The Ohio State University's Center for Cosmology and AstroParticle Physics

Search for Neutrino Oscillations at the South Pole

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ICRR Seminar – University of Tokyo

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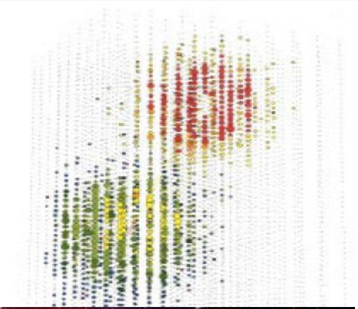
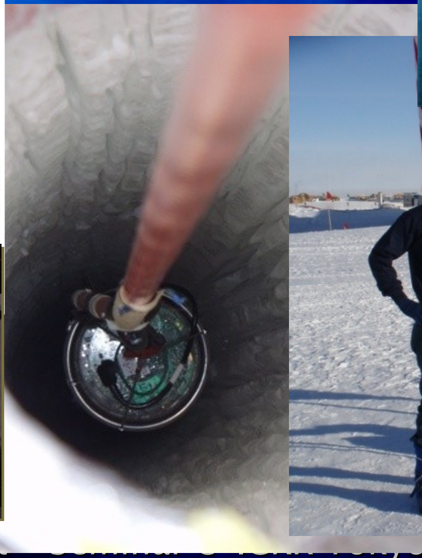
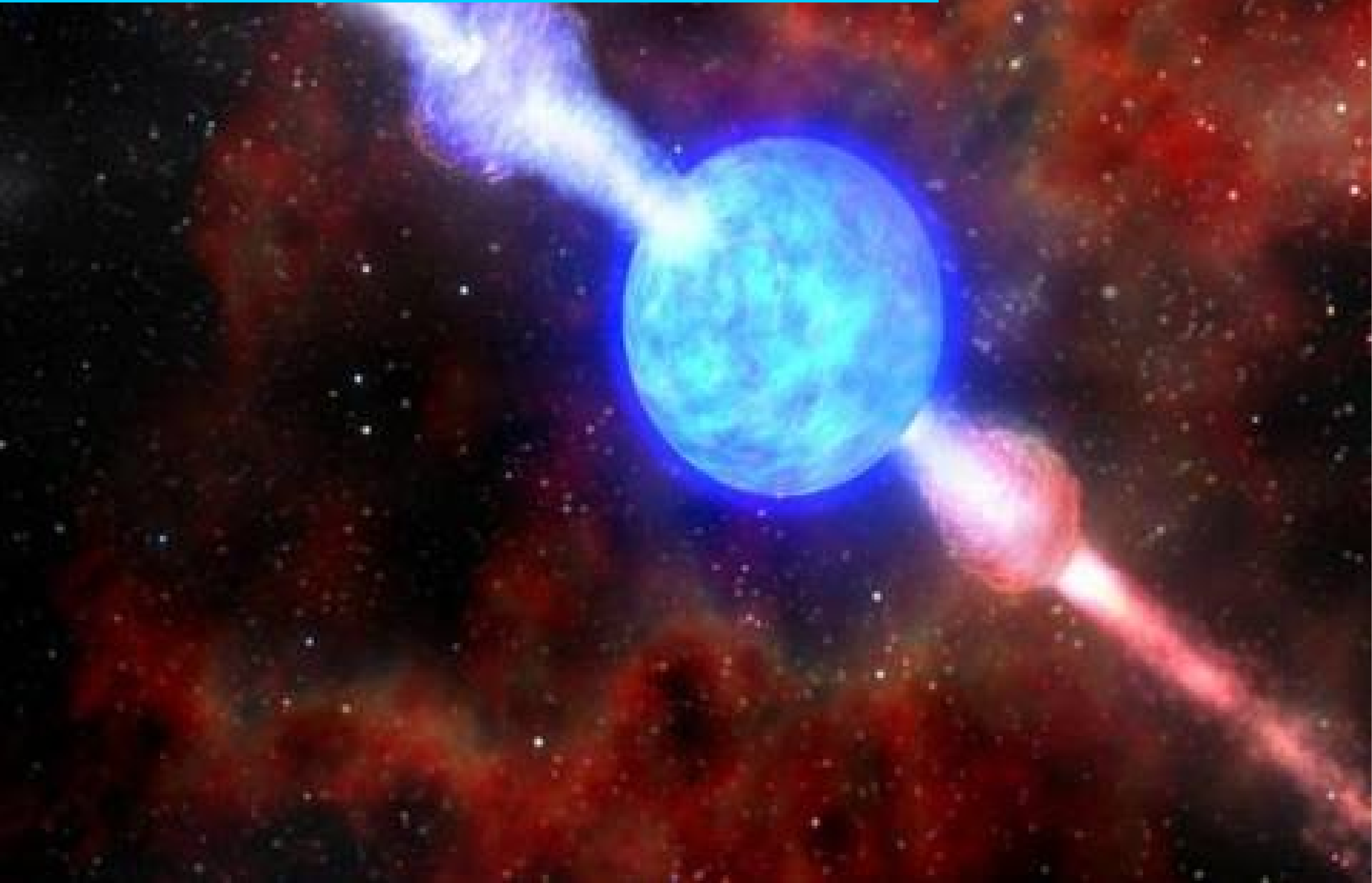
Outline

- Motivation
- The IceCube Neutrino Observatory
- Neutrino Oscillation
- Indirect Search for Dark Matter
- The Deep Core sub-detector
- Outlook – Deep Core Physics
- Conclusions





Motivation



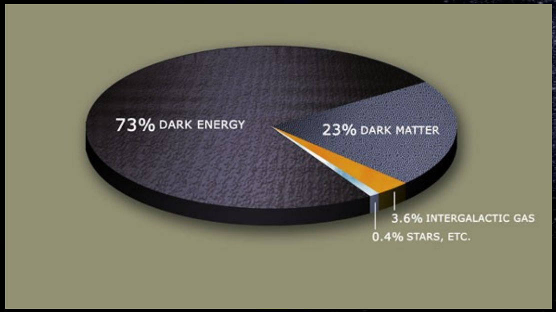
Some Questions

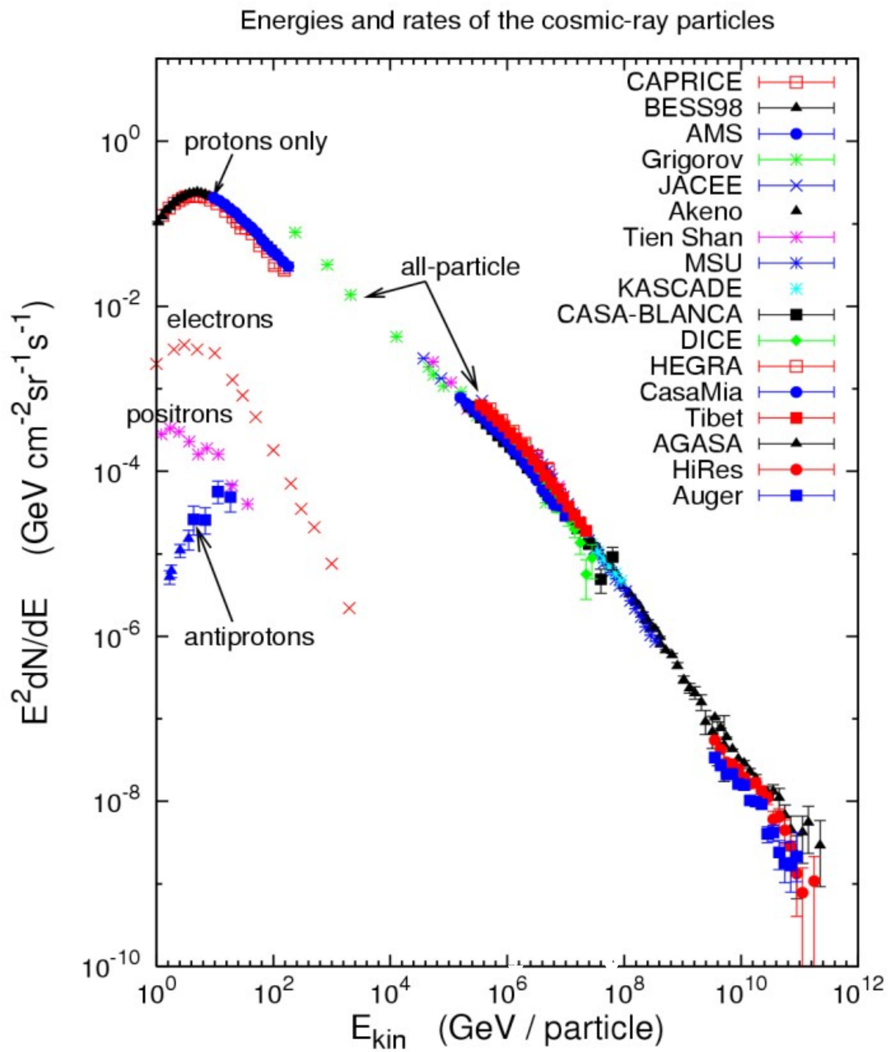
What are the sources of the cosmic rays ?

What are the most energetic phenomena in the Universe ?

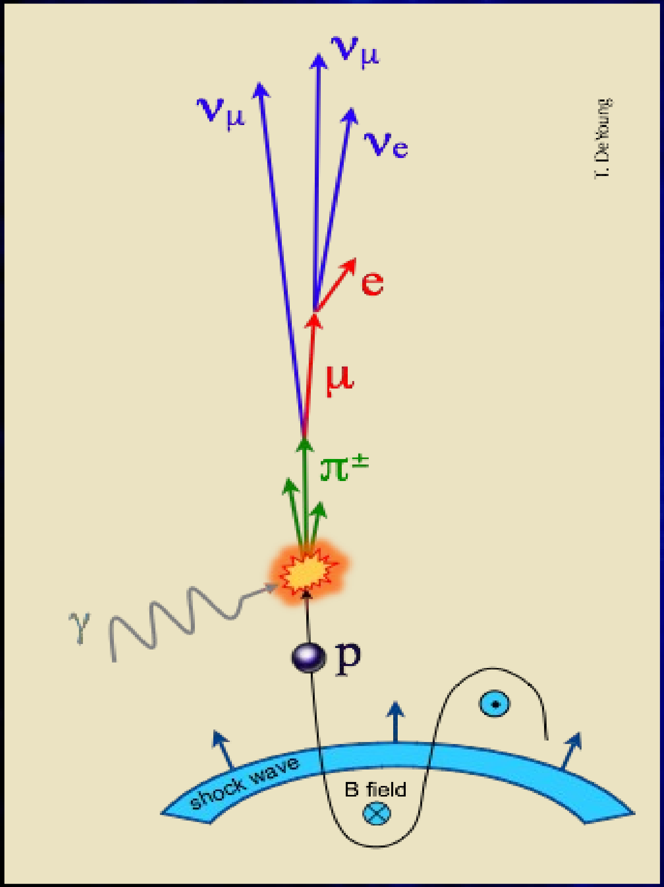
What is the nature of the acceleration mechanism to create these energetic events ?

What is the Universe made of ?
 – What is Dark Matter ?





Neutrino Sources



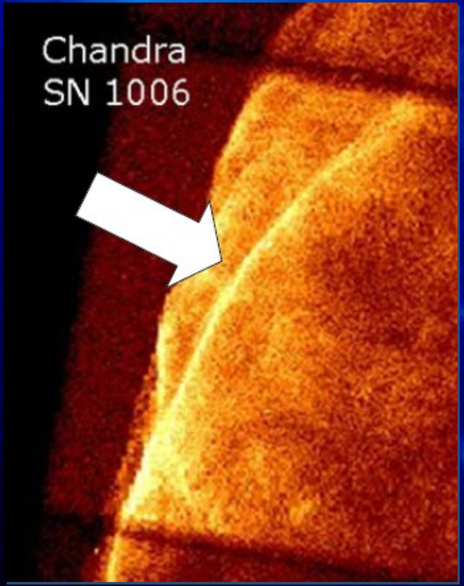
Protons interact in "target area" to produce pions:

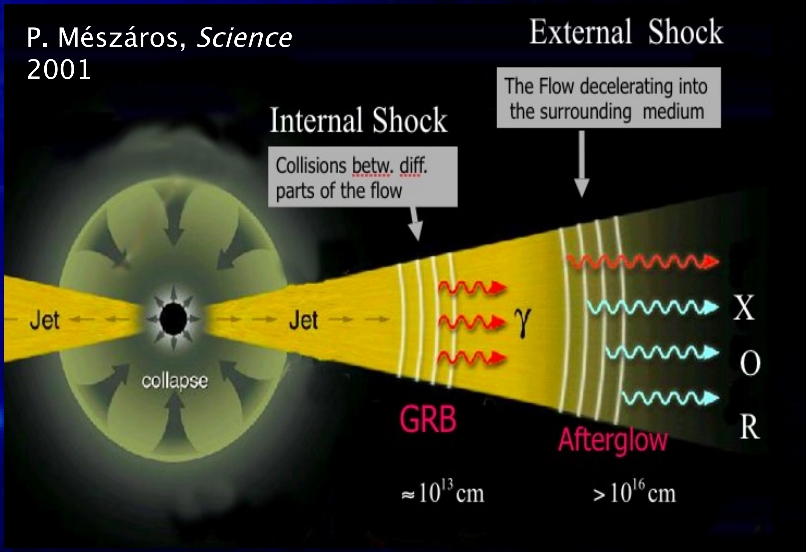
$$p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$
$$\rightarrow \pi^\pm \rightarrow \nu_e \nu_\mu \rightarrow \nu_e \nu_\mu \nu_\tau$$
$$(1:2:0) \qquad (1:1:1)$$

Neutral pions → Photons
Charged pions → Neutrinos
Oscillations result in 1:1:1 flavor ratio at detector

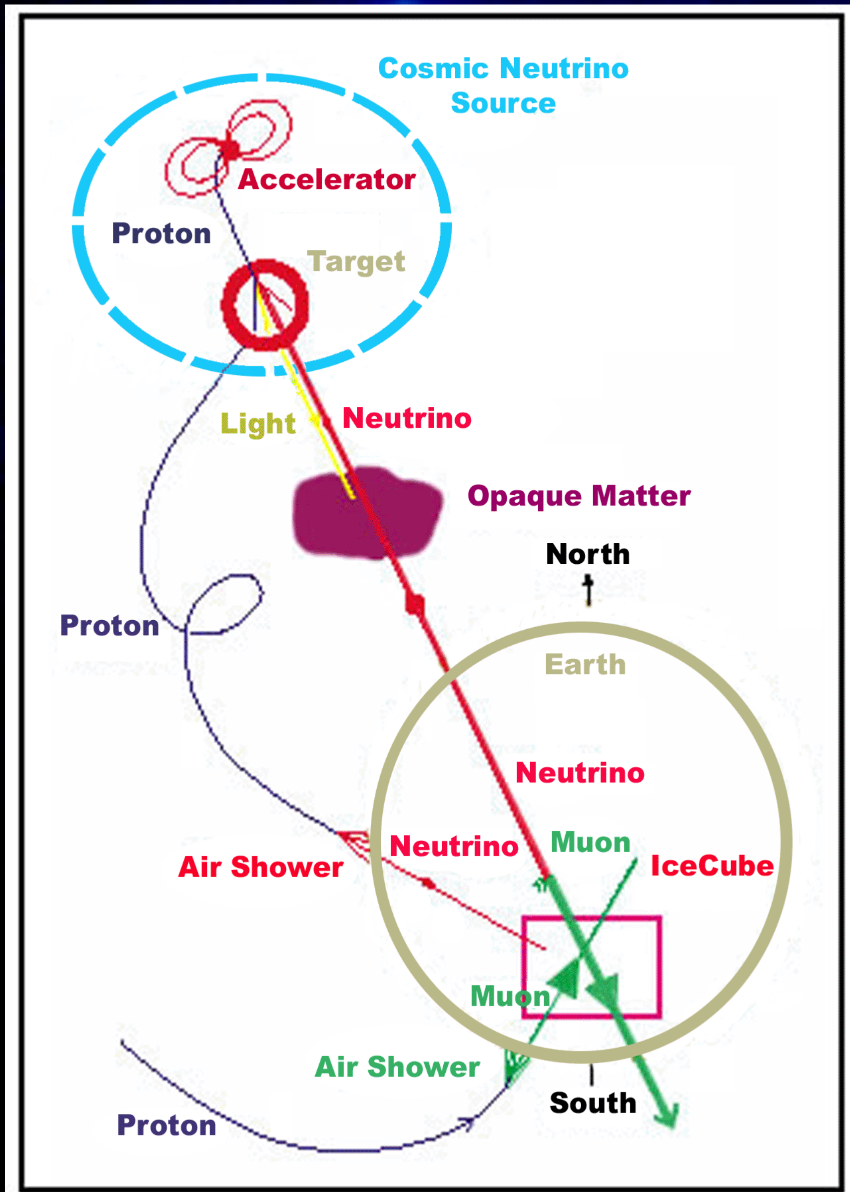
Source Candidates:

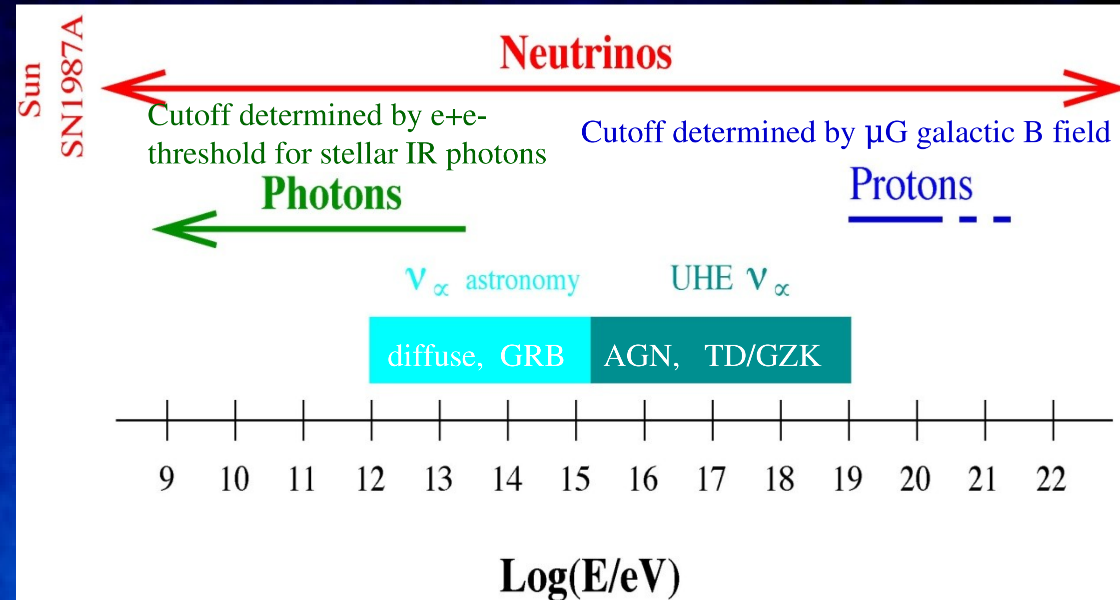
- Active Galactic Nuclei
- Supernova Remnants
- Gamma Ray Bursts
- ...





Astro Messengers





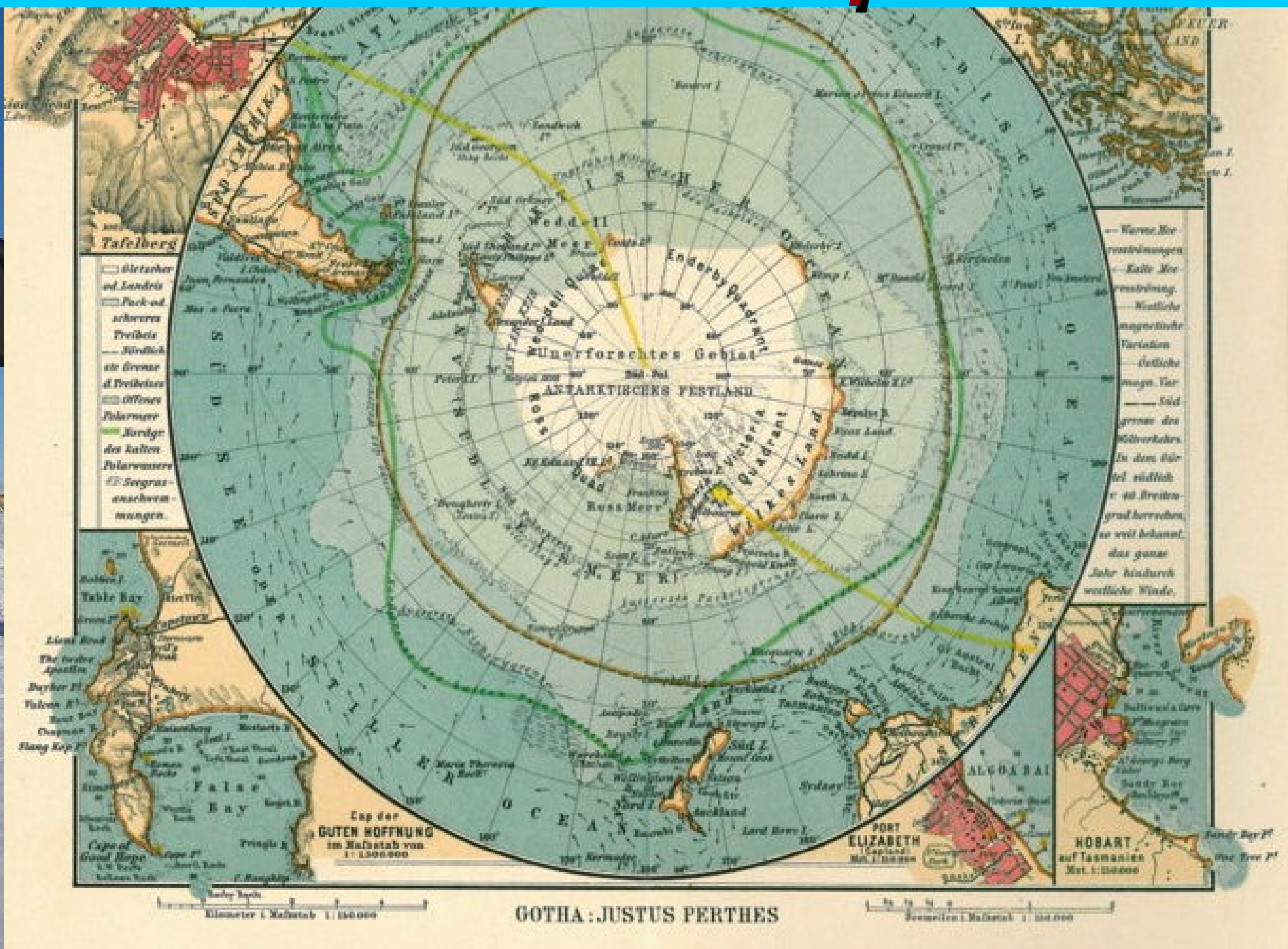
Neutrinos

- Unobscured view into depth of space
- Point back to their sources
- Cover entire energy spectrum **Protons**
- bent below 10 EeV
- above 50EeV GZK cut-off

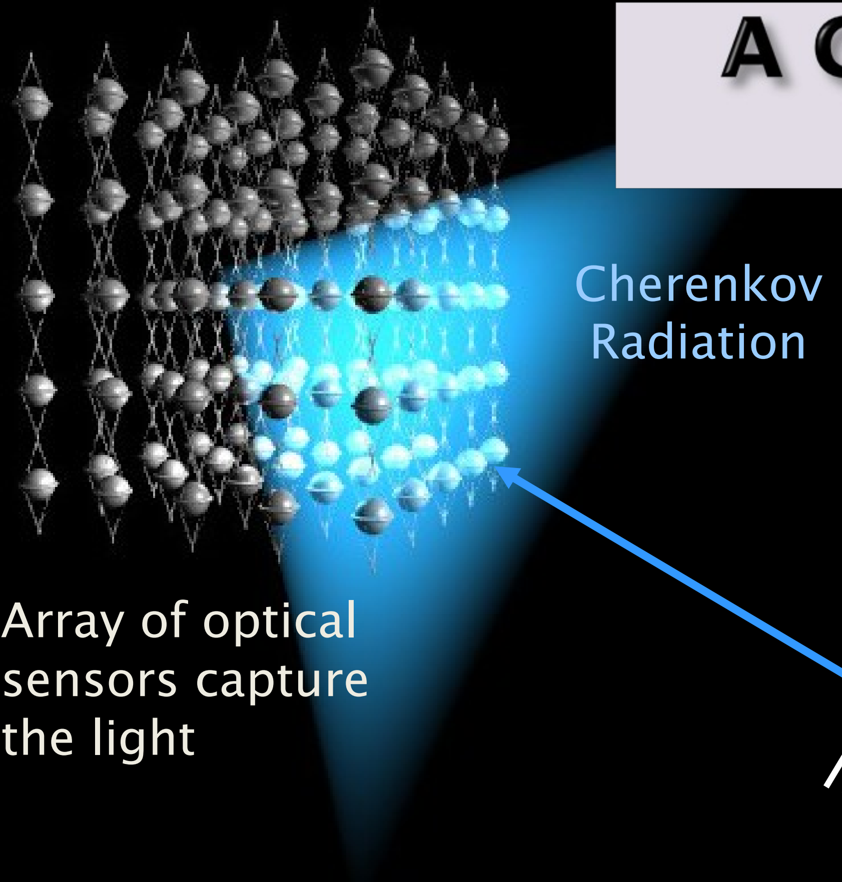
Photons

- scattered/absorbed above 50 TeV

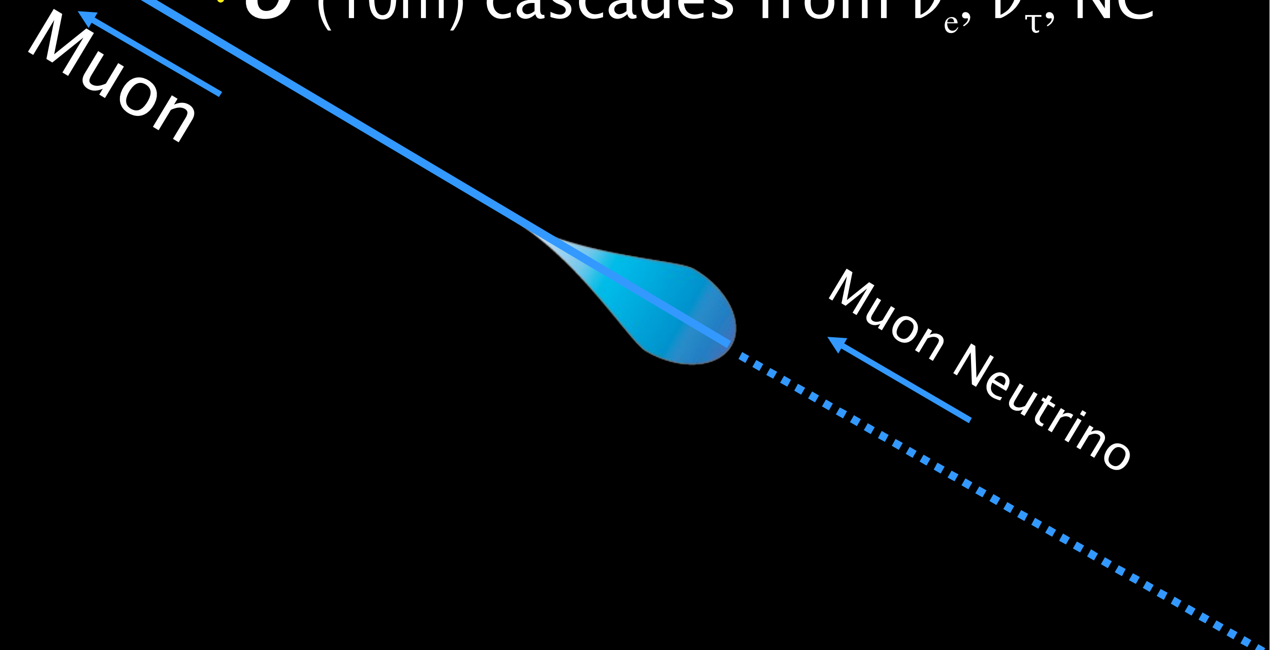
The IceCube Neutrino Telescope

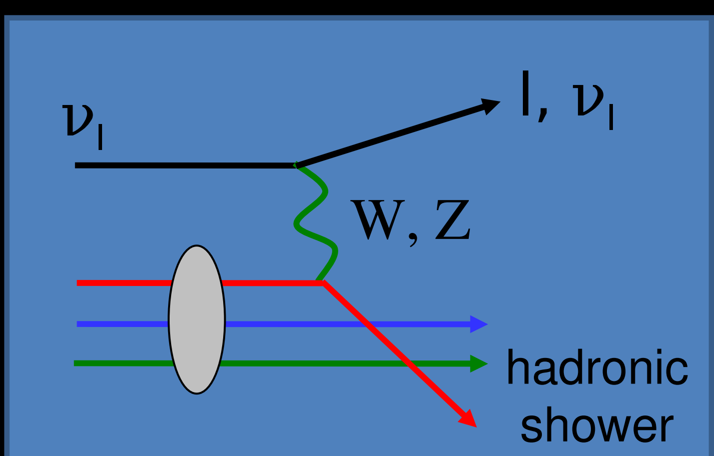


A Generic Optical Neutrino Telescope

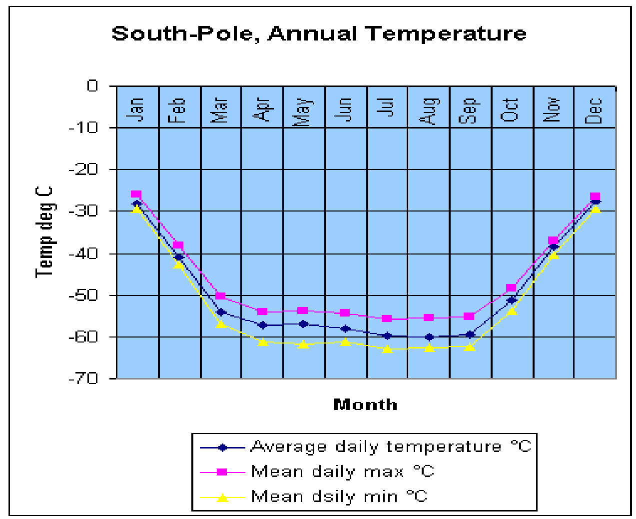


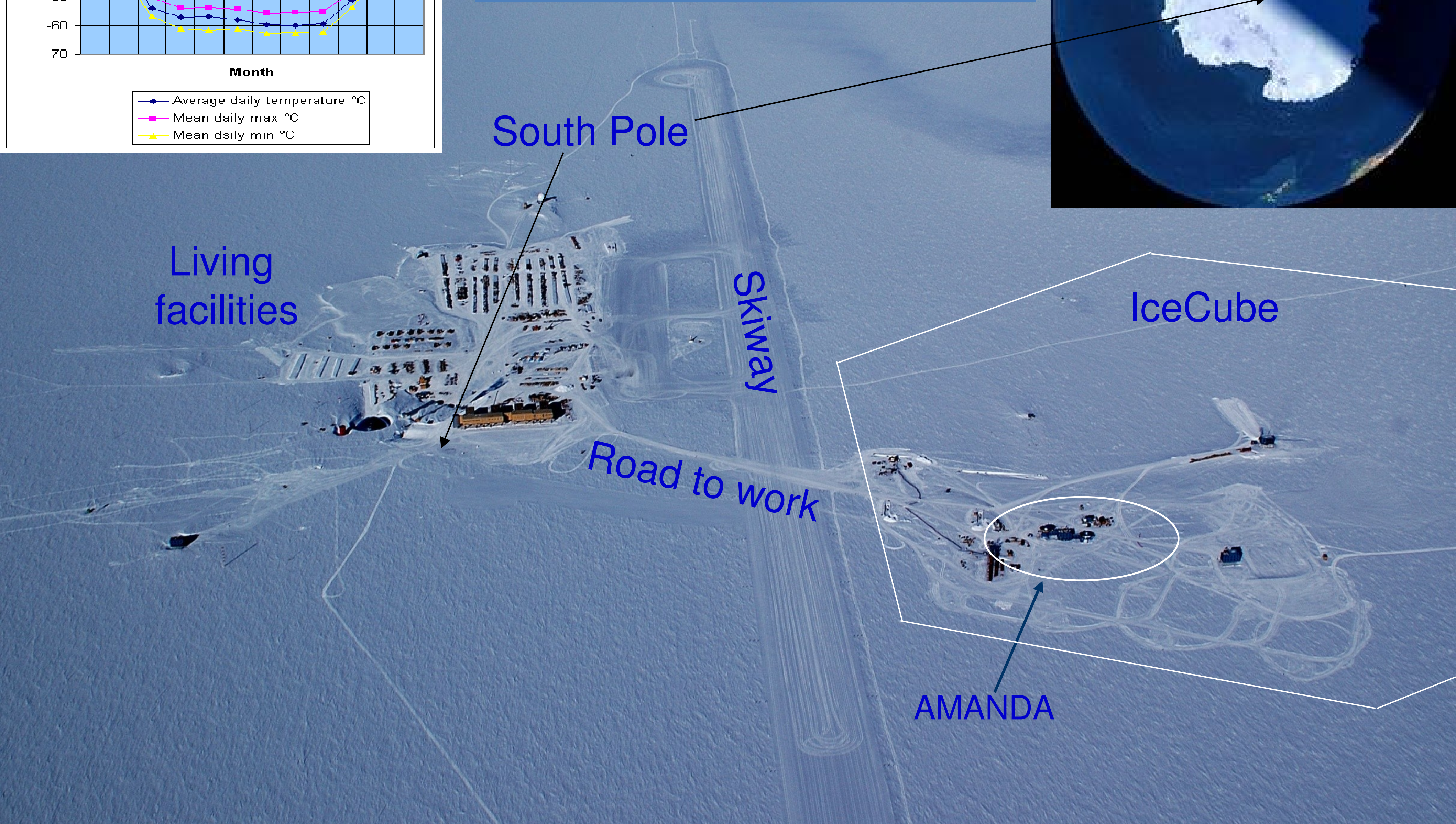
- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
- ***O*** (km) muons from ν_μ
- ***O*** (10m) cascades from ν_e, ν_τ, NC





Amundsen Scott South Pole Station





IceCube Detector Layout

IceTop (~50% complete)

- Surface air shower array
- 300TeV threshold

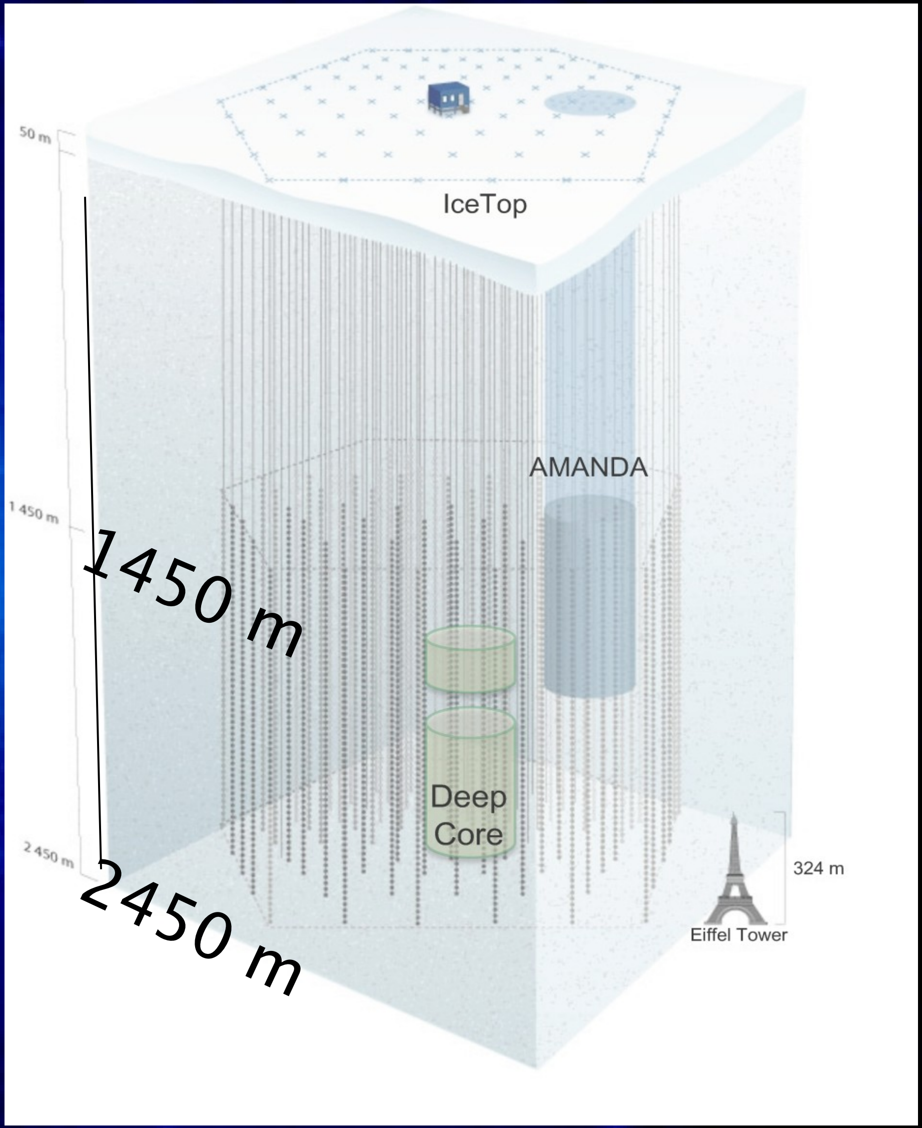
IceCube InIce (~50% complete)

- 80 Strings with 60 DOMs each
- Hexagonal pattern with an interstring distance of 125m
- Vertical DOM spacing of 17m
- Optimized for TeV range

Deep Core (construction starting now)

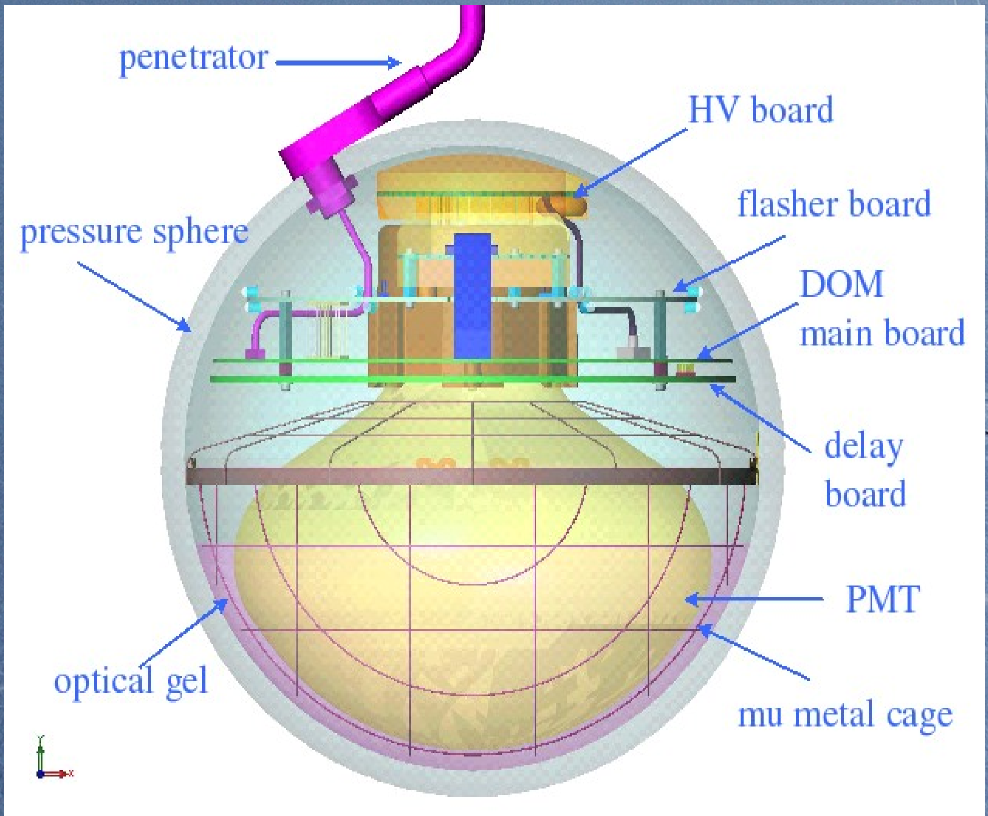
- 6 Strings with 60 High Quantum Efficiency DOMs (vert. spacing 7m)
- Low Energy extension (20-100GeV)
- First string will be deployed end of this year

IceCube will instrument a volume of one cubic kilometer of Antarctic ice by 2011



Digital Optical Module (DOM)

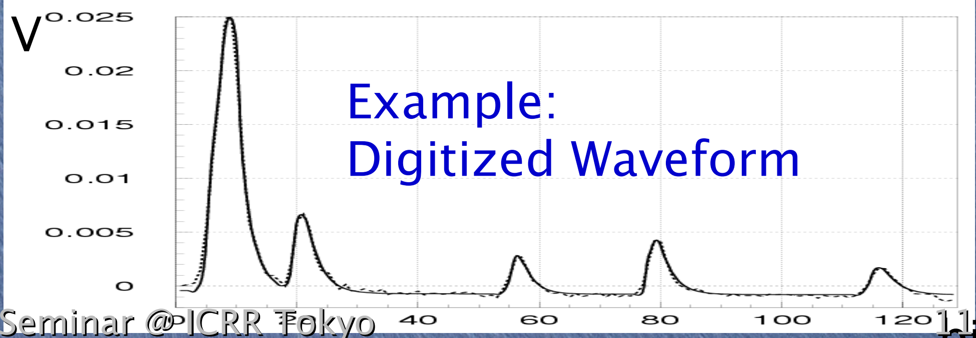
10 inch Hamamatsu PMT (R-7081-02)



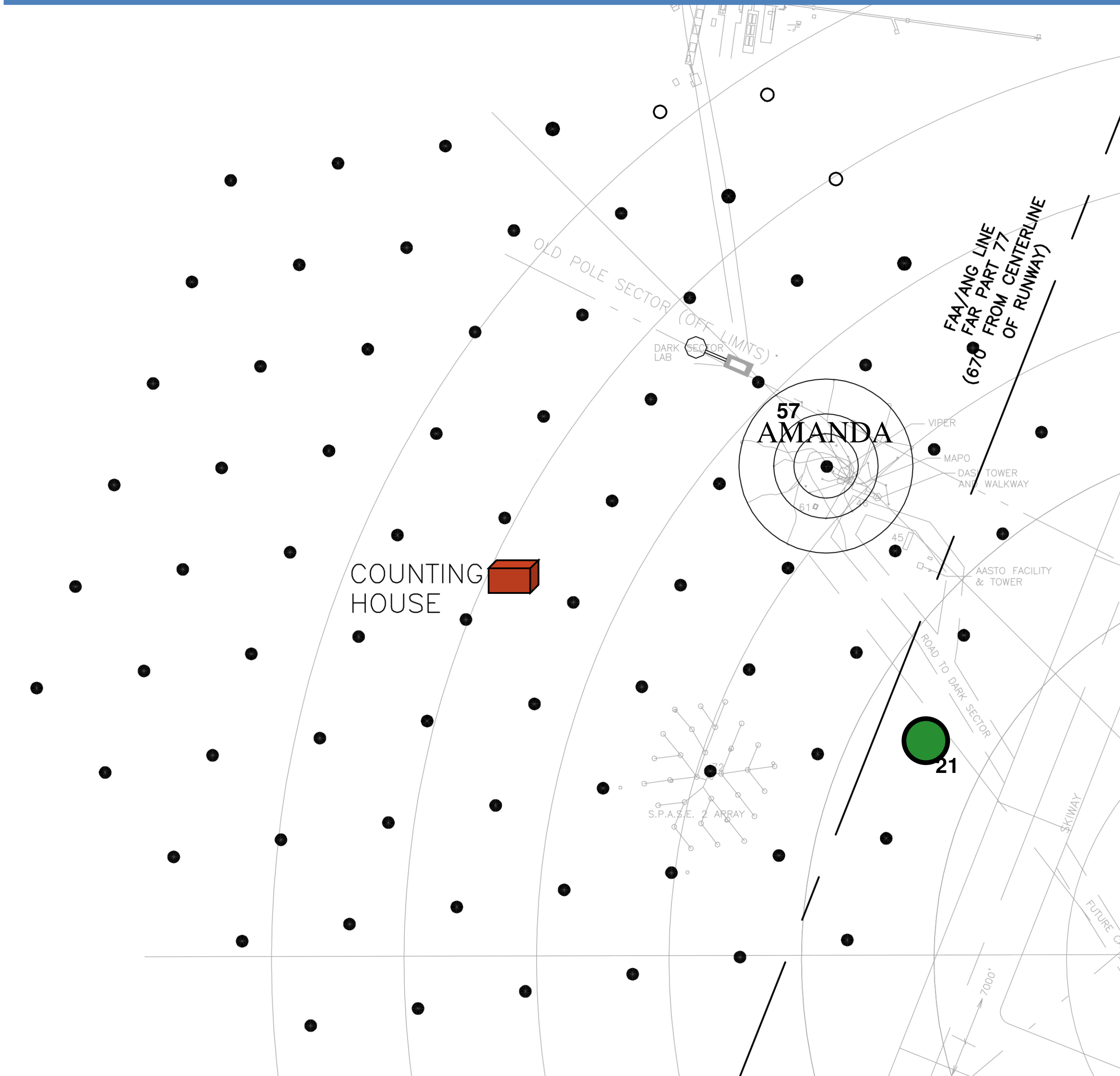
Measure individual photon arrival time:

- 2 ping-ponged four-channel Analog Transient Waveform Digitizers:
  - 128 samples (400 ns max range)
  - ~3.3ns bin
  - 400 pe / 15 ns
- fast Analog-to-Digital Converter:
  - 40 MHz
  - 6.4 μs range

- Dark Noise rate ~ 700 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Signal digitized in the ice



IceCube Deployment



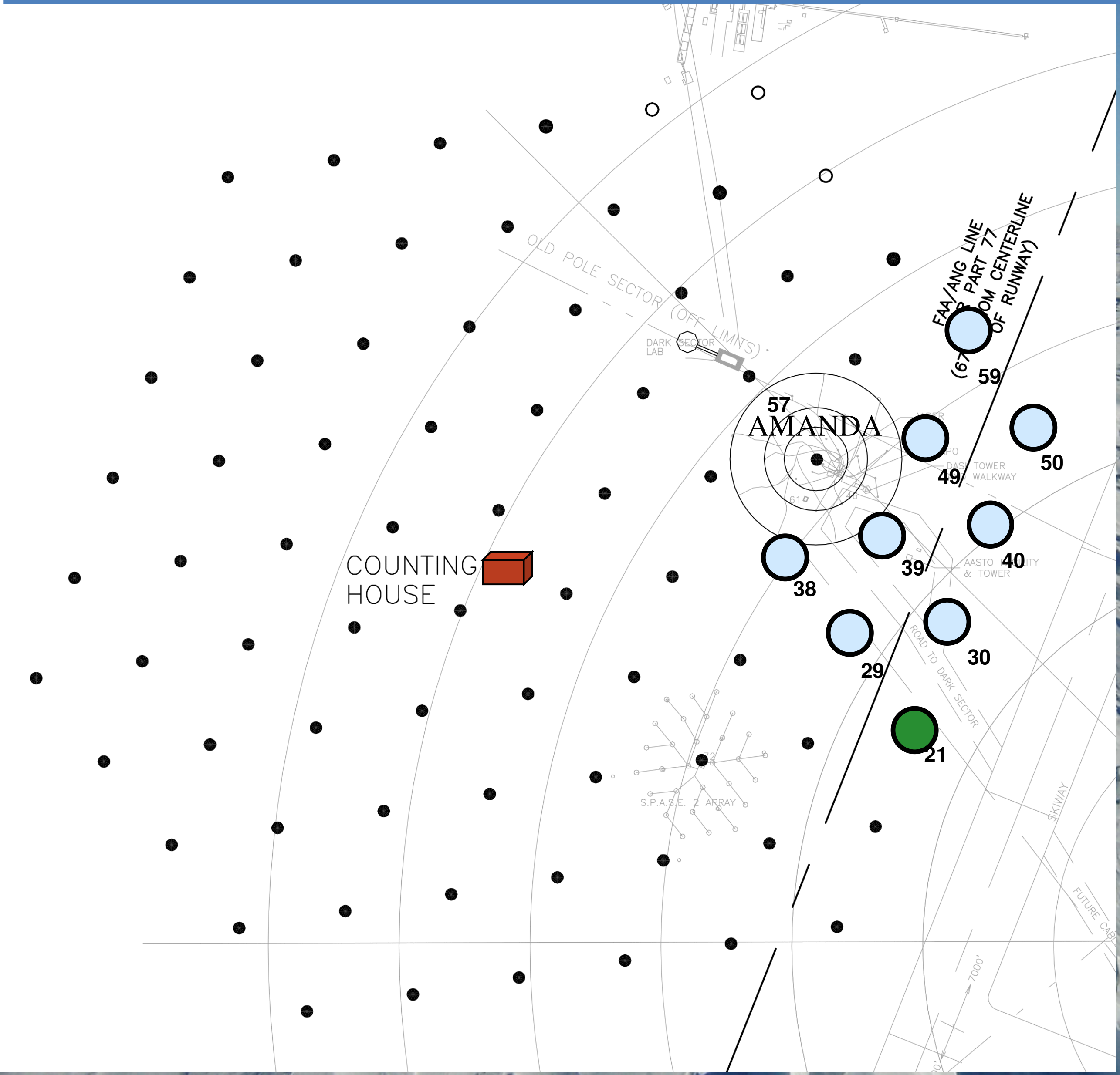
2004–2005

1 string deployed

First data

astro-ph/0604450

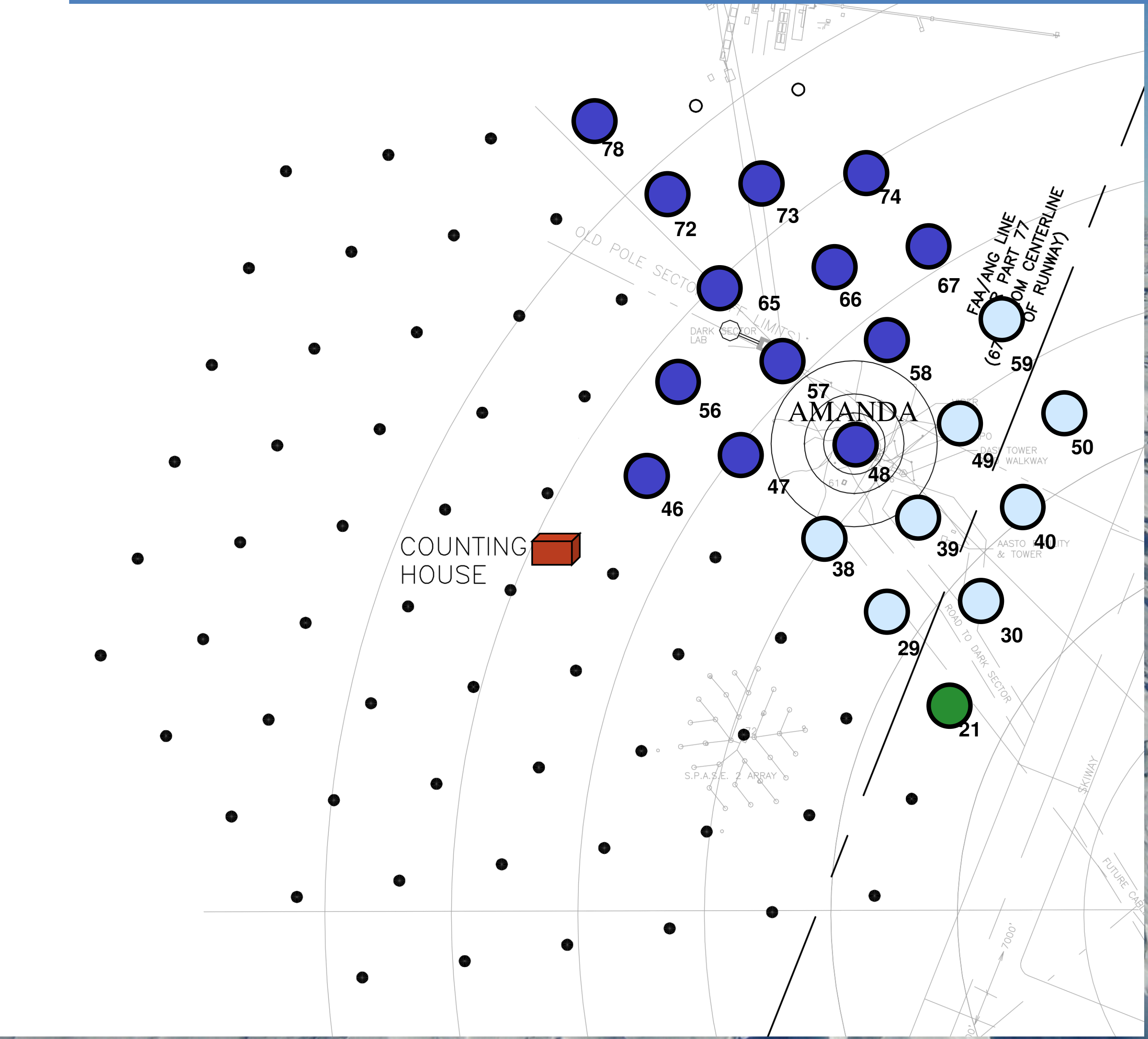
IceCube Deployment



2004-2005
1 string deployed
First data
astro-ph/0604450

2005-2006
8 string deployed

IceCube Deployment

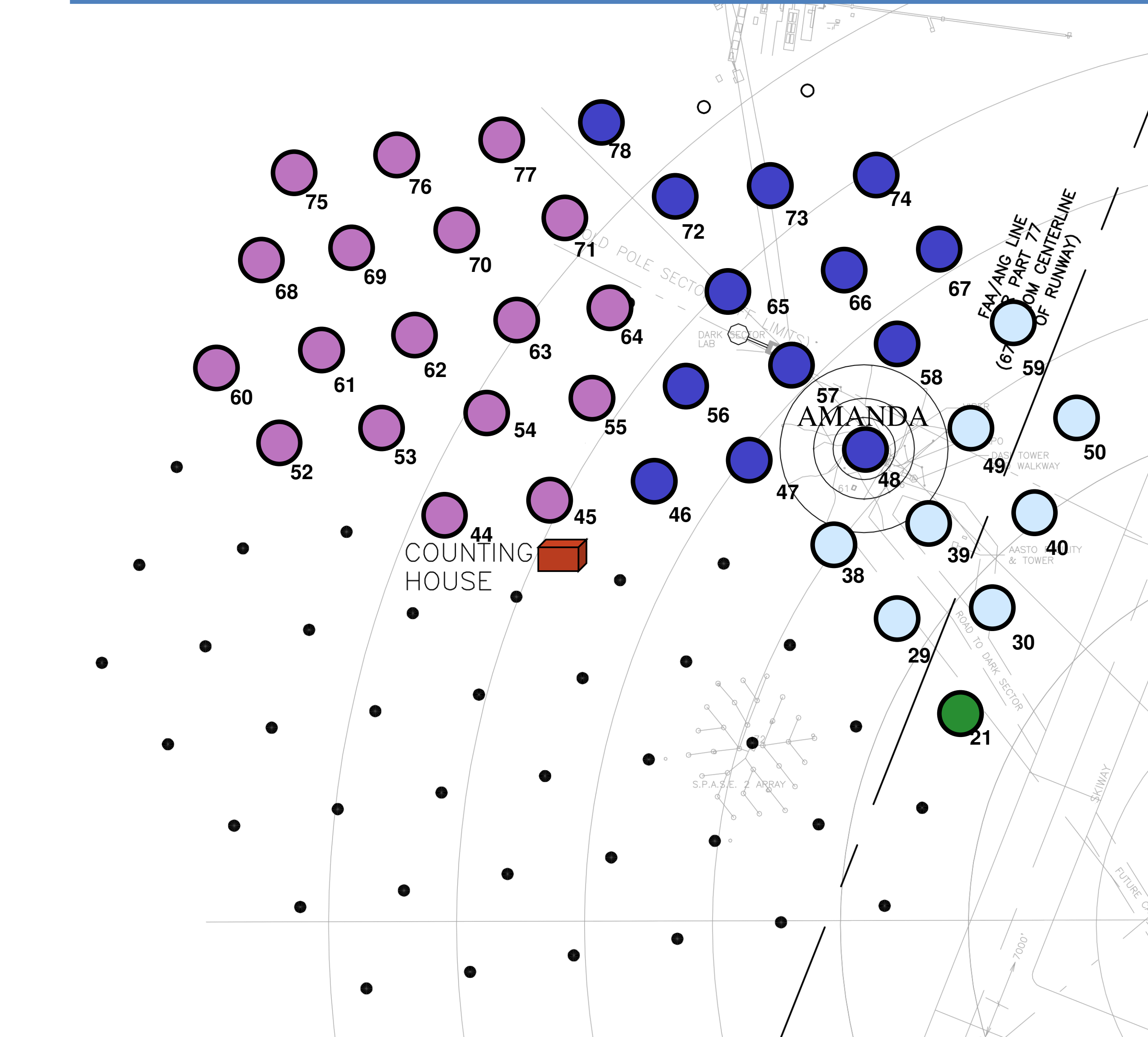


2004-2005
1 string deployed
First data
astro-ph/0604450

2005-2006
8 string deployed

2006-2007
13 strings deployed

IceCube Deployment



2004–2005
1 string deployed
First data
astro-ph/0604450

2005–2006
8 string deployed

2006–2007
13 strings deployed

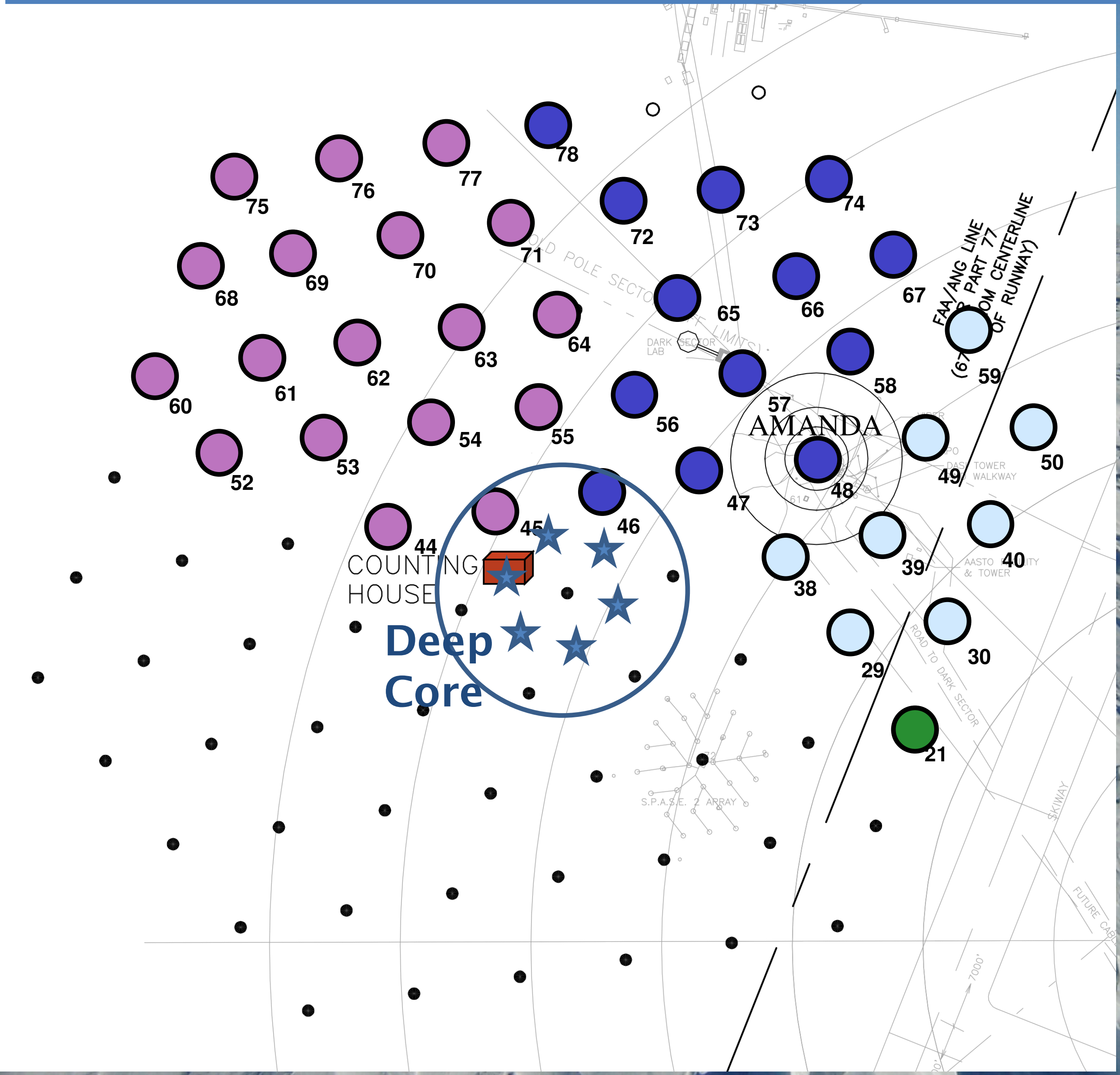
2007–2008
18 strings deployed

Total 40 Strings deployed

(50 % of full detector installed)

Completion by 2011

IceCube Deployment



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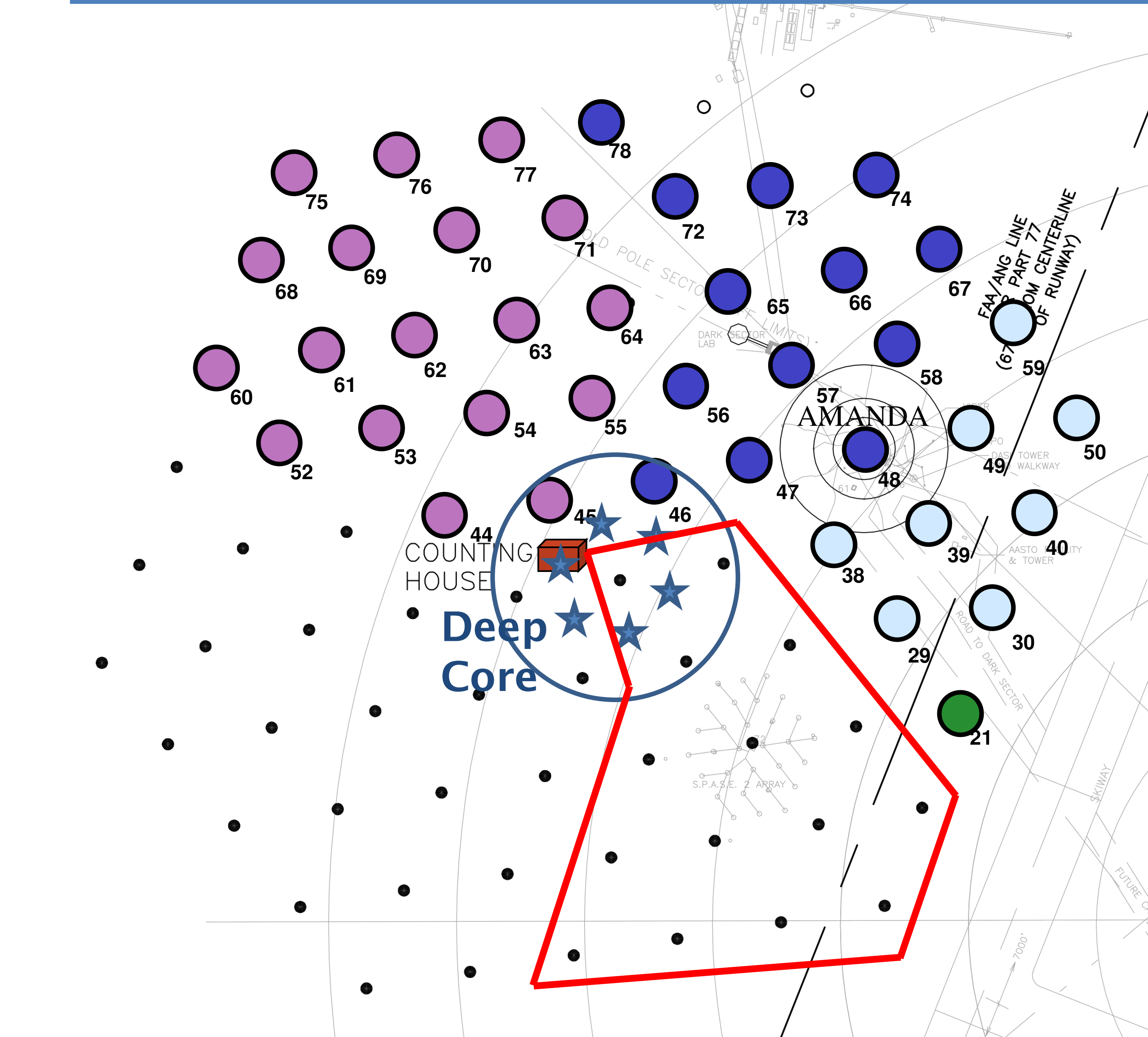

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Total 40 Strings deployed

(50 % of full detector installed)

Completion by 2011

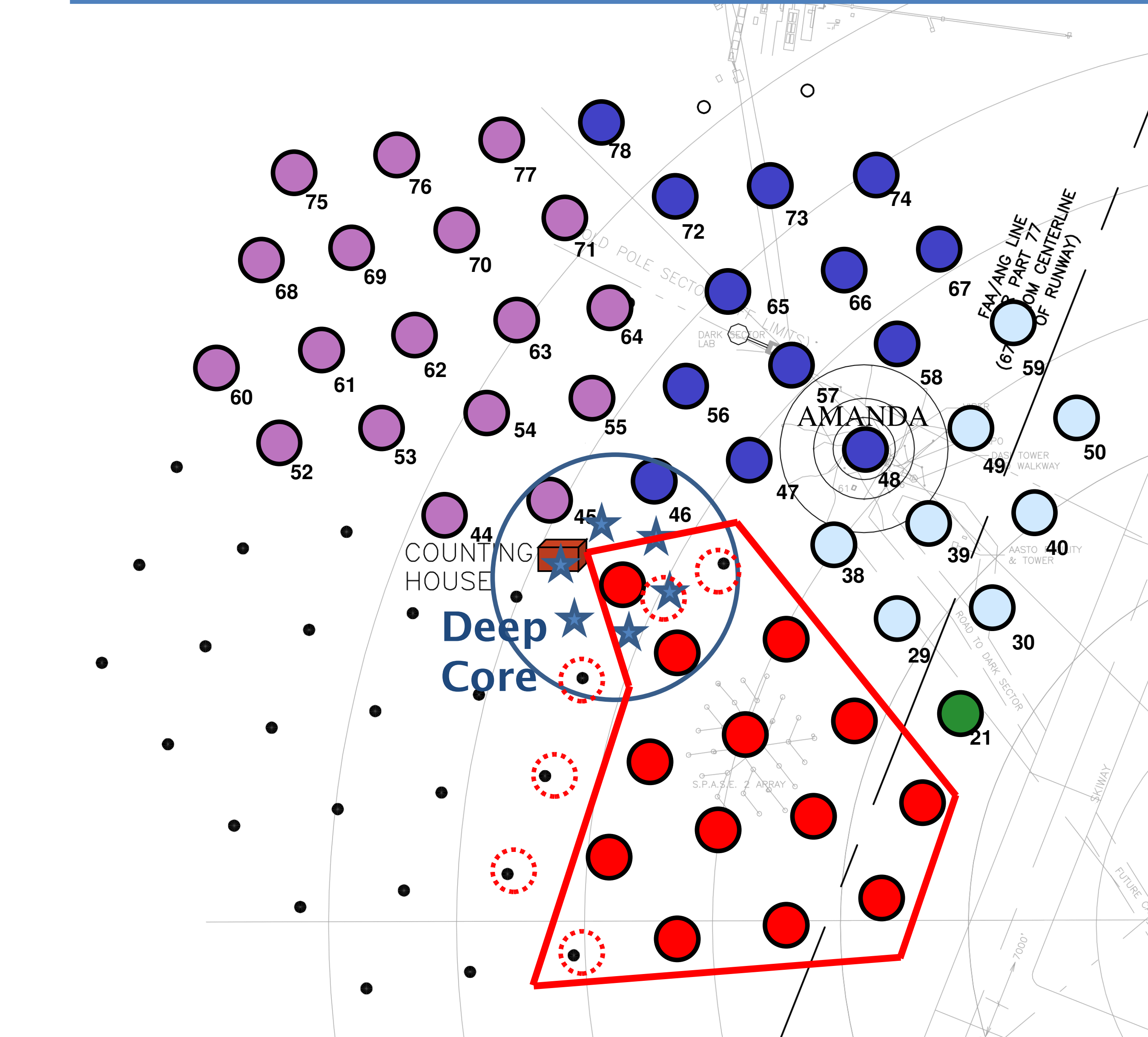
This season plan to deploy 16 strings (incl. 1 deep core string)

Deployment Status 08/09

- **13 Strings Deployed so far from 12/06/08**

Night-shift deployment team with the last DOM of String 27, December 8, 2008

IceCube Deployment



2004-2005
1 string deployed
First data
astro-ph/0604450

2005-2006
8 string deployed

2006-2007
13 strings deployed

2007-2008
18 strings deployed

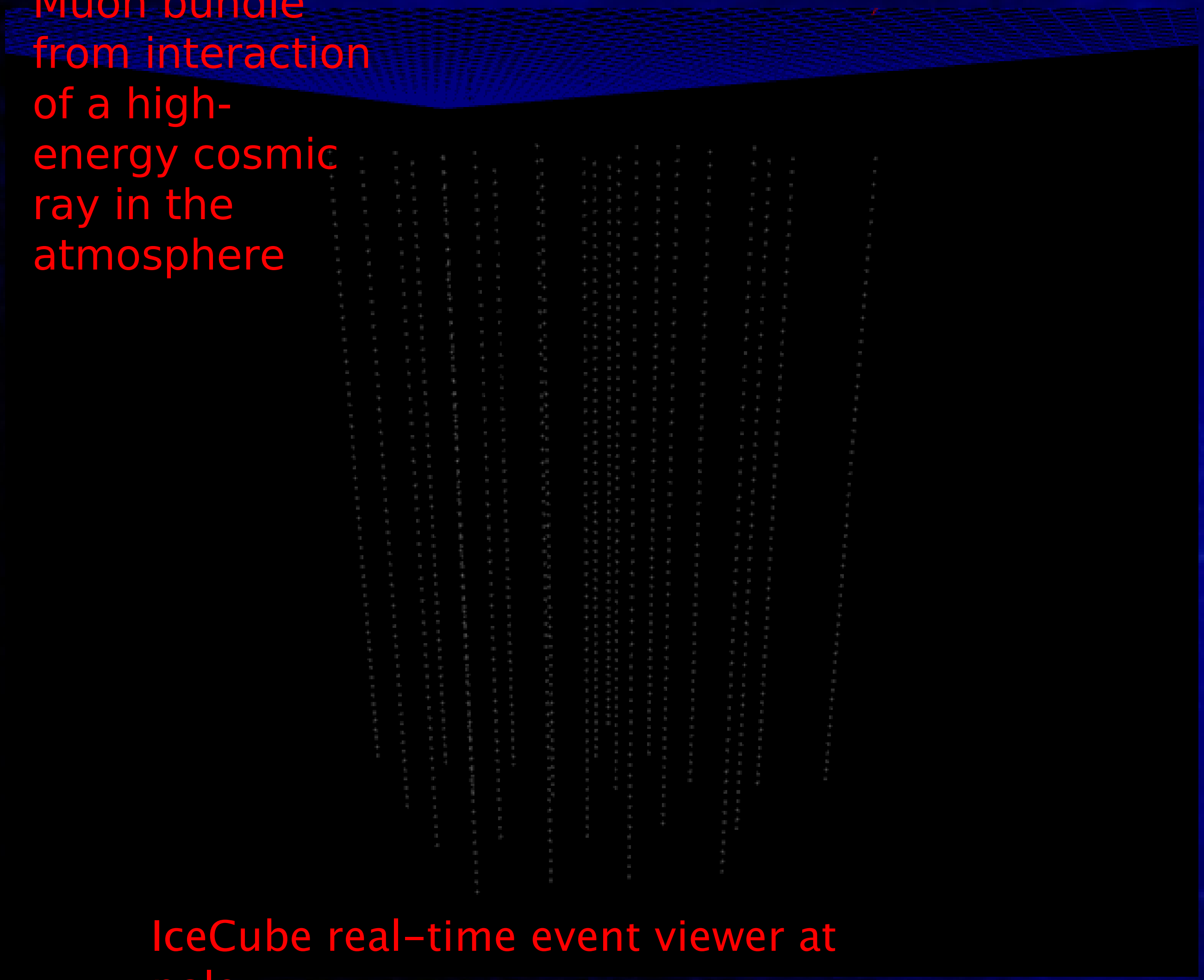
Total ~~40~~ 53 Strings deployed

Completion by 2011

This season plan to deploy 16 strings (incl. 1 deep core string)

Down-going muons

Muon bundle from interaction of a high-energy cosmic ray in the atmosphere

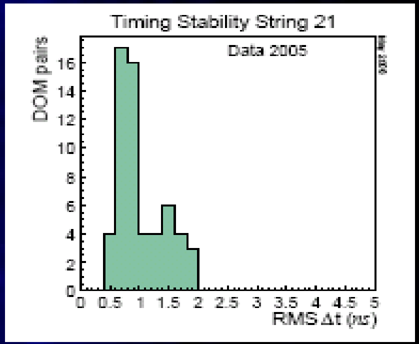


IceCube real-time event viewer at pole

Muons produced in air showers are ideal calibration beam for the detector:

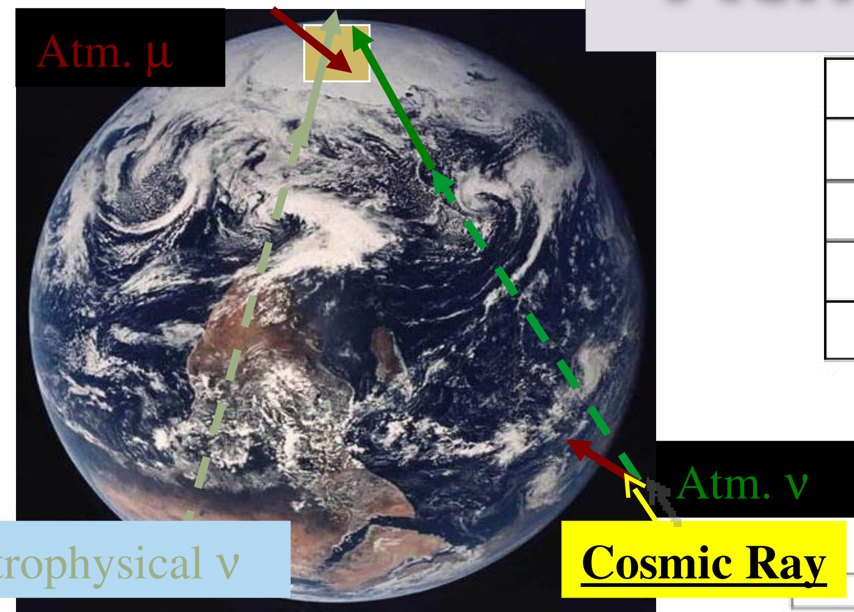
- Test track reconstruction
- Verify detector timing and stability

Timing stability ~ 2ns
[Nucl.Phys.B, Proc.Suppl. 175-176:409-414,2008.]



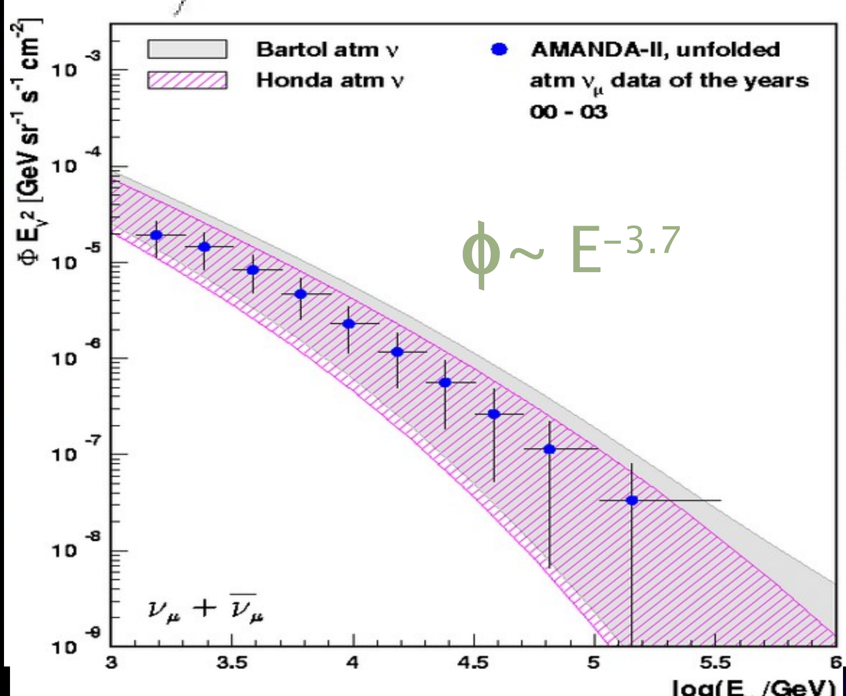
Problem: We cannot switch off the "calibration beam"

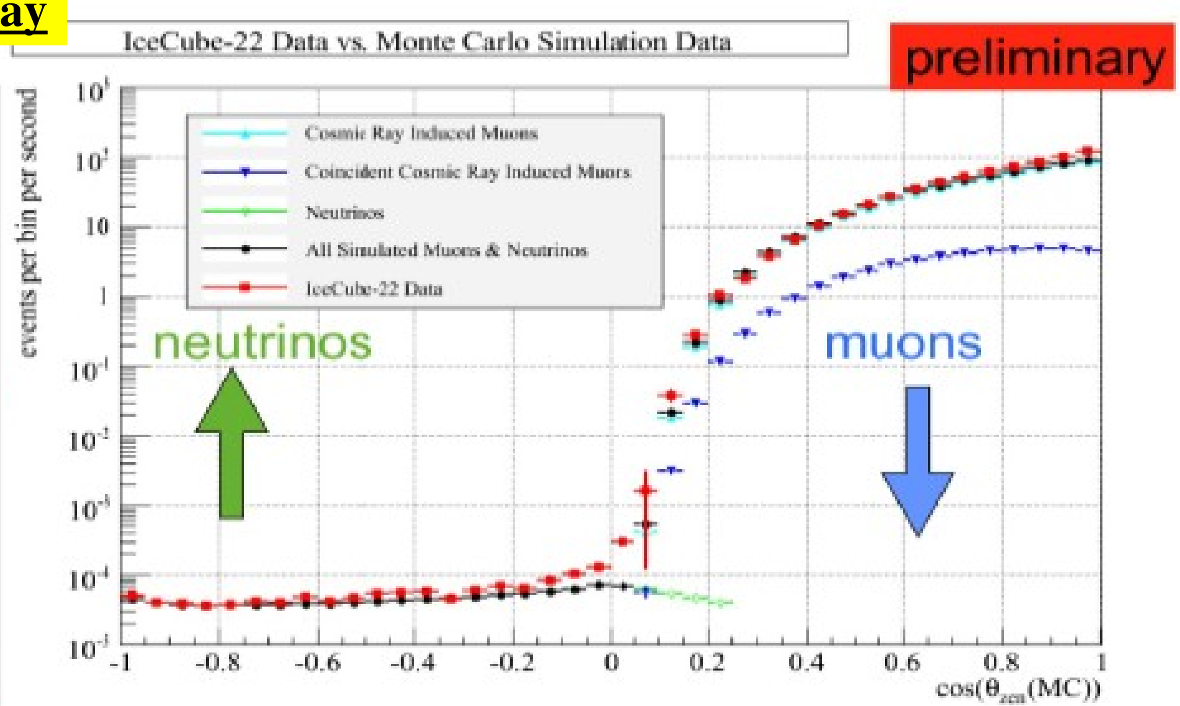
Atmospheric Neutrinos



Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40*	1200 Hz	110 / day
IC80*	1650 Hz	220 / day

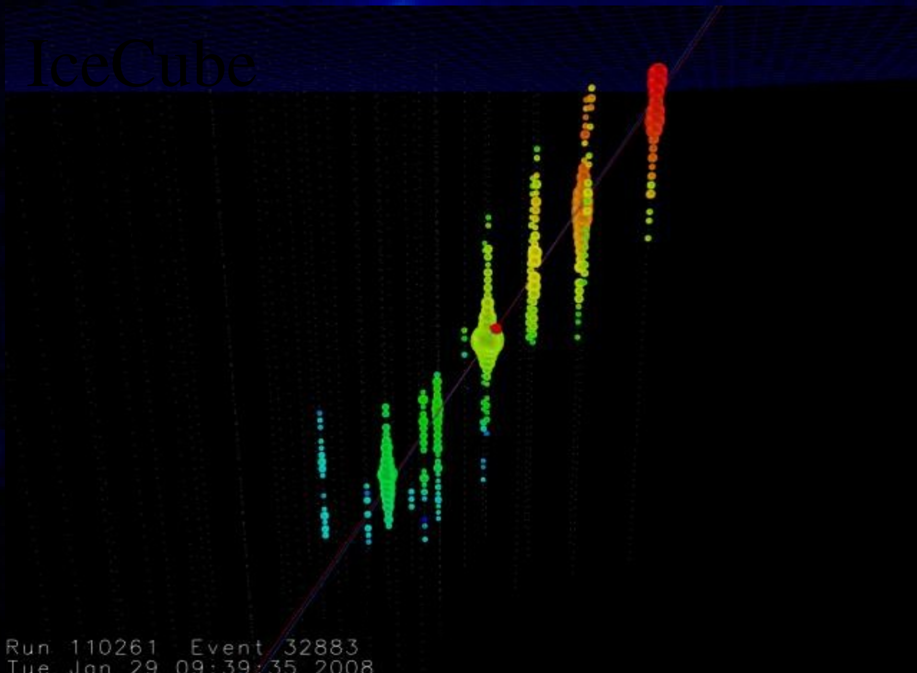
AMANDA: $O(10^9)$ events/yr
IceCube: $O(10^{10})$ events/yr



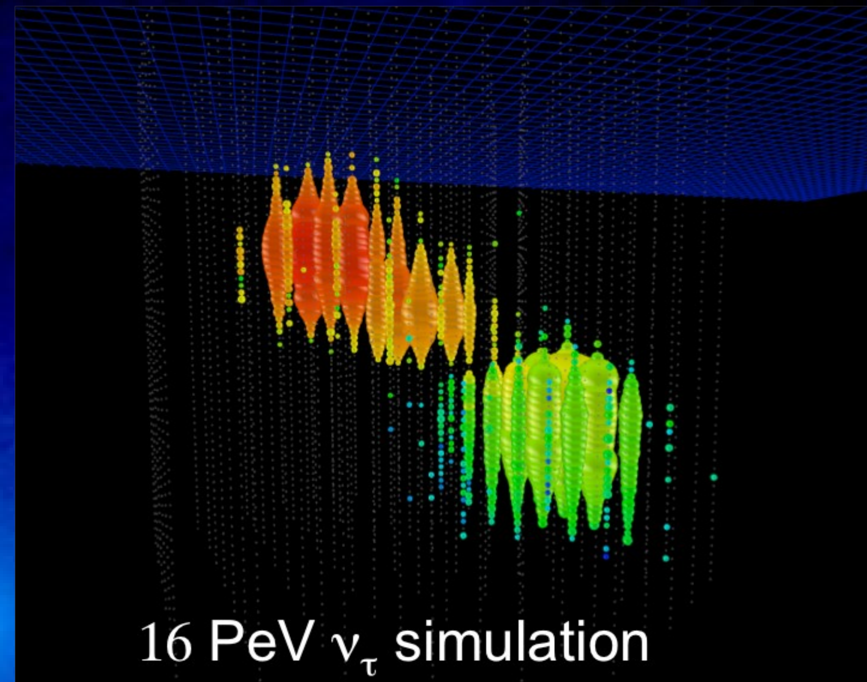


Neutrino Event Identification

Tracks



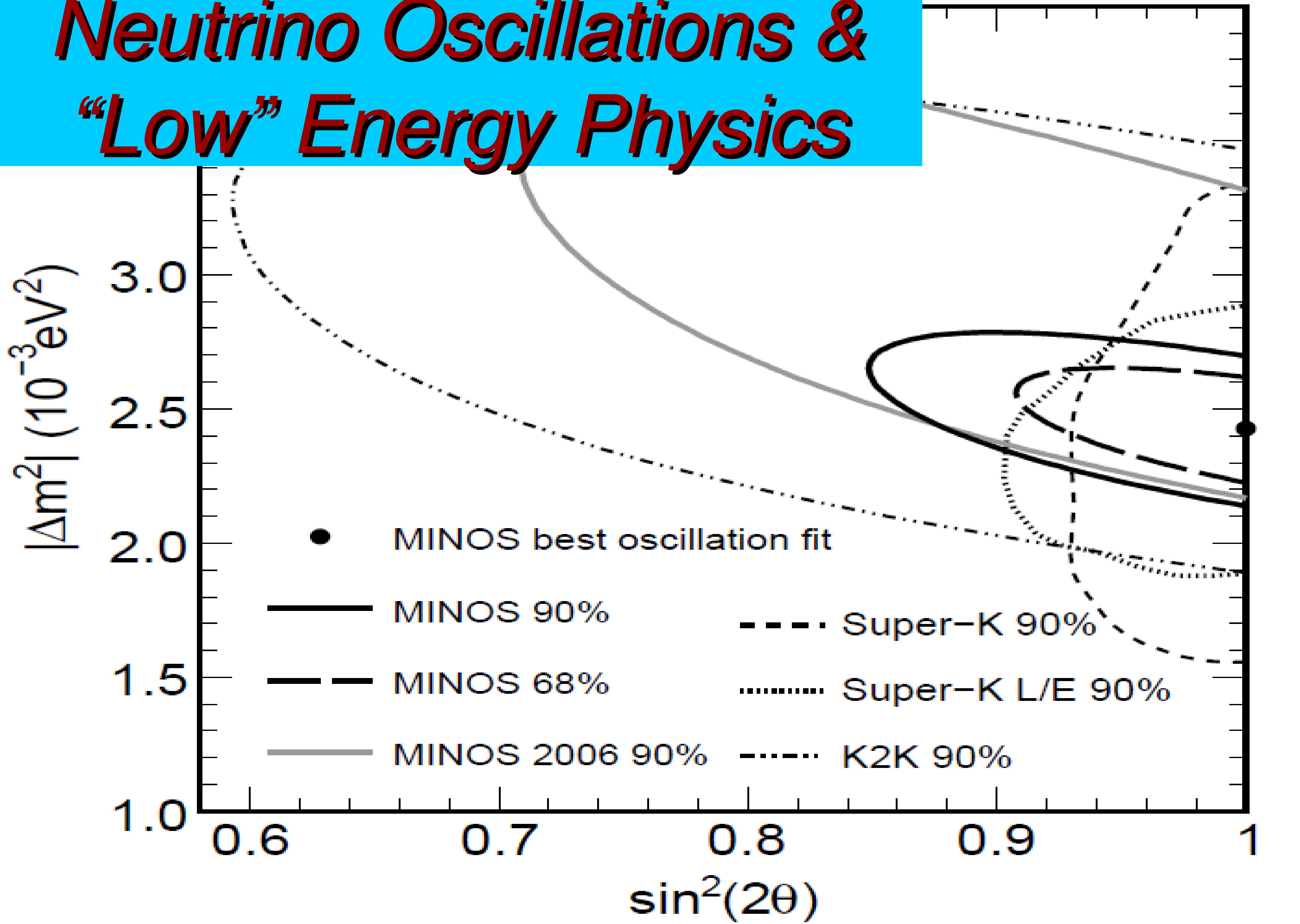
Cascades



Track-Like	IceCube	AMANDA
Time	2 ns	5-7 ns
Energy Resolution	0.3 – 0.4	0.3 – 0.4
Field of View	2π	2π
Noise Rate	low	
Angular resolution	<1°	~1.5-2.

Cascade-Like	IceCube	AMANDA
Time	2 ns	5-7 ns
Energy Resolution	0.18	0.18
Field of View	4π	4π
Noise Rate	low	
Angular resolution	30°	~30-40°

Neutrino Oscillations & "Low" Energy Physics



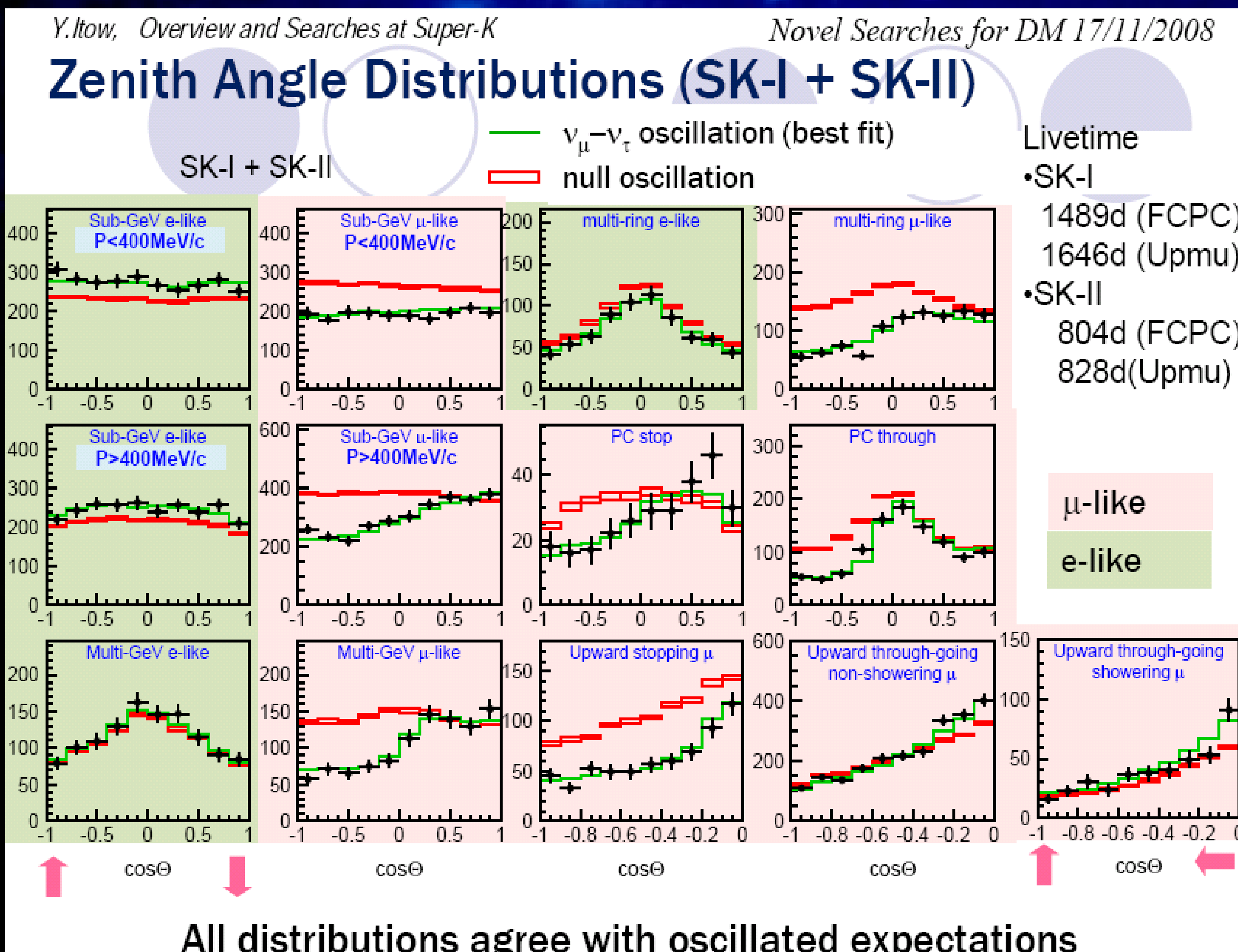
Atmospheric Oscillations

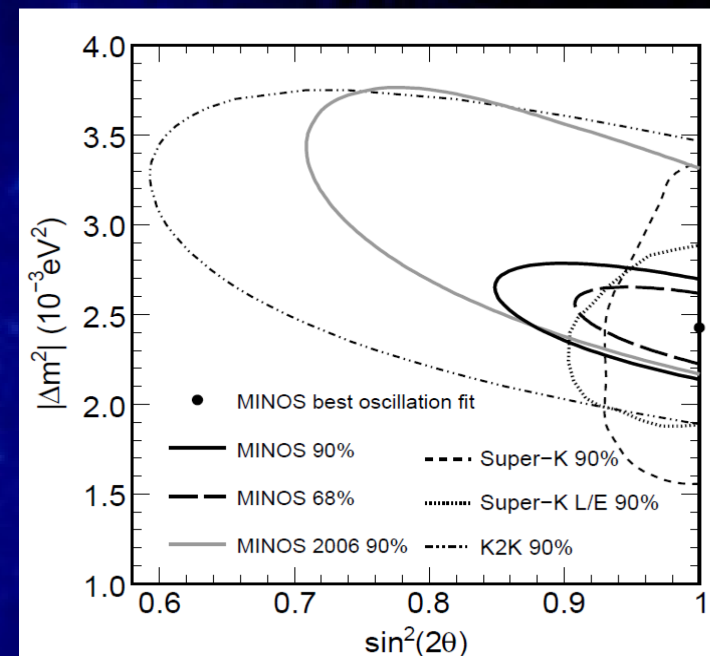
As $\Delta m^2_{atm} >> \Delta m^2_{sol}$

Atm. oscillations can be described with the 2 flavor assumption

$\nu_\tau <-> \nu_\mu$

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2 ($$





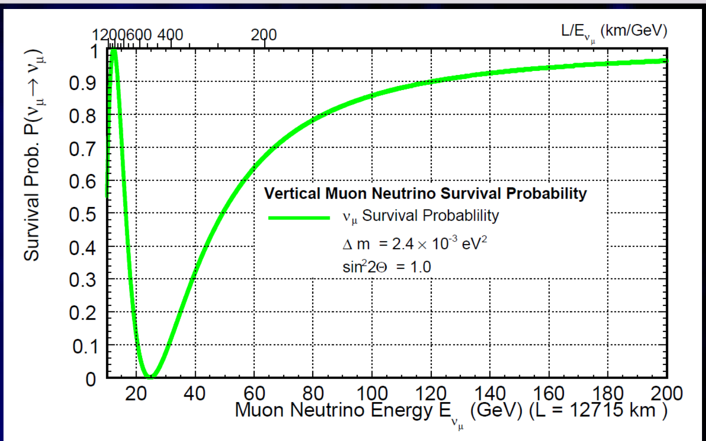
Motivations

Motivation for muon neutrino oscillation measurements with IceCube

- **Test oscillations at a different energy range (E_{ν_μ} ~ 30-100 GeV) than what is directly accessible by other experiments**
- **Same analysis framework is used for the Earth WIMP search**
- **Explore an energy region that has currently not been tested by any other analysis in IceCube**
  - **Open a new energy window. Especially important for low energy physics with Deep Core. Develop understanding of the interesting energy region now**
  - **Demonstrate detector understanding for IceCube in this new energy region**

The Basic Idea

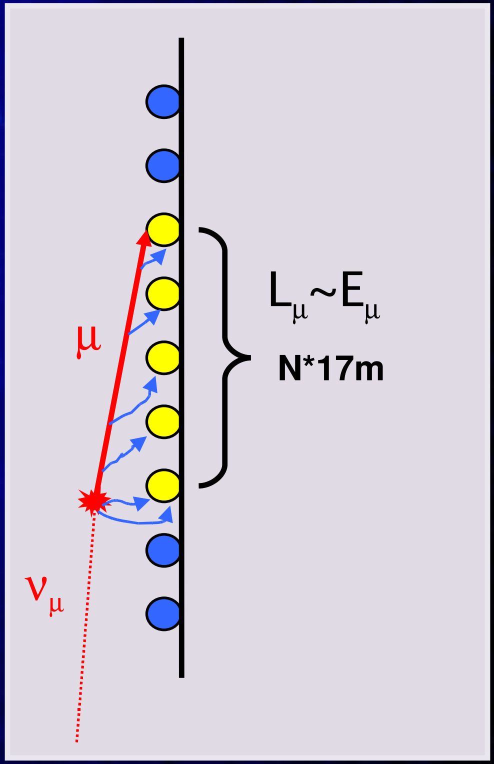
Oscillation effects are significant for energies below about 100 GeV (assuming a baseline of the order of the diameter of the Earth)



Lowest energy threshold in IceCube is realized in vertical events

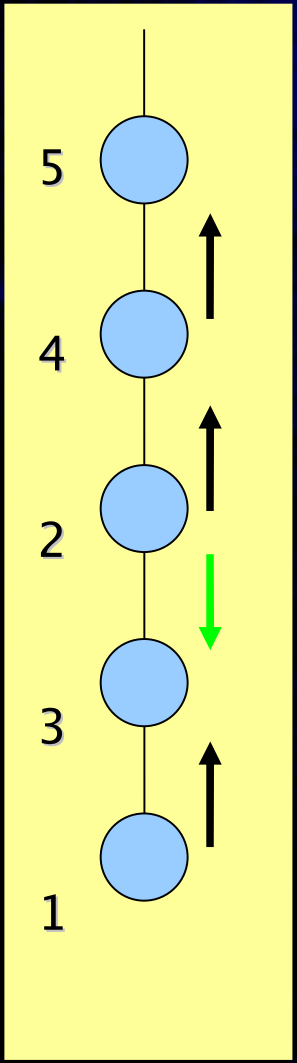
- IC22 ... Trigger threshold 8 DOMs hit
- IC40 ... New String trigger threshold 5 DOMs hit

Low energy muons have an energy loss of about $\Delta E \sim 1 GeV/5m$



- μ_{up}/μ_{down} could be used for normalization
  - difficult due to background contributions, "directionality" DOMs (face down)
- Related idea discussed in Albuquerque and Smoot, PRD.64.053008

Selection Criteria



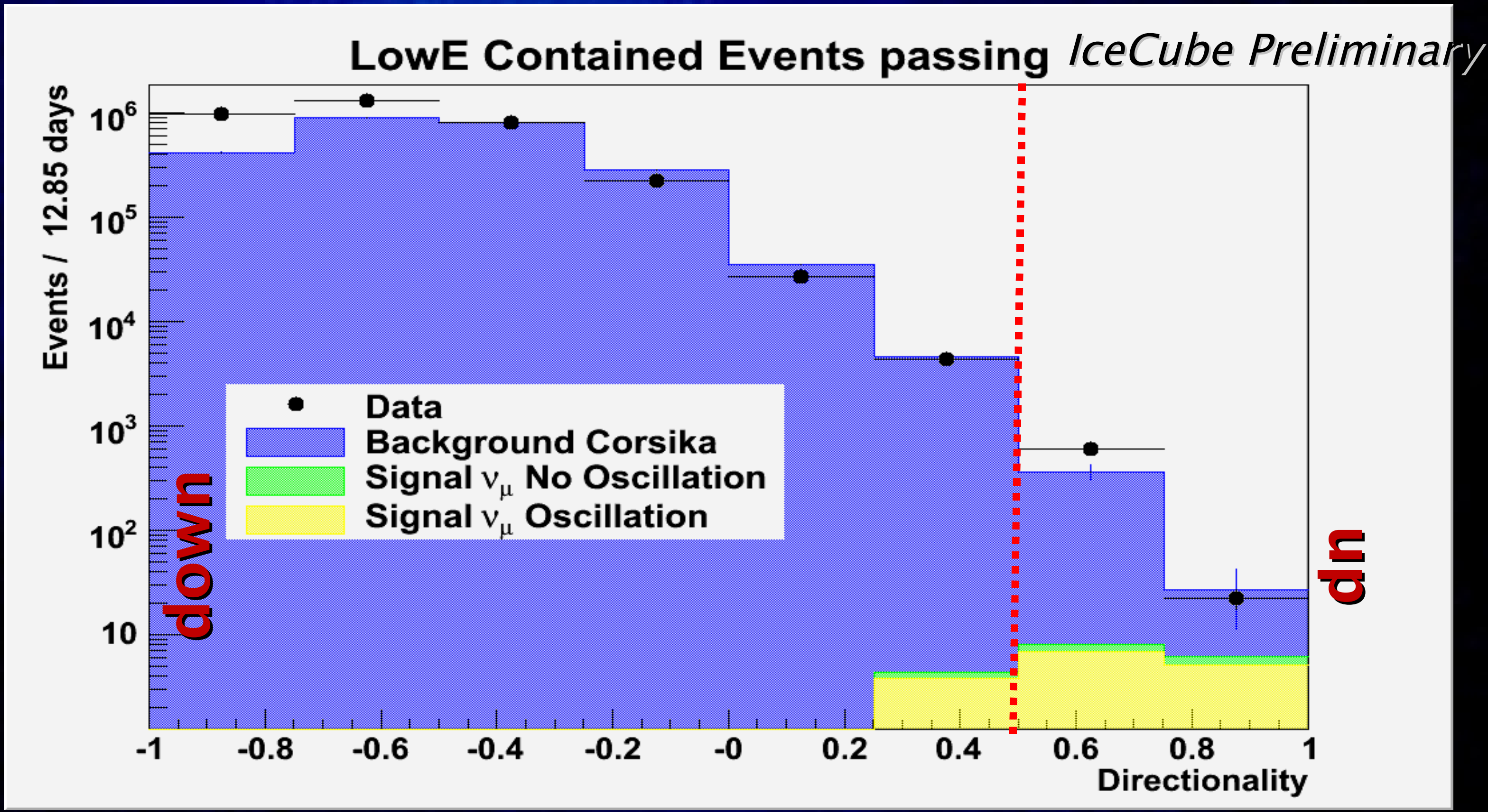
Directionality of track:

Compute time difference between DOMs and determine if it is up or down-going

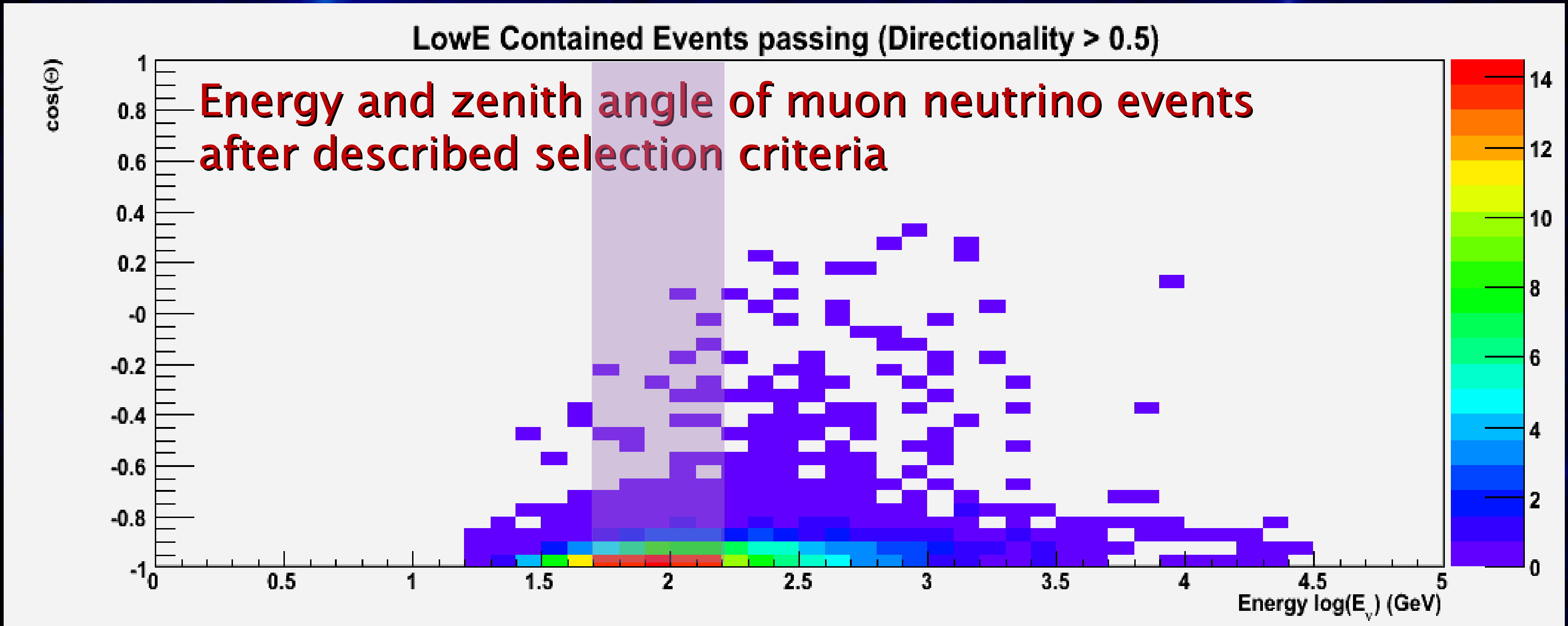
$n_{diff\_up} = 3$

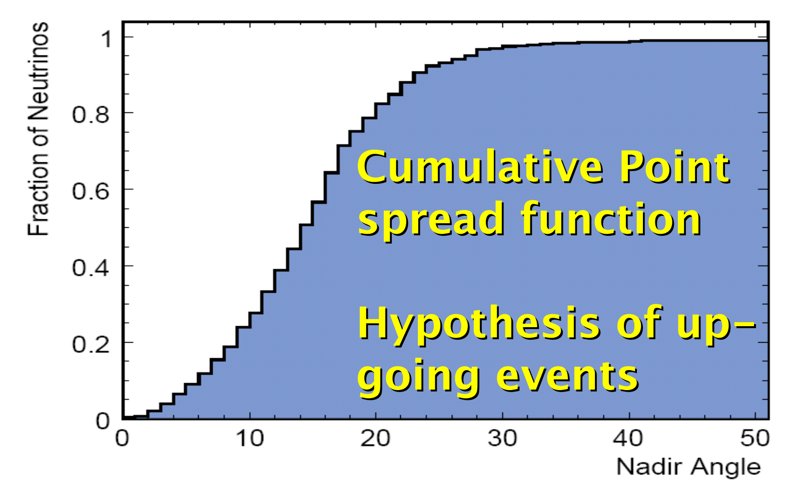
$n_{diff\_down} = 1$

$directionality = (n_{diff\_up} - n_{diff\_down})/(nch-1)$



Signal Distribution

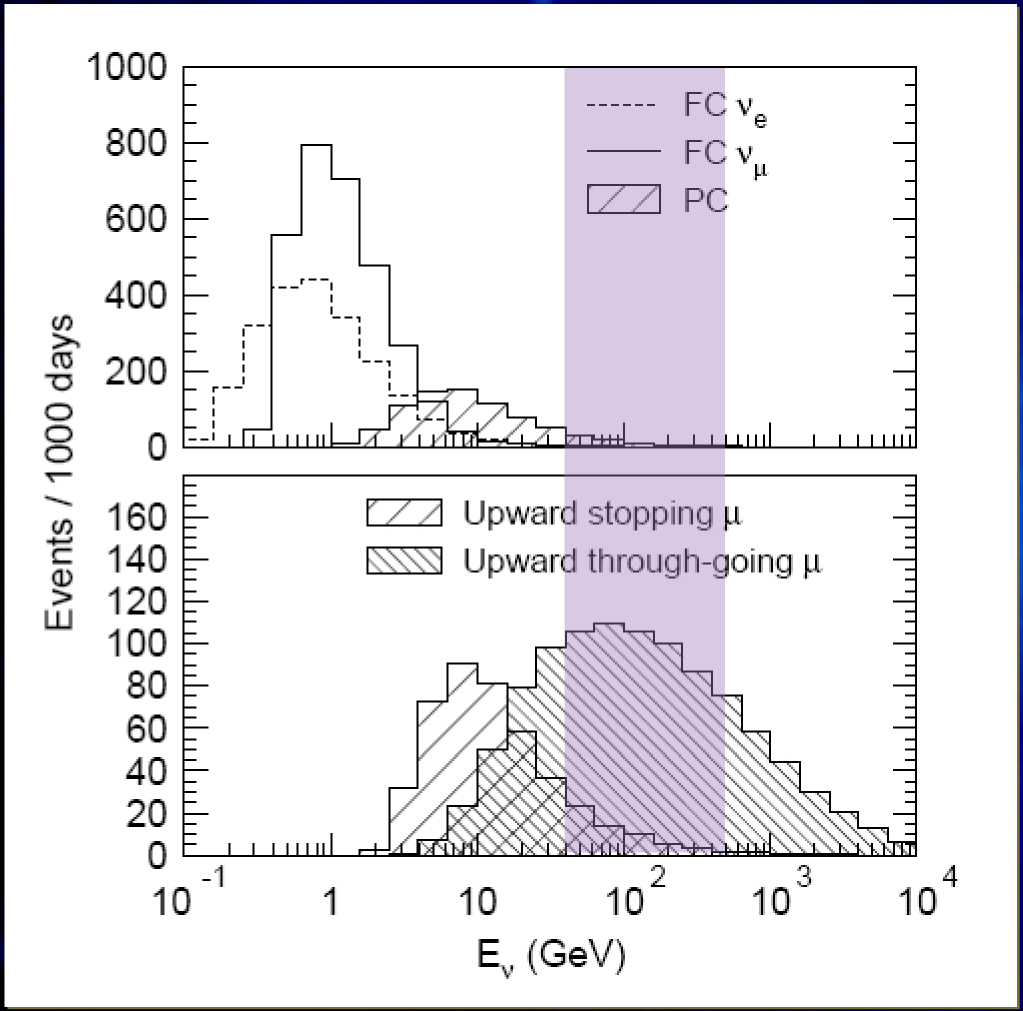




Signal sample dominated by vertical up-going events

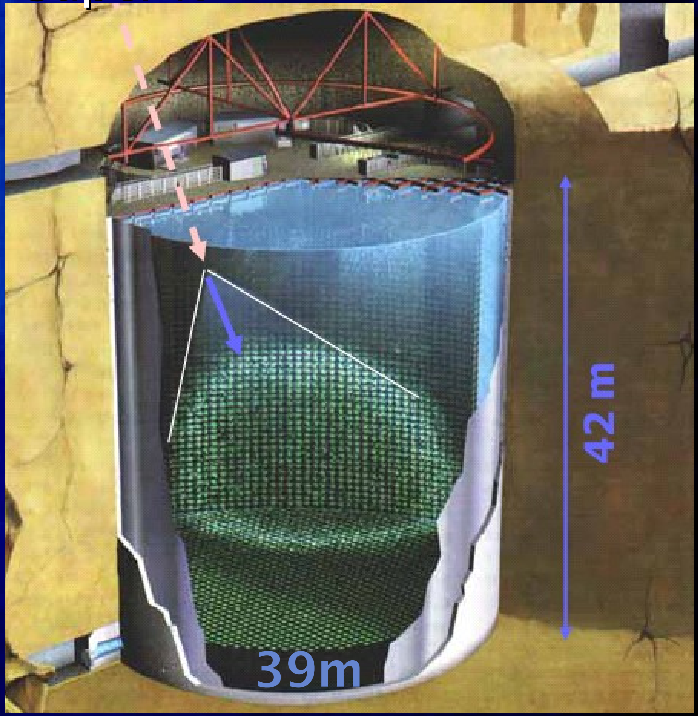
… but still factor of about 25 times more background than signal at this level

Energy Range Comparison



- IceCube can probe oscillations with fully contained events in a different energy range than Super K
  - Do not expect any deviations, but we have never really looked at this range

Super K



Analysis Strategy

Use small subset of data to cross-check if MC predictions agree with it:

3) Result on the small subset won't be statistically significant for the signal to avoid any later bias

5) Especially important as we are looking for the first time at a new region of "MC" parameter space

6)

Evaluate the entire dataset in final analysis

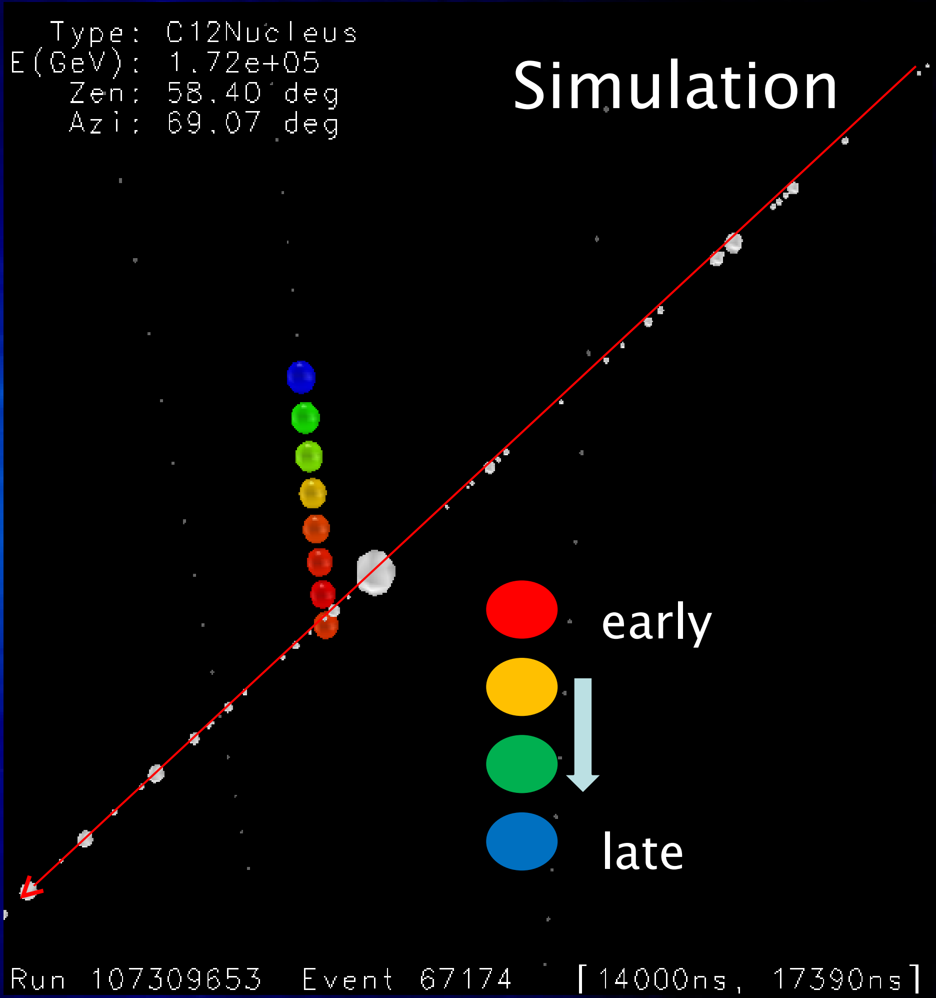
Use large sample of latest version background MC ; only a limited background MC dataset was available at the time of the analysis for the cross-check

Background / EventDisplay

Main remaining background:

Vertically up-going muon neutrino faked by down-going atmospheric muons that have a stochastic (example Bremsstrahlung) produced next to a string and do not produce any hits in the adjacent strings, this is especially true for outer string, which have less of a veto volume around them.

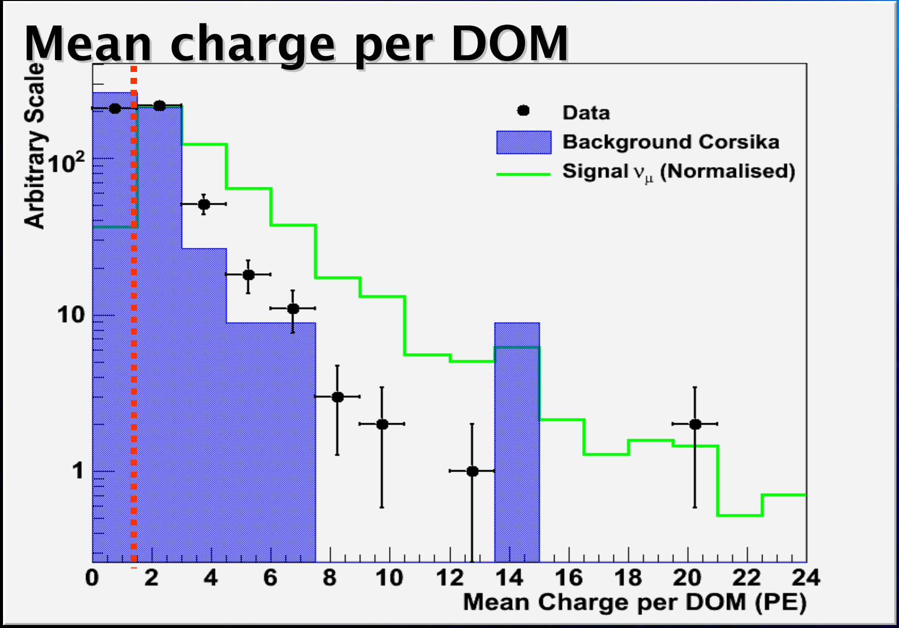
How to get ride of these events ?
-Light travels with c/n compared to c
-Inner strings are better isolated

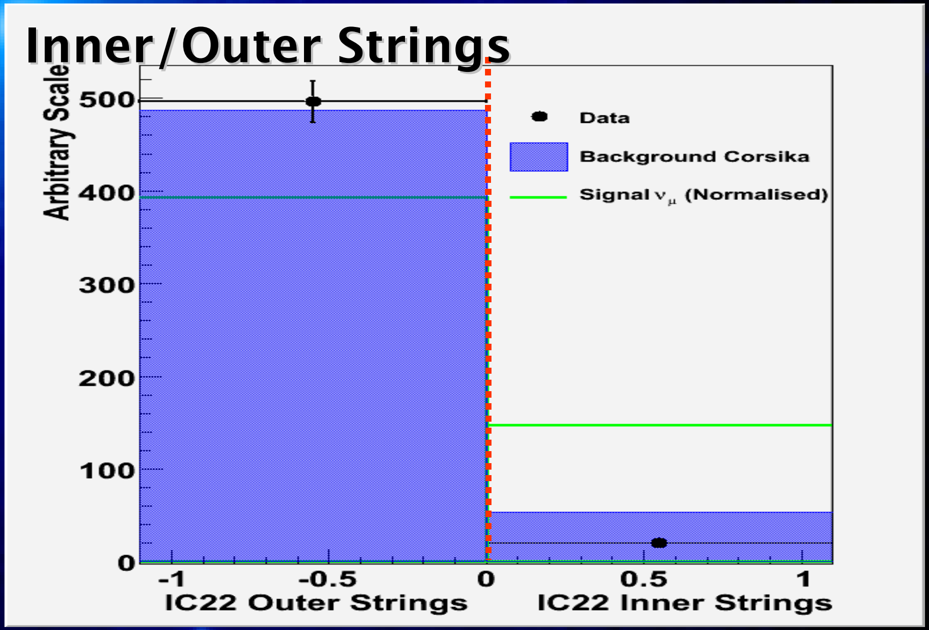


Further Selection Criteria

Available background MC was statistically limited, hence define selection criteria on individual distribution which are not strongly correlated and reduce it as much as possible to regain a “pure” signal dataset

- **Mean charge per DOM > 1.25 pe**
- **Total charge in first 500 ns >12 pe**
- **Inner strings only**
- **Directionality based on DOM pairs consistent with speed of light**
- **Veto events with hits in the top 5 DOMs**



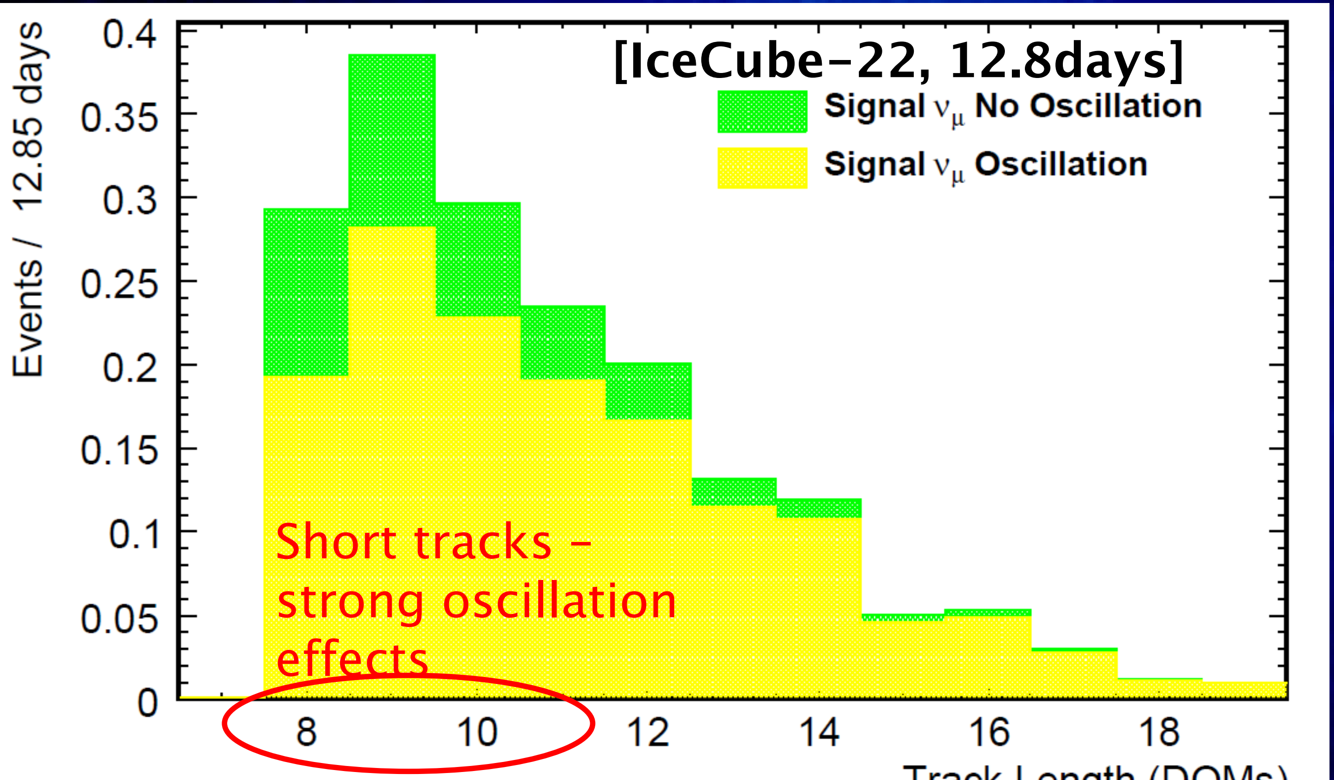


Signal Expectation

Selection criteria optimized on simulation which agrees well with data.

Background can be rejected effectively, however available background sample was statistics limited (equiv. 1.45days of livetime)

IC22 data subsample (**12.8days**) (<5% of total data) was used as cross-check.



C.Rott, ICHEP08 (arXiv:0810.3698)

After final selection expected:
Signal (Muon Neutrinos):
1.81 events (no-osc)
1.42 events (osc)
Background:
0.0 +/- 20.3

Observed in data:
3 Events

In agreement with predictions

Status / Plans

Initial IC22 results very promising

- Data and MC expectations agree
- Larger improved background MC dataset is now studied
- Systematic uncertainties and other effects being investigated
  - Neutrino flux uncertainty
  - Optical sensor efficiency
  - Ice effects (layers,...)
  - Kinematic smearing
  - Effect of tau
  - ...

IC40 data is also becoming available now

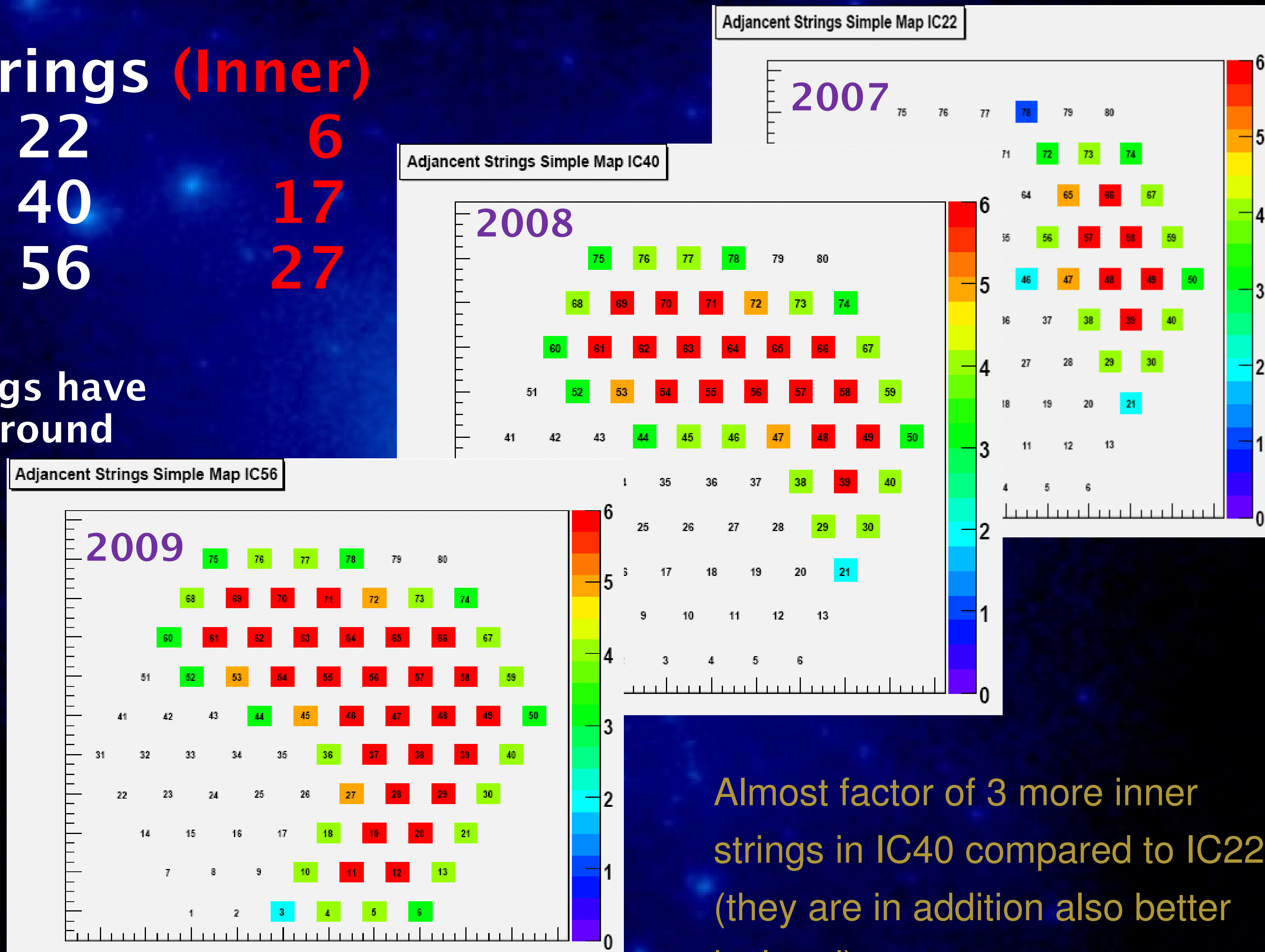
Analysis method can be almost directly be transferred from IC22 to IC40

Estimated sensitivity to oscillation parameters using expected IC40 results

Improvements through Detector size

Year	Strings	(Inner)
2007	22	6
2008	40	17
2009	56	27

Outer strings have high background

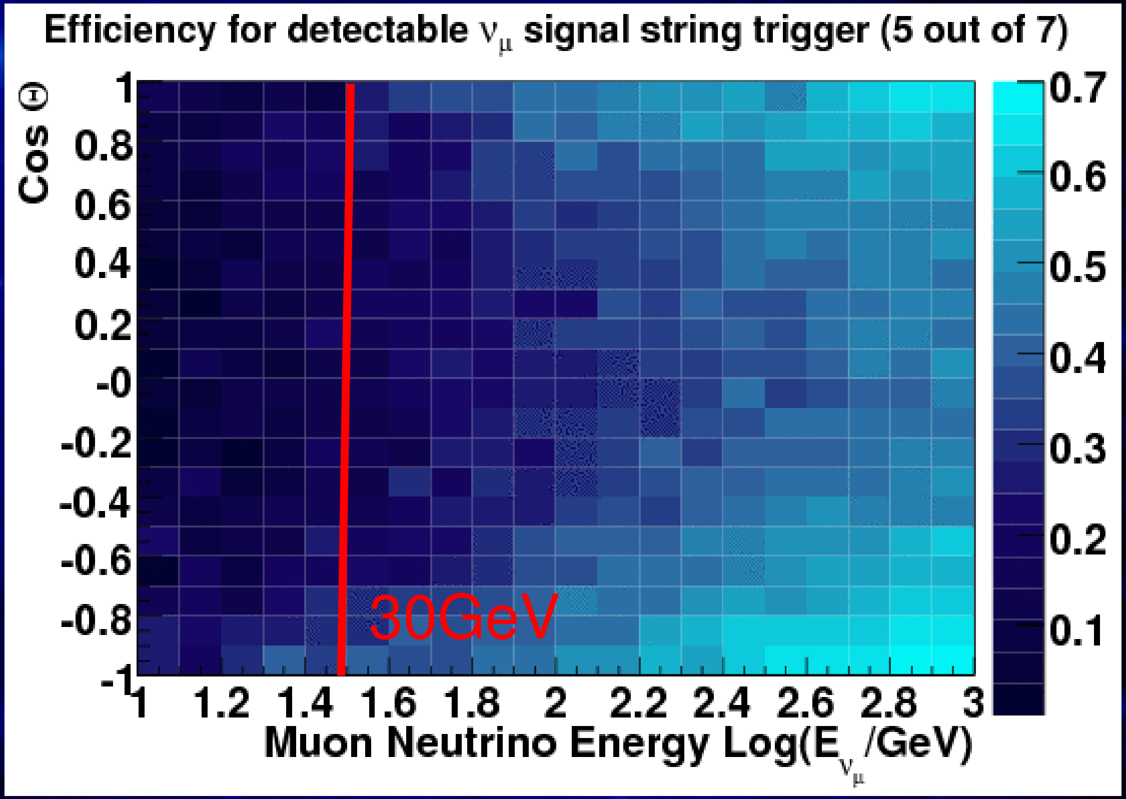


Almost factor of 3 more inner strings in IC40 compared to IC22 (they are in addition also better isolated)

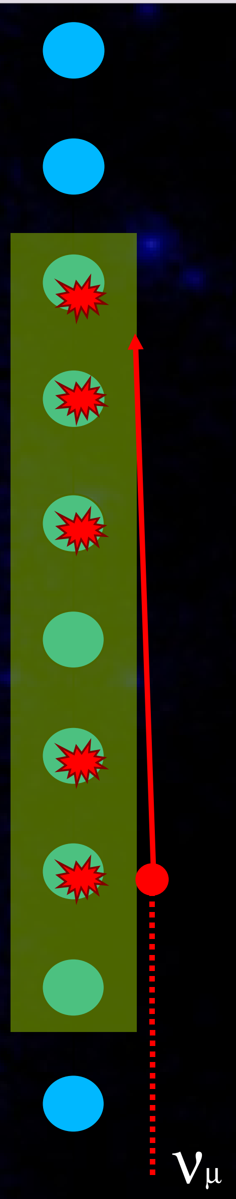
IC40 Improvements: String Trigger

- Topological trigger allow to lower the energy threshold further compared to the default multiplicity 8 trigger
  - Selects events based on a certain pattern present in the detector
- Beginning with IC40 data taking a string trigger has been added to IceCube's trigger

String Trigger:
5 DOMs hit within a series of 7 DOMs within a time window of 1500ns



Gross, Ha, Rott, Tluczykont, DeYoung, Resconi, & Wikström, ICRC 2007



Detectable events were defined as events that have at least one hit in the detector

IC40 Improvements Summary

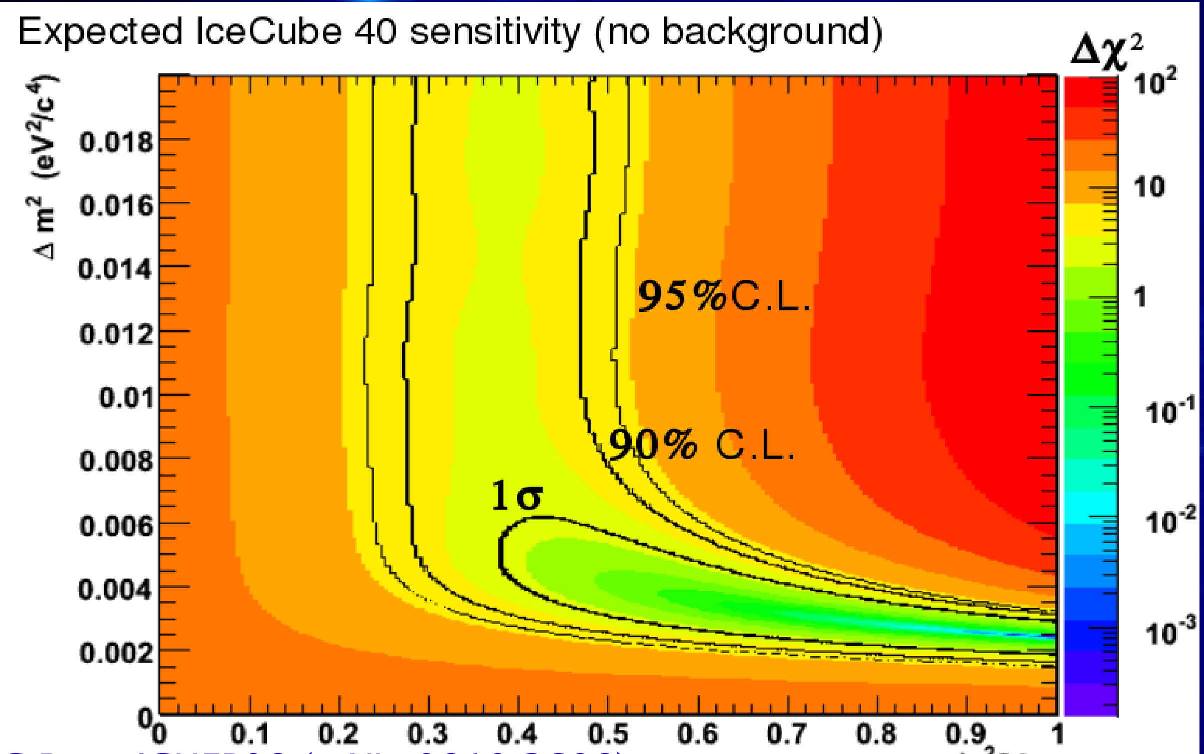
- 3x more inner strings
- 2x more events due to string trigger
- 10% improvement in filter efficiency
- Increased detector uptime
- Access to lower energies due to string trigger
  - Oscillation effects more pronounced

expect **x10** more stat. for IC40 compared to IC22

- Expect at least one order of magnitude more (candidate) signal events
- Further studies of these events will lead to a better understanding of low energy region and will benefit the analysis

Oscillation Sensitivity

Expected results of χ^2 test using the track length as energy estimator



C.Rott, ICHEP08 (arXiv:0810.3698)

CL	$\Delta\chi^2$
1σ	2.30
$90\% C.L.$	4.61
$95\% C.L.$	5.99

(m = 2)

Expect in the IC40 dataset to see oscillation effects

IceCube probes a different energy region compared to other oscillation experiments

Muon Neutrino Disappearance Analysis Conclusions

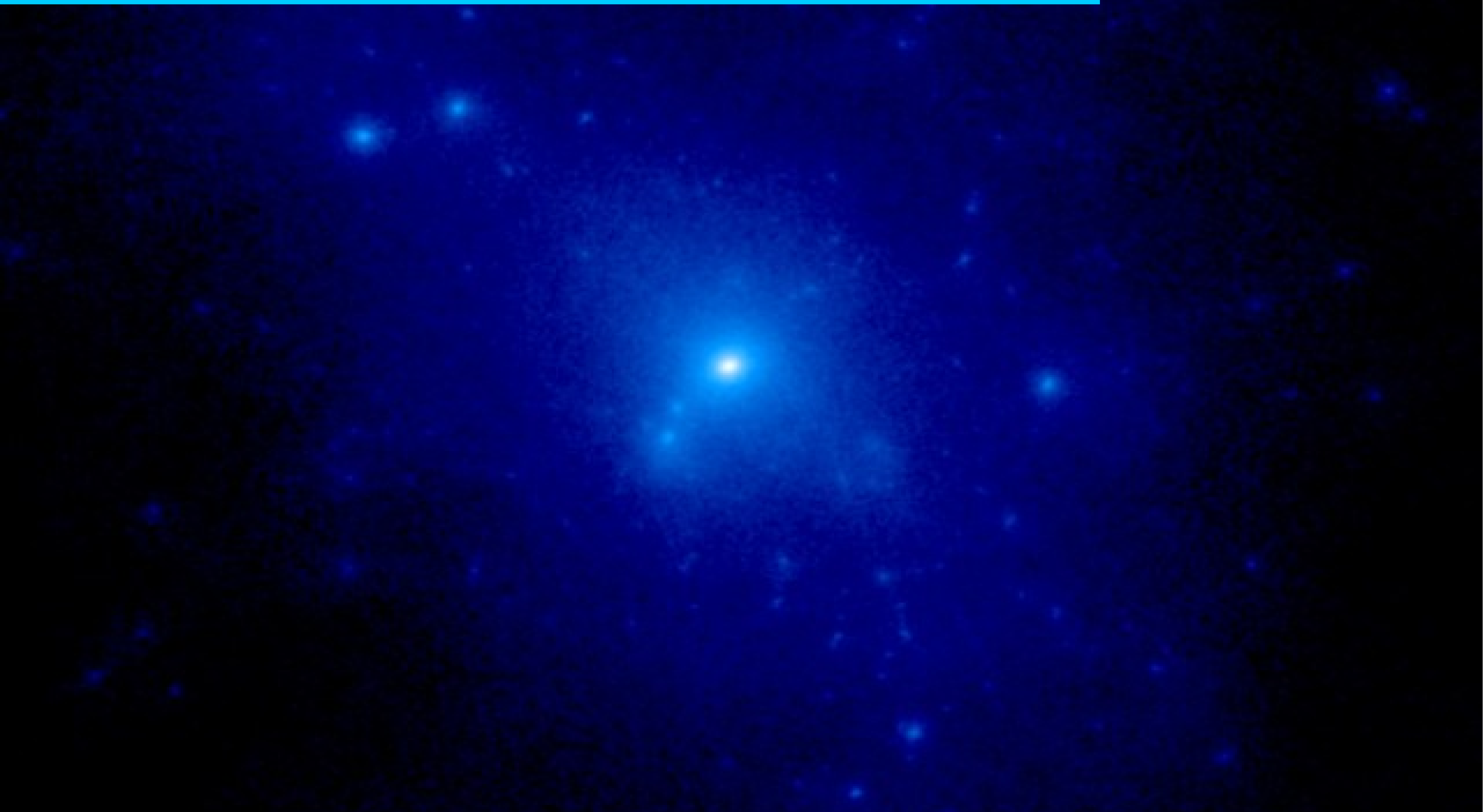
IC22 and IC40 analysis both in progress now

- Expect results at ICRC 09

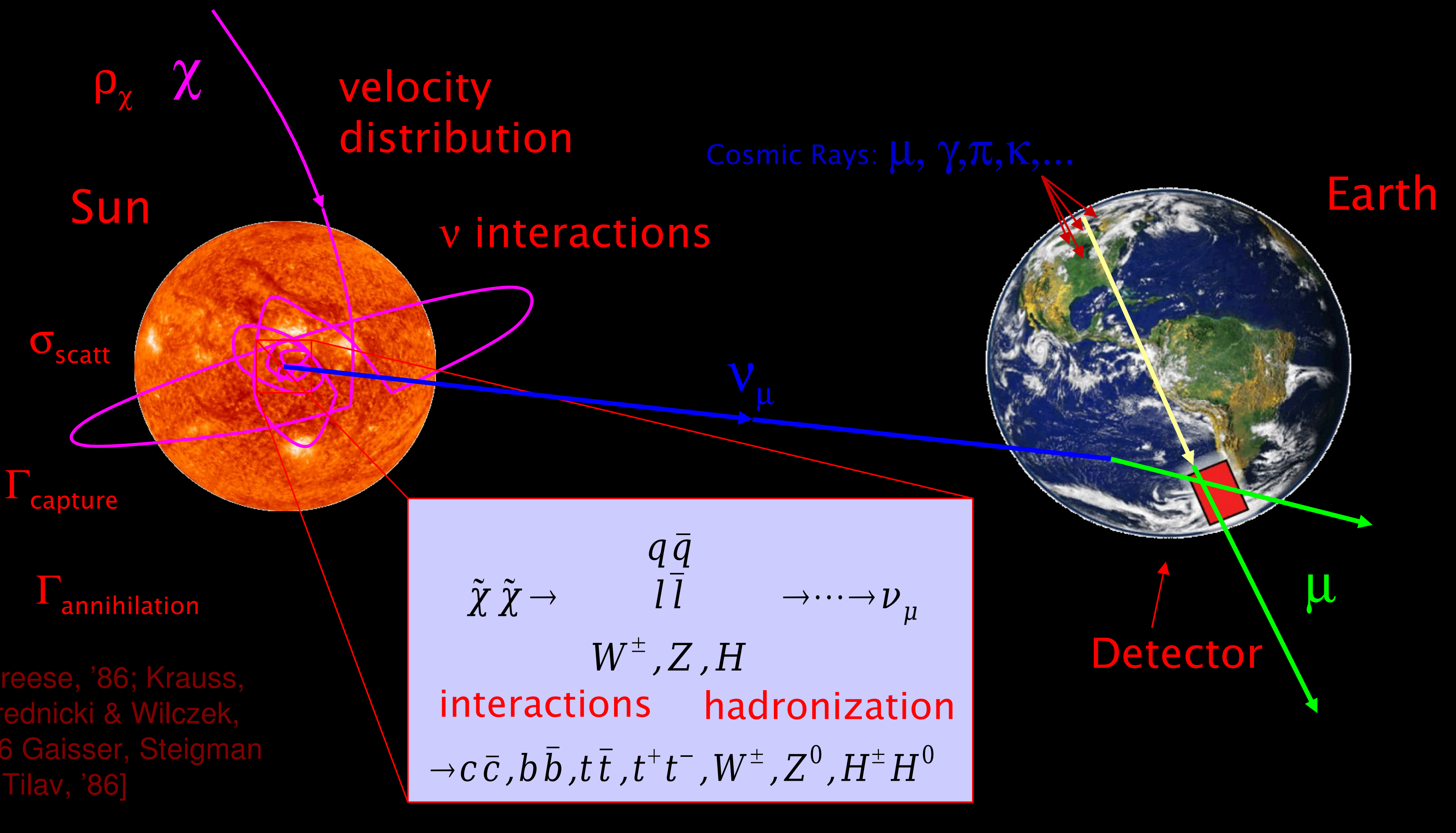
IC40 data is expected to be large enough to show first signs of observable oscillation effects

Oscillation analysis important test at low energy region, which is not well covered

Indirect Searches for Dark Matter



Solar WIMPs



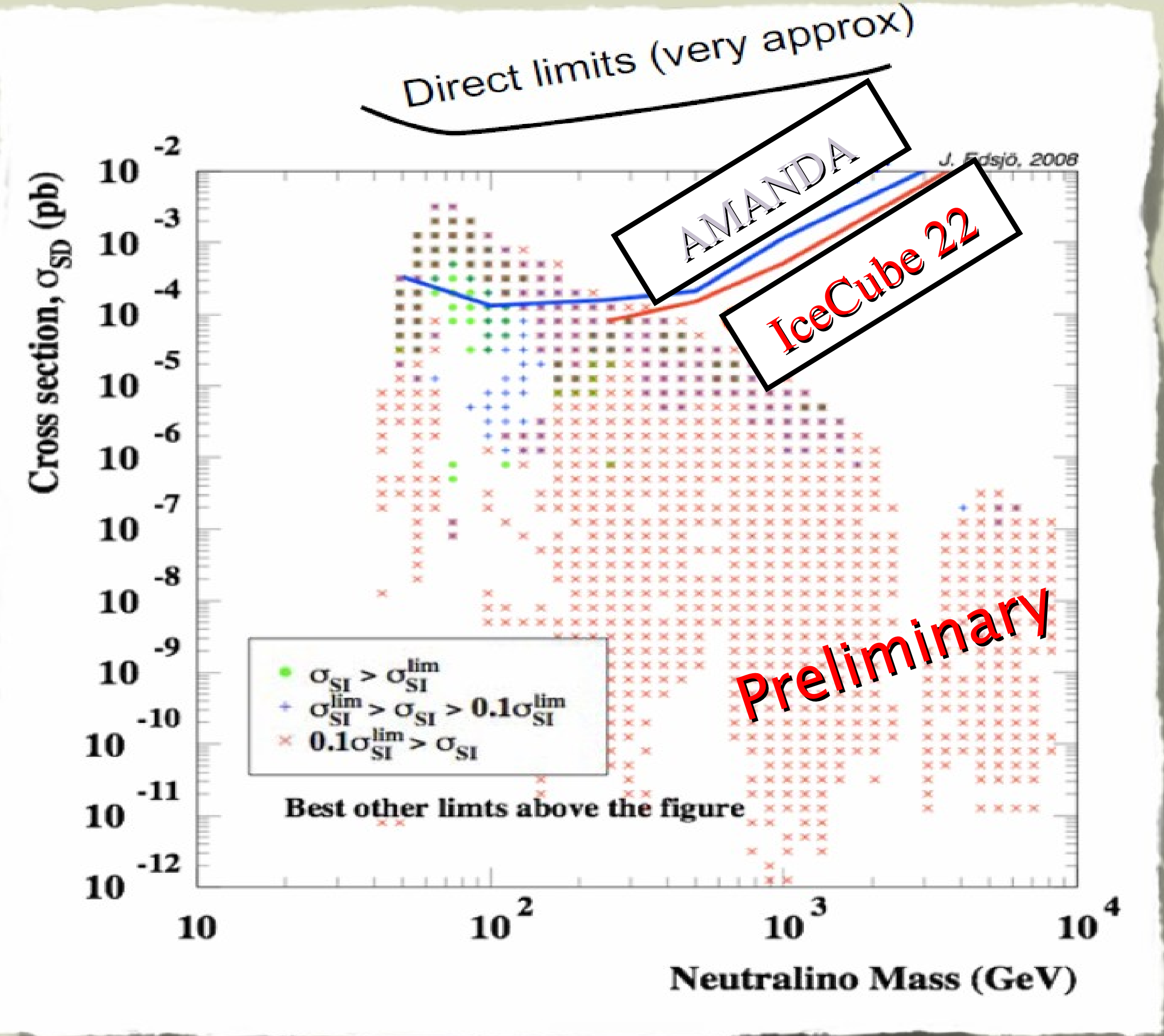
[Freese, '86; Krauss, Srednicki & Wilczek, '86 Gaisser, Steigman & Tilav, '86]

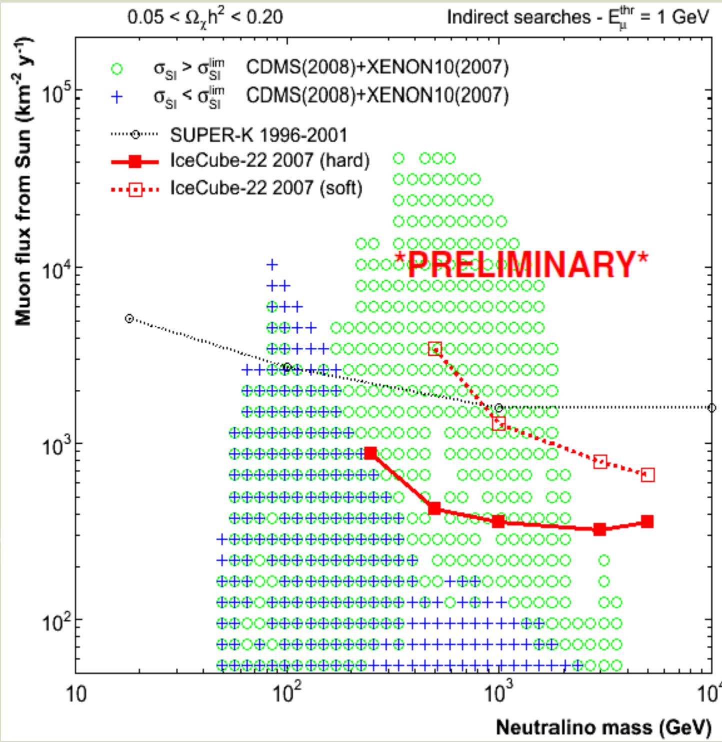
The Sun sinks maximally 23° below the horizon at the south pole

Solar WIMPs

[PRL in preparation]

spin dependent scattering

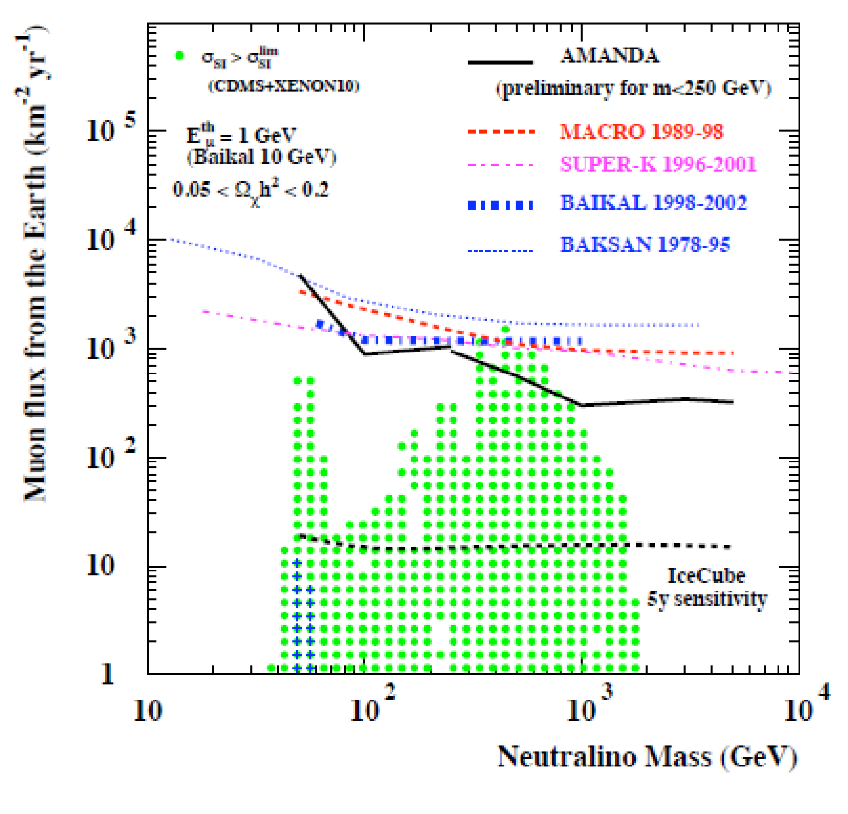


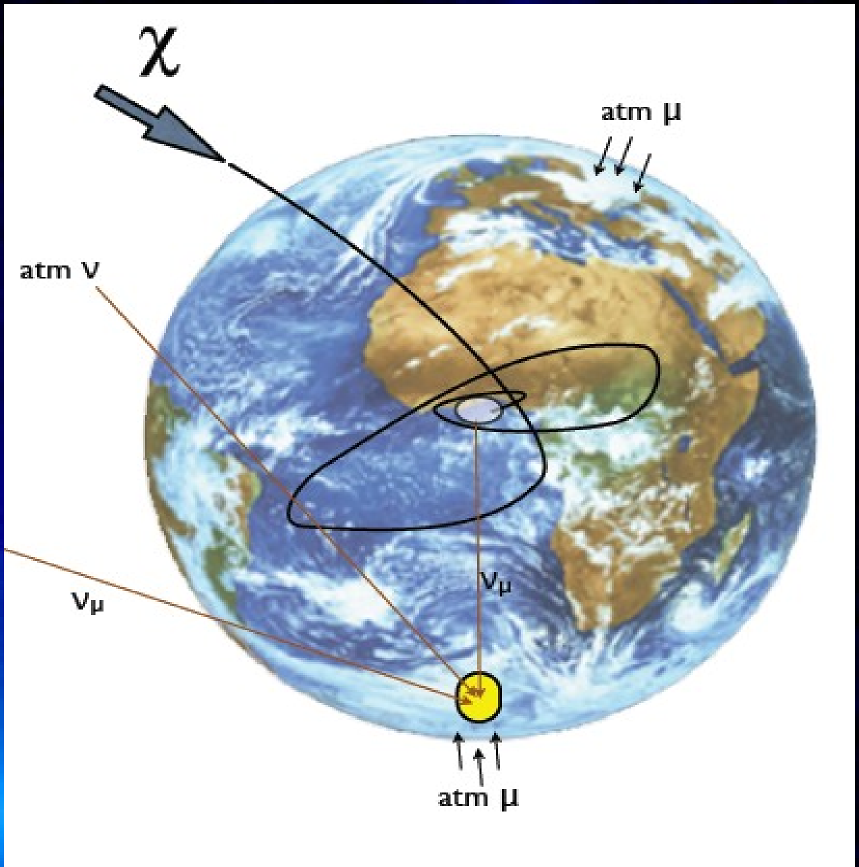


Stockholm University

Earth Wimps

- Place 90%C.L. limit on muon flux from the center of the Earth



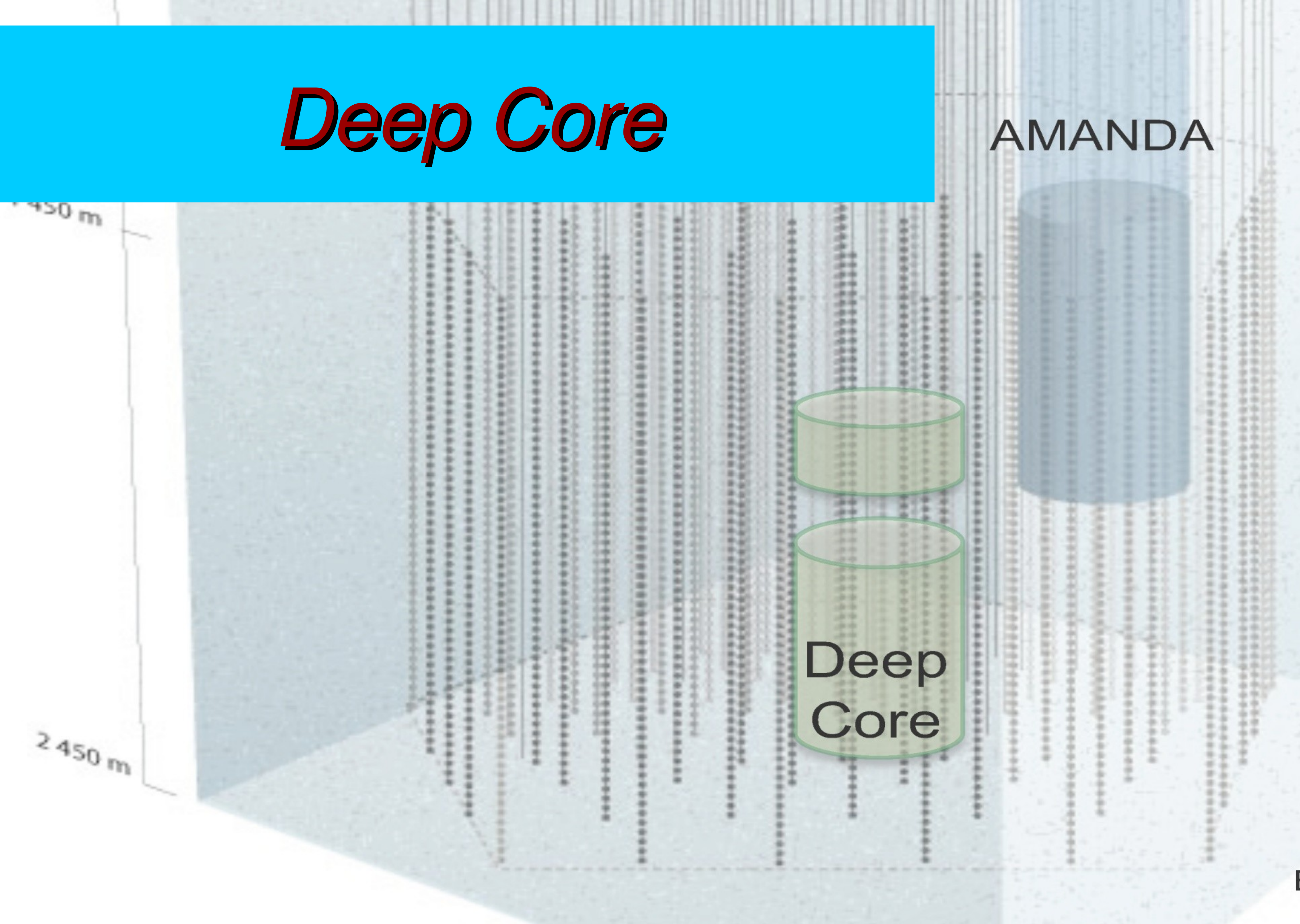


AMANDA Earth Wimp analysis on-going

IceCube Earth Wimp analysis on-going

- Understanding of low energy vertical tracks extremely important (relates closely to oscillation analysis)

Deep Core



Deep Core Extension

Deep Core Strings

- 6 strings with high quantum efficiency PMTs, densely spaced
- 7 "standard" IceCube strings

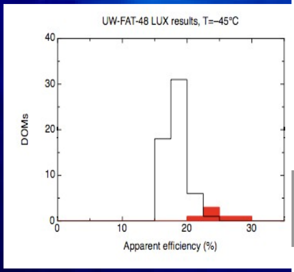
located in best ice (below 2100 m exceptionally clear)

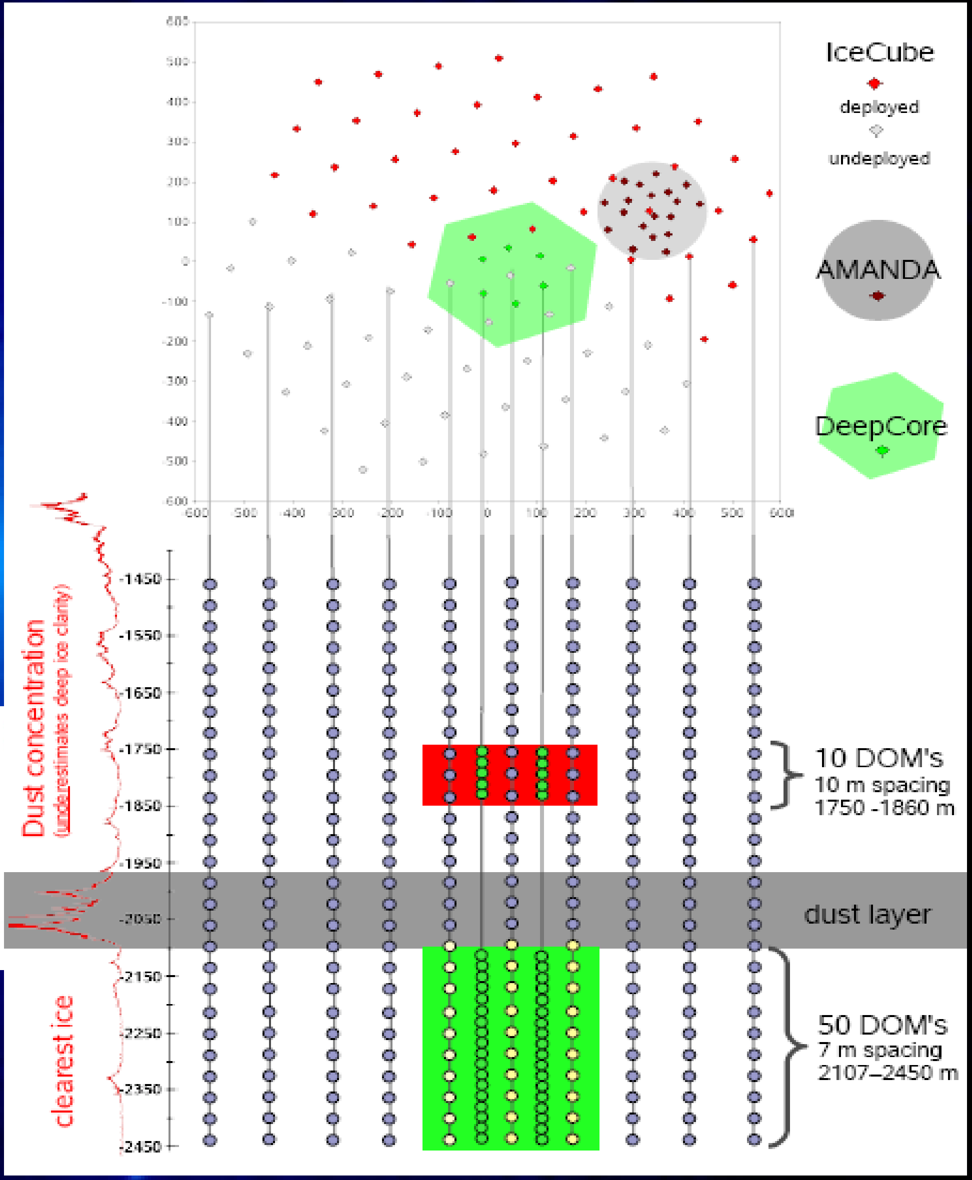
Interstring spacing 72m

Uses high Quantum Efficiency PMTs, that have about 40% higher efficiency

Located in the deep ice

- Lower atmospheric muon background
- Larger scattering length ~40m





Deep Core Low Energy Extension

Effective Veto against down-going muons from surrounding strings and DOMs above (~10^5 reduction in background)

Large veto region allows for 4π steradians (all sky) analysis

- Southern Sky
- Year around sun

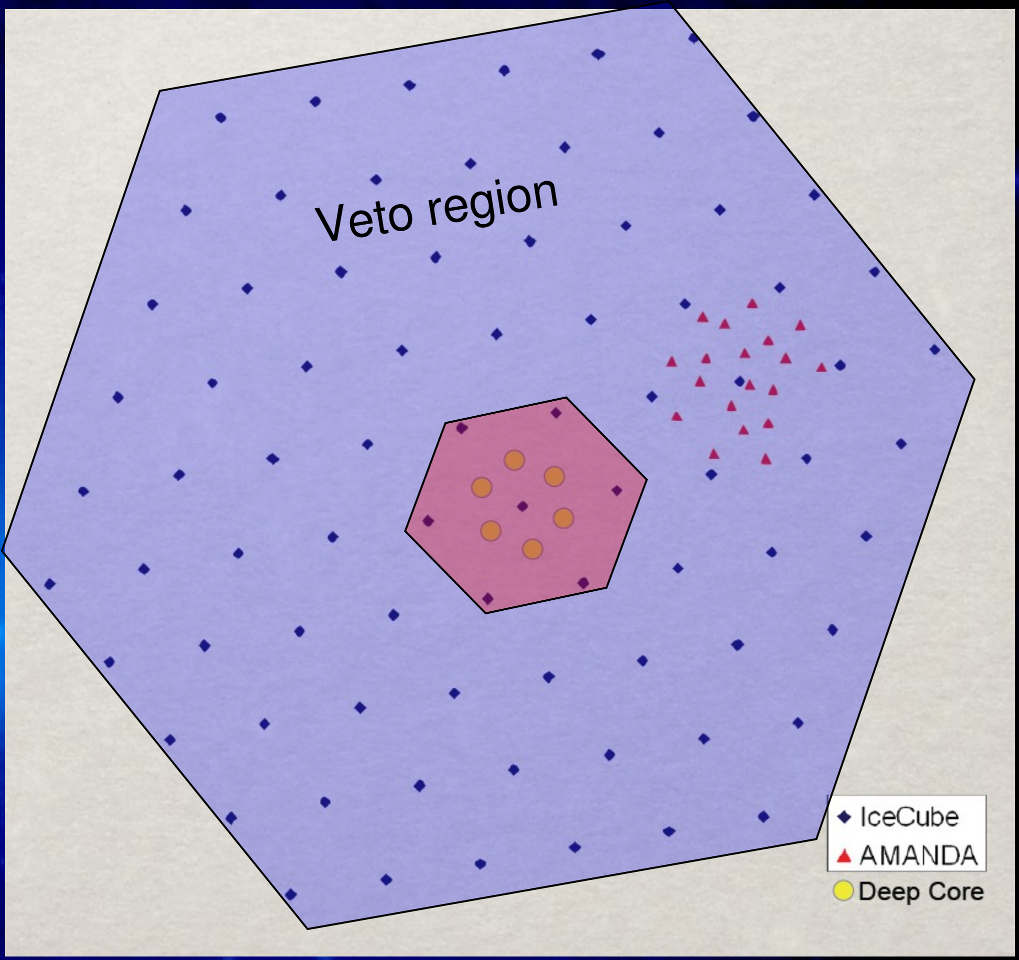
IceCube:

$D_{scatter}$=20m<< ½*$D_{interstring}$ =125m/2

Deep Core:

$D_{scatter}$=40m ~ ½ *$D_{interstring}$ =72m/2

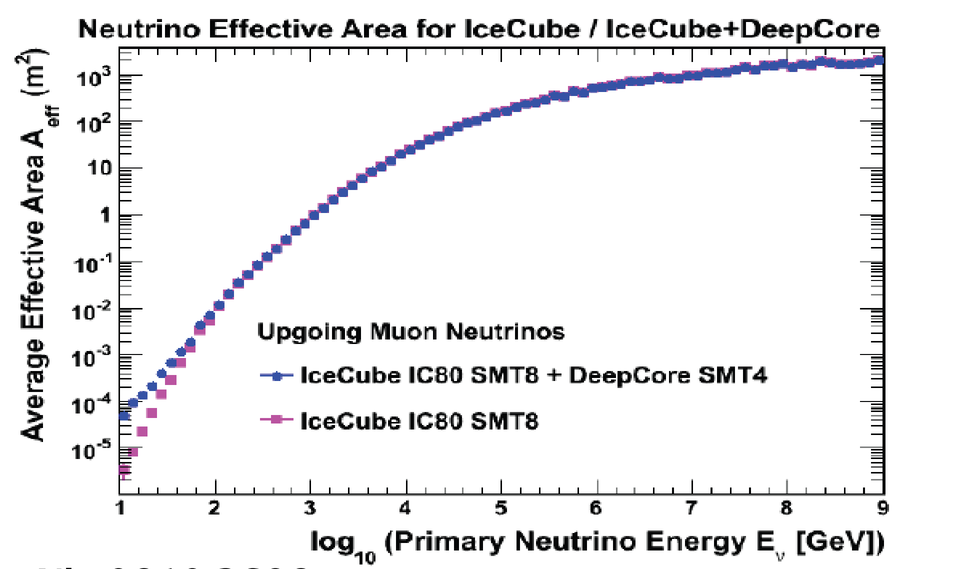
direct light



First Deep Core string this season (Jan 2009)

Physics with Deep Core

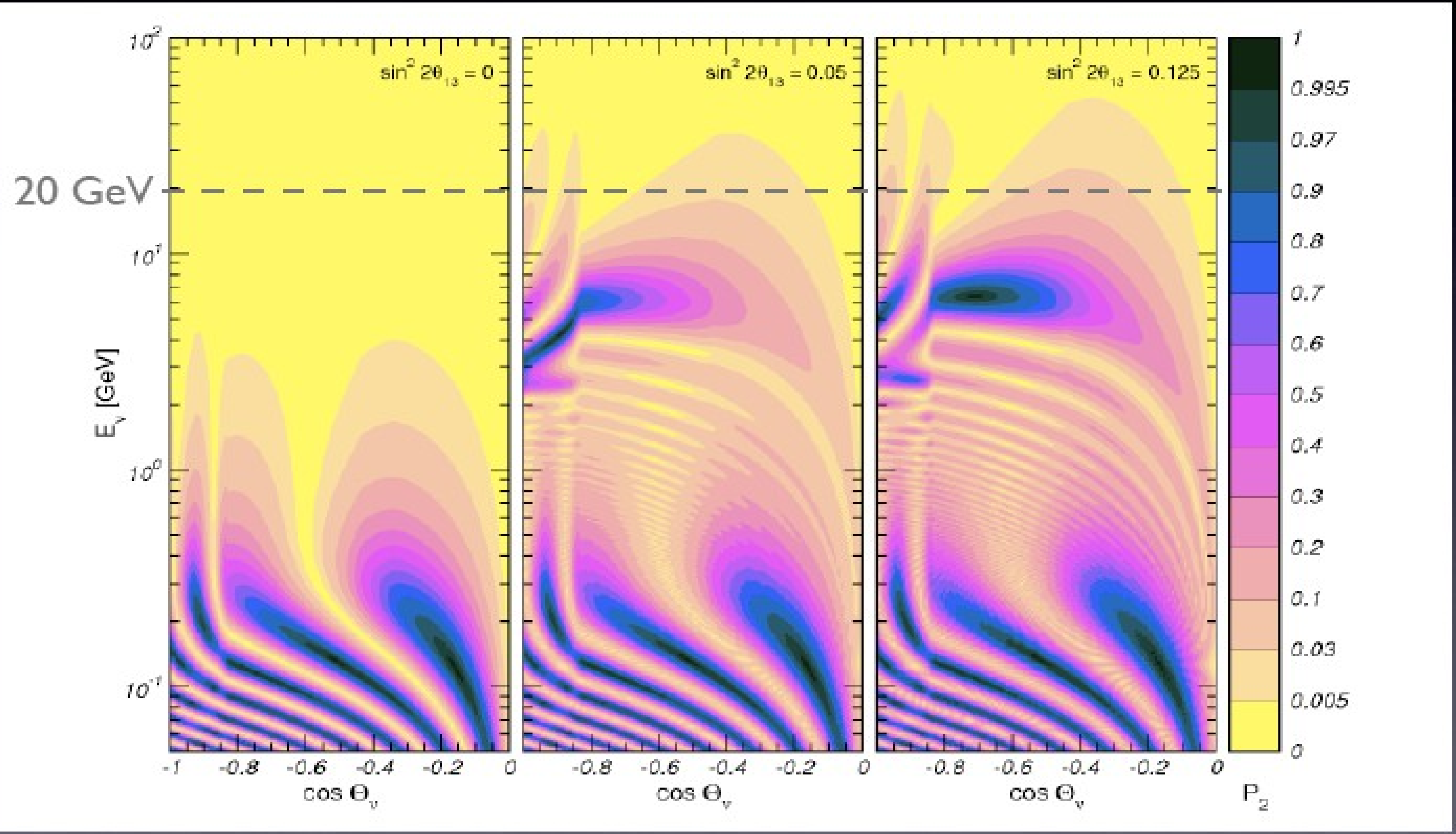
Southern Sky (Galactic Centre - Galactic plane)
Cascade direction and reconstructions
Atmospheric electron neutrino spectrum
Low energy atmospheric neutrinos
Oscillations
Neutrino Mass Hierarchy
Neutrino Tomography
Wimp improvements
...



arXiv:0810.3698

Mixing angles Θ_{13}

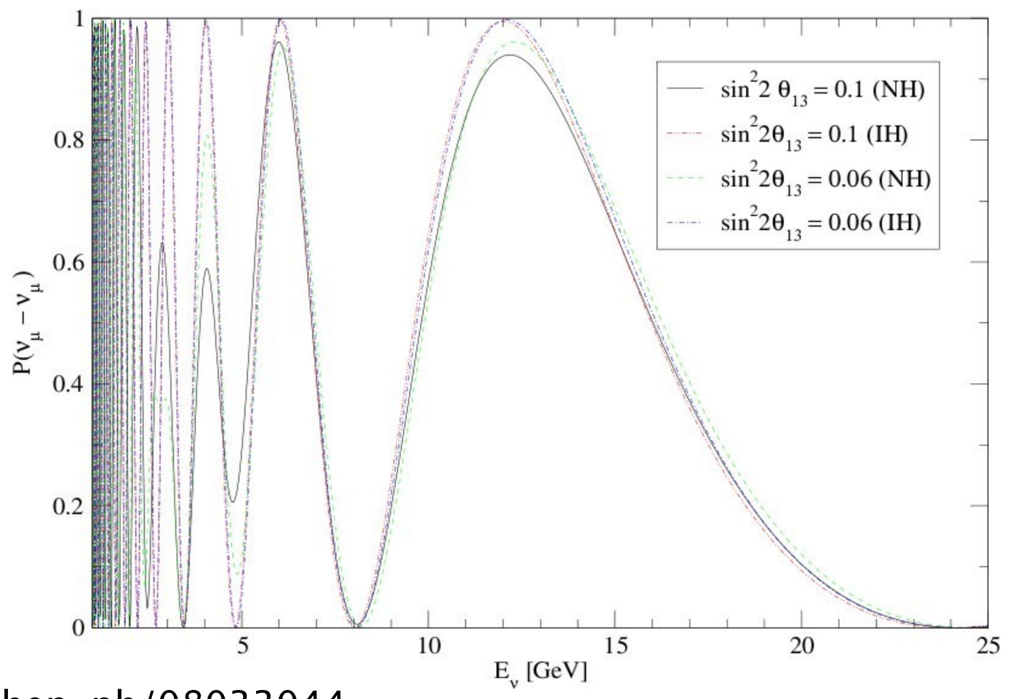
- Transition probabilities ($1 - P_{e \to e}$)



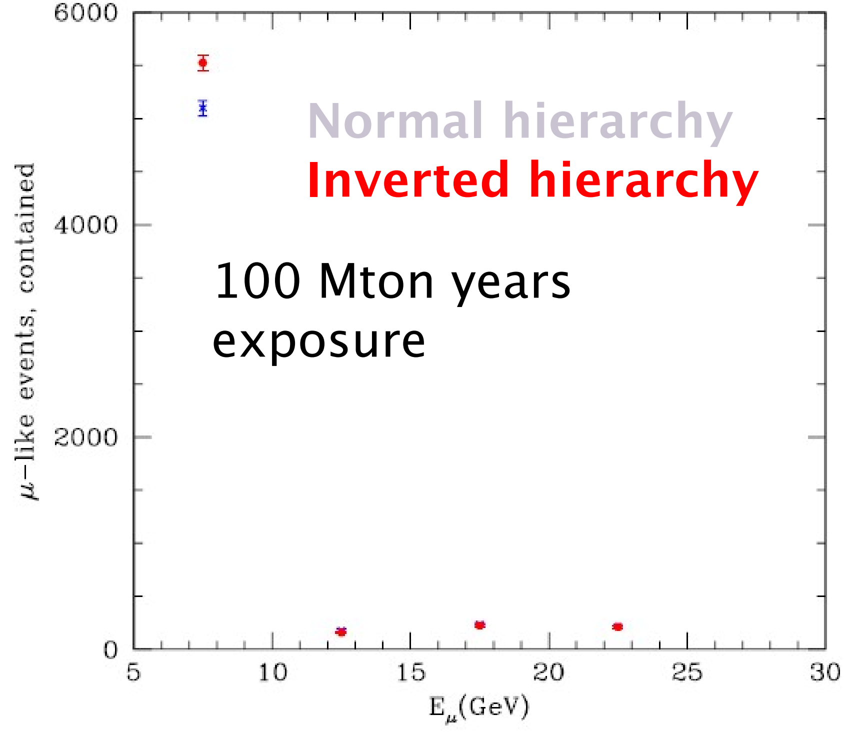
Akhmedov, Maltoni & Smirnov, hep-ph/0612285

Neutrino Mass Hierarchy

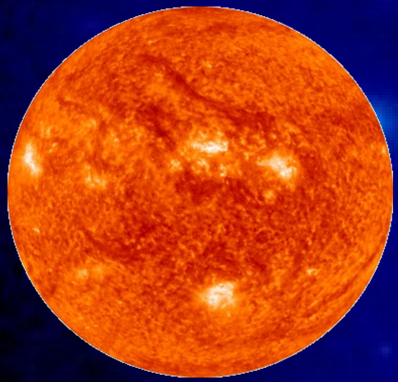
- Matter effects **enhance** the **oscillation probability** for (anti-) **neutrinos** if the mass hierarchy is **normal** (inverted)
- In the relevant energy range the anti-neutrino cross-section is smaller than that of neutrino by roughly a factor of 2

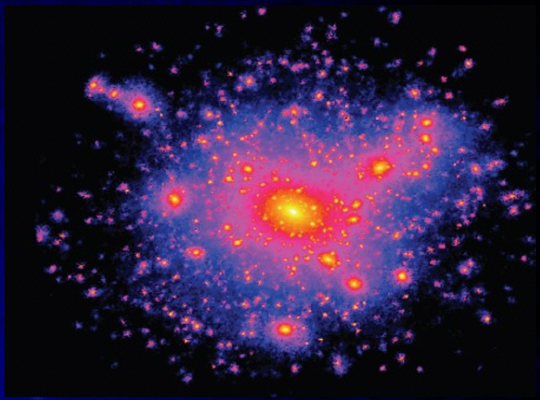


hep-ph/08033044



Dark Matter Searches





Solar	Earth	Halo
Background off-source on-source	Background simulations	Background off-source on-source
Muon neutrinos	Muon neutrinos	**Cascades**, Muon neutrinos
Neutrino Flux, **Scattering cross-section**	Neutrino Flux, ?	Neutrino Flux**, Self-annihilation cross-section**
Excess	Excess	**Anisotropy**, Spectrum
IceCube (+ Deep Core)	**IceCube** (+ Deep Core)	**DeepCore** (+ IceCube)

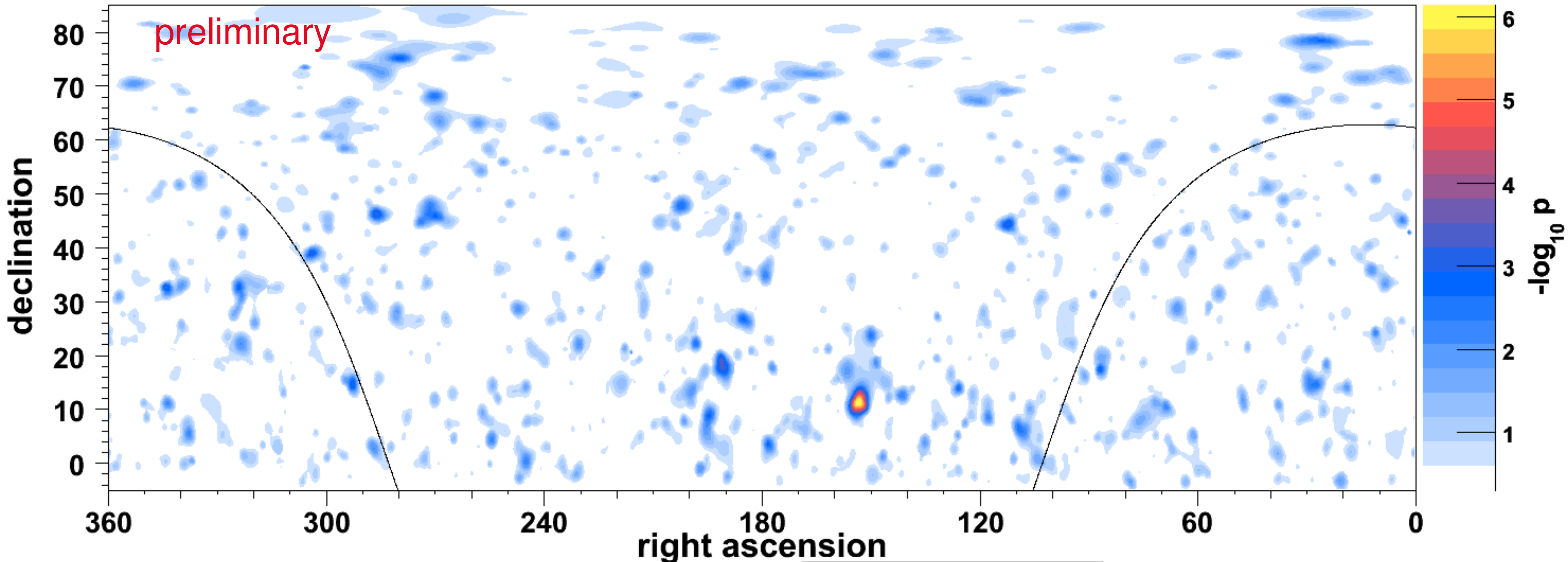
Conclusions

- **IceCube is taking data with the half completed detector**
- **This season plan to add at least 16 new strings**
  - **13 have been deployed so far this season**
  - **1 of the new strings will be a Deep Core String**
- **Deep Core will substantially enhance IceCube's low energy sensitivity**
- **Already now in a special sub-class of events (vertical/close to a string) we can study low energy neutrino (<100GeV)**
  - **Muon Neutrino Disappearance should be observable in the IC40**

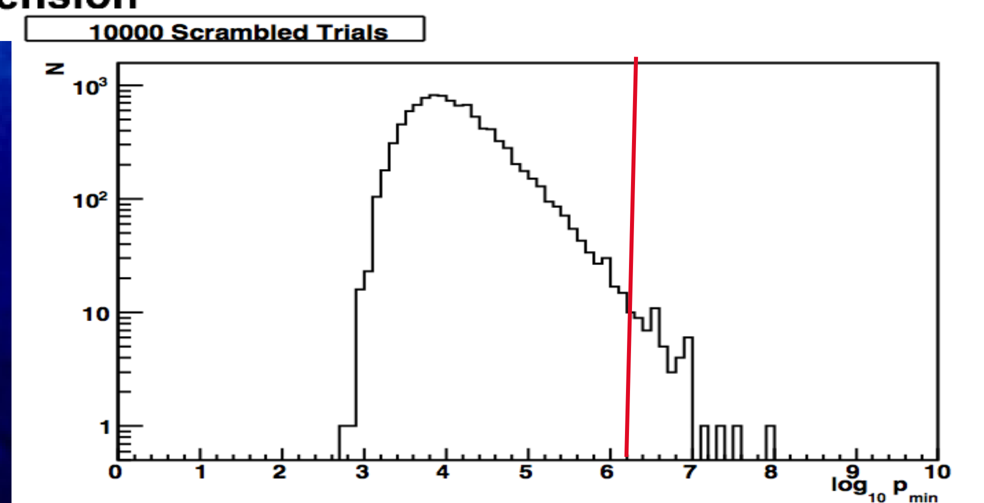
Physics Analyses in full swing now ... Expect many new results for ICRC 2009

Backup Slides

IceCube-22 Point Source Search



Hottest spot found at r.a. 153º , dec. 11º
est. nSrcEvents = 7.7   est. gamma = 1.65
max. llhRatio = 13.4
est. pre-trial p-value: $-\log_{10}(p)$: 6.14   (4.8 sigma)



Post-trials p-value of analysis is ~ 1.34%   (2.2 sigma) ...