Status of 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, C. Deaconu, S. De Kockere, E. Oberla, N. van Eijndhoven, C. Hast, E. Huesca Santiago, C.-Y. Kuo, U.A. Latif, V. Lukic, K. Nivedita, T. Meures, K. Mulrey, J. Nam, A. Nozdrina, J.P. Ralston, Z. Riesen, C. Sbrocco, M.F.H. Seikh, R. Stanley, J. Torres, S. Toscano, and S. Wissel

TeVPA 2022

key takeaways

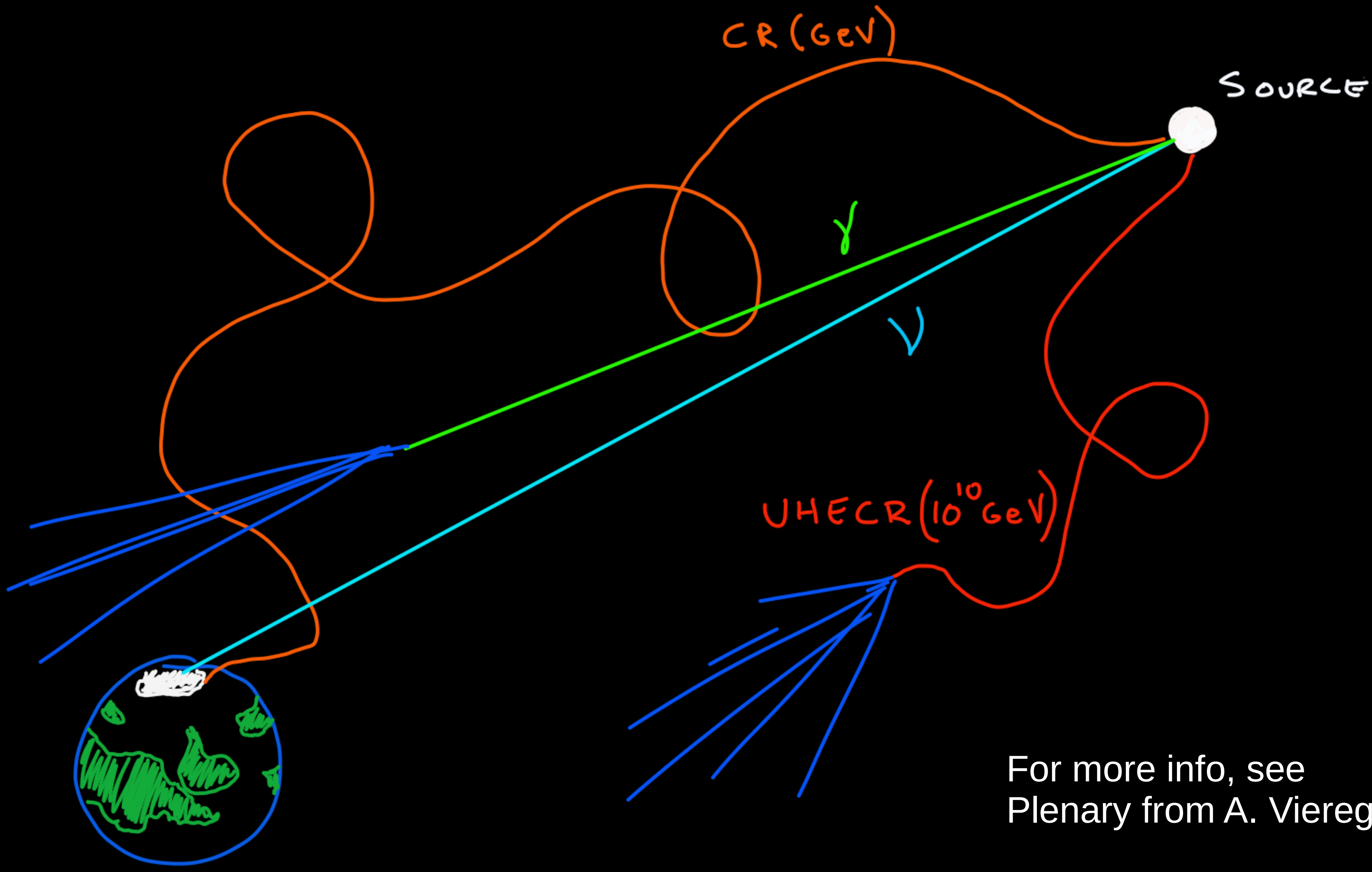
- The Radar Echo Telescope for Neutrinos(RET-N) is a new proposed system to ***target neutrinos with energies greater than 10^{16} electron volts (10PeV)*** via **active radar sounding**
- The method has been **validated in a test beam experiment** (SLAC T576 PhysRevLett.124.091101, arXiv:1910.12830)
- 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**, deployment ASAP
  - instrument paper: PhysRevD.104.102006 (arXiv:2104.00459)
- Radar detection of neutrinos is a complementary strategy to other radio and optical based methods, ***essential to a full picture of the UHE neutrino sky.***

Neutrino detection with radar

- In this talk I will:
  - Briefly motivate our work
  - 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:

Invitation: why neutrinos?



For more info, see
Plenary from A. Vieregg!

-Neutrinos can reach earth when other messengers can't
-Neutrinos point back to their source; not deflected in magnetic fields

Invitation: why neutrinos?

Neutrinos are the only <u>observed</u> particle with beyond-standard-model properties:

- *have mass (shouldn't?)*
- *oscillate between flavors (weird!)*

also...
only interact via the weak force (bizarre!)
are < 10^{-6} the mass of the electron (why?!)

(NOTE: none of this is addressed in this talk, but it is interesting)

So why haven't we seen any?

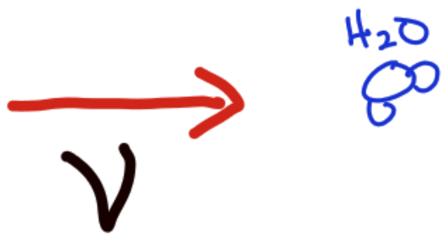
- Extremely low flux and small cross section. Lack of observation of >10PeV neutrinos in current detectors suggests the rate is as low as $1/km^2 sr/decade$ at this energy.
- 2 options:
  - scale up detector size (*expensive*)
  - wait a long, long time: (*boring*)

So why haven't we seen any?

- Extremely low flux and small cross section. Lack of observation of >10PeV neutrinos in current detectors suggests the rate is as low as $1/km^2 sr/decade$ 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.

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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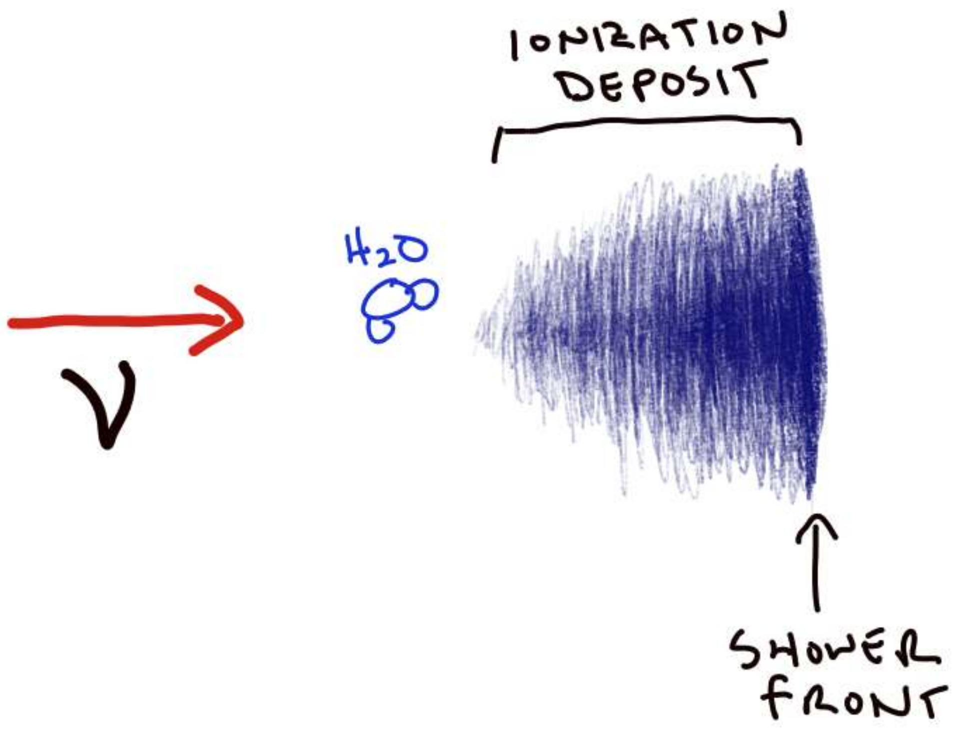

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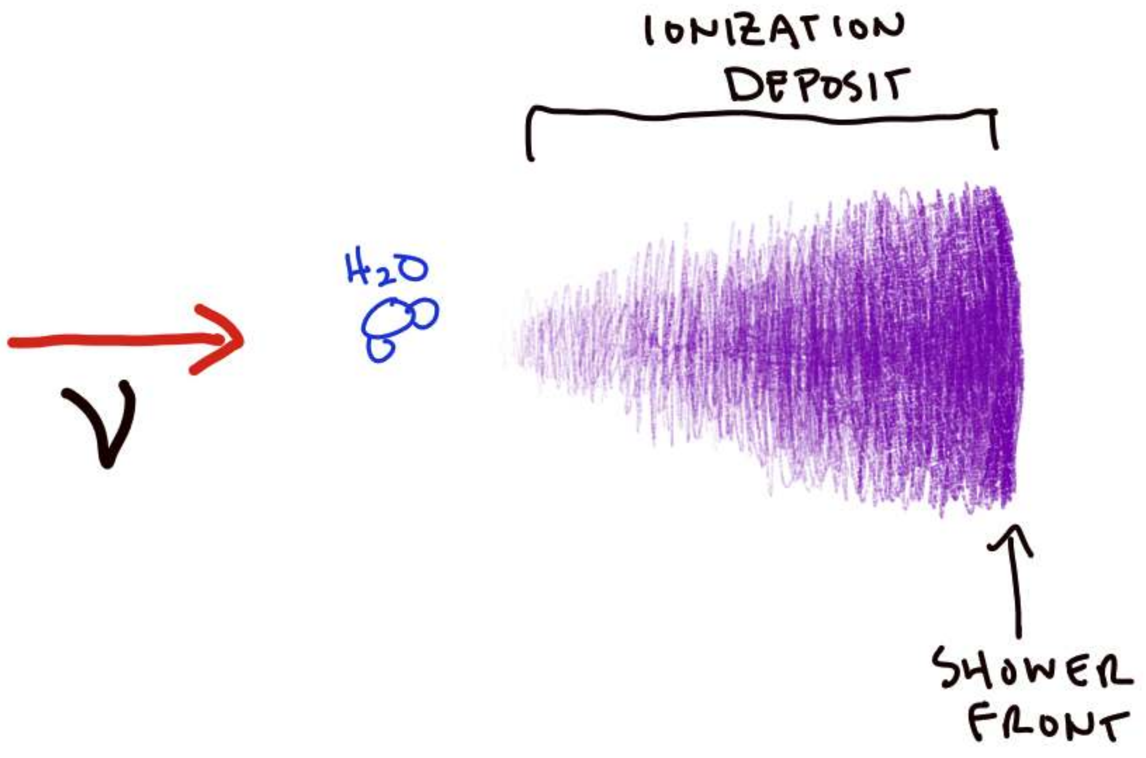

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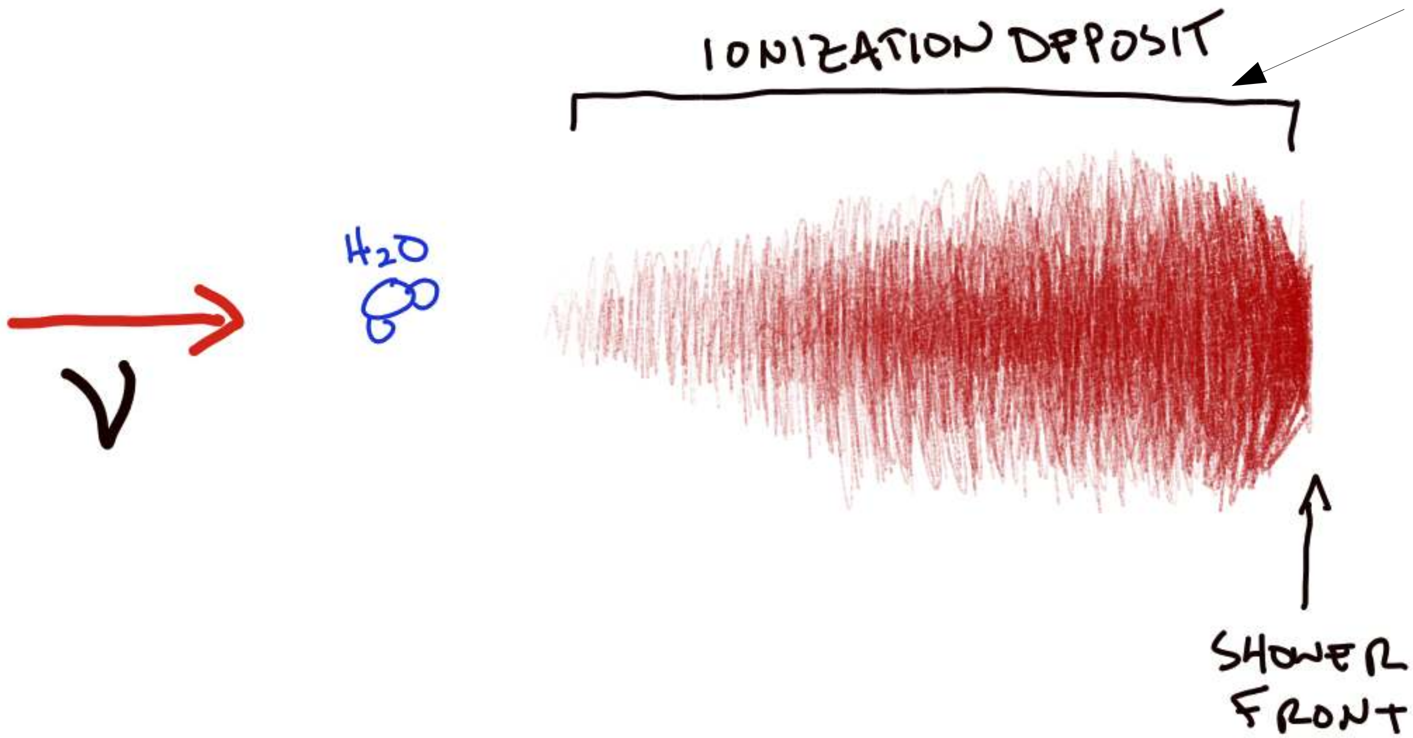
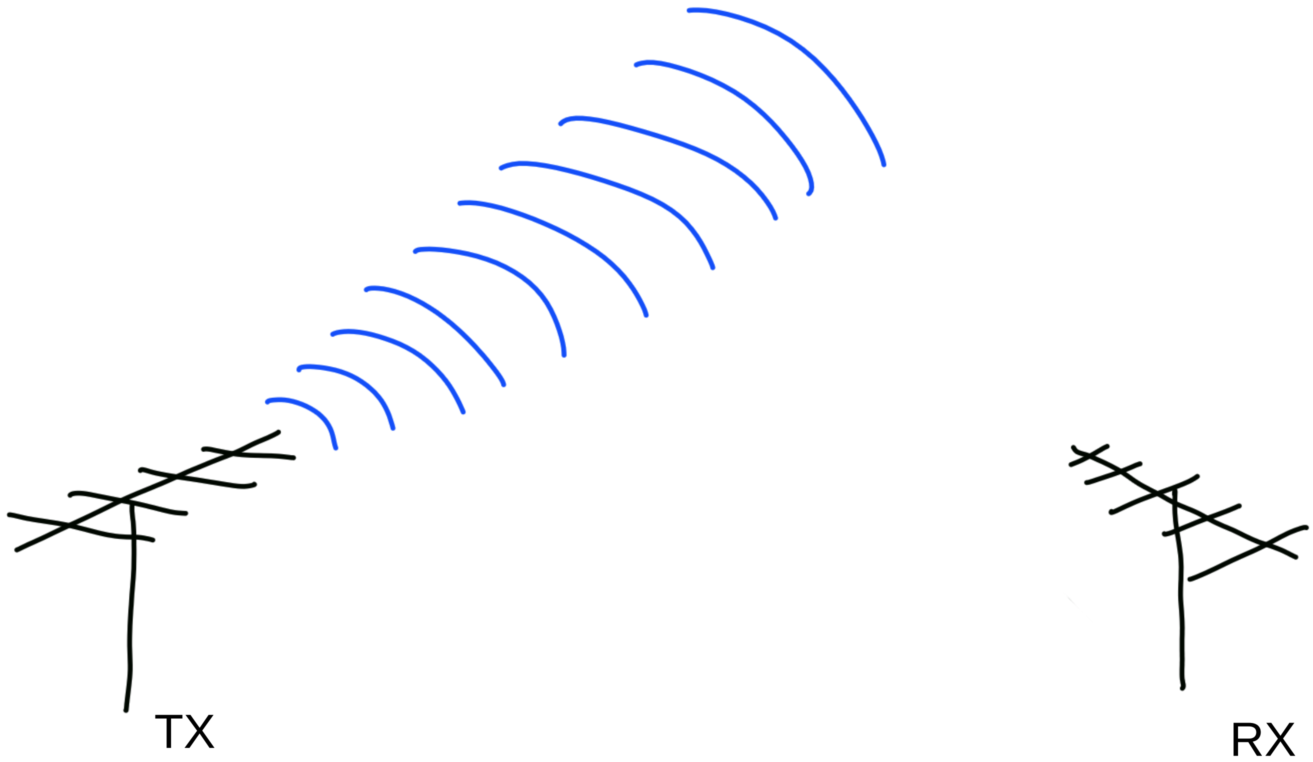


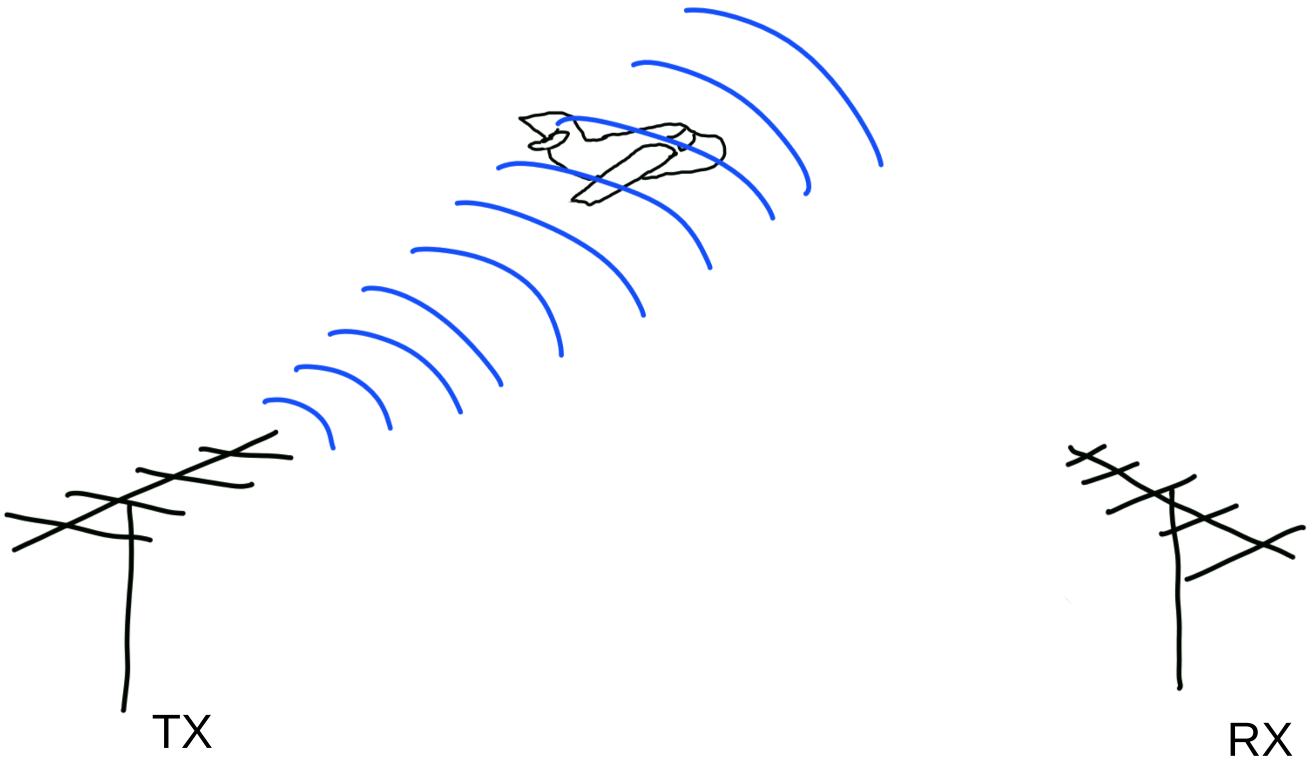
‘length’ of this deposit depends on the properties of the medium, the ‘lifetime’ of a free electron.

Concept #2: radar overview



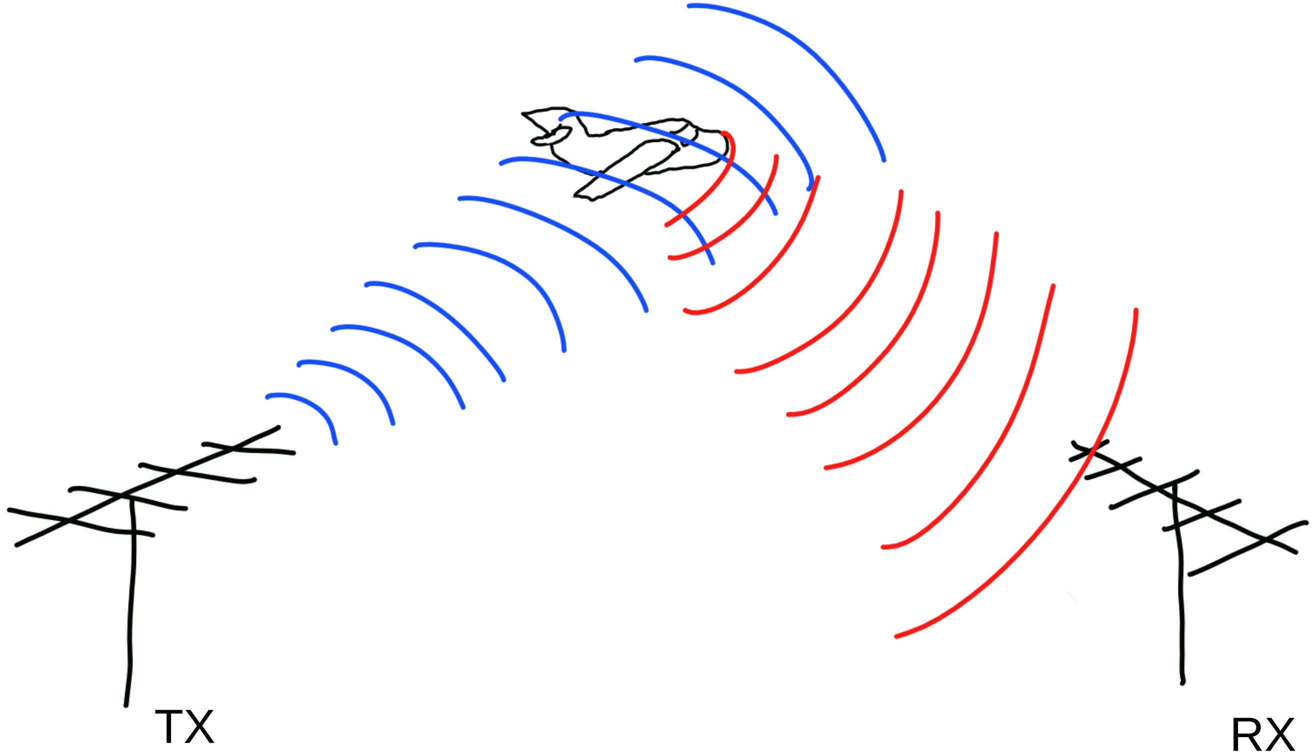
- Transmitter (TX) broadcasts a radio signal into a volume
- receiver(s)(RX) monitor this same volume

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)

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.**

- **Reflected signal is detectable over a wide solid angle, unlike the highly restricted aperture of passive detection methods.**

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

- **Can be scaled up**

radar is not new...

- 1941–1945:

  Blackett and Lovell @ Jordrell Bank observatory, UK set up a radio receiver to study 'anomalous reflexions' (sic) 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!

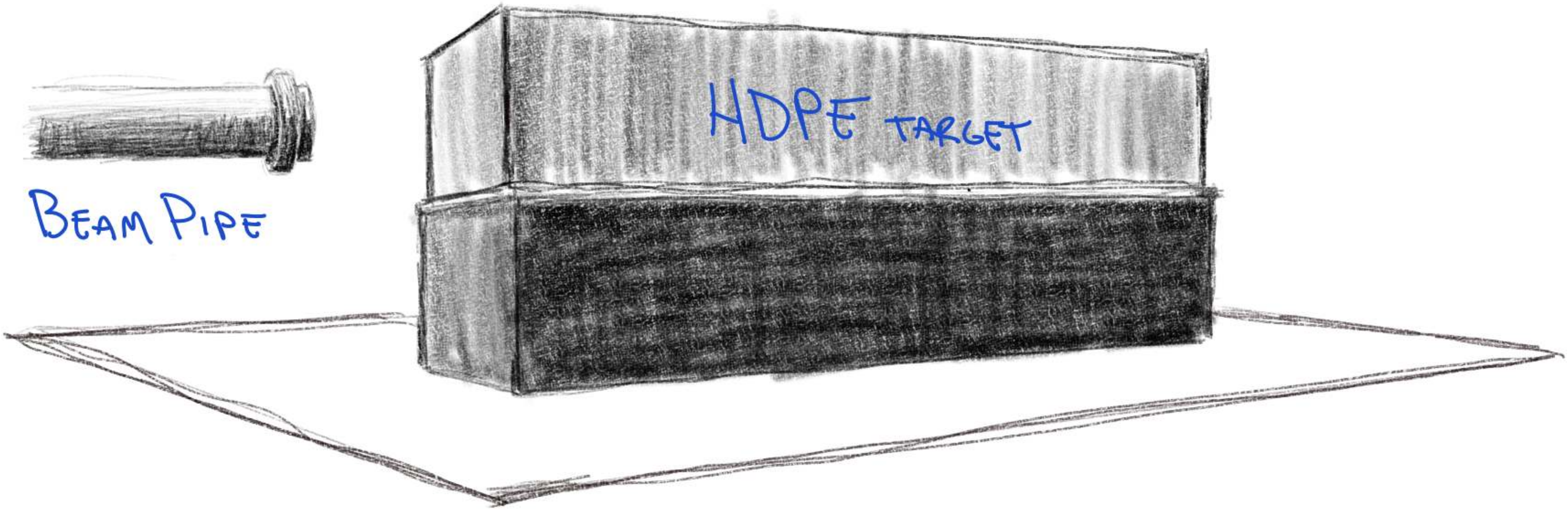
  ionization density too low, collision rate too high, free electron lifetime too short

  - 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
      - Increase in density of the material (1000x) means ionization density can overcome lifetime and collision issues
    - Lab experiments follow

  Long live radar!

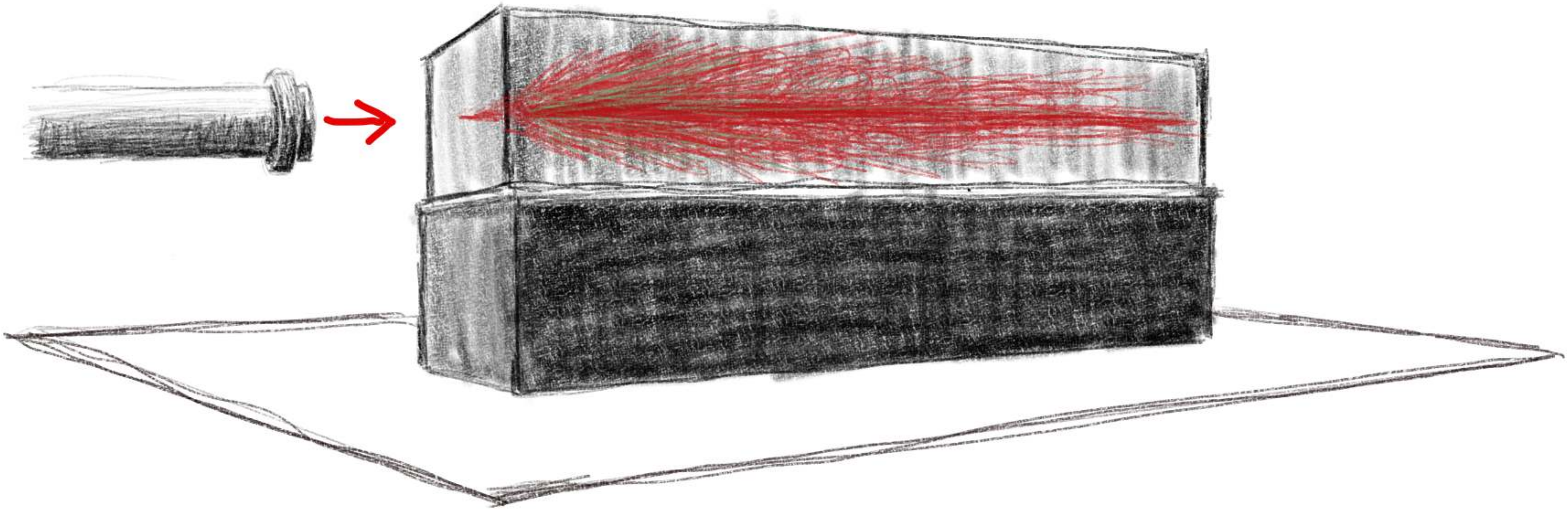
- For more information, see radarechotelescope.org

Idea:



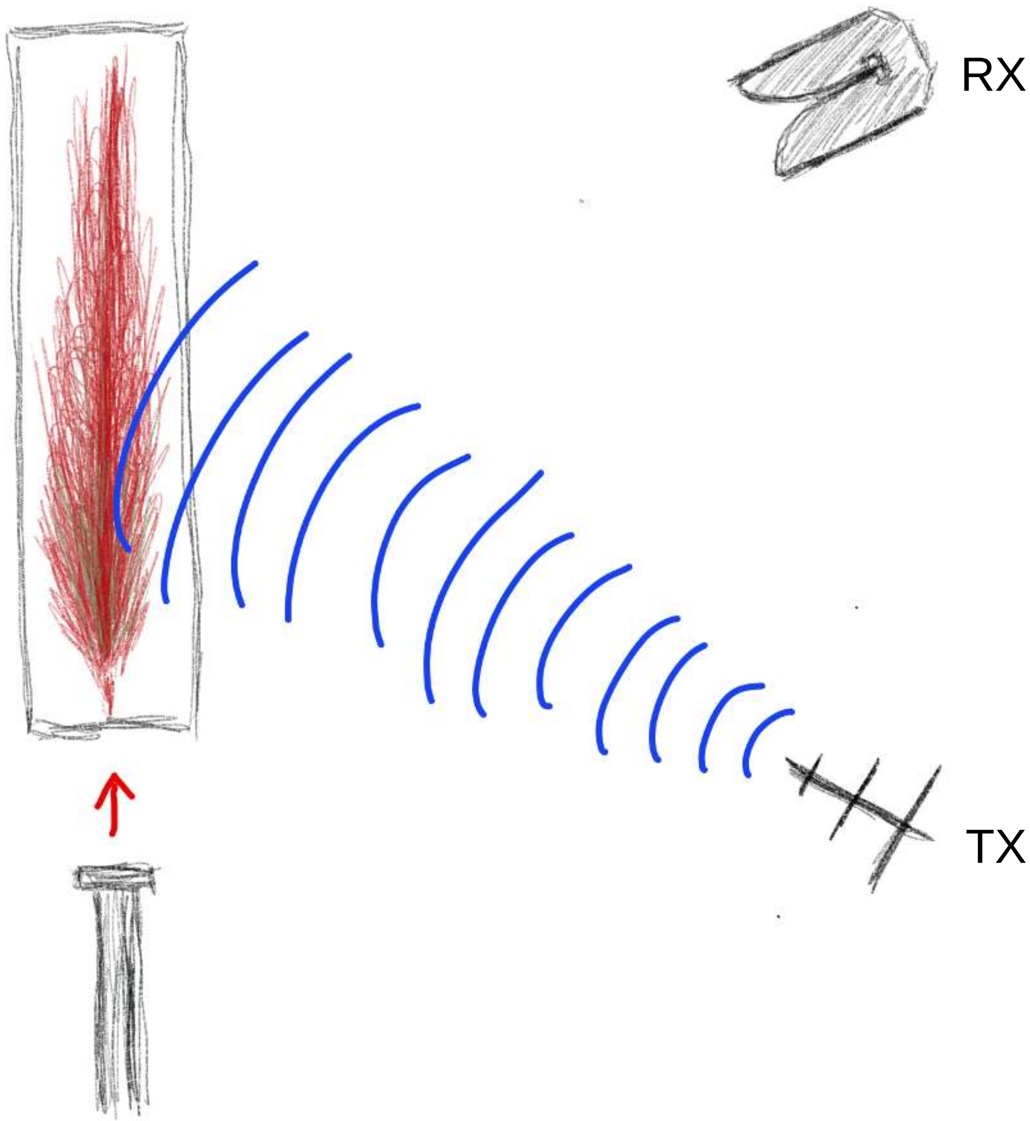
- **Direct a particle beam into a plastic target in the lab**
- beam: ~ neutrino
- target: ~ice

Idea:



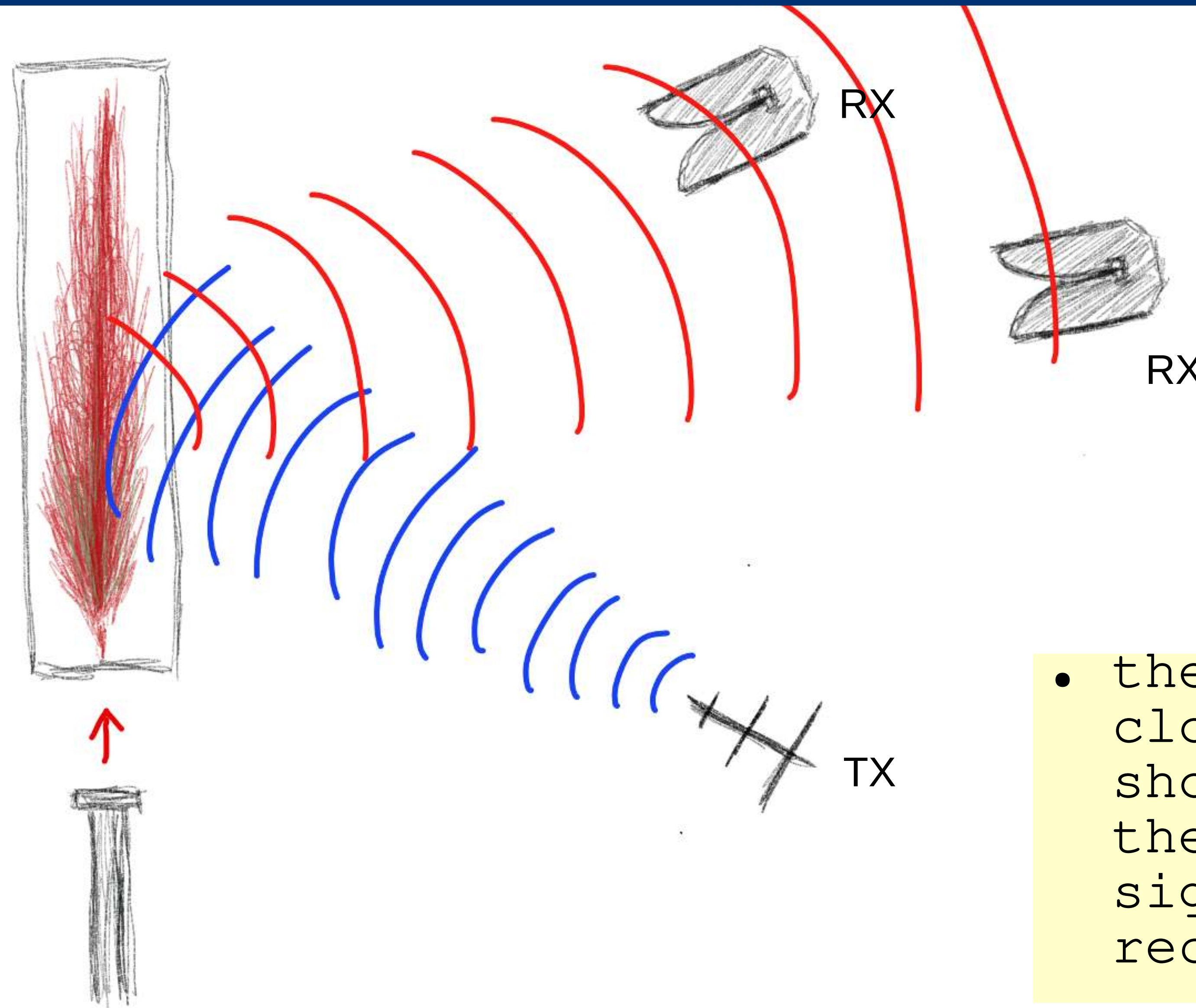
- As the beam enters the target, a cascade is created in the material

Idea:



- We interrogate the target with radio

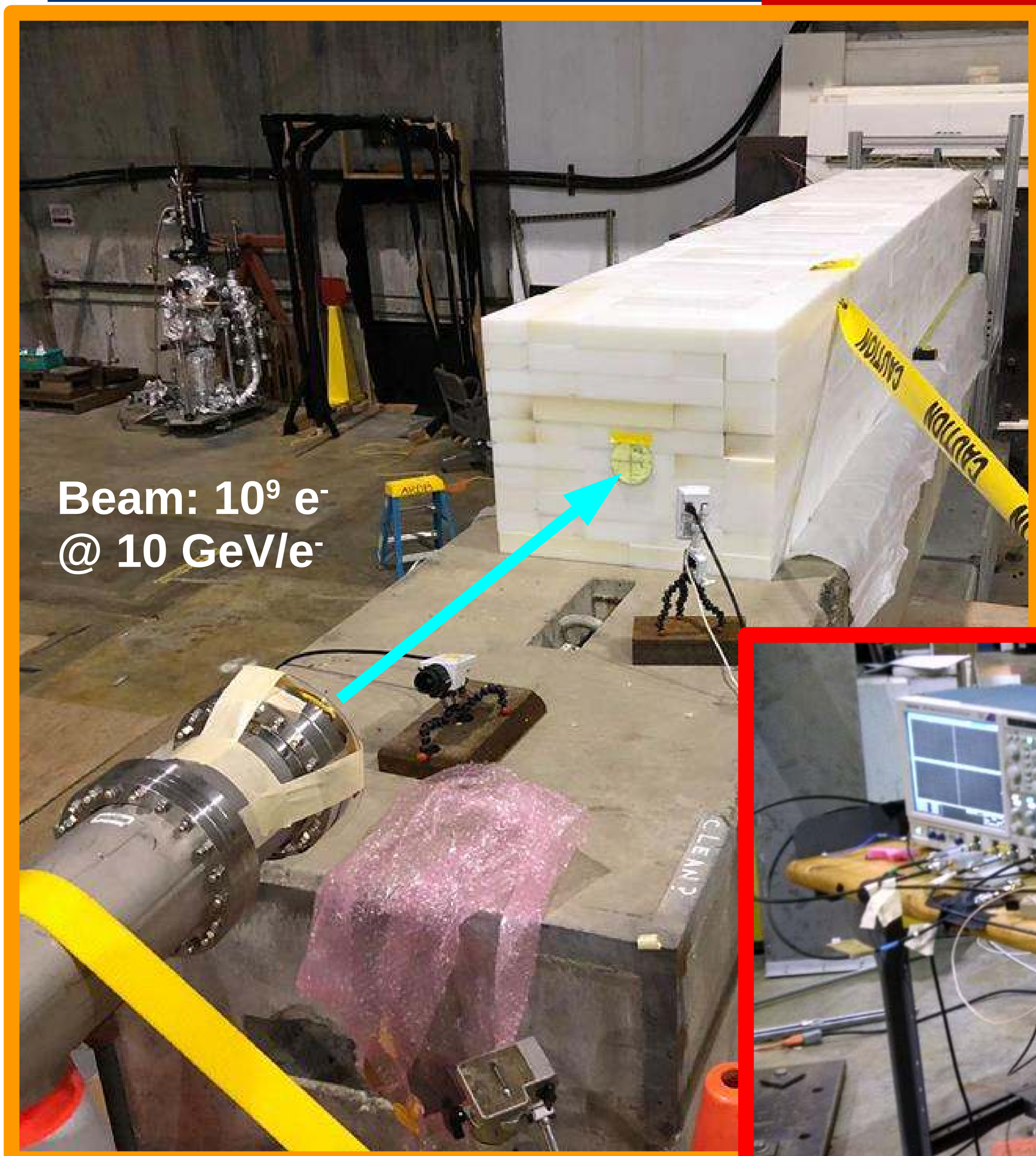
Idea:



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

SLAC End Station A

SLAC T576

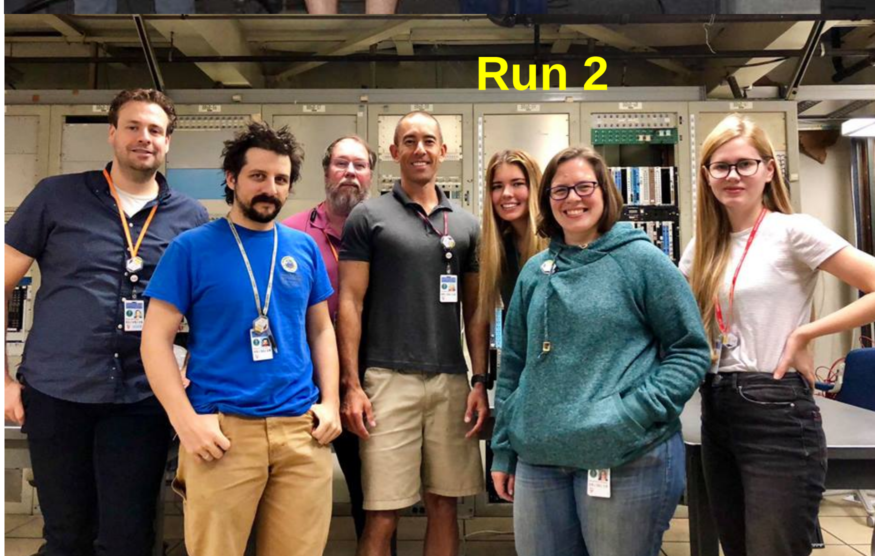


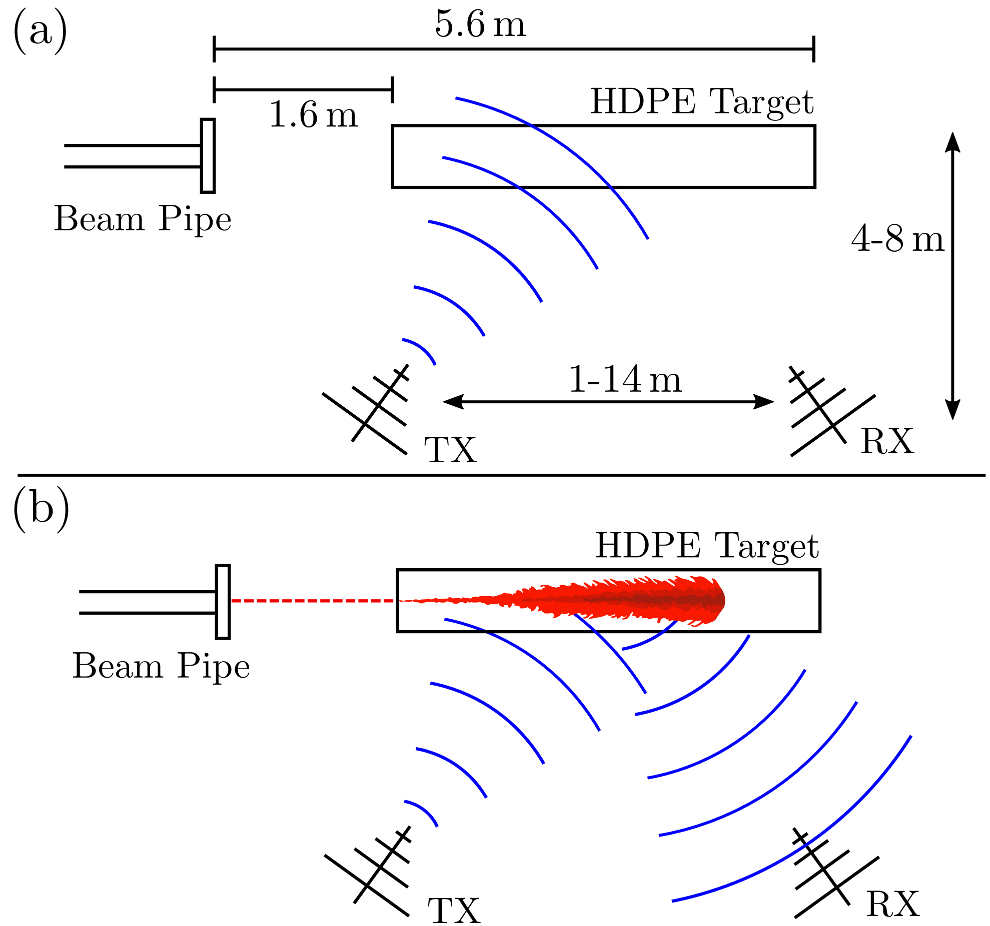
Beam: 10^9 e^-
@ 10 GeV/e^-
CAUTION

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

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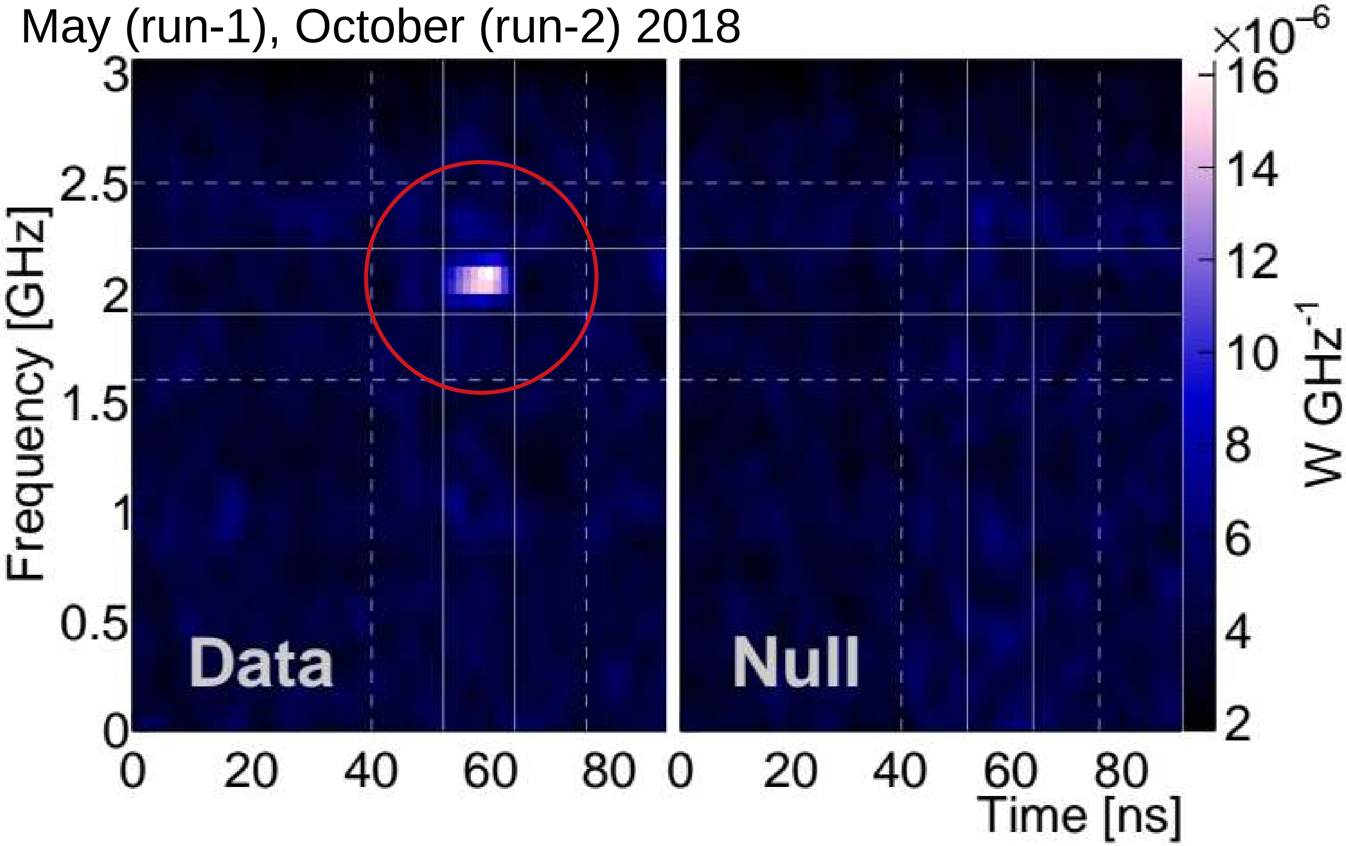

A signal was observed (here the bright blob at left) compared to a null hypothesis.

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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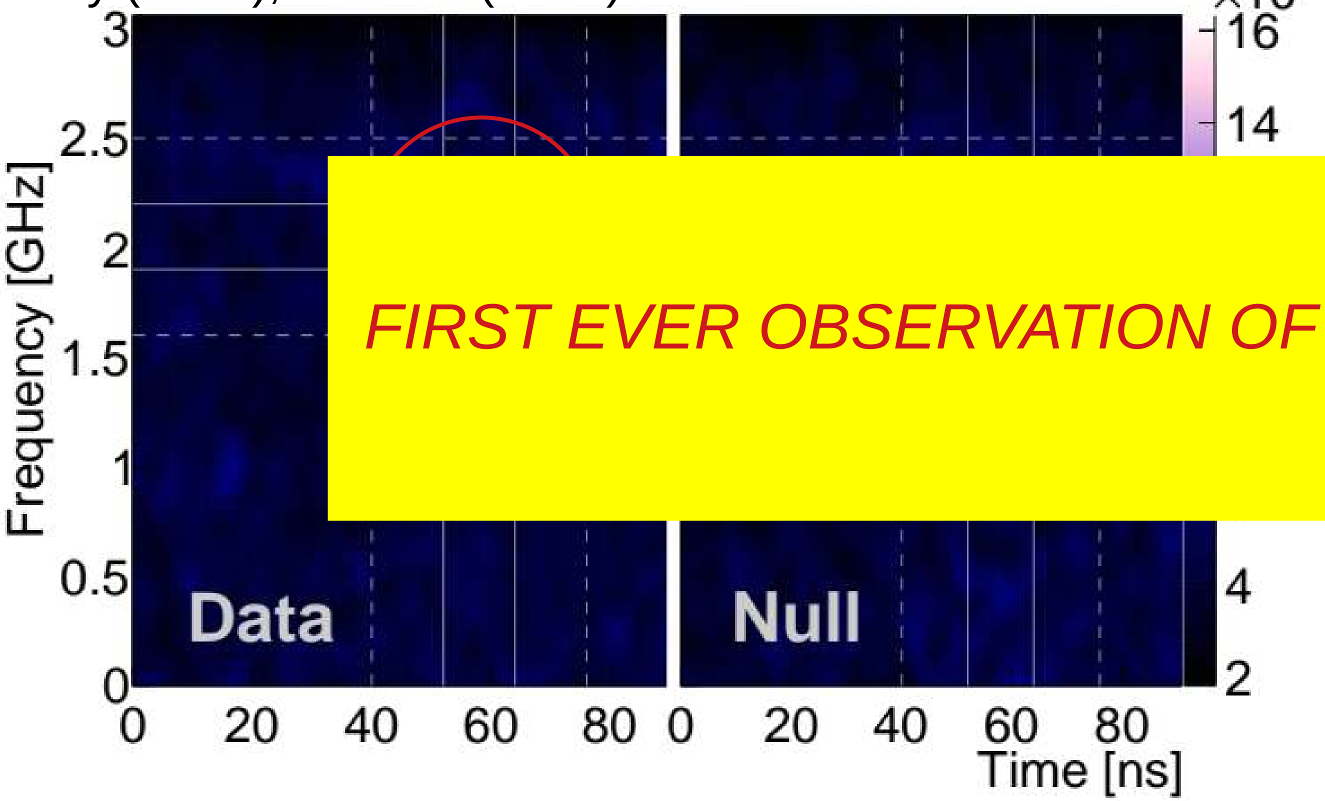

A signal was observed (here the bright blob at left) compared to a null hypothesis

FIRST EVER OBSERVATION OF THIS SIGNAL!

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Toward radar echo detection: T576

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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

physicsworld

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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.

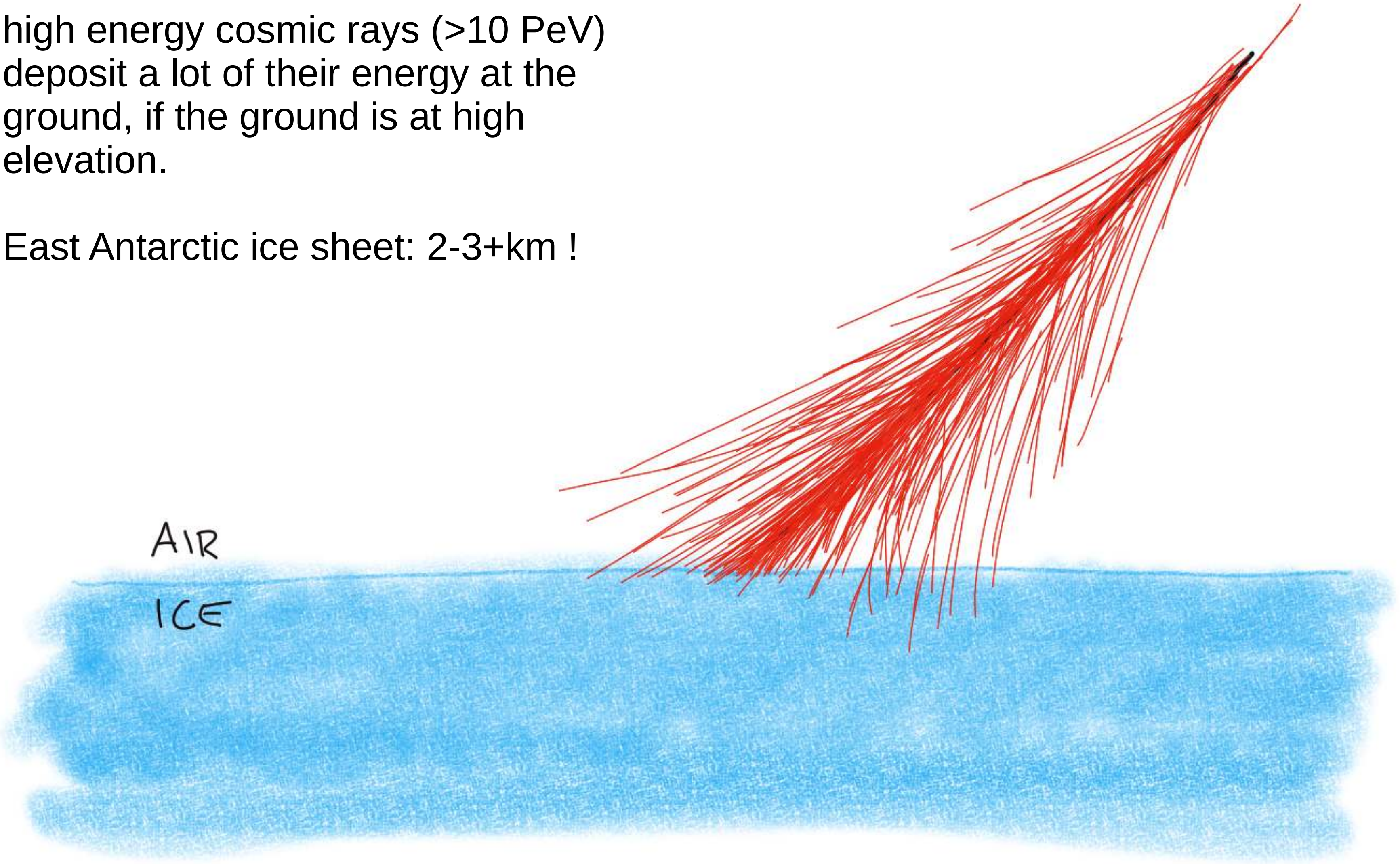
How to test in nature?

- 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...*but in the ice!*

Using cosmic rays

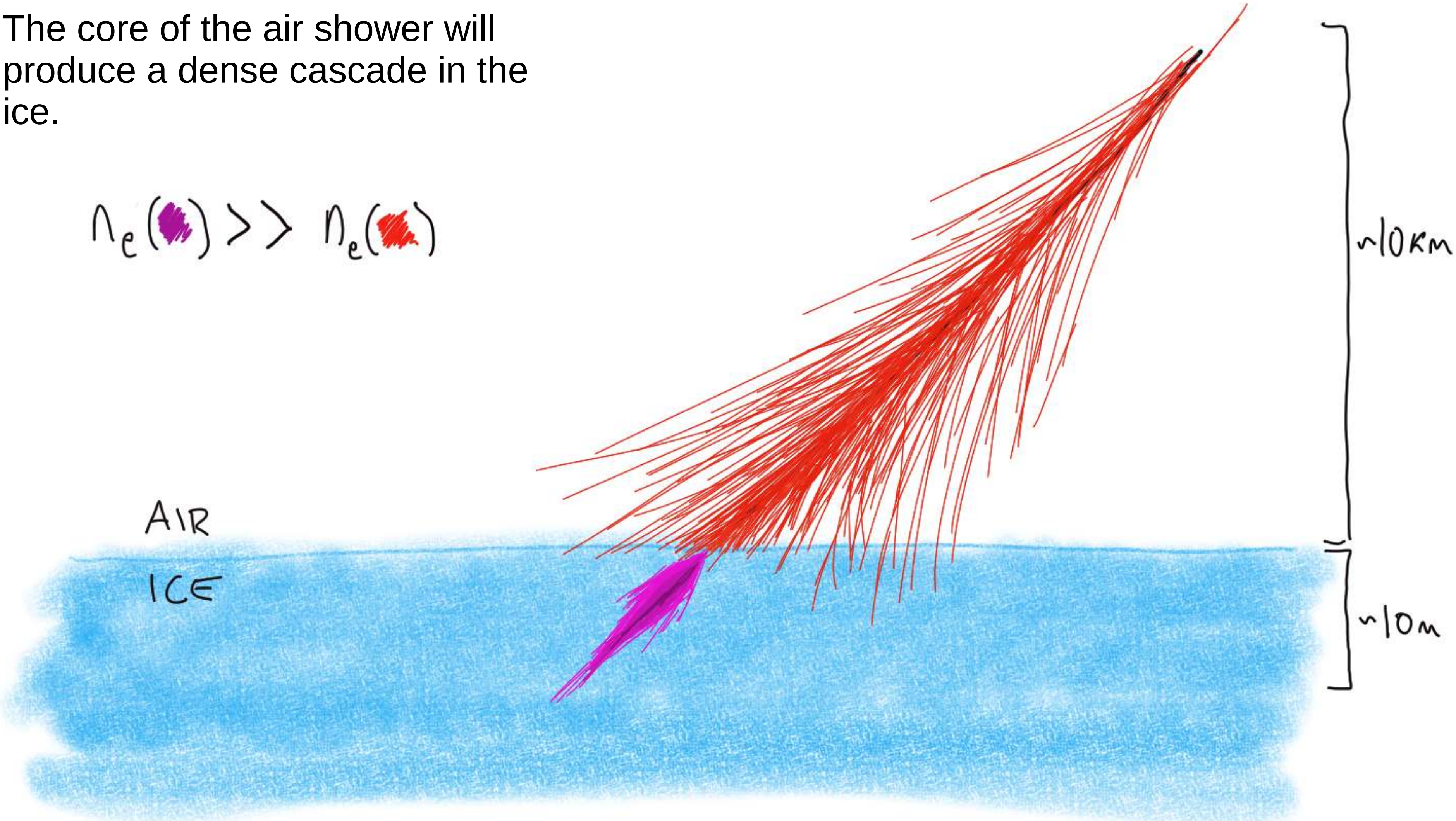
high energy cosmic rays (>10 PeV) deposit a lot of their energy at the ground, if the ground is at high elevation.

East Antarctic ice sheet: 2-3+km !



Using cosmic rays

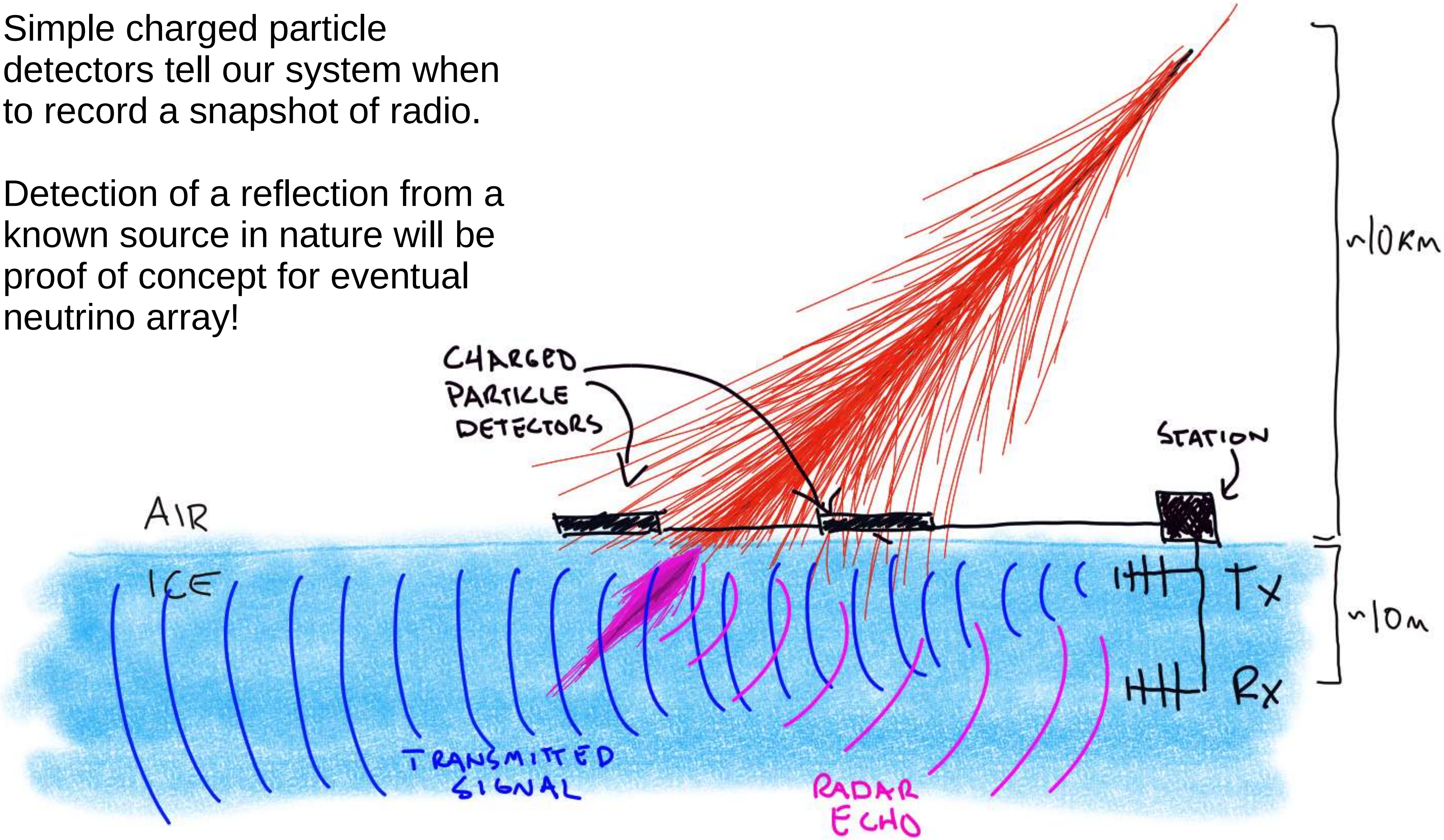
The core of the air shower will produce a dense cascade in the ice.



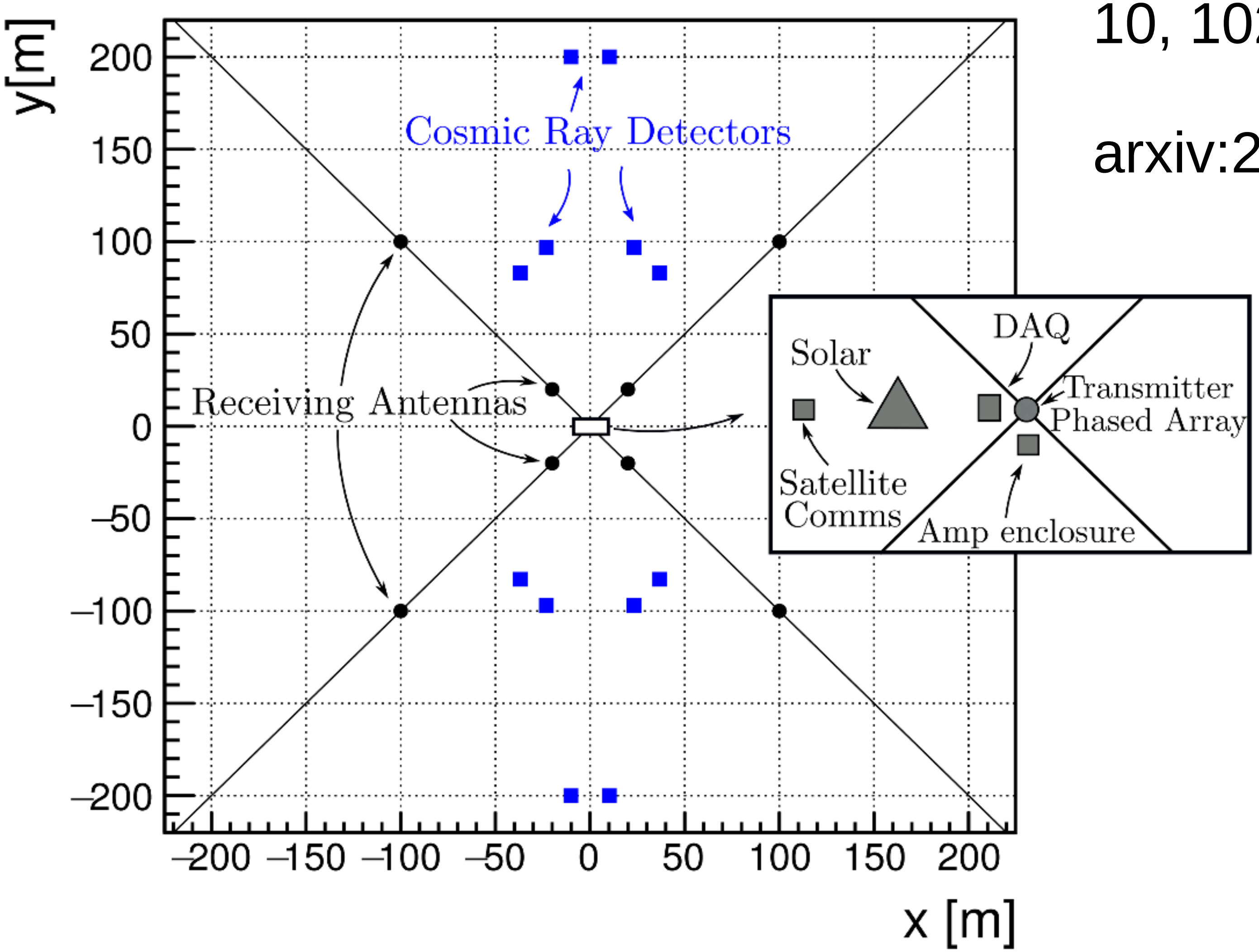
Using cosmic rays

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



Our paper:

Phys.Rev.D 104 (2021) 10, 102006

arxiv:2104.00459

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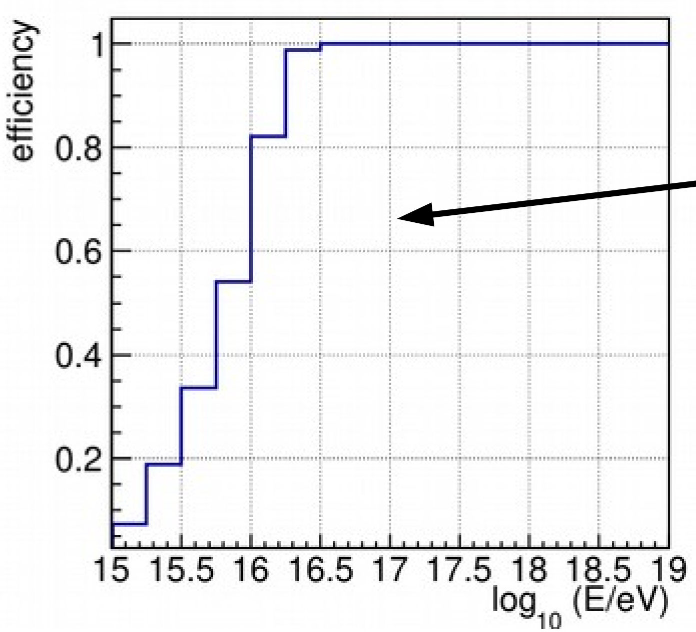
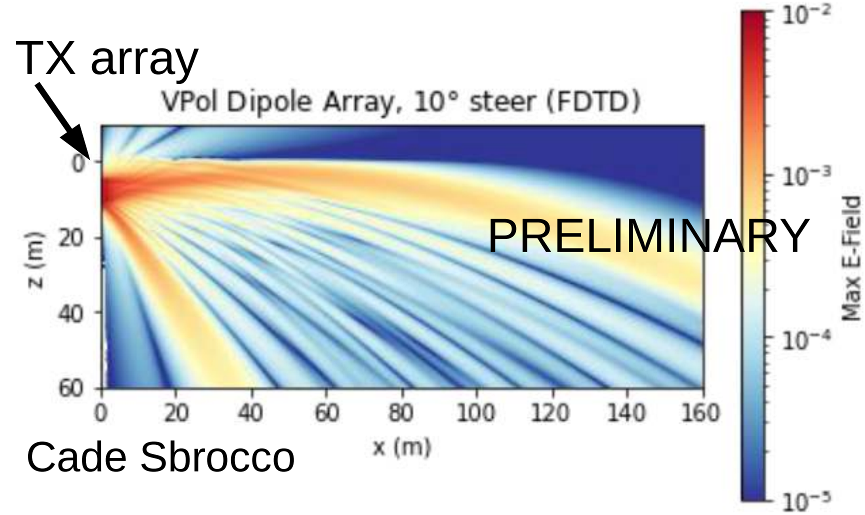


Surface system trigger efficiency curve (simulated).

Phased TX array

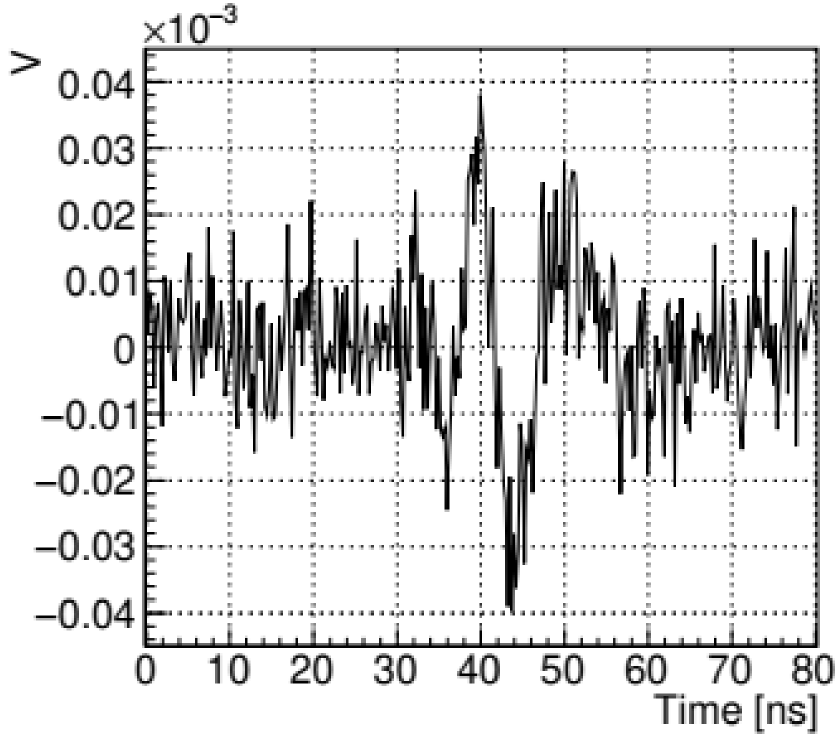


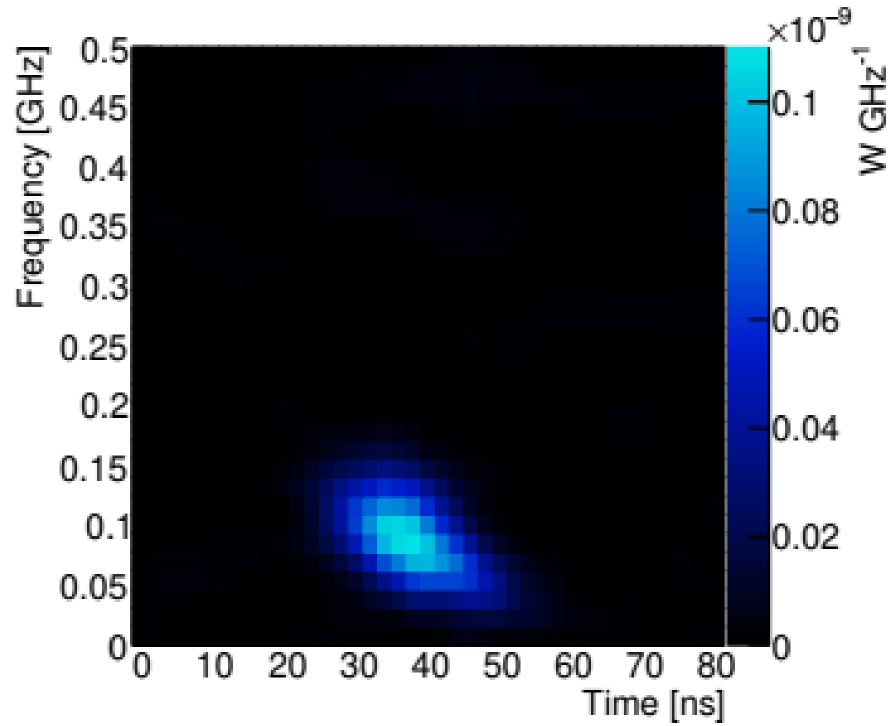
Cade Sbrocco

- Surface system ~100% efficient above $10^{16.5}$ eV (trigger on every event with possible radar signal)

- Phased transmitter (8 channels) allows us to steer the transmitted beam and get high gain transmission with low gain antennas

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, more results this session (D. Frikken) and *In Preparation*

Event rate

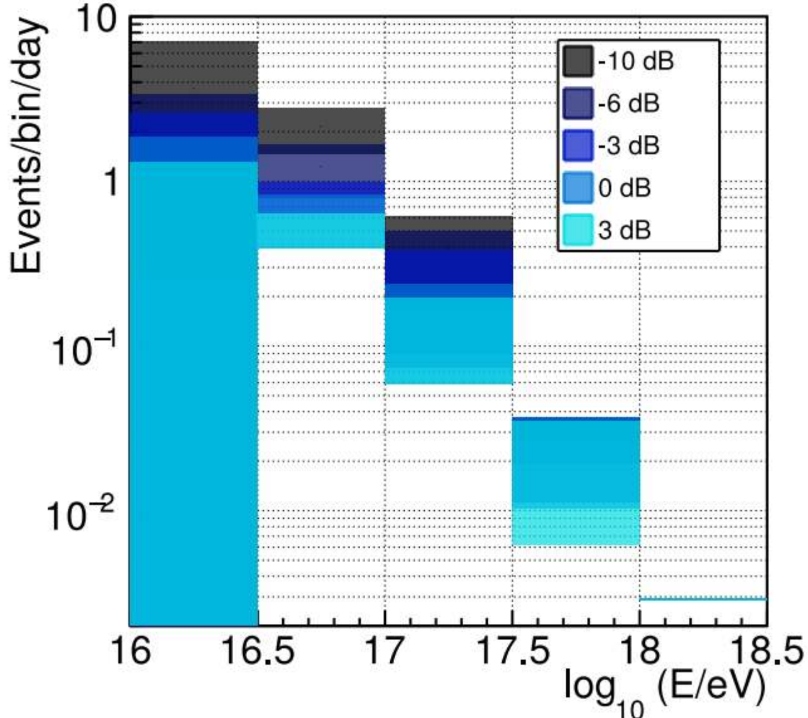
- Detailed simulations using Corsika, GEANT4, and RadioScatter give us an event rate (Rose Stanley and Simon De Kockere, VUB Brussels)
- 3 step process:

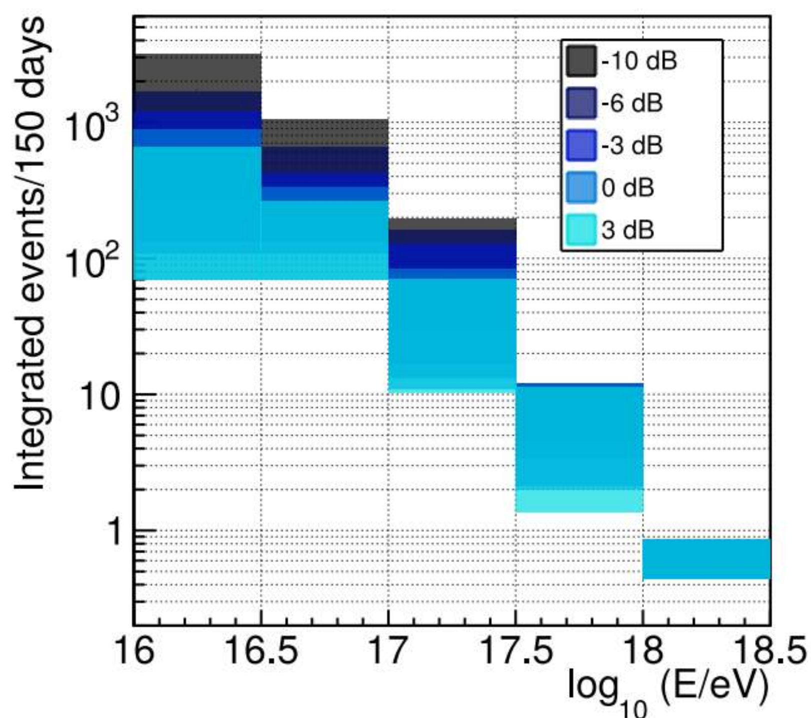
  1) **Corsika** showers were thrown with random distribution of zenith angles from 0–30 deg and energies from PeV to 10 EeV.

  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.

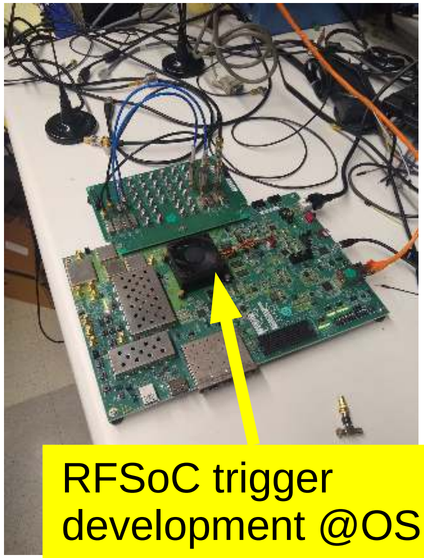
Right: Integrated events/season

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.

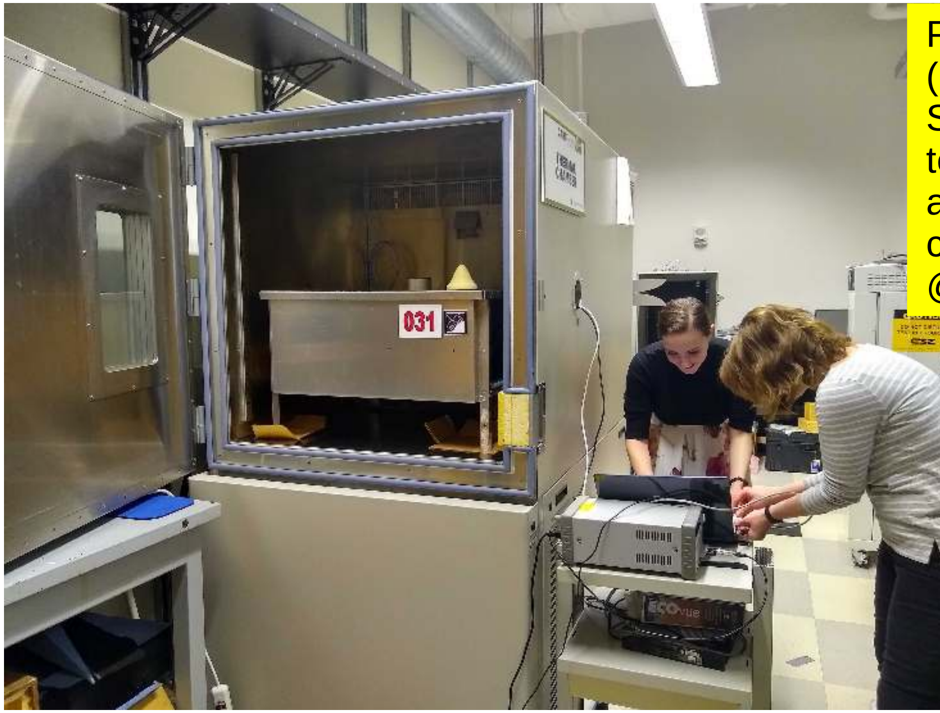
Hardware work in progress

Surface system deployment @VUB rooftop! Prof Katie Mulrey, Rose Stanley, Enrique Huesca Santiago, Prof. Krijn de Vries

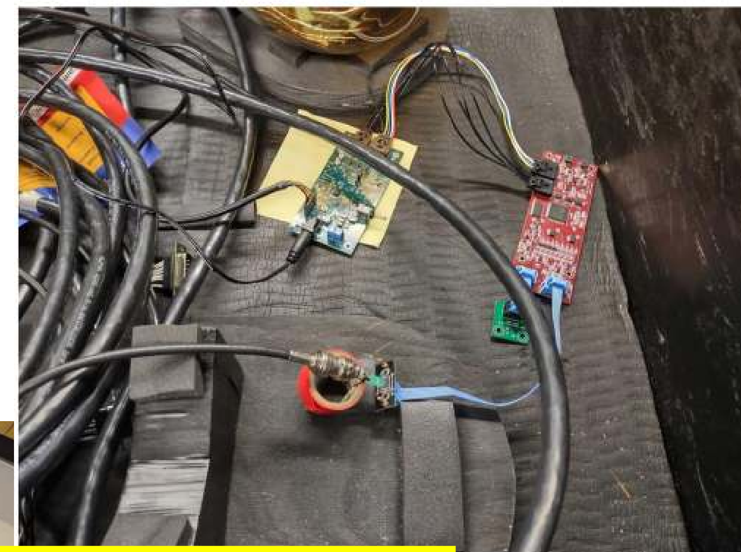


RFSoC trigger development @OSU!

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



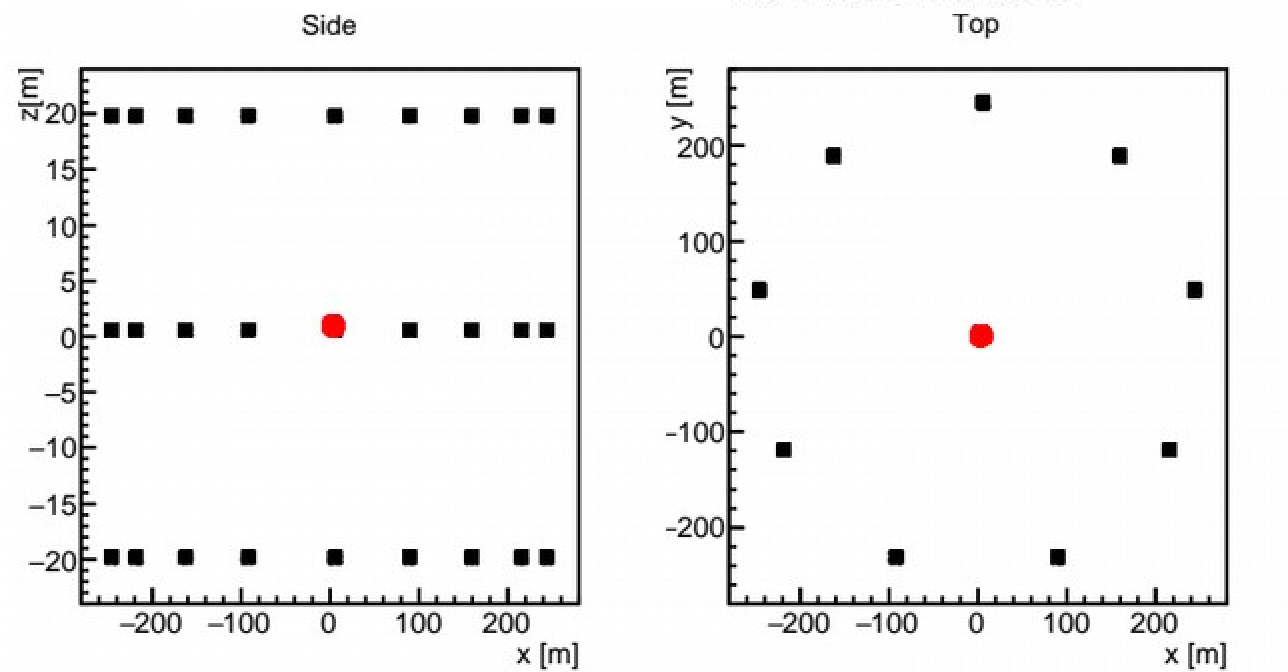
Dylan Frikken (OSU) performs system tests on scintillator panels (left) and readout electronics (above).

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

Deployment Timeline

- RET-CR will be deploying to the polar regions in the upcoming polar season(s).
- *DETAILS TO FOLLOW SOON!*

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.

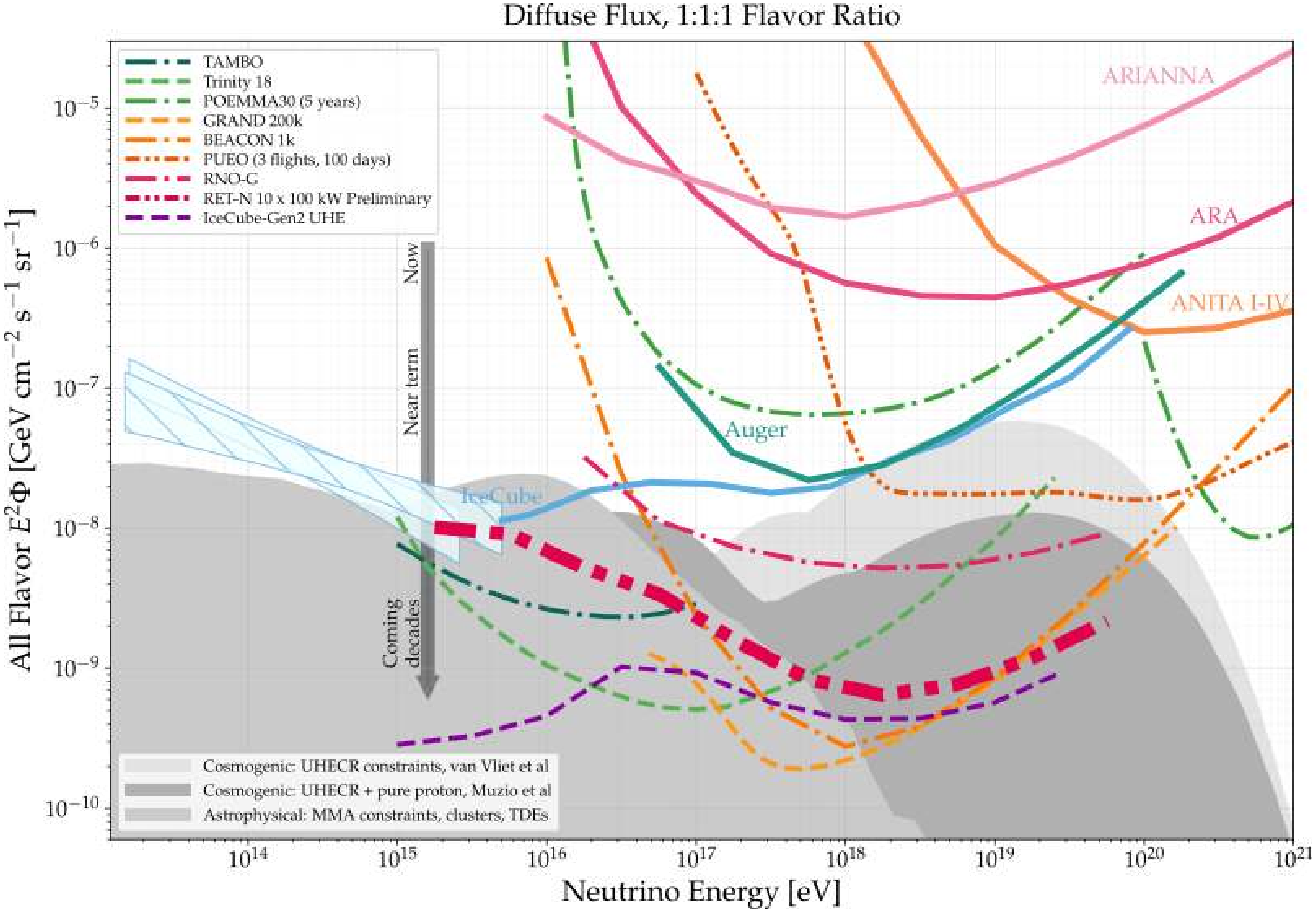
Event reconstruction and resolutions are also underway: see contribution 171, D. Frikken, this session

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



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

RET **10 stations,** (270 total receive channels) 10 years, thick red dashed curve, versus 100s-1000s of stations for other instruments.

Also shown: Many experiments with different sensitivities

Other RET Status Updates

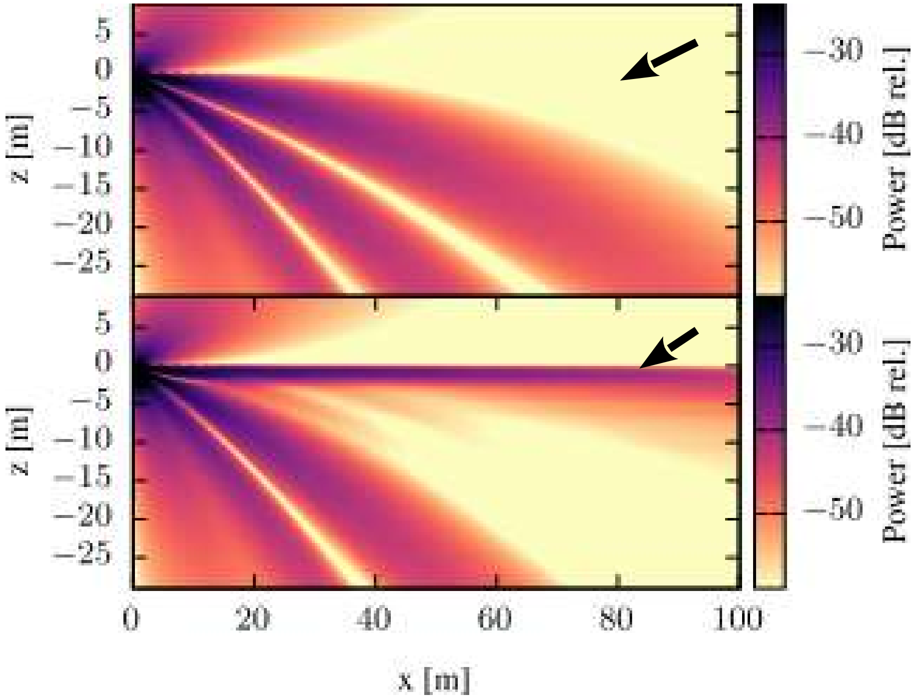
- Updating existing simulation codes RadioScatter (**Vesna Lukic** improving high-energy scaling, **Uzair Latif** implementing ray tracing) and ParaPropPython (**Alex Kyriacou** extending functionality and improving time domain response)
- **Dylan Frikken (this session!)** and **Vesna Lukic** working on reconstruction
- New, complementary macroscopic simulation (**Enrique Huesca Santiago**) is an independent code that will run fast and validate experimental results
- Antenna measurements (**Mohammad Ful Hossain Seikh**) and surface station studies (**Rose Stanley** and **Krishna Nivedita**) for RET-CR and RET-N help us better understand our simulations and sensitivity

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, studies for RET-N also well underway.

Thanks!

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! (see: 1908.10689,1805.12576)
- 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