New initiatives & Results in Radio Detection of High Energy Particles

Peter Gorham
University of Hawaii
& Jet Propulsion Lab

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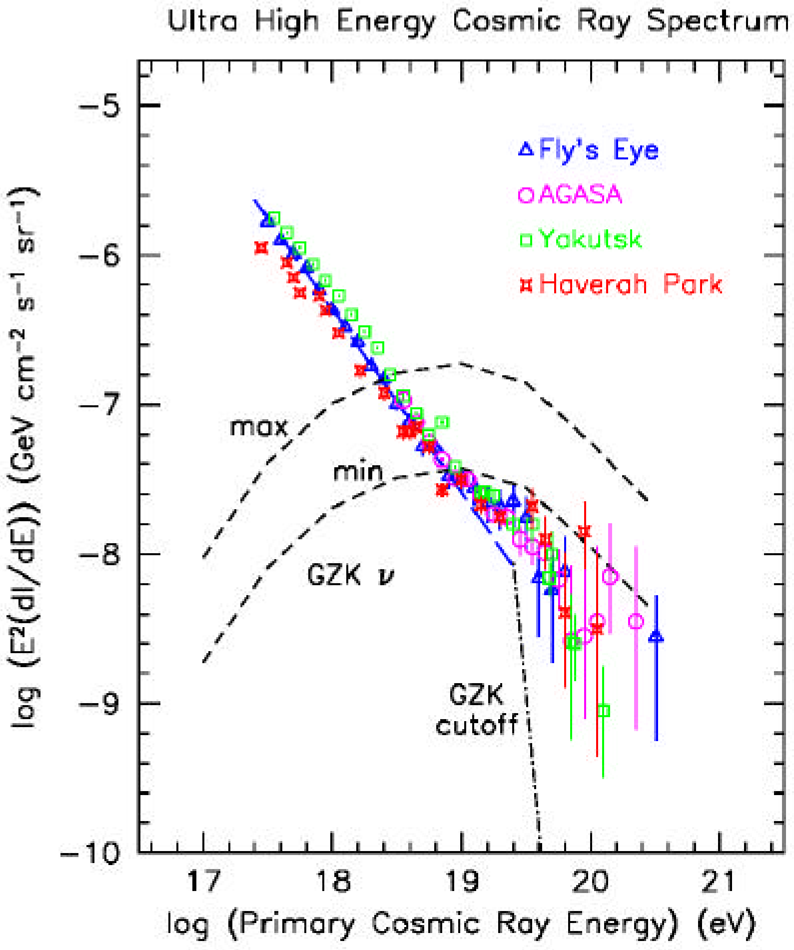
Scientific goal of radio detection

- GZK cosmic rays:
  - From whence??! And How??
- Standard Model:
  - We see the punch-through tail from distant sources: QSO’s, GRBs…
- If so: GZK neutrinos are the signature
  - Necessary and sufficient to confirm standard GZK model
  - If detected: a new standard candle of EeV neutrinos(!)



Why radio?

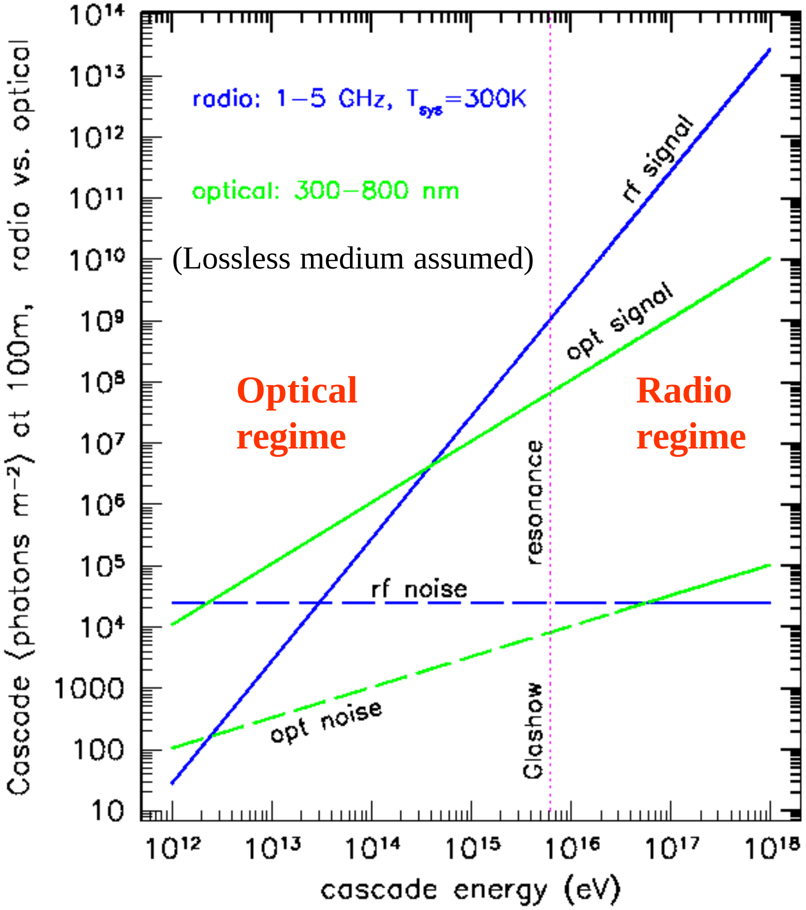
- GZK neutrino flux: ~1 per km^2 per day over 2π steradian
  - BUT interaction probability per km of water: ~0.2%

➔ A cubic Km detector may expect to see 1 event every 2 years in its fiducial volume!

- How can we get the ~100 km^3-sr volumes needed to detect GZK neutrinos at an acceptable rate?

- Answer: Askaryan process: coherent radio Cherenkov emission
  - EM cascades produce a charge asymmetry, thus a radio pulse
  - Process is coherent ➔ Quadratic rise of power with cascade energy
  - Radio emission exceeds optical secondary EM radiation at ~10 PeV, becomes completely dominant at EeV energies

Detecting the PeV to EeV cascade: Radio vs. optical



- Optical Cherenkov: strong in blue to UV--good match for PMTs
  - Signal is incoherent => intensity grows linearly with cascade energy

- Radio Cherenkov: broad spectrum, few MHz to ~10 GHz
  - RF SNR exceeds optical at ~Pev energies for 100 m distance to shower

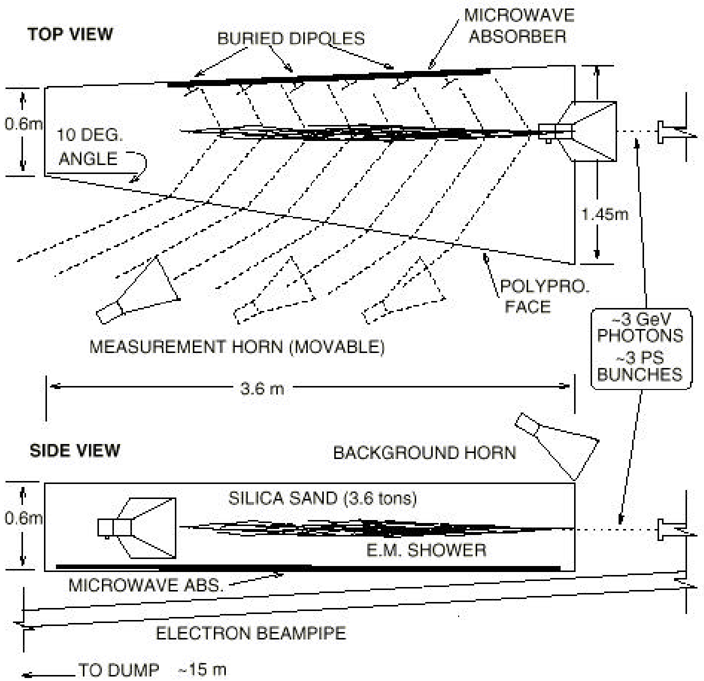
For >>PeV cascade detection:

- optical techniques proven, but
- radio technique can dominate over optical—

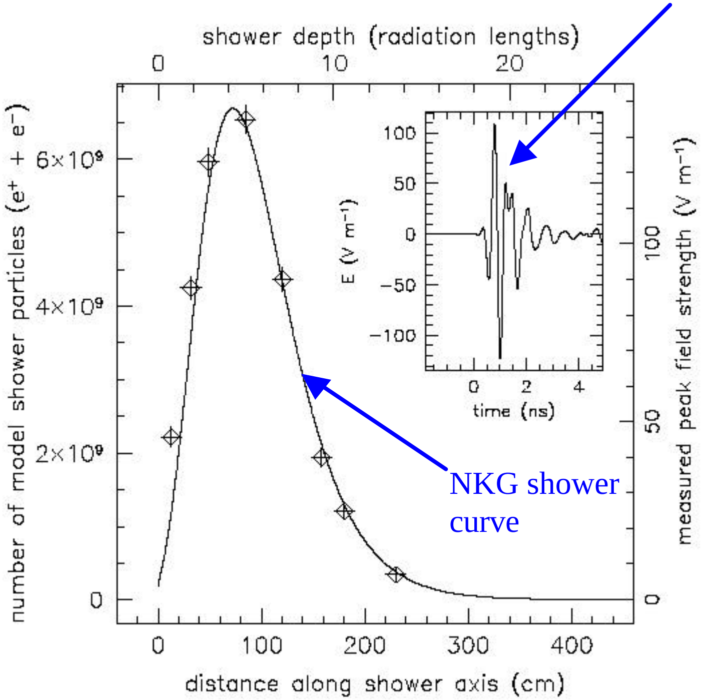
if radio-clear shower media can be found

Askaryan Confirmation: SLAC Lunacee II

Lunacee II target & initial results



Sub-ns pulse, Epp~ 200 V/m!



NKG shower curve

From Saltzberg, Gorham, Walz et al PRL 2001

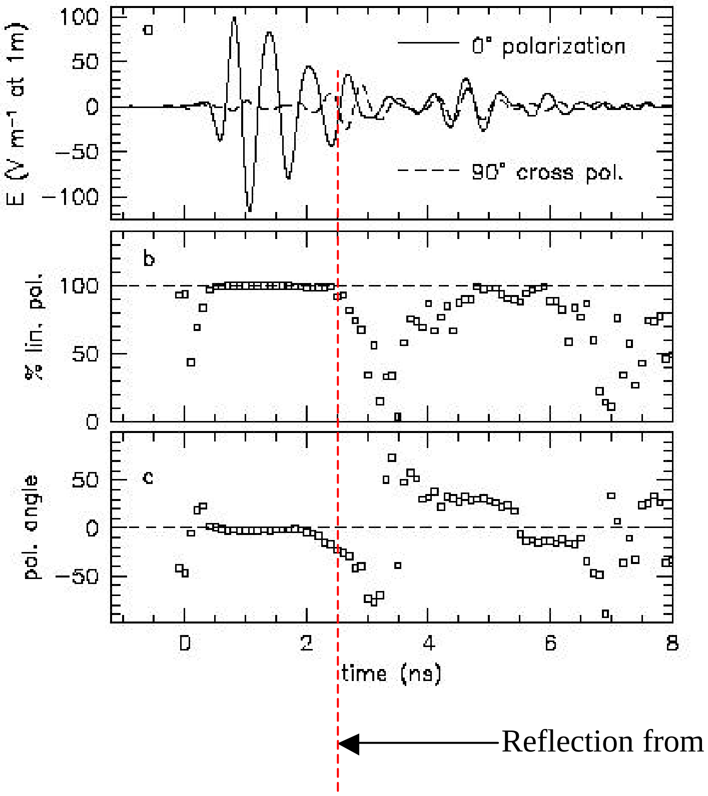
- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!

- Measured pulse field strengths follow shower profile very closely

- Charge excess also closely correlated to shower profile (EGS simulation)

Is it coherent Cherenkov radiation? **Yes!**

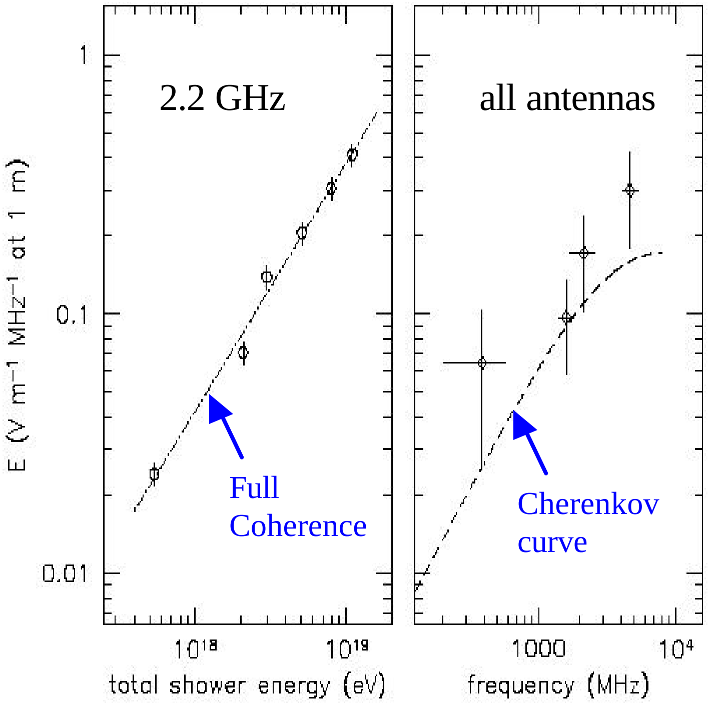
2.2 GHz data:



100% polarized

In proper plane

Reflection from side wall



2.2 GHz

all antennas

Full Coherence

Cherenkov curve

- 100% linearly polarized pulses

- Plane of polarization aligned with plane of Poynting vector and cascade track

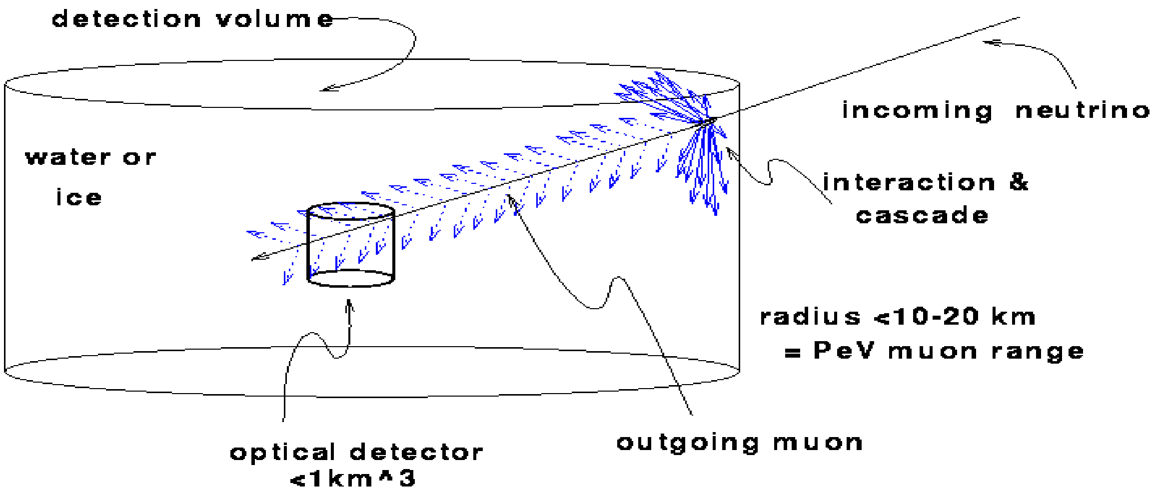
- No departures from coherence
  - field strength ~ Nγ ~ shower energy

- Frequency dependence also as expected for CR: E ~ ν dν

Current Initiatives in Radio Detection

- Goldstone Lunar ultra-high energy neutrino Experiment (GLUE)
  - Started at JPL in 1998, UCLA (Saltzberg) joined 1999; accepted to NASA Deep Space Network Radio Astronomy program 2000; ongoing
- Radio Ice Cherenkov Experiment (RICE)
  - Ongoing: Above AMANDA array at south pole station, U. Kansas, Bartol, Florida
- Salt-dome Shower Array (SalSA)
  - Goal: ~100 km^3 w.e. AMANDA-like radio array within a large salt dome
  - Near term efforts: testbed dev. to establish basic utility salt as detection medium
- Antarctic Impulsive Transient Array (ANITA)
  - NASA MIDEX proposal (October 2001); also NASA SR&T (Cosmic ray program)
  - Long-duration balloon mission, observes ~1M km^3 of ice sheet
- FORTE: Fast On-orbit Recording of Transient Events
  - LANL-supported analysis of DOE satellite data for GZK cosmic ray events
  - N. Lehtinen (Stanford 2001 PhD) postdoctoral work, begun in January 2002

PeV to ZeV Neutrino Cherenkov Telescopes:
Muon rangers vs. cascade detectors



Cascade Detectors:

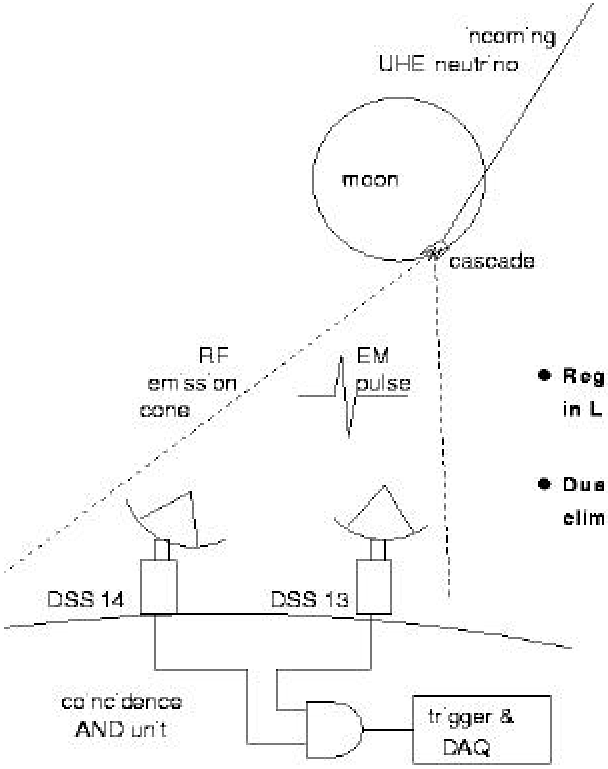
- Look for large burst of CR from primary cascade

- Requires very clear media to allow for coarse sensor spacing (or even external sensors)
- Calorimeter approach

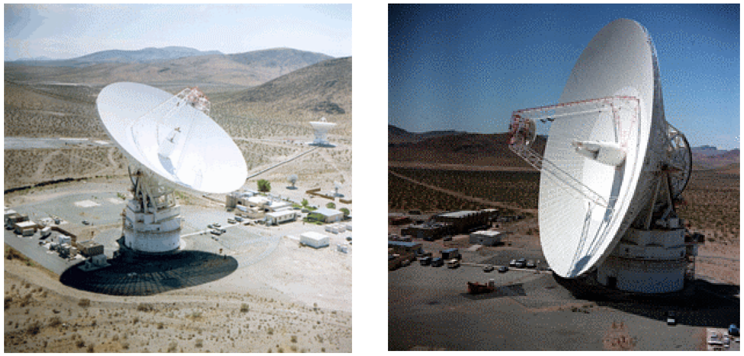
Muon rangers:

- Muon ranges in water & ice:
  R_{mu}~20-30 km at PeV-EeV energies
- Limitations:
  - EeV muons look like any other muon at end of range
    - ➔ **how to tell E?**
  - small acceptance solid angle

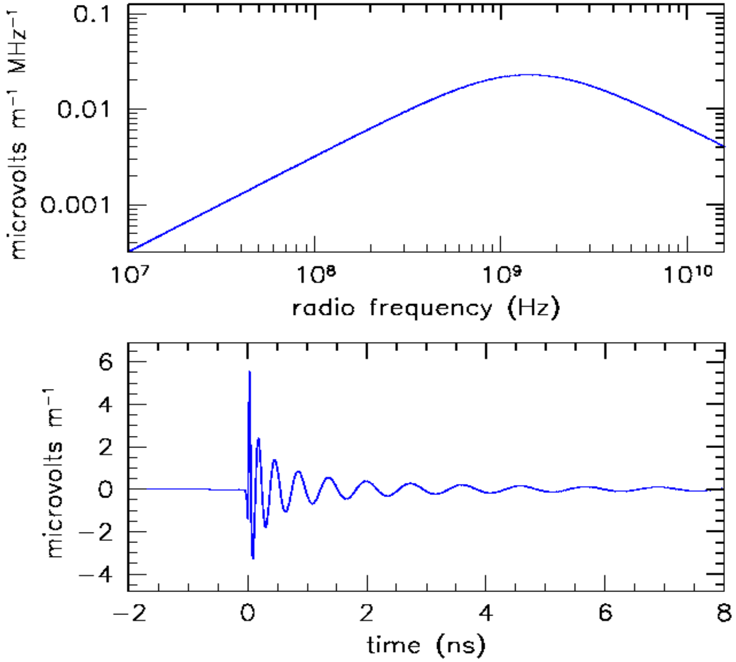
GLUE



- Regolith is transparent in L and S band (10-20cm)
- Dual antenna use eliminates terrestrial RFI



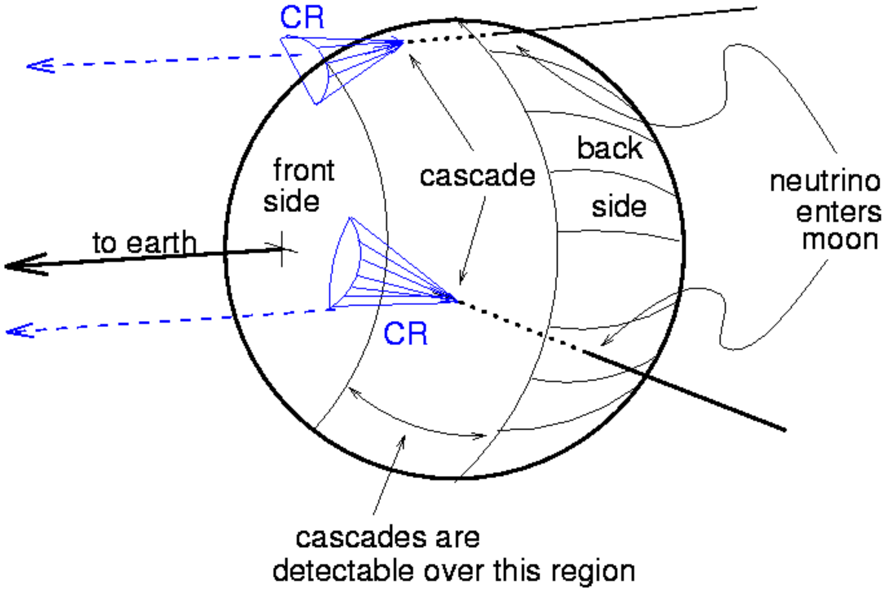
- RF pulse spectrum & shape

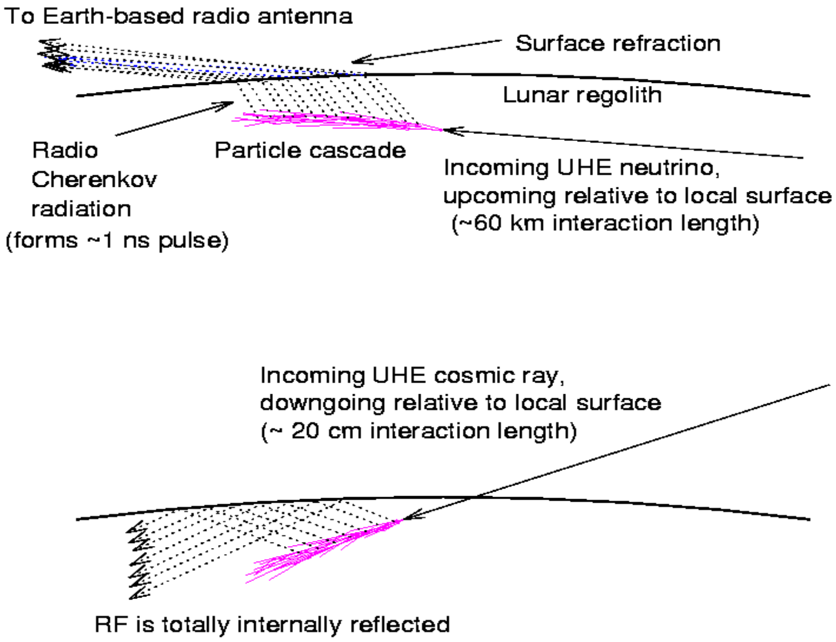


- Effective target volume: Antenna beam (~0.3 deg) times ~10 m moon surface layer

  ===> ~100,000 cubic km!!

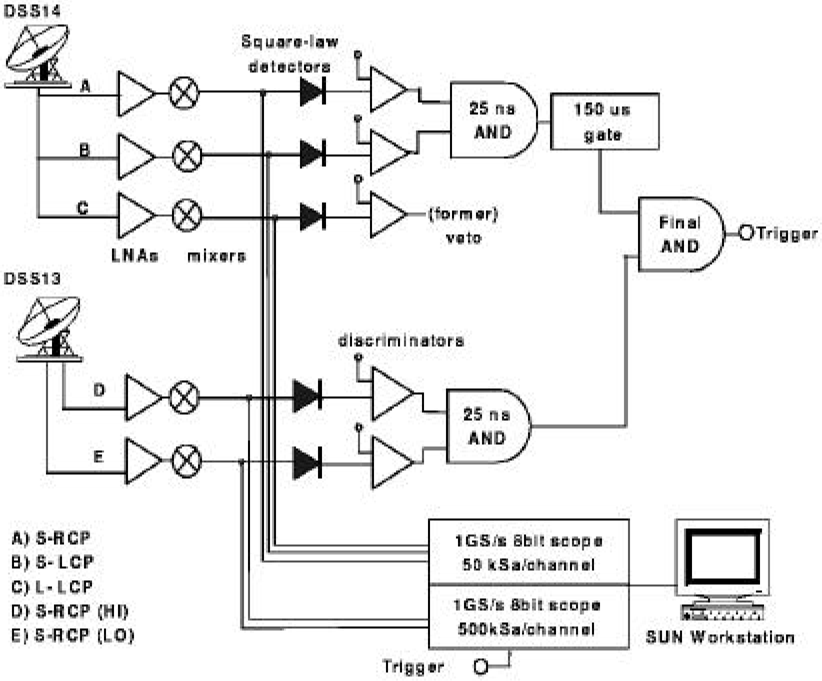
Lunar Regolith Interactions & RF Cherenkov radiation

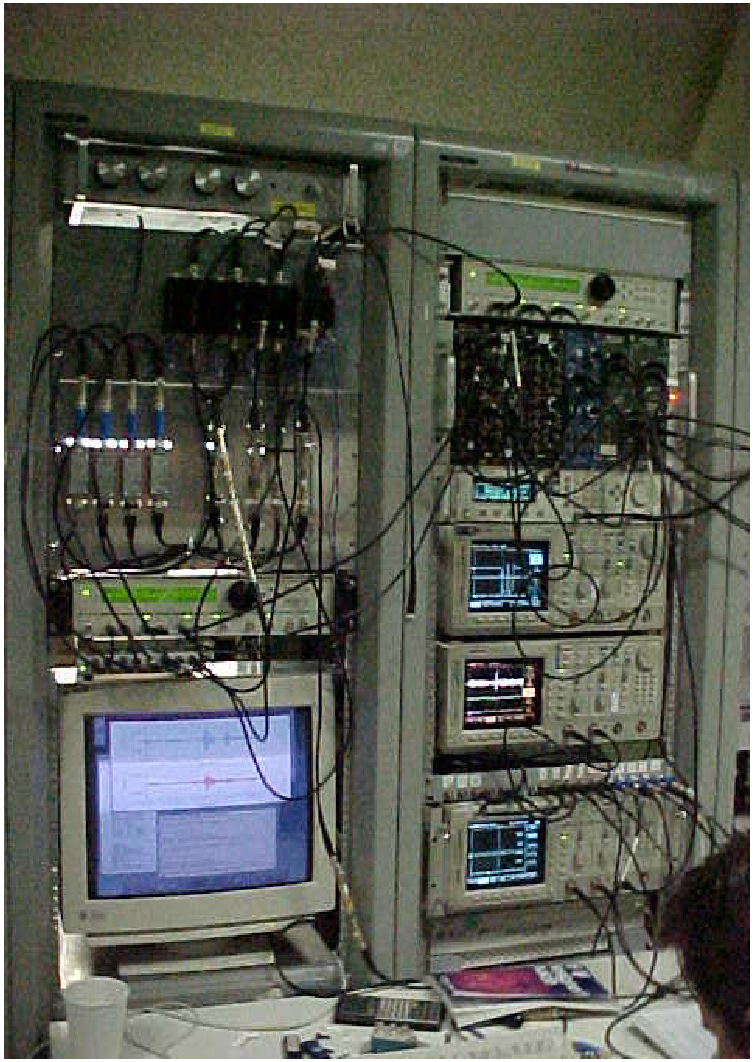




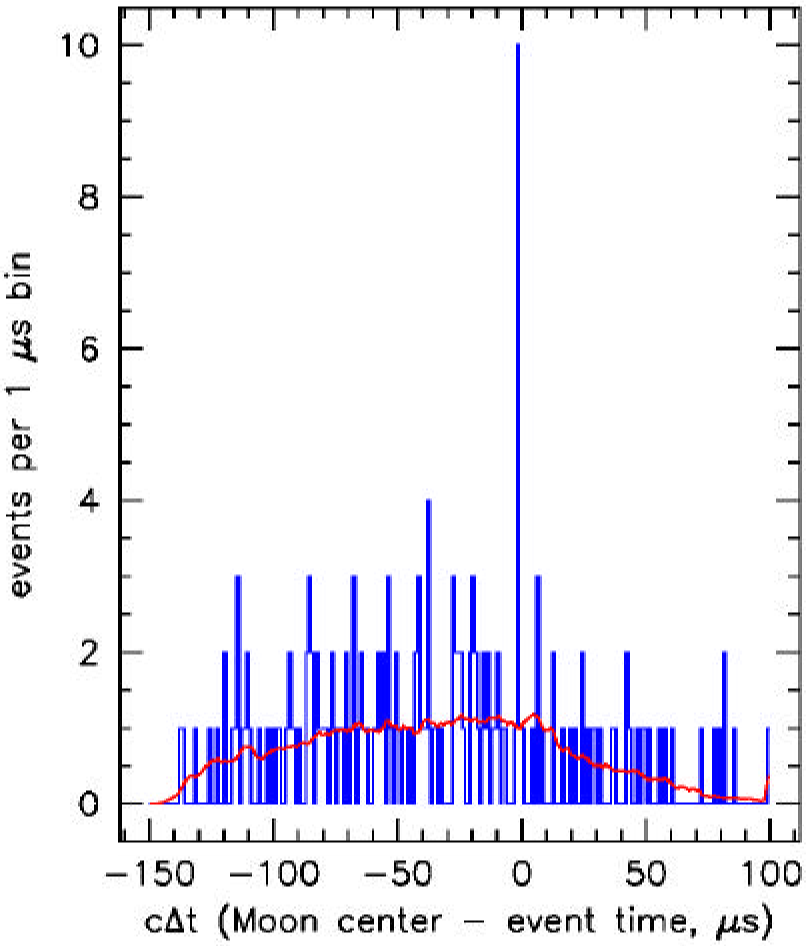
- At ~100 EeV energy, neutrino interaction length in lunar material is ~60km
- R_{moon} ~ 1740 km, so most detectable interactions are grazing rays, but detection not limited to just limb

GLUE hardware: dedicated rack at DSS 14 (70m)





Statistics of lower amplitude GLUE events



- Plot lower amplitude events as a function of interferometric delay:
    - about 1 lunar angular diameter per microsecond of delay offset

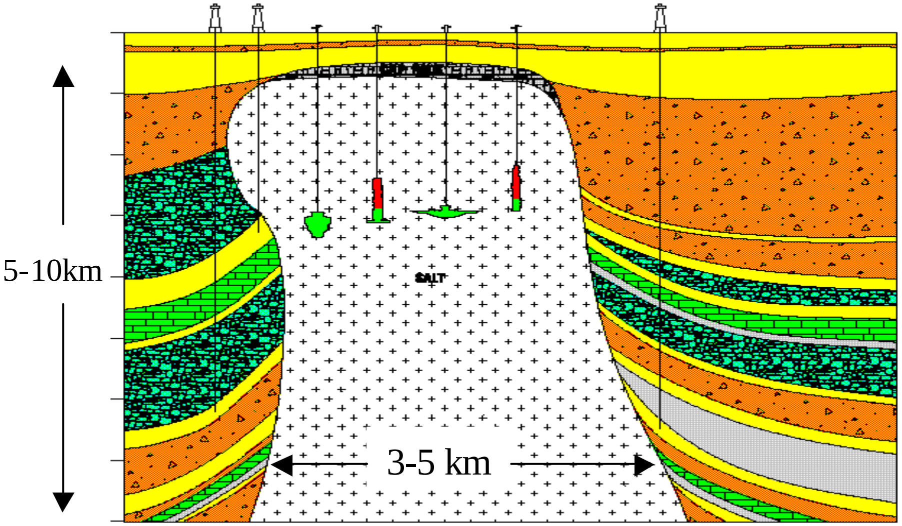
- Background weight determined by randomizing event UT within run period (bkg = red line)

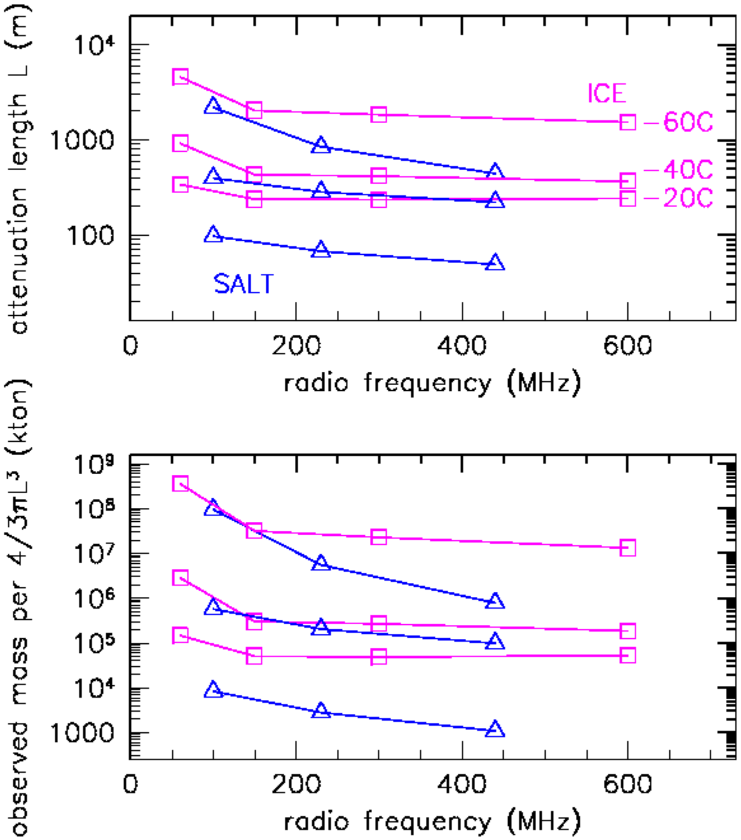
- Some concentration of events near correct lunar delay:
    - BUT: ~1.3 microsecond offset hard to explain—systematic error?

- If these are pulses of lunar origin:
    - if neutrinos ➔ high flux!
    - if super-GZK cosmic rays, then $A_{eff}\Omega \sim 300{,}000\ \mathrm{km}^2$ steradians

Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

- Natural salt can be extremely low RF loss: ~ as clear as very cold ice, 2.4 times as dense
- Typical salt dome halite is comparable to ice at -40C for RF clarity



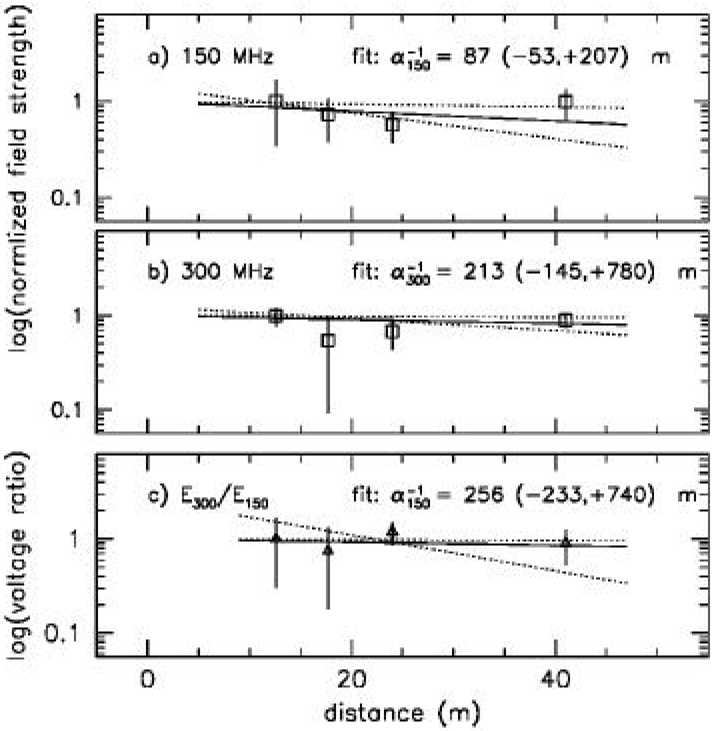


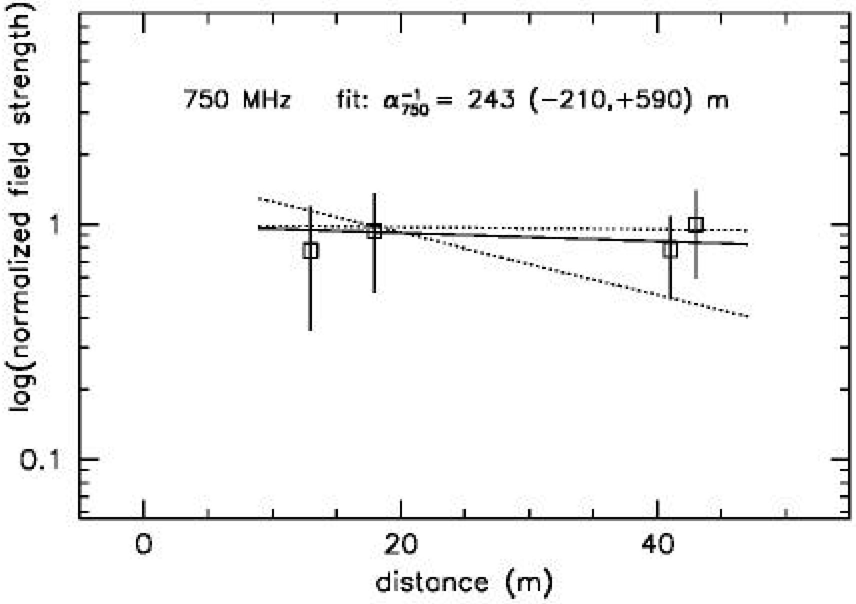
SALT curves are for (top): purest natural salt; (middle): typical good salt dome; (bottom) best salt bed halite.

Salt Measurements at WIPP & Hockley

- Supported through UCLA: DOE ADRP grant (Saltzberg)
- Results posted at hep-ex, in preparation for NIM:
  - WIPP: not so good……. Hockley Mine: very promising!

Results from Hockley Mine rock salt tests





- **All results consistent with >200 meter attenuation lengths**
- Supported by ground-penetrating radar results since early 1970's
  - Radar pulses sent through ~3 km of salt in some Gulf-coast salt domes

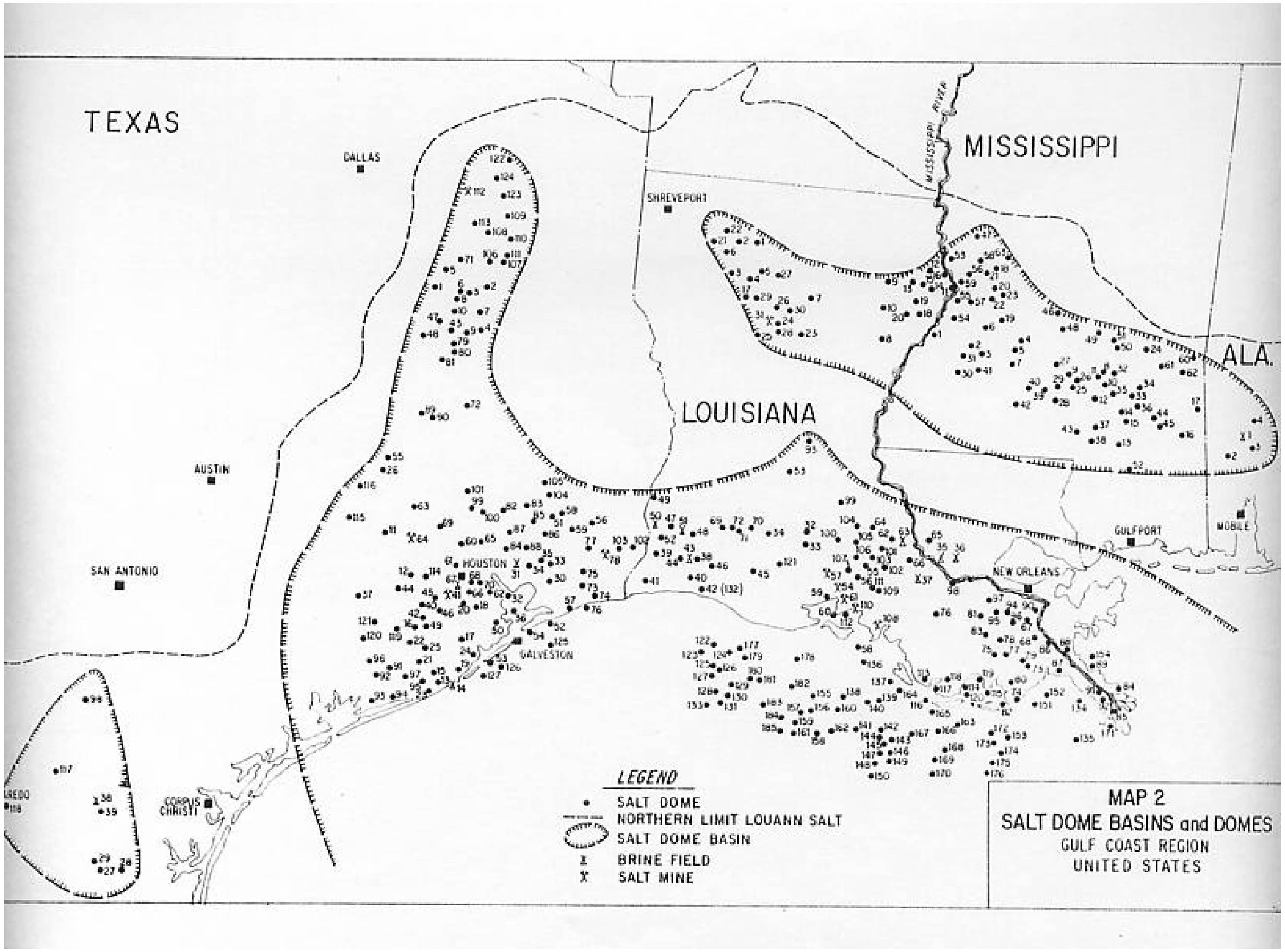
Summary of WIPP/Hockley results

- Rock salt is perhaps the clearest medium known for EM propagation
  - Usable frequency range from few MHz to ~10 GHz
  - Evaporite beds (WIPP) have problems with impurities, but salt domes appear to be purified through geologic processes

- No measureable bi-refringence or depolarization
  - Allows for possibility of polarization tracking
  - May be better than ice in this respect

- Several other salt domes known to be as good or better than Hockley
  - Avery Island (LA), Cote Blanche (LA), Grand Saline (TX)
  - Many others expected to be excellent but as yet unmeasured
  - Typical salt volume 50-100 cubic km per salt dome
  - Several hundred known known salt domes in Gulf coast area, probably thousands throughout the world

Gulf coast saltdomes



Salt dome demographics:

- Several hundred known—some are good source of oil
- Typical ~few km diameters, 5-10 km deep, starting from surface to over 3km in some cases

Hockley mine prototype

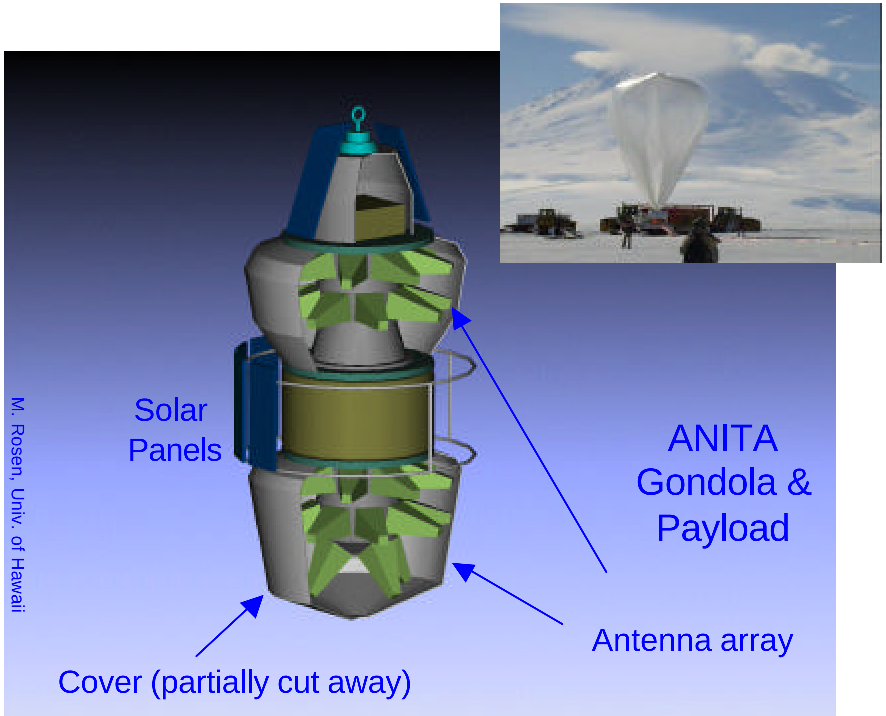
- Collaboration with UCLA, SLAC, (UCI preliminary)
- Cluster of 4-6 antennas, with trigger & DAQ
  - Insert into shallow boreholes within mine, ~40 m separation
  - Measure background noise levels, HE muons?
  - Effective volume ~1 cubic km water equivalent at 1 EeV

- Deploy in mine for 6-12 months, target date late 2003-2004
  - Existing seismic system (UT Austin) could provide fiber link to surface

- Testbed for a GZK neutrino detector!

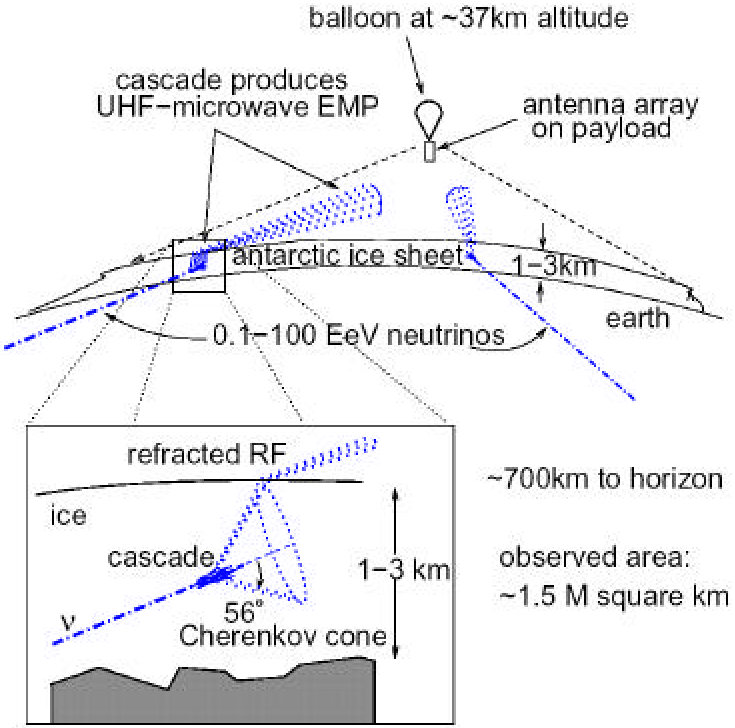
- *Emphasis on simplicity, scalability, low cost*

Antarctic Impulsive Transient Antenna (ANITA)

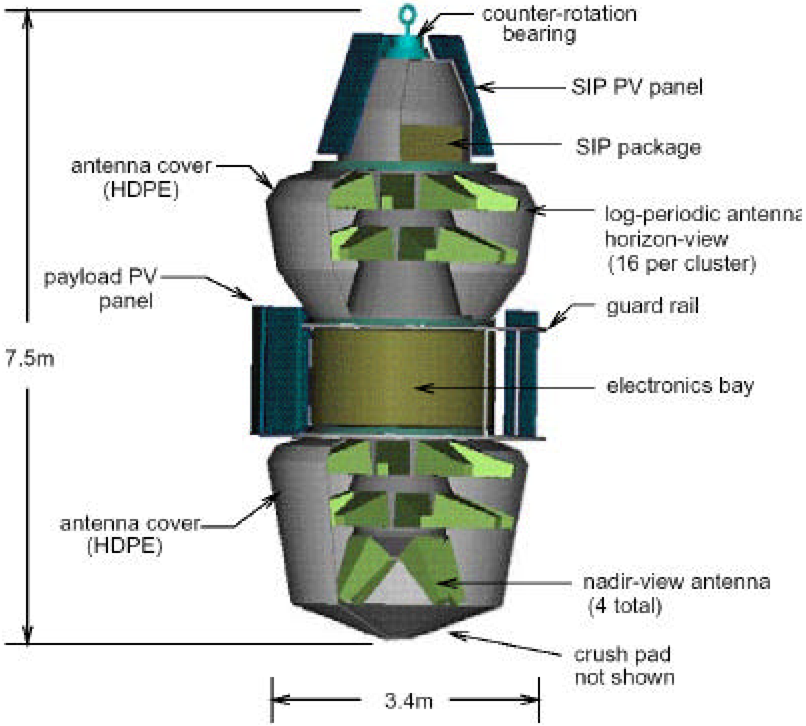


- ANITA Goal: Pathfinding mission for ultra-high energy cosmic neutrinos
- Science team: P. Gorham (PI), S. Barwick (UCI), J. Beatty, S. Coutu (Penn State), P. Evenson, J. Clem, D. Seckel (U.Del./Bartol), F. Halzen (Wisconsin), D. Kieda (Utah), J. Learned (UH), D. Saltzberg (UCLA), K. Liewer, S. Lowe, C. Naudet (JPL), A. Jacobson (LANL)

ANITA concept & payload



antenna cluster detail



- ANITA antennas view ~2pi sr with 60 deg overlapping beams
- Beam intensity gradiometry, interferometry, polarimetry used to determine pulse direction & thus original neutrino track orientation

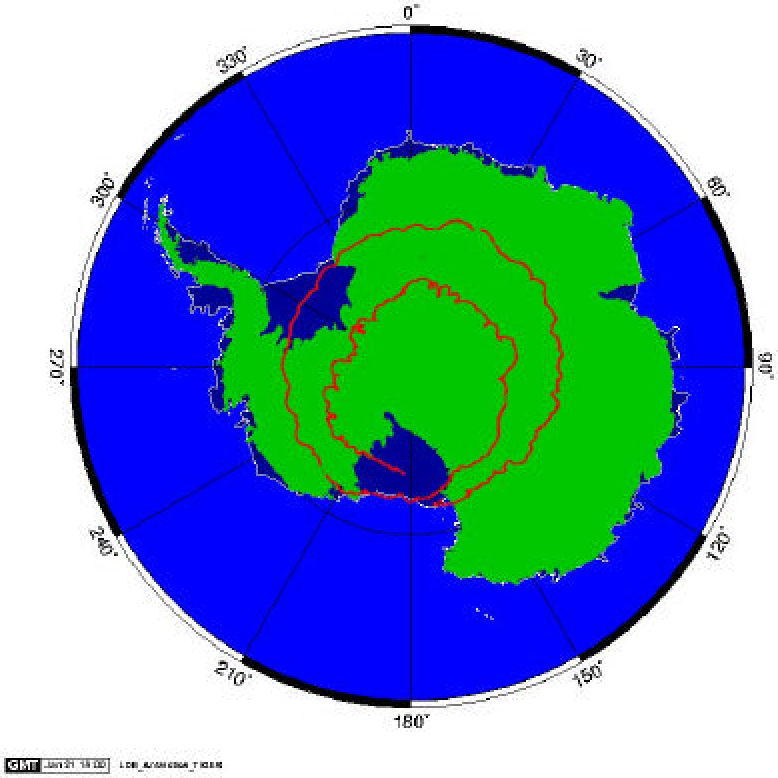
ANITA questions & issues

- What about RF interference?
  - Preliminary results from exisiting data: measured background levels are near thermal noise levels except within ~10-20 km of research stations
  - Still needs to be confirmed: piggyback mission planned

- How will ANITA cascade pulses be distinguished?
  - Askaryan pulse spectrum is unique in its bandwidth, coherence, polarization
  - Needs further study at accelerators, & under realistic receiver conditions

- How can ANITA determine track directions or cascade energy?
  - Answer: precision remains to be seen, but basic approach is:
    - Pulse direction from interferometry & beam amplitudes in adjacent antennas
    - Depth of cascade from spectral rolloff & known ice properties
    - Track angle from plane of polarization
    - Energy lower limit from combination of all of the above

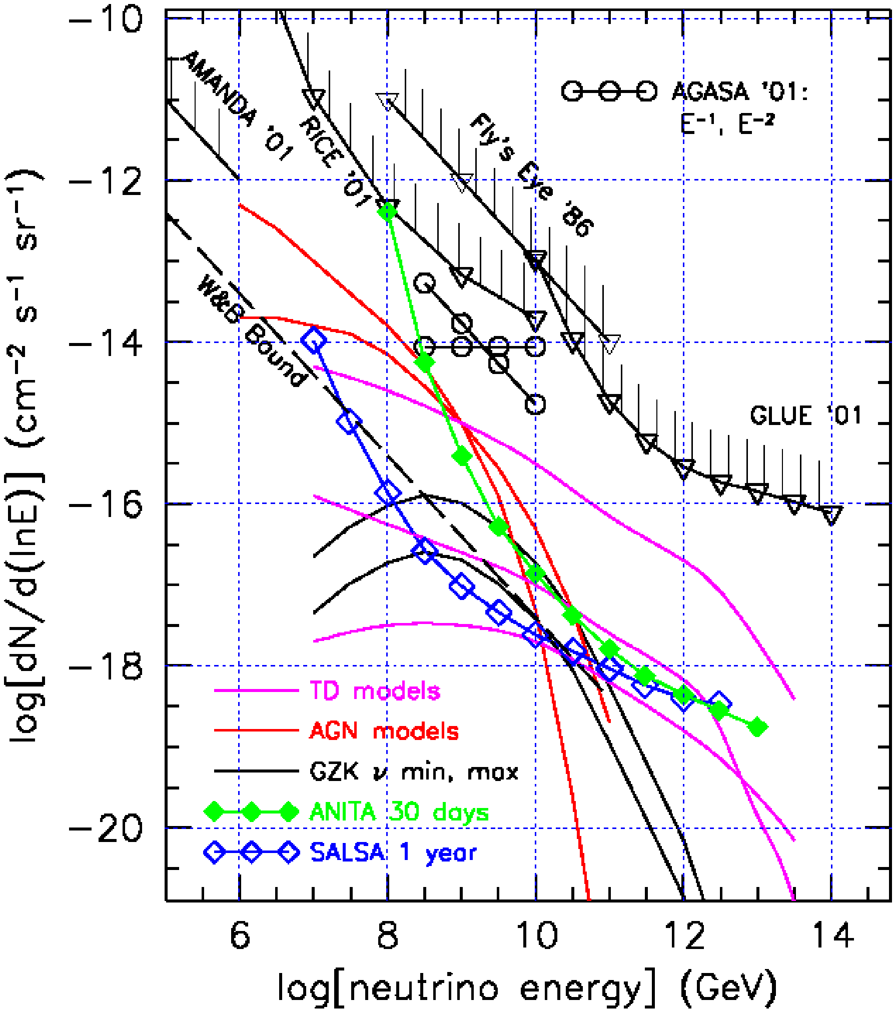
TIGER: the first >30 day circumpolar flight



Balloon actually moved further south during the second loop!

TIGER: Trans-Iron Galactic Element Recorder

Existing Neutrino Limits and Potential Future Sensitivity



- RICE, AGASA, Fly's Eye limits for ν_e only
- GLUE limits ν_μ & ν_e
  - ~50 hours livetime
  - Goal: 300 hrs over next 3 years
- SALSA & ANITA sensitivity:
  - Based on 2 independent Monte Carlo simulations

Models:

- Topological Defects: Sigl; Protheroe et al.; Yoshida et al.
- AGN: Protheroe et al.; Mannheim
- GZK neutrinos: Engel et al. '01

Potential GZK neutrino Detectors

Detector or Experiment	GZK threshold energy(1)	GZK Geometric volume(2)	target density	Effective interaction mass	Effective neutrino target area(3)	Accept-ance solid angle(4)	Aperture	actual or projected livetime/yr	GZK neutrino rate (minimum) (5)	GZK neutrino rate (maximum)
	EeV	**km^3**	**gm/cm^3**	**km^3 w.e.**	**km^2**	**ster**	**km^2 ster**	**sec/yr**	**events per calendar yr**	**events per calendar yr**
Active or completed:										
AGASA(6)	0.3	1000	1.00E-03	1	7.44E-04	2	1.49E-03	3.00E+07	9.8E-03	4.9E-02
AMANDA(7)	0.3	4	0.9	4	2.68E-03	1	2.68E-03	3.00E+07	1.8E-02	8.8E-02
GLUE(8)	300	100,000	2	200,000	1789	0.01	17.89	2.00E+05	1.9E-04	9.5E-04
Fly's Eye(9)	1	500	6.00E-04	0	3.44E-04	2	6.88E-04	3.00E+06	2.9E-04	1.4E-03
HiRes(10)	1	8500	6.00E-04	5	5.85E-03	2	1.17E-02	2.00E+06	3.3E-03	1.6E-02
EAS-TOP(11)	0.3	30	6.00E-04	0	1.34E-05	2	2.68E-05	1.00E+07	3.7E-05	1.9E-04
RICE(12)	0.3	1	0.9	1	6.69E-04	6	4.02E-03	3.00E+06	2.7E-03	1.3E-02
In construction or advanced planning:										
Auger(13)	1	1.50E+04	8.00E-04	12	1.38E-02	2	2.75E-02	3.00E+07	0.12	0.58
EUSO(14)	100	1.00E+06	1.00E-03	1,000	6.0	2	12.04	3.00E+06	1.5E-02	7.6E-02
IceCube(15)	0.3	40	0.9	36	2.68E-02	1	2.68E-02	3.00E+07	0.19	0.94
Telescope Array	1	3.00E+04	1.00E-03	30	3.44E-02	2	6.88E-02	2.00E+06	1.9E-02	9.6E-02
Proposed, pre-proposal, or conceptual										
OWL(16)	100	3.00E+06	1.00E-03	3,000	18.1	2	36.13	3.00E+06	4.6E-02	0.23
ANITA(17)	0.3	1.00E+06	0.9	900,000	669	0.01	6.69	2.50E+06	3.7	18.4
SALSA(18)	0.3	30	2.2	66	4.91E-02	6	0.29	3.00E+07	2.1	10.4
SuperRICE(19)	10	100	0.9	90	2.37E-01	6	1.42	3.00E+07	0.81	4.0

Notes to previous table

Minimum Integral GZK neutrino flux above energy E (cm^-2 sr^-1 s^-1) (maximum is 5X higher)

Energy (eV)	3.00E+16	1.00E+17	3.00E+17	1.00E+18	3.00E+18	1.00E+19	3.00E+19	1.00E+20	3.00E+20
integral flux	2.35E-17	2.35E-17	2.20E-17	1.40E-17	6.00E-18	1.90E-18	3.90E-19	4.20E-20	5.30E-21

NOTES:

(1) For detectors with lower thresholds, Ethr is set to 3e17 eV, which is where the GZK neutrino spectrum begins to peak.

(2) Physical volume over which neutrino interactions are detected either directly (cascades) or indirectly (muons)

(3) Effective target area at threshold. In some cases (detectors with thresholds below 3e18 eV) the target area may be a bit larger above threshold. This effect leads to some underestimate of the event rate since the entire decade from 1e17 to 1e18 contributes events due to the flat spectrum there

(4) For air showers, acceptance solid angle assumes ~70-90 degree horizontal showers over 2pi azimuth. For embedded detectors, solid angle is determined by earth shadowing (cascade detectors) and earth-shadowing+loss of available muon range above (muon ranging detectors).

(5) Based on recent estimates by Engel, Stanev, & Seckel (2001). Maximum values are for strong z-evolution. Rate is calculated assuming all events above energy threshold are seen at same effective aperture as threshold; thus underestimates rate by factor of ~2 for detectors with thresholds be

NOTE: these values do not assume full mixing of muon and tau neutrinos; in some cases fully mixed taus can improve aperture by factor of ~5-10.

(6) Estimates based on recently reported neutrino limits (Yoshidda et al. ICRC 2001).

(7) AMANDA estimates based on 0.1 km^2 muon collection area and up to 40 km muon range at 1EeV. Acceptance solid angle assumes ~10 deg usable over 2pi azimuth in ice at zenith angle centered around pi/2. Earth shadowing prevents detection of upcoming muons.

(8) Based on estimates from Gorham et al. RADHEP 2000 proceedings.

(9) Based on published limits on electron neutrino fluxes, updates with more recent estimates of cross sections.

(10) Assuming horizontal air showers are seen efficiently in stereo at R=15 km up to H=12km. Assumed air density value may be somewhat high.

(11) EAS-TOP collaboration has published limits for neutrino fluxes above 1 PeV for 575 days of operation. We extrapolate the sensitivity to EeV energies.

(12) RICE has published initial limits (Besson et al. RADHEP 2000 proceedings) based on 2 weeks of livetime. Livetime appears to be limited at present due to problems with interference. We have assumed a 10% duty cycle for the year; this could be higher.

(13) Based on estimates presented by S. Coutu, Aspen meeting 2002. Does not include sensitivity if tau neutrinos are fully mixed.

(14) Assumes 1 sr field-of-view at 350 km altitude and similar acceptance solid angle to air fluorescence detectors.

(15) Estimate based on muon detection with maximum range of 40 km in ice. Direct cascade detection can add up to 50% more in the GZK event rate if the is ~1 km^3 and the cascade events can be seen up to 300 m beyond the array edge.

(16) Assumed to be OWL stereo at ~700 km altitude.

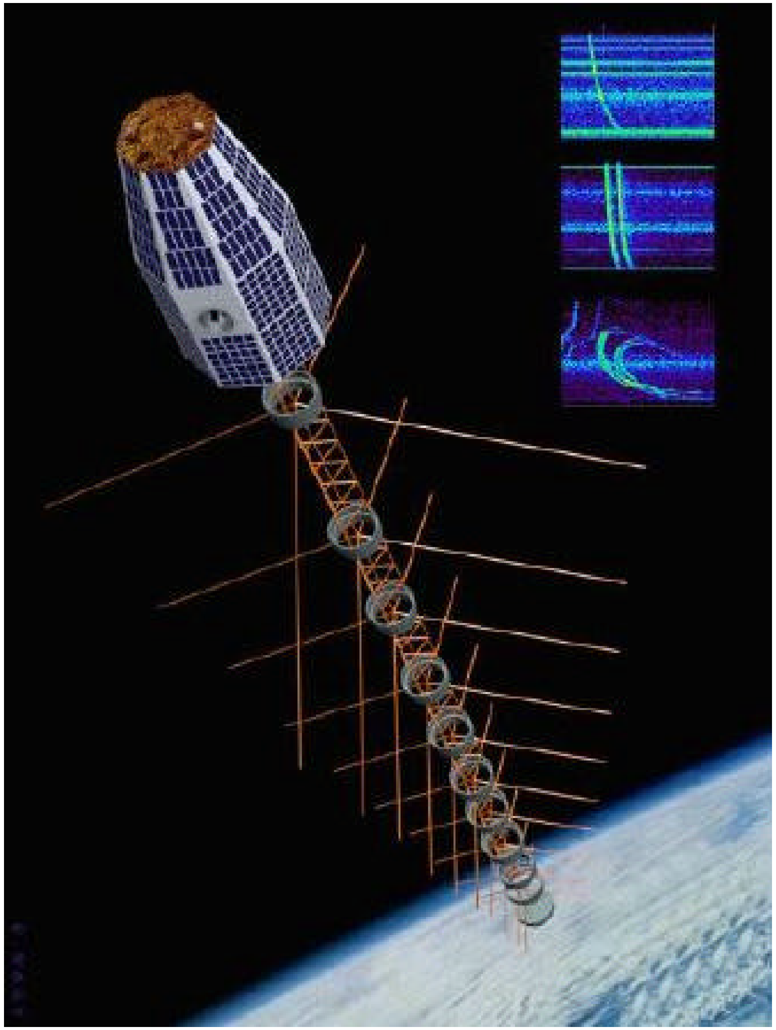
(17) Estimates based on ANITA proposal to NASA MidEx program, October 2001.

(18) Assumes 100 strings of 50% BW antennas centered at 150 MHz, in a salt dome with 200 m spacing, 300 m attenuation length at 300 MHz, a total of rock salt fiducial volume with cascades seen out to 500 m beyond the array edge. 4 antennas trigger at 4 sigma each event, both polarization. D. Saltz

(19) Based on published MC results from Seckel & Frichter (RADHEP 2000 proceedings, AIP 2001).

Peter Gorham, Feb. 2002 (gorham@phys.hawaii.edu). These numbers are approximate and subject to revision!

FORTE: A space-based EHE neutrino & cosmic ray detector?



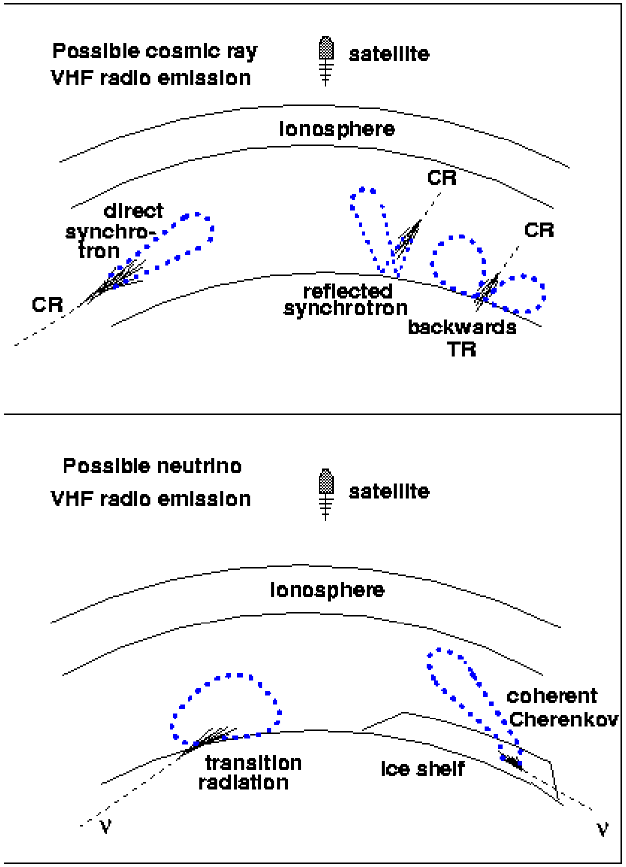
Fast On-orbit Recording of Transient Events

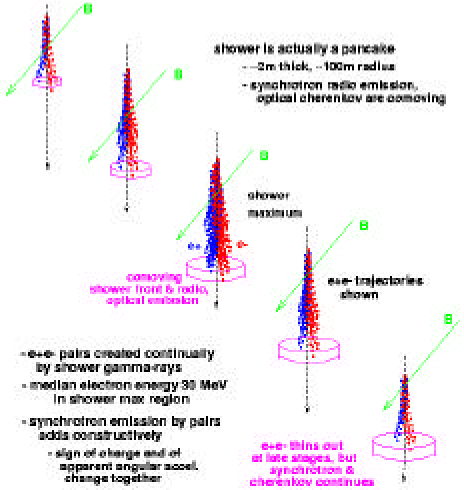
- Pegasus launch in mid-1997, 800km orbit
  - Testbed for nuclear verification sensing
  - US DOE funded, LANL / Sandia ops
  - Scientific program in lightning & related atmospheric discharges

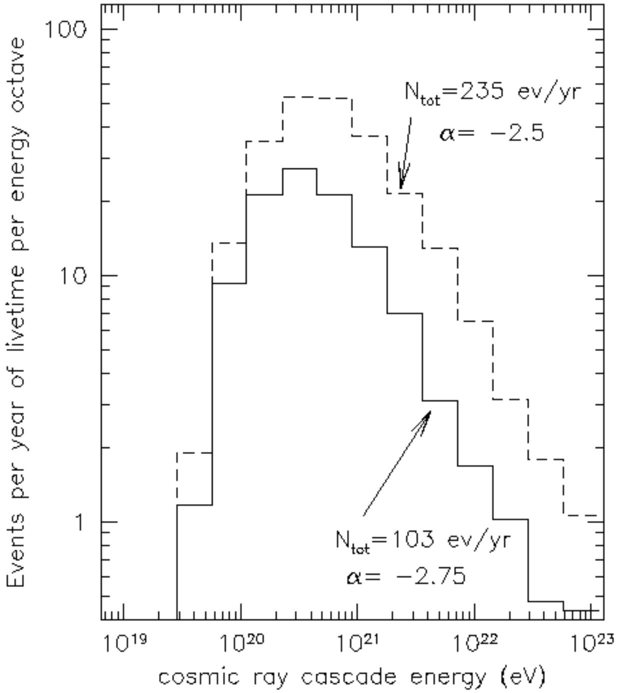
- 30-300 MHz (VHF) frequency range
  - ~3M impulsive triggers recorded to date

- FORTE can trigger on radio emission from giant air showers at E~100 EeV
  - Preliminary estimates: could be ~50 10^{20} eV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL,LANL) planned this year

Air Shower Radio Detection by FORTE

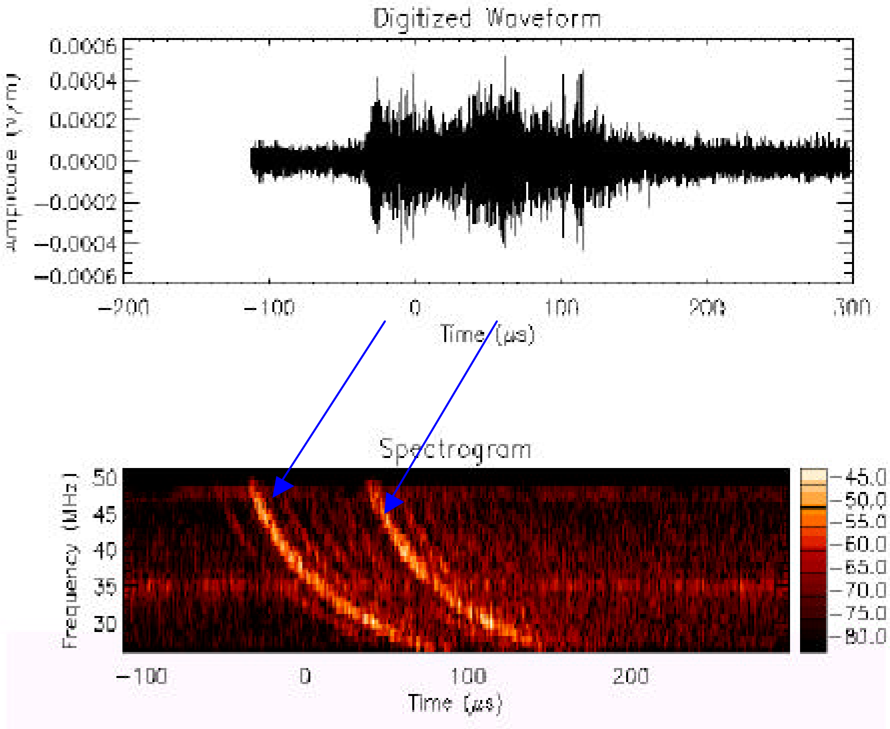


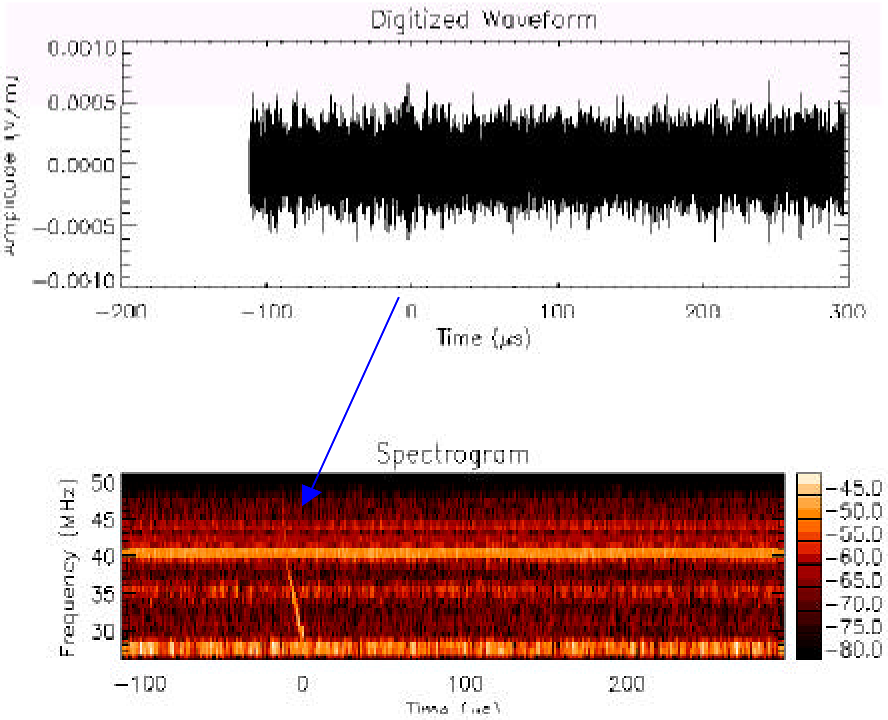




- Radio is “geo-synchrotron emission”—generic, but with complications from B, E
- Simulations indicate that FORTE could be highly sensitive to post-GZK spectrum
- Sensitivity limited by ~10% livetime, RF interference, & uncertainty in radio emission process

FORTE Data examples





- Typical lightning trigger
  - dispersion (curvature) due to ionosphere
  - multiple strikes
- Correlated to ground-based networks

- Isolated trigger
  - Band-limited, very short duration
  - No pre- or -post-trigger pulses close
  - No related pulses within several sec

Conclusions

- Radio Detection methods show great promise for neutrino detection in the PeV to EeV regime
- Radio methods already have set the only limits at ZeV neutrino energies
- GZK neutrino detection & characterization may be a reality within several years
- “Askaryan’s Excess”– a virtue not a vice!