Status of the Radio Ice Cherenkov Experiment (RICE)

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7th LOIS Workshop
17 June 2008

Focus of This Talk

Discuss new RICE limit on highly relativistic magnetic monopoles.

Magnetic Monopole Overview

- Dirac, 1931

$$g = \frac{e}{2\alpha} \approx 68.5e$$

- GUT Scale Monopoles ~ 10^{17} GeV
  - Diluted by inflation
- “Intermediate Mass Monopoles” (IMM’s)
  - 10^8 GeV?
  - 10^5 GeV?

Relativistic Magnetic Monopoles?

- Wick et al. ('03):
  - Mass<10^{14} GeV $\rightarrow$ relativistic
  - Energy ~ 10^{16} GeV

- Relativistic monopoles cause particle showers in ice.

  $\rightarrow$ Showers give off Cherenkov radiation.

  $\rightarrow$ Detection mechanism!

Radio Ice Cherenkov Experiment

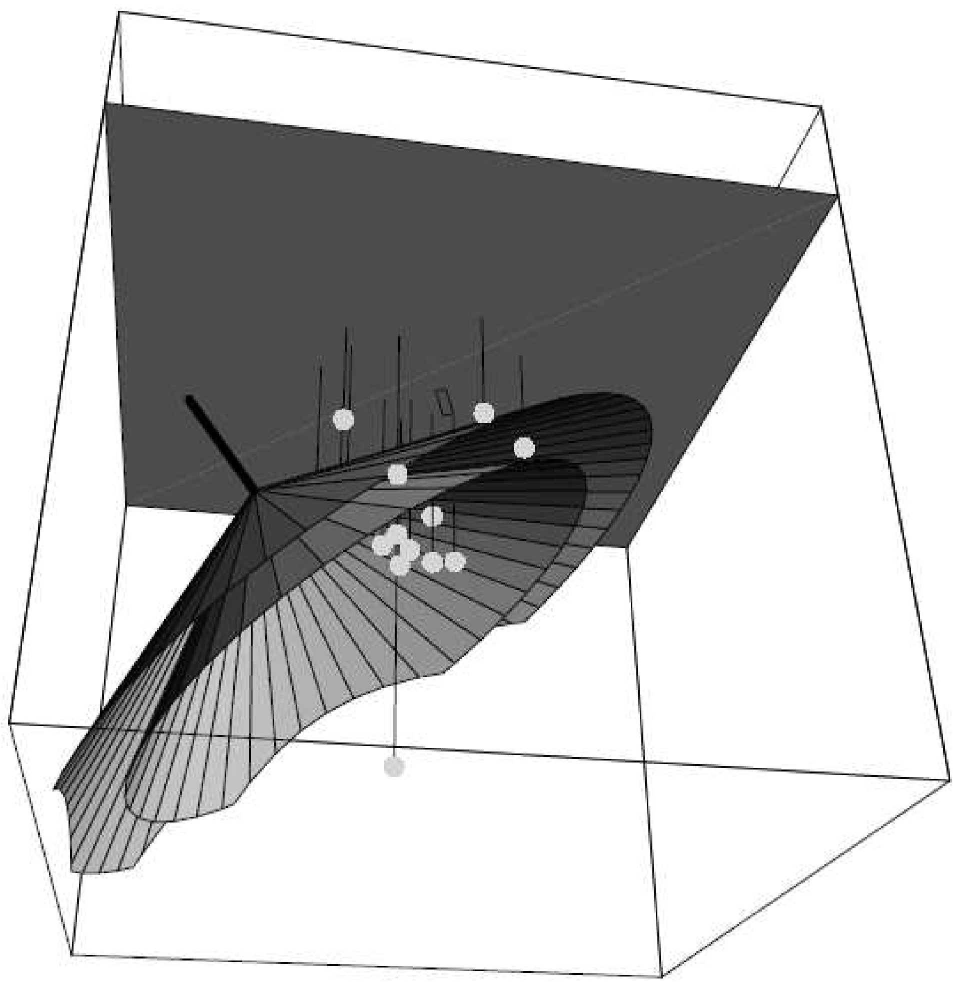


Figure Credit: Kravchenko et al., 2003

- Martin A. Pomerantz Observatory

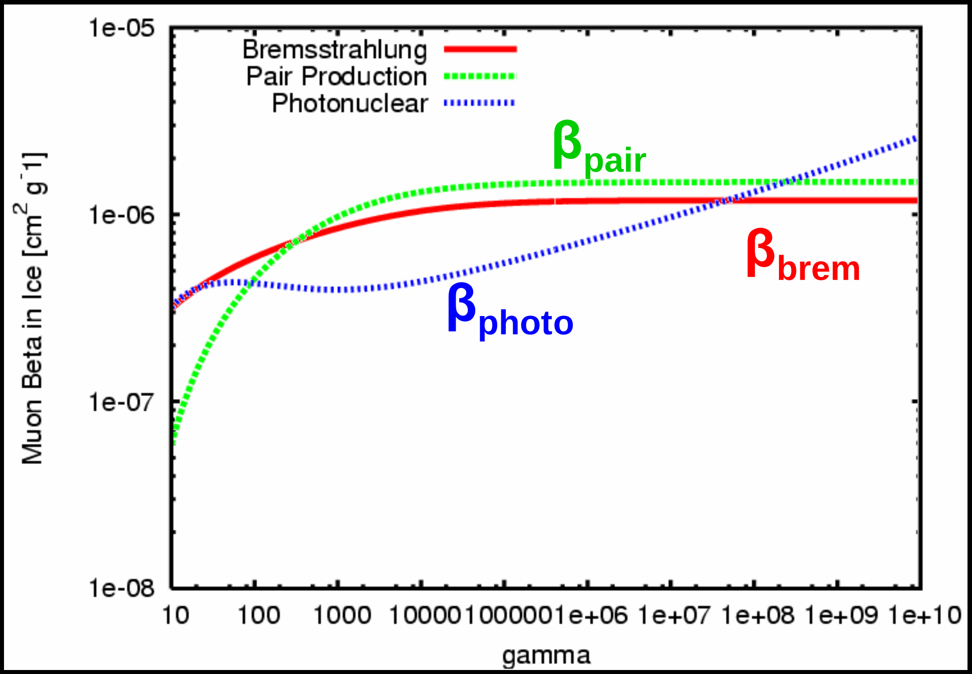
  (1km from S. Pole)
- 16 buried radio receivers in 200m by 200m by 200m area
- Detects Cherenkov radiation in 0.2GHz to 1GHz frequency range
- 2001-2005: No high-energy neutrino detected in 58.3 Msec of livetime.

Kravchenko et al., 2006

A Muon Energy Loss Model

Dutta, Reno, Sarcevic, & Seckel; hep-ph/0012350

$$-\frac{dE}{dx} = \alpha + \beta E$$



α = Ionization Energy Loss

$\beta = \beta_{brem} + \beta_{pair} + \beta_{photo}$

β_{brem} = Fractional energy loss from bremsstrahlung
β_{pair} = Fractional energy loss from pair production
β_{photo} = Fractional energy loss from photonuclear effect

From Muon to Monopole

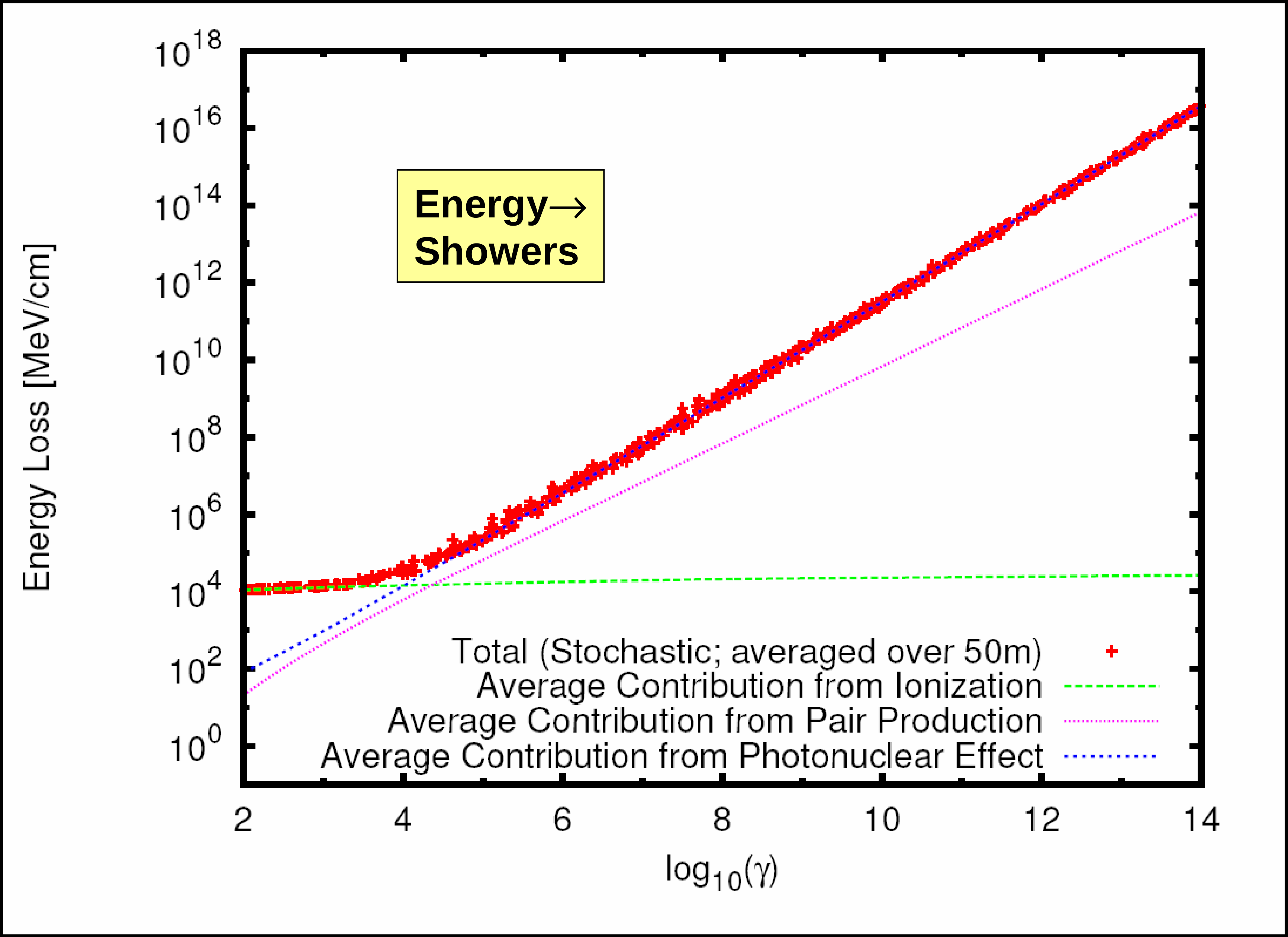
Changes:

- Muon mass → Monopole mass
- Neglect Bremsstrahlung ($dE/dx \propto 1/M$)
- Multiply dE/dx by $z^2 = (68.5)^2$

$$g = \frac{e}{2\alpha} \approx 68.5e$$

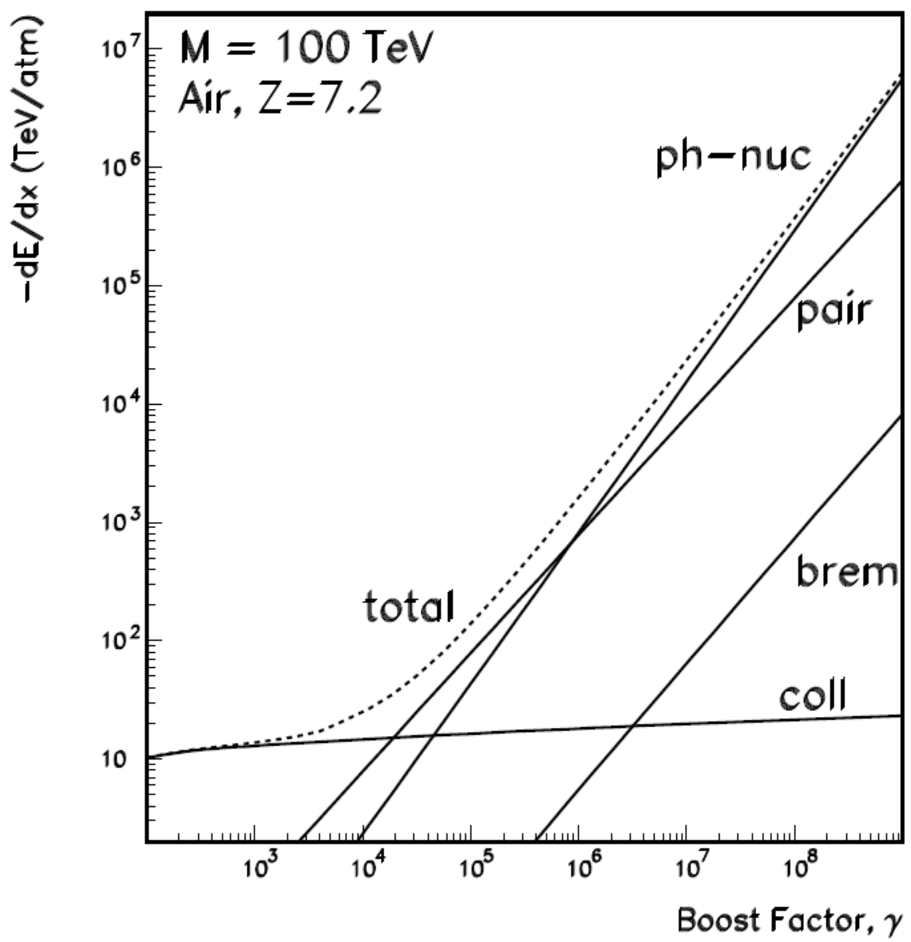
- Model-dependent hadronic interactions ignored

Energy Loss by 10^{16} GeV Monopoles

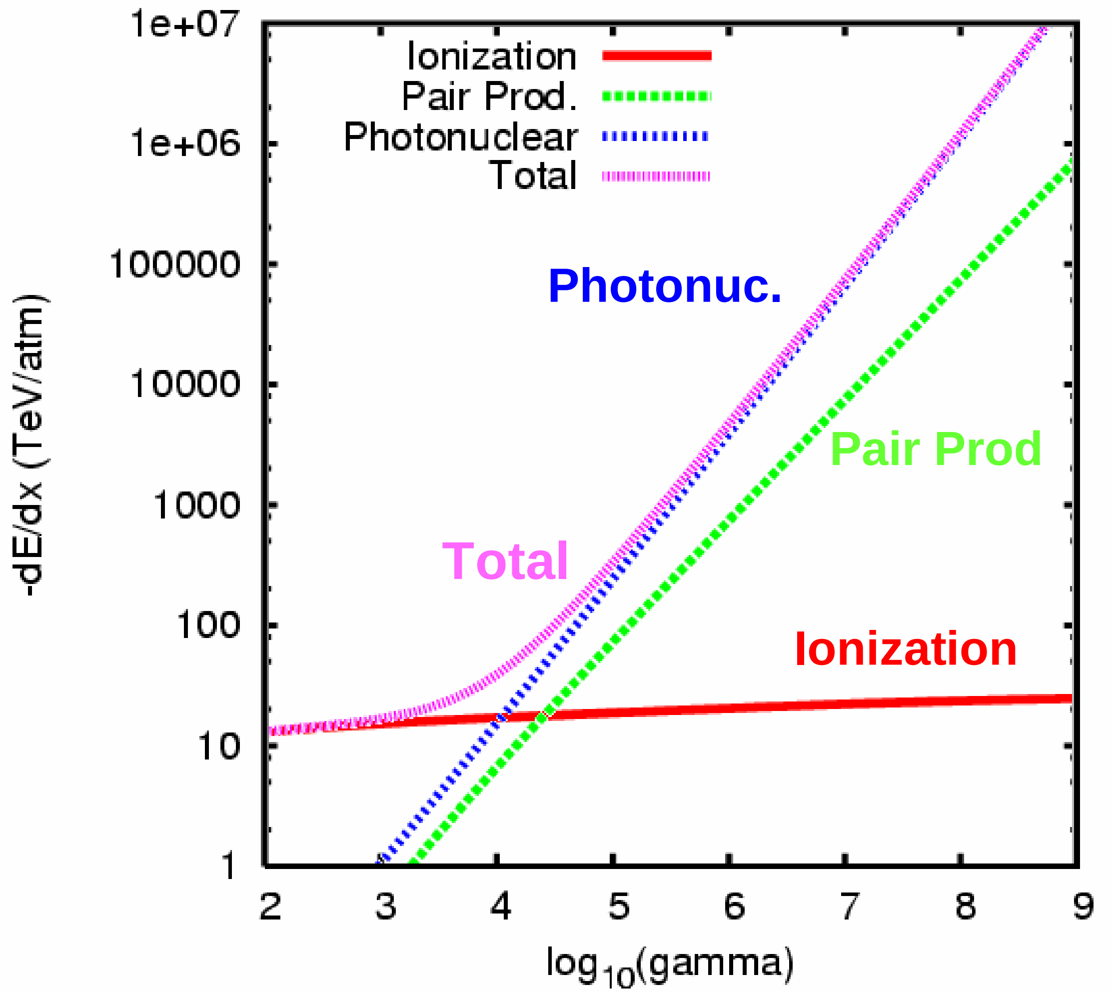


Side Note: Erratum

Wick et al. (2003)



This Work



("Same" photonuclear formula;
slightly different formulae for ionization & pair production.)

Monte Carlo 1: Random Trajectory

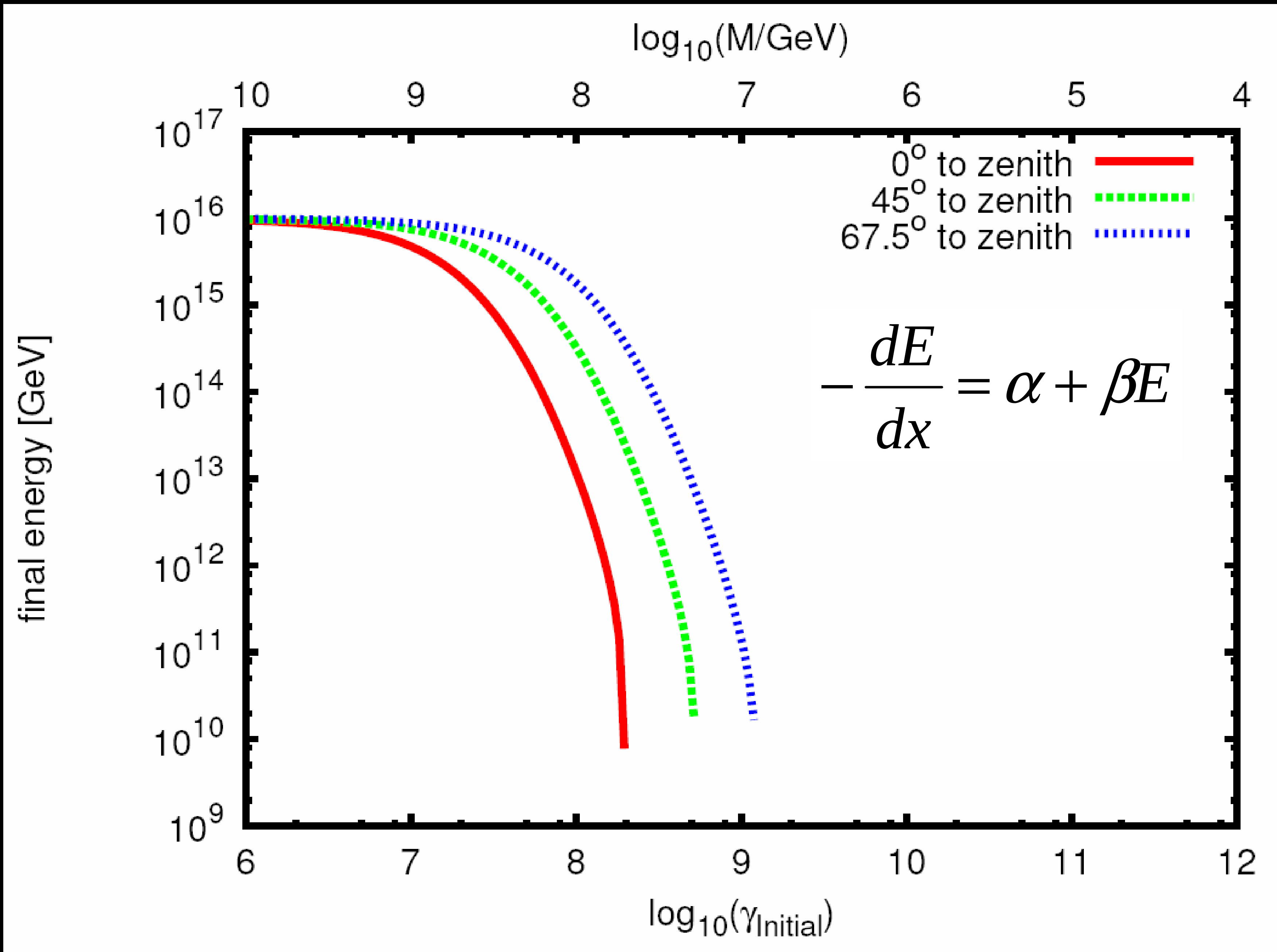
Generate random trajectory within 20km of RICE.

Upgoing:

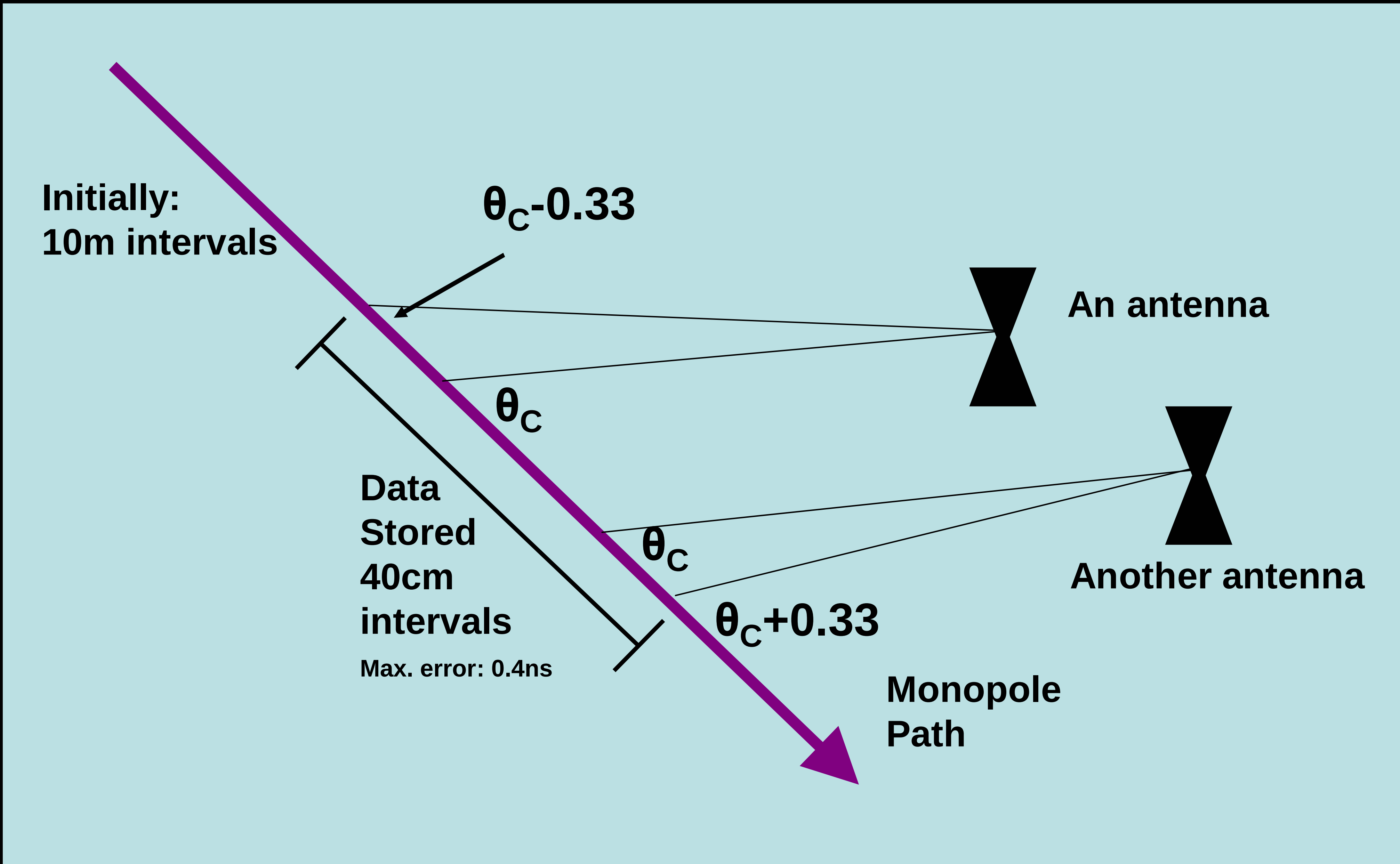
- Propagate monopole through:
  - Distance: column thickness in g/cm^2 from PREM
  - Medium: “standard rock”

Dziewonski & Anderson, 1981

Energy after Crossing Earth



Monte Carlo 2: Passage through Ice



More on Alignment

- 0.33rad = 2σ in Cherenkov angular distribution.

Half width is:

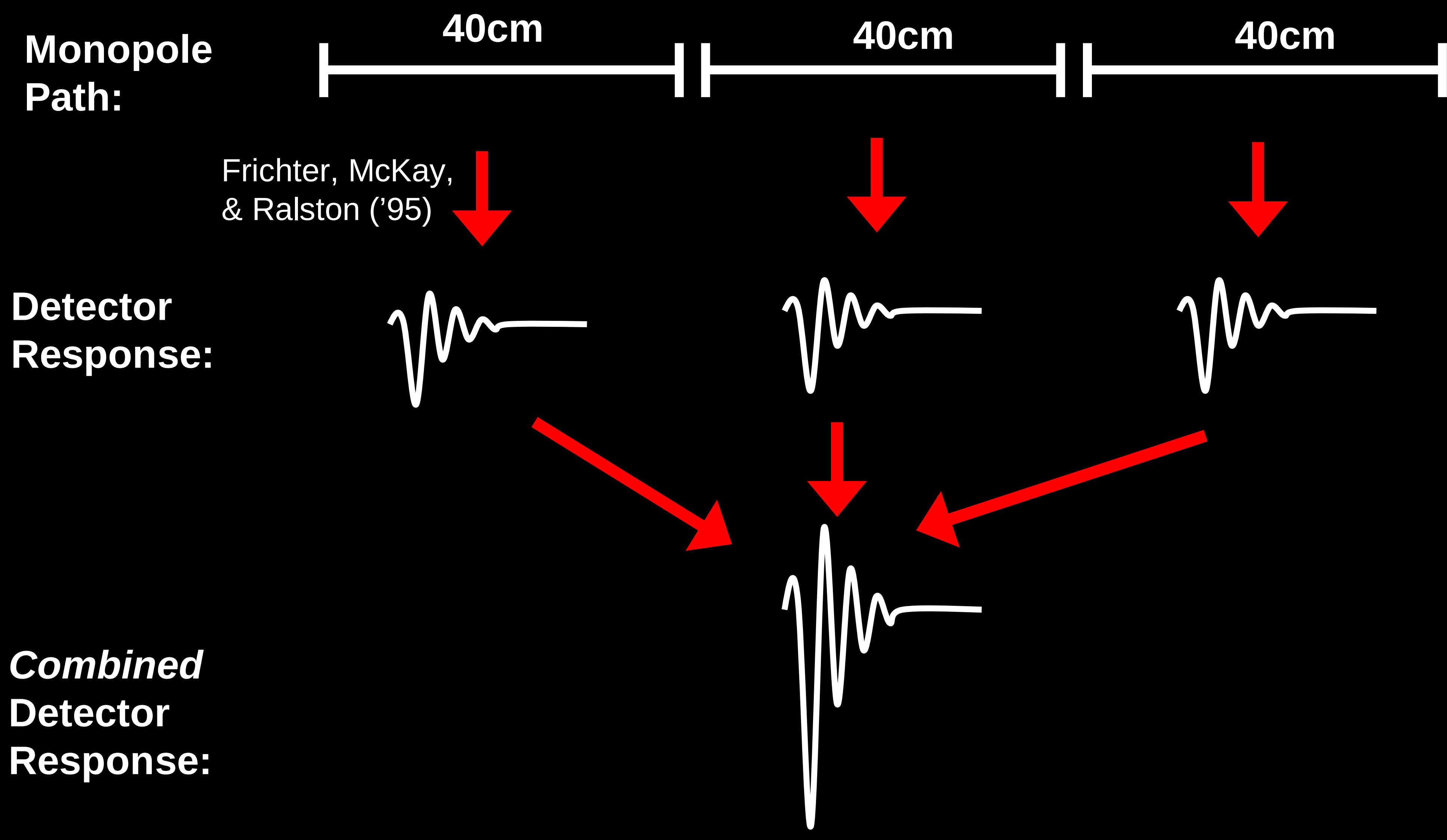
$$\sigma_\theta = 2.2^\circ \left[\frac{1 \text{ GHz}}{\nu} \right].$$

Alvaraz-Muñiz, Vázquez, and Zas, 2000

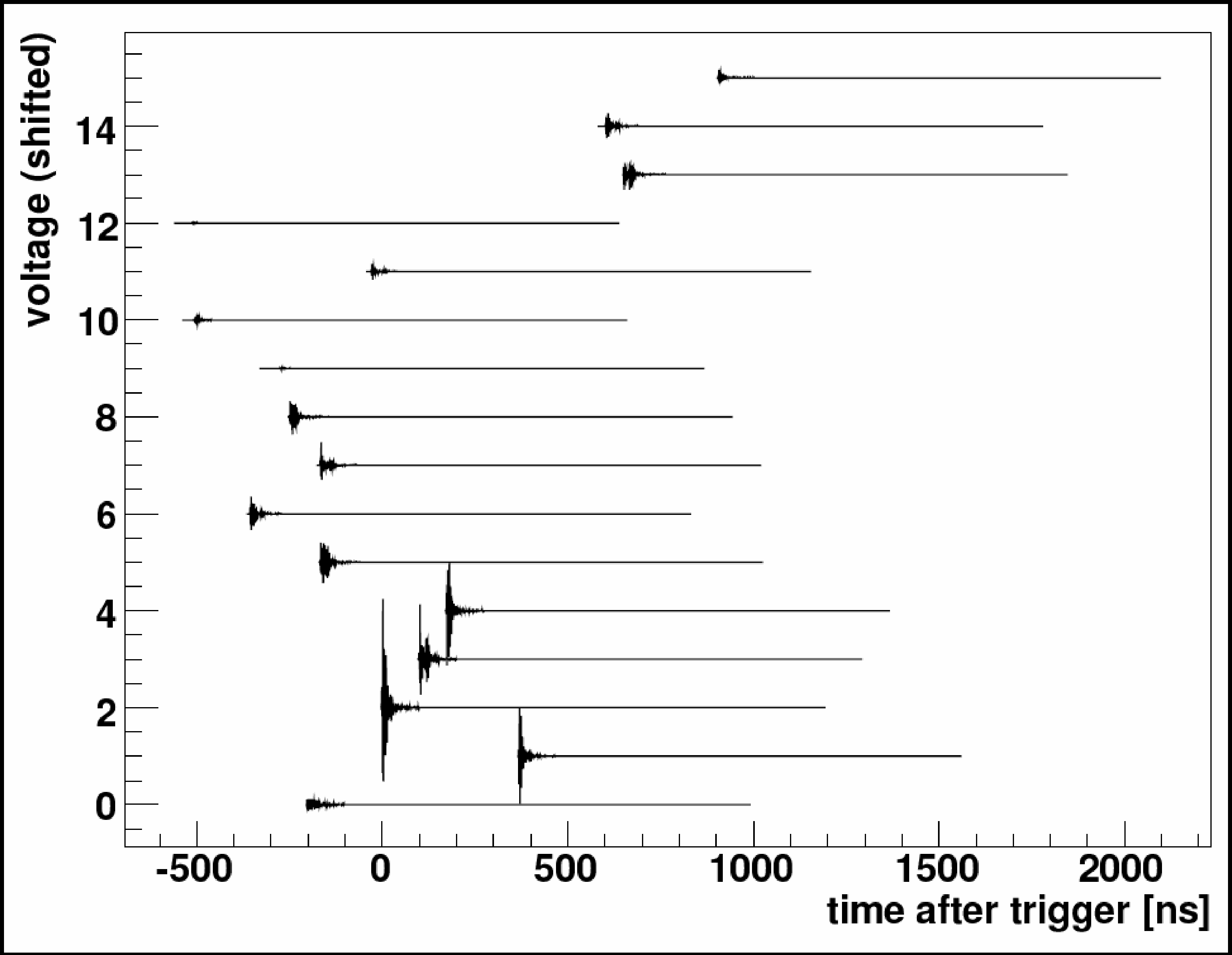
- Start data recording 550m before entering alignment and end 350m after leaving it.
  - Why? To always include first 1.2μs of signal at antennas

Monte Carlo 3: Detector Response

Treat each interval's energy loss as separate shower.



A Typical Voltage Profile



Monte Carlo 4: Analysis Cuts

- Send triggering monopoles through same reconstruction as RICE data.
- Greatest obstacle: Time over threshold cut
- 5% to 50% of events pass

Monte Carlo Corrections (1)

RadioMC

↓ **Remove ray tracing.**

"FriedRice"

Corrections:

- Ignore showers beyond visibility "horizon."
  - Horizon is function of antenna depth & source depth.
- Shift waveforms in time.
  - Based on parameterization of index of refraction in upper 175m of ice

Monte Carlo Corrections (2)

- 20km maximum impact parameter unnecessary.
- Run code once to estimate actual distance distribution of triggering monopoles, then run it again with gamma-dependent maximum impact parameter.

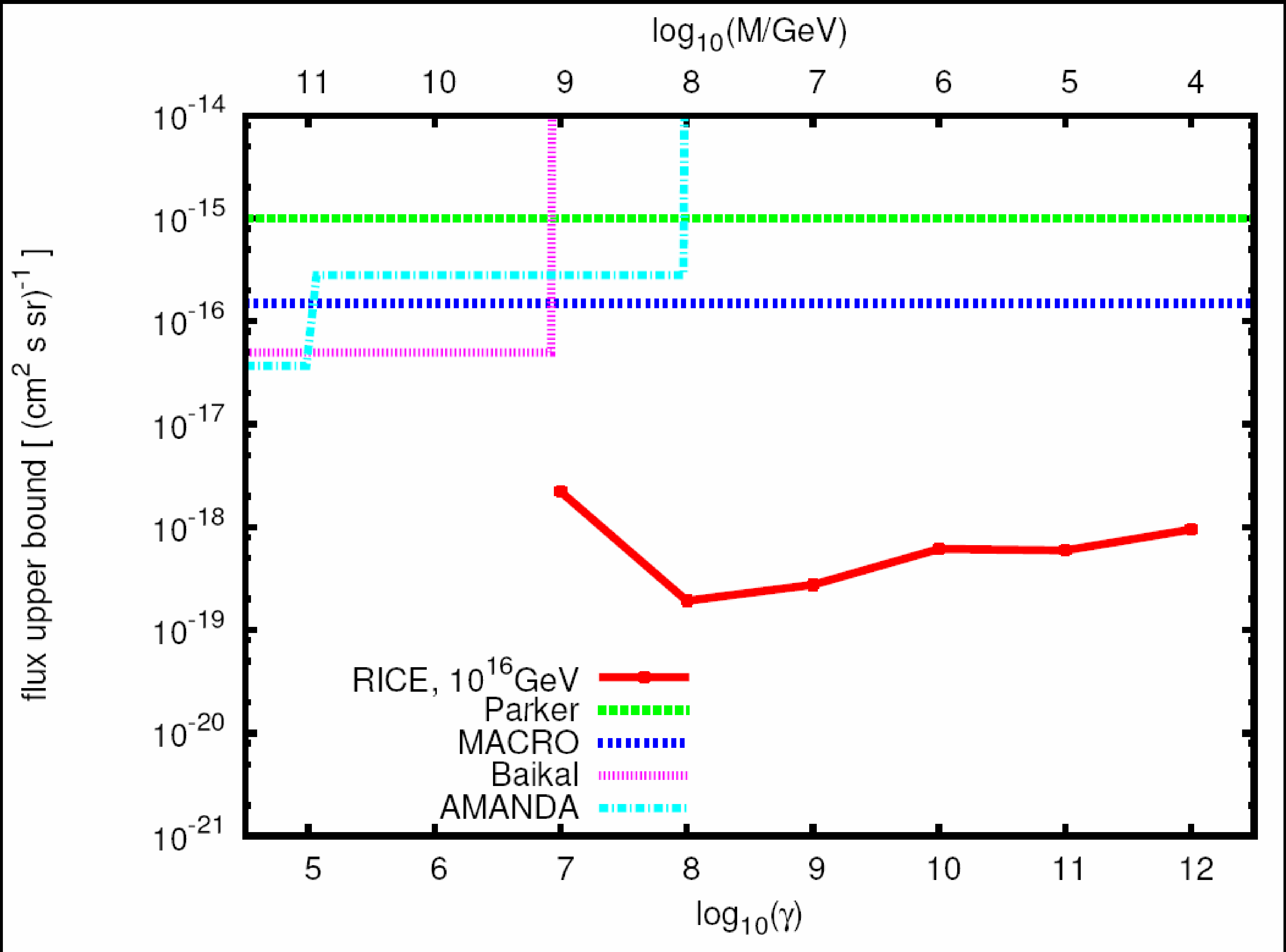
Calculation of Flux

$$\sigma_{eff} = \pi r^2 \cdot \left(\frac{\text{\# Monopoles Detected}}{\text{\# Monopoles Simulated}} \right)$$

$$F_b = \frac{n}{L \Omega \varepsilon \sigma_{eff}}$$

- σ_{eff} = cross-section
- r = maximum impact parameter
- F_b = upper bound on flux
- n=2.996 (gives 95% chance of event)
- L = livetime = 58.3×10^6 s
- $\Omega = 4\pi$
- ε = birefringence factor = .84

Flux Upper Bounds



Error Analysis

- Re-ran simulation at intermediate gamma value (γ=10^{10}) under following conditions:
  - Reduce voltage amplification by factor of 2
  - Reduce attenuation length by factor of 2
  - Add viewing-angle-based phase shifts
  - Increase energy loss by factor 10
- Changes not statistically significant

simulation	#detec.	$\frac{\sigma}{10^9 \mathrm{cm}^2}$
Original	24	6.6
Voltage Amplification Reduction	21	5.7
Attenuation Length Reduction	26	7.3
Signal Phase Shifting	21	5.7
Energy Loss Increase	19	5.0

Summary

- "Light" monopoles become relativistic.
- Monte Carlo shows RICE can detect these.
- Flux upper bounds < 10^{-18} $(cm^2\ s\ sr)^{-1}$

See it now…

arXiv:0806.2129

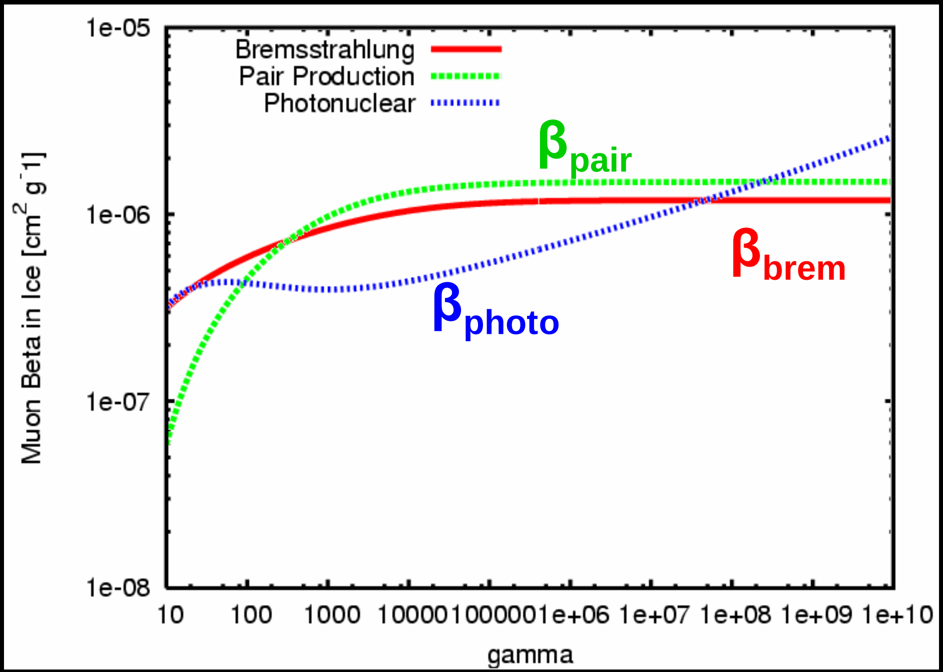
<Extra Slides>

A Muon Energy Loss Model

Dutta, Reno, Sarcevic, & Seckel; hep-ph/0012350

$$-\frac{dE}{dx} = \alpha + \beta E$$

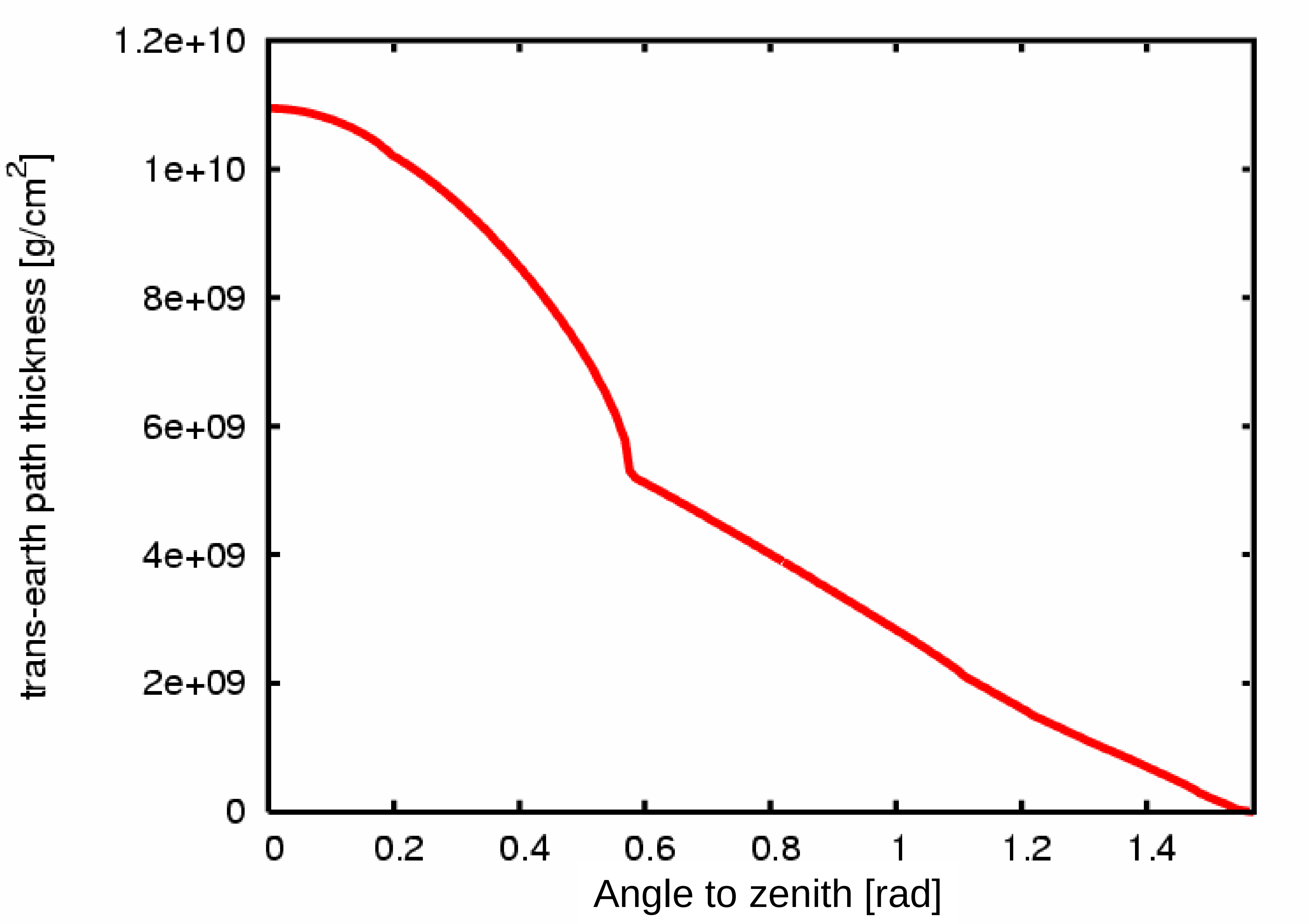
$$\beta = \frac{N}{A}\int_{y_{\min}}^{y_{\max}} y \frac{d\sigma}{dy} dy$$



$$\Delta E = \sum_{y_{\min}}^{y_{\max}} \frac{N}{A}(yE)\left(\Delta x \frac{d\sigma}{dy}\right)\Delta y$$

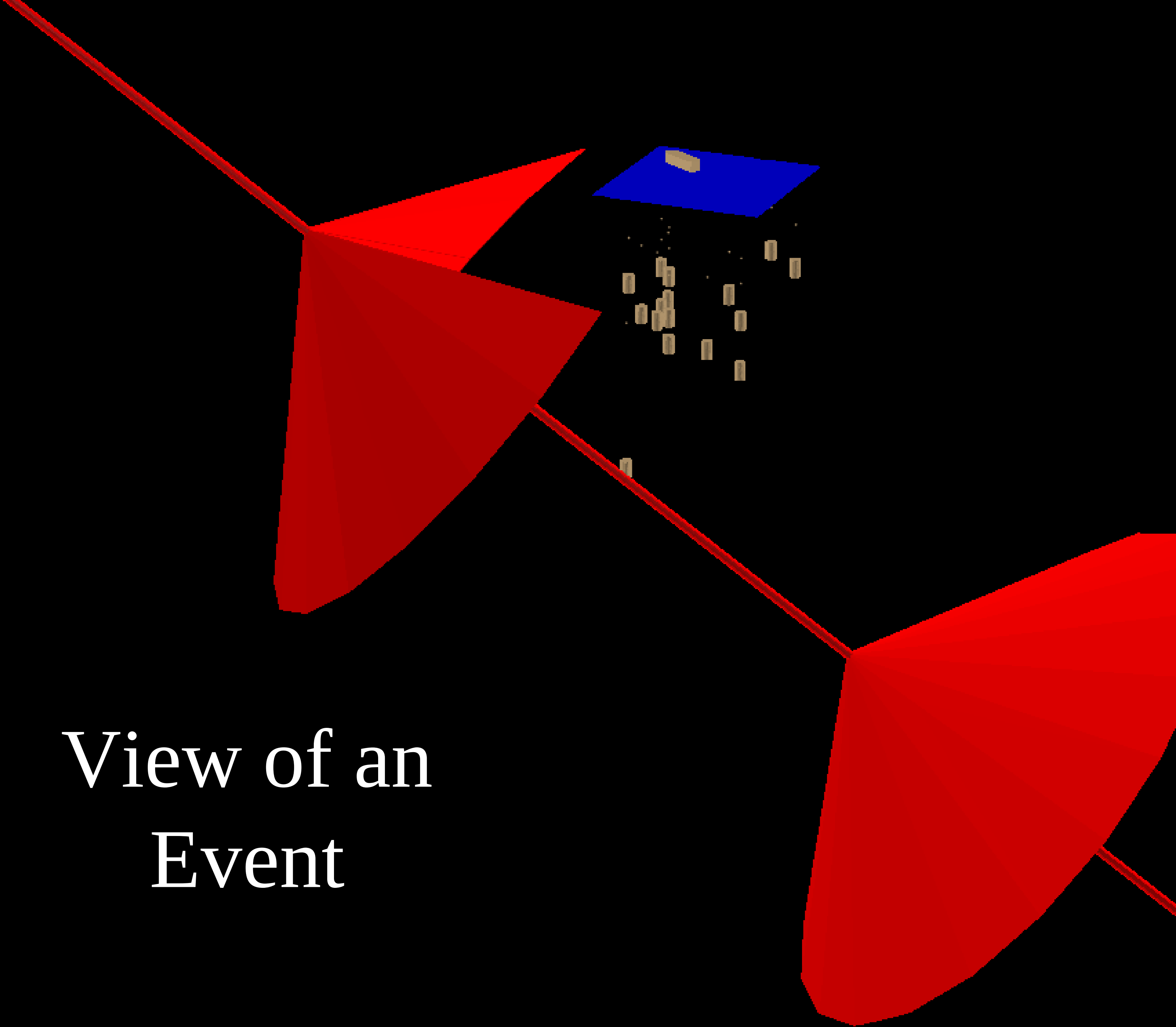
$$\langle n \rangle = \frac{N}{A}\Delta x \frac{d\sigma}{dy}\Delta y$$

Thickness of Earth



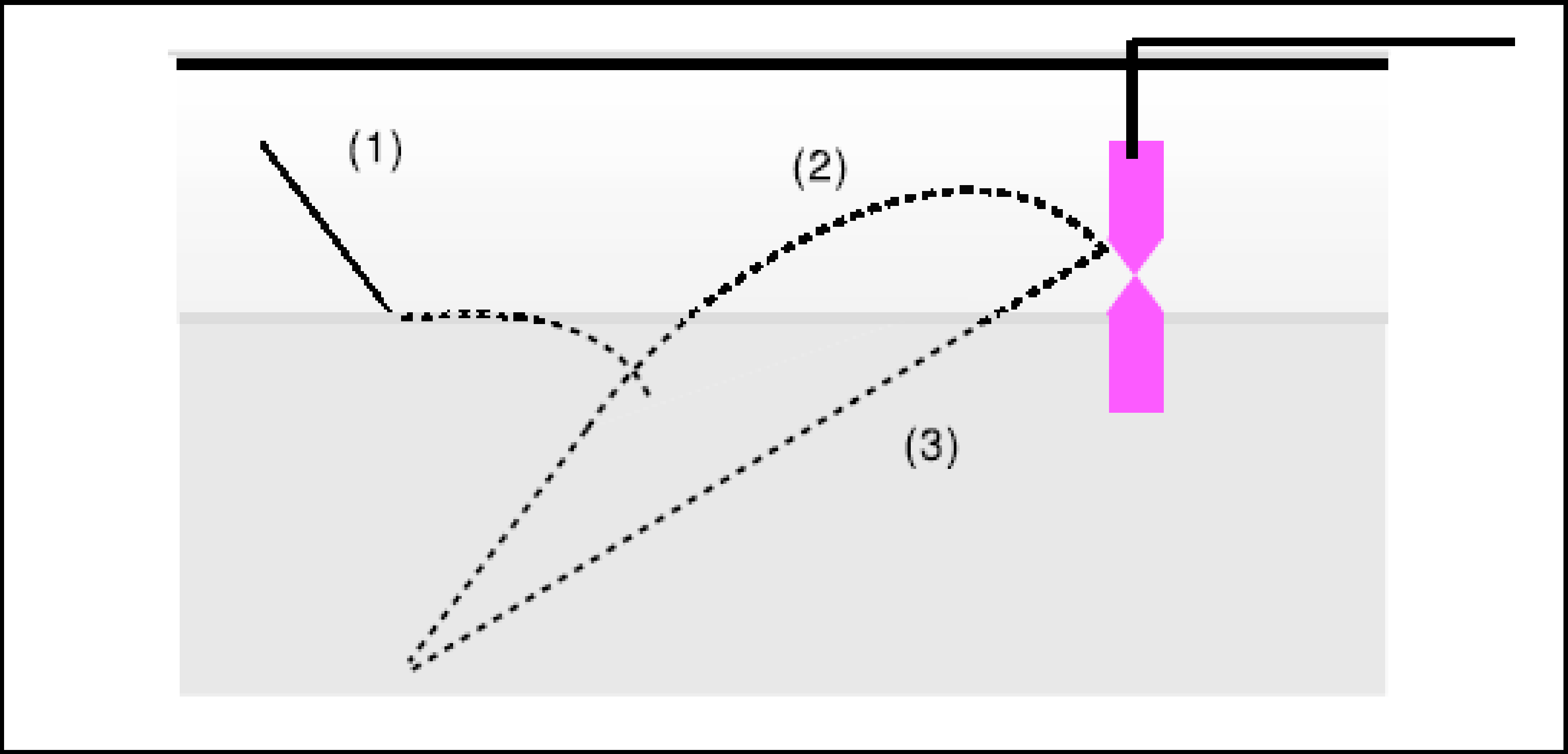
MC Simulation Results

$\log_{10}(\gamma)$	$\log_{10}(\frac{\text{mass}}{\text{GeV}})$	#sim.	r_m / km	#detec.	$\frac{\sigma}{10^9\text{cm}^2}$	$\frac{\text{flux bound}}{10^{-19}(\text{cm}^2\text{ s sr})^{-1}}$
6	10	1×10^4	3	0	<0.073	>560
7	9	1×10^4	3	90	1.8	22
8	8	1×10^4	5	342	21	1.9
9	7	1×10^4	10	67	15	2.8
10	6	1×10^4	12	24	6.6	6.2
11	5	1×10^4	14	19	6.8	6.0
12	4	1×10^4	14	13	4.3	9.5



View of an Event

Ray Tracing

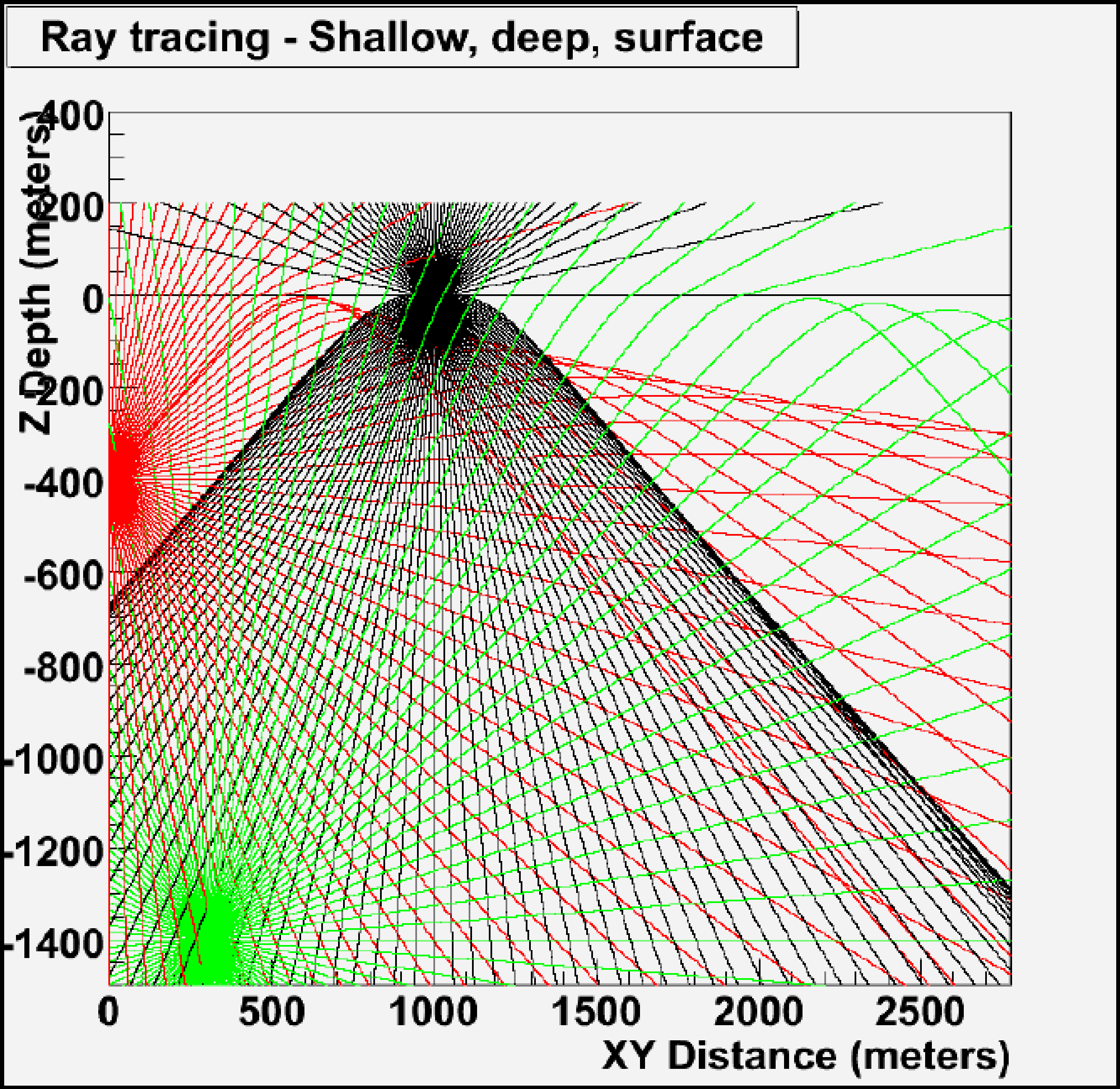


RICE Software Cuts

(Table from RICE 2006 paper.)

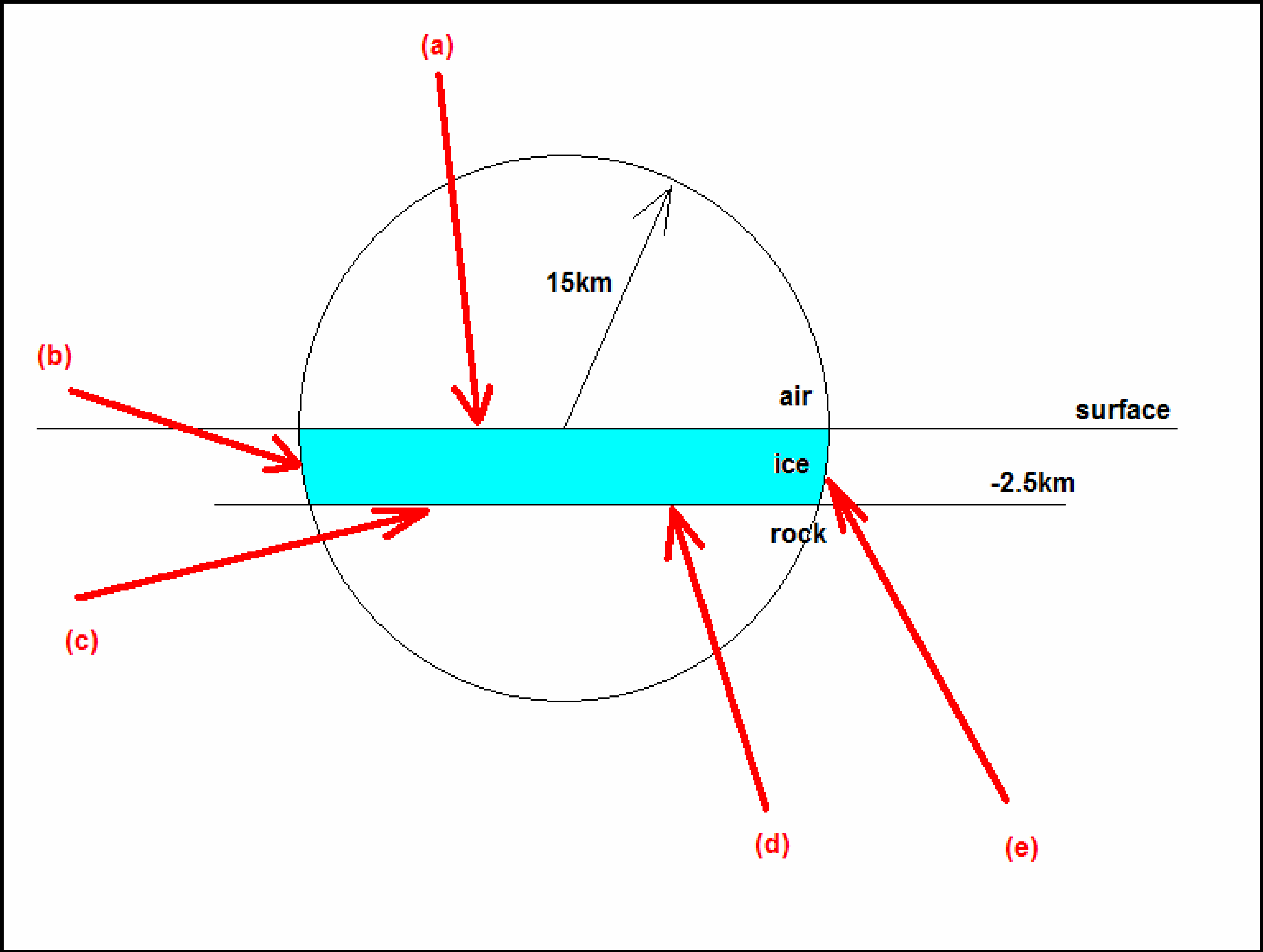
Selection Requirement	MC (%) EM showers	MC (%) Had shower	Data (%)
1) Initial sample	100	100	100
2) Acceptable Time-Over-Threshold (TOT):	100	100	39.341
3) ≥4 $5\|\sigma_{rms}\|$ hits:	100	100	33.223
4) ≥4 $6\|\sigma_{rms}\|$ hits:	100	100	16.842
5) Double-Pulse Rejection:	99.3	99.0	16.053
6) High quality 3-d vertex:	99.3	98.6	15.657
7) Vertex depth below firn:	89.9	92.8	1.119
8) Acceptable Total Time residuals:	86.5	90.1	0.927
9) Passing tighter Time-Over-Threshold:	84.0	86.0	0.919
10) ≤2 hits with large Time residuals:	82.2	83.0	0.855
11) Acceptable Spatial residuals:	81.3	79.4	0.190
12) Satisfying Cherenkov geometry:	74.9	72.1	0.038
13) ≥5 $6\|\sigma_{rms}\|$ **hits:**	67.4	66.2	0.031

Ray Tracing



Ray tracing - Shallow, deep, surface
Z Depth (meters)
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
0
500
1000
1500
2000
2500
XY Distance (meters)

The Setup



Could there be lighter monopoles?

- "Intermediate Mass Monopoles" (IMM's)
  - 10^8 GeV? ($\gamma \sim 10^8$) (Frampton & Lee, 1990)
  - 10^5 GeV? ($\gamma \sim 10^{11}$) (Frampton, 1990)

- Previous experiment
  - Search for Light Magnetic Monopoles (SLIM)
  - Seeks monopoles from 10^5 GeV to 10^{12} GeV
  - Current Limit: 2.76×10^{-15} $cm^{-2}s^{-1}sr^{-1}$
    - (MACRO: 1.4×10^{-16} $cm^{-2}s^{-1}sr^{-1}$)

Selected Sources

- RICE MC: I. Kravchenko *et al*. (RICE Collaboration), Phys. Rev. **D63**, 094020 (2001)
- Neutrino Flux Limits: I. Kravchenko *et al*. (RICE Collaboration), Phys. Rev. **D73**, 082002 (2006)
- PREM: A.M. Dziewonski and D.L. Anderson, Phys. Earth Planet In. **25**, 297 (1981)
- IMMs: S.D. Wick, T.W. Kephart, T.J. Weiler, and P.L. Biermann, Astropart Phys. **18**, 663 (2003)
- Muon Model: S.I. Dutta, M.H. Reno, I. Sarcevic, and D. Seckel, Phys. Rev. **D63**, 094020 (2001)
- MACRO: M. Ambrosio *et al*. (MACRO Collaboration), Eur. Phys. J. **C25**, 511 (2002)

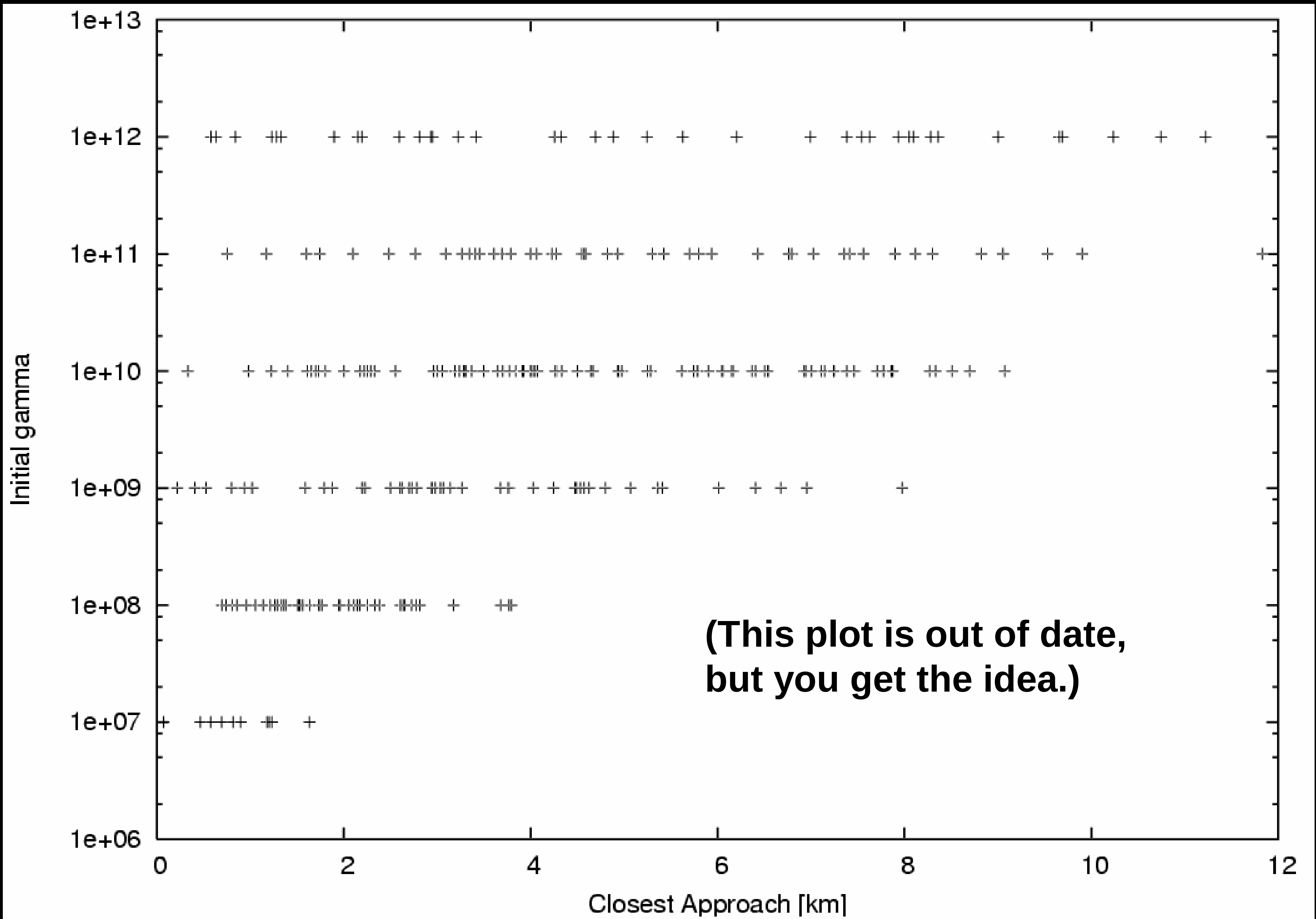
Magnetic Monopole Overview
Sources

- P.A.M. Dirac, Proc. Roy. Soc. London **A133**, 60 (1931)

- Gut Scale Monopoles ~ 10^{17} GeV
  - Diluted by inflation: A.H. Guth, Phys. Rev. **D23**, 347 (1981)

- “Intermediate Mass Monopoles” (IMM’s)
  - 10^8 GeV: P.H. Frampton and B. Lee, Phys. Rev. Lett. **64**, 619 (1990)
  - 10^5 GeV: P.H. Frampton, Phys. Rev. D60, 121901 (1999)

Distance Distribution



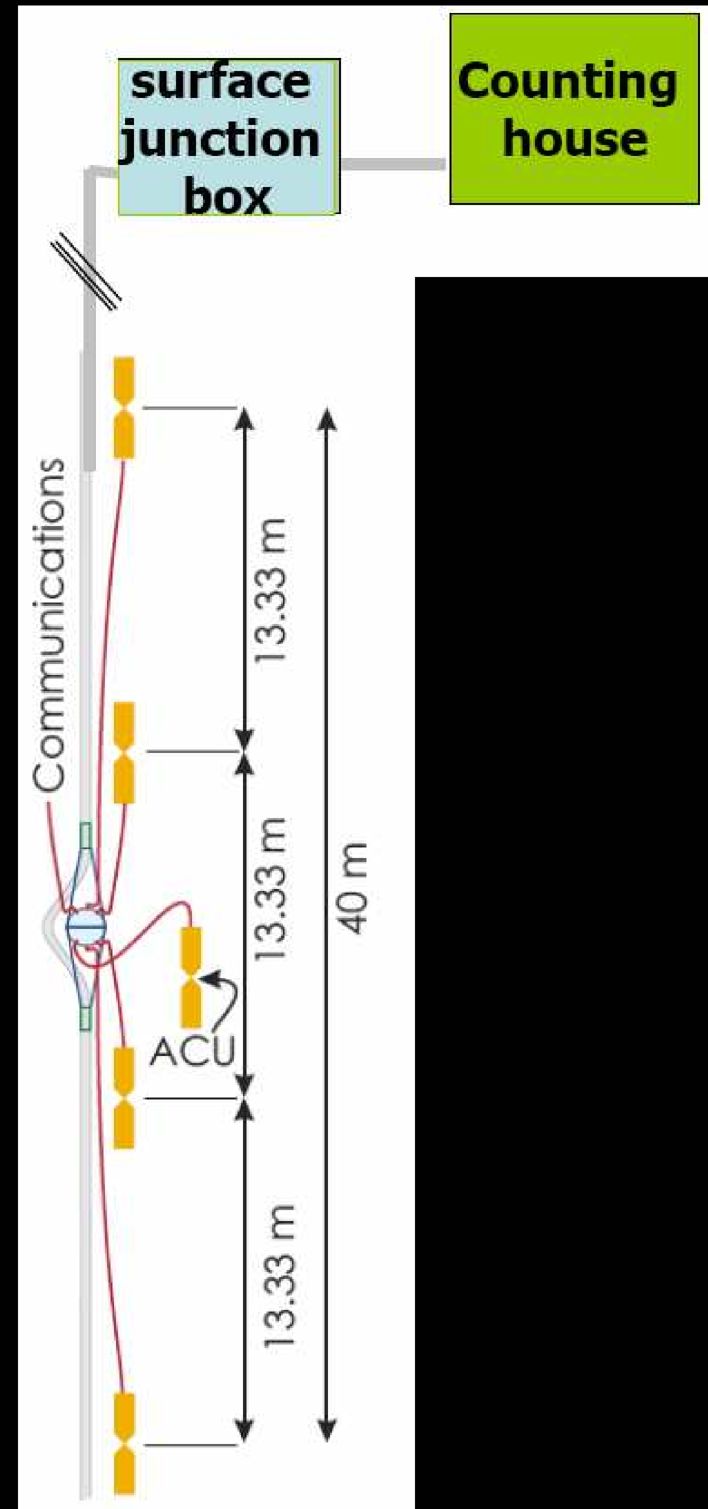
<AURA Overview>

The Next Step…

- AURA = Askaryan Under-ice Radio Array
- Goal: Take advantage of IceCube construction to implement next-generation radio neutrino telescope.

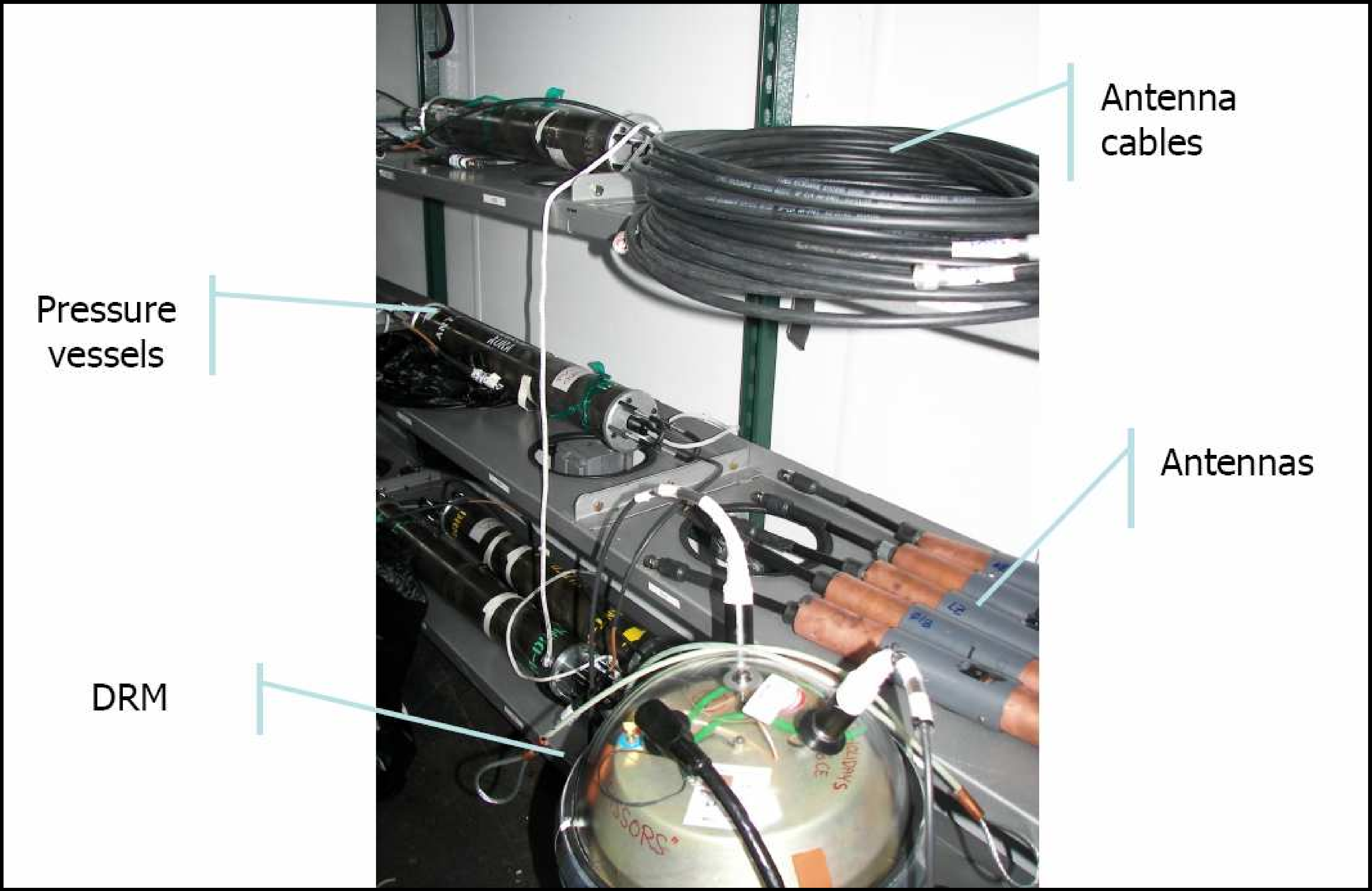
AURA Radio Clusters

- Make use of existing technology: deep holes, IceCube communications and power
  - Digital Radio Module (DRM) – Electronics
  - 4 Antennas
  - 1 Antenna Calibration Unit (ACU)
- Signal conditioning and amplification happen at the front end; signal is digitized and triggers formed in DRM.
- A cluster uses standard IceCube sphere, DOM main board, and surface cable lines.



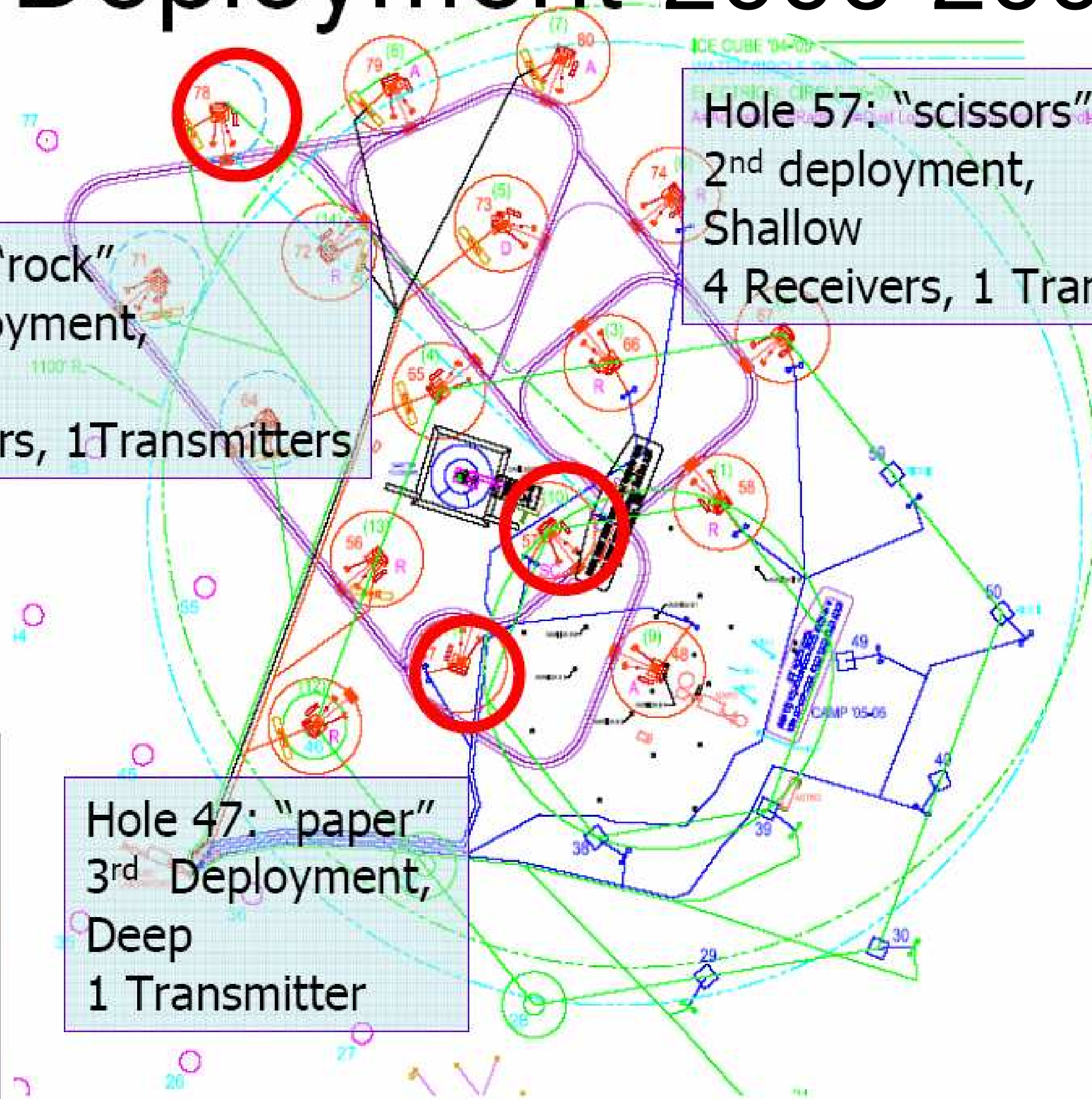
Slide Credit: Hagar Landsman

Waiting to be Deployed



Slide Credit: Hagar Landsman

Deployment 2006-2007



Hole 78 :"rock"
1st deployment,
Deep
4 Receivers, 1Transmitters

Hole 57: "scissors"
2nd deployment,
Shallow
4 Receivers, 1 Transm

Hole 47: "paper"
3rd Deployment,
Deep
1 Transmitter

Slide Credit: Hagar Landsman

Calibration / Characterization

- 2 full clusters (+3rd transmitter) in ice now.

- 3 more being lab-tested at U. Wisconsin & U. Kansas, to be deployed this Antarctic summer (possibly).

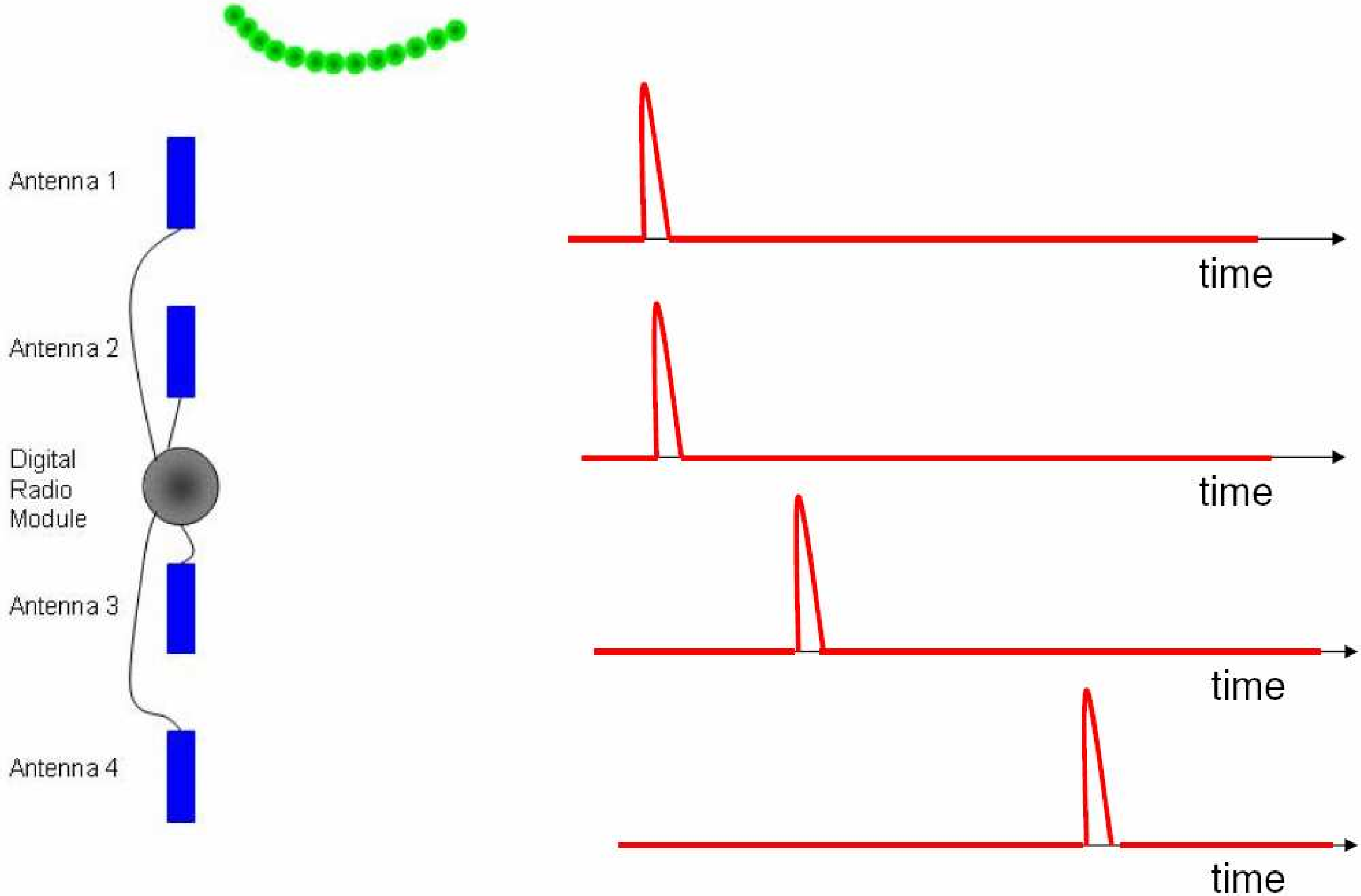
<More AURA Slides>

RF Signal

- Antennas:
  - Broad band dipole antennas
  - Centered at 400 MHz
- Front-end Electronics:
  - 450 MHz Notch filter
  - 200 MHz High pass filter
  - ~50dB amplifiers (+20 dB in DRM)
- LABRADOR Digitizer
  - Each antenna sampled with two 1GHz channels

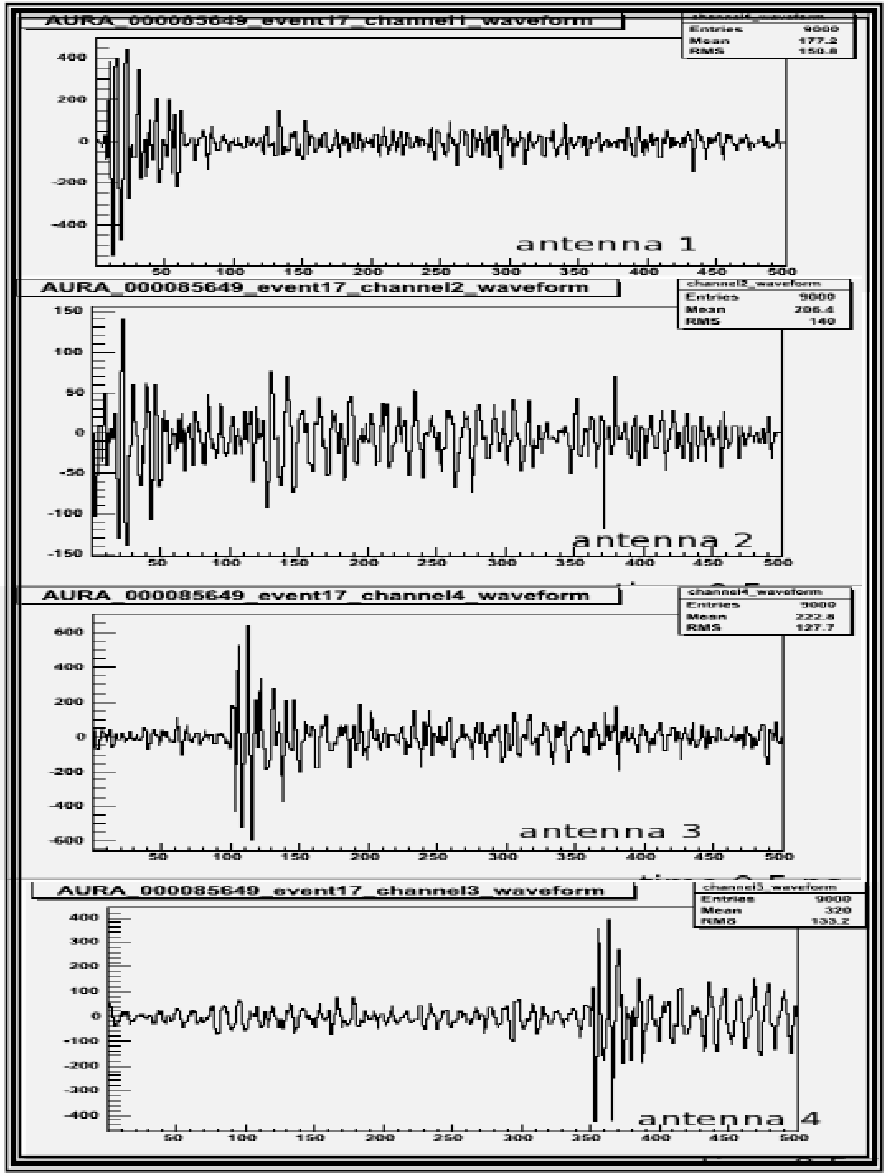
Slide Credit: Hagar Landsman

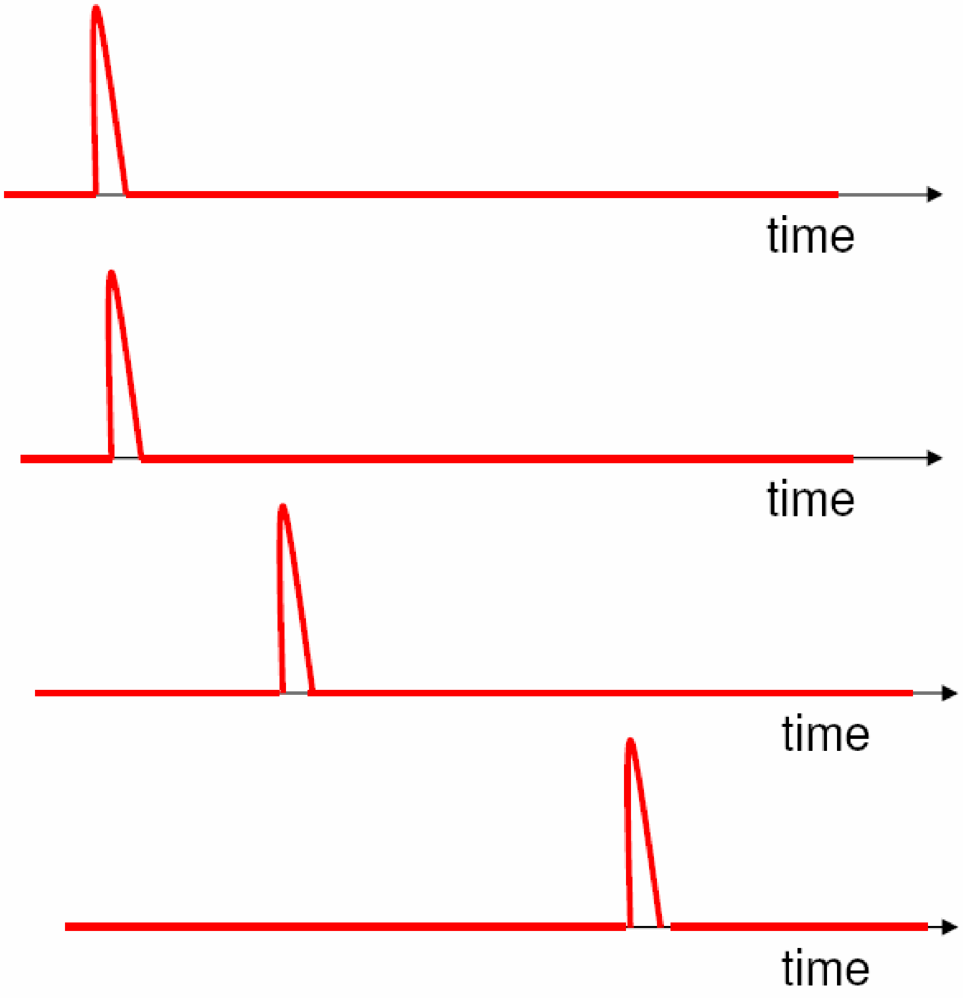
Down going event signature



Slide Credit: Hagar Landsman

Down going event candidate





Slide Credit: Hagar Landsman

Vertexing Ability