RF Transient Detection & UHE Muons

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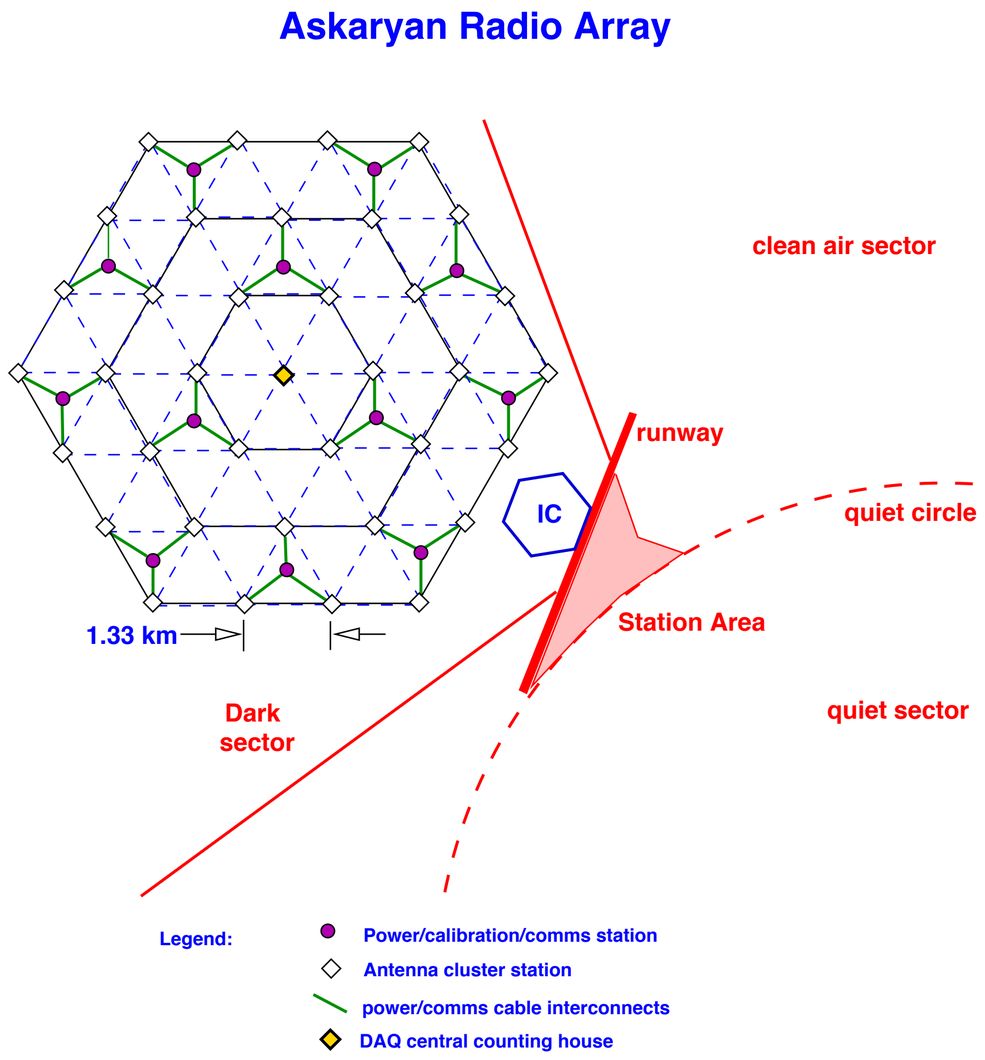
See also …

- This is talk is part of a loose trilogy which also includes
  - Hagar Landsman's talk in this session on current related hardware actually deployed in the ice and taking data (SATRA) …
  - Kara Hoffman's talk, also in this session on the ARA project based on these developments and currently to be deployed in the near future (coming 3 years)

Part I : Transient Detector MC Studies

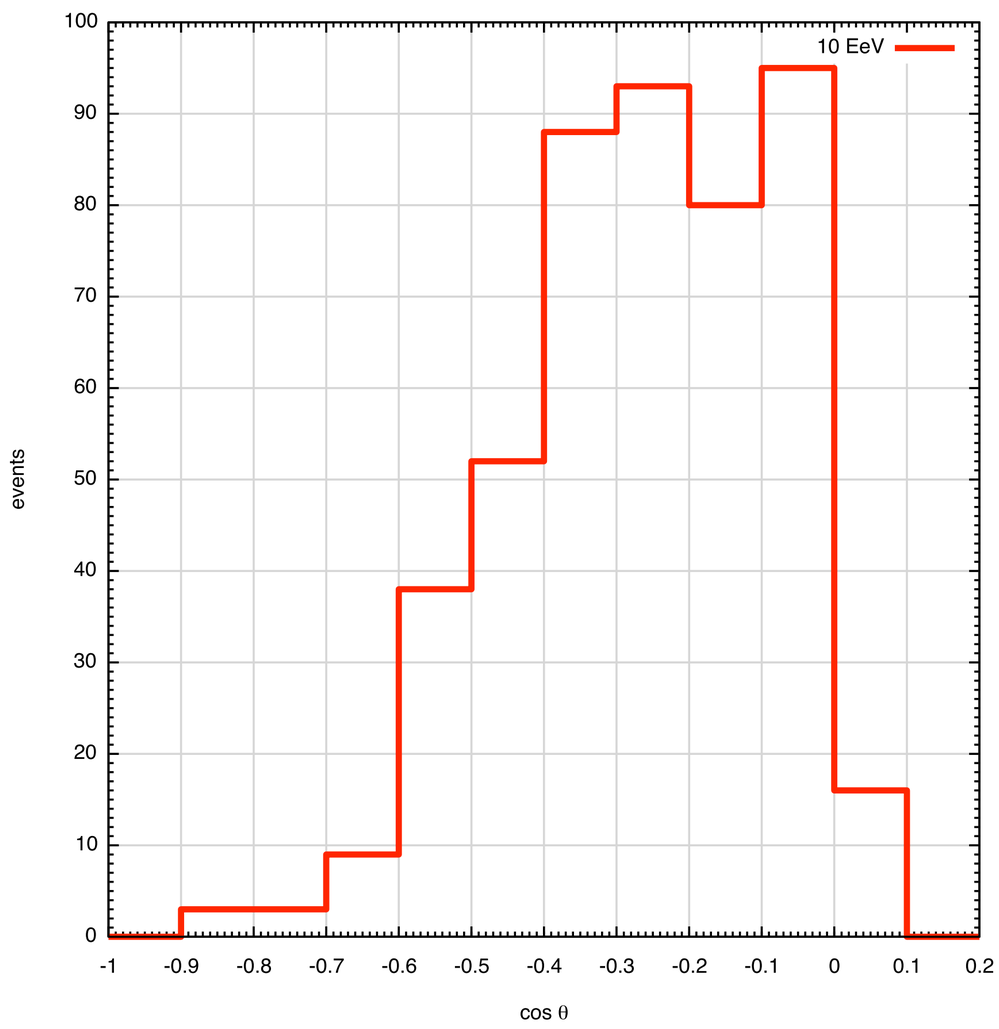
Askar'yan Radio Array

- I use the ARA design as a baseline for study as it
  - Already had someone think in some detail on optimization of neutrino signals
  - Represents an achievable goal in the coming years - it could be built for O(10 M$)
- To remind you - it is
  - 37 string clusters
    - Each cluster has 3-4 200 m strings
    - Each string has 2 Vpol + 2 Hpol broadband antennas (200 MHz - 1 GHz)
  - Total surface area ~ 80 km^2



Simulation of radio events

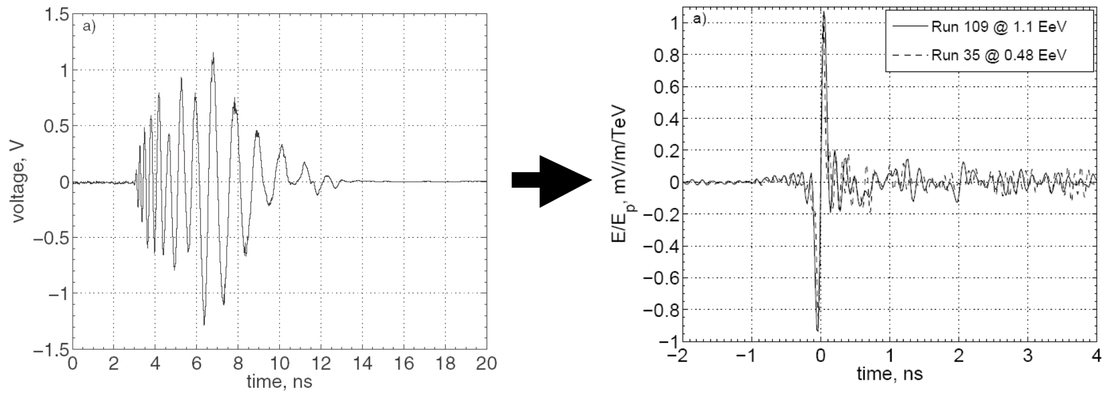
- I am but one of N (N > 3) MC simulators currently doing something with ARA-ish MC
- Probably one of the most simple simulators - 2000 lines of Java code (but nimble)
  - Limited ray-tracing
  - Antenna simulation is basic - only ideal dipoles modeled triggering at 4.5 σ
  - Earth shadowing effects are included
- Arrays formed using Jython scripts to describe geometry, drive simulation kernel, determine array triggering



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Transient detection vs. waveform readout





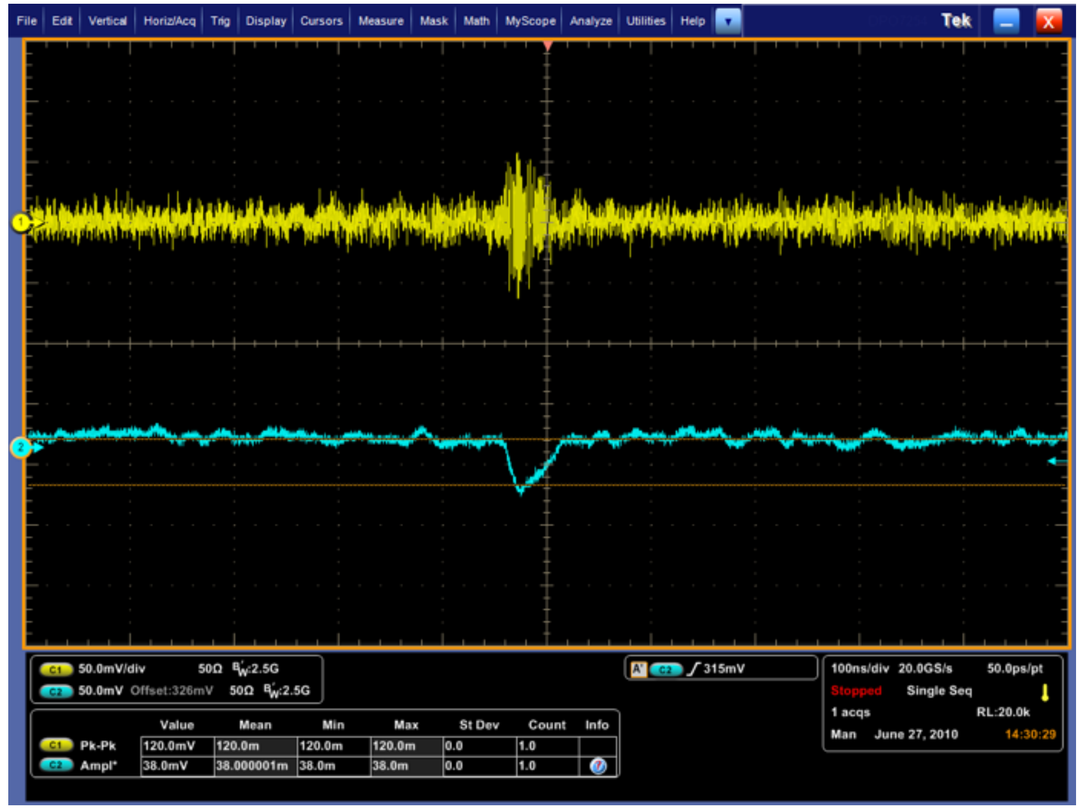
- Compelling simplicity
  - Detector easier / cheaper / lower power
  - Simulations easier
- Relies on pattern of large number of hits in an array to achieve equivalent event reconstruction - this is optical array technology.
- Each hit is compact packet - higher hit throughput to central trigger
  - Channel
  - Time
  - Amplitude
- But you cannot benefit from clustering because of limited time resolution - this is a WFD only domain - which in classical sense severely limits low energy performance.

- Extracts most information from antenna:
  - Sub-ns time precision
  - PSD manifestly contained in waveform
- Especially useful for rejection of anthropogenic backgrounds
- A single antenna / cluster of antennas can get vertex reconstruction to tens of meters and neutrino direction to O(10°). This is used in ARA to support sub-10^{18} eV events - where only 1 cluster is hit in majority of cases
- However on the downside
  - WFD information is bulky
  - More logic to control WF digitization
  - In general you need pay more attention to details of system

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Envelope detection /w/ log detectors

- Log detectors fast and have large BW
  - Typical rise times O(5 ns)
  - Typical fall times O(20 ns)
  - Compare to RMS detectors which are 10x slower
- Low power (75 mW / ch)
- Die size 2 mm x 3 mm



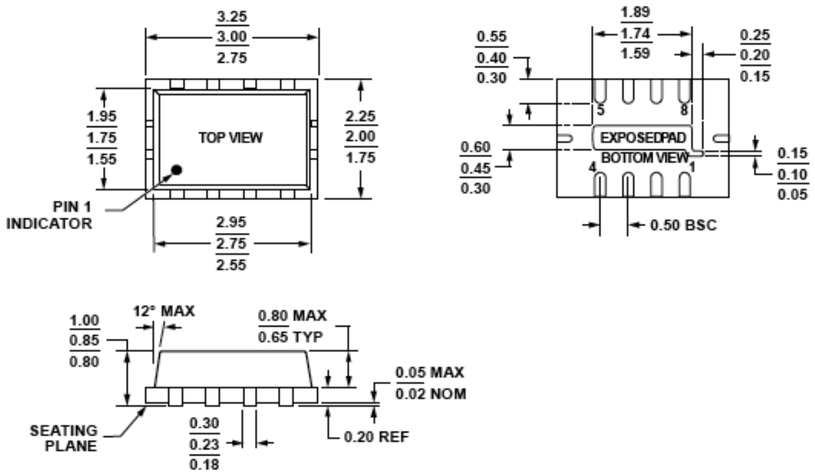
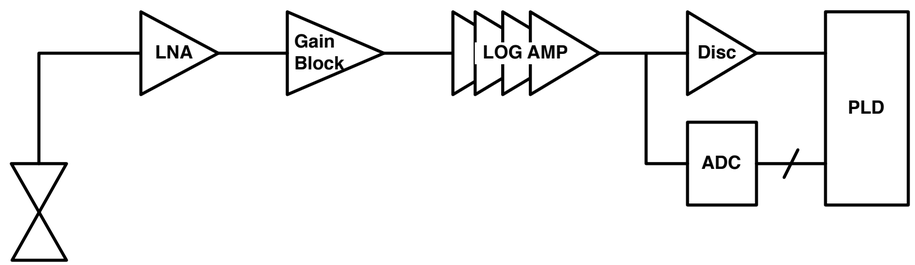
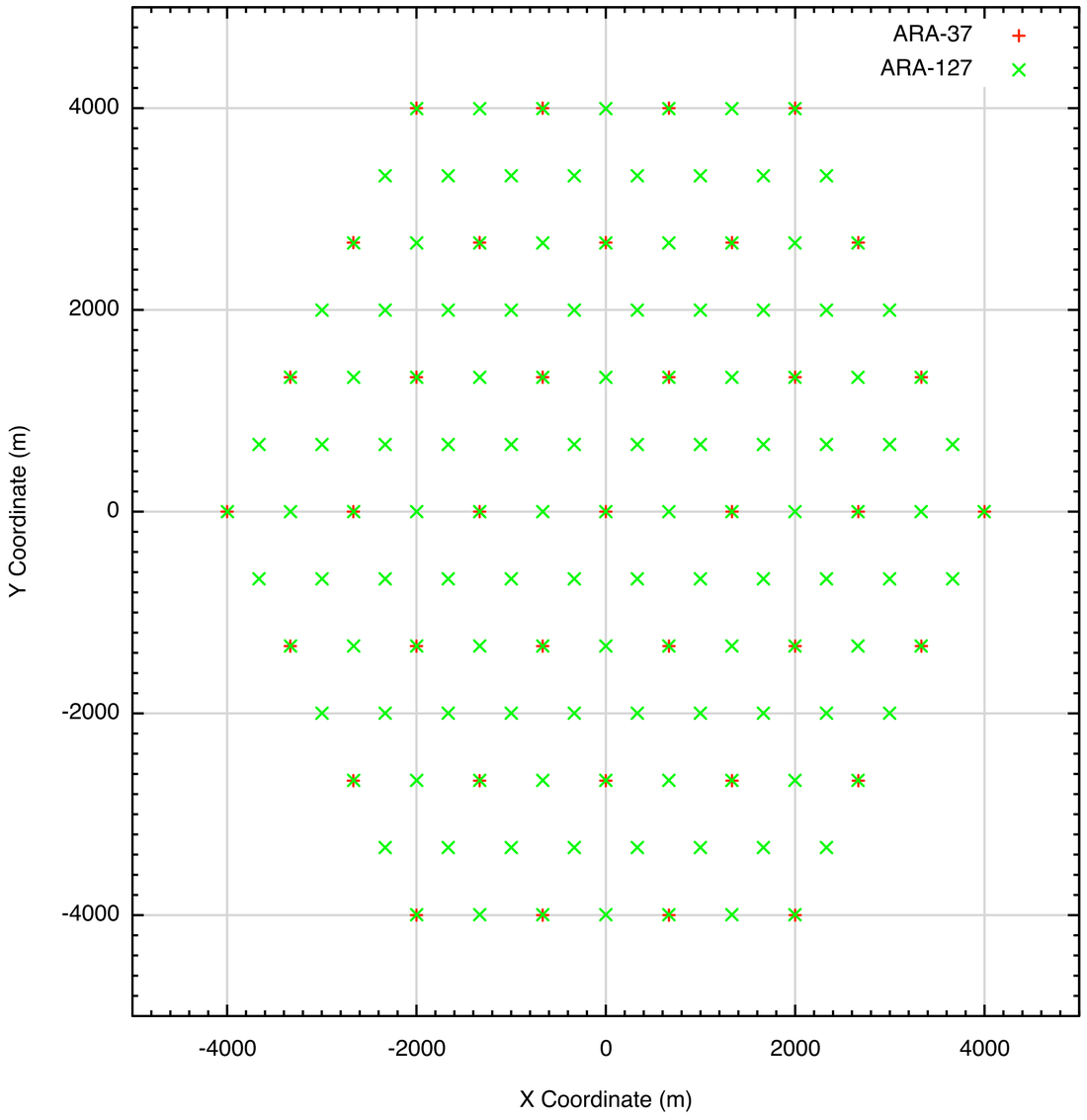


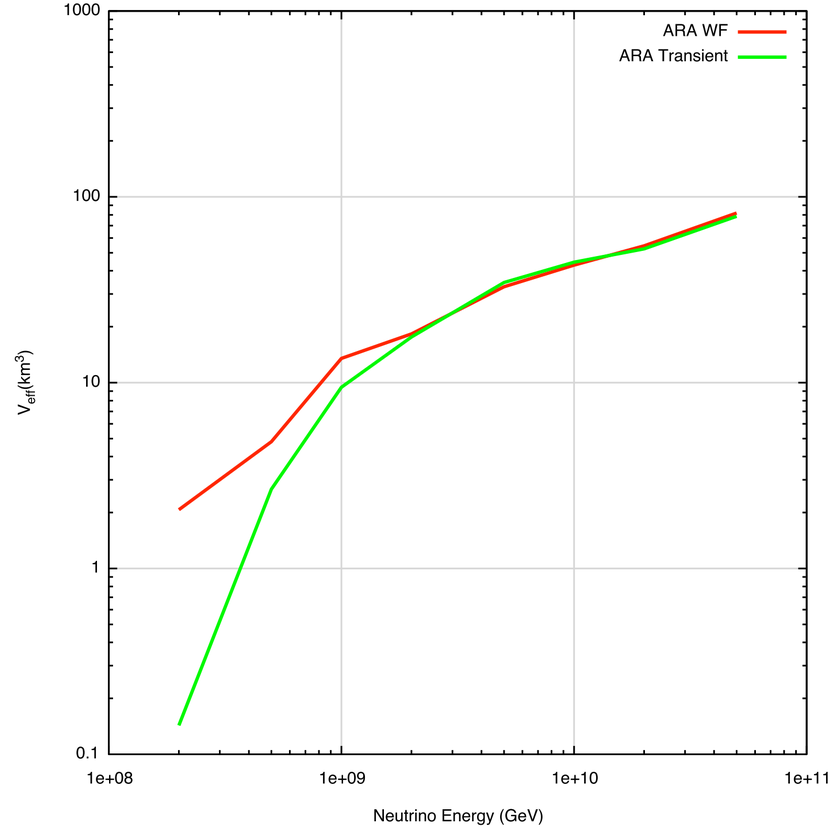
Figure 40. 8-Lead Lead Frame Chip Scale Package [LFCSP_VD]
2 mm × 3 mm Body, Very Thin, Dual Lead
(CP-8-1)
Dimensions shown in millimeters



Comparison: ARA transient vs ARA baseline



- Increase string density but move away from cluster concept to more even spacing of strings - same number of channels
- 37 string clusters on 1333 m baseline goes to 127 strings on 667 m baseline
- This is an equivalent amount of drilling



Vertex / Direction Reconstruction /wo/ WF

Vertex Reconstruction - Analytical Solution

Start with pair of ToF equations

$$(x_m - x_0)^2 + (y_m - y_0)^2 + (z_m - z_0)^2 = c^2(t_m - t_0)^2$$
$$(x_n - x_0)^2 + (y_n - y_0)^2 + (z_n - z_0)^2 = c^2(t_n - t_0)^2$$

Expand, subtract, and simplify to remove non-linear unknown terms - you are left with LSE

$$\begin{aligned} x_n^2 - x_m^2 - 2x_0(x_n - x_m) &+ \\ y_n^2 - y_m^2 - 2y_0(y_n - y_m) &+ \\ z_n^2 - z_m^2 - 2z_0(z_n - z_m) &= c^2\left[t_n^2 - t_m^2 - 2t_0(t_n - t_m)\right] \end{aligned}$$

This is then used as first guess for marginally more sophisticated NLLS fitter. Once vertex is found NDF algorithm can be run (NLLS).

Results for ARA-127

Energy	Fraction	VTX50	ANG50
500 PeV	47%	23 m	
1 EeV	64%	15 m	4.1°
2 EeV	76%	17 m	4.1°
5 EeV	84%	18 m	4.3°
10 EeV	84%	19 m	5.4°
20 EeV	91%	20 m	5.2°
50 EeV	91%	25 m	6.3°

Reconstruction (cont'd)

- Python reconstruction - using excellent numpy / scipy packages for linear algebra and numerical routines such as NLLS.
- Non-unity reco efficiency due to degenerate event topologies
- I think the reco gets worse at higher energies because I use extremely simple assumptions on propagation speed even where NLLS hypothesis could be much more sophisticalte
- Vertex reco extremely good - uses only hit timestamp with simulated 1 ns jitter.
- Neutrino direction finding algorithm fits only geometrical distribution of hits (no time information) to cone with width of 5°.
- This figure is competitive against 10° pointing resolution for WFD-based approach.

Conclusions to Part I

- So, transient detection doesn't seem to be much worse than WFD and maybe even gives better performance for UHE neutrino astronomy vis-à-vis angular resolution, but what is the real point of this?

- I make no hard claims to cost benefit yet as infrastructure costs ultimately kick in and probably are comparable to instrument costs. However, it will be cheaper in terms of actual construction cost → more channels can be deployed.

- As data from real hardware in operation at Pole this year shows - it is much easier to deal with a simpler detector. The burden of additional data management should not be underestimated as it retards analysis and ultimately publication of results:
  - Just dealing with large amounts of data
  - Bookkeeping associated with calibrations, exception handling, &c

- But, this is just the end of Part I; what about the muons ?

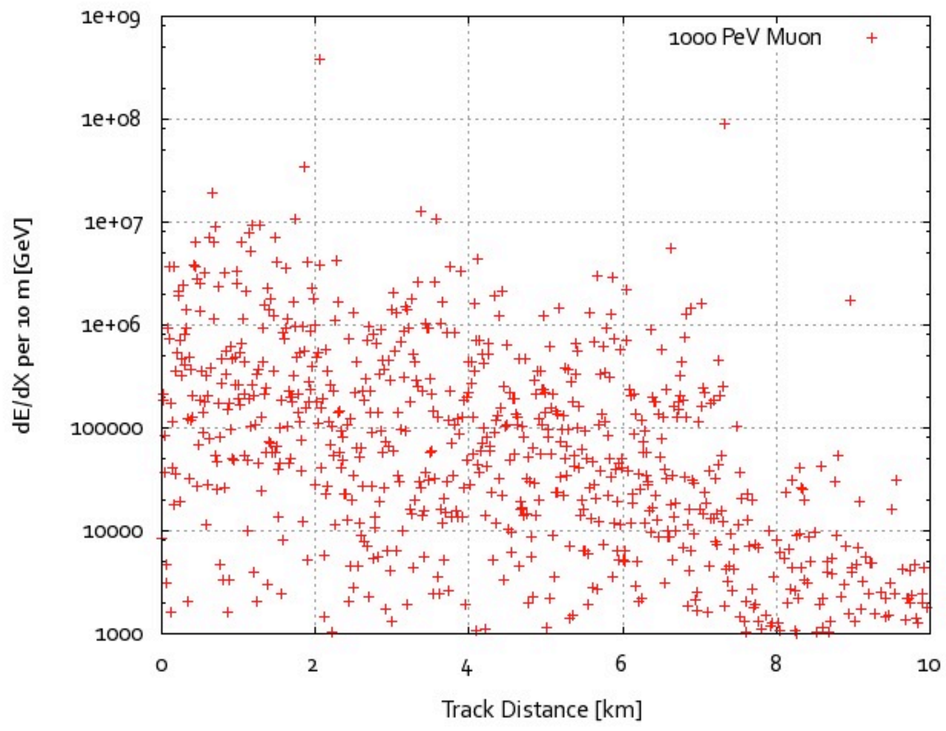
Part II : Muon Visibility in Radio

UHE muons in radio

- Muon energy loss at UHE is significant. They produce bright EM cascades.
- Are these secondary cascades also detectable by an array of radio antennas?
- As in the case of optical detectors, the muons present an opportunity to increase the effective volume. The distribution of energy loss is favorable in two ways:
  - Muons transport the point of radio emission closer to the receiver
  - Multiple, distributed showers have a better chance to strike receivers on the Cherenkov cone thus increasing signal energy, esp. at HF.
  - Gets around ray shadowing, maybe? Shallow arrays are possible again?
- On the down side, the cascades are weaker by some large factor.

$$\frac{dE}{dX} = a + b(E)E$$

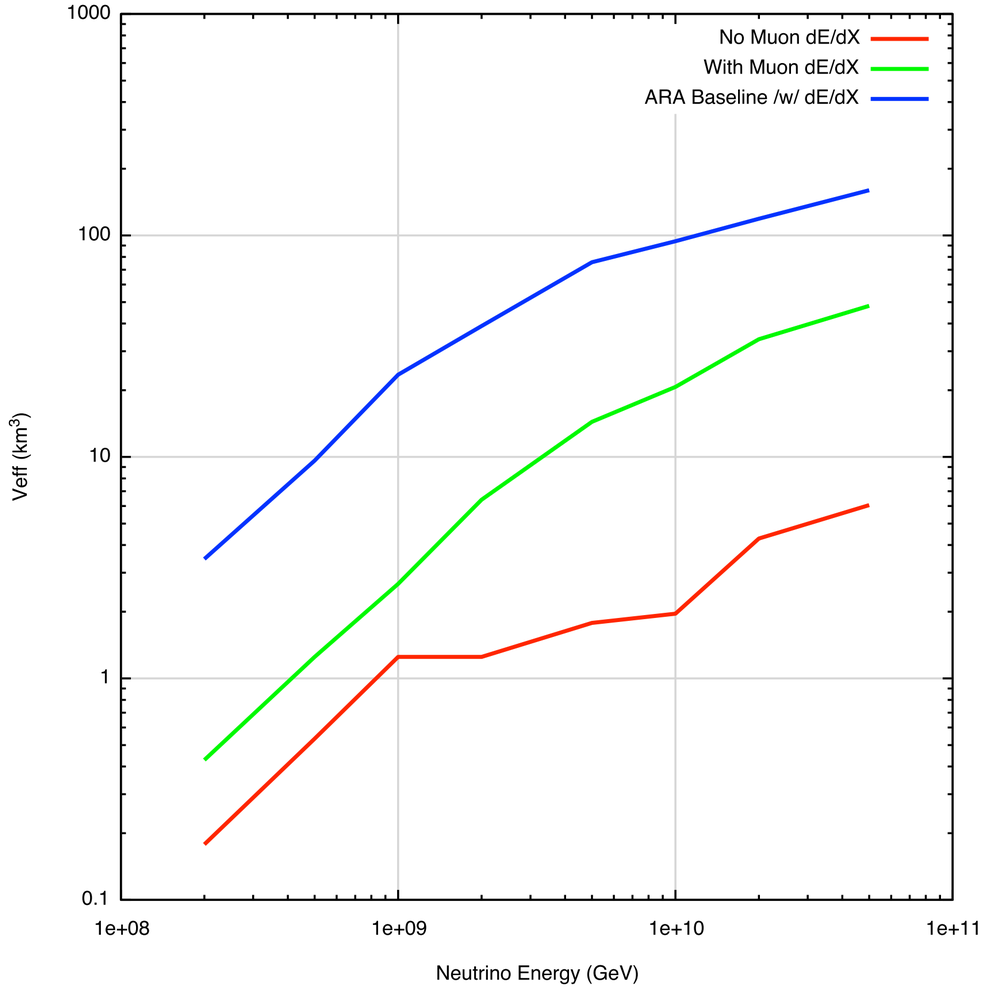
- The constant term is totally negligible at UHE.
- b(E) has weak dependence on energy but is approx 3.5E-6 at PeV and above. So, that means that a muon will lose approx 30% of its energy after traversing 1 km of ice.
- The actual stochastic energy loss is quite variable: to accurately simulate this I use D. Chirkin's **mmc** muon propagator.



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Depth dependence

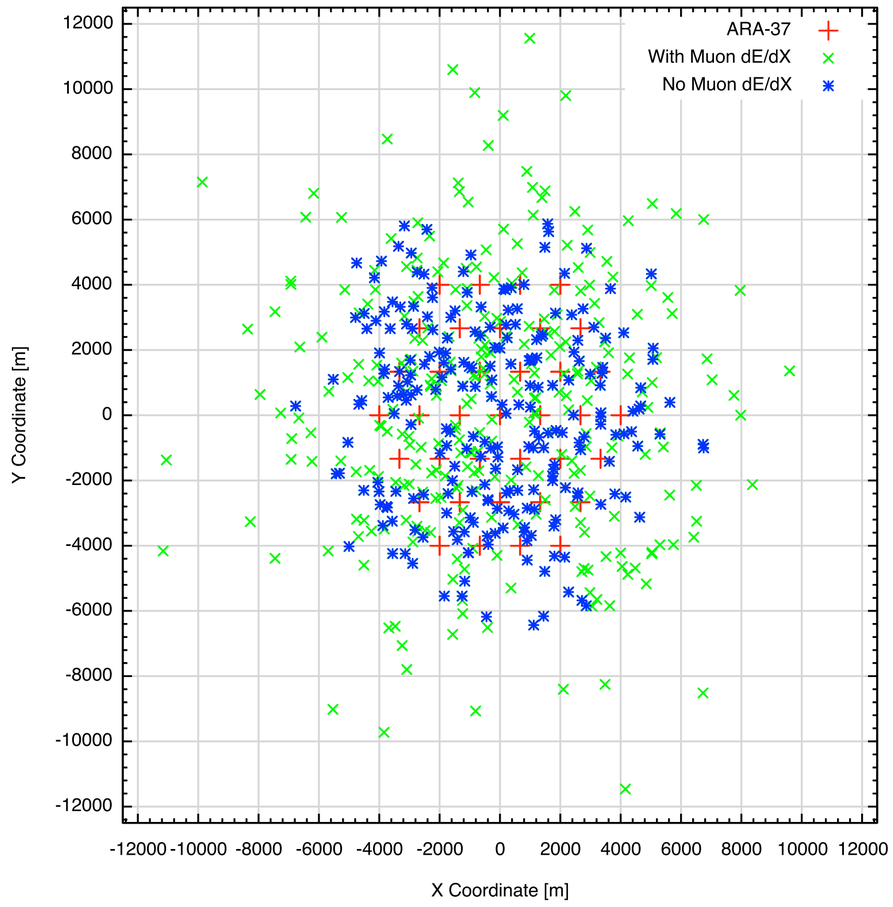
- An equivalent array at the surface performs much worse due to ray shadowing
- Inclusion of muon secondaries does revive a bit the effective volume which is abysmal without them
- Still about a factor of 5 worse than deep detector but also about a factor 5 better than surface detector without muon dE/dX
- In fact, you probably want to go deeper than the ARA baseline 200 m - muons come down mostly and thus are going to favor the deeper ice.

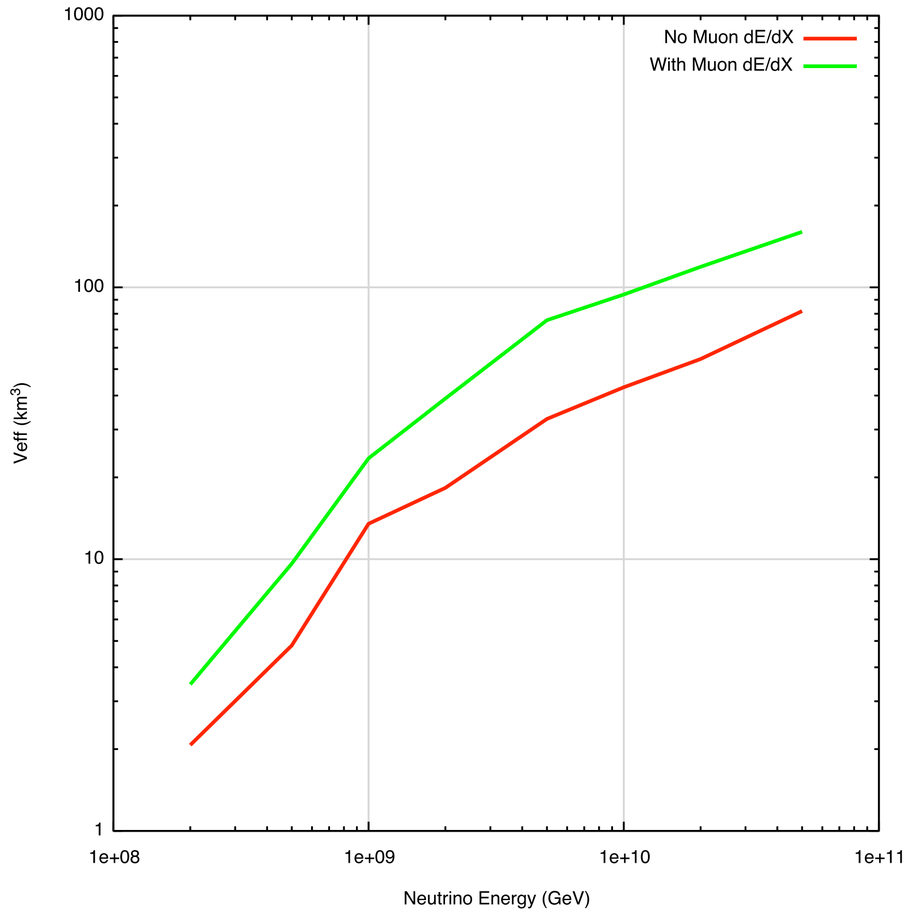


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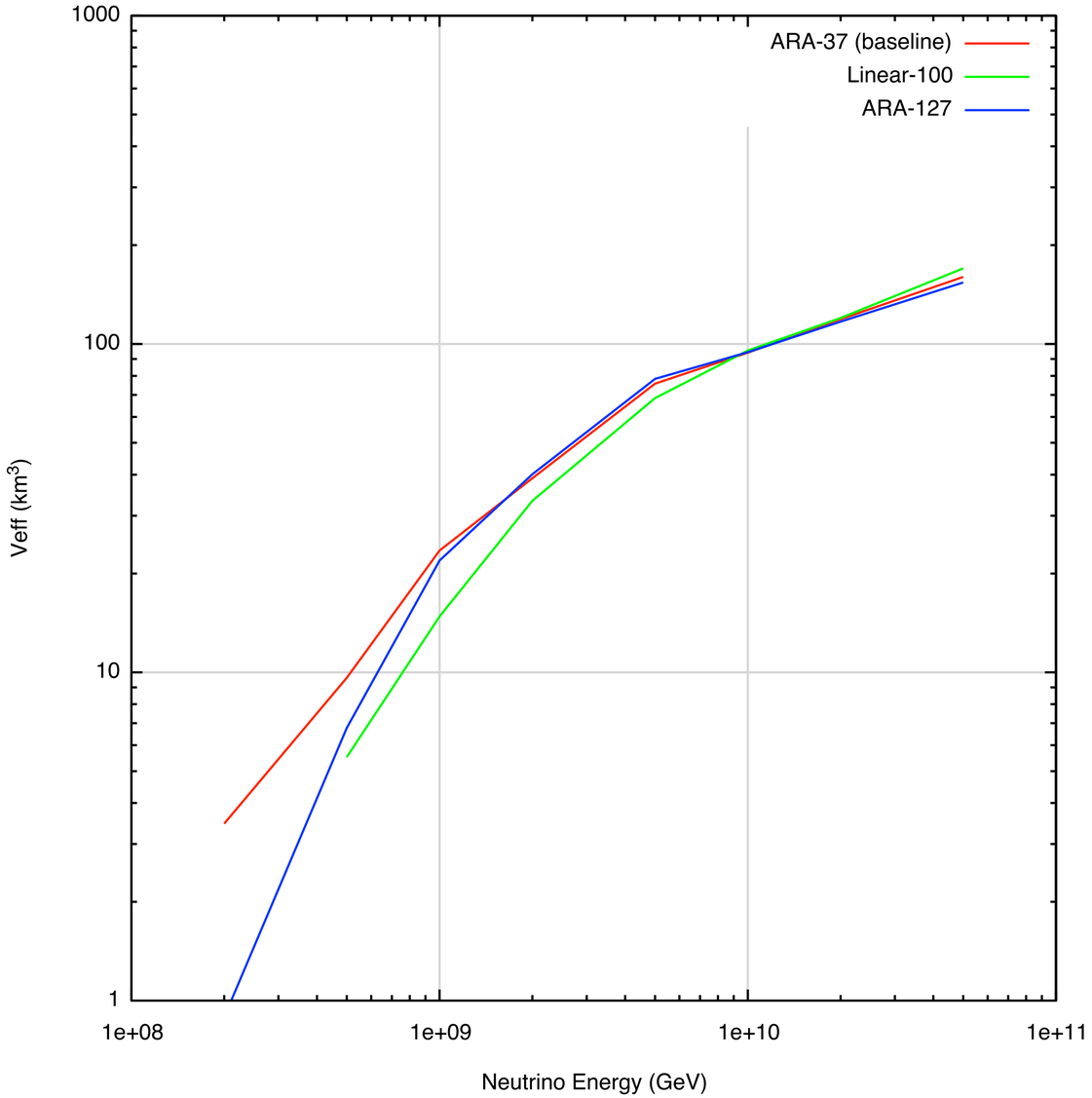
UHE muons in ARA-37 detector

- Results for ARA-37 geometry shown in figures at left.
- Simulation for this ARA-37 configuration assumes full WFD capture, not transient detector – baseline comparison





UHE muons in ARA-127 detector

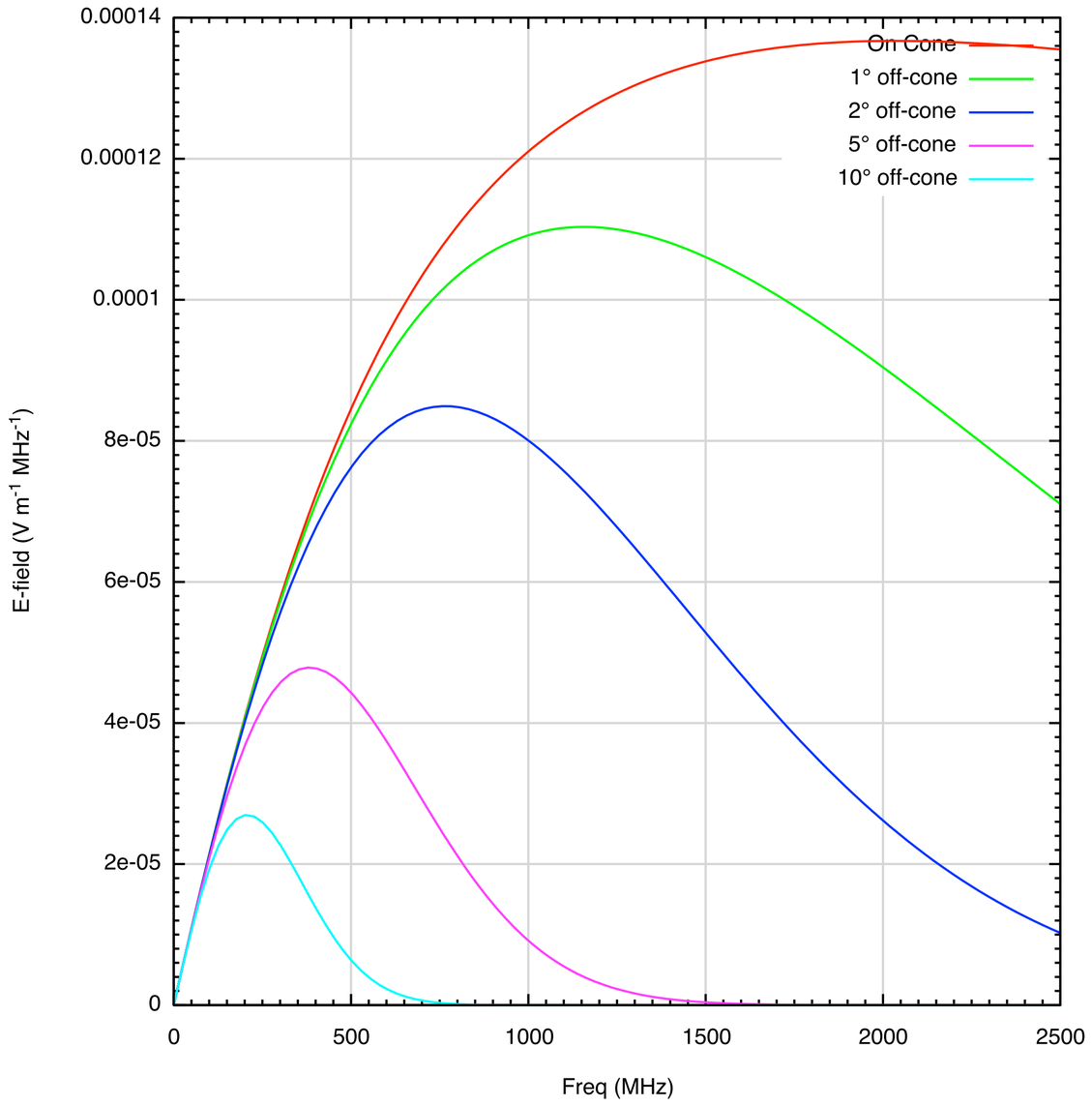


The Real Conclusions

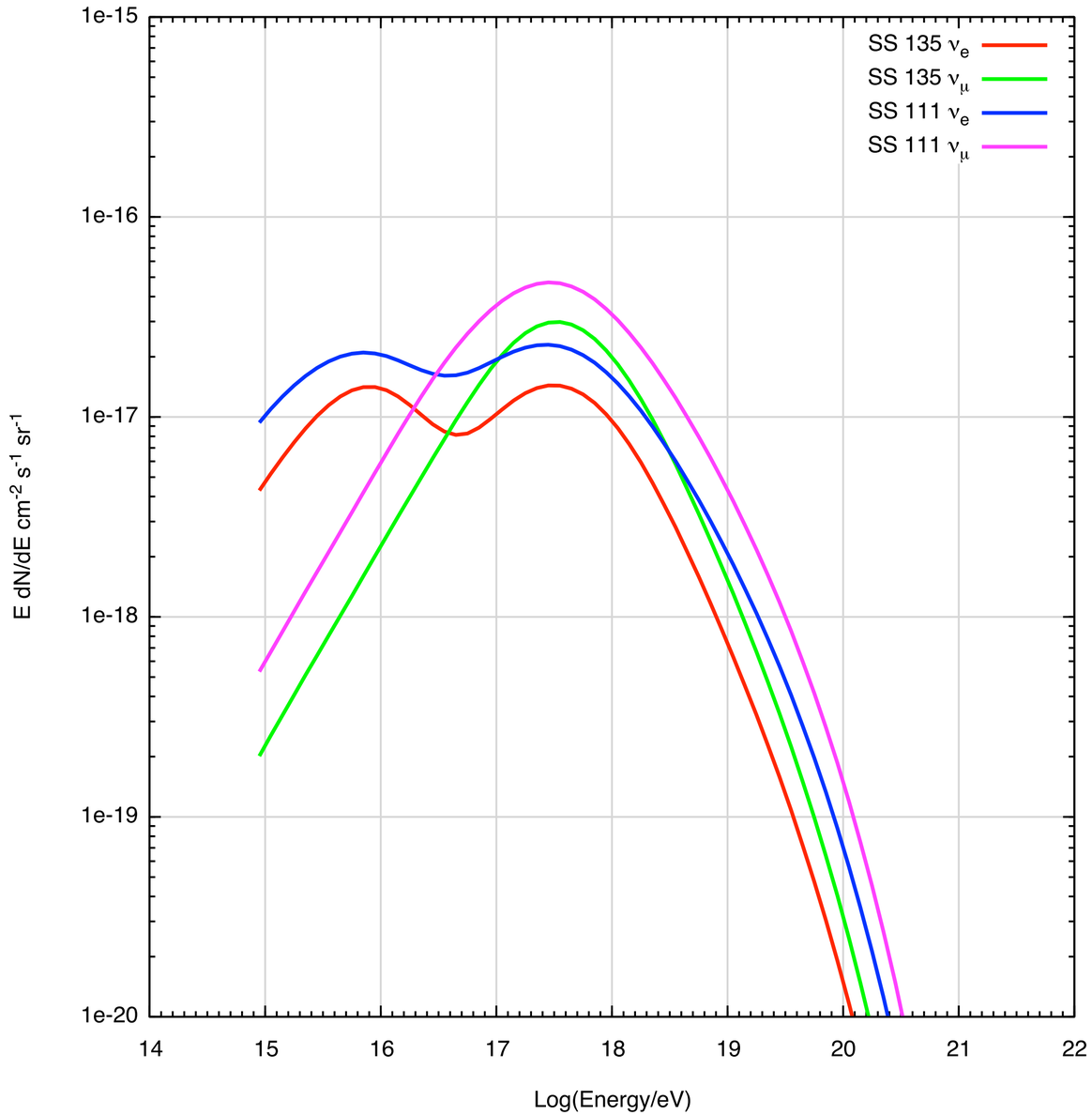
- Inclusion of stochastic losses from neutrino-induced μ makes significant contribution to detected event rate: almost flat factor of two over entire energy range of interest.
- Expected events from 1 yr ARA-37 under ESS 135h goes from 3.4 to 4.6 (you only get the 2x benefit in the μ channel)
- Veff at low energies of transient array is closer to WF array.
- Could be interesting to reopen studies of surface array - advantages are obvious
  - No drilling
  - Denser spacing
  - Bigger antennas

Backup slides

AVZ Parameterization

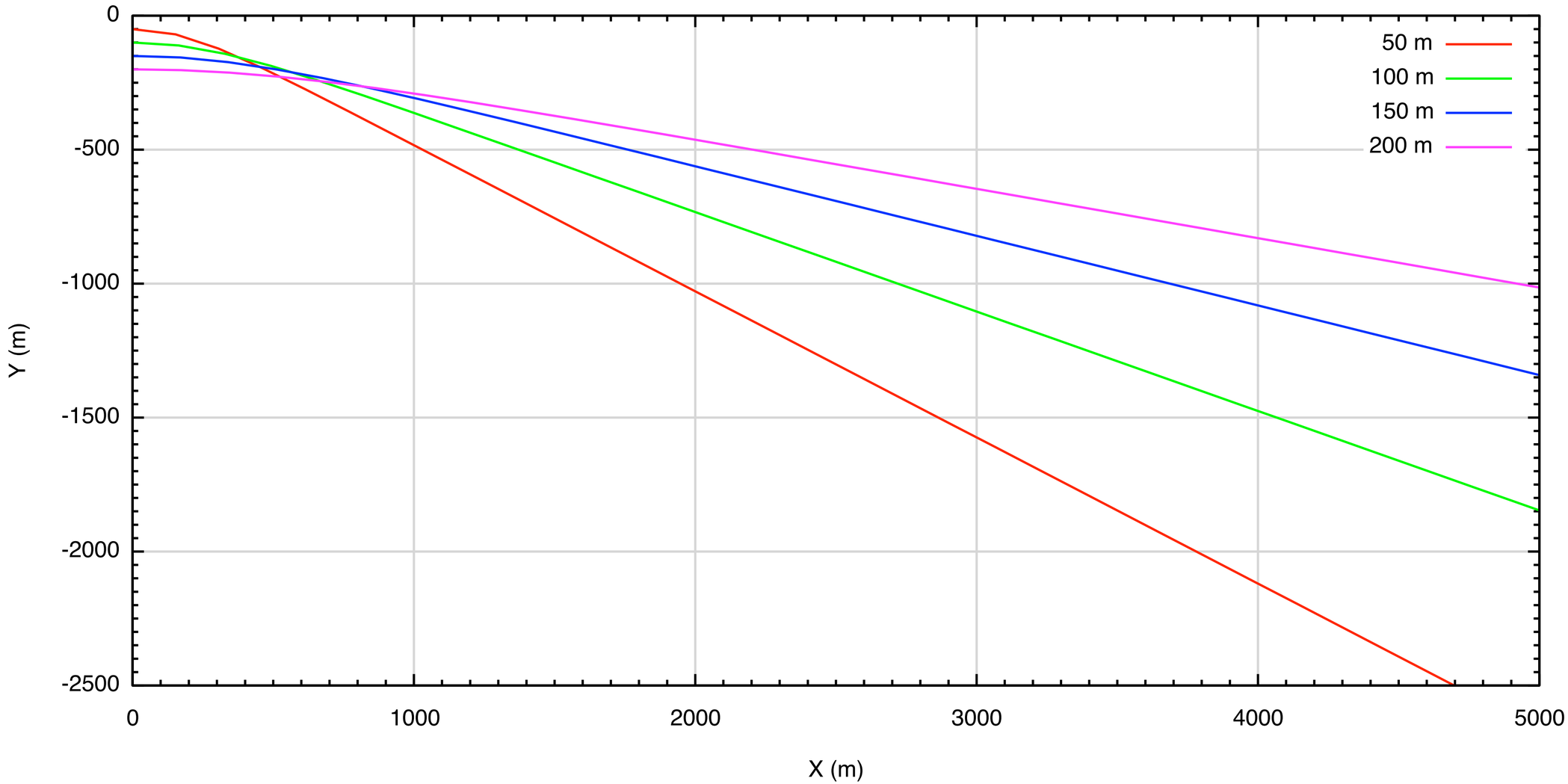


GZK Neutrino Fluxes



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Ray Tracing in Ice



MMC

```
EM 9 14000 1969 55 109 0
TR 1 ? hadr 4937.2 -3101.8 -1088.8 83.8 145.0 0 1.6057e+08 0
TR 2 ? mu+ 4937.2 -3101.8 -1088.8 83.8 145 43307.072 8.3943e8 0
TR 4 2 epair 4938.3716 -3102.6204 -1088.9554 83.8 145 0 6964553.9 4.7989804
TR 17 2 epair 4947.3851 -3108.9317 -1090.1507 83.8 145 0 323889.5 41.718536
TR 39 2 epair 4961.9225 -3119.1109 -1092.0787 83.8 145 0 1761896.3 101.2639
TR 55 2 epair 4972.9924 -3126.8621 -1093.5467 83.8 145 0 471403.06 146.6066
TR 68 2 epair 4982.4007 -3133.4499 -1094.7944 83.8 145 0 296143.82 185.14306
TR 78 2 epair 4987.7713 -3137.2104 -1095.5067 83.8 145 0 1971138.1 207.14116
TR 88 2 brems 4997.5559 -3144.0616 -1096.8043 83.8 145 0 608113.59 247.219
TR 100 2 epair 5003.137 -3147.9696 -1097.5445 83.8 145 0 377825.73 270.0796
TR 126 2 epair 5023.3099 -3162.0948 -1100.2198 83.8 145 0 1521537.7 352.70837
TR 165 2 epair 5046.9639 -3178.6575 -1103.3567 83.8 145 0 1202736 449.59534
TR 198 2 epair 5066.0221 -3192.0022 -1105.8842 83.8 145 0 8241919.8 527.65831
TR 199 2 epair 5066.0643 -3192.0317 -1105.8898 83.8 145 0 1005442.7 527.83114
TR 239 2 epair 5093.9232 -3211.5388 -1109.5844 83.8 145 0 536065.28 641.94198
TR 306 2 epair 5129.2445 -3236.271 -1114.2687 83.8 145 0 1783069.2 786.61879
TR 313 2 epair 5135.7507 -3240.8267 -1115.1315 83.8 145 0 2891785.2 813.26853
TR 324 2 epair 5143.5018 -3246.2541 -1116.1594 83.8 145 0 1388998 845.017
TR 325 2 epair 5143.717 -3246.4048 -1116.188 83.8 145 0 687963.01 845.8985
TR 341 2 epair 5149.4471 -3250.417 -1116.9479 83.8 145 0 4363648.5 869.36901
TR 352 2 epair 5153.7629 -3253.439 -1117.5203 83.8 145 0 1231608.9 887.04678
```

Event Physical Characteristics

