A Next Generation IceCube

Arlington, VA
April 24, 2014

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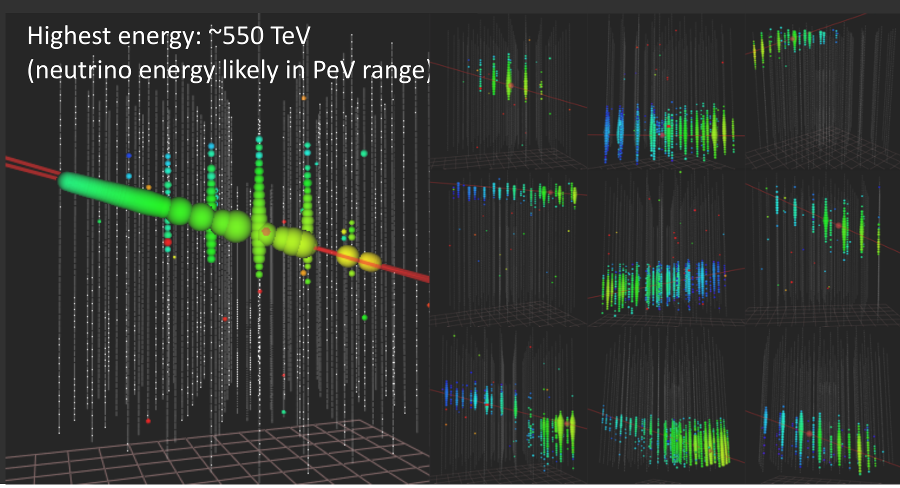
IceCube results

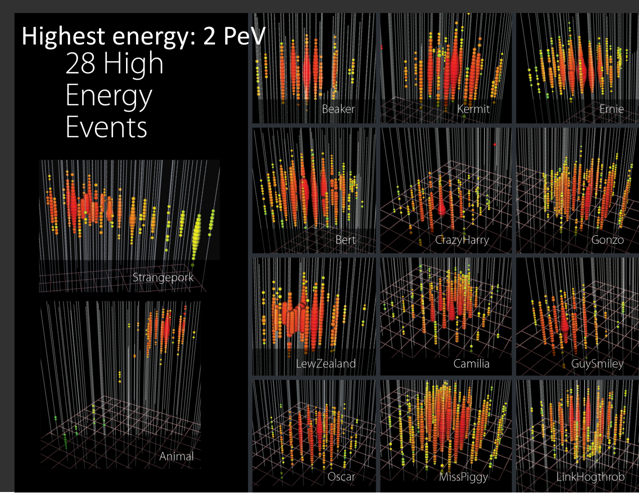
Through going muons

- Northern hemisphere
- Neutrino events (best fit) above 100 TeV muon energy:
  - Astrophysical: 10 events/yr
  - Atmospheric: 10 events/yr
- Significance in first 2 years of data: 3.9 sigma (prel.)

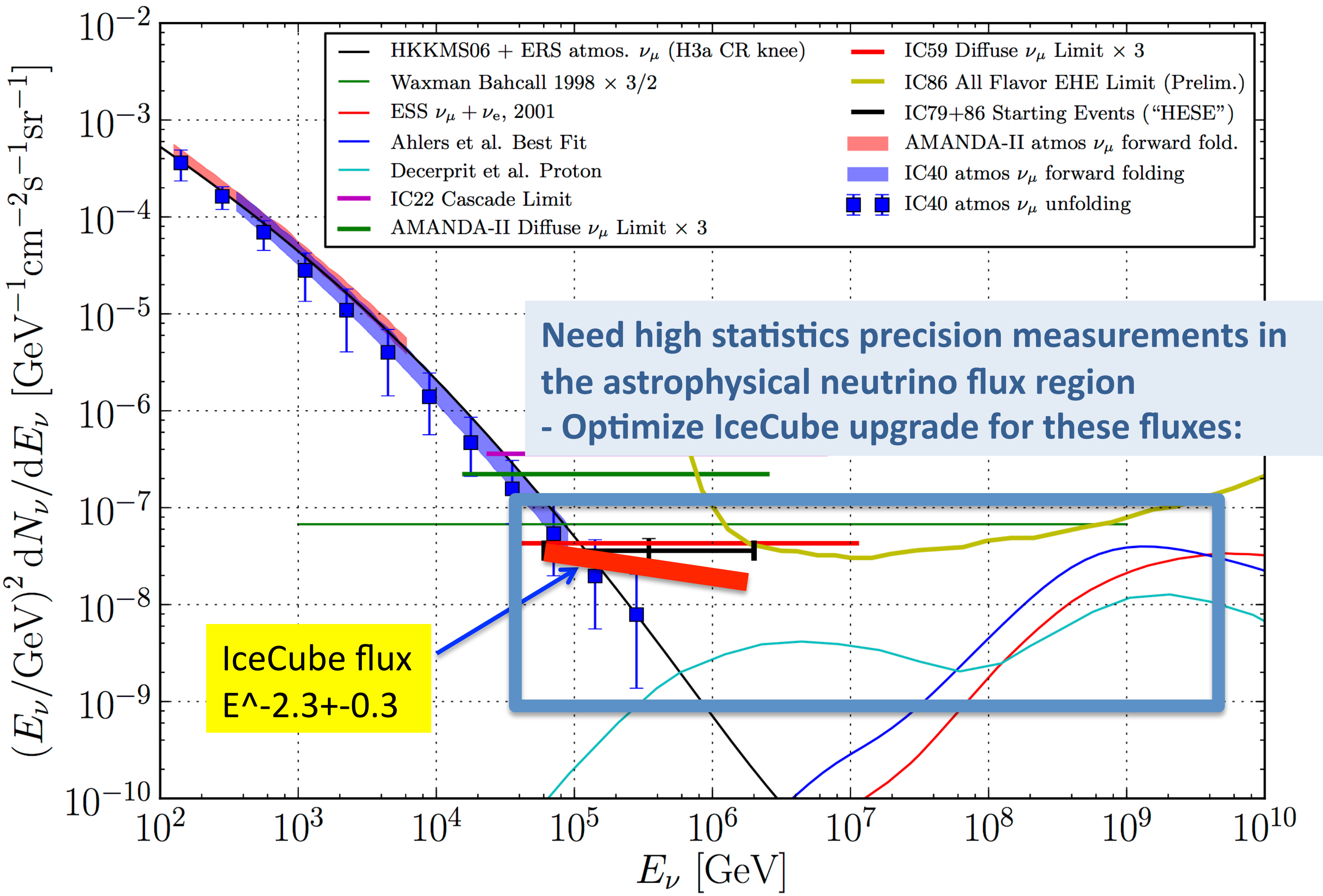


Events with contained vertex

- Mostly Southern hemisphere
- Neutrino events above 60 TeV:
  - Astrophysical: 6 /yr
  - Atmospheric: 1/yr
- Significance in first 2 years of data: 4.1 sigma



Evidence for astrophysical neutrinos
Energy range: 50 TeV to 2 PeV



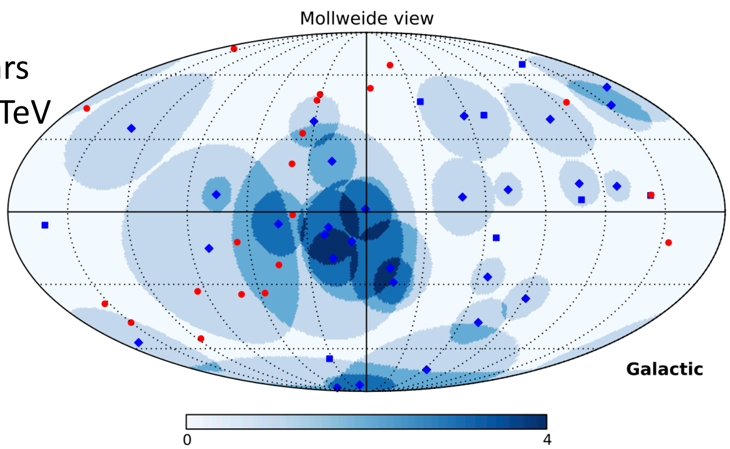
Defining Design goals

IceCube will collect in 10 years ….

Muon neutrinos

- 700,000 atmospheric neutrinos above 0.6 TeV
- ~90 astrophysical above 100 TeV muon energy
- Use those to **search for point sources**
  - **Transient astronomy**

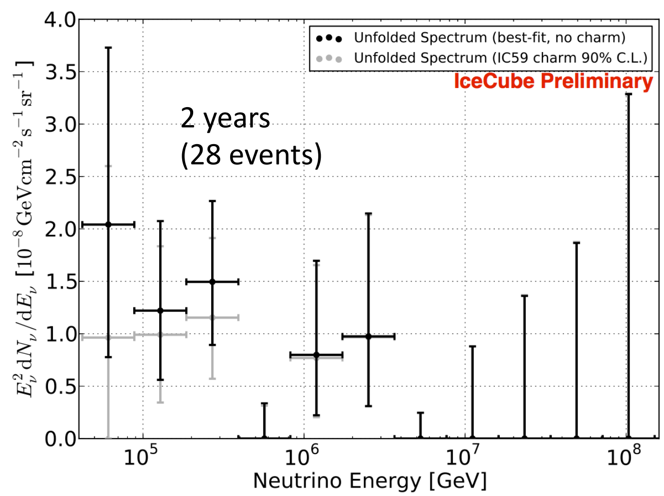
2 years
E>50TeV



→Need significantly more events
Muon effective area
→Good angular resolution

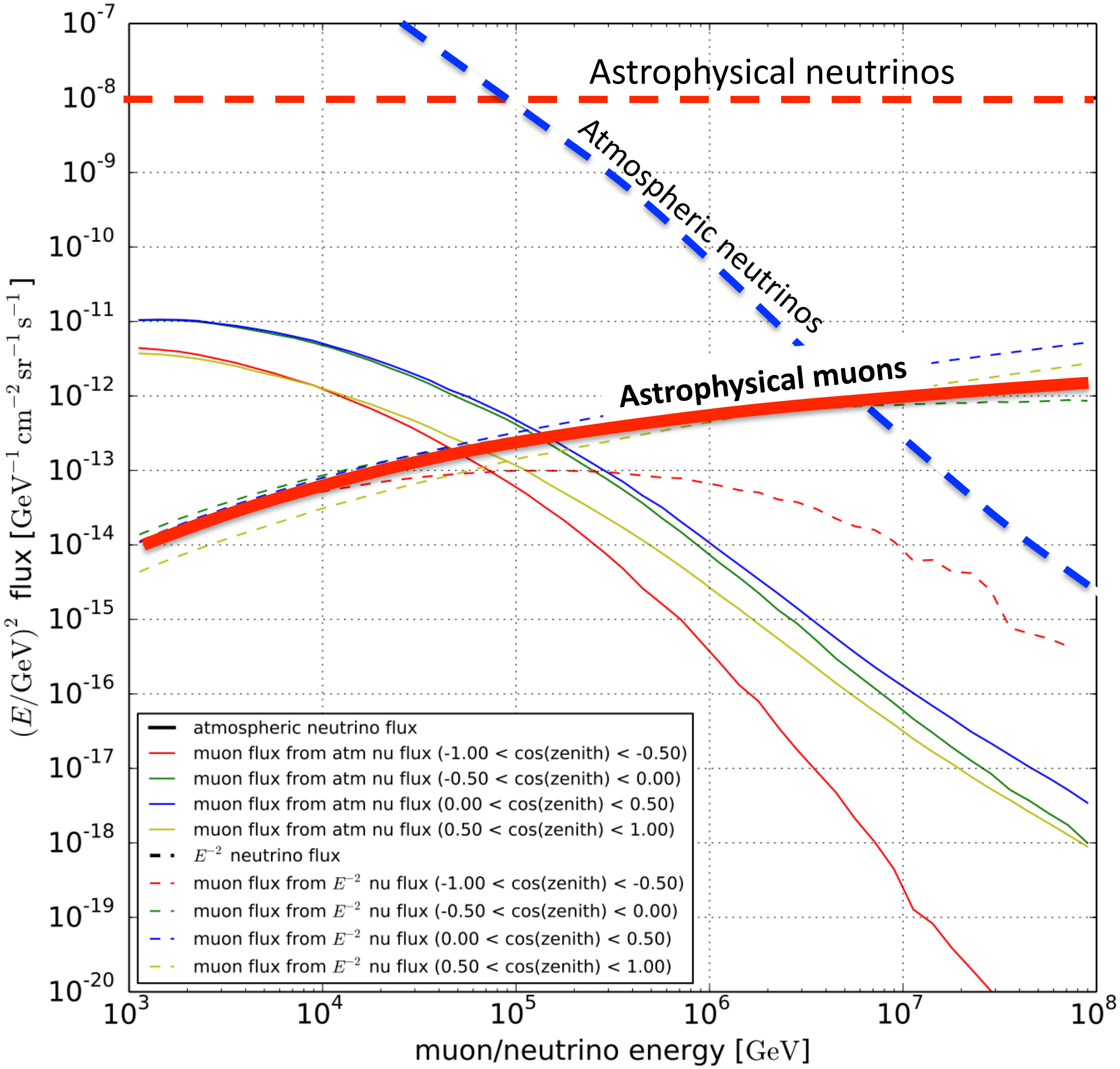
Cascade events

- nu_e and nu_tau dominated for astrophysical all flavor flux
- ~100 events at good energy resolution above 60 TeV
- ~10 events above 1 PeV
- Use those **for energy spectrum and flavor composition**

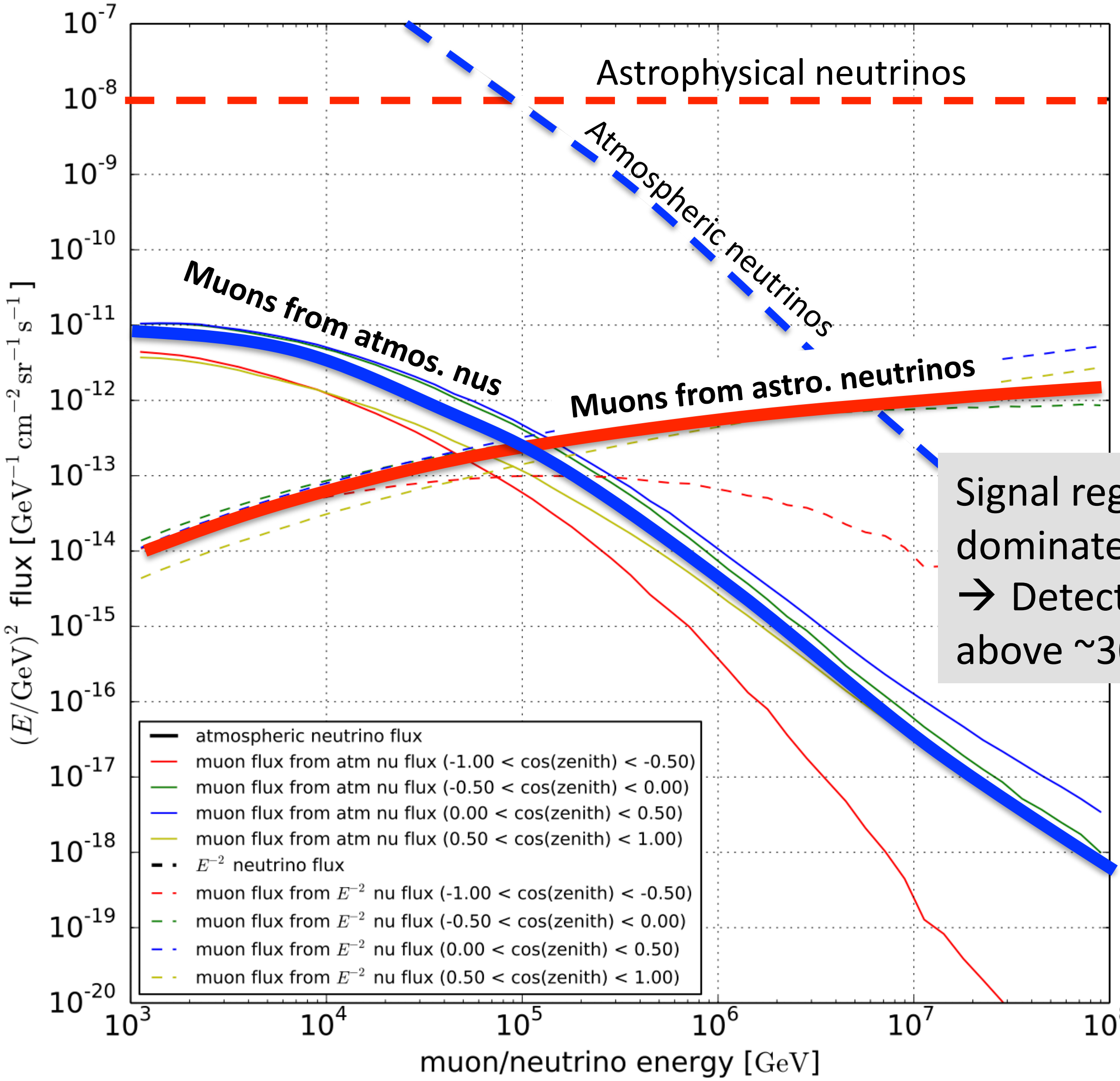


→Need significantly more events
effective volume
→Good energy resolution

Neutrino and muon fluxes



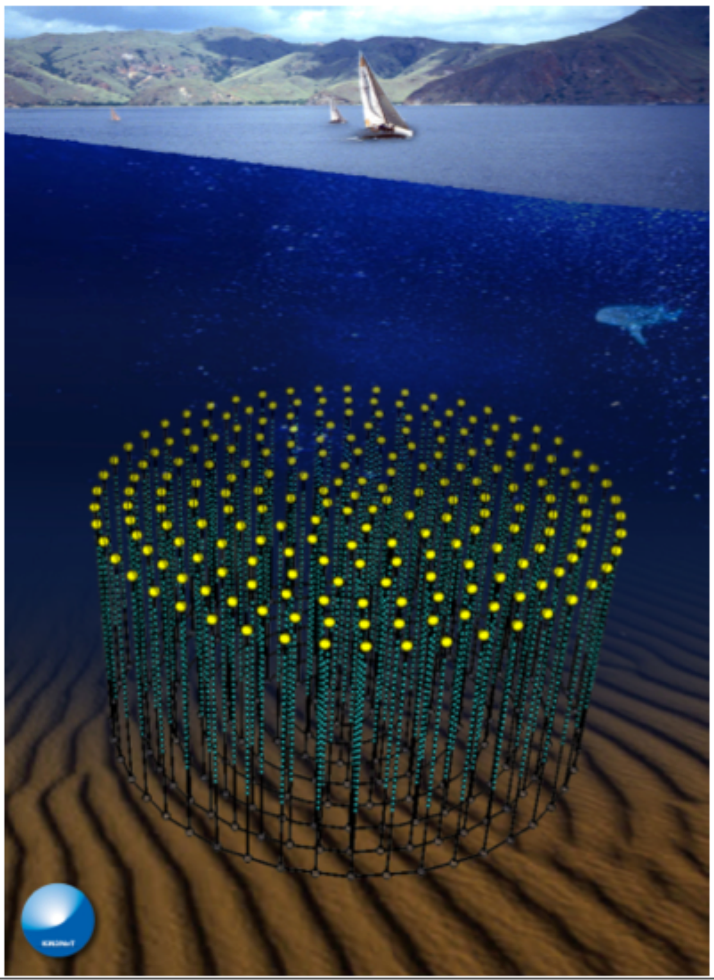
Neutrino and muon fluxes



Signal region begins to dominate above ~80 TeV
→ Detector should be efficient above ~30 TeV

Future plans for a large Mediterranean neutrino telescope

Scale: ~12000 optical modules
of 3xIceCube DOM optical sensitivity at three sites
(photo detection area: equivalent to 36000 IceCube DOMs)



Th

Status:
Phase 1 funded ((40M Euro) for stage 1 detectors at 2 sites.
Construction activities for phase 1 in preparation.
Estimated total cost: ~Euro 220M
(Mostly capital equipment)

50

Major components of a large detector facility - a next generation IceCube

- PINGU → talk by Ty DeYoung
  - Precision IceCube Next Generation Underground detector
  - Scale: 40 strings, densely packed inside IceCube's DeepCore detector
  - Physics goal: Neutrino mass hierarchy, neutrino physics, dark matter.
- High Energy component
  - Scale: 100 strings, 10,000 PMT, 5 - 10 km^3, 5 to 8 km^2
  - Physics goals: identify astrophysical sources of neutrinos and cosmic rays, neutrino and particle physics
  - Surface component like IceTop
- A large surface extension for vetoing downgoing background
  - Up to 6 km from detector; optimal size and density still in investigation

Other neutrino talks on experiments at the South Pole:

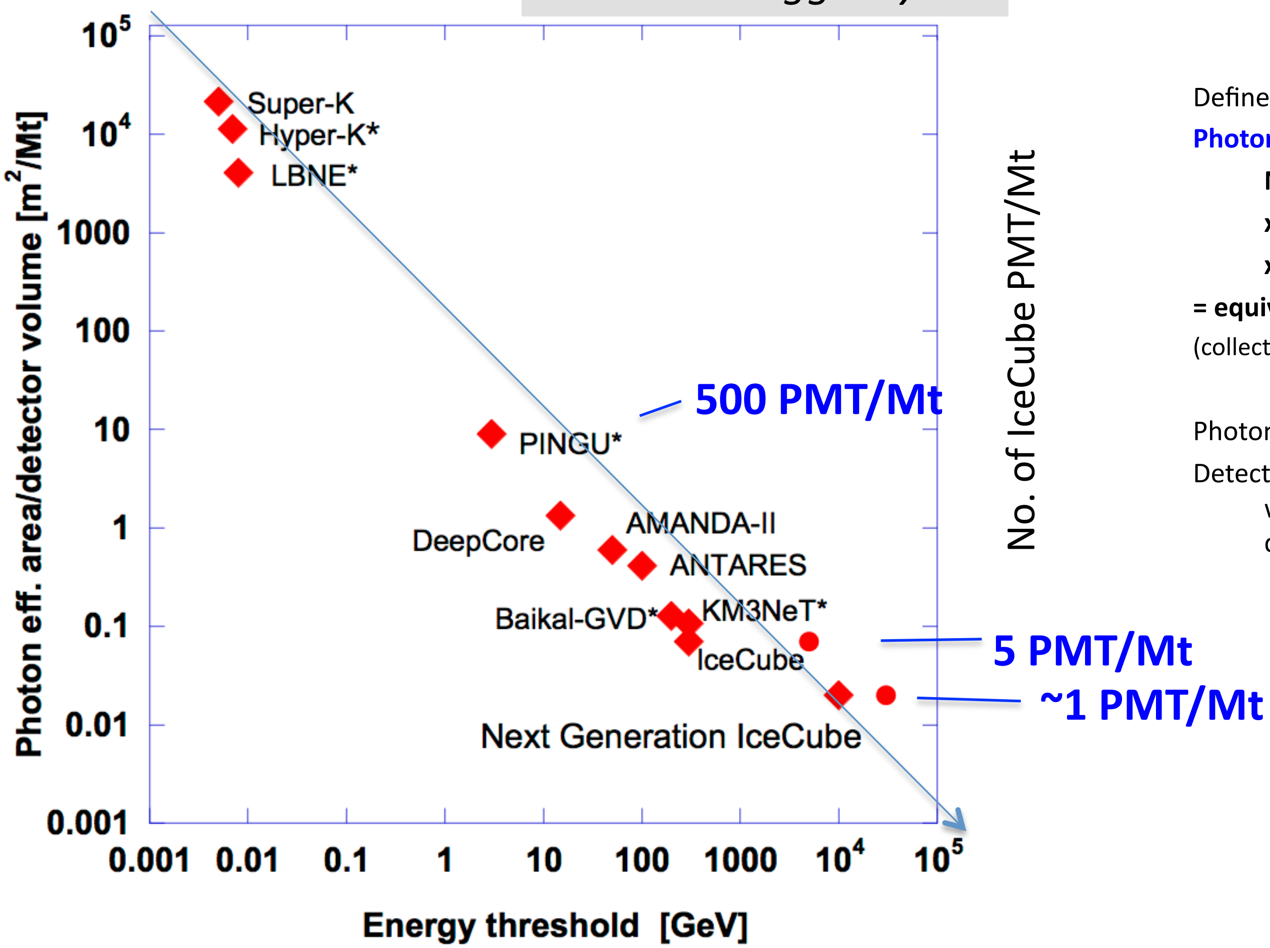
- DM-Ice → Reina Maruyama
- Cosmogenic neutrinos, radio detection → Amy Connolly

Water Cherenkov detectors: PMT coverage vs energy threshold

New evidence at higher energy → science requirement: focus on higher energy
We can reduce the PMT coverage (string density) by increasing the energy threshold.

Can we increase detection volume by an order of magnitude for similar cost?

This chart suggest yes.



Define:

Photon effective area =

Number of PMT

x Cathode area

x Quantum efficiency

= equivalent area of 100% photon detection.

(collection efficiency not included here.)

Photon effective area prop. ~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

Bert:
Energy 1 PeV

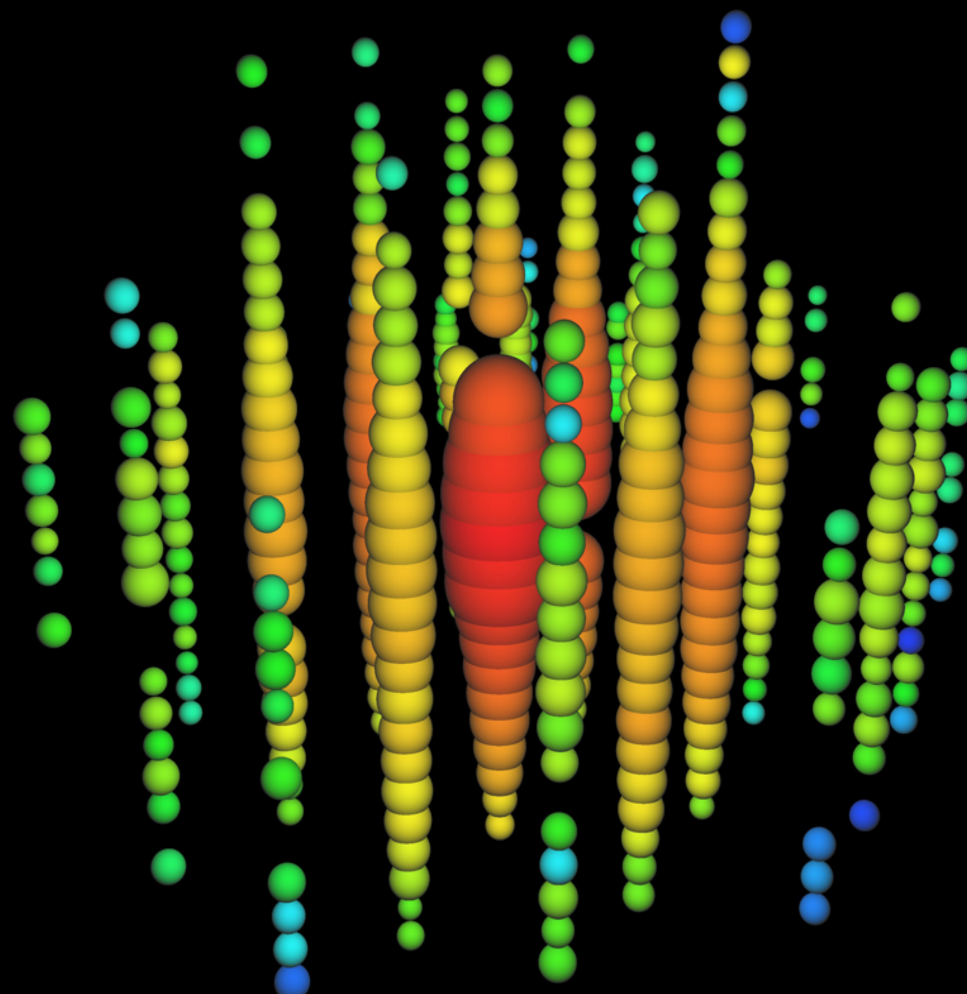
How well could we reconstruct this event with fewer strings?

Analyzed event using only subsets of 20 IceCube strings spaced at 250m.

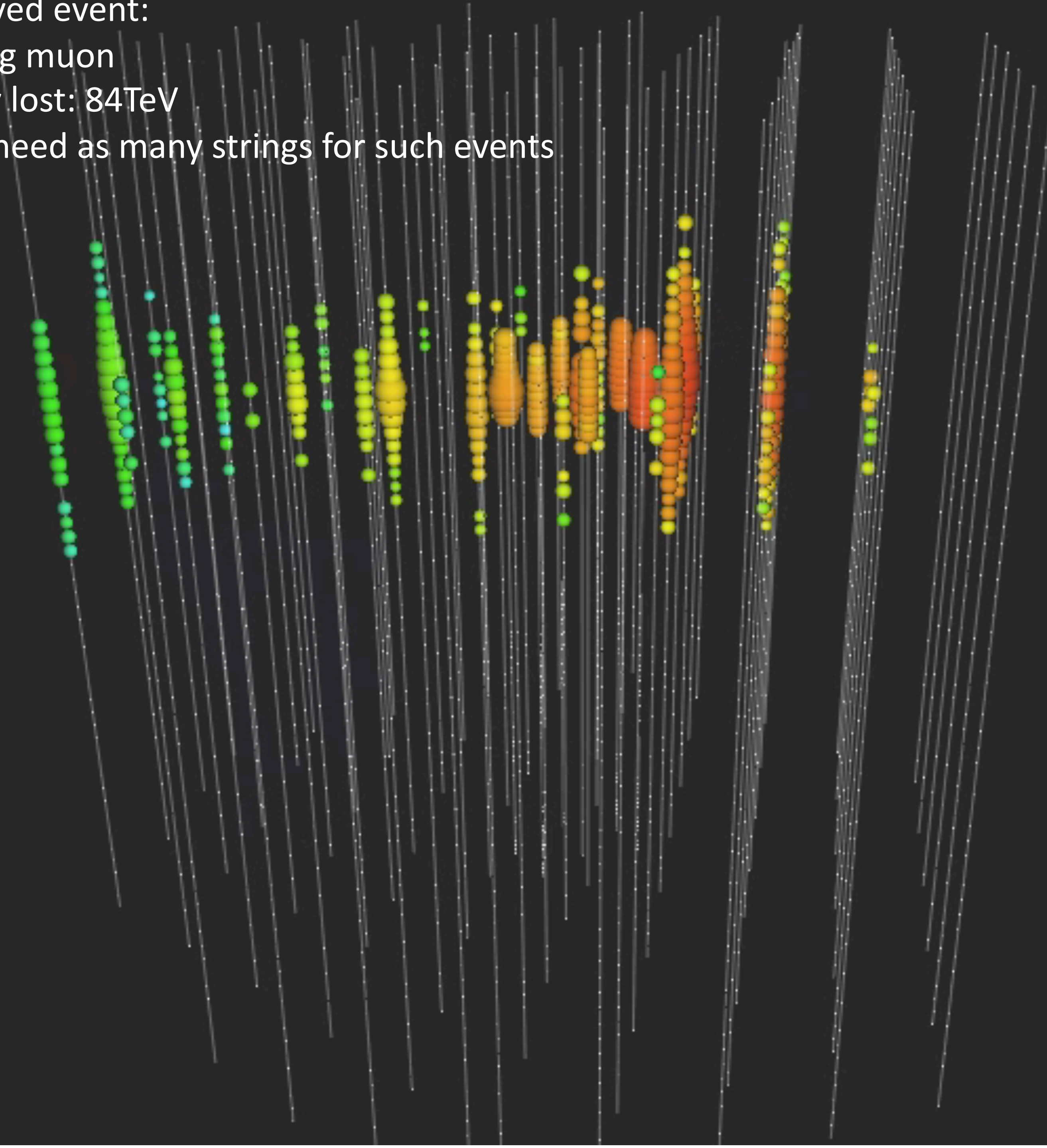
Result:
Vertex reconstruction:~ 12m
Angular resolution: ~30°
Energy resolution: 10%

Same result for Ernie, the other PeV event.

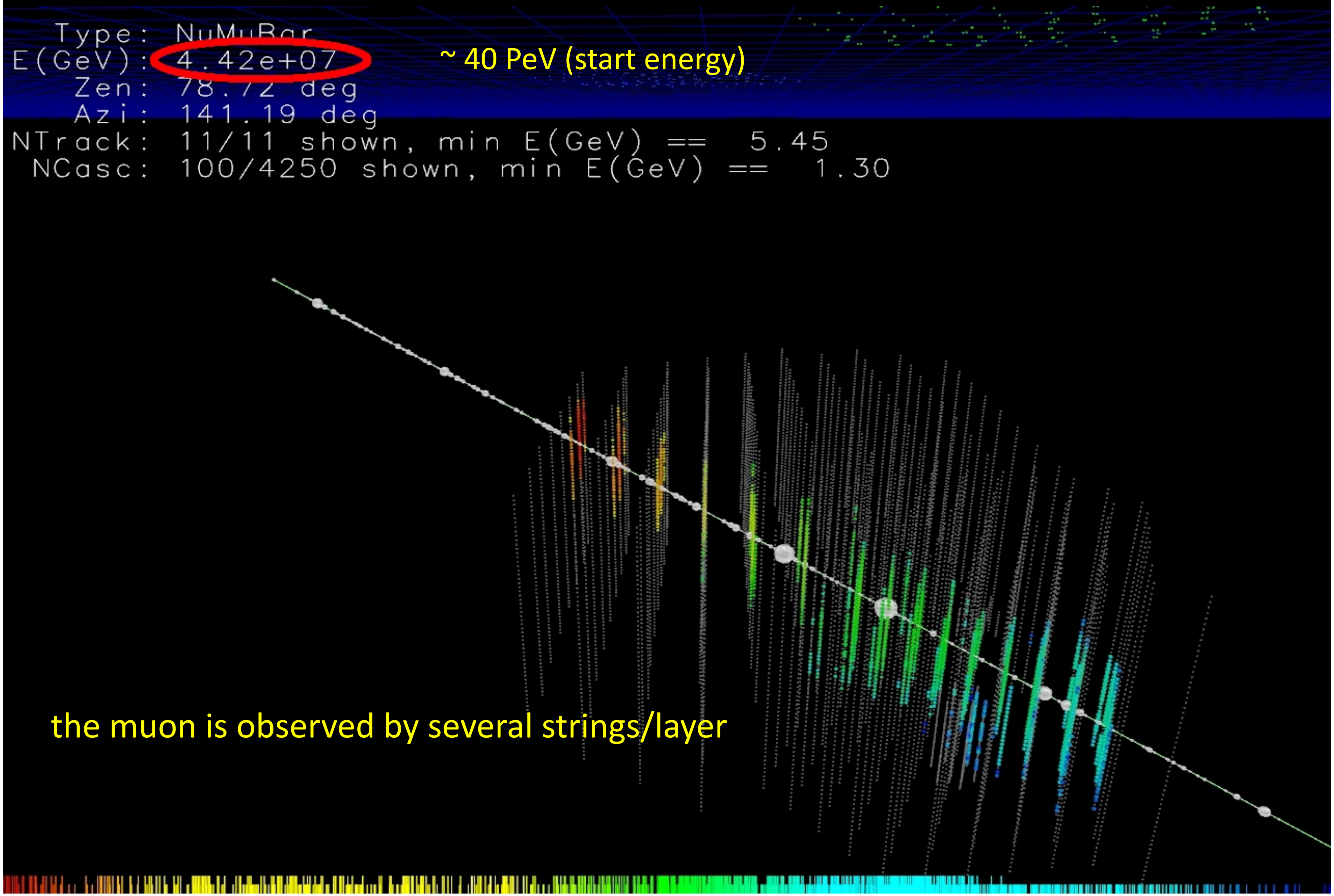
→ Don't need 100,000 photoelectrons to measure energy to 10%.



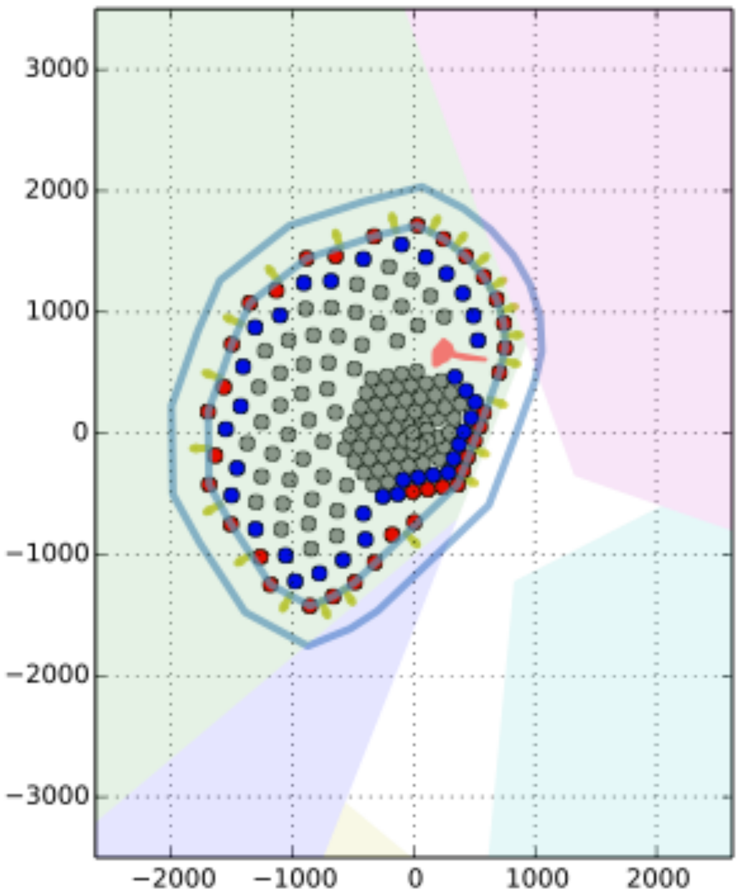
Observed event:
Starting muon
Energy lost: 84TeV
Don’t need as many strings for such events



Spacing 240m



Design studies



Investigation of geometries ongoing.
Initial idea: extend from IceCube.

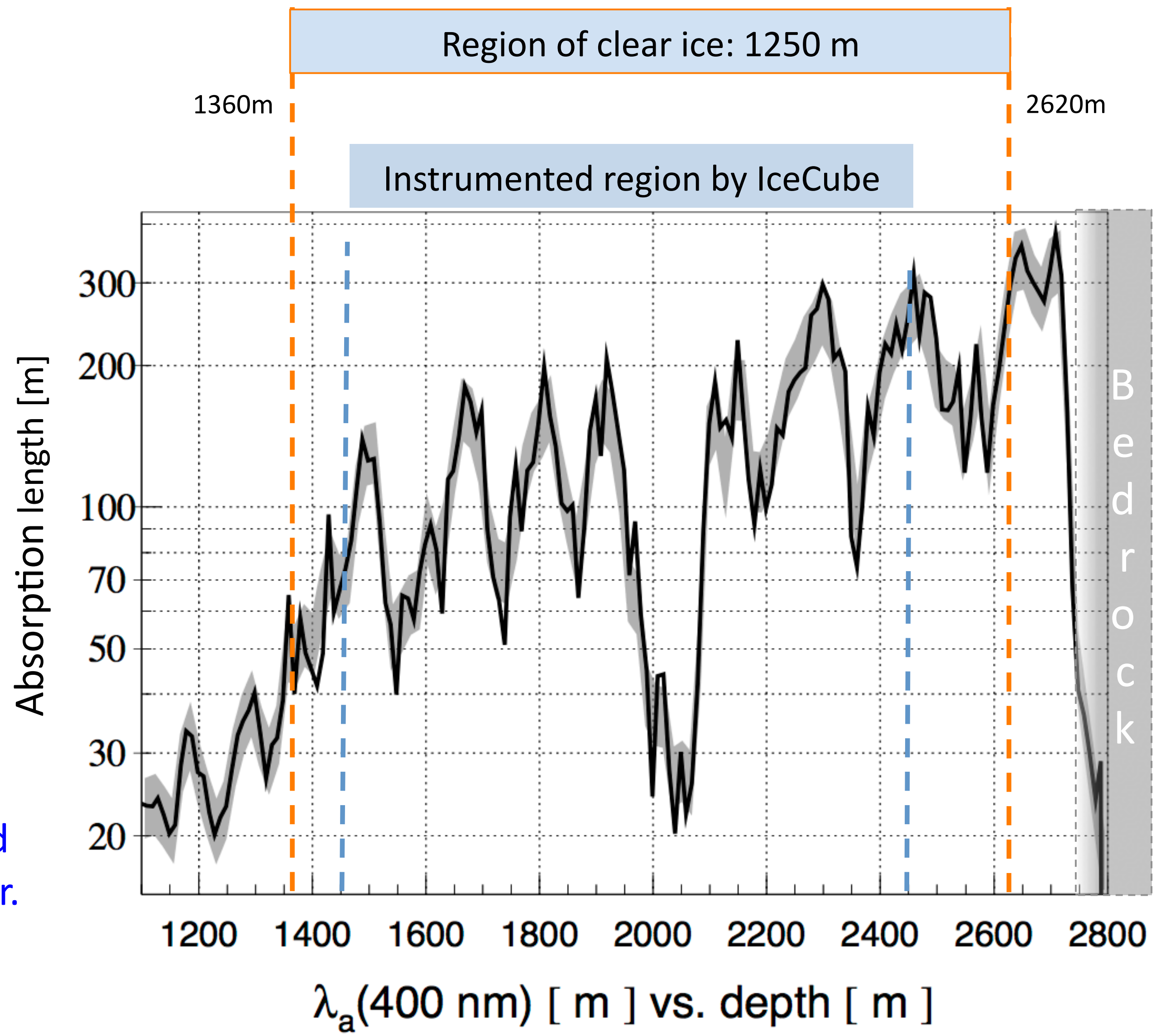
Configuration shown here:
96 strings, 240m spacing
Surface area: ~5 km^2

Volume: 5 * 1.3 = 6.5 km^3

Extending the region of ice to instrument with DOMs

- Bedrock estimated depth 2750m – 2850m
- 150 m to 200 m of very clear and usable ice below IceCube (need safety distance from bedrock)
- 100 m of good ice above

→Can make instrumented region 250 to 300m longer.



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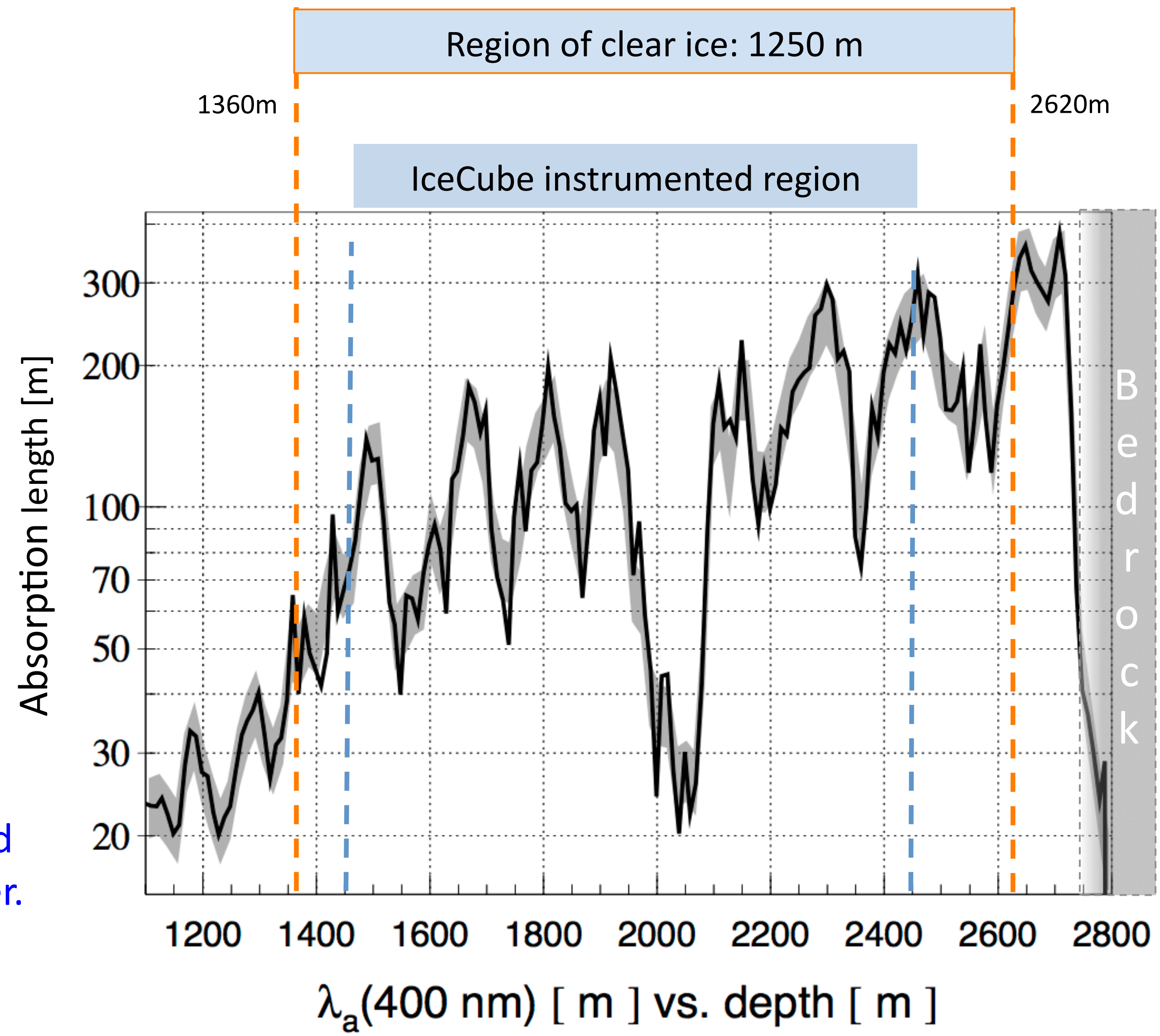
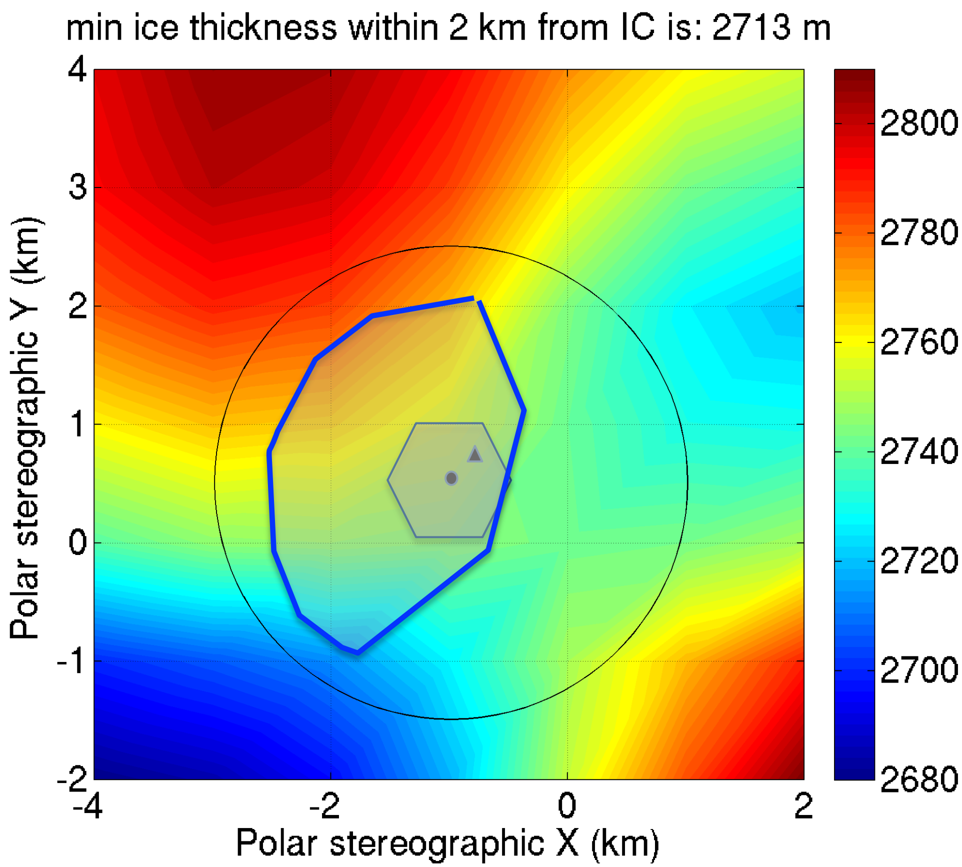
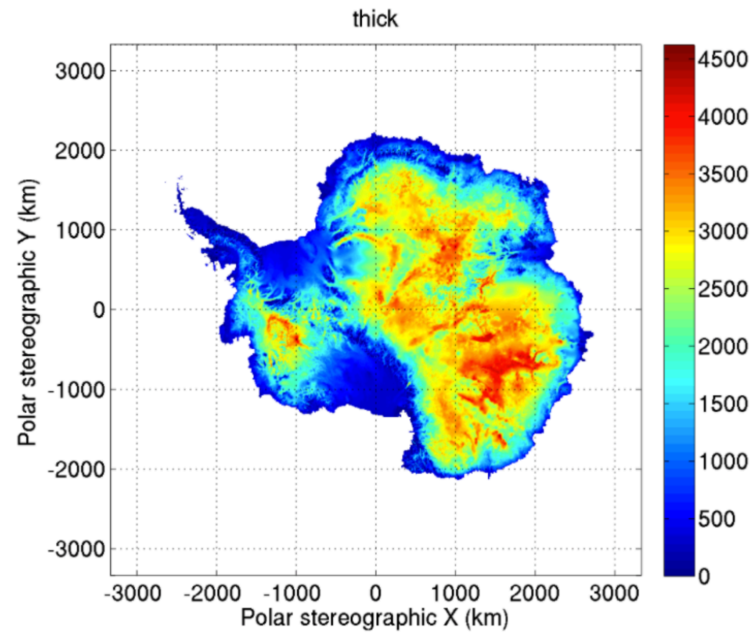


Ice thickness around South Pole

“Bedmap2” provides a depth map near the South Pole.
(compilation of multiple datasets)





- Bedmap2:
  Depth at IceCube: 2750m
  - Ice thickness in a 2 km radius from center of IC is 2713m (uncertainty is ≤ 83 m)
- Radio measurements (triangle location) [Besson et al. 2010, 2012]: 2857m ± 30m

* Bedmap2: http://www.the-cryosphere.net/7/375/2013/tc-7-375-2013.pdf

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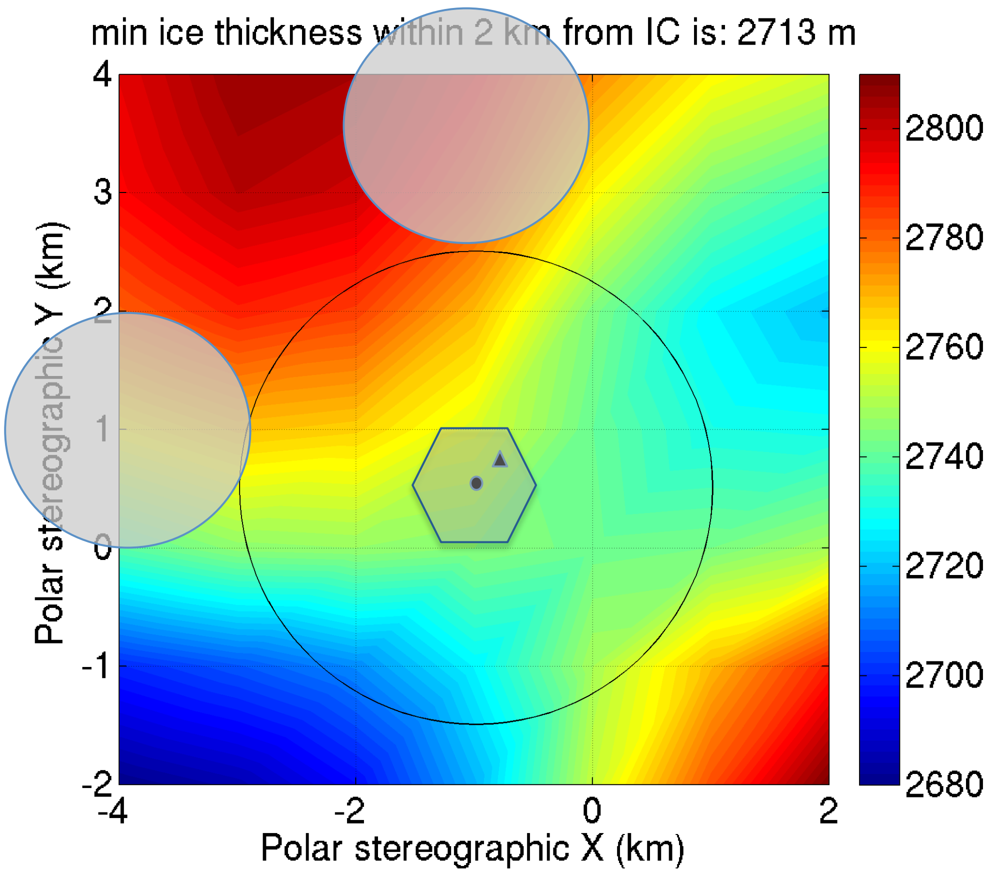

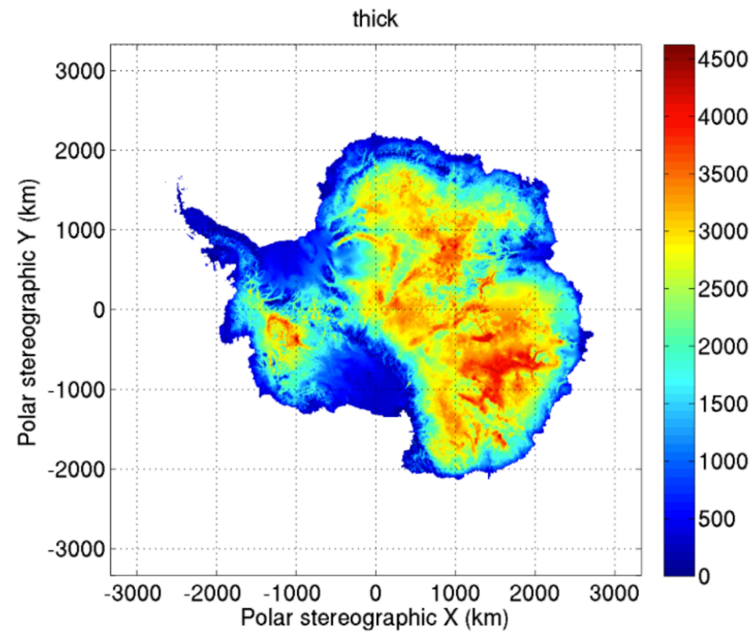

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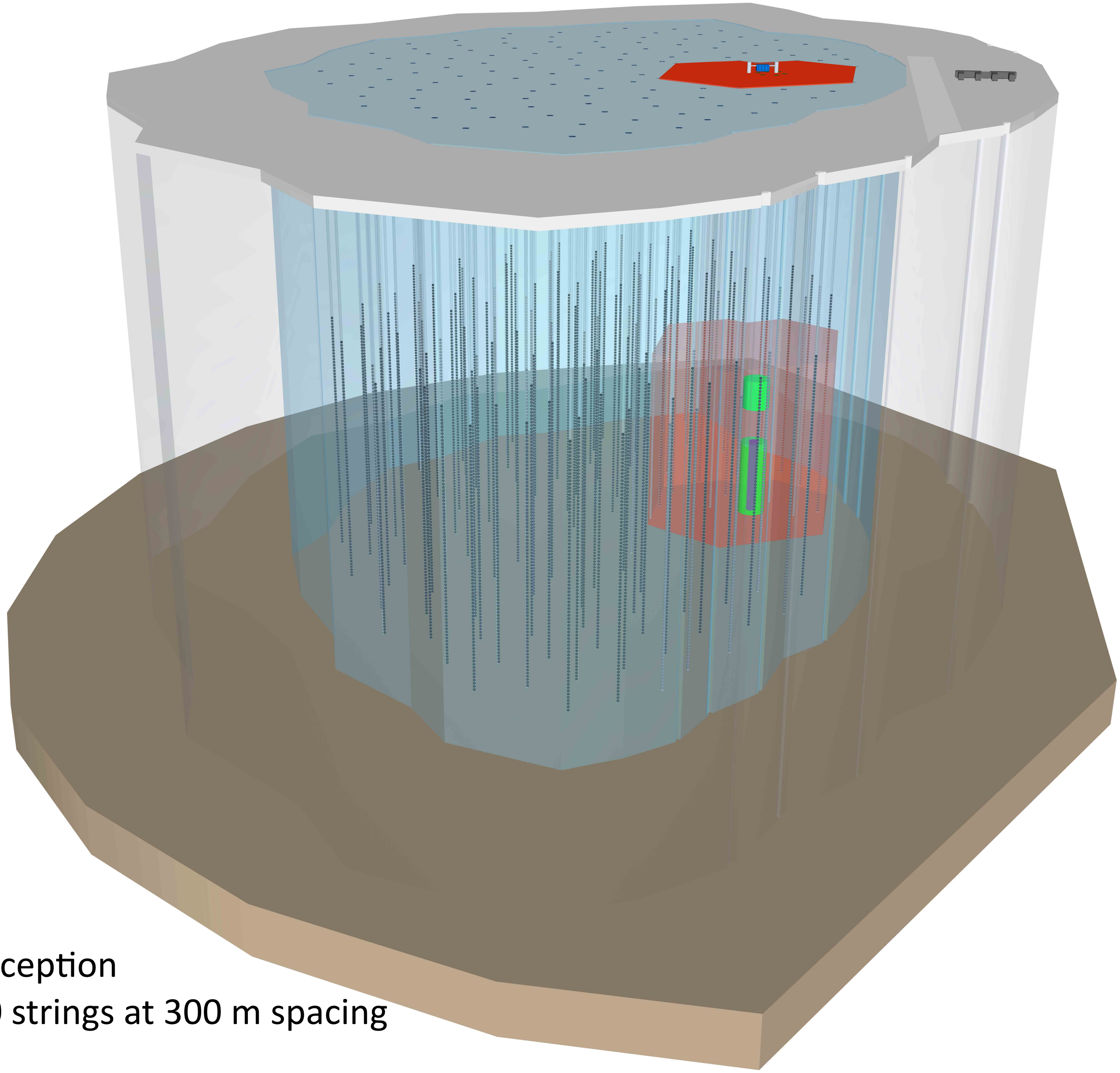
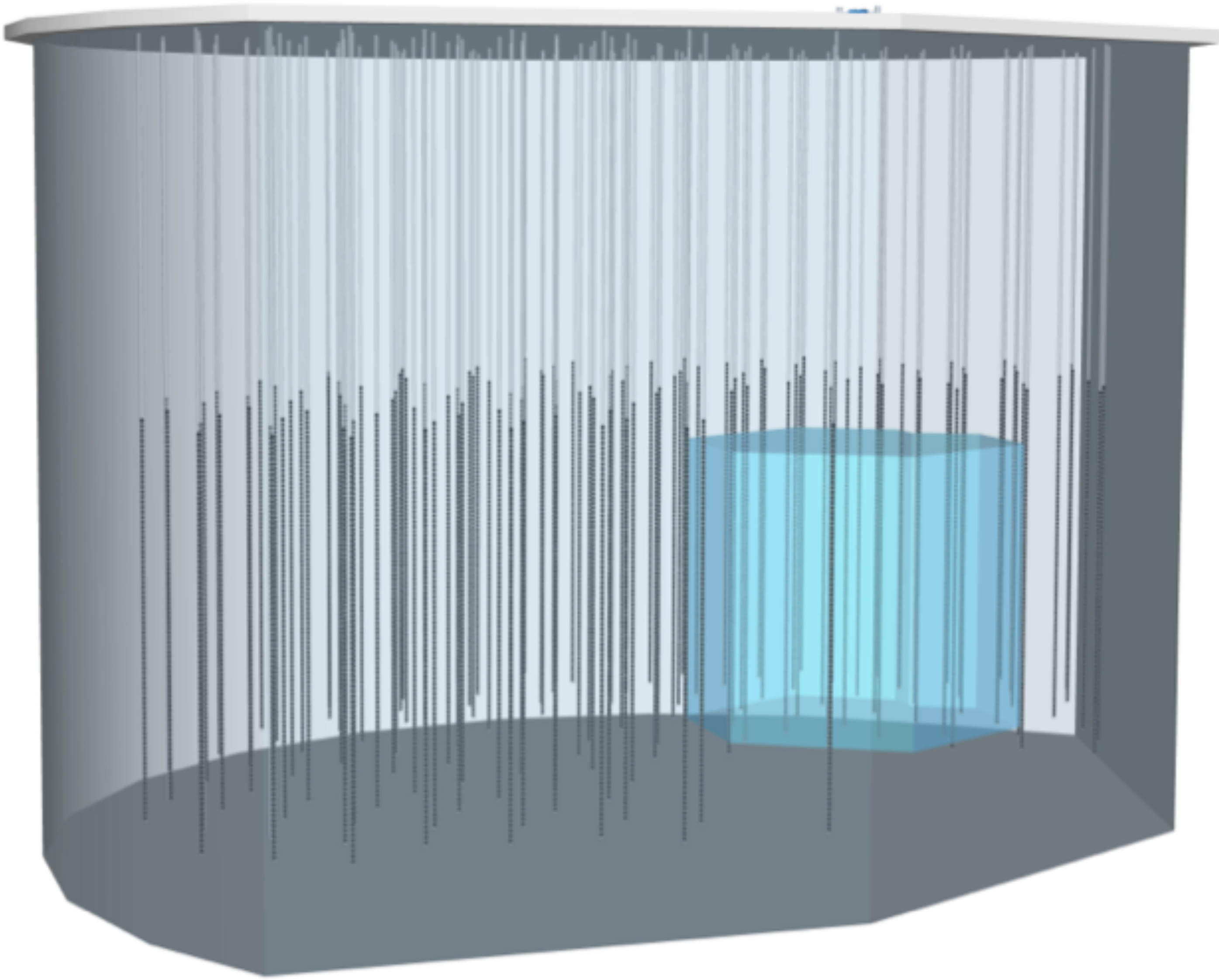
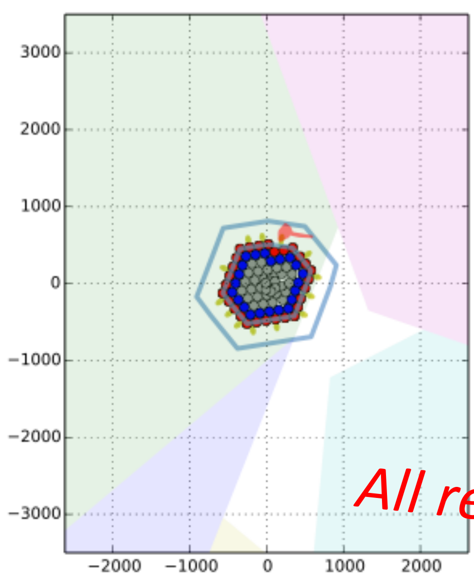


Artist conception
Here: 120 strings at 300 m spacing



Geometries

IceCube

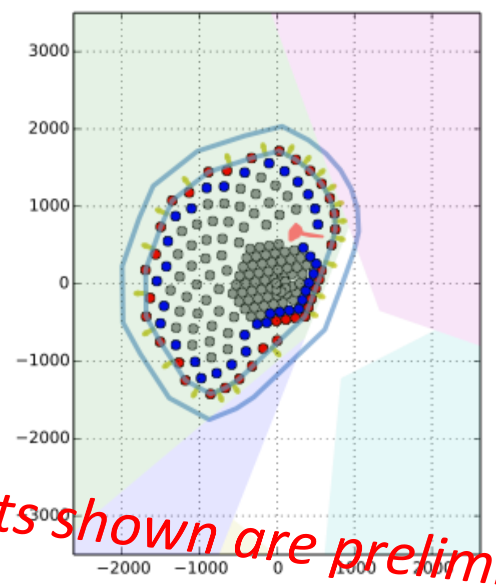


Top area (instrumented+60m border): 0.9 km^2

Volume: 0.9 km^3

Strings: IC86
spacing: ~125m

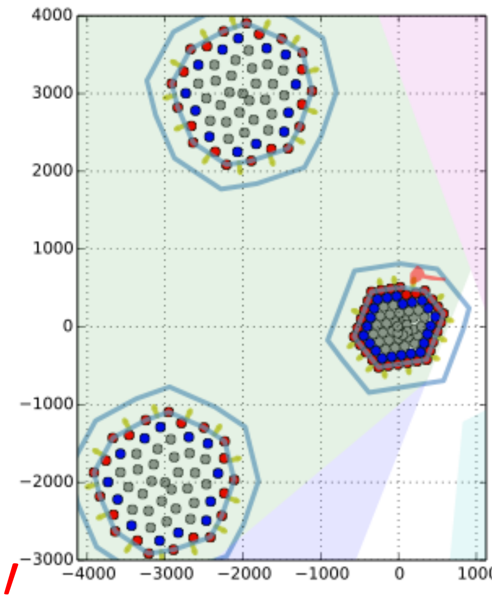
Sunflower 96



top area (instrumented+60m border): 5.3 km^2
Volume: 6.9 km^3

Strings: IC86+96
spacing: ~240m

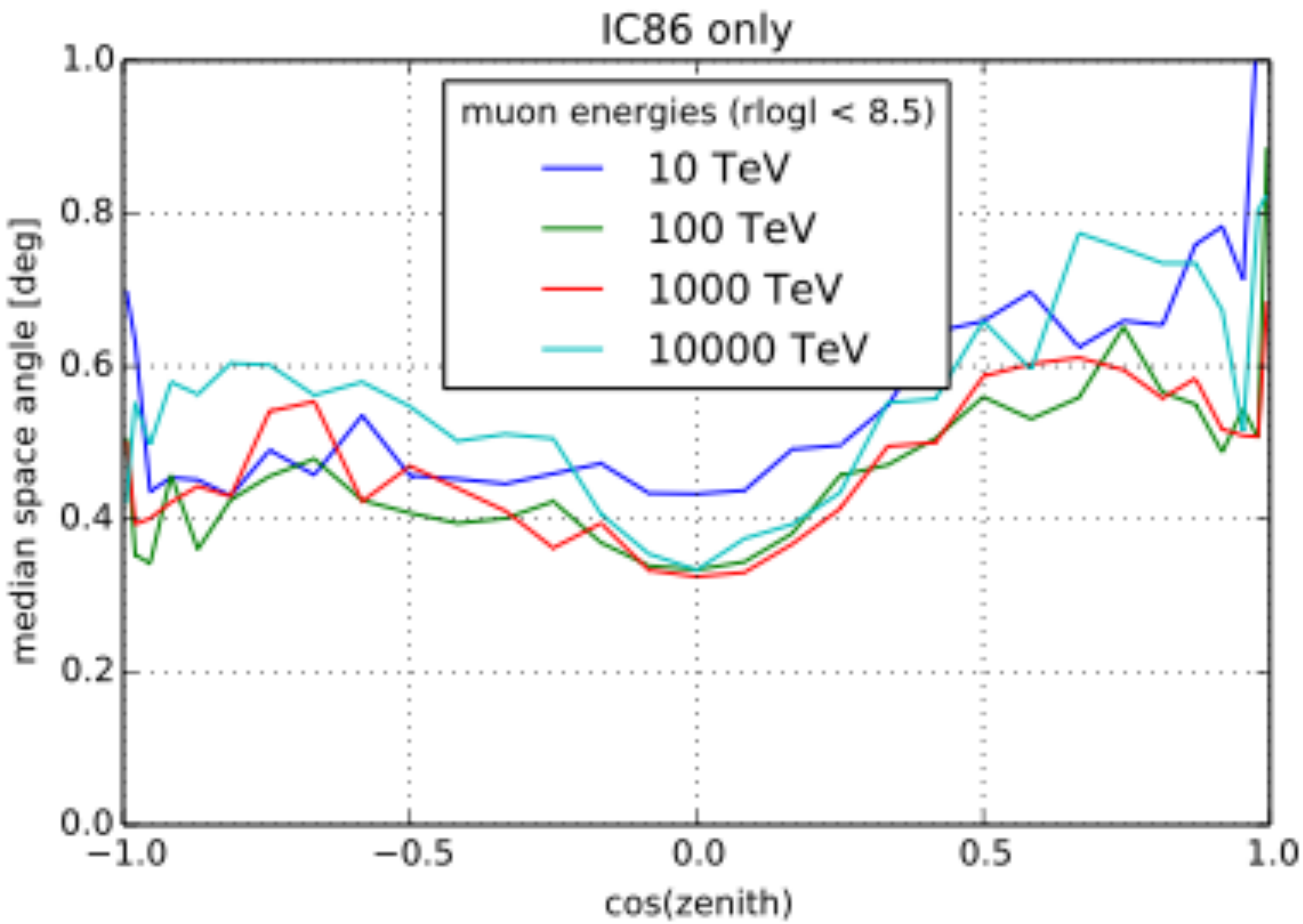
Supercluster

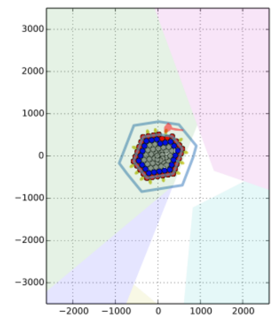


top area (instrumented+60m border): 5.6 km^2
Volume: 7.3 km^3

Strings: IC86+2x60
spacing: ~240m

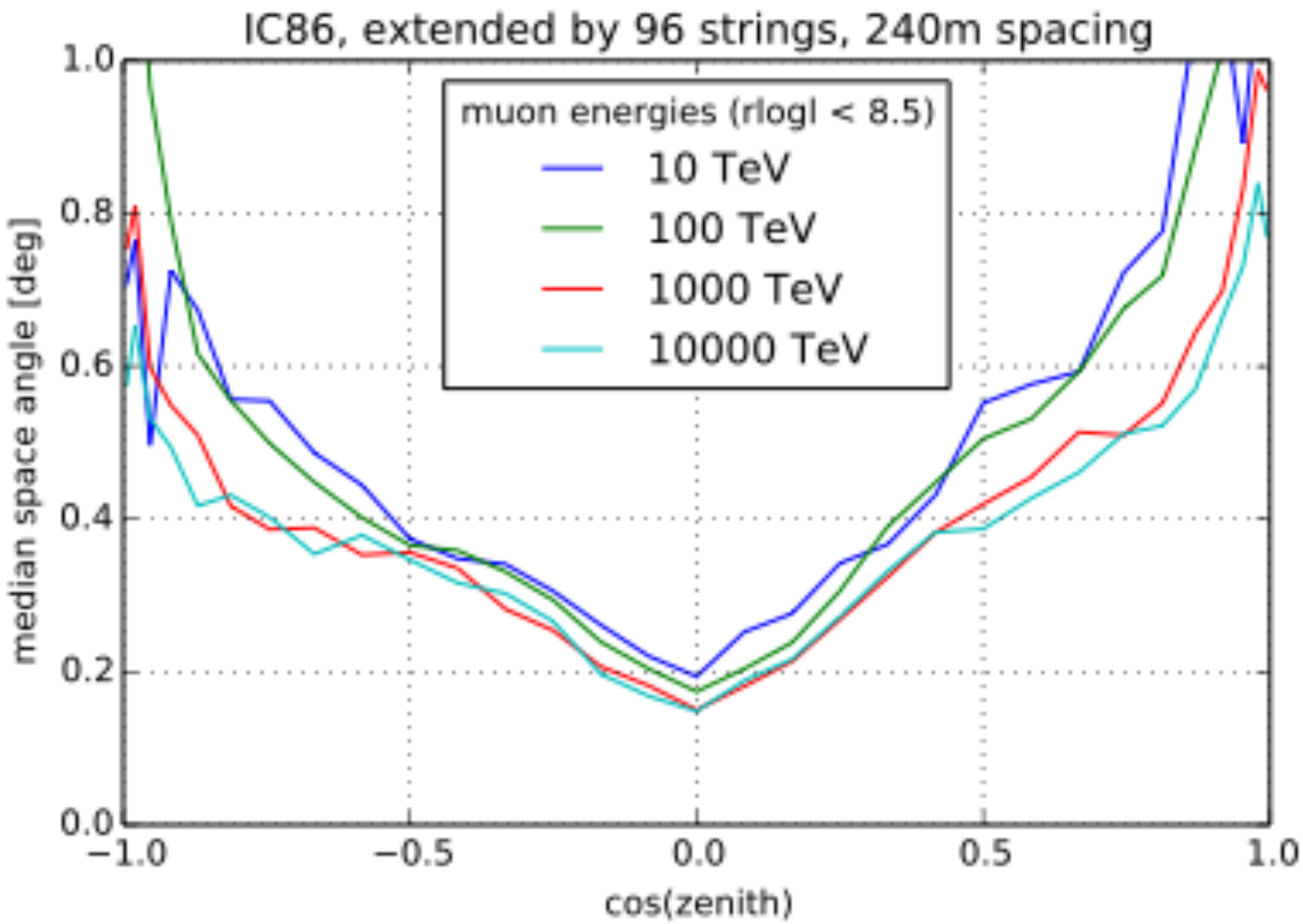
All results shown are preliminary!

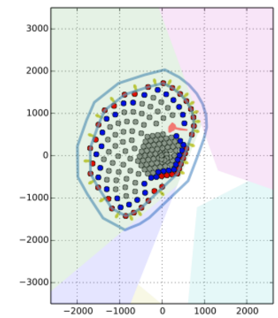




IceCube

angular resolution for fixed muon energies entering the detector





Sunflower 96

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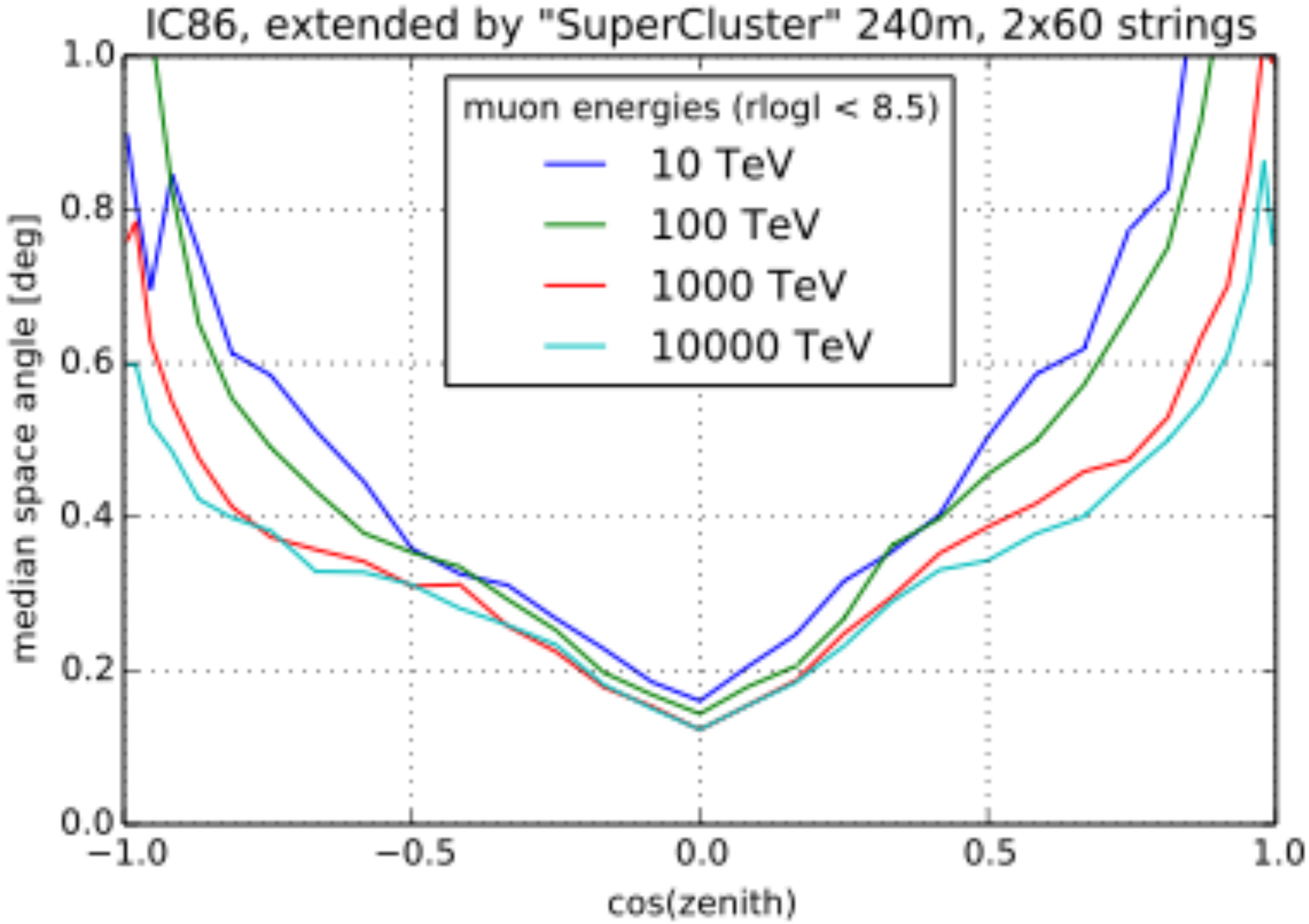
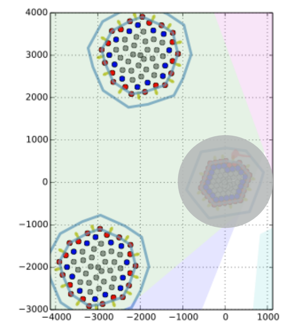


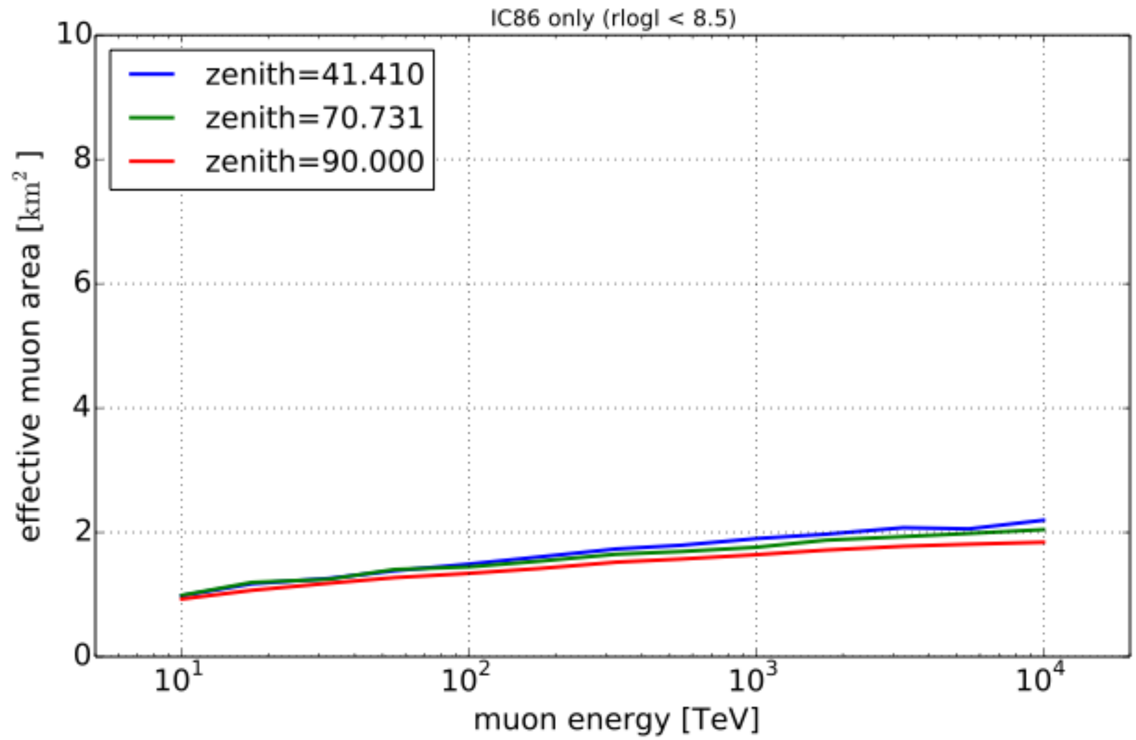


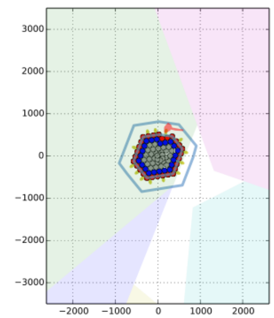
2x60-String Cluster

resolution for tracks in the sparse detectors; see previous slide for resolution of tracks in IceCube

Muon Effective Area (Simplified) (Loose Cuts)

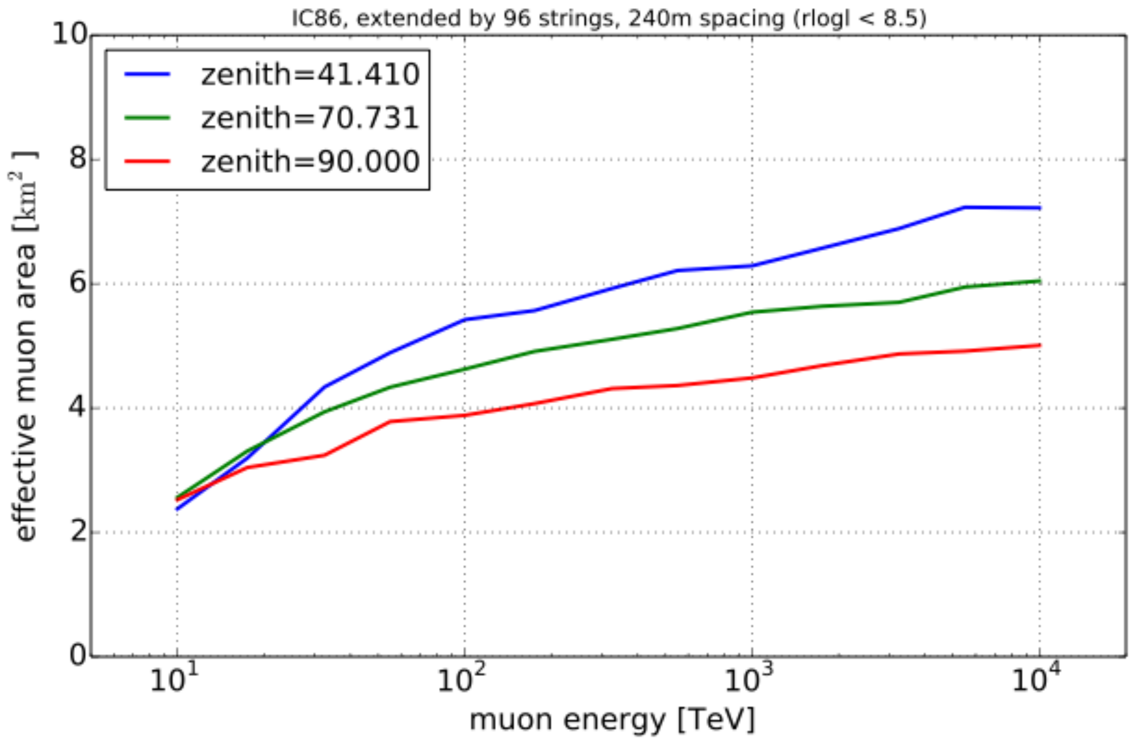
(accounting for 1.3km-long strings with 80 DOMs per string)

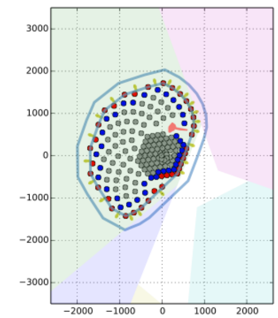




IceCube

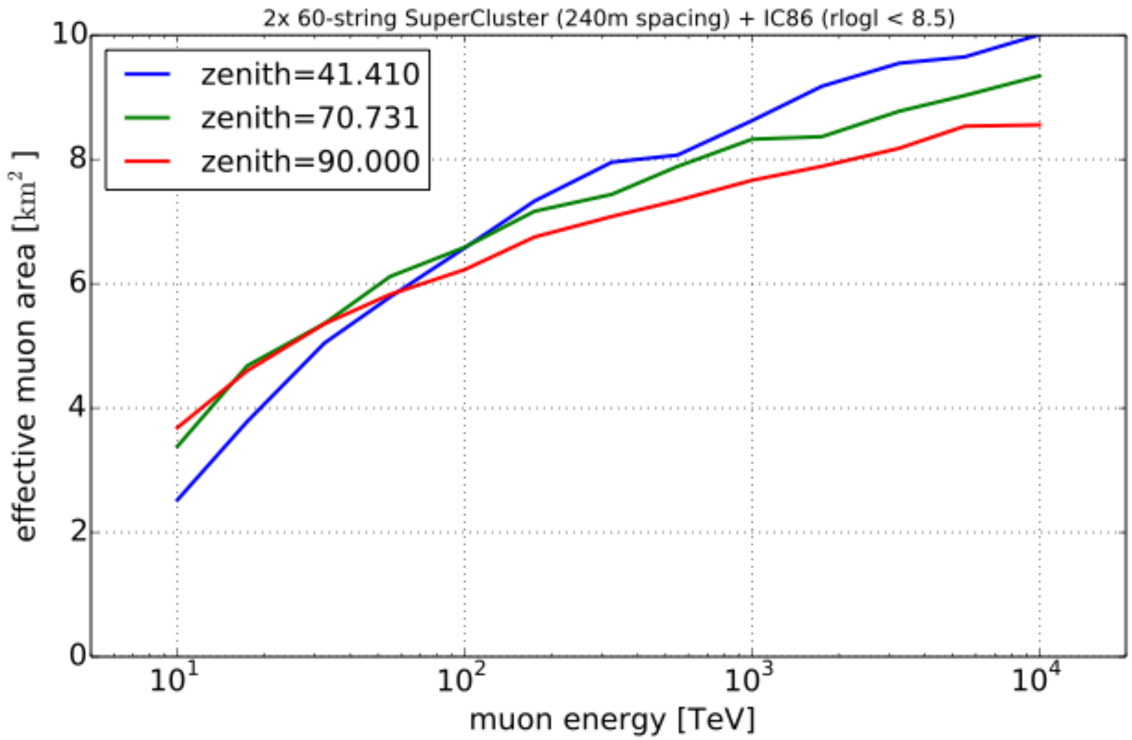
effective area for muons of fixed energy

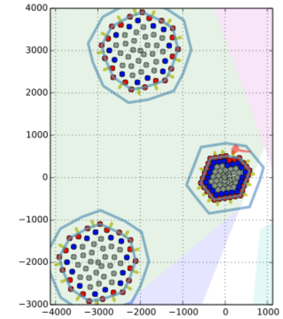




Sunflower 96

effective area for muons of fixed energy



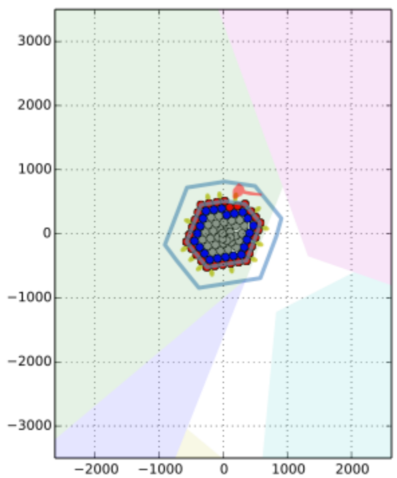


2x60-String Cluster + IC86

effective area for muons of fixed energy

Results

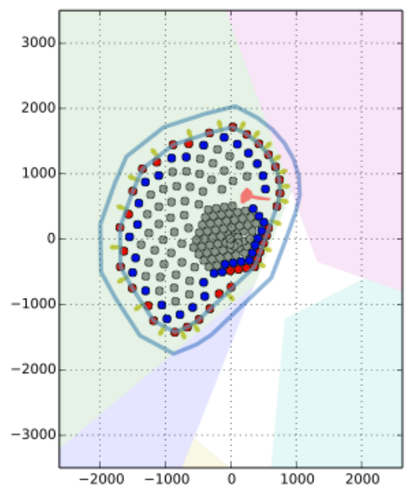
IceCube



strings: IC86

string spacing: ~125m

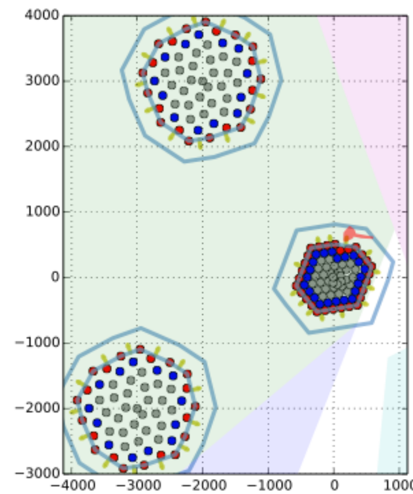
Sunflower 96



strings: IC86+96

string spacing: ~240m

Supercluster



strings: IC86+2x60

string spacing: ~240m

All results are preliminary!

Angular resolution (averages by eye):

IceCube	Sunflower 96	Supercluster
0.5°	0.4°	0.4°

Effective area

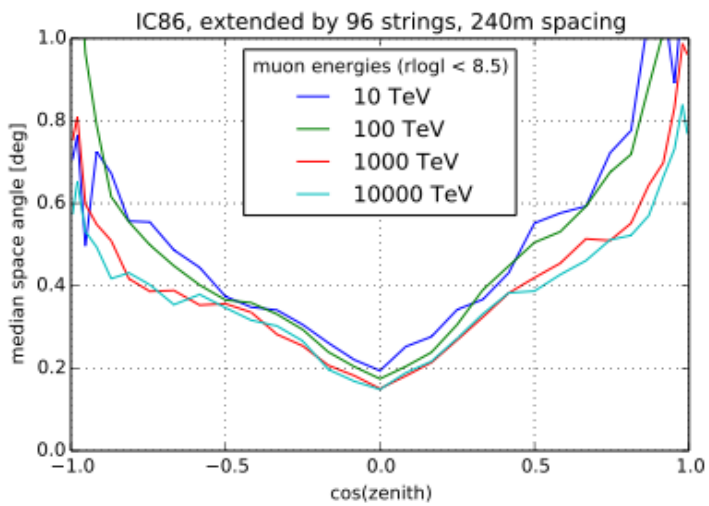
IceCube	Sunflower 96	Supercluster
1.6 km²	5.0 km²	6.5 km²

Geometry figures
IceCube vs Next generation IceCube

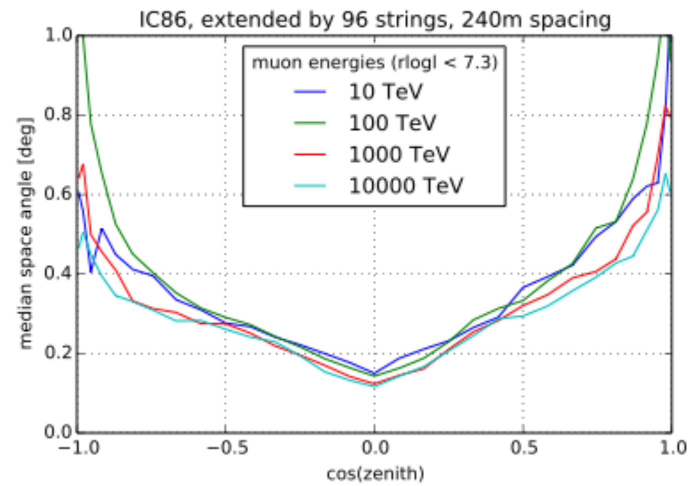
	IceCube	IceCube G2:
Top of instrumented region	1450	1380
Bottom of instr. region	2450	2650
Instrumented string length	1000	1270
Surface area/km^2	0.9	5 - 6
Average effective area (muons)	1.5	5
Intrumented volume/km^3	0.9	6.5
Energy threshold/muons [TeV]	0.5	10 - 30
self Veto volume (PeV)	0.5	4 - 5

Angular resolution
- dependence on quality of event selection

Loose cuts (5 hits on 3 strings each)



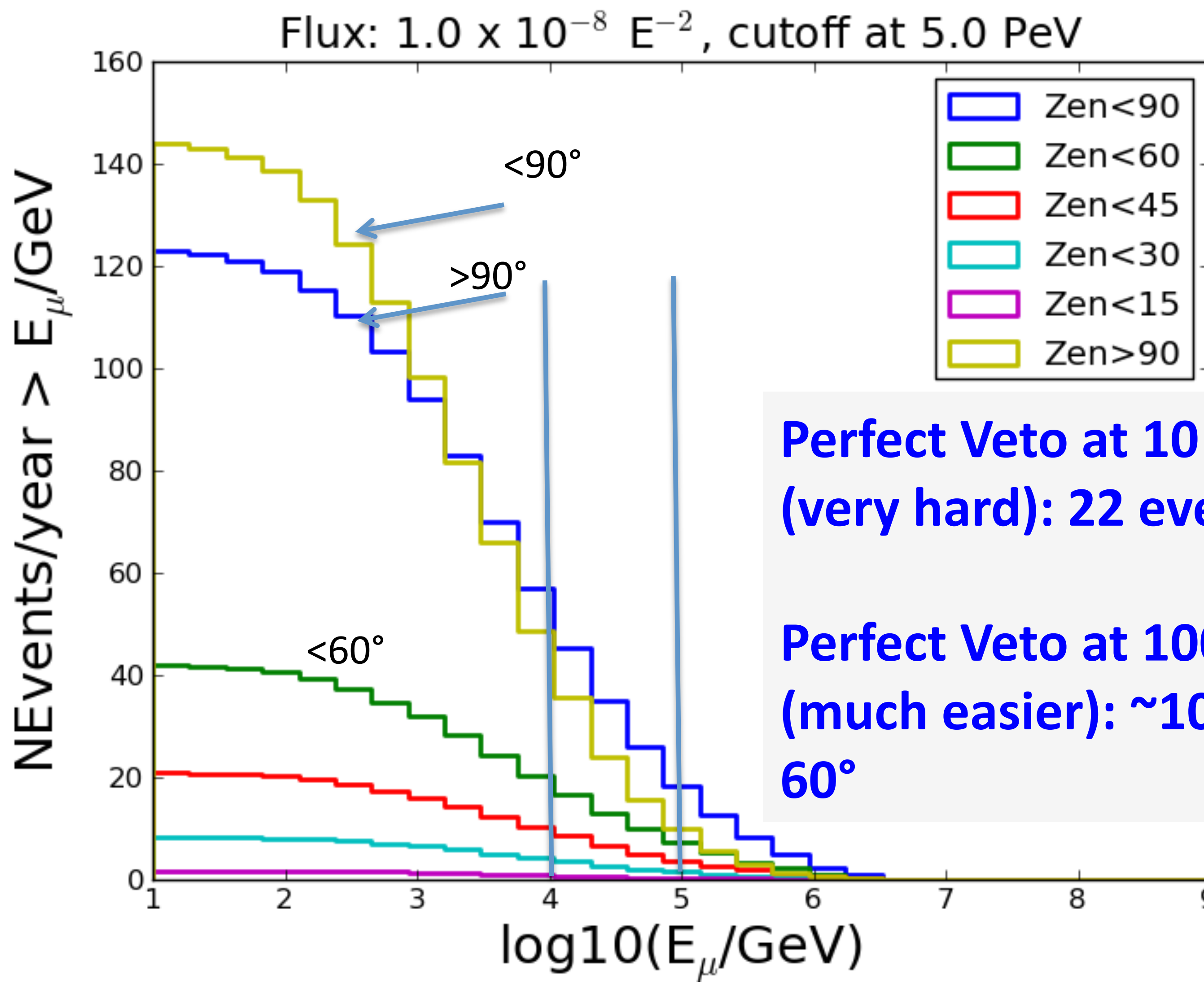
Very hard cuts: like in diffuse analysis



Event reconstruction appears fairly robust,
- only weak dependence on quality cuts.
- effective areas change 20% from loose to very hard cuts

String Extension	Spacing (m)	Zenith	effective muon area (rlogl 7.3)	effective muon area (rlogl 8.5)	angular resolution cos(0.5)
IC86+120	240	41.41	4.5	4.2	0.47
		70.731	4.1	5.2	
		90	3.8	6.3	
		Average	4.1	5.2	
IC86+96	240	41.41	4	5.3	0.5
		70.731	3.7	4.7	
		90	3.2	3.9	
		Average	3.6	4.6	
IC86+96	300	41.41	3.7	6	0.5
		70.731	3.7	5	
		90	3.3	4.1	
		Average	3.6	5	
IC86 ONLY		41.41	1.5	1.6	0.58
		70.731	1.5	1.6	
		90	1.5	1.6	
		Average	1.5	1.6	
Super Cluster 2x60 + I86	240	41.41	4.9	6.3	0.45
		70.731	5	6.3	
		90	5.1	6.1	
		Average	5	6.2	
Super Cluster 2x60	240	41.41	3.8	5.1	
		70.32	3.9	5.1	
		90	3.9	5	
		Average	3.9	5.1	

Cumulative Event Rates , E^-2.0

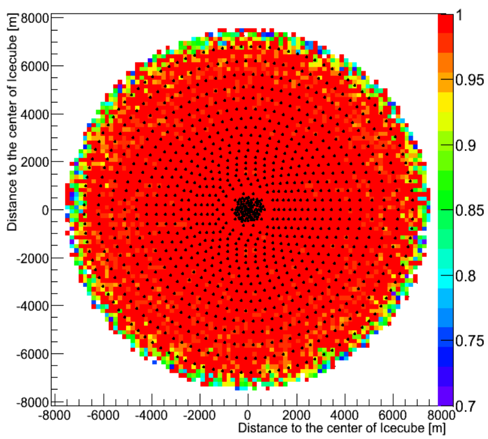


Perfect Veto at 10 TeV (very hard): 22 events < 60°

Perfect Veto at 100 TeV (much easier): ~10 events < 60°

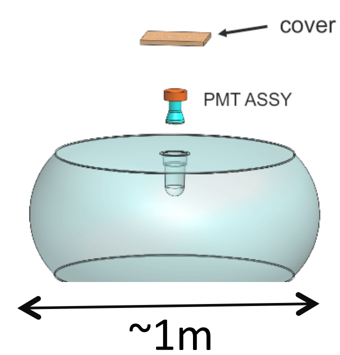
Expand surface veto (IceTop heritage)

- A surface veto above 1 PeV (cosmic primary) could reject most atmospheric muon AND neutrino background above 100 TeV.
- An efficient surface veto, 100 km^2, for 3 – 5 sr background free cosmic ν_μ and some cascade detection

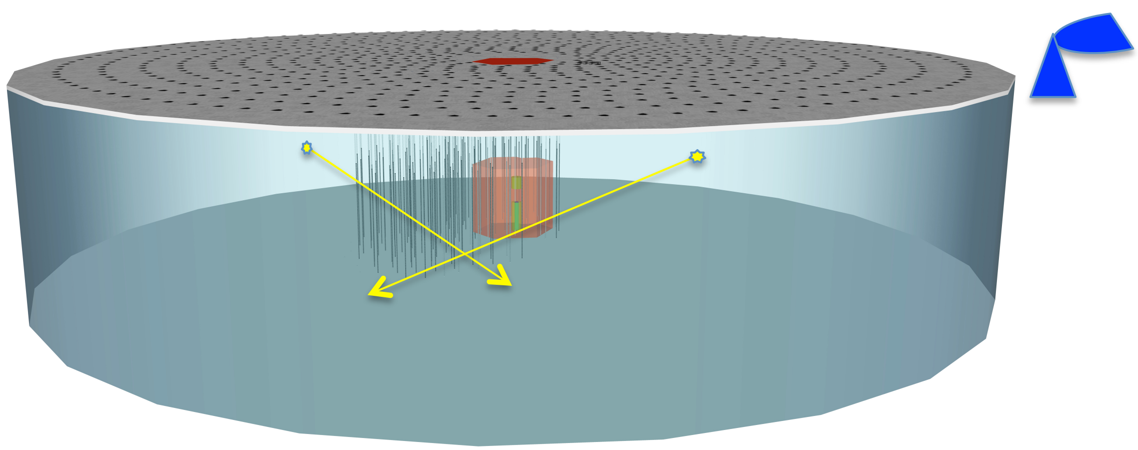


~1000 modules

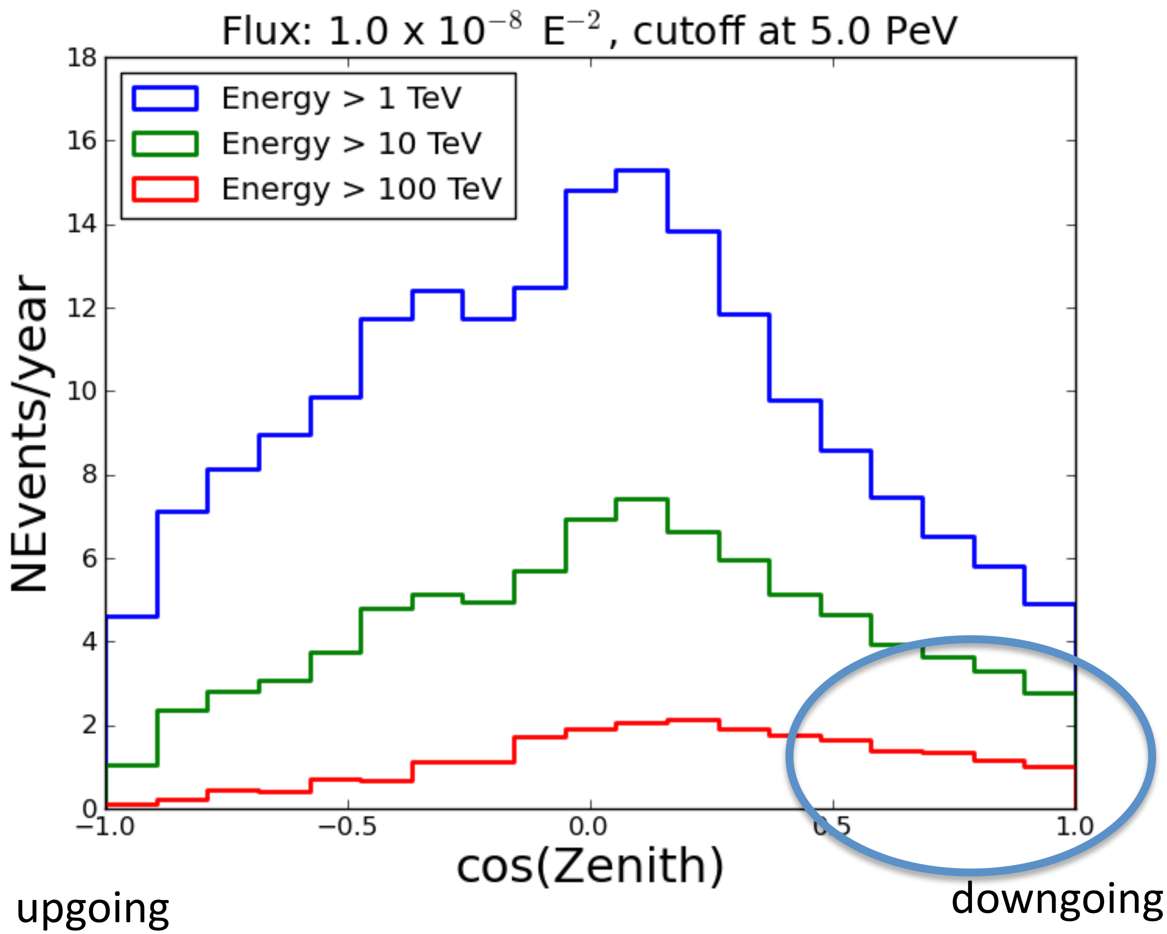
R&D under way



Air shower veto array



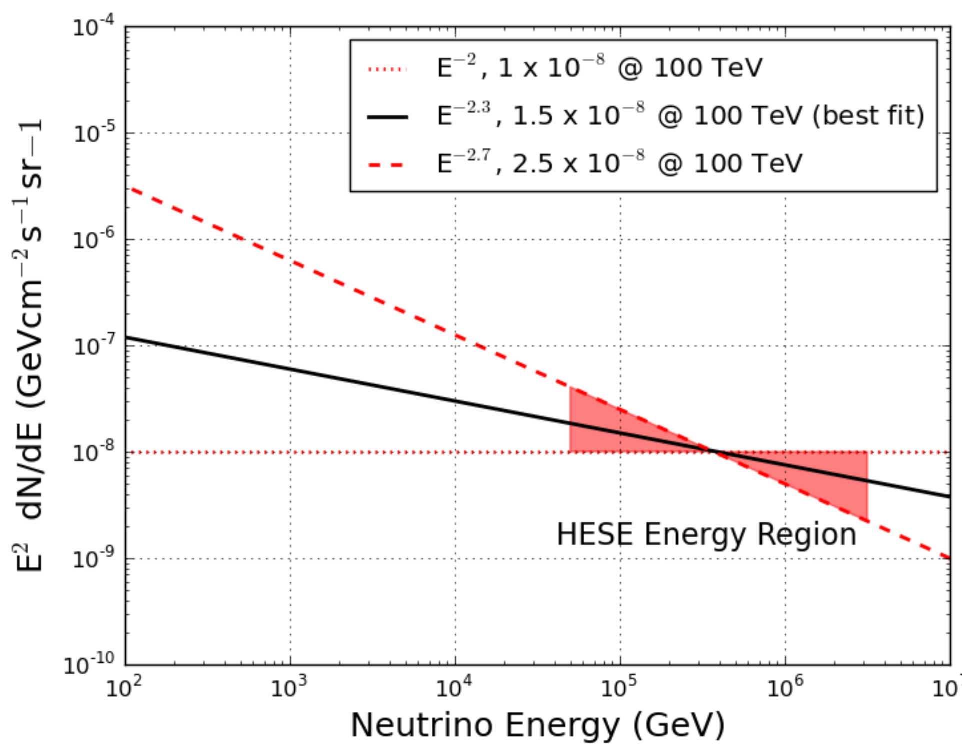
Muon rates from astrophysical flux in IceCube vs zenith angle



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

If we had a surface veto, 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



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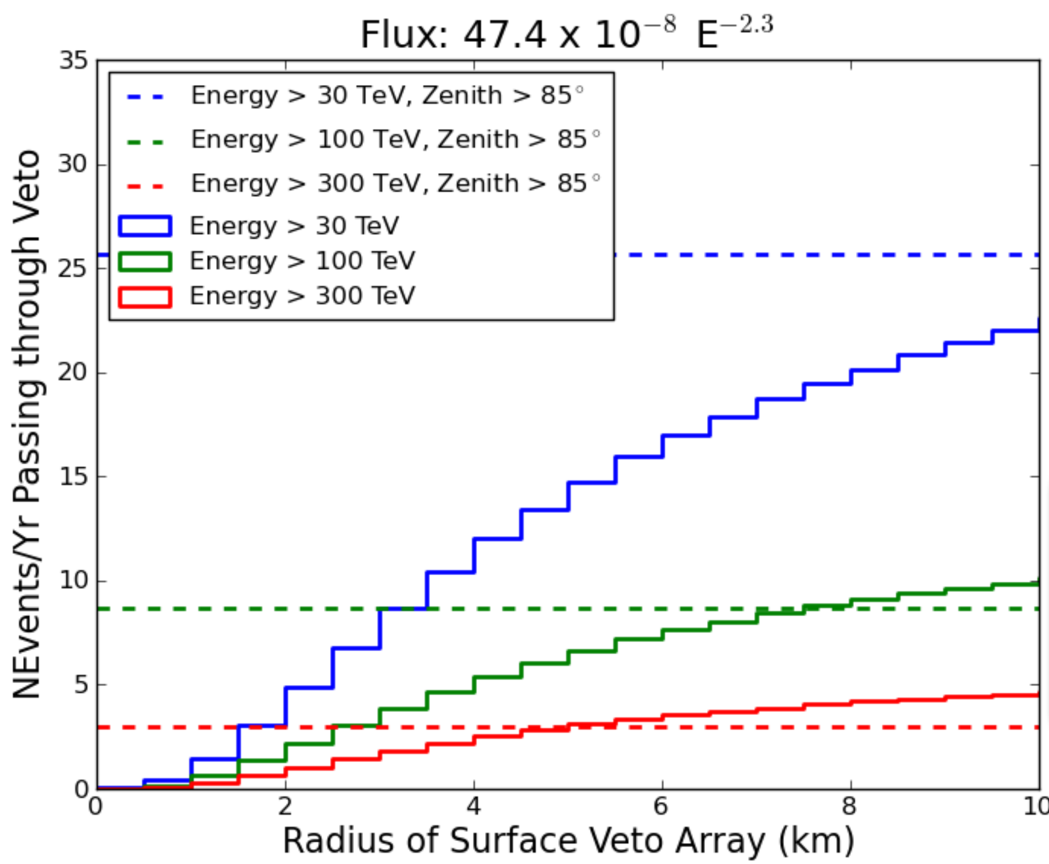
Northern hemisphere (upgoing, zenith > 85°)

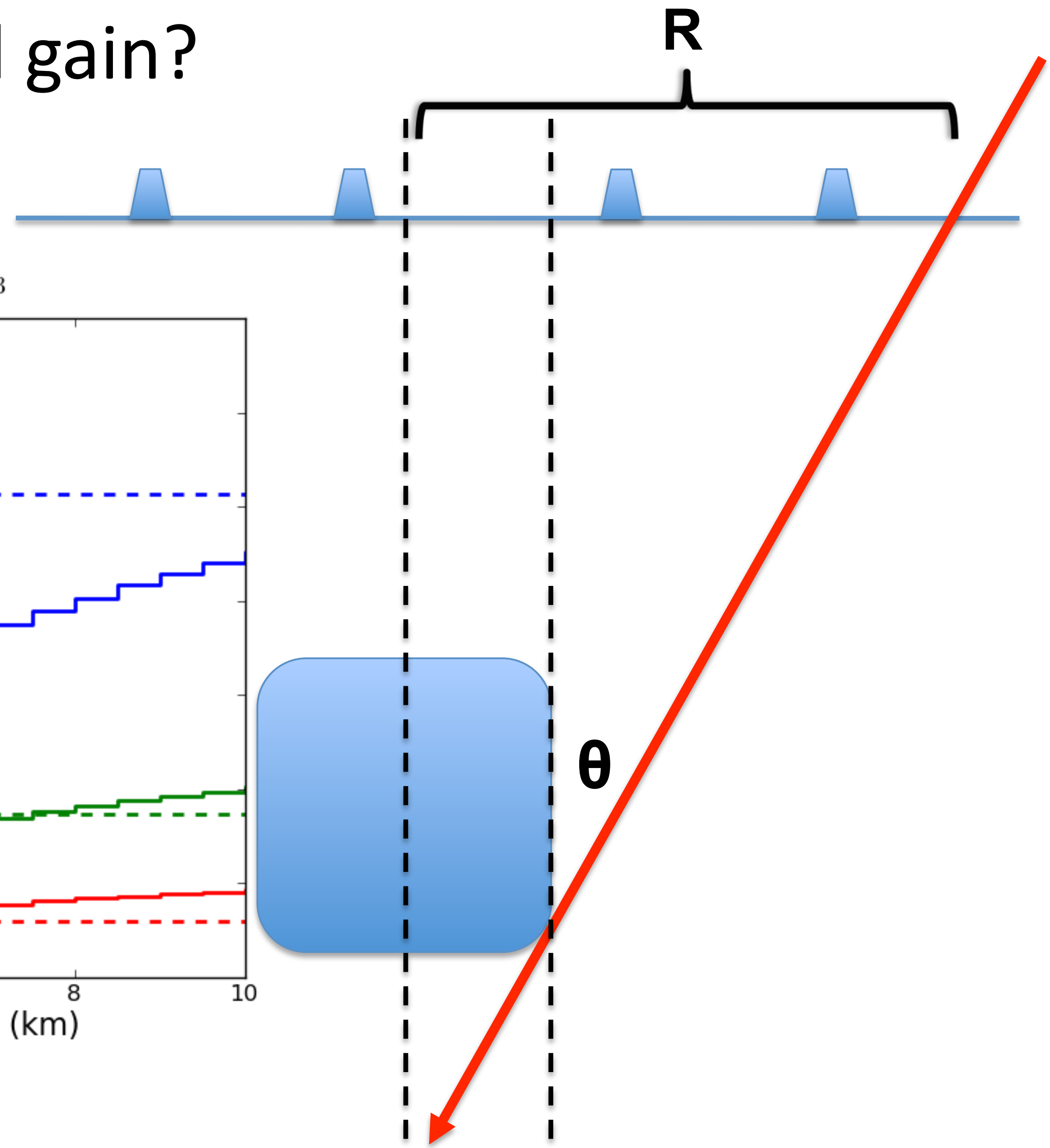
Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	9
$E^{-2.7}$	740	110	7
Atm.	15000	500	5

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?





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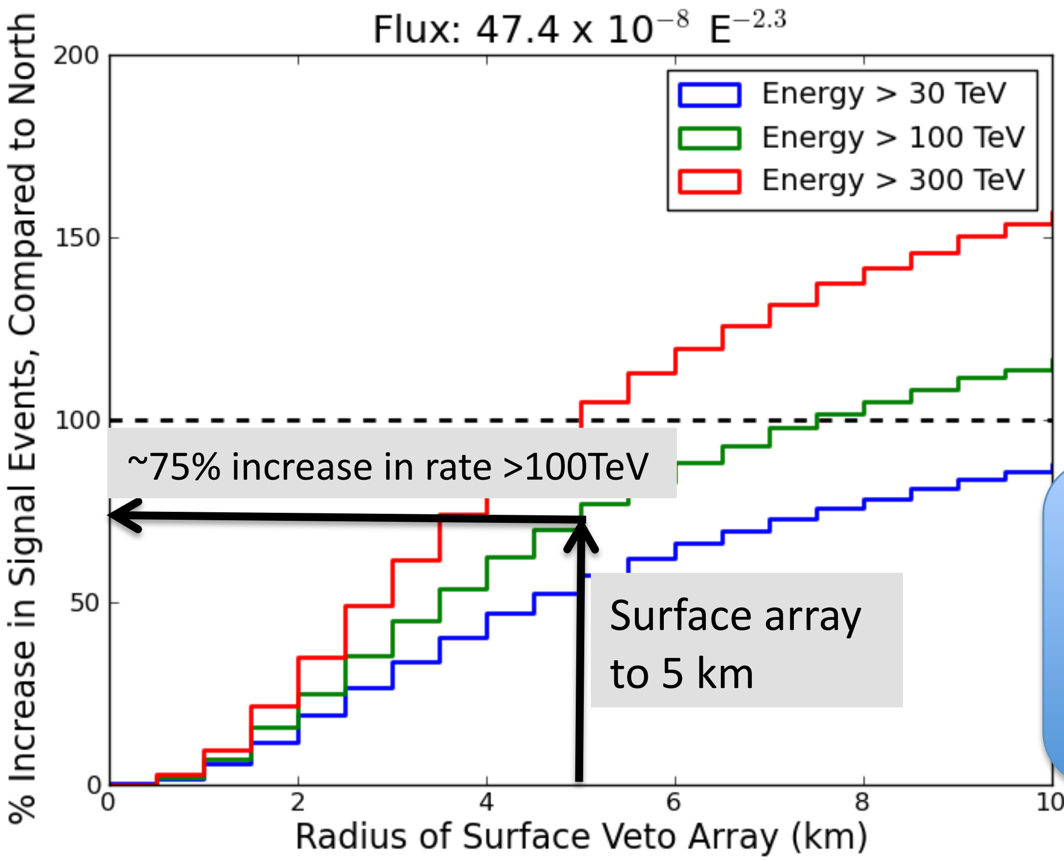
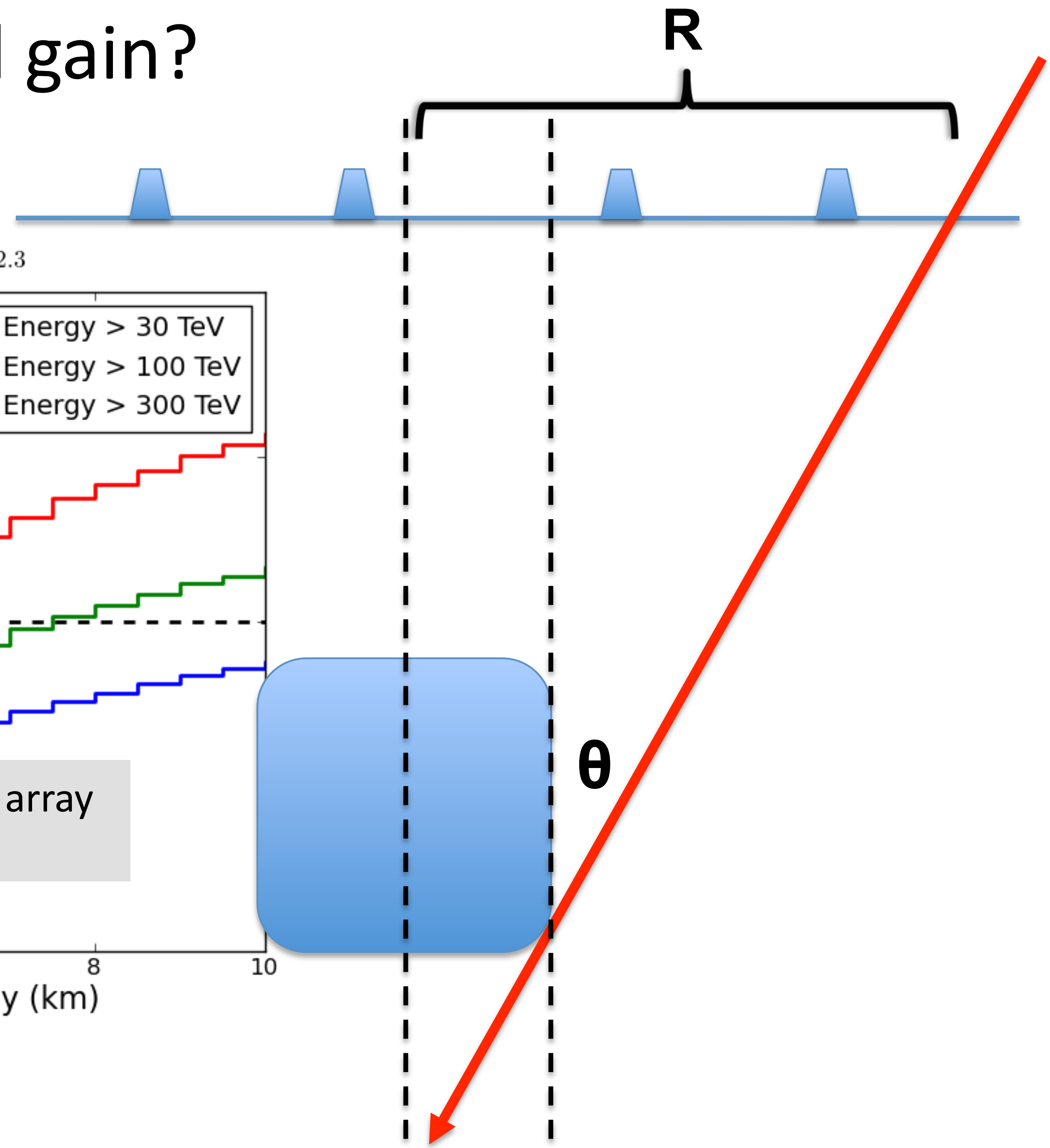




Total neutrino rates: nu_mu

Energy (muon at the detector) > 100 TeV

- IceCube rate: 9/year
- 96 strings, 240m spacing, 1.3 km length
  - Muon eff. area at 100 TeV: ~5 km^2 (factor 3)
- Ideal surface detector (with perfect veto out to 6 km):
  → multiply event rate by 1.75

Very preliminary

- Total event rate:
  - North: ~ 30 events
  - Adding South: 1.75 * 30 = 52 events
  - # of events above 80 TeV: 60 /year
  - **~600 astrophys. events with muon energy > 80 TeV in 10 years**
    80 TeV (muon energy): this the energy where astrophysical and atmospheric are 1:1
    → point source searches

Super cluster geometry (120 strings) would give 30% more: 800 events

Total neutrino rates: cascades (electron, tau-neutrinos and NC)

- IceCube rate (E>1 PeV)
  - 3 events (statistical uncertainty on best fit)
  - Eff. Volume: 0.5 km^3

- 96 strings, 240m spacing, 1.3 km length

- Effective volume
  - 100 TeV: 5 km^3
  - E > 1 PeV: ~7 km^3
  - Surface veto beneficial (no numbers)

- Event rates:
  - Expect 15 x event rate of IceCube Contained event analysis (15 x Bert and Ernie rate) at E > 1 PeV
  - **10 years: 150 events above 1 PeV (modulo statistical uncertainty of measured flux above 1 PeV)**

    → precise energy spectrum and flavor composition (incl. tau neutrinos)

DOMs, Strings and Drilling

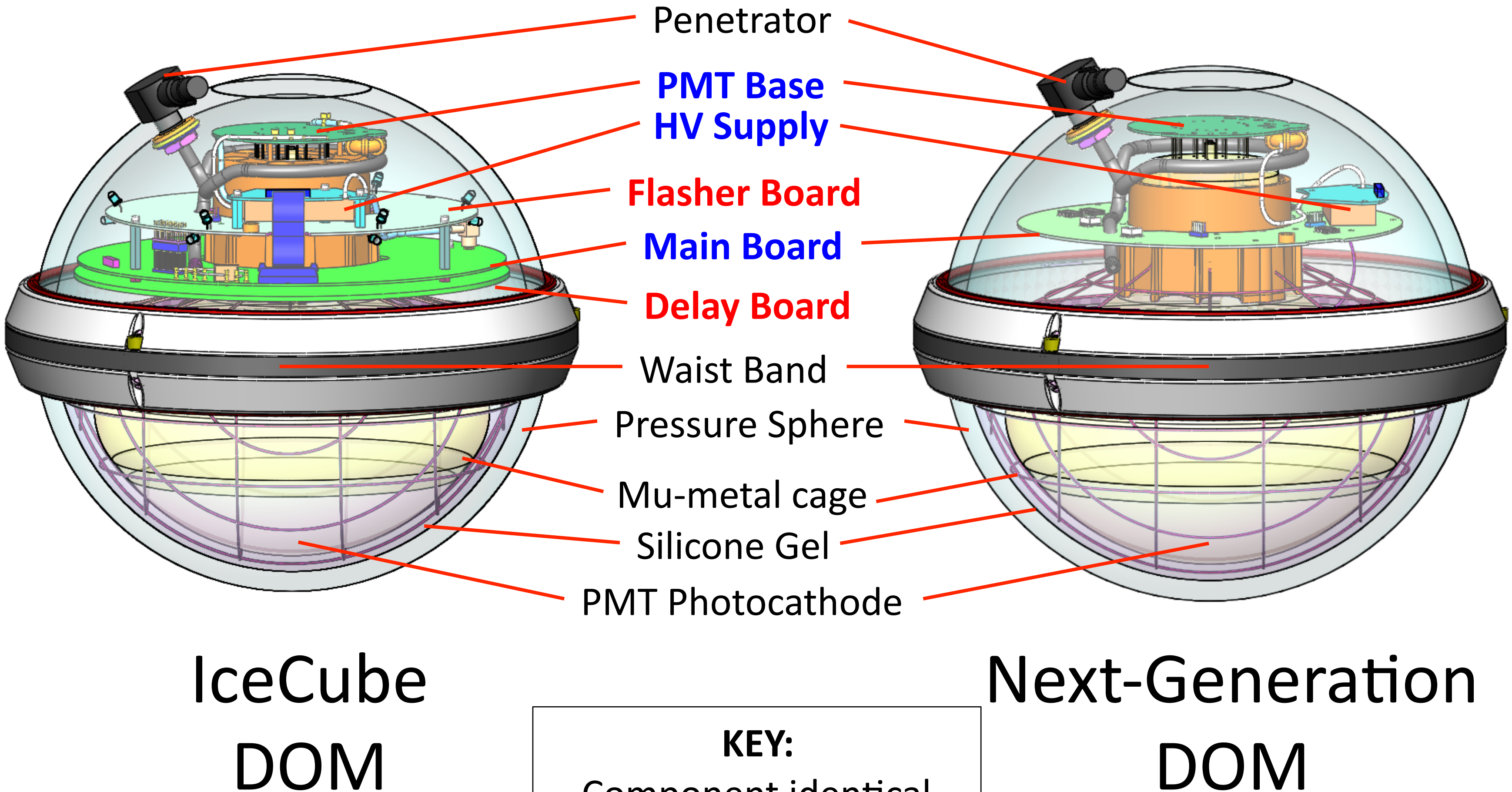
- Scale:
  - ~10,000 DOMs,
  - ~136 strings (including PINGU)
  - ~surface extension to ~6 km
- IceCube experience
  - Drilling is always a challenge!
  - Drilling is well understood, several seasons with 20 strings / season.
  - Challenges of larger distances, larger spacing

System Requirements Comparison

Requirement	IceCube	HEX / PINGU
Timing resolution	<3ns	Same as IC
LSB	0.13 mV	0.08 mV
Range (bits)	16 (3 channels)	14 (1 channel)
Calibration Circuitry	IC flasher	Precision flasher
Production Calibration	Minimal	Sampled
Hole Ice quality	Bubbles	Clearer than IC
Sensors-String/quad	60/4	80/8 (PINGU: 60/8)
PMT	Standard	High QE
Wired Coincidence	Yes	No
Hole Spacing	**125m**	**240m / 30m**
Vertical Spacing	17m	17m / 5m
Hub	**ICL**	**Top of hole / ICL**
Drill Design	**SES-based**	**Modular / transitional**

Next-Generation DOM*

Assumption for baseline



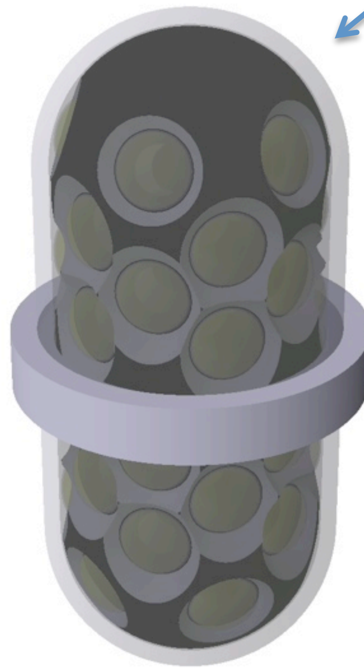
KEY:
Component identical
Component eliminated
Component redesigned

*P. Sandstrom *et al.*, VLVnT13 (Stockholm)

R&D on photodetector modules:

A multi-PMT optical module for the deep ice

Slide courtesy: A. Kappes

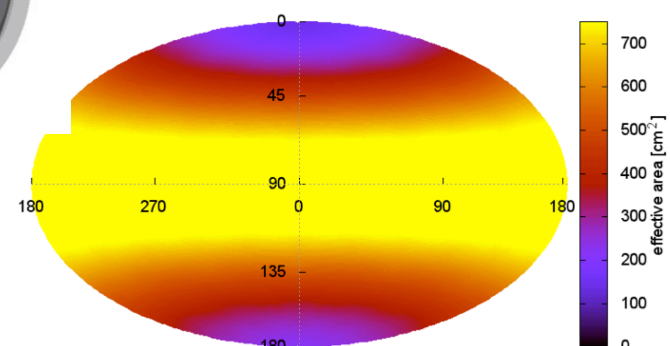


Features

- 41× 3” PMTs
- fits into standard IceCube bore holes
- based on proven **KM3NeT** design
- prototype to be tested in PINGU

Advantages

- 4π acceptance
- 3 times effective area of IceCube DOM @ similar price per photocathode area
- directional sensitivity
- no magnetic shielding needed



effective area

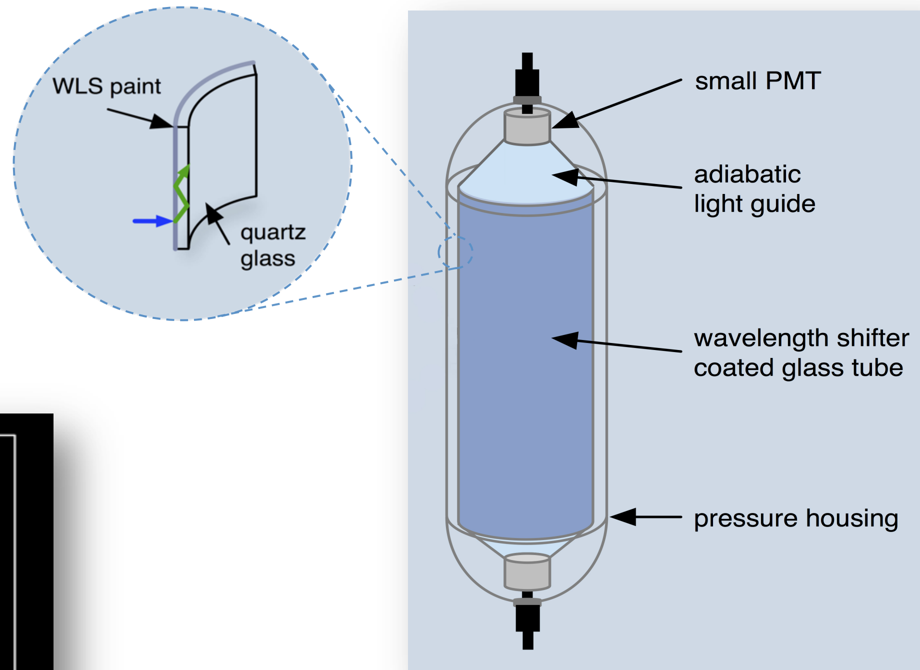
R&D on photodetector modules

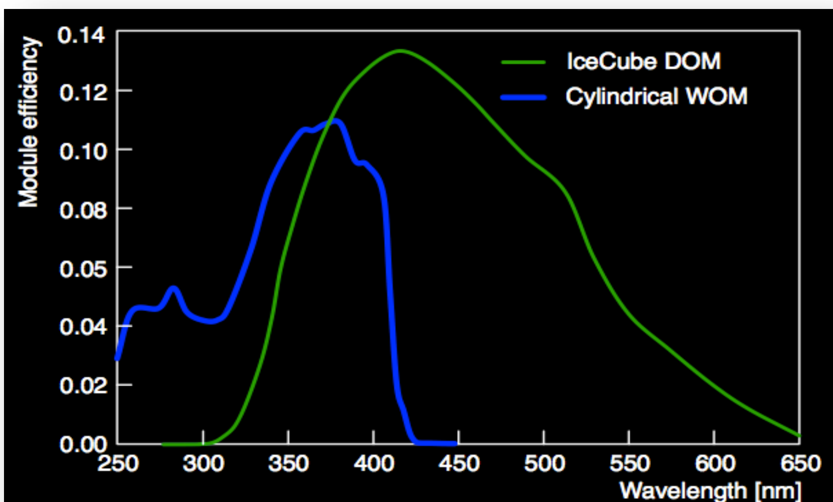
WOM: wavelength shifting optical module

Slide courtesy: S. Böser

Features
- large collection area
- low noise rate (few Hz)
- better UV sensitivity
- cost effective

- Self calibrating setup developed
- Prototype construction underway





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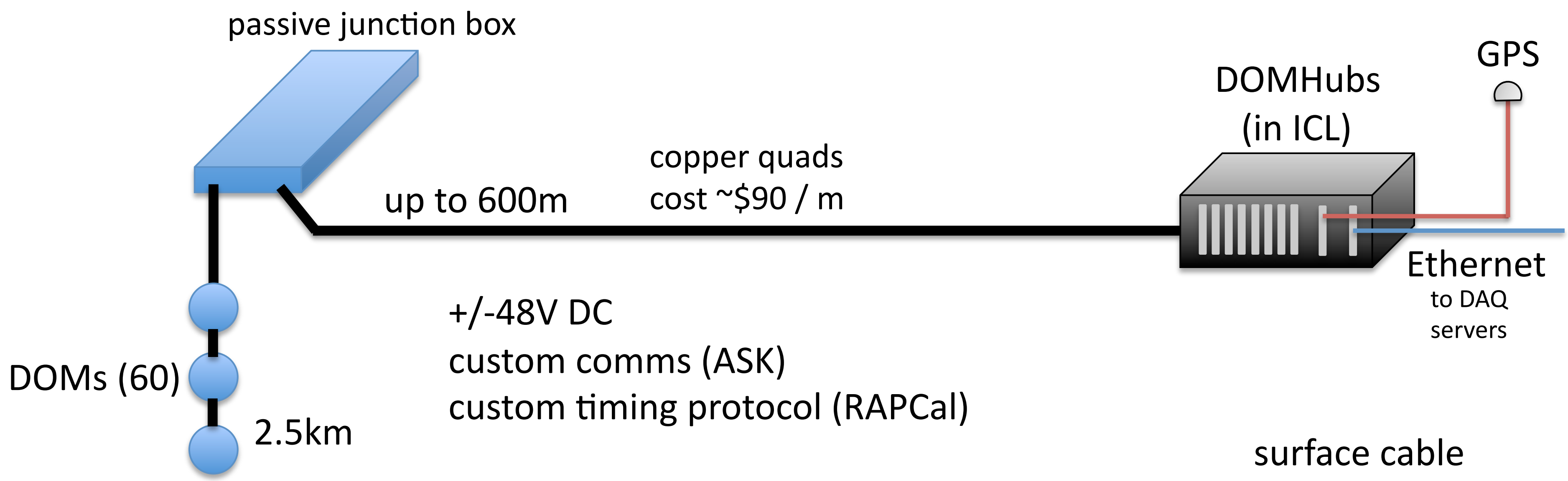
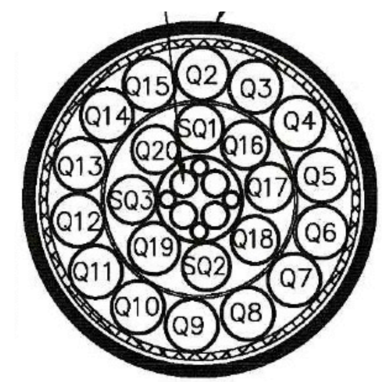
universitätbonn

DOM Readout (IceCube)

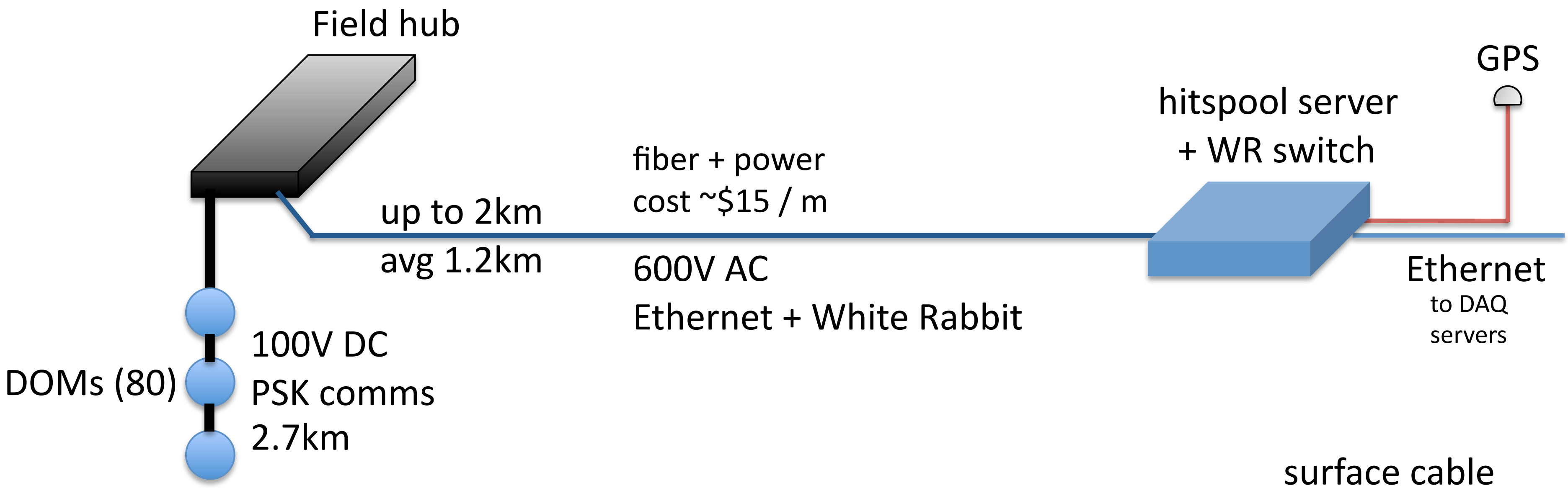




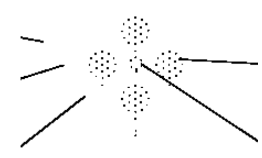
- IceCube scheme:
  - passive junction box at hole top
  - surface cable very similar to down-hole cable
  - readout computers (DOMHubs) in ICL

- Pros: easy to service DOMHubs; warm
- Cons: expensive; resistive losses add up; limited scalability

DOM Readout (Extension)



surface cable
cross-section



1.5 cm OD

- Hubs at top of hole
  - simplified DOM-to-Ethernet functionality (+timing)
  - AC high voltage + fiber to counting house
  - White Rabbit[*] to synchronize hubs

- Pros: reduced cable costs, power; higher-speed comms
- Challenges: cold; hubs not easily serviceable during winter

[*]J. Serrano *et al.*, ICALEPCS 2013 (San Francisco).

String Power Comparison

IceCube power / string	**510W**
DOMs (60)	240W
DOMHub (DOM readout)	125W
transformer + cable losses	145W
Next Generation power / string	**255W**
DOMs (80)	160W
Field Hub	50W
transformer + cable losses	45W

Power savings from:

- reduced DOM power (2W vs. 4W)
- reduced hub power (50W vs. 125W)
- more efficient transformers, power distribution

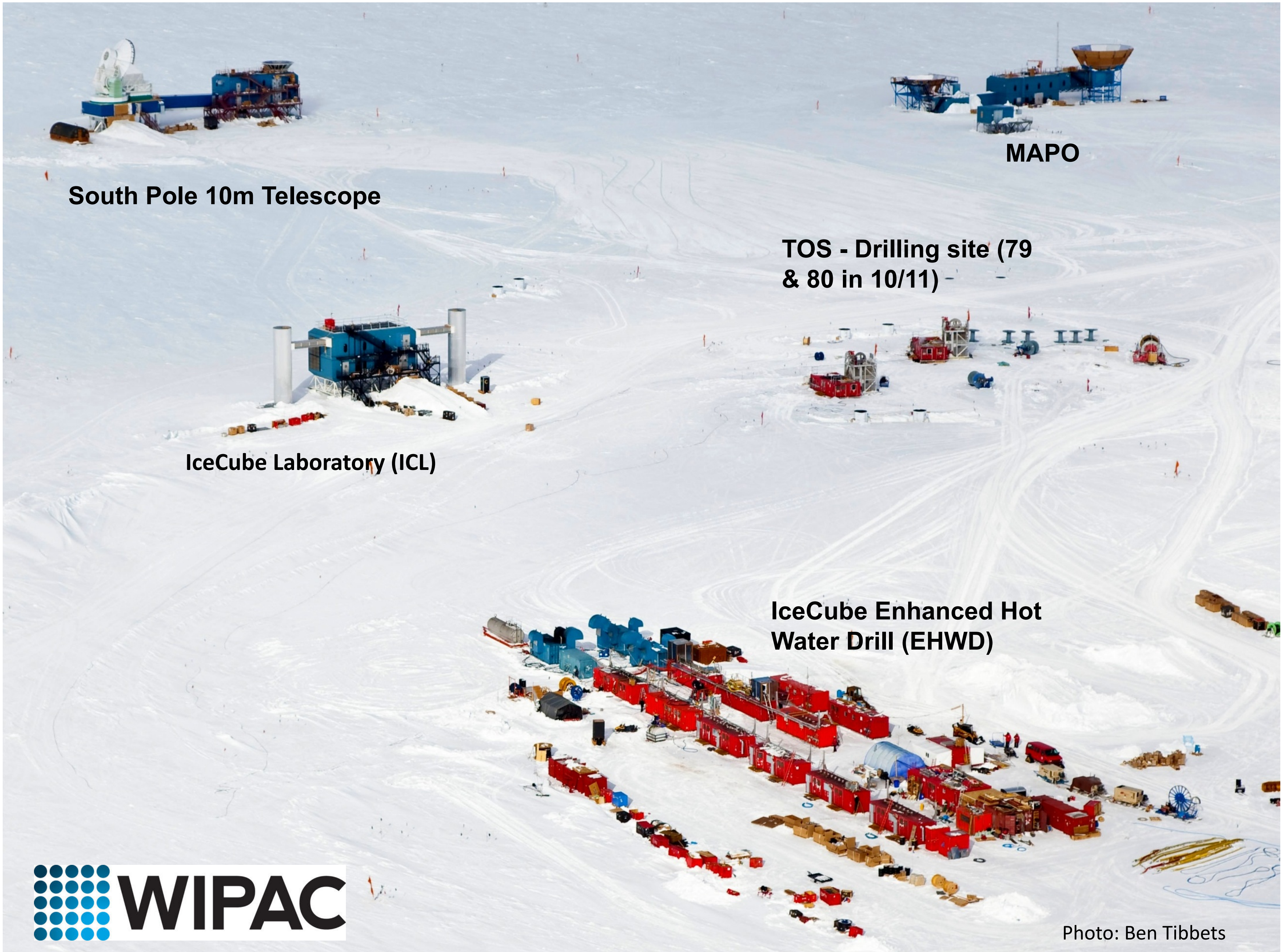
Challenge for drilling

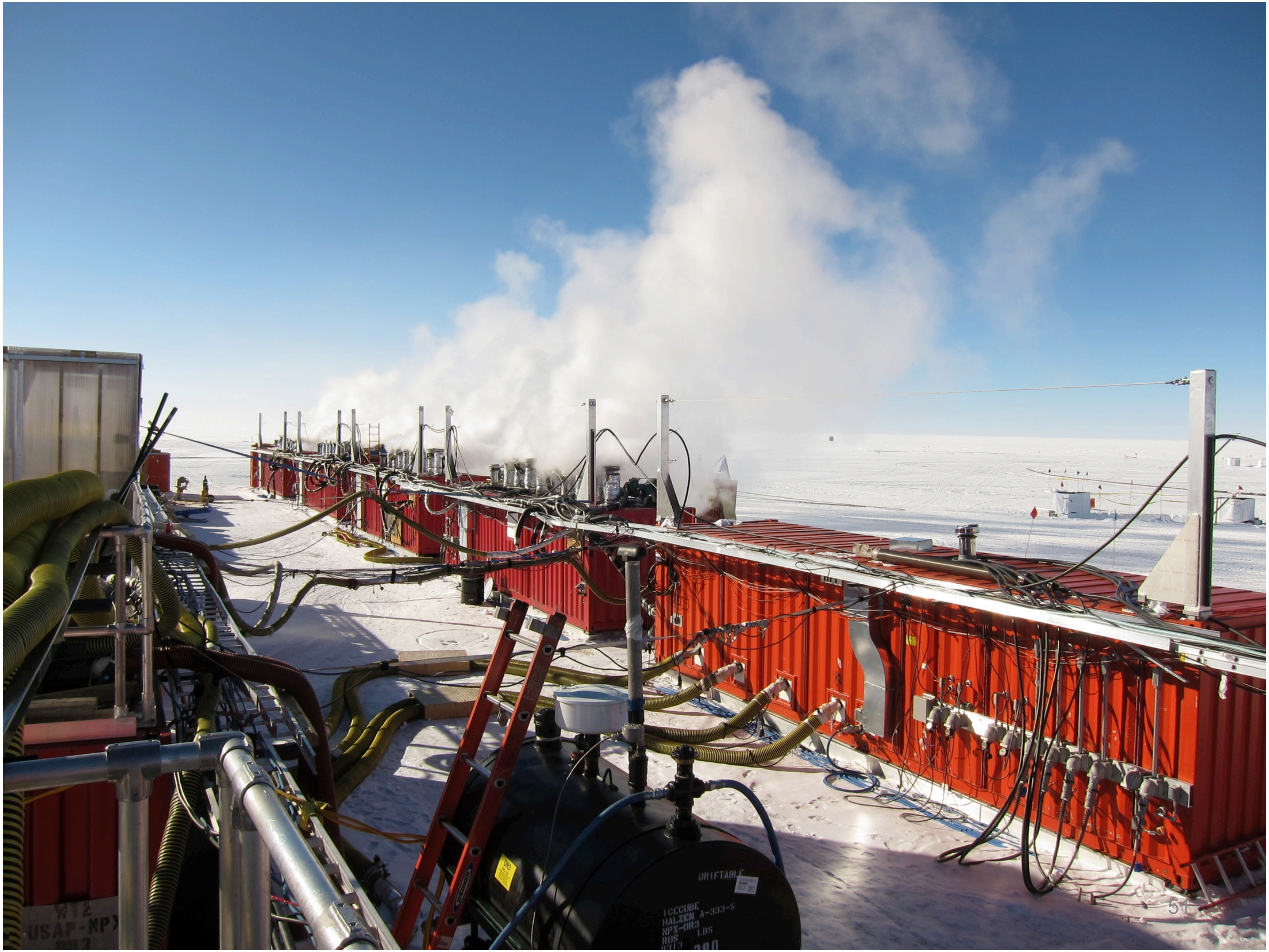
The scale of the task and the extension of the geometry requires changes to the drill heating plant:

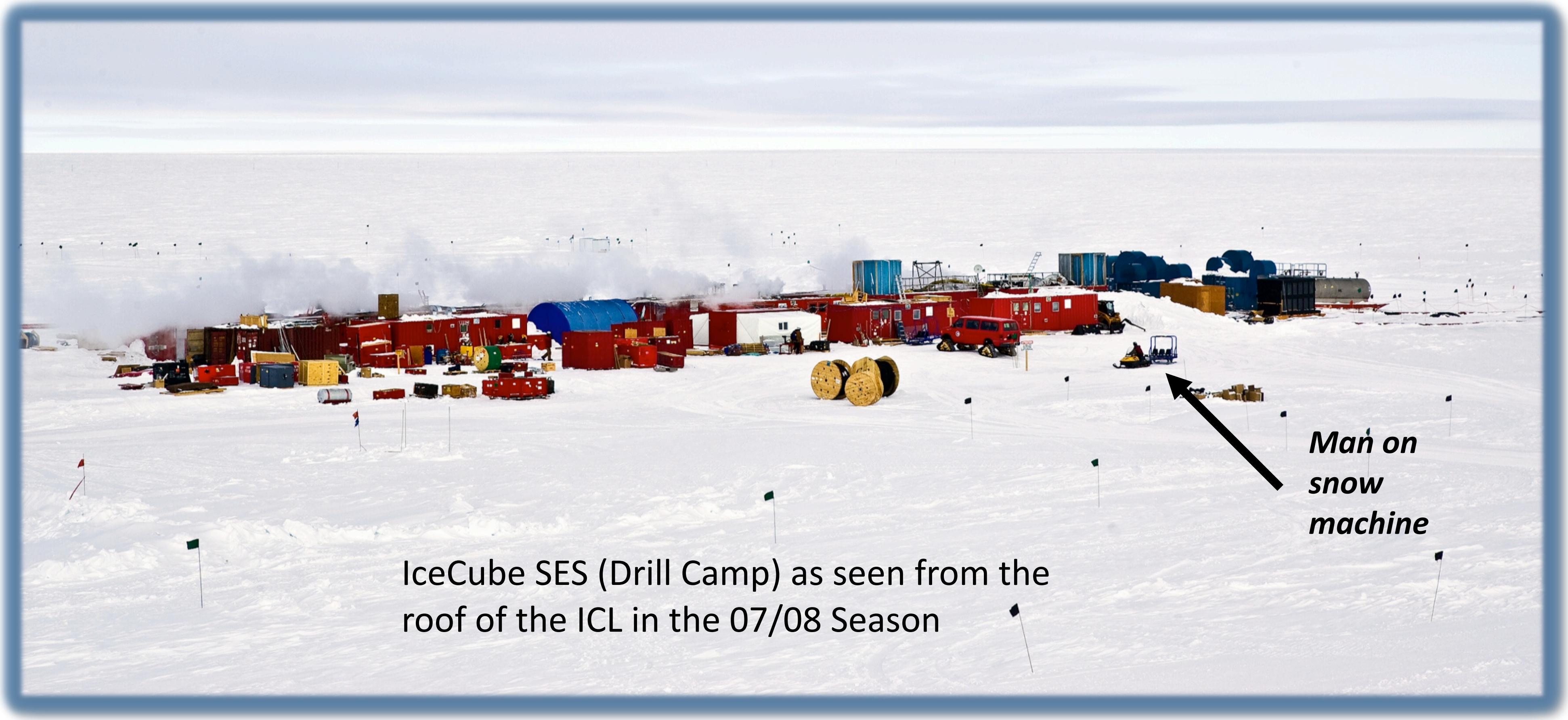
- Higher mobility
- Less complexity
- Simpler operation

Tower operations structure and hose reel:

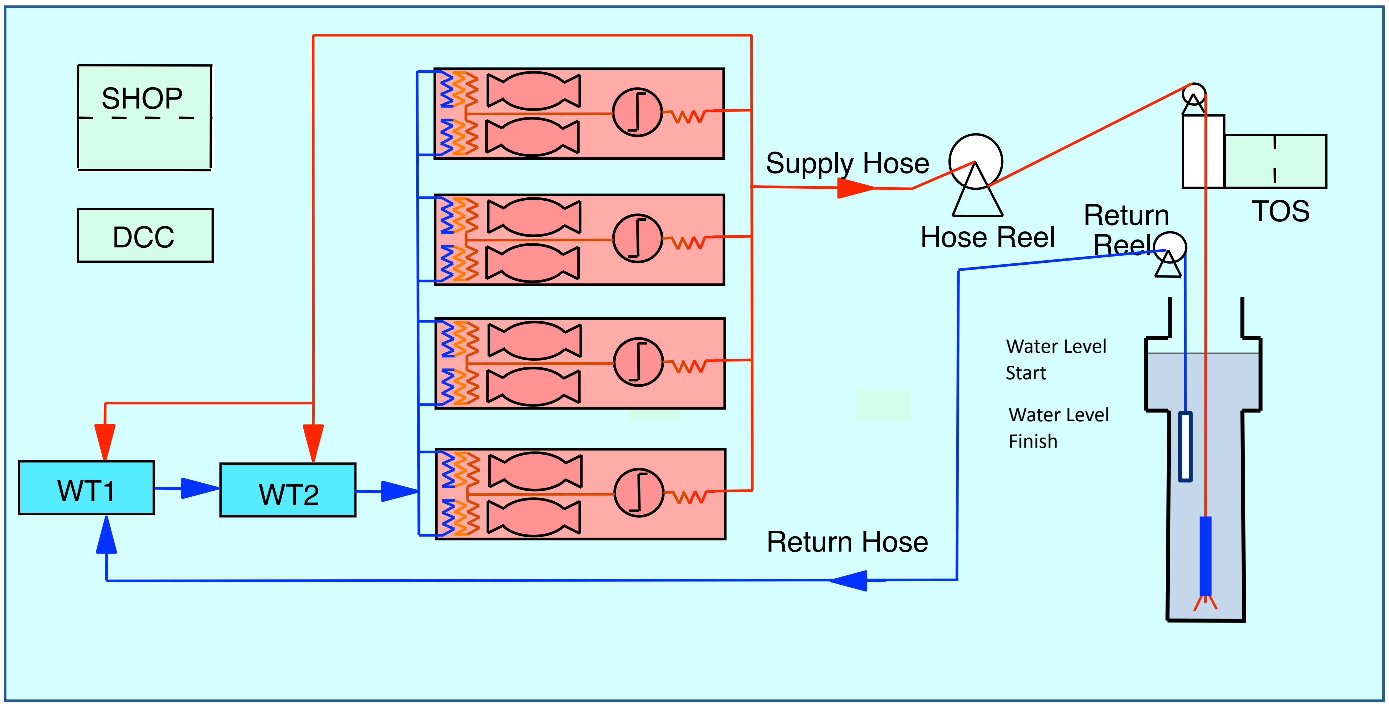
- No significant changes


South Pole 10m Telescope
MAPO
TOS - Drilling site (79
& 80 in 10/11)
IceCube Laboratory (ICL)
IceCube Enhanced Hot
Water Drill (EHWD)
WIPAC
Photo: Ben Tibbets


DRIFTABLE
ICECUBE
HALZEN A-333-S
NPX-DR3
ROS LBS


Man on
snow
machine
IceCube SES (Drill Camp) as seen from the
roof of the ICL in the 07/08 Season

Enhance Hot Water Drill – Generation 2 System Schematic

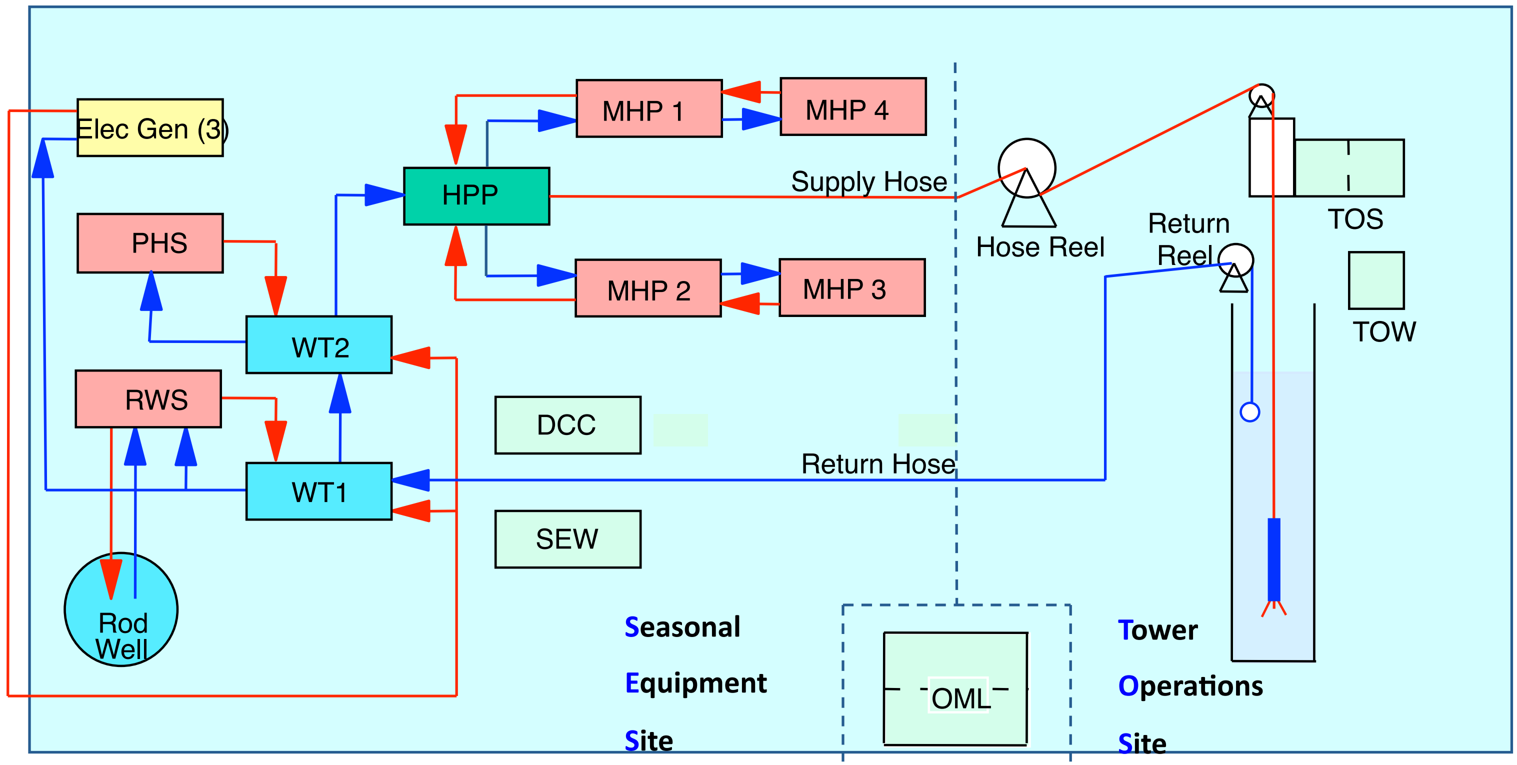


Supply: 200 GPM at 1000 psi and 190 F

Return: 192 GPM at 33 F   Make Up Water: None – From Hole

Power: 3.6 MW thermal, 1.4 MW electrical

(IceCube) Enhance Hot Water Drill – System Schematic



Supply: 200 GPM at 1000 psi and 190 F

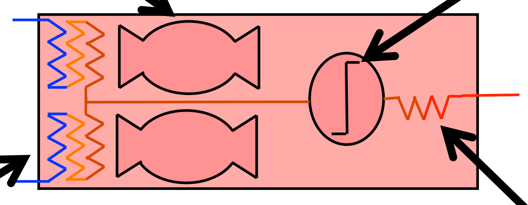
Return: 192 GPM at 33 F   Make Up Water: 8 GPM at 33 F

Power: 4.7 MW thermal, 300 kW electrical

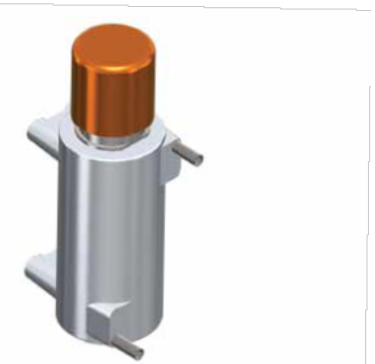
Detail: EHWD G2 Mobile Module

Capstone C200
MicroTurbine (x2)

Roto-Jet 2100 High Pressure Pump



Heat
Exhanger



Durex DFX750
Electrical Heater

Construction schedule scenario

Description	Strings Installed	Cumulative strings installed	Austal Summer
PINGU(+HEX)	8	8	18/19
PINGU	16	24	19/20
PINGU + HEX	18	42	20/21
HEX	20	62	21/22
HEX	20	82	22/23
HEX	20	102	24/25
HEX	20	122	25/26
HEX	14	136	26/27

The Next generation IceCube

There are still new ideas for naming …

The High-energy IceCube of the Next Generation

THE

The

High-energy

IceCube of the

Next

Generation

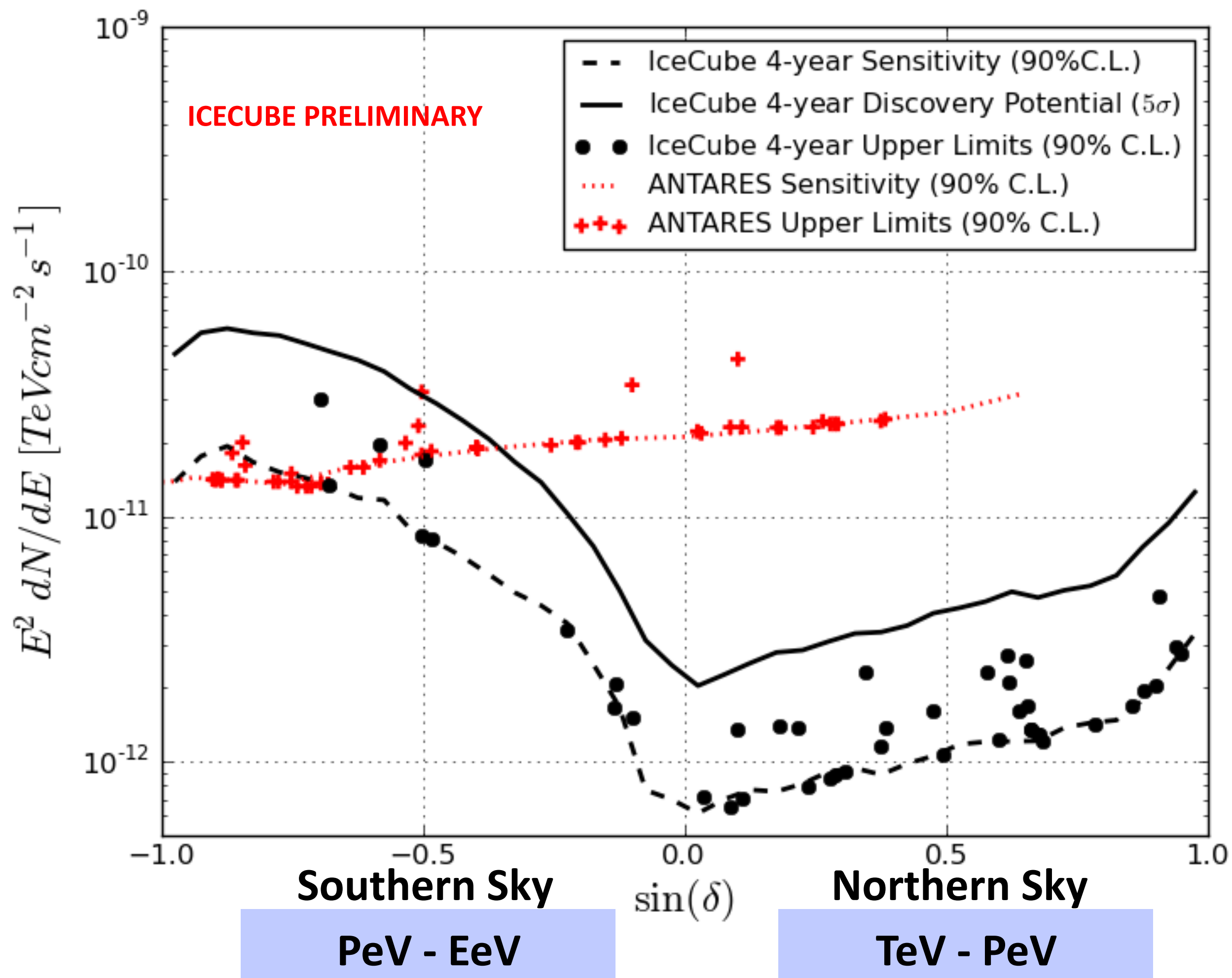
Findings and conclusions

- Investigated a Next Generation IceCube with a total of ~136 strings and 10,000 DOMs of IceCube (DeepCore) equivalent sensitivity.
- A high energy component of order 100 strings that yields factors 5 to 10 of higher event rates than IceCube at E>100TeV appears possible for neutrinos of all flavors. (factor 5 in muon, 7 in cascades at PeV)
- Surface veto not fully explored yet, new possibilities.
- PINGU, with 40 strings embedded in IceCube DeepCore for precision neutrino physics (→ DeYoung).
- Total project cost and construction time comparable to IceCube.
- R&D for design optimization still going on. It may result in reduction of cost and performance enhancements compared to the ones shown here.
- Science requirements not final. Total number of high energy strings may change to larger figure.

- Smaller auxiliary science projects could be coordinated with or if appropriate integrated in such a large facility.

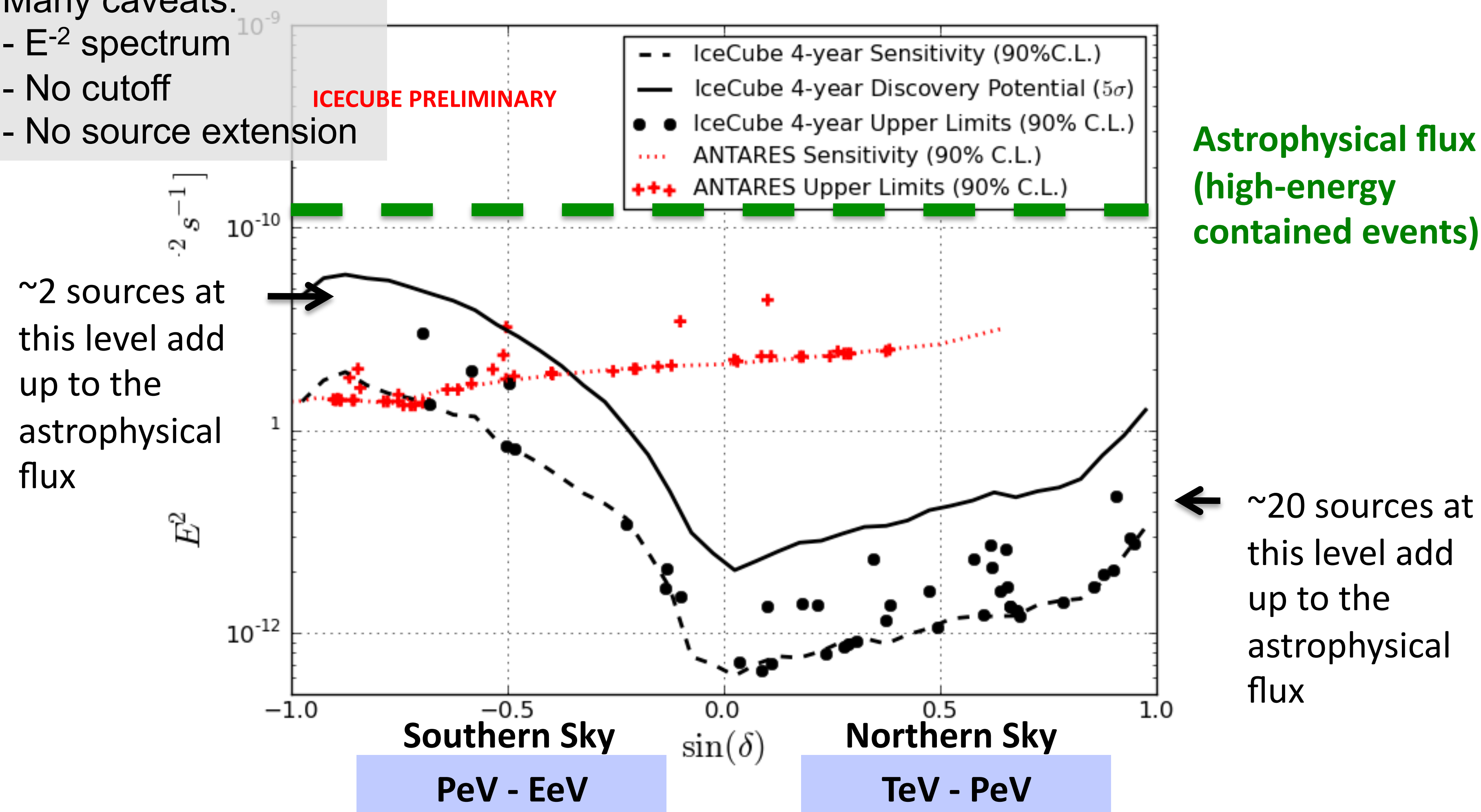
Backup slides

Combining point source limits with flux measurement constrains source population



Combining point source limits with flux measurement constrains source population

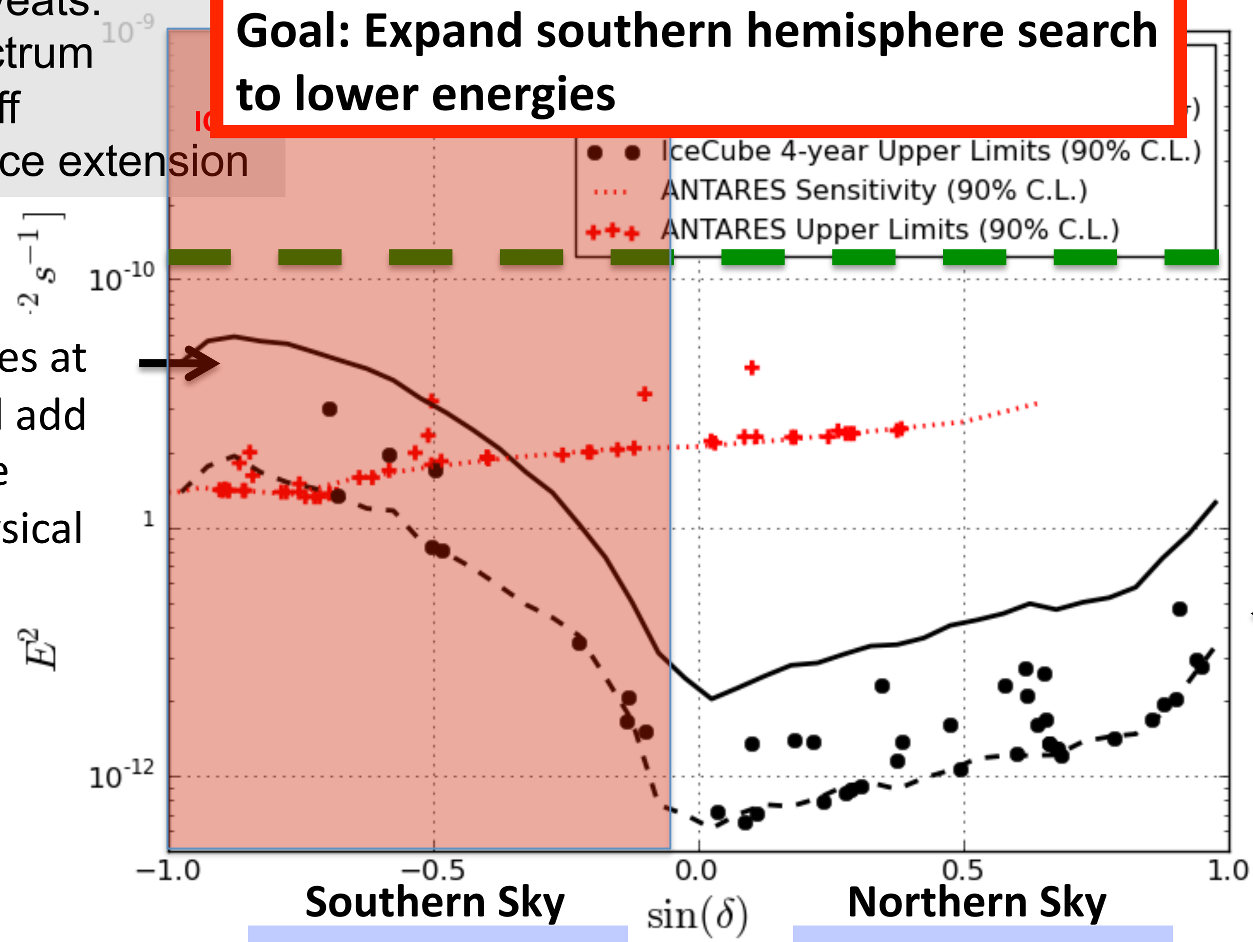
Many caveats:
- E^{-2} spectrum
- No cutoff
- No source extension



Combining point source limits with flux measurement constrains source population

Many caveats:
- E^{-2} spectrum
- No cutoff
- No source extension

Goal: Expand southern hemisphere search to lower energies



Astrophysical flux (high-energy contained events)

~2 sources at this level add up to the astrophysical flux

~20 sources at this level add up to the astrophysical flux

Southern Sky

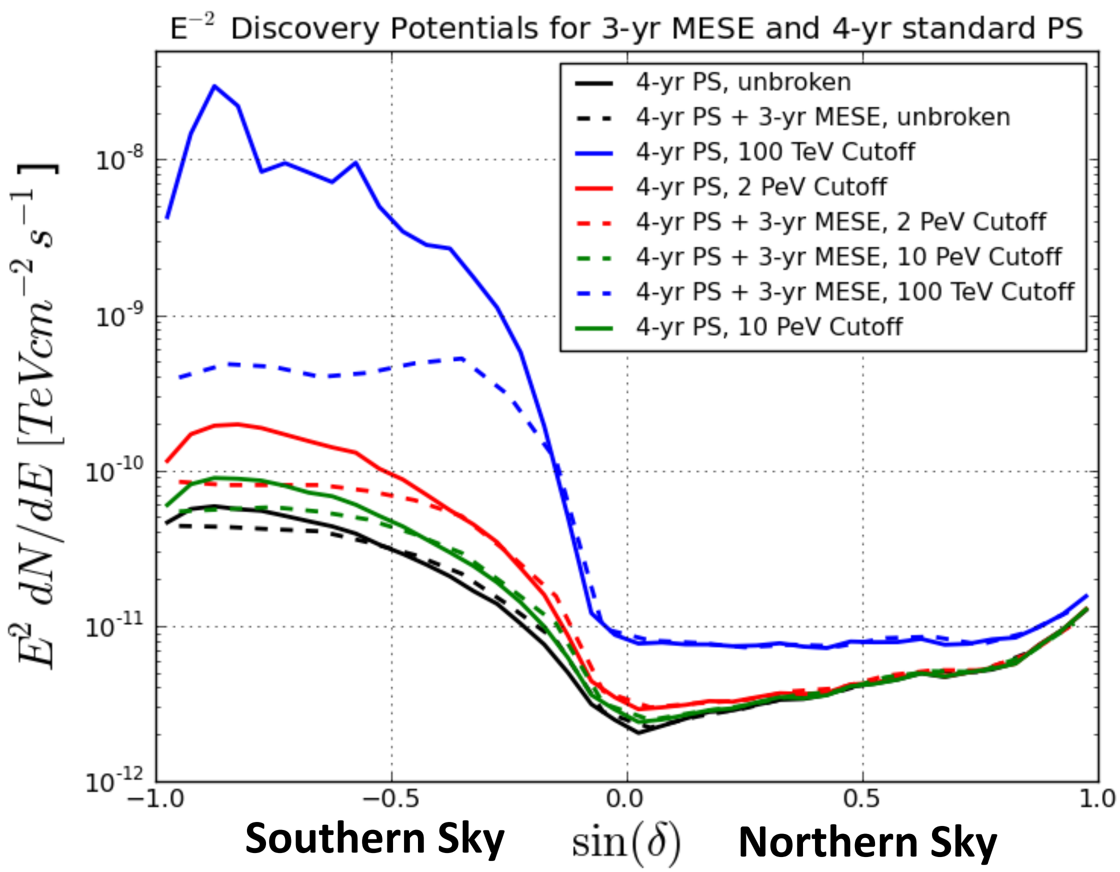
PeV - EeV

Northern Sky

TeV - PeV

Looking Ahead

- Analysis using starting tracks will improve sensitivity to sources in southern sky
  - Contained-vertex event veto with lower energy threshold
- Stay tuned for results!



Discovery potential for sources emitting E^{-2} spectra ending at:

100 TeV

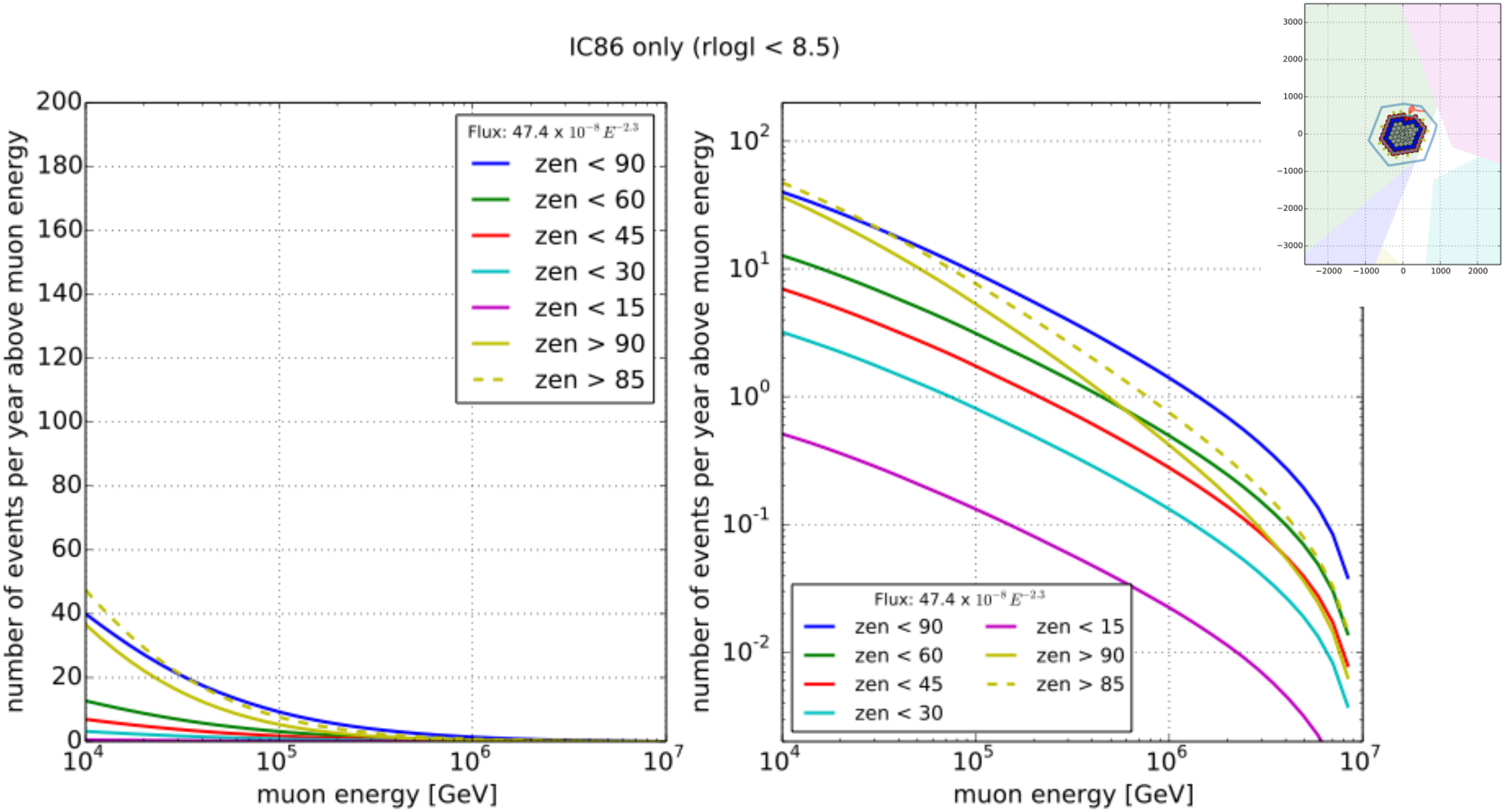
2 PeV

10 PeV

1000 PeV

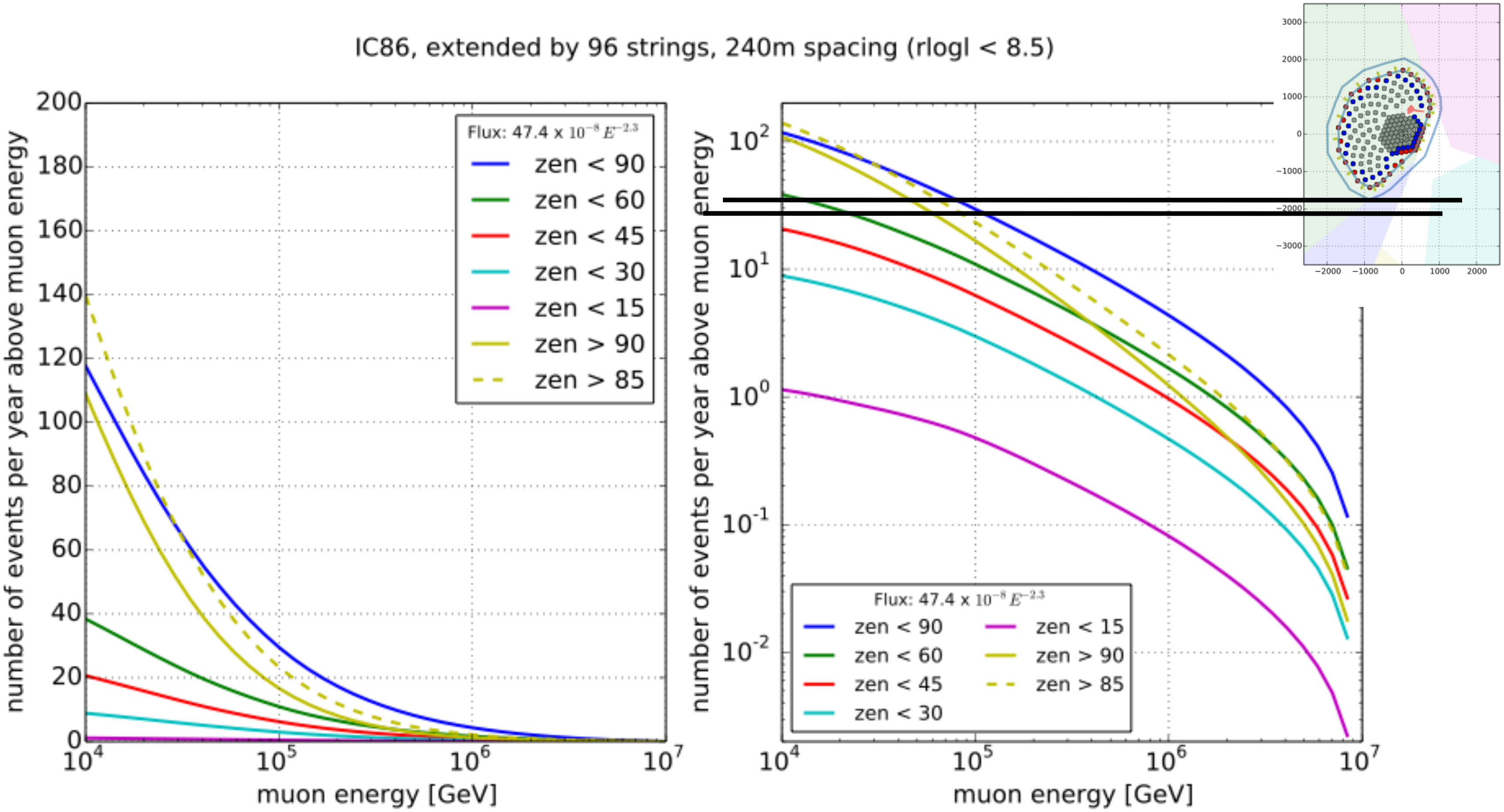
Solid – 4-yr Point Source

Dashed – 4-yr PS + 3-years of starting tracks



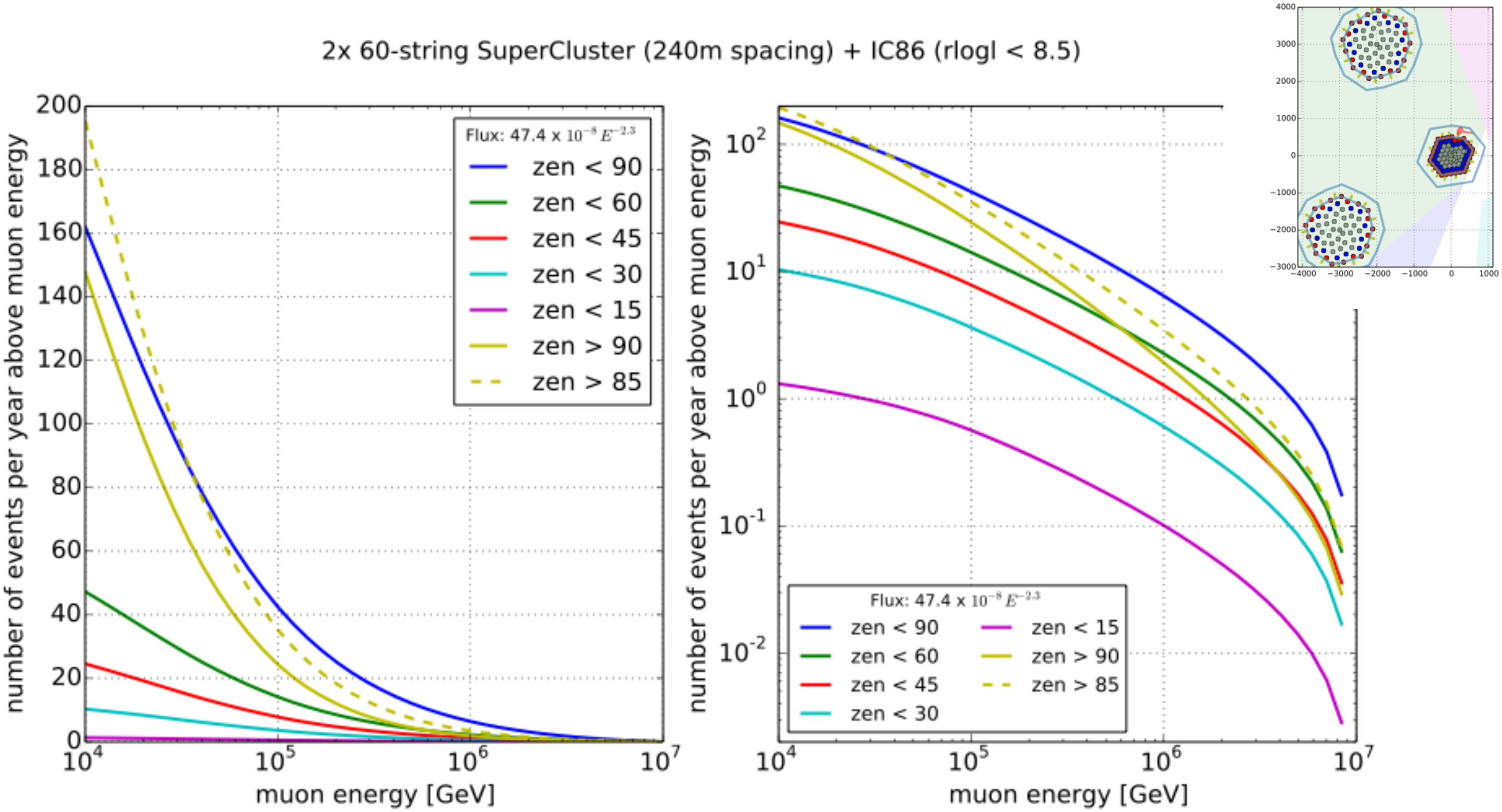
IceCube

cumulative event rates at various zenith angle ranges



Sunflower 96

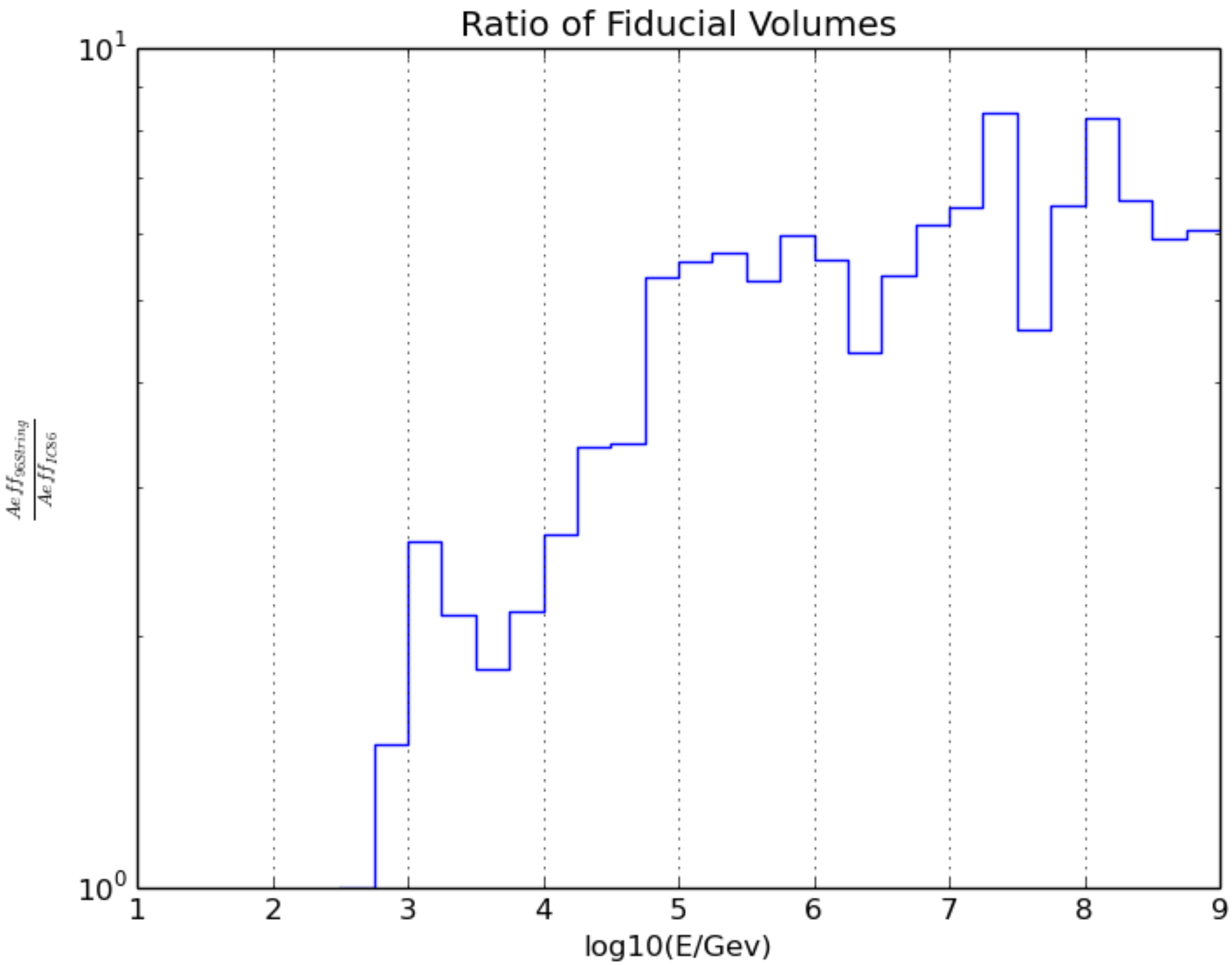
cumulative event rates at various zenith angle ranges

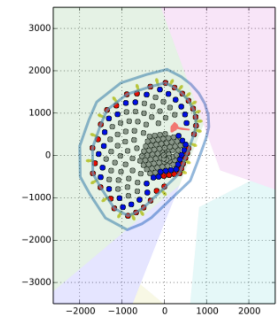


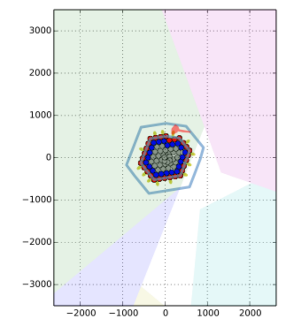
2x60-String Cluster + IC86

cumulative event rates at various zenith angle ranges

HESE-style veto?







Ratio Sunflower 96 / IceCube

(Christian) vs. neutrino energy