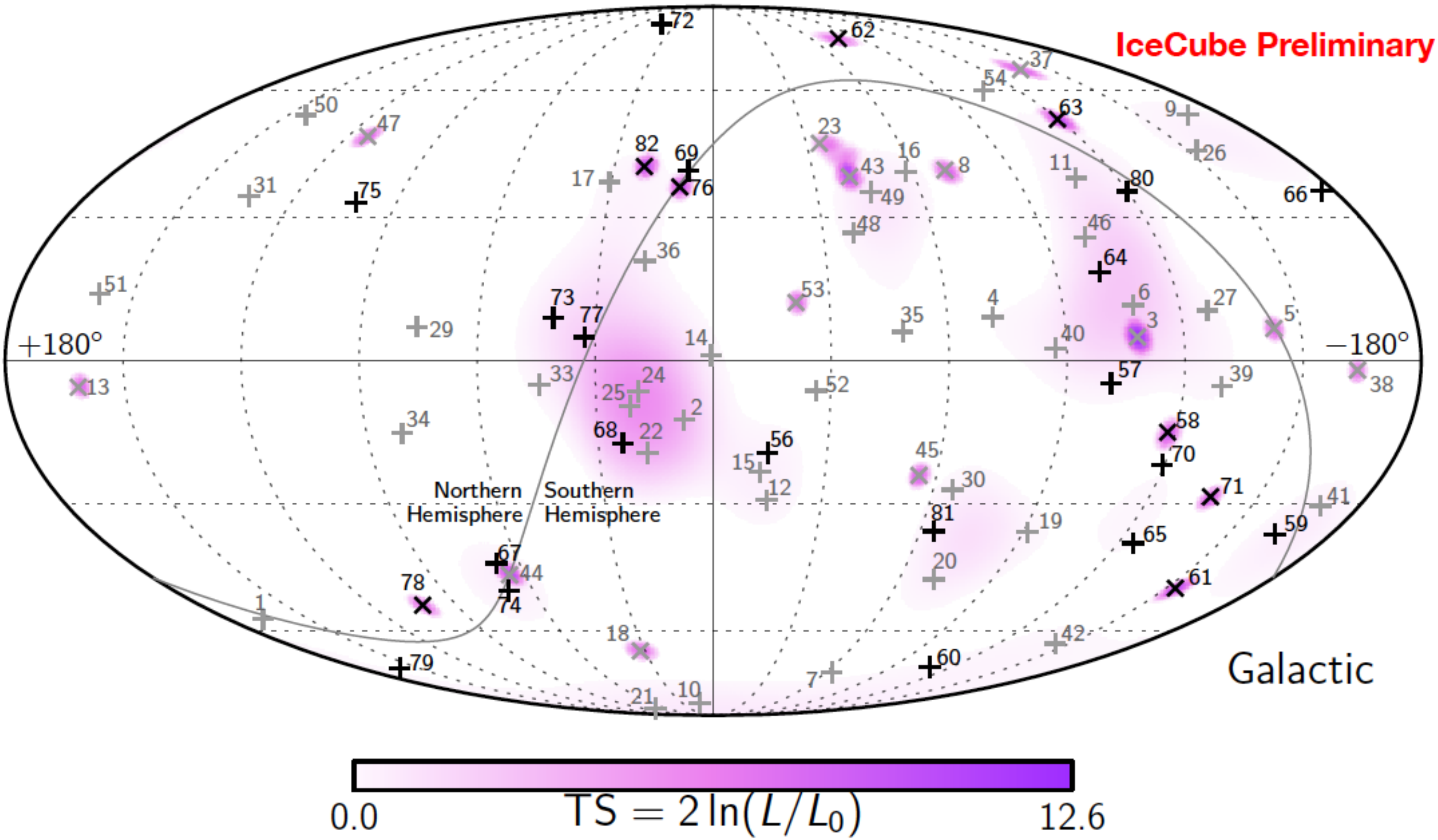
Highlight from ARA

K. Mase, Chiba Univ.
for the ARA collaboration

Universe seen with neutrinos

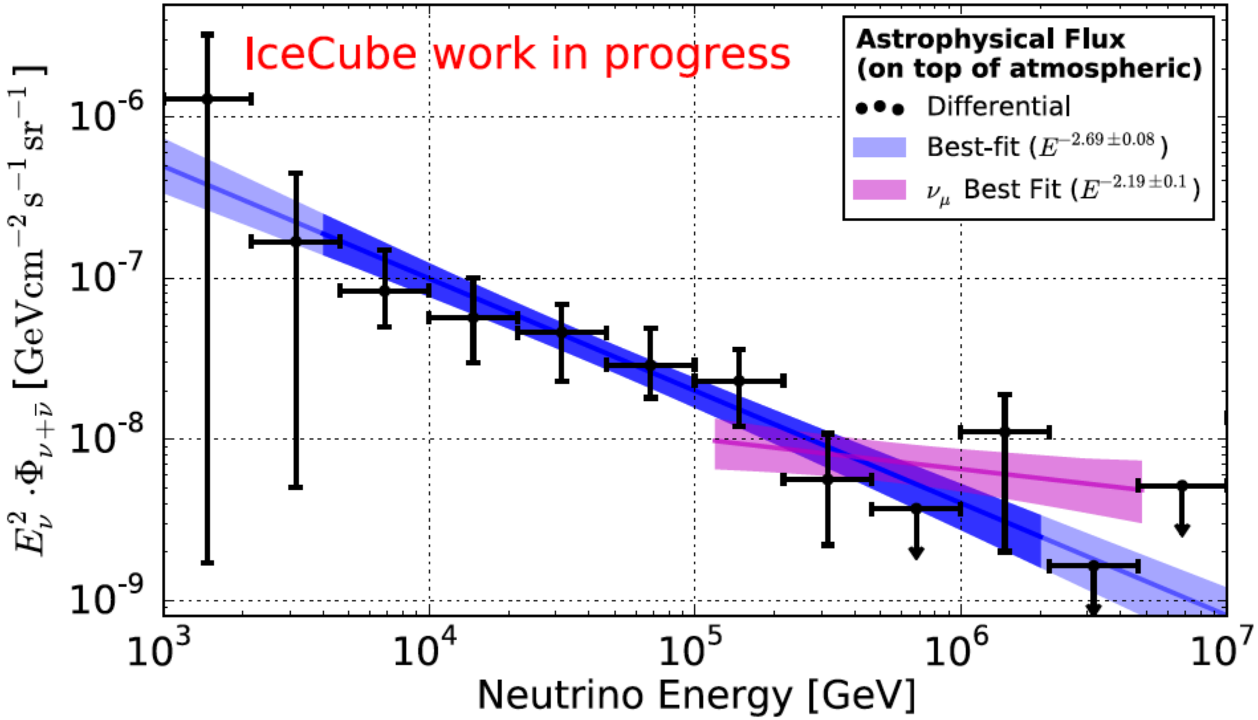


Neutrino astronomy has begun to open

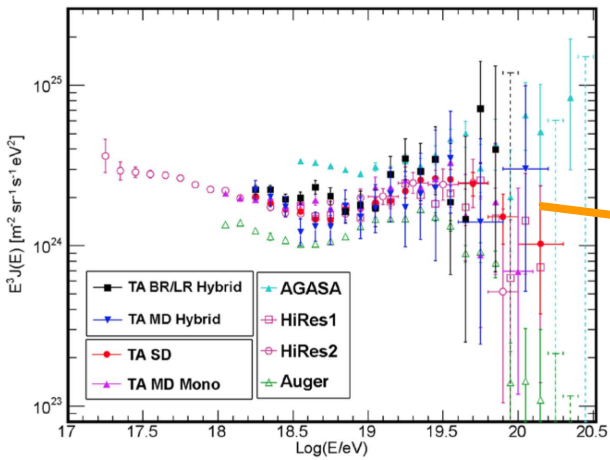
Astrophysical neutrinos

- ✓ Where do they come from?
- ✓ Single power law spectrum?
- ✓ No cut-off?
- ✓ Want to know the high energy tail → Larger telescope

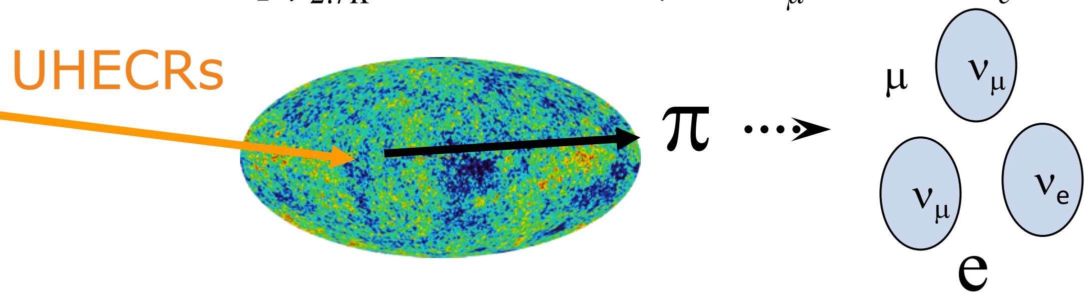
N. Wandkowsky, TeVPA 2017



Ultra high energy (UHE) neutrinos (> 100 PeV)



$$p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu_\mu} + \nu_\mu$$



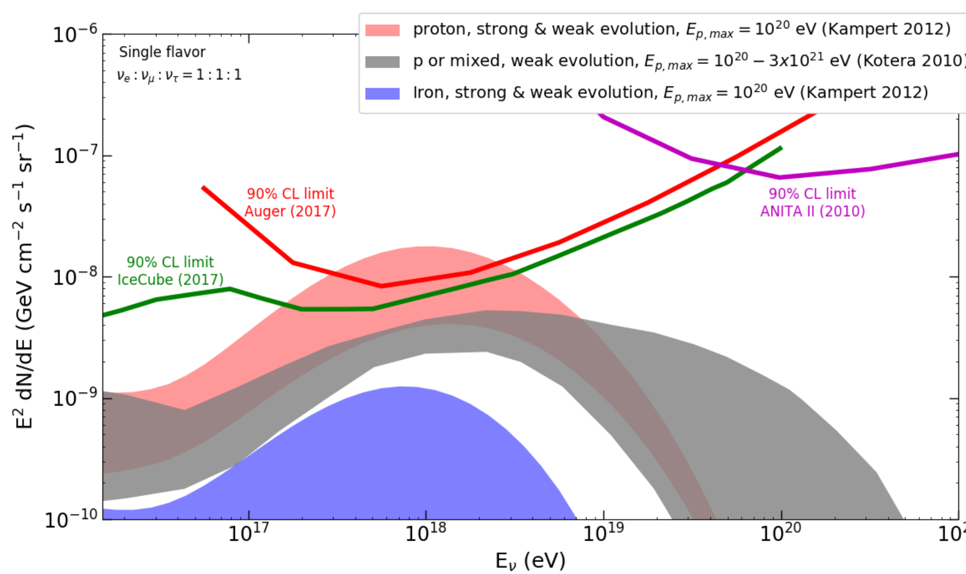
- ✓ Ultra high energy neutrinos (> 100 PeV) inevitably produced from UHECRs
- ✓ Neutrinos can shed light on the UHECR origin
  - ✧ Composition (proton/iron)?
  - ✧ Source evolution
  - ✧ Source position

IceCube upper limit: ~0.3 event/year

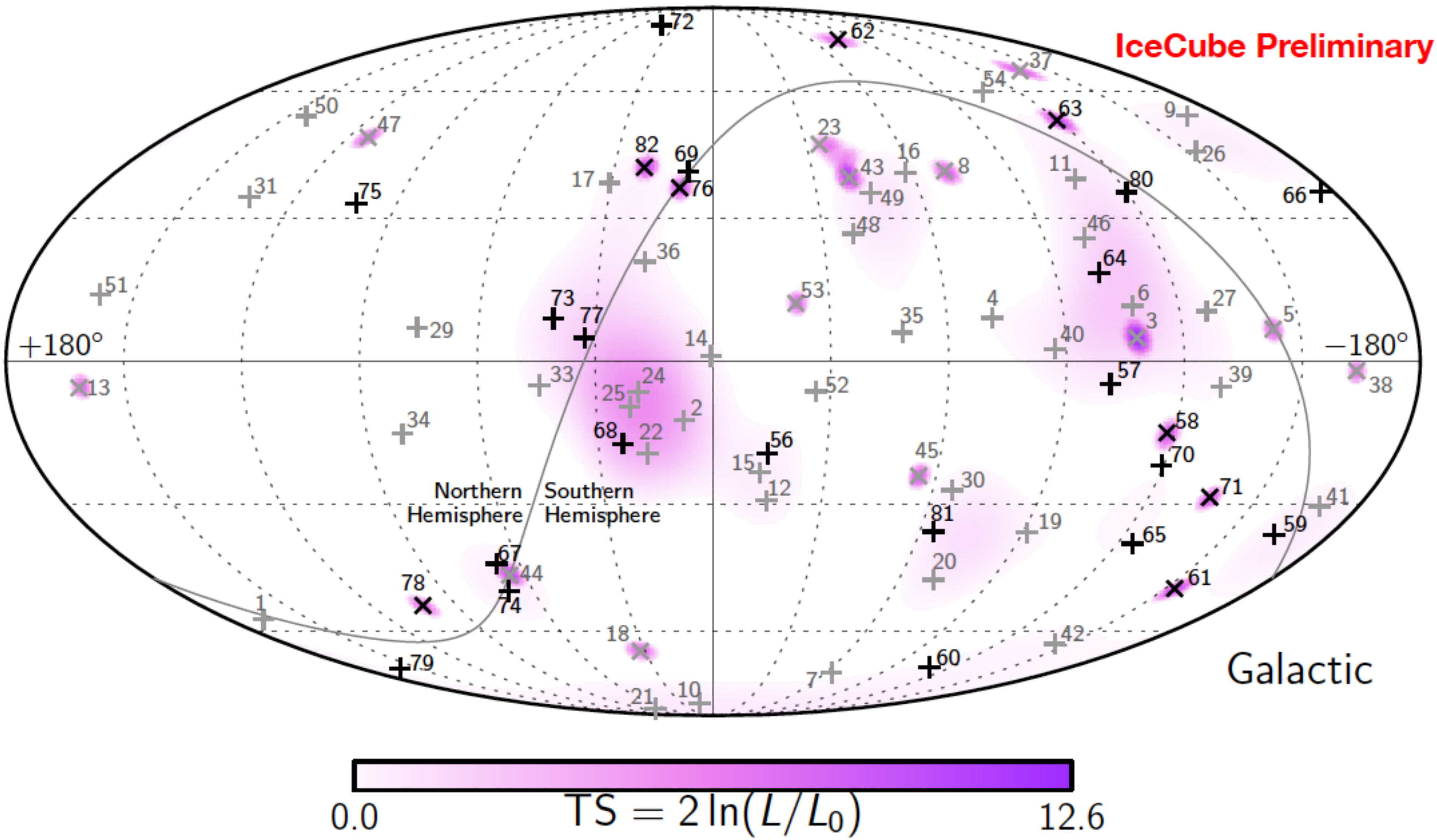
→ Want to detect UHE neutrinos

→ Larger telescope

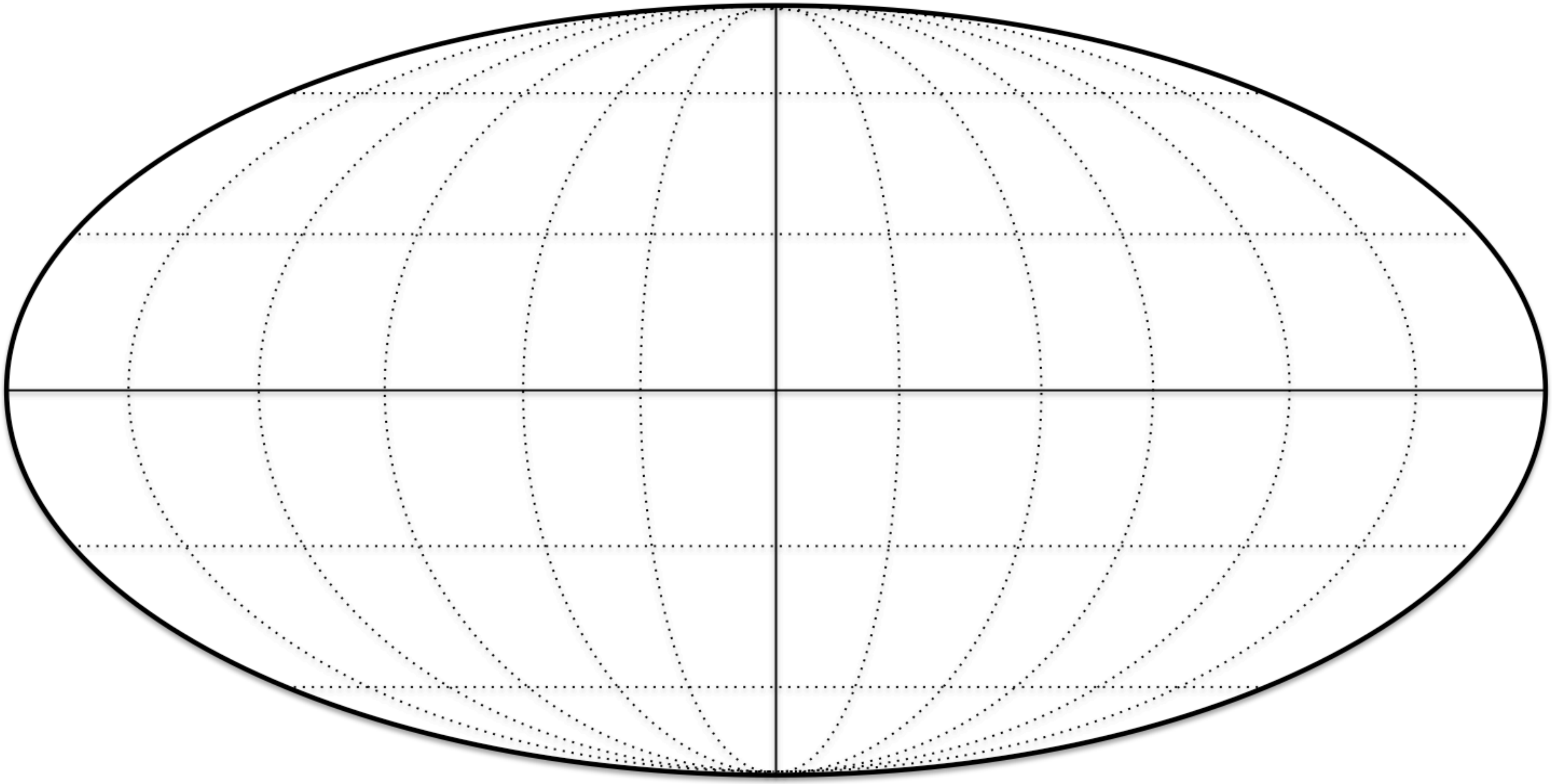
High light talk at ICRC, Jaime



Universe seen with neutrinos

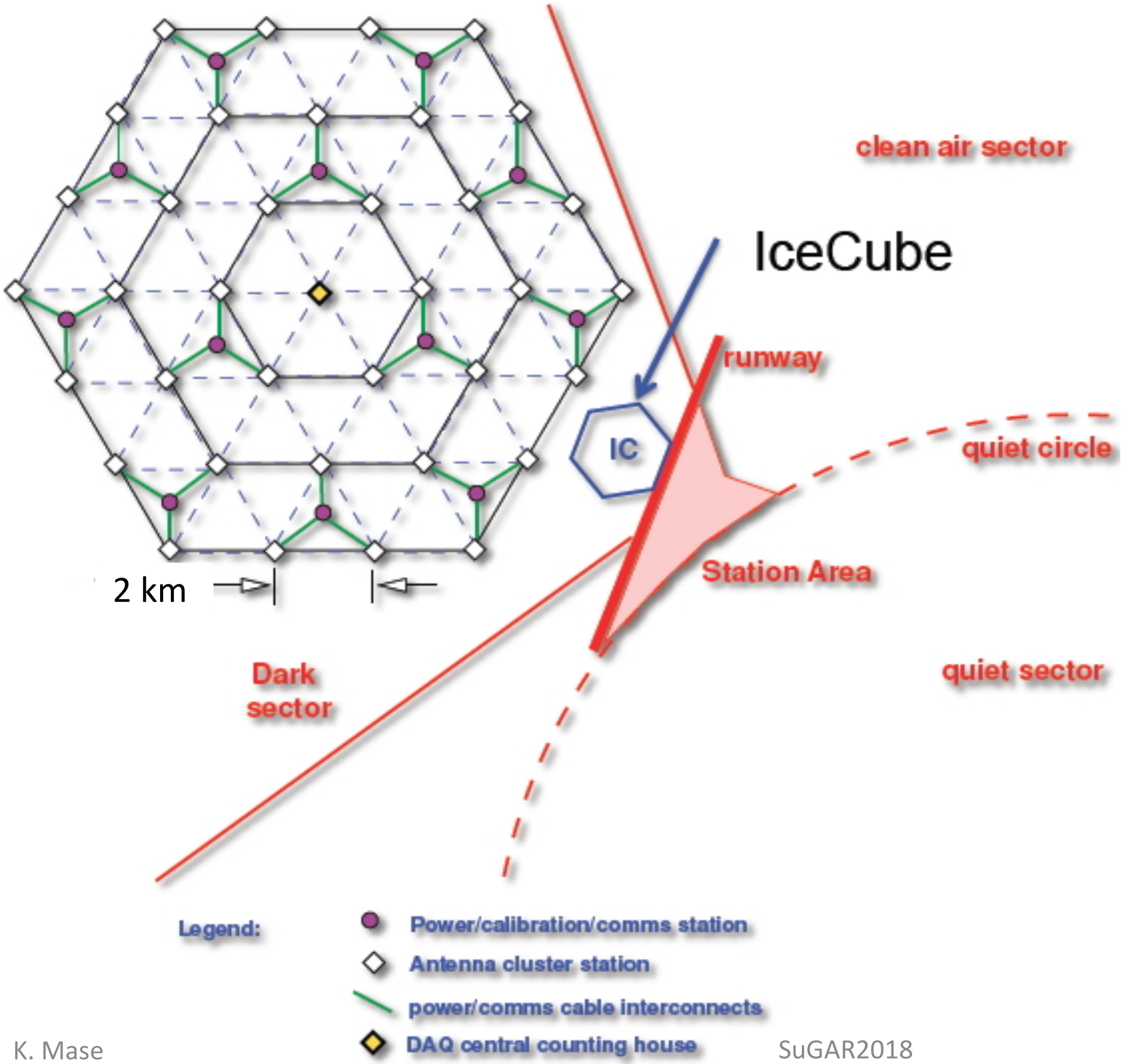


Universe seen with neutrinos (E>100 PeV)



Nothing seen yet

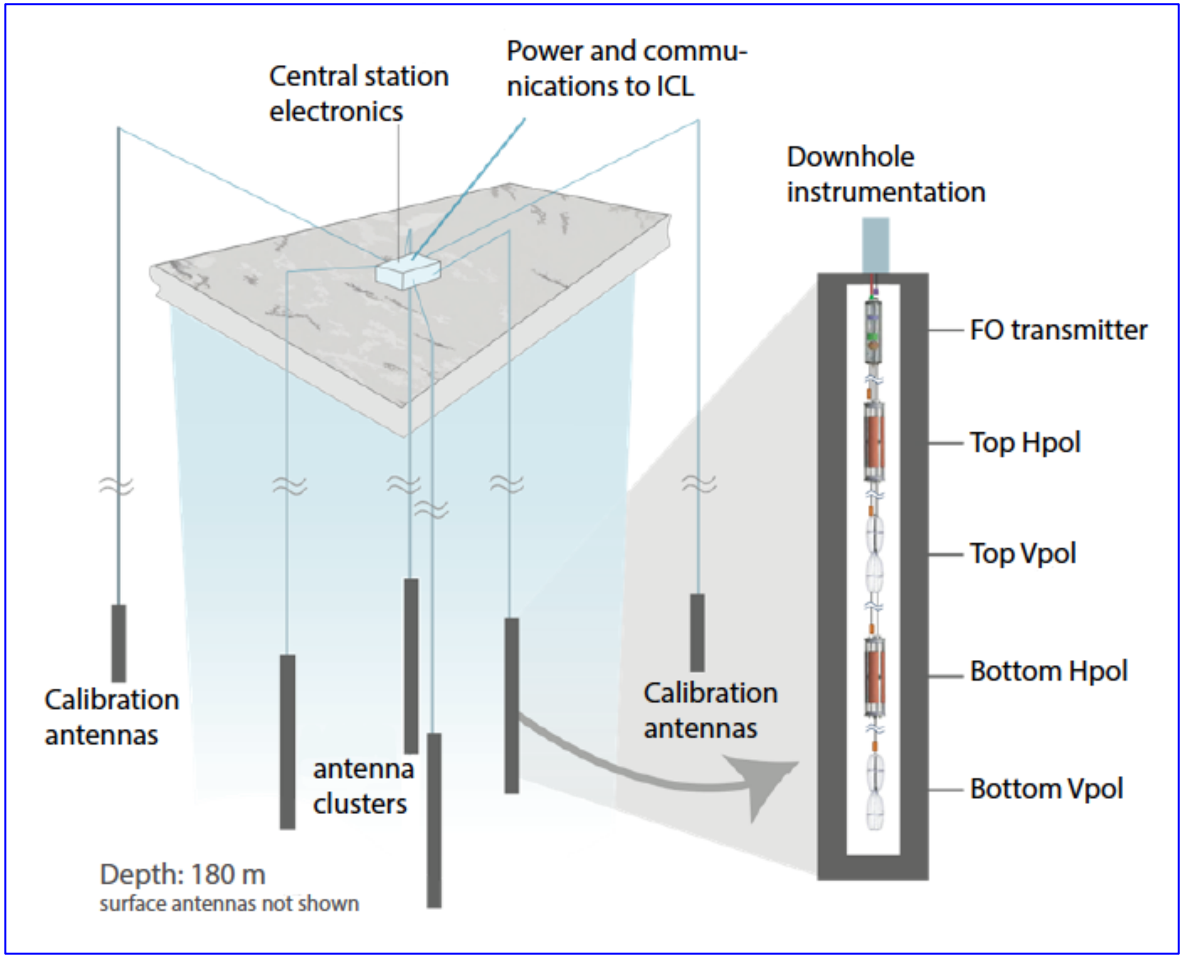
Askaryan Radio Array (ARA)



- ✧ Total surface area ~100 km^2
- ✧ ~x10 IceCube sensitivity @ trigger level
- ✧ ~x5 IceCube sensitivity @ analysis level
- ✧ Reasonable cost (~10 M$)
- ✧ 5 station running (2 more stations built this season)

ARA station

Astroparticle Physics **35** (2012) 457–477

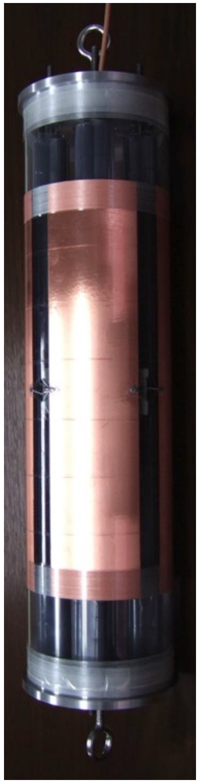


Antenna for vertically polarized radio

(Vpol antenna)

Antenna for horizontally polarized radio

(Hpol antenna)



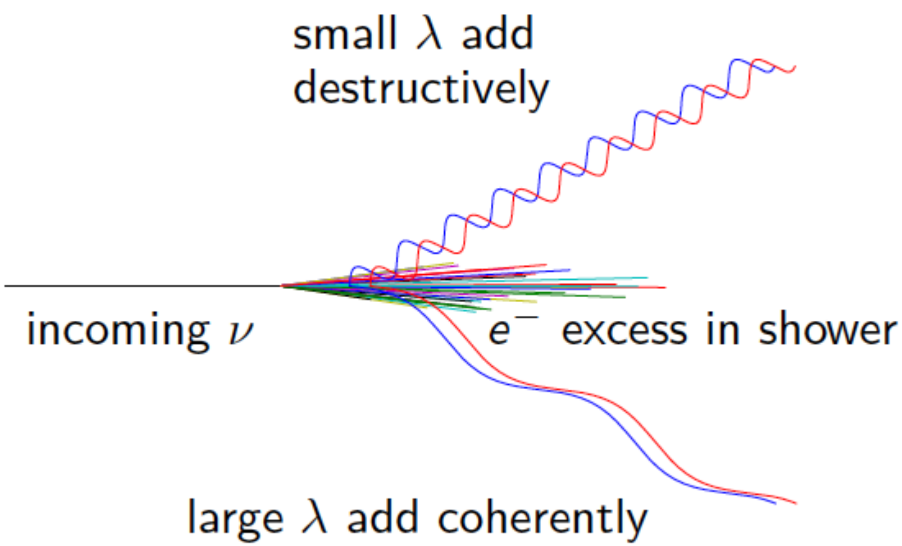
- Each station has 4 strings of 200m depth
- Each string has 2 Vpol + 2Hpol broadband antennas (200–800 MHz)

Askaryan effect

- 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower

  → **Askaryan effect**

G. Askaryan



Shower size << λ to be coherent

→ Dense material better

Cherenkov emission (Frank-Tumm result)

$$\frac{d^2W}{d\nu dl} = \frac{4\pi^2\hbar}{c}\alpha z^2\nu\left(1 - \frac{1}{\beta^2 n^2}\right)$$

in case N electrons,

z=1 (not coherent) → W ∝ N

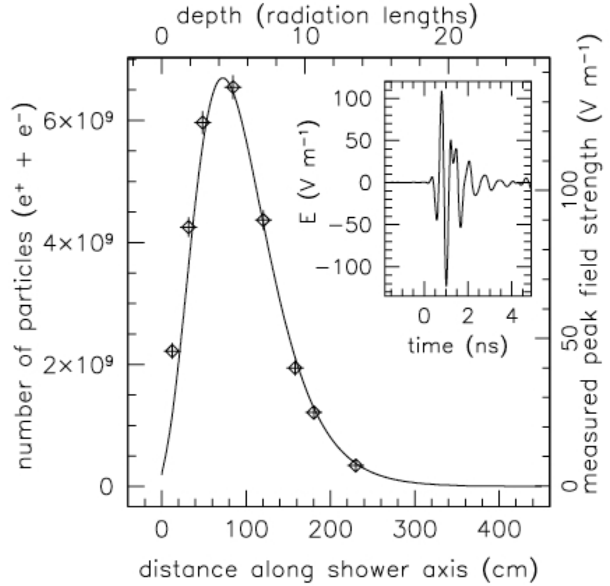
z=N (coherent) → W ∝ N^2

Power ∝ Δq^2 ∝ E^2, thus prominent at EHE (>~ 100 PeV)

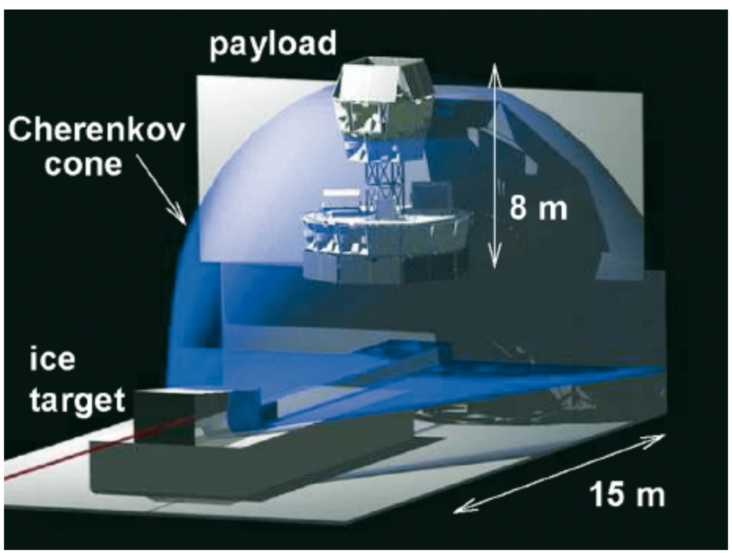
Verification of the Askaryan effect

- Askaryan effect has been verified using an accelerator
  - 2001: firstly confirmed at SLAC with Silica sand (D. Saltzberg et al.)
  - 2005: confirmed with salt (P. Gorham et al.)
  - 2007: confirmed with ice (P. Gorham et al.)

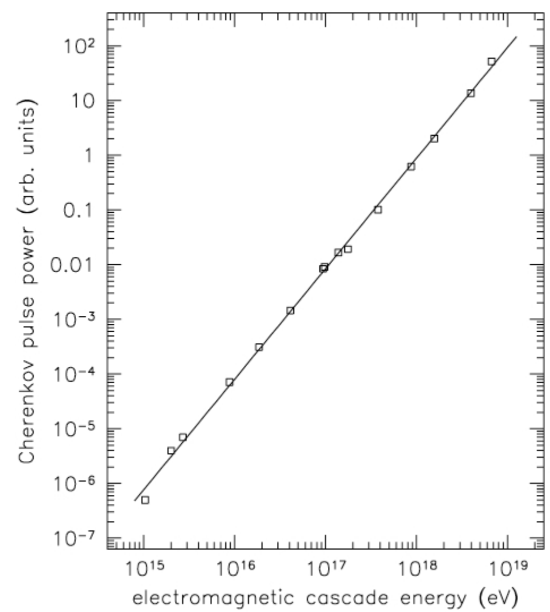
Saltzberg et al. PRL 2001



Gorham et al. PRL 2007



Gorham et al. PRD 2005

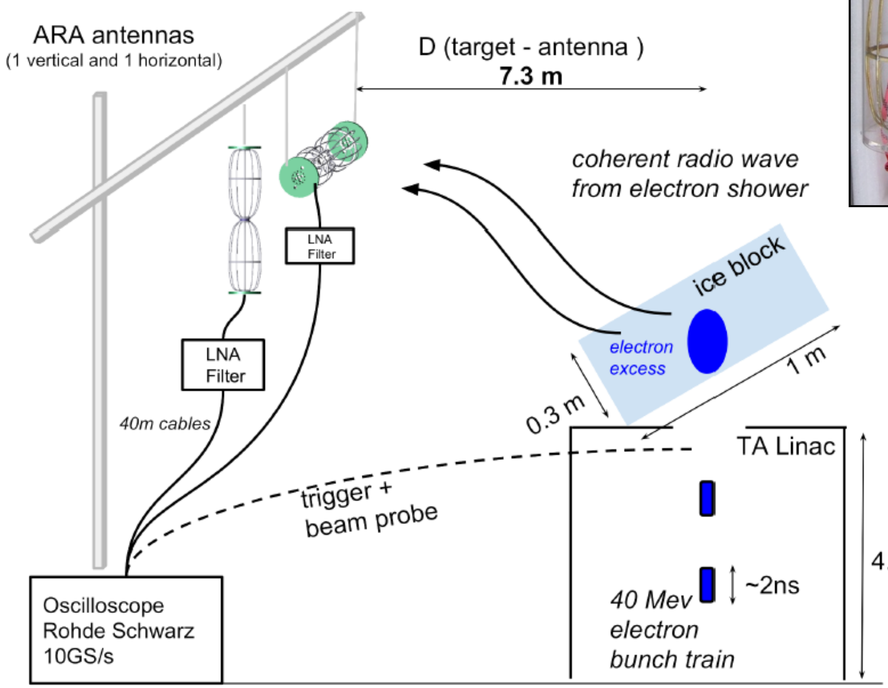


The ARA calibration with the TA-ELS (ARAcalTA)

Performed in January, 2015 at TA site, Utah

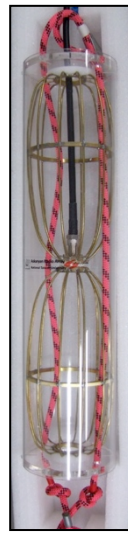
Purpose: Better understanding of the radio emissions and the ARA antenna

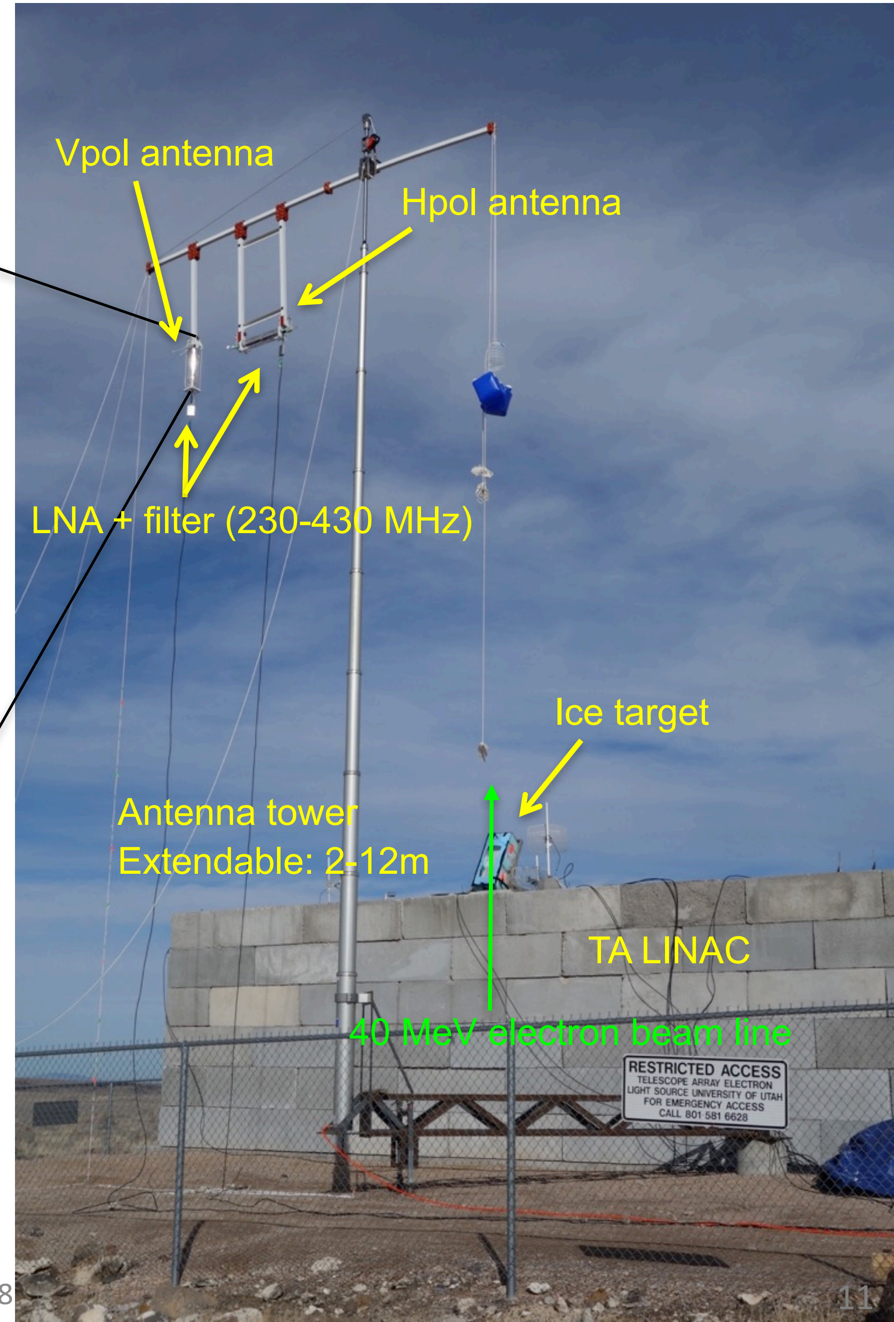
We measured
- ✧ Polarization
- ✧ Angular distribution
- ✧ Coherence



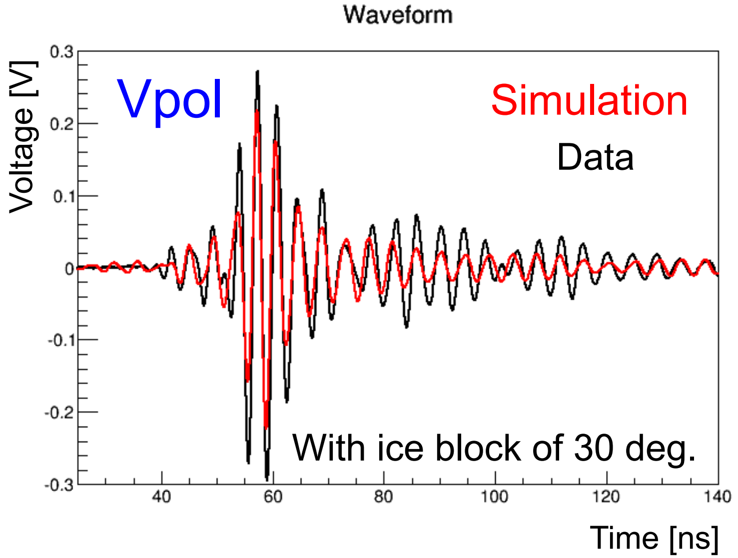
Bicone ARA antenna

150-850 MHz

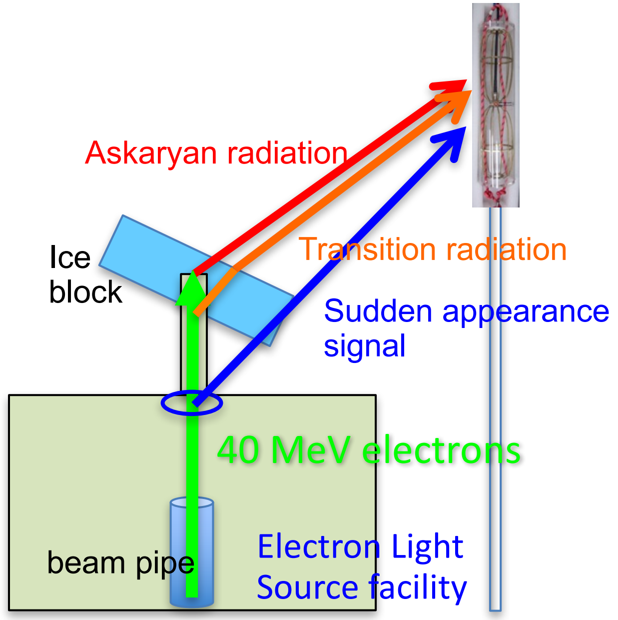


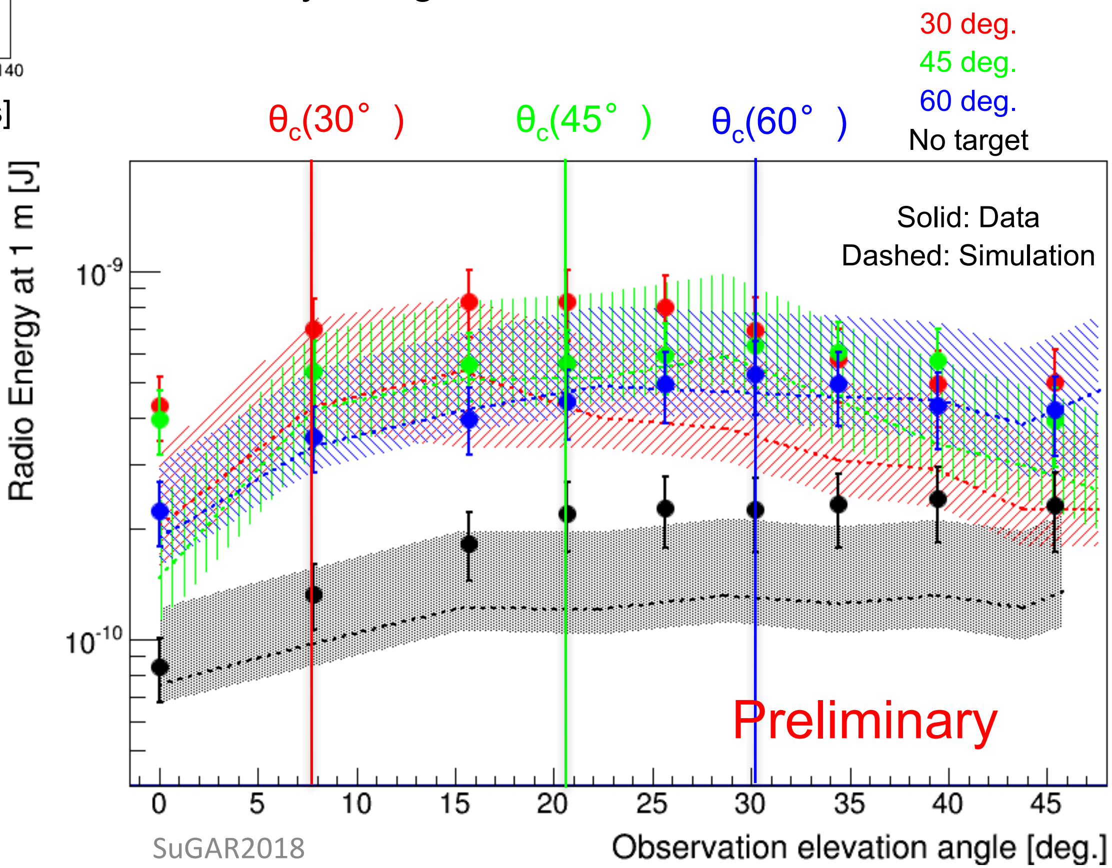


ARAcalTA results

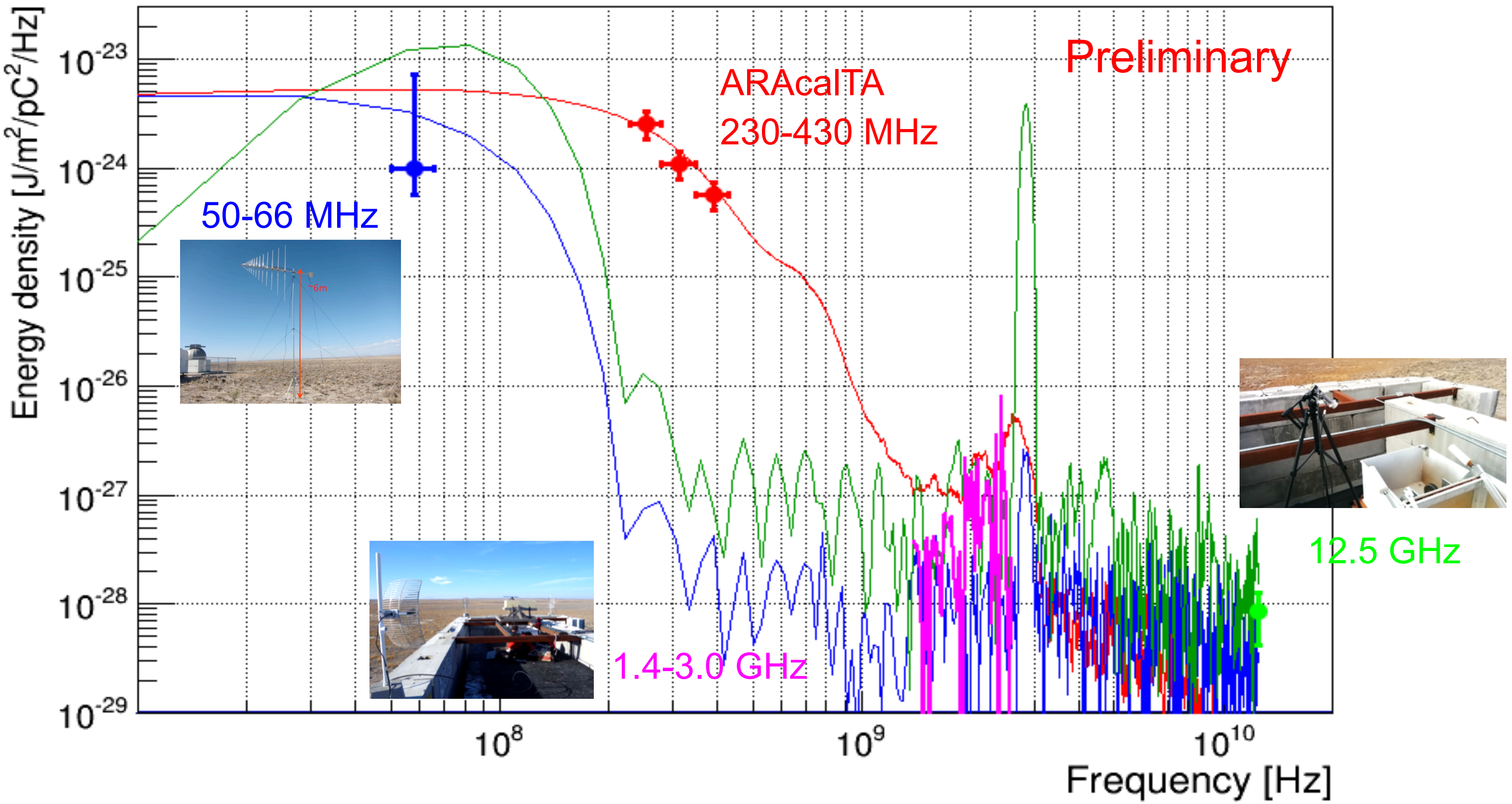


- Clearly polarized / coherent signal observed
- Consistent results between data and simulation including additional components of 60%
- Understand the observed signal within 60% uncertainty level
- Finalizing the analysis by confirming the Askaryan signal in simulation





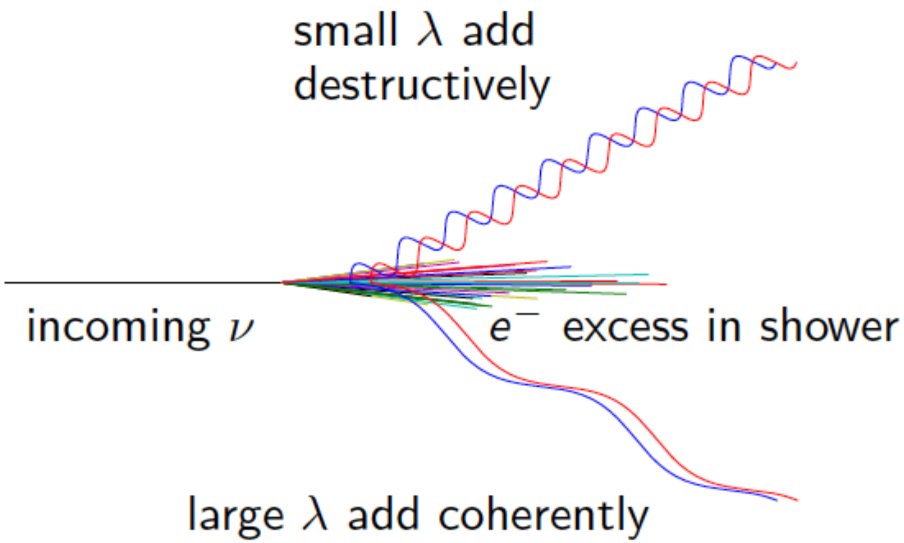
Sudden appearance signal



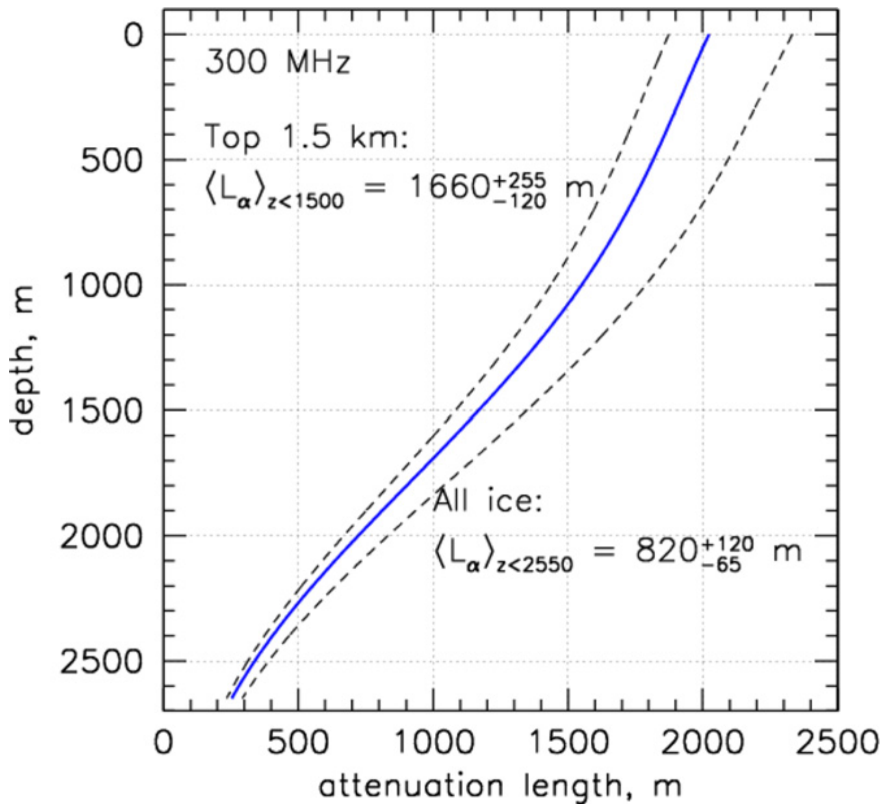
- ✓ Four experiments observed radio signals when electrons come out
- ✓ Well understood the signals
- ✓ Can be applicable for the UHECR detection

Why radio?

- ✓ Signal strength enhances by interference (Askaryan effect)
- ✓ Longer attenuation length (radio: 1 km, optical: 100 m)



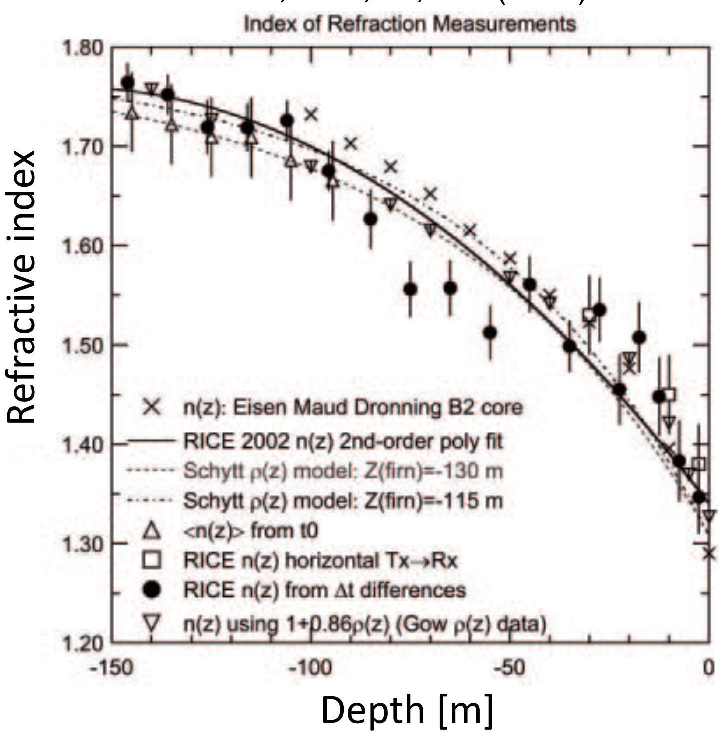
Shower size << λ to be coherent

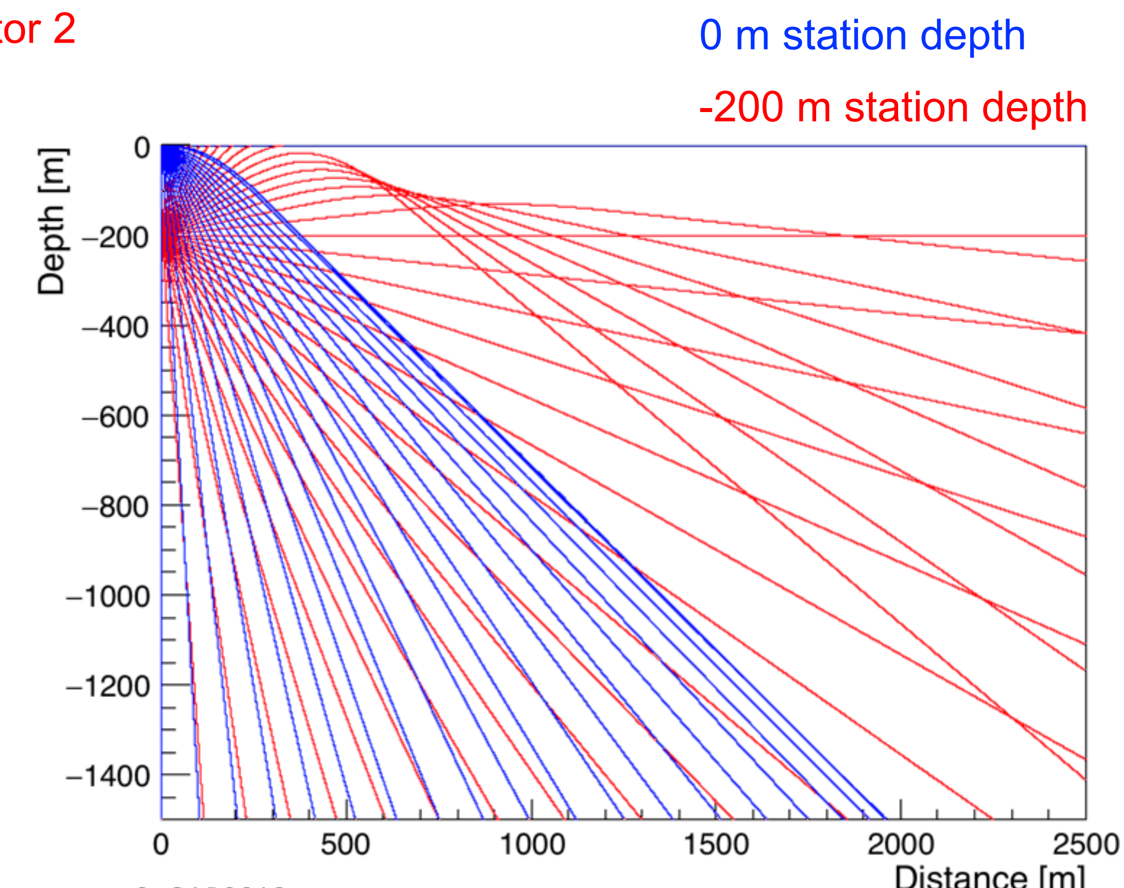


Shadow by shallow ice

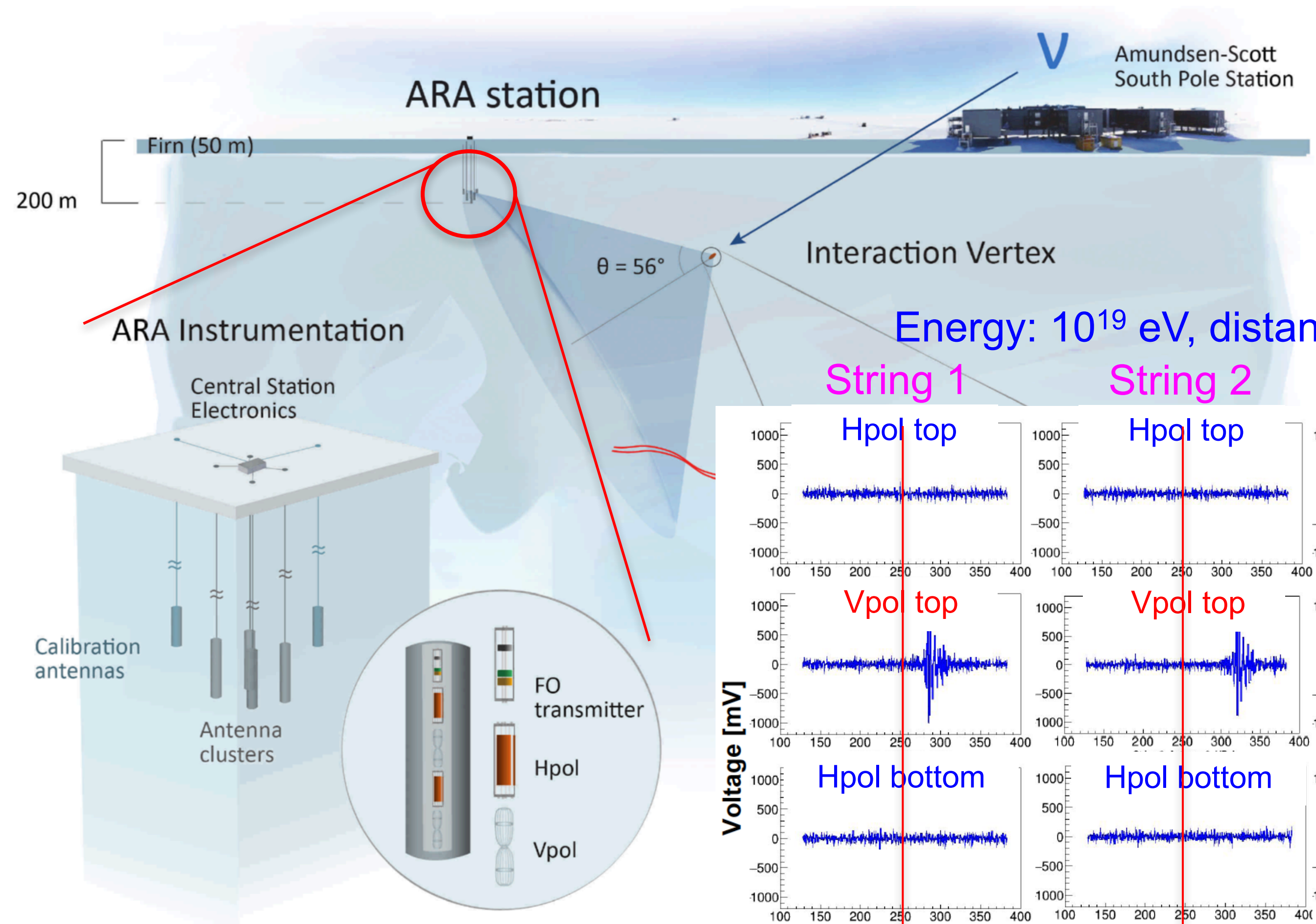
- ✓ Refractive index depends on the density
- ✓ Density depends on the depth (Shallow ice is not compressed yet)
- ✓ Makes a shadow because ray bends
- ✓ Effect is less at deeper than -150 m
- ✓ ARA deployed at -200 m
- ✓ Gain the effective area by ~factor 2

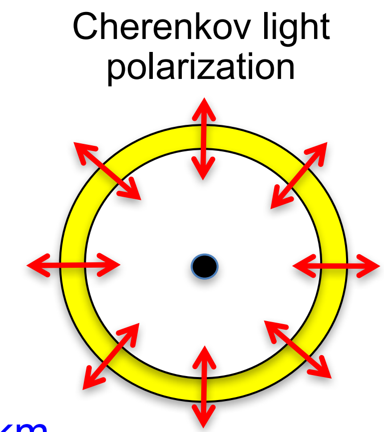
I. Kravchenko et al., JOG, 50, 171 (2004)



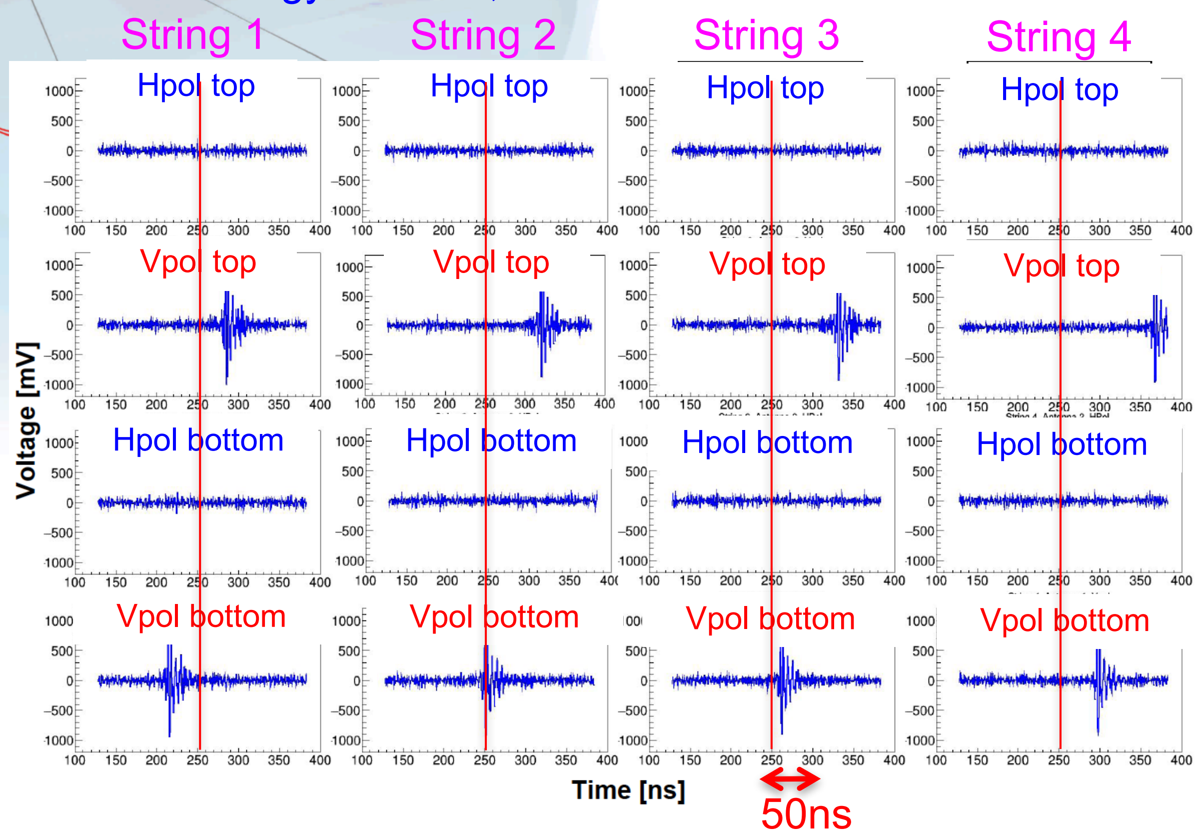


How to reconstruct Askaryan signals





Energy: 10^{19} eV, distance: 2 km

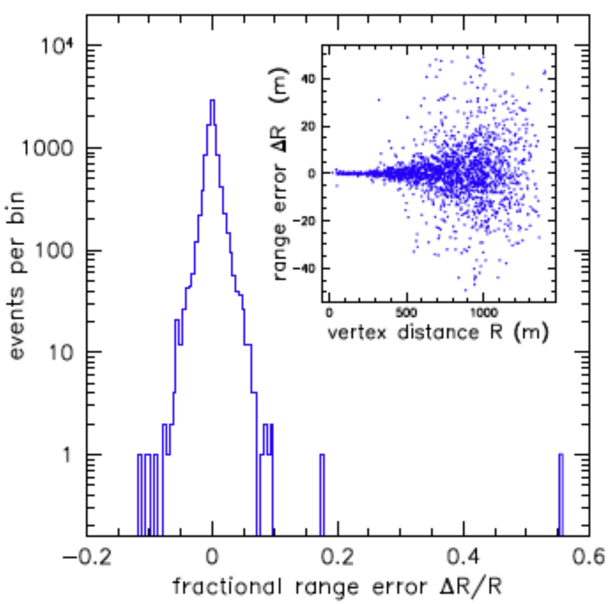


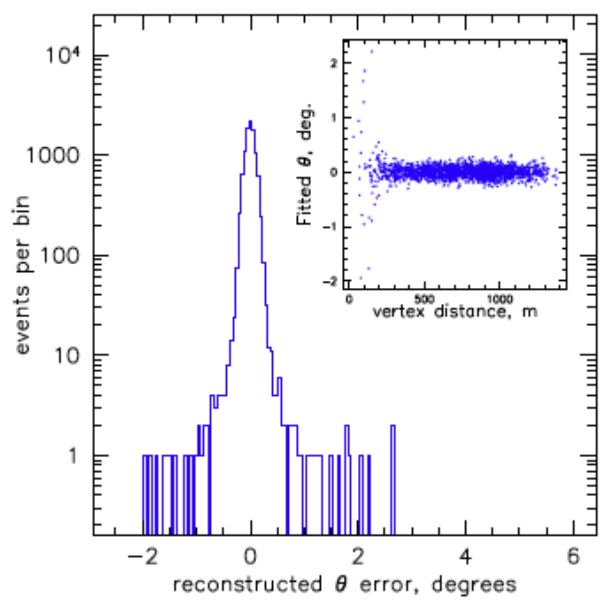
- ✓ Timing → vertex position and direction (~0.3°)
- ✓ Polarization → neutrino direction (<~6°)
- ✓ Understanding of our antenna is crucial

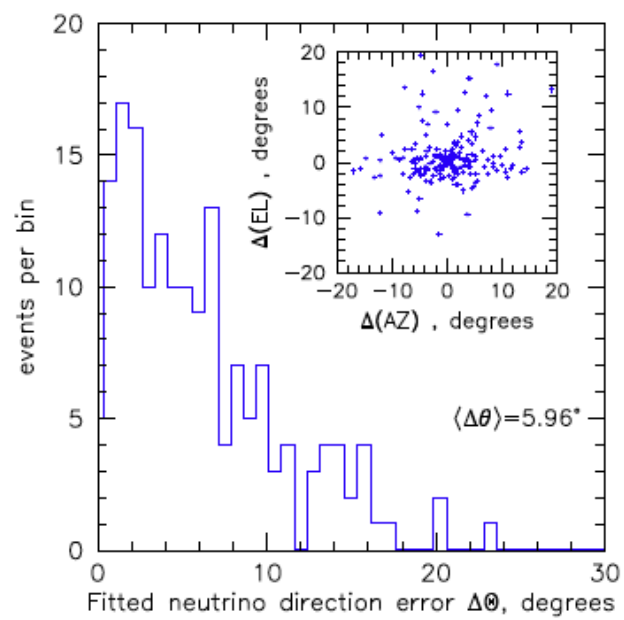
Resolutions

- ✓ Vertex distance resolution: 2% @ 1 km
- ✓ Vertex direction resolution: 0.3°
- ✓ Neutrino direction resolution: 6°
- ✓ Shower energy resolution: 2% @ 1 km
- ✓ Neutrino energy resolution is 100% dominated by the energy transfer to the cascade (Bjorken-y)

ARA collaboration, Astropart. Phys., 35 (2012) 457

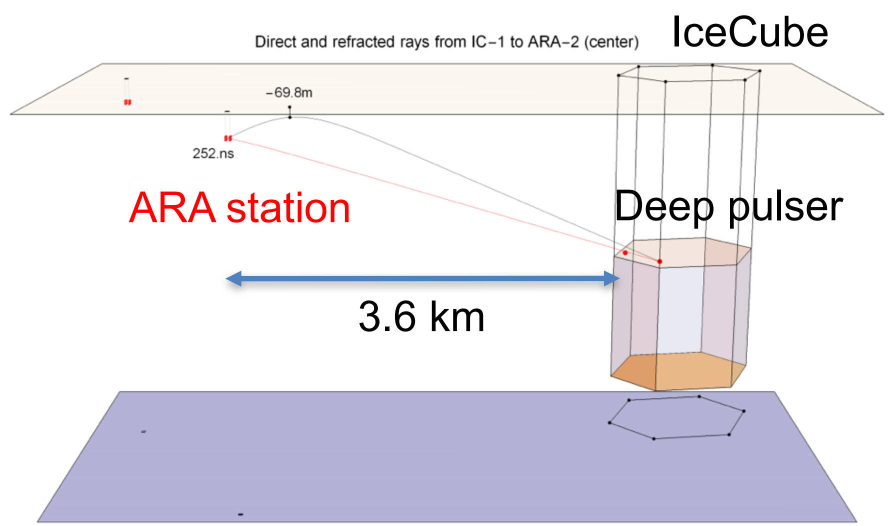




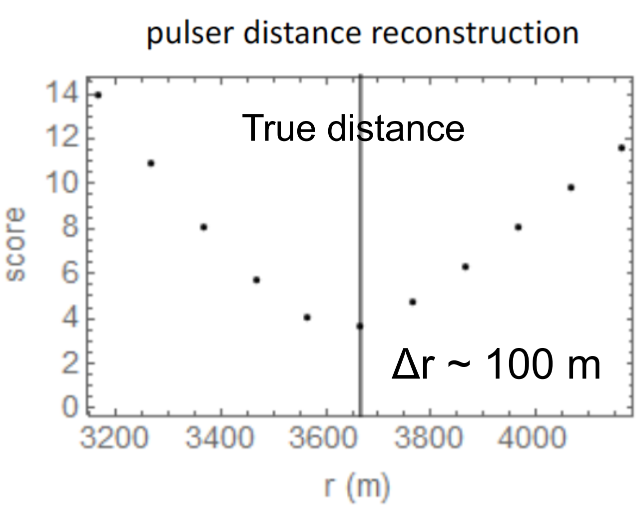


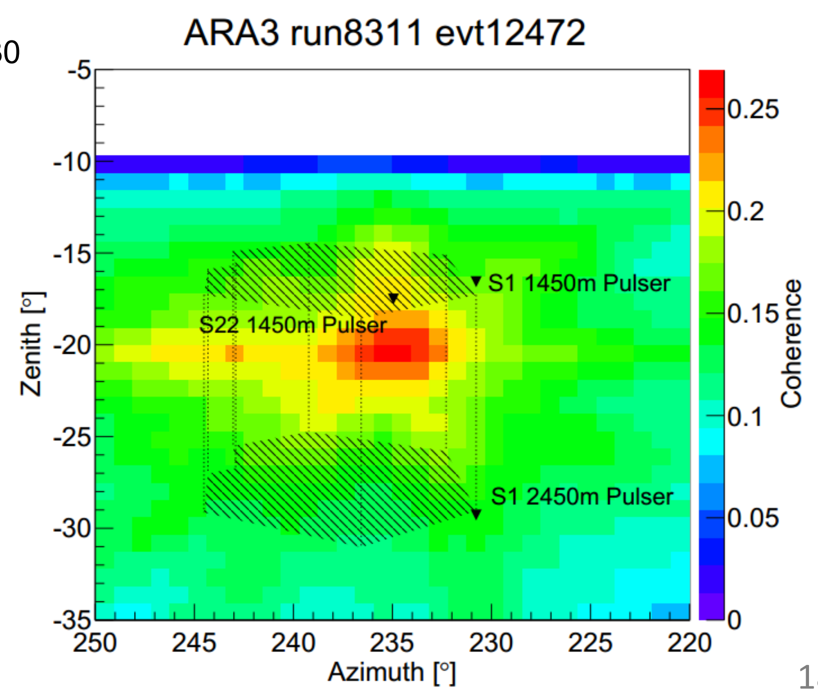
Verification with a deep pulser

- ✓ Verification of the reconstruction and the ice model by a deep pulser
- ✓ Vertex distance resolution of 3%
- ✓ Vertex direction resolution of ~1°
- ✓ Small angular offset
- ✓ Improve the ice model with another pulser (this season)



J. Kelly et al., PoS (ICRC2017) 1030





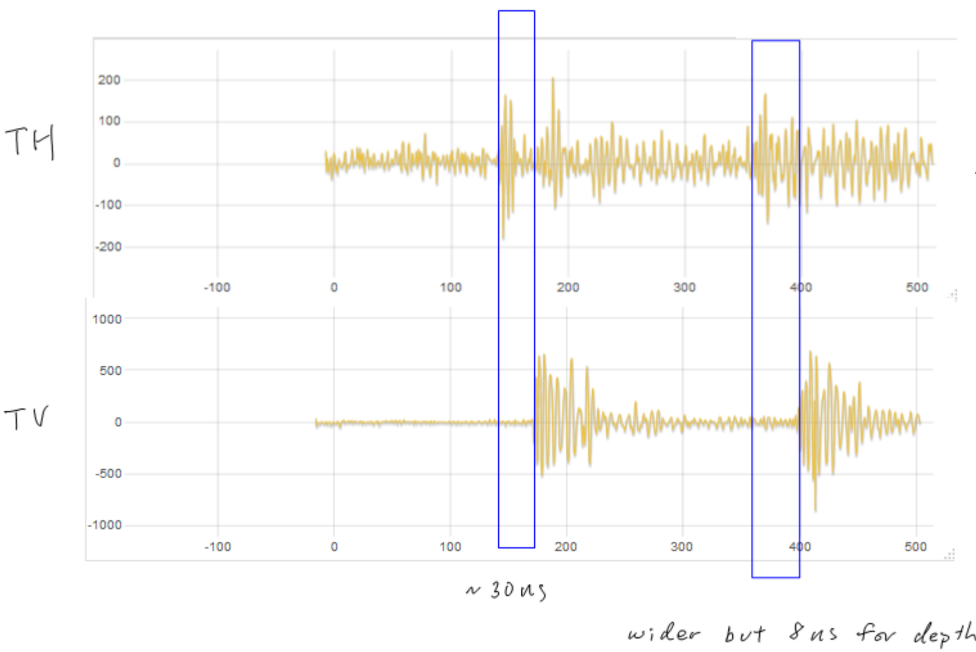
Birefringence

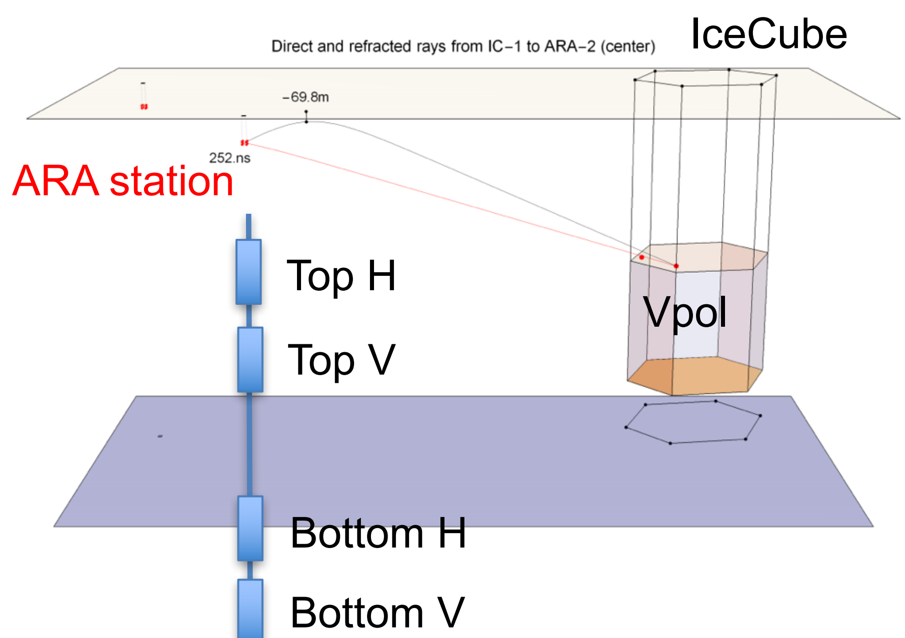
- ✓ Relatively strong Hpol signals observed from originally Vpol signals
- ✓ Hpol signal comes earlier than Vpol

→ Strong indication of birefringence (different refractive index)

Need to be taken into account for the neutrino direction reconstruction

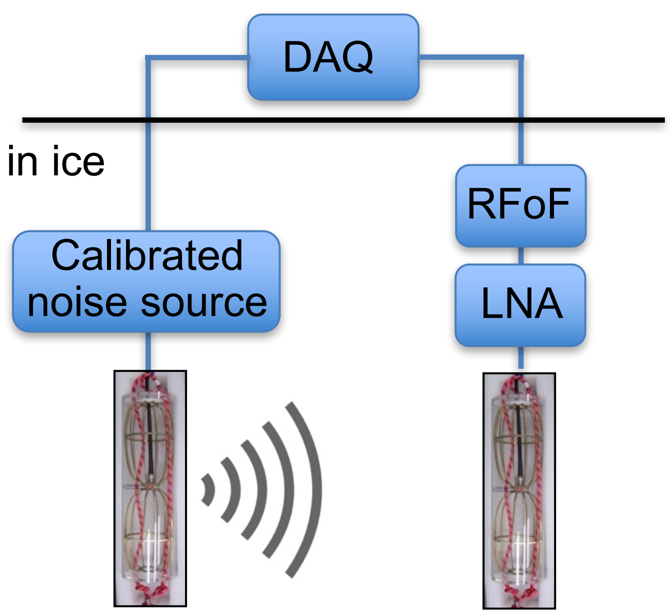
J. Kelly et al., PoS (ICRC2017) 1030

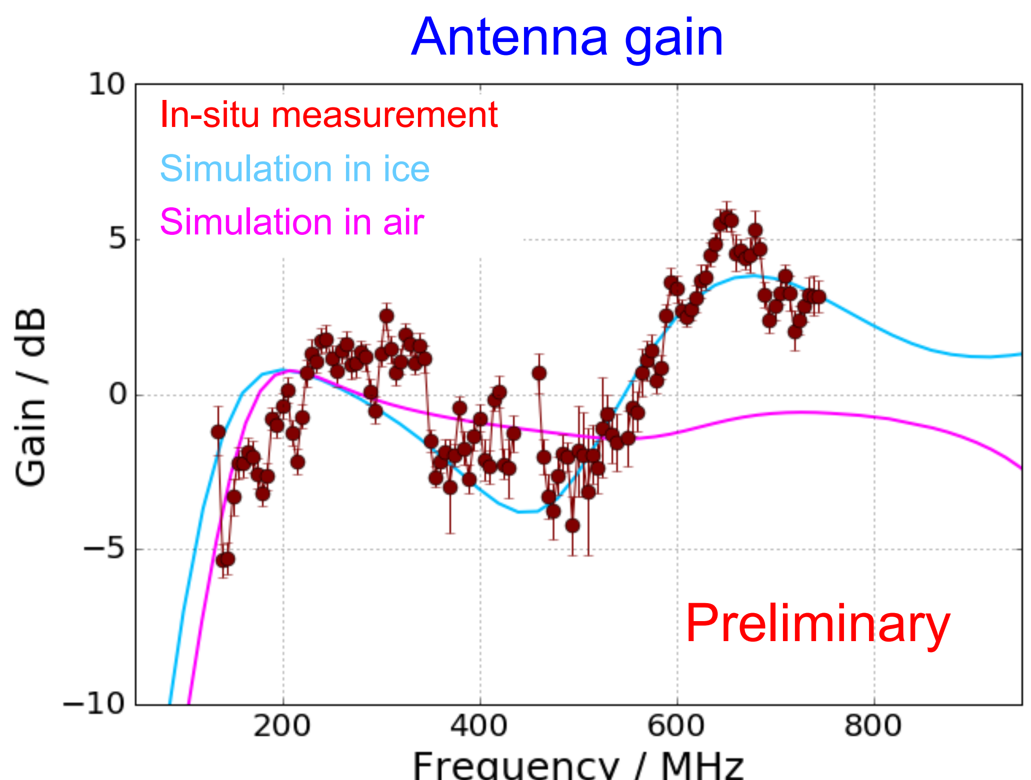




In-situ calibration and the verification

- ✓ Calibration in situ performed with the calibrated noise source
- ✓ Critical to the event reconstruction both for geometry and energy
- ✓ Antenna gain and system gain are obtained
- ✓ Verified with antenna simulation results
- ✓ Understand the gain above 500 MHz by improving the antenna simulation model
- ✓ Detector uncertainty: level of 30%

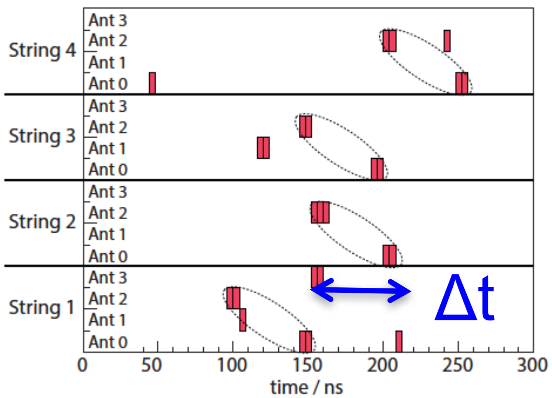




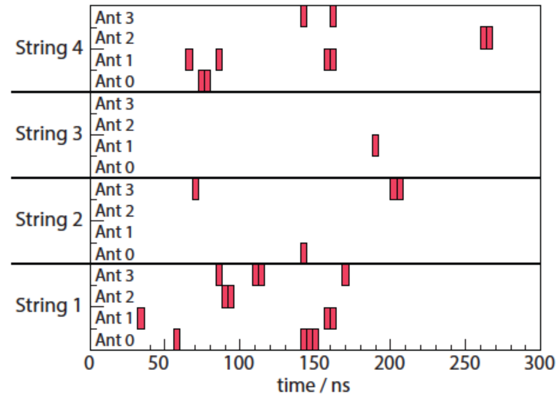
Search for UHE neutrinos

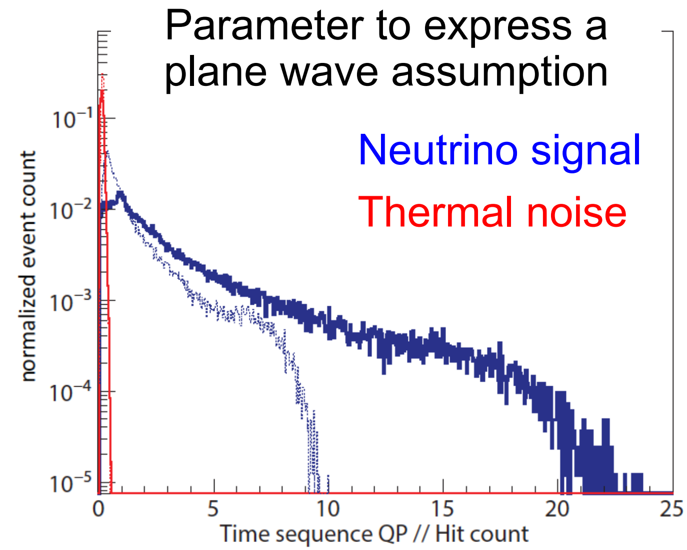
ARA collaboration, PRD, 93, 082003 (2016)

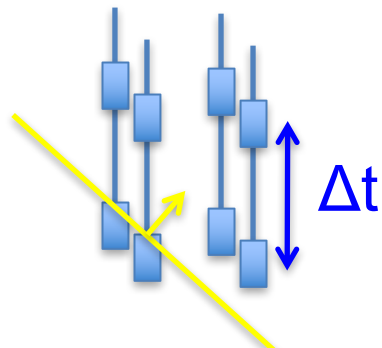
Neutrino signal



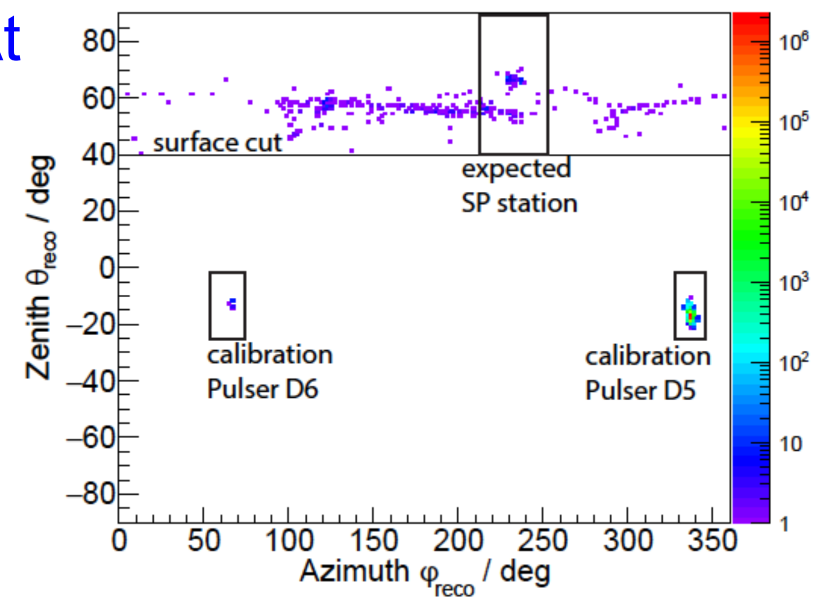
Thermal noise





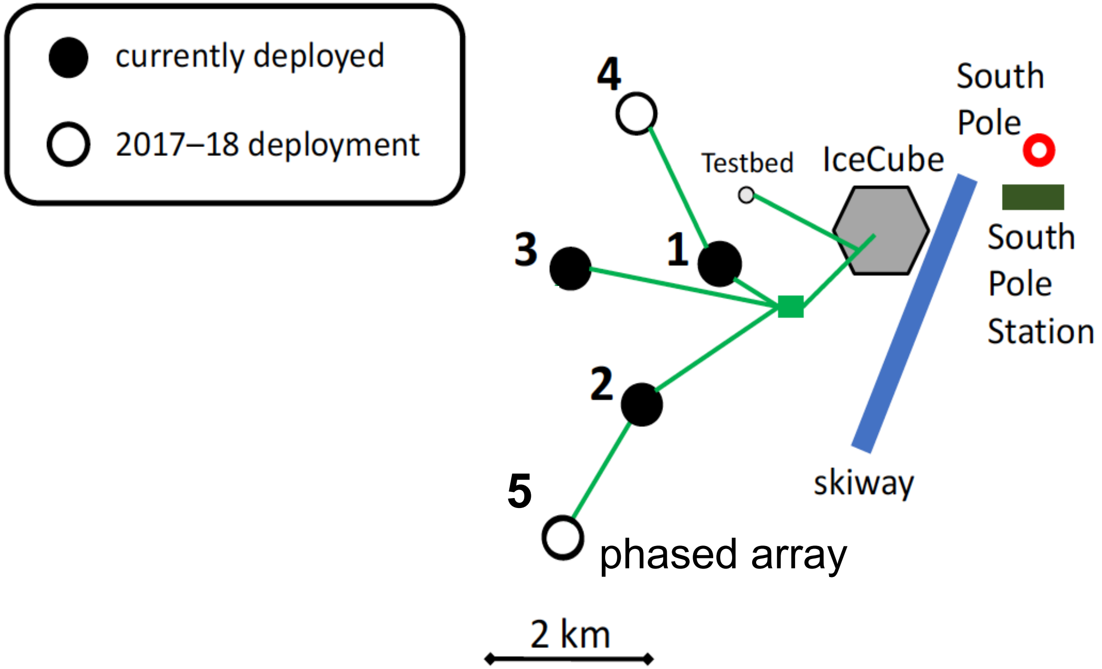


- ✓ Two main backgrounds:
  thermal and man-made noises
- ✓ Thermal noise has to be reduced by a factor of 10^{10}
- ✓ Timing information utilized
- ✓ Signal time delay (Δt) for pairs of two antennas is same for neutrino signals
- ✓ Man made noises left after the reduction of thermal noises



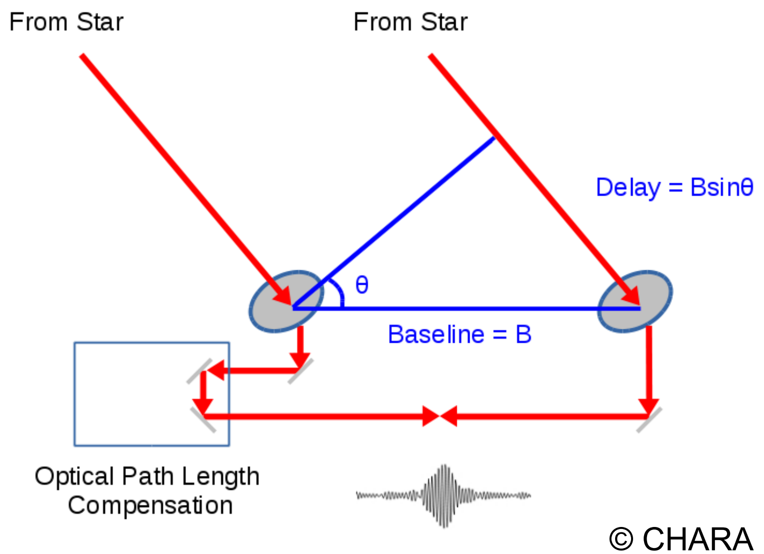
Current status and further plan

- Currently 5 stations
- 2 additional station installed
- Working right now at the South Pole
- Sensitivity will be comparable to IceCube @ 10^{18} eV

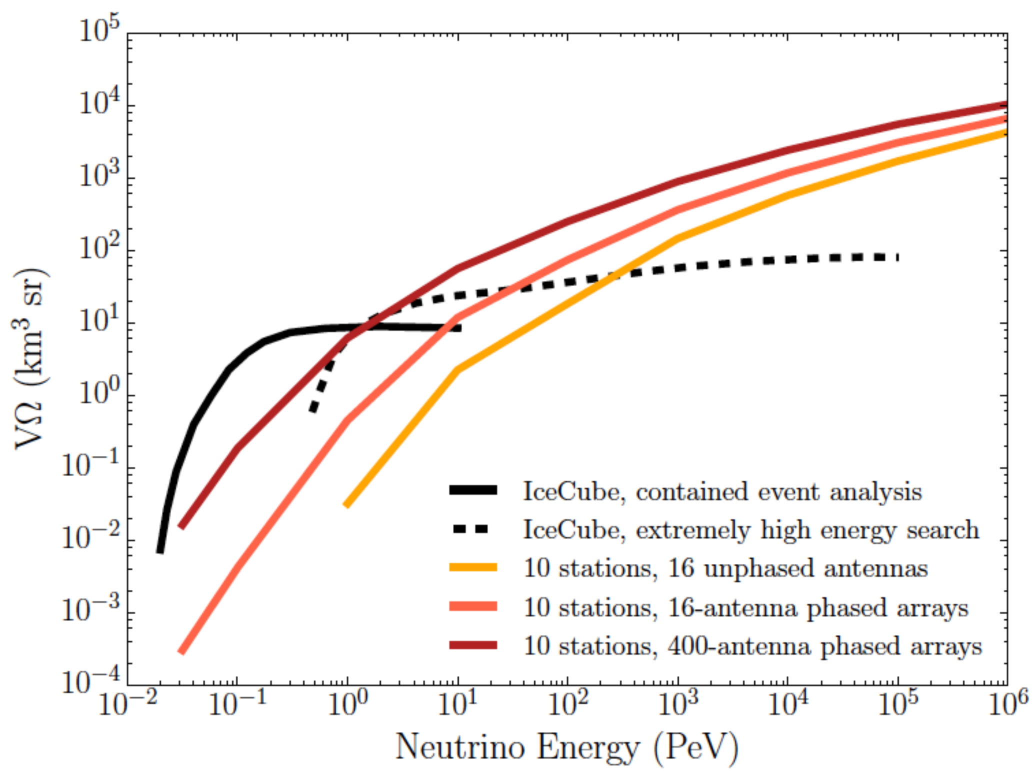


Phased array

- ✓ Current ARA energy threshold ~100 PeV → want to lower the energy threshold
- ✓ A. G. Vieregg et al. showed interferometry tequnique can lower the energy threshold and increase the sensitivity
- ✓ Interferometry: coherently sum signals from multiple antennas before trigger
- ✓ SNR goes up as sqrt(N)

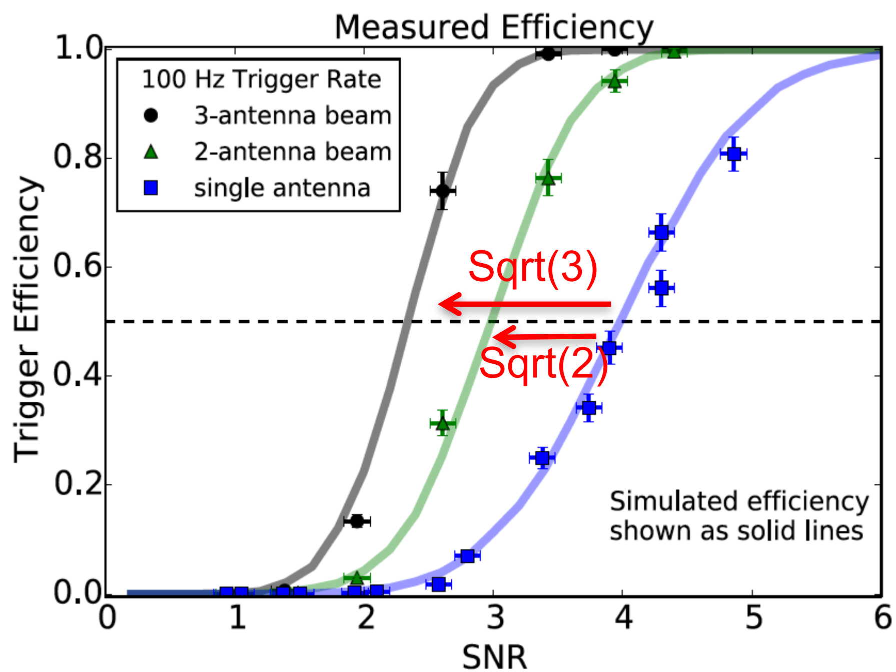


A. G. Vieregg et al., JCAP 2 (2016) 005



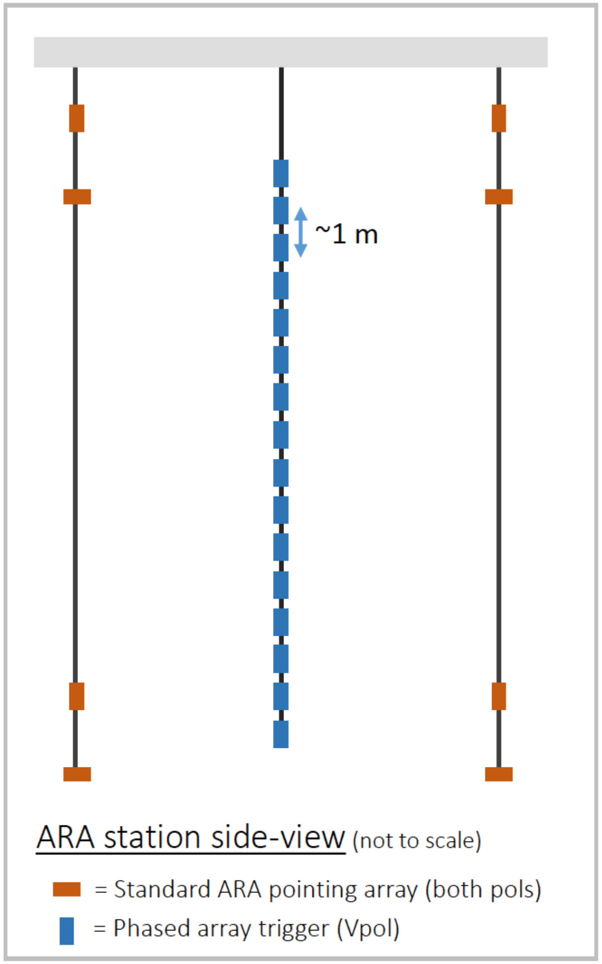
Test of phased array at South Pole

- ✓ Test at the South Pole this season (one station)
- ✓ Used as trigger (16 antennas)
- ✓ Tested at laboratory
- ✓ Installed at the South Pole



J. Avva et al., NIM A, 869 (2017) 46

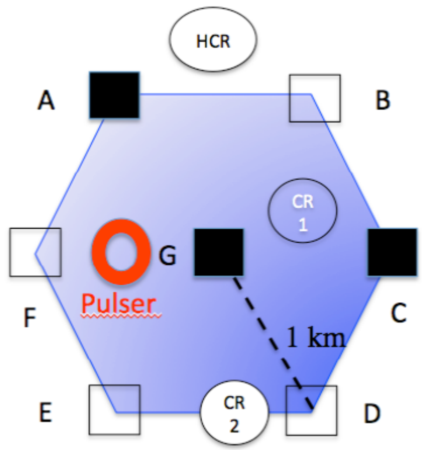
ARA phased array layout

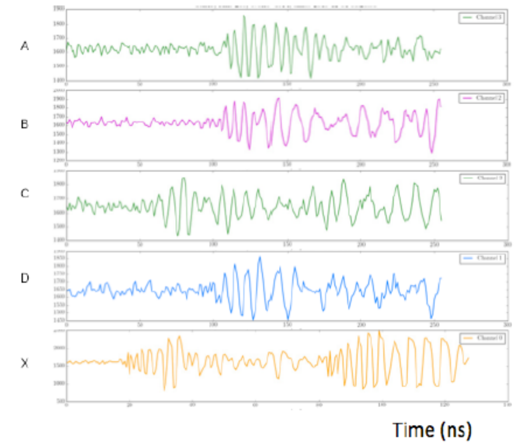


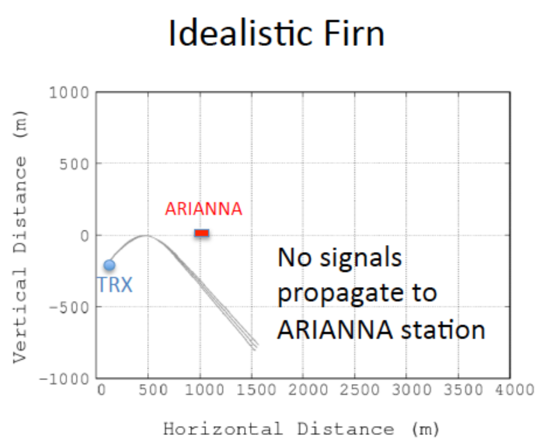
Horizontal propagation?

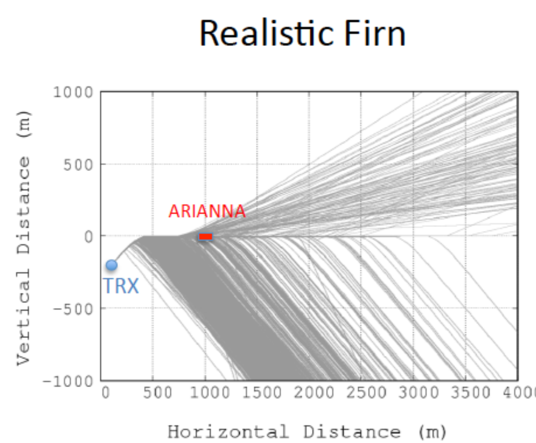
- ✓ ARIANNA group found horizontal propagation
- ✓ Non uniformity of the refractive index change (1% per 0.5 m) due to a seasonal snow accumulation can explain the data
- ✓ No need to bury antennas if horizontal propagation is true and useful for the event reconstruction
- ✓ Can reduce the installation cost significantly
- ✓ Further characterization of the signal is crucial for the future detector configuration

ARIANNA site @ Moore's bay







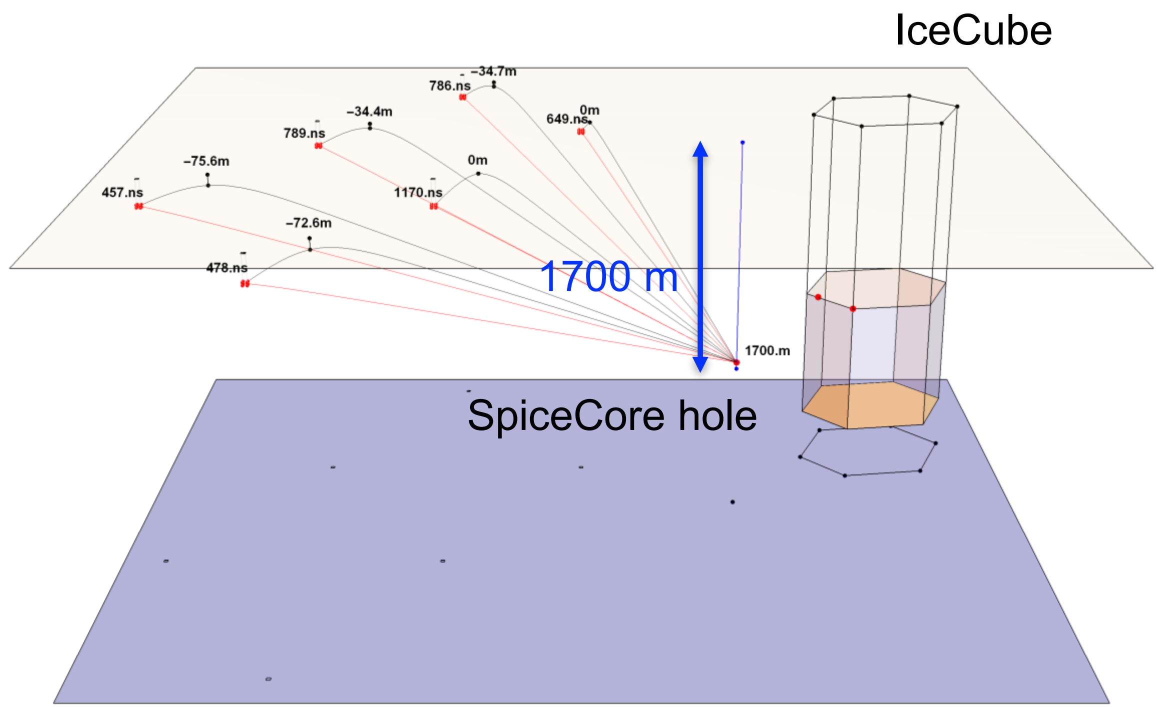


S. W. Barwick, PoS(ICRC2017)1042

Investigation of horizontal propagation at South Pole

- ✓ Tests at the South Pole performed this season
- ✓ Collaboration with ARIANNA
- ✓ Use SpiceCore for Tx antennas
- ✓ Received the signals by ARA stations / at surface for the ARIANA antenna
- ✓ Analysis on going

- ✓ Also useful for birefringence and the ice model



Summary

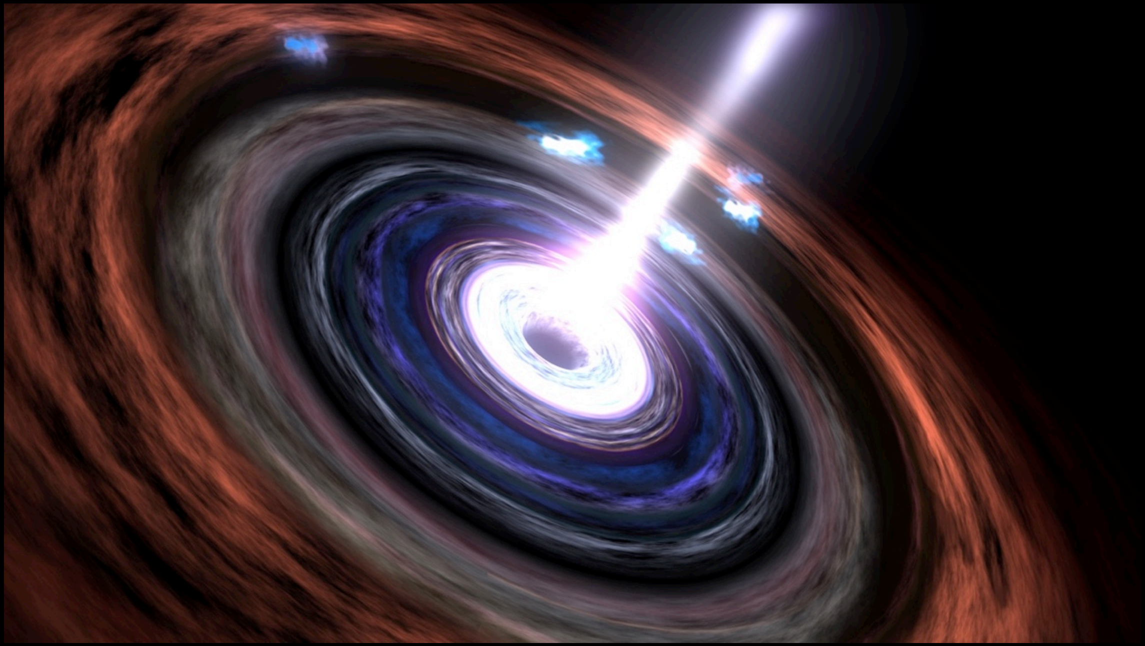
- Aiming to reveal ultra high energy phenomena in Universe above ~10 PeV
- Radio is the best method for the detection
- Reasonable cost (~10M $)
- 2 more stations deployed this season and 5 stations running
- Sensitivity similar to IceCube @ 1 EeV
- Phased array lowers the energy threshold (down to ~10 PeV) as well as increasing the sensitivity at 1 EeV
- Efforts to understand the ice as well as the detector

Thank you

Me

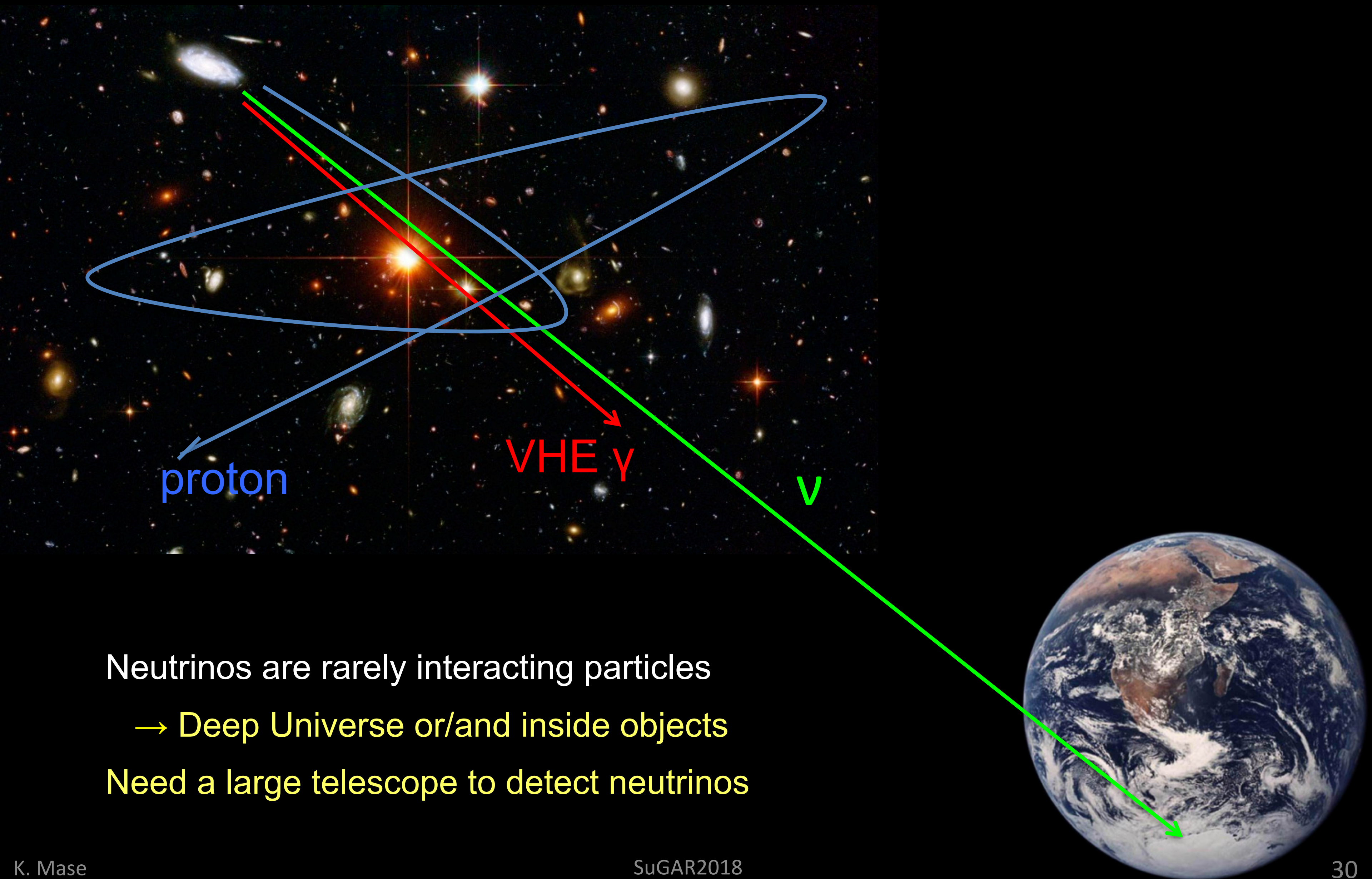
Astrophysics

- Understanding of what is happening / happened in the Universe
- Can “see” the history of the Universe by looking at distant place
- Test theories which can not be tested on the Earth
- Good example: gravitational wave (Observing the orbital speed of a binary pulsar, and then the direct measurement)
- I am interested in high energy phenomena in the Universe



NASA/Goddard Space Flight Center Conceptual Image Lab

Why neutrinos



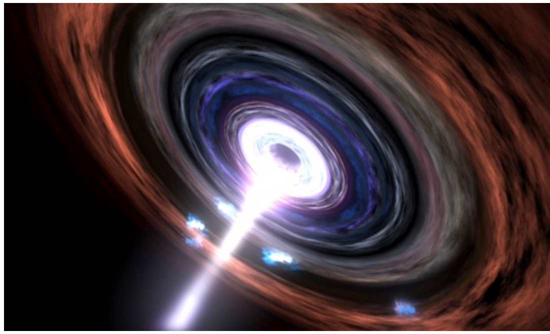
Neutrinos are rarely interacting particles

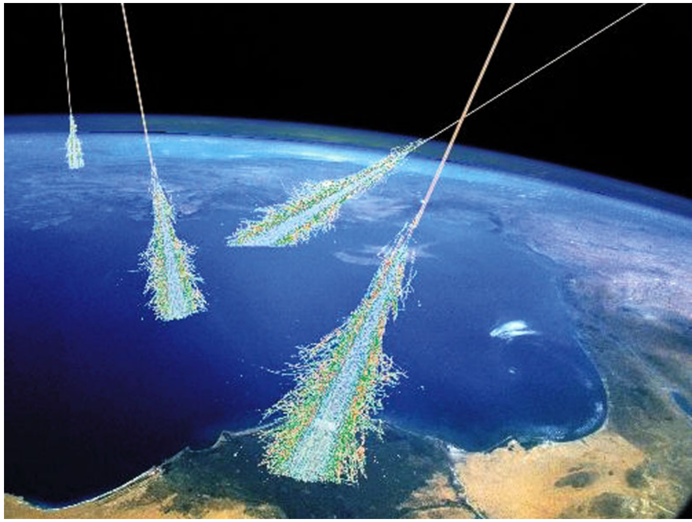
→ Deep Universe or/and inside objects

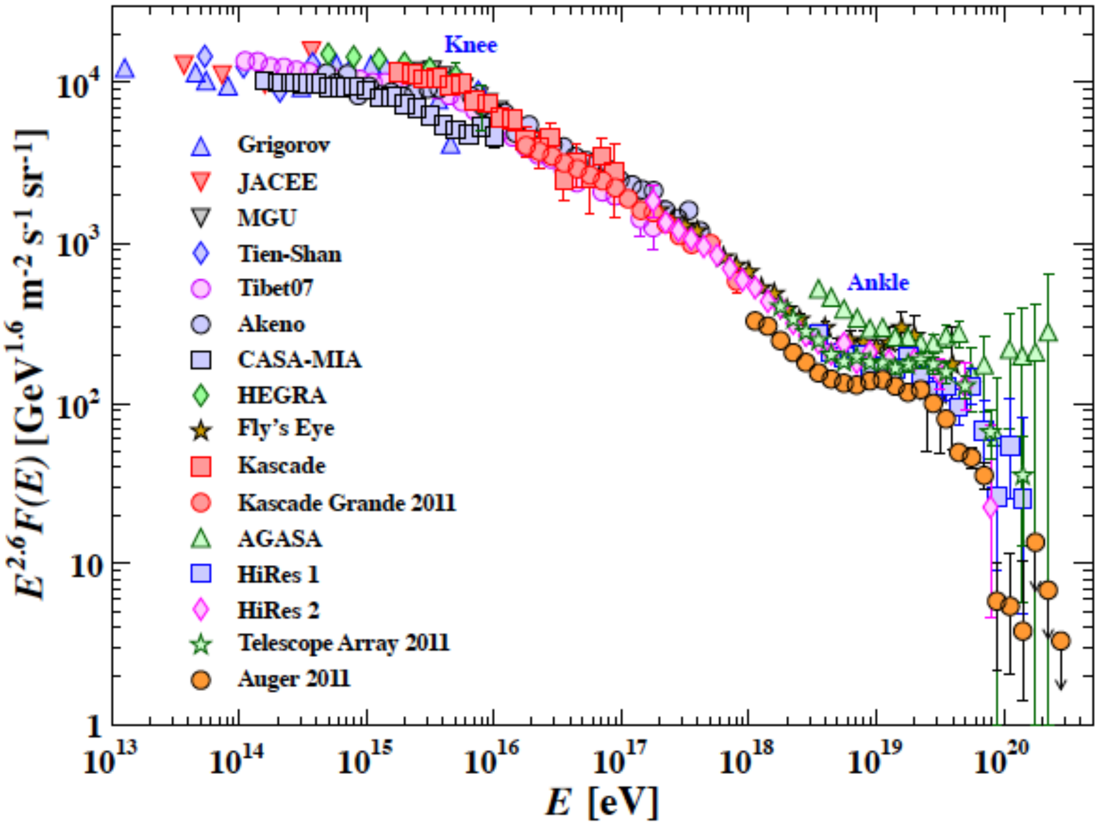
Need a large telescope to detect neutrinos

High energy particles from space: Cosmic rays

- ✓ Extend to 10^{20} eV
- ✓ Galactic and extragalactic components
- ✓ Origin not completely understood
  - → Want to know the origin







Multi messengers

Neutrino production is closely related to production of **cosmic rays** and **gamma rays**

$$p + p\,(\gamma) \rightarrow \pi^{\pm} / \pi^{0} + anything$$

$$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$

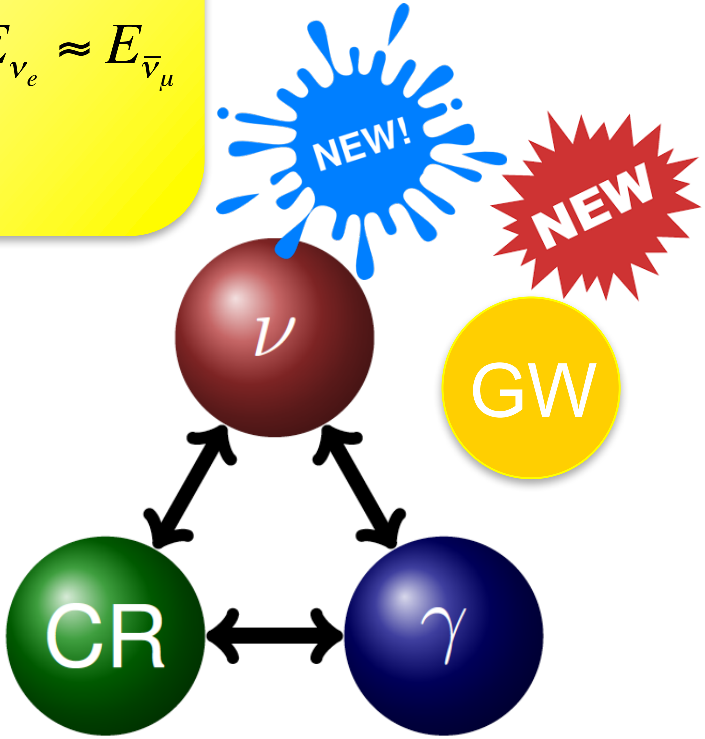
$$\mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu} \qquad E_{\nu_\mu} \approx E_{\nu_e} \approx E_{\bar{\nu}_\mu}$$

$$\pi^{0} \rightarrow 2\gamma$$

$$E_{\nu} \approx \frac{1}{20}E_{p} \qquad \because E_{\pi} \approx \frac{1}{5}E_{p}, E_{\nu} \approx \frac{1}{4}E_{\pi}$$

$$E_{\nu} \approx E_{\gamma}$$

To understand the high energy phenomena in the universe, all information should be utilized



Activities at Chiba

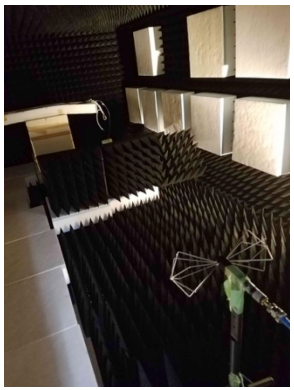
✓ Focus on understanding of the detector and the improvement

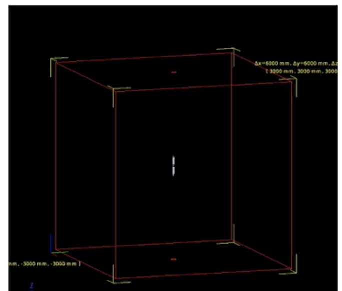
verification

Antenna gain in air (anechoic chamber measurement)

Antenna gain conversion between air and ice (Archambault)

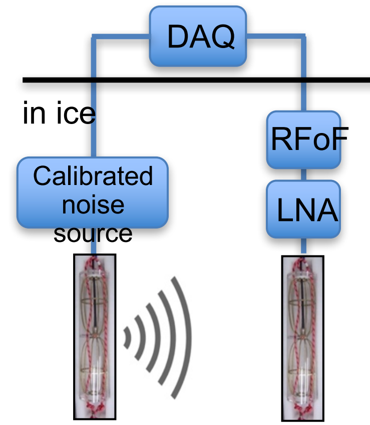
Antenna gain in ice (in-situ calibration (Kim))





Antenna gain in ice and air by simulation

verification



✓ Understanding of the antennas

→ Important for the neutrino energy estimation and direction using the polarization

✓ Optimization of antenna gain (Kurusu)

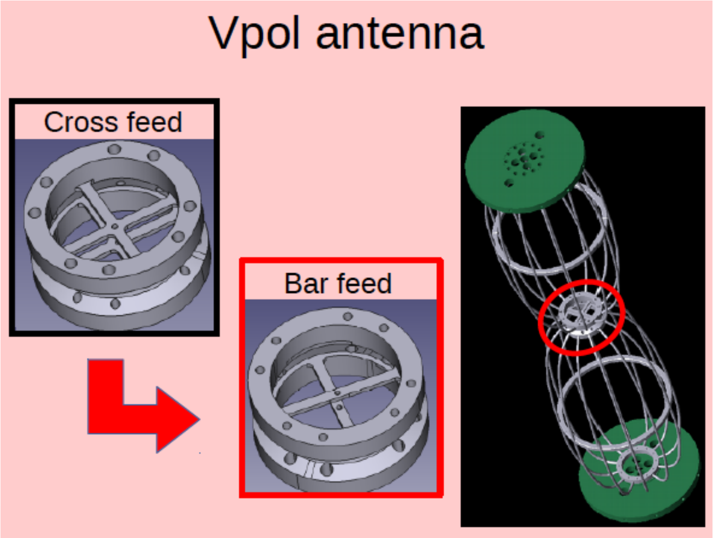
→ Antenna gain improved by ~20% → Signal increased by ~10%

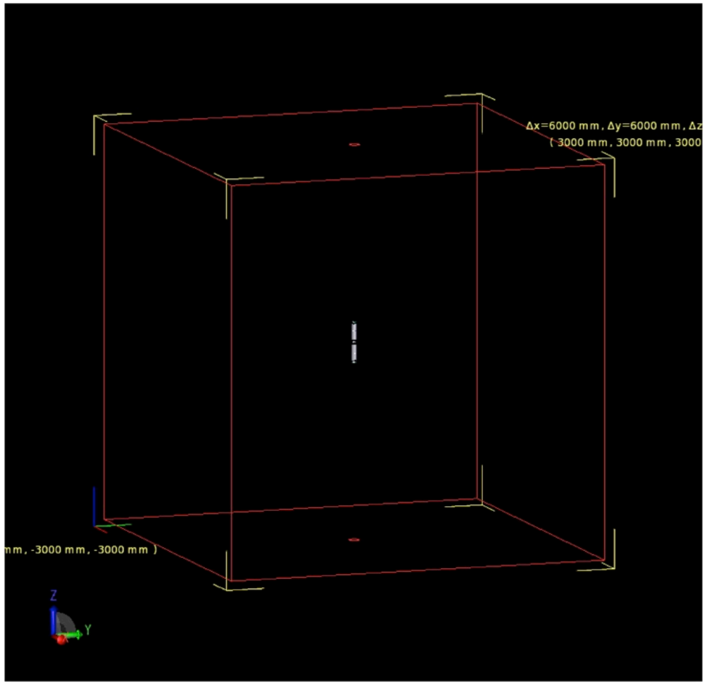
✓ Understanding of Askaryan signal (ARAcalTA experiment) (KM)

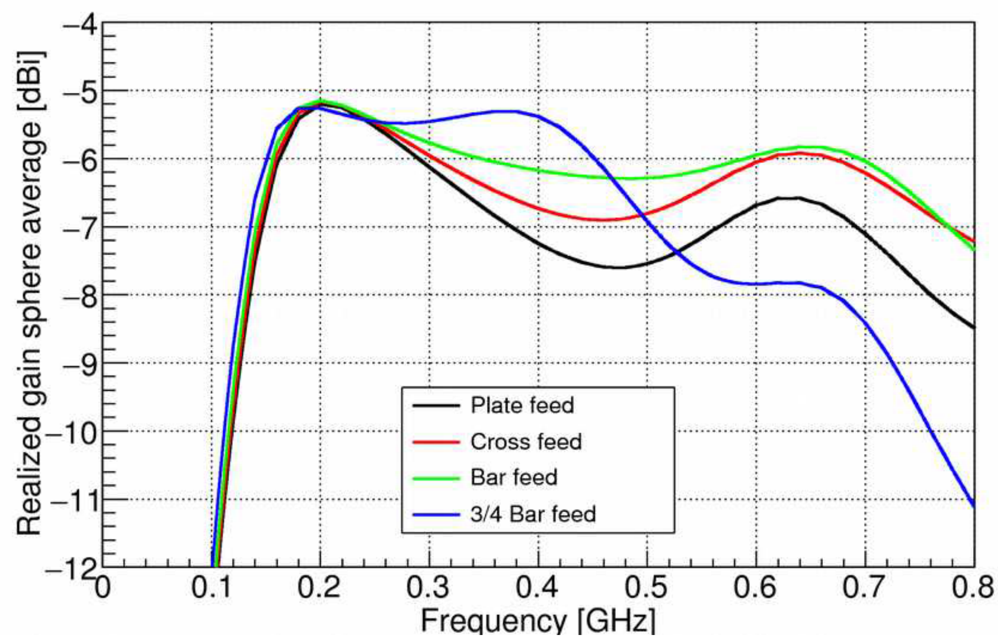
→ Confirmation of fundamental process

Antenna optimization

- ✓ Antennas have been optimized with a software with FDTD (Finite-Difference Time-Domain) method (calculating E-field and B-field by solving Maxwell's equations)
- ✓ Realistic model implemented
- ✓ With ice block
- ✓ ~20% gain improvement
- ✓ See Kurusu's poster

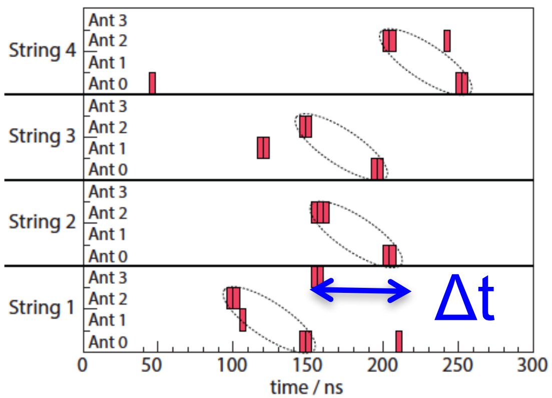




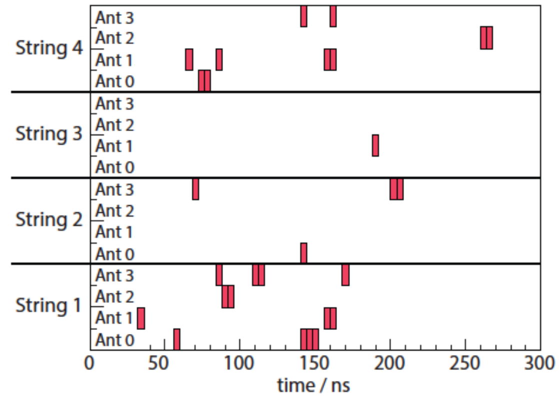


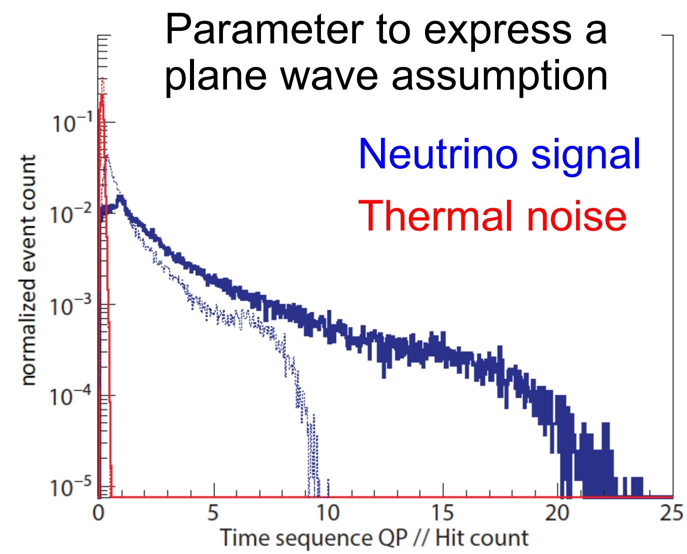
Background rejection

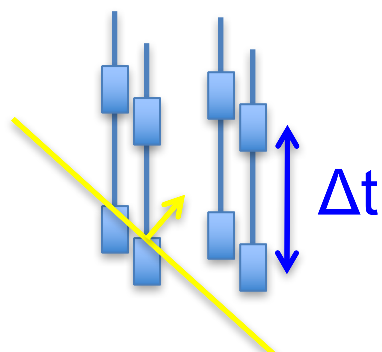
Neutrino signal

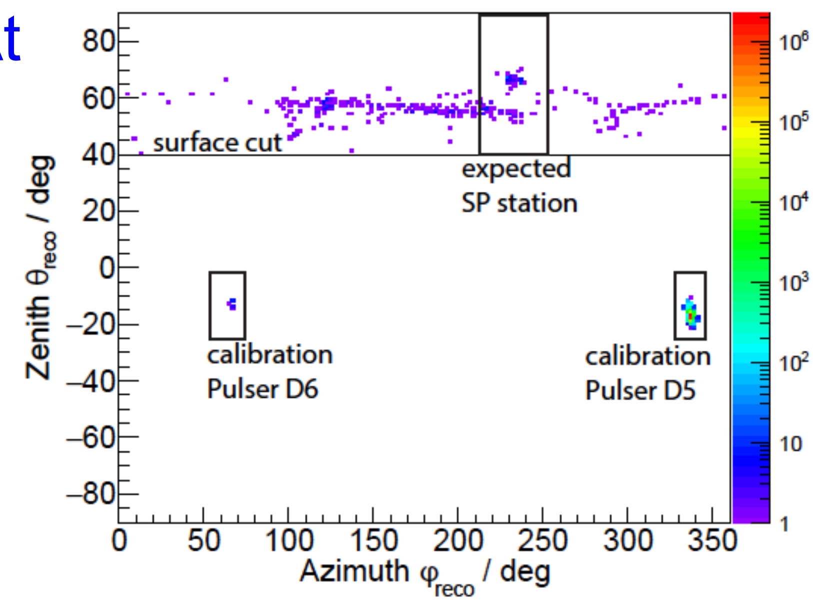


Thermal noise





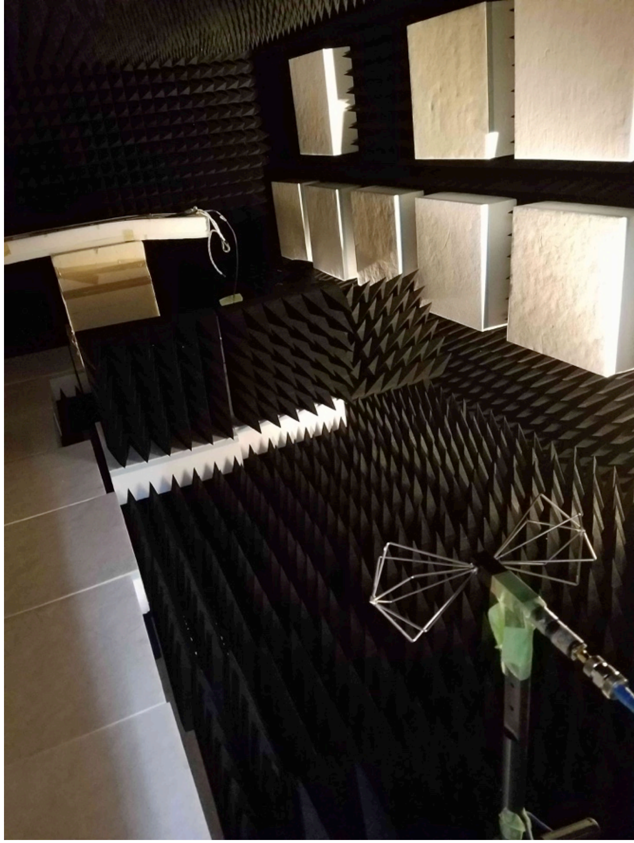


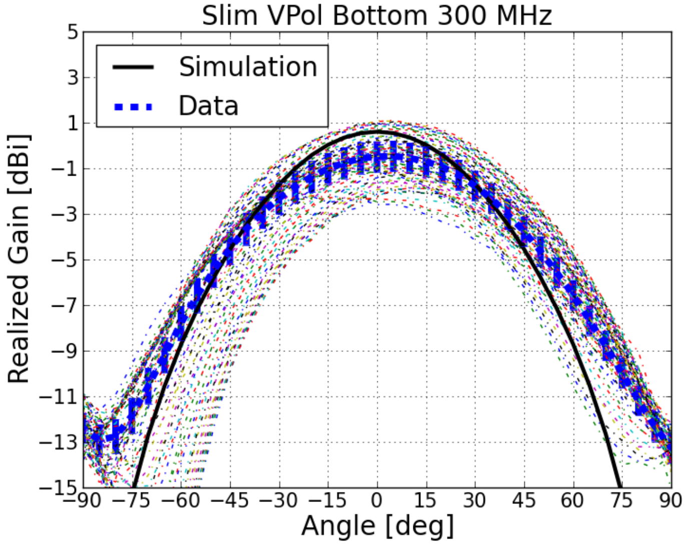


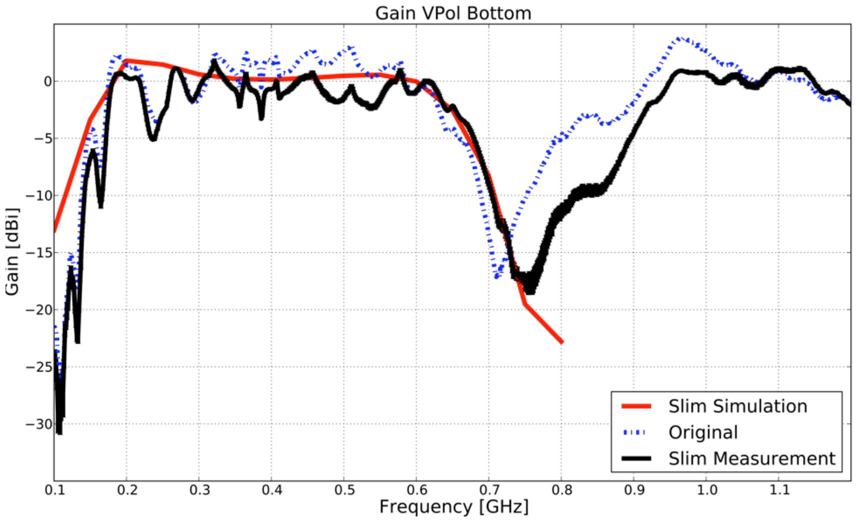
- ✓ Two main backgrounds:
  thermal and man-made noises
- ✓ Thermal noise has to be reduced by a factor of 10^{10}
- ✓ Timing information utilized
- ✓ Signal time delay (Δt) for pairs of two antennas is same for neutrino signals
- ✓ Man made noises left after the reduction of thermal noises

Understanding of the antenna

- ✓ Antenna characteristics have been measured in a anechoic chamber
- ✓ Reasonable agreement between measurement and antenna simulation (~30% level)







The ARA sensitivity