



April 23, 2025



PennState
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Outline

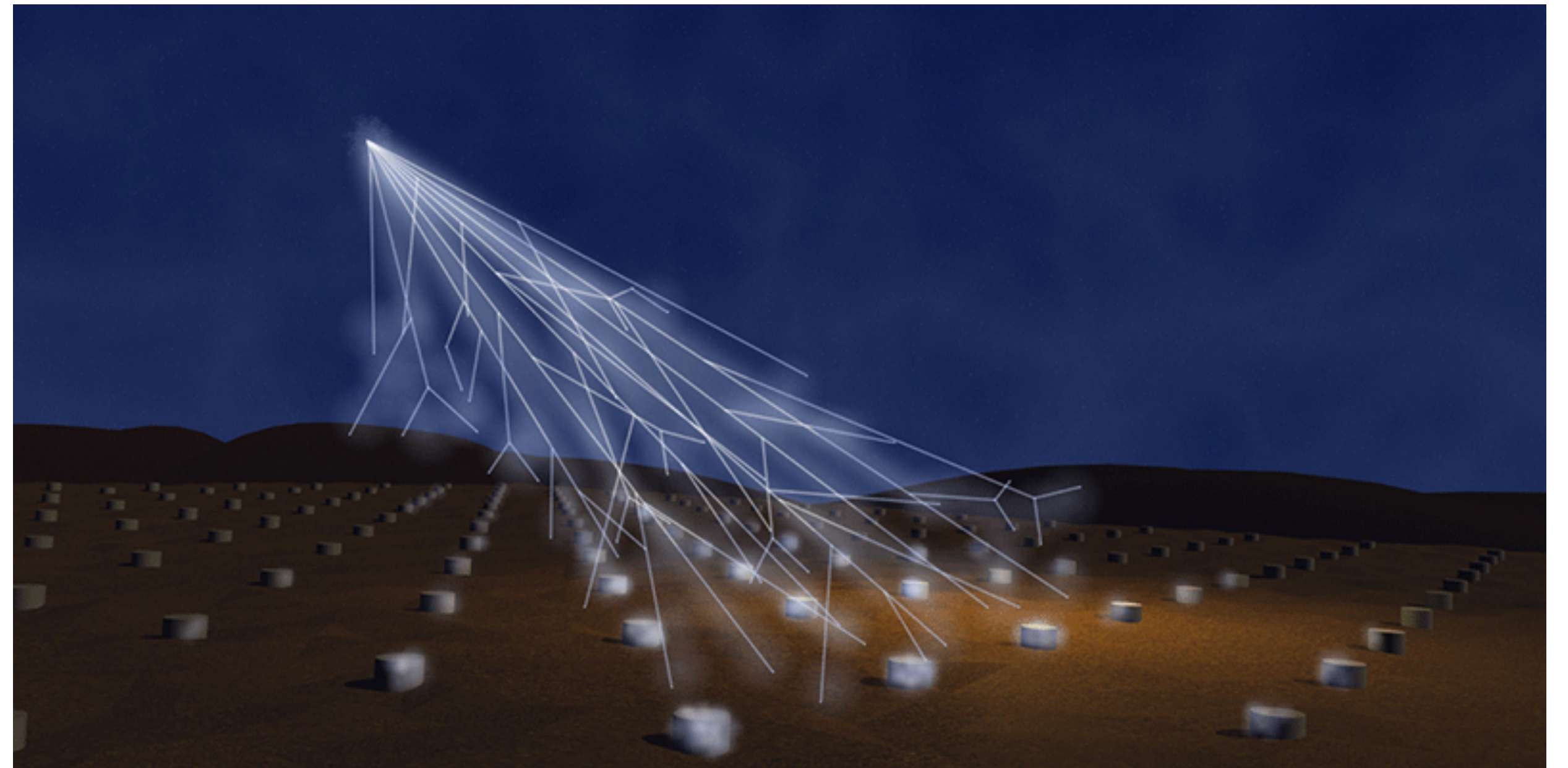
- **Overview of neutrino astrophysics**
- What does it take to build a UHE neutrino experiment?
- The future of the field

THE CENTURY-LONG SEARCH FOR COSMIC RAYS

VICTOR HESS, 1911

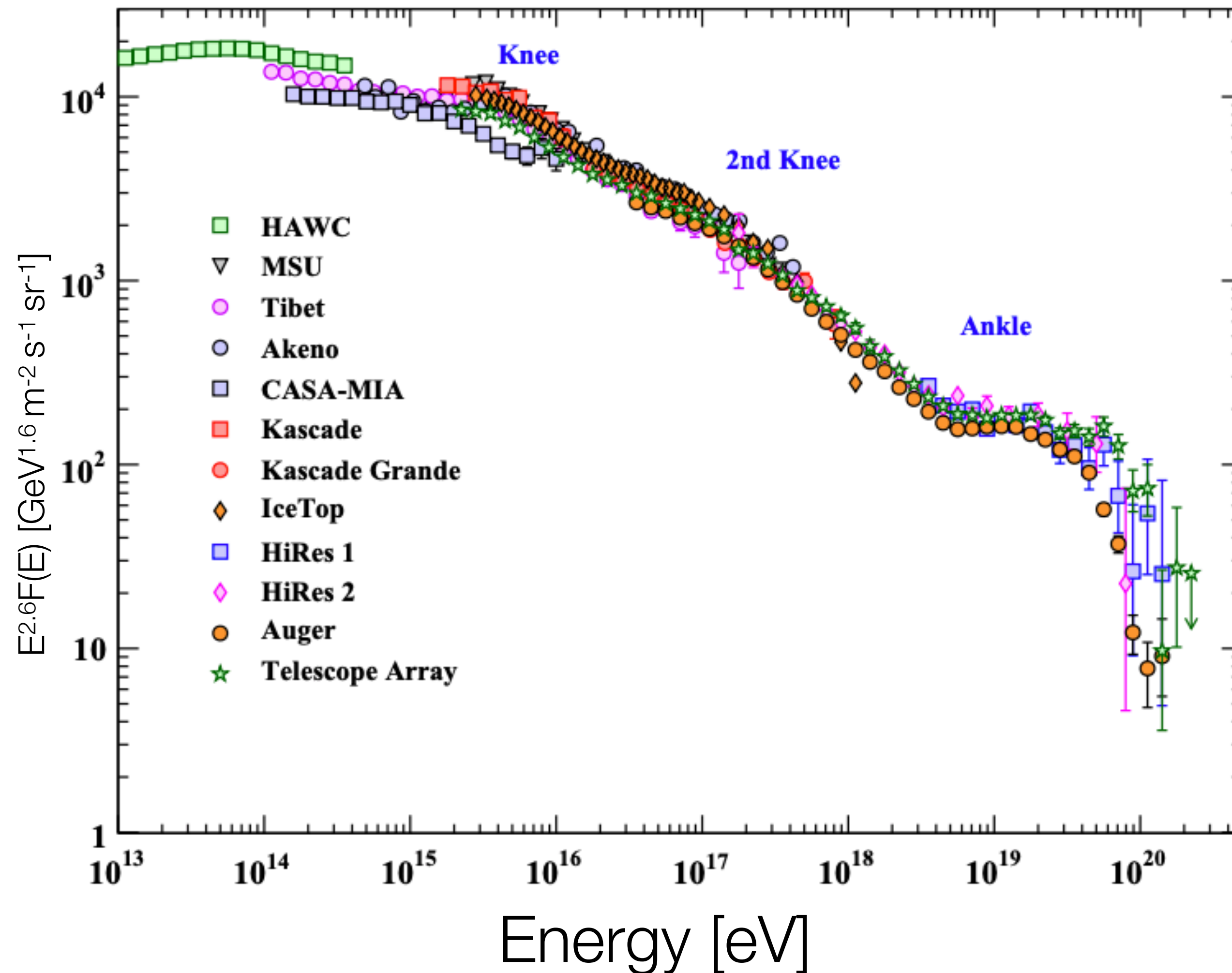


THE PIERRE AUGER OBSERVATORY,
PRESENT DAY



The Cosmic Ray Mystery

Cosmic Ray Flux

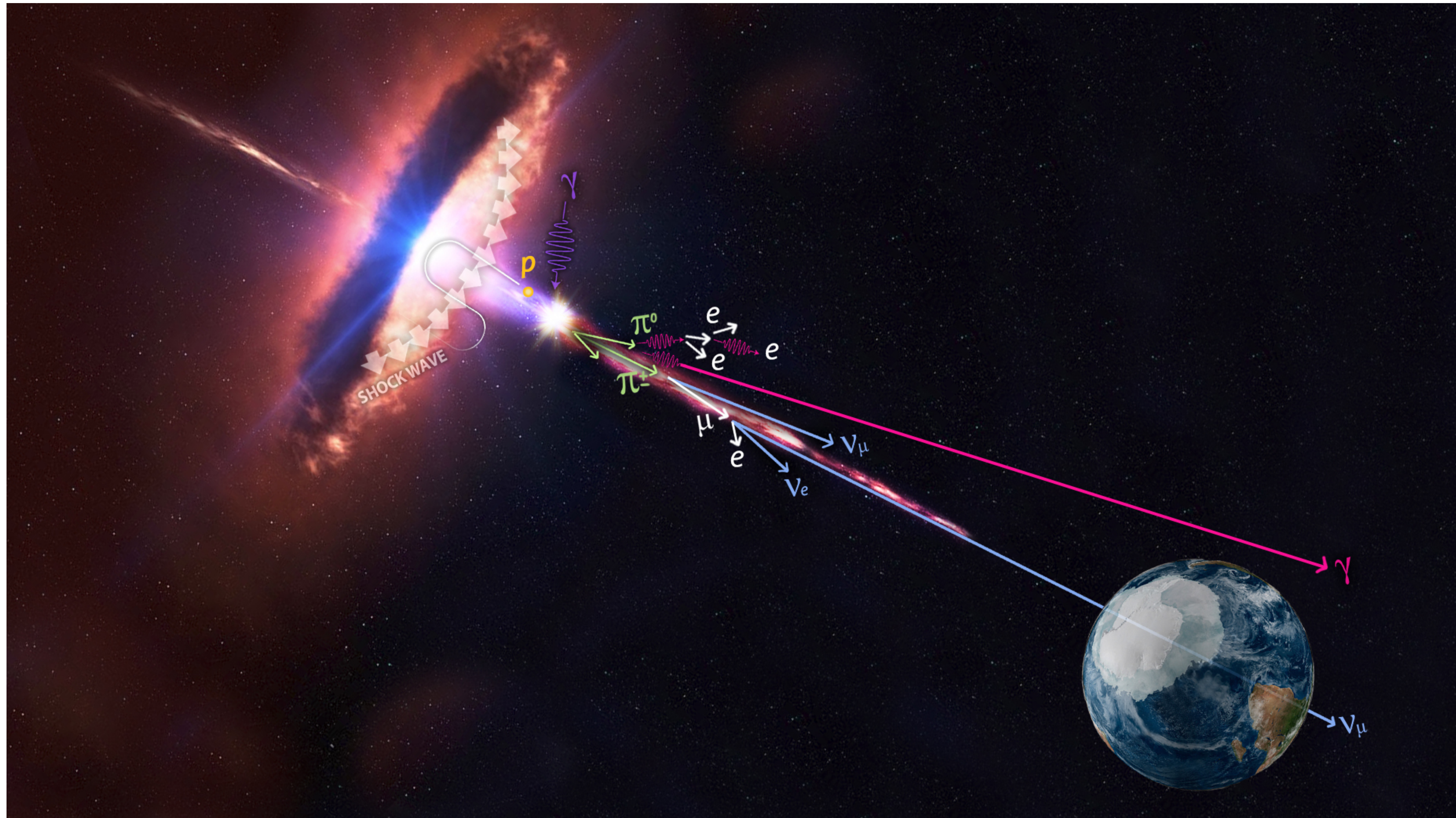


Where are the highest energy cosmic rays coming from?

Cosmic ray challenges:

- They don't point back to their sources due to magnetic fields
- They may interact as they propagate through the universe

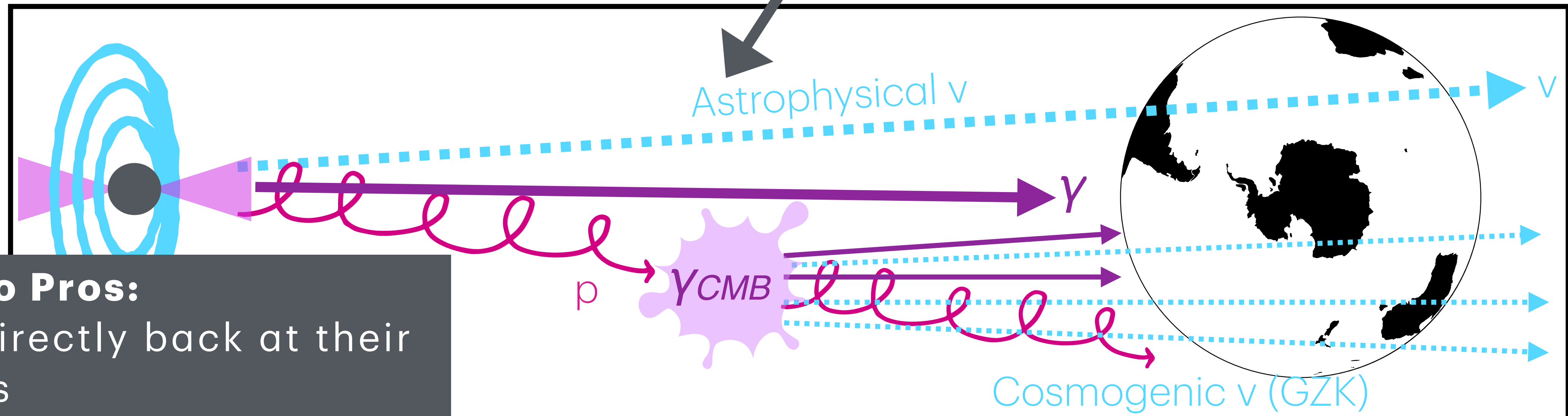
WHAT SOURCES ARE CREATING COSMIC RAYS?



“Ultra-high energy” = 10^{15} eV and above

What about ultra-high energy neutrinos?

Produced from ultra-high energy sources via cosmic ray interactions (p-p, p- γ)



Adapted from S. Wissel

Neutrino Pros:

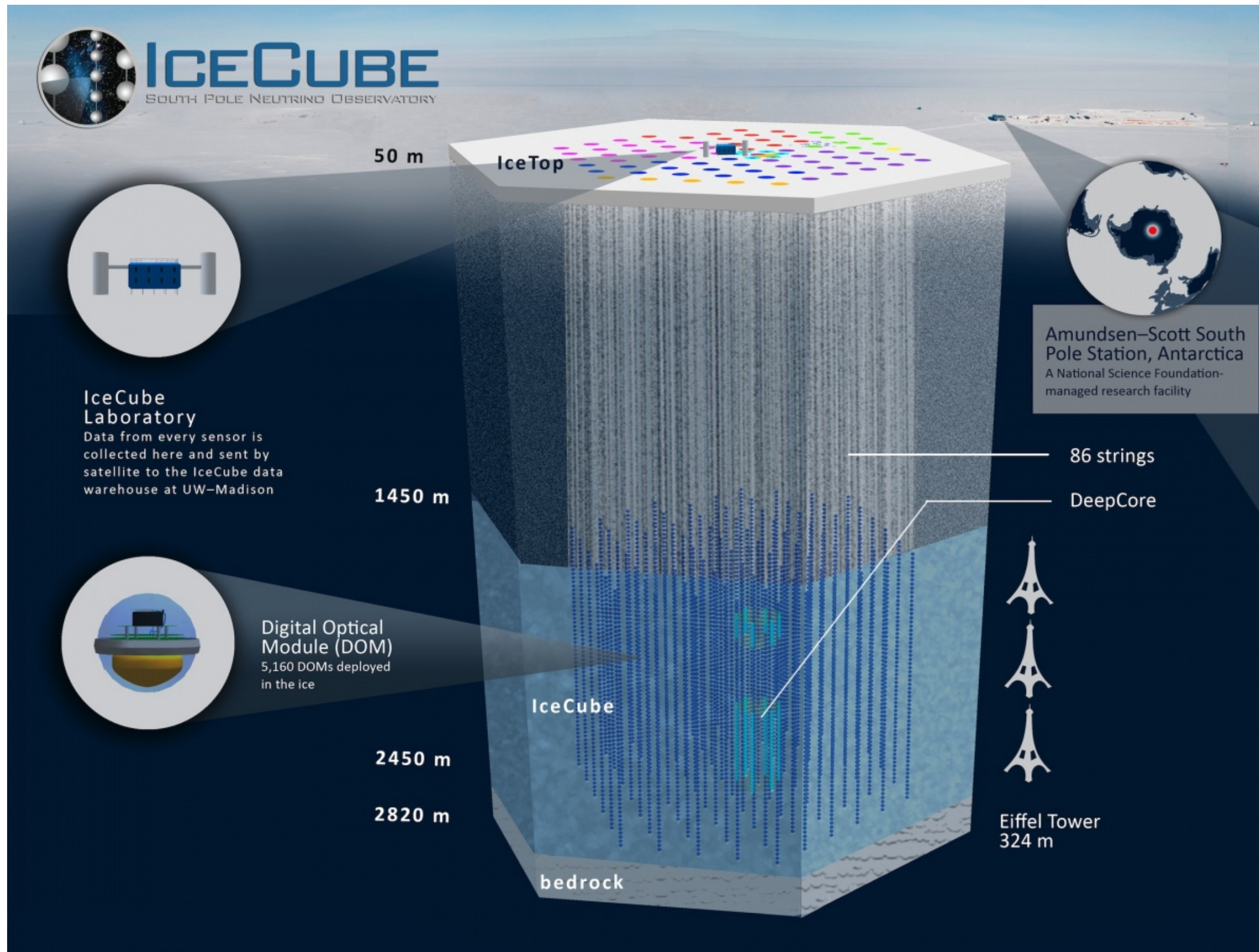
- Point directly back at their sources
- Capable of traveling extreme distances without interacting

Neutrino Cons:

- Capable of traveling straight through the Earth without interacting

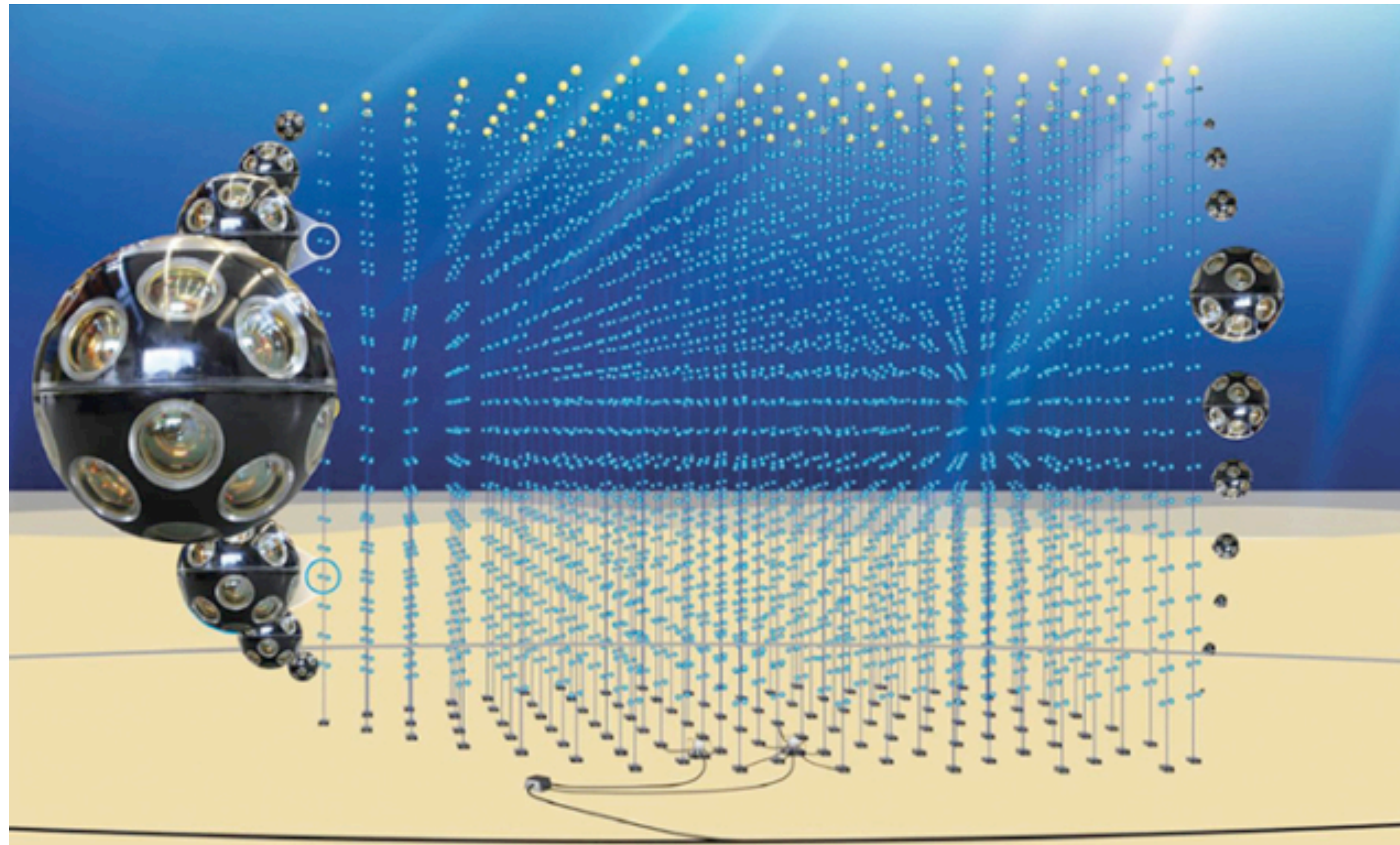
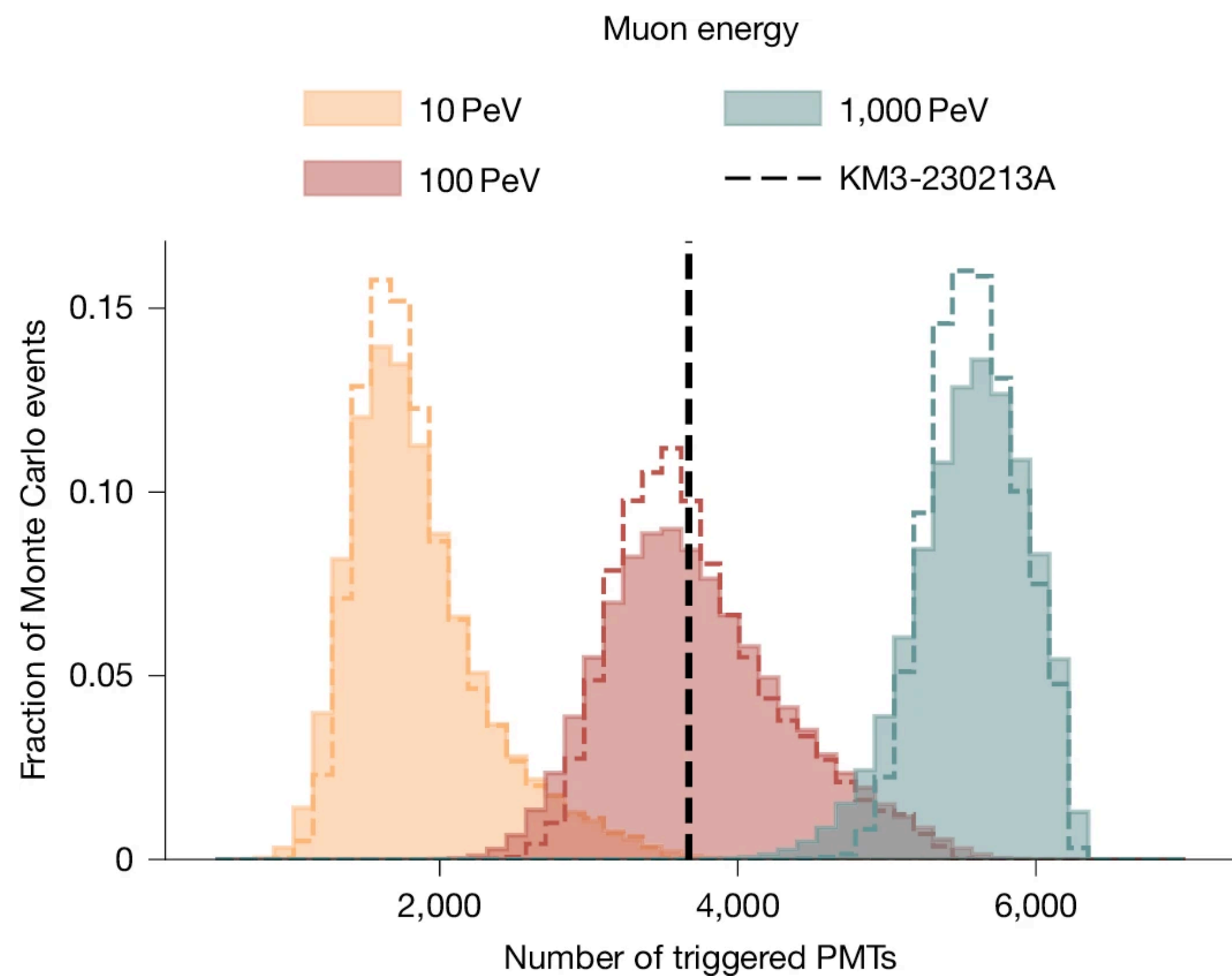
Produced by interactions between ultra-high energy cosmic rays and cosmic microwave background photons (e.g. GZK Mechanism)

Successes so far: IceCube!



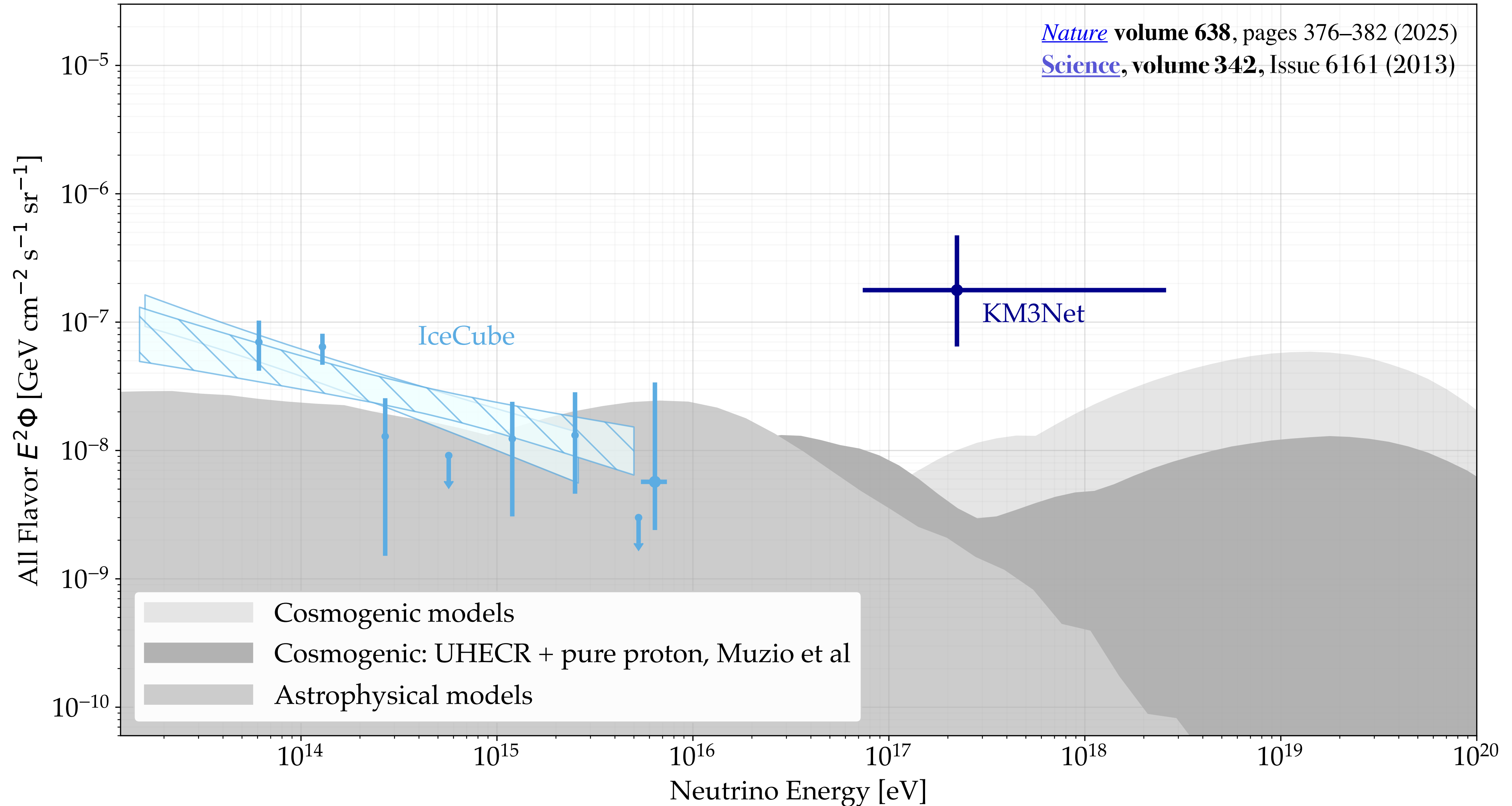
Successes so far: KM3NeT!

[*Nature* volume 638](#), pages 376–382 (2025): highest energy neutrino ever seen??

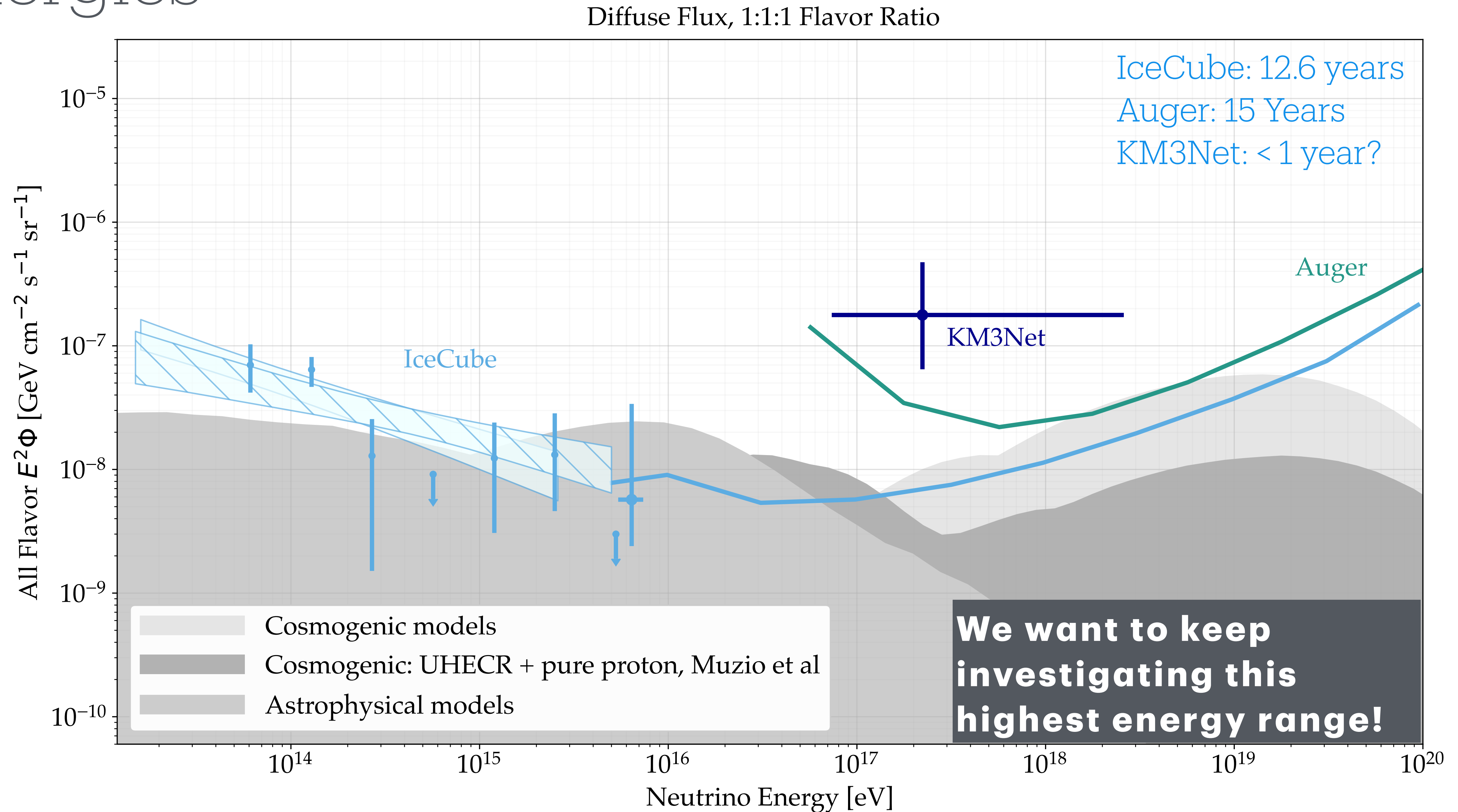


Neutrinos are expected (measured?) at higher energies

Diffuse Flux, 1:1:1 Flavor Ratio



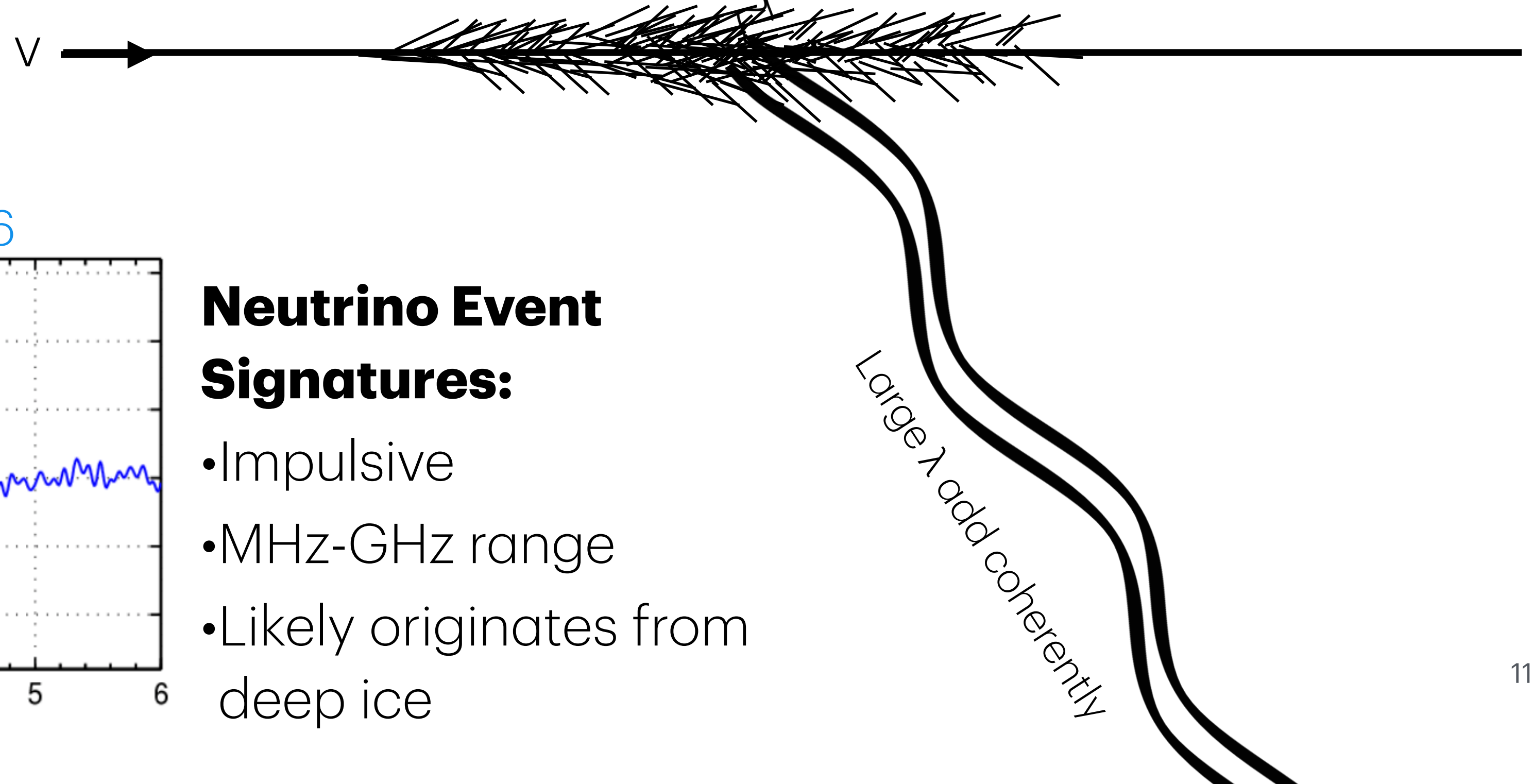
Neutrinos are expected (measured?) at higher energies



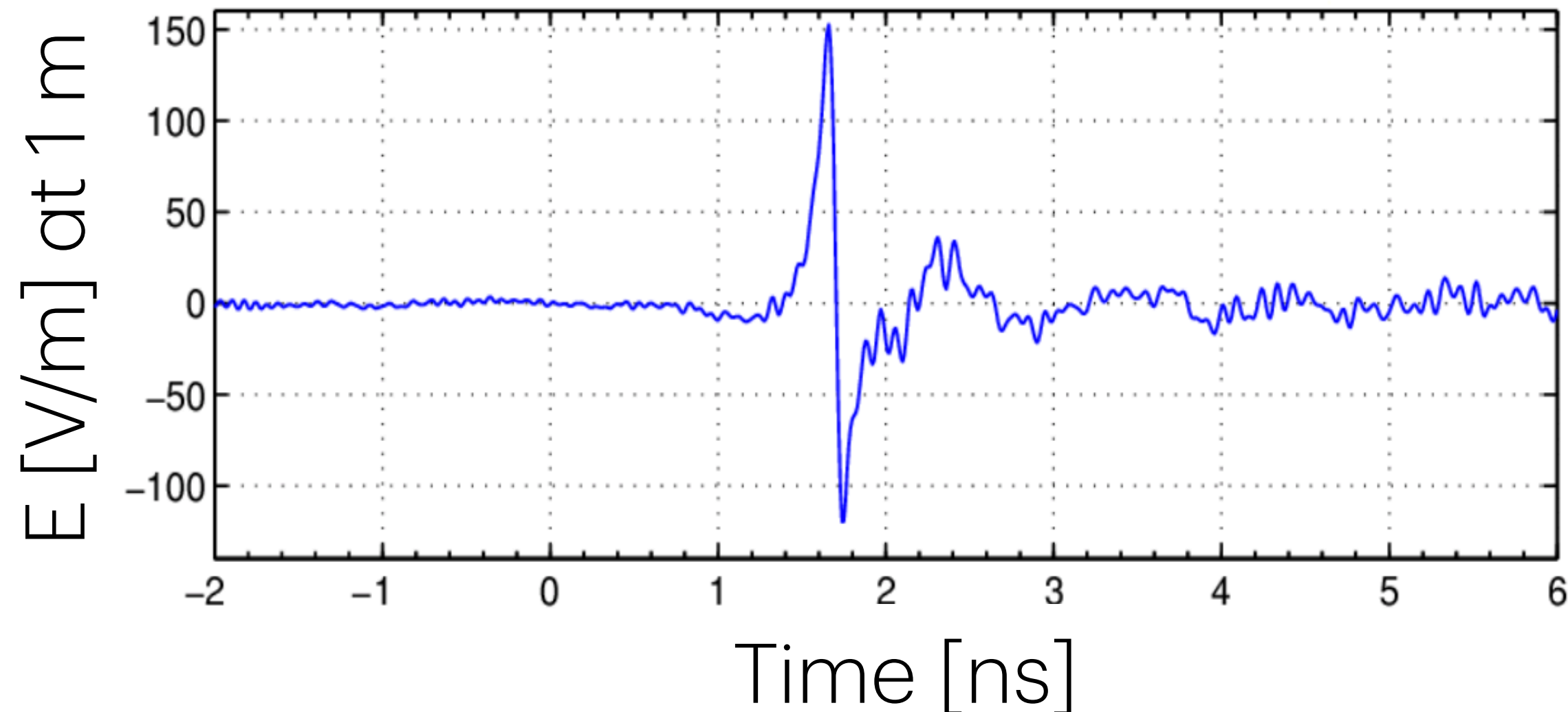
Instead of Optical, try Radio

Askaryan Radiation:

- Shower develops negative charge excess
- Coherent radiation for wavelengths $>$ shower width
- Best in dense, dielectric, radio-clear material
- Ice attenuation: **meters** in optical, **kilometers** in radio



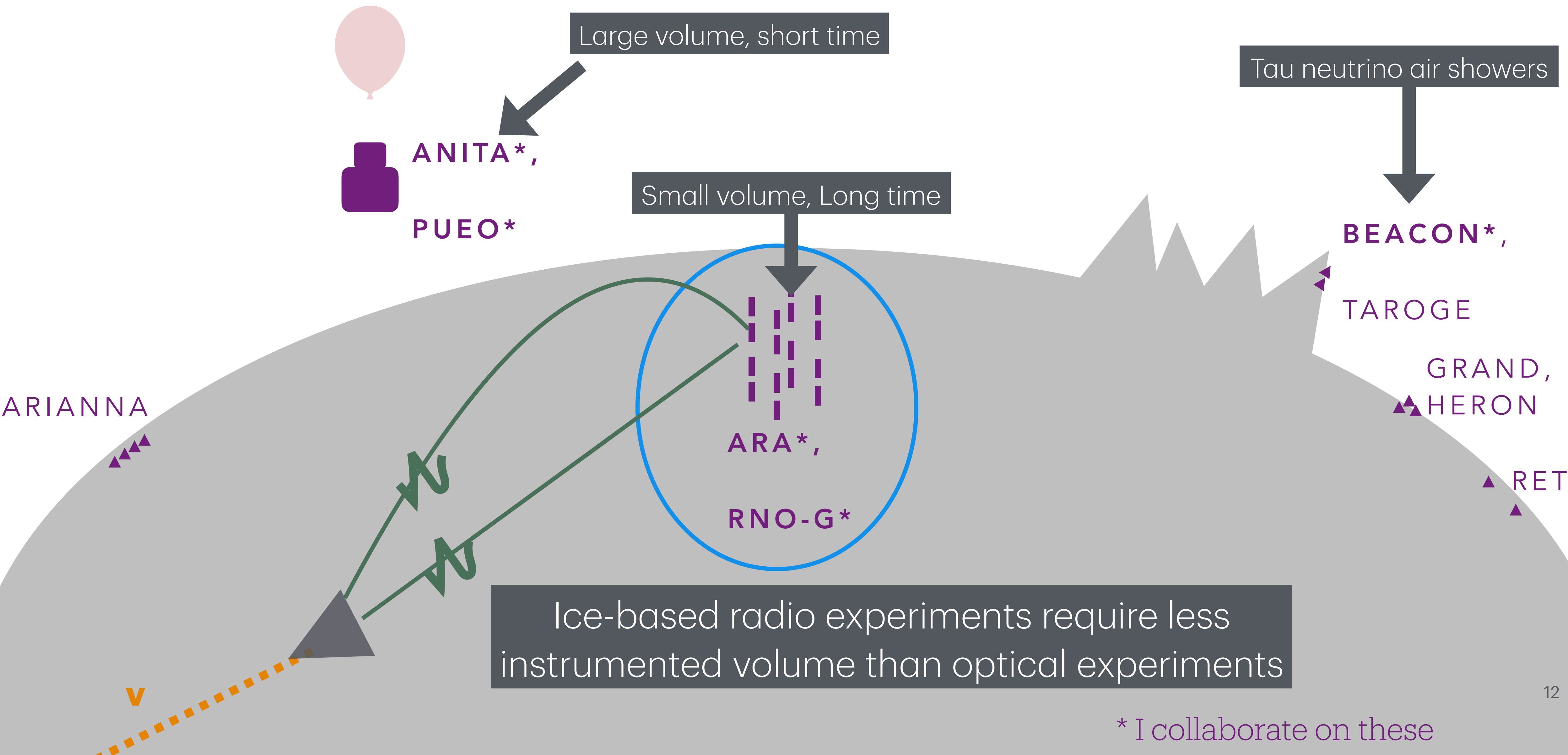
ANITA Collaboration, PRL 2006



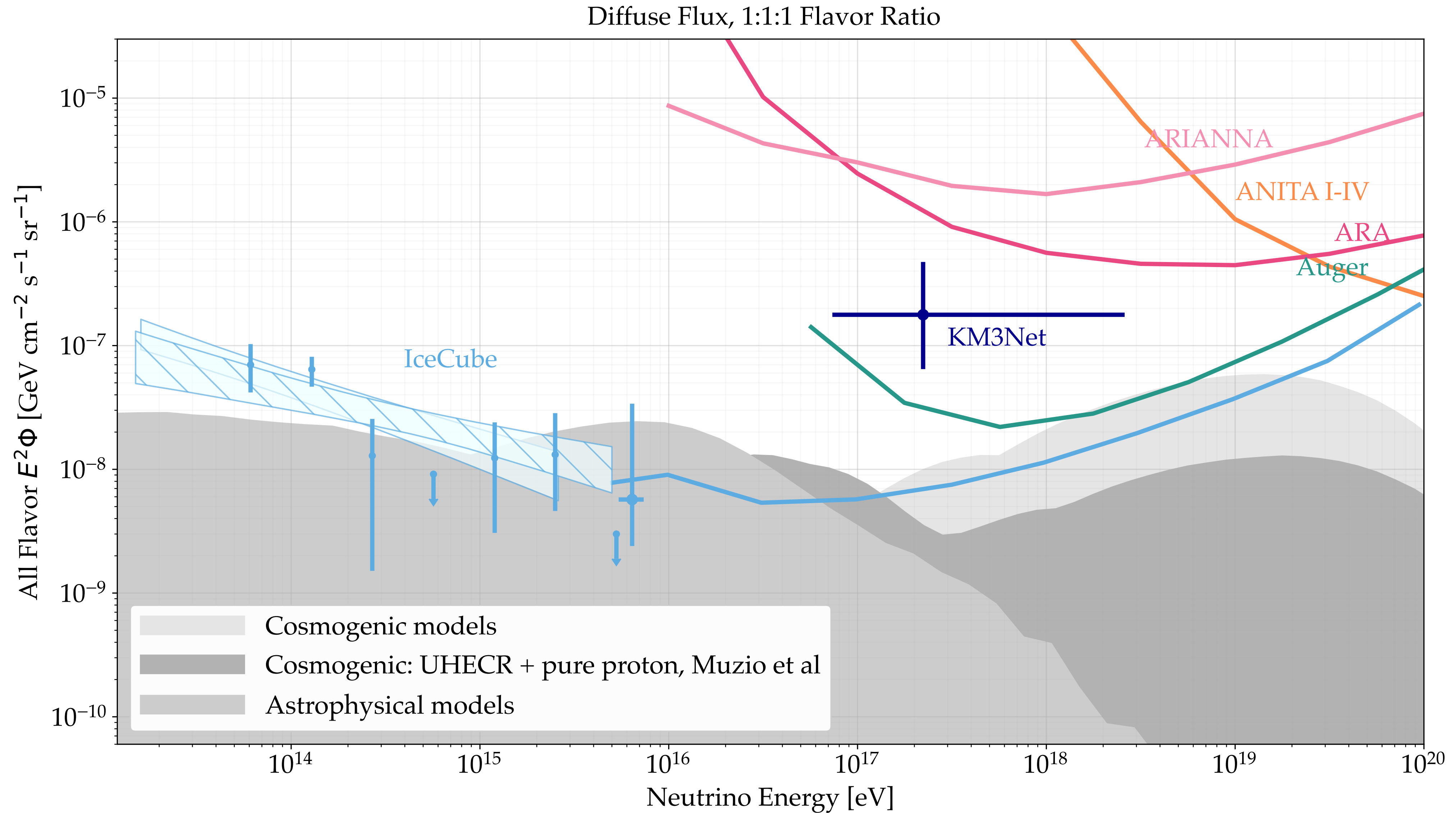
Neutrino Event Signatures:

- Impulsive
- MHz-GHz range
- Likely originates from deep ice

Lots of Radio-Based Experiments



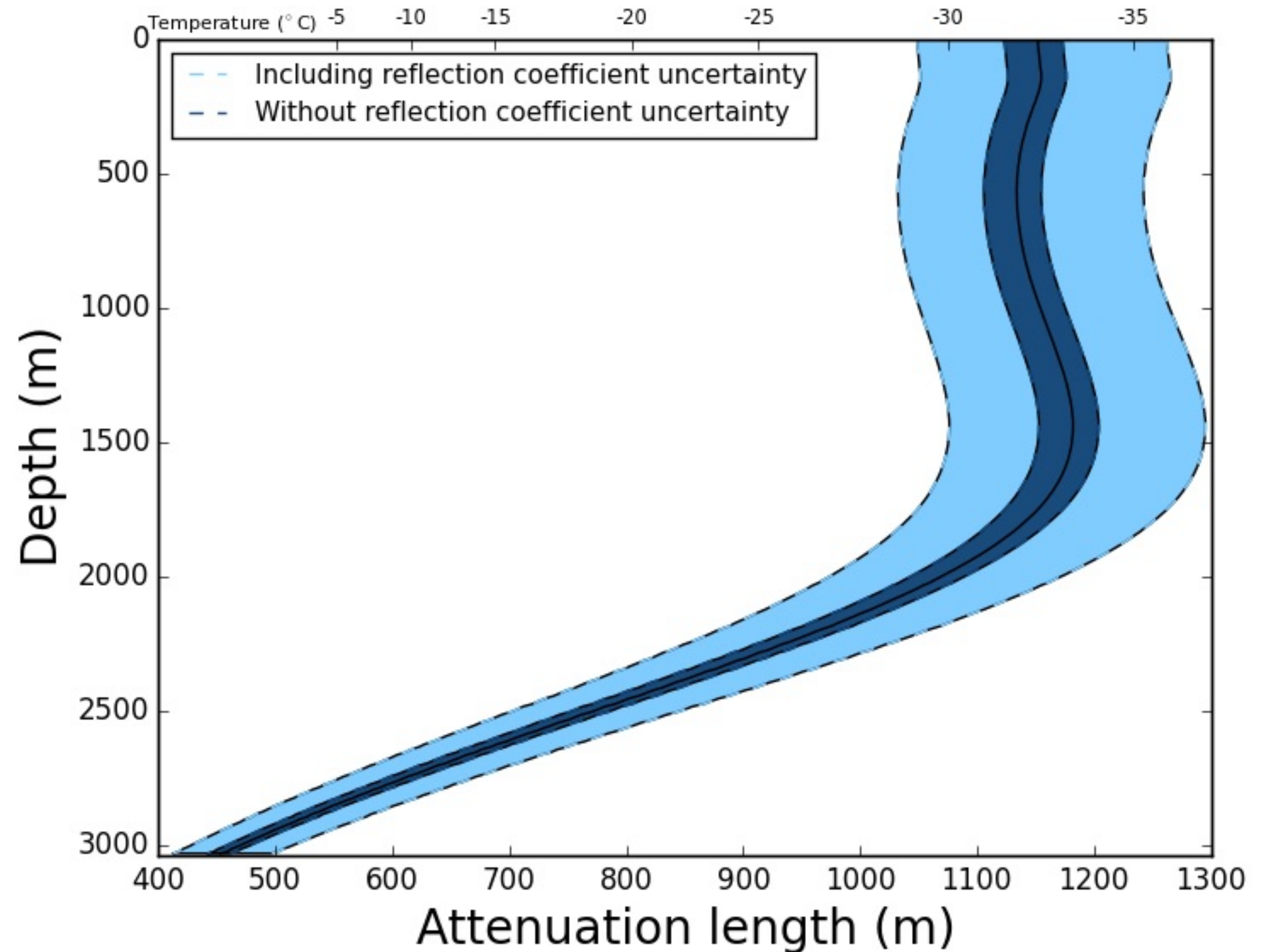
The current experimental landscape



How to build a ground-based
experiment at scale

First step: pick a site. South Pole or Greenland?

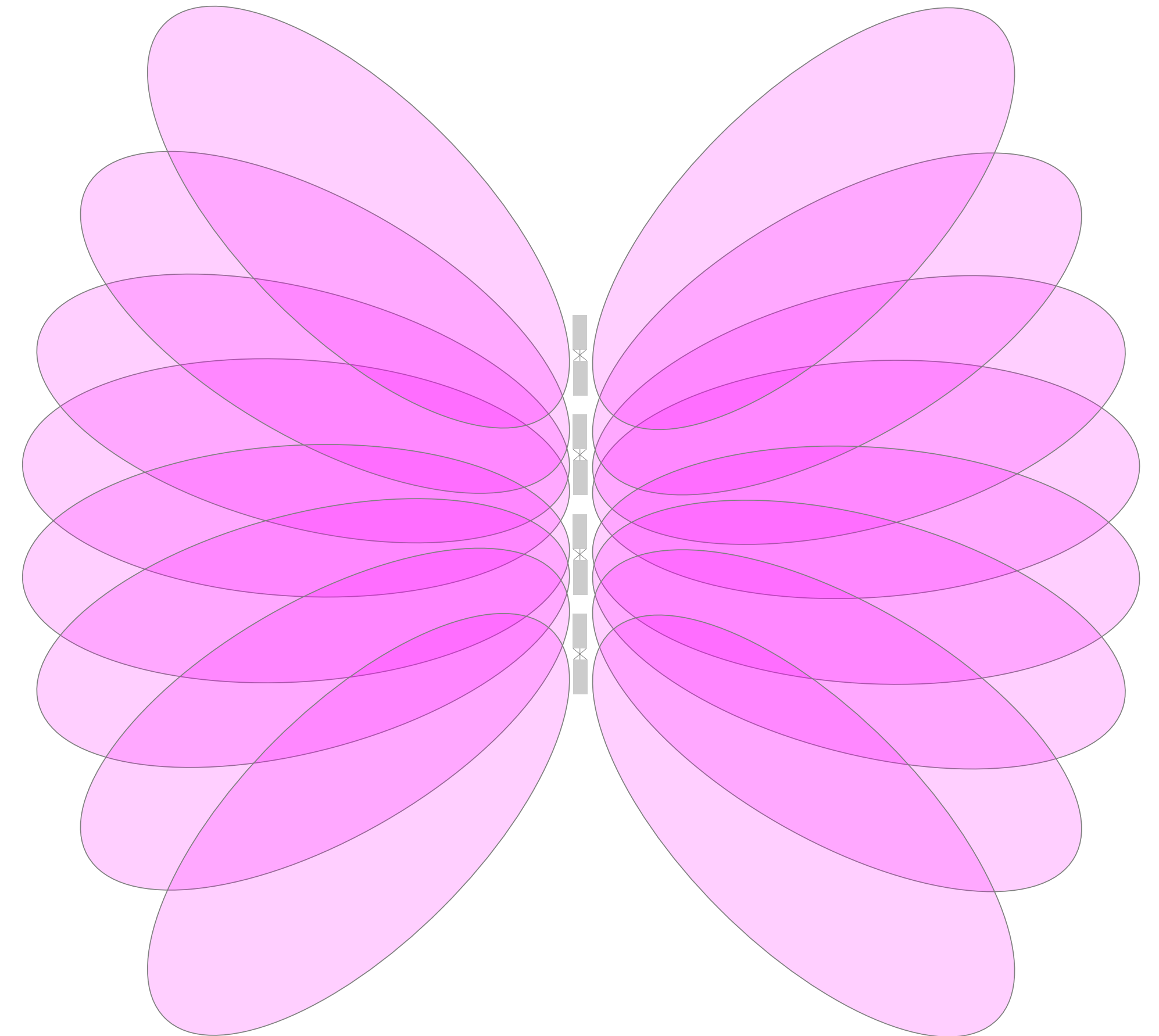
- Need somewhere with a lot of radio-clear ice
- South Pole can be logistically hard. Are there other options?
- First tests of radio response of ice in Greenland near Summit Station helped inform future designs!



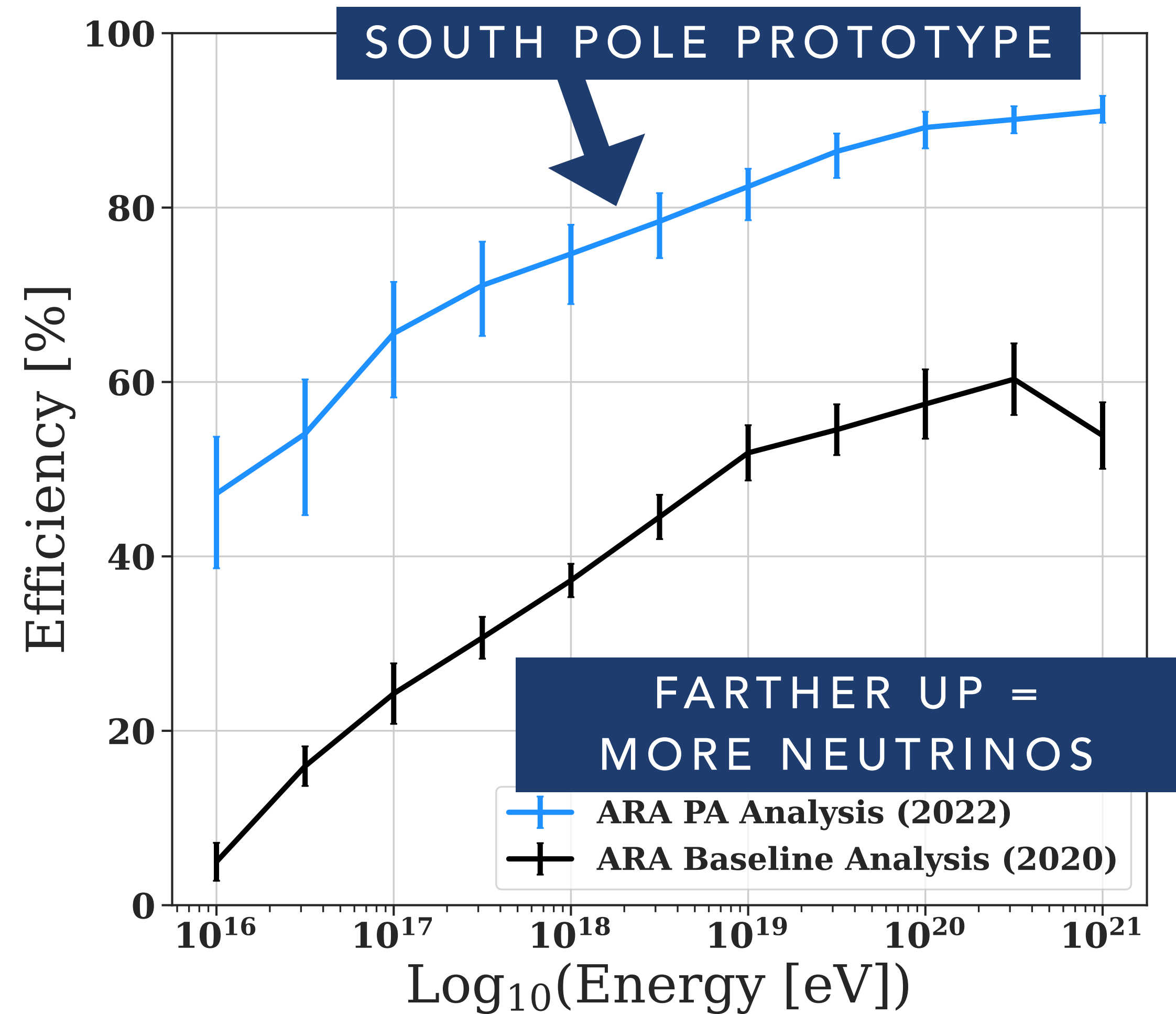
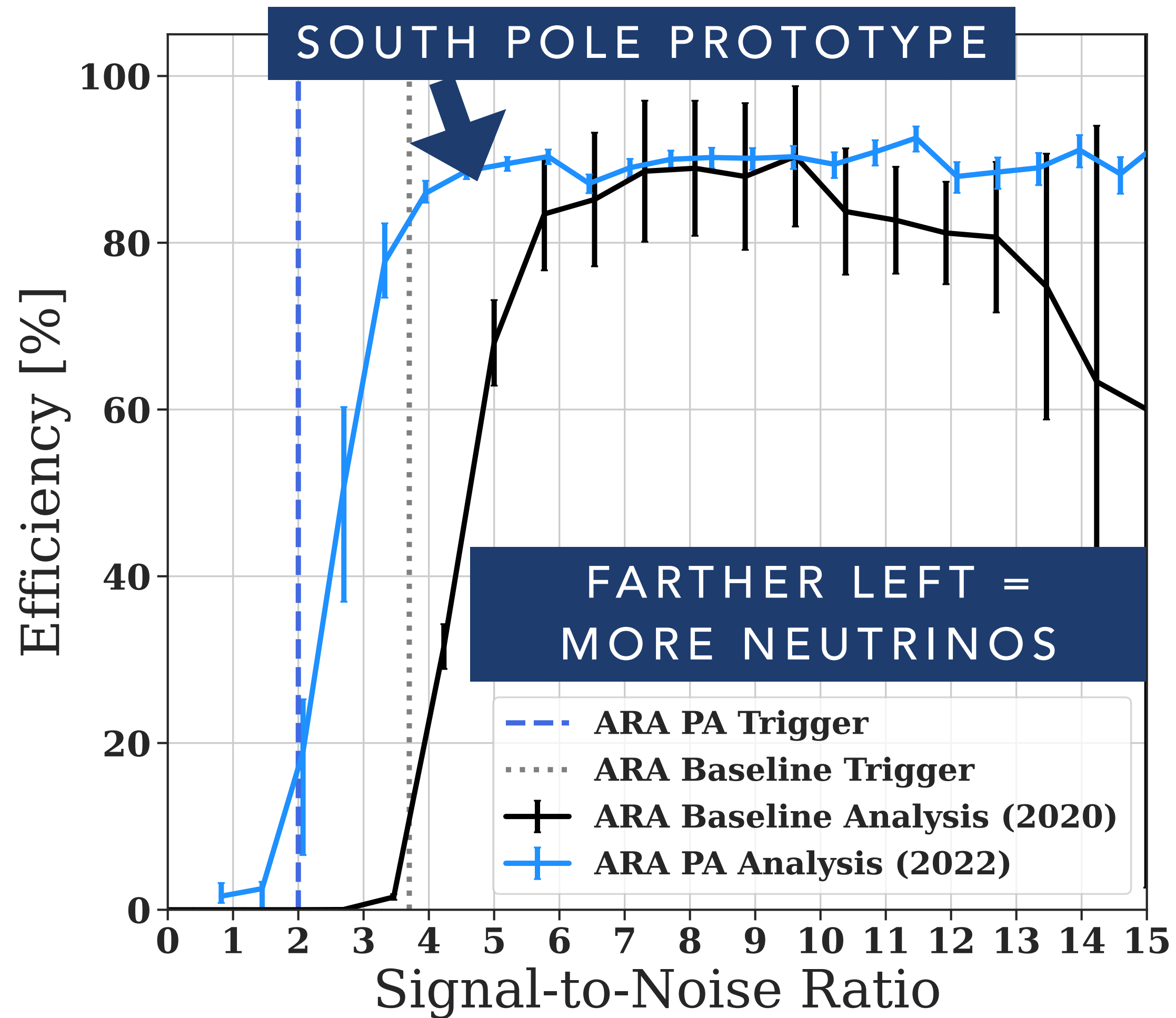
Second step: prototyping

- Typical triggers had focused on power: looking for coincident power within a given time window on multiple antennas
- Instead, try a trigger with power + direction and a compact antenna design
- Define directions ahead of time and try all directions simultaneously
- Plane wave signals will add coherently -> improved trigger efficiency for smaller signals

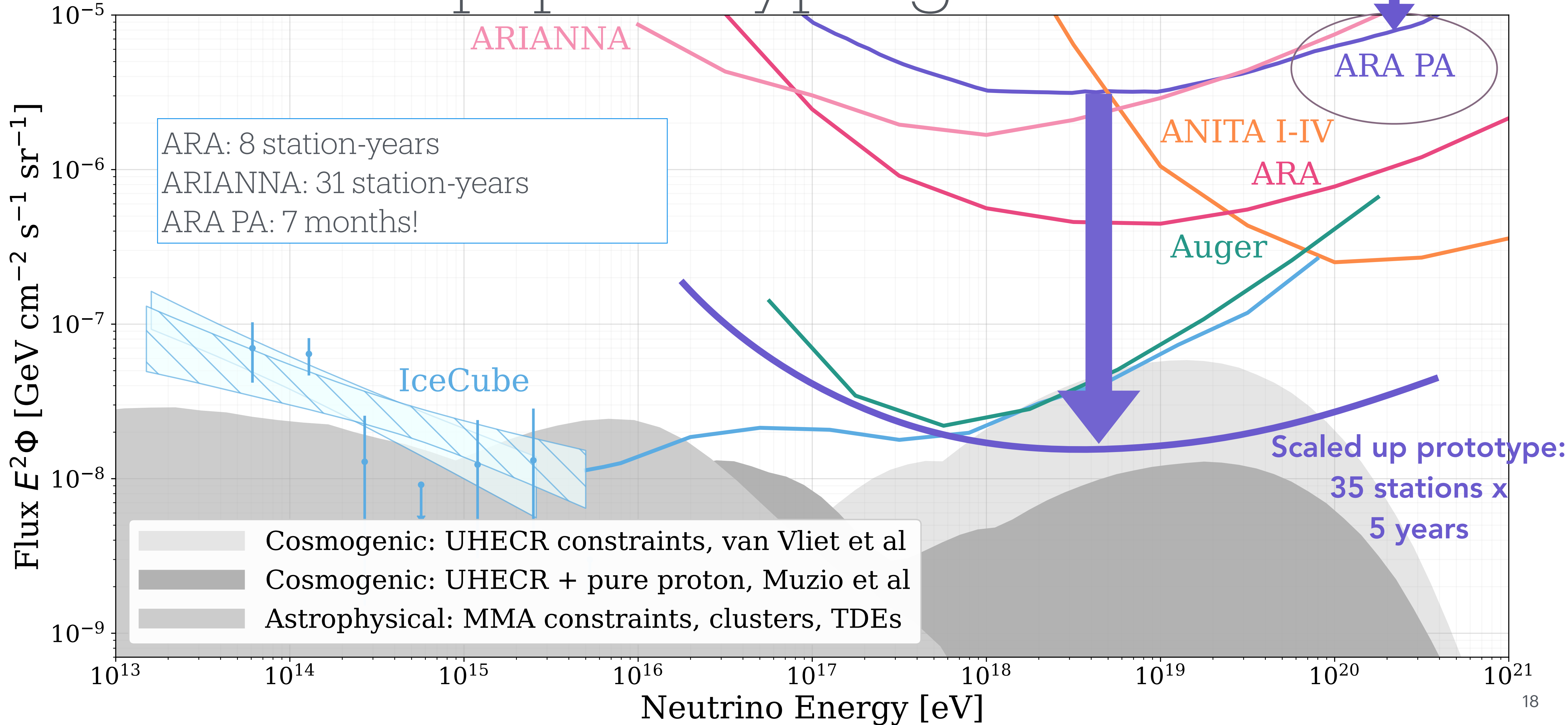
Phased Array Triggering: Power + Direction



Second step: prototyping

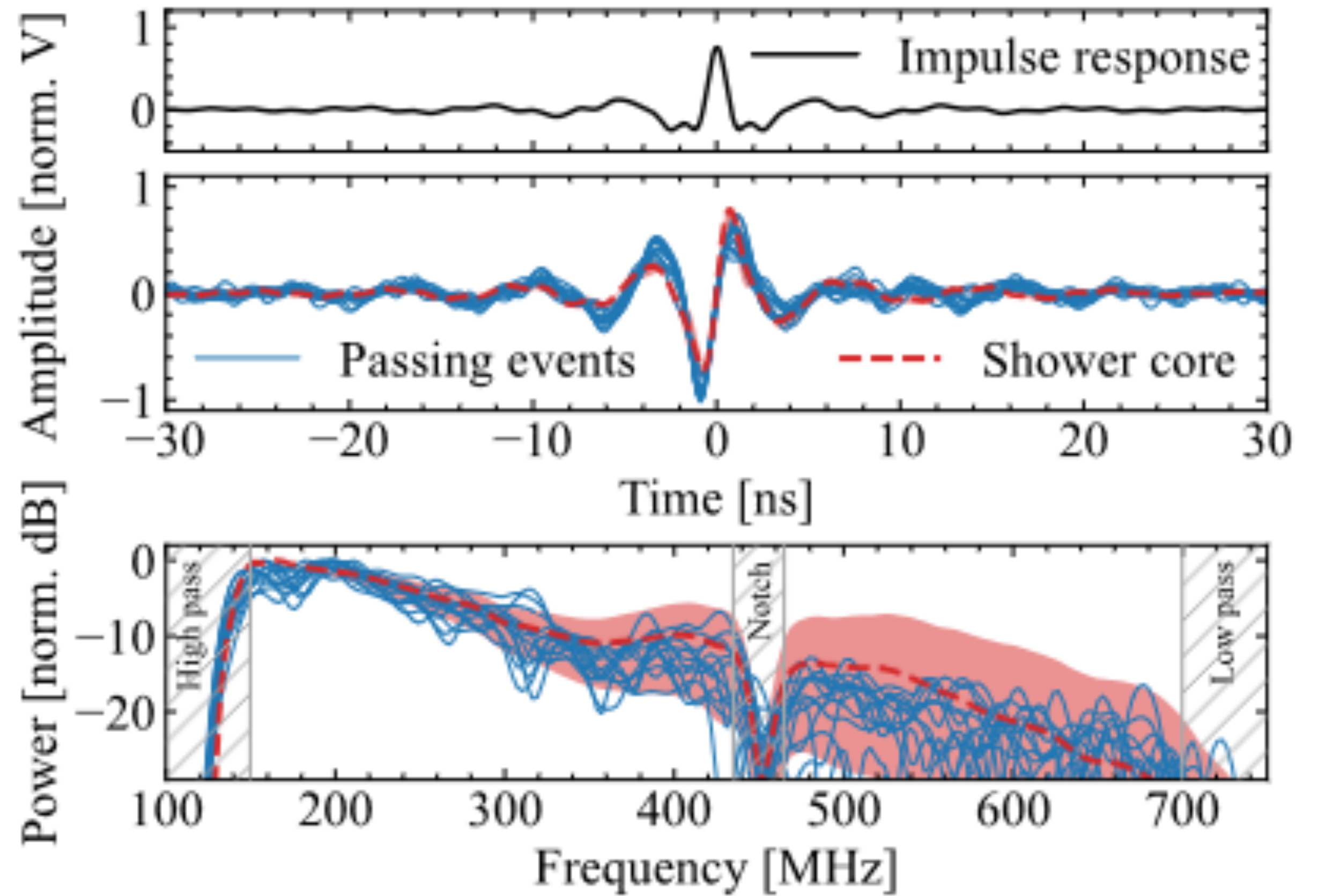
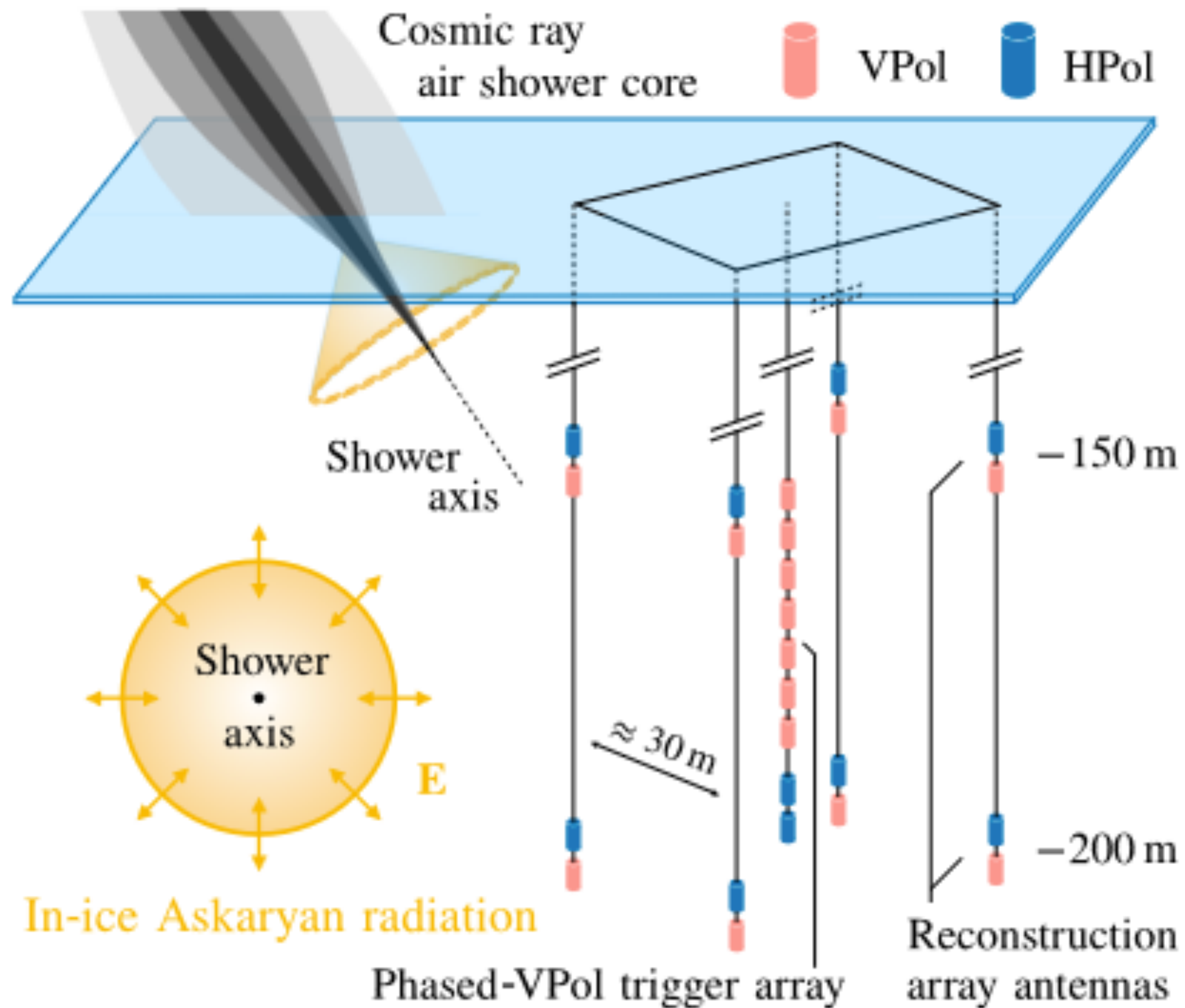


Second step: prototyping



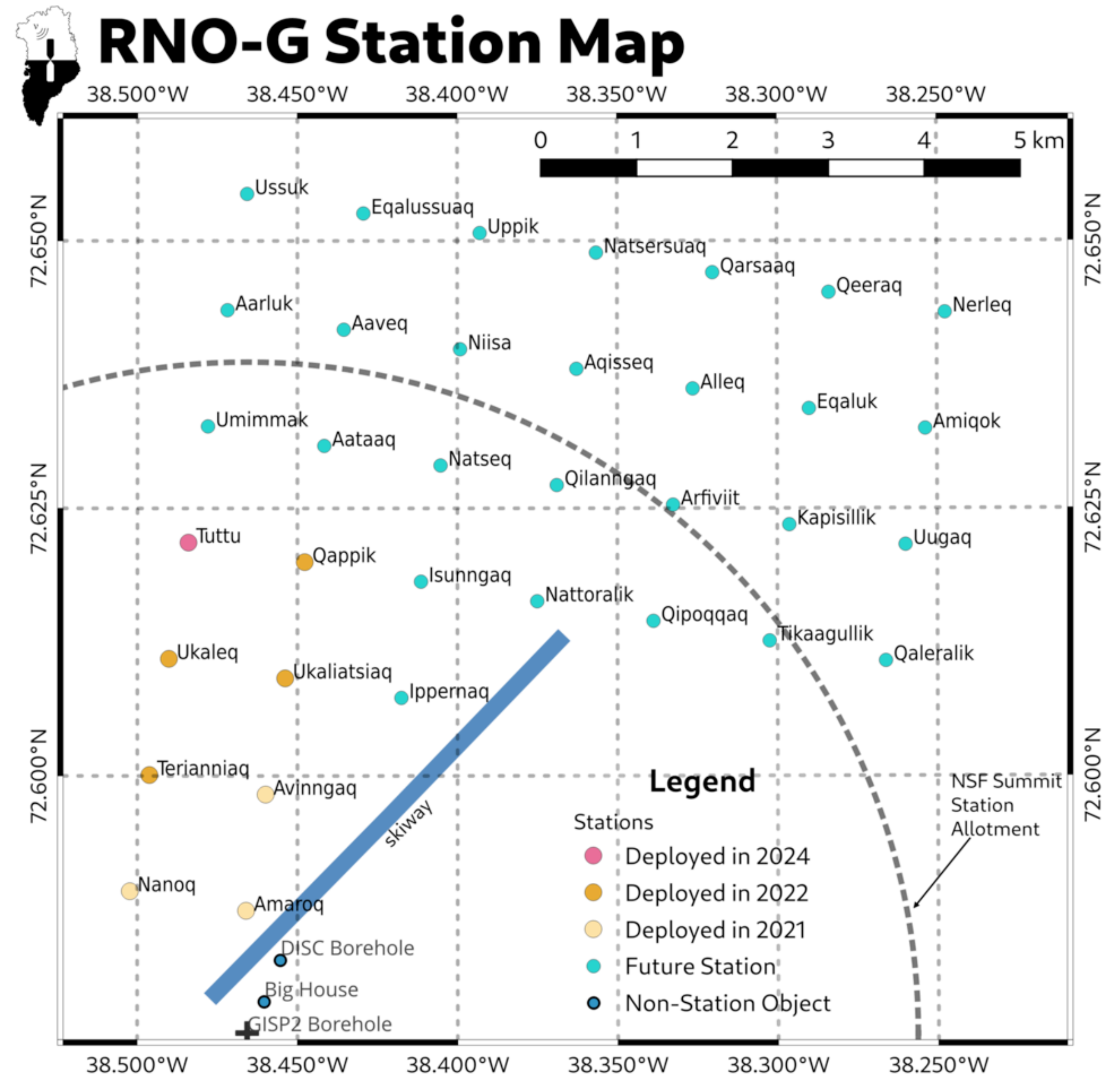
But wait... does Askaryan emission actually even happen in ice?

New results say yes!



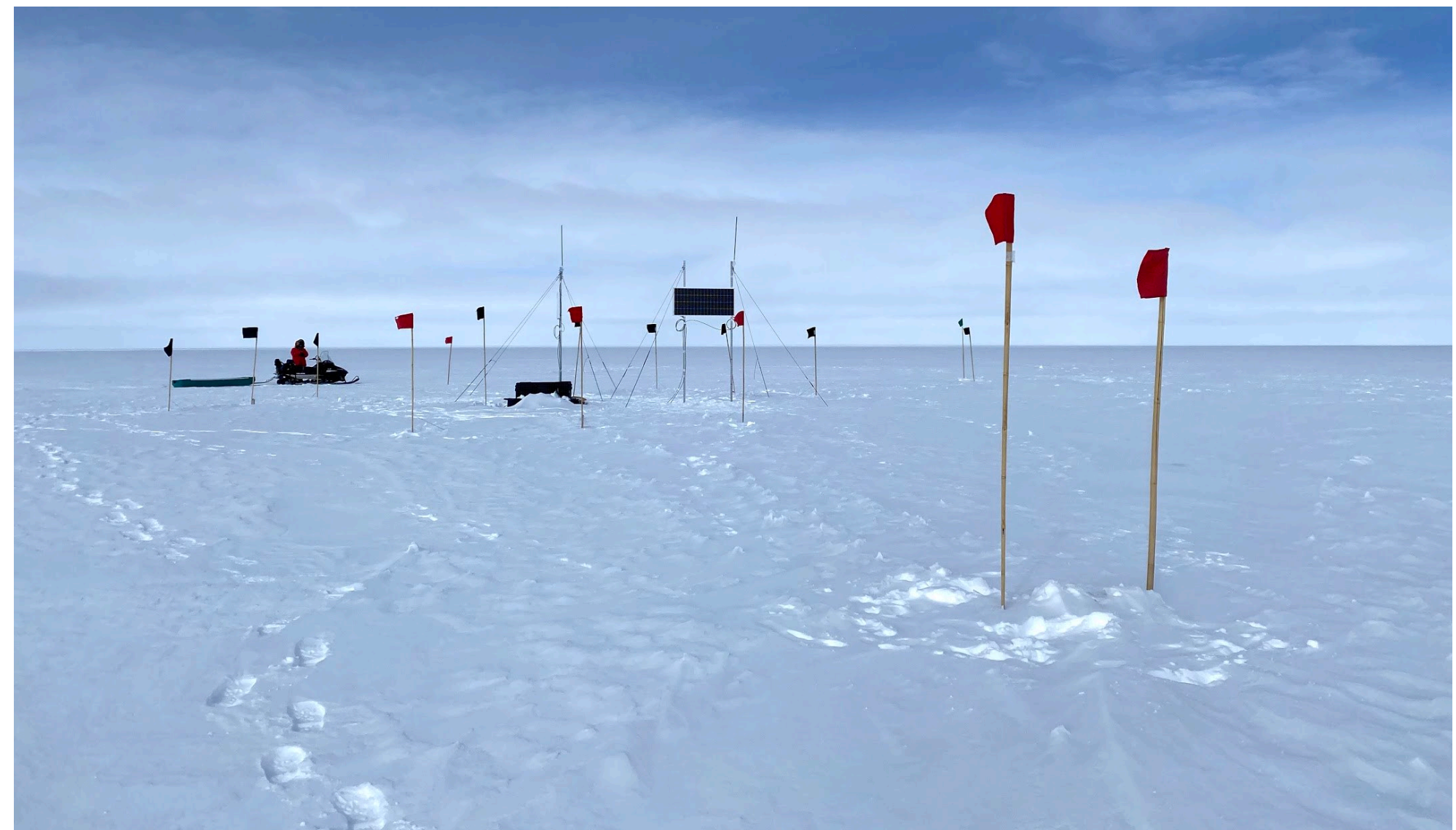
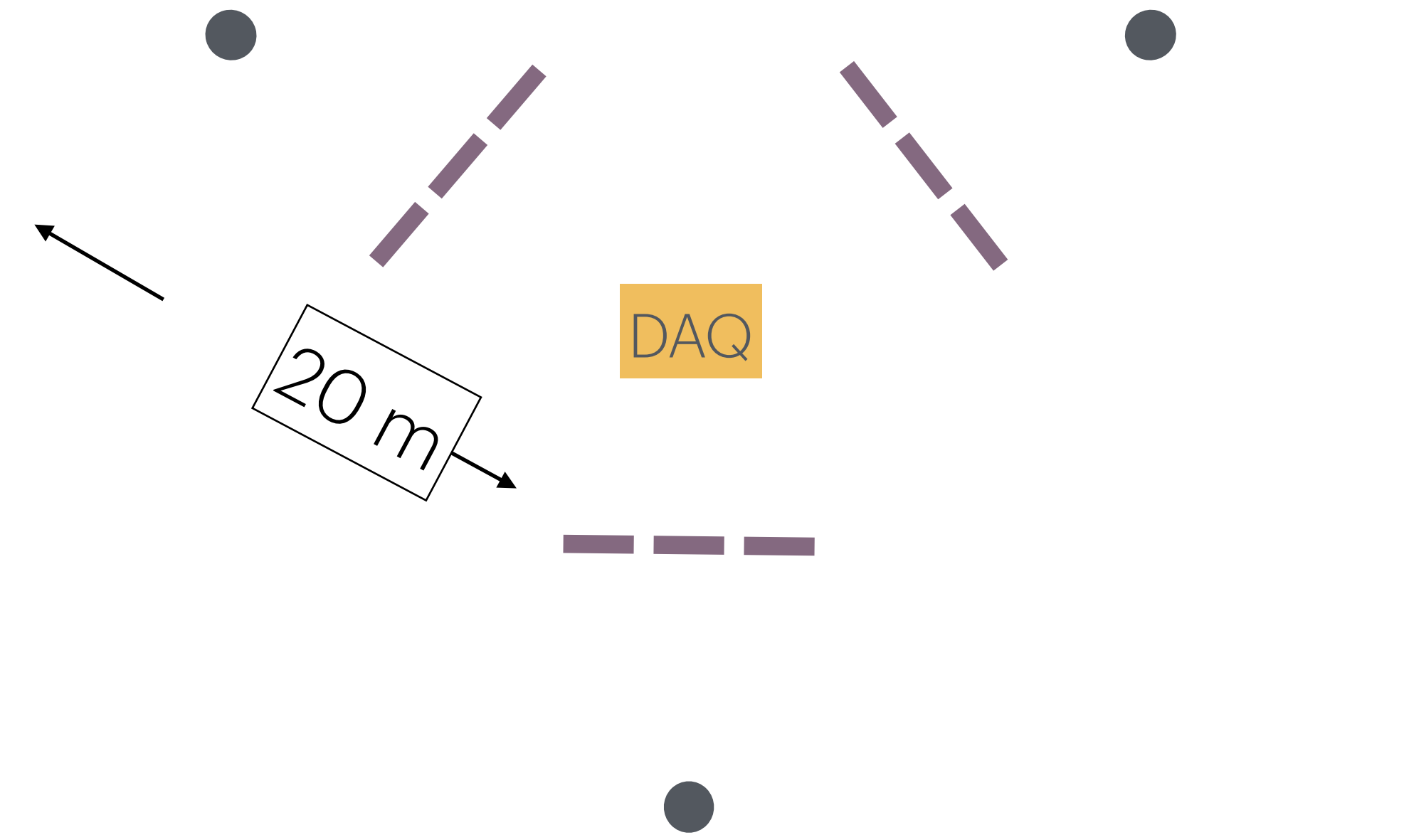
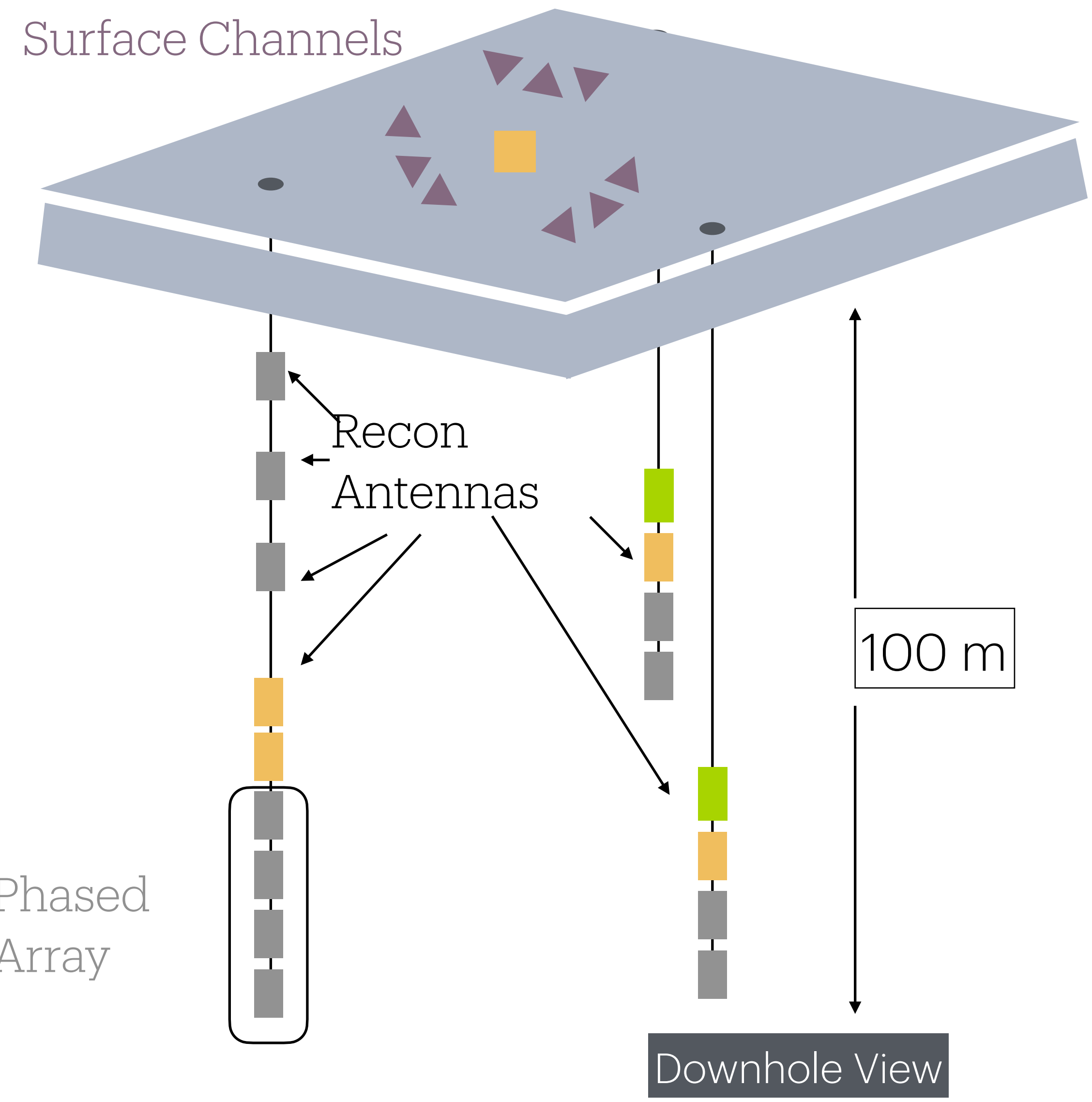
Third Step: try building at scale

- Need lots of individual phased arrays to accumulate enough livetime to see the very faint neutrino signal
- Enter the Radio Neutrino Observatory in Greenland (RNO-G): funded through European collaborators and the NSF
- Eight stations are already in the ice!



A single RNO-G Station

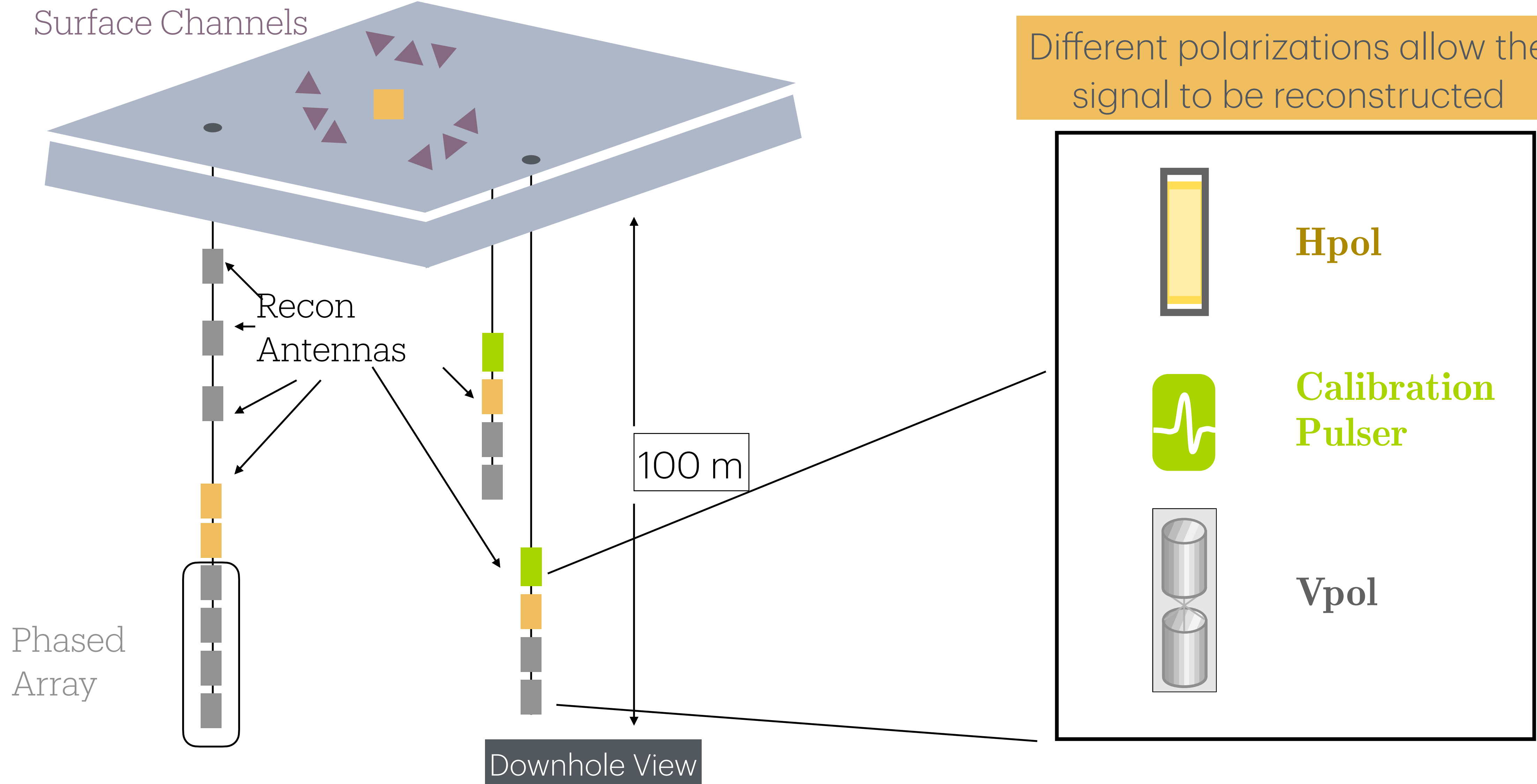
Bird's Eye View



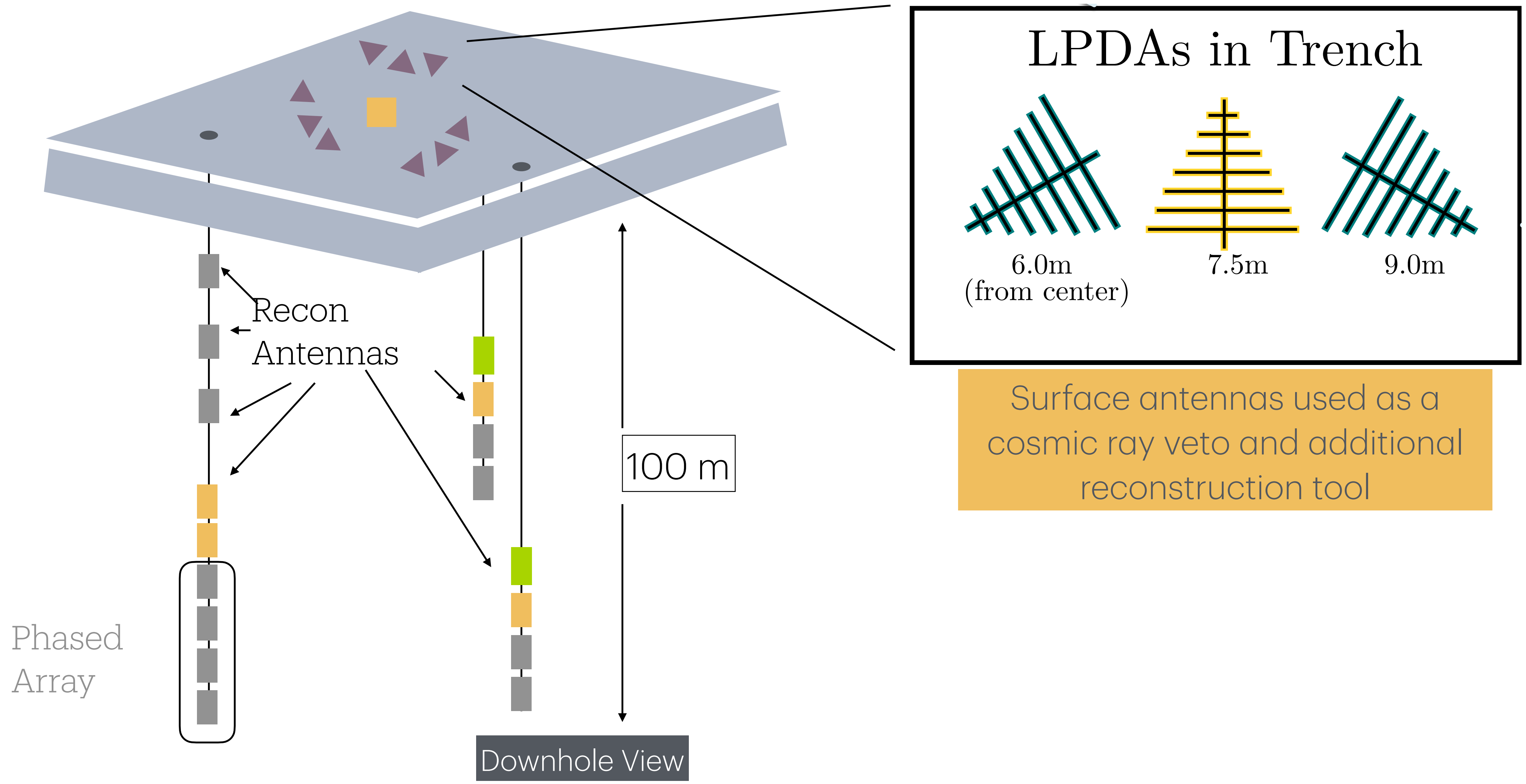
A single RNO-G Station

Surface Channels

Different polarizations allow the signal to be reconstructed



A single RNO-G Station



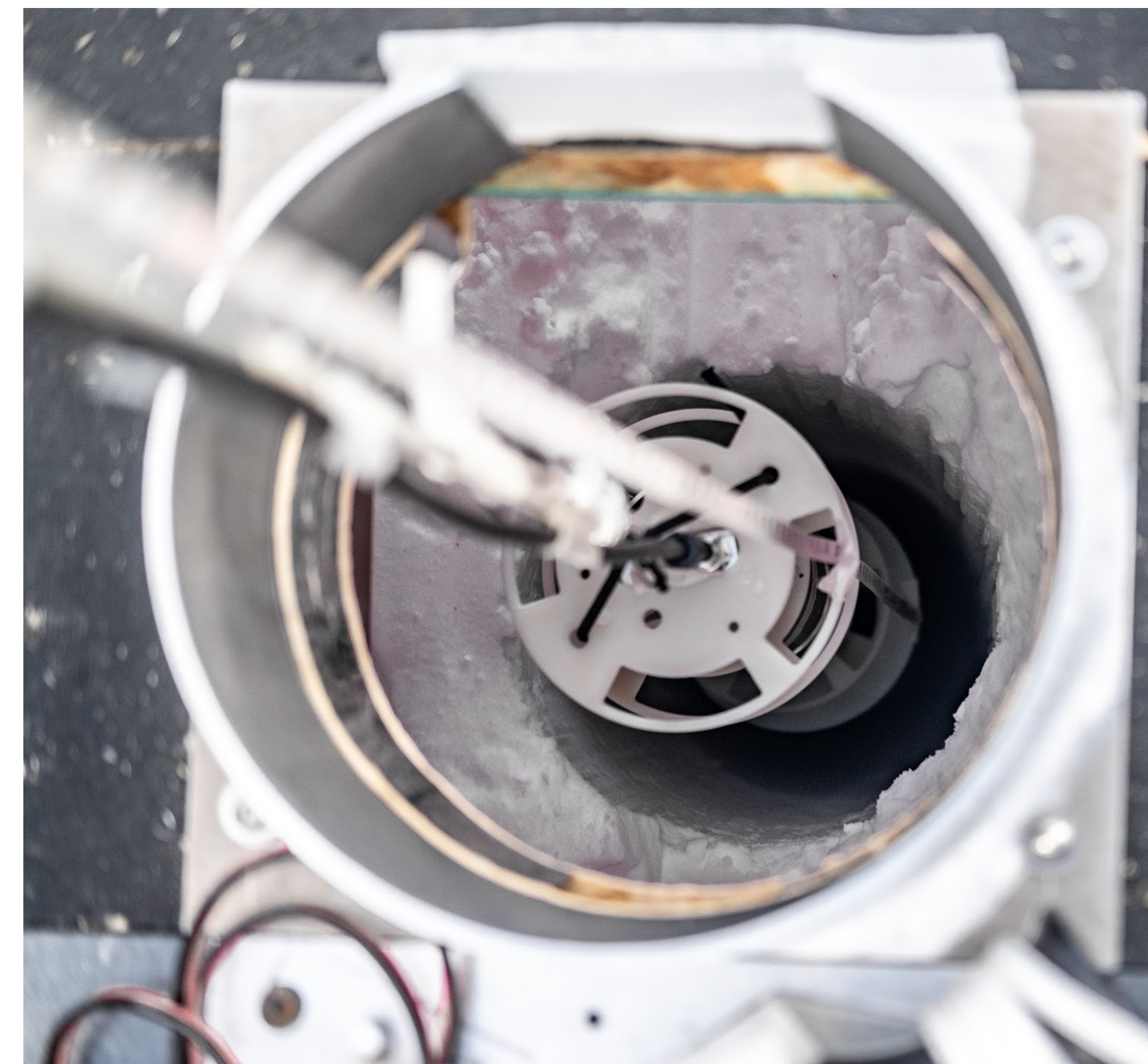
Antennas in Action!



VPol + LPDA



HPol



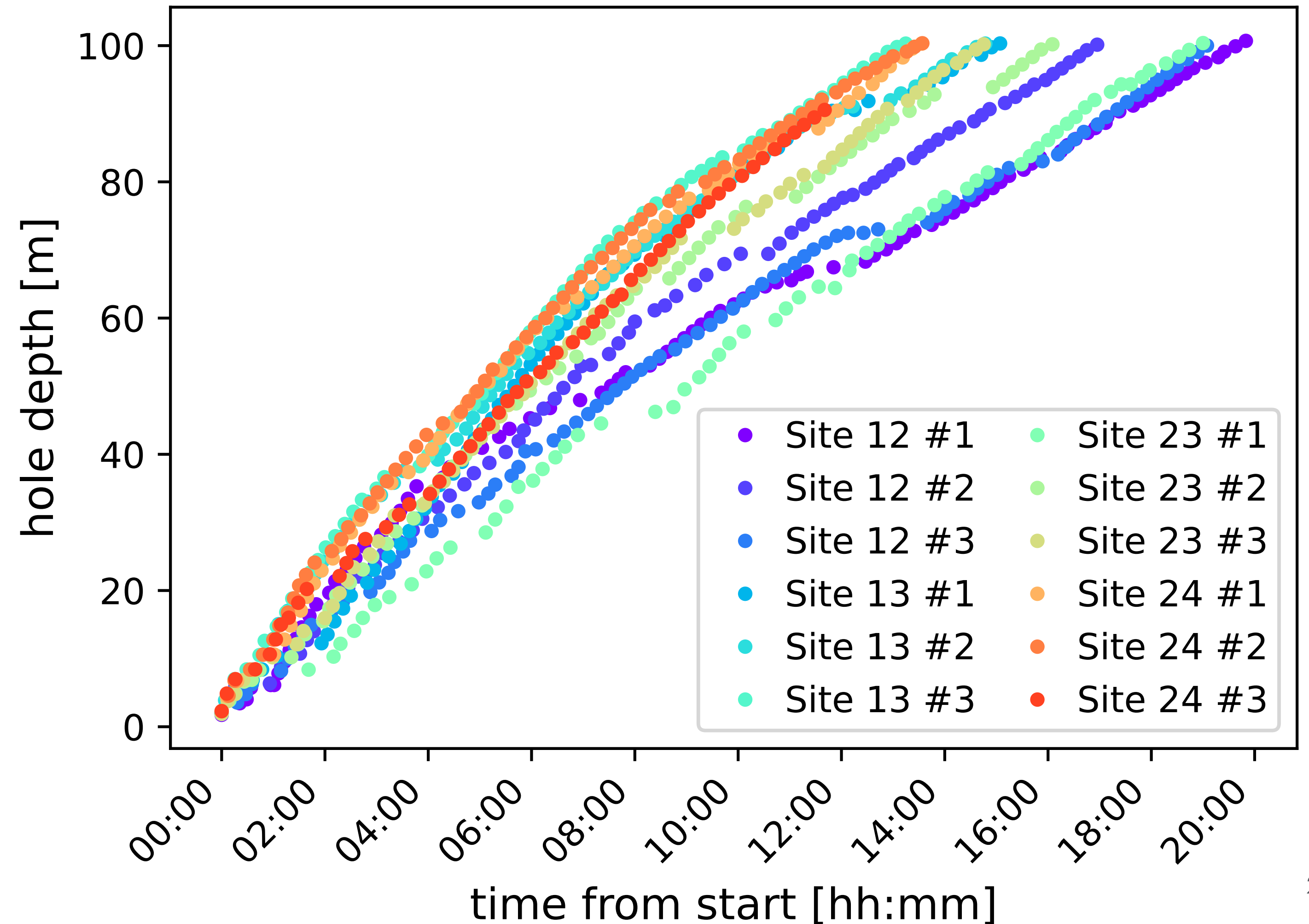
Antenna in deployment hole

Challenges

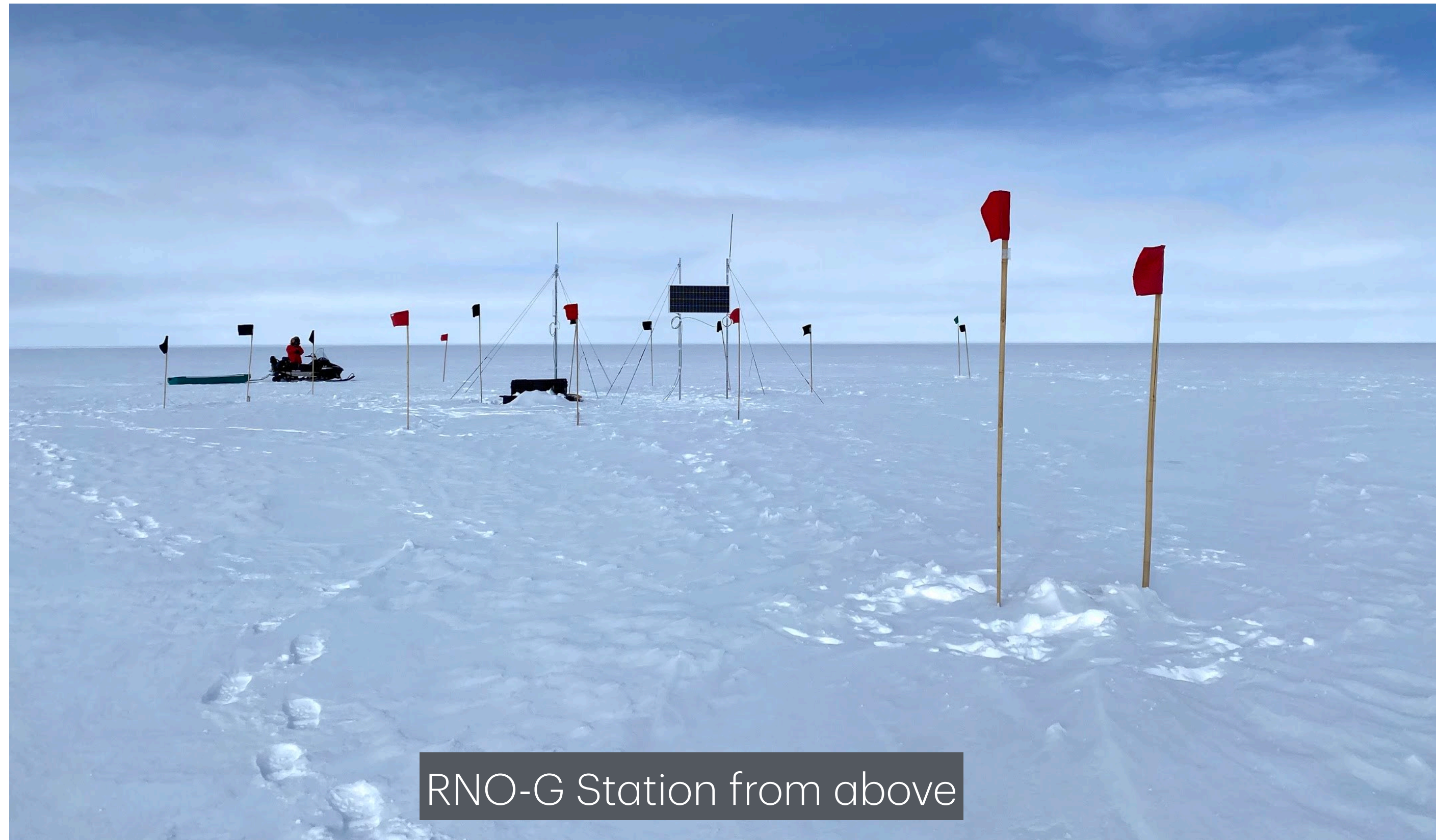
Challenge 1: Drilling

- BigRAID drill: electromechanical, designed specifically for RNO-G
- Drilling holes to 100 m takes time; logistically, it's very hard to drill fast.
- We are getting better at this! Each year, we are improving (and so is the drill)

Credit: Delia Tosi (U. Wisconsin)



Challenge 2: Snow accumulation



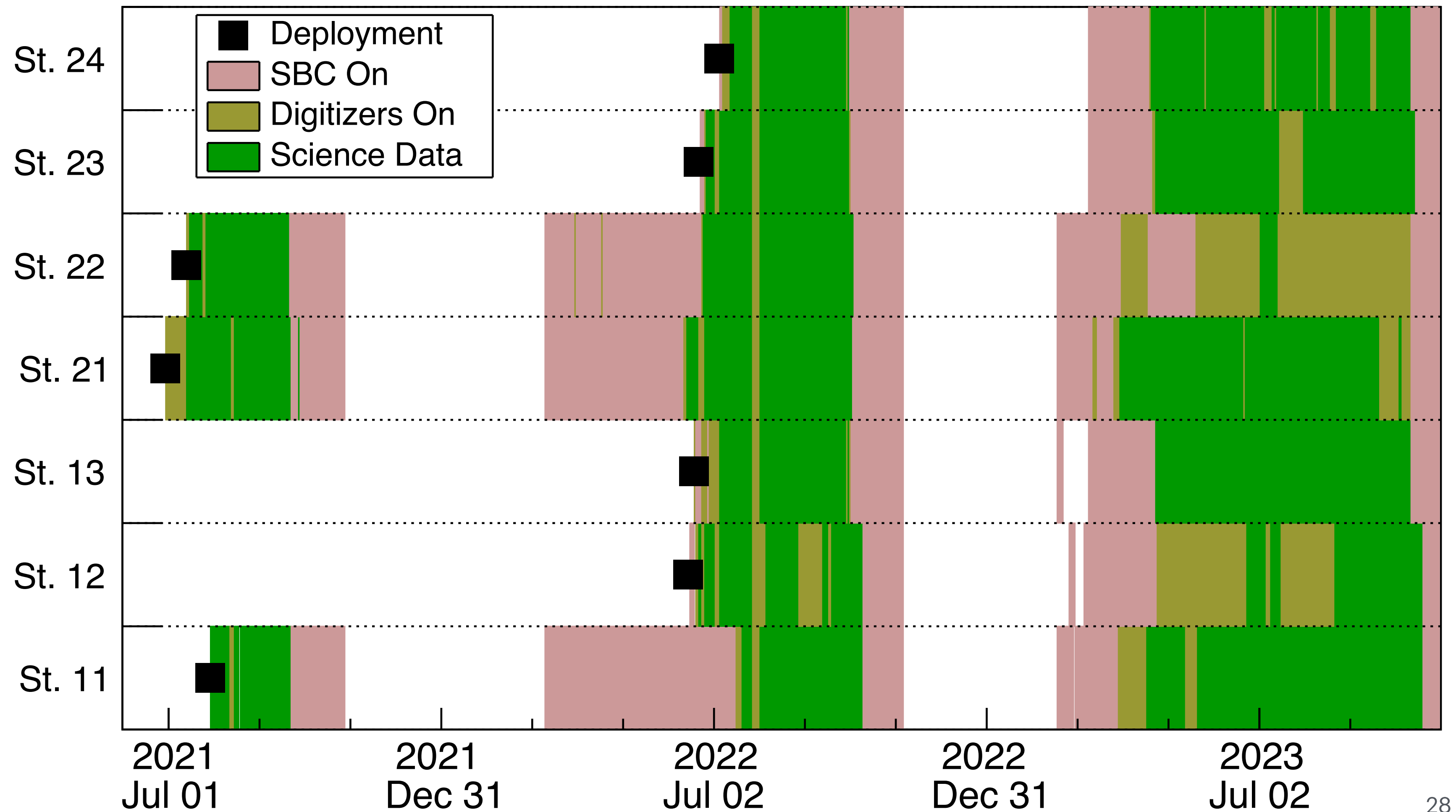
RNO-G Station from above



RNO-G Station from above- 2 years after deployment

Challenge 3: Daylight

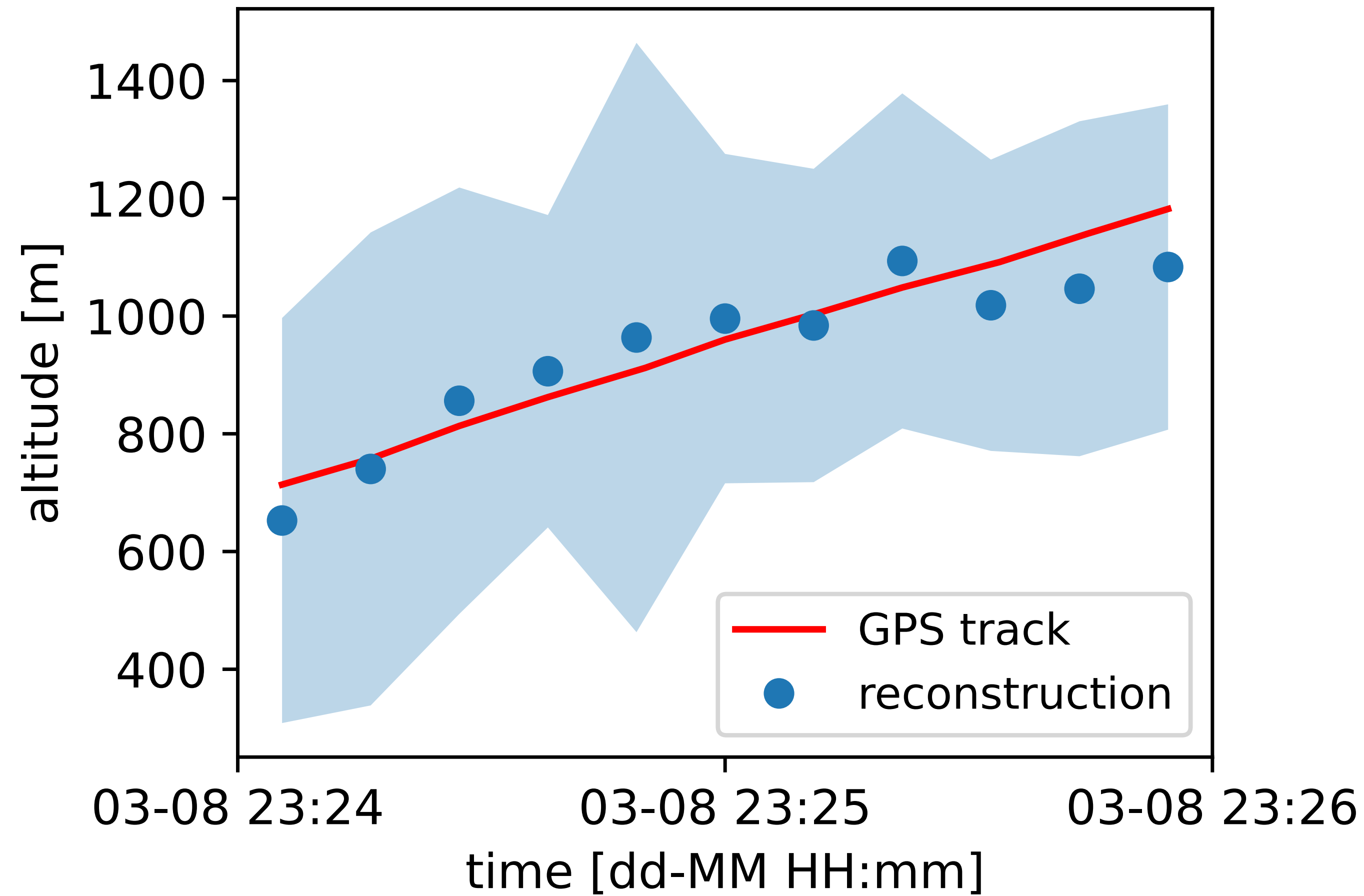
- RNO-G is solar powered- great for building stations many kms from Summit Station
- Downside: can only take data for ~6 months per year
- Wind power is a possible future option



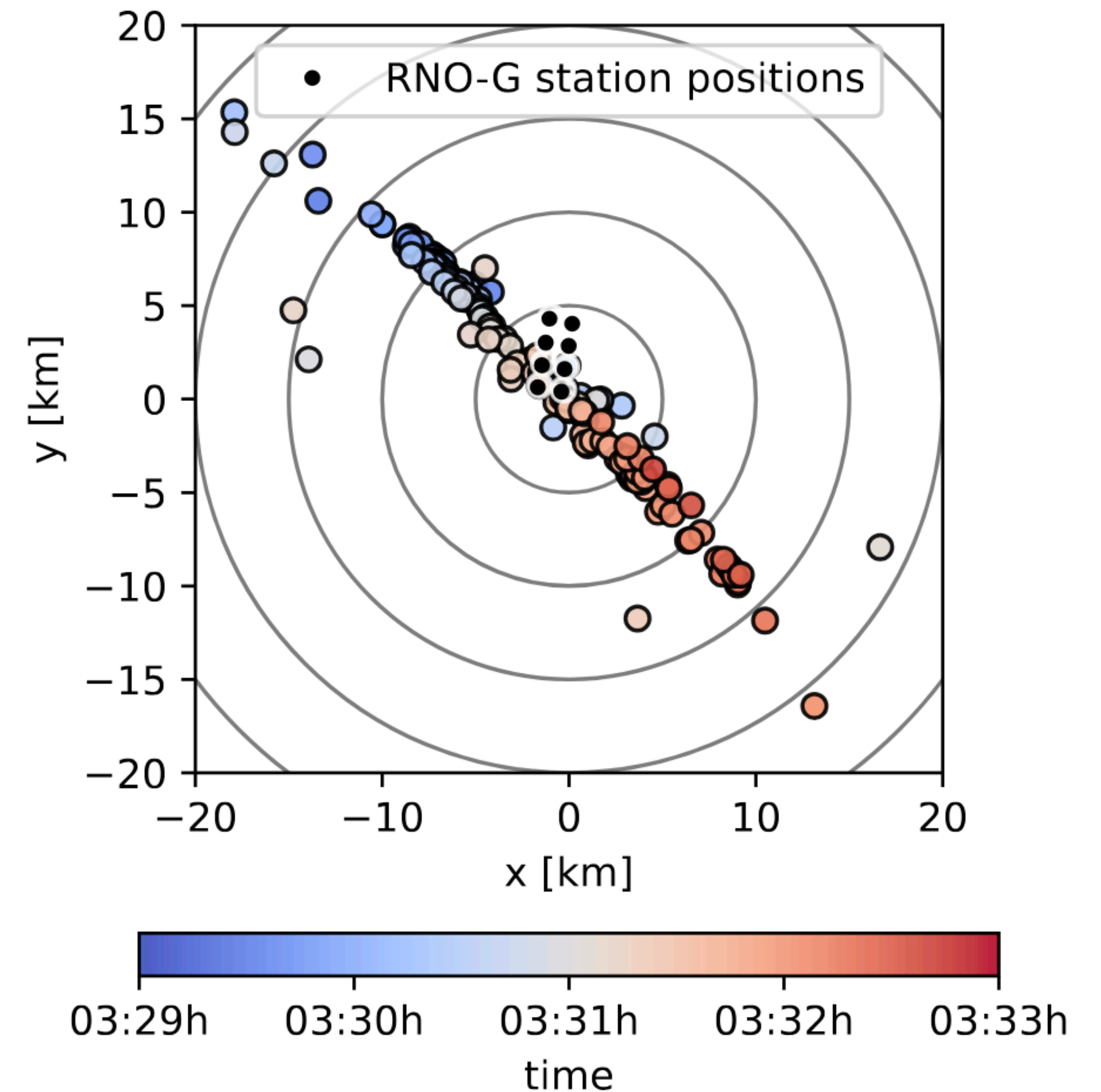
Credit: Cosmin Deaconu (UChicago)

Challenge 4: Human-made noise

Daily Weather Balloon



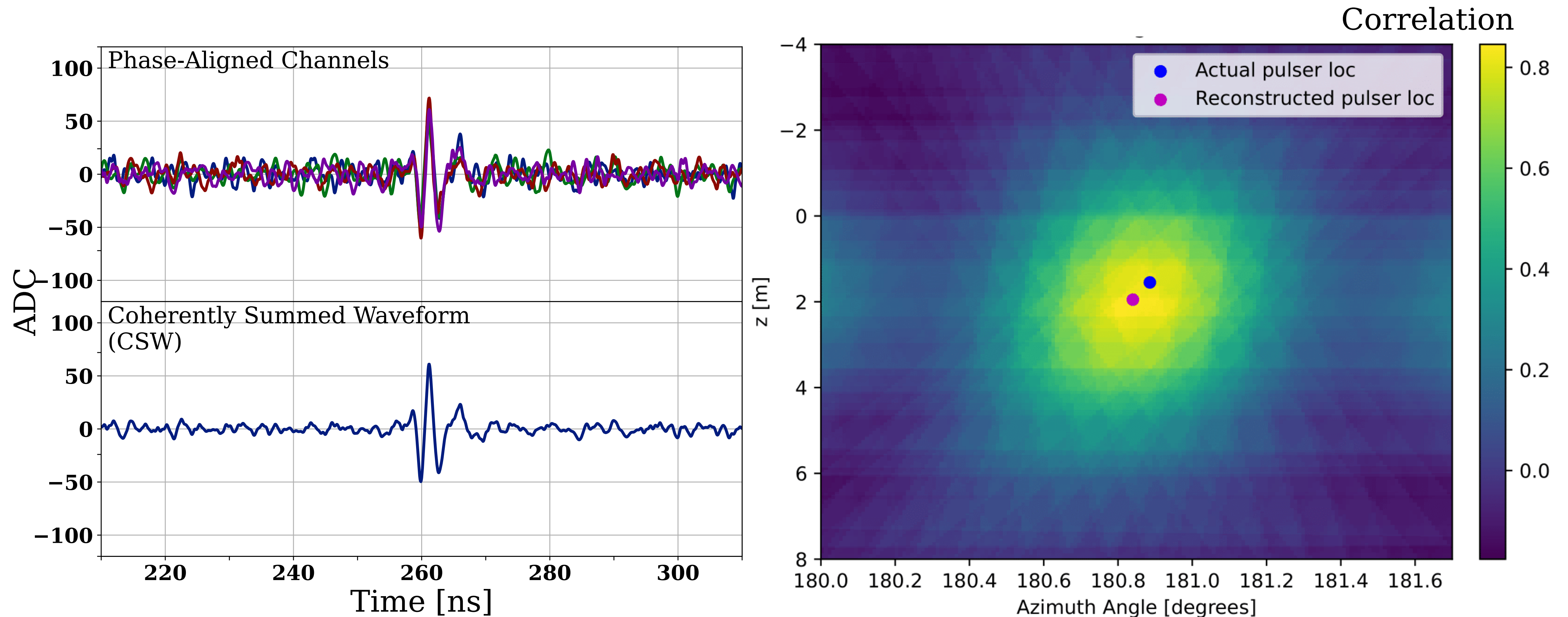
Commercial Airplanes



Led by Steffen Hallmann (DESY)

Challenge 5: Calibration

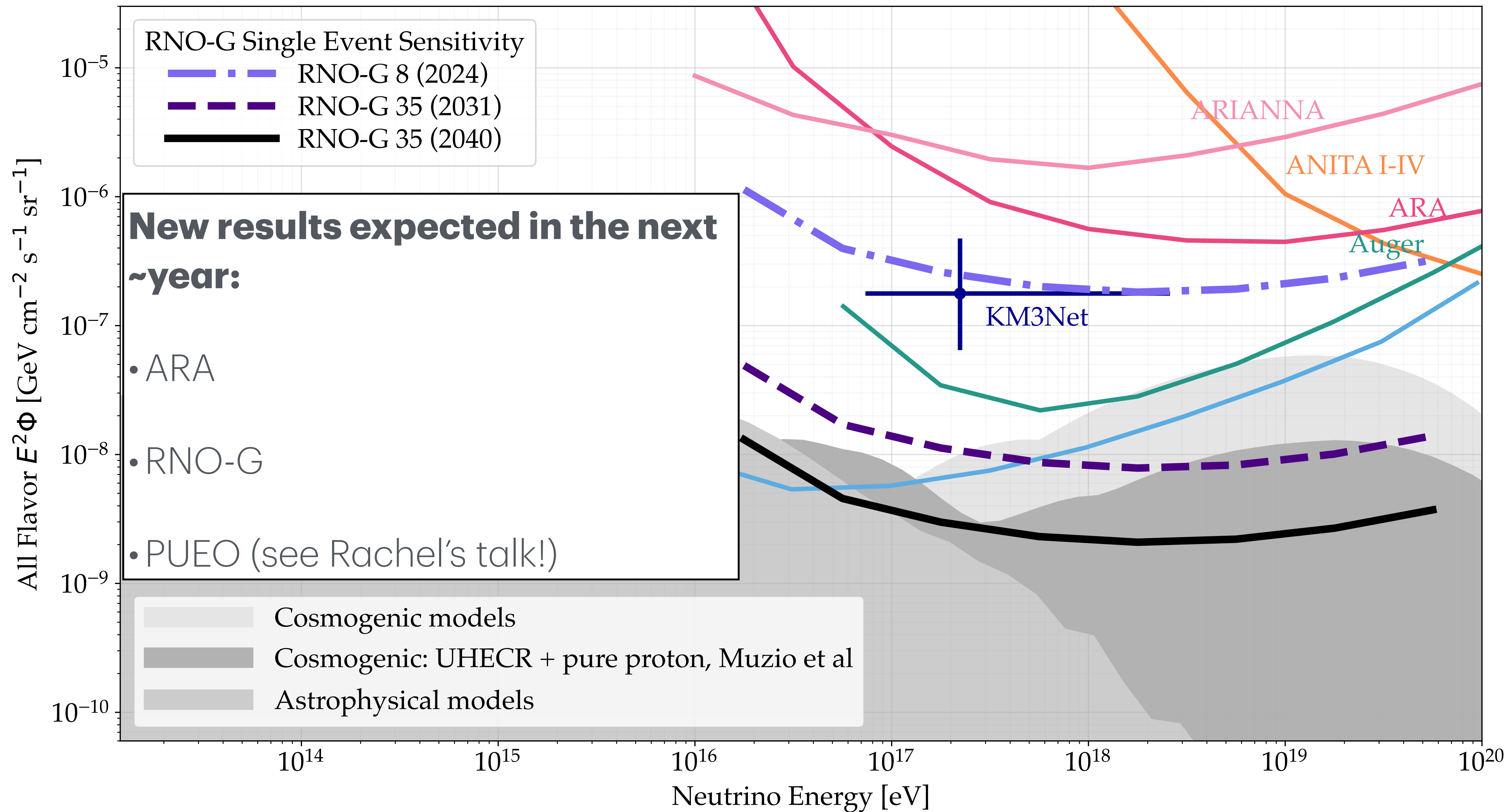
Need < 5 cm error on antenna locations- and a good ice model!



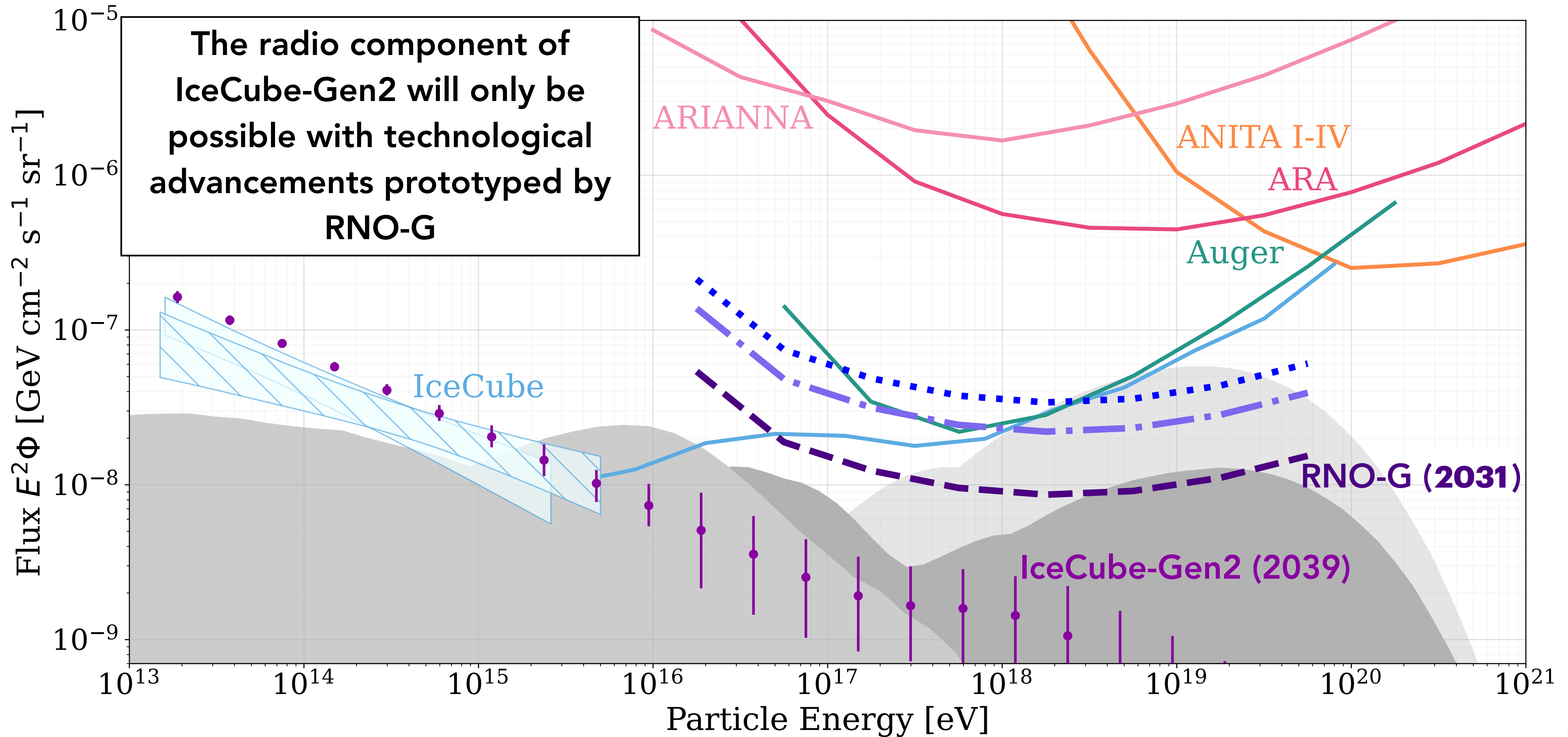
Credit: Bryan Hendricks (PSU)

Building towards the future

Diffuse Flux, 1:1:1 Flavor Ratio



Building towards the future



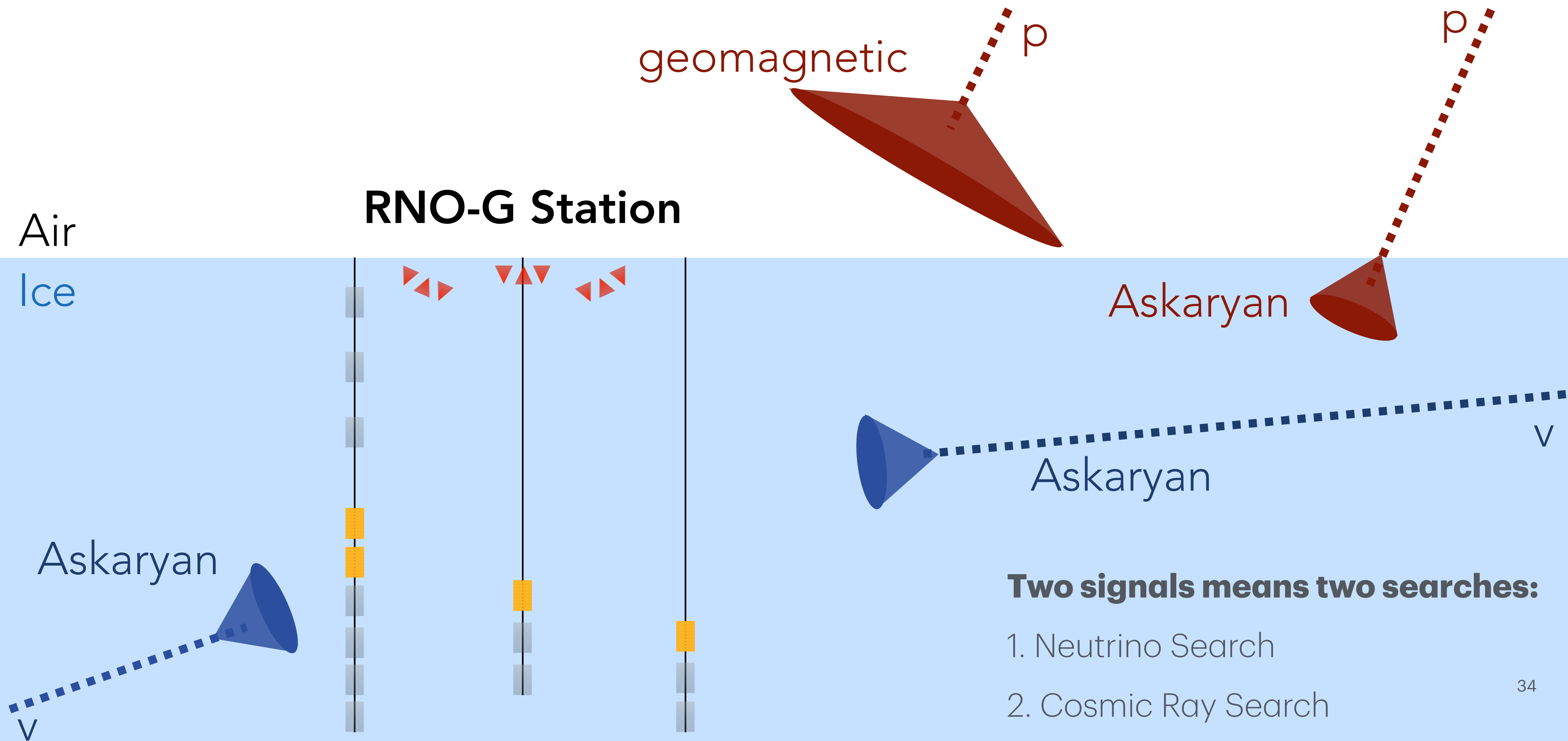
The Next 20 Years

Lots of exciting work on many fronts!

- **Optimistic scenario:** all of these experiments see neutrinos at the highest energies (i.e. the KM3NeT event is not an upward fluctuation!)
 - An excess of events motivates further investment in neutrino telescopes like IceCube Gen2. Maybe also multi-messenger implications?
- **Realistic scenario:** a few experiments see neutrinos
 - Future experiments can be targeted to see these sources
- **Pessimistic scenario:** no experiments see neutrinos
 - This still produces science: models are excluded, and eventually we rethink our understanding of particle physics at the highest energies



Two types of signals

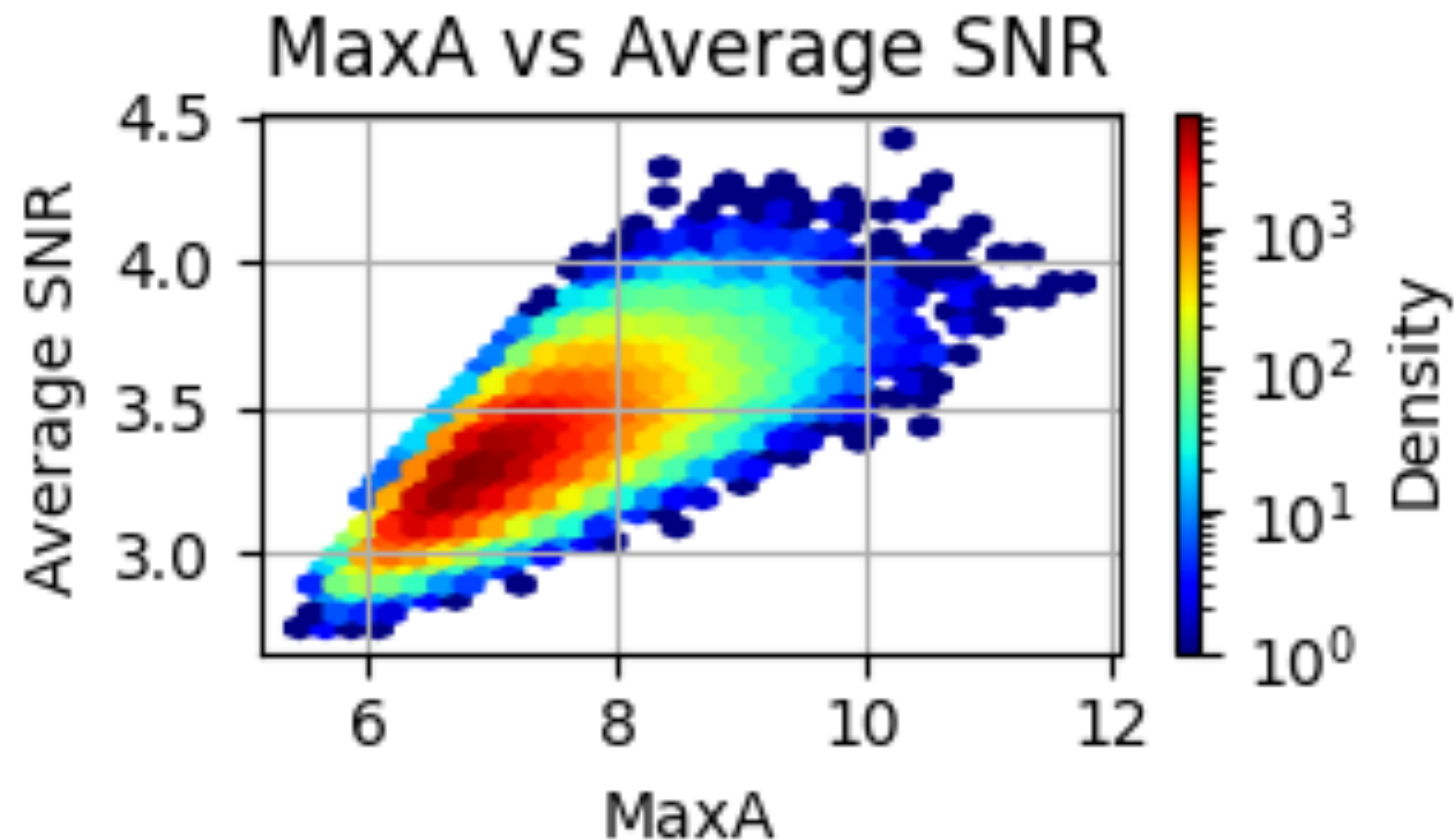


Two signals means two searches:

- 1. Neutrino Search
- 2. Cosmic Ray Search

Building an analysis pipeline

Creating variable distributions



$$SNR = \frac{V_{pp}}{2\sigma}$$

peak to peak voltage

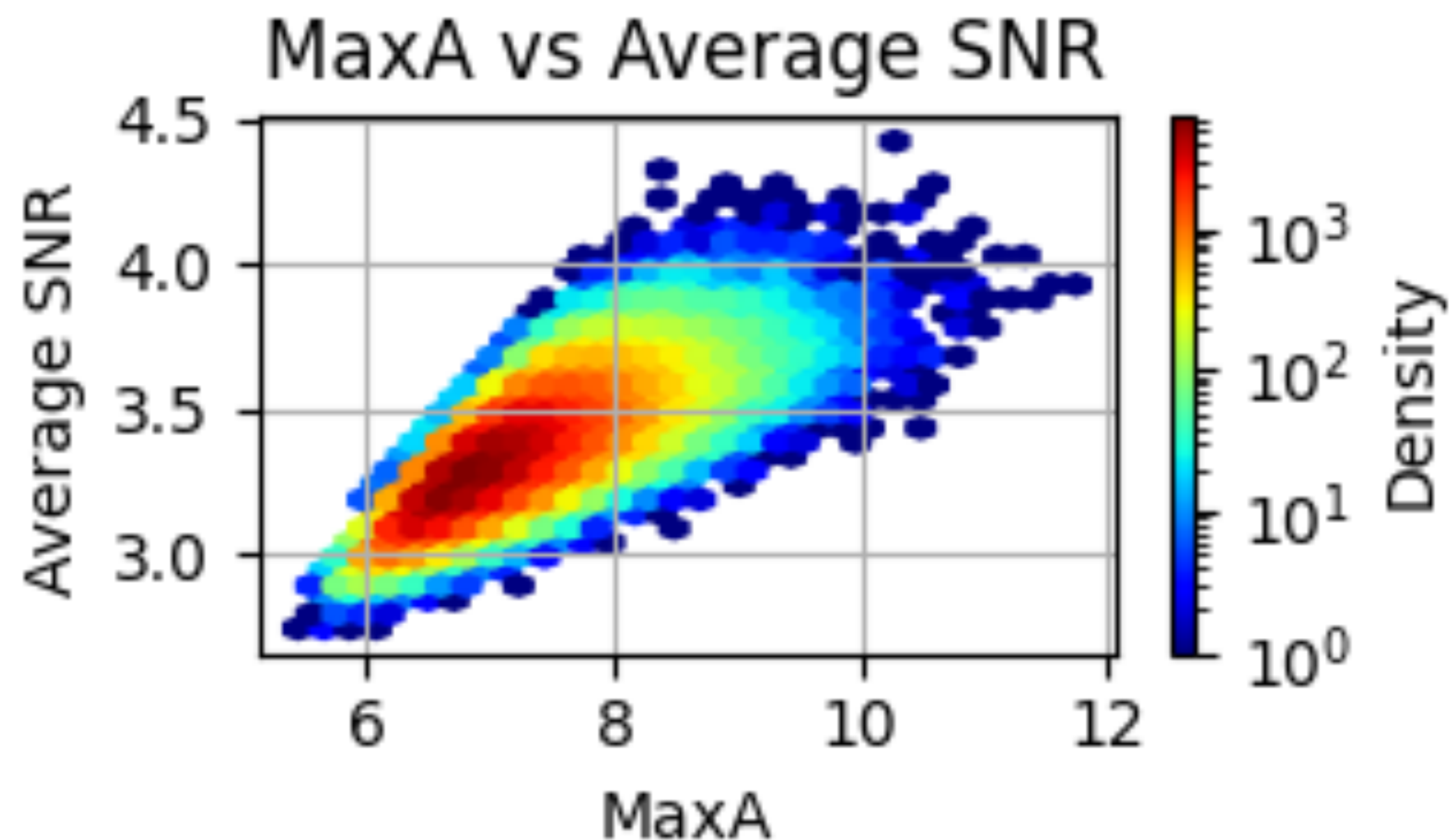
standard deviation of the noise

Maximum amplitude = "max A"

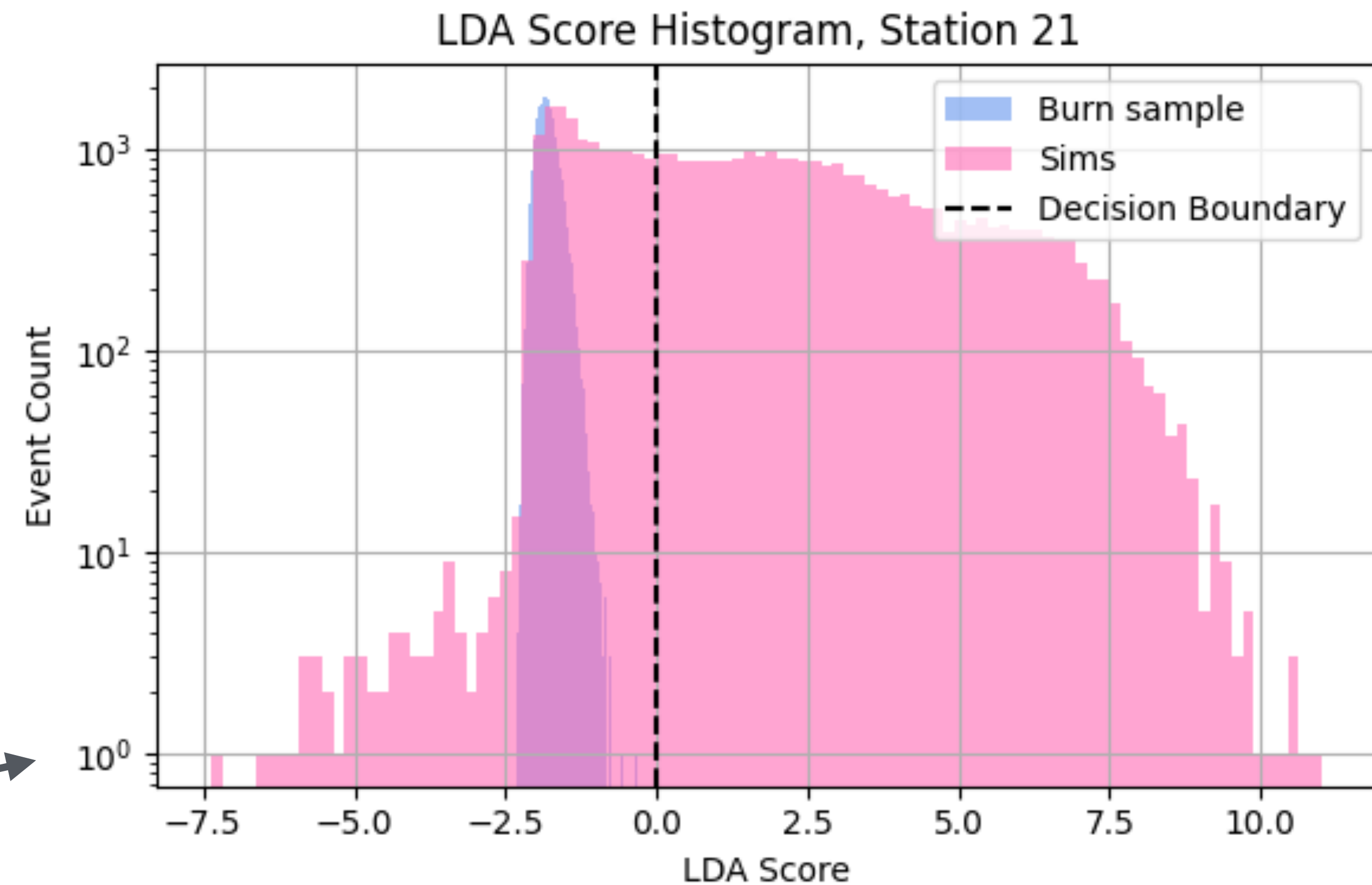
+ other variables: impulsivity, maximum correlation, surface correlation ratio

Building an analysis pipeline

Comparing data to cosmic ray simulation



↓
Combining all analysis variables into a linear discriminant



Building an analysis pipeline

Using *icemc* simulation as a playground for machine learning methods testing

