APS DPF Instrumentation Award Talk:

Observation and Applications of the Askaryan Effect

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

DPF - PHENO 2024 Meeting, Pittsburgh
May 17, 2024

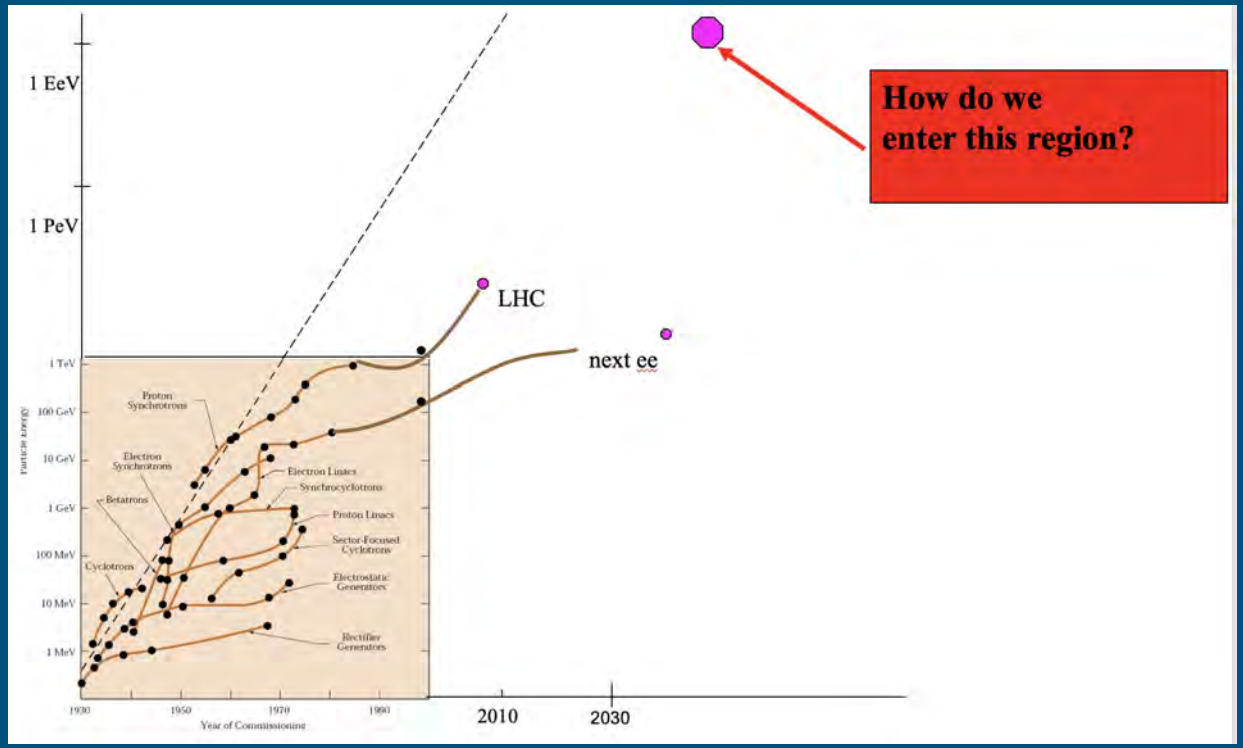
Shorter version of talk presented at CPAD-2023 (SLAC)

- "Accelerator Support of Radio Detection of High Energy Particles"
  - by David Saltzberg and Peter Gorham
  - https://indico.slac.stanford.edu/event/8288/contributions/7389/

- Also see the Early Career Instrumentation Award talk
  - "LArPix and LightPix: Scalable Readout for Large Cryogenic Detectors"
  - by Dan Dwyer
    - https://indico.slac.stanford.edu/event/8288/contributions/7390/

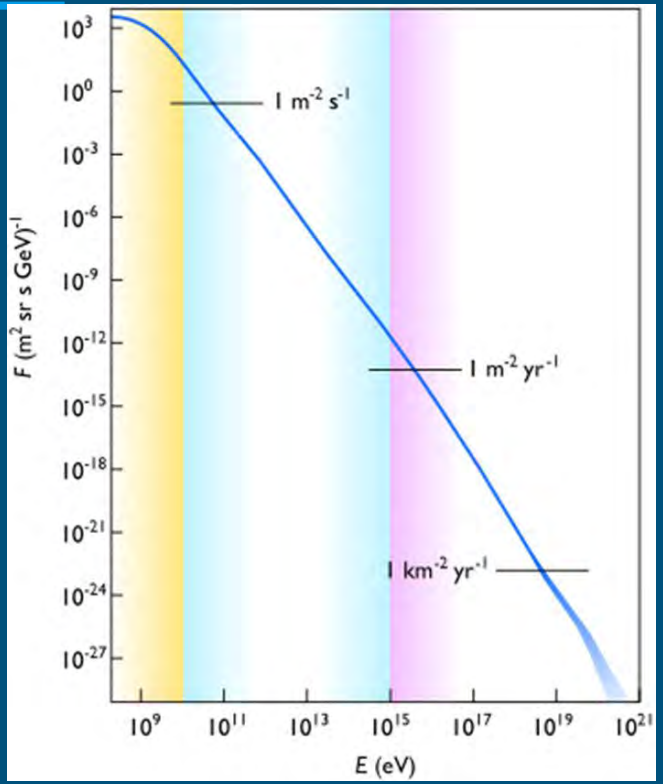
Modified from A. W. Chau and M. Tigner

Accelerator Physics challenge: "The Livingston Plot"



Modified from A. W. Chau and M. Tigner

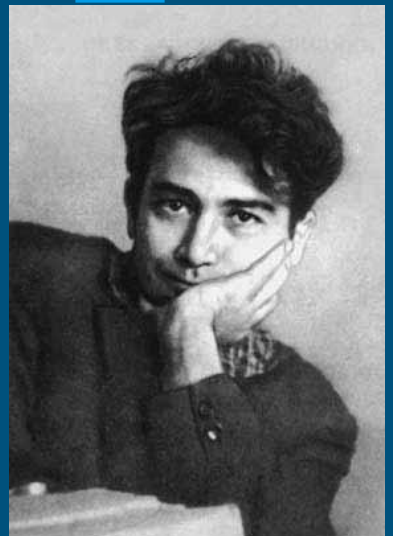
Cosmic Ray physics:
How to detect the rarest particles?



S. Swordy, Space Sciences Reviews, 2001

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

Using Large Natural Media: Transparent to Radio



G. Askaryan biography: Boris Bolotovskii

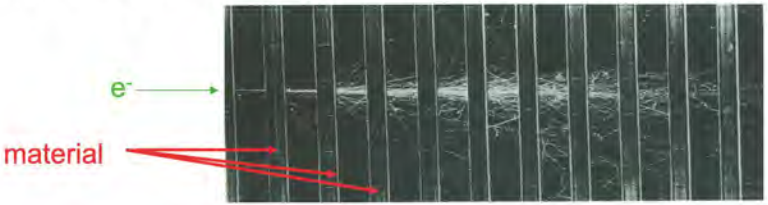
Gurgen Askaryan (1928-1997): prominent Soviet-Armenian physicist, discoverer of self-focusing of light, pioneer in light-matter interactions, and visionary in interaction of high energy particles with matter

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

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

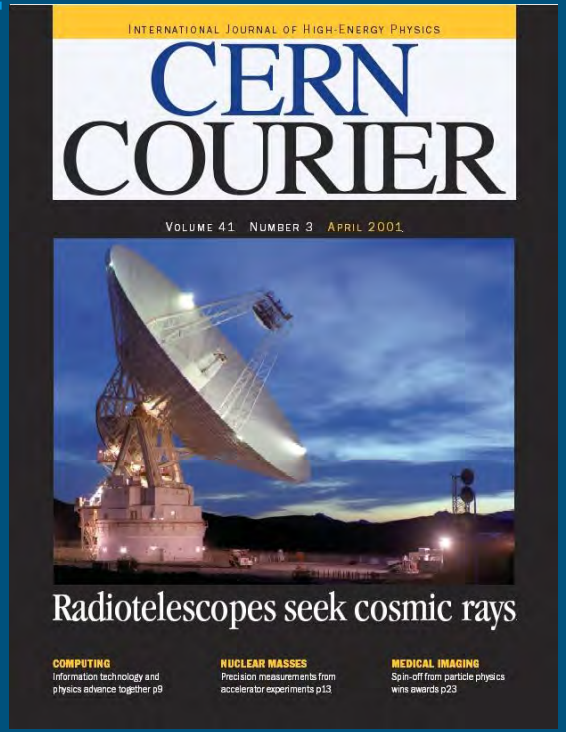
As is well known to this audience:

$P_{Cherenkov} \propto \nu\,\Delta\nu$ (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 and others 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)

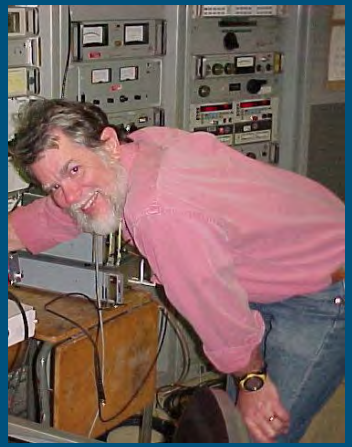
The GLUE control room (1998-2003)

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

Peter Gorham

More GLUE Folks

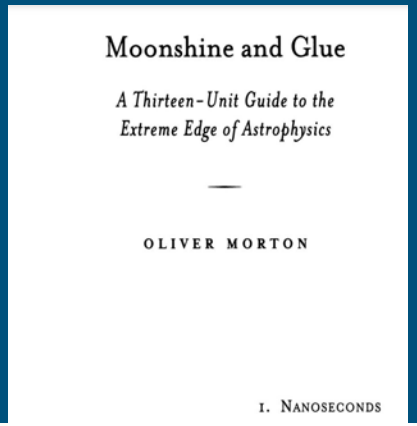
Chuck Naudet



Kurt Liewer

Dawn Williams

+an article in "American Scholar"



The Argonne Wakefield Accelerator (AWA)

Dick Konecny

Paul Schoessow

Ordering the target:

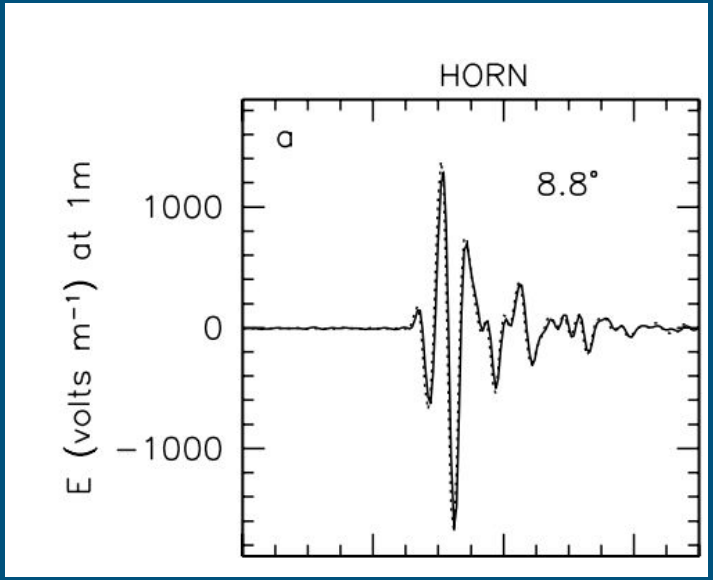
-- "*What kind of gas station do you operate?*"

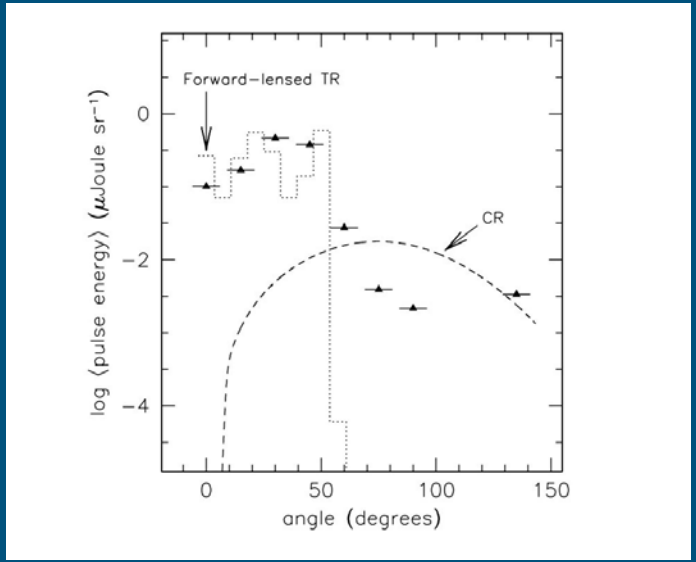
6 ✕ 100lb. bags of silica sand

+ Wei Gai, John Power, Manoel Conde

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

AWA results





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)

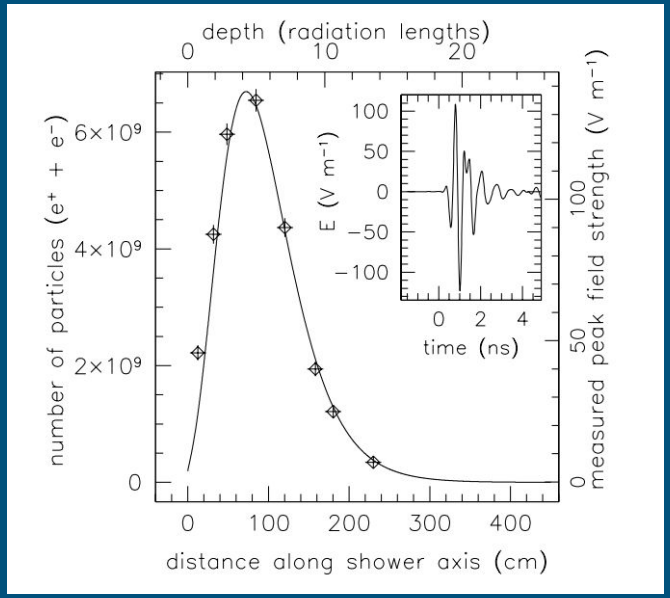
Lots of volunteer help

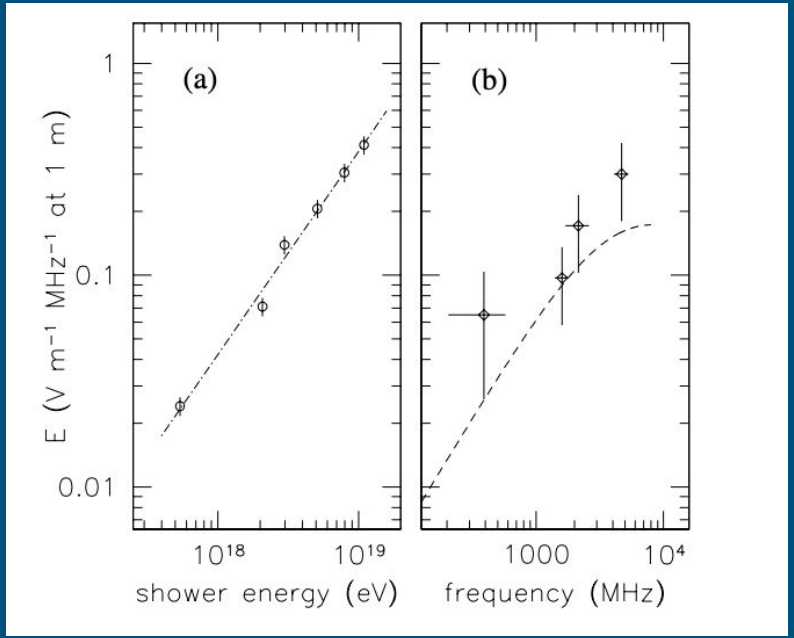
The amazing Dieter Walz!

"There's a cat in your target!"

Very clear results

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





Field of Radio Detection of High Energy Particles had a renaissance

RADHEP-2000

First International Workshop on
Radio Detection of High-Energy Particles

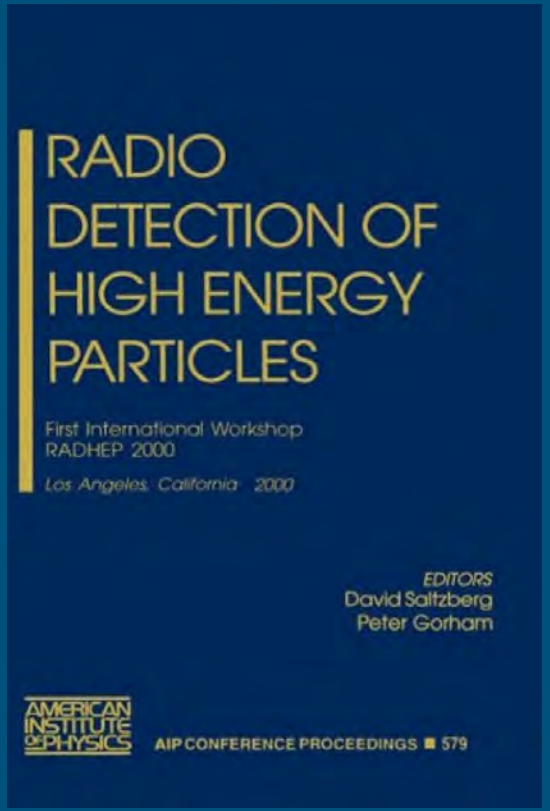
** Trasnsparencies **

** 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

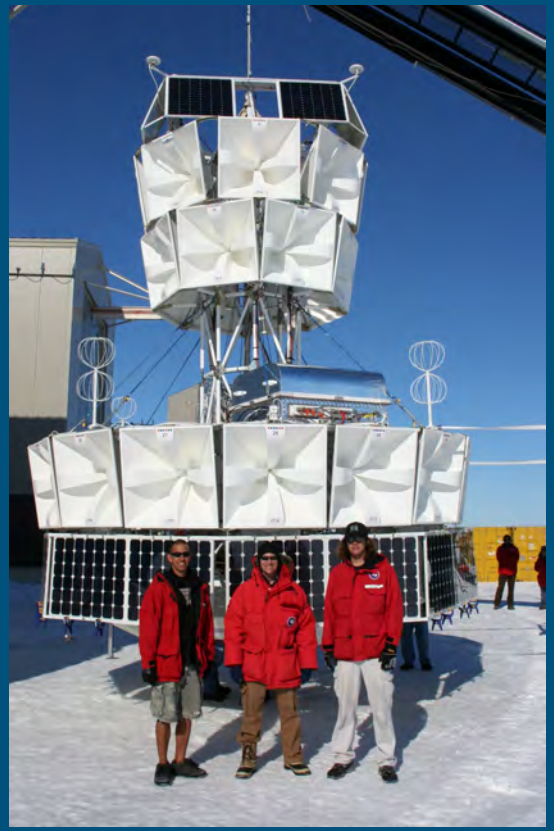
4 tons of "salt licks"
+ a year's supply of Morton's salt from Menlo Park Safeway

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

Thank you, Carsten Hast!

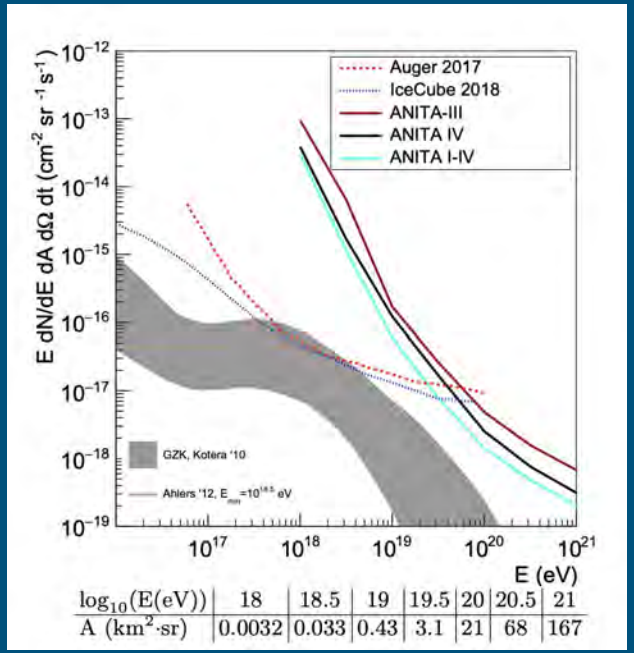
ANITA

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



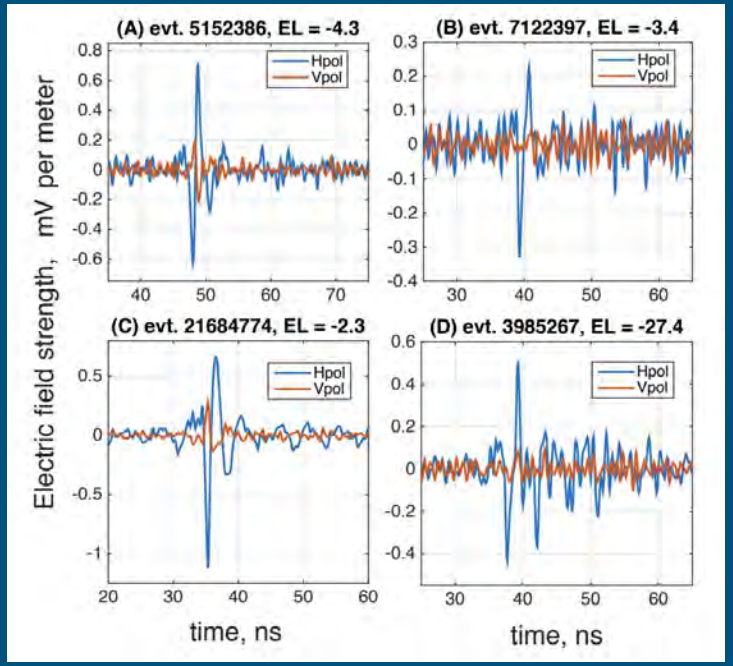
Christian Miki, PG, & Brian Hill

A major NASA mission, enabled by the accelerator results



$\log_{10}$(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



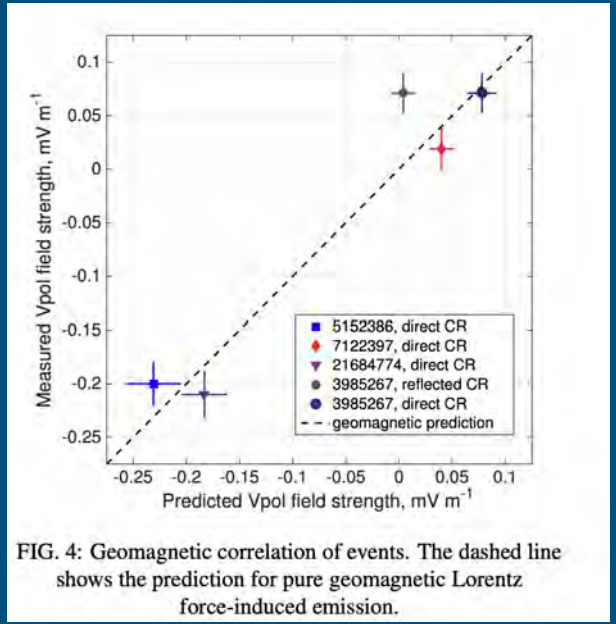


FIG. 4: Geomagnetic correlation of events. The dashed line shows the prediction for pure geomagnetic Lorentz force-induced emission.

Clearly need to understand cosmic ray emission too.

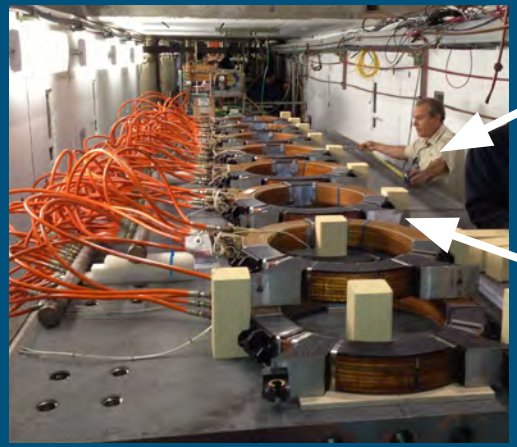
The SLAC magnetic experiments

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

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

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

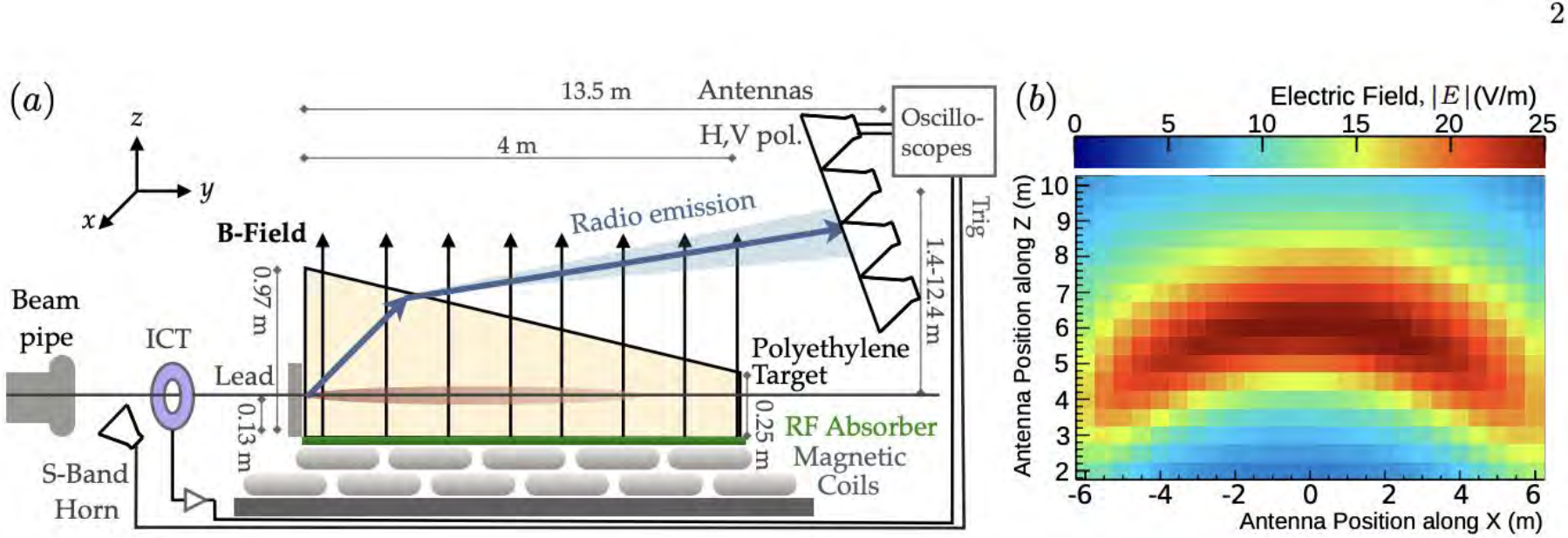
Katie Mulrey

credit: Steven Prohira

Many thanks also to Keith Jobe

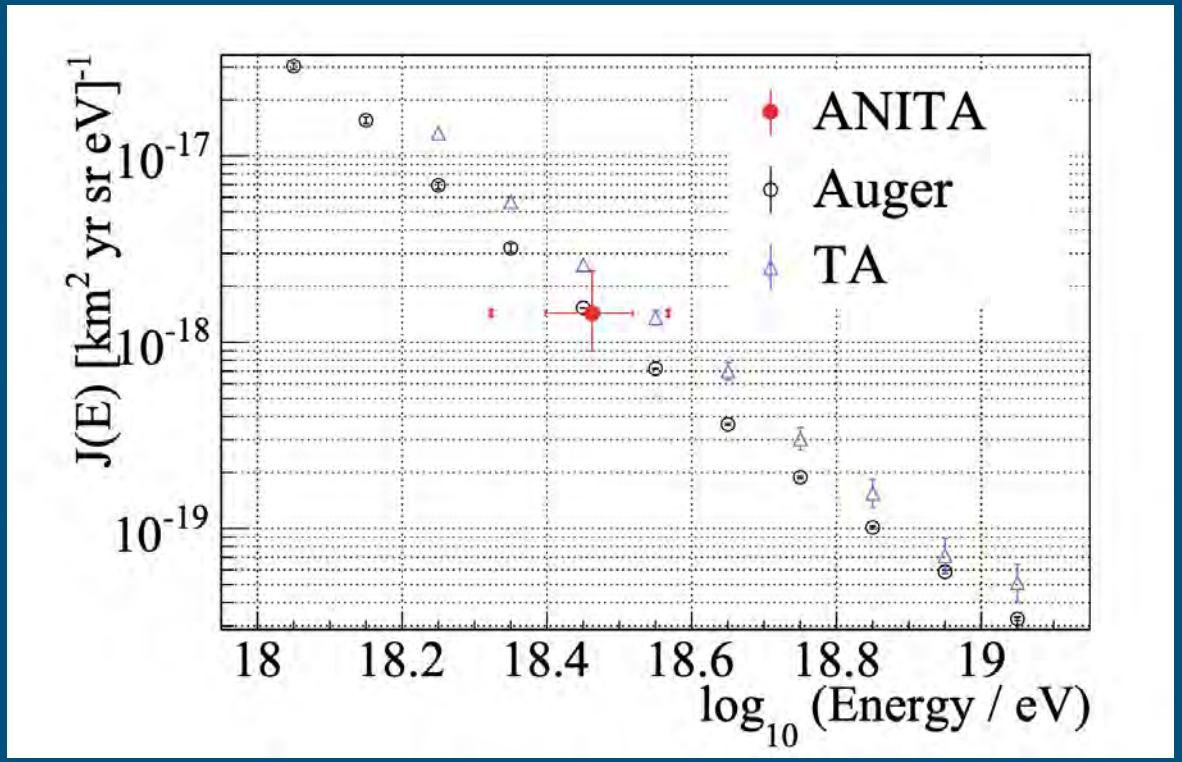
Results

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

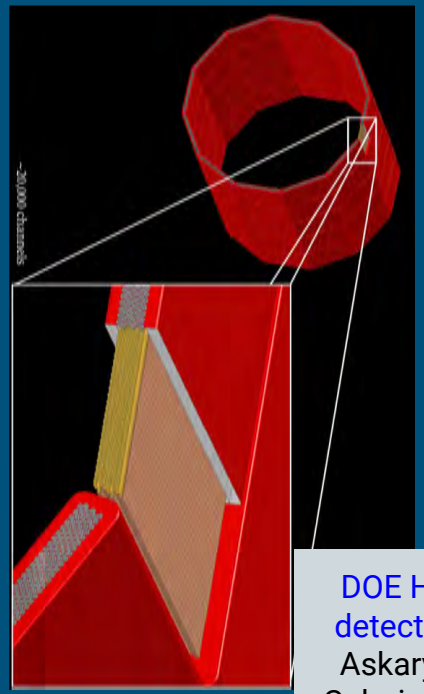


Presented by Harm Schoorlemmer at the International Cosmic Ray Conference (ICRC)

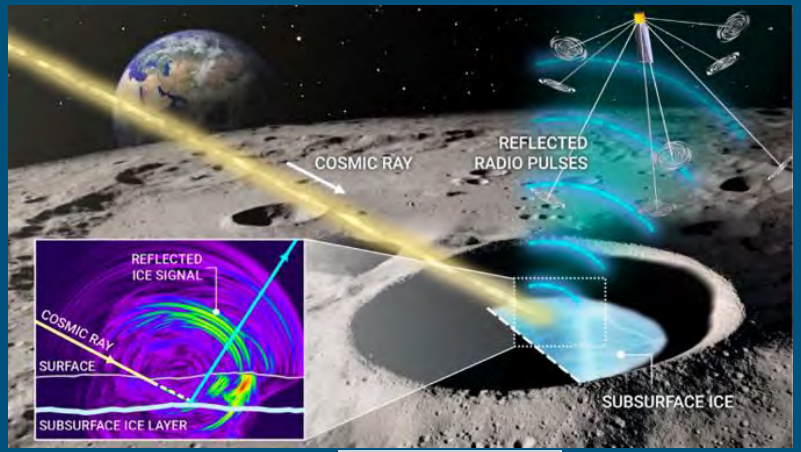
Astropart.Phys. 77 (2016) 32-43

Current and future applications

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



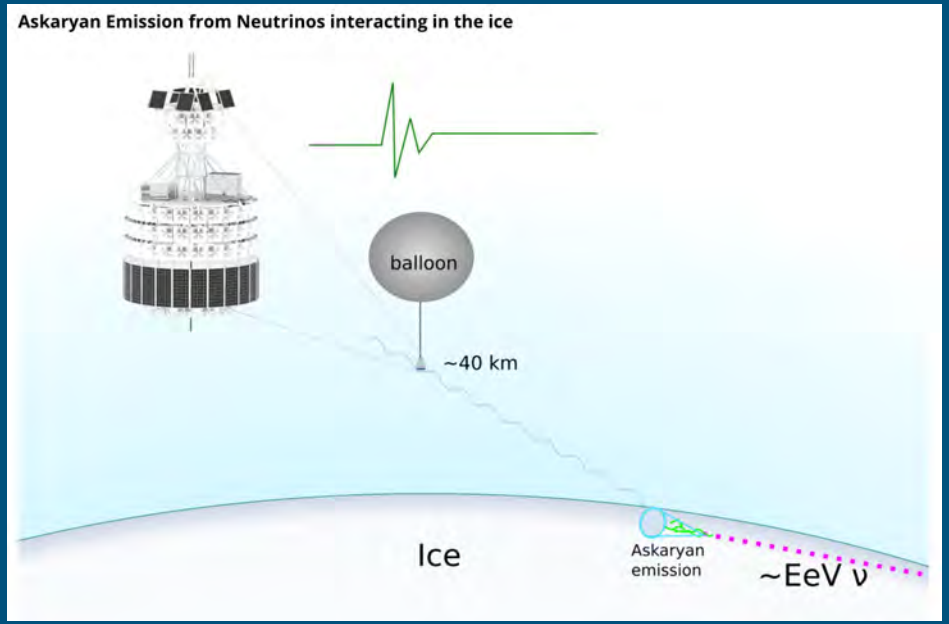
DOE HEP detectors: Askaryan Calorimeter Experiment (ACE)



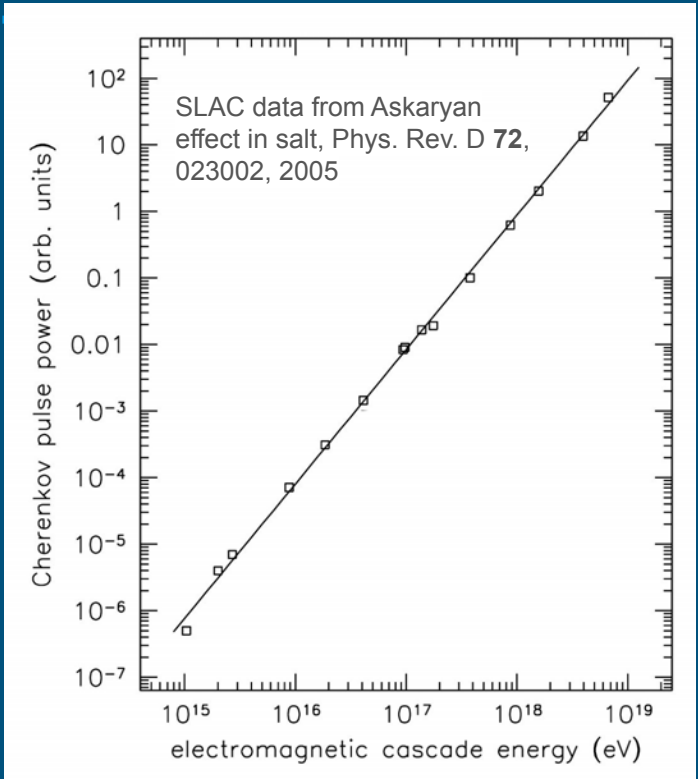
NASA Planetary: Cosmic Ray Lunar Sounder (CoRaLS)

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



Can we use Askaryan signal for HEP detectors?

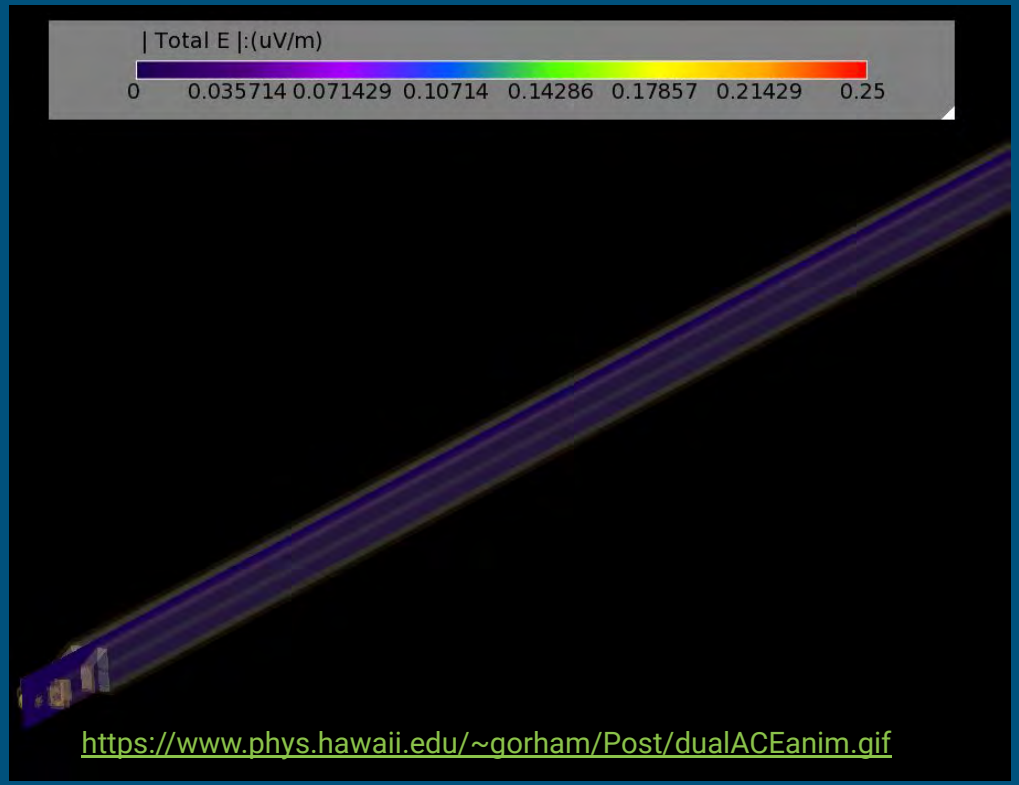


Phys.Rev.Accel.Beams 21 (2018) 7, 072901

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

- 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

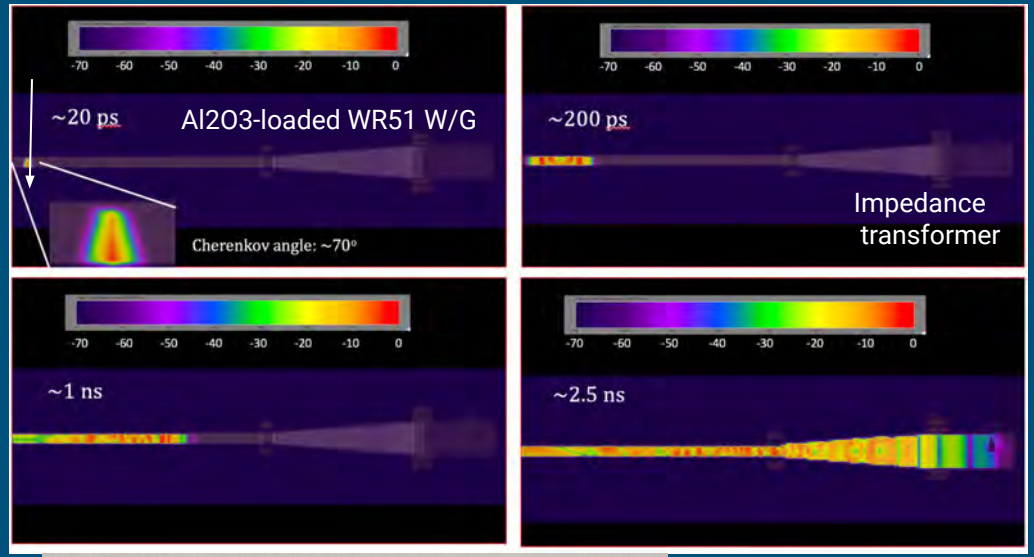
Loaded waveguide microwave fields

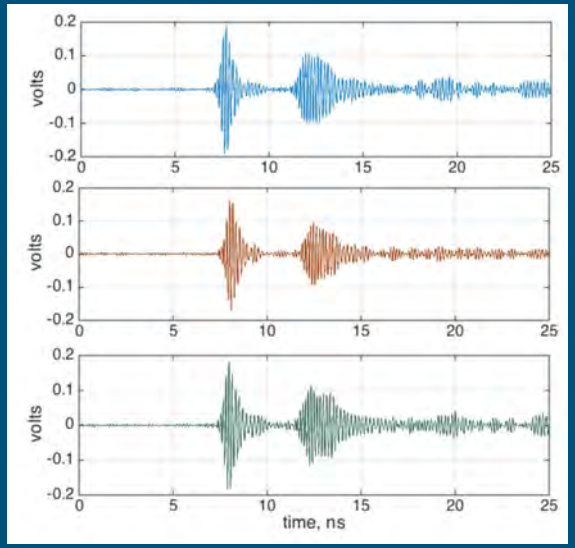


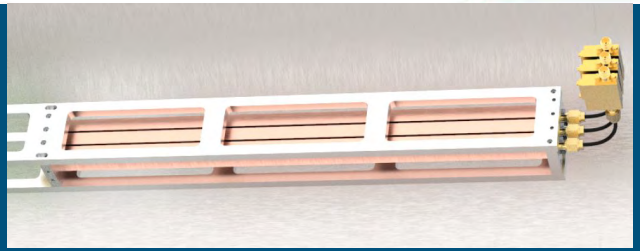
https://www.phys.hawaii.edu/~gorham/Post/dualACEanim.gif

- 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

Askaryan Calorimeter Experiment (ACE)







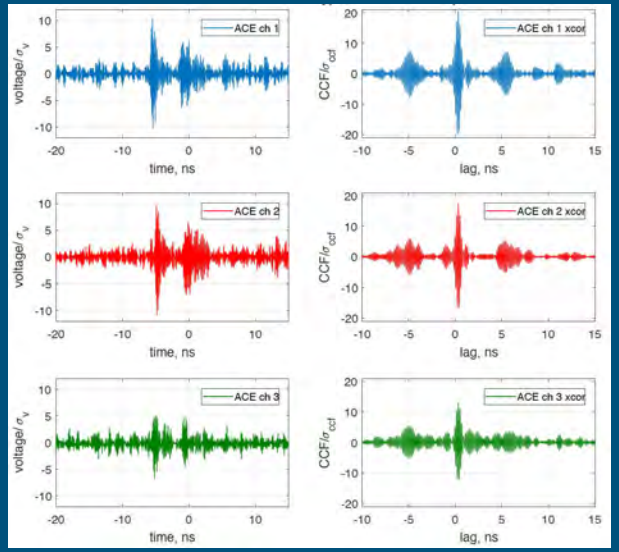
Alumina & copper are the detector materials → **extremely rad hard**

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

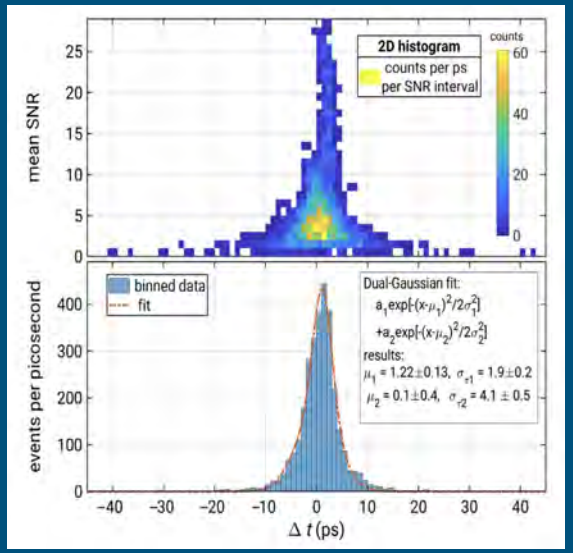
Currently funded under DOE HEP Detector R&D

Calorimeters with picosecond timing

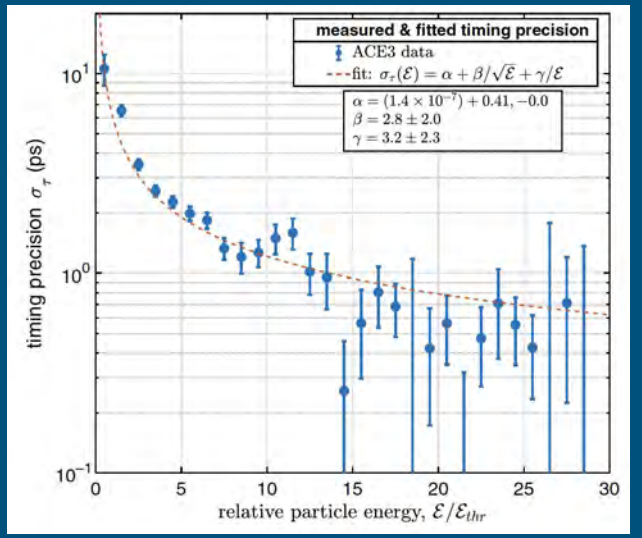
Raw data+ thermal noise cross-correlation



timing distribution & fits



time resolution vs. relative energy

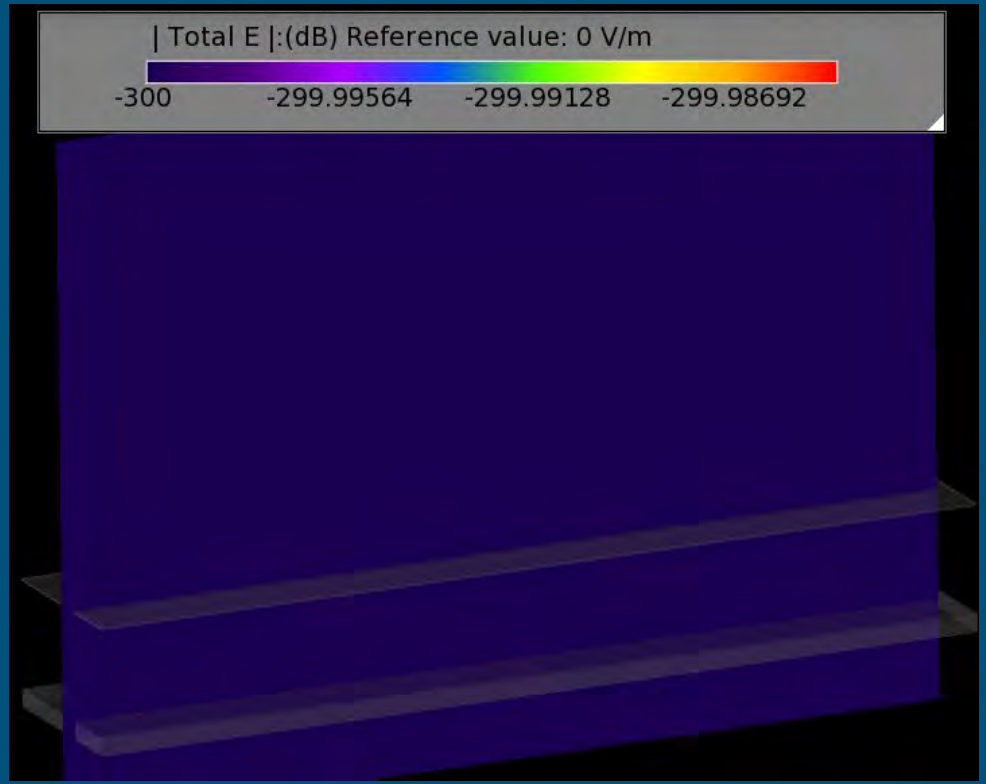


- Thermal noise (with cryo LNAs, left) sets particle/shower detection limit
  - Currently 10s to 100s of GeV (depending on LNA) → FCC-hh applications (blue-sky!)
- Center/Right: single element dt ~10ps at least count, <2 ps at SNR~5, sub-ps at high SNR
- **We are in a cryo/RF revolution (driven by quantum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

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

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

Cosmic Ray Lunar Sounder (CoRaLS)

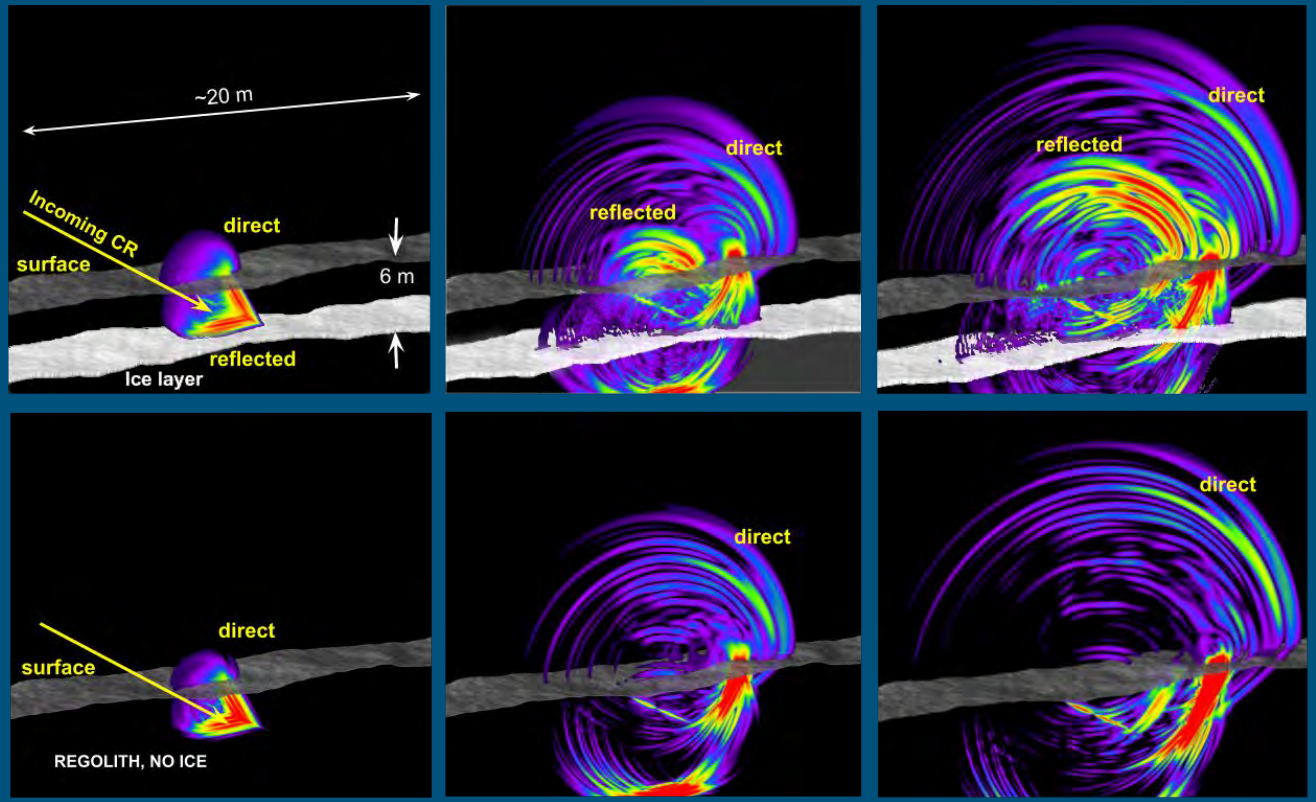


https://www.phys.hawaii.edu/~gorham/Post/iceSignal_ideal.gif

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

- 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!

CoRaLS: realistic subsurface bistatic sims



- Huge ice deposits seen on Mercury in permanent shadows
- Why not the Moon? Buried?!
- LCROSS (Lunar Crater Observation and Sensing Satellite) 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
-

Conclusion:

Accelerator confirmation of Askaryan effect has had wide-ranging consequences

- 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 with their beamlines and dedicated scientists