Radio detection of UHE neutrinos

David Seckel

Current Topics in Astroparticle Physics
Munich, Nov ~~9~~ 2022

11 bah!

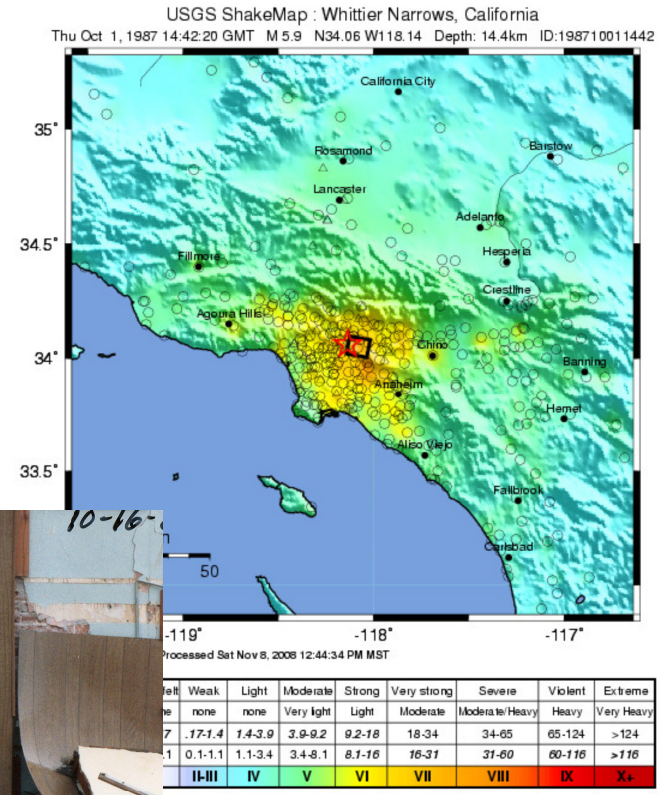
or … What have I been doing for 25 yrs?

Topics

- Georg & astroparticle physics
- Current topic in particle astrophysics – need for a BIG detector – 1000 x IceCube
- Radio technique
- ARA as an example
- RNO-g/Gen2
- What about Astroparticle (BSM) physics .. Q inspired by Georg and 201009a

Georg …

- 1987
- Travels with Georg
  - Don't do Physics and Drive
  - Be careful where you go ..
- Astroparticle physics is hard



What about Astroparticle physics ?

- Particle astrophysics: using particles to study stars & probe the Universe
  … Multi messenger astronomy

- Astroparticle physics: Use observation of stars to infer properties of matter
  … need to know SM really well!

- Overlap: Use natural particles to study particle physics
  - 1st do the particle astrophysics
  - 2nd do the astroparticle physics
    … ν-oscillations (solar, atmospheric), SN neutrinos, DM in CR

- New particles discovered in the beam
  … e.g. … μ, π a, γ', sterile ν

A current topic in particle astrophysics

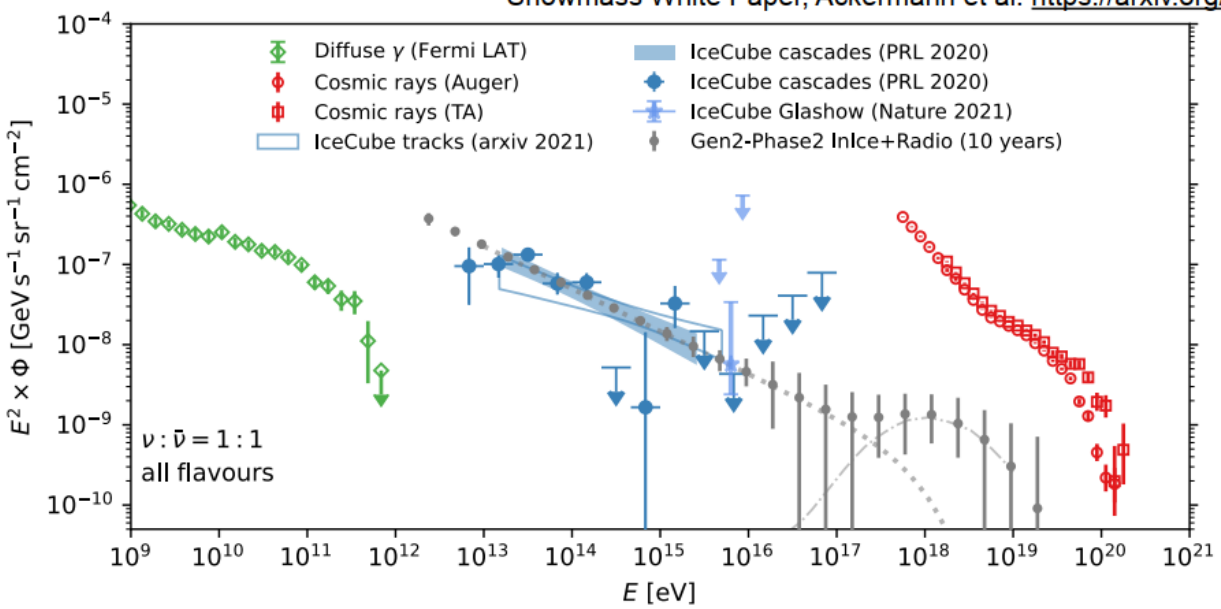
- Multi-messenger astrophysics
- IceCube Gen2
- Radio component for UHE neutrinos
- A little history … (from my view)

Why do we need a *big* detector (borrowed from Anna Nelles – ARENA 22)

"IceCube-Gen2 will play an essential role in shaping the new era of multi-messenger astronomy, fundamentally advancing our knowledge of the high-energy universe."

IceCube-Gen2: The Window to the Extreme Universe , https://arxiv.org/abs/2008.04323, *J.Phys.G* 48 (2021) 6, 060501

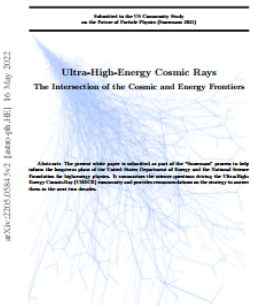
Snowmass White Paper, Ackermann et al. https://arxiv.org/abs/2203.08096v1



Or this version … (from Jorge Horandel)

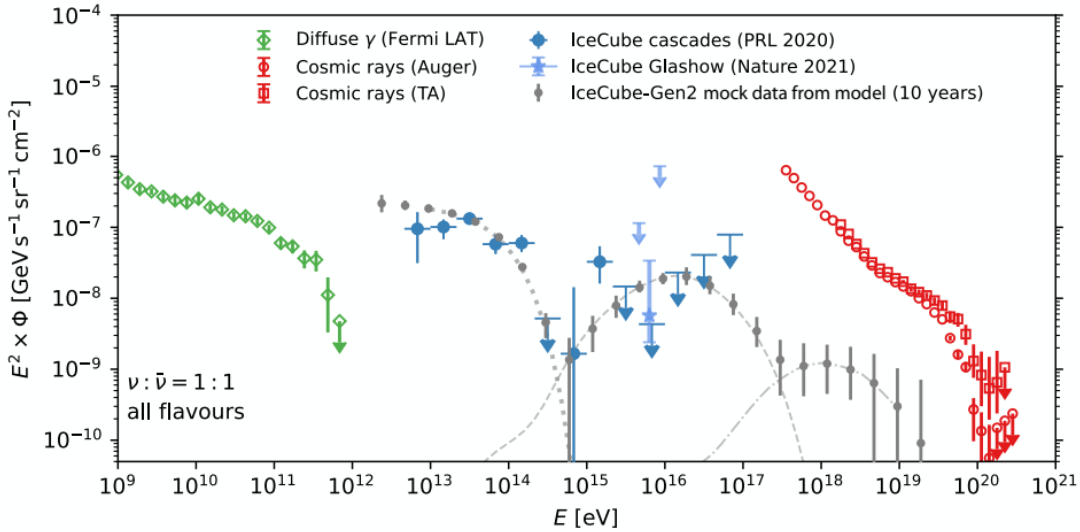
Multi-messenger astroparticle physics beyond 2030

protons, nuclei, gamma rays, neutrinos, (gravitational waves)



The road ahead as outlined in a Snowmass white paper:

- **Multi-messenger astroparticle physics**

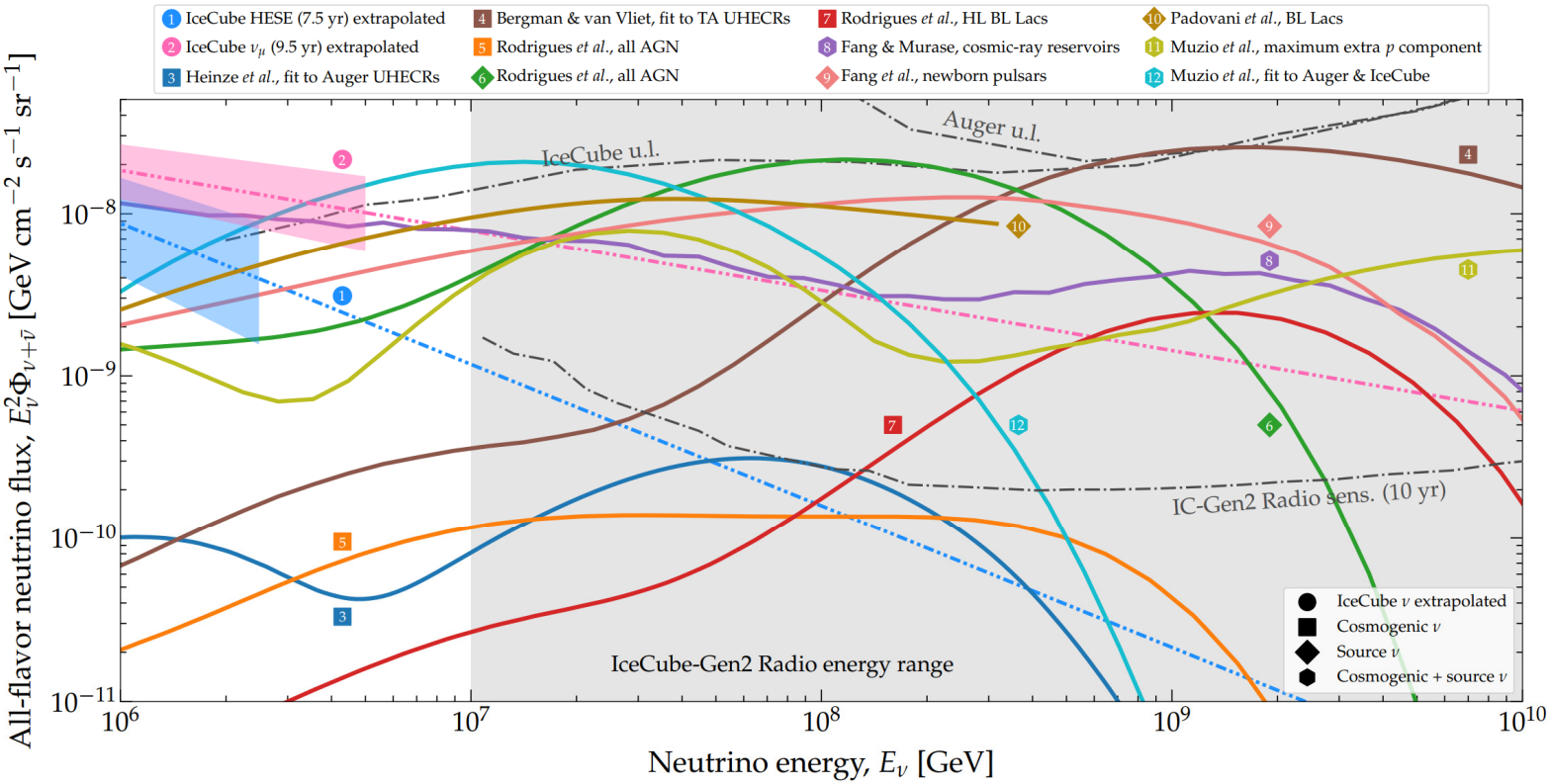


arXiv: 2205.05845

GCOS - Jörg R. Hörandel - ARENA 2022 5

A collection of models …

Valera, Bustamante, Glaser
arXiv:2210.03756v1 [astro-ph.HE] 7 Oct 2022

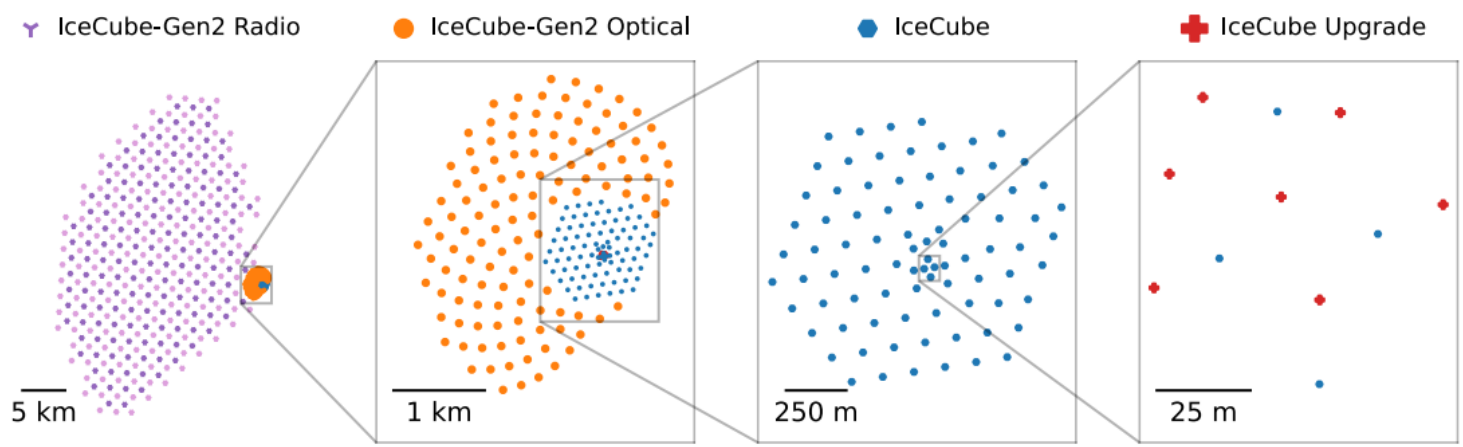


IceCube Gen-2 at ARENA.

https://indico.cern.ch/event/826366/timetable/#20220610.detailed

Borrowed shamelessly from Anna Nelles

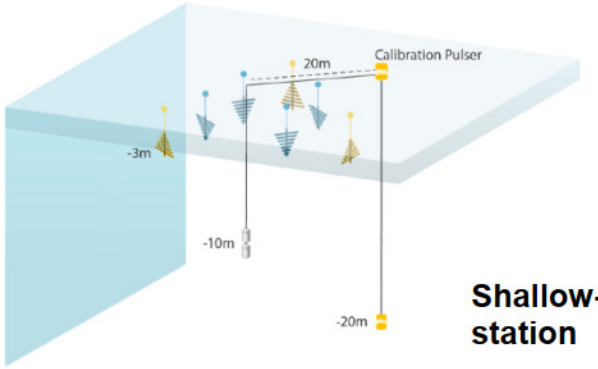
- IceCube-Gen2 is envisioned as combination of **extension of optical array**, **surface air shower array** and **in-ice radio neutrino array**
- Project costs similar to IceCube, radio array 10% of total costs
- Technical Design Report in progress
- First milestone: favorably reviewed in Astro 2020 US Decadal Survey



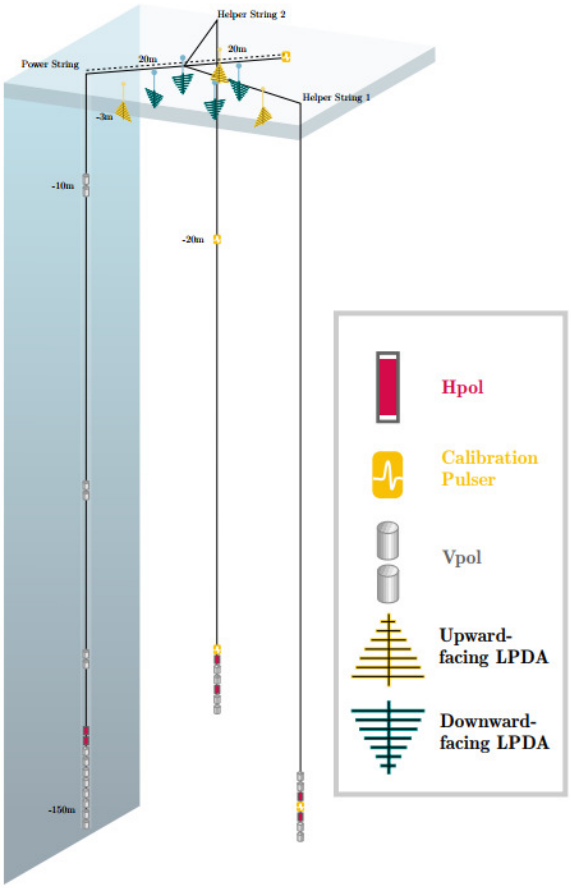
Coming to a reference design for IceCube-Gen2

Rationale for radio stations

- Chose combination of shallow stations and hybrid stations
  - 150 meter depth: larger firn at South Pole (= useful to go deeper than RNO-G)
  - Revised shallow antenna positions as compared to RNO-G & ARIANNA
  - Additional calibration pulsers



Shallow-only station

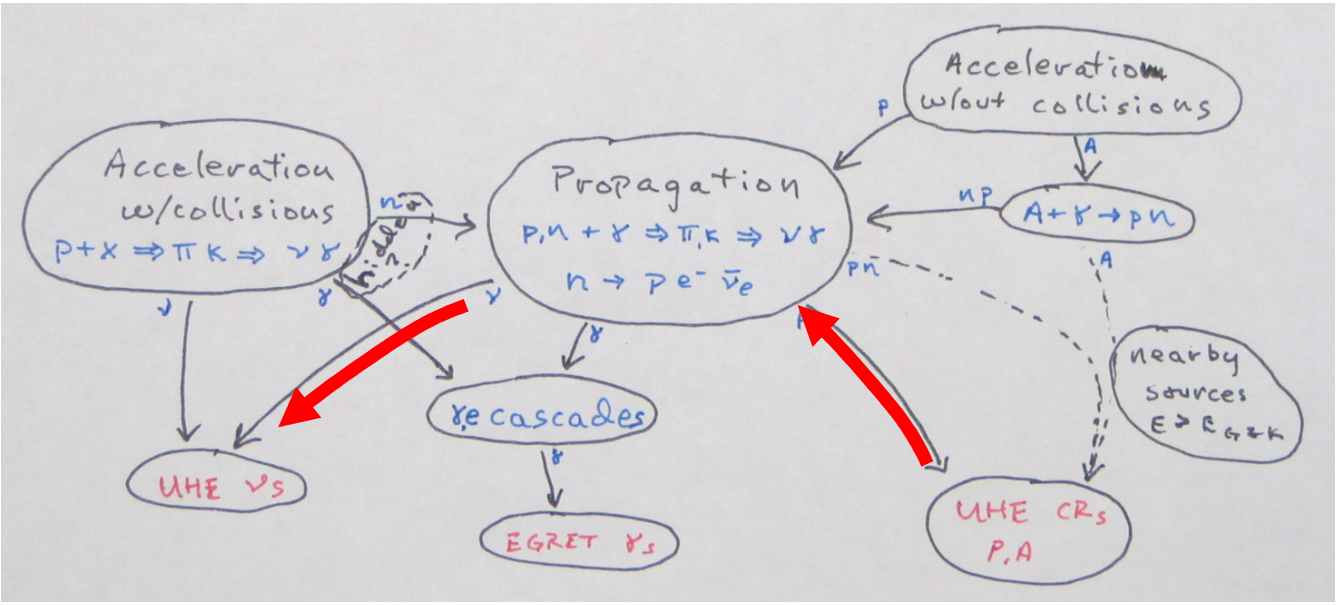


Hybrid station

DESY. Nelles, ARENA 2022

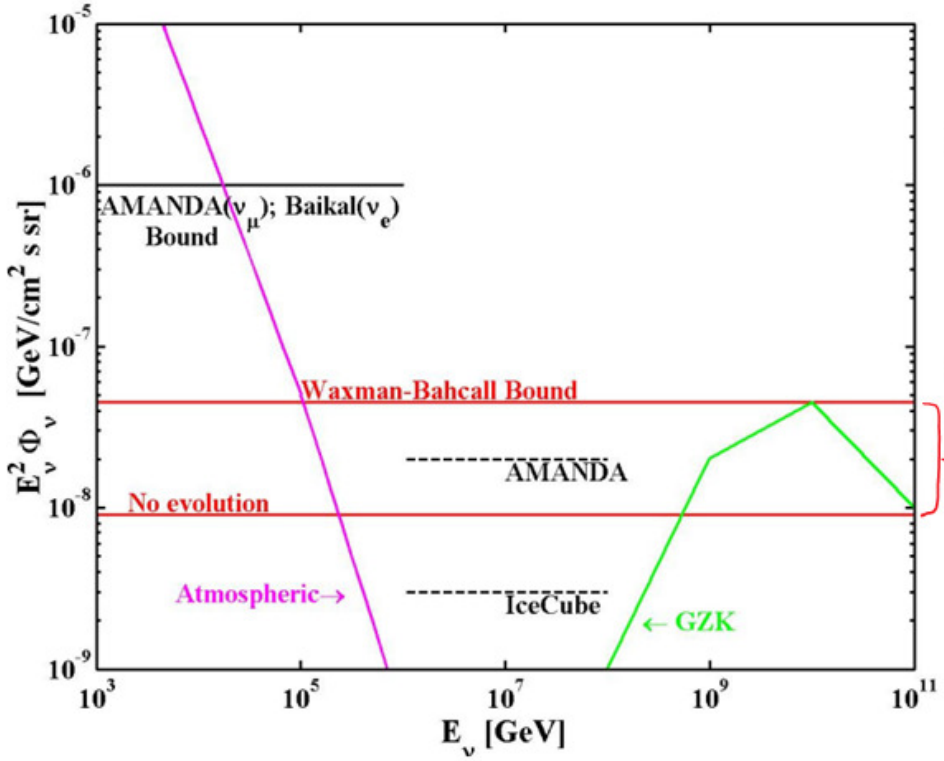
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS 7

Historical perspective of UHE production (drawn in 2004, but could have been in '94)



1. Acceleration predictions depend on scenario – could be "no ν's".
2. "GZK" neutrinos are guaranteed – a guide for experiment design.
3. Still some model dependence.
4. Constraints from EGRET & UHECR
5. $E_\nu \sim .05\ E_p$

Expectations: Waxman & Bahcall "bound"



Source

Energy budget

UHECR's @ 10^{19} eV

0.1 ν per proton

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

Propagation

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

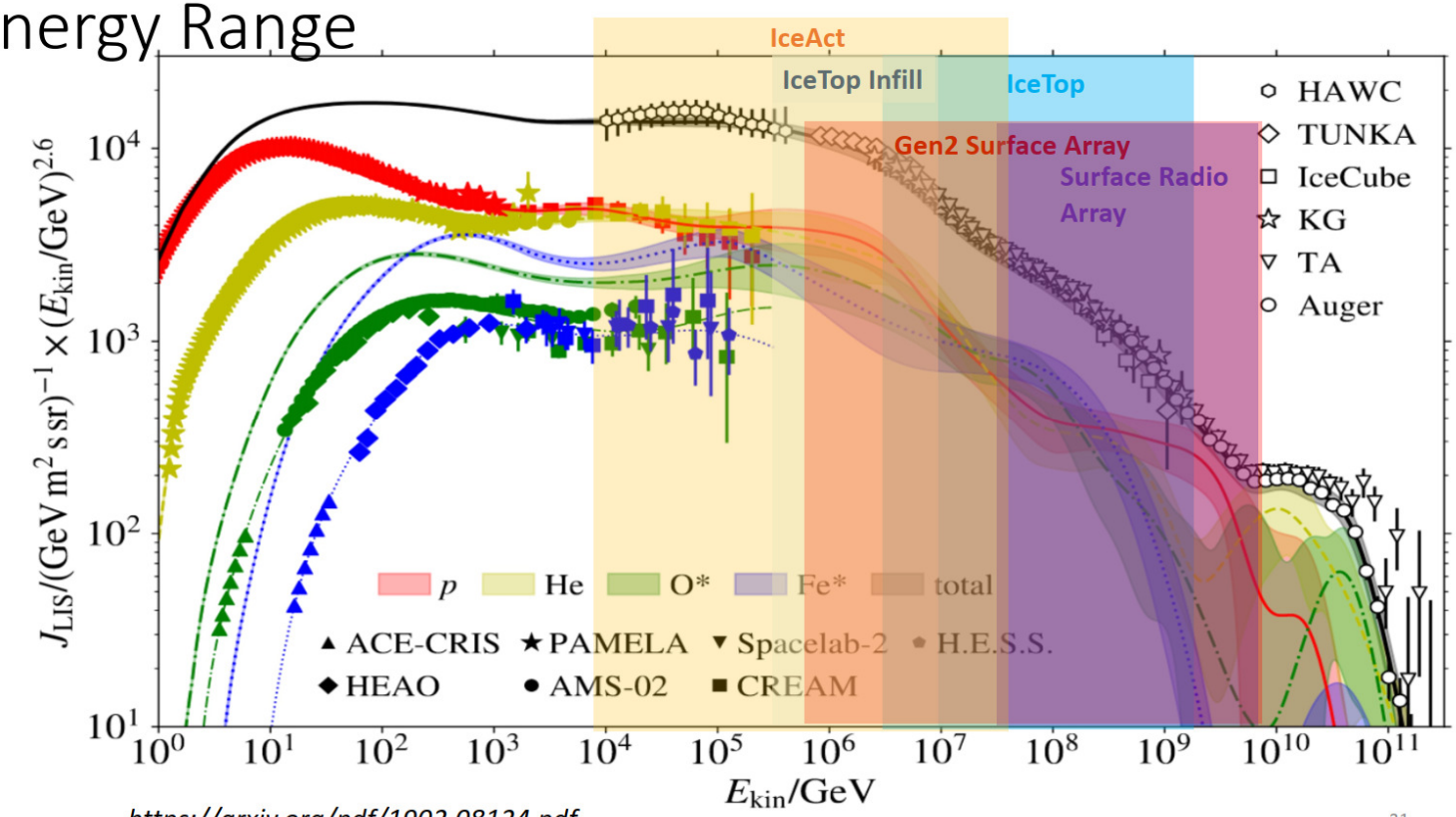
$\pi^+ \to \mu^+ \nu_\mu$

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

Waxman (NESS 2002)

CR not just protons

Energy Range



https://arxiv.org/pdf/1902.08124.pdf

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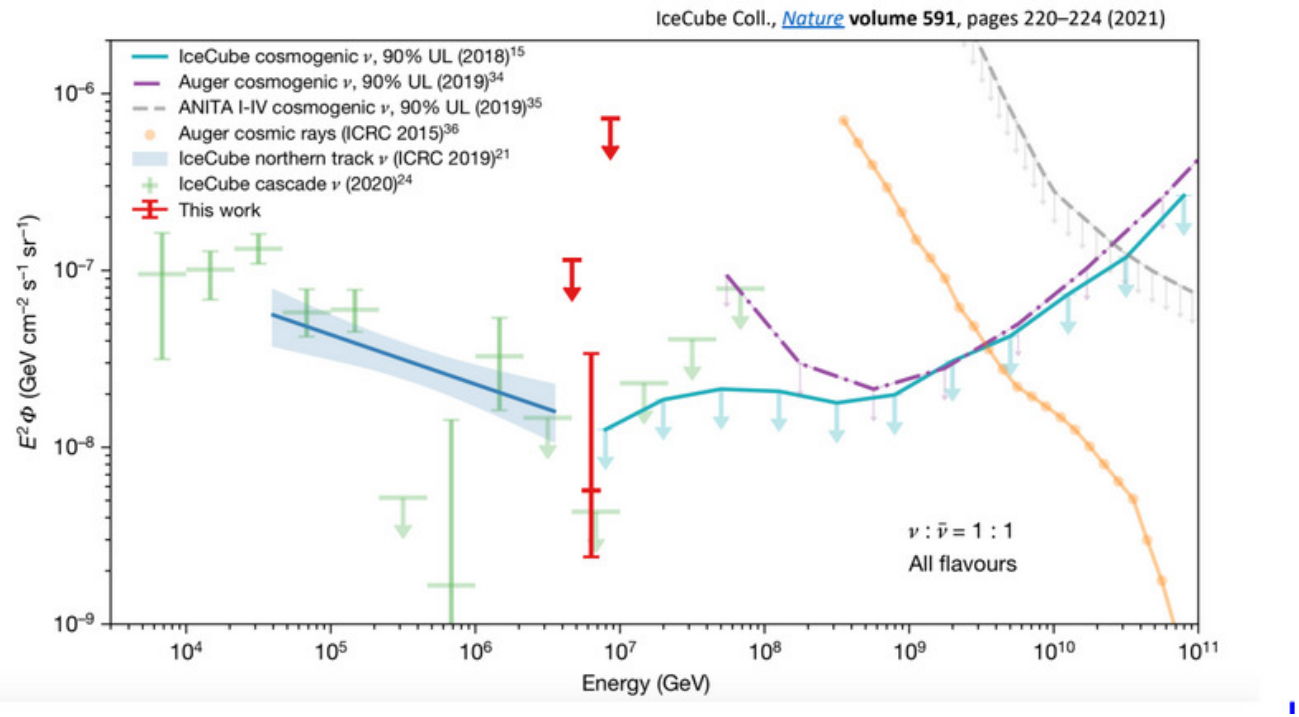
IceCube sees astrophysical neutrinos



UHE (EeV+) considerations 100+ km^3

$$\int_{E_T} \phi \sigma \, dE \sim E_T^{-0.7} \Rightarrow$$

$\phi \sim E^{-2}$, $\sigma \sim E^{-3}$

PeV → EeV

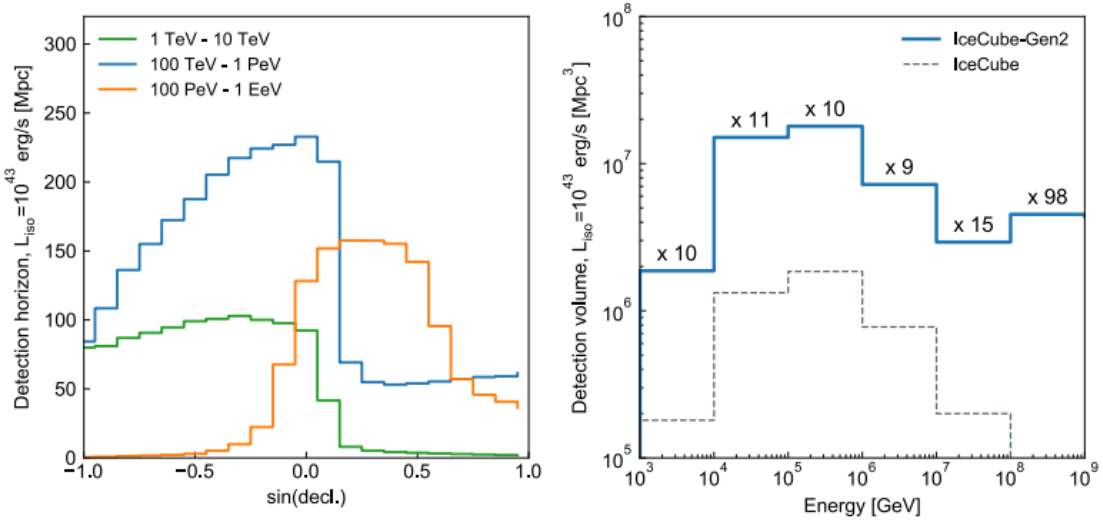
1 km^3 → 100 km^3

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

Science with IceCube-Gen2

More to come in the Technical Design Report

- Radio array complements the high energy capabilities of the optical array of IceCube-Gen2, delivers much improved flux detection capabilities at high energies
- Combined analyses will provide full energy spectrum coverage, although different angular coverage

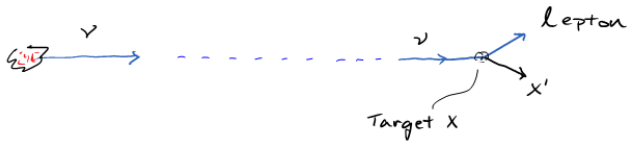


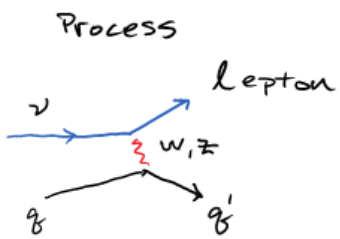
IceCube-Gen2, Technical Design Report, WORK IN PROGRESS

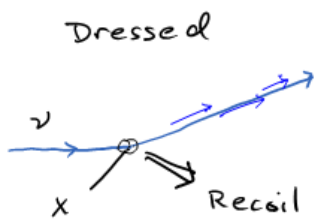
Radio detection of UHE neutrinos

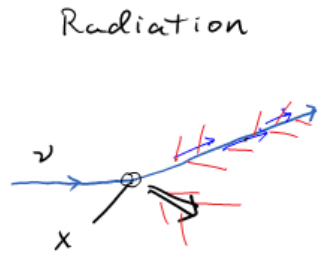
- Neutrino detection … UHE bigger than IceCube
- Electromagnetic radiation from cascades
- Antennas, DAQ, …
- Environment

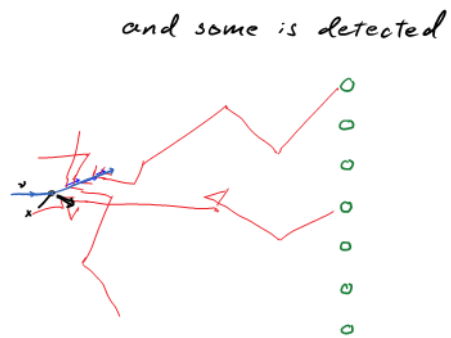
Neutrino detection

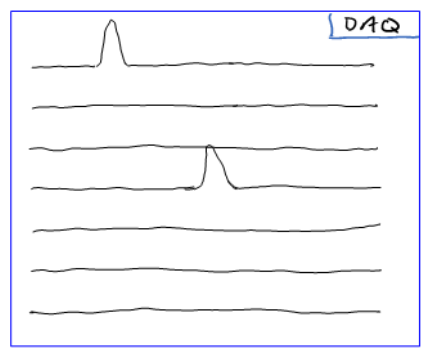






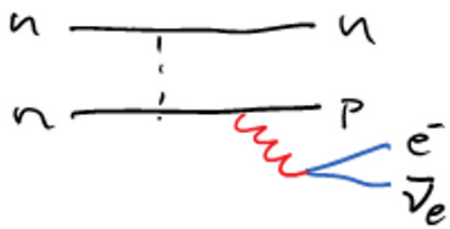


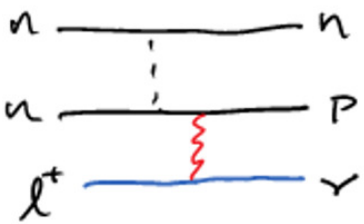




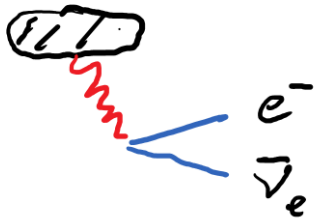
Several pages of notes on neutrinos …

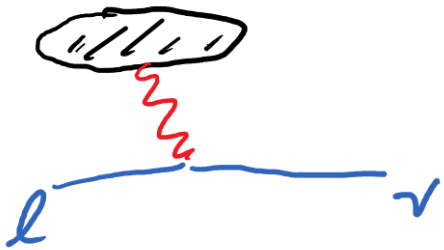
- SM Lagrangian
- Production
  - Thermal
    - Scattering
    - Beta decay
  - Mesons
  - Hadronic cascades
  - γp- reactions





- Interactions
  - Charged and neutral currents
  - Deep inelastic
  - Glashow





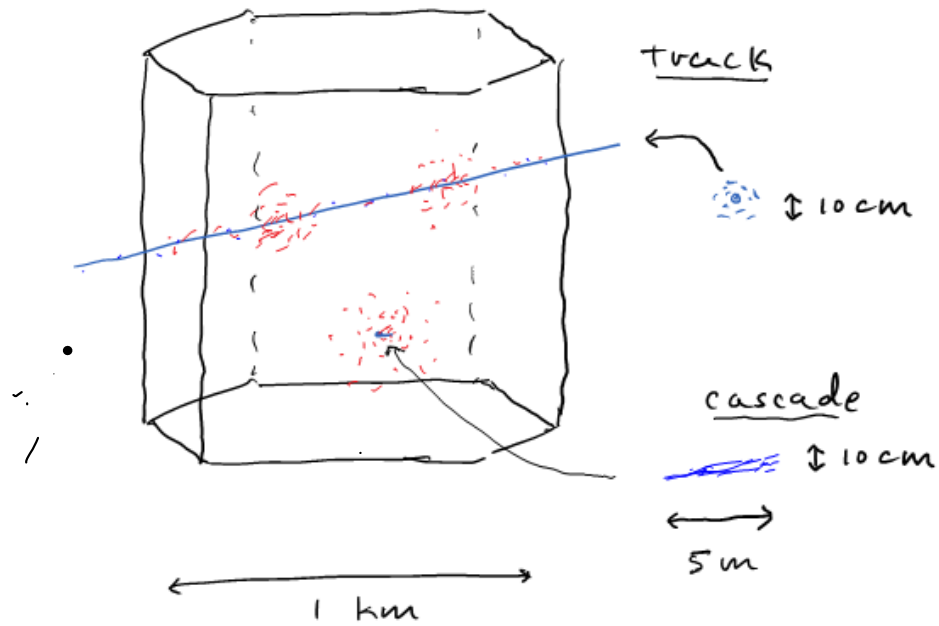
Optical radiation in ice … IceCube

ICE	λ_{abs}	λ_{se}
X_r	100	25

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

$$N \sim \left(\frac{L}{X_R}\right)^3 \sim 8000$$ actual 5160

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



But what to do for EeV ?

- 1000 x volume, but optical radiation volume doesn't increase with E
  V ~ Log(E) – driven by absorption of photons

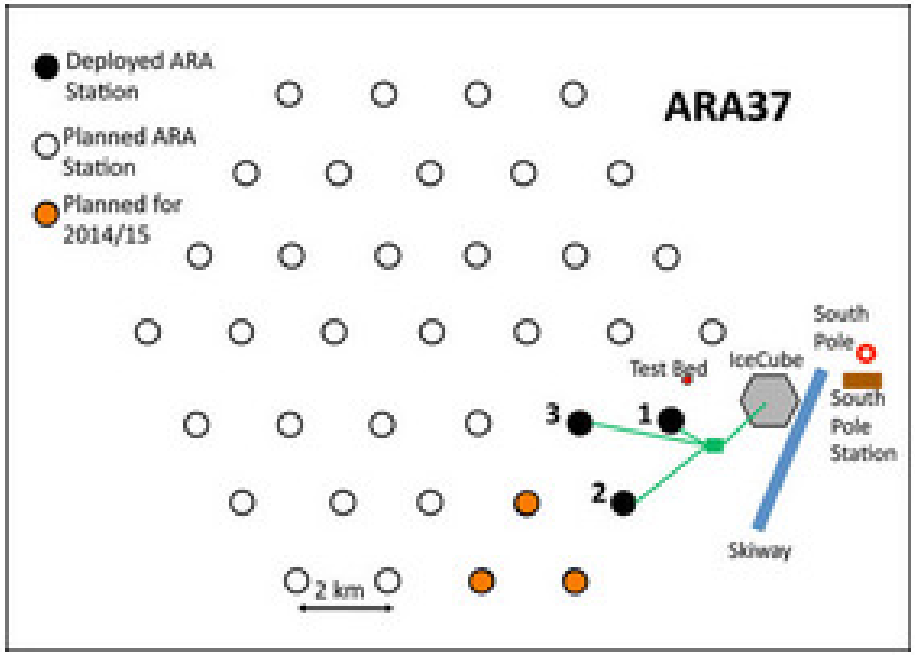
  so – millions of sensors … bah

- Note: Gen-2 optical sensitivity still below 10 PeV

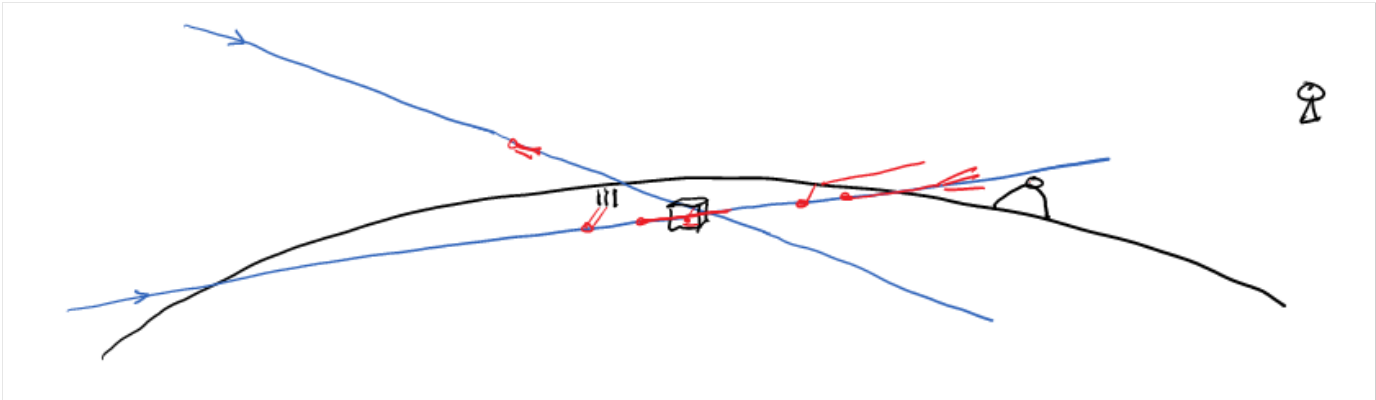
- Radio absorption length … km … sensors farther apart … but how to collect data – from multiple sensors
  - array of single sensors – readout problem
  - sophisticated sensor => station

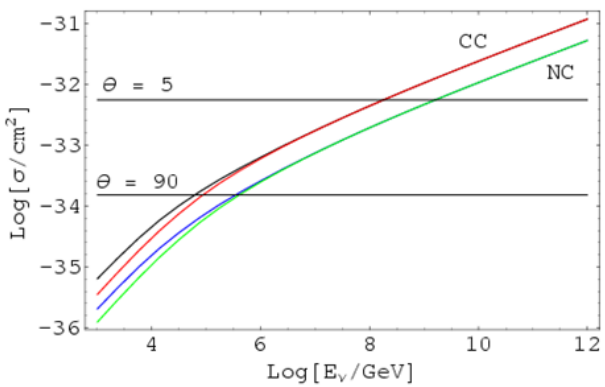
Radio frequency radiation

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



HE detection strategy





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

$$A = N_t \sigma$$

$$N_t = n V = n A_0 l$$

Radio technique (~ 150-800 MHz)

- Quick survey of efforts
  - but focus on ARA: Askaryan Radio Array
- Introduce ARA
- Radio technique
  - radio emission from showers
  - propagation
  - reconstruction and simulation
  - advanced trigger
- RNO-G, Gen-2

Radio efforts

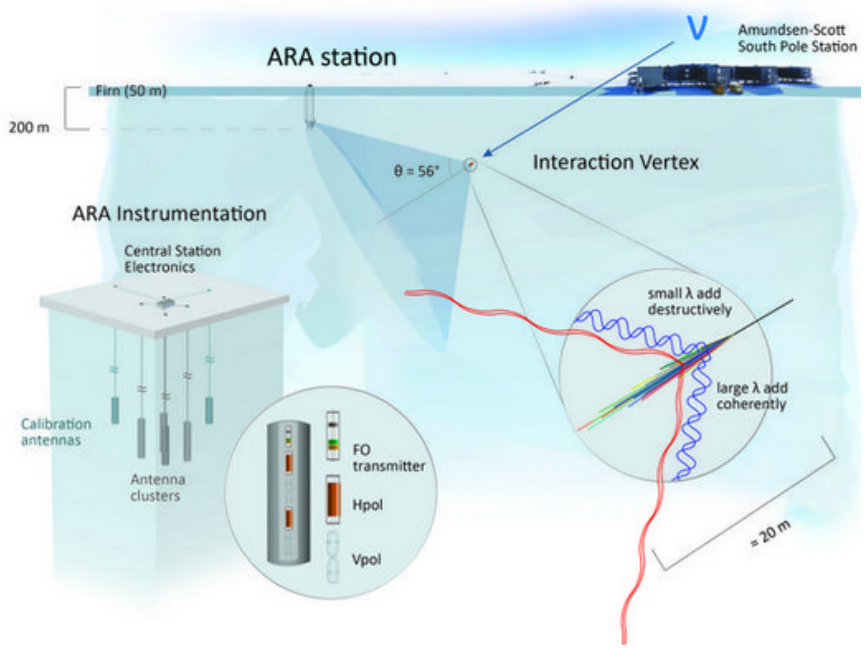
- In-situ
  - RICE – south pole exploration (10^{17} eV)
  - SALSA – salt dome. paused.
  - ARA – south pole prototype/discovery ($10^{17.5}$ eV)
  - ARIANNA – Ross ice shelf. prototype/discovery (10^{17} eV)
  - RNO-G – Summit, Greenland. discovery, tech development
    → GEN-2 full science instrument

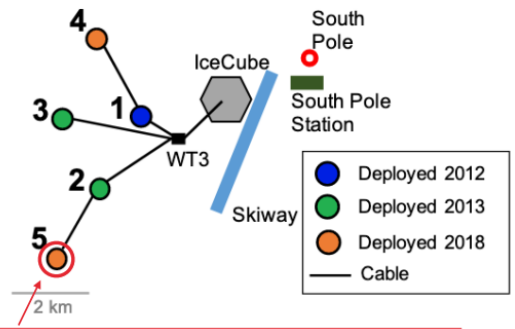
- Remote (higher threshold)
  - ANITA – ongoing (10^{19} eV) → PUEO
  - EVA – development stage (10^{18} eV)
  - Lunar observations (10^{20+} eV) – numerous starts, being reevaluated
  - Spacecraft: LORD (Lunar orbit), Forte(Earth orbit) , PRIDE (Europa)

- τ-channel
  - GRAND
  - BEACON

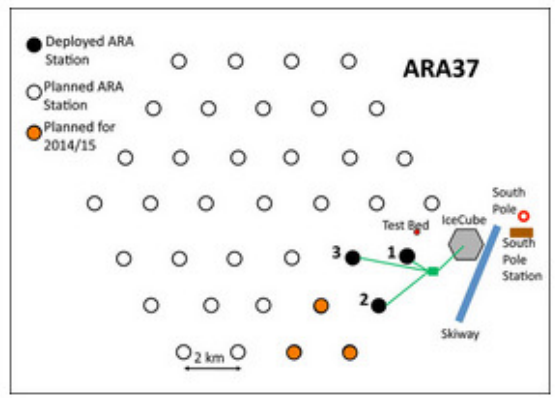
Radio – ARA version

see Simona Toscana at ARENA

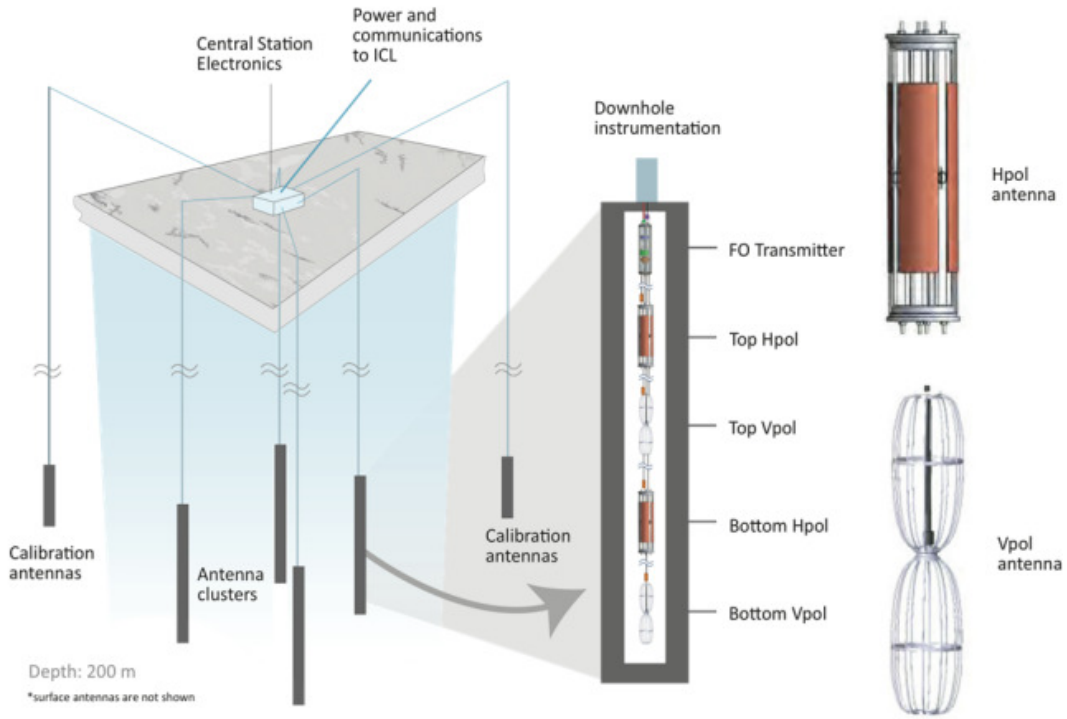




Equipped with a low-threshold "phased-array" trigger (talk by K. Hughes)



ARA station


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

ARA DAQ

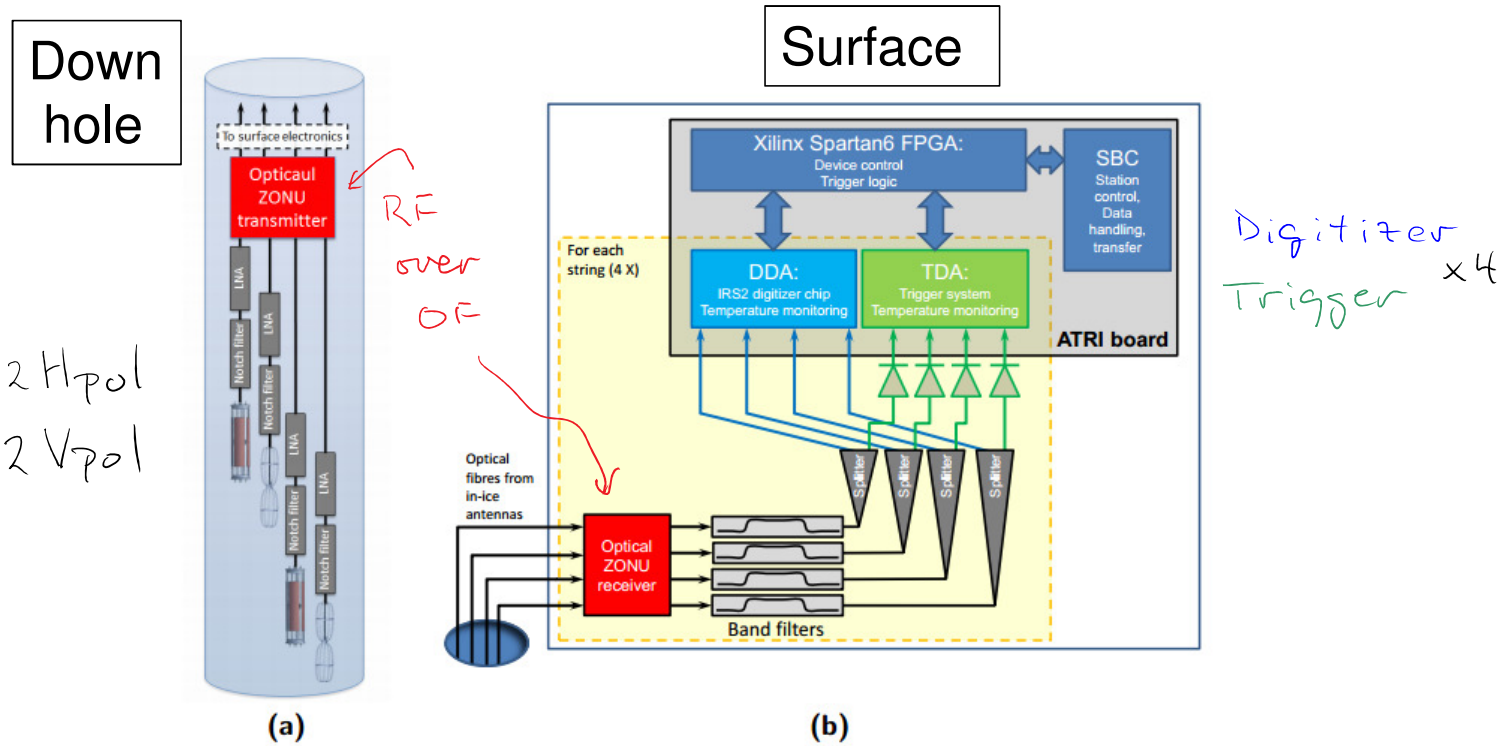
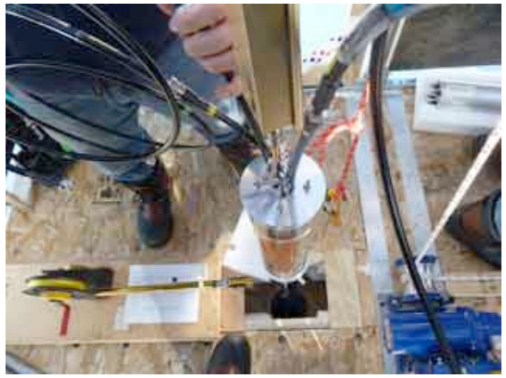


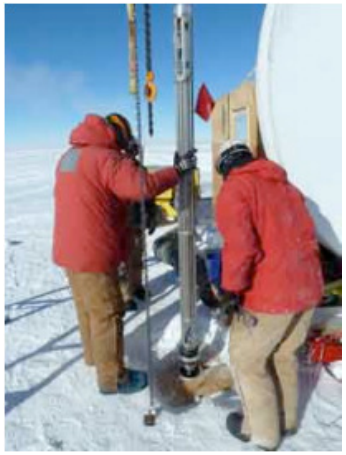
Figure 4.8: *(a) A schematic view of the key components in the ARA in-ice readout chain and (b) the DAQ system. Parts in the yellow shaded area are displayed for one string only, for visibility reasons. In reality they appear four times in each DAQ.*

T. Meures

ARA construction

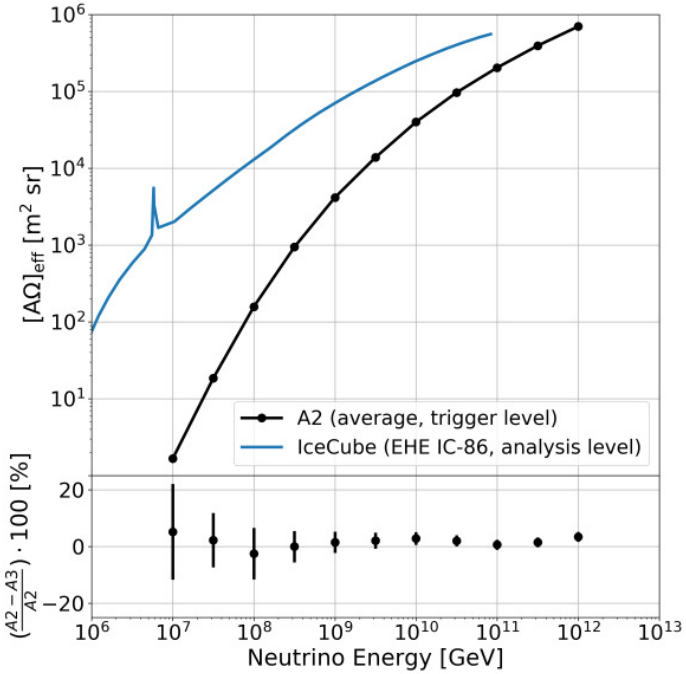
- 2010: Testbed
- 2011: ARA-1
- 2012: Improved drill ARA-2,3
- 2013: ARA-2,3 75%
- 2014: ARA-2,3 95%
- 2017: ARA-4,5 (with advanced trigger)





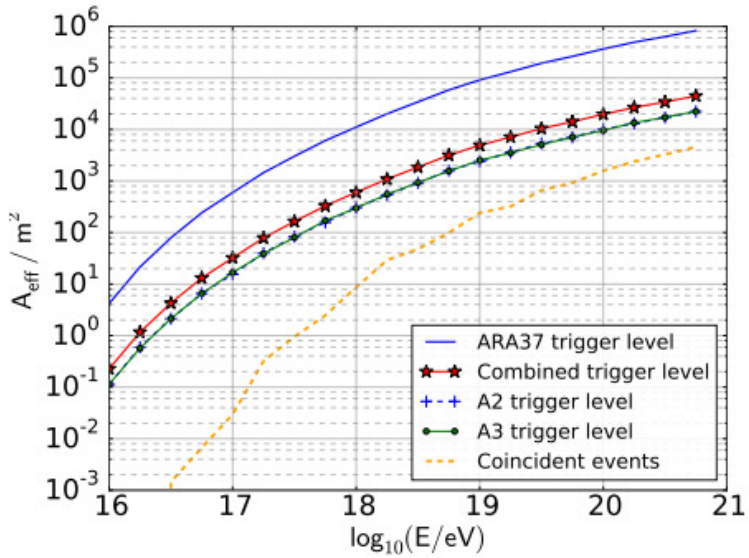
Results

2x4 sta.yr



Phys. Rev. D 102, 043021 (2020)

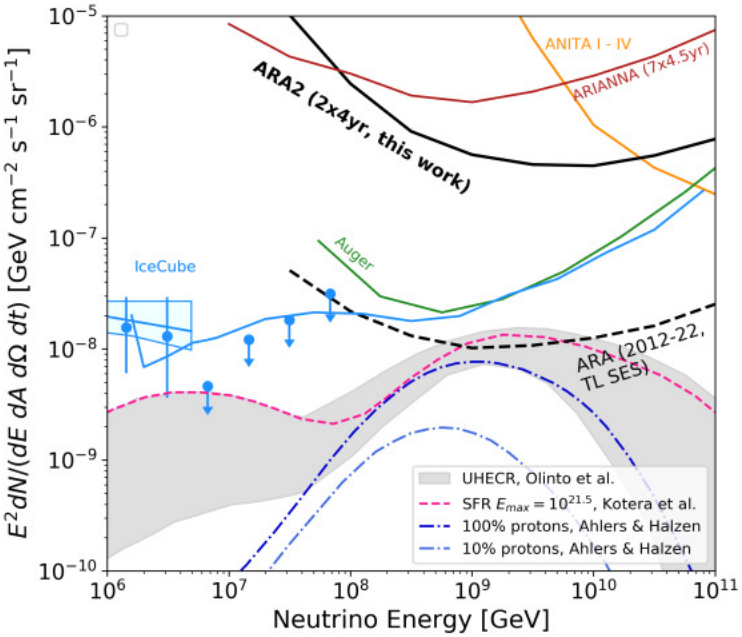
2 x 10 sta.month



Phys. Rev. D 93, 082003 (2016)

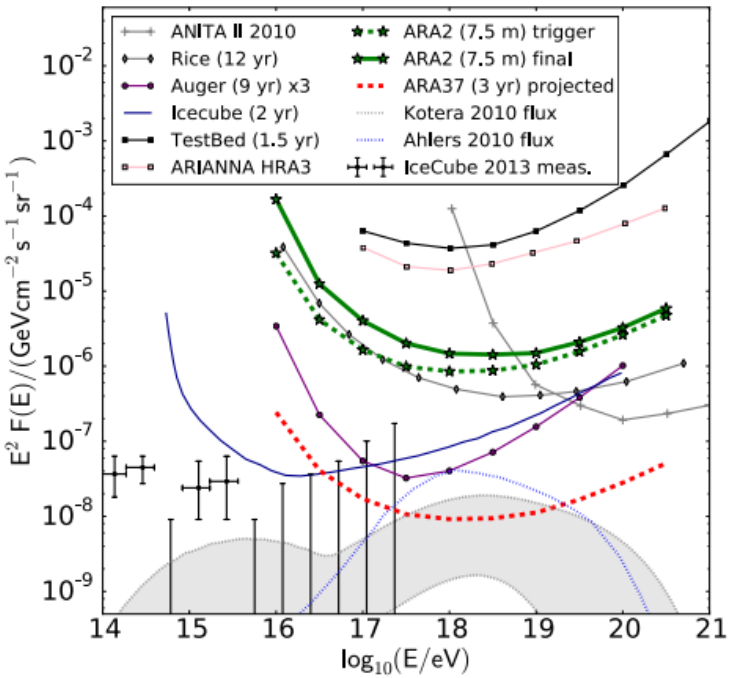
Results

2x4 sta.yr



Phys. Rev. D 102, 043021 (2020)

2 x 10 sta.month (2014)



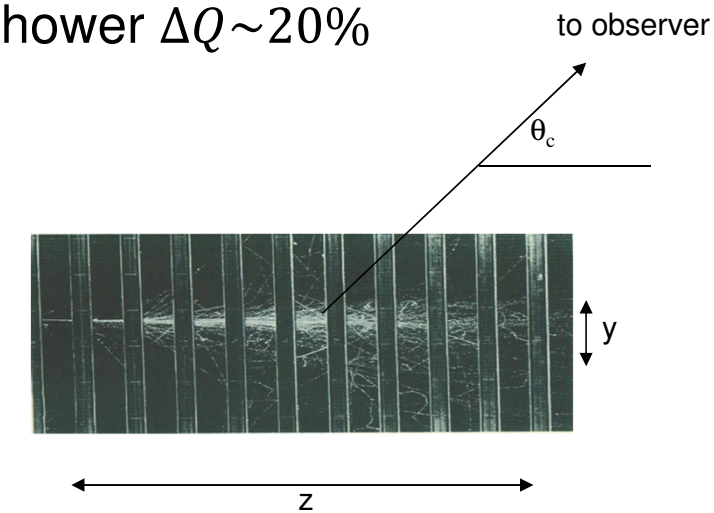
Phys. Rev. D 93, 082003 (2016)

Radio technique

- Radiation from showers
- Radio propagation through glacial ice
- Field of view of station
- Demonstration with deep/distant pulsers
- Analysis
  - Simulation
  - Reconstruction
  - Machine learning

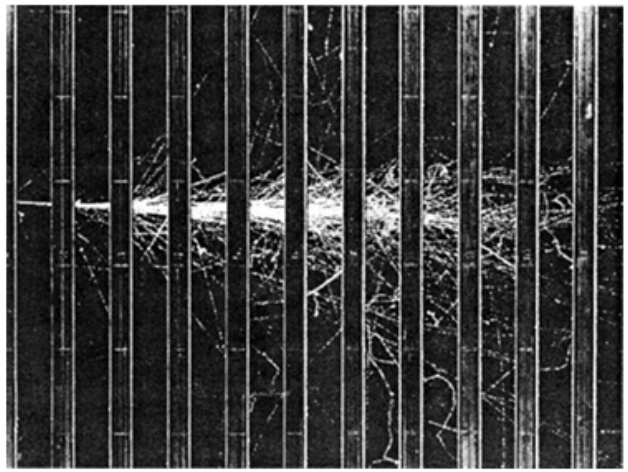
Radio emission

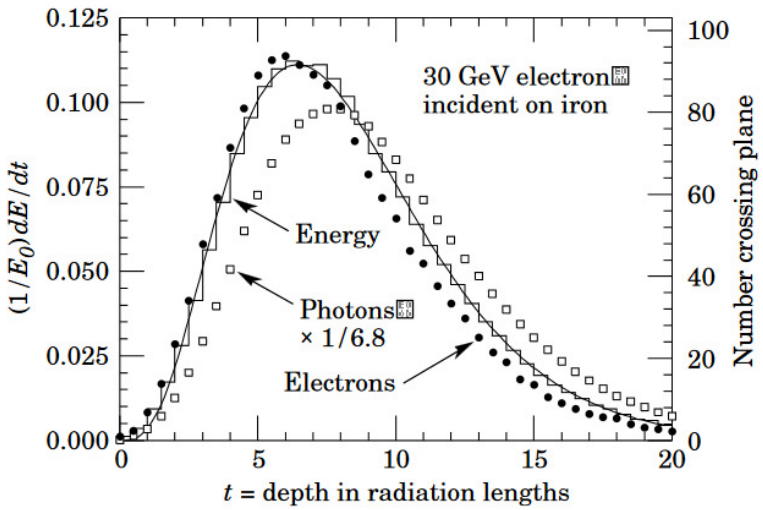
- net charge in shower $\Delta Q \sim 20\%$
  - compton
  - delta rays
  - annihilation



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

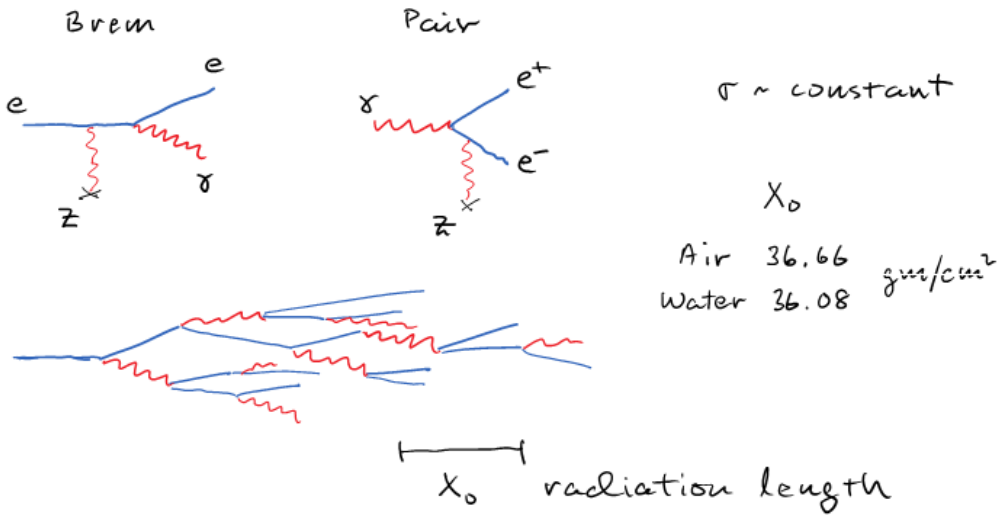
em cascades




30 GeV electron
incident on iron
Energy
Photons
× 1/6.8
Electrons
$(1/E_0)dE/dt$
Number crossing plane
t = depth in radiation lengths
0.125
0.100
0.075
0.050
0.025
0.000
100
80
60
40
20
0
0
5
10
15
20

Electromagnetic cascades: longitudinal

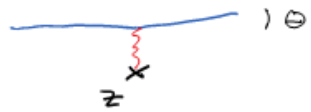
- early - $E_s > E_c$ - critical energy ~ 80 MeV



- late - $E_s < E_c$

Electromagnetic cascades: profiles

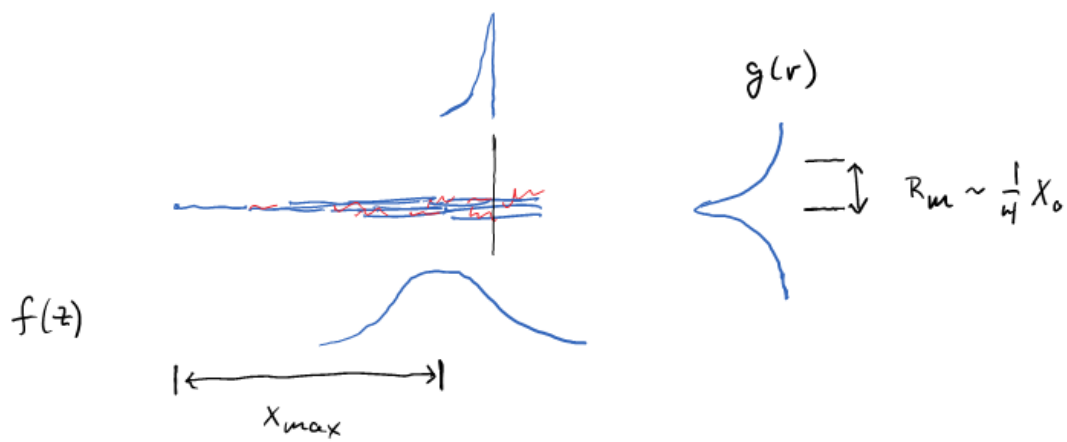
- Coulomb scattering



- Profiles

$$\rho(\vec{x}, t) = f(z)\, g(r)\, h(z - ct)$$

$$h(z-ct) \sim \delta(z-ct)$$



$$X_{max} = \ln(E/E_c)\, X_0 \approx 6\ \mathrm{m} \quad \text{PeV-ice}$$

Hadronic showers & LPM effect

- LPM: above PeV … Pair and brem processes suppressed, showers are lengthened and are “lumpier”

- pi_0 decay: above PeV … pi_0 interacts before it decays

- > PeV
  - Hadronic showers – develop to compact em cascades (very few muons)
  - em showers – are stretched, with narrower radiation patterns

Some equations …

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

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

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

$\Uparrow$

Defines Coherence

longitudinal

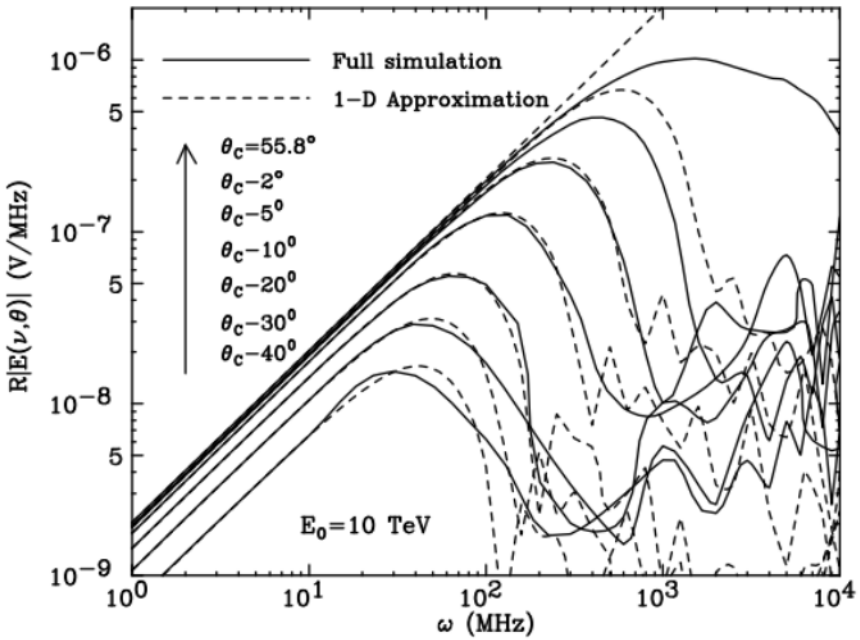
shower front

Transverse

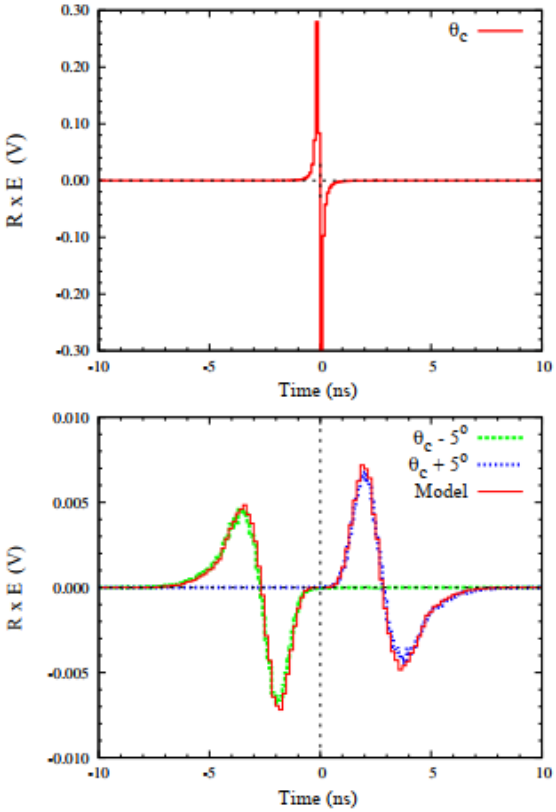
$$\vec{J}(\vec{x},\, t) = \rho(z)\,\delta(z - ct)\,\vec{j}(r,\, \theta)$$

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

Askaryan pulses in frequency and time domain

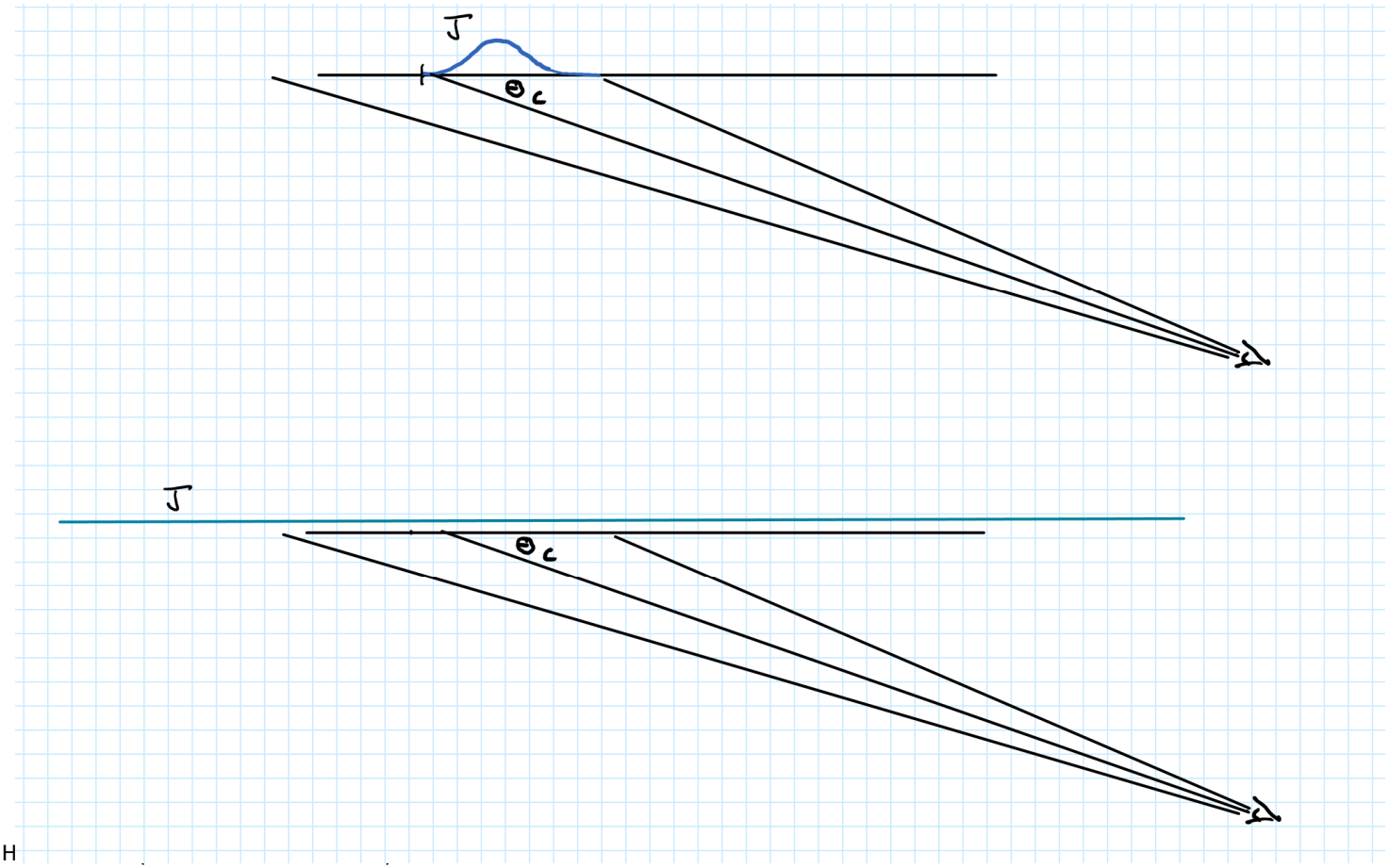


Alvarez-Muniz, Vasquez, Zas



Alvarez-Muniz, Romero-Wolf, Zas

Relation to Cherenkov emission

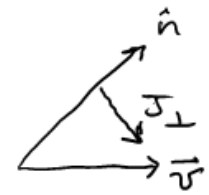


Strength & Polarization

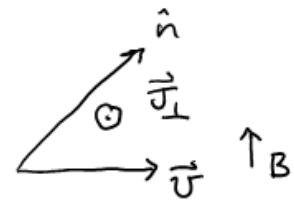
$$\vec{J}_\perp = -(\hat{n} \times \hat{n} \times \vec{J})$$

20%

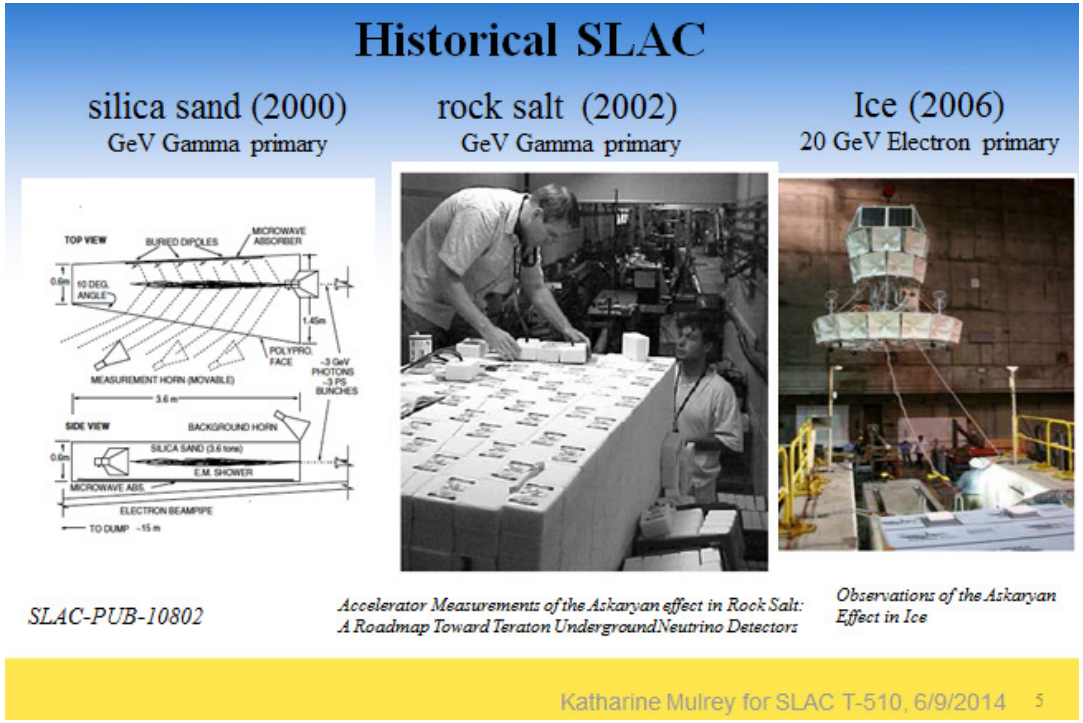
Askaryan $\quad \vec{J} = n(z)\, \Delta Q\, \vec{v}$



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

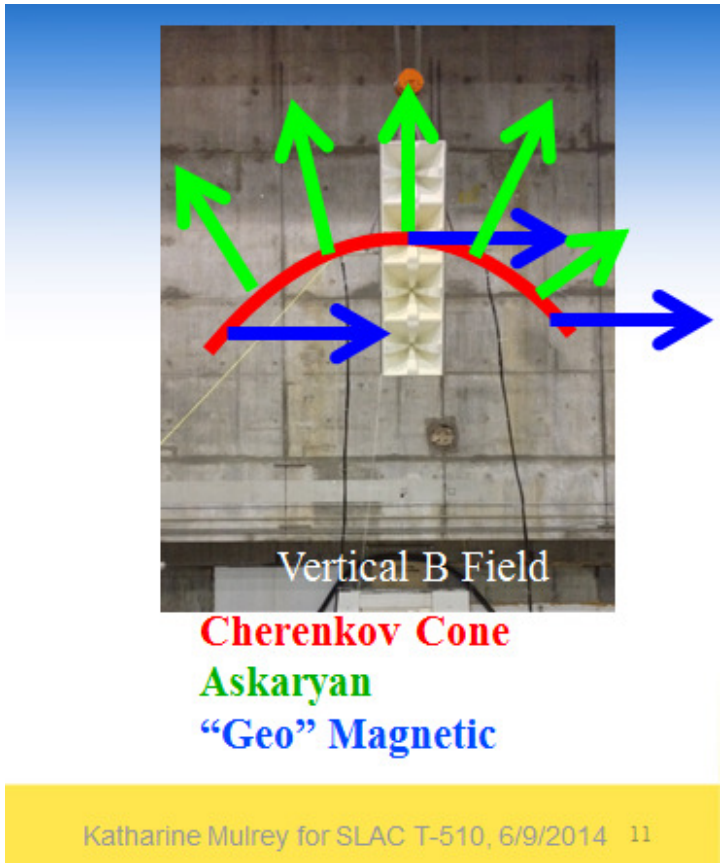


SLAC


Historical SLAC
silica sand (2000)
GeV Gamma primary
rock salt (2002)
GeV Gamma primary
Ice (2006)
20 GeV Electron primary
TOP VIEW
BURIED DIPOLES
MICROWAVE ABSORBER
10 DEG. ANGLE
POLYPRO. FACE
MEASUREMENT HORN (MOVABLE)
SIDE VIEW
BACKGROUND HORN
SILICA SAND (3.6 tons)
E.M. SHOWER
MICROWAVE ABS.
ELECTRON BEAMPIPE
TO DUMP
SLAC-PUB-10802
Accelerator Measurements of the Askaryan effect in Rock Salt: A Roadmap Toward Teraton UndergroundNeutrino Detectors
Observations of the Askaryan Effect in Ice
Katharine Mulrey for SLAC T-510, 6/9/2014
5

SLAC T-510

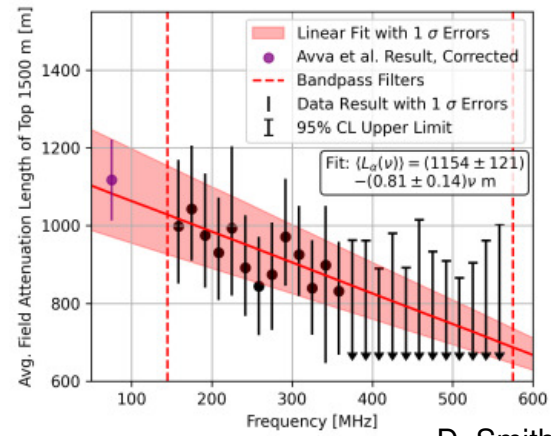

BEAM
EMERGENCY
OFF


Vertical B Field
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

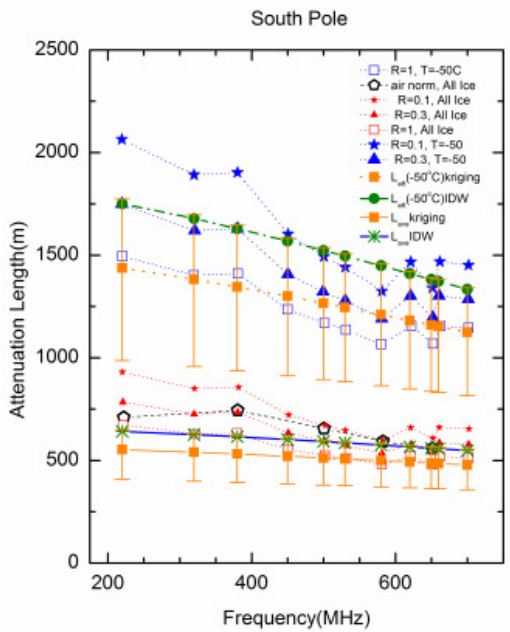
Summit Sta, Greenland

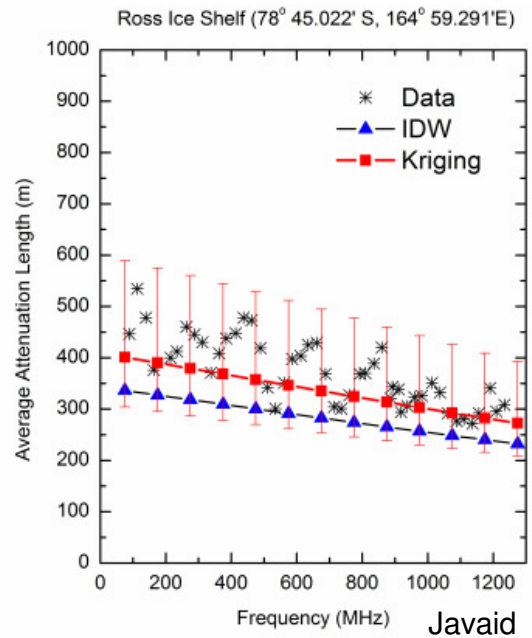


D. Smith

T= -50

<T>



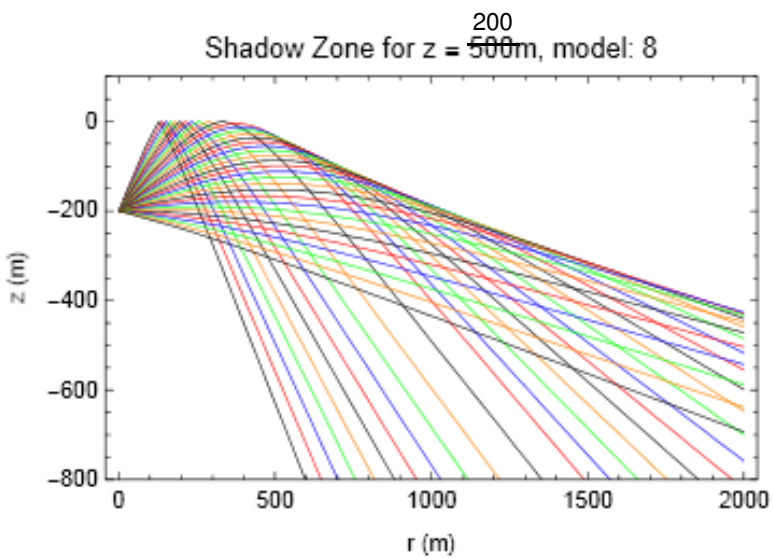


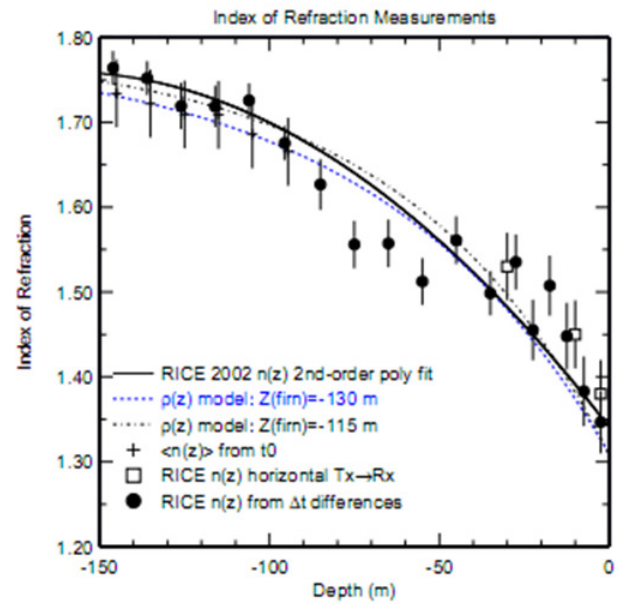
Javaid

Ray optics

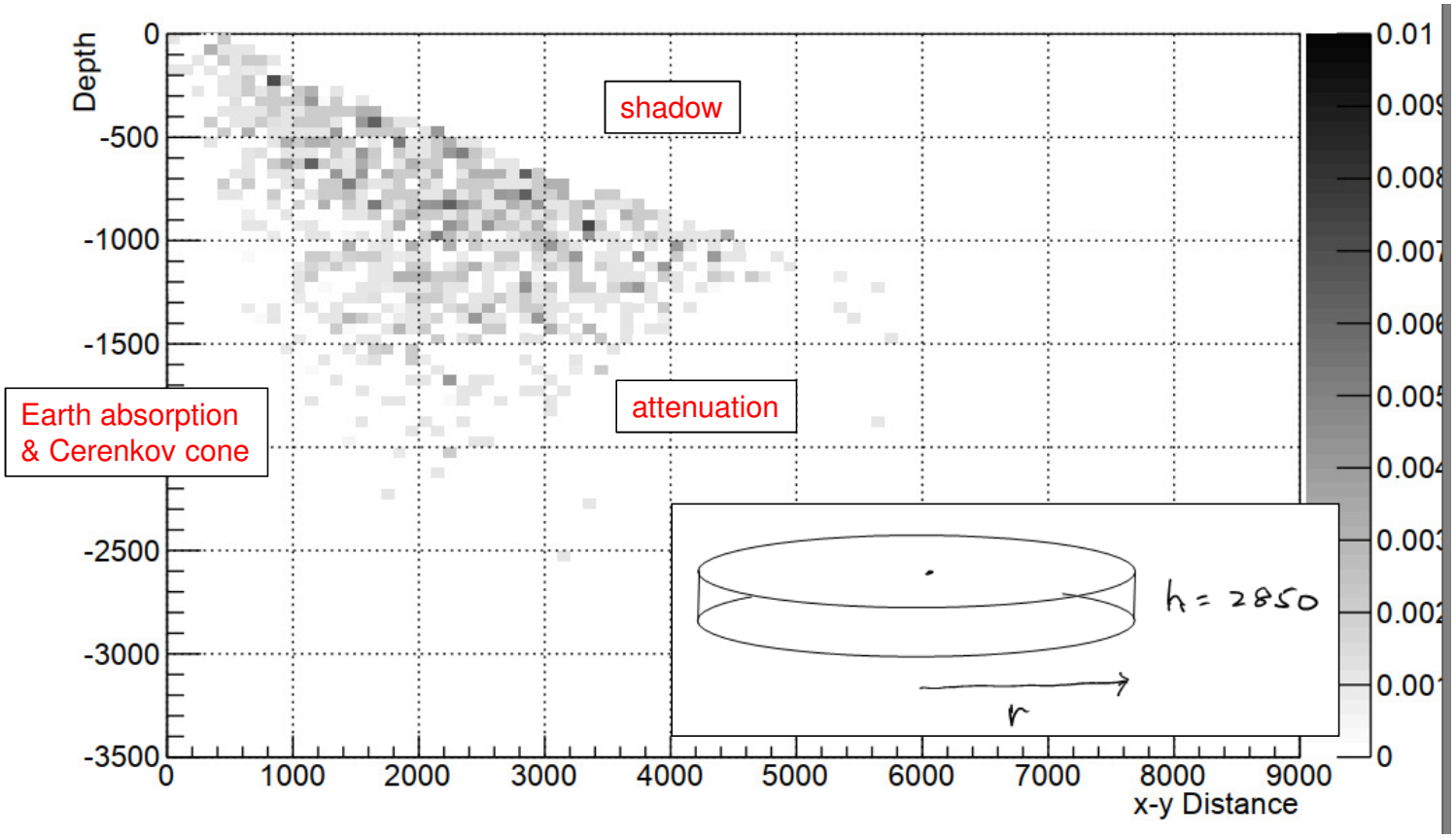
RICE

$n_0 = 1.78$

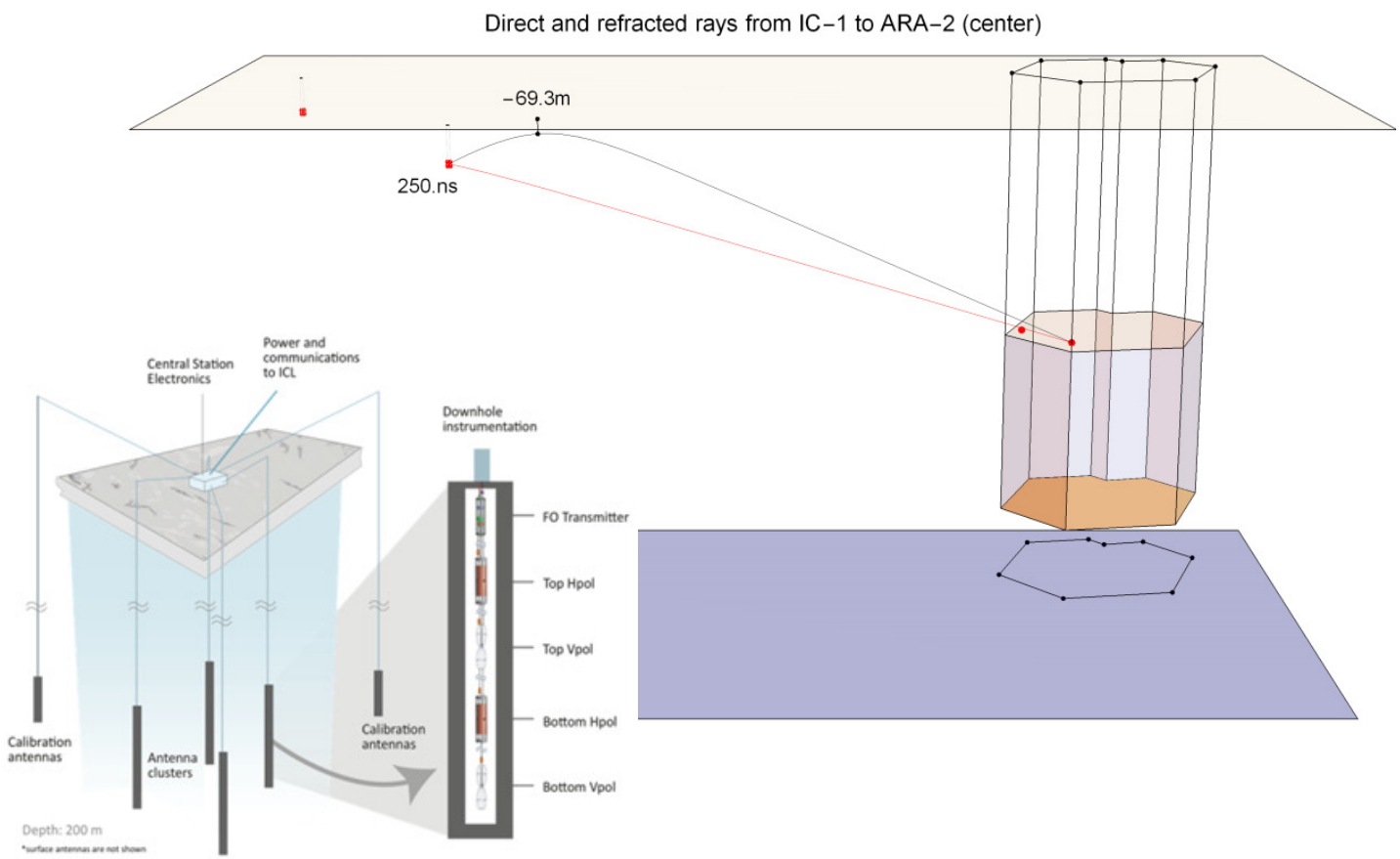




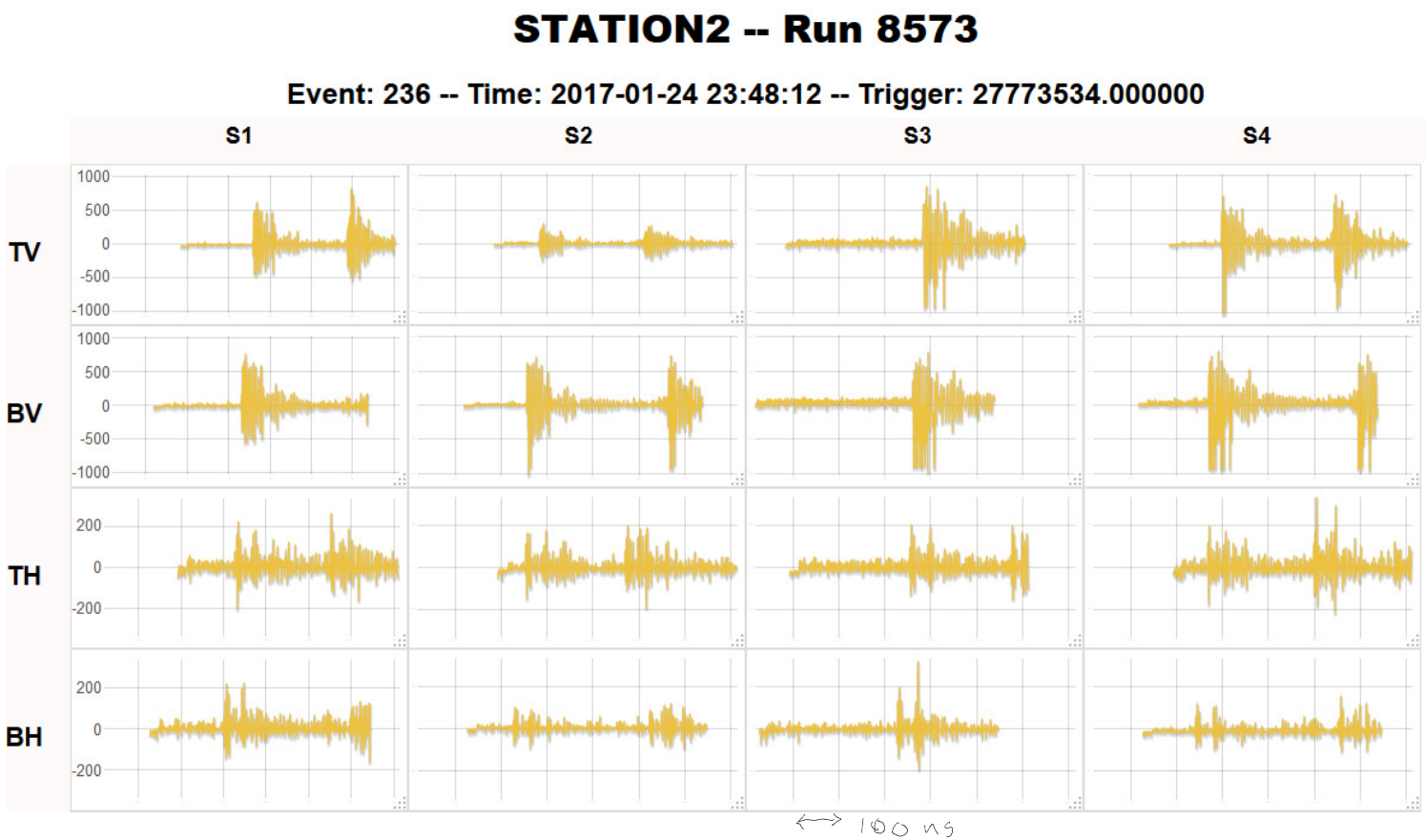
Simulation @ $10^{18.5}$ eV



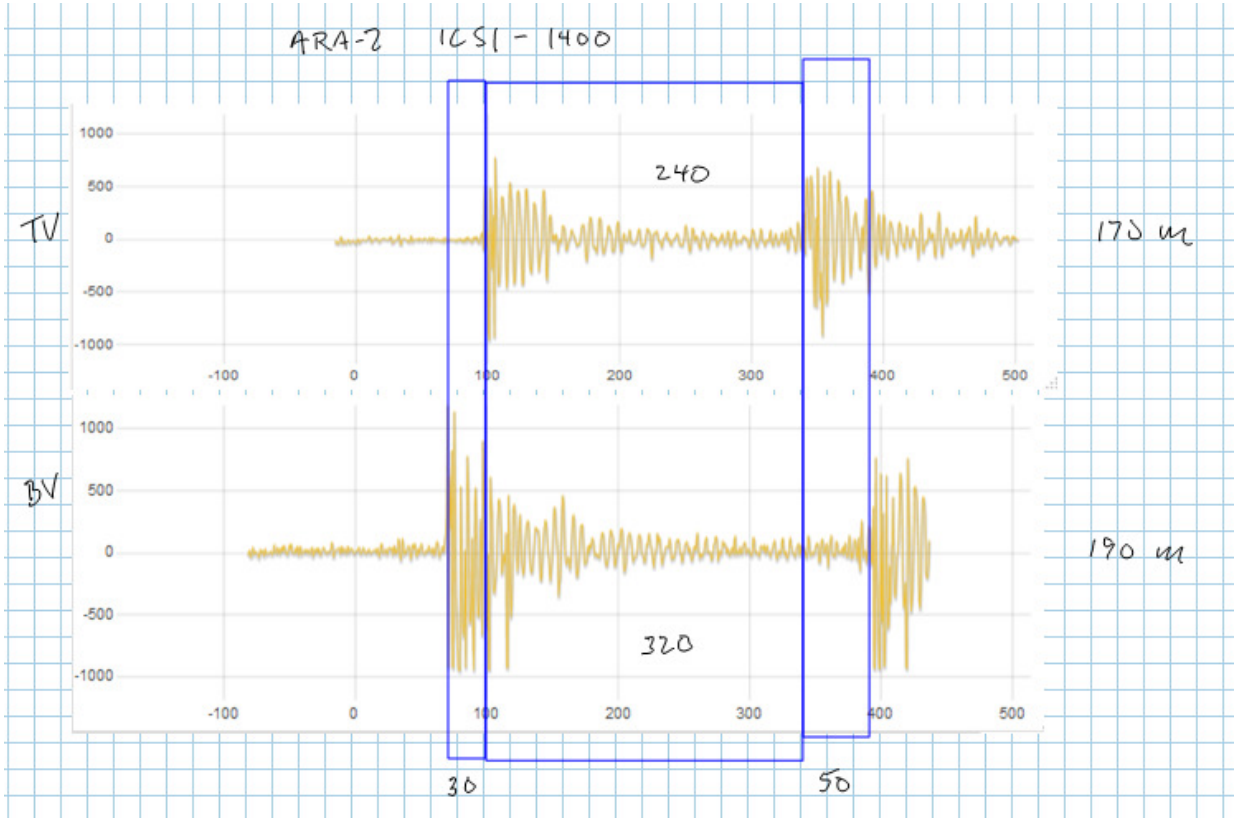
Deep Pulsers



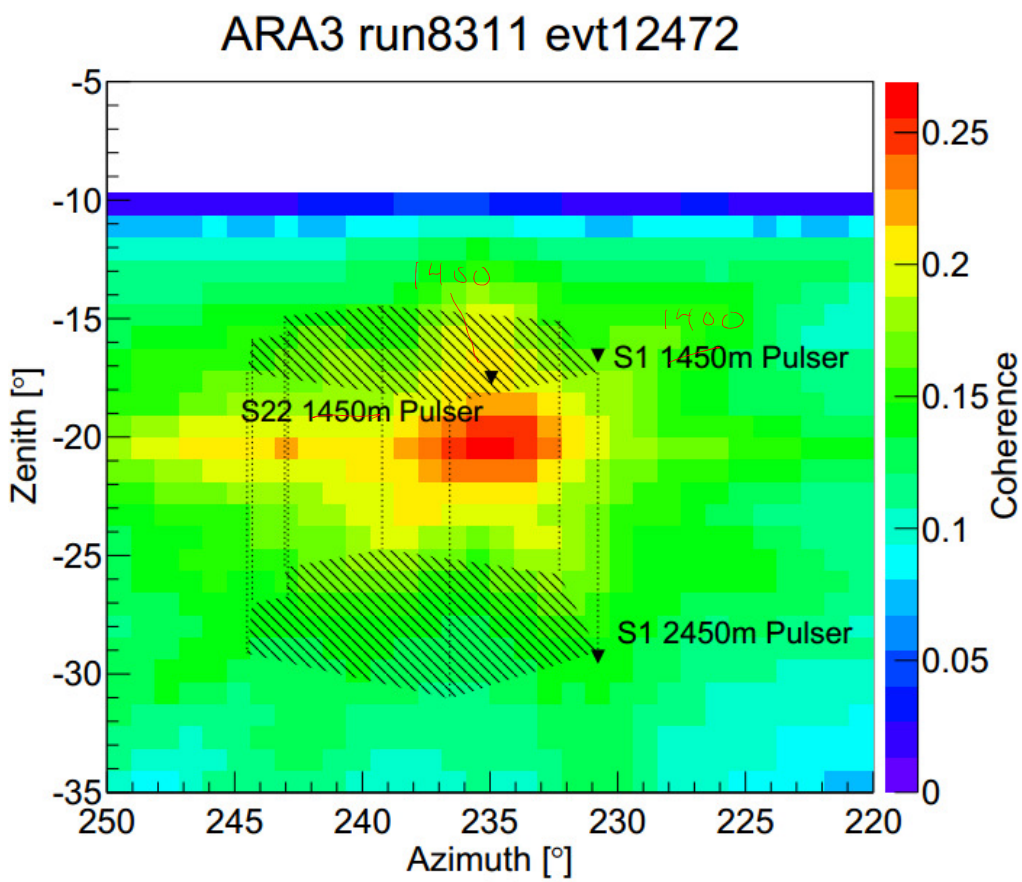
Deep pulsers



Pulse quality and timing

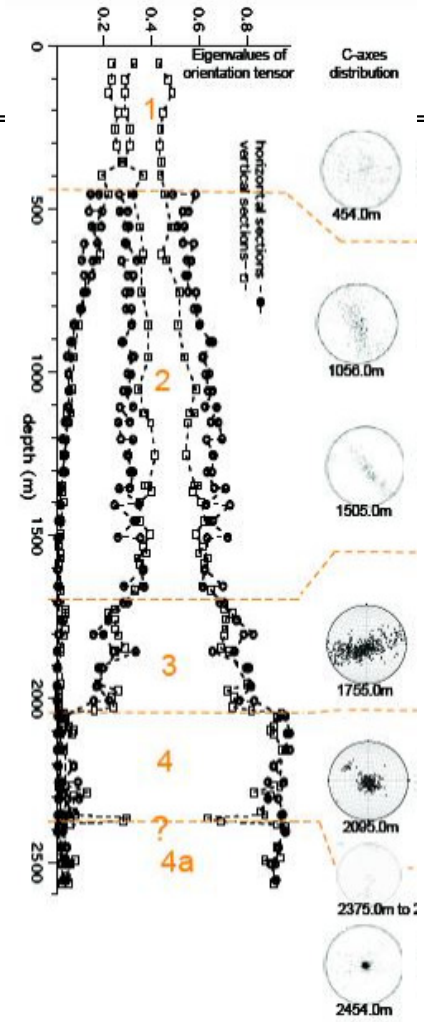


Event reconstruction of direct pulse (M-Y Lu)



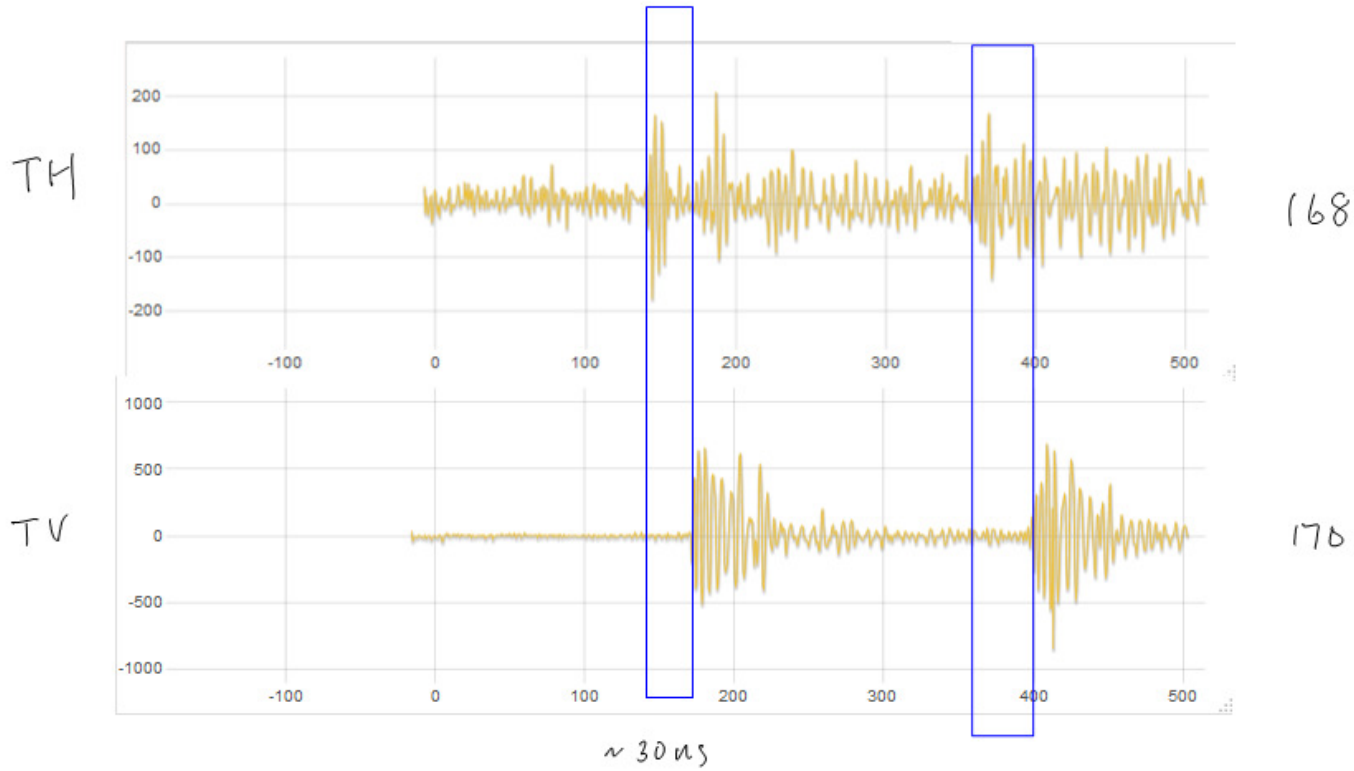
Propagation: birefringence

- 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



$t_{tot} \sim 4000\,m$ @ $6\,ns/m$

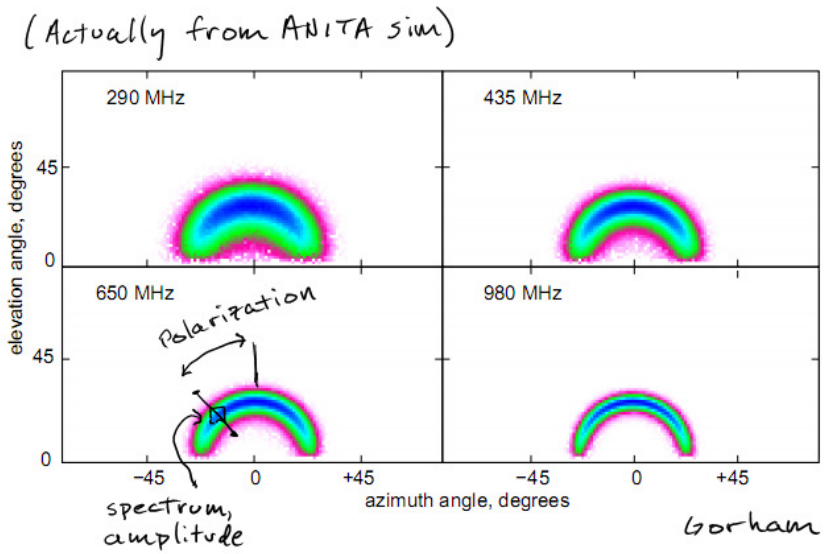
$25\,\mu s$

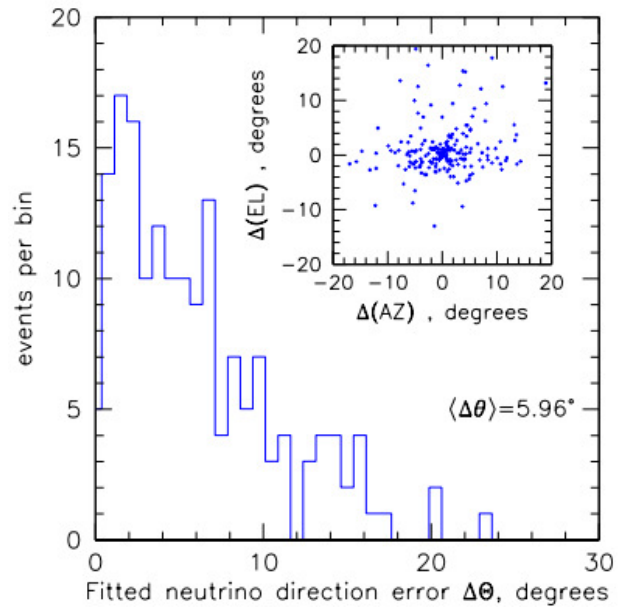
$\frac{\Delta n}{n} \sim 10^{-3}$

wider but 8 ns for depth

Event reconstruction

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

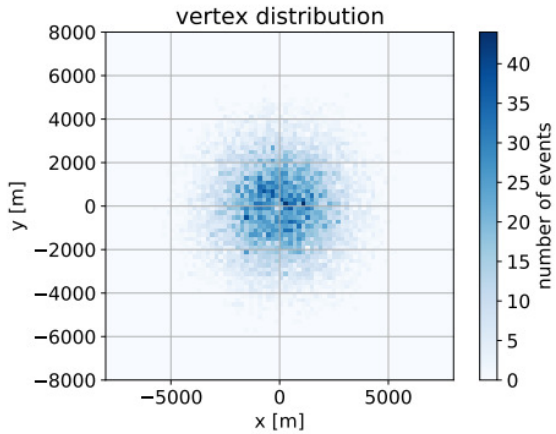




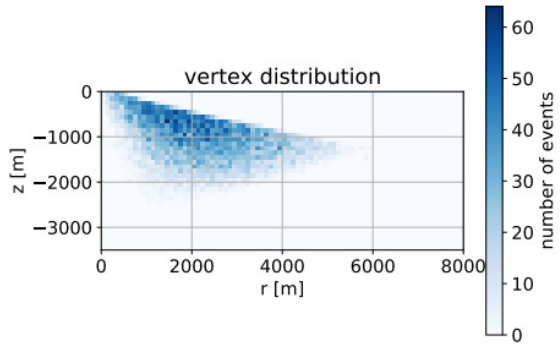
Modern simulation tools

- ARA: ARASim, PyRex
- RNO-G, Gen-2: NuRadioMC
  - Event summary's in HDF format (easy to use)
  - Waveform details in proprietary binary format
- ARA-2 and nuRMC: Some cross-over work

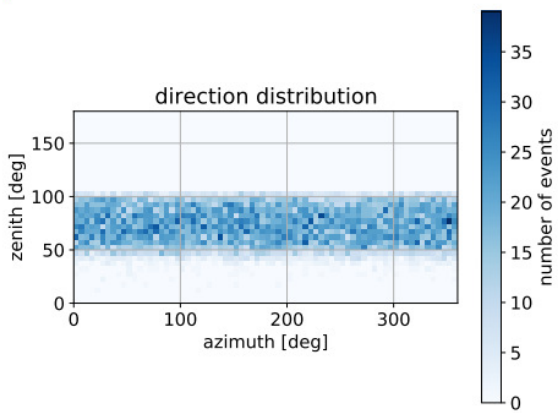
Event distributions



(a)



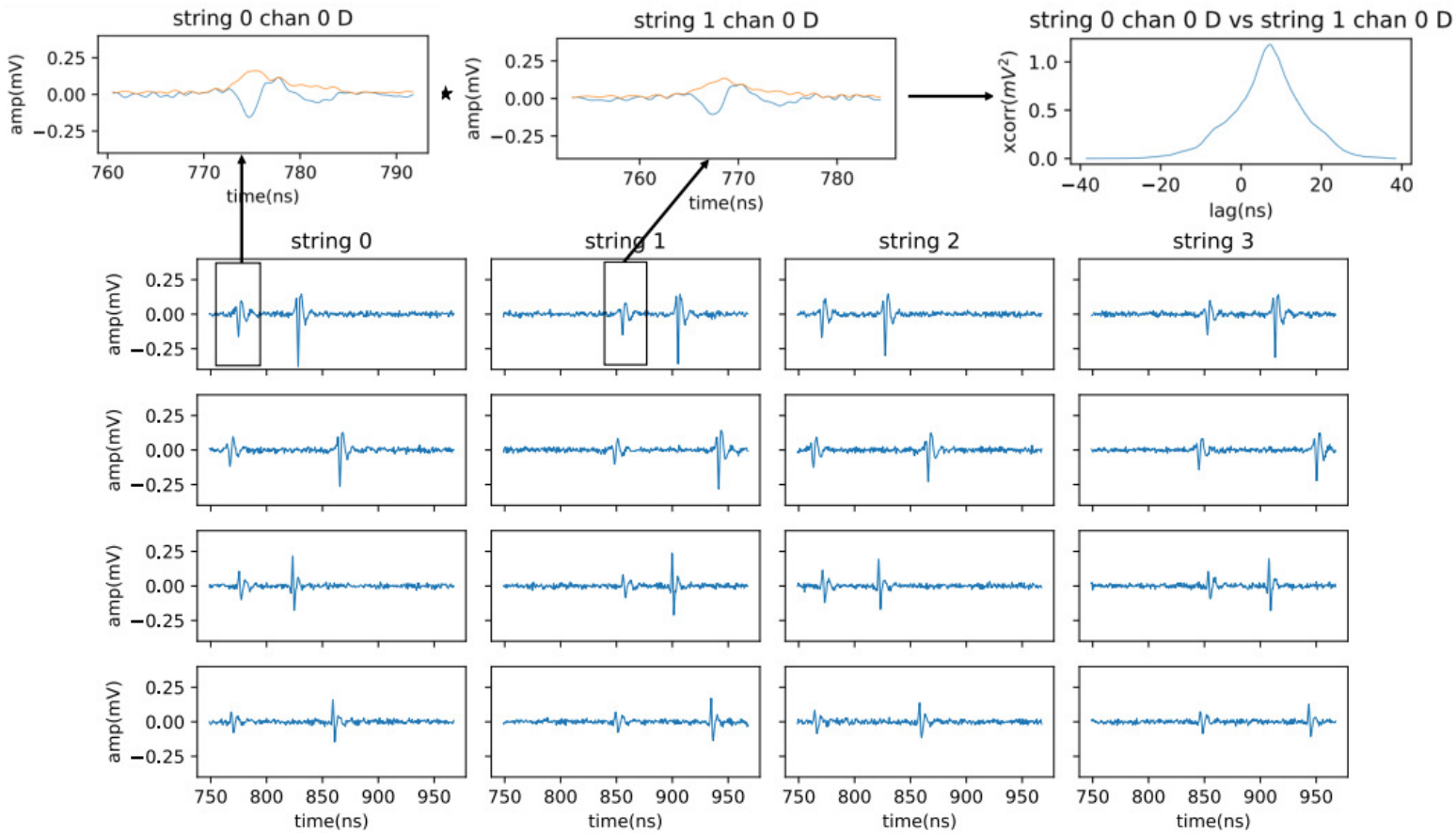
(b)



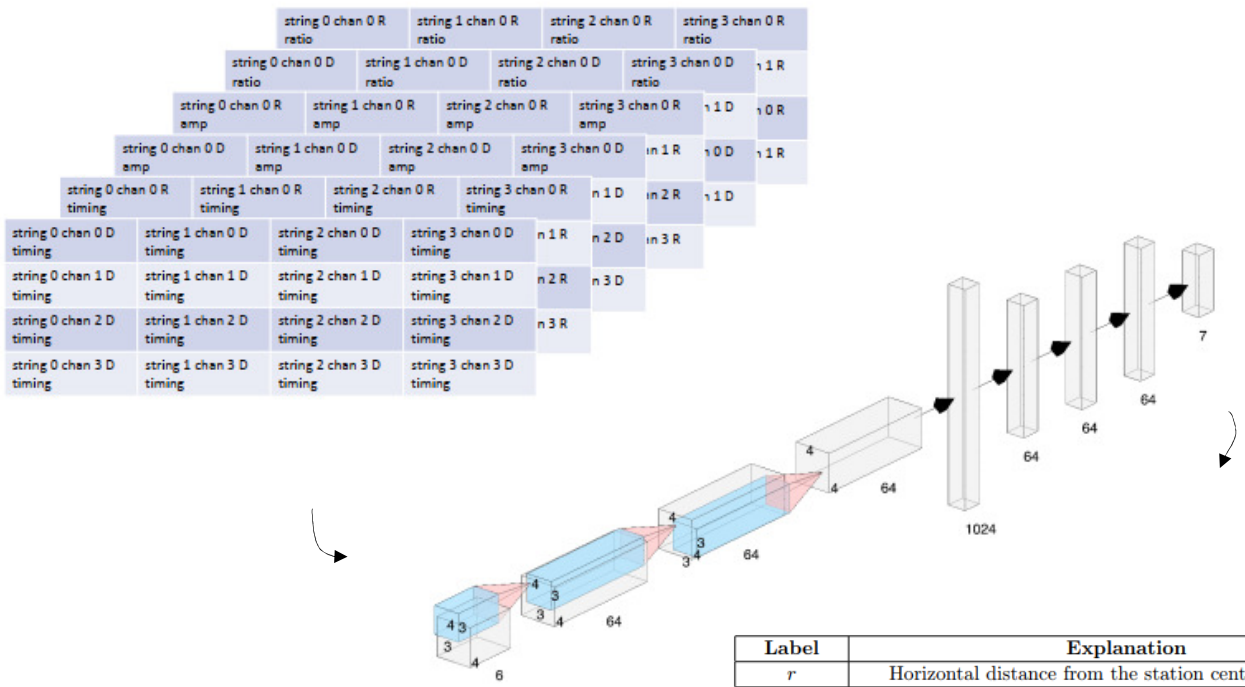
(c)

Yue Pan: dissertation
ARA-2 sim using nuRMC
Log(E/eV) = 18.5

An event with timing



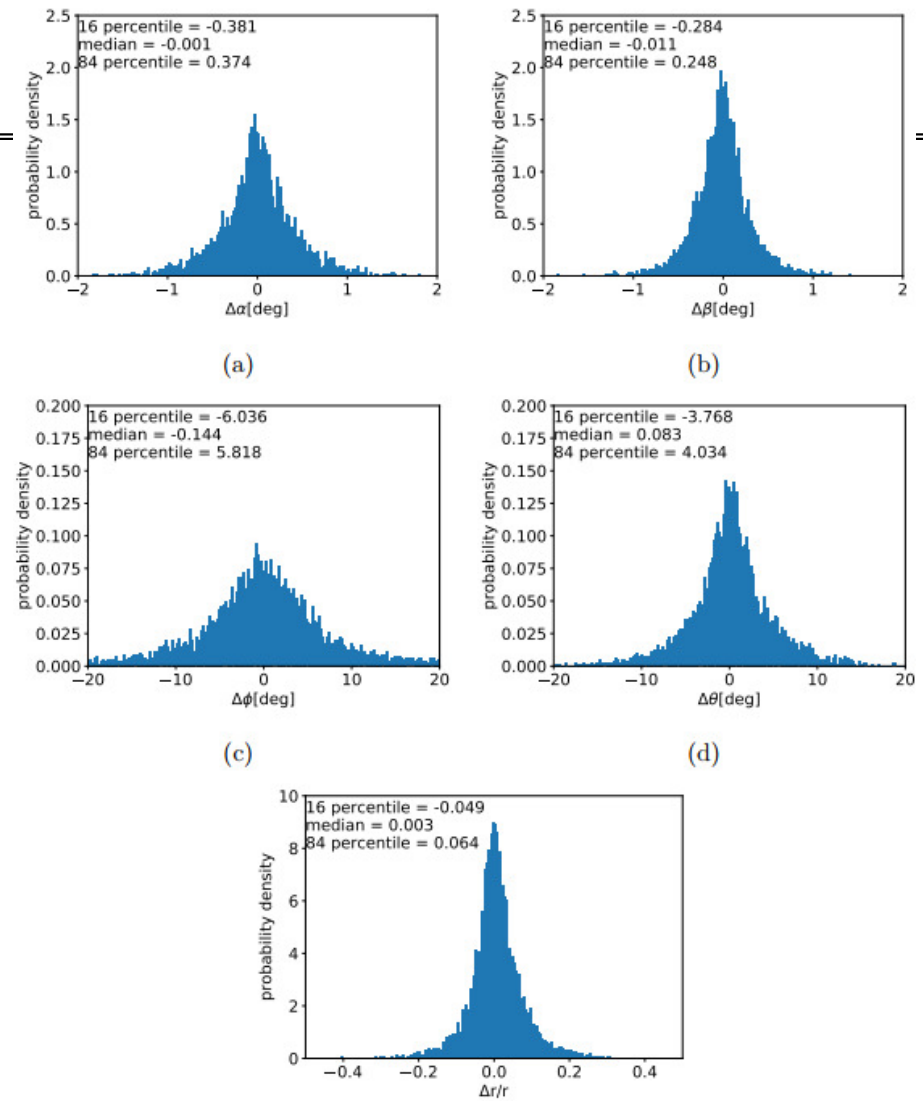
CNN Reconstruction (Yue Pan)



Label	Explanation	Loss
r	Horizontal distance from the station center to a vertex	MSPE
$\sin\alpha, \cos\alpha$	Azimuth angle from the station center to a vertex	MSE
β	Zenith angle from the station center to a vertex	MSE
$\sin\phi, \cos\phi$	Azimuth angle pointing back to where a neutrino comes from	MSE
θ	Zenith angle pointing back to where a neutrino comes from	MSE

Reco w/CNN

- α vertex az
- β vertex zen
- φ neut az
- θ neut az
- $\Delta r/r$ vertex

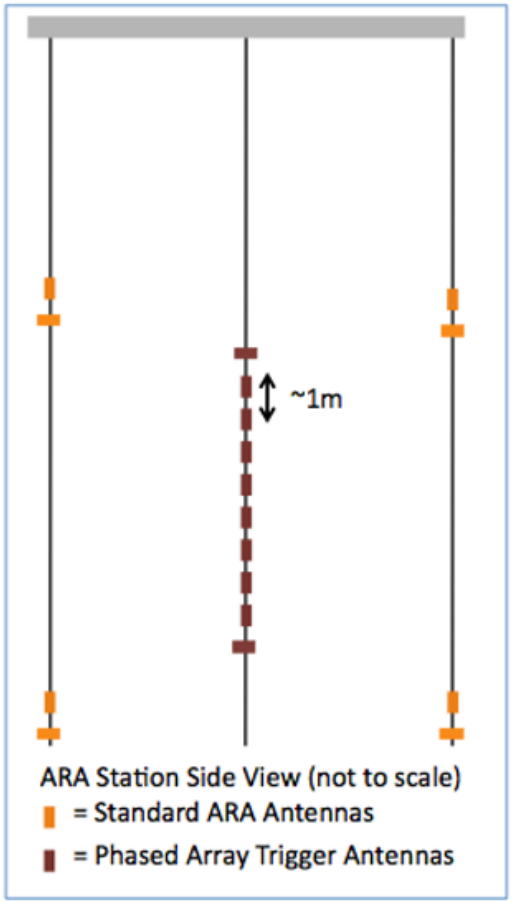


Lessons learned from ARA

- Need for better trigger
- DAQ reliability
- Scalable drill/deployment
- Concerns about backgrounds from cosmic rays
  - geomagnetic radiation from air shower
  - shower core hits the ice
  - prompt muons w/catastrophic dE/dx

Advanced trigger

- Phased array
  - 8 vpol antennas
  - tight spacing
  - real time digitizer
  - form beams in fpga
- Improve S/N by Sqrt[8]
- Installed at ARA 5



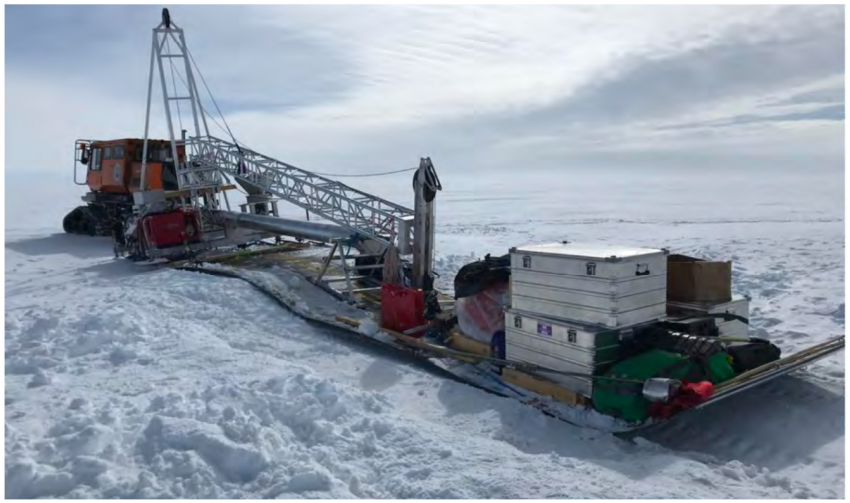
New drill … mechanical – not melting

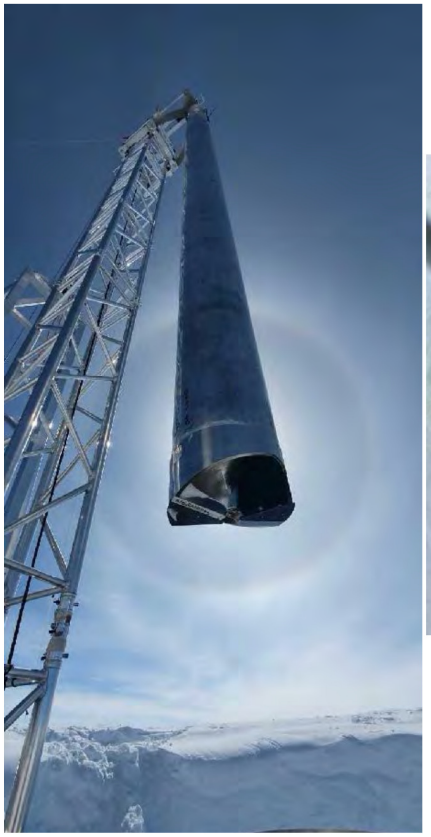
(Courtesy Steph Wissel, ICRC 2021)

RNO-G Drill

See D. Smith PoS(1058) for more on the instrument hardware

- **BAS BigRAID Drill**
  Custom auger drill developed for RNO-G by the British Antarctic Survey
- 11-inch diameter holes
- Capable of drilling 1 hole to 100 m in 1 shift (2 people)
  - Most holes drilled this season are 2 shifts / hole

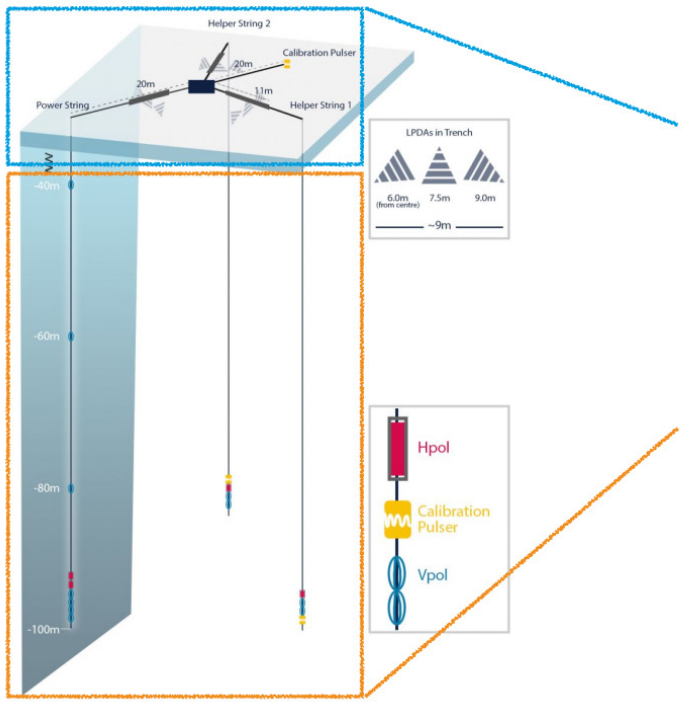


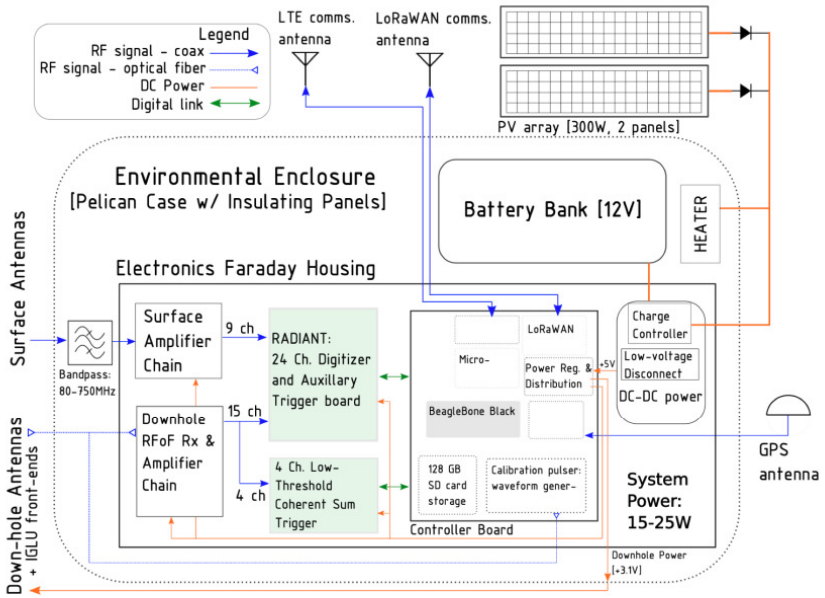


RNO-G station (Hallmann)

RNO-G station

Hybrid station design





- station layout combines:
  - shallow (~3m) LPDAs (à la ARIANNA)
  - deep (~100m) VPols and HPols with 4-channel phased array trigger (à la ARA)

DESY. RNO-G: Status Update, ARENA2022, Steffen Hallmann 6

RNO-G (thanks to Steffen Hallmann; ARENA 22)

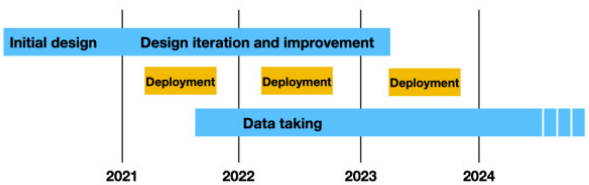
RNO-G deployment schedule

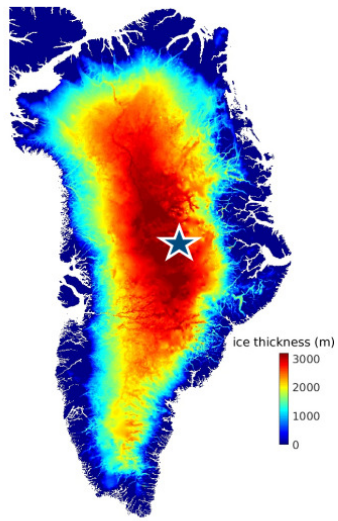
- RNO-G is under construction at Summit Station

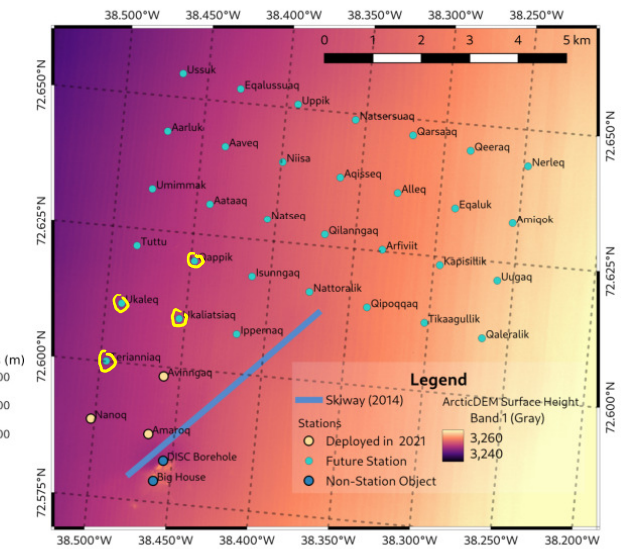
- 35 stations fully funded
- first 3 stations deployed in 2021

2022 deployment on-going:

- aim for up to ~~6~~ 4 additional stations
- drilling team: preparations, improvements to drill, first "new" holes completed
- deployment team flying in tomorrow

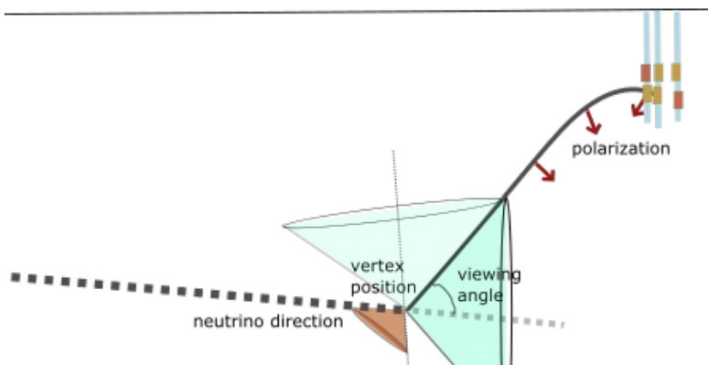


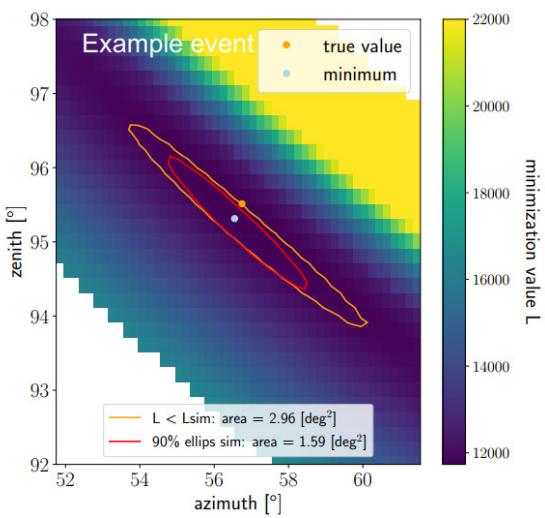




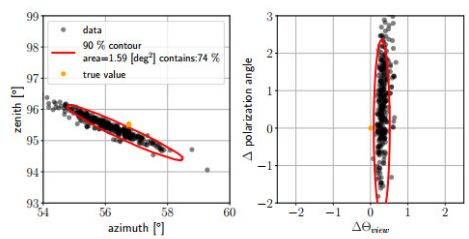
https://uppsala.box.com/s/oyldlu31cpd9f9sxwpph5v4yrqj62ro9

RNO-G reco (Ilse Plaisier for the RNO-G collaboration)

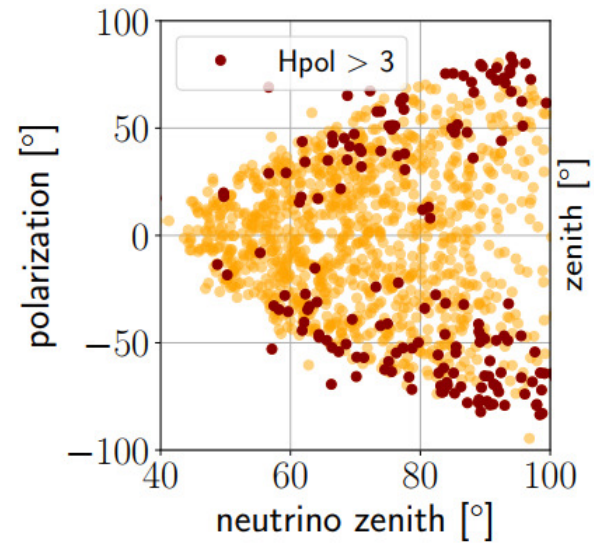




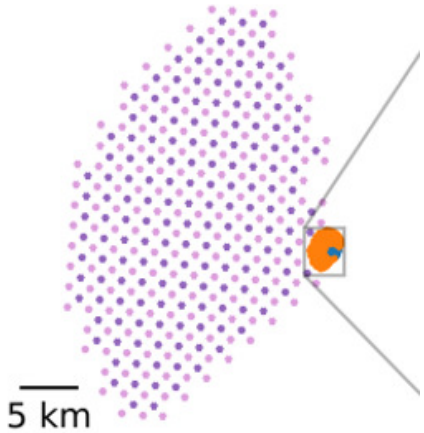
- Describe area of the spread in reconstruction

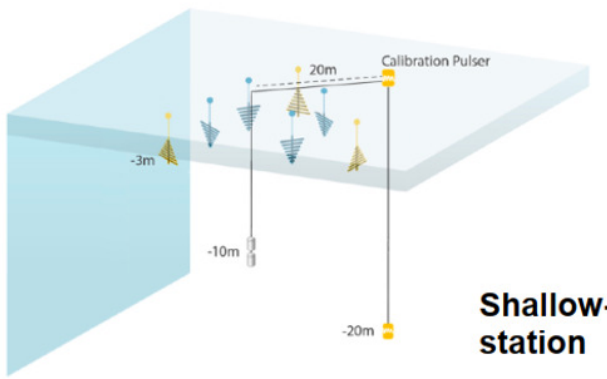


- Uncorrelated Gaussian assumption for polarization and viewing angle distribution
- Contour of equal probability is ellips

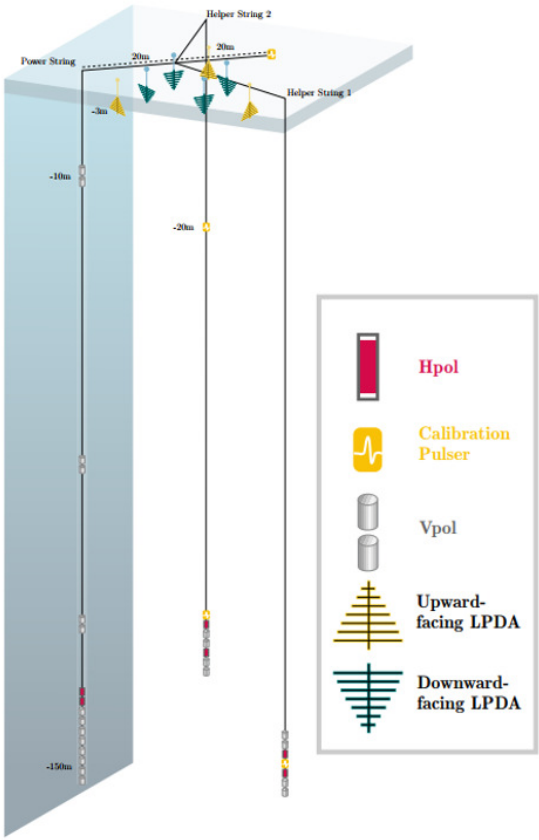


Gen-2 (RNO-G is similar “hybrid station”)





Shallow-only station



Hybrid station

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS 7

Summary

- Thank you, Georg!

- Particle astrophysics topic:
  - MMA: Neutrinos as messengers at high energies
  - Radio extends reach of IceCube Gen2
  - ARA, RNO-g … Gen2

- What about 221009a?
  - Rumors of 18 TeV gamma from z = 0.15
  - Axions/alps gamma -> a -> gamma

  …. I was hoping to have some in person converssations, but …

Backup

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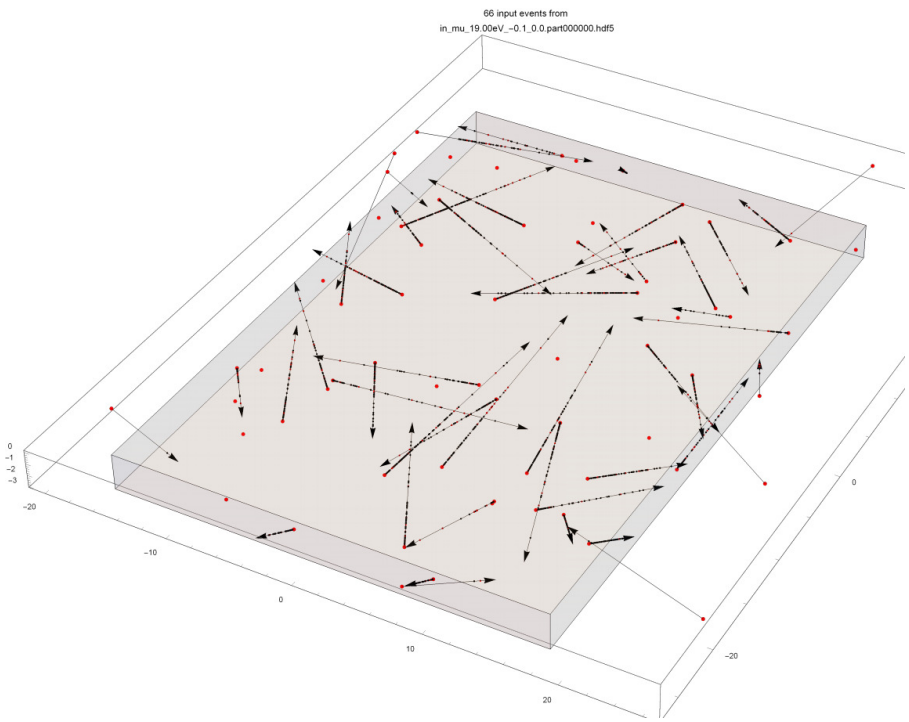
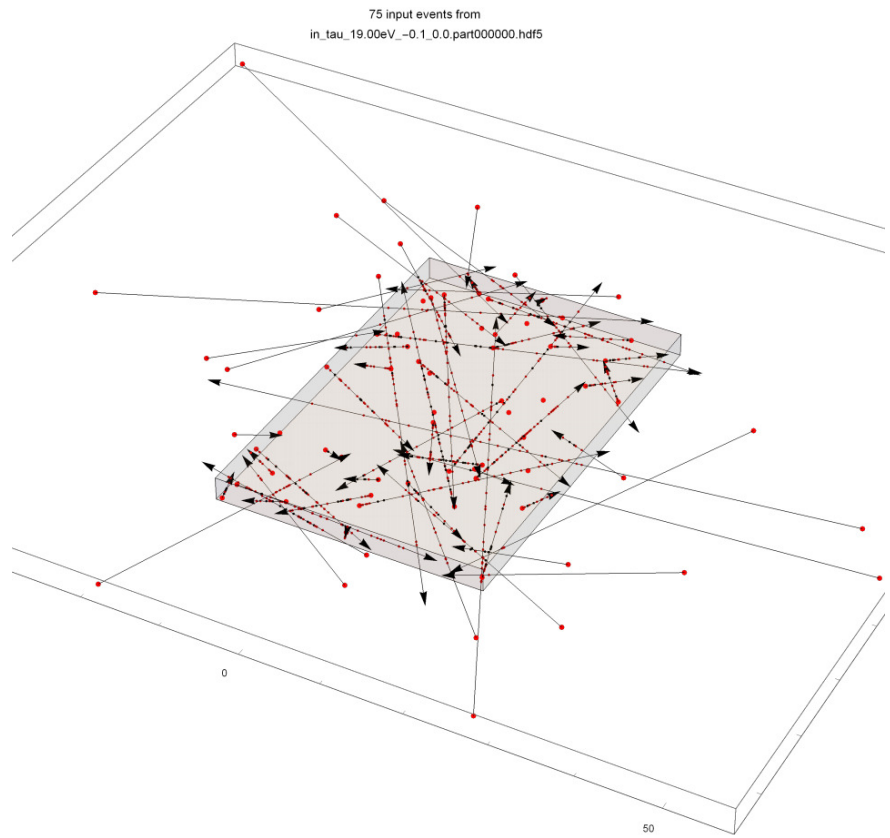
Gen-2 Sims

primary and secondary events mu/tau: 10^19 cos zen: (-0.1,0.0)





Qualitative description of events with Cerenkov Ring