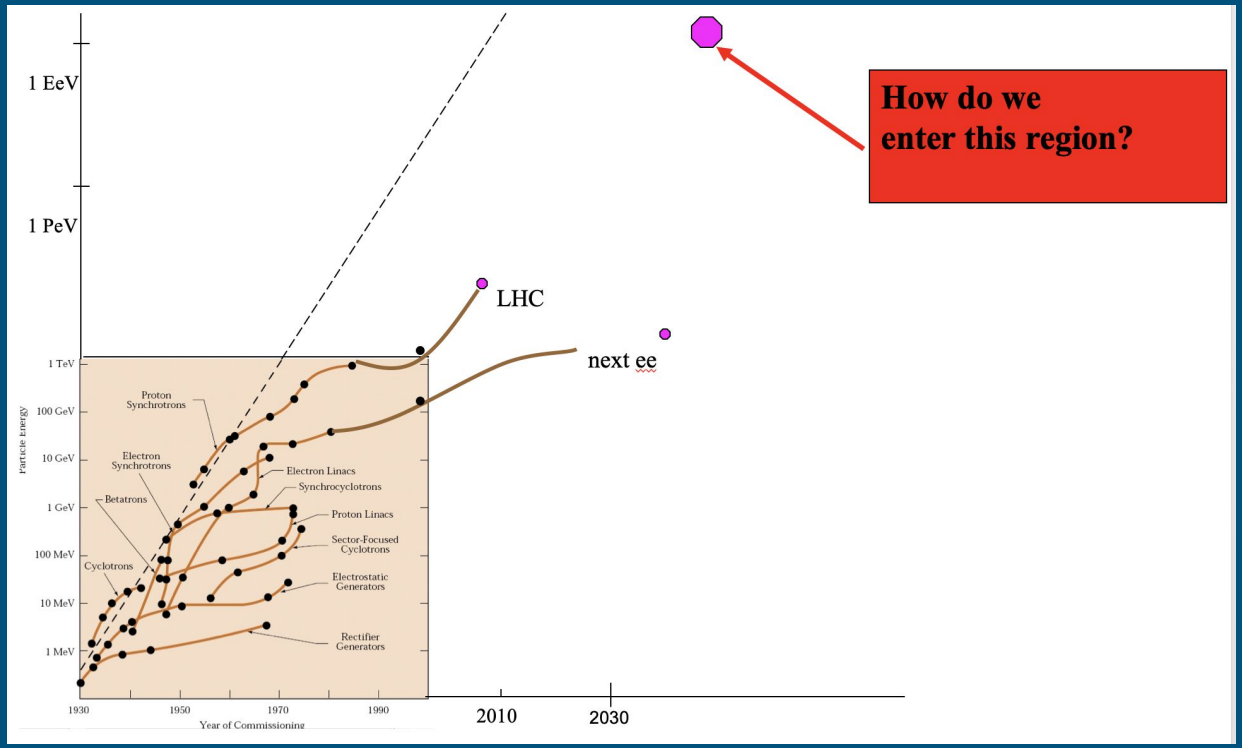
Accelerator Support of Radio Detection of High Energy Particles

Peter Gorham (U. Hawai'i)
David Saltzberg (UCLA)

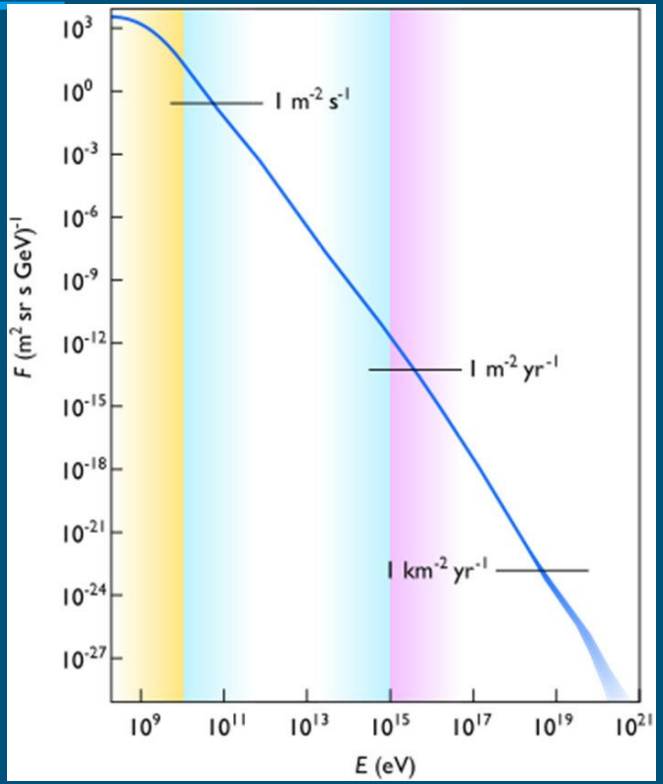
CPAD workshop Nov. 8, 2023

Accelerator Physics challenge: "The Livingston Plot"



Modified from A. W. Chau and M. Tigner

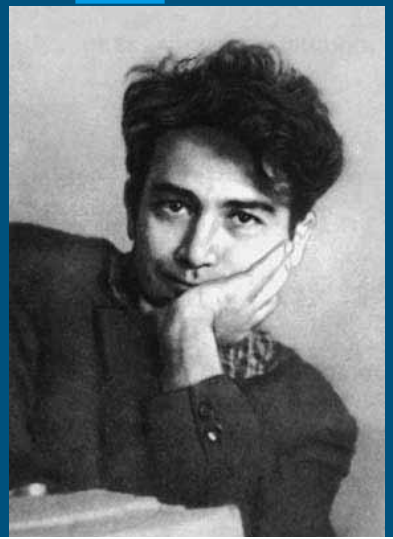
Cosmic Ray physics:
How to detect the rarest particles?

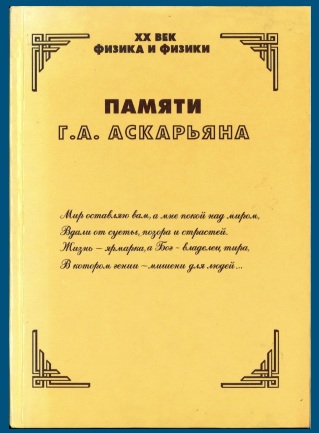


S. Swordy, Space Sciences Reviews, 2001

- Cosmic rays are as rare as 1 /square kilometer /century
- No man-made detector is large enough

Using Large Natural Media: Transparent to Radio





G. Askaryan biography: Boris Bolotovskii

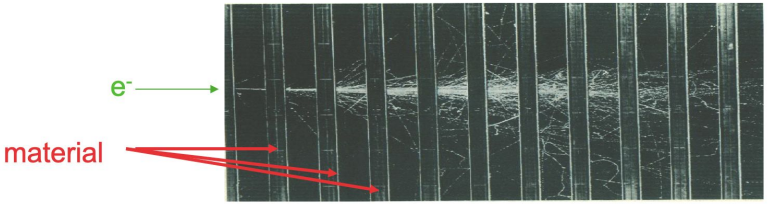
Gurgen Askaryan (1928-1997): prominent Soviet-Armenian physicist, discoverer of self-focusing of light, pioneer in light-matter interactions, and visionary in interaction of high energy particles with matter

- Mapped it out in the 1960s:
- Lunar Regolith
  - combines two Greek words: *rhegos* (ῥῆγος), 'blanket', and *lithos* (λίθος), 'rock'.
- Antarctic Ice
  - Up to 4km deep
- Salt "domes"
  - Uplifted & purified ancient Sea Beds

G. A. Askaryan, 1962, JETP 14, 441; 1965, JETP 21, 658, ...

The Askaryan Effect

UHE event will induce an e/γ shower:



In electron-gamma shower in matter, there will be ~20% more electrons than positrons.

Compton scattering: $\gamma + e^-_{(\text{at rest})} \rightarrow \gamma + e^-$

Positron annihilation: $e^+ + e^-_{(\text{at rest})} \rightarrow \gamma + \gamma$

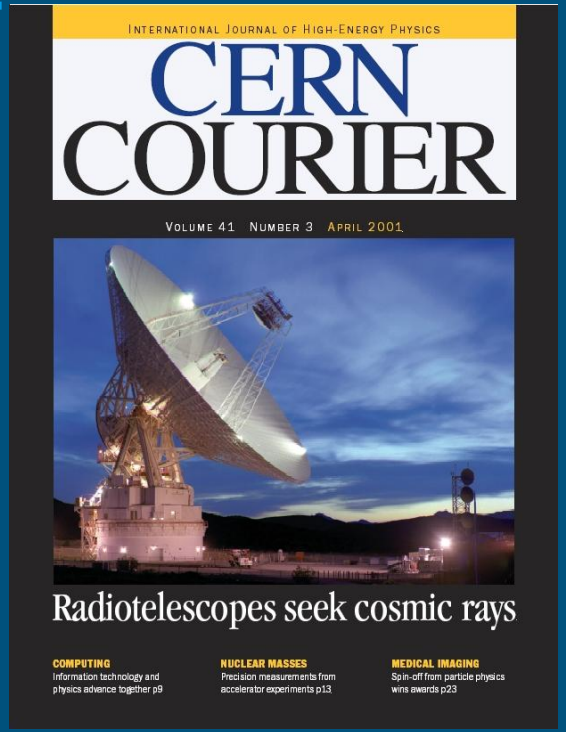
As is well known to this audience:

$P_{\text{Cherenkov}} \propto \nu \, \Delta\nu$ (includes radio!)

- High Energy showers create radio.
- Assuming
  - There is a charge excess of 10-30%
  - Coherence factor among 10^{10} charges
  - No plasma shielding
  - No unknown unknowns.
- Had to convince the field
- Modern simulations
  - first by Francis Halzen, Enrique Zas, Todor Stanev further established effect
  - FH: "I stake my career on it!"
  - We have relied heavily on subsequent theory work by Jaime Alvarez-Muñiz and Seckel

Pioneering work by Dave Besson with antennas on Amanda strings
and pioneering ideas by Dagkesamanskii, Gusev, & Zheleznykh, incl. at Russian Antarctic base, Vostok

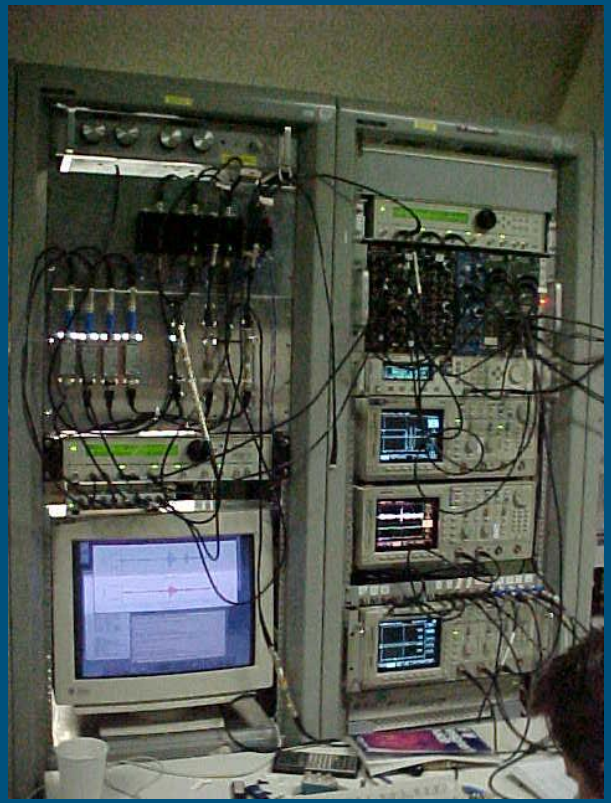
The Goldstone Lunar ultra-high energy Neutrino Experiment (GLUE)

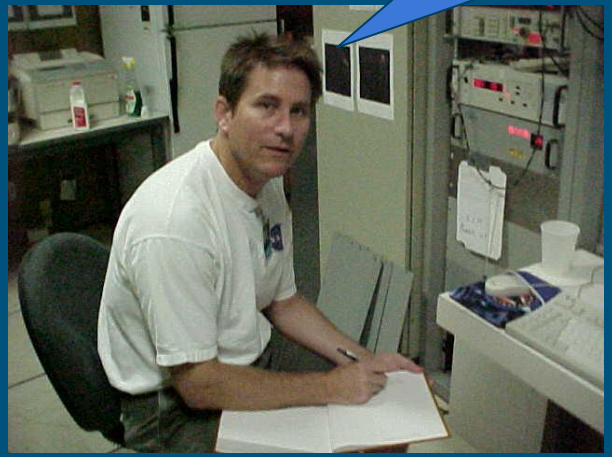


- Peter Gorham, Chuck Naudet, Kurt Liewer then of JPL. Access to the amazing 70m Deep-Space Network (NASA/JPL/Caltech) Goldstone radio telescope and its partners
- Peter came to UCLA, invited D.S. to join (with grad student Dawn Williams)

Inspired by Parkes radio telescope experiment (Hankins, Ekers, O'Sullivan MNRAS 1996)

The GLUE control room (1998-2003 (check this))





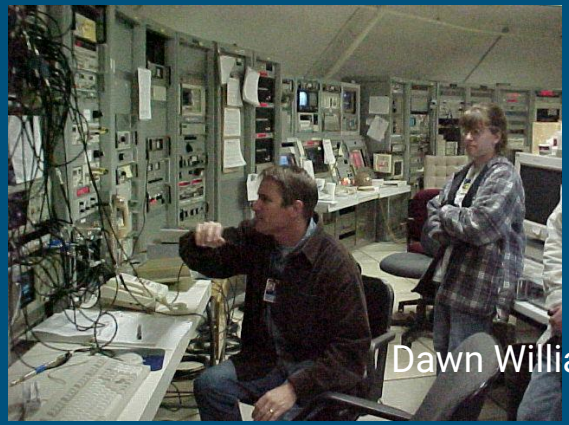
Peter: "David, you are an accelerator-based guy. Can we show we are not wasting our time?

Peter Gorham

More GLUE Folks

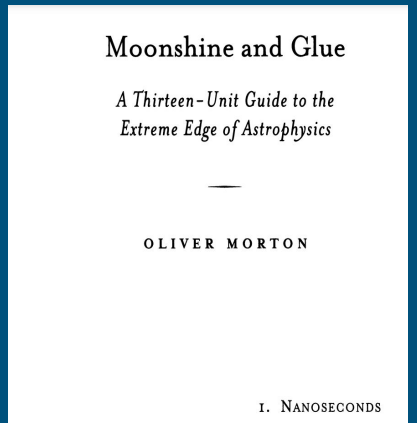
Chuck Naudet

Kurt Liewer

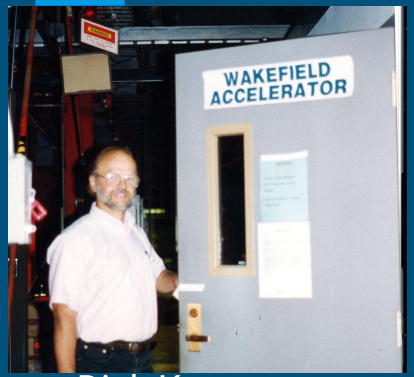


Dawn Williams

+an article in "American Scholar"

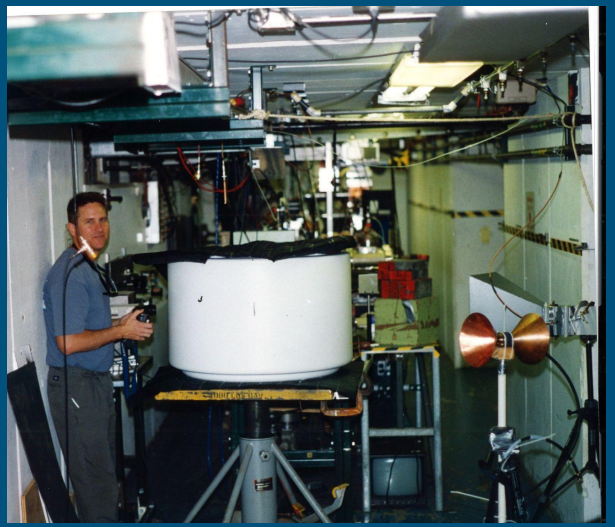


The Argonne Wakefield Accelerator (AWA)



Dick Konecny

Paul Schoessow



Ordering the target:

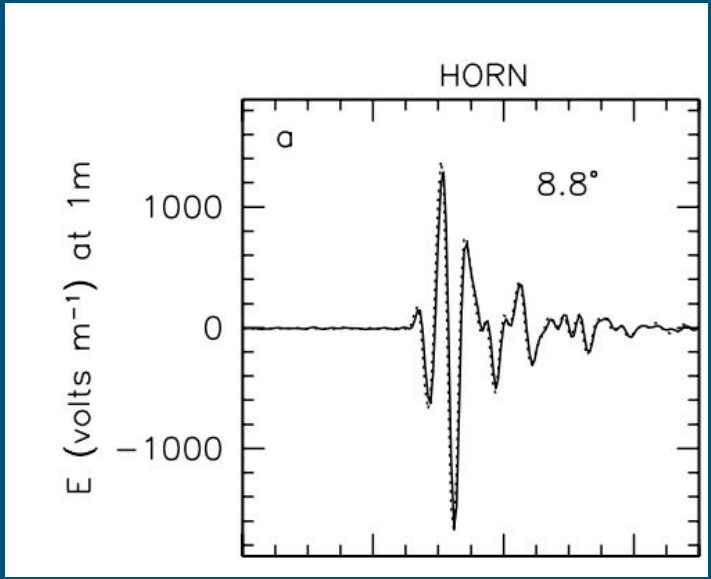
-- "*What kind of gas station do you operate?*"

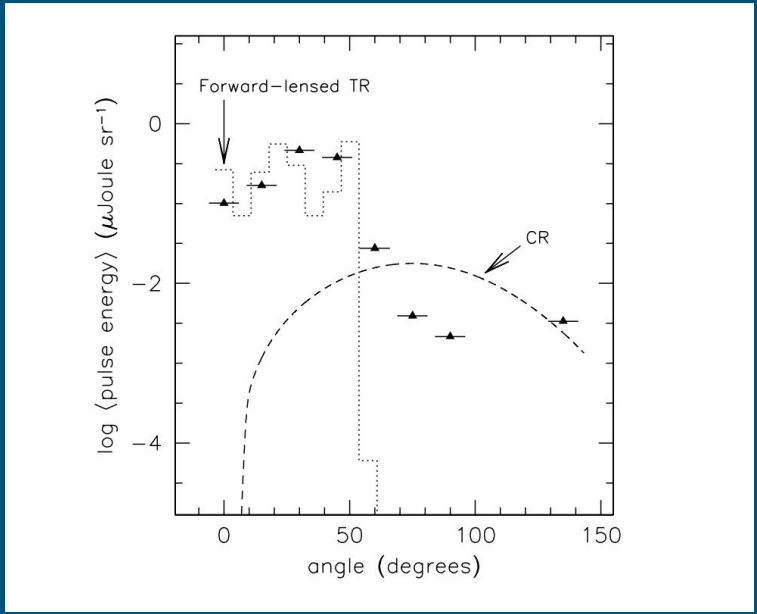
6 ✕ 100lb. bags of silica sand

+ Wei Gai, John Power, Manuoel Conde

AWA results

Phys.Rev.E 62 (2000) 8590-8605





Suggestive but not yet the "slam dunk" to the community.
Hard to separate Cherenkov Radiation from Transition Radiation

PG: "Always publish"
AWA paper → invitation to SLAC by Al Odian

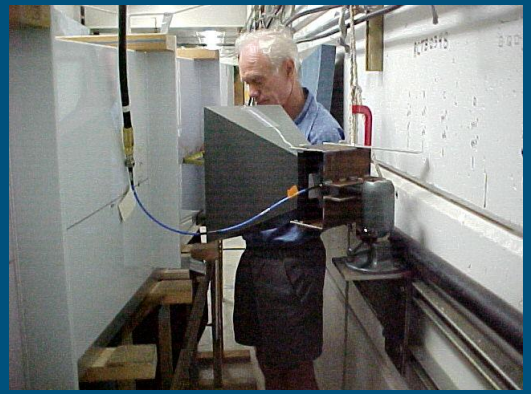
15 GeV electron beam--> 2 GeV photon beam at SLAC's Final Focus Testbeam

Now 4 tons of sand

"The Kitty Litter Experiment"

(wet sand does not transmit)

Lots of volunteer help

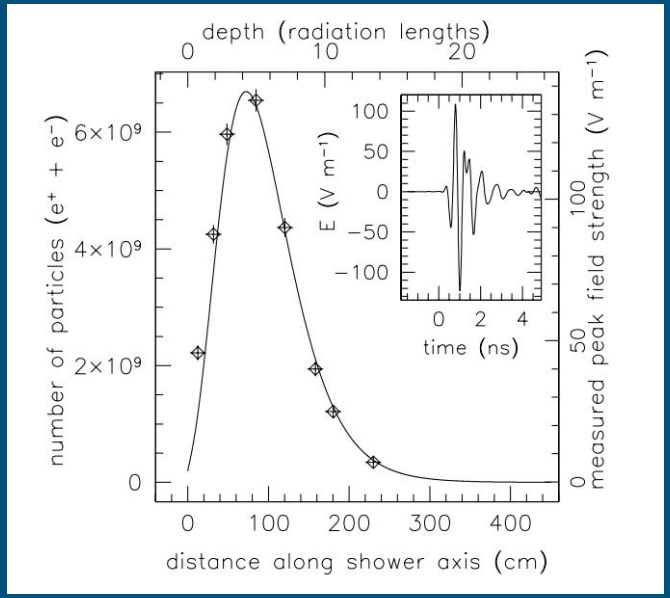


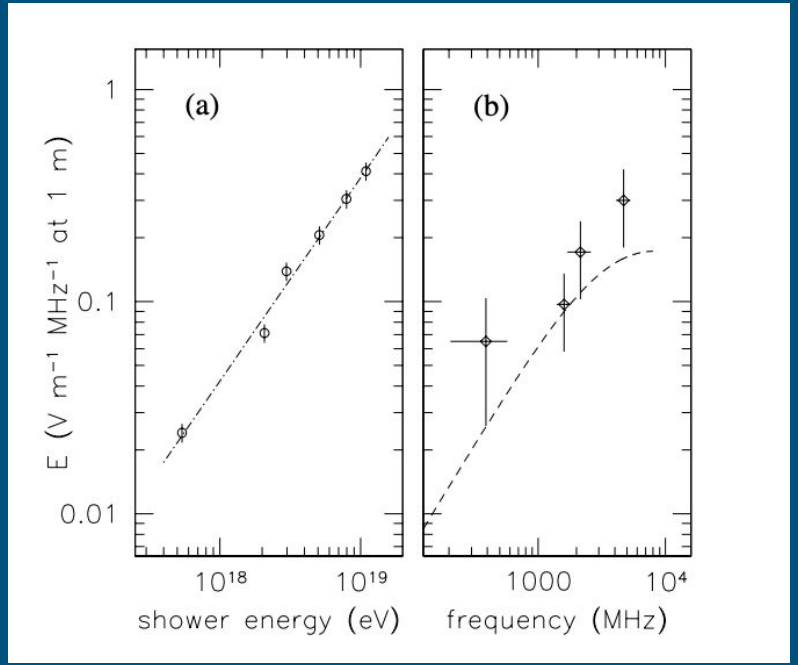
The amazing Dieter Walz!

"There's a cat in your target!"

Very clear results

Phys.Rev.Lett. 86 (2001) 2802-2805

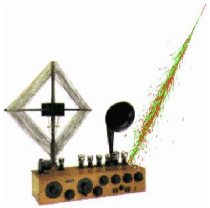




The field of Radio Detection of High Energy Particles had a renaissance

RADHEP-2000

First International Workshop on
Radio Detection of High-Energy Particles



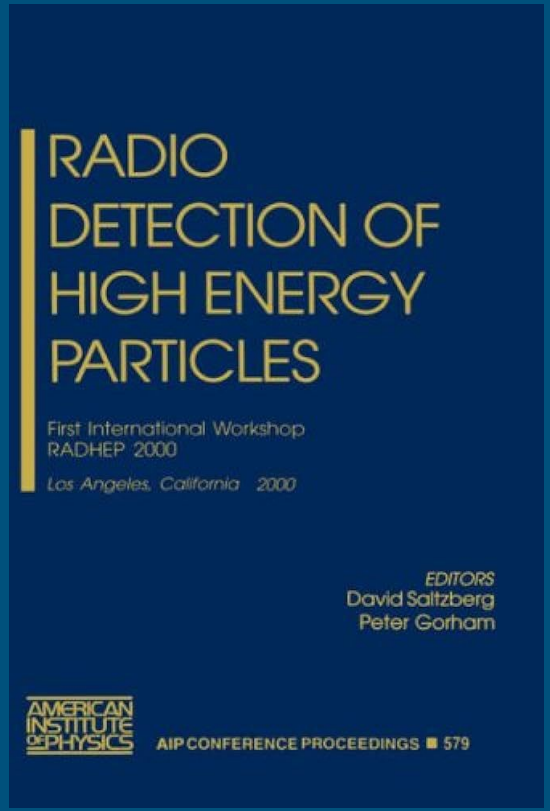
**** Trasnsparencies ****

**** Write-ups ****

**** Worshop Photos ****

**** List of Participants****

UCLA Faculty Center
University of California, Los Angeles
November 16-18, 2000



Many wonderful Askaryan Experiments at SLAC

"Yes, you can iron ice."
---Abby Vieregg & Amy Connolly

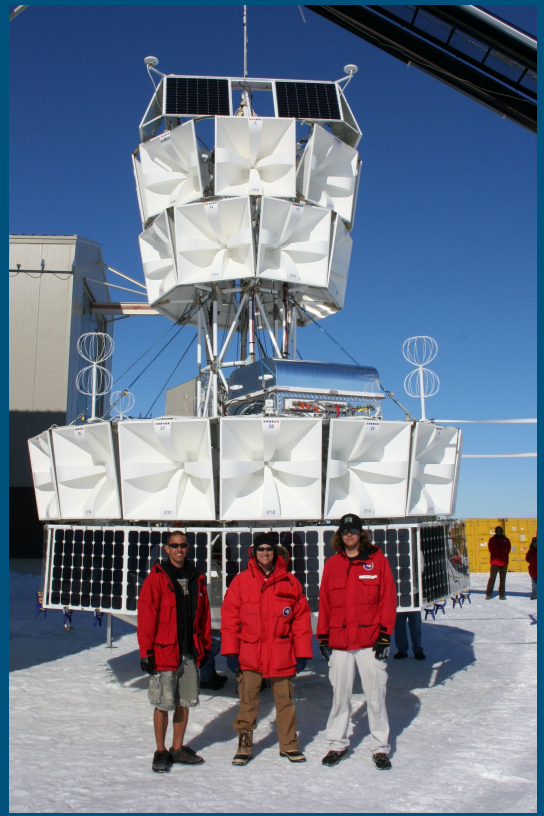
4 tons of "salt licks"
+ a year's supply of Morton's salt from Menlo Park Safeway

Thank you, Carsten Hast!

(No power cords were daisy chained, we promise)

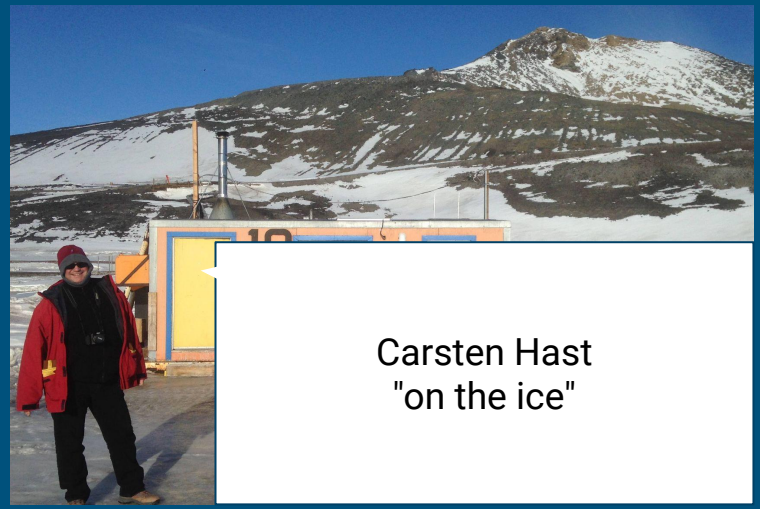
Many papers, e.g., Phys.Rev.D 99 (2019) 12, 122001

ANITA



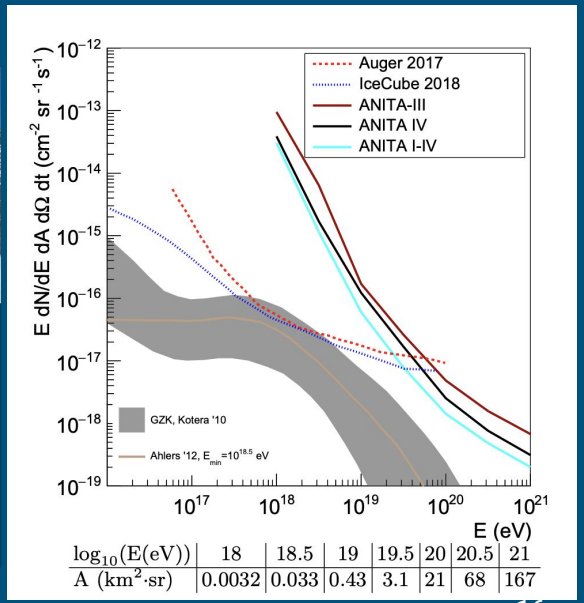
Christian Miki, PG, & Brian Hill

A major NASA mission, enabled by the accelerator results



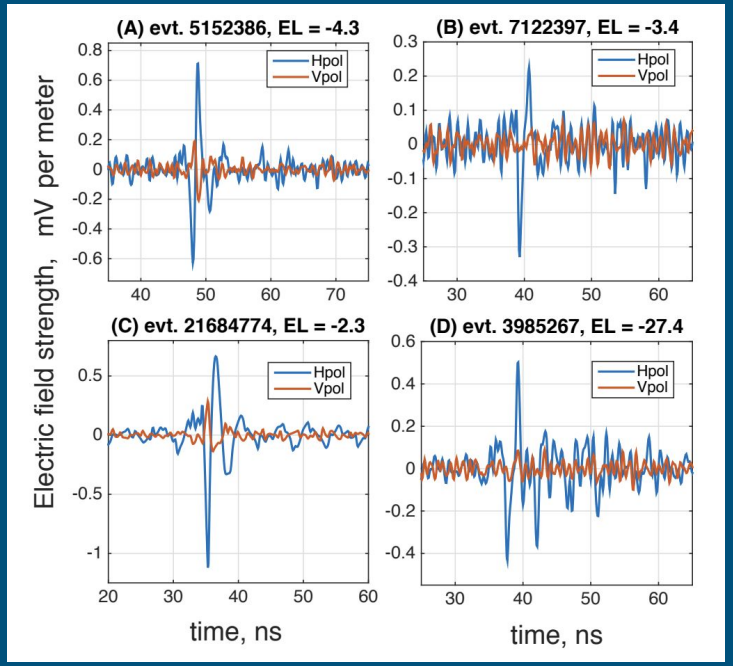
Carsten Hast
"on the ice"

Credit: Steven Prohira



$\log_{10}$(E(eV))	18	18.5	19	19.5	20	20.5	21
A (km^2·sr)	0.0032	0.033	0.43	3.1	21	68	167

Unexpected(?) events from ANITA



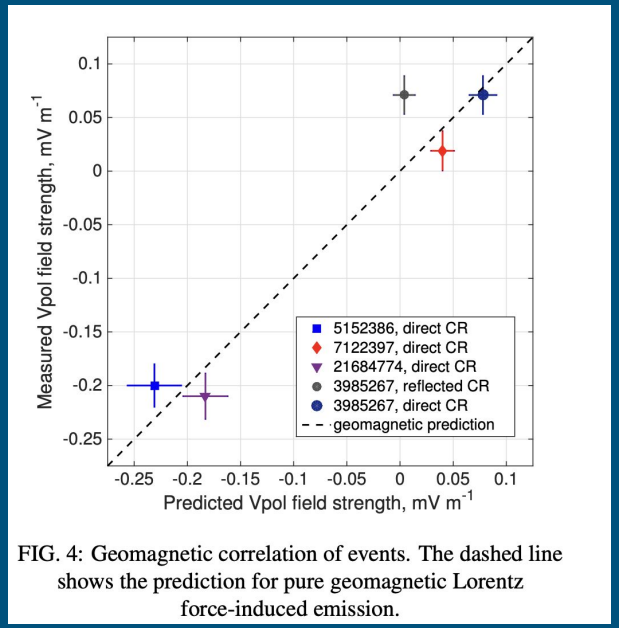


FIG. 4: Geomagnetic correlation of events. The dashed line shows the prediction for pure geomagnetic Lorentz force-induced emission.

Clearly need to understand cosmic ray emission too.

Phys.Rev.Lett. 116 (2016) 14, 141103

The SLAC magnetic experiments

Inspired by the ANITA cosmic-ray events

Led by the young people. In particular Konstantin Belov, Katie Mulrey, Andres Romero-Wolf, Stephanie Wissel, and Anne Ziles

Now Peter & David could serve as the old(er) folks.

K. Belov

Magnets for charge splitting
... and for the Big Bang Theory
(caught by Carsten)

Warner Bros./CBS

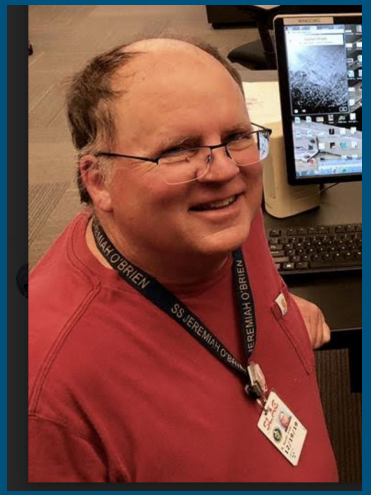
The magnetic experiments - the young people take charge

4 ton LPDE target
(inclined to release release emission)

Andres Romero-Wolf and Stephanie Wissel

Katie Mulrey

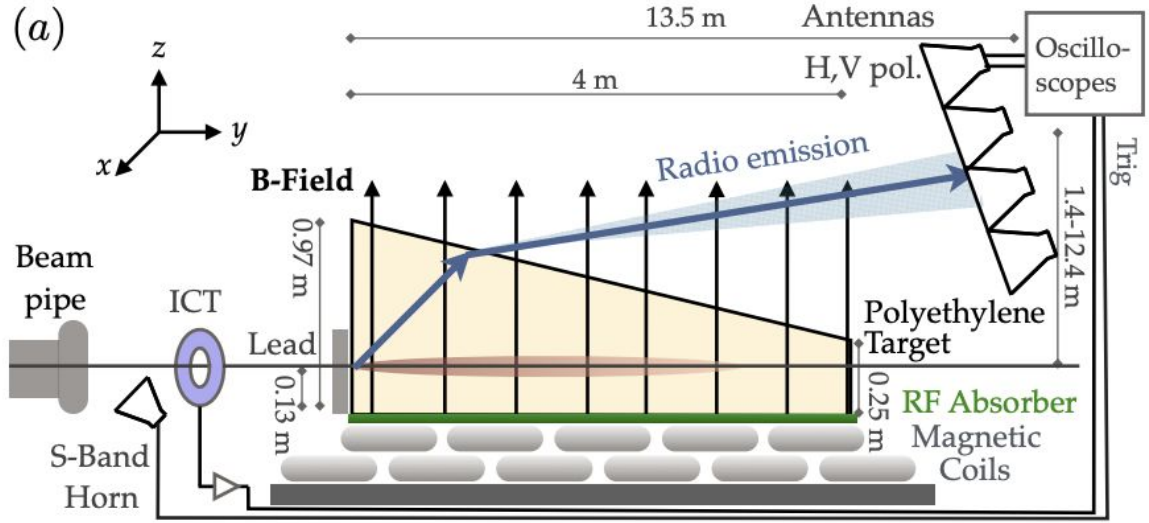
credit: Steven Prohira

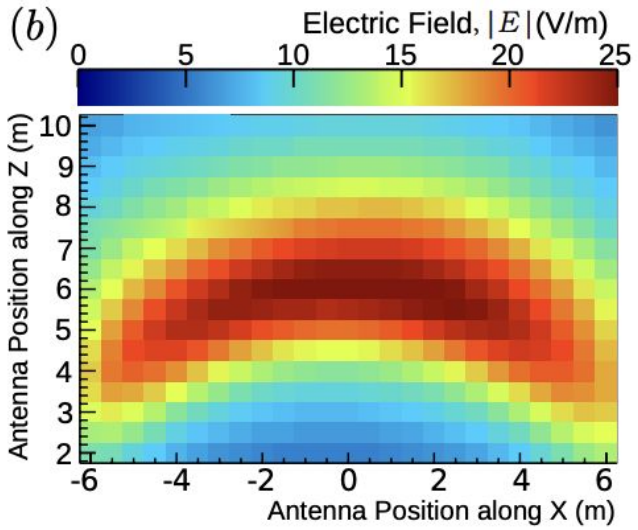


Many thanks also to Keith Jobe

Results

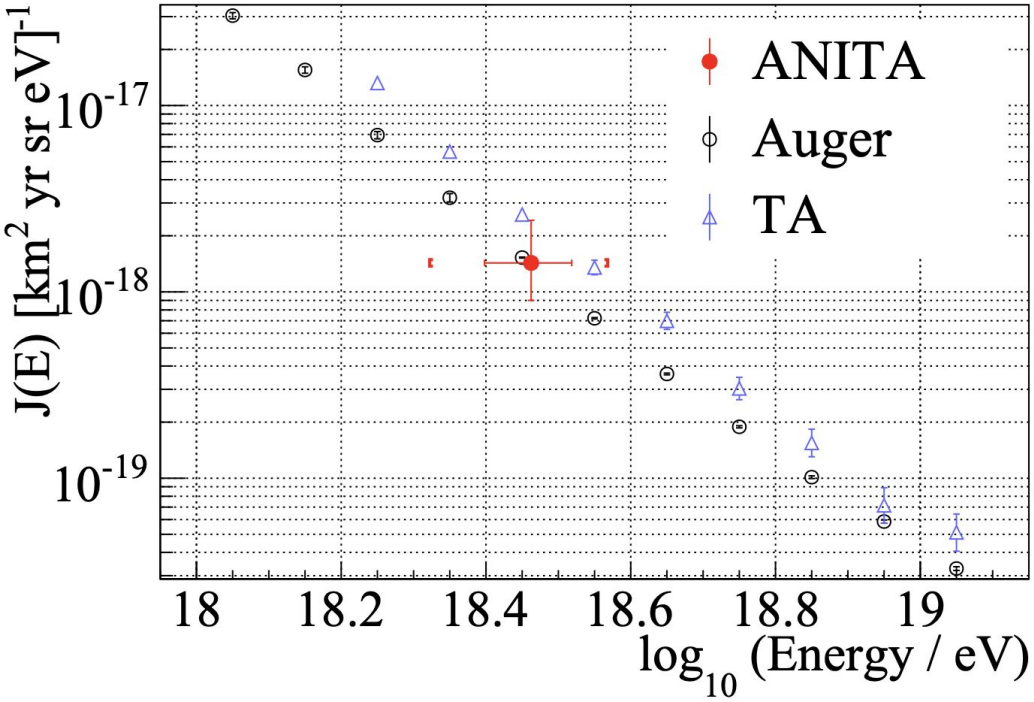
Phys.Rev.Lett. 116 (2016) 14, 141103





Excellent collaboration with the two theories: "ZHS" and "Endpoints".
Led to mutual understanding and agreement.

The first all-radio UHE cosmic ray results



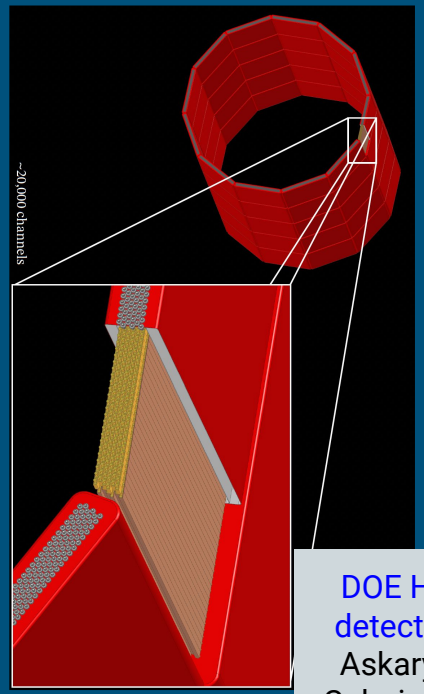
Presented by Harm Schoorlemmer at the International Cosmic Ray Conference (ICRC)

credit: Stephanie Wissel

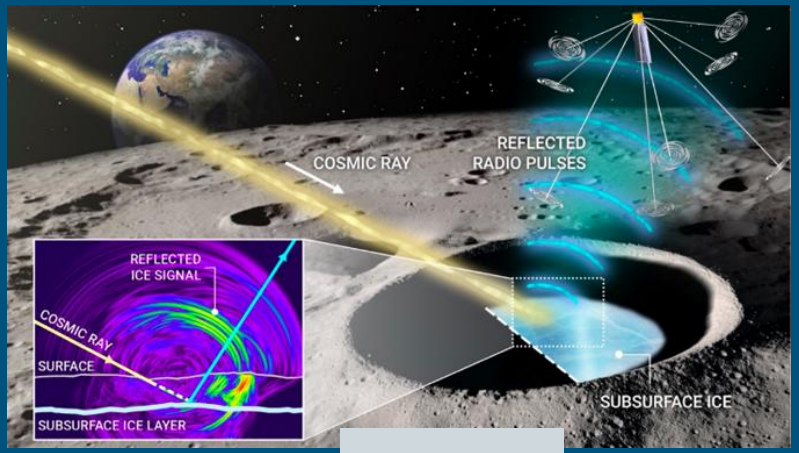
Astropart.Phys. 77 (2016) 32-43

Current and future applications

NASA Pioneers: Payload for Ultra-high Energy Observations (PUEO)

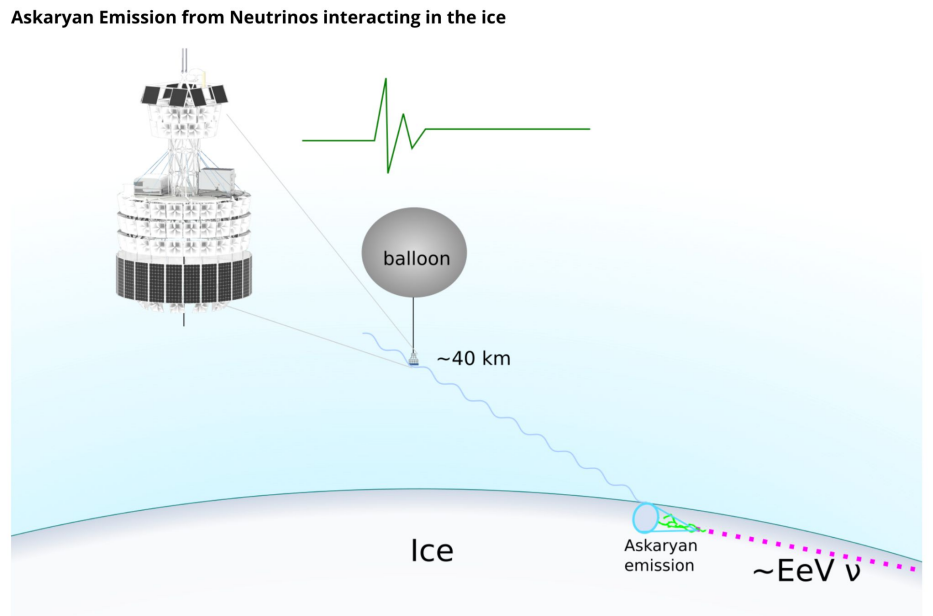


DOE HEP detectors: Askaryan Calorimeter Experiment (ACE)



NASA Planetary: Cosmic Ray Lunar Sounder (CoRaLS)

PUEO

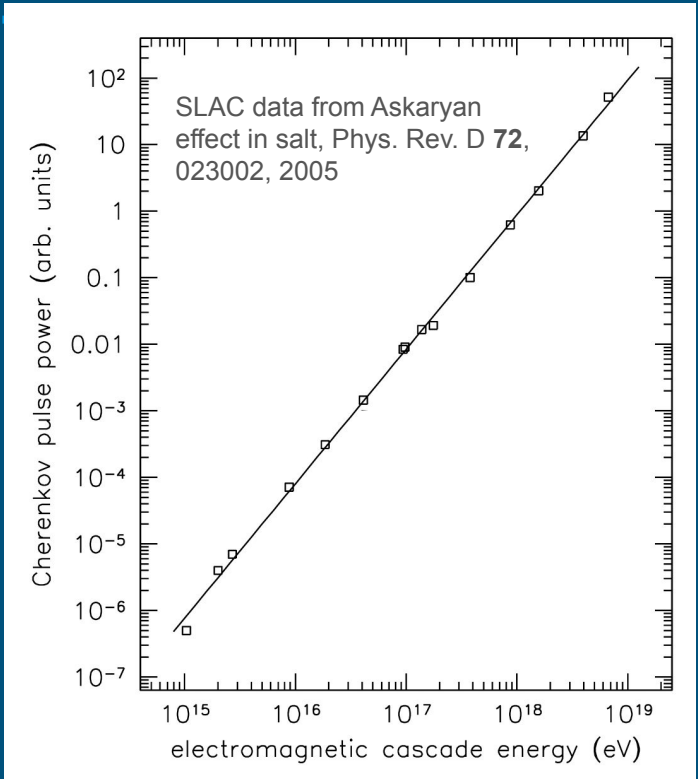


- PUEO is the successor to ANITA, led by a former Saltzberg student, Abby Vieregg (U. Chicago, P5 member)
- Payload funded by NASA *Astrophysics Pioneers* program, $20M class long-duration balloon mission
- Should exceed ANITA sensitivity by > 1 order of magnitude
- Will detect EeV cosmogenic flux if not astrophysically suppressed

Phys.Rev.Accel.Beams 21 (2018) 7, 072901

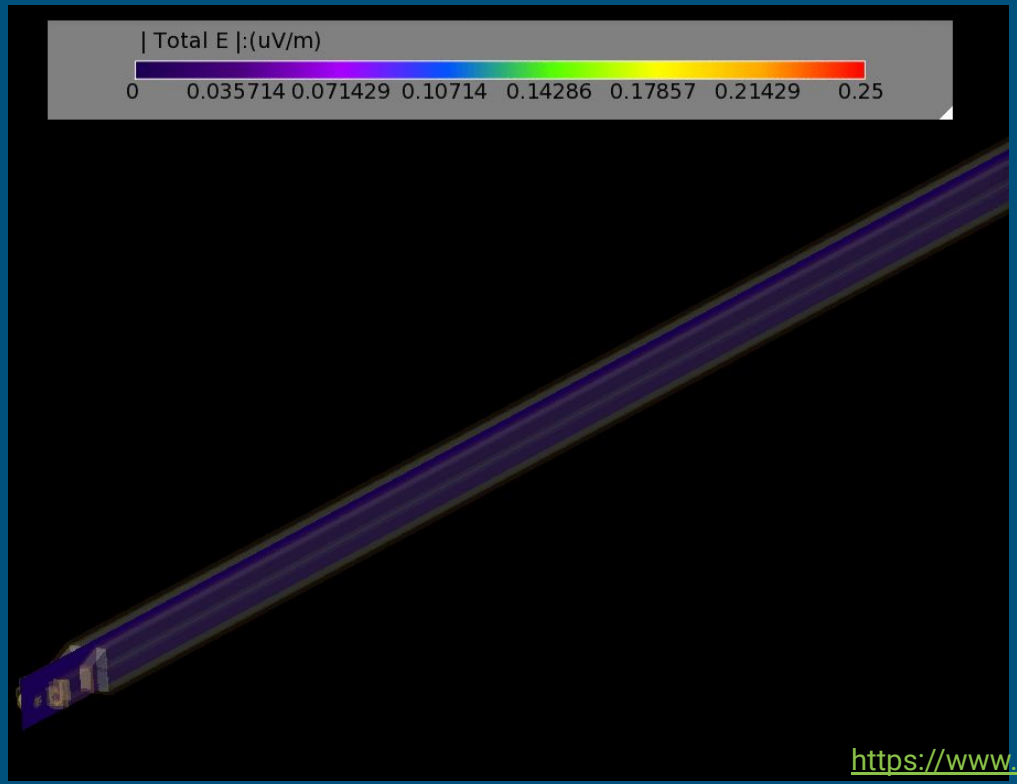
Phys.Rev.Accel.Beams 25 (2022) 10, 102901

Can we use Askaryan signal for HEP detectors?



- At extremely high energies, radio Cherenkov pulse is perfectly correlated to shower energy
- Calorimetric response extends down to the GeV range, but thermal noise prevents single-photon detection
- Suggests that we explore Askaryan effect for calorimeters with ultra-high dynamic range

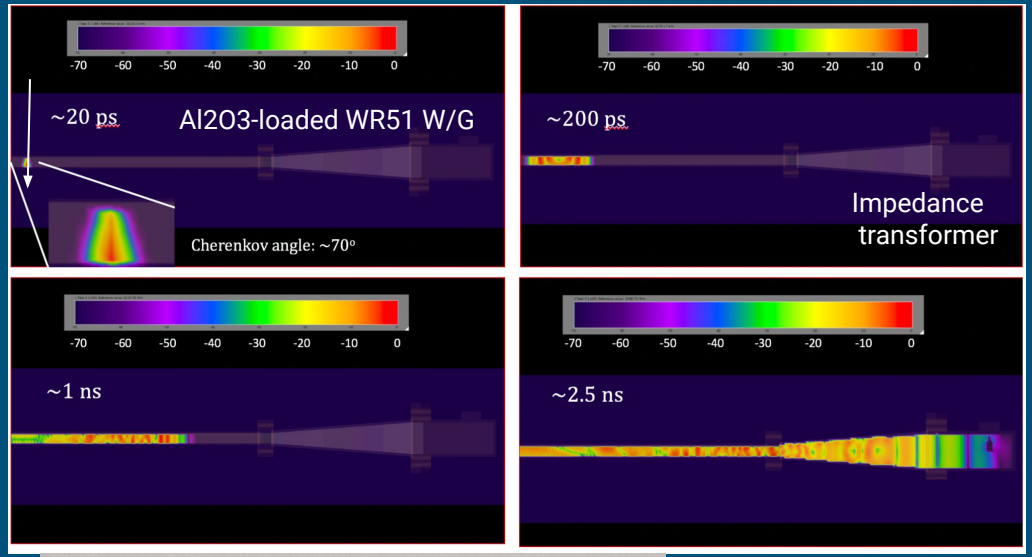
Loaded waveguide microwave fields

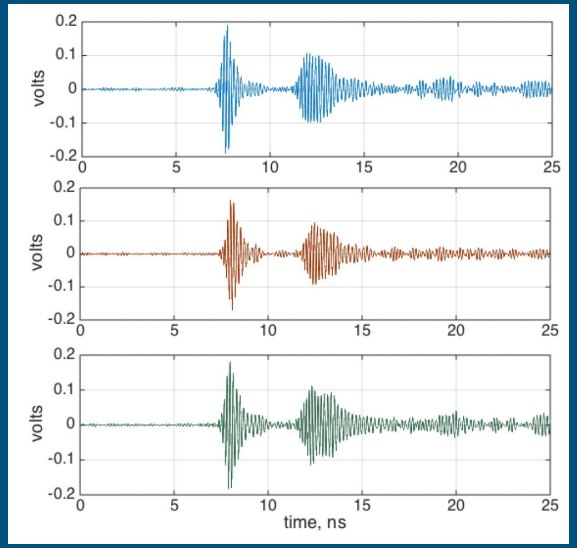


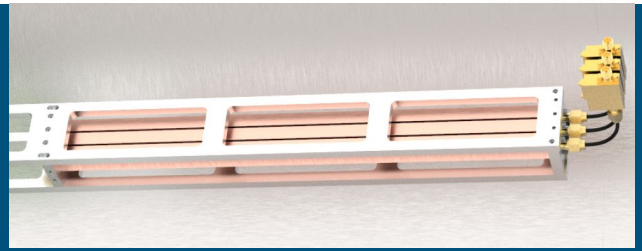
- Single charged particle passes vertically through Al2O3-loaded WR-51 (6mm high) stacked pair at upper right
- 4-8 GHz microwave Cherenkov in TE10 waveguide mode
- Group delay vs. frequency near cutoff gives very long low-frequency tail of emission
- Risetimes an order of magnitude faster than silicon

https://www.phys.hawaii.edu/~gorham/Post/dualACEanim.gif

Askaryan Calorimeter Experiment (ACE)







Alumina & copper are the detector materials → **extremely rad hard**

Microwave Cherenkov pulse from transiting shower can be easily timed to the picosecond level → **5D calorimetric timing planes**

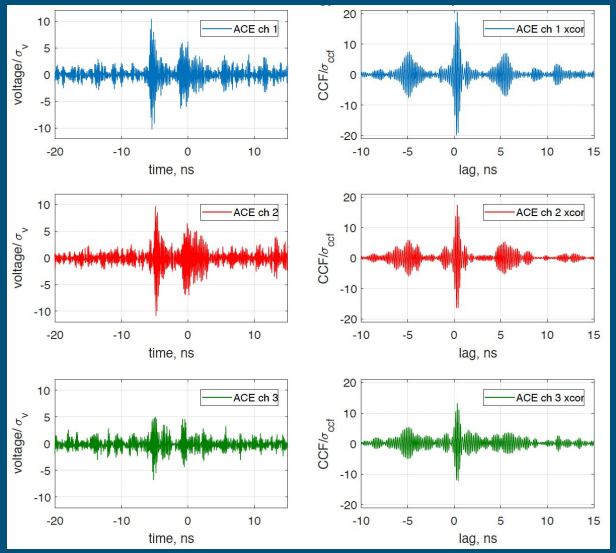
Currently funded under DOE HEP Detector R&D

Phys.Rev.Accel.Beams 21 (2018) 7, 072901
Phys.Rev.Accel.Beams 25 (2022) 10, 102901

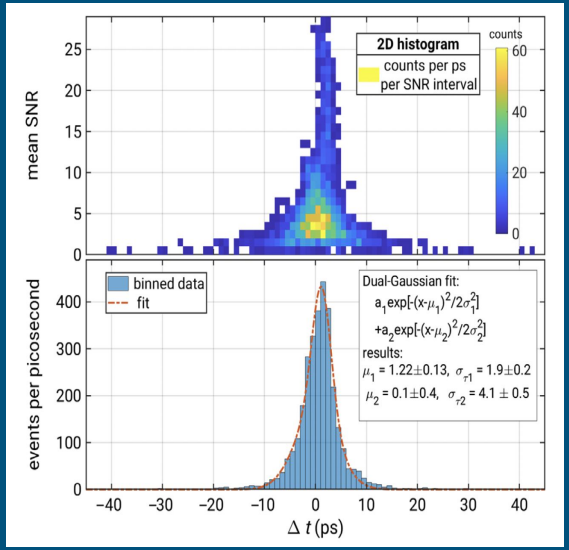
Calorimeters with picosecond timing

Raw data+ thermal noise

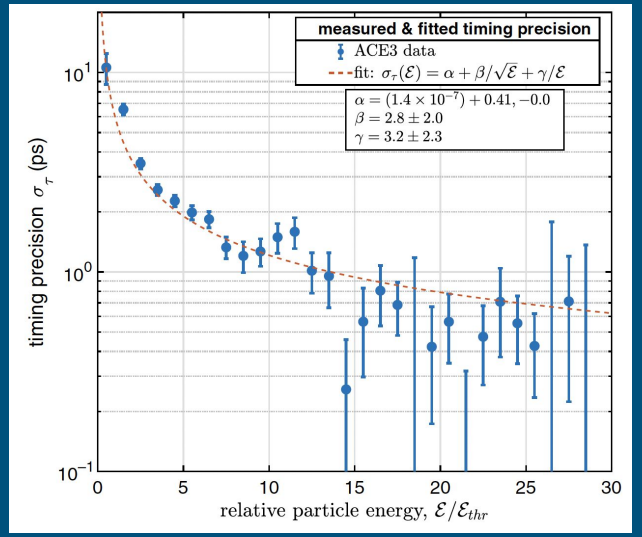
cross-correlation



timing distribution & fits



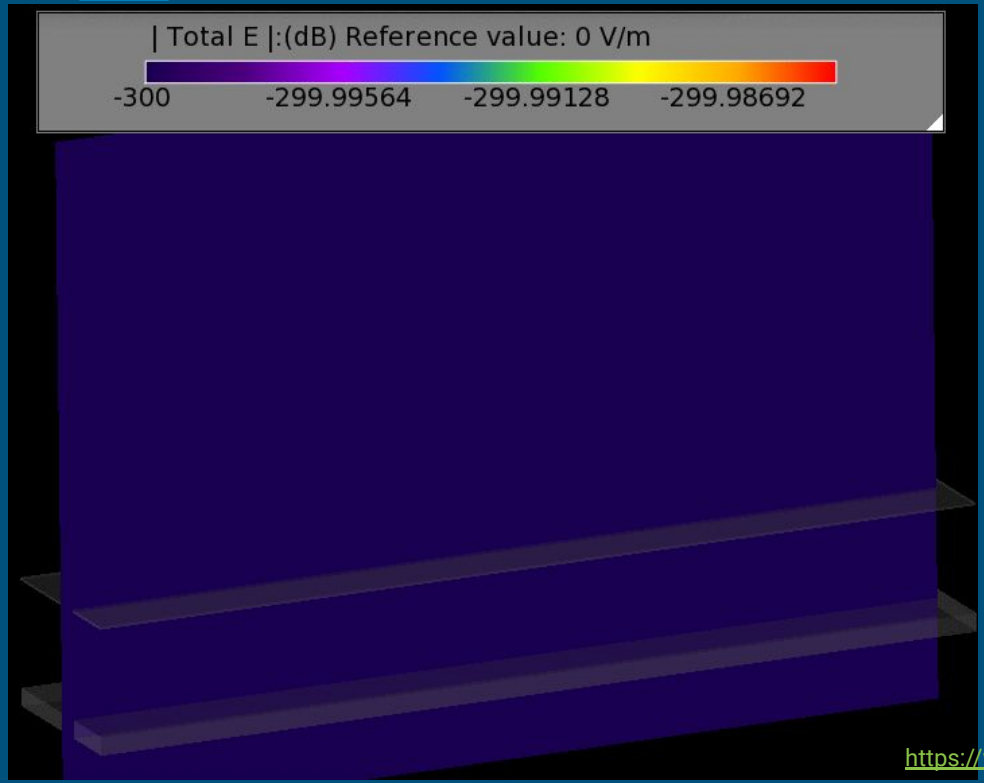
time resolution vs. relative energy



- Thermal noise (with cryo LNAs, left) sets particle/shower detection limit
  - Currently 10s to 100s of GeV (depending on LNA) → FCC-hh applications (blue-sky!)
- Center/Right: single element dt ~10ps at least count, <2 ps at SNR~5, sub-ps at high SNR
- **We are in a cryo/RF revolution (driven by quantum computing), so this could change soon!**

E.S. Costello, et al., Lunar Polar Volatiles 2022 (LPI Contrib. No. 2703)

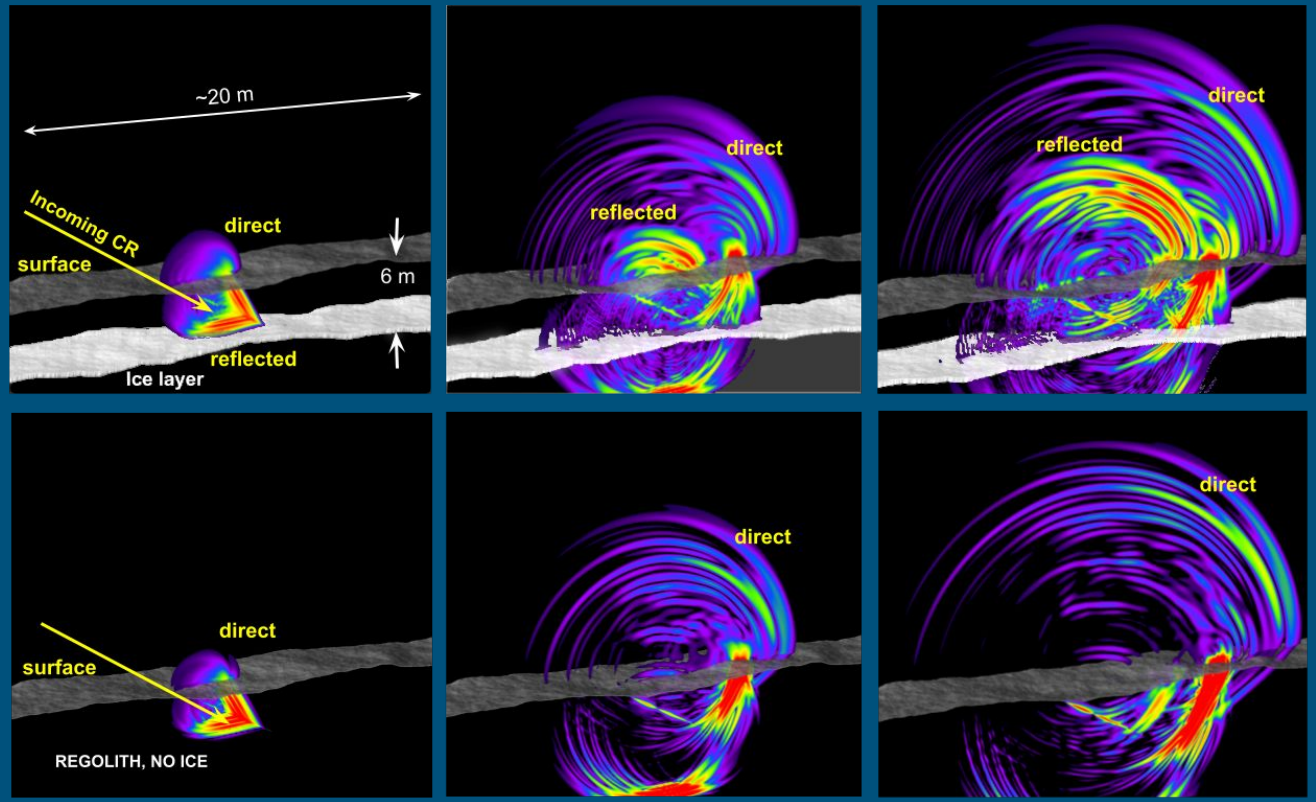
Cosmic Ray Lunar Sounder (CoRaLS)



- Cosmic rays impact the lunar regolith continuously, creating subsurface RF pulses
- These will reflect off buried ice layers if they are within ~20m of the surface in permanently shadowed polar regions, can be detected by **lunar orbiter**
- CoRaLS was just awarded $3M for TRL advancement in NASA's Planetary science division
- Also a possible surface instrument for Artemis Lunar lander!

https://www.phys.hawaii.edu/~gorham/Post/iceSignal_ideal.gif

CoRaLS: realistic subsurface bistatic sims



- Huge ice deposits seen on Mercury in permanent shadows
- Why not the Moon? Buried?!
- LCross impact excavated ~5m, saw water vapor
- Need subsurface radar to probe 3-30 meters for potential large ice deposits

Much debt to Gary Varner

- Gary's help and companionship through these times was essential, and a highly treasured memory.
- We are proud to join him as recipients of the APS/DPF Instrumentation Award
- Note there is a symposium dedicated to Gary on Friday at 11

Conclusion:
Accelerator confirmation of Askaryan effect has had wide-ranging consequencs

- Coherent Radio Cherenkov is essential to PeV-to-EeV neutrino astronomy
  - Many projects completed, current, and planned, with world-beating constraints in place
- Coherent microwave Cherenkov enables new HEP detectors for future colliders (FCC-hh as example)
  - Dynamic range and radiation hardness are outstanding characteristics
  - Picosecond timing derives from high bandwidth and high frequencies
  - Advances in cryogenics and microwave low-noise amplifiers may boost this sooner
- Coherent radio Cherenkov from cosmic rays showering in airless solar system bodies may provide probes that no other method can rival!

Final Remarks

- Thank you to the DPF for this wonderful award:

"for their experimental proof and subsequent characterization of radio emission from high-energy particle cascades, the Askaryan Effect, which has been used in searches for the highest energy astrophysical (PeV and EeV) neutrinos."

- It is really terrific to have this old work memorialized.
- The work is only possible with many junior colleagues who saw this through
- Work supported by Department of Energy (incl. early-career awards), NASA, and National Science Foundation
- And this could not have been done without the National Labs (esp. SLAC) with their beamlines and dedicated scientists