Infrastructure for neutrino astroparticle physics

Allan Hallgren Uppsala university

Partikeldagarna 2017

1. The IceCube Upgrade (talk by Chad Finley)
   Covers neutrino energies up to 10 PeV

2. The Radio Array, This talk.
   Covers neutrino energies from 10 PeV

Infrastructure proposal prioritized by UU and SU

Why Radio Array?

- High Energy Neutrino telescopes based on the Optical Cherenkov Technique now established (IceCube/TIU, Antares -> Km3NeT, Baikal->GVD)

  Size $\sim \mathrm{km}^3$ → Energy range < 10^{16} eV

- Radio Array for Extremely High Energy (EHE) ν-detection is being developed.
  - Several concepts suggested, some are being tested.
  - Want "low" threshold, sensor need be close to interaction to reach down to 10^{16} eV (challenging)
  - Radio Frequency antennas embedded in ice/firn most realistic and cost effective option
  - Size (e.g. ARIANNA) ~ 750 km^3

    $\mathrm{cost}/\ \mathrm{km}^3 << \mathrm{than\ optical}$, but worse resolution

In-Ice Radio Arrays

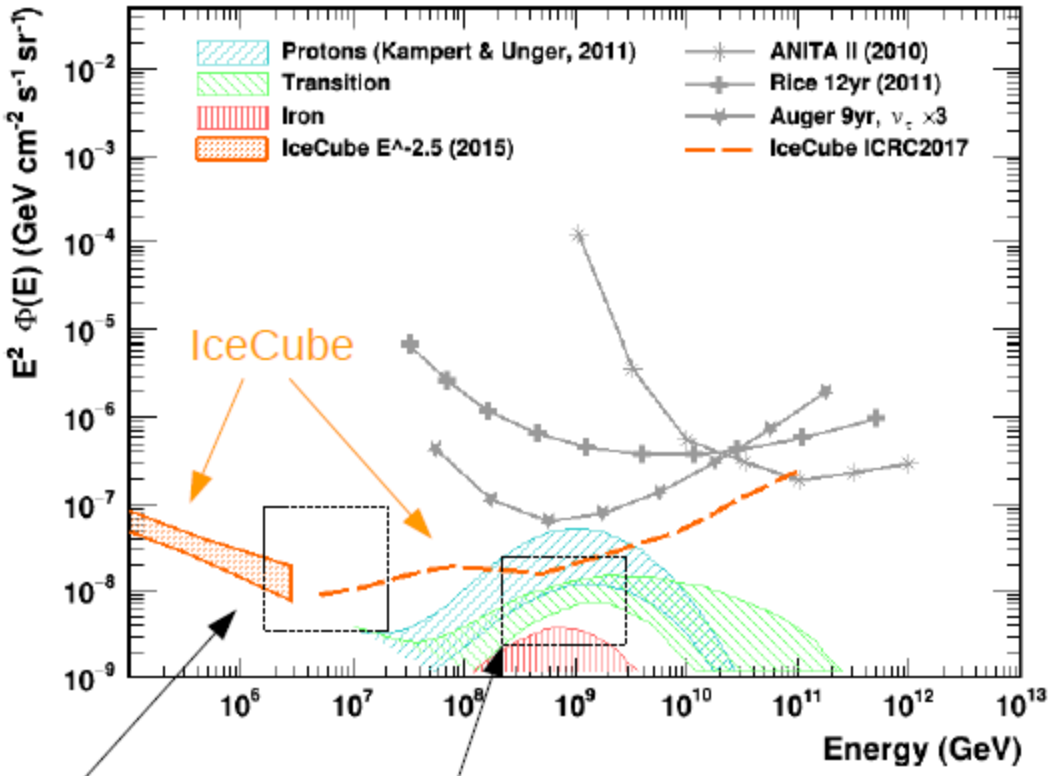
Three initiatives under development for in-ice radio-based neutrino telescopes:

- GNO (**G**reenland **N**eutrino **O**bservatory) at summit station, investigated ice properties and did initial test. No array installed yet.
- ARA (**A**skaryan **R**adio **A**rray) at the South Pole Station, now 3 stations installed, at some km distance from IceCube.
- ARIANNA (**A**ntarctic **R**oss **I**ce-shelf **AN**tenna **N**eutrino **A**rray) on 465 m thick, floating ice on Antarctic coast. Stations deployed: 7 for ν (installed 2012-14), 2 for CR (2015-16),

  +1 for of horizontal showers (2016, ν_τ-interactions in surrounding mountains)

We are working with the ARIANNA team → most of this talk

Science Goals of the ARIANNA Array



Extend IceCube Flux to higher energies

Probe pessimistic iron-only GZK flux predictions

From C. Persichilli @ TeVPA 2017

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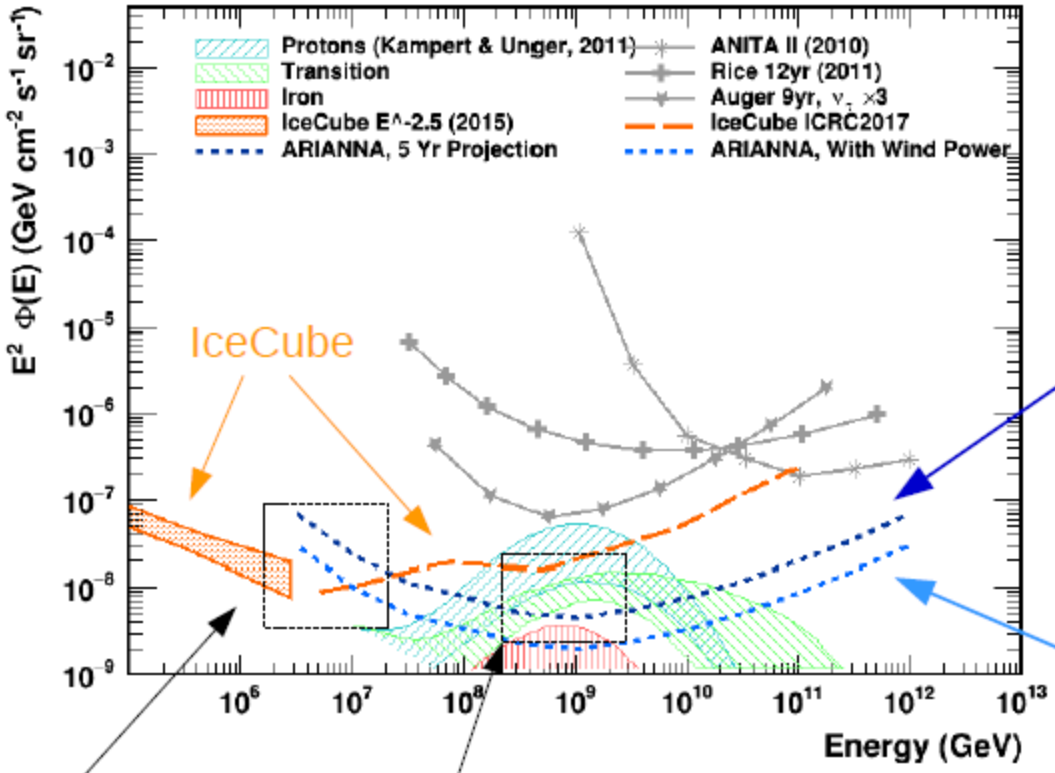


Extend IceCube Flux to higher energies

Probe pessimistic iron-only GZK flux predictions

Baseline ARIANNA

- 1296 Stations
- 1km separation
- 5 years of run-time
- Assume 90% analysis efficiency
- Average livetime fraction of current pilot stations

With wind power

- Extends operation through Antarctic Winter
- Currently being tested

Wind power is being developed in Uppsala in collaboration with expert , Professor Hans Bernhoff

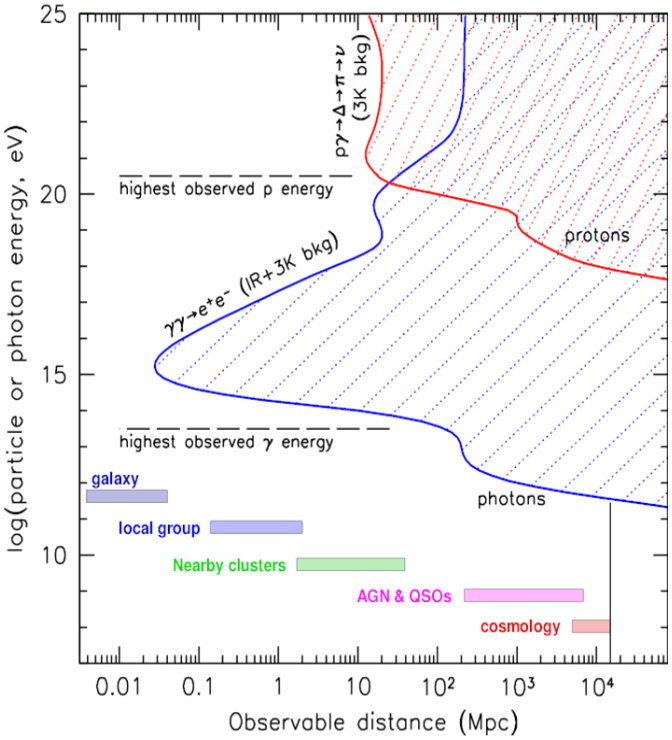
From C. Persichilli @ TeVPA 2017

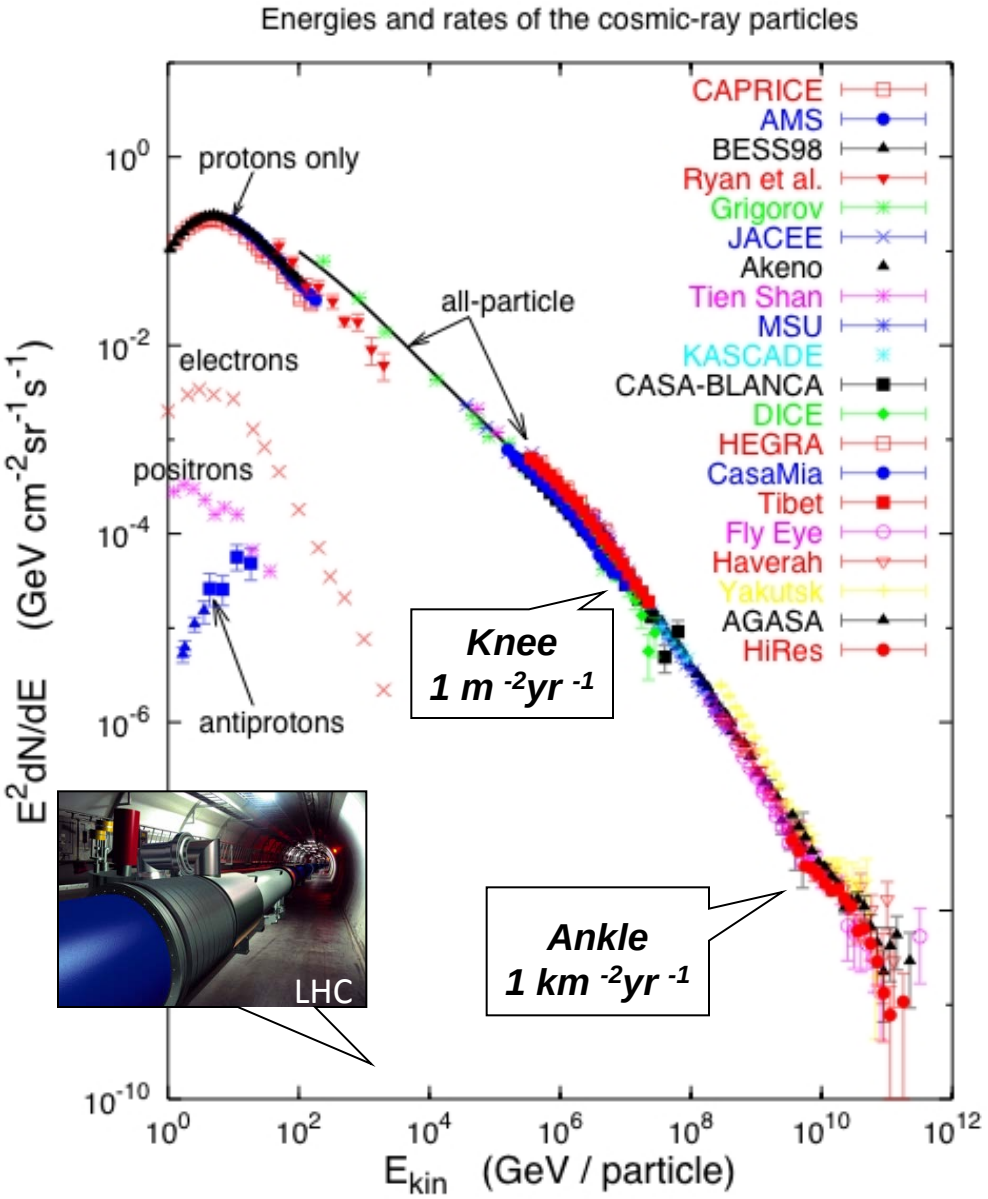
CR spectrum and GZK/BZ neutrinos

Protons interact with CMBR

→ ν produced

→ E 10^{17} - 10^{19} eV





Greisen–Zatsepin–Kuzmin / Berezinsky–Zatsepin

Detection mechanism proposed by G. Askaryan (1962):
Measure the coherent RF signal generated by neutrino interaction in dielectric media (such as ice)

charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower

moves as a compact bunch, a few cm wide and ~1cm thick → Moving net charge in a dielectric

Emission at 'cherenkov'-angle

But wider than optical

$\lambda \gg R_M$ Add coherently!

-> Radio-waves

emitted power $\propto N^2 \propto E^2$

nucleus

ν

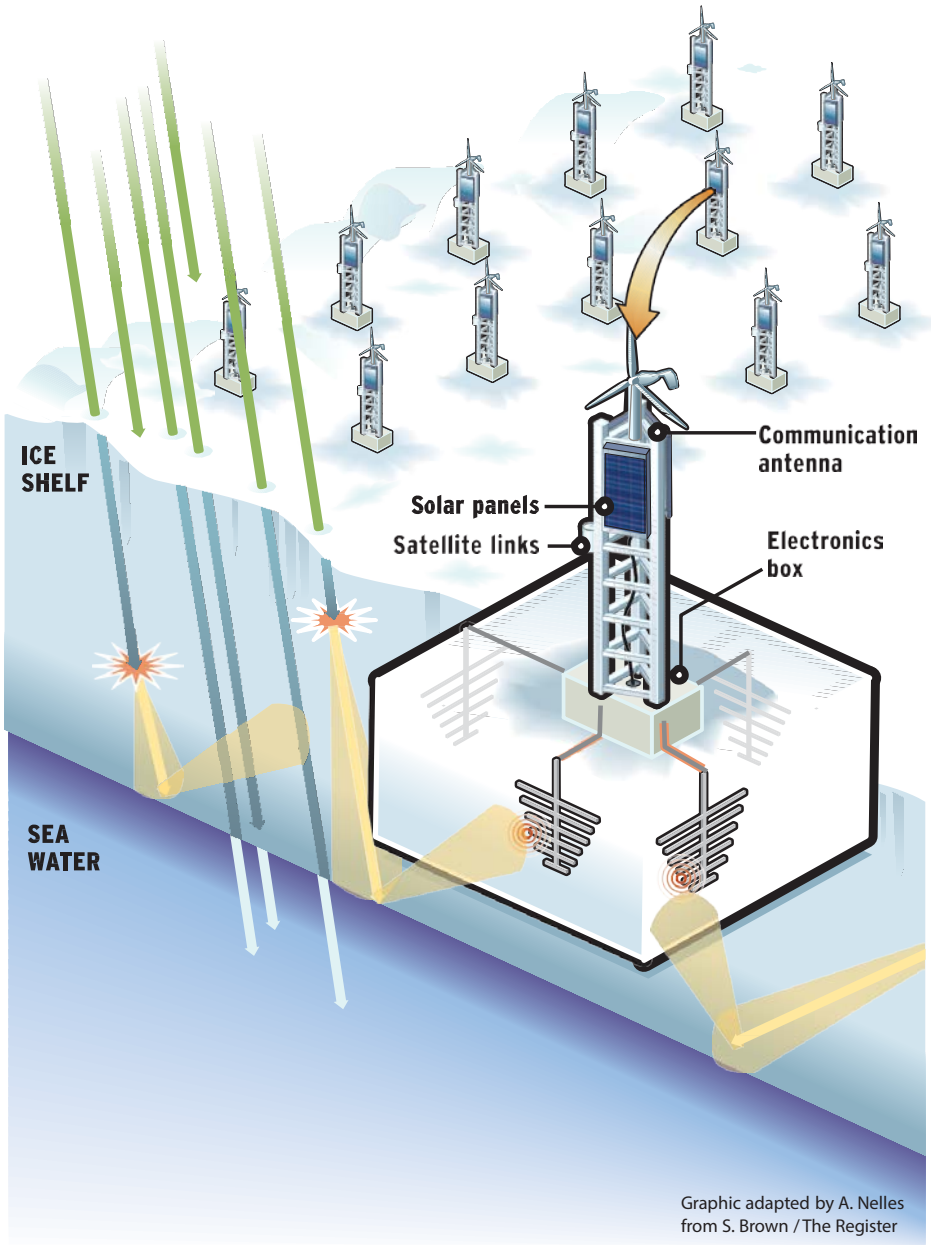
$E > 10^{17}$eV

Particle cascade

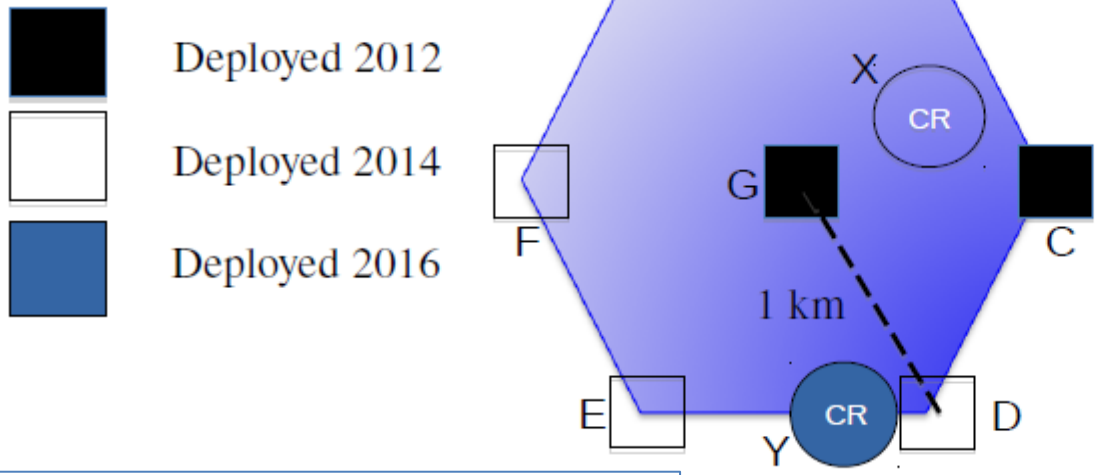
electric field strength proportional to the square of the shower energy

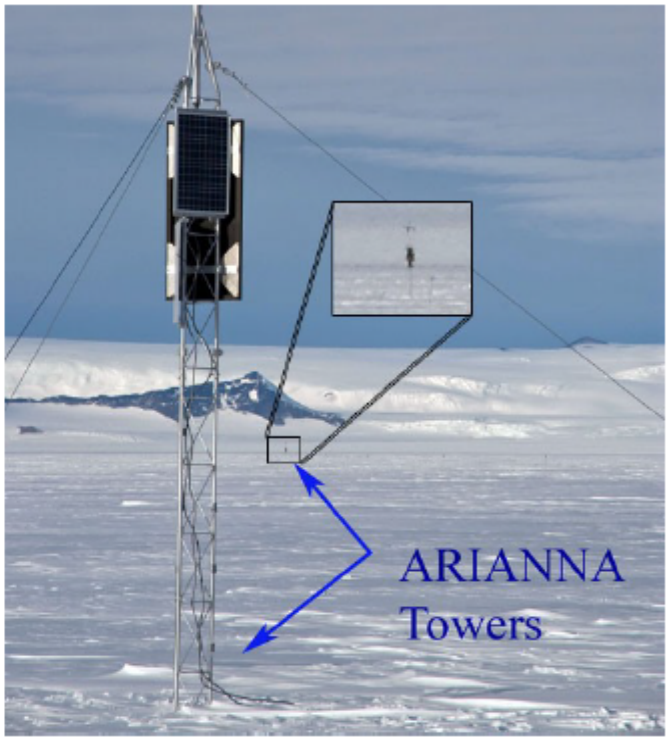
Concept of ARIANNA

- **Independent antenna stations** can be installed at low costs on the surface
- **High gain antennas (50 - 1000 MHz)** can be used to instrument a large volume
- **Ross ice-shelf** (Size of France), Moore's bay, 110 km from McMurdo
- Ice-water boundary **almost perfect reflector** for radio emission
- **Solar** (and wind ?) **power**
- **Real-time data** transfer via satellite, SBD
- Array of about 1300 stations needed, **36km * 36km**, grid with 1 km spacing
- ~ 30 Million USD



Current State of ARIANNA: The HRA



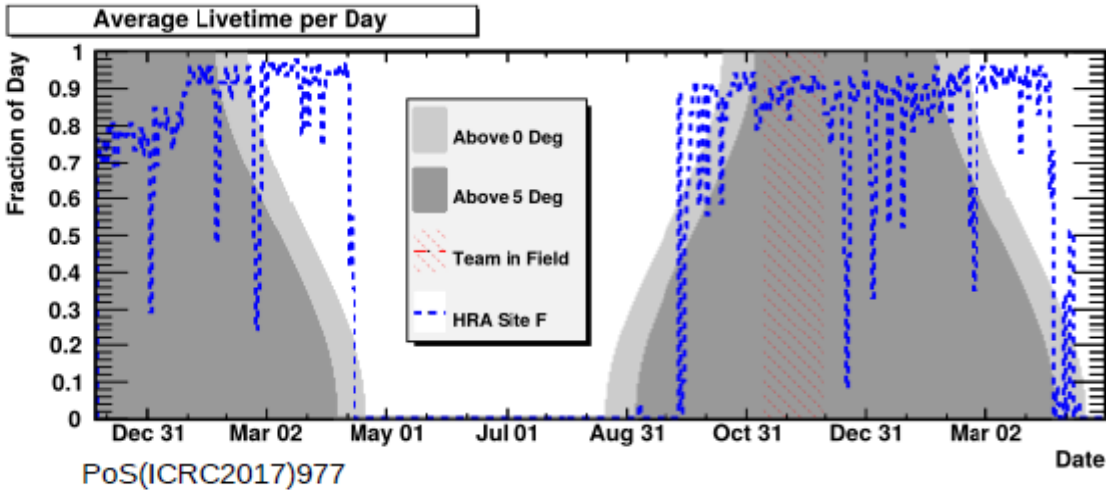


From C. Persichilli @ TeVPA 2017

Useful Livetime for analysis, adjusted for DAq deadtime, and data transmission

- System survives the Antarctic winter and function correctly in the spring
- 90% livetime is typical during normal operation
- Dips in livetime due to bulk data transfers and storm periods
- Average Livetime of 149 days per HRA Station in 2016-2017 seaso

Update: All station restarted September 2017



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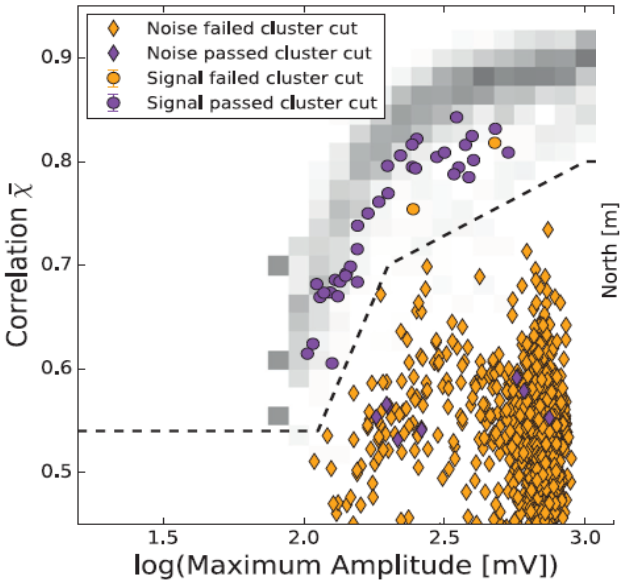
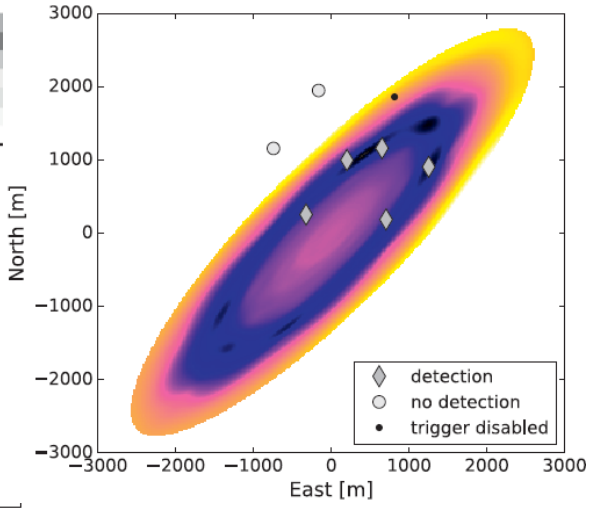
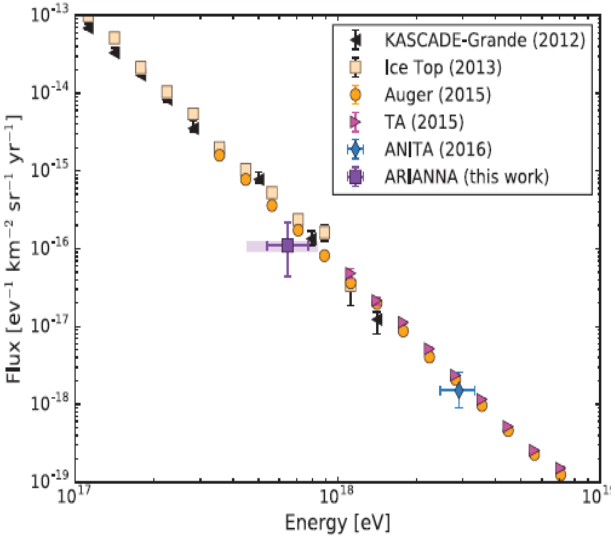
Cosmic rays

Astroparticle Physics 90 (2017) 50







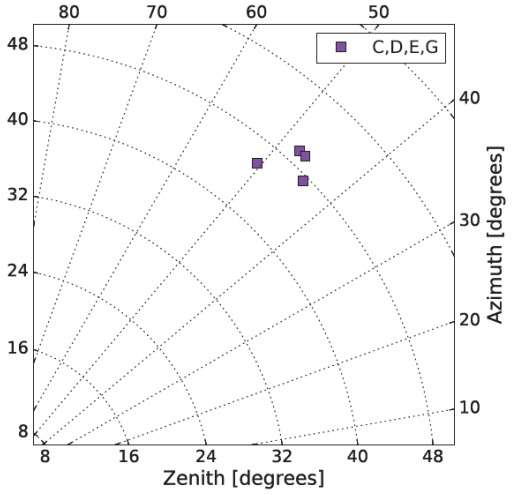


Fig. 11. The reconstructed signal arrival directions corresponding to the five-fold coincidence event. The event has been detected in the standard stations C, D, E, and G, as well as station X.

ARIANNA detects CR events – use as test beam!

Self triggered, possible as low noise level

Rate in agreement with expectation

Methods from LOFAR & AERA used

38 events detected in special station w upward antennas

Some events additionally detected in other stations

One event detected in CR station + 4 down-looking stations

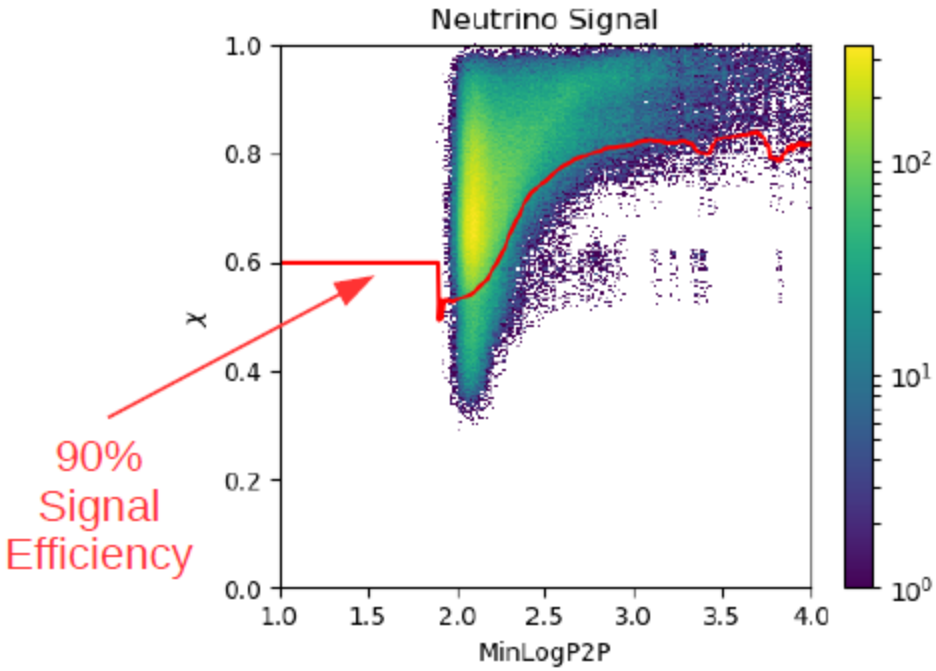
Angular resolution also in backward (**!**) direction

New dedicated station, four upward antennas deployed Dec. 16 to increase rate and quality

CR events can be efficiently suppressed from ν channel !

HRA Neutrino Search Efficiency

From C. Persichilli @ TeVPA 2017



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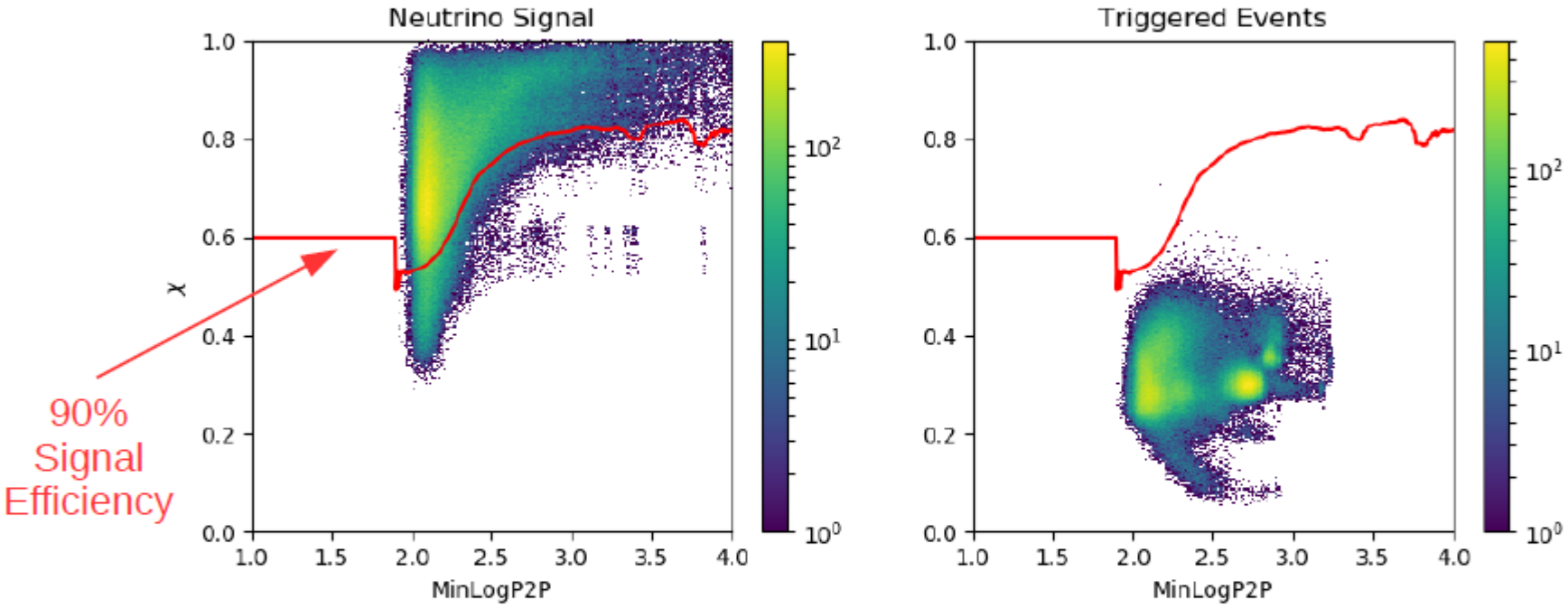
HRA Neutrino Search Efficiency

From C. Persichilli @ TeVPA 2017

All HRA Triggered Events* from Dec 2015 to Mid April 2017



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*Some stations have different model amplifiers, and are not shown for simplicity.

HRA Neutrino Search Efficiency

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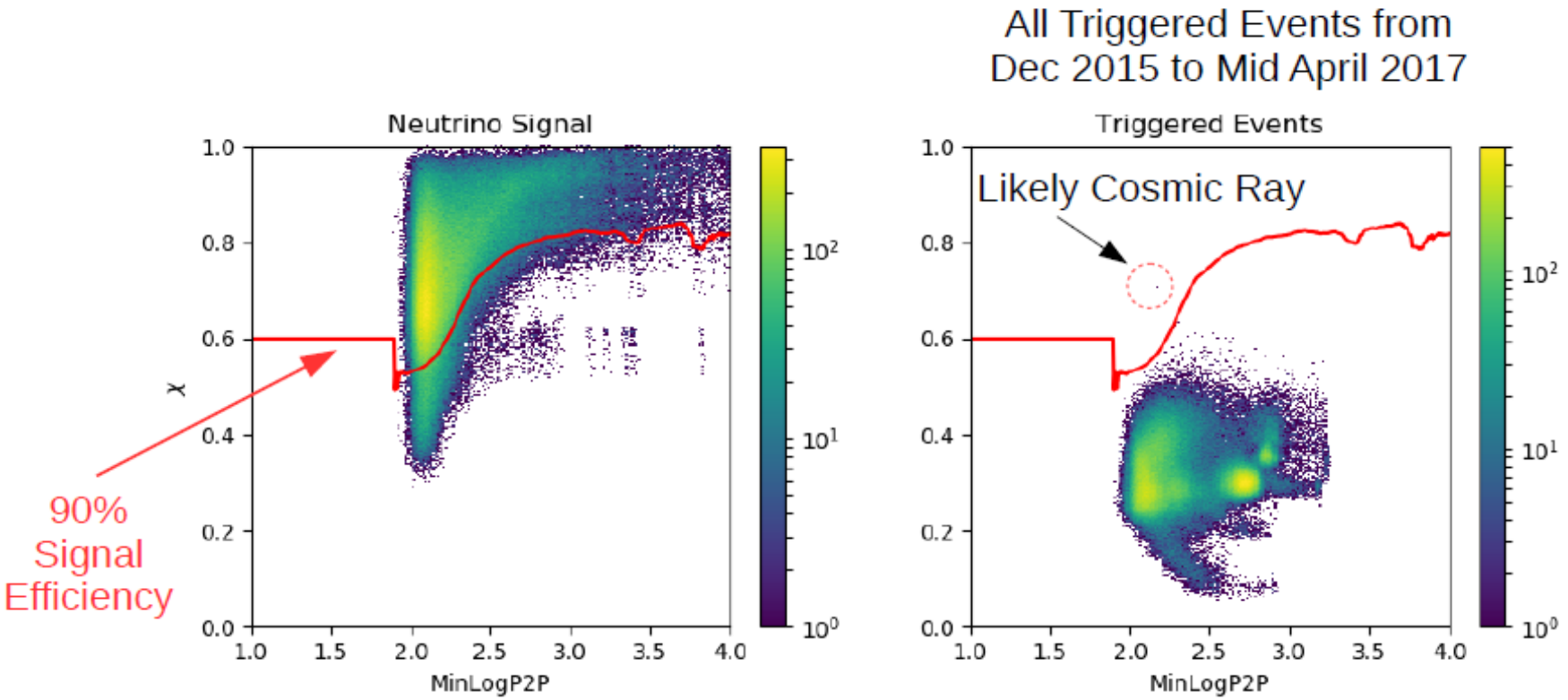

- Upward facing antennas will be necessary to tag cosmic rays (already planned)
- 90% signal efficiency is achievable with a simple analysis, and a plausible projection for a full ARIANNA deployment

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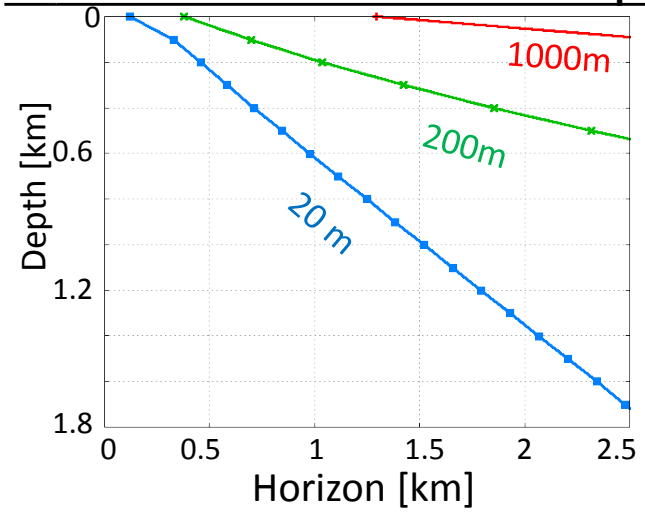
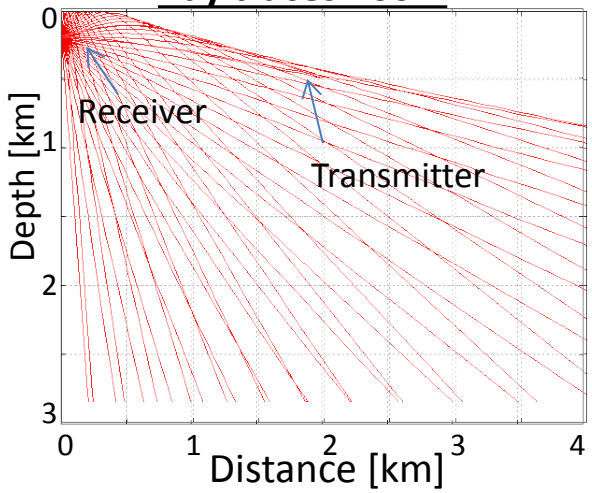
*Some stations have different model amplifiers, and are not shown for simplicity.

Theory: Ray propagation in firn gives shadowing

Horizon for 3 different receiver depths



Ray traces 200m



Firn, the layer of packed snow over the ice, has a gradual shift of density

→ gradual shift of refractive index

→ bending down of rays

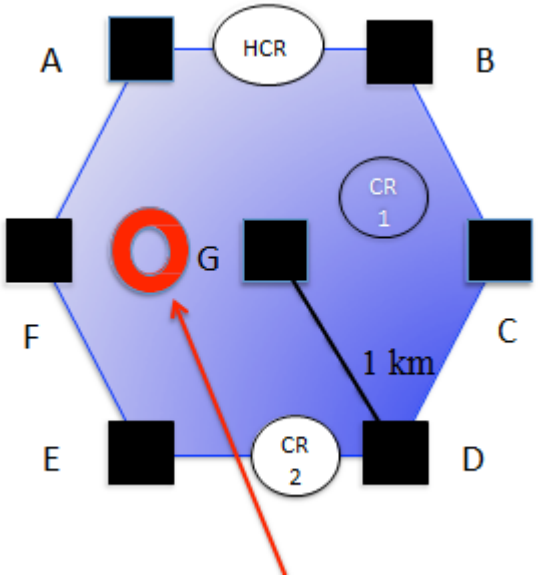
→ "shadowing"

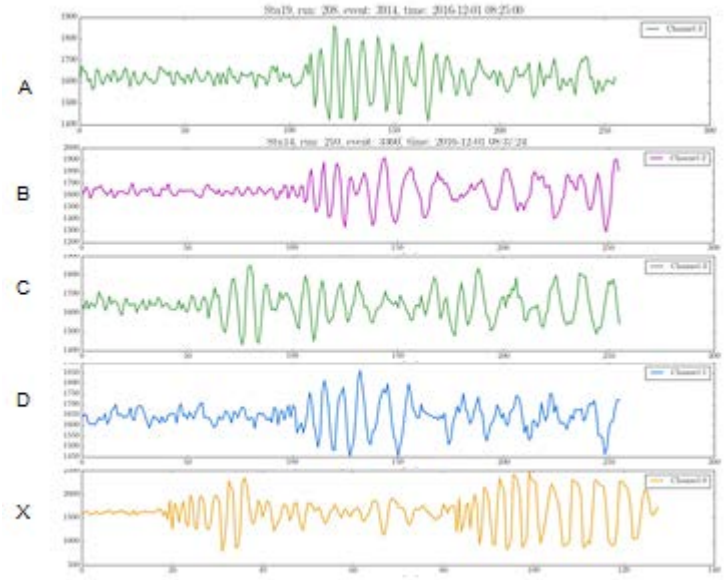
→ Other ice based detectors (ARA, GNO) needs to drill deep holes to widen horizon and see more events

→ Constrains choice of antennas and station geometry, deployment logistics and increases cost

Not as important for ARIANNA on Ross Ice Shelf, most events seen on reflection from bottom of ice, but can increase V_{eff} and possibly give some double detection events

Test of propagation for ARIANNA





Dipole pulser buried at depth of 20m
Vertical polarization
Should not be seen at distance
if complete shadowing

December 2016
Signals seen in all stations
Revise theory, Snells law ???

Similar effect found in ARA and GNO, but had been ignored……
Now working together to understand and quantify effect.

Future work

Field work this season

- Deploy stations with new 8 ch DAQ electronics
- Install ARIANNA type station at South Pole
- Measure noise with ARIANNA equipment at Pole
- Study ice properties, esp. horizontal propagation at both sites
- Test for wind power with new turbine at ARIANNA site

Simulation and detector modelling

ARIANNA is working together with the ARA and GNO simulation teams to verify codes and to understand detector performance better.

FUNDING:

Plan to submit application to NSF during 2018 (US team)

Field team just arrived at Moores Bay

Link to twitter at arianna.ps.uci.edu

Conclusions

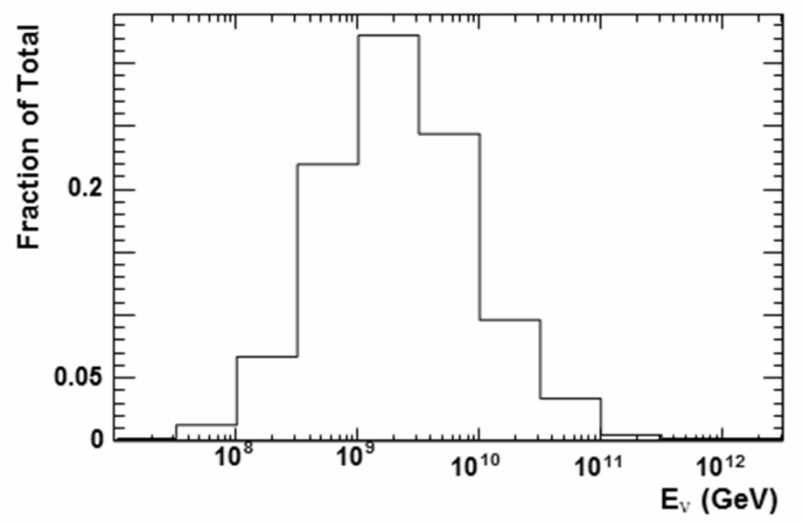
- The detectors of the HRA are now running robustly, with a typical livetime of 90%
- Moore's Bay' is a world-class location for radio based neutrino searches
- Our cosmic ray tag from upward antennas is necessary to distinguish neutrino signal, and has the potential to measure CR fluxes up to 10^20 eV with an independent technique
- A full deployment of ARIANNA should be able to probe all but the most conservative iron-only GZK spectra, even without any further livetime or sensitivity improvements

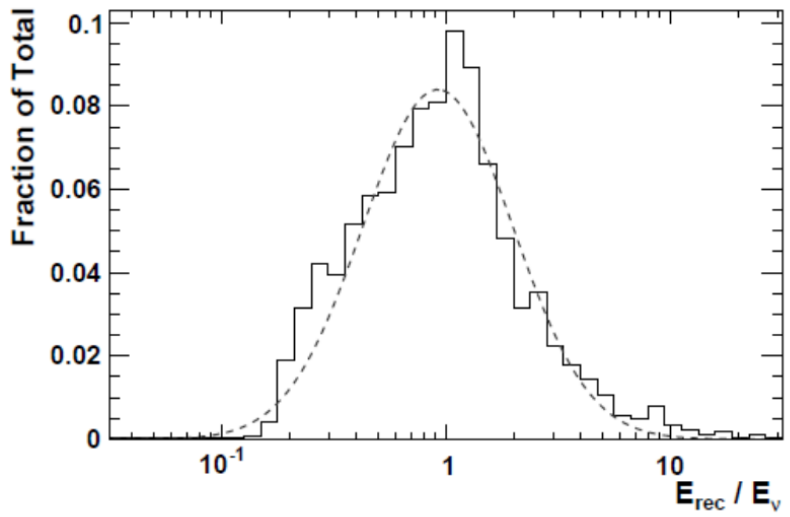
From C. Persichilli @ TeVPA 2017

END

Spectral response & energy resolution

(simulation, in situ beam to weak.....)





For 'typical' input spectrum

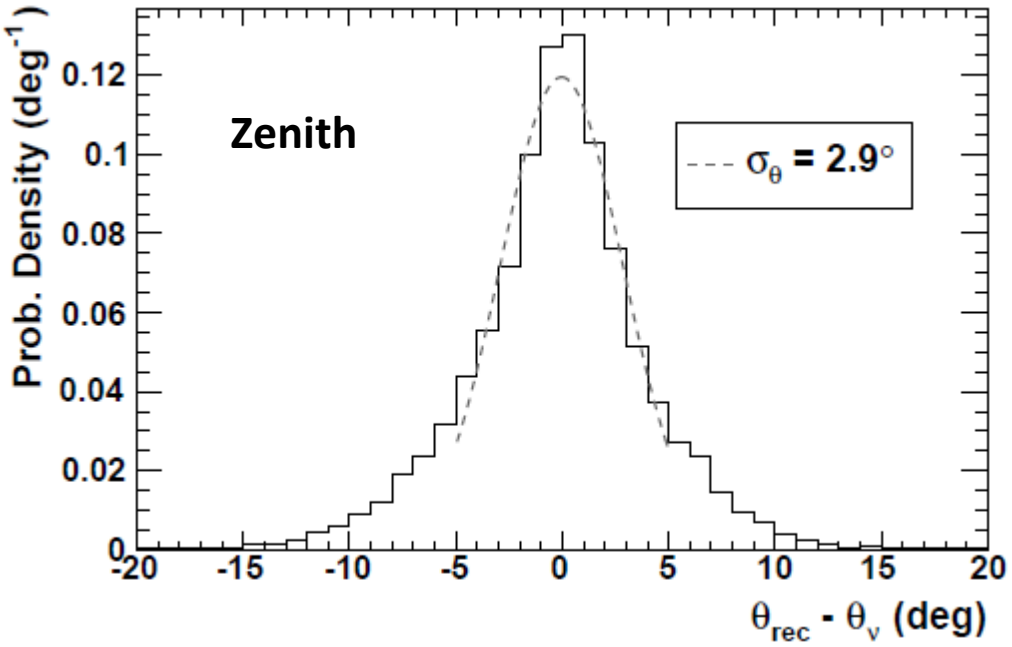
Threshold at 10^{17} eV
Flux limits upper end

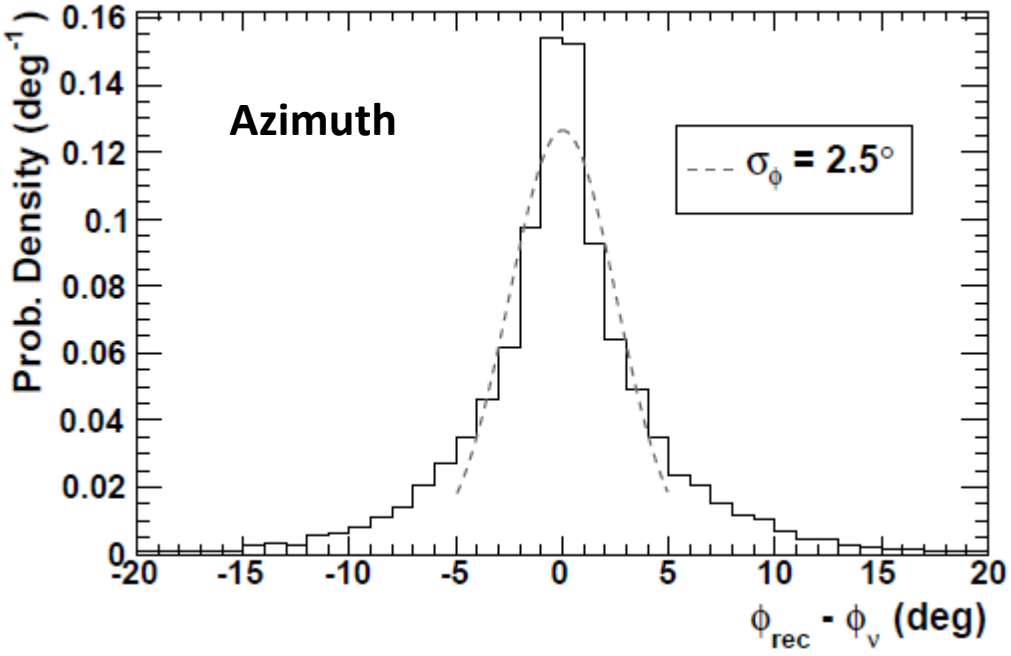
Energy resolution

Dominant factors contributing is uncertainty on angular distance to cherenkov angle and variations in transfer of neutrino energy to shower. Distance, reflexion, antenna response contributions smaller.

Energy resolution
in range 2.2 – 5 on ratio E-rec/E-neutrino

Simulation results prior to Horizontal propagation





Angular resolution

Timing of signals on the different antennas, 100 ps, give direction of RF within 1 degree.

Cherenkov radiation is polarized,

→ different amplitudes in the antennas with different orientation

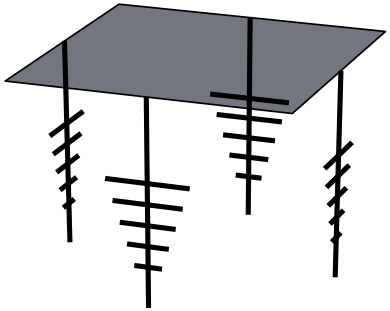
→ direction of incoming neutrino.

Resolution on
Zenith and Azimuth of about
2.5 – 3 degree.

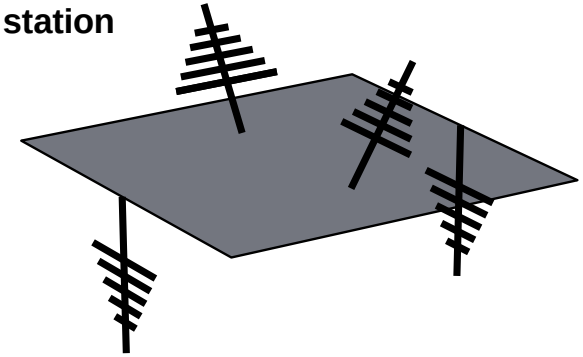
Simulation results prior to Horizontal propagation

Cosmic ray station in ARIANNA

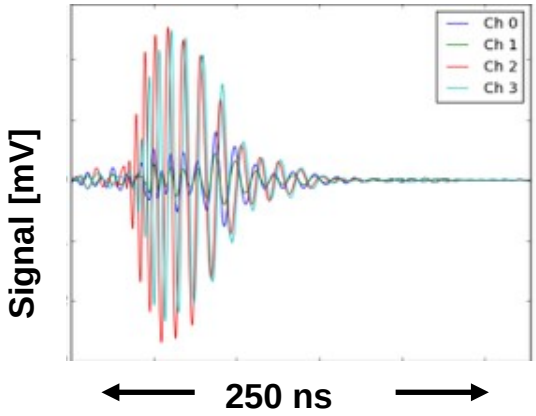
7 regular stations



1 “Cosmic Ray” station



Signal search strategy



Signal + Detector simulation (**Cosmic rays** and **neutrinos**)

Search for events with good correlation with **template**

Find **cosmic ray** candidates

Search for **neutrino** signals

Search for coincidences in other stations

Use measured event as new template

Confirm and reconstruct **cosmic rays**

No candidates

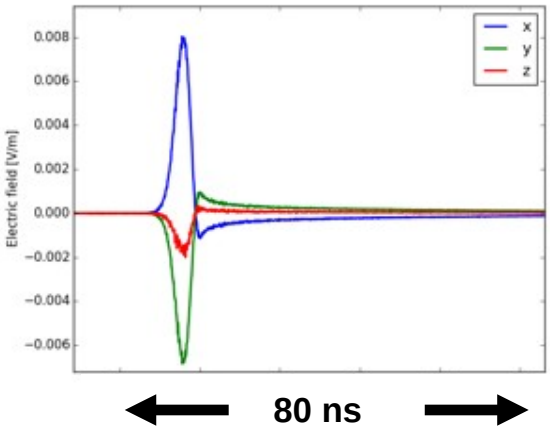
Candidates

Neutrino limits

Event recon-struction

Cosmic Rays

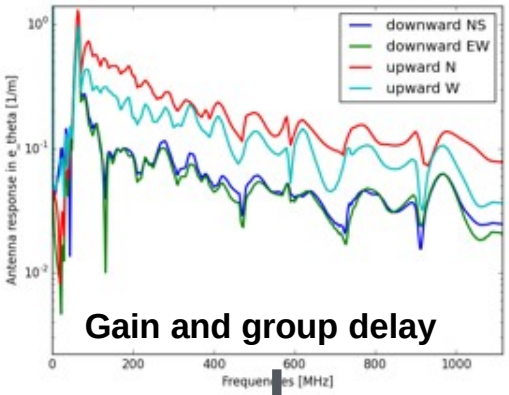
Raw electric field pulse



80 ns

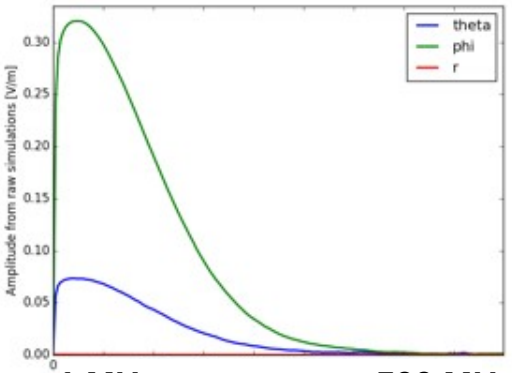
Convolve with

Antenna response



Gain and group delay

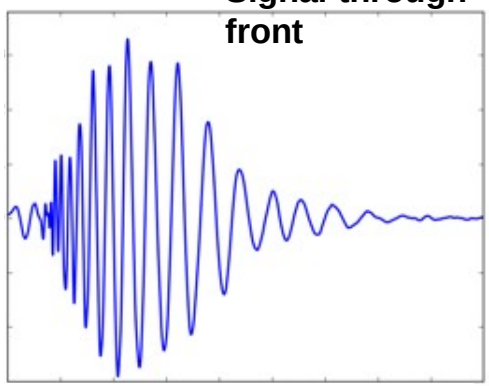
Raw electric field spectrum



1 MHz **500 MHz**

Signal through front

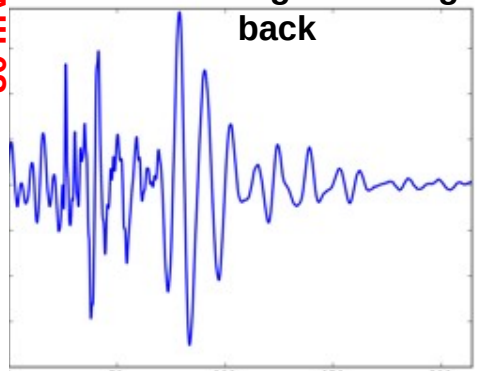
300 mV



150 ns

Signal through back

30 mV



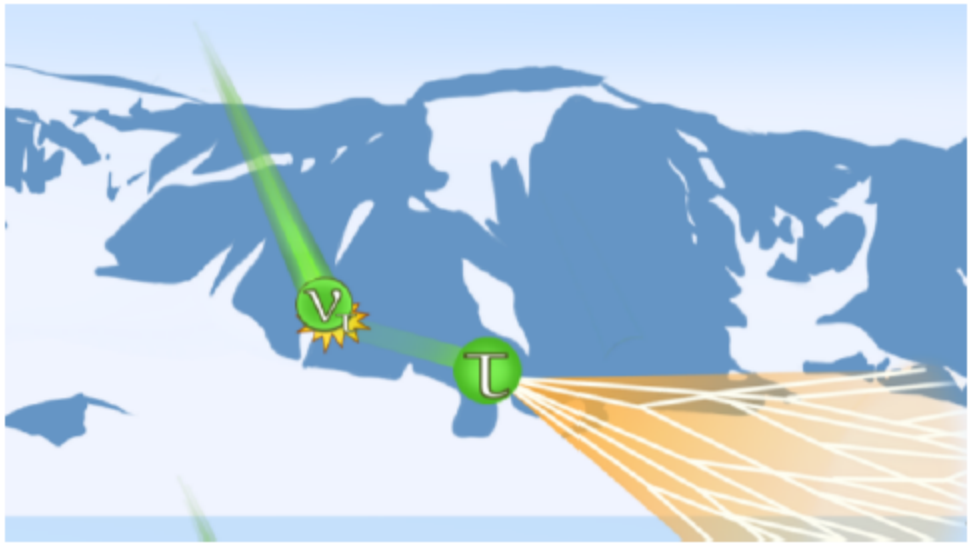
200 ns

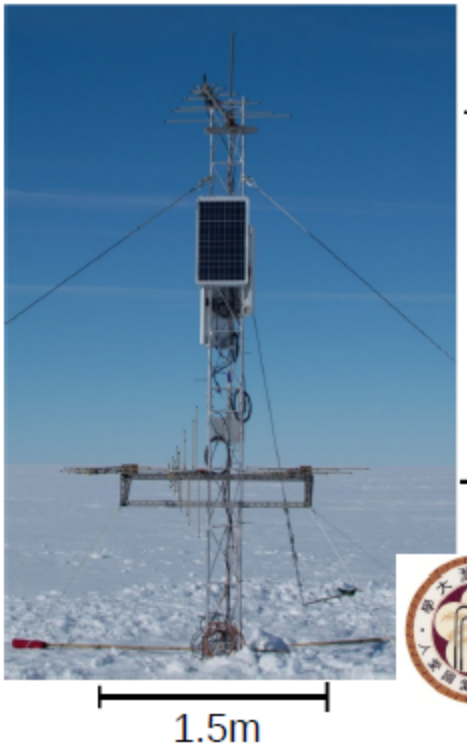
- Air shower signals through front-lobe of LPDA have a **unique characteristic**
- High frequency chirping followed by lower frequencies
- Due to short broadband pulses and group delay of antenna

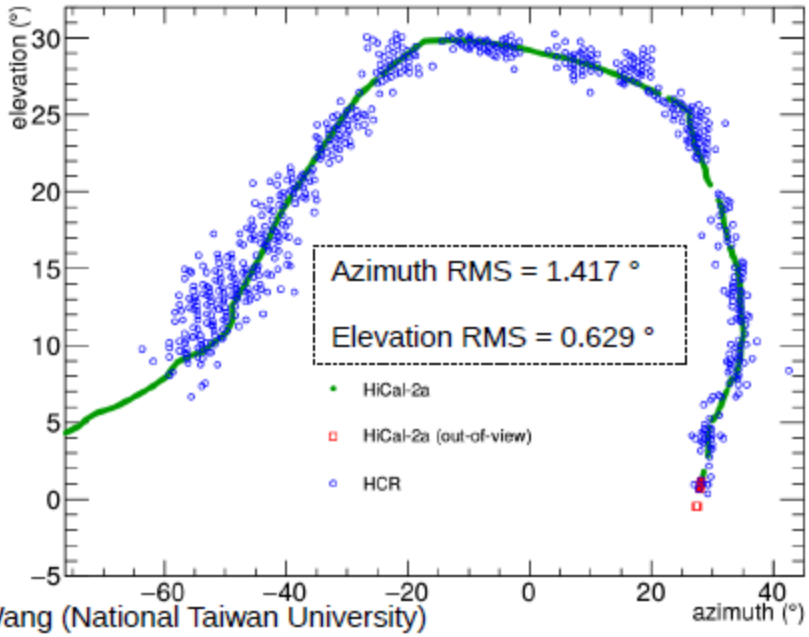
From Anna Nelles @ ARENA 2016

From C. Persichilli @ TeVPA 2017

ν_τ detection In Radio





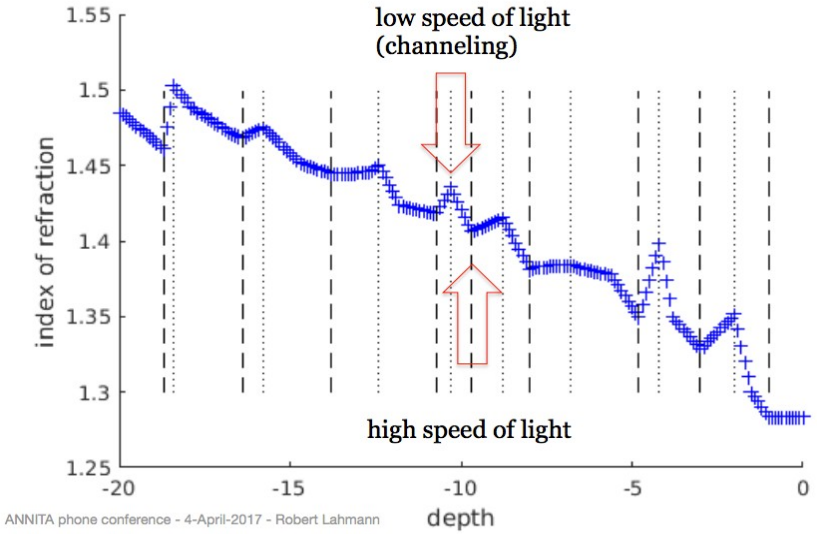


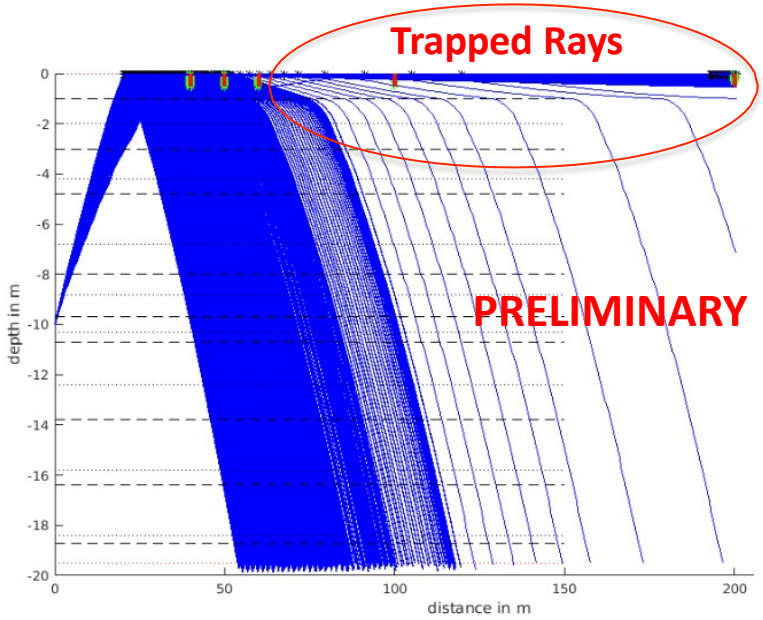
S. Wang (National Taiwan University)
PoS(ICRC2017)358

- Sucesfully identified and tracked pulses from HiCal
- Same ARIANNA electronics, with different antennas and layout
- 68 CR air-shower candidates in preliminary search

NTU group joined to test ν_τ induced horizontal air showers at ARIANNA site

Models of realistic firn density profiles show trapping − R. Lahmann (Erlangen)





Significant (few percent) departure from smooth variation of density at Moore'sBay; Similar variation at SP

Included: reflection and refraction, some scatter (un-even layers)
Next: better model scattering

NEEDS MORE MEASUREMENTS

PLANNED FOR 2017-18 SEASON, BOTH SOUTH POLE and MOORES BAY