

# Detecting Ultra High Energy Neutrinos with the Radar Echo Telescope

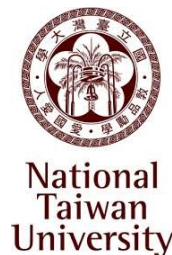
**Steven Prohira**

OSU CCAPP Fellow, OSU President's Postdoctoral Scholar

On behalf of Radar Echo Telescope: K.D. de Vries, P. Allison, J. Beatty, D. Besson, A. Connolly, S. De Kockere, N. van Eijndhoven, C. Hast, E. Huesca, 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. Wissel,

27 May, 2020

SLAC FPD Seminar



# 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' proposal submitted Dec '19, pending.
- RET-N is projected to have good sensitivity to *neutrinos in the 10-100 PeV range*, making it a promising complementary technology to optical (IceCube, ANTARES, BaikalGVD, KM3NeT...) and other radio (RICE, ARA, ANITA, ARIANNA, RNO, BEACON, GRAND...) methods for UHE neutrino detection



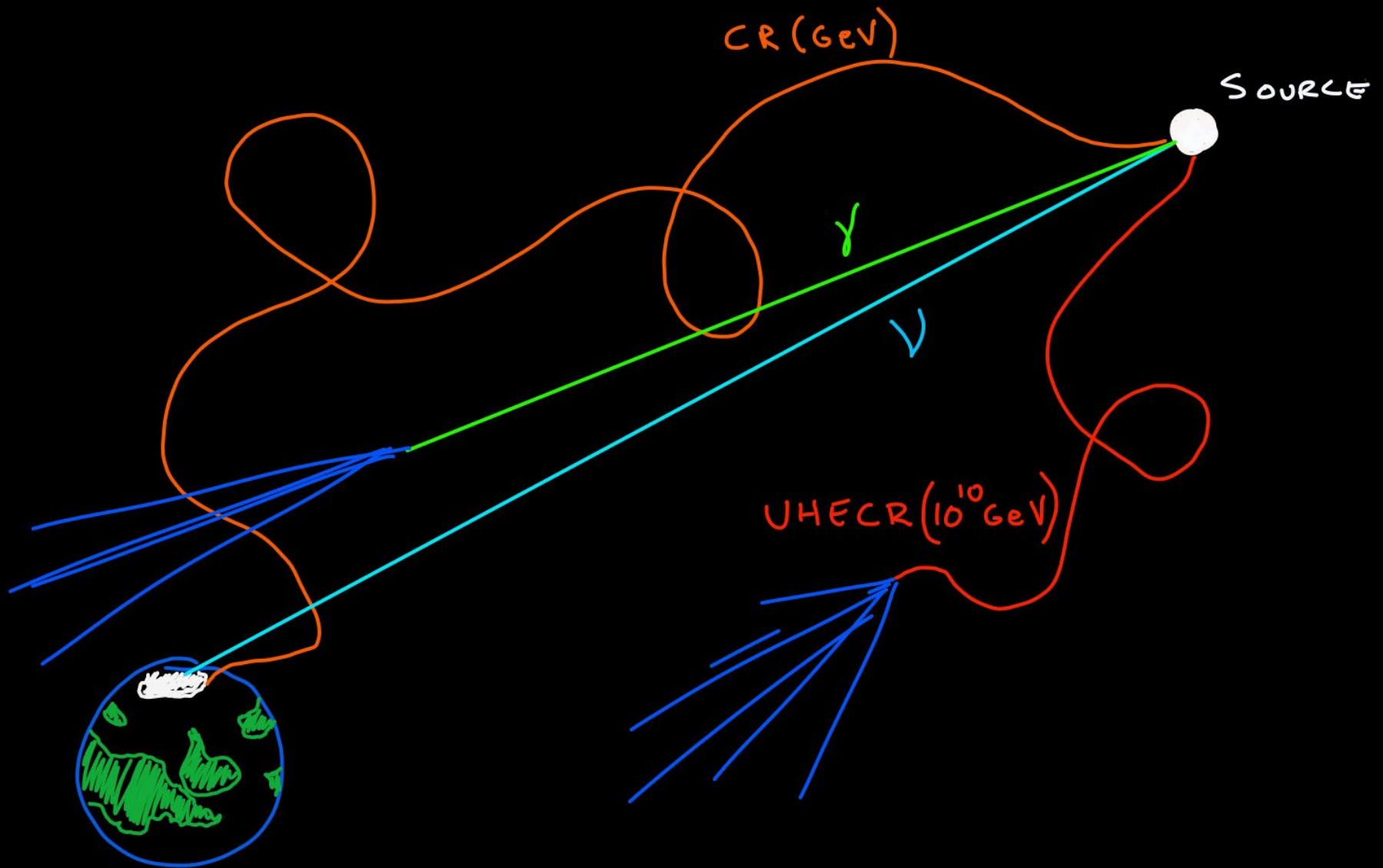
# Outline

- **Introduction**
  - The UHE neutrino picture
  - Conceptual overview
- **Motivation**
  - Historical overview
  - Theoretical background
- **Experimentation**
  - SLAC T576, experiment and results
- **The Radar Echo Telescope for neutrinos and Cosmic Rays**

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# Introduction: why neutrinos?



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

# Introduction: why neutrinos?

*Neutrinos are the only observed particle with beyond-standard-model properties:*

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

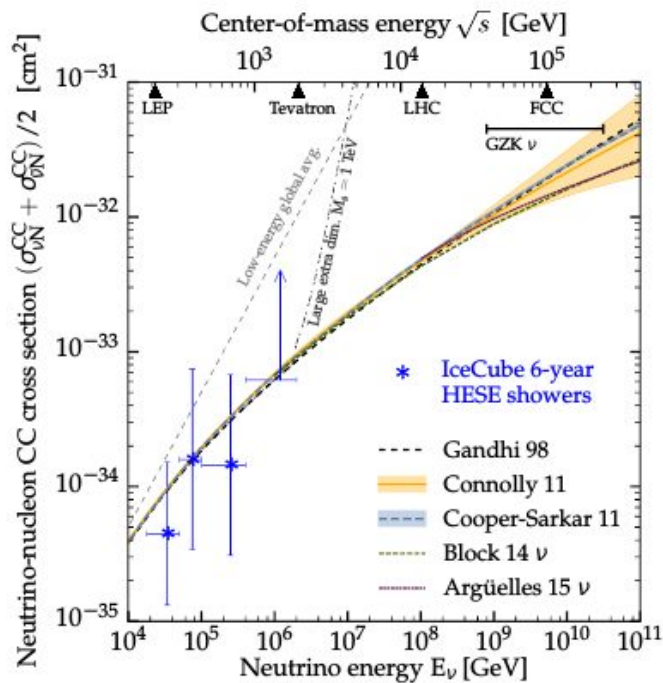
*also...*

*only interact via the weak force. (bizarre)*

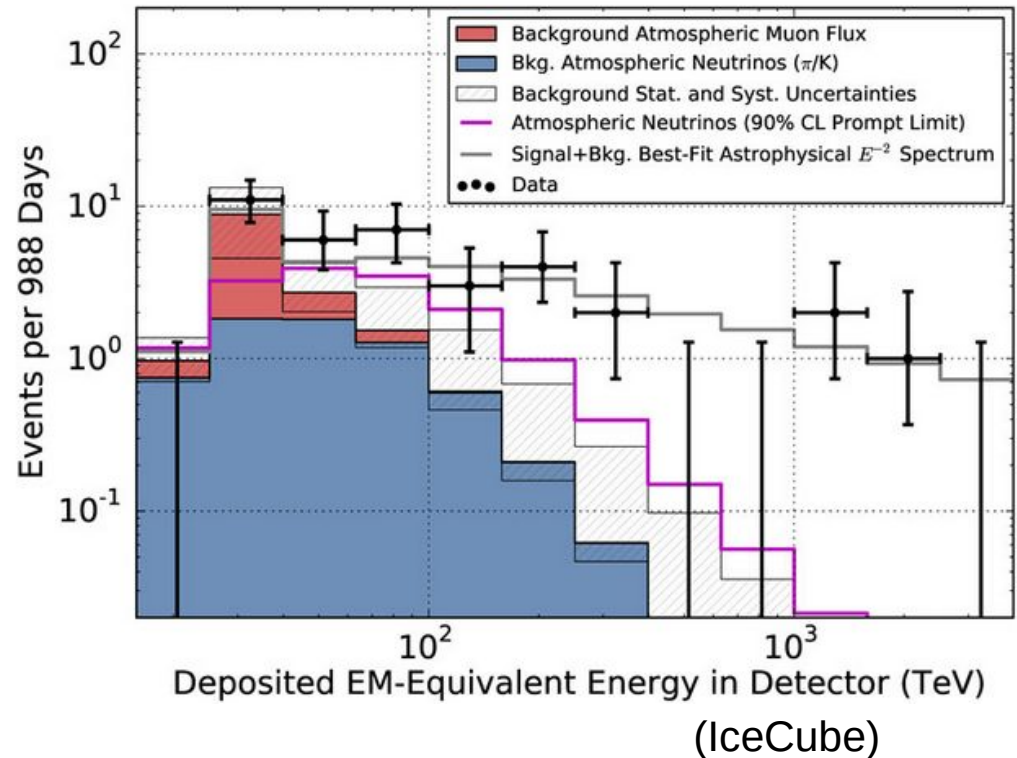
*are  $< 10^{-6}$  the mass of the electron. (why?)*

(NOTE: none of this is addressed in this talk)

# Introduction: Why ultra-high-energy (UHE) neutrinos?



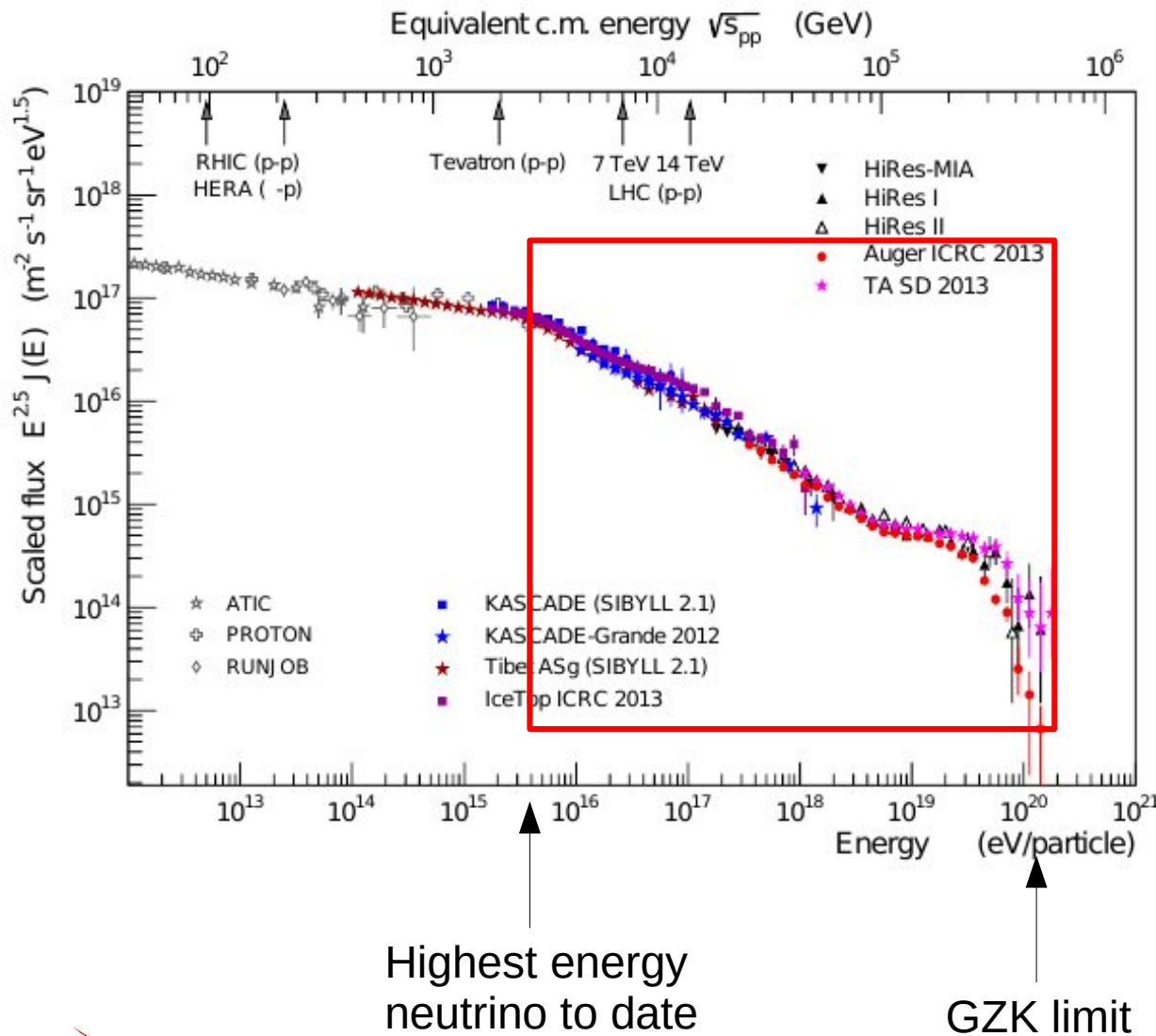
(Connolly and Bustamante 2019)



(IceCube)

- Sources of UHE neutrinos (and cosmic rays) unknown
- interaction cross sections unconstrained
- center-of-mass energies accessible beyond range of colliders

# Introduction: why UHE neutrinos?



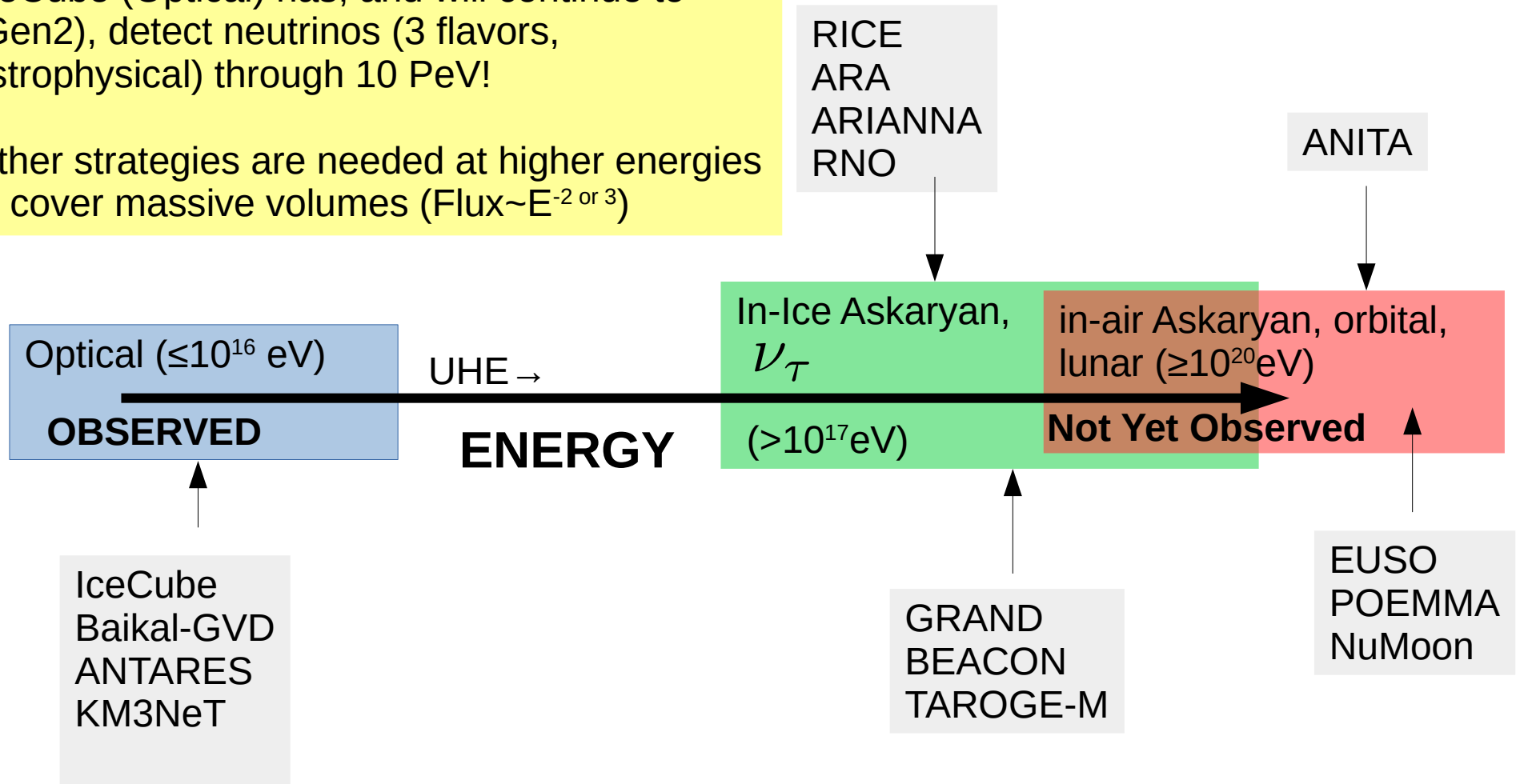
- cosmogenic nu flux comes from ultra-high-energy cosmic ray (UHECR) interaction with CMB photons
- UHECR flux at earth extends up to the GZK limit, UHE neutrinos are there to be detected AT LEAST up to GZK (probably...)
- remember: neutrinos make it to us when UHECR don't!



# The Big (UHE neutrino) Picture

IceCube (Optical) has, and will continue to (Gen2), detect neutrinos (3 flavors, astrophysical) through 10 PeV!

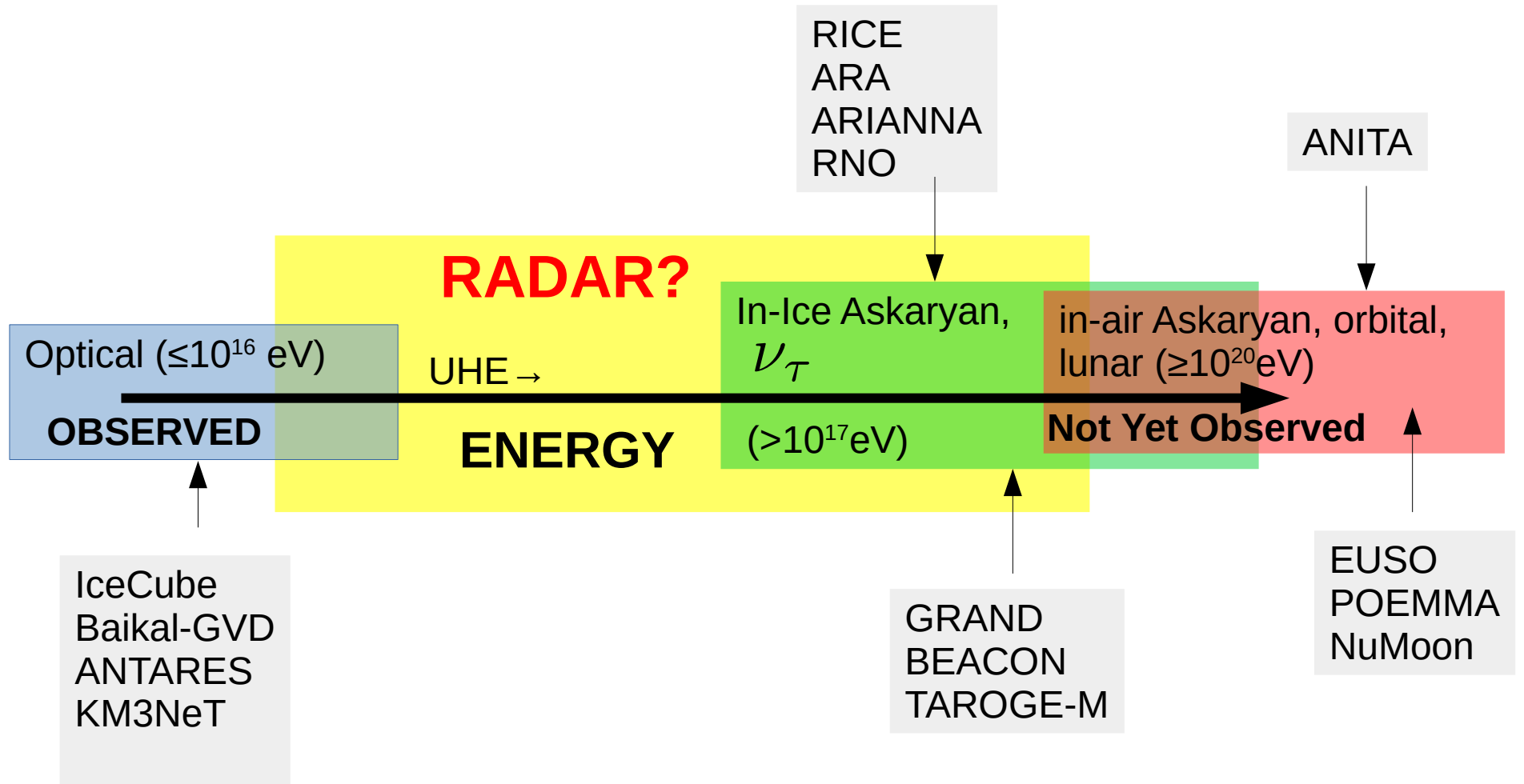
Other strategies are needed at higher energies to cover massive volumes (Flux  $\sim E^{-2}$  or  $3$ )



*non-exhaustive list of experimental efforts*

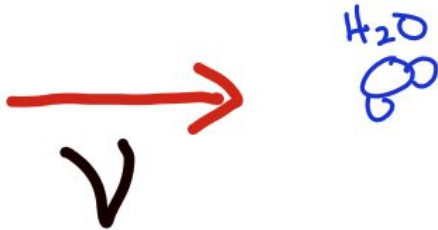


# The Big (UHE neutrino) Picture



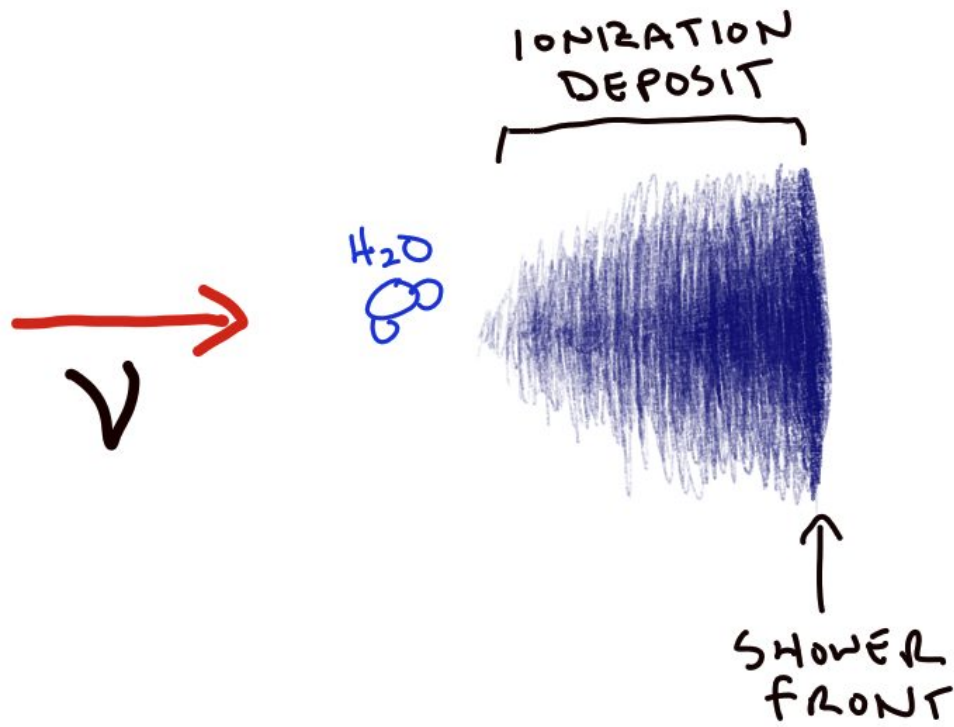
# Concept #1: particle cascades

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



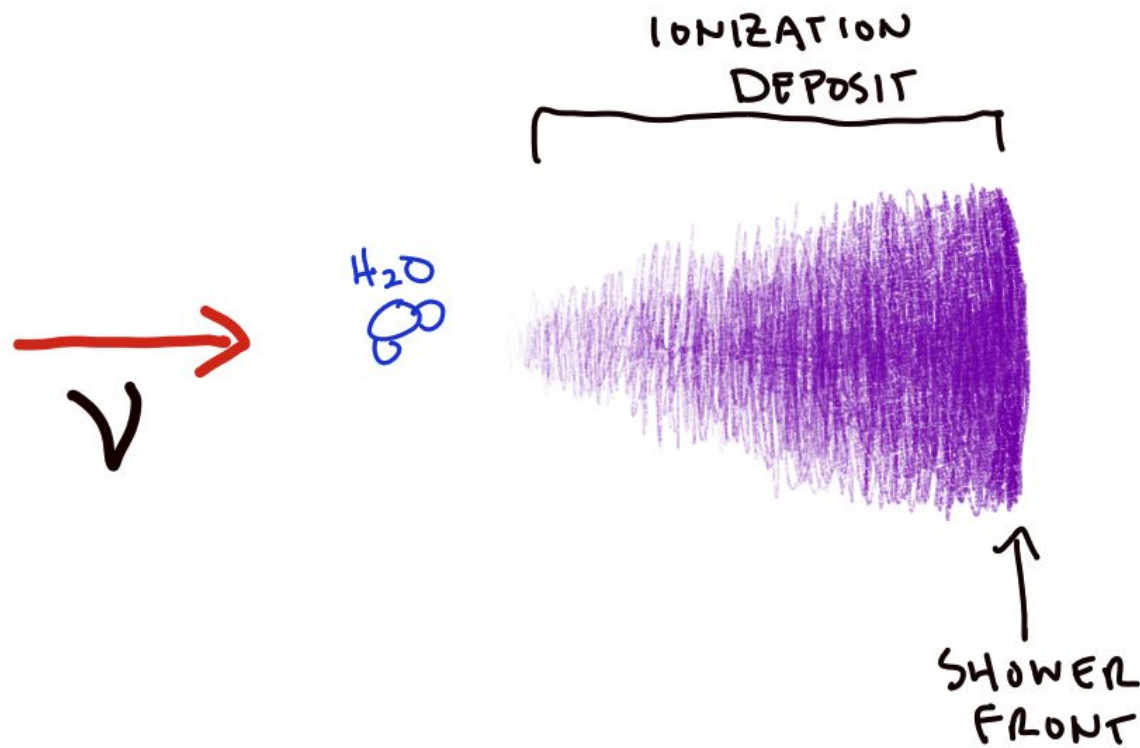
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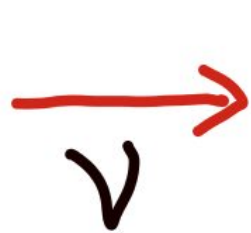
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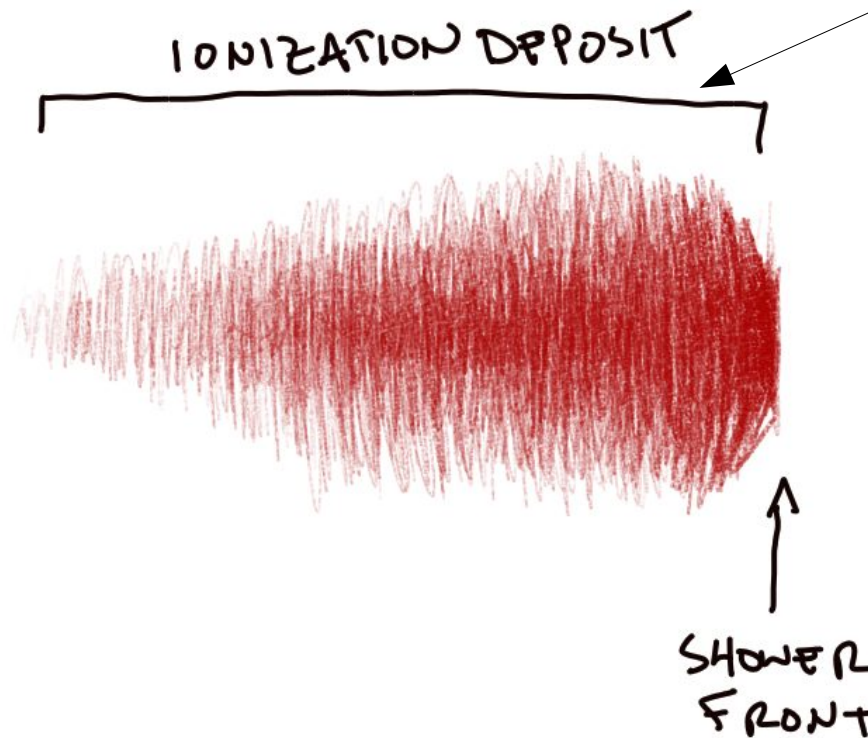


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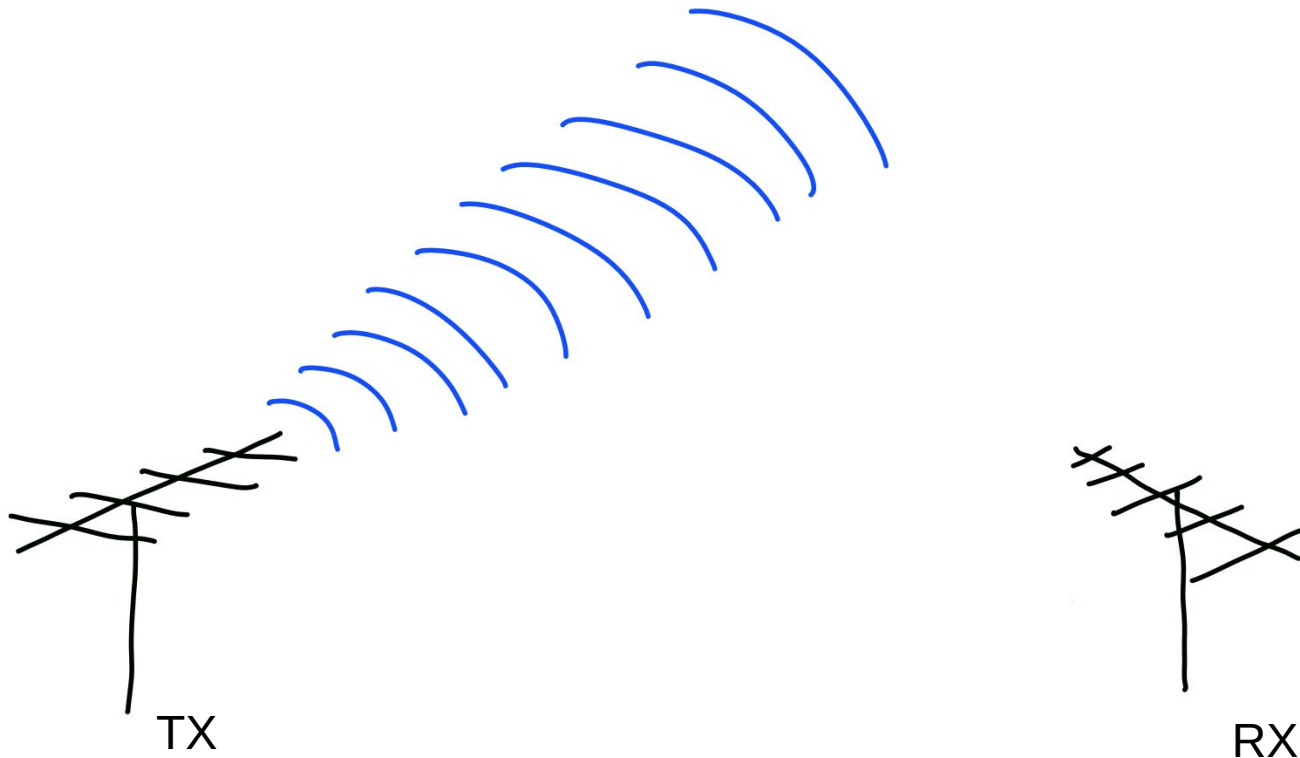


H<sub>2</sub>O



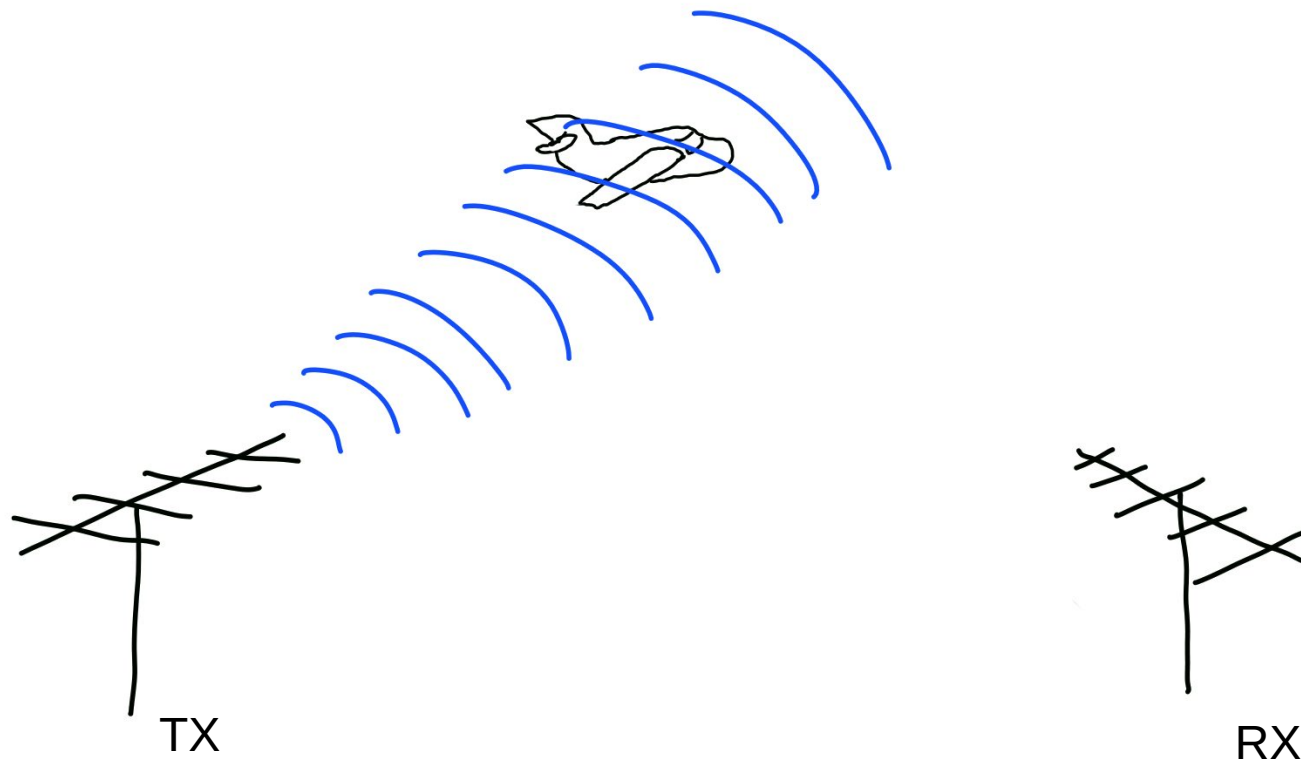
'length' of this deposit depends on the properties of the medium, the 'lifetime' of a free electron.

# Concept #2: radar overview



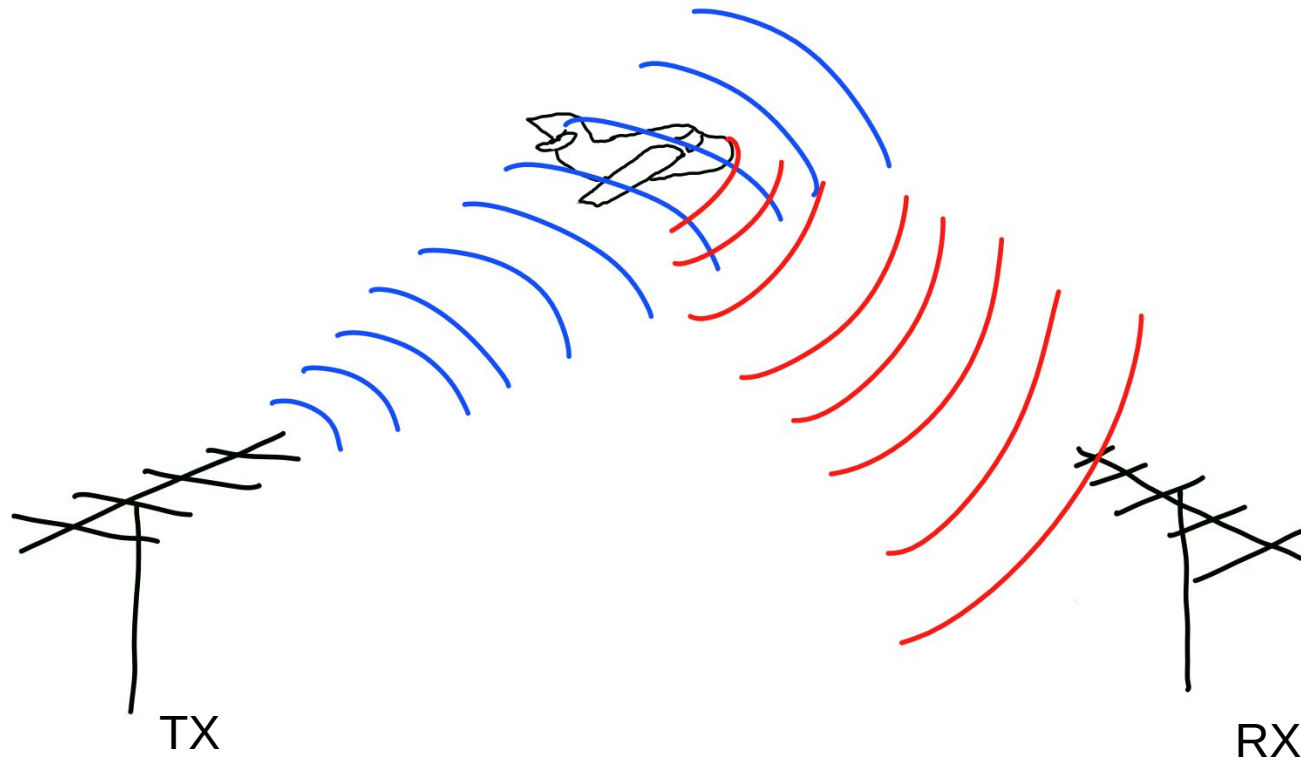
- Transmitter (TX) broadcasts a radio signal into a volume
- receiver(s) (RX) monitor this same volume

# Concept #2: radar overview



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- if a reflective surface lives in this volume, the transmitted signal will be reflected to the receiver(s)

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# radar detection of neutrinos

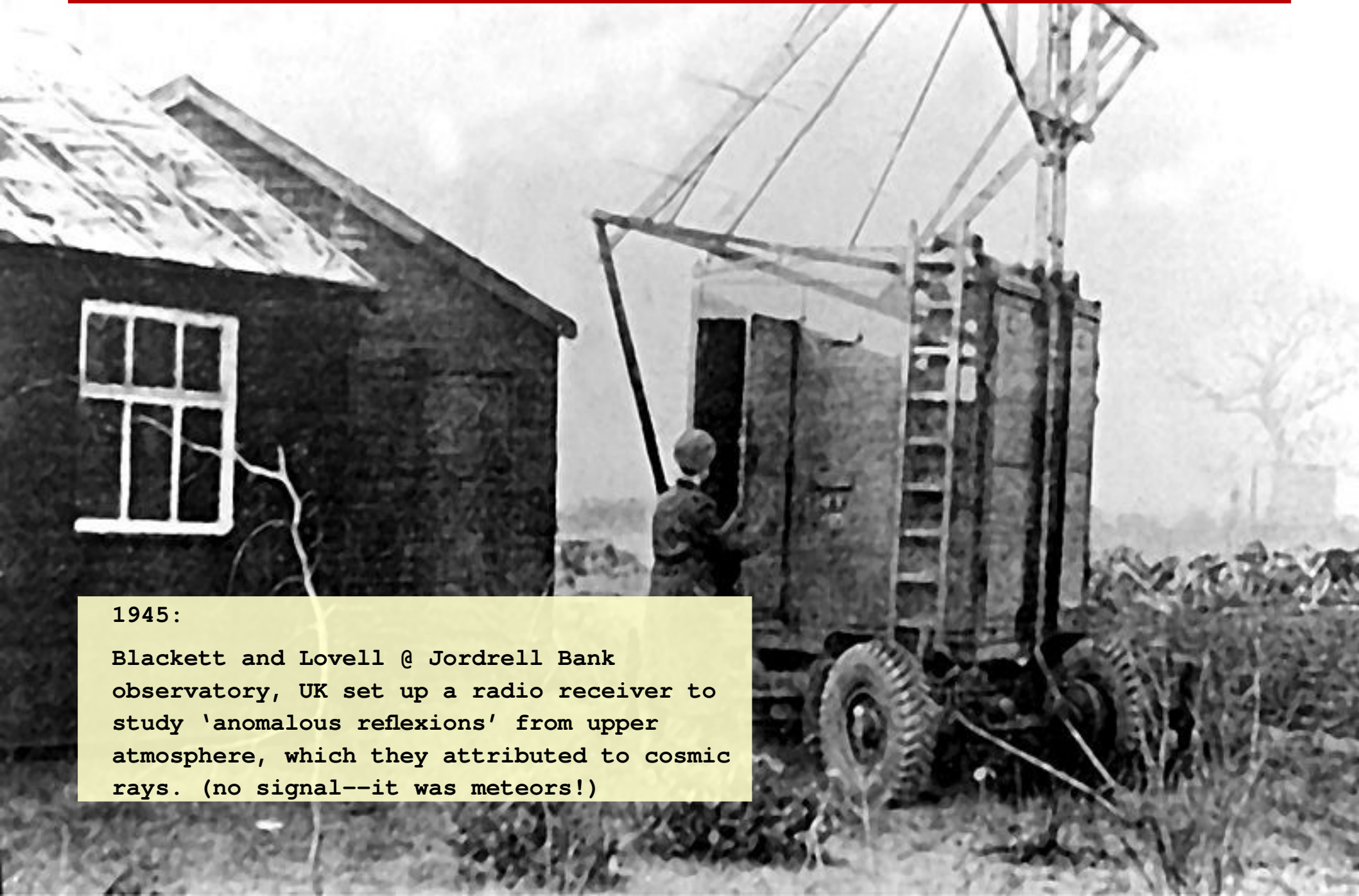
*(Simple) Big Picture Concept:*

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

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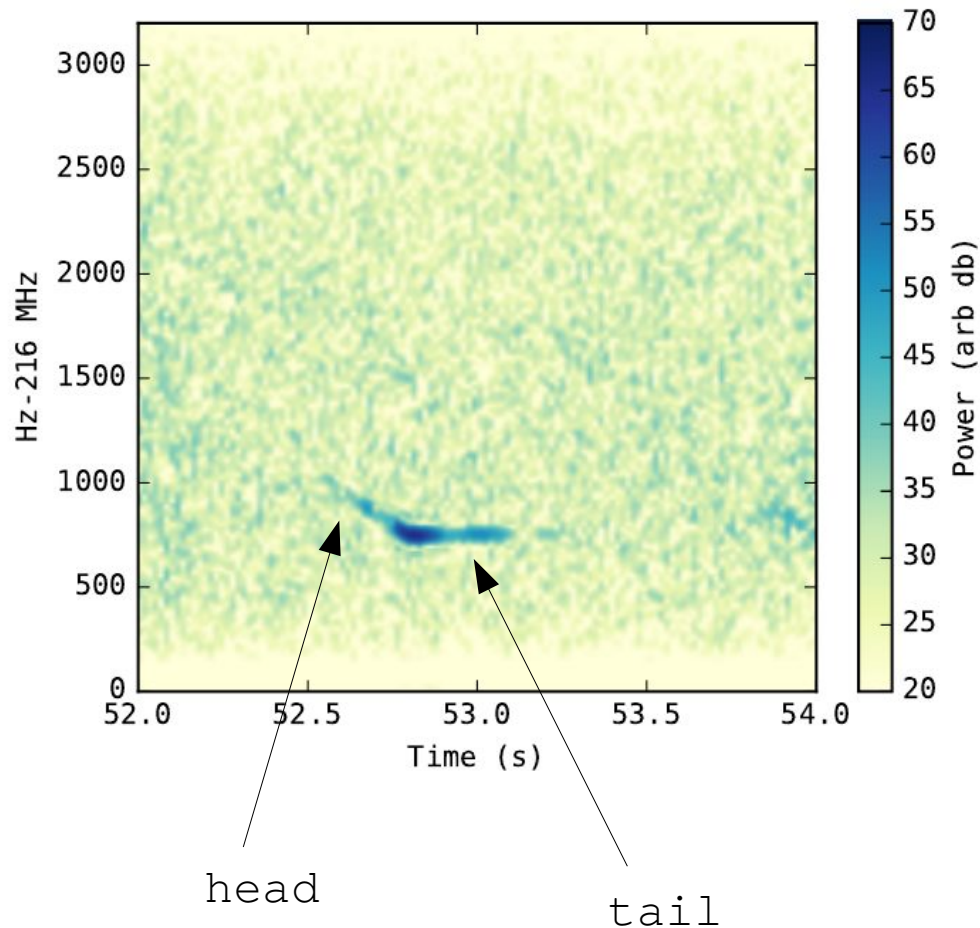
radar is not new...



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

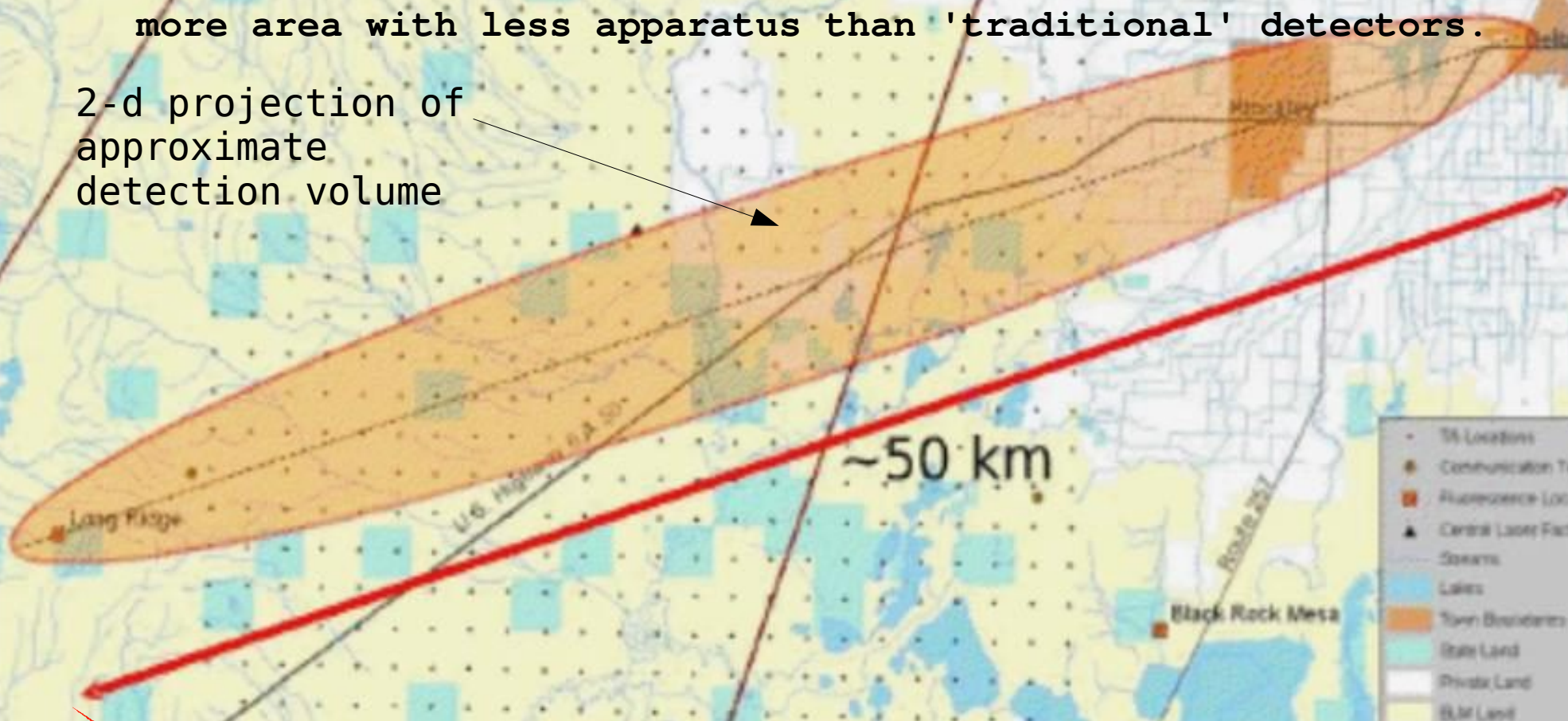
- meteorites ablate at ~100km in the atmosphere
- produce a large dense trail of ionization: dense enough to reflect radio
- 'head echo' shifts in frequency because it moves
- tail is stationary and results in a monochromatic return.

# 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



# Telescope Array RADAR (TARA)

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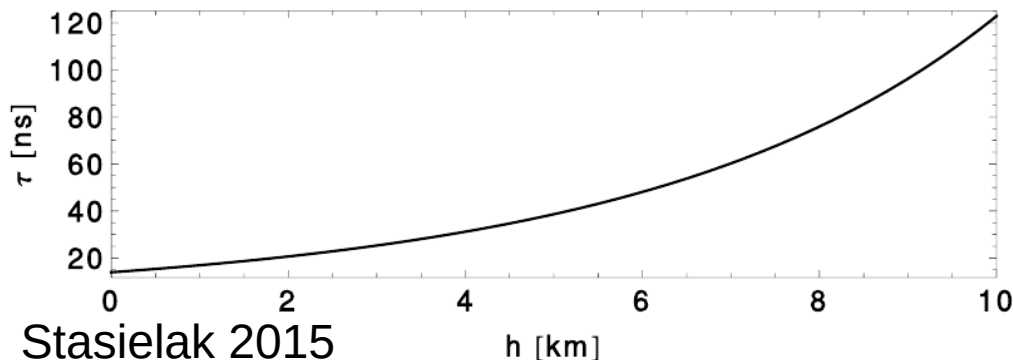
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2-d projection of approximate detection volume

TARA ran for several years, and reported no signal

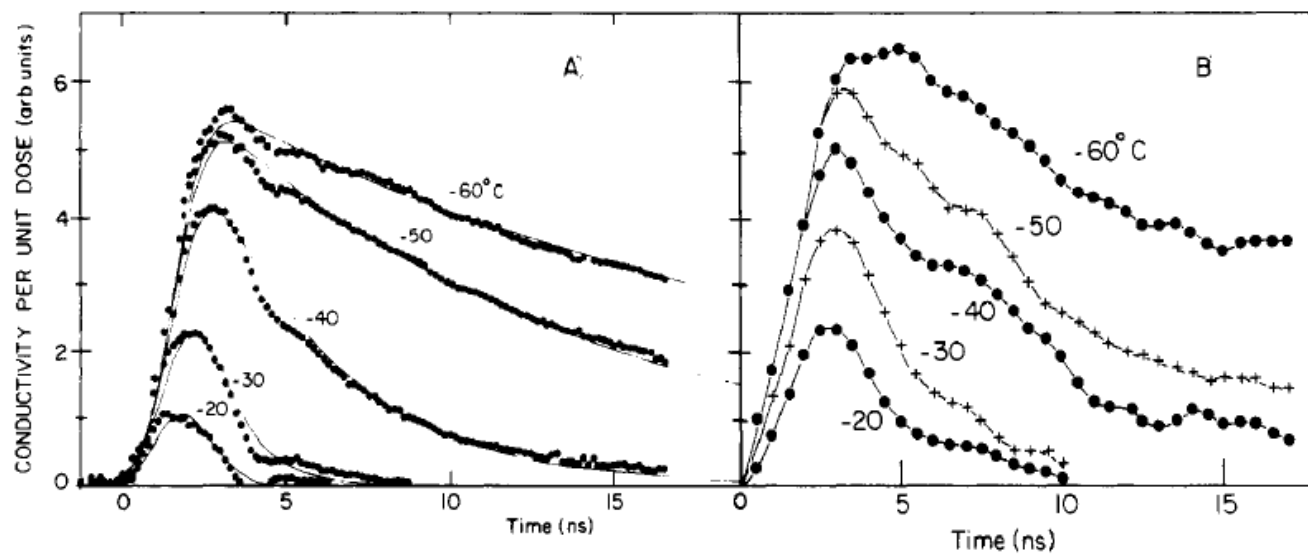
ionization densities not high enough in air due to collisions and short plasma lifetime (see left)

10.1016/j.astropartphys.2016.11.006



# 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  $\sim 10^6$ - $10^7$  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

# particle-level model

- main approximation of macroscopic models is shower development
- can take another approach: current monte carlo programs (GEANT4) have well verified shower development
- incorporate a radio scattering module into a monte carlo program, use individual equation of motion, *including collisions*, calculate scattered signal from first principles.
- EOM well established; plasma properties well understood; put it all in, see what happens.
- has been incorporated into a program called RadioScatter (c++, open source, built on ROOT, can run in any monte carlo program):

<https://github.com/prchyr/RadioScatter>

# derivation of the field

- The single particle EOM for a free charge, subject to **collisions**, is

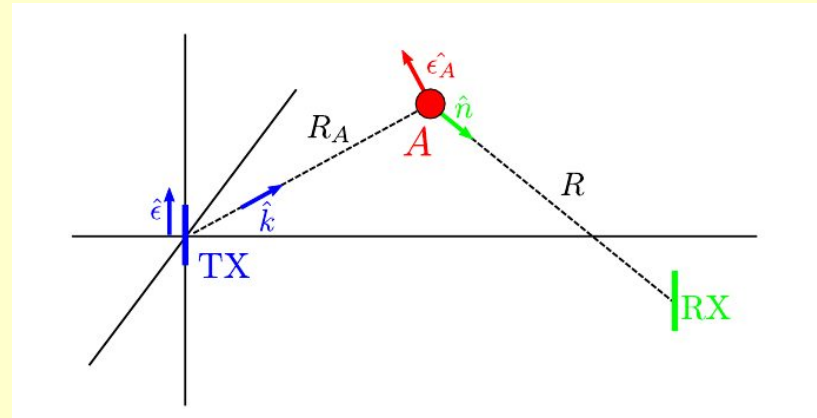
$$m(\ddot{\mathbf{x}}_A + \dot{\mathbf{x}}_A \nu_c) = qE_0 e^{i(\mathbf{k} \cdot \mathbf{R}_A - \omega t)} \hat{\epsilon}_A$$

for charges with negligible velocity, the electric field is:

$$\mathbf{E}_A = \frac{q}{R^2} \hat{n} + \frac{q}{c^2} \left[ \frac{\hat{n} \times (\hat{n} \times \ddot{\mathbf{x}})}{R} \right]_{ret}$$

the wave vector

$$k \approx \frac{\omega}{c} \left[ 1 + \frac{\omega_p^2}{2} \left( \frac{1}{\omega^2 - i\omega\nu_c} \right) \right]$$



is written in terms of the plasma frequency, and the imaginary part,

$$\omega_p = \sqrt{\frac{4\pi n_e q^2}{m}}$$

$$\beta = \text{Im}[k] = \frac{\omega_p^2}{2c} \left( \frac{\nu_c}{\omega^2 + \nu_c^2} \right)$$

represents a damping of the wave as it penetrates the plasma. this damping is a function of the density of the plasma and the medium.

# derivation of the field

- plugging in gives the expression,

$$\mathbf{E}_A = \frac{q^2 \omega}{c^2 m (\omega + i\nu_c)} \left[ \frac{\hat{n} \times \hat{n} \times \mathbf{E}_I}{R} \right] \exp \left[ -\frac{\omega_p^2}{2c} \left( \frac{\nu_c}{\omega^2 + \nu_c^2} \right) x \right]$$

which simplifies to

$$\mathbf{E}_A = \frac{\alpha E_I e^{-\beta \omega_p^2 x}}{R} \hat{n} \times \hat{n} \times \hat{\epsilon}_A$$

with the constants alpha and beta a function of the plasma number density, the collision rate (also a function of the density) and the interrogating frequency.

- we use this expression within RadioScatter, using collisional frequency for species s,

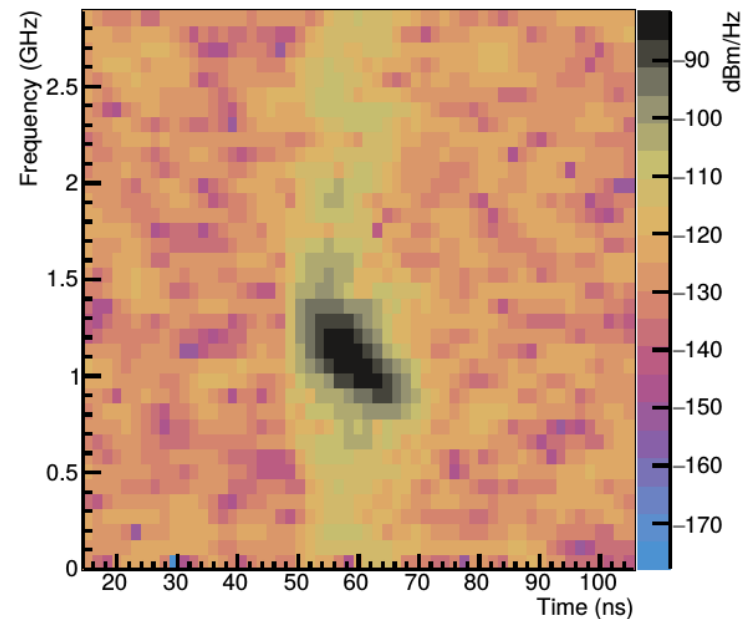
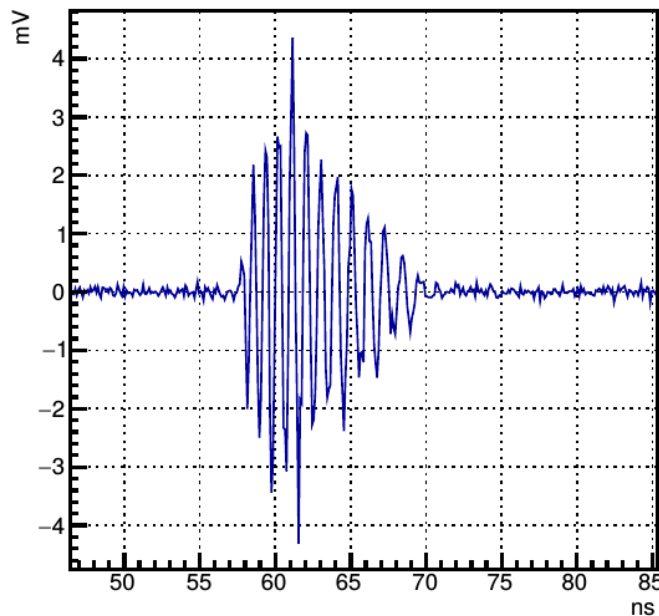
$$\nu_c = \sum_s n_s \bar{v}_e \sigma_s$$

where sigma is the collision cross section for an electron on a constituent of species s

# making the signal

- using E field from before, sum over all particles. assume a plasma lifetime of some duration, sum over all extant particles which would be causal at the receiver

$$\text{Re} [\mathbf{E}_{tot}] = \frac{1}{T} \sum_{n=1}^N \int_t^{t+T} \Theta(t' - t_n^i) \Theta(t_n^f - t') \text{Re} [\mathbf{E}_n(t')] dt'$$



(RadioScatter arXiv:1710.02883, S. Prohira and D. Besson)

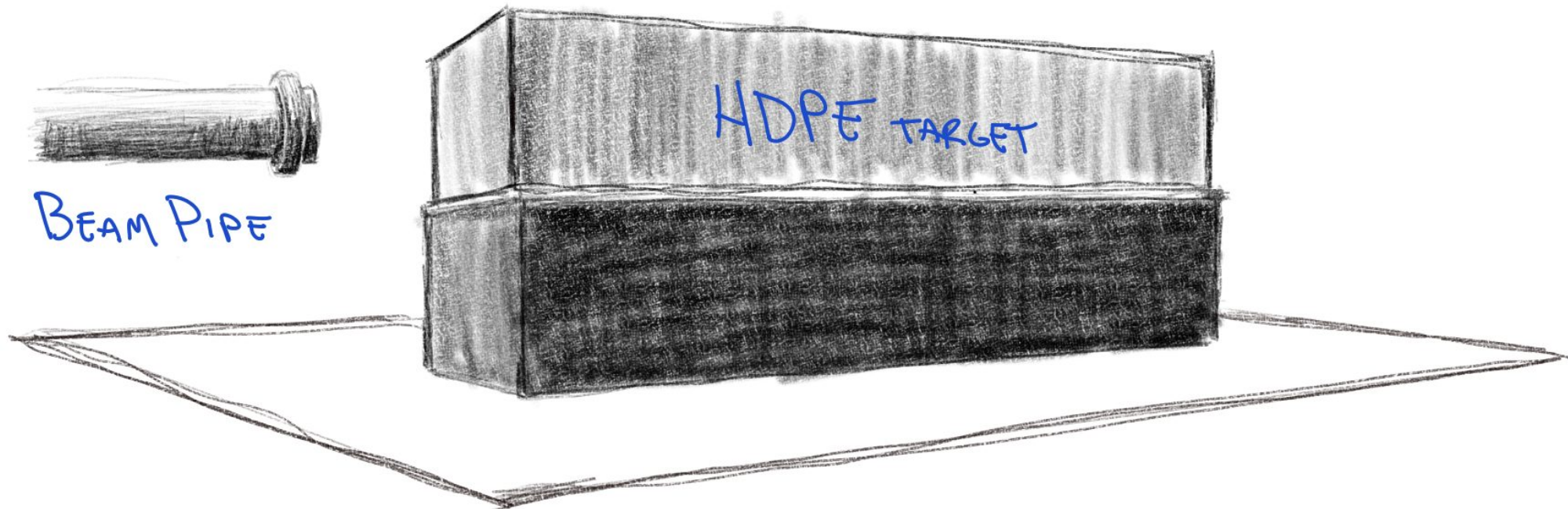
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# Early efforts

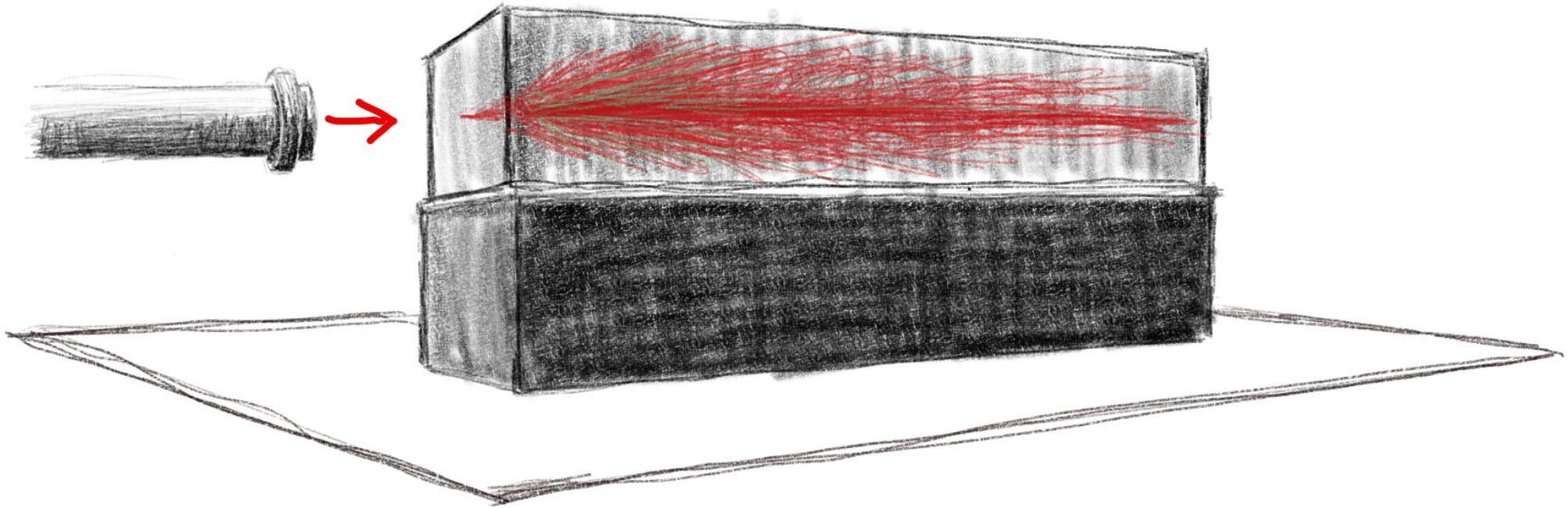
- Several groups have tested for this effect
- Chiba et. al 2013 showed that you can reflect radio from an ionization deposit in a dense material
  - experiments performed in rock salt and ice
  - used an MeV beam to heat the material
  - proof of concept for radar scatter in dense media
- Experiments at the Telescope Array Electron Light Source also performed
  - 40MeV beam into block of ice, just too small to record a scatter

# Idea :



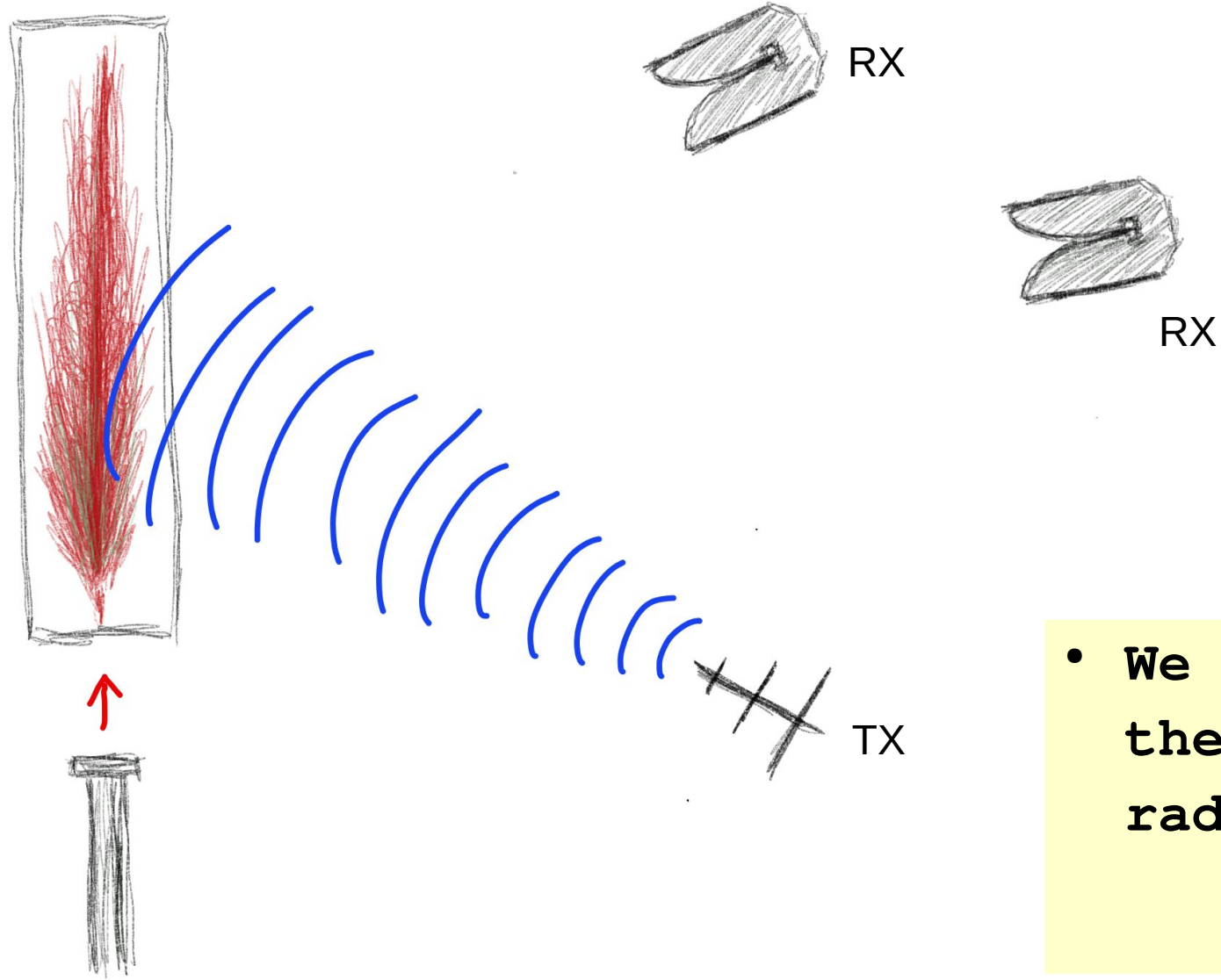
- Direct beam ( $\sim 10^9$  e<sup>-</sup> @ 10GeV/e<sup>-</sup>) into a target of high-density polyethylene (HDPE)
- beam:  $\sim 10^{19}$  eV neutrino
- target:  $\sim$ ice ( $n=1.51$ , density and plasma lifetime comparable to ice, 11eV first ionization) (Weingart 1972)

# Idea :



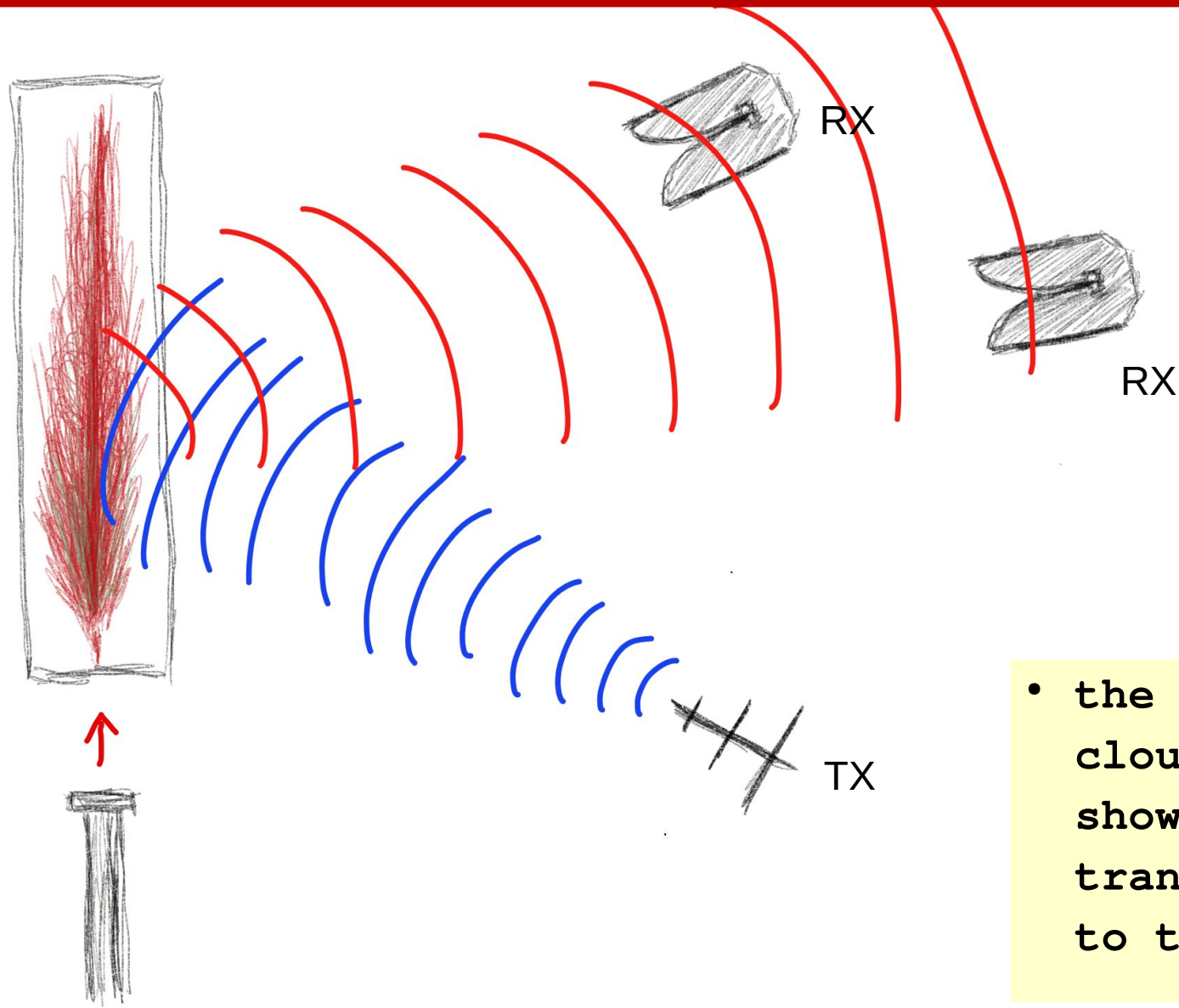
- As the beam enters the target, a cascade is created in the material

# Idea :



- We interrogate the target with radio

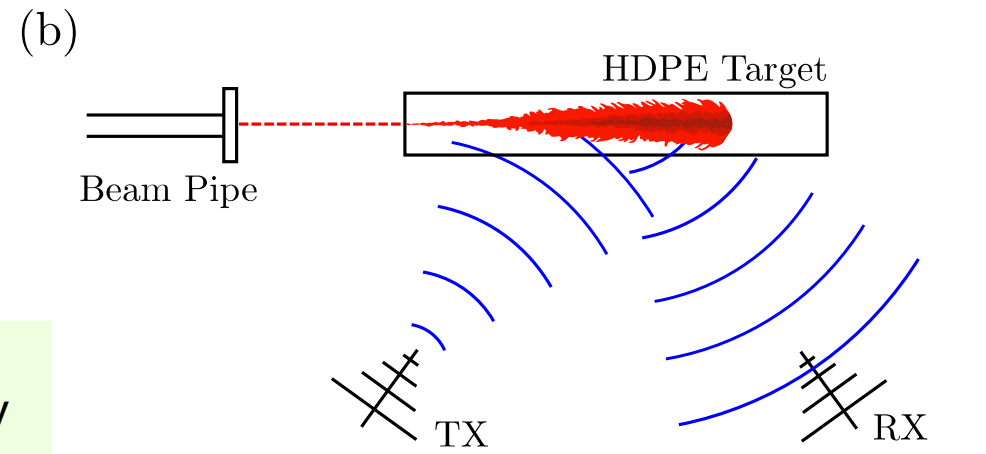
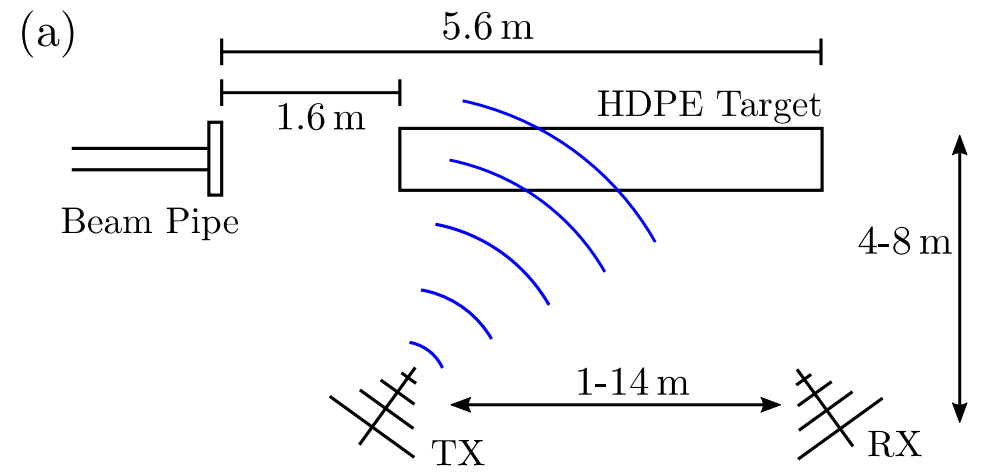
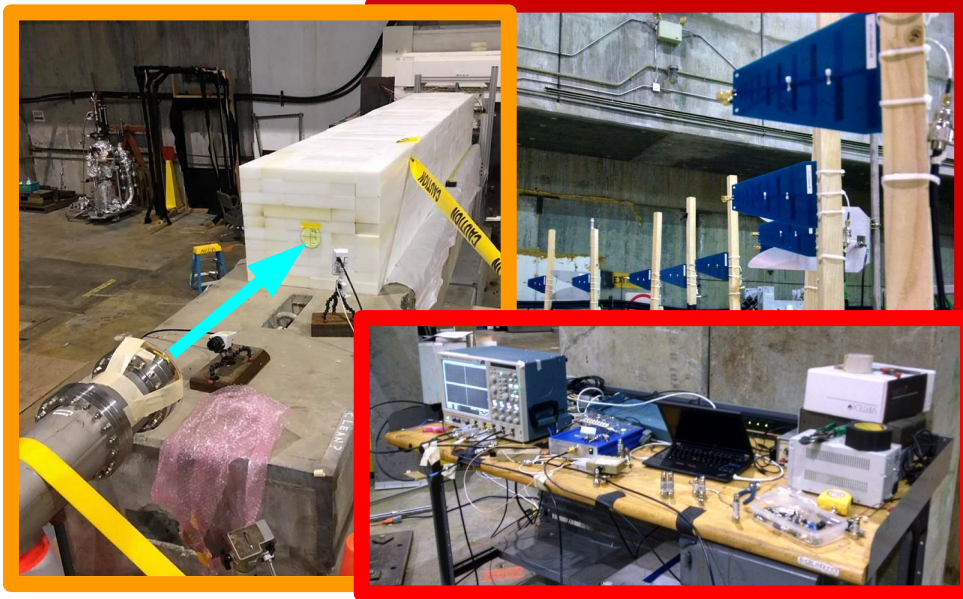
# Idea :



- 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



First run funded by DOE office of Science Graduate Student Research Award, sponsored by Carsten Hast of FACET/test beams



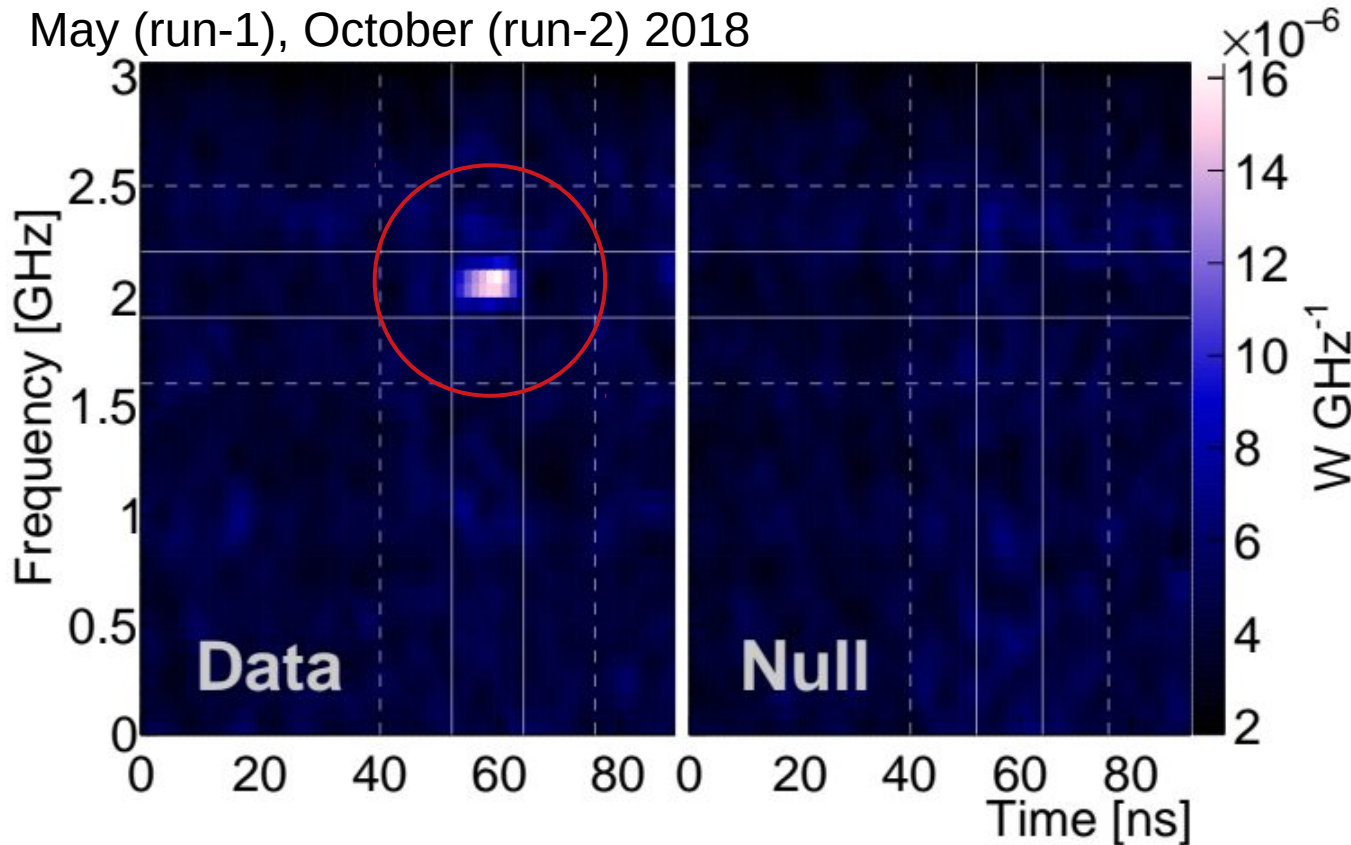
2 June 2020

Steven Prohira--SLAC FPD Seminar



# 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
- arXiv:1910.11314
- arXiv:1910.12830

PHYSICAL REVIEW LETTERS 124, 091101 (2020)

Editors' Suggestion

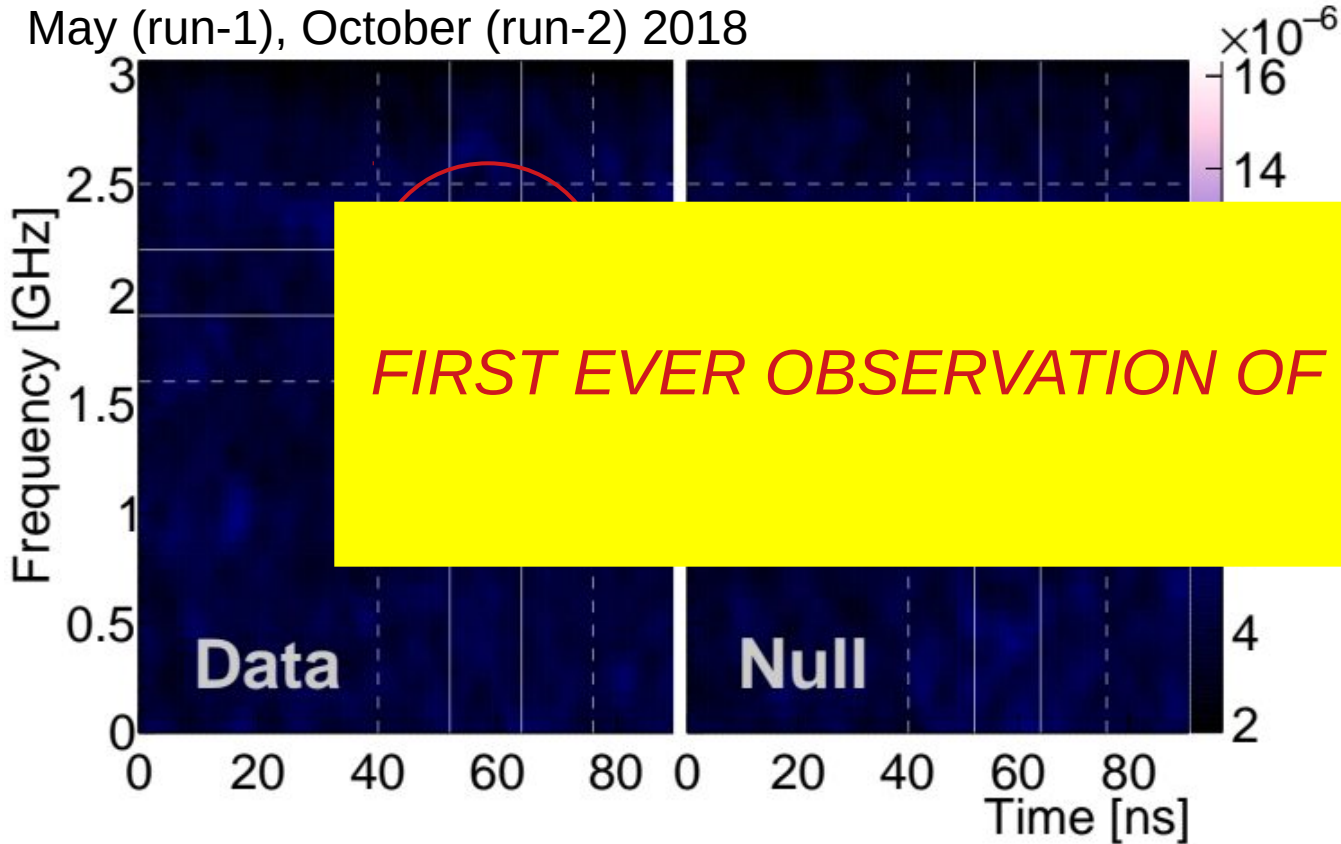
Featured in Physics

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

S. Prohira<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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# 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.

Steven Prohira--SLAC FPD Seminar



2 June 2020

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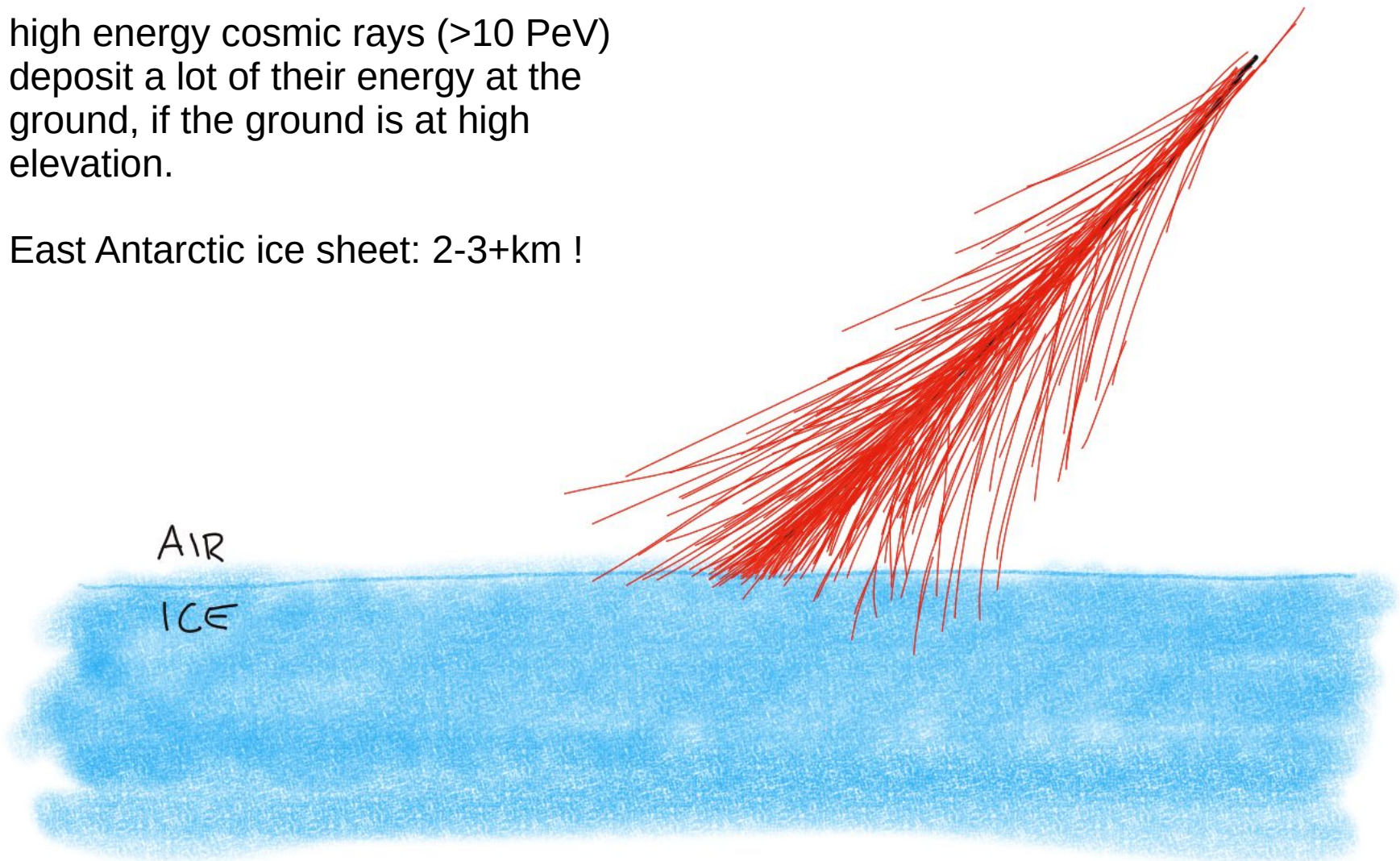
# How to test in nature?

- 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.

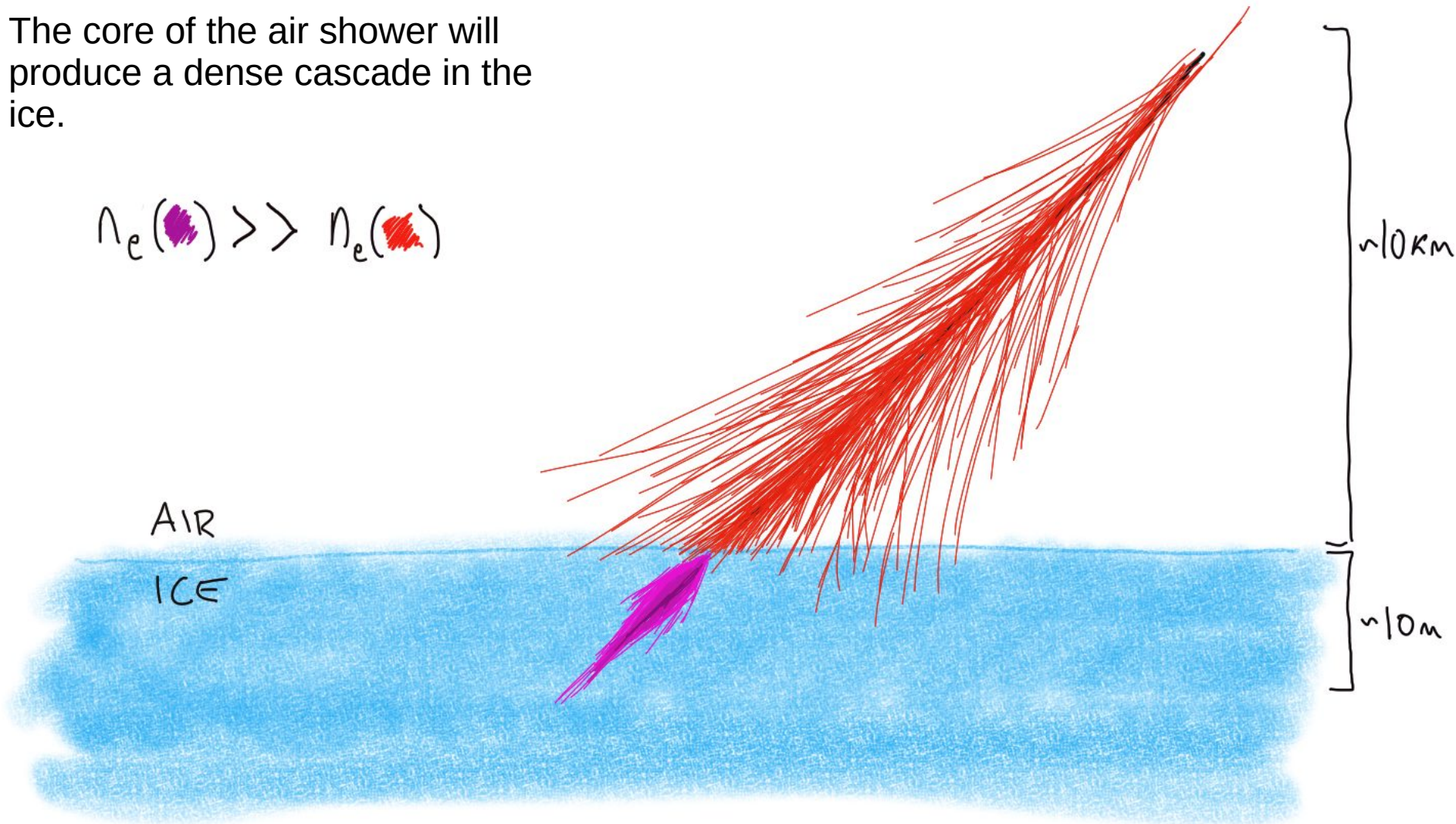
East Antarctic ice sheet: 2-3+km !



# Using cosmic rays

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

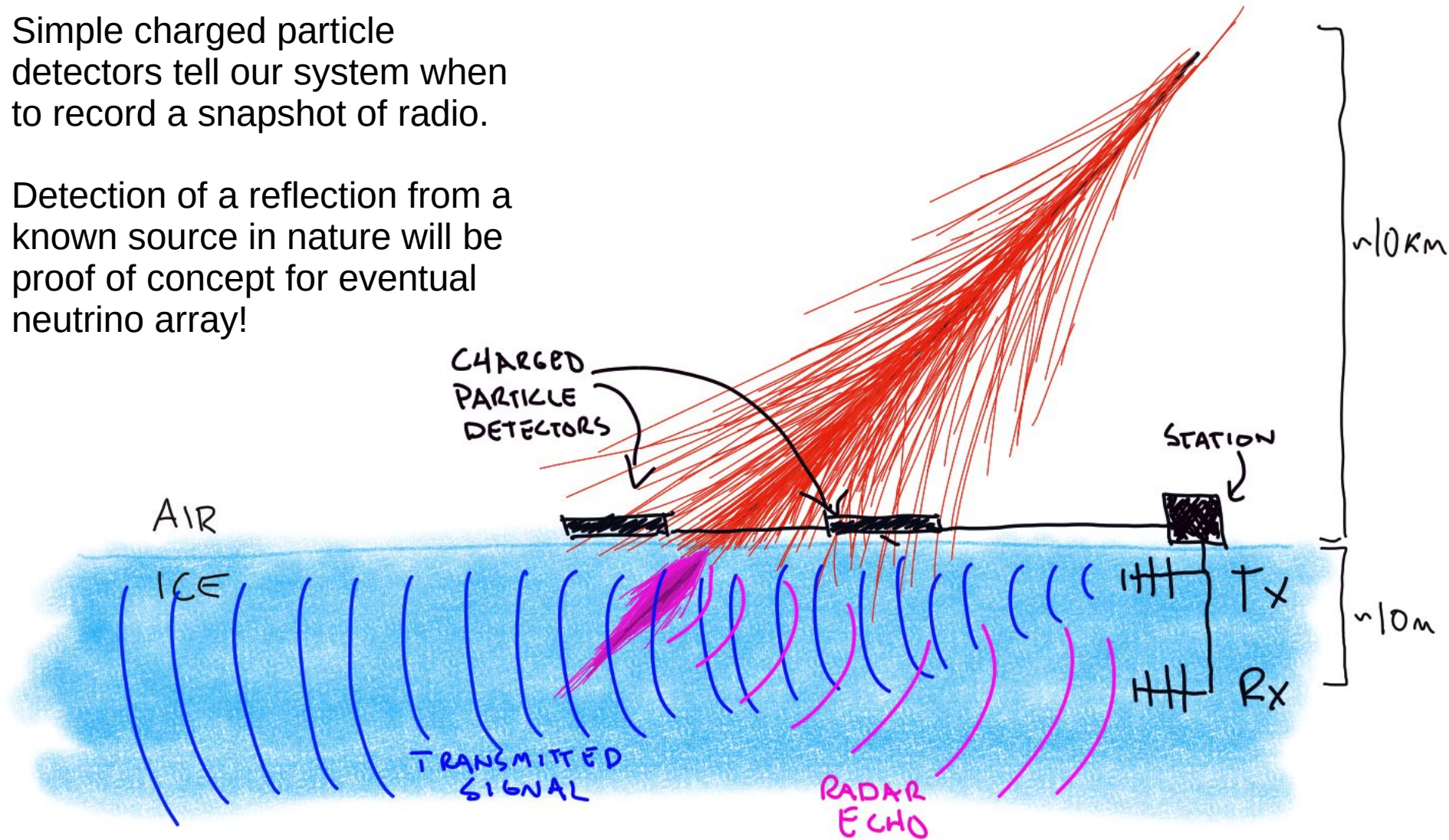
$$N_e(\text{purple}) \gg N_e(\text{red})$$



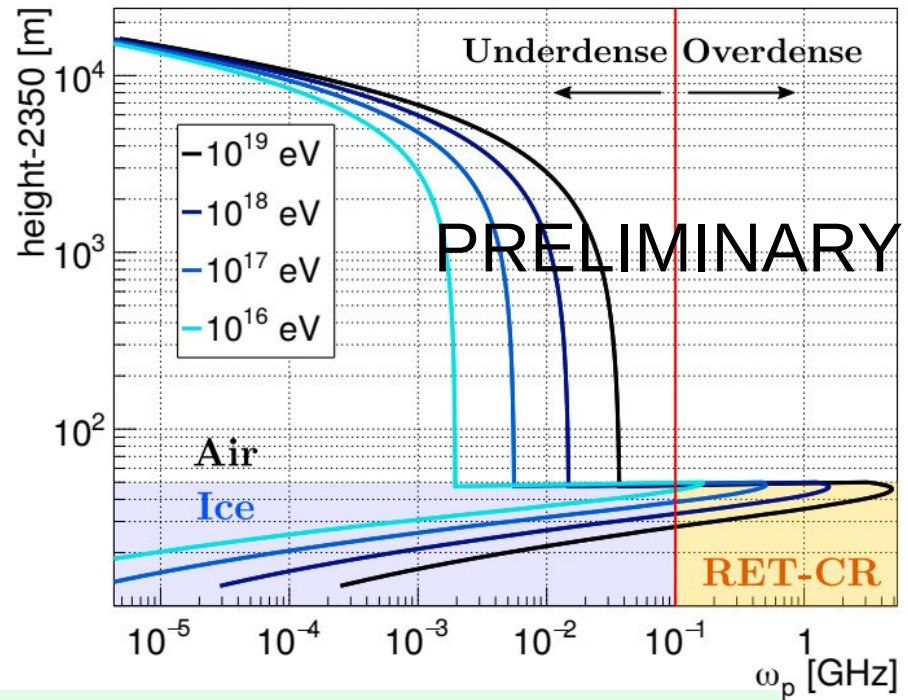
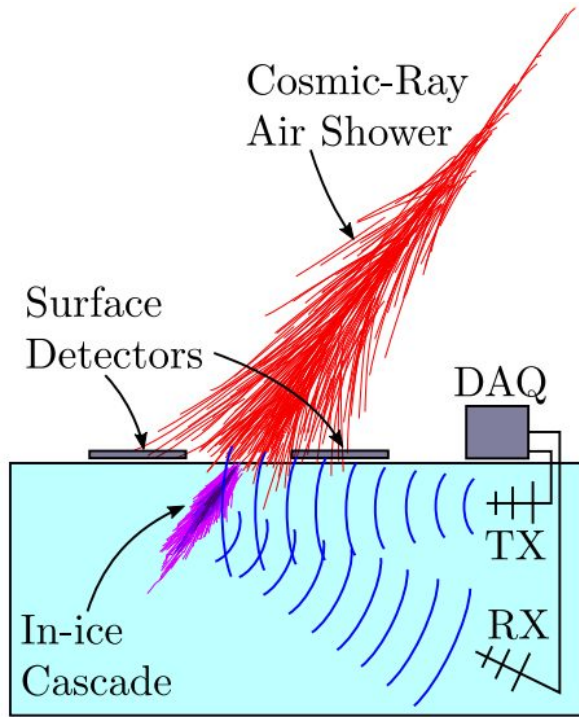
# Using cosmic rays

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



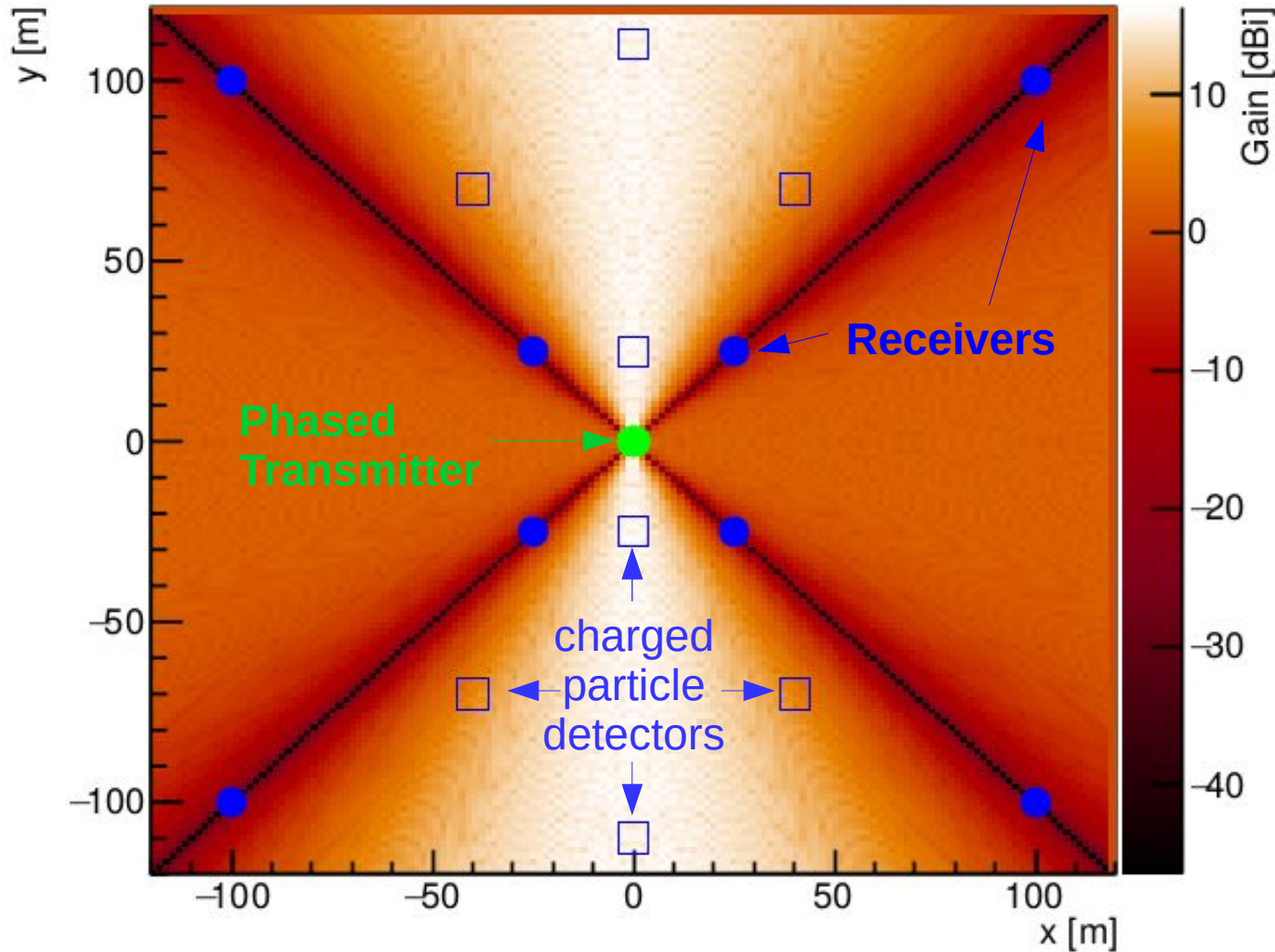
In-nature test beam: cosmic rays *IN THE ICE!!*

NSF Collaborative Research Proposal submitted Dec. 2019, result imminent.

OSU-lead, PI: S. Prohira, CO-I: A. Connolly, J. Beatty. KU, CO-I: D. Besson)

Extensive support from IIHE-Vrije University Brussels via KD deVries et.al.

the  
**RADAR ECHO TELESCOPE**  
 for COSMIC RAYS



central phased array of 8 dipoles gives a peak gain of ~16dBi in two directions.

Illuminated region is ~45 degrees x 2 in width

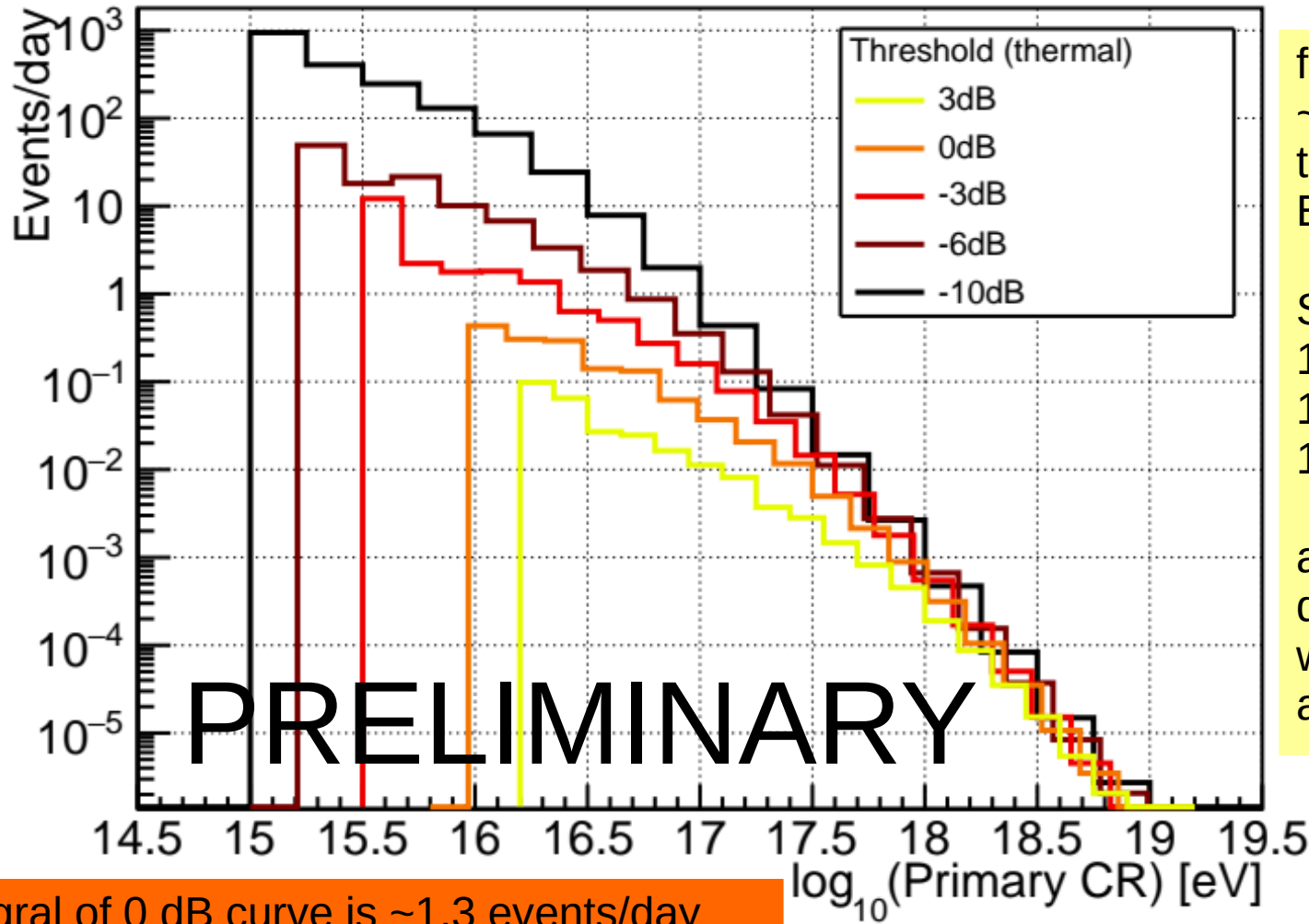
this configuration produces deep nulls along the diagonals, where receivers (blue dots) can go

blue squares are CR stations (being developed by K. Mulrey of Vrije University Brussels)

# Event rates-3 antenna coincidence

~1kW *radiated* power

$$\frac{dN}{dAdt} \sim \frac{1}{10^4 m^2 day} @10^{17} eV$$



for a 100m x 100m area,  
~1/day @10<sup>17</sup>eV. Then  
the flux is approximately  
E<sup>-3</sup>.

So flux:  
1000/day at @10<sup>16</sup>eV  
1/day @10<sup>17</sup>eV  
1/1000 days @10<sup>18</sup>eV

and our event rate  
depends upon how well  
we can detect cascades  
at lower energies.

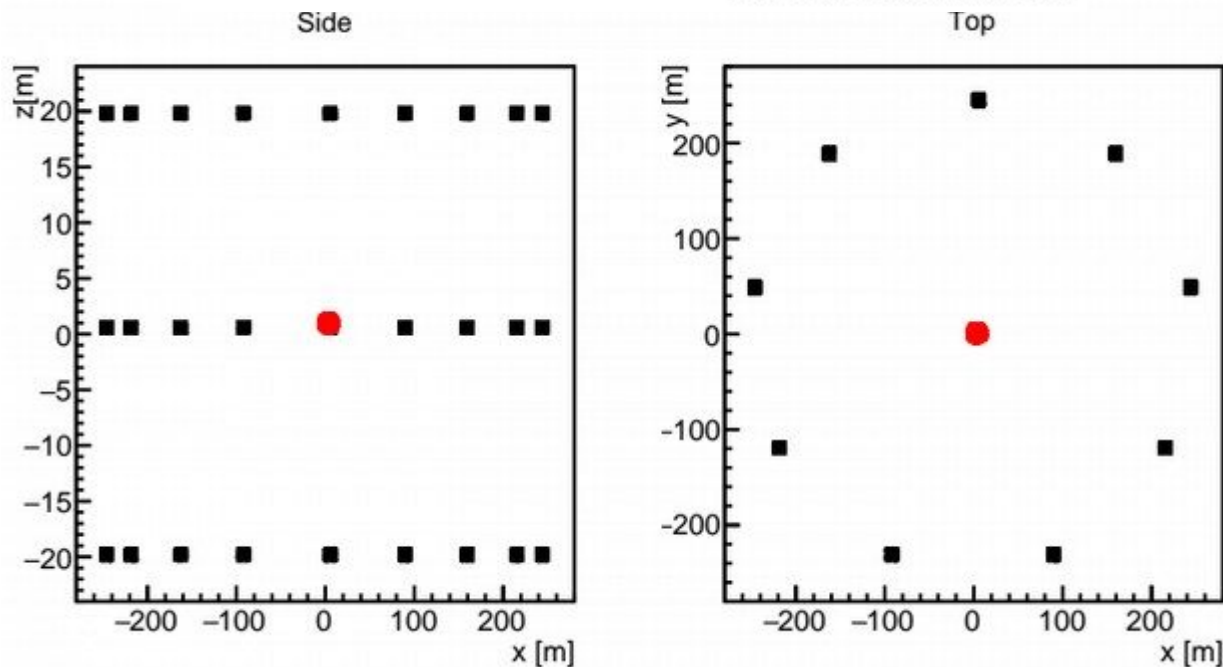
Integral of 0 dB curve is ~1.3 events/day

Integral of -3 dB curve is ~20 events/day

# the RADAR ECHO TELESCOPE



for NEUTRINOS



potential station configuration.

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

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

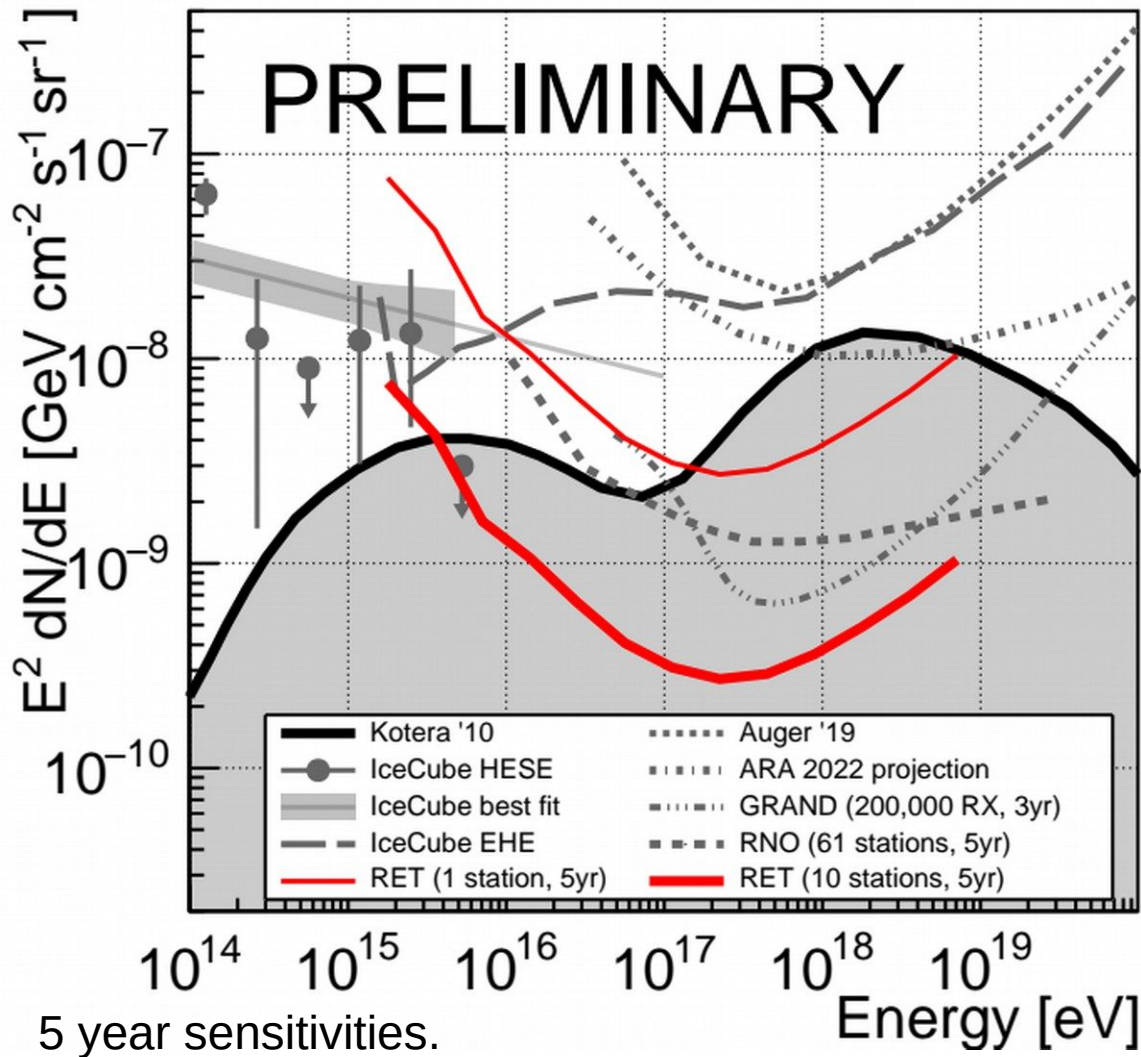
For the following sensitivity plot, this represents **1 station**:

- 1 transmitter @ 40 kW (same power as TARA experiment arXiv:1405.0057 )
- 27 receivers on radial 'spokes'
- spacing optimized to target lower energy cascades
- longer TX-RX baselines = higher energy primary, shorter = lower.



# RET-N projected sensitivity

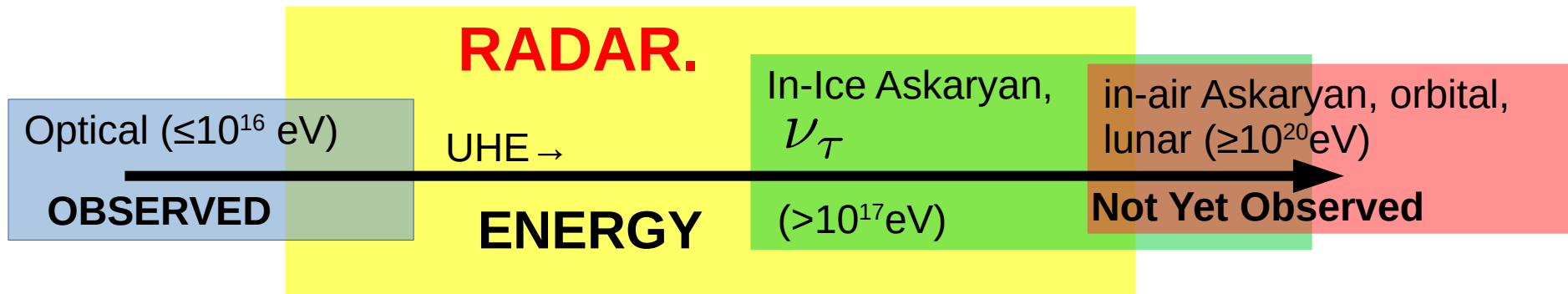
RET: 1 station = 1 TX, 27 RX



- Sensitivity here for the station as defined on previous slide.
  - assumes triggering at 0dB SNR
    - 0dbSNR triggers are practical for radar systems, see: [arXiv:1709.08587](https://arxiv.org/abs/1709.08587)
  - for comparison are various other experimental limits/detections
  - a single station is competitive with existing and projected limits at 100PeV, and directly probes some flux models
- 
- optimization still in progress. looking into:
    - transmitter configurations
    - modulation routines for transmitted signal
    - receiver spacing/design
    - advanced trigger routines
  - all of which lower energy threshold



# The Big Picture



*Toward a comprehensive, complementary UHE neutrino detection program.*

# Thanks !



2 June 2020

Steven Prohira--SLAC FPD Seminar

