Status of the Radar Echo Telescope (RET)

Steven Prohira

CIPANP 2025

June, 10, 2025

What is the Radar Echo Telescope?

- **The Radar Echo Telescope (RET)** is a **next-generation ultrahigh energy neutrino detector**

  But before we get to RET...

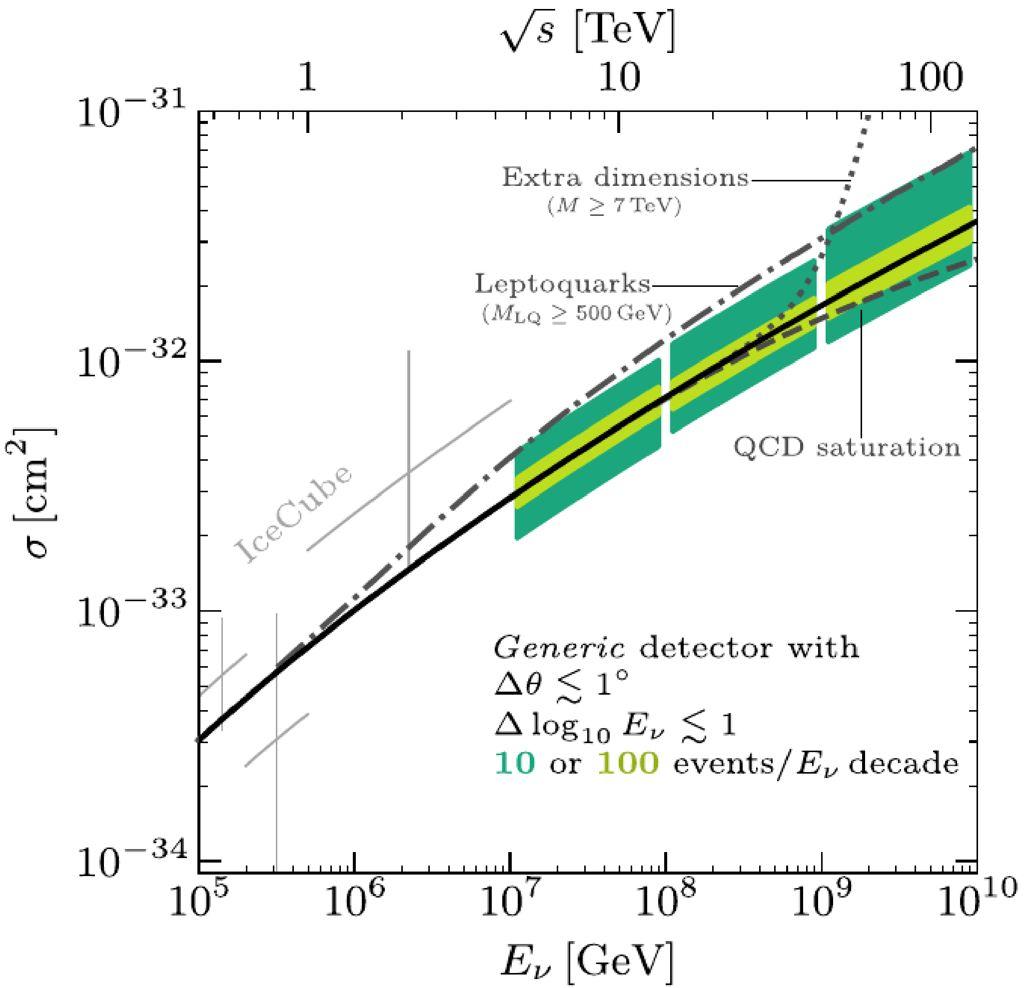
- Why do we care about **ultrahigh energy (UHE) neutrinos?**
  - Two avenues of interest:
    - Particle physics
    - Astrophysics

Why neutrinos?

- Neutrinos **are** a part of the standard model
- **But...**they have properties that **are not explained** by the standard model
  - Most notably: neutrino oscillations indicate nonzero neutrino masses!
- They therefore an observed particle that gives us a glimpse into physics **beyond the standard model!**

UHE neutrinos – Particle

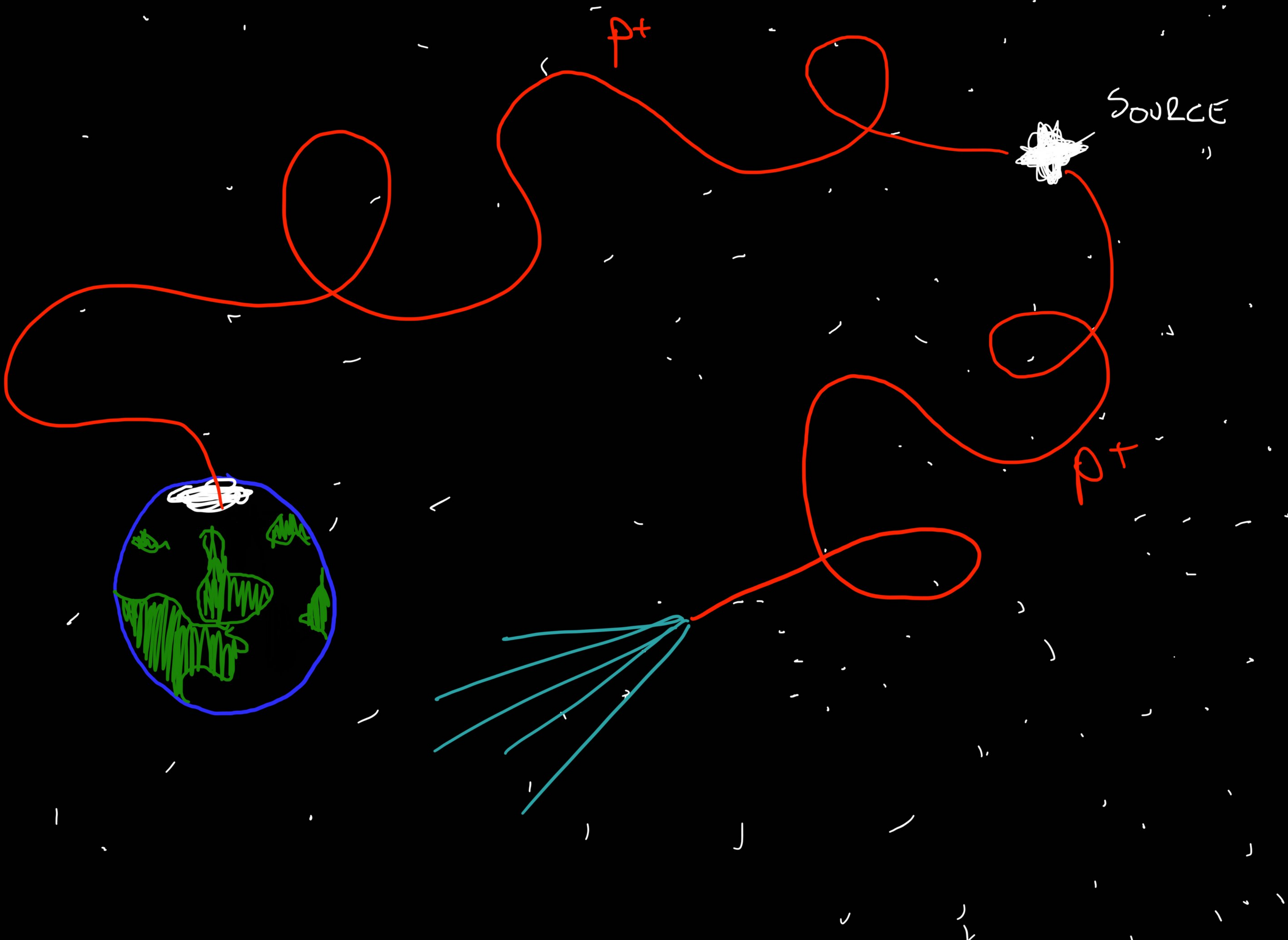
- Ultrahigh energy (UHE), above 10^16ish eV
- Figure shows the standard model neutrino-nucleon cross section
- For a **generic detector with 1 degree angular resolution and 1 decade energy resolution, tens of events** may constrain some BSM physics models!
- Moreover: complementary measurements ***from different detectors*** can span the parameter space!



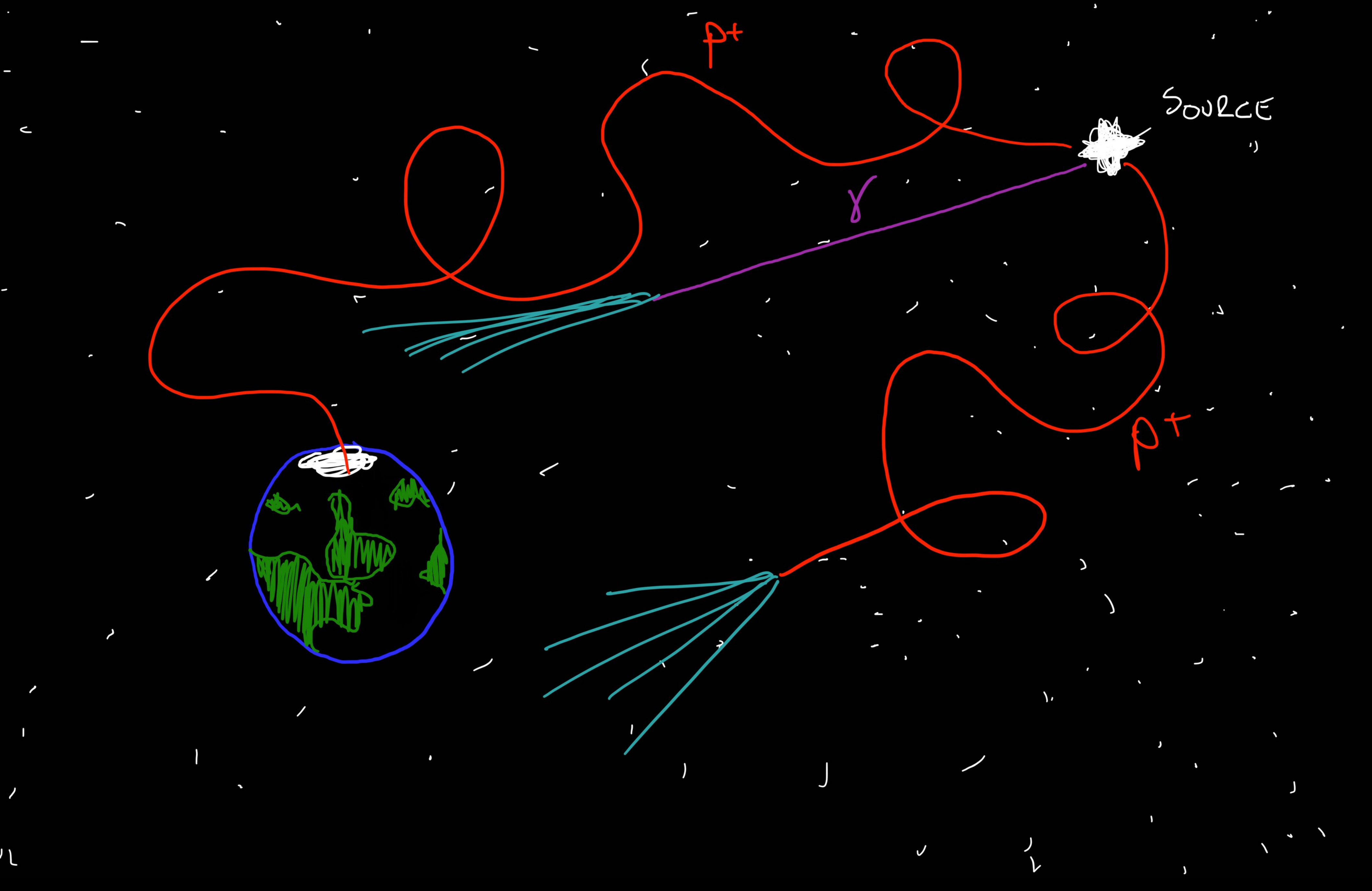
Esteban, Beacom, **SP** arxiv:2205.09763

UHE neutrinos-astrophysics

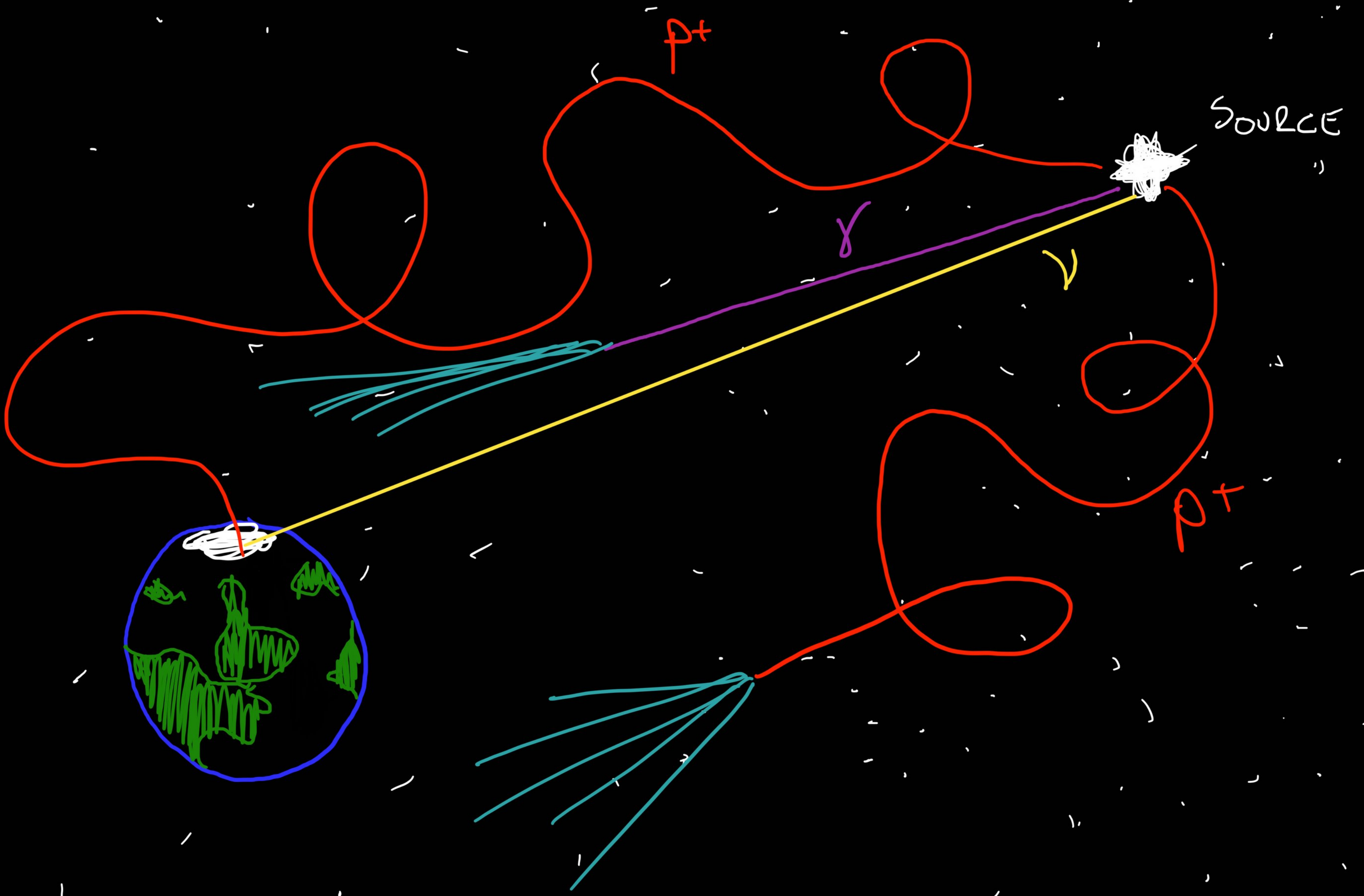
UHE neutrinos-astrophysics



UHE neutrinos-astrophysics

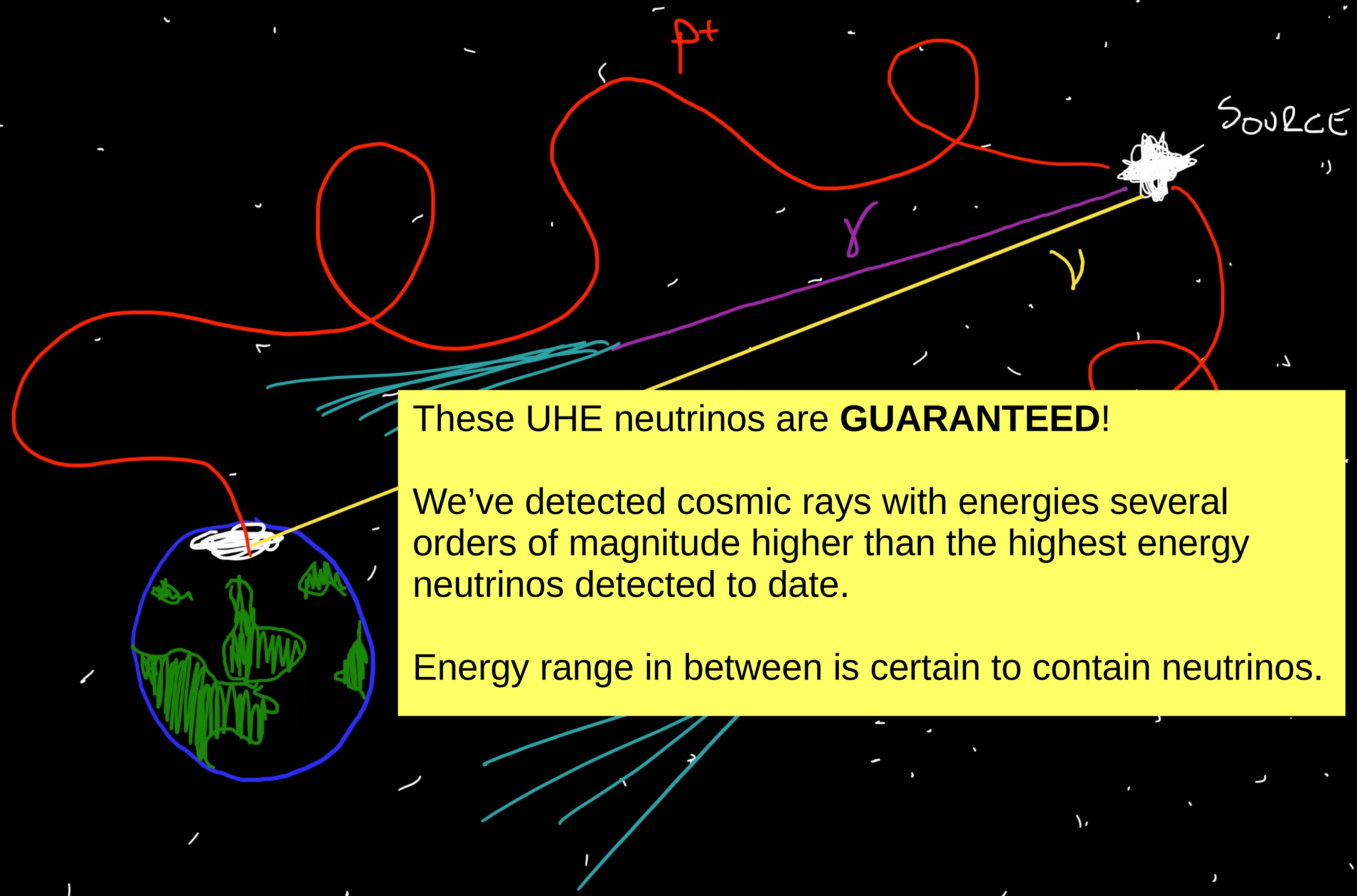


UHE neutrinos-astrophysics



-Neutrinos can reach earth when other particle messengers cannot
AND they point back to their sources!!

UHE neutrinos-astrophysics



These UHE neutrinos are **GUARANTEED**!

We've detected cosmic rays with energies several orders of magnitude higher than the highest energy neutrinos detected to date.

Energy range in between is certain to contain neutrinos.

-Neutrinos can reach earth when other particle messengers cannot
AND they point back to their sources!!

So why haven't we seen any?

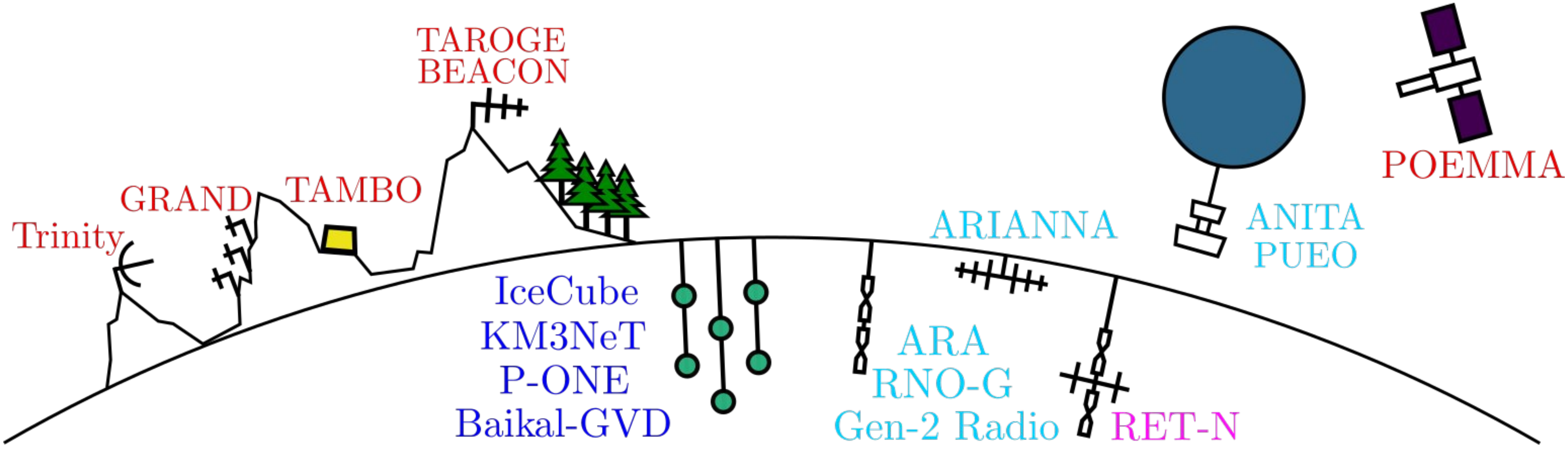
- Extremely low flux and small cross section. Lack of observation of >**100PeV*** neutrinos in current detectors suggests the rate is as low as 1/km^{3}sr/decade at this energy.
- 2 options:
  - scale up detector size (*expensive)*
  - wait a long, long time: (*boring)*

** until KM3Net's recent detection, this used to say 10PeV!*

So why haven't we seen any?

- Extremely low flux and small cross section. Lack of observation of >100PeV neutrinos in current detectors suggests the rate is as low as $1/km^3 sr/decade$ at this energy.
- 2 options:
  - scale up detector size (*expensive*)
  - wait a long, long time: (*boring*)
- *Or actually...3rd option*
  - develop a new technology that can instrument a much larger volume much more efficiently
    - want to not only detect UHE neutrinos, but study them. for that, we need statistics.

RET in context



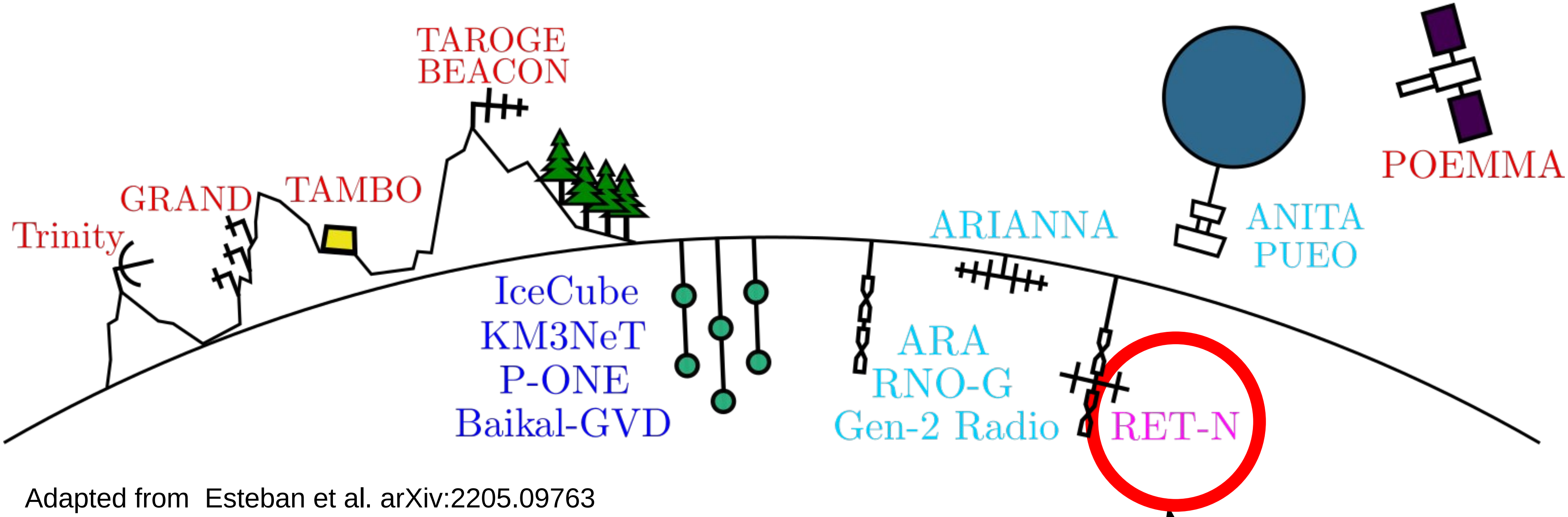
Adapted from Esteban et al. arXiv:2205.09763

Tau neutrino (optical+radio)
Askaryan (radio Cherenkov)
In-ice Optical Cherenkov
Radar

This cartoon shows many of the current and proposed experiments to measure VHE and UHE neutrinos.

Each has strengths and weaknesses, but the different physics underlying each method provides **different observables.**

RET in context

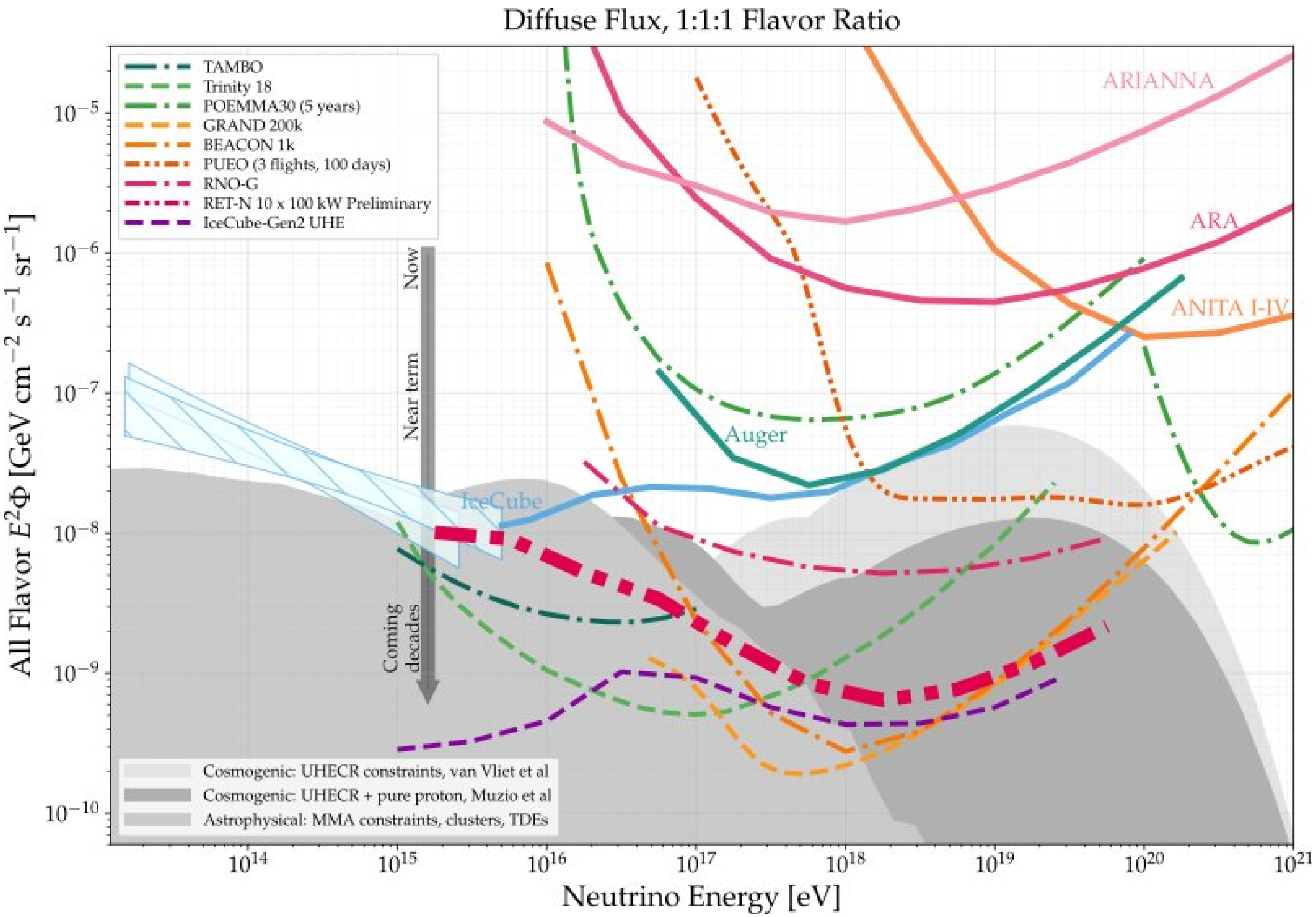


Adapted from Esteban et al. arXiv:2205.09763

Tau neutrino (optical+radio)
Askaryan (radio Cherenkov)
In-ice Optical Cherenkov
Radar

Today I'm going to discuss one new (old) technology (*though they are all interesting and promising!*) **the radar echo method.**

RET sensitivity in context



Adapted from UHE neutrinos Snowmass paper arXiv:2203.08096, highlighting RET curve.

RET **10 stations,** 10 years, thick red dashed curve (highlighted for emphasis)

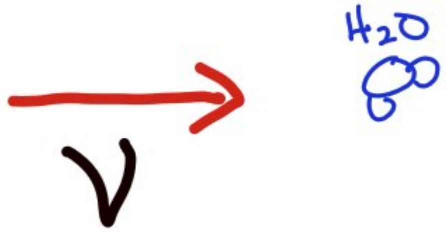
To my knowledge, we require the fewest number of stations of any ground-based radio method.

Also shown: Many experiments with different sensitivities

More on this later.

Concept #1: particle cascades

- relativistic cascade particles are produced through neutrino interactions
- cascade particles *ionize* the material, leaving behind a dense, short-lived cloud of charge



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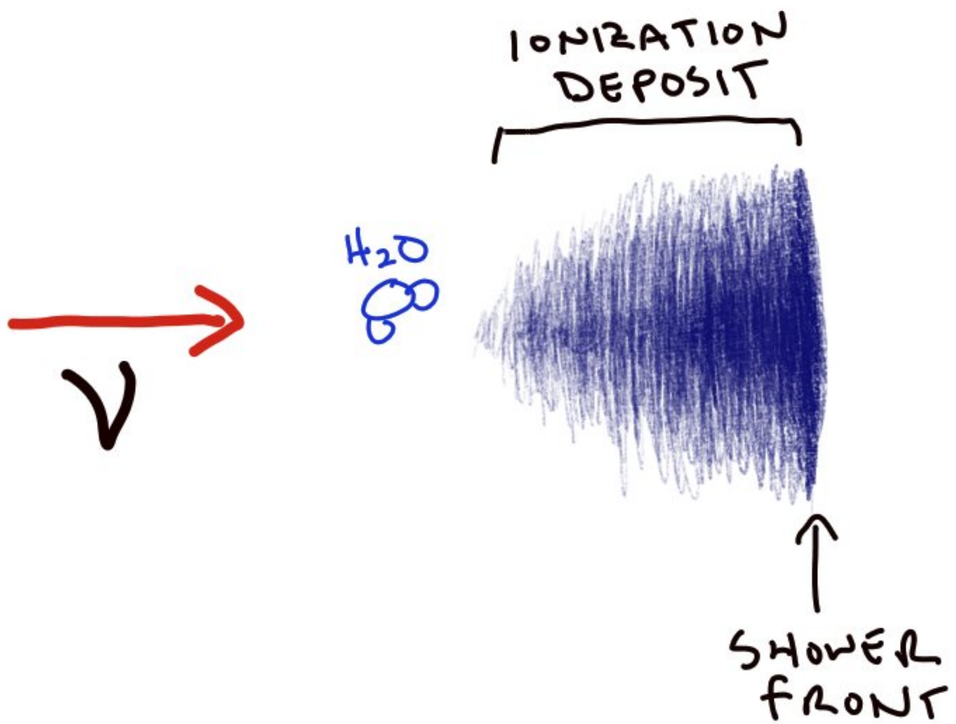

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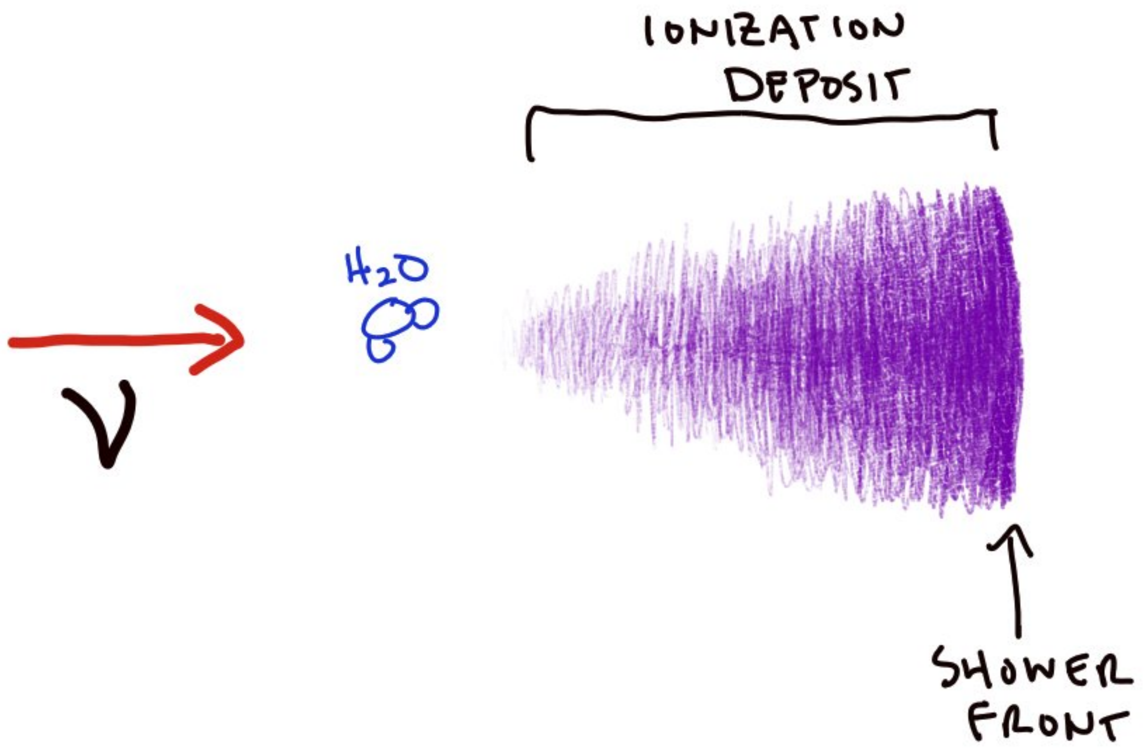

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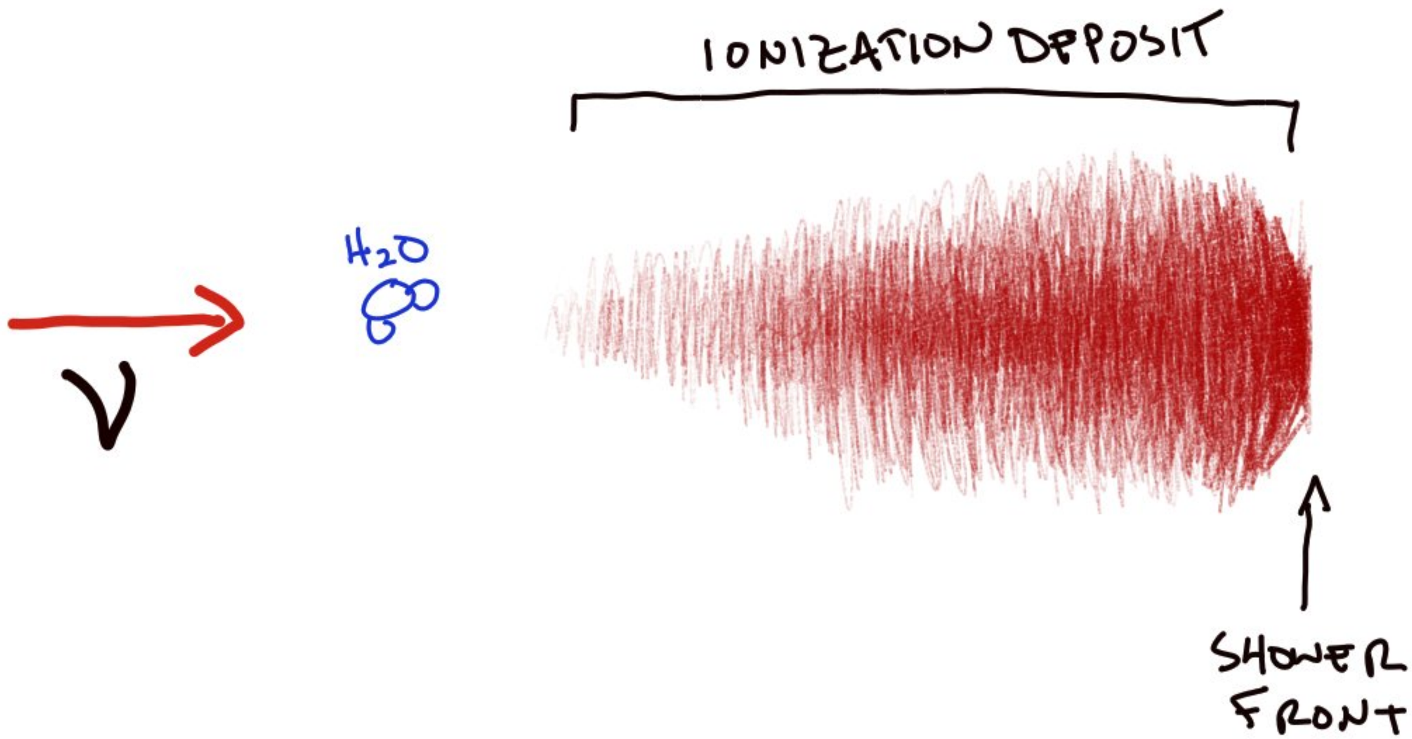
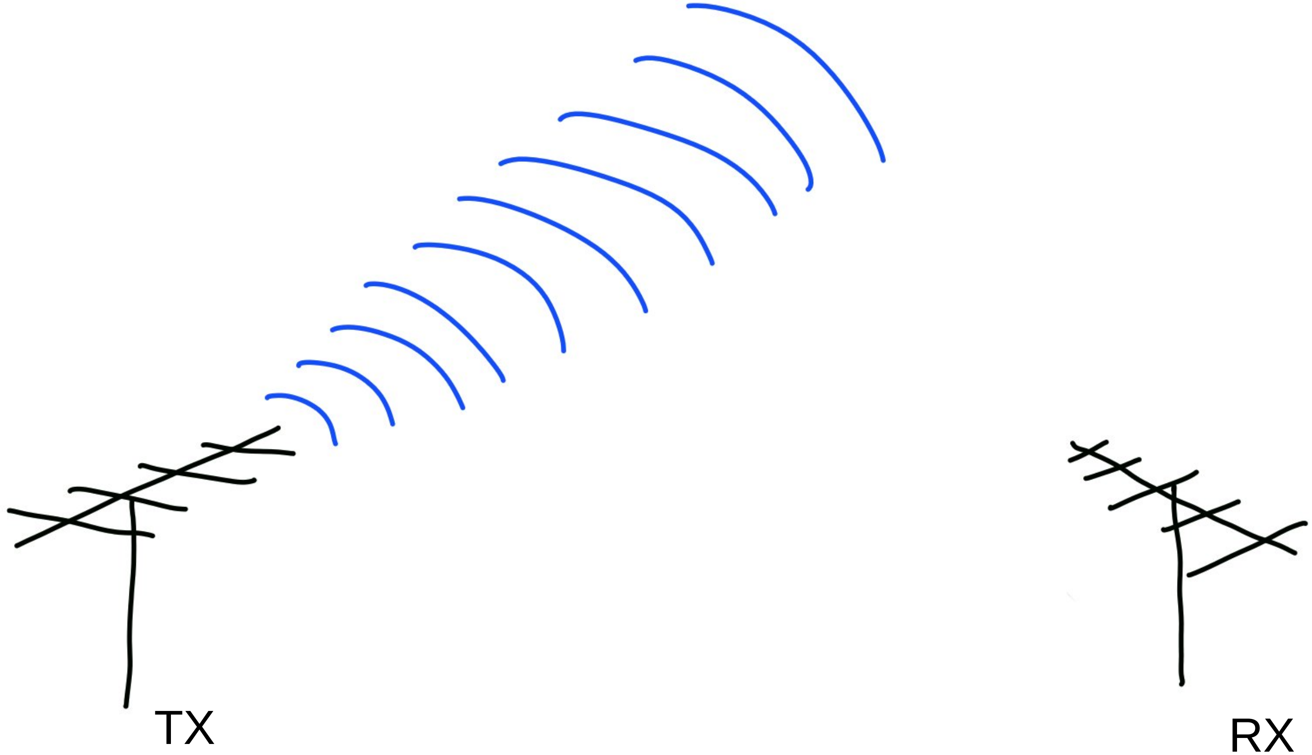
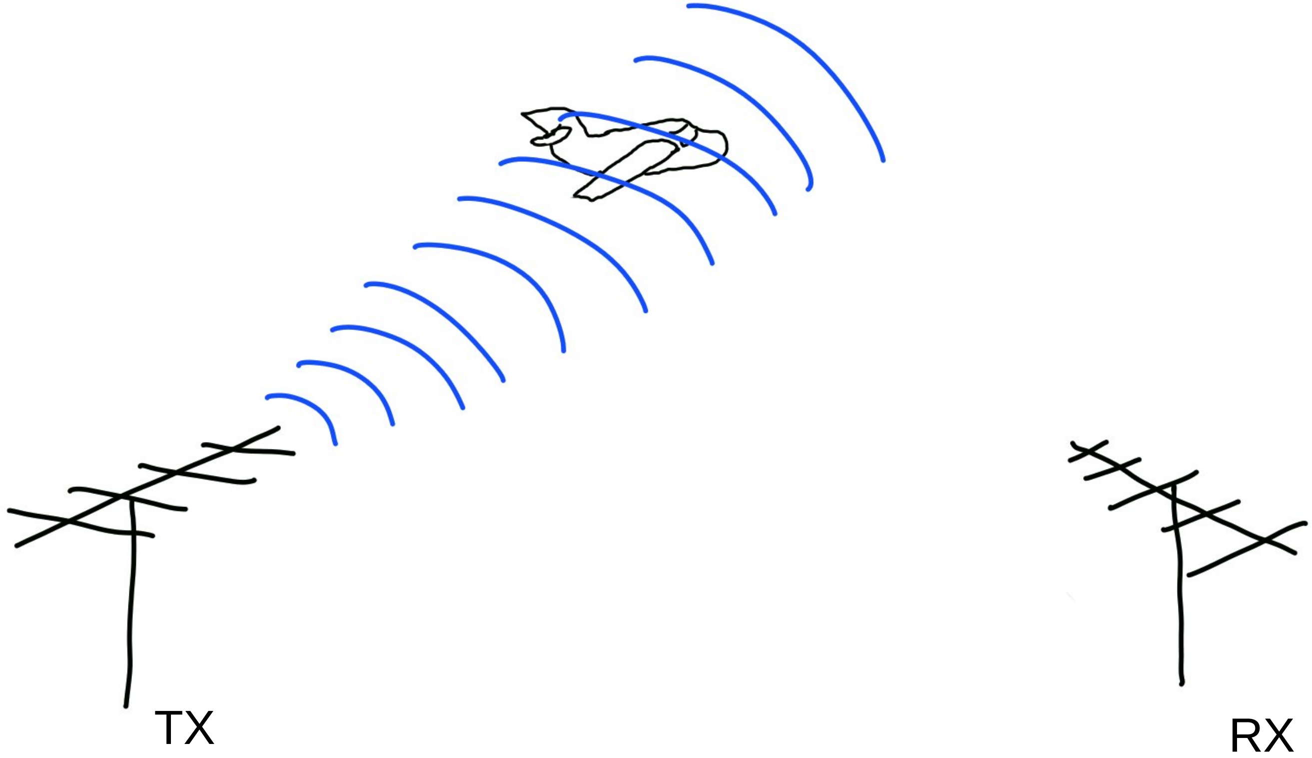


Concept #2: radar overview



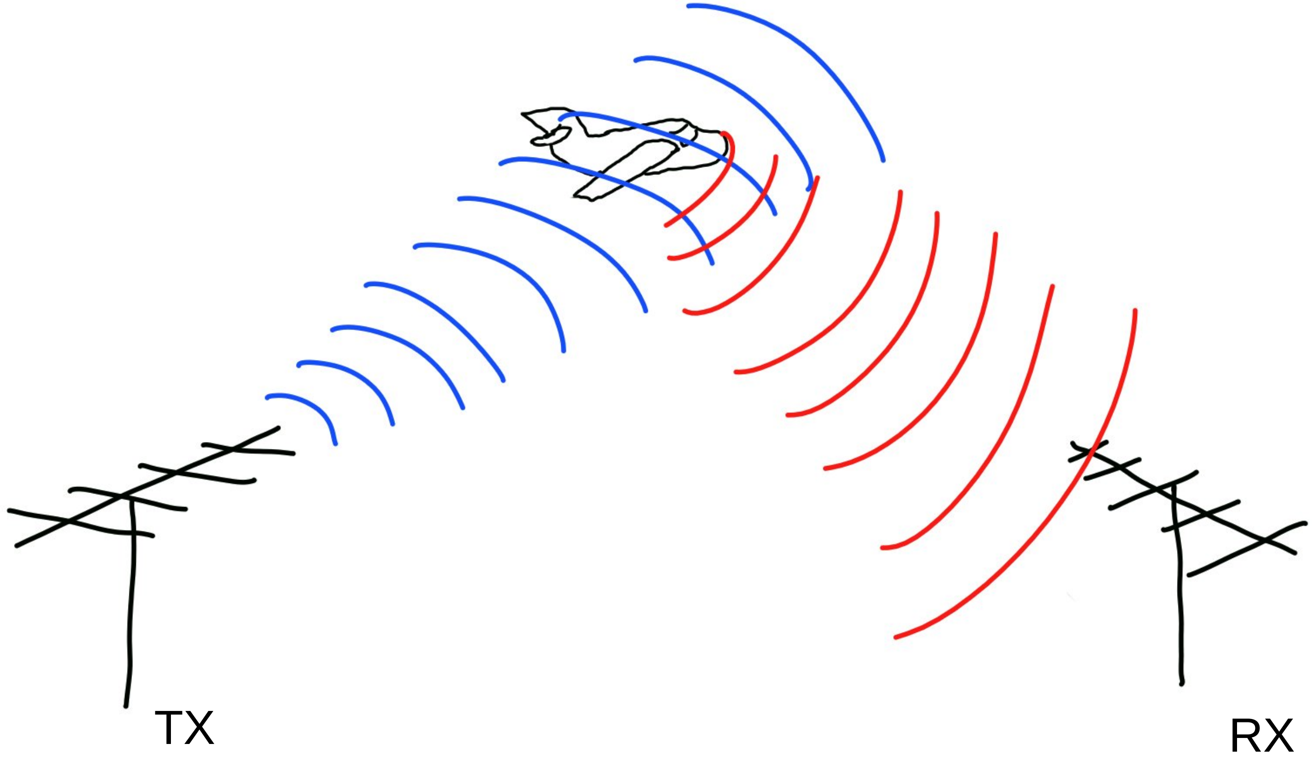
- Transmitter (TX) broadcasts a radio signal into a volume
- Receiver(s)(RX) monitor this same volume

Concept #2: radar overview



- Transmitter (TX) broadcasts a radio signal into a volume
- Receiver(s)(RX) monitor this same volume
- If a reflective surface lives in this volume, the transmitted signal will be reflected to the receiver(s)

Concept #2: radar overview



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radar detection of neutrinos

(Simple) Big Picture Concept:

Bounce radio waves off of the ionization deposit left in the wake of a neutrino-induced cascade.

Not a new idea!

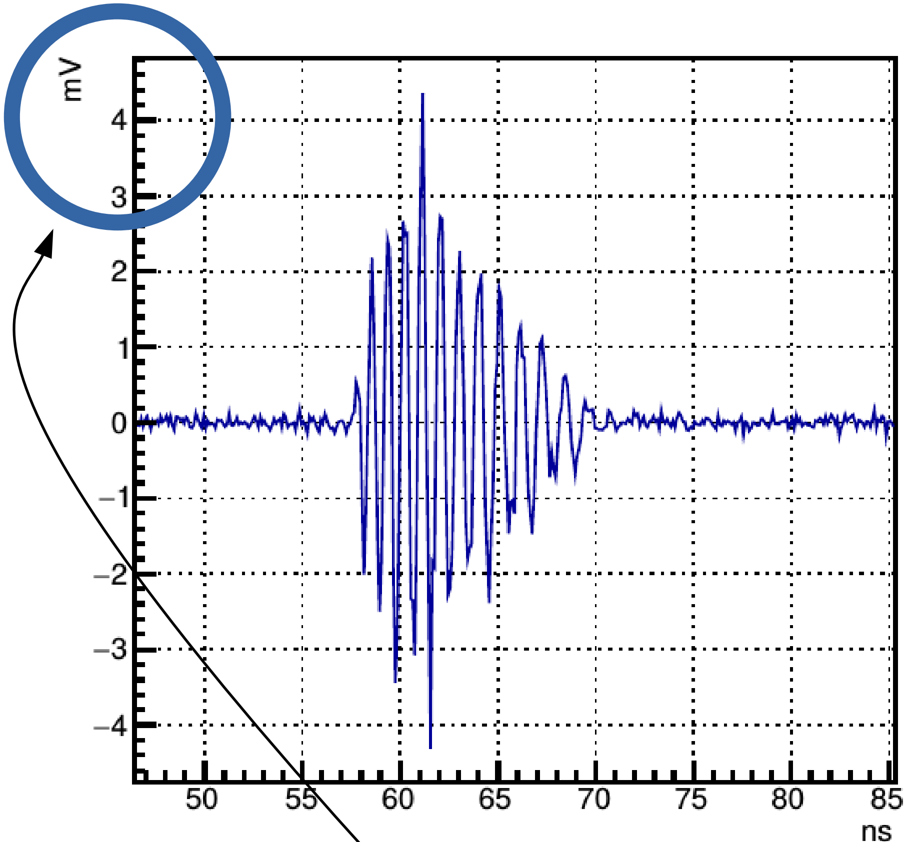
Idea to detect cosmic rays *in the atmosphere* dates back to 1940, with additional experimentation in the 60s and early 2000s
(for history and references: radarechotelescope.org)

Radar is dead. Long Live Radar!

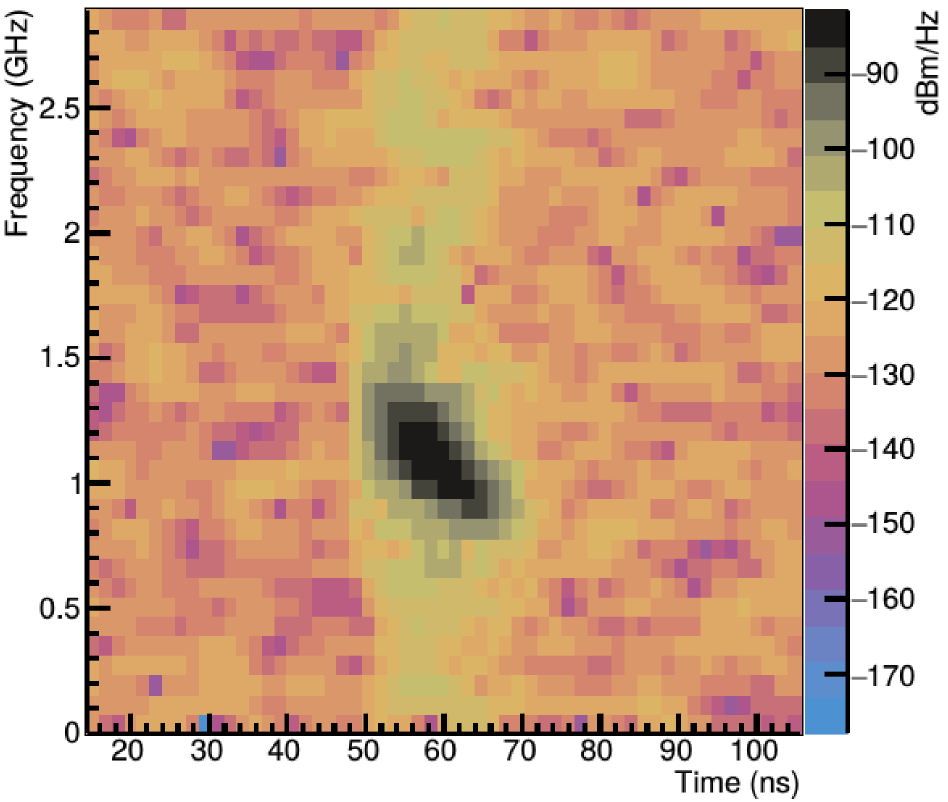
RET Co-PI

Turns out the ionization density in air is not high enough (for several reasons) for this to work in air. But what about in ice? K.D. De Vries, K Hansen and T Meures and Chiba et al. in 2000s that this could work for neutrinos

making the signal

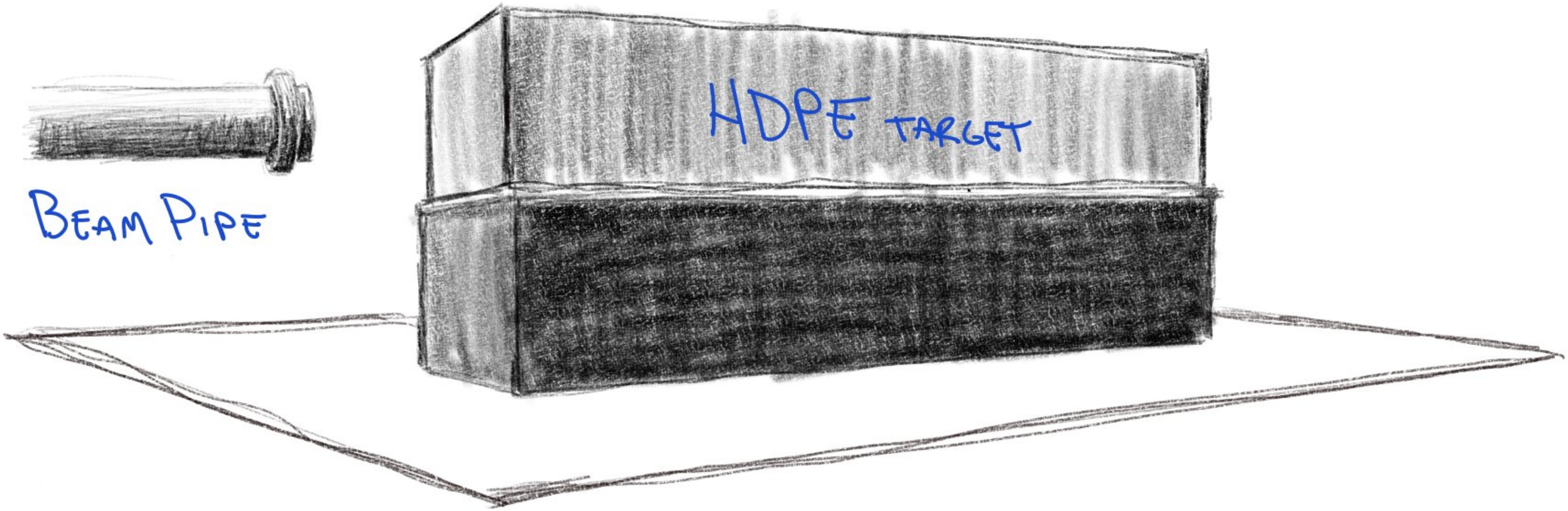


arXiv:1710.02883



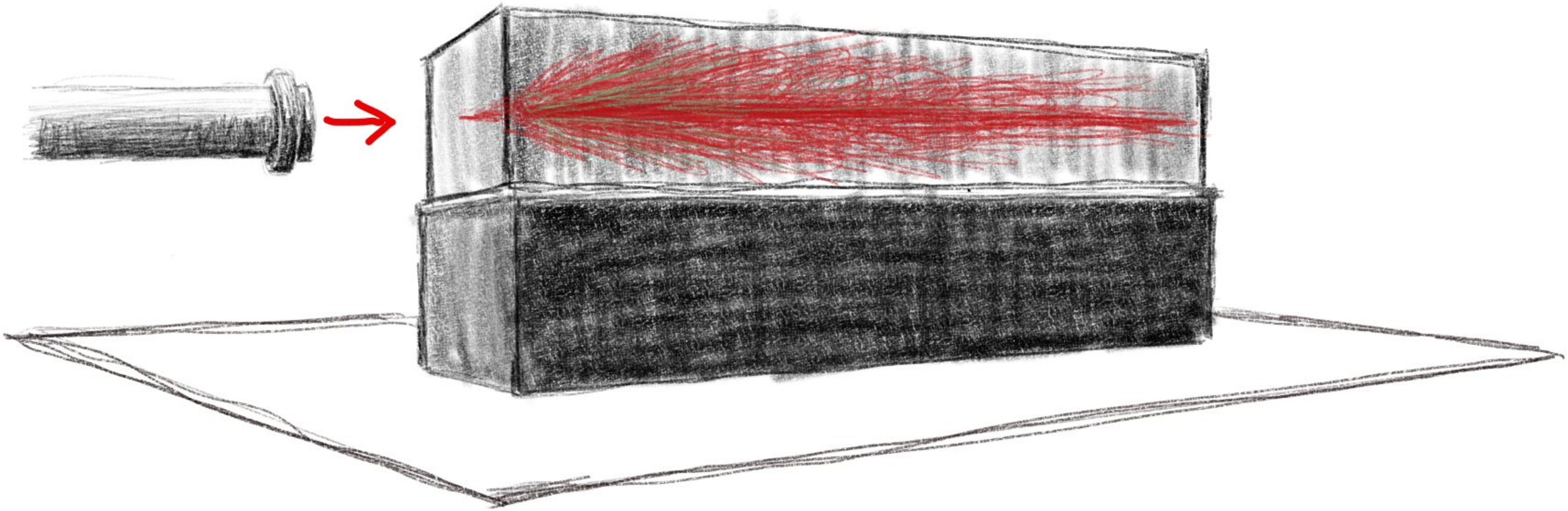
We can detect this!!

Idea:



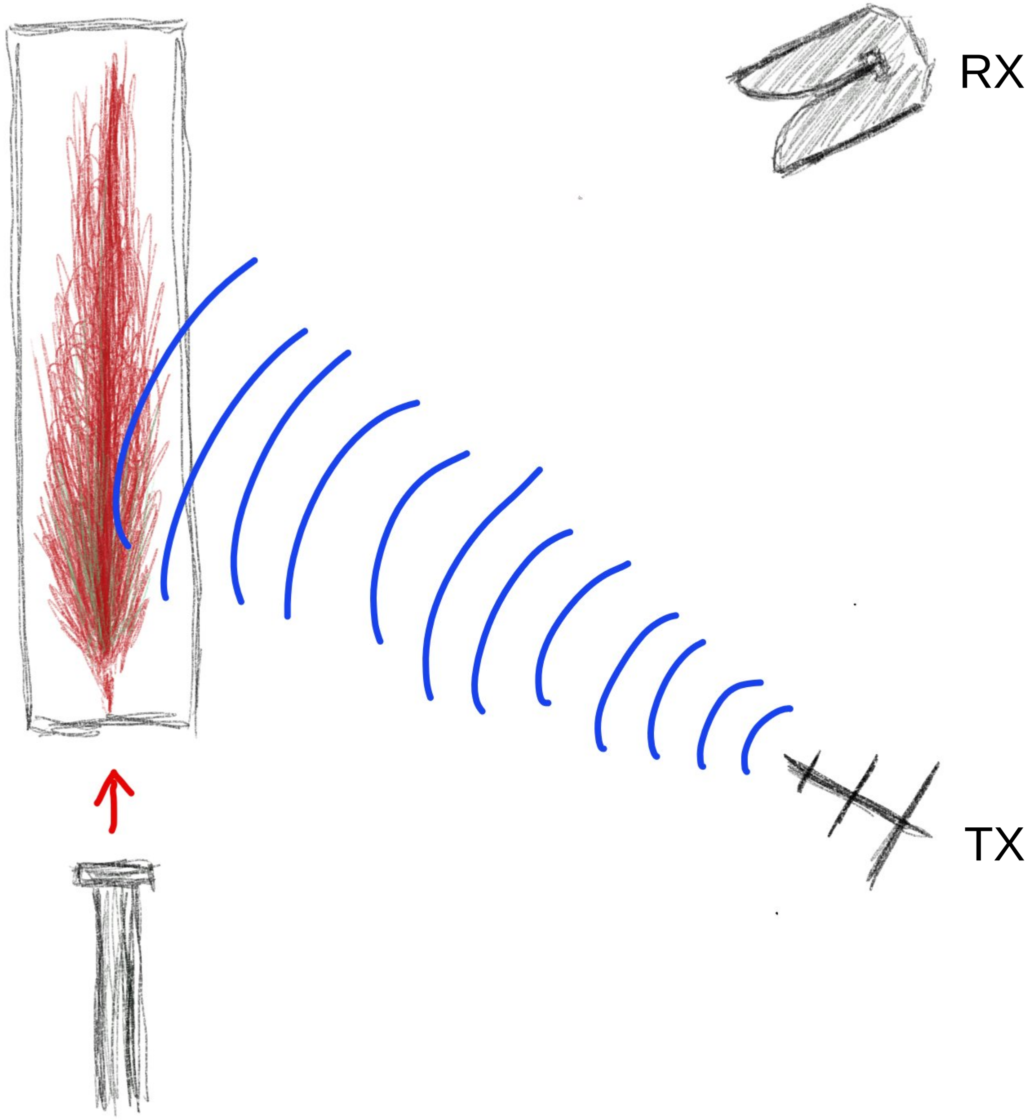
- **Direct a particle beam into a plastic target in the lab**
- beam: ~ neutrino
- target: ~ice

Idea:



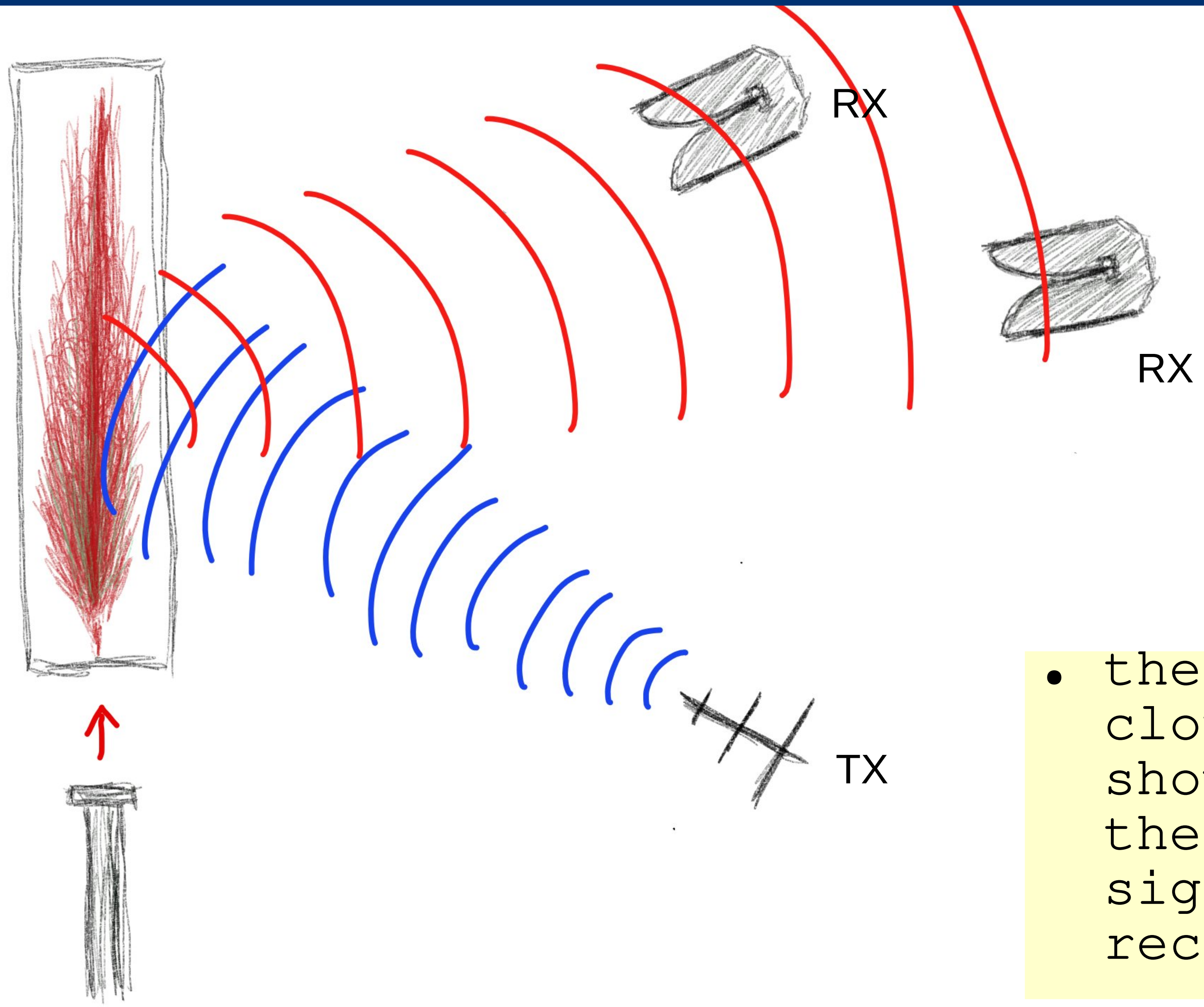
- As the beam enters the target, a cascade is created in the material

Idea:



- We interrogate the target with radio

Idea:

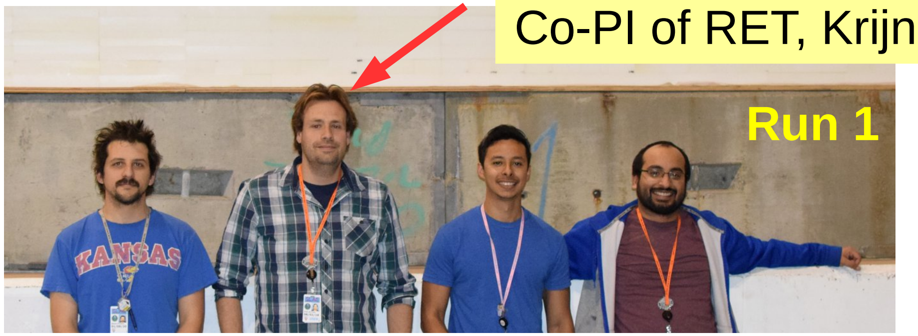


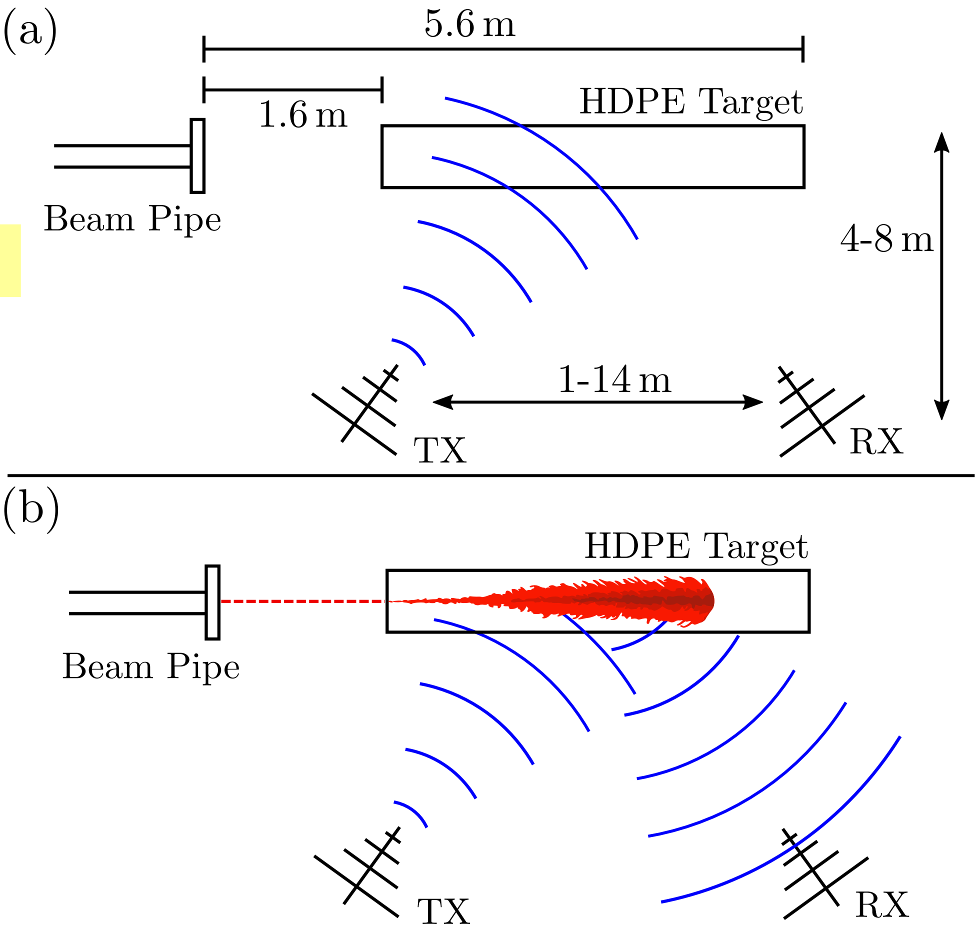
- the ionization cloud of the shower reflects the transmitted signal to the receivers

Toward radar echo detection: T576

May (run-1), October (run-2) 2018

Co-PI of RET, Krijn de Vries



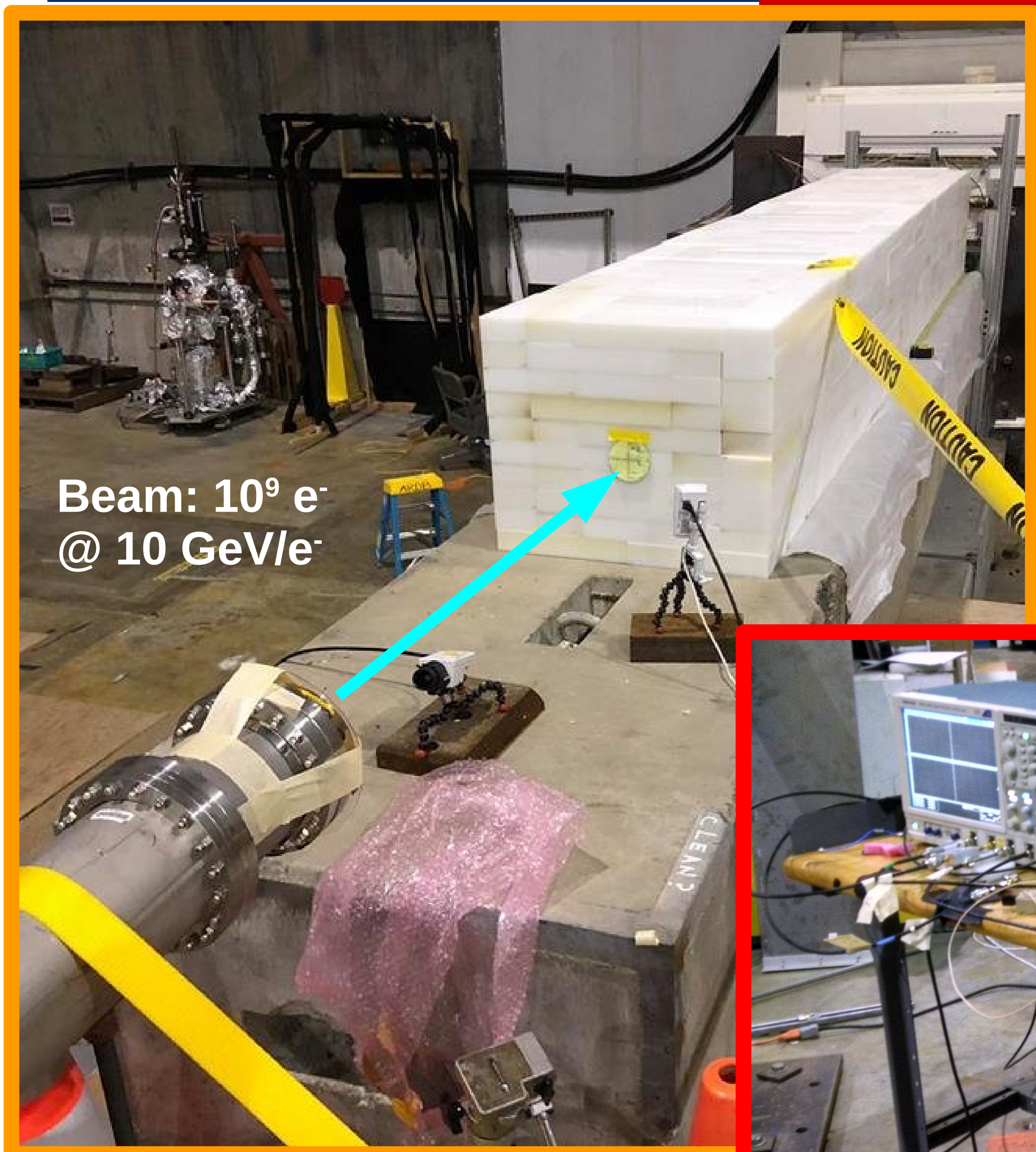


SLAC NATIONAL ACCELERATOR LABORATORY

Original DOE proposal: Besson(KU), Prohira(KU), Wissel (PSU)

SLAC End Station A

SLAC T576



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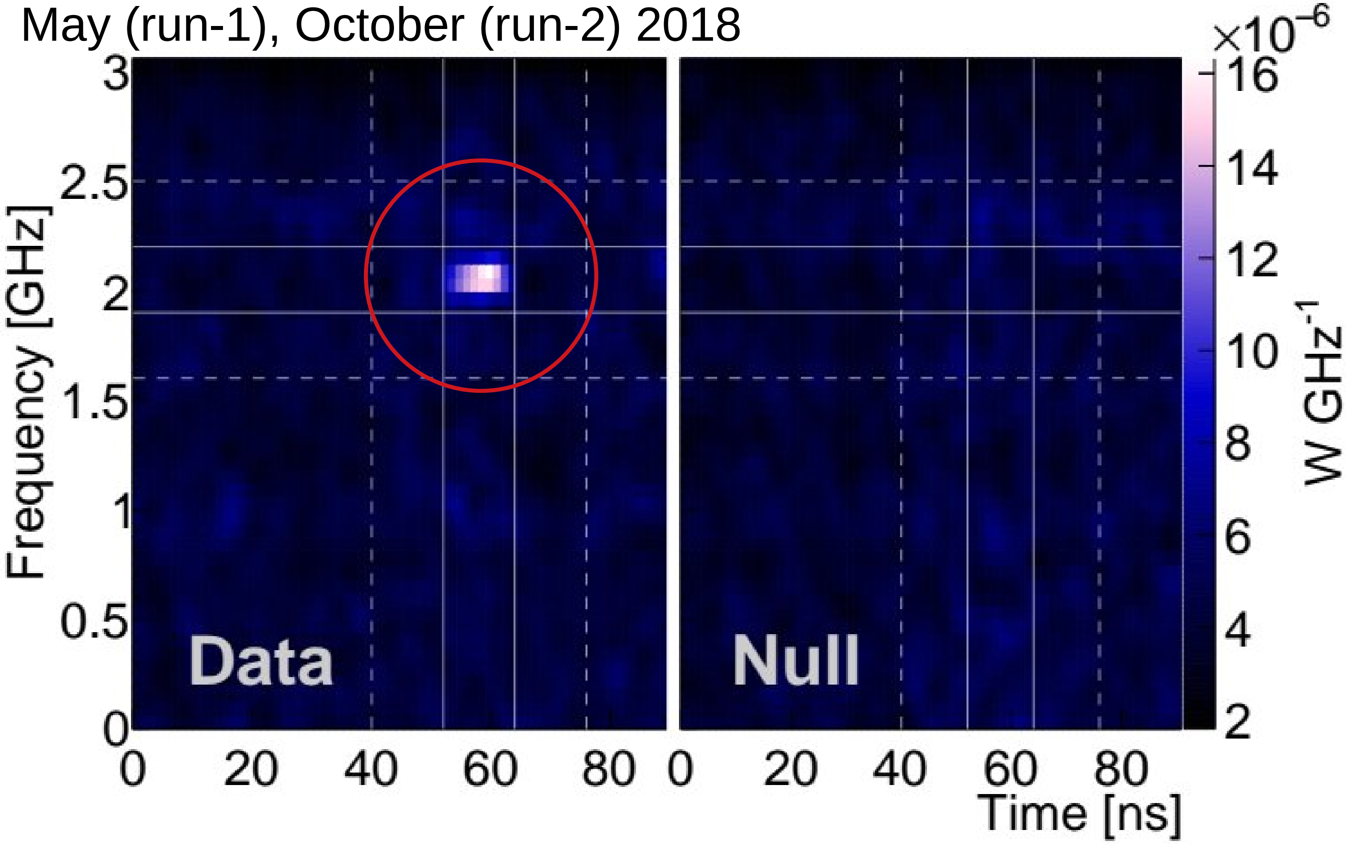

A signal was observed (here the bright blob at left) compared to a null hypothesis.

Observed at multiple transmit frequencies and in multiple receive antennas

details:
- arXiv:1810.09914
- arXiv:1910.11314
- arXiv:1910.12830

PHYSICAL REVIEW LETTERS **124,** 091101 (2020)

Editors' Suggestion | Featured in Physics

Observation of Radar Echoes from High-Energy Particle Cascades

S. Prohira,[1,*] K. D. de Vries,[2] P. Allison,[1] J. Beatty,[1] D. Besson,[3,4] A. Connolly,[1] N. van Eijndhoven,[2] C. Hast,[5] C.-Y. Kuo,[6] U. A. Latif,[3] T. Meures,[7] J. Nam,[6] A. Nozdrina,[3] J.P. Ralston,[3] Z. Riesen,[8] C. Sbrocco,[1] J. Torres,[1] and S. Wissel[8]

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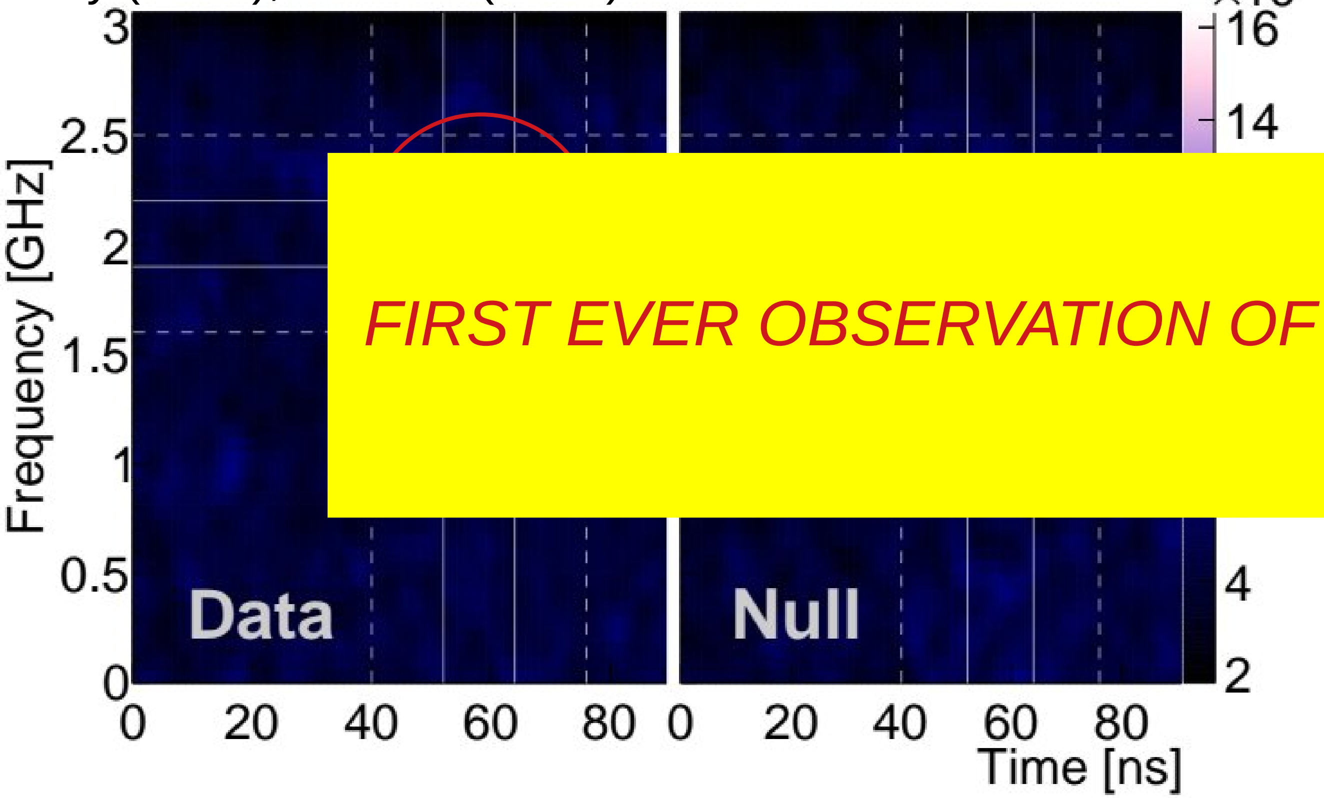

FIRST EVER OBSERVATION OF THIS SIGNAL!

A signal was observed (here the bright blob at left) compared to a null hypothesis

...iple ...ies and ...e

details:

arXiv:1810.09914
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DOI:10.1063/PT.6.1.20200403a

3 Apr 2020 in Research & Technology

Radar points the way to detecting cosmic neutrinos

A laboratory experiment at SLAC makes the first observations of radio-wave reflections from the ionization trails of particle cascades in matter.

R. Mark Wilson

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ASTROPARTICLE PHYSICS | RESEARCH UPDATE

Radar could detect cosmic neutrinos in Antarctic ice

28 Jan 2020

APS physics Journals Physics Magazine PhysicsCentral APS News

Physics ABOUT BROWSE PRESS COLLECTIONS

Focus: Catching Neutrinos on Radar

March 6, 2020 • *Physics* 13, 33

Radar could detect ultrahigh-energy neutrinos from space, according to experiments using electrons as neutrino stand-ins.

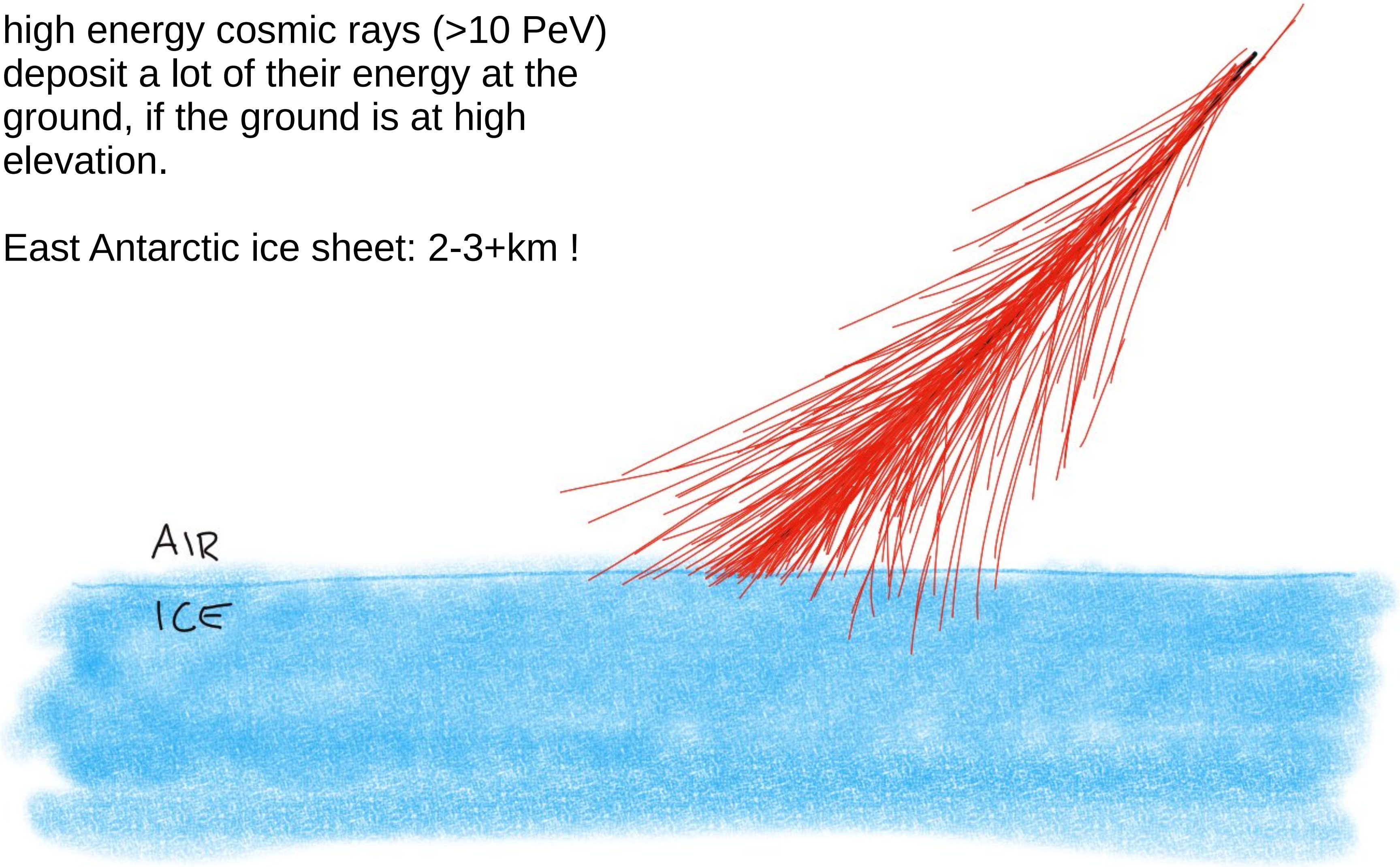
How to test in nature?

- OK let’s say we get out to an ice sheet, and put a radar system in nature. and see a blip, could be from a neutrino. *prove it!*
- first test on a known source: cosmic rays

Using cosmic rays

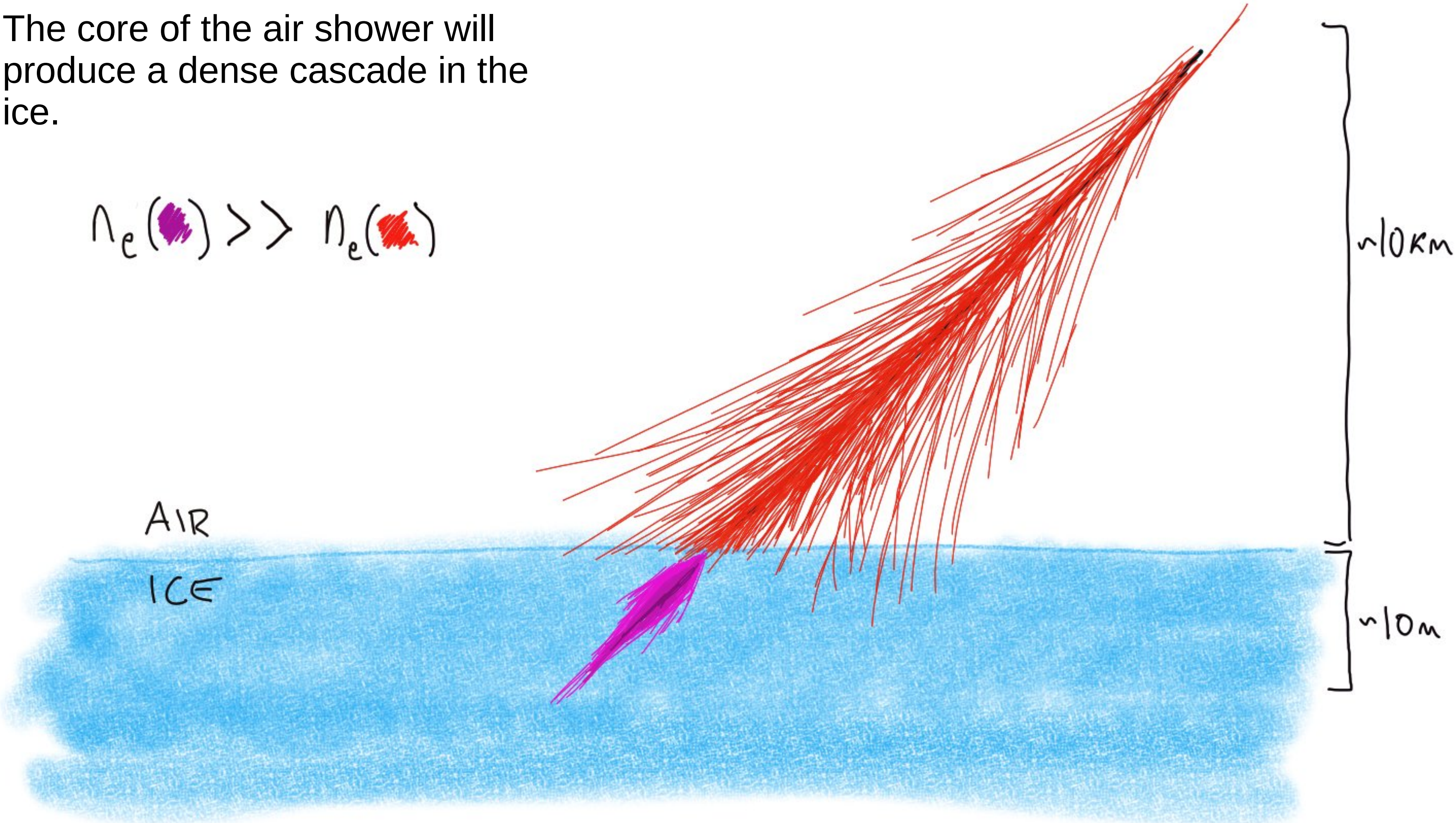
high energy cosmic rays (>10 PeV) deposit a lot of their energy at the ground, if the ground is at high elevation.

East Antarctic ice sheet: 2-3+km !



Using cosmic rays

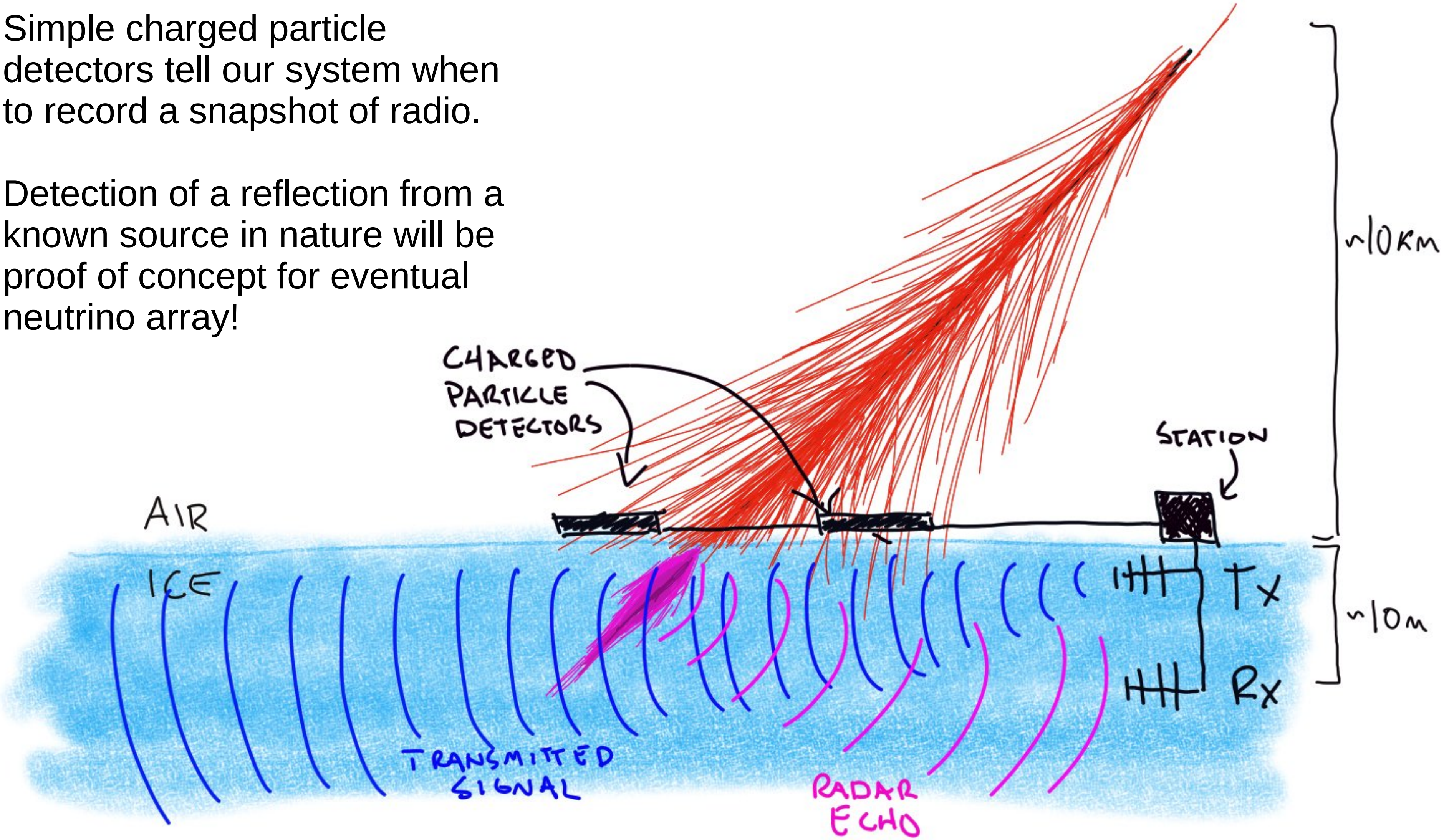
The core of the air shower will produce a dense cascade in the ice.



Using cosmic rays

Simple charged particle detectors tell our system when to record a snapshot of radio.

Detection of a reflection from a known source in nature will be proof of concept for eventual neutrino array!



the RADAR ECHO TELESCOPE for COSMIC RAYS

PhysRevD.104.102006, SP et. al 21

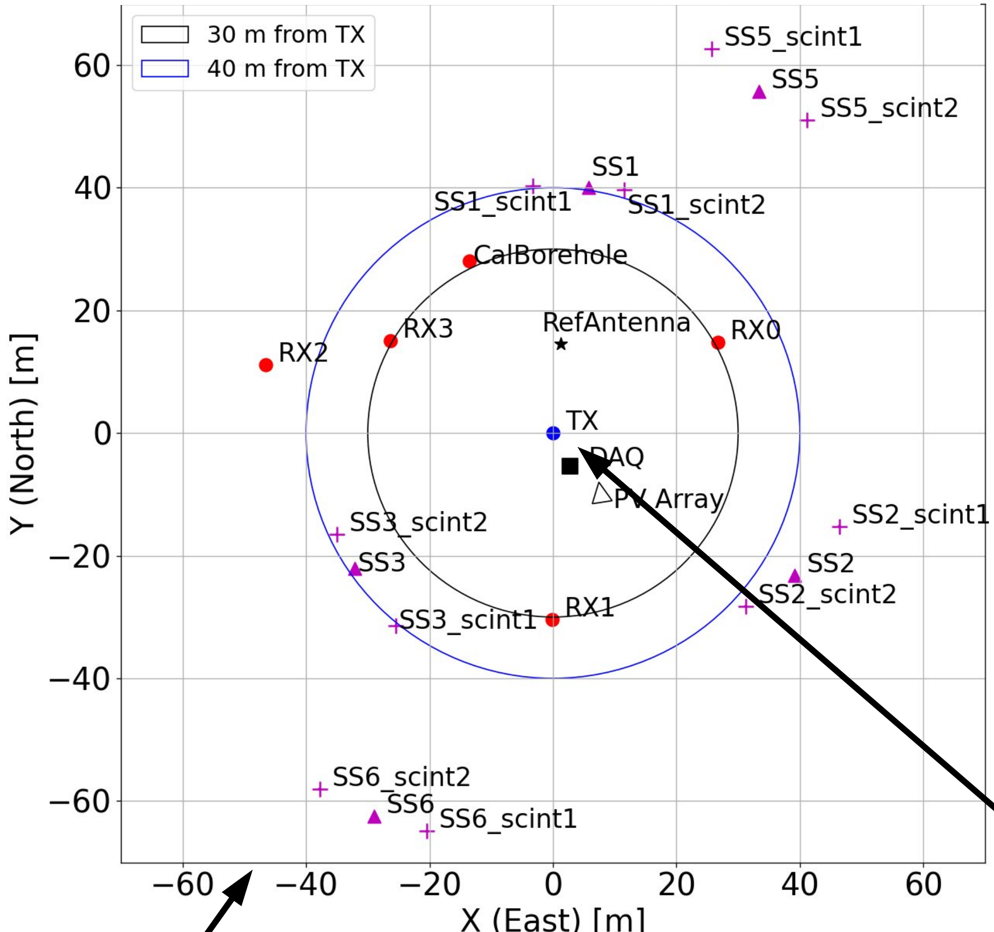
Central data acquisition system.

3 receivers

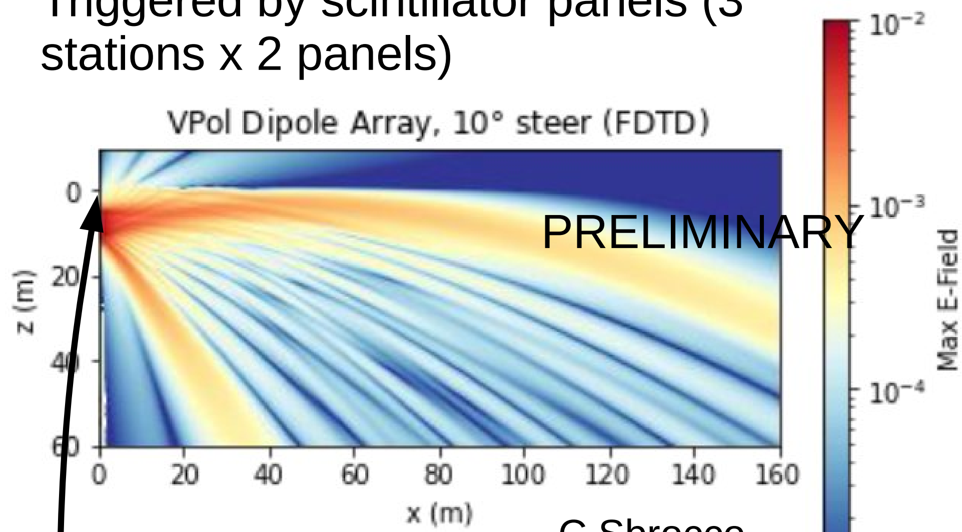
8 antenna phased array (below)

Active, adaptive transmitter cancellation

Triggered by scintillator panels (3 stations x 2 panels)



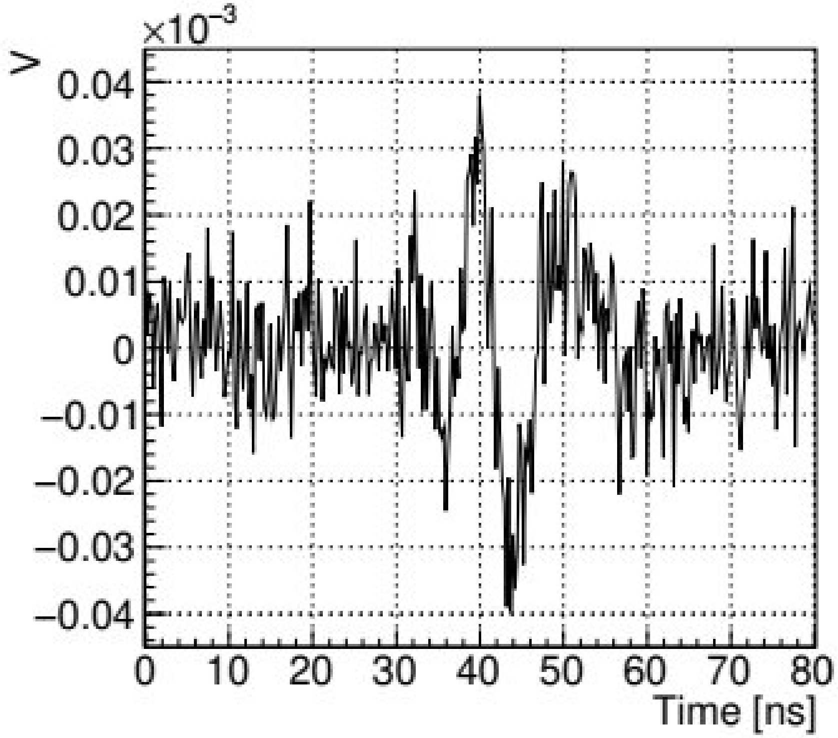
Station layout
As deployed May 2024

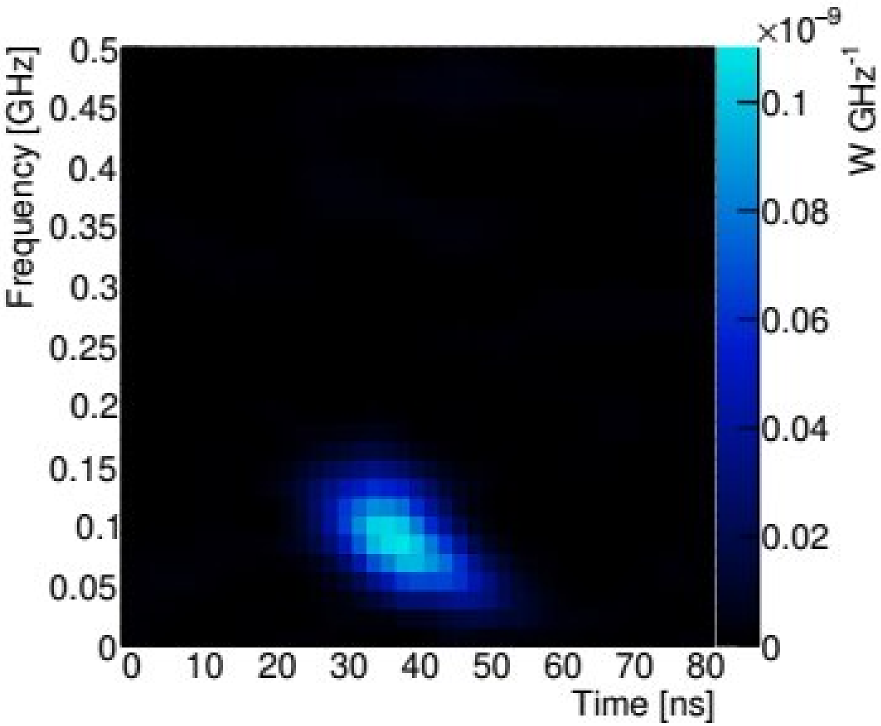


C.Sbrocco and L. Deer (OSU)

Phased TX array

Expected signal





The radar echo signal has some interesting signal properties that we can use to trigger on, for example, a strong frequency shift for some geometries. *MORE DETAILS COMING SOON...*

RET-CR status

May 2023

Dylan Frikken (OSU) on the coring drill!

Rose Stanley (VUB), Enrique Huesca Santiago (VUB), and I deploying an antenna (the ol' “hand winch”)

RET-CR status

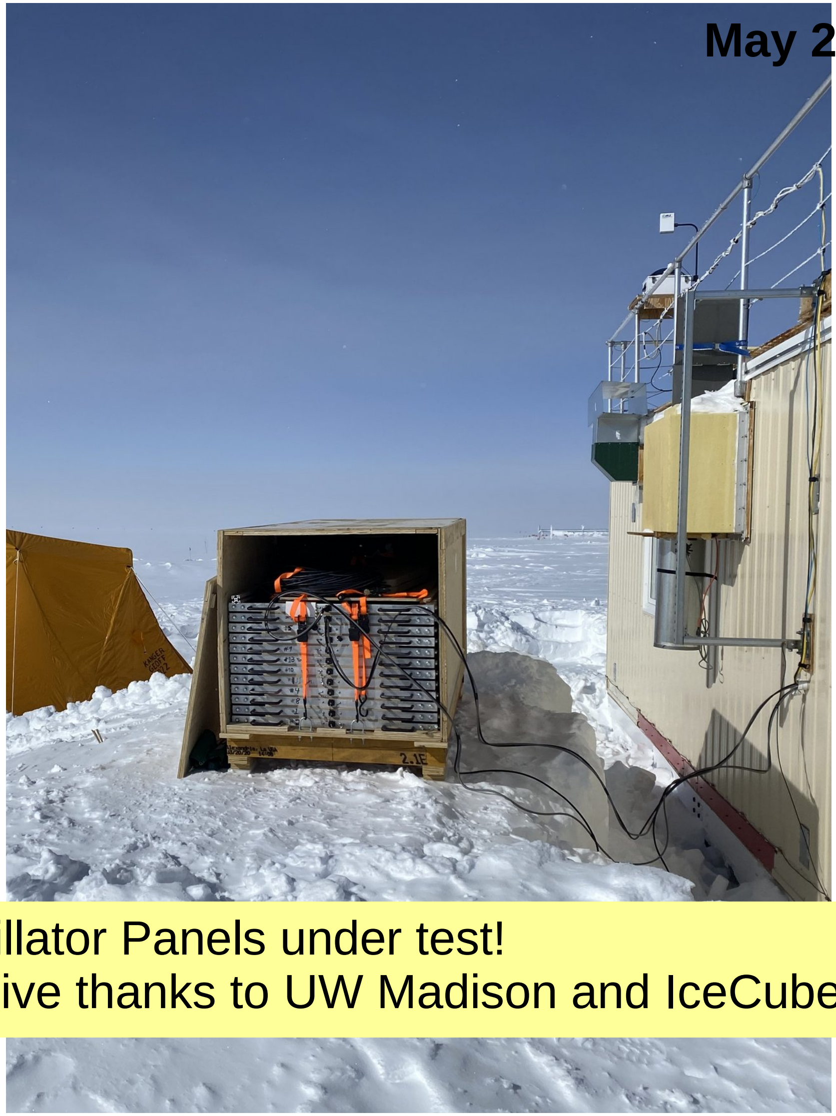
May 2023

Dylan and Rose assembling antennas

Down the borehole!

RET-CR status

May 2023



Scintillator Panels under test!
Massive thanks to UW Madison and IceCube!

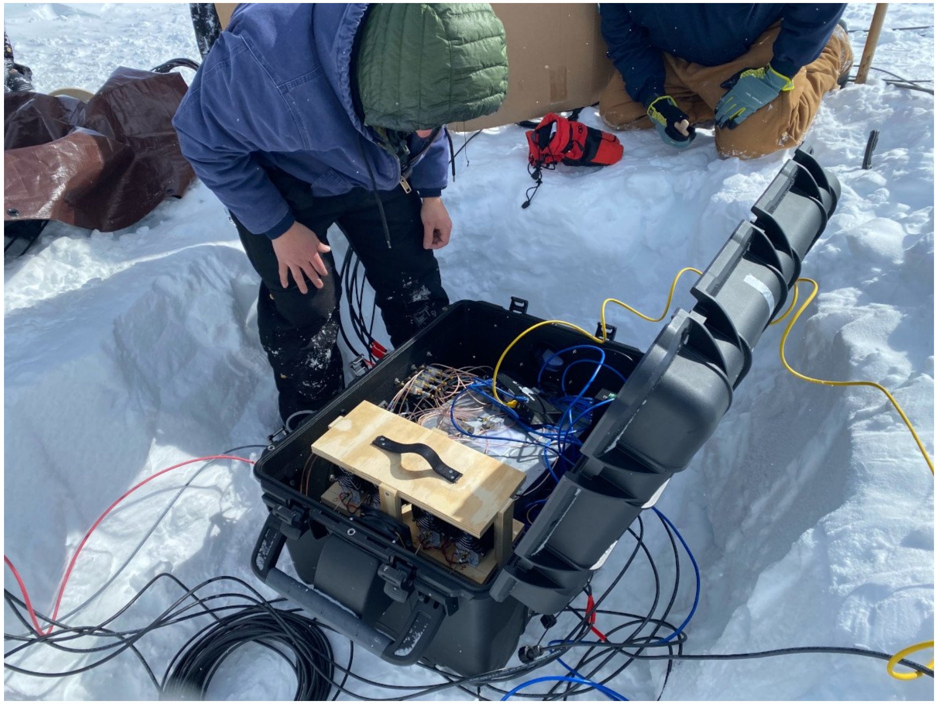
(L-R) Rob Young, Enrique Huesca Santiago, Dylan Frikken, Rose Stanley, me

How to build a melting probe:

Put a bunch of power amps into a snow vault.

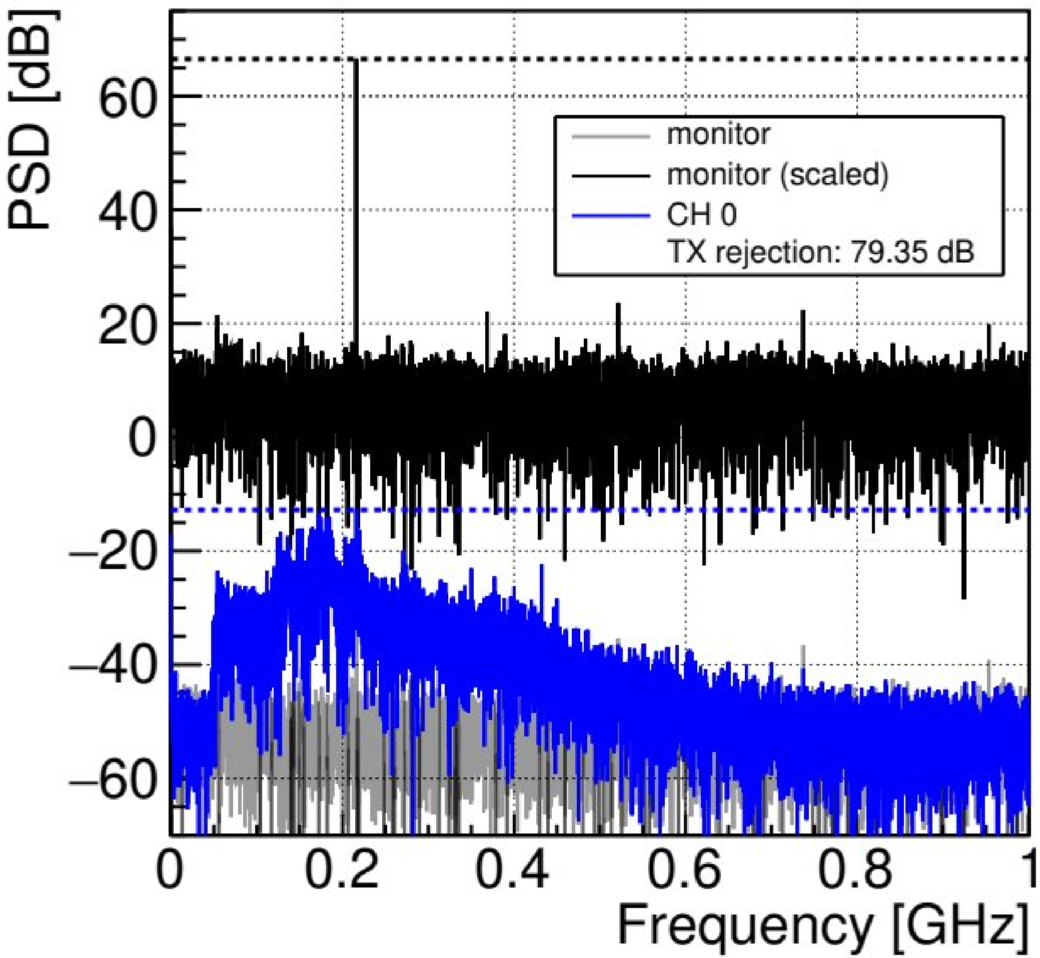
May 2023...

...July 2023



First run was a technical success but experimental failure. Info here: arxiv:2409.07511
Thanks to Summit Station staff for digging us out!

Transmitter cancellation



Important technical aspects were achieved:

transmitter would saturate receivers, so we actively cancel.

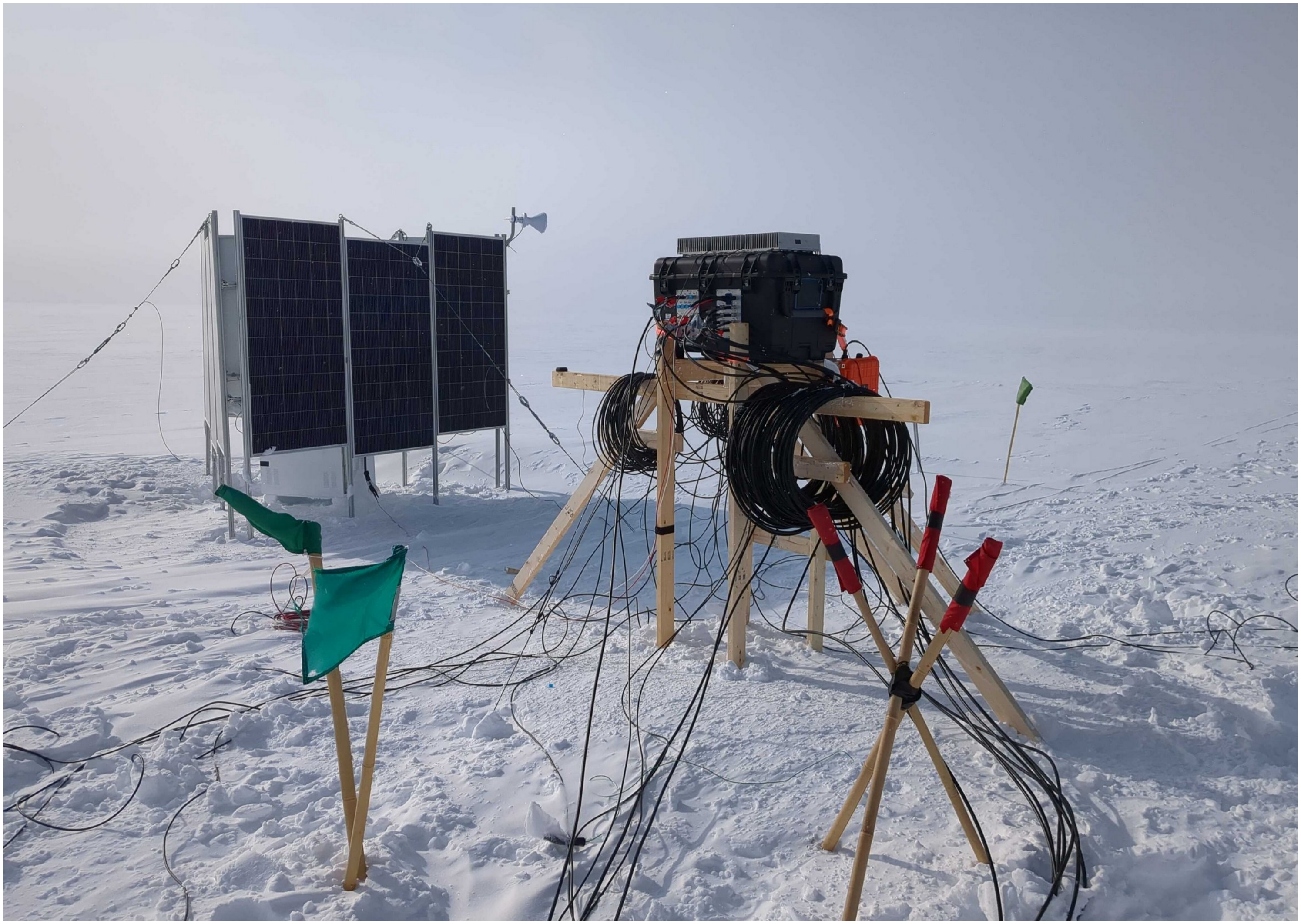
Here, an unamplified monitoring antenna ia scaled by 59dB to demonstrate the level of RF reaching the amplified receiver channels.

nearly 80dB rejection!

May 2024 redeploy

assisted by RET grad students: Dylan Frikken (OSU), Simon De Kockere (VUB)

No melty

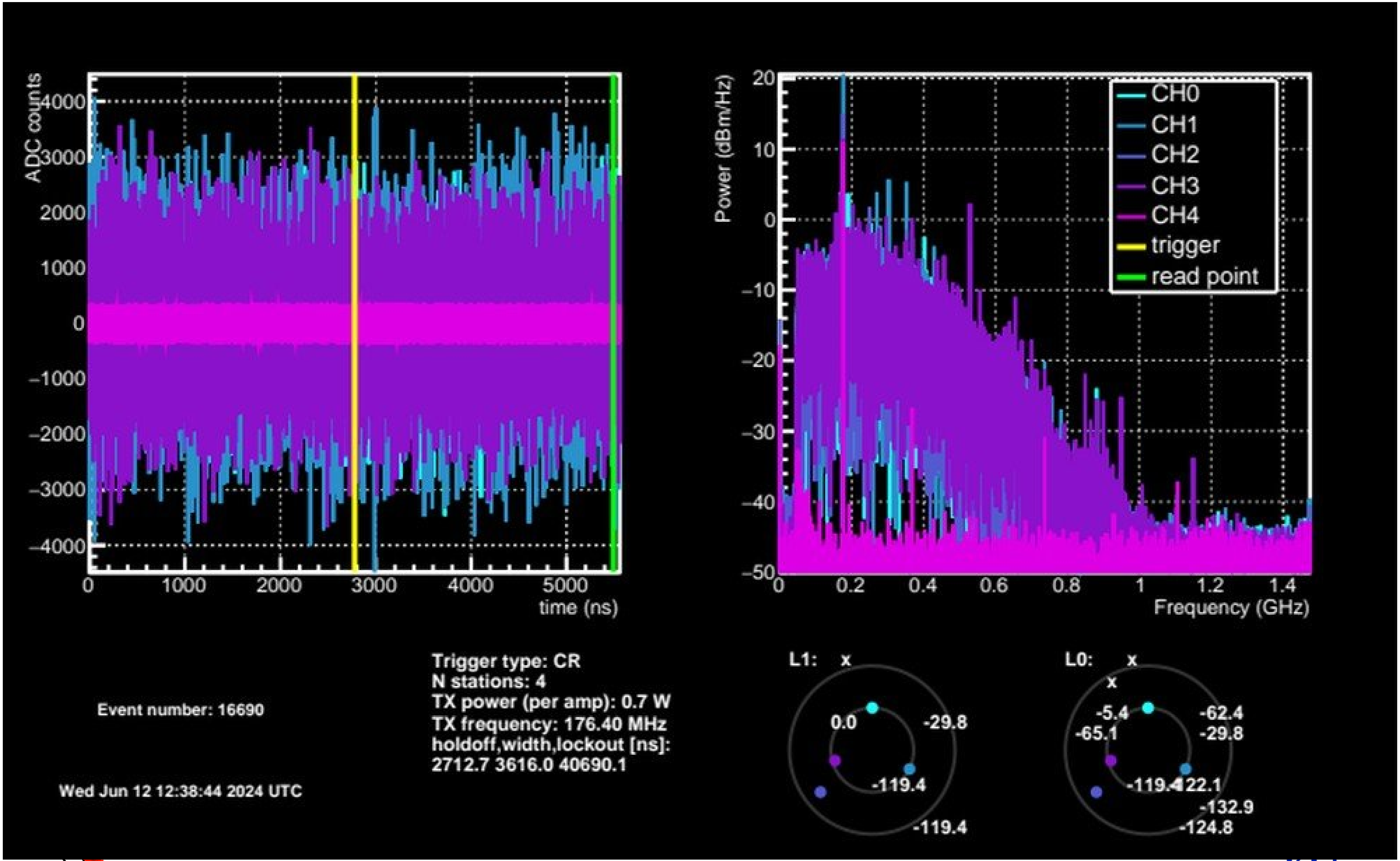


Instrument as deployed May 2024 with additional deployment assistance from KU postdoc Alex Kyriacou and KU grad student Curtis McLennan

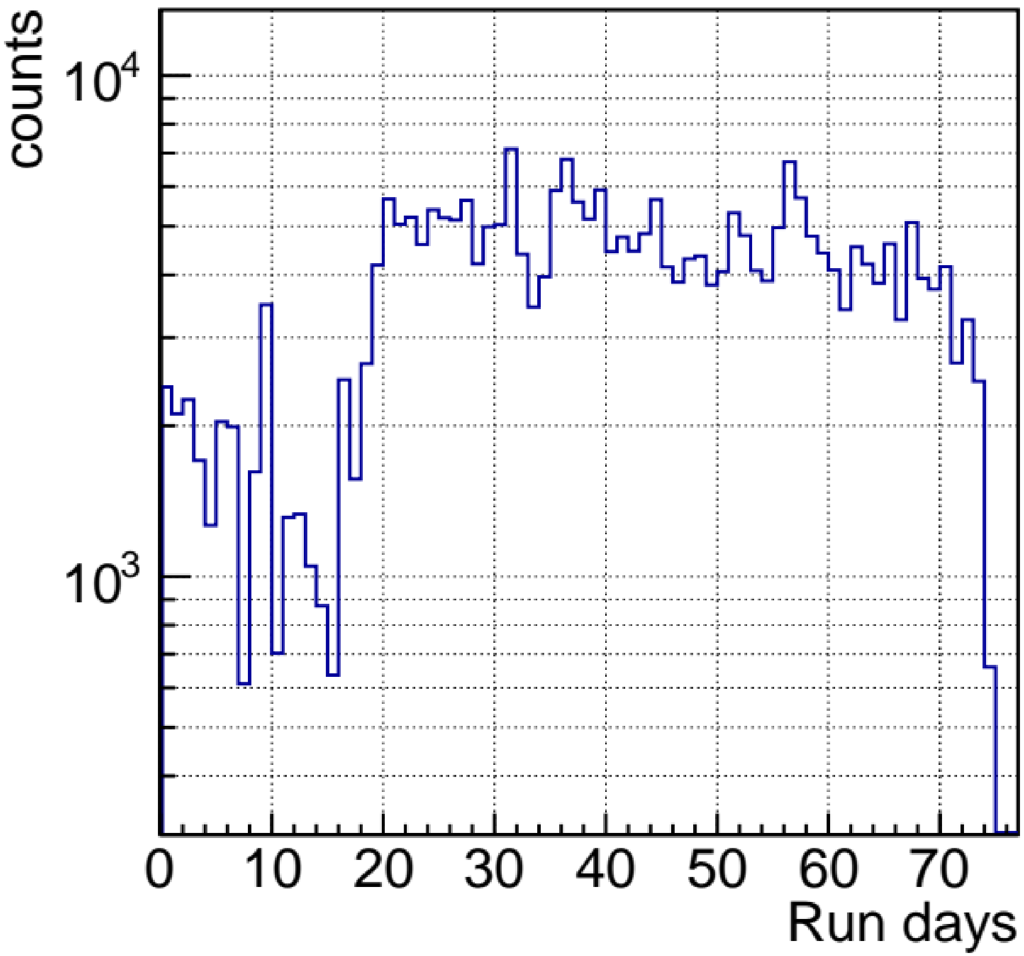
Aug 2024, data run complete

RET co-PIs Krijn de Vries (VUB) and Katie Mulrey (Radboud)
with ~almost~ the last of the equipment (Summit Station in the background)

Data!


ADC counts
time (ns)
Power (dBm/Hz)
Frequency (GHz)
CH0
CH1
CH2
CH3
CH4
trigger
read point
Event number: 16690
Wed Jun 12 12:38:44 2024 UTC
Trigger type: CR
N stations: 4
TX power (per amp): 0.7 W
TX frequency: 176.40 MHz
holdoff,width,lockout [ns]:
2712.7 3616.0 40690.1
L1:
0.0
-29.8
-119.4
-119.4
L0:
-5.4
-65.1
-62.4
-29.8
-119.4
122.1
-132.9
-124.8

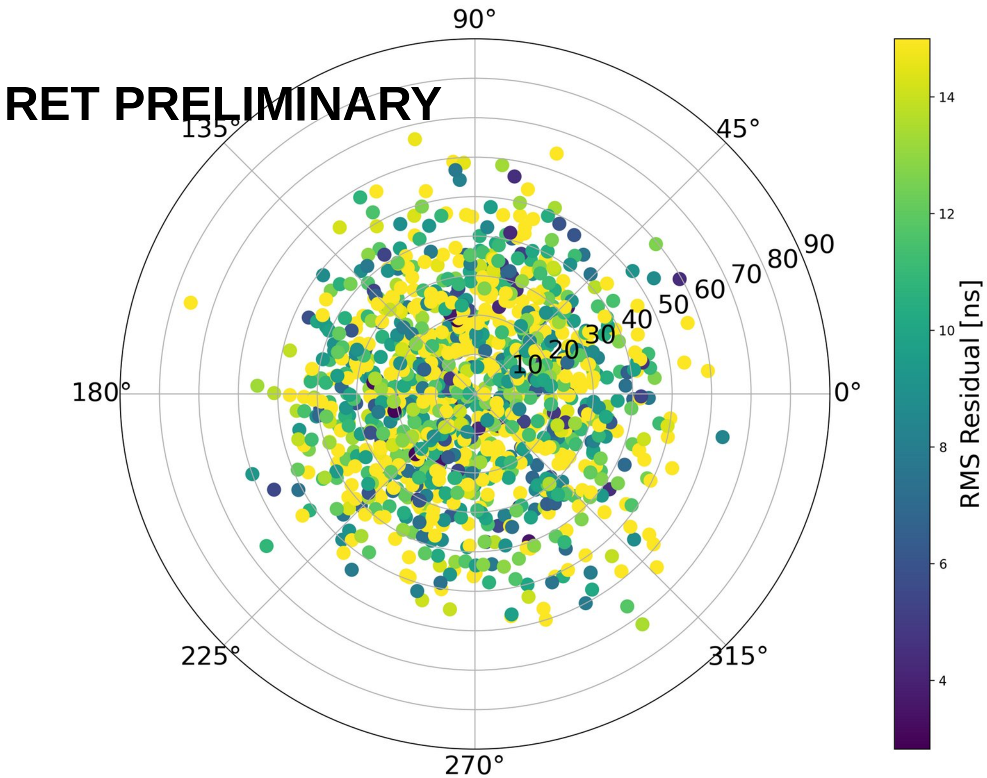
Data!



~4000 CRs per day!!!

note: these are the events that triggered the cosmic ray scintillator panels only, we have yet to analyze these for associated radar echoes.

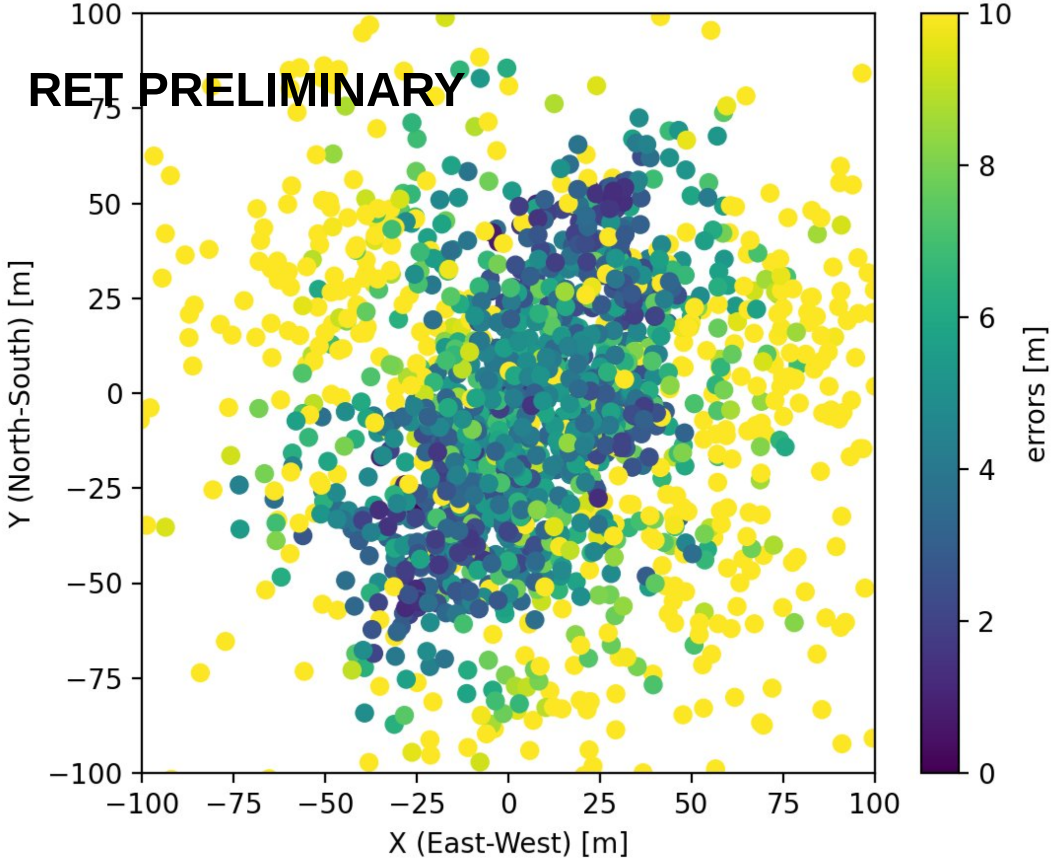
Cosmic ray reconstruction



Krishna Nivedita (Radboud U)

- Trigger pulse timing of scintillator panels gives us arrival direction and core position of arriving cosmic rays
- Plotted is arrival azimuth and zenith angle, with the color given by the rms of the total timing error.

Cosmic ray reconstruction

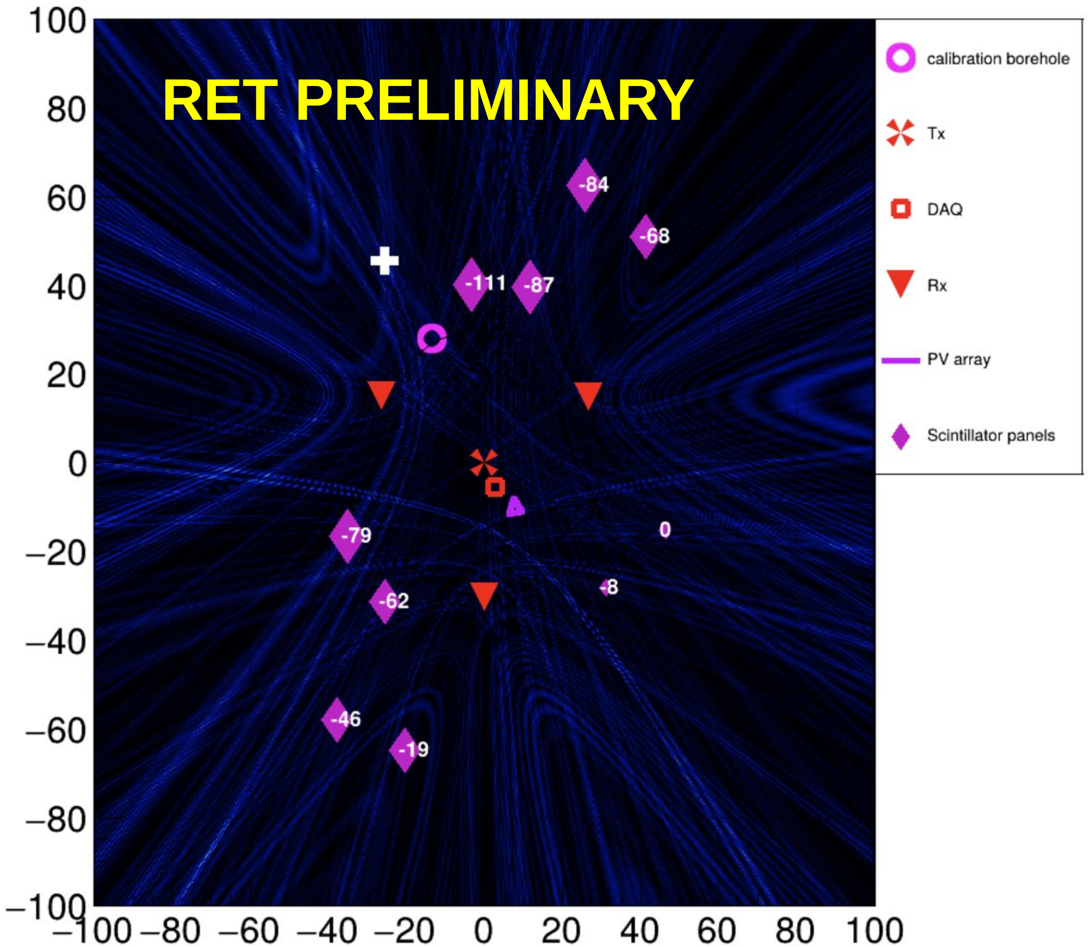


Krishna Nivedita (Radboud U)

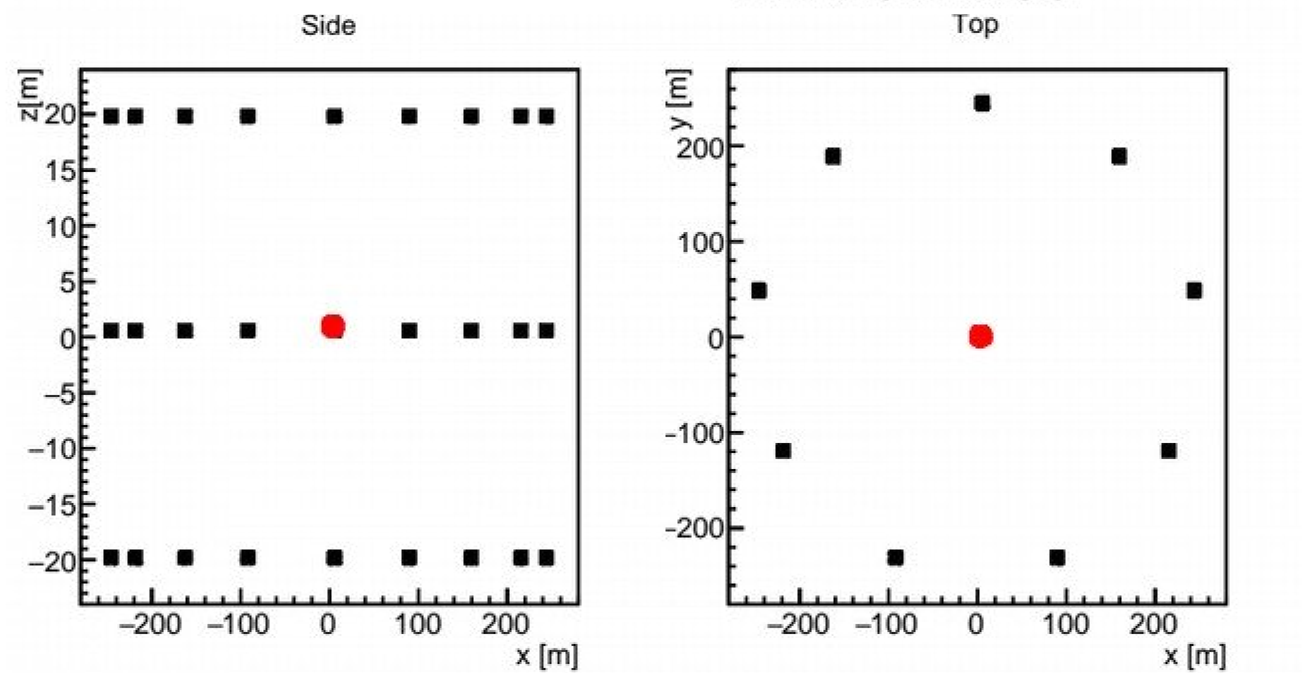
- Preliminary core position reconstruction based on charge deposition in our surface array
- With few panels, fitting is challenging but we're nearing reliable core position fits that can be used for the echo search!

Preliminary reconstructions

- Reconstruction of the events with the in-ice antennas
- At right, cosmic-ray triggered event from 10% 'burn' sample used to train our analysis variables
- For more, D. Frikken (et al.) at ICRC2025



Dylan Frikken (OSU)



Left: potential station configuration. z=0 here is at 1.5km below the ice of a polar ice sheet

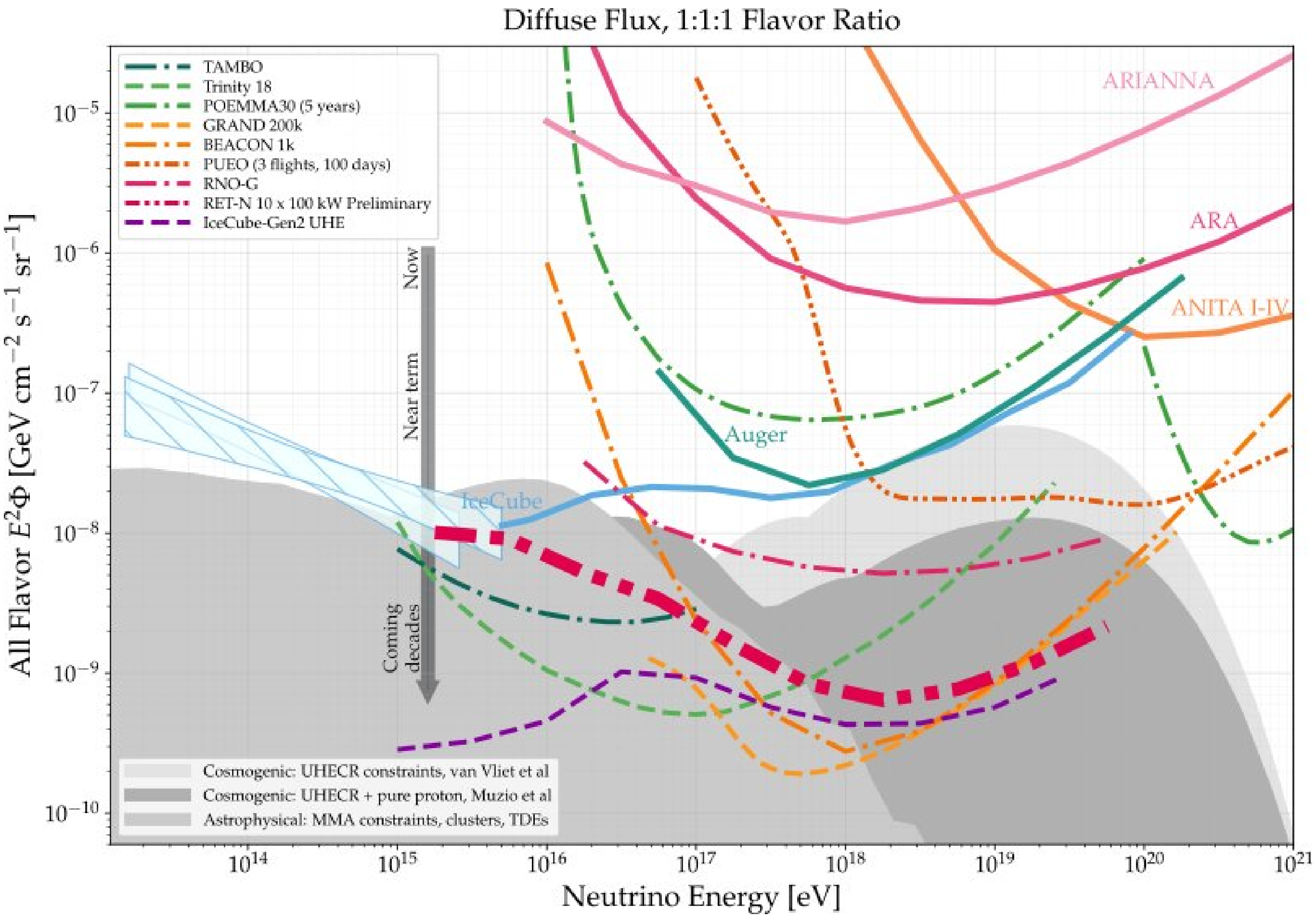
Final station layout to be based on what we learn from RET-CR.

Possible station layout, transmitter and receivers buried in the ice.

For the following sensitivity plot, this represents ***1 station:***

- -1 transmitter @ 100 kW (**same power as a typical FM radio station**)
- -27 receivers on radial 'spokes'
- -spacing optimized to target lower energy cascades
  - -longer TX-RX baselines = higher energy primary, shorter = lower.

RET sensitivity in context



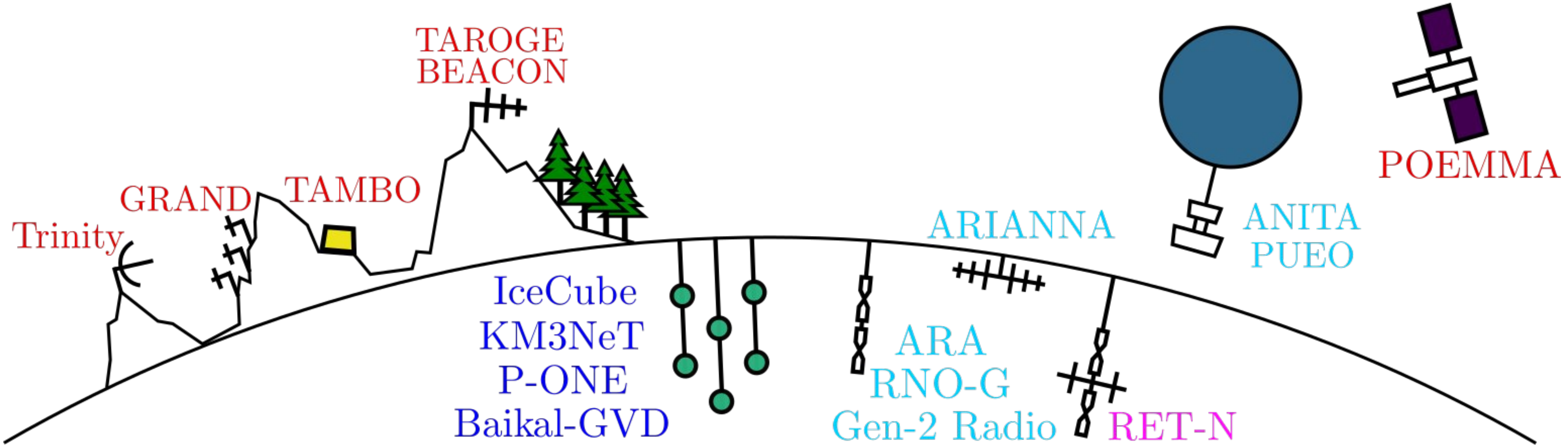
Adapted from UHE neutrinos Snowmass paper arXiv:2203.08096, highlighting RET curve.

RET **10 stations,** 10 years, thick red dashed curve (highlighted for emphasis)

To my knowledge, we require the fewest number of stations of any ground-based radio method.

Also shown: Many experiments with different sensitivities

Complementary UHE neutrino detectors



Adapted from Esteban et al. arXiv:2205.09763

Tau neutrino (optical+radio)
Askaryan (radio Cherenkov)
In-ice Optical Cherenkov
Radar

Complementary measurements of the UHE neutrino sky!

thanks!

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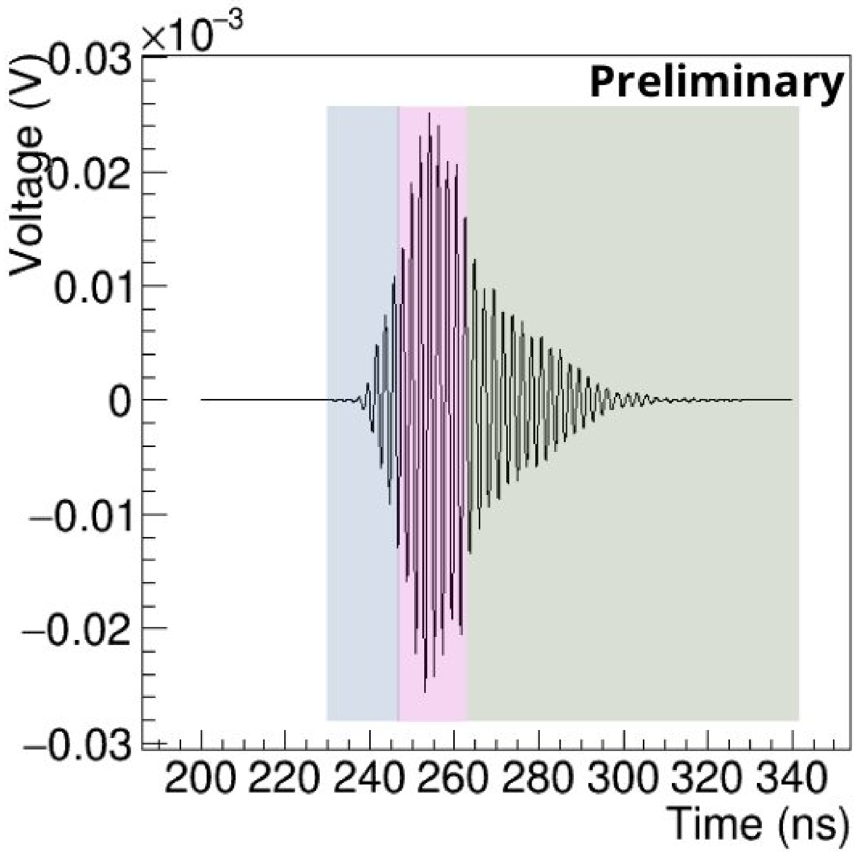
DON'T FORGET YOUR CHARGER

backup

RET signal properties

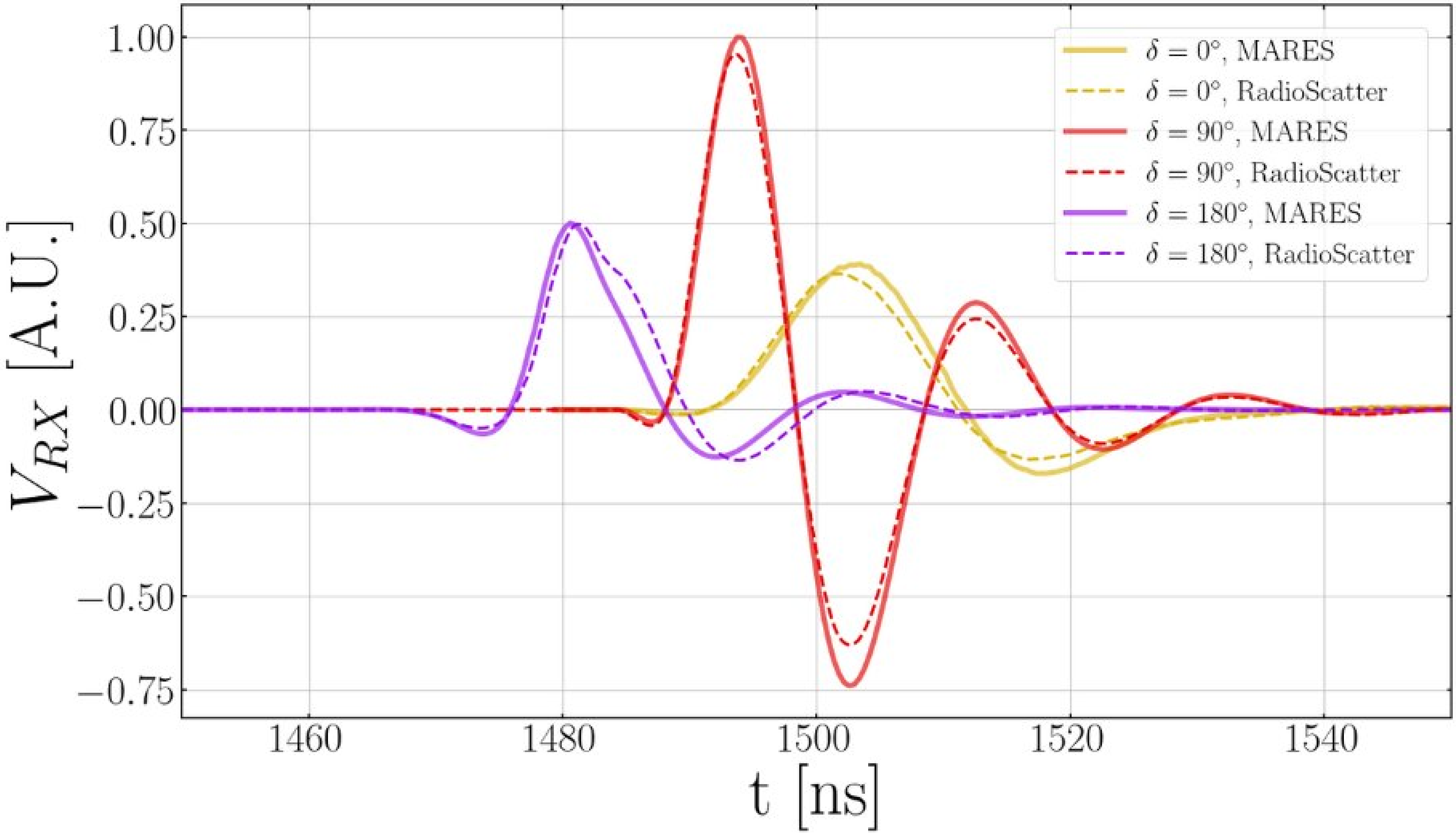


- Three phases of a RET event:
  - Cascade development
  - Cascade as a static reflector
  - Recombination/Attachment

Credit: D. Frikken (OSU)

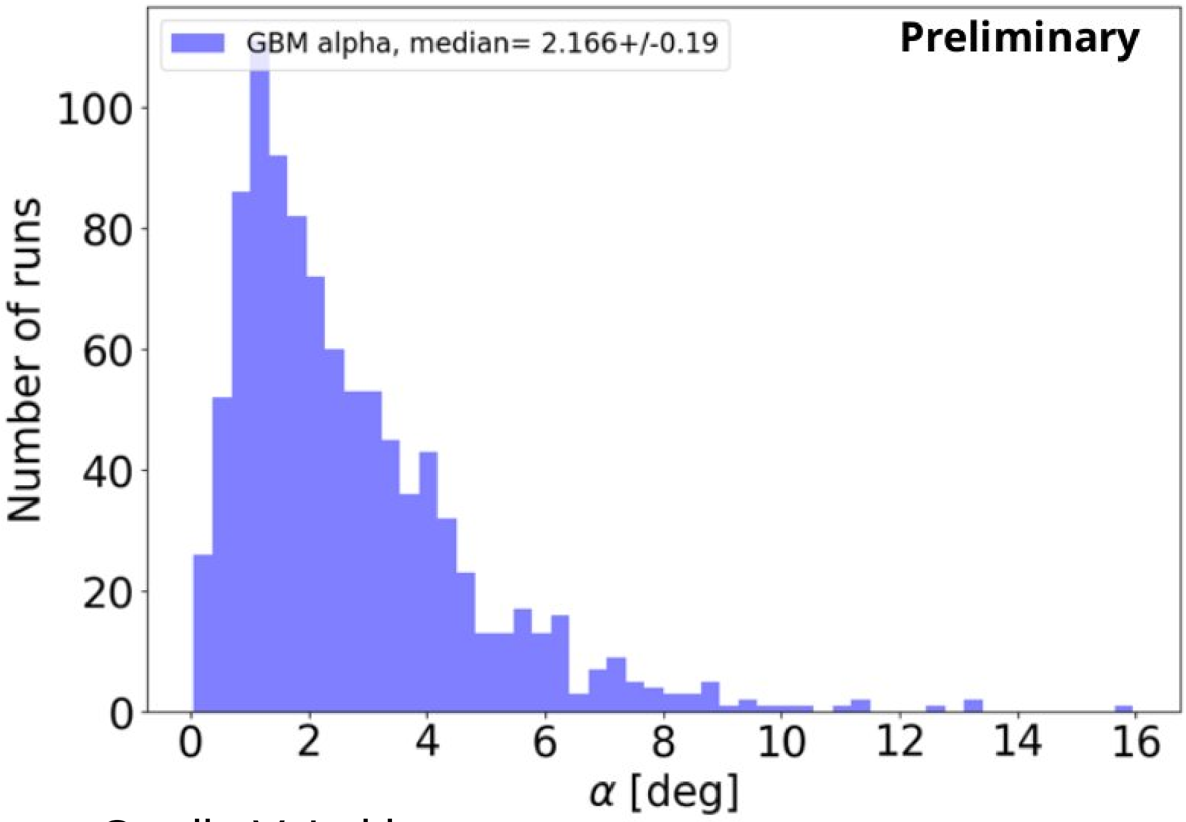
The signal itself has distinct phases, each of which provides different observables. We can use these observables for energy and angular reconstruction.

Two independent simulation frameworks



arxiv:2310.06731, E. Huesca Santiago et al. (RET)

Direction Reconstruction



Credit: V. Lukic

- preliminary resolution on direction reconstruction.
- alpha is the angle between true and reconstructed arrival direction for an RET-N station
- Non-optimized, still close to 1 deg benchmark.

RET timetable