The Radar Echo Telescope for Cosmic Rays

Steven Prohira and Krijn D. de Vries

On behalf of the Radar Echo Telescope Collaboration:
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ICRC 2021

European Research Council
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key takeaways

- The Radar Echo Telescope for Neutrinos and Cosmic Rays (RET-N and RET-CR) is a new proposed system to *target neutrinos with energies greater than 10^{16} electron volts (10PeV)* (ultra high energy [UHE])
- RET-CR is a pathfinder, prototype 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:
  - Cosmic-ray detection hardware already undergoing in-field testing
  - Trigger development and testing underway
  - instrument paper under review at PRD: arXiv:2104.00459

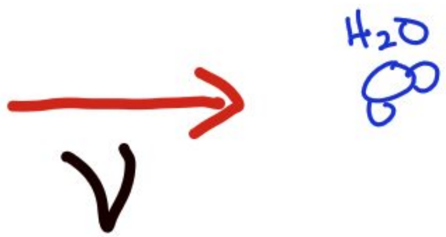
Neutrino detection with radar

- Ultimate goal of RET is to detect UHE neutrinos.
  - please see contribution 1214, KD de Vries, the Radar Echo Telescope for Neutrinos
- The radar echo method has been verified in the laboratory. RET-CR is a bridge between our in-lab experimental results and a full-scale neutrino detector.
- So...

  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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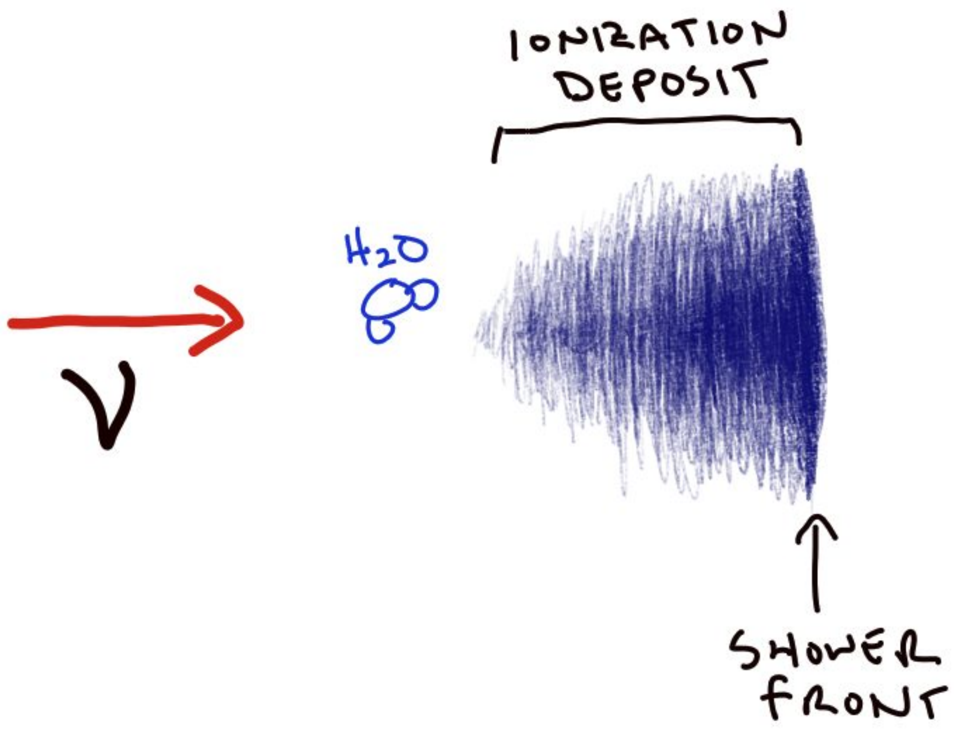

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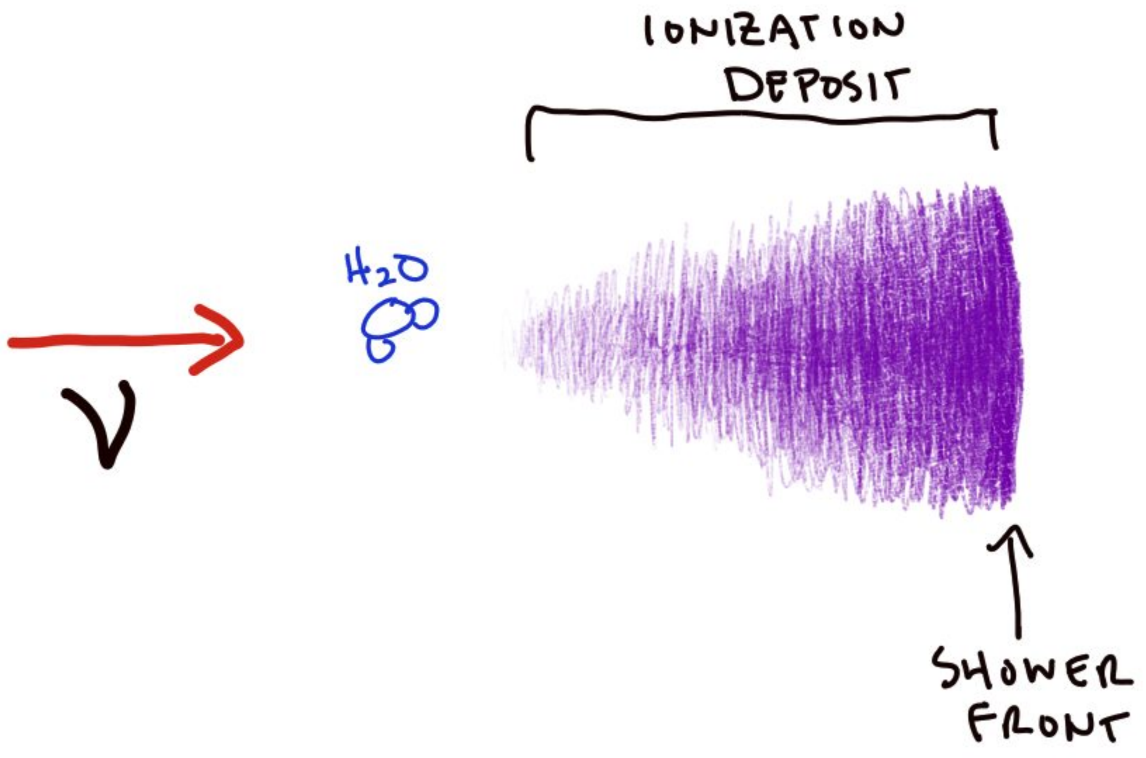

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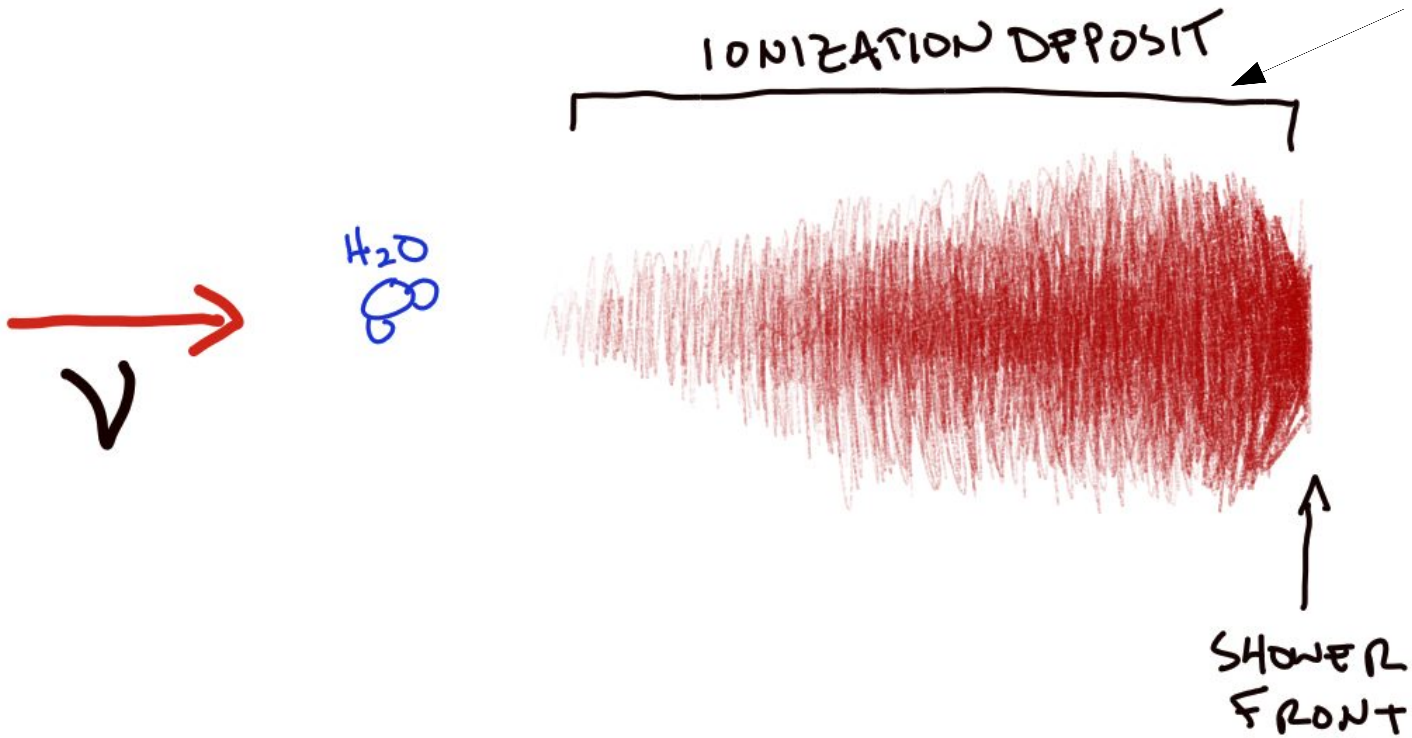
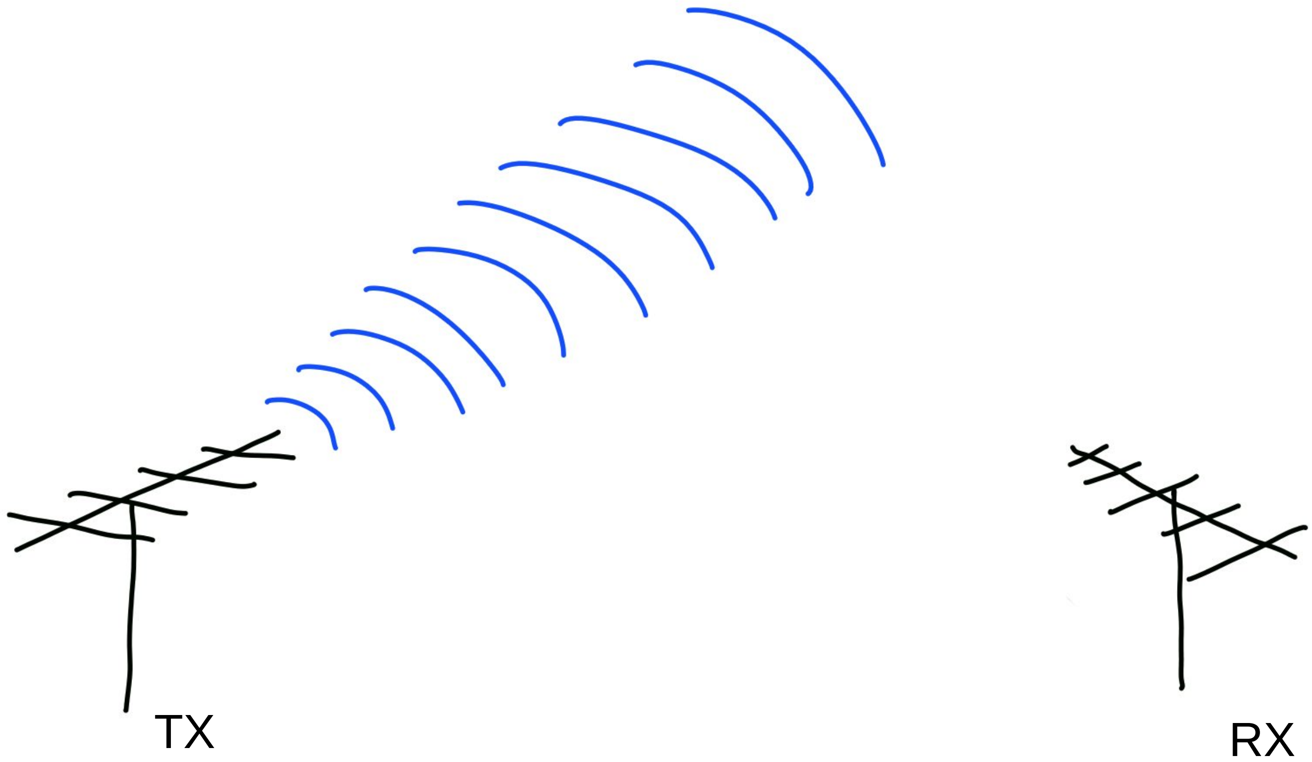


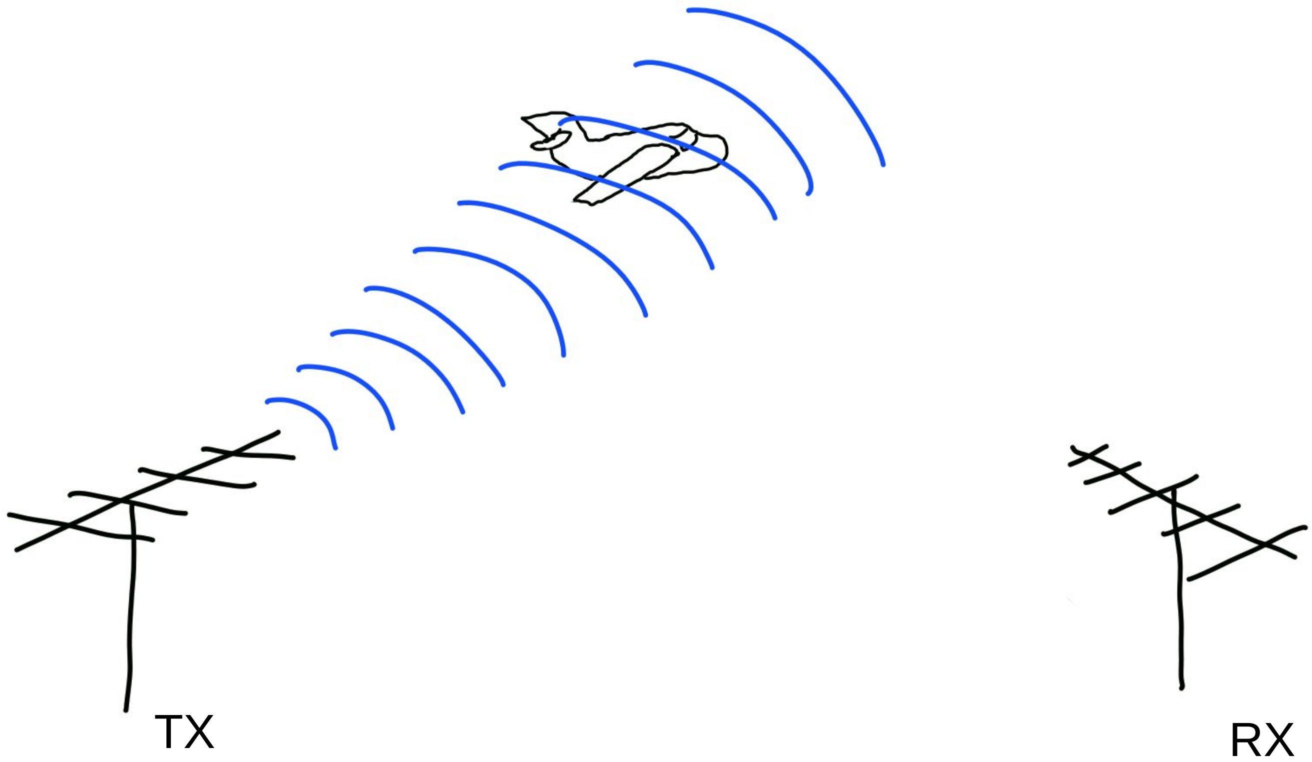
‘length’ of this deposit depends on the properties of the medium, the ‘lifetime’ of a free electron.

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)

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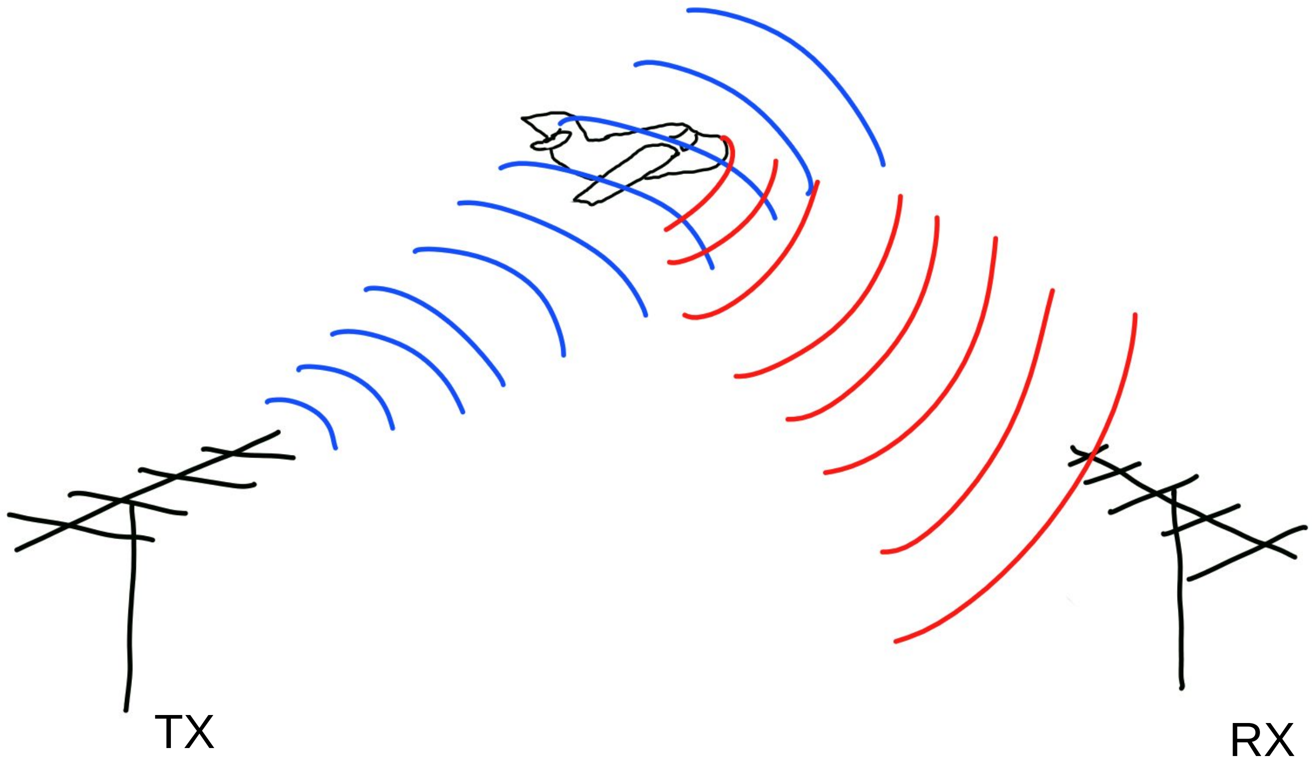

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radar detection of neutrinos

(Simple) Big Picture Concept:

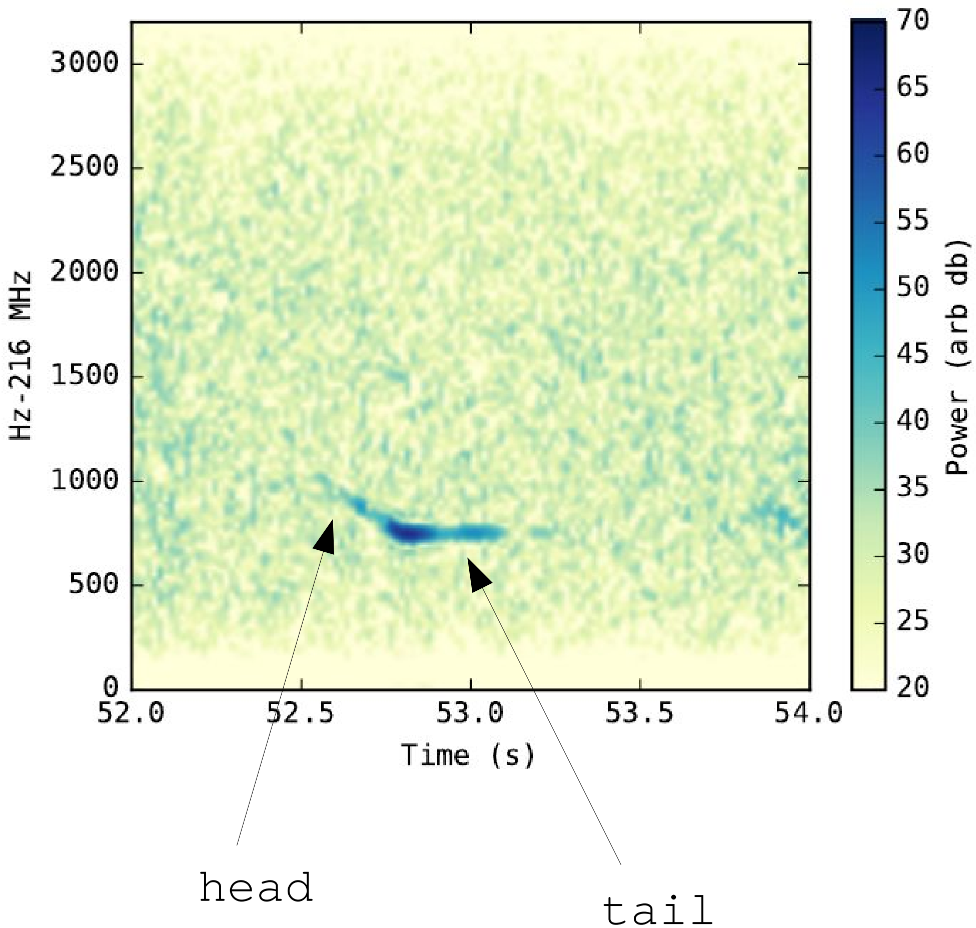
Bounce radio waves off of the ionization deposit left in the wake of a neutrino-induced cascade.

radar 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!)

radar detection of meteors



- ~700Hz is the downconverted frequency of the transmitter

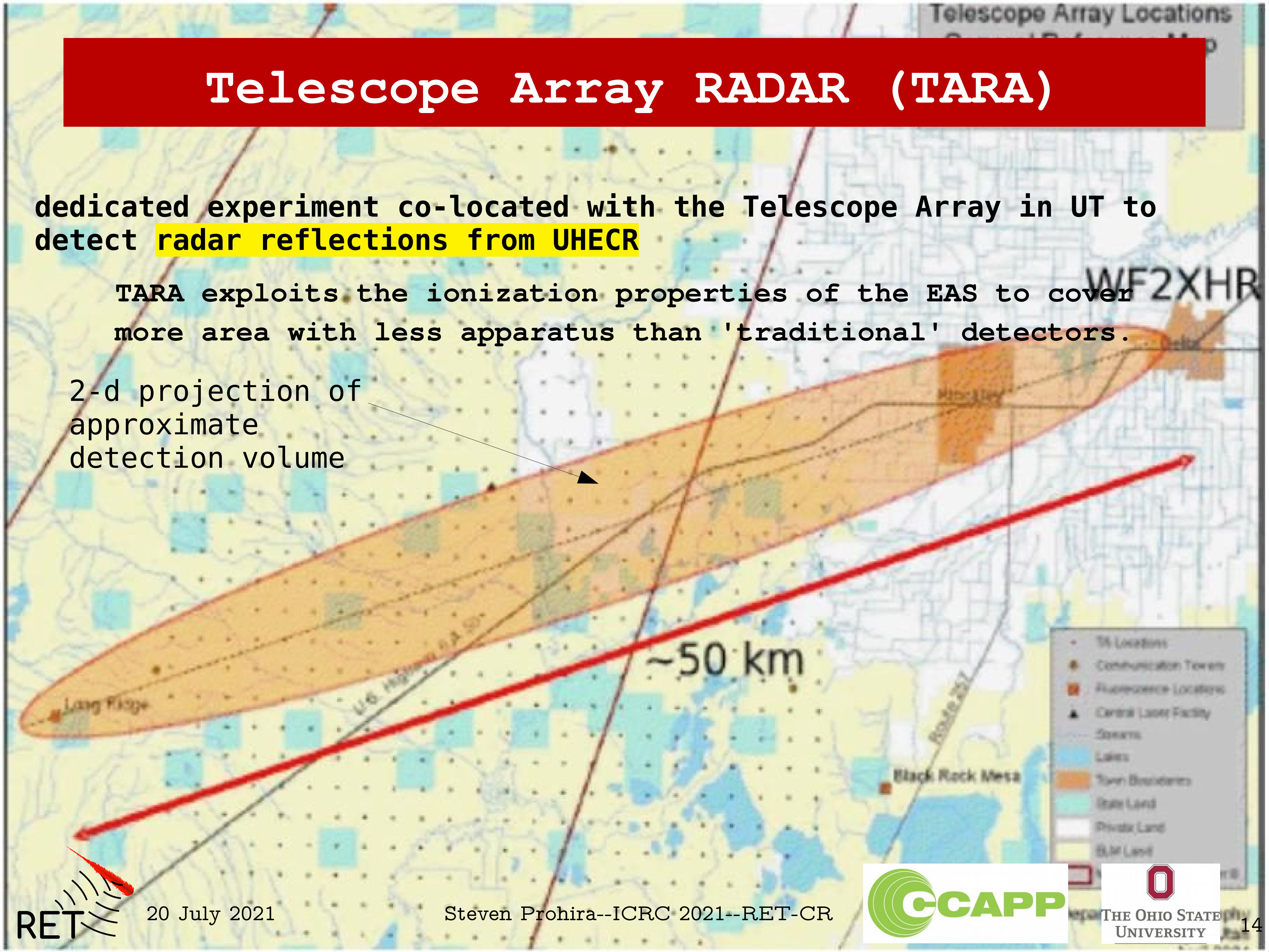
- **meteorites ablate at ~100km in the atmosphere**
- **produce a large dense trail of ionization: dense enough to reflect radio**
- **'head echo' shifts in frequency because it moves**
- **tail is stationary and results in a monochromatic return.**

Telescope Array RADAR (TARA)

dedicated experiment co-located with the Telescope Array in UT to detect radar reflections from UHECR

TARA exploits the ionization properties of the EAS to cover more area with less apparatus than 'traditional' detectors.

2-d projection of approximate detection volume



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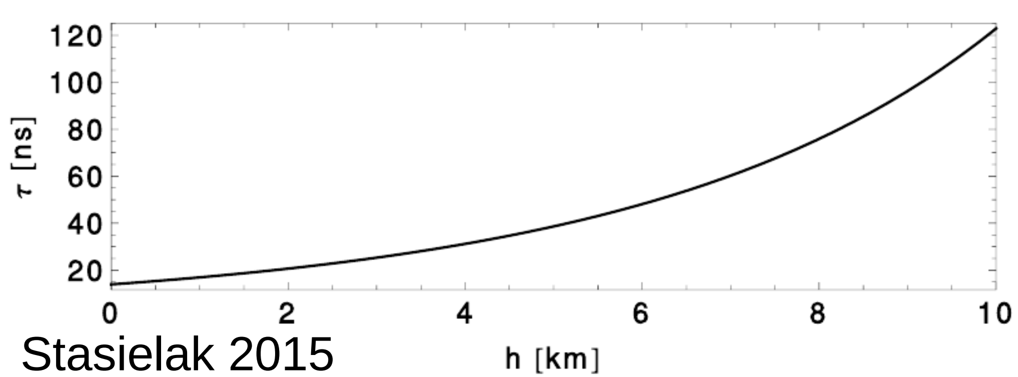
TARA ran for several years, and reported no signal

ionization densities not high enough in air due to collisions and short plasma lifetime (see left)

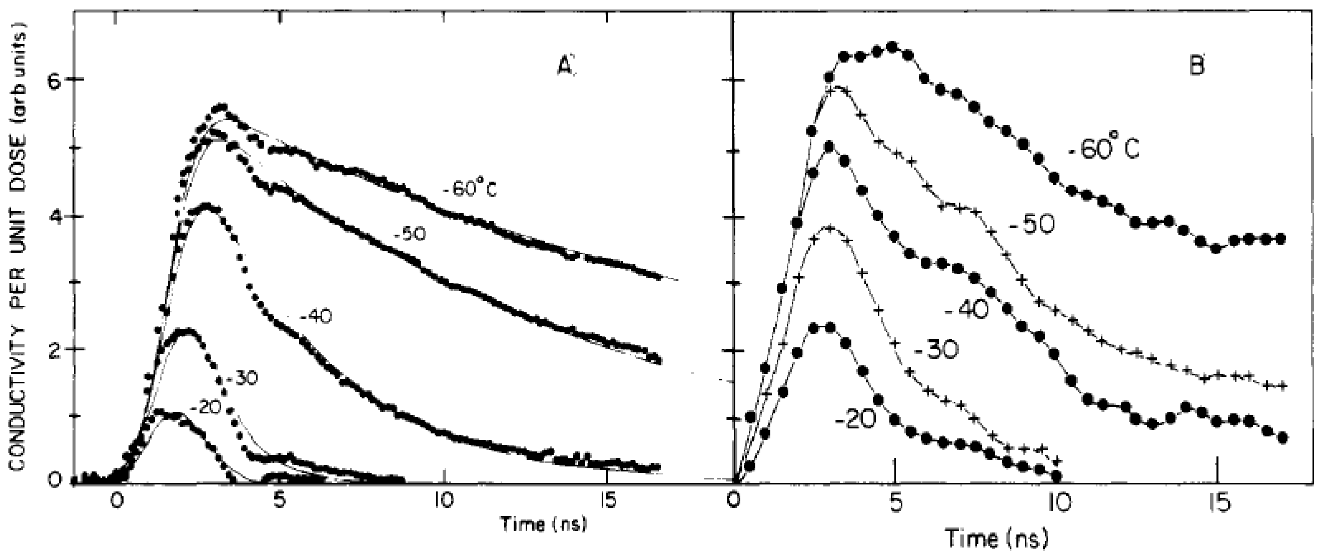
10.1016/j.astropartphys.2016.11.006



Stasielak 2015

What about in-ice?

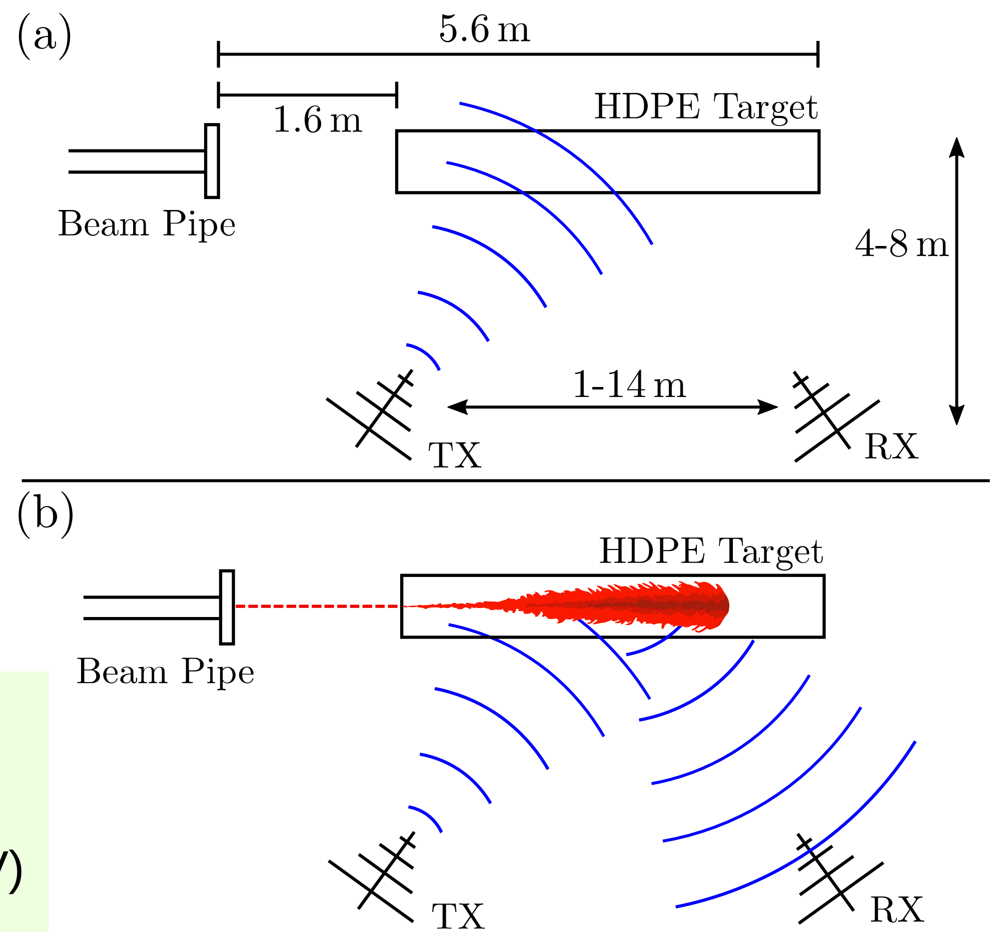
- density of ice 1k times higher than air...
- cascade is ~10m long instead of ~10km
- number density of ionization in ice is *much* greater than air!
- plasma lifetime ~1-10ns
- can we detect cascades using radar in ice?
  - K. Hanson, KD de Vries, T. Meures 2013, Chiba et.al 2013



J. Phys. Chem. 1983, 87, 4089-4092

Toward radar echo detection: T576

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



at right:
a) illuminated a plastic target with radio

b) Fired SLAC's electron beam (10^9 e⁻ @ 10GeV) into the plastic target.

beam ~ UHE neutrino
plastic ~ ice

attempt to record a radar echo from the cascade

SLAC NATIONAL ACCELERATOR LABORATORY

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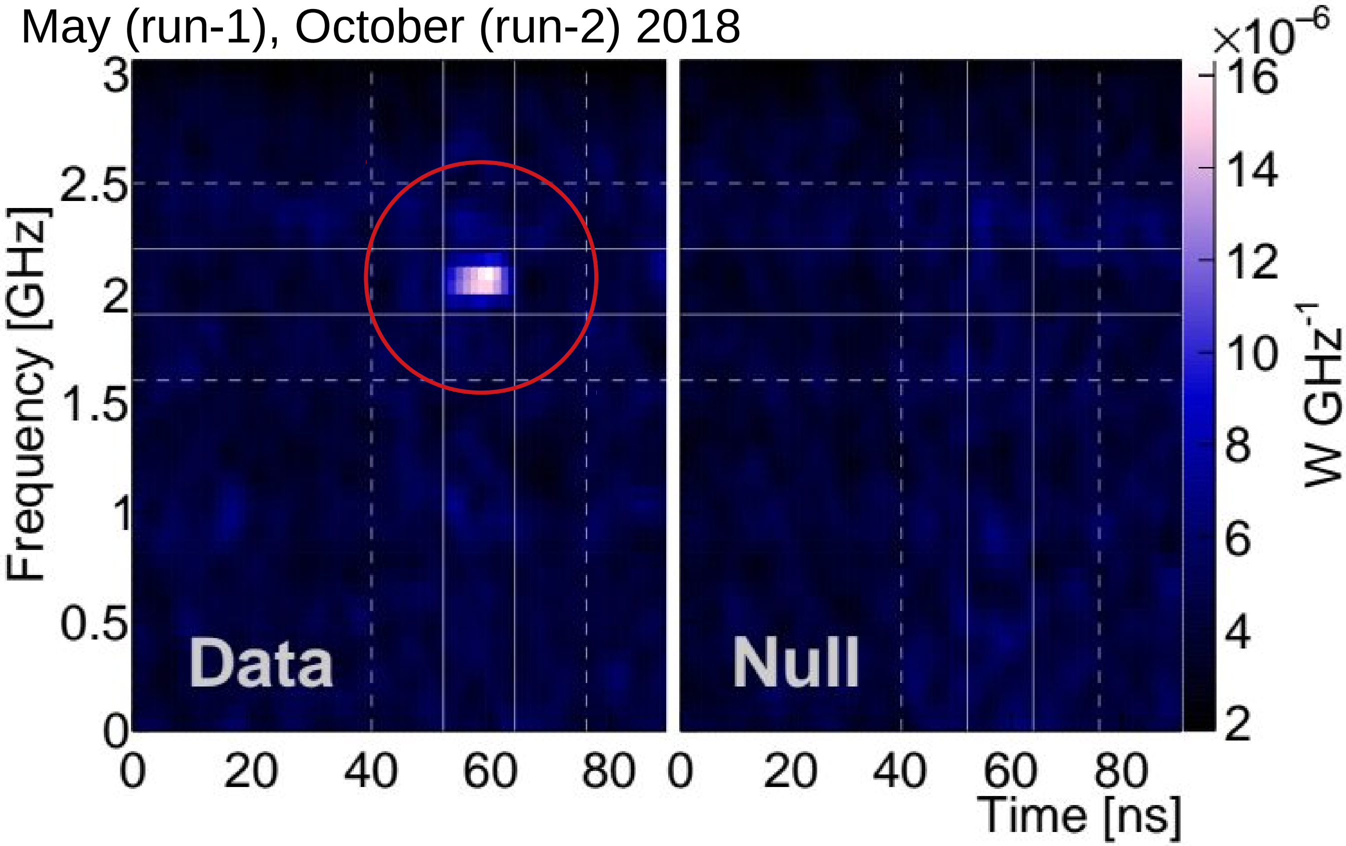

A signal was observed (here the bright blob at left) compared to a null hypothesis.

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

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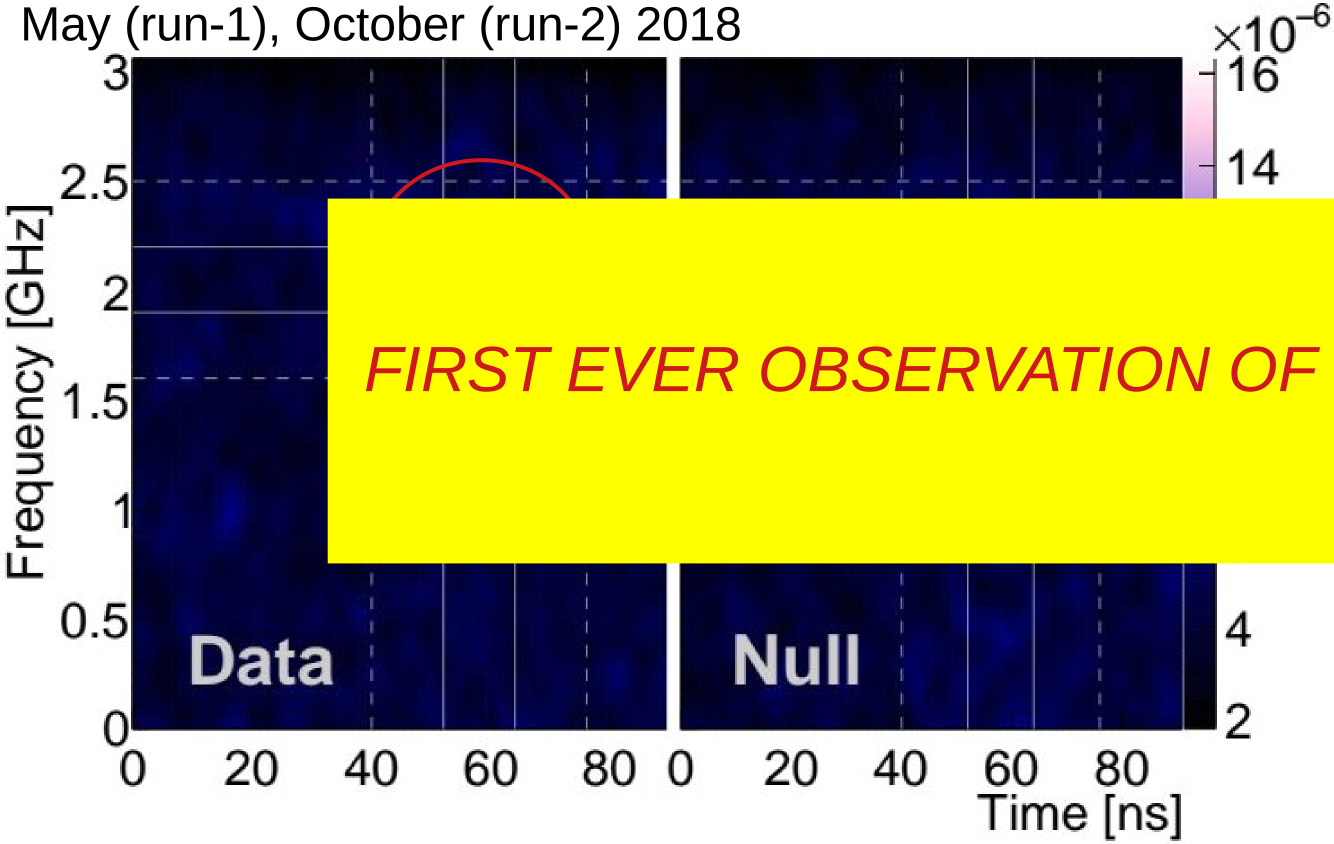

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FIRST EVER OBSERVATION OF THIS SIGNAL!

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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

IOP Publishing

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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

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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.

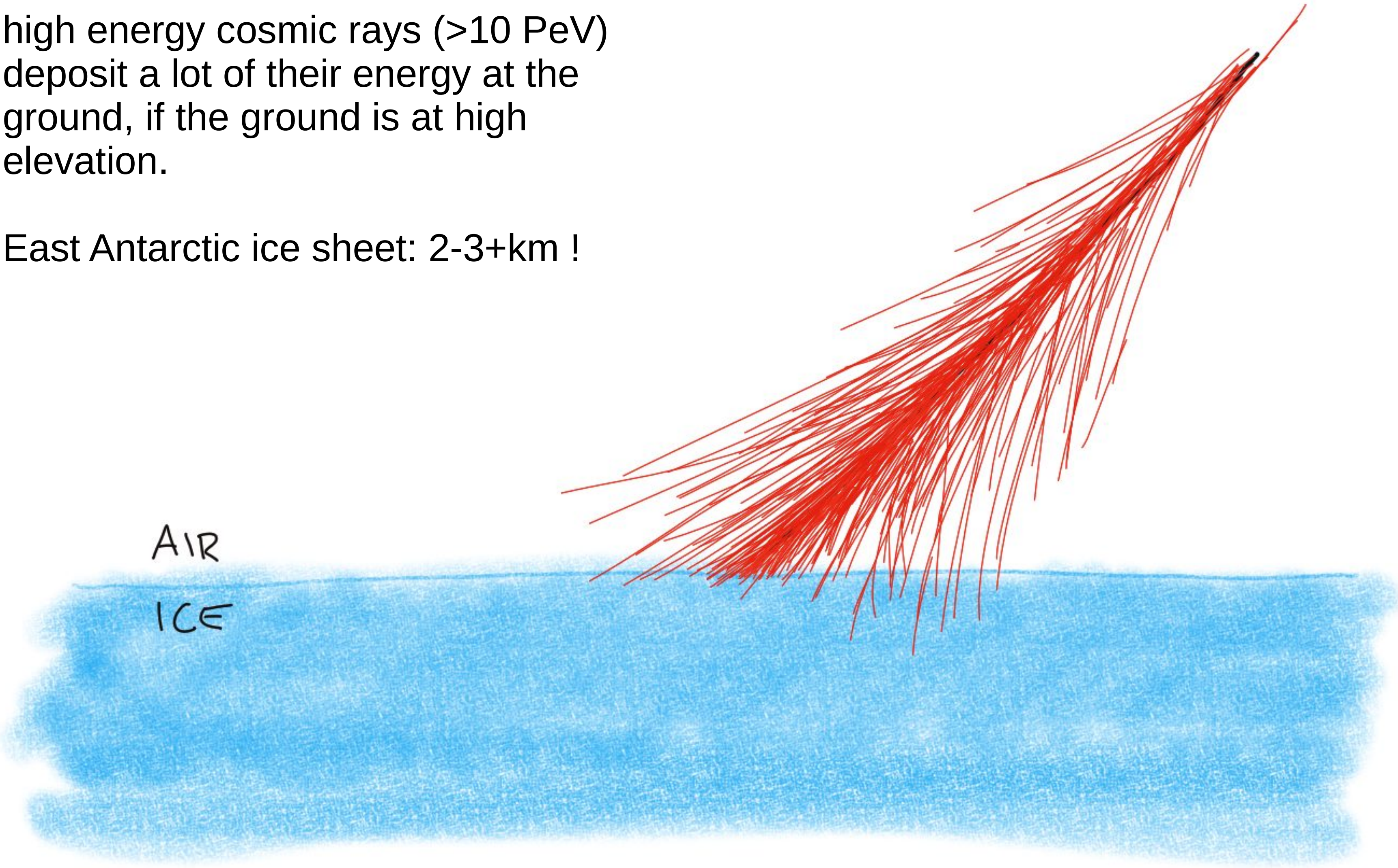
How to test in nature?

- **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...*but in the ice!***

Using cosmic rays

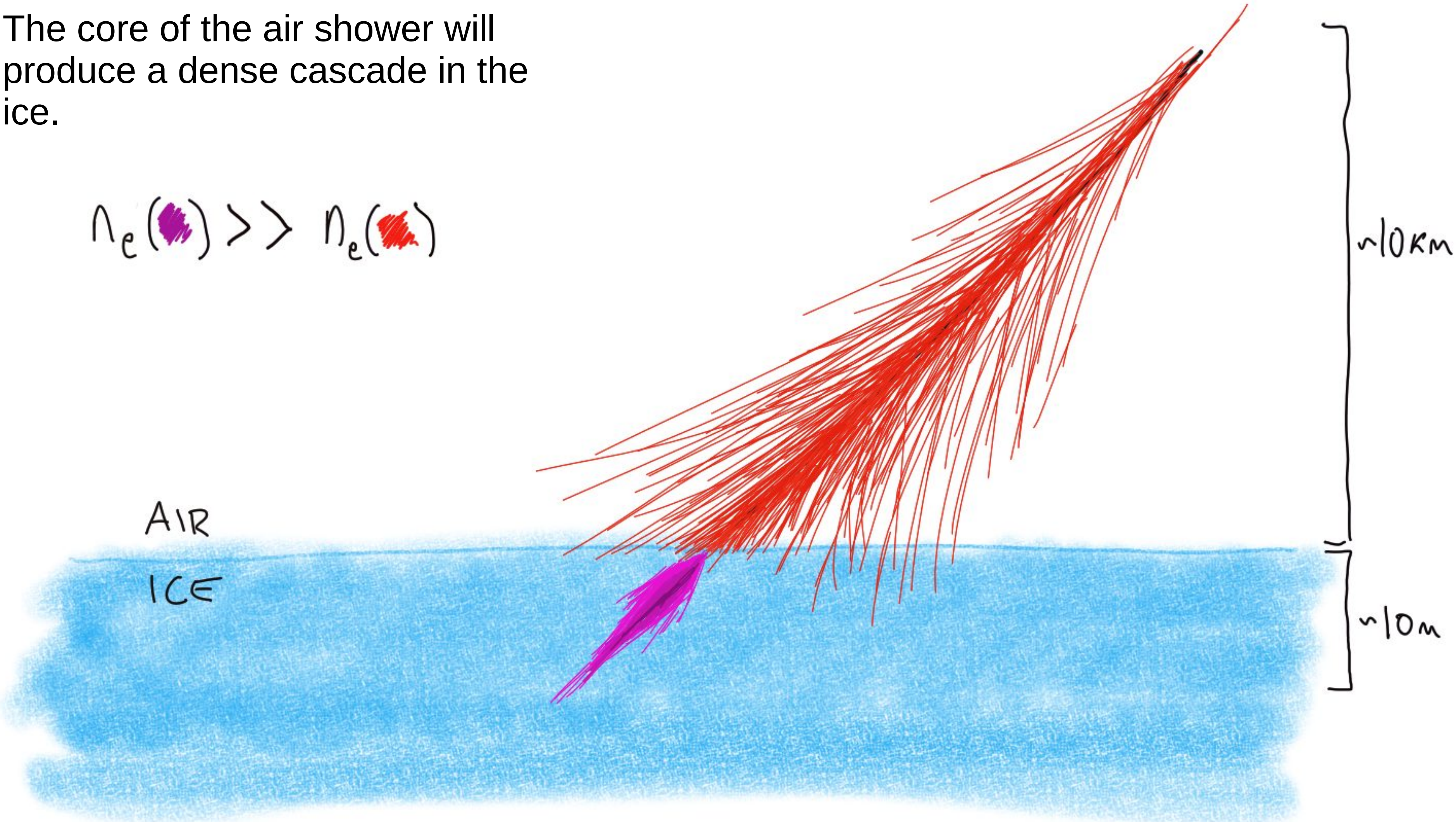
high energy cosmic rays (>10 PeV) deposit a lot of their energy at the ground, if the ground is at high elevation.

East Antarctic ice sheet: 2-3+km !



Using cosmic rays

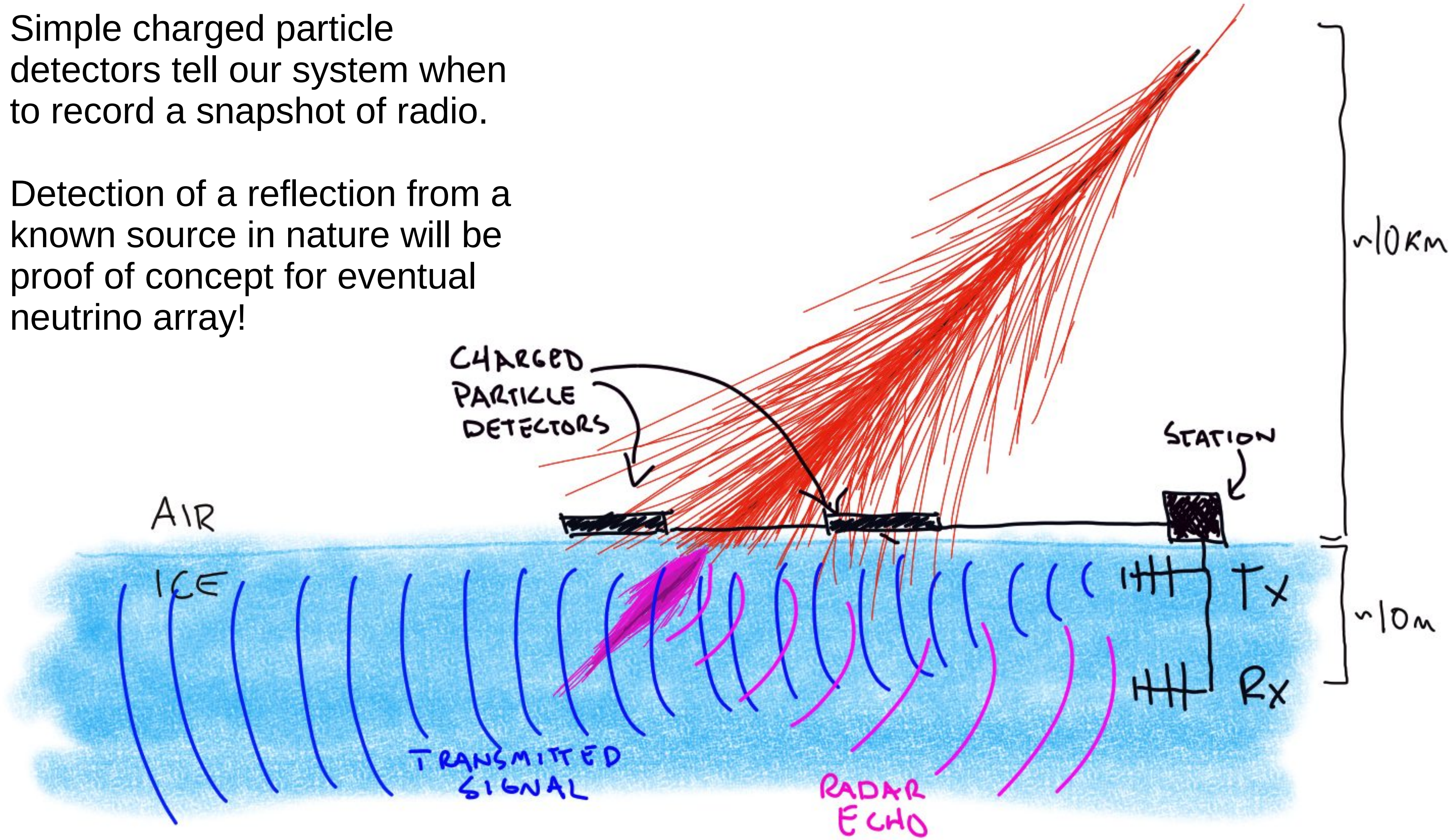
The core of the air shower will produce a dense cascade in the ice.



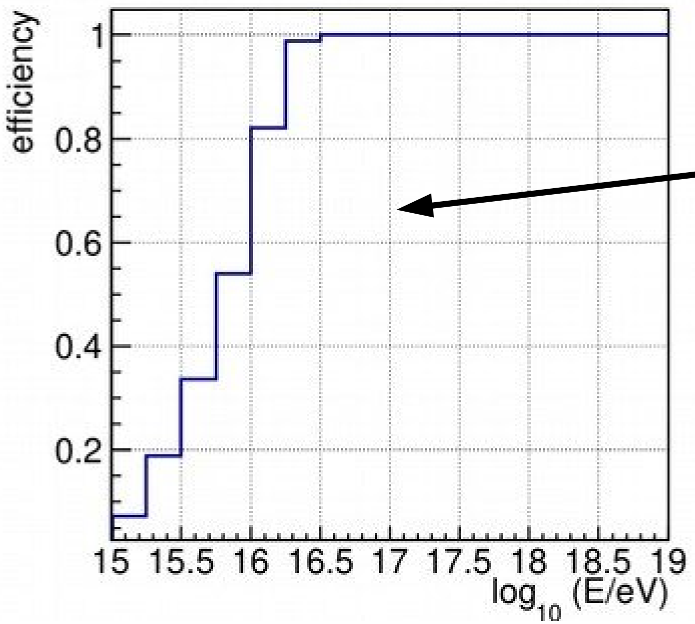
Using cosmic rays

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

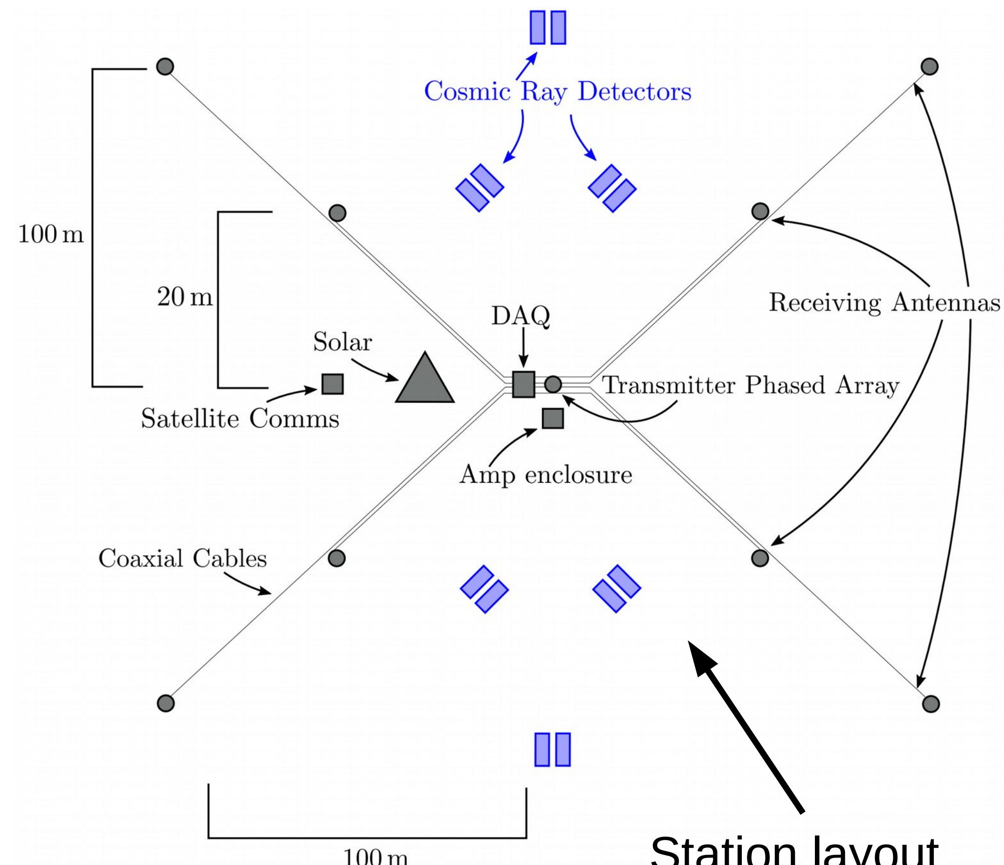
Detection of a reflection from a known source in nature will be proof of concept for eventual neutrino array!



the RADAR ECHO TELESCOPE for COSMIC RAYS

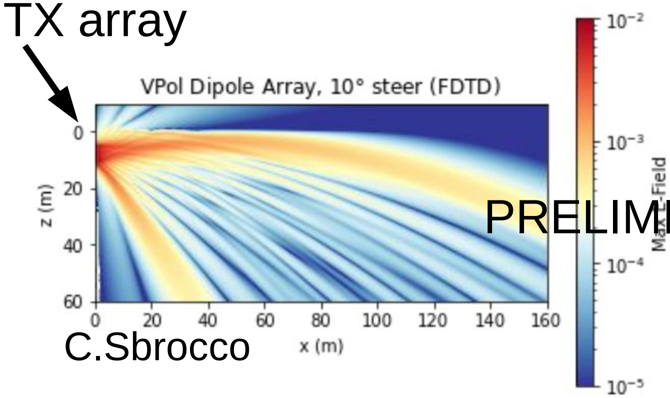


Surface system trigger efficiency curve (simulated).



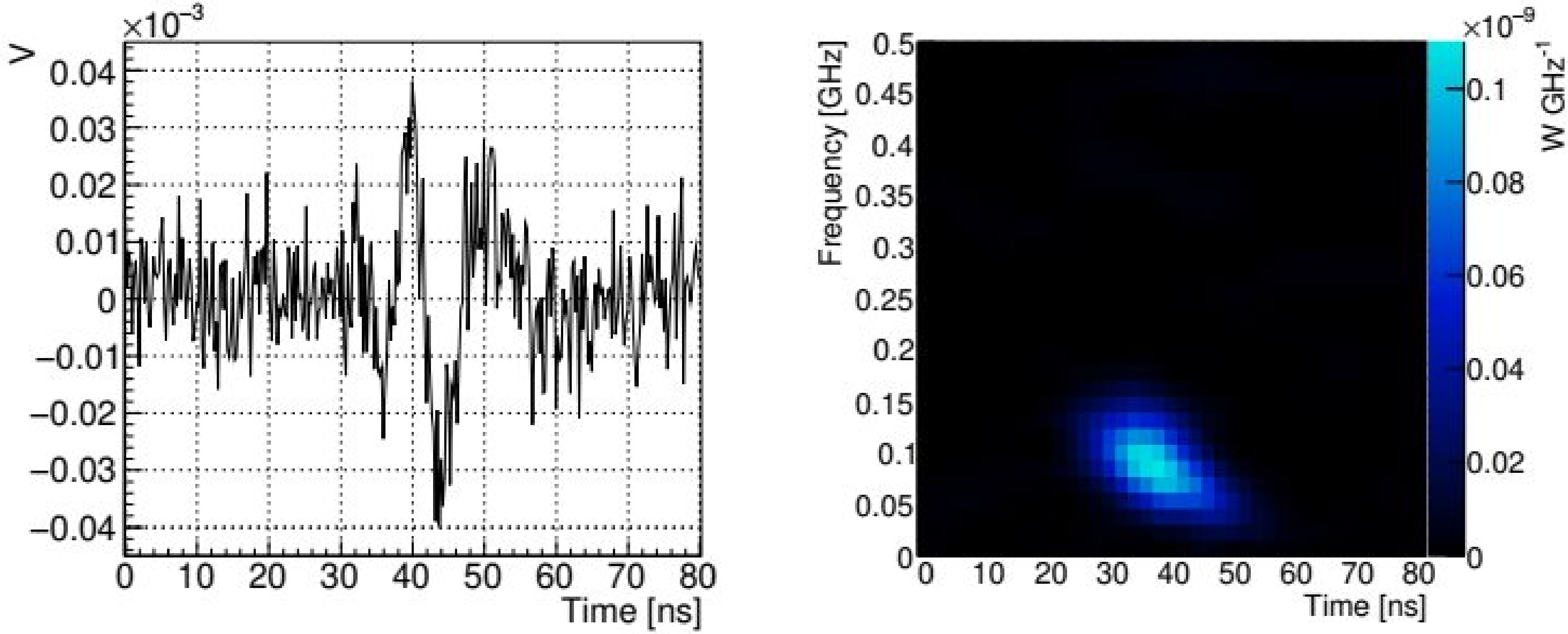
- Surface system ~100% efficient above $10^{16.5}$ eV (trigger on every event with possible radar signal)
- Station is 8 RX at varying baselines, and an 8 antenna vertical phased array, to optimize near-surface gain
- *Adaptive filtration* used to cancel the TX

Phased TX array



C.Sbrocco

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.

-For details, please see contribution 1329, D Van den Broek, E. Huesca Santiago, U. Latif and V. Lukic, "Vertex and energy reconstruction of UHE particles using in-ice radar for the RET experiment"

Event rate

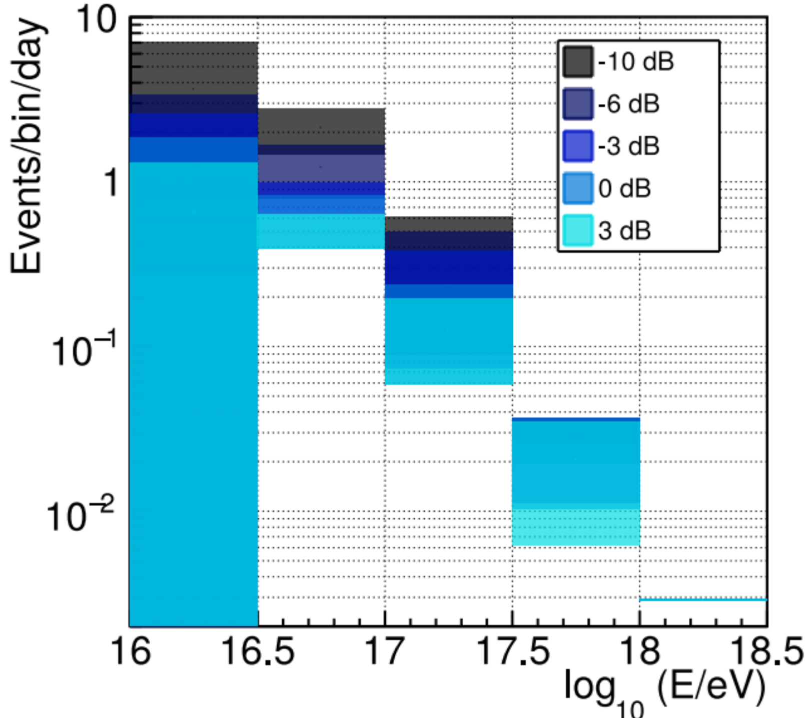
- Detailed simulations using Corsika, GEANT4, and RadioScatter give us an event rate
  - please see contribution 1147, R. Stanley, S. De Kockere, "Simulation and Optimization for the Radar Echo Telescope for Cosmic Rays"
- 3 step process:

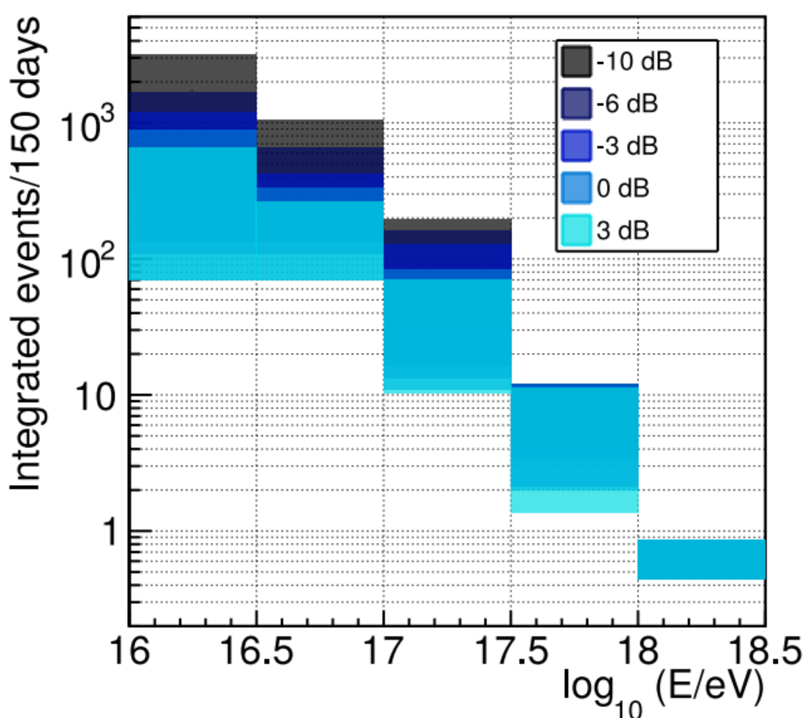
  1) Corsika showers were thrown with random distribution of zenith angles from 0-30 deg and energies from PeV to 10 EeV.

  2) Corsika output at the surface was propagated into ice using GEANT4

  3) RadioScatter was used to simulate the radio scatter from the GEANT4 ionization deposits

Event rate





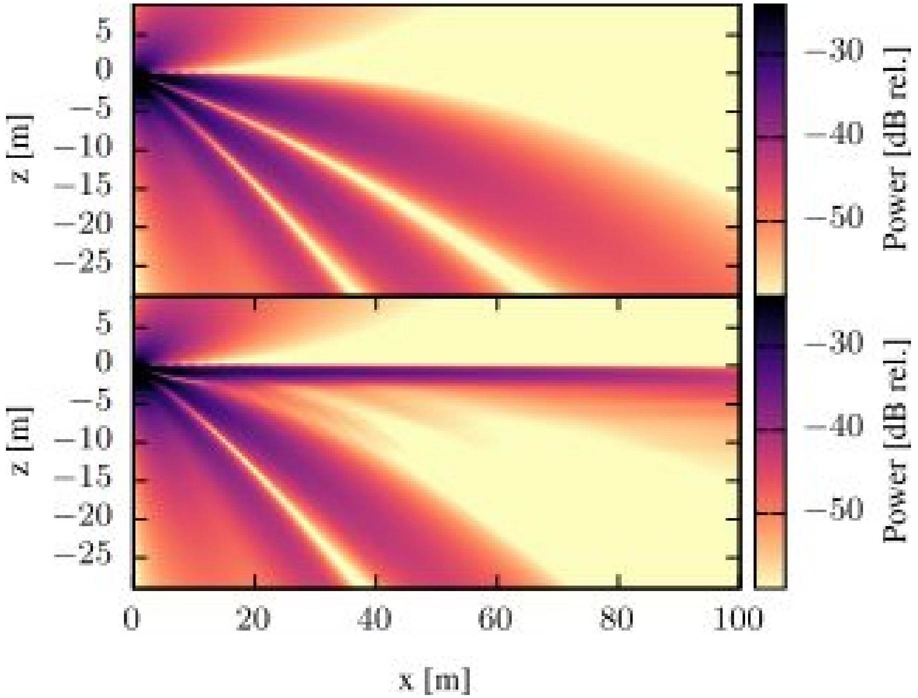
Left: events per energy bin per day.

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.

Ice Properties

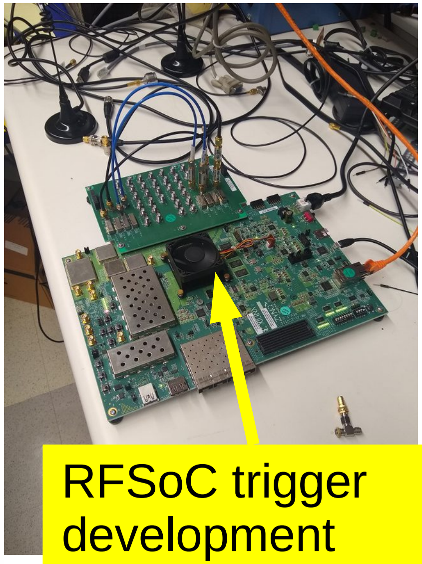


- For a transmitter 1m below the surface.
- Top: purely functional, smooth index of refraction profile
- Bottom: accounting for measured density fluctuations in the ice; big differences in propagation!
- Details:
  - please see contribution 1039 "Application of parabolic equation methods to in-ice radio wave propagation for ultra high energy neutrino detection experiments

- **The ice near the surface of a polar ice sheet is highly variable in density (and therefore index of refraction)**
- **in-situ measurements and detailed simulations are key to understanding local radio wave propagation**

Hardware work in progress

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



RFSoC trigger development @OSU!

Summary

- RET-CR is a pathfinder experiment that uses the radar echo method to detect particles of the highest energies.
- RET-CR targets the in-ice cascade produced when UHE cosmic rays reach a high elevation ice sheet and cause a cascade within. We expect about one event per day.
- With deployment in the next few years, RET-CR will be a springboard to RET-N, which will seek echoes from the highest energy neutrinos!
- Please stay tuned...

Thanks!