Coherent radar reflections from an electron beam induced particle cascade: Toward radar-based UHE neutrino detection

S. Prohira, K.D. de Vries, P. Allison, J. Beatty, D. Besson, A. Connolly, N. van Eijndhoven, C. Hast, C.-Y Kuo, U.A. Latif, T. Meures, J. Nam, A. Nozdrina, J. Ralston, Z. Riesen, D. Saltzberg, C. Sbrocco, J. Torres, S. Toscano, S. Wissel, X. Zuo

(T-576)

31 July 2019

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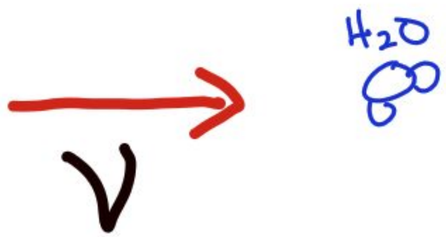
Background:particle cascades overview

- **When a high energy (>10^{16} eV) particle interacts in a dense medium (like ice), it will create a cascade of secondaries O(1-10 m) in length**
- **these secondaries will *ionize* the material, leaving behind a dense, short-lived cloud of charge**



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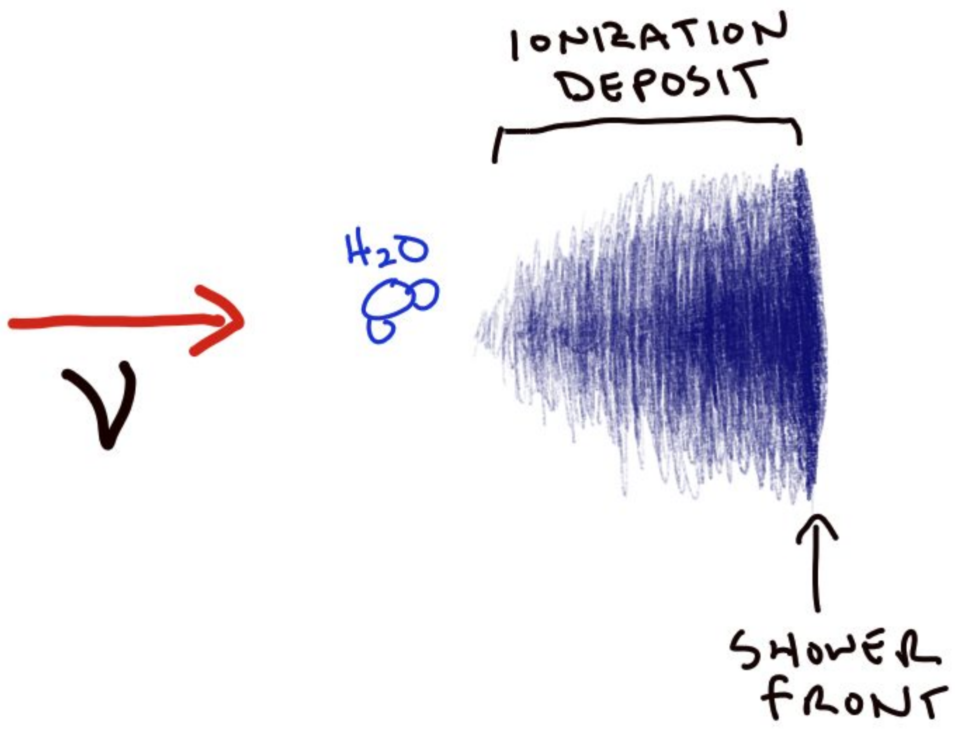

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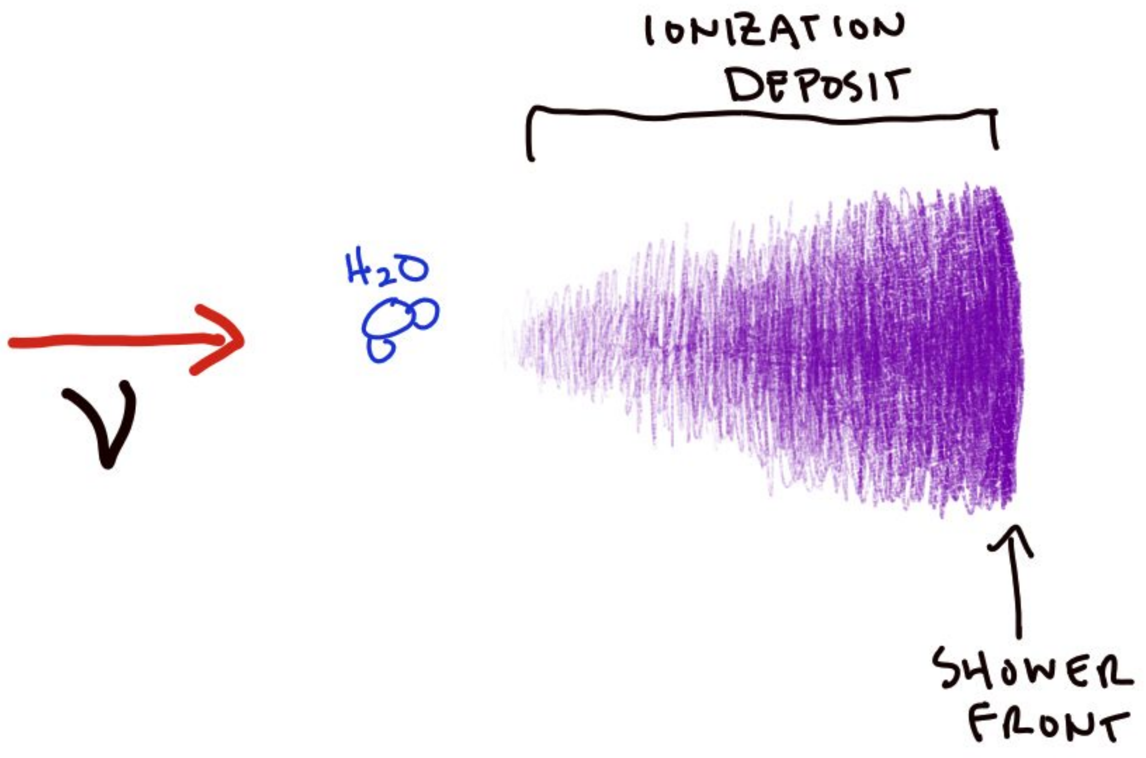

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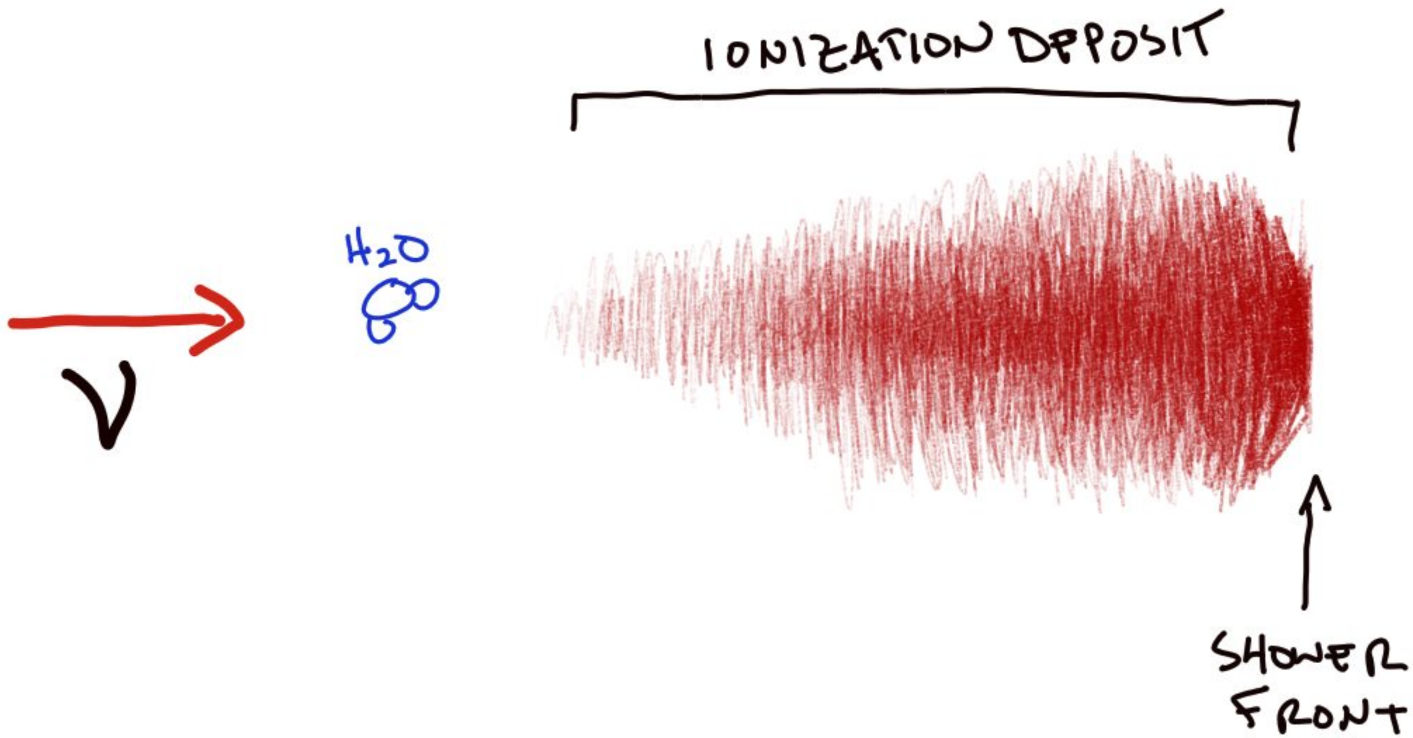
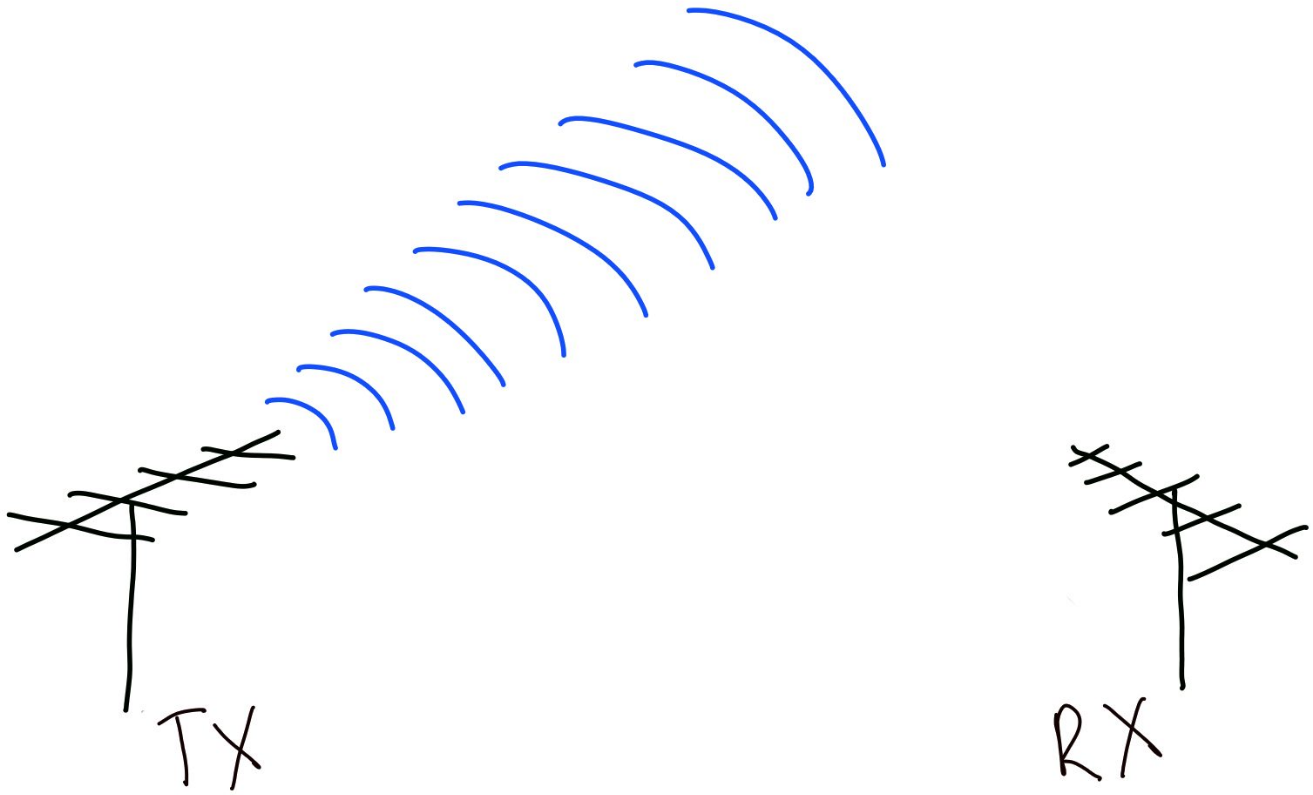
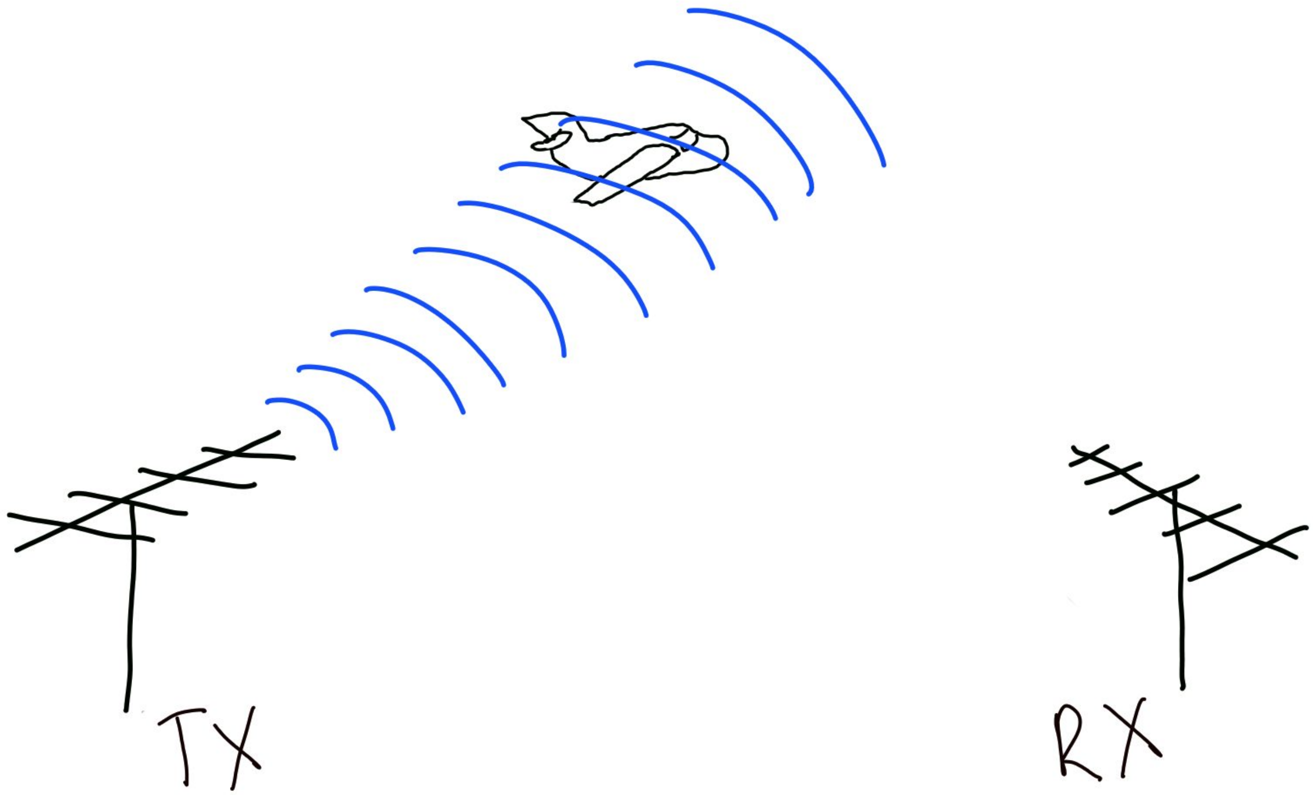


Background: radar overview



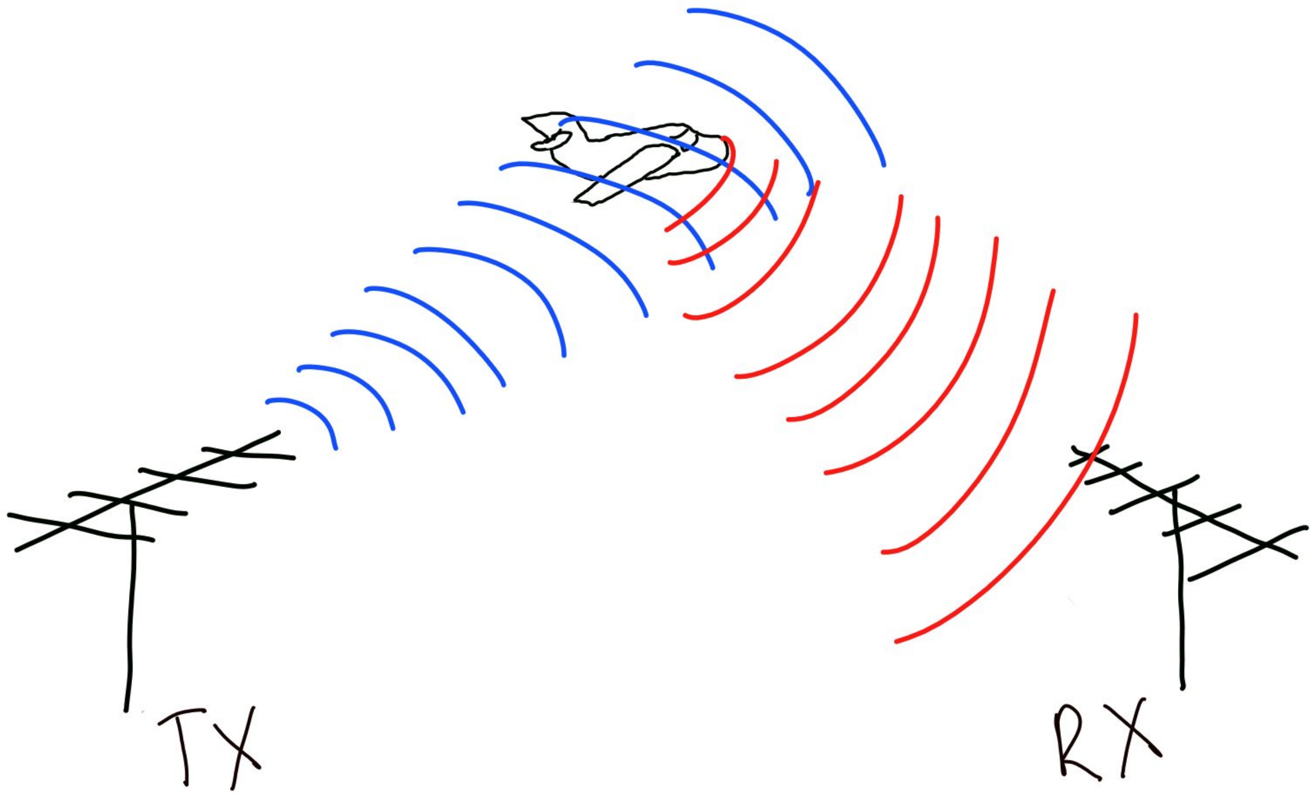
- **Transmitter (TX) broadcasts a radio signal into a volume**
- **receiver(s)(RX) monitor this same volume**

Background: radar overview



- Transmitter (TX) broadasts 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)

Background: radar overview



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Motivation: UHE neutrino detection

Questions:

1) Can we use the radar method to detect the cascades from UHE neutrino interactions in the ice?*

2) If so, what is the projected sensitivity?

*some of you may remeber that Telescope Array RAdar (TARA)[Belz, Besson et.al] tried this to detect in-air cosmic ray showers. plasma density too low in air! (attachment/collision rate too high) 10.1016/j.astropartphys.2016.11.006

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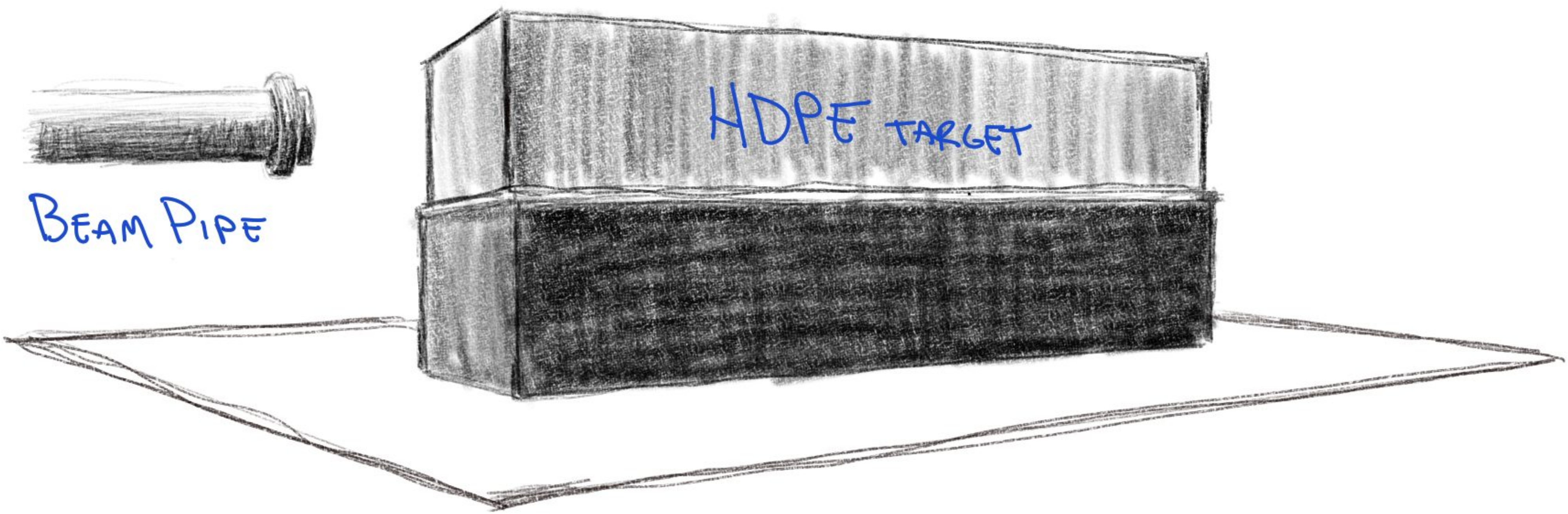
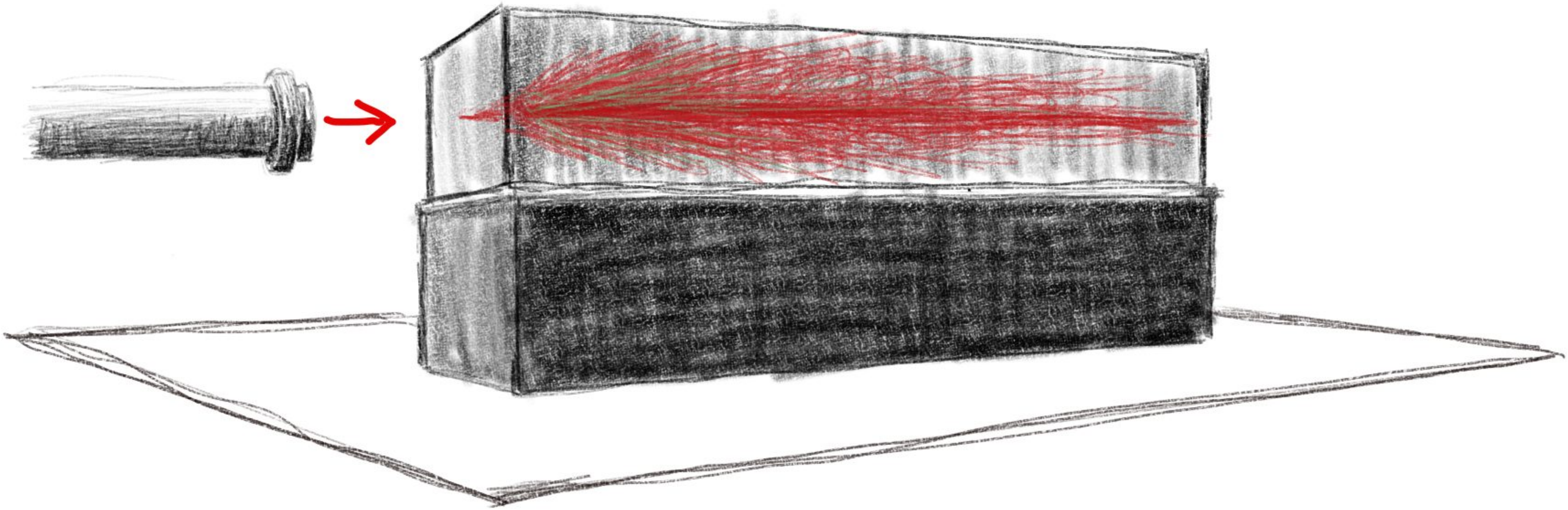
SLAC T-576



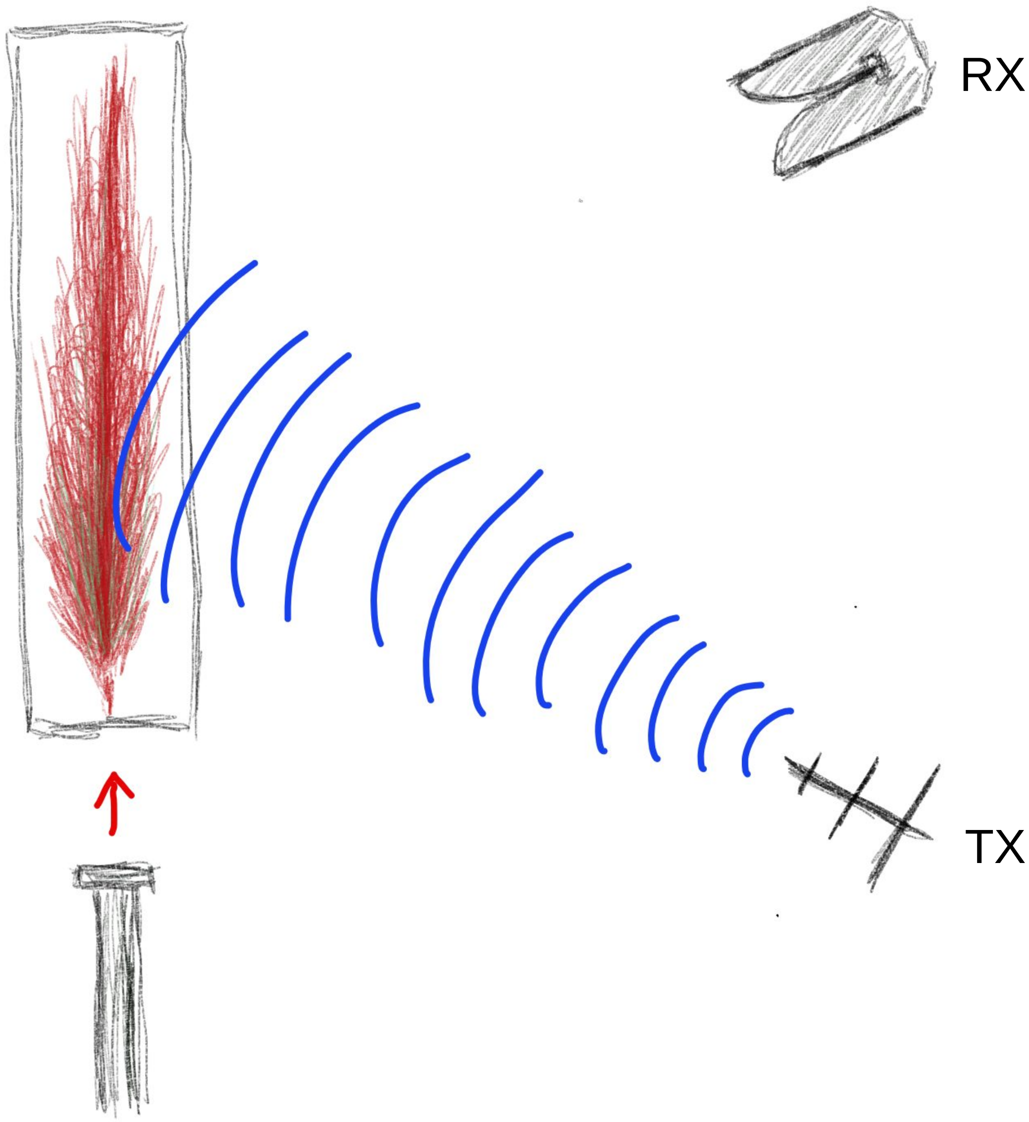
- At End Station A at SLAC, users had access to the full beam (~10^9 e^- @ 10GeV/e^-)
- We directed this beam into a target of high-density polyethylene (HDPE)
- beam: ~ 10^{19} eV neutrino
- target: ~ice (n=1.51, density comparable to ice, 11eV first ionization)

SLAC T-576



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

SLAC T-576



- We interrogate the target with radio

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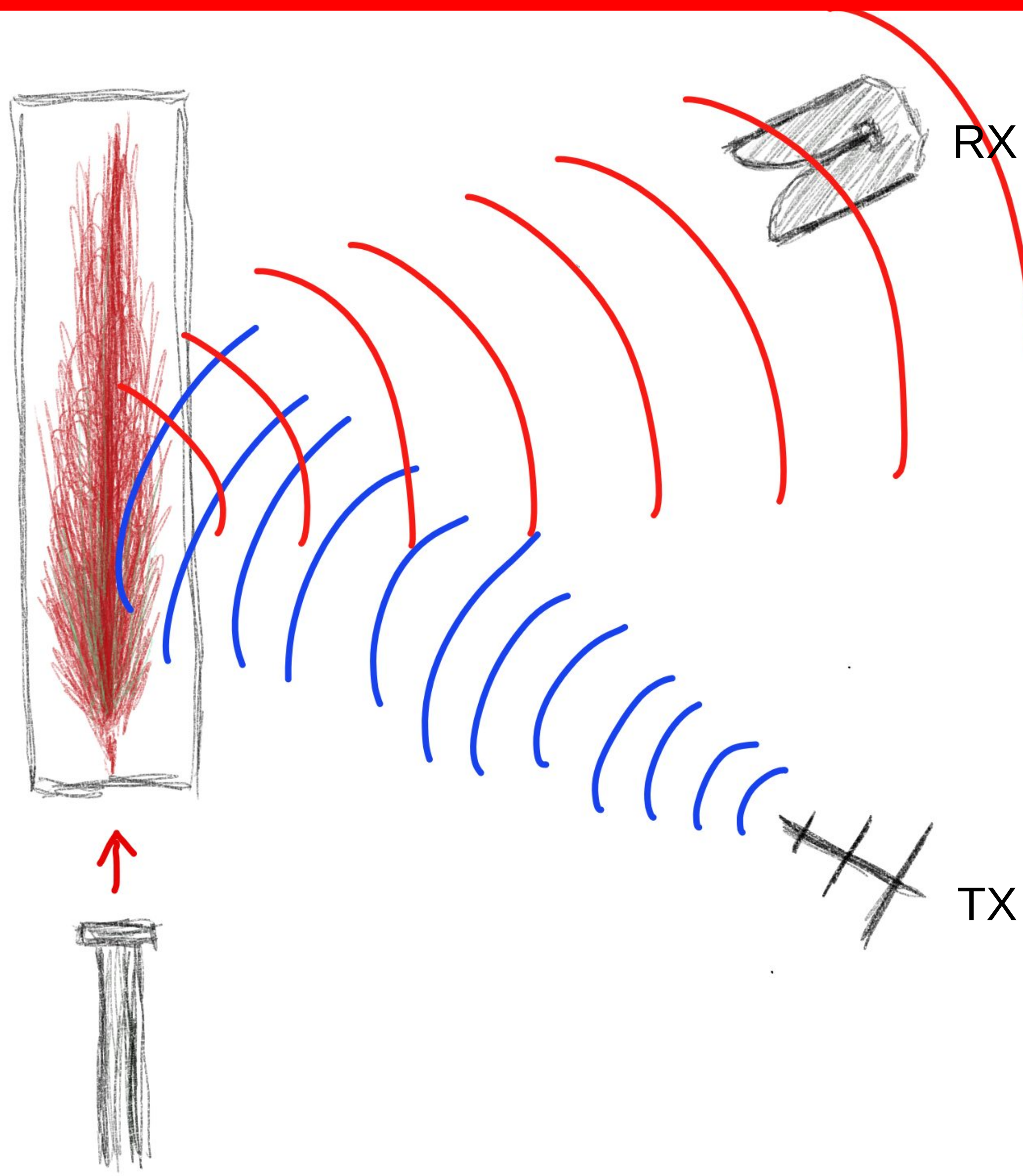


- the ionization cloud of the shower reflects the transmitted signal to the receivers

SLAC T-576

SLAC NATIONAL ACCELERATOR LABORATORY

Experiment T576 at SLAC:

use a HDPE target as a proxy for ice,
N ~ 10^9 e @ 10^9 eV beam as proxy for
1 EeV neutrino.

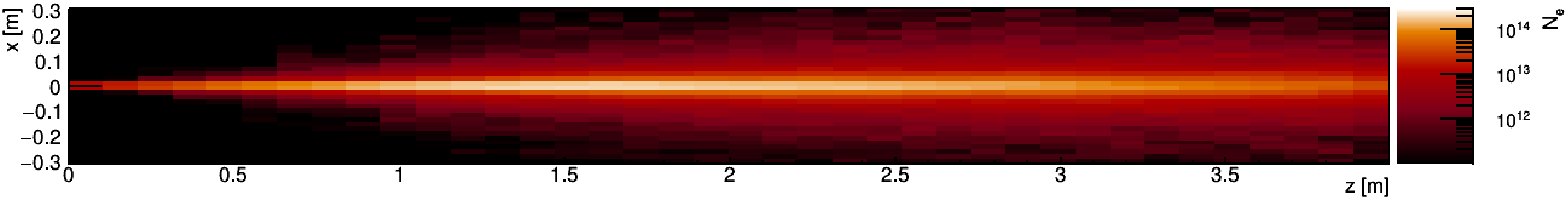
results from first run (May 2018) are out.
results from second run (Oct-Nov 2018) in this talk.

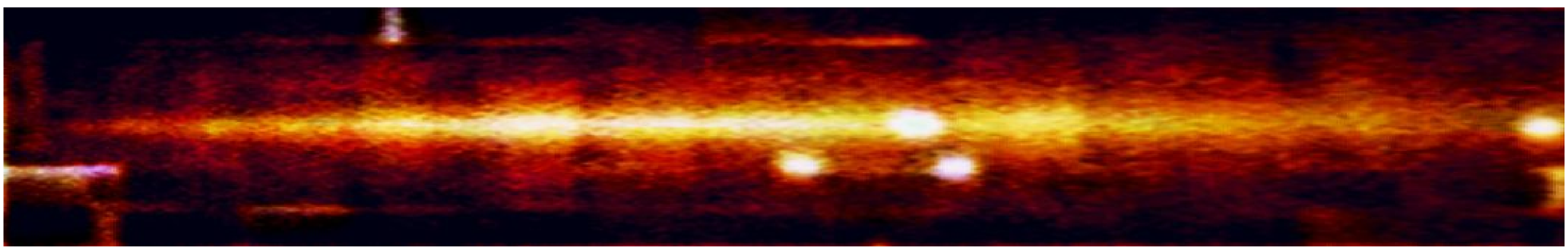
arXiv:1810.09914, subm. to PRD

Suggestion of Coherent Radio Reflections from an Electron-Beam Induced Particle Cascade

S Prohira[1,2], K. D. de Vries[3], D. Besson[4,9], A. Connolly[1,2], C. Hast[5], U. Latif[4], T. Meures[6], J.P. Ralston[4], Z. Riesen[7], D. Saltzberg[8], J. Torres[1], S. Wissel[7], and X. Zuo[8]

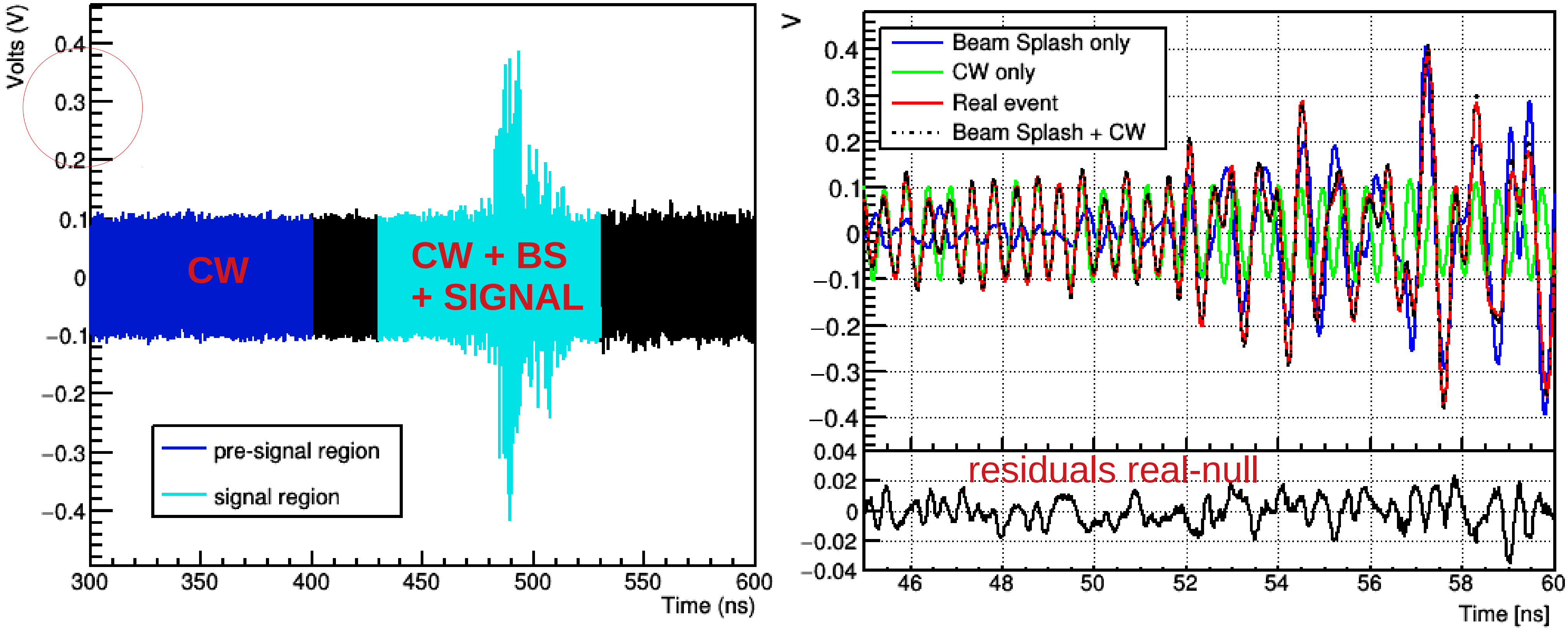
beam profile





- top: simulated ionization deposit from GEANT4
- bottom: false-color image of the target, after the T576 run, where 'burn marks' in the target are visible
  - hot 'dots' are burn marks made during other uses of the target.
- very nice visual confirmation of energy deposition within the target

Raw Data -> Null Data



- continuous-wave (CW) RF was used to interrogate the shower
- the primary RF noise from the beam (transition radiation, reflections, ***neither of which would be present in nature,*** plus beamed Askaryan) we call the 'beam splash' (BS)
- produce 'null data' from a combination of pre-signal region CW and transmitter-off beam splash
- train analysis on 'null data' which serves as our null hypothesis

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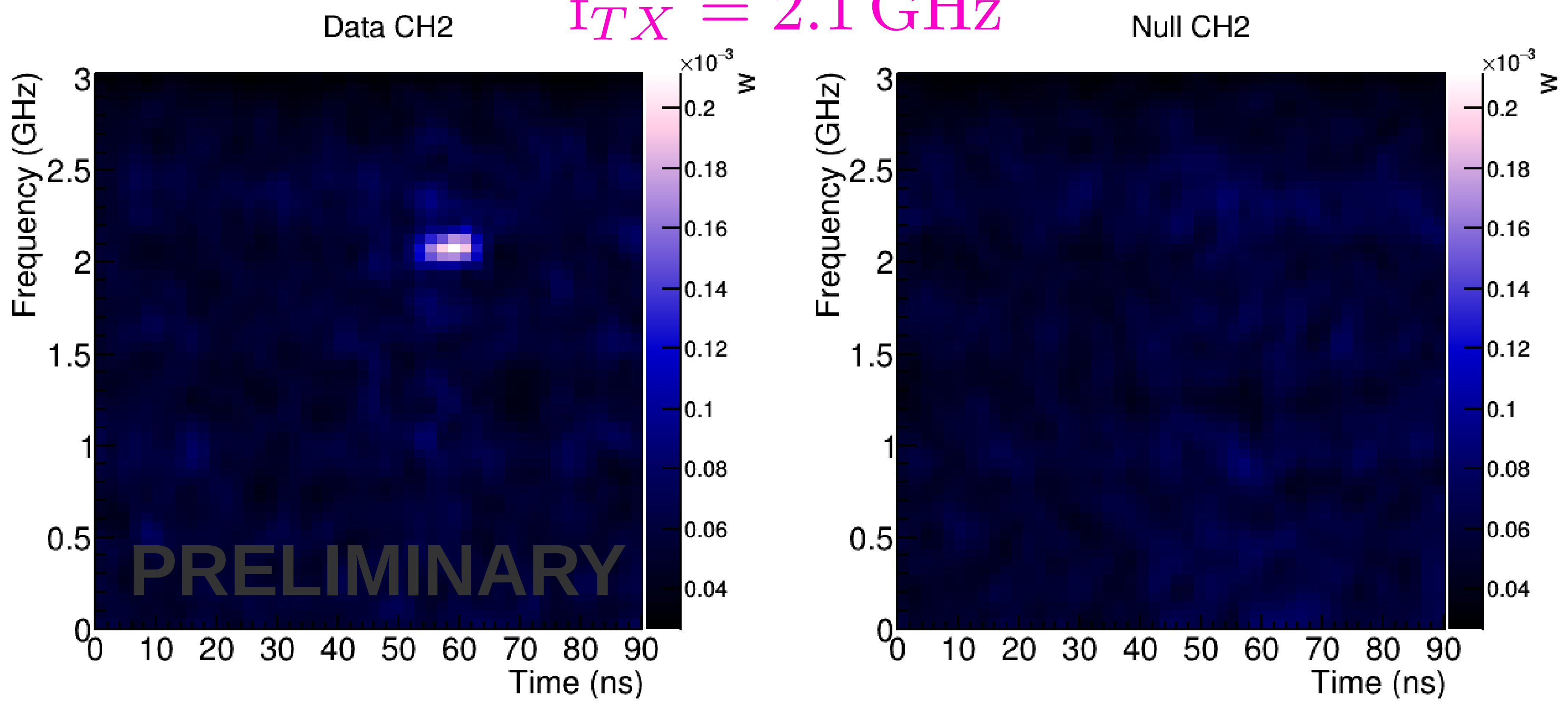
Observation of signal

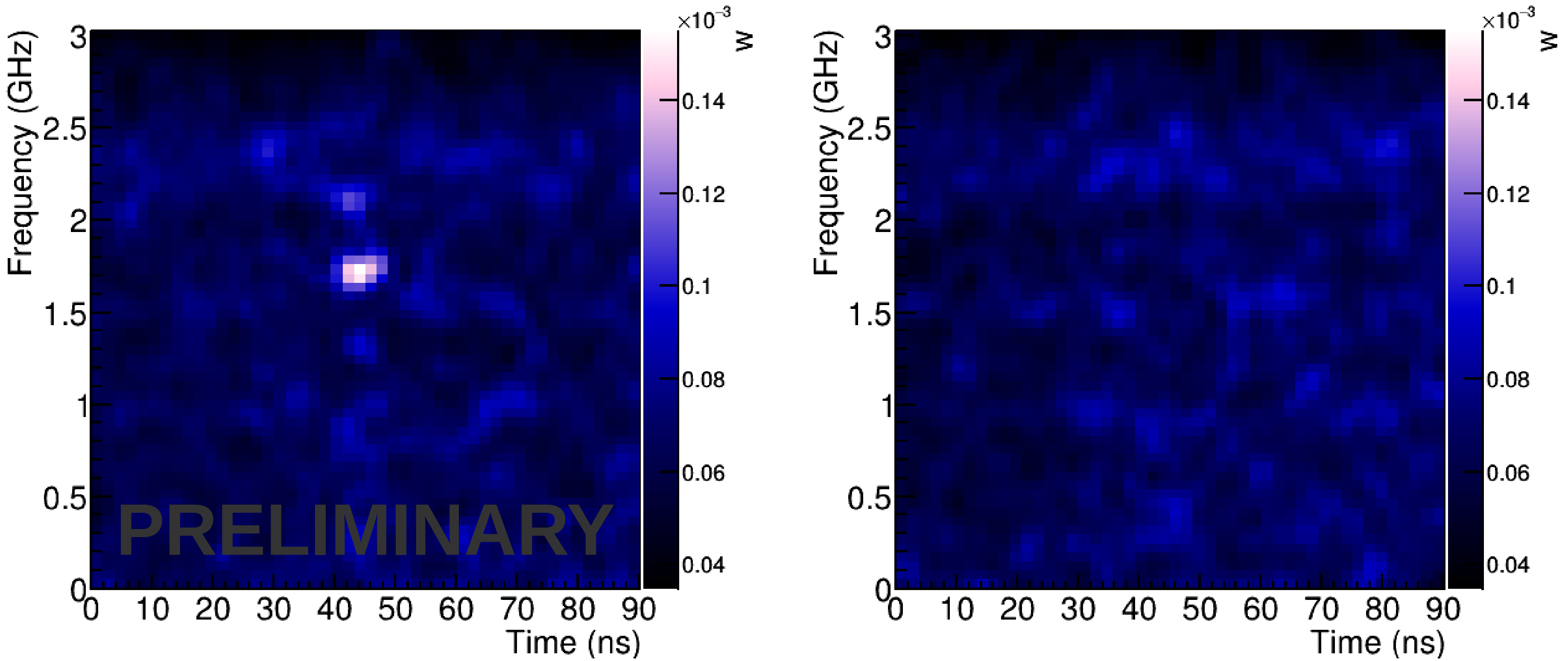
$f_{TX} = 2.1\,\text{GHz}$



- After employing a *blind* matrix-decomposition-based analysis technique, an excess was observed over the null data (analysis details ACAT2019 proceedings, out soon IOP conf.ser.)
- this configuration-horizontal polarization, 1GHz high-pass filter, LPDA dish style antenna
- average spectrogram of 200 events at one configuration
- observed at multiple frequencies in multiple antennas/channels

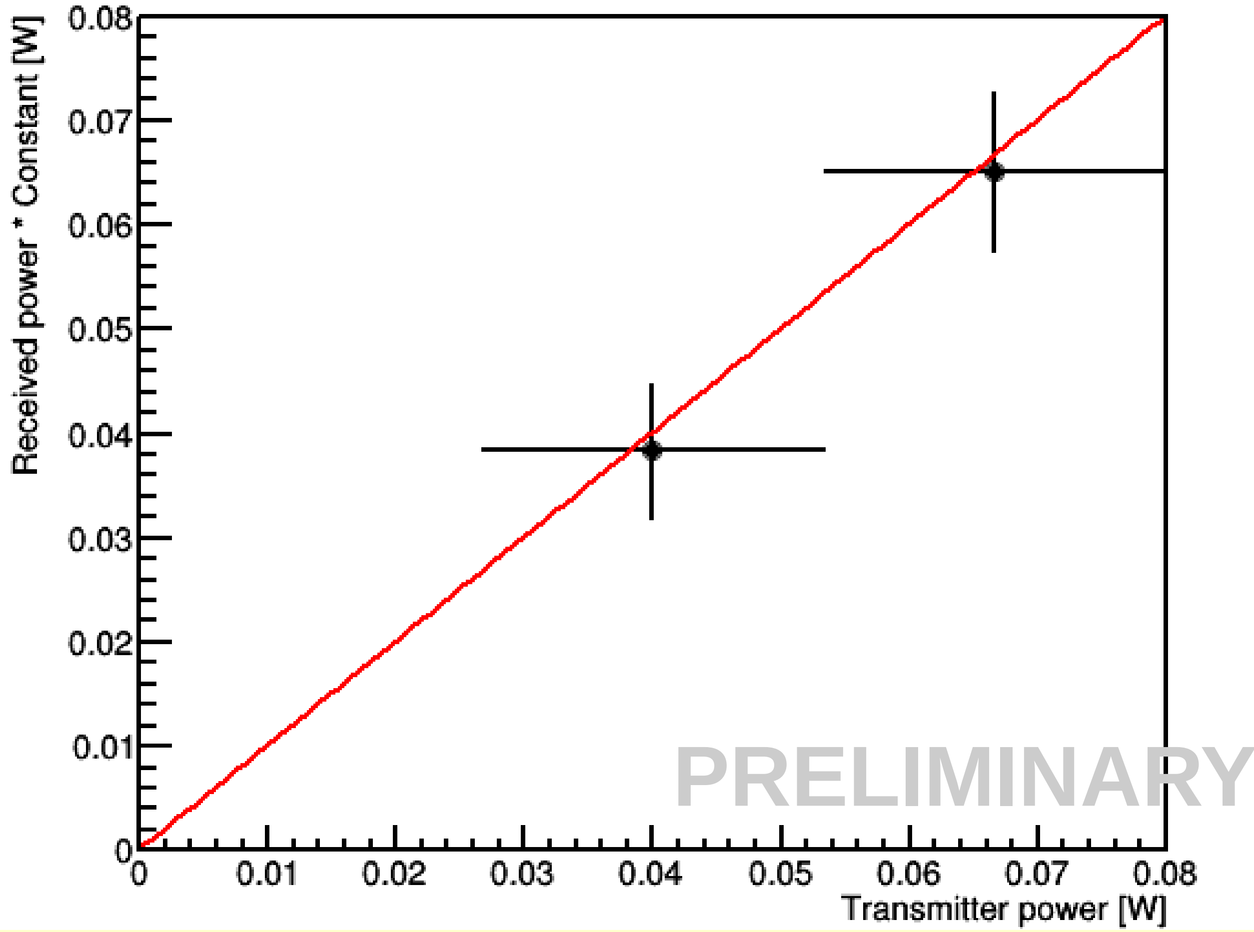
Observation of signal

$\mathrm{f}_{TX} = 1.75\,\mathrm{GHz}$



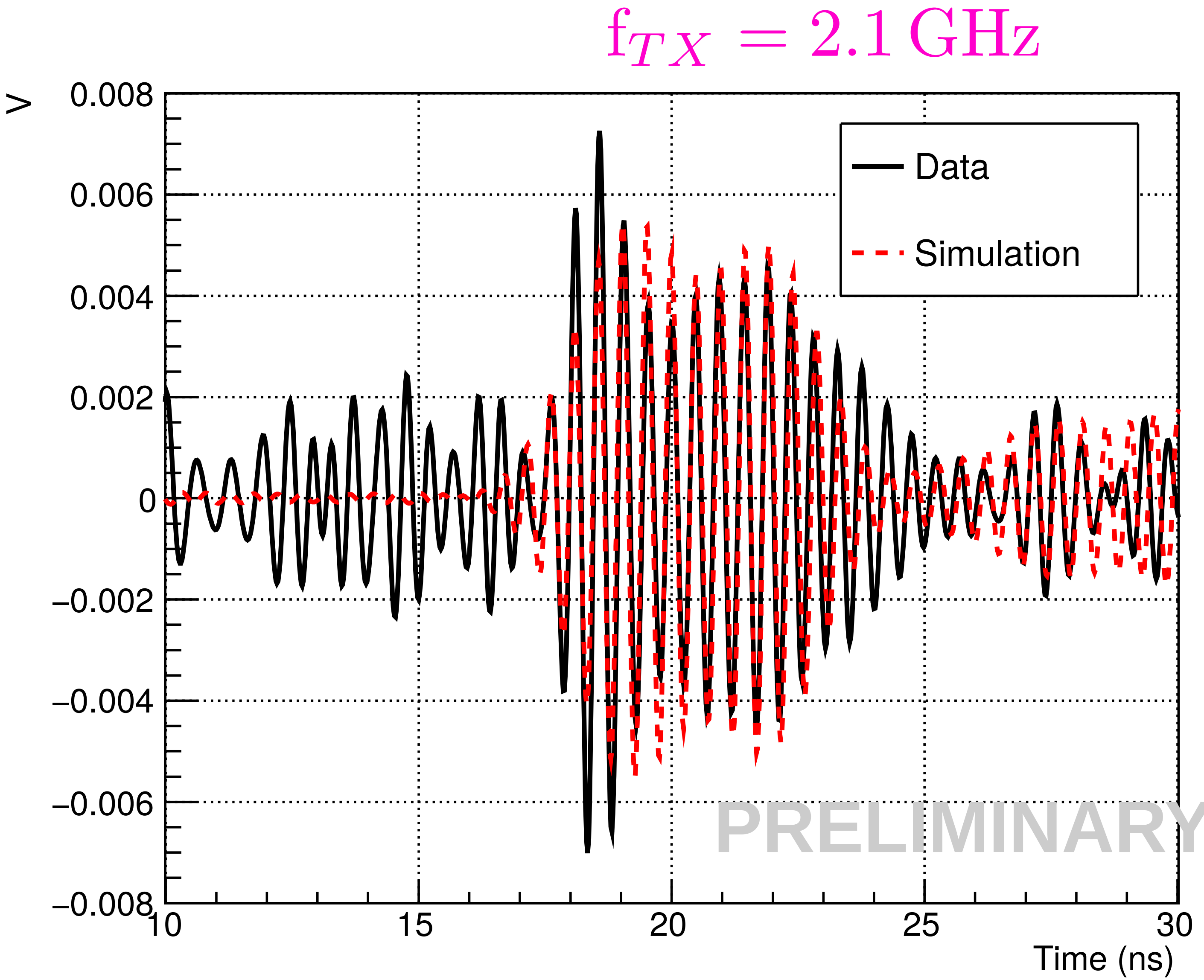
- **visible in multiple channels, in multiple antennas, and at multiple frequencies**
- **vivaldi-style antenna**
- ***but is it radar?***

power scaling



- **received signal power scales with transmitted power**
- **took data at many output power settings–unfortunately, data from this sub–run was corrupted.**
- **We show here one clear instance of scaling at two output power levels**

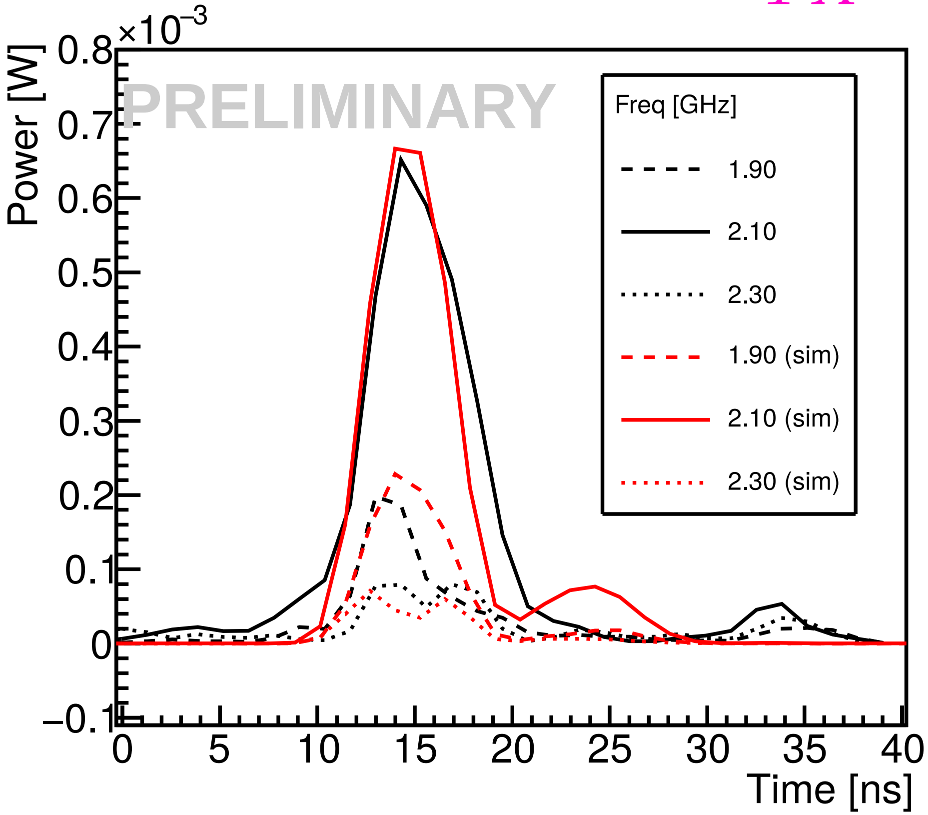
comparison to simulation

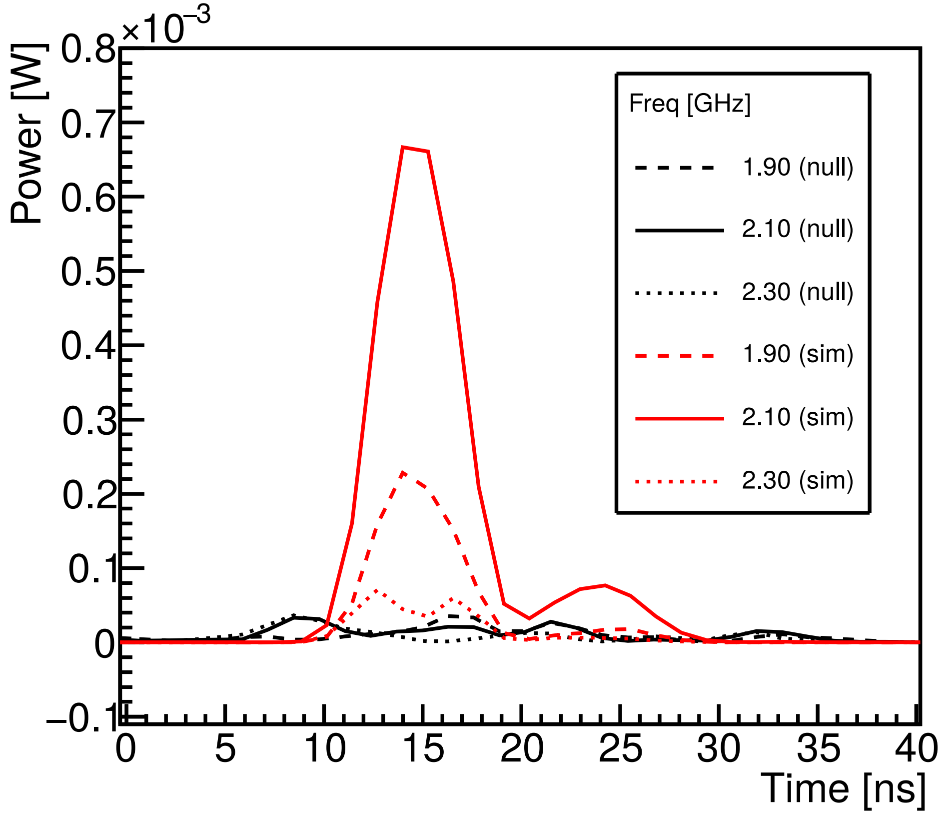


- comparison of high-SNR signal average to FDTD simulation.
  - simulation is scaled up by +2dB
- in this simulation, GEANT4 profile of the time-dependent ionization was used with a 1ns ionization lifetime
- includes realistic antenna models, and HDPE target
- double-peak structure indication of reflections within the target

comparison to simulation

Data $\mathrm{f}_{TX} = 2.1\,\mathrm{GHz}$ Null





- comparison of spectral content of high-SNR average to FDTD simulation
  - FDTD signal has been scaled by +2dB
- averaged via cross-correlation of signals very near to level of noise: subject to possible sub-ns mis-alignments in the average
- line styles are same frequency for data/null and simulation

Motivation: UHE neutrino detection

Questions:

1) Can we use the radar method to detect the cascades from UHE neutrino interactions in the ice?

We observe a signal consistent with a radar reflection from a plasma produced by a high energy cascade.
Assuming the electron beam + HDPE target is a good proxy for a neutrino, things are looking promising.

2) If so, what is the projected sensitivity?

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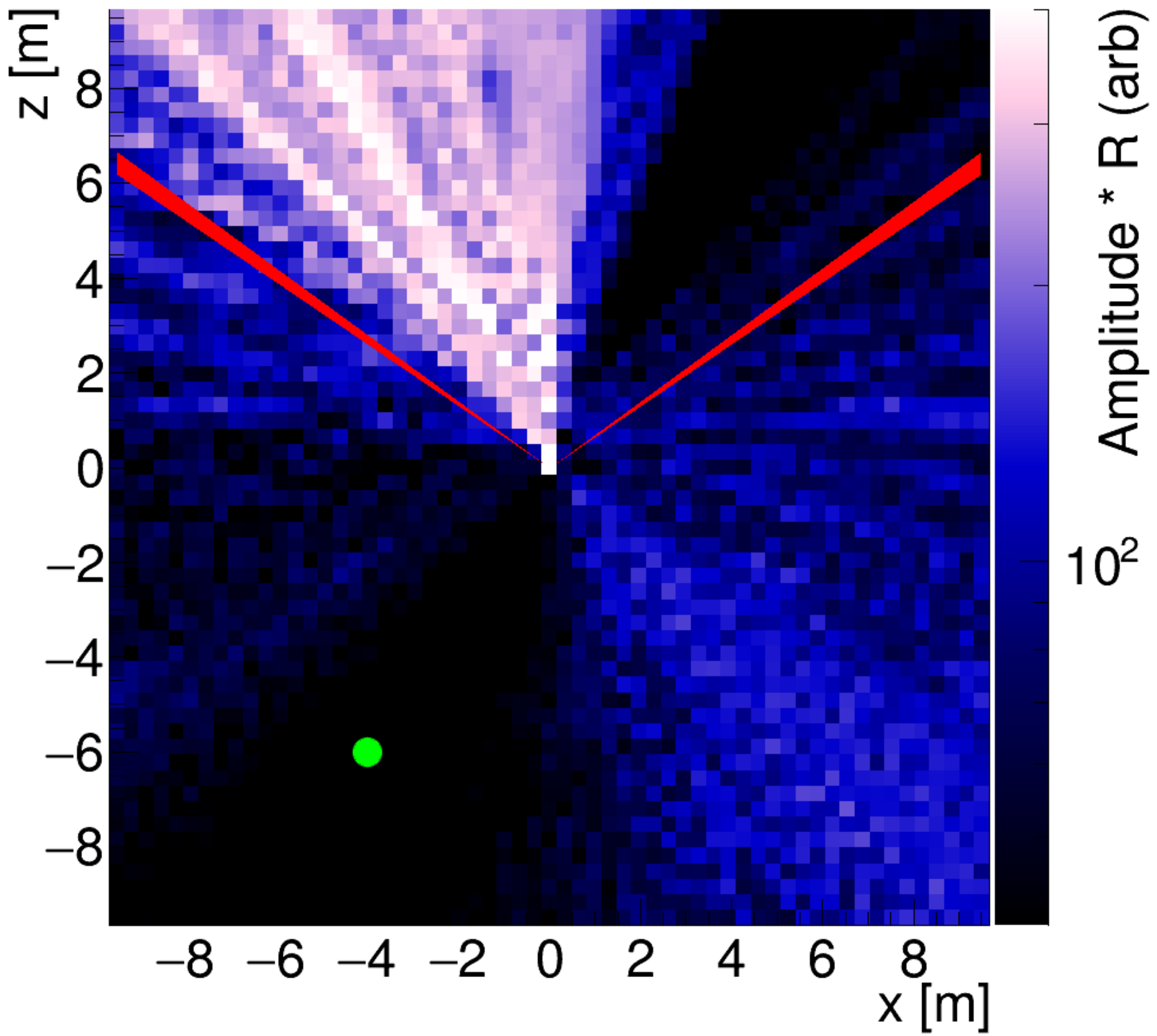
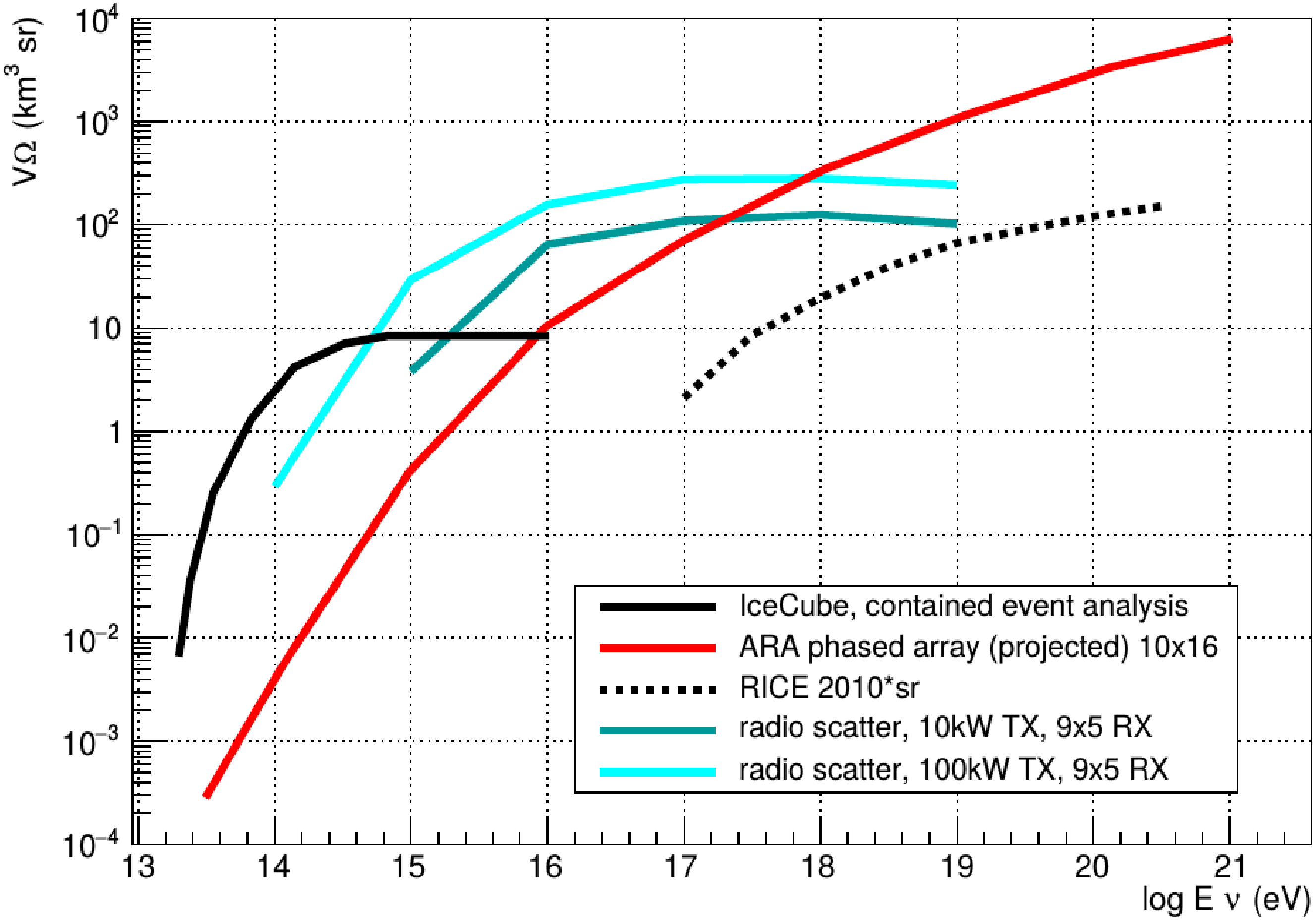
geometric acceptance



- huge increase in aperture compared to current radio strategies
  - Askaryan emission is highly beamed on a thin cone (solid red)
- heatmap of receiver amplitudes with shower at 0,0
- green is TX

what is the sensitivity?



10.1016/j.nima.2018.12.027

For radio, effective volume is the volume of the area to which your receivers are sensitive.

simulations show radar is competitive with icecube above 1PeV, and better than any existing tech up to ~1EeV

made using a 1ns plasma lifetime. Conservative estimate based on these results!

this is for a single 10kW (effective radiated power [beamed] not power consumption) transmitter and 9 strings. could be optimized for multiple, lower-power transmitter (typical FM radio station O(100kW))

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2) If so, what is the projected sensitivity?

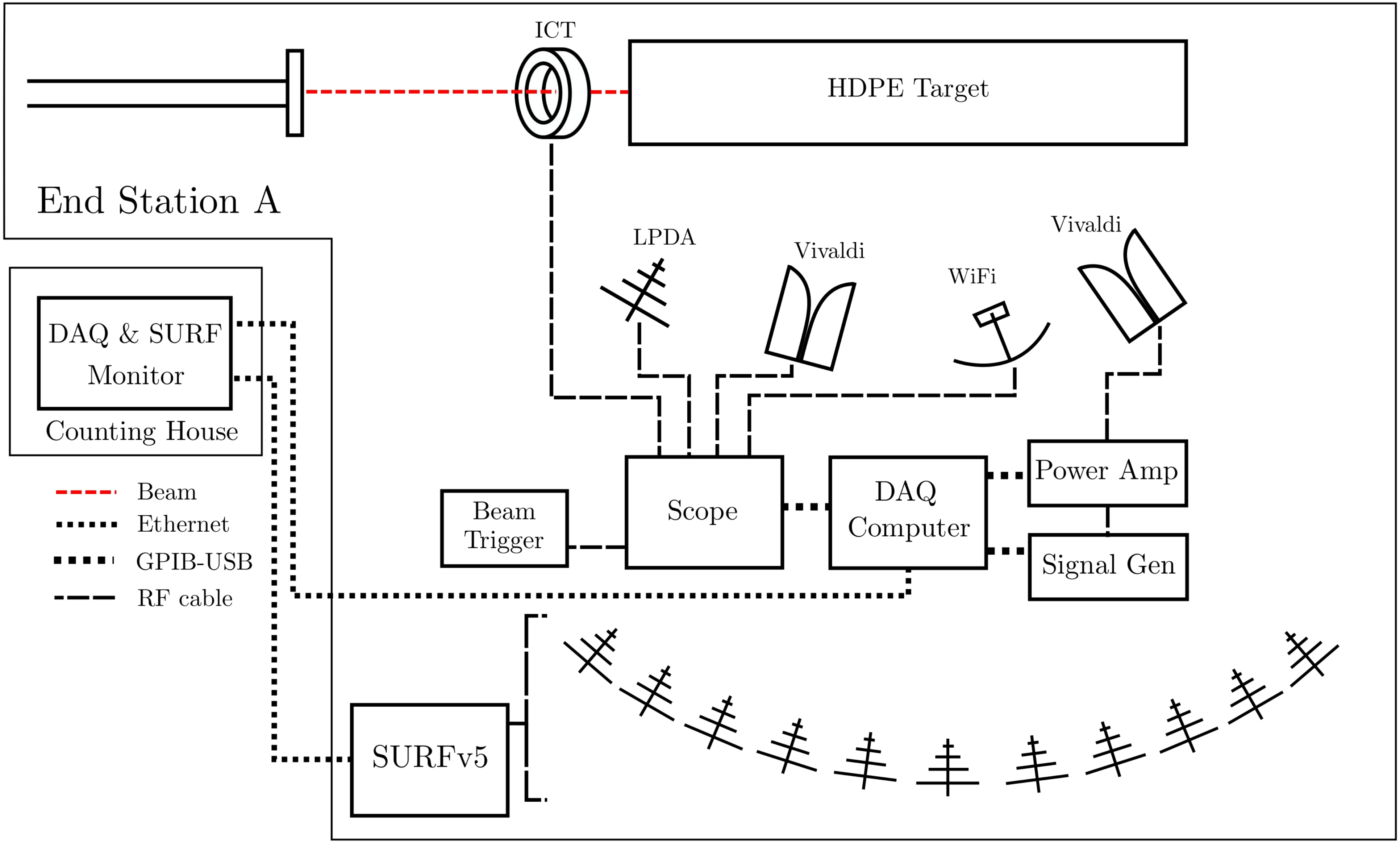
Competitive with IceCube at PeV energies, better than any other method at PeV<E<EeV, largely due to geometric acceptance

conclusions

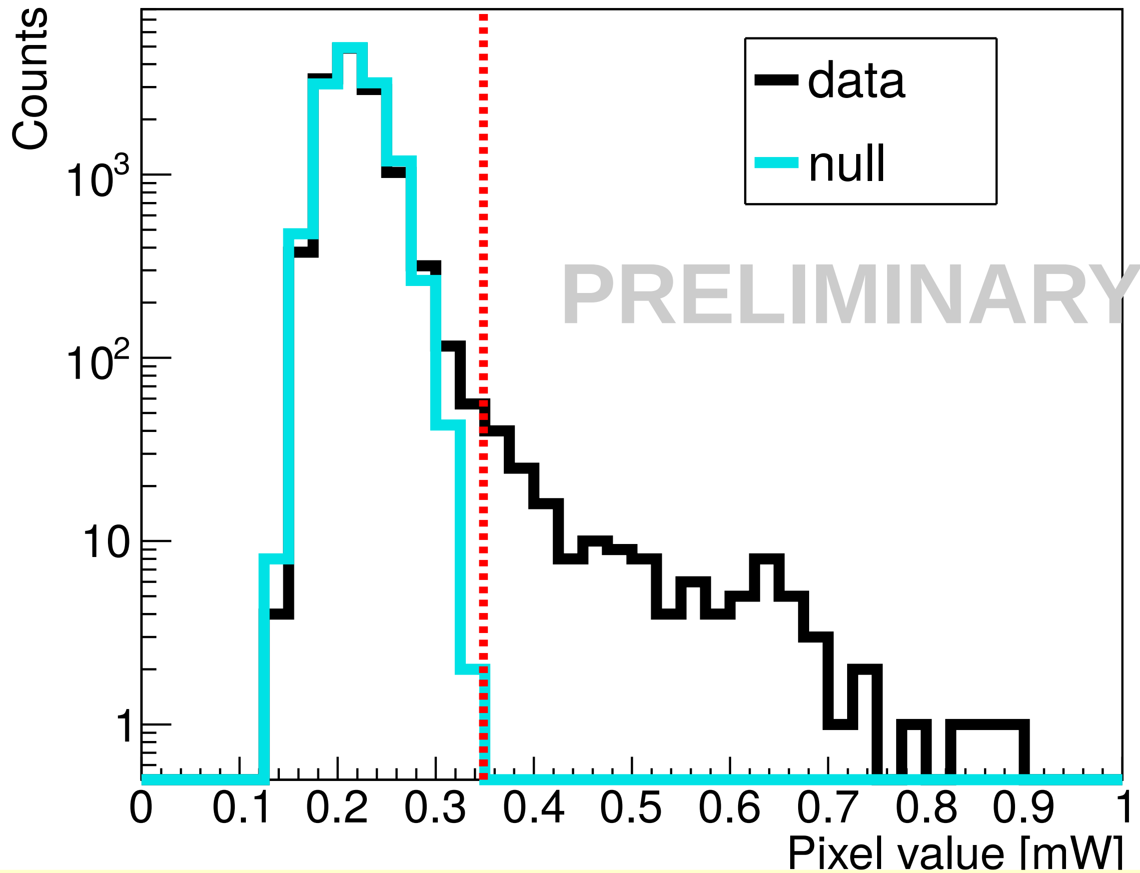
- **SLAC T-576 ran in 2018 to measure radar reflections from a particle shower**
- **We observe a signal consistent with a radar reflection from plasma produced by a high energy particle cascade**
  - **power scaling with transmitter power is observed**
  - **good agreement with simulation in time**
  - **good agreement with simulation in spectral content**
- **projected sensitivity to UHE neutrino detection is best among existing methods for PeV<E<EeV**
- **next steps:**
  - **Analyze the data taken by a second DAQ, and further analyze these data here**
  - **investigate a next test on an in-nature signal**
- ***compelling evidence for a new method for ultra-high-energy neutrino detection!***

backup

SLAC T-576


ICT
HDPE Target
End Station A
LPDA
Vivaldi
WiFi
Vivaldi
DAQ & SURF
Monitor
Counting House
Beam
Ethernet
GPIB-USB
RF cable
Beam
Trigger
Scope
DAQ
Computer
Power Amp
Signal Gen
SURFv5

Observation of signal

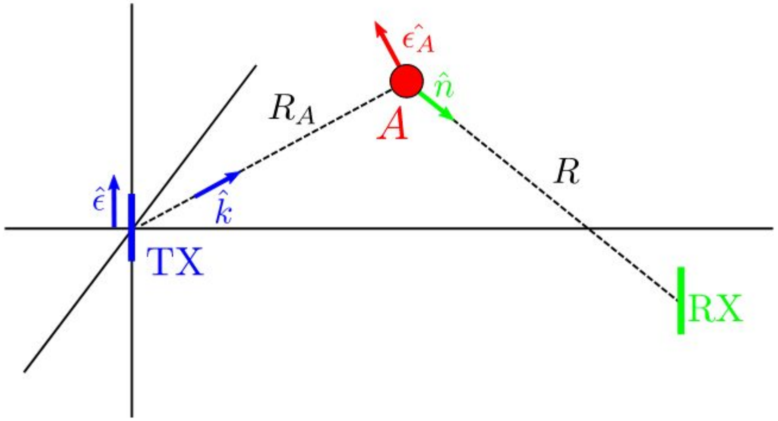


- **histogram of all pixel values between 1 and 2.5 GHz for the horizontal polarization, 2.1 GHz average spectrograms.**
- **red dashed line is 5 sigma of the null distribution histogram, showing a clear excess**
- ***but is it radar?***

“smoking guns”

- **Siulations show that many “smoking gun” signals that might separate signal from background turned to be very difficult to detect/not viable *in the beam test context***
  - **TX distance trending**
  - **RX distance trending**
  - **angular characterization**
- **for details, see forthcoming publication**

can it work?



Assuming transmitter (TX) broadcasting continuous-wave (CW), scattered field from a single electron (label A) is:

$$\mathbf{E_A} = \frac{\alpha E_I}{R} \hat{n} \times \hat{n} \times \hat{\epsilon_\mathbf{A}} \tag{1}$$

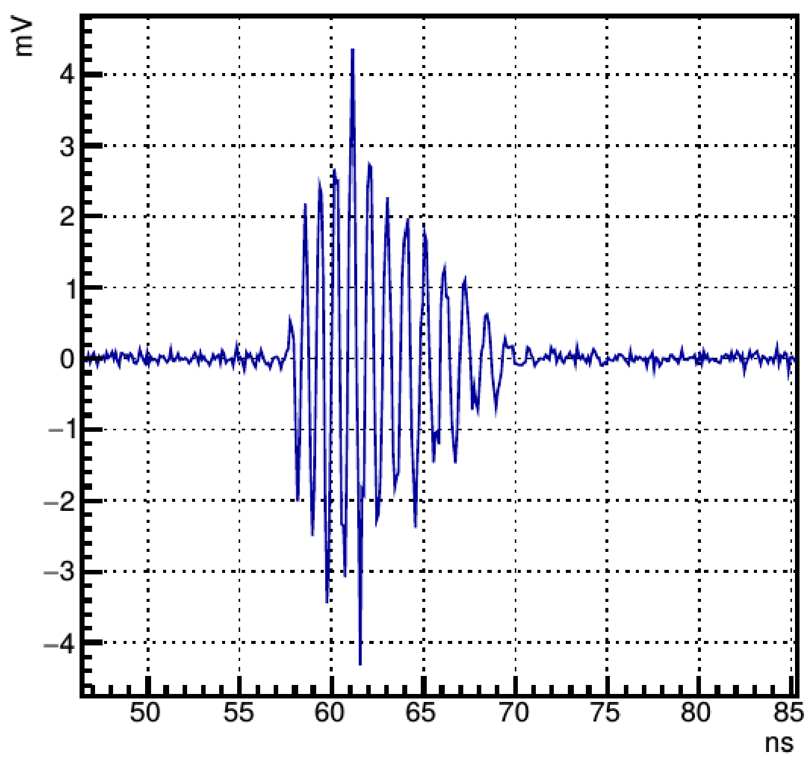
the vectors are simply for polarization, and E_I is the incient field, from the TX, at the electron A with all of the propagation through the medium and the plasma folded in. α is the reflection coefficient, with units of length,

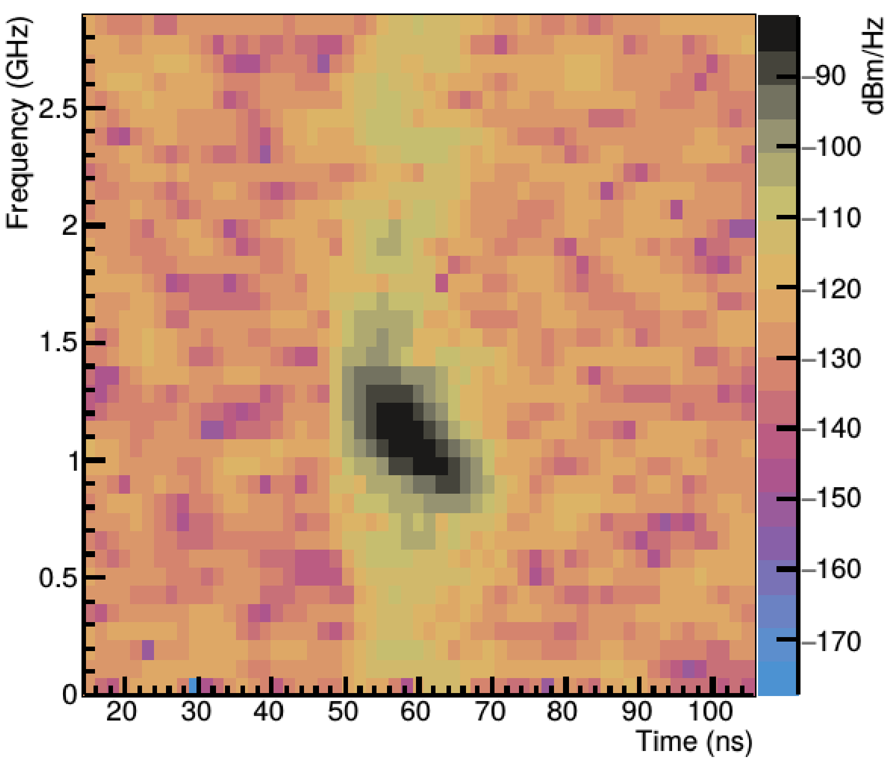
$$\alpha = \frac{q^2 \omega}{c^2 m(\omega + i\nu_c)} \tag{2}$$

can it work?

Then, summing over all the particles ($\mathbf{E_A}$ from last slide now indexed with n) in a shower gives:

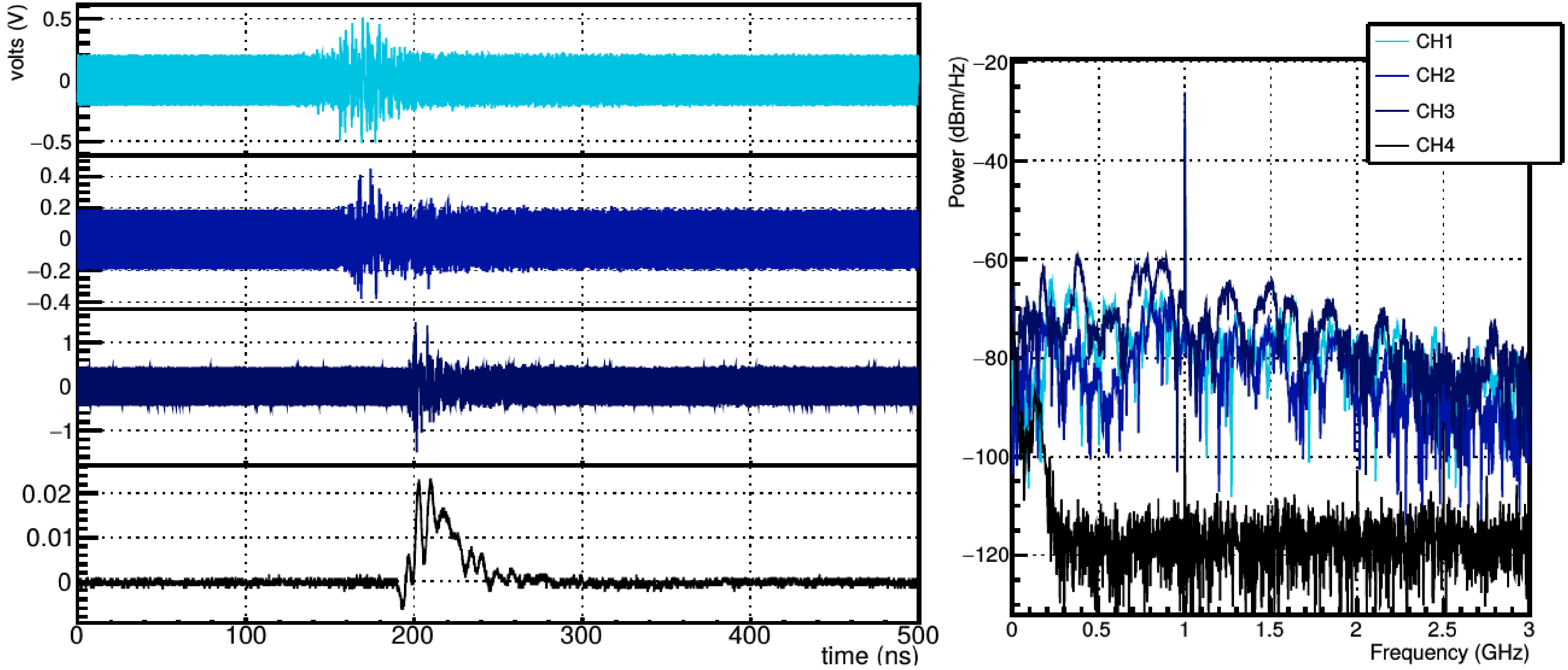
$$Re\left[\mathbf{E}_{tot}\right] = \frac{1}{T}\sum_{n=1}^{N}\int_{t}^{t+T}\Theta(t'-t_n^i)\Theta(t_n^f-t')Re\left[\mathbf{E}_n(t)\right]dt, \quad (1)$$



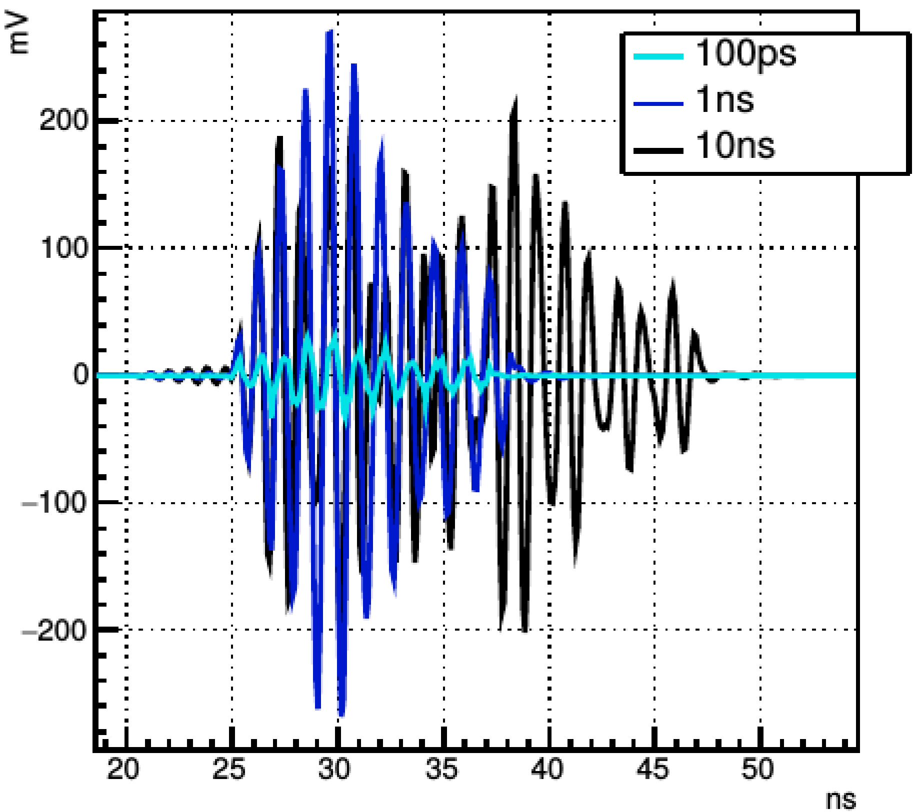


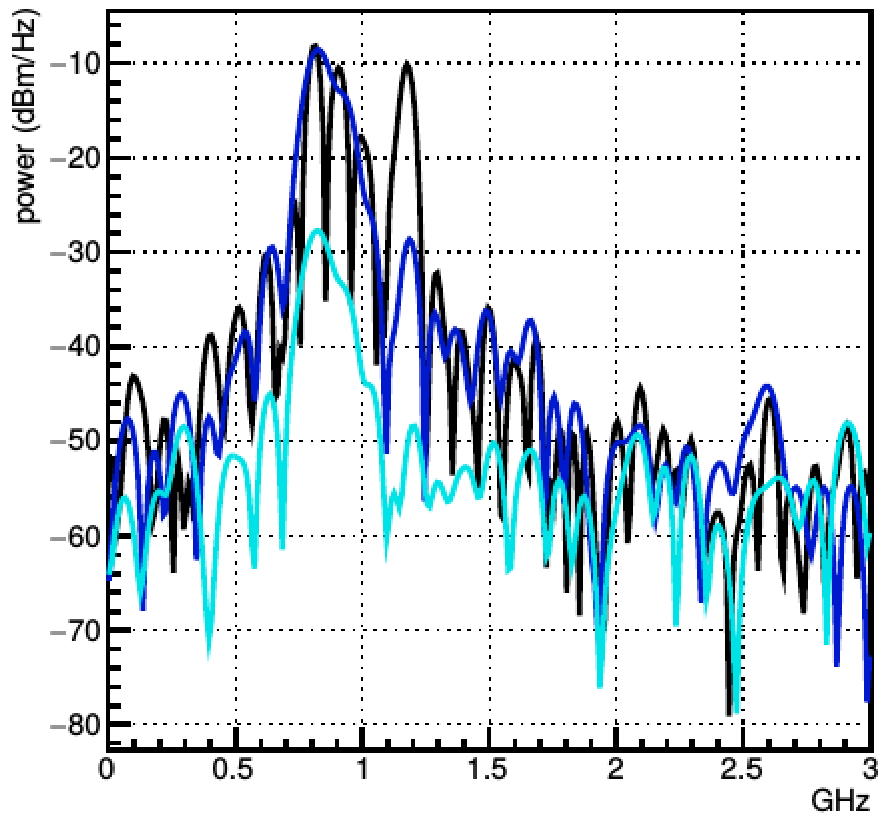
Simulation (RadioScatter arXiv:1710.02883) shows that things look pretty good...

raw data-run1



plasma lifetime

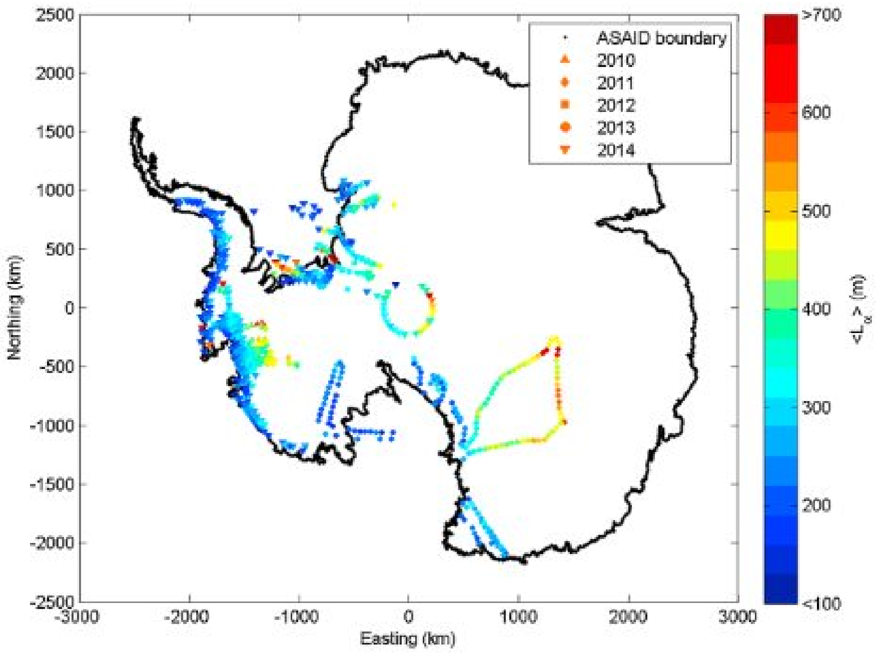


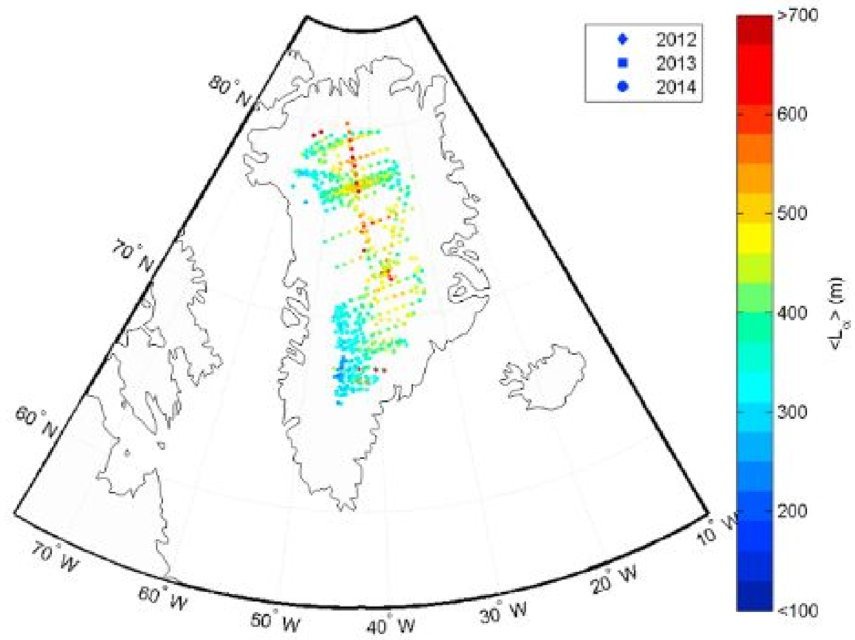


signals vary based on the free electron (plasma) lifetime.

simulation shows return signals for very short lifetimes.

attenuation length in ice

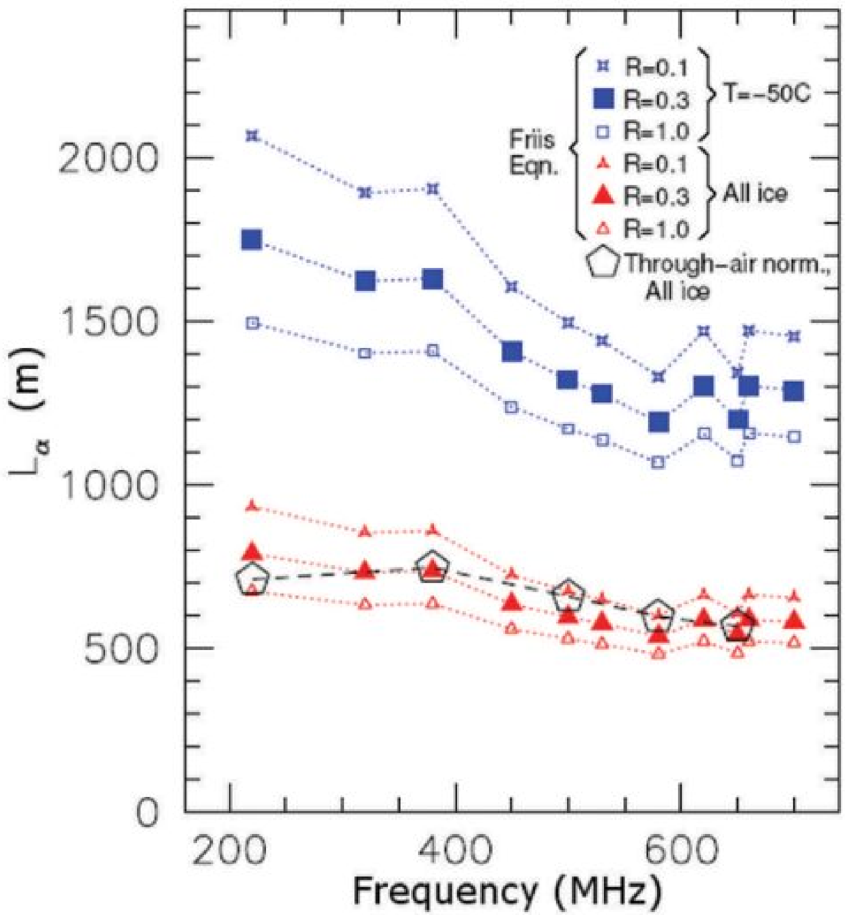




measurements from CReSIS experiment at KU (Stockham, Besson et.al.)

why radio?

- up at 100Mhz-1Ghz frequencies, the attenuation of RF fields is very low relative to optical
- can "see" further, and therefore instrument a larger volume.



Barwick,Besson,Gorham,Saltzberg 2005