

# Radar Detection of Ultrahigh Energy Neutrinos with the Radar Echo Telescope

**Steven Prohira**

On behalf of the Radar Echo Telescope Collaboration:

K.D. de Vries, P. Allison, J. Beatty, D. Besson, A. Connolly, P. Dasgupta, S. De Kockere, N. van Eijndhoven, C. Hast, E. Huesca Santiago, C.-Y. Kuo, U.A. Latif, V. Lukic, T. Meures, K. Mulrey, J. Nam, A. Nozdrina, J.P. Ralston, Z. Riesen, C. Sbrocco, R. Stanley, J. Torres, S. Toscano, and S. Wissel,

Snowmass 2022



European Research Council  
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THE UNIVERSITY OF  
KANSAS



# key takeaways

- The Radar Echo Telescope for Neutrinos (RET-N) is a new proposed system to *target neutrinos with energies greater than  $10^{16}$  electron volts (10PeV)* via **active radar sounding**
- The method has been validated in a test beam experiment (SLAC T576 PhysRevLett.124.091101, arXiv:1910.12830)
- The Radar Echo Telescope for Cosmic Rays (RET-CR) is an NSF-funded pathfinder experiment using an in-nature test-beam to develop the *radar echo* method.
  - NSF Collaborative Research, 'Windows on the Universe' PHY2012980 autumn 2020; also ERC/FWO funded via KD de Vries 2018
- RET-CR is under development:
  - Hardware construction and testing underway
  - instrument paper: PhysRevD.104.102006 (arXiv:2104.00459)
- Radar detection of neutrinos is a complementary strategy to other radio based methods, *essential to a full picture of the UHE neutrino sky.*

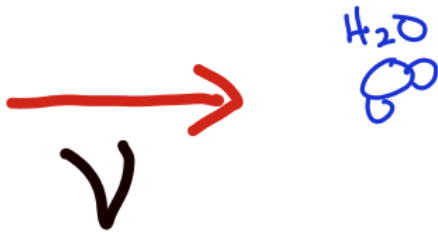
# Neutrino detection with radar

- In this talk I will:
  - Explain the radar echo method
  - Present results of lab-based measurements and method validation
  - Outline the technology and instrumentation under development and required to detect neutrinos
  - Put RET in context with other experimental efforts
- So, to begin...

What is the radar echo method? 2 concepts:

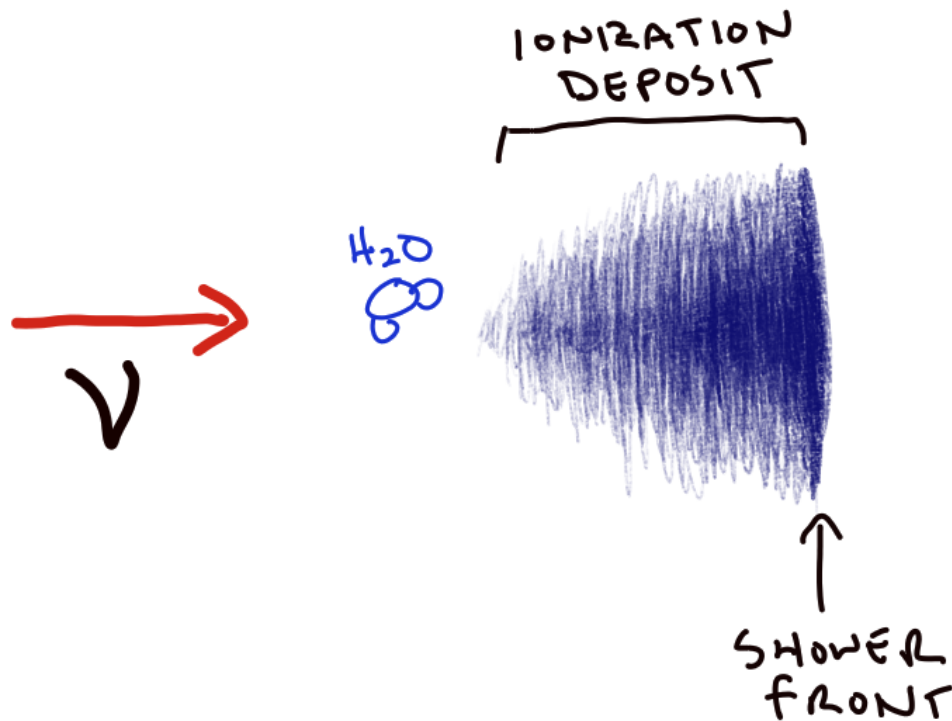
# Concept #1: particle cascades

- high-energy primary interactions create cascades of relativistic particles
- cascade particles *ionize* the material, leaving behind a dense, short-lived cloud of charge



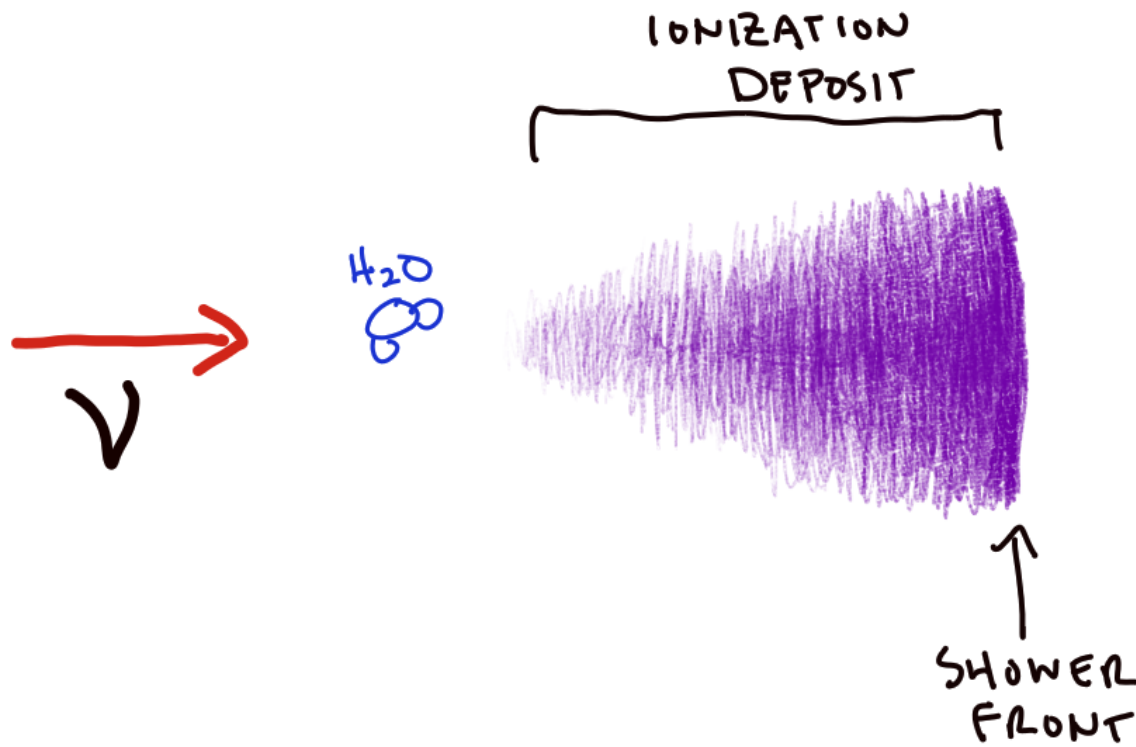
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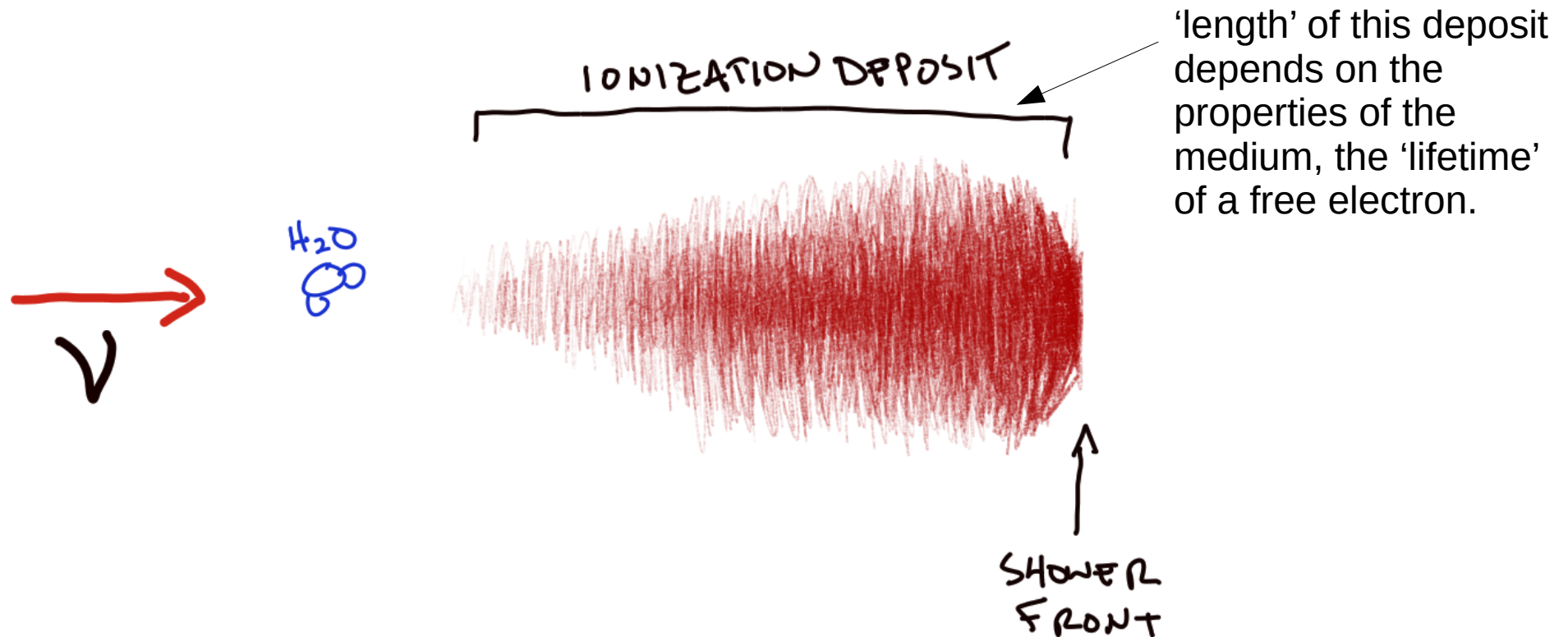
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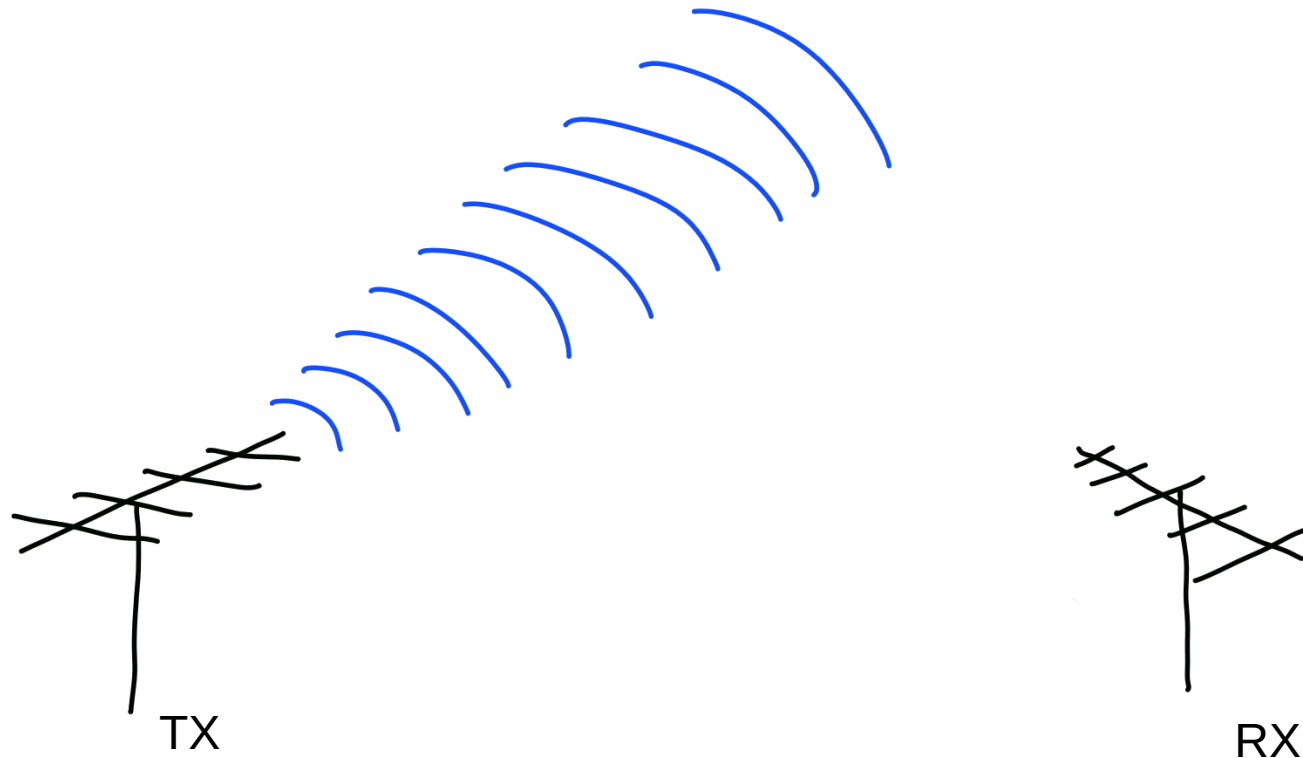


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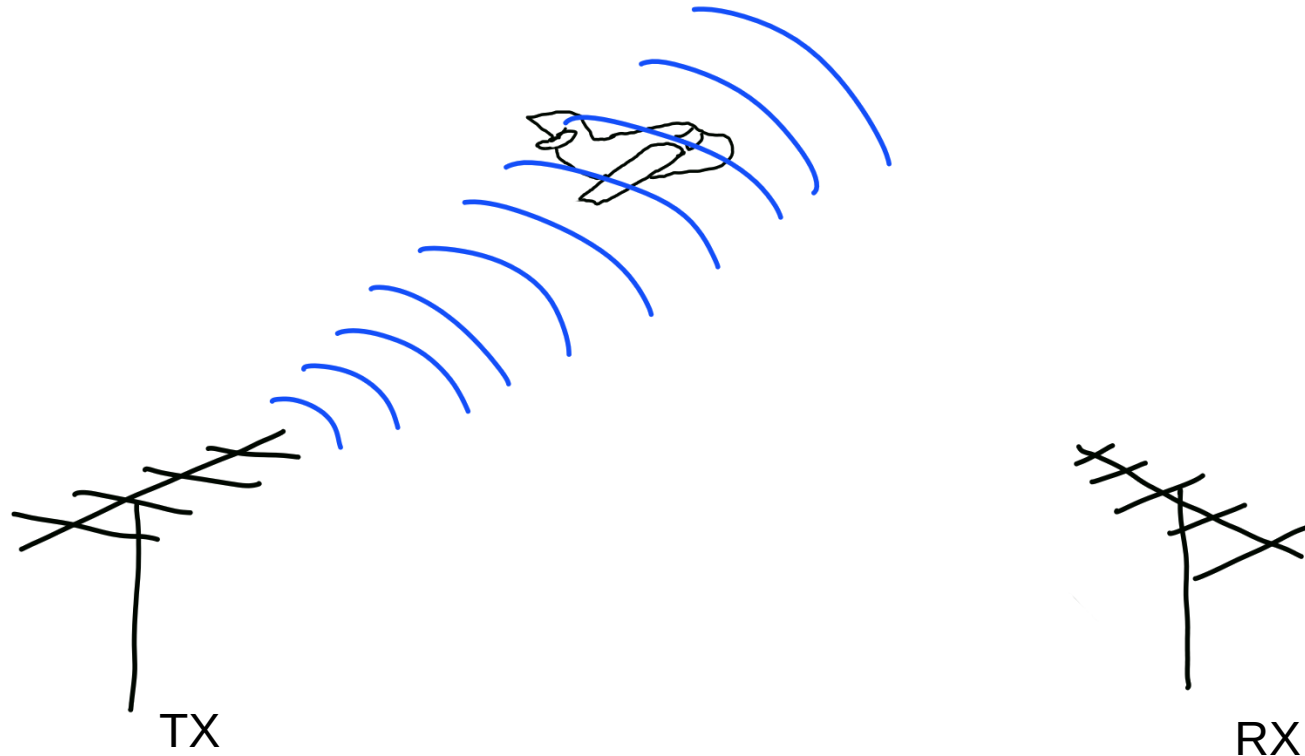


# Concept #2: radar overview



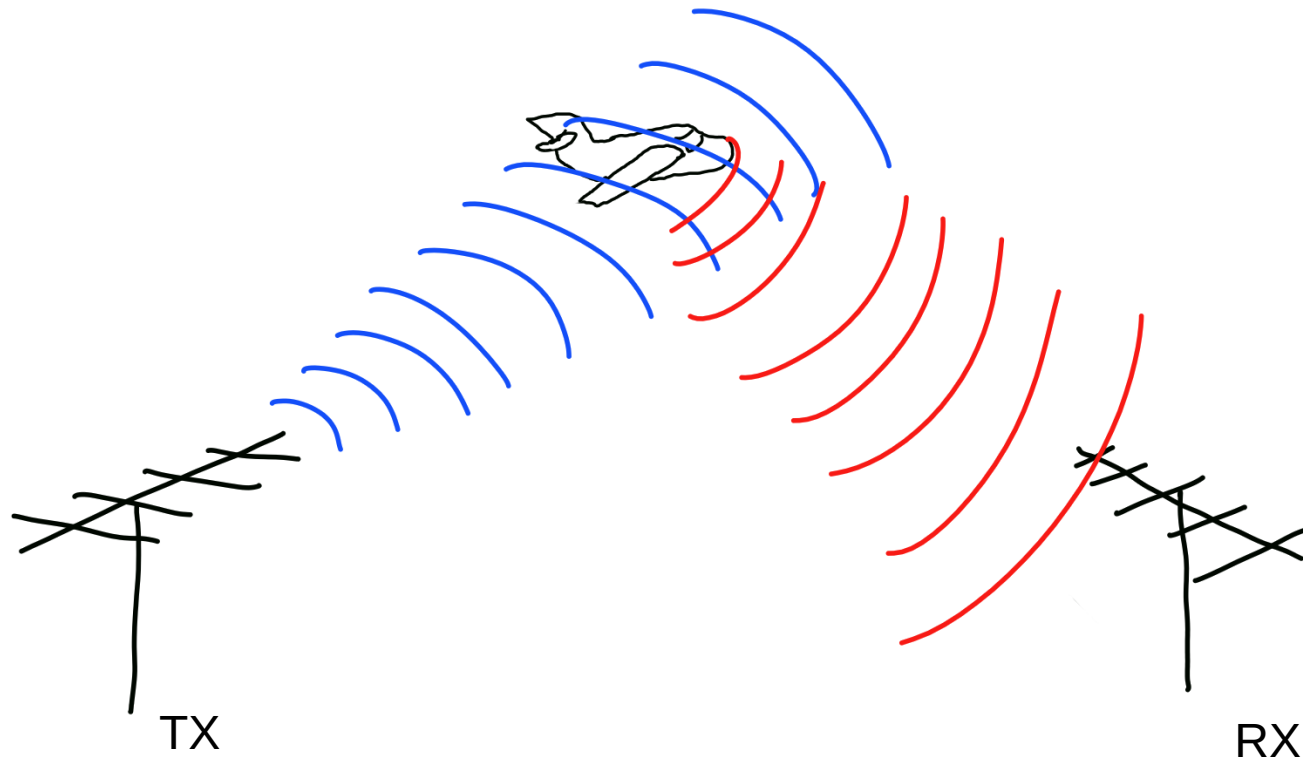
- Transmitter (TX) broadcasts a radio signal into a volume
- receiver(s) (RX) monitor this same volume

# Concept #2: radar overview



- Transmitter (TX) broadcasts a radio signal into a volume
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- 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.*

# radar detection of neutrinos

Key advantages of radar:

Active sounding gives control over parameters of the transmitted signal (spectral content and amplitude),  
**unique to the radar echo method.**

**Simple but flexible** technology, allows for real time alteration of transmitted signal modulation and trigger routines

**Scalable**

# radar is not new...

- 1941-1945:

Blackett and Lovell @ Jordrell Bank observatory, UK set up a radio receiver to study 'anomalous reflexions' from upper atmosphere, which they attributed to cosmic rays. (no signal--it was meteors!)



# Fast forward...

- Brief history of the method:

- 1940s-50s:

- Radar invented, proposed as a way to detect **cosmic ray extensive air showers in air**, proved not feasible (excellent history by A.C.B Lovell: rsnr.1993.0011)

- 1960s:

- renewed efforts with similar results in Japan

- 2000's:

- Renewed interest sparked by Gorham, then a dedicated experiment TARA attempted it on a large scale, saw no signal

Radar is dead!

ionization density too low, collision rate too high, free electron lifetime too short

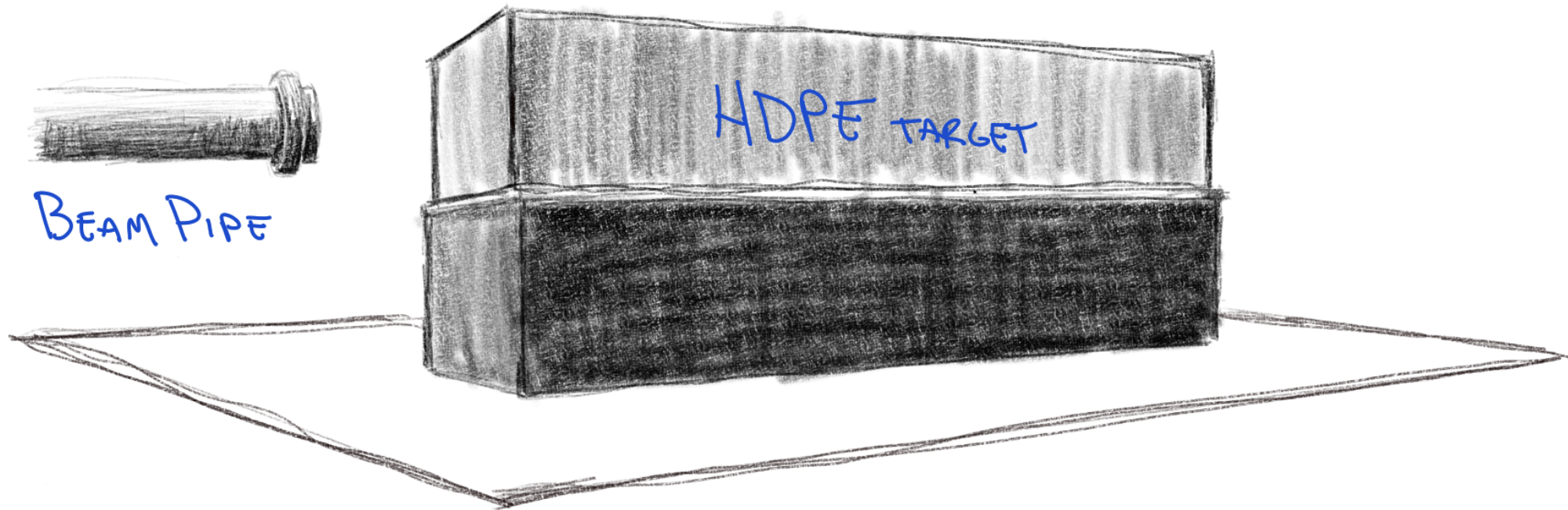
- 2010's:

- Several groups (Chiba et al., de Vries et al.) theorized method could be used **to detect neutrinos in ice** rather than CR in air
    - Lab experiments to follow...

Long live radar!

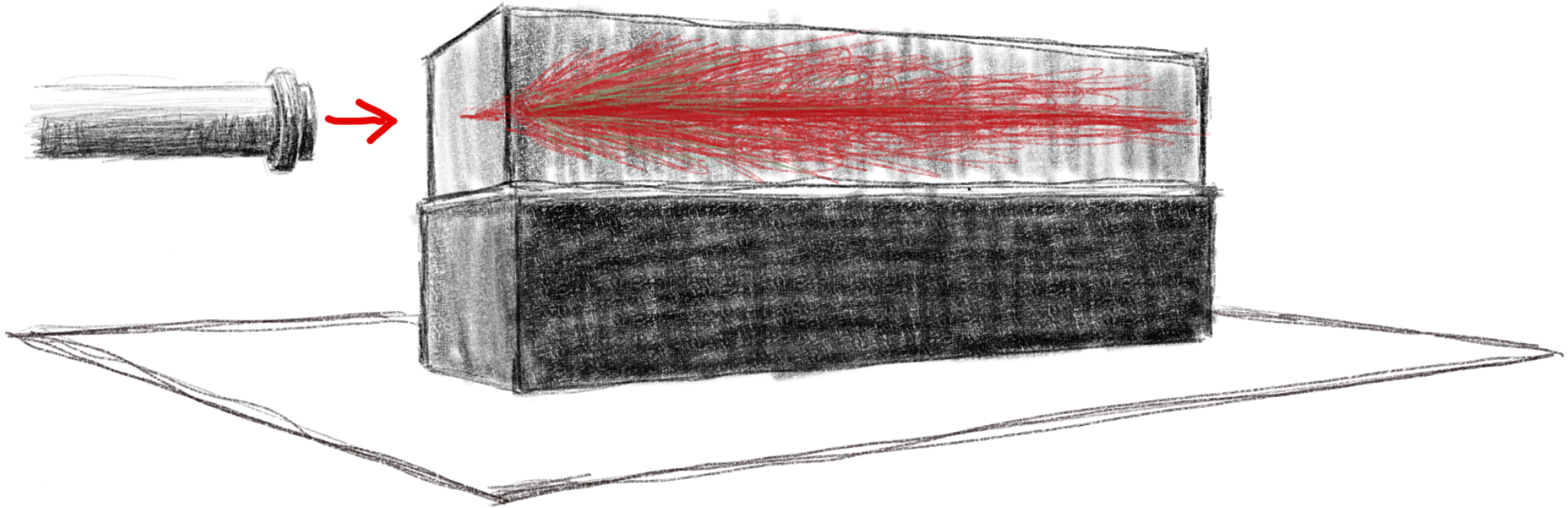
- For more information, see [radarechotelescope.org](http://radarechotelescope.org)

# Idea :



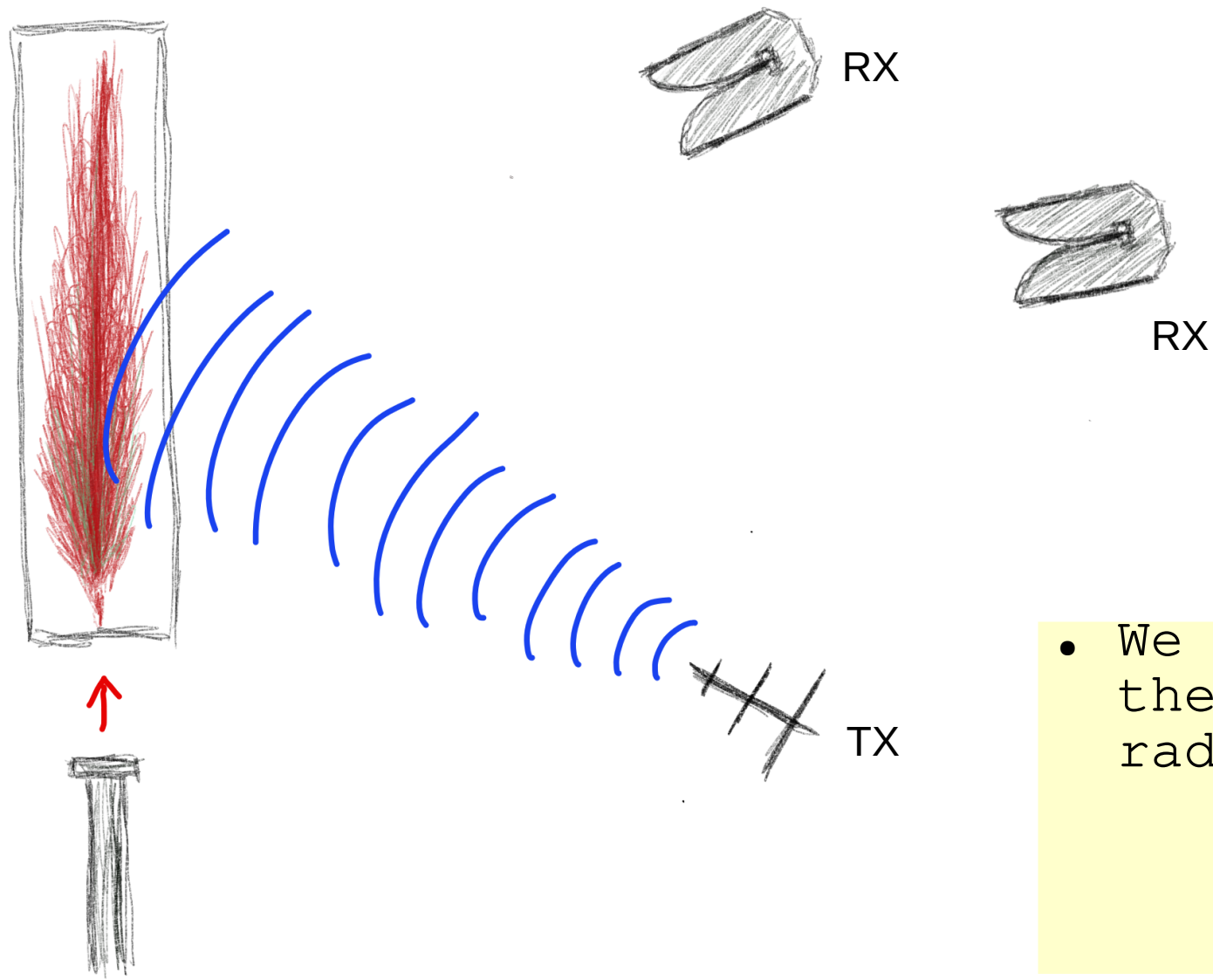
- Direct a particle beam into a plastic target in the lab
- beam: ~ neutrino
- target: ~ice

# Idea :



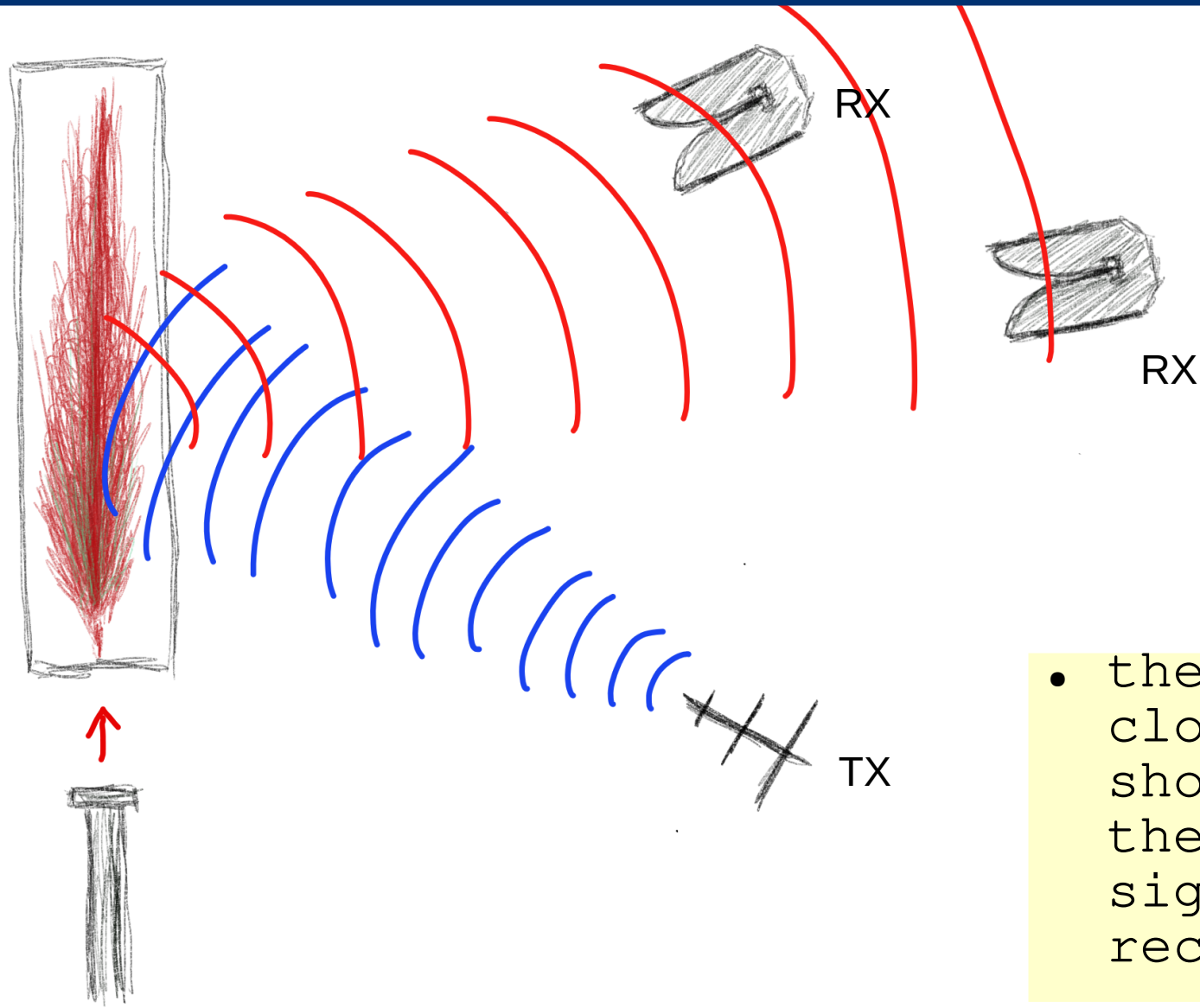
- As the beam enters the target, a cascade is created in the material

# Idea :



- We interrogate the target with radio

# Idea :



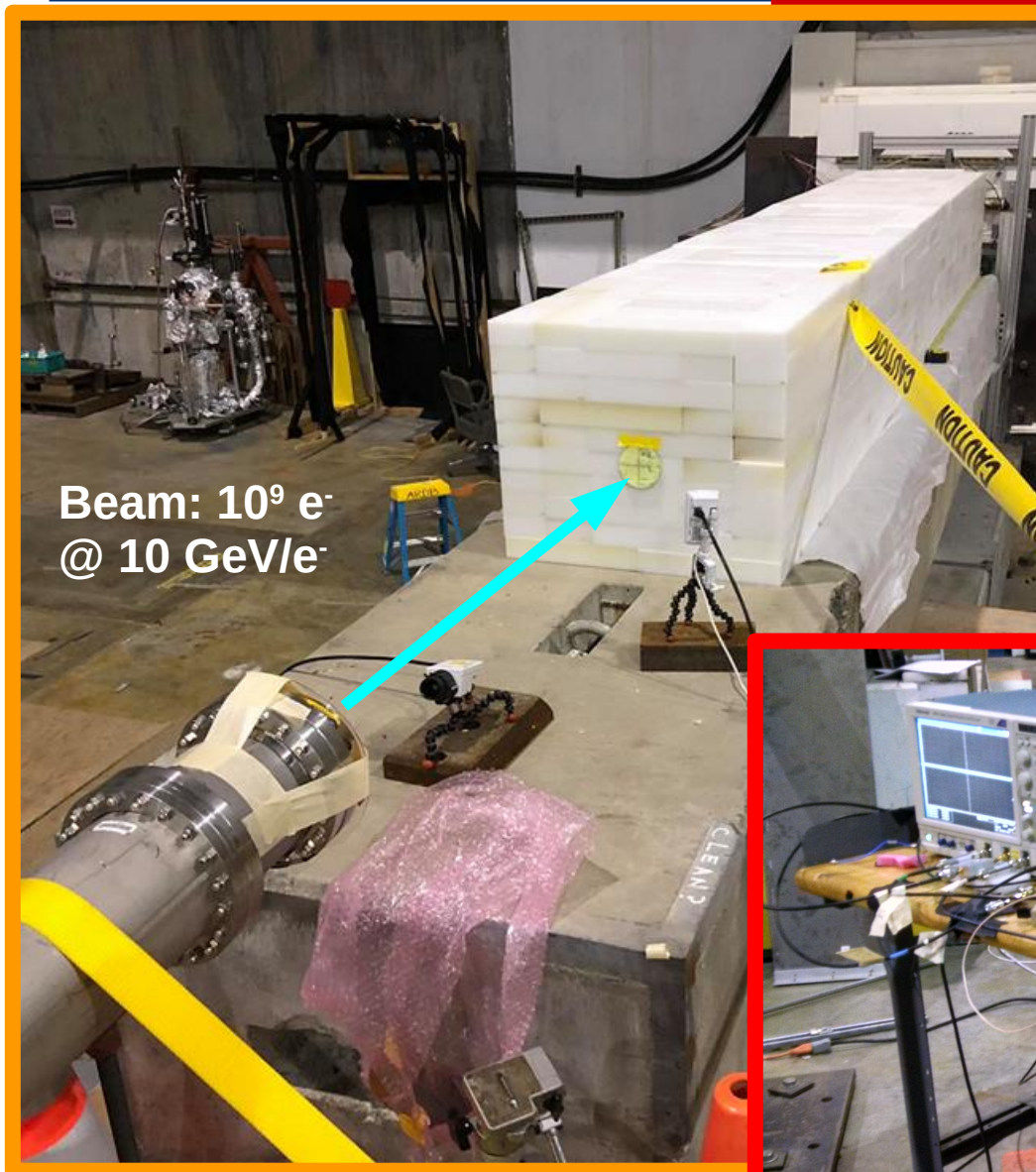
- the ionization cloud of the shower reflects the transmitted signal to the receivers

# SLAC End Station A

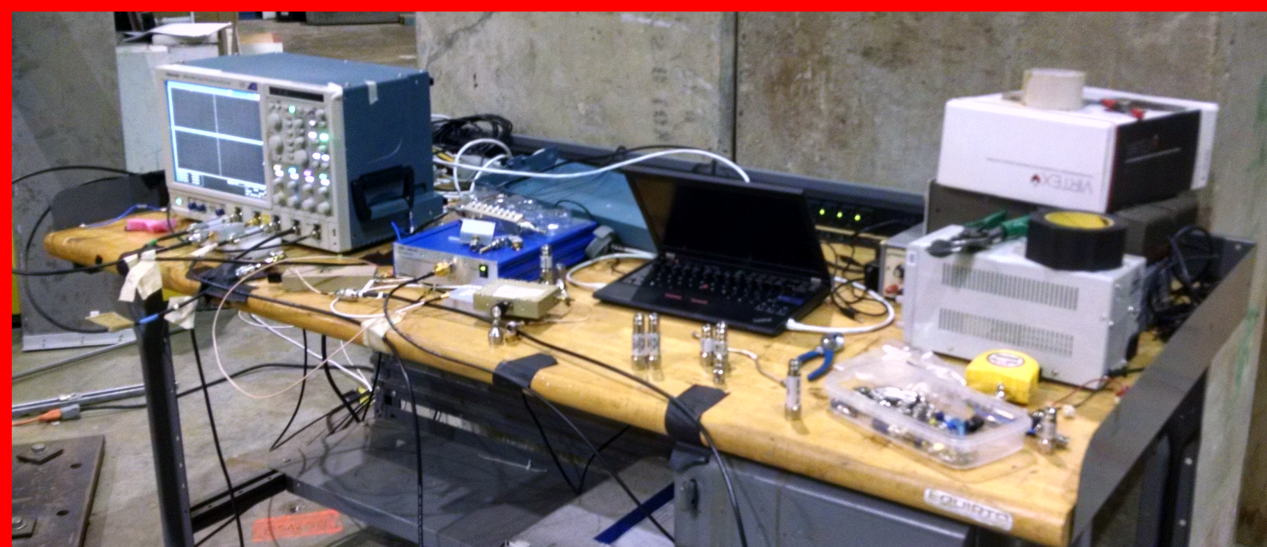


Human for scale

# SLAC T576

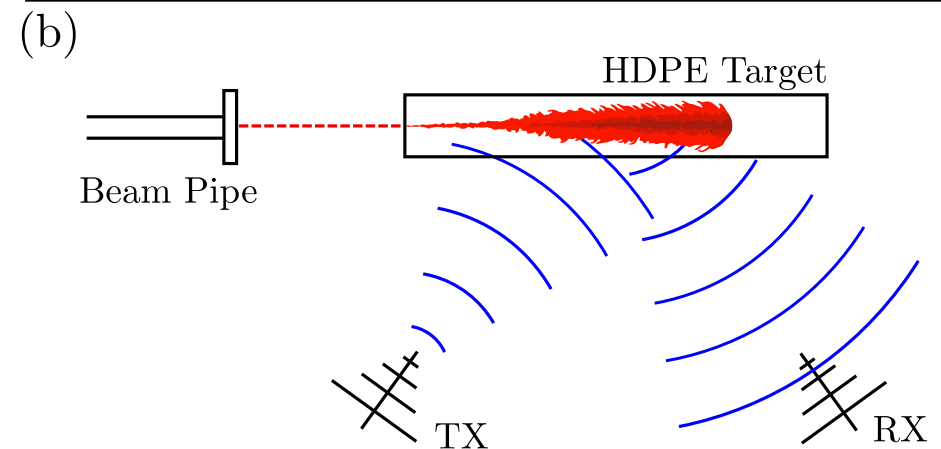
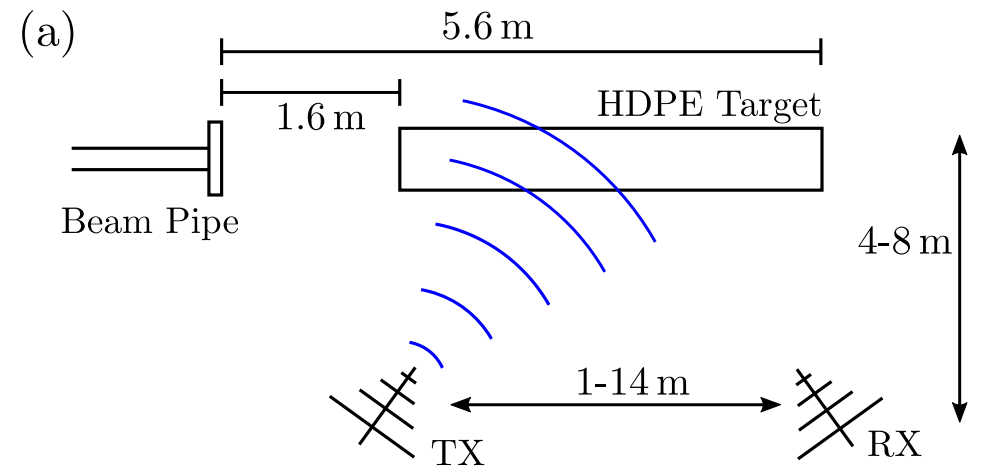


Custom LPDA from  
National Taiwan  
University, Nam group



# Toward radar echo detection: T576

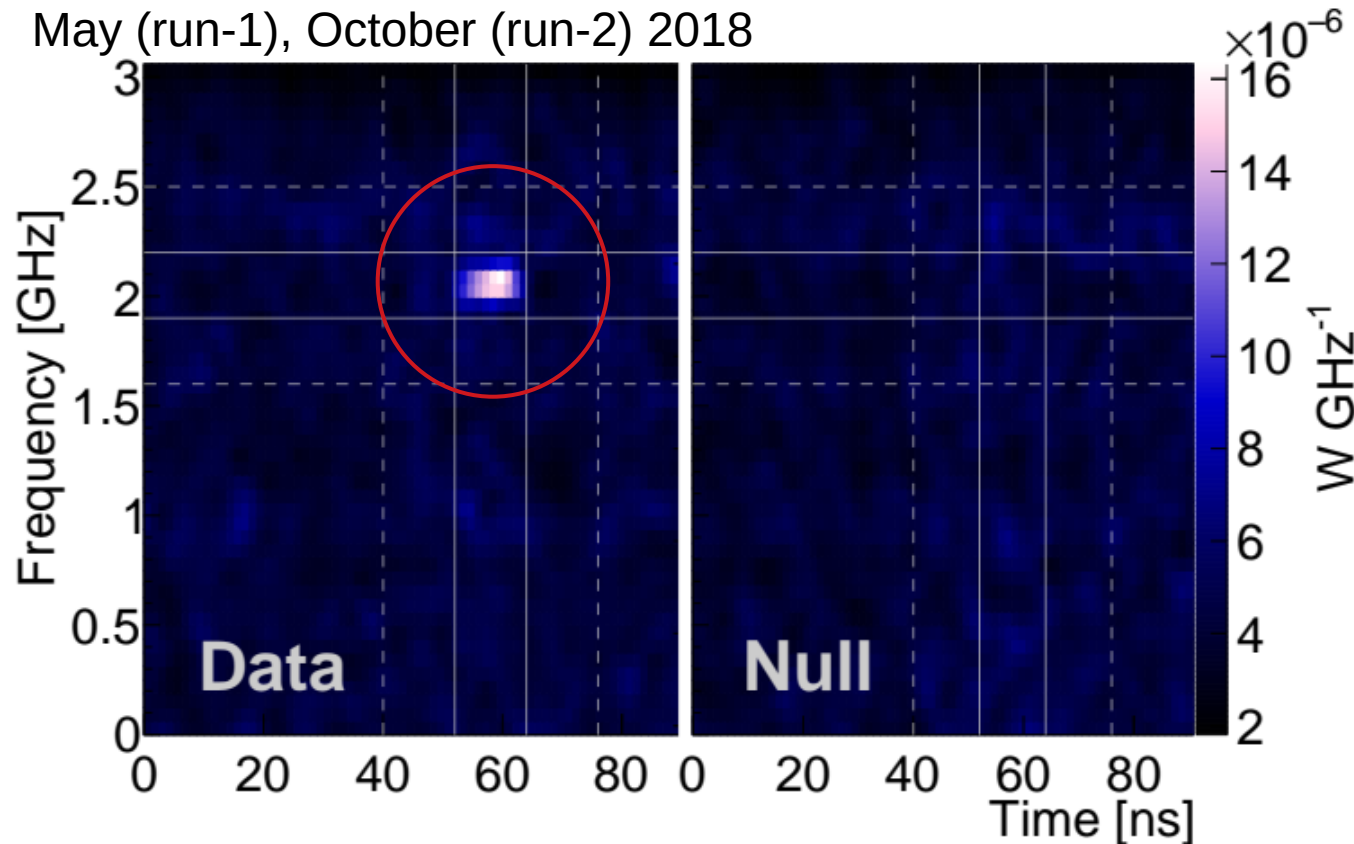
May (run-1), October (run-2) 2018



**SLAC** NATIONAL  
ACCELERATOR  
LABORATORY

# Toward radar echo detection: T576

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



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](https://arxiv.org/abs/1810.09914)

[arXiv:1910.11314](https://arxiv.org/abs/1910.11314)

[arXiv:1910.12830](https://arxiv.org/abs/1910.12830)

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

Editors' Suggestion

Featured in Physics

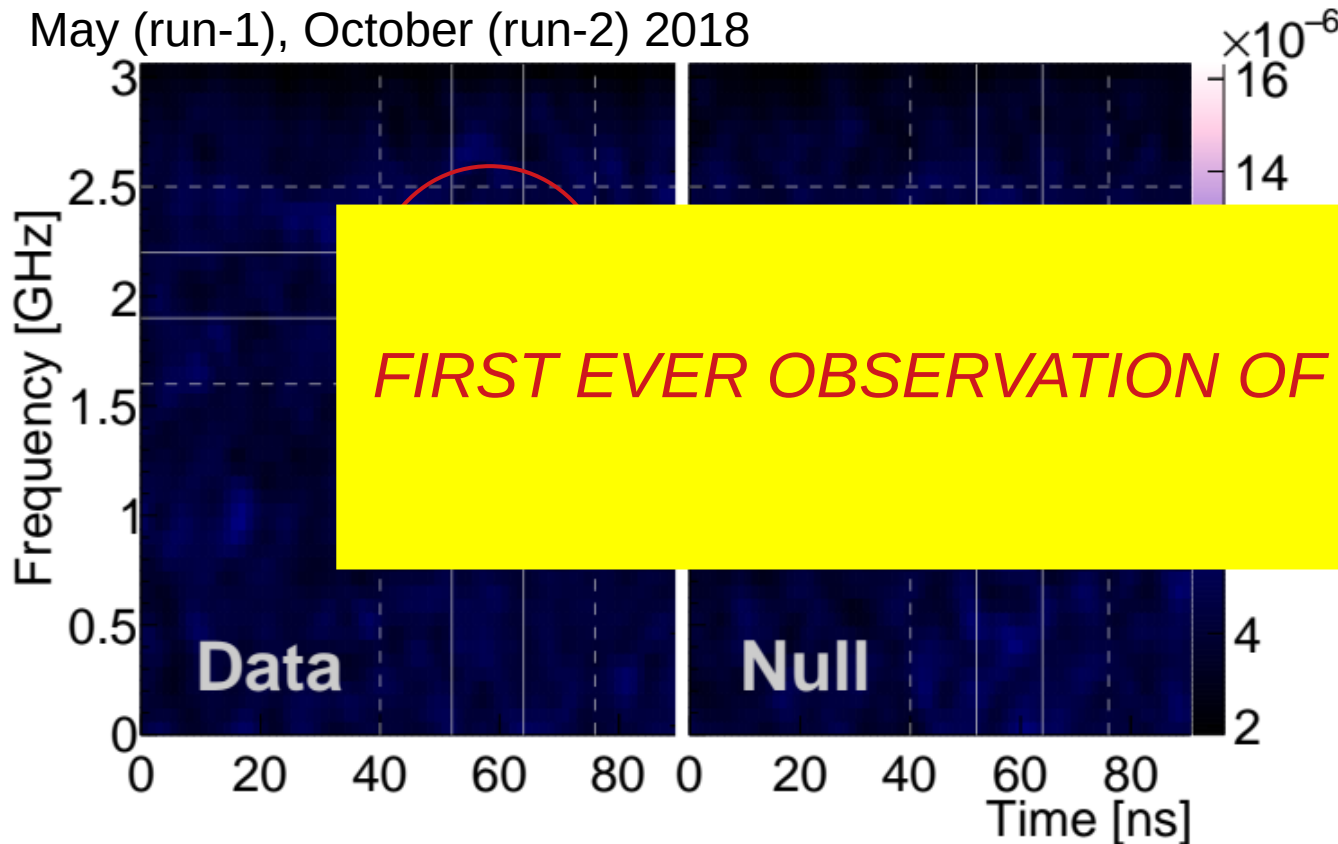
## Observation of Radar Echoes from High-Energy Particle Cascades

S. Prohira<sup>1,\*</sup>, K. D. de Vries<sup>2</sup>, P. Allison<sup>1</sup>, J. Beatty<sup>1</sup>, D. Besson<sup>3,4</sup>, A. Connolly<sup>1</sup>, N. van Eijndhoven<sup>2</sup>,  
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7.19.2022

S. Prohira----RET--Snowmass

# Toward radar echo detection: T576



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

**FIRST EVER OBSERVATION OF THIS SIGNAL!**

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# Toward radar echo detection: T576

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### Radar could detect cosmic neutrinos in Antarctic ice

28 Jan 2020



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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

## 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.

7.19.2022

S. Prohira----RET--Snowmass



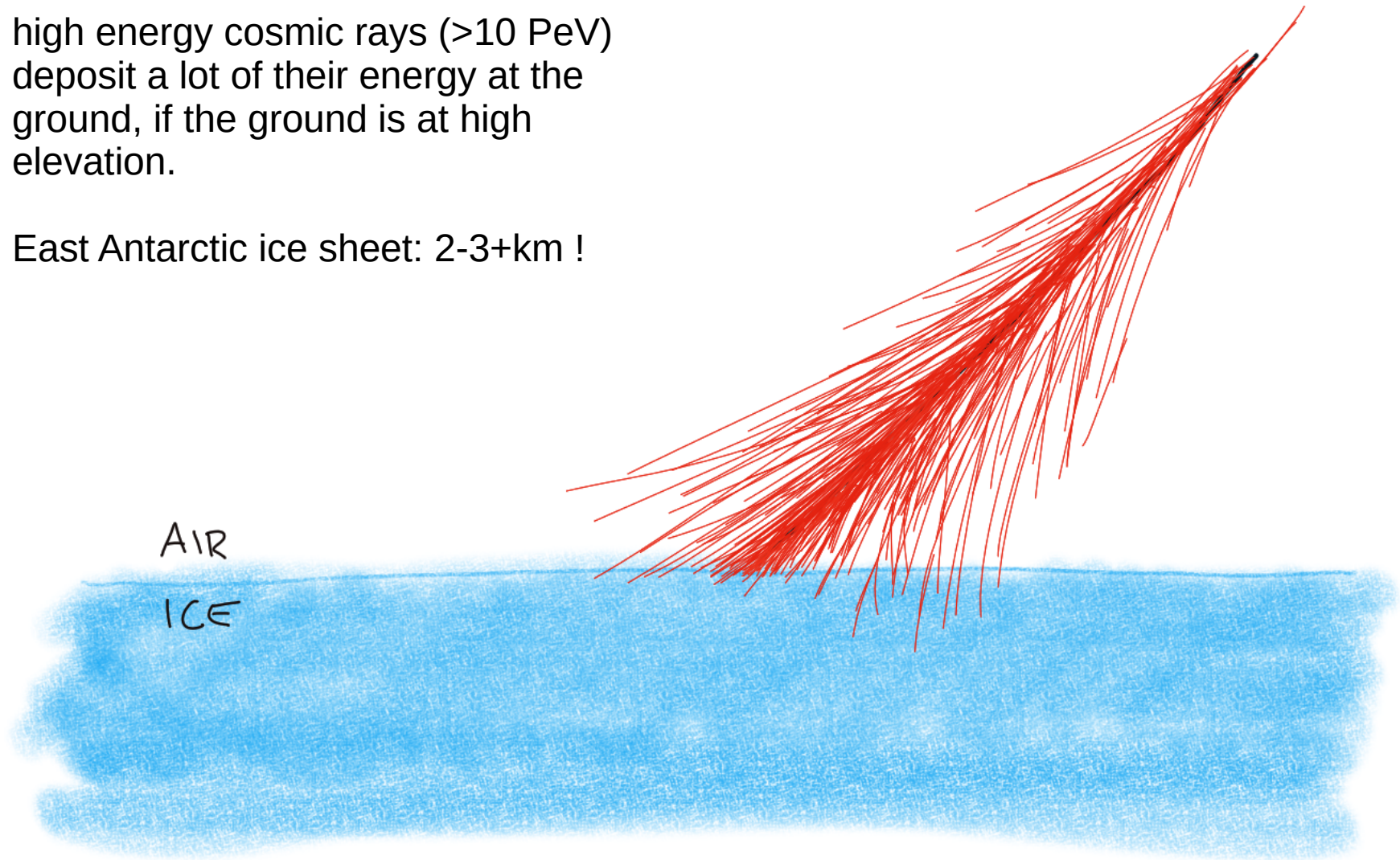
# How to test in nature?

- 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...*but in the ice!*

# 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.

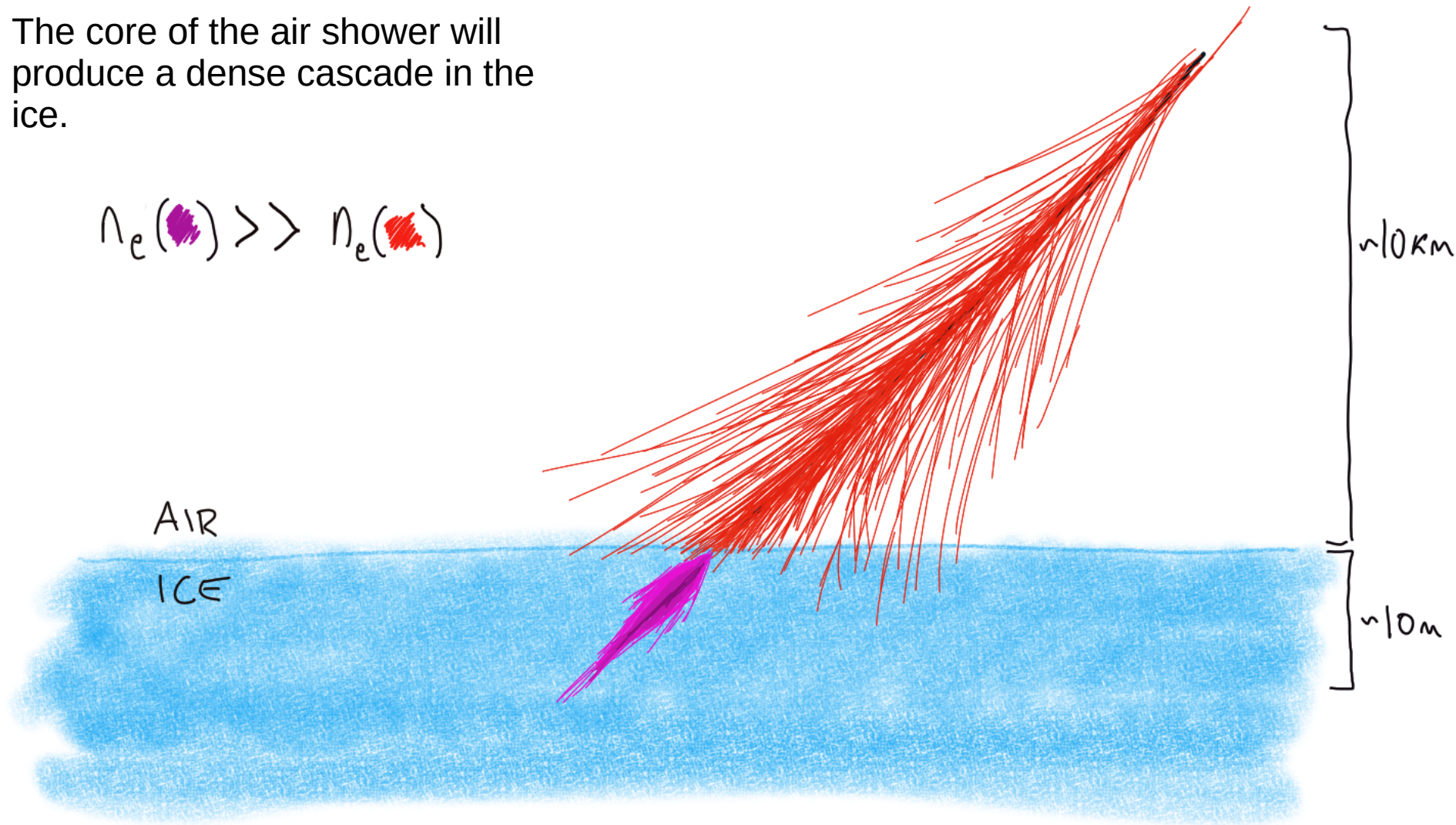
East Antarctic ice sheet: 2-3+km !



# Using cosmic rays

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

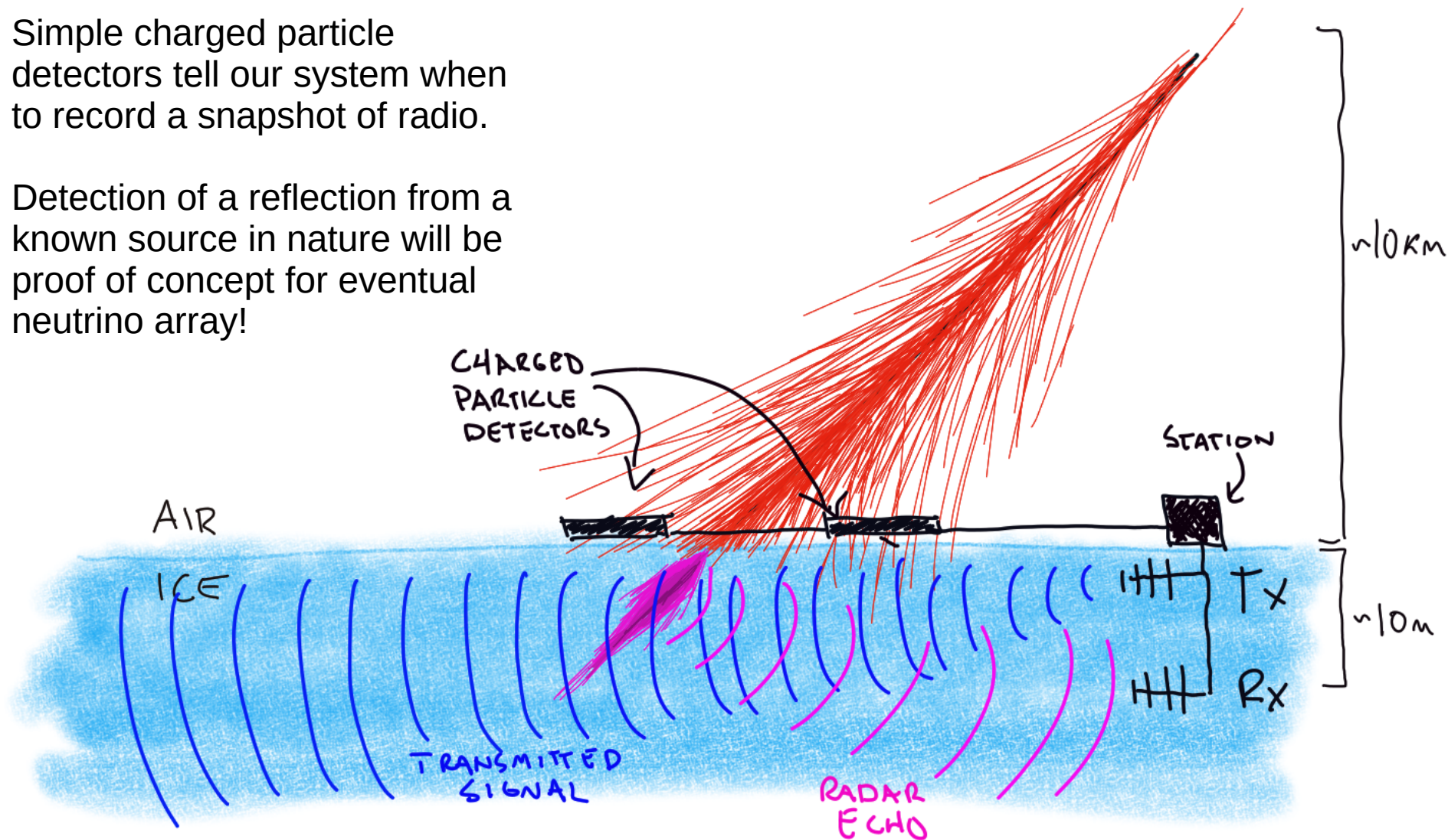
$$n_e(\text{purple}) \gg n_e(\text{red})$$



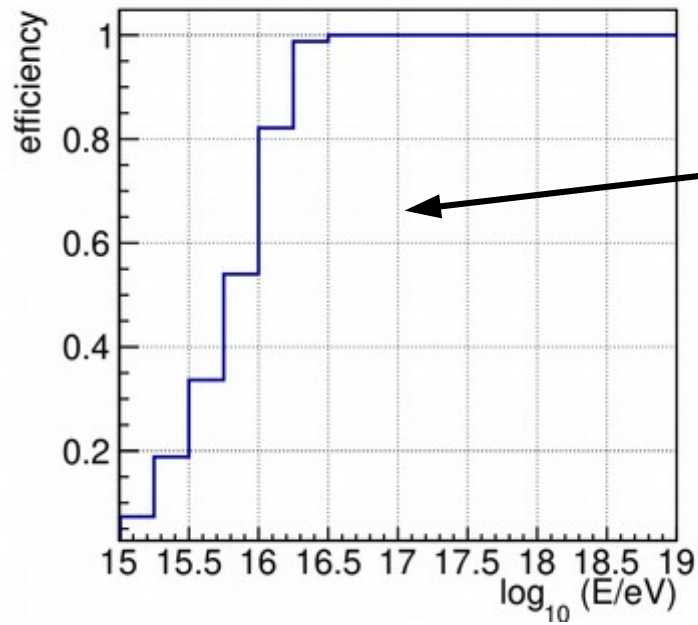
# Using cosmic rays

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

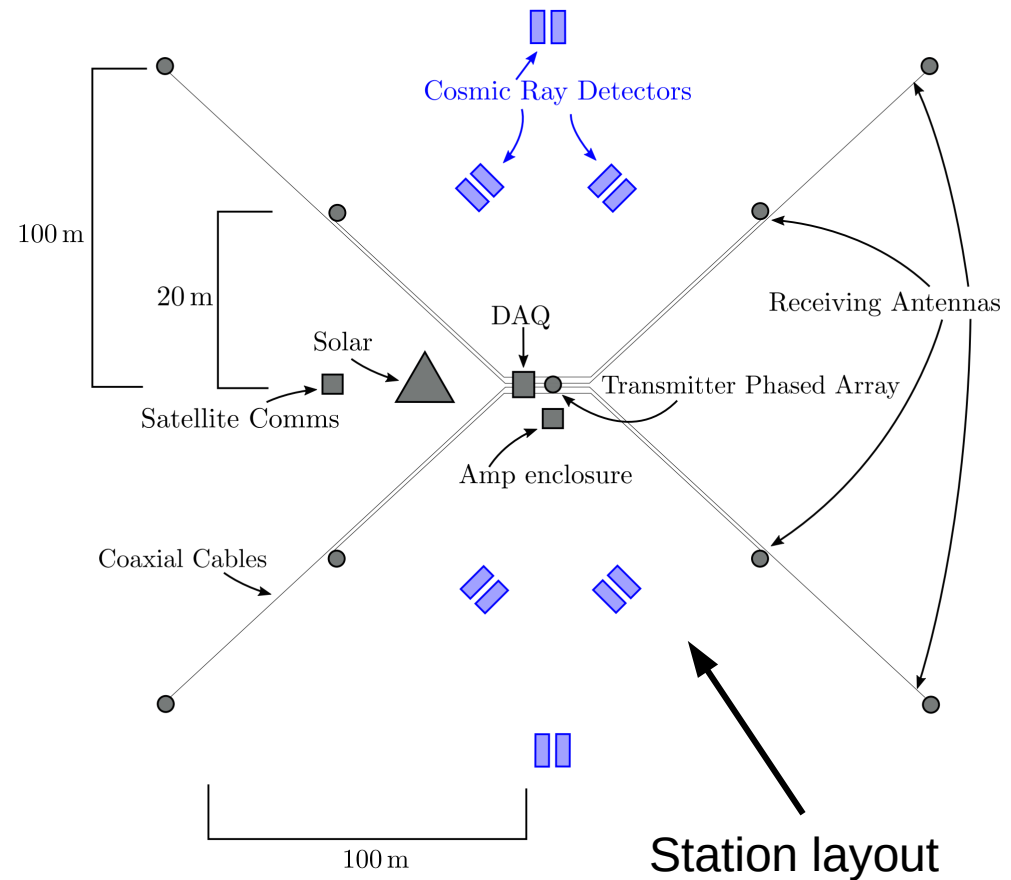
Detection of a reflection from a known source in nature will be proof of concept for eventual neutrino array!



# the RADAR ECHO TELESCOPE for COSMIC RAYS



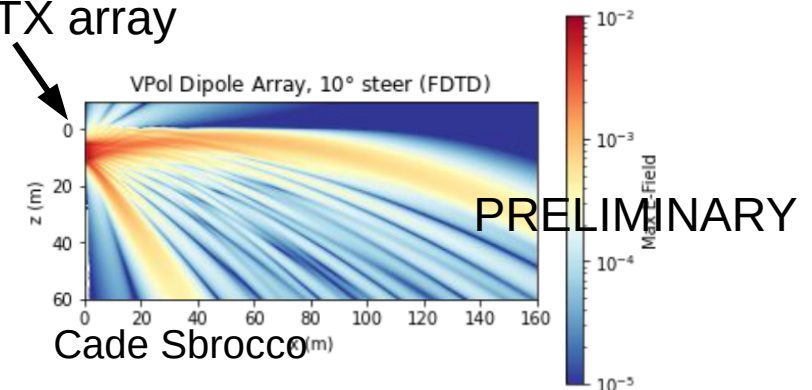
Surface system trigger efficiency curve (simulated).



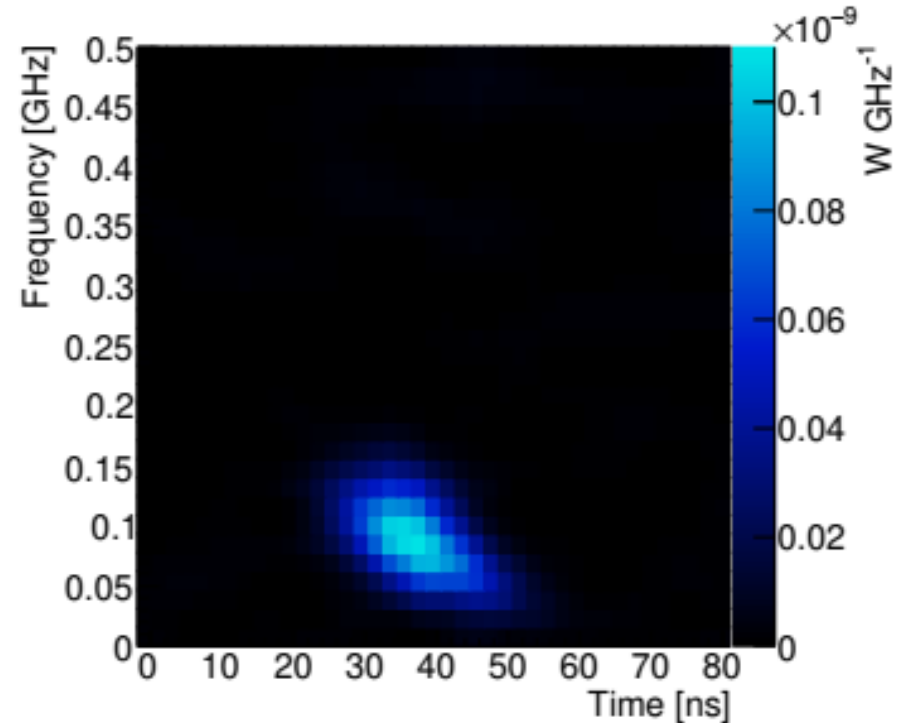
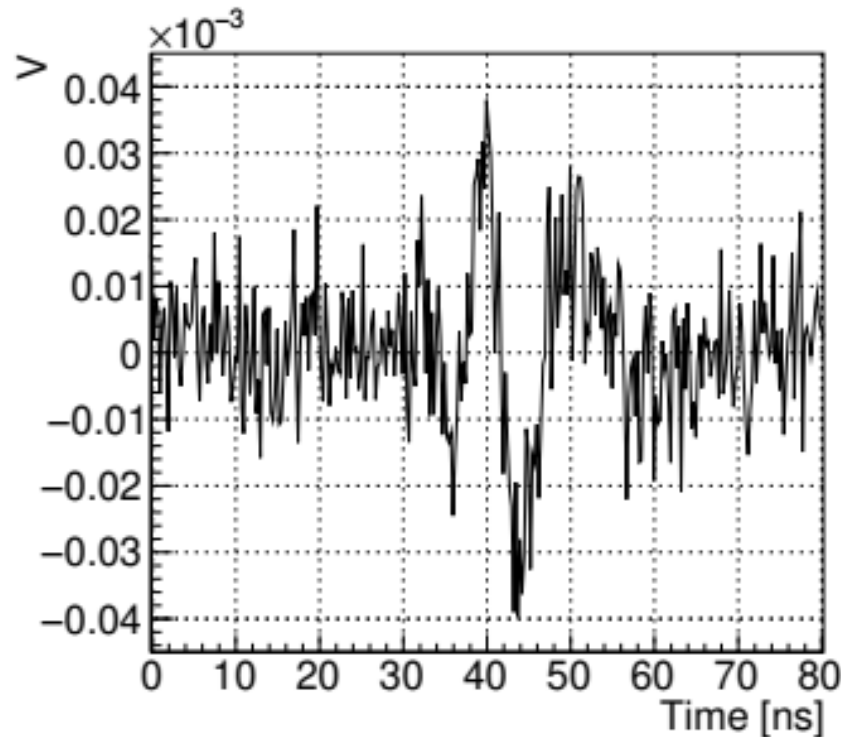
Station layout

- Surface system  $\sim 100\%$  efficient above  $10^{16.5}$  eV (trigger on every event with possible radar signal)
- Station is 8 RX at varying baselines, and an 8 antenna vertical phased array, to optimize near-surface gain
- *Adaptive filtration* used to cancel the TX

## Phased TX array



# Expected signal

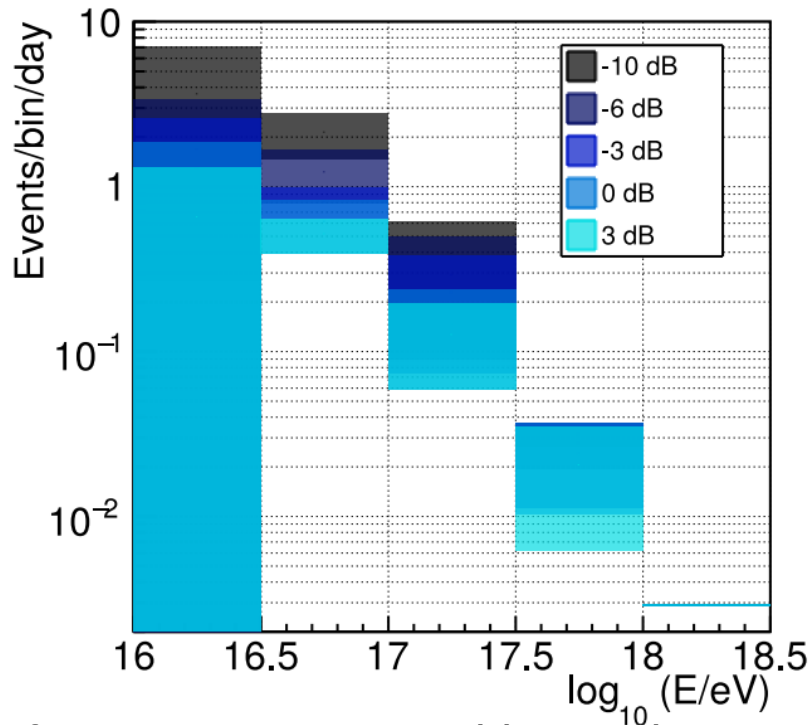


The radar echo signal has some interesting signal properties that we can use to trigger on, for example, a strong frequency shift for some geometries. Preliminary: [pos.sissa.it/395/1211](http://pos.sissa.it/395/1211), more results *In Preparation*

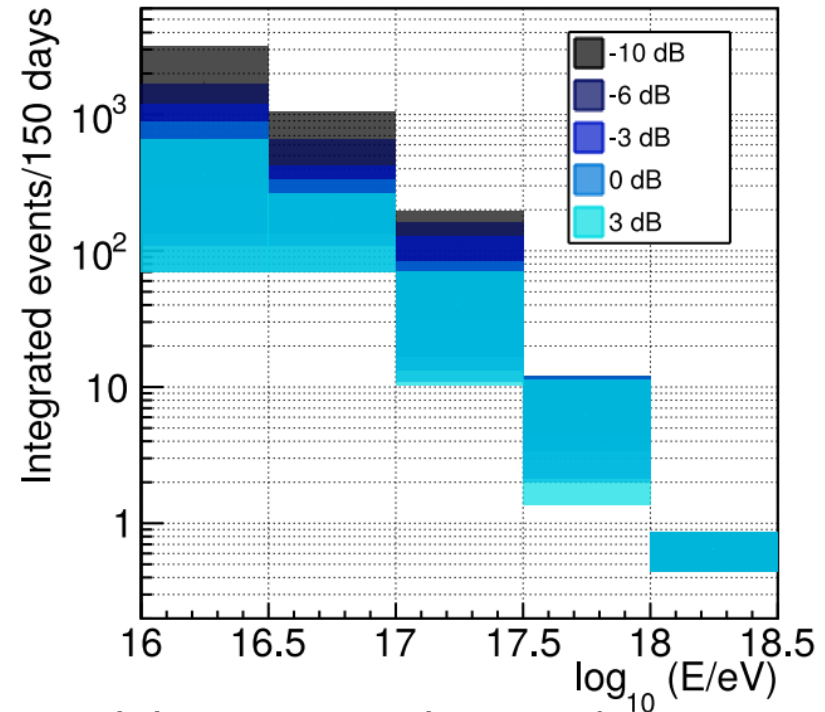
# Event rate

- Detailed simulations using Corsika, GEANT4, and RadioScatter give us an event rate (Rose Stanley and Simon De Kockere, VUB Brussels)
- 3 step process:
  - 1) **Corsika** showers were thrown with random distribution of zenith angles from 0-30 deg and energies from PeV to 10 EeV.
  - 2) Corsika output at the surface was propagated into ice using **GEANT4**
  - 3) **RadioScatter**  
(<https://github.com/prchyr/RadioScatter/releases/tag/v1.1.0>) was used to simulate the radio scatter from the GEANT4 ionization deposits

# Event rate



Left: events per energy bin per day.



Right: Integrated events/season

We expect to see **~1 event every day** or so with energies at or above 100 PeV.

After a full season (approx 150 days), expect hundreds of events with which to train our trigger routines.

# Hardware work in progress



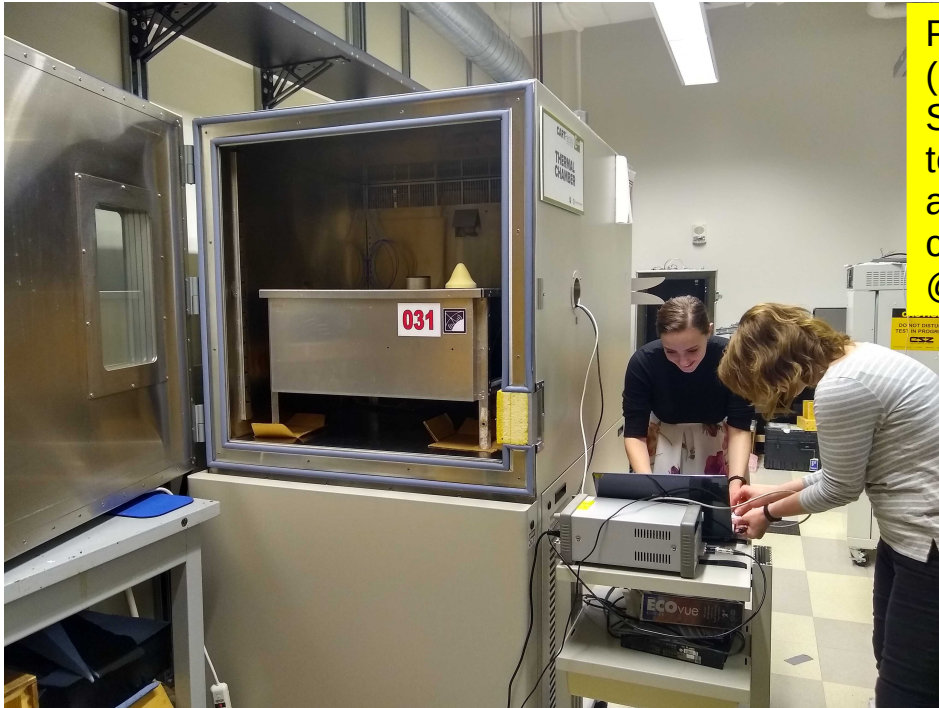
Surface system  
deployment  
@VUB rooftop!  
Credit: K Mulrey,  
R. Stanley, E.  
Huesca Santiago,  
KD de Vries



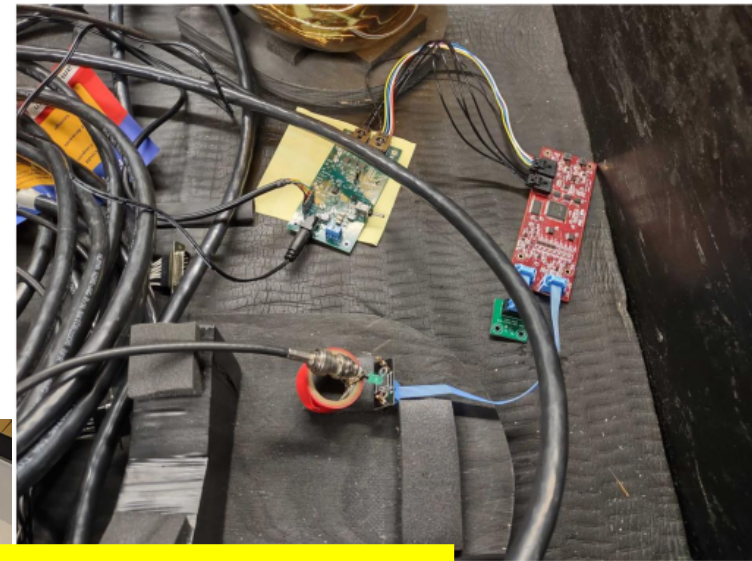
RFSoc trigger  
development  
@OSU!



# Hardware work in progress



Prof. Katie Mulrey (Radboud) and Rose Stanley (VUB) cold-testing some electronics at the inaugural RET collaboration meeting @OSU in April 2022

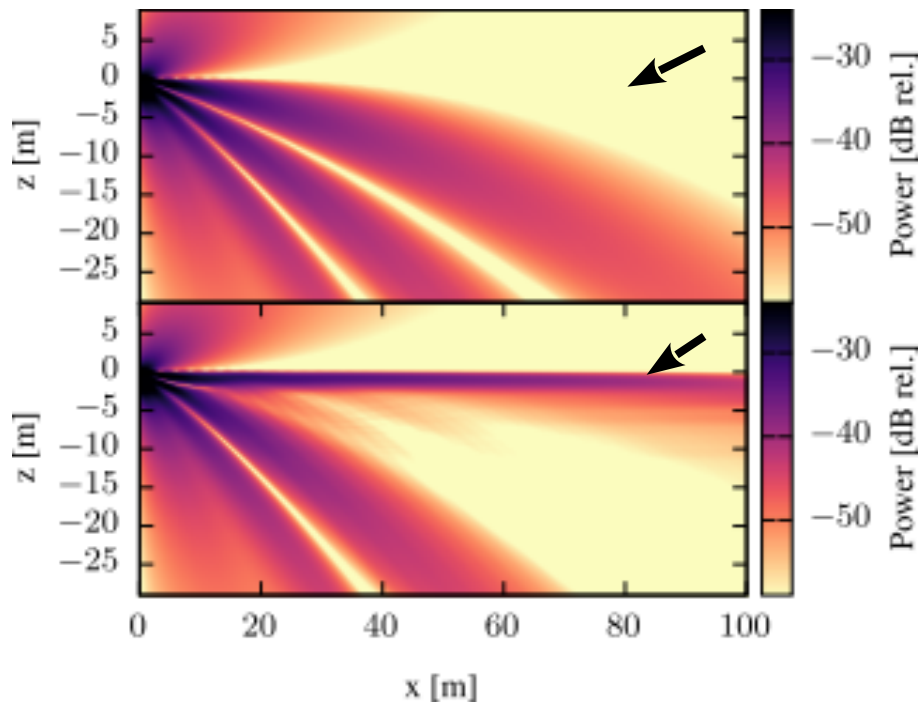


Dylan Frikken (OSU) performs system tests on scintillator panels (left) and readout electronics (above).



Panels courtesy of IceCube, thanks to Delia Tosi, Matt Kauer, and Chris Wendt

# Ice Properties

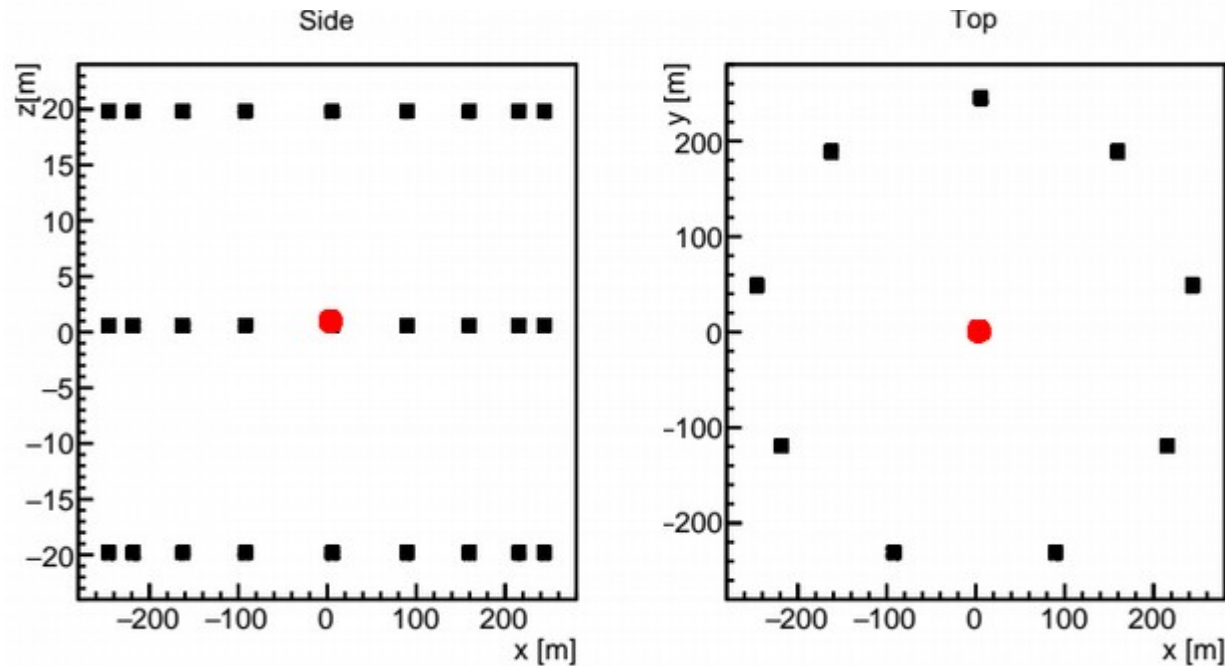


- For a transmitter 1m below the surface.
- Top: purely functional, smooth index of refraction profile
- Bottom: accounting for measured density fluctuations in the ice; big differences in propagation!
- Modeled using parabolic equations, details: PhysRevD.103.103007 (arXiv:2011.05997)

- The ice near the surface of a polar ice sheet is highly variable in density (and therefore index of refraction)
- Polar ice is birefringent, which has implications for these detectors, see e.g. PhysRevD.105.123012
- In-situ measurements and detailed simulations are key to understanding local radio wave propagation

# the RADAR ECHO TELESCOPE

for NEUTRINOS



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

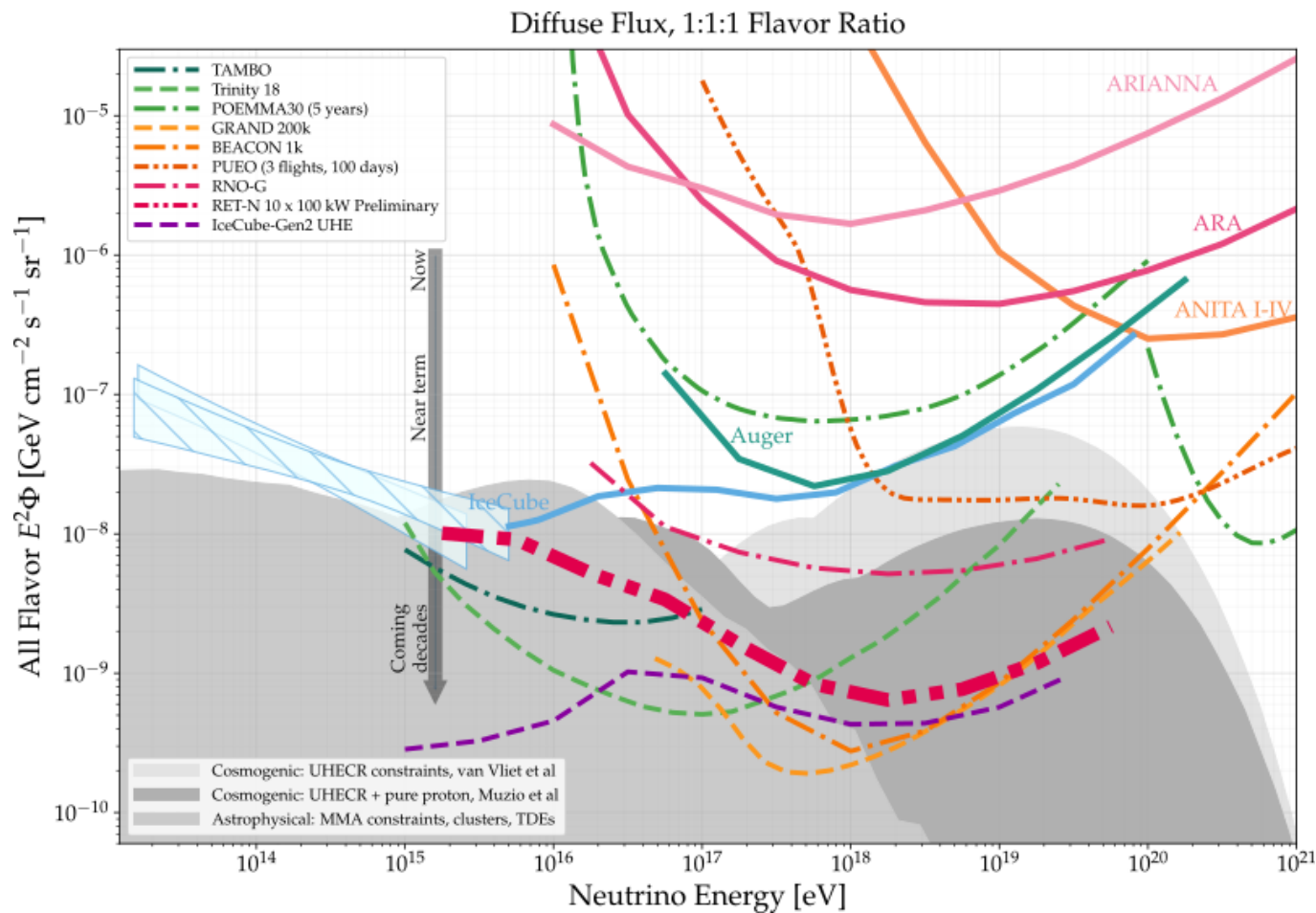
Final station layout to be based on what we learn from RET-CR.

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 an 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



RET **10 stations**, 10 years, thick red dashed curve, versus 100s-1000s of stations for other instruments.

Also shown: Many experiments with different sensitivities

How do we decide what to build?

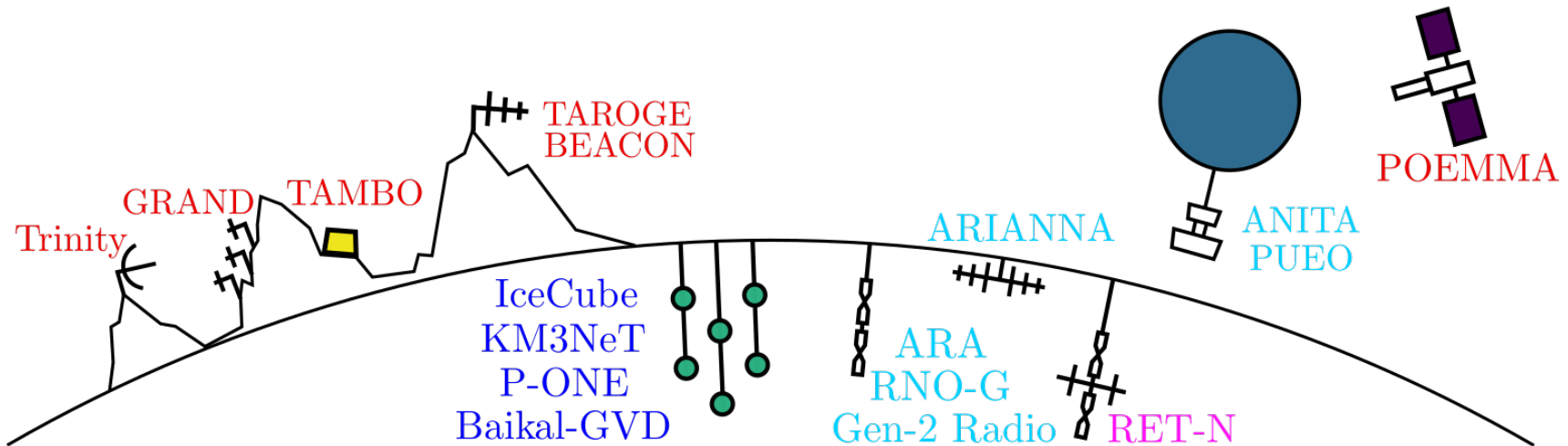
My opinion:  
**everything**

for good reasons...

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



# Complementary UHE neutrino detectors



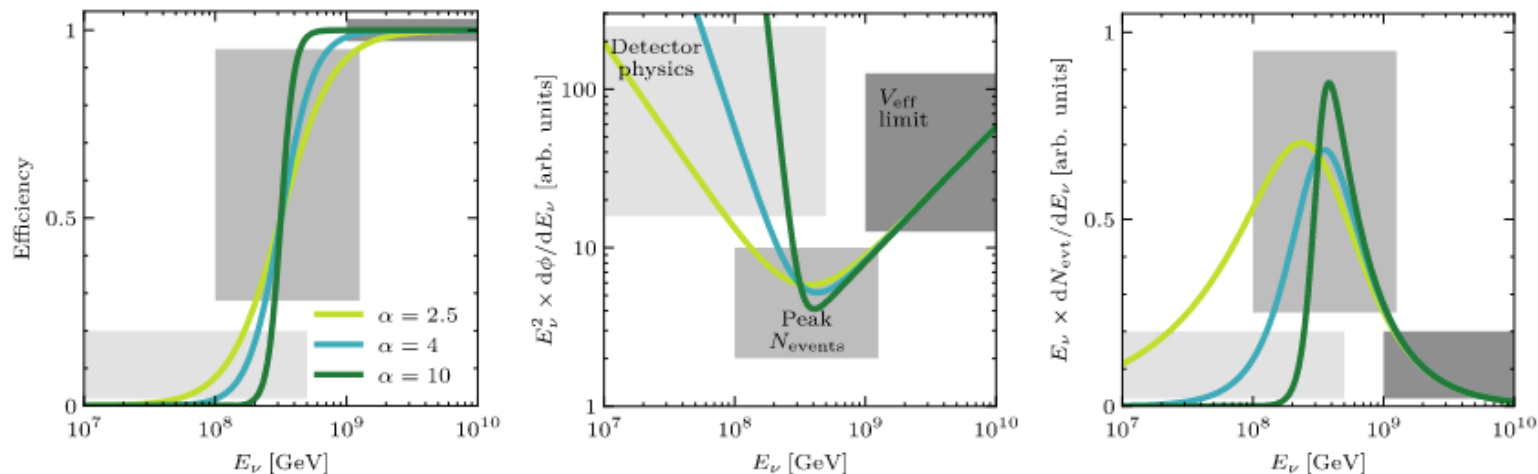
Adapted from Esteban et al. arXiv:2205.09763

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**.

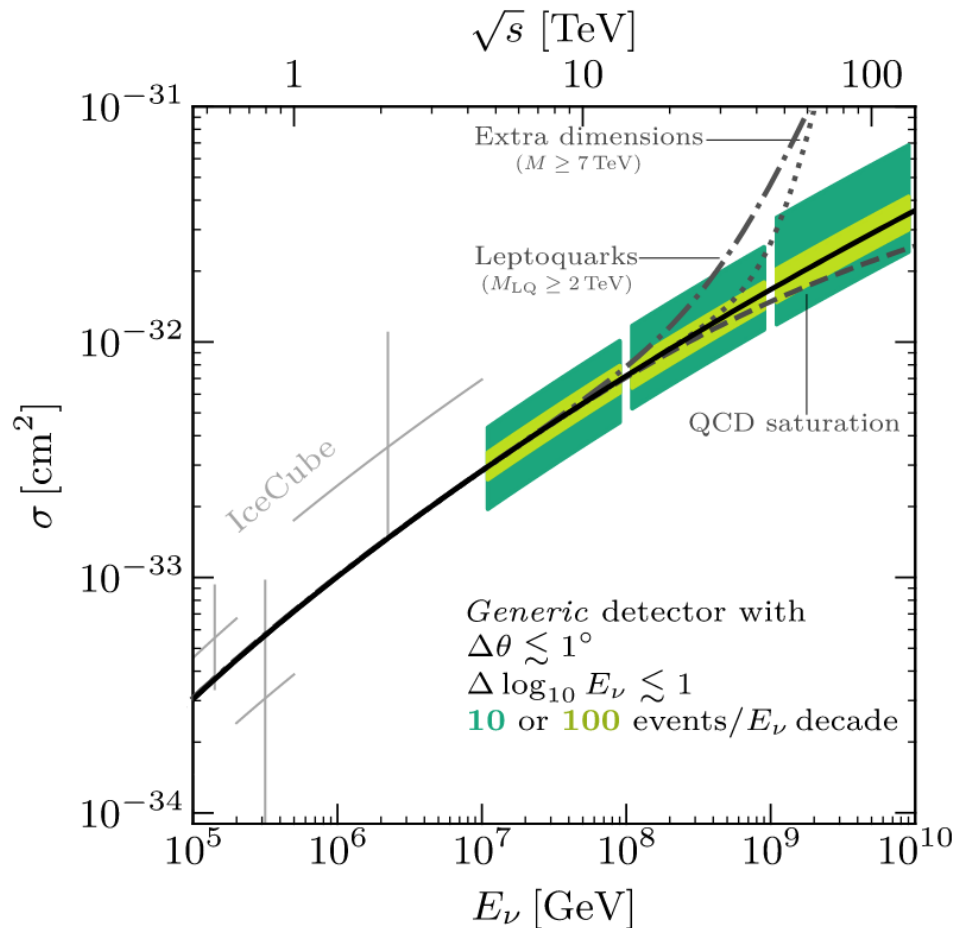
# Understanding sensitivities



Esteban et al. arXiv:2205.09763

- Center: this is an  $E^2$  flux plot of example sensitivities, typical of UHE sensitivity curves
- Left: corresponding threshold curves
- Right: corresponding number of events assuming some power law flux
- takeaway: Shape of sensitivity determines where your neutrinos come from. Different experiments have different characteristic energies and shapes. **Multiple experimental efforts guarantee coverage of the landscape!**

# Example: UHE cross sections



Esteban et al. arXiv:2205.09763

- With 10 events per E decade, the UHE neutrino cross section can be measured, and can begin to constrain some BSM models
- Detectors must meet minimum criteria for resolution in energy and angle, but that's it.
- **Different experiments can measure different energy bins**

# Summary

- The radar echo method is a flexible, scalable technology for UHE neutrino detection
- Complementary measurements with other instruments (Askaryan, tau neutrino, optical) provides robust measurements and a more complete picture of the UHE neutrino sky
- RET-CR is under development with deployment imminent.

Thanks!