Scattering GHz Radio Waves from Ice Targets at the Telescope Array ELS Facility

Seminar at UC Louvain, Belgium

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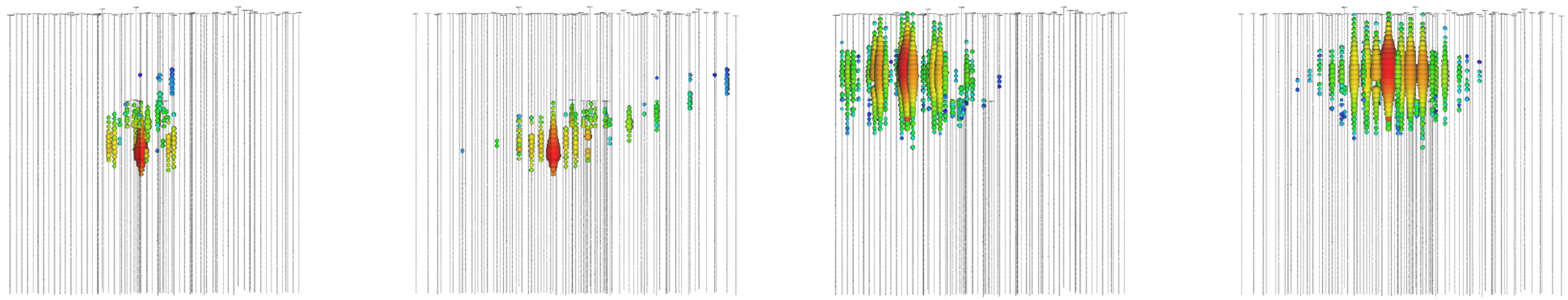
Outline

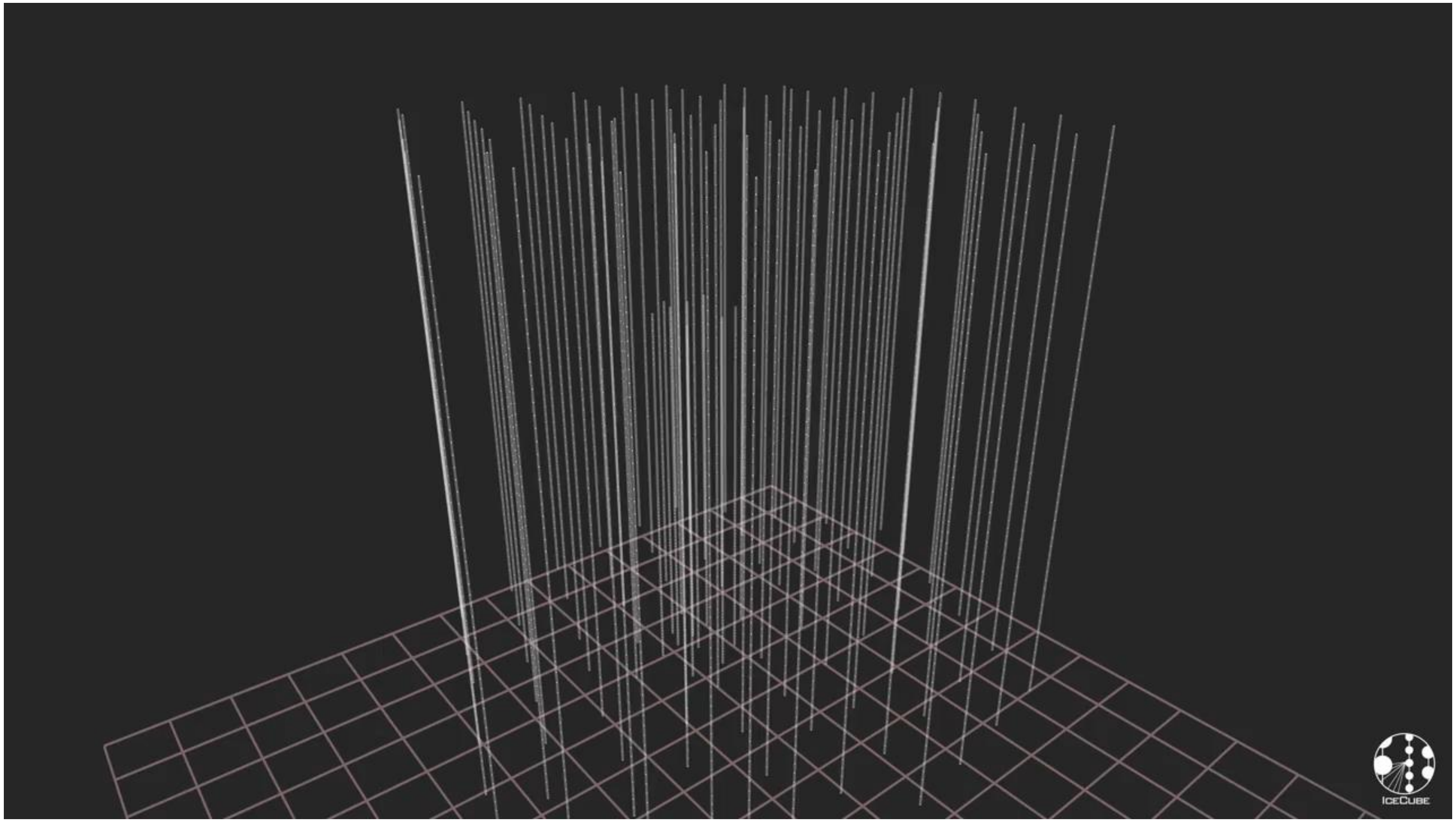
- Motivation: VHE neutrino detection between optical and radio.
- Theoretical Background
  - Scattering EM waves off of plasmas
  - Detection of EAS via RADAR method
  - Creation of free charges in dense media
  - Ice scattering experiments U. Delft
- The Measurement
  - The ELS facility at the Telescope Array BRMFD site.
  - Our experimental setup as parasite to Chiba measurement.
  - A first look at some data recovered.



Motivation

Bridging optical and Askaryan Radio

Era of HE Neutrino Astrophysics is Here

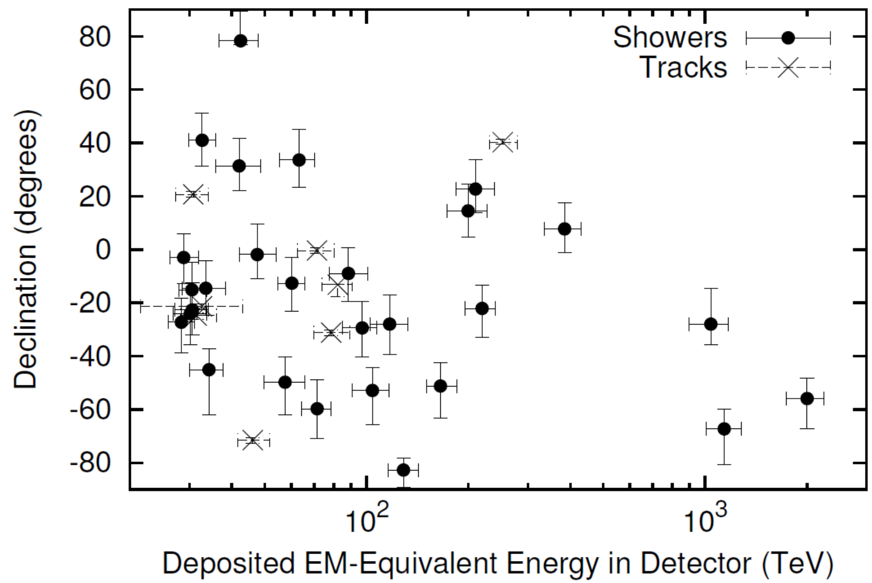


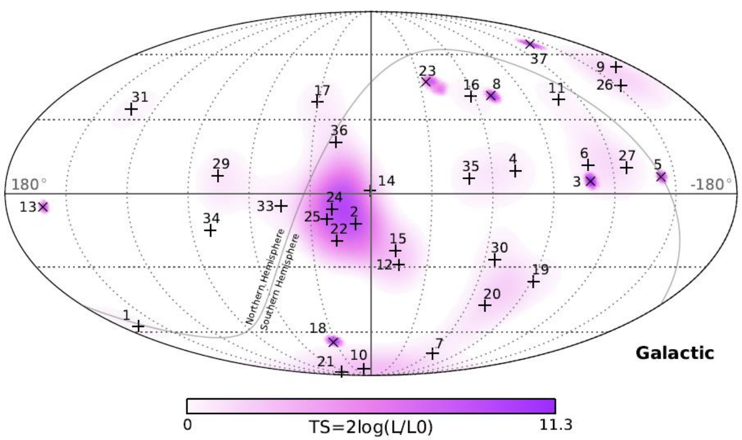
Origins may be uncertain but we do know these are gigantic depositions of energy in the ice with showers spanning 5-7 m longitudinal and 10's of cm lateral dimensions.

Observation of Astrophysical Neutrinos by IceCube

Phys. Rev. Lett. **113** (2014) 101101

37 events in latest published sample of 3-years (988 d) of IceCube data are strongly indicative of neutrinos of astrophysical origin with flux approx. equal to WB flux.



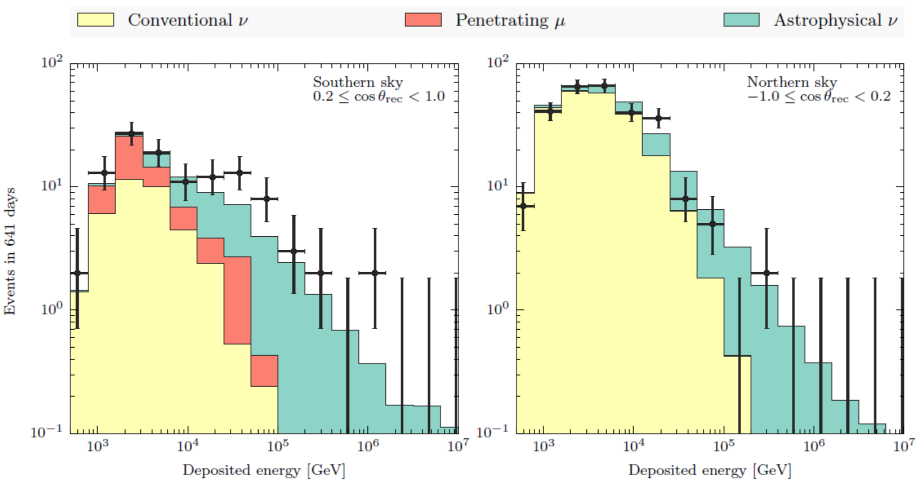


Event statistics rather limited. Adding 4th year gives additional 17 events (reconstructions of angles and energies still not final). Flux consistent with isotropic "diffuse" flux following E^{-2} power spectrum.

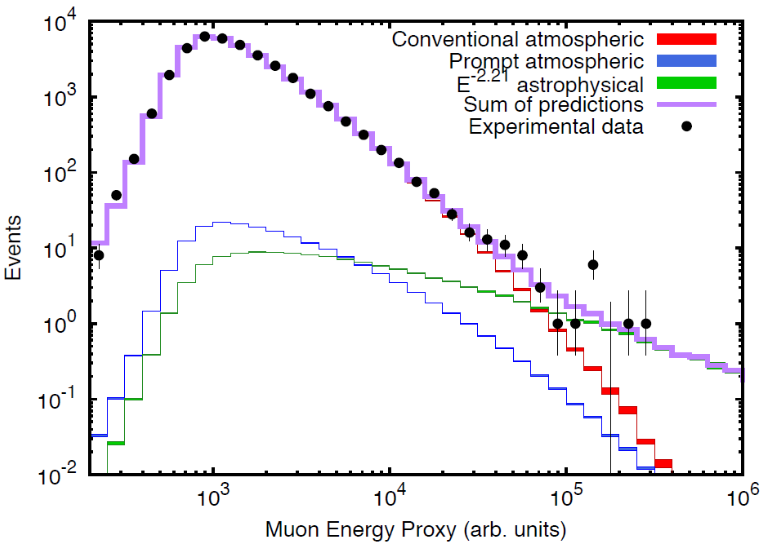
Confirmation via other analyses

Phys. Rev. D **91** (2015) 022001

Extension of veto techniques to lower energies → 388 additional events from 1 TeV to 1 PeV (87 expected from astrophysical origin, < 20 from prompt meson decay)

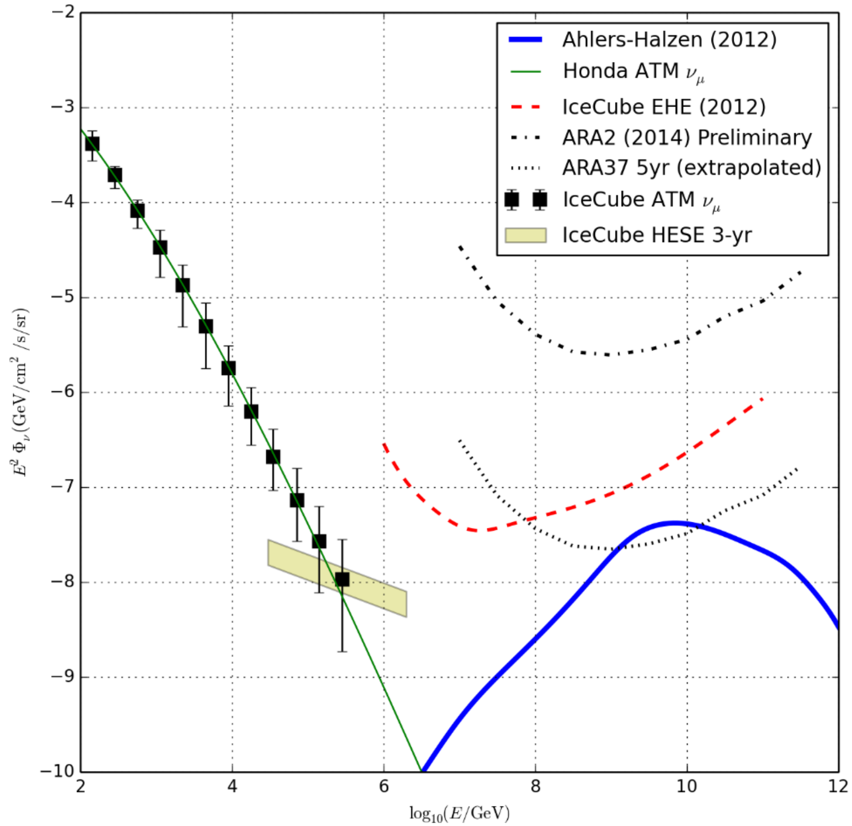


Through-going muon result (figure at right) also rejecting non-astrophysical result at > 3.5 σ



What happens at PeV Scale?

- E^{-2} spectral index would indicate ½ dozen events above 1 PeV while we see 3. Is this significant?
- Rate of > PeV events in IceCube detector is 1 per year → patience is needed while we accumulate statistics in this region.
- Unlikely to observe events at 10 PeV and above.

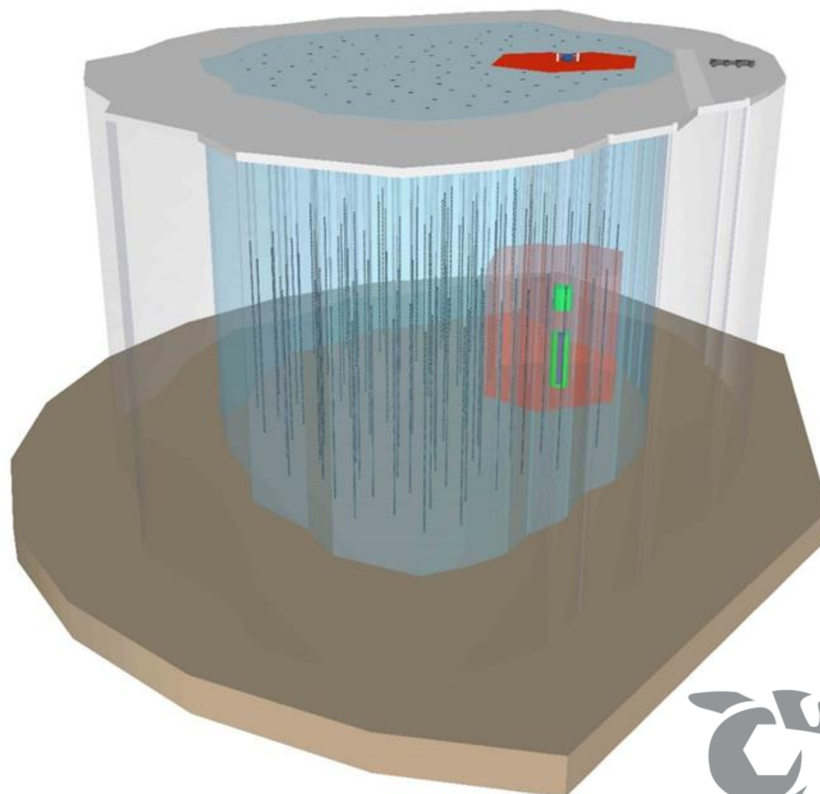


Gen2 IceCube

A primary goal of Gen2 IceCube (white paper released Dec 2014) is to increase by an order of magnitude the effective volume of the existing IceCube facility for high energies – 100 TeV and above.

This is to be done by deploying improved optical sensors – O(100) strings dedicated to the High Energy eXtension – 250 to 300 m apart.

Construction could begin as early as 2018, however, final deployments extend well into the 20's.



GENTWO
Next Generation IceCube Project

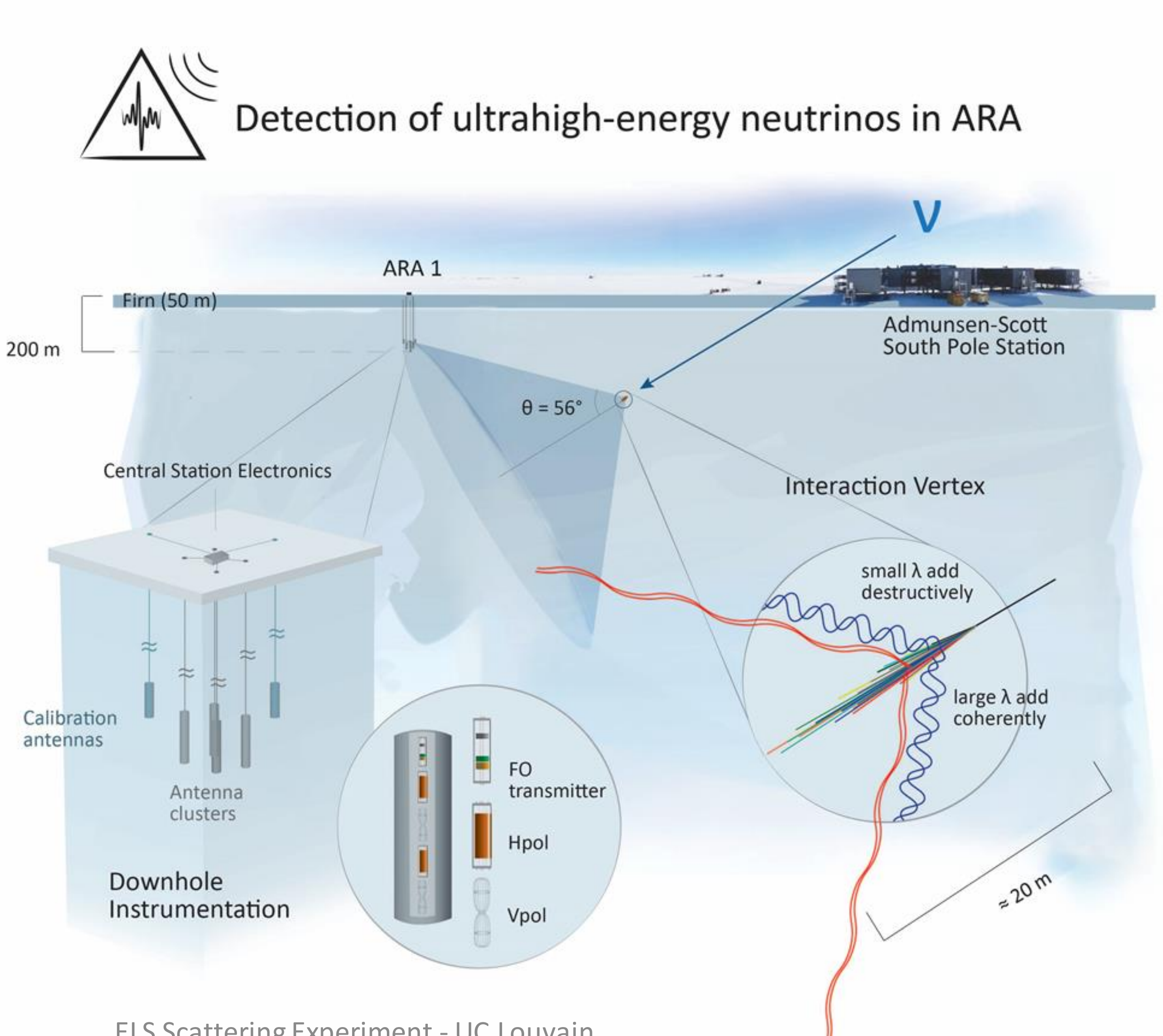
(Passive) Radio for UHE Neutrinos

South Pole Ice is very transparent at radio frequencies, at 0.1 to 1 GHz: > 1km.

Plan: build sparse array covering O(100 km^2) to study neutrinos at the extreme end of the energy spectrum.

Three stations deployed 2012/13 and operating two of them. Science results to come out soon.

http://arxiv.org/abs/1404.5285
http://arxiv.org/abs/1105.2854



ARA's advantages & disadvantages

- Advantages
  - Askaryan radiation understood and modeled – we know how to reconstruct neutrino directions and energies.
  - Askaryan effect has been confirmed in test beam experiments at SLAC and elsewhere
  - Passive technology, in principle low-power receivers can be deployed en masse over extremely large areas
- Disadvantages
  - Askaryan radiation is broadband – receivers system are more complex than narrowband.
  - Antennas should be deployed up to 100's of meters below firm layer. Drilling not easy even small holes.
  - Neutrinos still must come from near horizontal.

Active Sounding using EM Radiation

In other words … RADAR

Detection of Extensive Airshowers with RADARs

Idea has been present for many decades and experiments stretching back 50 years are known, alas, without any mention of results.

Gorham revisited the topic of RADAR detection of EAS in Astropart. Phys. **15** (2001) 177 benefiting from decades of experience using powerful radars for detection of meteorites and lightning ionization columns.

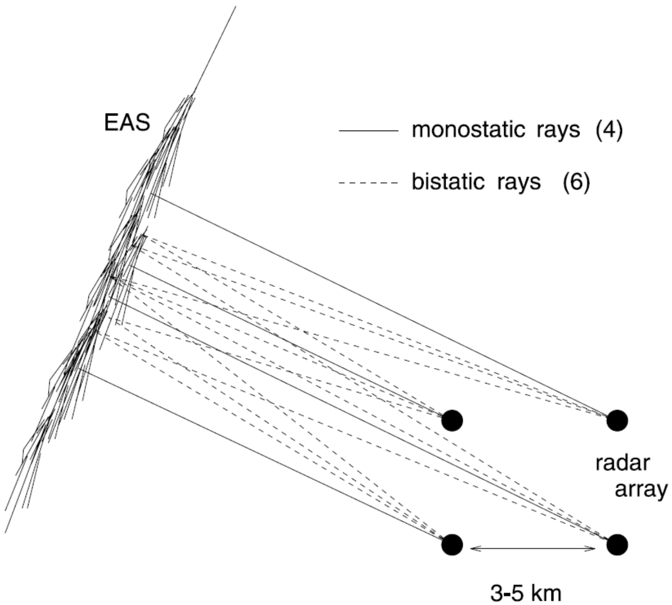
In analogy to meteor/lightning detection, Gorham postulated that ionization of air columns by EAS would produce transient plasmas.

Scattering of EM from plasmas is divided into two regions depending on whether the sounding radiation is above or below the *plasma frequency:*

$$\nu_p = 8.98\,\mathrm{kHz}\sqrt{n_e}$$

- Above the plasma frequency the plasma is said to be **overdense** and acts as a conductor (Gorham used thin-wire approximations in his work).
- Below the plasma frequency the EM radiation is **underdense** and scattering goes as Thomson cross-section – many orders of magnitude weaker.

Bistatic Radars / Radar Cross Sections



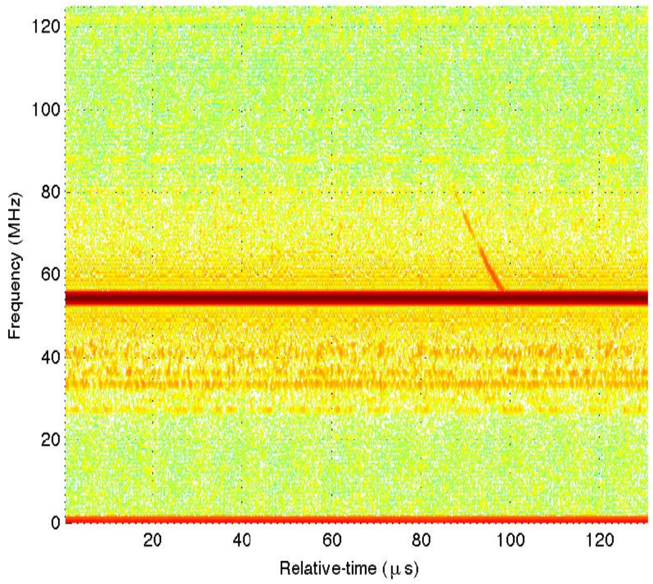
Bistatic Radar Equation

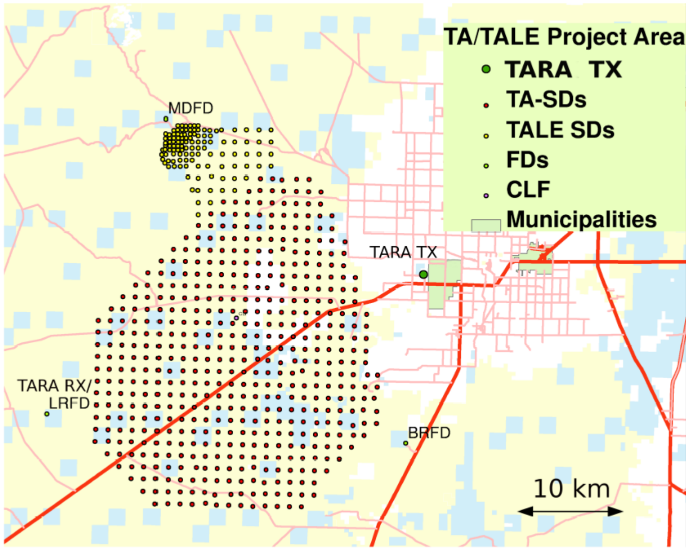
$$P_R = P_T \cdot \frac{G_T}{4\pi R_T^2}\sigma \cdot \frac{G_R}{4\pi R_R^2}\frac{\lambda^2}{4\pi}$$

Not known in above is the RCS (sigma) which Gorham approximates by thin wire and obtained reasonable SNR for realistic geometries.

For ice (considered later) if we take some small fraction of geometric cross section then also obtain SNR >> 1. Note equation in ice must be modified to account for attenuation length of radio in ice (1 km).

Telescope Array Radar (TARA)



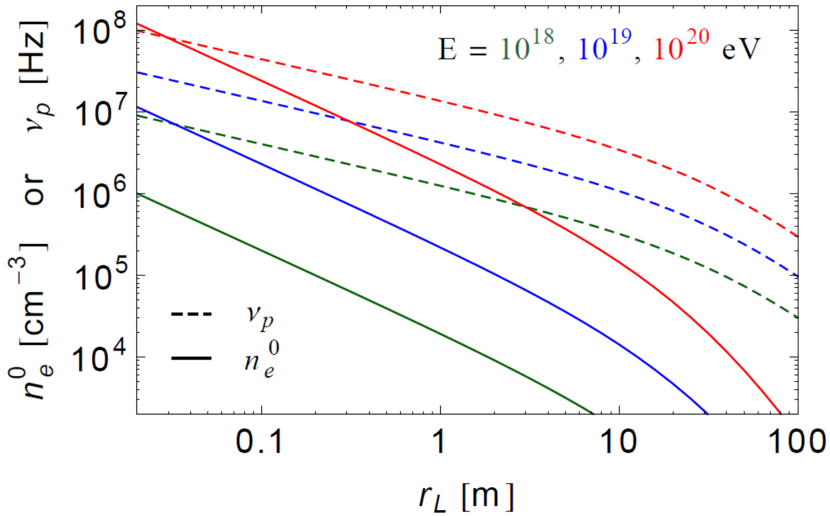


A simulation of the *chirp* signal expected from reflection of CW off of 10 EeV CR interacting midway between Tx and Rx sites. Chirp comes from Doppler shift of relativistic EAS shower front.

TARA uses repurposed CW TV Tx @ 54.1 MHz and 40 kW total power. Receivers are 40 km distant across TA SD array: *bistatic radar* configuration.

Comparison to EM cascades in ice

EAS electron densities



From Stasielak, Engel, et al.
arXiv:1411.7295

$$\nu_p = \sqrt{n_e} \approx 0.5\,\mathrm{MHz}\sqrt{E_p\,[\mathrm{GeV}]}$$

1000x higher density of ice relative to sea level atmosphere → geometry of EM showers is greatly compressed → electron densities are in general much higher. We assume:

$$E_c = 0.0786\ \mathrm{GeV}$$
$$X_0 = 36.08\ \mathrm{g/cm^2}.$$
$$L_0 = \frac{36.08\ \mathrm{g/cm^2}}{0.92\ \mathrm{g/cm^3}} = 39.22\ \mathrm{cm}.$$

and for a Heitler/NKG hybrid shower model (see paper) we get the simple expression for particles at shower max:

$$N_{max}^{NKG} = 1.27\ E_p[\mathrm{GeV}].$$

Finally for electron density we obtain:

$$n_e \simeq 3500\ E_p\ [\mathrm{GeV}]\mathrm{cm}^{-3}$$

Radar Scattering from EM Cascades in Ice

- So, good news is plasma frequencies in dense media such as ice are a fair bit lower in frequency → of order 100's MHz for PeV scale EM cascades like seen in IceCube.
- For these frequencies, attenuation of RF in ice is very long – larger than 1 km
- Surface deployments of Tx and Rx OK– no drilling!
- Unknowns are rather daunting, however:
  - Plasma lifetime – ionized electrons will recombine and eventually (immediately?) plasma is dissipated
  - Plasma collision frequency – sounding radiation must be below plasma frequency and simultaneously above the collisional frequency for scattering to take place. Stasielak et al. argue this effectively nullifies overdense scattering for EAS.

Delft Studies

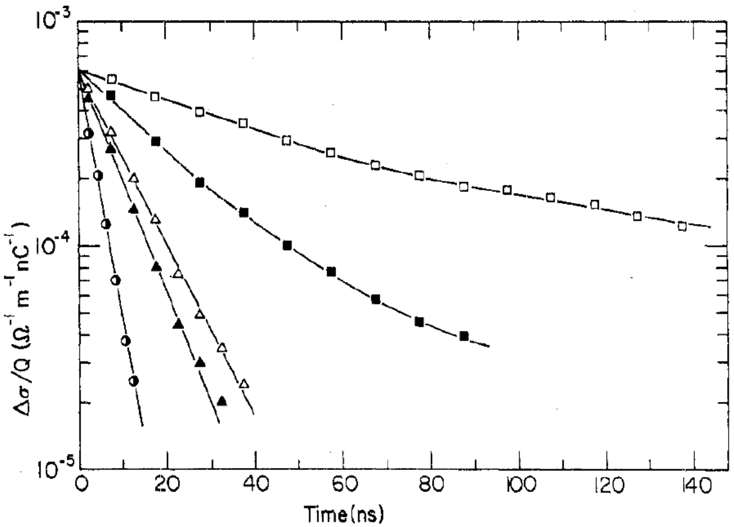


Figure 2. Change in conductivity per nanocoulomb with time following pulse irradiation, 2.5 ns, of ice for the following conditions of temperature in degrees centigrade and beam charge in nanocoulomb in parentheses: (◑) −46.2 (1.37 and 0.25); (▲) −55.9 (1.38); (△) −55.9 (0.23); (■) −79.8 (1.51); (□) −79.8 (0.24).

Warman, de Haas, and Verbene. *J. Phys. Chem.* **84** (1980) 1240

- Scattering X-band microwaves from cold ice which they report as conductivity changes.
- Irradiation of ice with 3 MeV electron beam; total beam charges of order nC.
- They note at temperatures below -40 C, transients in conductivity rise from ~ps lifetimes to 10's of ns.
- In addition, even at higher temperatures, between -10 C and – 40 C, a very weak conductivity change but much longer lived – O(100's) ns – observed. Attributed to positive charge carriers.

Summary Part I

- Motivation: find new detection technology for neutrinos in PeV – 100 PeV region.
- Future proposed optical observatories online on timescale of 10 years to dramatically improve statistics in this region.
- Active sounding has been tried for detection of EAS with no positive results thus far.
- Situation in dense media possesses certain advantages but significant unknowns which could be gamestoppers – very high risk.
- Therefore, what can be cheaply done now to answer some basic feasibility questions?

The ELS Facility

Telescope Arrays Fluorescence Detector End-to-End Calibration Tool

Design: LINAC in a Shipping Container

Parameter	Value
Beam Energy	40 MeV
Beam Intensity	10^9 e^- per pulse
Rep. Rate	< 10 Hz
Pulse Width	3.5 ns - 1 μs

Originally conceived of (and still serving) for calibration of TA fluorescence detector (FD) on Black Rock Mesa. FD camera images fluorescence from beam at distance of O(100m) → no atmospheric effects.

Full array calibrated with Central Laser Facility.

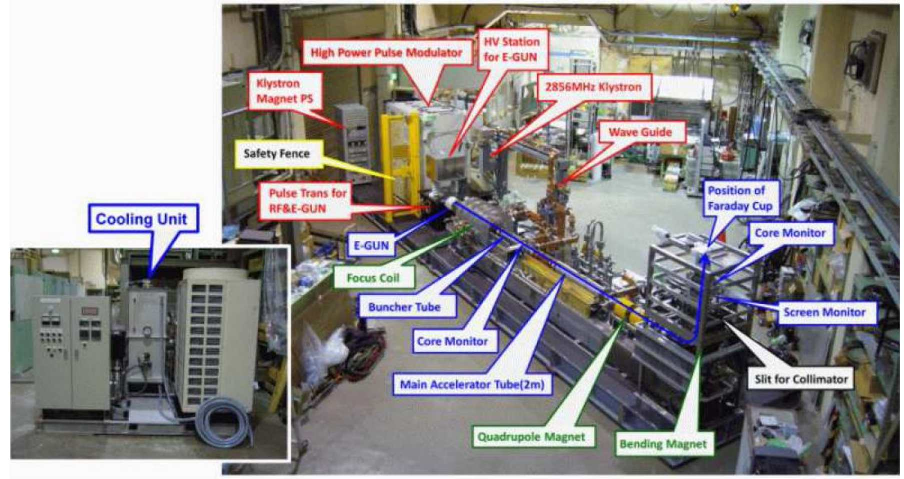
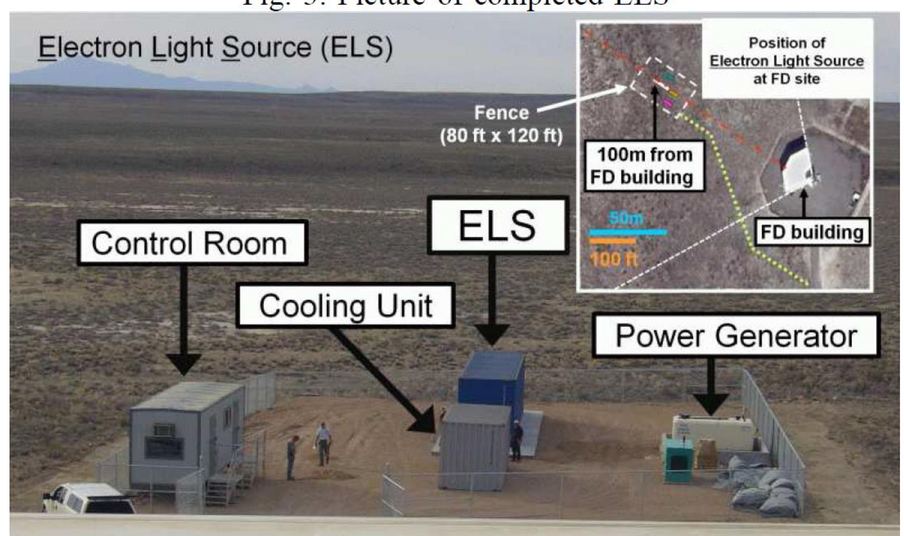
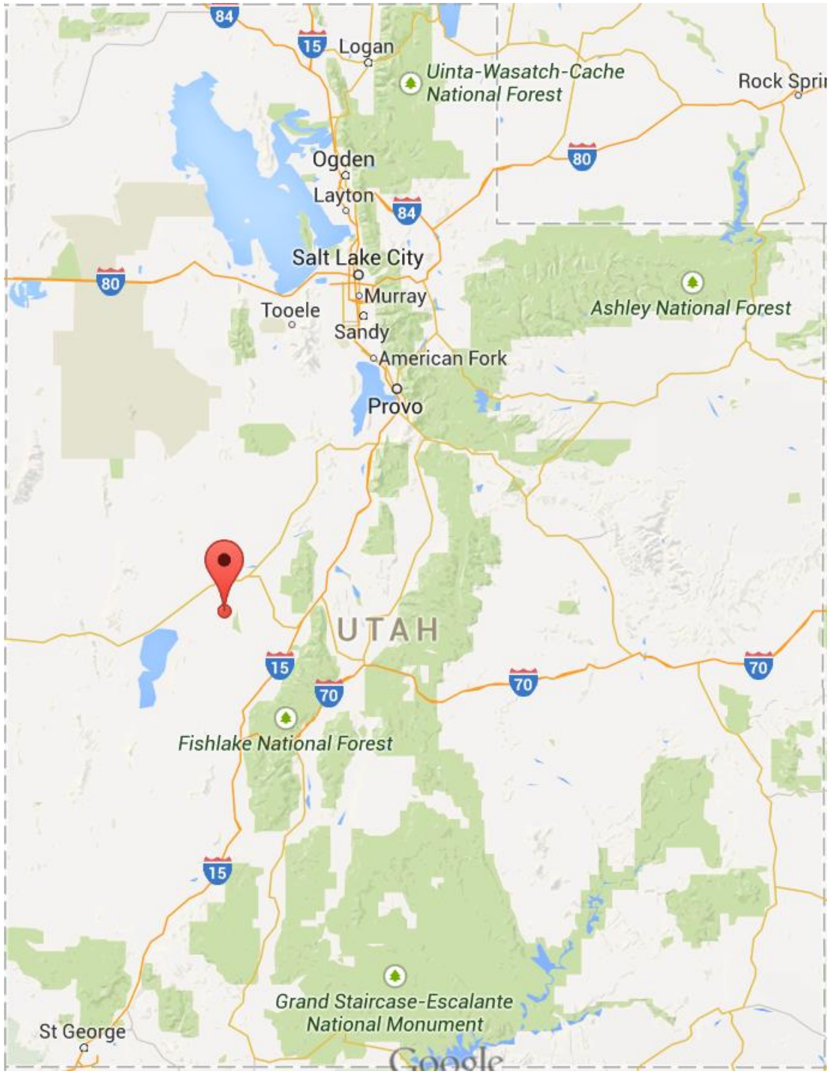


Fig. 3: Picture of completed ELS

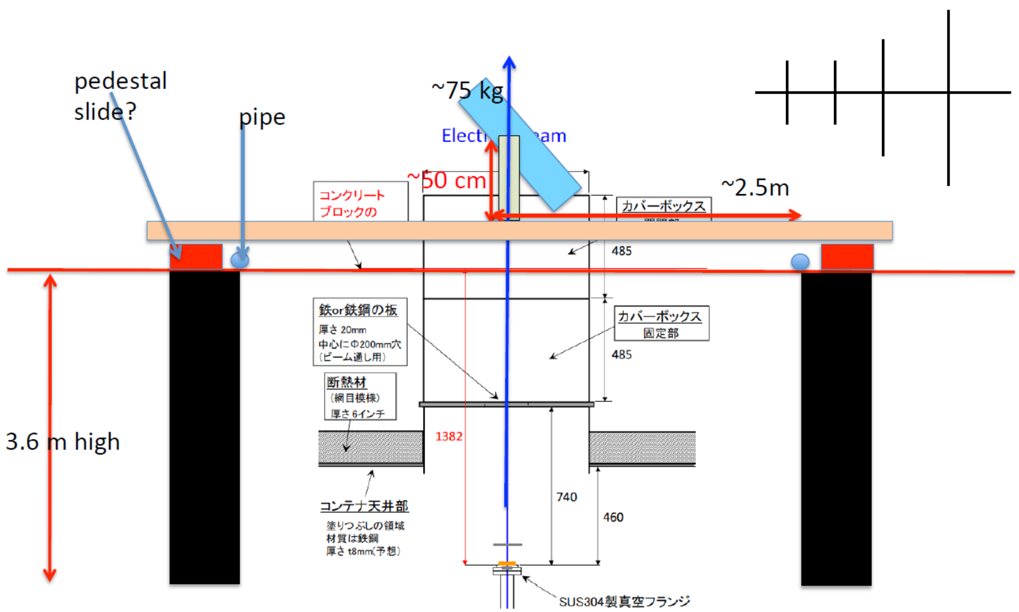


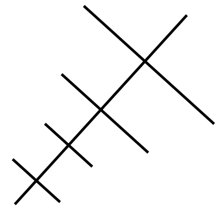
T. Shibata et al. Proc 31st ICRC (2009)

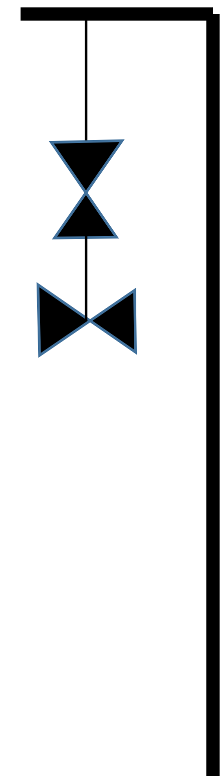
Location: 20 km SW of Delta, UT



Our Ticket In: S. Yoshida Group (Chiba)







Experimental Setup

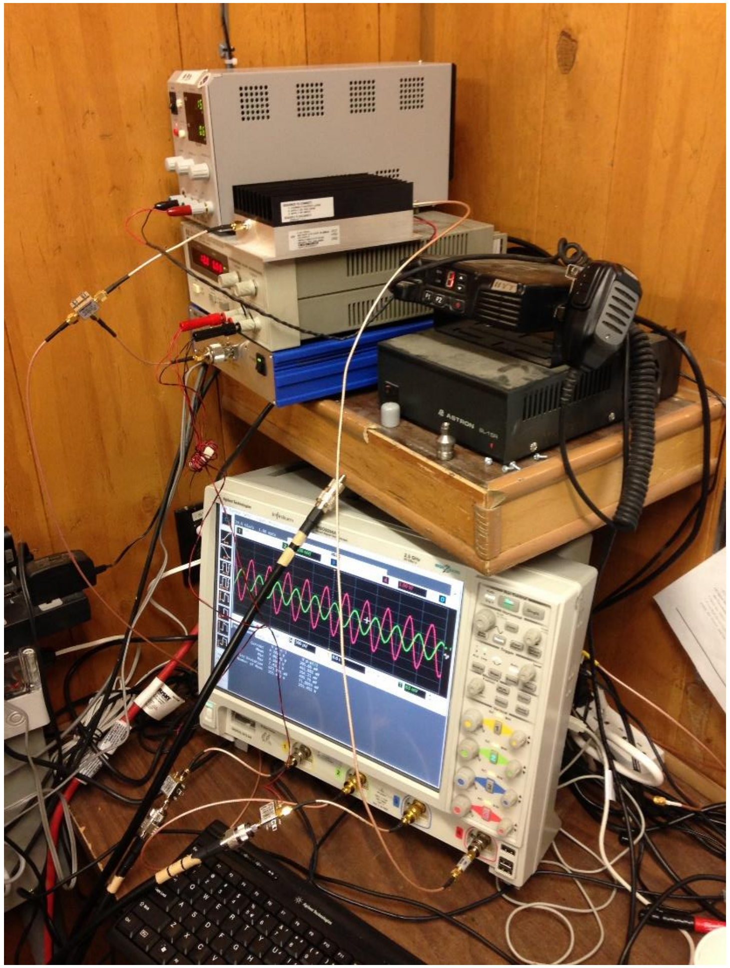
Being a parasite experiment (not even sure we were going to get to run) we optimized on inexpensive hardware:

- Tx/Rx antennas: high-gain (20 dBi) WiFi antennas from amazon.com
- Signal generator: Mini Circuits SSG-6000RC 0-6 GHz RF synthesizer with variable attenuation control. USB computer control.
- Transmit power amplifier: 1 Watt ZHL-42W+
- Receive gain blocks: ZX60-6013-S+
- 120’ of low loss LMR-400 cable on Tx
- 100’ / 120’ LMR-400 on CH1/CH3 Rx
- $3 Home Depot cement fence feet and PVC piping - $1 per foot.

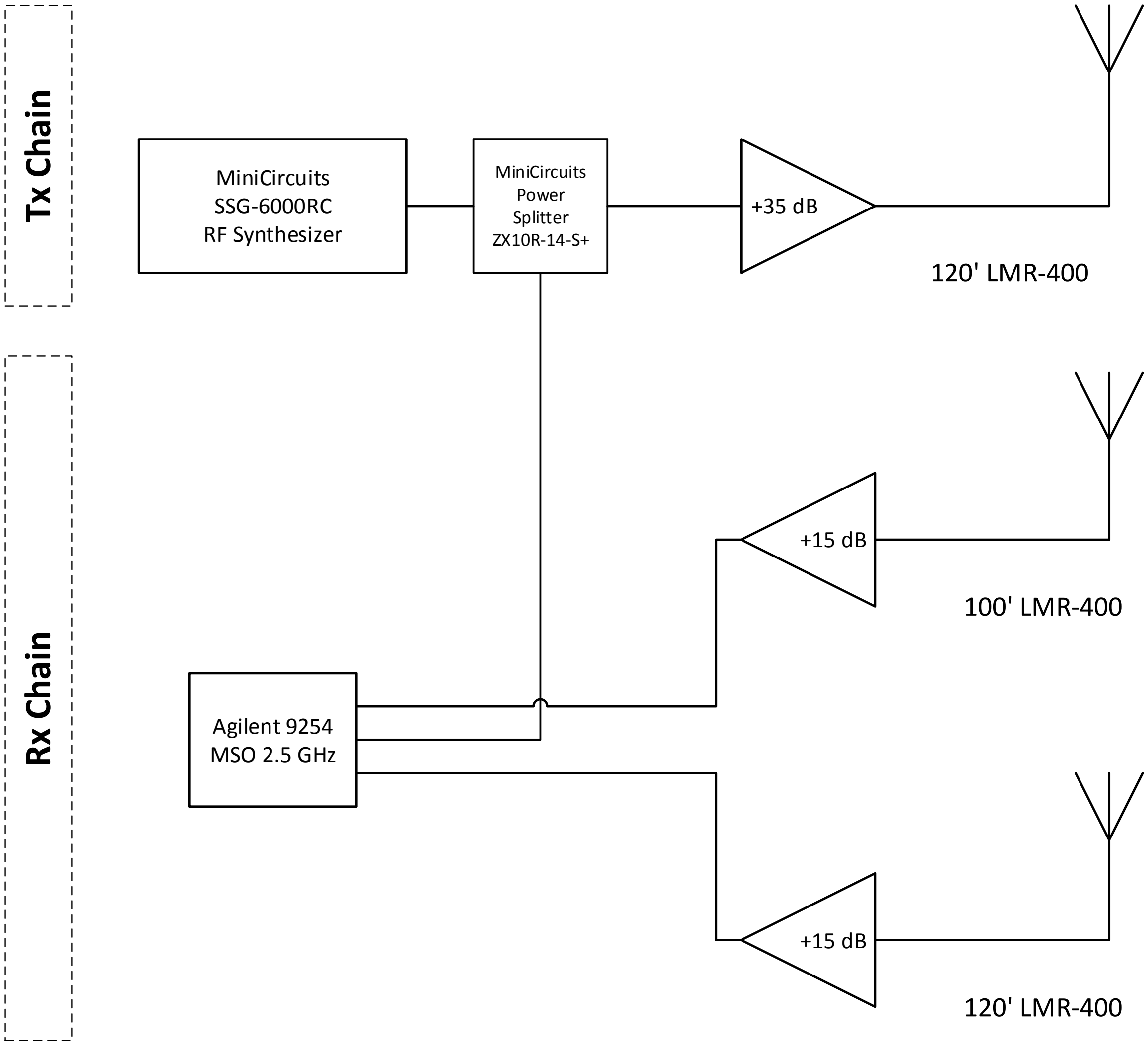
Data Acquisition

All waveform captures taken with master trigger from ELS – beam was mostly synchronous:

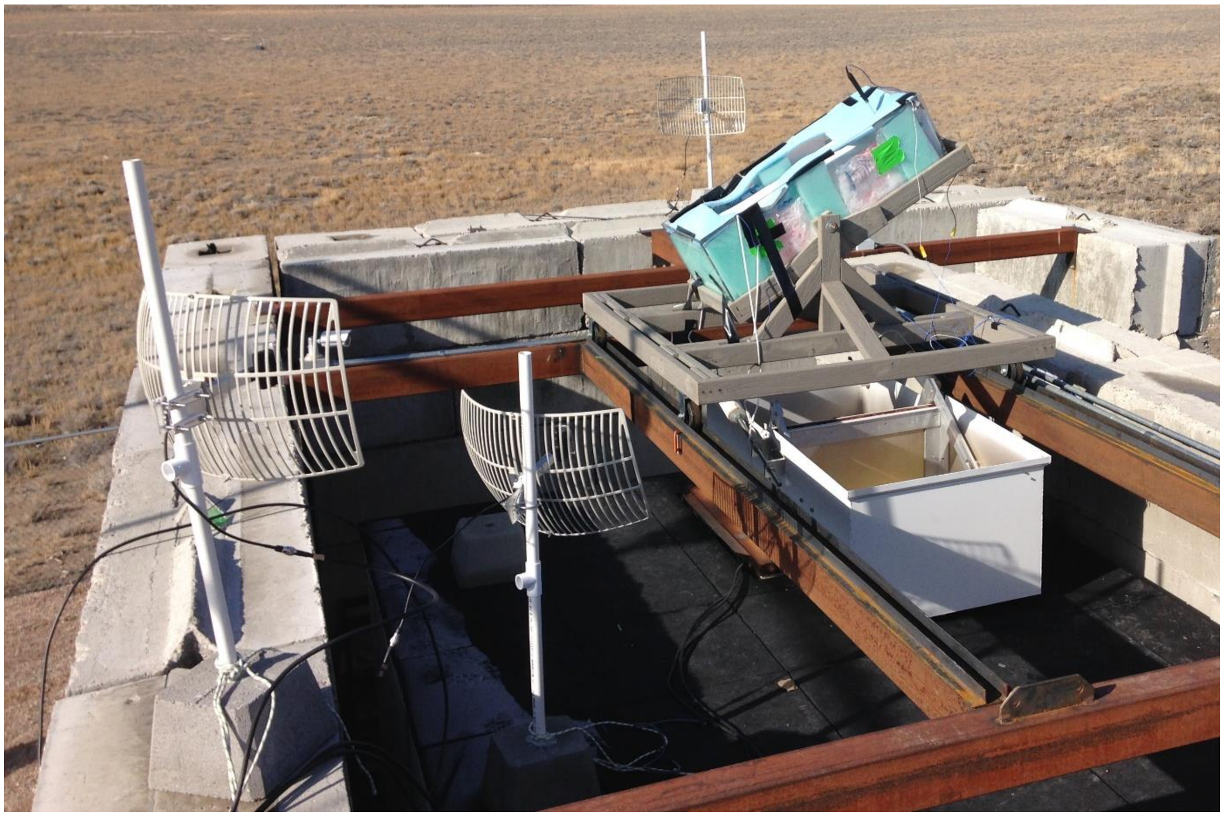
- Data acquisition system: Agilent 9254 MSO (2.5 GHz, 20 GSPS. Readout via TekVISA scripts written in Python (Aongus).
- Wall current monitor to get real-time beam current was recorded by Chiba group.
- Captures of 1 Tx and 2 Rx antennas along with digitized master trigger signal. Acquisition clocks synchronized by NTP but I noted a 2-3 s clock offset when trying to match Chiba WCM.
- 20 us capture window @ 10 GSPS

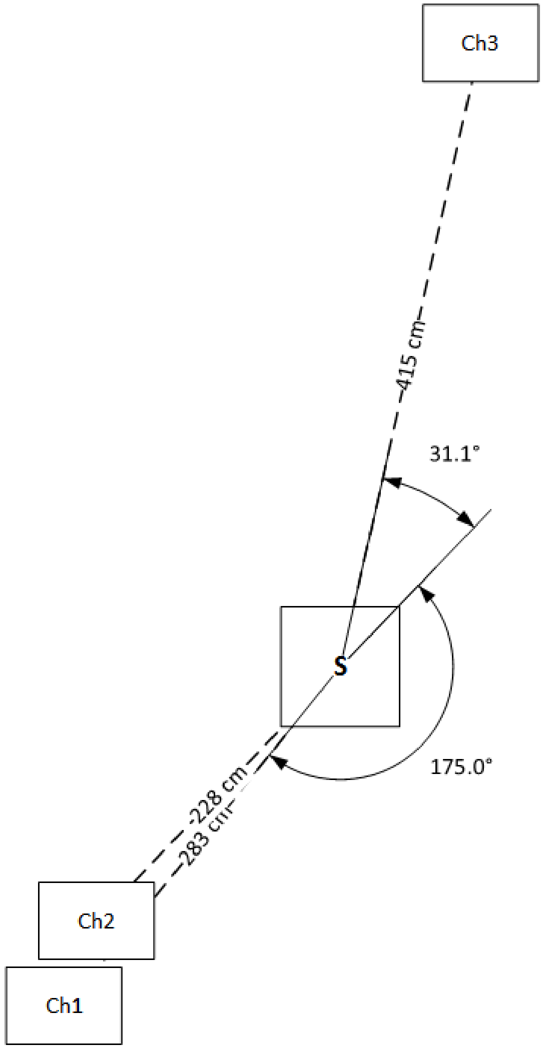


Signal Chain



Scattering Geometry





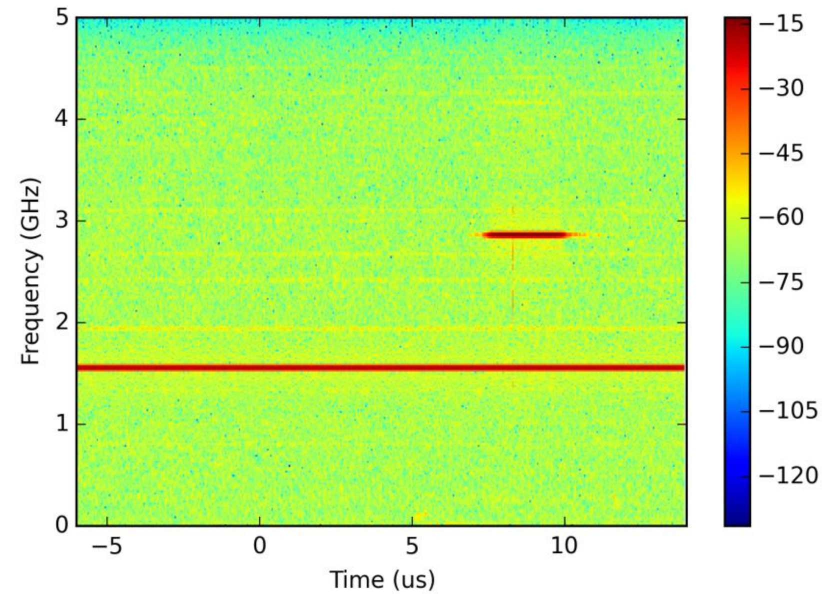
First Results

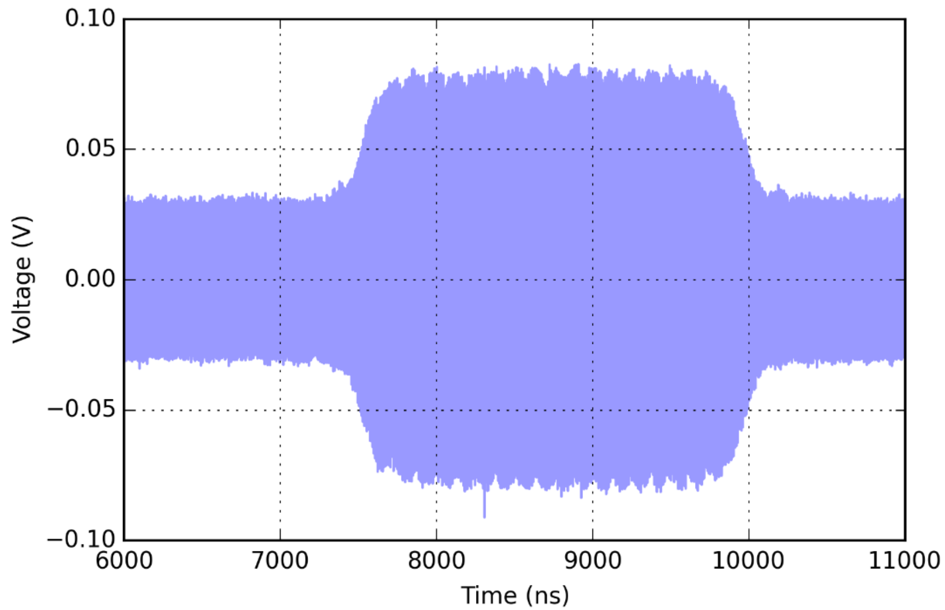
Overview of Data Taking

- ELS facility beam started on Jan 11th. We had beam a total of 7 days.
- Each day the beam lasted approx. 5 hours with several interruptions per day to change configurations.
- The ELS beam rate was fixed at 0.5 Hz
- Our livetime was just over 4 hours and includes 28739 data points spanning various configurations of targets driven by the Chiba group.
- In all cases the Chiba group desired a very short spill – O(3-5) ns to simulate Askaryan radiation. However, this came at the expense of some beam charge: all except the first few runs ran at 40 pC instead of the intended 160 pC because of filament heating problems.

Time & Frequency Domain Tx @ 1.55 GHz

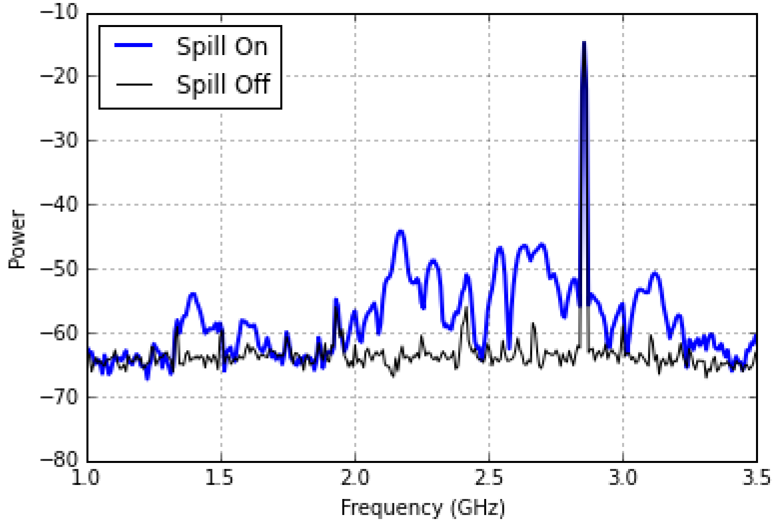
Unfortunate surprise klystron 2.857 GHz EMI was very strong → problem for limited dynamic range of receiver system.

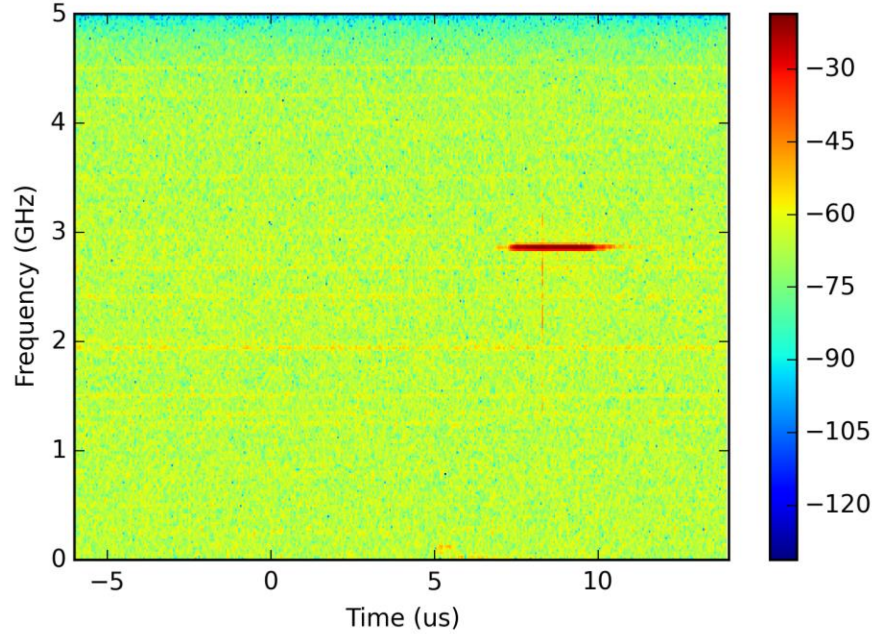


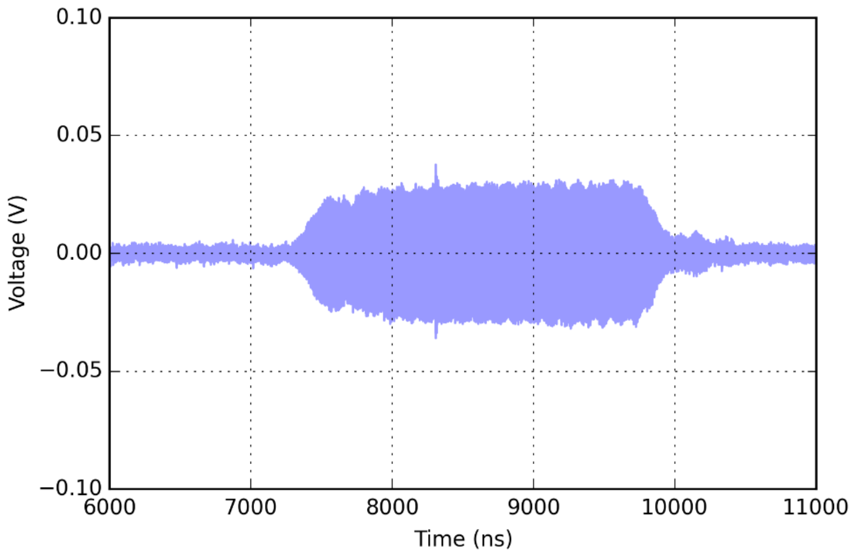


Sudden "birth" signal? the spur clearly visible at 8.3 us in T/F is seen also by the Chiba group looking for Askaryan. Not related to our Tx. Not TR.

Time & Frequency – No Tx





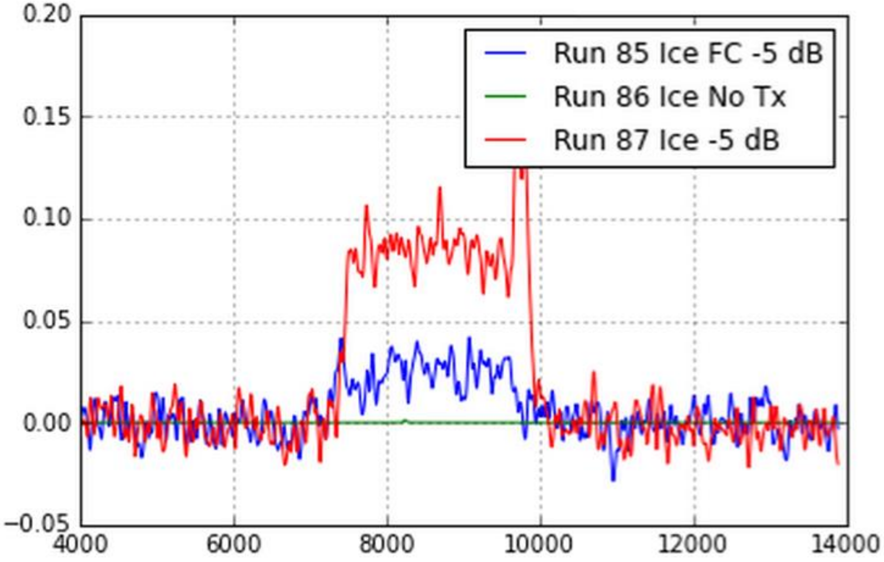


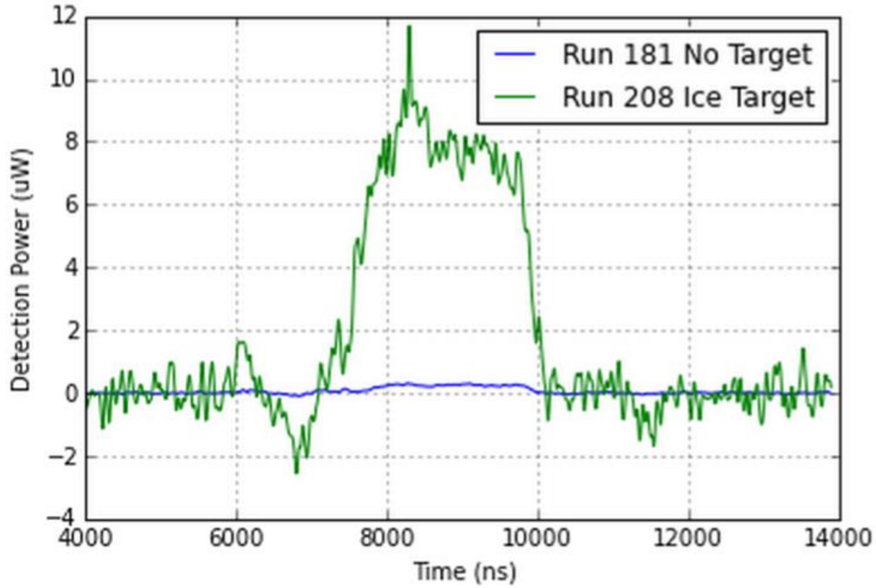
This transient is under investigation by both groups → serious background for Askaryan and any scatter signal. It's not TR as it is present even without any target. Postulate emission from sudden appearance of beam current outside of accelerator pipe.

Scattering of Sounding RF Observed?

Very preliminary …

Strange Signal which Occupies 2.5 us Klystron Activation Time





This would be really weird: the beam has been confirmed via Faraday Cup and Wall Current Monitor to occupy only O(5 ns) around 8.33 us. However we see a signal at the Tx frequency +/- 20 MHz which scales with the Tx power and behaves sort of right with respect to choice of target or whether or not beam blocked by Faraday Cup for charge calibration. Asking the LINAC experts if any possibility for acceleration of residual stuff. **Most likely an instrumental effect.**

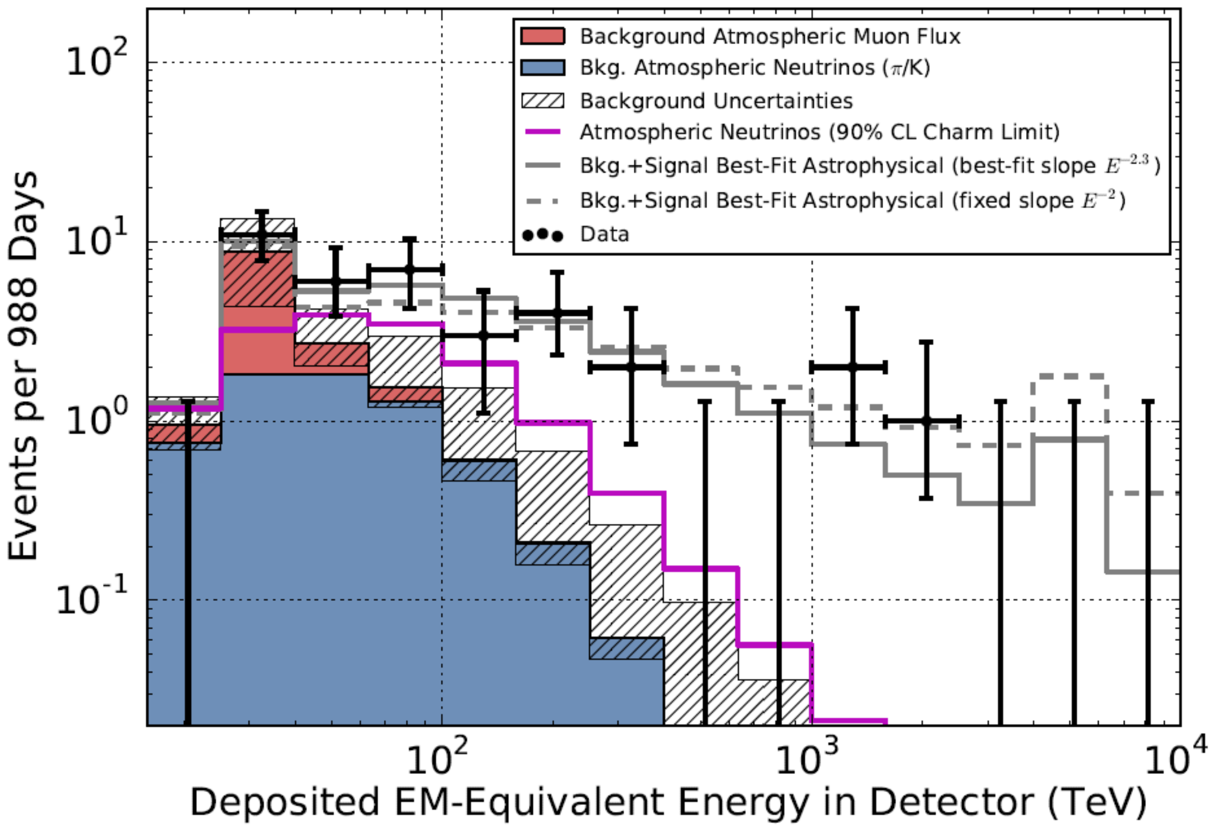
Conclusions

- Clearly a lot of analysis left to do. Moreover, the theoretical treatment of scattering in serious need of attention.
- We (KH, KdV, AoM, TM) have been working on modeling of scattering – in particular KdV. Two methods being used: (a) semi-analytical; (b) computational electrodynamics using FDTD solver.
- As parasite experiment we didn't really have any say in configuration at ELS. But this was a great opportunity and analyzing the data has made us think about designs for future beam tests – looking into possibilities at Fermilab test beam facility.

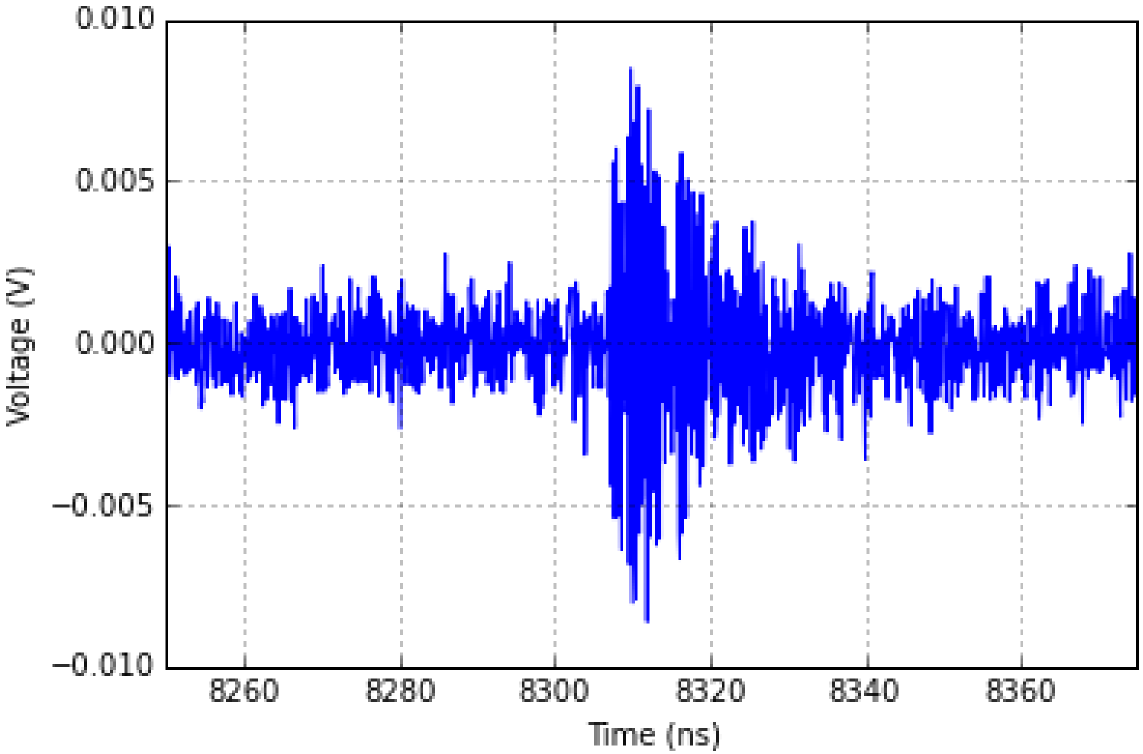
The End

Backups Follow

HESE 3-yr Deposited Energy



"Elmo" with Klystron Filtered Out



Cable / Amp Characterization