Radiowave Detection of Ultra High Energy Cosmic Neutrinos and Cosmic Rays

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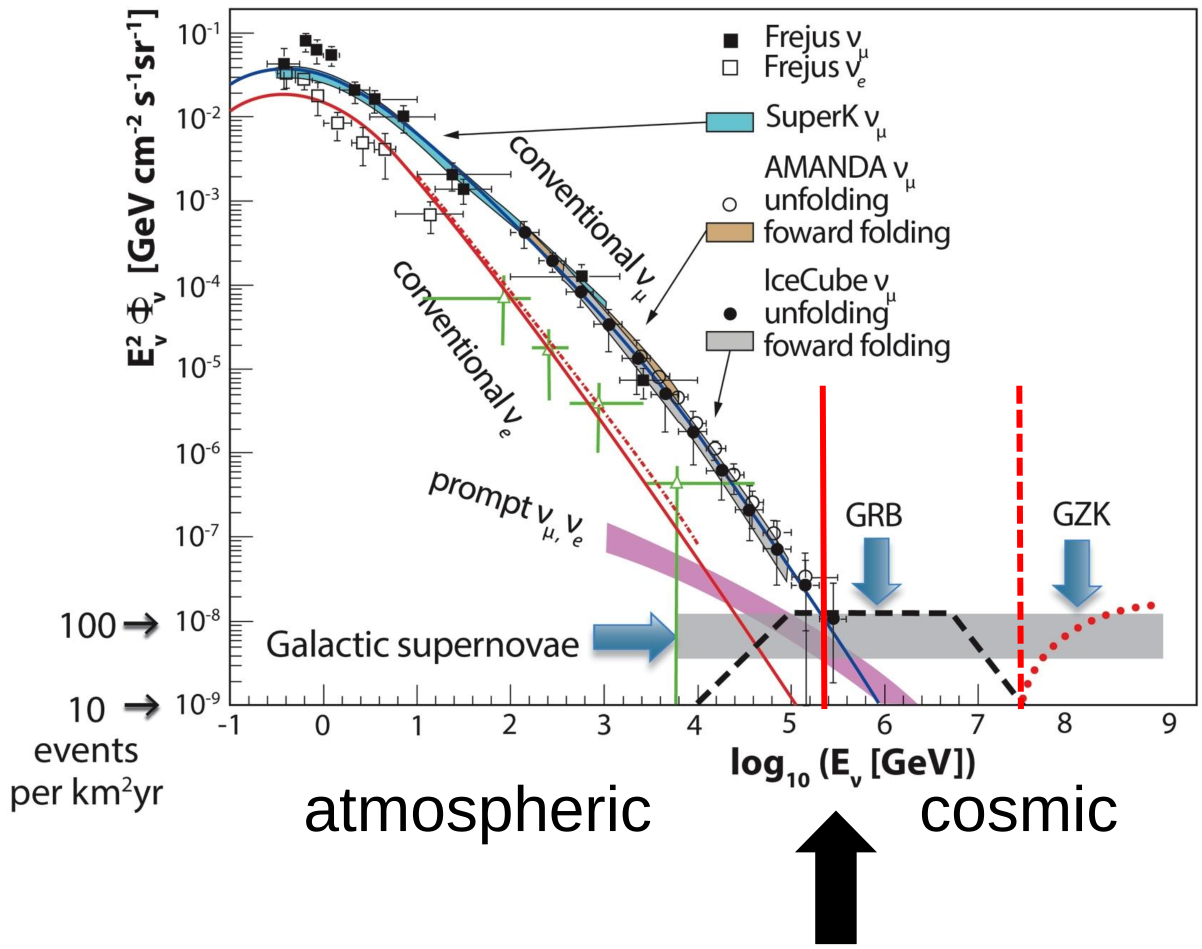
Ultra High Energy Cosmic Neutrinos: Two Regimes and Two Approaches

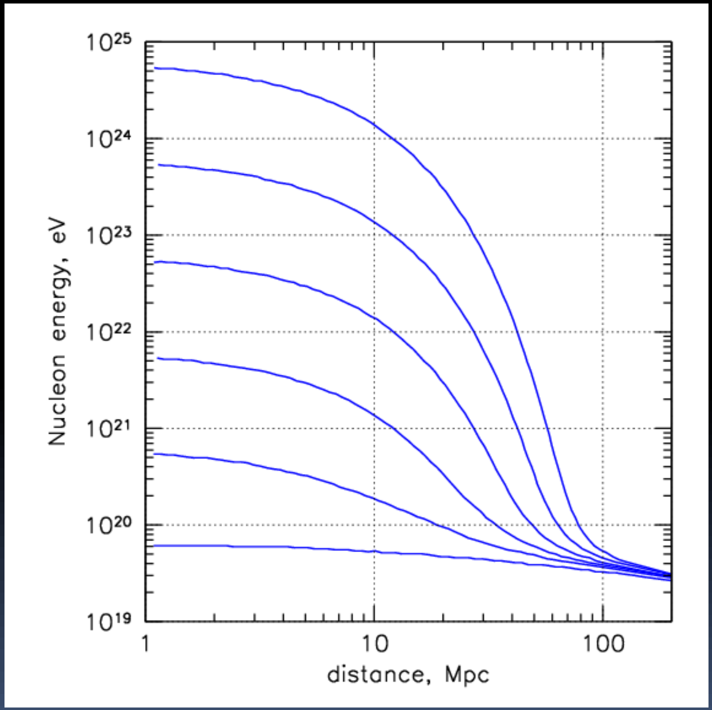
- cosmic neutrinos: energy > 100 TeV
- atmospheric background: 1~2 events per year

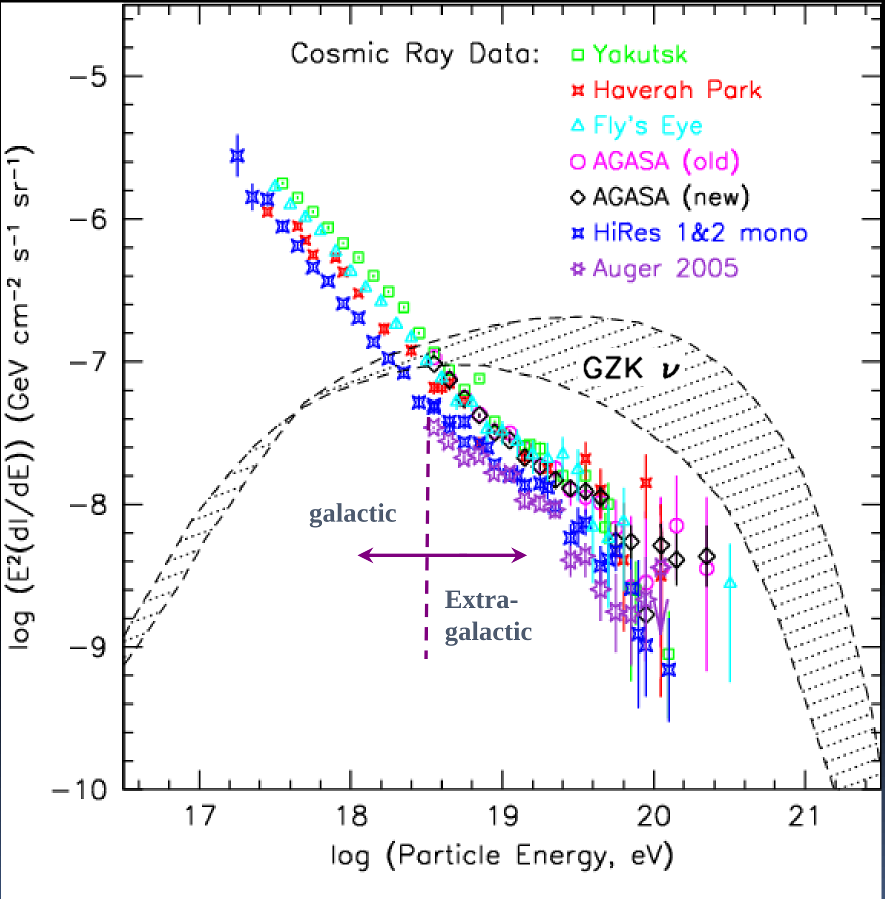
$$\Phi_{\nu} \equiv \frac{dN}{dE} \approx \frac{1}{E^2}$$



“GZK neutrino” must exist!

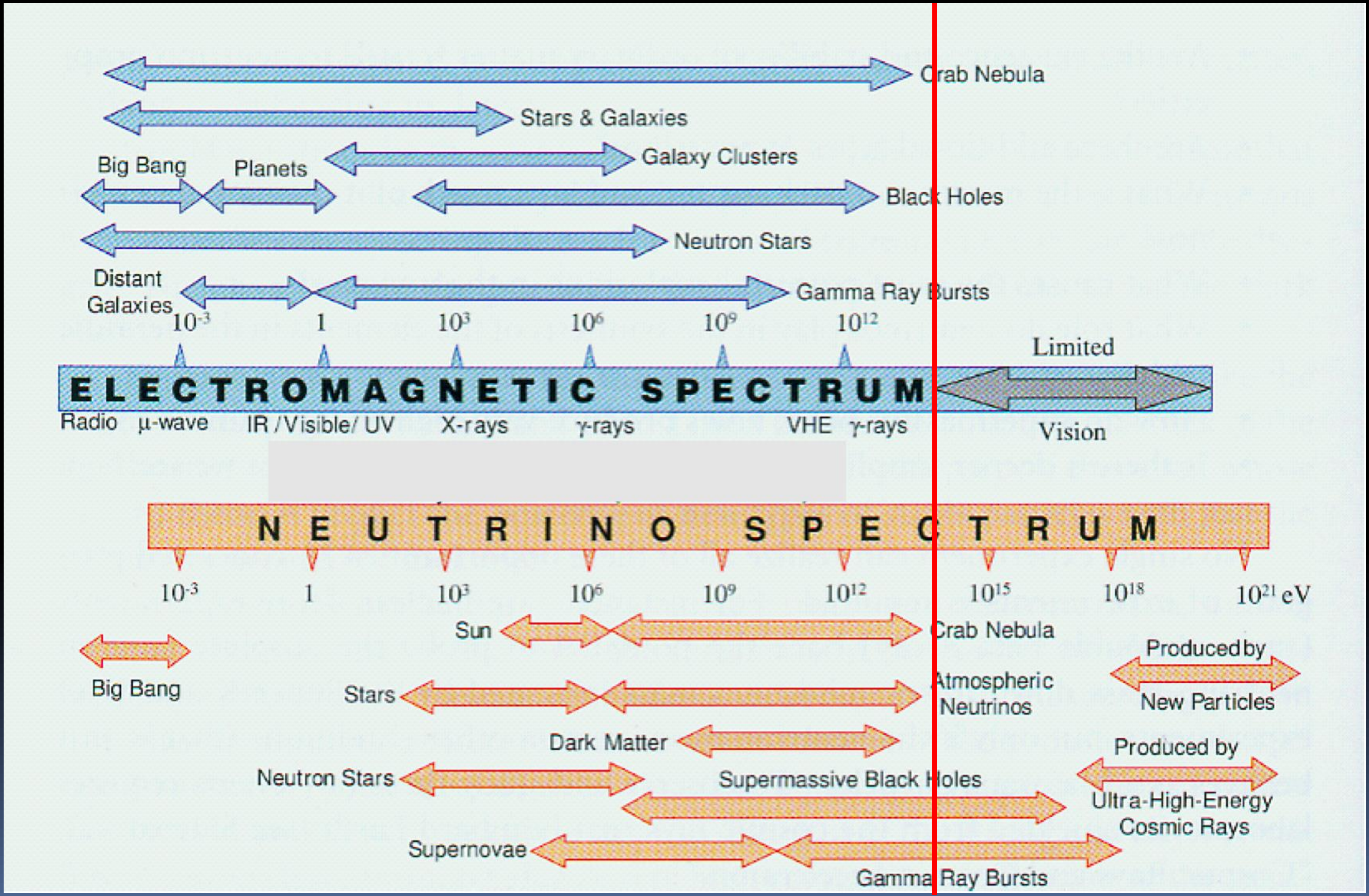
$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm}$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$





Neutrinos at $10^{17\text{-}19}$ eV required by standard-model physics

Unique window for UHE cosmos



Astrophys Potentials

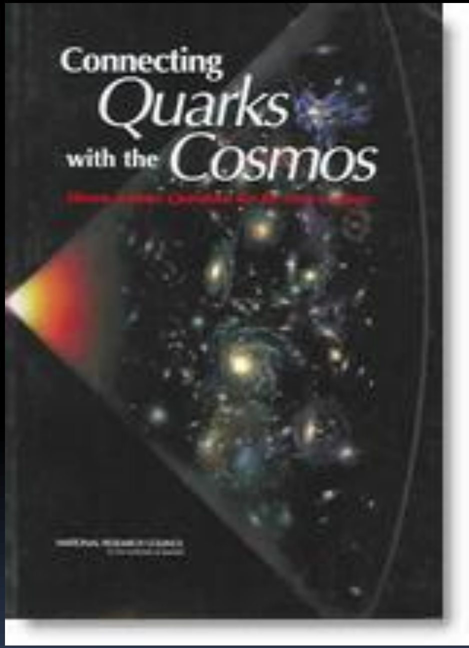
- Origin of UHECR beyond the ankle:

One of 11 science questions for the new century:

(US NRC Turner Committee Report, 2003)

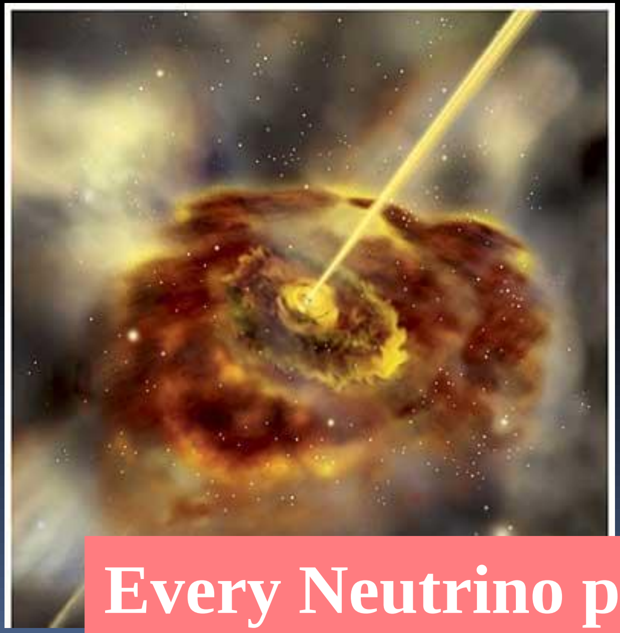
"How do cosmic accelerators work and what are they accelerating?"

$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm}$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$



- UHECR: Top-down or bot tom-up?
- If bottom-up, what acceler ates the cosmic particles?
- Where are the sources?
- GZK neutrino spectrum an d directions

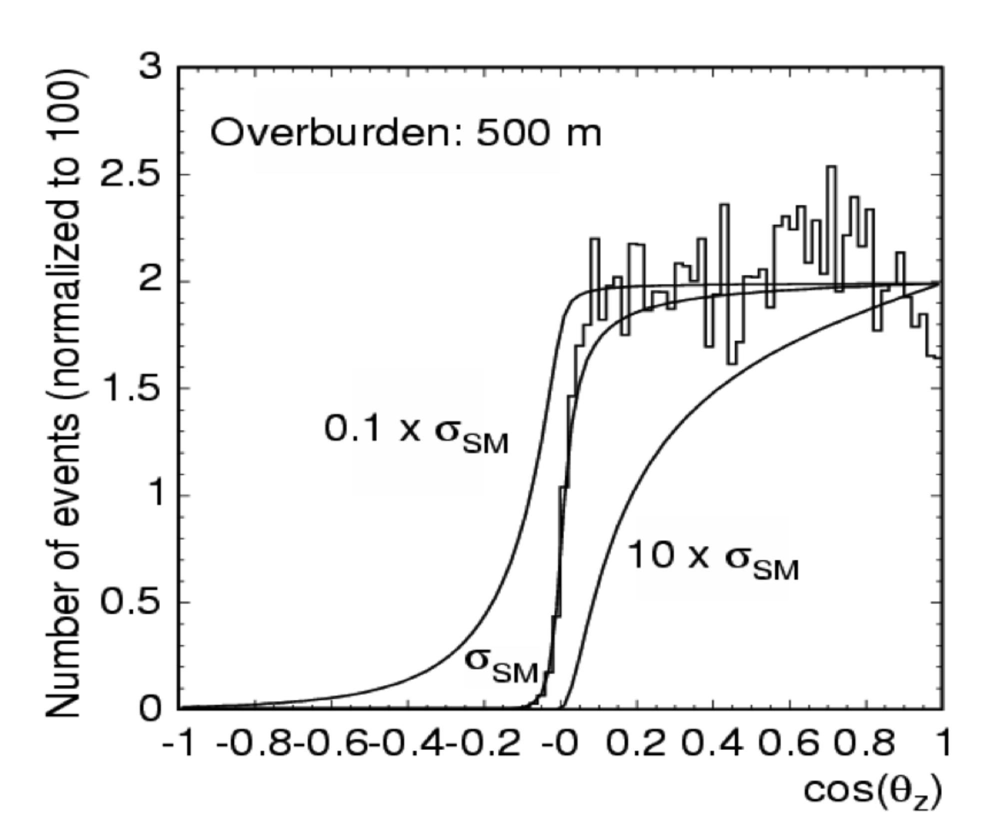
indispensable

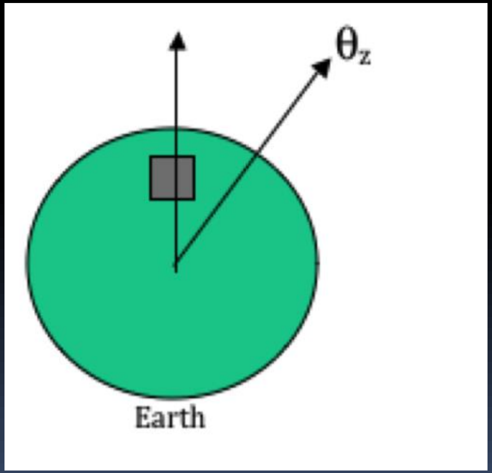


Every Neutrino points back to its source !

Particle Physics Potentials

Simulations indicate that ~30% cross-section measurement is doable with 100 ν events.





A. Connolly, Int. J. Mod. Phys. A 21, Suppl. 1, 163 (2006).

Evolution of ν Flavors In-flight: ν Oscillations and Decays

Two major discoveries about neutrinos in the past 20 years
:

1. Neutrinos oscillate;
2. Neutrinos have mass.

1. Neutrin

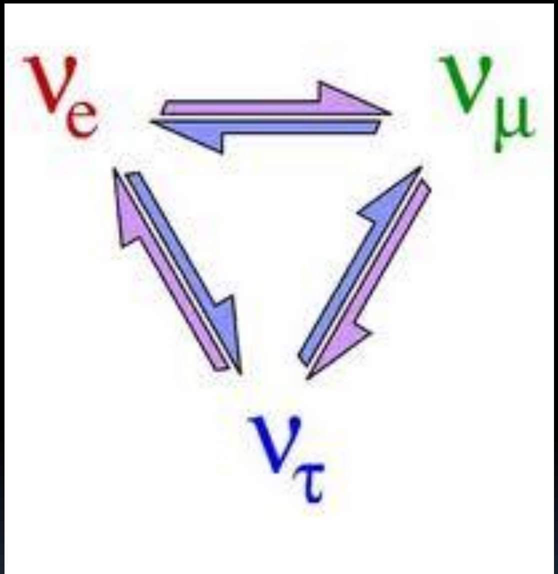
$$p + \gamma_{2.7K} \to \Delta^* \to n + \pi^{\pm}$$

$$\hookrightarrow \mu\nu$$

$$\hookrightarrow e\nu\nu$$

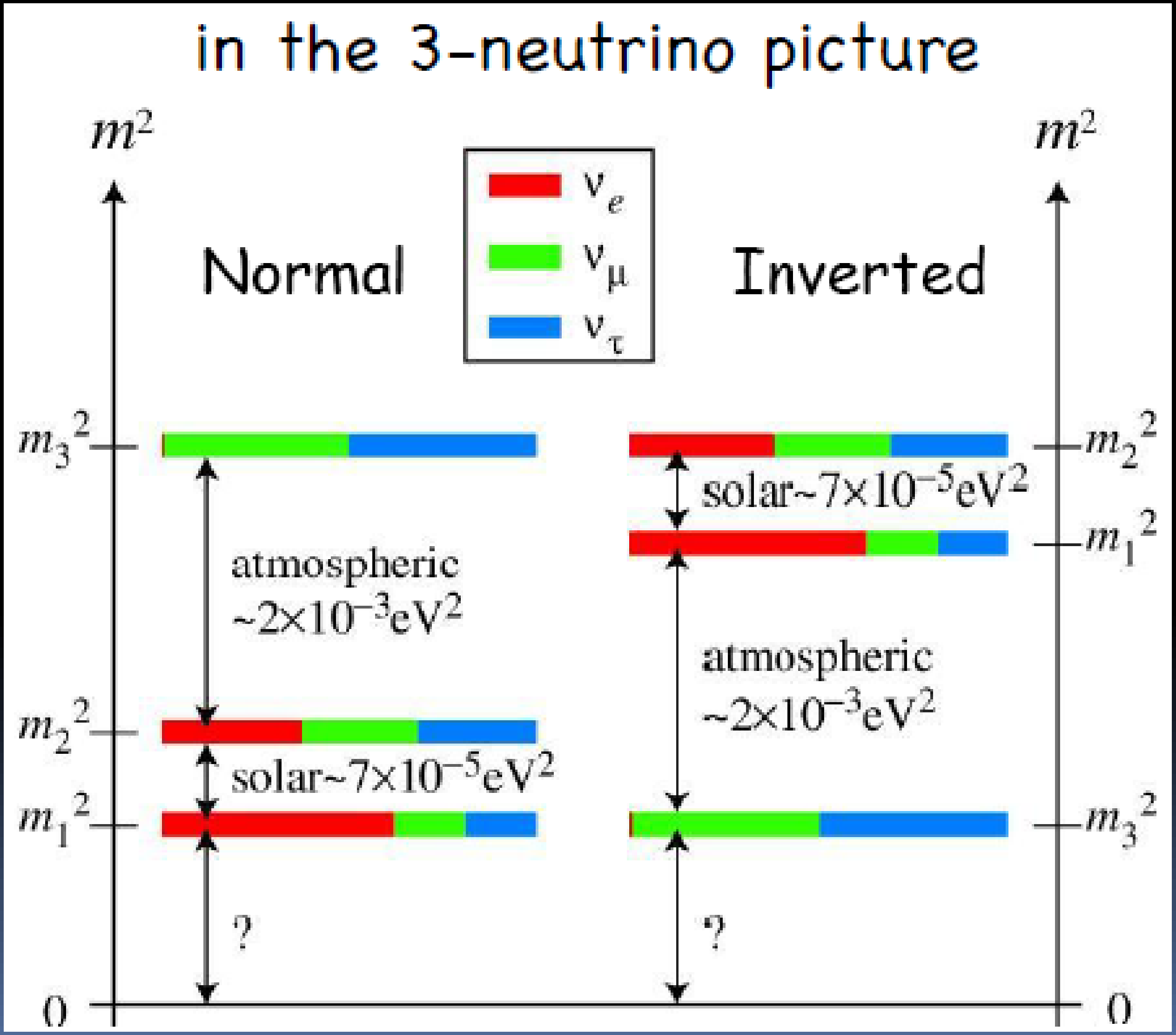
$$f_e^S : f_\mu^S : f_\tau^S = 1 : 2 : 0$$

→ $f_e^E : f_\mu^E : f_\tau^E = 1 : 1 : 1$



The periodic change of neutrino flavor from one type into another is referred to as neutrino oscillations.

Possible neutrino mass hierarchies



Evolution of ν Flavors In-flight: ν Oscillations and Decays

Two major discoveries about neutrinos in the past 20 y ears:

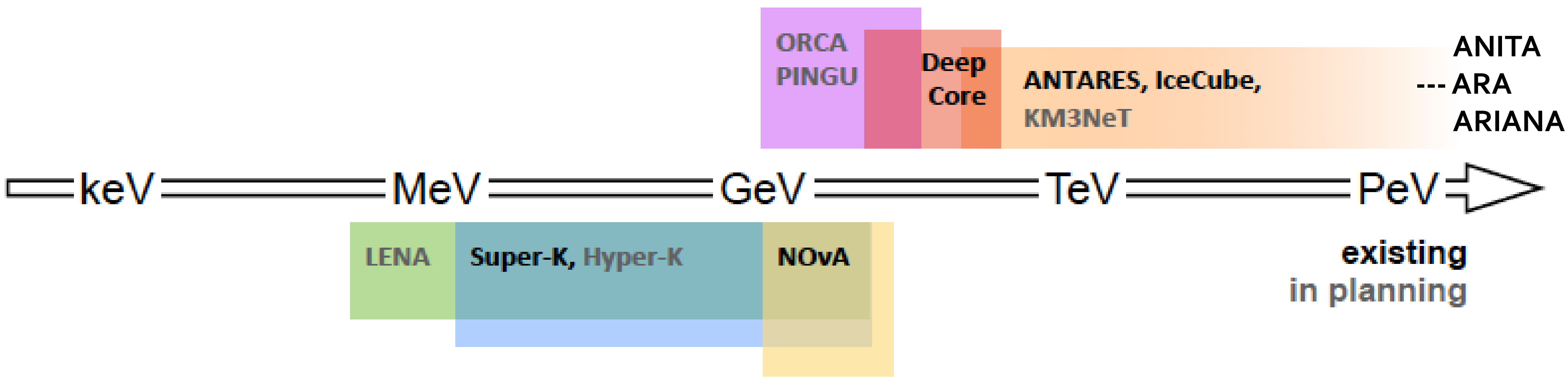
1. Neutrinos oscillate;
2. Neutrinos have mass.

2. Neutrino Decay [Learned & Pakvasa (1995), Beacom et al. (2003)]

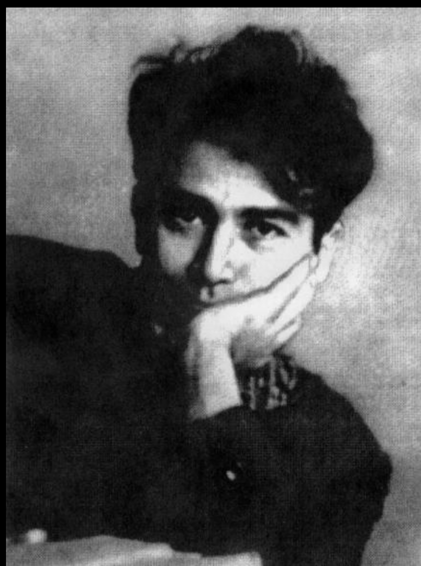
Normal Hierarchy: $f_e^E : f_\mu^E : f_\tau^E = 2/3 : 1/8 : 5/24$

Inverted Hierarchy: $f_e^E : f_\mu^E : f_\tau^E = 0 : 2/5 : 3/5$

Approach 1 for Regime 1: Optical Cherenkov from Muon

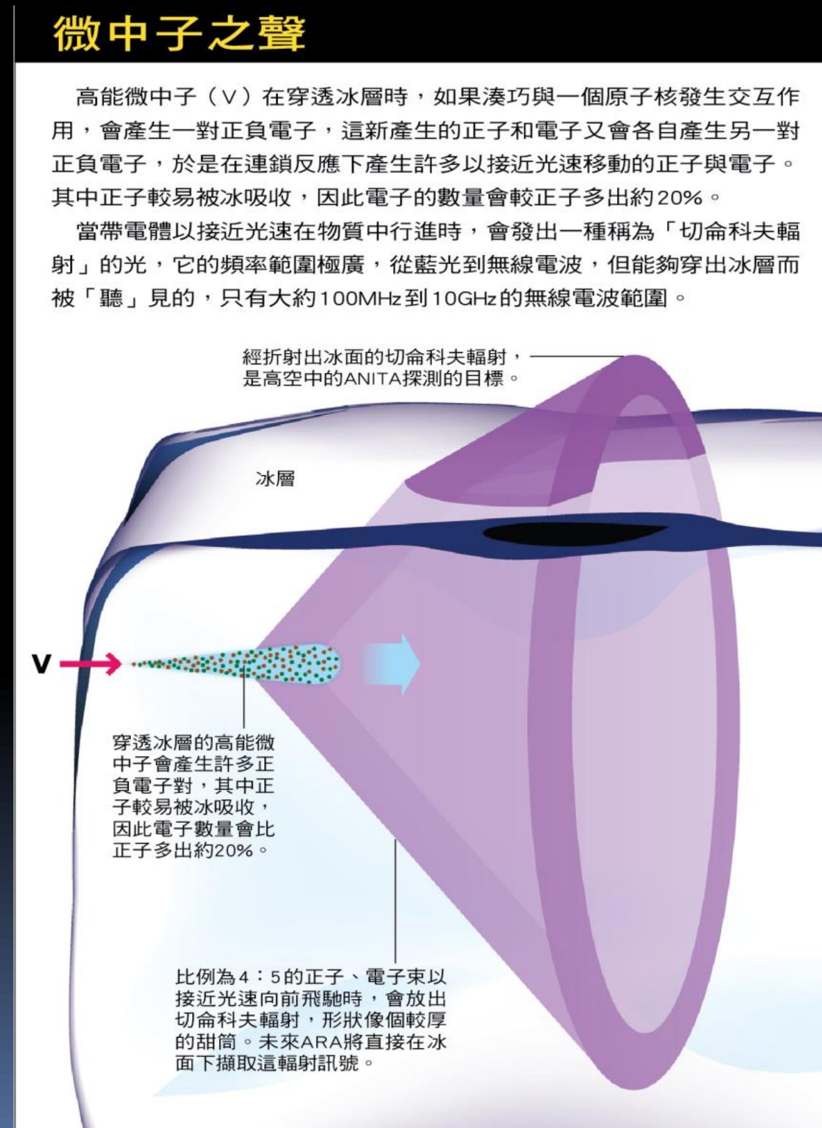


Approach 2 for Regime 2: Askaryan Effect – Radiowave Cherenkov from nuetrino shower



Gurgen A. Askaryan 1928-1997

Cherenkov radiation: coherent at radiowave!



SLAC Beam Test- Mini-Antarctica (June 2006)

ANITA made the cover of PRL
(SLAC beam Test setup)

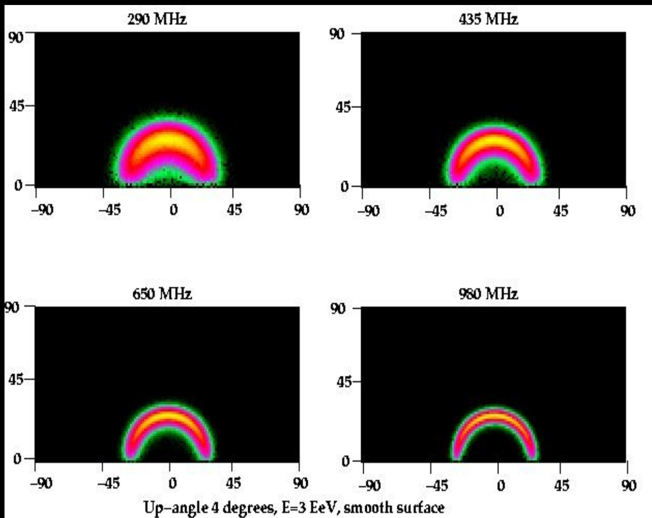
Absolute gain Calibration with real Askaryan pulse

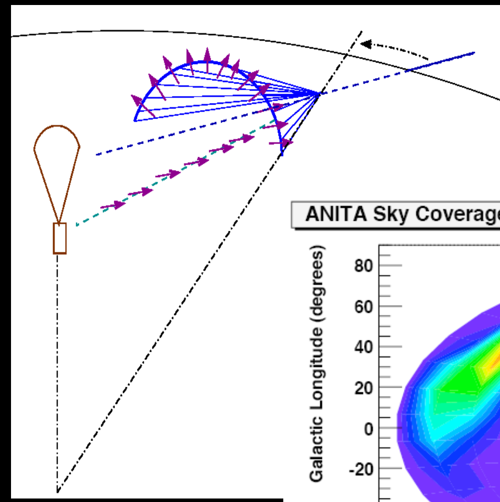
Mini-Antarctica with 10 tons of ice target

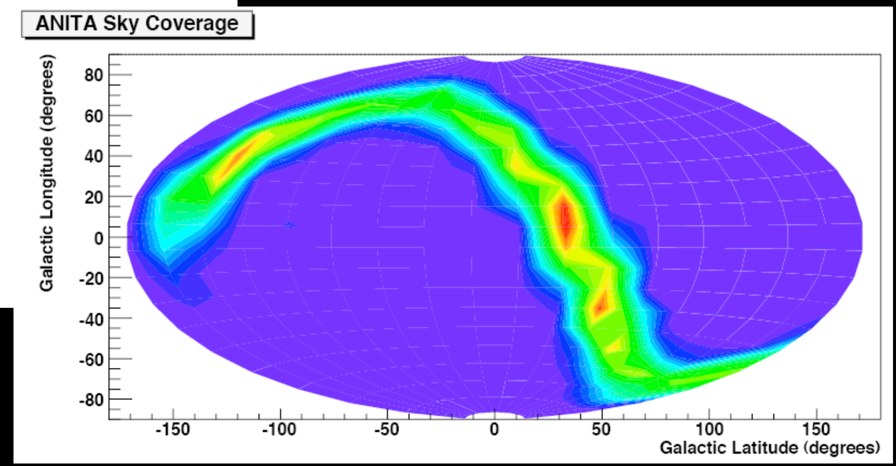
28.5 GeV electron beam (10^9 electrons)

First measurement of Askaryan effect in Ice

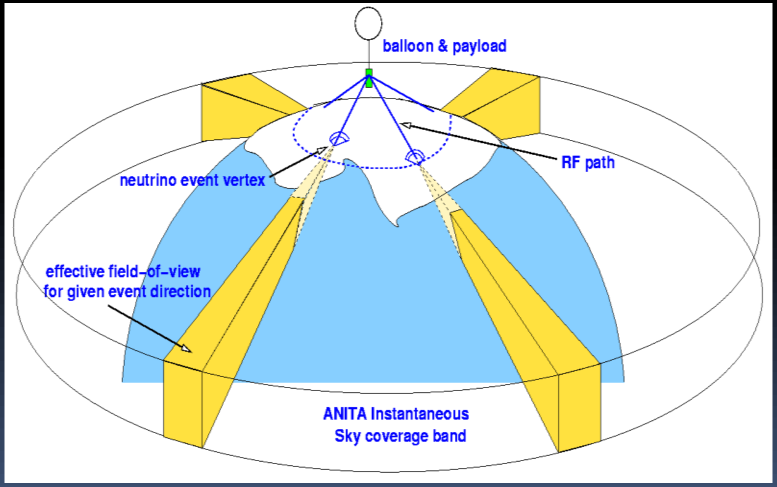
ANITA as a neutrino radio telescope





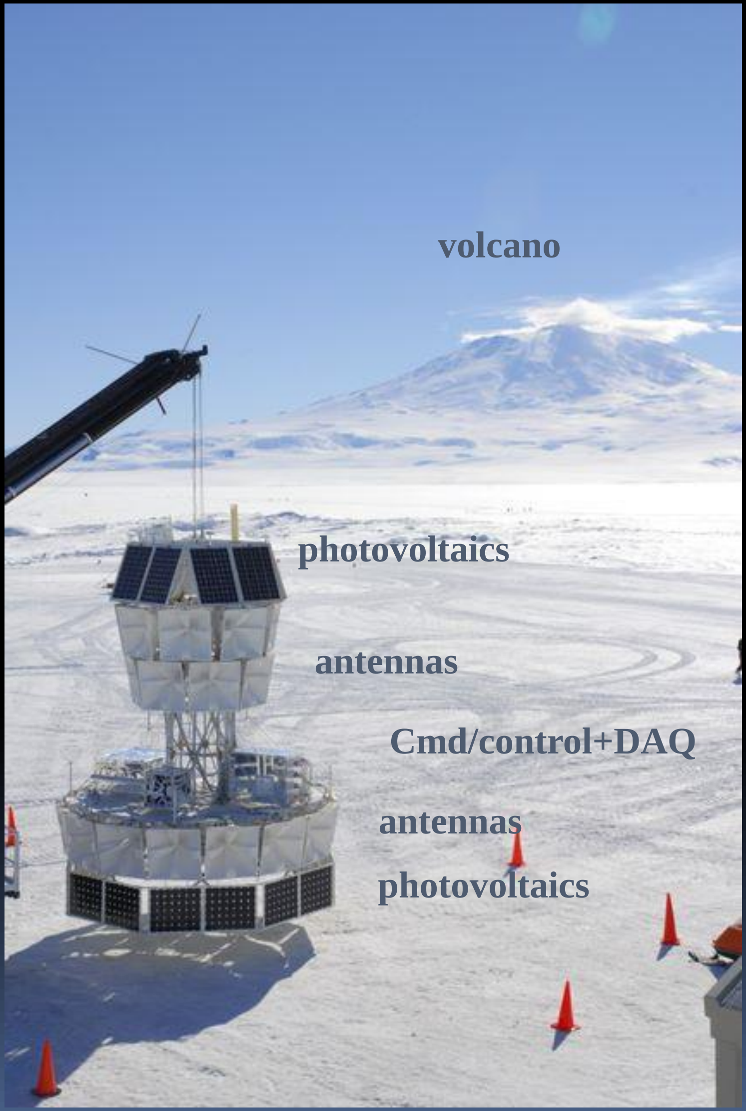


Brian Mercurio & Chris Williams, OSU



- Pulse-phase interferometer (<30-60 ps timing) gives intrinsic resolution of $<0.3^o$ elevation by $\sim 1^o$ azimuth for **arrival direction of radio pulse**
- **Neutrino direction** constrained to $\sim<2^o$ in elevation by earth absorption, and by $\sim 5\text{-}7^o$ in azimuth by observed **polarization angle of detected impulse**

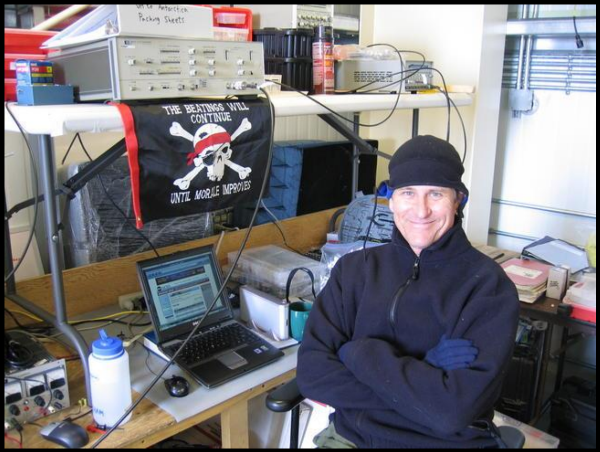
Pre-launch rollout



Photos: J. Kowalski

- Launch from ~80m deep Ross Ice She lf (floats on Ross Sea)
- ~8 miles from McMurdo Station
- Affords flat, stable 1-mile diameter la unch pad

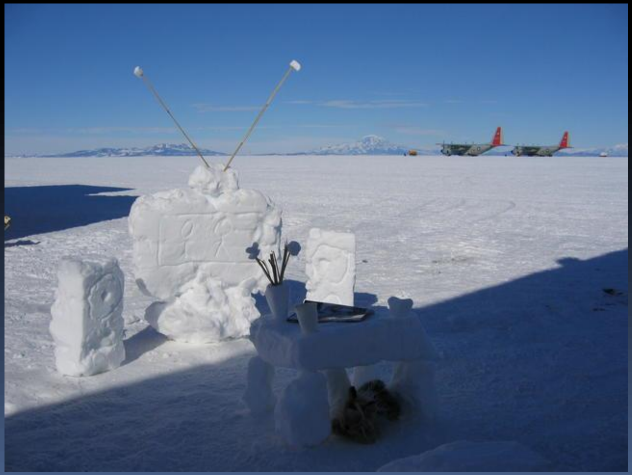
Life in McMurdo



Peter Gorham: Close the door please!

Everything needs to be recycled in McMurdo…

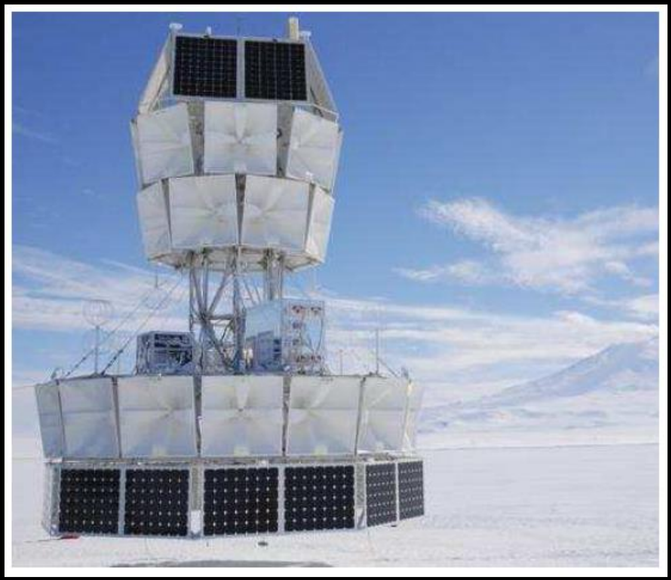
Deluxe suite…

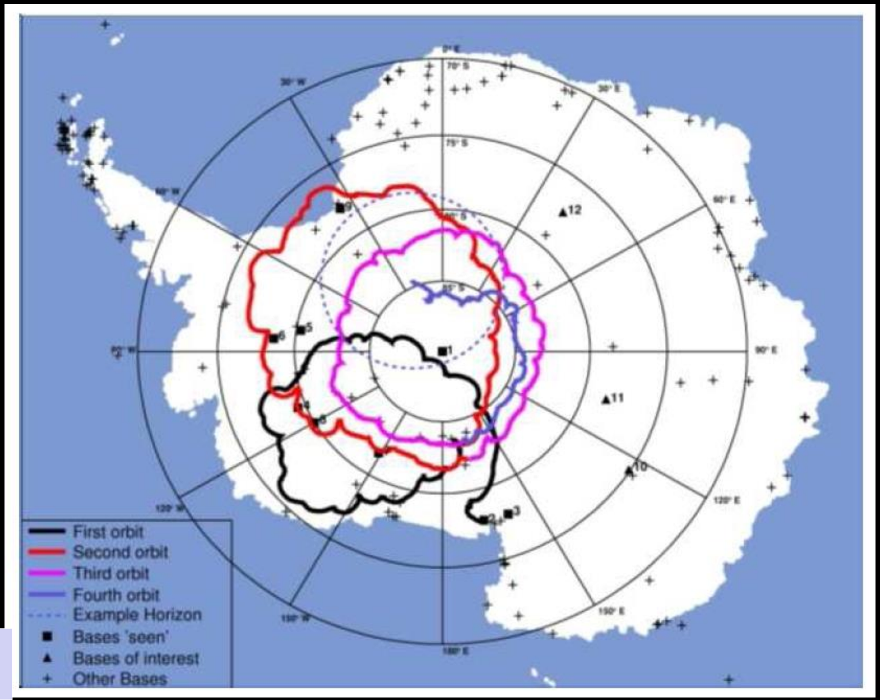


that comes with furniture…

and penguins

ANITA-1

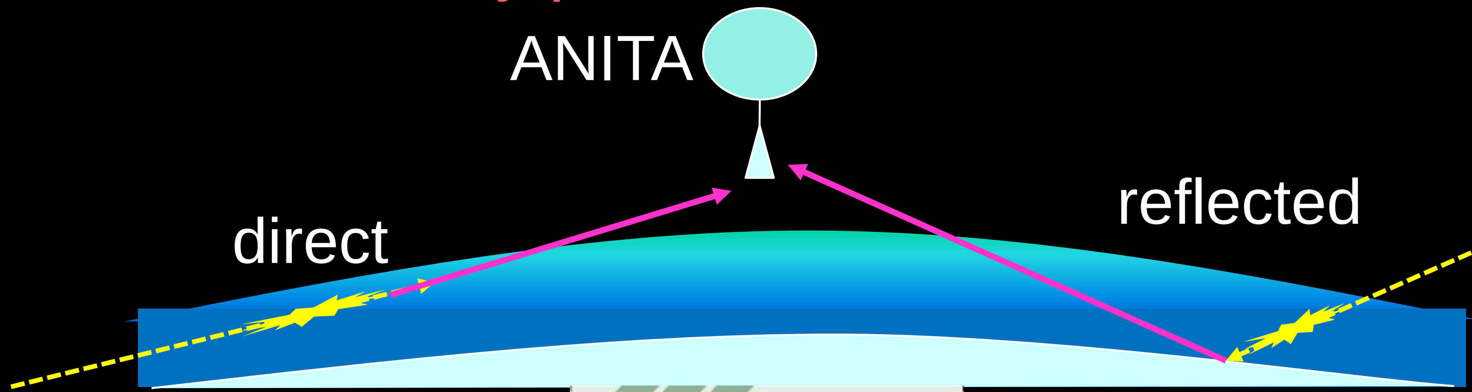


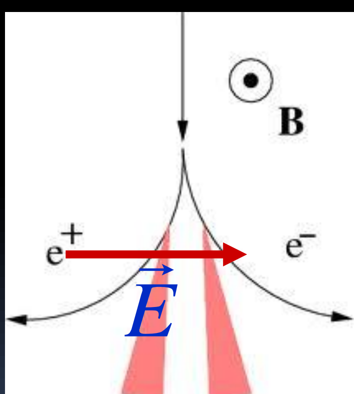


Live Days	17.3
Antennas	32
Quality Events	8.2M

Accidental Discovery of UHECR by ANITA-1

Geosynchrotron radiation induced by UHECR air shower at Pole is horizontally polarized






PHYSICAL REVIEW LETTERS

8 OCTOBER 2010

American Physical Society

APS physics

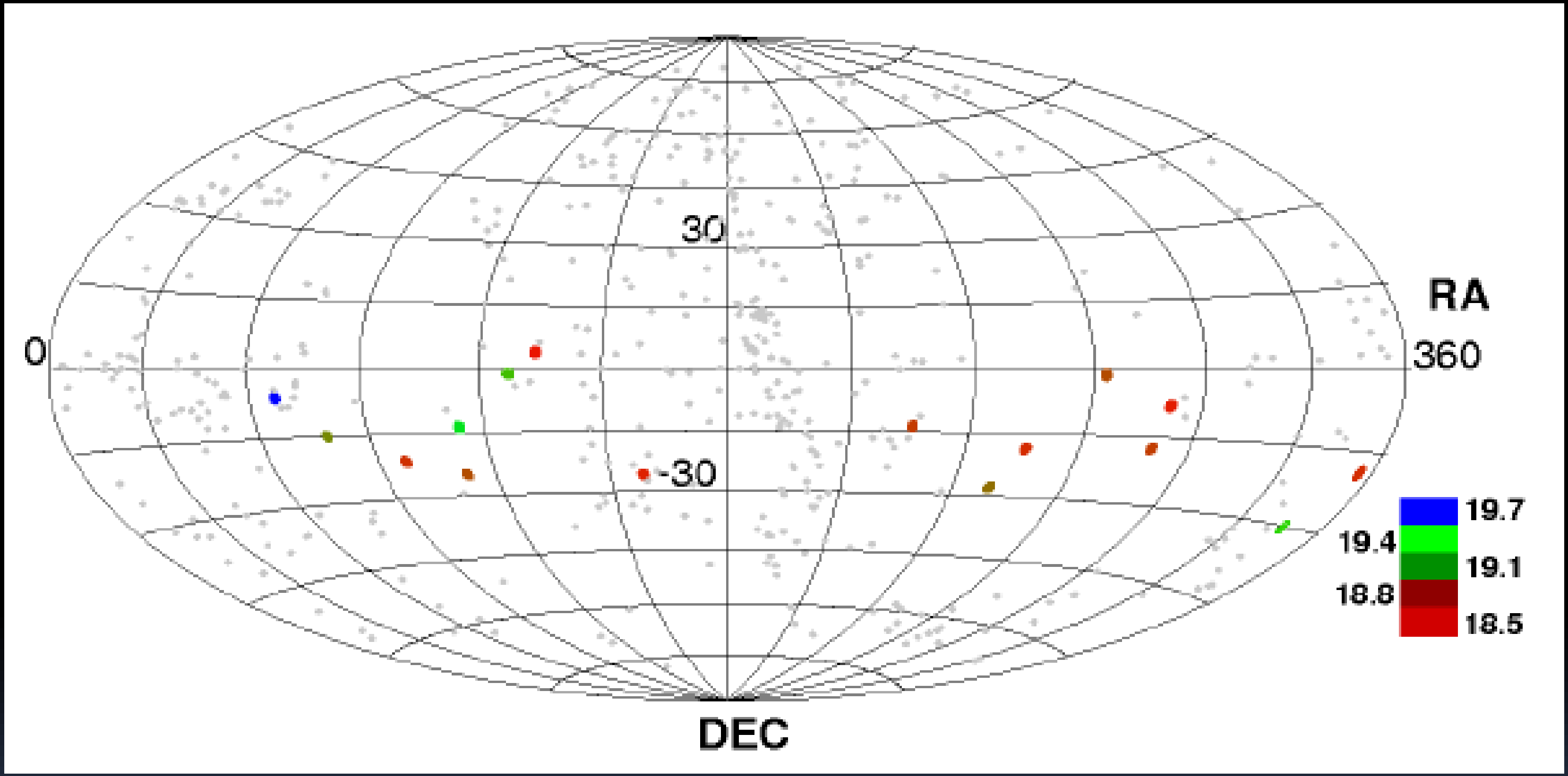
Volume 105, Number 15

H-pol Events	16
V-pol Events	0

Jiwoo Nam of NTU first found such events!

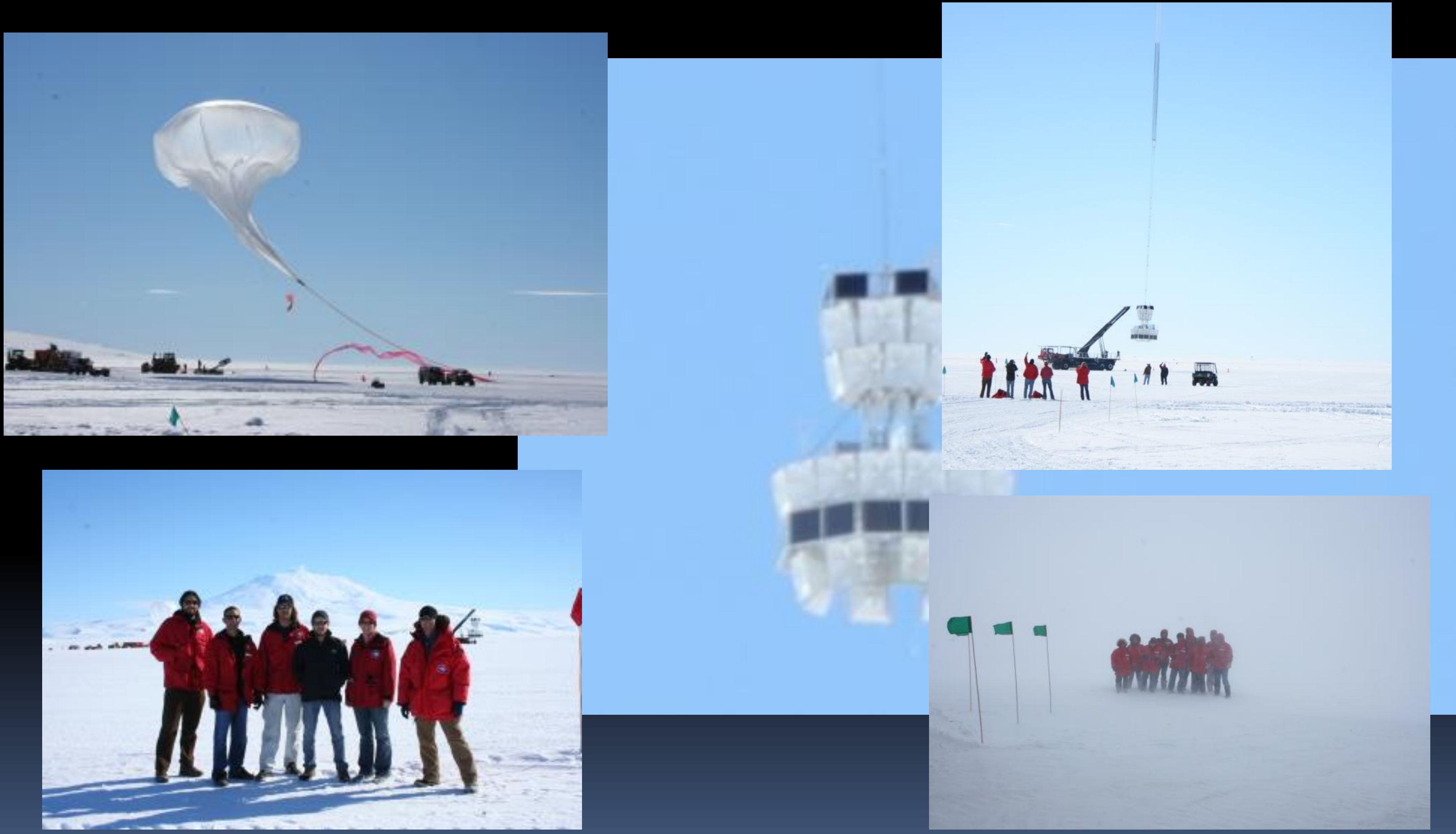
Provides a new and efficient way to detect UHECR!

Energy scale, directions

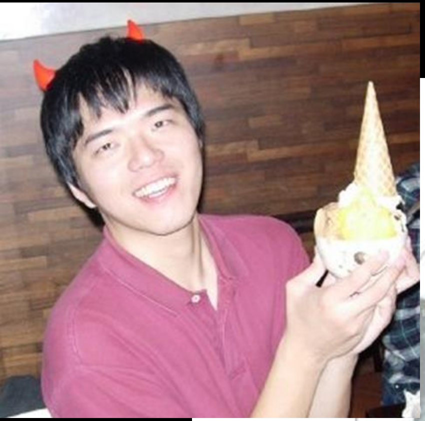


$$\langle E \rangle = 1.5^{+2}_{-0.4} \times 10^{19}\, eV$$

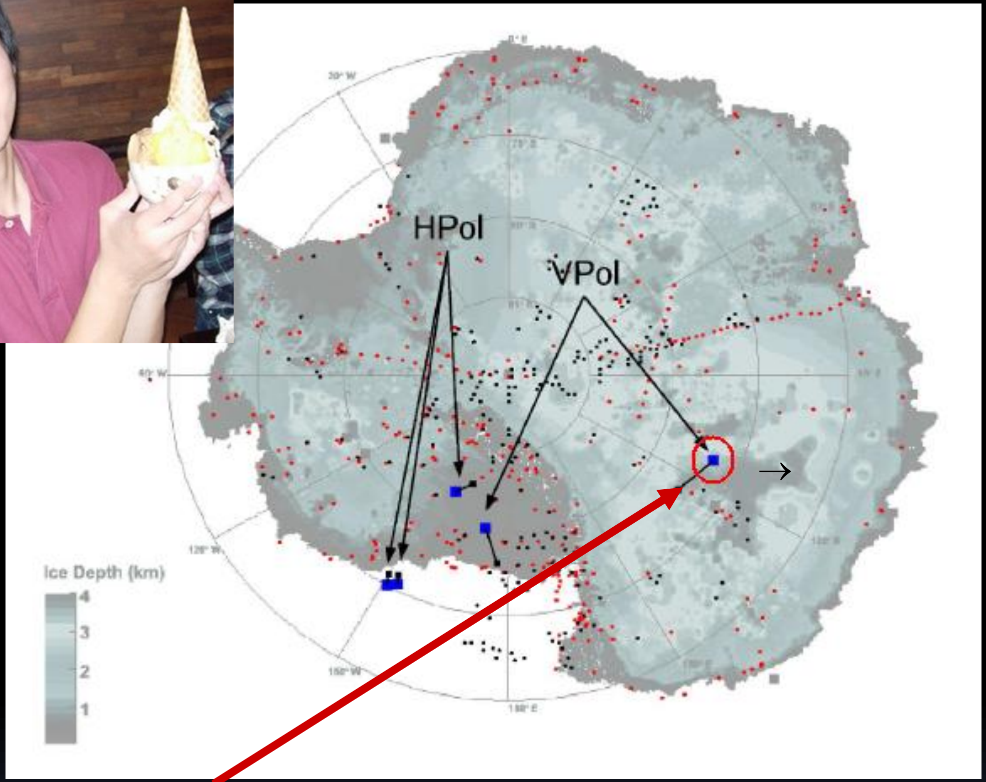
ANITA-2 launched in Dec. 2008

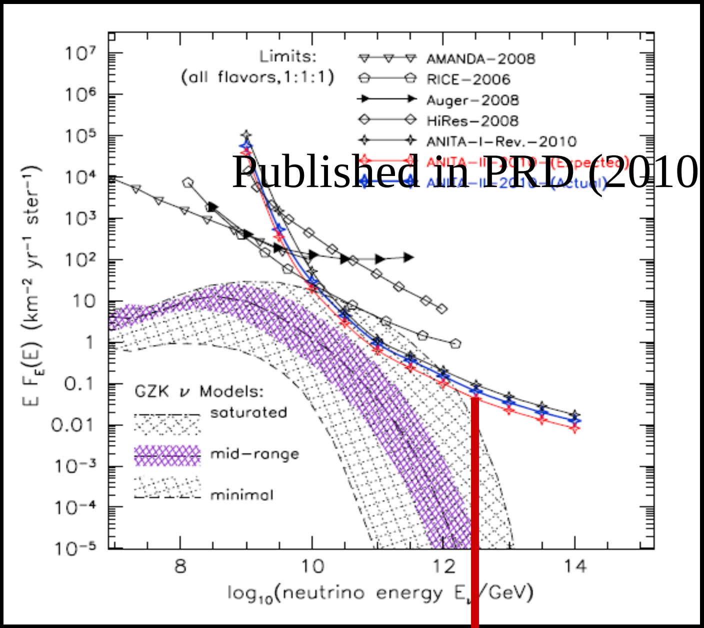


One candidate GZK neutrino found!

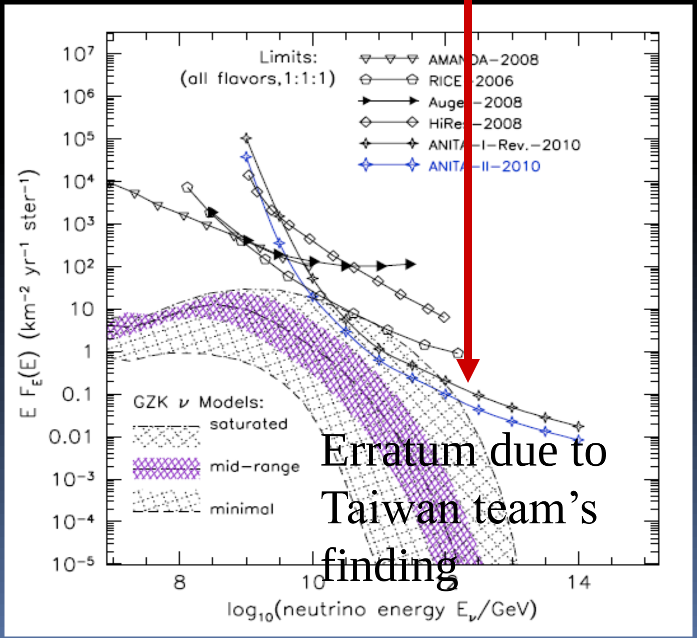


Ruo-Yu Shang





Published in PRD (2010



Erratum due to Taiwan team's finding

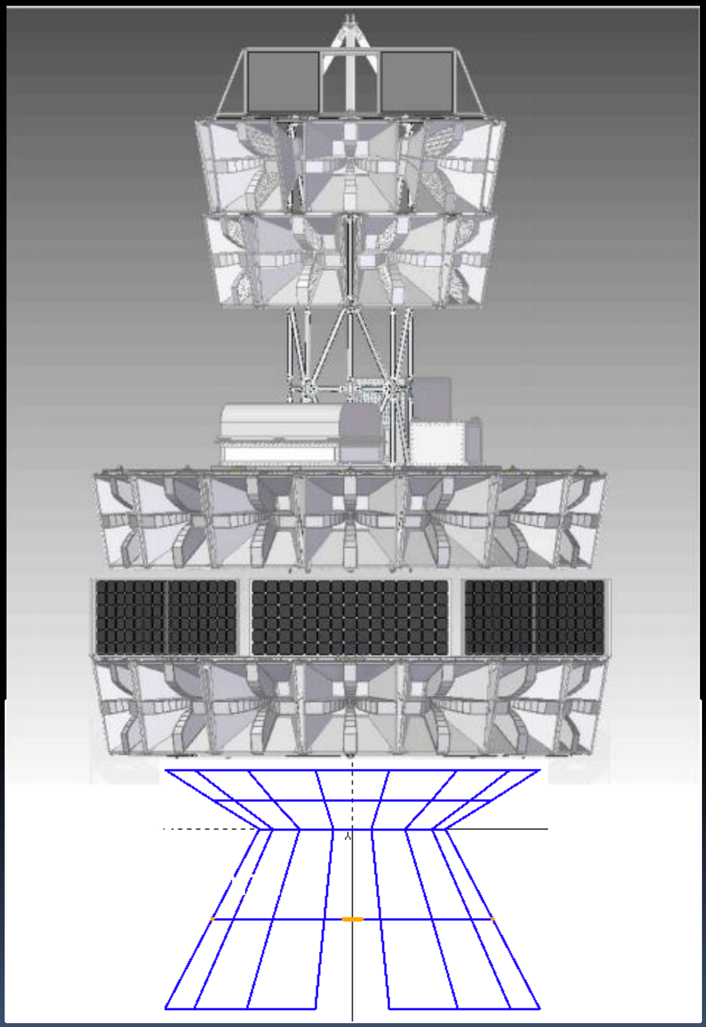
Taiwan NTU team has identified a 'false' event (2010).

H-pol Events	3
V-pol Events	2 → 1

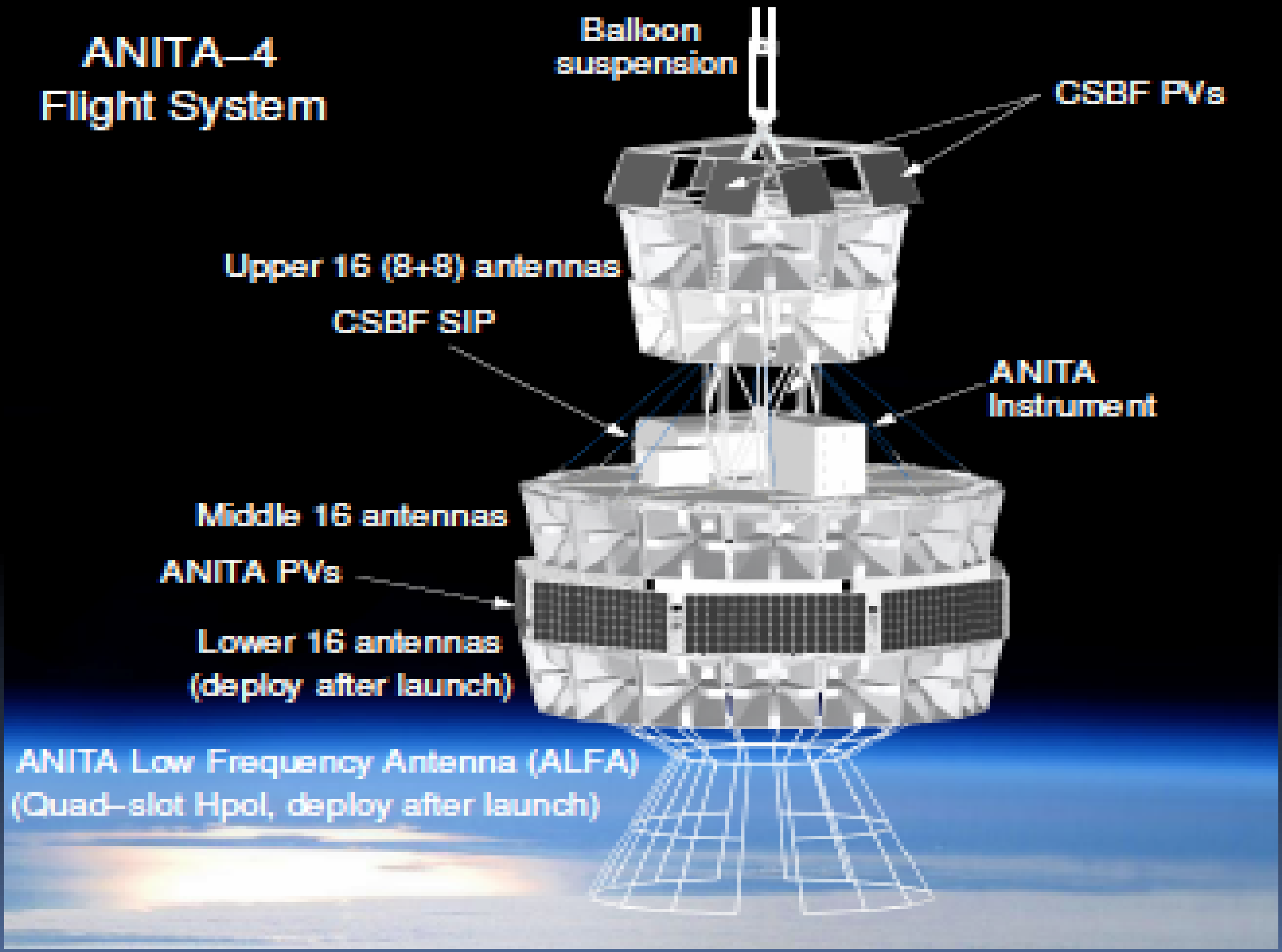
ANITA-3 Launched in Dec. 2014

- ANITA–3 launched in Dec 2014
  - Turning on H–pol trigger for UHECRs
    → Primary goal of mission
  - New correlation trigger
    → ~ factor 2 improvement
  - Low frequency antenna
    → 50% better efficiency in 180–300 MHz
  - 8 more antennas
    → 10% Improve
- Overall more than factor ~2 improvement
- Flew for 22 days
- Data analysis in progress

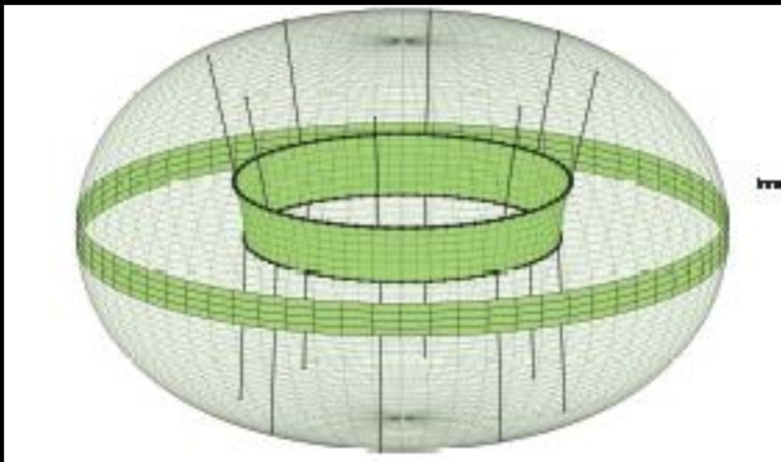
ANITA-3

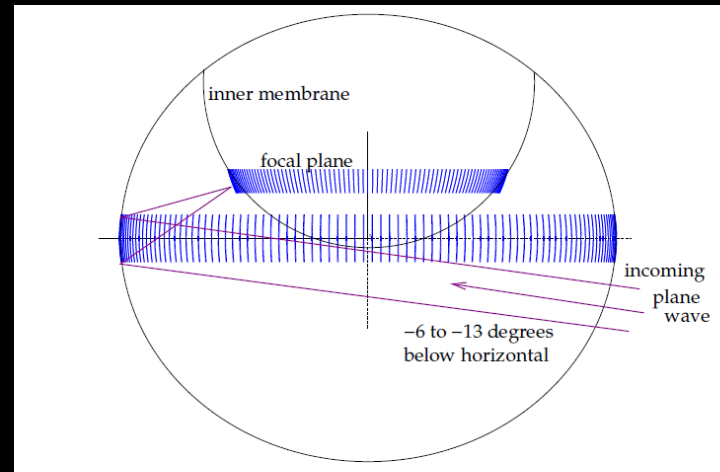


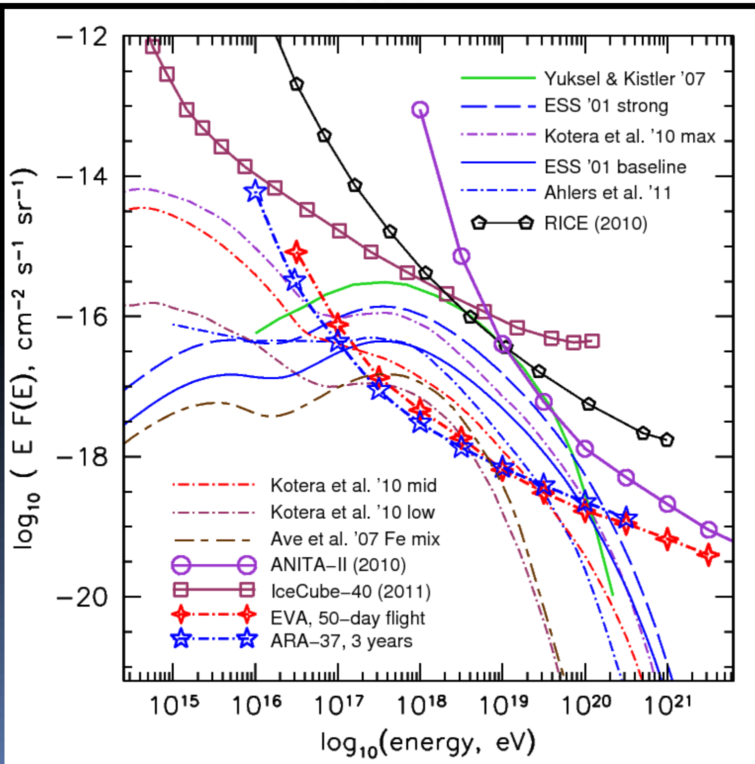
ANITA-4 mission approved by NASA for flight in 2017



Beyond ANITA: Exavolt Antenna (EVA)

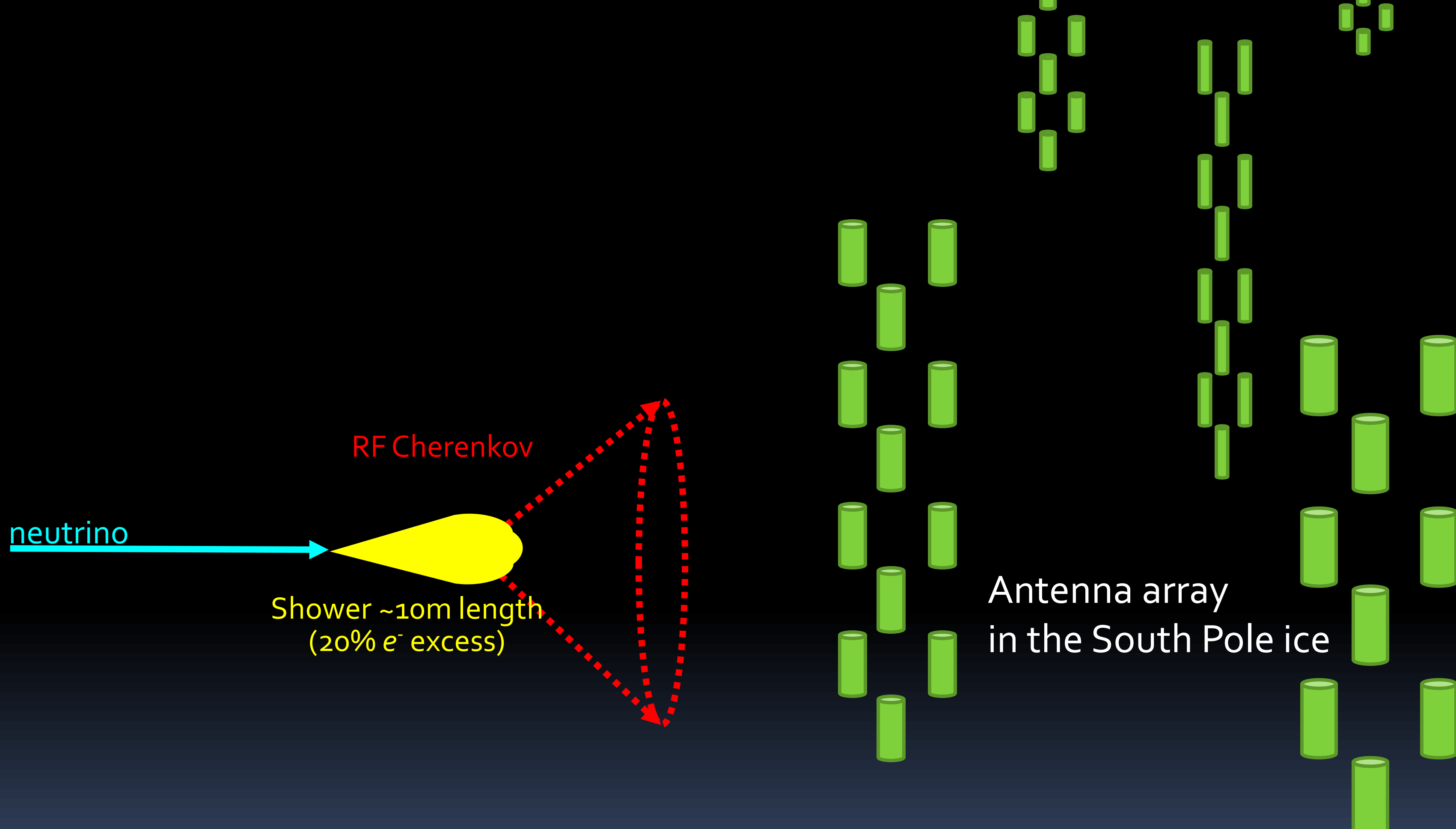






- NASA super-pressure balloon as a RF reflector→ Lower the threshold
- Hits all current self-consistent cosmogenic neutrino models
- Sensitivity up to 2 orders of magnitude over ANITA3&4
- 15,000 UHECRs events are detectable

ARA (Askaryan Radio Array)



Radio Attenuation Length: ~1 km (ten times longer than optical)

ARA37 (Askaryan Radio Array)

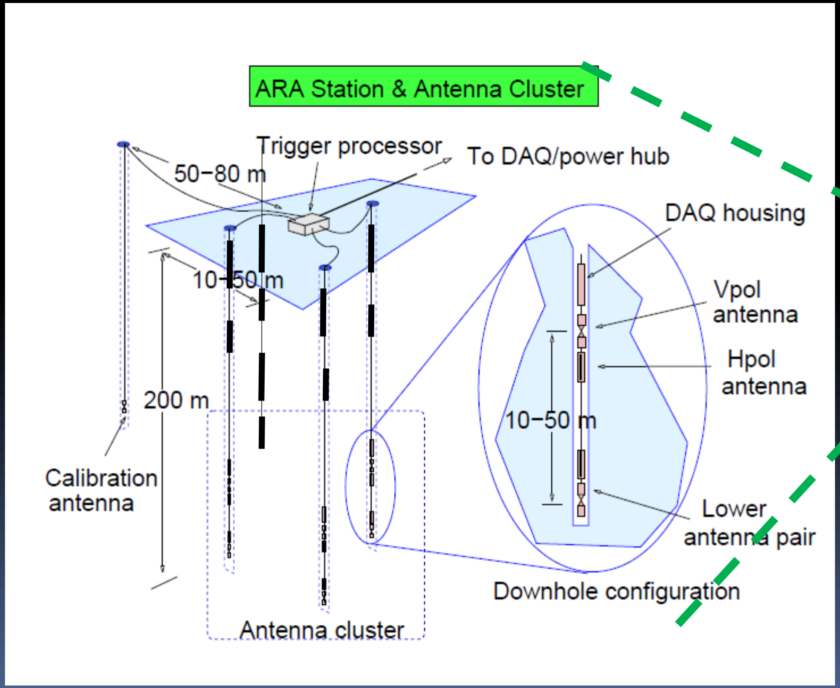
37 4-string, 16-antenna stations covering 100km^2 w. 3-5 ν/yr

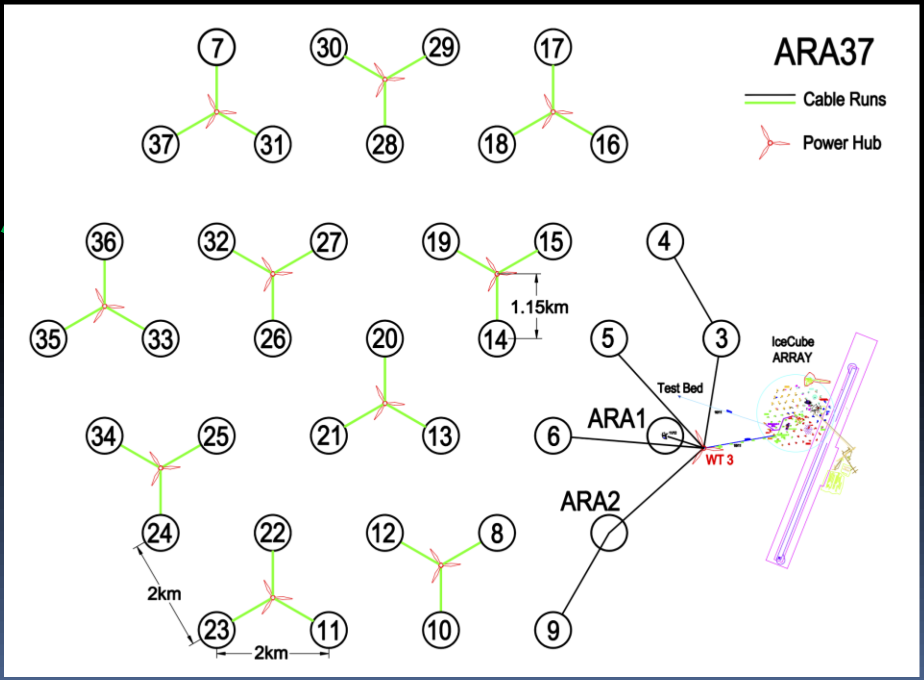
Taiwan team will contribute 10 stations, or ¼ of ARA.

Angular resolution: ~ 6°,

Energy resolution: dominated by Bjorken *y* →

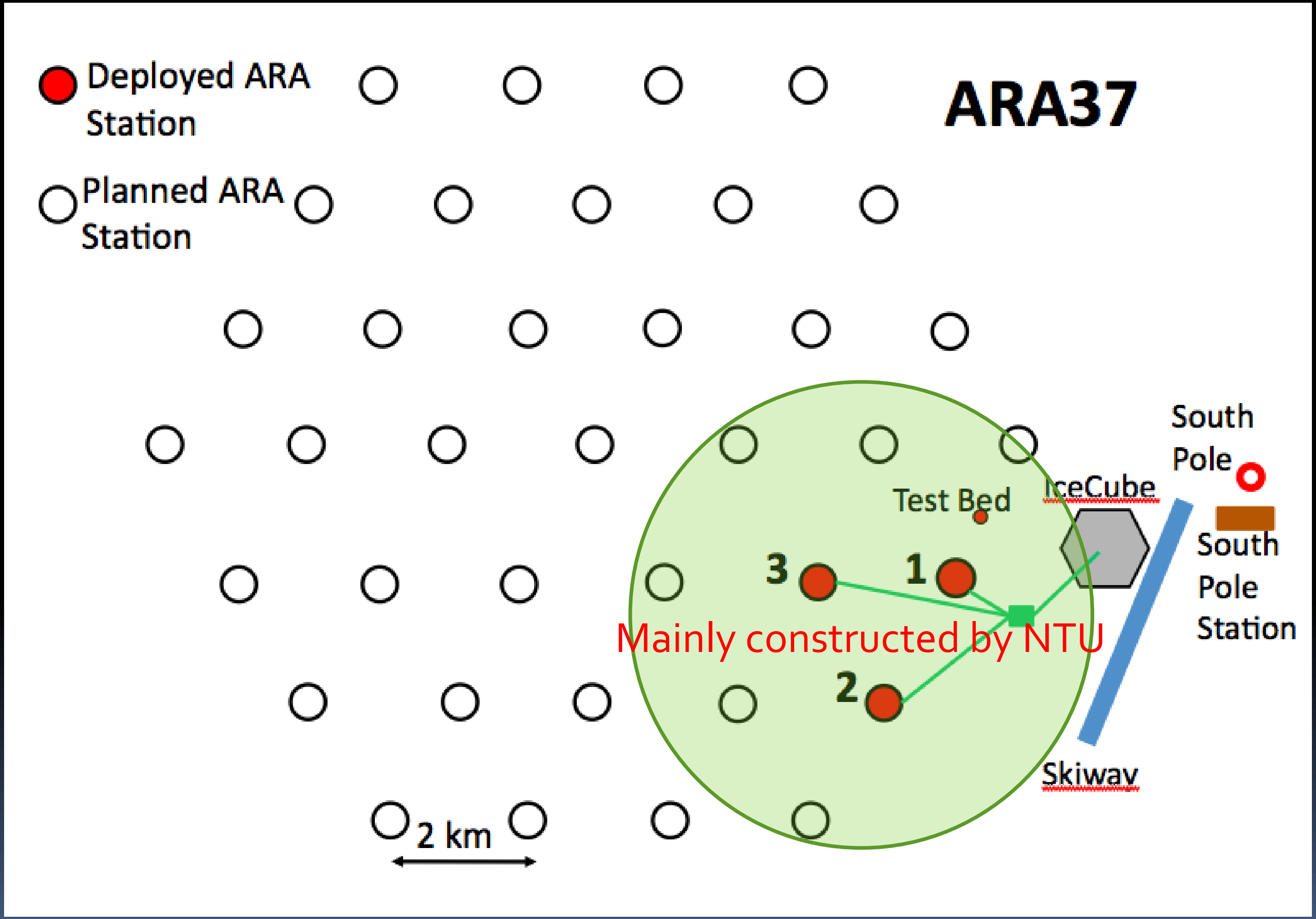
$\Delta E/E \sim 1$ @ 3x10^{18} eV





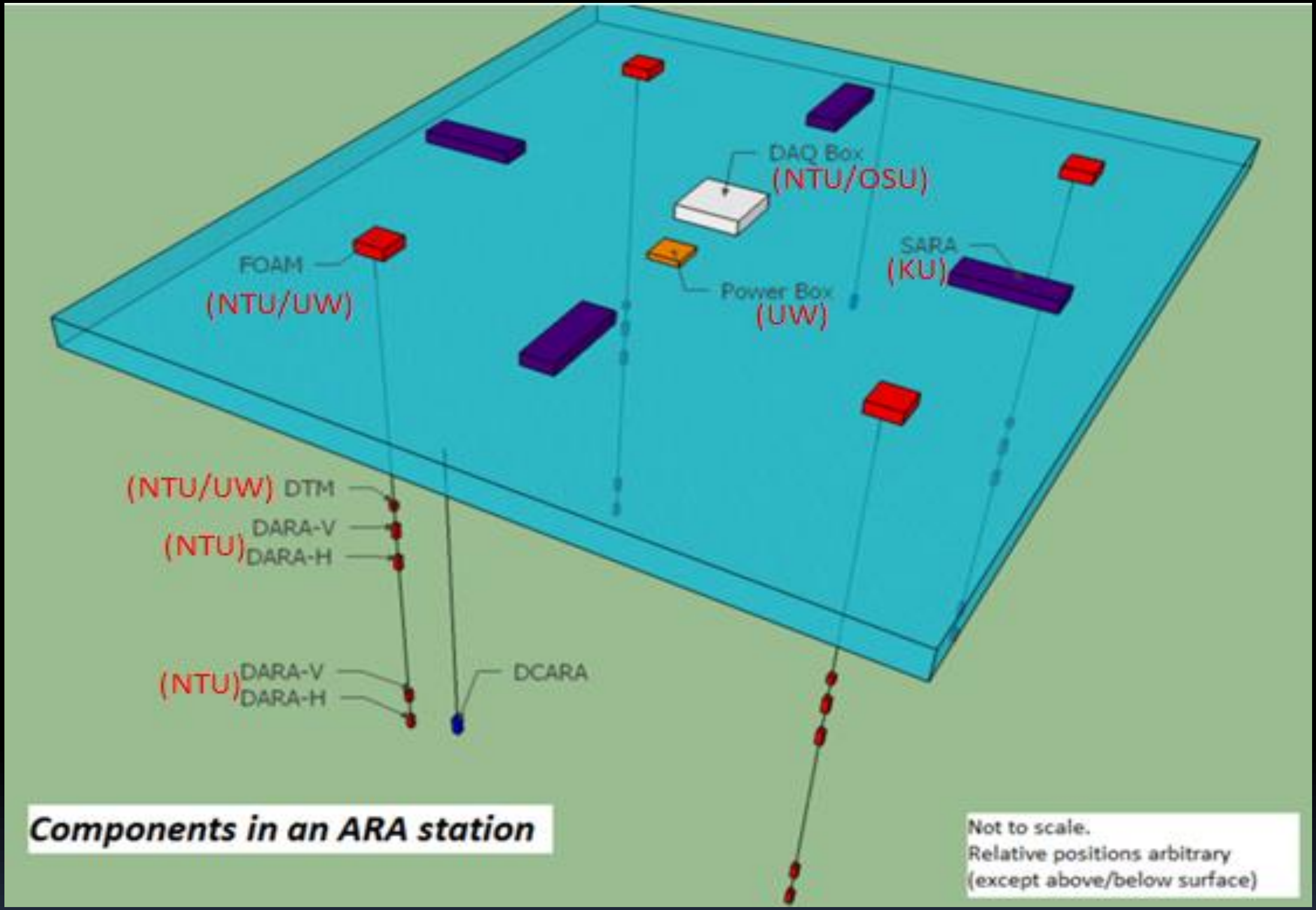
ARA

a large radio neutrino detector at the South Pole



Areal coverage: 150km²

ARA Station Geometry



4 RX strings + 2 calibration strings

2 V-pol + 2 H-pol / string = total 16 antennas

Nice vertexing with interferometry technique

→ Excellent background rejection

ARA Hardware

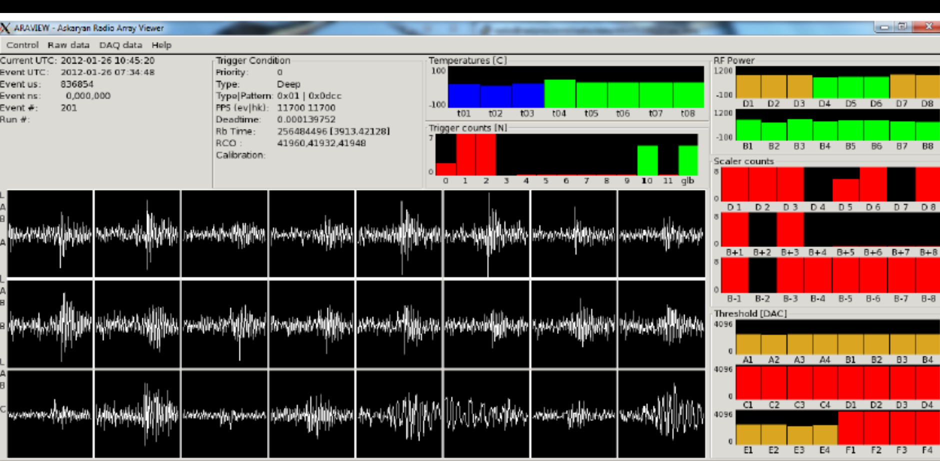
DAQ

RF over Fiber

Antenna

Low Noise Amp

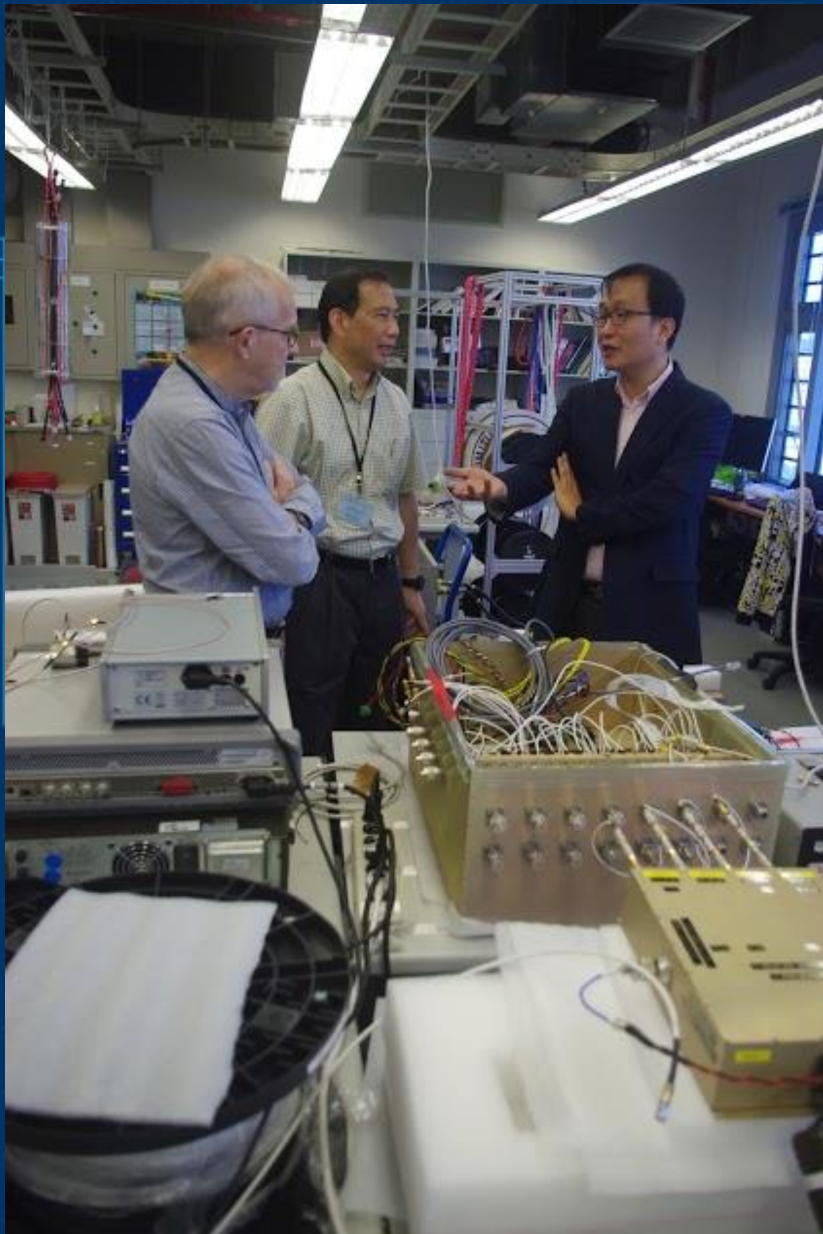
ARA1 Station Deployment (Jan 2012)



Successful Deployment of the ARA-1 Station
4 strings (at ~120 m depth)
16 Antennas
← Calibration pulser events

Taiwan’s first major science project at South Pole

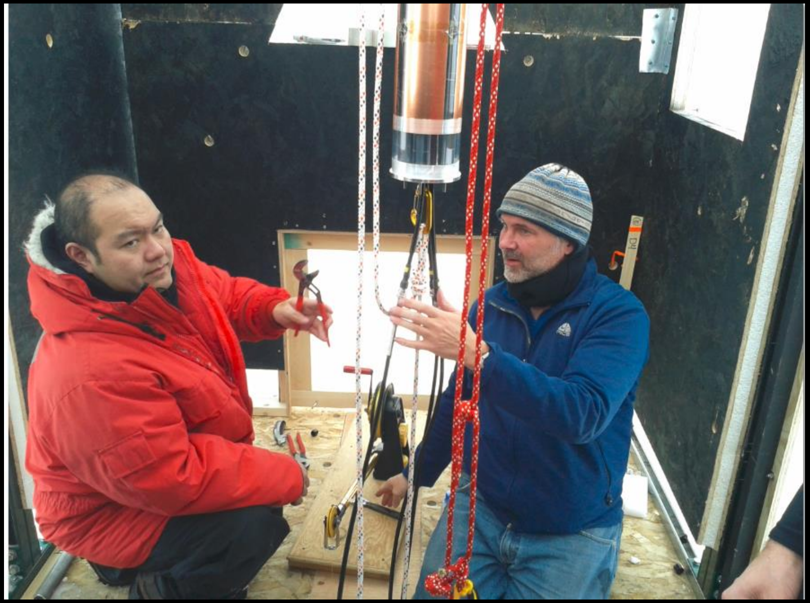
Collaborators come from all over the world to NTU



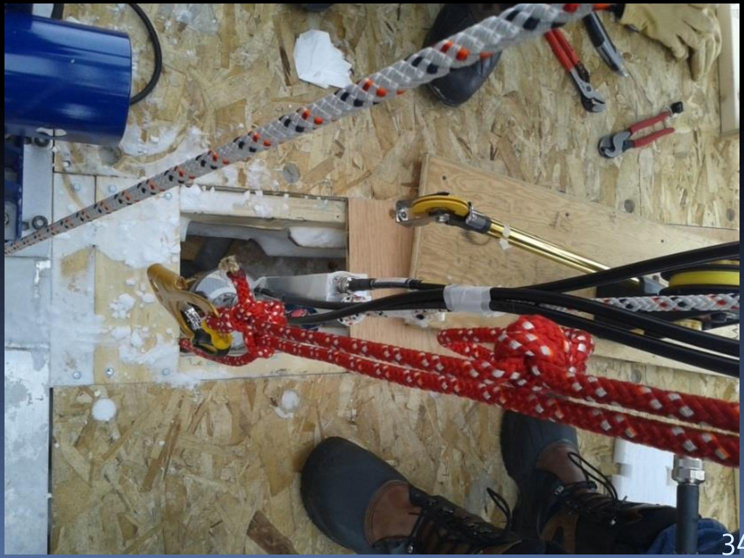
ARA Integration / Cold Temperature Test (2012, NTU)

ARA Deployment (2012-2013)

ARA Drilling System



Antenna deployment



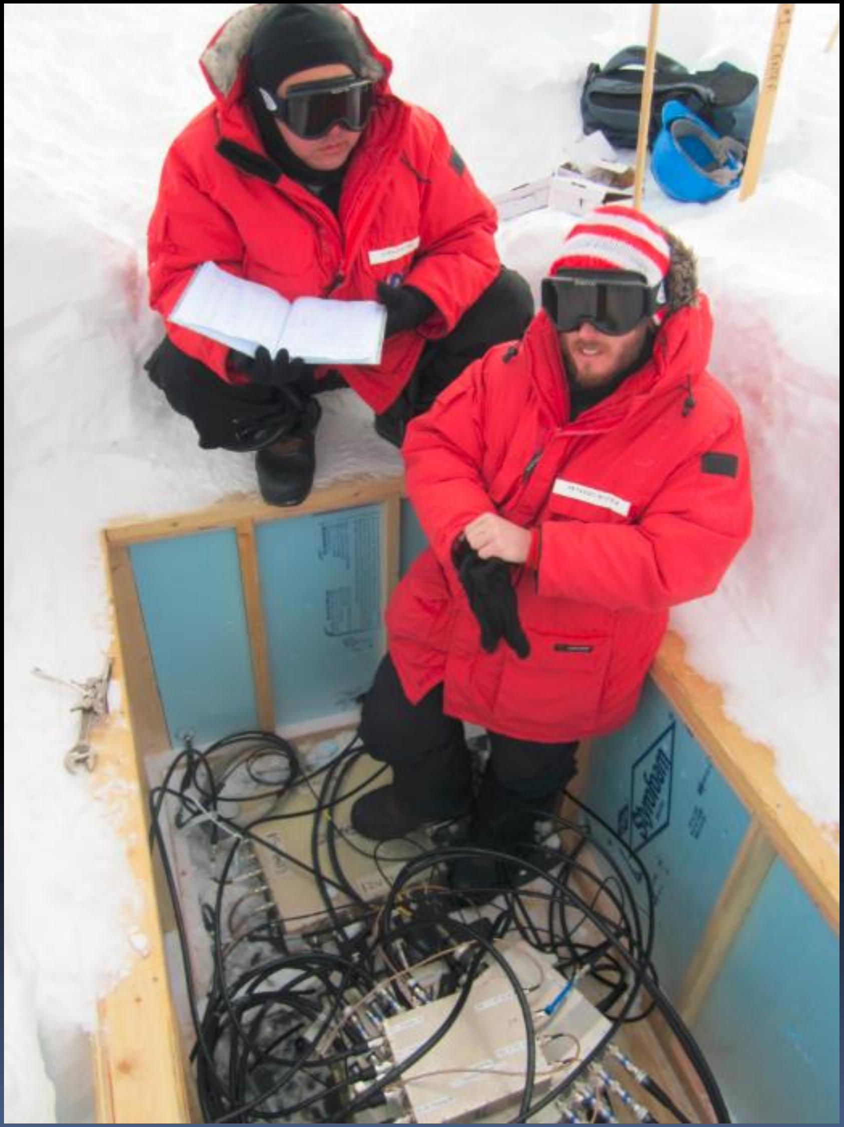
Successful season

12 dry holes (~ 200 m)

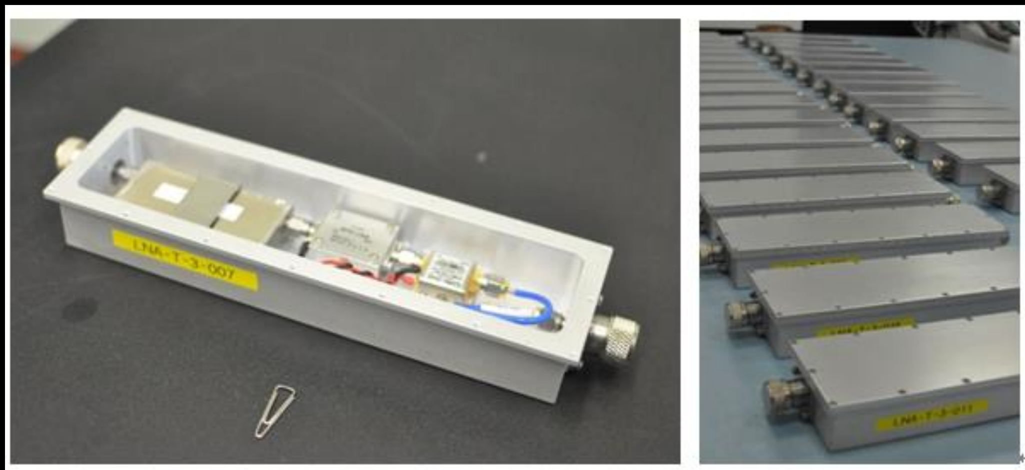
Two station ARA-2,-3 deployed
→ running smoothly

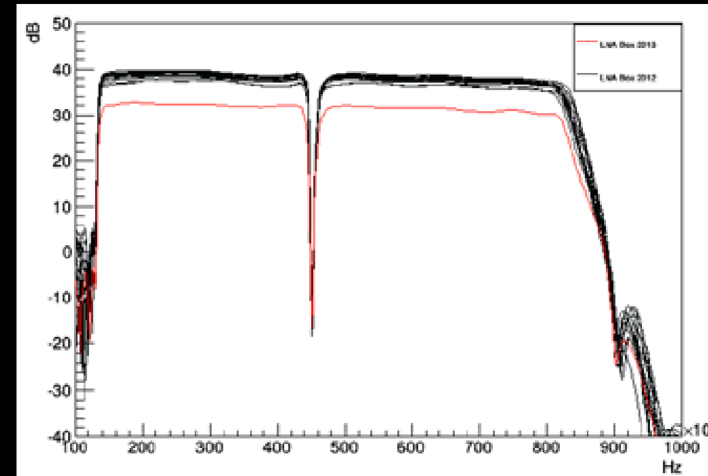
Expect science results next year

ARA Deployment (2012-2013)



ARA 4-5 Instruments (2013-4) built at NTU
Currently constructing ARA 6-7

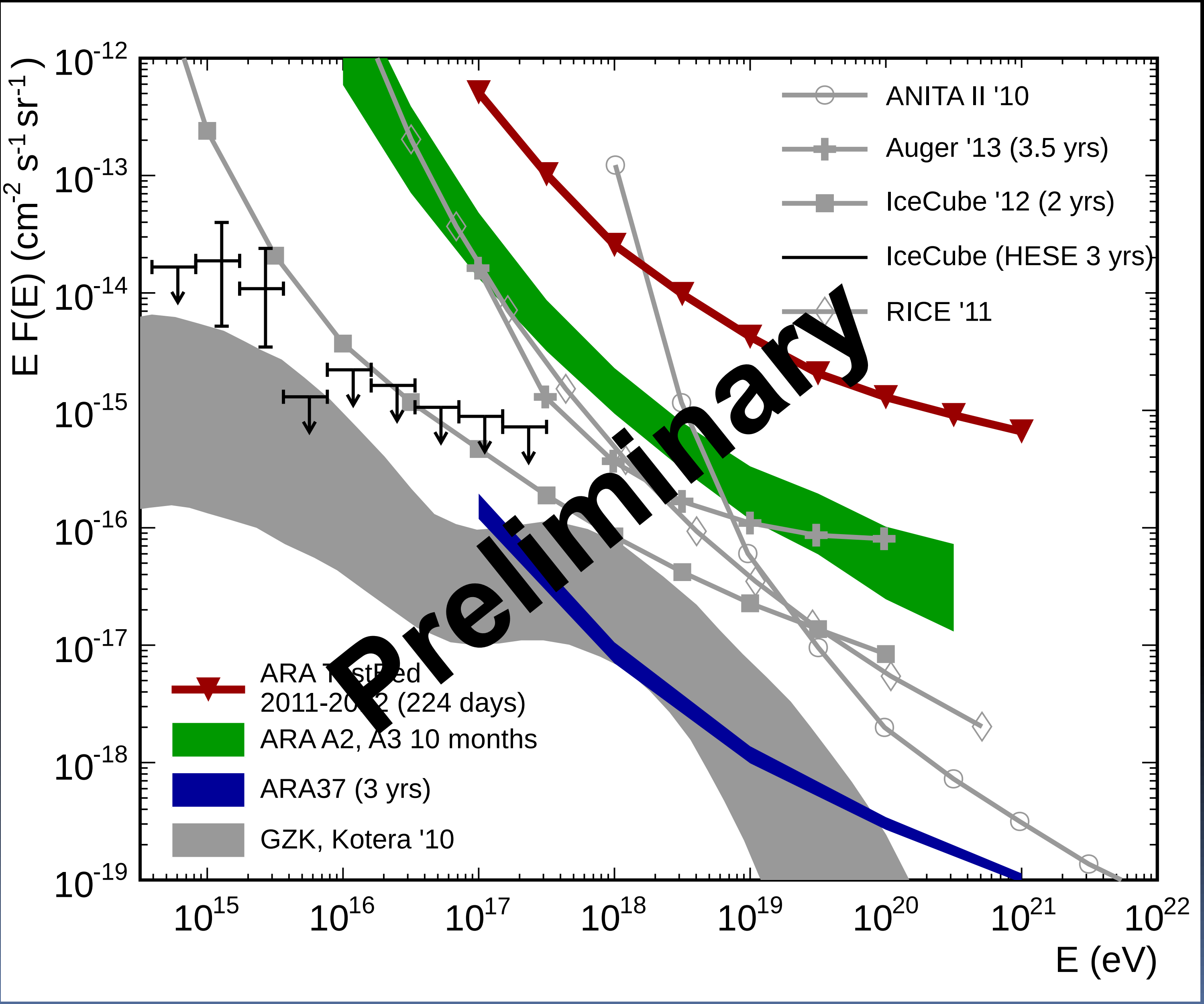




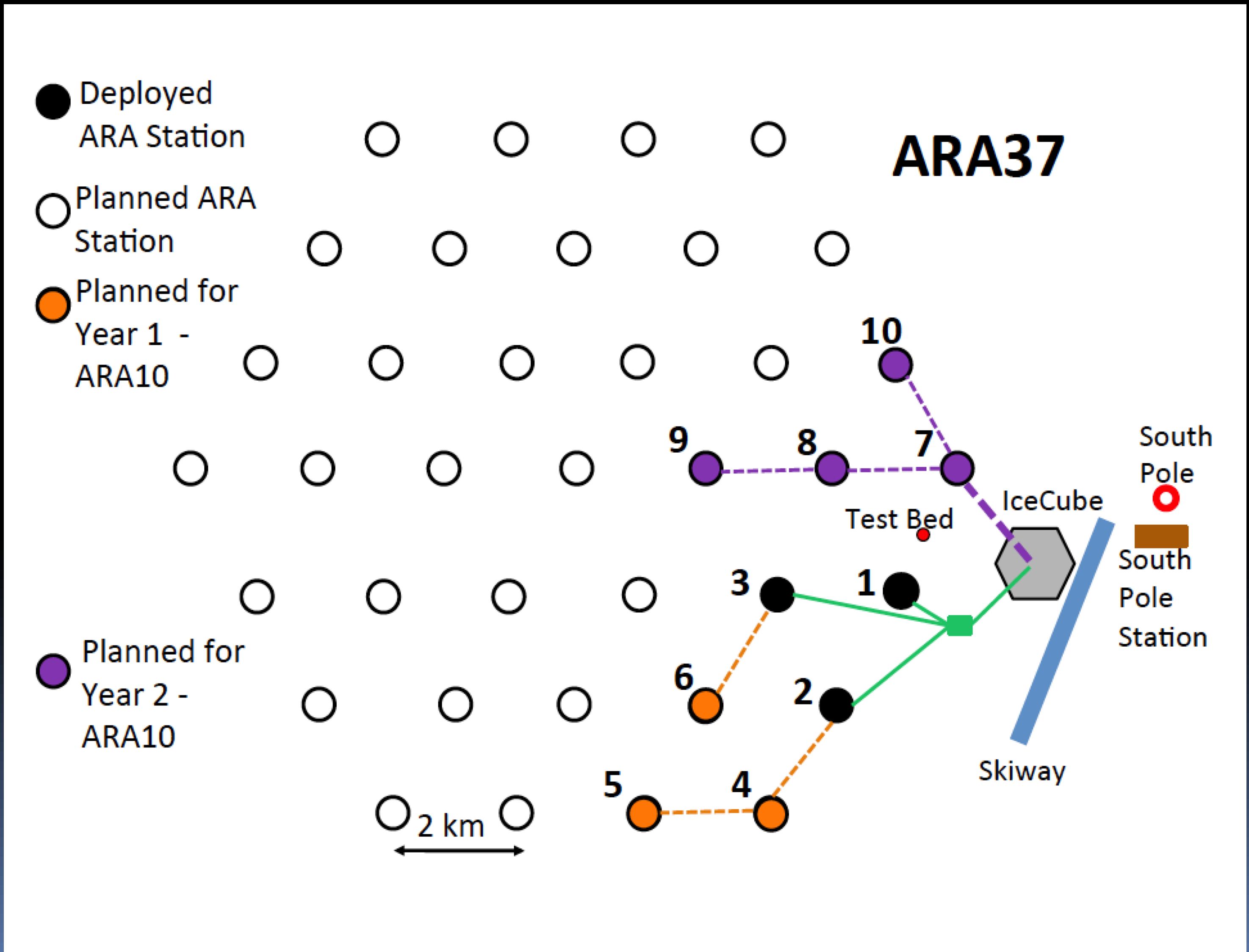
40 LNA Boxes for ARA 4-5 Ready. All NTU-LNA!

All downhole Antennas (H-pol & V-pol) ready!

ARA2-3 Results

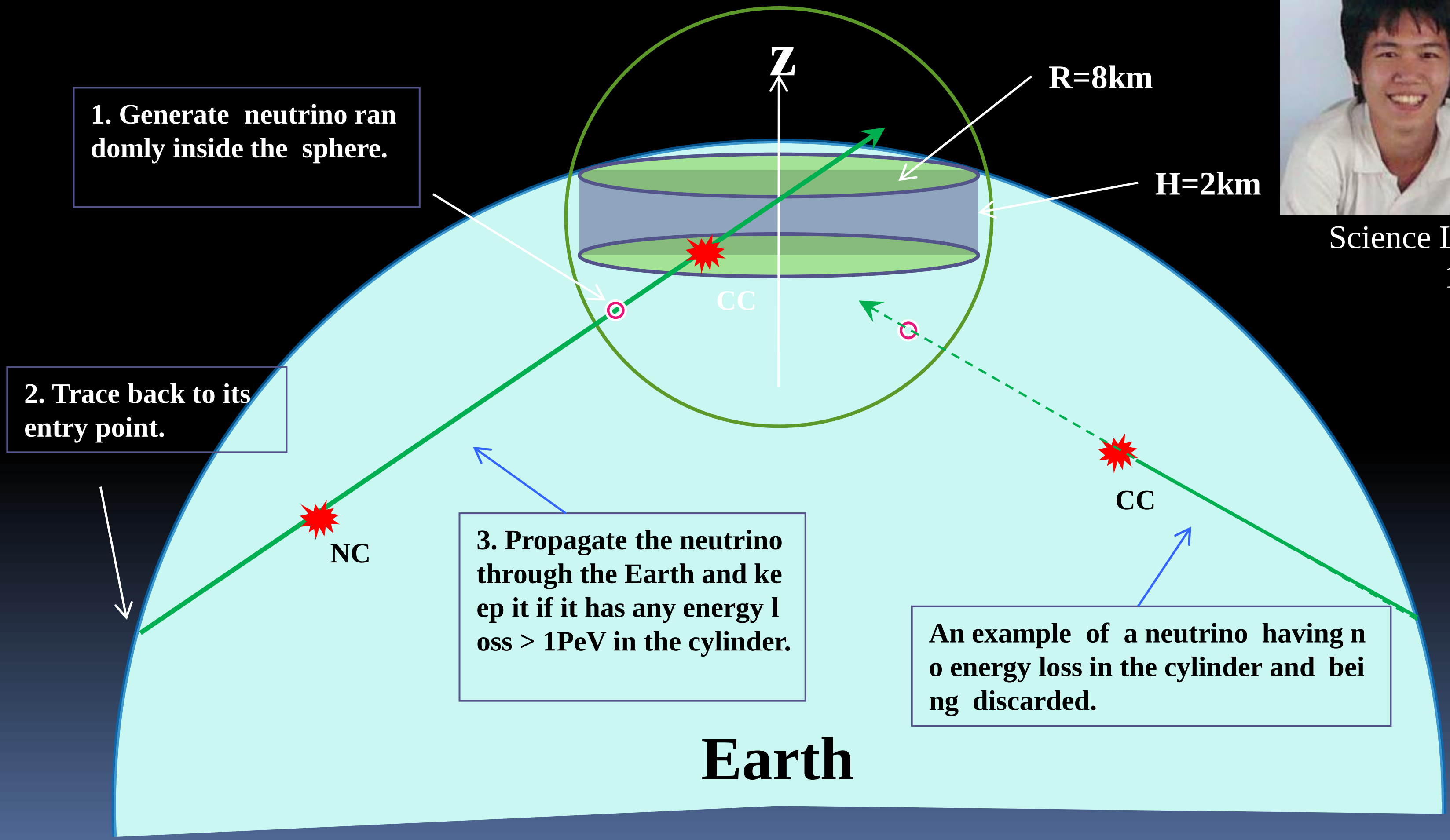


ARA Deployment Strategy
-ARA10 proposal to MOST & NSF pending



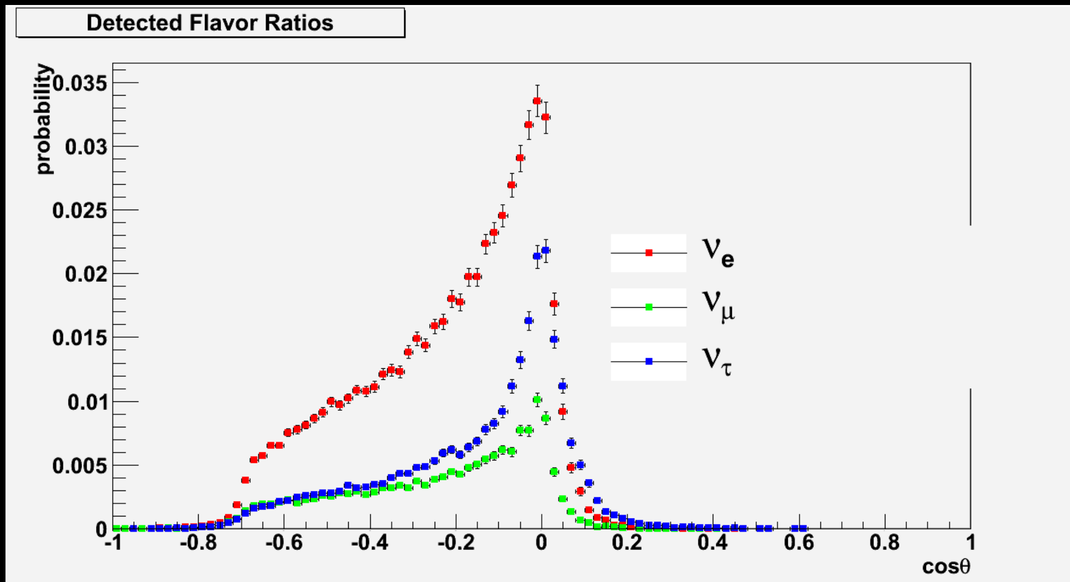
Generation and Selection of Neutrino Samples

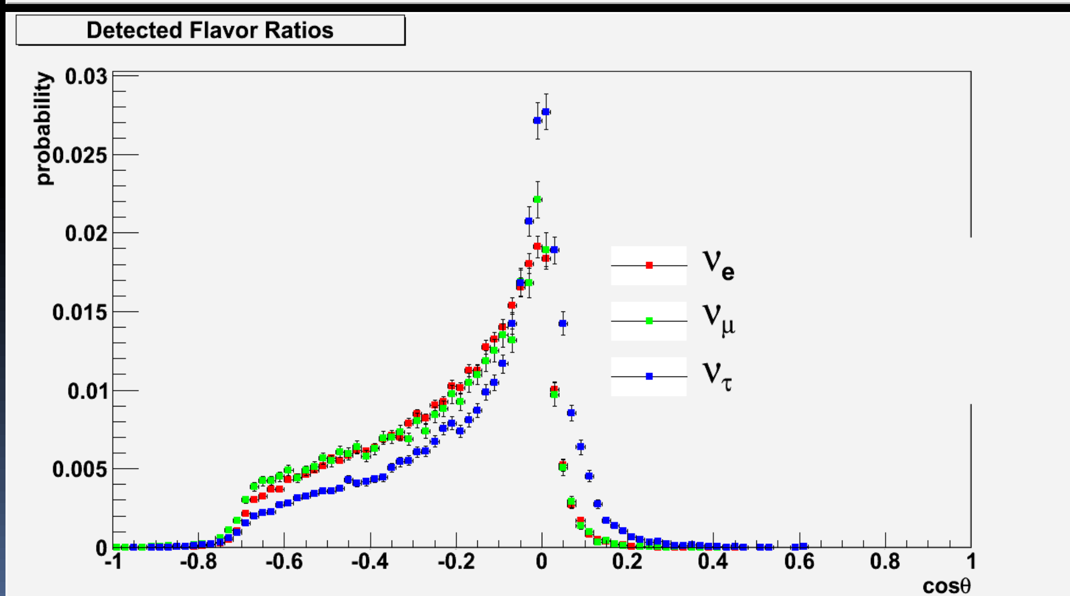
- A cylinder 8km in radius and 2km in height is set (medium: ice).



Science Lecture 111211

Direction Distribution of Detected Neutrino Events





(upper plot)

Station spacing:1.33km.

Neutrino flavor ratios: 1:1:1.

The flavor ratios of detected events over all sky:

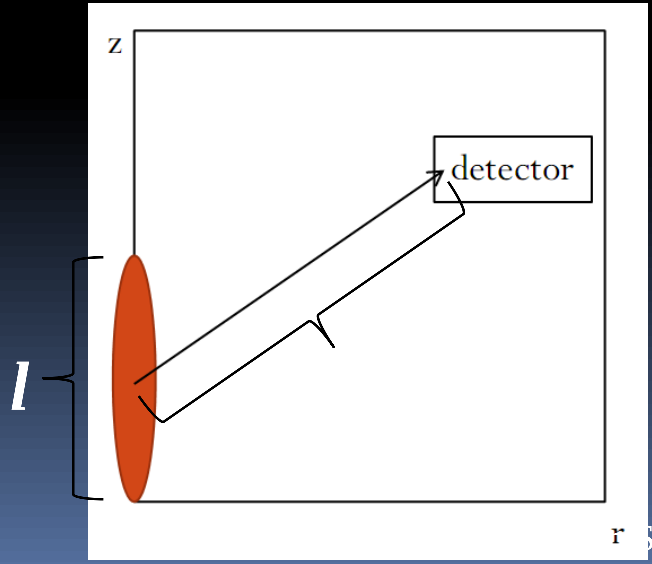
0.5850 (± 0.0039) : 0.1527 (± 0.0016) : 0.2623 (± 0.0024).

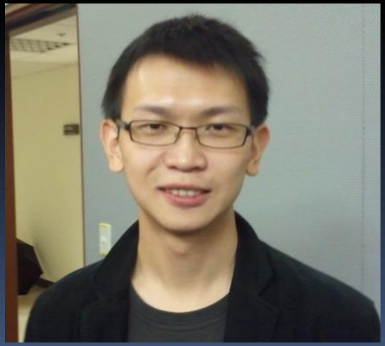
(lower plot) comparison of curve shapes (the scale of y-axis is arbitrary.)

Tau neutrino has a different shape from the other two.

Cherenkov Radiation in Near-field

- At ultra-high energy scale (> 10^{18}eV), EM showers will be extended due to the ***Landau-Pomeranchuk-Migdal*** effect.
- The shower size (l) becomes comparable to the detection distance (R): $l \sim 50$m at 10^{18}eV, 300m at 10^{20}eV; $R \sim 500$m.
- The common far-field approximation fails in this case.
  => need to consider the ***near-field*** effect!!

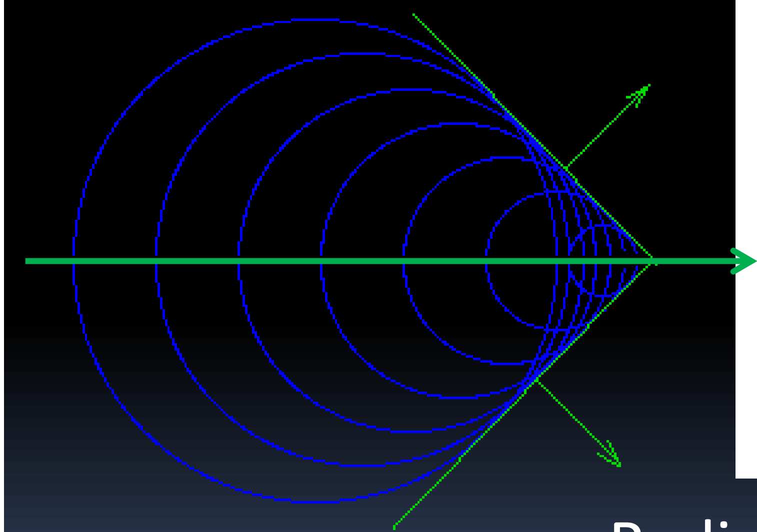


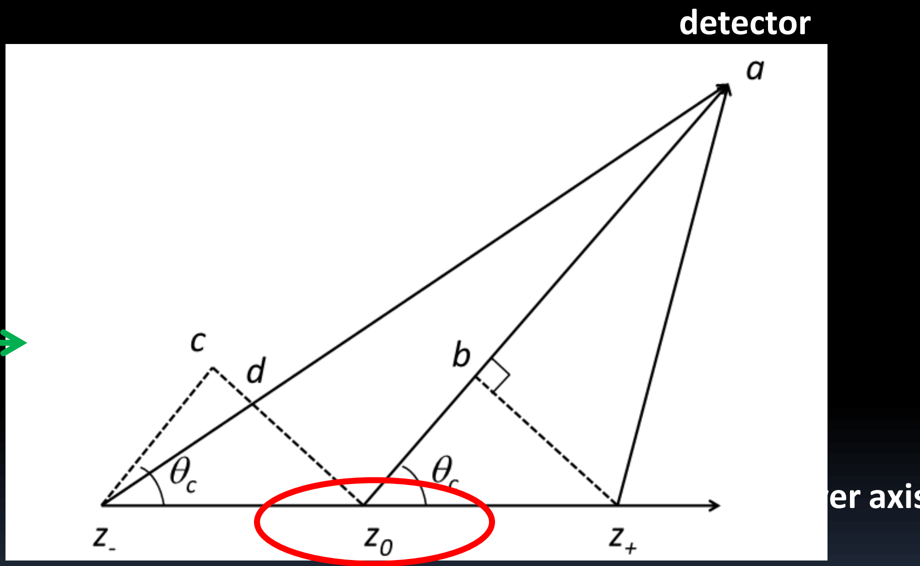


Chiayu Hu

Squeezing Effect

- Peculiar behavior of Cherenkov radiation:
  Signal emitted from ***z_0*** arrives the detector ***first***!!

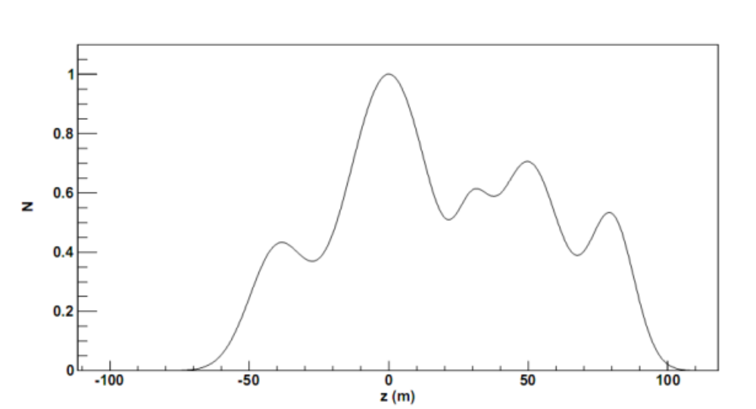




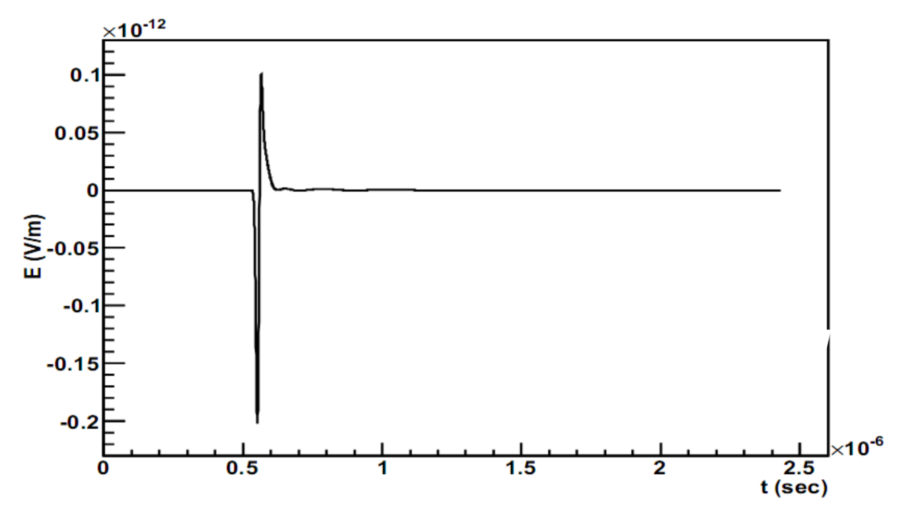
Radiation emitted from this region arrives the detector almost simultaneously
=> *Largely enhances the signal!!*

Generic Feature of the Waveform

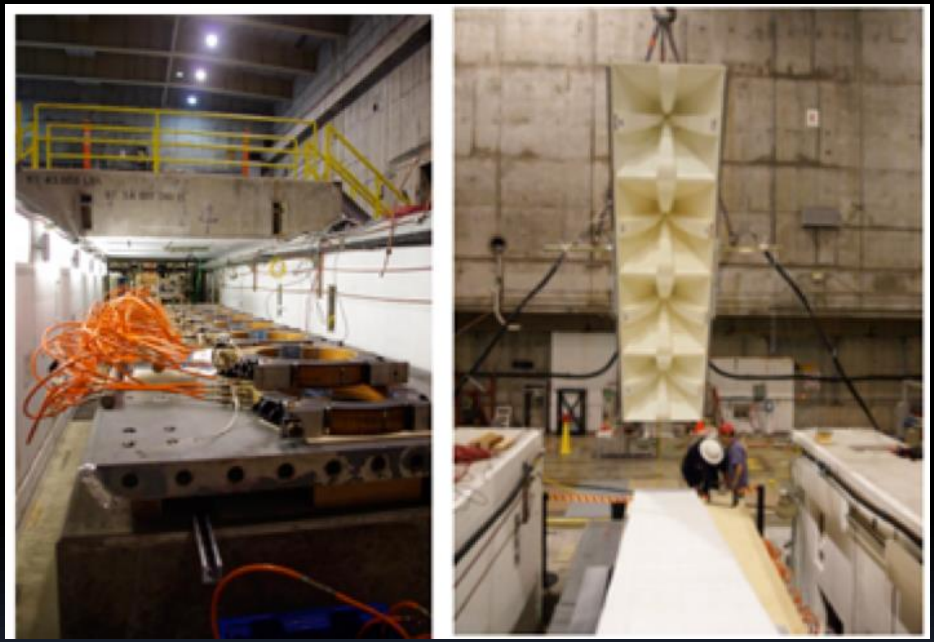
- LPM-elongated showers have a ***stochastic multi-peak*** structure (can be viewed as superposition of many sub-showers).

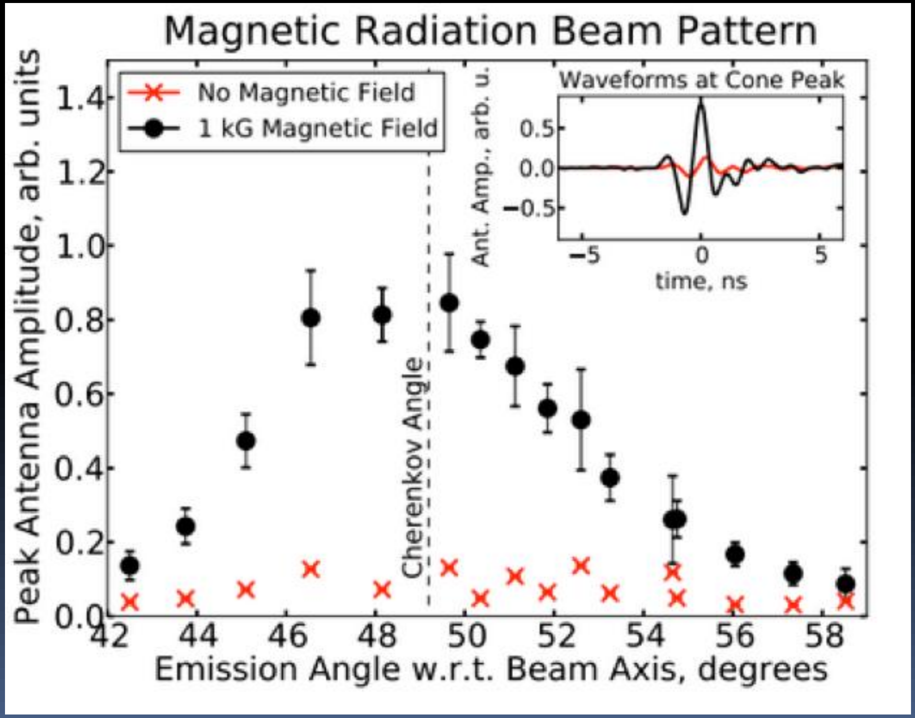


- Due to the enhancement of squeezing effect, the waveform displays a ***bipolar & asymmetric*** feature, regardless of the difference of multi-peak structure from shower to shower.



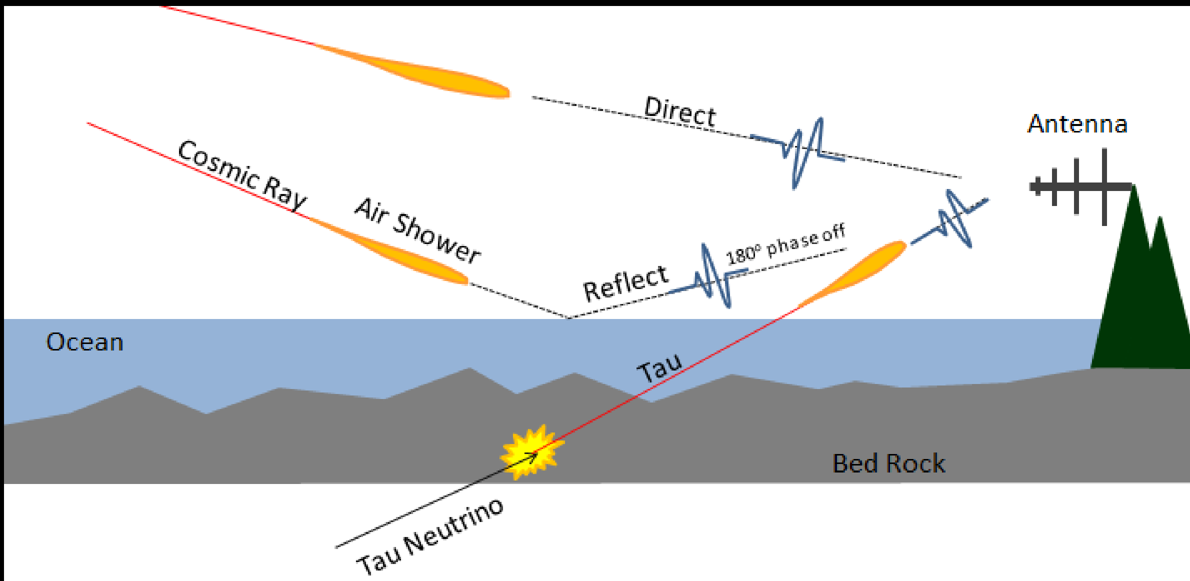
SLAC T-510: Radio-Synchrotron Emission by Shower (2014)

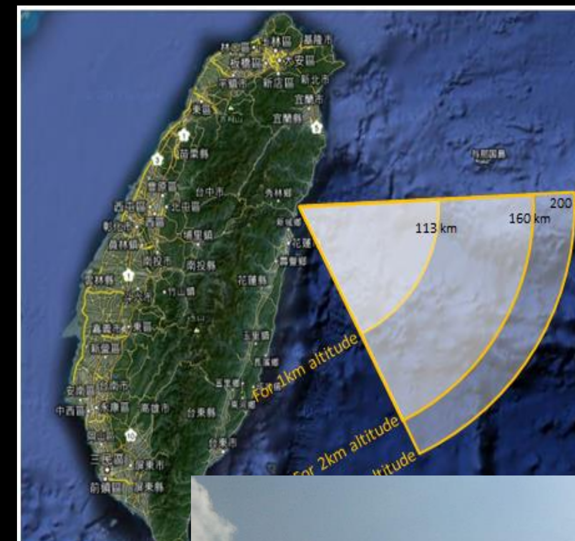


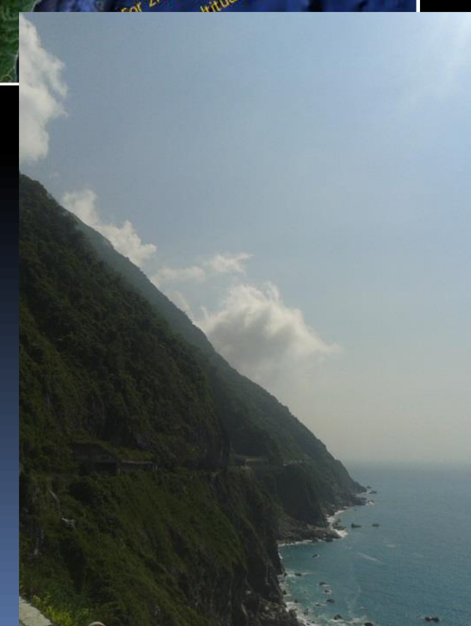


TAROGE (太魯閣)

Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emission







- Radio Antenna Arrays on top of high mountain
- Looking toward the ocean

→ Many high mountains (2-3km) on the East Coast

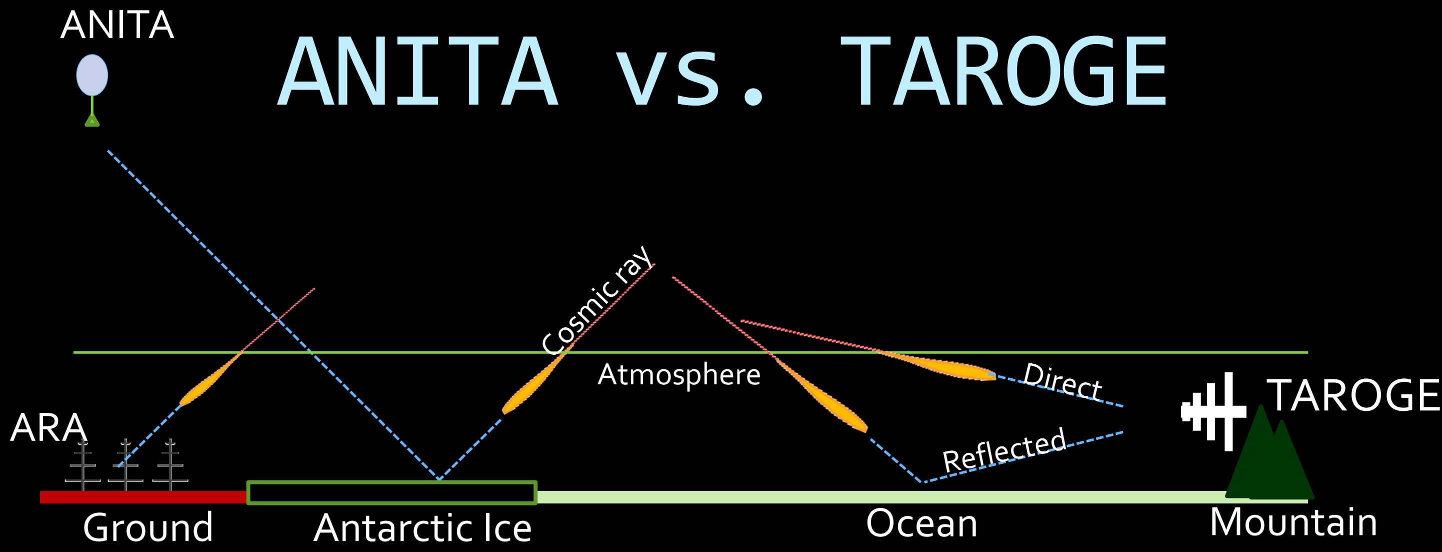
- Searching air-shower induced radio pulses

→ Large coverage (up to the horizon)

→ High Duty Cycle (~100%)

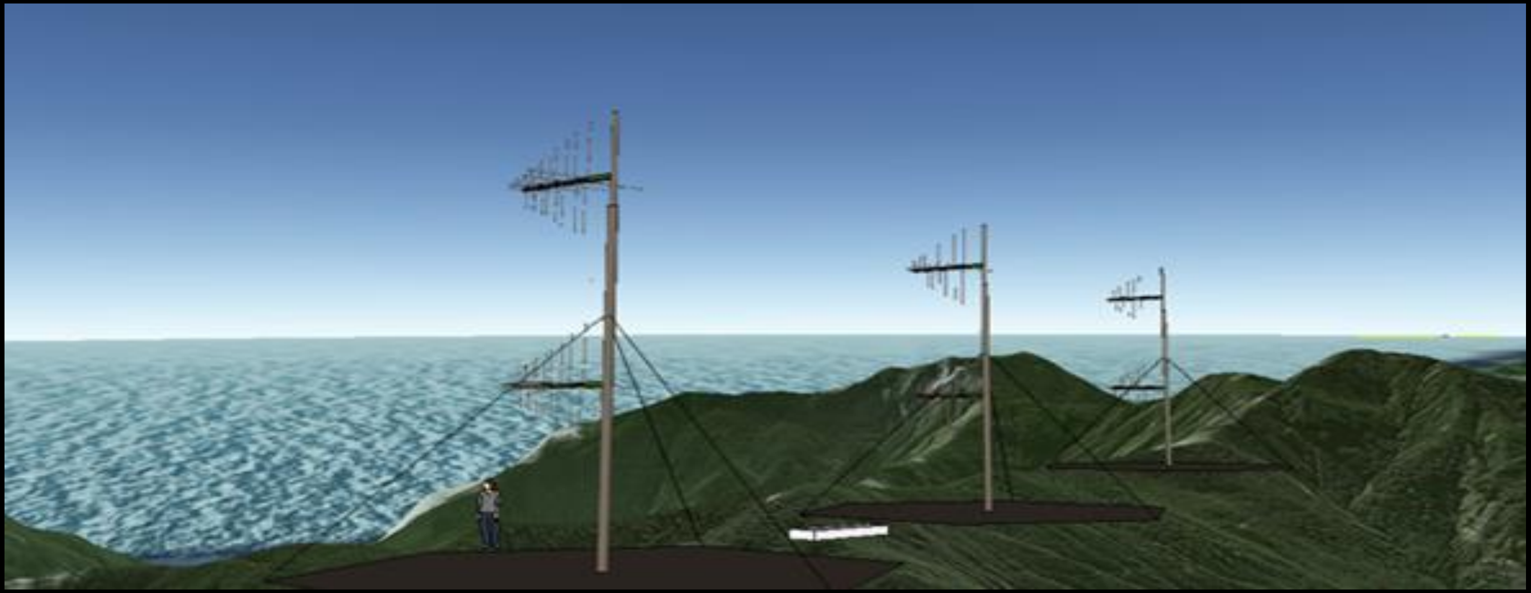
Smaller coverage than ANITA but lower threshold

ANITA vs. TAROGE



Parameter	ANITA-I	TAROGE (2km)	Factor
Detection Area	1.1×10^6 km^2	2.2×10^4 km^2	0.02
Operation Time	30 days / 3 years	3 years ☺	36.5
Signal Direction	Reflected	Direct + Reflected ☺	1.5
Frequency	200 MHz – 1GHz	100-300 MHz ☺	
Integrated Signal Power	70 pW	130 pW ☺	
Geo-magnetic Field	60 uT	45 uT	
Observation Height	35 km	2 km	
Shower Height	10 km	10 km	
Radio Path Length	45/cosθ km	12/cosθ km ☺	
Energy Threshold	5×10^{18} eV	1.4×10^{18} eV ☺	
CR integrated Flux ($E^{-2.7}$)	9×10^{-33}	80×10^{-33} ☺	8.9
Net Factor			9.7
Number of Events	16 (1 flight/3 yrs)	155 / 3 yrs ☺	

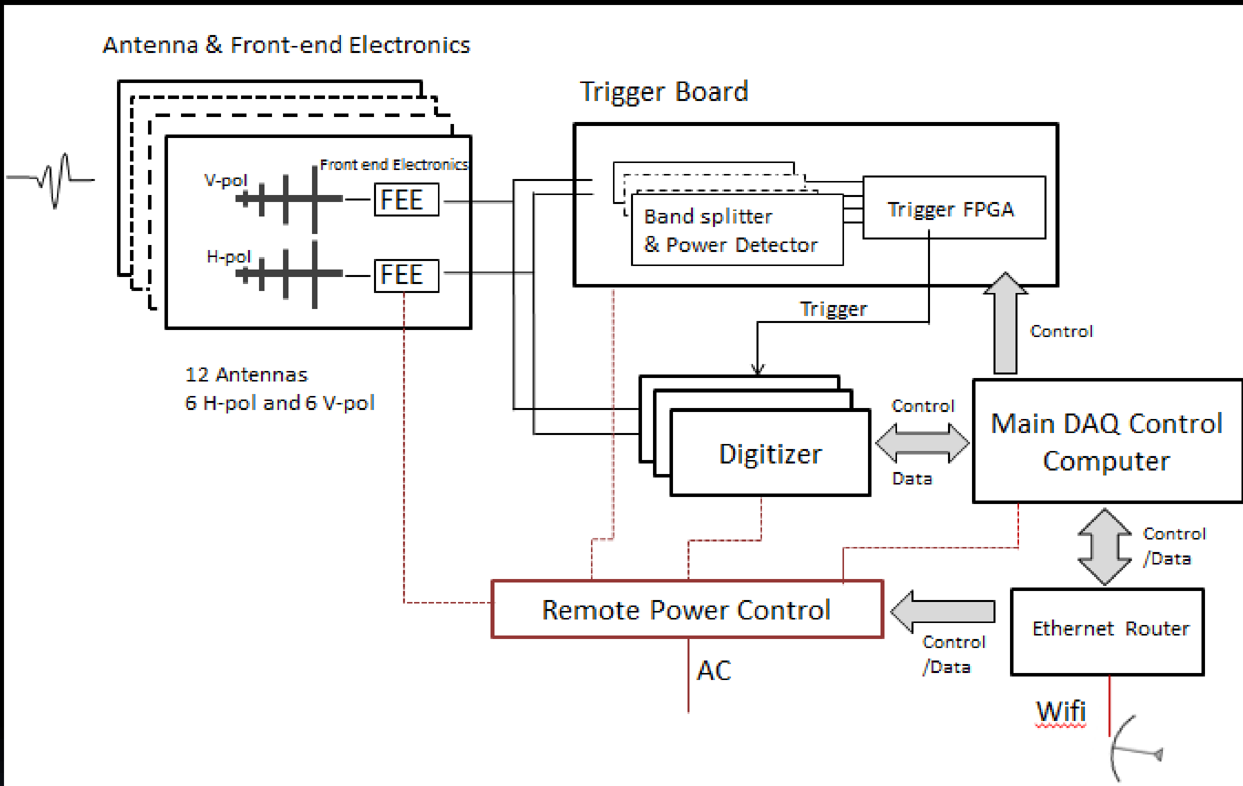
TAROGE Station

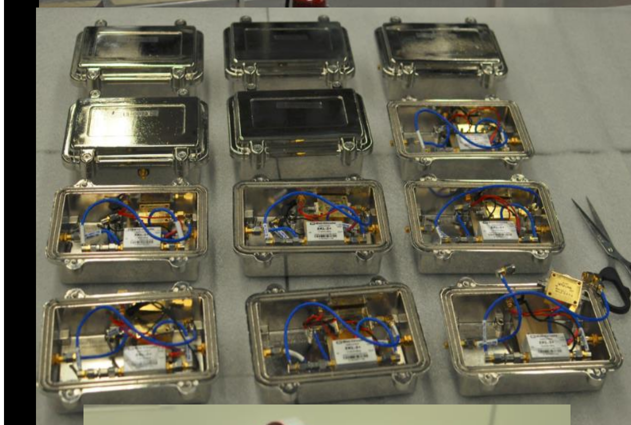


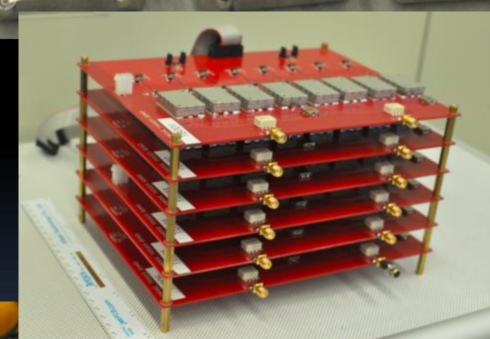
- Dual polarized LPDA Antennas (100-300 MHz)
- 3 masts and 6 antennas (interferometry available)
- Use affordable commercial digitizer
- Funded for initial study (NSC frontier prog.)
- Prototype 2013 → Full station 2014

Straight forward for future extensions

TAROGE System







12 LPDA antennas (6 H-pol 6 V-pol)
NTU LNA
Multi-band, Multi-antenna trigger
Commercial Digitizers

TARGE Prototype (2014)

1000 m altitude site in HePing (T-Cement)

12 LPDA Antennas

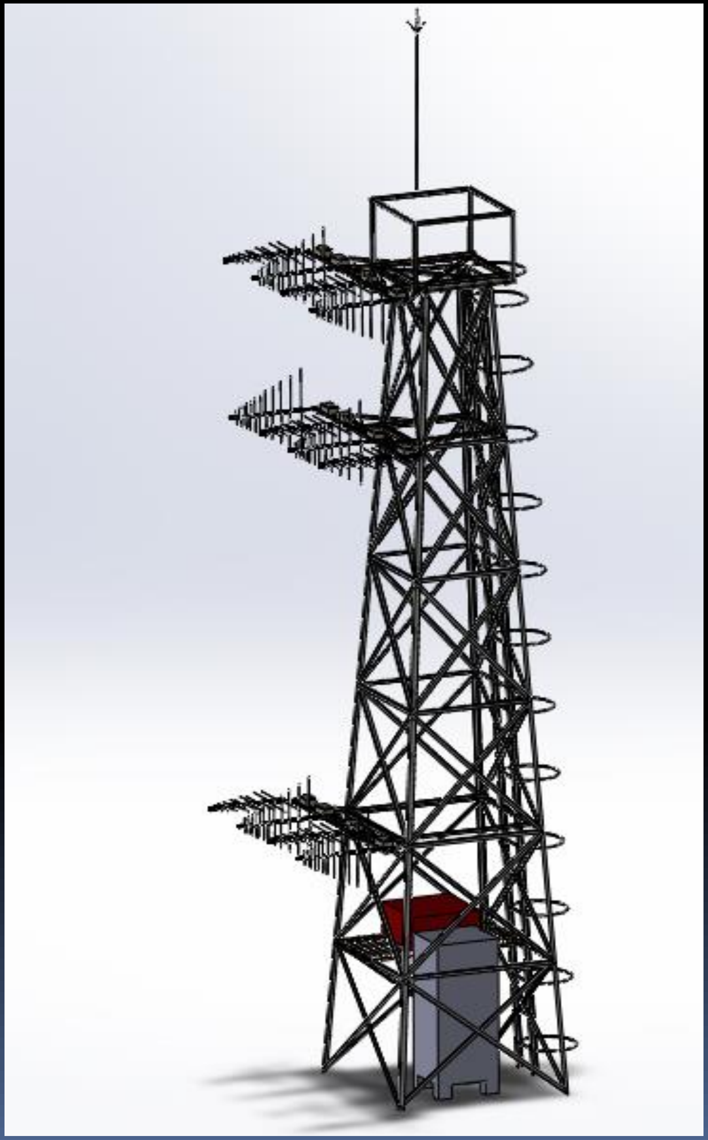
6 V-pol, 6 H-pol

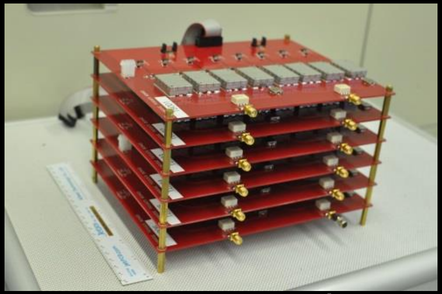
100-300 MHz Band

4 Multi-band trigger

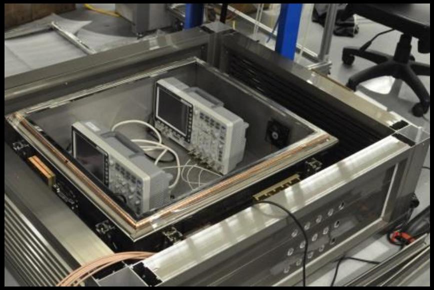
In-house LNA, Commecial digitizer (made in TW)

Commissioning July 2014





Trigger Boards



DAQ Box

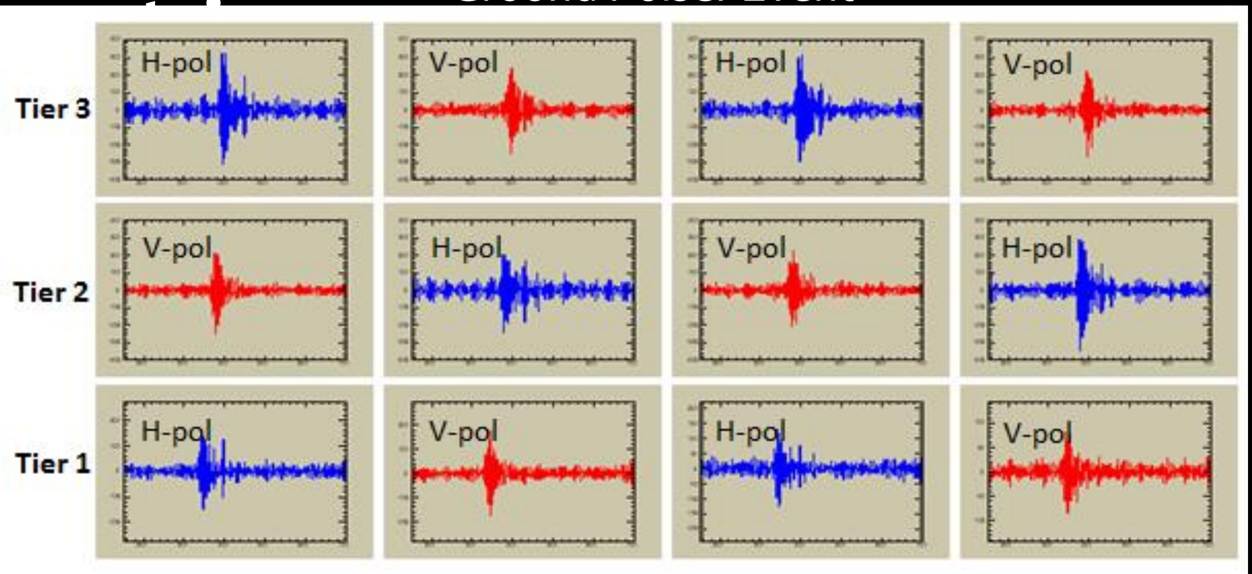
Antennas / LNA Mount

TAROGE-1 Station

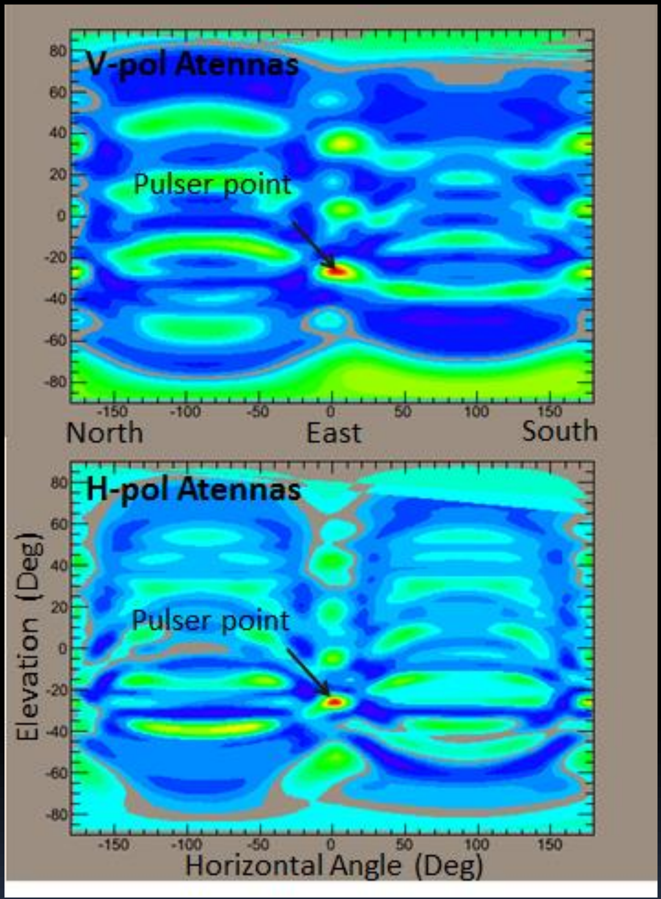
- Prototype station at 1km height @ Heping
  12 Antennas (6 V-pol + 6 H-pol)
- Deployed in July 2014
- Minor damage when typhoon hit
- Steady operation so far

TAROGE-1 Validation / Calibr

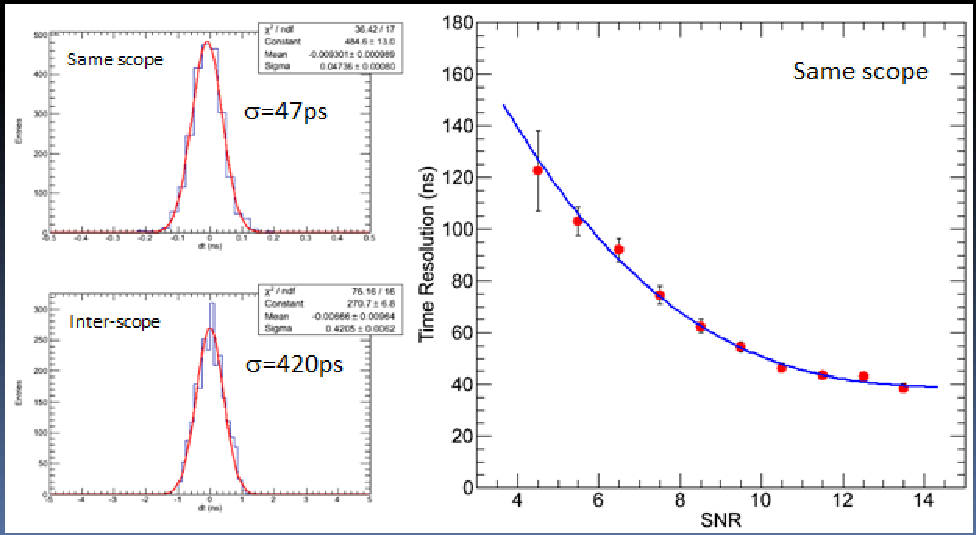
Ground Pulser Event



Interferometry map



Time Resolution



Noise survey / Detailed calibrations for Sensitivity / Anthropogenic noise rejection Studies in progress

TAROGE Plan

TAROGE-2 station got funded, to be built in Summer 2015

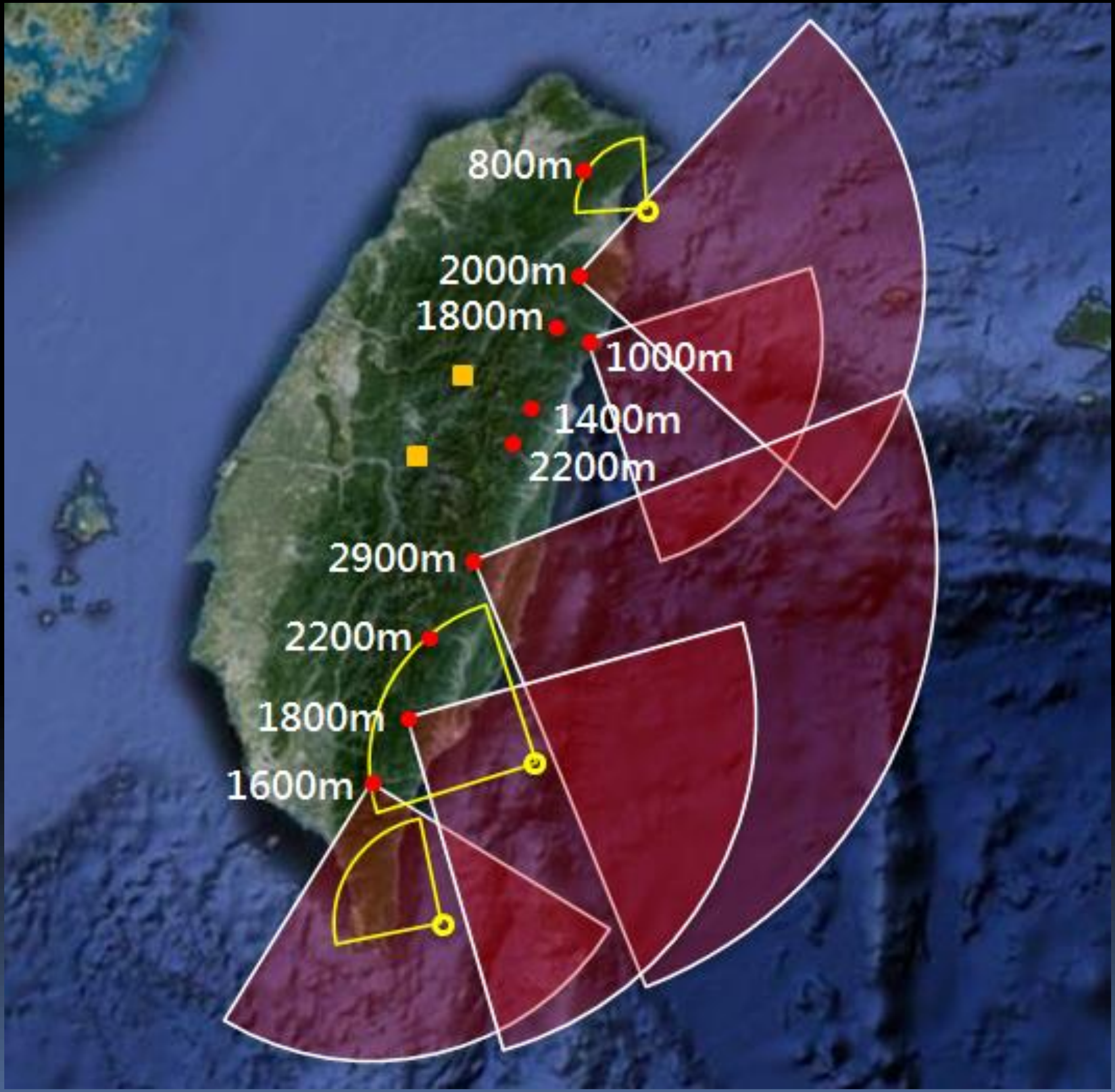
Site survey in progress

-~ 2 km elevation

- Costal mountain site & deep mountain site (tau neutrinos)

TAROGE-15 proposal submitted to MOST Vanguard program

TAROGE 10+5



Site Survey

This line denotes the mountains which alttitude = 3000+-100m

LeCosPA Experimental Group

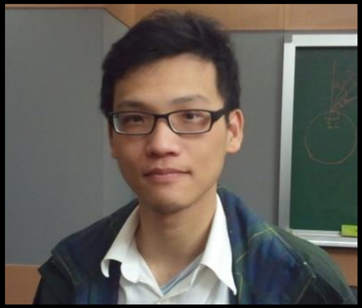
National Taiwan University


Pisin Chen


Ming-Huey A. Huang


Jiwoo Nam


Chin-Hao Chen

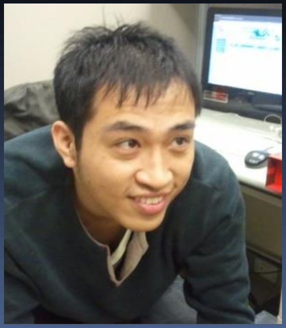

Tsungche Liu


Jerry Shiao


William Chen


Shihao Wang


Chihching Chen


Janjung Huang


LiCe Hu


Shih-Ying