A Next Generation IceCube:
- the case for and challenge of a surface veto
- considerations for an Askaryan radio detector

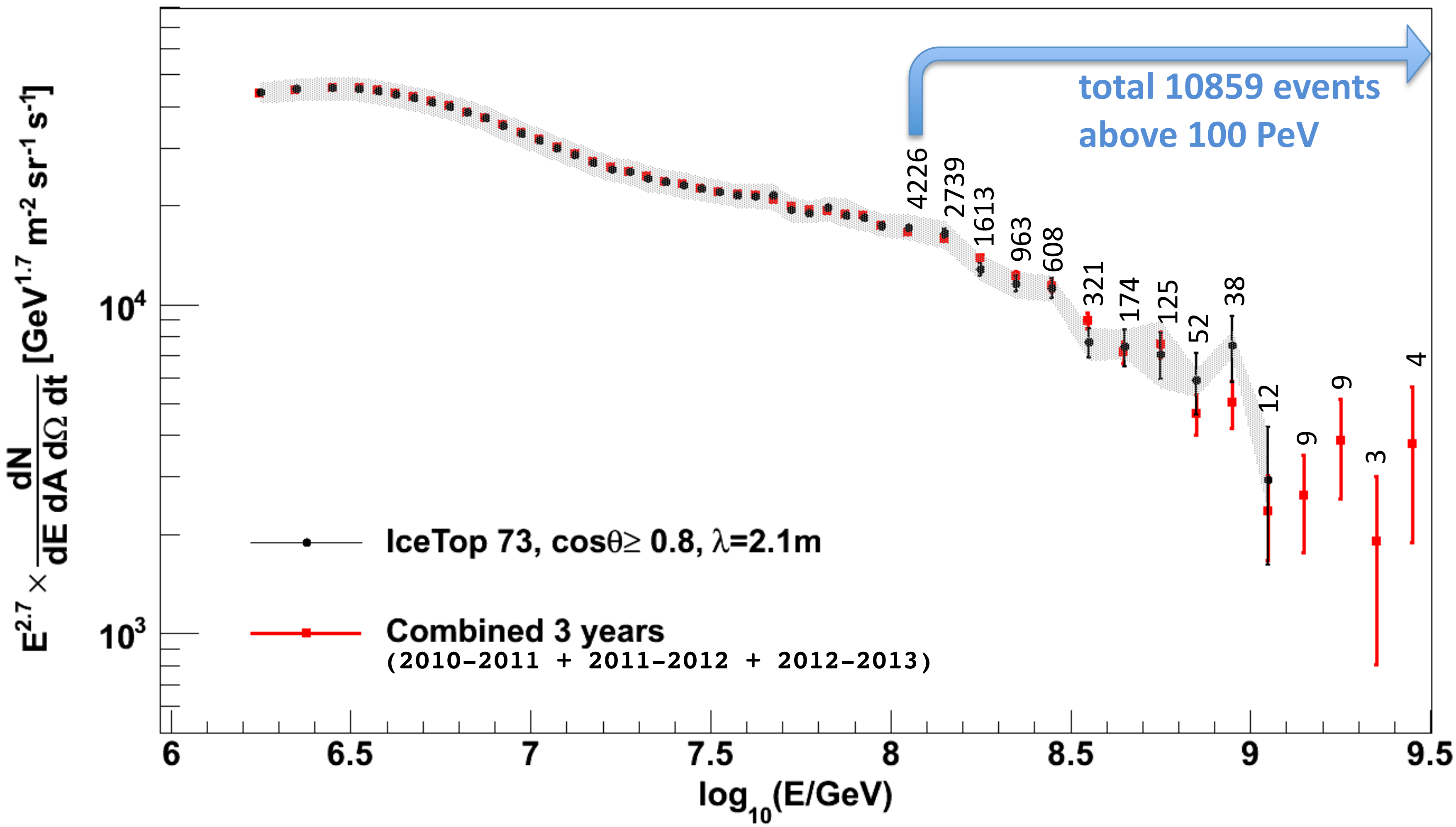
IceCube SAC meeting

October 2015, Madison

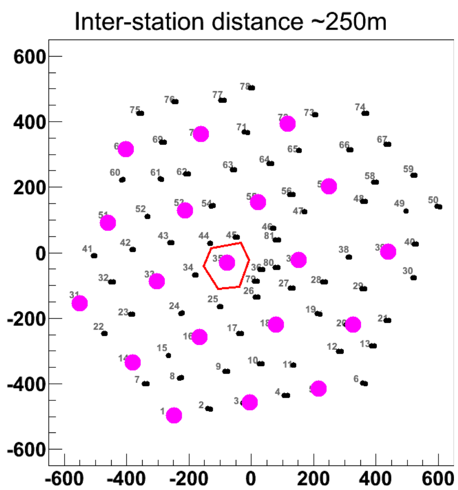
Albrecht Karle

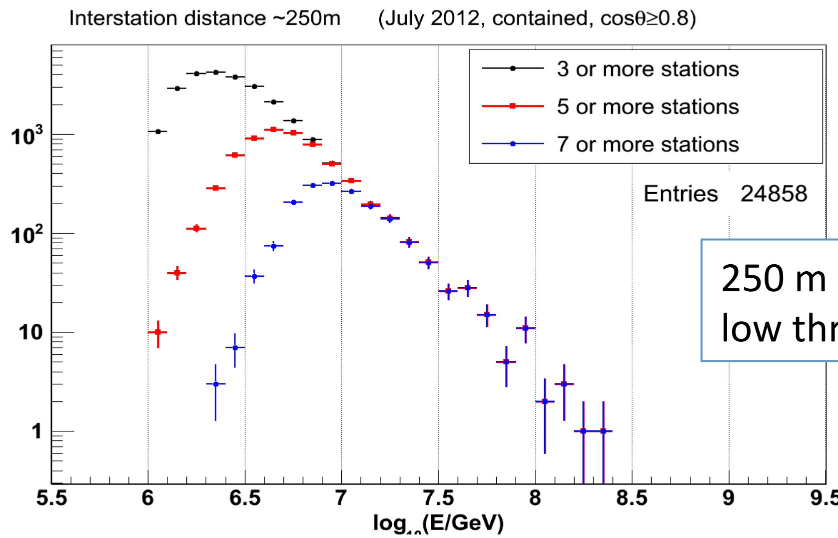
Cosmic rays with IceTop & IceCube

Spectrum measured by IceTop (2.67 yrs livetime)



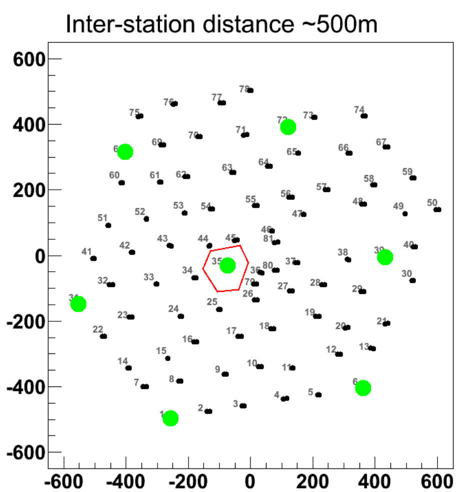
- Predefine “New” arrays with 250m and 500 m spacing
- Count stations from the “New” list participating in the event.

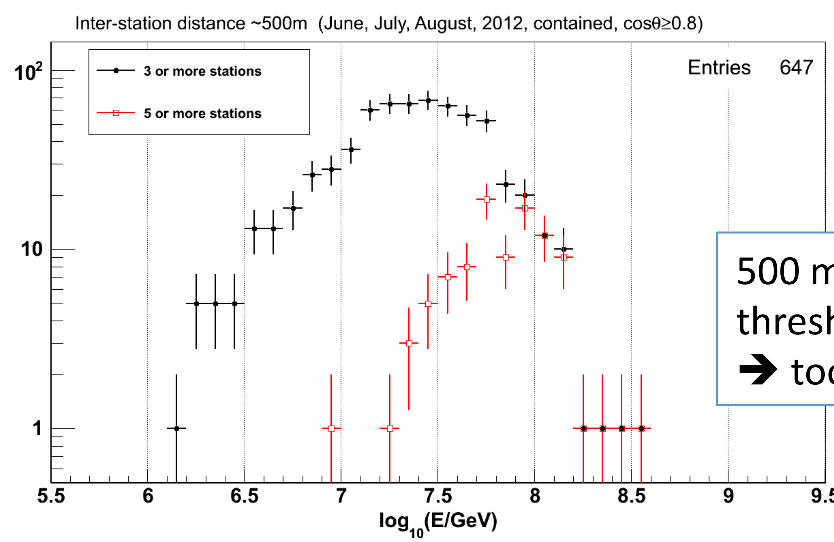




250 m spacing:
low threshold ~10 PeV

300-350m spacing
seems optimal
for ~50 PeV threshold



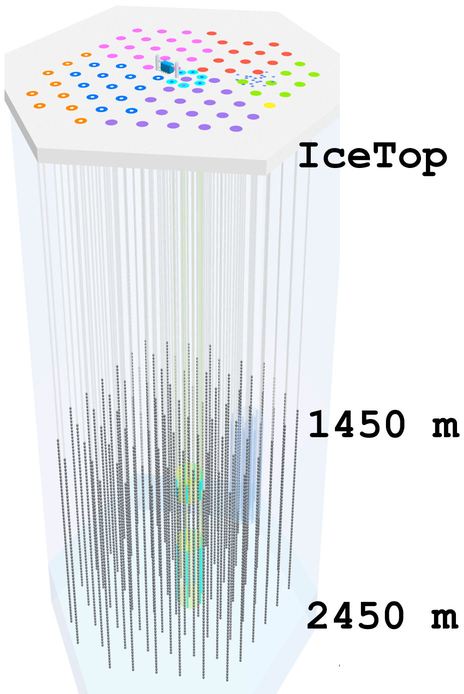


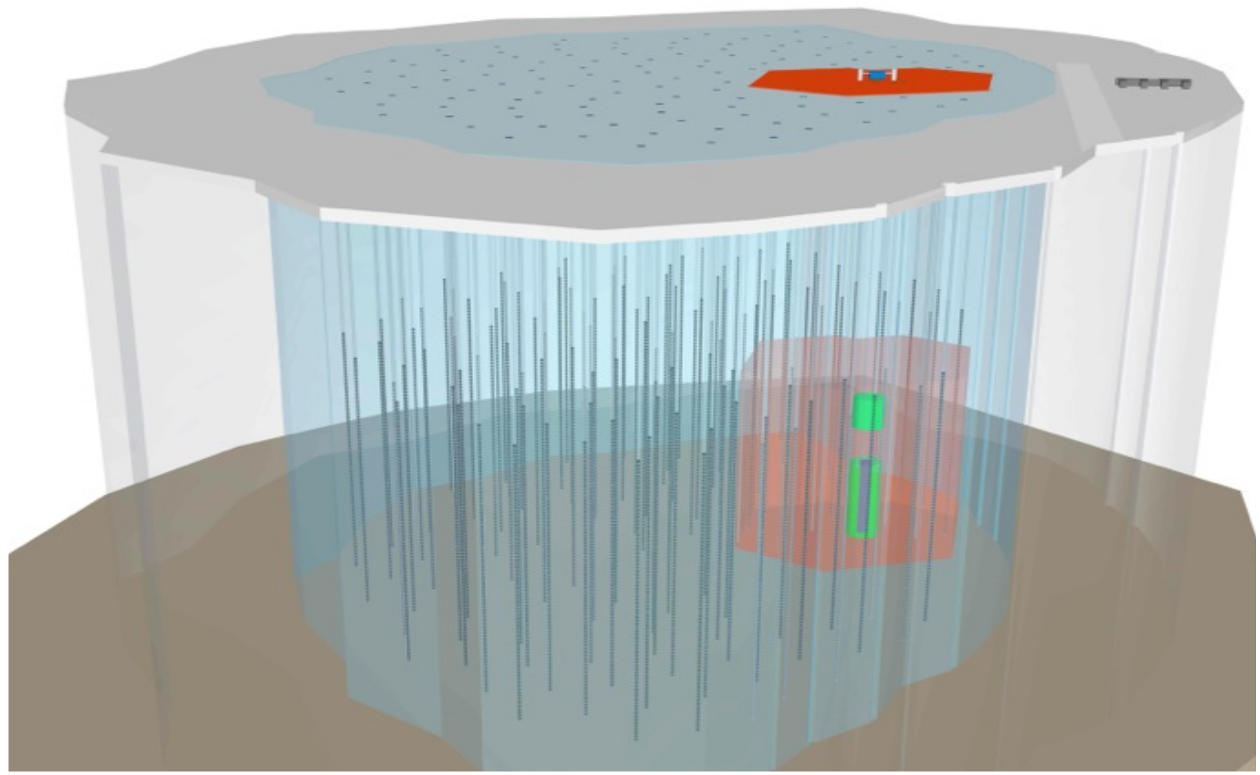
500 m spacing:
threshold moves to 100 PeV
➔ too high

Note: Auger infill: 85 detectors in two grids of 750m (covering 23.5 km2) and 433m (covering 5.9 km2) spacing.
TALE: 100 scintillator counters at 400m spacing

Aperture for coincident events: neutrinos, gammas, cosmic rays

0.26 km² sr → ~ 10 km² sr

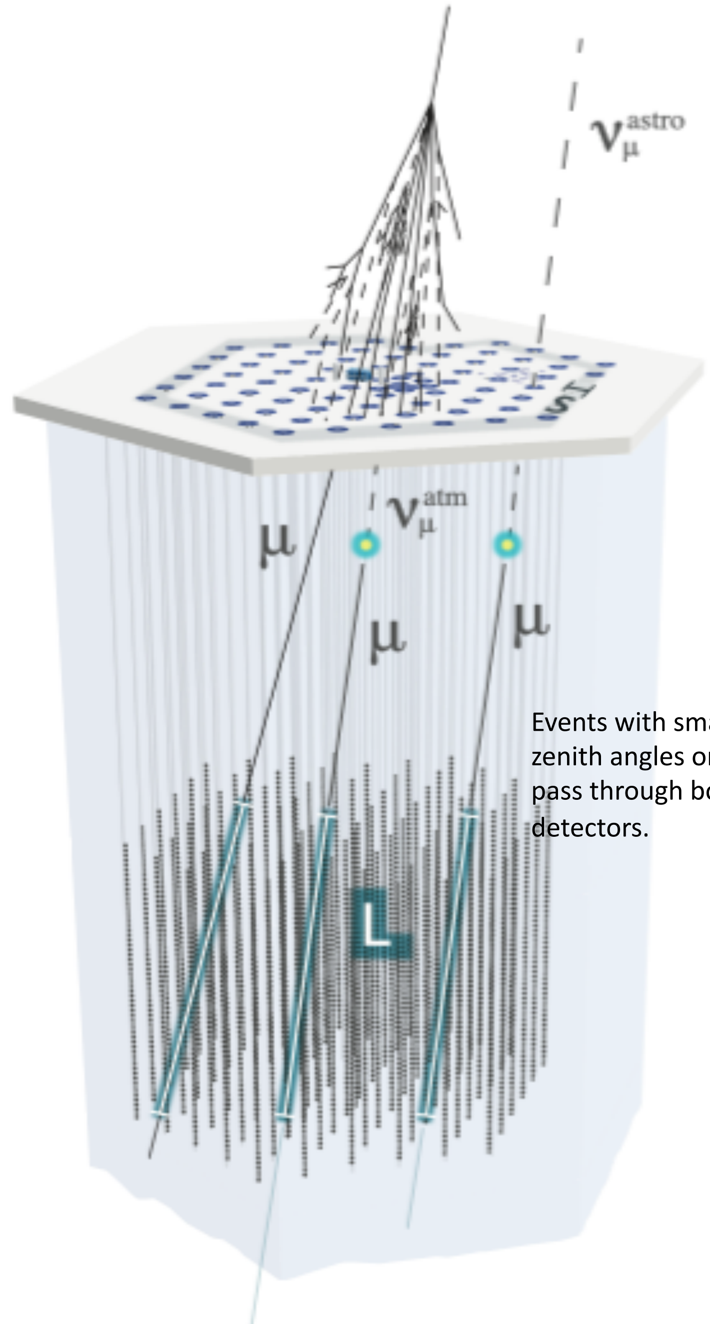




IceTop as veto

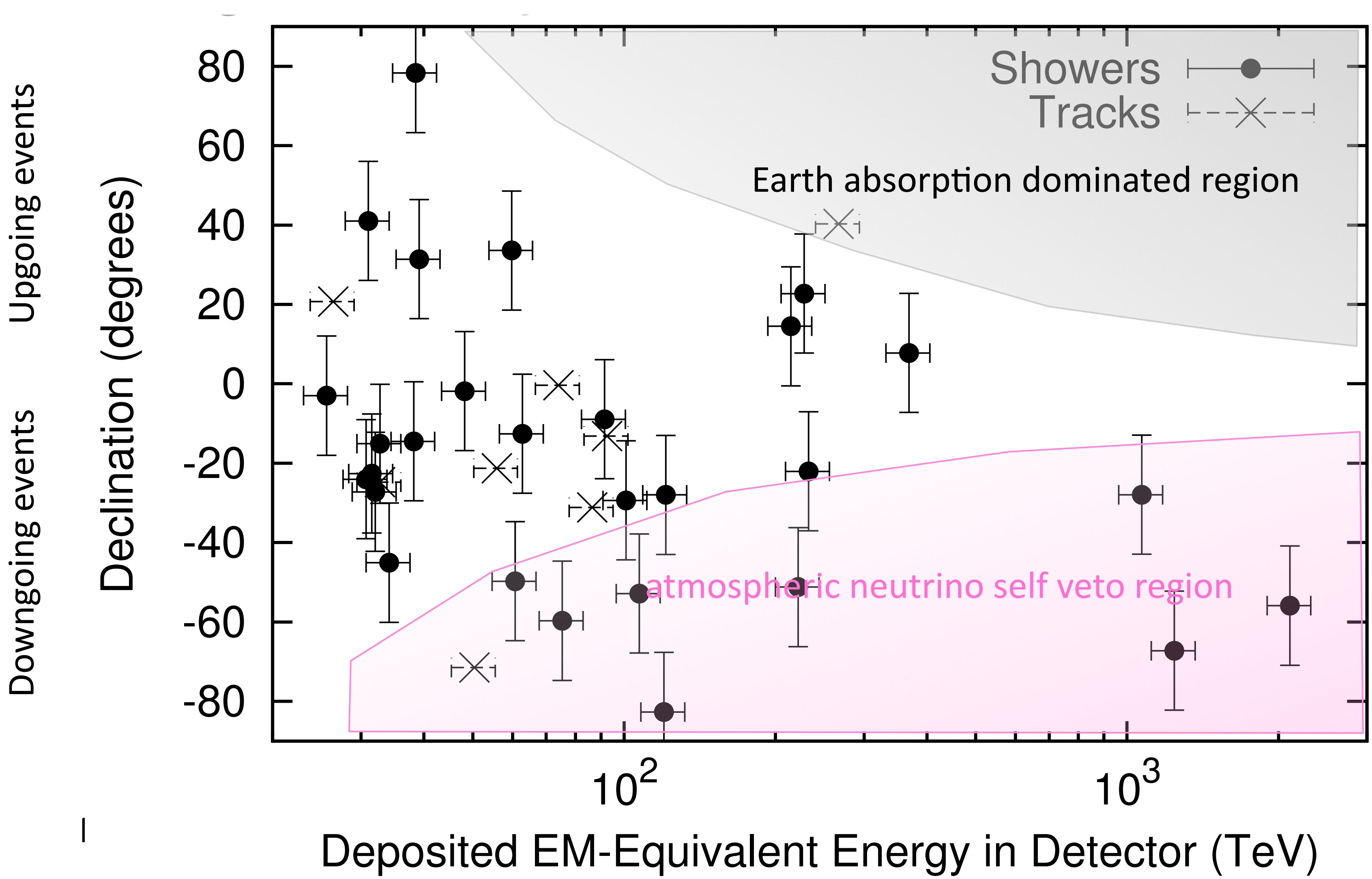
- Reject atmospheric muons (and neutrinos) from air shower.
- Above about 100 to 200 TeV every muon track is most likely astrophysical if the shower axis is aligned with IceTop.

IceTop is too small for serious science impact that is not why it was built.
However, we can test the technique.



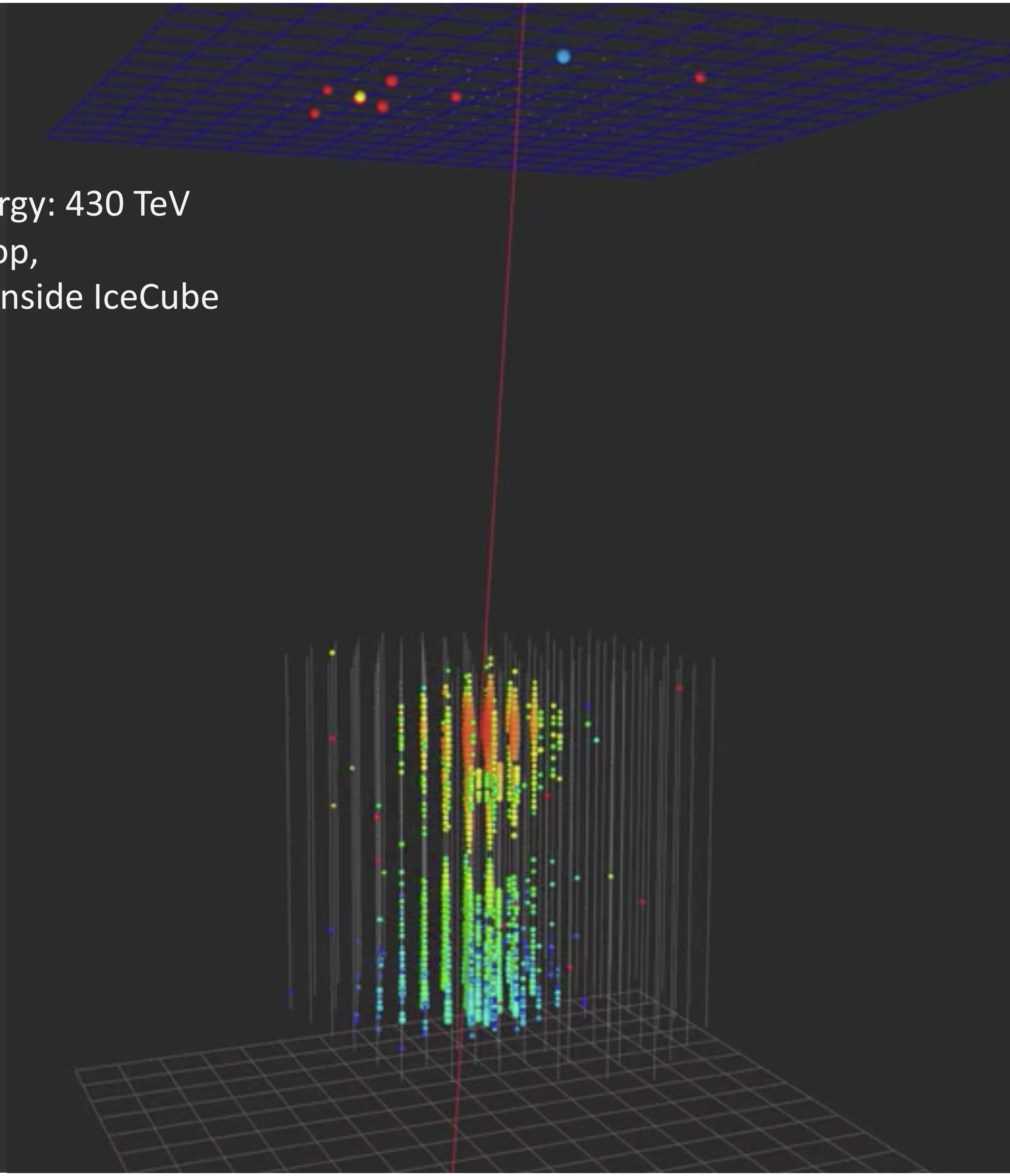
Events with small zenith angles only pass through both detectors.

Reminder: High energy starting events):
Declination vs energy



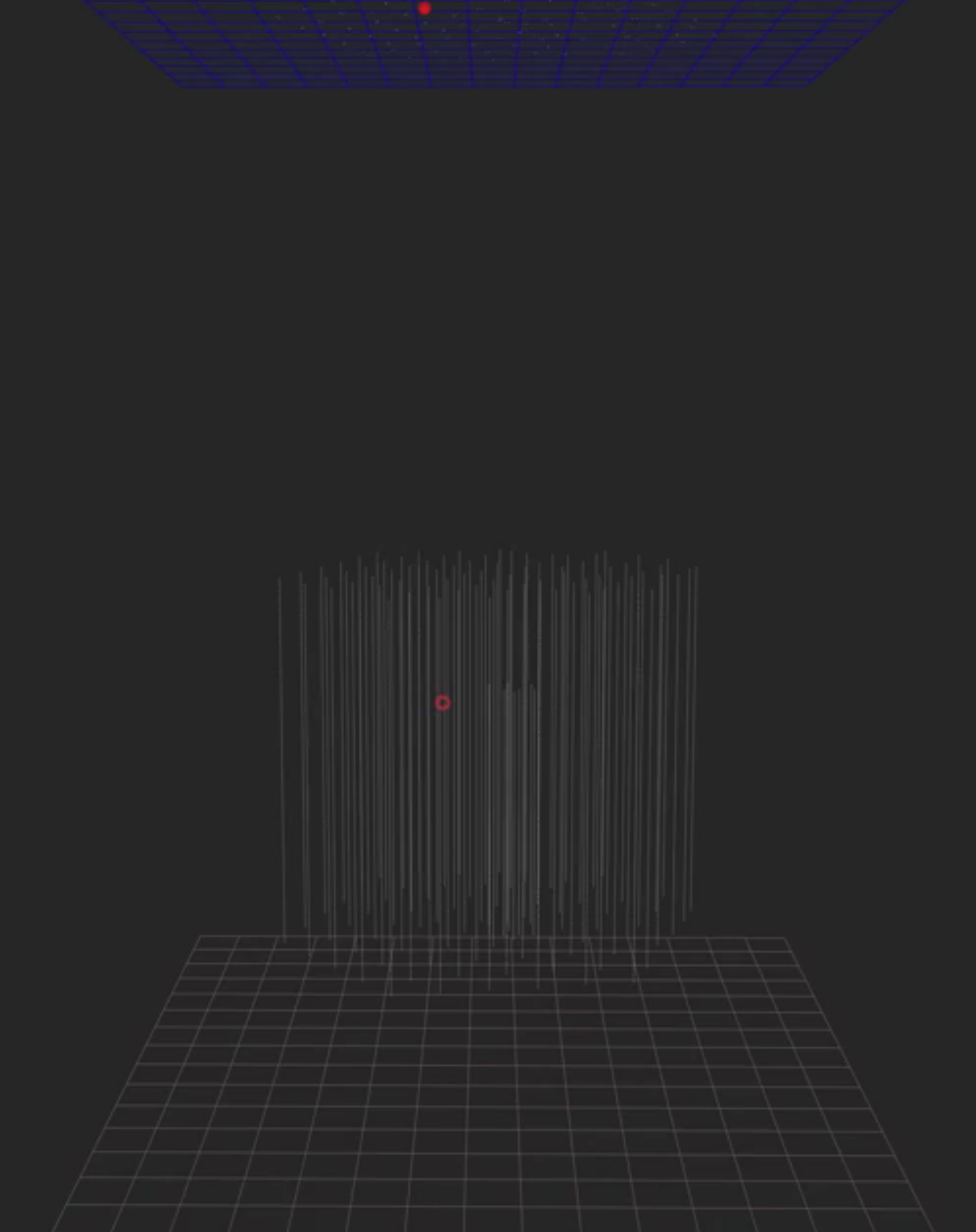
Most events in Southern hemisphere (downgoing).

Deposited energy: 430 TeV
No hits in IceTop,
Vertex clearly inside IceCube
(“HESE” Veto)

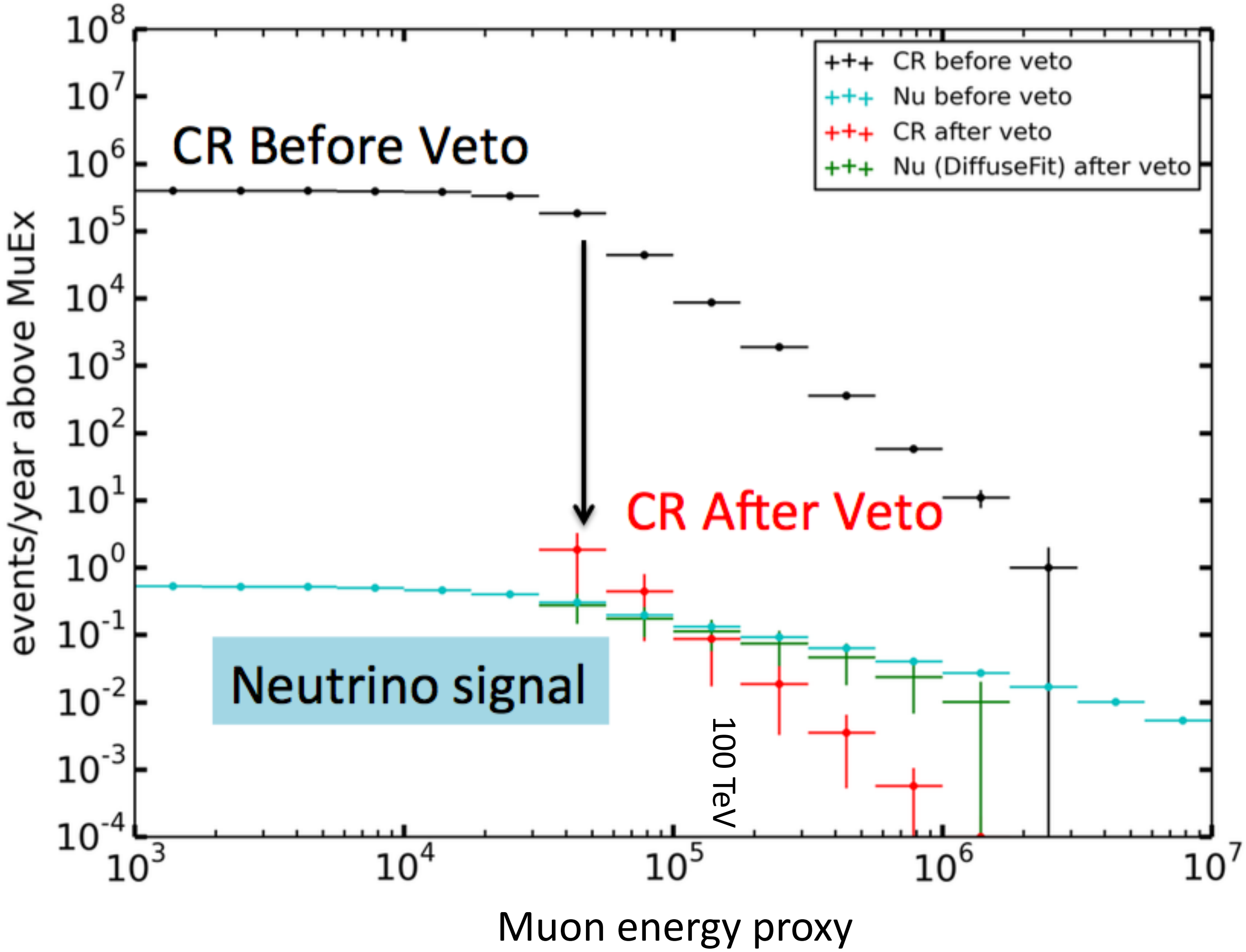


Almost vertical muon neutrino event

Deposited energy: 430 TeV
No hits in IceTop,
Vertex clearly inside IceCube
("HESE" Veto)



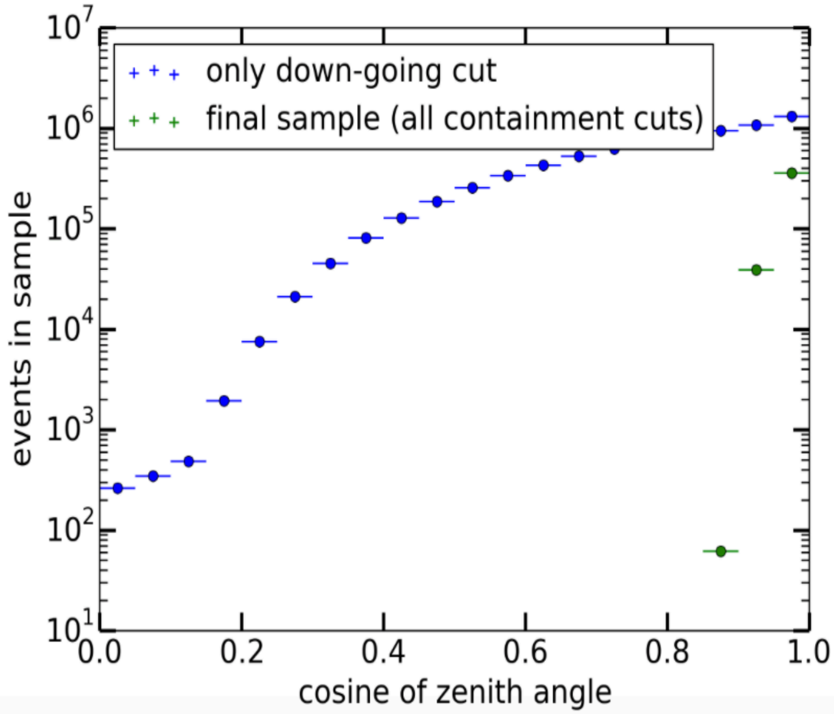
Veto efficiency for IceTop

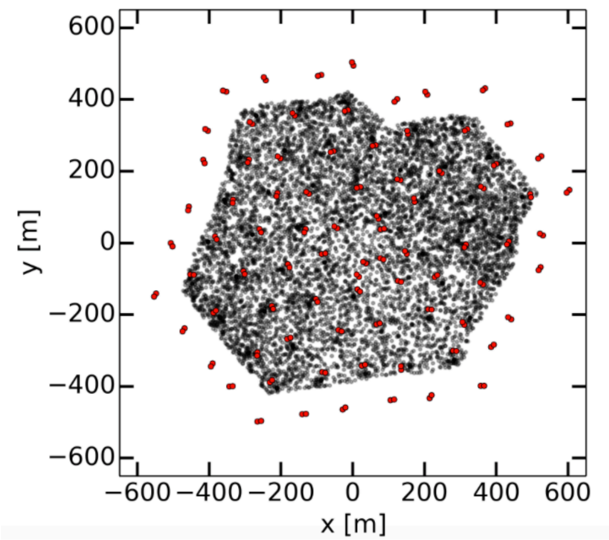


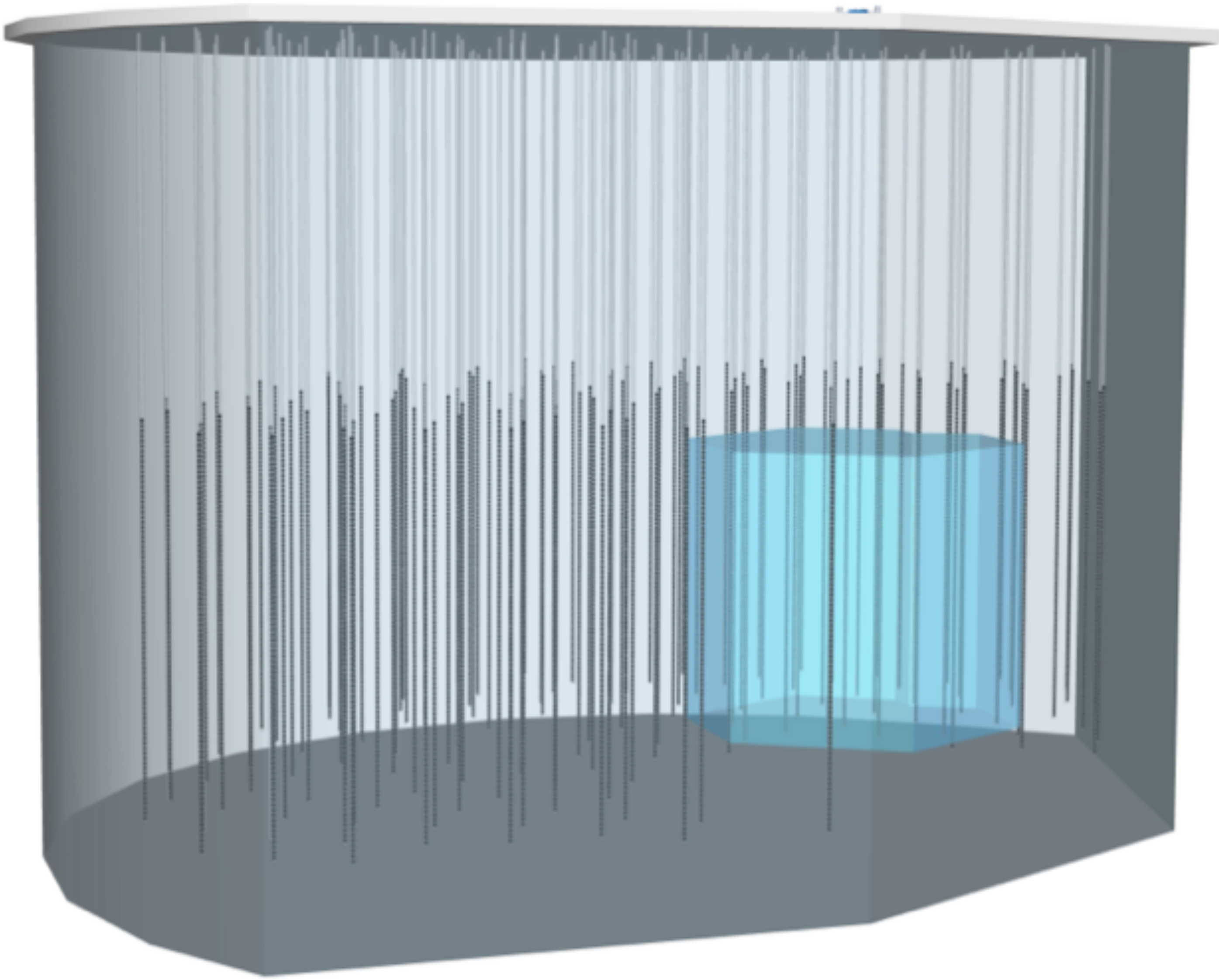
→ Neutrinos begin to dominate energies above 150 TeV (muon energy)

Veto efficiency for IceTop

Zenith angle coverage very small: only almost vertical events pass.
Is a large detect worth the gain in neutrino events.

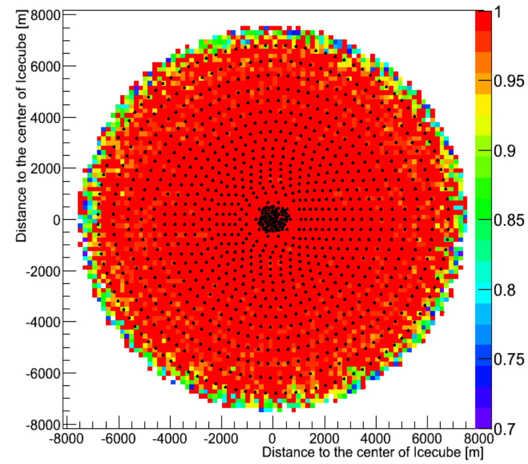




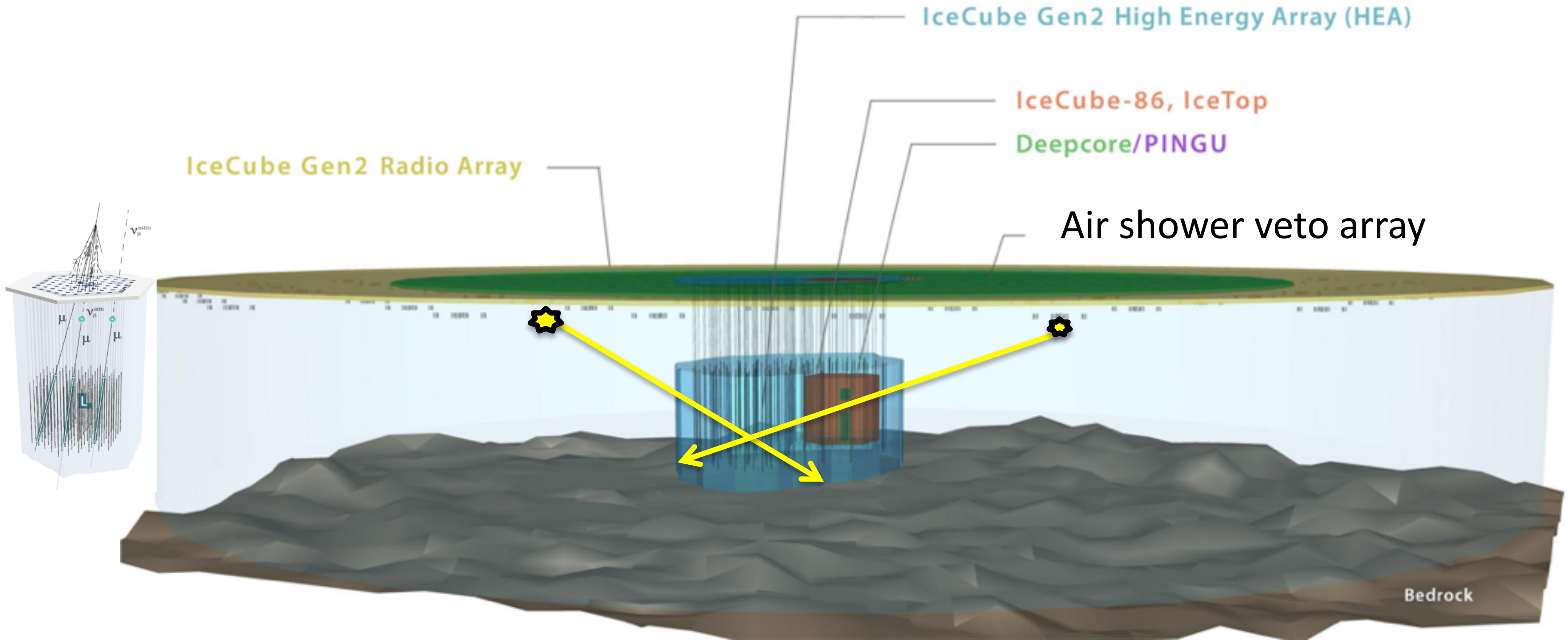


Extended surface veto detector

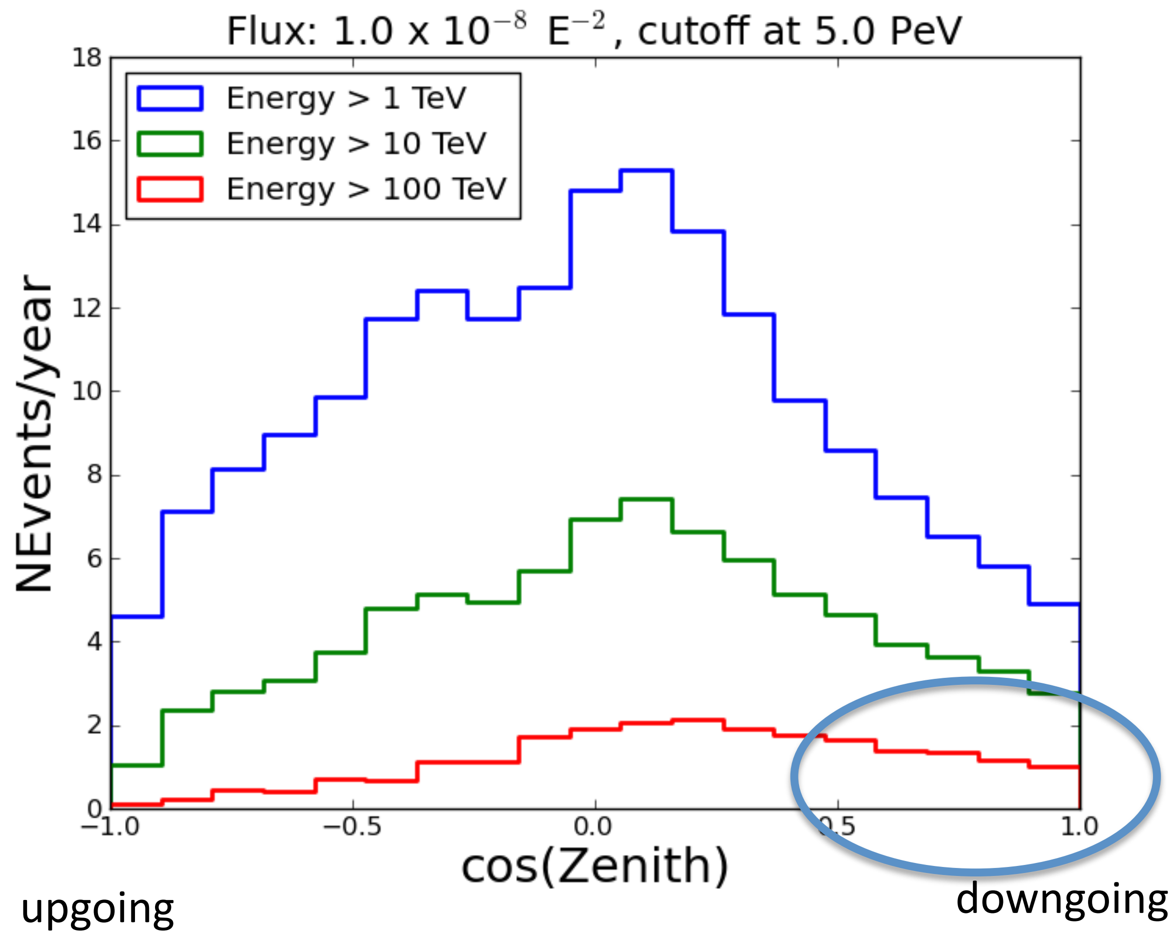
Can make use of the huge neutrino target volume outside the instrumented volume.



2000 to 10000 surface detectors



Muon rates from astrophysical flux in IceCube vs zenith angle



Can we detect some more of these?
We do that already at some level in the HESE analysis (contained neutrino vertex)

If we had surface veto in IceCube, how many signal events would we gain?

IceCube only numbers

- Normalizations for each flux chosen using IceCube flux results (HESE contours)
- All fluxes are simulated without any cutoff

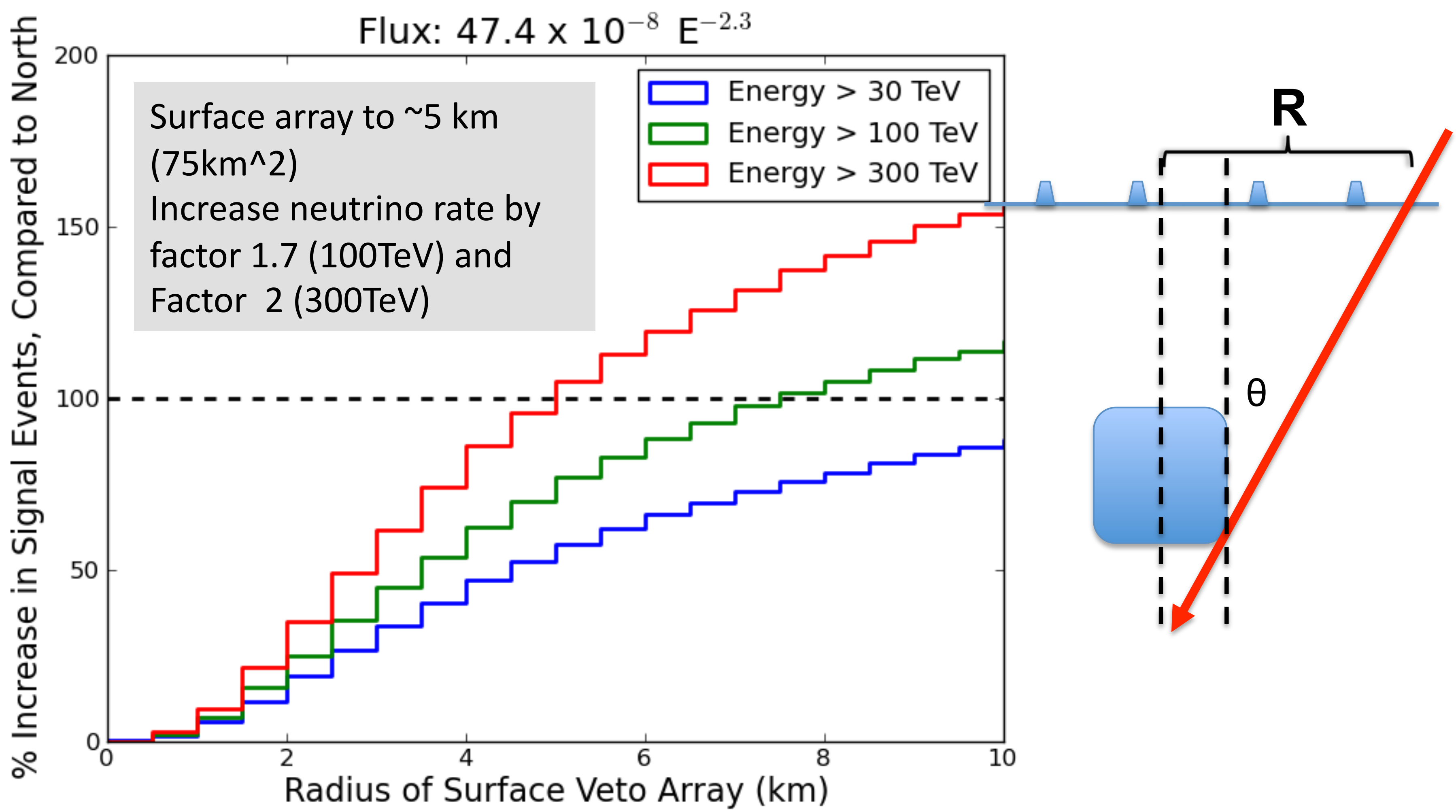
Northern hemisphere (upgoing, zenith > 85°)

Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	**9**
$E^{-2.7}$	740	110	7
Atm.	15000	500	5

Southern hemisphere (< 85°) (downgoing, zenith < 85°)

Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	80	44	18
$E^{-2.3}$	160	57	**13**
$E^{-2.7}$	590	100	10
Atm.	10500	350	5

If we had a surface veto, how many signal events would gain?



Add flux but also specific source candidates

- Interesting sources are between 45 deg and ~60 deg zenith angle
- would suggest ~ 75 km^2

Source	Declination
Vela region	~ -45°
Centaurus A	-43°
RX J1713-3946	-40°
PKS 2155-304	-30°
Galactic Center region	-29°

Scintillator panels Shipped to Pole for testing

PMT + electronics

Weight of one panel: 204 lbs movable by:

- 3 strong people
- 4 weaker people
- 1 Matt

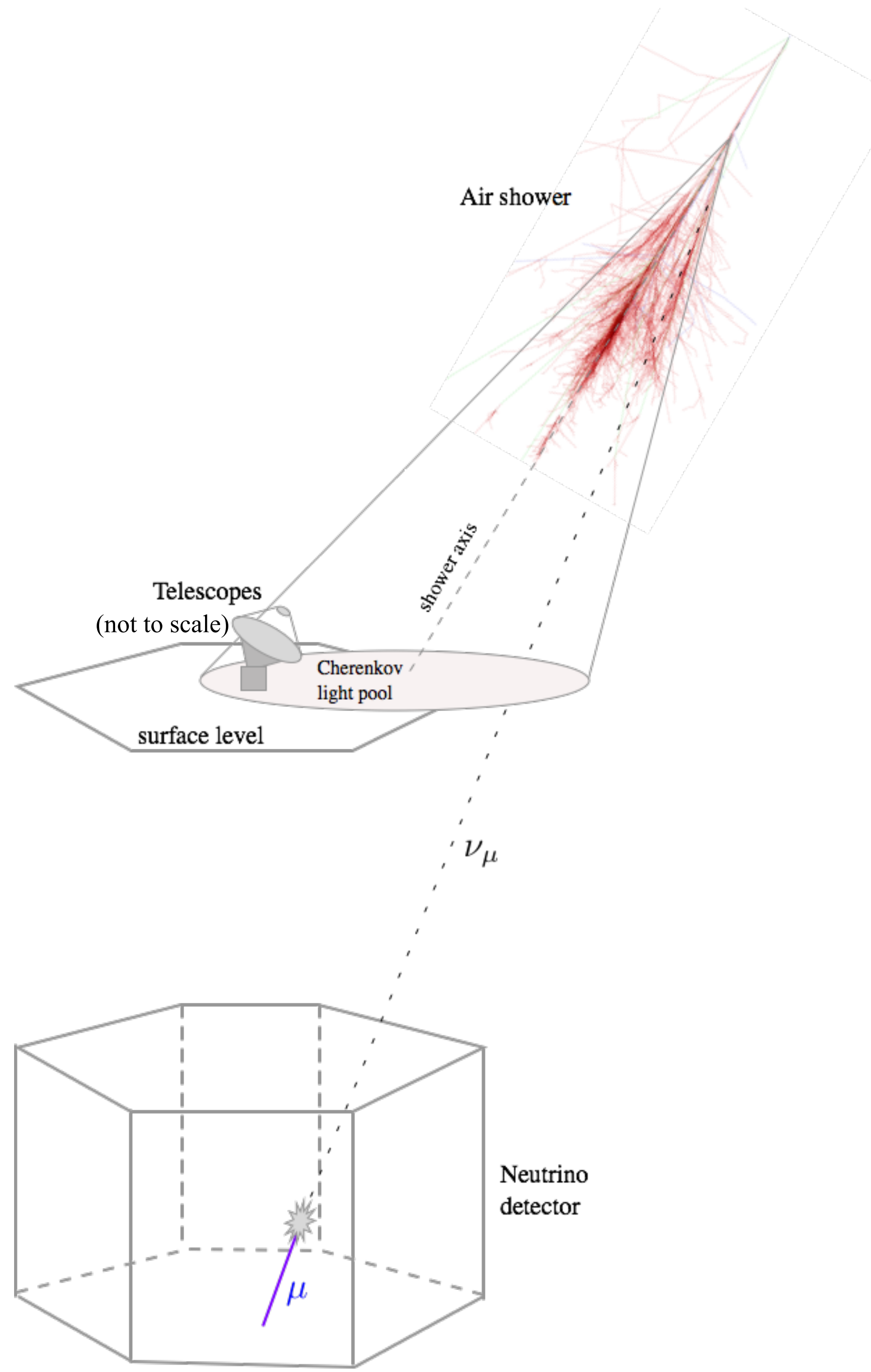
A) "Pizza-Banana"
#1:Pizza_Margherita
#3:Banana_Pancake
B) "Grilled-Muffin"
#2: Grilled_Cheese
#4: English_Muffin
Spare: Garlic_Naan

Total cargo:

- One crate containing the 4 panels + cables.
- One additional box shipped with spare parts and one additional DAQ box

Air Cherenkov Veto

- Several attractive features:
  - Intrinsic directionality
  - Relatively large natural spacing – light pool diameter of hundreds of meters
  - Low energy threshold (~50 TeV?) possible – simulations ongoing & in situ data coming
  - Moderate cost, $\mathcal{O}$($100k-$3M) per km^2 footprint, depending on sky coverage and threshold
- Challenges:
  - Restricted duty factor (10-20%?)
  - Need to keep optical elements snow-free – SPT experience



Summary/Conclusions on Veto

- IceTop can veto background above ~150 - 200TeV muon energy at zenith angles.
- Background drops rapidly with energy (more than factor 10 for every factor 2 in energy).
- Initial studies suggest that a veto detector can be cost effective component of an upgrade. However, cost are not insignificant and details matter. Still more work to do.
- Working model for Gen 2 veto design parameters:
  - Area: 75km^2
  - Energy threshold: 100 TeV (muon energy in deep detector)
  - Detector coverage: 0.5 to 1×10^{-3} (eg.: 10,000 x $7.5m^2$, for ref.: MINOS used about 30,000 m^2)
  - Cost : $40M to $50M (very rough estimate)
- Core array (high quality surface detector station above each Gen2 string: Cosmic ray science (30x rate of IceCube/IceTop)

There are still open questions:

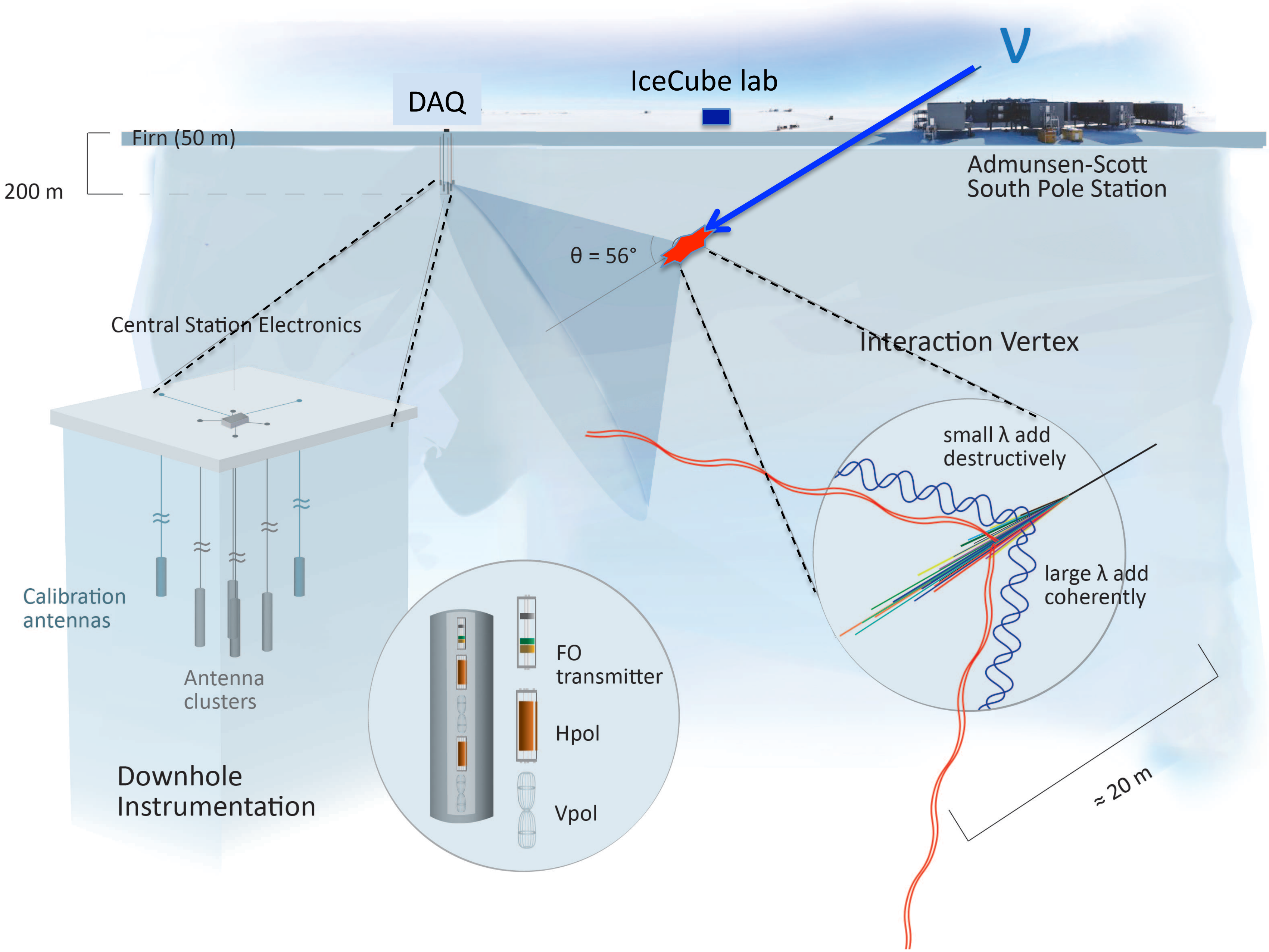
- **Maintenance** (snow drift)
- Environmental impact considerations
- How much do muons contribute at larger zenith angles?

Radio detection and Gen2

IceCube SAC meeting
October 2015

Albrecht Karle
University of Wisconsin-Madison

Detection of ultrahigh-energy neutrinos in ARA



Radio detectors, quick review

1) Be as close as you can be to events (so signals appear strong at the detector)

→ Directly embed antennas in ice

(Thresholds: ANITA (balloon borne): 10^19 eV, ARA (in-ice): ~10^16.5eV)

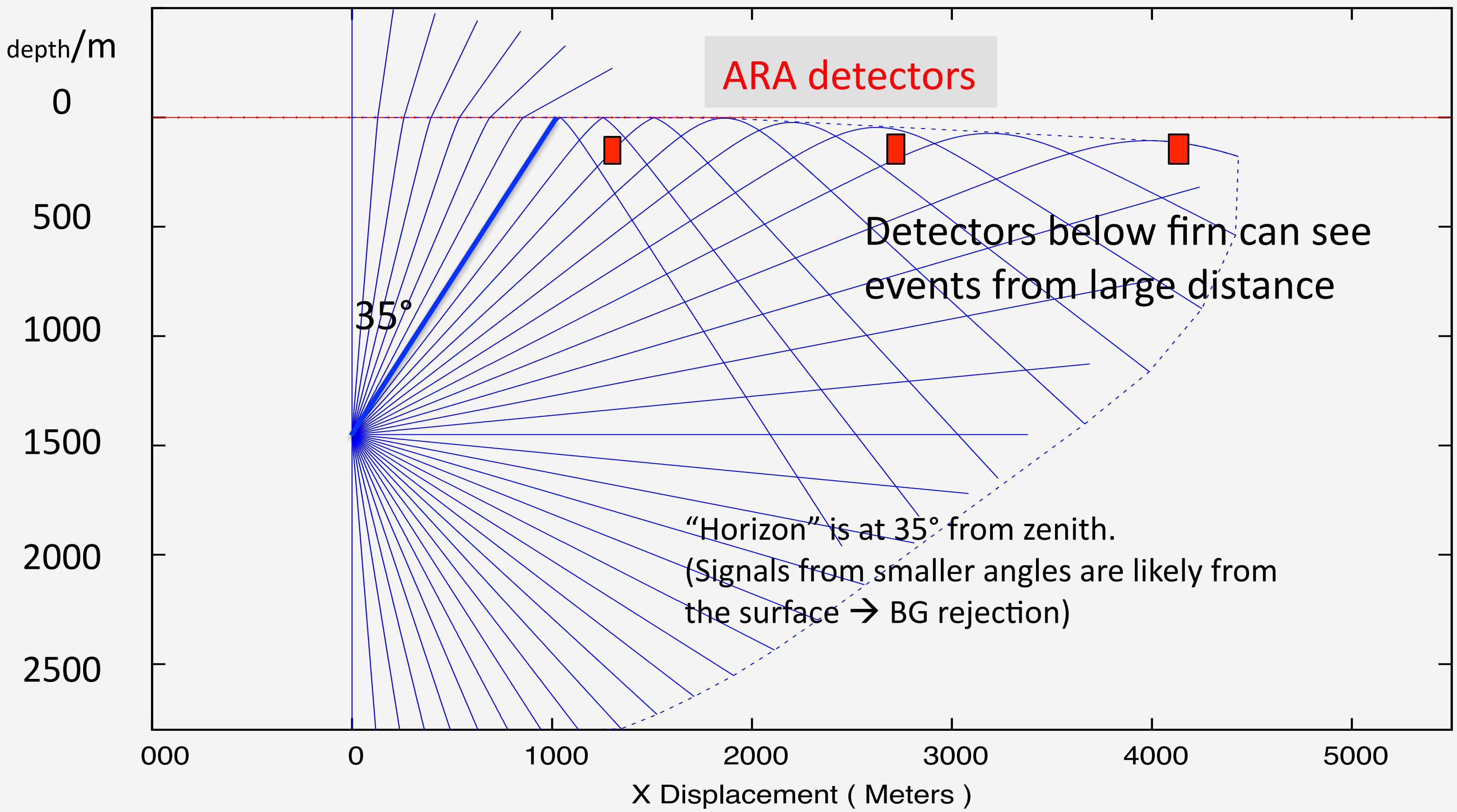
2) Need radio-transparent ice to see far away

3) Need as much solid angle as possible:

→ Ideally go below firn layer (below ~100m), so constrained to fit in a hole;

at the end a cost benefit calculation (drilling vs hardware)

Calibration pulser deployed with IceCube at 1500m observed with ARA detectors in more than 3 km distance



Askaryan Radio Array

Currently installed: 3 design stations + 1 shallow prototype Testbed

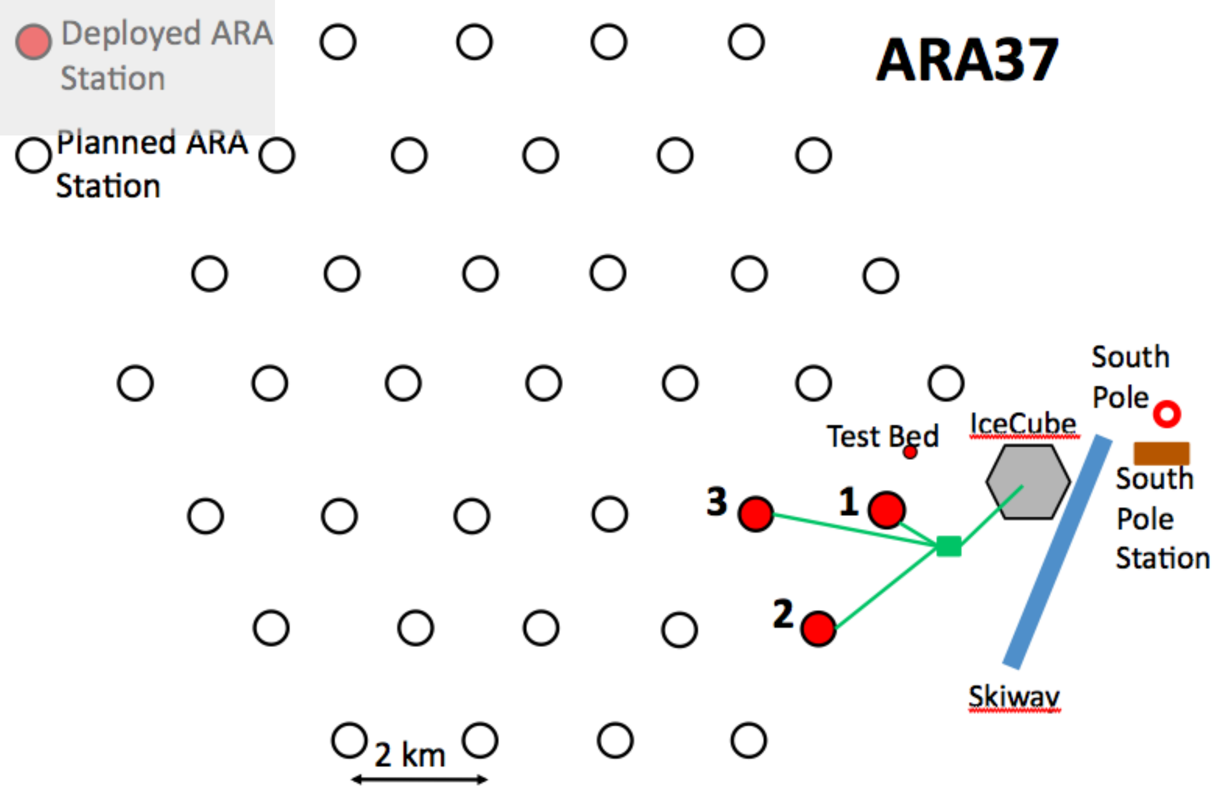
Each station is an autonomous neutrino detector

- 2 km spacing to maximize total sensitivity

Next installation phase

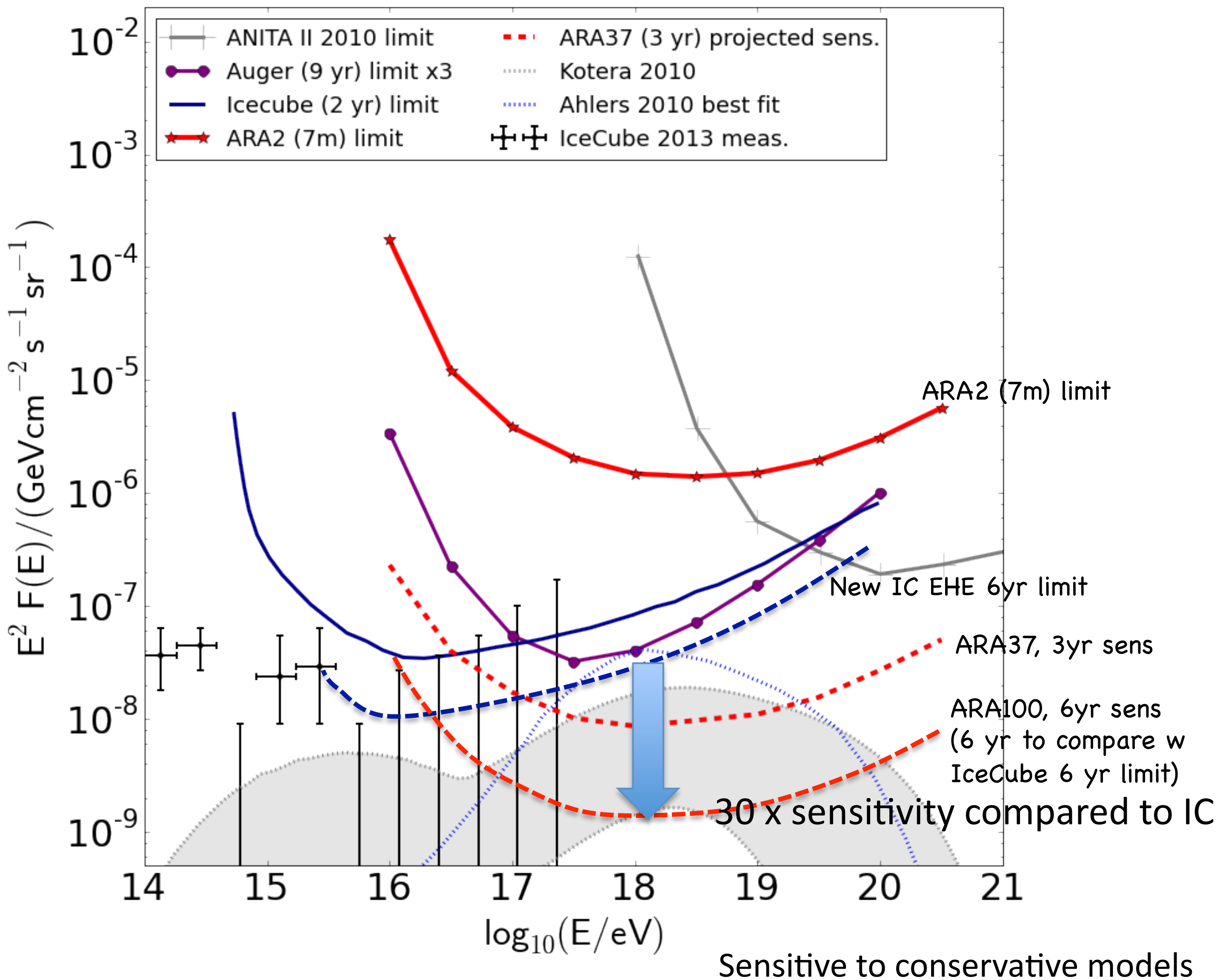
- 2 - 4 more stations

Full ARA37 covers ~100km^2

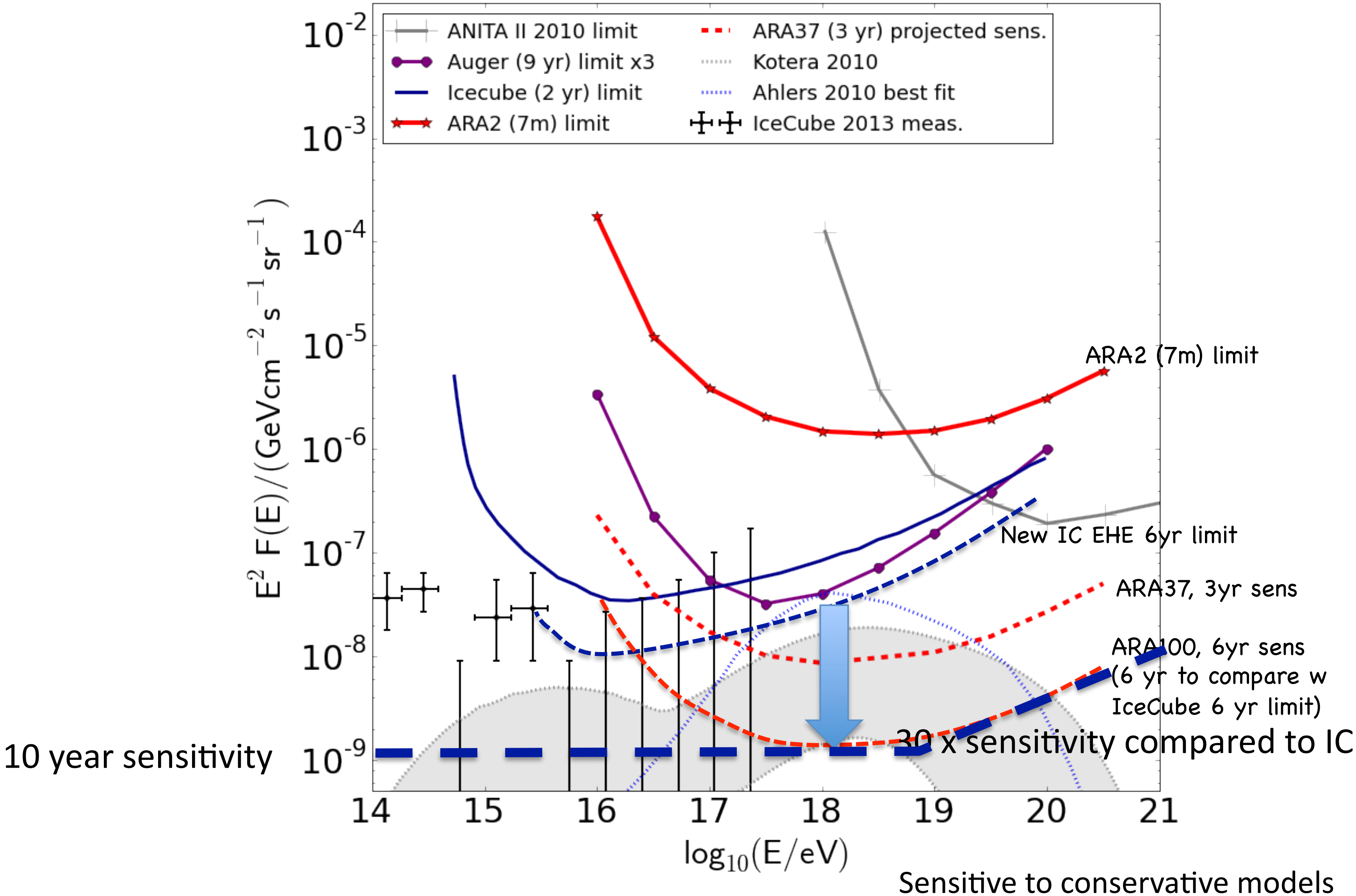


Gen2 science goals at the super PeV energies

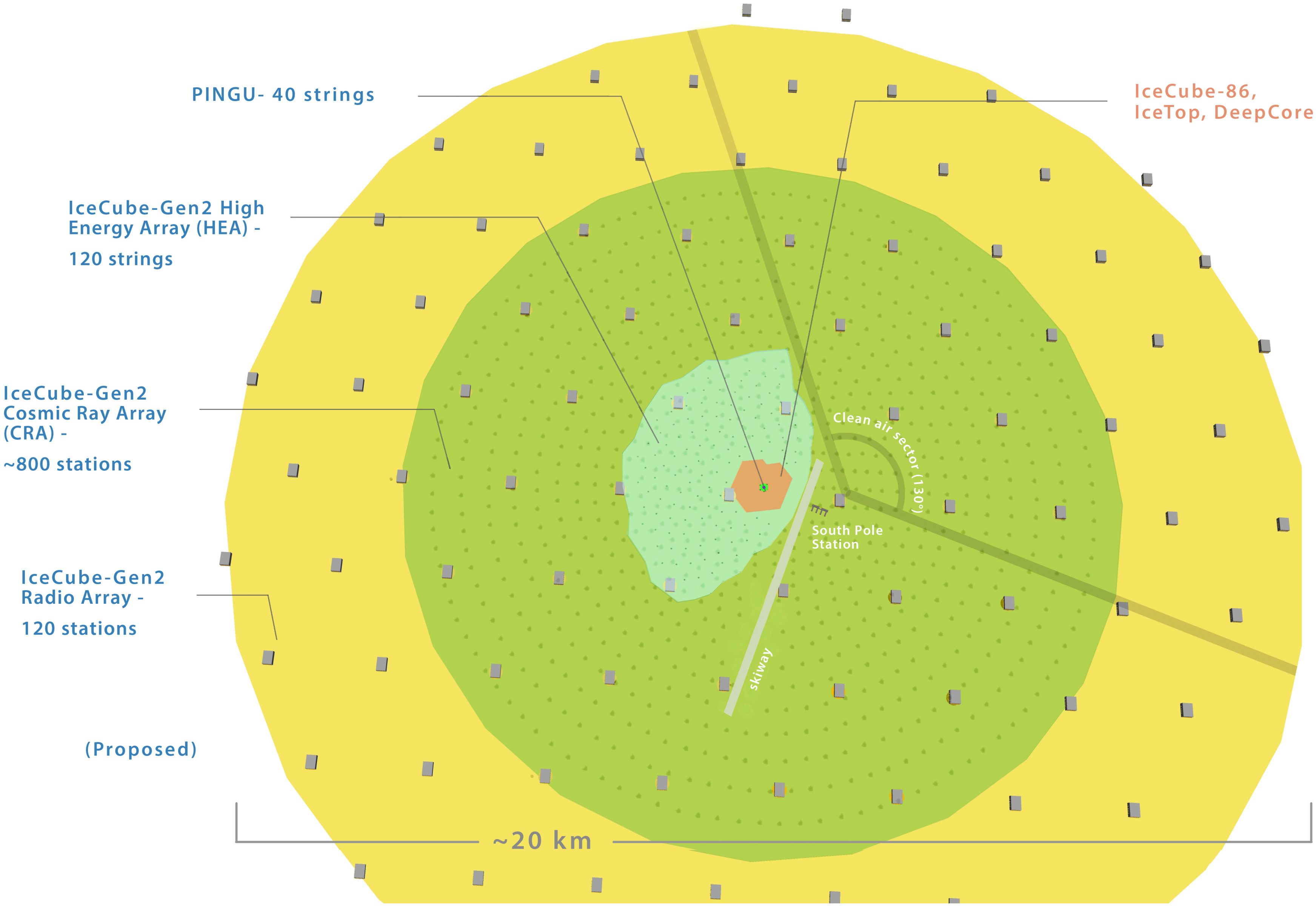
- Cosmogenic (GZK) neutrinos
  - Build a sufficiently large detector to probe even conservative models with low fluxes: 100 PeV to 10 EeV
- Super PeV neutrino flux,
  - IceCube events observed to beyond 3 PeV, possibly close ~10 PeV
  - Measure this spectrum and extend to higher energies: PeV to 100 PeV



ANITA II 2010 limit
Auger (9 yr) limit x3
Icecube (2 yr) limit
ARA2 (7m) limit
ARA37 (3 yr) projected sens.
Kotera 2010
Ahlers 2010 best fit
IceCube 2013 meas.
$E^2 F(E)/(GeVcm^{-2} s^{-1} sr^{-1})$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
14
15
16
17
18
19
20
21
$\log_{10}(E/eV)$
ARA2 (7m) limit
New IC EHE 6yr limit
ARA37, 3yr sens
ARA100, 6yr sens
(6 yr to compare w
IceCube 6 yr limit)
30 x sensitivity compared to IC
Sensitive to conservative models


ANITA II 2010 limit
Auger (9 yr) limit x3
Icecube (2 yr) limit
ARA2 (7m) limit
ARA37 (3 yr) projected sens.
Kotera 2010
Ahlers 2010 best fit
IceCube 2013 meas.
$E^2 F(E)/(GeVcm^{-2}s^{-1}sr^{-1})$
$\log_{10}(E/eV)$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
14
15
16
17
18
19
20
21
ARA2 (7m) limit
New IC EHE 6yr limit
ARA37, 3yr sens
ARA100, 6yr sens
(6 yr to compare w
IceCube 6 yr limit)
30 x sensitivity compared to IC
10 year sensitivity
Sensitive to conservative models

IceCube-Gen2 Facility

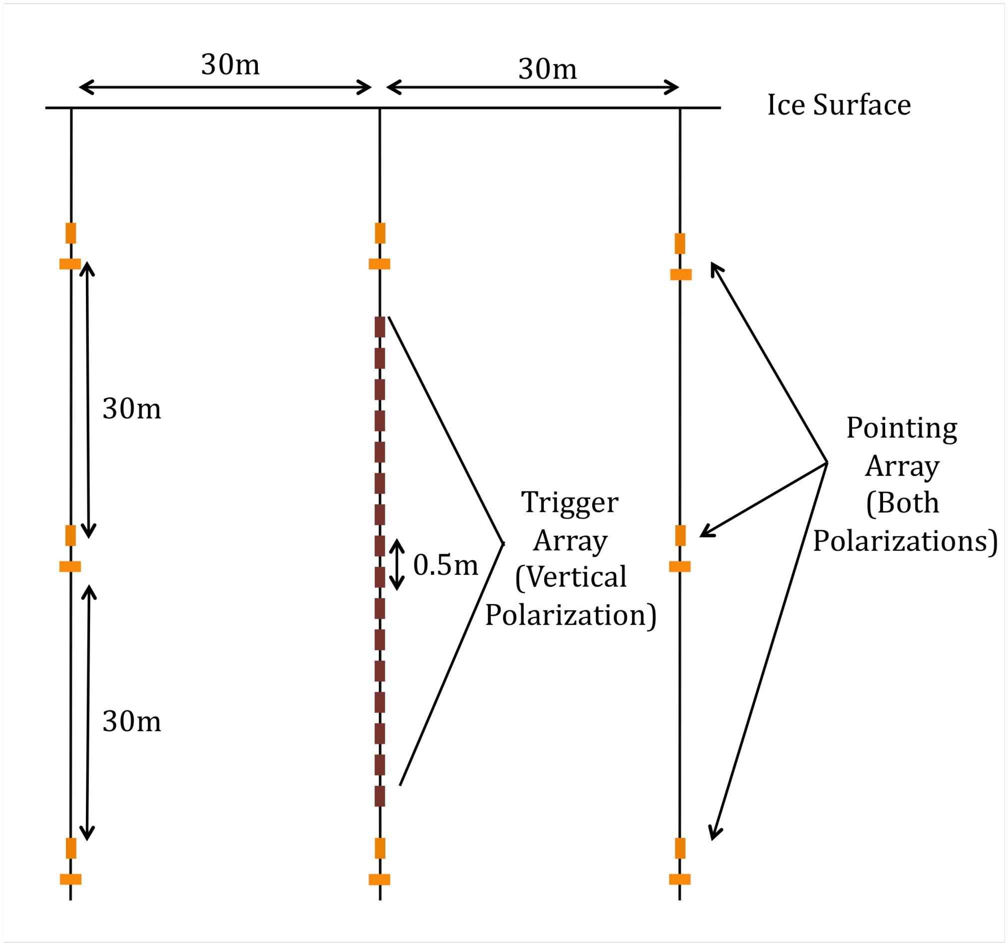


Increasing the energy range

- Can radio narrow the gap to the optical in ice Cherenkov detector?

How Do You Push Down to ~PeV with Radio?

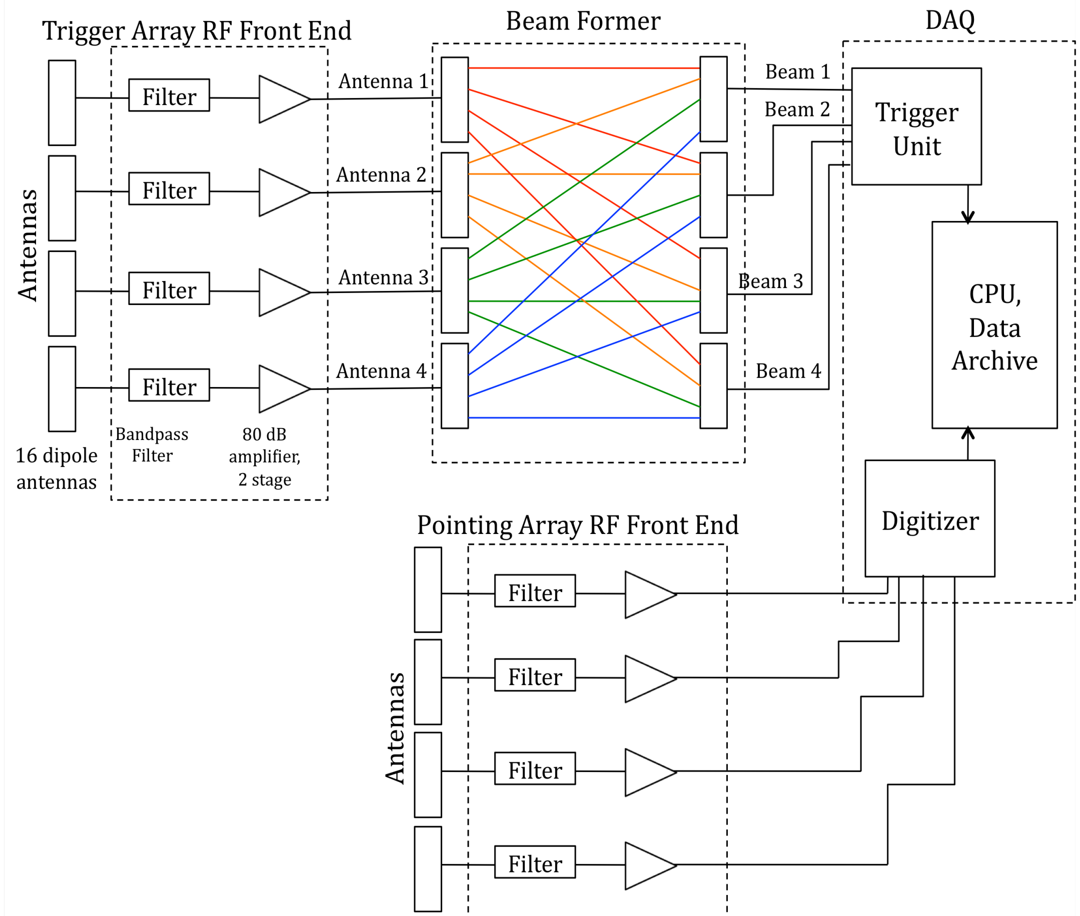
- Need to achieve the highest signal to noise in the detector as possible to see small signals
  → Need extremely high effective gain antenna
- Problem: high gain antennas don't fit down holes, and extremely high gain antennas are hard to make
  – Answer: a phased array of low-gain antennas

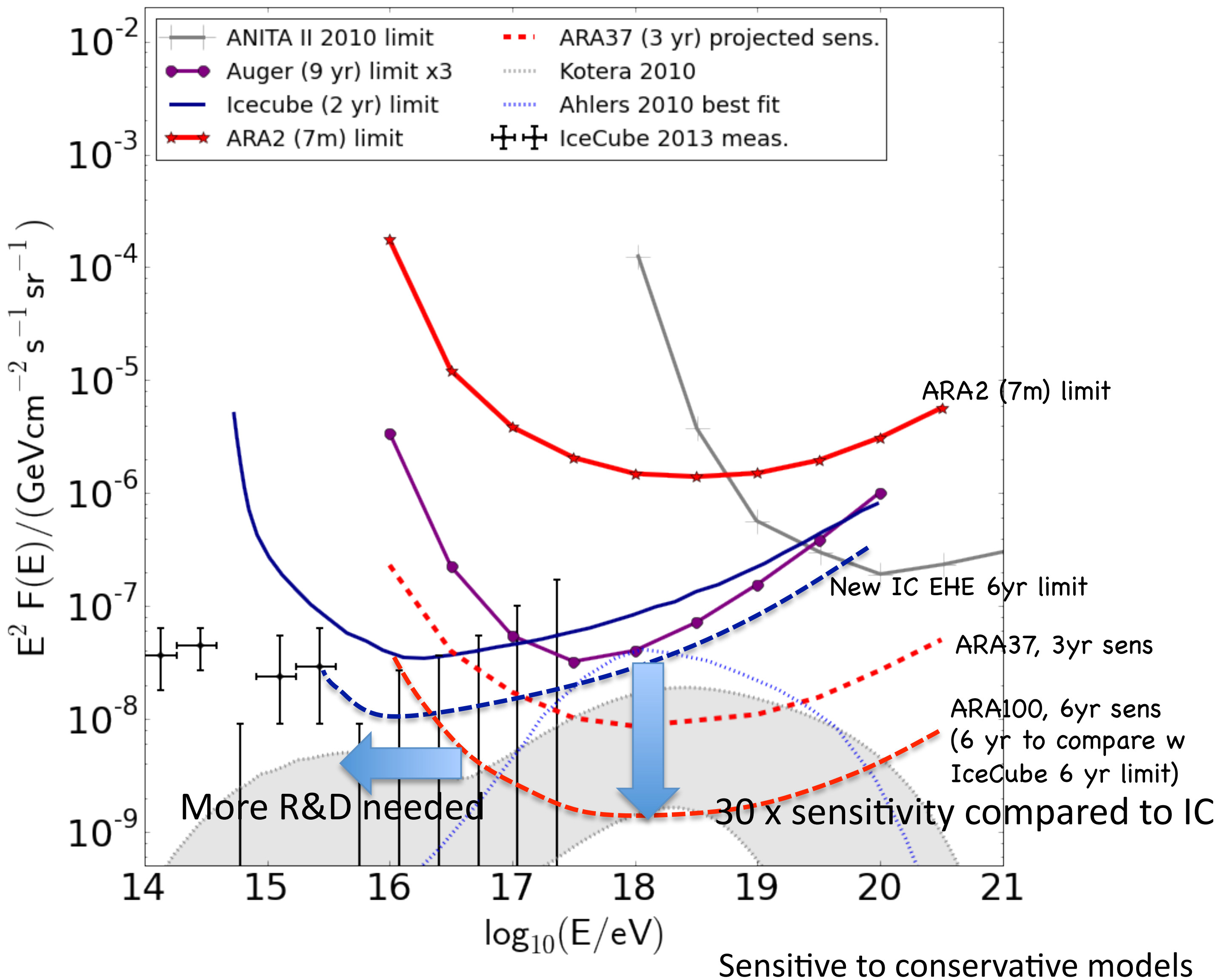


Slide: courtesy A. G. Vieregg

A Phased Array for PeV and UHE Neutrinos

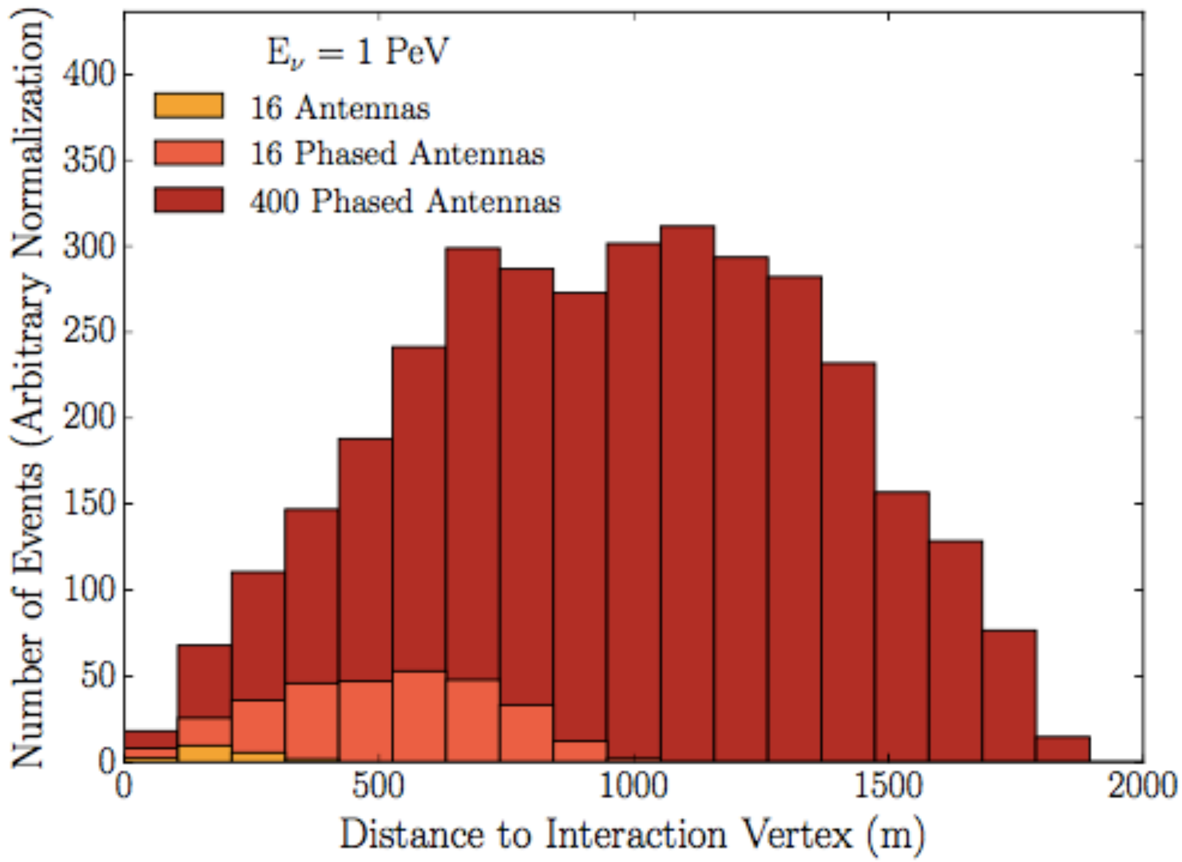
- Beamforming: for a given incident direction, calculate the system delay required between antennas to see the signal in-phase in all the antennas
- The signal is correlated between antennas and noise is uncorrelated: increase the SNR as sqrt(N)
- Create many beams at once to cover the solid angle of interest
- Analog or digital





ANITA II 2010 limit
Auger (9 yr) limit x3
Icecube (2 yr) limit
ARA2 (7m) limit
ARA37 (3 yr) projected sens.
Kotera 2010
Ahlers 2010 best fit
IceCube 2013 meas.
ARA2 (7m) limit
New IC EHE 6yr limit
ARA37, 3yr sens
ARA100, 6yr sens
(6 yr to compare w
IceCube 6 yr limit)
More R&D needed
30 x sensitivity compared to IC
$E^2\ F(E)/(\mathrm{GeVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1})$
$\log_{10}(E/eV)$
Sensitive to conservative models

Figure from 1504.08006



Threshold: ~ 1/sqrt(N_antennas)

Radio and Gen2

- Inclusion of radio array offers unified energy coverage from 100 TeV to 10 EeV at a level of 10^-8/year at a relatively modest cost ($20 to 30M)

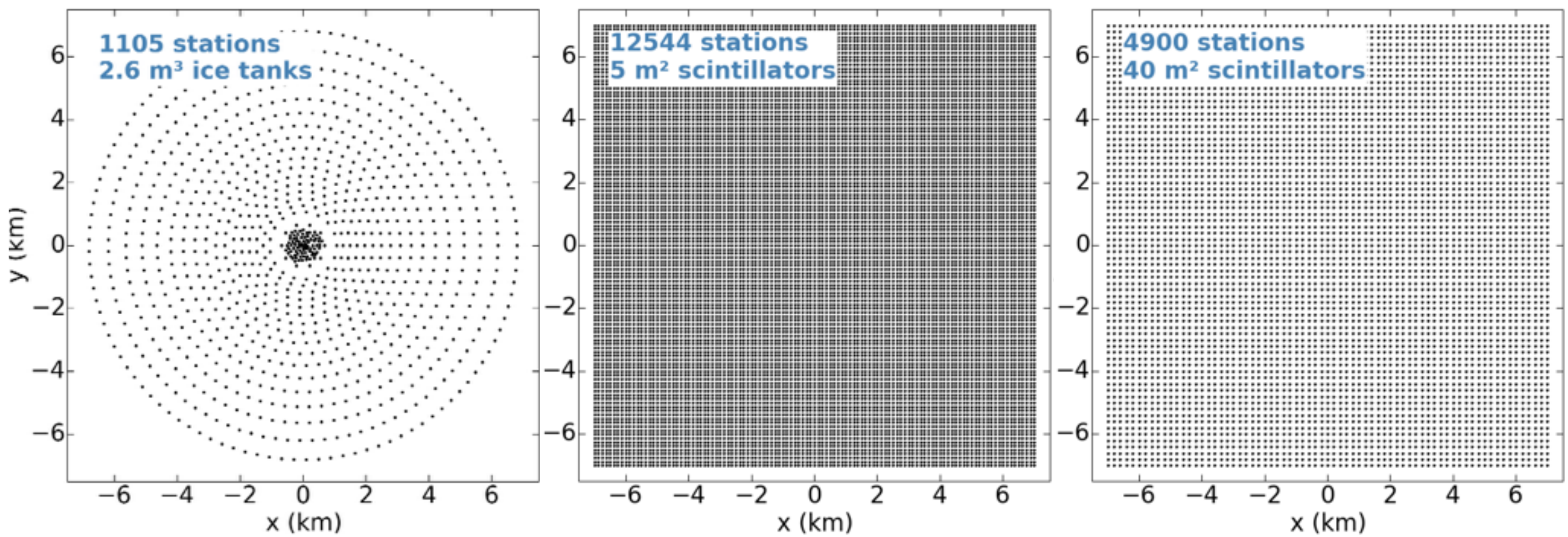
What is the requirement for background rejection?

- For diffuse flux discovery: high purity signal needed. But we don't need that anymore.
- Point source searches:
  - In the Northern hemisphere the ratio is 1:1 above 100 TeV
  - **1:1 is a reasonable benchmark for comparison**
    (at higher energies we can also reject atmospheric neutrinos.)

→For a surface array of 6 km radius the allowed background rate

~ 10 events/yr (IceCube)

~ 40 events/yr (Gen2)



Fill Factor 2×10^{-5}

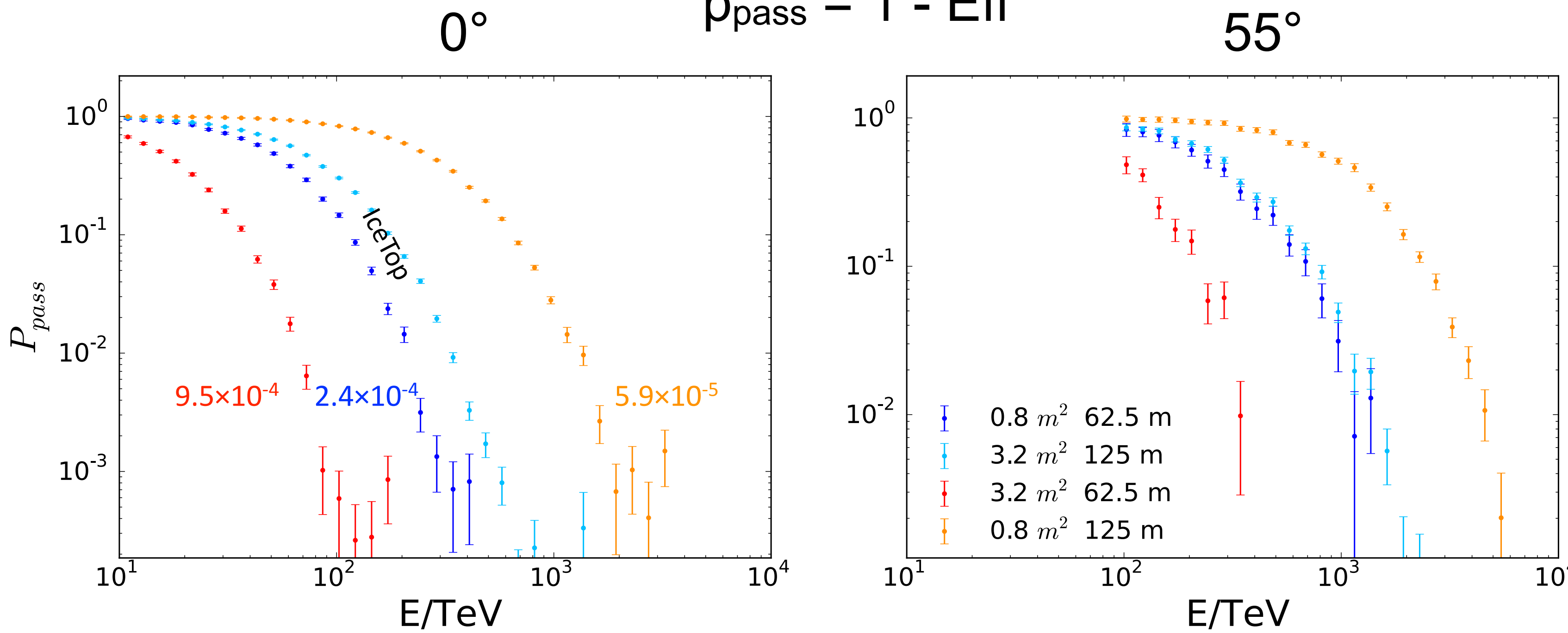
Fill Factor 3.2×10^{-4}

Fill Factor 1×10^{-3}

~IceTop

Passing rates for air showers

$p_{pass} = 1 - \mathrm{Eff}$

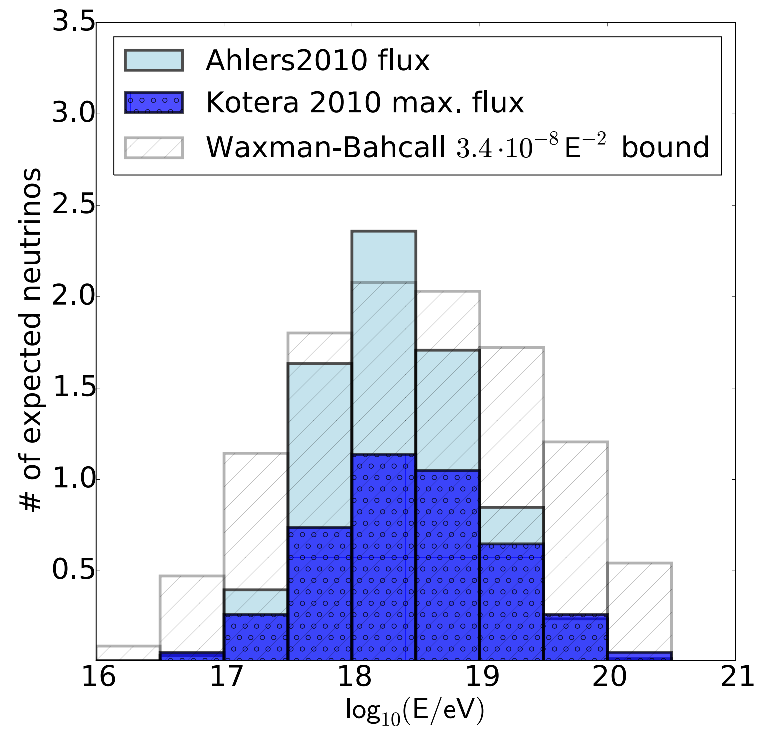


Backup on radio

Comments

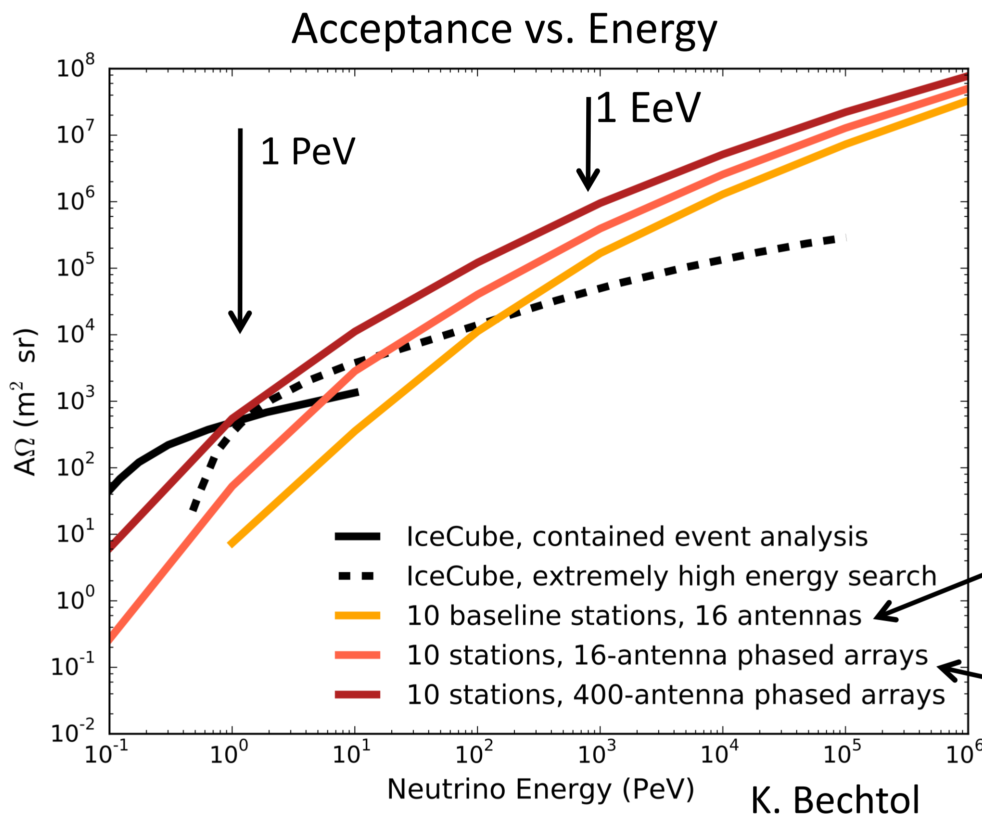
- Cost: ARA37 scale detector, total project cost: $8M
  - (substantial funding at Non-US groups, also for Gen2.)
- Investigating possibilities to lower energy threshold by "phased array" (or interferometric trigger)

Design:
Expect that design of a large array will be significantly different
Compared to current ARA:
- Possibly shallower (50m vs 200m)
- Higher integration of electronics,
- Phased array trigger elements



Events expected in ARA 37 in 3 years.

Acceptanc Summit

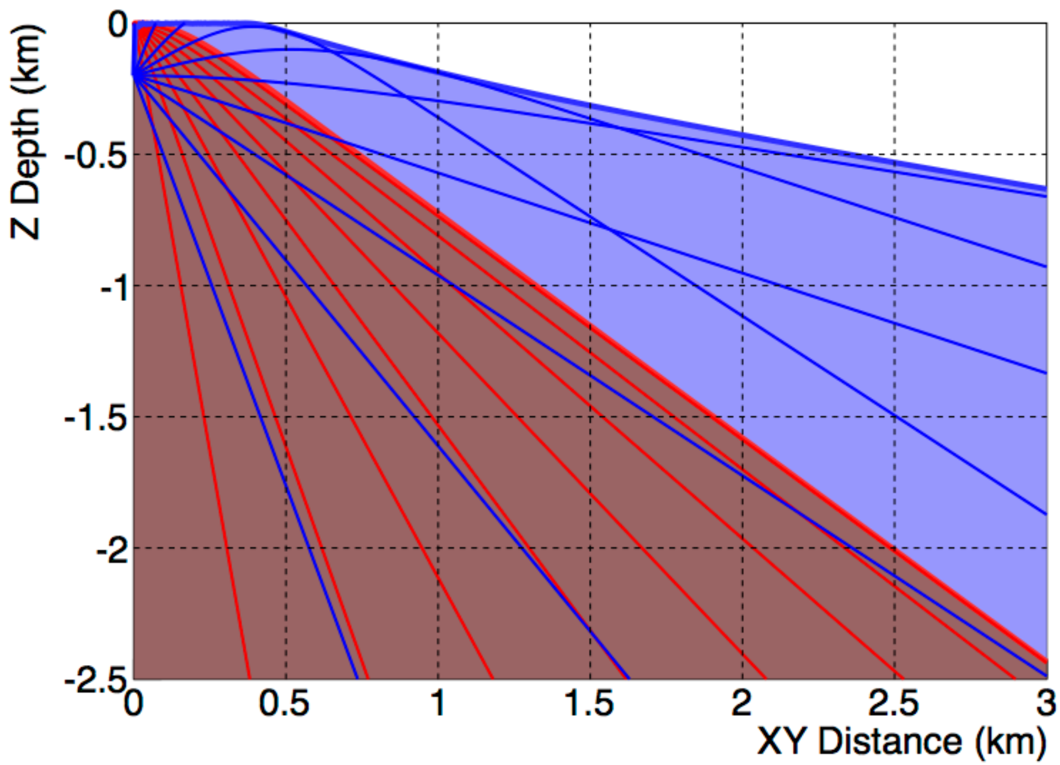


Current approach of ARA, ARIANNA (triggering on each antenna separately)

The phased array outlined earlier (triggering on the coherent sum of antennas)

- Stations act independently and are far apart
- Increase is x10 at low energies and x3 at high energies simply from phasing (yellow → orange)
- Phasing 400 antennas provides good energy overlap with IceCube above 1 PeV

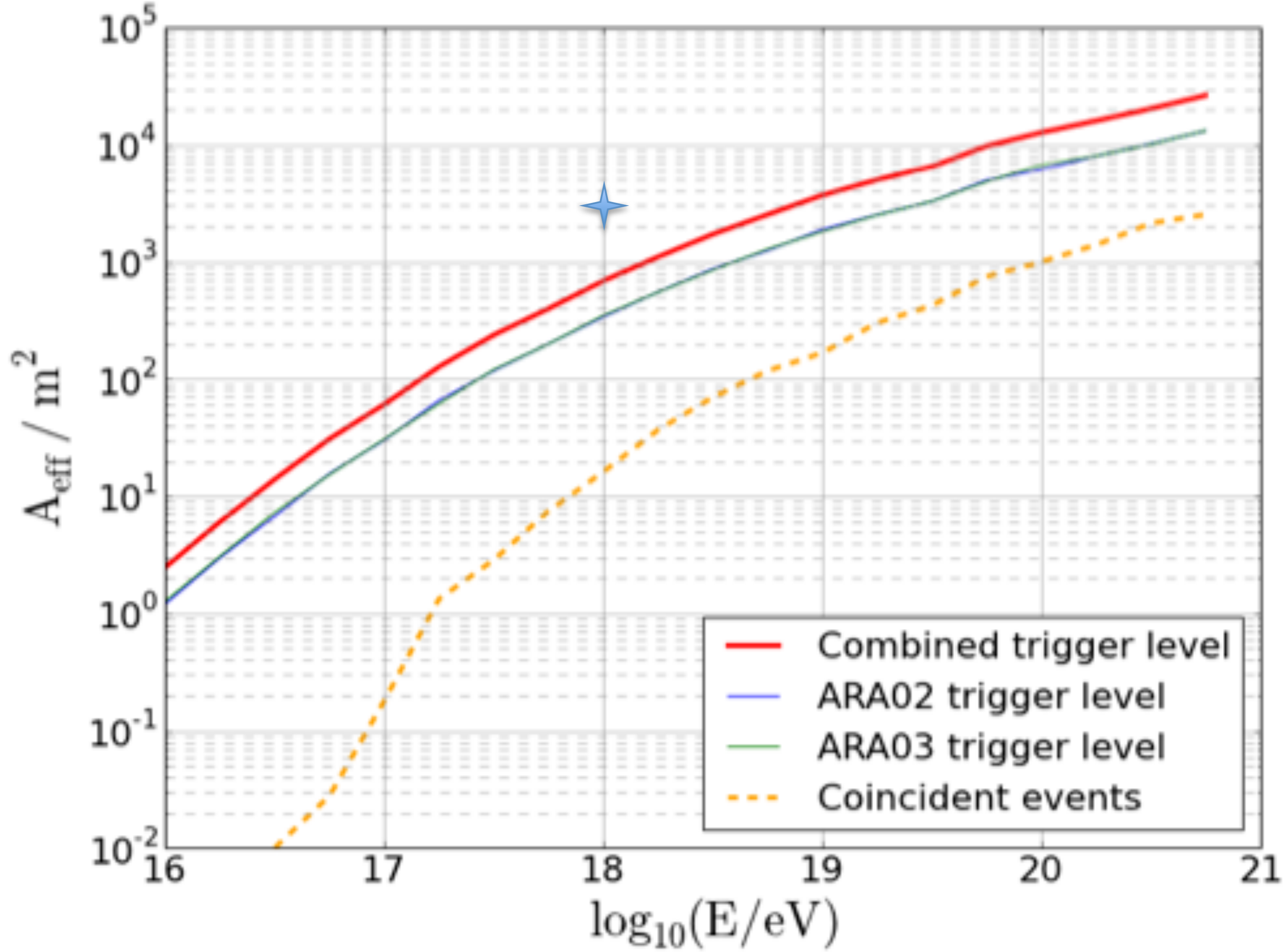
Importance of deployment depth



Red: antenna at 30 m

Blue: antenna at 200 m

- Index of refraction changes rapidly below surface (‘firn’ – compacted snow)
  - 1.35 at surface -> 1.78 below 150 m
  - Significant ray bending – limits observable volume
  - 200 m antennas vs. 30 m deep: factor 3.2 in effective volume (smaller at lower energies)



10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
A_{eff} / m^2
16
17
18
19
20
21
$\log_{10}(E/eV)$
Combined trigger level
ARA02 trigger level
ARA03 trigger level
Coincident events

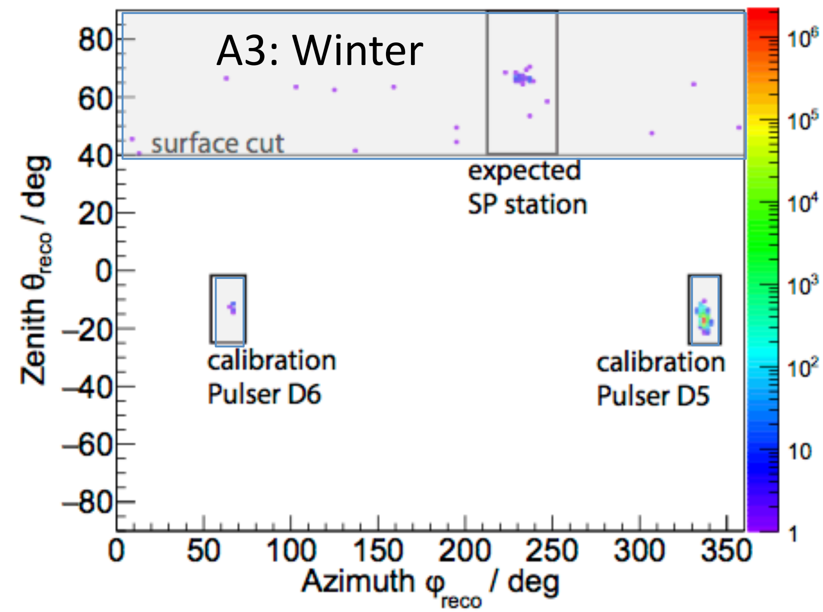
Final event selection: skymap and final cuts

Final skymap: 2 stations, 10 months of data (2013)

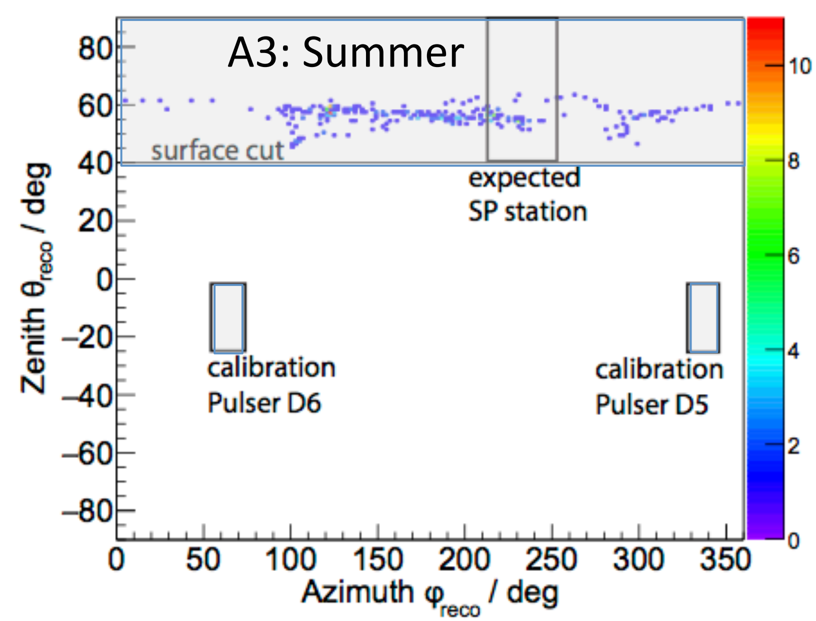
1. Cut on event quality:
   1. Reconstruction quality (residual)
   2. TimeSequence algorithm
2. Cut on signal region in ice
   1. reject surface events: zenith angle > 40
   2. Exclude pulser location

Result after unblinding:

- No neutrino candidates, set upper limit with systematic errors
- Expected (total):
  - 0.1 neutrinos,
  - 0.02 background

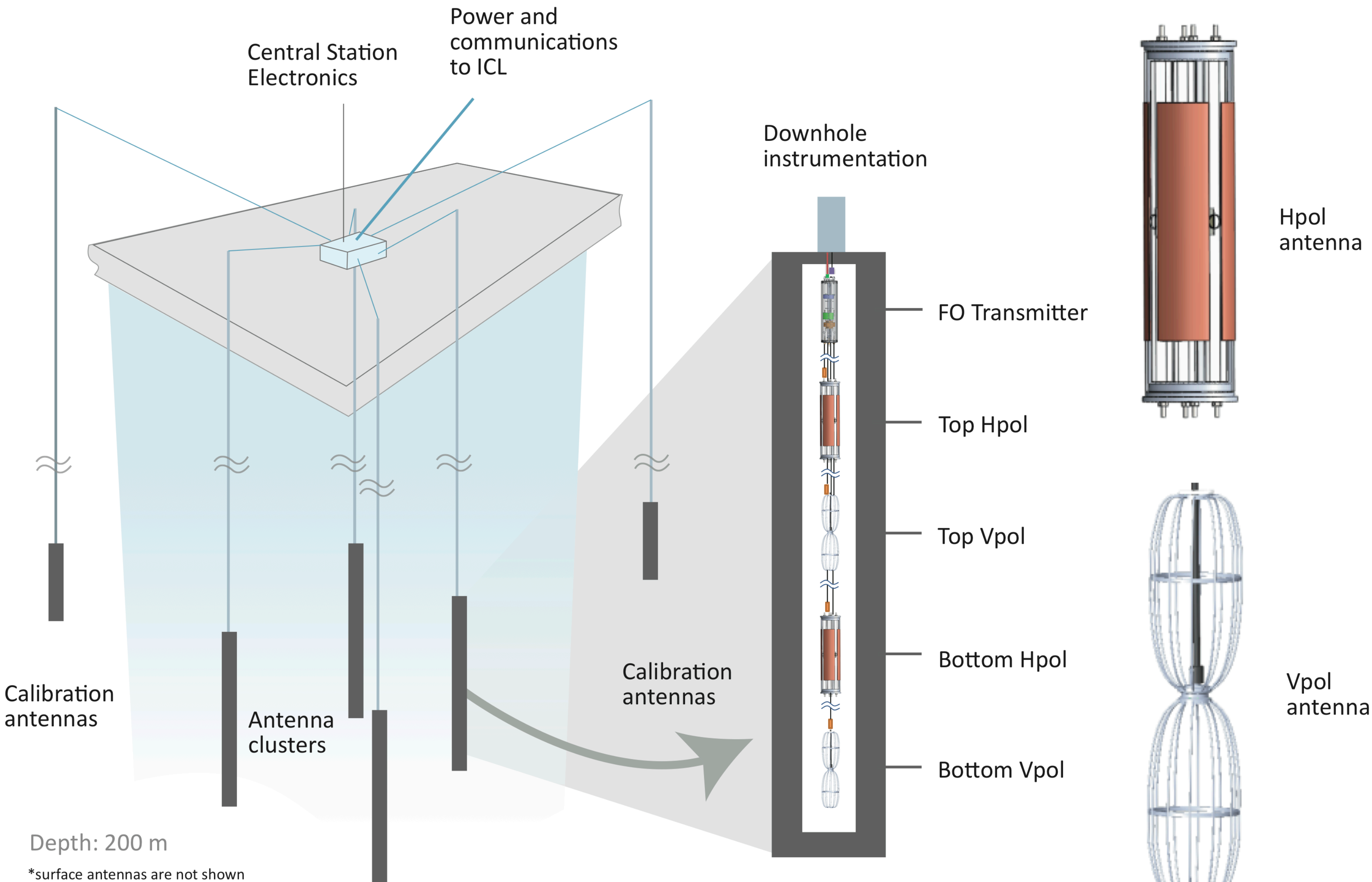


(a)



(b)

ARA Station


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

Calibration

There is no physics background like in water/ice Cherenkov neutrino detectors:

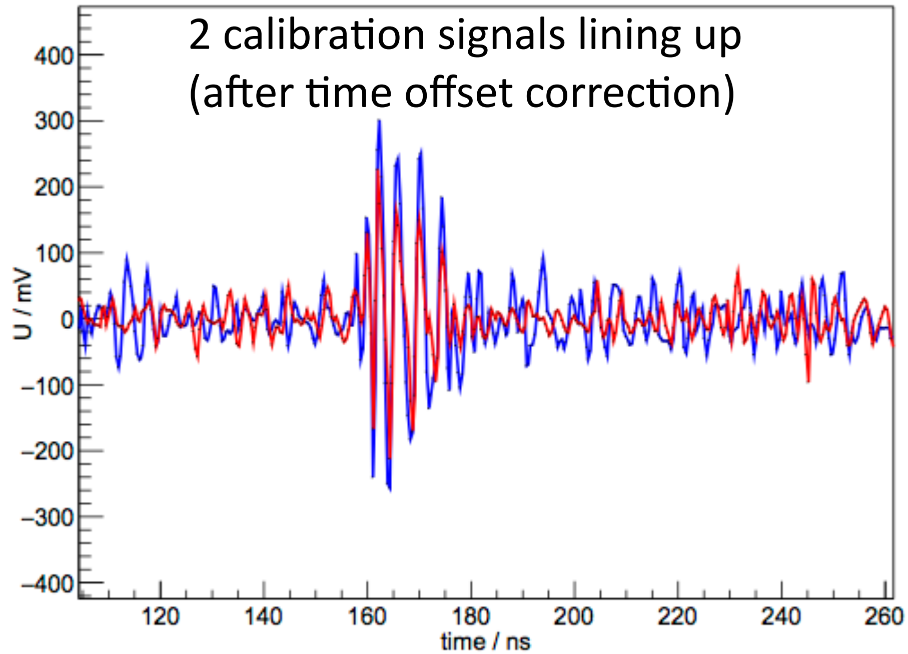
No muons, no atmospheric neutrinos,
no equivalent to single photo electrons
Only thermal noise and man made backgrounds.

→ ARA uses various radio pulsers:

- Local pulser antennas, embedded with detector
- Deep pulser (1500m) deployed with IceCube
- Pulser on IceCube lab building
- Portable pulsers from the surface

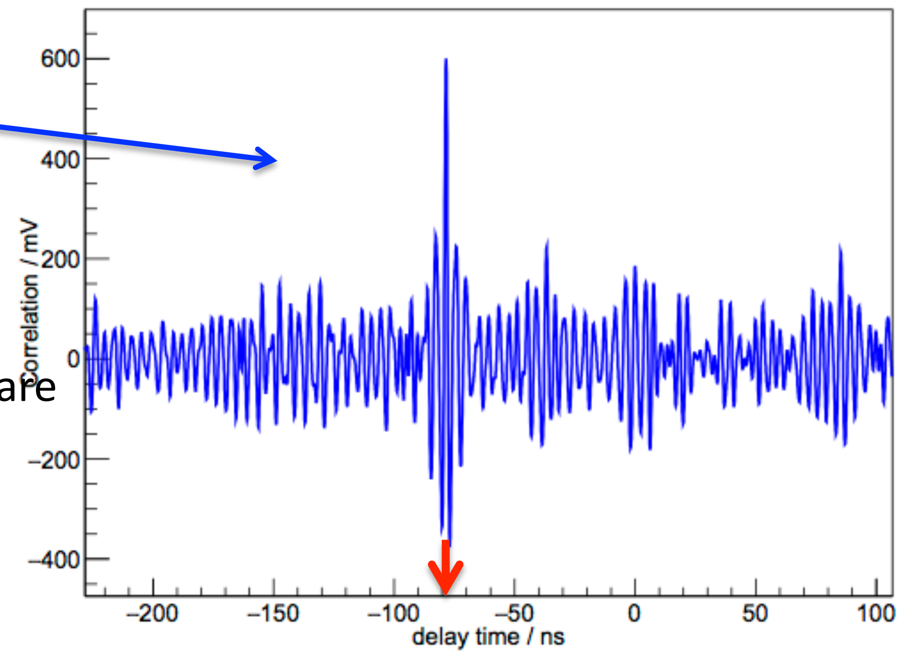
Reconstruction

Based on time differences of signals of antenna pairs.



How to measure a time difference?

Shift in time such that they maximize the correlation function.



Typical resolution: 100psec

Do this for all time differences and compare minimize