Weak signal extraction using matrix decomposition:
with application to detection of ultra high energy neutrinos

s prohira

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CCAPP

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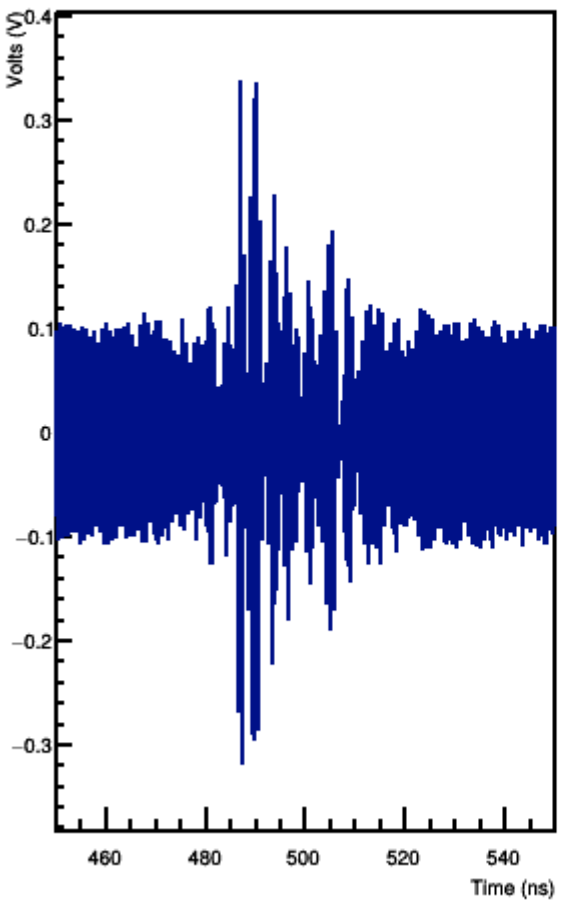
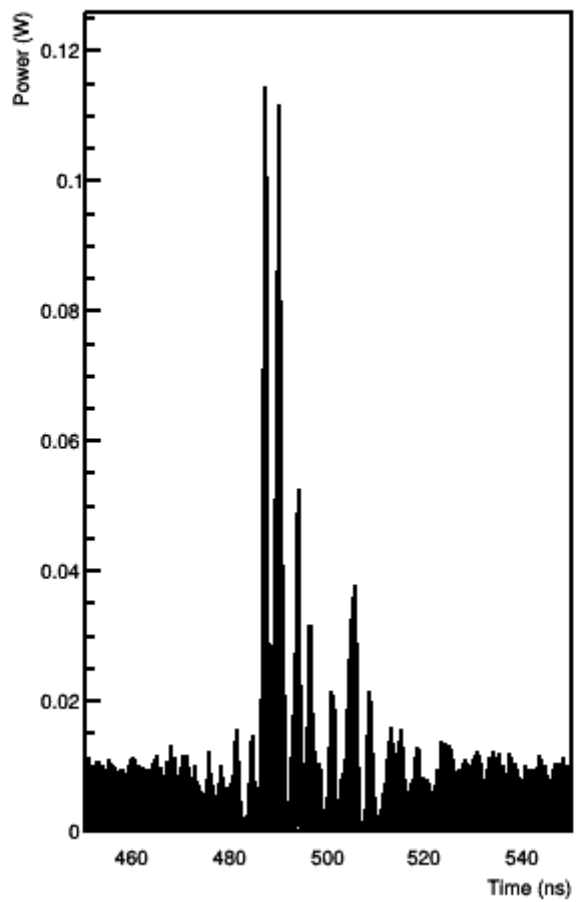
outline

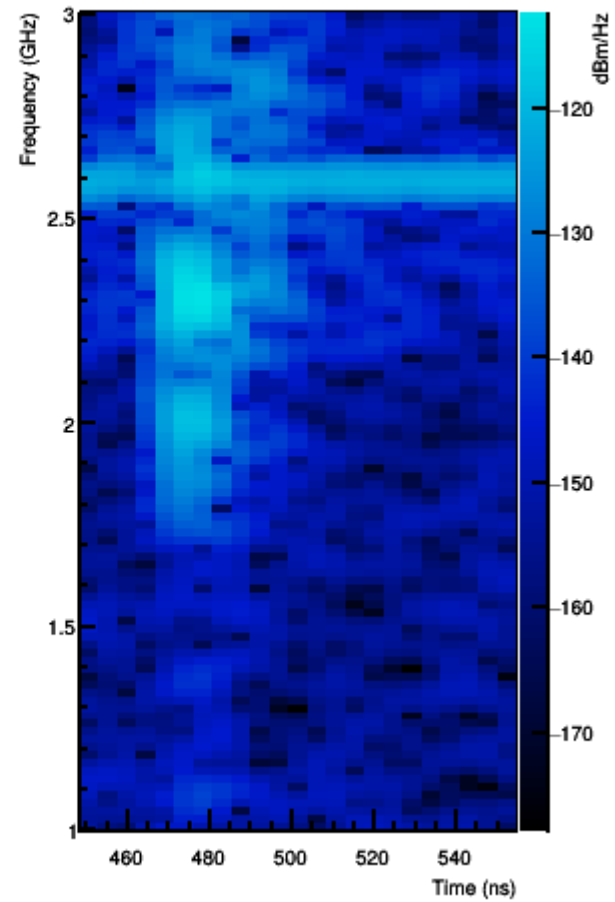
- motivation: weak signal extraction in radio-based experiments
  - what is `weak'?
- why radio? high-energy *neutrinos*
- matrix decomposition
- expansion in a basis and filtering
- application: experiment T576 at SLAC
  - Radar detection of an electron-beam induced particle cascade
- outlook for future analyses and discussion

weak signals in radio

- in radio analyses, we deal mainly with time series of voltage, power, or spectral information:

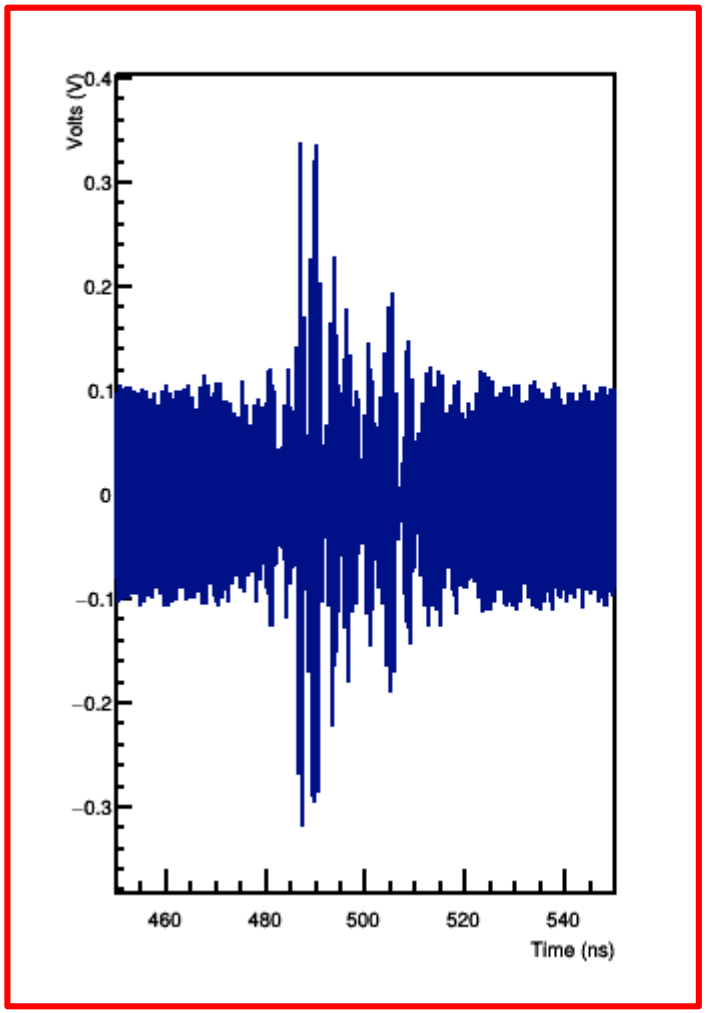


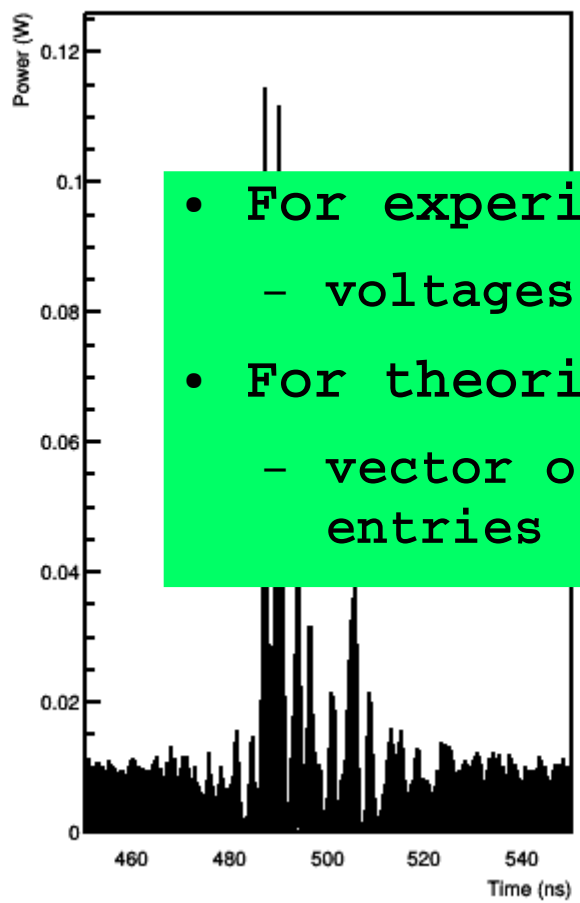


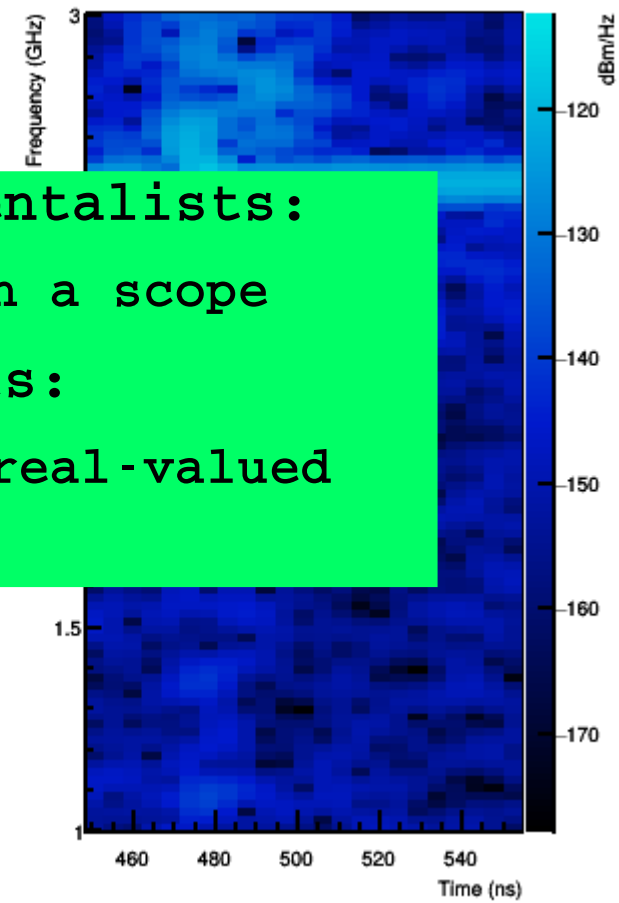


weak signals in radio

- Focusing on V(t): what happens when a signal is 10% the size of the background? 1%?



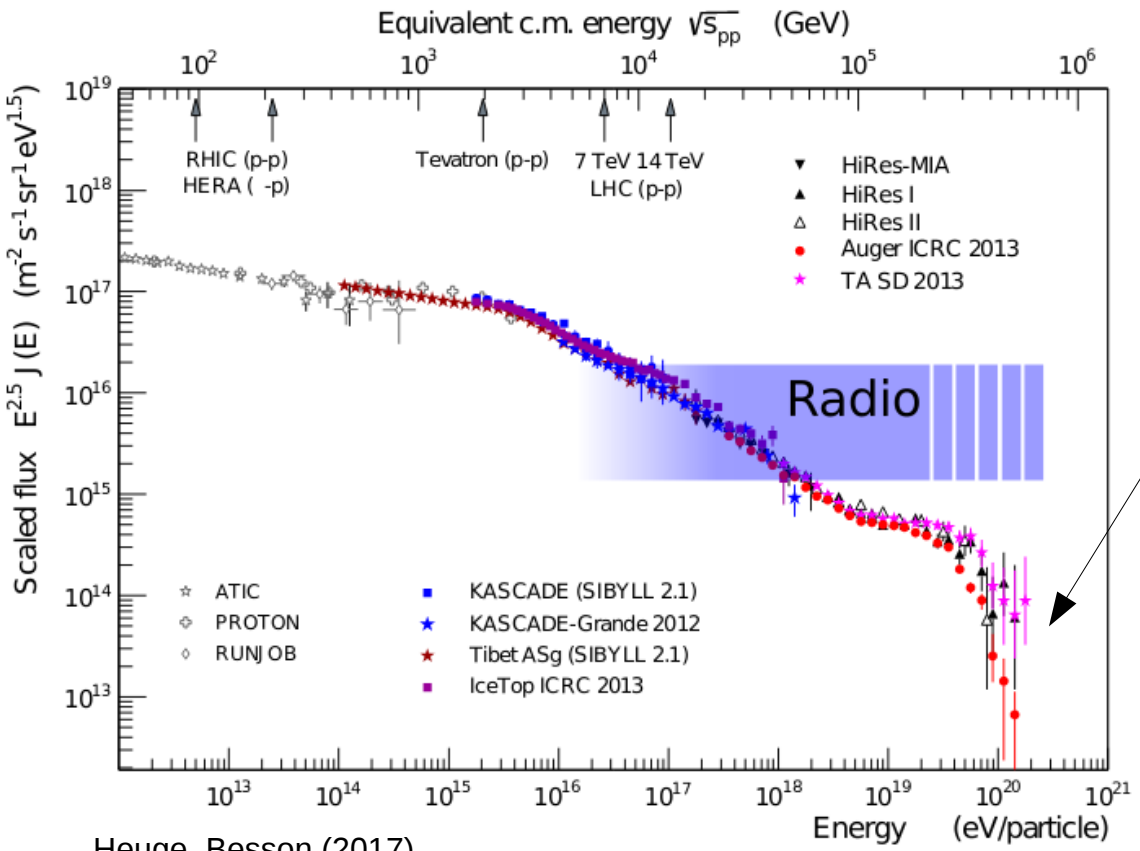




- For experimentalists:
  - voltages on a scope
- For theorists:
  - vector of real-valued entries

weak signals in radio

- Why am i talking to you about radio?



Heuge, Besson (2017)

at ultra-high energies, flux of cosmic rays and *cosmic-ray neutrinos* drops dramatically

1 $km^{-2}century^{-1}$ at the highest energies!

detection of cosmic ray neutrinos remotely, via **radio** methods, is the way to extend up to the highest energies.

- The technique presented here applies to a new method to detect neutrinos with energies above 10^{15} eV: ***radar***

weak signals in radio

- If backgrounds are known exactly, the only limit to extraction is noise. e.g.:

$$V_i = b_i + s_i + n_i$$

where V is our data vector,
b is a background vector,
s is our signal vector, and
n is uncorrelated (random) noise

- many techniques to 'dig out' signals from noise, if backgrounds are exact; then `weak' is defined relative to (uncorrelated) noise.
  - only limits then are (generally) technical
- but...what if the backgrounds aren't exact?
- what if they cannot be known *a priori*?
- what if the background variation is greater than the amplitude spread of the signal?

matrix decomposition

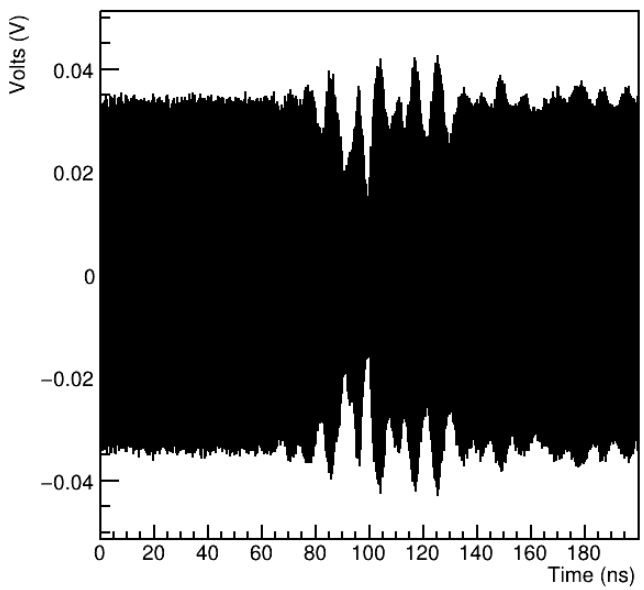
- let's assume that our `data' consists of:
  - random phase sine waves
  - impulsive radio bursts
  - uncorrelated noise
  - a very small (~1%) signal

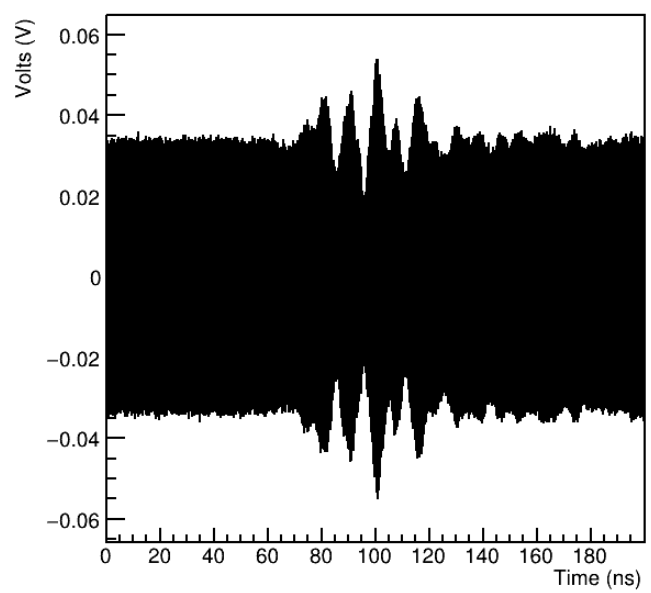
$$V^i_{data} = \boxed{b_i + c_i} + n_i + s_i$$

combination unknown: makes complete background subtraction impossible

- Then let's assume we can generate `null data' that mimics the real data, <u>minus the signal</u>
  - examples:

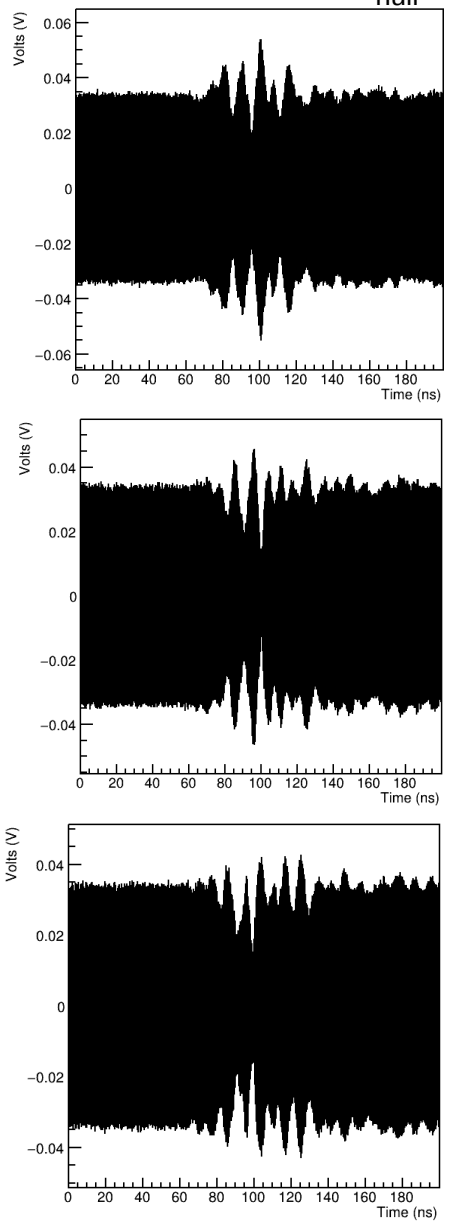
$$V^i_{null} = \boxed{b_i + c_i} + n_i$$





matrix decomposition

Null vectors V_{null}

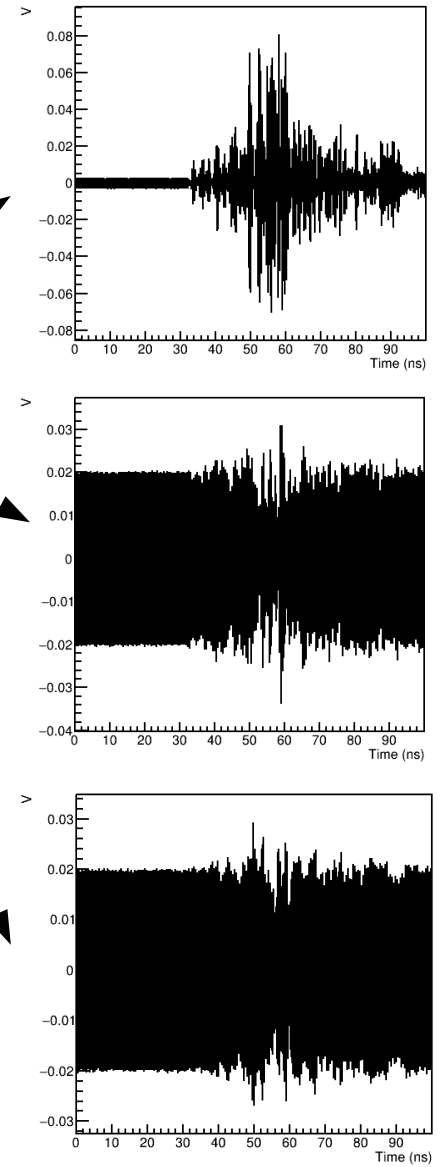


Matrix

↓

Decompose (SVD, eigen)

Basis *patterns f*



decomposition produces a *basis of patterns* made from the null data itself.

similar methods exist in many disciplines: principal-component analysis, Karhunen-Loeve, etc.

novel application to radio:

Bean, *Ralston*, Snow arXiv:1008.0029

filtering and expansion in a basis

To filter data, one expands a data vector V_{data} in the filter basis, with vectors f,

$$c^0 = f^0 \cdot V_{data}$$

and

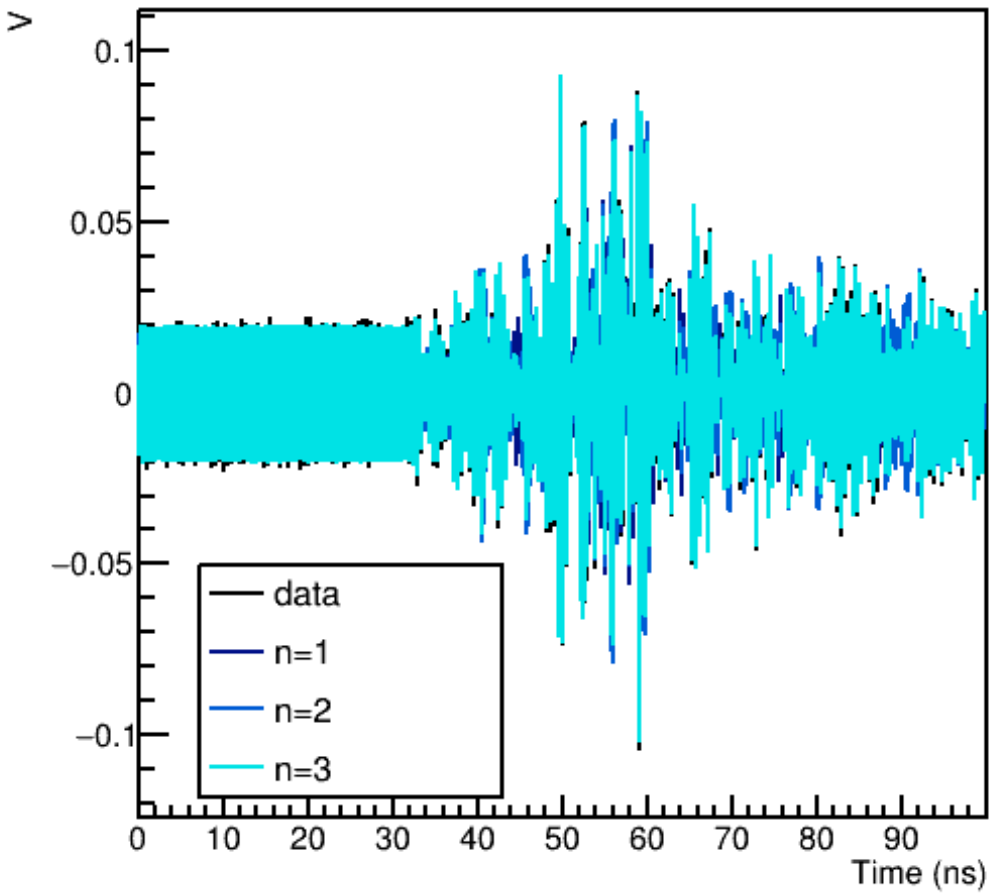
$$c^N = f^N \cdot V_{data}$$

where the expansion coefficients are labelled c. then the expansion of this data vector, up to order n, in the filter basis, produces the filter vector F:

$$F_j^n = \sum_{i=0}^{n} c^i f_j^i$$

and then the filtered data V_{filt} is simply

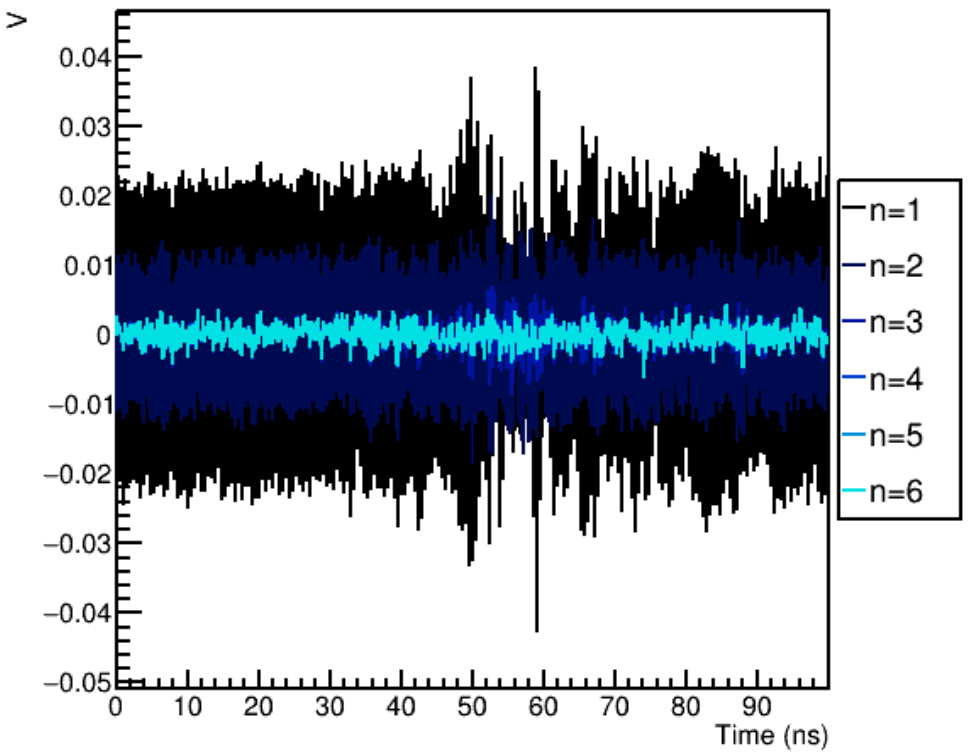
$$V_{filt} = V_{data} - F^n$$



expansion in n patterns

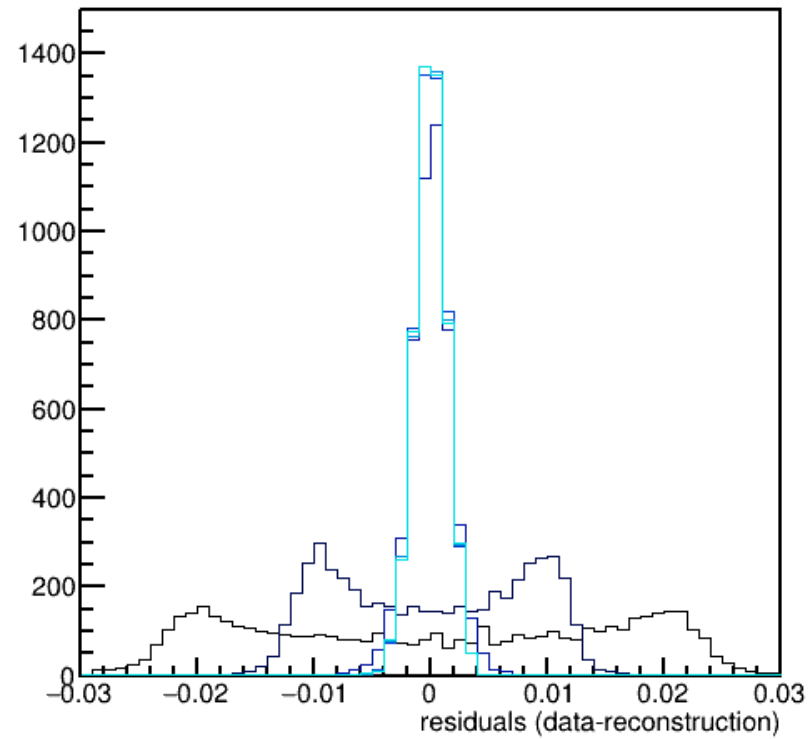
filtering and expansion in a basis

$$\mathrm{V}_{dat} - F^n$$



addition of more basis patterns in the expansion improves the filter

$$\mathrm{V}^i_{dat} - (V_{dat} - F^n)^i$$

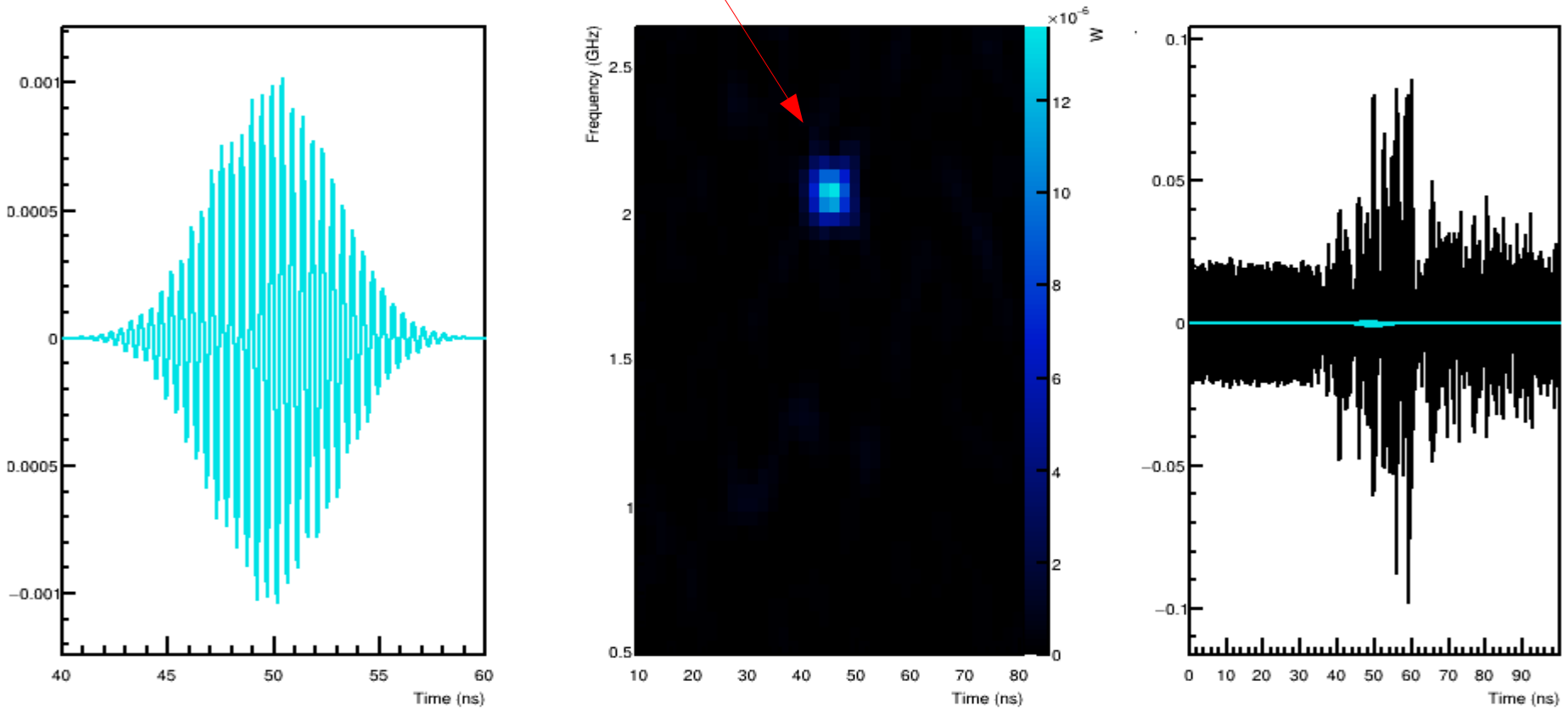


improvement becomes modest but continues to high n

filtering and expansion in a basis

to test our filter, we can inject a signal a signal at ~1% background amplitude

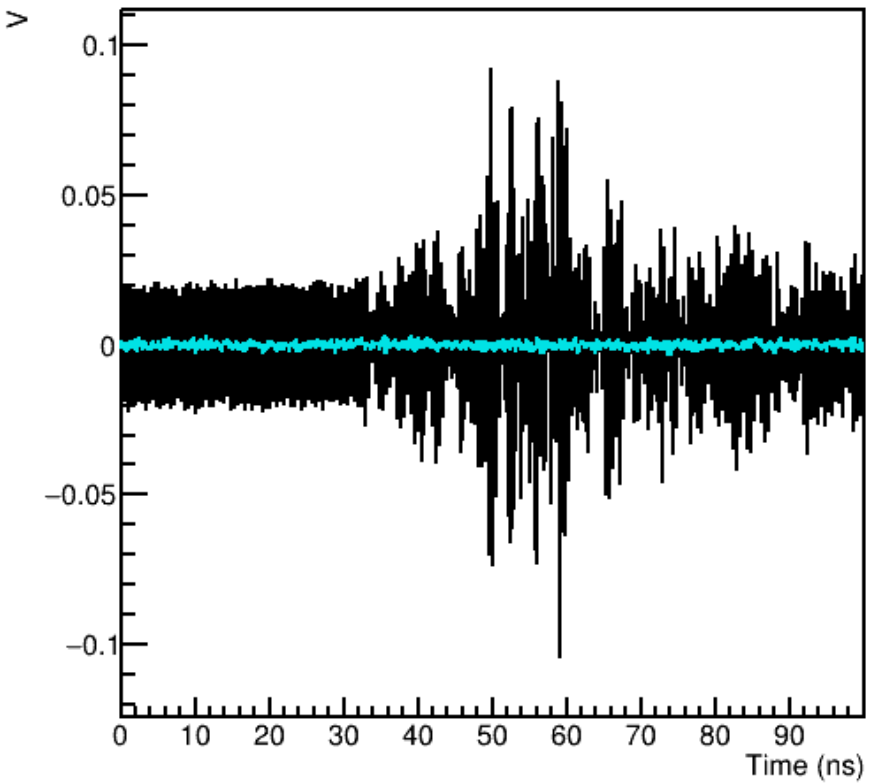
we make it monochromatic at 2.1 GHz, and with random phase.

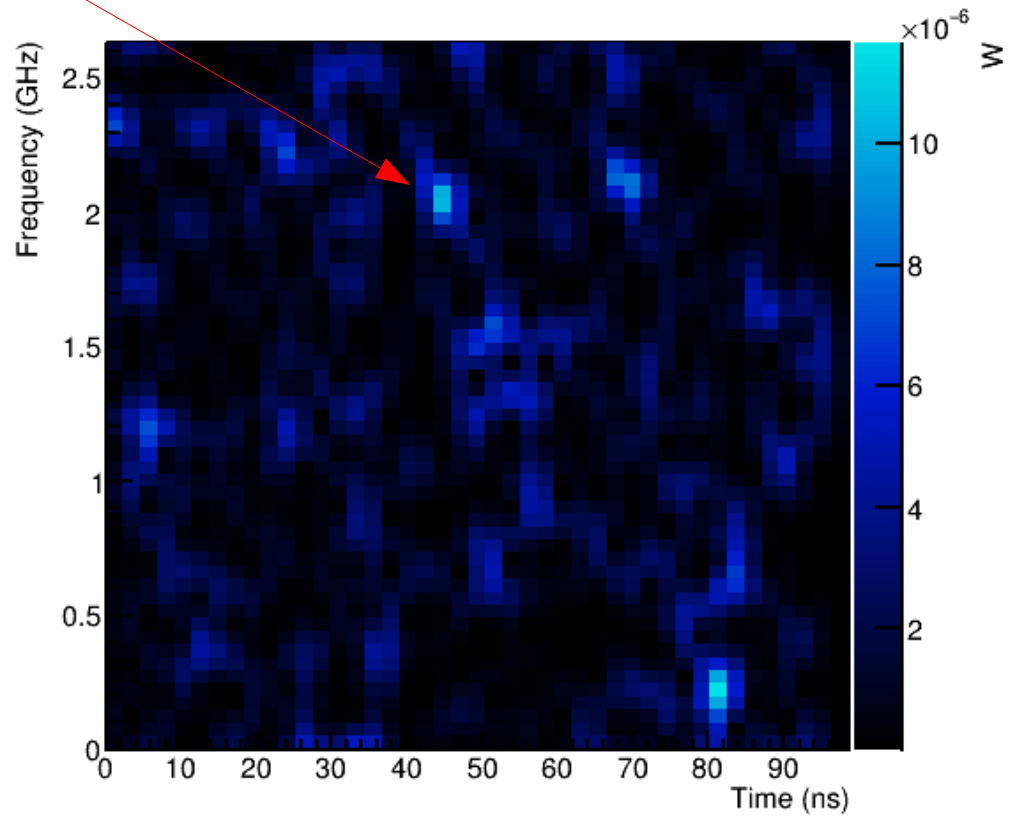


filtering and expansion in a basis

here we show the result of filtering this particular event.

we see a hint of a signal at the correct point, but other `blobs' are of similar amplitude

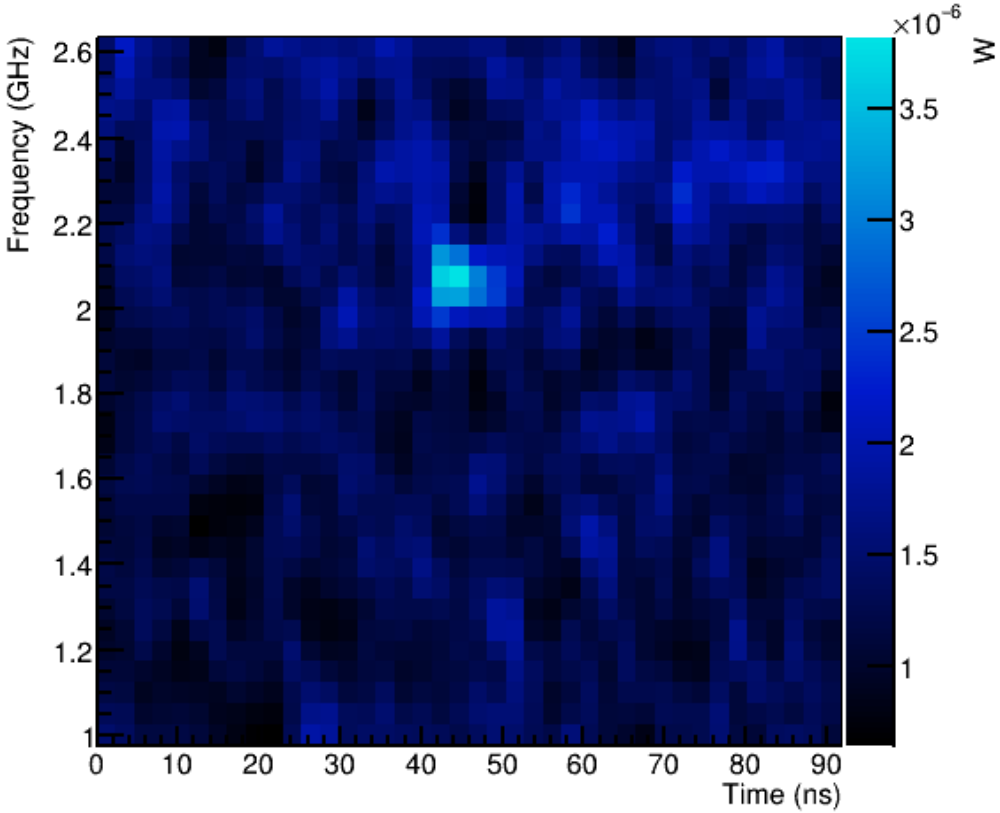




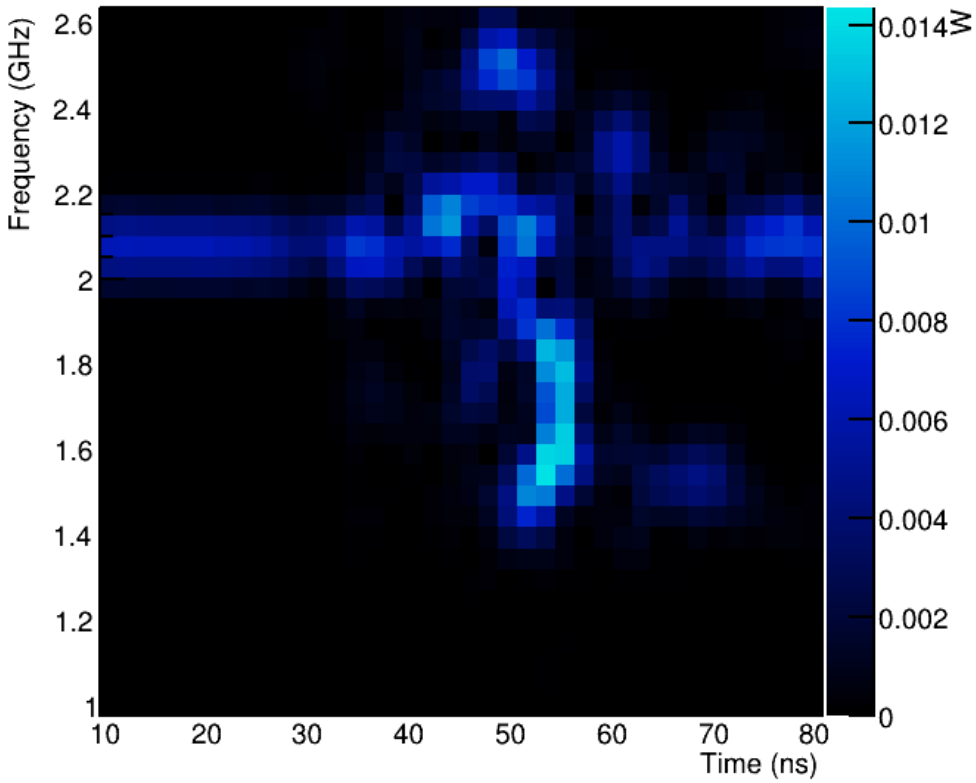
the original data vector (with injected signal) and the remiander after filtration

filtering and expansion in a basis

averaging a hundred events, each with an injected signal with random phase, we see a distinct signal pop out of the background. we have extracted a random phase signal buried at ~1:100 in noise and random-phase background.



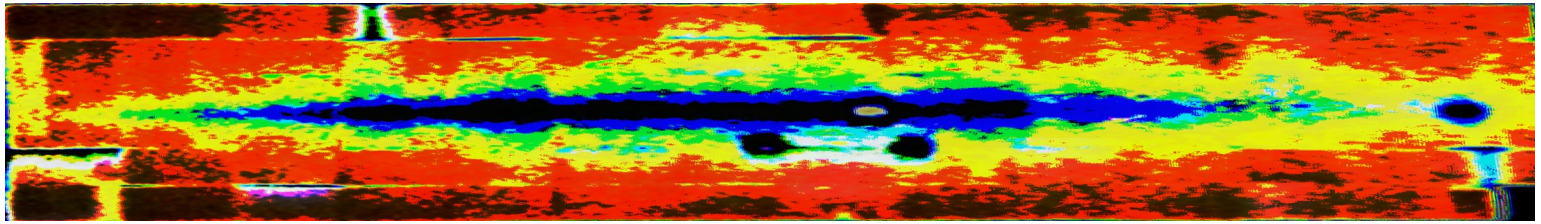
extracted signal



original event

application: SLAC experiment T576

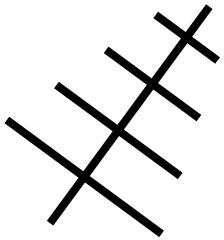
shower created in the target (HDPE)



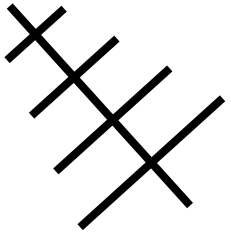
(actual beam profile)

10 GeV electron beam, $N=10^9$

incident radio is reflected



Towards detecting ultra-high-energy neutrinos with radar



transmitter

receiver

application: SLAC experiment T576

SLAC NATIONAL ACCELERATOR LABORATORY

.

results from first run (May 2018) are out
results from second run (November 2018) forthcoming! (ICRC2019)

arXiv:1810.09914

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

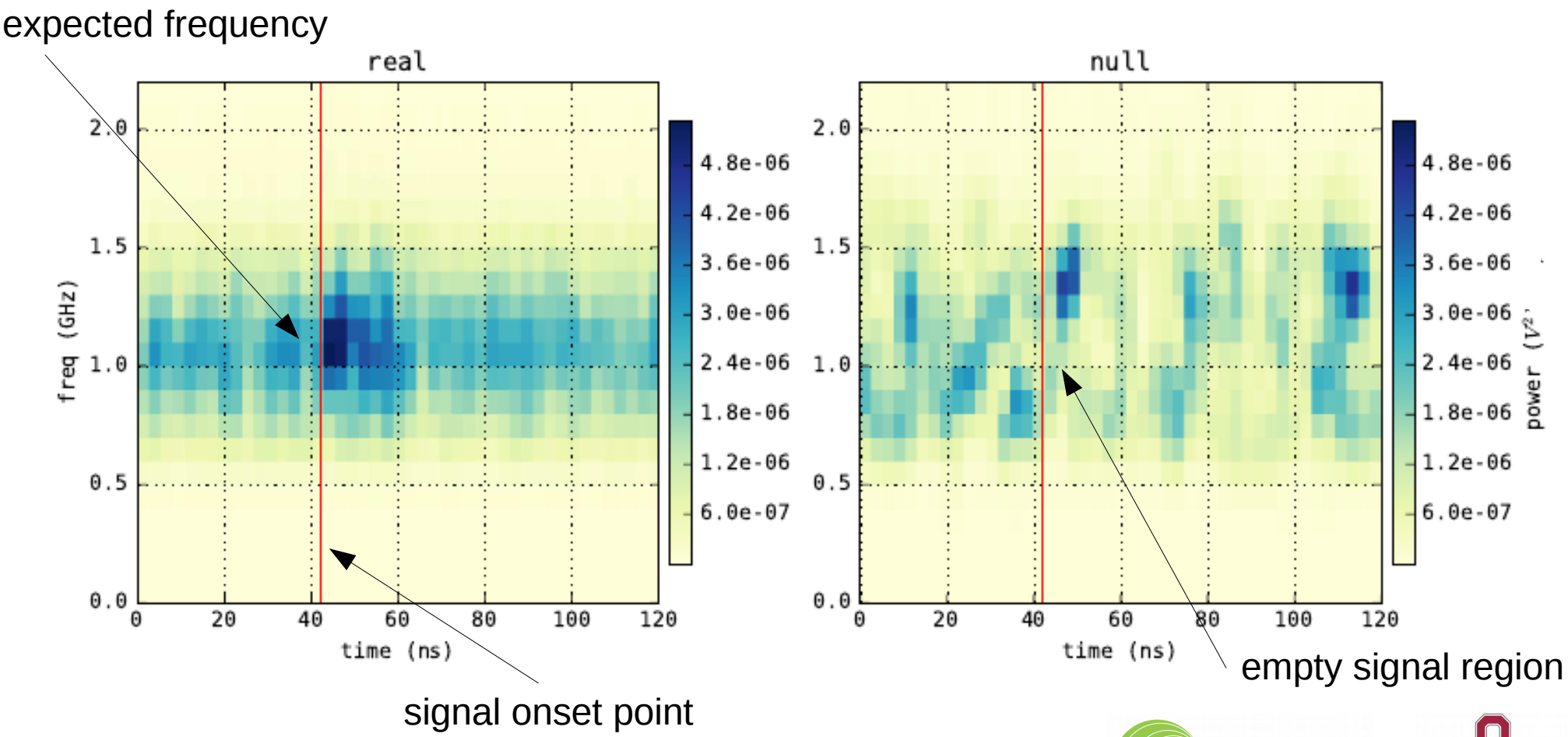
S Prohira[1,2], K. D. de Vries[3], D. Besson[4,9], A. Connolly[1,2], C. Hast[5], U. Latif[4], T. Meures[6], J.P. Ralston[4], Z. Riesen[7], D. Saltzberg[8], J. Torres[1], S. Wissel[7], and X. Zuo[8]

+ A. Nozdrina, J. Beatty, J. Nam

application: SLAC experiment T576

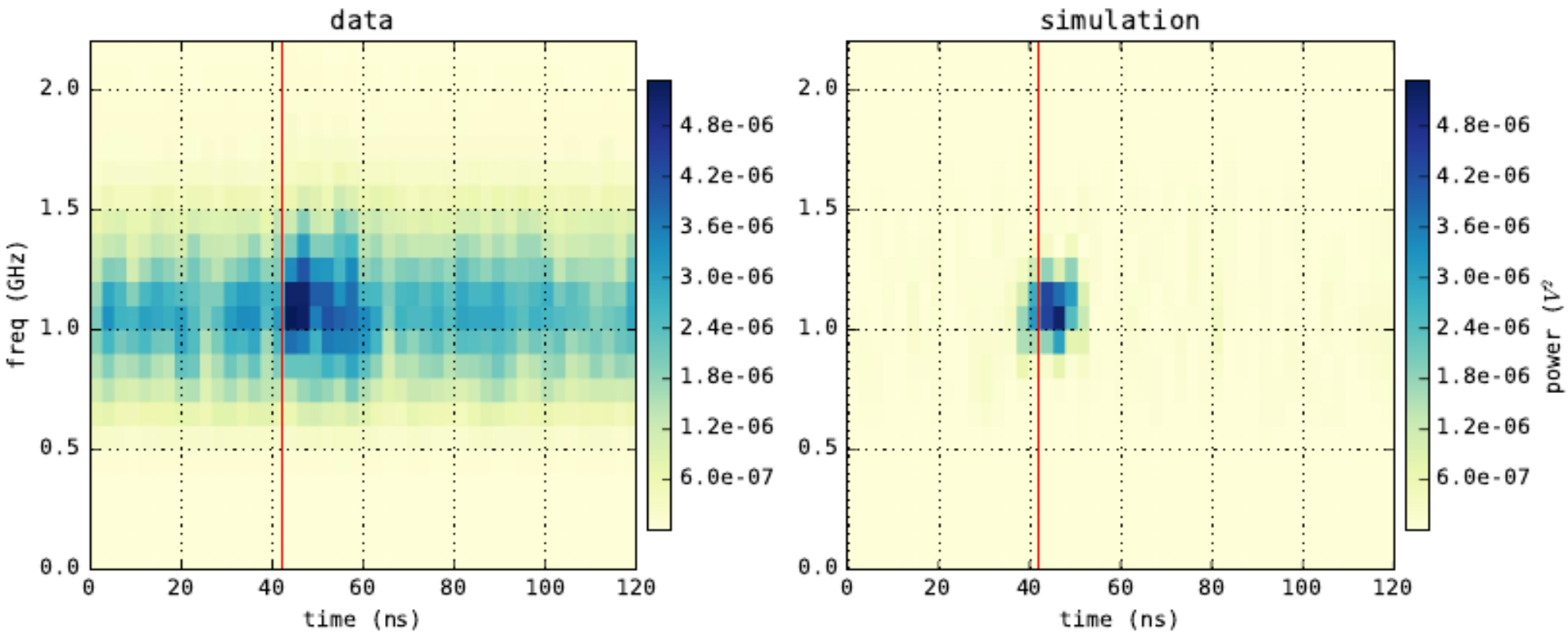
Run 1 analysis finds evidence for a signal-region excess at 2.4 σ over a null hypothesis.

used the technique outlined here to extract a weak signal.

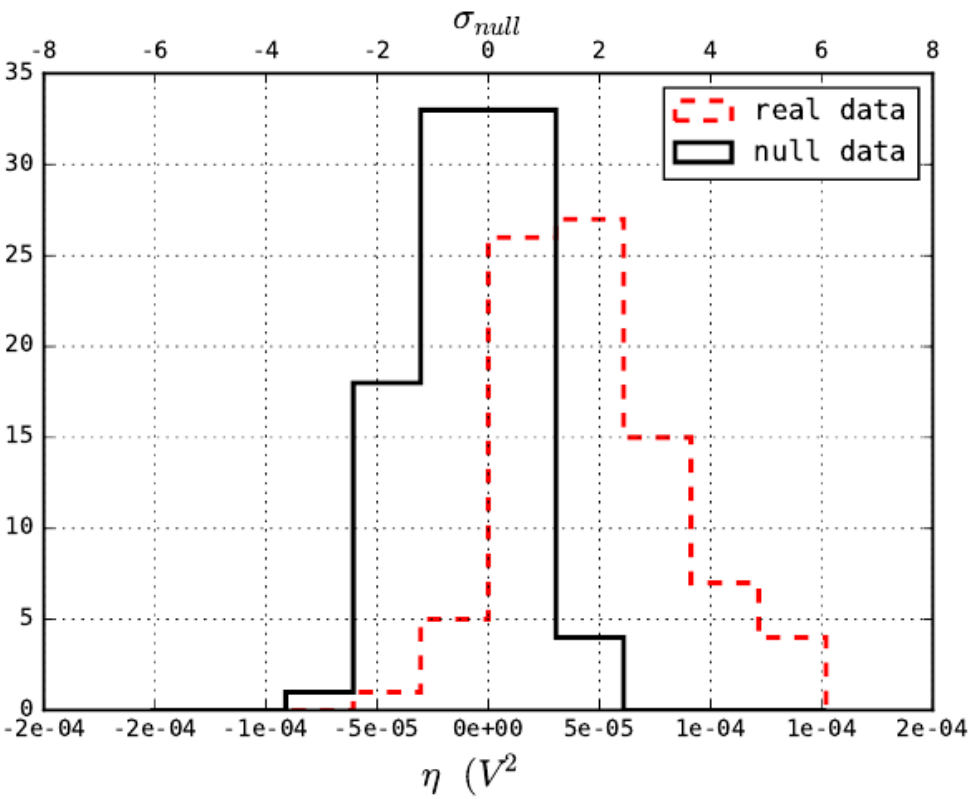


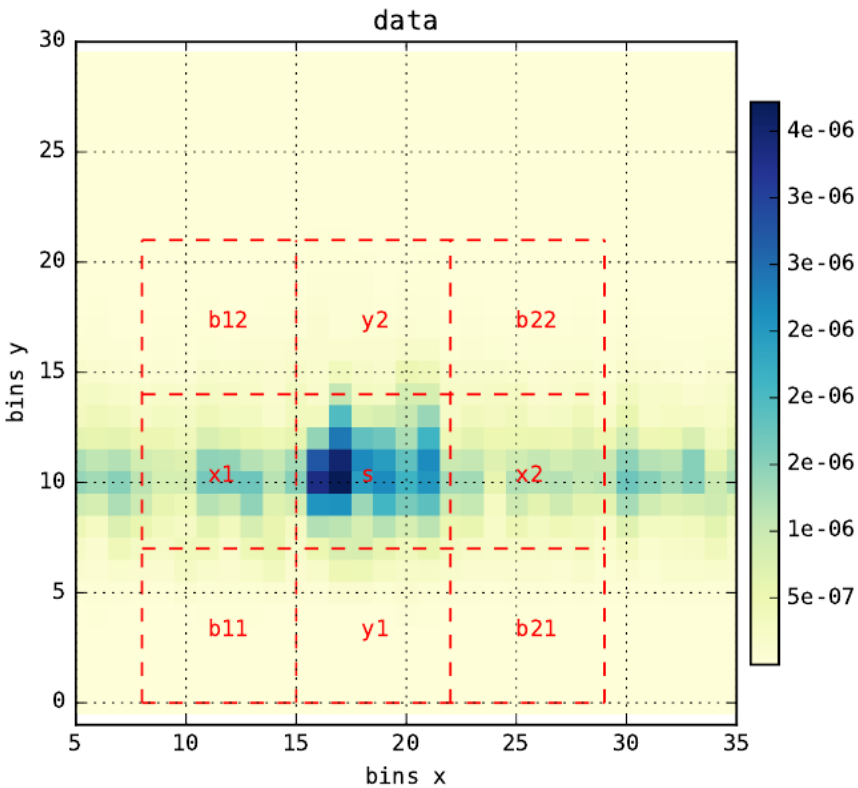
application: SLAC experiment T576

comparing to simulation, the agreement is quite good.



significance from run 1





Established a signal excess at 2.4 sigma via sideband subtraction.

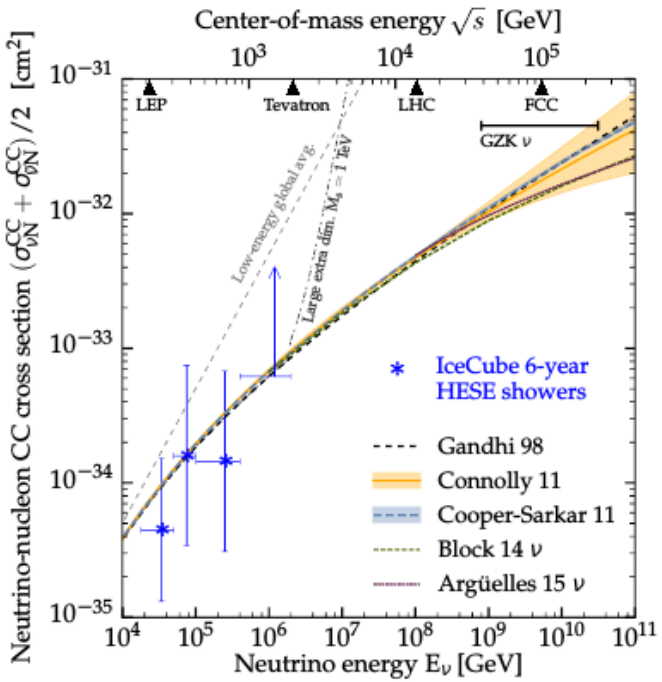
conclusions, next steps

- matrix decomposion methods are a powerful tool for pattern-based filtration of time-domain signals
- weak signals can be extracted from large backgrounds
- application to real data looks promising
- much more to be done...and more to learn!

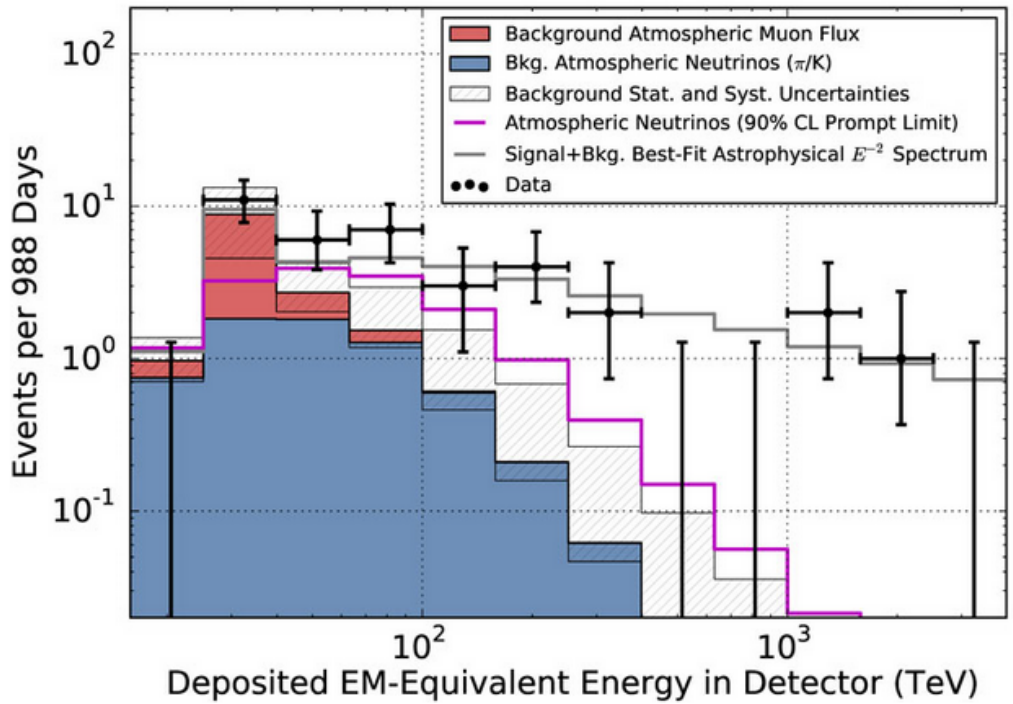
thanks!

backup

why UHE neutrinos?



(Connolly and Bustamante 2019)



(IceCube)

- above ~few PeV, scattering cross section and flux (and source) of UHE nu not constrained by experiment.
- neutrinos travel on straight lines and through matter-probe into now-unseeable parts of the universe.

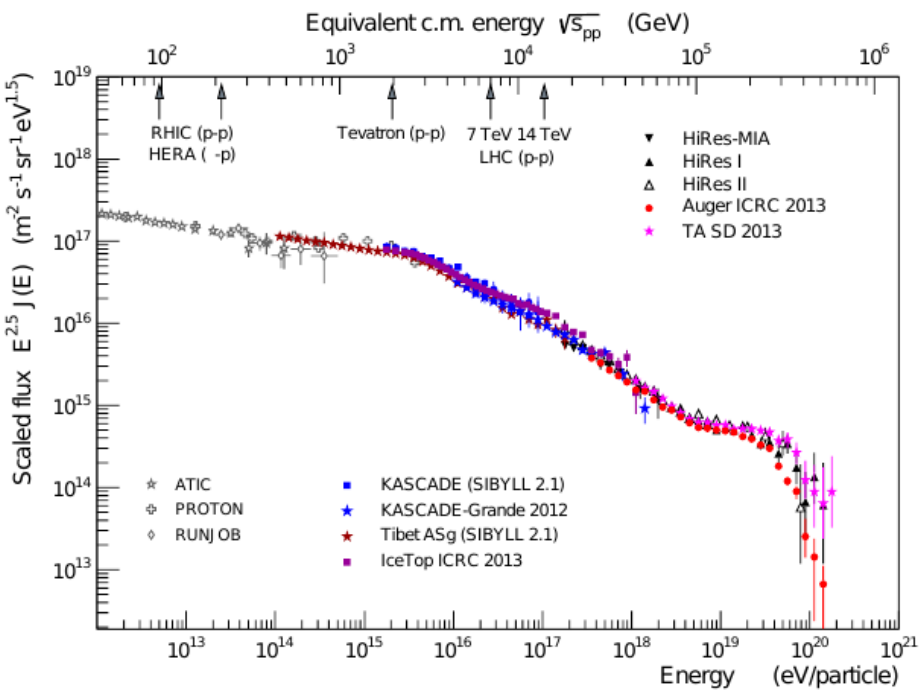
why UHE neutrinos?

"Because it's* there."
-G. Mallory

*probably

why UHE neutrinos?

"Because it's* there."
-G. Mallory



- cosmogenic nu flux from UHECR interaction with CMB photons
- UHECR flux at earth extends up to the GZK limit, UHE neutrinos are probably there to be detected

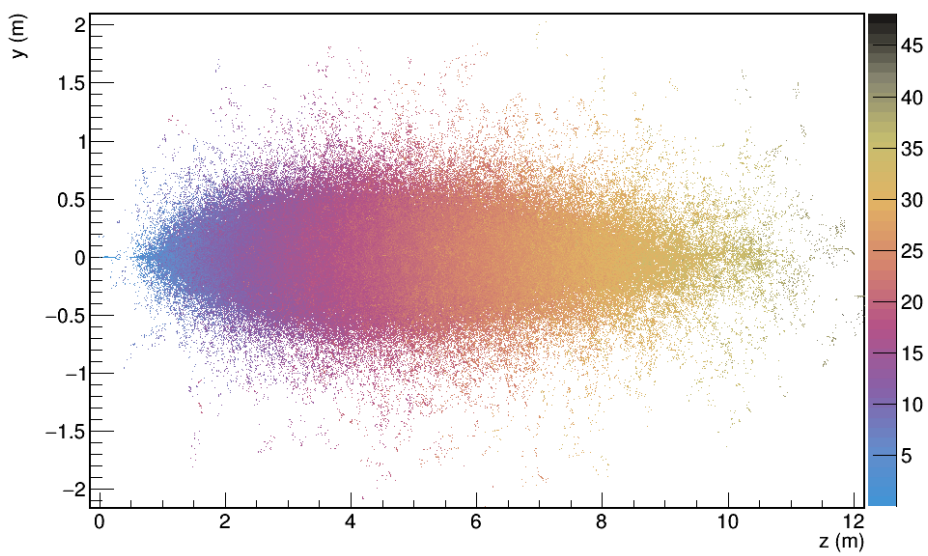
*probably

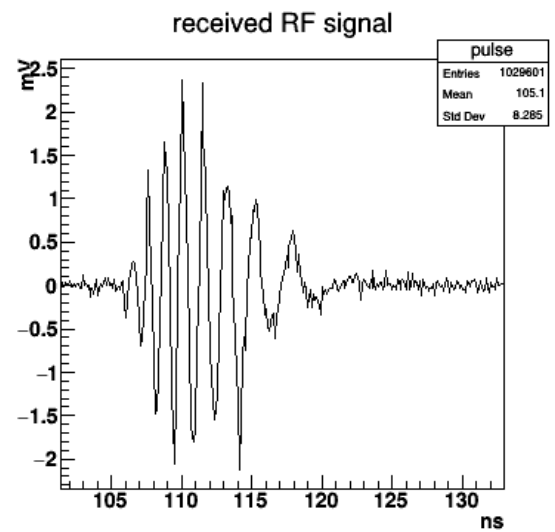
how to detect UHE neutrinos

- collision between a high energy particle (like a neutrino) and a water ice molecule produces a shower of secondaries (as below)
- if this shower happens in a region that a detector is sensitive to...

  detected!

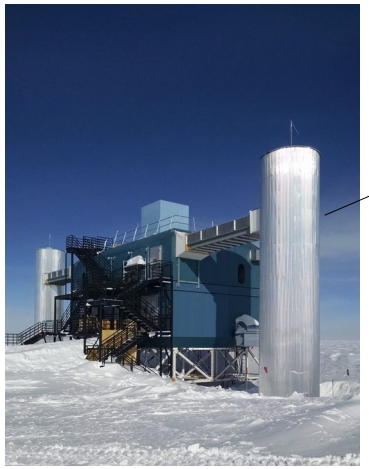
- 2 ways to detect shower (really the same):
  - optical
  - radio frequency (RF)
- cannot directly measure the primary nu, must reconstruct primary based on the properties of the detected shower.

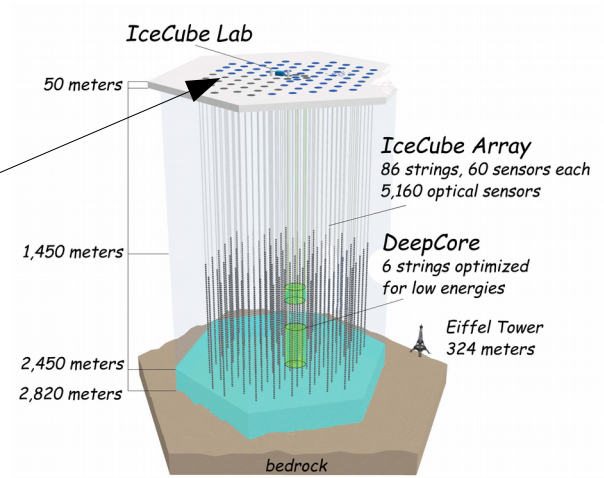




how to detect UHE neutrinos

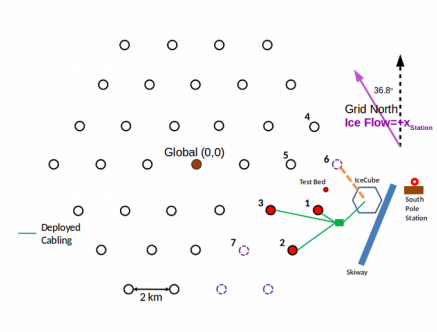
- Optical:
  - AMANDA, IceCube

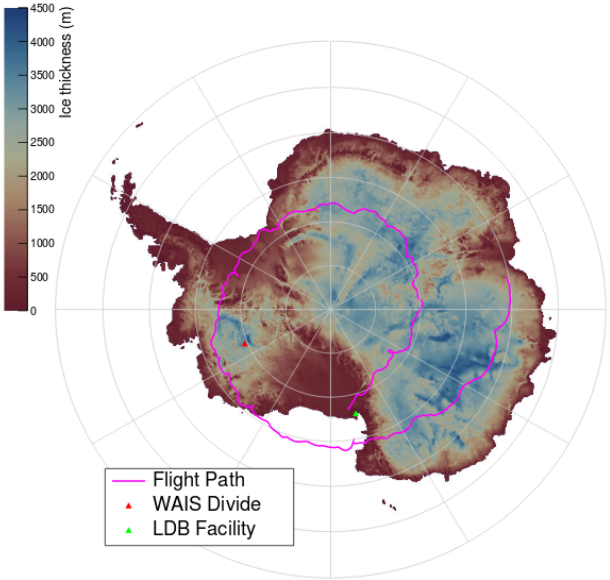




detect the primary indirectly by detecting the cascade produced from the original nu interaction.

- Askaryan/Radio:
  - RICE, ARA,ANITA, ARIANNA



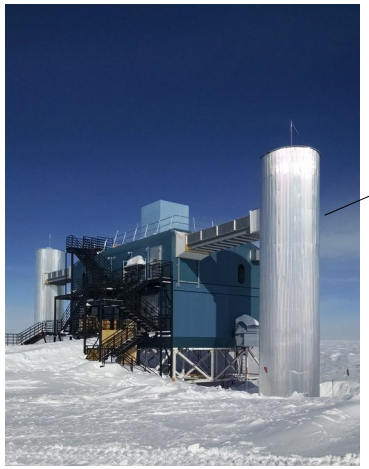


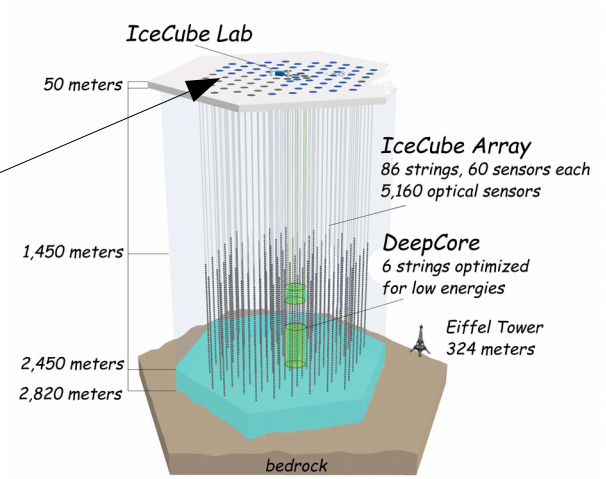
IceCube (~10^15 eV) → ANITA (10^21eV)

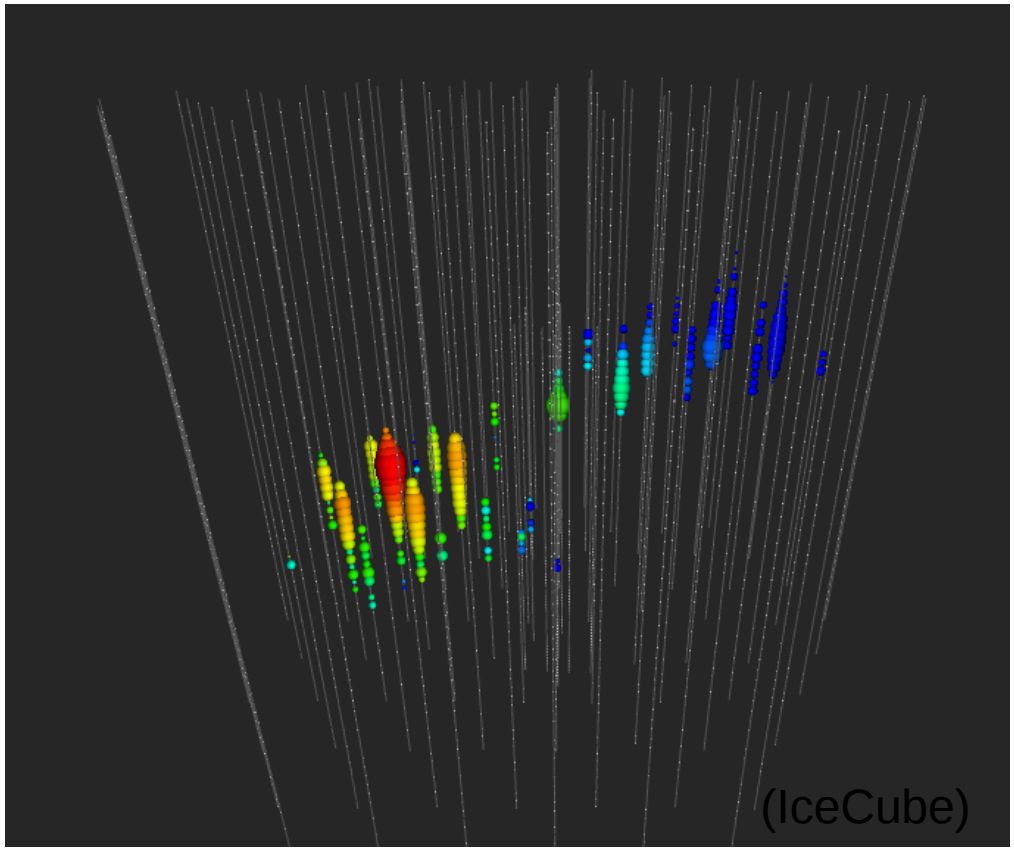
ENERGY

how to detect UHE neutrinos

- Optical:
  - AMANDA, IceCube





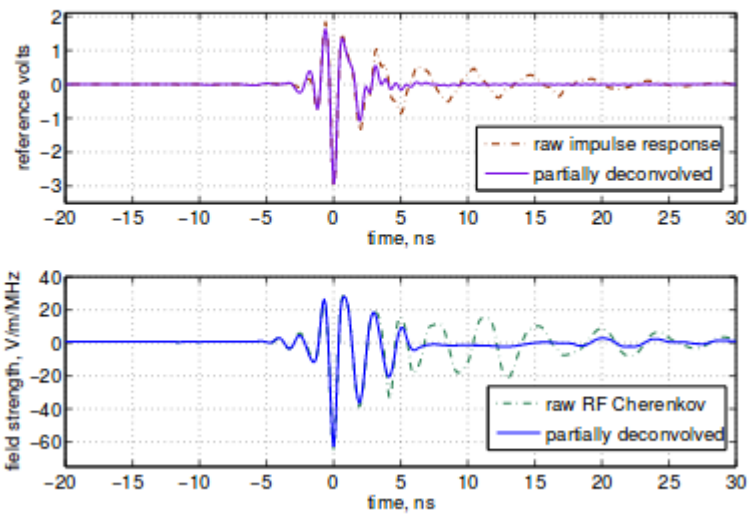


optical regime: UHE neutrino creates a cascade which emits Cherenkov light. light is detected by optical modules.

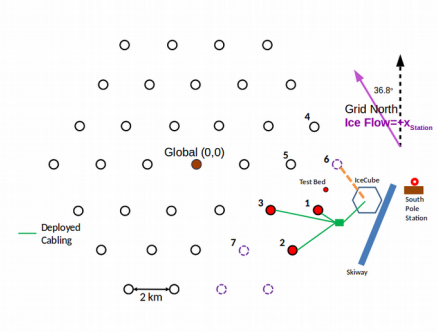
IceCube (~10^15 eV)

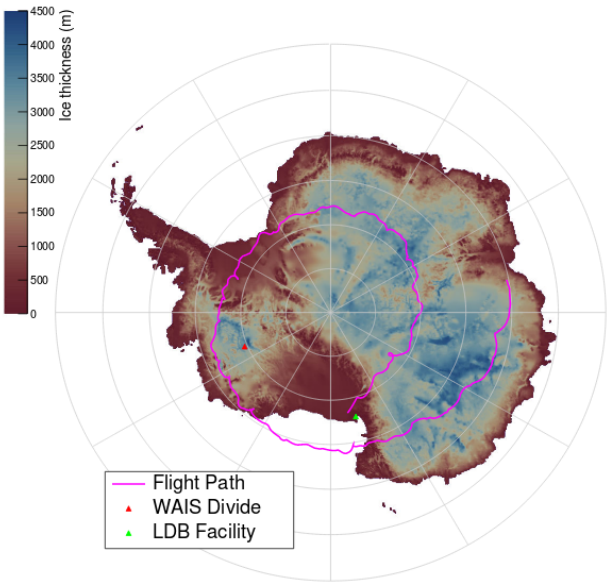
ENERGY

how to detect UHE neutrinos



- Askaryan/Radio:
  - RICE, ARA,ANITA, ARIANNA





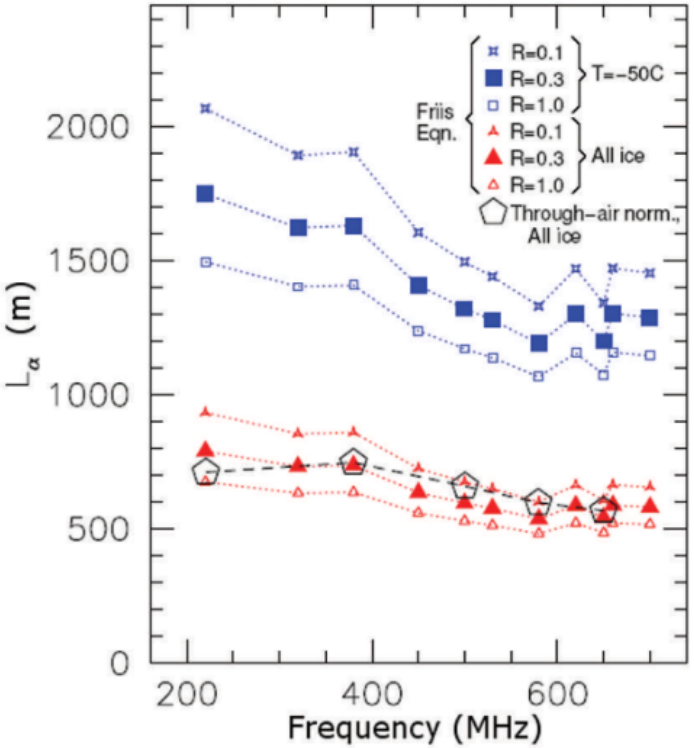
Askaryan effect is coherent radio-frequency Cherenkov. pulses as above (P. Gorham et. al. ANITA) can be detected byRICE/ ARA/ANITA

P(W) ~N^2

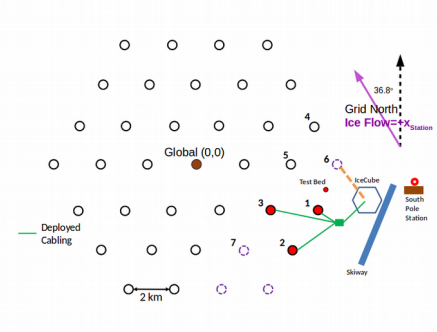
ANITA (10^21eV)

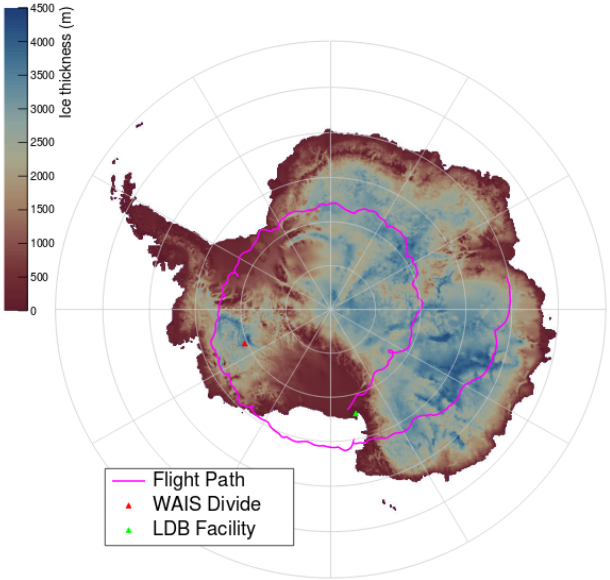
ENERGY

why radio?



- Askaryan/Radio:
  - RICE, ARA,ANITA, ARIANNA





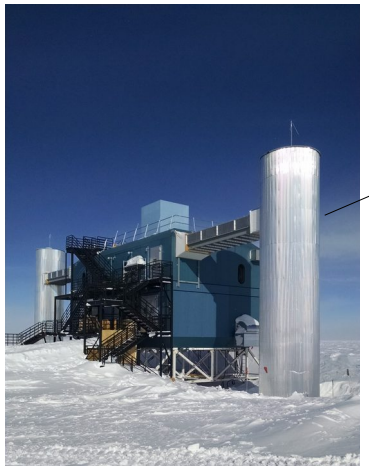
- up at 100Mhz-1Ghz frequencies, the attenuation of RF fields is very low relative to optical
- can “see” further, and therefore instrument a larger volume.

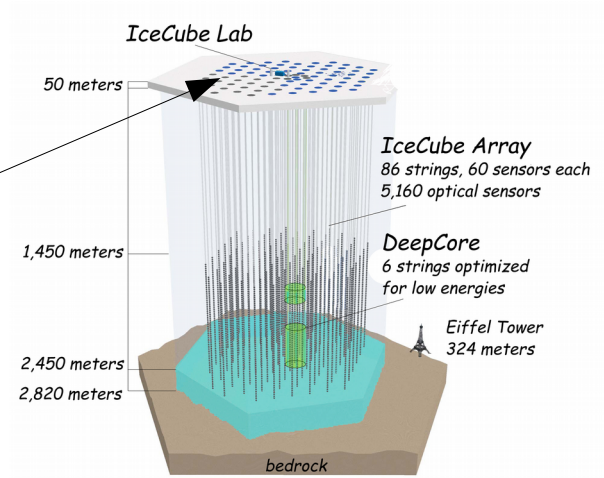
ANITA (10^21eV)

ENERGY

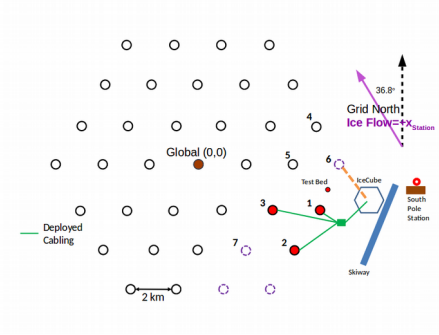
why radar?

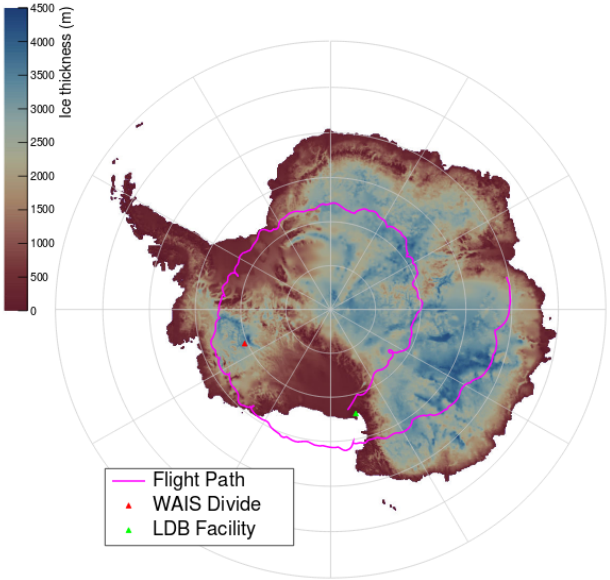
- Optical:
  - AMANDA, IceCube





- Askaryan/Radio:
  - RICE, ARA,ANITA, ARIANNA





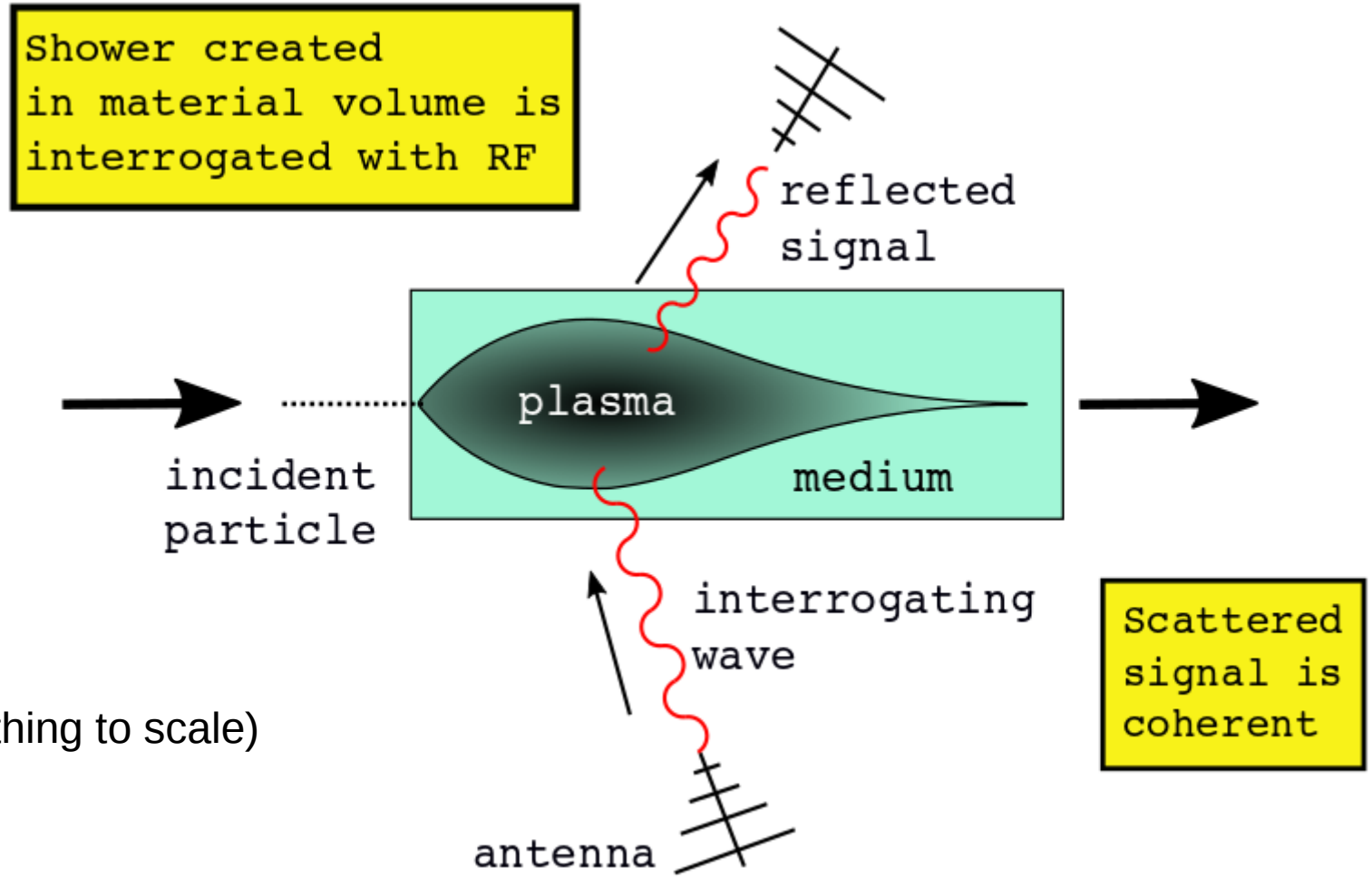
*Optical has upper limit due to volume
*Radio has lower limit due to physics and limited aperture!

RADAR is the best bet for bridging the gap

IceCube (~10^15 eV) **RADAR?** ANITA (10^21eV)

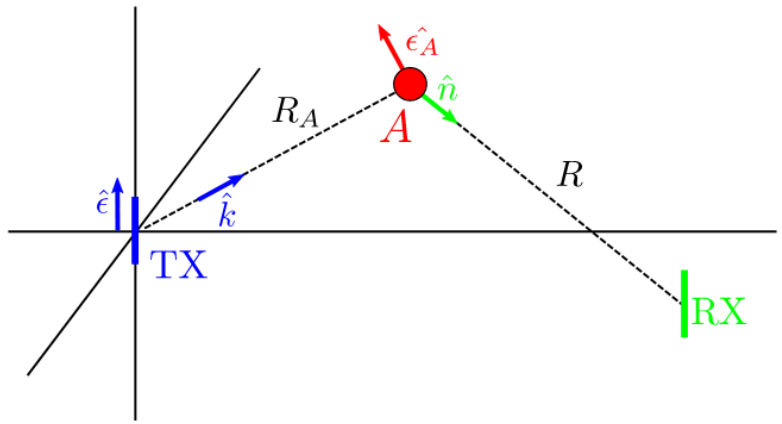
ENERGY

what is radar UHE detection?



(nothing to scale)

can it work?



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

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

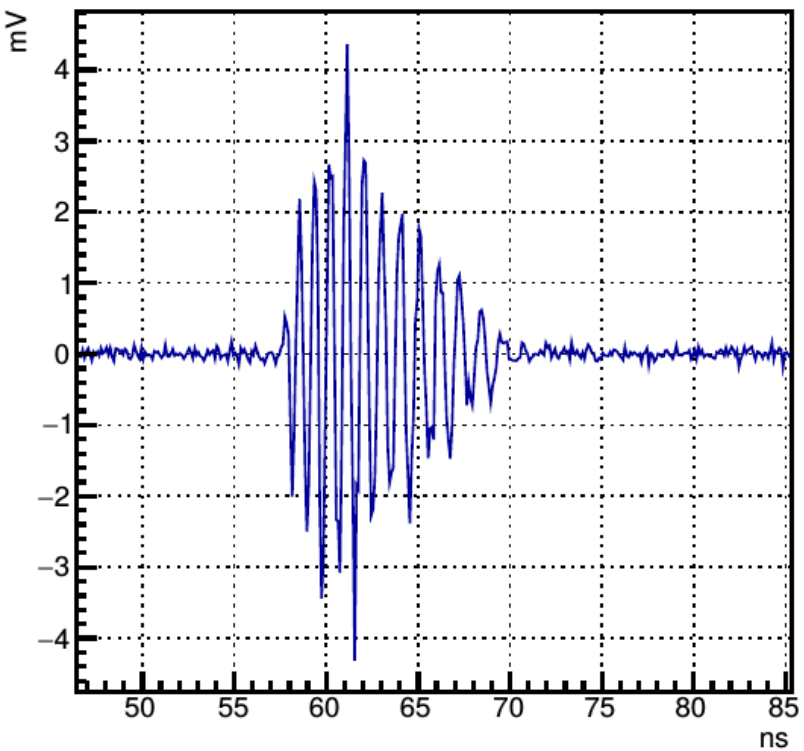
the vectors are simply for polarization, and E_I is the incient field, from the TX, at the electron A with all of the propagation through the medium and the plasma folded in. α is the reflection coefficient, with units of length,

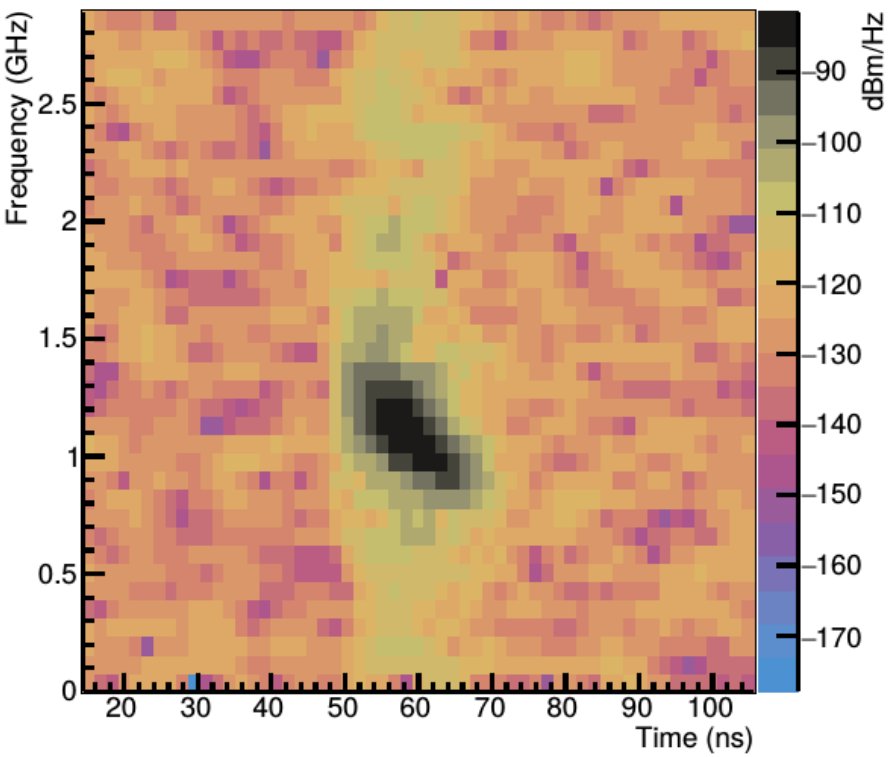
$$\alpha = \frac{q^2 \omega}{c^2 m(\omega + i\nu_c)} \tag{2}$$

can it work?

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

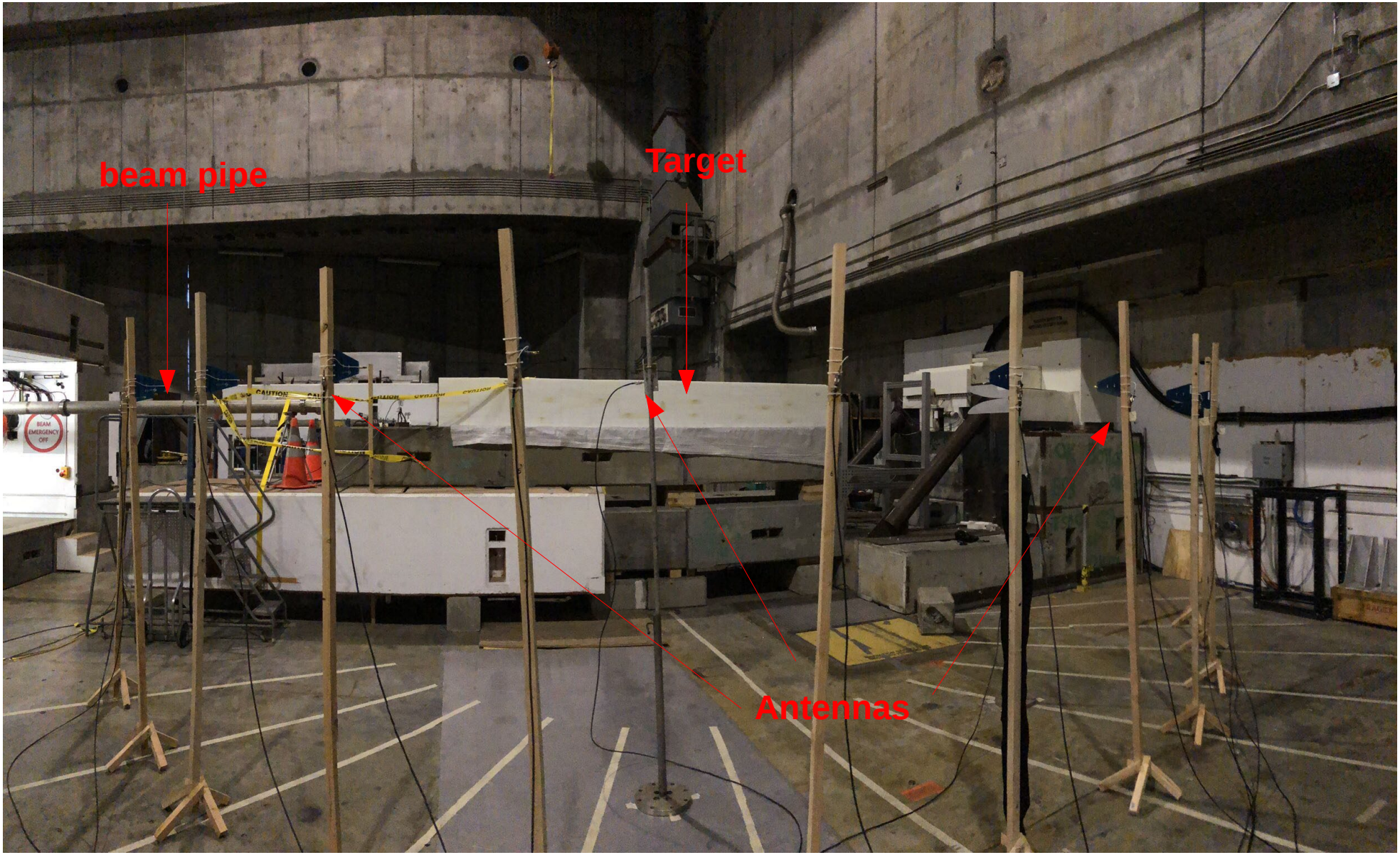
$$Re\left[\mathbf{E}_{tot}\right] = \frac{1}{T}\sum_{n=1}^{N}\int_{t}^{t+T}\Theta(t'-t_n^i)\Theta(t_n^f-t')Re\left[\mathbf{E}_n(t)\right]dt, \quad (1)$$





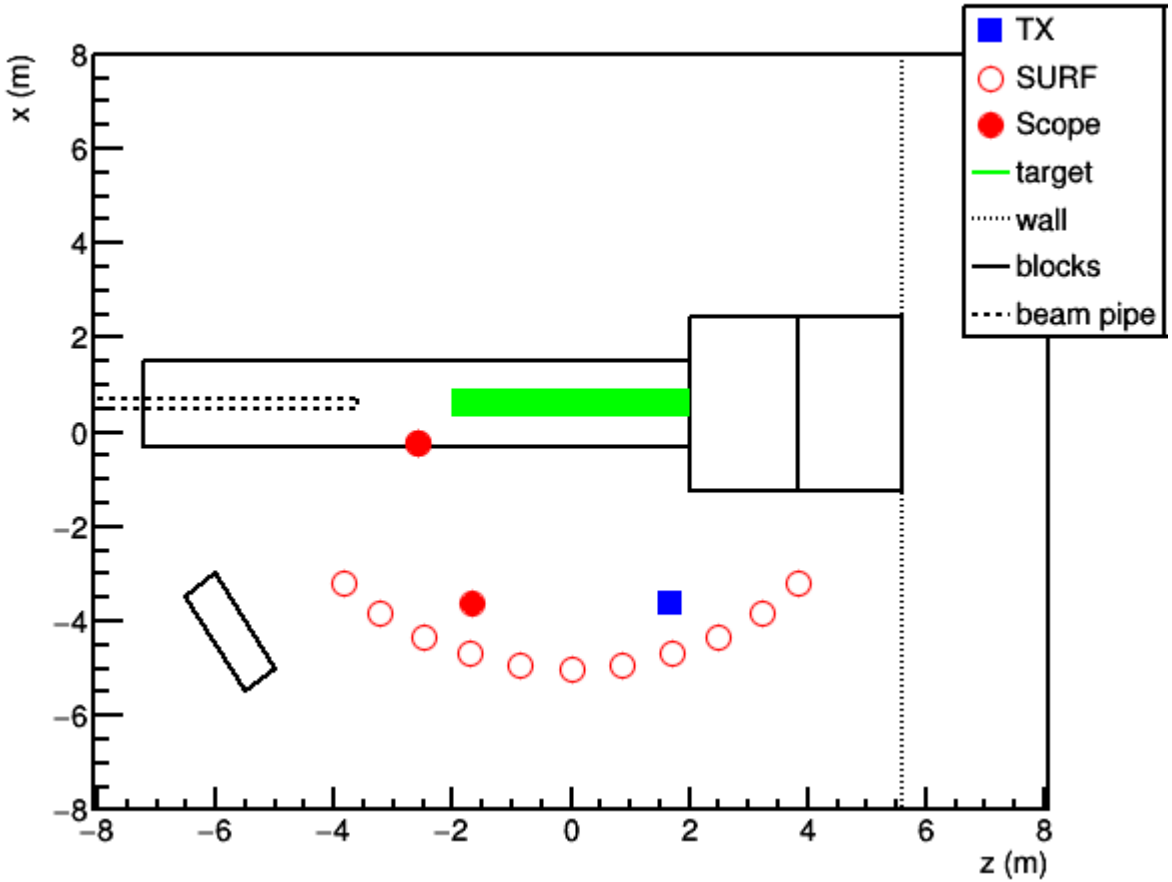
Simulation (RadioScatter arXiv:1710.02883) shows that things look pretty good...

does it work?



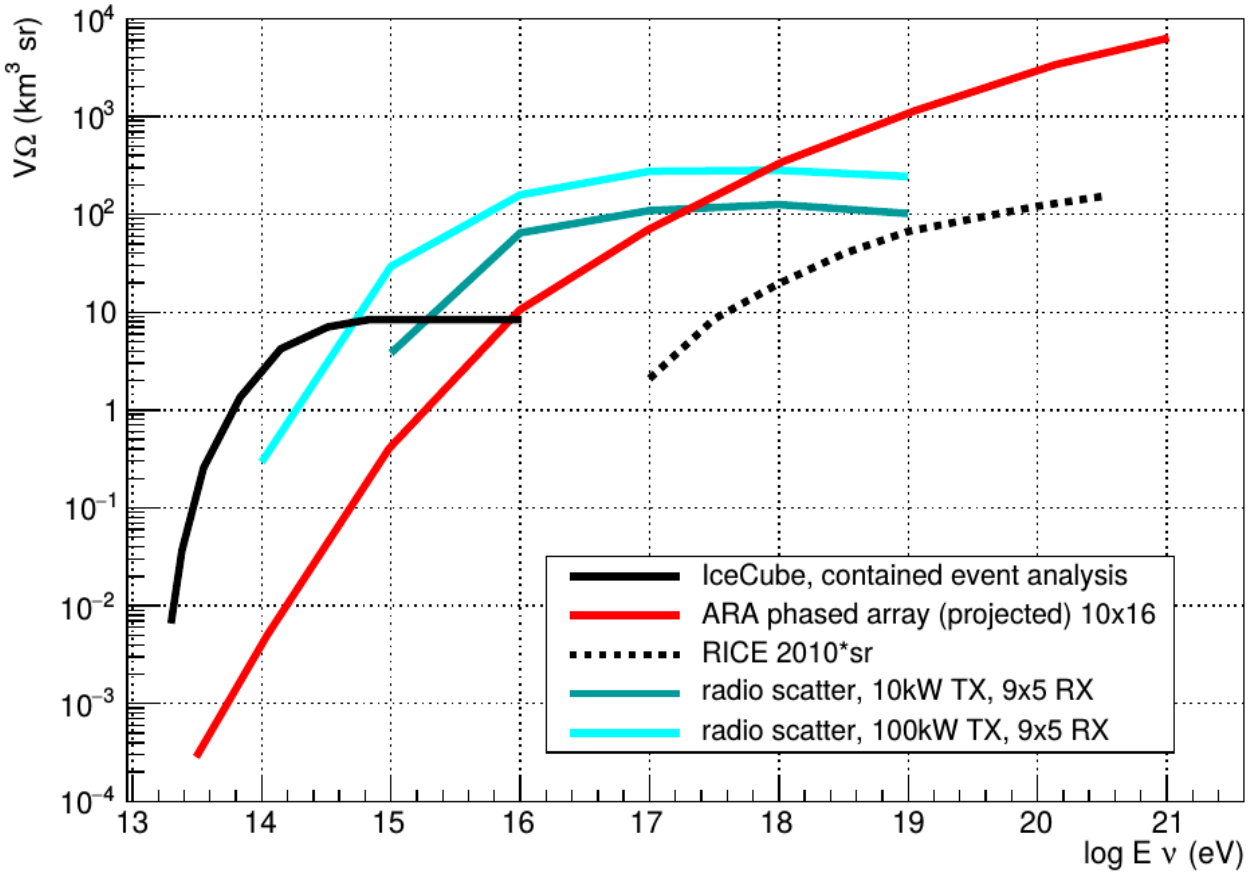
does it work?

run 2 dataset contained multiple DAQs, many more channels, and data taken for several ‘smoking guns’. (sorry, can’t show results yet...)



12-channel DAQ developed at OSU (P. Allison et al) represented by open circles, to characterize the signal as a function of azimuth.

what would a future detector look like?



Effective volume:
Measure of the amount of sensitive material for your detector

for radio, it 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

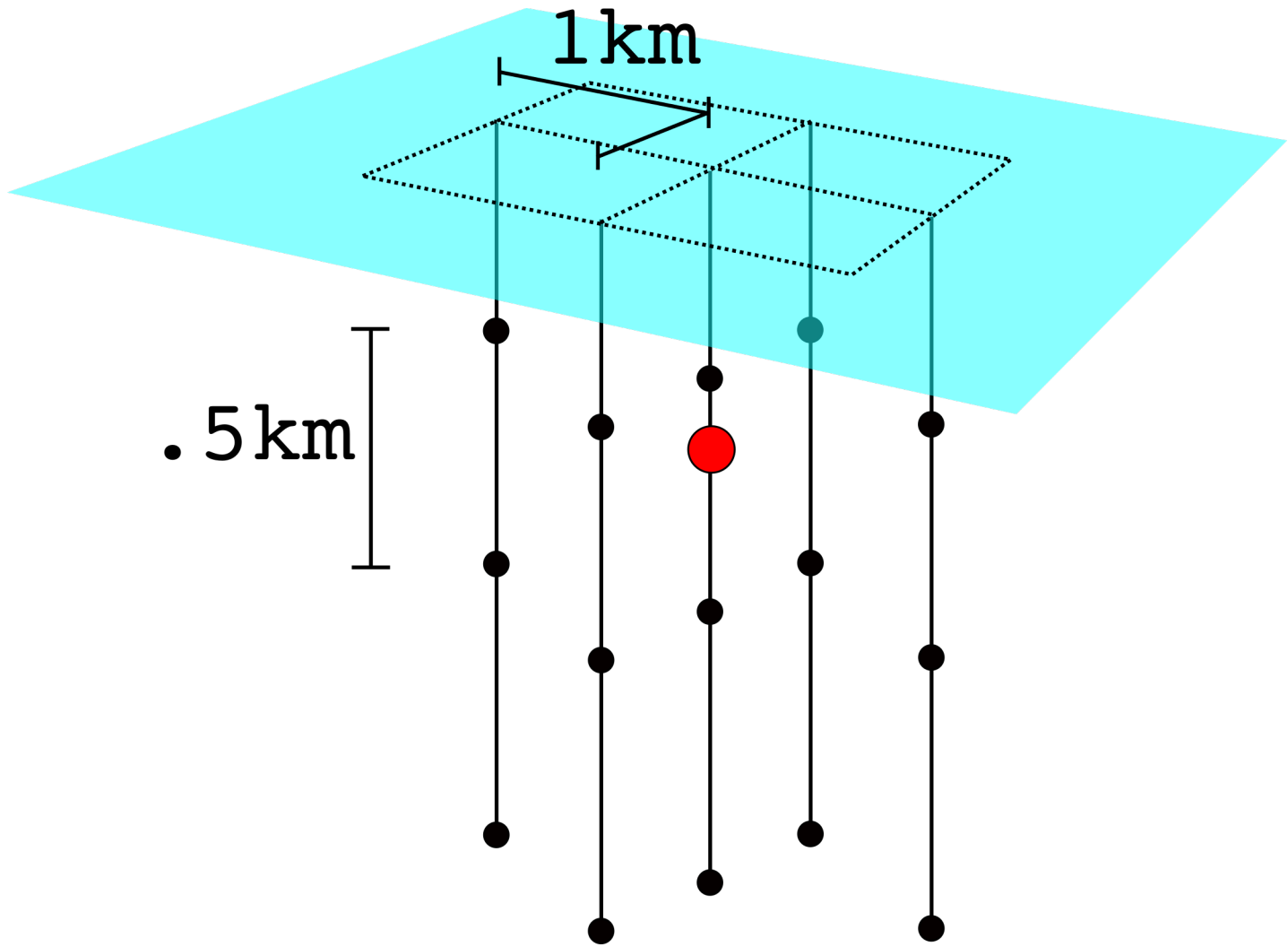
using same settings as simulation which matched run 1 result.

what would a future detector look like?

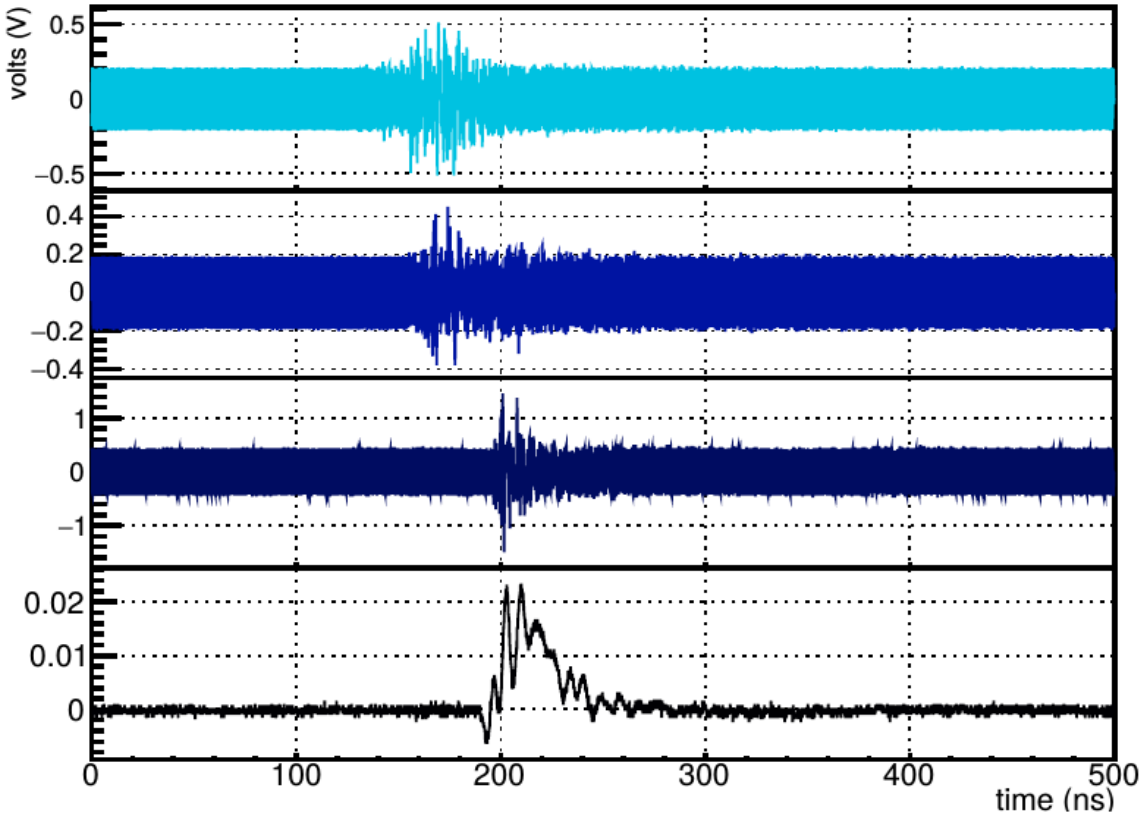
sensitivity curves on previous slides for a similar layout.

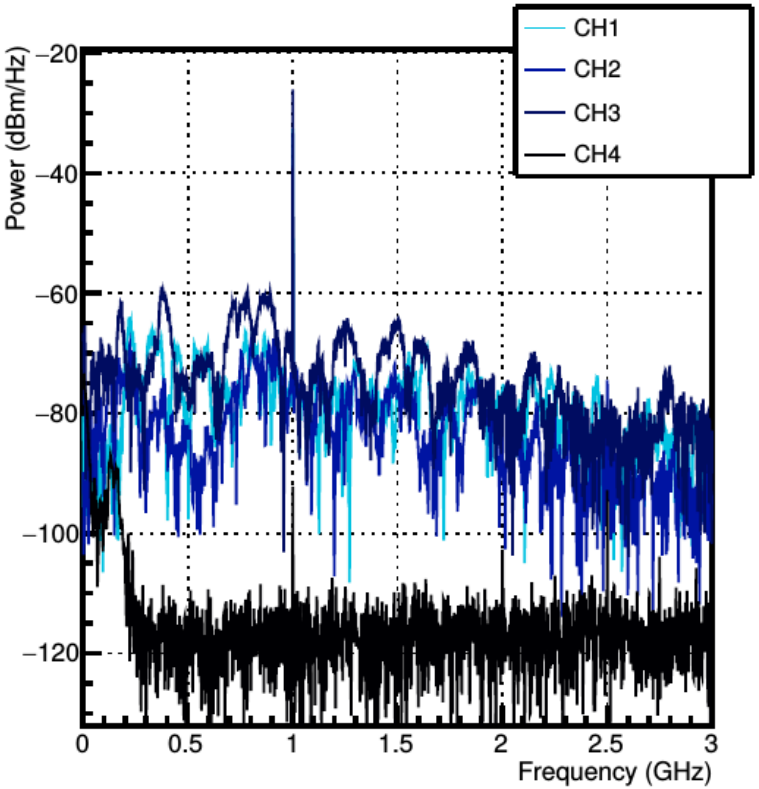
deep detectors in ice, larger than icecube but *same if not better sensitivity with .001 the # of detectors!*

large ice sheet is needed, preferably location far away from other experiments.

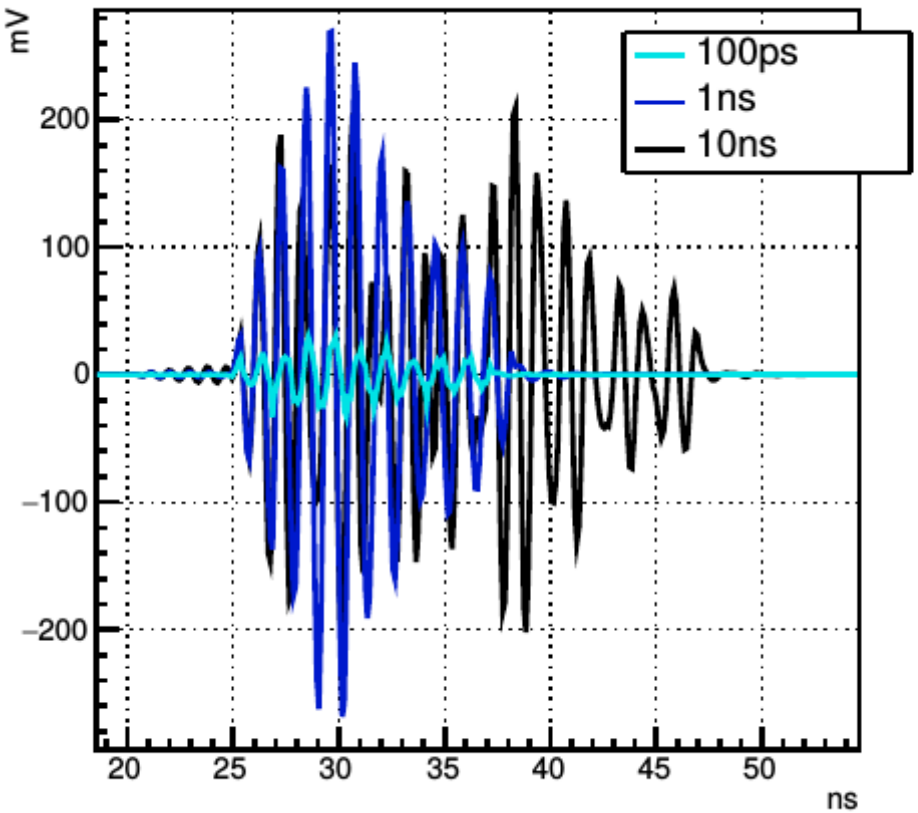


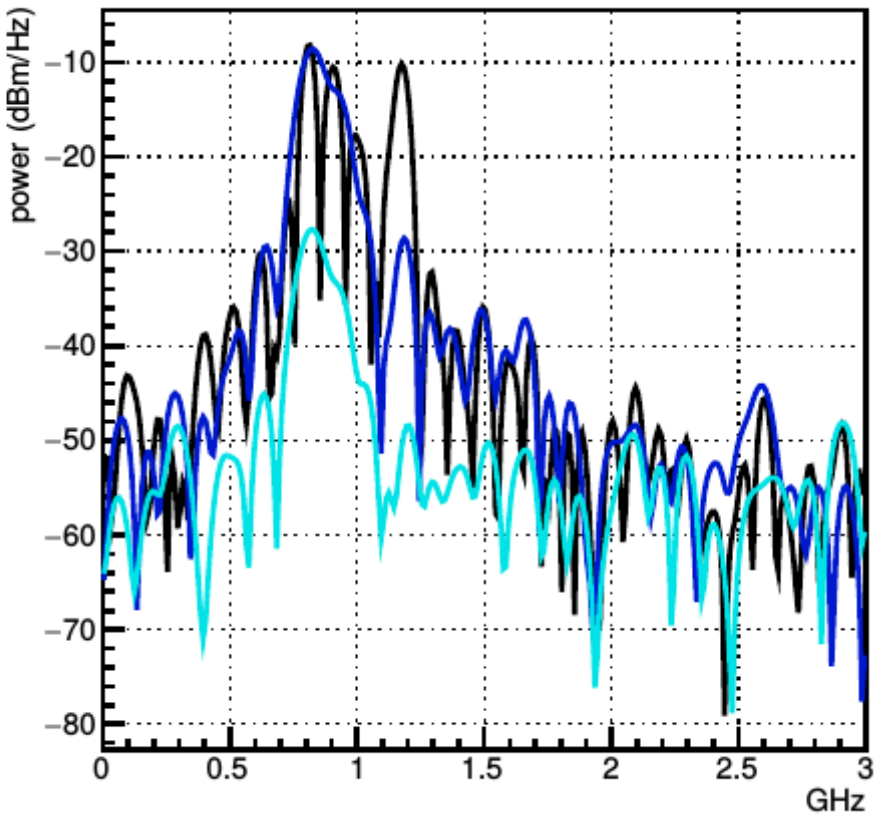
raw data


volts (V)
0.5
0
−0.5
0.4
0.2
0
−0.2
−0.4
1
0
−1
0.02
0.01
0
0
100
200
300
400
500
time (ns)


CH1
CH2
CH3
CH4
Power (dBm/Hz)
−20
−40
−60
−80
−100
−120
0
0.5
1
1.5
2
2.5
3
Frequency (GHz)

plasma lifetime

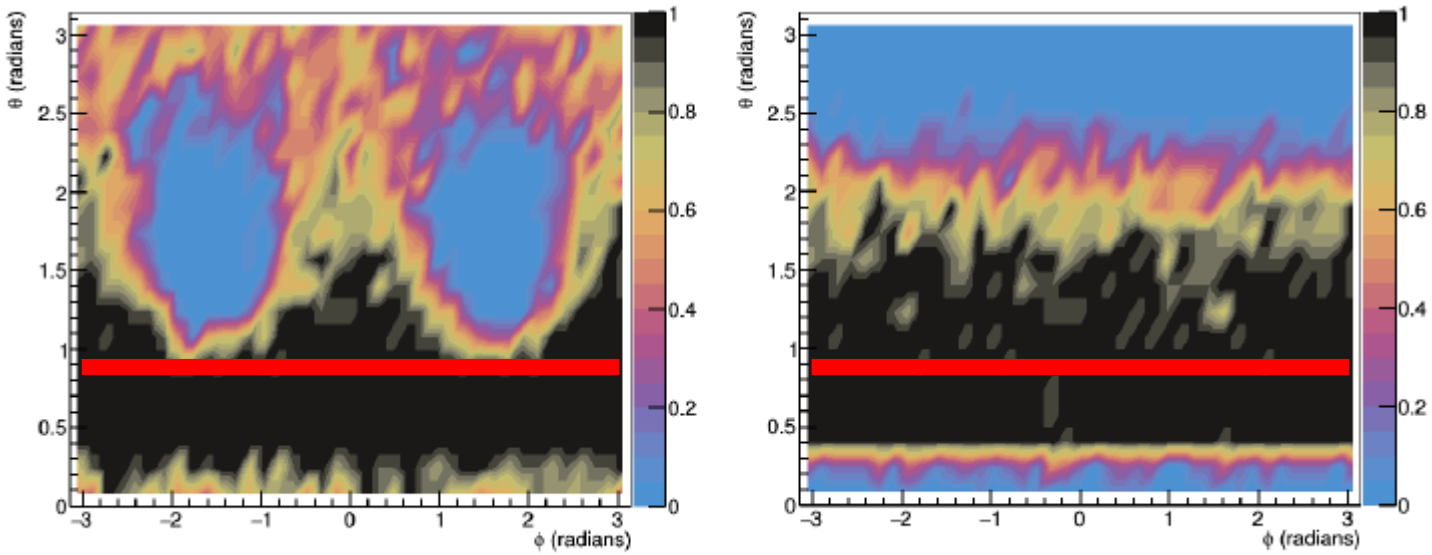




signals vary based on the free electron (plasma) lifetime.

simulation shows return signals for very short lifetimes.

geometric acceptance

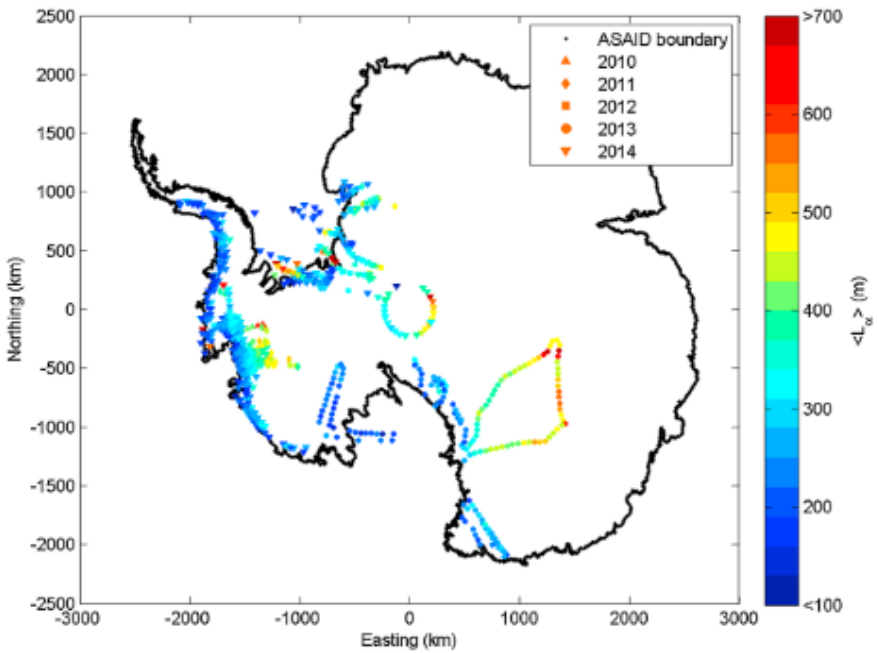


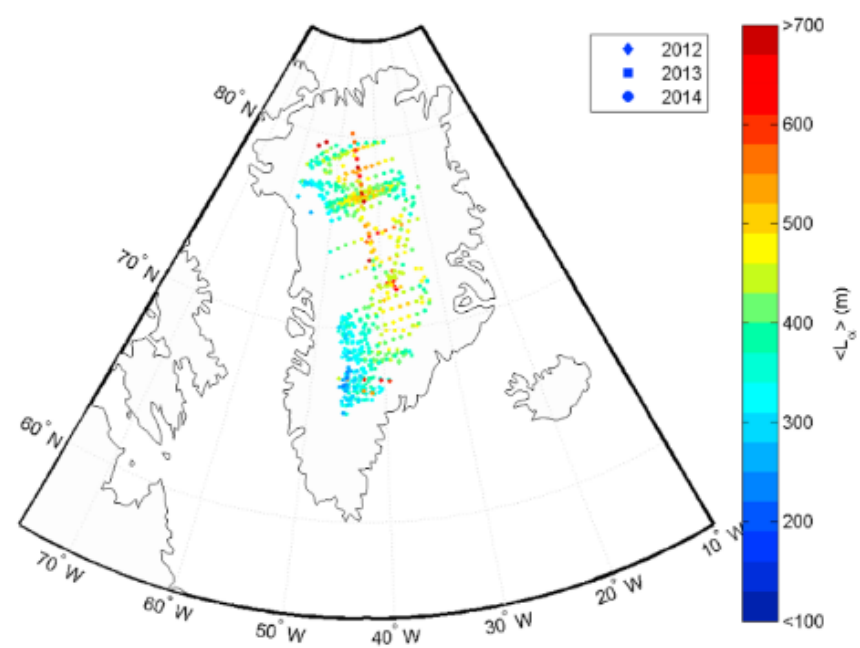
trigger threshold curves for a static shower and TX
RX is moved around the solid angle of the shower

left: vertical polarization
right: horizontal polarization

red: geometric acceptance for 5 sigma Askaryan signal in ice
(~5 degrees)

attenuation length in ice





measurements from CReSIS experiment at KU

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.