Askaryan Calorimeter Experiment (T-530): New Detector Research and Development

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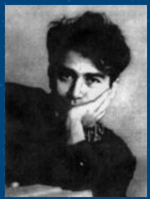
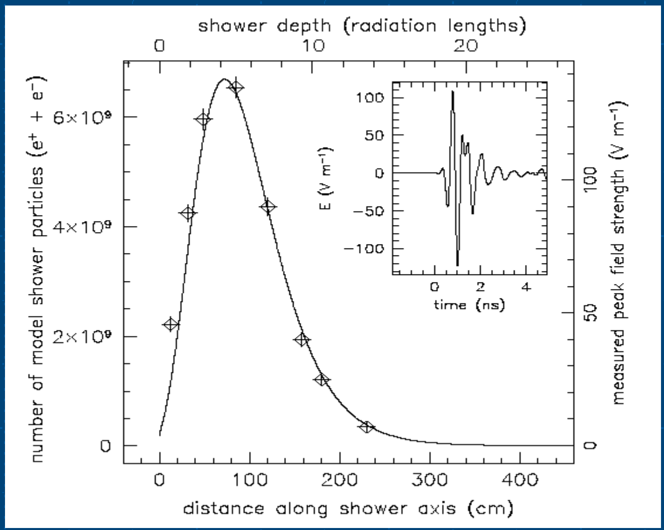
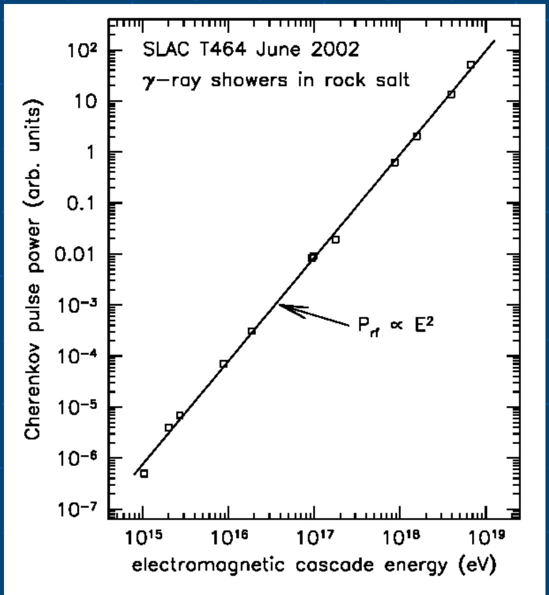
Askaryan Effect: confirmed in 2001 at SLAC





Saltzberg & Gorham et al. PRL 2001

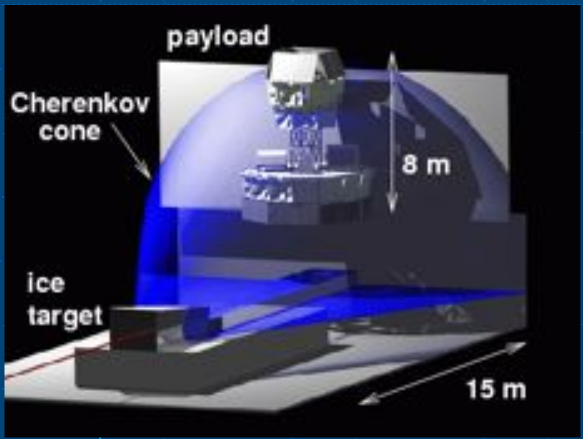
David Saltzberg, UCLA



Gorham et al. PRD 2003

- Coherent radio emission from excess negative charge in an EM shower
  - e- upscattered into shower, e+ annihilated → ~20% -ve asymmetry
- "Shower" in solid media: thin disk of HE particles (mm thick, few cm wide)
  - These also occur in the atmosphere due to high energy cosmic rays
    - But are much more diffuse: ~meter thick and tens of m wide
- → At radio wavelengths longer than ~10-20 cm a shower in **ice**:
  - **appears as a single charge of $Z \sim 10^8$ → $Z^2 = 10^{16}$ x single e-**

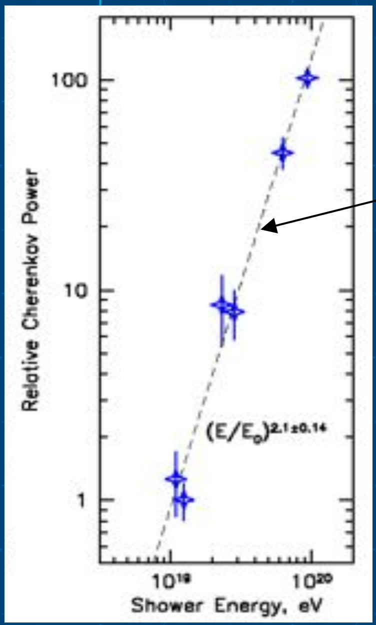
SLAC T486: Askaryan RF pulses from ice

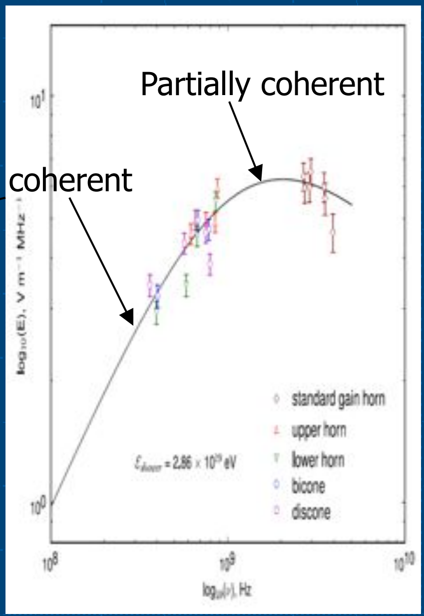


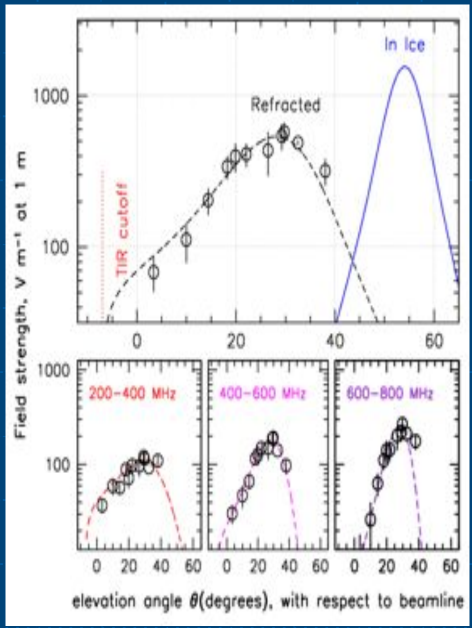
End Station A, SLAC, 2006

Thanks to P. Chen, C. Hast, SLAC

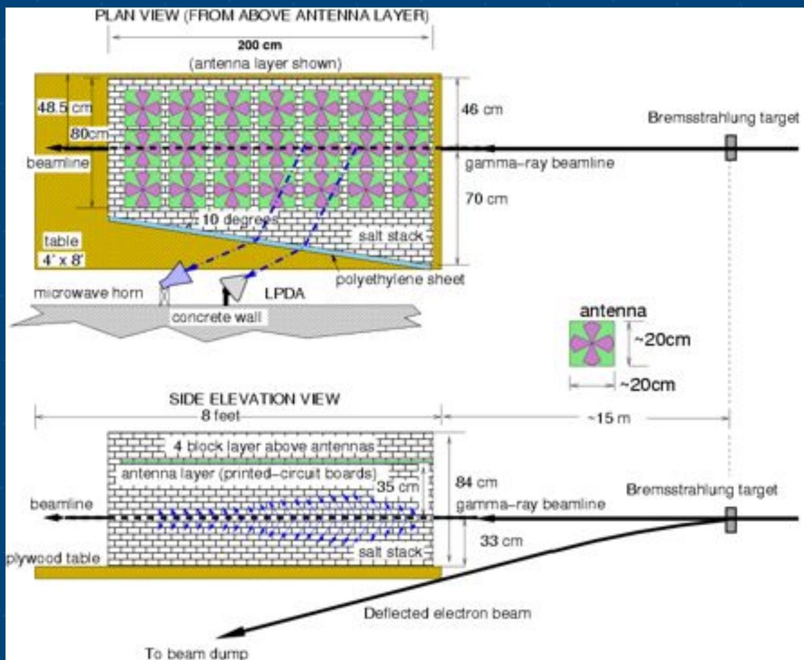
- SLAC e^- showers with composite energy same as UHE neutrinos
  - 10^{8-9} x 28 GeV $=2.8 \times 10^{19}$ eV
- Coherent radio power, consistent with theory
- 1st direct observation of radio Cherenkov cone

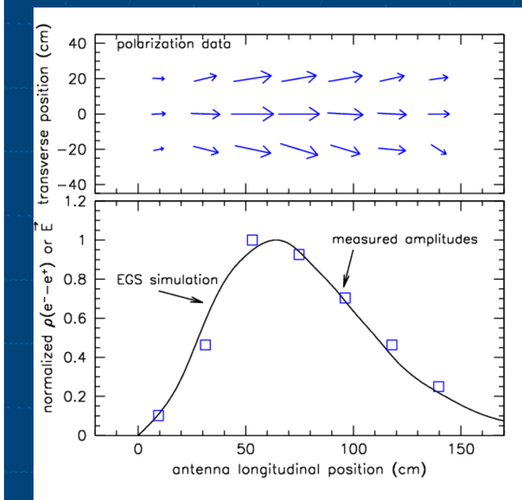


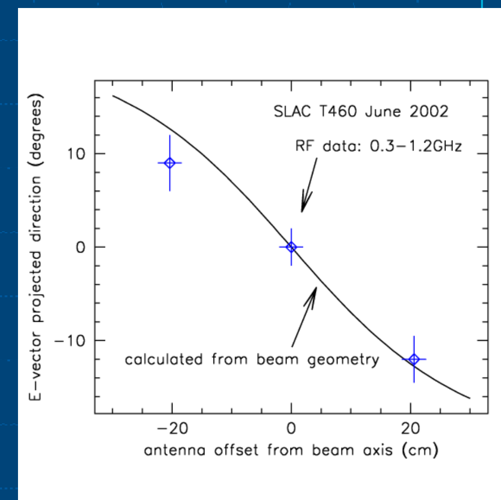




SLAC T460: Askaryan in salt

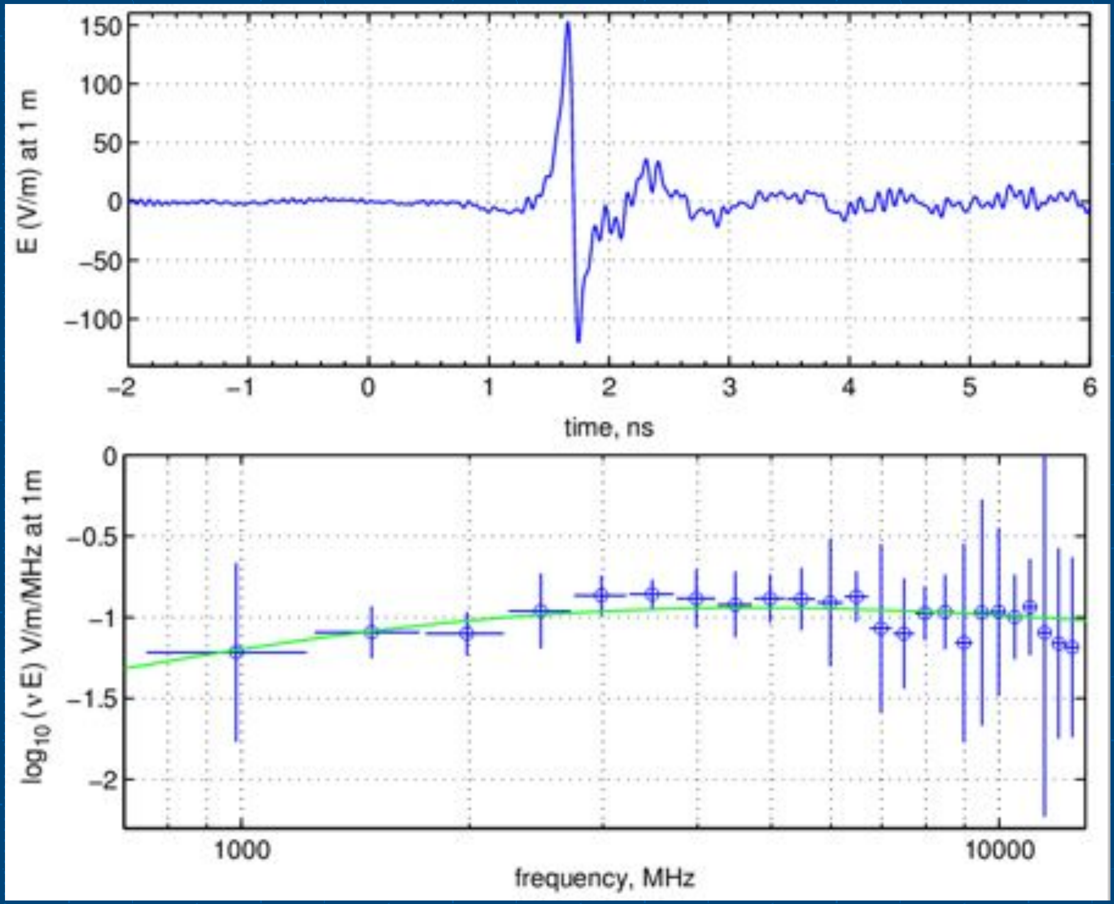






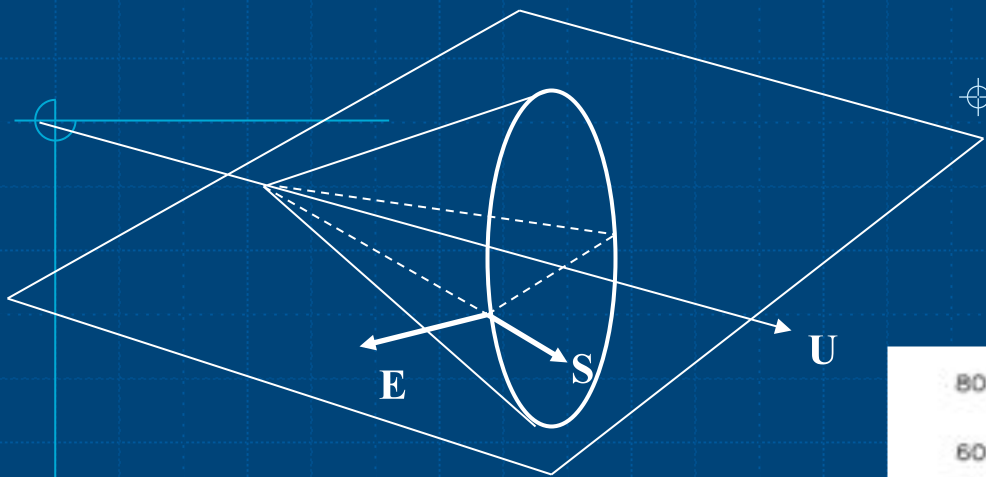
- T460: a first-order Cherenkov calorimeter with embedded dual-polarization bowtie antennas (0.2-1GHz), ultra-pure salt target
- Antennas measured polarization plane and pulse amplitude over ~10 RL
- No antenna phasing (eg. imaging) possible then, but....?

T460: intrinsic Askaryan radio spectrum



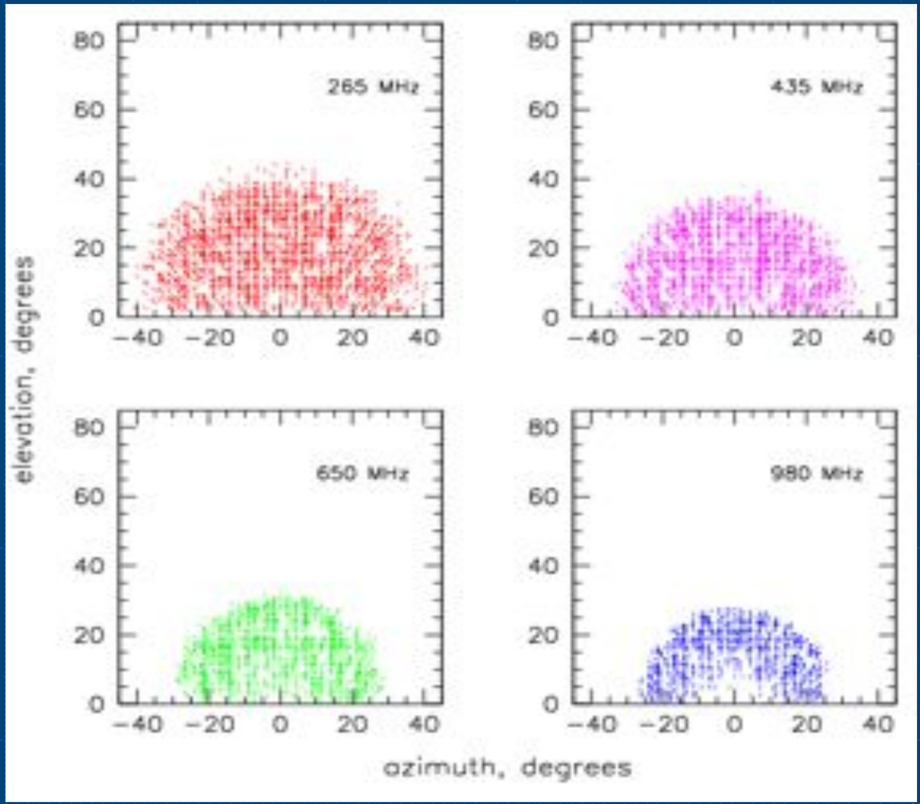
- Ultra-broadband measurements enabled us to measure full-band Askaryan emission (0.5-15 GHz) in salt
- Idealized point-particle Cherenkov would rise linearly with frequency
- Form factor of shower flattens spectrum above ~3-4 GHz
- → Still extremely broadband!

Cherenkov polarization tracking

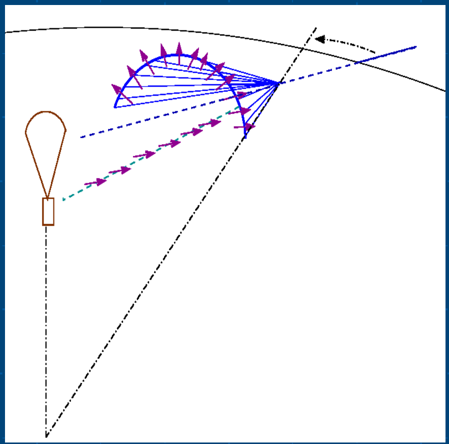


- At a single place in Cherenkov cone
  - Polarization plane related to incident neutrino azimuth relative to arrival direction of impulse

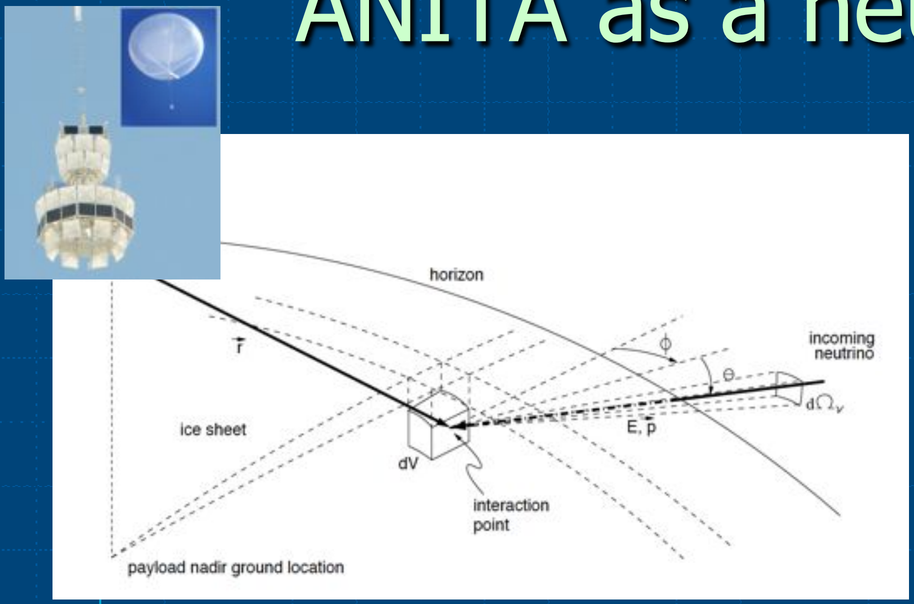
Cherenkov radiation predictions:
- 100% linearly polarized
- plane of polarization aligned with plane containing Poynting vector **S** and particle/ cascade velocity **U**

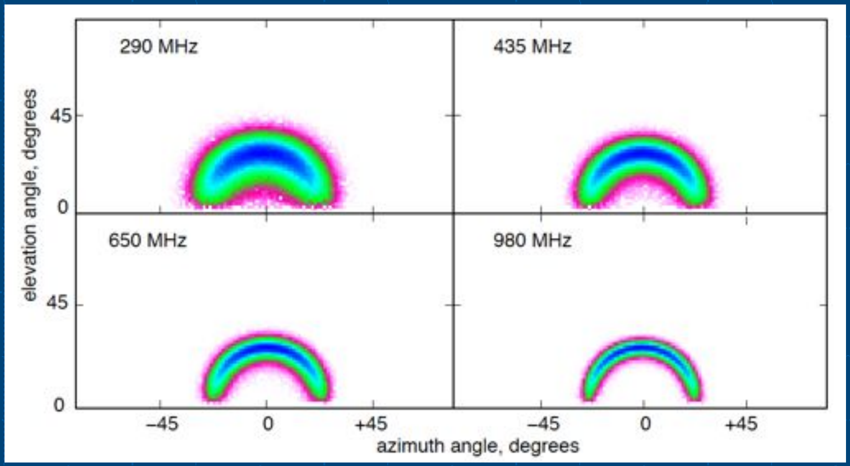


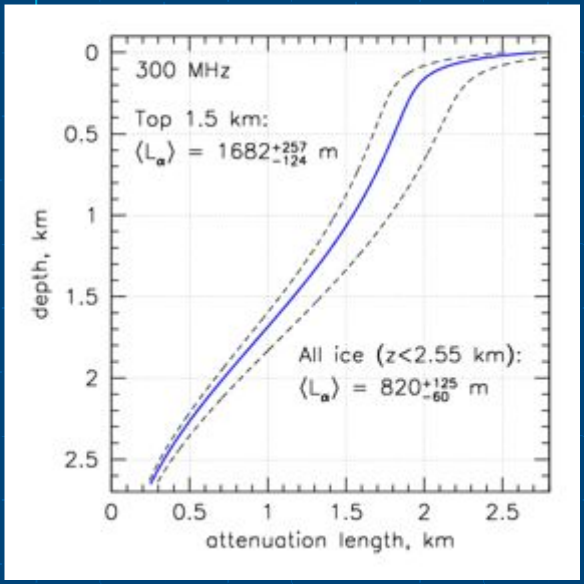
Antennas riding on a balloon above Antarctica can detect Cherenkov rings emerging from interactions within the ice → ANITA: Antarctic Impulsive Transient Antenna



ANITA as a neutrino radio telescope







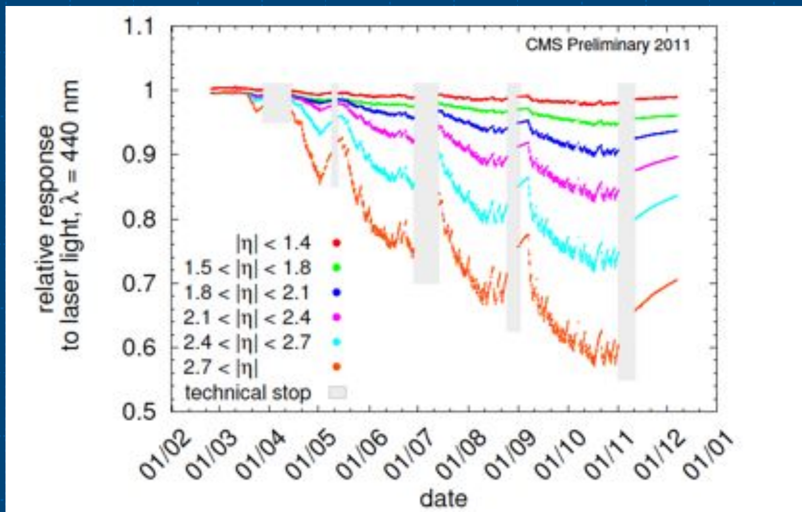
- Payload sees ~1.5 M km^2 area at float altitude of 36km
  - Ice RF attenuation length ~1.7 km in upper 1.5km
    → Effective neutrino target volume → ~3M km^3
- But over this large an area many other processes – atmospheric, anthropogenic, electrostatic – may produce radio impulses
  - → events are analyzed for polarization and direction
  - → Vpol, isolated → **neutrino candidate**
  - → Hpol or Vpol, non-isolated → **background**
  - → Hpol, isolated ….?

How does this relate to HEP detectors?

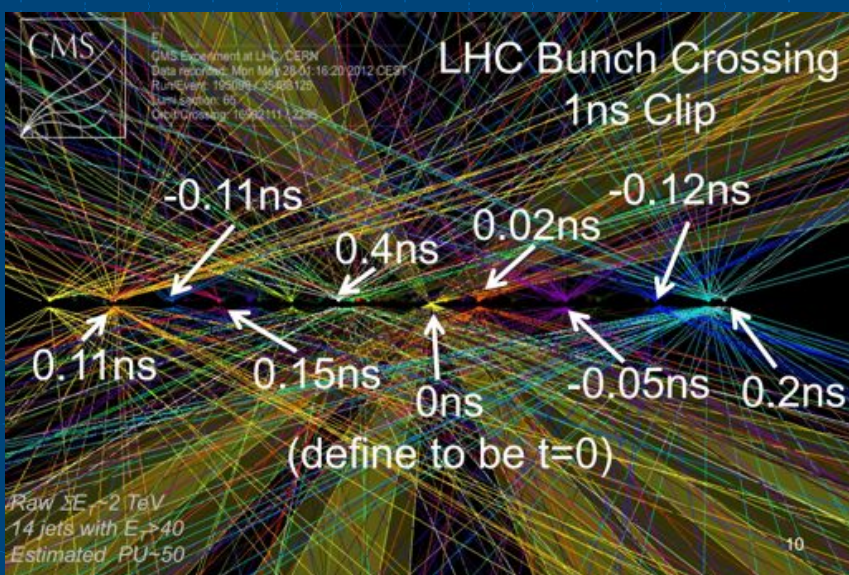
- Askaryan process is directly proportional to shower energy
  - Calorimeters are an obvious application
- Radio detectors (eg. copper antennas) have ridiculously high dynamic range (pWatts to Kwatts) and rad hardness
  - It is hard to melt copper!
- Radio receivers are of compelling interest to almost every segment of technology – consumer, business, military
  - → economy of scale and quality of development is unparalleled!

- Development of detectors for coarse measurements in unbounded natural dielectrics can now be applied to bounded, precision measurements in controlled dielectrics

100 TeV, few x 10^{35} cm^{-2} s^{-1} ??

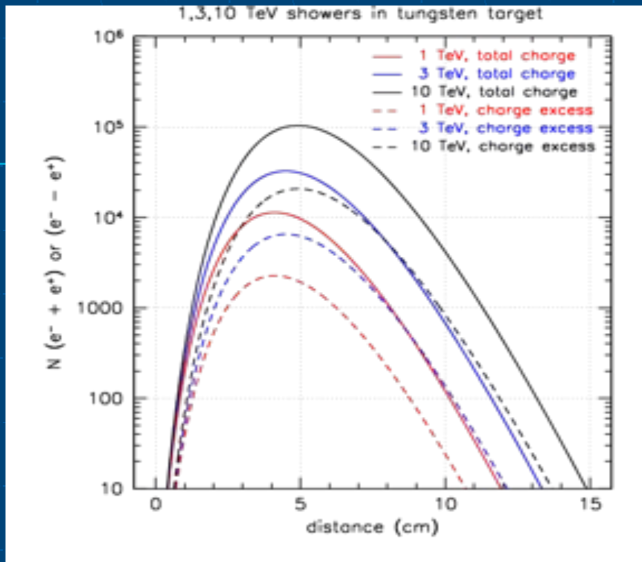


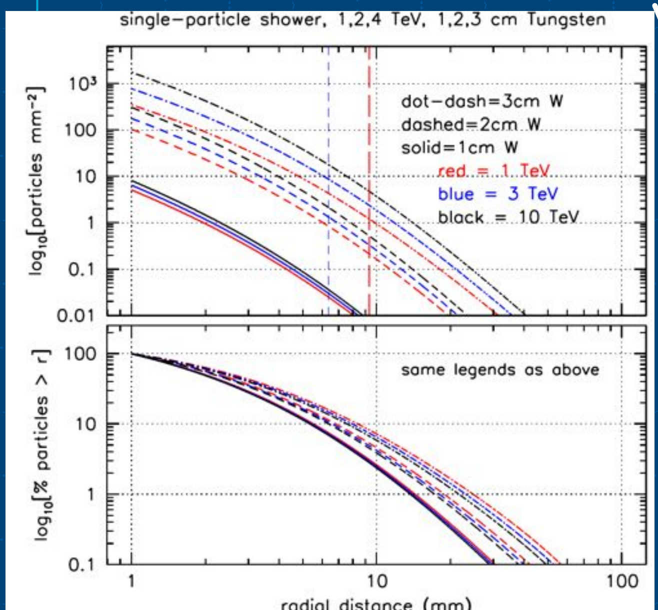
F. Ferri 2012



- Tens of Gigarad, at η > 2.5 for 3000 fb^{-1},
  - ~100 Grad at 15K fb^{-1}
  - η ~ 6 , Tera-rad?
- Kilowatts of beam power in calorimeter
- Pileup of ~hundreds per beam crossing
- At η ~ 6-7 or more, even the beam pipe is a problem
  - A 0.8mm Be pipe, 200-600x thickness, already 1-2 X0

Considerations for a next-gen collider detector





- At 100 TeV CM collider energies and above, individual particle interactions can deposit ~10 TeV a single sub-shower
- Example: parametric shower estimate for TeV EM shower in W
  - 100s to 1000s of relativistic particles per mm^2 at shower maximum and beyond
  - Showers in tungsten extend several cm radially
  - Pile-up will require mm or better resolution
- Current technology will suffer from dynamic range limits at very high beam currents, and from radiation damage in forward detectors

$$\mathbf{A} = \frac{\mu_o}{4\pi}\int \underbrace{\frac{\mathbf{J}e^{-ikr}}{r}}_{\substack{kr<<1 \\ (r<<\lambda)}} dv \approx \frac{\mu_o}{4\pi}\int \frac{\mathbf{J}}{r} dv$$

- A radio detector could:
  - Reconstruct either segmented samples of, or maybe the *entire* vector potential of, showers generated during the beam crossing
  - Either by measuring current segments in a waveguide-segmented detector
  - Or by full interferometric imaging

Next gen forward calorimeter ….

Sequential W’ boson

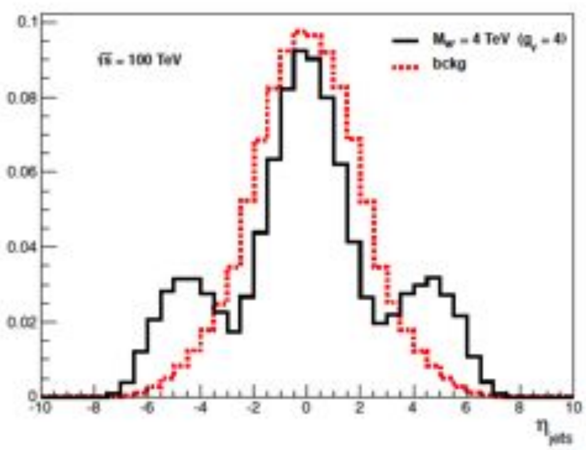
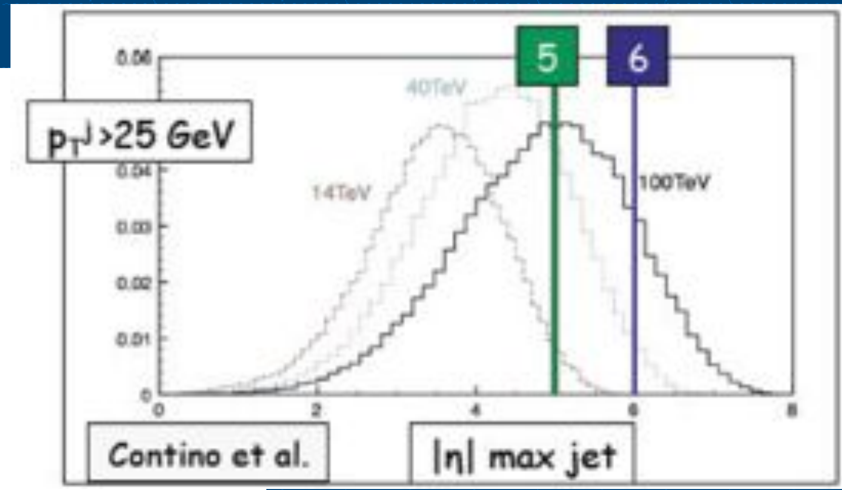


Figure 4: (Normalized) rapidity distribution of all of the final jets which have passed the acceptance requirements in eq. (8), with the exception of the $|\eta_j|$ restriction, for the total background (red dashed curve) and the signal with $m_{W'} =$ 4 TeV, $g_V = 4$ (black curve) at a 100 TeV pp collider.

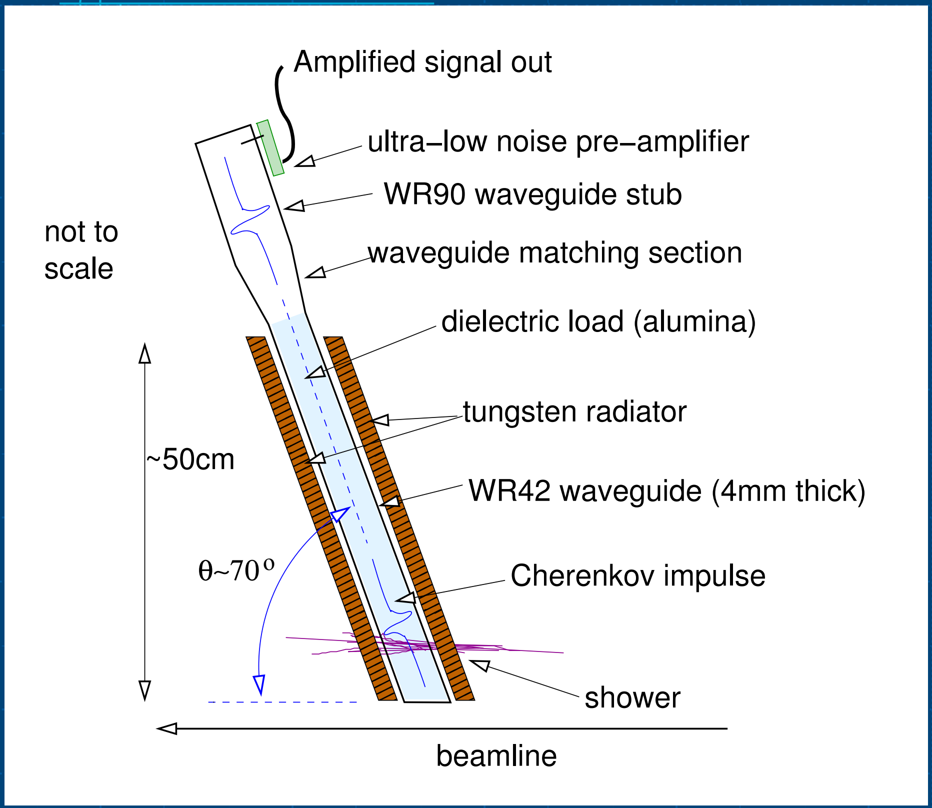
Mohan & Vignaroli 1507.03940



Talk by D. Winn

- High η is a hard world, but could be rich physics
- Example: W’ high-η ‘wings’ above bkg
- | η | max jet range at 100 TeV→ 8 (=0.038 deg, 7mm@10m)?!

Askaryan Sampling Calorimeter Element



- First cut: dielectric-loaded waveguide
- Tungsten slabs to compress shower
- Alumina-loaded waveguide to measure Askaryan pulse over shower segment
- OTS low-noise amps can now get to 40K noise at room temperature, ~4 K at LHE temperatures
  - Thermal noise in radio is one of the biggest limitations → all EM modes are 'pre-loaded' with noise photons

Energy threshold, resolution

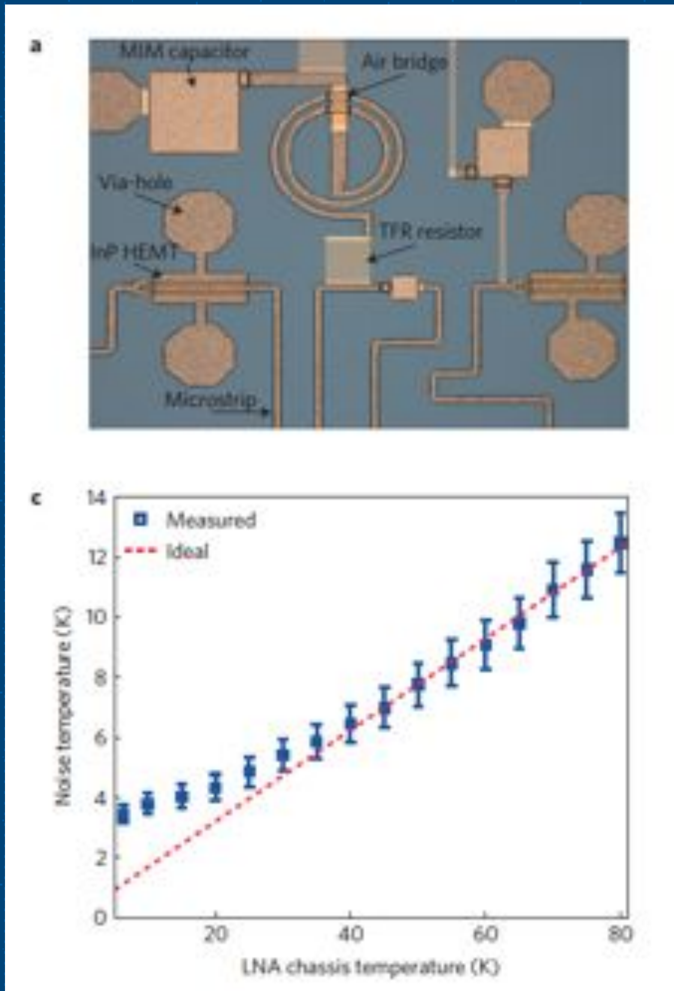
$E_{thr} \sim \Delta E \sim$ 6 GeV x [(4 GHz/Δf) (3.15/n) ((T_{LNA}+T_{sys})/1 K)]$^{1/2}$
x (10 GHz/f_0)(X_0/7cm)

Δf = bandwidth, n= microwave index of refraction, T_{LNA} = low-noise amp effective temperature, T_{sys} = target + WG effective temperature, f_0 = operating center frequency, X_0 = radiation length of material

For T-530 conditions, ~ 70-130 GeV (but uncertainties are large!)
For best OTS devices currently, probably around 20 GeV

- Energy resolution scales from SLAC beam tests, gives ~6 GeV achievable for future LHe cryogenic detector (idealized)
- 10 ps timing will give mm-level position resolution
- Dynamic range: 10,000 or more (depending on IP3 of receiver)
- Lower energy threshold: denser materials, higher operating frequency, or LNAs with 'magic' cooling?

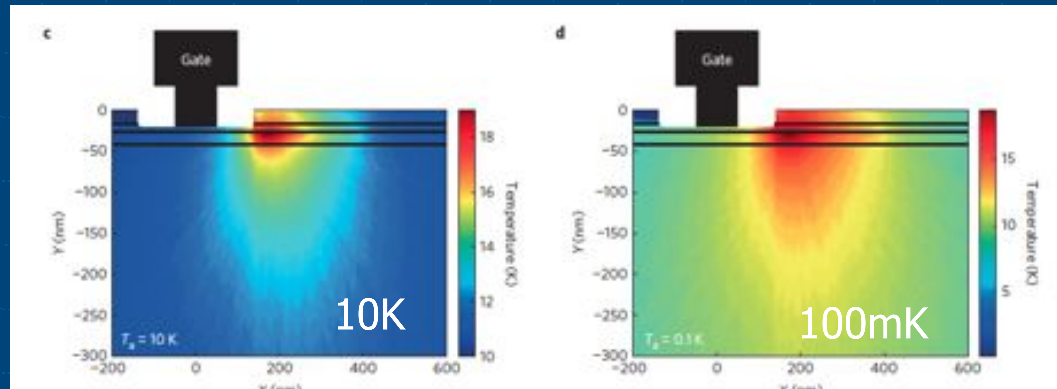
Problem: Phonon radiation LNA cooling limit?



Phonon black-body radiation limit for heat dissipation in electronics

J. Schleeh[1], J. Mateos[2], I. Íñiguez-de-la-Torre[2], N. Wadefalk[3], P. A. Nilsson[1], J. Grahn[1] and A. J. Minnich[4*]

Schleeh et al Nature 2014



- At ultra-low temps, devices cool by phonon blackbody radiation
- But near 0K, available # of phonon states contracts drastically
- Lattice electron gas has fewer and fewer cooling channels
- → result is a noise floor at ~4K
- Can this be overcome??

RF/microwave thermal noise

- At $kT >> h\nu$, all temporal and spatial modes of the electromagnetic field are full of degenerate photons
  - Room temperature 296K, $kT \sim 600\ h\nu$ at 10 GHz
- How to get to `photon-counting' in microwave?
  - At T ~0.5K $kT \sim h\nu$ at 10GHz → in transition region
- Detector only need LN2 (eg. ultra-low emissivity) but what about LNA?
- Cooled masers in the 80's and 90's: ~1-2K w/ LHe
  - → Are cooled HEMTs really a step backward? – Here is another pHEMT LNA from the same group (but optimized):

IEEE ELECTRON DEVICE LETTERS, VOL. 33, NO. 5, MAY 2012

Ultralow-Power Cryogenic InP HEMT With Minimum Noise Temperature of 1 K at 6 GHz

J. Schleeh, G. Alestig, J. Halonen, A. Malmros, B. Nilsson, P. A. Nilsson, J. P. Starski, N. Wadefalk, H. Zirath, and J. Grahn

- Photon-noise limited counting in microwave would be an enabling tech.
- Maybe in the next decade(s?) before 100 TeV, this will get sorted out !

SLAC T-530 Askaryan Cherenkov Experiment

- Gorham, Varner, J. Bynes (grad), C. Miki, B. Hill (engineering) (UH); D. Saltzberg & S. Wissel (UCLA), C. Hast & K. Jobe (SLAC)

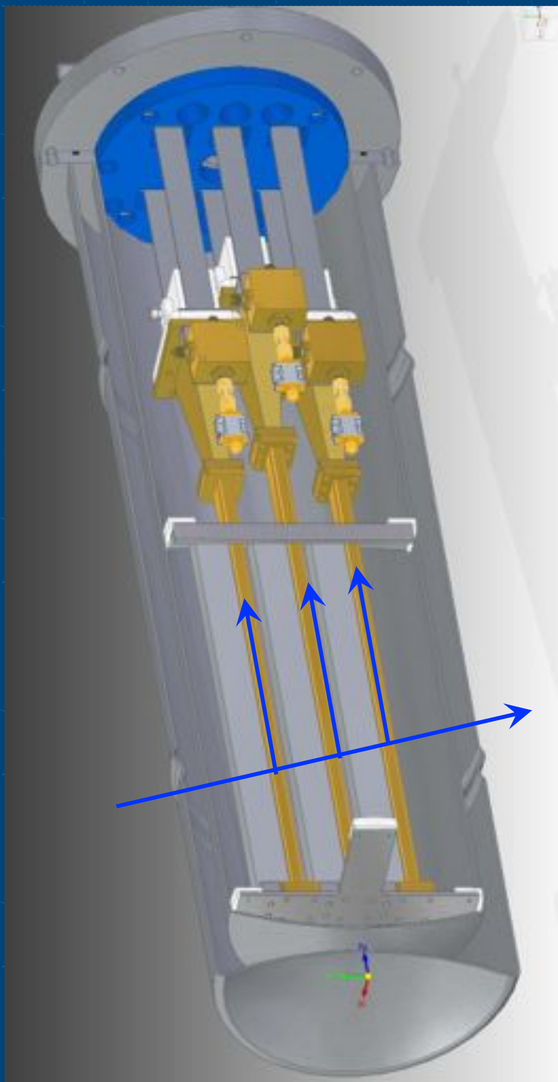
- August 2-12, 2nd run scheduled for October

- Run between 10^{1} – 10^{4+} electrons per bunch at between 4-13 GeV (gives 40 GeV to ~100 TeV showers)
  - Test is EM showers only, but will set scaling for hadronic as well

- MPPC (eg. Si pmt) bunch current readout (G. Varner, J. Bynes)

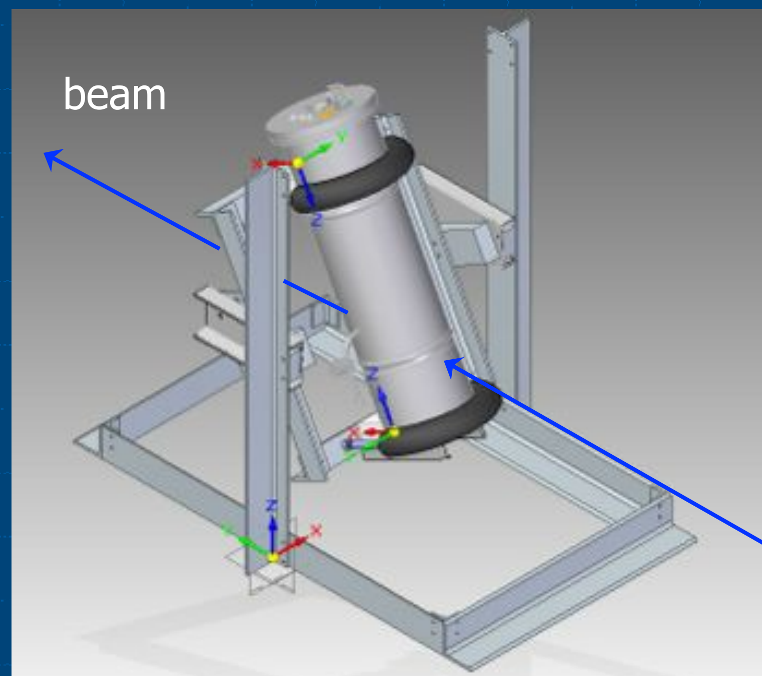
- Goals: establish basic scale of radio Cherenkov in Alumina-loaded waveguide, measure timing and energy resolution

T-530 ACE design & plans



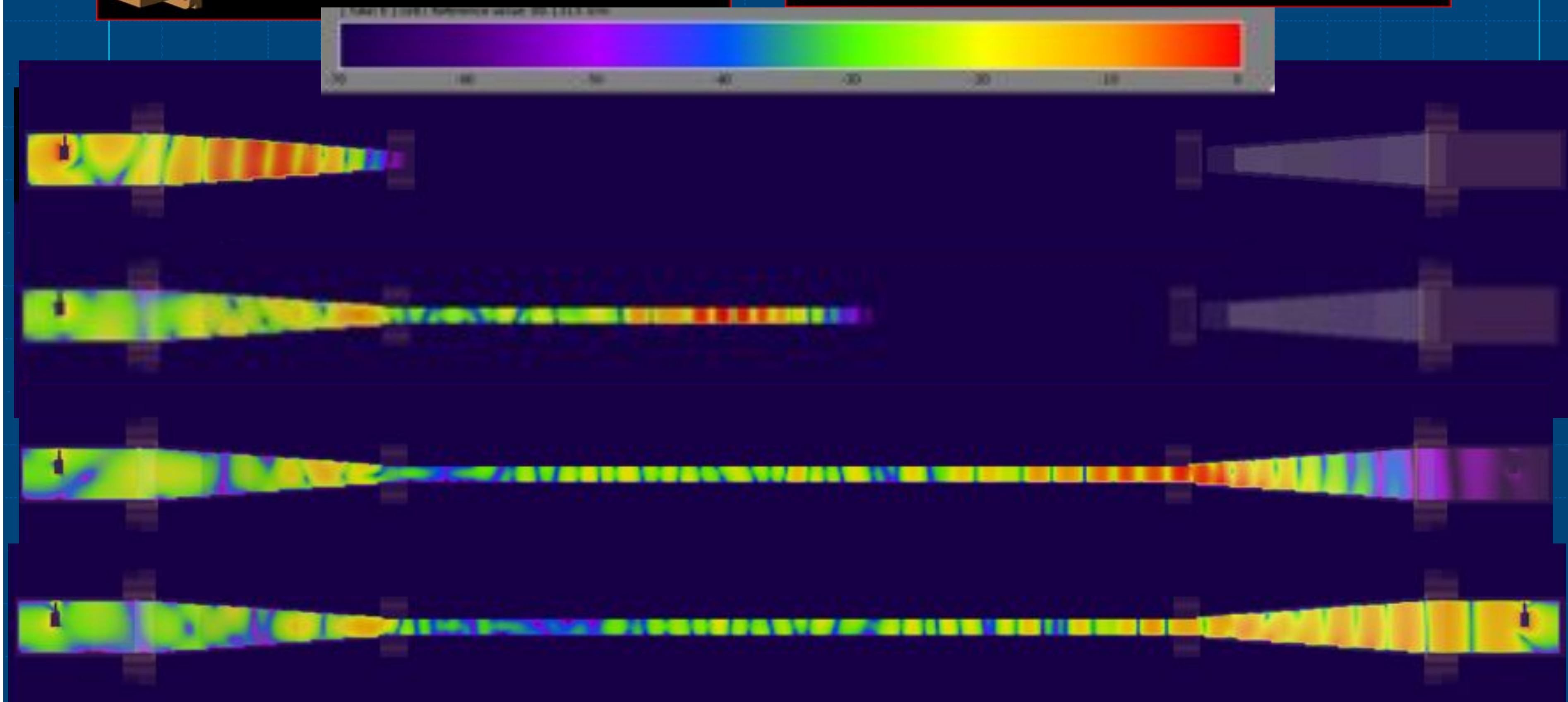
- Use a standard LN2 dewar, can house 3 waveguide elements + transitions
- Dewar can be tilted to show angular dependence
- Miteq LNAs also sit in LN2, should clearly give ambient temp. scaling

beam



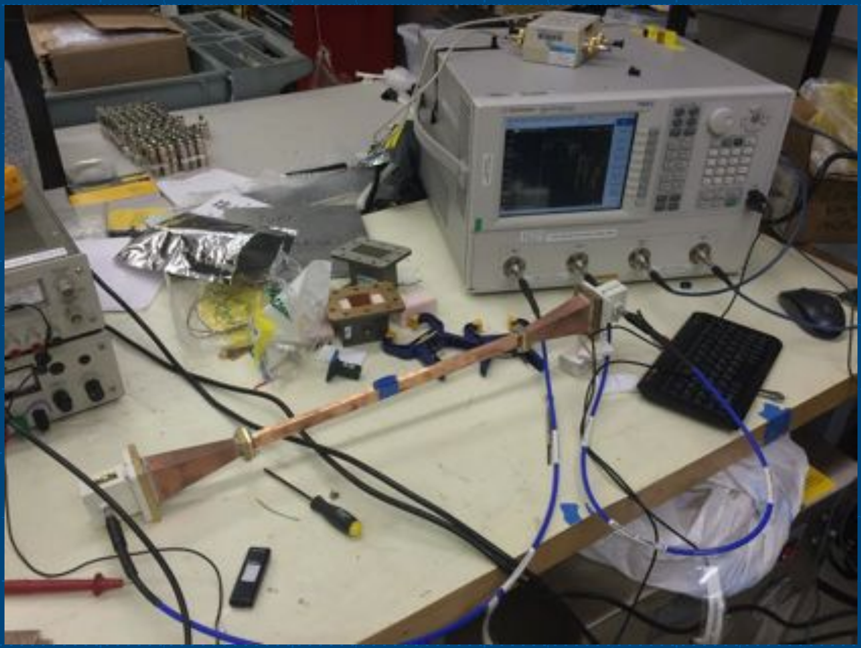
Fdtd Simulations

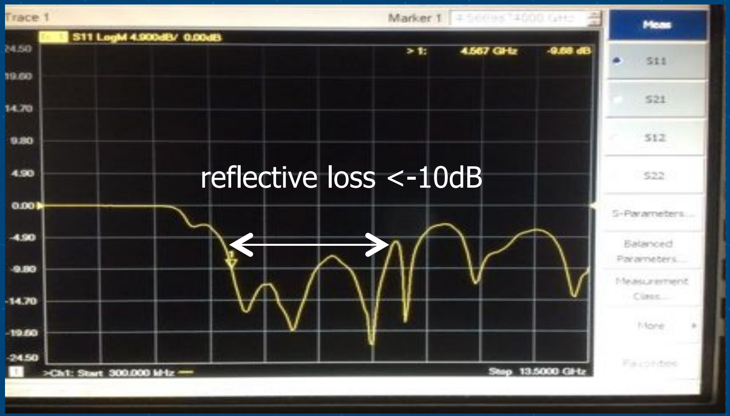
Field propagation



Back-to-back wg transition → confirm reciprocity

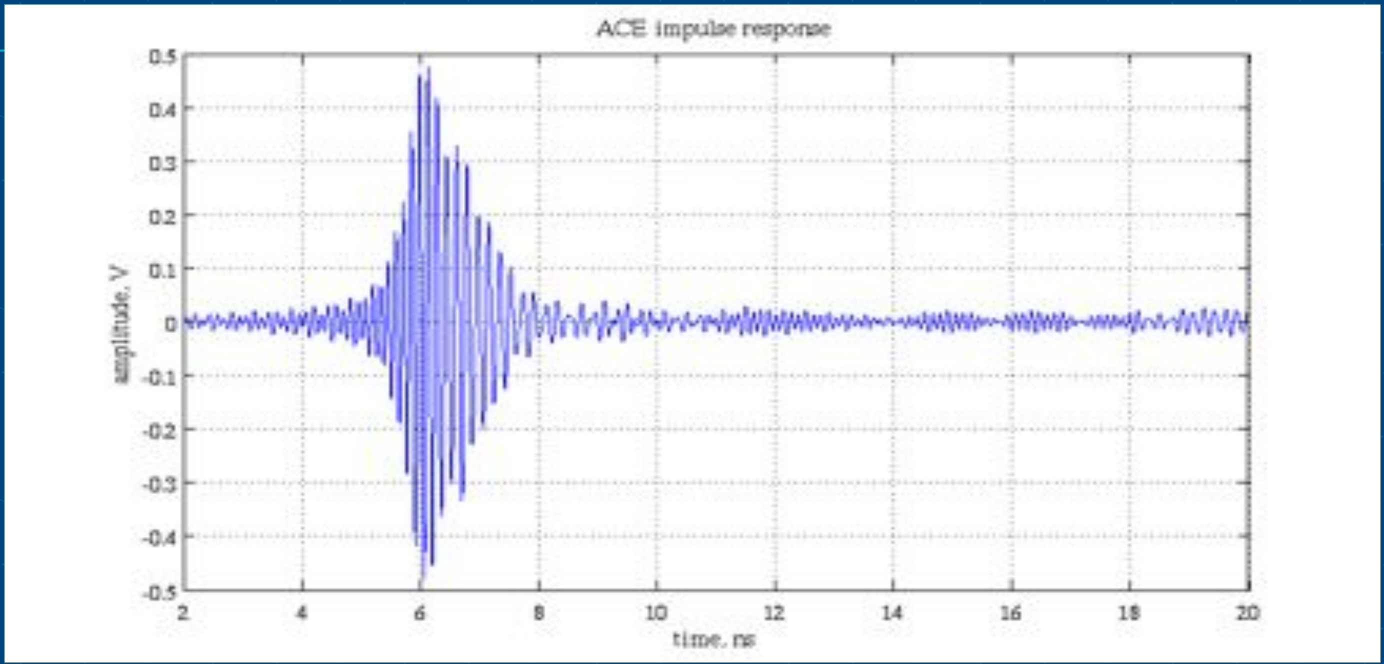
Fabrication & testing





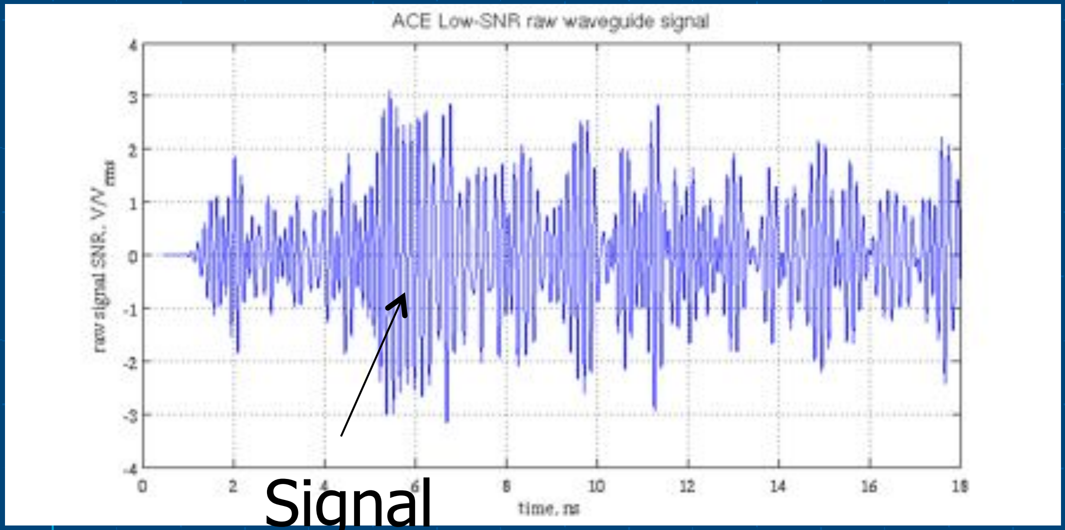
- Alumina (n_{radio} = 3.1, loss tangent ~0.0001) used as dielectric load
- Takes wr-51 (15-21 GHz) down to 5-8GHz, but also impedance to 17 ohms!
- Tapered matching transition section to standard wr-159 waveguide-to-coax adapters → Loaded waveguides are a challenge to work with!
- Transition worked beautifully, low reflection and insertion losses!

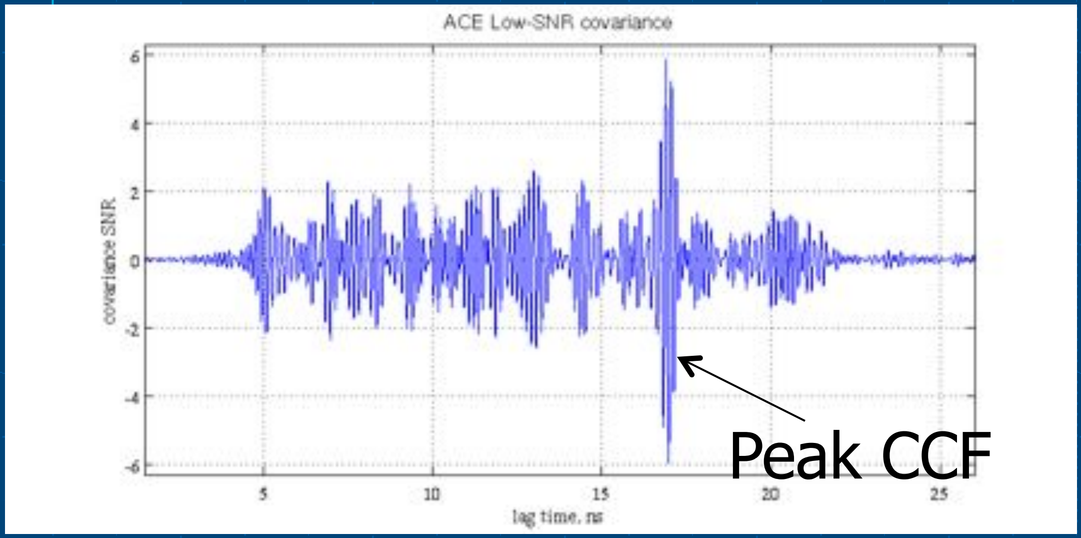
Measured time-domain impulse response



- Waveguide transmission band is 5.5-7GHz with almost no loss, 5-8 GHz usable
- Impulse response shows ~2ns envelope modulated at 5-8 GHz → good for cross-correlation detection

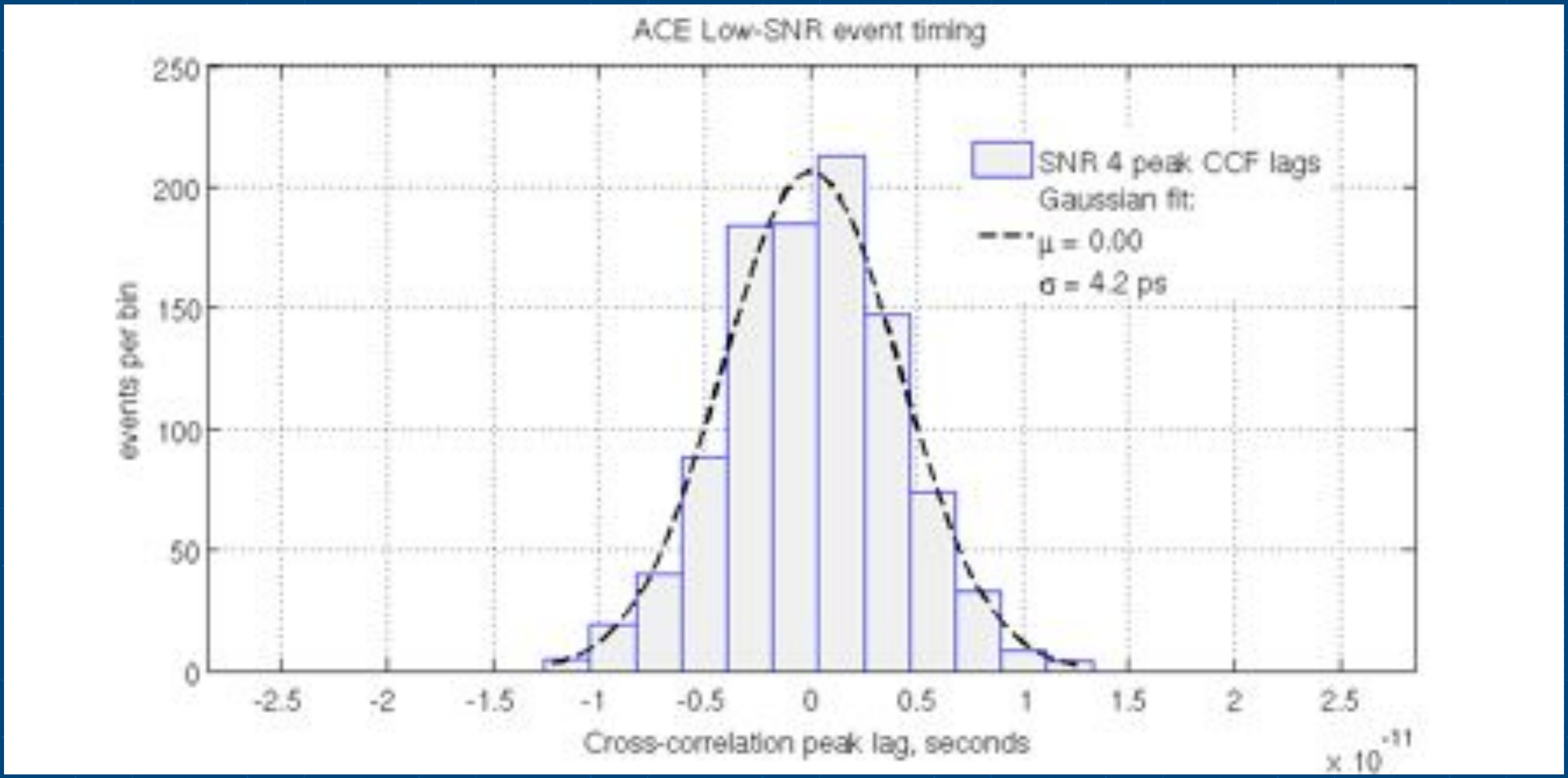
Time-domain resolution studies





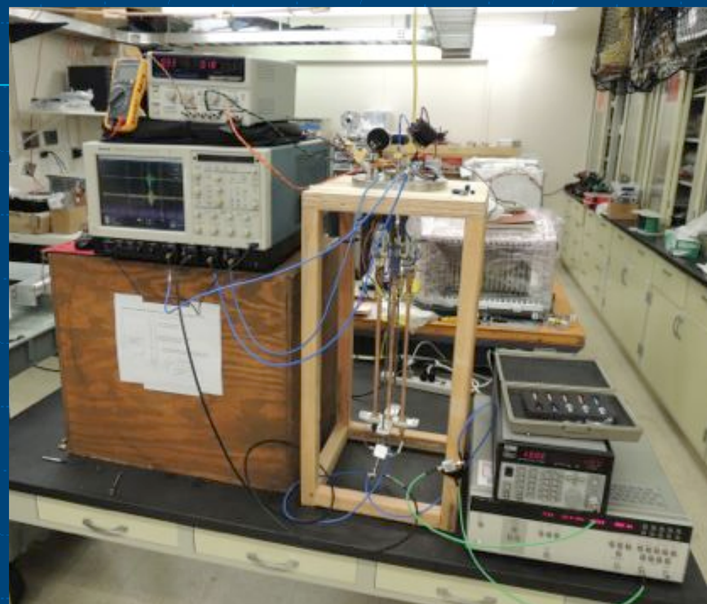
- Can superpose thermal noise onto impulse response
  - Study threshold detection SNR
- Reliable detection down to SNR<~3
  - Example to left
- Cross-correlation with impulse template gives precise timing location
  - Here the offset is due to additional padding of template window

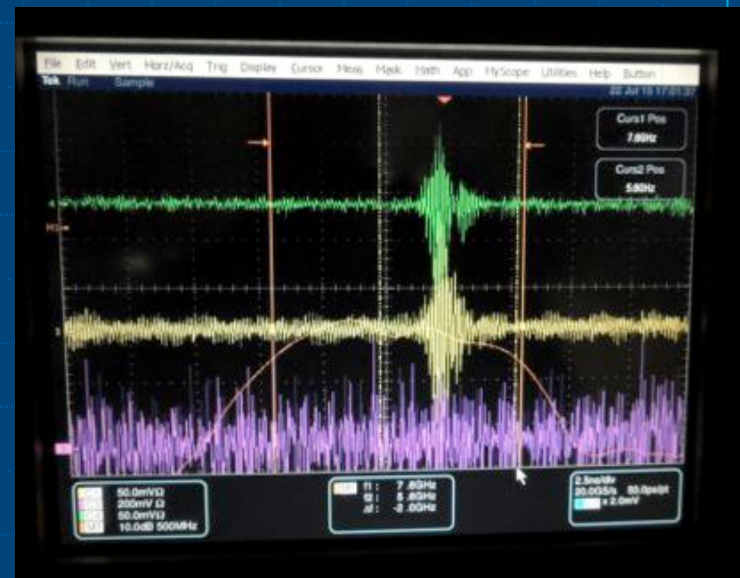
ACE Timing simulation results



- 4.2 ps timing resolution expected with current ACE prototype at SNR~4
- Corresponds to 0.4mm resolution in Alumina → better than predicted
- 0.4mm at 10m from vertex: ~10 arcsec angular resolution!

ACE lab tests (ongoing)





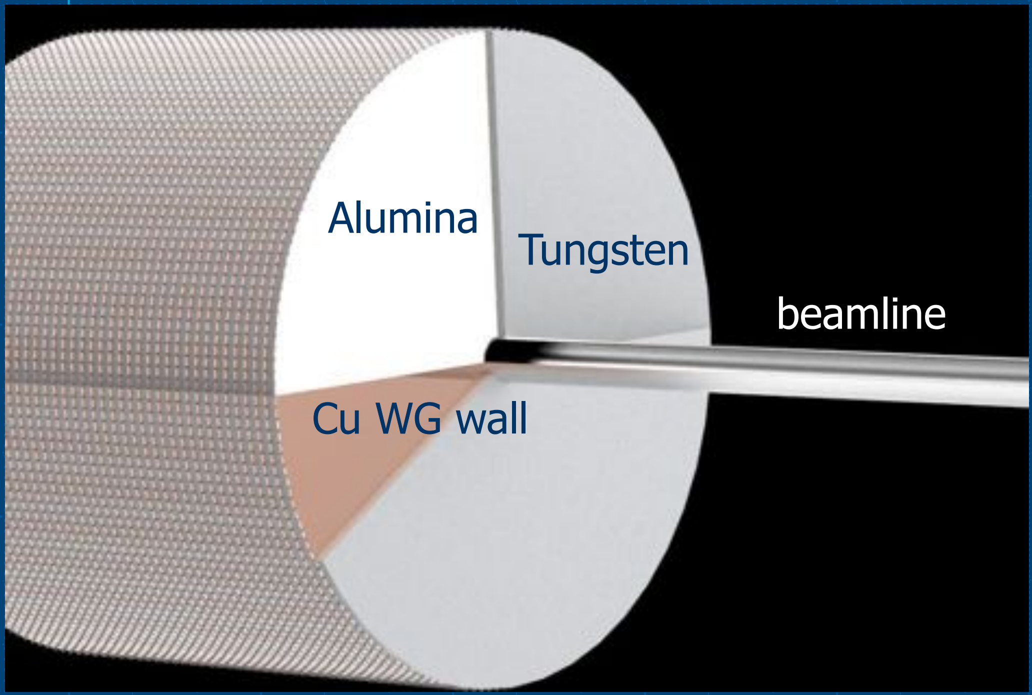
- System installed for thermal noise, isolation, throughput testing

- Performance looks excellent so far

Looking forward

- ACE has possible applications to both hadron and EM calorimetry
- High- η region (highest radiation, most dense shower distribution) seems the most promising area of hadronic physics
  - Small-x physics, non-perturbative, probes gluon structure function → a new (and wild) frontier in HEP?
  - Hard to guess what tools will be needed until we get there…
- For EM calorimetry, precision at very high shower energies will depend on detector saturation and linearity
- ACE elements might be interspersed with tracking elements to pick up sub-threshold tracks and showers → hybrid detector

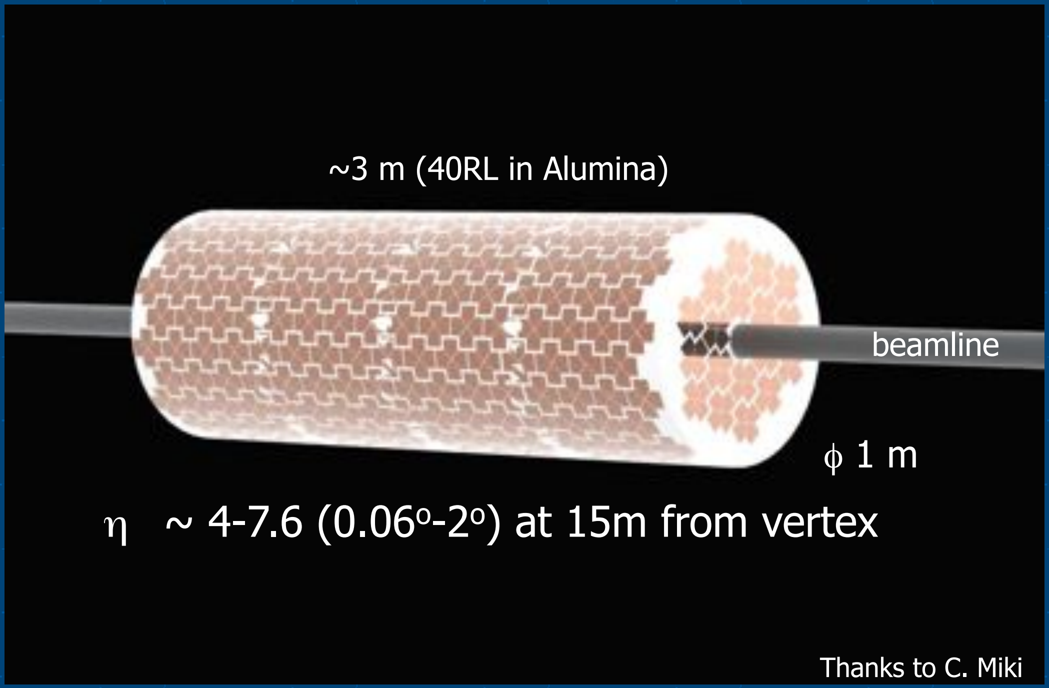
Sampling hadron calorimeter concept

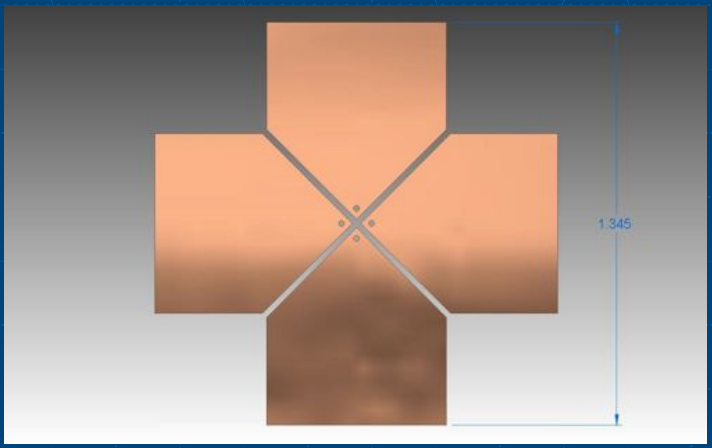


W-Alumina parallel-plate
Waveguide sandwich, ~10 λ_N
~1m diameter
Peripheral RF probes provide signal readout

- Geometry similar to a sandwich calorimeter
- Tungsten layers followed by Alumina-loaded waveguide layers
- Readout through SMA edge connectors to LNA
- All inside cryostat
- Waveguide could be standard channels or parallel plate modes, TEM guides, or a hybrid
- Ultra-high dynamic range and excellent timing resolution are selling points
- But: how to damp 'ringing' to <<25ns?

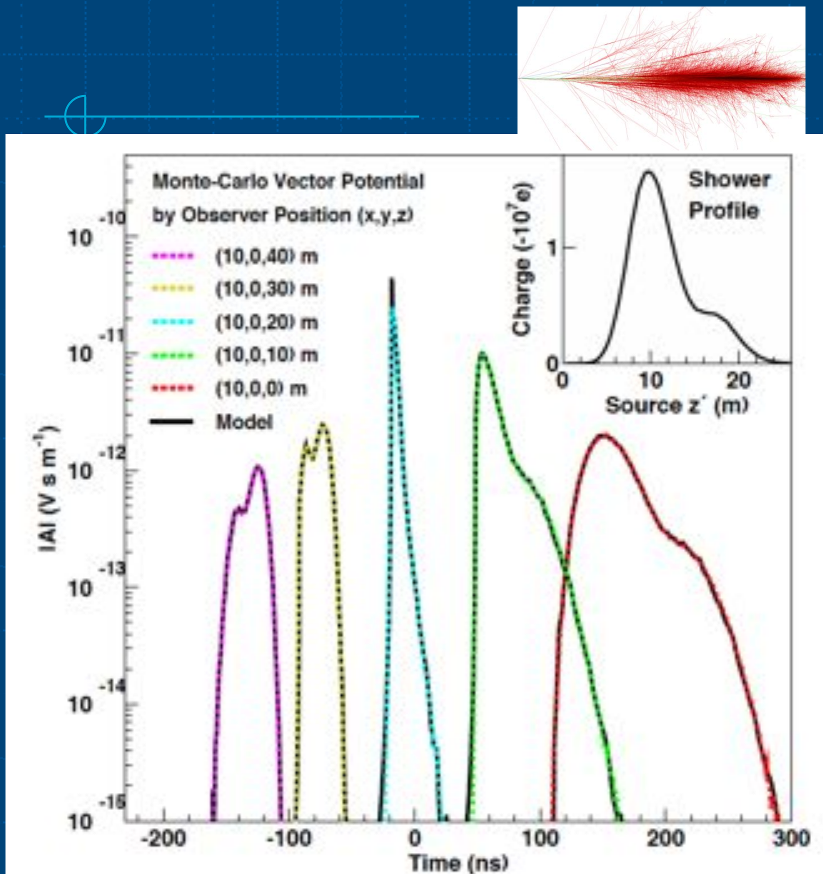
EM forward calorimeter `concept’



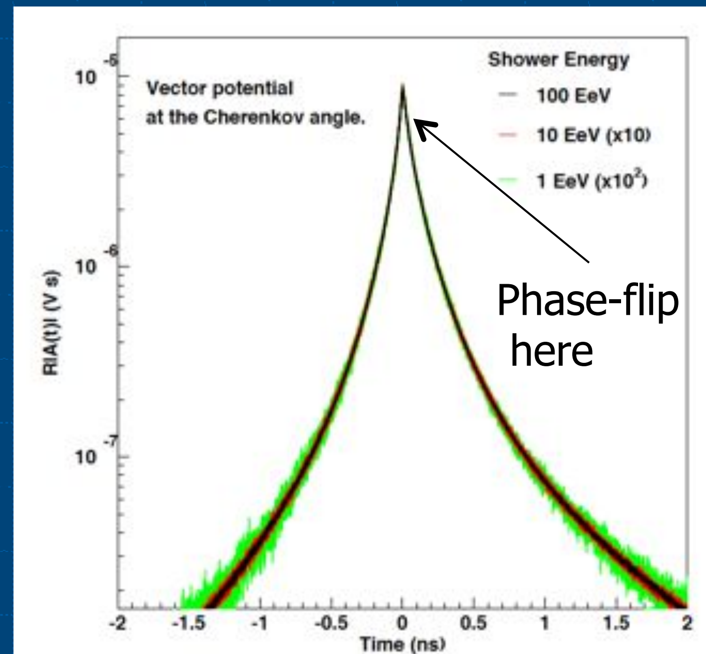


- Solid Alumina ‘crystal’ (eg. composite monolith)
- Surface antenna array (enclosed in cryostat)
- Dual-pol broadband patch antennas, ~1-10 GHz
- Invert E-field → vector potential → 4-currents
- Still need to address ringing problem for rapid bunch cycle times

Shower imaging by vector potential



Work done by J. A. Muniz,
A. Romero-Wolf & E. Zas arxiv 1106.6283



- Each 'observer' (eg. antenna) location is sensitive to different field components of the shower
- Highest coherence at exact Cherenkov angle, but partial coherence at other angles due to differential current elements
- Mathematics of inversion E(x,t) → J(x,t) is now available

Summary

- After almost 15 yrs, Askaryan process is now basis for mainstream methodologies for particle detection in the Cosmic Frontier
  - SLAC has been involved in virtually all experimental research on this process
- It seems a good time to take a hard look at this for the Detector & Energy frontiers, ACE will define initial parameters
- Gurgen Askaryan and John Jelley would be thrilled!