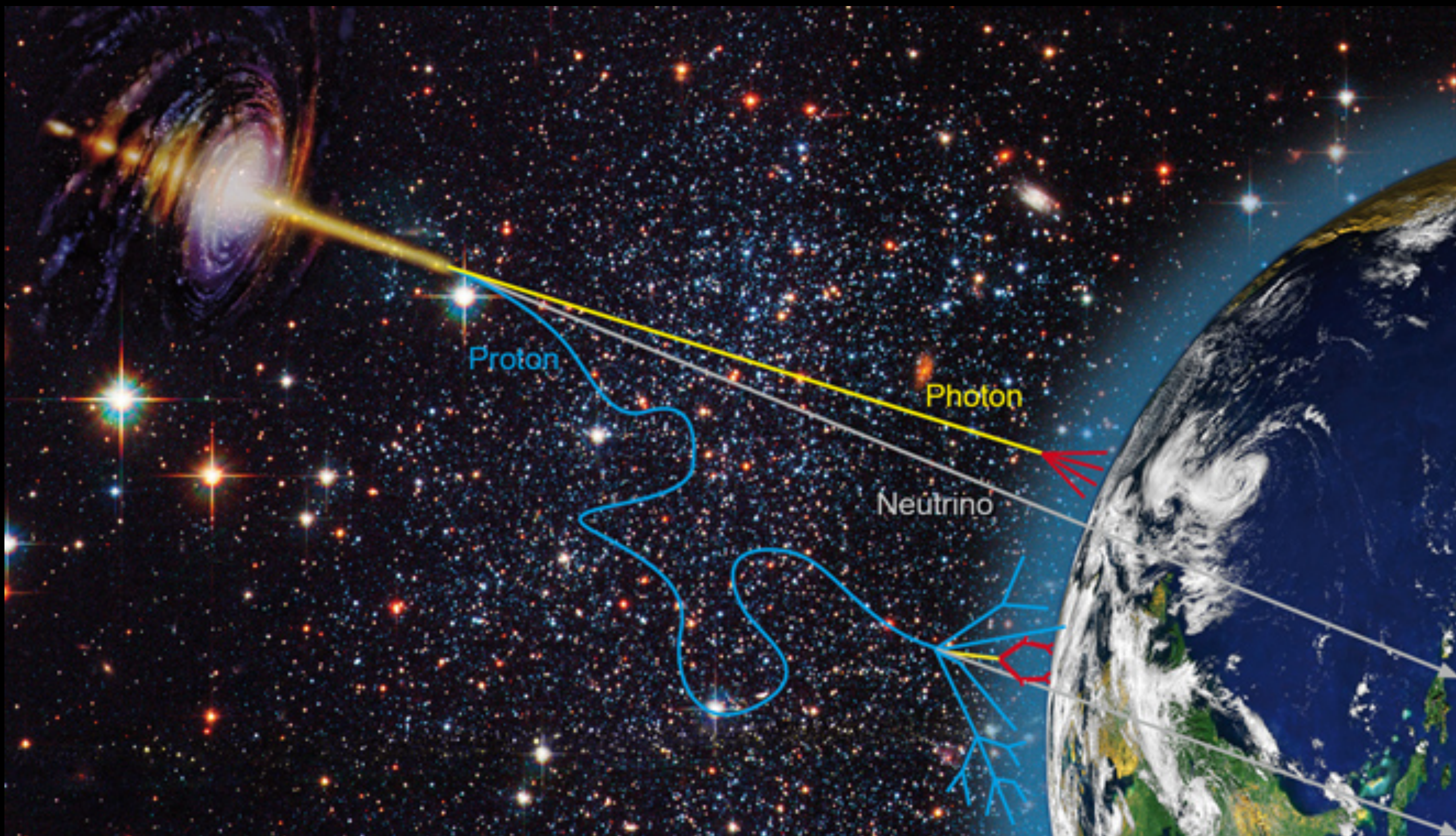
Triggers and Thresholds in High-Energy Neutrino Astrophysics

Brian Clark

Department of Physics
The Ohio State University

PGSC Graduate Summer Talk

June 28, 2016


Proton
Photon
Neutrino

Studying Neutrinos

Dual Motivation

- **Astrophysics: Neutrinos are the only probes of the highest energies at cosmic distances (>100 MPc)**
  - Cosmic rays attenuated by Greisen-Zatsepin-Kuz'min effect:

$$\text{EX: } p + \gamma \rightarrow n(p) + \pi^+(\pi^0)$$

  - Gamma rays annihilate on ambient photons
- **Particle Physics: Probe physics at above LHC energies**

Hard to Study: Rare and Weakly Interacting

- **Neutrinos have low fluxes and low cross sections**
- Example: model for EeV neutrinos from the Berezinsky-Zatsepin flux

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

  - ~10 $\nu/km^2/yr$ *arrive* at earth
  - But, low cross sections: $\sigma = 10^{-31} cm^2$
  - So $< 5\times10^{-2}$ $\nu/km^3/yr$ *interact* in ice ($\rho = 0.9\ g/cm^3$)

Conclusion: Need enormous volumes of detector

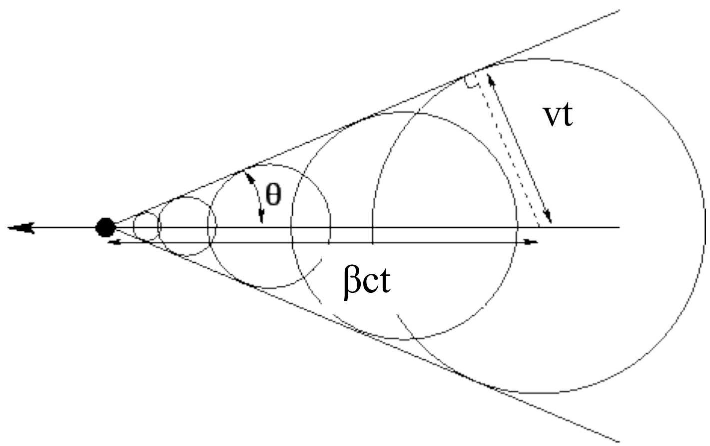
Neutrino Interactions

- Two varieties of interactions: Charged current (CC) and Neutral Current (NC)

CC: $\nu_\ell + N \rightarrow \ell + X$ NC: $\nu + N \rightarrow \nu + X$

$\ell \rightarrow EM\ Shower$ $X \rightarrow Hadronic\ Shower$

- Products are ultra-relativistic ($\beta \approx 1$) and emit Cherenkov radiation if they interact in dense dielectric media (i.e., water, ice)
- Intensity is greatest at Cherenkov angle θ_C

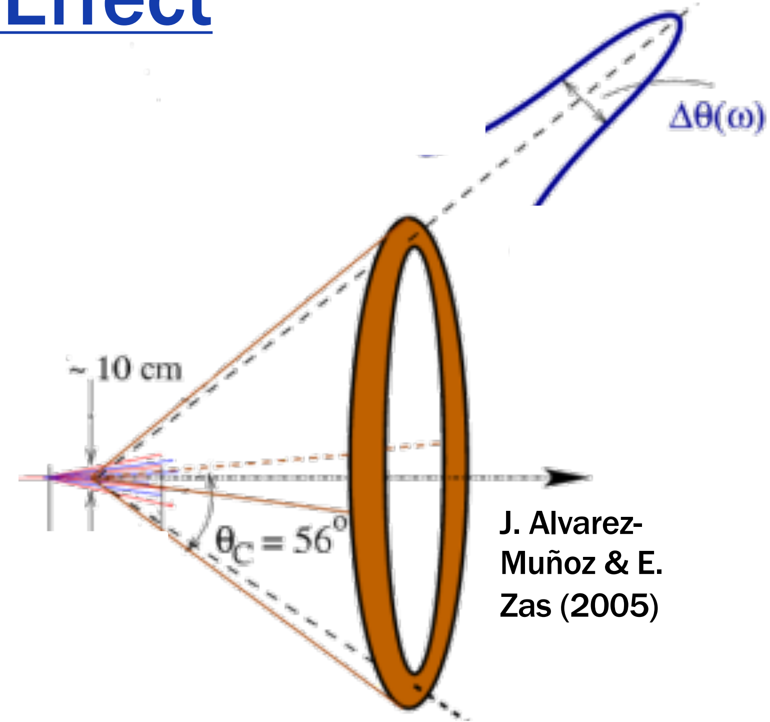


$$\cos\theta_C = \frac{1}{n\beta}$$

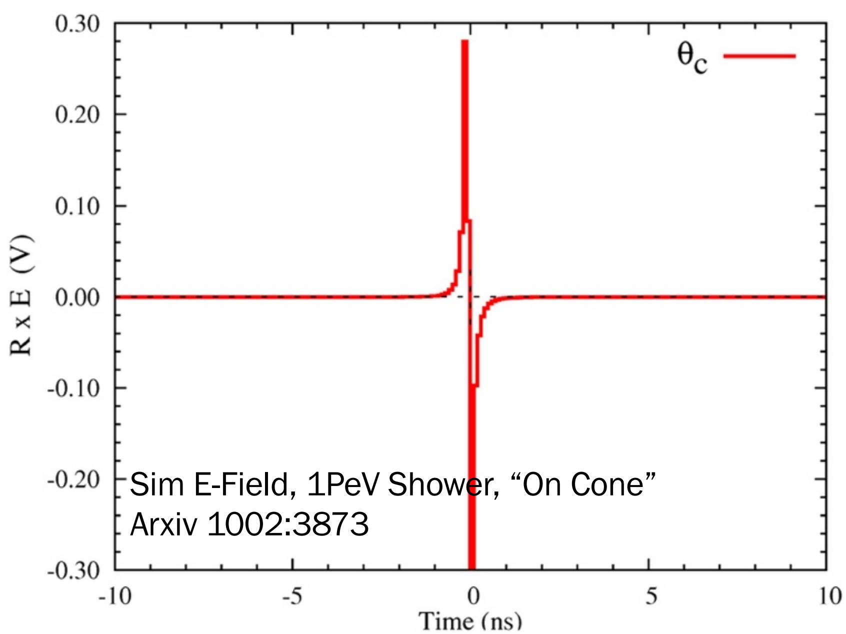
- Two types of Cherenkov radiation of interest: Optical and Radio

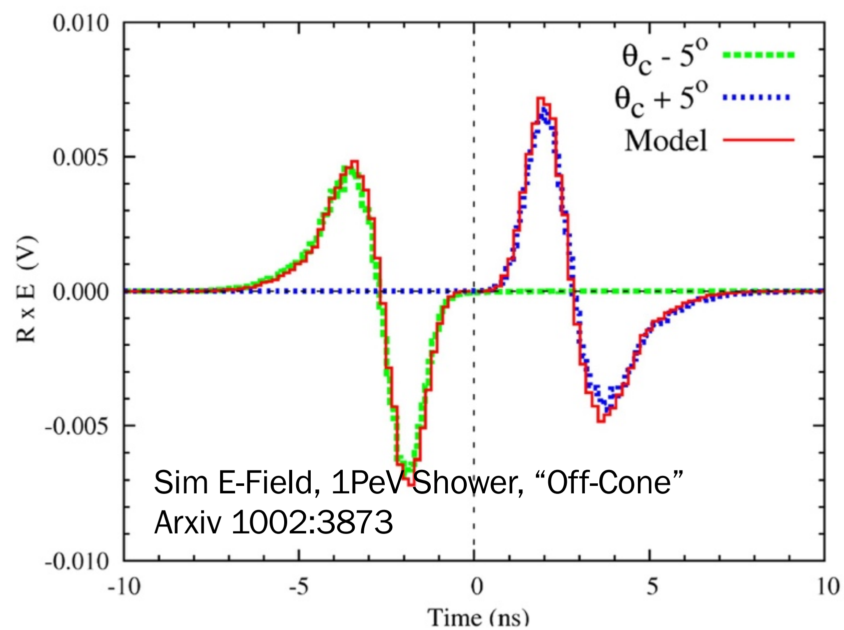
Radio Cherenkov Effect

- The ν-N showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add *coherently*
- Broadband (200 MHz ⟶ 1.2GHz) radio *pulse*
- Conical emission (57° in ice); strongest on cone



J. Alvarez-Muñoz & E. Zas (2005)





ANITA and ARA

Design Idea: Observe *radio* Cherenkov light from ν-N interactions

ANtarctic Impulsive Transient Antenna-2

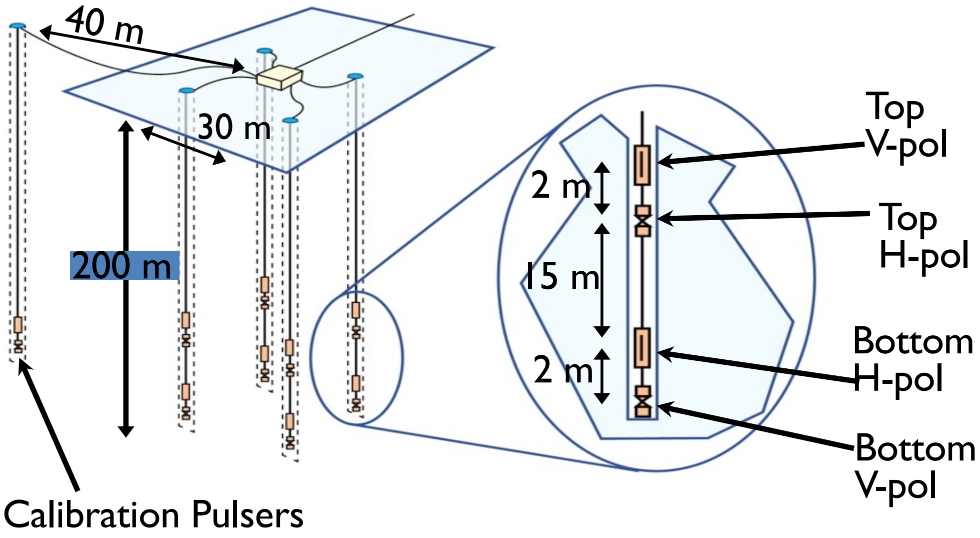
- Array of 40 dual polarized antennas (100-1200 MHz bandwidth)
- Flown by NASA balloon; altitude 40 km
- Observes 10^6 km^2 of ice
- Energy range: is $10^{18} \rightarrow 10^{21+}$ eV

Askaryan Radio Array

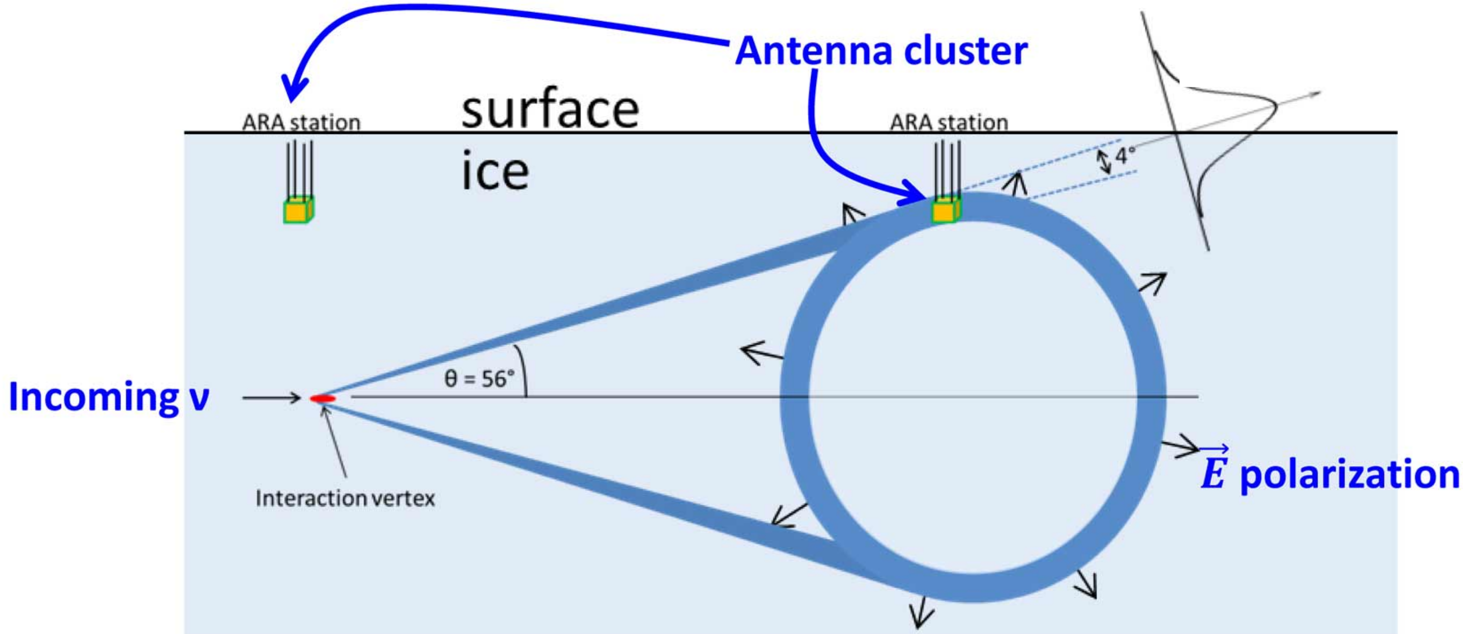
- Array of 16 antennas (8 vpol, 8 hpol, 200-850 MHz bandwidth)
- Buried in cubical lattice at 200m depth
- ARA37 observes 10^2 km^2 of ice
- Energy range: $10^{16} \rightarrow 10^{19}$ eV

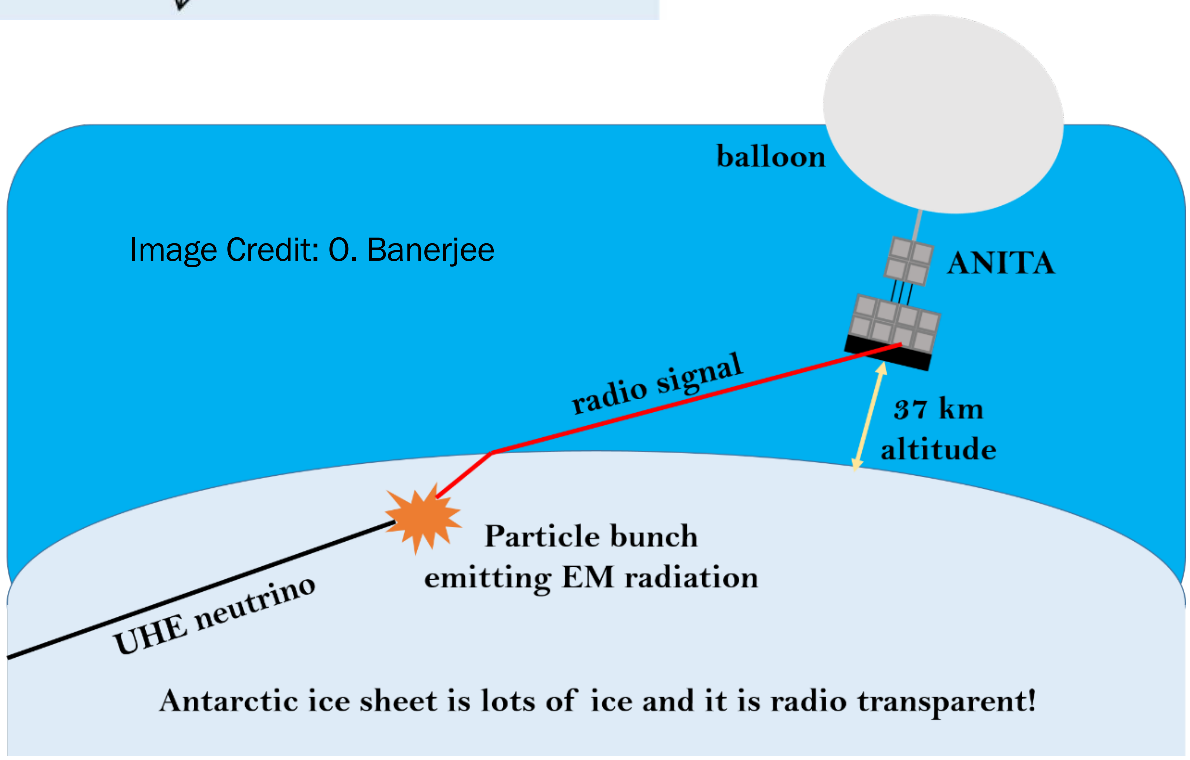
Backgrounds

- Radio blackbody (thermal) emission of ice
- Continuous wave (CW) sources: satellites, radios, …
- Electromagnetic interferences: lighters, static discharge, …



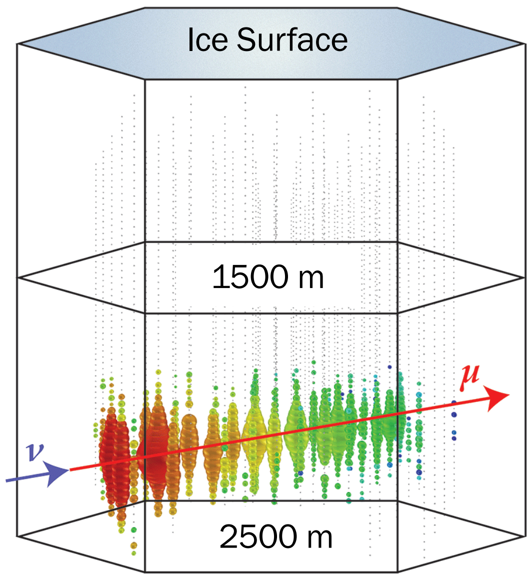
ARA and ANITA Detector

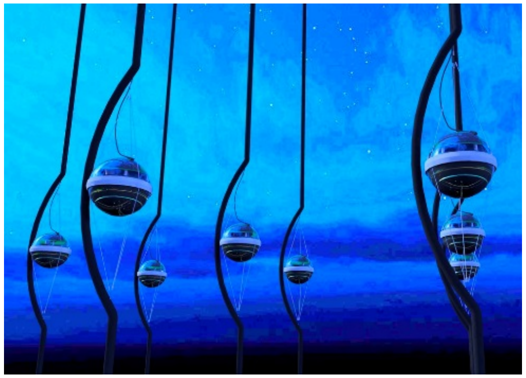




IceCube

Design Idea: Observe *optical* Cherenkov light from ν-N interactions



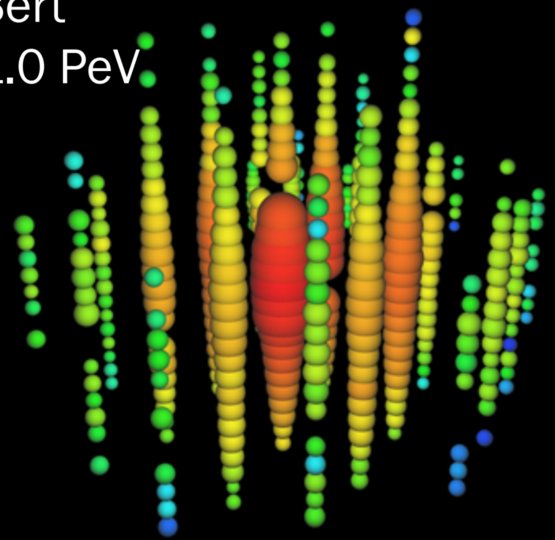


Hardware Highlights

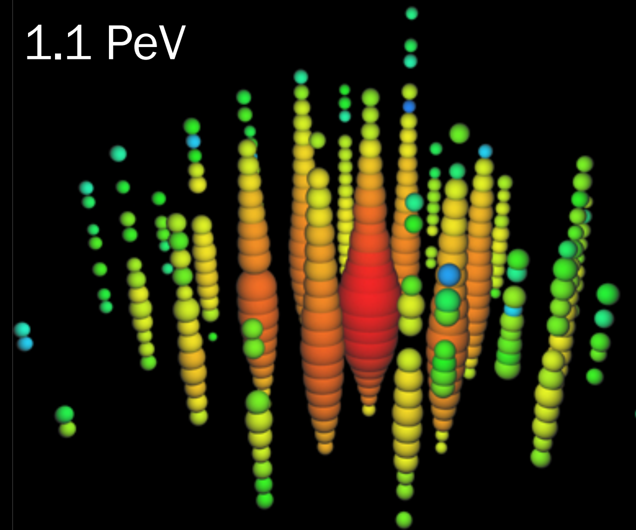
- 5160 photo-multiplier tubes (PMTs) buried in the Antarctic Ice
- **PMT + electronics = Digital Optical Module (DOM)**
- Deployed 1.5-2.5 km deep in a lattice
- Total instrumented volume of 1 km^3
- Energy range: $10^{10} \rightarrow 10^{15}$ eV

IceCube Backgrounds

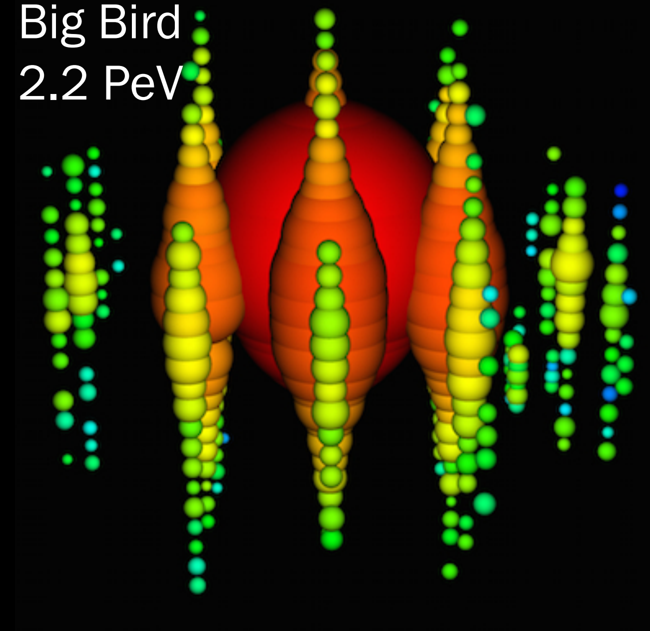
- **Dark Rate of PMTs: 500 Hz**
  - "Random hit rate"
  - Cathode thermal emission + radioactive decay of glass/ electronics/ ice
- **Atmospheric ν + μ: 3 - 30Hz**
  - Cosmic rays interact in atmosphere
  - Pions + kaons decay to neutrinos and muons



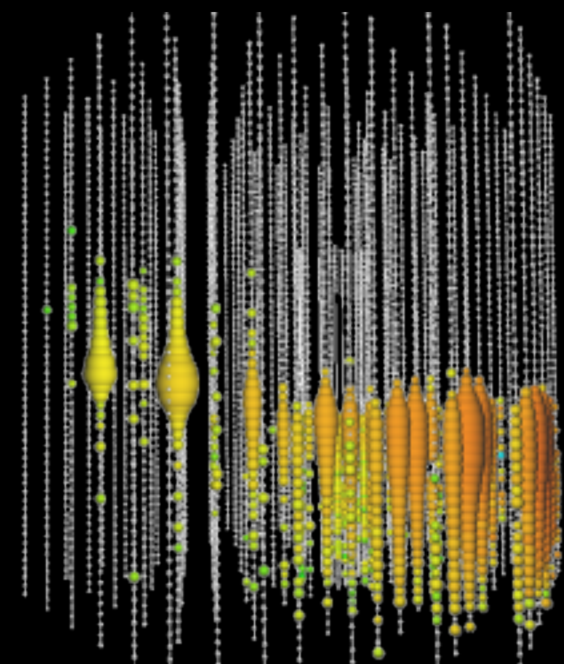
Bert
1.0 PeV



Ernie
1.1 PeV



Big Bird
2.2 PeV



Unnamed ☹
2.6 PeV

Triggering and Experimental Sensitivity

Trigger Motivation

- Constant readout and storage of a sensor is not practical
- Need ways to discriminate between the rare astrophysical events and the common backgrounds

How to Evaluate Trigger

- **Energy "Threshold"**
  - Energy below which an experiment expects to detect no (or few) events
  - Falling spectra → want low energy thresholds
- **Effective Volume**
  - Encodes the "aperture" for event collection
  - Computed by Monte Carlo: interact N_{int} neutrinos, in volume V_{int}, detect N_{det}

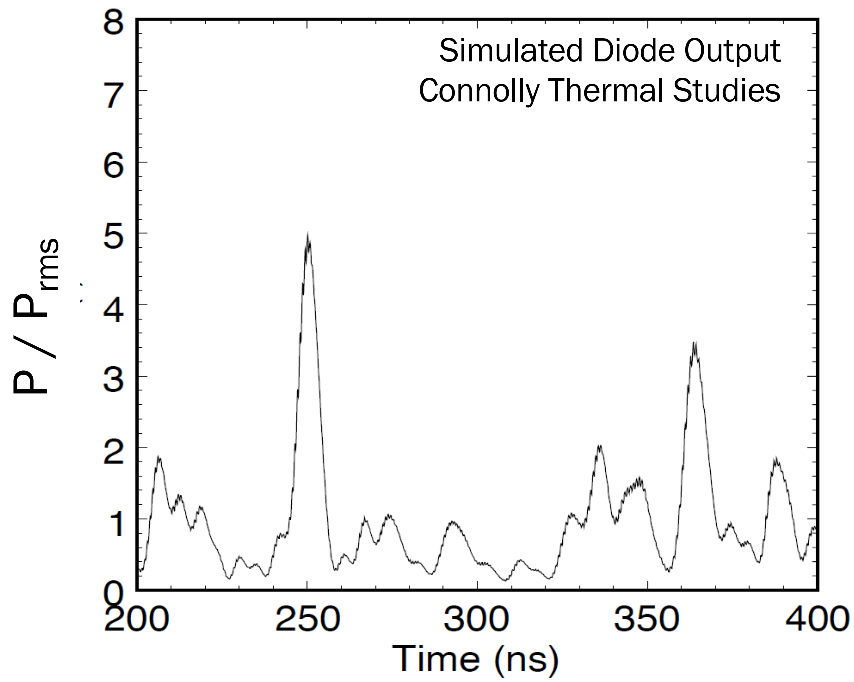
$$V_{eff}(E) = \frac{N_{det}(E_\nu, \vec{r})}{N_{int}} \times V_{int}$$

ARA Trigger

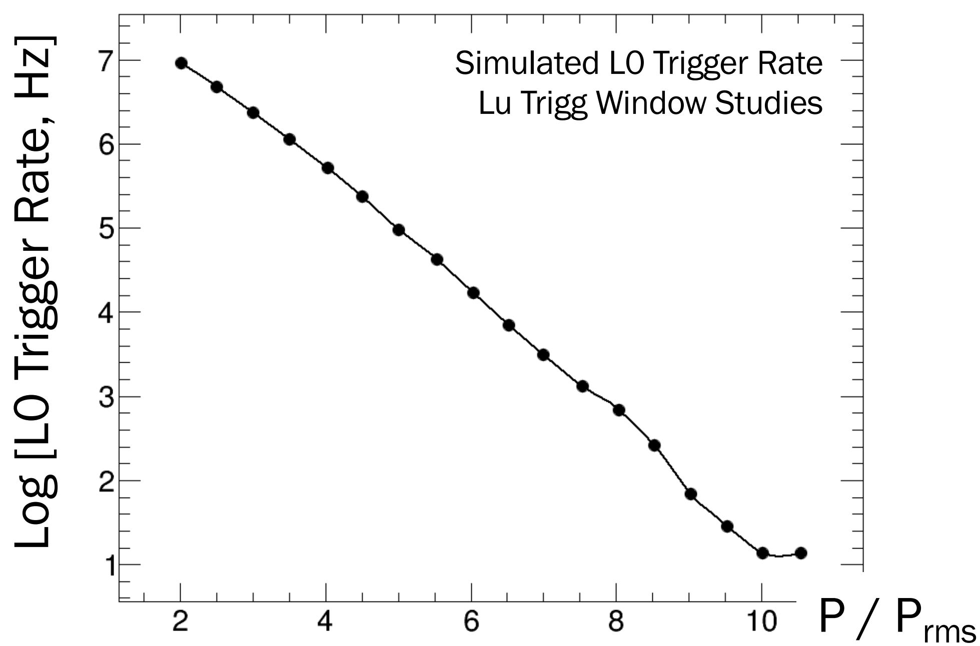
Hardware Constraints: Storage space: 5.4 TB/yr → 5 Hz max *storable* trigger rate

Trigger Process: 2 Tiers

- **L0: Power Threshold violation in single antenna : 10 kHz** ← **Impulsive**
  - Power detection done in a diode
  - Trigger = Excursion over power threshold P_{th}
  - Current threshold = 5-6 × root mean square thermal noise power P_{rms}
- **L1: 3/8 same pol L0 triggers in 170 ns window : 5-25 Hz** ← **Plane-Wave-Like**



$$R_{L0} \propto e^{-\frac{P_{th}}{P_{rms}}}$$



ANITA-2 Trigger

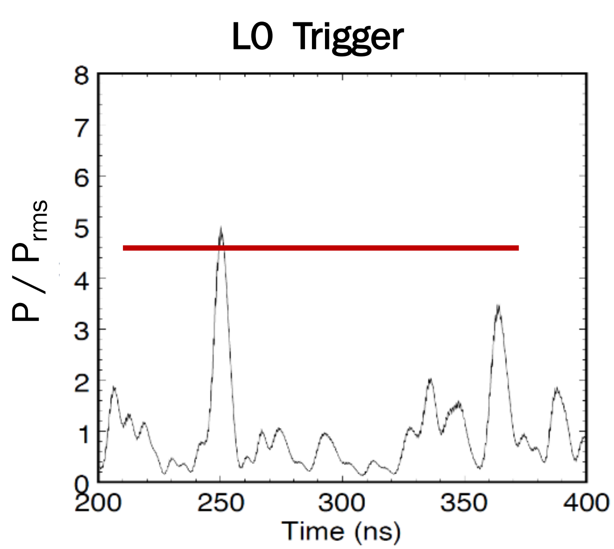
Hardware Constraints: 30 Hz max “write-to-disk” rate

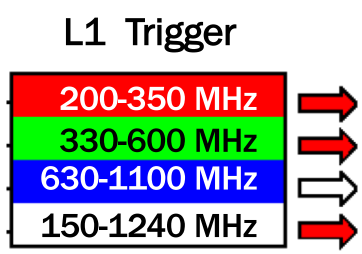
Trigger Process: 4 Tiers (L0 → L3)

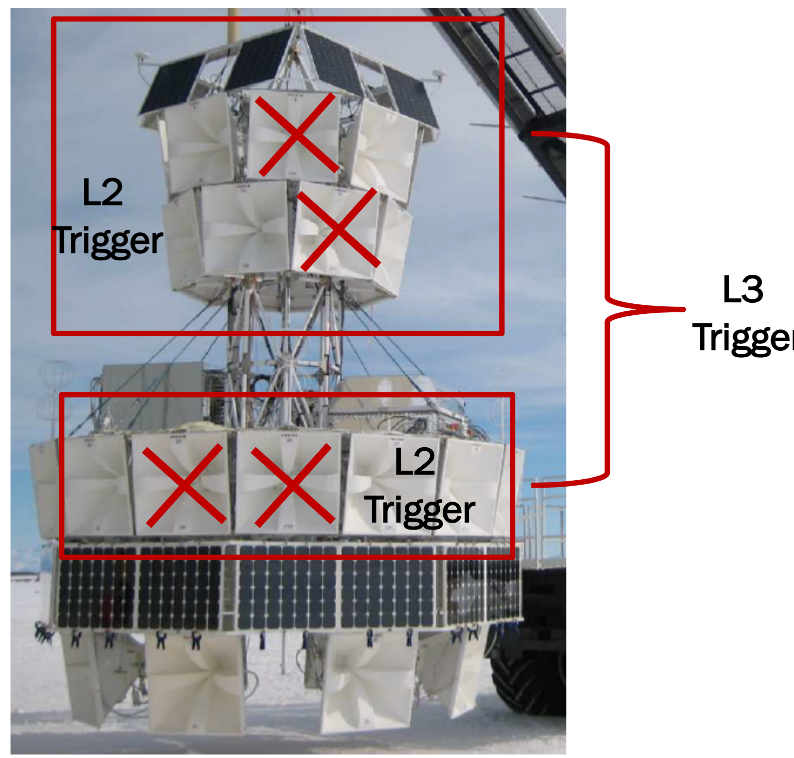
- Banded signal: 3 sub (200-350, 330-600, 630-1100 MHz) and 1 full (150-1240 MHz)

- L0: Power Threshold violation ($3.7 \times P_{rms}$) in single band: ~1-14MHz ← **Impulsive**
- L1: Antenna with 2/3 sub-bands + full band in 10 ns: 200 kHz ← **Broadband**
- L2: 2/3 adjacent L1 triggered antennas in 20 ns: 3 kHz
- L3: 2 rings with L2 triggers in 30 ns: 10 Hz

(L2 and L3: **Plane-Wave-Like**)

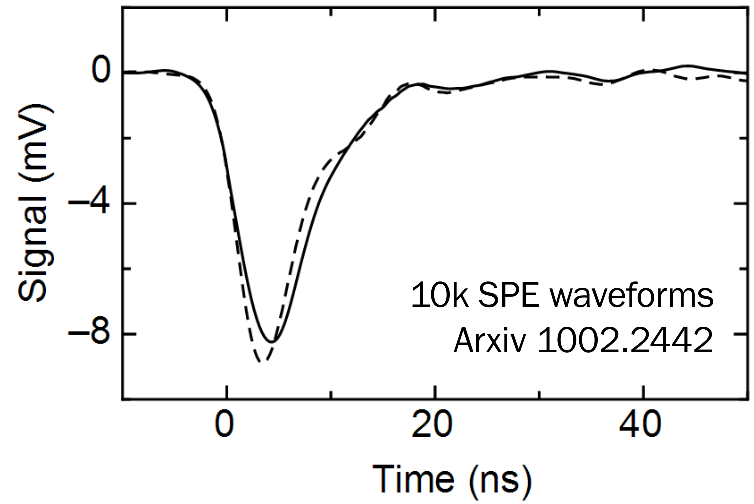






IceCube Trigger

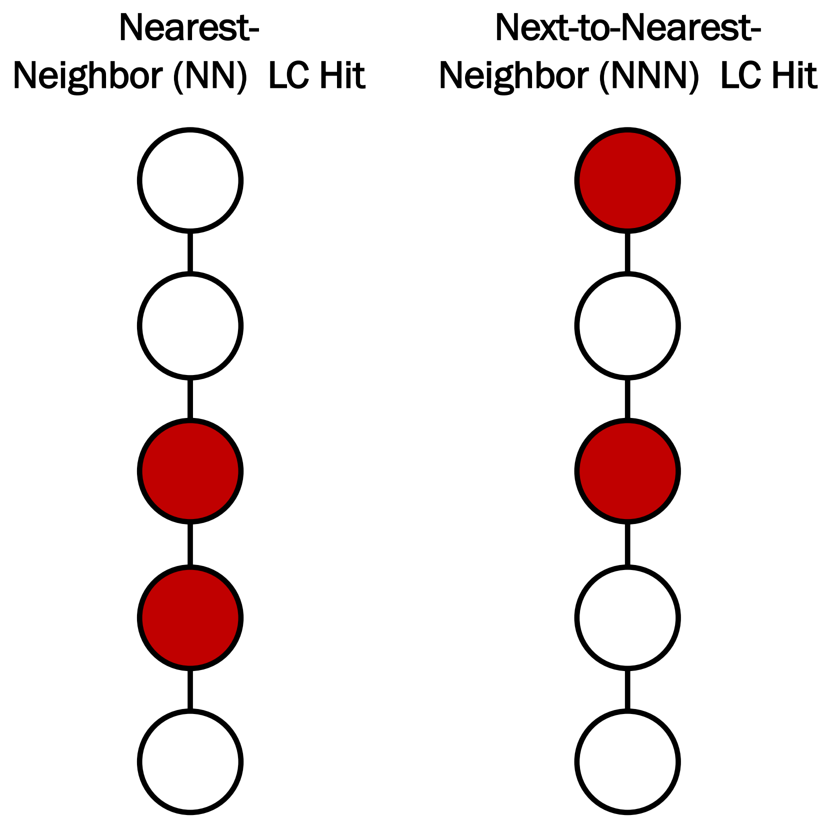
Hardware Constraints: 900 kB/sec/string transmission speed to the surface data recorder
⟶ <88 Hz/DOM max trigger rate



Trigger Process

1. 0.25 Single Photoelectron Equivalent height in a single DOM
2. Simple Multiplicity Trigger: Local Coincidence (LC) in 5-8 DOMs in 5 μs window
   - "LC" means a hit in a NN or NNN DOM within 2 μs
   - **The LC rate/DOM ~5-15 Hz**

- No loss of physics signal
  - Isolated events from muons are rare
  - Most muons hit many DOMs (10 GeV muon hits ~10 DOMs)



ANITA + ARA: Sensitivity and the Trigger

Signal Dependence on the Physics

- Triggering on signal strength relative to background

$$SNR = \frac{V_{signal}}{V_{rms}}$$

- V_{signal} is linearly proportional to Electric Field of shower

$$V_{signal} \propto |\vec{E}|$$

- Electric Field Dependencies
  - Linearly on Shower (Neutrino) Energy
  - Inversely on distance to shower
  - Gaussian "Viewing Angle"

$$|\vec{E}(E_0, R, \theta)| \propto \frac{E_0}{R} \exp\left(-\frac{\theta - \theta_C}{2.2^\circ}\right)^2$$

ANITA + ARA: Sensitivity and the Trigger (2)

Energy Thresholds

- **At threshold, experiments most sensitive to electron neutrinos**
  - Charged Current: $E_0 \propto 0.8 \cdot E_\nu$
  - Neutral Current: $E_0 \propto 0.2 \cdot E_\nu$

$$V_{signal} \propto \frac{E_0}{R} \exp\left(-\frac{\theta - \theta_C}{2.2^\circ}\right)^2$$

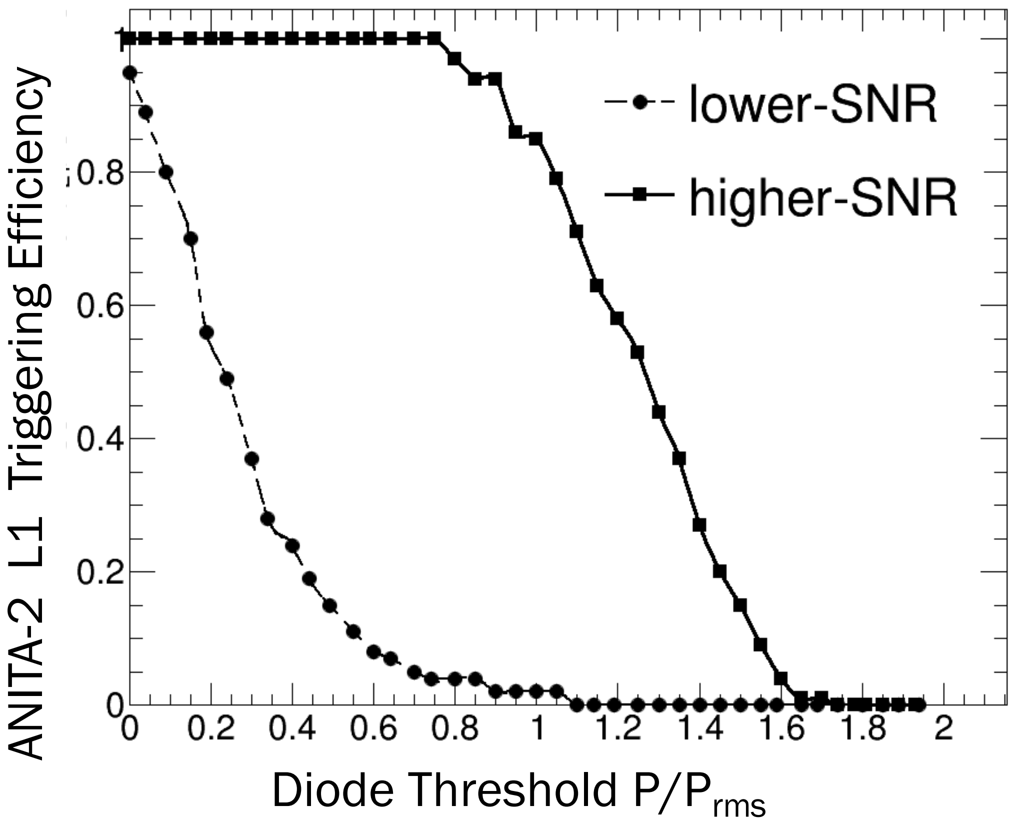
Importance of Thresholds

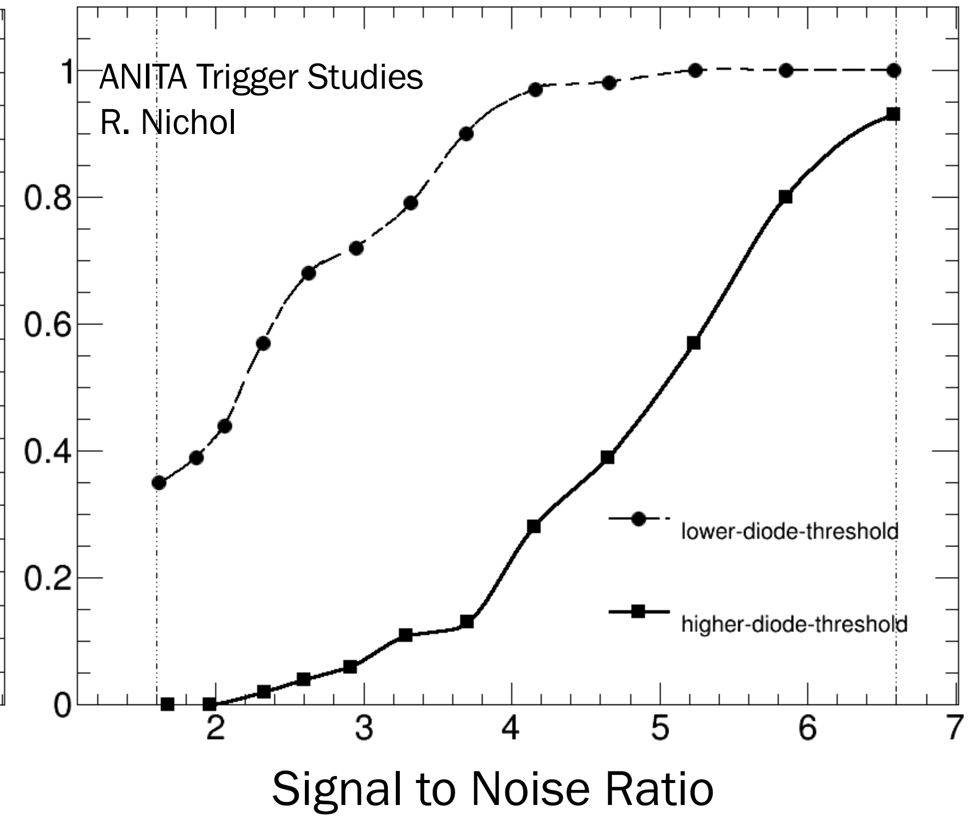
- **Lower thresholds = weaker electric fields pass the trigger**
- For fixed SNR, can have…
- Events of lower energy
- Events from further distances away
  - ANITA is 100x further away than ARA, and has 100x the the energy threshold
- More accepted viewing angles
- Larger effective volumes: $V_{eff} \propto R^3$

ANITA and ARA: Triggering Efficiency

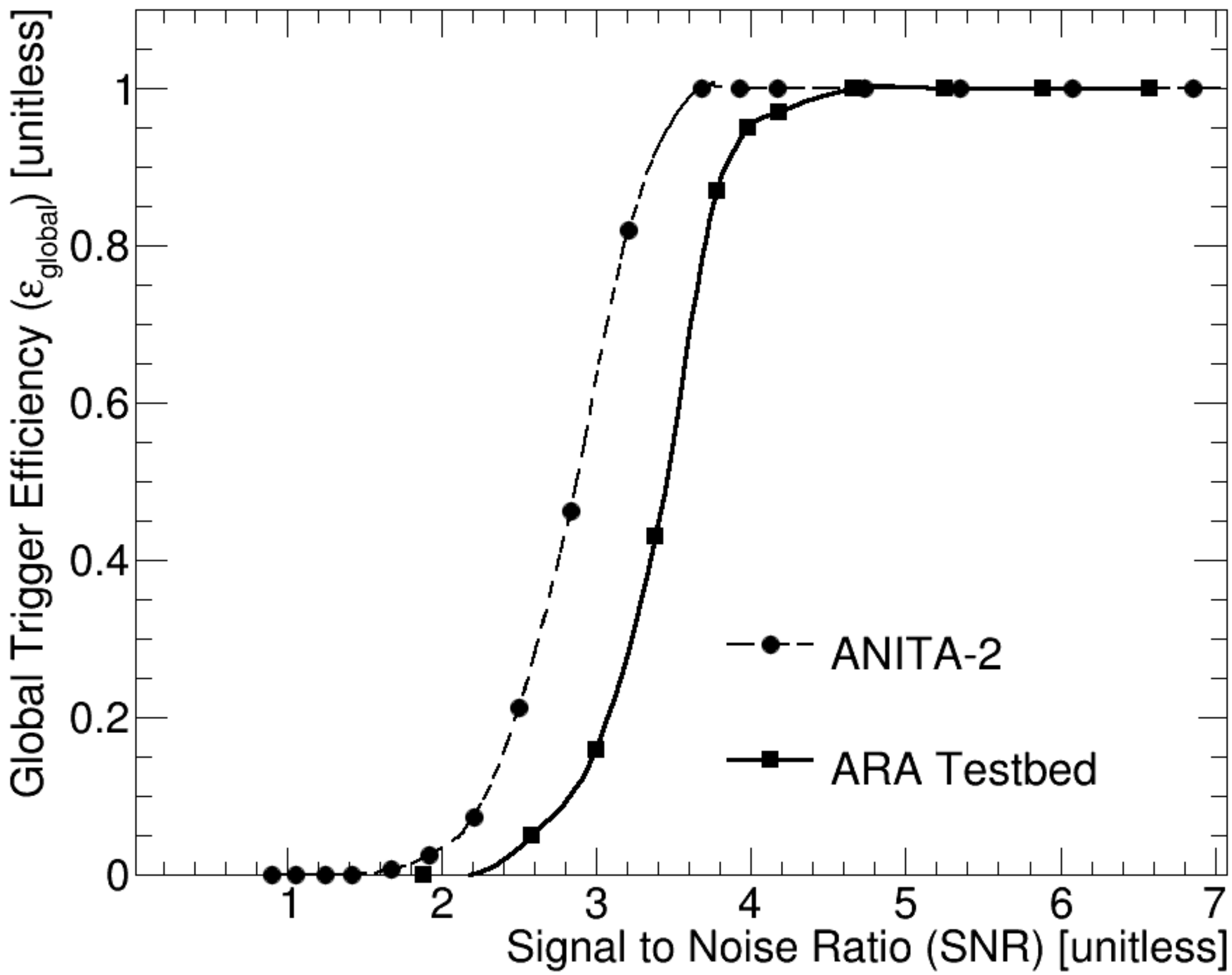
Trigger Efficiency

- Triggers are not perfect
- Have an *efficiency (ε)* for detecting a pulse when it is present
- Depends on SNR of the incoming pulse and diode threshold
- **High thresholds ⟶ Low efficiency for weak pulses**





ANITA and ARA Global Triggering Efficiency



IceCube Energy Threshold

Muon Energy Loss in IceCube

- Parametric form for charged particle energy loss

$$\frac{dE}{dx} = -a - bE$$

Ionization: $a = 2\ MeV\ cm^2/g$ Brem + PP + PN: $b = 4.2\times10^{-6} cm^2/g$

- Muon track length: **logarithmic energy dependence**

$$L \approx \frac{1}{b}\ln\left(1+\frac{E_\mu b}{a}\right) = 2.6\ km \cdot \ln\left(1+\frac{E_\mu}{500\ GeV}\right)$$

Energy Threshold

- In practice: # triggered DOMs gives track length, solve for E_μ
- **Minimum detectable energy set by minimum detectable track length**
- Bulk array 5-LC trigger $\rightarrow \mathrm{L} = 5\cdot 17m = 85\ m \rightarrow E_\mu = 18\ GeV$

Lower LC thresholds = lower energy events

Summary of Triggering Knowledge

- Two competing effects govern the trigger
  - **Physics reach:** always want to lower/ weaken thresholds
  - **Hardware limitations:** cannot exceed hardware constraints
  - Tradeoff required: lower thresholds mean higher event rates

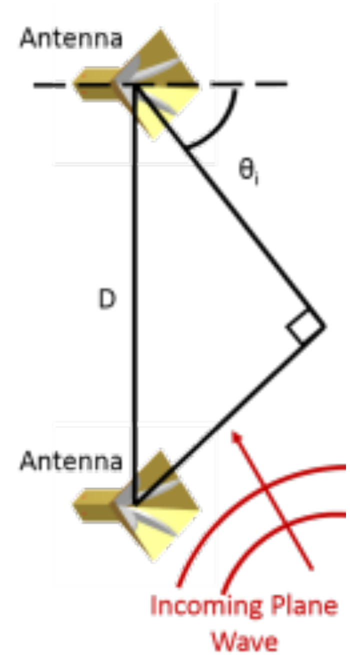
- Need to optimize the trigger
  - **Choose combination of trigger parameters to maximize sensitivity**
  - Minimize the minimum detectable signal
  - Maximize the effective volume

Optimizing a Trigger

	Step	ARA Example
1	Pick figure of merit to optimize	Effective volume
2	Identify input parameters and constraints	Time window; must allow light to traverse the array
3	Identify maximum trigger rate	5 Hz data storage limitation
4	Implement the Trigger in Monte Carlo	AraSim
5	Run Monte Carlo on all possible parameter combinations allowed by max trigger rate	Different time windows, diode thresholds, etc, all with R_{global} < 5Hz
6	Choose combination optimizing figure of merit	Which combination gave max effective volume?

Phased Array Technique

$$\theta_i = \arcsin\left(\frac{c\,\Delta t}{D}\right)$$



Strategy: Signal Averaging

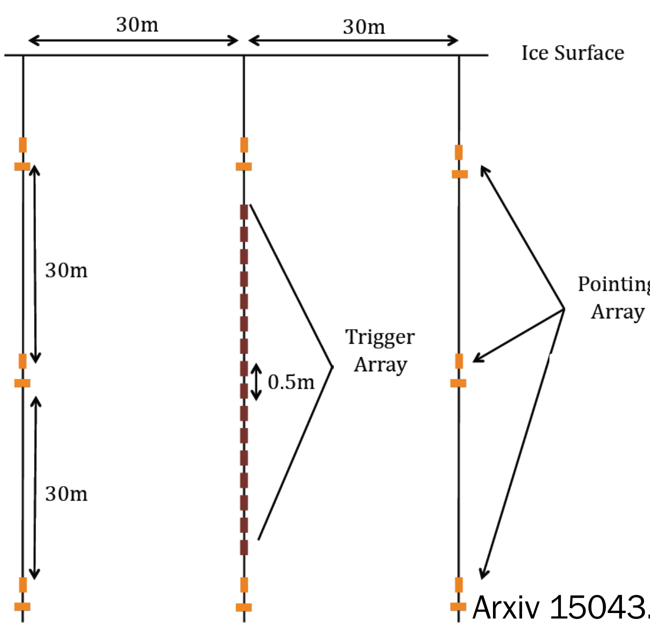
- **Strategy for lowering SNR: reduce background with signal averaging**

$$SNR \propto \frac{V_{signal}}{V_{noise}} \propto \frac{N}{\sqrt{N}} \propto \sqrt{N}$$

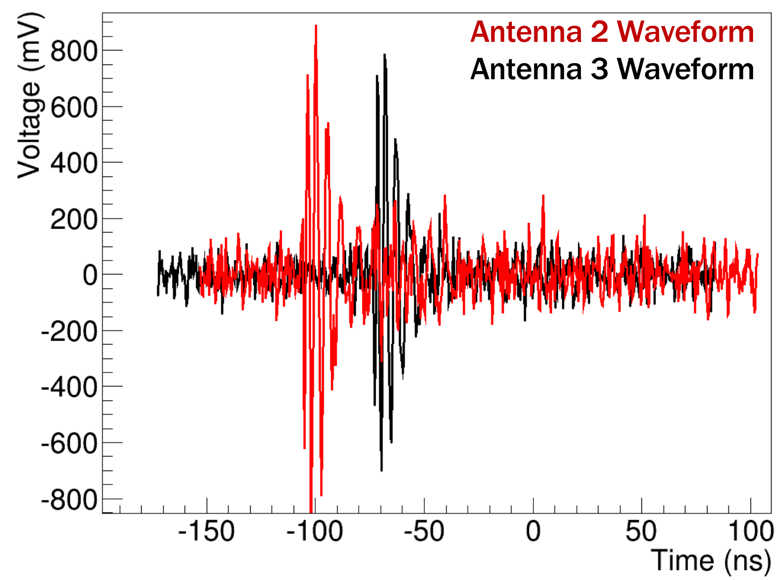
- To get multiple *copies* of the waveform, used multiple *antennas,* and perform the coherent sum ("beamform")
- To see multiple arrival directions, choose different time delays

Design Ideas

- **The more antennas the better ⟶** pack antennas densley
- Situate "trigger antennas" amongst "pointing antennas"



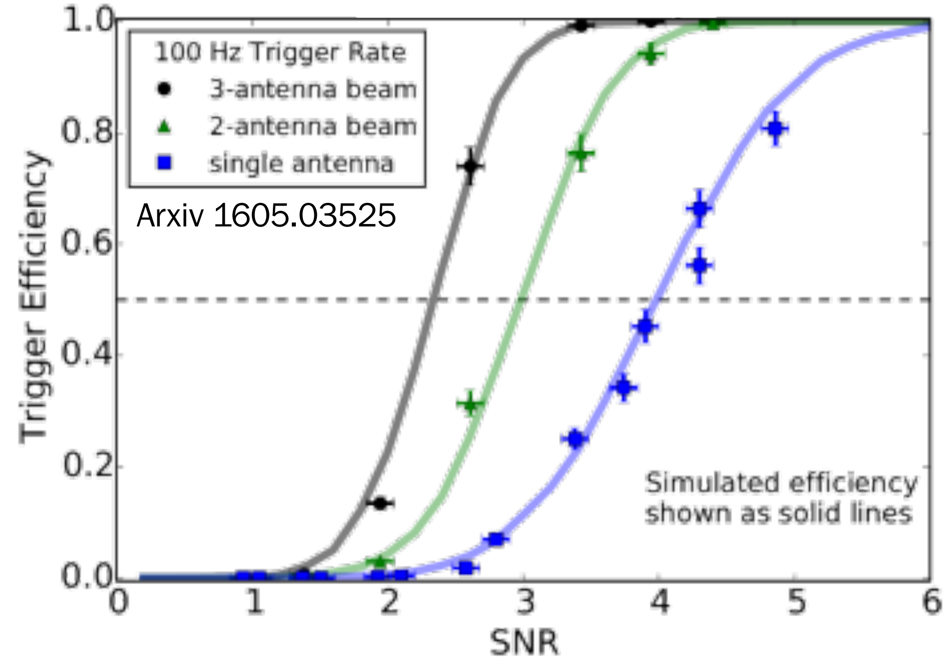
Arxiv 15043.038006



Phased Array Benefits and Challenges

Benefits

- **Principle benefit: reduced thresholds**
- Access to weaker electric fields allows
  - $\sqrt{N}$ Lower energy events
  - Events from $\sqrt{N}$ further away
  - Larger effective volumes
- Higher efficiency at low SNR
- Ability to turn off "loud" beams
- Advanced stage: real-time beam steering



Challenges

- Finite number of beams
- Complicated firmware
- Densely packing a borehole is hard
- High cost for many antennas and many boreholes (~$3-4k/borehole)
- Prototype challenges: operating "parasitically" on the ARA stations requires triggering firmware revisions

Summary

1. Trigger thresholds govern the accessible physics, particularly the energy

2. Optimizing the Trigger is important

3. Phased array techniques are promising ways to lower thresholds

The Connolly Group and my research is generously supported by:

- NSF GRFP Award DGE-1343012
- NSF CAREER Award 1255557
- NSF Grant 1404266 and NSF BigData Grant 1250720
- The Ohio Supercomputer Center
- The OSU Department of Physics and Astronomy
- The OSU Center for Cosmology and Astroparticle Physics
- US-Israel Binational Science Foundation Grant 2012077