Radio detection of ultra-high energy neutrinos: present and future

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YITP workshop
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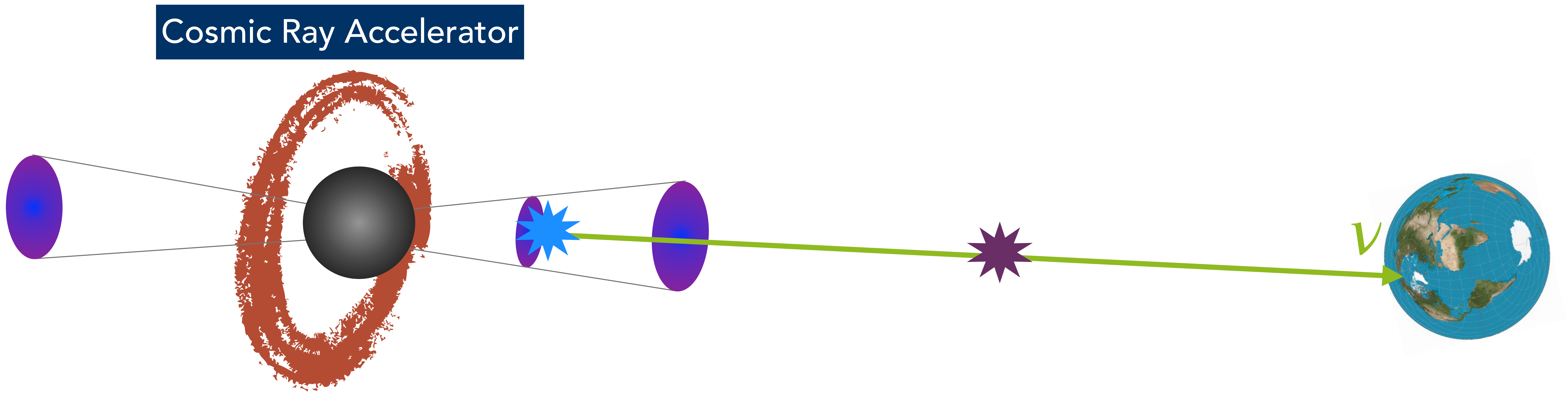
NEUTRINOS AT ENERGIES ULTRA-HIGH ENERGIES (UHE, >PEV)



Astrophysical ν's:

Cosmic ray interactions at the sources

Cosmogenic ν's:

Ultra-high-energy cosmic ray interactions during propagation

NEW WINDOW WITH UHE NEUTRINOS

➤ **Astrophysical ν's:**

Neutrino sky beyond PeV?

➤ **Cosmogenic ν's:**

UHECR origin?

New Window with UHE Neutrinos

How to Design an UHE In-Ice Radio Detector?

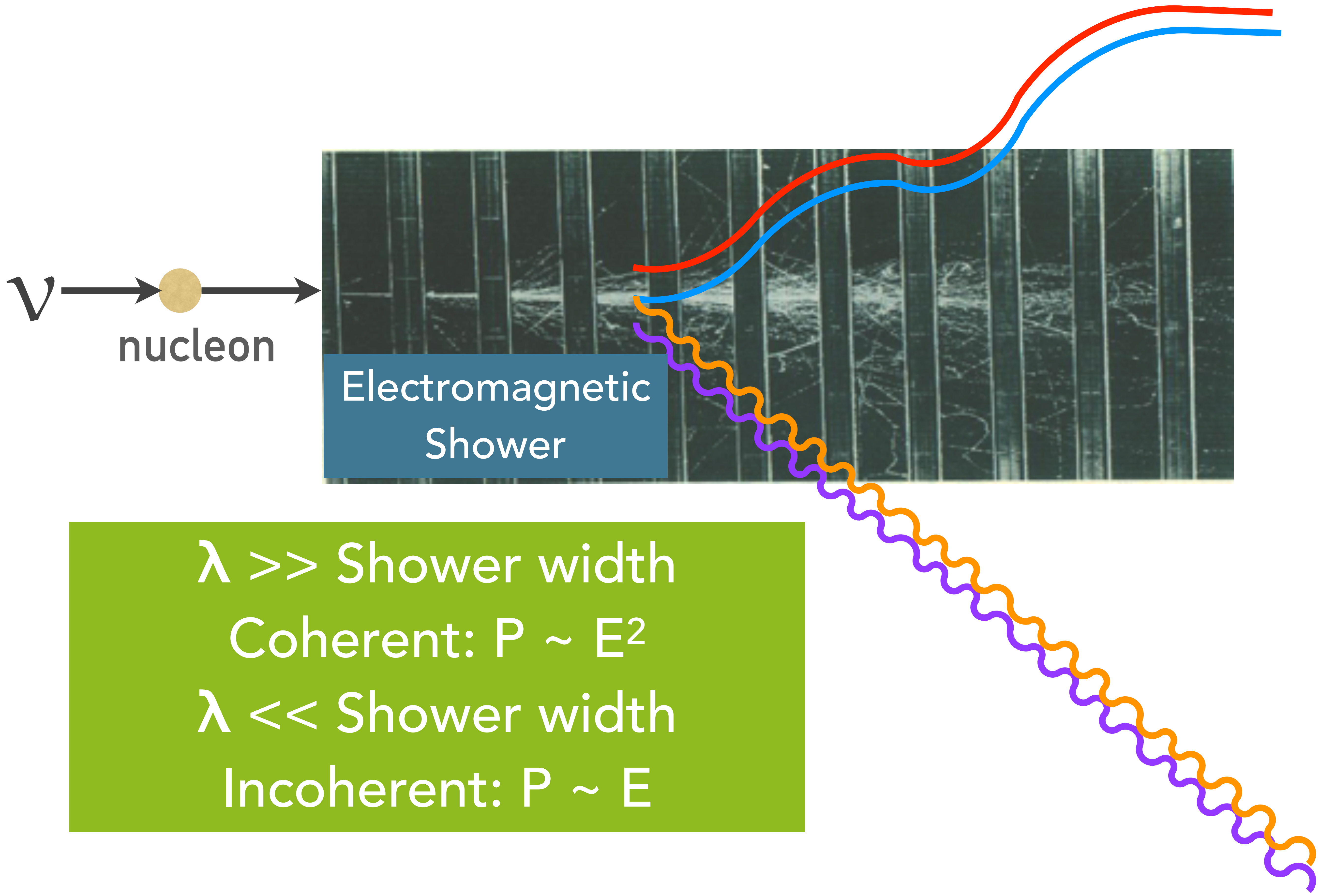
Goal: build an efficient detector to all flavors of UHE neutrinos with required large effective area & minimal instrumentation

Let's step through the design process to build up to 10^{-8} (now), 10^{-9} (soon), 10^{-10} (next gen)

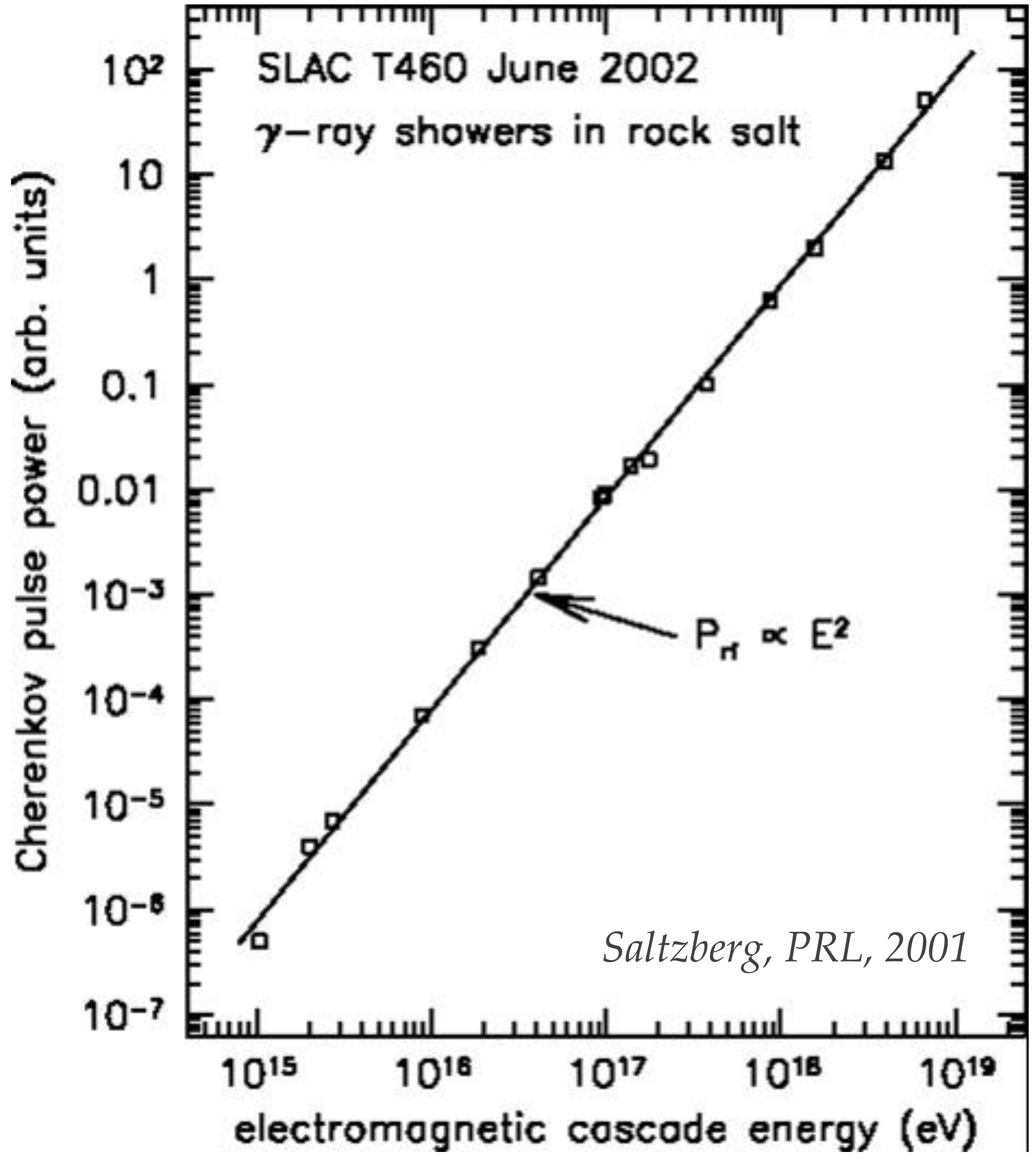
ASKARYAN RADIATION IN ICE

- All the shower particles generate Cherenkov emission
- 20% **charge asymmetry** + **compact shower** from evolution in **dense** medium results in **coherent signal** at radio wavelengths
- **Broadband** up to wavelengths comparable to the shower size

Stronger than optical at UH energies



λ >> Shower width
Coherent: P ~ E^2
λ << Shower width
Incoherent: P ~ E

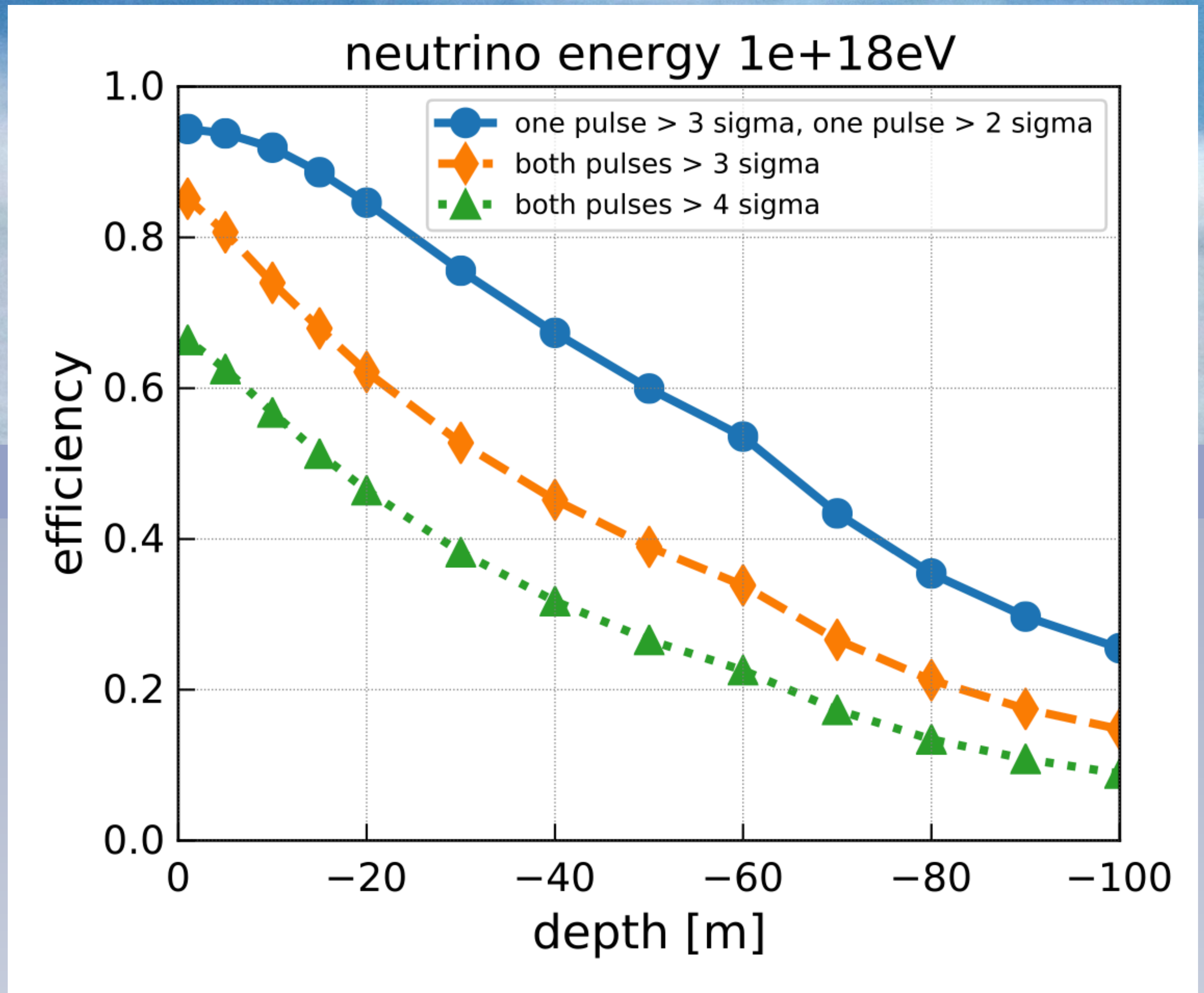


Step 2: How Do I Observe the Radio?

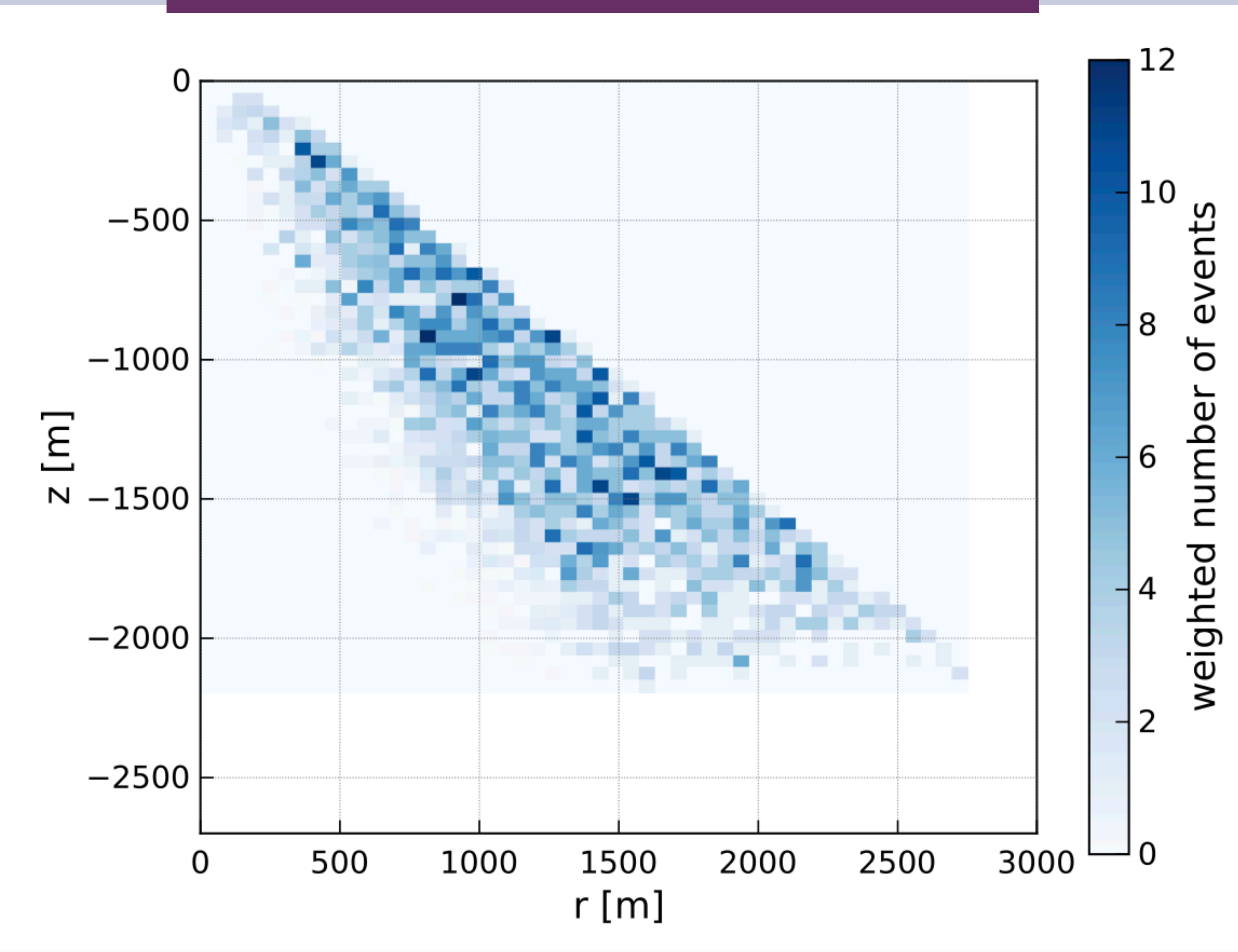
if there's water, signal reflects off bottom surface

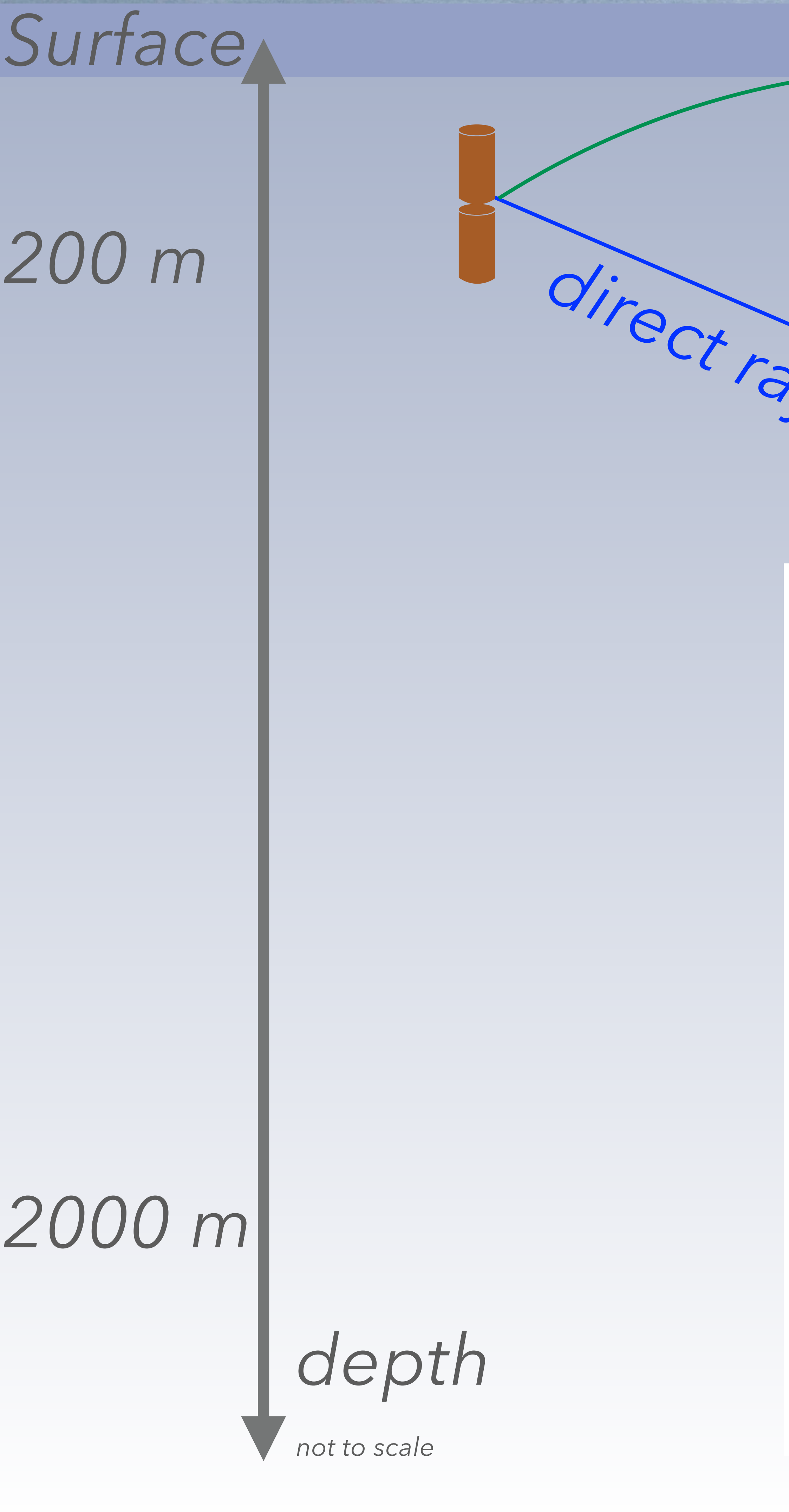
Step 3: At What Depth should I build my detector?

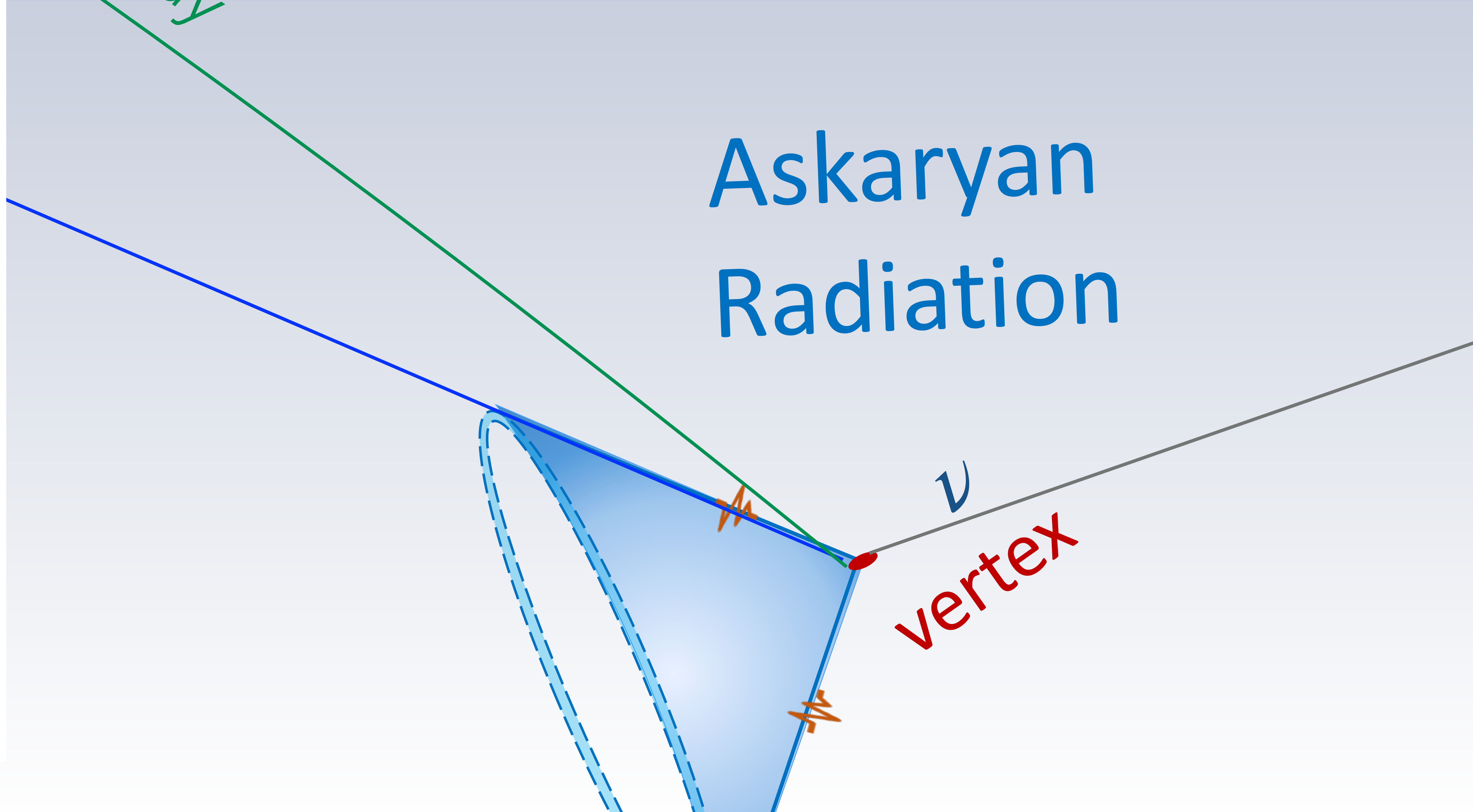
Fraction of Coincident DnR rays decreases with depth



Effective volume increases with depth





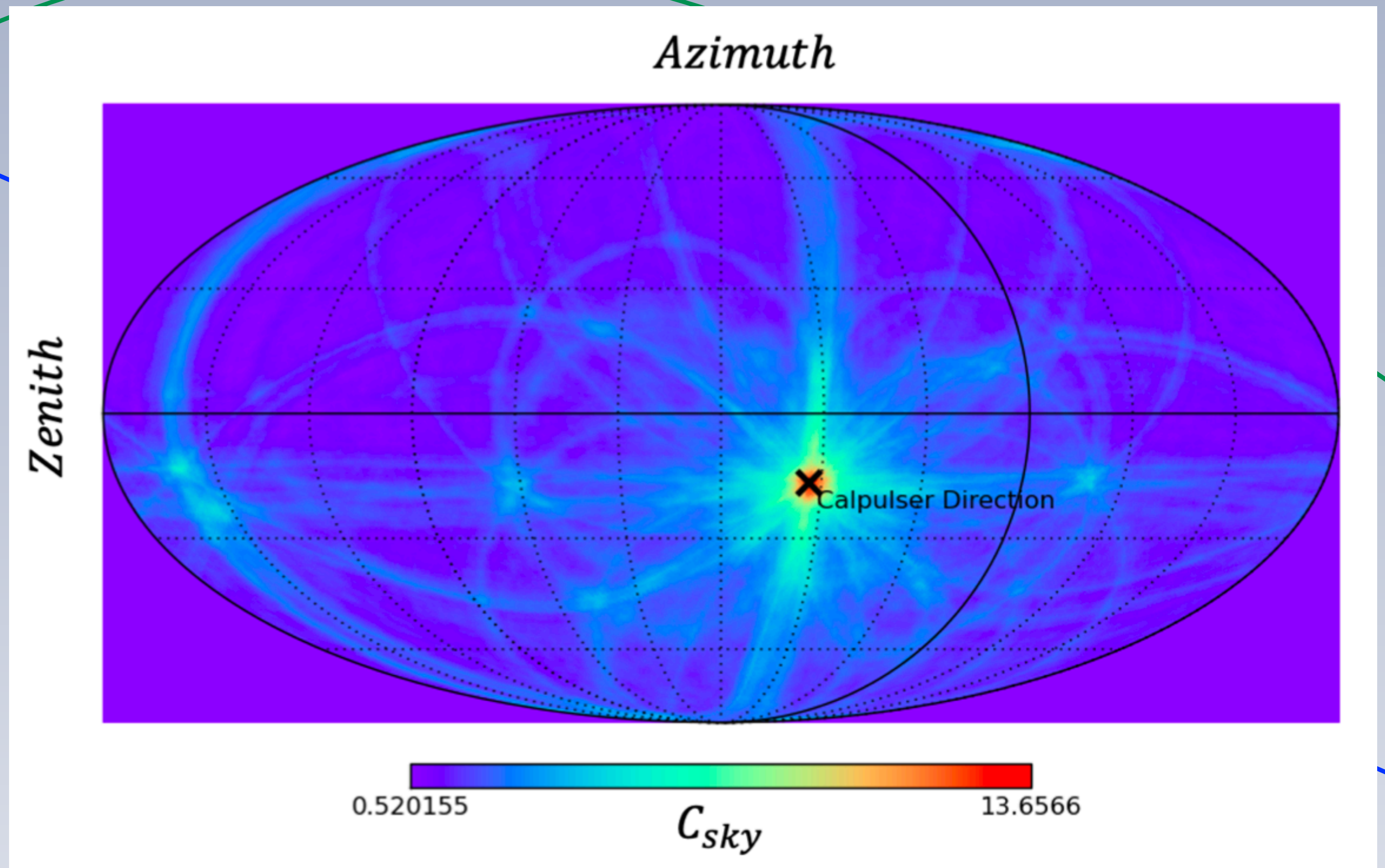


Step 4: How Many Channels?

Surface

200 m

Multiple antennas at each station reconstruct radio signal via interferometry



$\mathcal{O}(10)$ channels per station

$\mathcal{O}(10^2 - 10^3)$ stations for $E^2F \sim 10^{-10}$

Space them by ~ attenuation length so effective volume increases (nearly) linearly

2000 m

depth

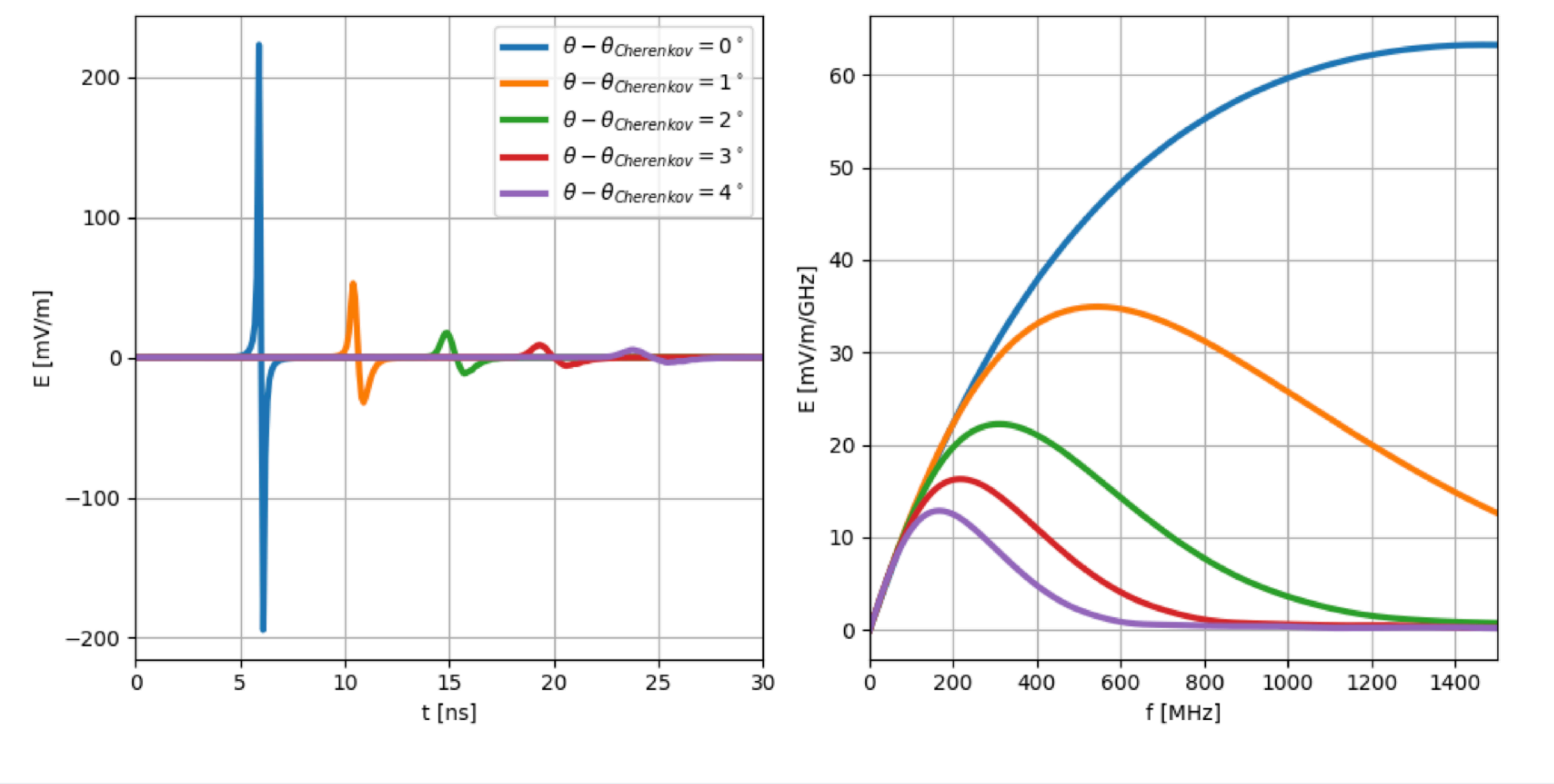
not to scale

$L_{atten} \sim 1$ km

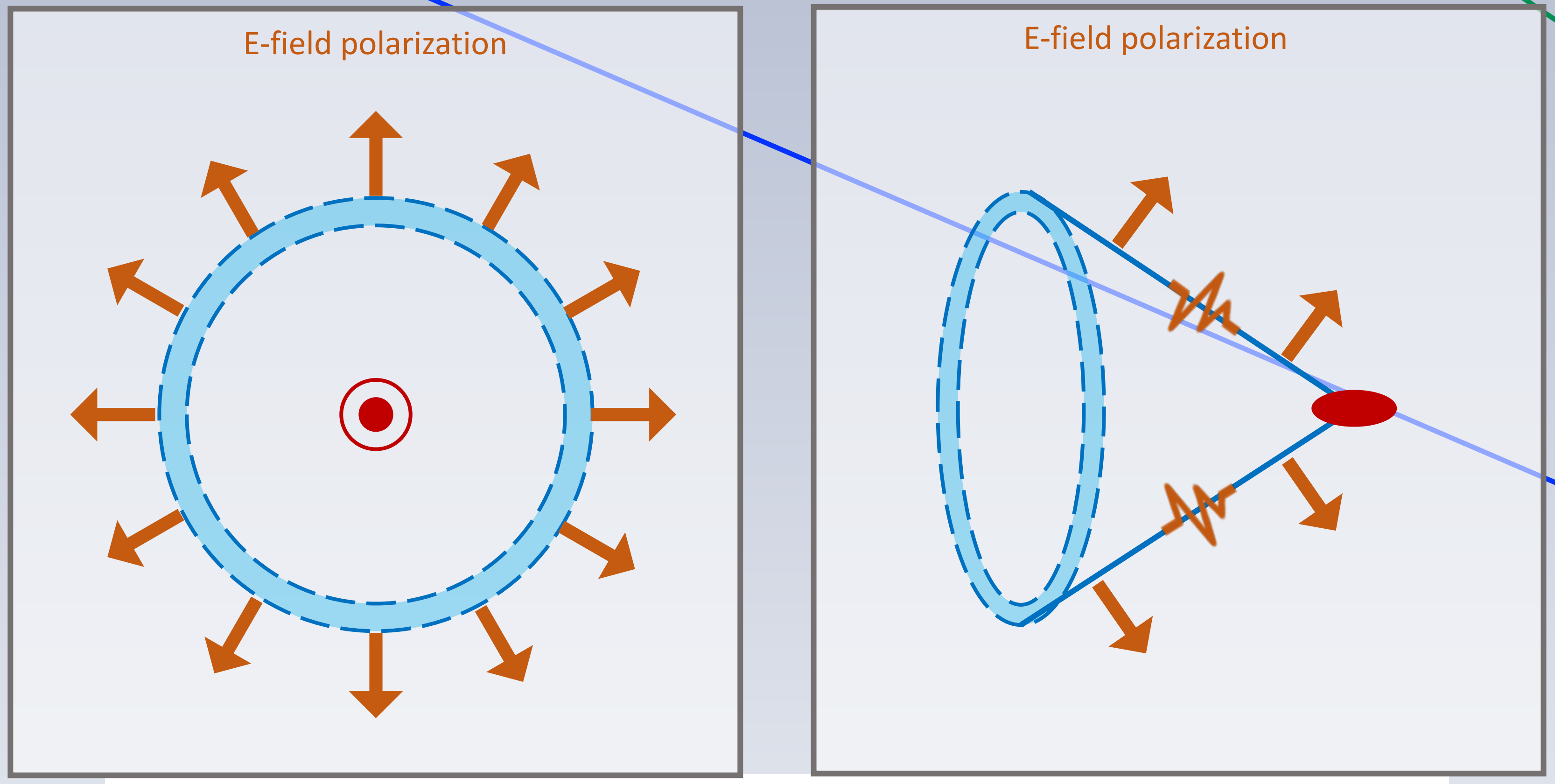
ν

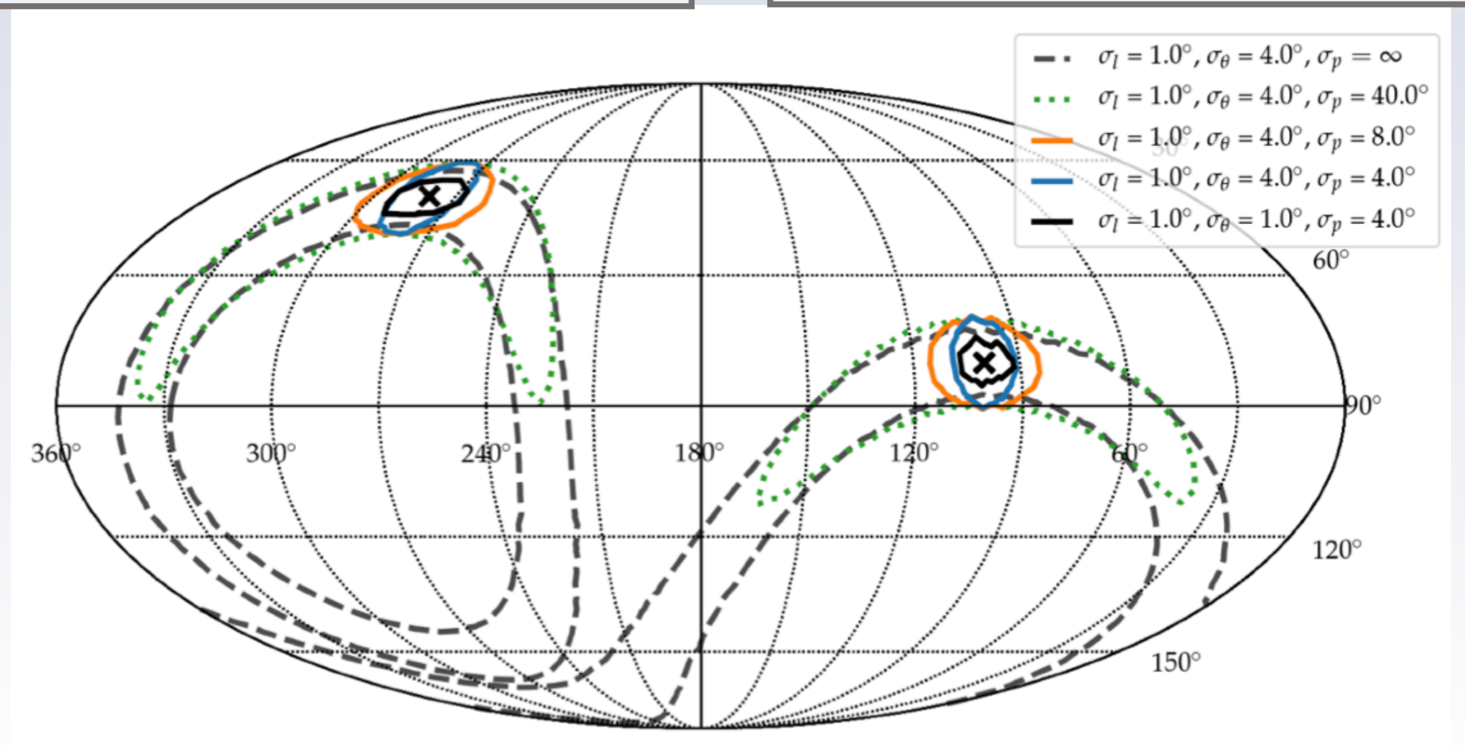
Step 5: How Do I Reconstruct Neutrino Events?

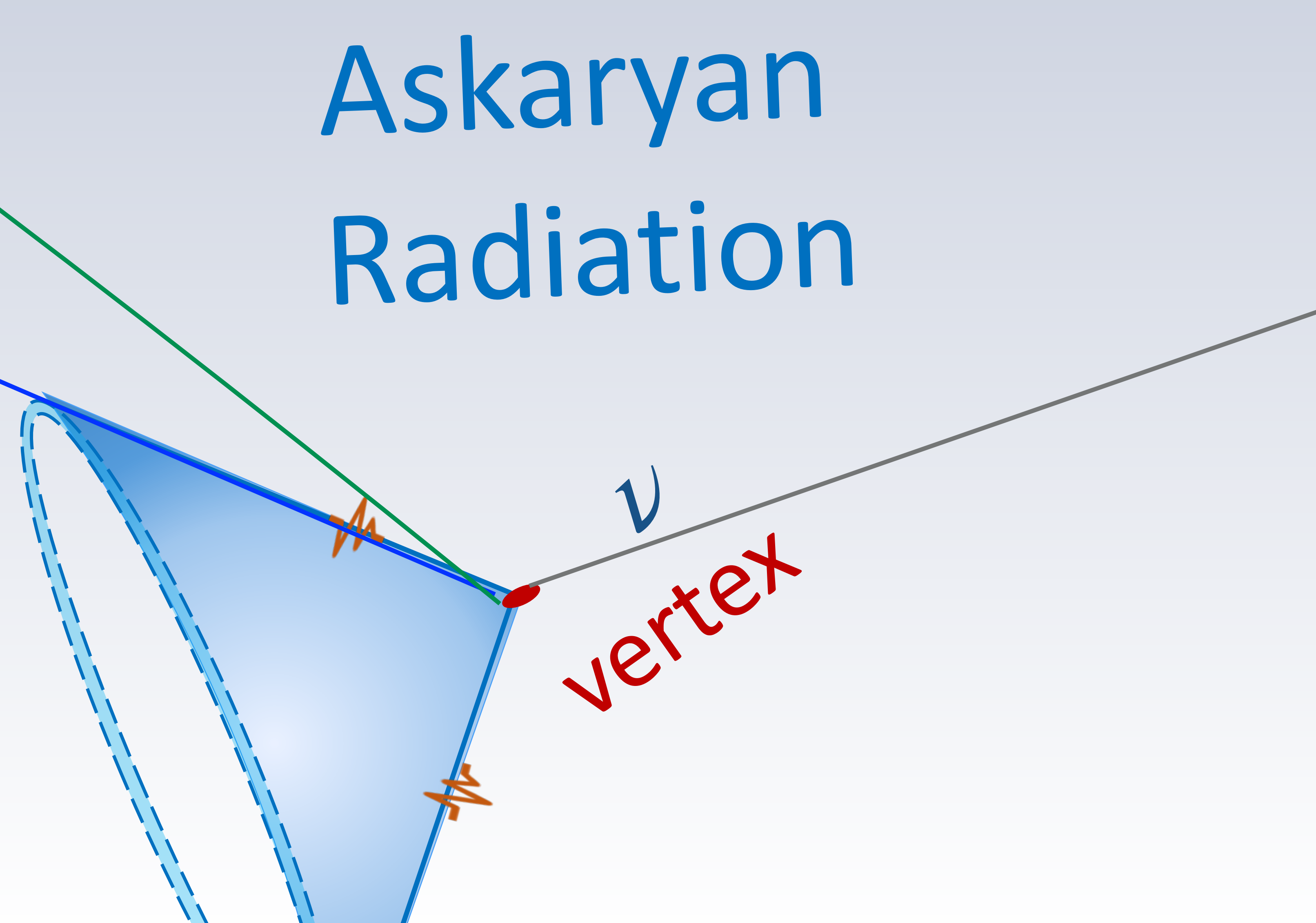
Use frequency spectrum to determine angle off-cone



Use polarization to find neutrino direction to ~ degree scale





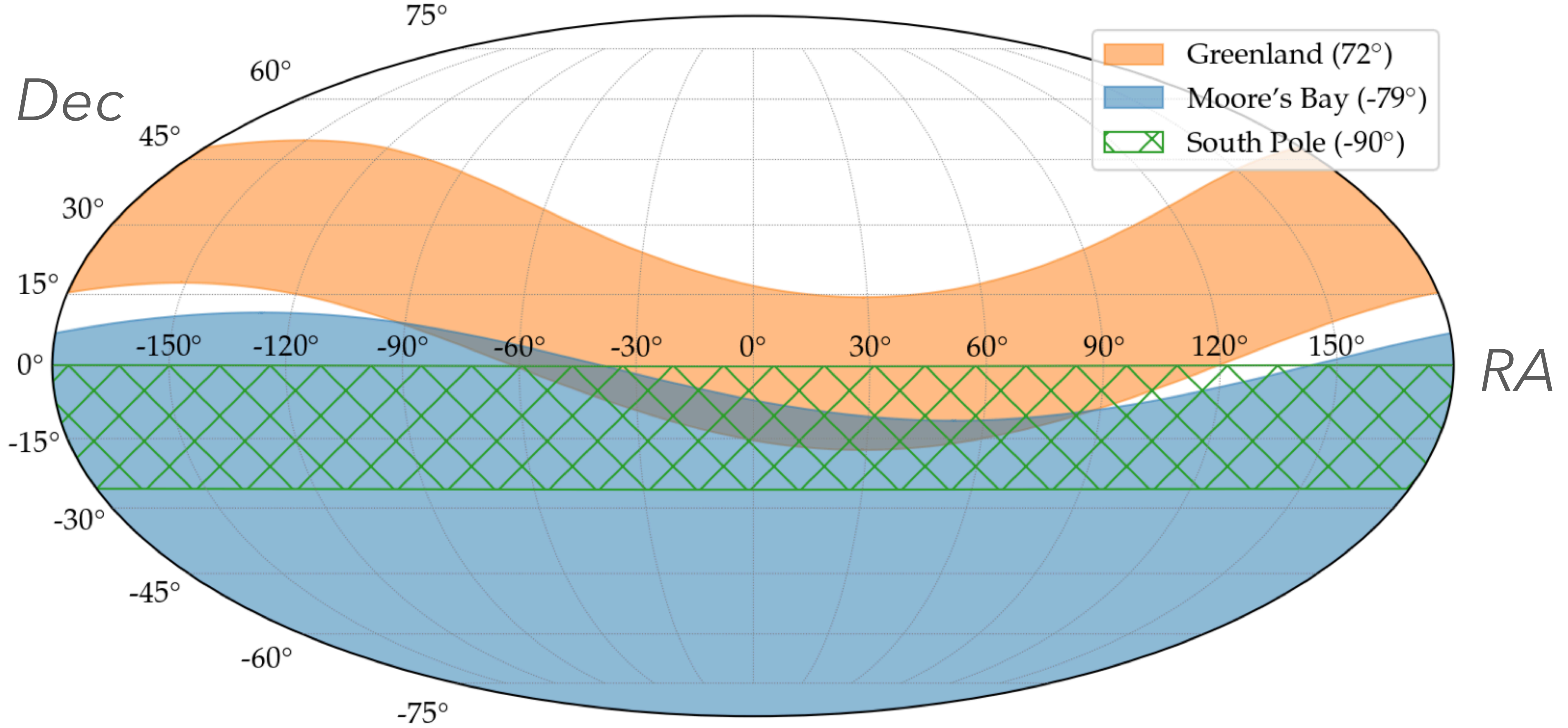


Step 6: Where?

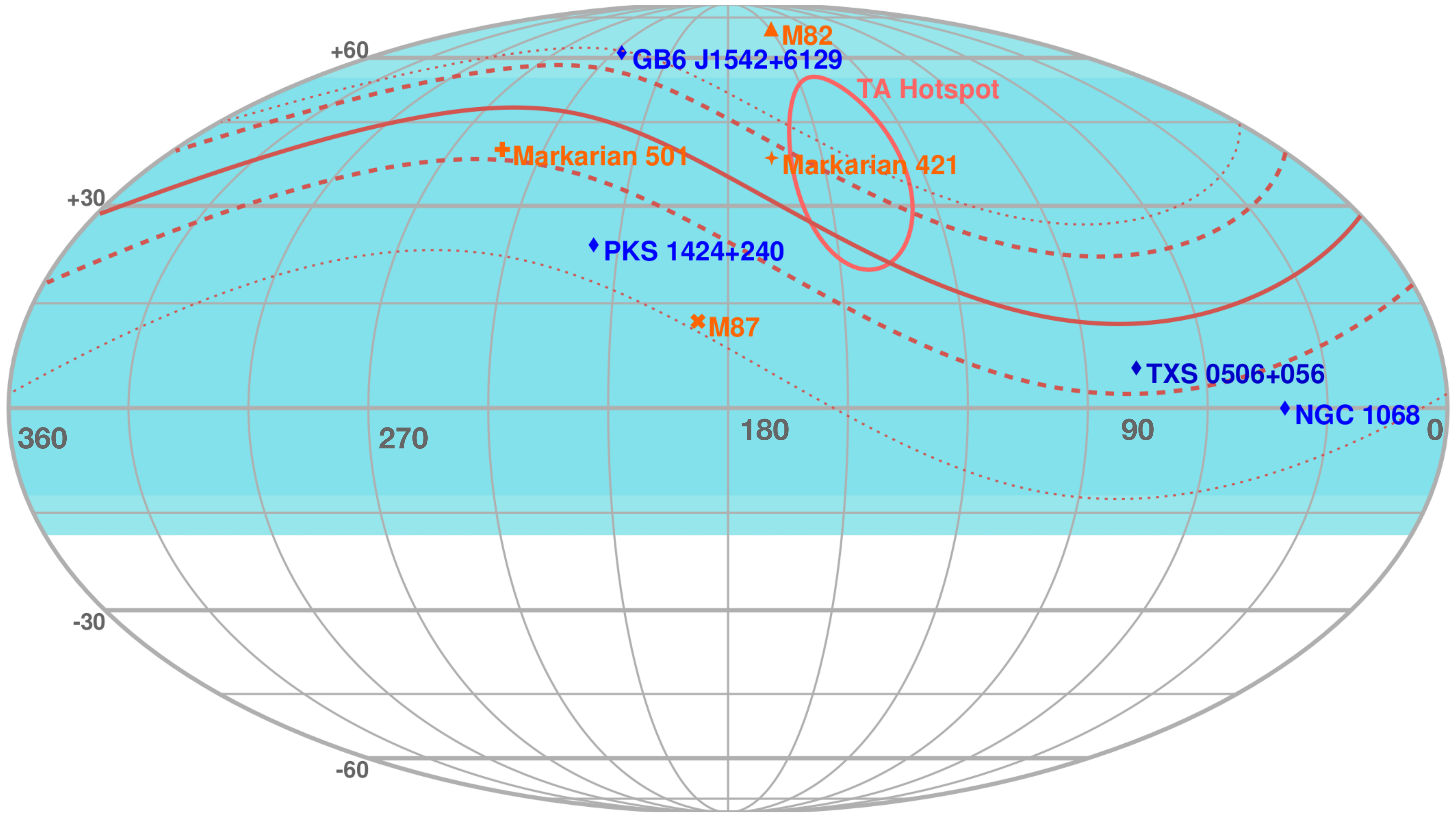
Location, Location, Location

- **South Pole** (ARA, ARIANNA-200, Gen2): Identical view of UHE neutrino sky as IceCube, deep glacial ice yields the longest attenuation lengths → largest effective volume/station
- **Moore's Bay** (ARIANNA): Lower polar latitude + reflections off bottom surface of ice shelf yield broadest sky coverage
- **Summit Station** (RNO-G): Lower polar latitude in the North → broader sky coverage that overlaps with IceCube's hotspots at lower energies

Radio Detector Instantaneous Sky Coverage



RNO-G Sky Coverage



Three Experiments With Different Designs

Surface design, Deep design, Hybrid Design

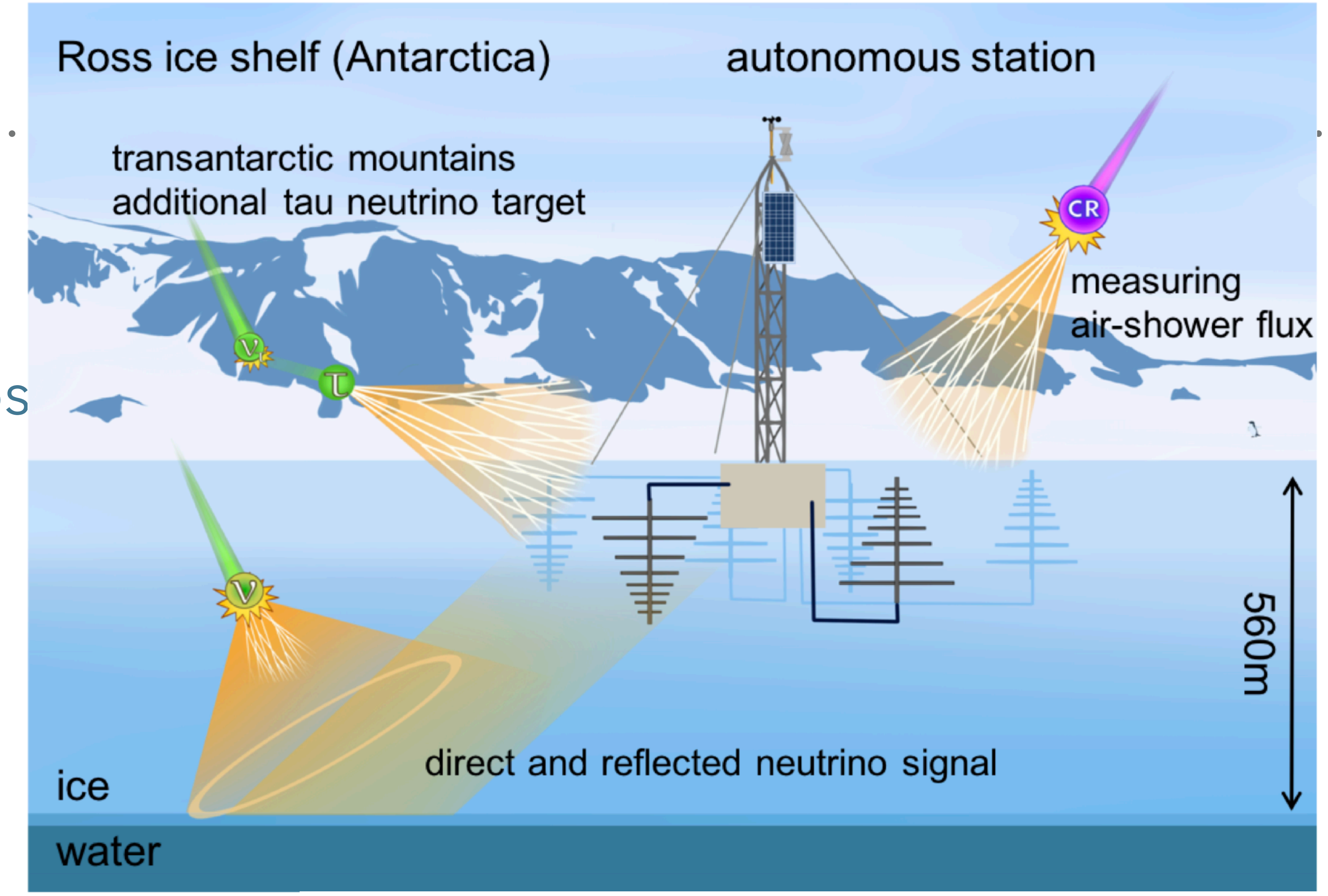
ARIANNA ARA RNO-G

SURFACE ARRAY: ARIANNA

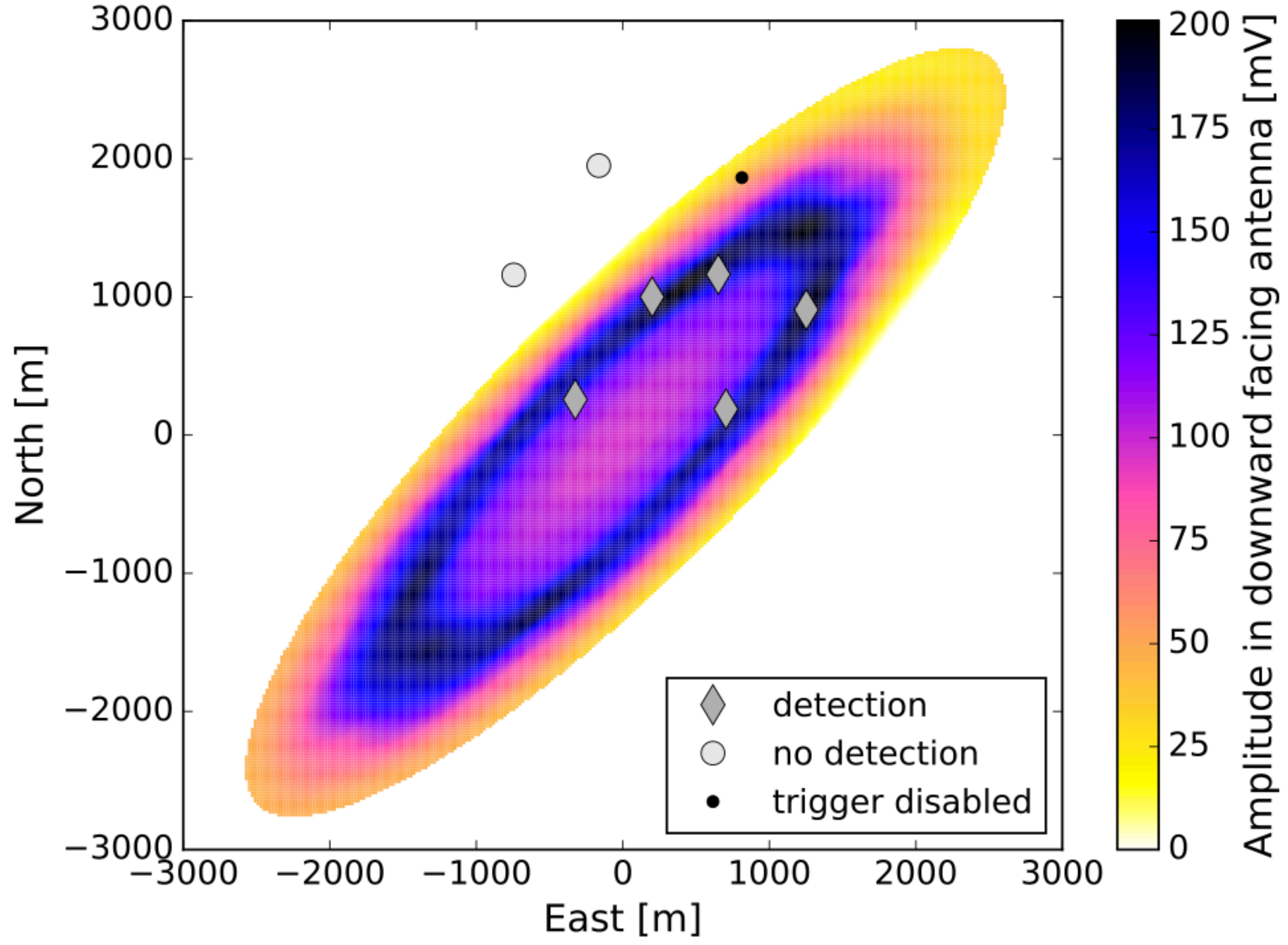
arXiv:1909.00840

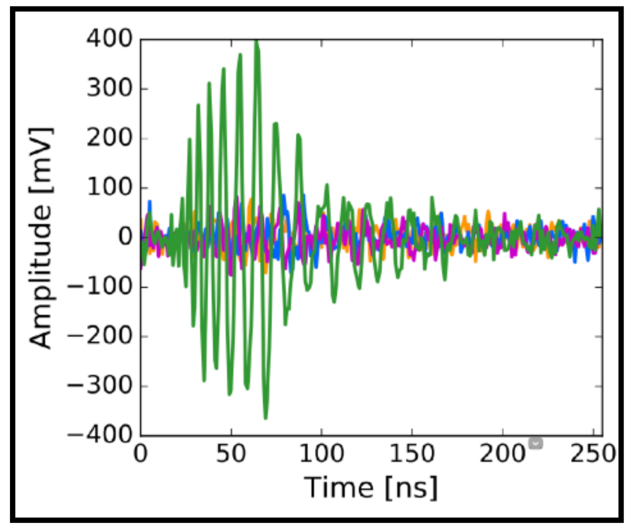
arXiv:1612.04473

- ➤ Reflections off the bottom surface of the ice shelf enhance the signal
- ➤ Nearby mountains provide target for tau neutrinos
- ➤ Identical high gain antennas at surface good for pointing & CR veto
- ➤ Fast deployment & autonomous stations with satellite comms.

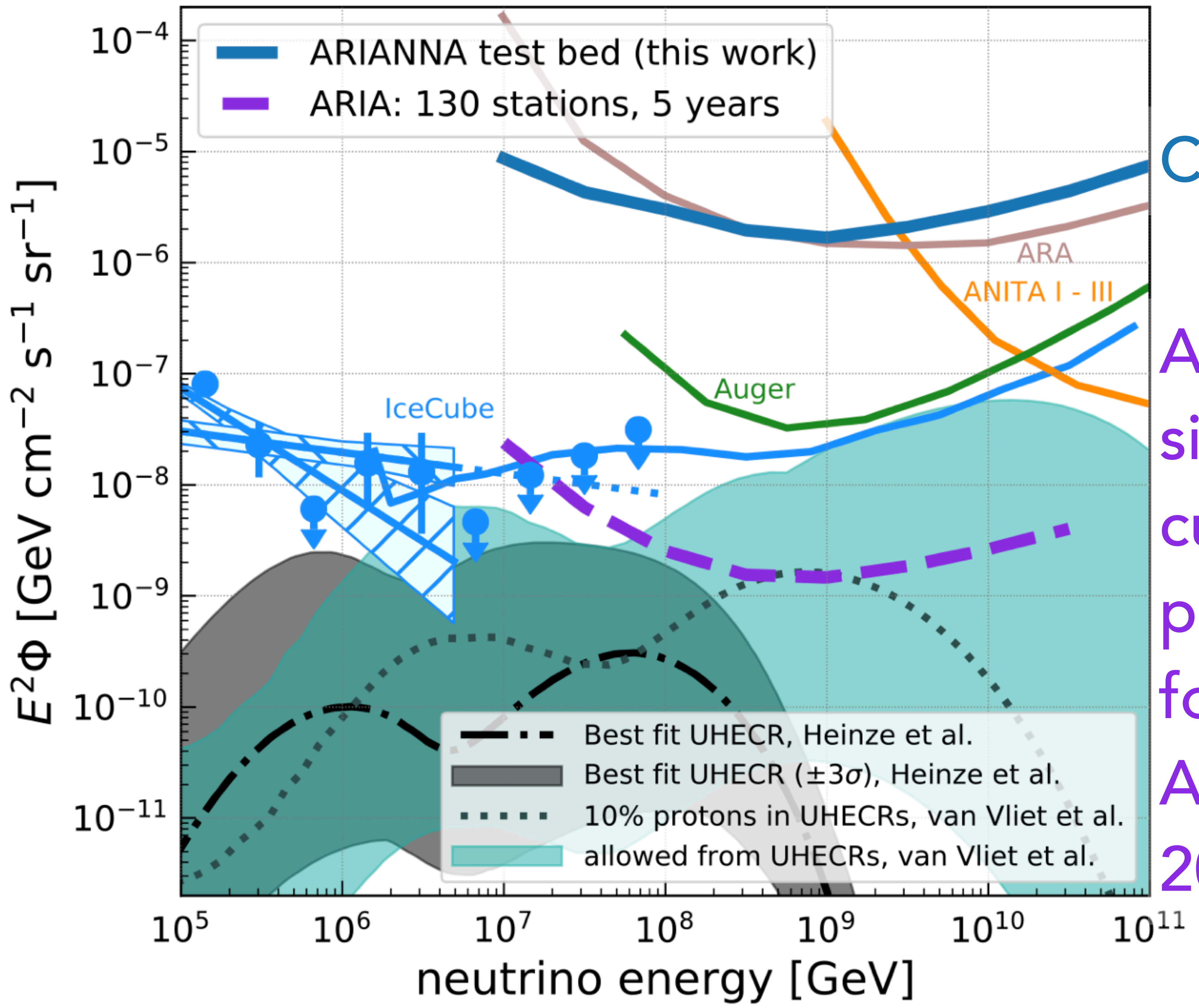


Cosmic Ray Events





Neutrino Search

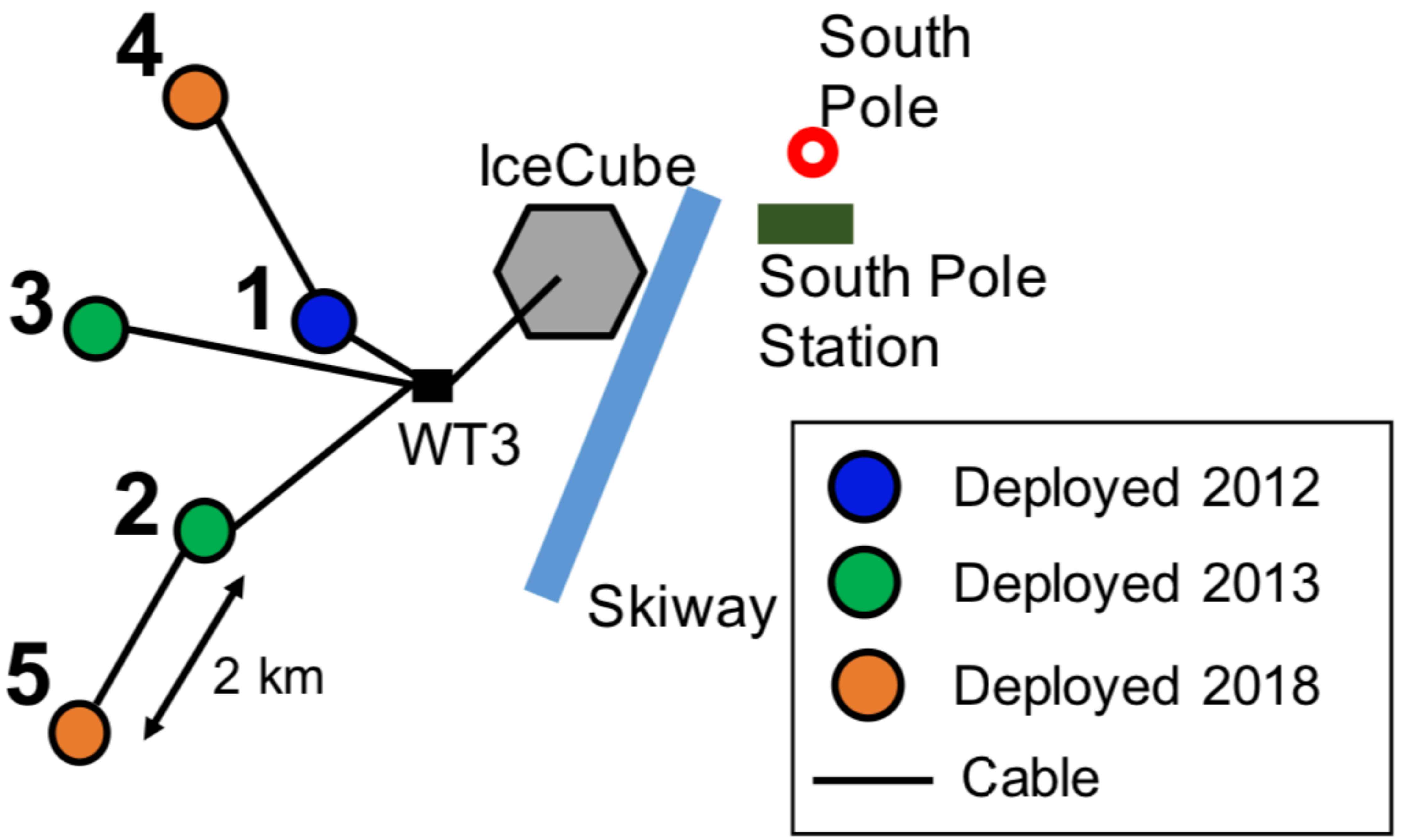


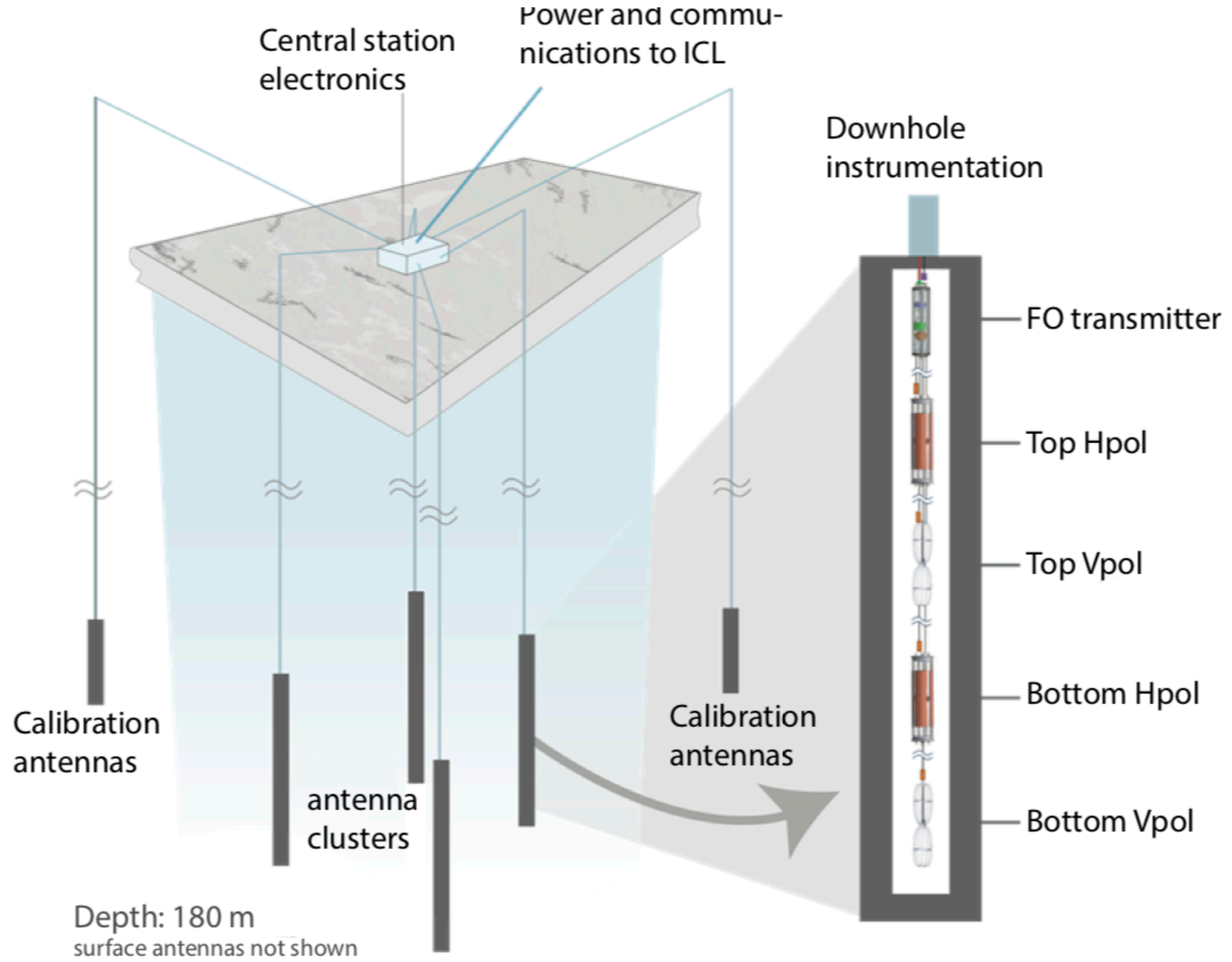
Current UL

ARIA-130 similar to current proposal for ARIANNA-200

DEEP ARRAY: ARA

- Largest effective volume per station just by going deep
- ~10 years of accumulated exposure
- Phased array triggering enables low thresholds
- Year-round observations
- <u>Ongoing studies</u>:
  neutrino searches in 10 year data set & PA, cosmic ray search, point source searches



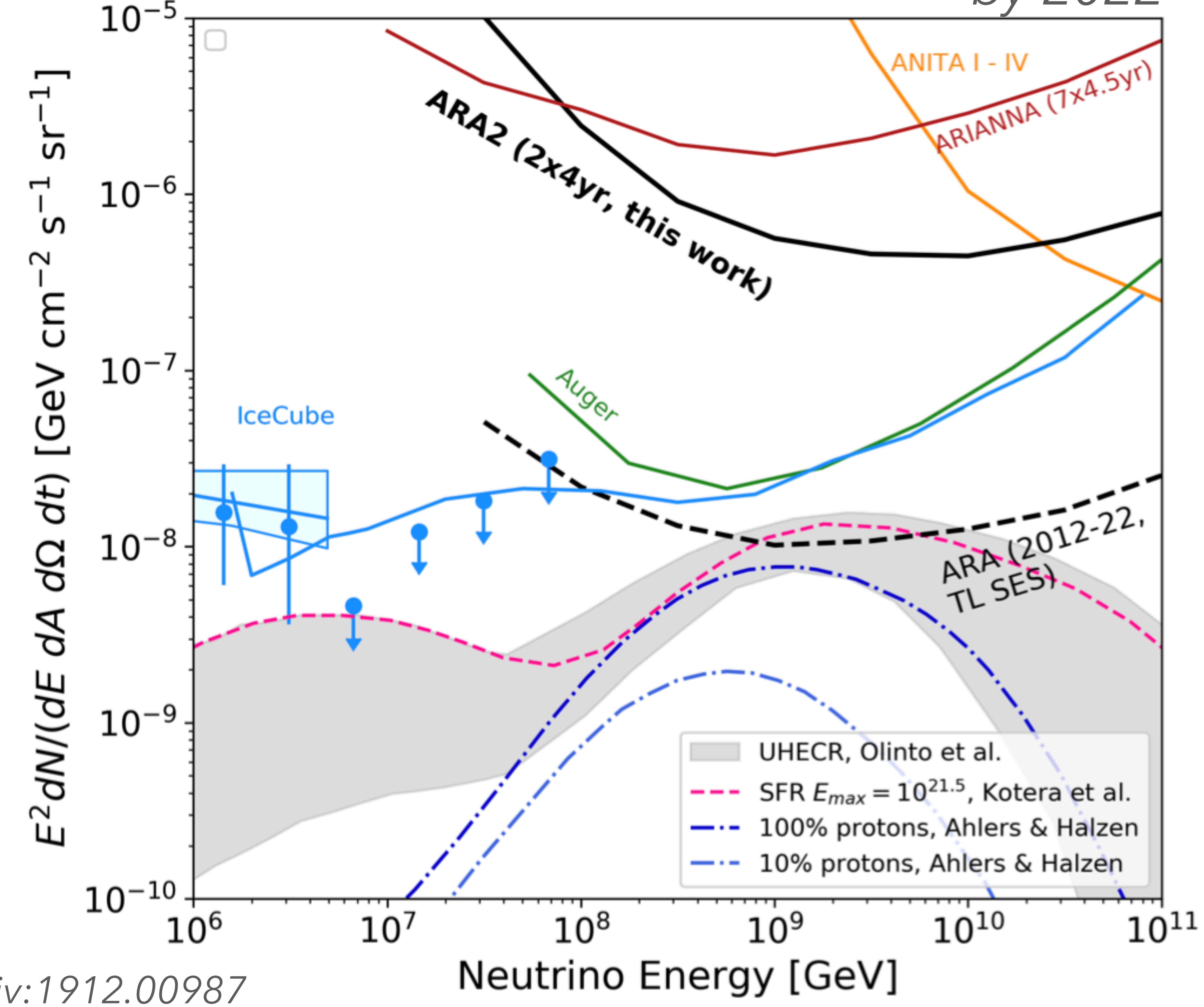


ARA Progress & Prospects

Neutrino Search

Signal-agnostic search in 2 stations, 4 years

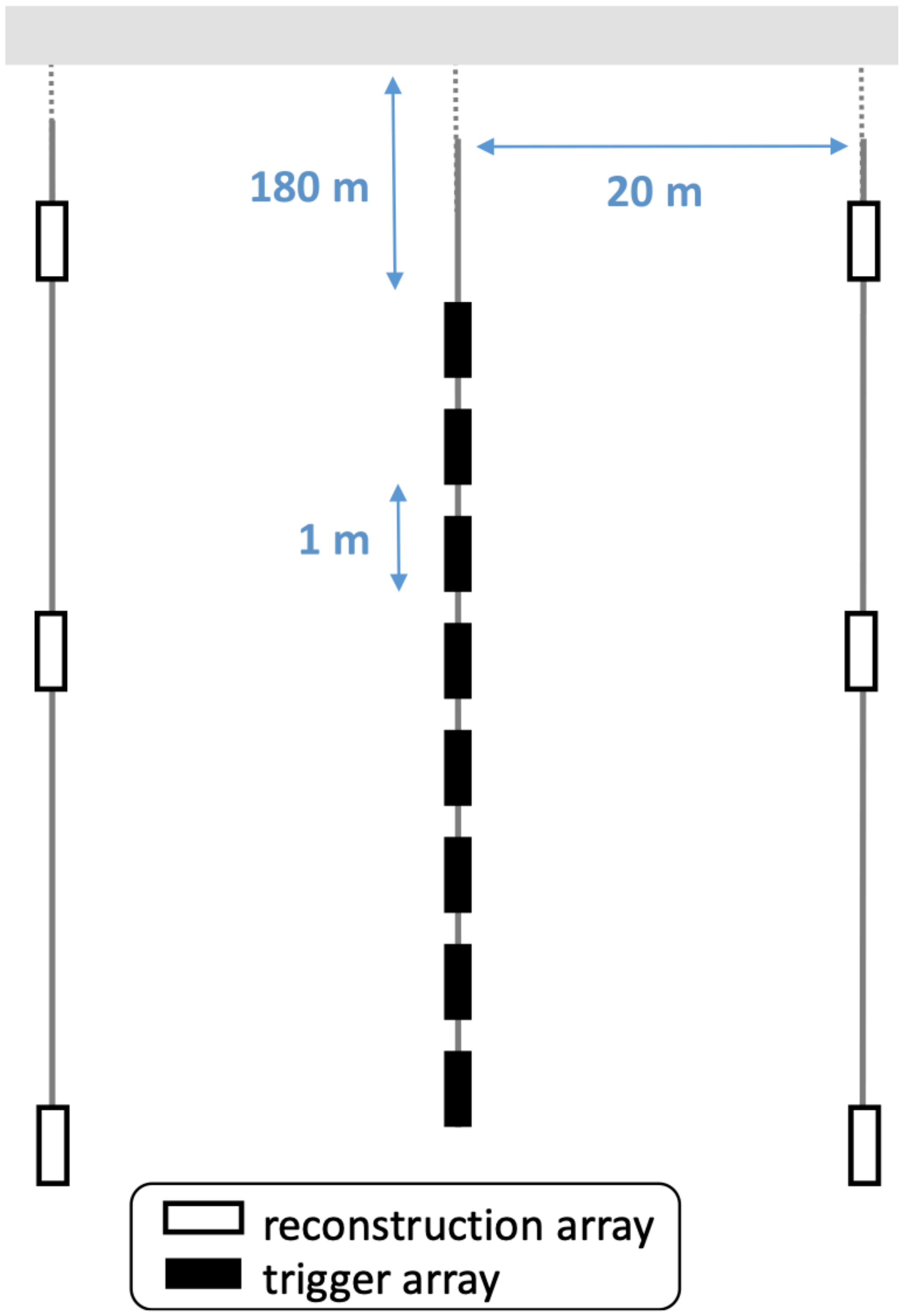
Exposure expected to improve on current limits by 2022



arXiv:1912.00987

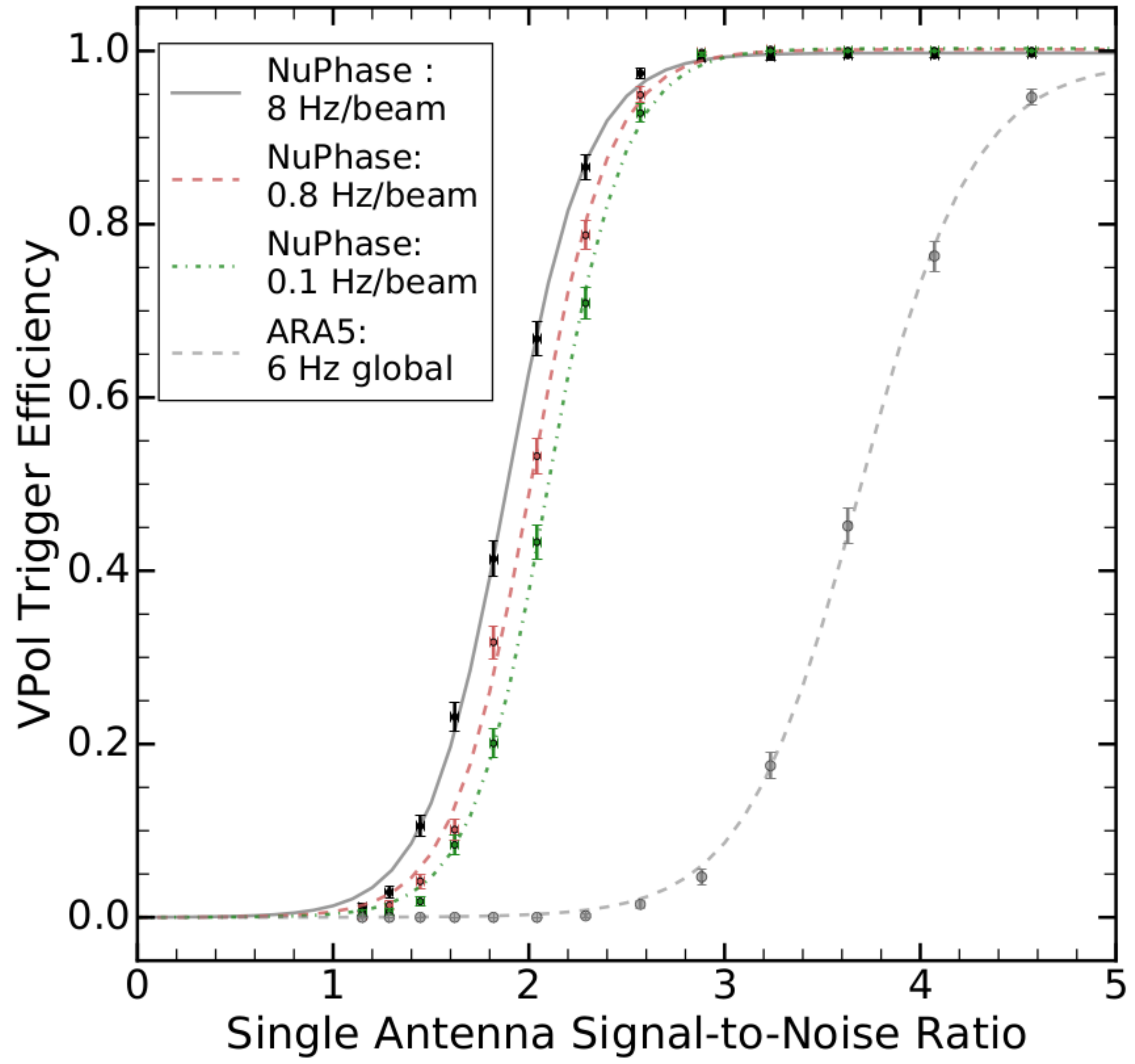
Low Thresholds from Phased Arrays (PA)

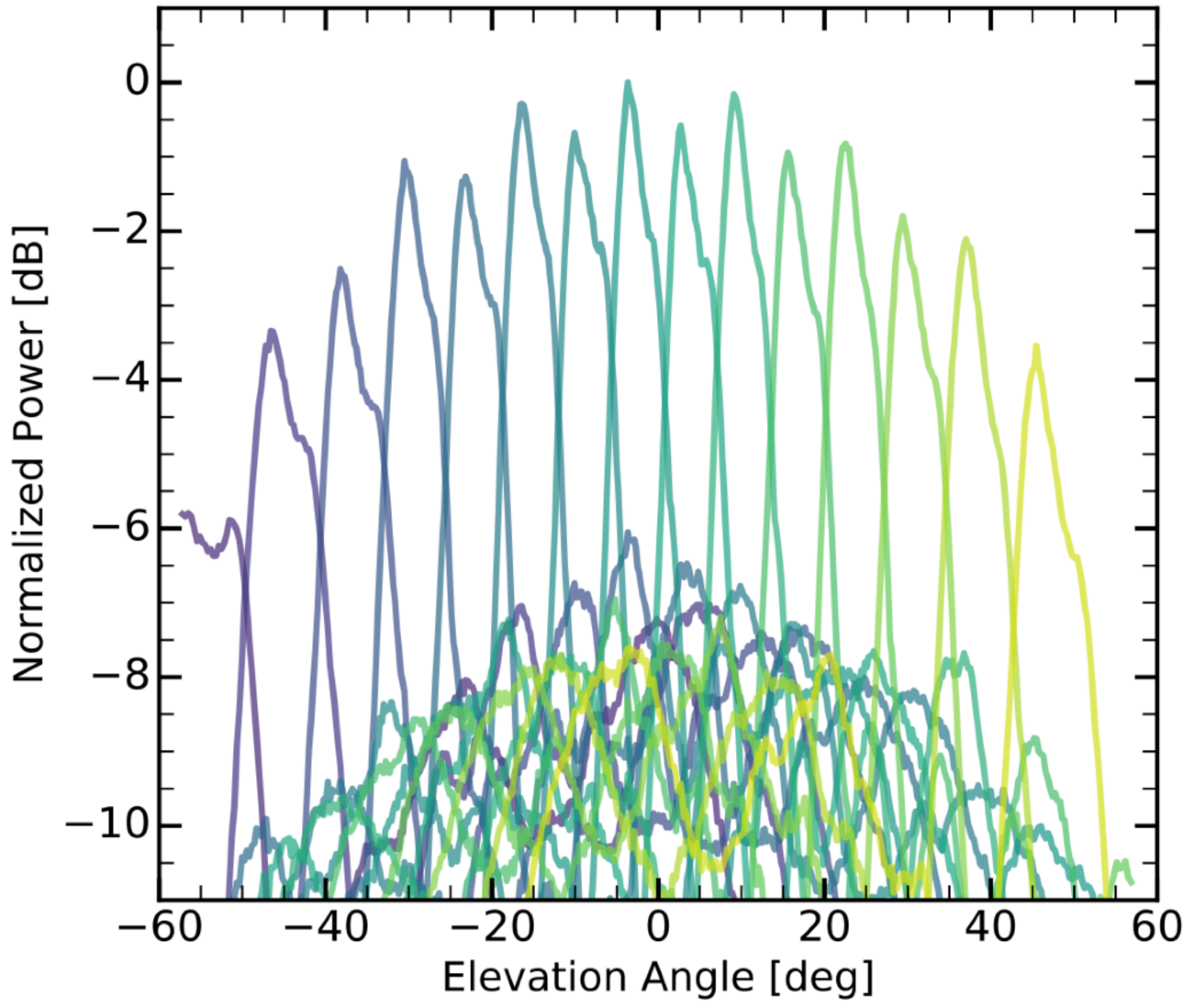
Build *High* Gain antennas from *Low* Gain Ones



SNR ~ $\sqrt{N}$
Multiple beams→ full coverage
Analysis with A5 PA ongoing

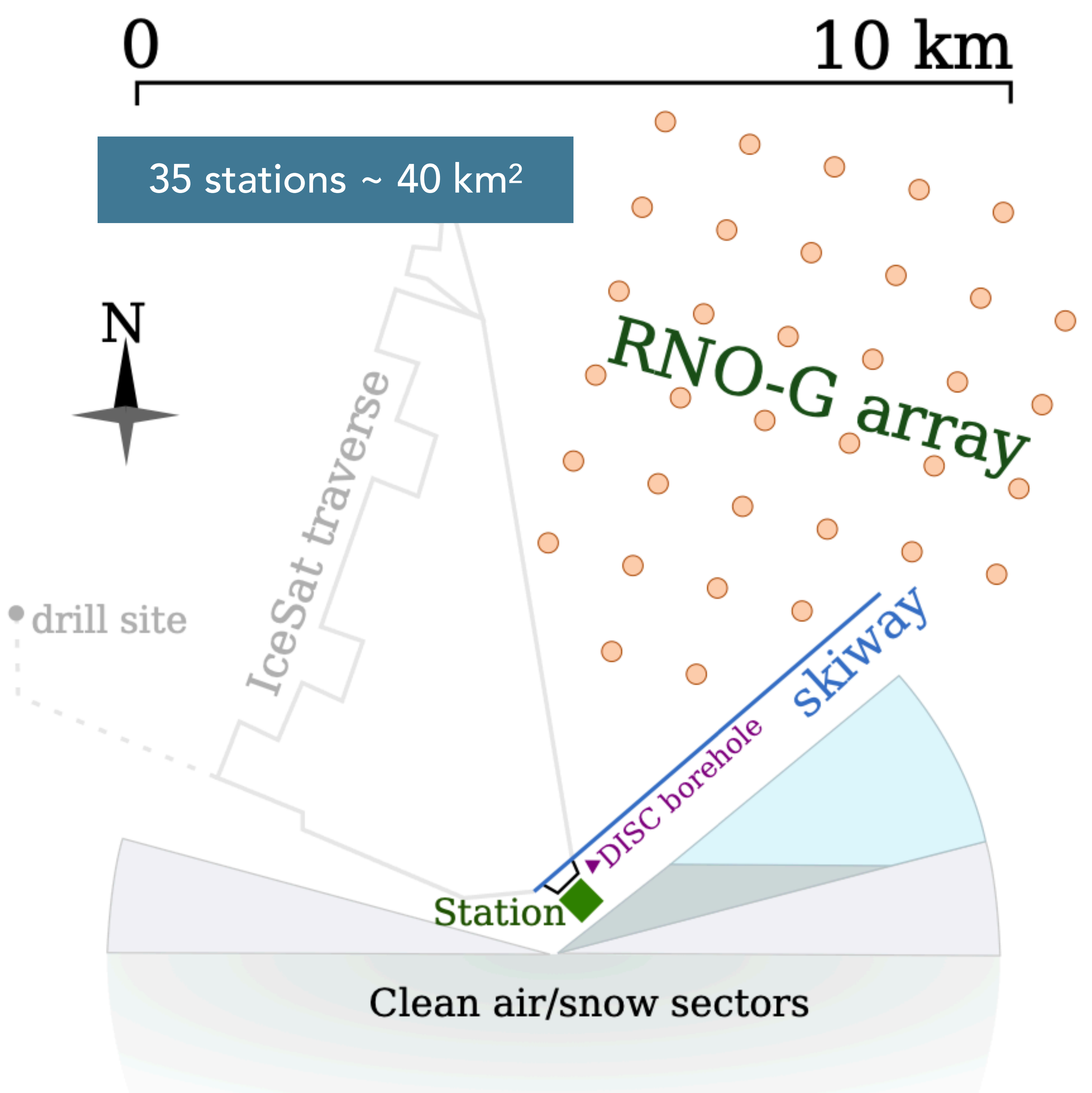
arXiv:1809.04573

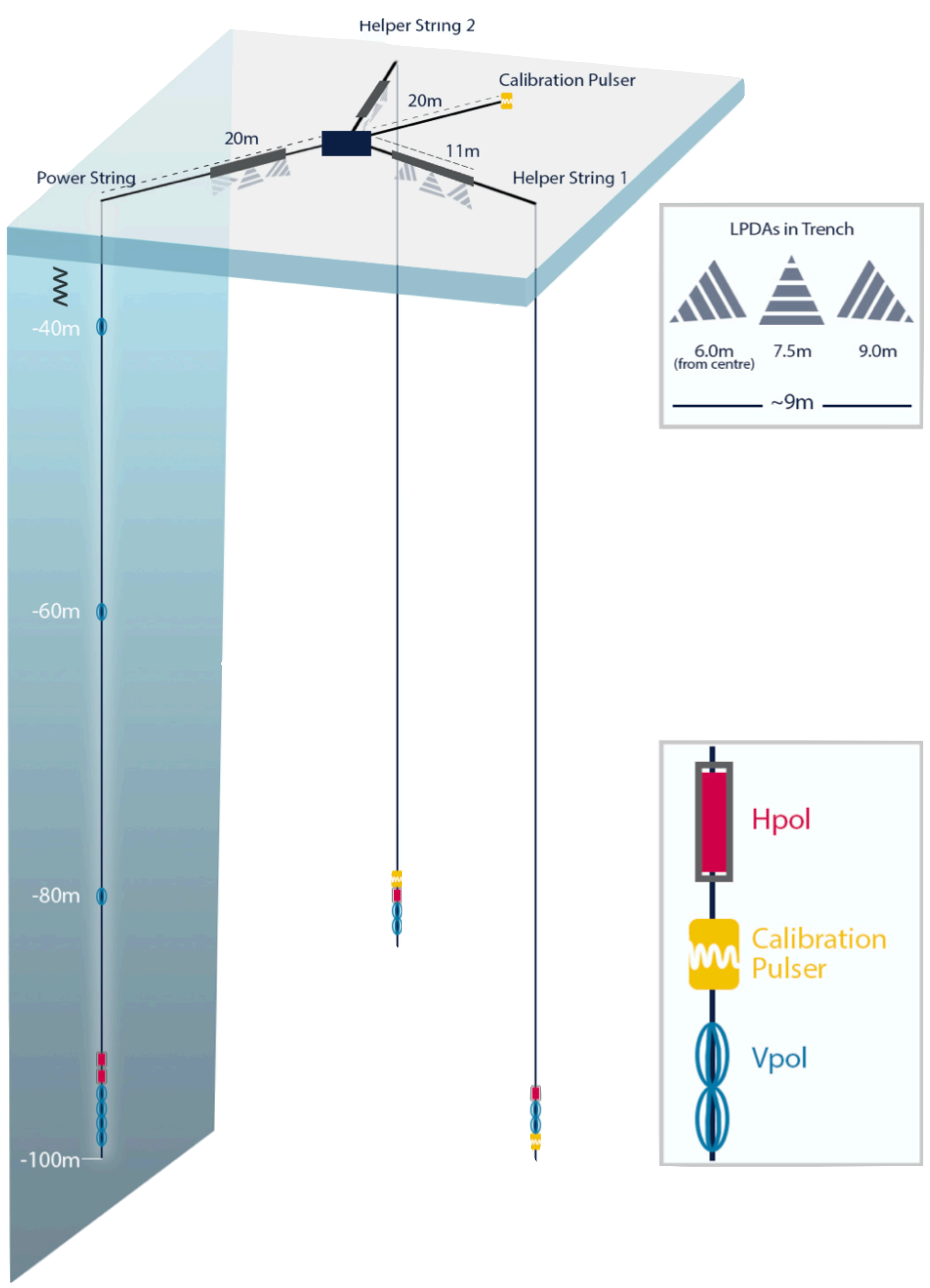




HYBRID DESIGN: RNO-G

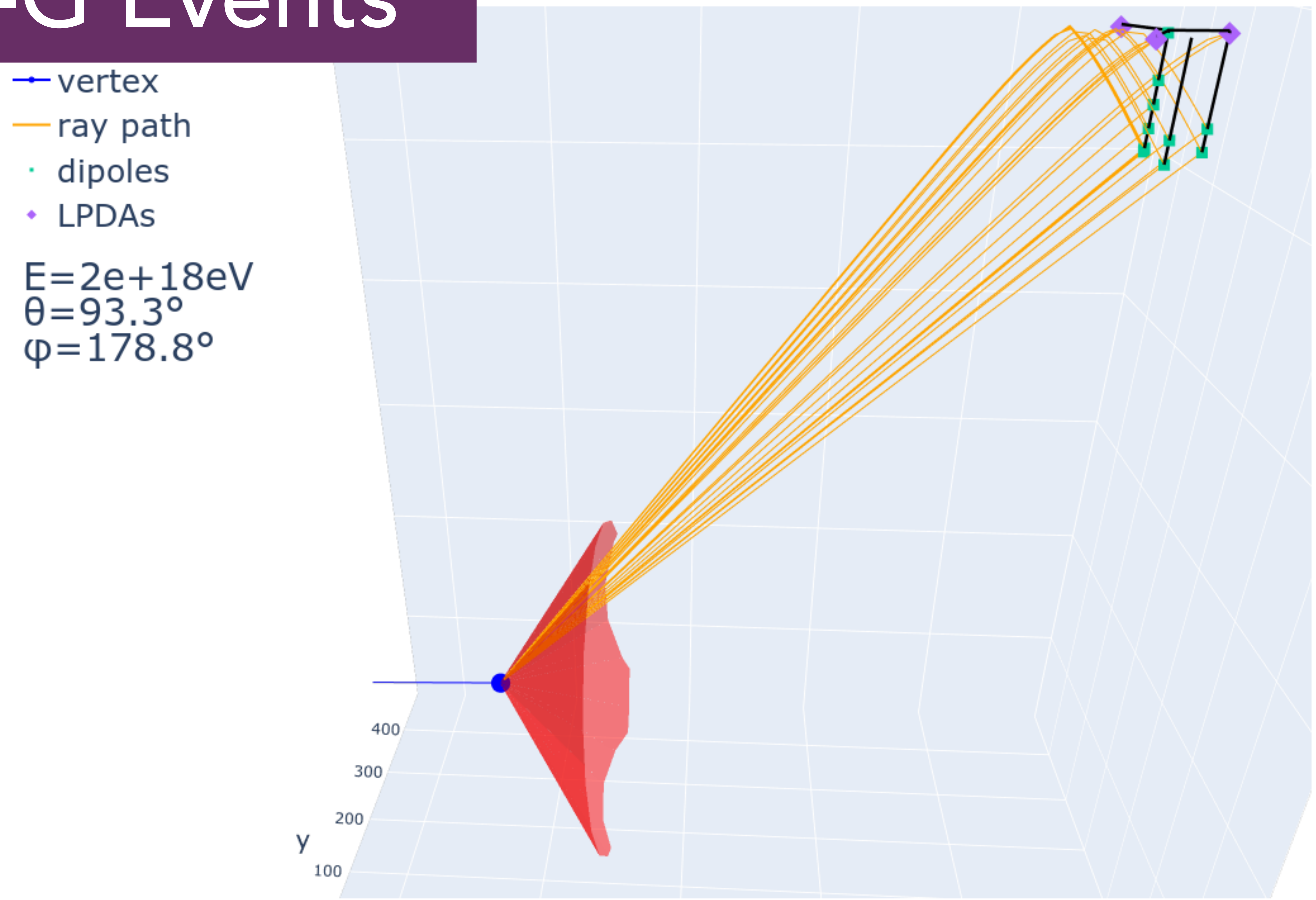
- ➤ Largest footprint
- ➤ Deep phased array trigger
- ➤ Surface antennas for improved pointing,
  CR veto, independent trigger
- ➤ 24/7 comms: LTE + satellite
- ➤ Low power design for scalability – targeting 10% demonstrator for Gen2-radio
- ➤ Testing out deployment strategies & new drilling options

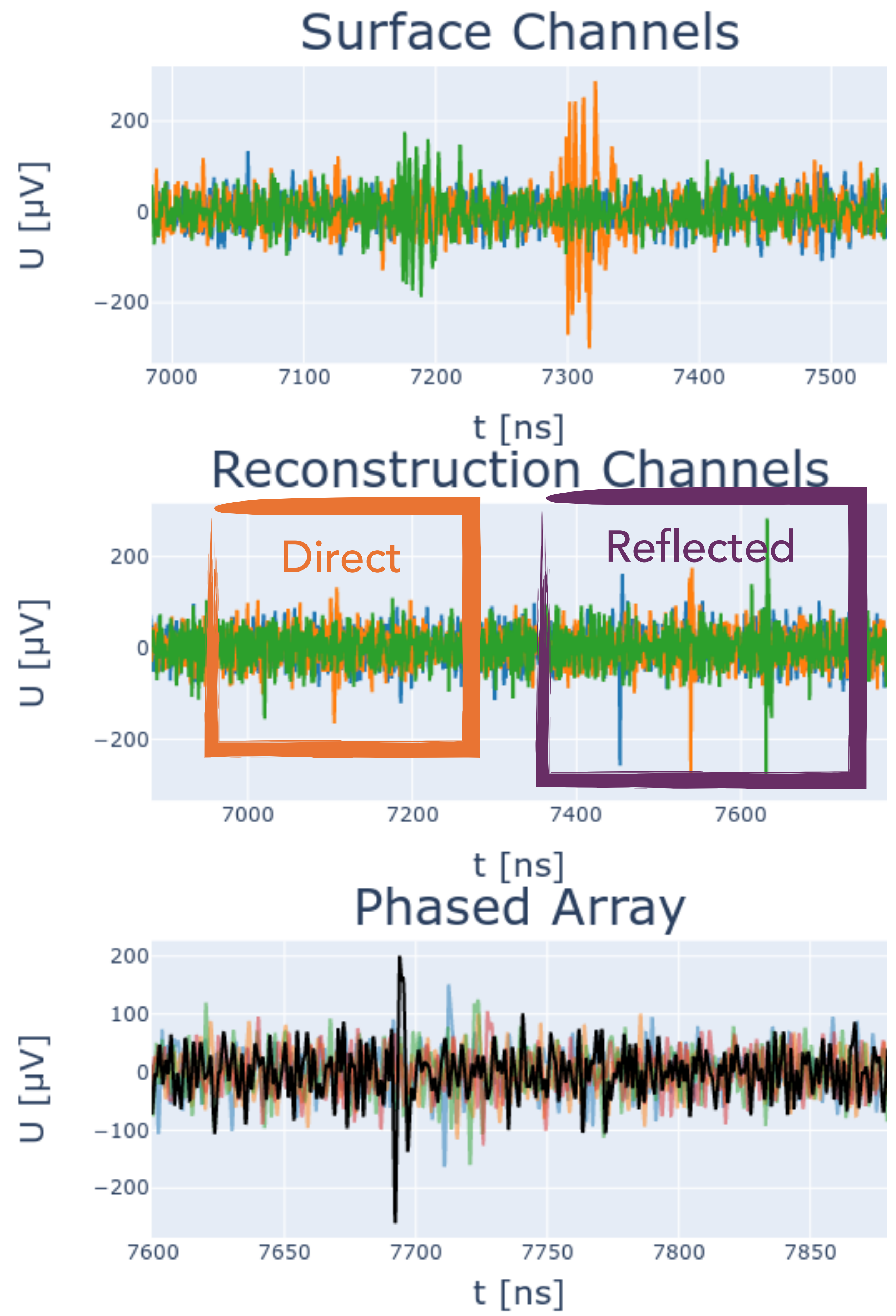




Current (COVID-friendly) deployment plan:
up to 10 stations 2021, 25 stations 2022-2023

RNO-G Events



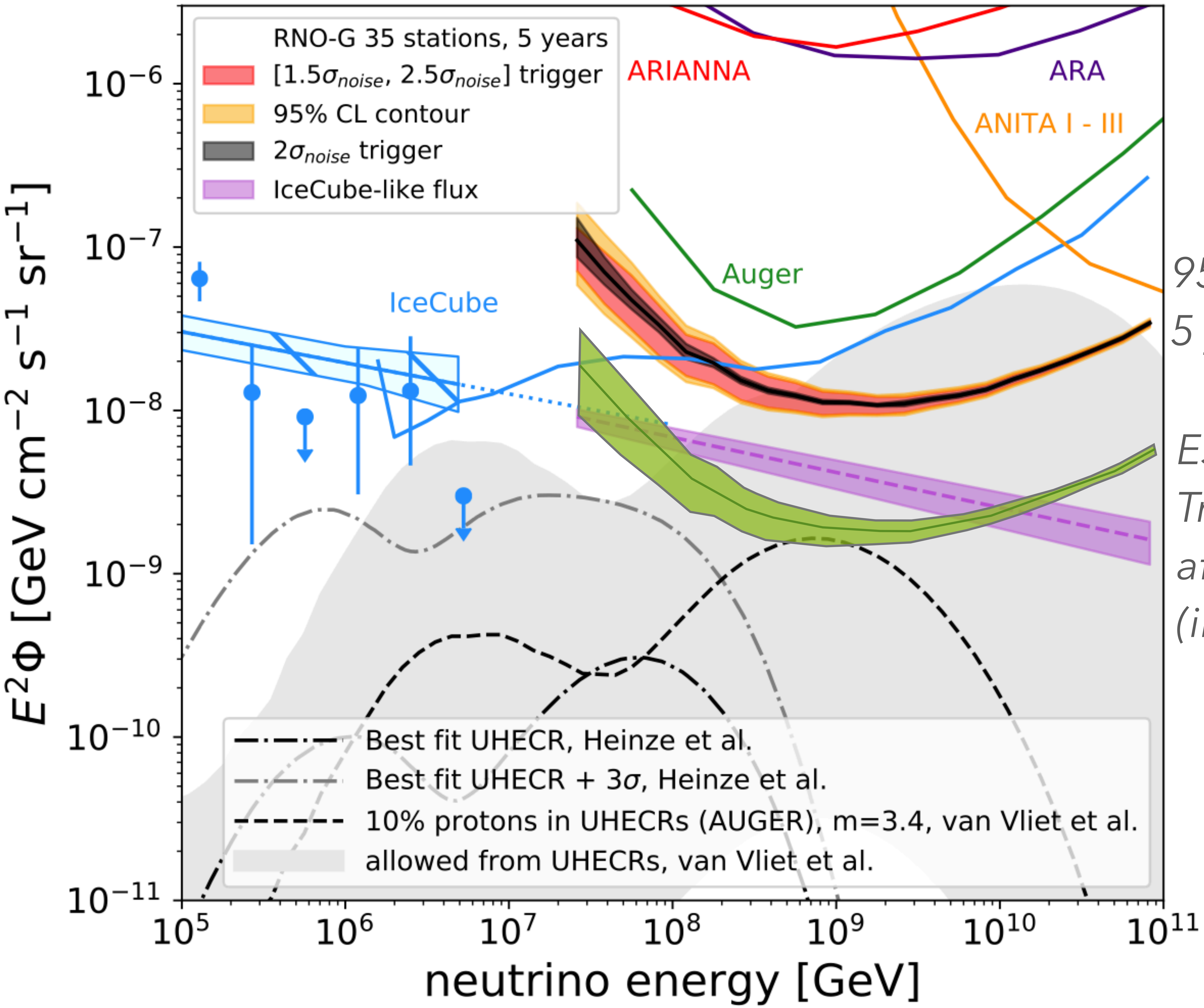


➤ **Two Types** of **Golden Events for Reconstruction:** (~20% each of the events at 10^{18} eV)

1. **Direct** *and* **reflected** signals on the downhole antennas
2. **Surface-Deep Coincident** Events

This event has both.

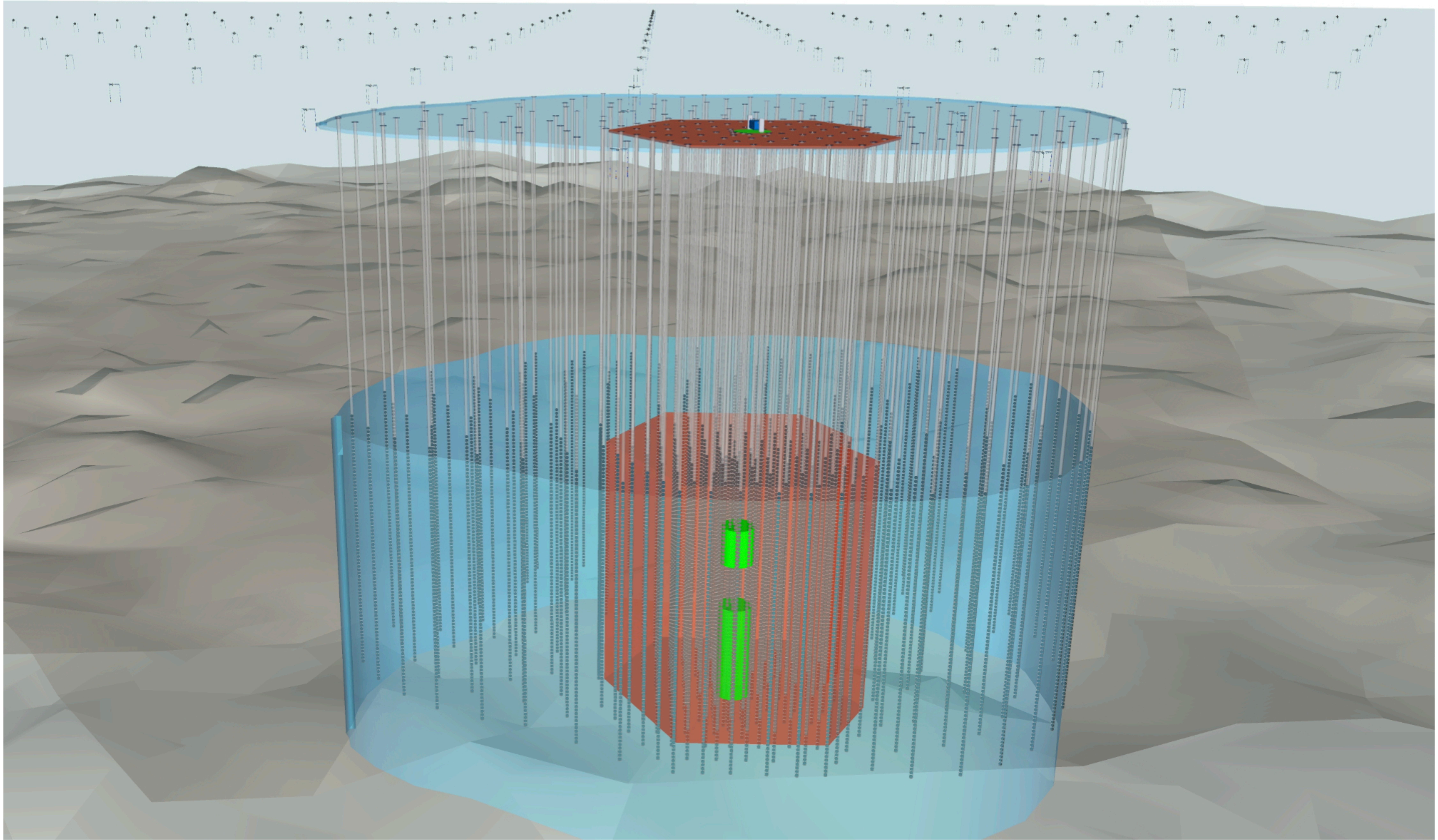
RNO-G Expected Sensitivity



95% CL Upper limit 5 years

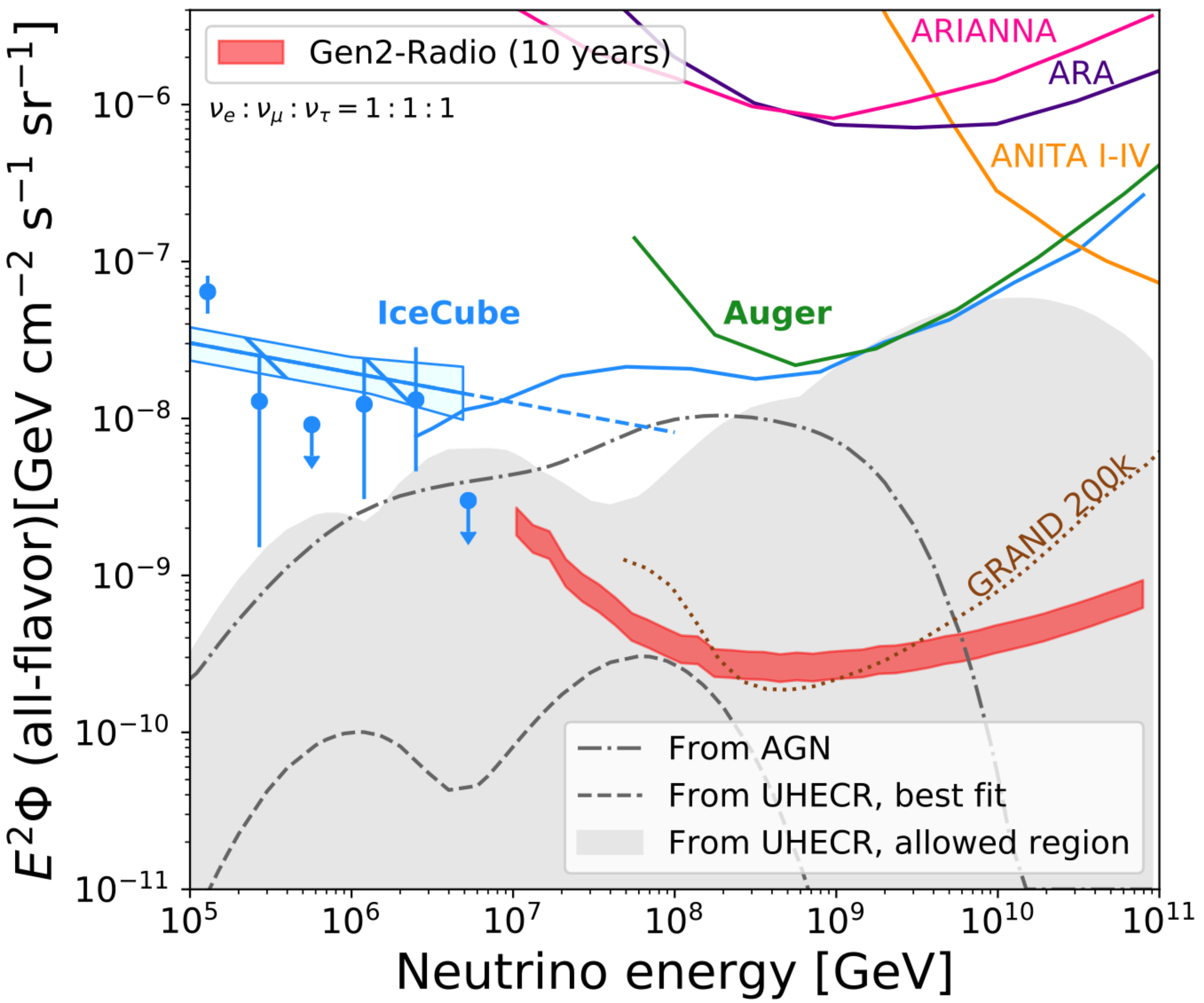
Estimate of Trigger level sensitivity after 10 years (including 70% lifetime)

ICECUBE-GEN2

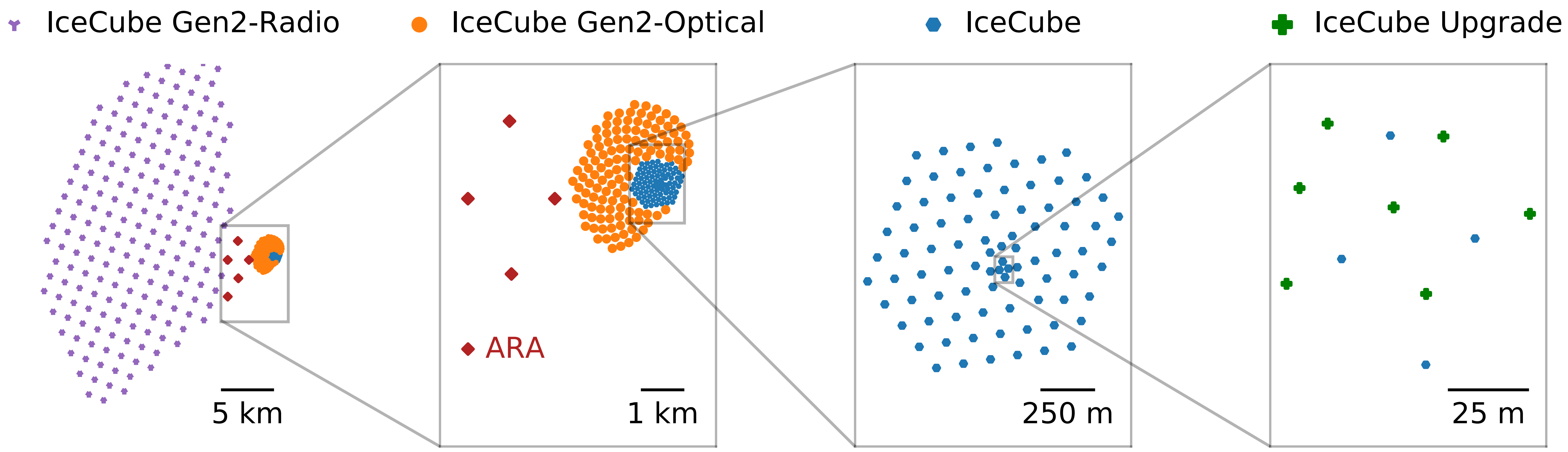


IceCube-Gen2 Radio

- **Goals**: expand Gen2 energy range and improve sensitivity in EeV range with sparse radio array
- Building on advancements through ARIANNA, ARA
  - R&D with RNO-G, proposed ARIANNA-200
- Working Group & Task Force developing the design *now*



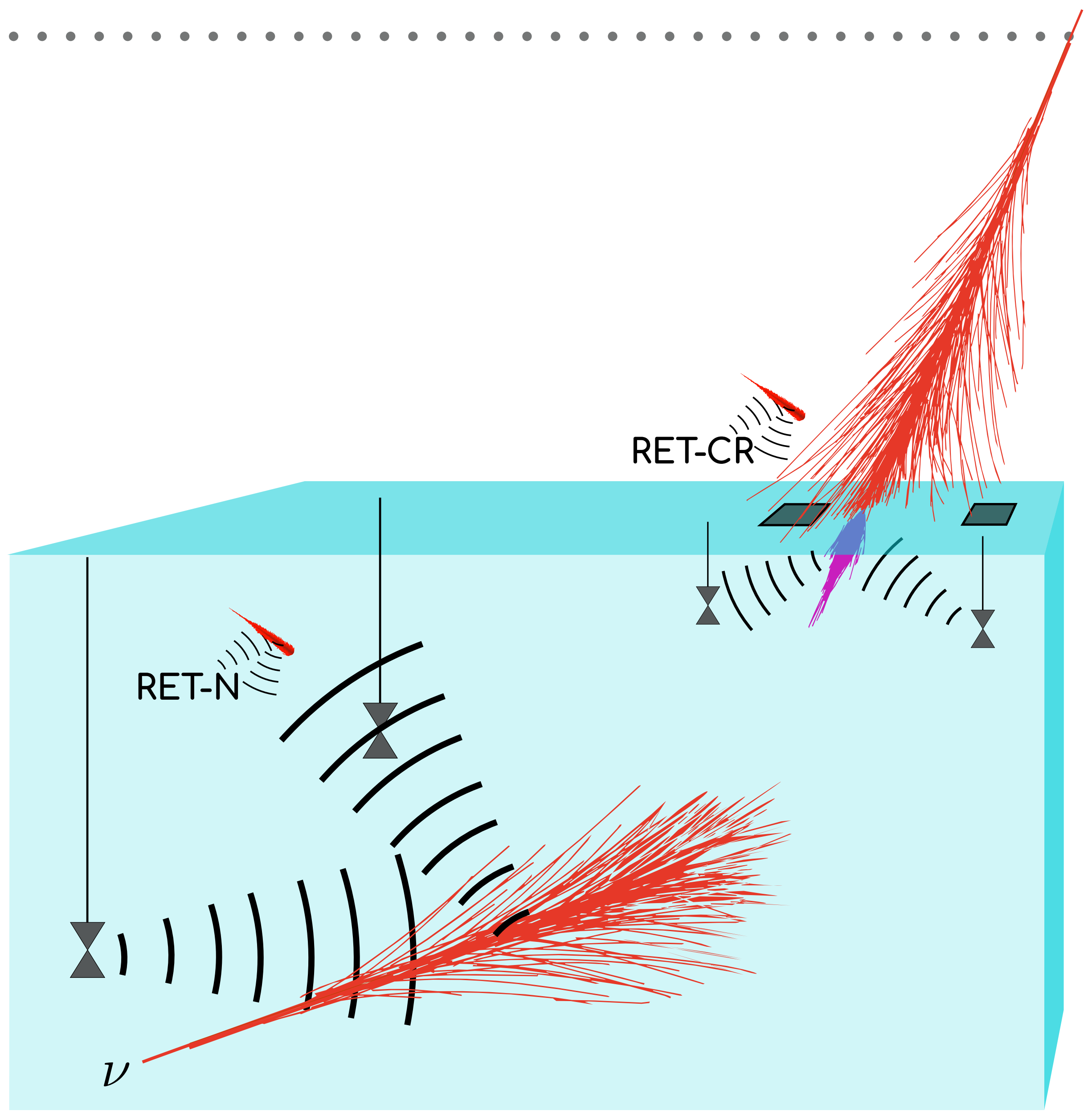
Cover 200 km^2 sr

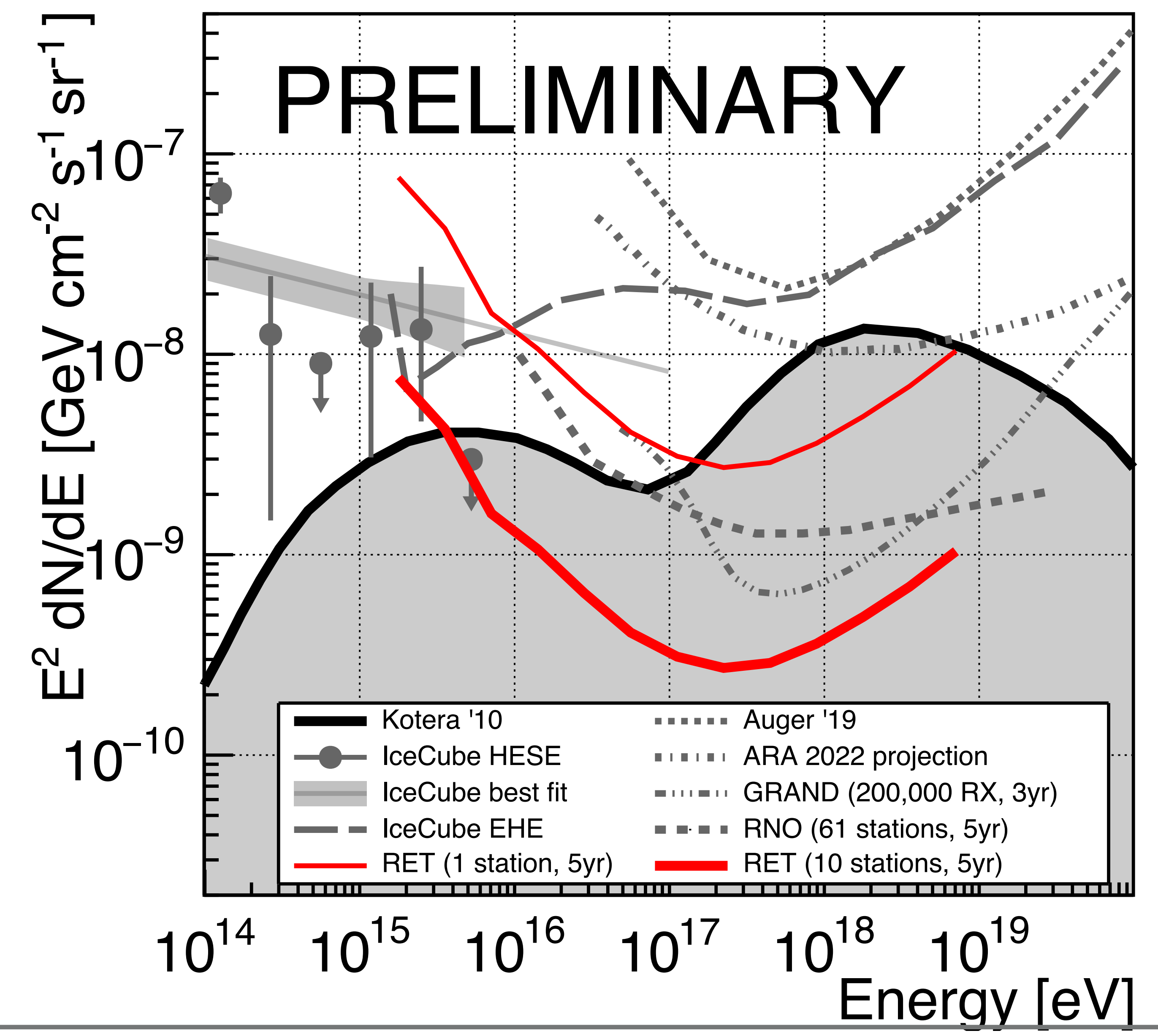


Radar Echo Telescope

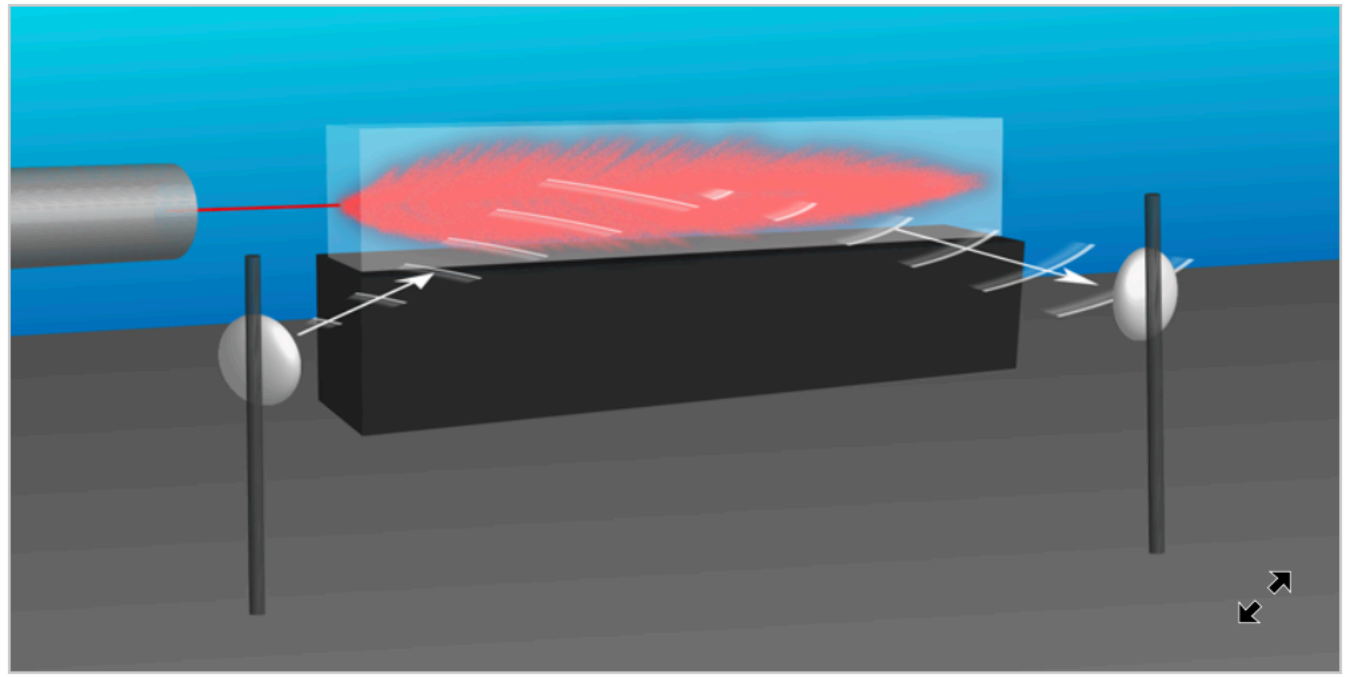
1910.12830

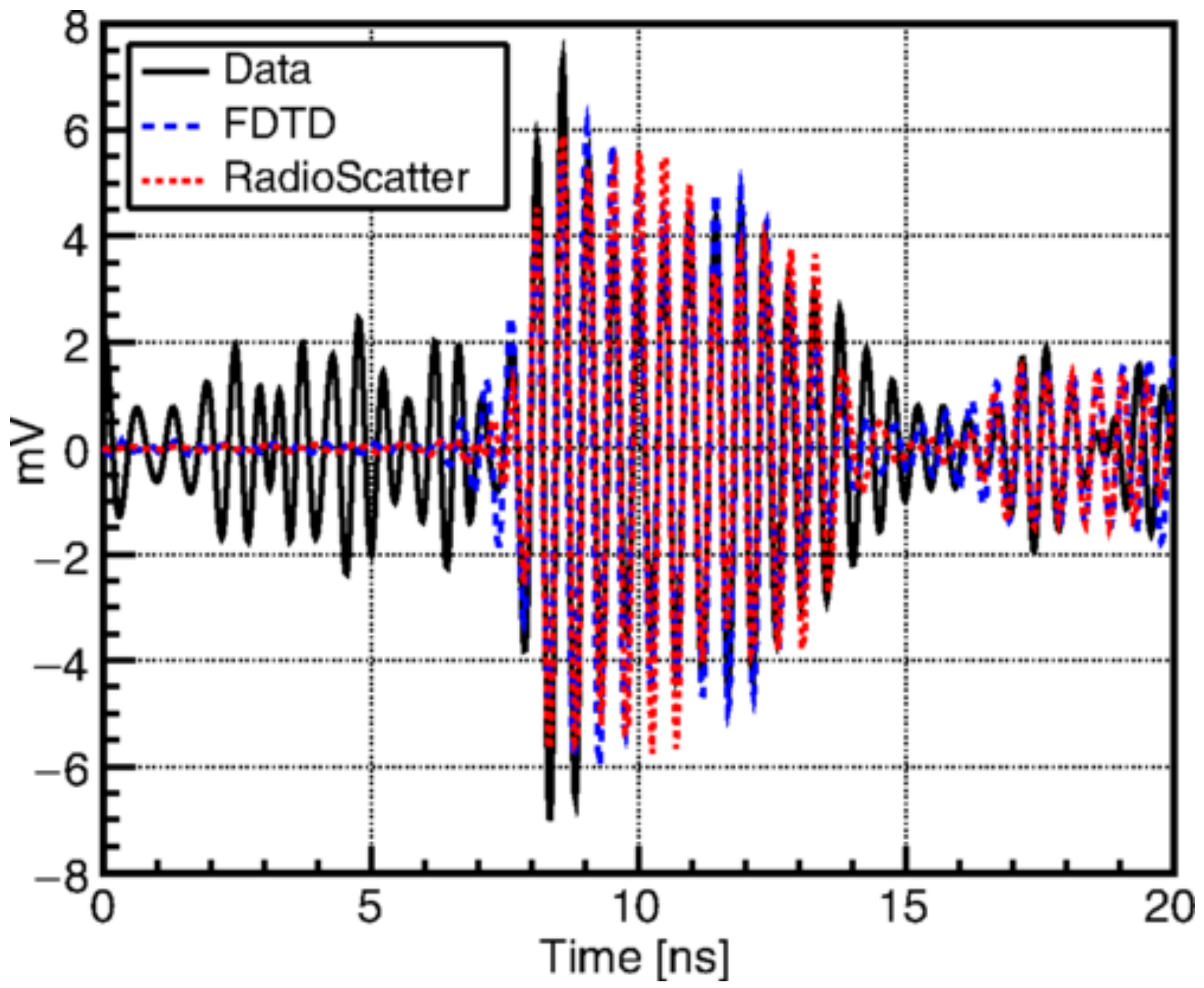
- Targeting PeV to EeV energy scale with radar bounce off in-ice showers
- Prototype expected to demonstrate with in-ice CR showers in Antarctica

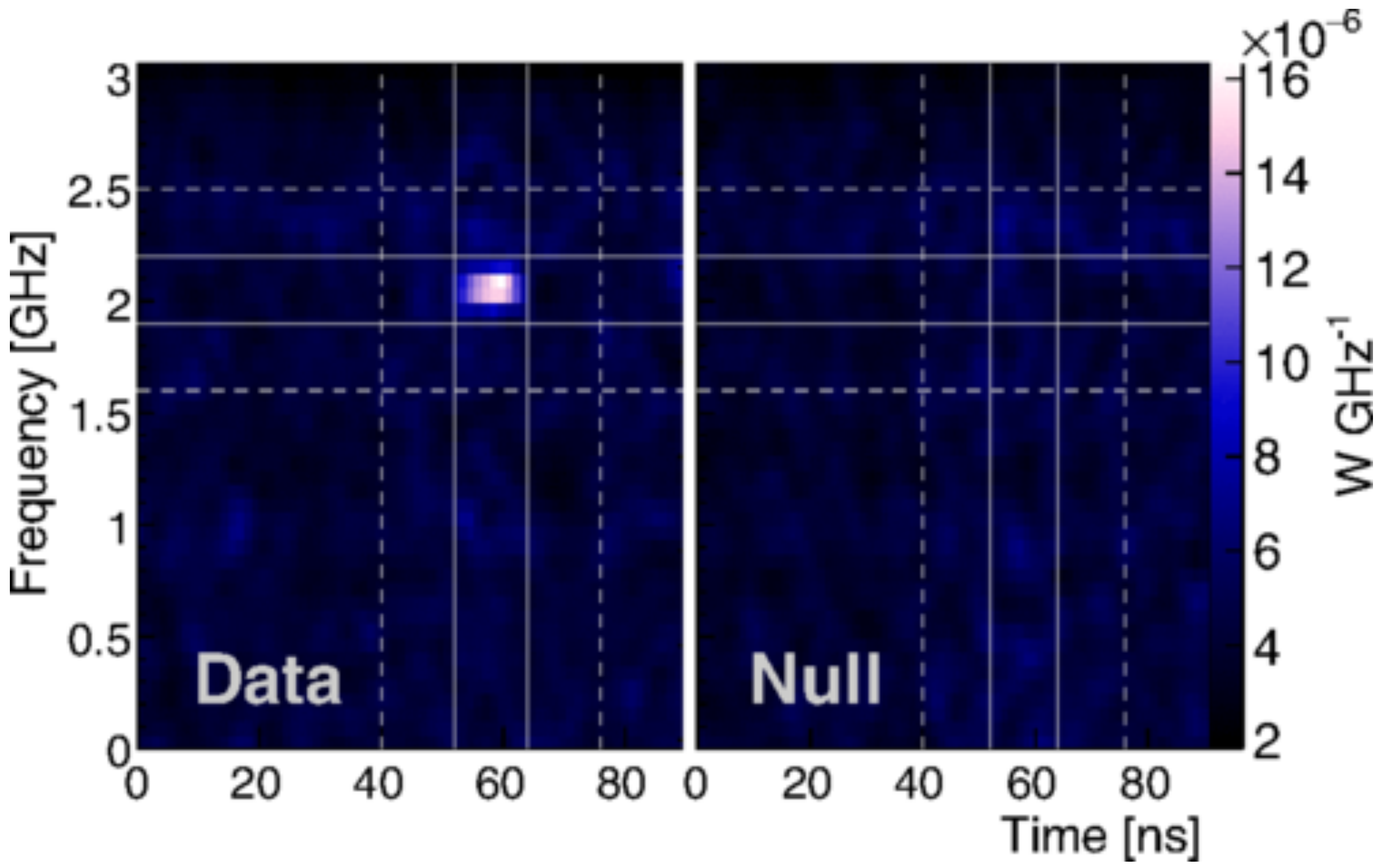




- T576 lab experiments confirm radar bounce off particle showers in dense dielectric HPDE







SUMMARY AND OUTLOOK

- **Take Home Message:**
  - Radio ice detectors have matured
  - Need to scale up, both to develop the hardware and to search for the first UHE neutrinos
- **Targeted physics in next decades:**
  - Expect current instruments to constrain the proton fraction of cosmogenics and strong astrophysical models within ~5 years and improve on this through a scaled approach over the next decades
- **What do we need to accomplish?**
  - **Observations:**
    - Observe a **UHE Neutrino**!! (Unclear *when* nature will permit…)
    - Improve analysis techniques to quickly reconstruct events at high precision, reject backgrounds, point source and transient searches
  - **R&D for Gen2:** Outline planned design, demonstrate scalable hardware & analysis tools, connect to real-time multi-messenger astrophysics systems