Status of the RICE Experiment: $E_{\nu_e} > 10^{14}$ eV

Radio Ice Čerenkov Experiment (part of AMANDA)

URL: http://kuhep4.phsx.ukans.edu/˜iceman/index.html

'Radio Ice Cerenkov Experiment'

'RIding on the Coatails of the AMANDA Experiment'

The RICE Federation (and interested parties):

- Winterover support @ Pole: Darryn Schneider, Mike Boyce
- Bartol Research Institute: Dave Seckel, Glenn Spiczak
- Florida State University: George Frichter.
- KU: Chris Allen, Alice Bean, Roman Buniy, Dave Besson, DJ Box, Eben Coppel, Tim Donohue, Ryan Dyer, Doug McKay, John Ralston, Soeb Razzaque, Dave Schmitz, Suruj Seunarine.
- MIT: Ilya Kravchenko.

RICE Physics: UHE neutrinos: $E_{\nu_e} > 10^{14} eV$

- Astroparticle Physics: Probe of distant sources: protons, photons absorbed on IR starlight/CMB background⇒Neutrinos offer best reach in distance/energy

  Unexplored regime: AGN, monopole decays, topological defects, non-S.M. physics...

  EAS EHECR spectrum measured to 3×10^{20}eV

  Σ(Fly's Eye + AGASA + Hi Res): ∼20 super-GZK events in last decade. NO GZK CUT-OFF!

  If GRB+EHECR have same source, GRB + neutrino 'flash' simultaneous!

- HEP: Information on $\sigma^{CC}_{\nu_e+N}(Q^2 \sim (10^{14}eV)^2)$; alternately:

- Geophysics: Neutrino tomography ('X-ray'ing Earth):

  Large $\sigma^{CC}_{\nu_e+N}(Q^2 \sim (10^{14}eV)^2) \Rightarrow$ measured $\frac{dN_\nu}{dcos\theta}$ gives earth absorption (i.e., thickness; astro-ph/9909038, Ralston, Jain, & Frichter)

+ Scientific overlap with SPASE and AMANDA at South Pole

Radio Detection Idea

1. $\nu_e + n \to p + e^-$ in dense medium (ice)
2. $e^+ \to e^+e^-\gamma \to$ .... shower development
3. $\gamma + e^-_{atomic}$, $e^{\pm}e^-_{atomic}$ collisions sweep negative charge into developing shower; shower acquires net negative charge $Q_{net} \sim 0.25\frac{E_{shower}}{GeV}$

   $\Rightarrow$relativistic pancake: $\sim$1 cm thick, $2r_{Moliere}$ $\sim$10 cm in diameter, moving at 3×10^8m/sec ($> c_{local}$)

   $\Rightarrow$Each particle in developing shower emitting (broadband) Čerenkov radiation

   $\Rightarrow$Č-Signal at detector is resultant of E-field vectors from many overlapping Č-cones
4. For $\lambda >> 2r_{Moliere}$, emitting region can be treated as a single blob of net negative charge ($\lambda \to \infty$ $\Rightarrow$emitting region$\to$point source)

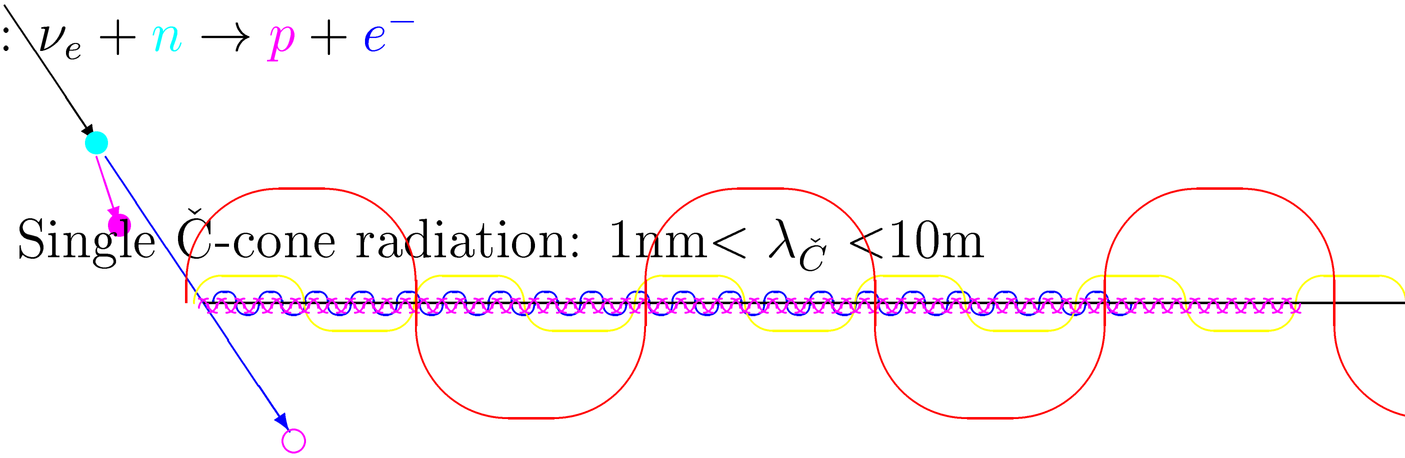
   (i.e., not sensitive to phase relationship of (Č-radiation) EM waves from one Č-cone to the next)

   $\Rightarrow$Radio "Coherence"; Short wavelength signal incoherent
5. Note: All e^- shower power dumped into $l \sim 40X_0 \sim 10m$; μ^- radiates continuously (i.e., less concentrated) over $l \sim 500m$

   (For single μ at v=c, (ČR-power/$\frac{dE}{dx}_{mini} - power$) $\sim 6 \times 10^{-5}$, assuming $\frac{dE}{dx}_{mini} - power$ =1.991 MeV/cm, and assuming ČR detected from 310-500 nm ($\sim$200 photons/cm)
6. Important: + Cold ice is RF transparent ($\lambda_{atten} \sim 1km$ for $f_0 \sim 1GHz$)

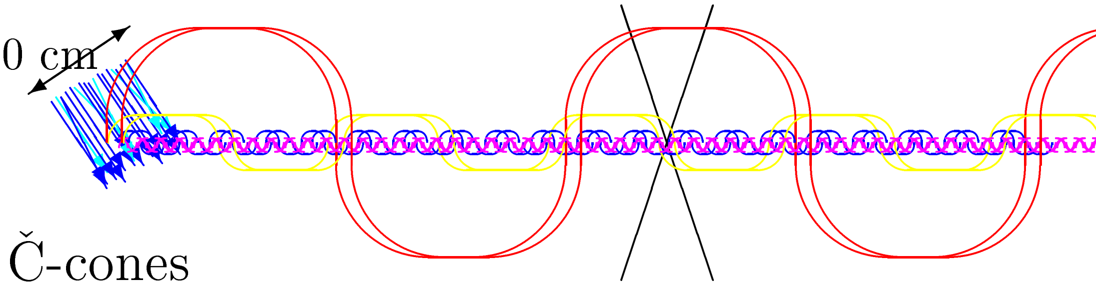
   (Perhaps salt target? WIPP meeting 6/12/00–6/14/00)
7. $\Rightarrow V_{eff} \sim km^3$ per antenna for $E_\nu \sim 10^{15}$eV, $E_\nu \uparrow \Rightarrow V_{eff} \uparrow$

t=0 ns: $\nu_e + n \rightarrow p + e^-$



t<1ns: Single Č-cone radiation: 1nm< $\lambda_{\check{C}}$ <10m

t:1-20ns: $N + e^- \rightarrow N' + e^- e^+ \gamma e^- e^+ \gamma e^- e^-_{ice} \gamma e^- e^-_{ice} \ldots$



t >20ns: $N_{e^-} > N_{e^+}$ Č-cones

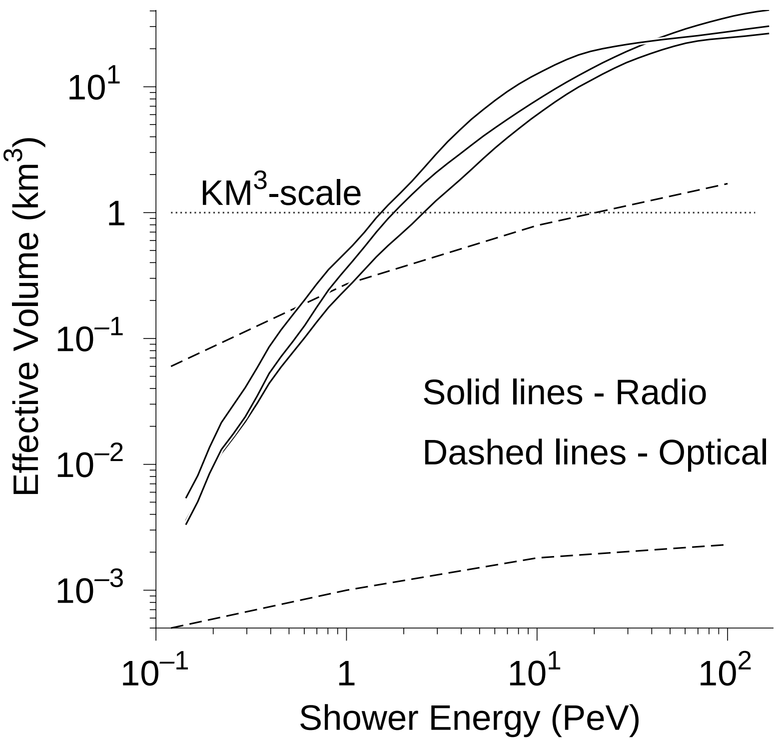
$\lambda_{\check{C}} > .1\text{m} \Rightarrow |\vec{E}^{\check{C}}_{net}| \propto N_{e^-}$ (coherent sum)

$\lambda_{\check{C}} << .1\text{m} \Rightarrow |\vec{E}^{\check{C}}_{net}| \propto \sqrt{N_{e^-}}$ (incoherent sum)

Summary: For wavelengths > shower size (∼10 cm)
'Shower'=single 'blob' of charge Q=$(N_{e^-} - N_{e^+})q_e$.
However, for small λ, shower details important ⇒
less radiated shower energy contained at small λ's.

Optical/Radio Comparison

V_{eff}: (Adapted From B. Price, astro/ph 9510119, and G. Frichter, astro-ph/9606008) Top dashed line = AMANDA-B



N.B.: primary difference, 5 PeV $\nu_\mu \to \mu$ vs. $\nu_e \to e$: μ: Q=1e, producing Č-rad over ∼1 km, losing ∼10% of total energy every ∼100 m to catastrophic brem.

e: Q=250,000e, producing Č-rad while dumping all energy into ∼3 m.

N.B. AMANDA+RICE co-detection locates $\vec{d}$ to vertex through 'flash-and-boom'.

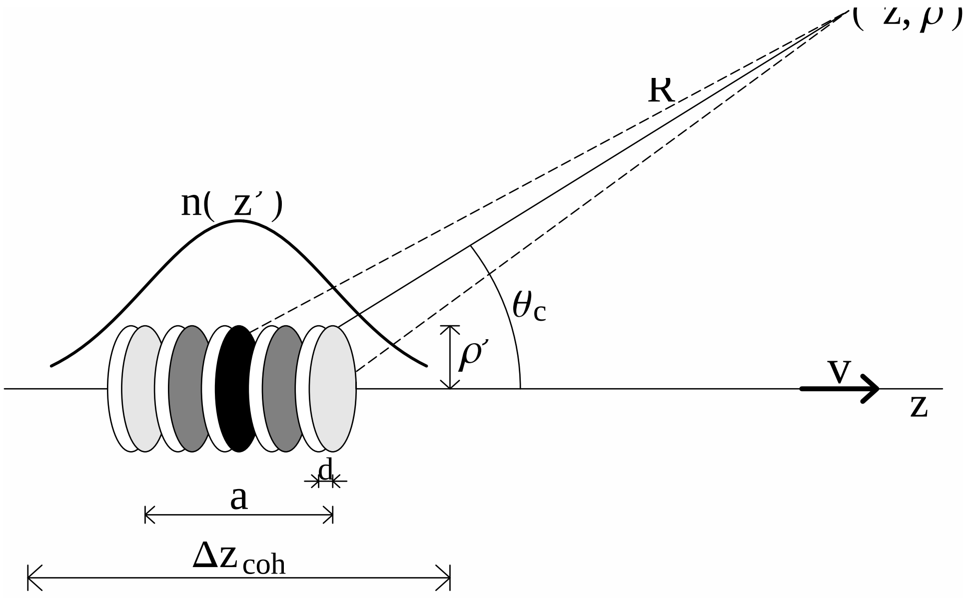
NOTE High Energy RICE Threshold (1 PeV):

- μ, ν_μ bkgnds. small: For 330 element array, expect ∼1-10 μ detected per year (Gondolo, Thunman); ∼100(/200) detected ν_e in SS(/SP) model, but no μ backgrounds to calibrate on

Radio Coherence Measurements

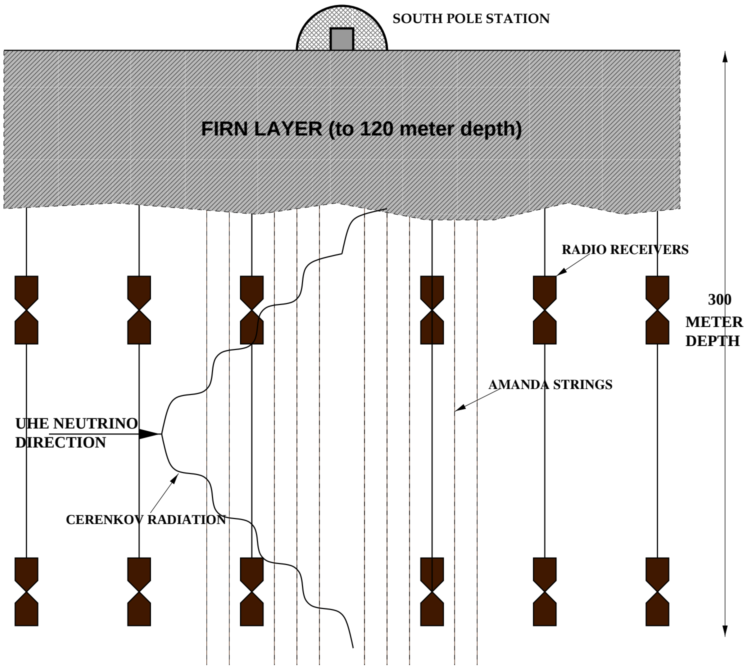
- Radio coherence observed in EAS showers (different mechanism), and also from an electron beam in air
- First Beam Test in a dense medium at ANL, 9/99 (Gorham, Saltzburg, et al., hep-ex/0004007: RF Measurements of Coherent Transition and C-Radiation), but complications:

  Fresnel zone (see longitudinal extent of charge) vs. Fraunhofer zone (spherical geometry; excess charge is point-like)



- Čerenkov vs. Transition Radiation
- Redone with photon beam, 8/00: strong evidence for observation of long-wavelength CR coherence from FFT, polarization measurements. hep-ex/0011001: Observation of the Askaryan Effect: Coherent μwave Č-Emission from Charge Asymmetry in HEP Cascades

Basic RICE concept/schematic:



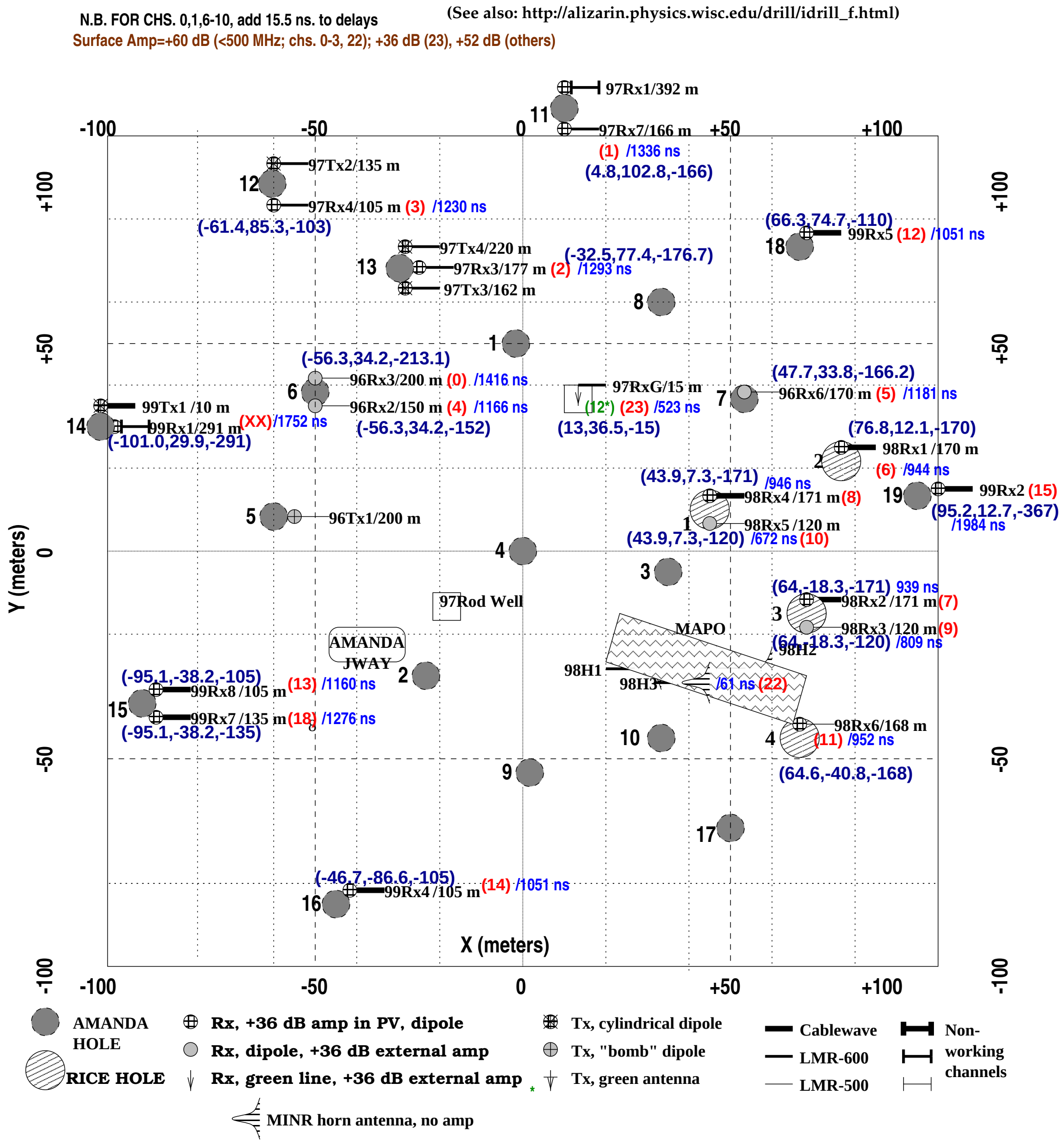
Present RICE Configuration (since 2/15/00)

- 20 receivers - 18 dipoles plus amplifiers (250 MHz$\pm$50 MHz), 1 "line" antenna (WWII surplus), 3 horn antennas on surface (100 MHz–3 GHz).

  16 with waveforms (HP54542 scopes, 500 MHz BW, 2 GSa/sec)

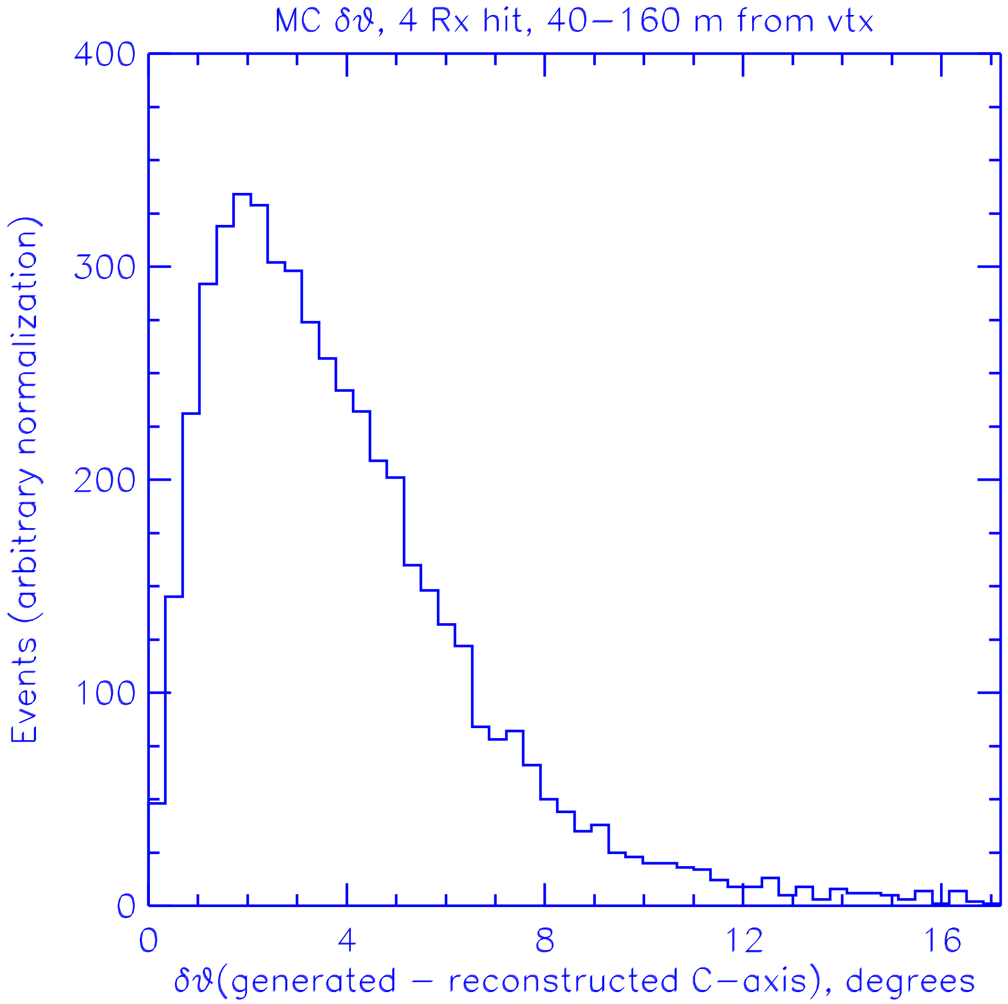
  36 dB amplification in-ice, 52 dB on-surface

- Each channel: half-wave dipole$\rightarrow$+36 dB amp$\rightarrow$$\sim$300 m Heliax coaxial cable$\rightarrow$high-pass filter$\rightarrow$+52 dB amp$\rightarrow$50-50 power splitter$\rightarrow$trigger crate/HP54542 digital scope

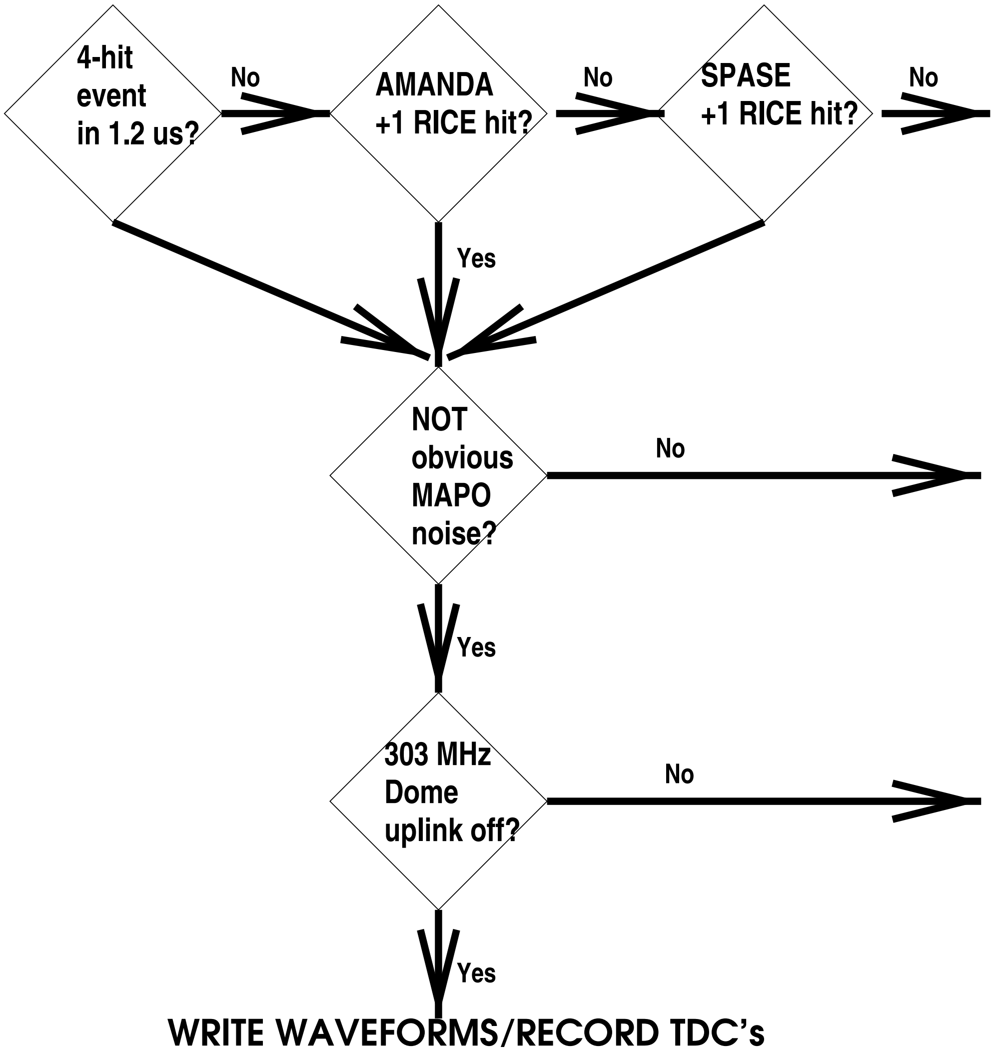


Estimated angular resolution

1. Strongly dependent on event geometry, assess by MC
2. Typical values: 4-hit event, antennas 40-140 m from vertex point, smear times by σ_t=20 ns, reconstruct incident neutrino direction and compare with generated neutrino direction.



Trigger



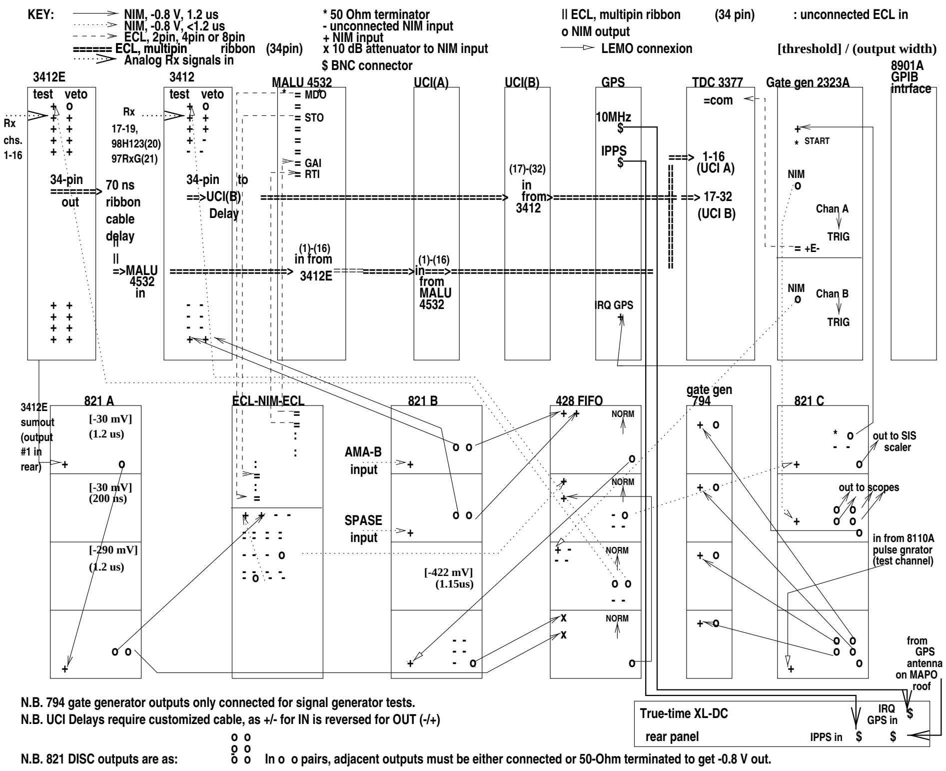
- If L1 trigger passed, write waveforms (HP54542A) to disk

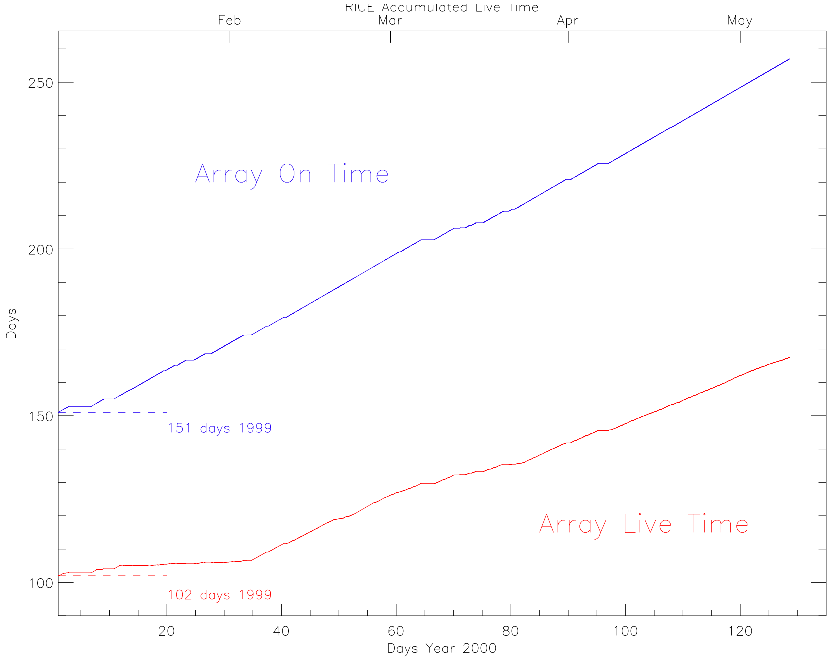
  Maximum L1 rate: 38 Hz (2/05/00), now 60 Hz (4/01/00)

  Typical data-taking rate $\sim 10^{-2}$ Hz

  Typical livetimes depend on discriminator thresholds, ∼80%

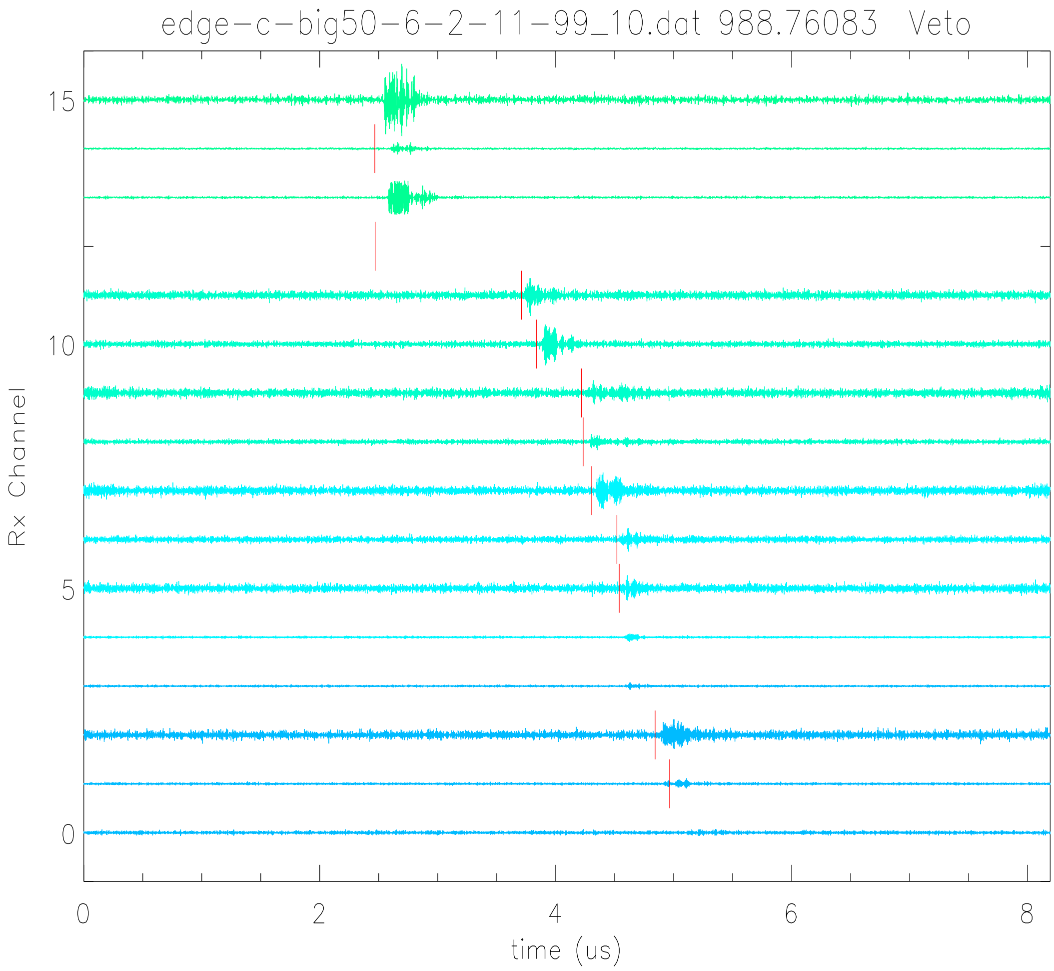
  5/19/00: software veto of 303 MHz bkgnd. complete.


KEY:
NIM, -0.8 V, 1.2 us
NIM, -0.8 V, <1.2 us
ECL, 2pin, 4pin or 8pin
ECL, multipin ribbon (34pin)
Analog Rx signals in
* 50 Ohm terminator
- unconnected NIM input
+ NIM input
x 10 dB attenuator to NIM input
$ BNC connector
|| ECL, multipin ribbon (34 pin)
o NIM output
LEMO connexion
: unconnected ECL in
[threshold] / (output width)
3412E
3412
MALU 4532
UCI(A)
UCI(B)
GPS
TDC 3377
Gate gen 2323A
8901A GPIB intrface
test veto
Rx chs. 1-16
Rx 17-19, 98H123(20) 97RxG(21)
34-pin out
70 ns ribbon cable delay
=>MALU 4532 in
34-pin to ==>UCI(B) Delay
MDO
STO
GAI
RTI
(1)-(16) in from 3412E
(17)-(32) in from 3412
(1)-(16) in from MALU 4532
10MHz
IPPS
IRQ GPS
=com
1-16 (UCI A)
17-32 (UCI B)
START
NIM
Chan A
TRIG
Chan B
3412E sumout (output #1 in rear)
821 A
[-30 mV] (1.2 us)
[-30 mV] (200 ns)
[-290 mV] (1.2 us)
ECL-NIM-ECL
AMA-B input
SPASE input
821 B
[-422 mV] (1.15us)
428 FIFO
NORM
gate gen 794
821 C
out to SIS scaler
out to scopes
in from 8110A pulse gnrator (test channel)
from GPS antenna on MAPO roof
True-time XL-DC
rear panel
IRQ GPS in
IPPS in
N.B. 794 gate generator outputs only connected for signal generator tests.
N.B. UCI Delays require customized cable, as +/- for IN is reversed for OUT (-/+)
N.B. 821 DISC outputs are as:
In o o pairs, adjacent outputs must be either connected or 50-Ohm terminated to get -0.8 V out.


RICE Accumulated Live Time
Feb
Mar
Apr
May
250
200
150
100
Days
Array On Time
151 days 1999
Array Live Time
102 days 1999
20
40
60
80
100
120
Days Year 2000

Typical Event (Surface-generated bkgnd.)

Scope traces ordered 0→15: furthest→closest to MAPO



Data Analysis - Ingredients

1. Select 8/00 data from 1/99-11/00 sample (low thresholds)
2. Channel-to-channel timing calibration

   Use pulses (5 ns) from Tx to determine t_0 offsets.

   χ^2 minimization of Rx timing residuals.

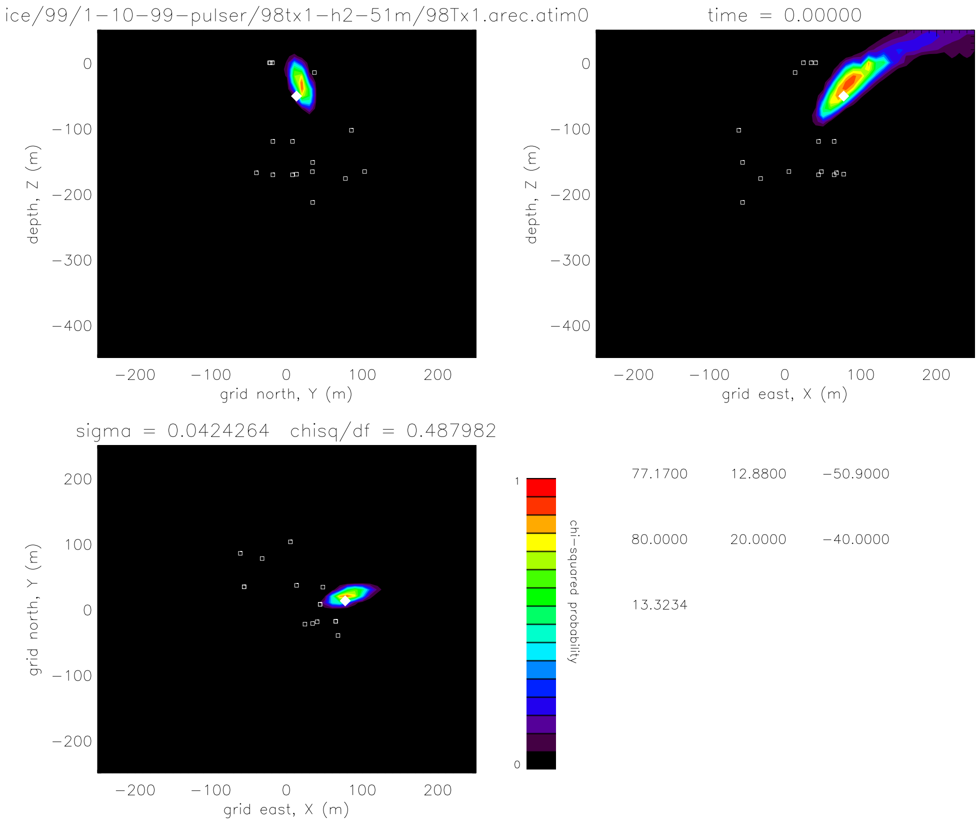
   Iterate residuals until χ^2 minimized.

   Typical δt shifts to t_0 ~20 ns.

   After calibration, reconstruct Tx location to ~5 m.

   TIMING info only thus far, no amplitude info used.

   Amplitude calibration in progress



Data Analysis - Ingredients (cont.)

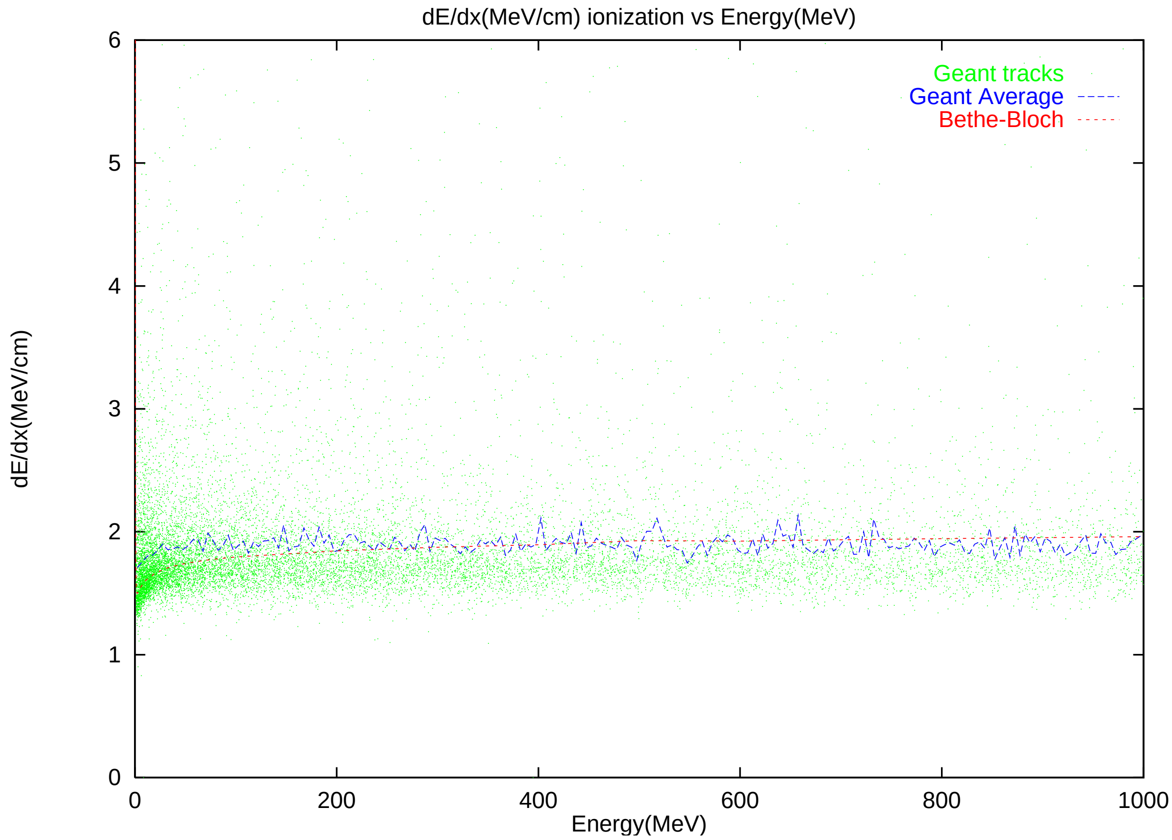
1. Čerenkov power in shower: $\frac{\vec{E}^{ZHS}_{Cerenkov}}{(e^- - e^+)^{ZHS}} = \frac{\vec{E}^{GEANT}_{Cerenkov}}{(e^- - e^+)^{GEANT}}$

   I.e., a given charge excess produces same E field strength in both ZHS and GEANT.

2. HOWEVER, both track length and charge excess in GEANT is smaller than ZHS by ∼40%.

   Basic checks: E,p conservation, geometric characteristics vis-a-vis X_0 and $R_{Moliere}$; also check dE/dx: $l_{tot} \sim E_0 / < dE/dx >$ if dE/dx dominant inelastic process (nuclear recoil also inelastic).

   GEANT: 450 m, ZHS: 660 m. ∼100 GeV/1.8 Mev/cm?



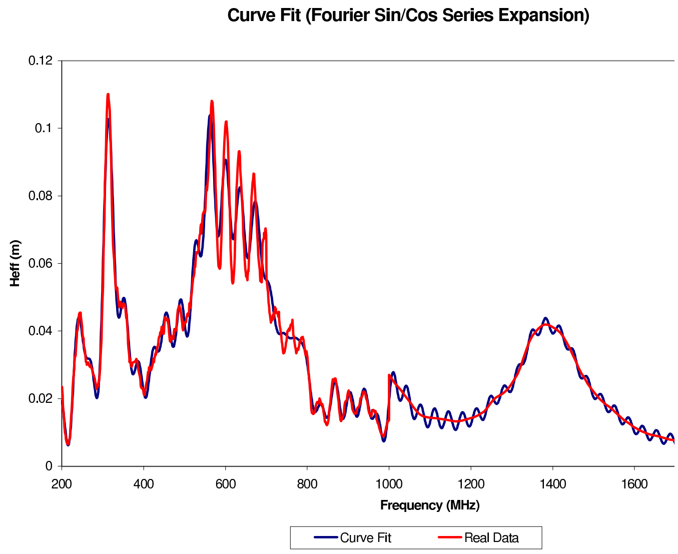
3. Fresnel vs. Fraunhofer: if near-field, then long. extent of shower important in calculation: astro-ph/000340 (Ralston/Buniy)

Data analysis - antenna calibration/response function

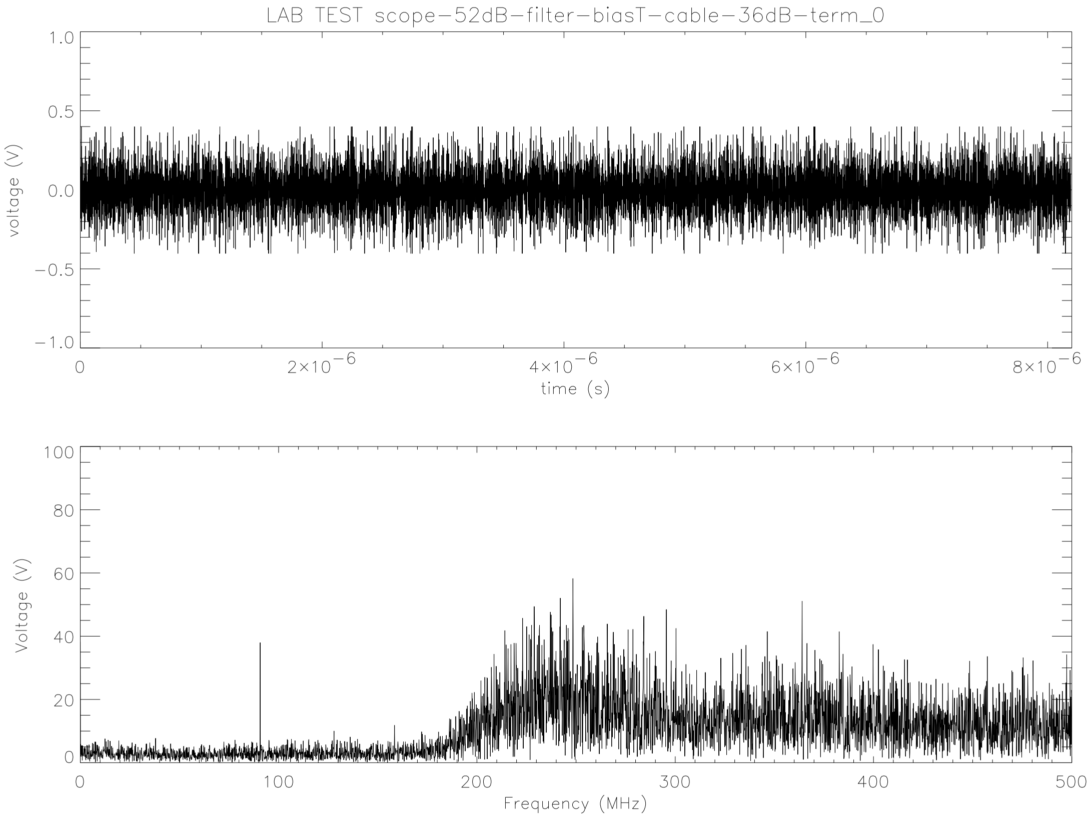
1. Use sun as a calibrated RF source (Peter Gorham)?
2. Efficiency msrmnts on KU antenna testing range (KUATR) in progress; *in situ* msrmnts.

   (Balun-less receivers ≈ receivers w/ baluns)

   Orientation wrt AMANDA cable still to be calibrated w/ Tx data



Amplifier Gain (Calibrate to 250K $T_{thermal}$, e.g.)



Gains cross-checked with I_{bias} vs. gain measurements from lab.

Cable losses (spec'ed in lab, close to mfr. specs)

Data Analysis - Ingredients (cont.)

- Attenuation of signal in ice (transparency)

  Use CW data; measure signal strength in a bandwidth B:

  $S_{measured} = S_{antenna}(Gain)$

  $N_{measured} = N_{thermal}(Gain)$

  Ratios of $S : N$ can be used to extract transparency, knowing that $S \propto e^{\frac{-2\alpha}{r}}/r^2$

  $(S/N)_1 = e^{-2r_1/\alpha} cos^4\theta_{Rx1,Tx}/r_1^2$

  $(S/N)_2 = e^{-2r_2/\alpha} cos^4\theta_{Rx2,Tx}/r_2^2$

  Slope of S/N vs. r_i gives α (verified with MC)

  Typical measurement gives α ~250 m,

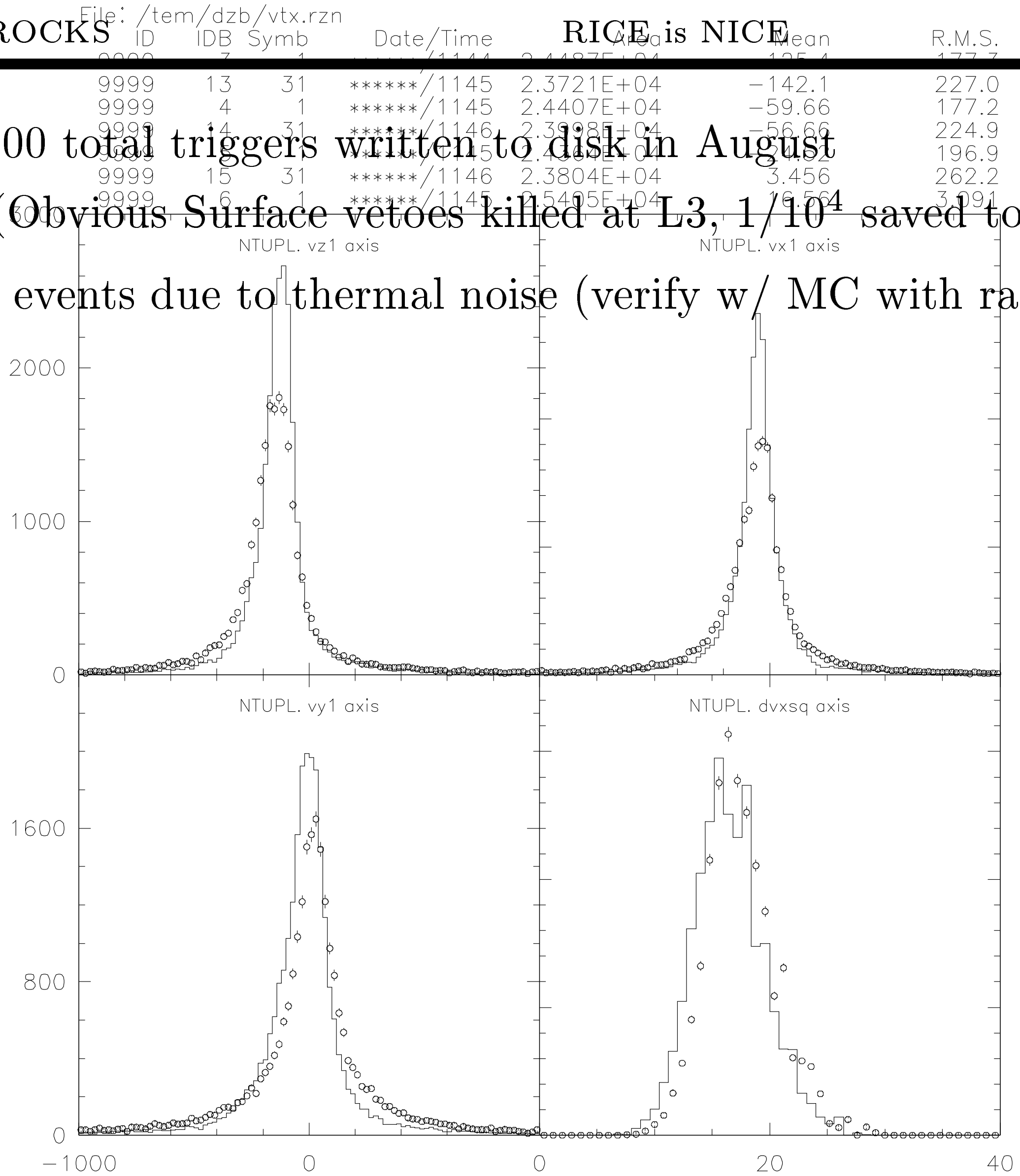
  BUT: (S,N) do not seem to scale together

- For now, use combination of $\epsilon_{ice}(Temperature)$ and $Temperature_{ice}(depth)$

1. ∼13000 total triggers written to disk in August

   (Obvious Surface vetoes killed at L3, $1/10^4$ saved to disk)

2. Most events due to thermal noise (verify w/ MC with random TDC's)



3. Therefore, require >4 hits 5σ above $\sigma_{RMS\ voltage}$

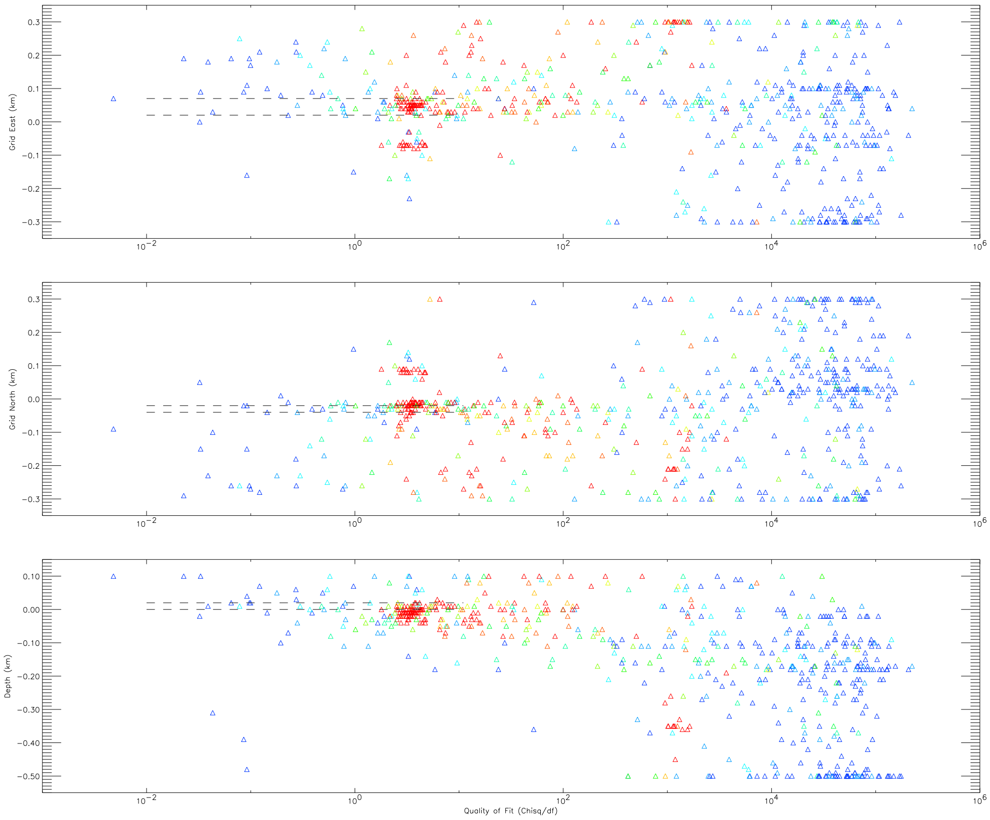
   (∼87% efficiency for signal)

4. +suppression of obvious non-signal (pulse trains, e.g.)

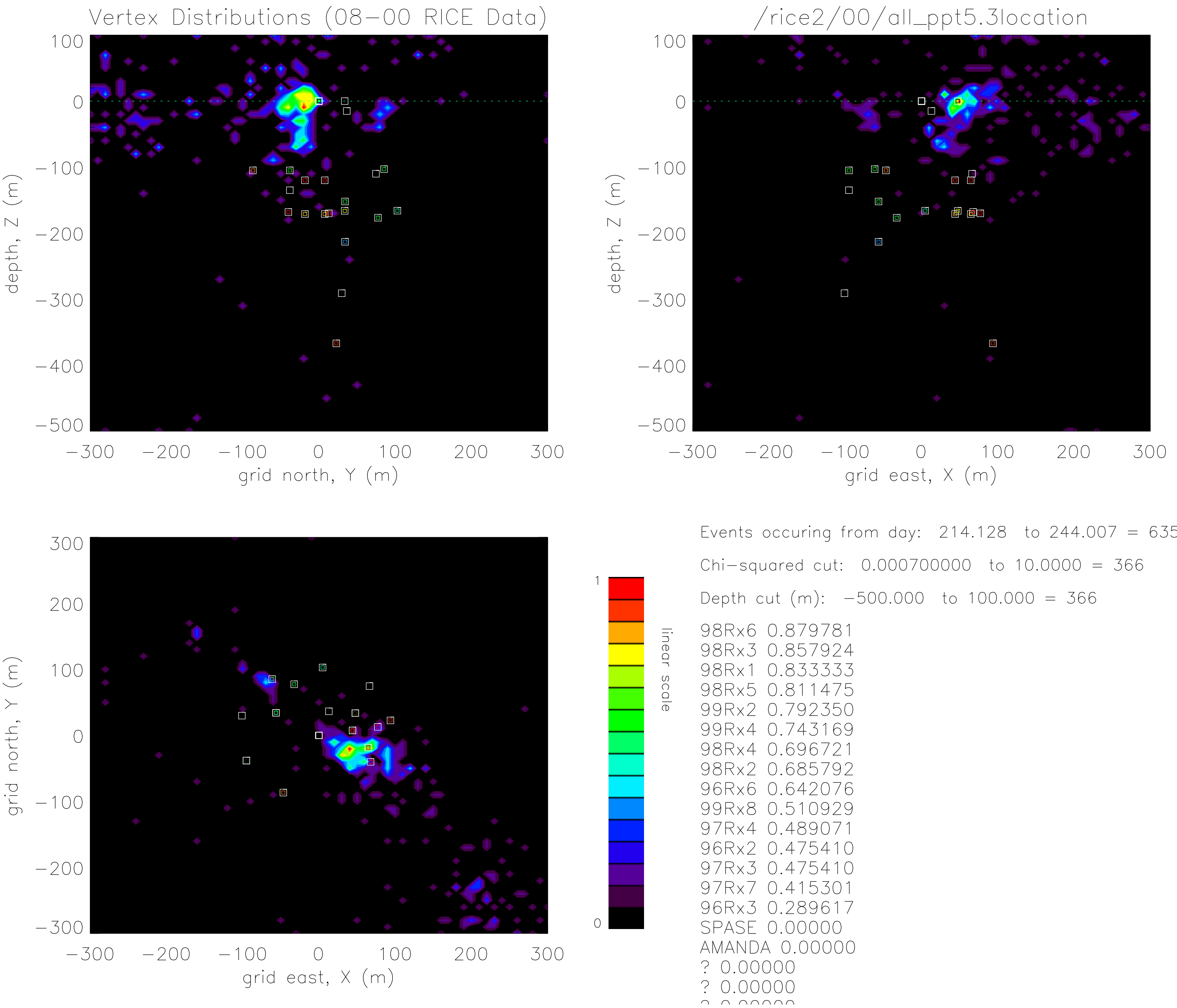
   (NO signal loss, based on "clean" transmitter test data)

5. ⇒∼200 events

6. Plot vertex distribution as function of χ^2 of vertex solution, by hit multiplicity



Grid East (km)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Grid North (km)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Depth (km)
0.10
0.00
−0.10
−0.20
−0.30
−0.40
−0.50
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Quality of Fit (Chisq/df)

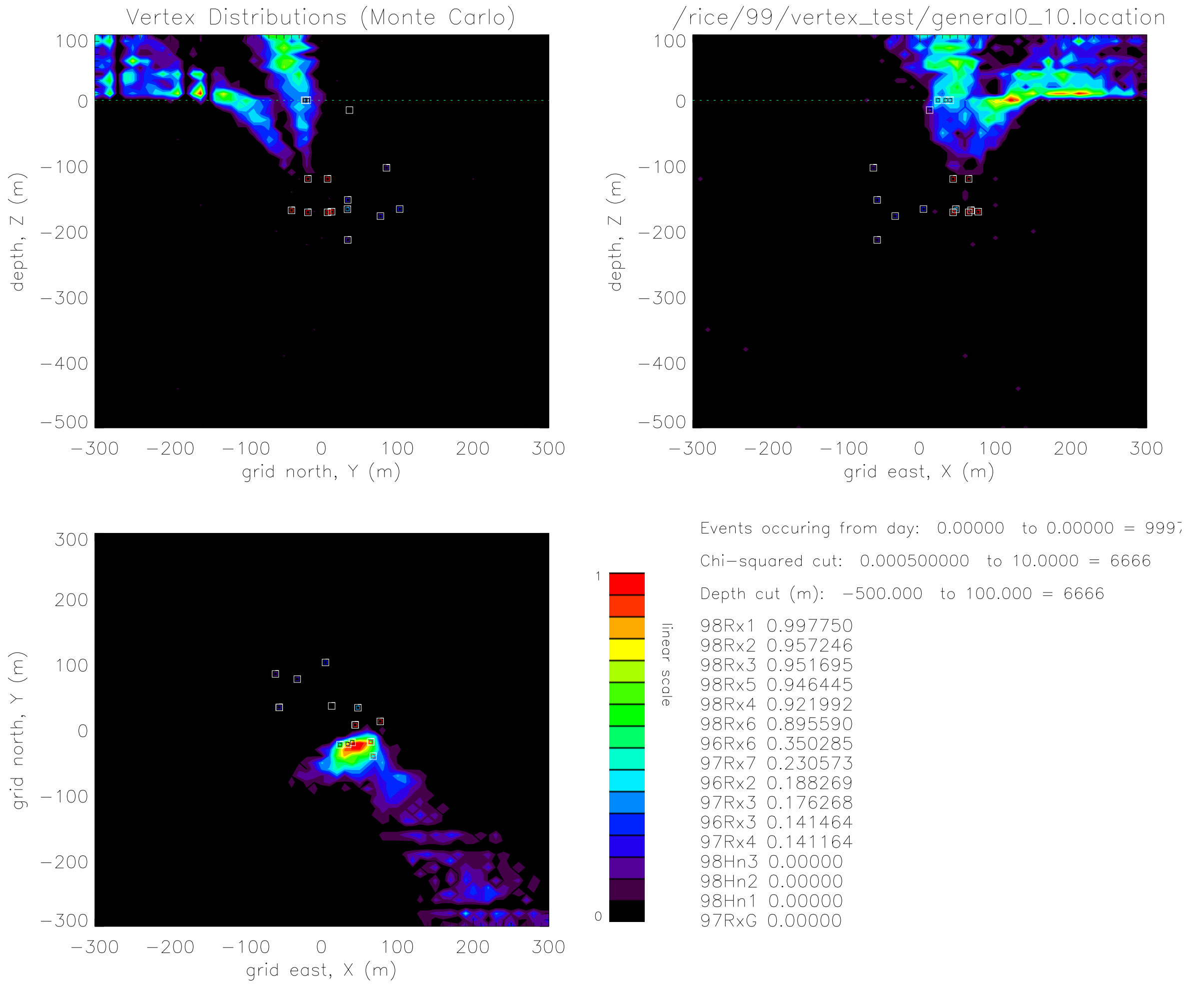

Vertex Distributions (08−00 RICE Data)
/rice2/00/all_ppt5.3location
depth, Z (m)
grid north, Y (m)
grid east, X (m)
grid north, Y (m)
linear scale
Events occuring from day: 214.128 to 244.007 = 635
Chi−squared cut: 0.000700000 to 10.0000 = 366
Depth cut (m): −500.000 to 100.000 = 366
98Rx6 0.879781
98Rx3 0.857924
98Rx1 0.833333
98Rx5 0.811475
99Rx2 0.792350
99Rx4 0.743169
98Rx4 0.696721
98Rx2 0.685792
96Rx6 0.642076
99Rx8 0.510929
97Rx4 0.489071
96Rx2 0.475410
97Rx3 0.475410
97Rx7 0.415301
96Rx3 0.289617
SPASE 0.00000
AMANDA 0.00000
? 0.00000
? 0.00000

Source Distribution Commentary

1. Most reconstructed event vertices consistent with surface generated noise.

2. Can also estimate channel-to-channel intrinsic timing resolution by using full RICE Monte Carlo simulation of surface sources and smearing Rx-to-Rx times until MC plot "looks" like data.

   Smear by 20 ns:

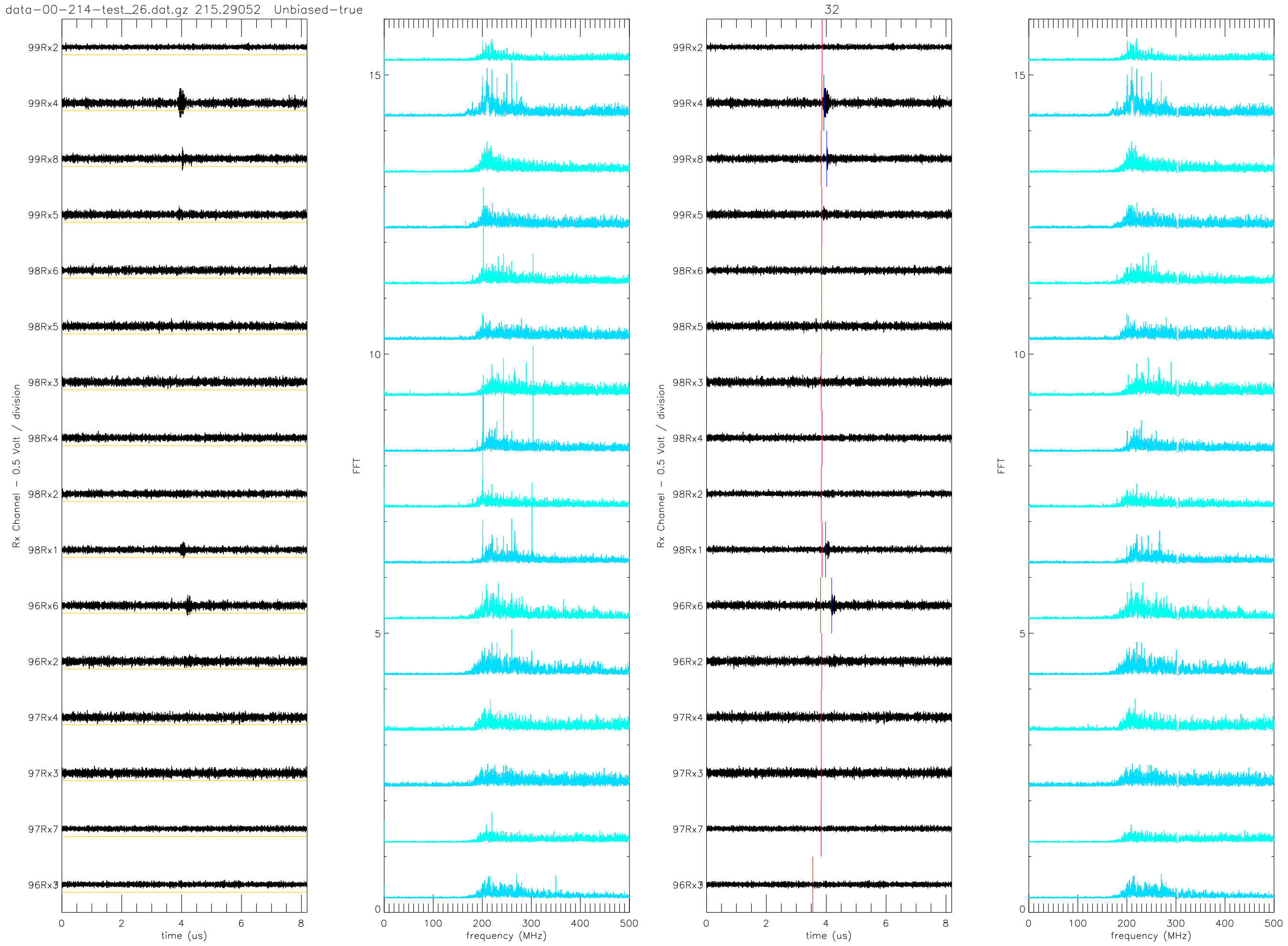


Source Distribution Commentary, cont.

1. $\approx$3 events give good χ^2 below vertex, and have waveforms showing apparently "distinct" pulses.

   Distributed roughly uniform over August, 2000.

   No obvious channels always "on".



Source Distribution Commentary, cont.

1. Compare waveforms with:

   Noise events with large χ^2 (SEE FIG)

   MC generated AMANDA-PMT noise (should be suppressed by filter, but what is exact suppression factor?) (SEE FIG)

2. To do: Compare waveforms, χ^2 vs. depth, hit multiplicity distribution, vertex location distribution, Č-axis directional distribution with:

   MC noise bkgnd. (dead reckon?), MC AMANDA-PMT bkgnds, MC surface RF bkgnds, MC downgoing muons, MC stopping showers.

   MC real neutrino events superimposed on background noise.

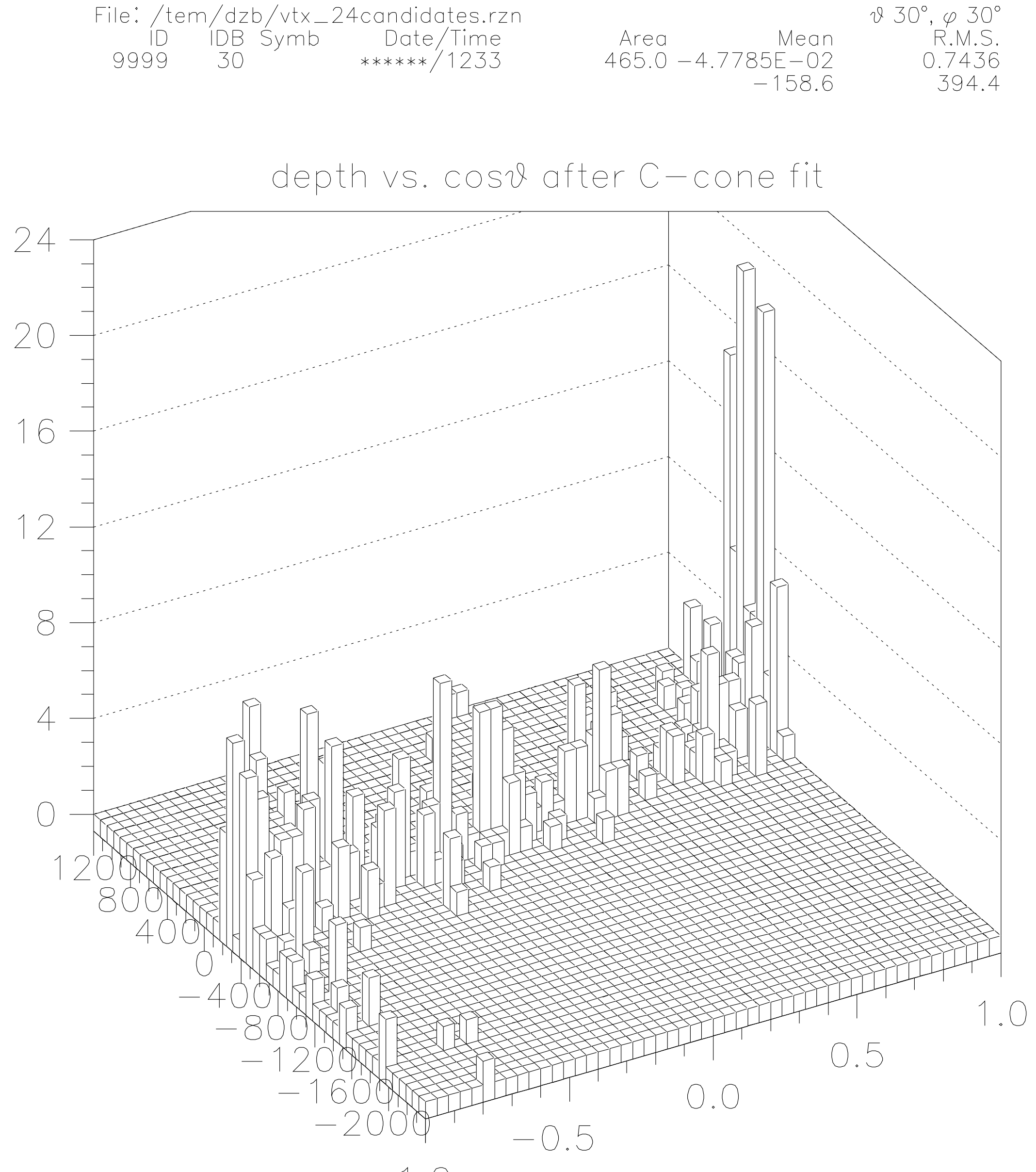
3. Also use AMPLITUDE information to check vertex reconstructed by timing! (TBD)

4. vis-a-vis directional information (stress: so far, have only found vertices)

5. Other considerations: Crosstalk between channels on same string? Noise generated at surface within DAQ crate?

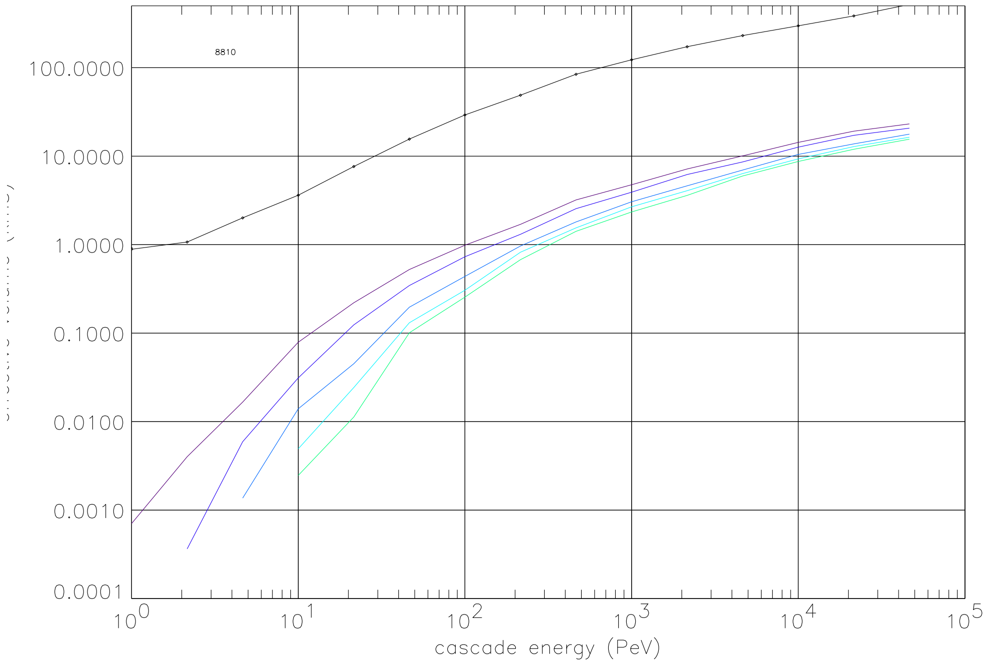
6. Exotica: Ice cracking? The Thing?

   First estimate of superimposing Č-cones on these event vertices:


File: /tem/dzb/vtx_24candidates.rzn
ϑ 30°, φ 30°
ID IDB Symb Date/Time Area Mean R.M.S.
9999 30 ******/1233 465.0 -4.7785E-02 0.7436
-158.6 394.4
depth vs. cosϑ after C-cone fit
24
20
16
12
8
4
0
1200
800
400
0
-400
-800
-1200
-1600
-2000
-0.5
0.0
0.5
1.0

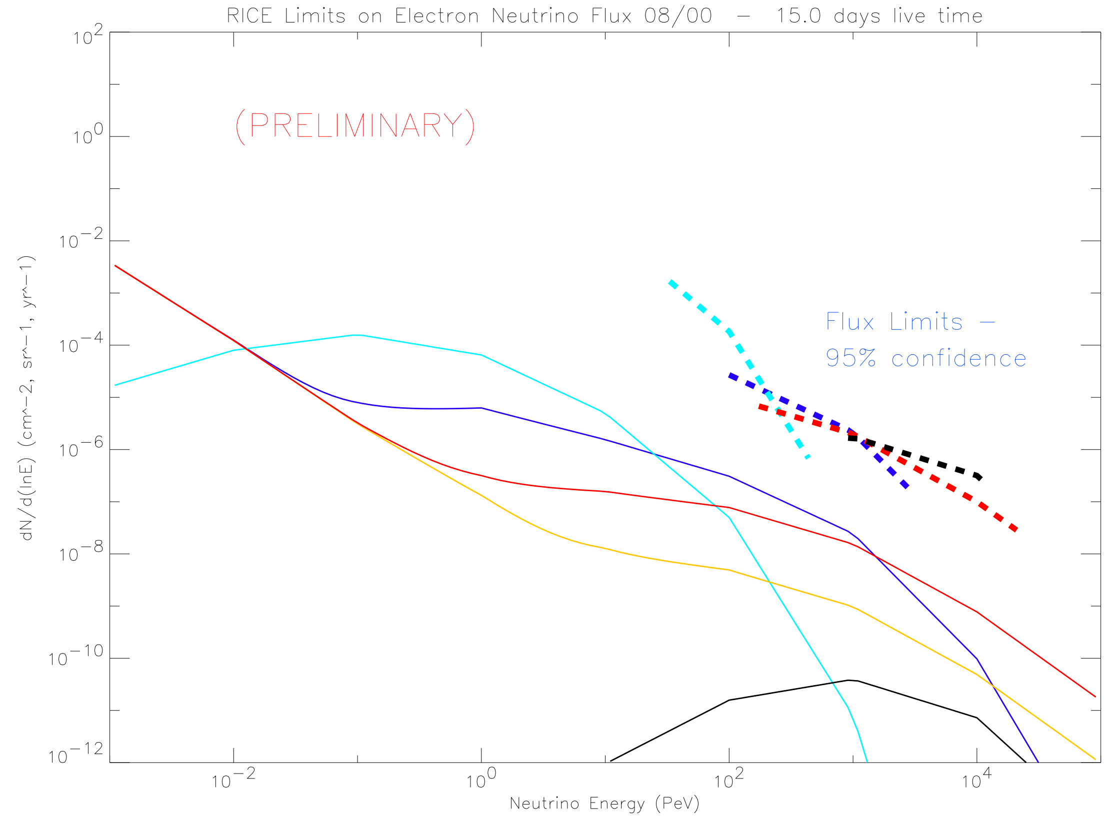
Generation of Upper Limit on Flux

1. If NONE of the waveforms are signal (still to be conclusively demonstrated), can calculate U.L.
2. MC gives $V_{effective}$ as f(E_{ν_e}) (incl. LPM)



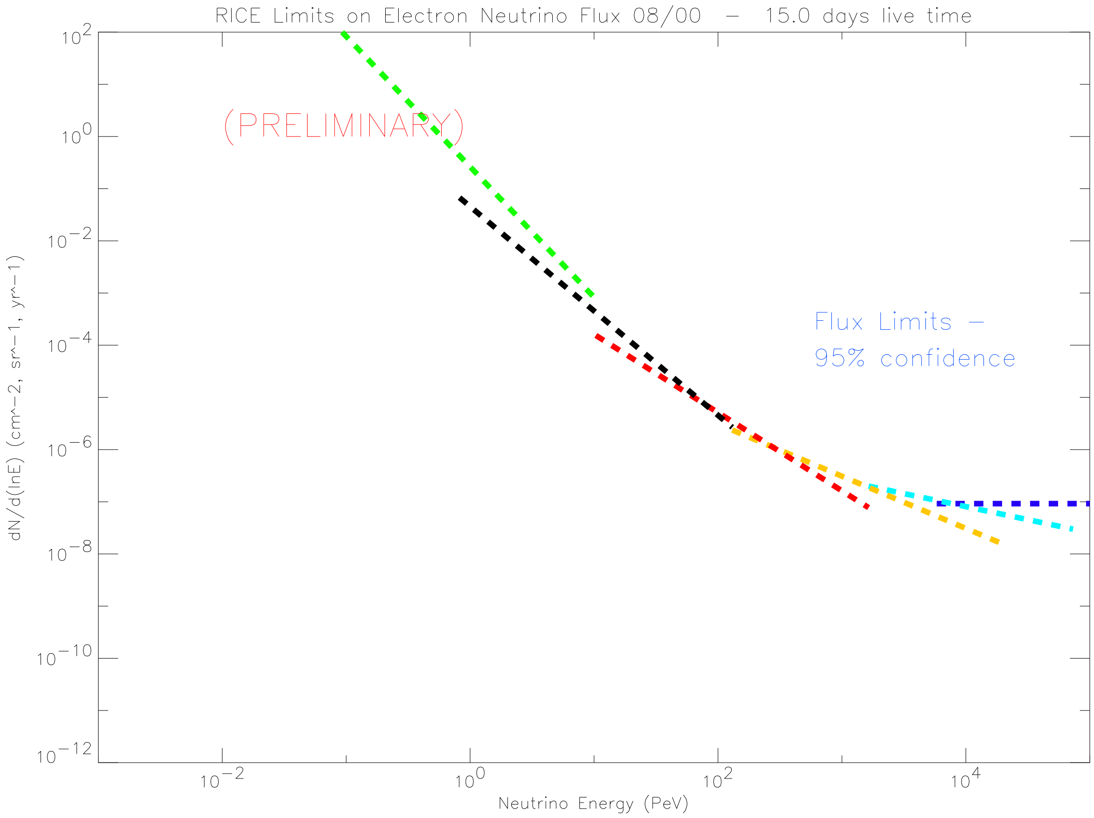
3. No. cascades/m^3/yr. calculated for 5 flux models.
4. Product of 1) and 2) gives the N_{evts}/yr. as f(E_{ν_e}).
5. Integrate 3) over energy⇒Tot. no. evts. for each of models.
6. Each integral dominated by some energy range (model dependent)

   (Trade-off between $\frac{dN}{dE}$(E)↓ vs. V(E)↑)
7. determine how large can the flux be for each model s.t. we would see zero events 90% of the time (plotted as the flux limit, 8/00 data ONLY)



Light Blue – Stecker, Dark Blue – Protheroe, Red – Mannheim B, Gold – Mannheim A, Black – Yoshida & Teshima GZK or plot using a "generic" $E^{-\gamma}$ flux

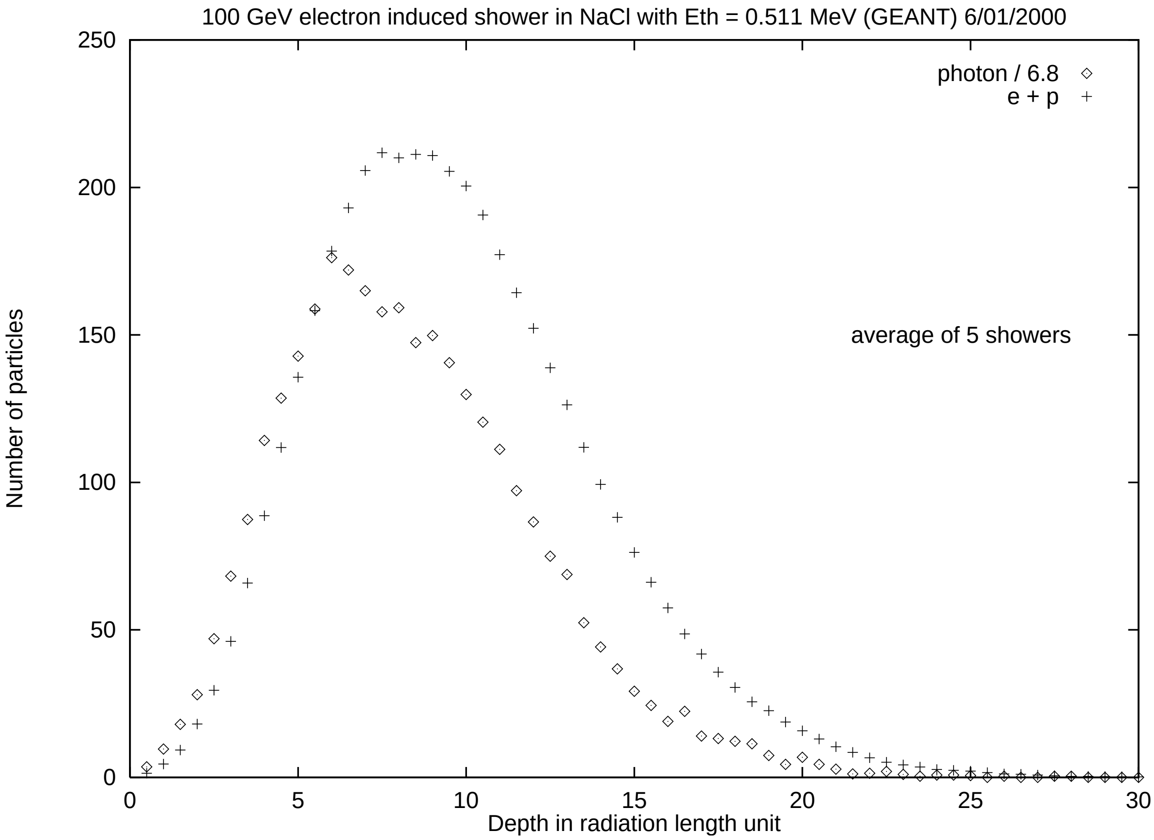
γ=3.5$\rightarrow$ γ=1.0 (left to right)

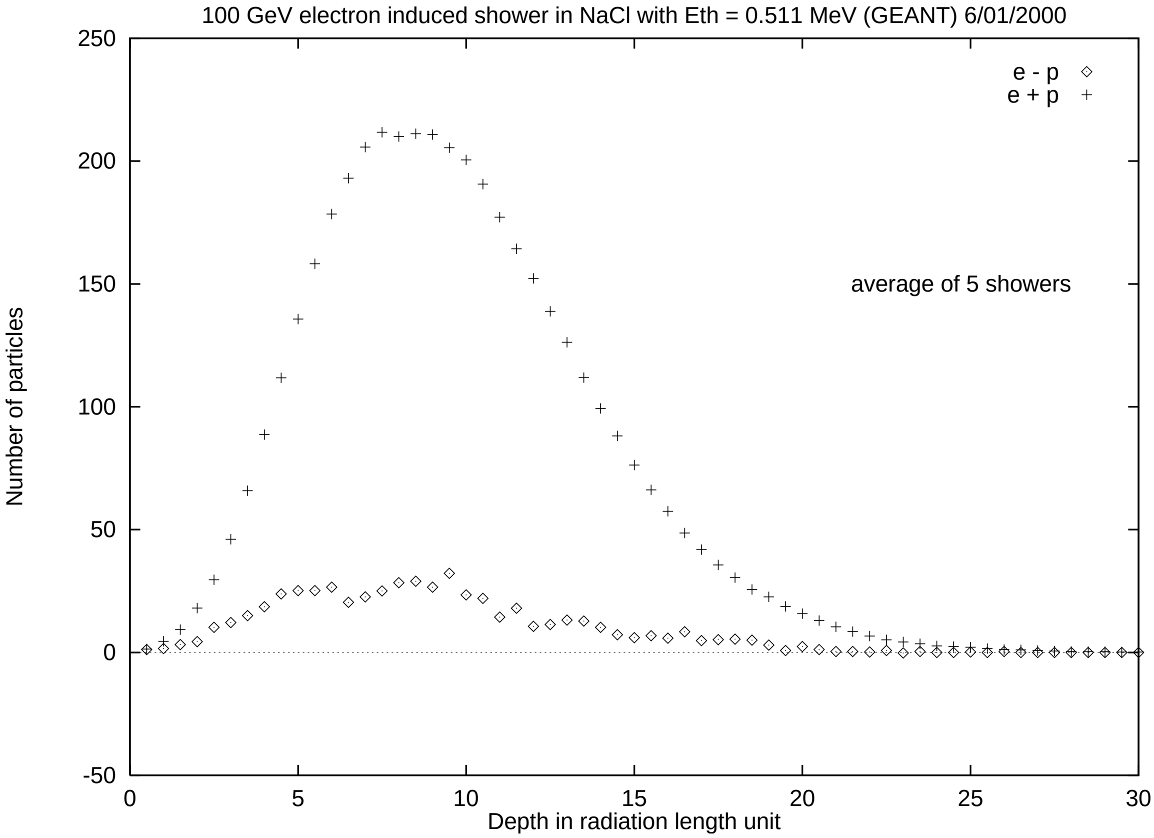


Prospects for Salt Detection of Neutrinos

- KEY QUESTION: What is absorption of RF by salt? Dielectric constant ϵ: $\epsilon(\omega) = \epsilon_{Re}(\omega) + i\epsilon_{Im}(\omega)$
- Complex index of refraction n(w) defined as:
  $\vec{n}(\omega) = [\epsilon(\omega)]^{1/2} \sim n(\omega) + ik(\omega)$;
  $l_m = l_v/n(\omega)$.
- Damping constant $k(\omega)$ related to absorption coefficient $a(\omega)$:
  $a(\omega) = 4\pi/l_v k(\omega)$
- Intensity of light I $I = I_o exp(-ad)$; $1/a =$ "penetration depth"
- Suppose $\epsilon_{Re} = 1$, $\epsilon_{Im} = 10^{-4}$ ($tan\delta = \frac{\epsilon_{Im}}{\epsilon_{Re}} = 10^{-4}$),
- $n(\omega) \sim 1$, $k(\omega) \sim 10^{-2} \Rightarrow a(\omega) \sim .01/m$
  $a(\omega)_{\mathrm{Ice}} \sim .001/m$
- BUT shower more compact than for ice (X_0^{Ice} ~40 cm; X_0^{NaCl} ~10 cm.
- N.B. Vernon Jones, formerly of LSU, now head of NASA's Solar Heliometric Observatory at the Goddard Flight Center, investigated the possibility of acoustic detection of neutrinos in salt domes (Jefferson Island Salt Mine near Gulf coast) in 1980. However, that initiative came to an abrupt end in October, 1980, when the Jefferson Island Salt Mine near the Gulf coast was flooded with water as a result of an oil drilling accident (drilling by TEXACO).
- Plan: obtain a trigger from Cerenkov light in the salt crystals and obtain acoustic signals from shower cores (initiated by high energy neutrinos) in the salt. Cables were strung between computer/data handling system on the surface and hydrophones, etc.

GEANT Study of charge excess built up by EM shower (Soeb/Suruj)





1999-00 campaign, summary

- 7 99Rx deployed, 1 99Tx deployed

  2 Rx in hole #14 failed; 1 Rx failure during re-freeze, 1 Rx failure one mo. after re-freeze, during trenching

- Installed new DAQ software

  Faster surface veto based on TDC times, detailed timing studies of system

Future Plans/Hardware (@ Pole: 12/19/00-1/3/01)

- Detailed Tx tests (calibration); horizontally & vertically
- Amplitude calibration of Rx
- Take trigger from AM-A, (incl. turn horn pointing down to AM-A??)
- More surface Tx tests, incl. horns.

  Dedicated transparency tests w/ horns through firn

- Possible long-baseline Tx study using cores drilled for climatology study for M. Battle (use Optical Fiber??)
- Swap in faster PC/new DAQ software
- DAQ upgrade

  Rewire and extend DAQ beyond 16 chs.

  Determine source of $\sim$10 ns TDC jitter

  Various software mods to be installed

- Analyze AMANDA/RICE, SPASE/RICE overlap triggers

Conclusions

- 1st pass calibration of: amplifiers, timing, antennas, shower power (MC) complete.

  Beam test results important confirmation of Č-rad

- Analyzing ~10% of total data collected thus far, obtain sensitivity approaching ≈1 order of magnitude from model predictions.

- Effective volume improvements to be gained by:

  Optical fiber signal transmission

  Higher gain antennas

  "Smarter triggering" (more sophisticated on-line pattern recognition)

- More MC work needed to firm discrimination for signal vs. noise.

- RICE will continue as a dedicated ICECUBE task

- Extend to salt?