Earth vs. Neutrinos

First measurements of neutrino absorption in the Earth and the muon neutrino-to-nucleon cross section above 1 TeV with the IceCube Detector

Dr. Sandy Miarecki

US Air Force Academy

Fermilab Seminar

29 March 2018

Brief history

- Accepted to UC-Berkeley in 2007
- Flying back to Texas on Southwest Airlines after house-hunting in Berkeley
- Bob Stokstad and I started chatting
- He invited me to visit LBL after I arrived
- Met everyone in group meeting in Fall 2007
- Did a summer project in 2008
- Signed up officially in 2010 after Masters completion

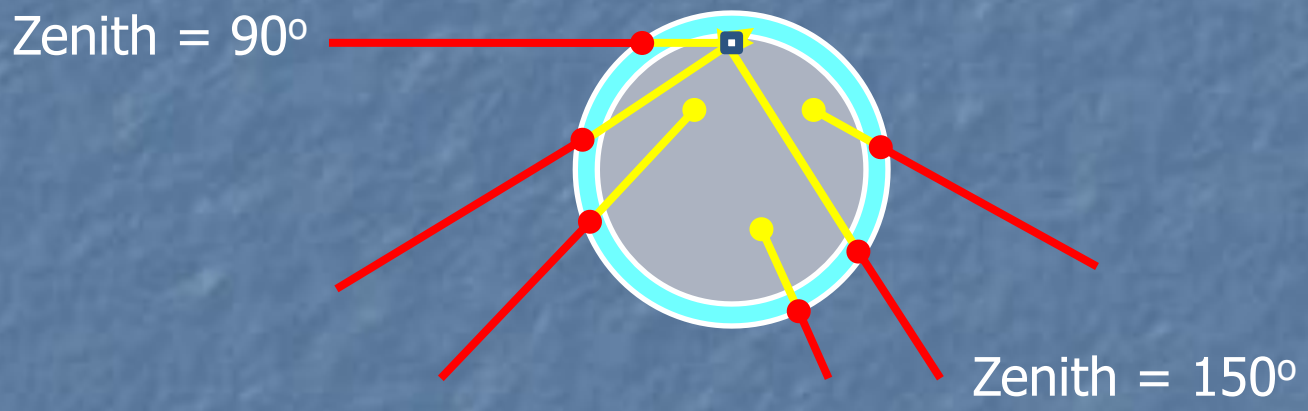
Beginning of the project

- Spencer Klein was my advisor
- He suggested the idea of measuring the muon neutrino-nucleon cross section by measuring the differential absorption of neutrinos in the Earth
- LOVED the idea, combined many of my scientific interests (project name from bad movie '2012')
- But, many requirements for project and several hurdles to overcome

The idea

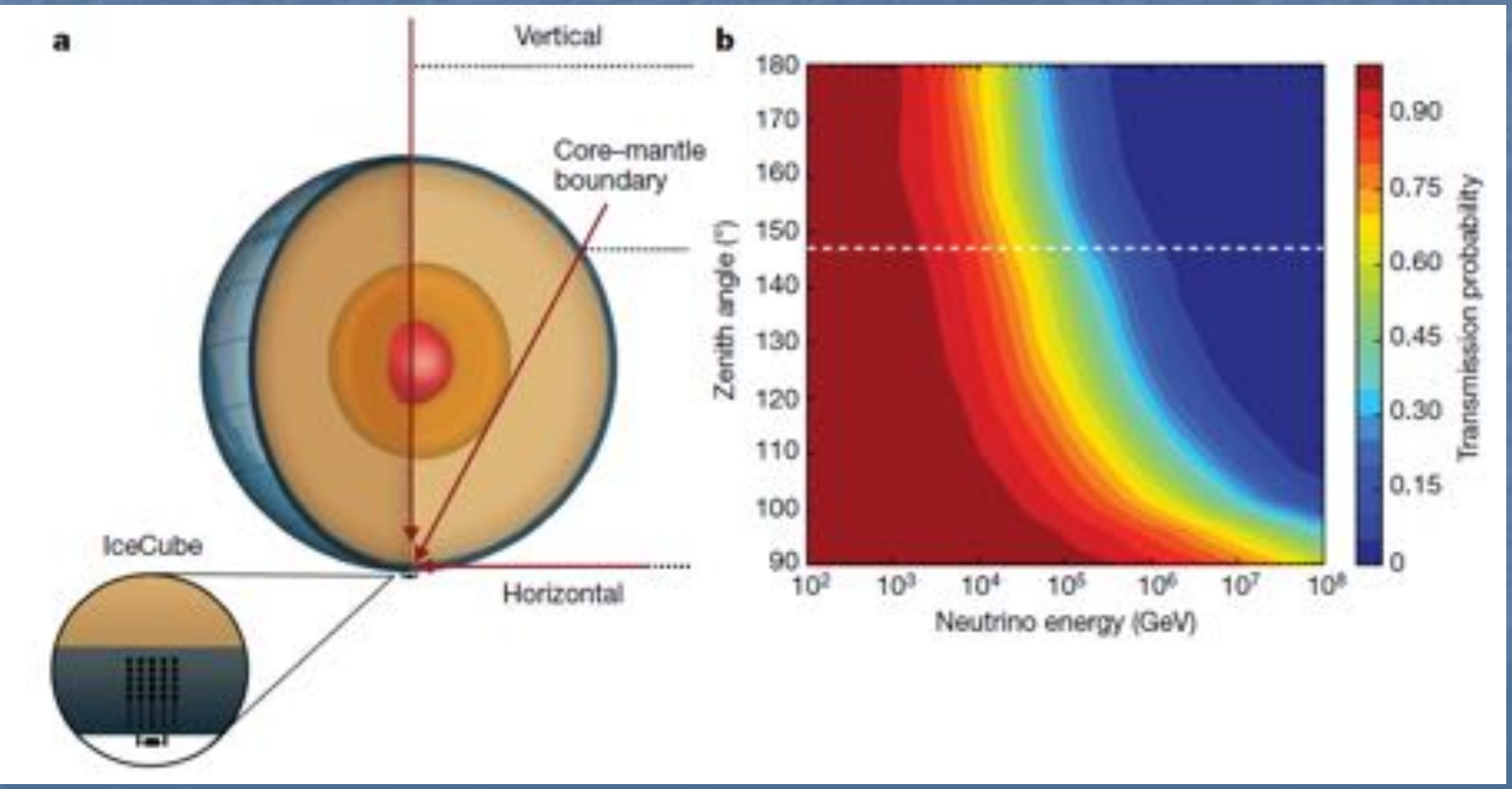
- Determine the number of neutrinos per angle and energy at Earth's surface
- Count the number of muons per angle and energy that are detected at IceCube
- Perform a 2D fit of actual number to expected number for various cross sections
- Determine the muon neutrino to nucleon cross section

Variable neutrino paths



- Use cosmic rays as source of muon neutrinos
- With the Earth acting as the "target", the distribution of muons in the detector should change with zenith angle and energy
  - Fewer neutrinos arriving at IceCube at high zenith angle, especially at higher energy

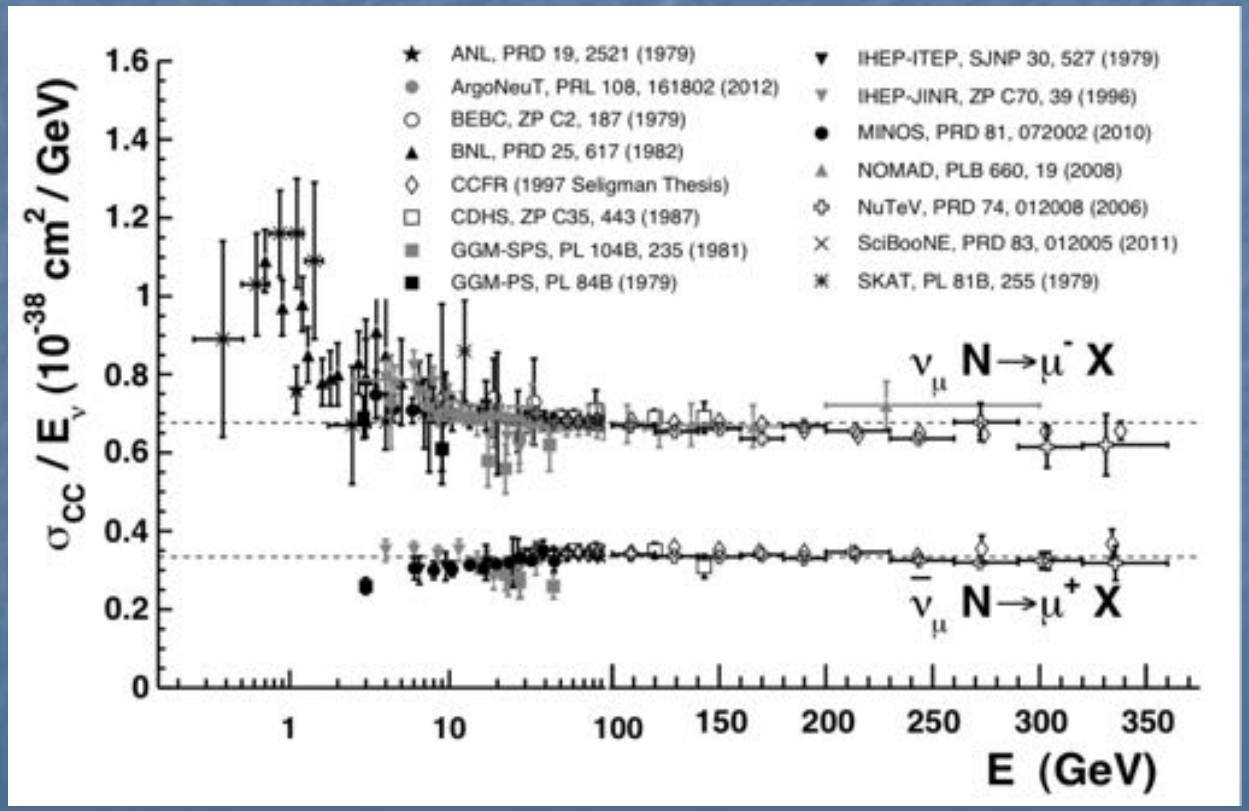
Absorption in the Earth



Nature, volume 551, pp 596–600 (30 Nov 2017)

Previous results

- Accelerator summary: Particle Data Group



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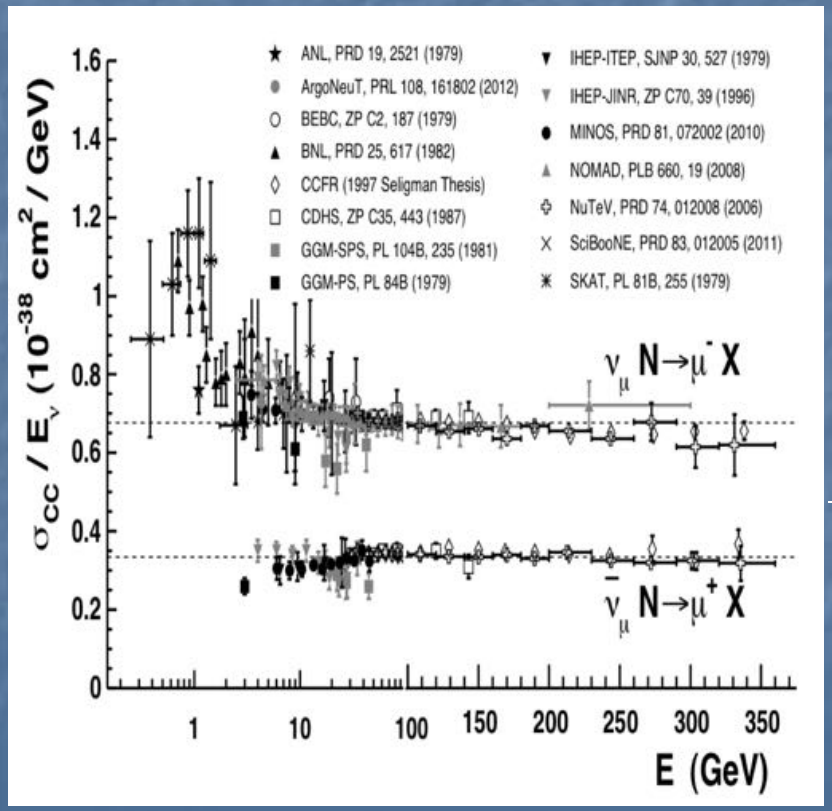


This result

+

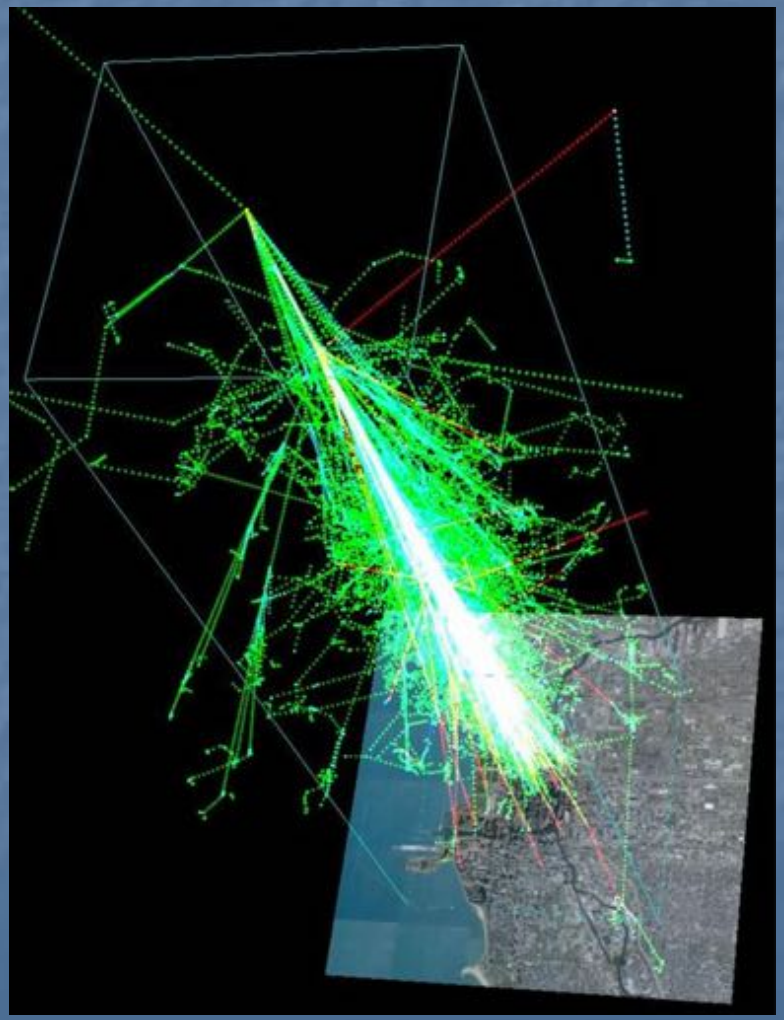
Analysis requirements

- Source of high-energy neutrinos
- Large detector = IceCube
- Earth density/composition model
- Neutrino cross section model
- Event selection for pure muon sample
- Software to determine energy and zenith
- Simulation for comparison to data
- Fitter to do the comparison

Source of high-energy neutrinos

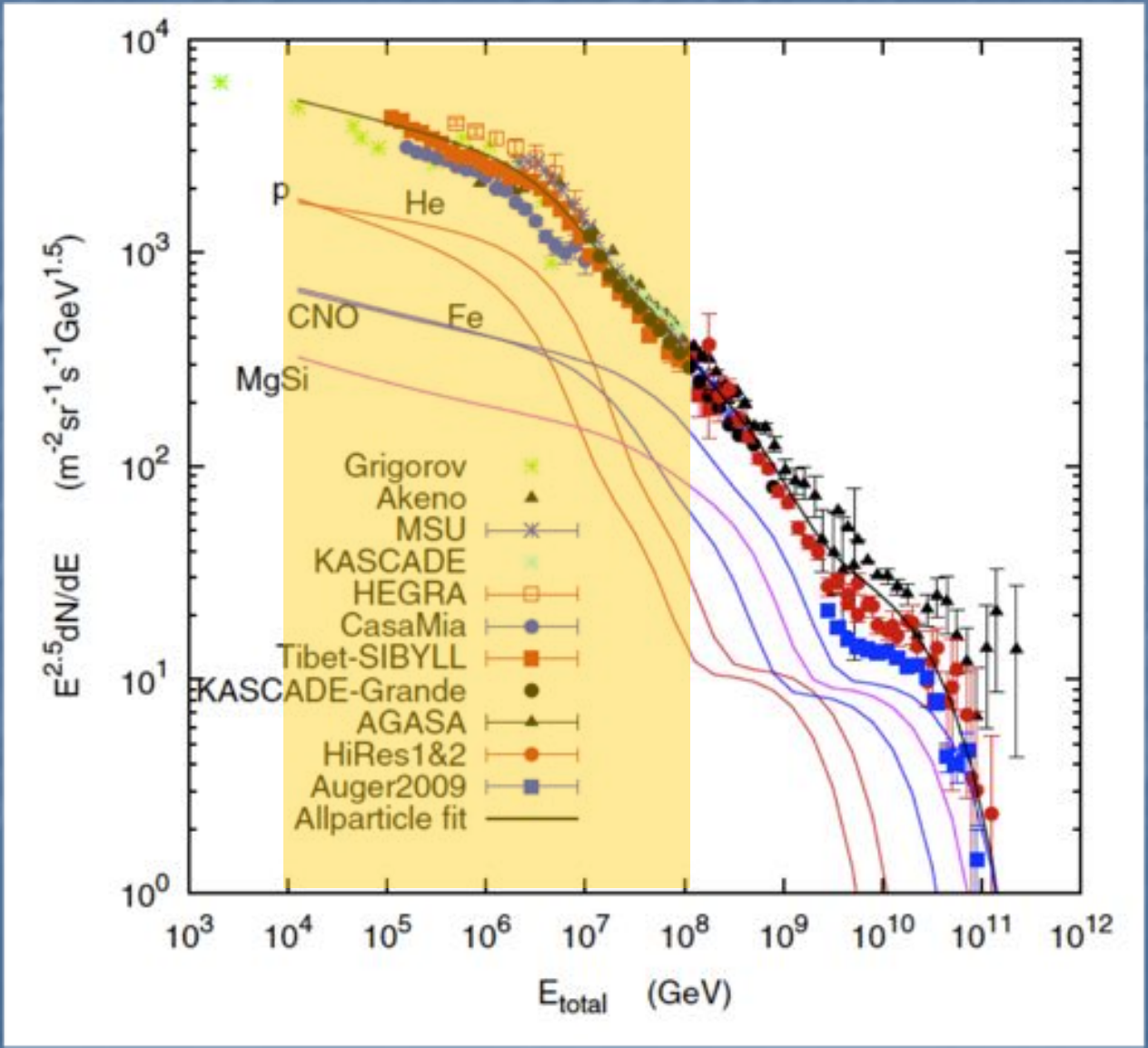
Cosmic Rays

- First seen by Victor Hess in 1912 (Nobel Prize 1932)
- Particles from space
- Mostly protons (low E) and heavier nuclei (high E)
- Cosmic rays collide with atmospheric atoms
- Simulation of TeV proton shower over Chicago



Dinoj Surendran via Wikimedia Commons

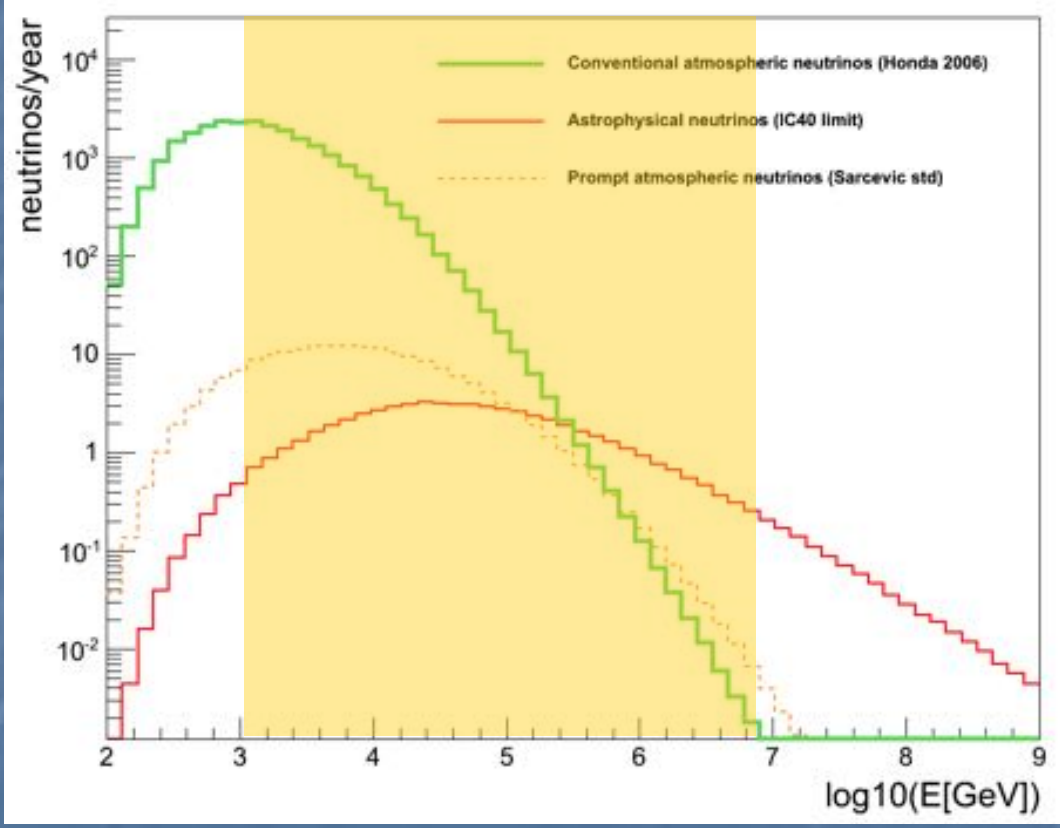
Cosmic ray spectrum



https://arxiv.org/pdf/1111.6675.pdf

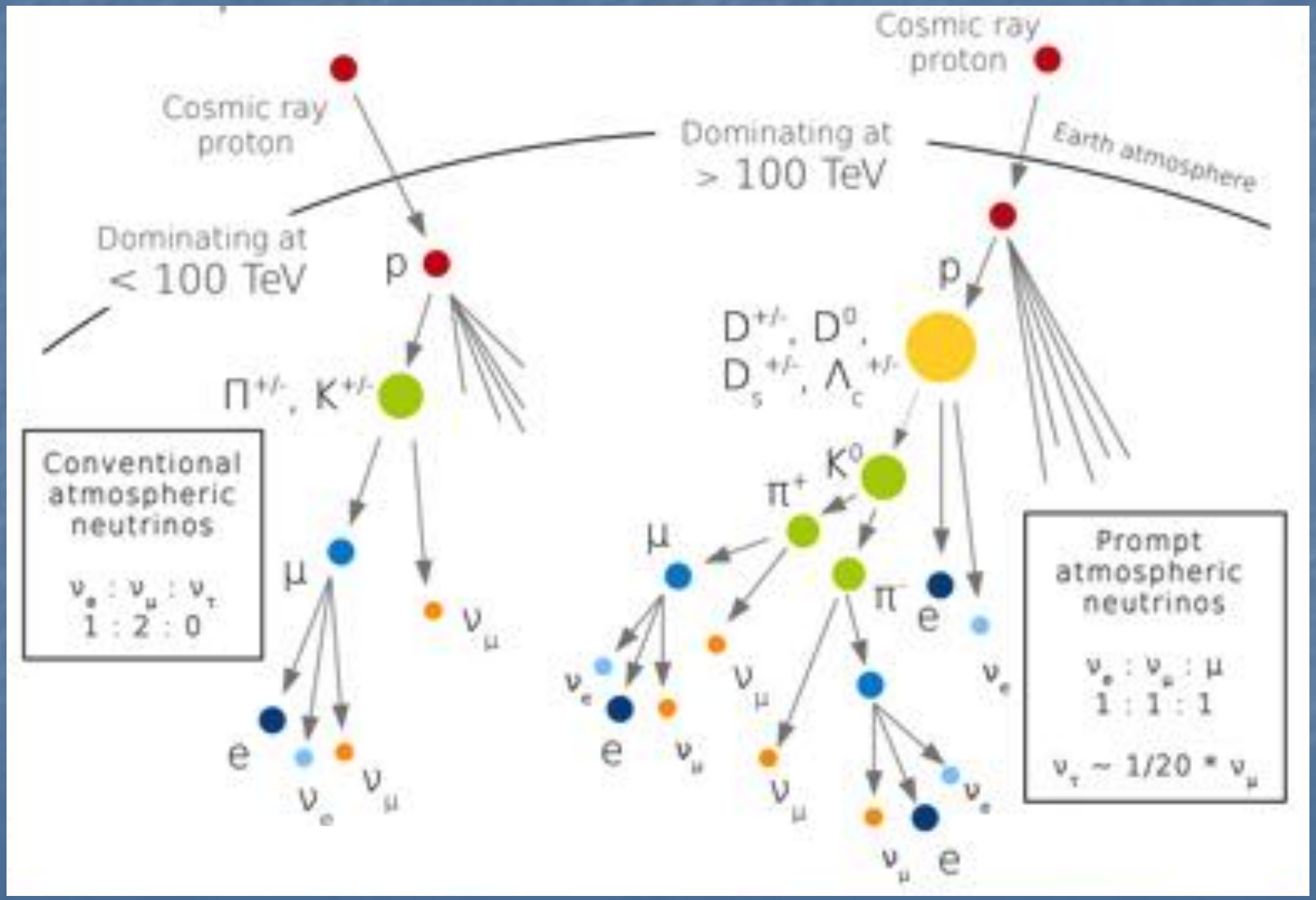
3 'types' of neutrinos

- Atmospheric
  - Conventional
  - Prompt (charm)
- Astrophysical
  - Arrive as neutrinos



IceCube Collaboration

Particle cascades

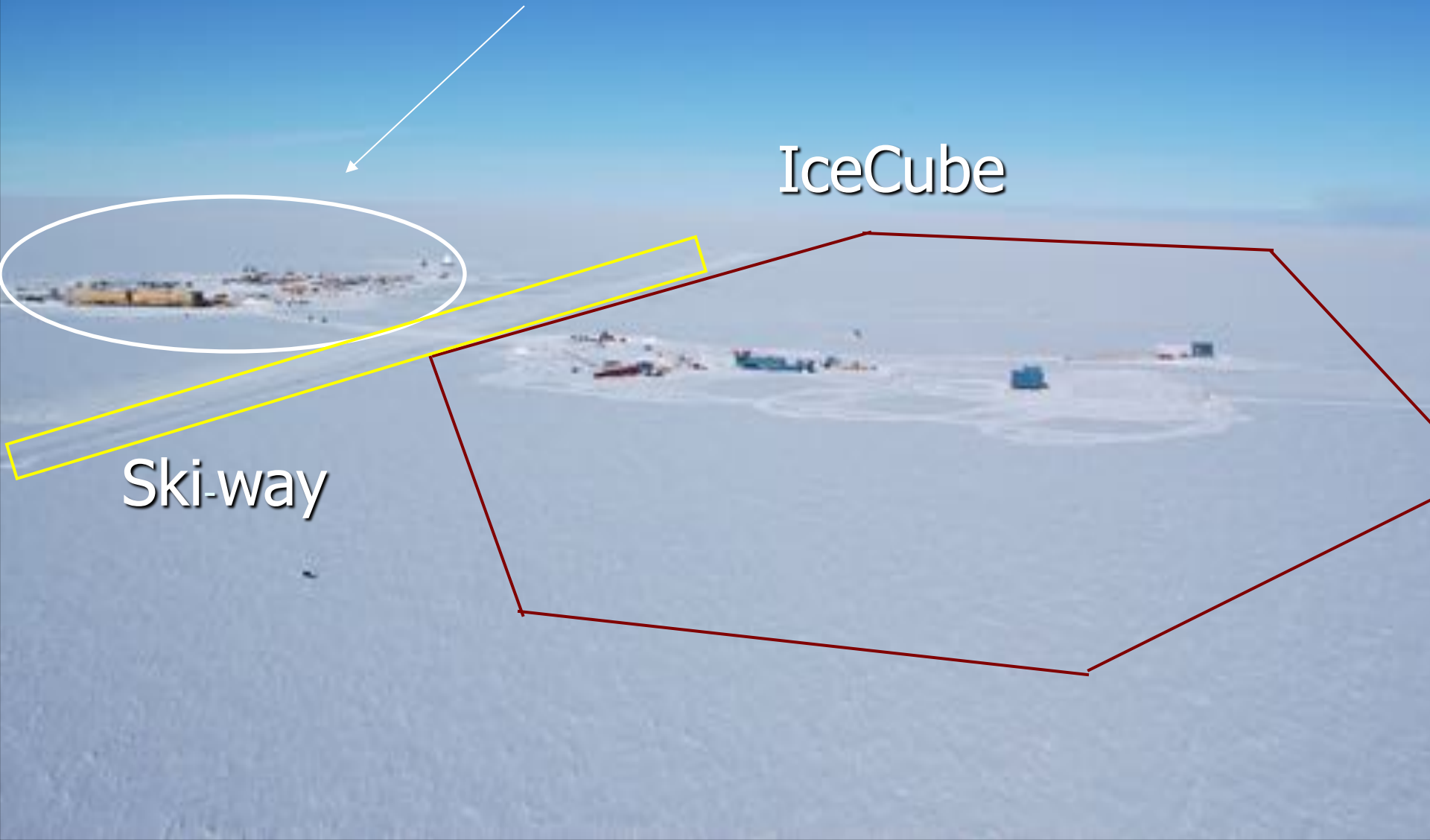


Anne Schukraft, NOW2012, Italy

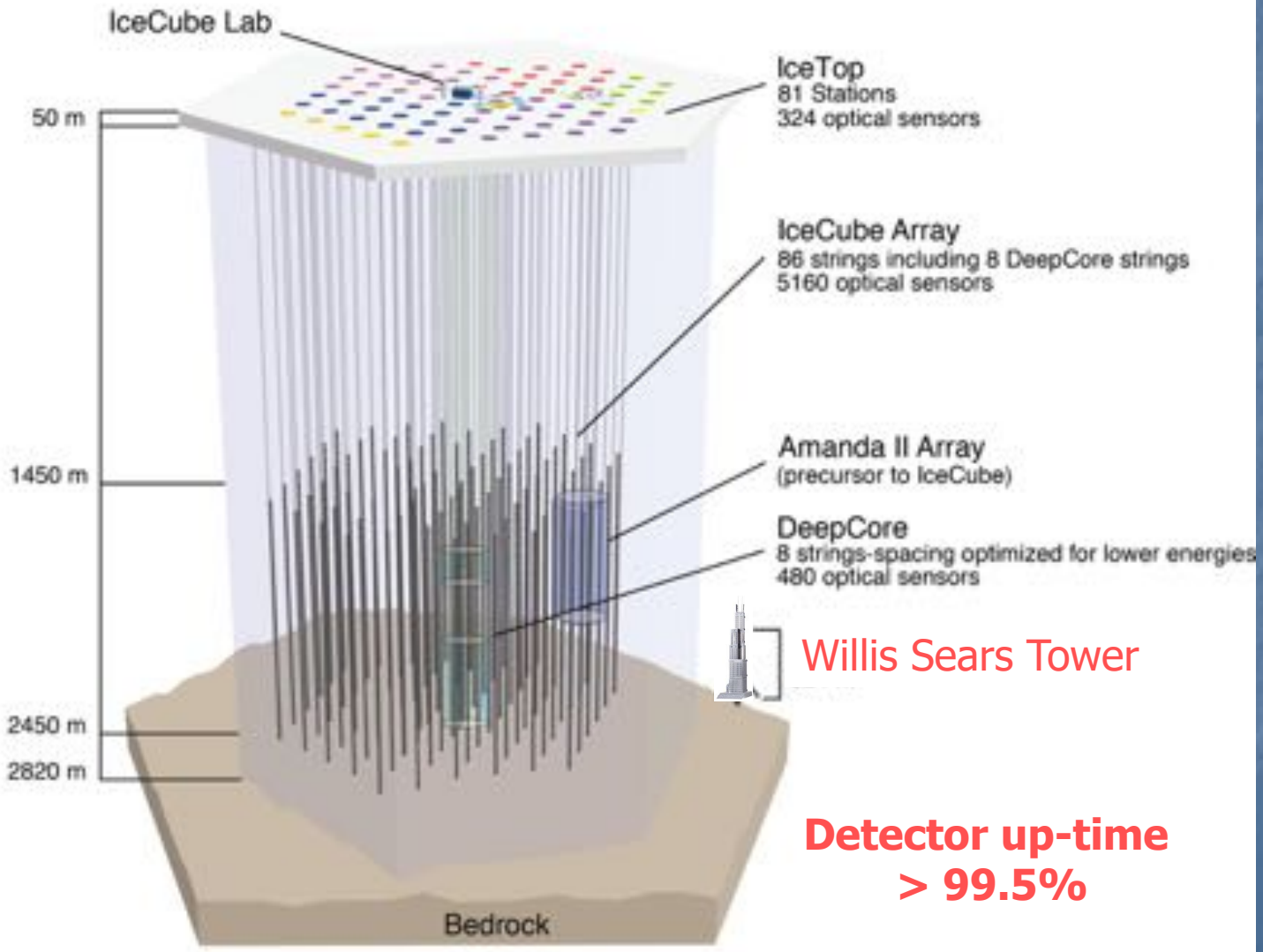
IceCube Detector

IceCube Collaboration

Amundsen-Scott Station



IceCube Detector

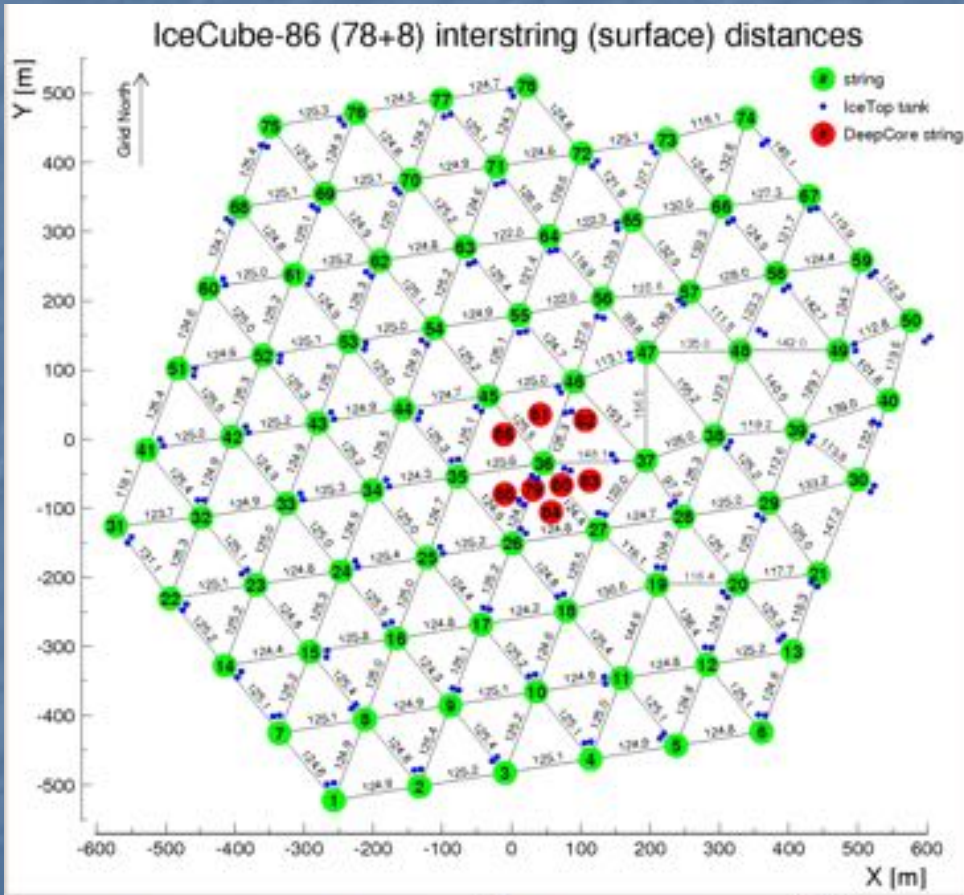


Detector up-time > 99.5%

gallery.icecube.wisc.edu

IceCube Detector

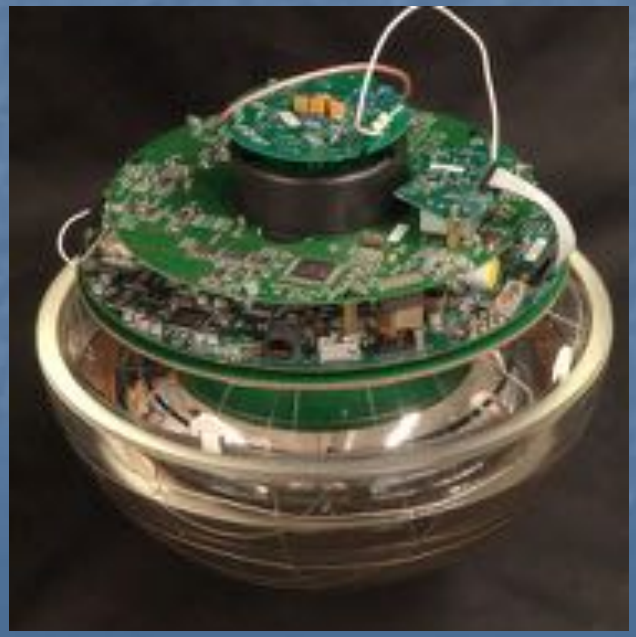
- 86 strings with 60 sensors each = 5160
  - 125-m hexagonal grid
  - 1450 to 2450 m deep
  - 1 cubic km of volume
- Surface array = IceTop
  - 2 tanks above 81 strings
  - 2 DOMs per tank
- Completed Dec 2010



gallery.icecube.wisc.edu

IceCube Sensors

- IceCube sensors = DOMs
  - Digital Optical Modules
  - 1/2" thick bathosphere



gallery.icecube.wisc.edu

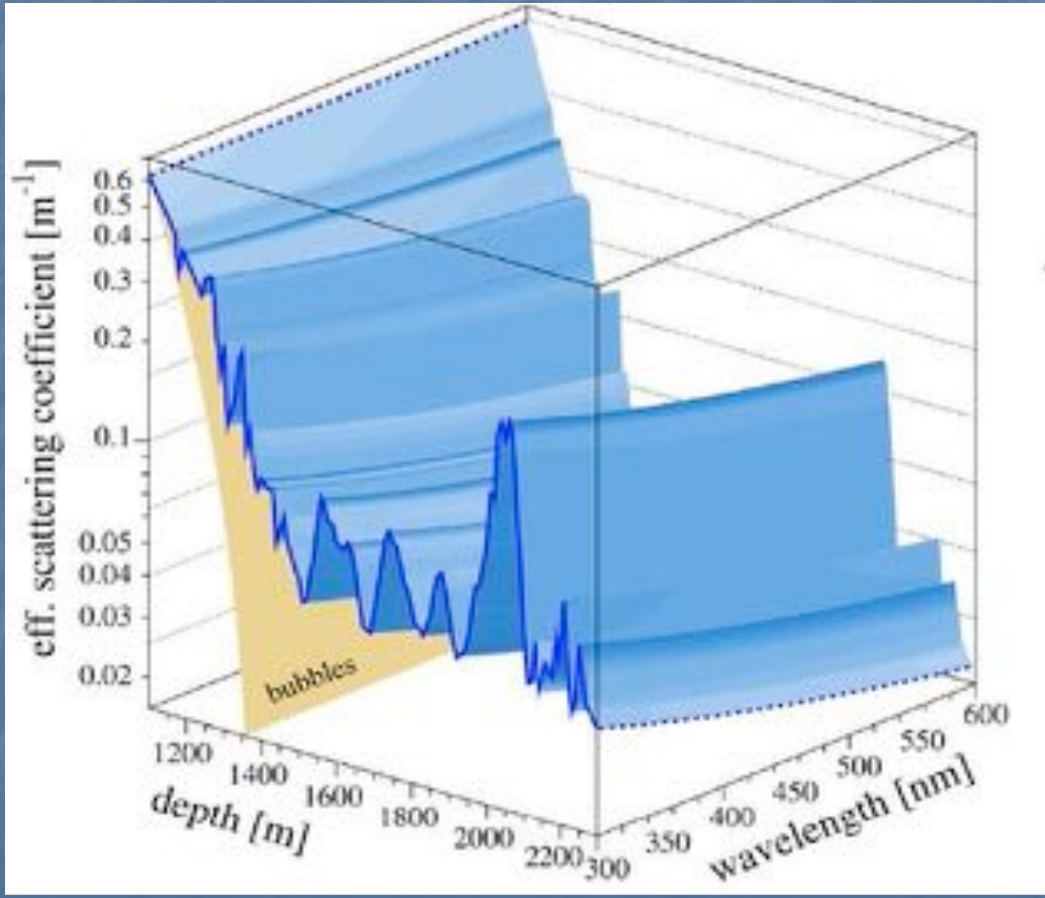
gallery.icecube.wisc.edu

DOMs

- Each DOM acts independently
  - Hamamatsu 25 cm photomultiplier tube
- Electronics record arrival times of photons
  - Accuracy 2×10^{-9} sec, uses GPS signals
- LEDs produce calibrated light pulses -> ice model
- When triggered, DOM transmits digital data package to the surface
- More than 98% of the deployed DOMS are still functioning to specifications

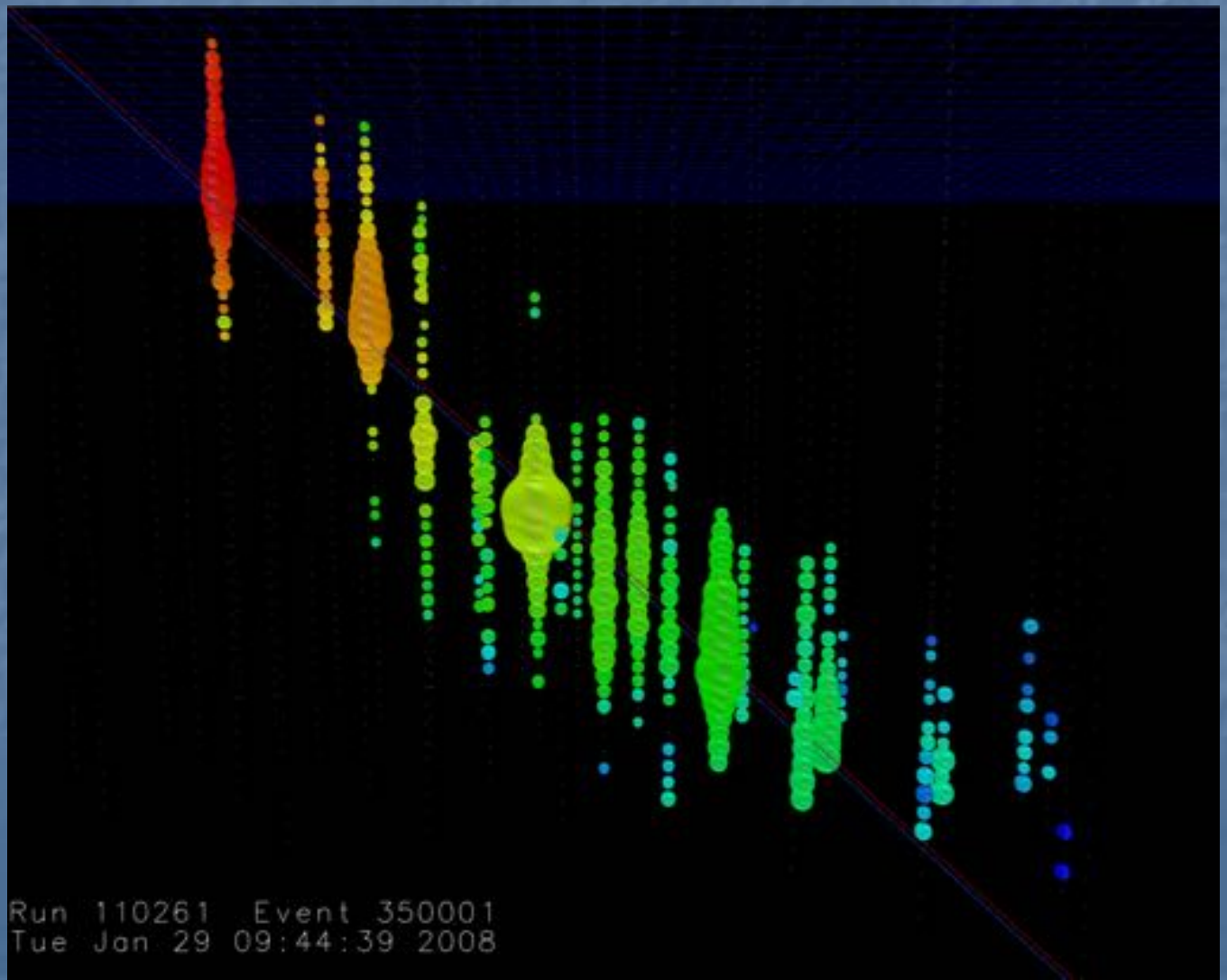
Glacial ice: Problems with dust

- Clearest ice on the planet in the deepest ice layers
- Bubbles in upper layers scatter light
- Dust layers in the ice scatter light
- Big spike in dust around 2100 m



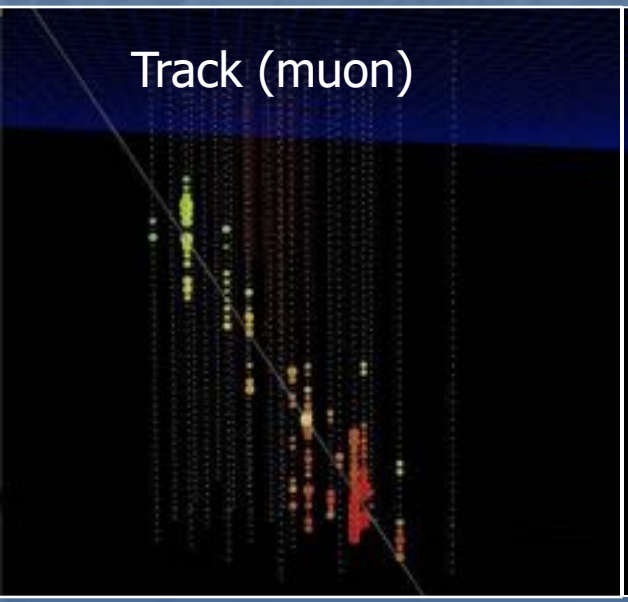
Journal of Geophysical Research 111 (2006) D13203

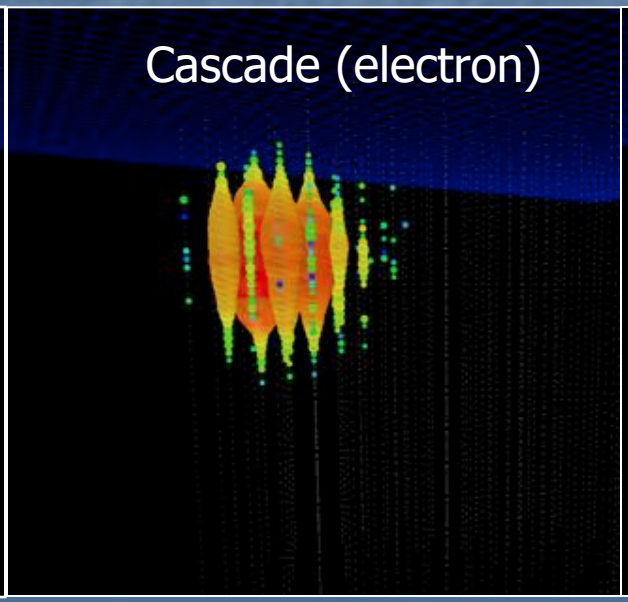
IceCube Event

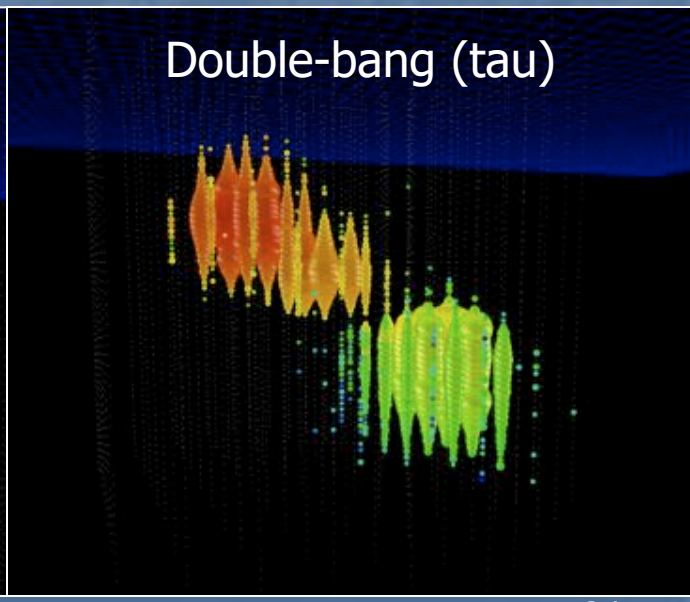


IceCube events

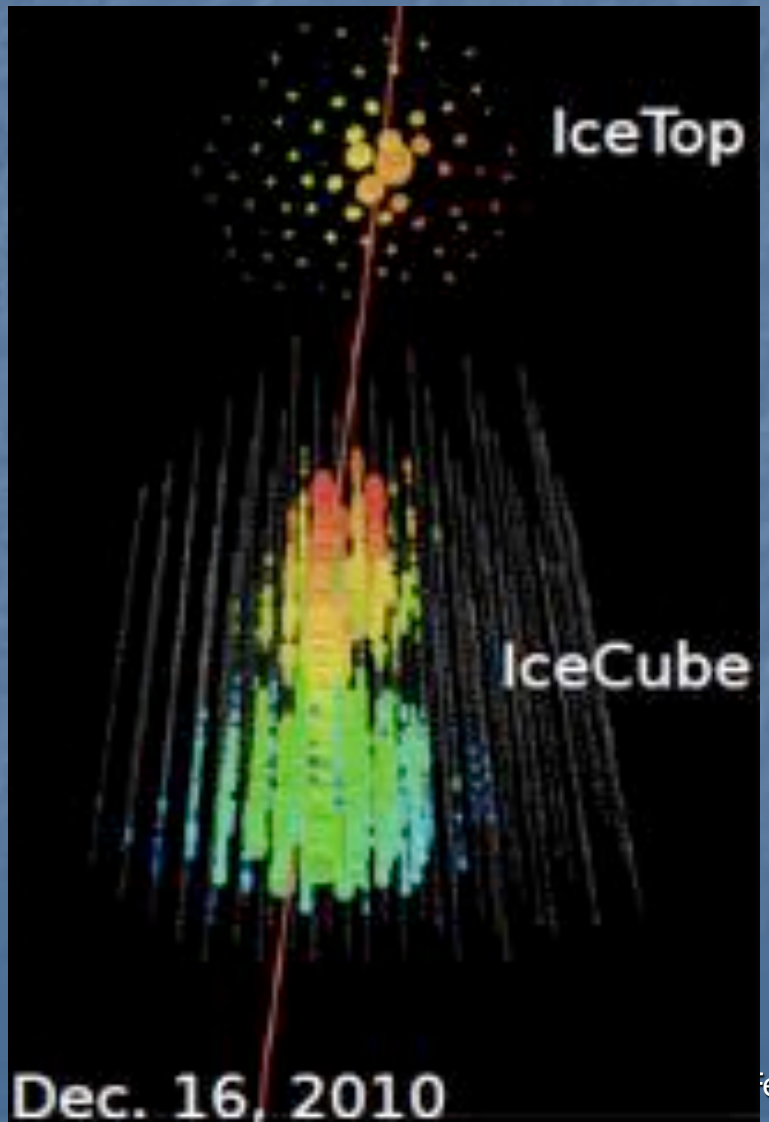
- Detects 3 flavors of neutrinos
  - Track (muon)
  - Cascade (electron)
  - Double-bang (tau)







Huge Air Shower



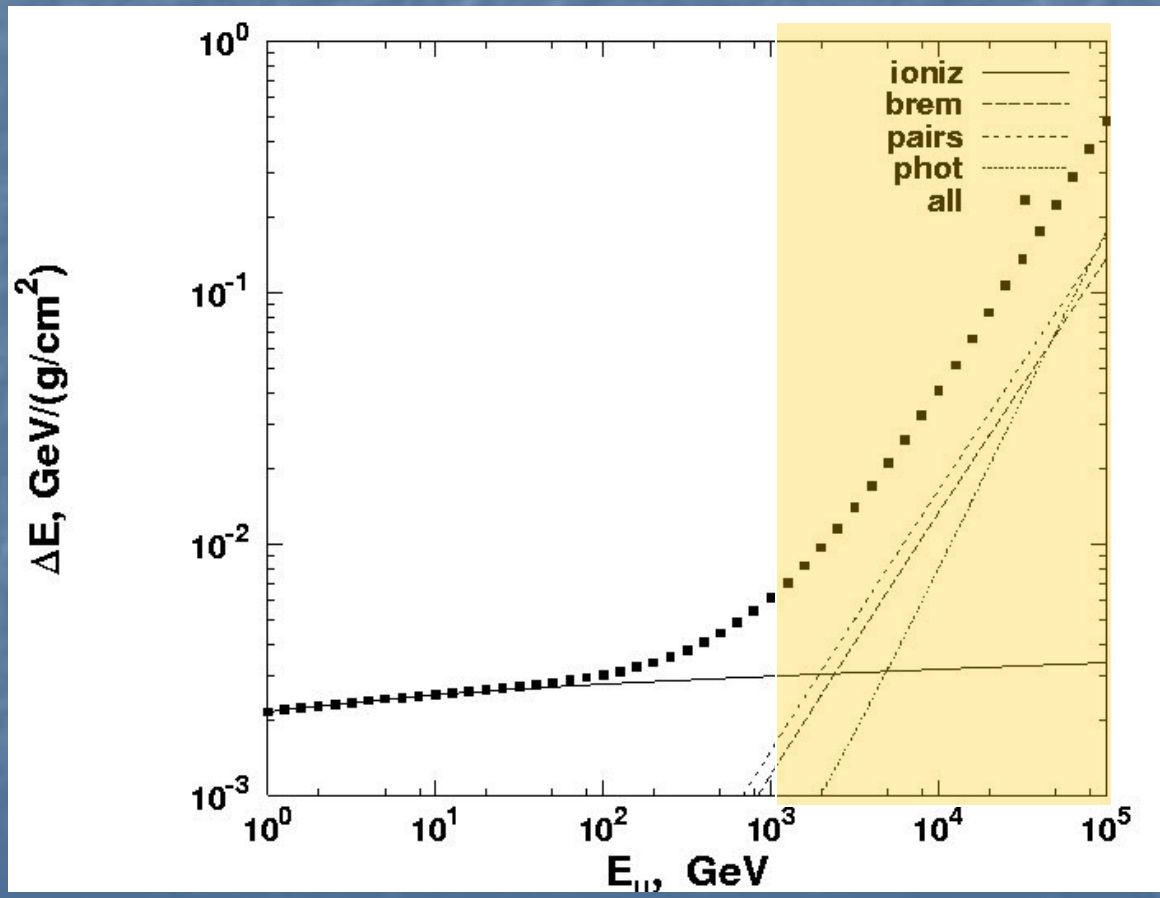
- One of the biggest events that we have seen yet
- Estimated EeV energy 10^{18} eV

Requirements

- Good muon energy resolution
- Good muon track resolution

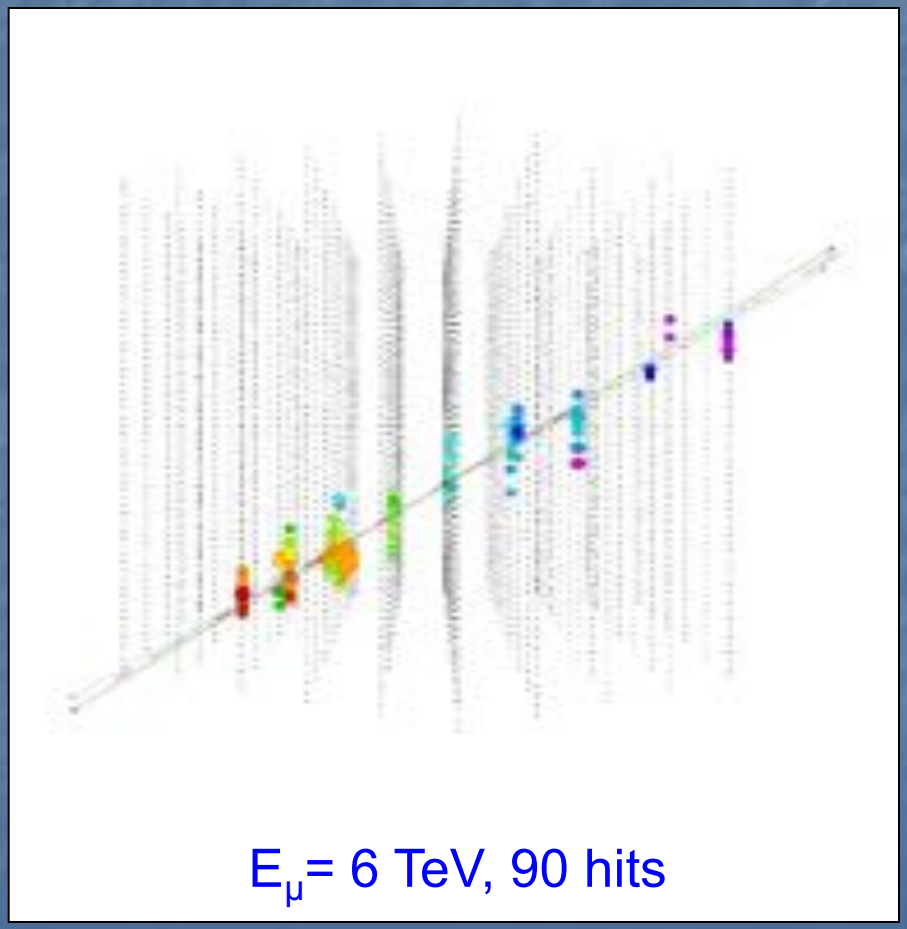
Physical processes

- Pair production
- Bremsstrahlung
- Photo-nuclear
- Ionization
- Cherenkov radiation

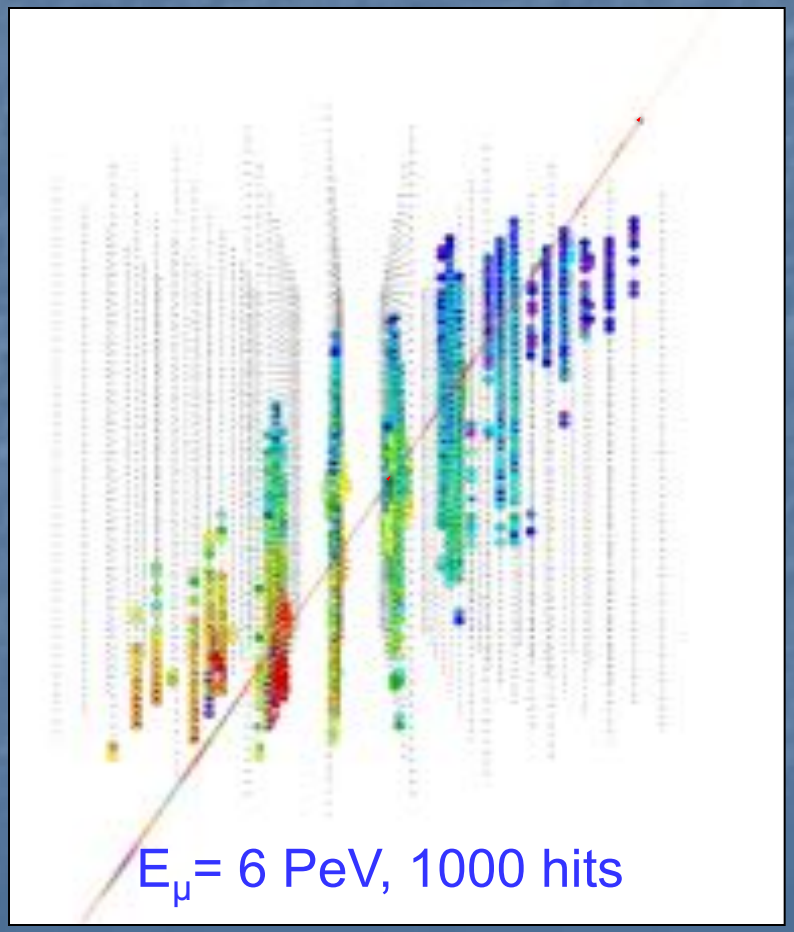


Energy Differences

1000 times bigger



Kinetic energy of a big mosquito



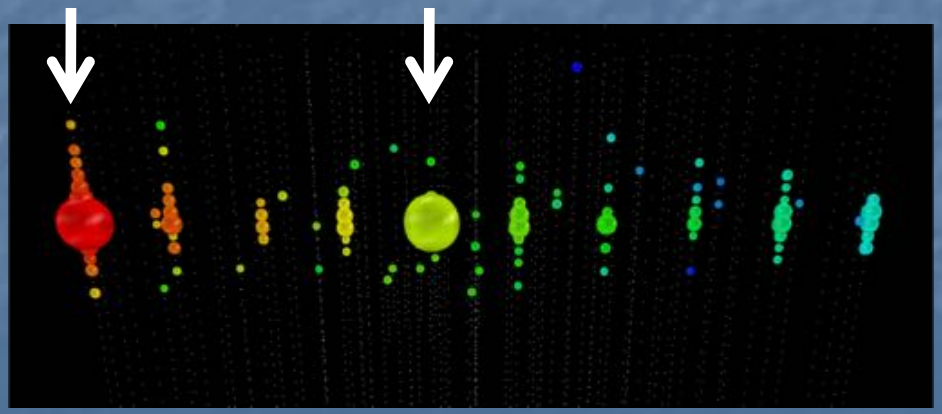
Energy to light a 1 W bulb per sec

Problem: energy resolution

- Previous muon energy estimators had error of 0.3-0.4 in $\log_{10}$(muon energy)
  - Example: 10 TeV (4.3 TeV to 23.4 TeV)
- We needed something better

Stochastic energy loss

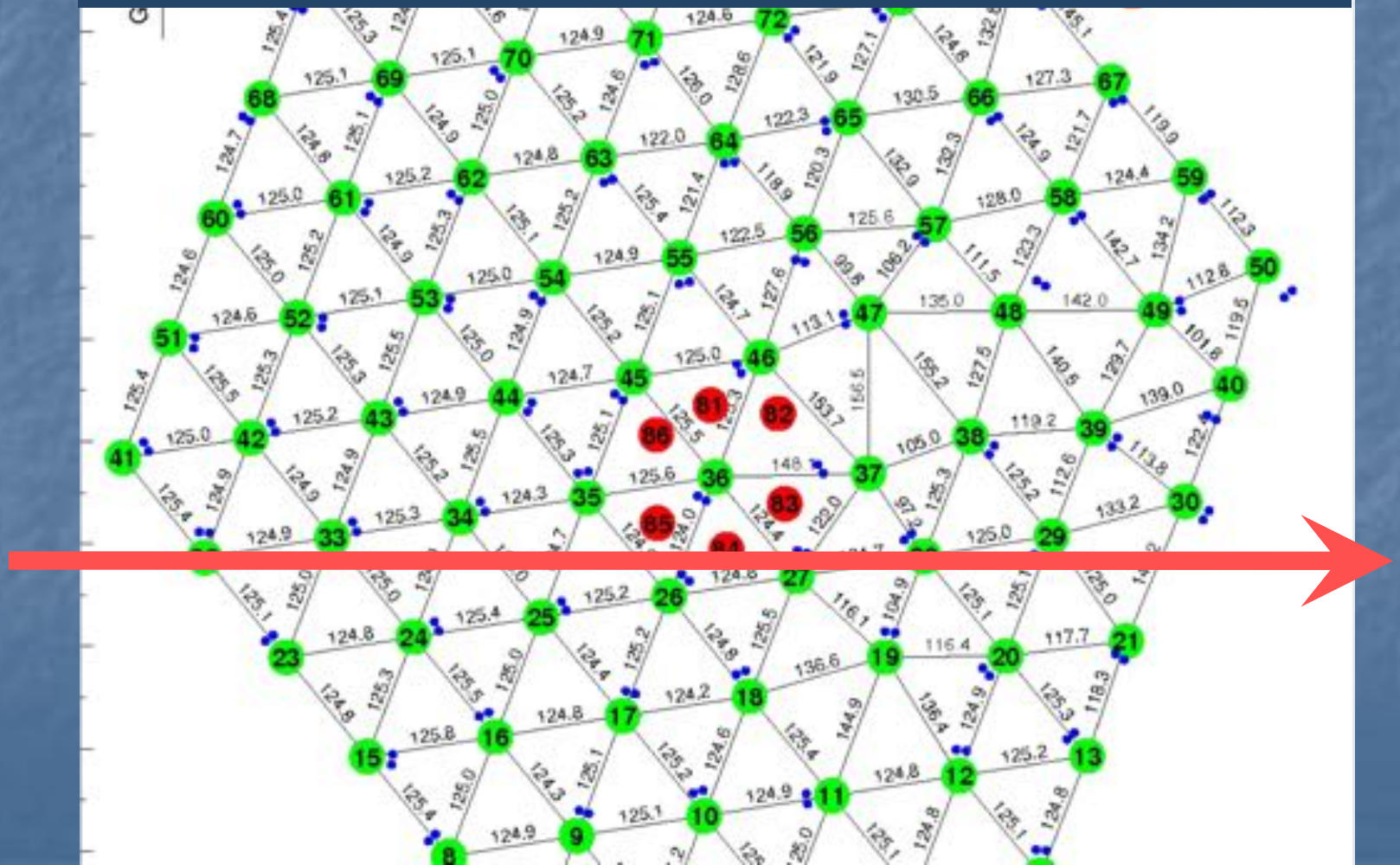
- Energy loss relation: $dE_\mu/dx = a + b\,E_\mu$
- Old method skewed by large random energy losses
- New method puts energy loss into bins
  - Omit highest bins (truncation) before calculation
- Paper published in NIM-A and on arXiv



10 TeV muon

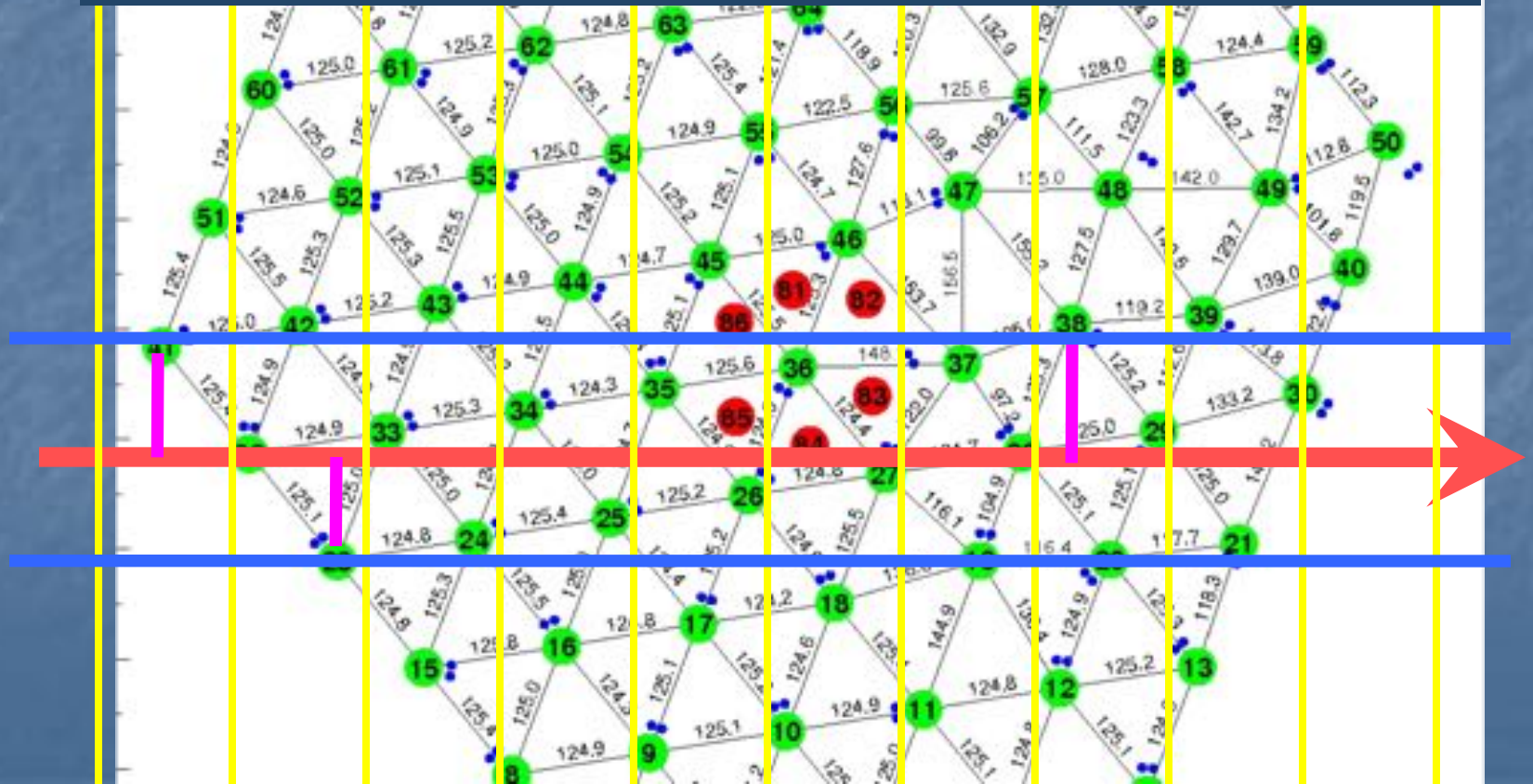
Binning the Muon Energy

Muon goes through the detector, and the track is reconstructed (red line)



Binning the Muon Energy

Cut the track into 120 meter bins
Calculate the position of closest approach for each DOM to figure out the proper bin (pink lines)
Add up the PE within 80 meters of track (blue lines)



Binning the Muon Energy

Add up all the actual PE seen by the DOMS for each bin

251	32	13	23	220	36	22	10	25	21
7	8	6	7	8	4	6	5	4	8

Add up all the expected PE from simulation for each bin

Binning the Muon Energy

Then make ratios of actual/expected PE per bin

36.0	4.0	2.2	7.7	27.0	9.0	3.7	2.0	6.3	2.6

Binning the Muon Energy

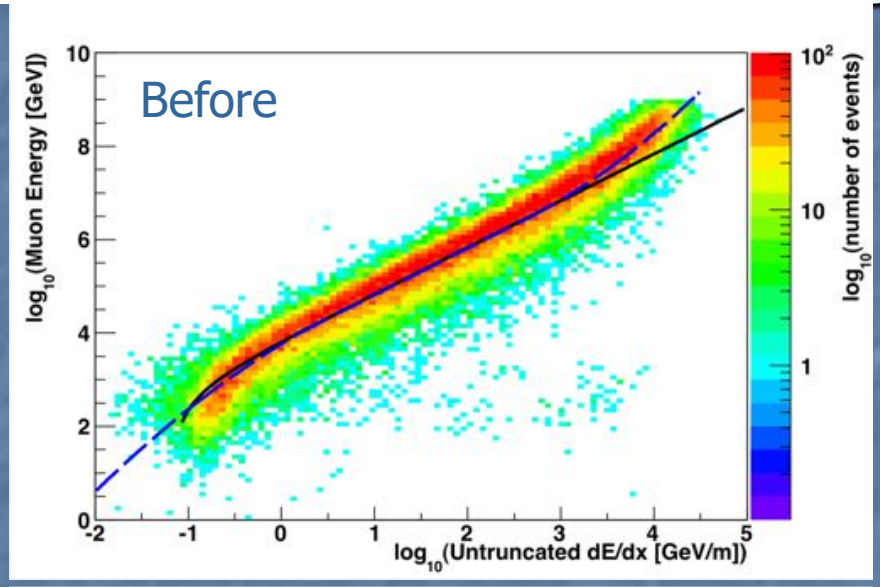
Delete the bins with the highest ratios (40% cut shown)

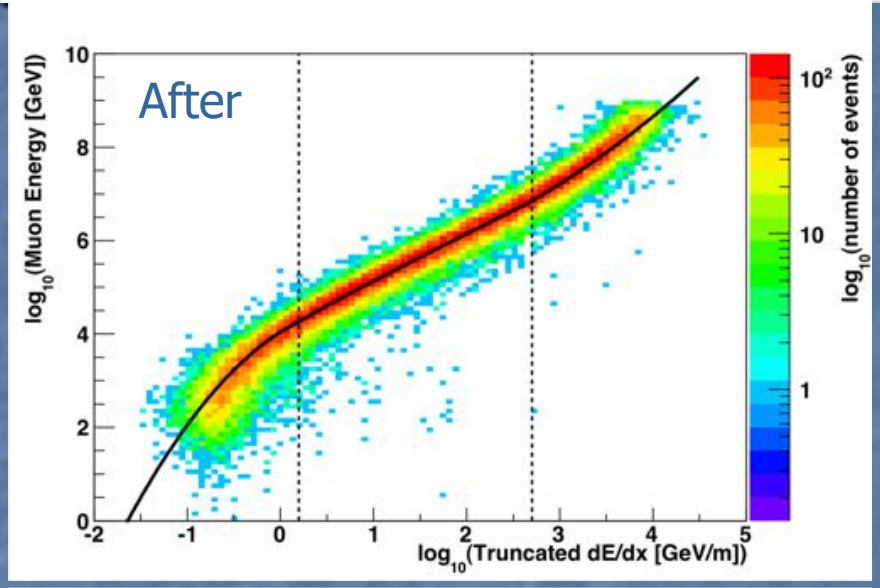
Binning the Muon Energy

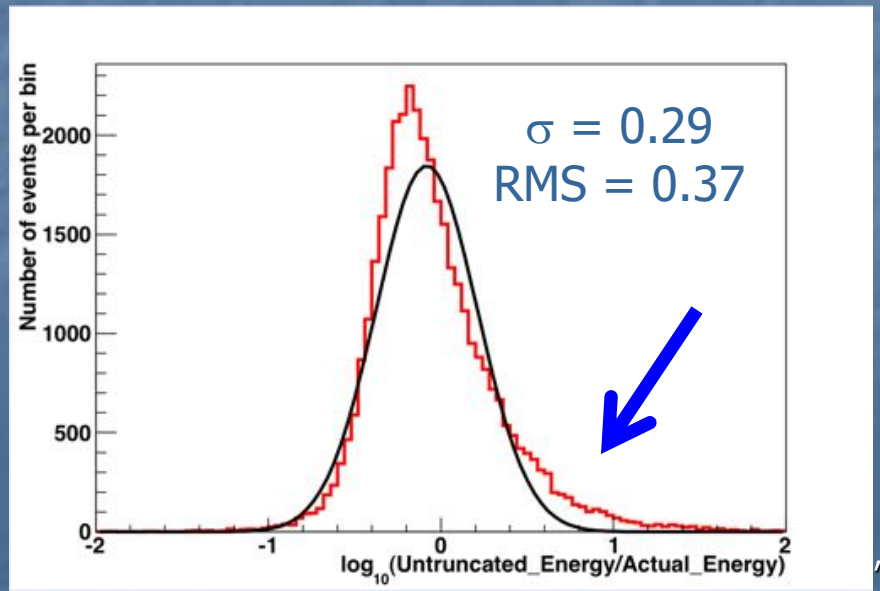
Divide the remaining total PE (actual/expected) to get a new dE/dx (multiple of 1 GeV/m from simulation)

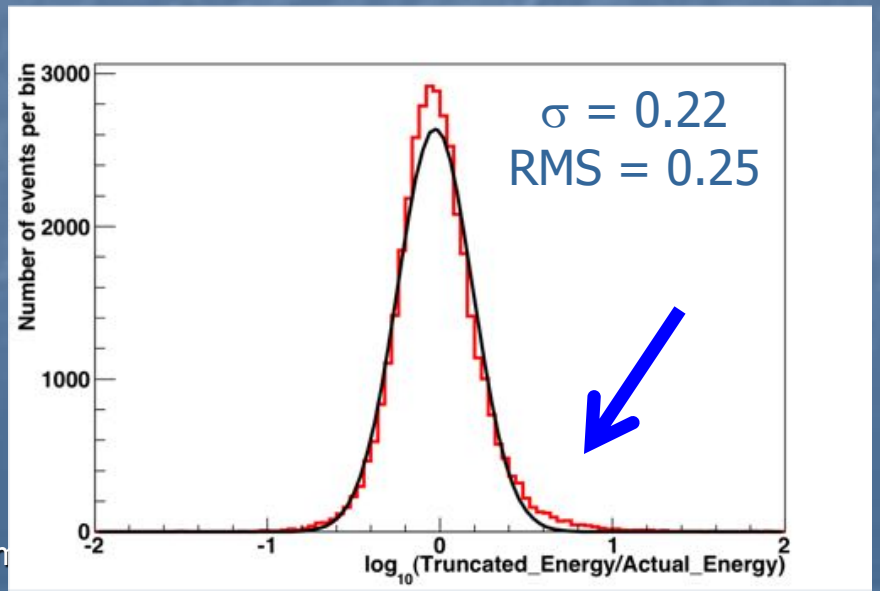
32	13			22	10	25	21	= 123
8	6			6	5	4	8	= 37

Truncated Energy









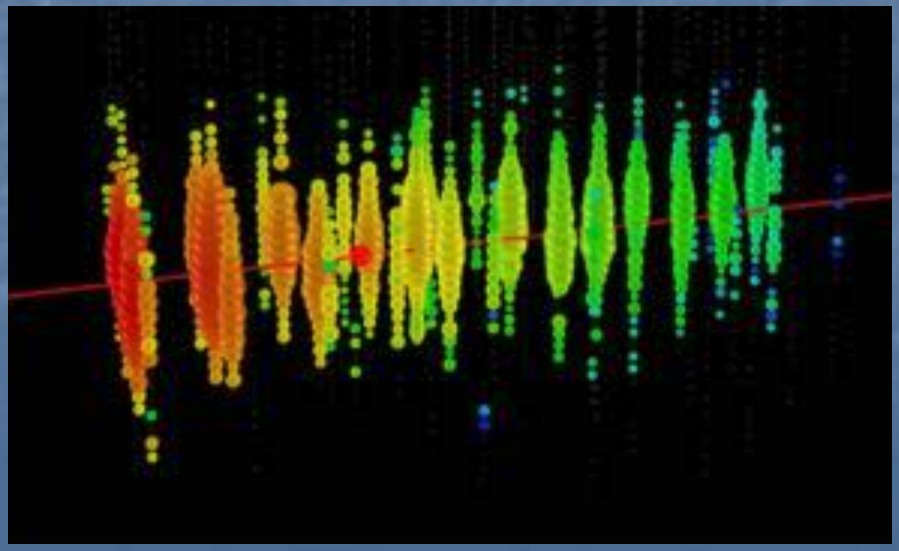
NIM–A 703 (2013) 190–198, arXiv:1208.3430

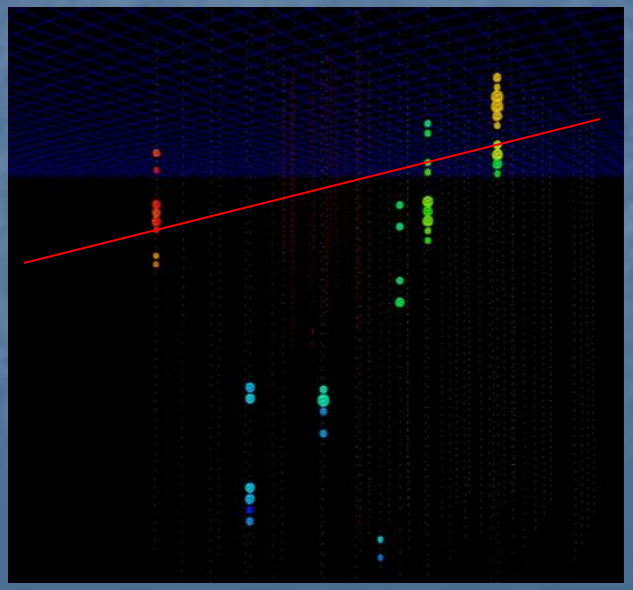
Resolution improvement

- Old resolution = 0.3 to 0.4 in $\log_{10}$(muon energy)
- New resolution = 0.2 to 0.3
- >35% improvement in energy range > 1 TeV, with better resolution at higher energies

Muon track reconstruction

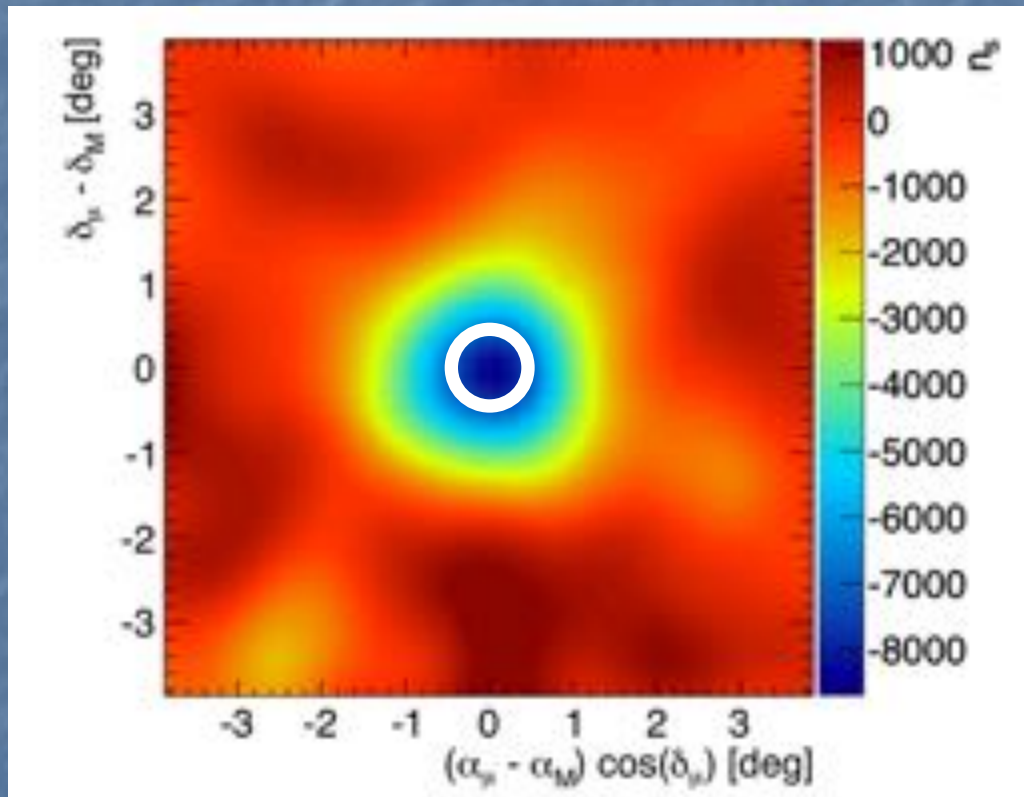
- Likelihood reconstruction (time & energy)
  - Reconstruction fed a first-guess "seed"
  - If seed is very wrong, reconstruction is bad
  - Better results for $E_\mu > 1$ TeV





Moon Shadow

- Lower number of muon events when Moon is in the way
- < 1 deg error

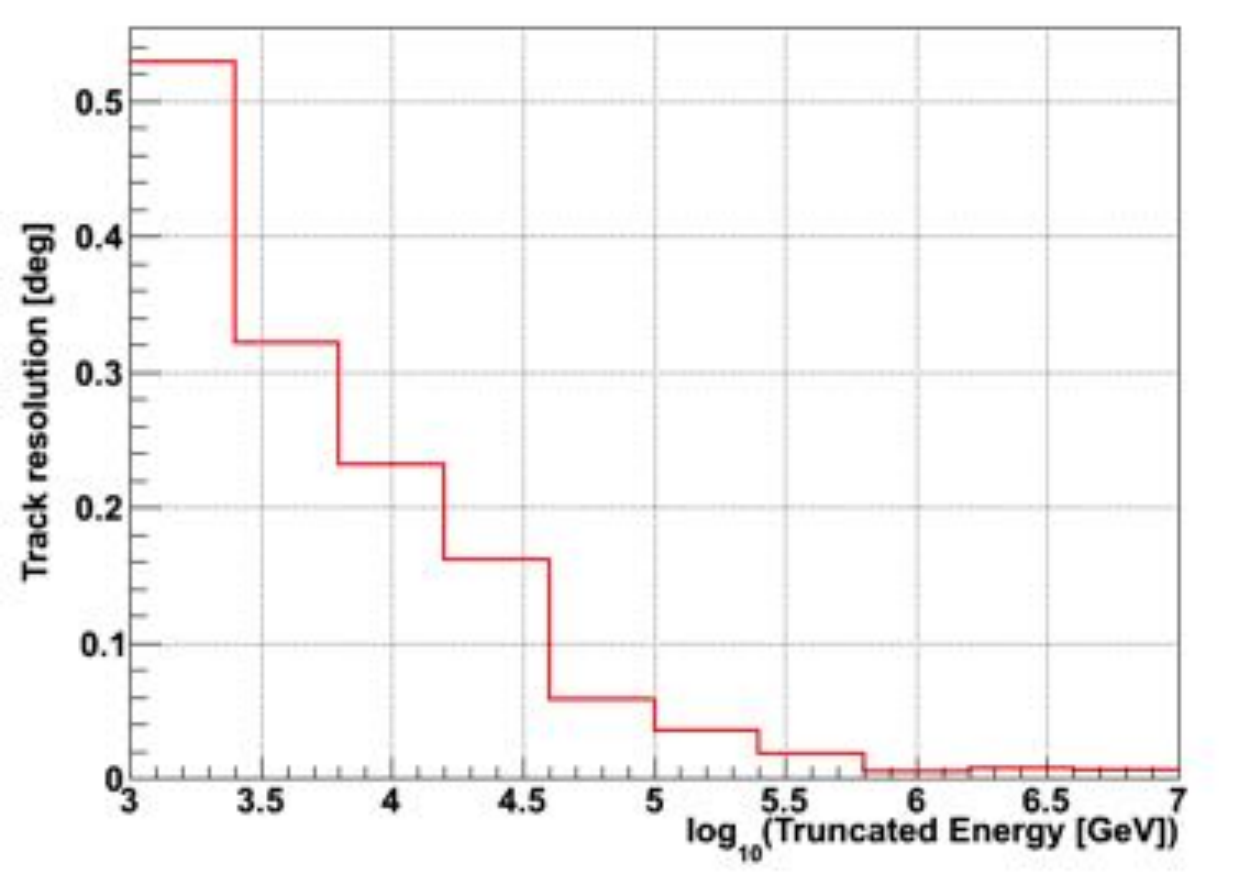


Contour plot of the muon deficit as measured by IceCube in the region around the Moon's position, the so-called on-source region. Image IceCube Collaboration

Gladstone, arxiv:1111.2969

Zenith for data events

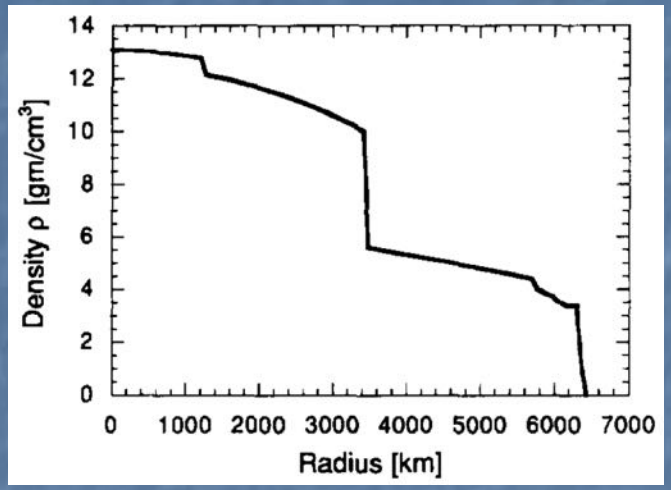
- Less than 0.55 deg error between reconstructed and true zenith



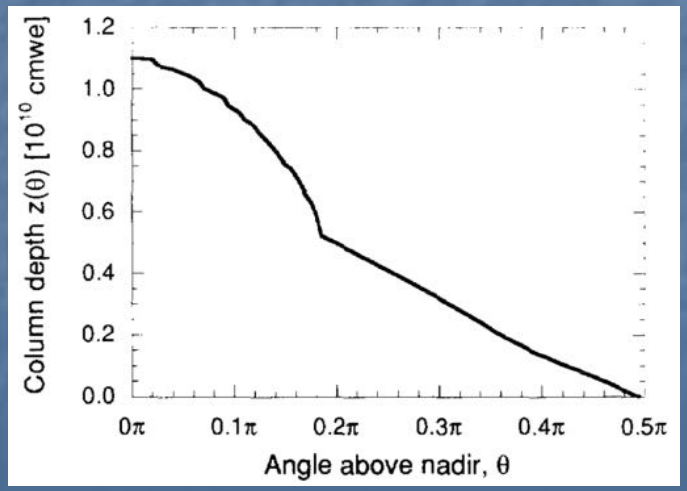
Miarecki PhD dissertation, UC Berkeley, Dec 2016

Earth model

Earth model (PREM)



Dziewonski, "The Encyclopedia of Solid Earth Geophysics," 1989



Gandhi et al, Astroparticle Physics 5 (1996) 81

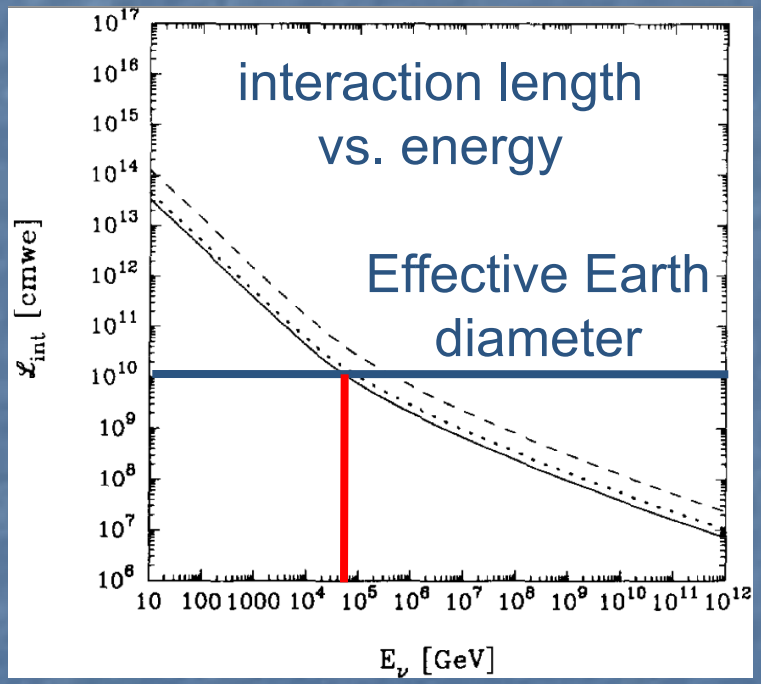
Preliminary Reference Earth Model 1981 (Dziewonski and Anderson, Physics of Earth and Planetary Interiors 25 (1981) 297–356)

- Determined from seismic studies

- Column depth mostly linear except near inner/outer core
- Essentially unchanged since inception (small uncertainties)

Absorption length

- Neutrino absorption length = Earth diameter for energy ~ 40 TeV
- Should be able to detect measureable absorption above this energy



R. Gandhi et al, arXiv:9512364v1

Target issues

- Neutrino oscillations within the target
  - Negligible at the high energies of analysis
  - E/L is the relevant parameter

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\vartheta)\sin^2(1.27\Delta m^2 L/E)$$

Alberto Marchionni, INSS 2011, Geneva

Neutrino cross section model

Standard Model ν_μ and $\bar{\nu}_\mu$ cross sections

	E_ν[GeV]	σ_{CC}[pb]	up %	down %	σ_{NC}[pb]	up %	down %
ν_μ	50	0.32	4.1 %	-2.3 %	0.10	3.8 %	-1.9 %
	100	0.65	3.8 %	-2. %	0.20	3.5 %	-1.8 %
	200	1.3	3.5 %	-1.8 %	0.41	3.2 %	-1.6 %
	500	3.2	3.2 %	-1.7 %	1.0	2.9 %	-1.5 %
	1000	6.2	3.0 %	-1.6 %	2.0	2.7 %	-1.4 %
	2000	12.	2.7 %	-1.6 %	3.8	2.4 %	-1.3 %
	5000	27.	2.3 %	-1.5 %	8.6	2.1 %	-1.3 %
	10000	47.	2.0 %	-1.4 %	15.	1.8 %	-1.2 %
	20000	77.	1.8 %	-1.3 %	26.	1.6 %	-1.1 %
	50000	140.	1.5 %	-1.2 %	49.	1.3 %	-1.0 %
	100000	210.	1.4 %	-1.2 %	75.	1.2 %	-1.0 %

	E_ν[GeV]	σ_{CC}[pb]	up %	down %	σ_{NC}[pb]	up %	down %
$\bar{\nu}_\mu$	50	0.15	15.0 %	-9.0 %	0.05	12.0 %	-6.4 %
	100	0.33	13.0 %	-7.4 %	0.12	11.0 %	-5.7 %
	200	0.69	12.0 %	-6.5 %	0.24	9.6 %	-5.1 %
	500	1.8	11.0 %	-5.7 %	0.61	8.6 %	-4.6 %
	1000	3.6	9.4 %	-5.2 %	1.2	7.8 %	-4.2 %
	2000	7.0	8.3 %	-4.6 %	2.4	7.0 %	-3.8 %
	5000	17.	6.5 %	-3.7 %	5.8	5.7 %	-3.2 %
	10000	31.	5.1 %	-3.0 %	11.	4.6 %	-2.7 %
	20000	55.	3.8 %	-2.3 %	19.	3.6 %	-2.1 %
	50000	110.	2.5 %	-1.7 %	39.	2.4 %	-1.5 %
	100000	180.	1.9 %	-1.4 %	64.	1.7 %	-1.2 %

Baseline SM σ_ν for 1-100 TeV

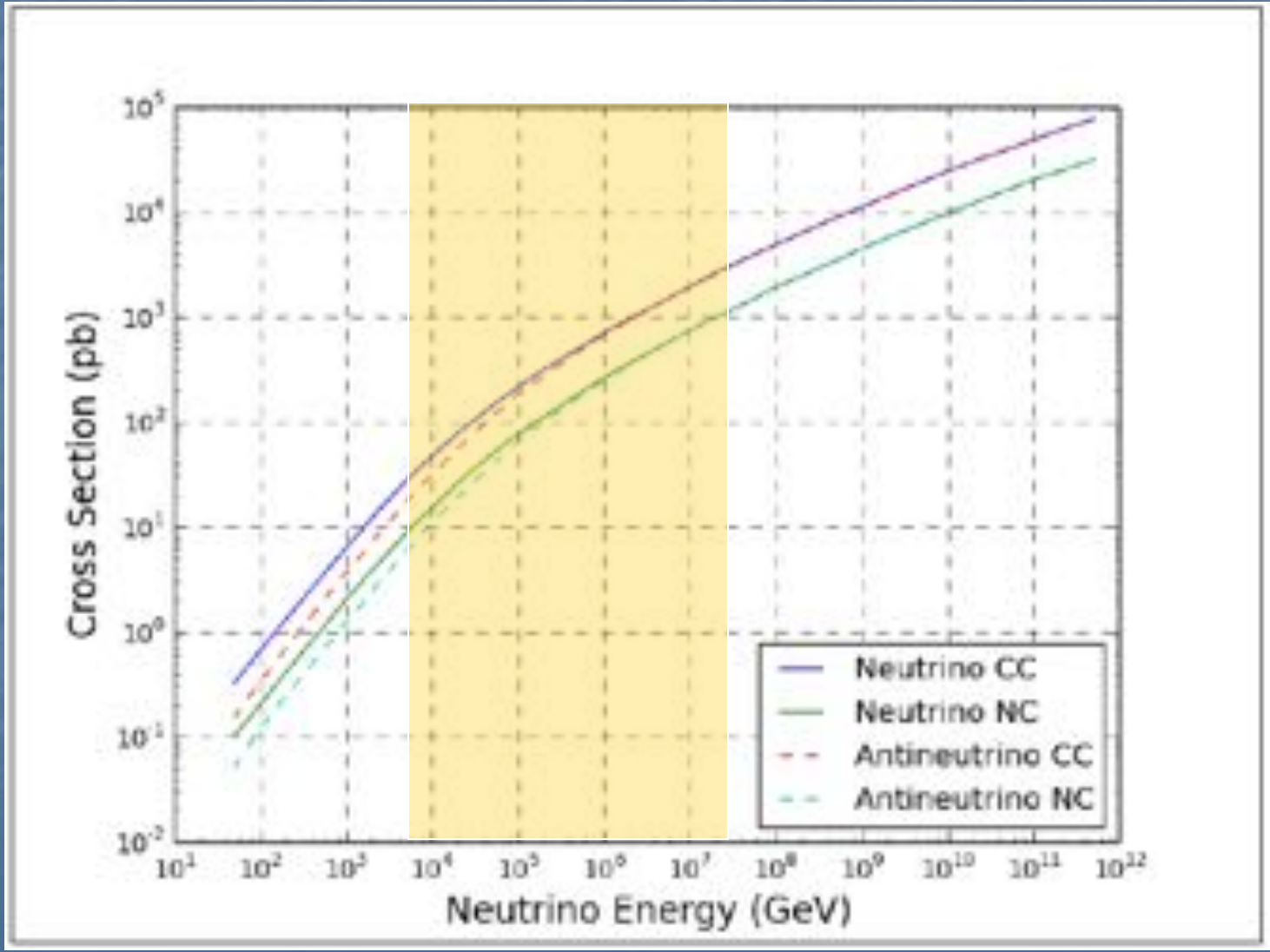
$\sigma_{CC}(\nu_\mu) \sim$ 6-210 pb

$\sigma_{CC}(\bar{\nu}_\mu) \sim$ 4-180 pb

Errors from theory predictions small compared to uncert.

Cooper-Sarkar, Mertsch, Sarkar (2011), Journal of High Energy Physics 08 (2011) 042, arXiv:1106.3723

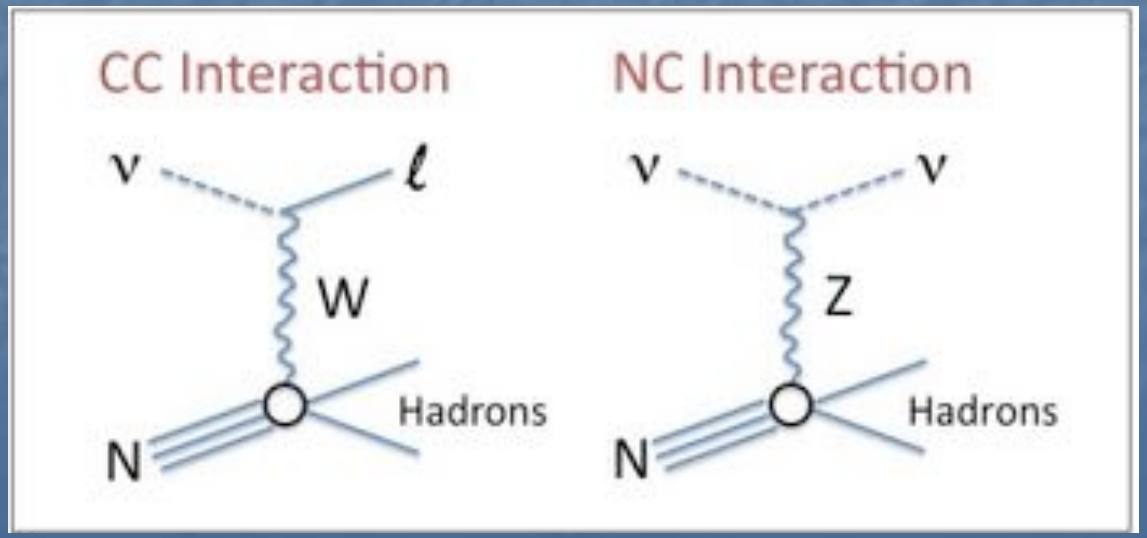
Cross section calculation



Data from Cooper-Sarkar, Mertsch, Sarkar, Journal of High Energy Physics 08 (2011) 042, arXiv:1106.3723

Result as multiple of CSMS

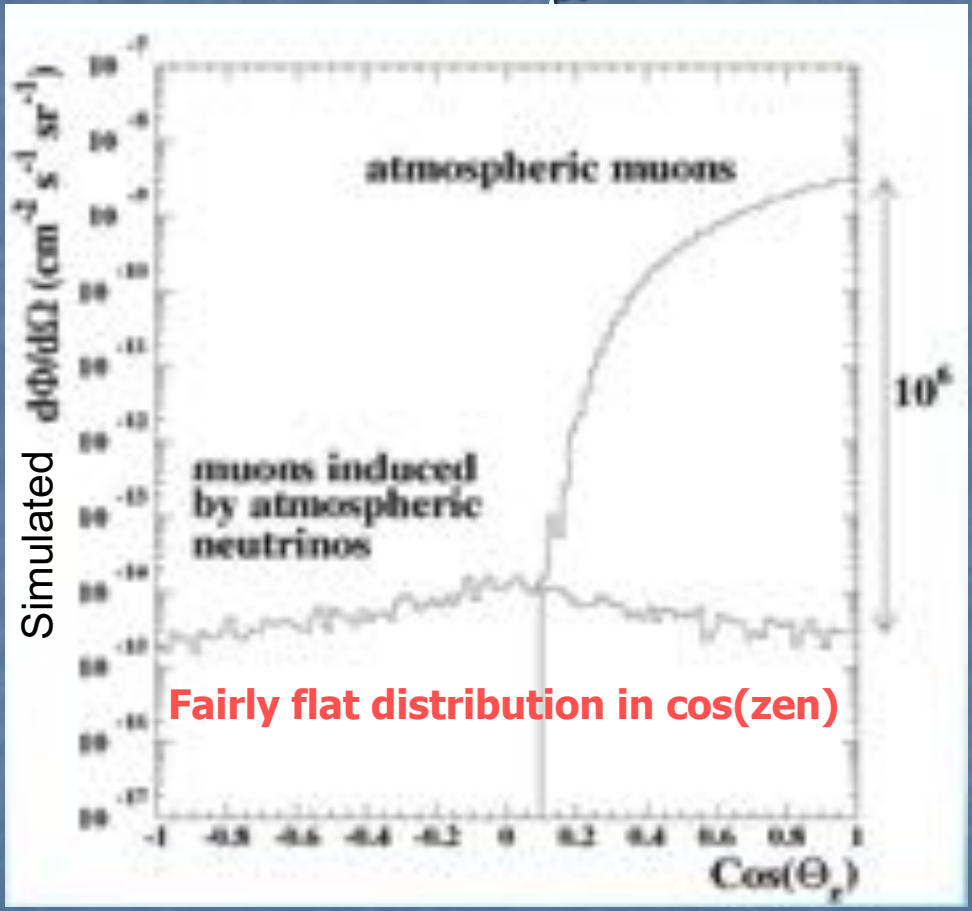
- Result given as multiple of Standard Model (SM) prediction from CSMS
- Assumes NC and CC cross sections scale at the same time by the same amount



Event selection

Finding the μ from ν_μ

- Atmospheric muons also created by CR
  - 10^6 x more abundant than μ from ν_μ
- Use Earth as a shield and look below the horizon
  - Cos(zenith) < 0



Dawn Williams, Xtreme Astrophysics Symposium, August 2012

The challenge

- 100 million events per second
- 99.9999% of events are muons from cosmic rays
- 0.0001% are upgoing muons from neutrinos

Event selection

- Chris Weaver, then graduate student at University of Wisconsin-Madison
  - Now Dr. Chris Weaver at University of Alberta-Canada
- Sample of high-energy muons from IC79 with more than 99.5% purity

Christopher Weaver, PhD thesis, University of Wisconsin-Madison, 2015

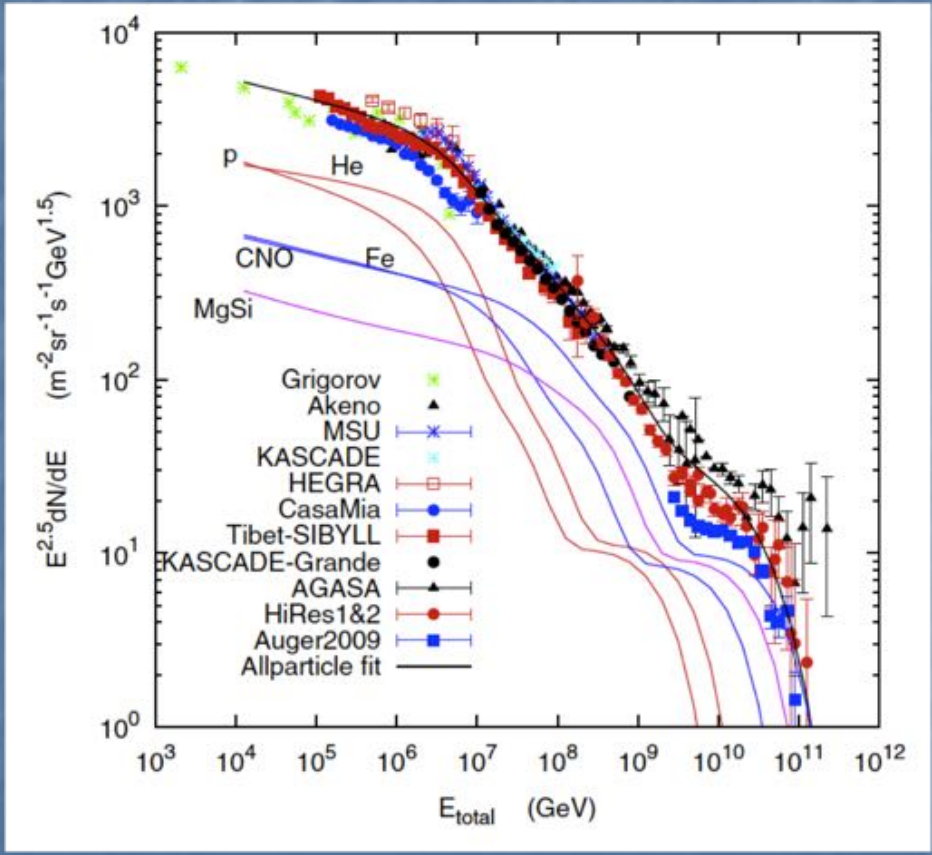
Simulation

Neutrino generator

- Existing NeutrinoGenerator (NuGen) simulation (based on ANIS)
  - Earth model PREM
  - CSMS neutrino cross section model
  - SPICE-Mie ice model
  - Gaisser-Stanev-Tilav H3a cosmic ray model
  - Gaisser neutrino model

H3a cosmic ray model

- Combination of source populations to create full spectrum of cosmic rays seen



T. K. Gaisser, T. Stanev, and S. Tilav, "Cosmic Ray Energy Spectrum from Measurements of Air Showers," Frontiers of Physics (Beijing) 8 (2013) 748–758, arXiv:1303.3565

Gaisser neutrino model

- Predict the number of neutrinos at surface
  - Monte Carlo simulations and NeutrinoFlux

$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos\theta \, E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu} \cos\theta \, E_\nu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu} \cos\theta \, E_\nu/\epsilon_{\mathrm{charm}}} \right\}, \quad (1)$$

ERS prompt model

- Prompt atmospheric neutrino model used was Enberg-Reno-Sarcevic (ERS) 2008
  - Newer model (BERSS) available, but previous experiments used ERS for results
  - BERSS flux shape ~ same, only scaling

R. Enberg, M. H. Reno, and I. Sarcevic, “Prompt neutrino fluxes from atmospheric charm,” Physical Review D78 (2008) 043005, arXiv:0806.0418

A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic, and A. Stasto, “Perturbative charm production and the prompt atmospheric neutrino flux in light of RHIC and LHC,” Journal of High Energy Physics 06 (2015) 110, arXiv:1502.01076

Astrophysical neutrinos

- Basic E^{-2} flux, with floating parameters

$$\Phi_\nu = \phi \cdot \left(\frac{E_\nu}{100\ TeV} \right)^{-\gamma}$$

units 10^{-18} GeV^{-1} cm^{-2} sr^{-1} s^{-1}

- Prior chosen = "Global Fit" from IceCube
  - Multi-year analysis of multiple signal types
  - ϕ =2.3 ($\pm$0.5) γ=2.56 ($\pm$0.12)

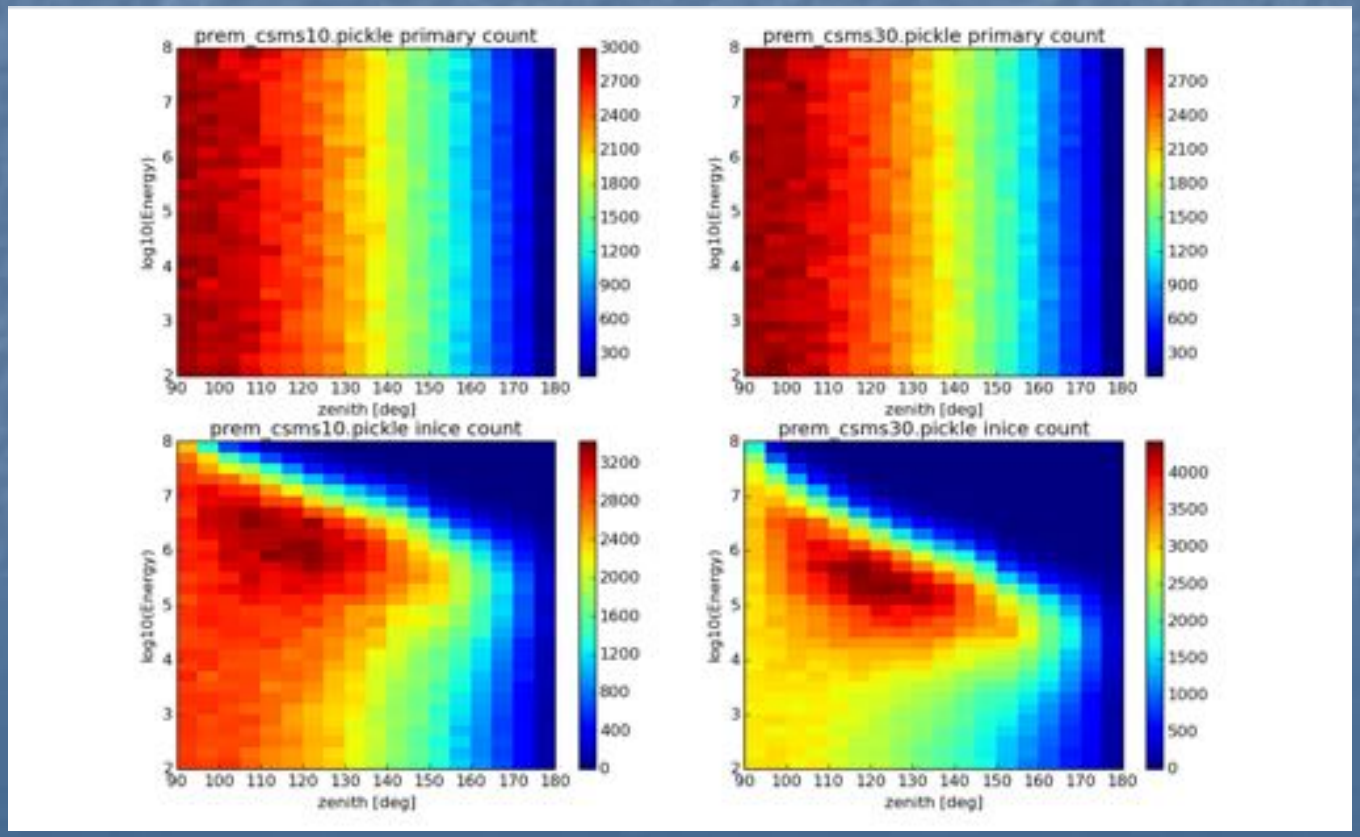
IceCube Collaboration, Astrophysical Journal 809 no. 1, (2015) 98, arXiv:1507.03991

Simulated cross sections

- Run program for different cross sections
  - Accounting for NC and CC interactions in Earth
  - Compare 1.0x SM to 3.0x SM

INPUT
1x SM

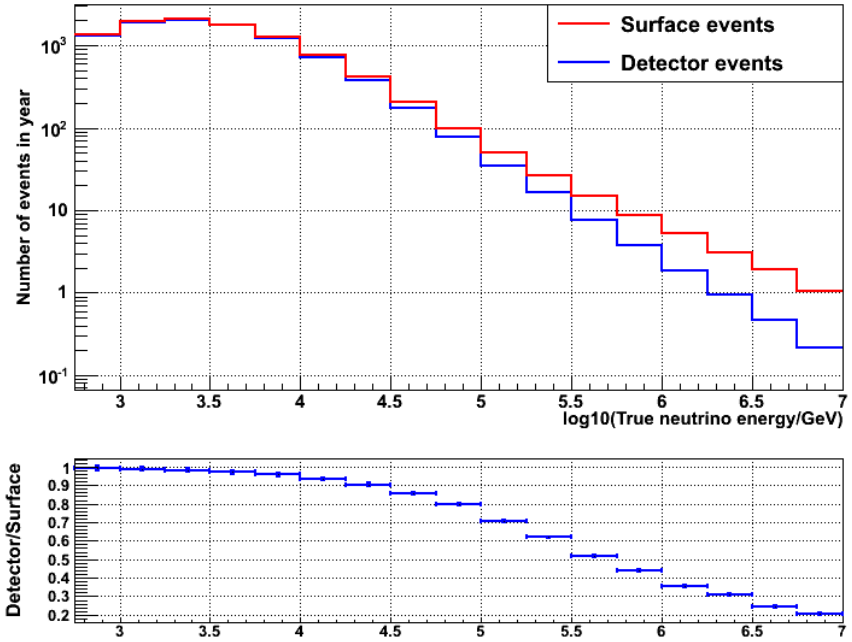
OUTPUT
1x SM

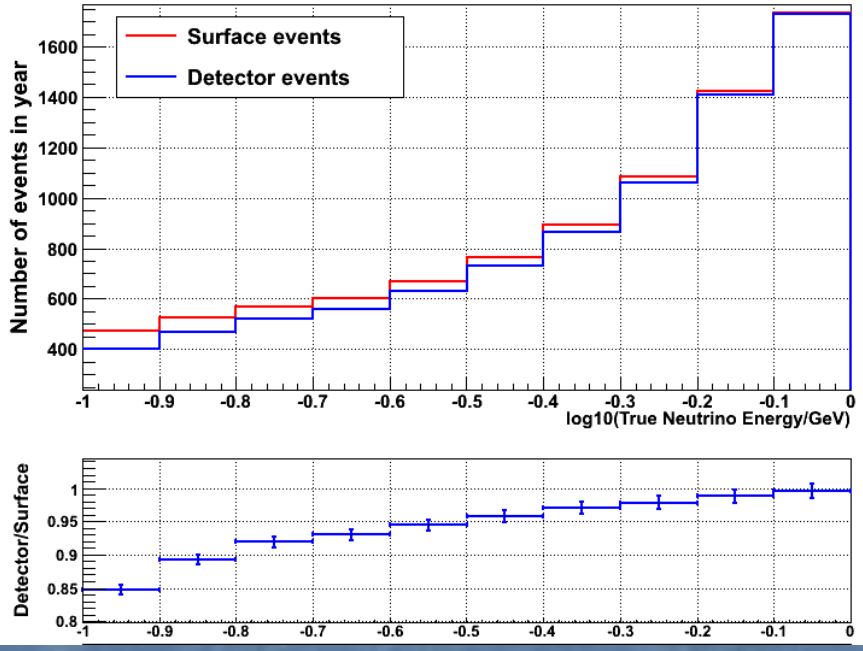


INPUT
3x SM

OUTPUT
3x SM

Compare surface events to detected events (1.0x SM)

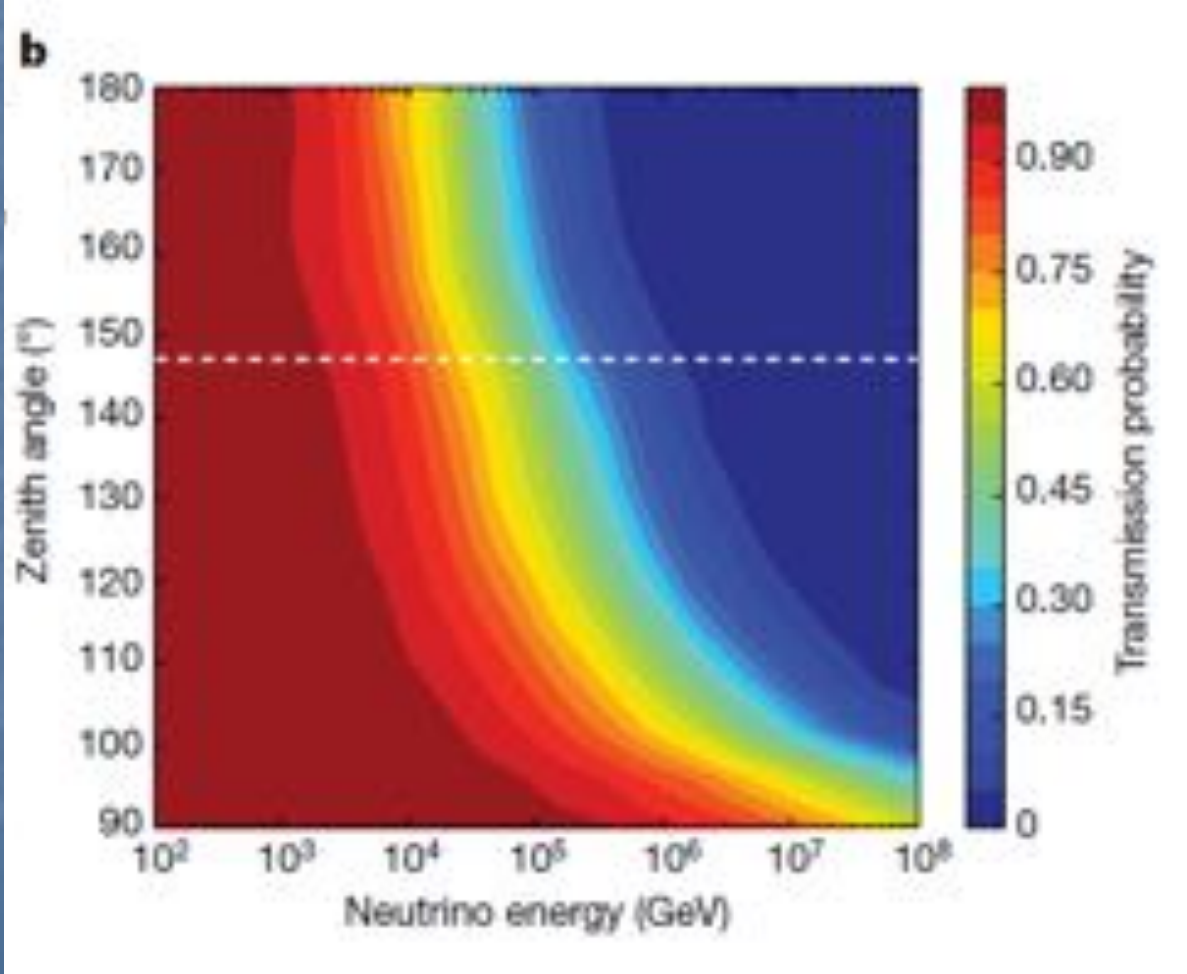




Miarecki PhD dissertation, UC Berkeley, Dec 2016

- Red = surface
- Blue = detector (after transiting Earth)

2D plot of absorption for 1.0x SM



Nature, volume 551, pp 596–600 (30 Nov 2017)

Least likelihood fit

Least likelihood fit

- Fitter uses a least likelihood fit method
  - Events binned in cos(zenith) and $\log_{10}(E_\mu)$
    - Cos(zen) offsets some effects of the solid angle (smaller bins at horizon), range 0 to -1.0
    - $\mathrm{Log}_{10}(E_\mu)$ allows full energy range from 3.0 to 7.0
  - Compare bin contents of expected to actual
- Find best cross section, compared to SM

Data events

- 10,784 muon events in IC79 (2010 to 2011)

$\log_{10}$ (energy range)	cos(zenith) -1.0 to -0.9	-0.9 to -0.8	-0.8 to -0.7	-0.7 to -0.6	-0.6 to -0.5	-0.5 to -0.4	-0.4 to -0.3	-0.3 to -0.2	-0.2 to -0.1	-0.1 to 0.0
3.00-3.25	224	246	282	307	306	336	435	545	648	791
3.25-3.50	149	208	232	219	267	281	358	458	567	699
3.50-3.75	86	85	111	118	113	171	195	245	288	424
3.75-4.00	35	52	32	56	54	68	92	132	149	172
4.00-4.25	11	2	2	18	26	25	29	32	53	64
4.25-4.50	1	6	6	5	11	19	9	22	21	42
4.50-4.75	1		2	2	4	6	3	6	21	14
4.75-5.00		2		2	3	2	1	3	7	8
5.00-5.25				1		2		2	3	4
5.25-5.50			1			1	1			1
5.50-5.75								1		1
5.75-6.00								1	1	
6.00-6.25										1
6.25-6.50										
6.50-6.75										
6.75-7.00										

Miarecki PhD dissertation, UC Berkeley, Dec 2016

Fit parameters

- Cross section (XS)
- XS * conventional flux
- XS * prompt flux
- XS * astrophysical flux
- Astrophysical energy coefficient
- Cosmic ray energy coefficient
- DOM efficiency
- Kaon-pion ratio
- ν to $\bar{\nu}$ ratio

Combined result

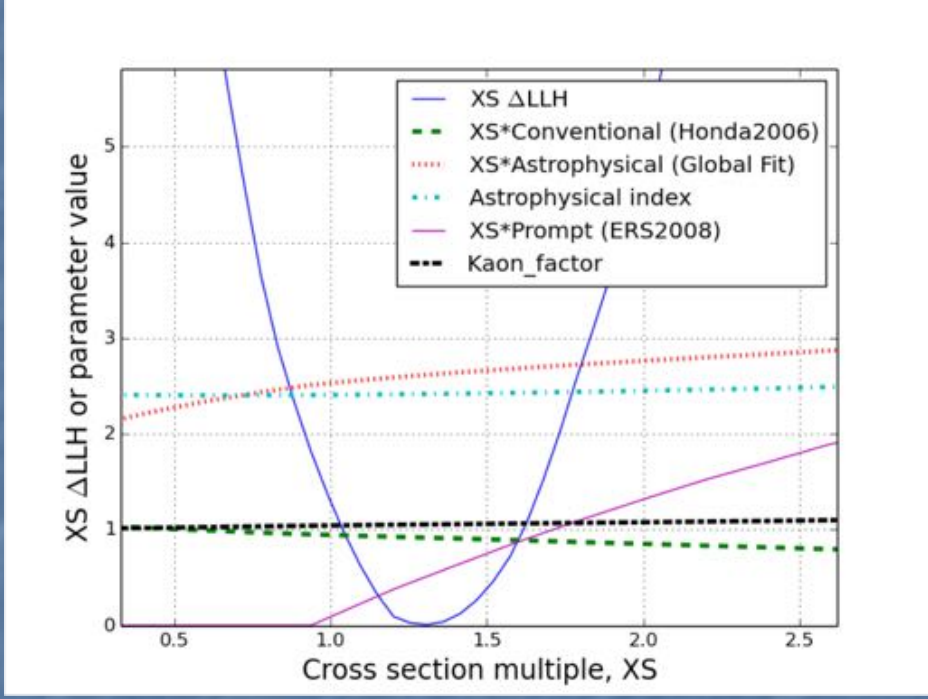
- IceCube cannot separate μ from $\bar{\mu}$
- Result is a combination of cross sections
- Comparison is made to total cross section weighted by flux

+

Initial fit results

- 1.30x SM
  - (+0.21 -0.19 stat)
  - (+0.24 -0.19 syst)

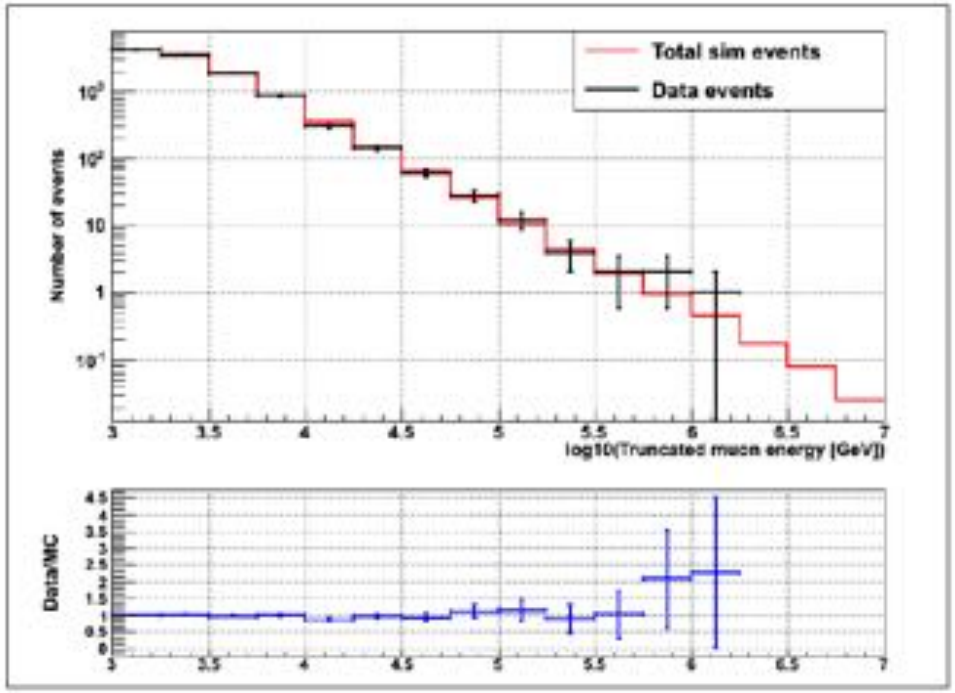
- Uncertainty mixture of statistical and systematic from uncertainties in nuisance parameters
- Isolate statistical by refitting with nuisance parameters fixed to preferred values

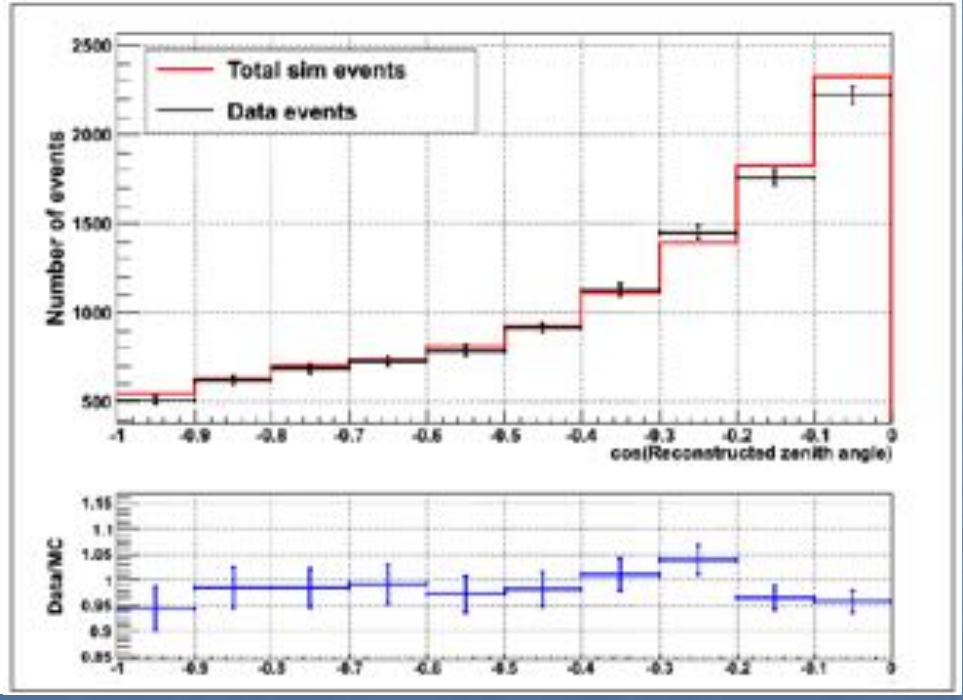


Miarecki PhD dissertation, UC-Berkeley, 2016

Compare results to data

- 1D plots in muon energy and zenith angle
  - Data to MC ratio in bottom section





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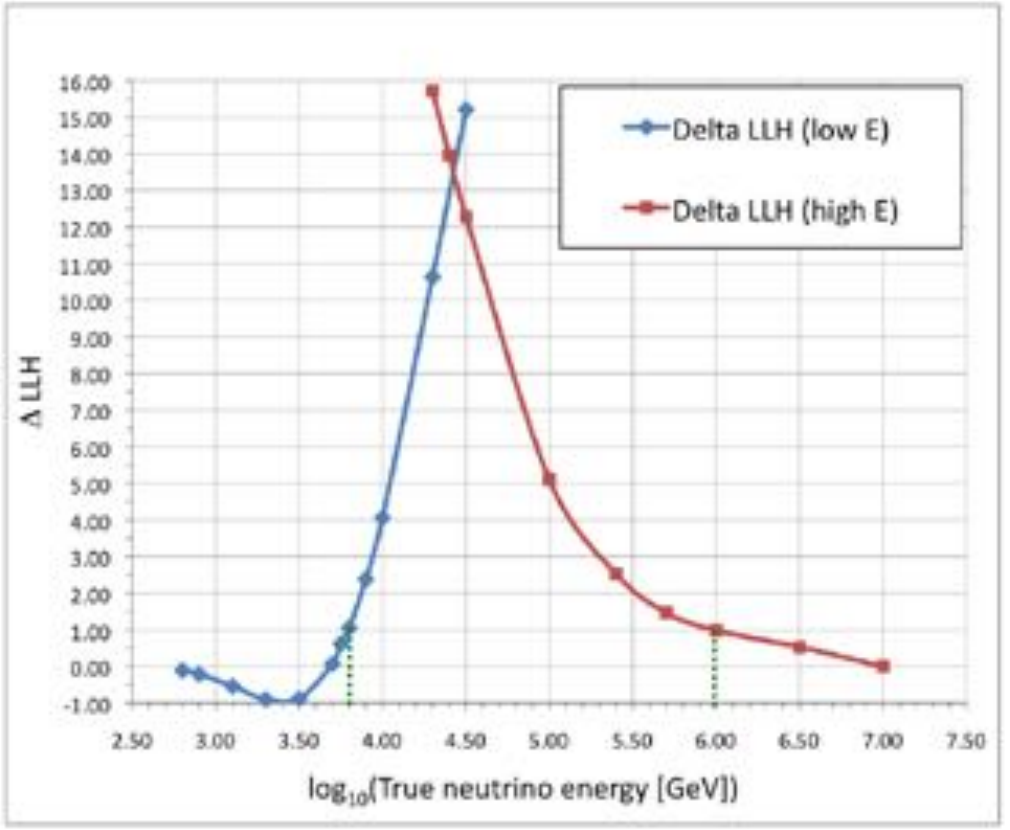
Energy range

- Energy range of 6.3 TeV to 980 TeV



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Systematic uncertainty analysis

Systematic uncertainty

- Several sources of uncertainty could not be parameterized for fitter
  - Ice model
  - Hole ice
  - Earth model
  - Atmospheric temperature variation
  - Astrophysical neutrino flux uncertainty

Ice model

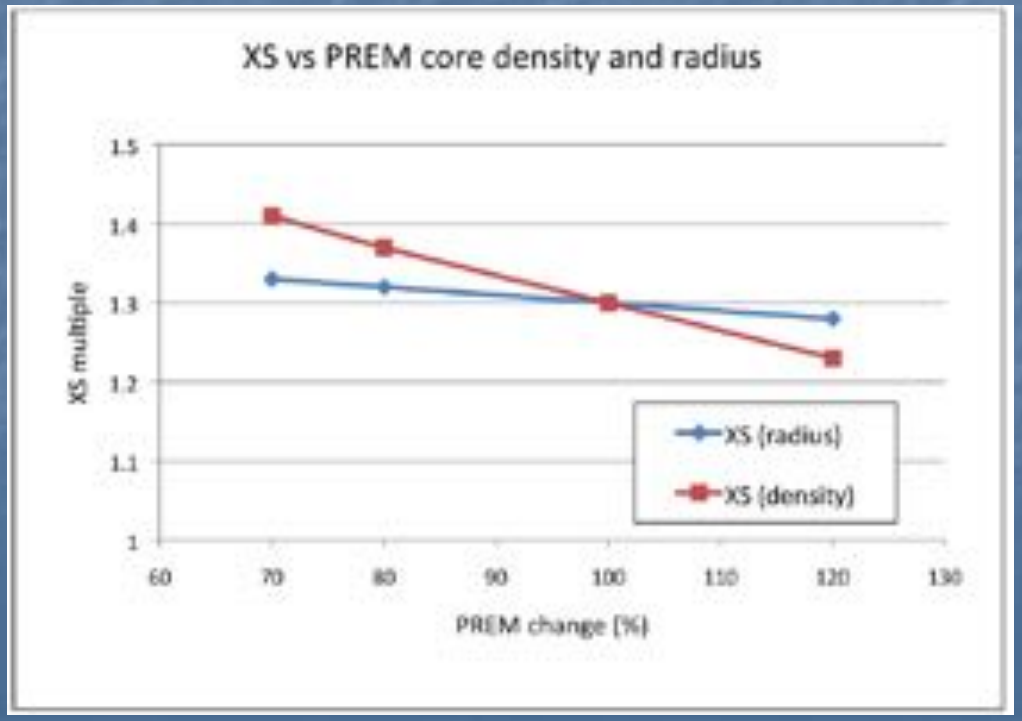
- SPICE-Mie as basis model
  - +10% absorption
  - +10% scattering
  - -7% scattering/-7% absorption
- Error: (+0.31 -0.38) x SM
  - Largest uncertainty of analysis
- Better ice models available with IC86+

Hole ice

- Pristine glacial ice altered when melted for DOM installation and refreezes
  - Higher dust and bubble content
  - Might affect absorption and scattering
- Error: (+0.04 -0.00) x SM

Earth model

- Although PREM has been stable since inception in 1981, we used ±10%
- Error: (±0.04) density, (±0.01) radius



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Temperature variation

- Simulation uses Standard Atmosphere, which is not representative of seasonal changes
  - Should average out over a year's data
  - Checked using kaon and pion equation and different temperatures
- Error: (+0.00 -0.04) x SM

Astrophysical flux

- Used all of the results to-date to check for uncertainty based upon choice of prior
- Error: ($\pm$0.10) x SM

Result name	Best fit E^{-2}	Best fit flux	Energy range
HESE-4 (prelim) [214]	0.84 ($\pm$0.3)	2.2 ($\pm$0.7) x $E^{-2.58\pm0.25}$	60 TeV - 3 PeV *
van Santen [216]	1.22 ($\pm$0.5)	2.06 ($^{+0.35}_{-0.26}$) x $E^{-2.46\pm0.12}$	25 TeV - 1.4 PeV
Binder [212]	0.6 ($^{+0.3}_{-0.2}$)	2.3 ($\pm$0.4) x $E^{-2.6\pm0.15}$	35 TeV - 1.9 PeV
Weaver [205]	0.99 ($^{+0.39}_{-0.34}$)	1.7 ($^{+0.6}_{-0.8}$) x $E^{-2.2\pm0.2}$	330 TeV - 1.4 PeV
Cascades [217]	-	2.3 ($\pm$0.7) x $E^{-2.67\pm0.13}$	10 TeV - 1 PeV *
Global Fit (all) [218]	1.73 ($^{+0.63}_{-0.50}$)	2.23 ($^{+0.40}_{-0.37}$) x $E^{-2.50\pm0.09}$	25 TeV - 2.8 PeV
Global Fit (north) [218]	-	0.7 ($^{+1.0}_{-0.5}$) x $E^{-2.0+0.3-0.4}$	25 TeV - 2.8 PeV
Global Fit (south) [218]	-	2.3 ($\pm$0.5) x $E^{-2.56\pm0.12}$	25 TeV - 2.8 PeV
Multi-Year (prelim) [138]	0.46 ($^{+0.24}_{-0.19}$)	0.82 ($^{+0.30}_{-0.26}$) x $E^{-2.08\pm0.13}$	170 TeV - 3.8 PeV

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Combined systematic uncertainties

- Total (+0.40 -0.44) x SM

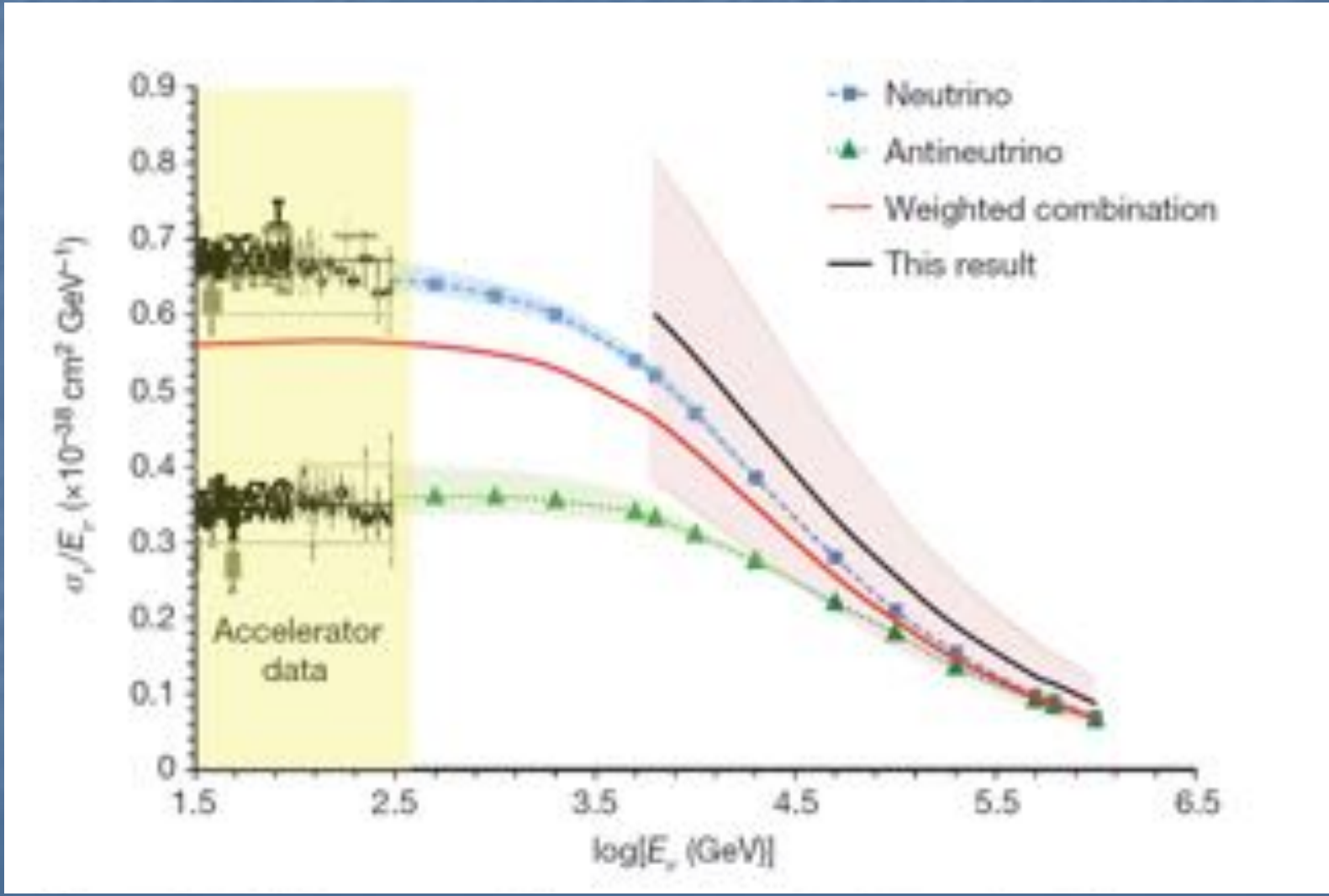
Uncertainty source	Systematic error (+)	Systematic error (-)
Ice model	+0.30x	-0.38x
Hole ice	+0.04x	-0.00x
Earth core density	+0.04x	-0.04x
Earth core radius	+0.01x	-0.01x
Atmos. temp. model	+0.00x	-0.04x
Astrophysical+prompt prior	+0.10x	-0.10x
Fit parameter uncertainty	+0.24x	-0.19x
TOTAL	+0.40x	-0.44x

Miarecki PhD dissertation, UC-Berkeley, 2016

Final result

- 1.30 (+0.21 -0.19 stat) (+0.40 -0.44 syst) x SM expectation
- In agreement with SM (CSMS)
  - NC and CC scaled together
  - ν and $\bar{\nu}$ combined (flux weighted)
- Did not see increase in cross section at higher energies predicted by some theories

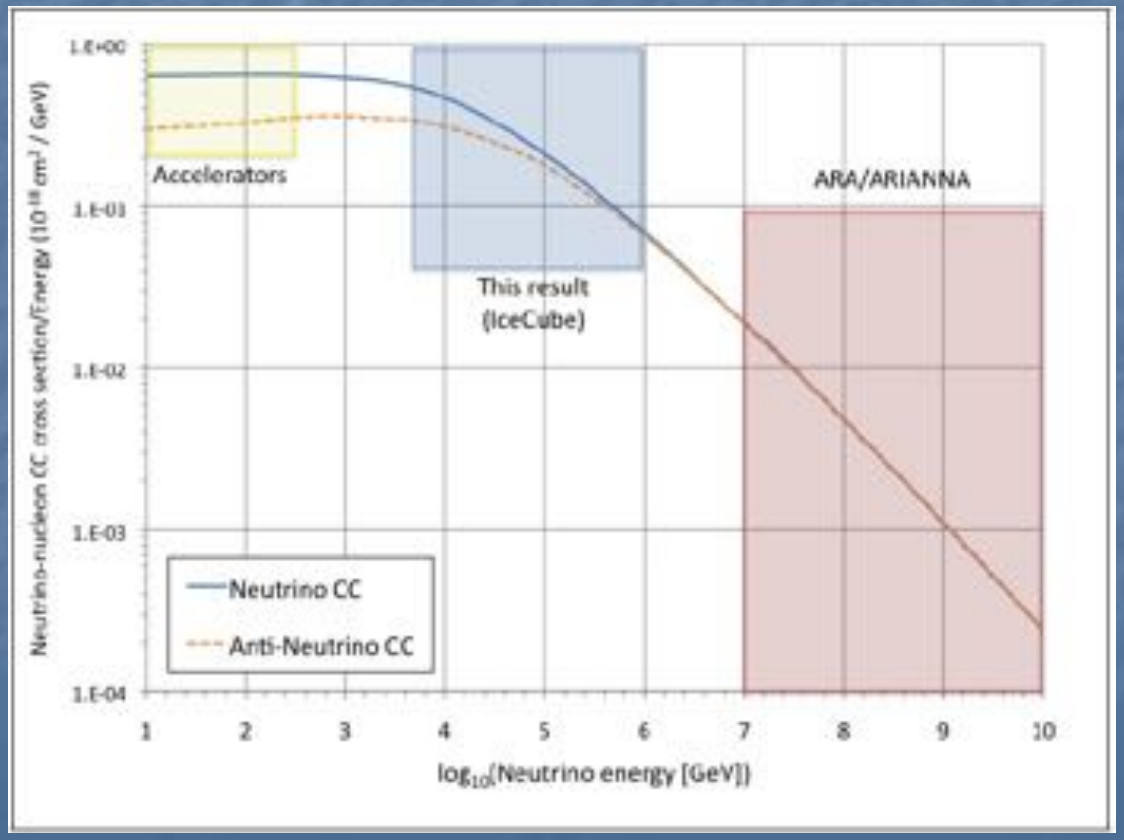
Final result



Nature, volume 551, pp 596–600 (30 Nov 2017)

Future studies

- Repeat analysis using multi IC86 years
- Analyses with radio detectors (ARA, ARIANNA)



Miarecki PhD dissertation, UC-Berkeley, 2016

Questions?

Video

- https://www.youtube.com/watch?v=OdWZA5UxmOk

South Pole fun facts

- Day is 6 months long
- Night is 6 months long
- Ave temp= -18 F (summer), -76 F (winter)
  - One of driest places on Earth
  - Snow drifts in on wind
- Altitude is 9,300 feet
  - On top of moving glacier
- Amundsen-Scott Station
  - Since 1956

South Pole Station

Drilling equipment

Laying cable by hand

Christmas at the Pole

Don’t Fall In!

IceCube counting house

True 4-wheel drive

Time for hobbies

Fresh food delivery

C-130 on Skis

Chinstrap penguin

Gentoo penguin

Adelie penguins

Aurora and Galaxy

Sandy's military service

T38 instructor pilot

Test Pilot School

Can you find me?

Retirement 2007

My family

Graduation (again)

Flickr page

- https://www.flickr.com/photos/9832165@N05/albums

The End

Backup slides

DOM stats

- Power consumption: 3W
- deadtime < 1%
- Dark noise rate < 400 Hz
- Local Coincidence rate ~ 15 Hz

PMT: Hamamatsu 10”

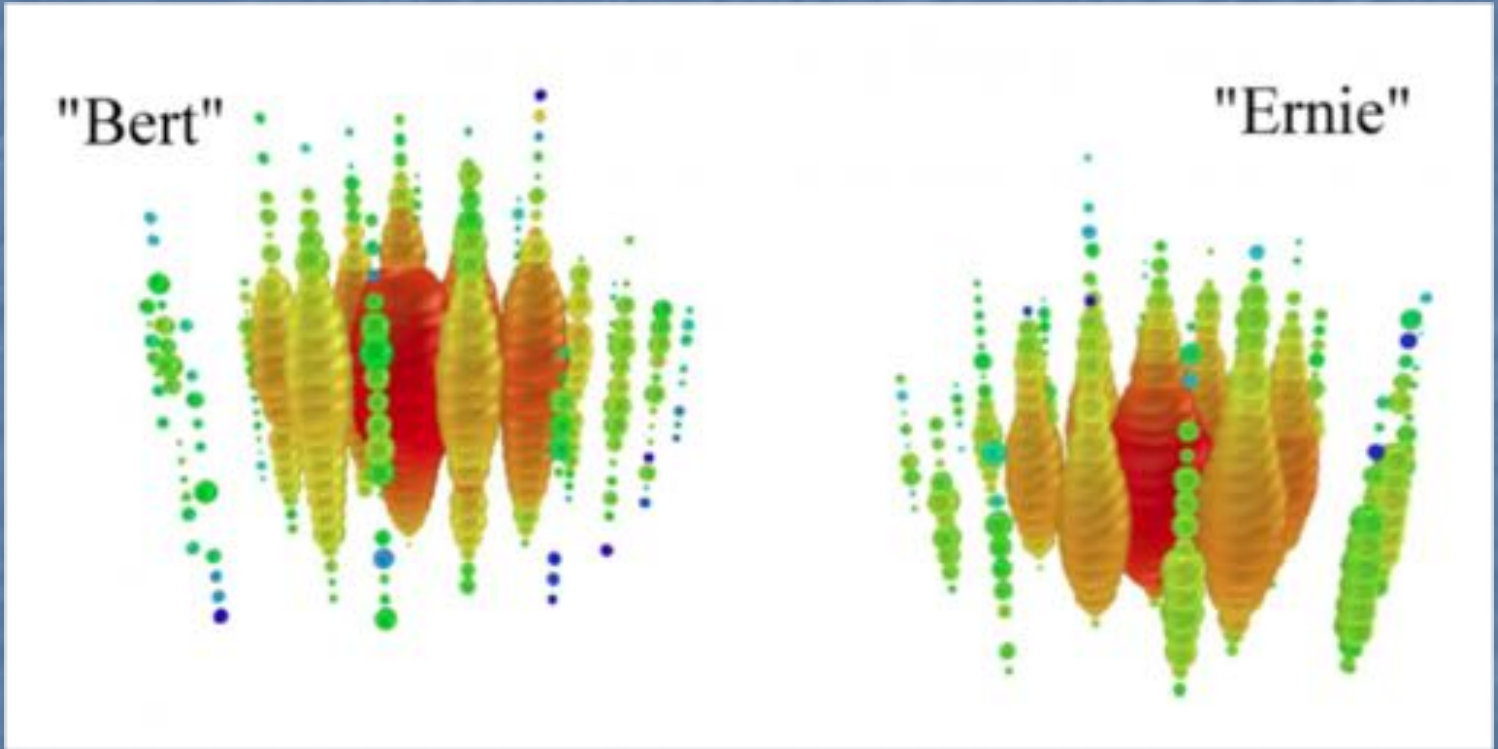
PMT output collected with waveform digitizers:

- ATWD: 3 channels, sampling 300 MSPS, capture 400 ns with a nominal gain ratios 0.25:2:16.
- FADC: sampling 40 MSPS, capture 6.4 μs

Combined they provide wide dynamic range: from single p.e. to thousands p.e.

Not the right IceCube

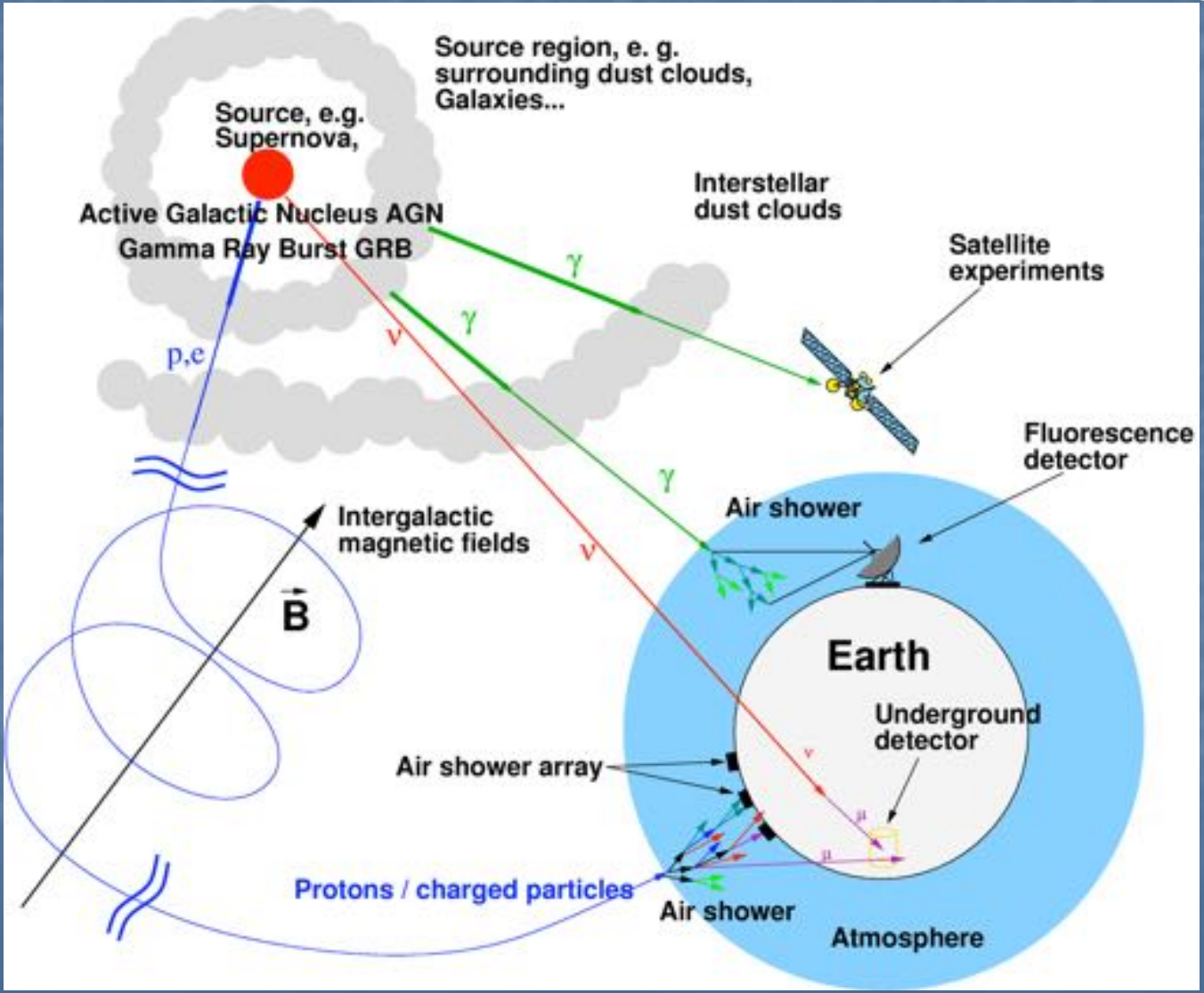
Bert and Ernie



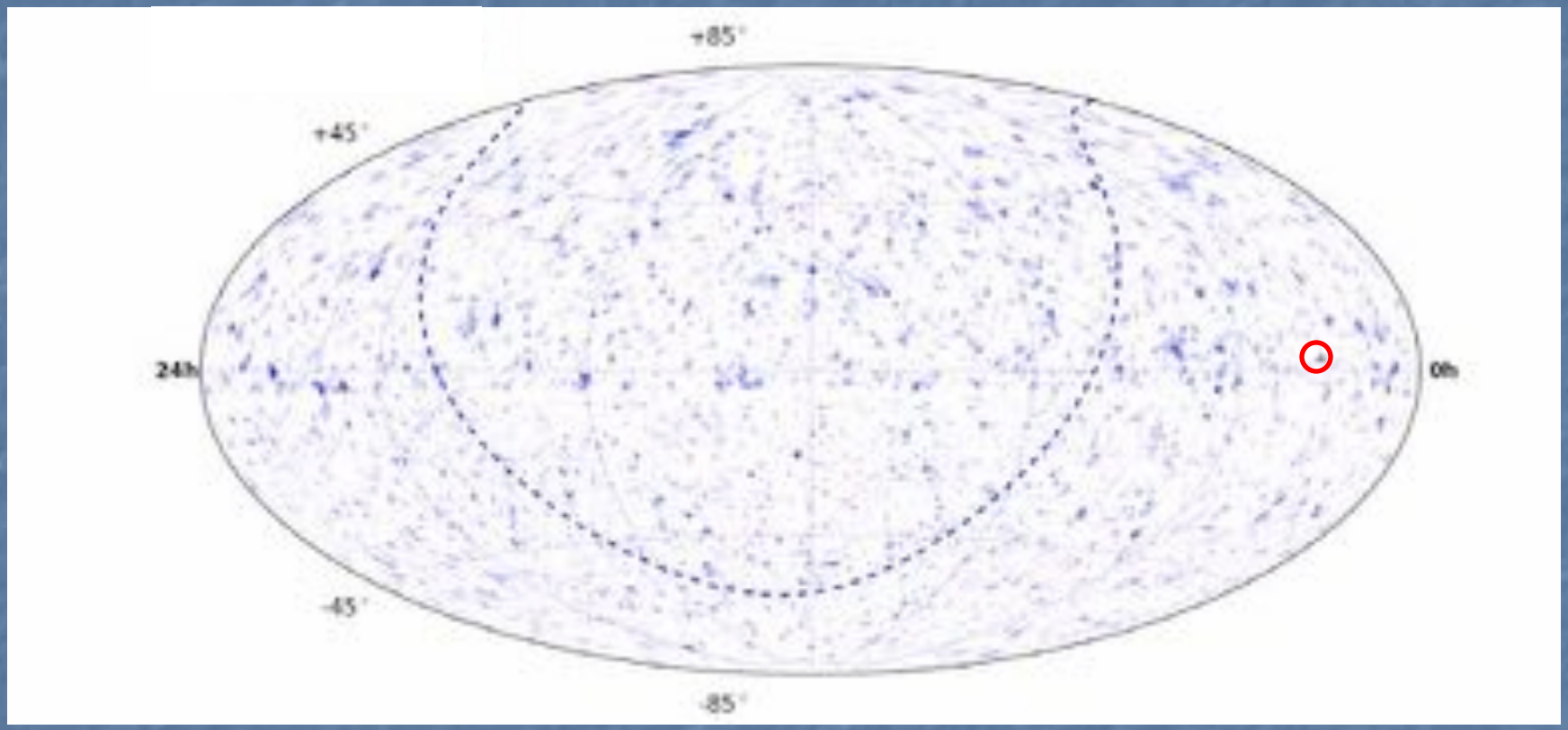
- High energy electron neutrinos

Then it gets confusing

Cosmic rays and B fields



Neutrino Sky Map (3 yr)



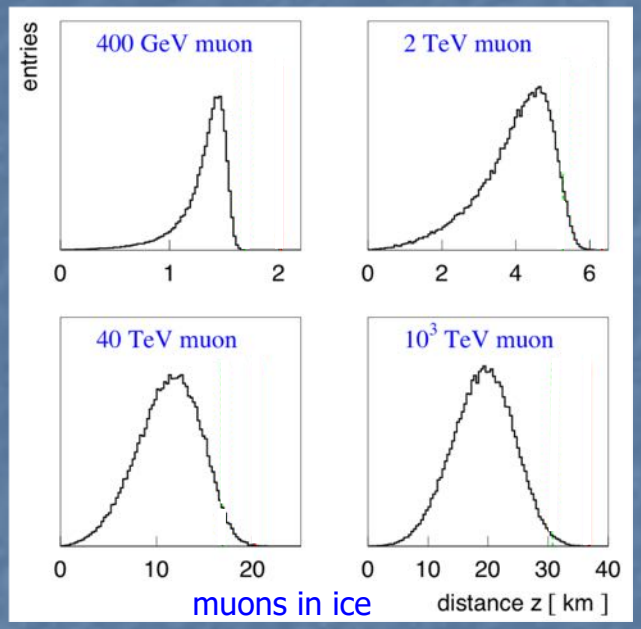
- Have not found anything significant, yet
- Other charged particles are bent by B field

Other IceCube research

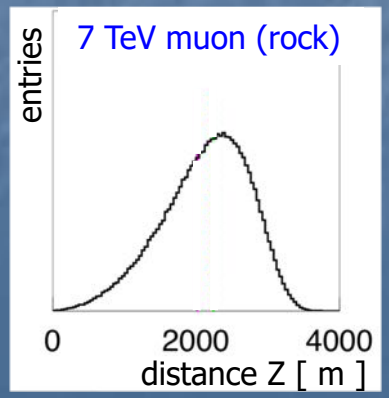
- Point sources of high-energy neutrinos
- Cosmic ray composition
- Dark matter
- Neutrino oscillations
- Astrophysical neutrino flux
- Supersymmetry
- Monopoles and other exotics

Muon track length

- Converting E_μ to E_ν
  - Muon track length distribution
- Example: ~10 TeV muon detected
  - Beginning of track from 15 TeV ν?
  - End of track from 50 TeV ν?



D. Chirkin, W. Rhode, arXiv: 0407075v2 (2008)

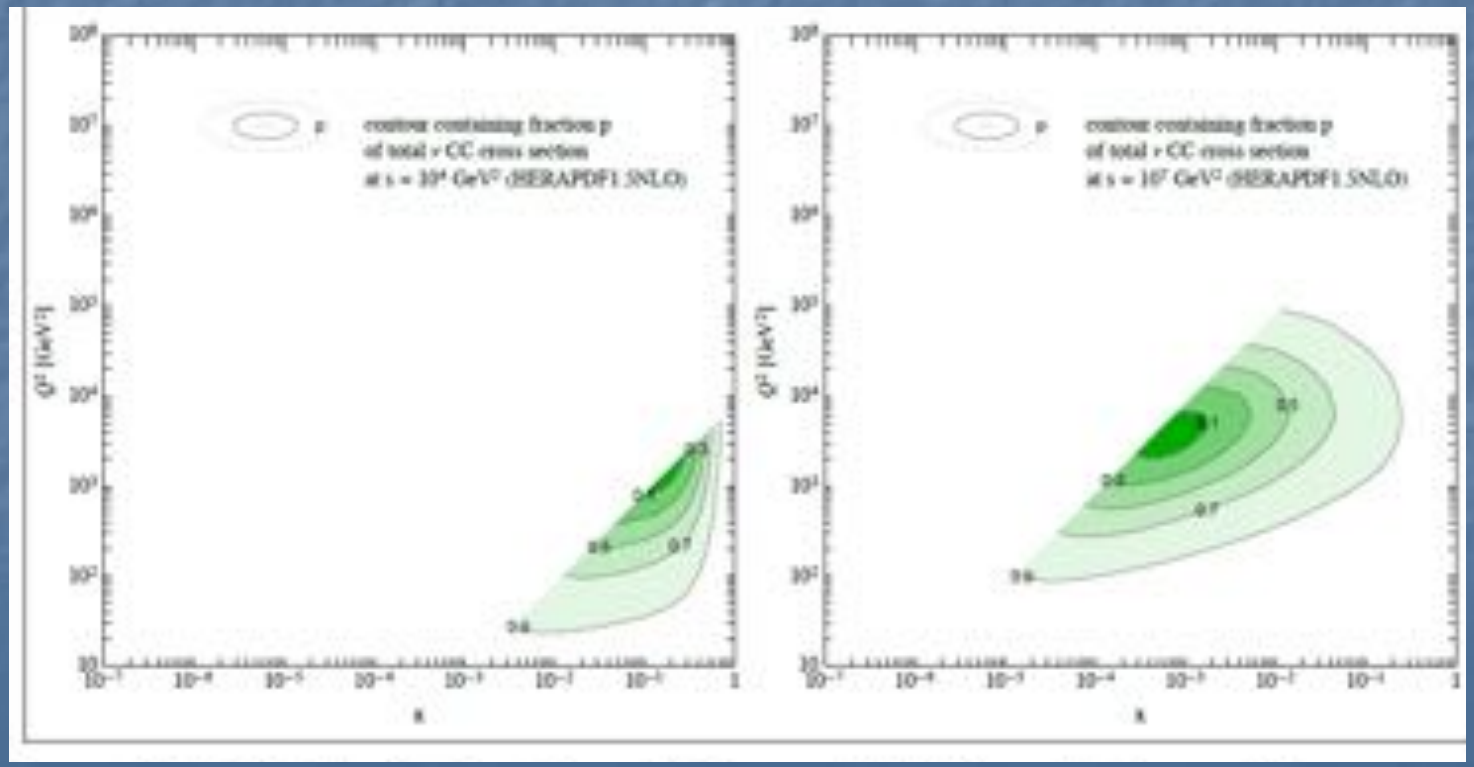


Simulation explanation

- NUGEN (neutrino generator)
  - based on All Neutrino Interaction Simulation (ANIS) [ice-rock interface, PREM, NC, but not neutrino oscillations]
  - Isotropic distribution on Earth surface, weighted by Honda model, propagated to Pole
- Propagated through ice by Muon Monte Carlo (MMC) [detailed models of energy loss]
- Photonics determines number and timing of expected PE, including detector effects
- Flux adjusted, and weighted by flux

x and Q^2

- Estimates for x and Q^2 for the energy range of this analysis:
- $10^{-4} < x < 0.5$ and $10^3 < Q^2 < 10^5$ GeV^2.

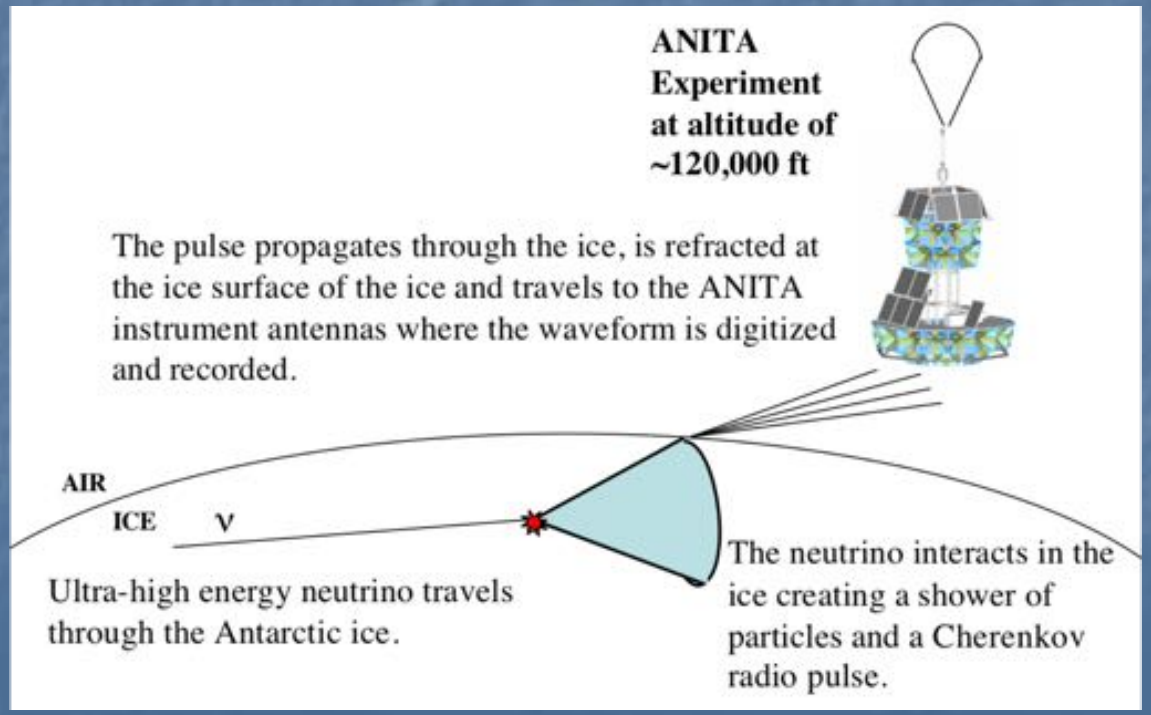


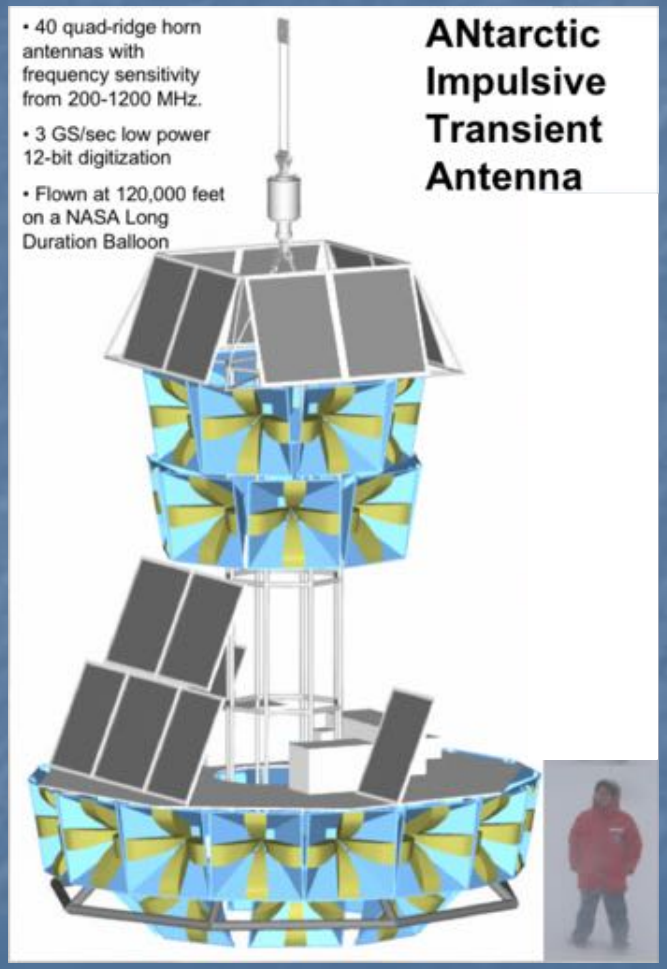
Previous results: ANITA

- ANITA set limits:

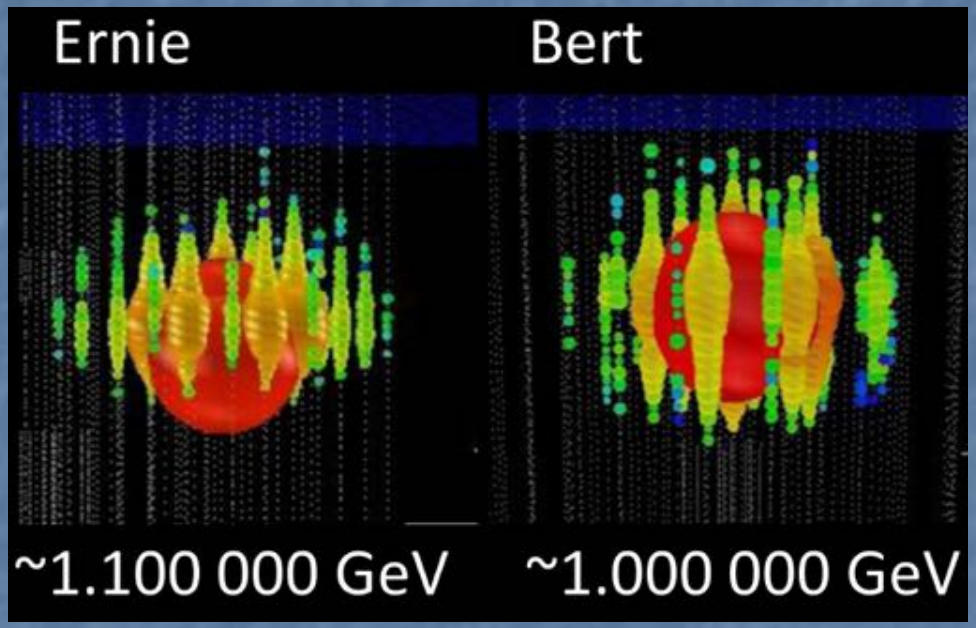
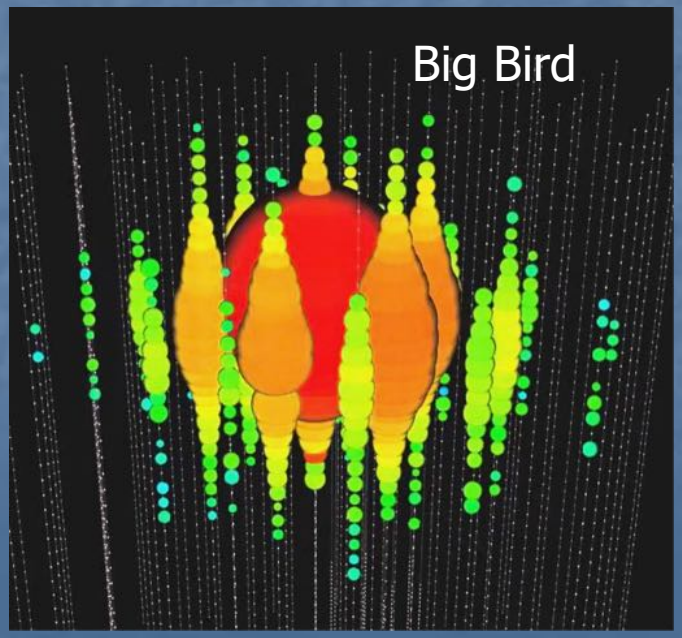
  $\sigma_\nu < 26 \times \sigma_{sm}$ for

  $10^{6.5} < E_\nu < 10^9$ TeV





Link and Miocinovic, Neutrino 2004, Paris and PhD thesis, Fenfang Wu, Univ of CA Irvine 2009.

Other big events

- Big Bird = 2 PeV
- Bert = 1 PeV
- Ernie = 1 PeV