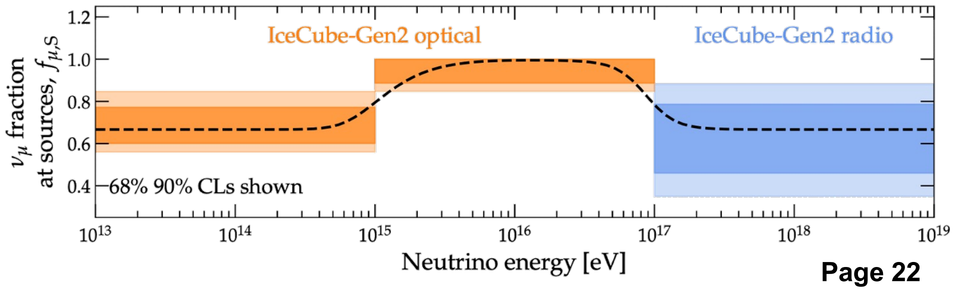
V. B. Valera, M. Bustamante and C. Glaser, JHEP 06 (2022) 105
I. Esteban, S. Prohira, J. Beacom, Phys. Rev. D 106, 023021

A. Coleman et al. arXiv:2402.02432
A. Garcia-Soto PRD 107, 033009 (2023)

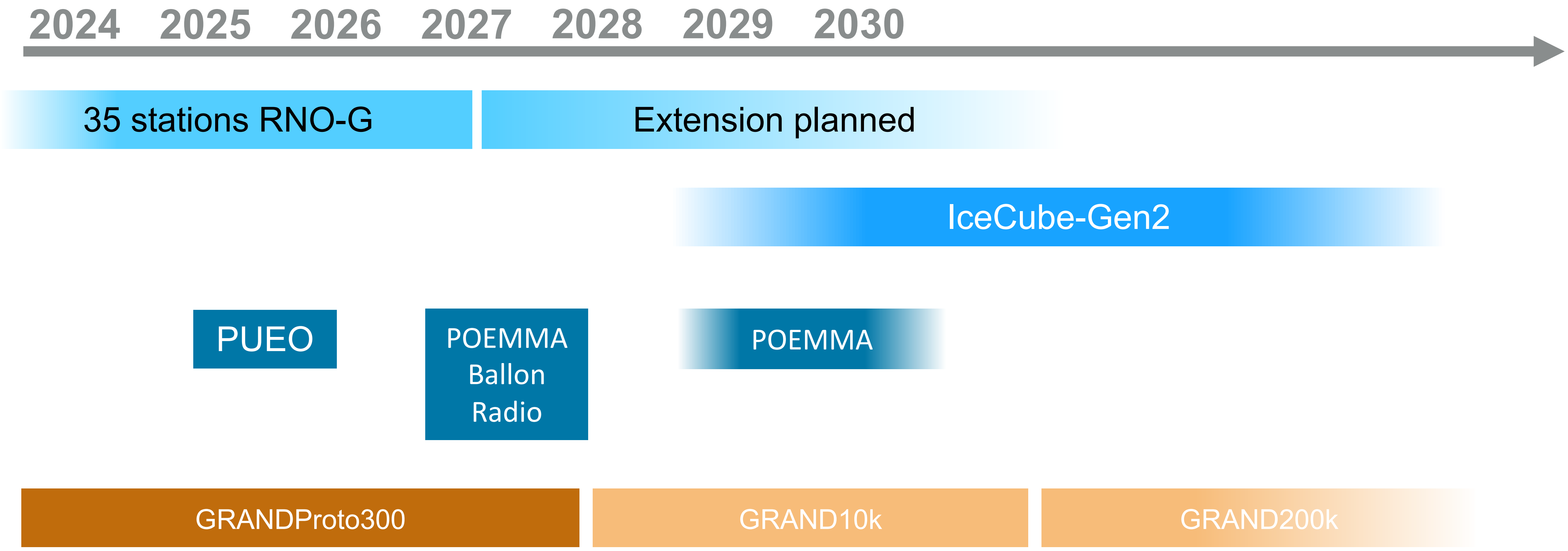
- Expect 3° angular resolution and 65% energy resolution (68% containment) (GRAND: 0.1° angular resolution)





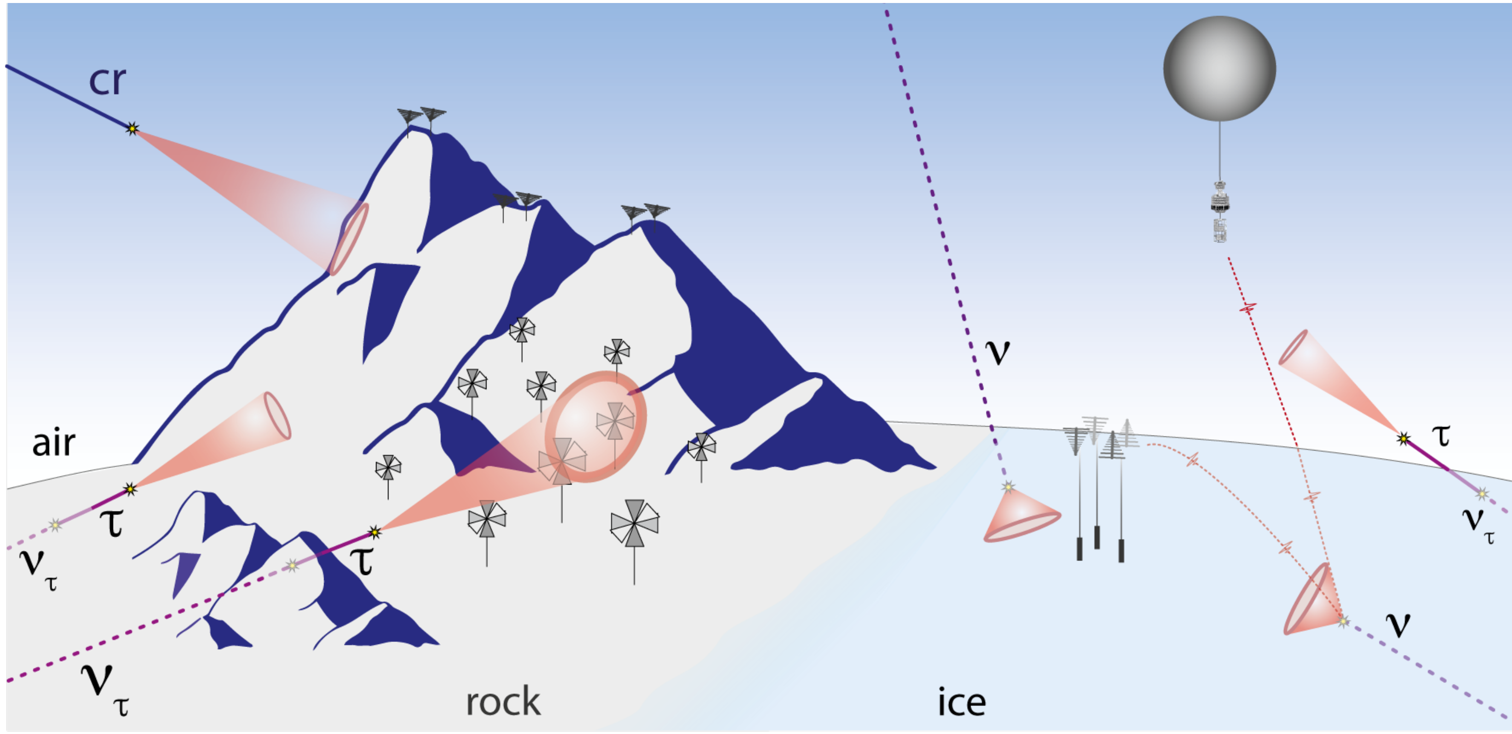


Timelines and perspectives



Summary

- Radio detection of neutrinos builds on sound and solid theoretical modelling and successful track-record in experimental techniques
- RNO-G first midscale project that takes shape and has the chance for a neutrino detection
- Experiments in mountain regions are explored (e.g., GRAND, BEACON, TAROGE)
- Large scales arrays planed, e.g., GRAND10k, IceCube-Gen2
- PUEO will clarify anomalous event
- Lots of interesting science at the highest energies e.g.
  - Multi-messenger observations
  - Origin of UHECR
  - Flavor ratio
  - Fundamental physics



Additional information

Experimental strategies

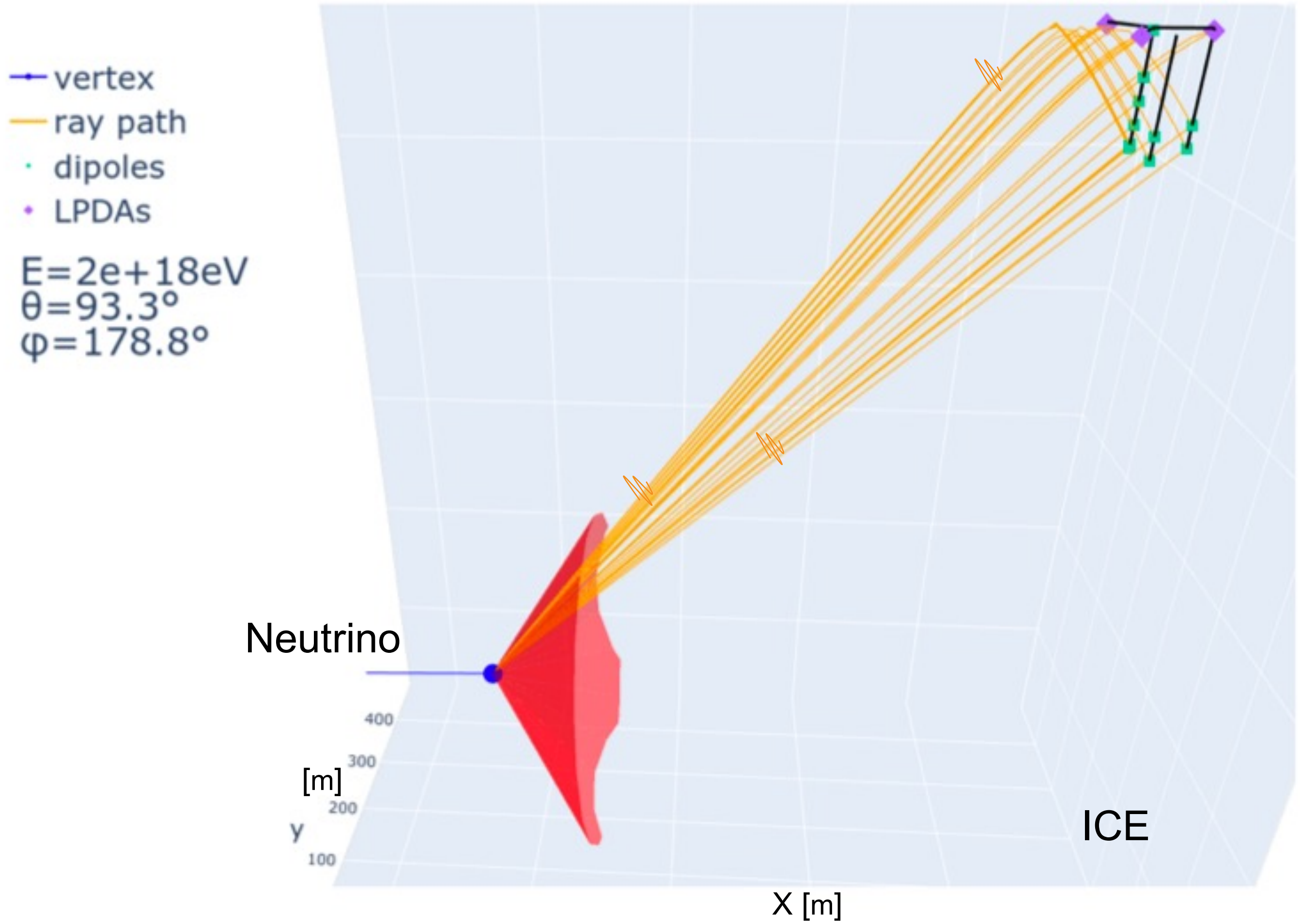
Focus on radio neutrino experiments

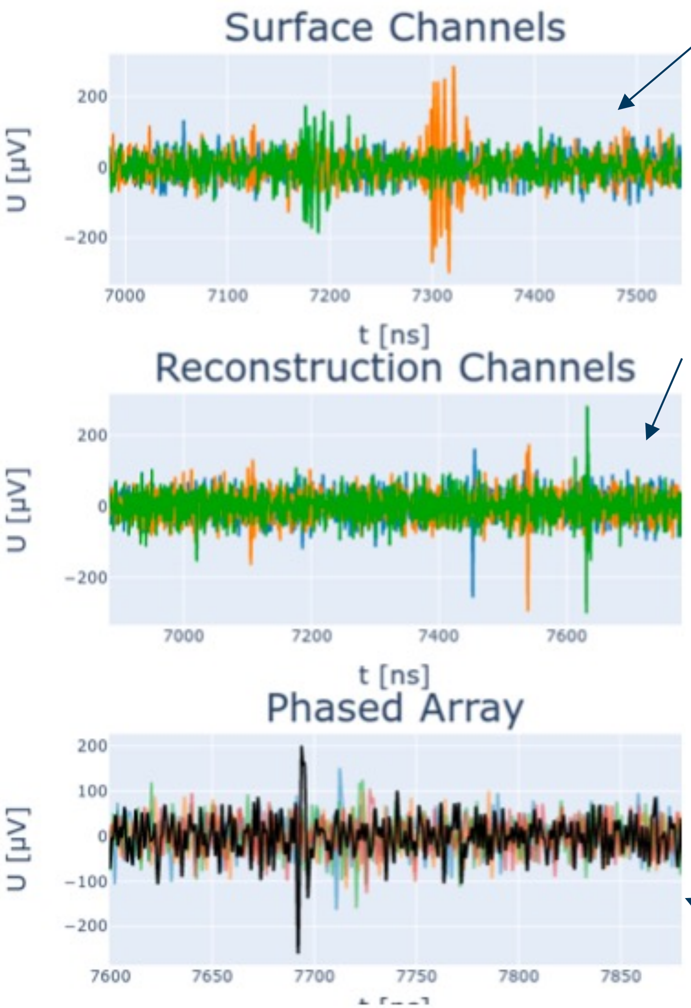
Antenna Site	Neutrino interaction	Flavor	Shower energy	Zenith angle arrival direction	Antenna configuration
Valley	Rough surface	Tau	$> 10^{17}$ eV	Up to 10° above the horizon	Many single antennas
Mountain Top	Earth skimming, rough surface	Tau	$> 10^{17}$ eV	Below the horizon	Beamforming array
In-ice	In-ice	all	$> 10^{16}$ eV	Above the horizon and 10° below the horizon	Station with trigger array and reconstruction channels
Ballon	In-ice, earth skimming	all, tau	$> 10^{18}$ eV	Below the horizon	Payload with horn antennas and low freq. antennas

Status on experiments

	Method	Data taking	Science results	Funding	Note
GRAND	Earth skimming	13 antennas	In prep.		Site for GRANDProto300 approved, Dunhuang, Gansu Province, China
BEACON	Earth skimming	8-ch. Prototype running since 2018	cosmic ray candidates		Upgraded with more antenna and scintillators to understand radio self-trigger
TAROGE-M	Earth skimming	26 days of data	Cosmic rays		Data successful analyzed
PUEO	Ballon, ice			funded	Will fly Dec. 2025-2026
POEMMA	Satellite, atmosphere	Short pilot missions		Decided soon	POEMMA-Ballon-Radio
RNO-G	Deep&shallow in-ice	7 Stations with 24 ch.	cosmic ray candidates, solar flares	35 stations are funded	10 more stations in 2025, drilling works!
IceCube-Gen2	Deep&shallow in-ice	-	-	TDR done	Depends on NSF and Southpole logistics

Neutrino Event Simulation





Measure and trigger cosmic rays

Reconstruct event parameters (energy, direction,..)

Deep trigger, finds the right pulses