National Taiwan University
Leung Center for Cosmology and Particle Astrophysics

Askaryan Radio Array (ARA) Capability Simulation:
Event Reconstruction of Ultra High Energy Neutrinos

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Outline

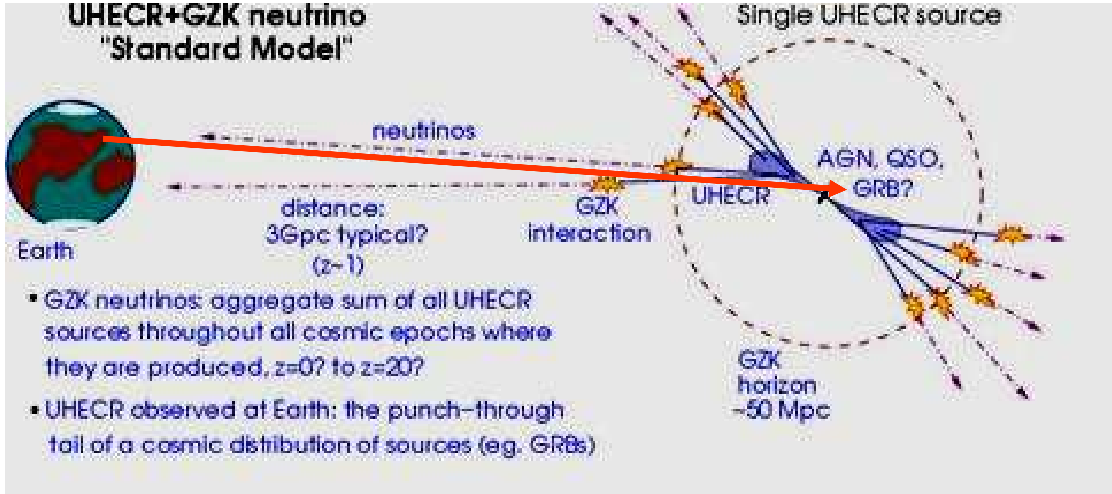
- Motivation: identify cosmic accelerators with UHE(10^{17}eV to 10^{20}eV) neutrinos
- Detection of UHE neutrinos in ARA
- Simulation of reconstruction capability of ARA
- Optimization of the detection efficiency and neutrino angular resolution

Approach the Topic "Cosmic Accelerators" with UHE Neutrinos

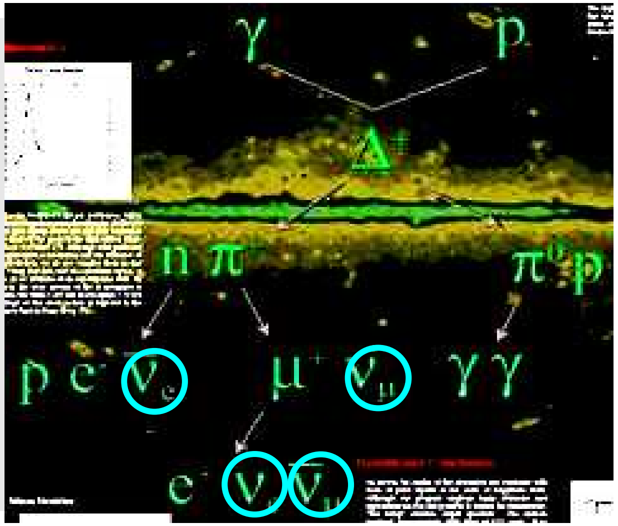
bottom-up scenario

GZK Process
(Greisen, Zatsepin, Kusmin)

neutrinos guaranteed by UHECR



From ANITA collaboration



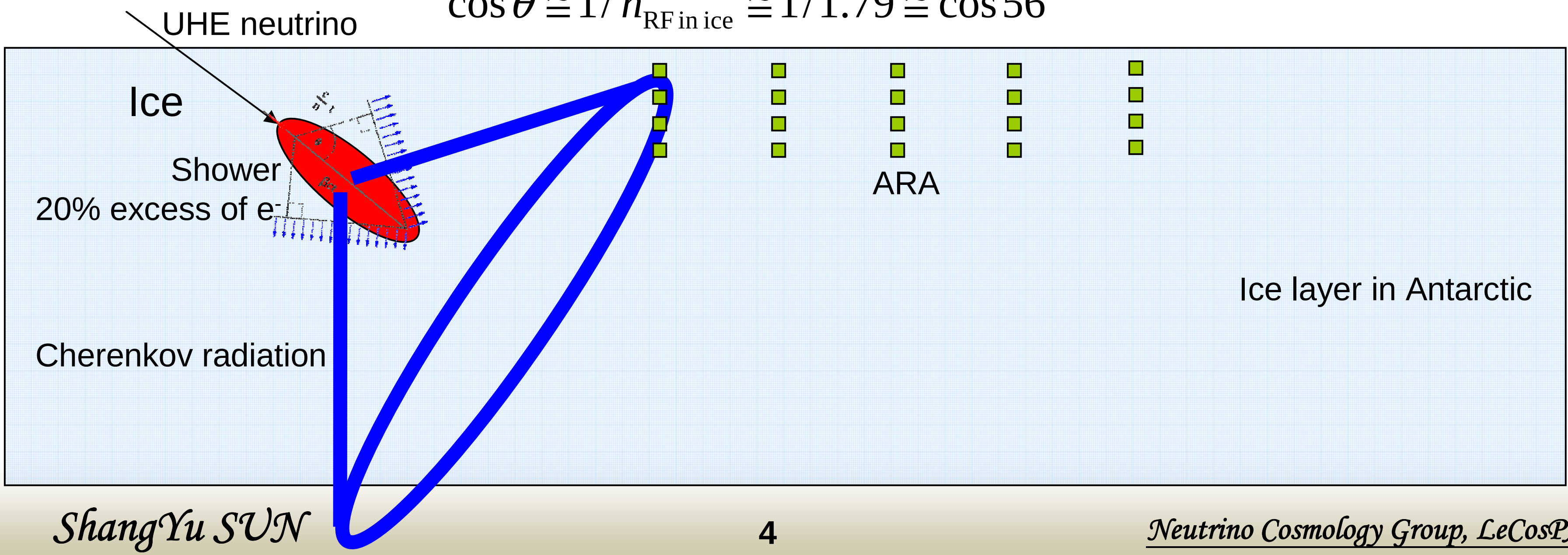
John A. Cairns et.al., Simulation of the GZK neutrino flux from cosmic ray spectrum, 2005/07/14

On Earth, we might, with UHE neutrino, **point back** to cosmic accelerators. Thus, the angular resolution is particularly important to identify these accelerators.

To Detect UHE Neutrino: with Radio Chenenkov Wave from Askaryan Effect

- UHE neutrino has charge or neutral current interaction with mater, causing particle shower.
- Askaryan Effect: shower induced by high energy particle has 20% excess of negative charges.
- Fast moving charges in matter result in Cherenkov radiation.
- ARA will detect strong signal of coherent radio wave.

$$\cos\theta \cong 1/n_{\mathrm{RF\,in\,ice}} \cong 1/1.79 \cong \cos 56^{\circ}$$



Conceptual Design of ARA

- Ice in Antarctic is a massive target for neutrino to interact with.
- RF band is coherent and strong among all the signals from the interaction.
- RF wave attenuation is small in ice (~1km). Low temperature. Radio quiet.

=> Choose Antarctic as experiment site

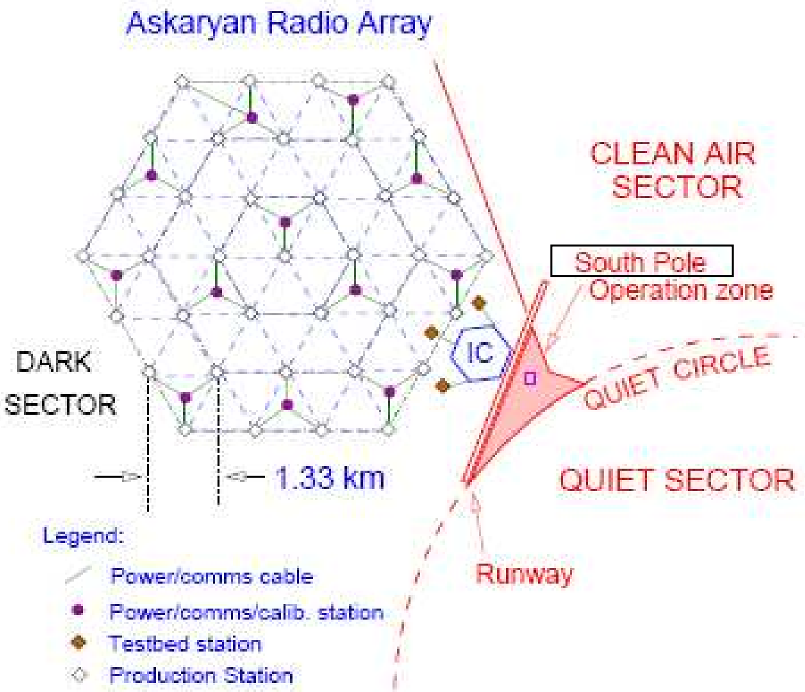


Figure 2: Planned layout of the 37 ARA stations with respect to the South Pole Station and associated sectors.

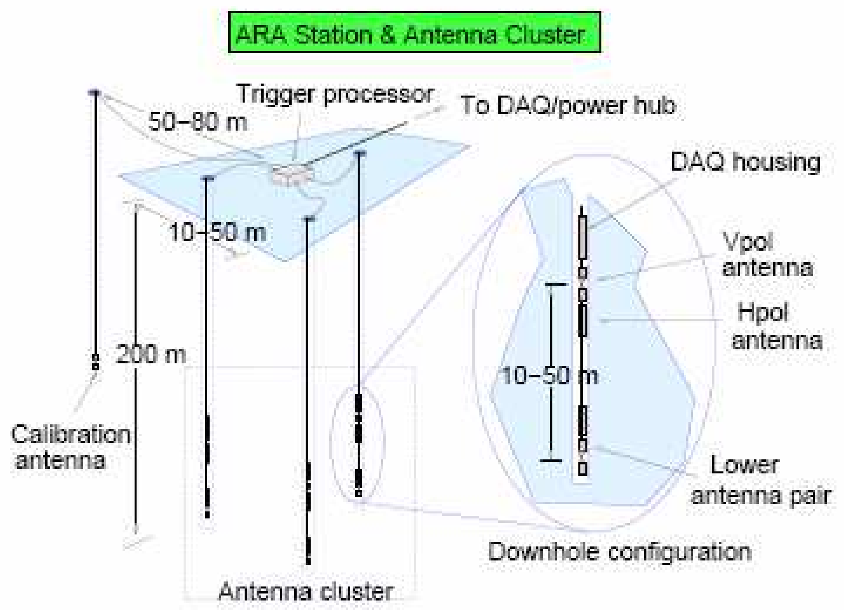
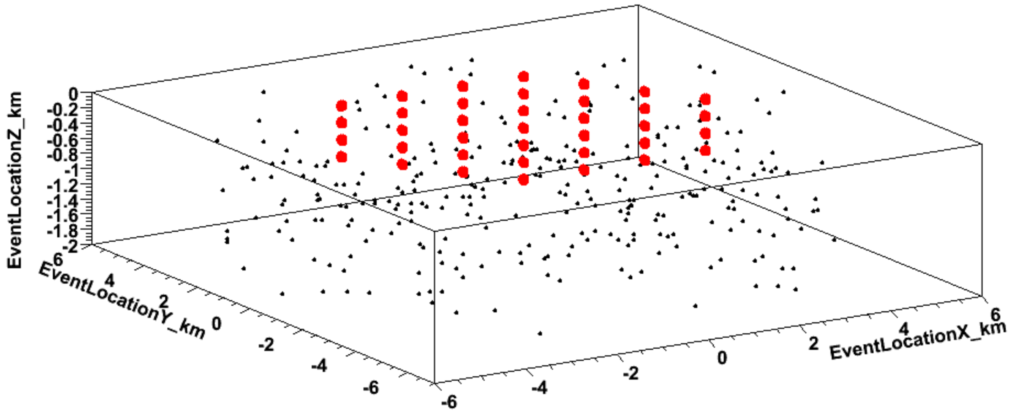


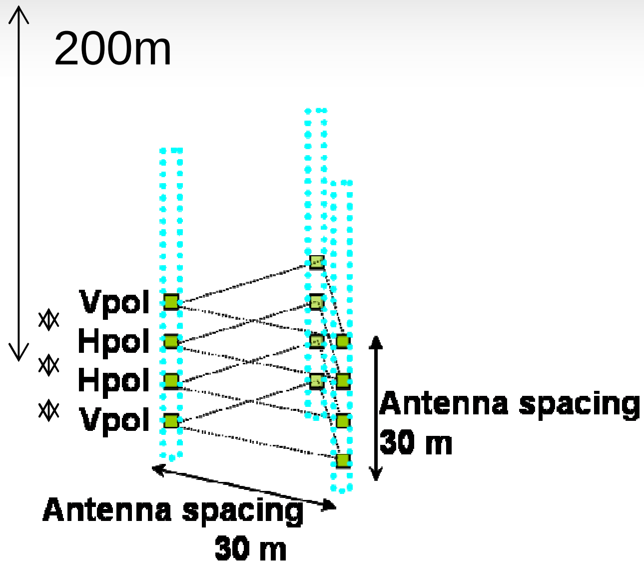
Figure 4: ARA Station layout and antenna cluster geometry.

From ARA proposal

Simulation Setups: ARA Geometry and Parameters Generated

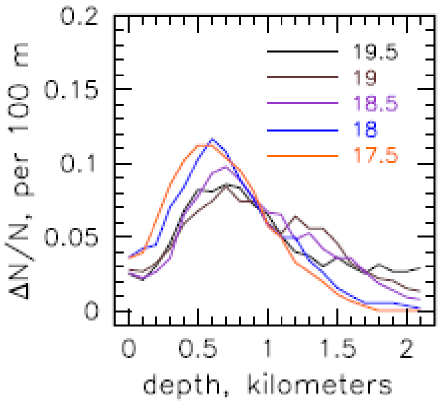
Red Dot: ARA station
black dot: generated shower location **x,y,z**

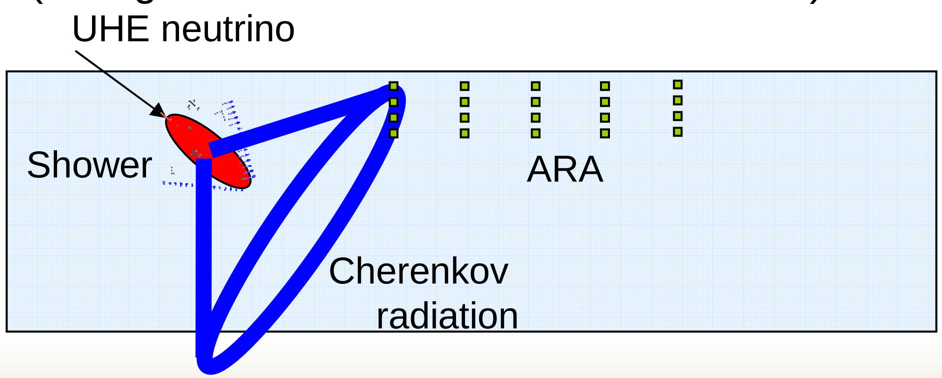




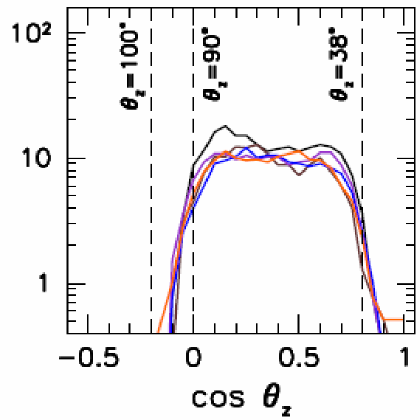
For each event, six parameters are generated
x, y, z, (shower location)
theta, phi,(neutrino moving direction)
v (voltage measured at the shower location)

z

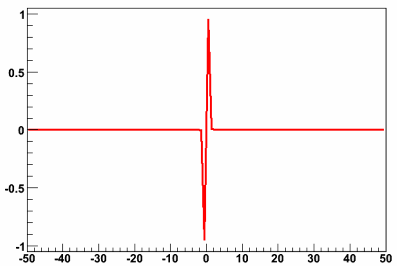




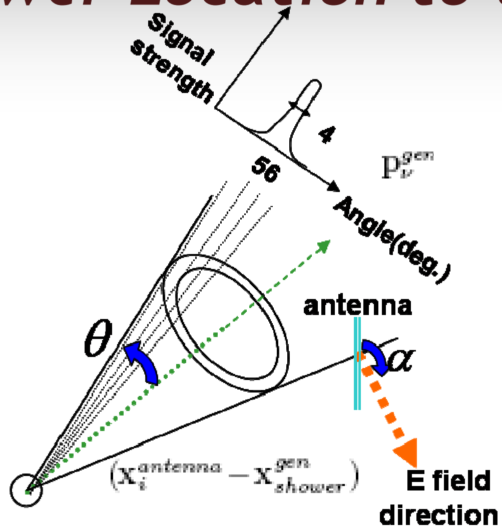
theta



Simulation Methods: from the Shower Location to the Antenna



$$y = x \cdot e^{-x^2/2\sigma^2} \qquad \sigma = 0.4ns$$



$$E_{total} = (c\Delta t) r^2 \Omega \cdot \rho(r)$$

$$\rho(r) \propto [E(r)]^2$$

$$\Rightarrow E(r) \propto \frac{1}{r}$$

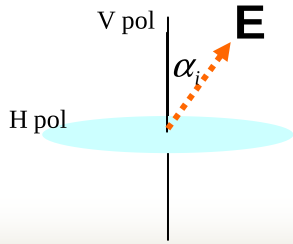
E field dies out 1km

1km

$$V_i^{real} = V_0^{gen} \cdot \frac{D_0}{\sqrt{(\vec{x}_{gen} - \vec{x}_i)^2}} \cdot e^{-\sqrt{(\vec{x}_{gen} - \vec{x}_i)^2} / \text{attenuation\_length}}$$

$$\cdot A \cdot e^{-(\theta_i - 56^\circ)^2 / 2\sigma^2}$$

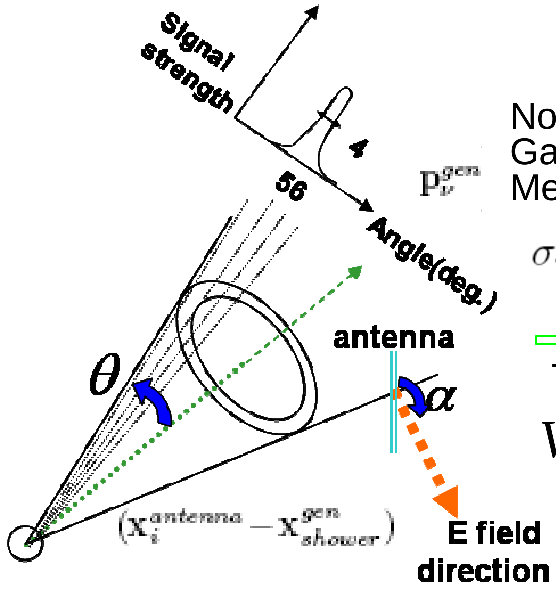
$$\cdot \begin{cases} \sin\alpha_i, & \text{for H pol antenna} \\ \cos\alpha_i, & \text{for V pol antenna} \end{cases}$$



$$\overrightarrow{RF} \times (\overrightarrow{RF} \times \vec{\nu})$$

$$(\mathbf{x}_i^{antenna} - \mathbf{x}_{shower}^{gen}) \times \left[(\mathbf{x}_i^{antenna} - \mathbf{x}_{shower}^{gen}) \times \mathbf{p}_\nu^{gen} \right]$$

Simulation Methods: the Waveform



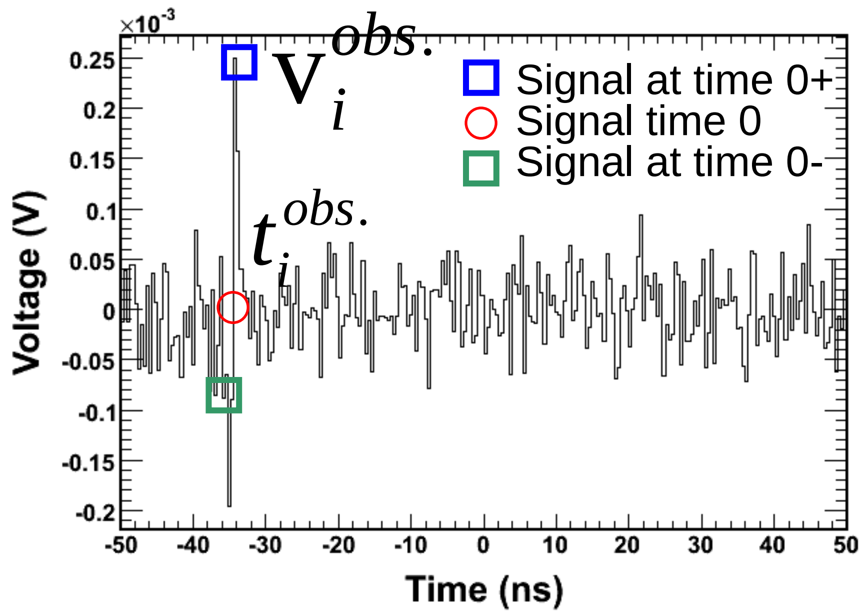
Noise
Gaussian random
Mean 0

σ_{noise} 0.035 mV

Trigger condition

$V_i^{real} > 7\sigma_{noise}$

256 bins, 100 ns

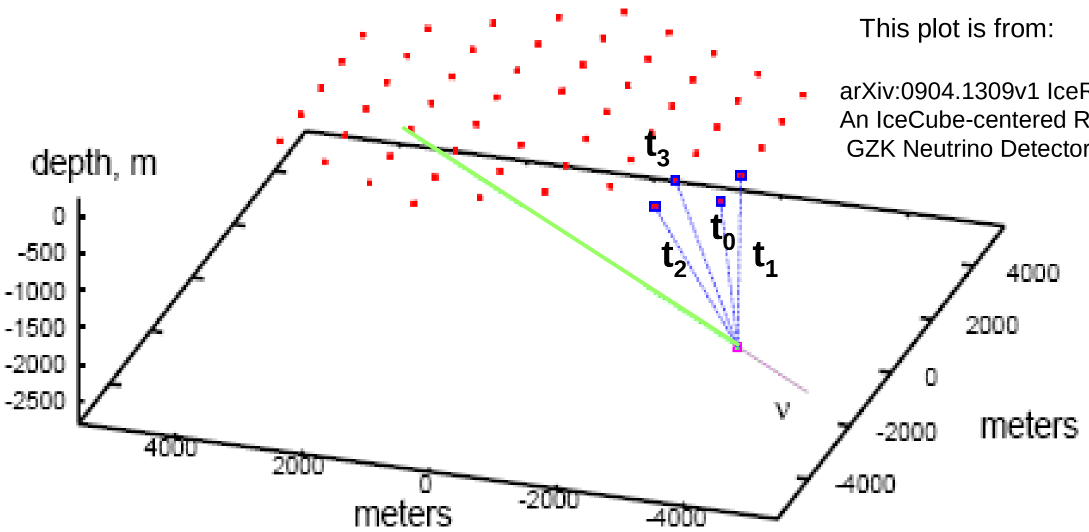


The bin with positive value and the most close to the crossing

V=0 the crossing $t_i^{obs.}$

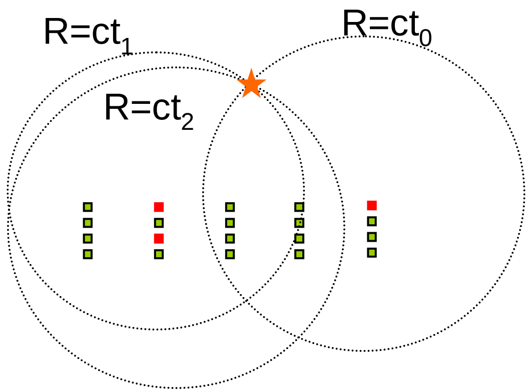
The bin with negative value and the most close to the crossing

Chi Square for the Reconstruction of Shower Vertex



This plot is from:

arXiv:0904.1309v1 IceRay: An IceCube-centered Radio-Cerenkov GZK Neutrino Detector, P. Allisona, J. Beattyb, P. Chenc,



$$\chi^2 = \sum_{\text{all triggered antennas, } i} \left[\frac{\Delta t_i^{obs.} - \Delta t_i^{hypos.}(x_{sh}, y_{sh}, z_{sh})}{\sigma_t} \right]^2$$

$$\Delta t_i = t_i - t_0$$

t_i is the RF travelling time to antenna i

t_0 is the antenna receiving the strongest signal

Reconstruction of Neutrino Direction

$$\chi^2 = \sum_{\text{all triggered antennas, } i} \left(\frac{(V_i^{obs.} - V_i^{hypos.})}{\sigma_V}\right)^2$$

$V_i^{obs.}$: observation data

$$V_i^{hypos.}(\vec{x}_{rec.}, V_0^{hypos.}, \vec{v}_{hypos.}) = \frac{V_0^{hypos.} e^{-\sqrt{(\vec{x}_{rec.} - \vec{x}_i)^2} / \text{attenuation length}}}{D_0 \sqrt{(\vec{x}_{rec.} - \vec{x}_i)^2}}$$

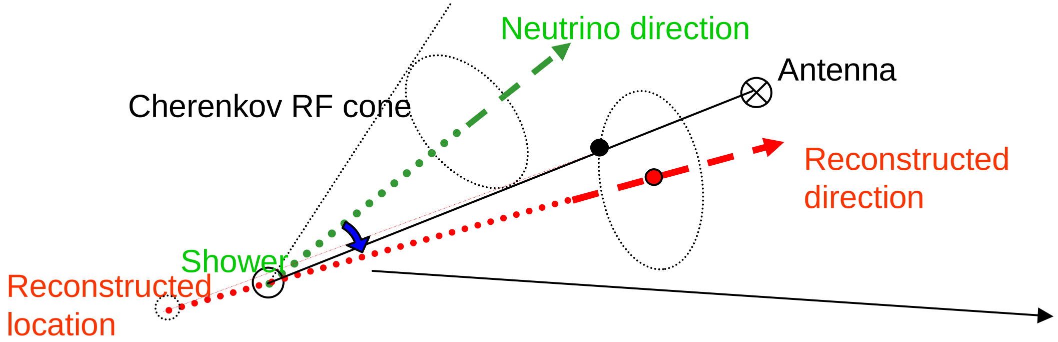
$$\cdot A \cdot e^{-(\theta - 56^\circ)^2 / 2\sigma^2}, \quad \theta : angle(\vec{v}_{hypos.}, \vec{x}_{rec.} - \vec{x}_i)$$

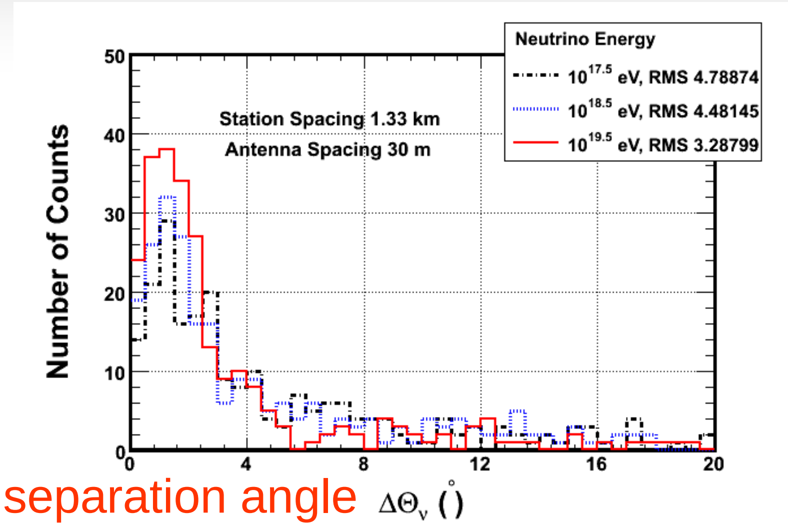
$$\cdot \begin{cases} \sin\alpha, & \text{for H pol antenna} \\ \cos\alpha, & \text{for V pol antenna} \end{cases}$$

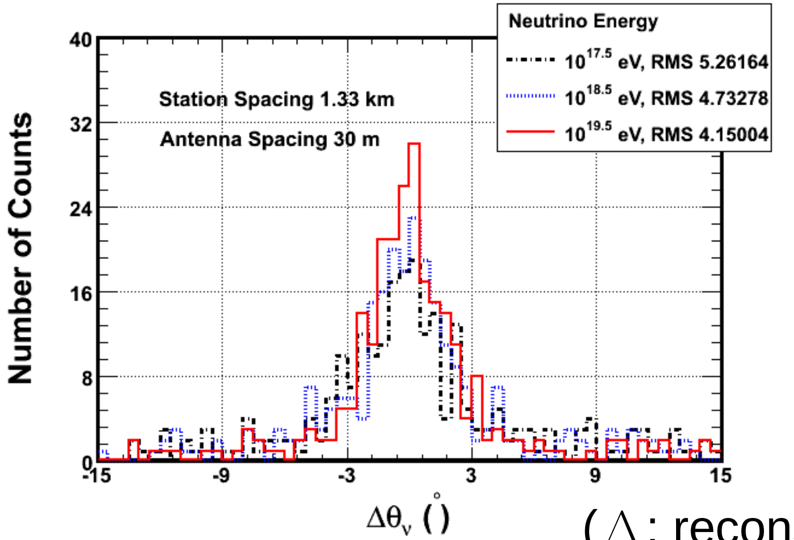
$$\theta(\vec{v}_{hypos.}, \vec{x}_{rec.} - \vec{x}_i)$$

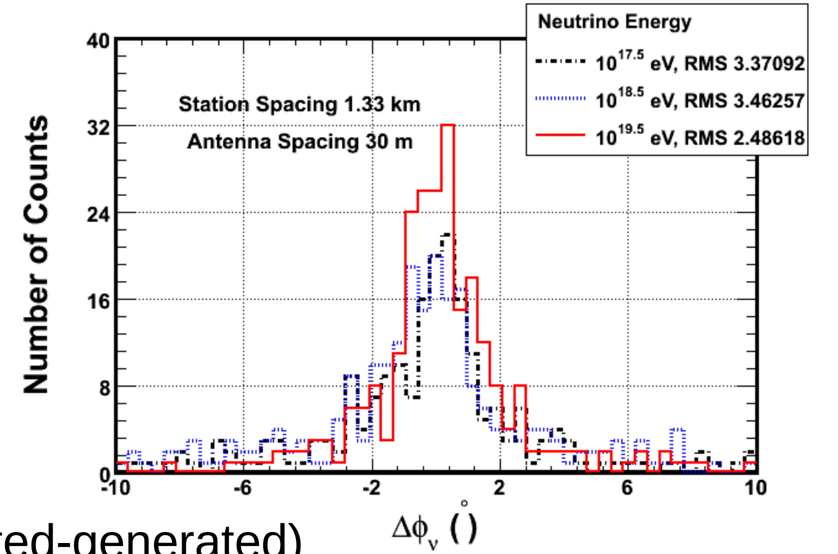
$$\alpha(\vec{v}_{hypos.}, \vec{x}_{rec.} - \vec{x}_i)$$

Neutrino Angular Resolution





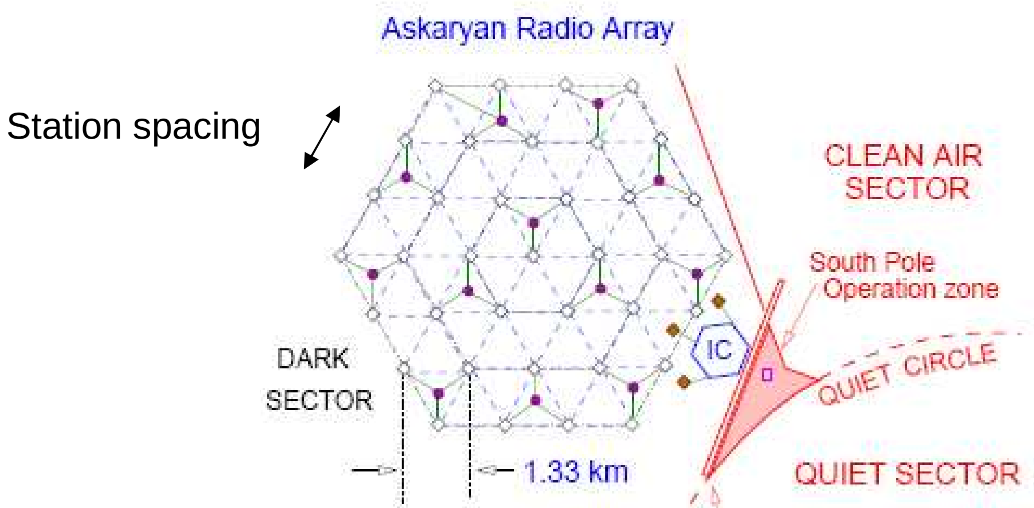


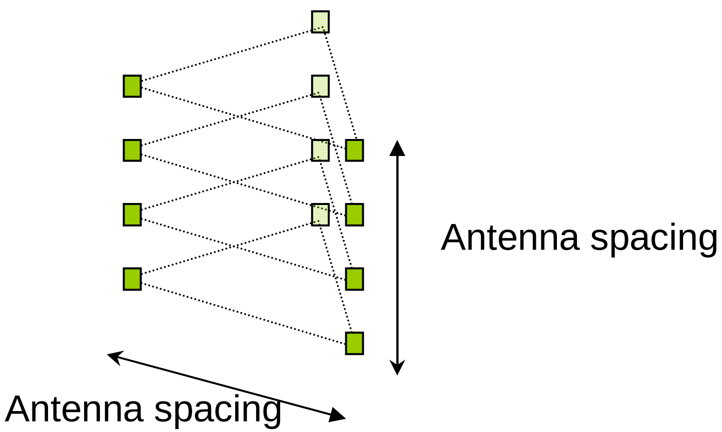


(△ : reconstructed-generated)

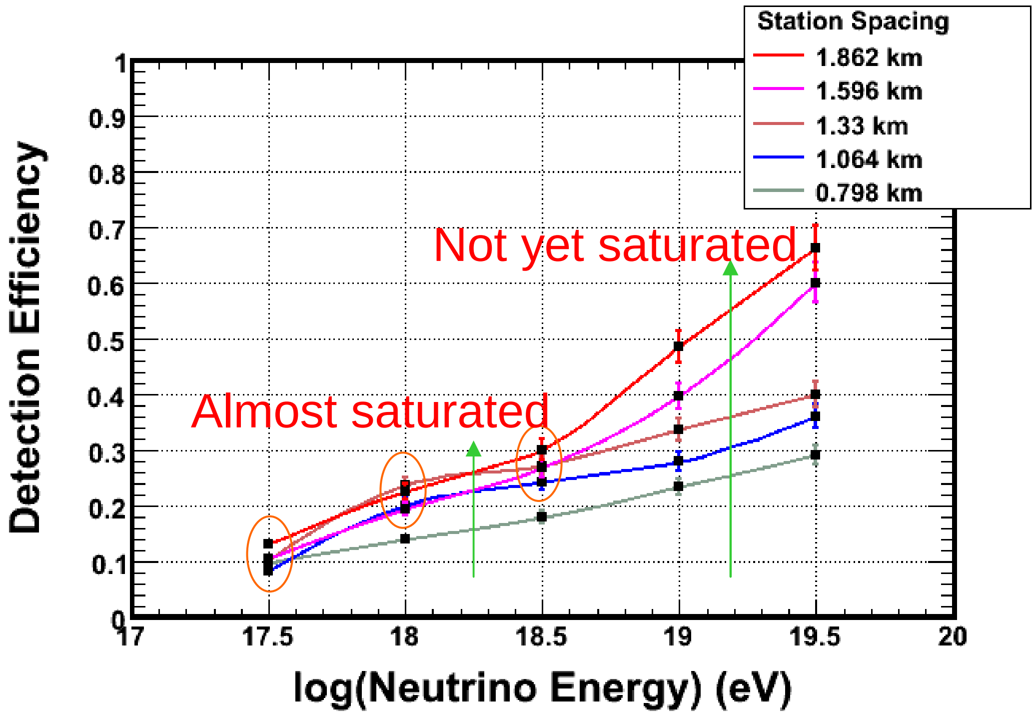
Optimization: detection efficiency versus resolution

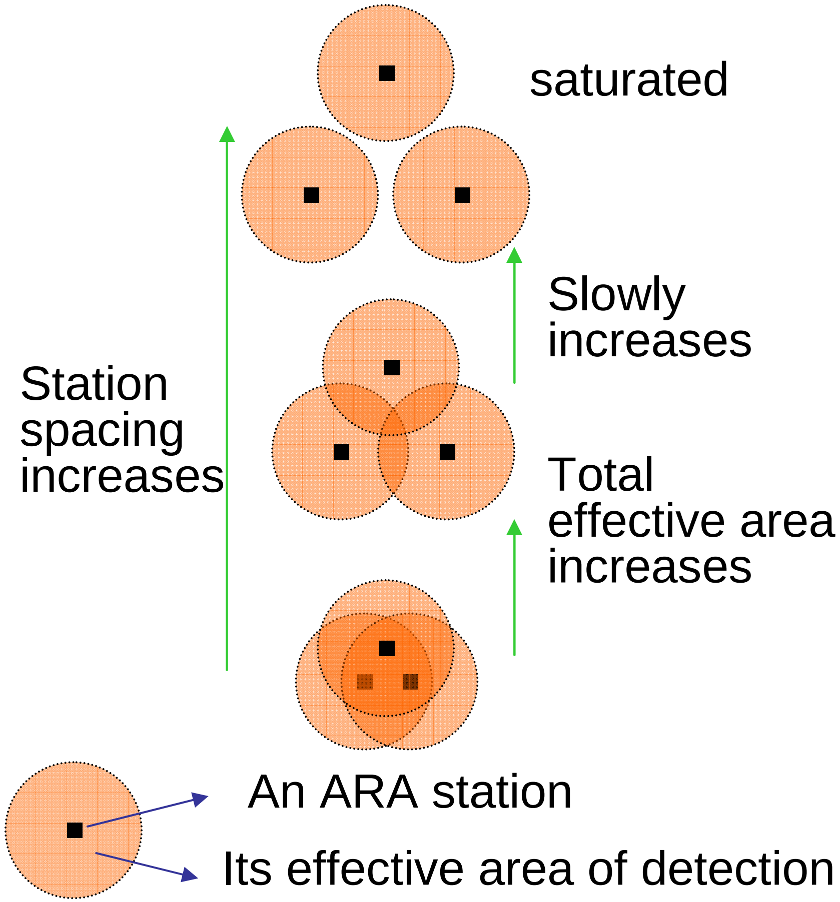
variables: antenna spacing, station spacing





Detection Efficiency

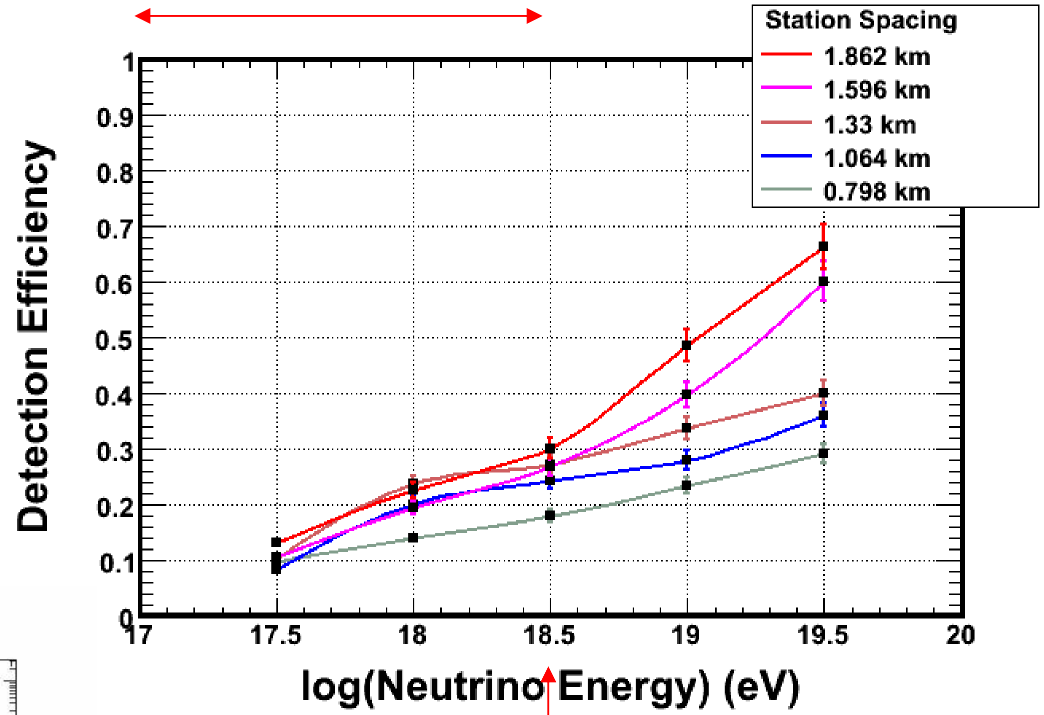




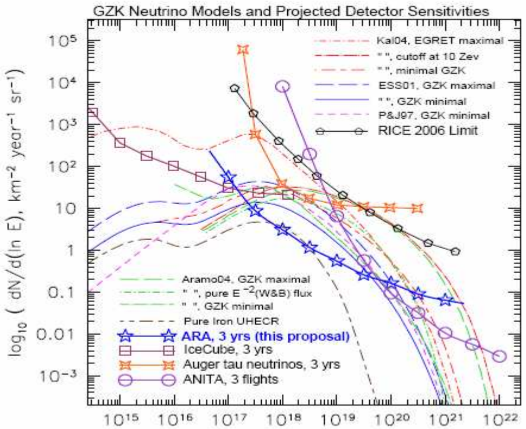
Neutrinos with higher energy makes signals travel farther away: they provide larger effective area

To Optimize Detection Efficiency

Majority regime in GZK neutrino flux



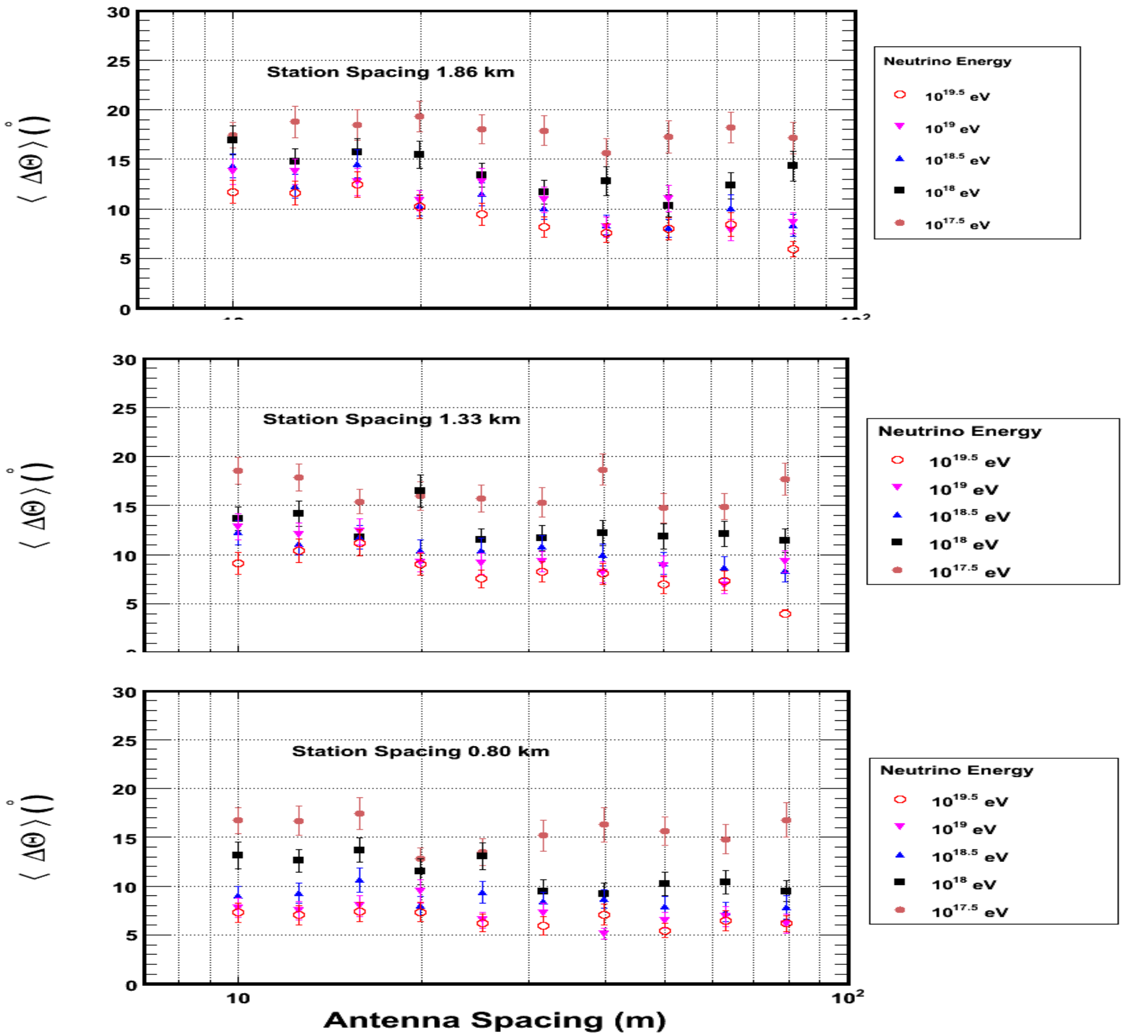
GZK neutrino flux begins quick dropping

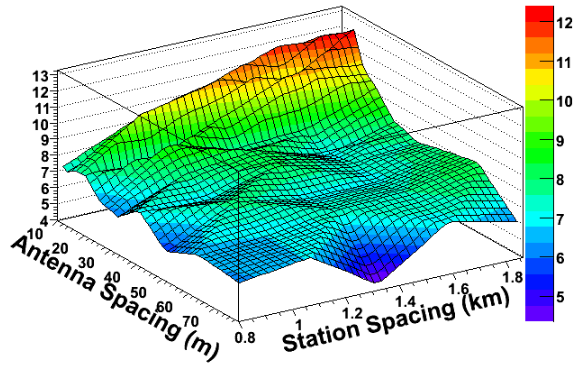


ARA proposal

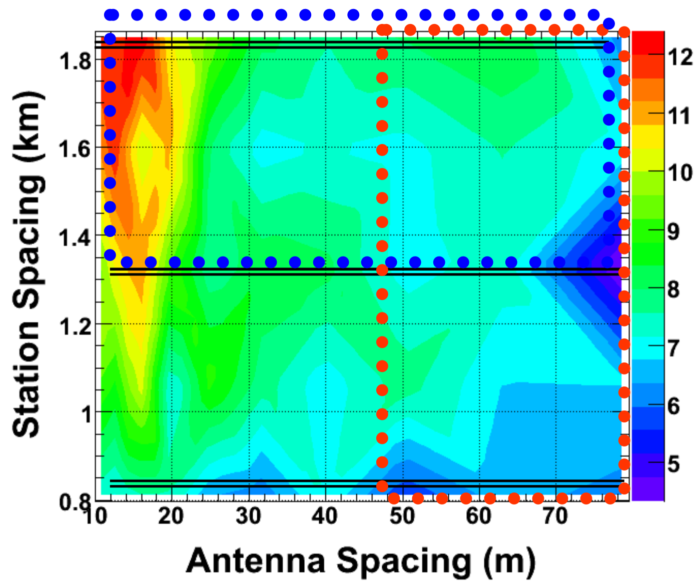
Choose the station spacing of 1.33 km or larger to make sure ARA can capture most GZK neutrinos

Neutrino Angular Resolution
vs. Antenna Spacing, Station Spacing, Neutrino Energy





Neutrino energy $10^{19.5}$ eV



"equal to or larger than 30m" makes the resolution better

Summary

- Detection efficiency: grows when station spacing increases. For higher neutrino energy level, larger station spacing is required to saturate the growing of detection efficiency.

- Neutrino angular resolution: when the station spacing decreases or the antenna spacing increases, the resolution$_{i}$ gets better.

- Geometry Optimization

  Priority: 1.effective area 2. neutrino angular resolution

  Variables: 1.antenna spacing 2.station spacing

  Conclusion:

  Station spacing 1.33 km makes effective area almost saturated for neutrinos with energy under $10^{18.5}$ eV.

  Antenna spacings equal to larger than 30m make neutrino angular resolutions better. Their resolution ranges from 5 to 15 degrees for different energy levels(10^17.5 to 19.5).

BACKUP

RF Wave Property in Ice: Field Attenuation Length

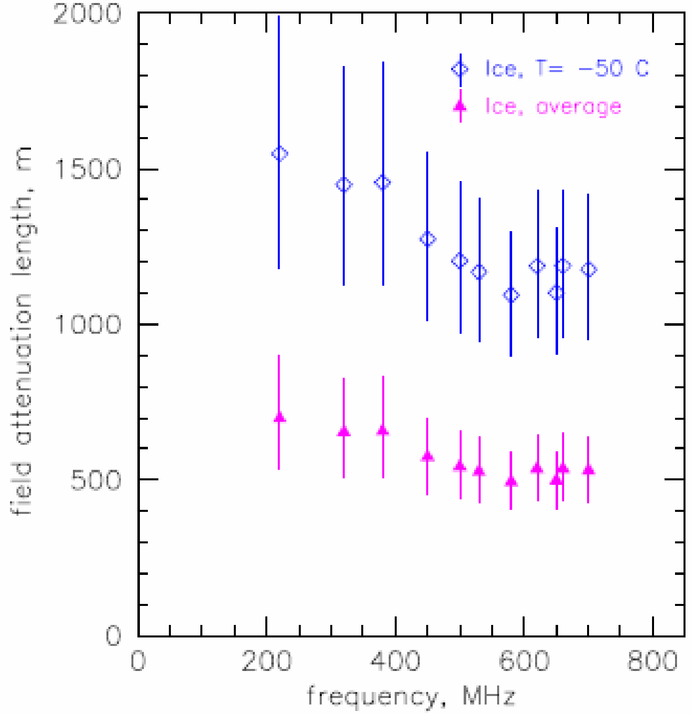


FIG. 4: South pole ice attenuation measurements made in 2004.

IceRay proposal

BACKUP

RF Wave Property in Ice: Ddifferential Refraction Index

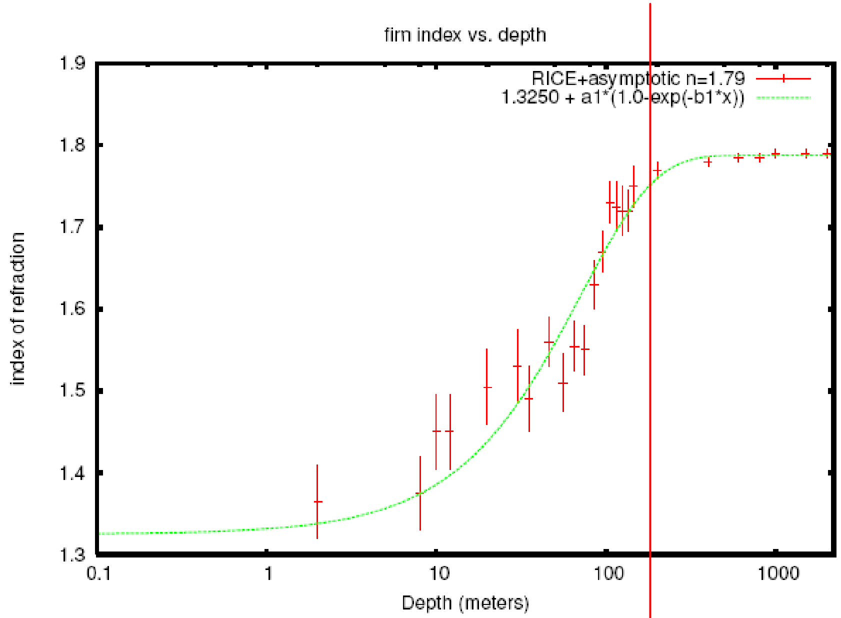
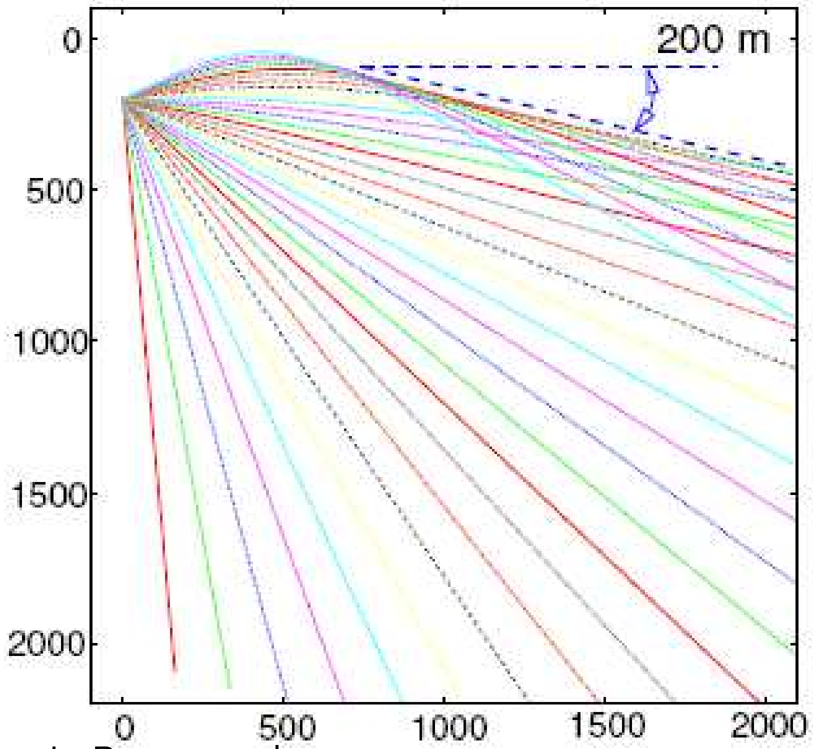


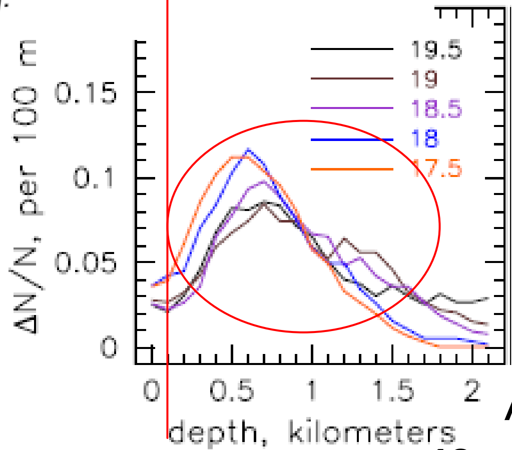
FIG. 6: *Index of refraction in firn at South Pole station, based on data from the RICE experiment [28].*

IceRay proposal



IceRay proposal

Event distribution over depth



ARA proposal

BACKUP *Convert V_0^{gen} to Neutrino Energy*

V_0^{gen} 3V

at 1km
3/3
=1V

Neutrino energy
$2*10^{20}$ eV

Askaryan effect in ice
Experiment at SLAC

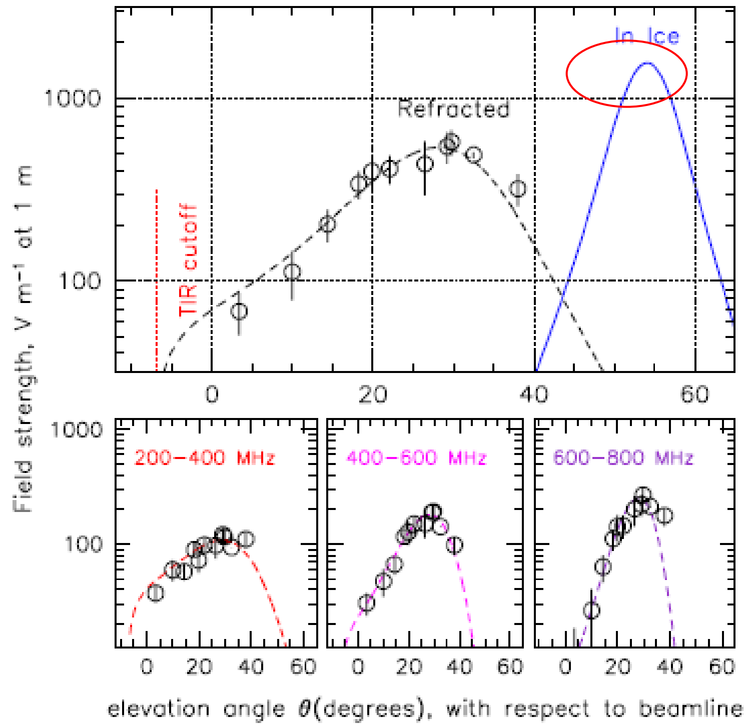


FIG. 5: Top: Angular dependence of the radiation for both the in-ice and refracted case, for a frequency range from 200-800MHz, compared to data. The data errors are combined statistical and systematic, but with an overall normalization that arbitrary here (but see Fig. 4 for the normalization factor). The in-ice and refracted curves are the theoretical expectation for a shower in ice at a beam current of 10^9 e^- per bunch and 28.5 GeV electrons, and the refraction includes only geometric optics. Bottom: Same as top for three different sub-frequency bands.

PhysRevLett.99.171101

ANITA collaboration

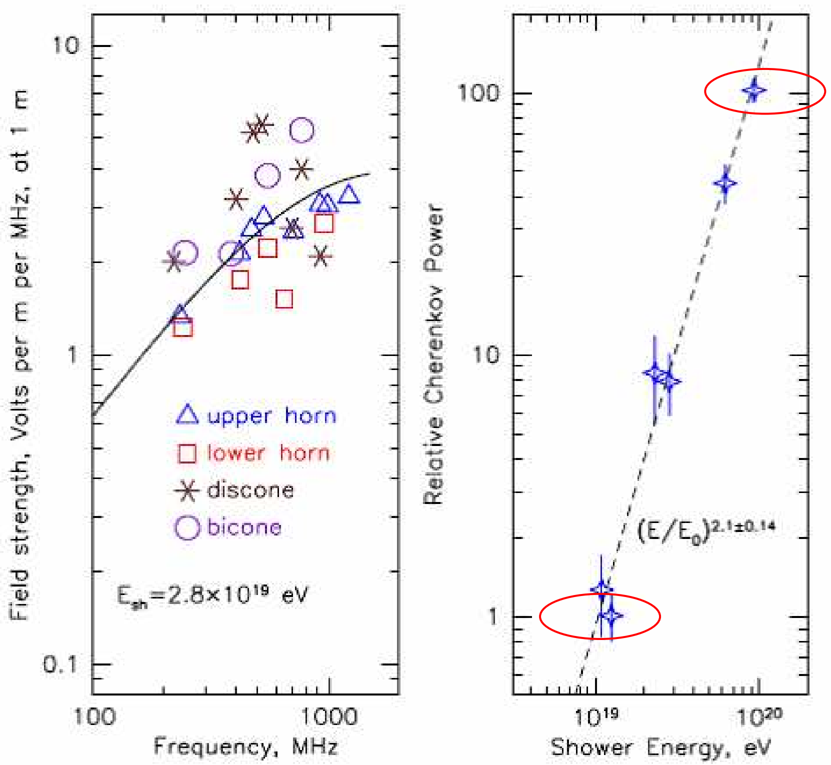
1500 V at 1m

at 1 km
1500/1000/3 V
=0.5 V

10^(9+1.5+9)=10^19.5
Neutrino energy 10^{20} eV

BACKUP

Askaryan Effect in Ice: Field strength vs. Frequency in Radio Band and Radiative Cherenkov Power vs. Shower energy



PhysRevLett.99.171101

ANITA collaboration

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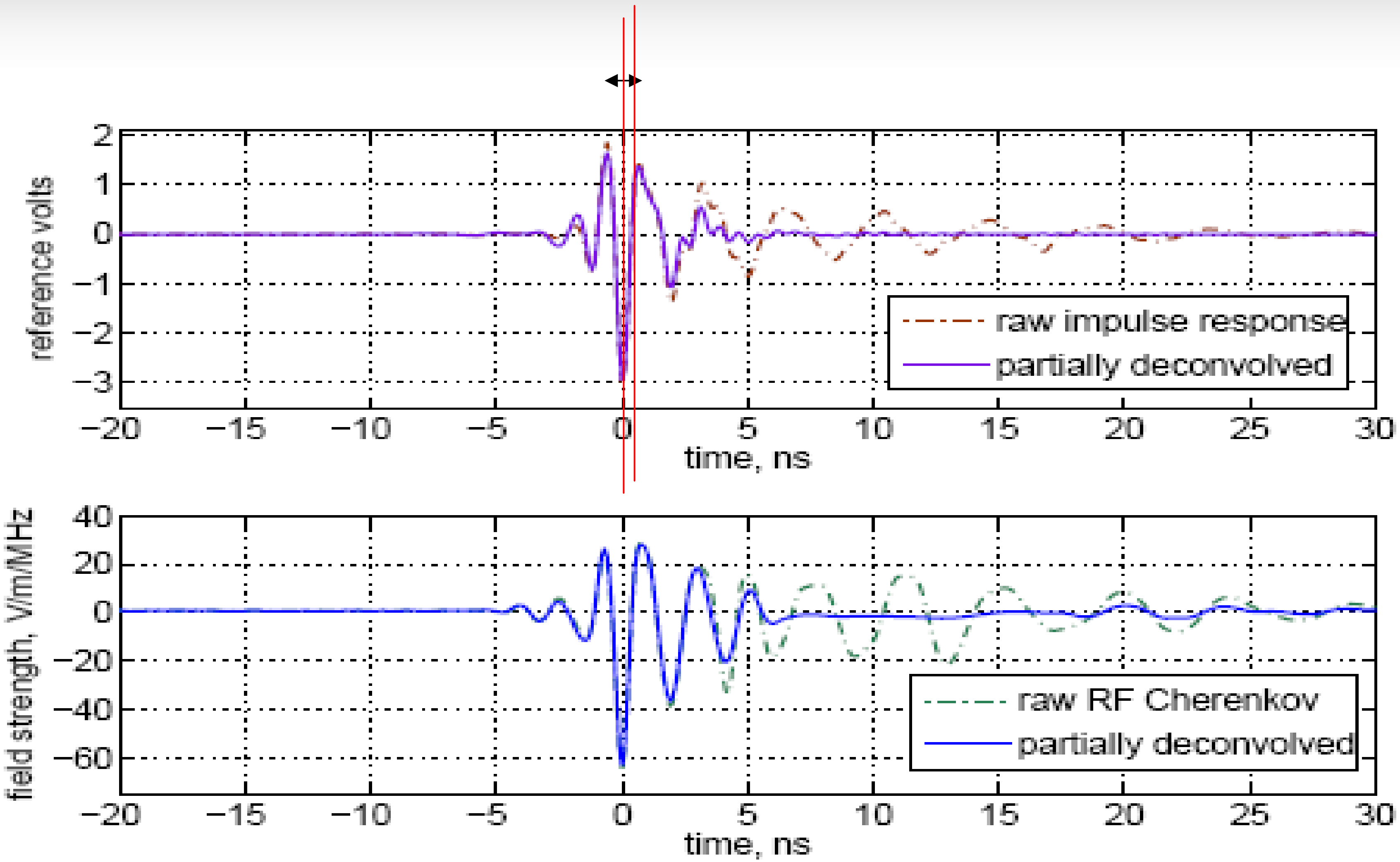
Askaryan effect in ice: Radio Cherenkov Waveform

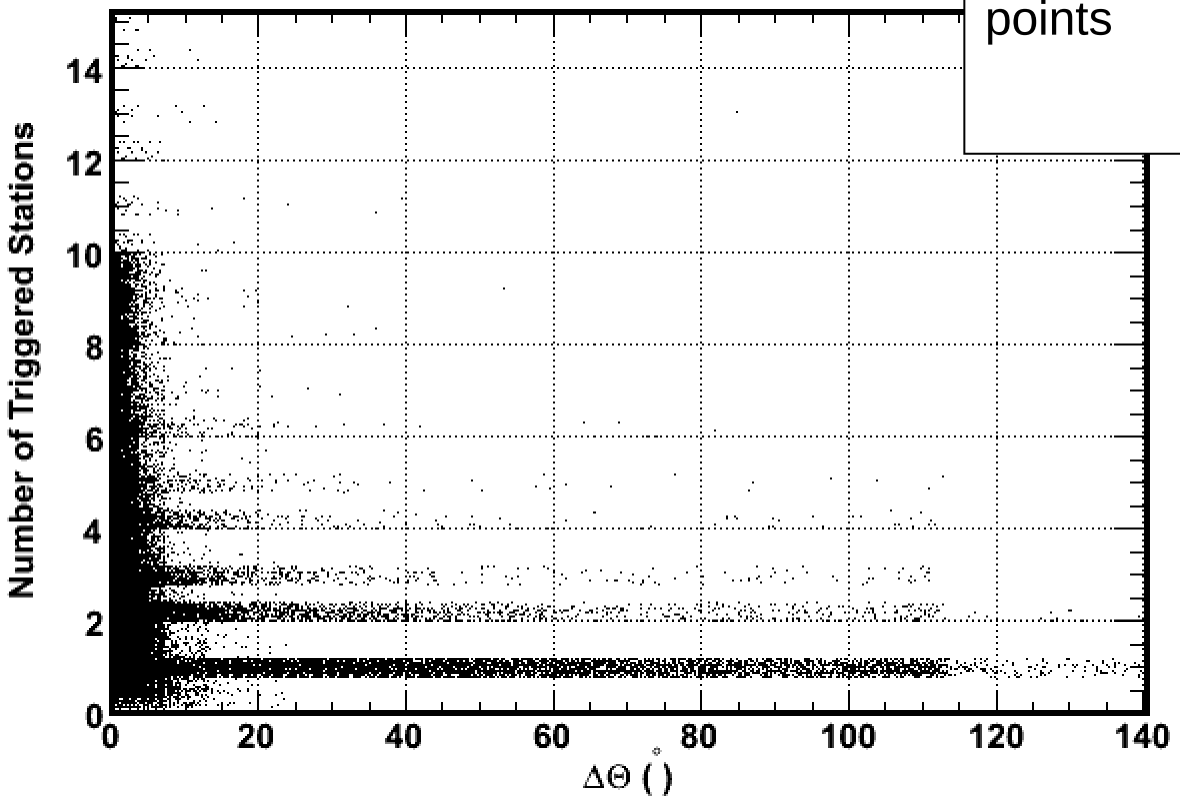


PhysRevLett.99.171101

ANITA collaboration

Backup Slide

280*5*5*10
points



BACKUP

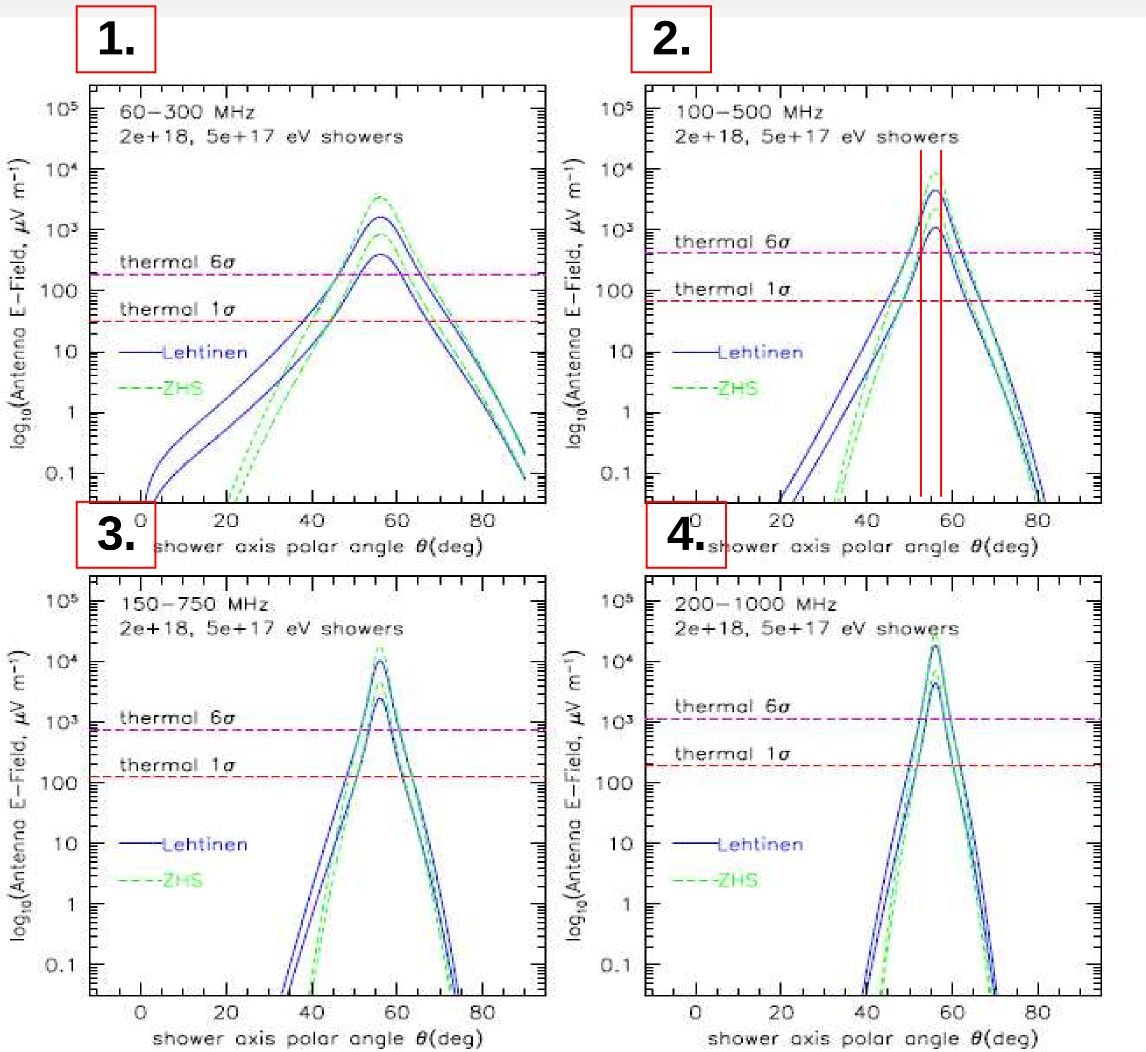
Askaryan Effect in Ice: Angular Dependence of Cherenkov Field Strength

Frequency
F1<F2<F3<F4

Cone Width
W1> W2> W3> W4

E Field
E1< E2< E3<E4

The higher frequency,
the higher
radio power



IceRay proposal

BACKUP

ARA: Who Does What

~80 people, 16 institutes

Table 1: Collaboration personnel who will participate in array development and data analysis.

	Institution	Funding	Personnel Category† [1]	[2]	[3]	[4]
Am	*US Participants:*					
	Univ. Wisconsin	NSF	2	1	1	2
	Univ. Maryland	NSF	2	1	2	2
	Univ. Hawaii		2	2		
	Univ. Kansas	NSF	1		2	12
	Univ. Delaware	NSF	1	1	1	1
	Ohio State Univ.	NSF	1	1		
	Univ. Alabama	NSF	1			1
	Colorado St. Univ.	NSF	1		1	2
	Penn St Univ.	NSF	1		1	
	Univ. Nebraska	NSF	1			1
As(2)	*Taiwan:*					
	Nat'l Taiwan Univ.	LeCosPA NSC	1	2	7	1
	Belgium:					
	Univ. Bruxelles	FNRS	2	1	1	1
Eu(3)	*United Kingdom:*					
	Univ. Coll. London		2	1	2	2
	Japan:					
	Chiba Univ.	JSPS	1	1	1	1
	Germany:					
	DESY	BMBF	1		1	
	Univ. Wuppertal	BMBF	1		1	

†[1] Senior Personnel;[2] Postdocs;[3] Grad. Students; [4] Undergrads.

ARA proposal

Table 3: Milestones for the array construction.

ID	Milestone	Owner	Date
1	Preliminary System Design Review. Include all major subsystem assemblies.	UMD	Sep 2010
2	Ship Testbed prototype instrumentation to Pole	UH	Oct 2010
3	Design, construct and ship to Pole the Ice Drill	UW	Aug 2011
4	Design, integrate, test and ship 4 pre- production In Ice Instrumentation clusters after Shipment Readiness Review.	UH	Sep 2011
5	Design, construct and test Remote Stations. Ship prototype to Pole after Shipment Readiness Review.	KU	Sep 2011
6	Commission Ice Drill	UW	Dec 2011
7	Install and Commission 4 Radio Stations at Pole	UW	Feb 2012
8	Final Critical Design Review & Production Readiness Review	KU	Apr 2012
9	Instrumentation Shipment Readiness Review. Initial verification of data stream showing detector will meet Science objectives.	UW	Sep 2012
10	Instrumentation Shipment Readiness Review. Final verification of data stream showing detector will meet Science objectives.	UMD	Sep 2013
11	Integrated, test and ship 33 production In Ice Instrumentation clusters.	UW	Sep 2014

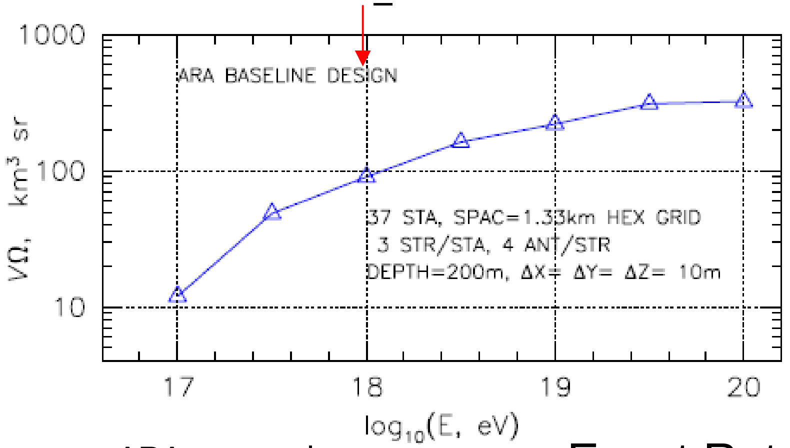
ARA proposal

BACKUP

ARA: Acceptance, Event Rate, Flux

acceptance

L_int:1200km in water



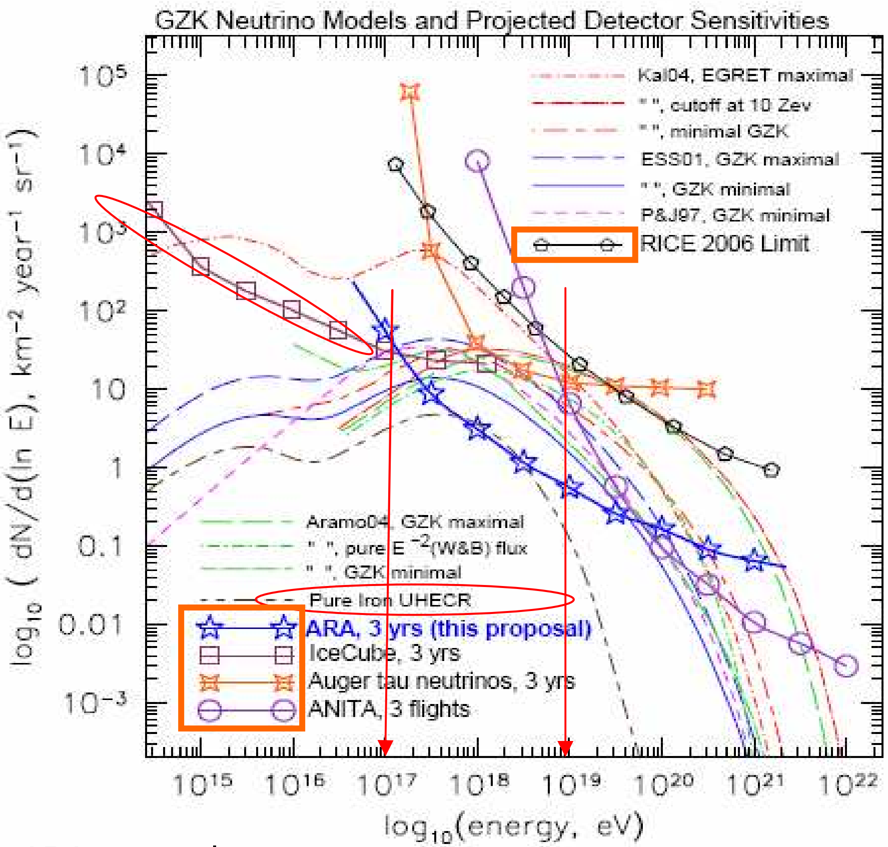
ARA proposal

Event Rate

Table 2: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2006 ANITA-1 flight with predicted events per year from ARA.

Model & references	N_ν:	ANITA, 1st flt	ARA, yr^{-1}
Baseline BZ models			
Protheroe & Johnson 1996 [58]		0.22	7.0
Engel, Seckel, Stanev 2001 [59]		0.12	3.5
Barger, Huber, & Marfatia 2006 [60]		0.38	4.9
Strong source evolution BZ models			
Engel, Seckel, Stanev 2001 [59]		0.39	11.1
Barger, Huber, & Marfatia 2006 [60]		0.89	17.6
Yuksel & Kistler 2007 [61]		0.56	26.4
Waxman-Bahcall (WB) fluxes:			
WB 1999, evolved sources [17]		0.76	7.4
WB 1999, standard [17]		0.27	2.6
All-Iron UHECR composition:			
Ave et al. 2005 [62]		0.00	0.74

ARA proposal

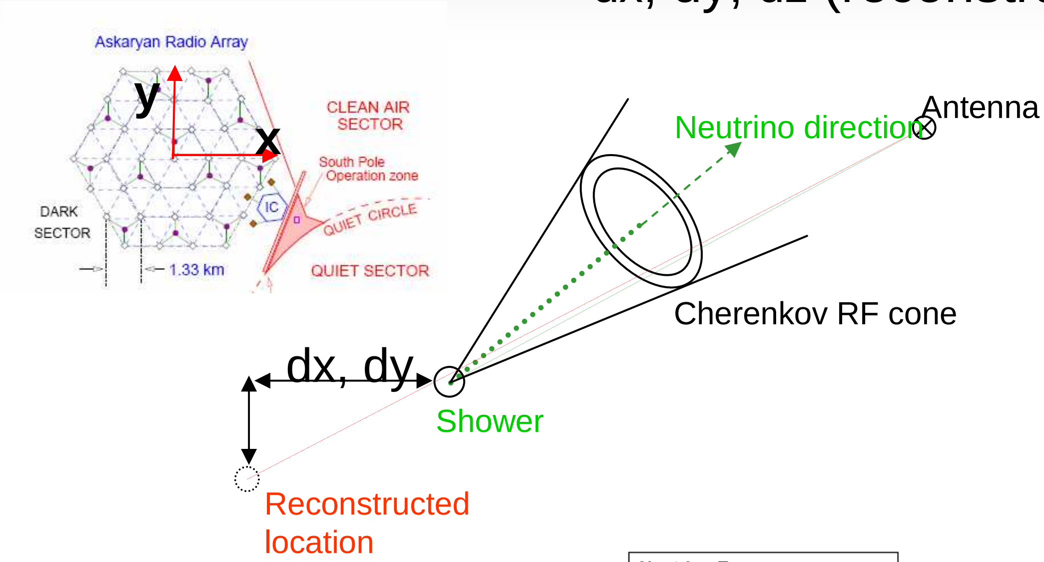


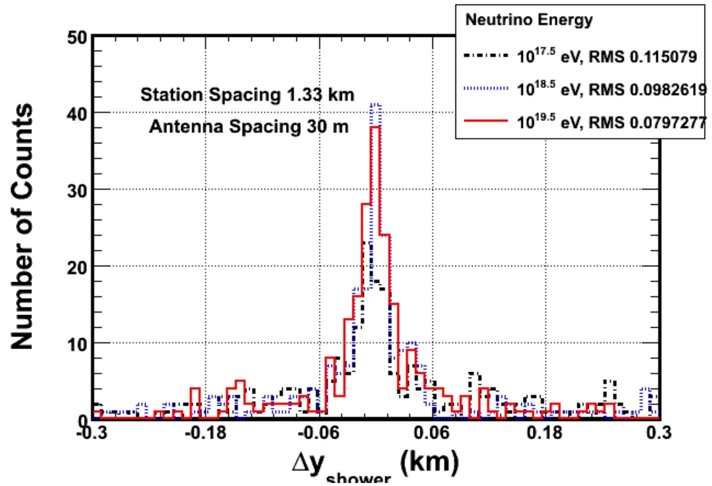
ARA proposal

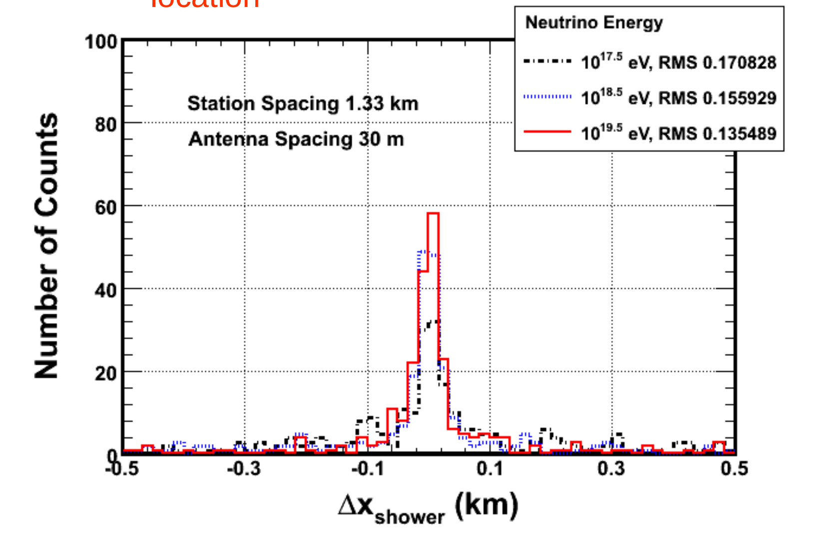
BACKUP

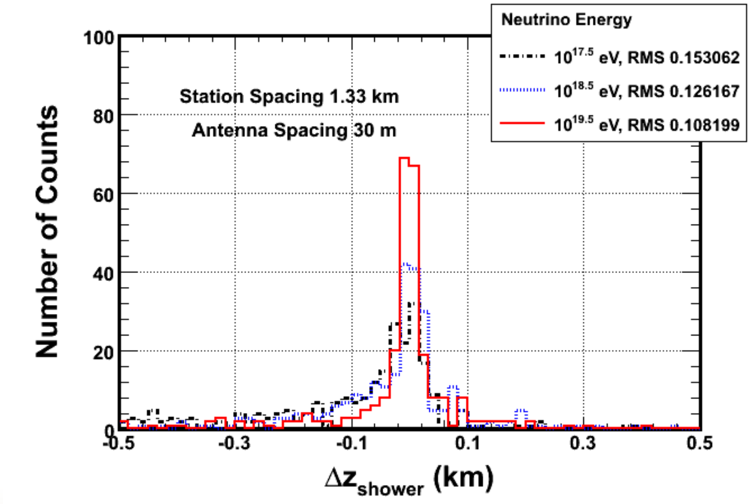
Resolution of Shower Vertex

dx, dy, dz (reconstructed-generated)



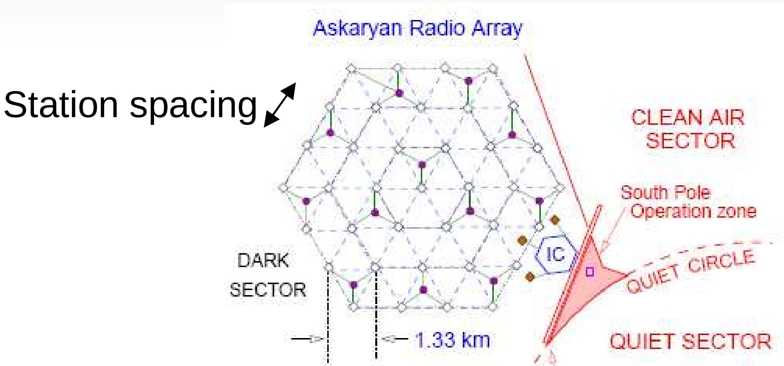


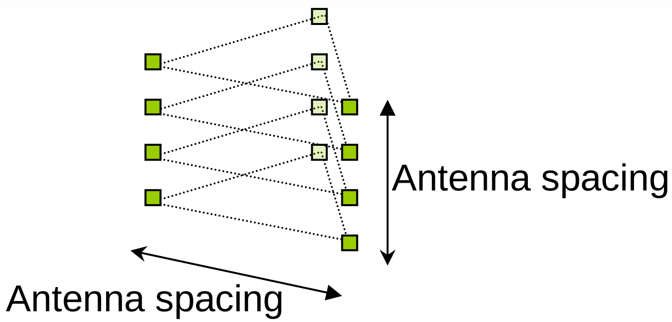




Optimization: detection efficiency versus resolution

BACKUP *variables: antenna spacing, station spacing*





station spacing decreases ⇒ target volume decreases ⇒ detection efficiency decreases

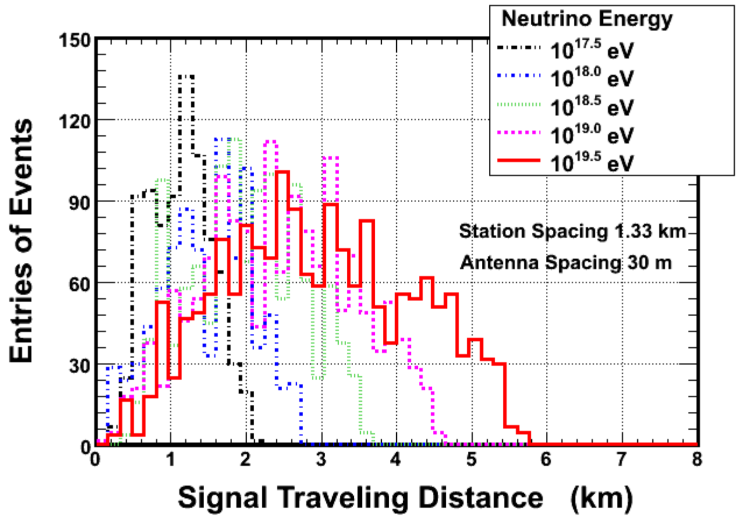
antenna spacing
or station spacing decreases

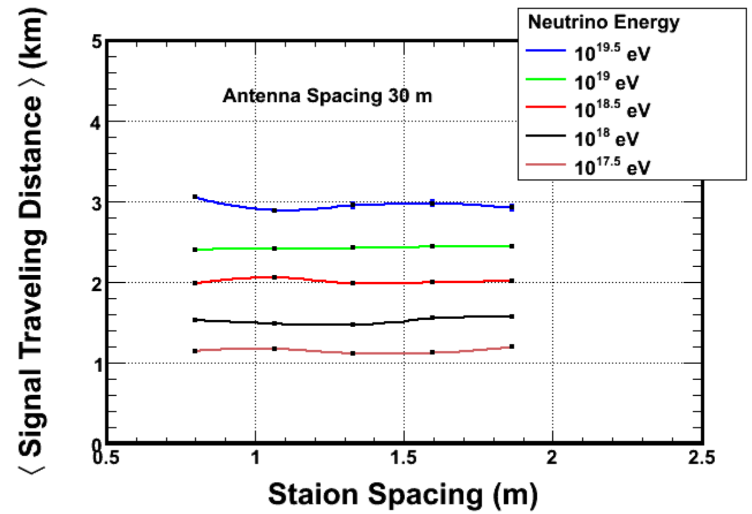
⇒ the number of triggered antennas increases ⇒ resolution better

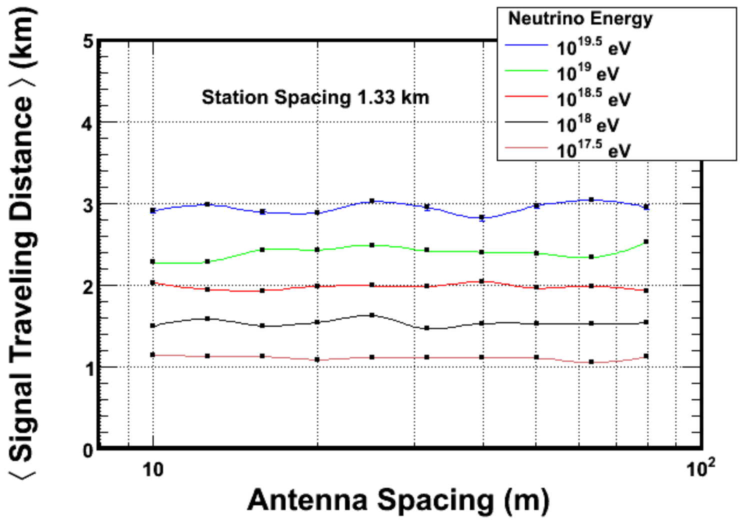
⇒ the signal differences between triggered antennas decreases (arrival time differences, voltage differences) ⇒ resolution worse

BACKUP

Signal Travelling Distance Distribution (from the shower location to triggered antennas)



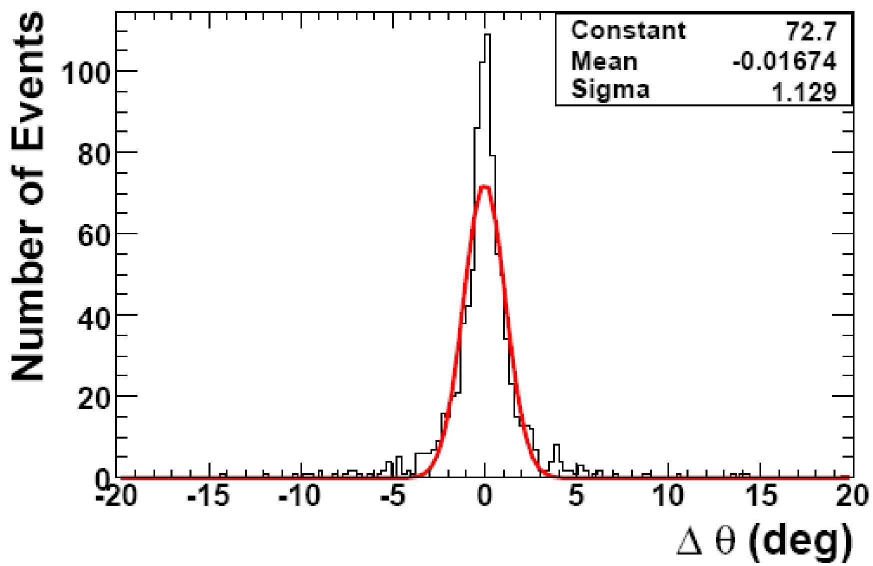




Compare ARA with ARIANNA

Antarctic Ross Ice Shelf ANtenna Neutrino Array (ARIANNA)

simulation of angular resolution of neutrino direction



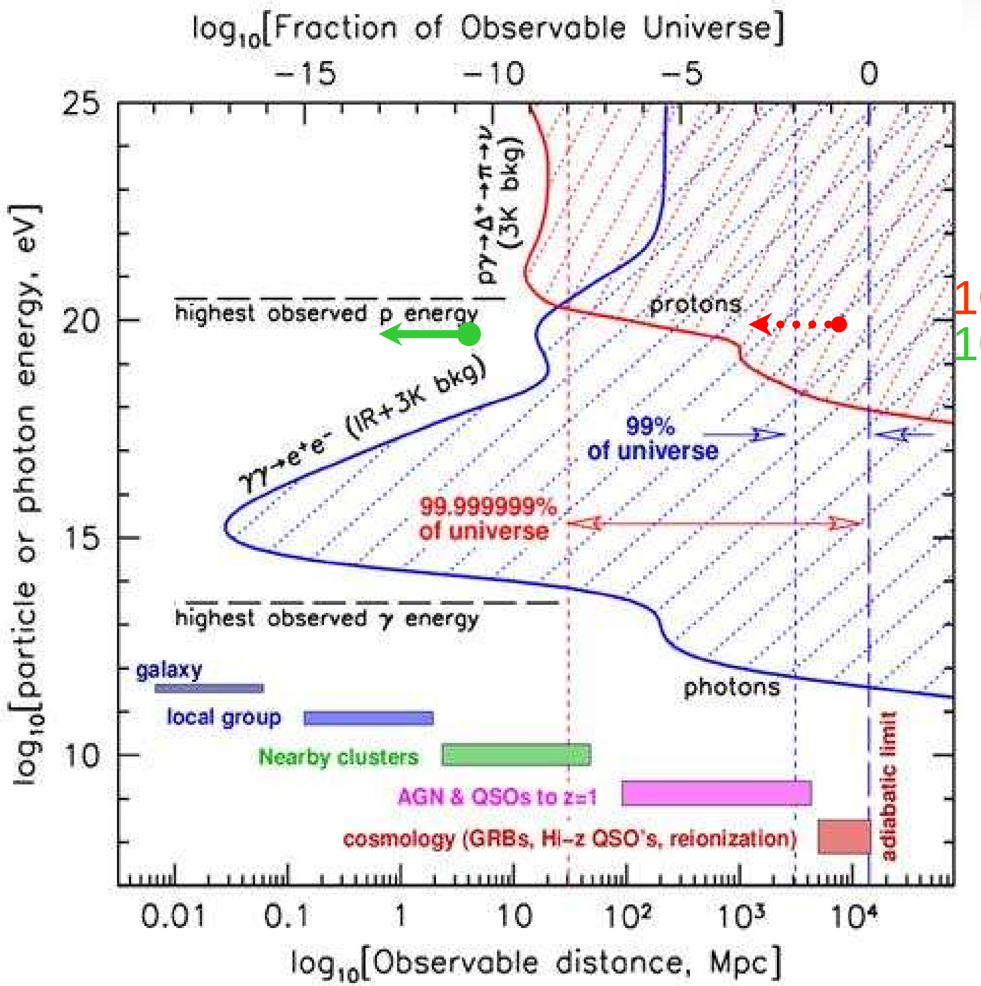
F. Wu, J. Nam, Proceedings of the 30th International Cosmic Ray Conference (2007).

ARA
Station spacing 1.33km
Antenna spacing 30 m
4.5 ~ 5.5 deg.

ARIANNA	Station grid of 300 m	11 stations per km square	13 times larger
ARA	Station spacing of 1.3 km	0.85 stations per km square	

BACKUP

Role of UHE Neutrino in Astrophysical Observation



10^{20}eV protons from AGN cannot be seen

10^{20}eV protons from local group can be seen

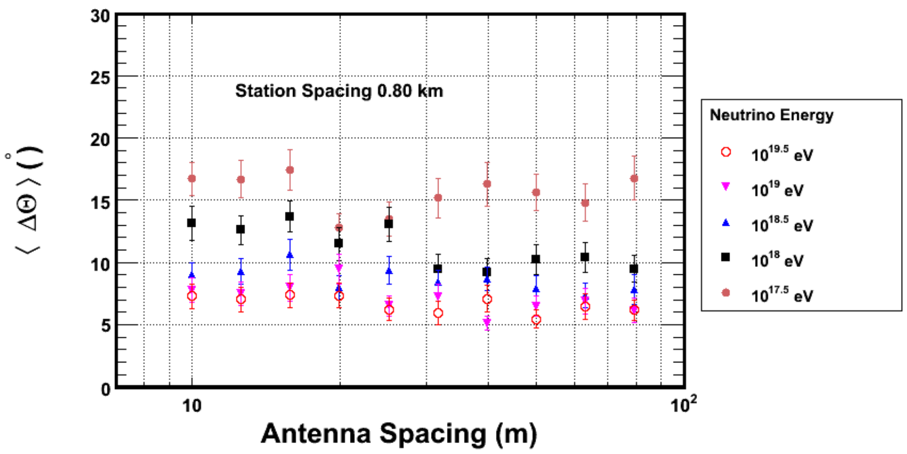
For the observation of UHE events, photons and protons only unveil 1% mysteries of our universe !

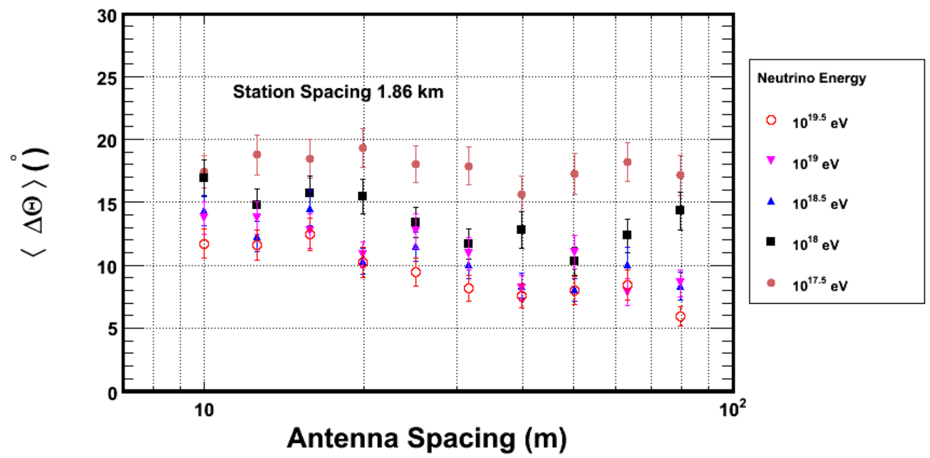
UHE neutrino can be a better choice because of its small cross section and charge-neutral property.

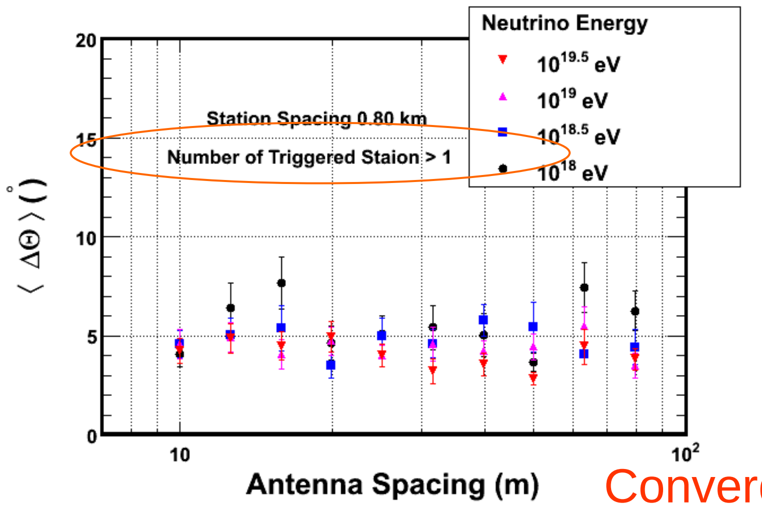
P. Gorham, *1st International Workshop on the Saltdome Shower Array* (SLAC, 2005).

BACKUP

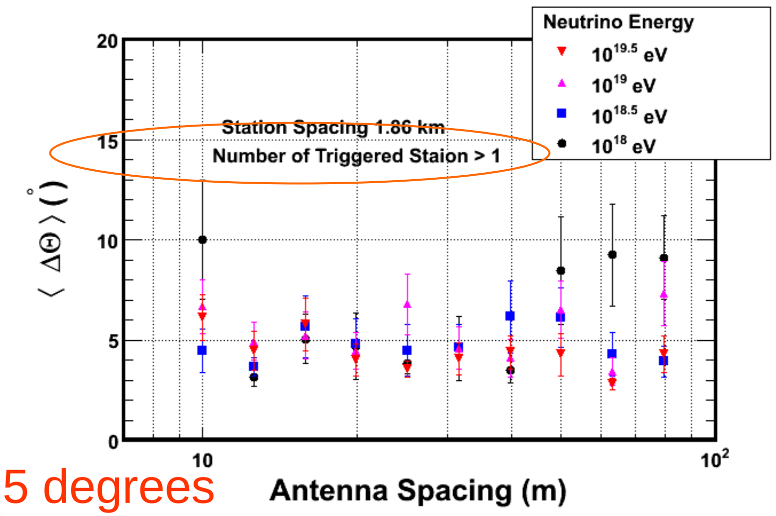
Effect of Requiring "# of Triggered Station >1"







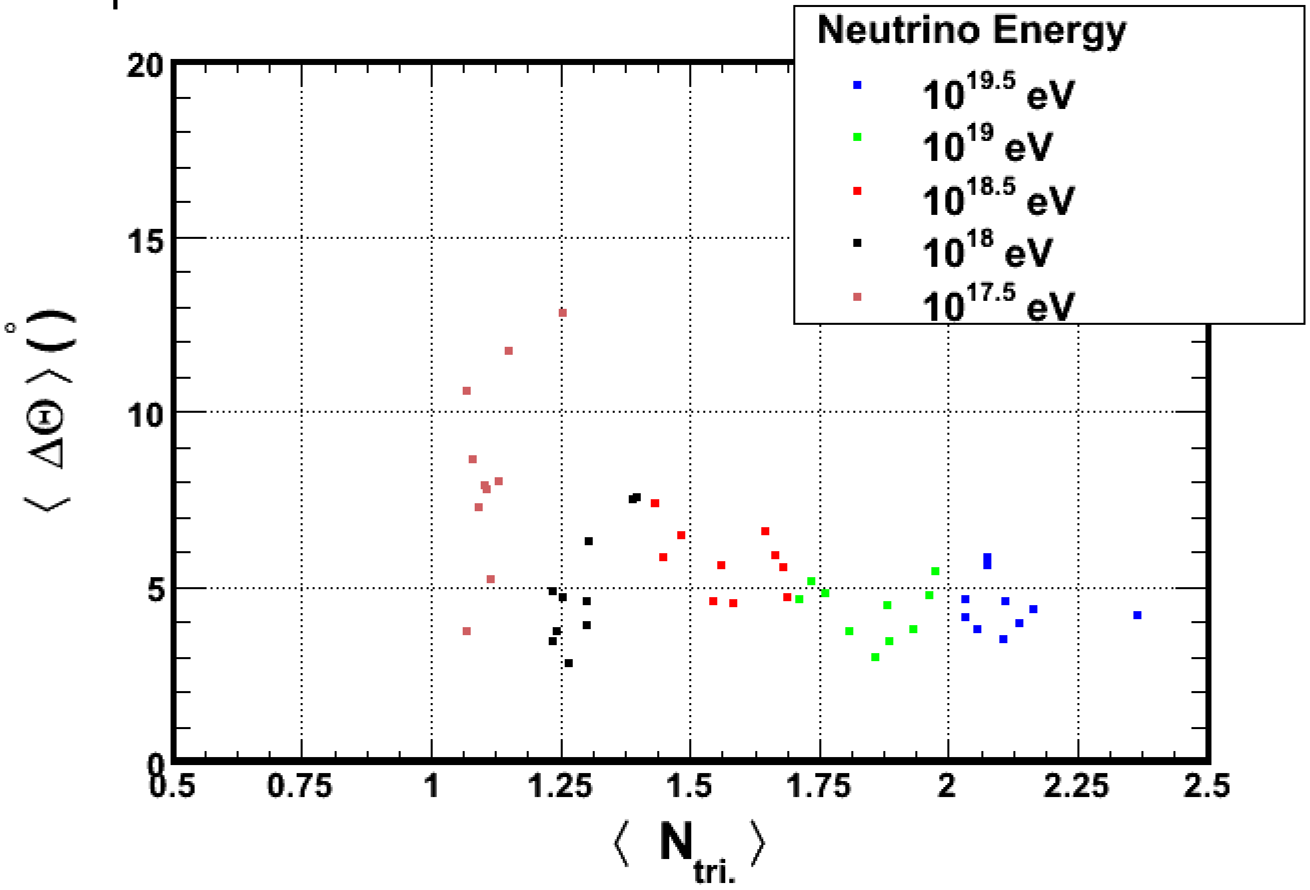
Converged to ~ 5 degrees



BACKUP

Is "the # of triggered stations" strongly related to "the neutrino angular resolution"?

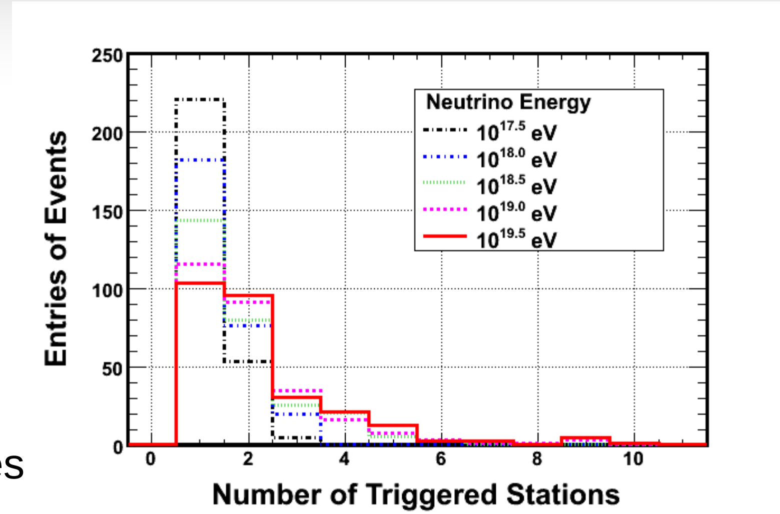
One point represents 300 detected events.



A larger ***# of triggered stations*** guarantees a better resolution

BACKUP

Distribution of the Number of Triggered Stations



N_{trig} slightly increases
as the antenna spacing increases

N_{trig} **decreases**
as the station spacing increases.
Obvious for higher energy levels.