Optical and radio techniques for detecting astrophysical neutrinos

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Outline

- Continue 1st lecture
  - cascades & tracks
- HE expectations
  - goals, rates and target volume
    - PeV
    - EeV and cosmogenics
  - how to instrument km^3 w.e.
    - direct
    - radiation
    - in situ/remote
    - τ-tracks
- optical
  - IceCube overview (others)
  - source and propagation: best photon info
  - photon detectors to use this info
  - comments on analysis
- radio
  - overview of experiments
    - in-situ
    - remote (anita, lunar)
  - ARA
    - radio emission
    - propagation
    - radio detectors; antennas etc.
    - propagation
  - GRAND
- summary

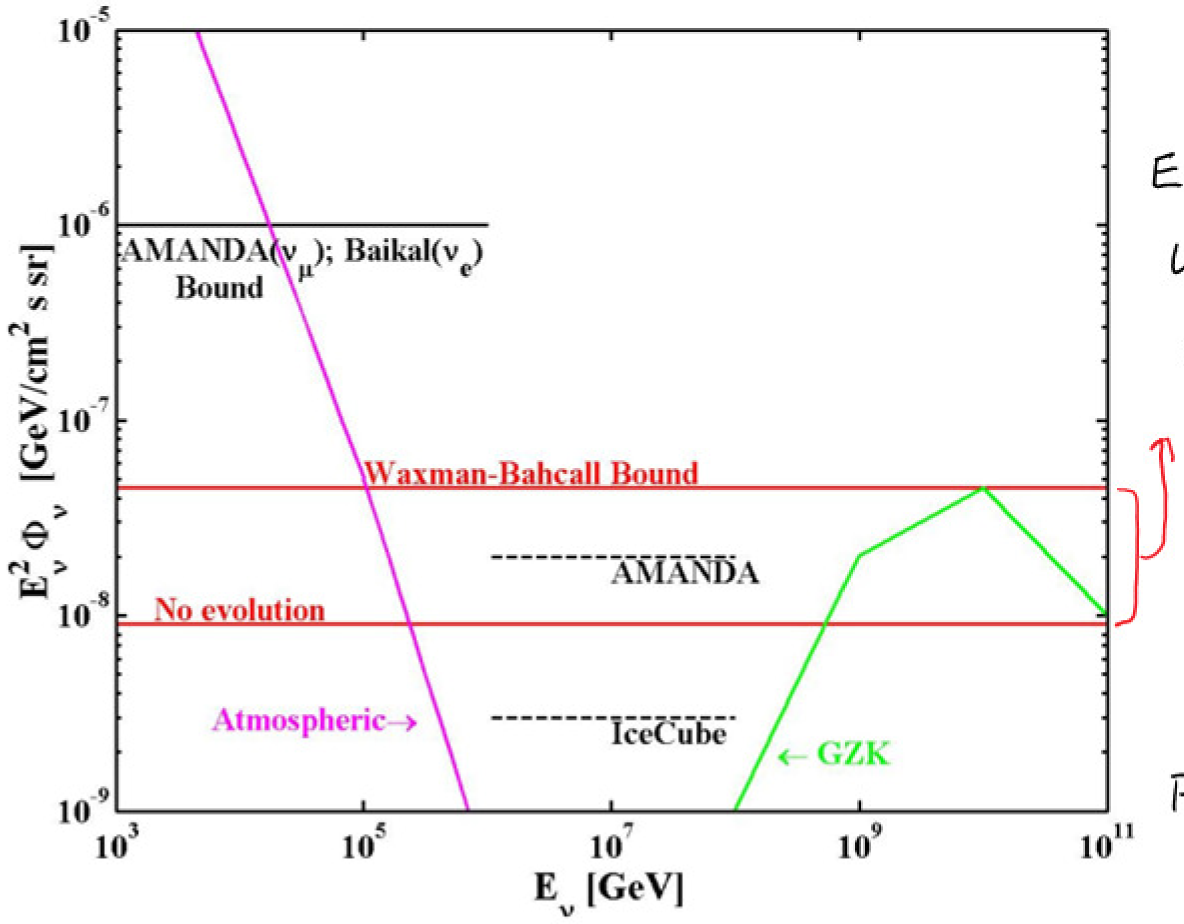
Interlude … cascades, tracks

- continue discussion of cascades and tracks

  … return

- Discuss high energy detectors
  - beginning with science objectives

Expectations: Waxman & Bahcall "bound"



Waxman (NESS 2002)

Source

Energy budget

UHECR's @ 10^{19} eV

0.1 ν per proton

$\phi \sim E^{-2}$

Propagation

$p\gamma \to \Delta^+ \to n\pi^+$

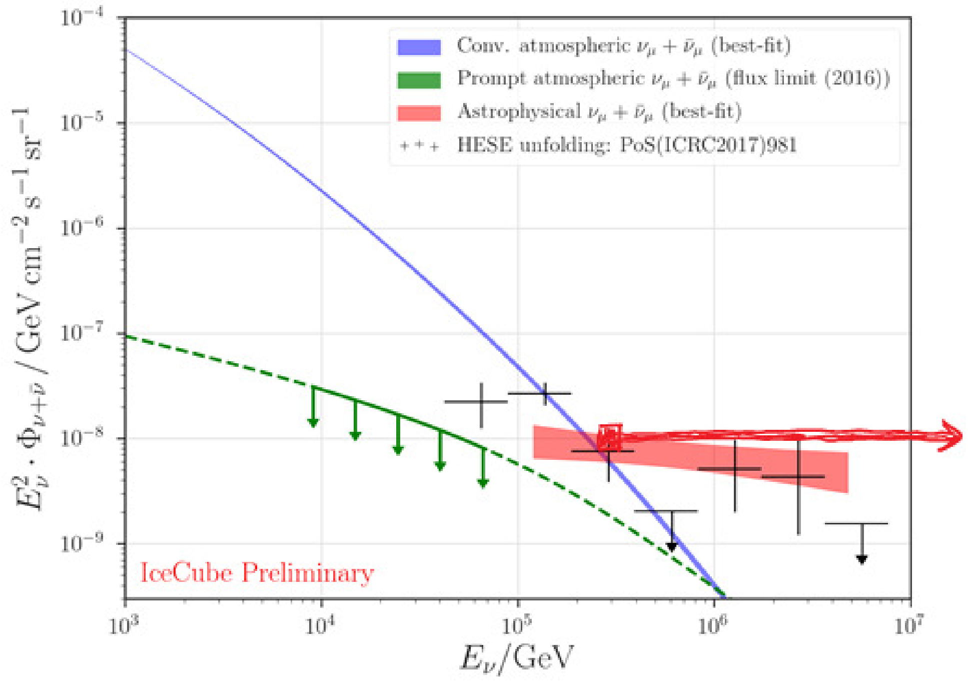
$\pi^+ \to \mu^+ \nu_\mu$

$\hookrightarrow \bar{\nu}_\mu e^+ \nu_e$

Detector scaling: TeV-PeV

- Estimate needed volume

Observe $\phi = E^{-2}$ flux above atm. neutrinos



$$N = \phi A \Omega t$$

$$\llcorner A = n\sigma V$$

$$V = \frac{1}{\phi n \sigma \Omega t} = \boxed{1\ \mathrm{km}^3}$$

$$\phi = \int_{E_T} \frac{\phi_0}{E^2} = \frac{\phi_0}{E_T} = 3 \cdot 10^{-14}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$n = 5.5\ 10^{23} \quad t = 3\ 10^{7} \quad \Omega = 2\pi$$

$$\sigma(3 \cdot 10^5\ \mathrm{GeV}) \simeq 3 \cdot 10^{-34}$$

UHE (EeV+) considerations 100+ km^3

$$\int_{E_T} \underset{E^{-2}}{\phi}\;\underset{E^{.3}}{\sigma}\; dE \sim E_T^{-0.7} \Rightarrow \quad \begin{array}{l} \text{PeV} \to \text{EeV} \\ 1\,\text{km}^3 \to \boxed{100\,\text{km}^3} \end{array}$$

- Astrophysics uncertain 1990's
- GZK neutrinos Guaranteed ! 2000's
- UHECR's getting heavier ~~Guaranteed~~ 2010
- IceCube … 2015
  - astrophysical neutrinos Guaranteed !

Detection strategy

- total size: area/volume/mass/number of targets

- array of sensors
  - at least one sensor per event
  - volume of event … number of sensors > Vtot / Vevent

- direct detection of shower particles (secondaries)
  - cascades
  - tracks
  - water/air

- radiation from event
  - event volume with radiation
  - optical
  - radio
  - remote detection

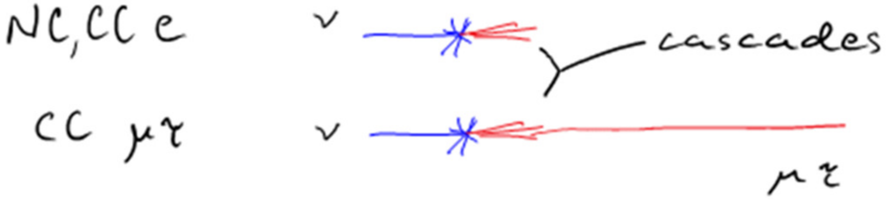
TeV-PeV … km^3

- detector size

$V = 1\ \mathrm{km}^3\ \mathrm{w.e.}$

$N_o = 6 \cdot 10^{23}\, 10^{15} \simeq 6 \cdot 10^{38}$ nucleons

- size of event



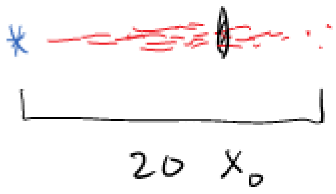
Detect particles in cascade ?

- volume of cascade/track

$$V = l\,A$$

Direct detection of cascades in water/ice

Volume of cascade

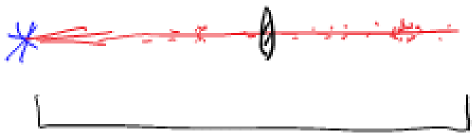


$R_m \sim \frac{1}{4} X_0$ $V \sim X_0^3$

$X_0 \sim 40$ cm $V \sim 10^5\ \text{cm}^3$ $10^{-10}\ \text{km}^3$ $\underline{\underline{10^{10}}}$ sensors

direct detection of tracks in water/ice

- volume of μ-track

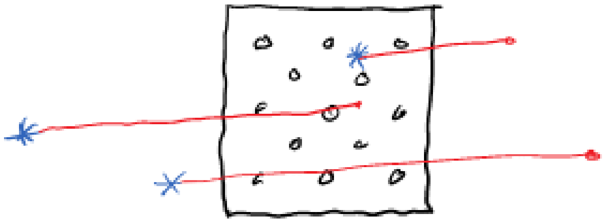


$\updownarrow \quad R_m \sim \frac{1}{4} X_0 \qquad V \sim X_e^2 X_\mu$

$X_\mu = \frac{1}{\beta_\mu} \sim 3 \text{ km}$

$X_\mu \sim 10^4 X_e \qquad V_\mu \sim 10^4 V_{cascade} \qquad 10^6$ sensors

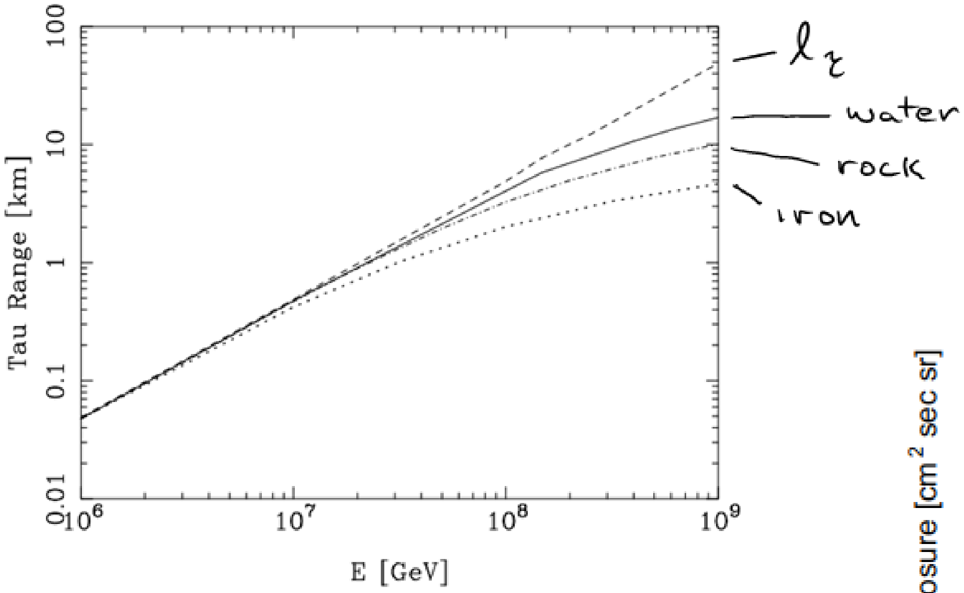
- external



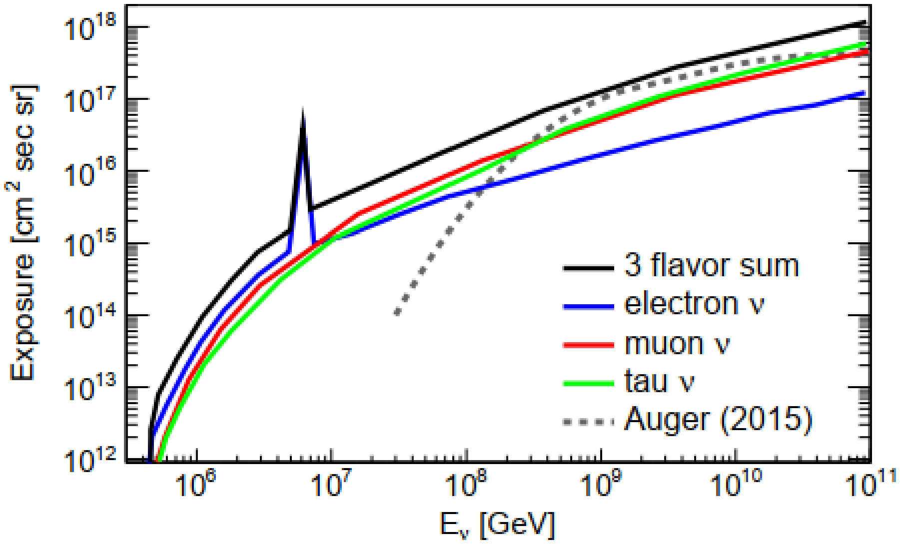
τ-tracks

$$X_\tau \to \frac{1}{\beta_\tau + 1/\ell_\tau} \simeq \frac{\lambda_\tau \ell_\tau}{\lambda_\tau + \ell_\tau}$$

w/ $\lambda_\tau \simeq 20$ km $\quad \ell_\tau = 50$ km E/EeV



IceCube EHE analysis



Air/water

- Density

$$n_{air} \sim \frac{1}{1000} n_{water}$$

$$X_0(air) \sim 1000\ X_0(water)$$

- Target mass per sensor

$$N_t = nV \sim nX_0^3 \sim X_0^2 \sim \frac{1}{n^2}$$

$$\Rightarrow N_{sensors}(air) \sim 10^{-6} N_{sensors}(water)$$

$\Rightarrow$ Direct detection w/ 10^4 sensors

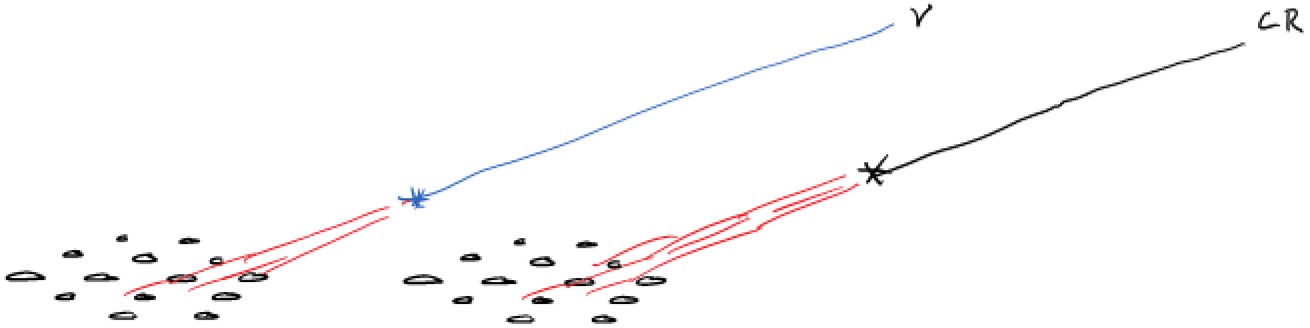
- Check

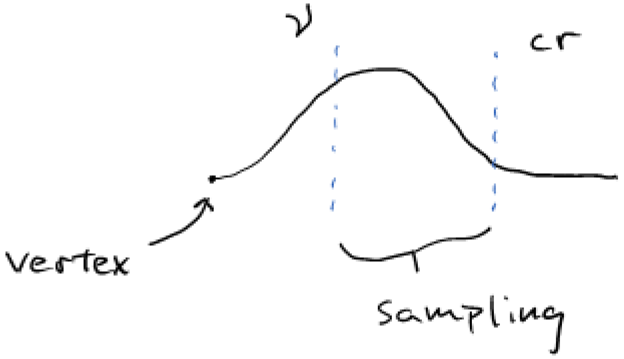
$$P_A = \rho g h \qquad h = 10\,m\ w.e. = 10^{-2}\,km$$

Auger: $A \cdot h = 3600 \cdot 10^{-2} = 36\ km^3$ w.e.

neutrino detection by air shower array

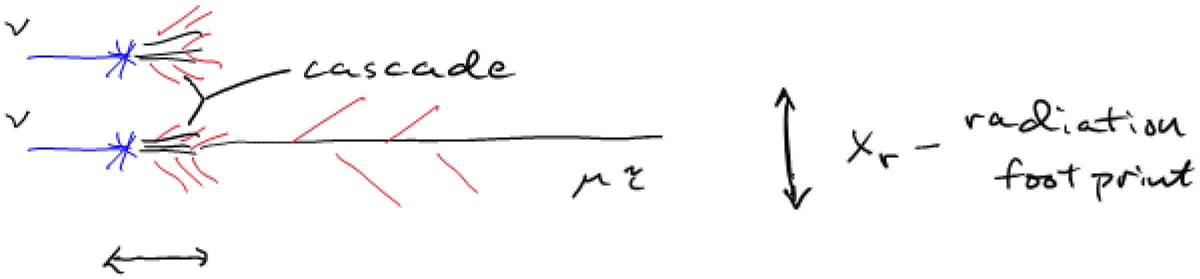
- Background of CR air showers





Details of shower profiles

Radiation



also use X_r ?

$X_0 \rightarrow X_r$

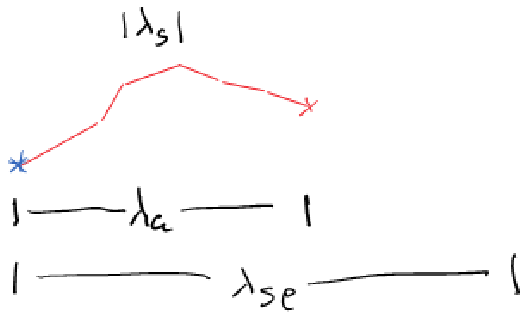
Cascade: $V_{\text{rad sensor}} \sim \left(\frac{X_r}{X_0}\right)^3 V_{\text{dir sensor}}$

Track: $V_{\text{rad sensor}} \sim \left(\frac{X_r}{X_0}\right)^2 V_{\text{dir sensor}}$

Optical radiation in ice

ICE	λ_{abs}	λ_{scat}	λ_{se}
X_r	100	2	25

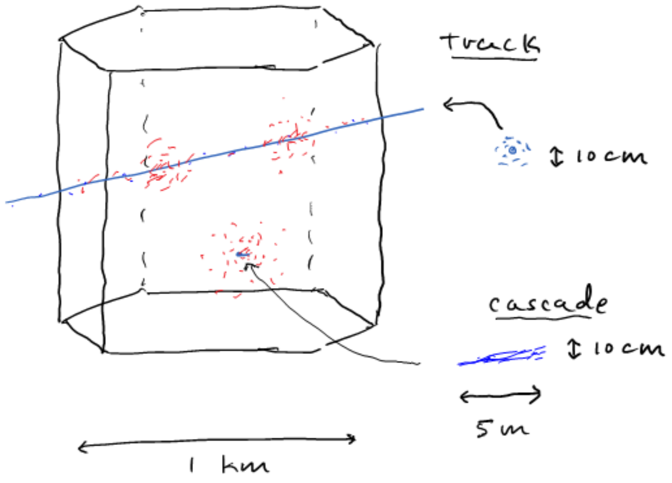
$$X_r \sim \sqrt{\lambda_{abs}\lambda_{se}} \sim 50\ m$$



Cascades $X_0^3 \to X_r^3 \sim 10^6 - 10^7\ X_0^3$ ⇒ 1000–10,000 sensors

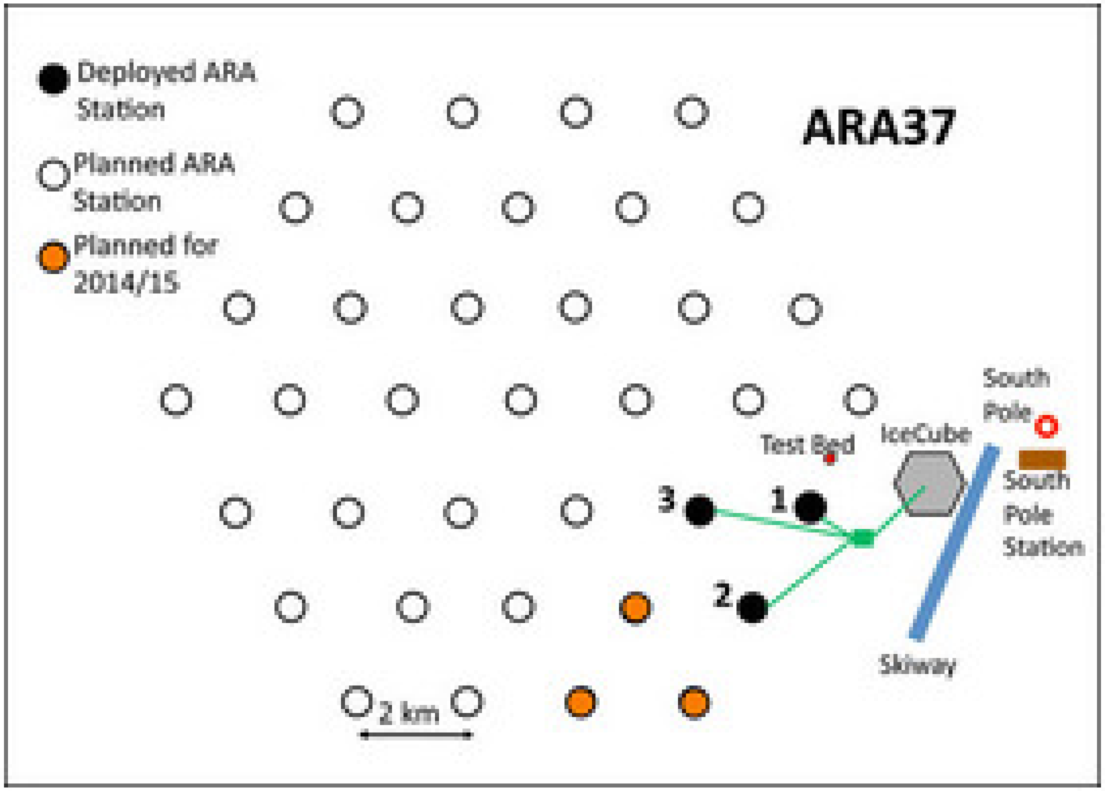
$\mu\cdot$ tracks $X_0^2 \to X_r^2 \sim 10^4\ X_0^2$ ⇒ few 100 sensors

https://icecube.wisc.edu/viewer/hese

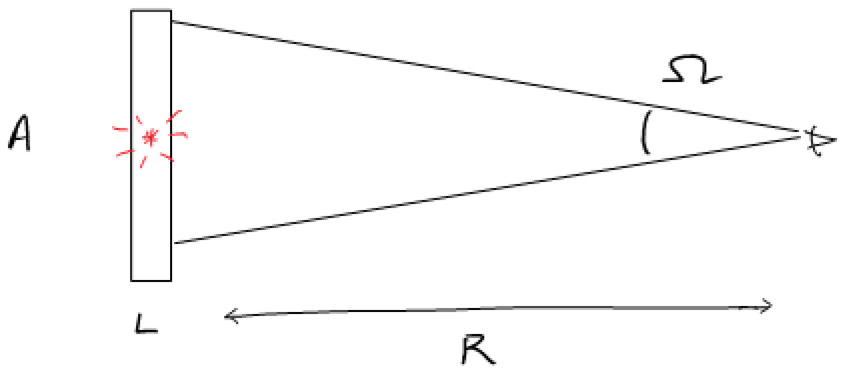


Radio frequency radiation

- Attenuation lengths in polar ice ~ 1km permits a much sparser array. For example …



Remote strategy: exposure v. threshold



$$\Gamma = \int_{E_{thr}} \phi n V \sigma \, dE$$

$V = AL$ $A = \Omega R^2$

$\phi = \phi_0 E^{-\alpha}$ $E_{thr} \sim R$

↑

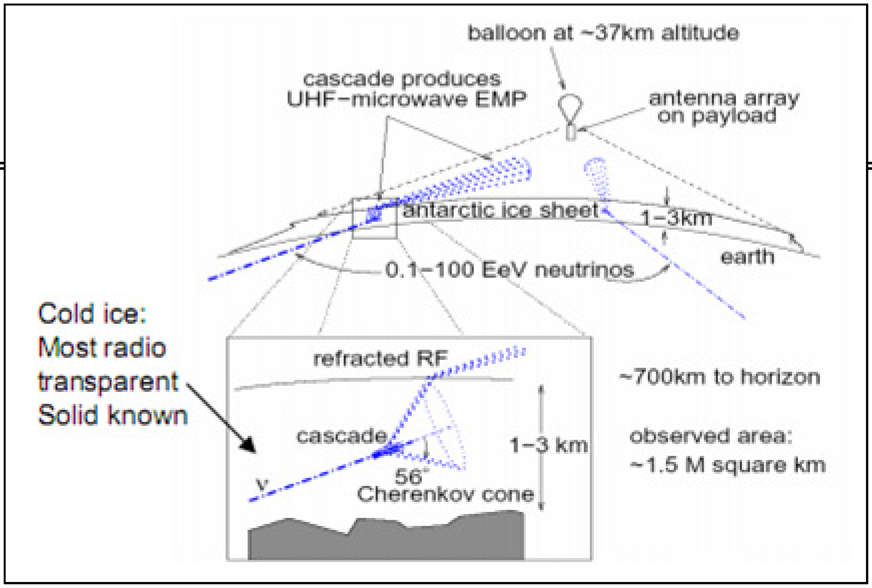
for radio

$$\Gamma \sim \int_{E_{thr}} E^{-\alpha} R^2 \, dE \sim E_{thr}^{1-\alpha} R^2 \sim R^{3-\alpha}$$

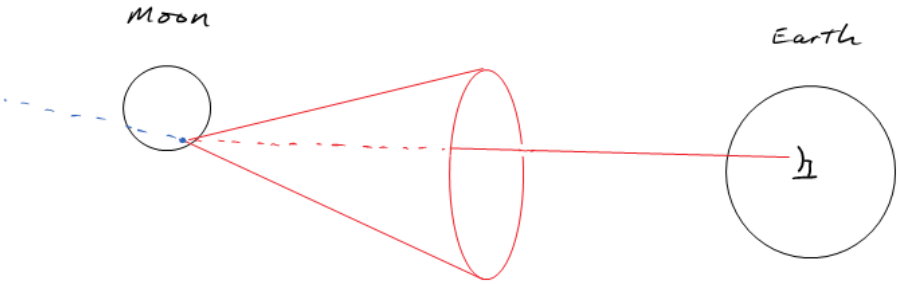
$$\left.\begin{array}{ll} E^{-3} & \text{OK} \\ E^{-2} & \text{wins} \end{array}\right\} \text{Remote can be good strategy}$$

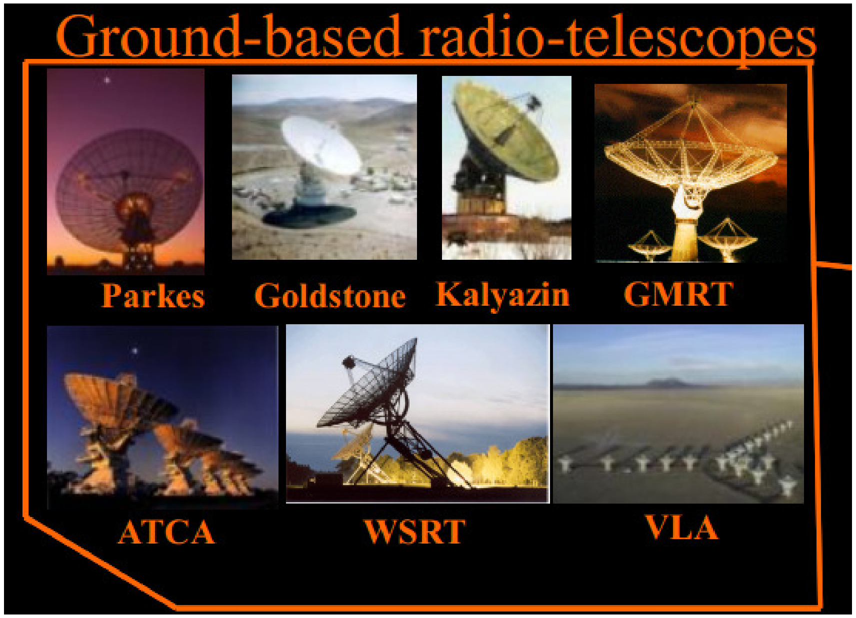
Remote applications

- ANITA (Balloon)



- Lunar observations



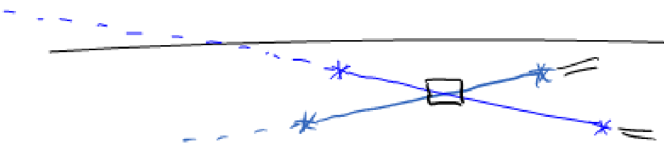


The τ-channel

External events — X_τ 20 km w.e. ··· 5 X_μ 1000 Atm.

But ··· ① No vertex ΔE_ν big ② Require τ Decay ?

IceCube



$X_\tau > X_\mu$

limited gain $\theta > 0$

Upward events attenuated

Auger

external τ increases target mass for $\Delta\Omega$

GRAND

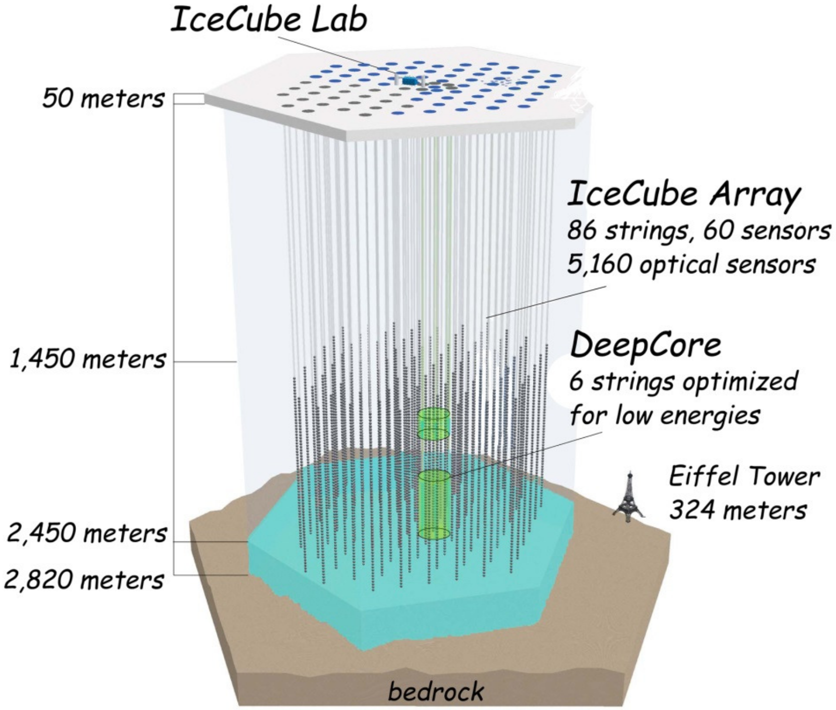
Mountains help with $\Delta\Omega$

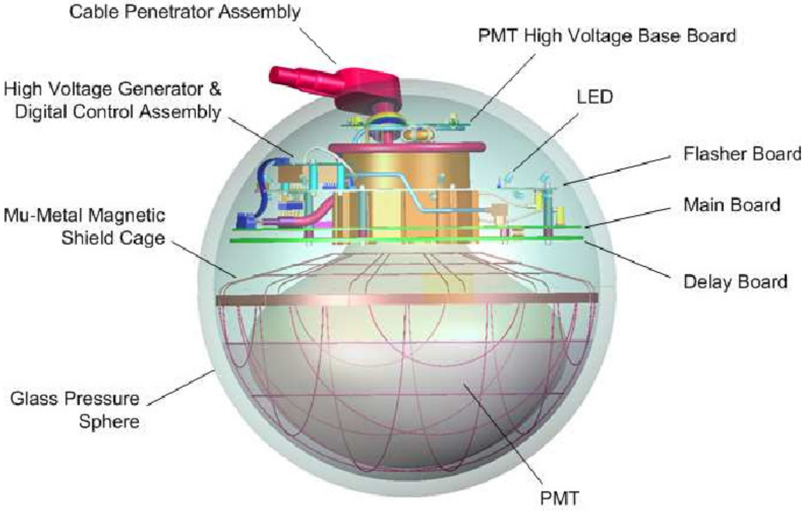
Strategies

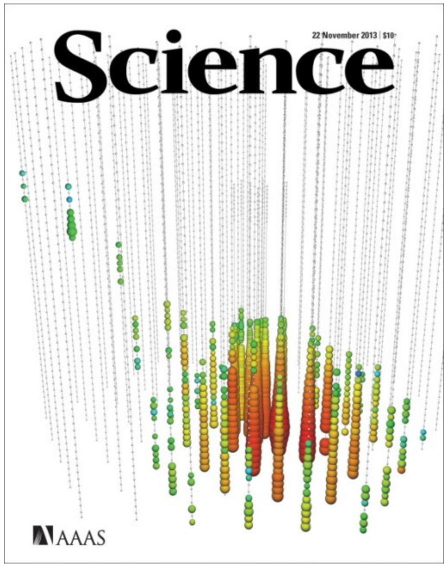
- direct shower detection (air showers)
- optical radiation (water/ice)
  - also air cherenkov
- radio
  - in situ
  - remote observations
- τ-channel and external events

- IceCube – optical
- ARA – radio

IceCube overview

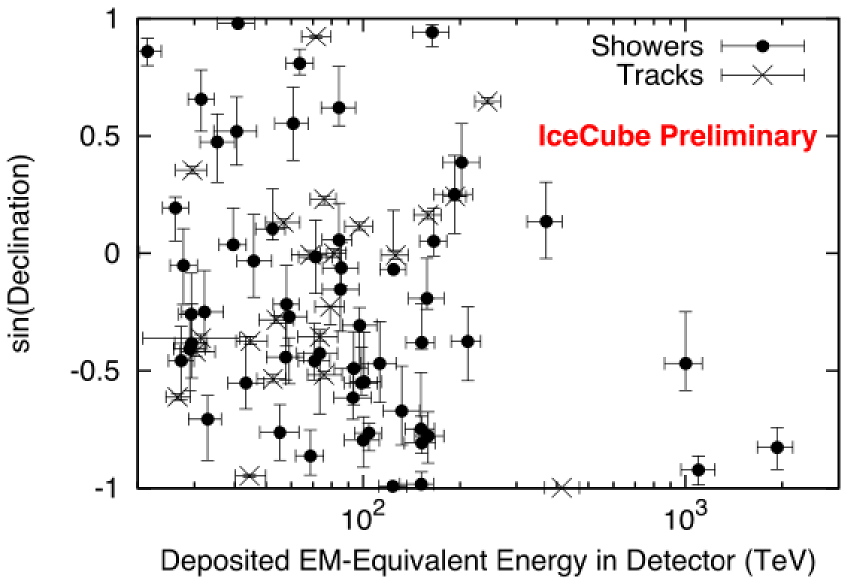


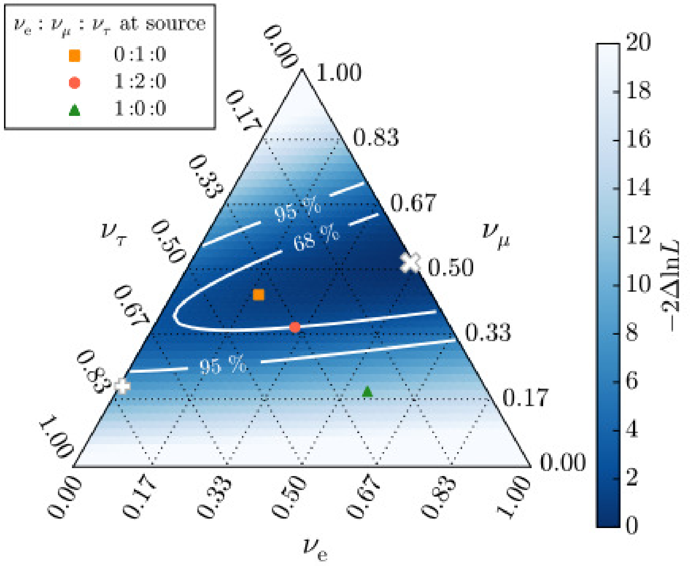


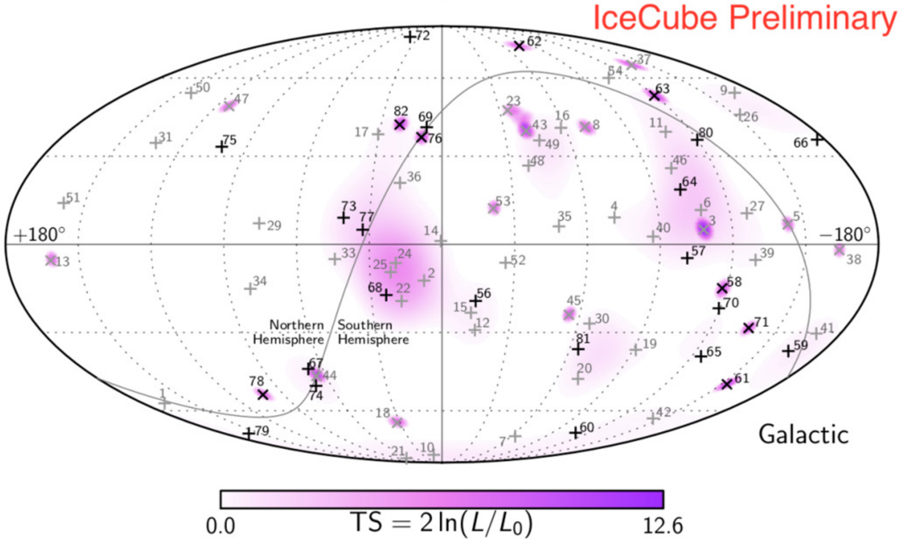


IceCube astrophysical neutrinos

- Energy
- Direction
- Particle ID







Reconstruction, Ice, Sensors, Calibration

- Reconstruction
  - energy
  - direction
  - event topology

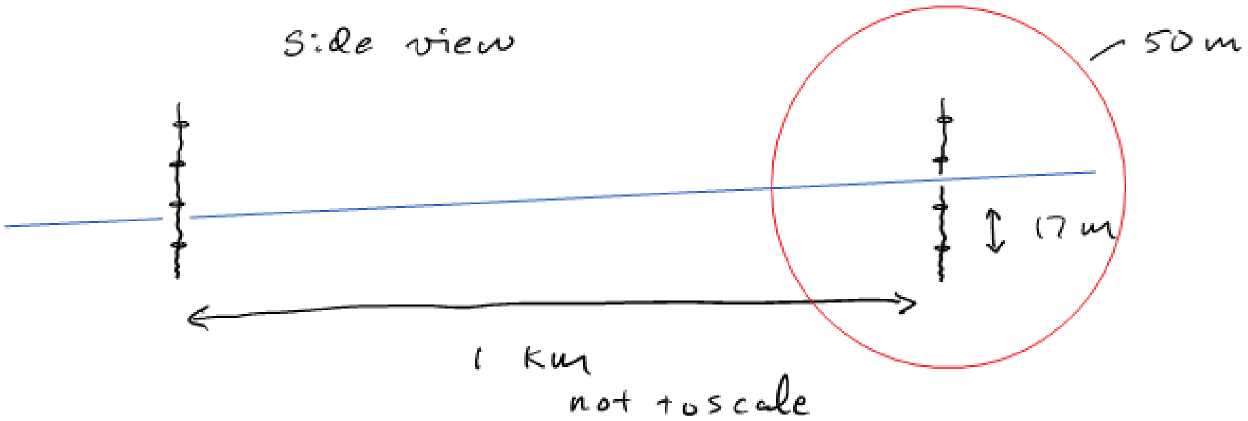
- Ice modeling
  - photon propagation
  - flasher system
  - bulk, hole, bubbles, cables

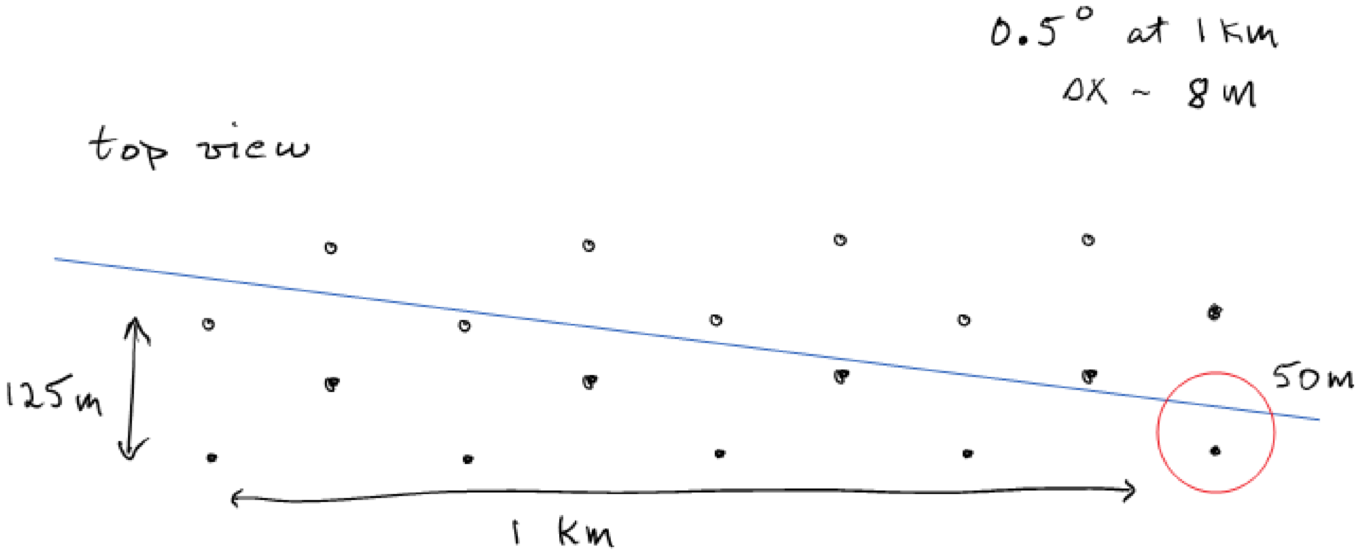
- Sensors and Calibration

Energy calibration

- ~10% systematic due to DOM efficiency
  - small pulses contribute charge to multi-pe hits but do not count as single pes
- affects many analyses, e.g. cosmic ray composition
  - deep muons/surface energy increases with A, but calibration affects estimate of deep muons.

Direction of tracks





event topology

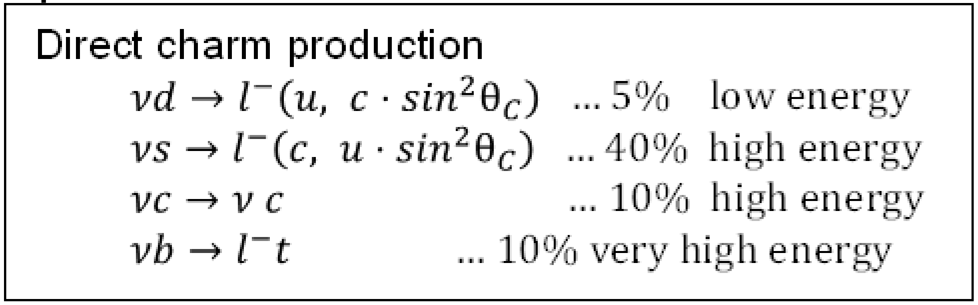
- Hadronic content of showers
  - see notes under hadronic cascades in lecture 1.

		Had	EM	Track
NC	all	✓		
CC	ν_e	✓	✓	
	ν_μ	✓		✓
	ν_τ	✓ $(1+\frac{3}{5})$	$1/5$	$1/5$

Identifying hadronic cascades

- Hard … X_{max} and sensor spacing ?

- Prompt light from μ
  - Heavy Q at neutrino vertex
  - prompt Q from hadronic processes
  - conventional μ



Direct charm production

$\nu d \rightarrow l^{-}(u,\ c \cdot sin^2\theta_C)$ ... 5% low energy

$\nu s \rightarrow l^{-}(c,\ u \cdot sin^2\theta_C)$ ... 40% high energy

$\nu c \rightarrow \nu\ c$ ... 10% high energy

$\nu b \rightarrow l^{-}t$ ... 10% very high energy

- echo's
  - μ: decay 2.2 μs delay
  - n: $np \rightarrow D\gamma$ 2.2 MeV ~ms delay
  - luminescence (shape and efficiency e vs had)

Optical radiation generated in-ice

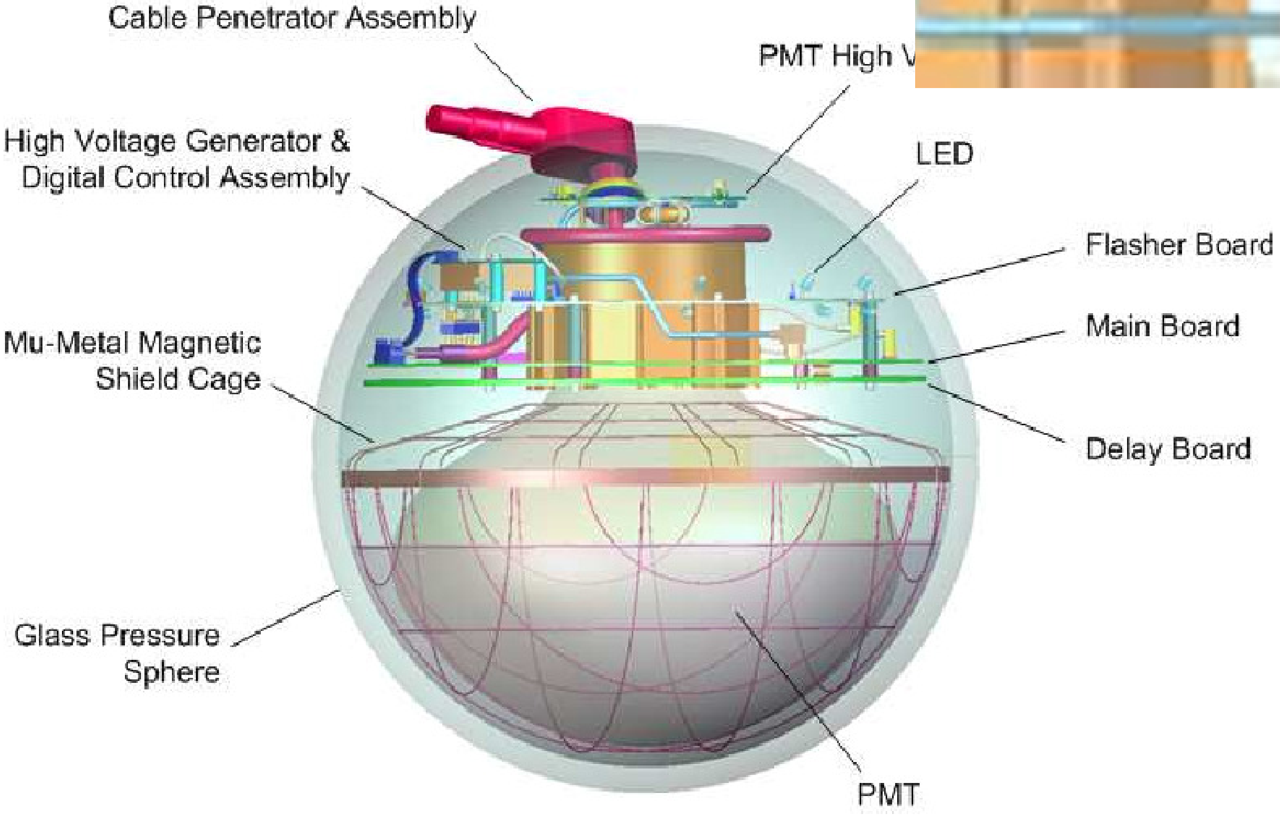
- Cerenkov light
  - angular distribution of γ's and electrons
- scintillation (luminescence)
  - low yield, delayed,
    - different yield (pulse shape) for hadrons and electrons ?
- Propagation
  - scattering
  - scattering function $\frac{d\sigma}{d\cos\theta}$
  - absorption

Determining ice properties

- Dust loggers
- Flashers
- Standard candle
- Swedish Camera
- Muons

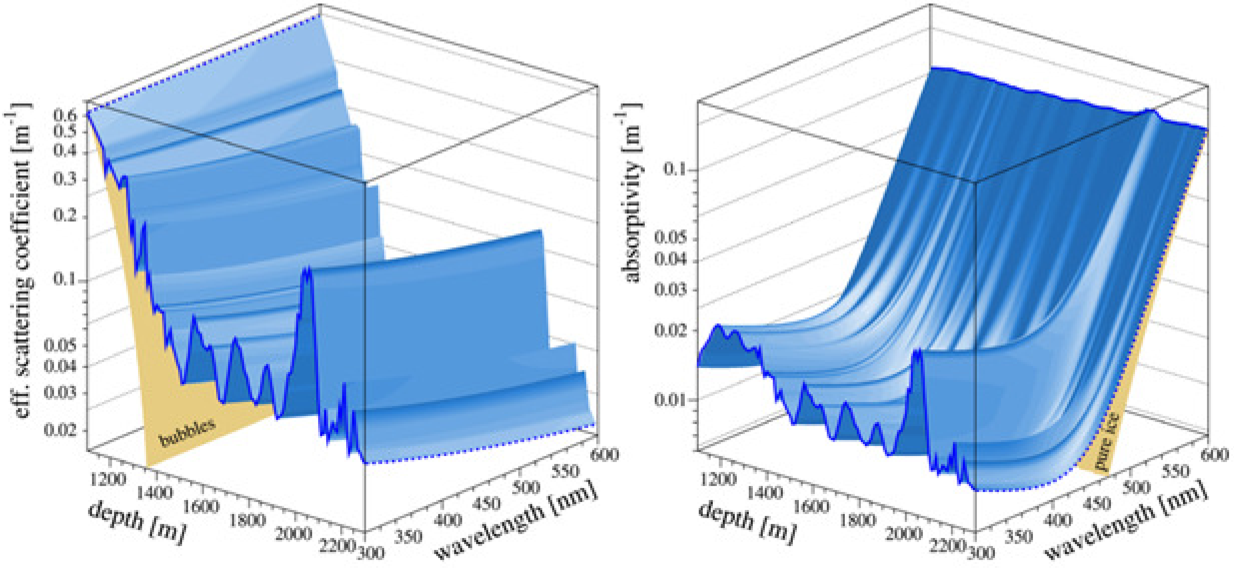
- Caution: the discussion of IceCube optical properties has some gaps in detail. The material was not presented in the room, but I leave it here in case it is of interest. Feel free to ask questions. I also did not give a discussion of DOM properties, or plans for new types of DOMs for an upgraded IceCube.

Flashers


Cable Penetrator Assembly
PMT High V
High Voltage Generator &
Digital Control Assembly
LED
Flasher Board
Main Board
Mu-Metal Magnetic
Shield Cage
Delay Board
Glass Pressure
Sphere
PMT

Ice properties

From AMANDA data



$\sum_i n_i \sigma_{si} (1-g_i)$

$g_i = \langle \cos \theta \rangle$

$\sum_i n_i \sigma_{ai}$

Evolution of ice models

- AHA
- Spice MI
- Spice Li
- tilt
- anisotropy

Optical propagation simulation

- Fit to flasher data

- 4 types of impurities
- 2 scattering functions
- 10 m layers with tilt
- independent parameters for
  - absorption
  - effective scattering
- anisotropy along ice flow

Radio detection of UHE neutrinos

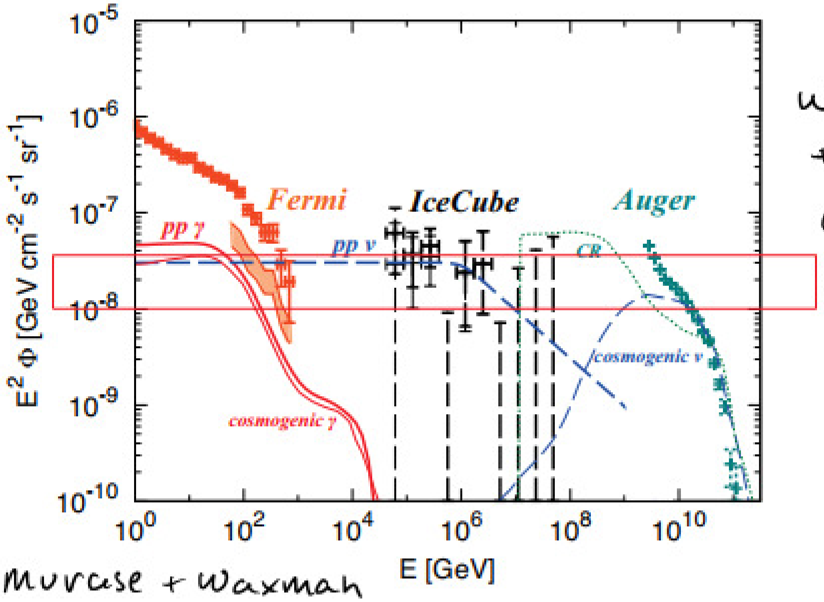
- Science goals
  - gzk
  - astrophys nu’s above icecube

- detector concepts
  - optical water/cerenkov
  - air - direct/tau channels
  - radio overview

- ARA
  - intro to ARA
  - radio emission
  - propagation
  - triggering/threshold
  - reconstruction
  - phased trigger

- GRAND (τ-channel)

Why radio …



Murase + Waxman

Waxman + Bahcall

$\phi \sim E^{-2}$

Recall, for E^{-2}

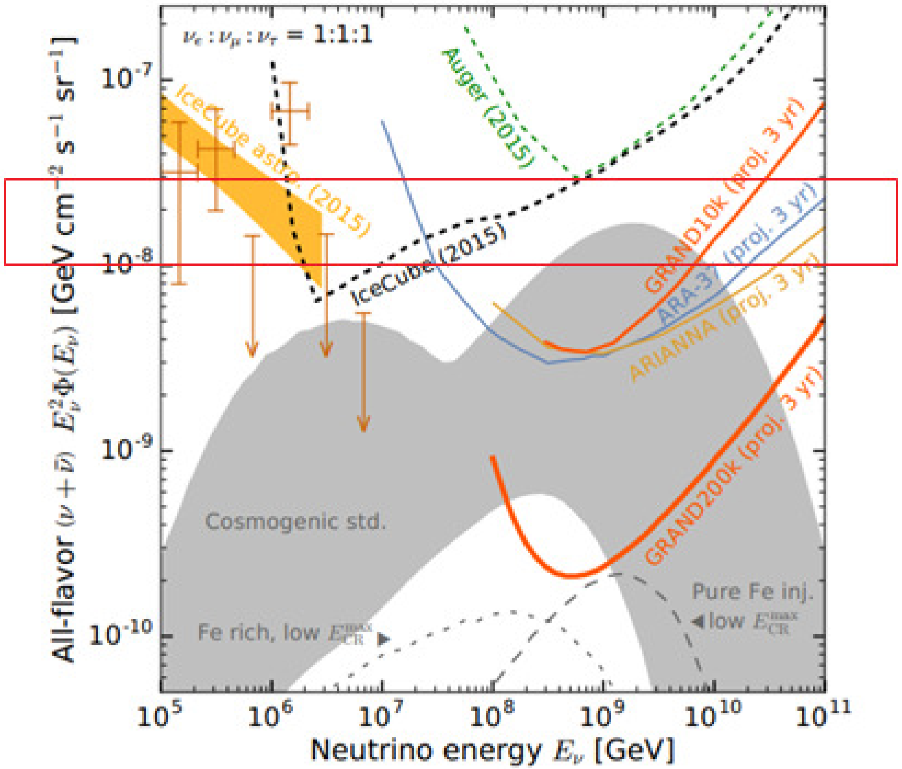
$1\ \text{km}^3$ @ PeV

$V \Rightarrow 100\ \text{km}^3$

And $\phi_0 \rightarrow 0.1\ \phi_{WB}$

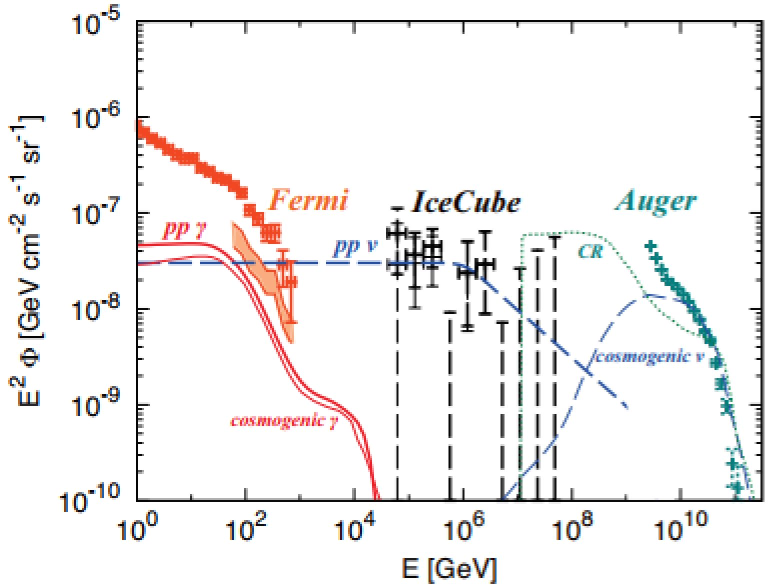
so $\boxed{V \Rightarrow 1000\ \text{km}^3}$

GRAND



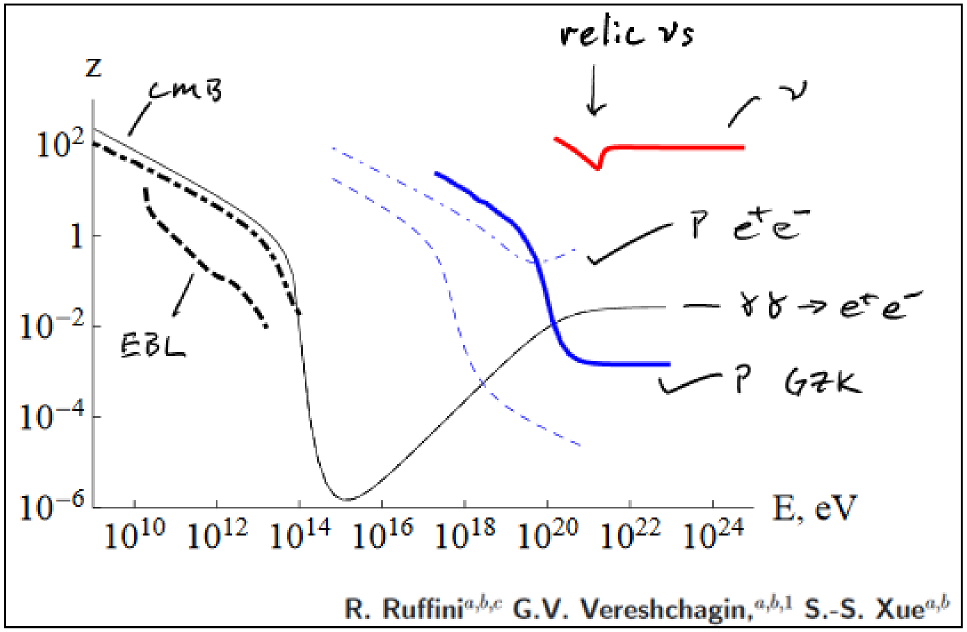
Fang,

Fermi diffuse constraint



- injected energy cascades to ~500 GeV
- Suppose $\phi = \phi_0 E^{-2}$ with f_{em}
- $E_{em} = \int \phi_0 E^{-2} f_{em} E \, dE$

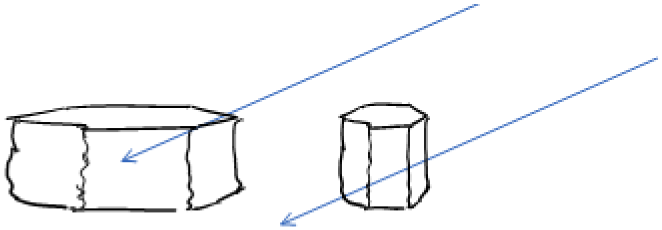
$f_{em} \phi_0 \; 2.3 \left(\log_{10} E_{max} - \log_{10} E_{min} \right) \le E_{fermi}$



R. Ruffini[a,b,c] G.V. Vereshchagin,[a,b,1] S.-S. Xue[a,b]

Technical concepts

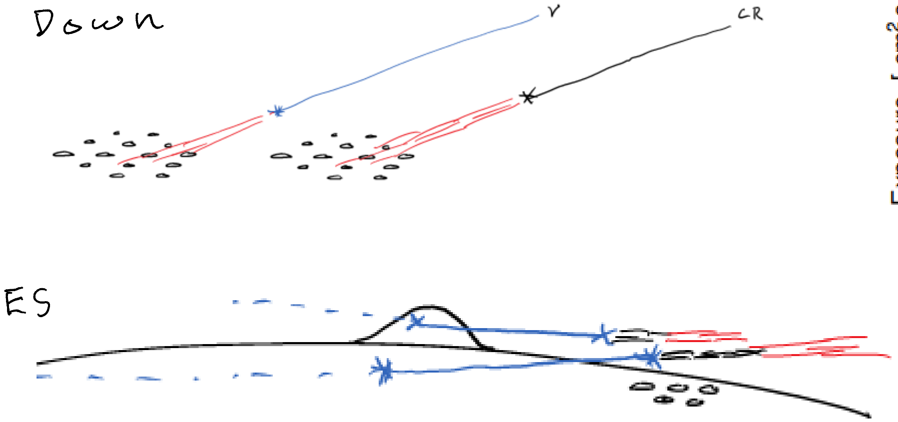
- water Cerenkov
  - IceCube Gen2

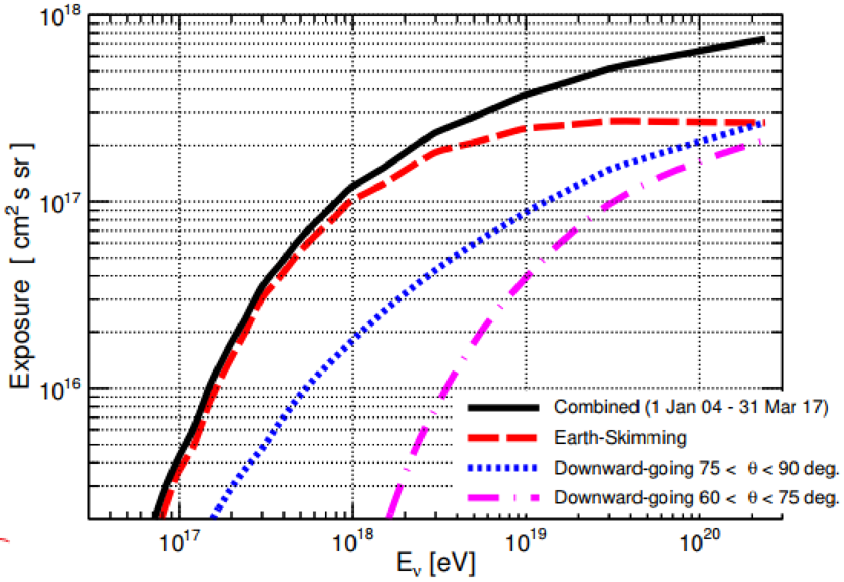


$V \to 10\,V$

$A_\perp \to 5\,A_\perp$

- Air shower array
  - AUGER





Radio technique (~ 150-800 MHz)

- Mention ongoing efforts
  - but focus on ARA: Askaryan Radio Array

- Introduce ARA

- Radio technique
  - radio emission from showers
  - propagation
  - reconstruction and simulation
  - advanced trigger

- GRAND

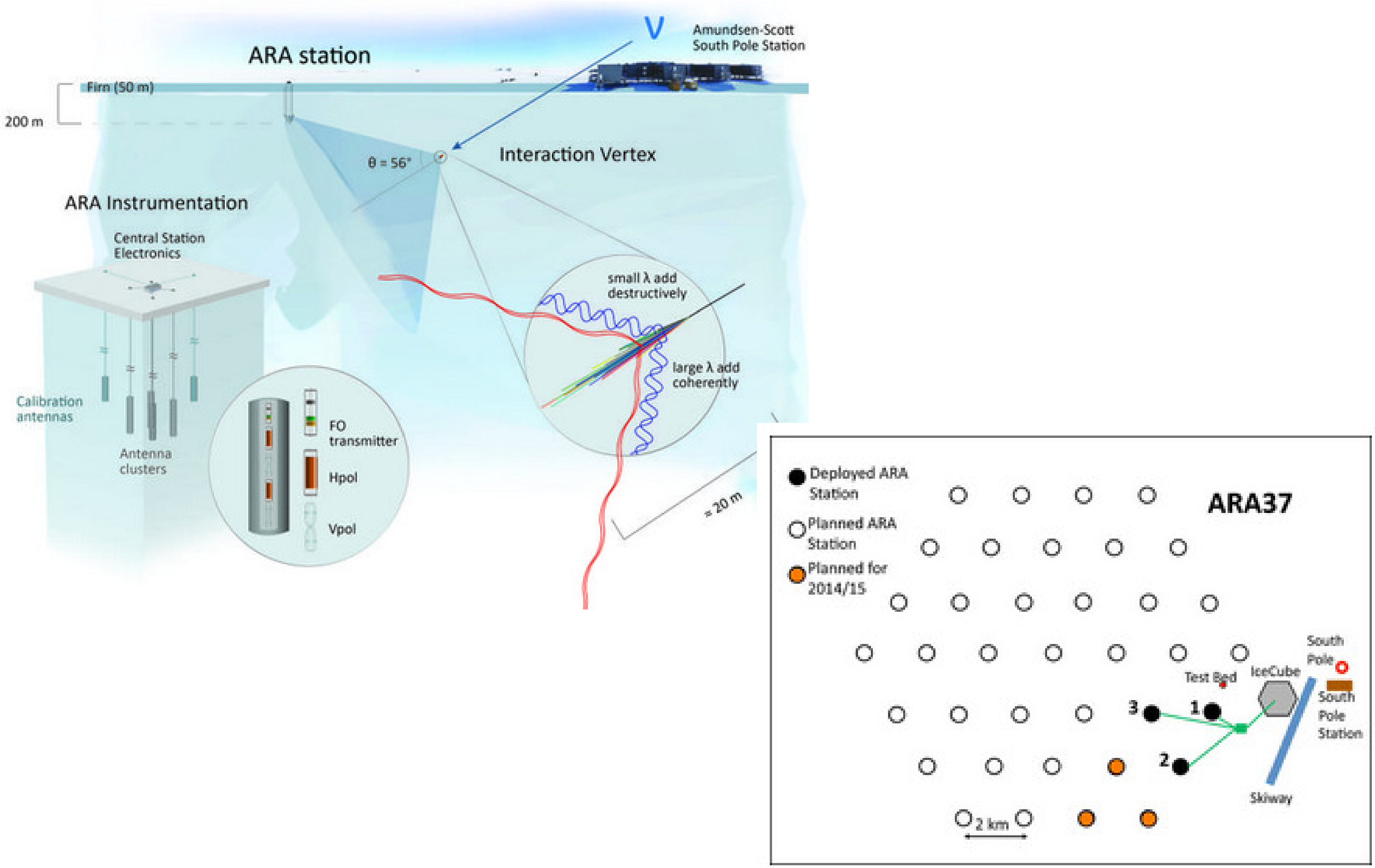
Radio efforts

- In-situ
  - RICE – south pole exploration (10^{17} eV)
  - ARA – south pole prototype/discovery ($10^{17.5}$ eV)
  - ARIANNA – Ross ice shelf. prototype/discovery (10^{17} eV)
  - GNO – Summit, Greenland. investigation
  - SALSA – salt dome. paused.

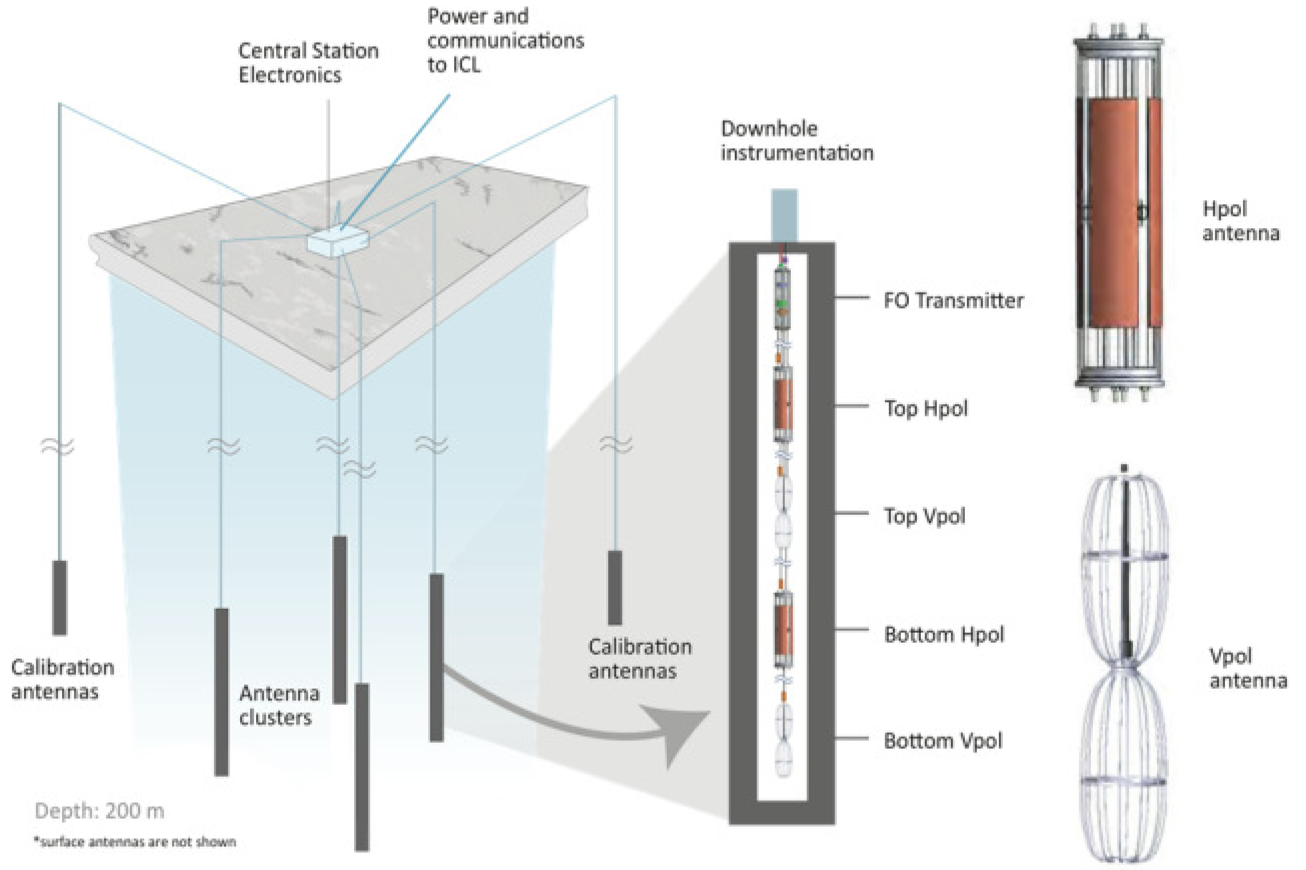
- Remote (higher threshold)
  - ANITA – ongoing (10^{19} eV)
  - EVA – development stage (10^{18} eV)
  - Lunar observations (10^{20+} eV) – numerous starts, being reevaluated
  - Spacecraft: LORD (Lunar orbit), Forte(Earth orbit) , PRIDE (Europa)

- GRAND – τ-channel

Radio – ARA version



ARA station


Central Station Electronics
Power and communications to ICL
Downhole instrumentation
FO Transmitter
Top Hpol
Top Vpol
Bottom Hpol
Bottom Vpol
Hpol antenna
Vpol antenna
Calibration antennas
Antenna clusters
Calibration antennas
Depth: 200 m
*surface antennas are not shown

ARA DAQ

Down hole

Surface

2 Hpol
2 Vpol

RF over OF

Digitizer
Trigger
x4

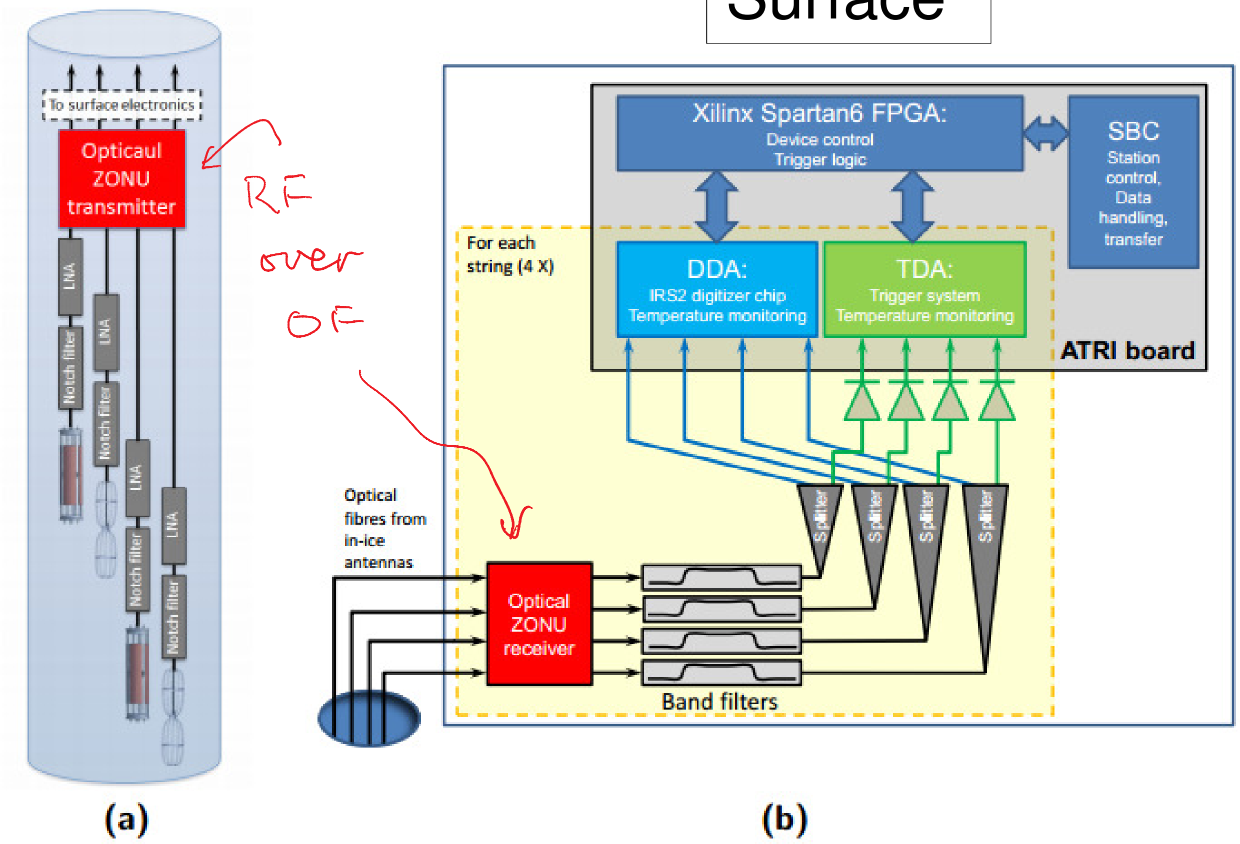


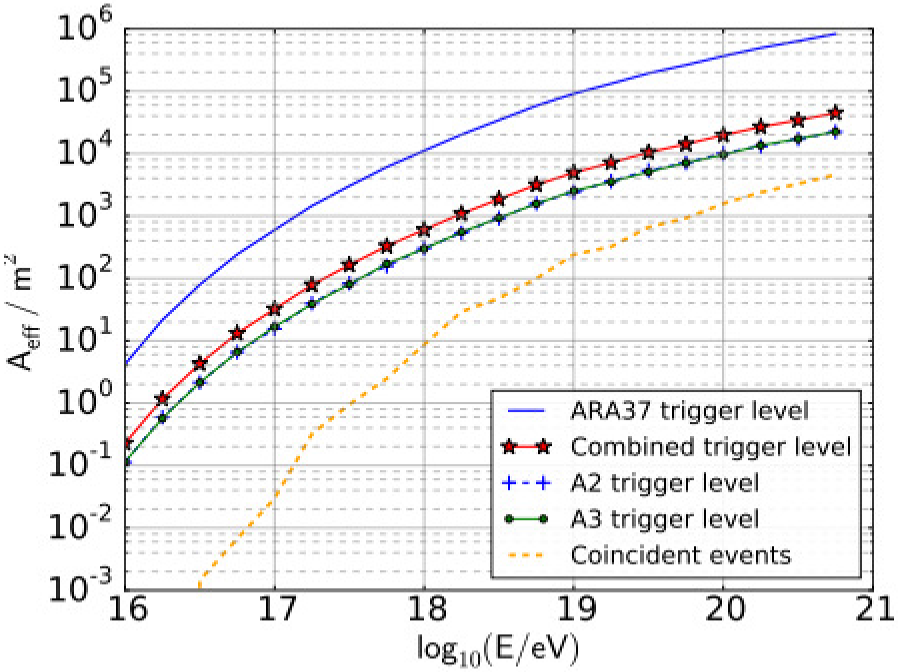
Figure 4.8: *(a) A schematic view of the key components in the ARA in-ice readout chain and (b) the DAQ system. Parts in the yellow shaded area are displayed for one string only, for visibility reasons. In reality they appear four times in each DAQ.*

T. Meures

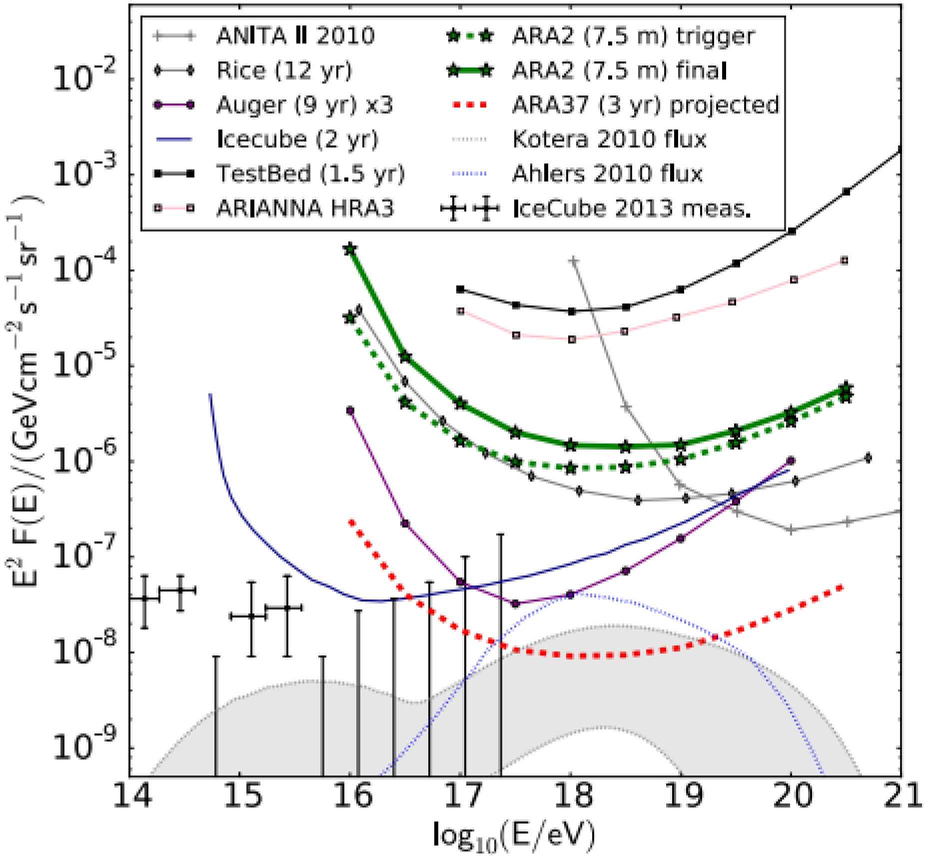
ARA construction

- 2010: Testbed
- 2011: ARA-1
- 2012: Improved drill ARA-2,3
- 2013: ARA-2,3 75%
- 2014: ARA-2,3 95%
- 2017: ARA-4,5 (with advanced trigger)

Results



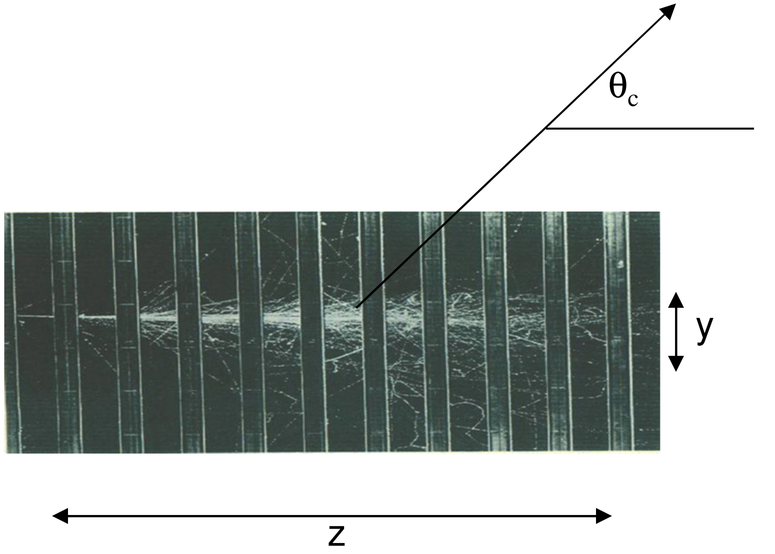
A_{eff} / m^2
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
16
17
18
19
20
21
$\log_{10}(E/eV)$
ARA37 trigger level
Combined trigger level
A2 trigger level
A3 trigger level
Coincident events



E^2 F(E)/(GeVcm^{-2}s^{-1}sr^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
14
15
16
17
18
19
20
21
$\log_{10}(E/eV)$
ANITA II 2010
Rice (12 yr)
Auger (9 yr) x3
Icecube (2 yr)
TestBed (1.5 yr)
ARIANNA HRA3
ARA2 (7.5 m) trigger
ARA2 (7.5 m) final
ARA37 (3 yr) projected
Kotera 2010 flux
Ahlers 2010 flux
IceCube 2013 meas.

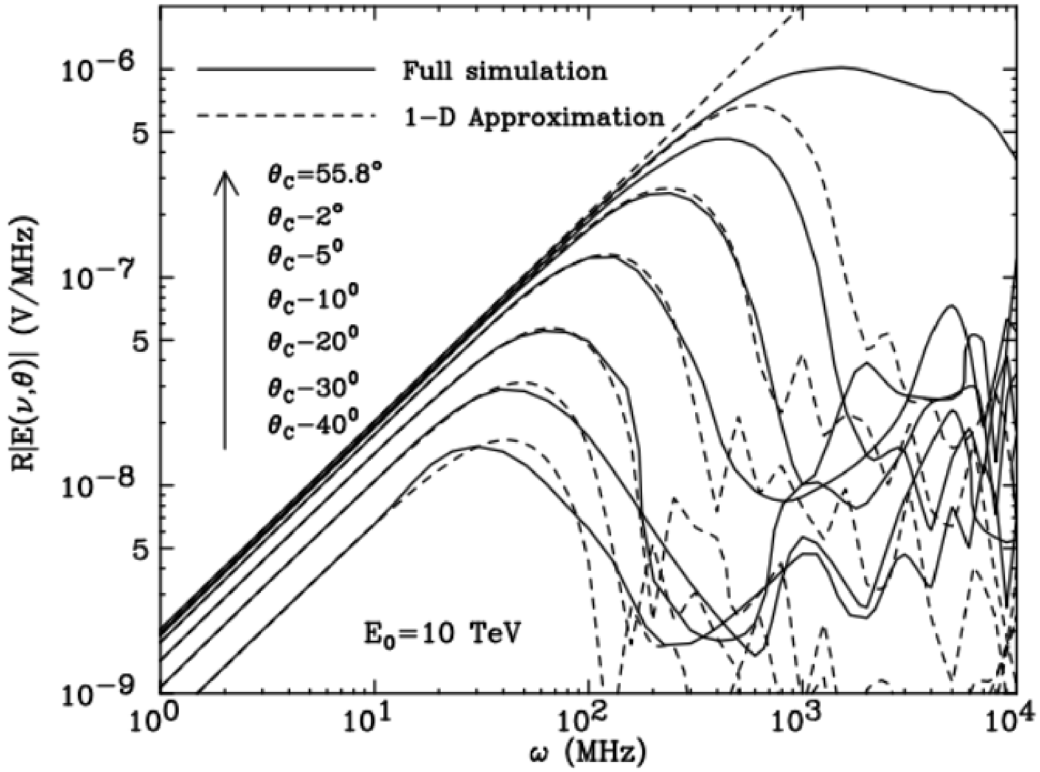
Radio emission

- net charge in shower $\Delta Q{\sim}20\%$
  - compton
  - delta rays
  - annihilation

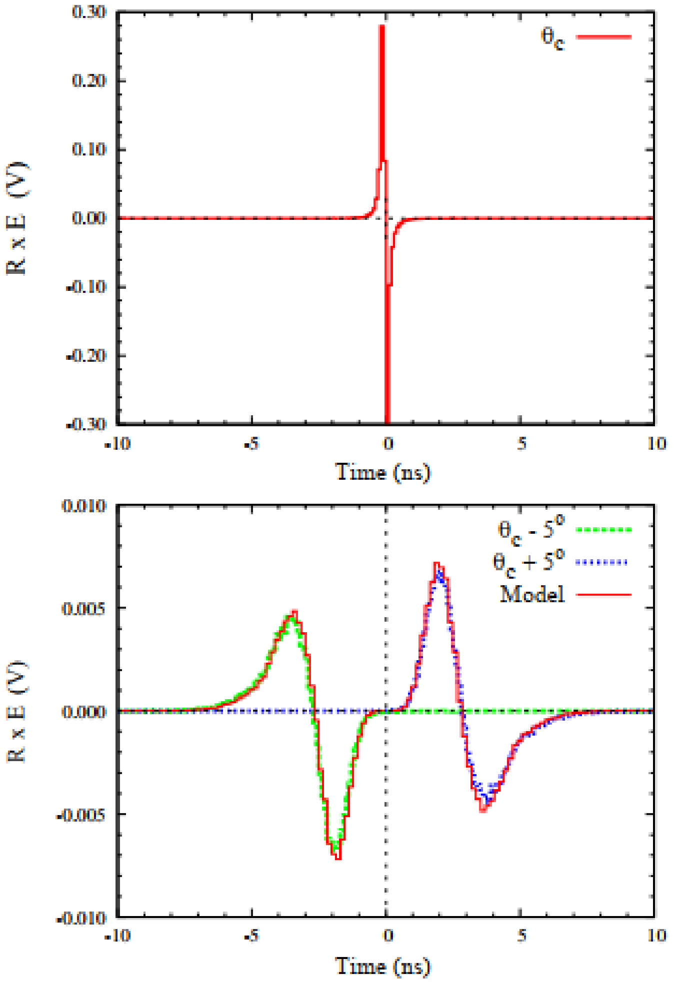


- shower front is narrow: Large Q, with form factor, moving at $\beta n > 1$, Cherenkov emission at $Cos[\theta_c] = \frac{1}{\beta n}$.

Askaryan pulses in frequency and time domain



Alvarez-Muniz, Vasquez, Zas



Alvarez-Muniz, Romero-Wolf, Zas

Some equations …

Polarization ⇐ $J_\perp = -\hat{n} \times \hat{n} \times \vec{J}$

$$\vec{E}(x,\,t) = -\frac{1}{c}\,\frac{\partial\vec{A}}{\partial t} = i\,\frac{\omega}{c}\,\vec{A}(x,\,t)$$

$$\vec{A}(x,\,t) = \int d^3x'\,dt'\,\frac{1}{|\vec{x}-\vec{x}'|}\left[\hat{n}\times\left(\hat{n}\times\vec{J}(\vec{x}',\,t')\right)\right] e^{i\phi(\vec{x}',t';\;\vec{x},t)}$$

⇑

Defines Coherence

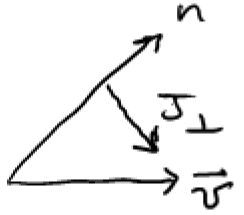
$$\vec{J}(\vec{x},\,t) = \overset{\text{longitudinal}}{\rho(z)}\,\overset{\text{shower front}}{\delta(z-ct)}\,\overset{\text{Transverse}}{\vec{j}(r,\,\theta)}$$

$$\phi(\vec{x},\,t) = 2\pi f\left[\underbrace{t(1-n\cos(\theta))}_{\text{Cherenkov}} + \underbrace{n\,\frac{y}{c}\,\sin(\theta)}_{\text{Transverse form factor}}\right]$$

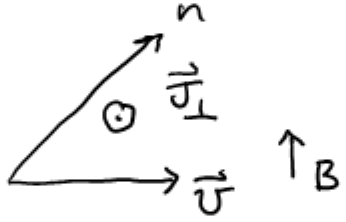
Strength & Polarization

$$\vec{J}_\perp = -(\hat{n} \times \hat{n} \times \vec{J})$$

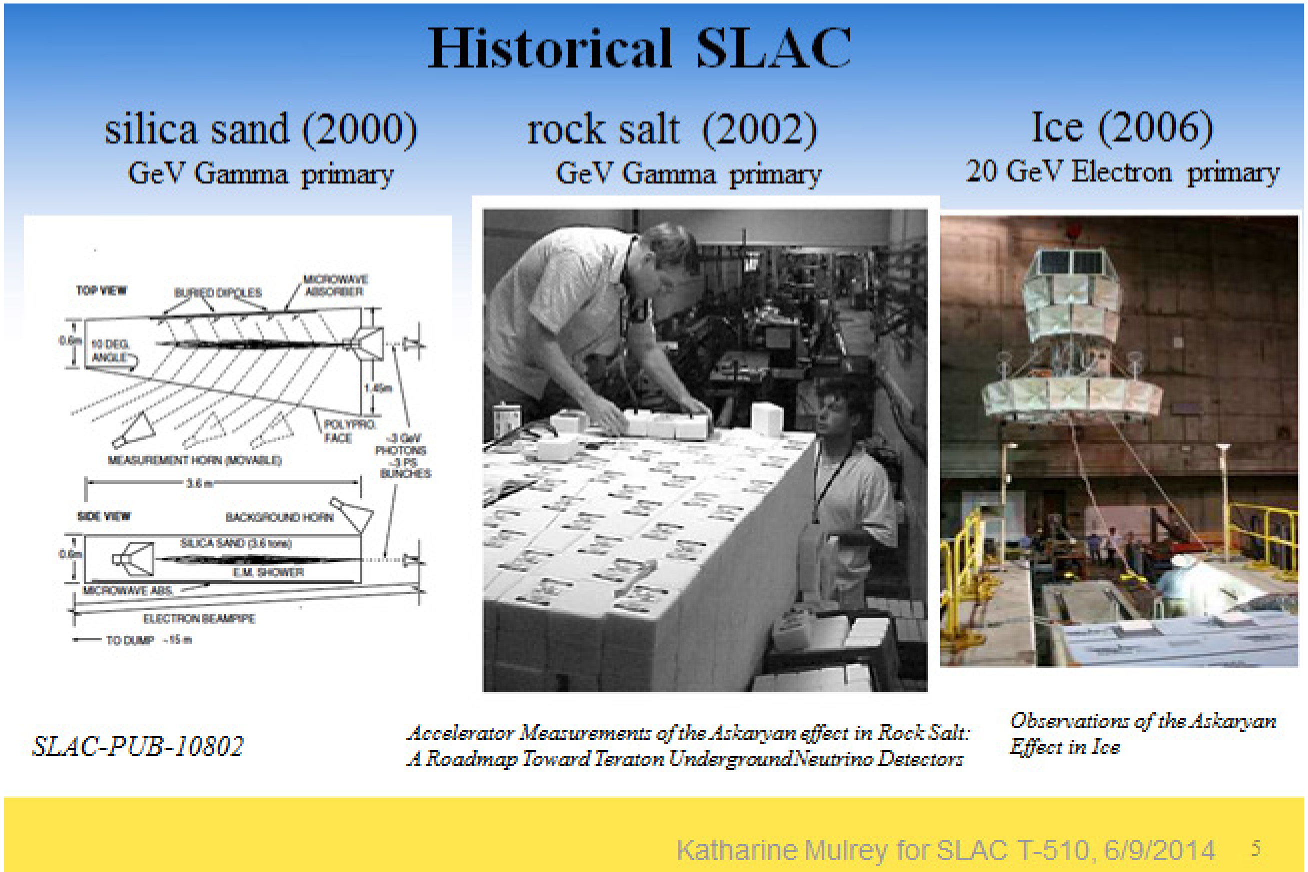
Askaryan $\quad \vec{J} = n(z)\, \overset{20\%}{\overset{\downarrow}{\Delta Q}}\, \vec{v}$



Geomagnetic $\quad \vec{J} \propto n(z)\; q^2\, \frac{\tau}{m}\; \vec{v} \times \vec{B}$



SLAC



Historical SLAC

silica sand (2000)
GeV Gamma primary

rock salt (2002)
GeV Gamma primary

Ice (2006)
20 GeV Electron primary

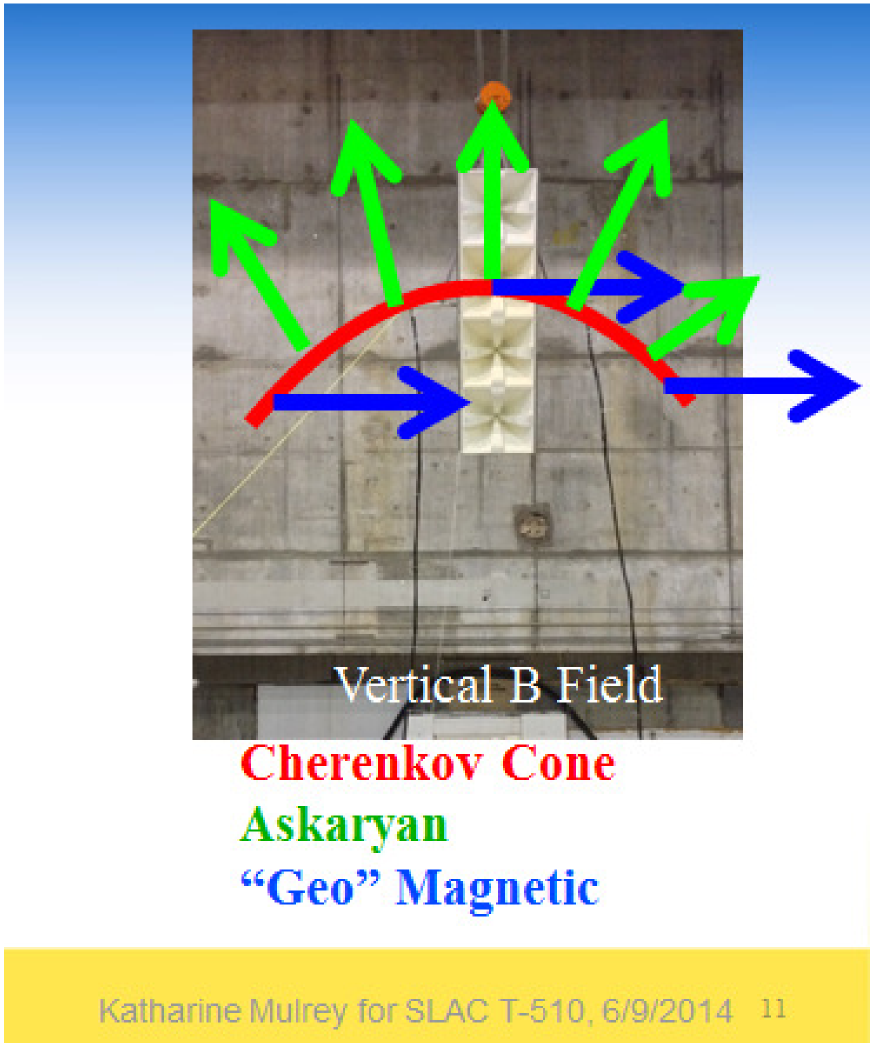
SLAC-PUB-10802

Accelerator Measurements of the Askaryan effect in Rock Salt: A Roadmap Toward Teraton Underground Neutrino Detectors

Observations of the Askaryan Effect in Ice

Katharine Mulrey for SLAC T-510, 6/9/2014 5

SLAC T-510

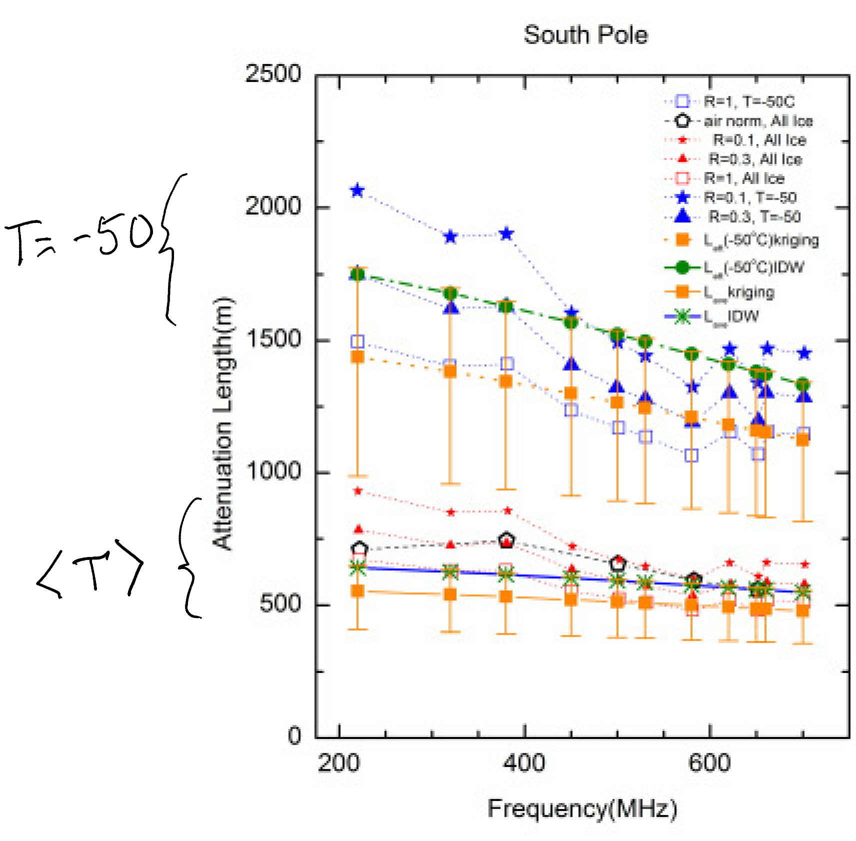


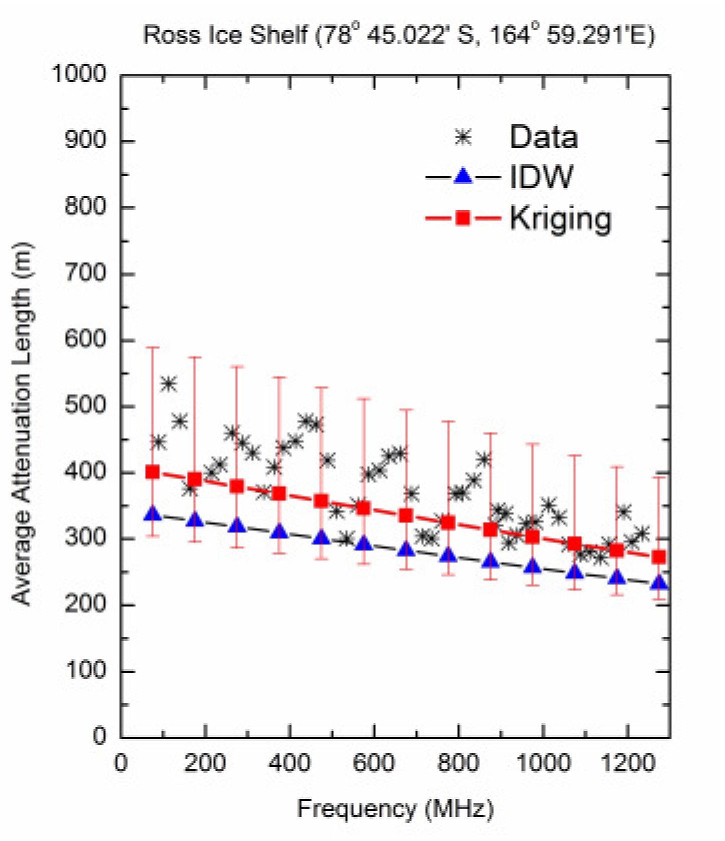
Cherenkov Cone
Askaryan
“Geo” Magnetic

Katharine Mulrey for SLAC T-510, 6/9/2014 11

attenuation in polar ice

- Depends on mobility of protons (H)
  - ice temperature, impurities, frequency



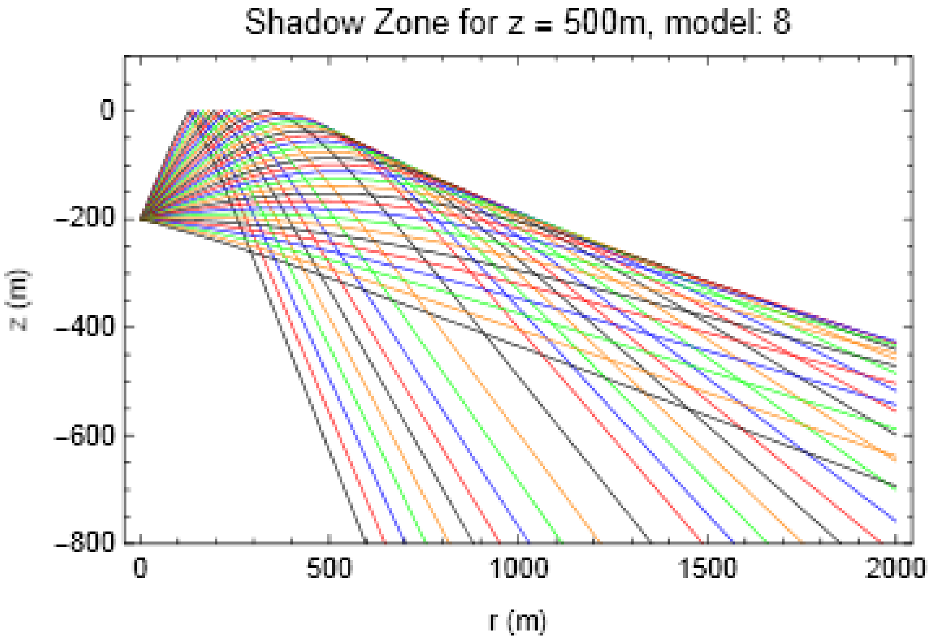


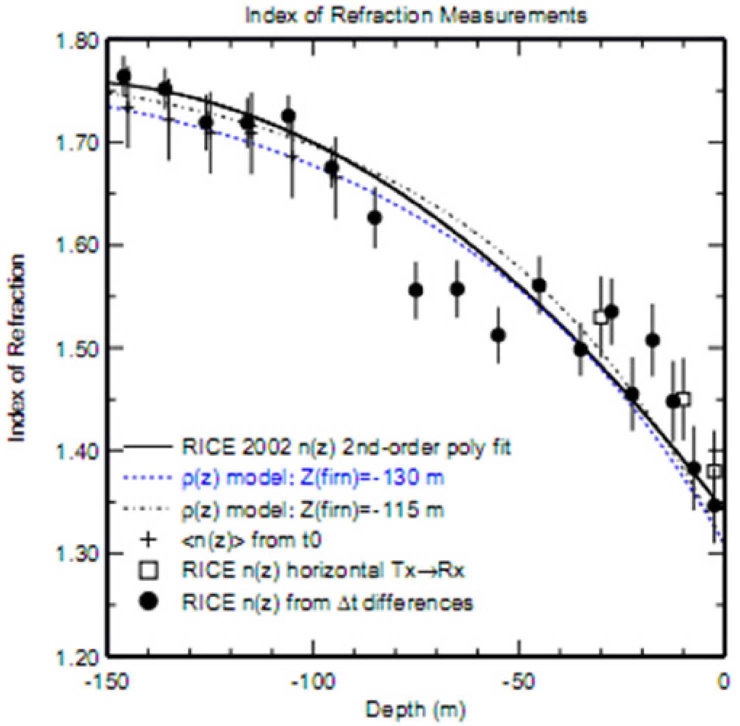
Javaid

Ray optics

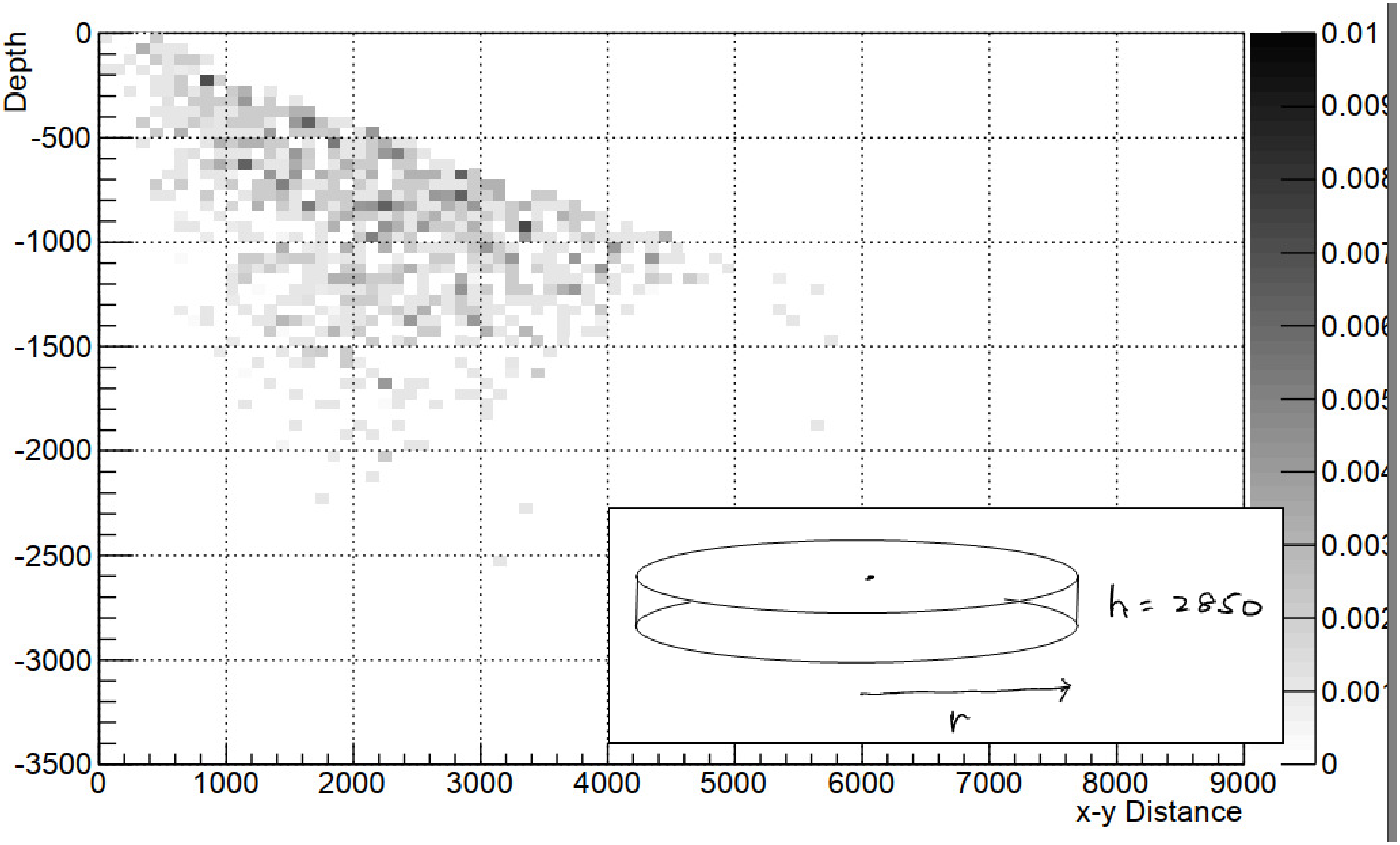
RICE

$n_0 = 1.78$

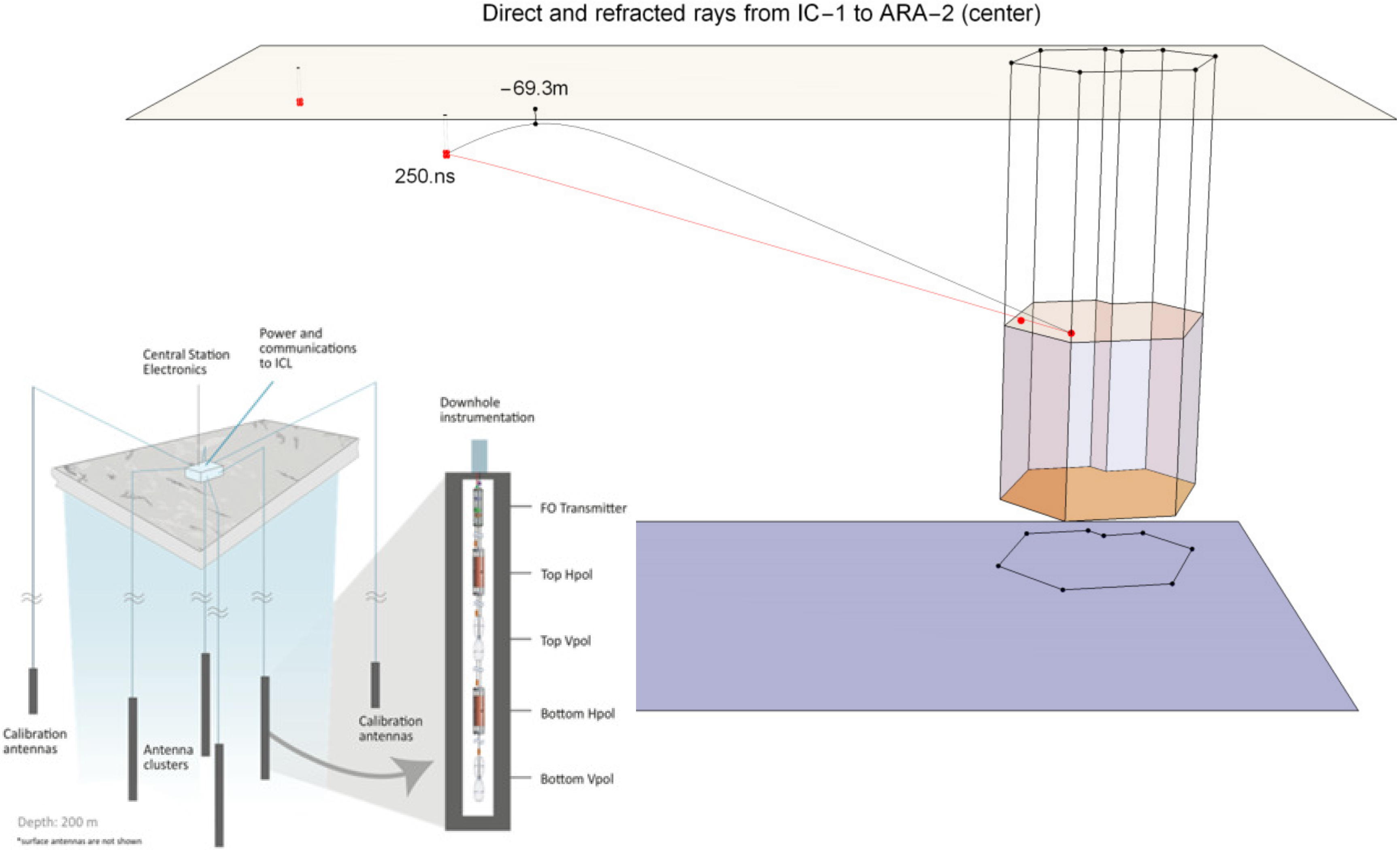




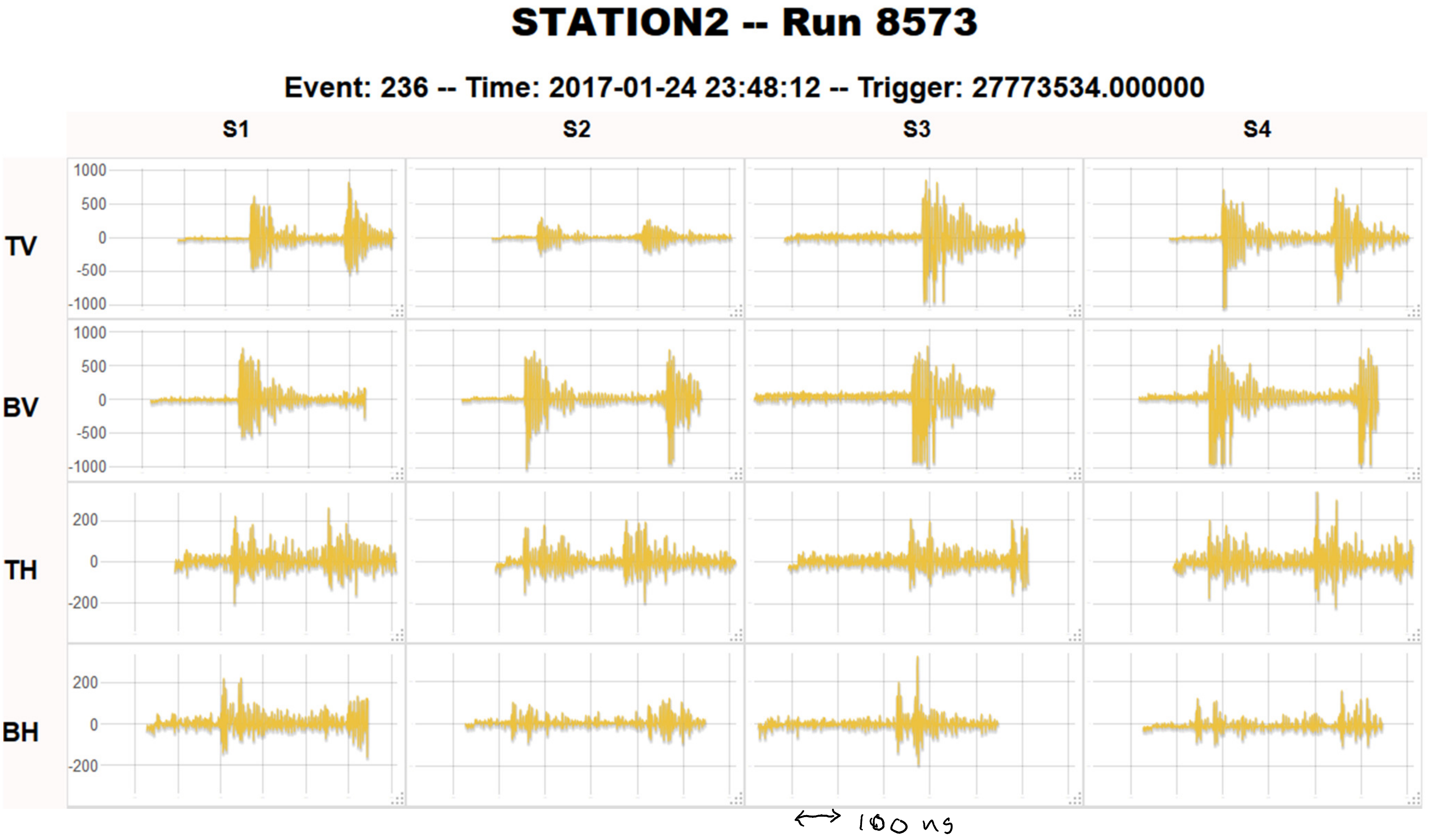
Simulation @ $10^{18.5}$ eV



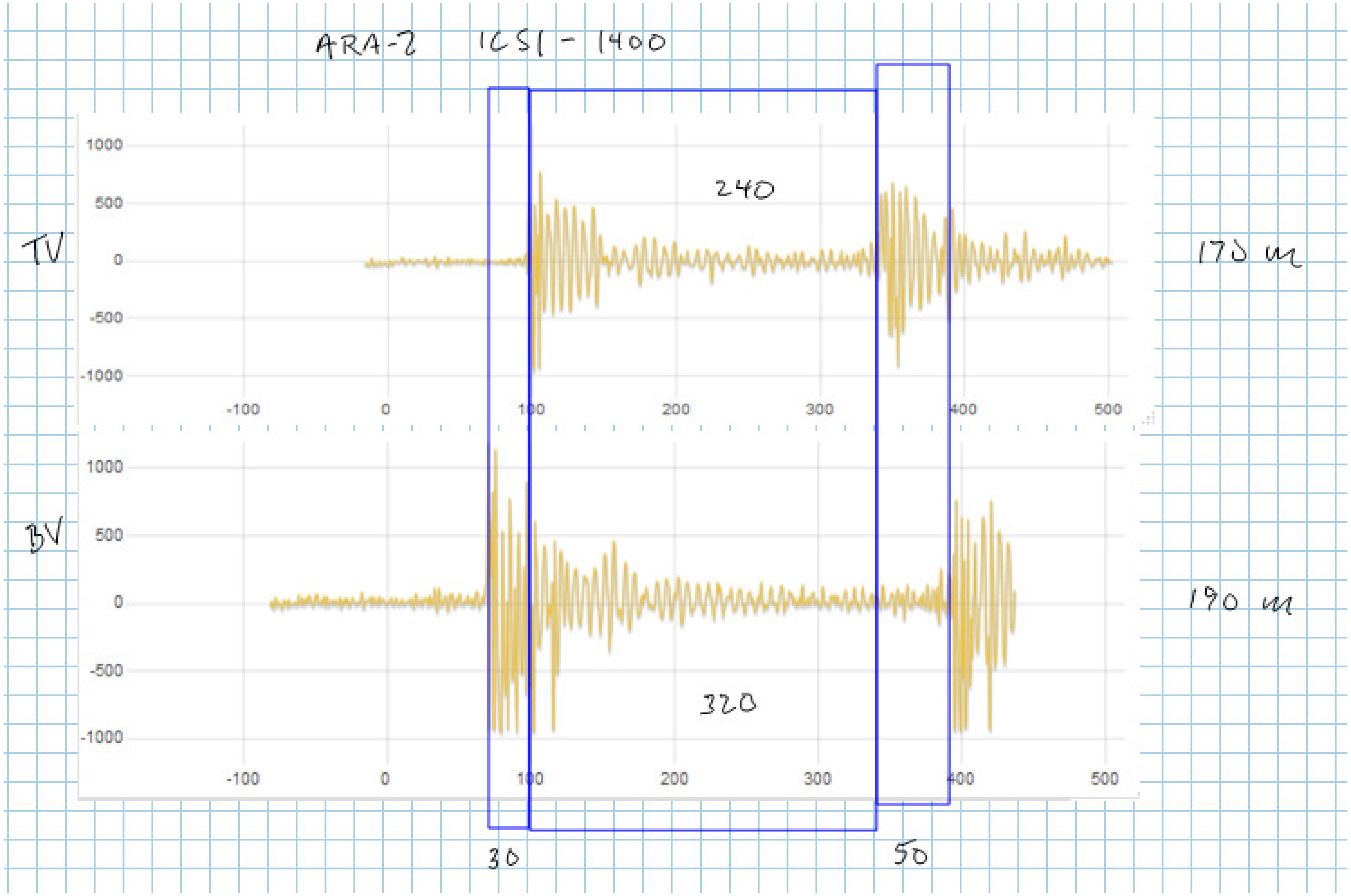
Deep Pulsers



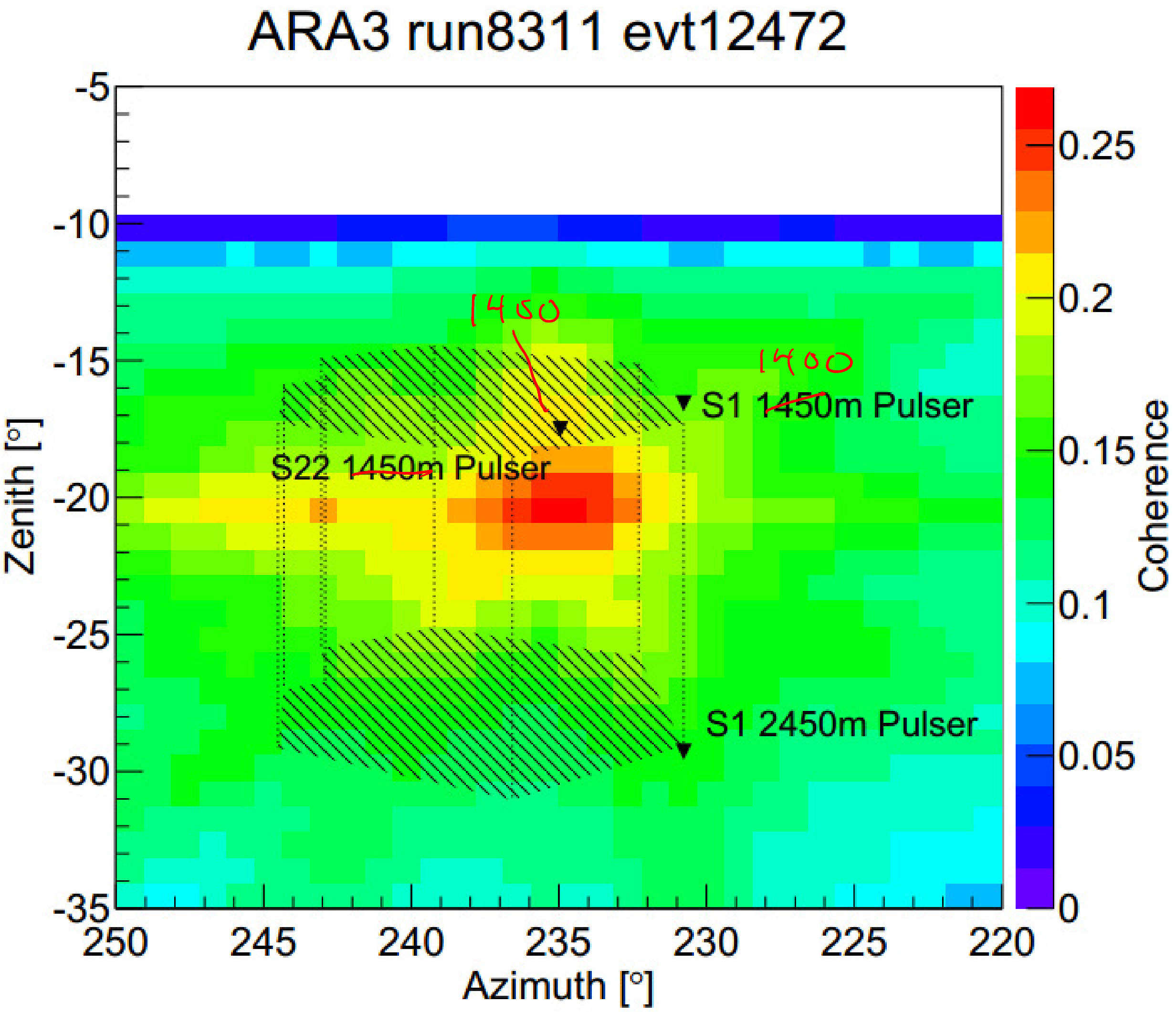
Deep pulsers



Pulse quality and timing



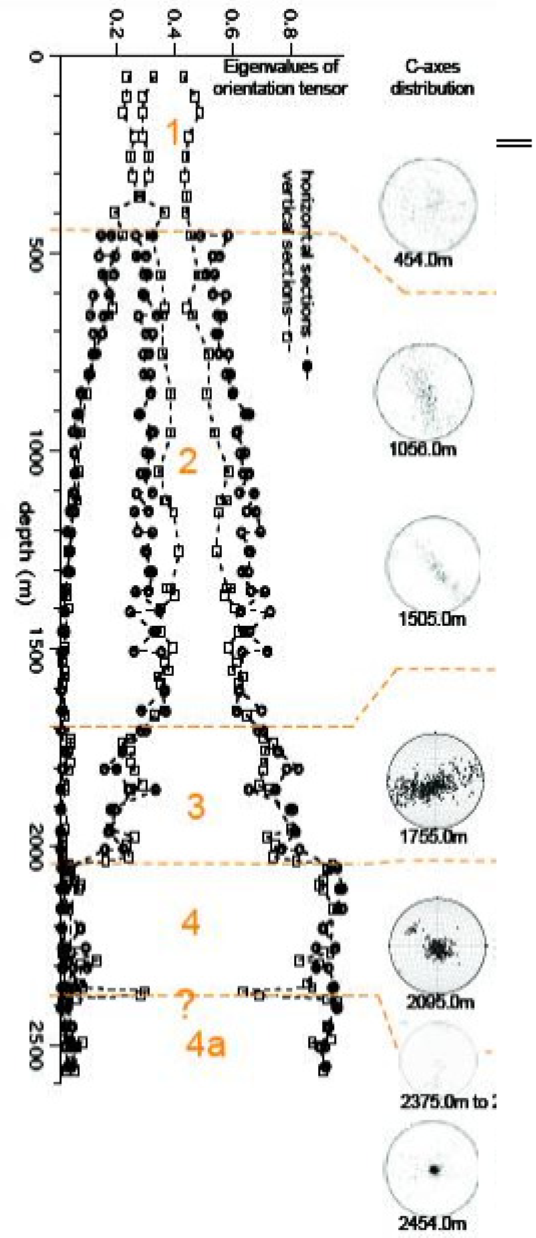
Event reconstruction of direct pulse (M-Y Lu)



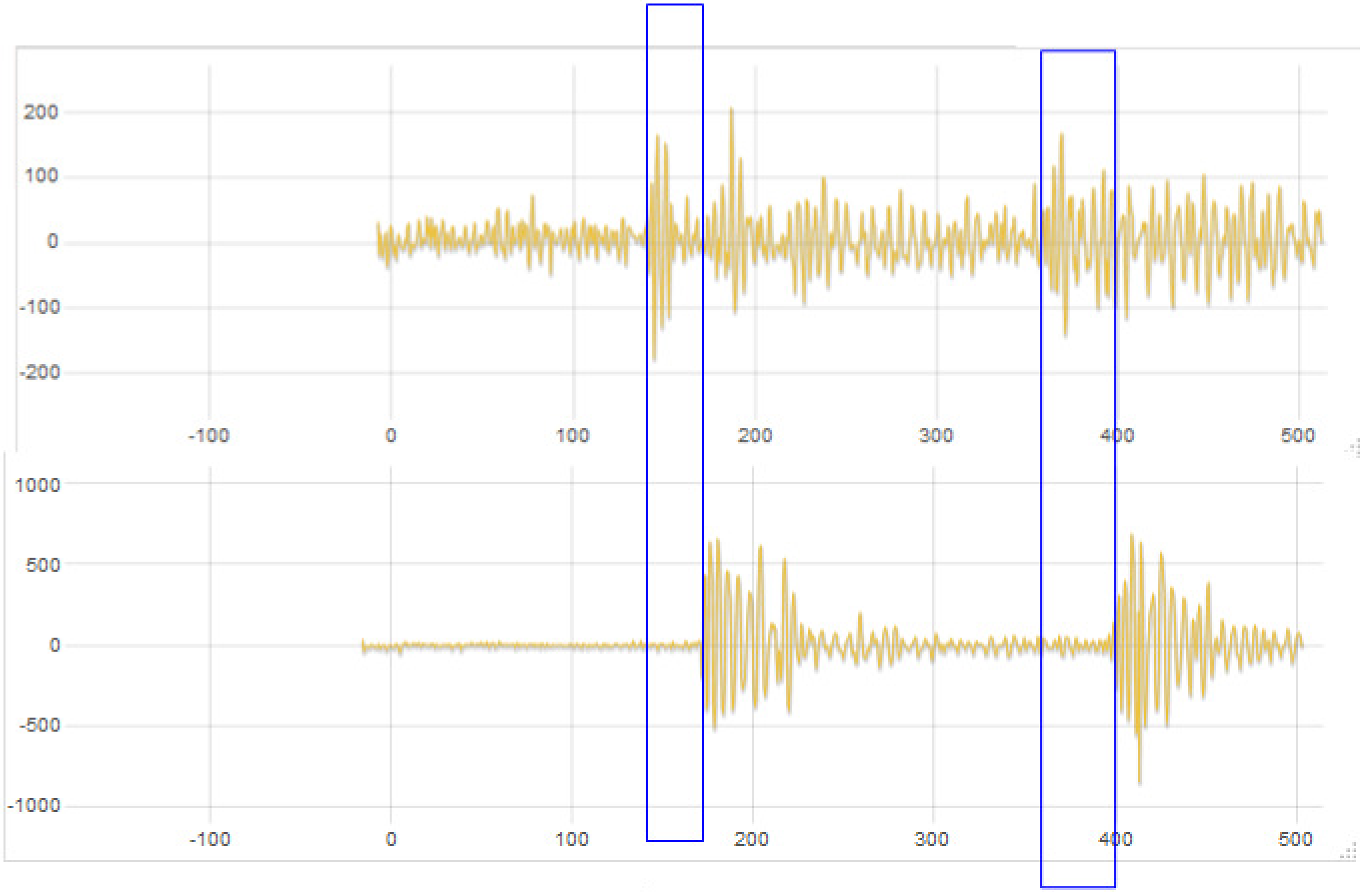
Propagation: birefringence

- We don’t simulate this, but …
- dn/n ~ 10^{-3} is possible
- dt = 5 ns per km.
- Predict Hpol arrives first

c-axis
at vostok



birefringence



TH

168

TV

170

~ 30ns

t_{tot} ~ 4000m @ 6ns/m

25 μs

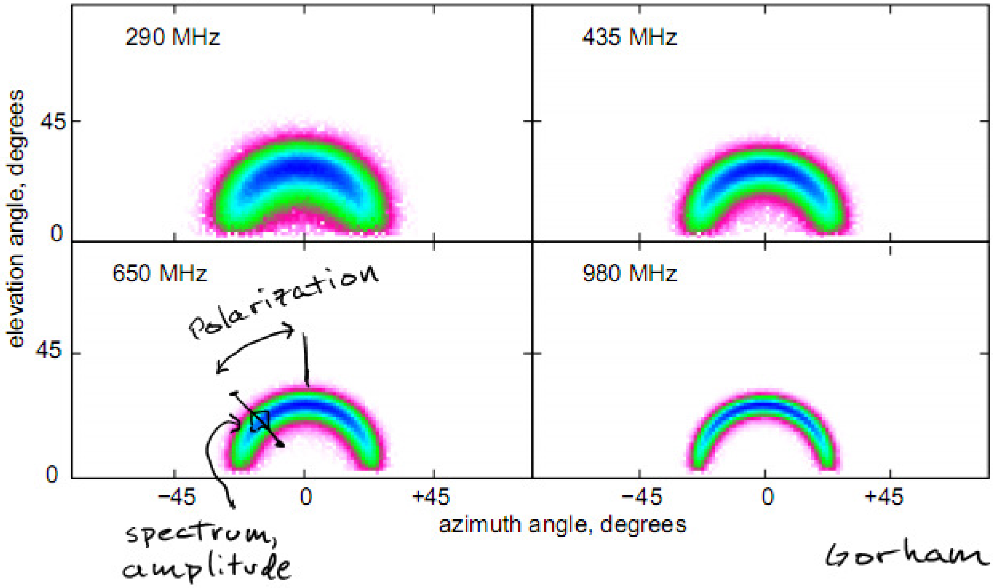
$\frac{\Delta n}{n} \sim 10^{-3}$

wider but 8ns for depth

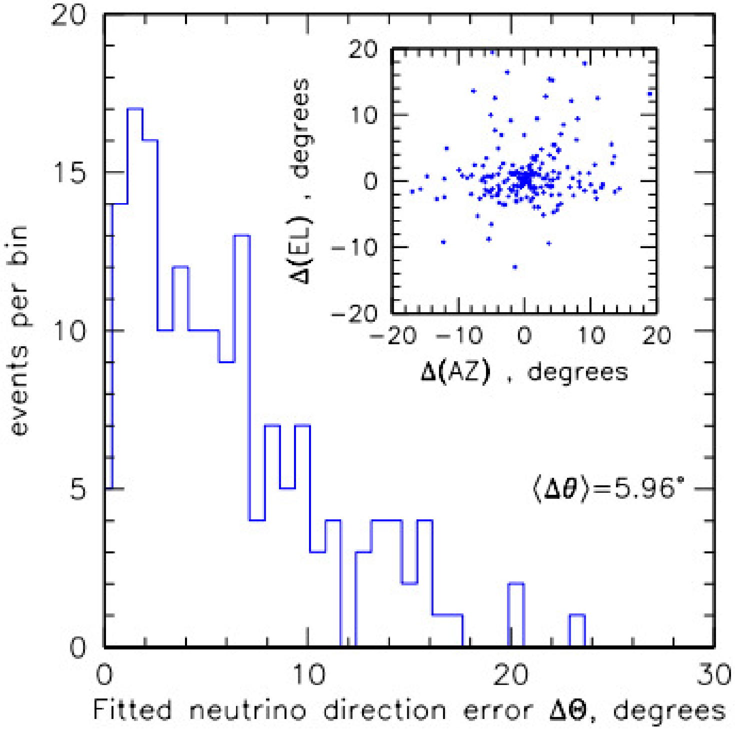
Event reconstruction

- Energy
  - distance
  - location in C-cone
  - $d\sigma/dy$
- Neutrino direction
- Flavor

(Actually from ANITA sim)

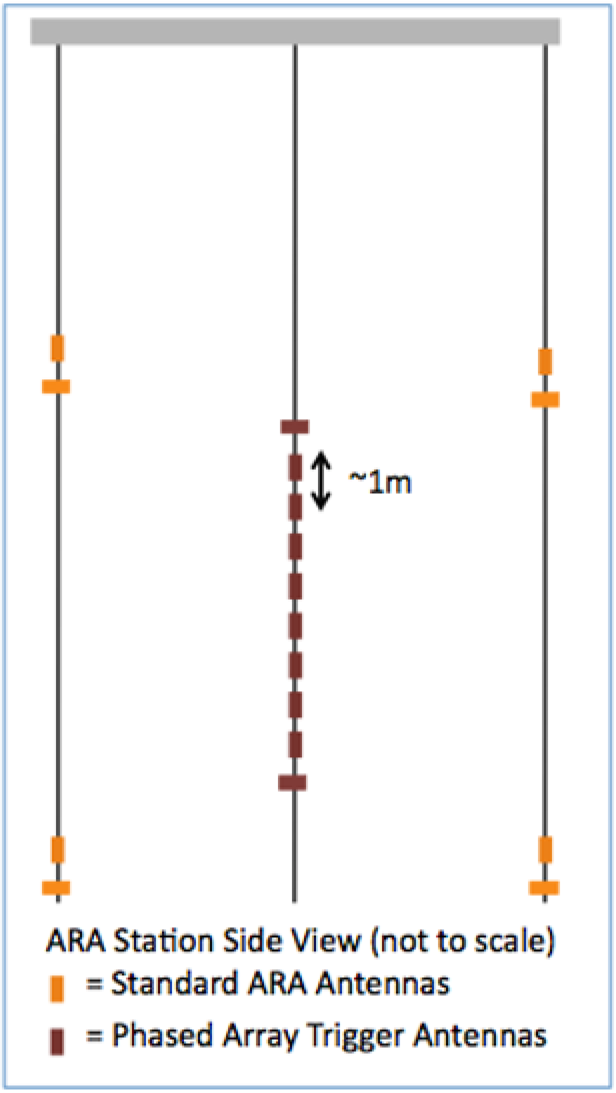


Gorham



Advanced trigger

- Phased array
  - 8 vpol antennas
  - tight spacing
  - real time digitizer
  - form beams in fpga
- Improve S/N by Sqrt[8]
- Installed Jan 2018
  - testing



ARA Station Side View (not to scale)

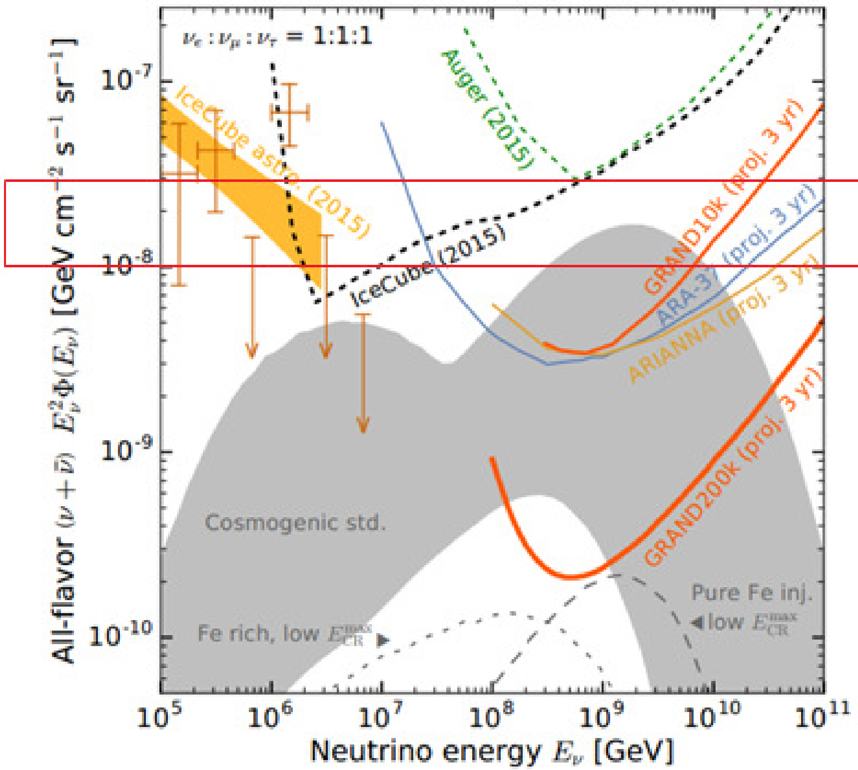
🟧 = Standard ARA Antennas

🟥 = Phased Array Trigger Antennas

GRAND

- Explore the world for locations for τ-channel

- GRAND
  - 10000
  - 200000



GRAND

Antarctic canyons?

Vast hidden canyons and mountain ranges discovered in Antarctica

The enormous size of the troughs took scientists by surprise.

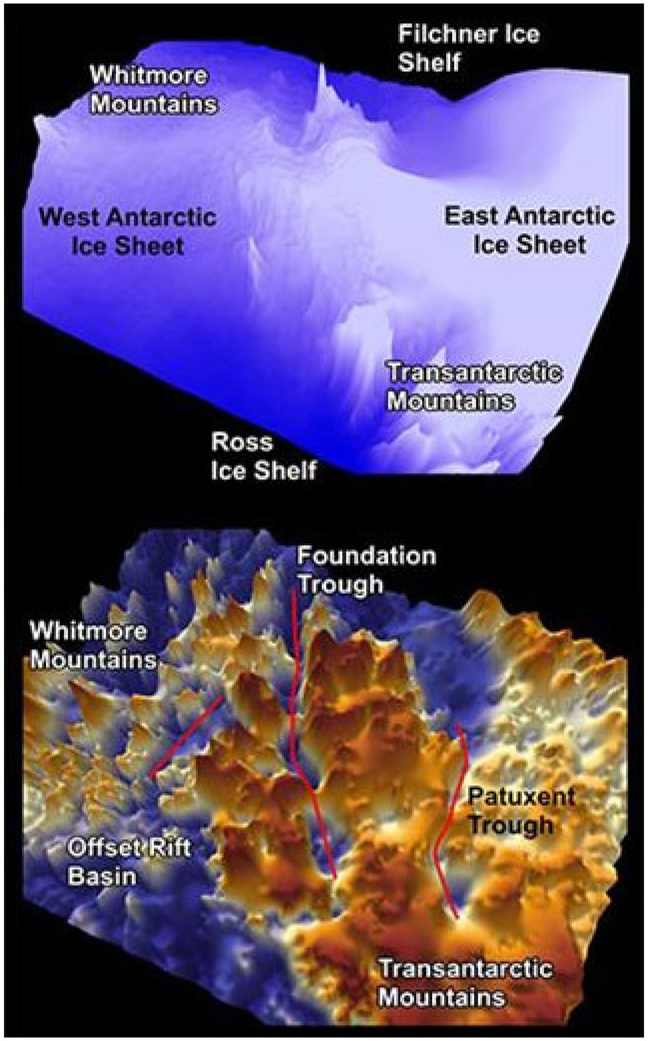
ℓ 350 km

w 50

h 3 ?

V= 50000 km

+ τ-channel



Summary

- Neutrino "detection" has many stages
  - production, propagation, interaction
  - final state products, radiation & propagation, detector
  - analysis

- HE physics, radiation techniques, machine learning (?)

- TeV-PeV
  - water/ice Cherenkov
  - IceCube operating 10 yrs

- To infinity and beyond (EeV)
  - radio techniques
  - many variations of radio detection