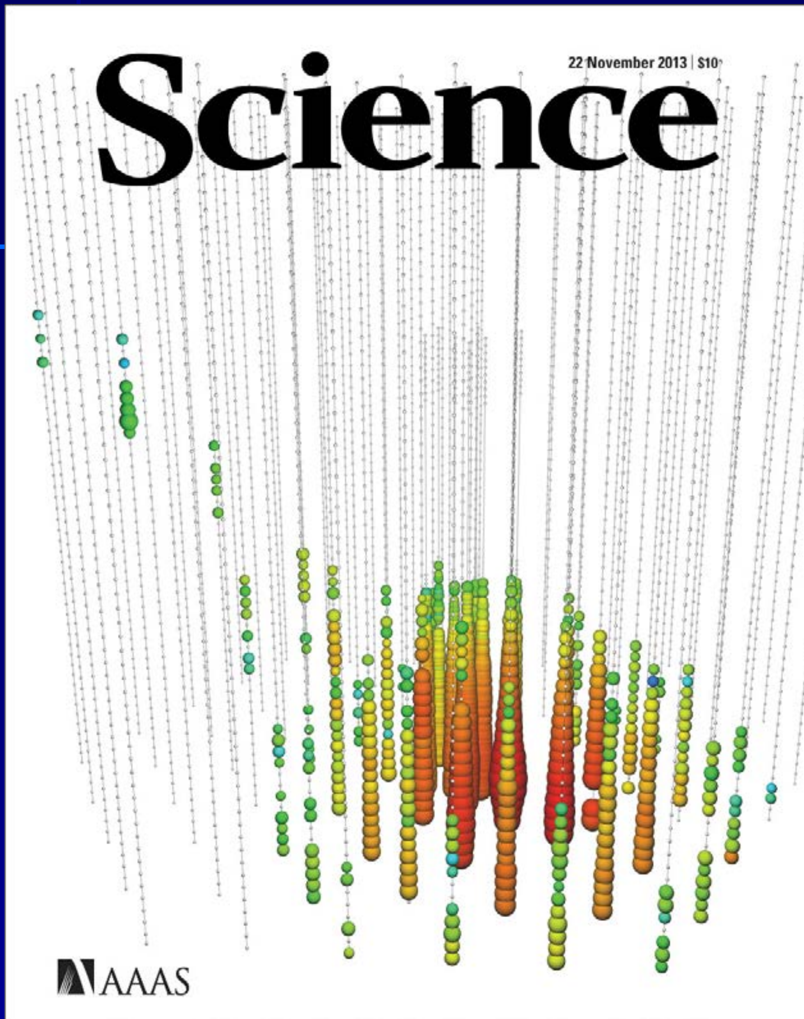
IceCube: Revealing a Neutrino Picture of the Cosmos

- Introduction
- Detector Description
- Neutrino Window to the Cosmos, Dawn of Neutrino Astronomy.
- Other Physics
- Future Plans
- Conclusions

Ali R. Fazely for the IceCube Collaboration.
icecube.wisc.edu
Miami Conference, December 16 -22, 2015

IceCube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Science
AAAS


PHYSICAL
REVIEW
LETTERS
Articles published week ending 12 JULY 2013
Published by
American Physical Society
APS
physics
Volume 111, Number 2

What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies
- We are in our 12th project year and data taking with the full detector (86 strings) began in May 2011
- IceCube is the largest Neutrino Telescope in operation
- IceCube has opened up a neutrino window to the cosmos and has ushered in the dawn of Neutrino Astronomy. Science Cover Article November 22nd 2013, and PRL Cover, July 12, 2013.
- http://icecube.wisc.edu/

The IceCube Collaboration

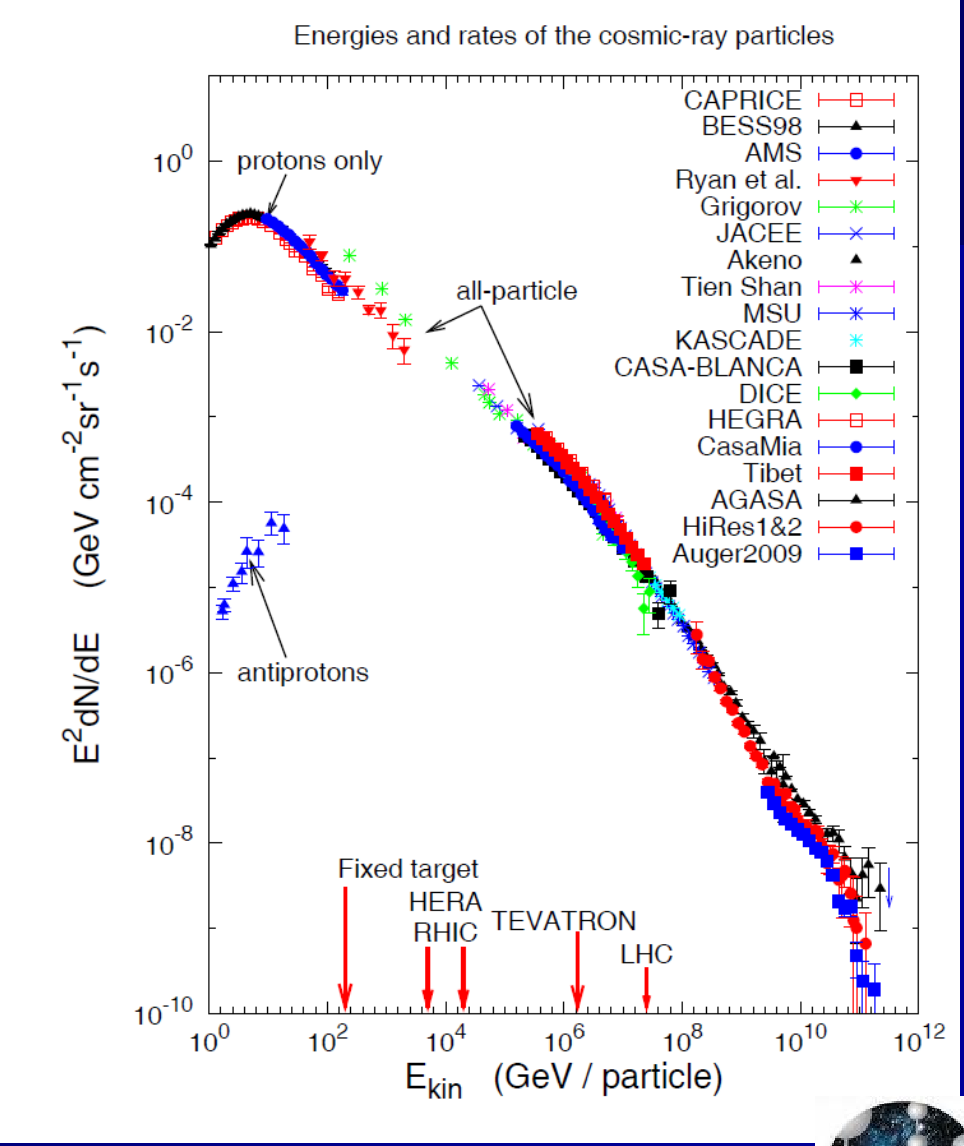
Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Cosmic Rays: A century old puzzle

Balloon flights
1911-1913

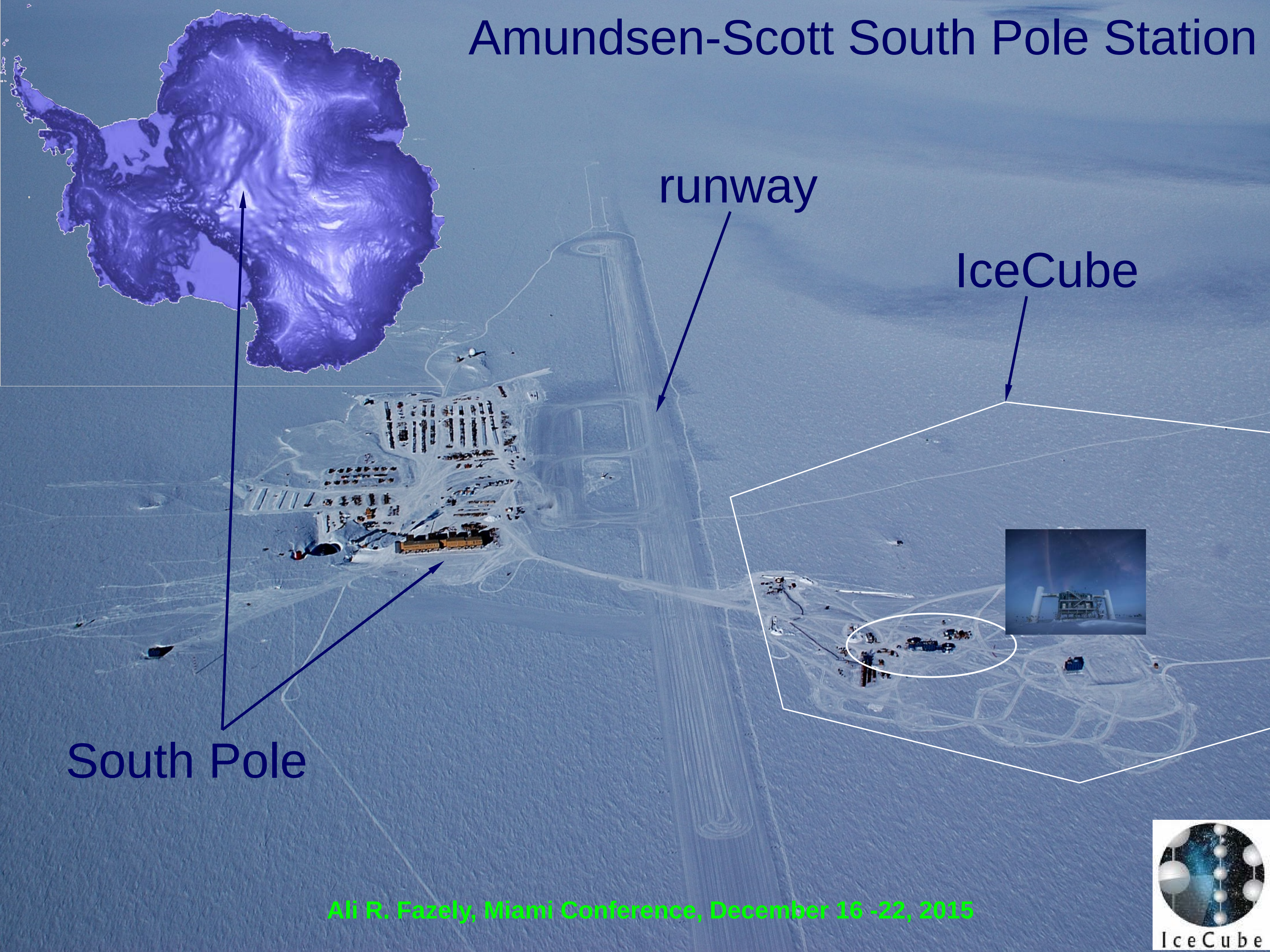
Victor Hess
Nobel Prize
1936



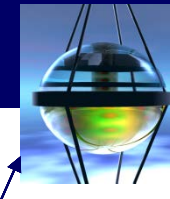
- Power law over many decades
- Origin Unknown

IceCube

Amundsen-Scott South Pole Station



The IceCube Detector

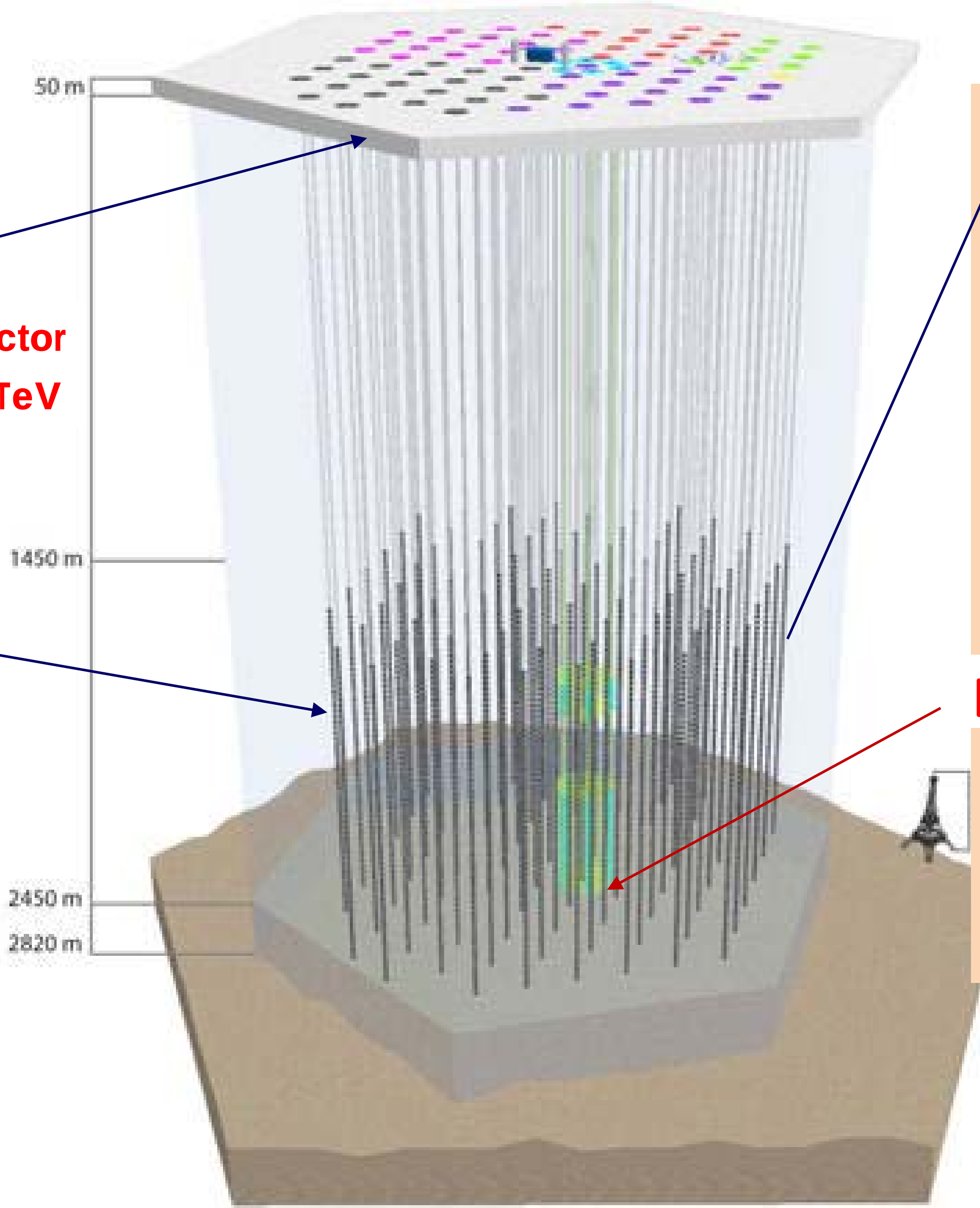


IceTop

Air shower detector threshold ~ 300 TeV

InIce

86 Strings, 60 Optical Modules per String

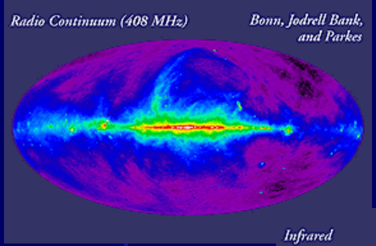


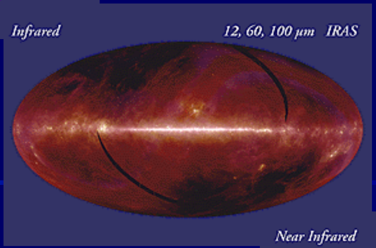
- ✓Completion: December 2010
- ✓86 strings
- ✓2010: 79 Strings
- ✓2009: 59 Strings
- ✓2008: 40 Strings

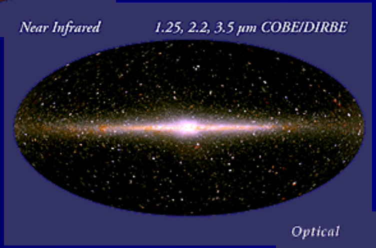
Deep Core

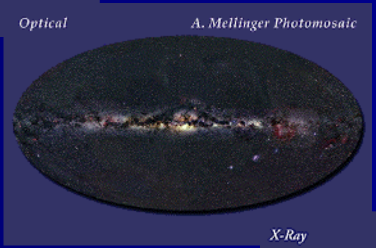
IceCube

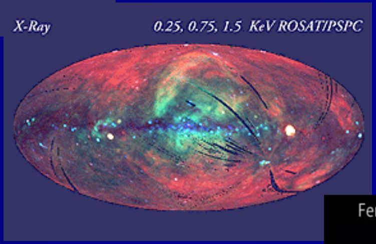
Observing the Universe

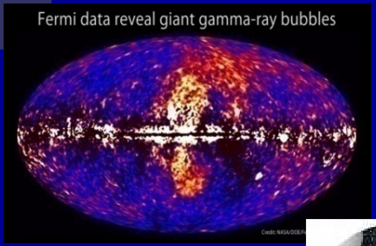


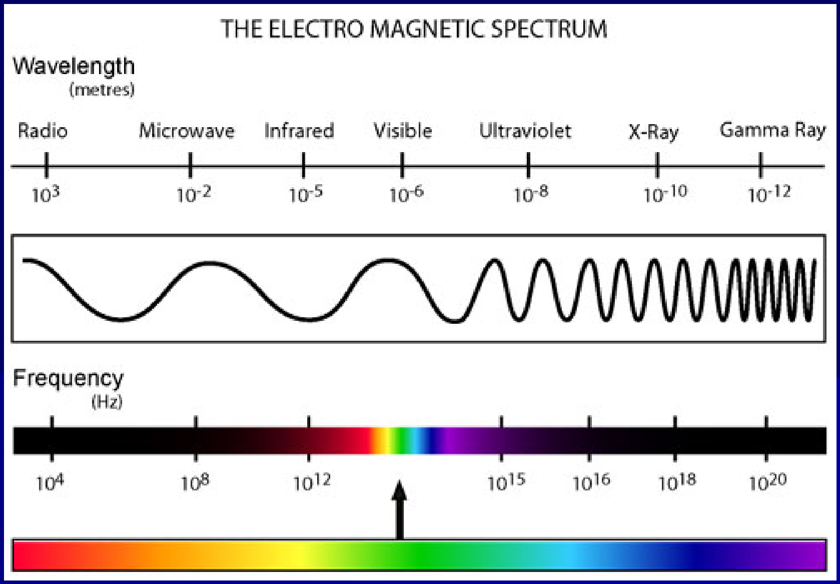








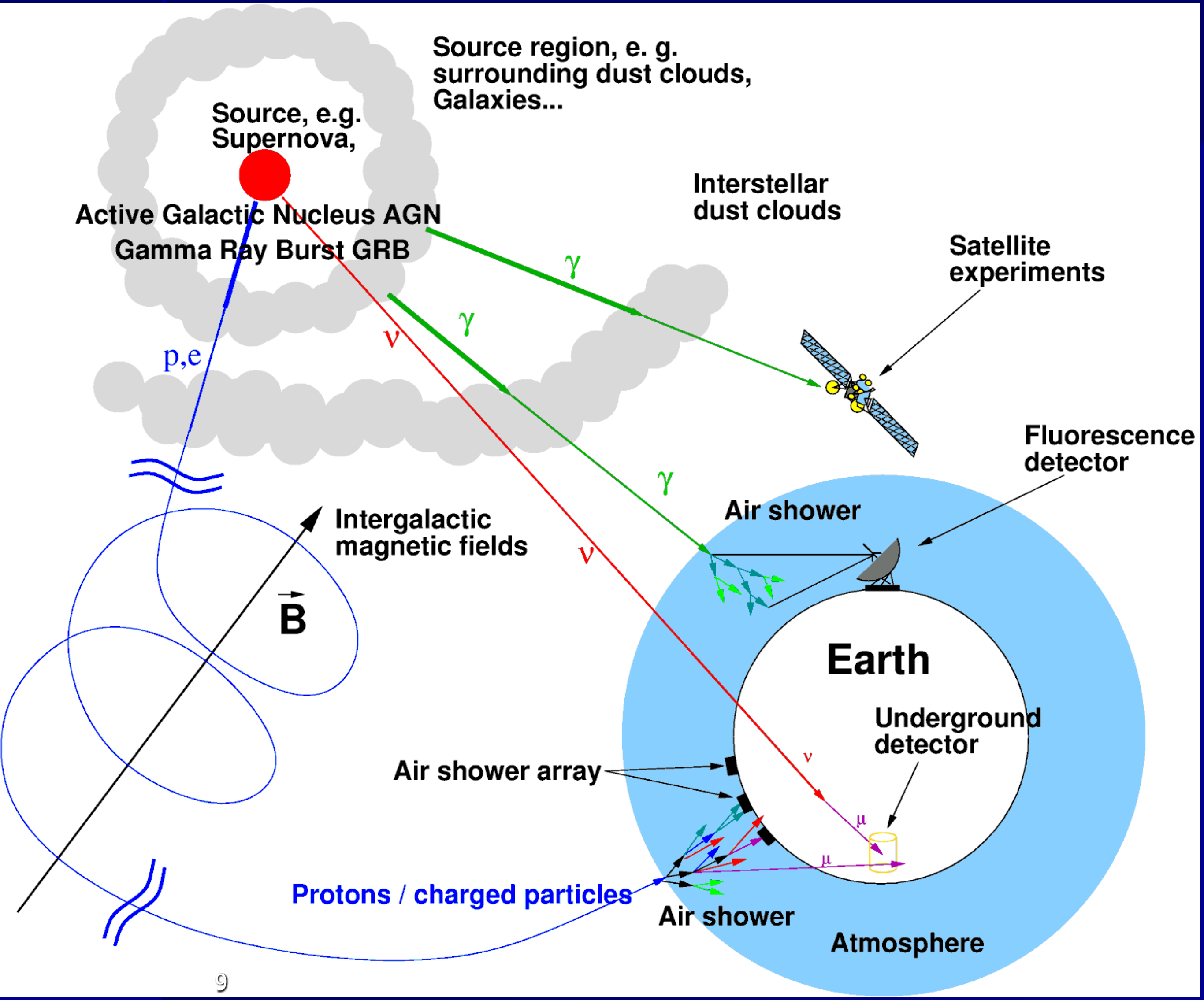




http://mwmw.gsfc.nasa.gov/mmw_allsky.html

IceCube

Neutrinos as Cosmic Messengers



p *Protons:* **deflected by magnetic fields.**

γ *Photons:* **easily absorbed by CMB backgrounds.**

ν *Neutrinos:* **not deflected by magnetic fields. Low interaction cross-section.**

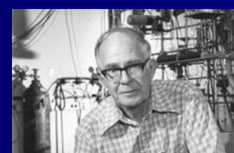
IceCube

Slow History of Neutrinos!

1930 Pauli proposes Neutrinos

1956, Reines and Cowan discovery of neutrinos

1967, Davis Solar Neutrinos and their deficits

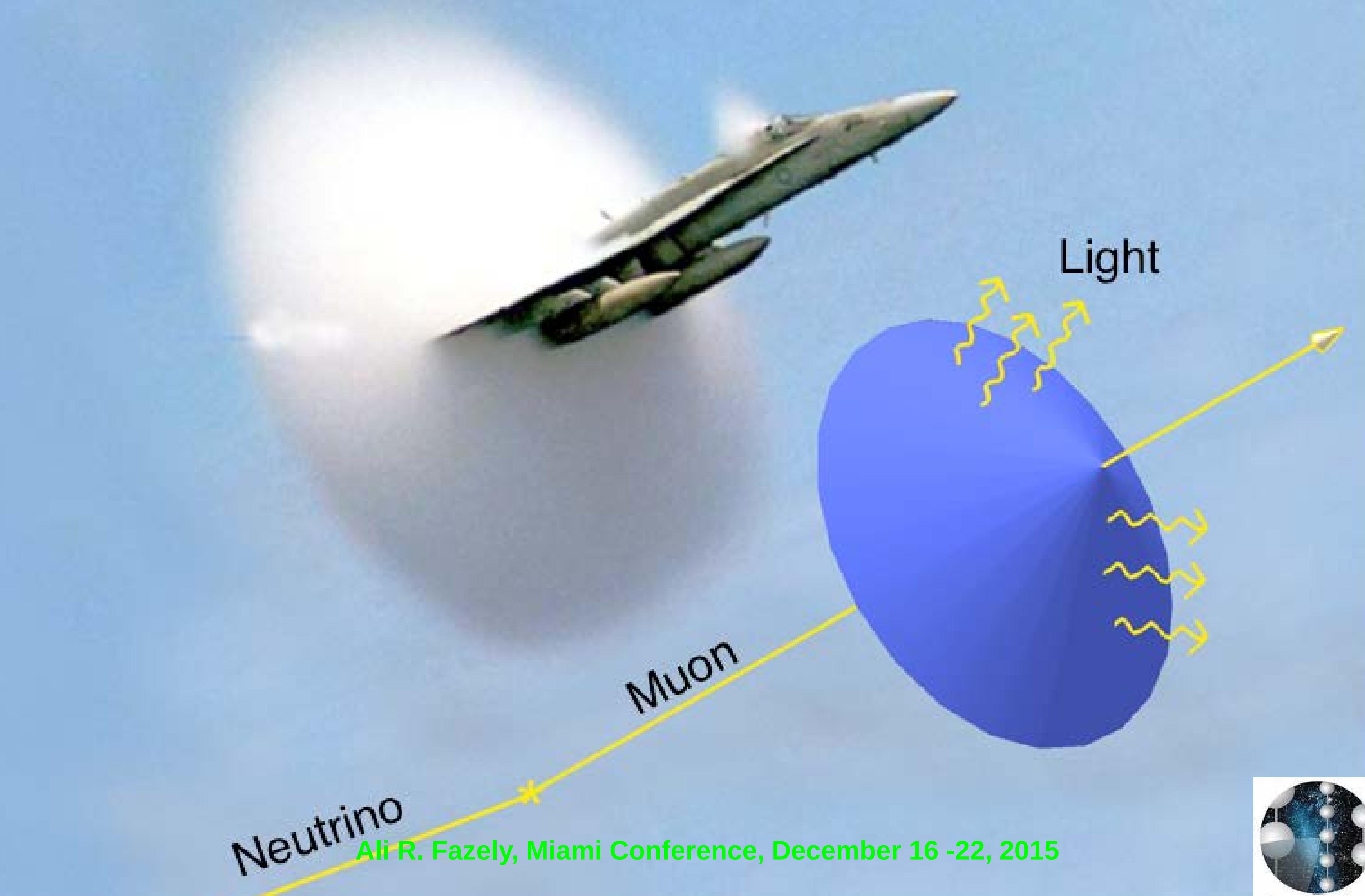


1987 Supernova IMB, Kamioka

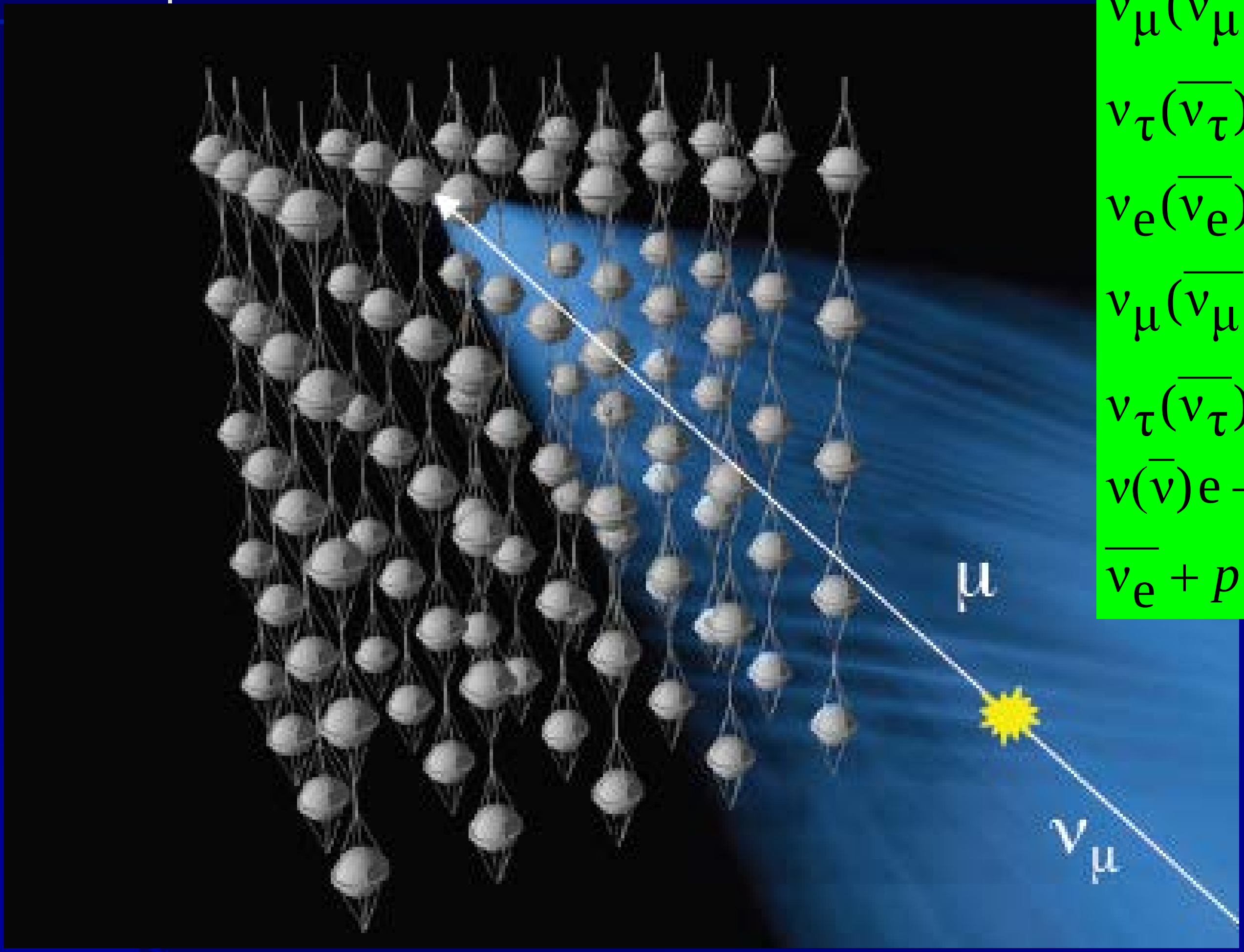
1998 Neutrino Oscillations, Super-K

2013 Dawn of Neutrino Astronomy

Cerenkov Radiation - the electromagnetic "sonic boom"



Neutrino interactions



$$\nu_e(\overline{\nu_e}) + {}^{16}\mathrm{O} \rightarrow e\,(e^+) + X \quad (CC)$$

$$\nu_\mu(\overline{\nu_\mu}) + {}^{16}\mathrm{O} \rightarrow \mu(\mu^+) + X \quad (CC)$$

$$\nu_\tau(\overline{\nu_\tau}) + {}^{16}\mathrm{O} \rightarrow \tau\,(\tau^+) + X \quad (CC)$$

$$\nu_e(\overline{\nu_e}) + {}^{16}\mathrm{O} \rightarrow \nu_e(\overline{\nu_e}) + X \quad (NC)$$

$$\nu_\mu(\overline{\nu_\mu}) + {}^{16}\mathrm{O} \rightarrow \nu_\mu(\overline{\nu_\mu}) + X \quad (NC)$$

$$\nu_\tau(\overline{\nu_\tau}) + {}^{16}\mathrm{O} \rightarrow \nu_\tau(\overline{\nu_\tau}) + X \quad (NC)$$

$$\nu(\bar{\nu})\,e \rightarrow \nu(\bar{\nu})\,e\,(CC, NC)$$

$$\overline{\nu_e} + p \rightarrow e^+ + n,\ Supernova\,(CC)$$

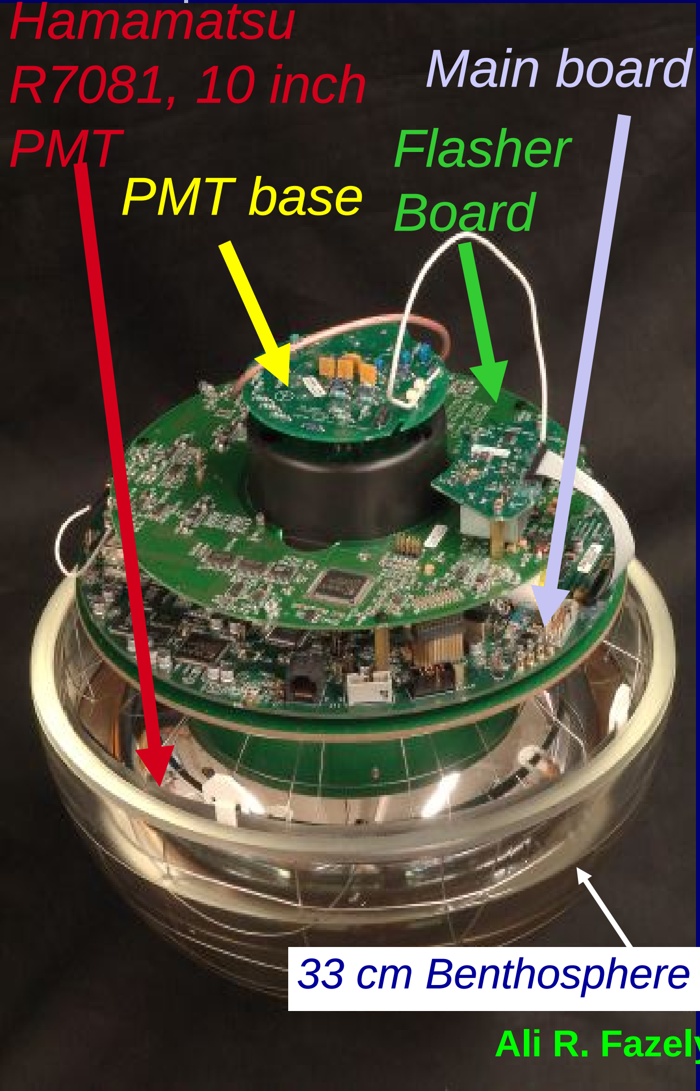
Digital Optical Module

IceCube

Sensing Neutrino Light

IceCube “Digital Optical Module” (DOM)

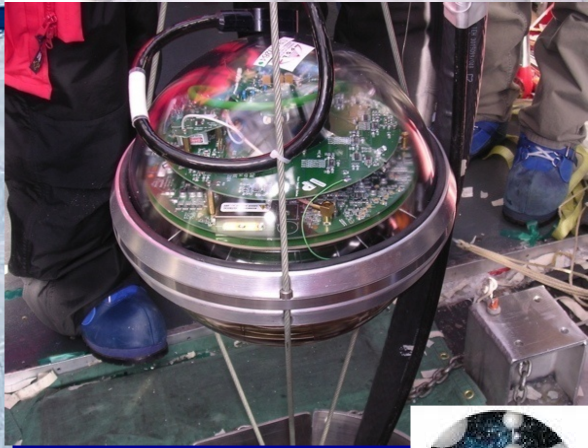
Power consumption: 3W



- Measure arrival time of every photon
- 2x 300MHz waveform digitizers
- 1x 40 MHz FADC digitizer
- Can trigger in coincidence w/ neighbor DOM
- Transmits data to surface on request
- Data sent over 3.3 km twisted pair copper cable
- Knows the time to within 3 nanoseconds to all other DOMs in the ice

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized periodically to precision of O(2 nsec)

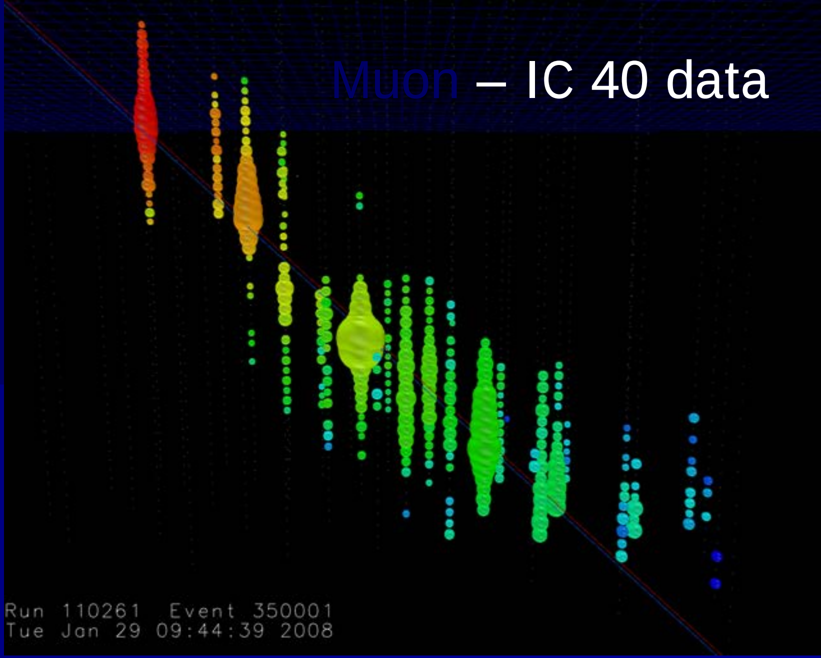
IceCube Construction

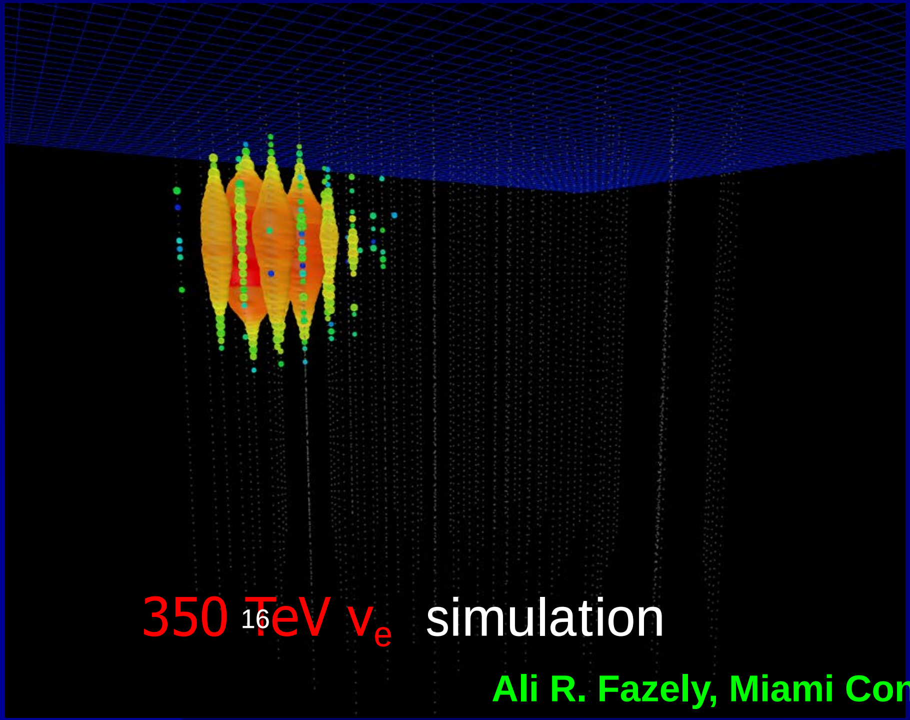


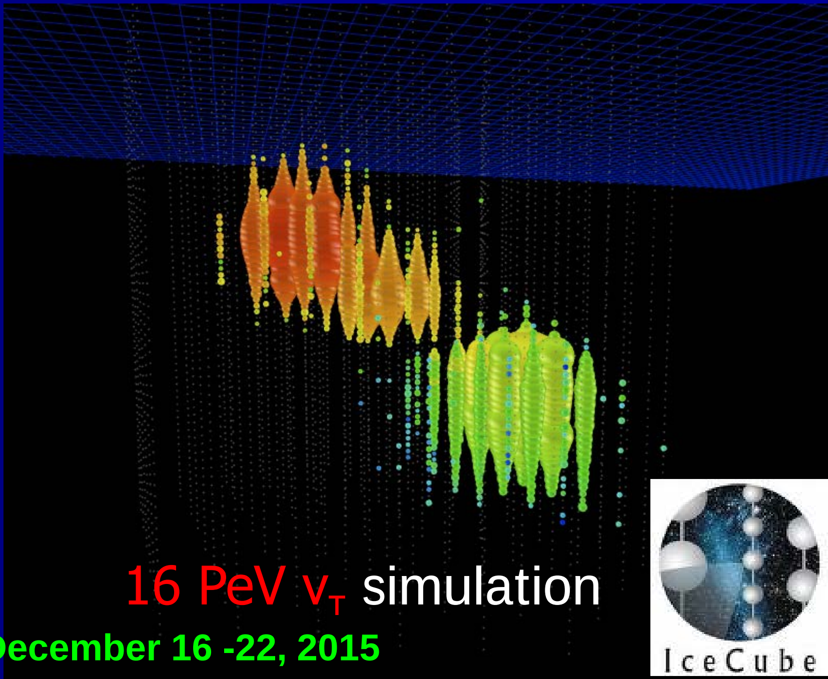
IceCube

Event Topologies

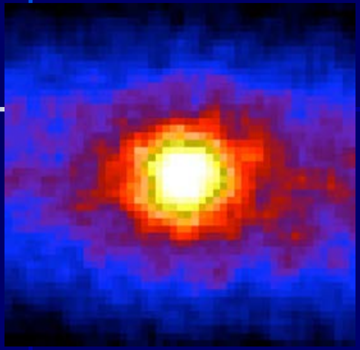
- ν_μ produce μ tracks
  - Angular Res ~ 0.7^0
  - Eres log(E) ~ 0.3
- ν_e CC, ν_x NC create showers
  - ~ point sources, 'cascades'
  - Eres log(E)=0.1-0.2
- ν_τ double bang events, others





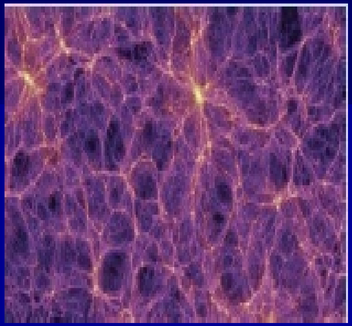


Real and Possible ET Neutrino Sources

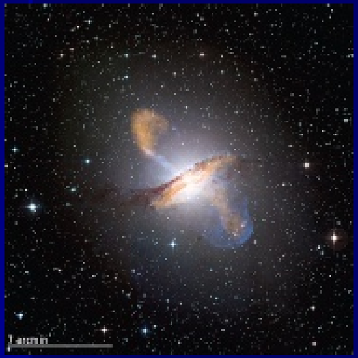


Solar Neutrinos

Supernova 1987A

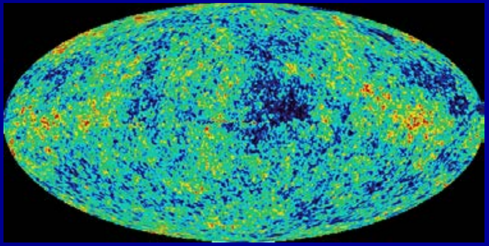


Dark Matter?



Active Galactic Nuclei

Gamma Ray Bursts

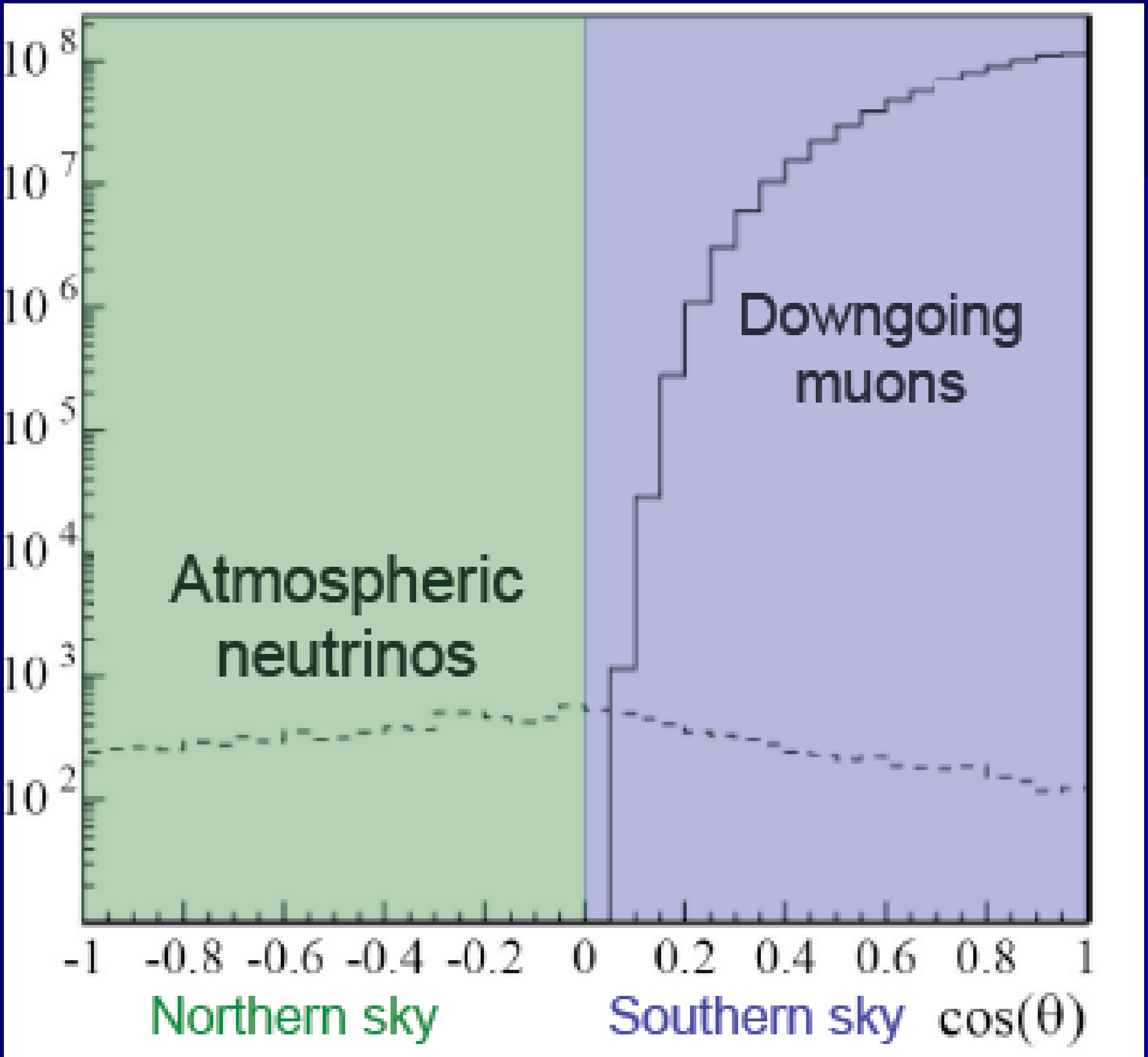


Cosmogenic Neutrinos

Backgrounds

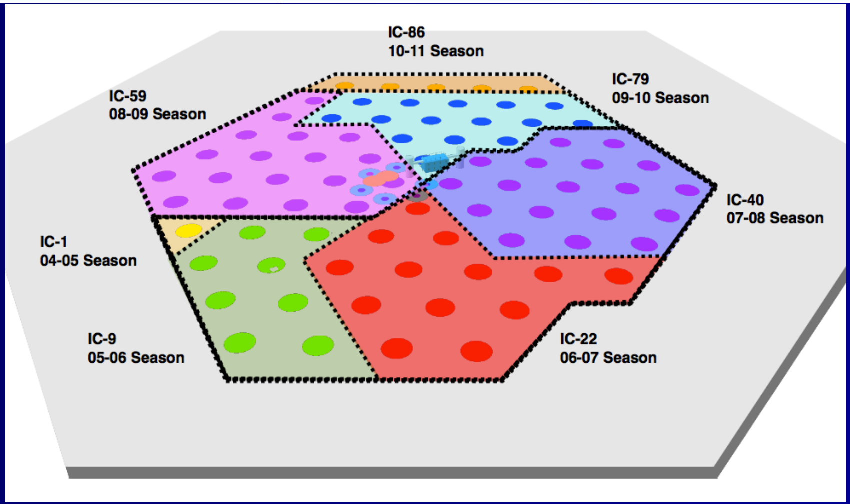
The majority of triggers in IceCube are from atmospheric muons

We record over 6 x10^9 muons and 74,000 atmospheric muon neutrinos per year.



IceCube History and Rates

Configuration	Date	Livetime	μ-rate (Hz)	ν-rate/day
AMANDA(19)	2000-06	3.8 years	100	5
IC9	2006	137 days	80	1.7
IC22	2007	275 days	600	28
IC40	2008-09	376 days	1100	38
IC59	2009-10	348 days	1900	125
IC79-DC6	2010-11	1.0 year	2250	170
IC86-DC8	5/2011-present		2700	190



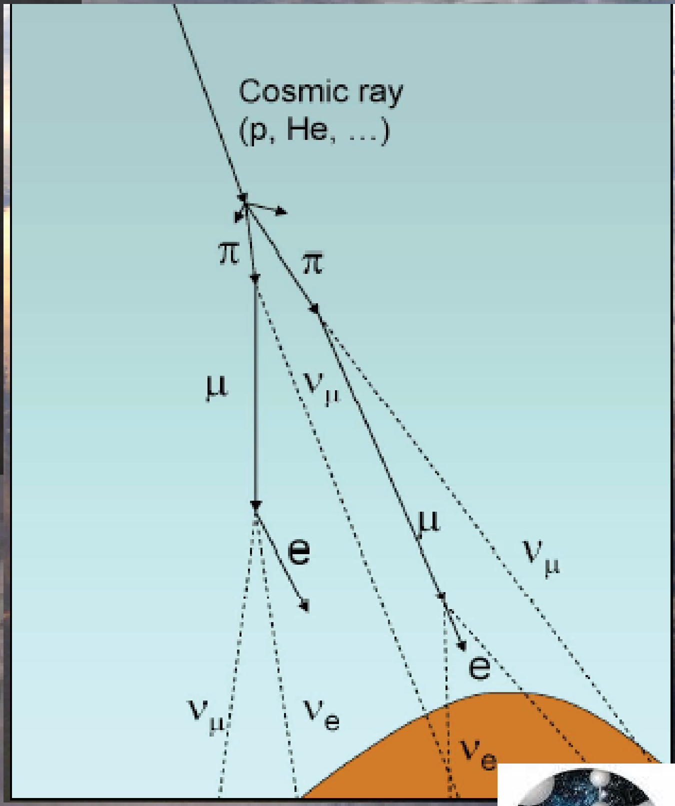
Atmospheric Neutrinos

- Main Background to Astrophysical Search
- Created by high energy cosmic rays colliding with O and N in the Earth's atmosphere
- Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)
- Conventional ~ $E^{-3.7}$ Spectrum
- Prompt ~ $E^{-2.7}$ Spectrum

$$p + \mathrm{O}\ N \rightarrow \pi^{+}, K^{+}, D^{+}, \text{etc.}$$

$$\pi^{+} \rightarrow \nu_{\mu} + \mu^{+}$$

$$\mu^{+} \downarrow\ \bar{\nu}_{\mu} + e^{+} + \nu_{e}$$

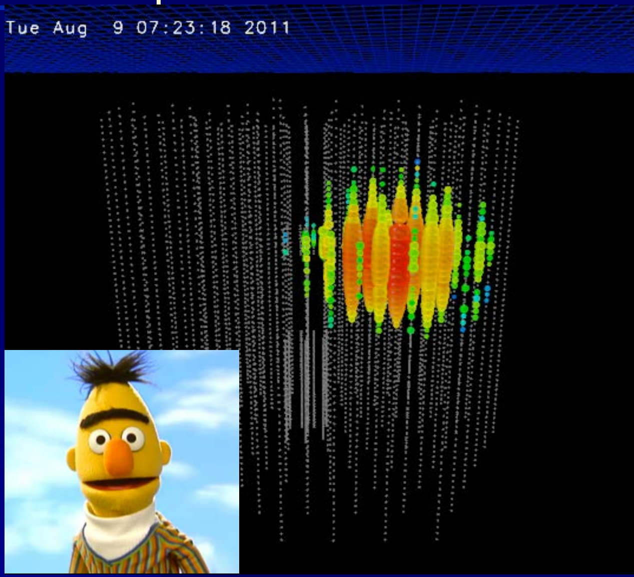


Observation of Highest Energy Neutrinos Dubbed “Bert, Ernie & Big Bird”.

(PRL 111 021103 2013)

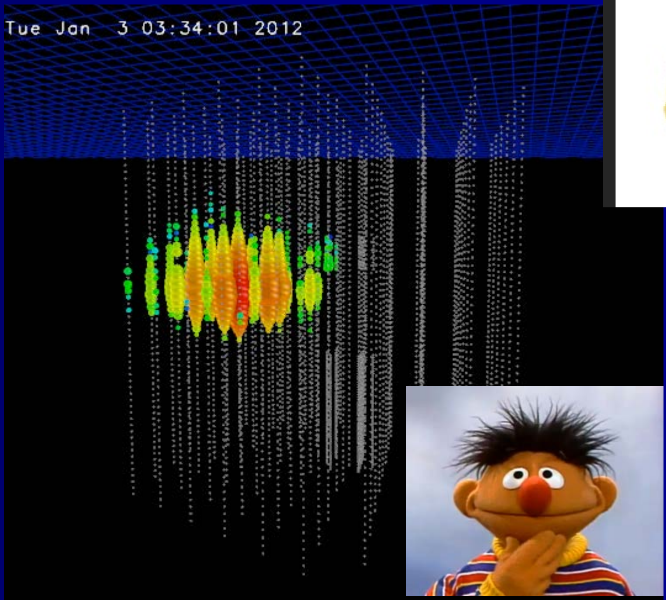
ν_eCC on nuclei or electrons or ν_x NC on nuclei and electrons

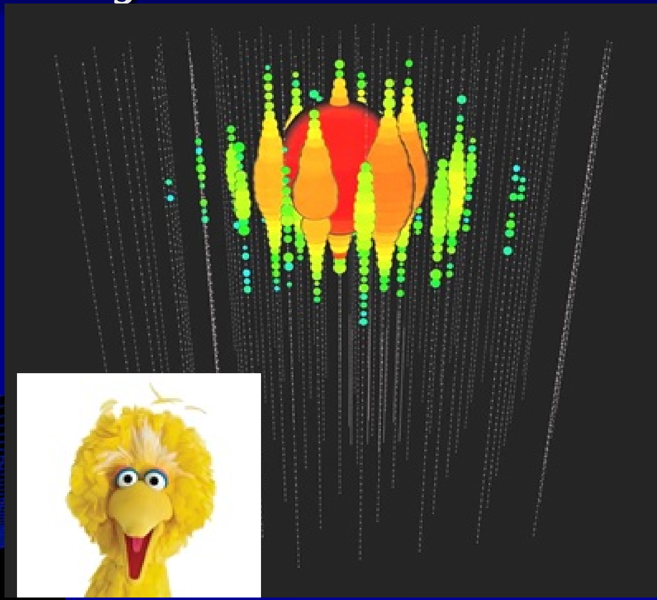
Angular resolution on cascade events at these energies ~10°



Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: 7.0×10^4
NDOM: 354
1.04 ± 0.16 PeV

Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6×10^4
NDOM: 312
1.14 ± 0.17 PeV





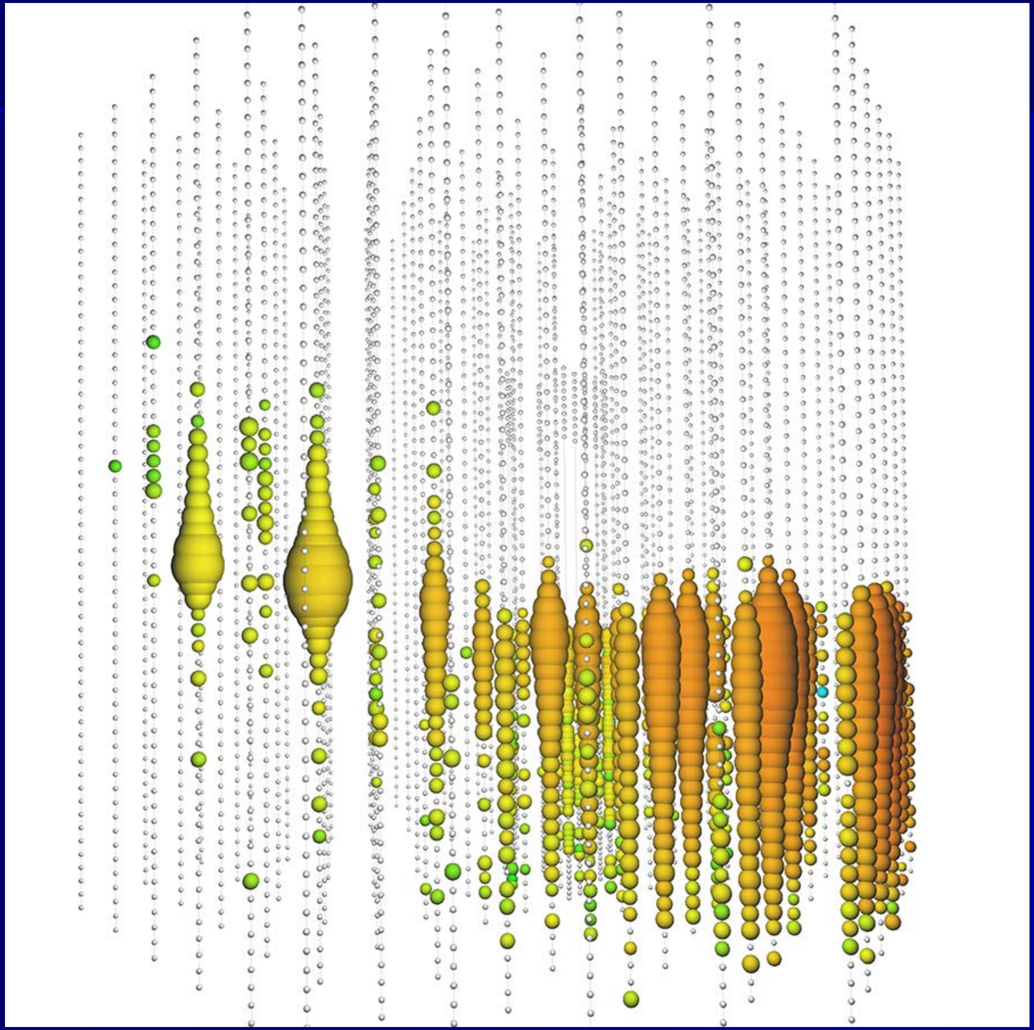
Dec, 4th, 2012
$2.2 \pm$ PeV

IceCube

Observation of Highest Energy Neutrinos

2.6 ± 0.3 PeV, observed June 11, 2014

(ICRC 2015, July 30 to August 6, 2015, The Hague, The Netherlands.)



Backgrounds for “Bert & Ernie”

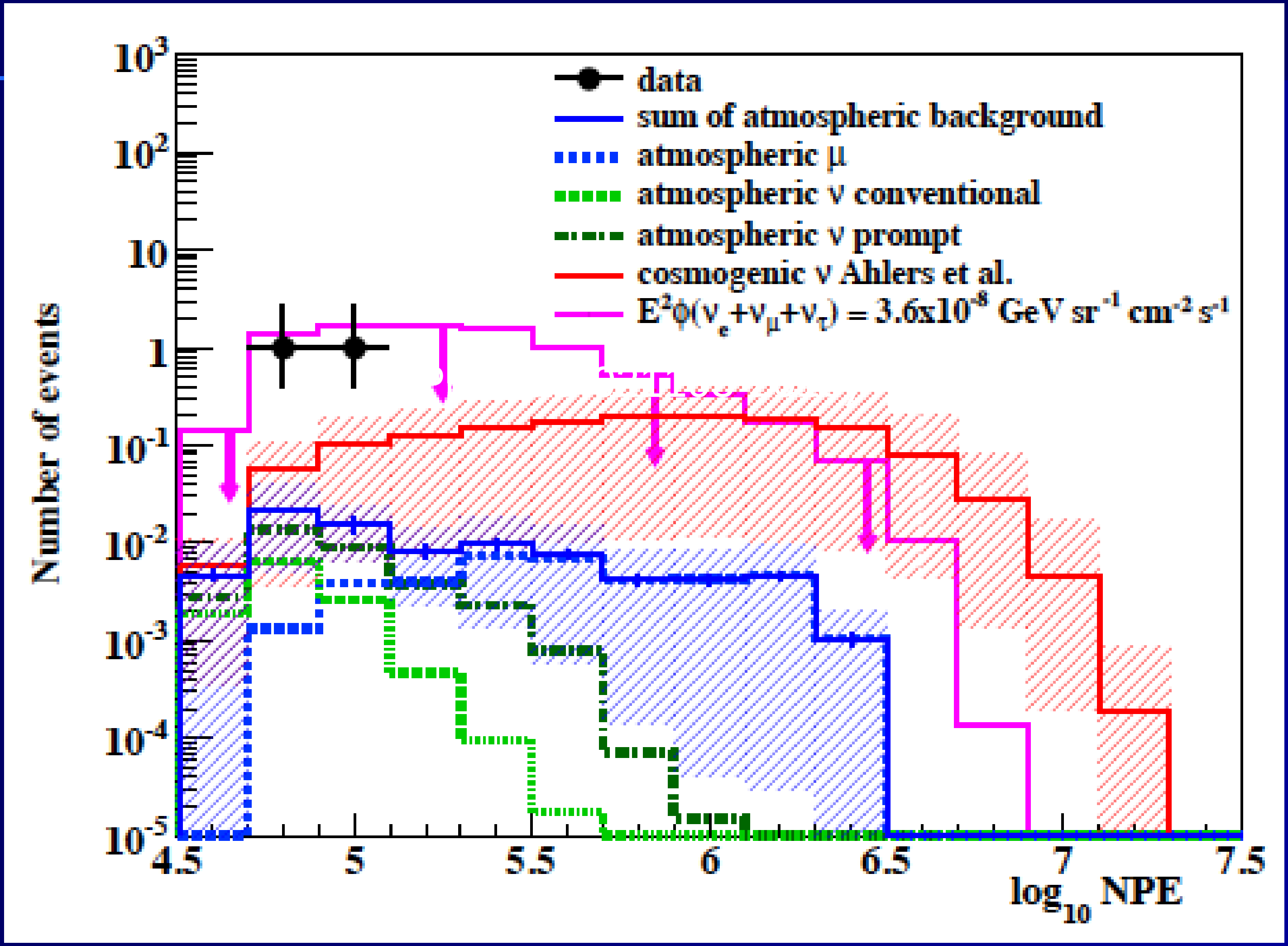
Background Source	Contribution Level (~ 616 days)
Atmospheric Muons	0.038 ± 0.004
Neutrinos from pion and Kaon Decay	0.012 ± 0.001
Prompt Neutrinos from Charm Production *	0.033 ± 0.001
Total	0.082 ± 0.001

* R. Enberg, et al., PRD078 043005 (2008)

Significance = 2.8σ

NPE Distributions

(PRL 111 021103 2013)

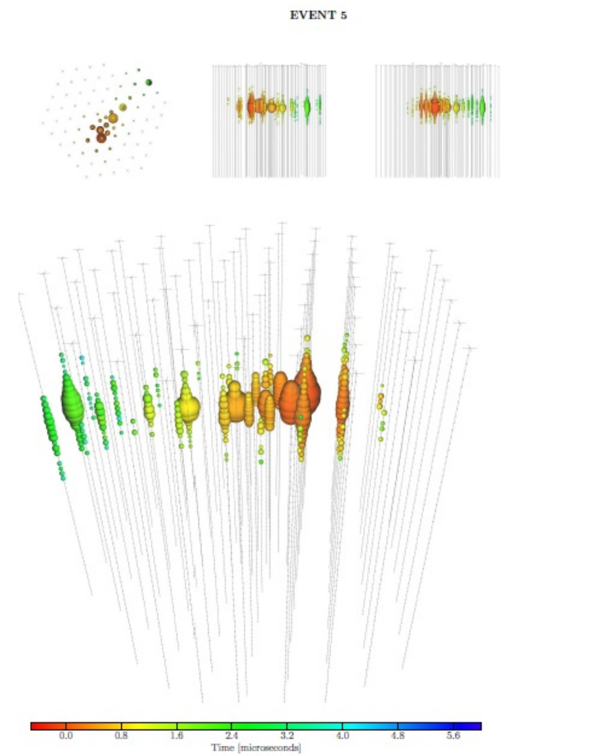


Results

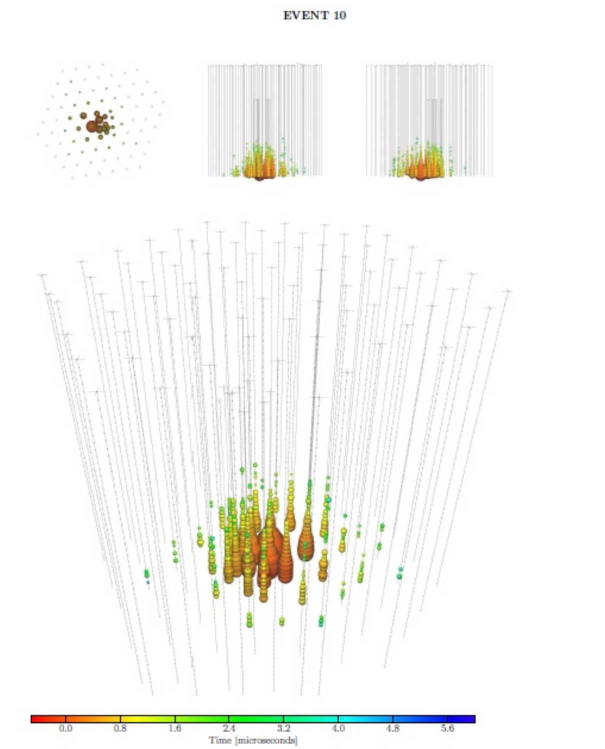
IceCube: Science 22 Vol. 342 no. 6161 (2013), Phys. Rev. Lett.113 (2014) 101101

Physics Cuts

1) PMT charge, Q > 6000 p.e., contained events within detector fiducial volume
2) Accept both tracks and cascades
3) Veto background atmospheric μ and neutrinos
4) 60 TeV < Edep < 3 PeV



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	−0.4	110.6	$\lesssim 1.2$	Track



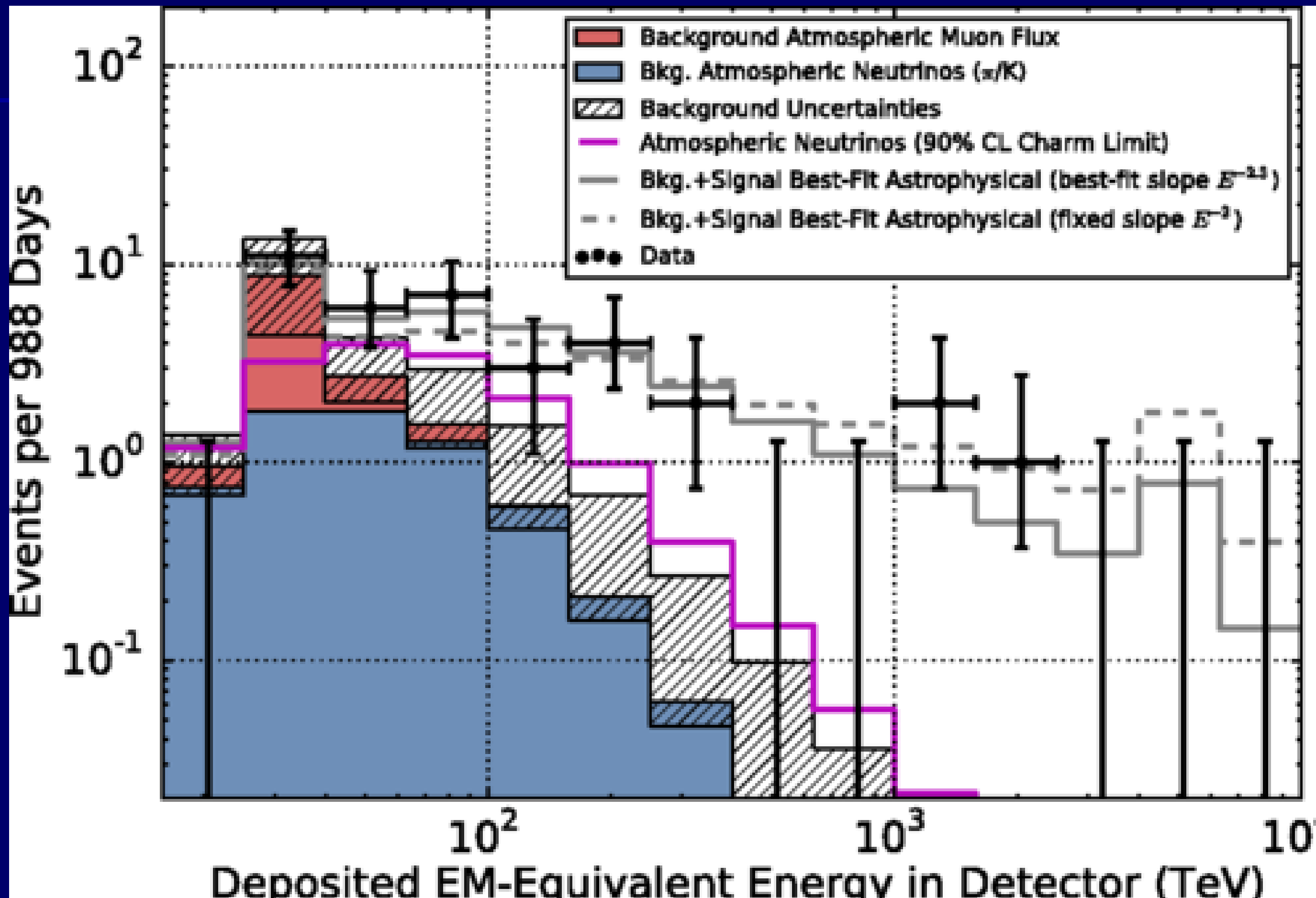
Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$97.2^{+10.4}_{-12.4}$	55695.2730442	−29.4	5.0	8.1	Shower

High-Energy Extraterrestrial Neutrinos in the IceCube Detector

37 events, (9 tracked, 28 cascades) observed.

Backgrounds are disfavored at a Significance of 5.7σ

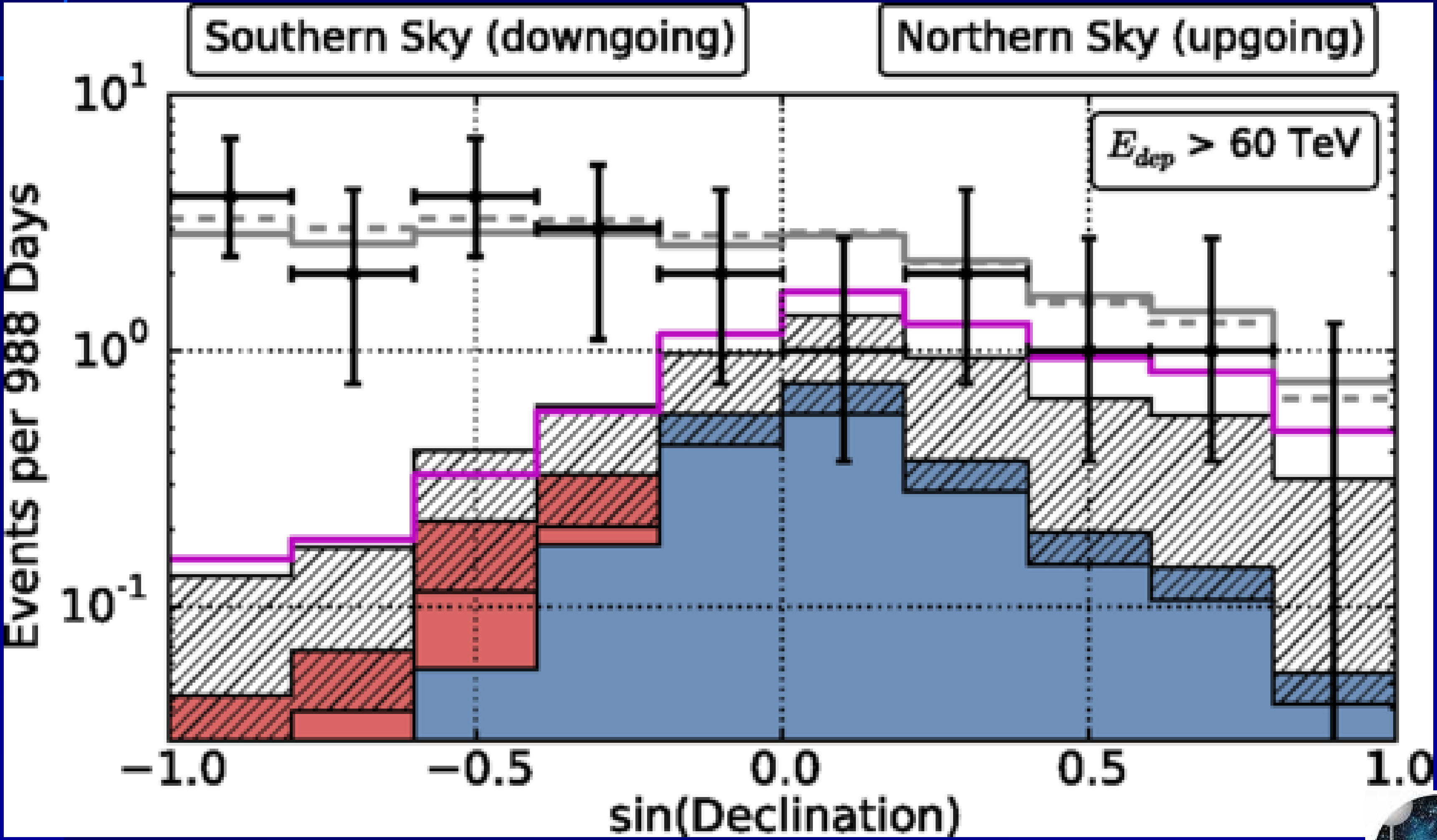
PRL 113 (2014) 101101



$$E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

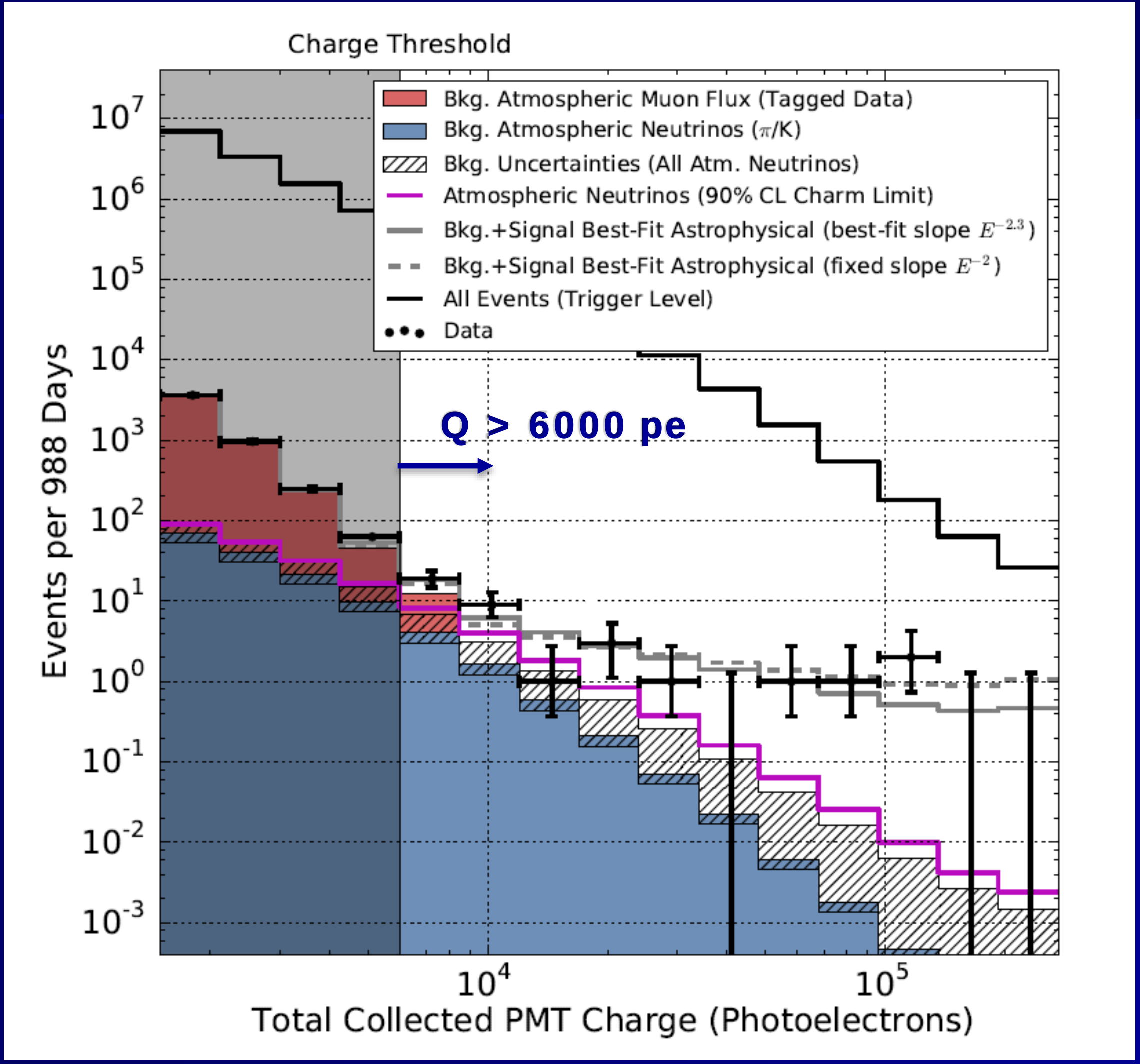
Results, Declination

PRL 113 (2014) 101101



Results, PMT Charge

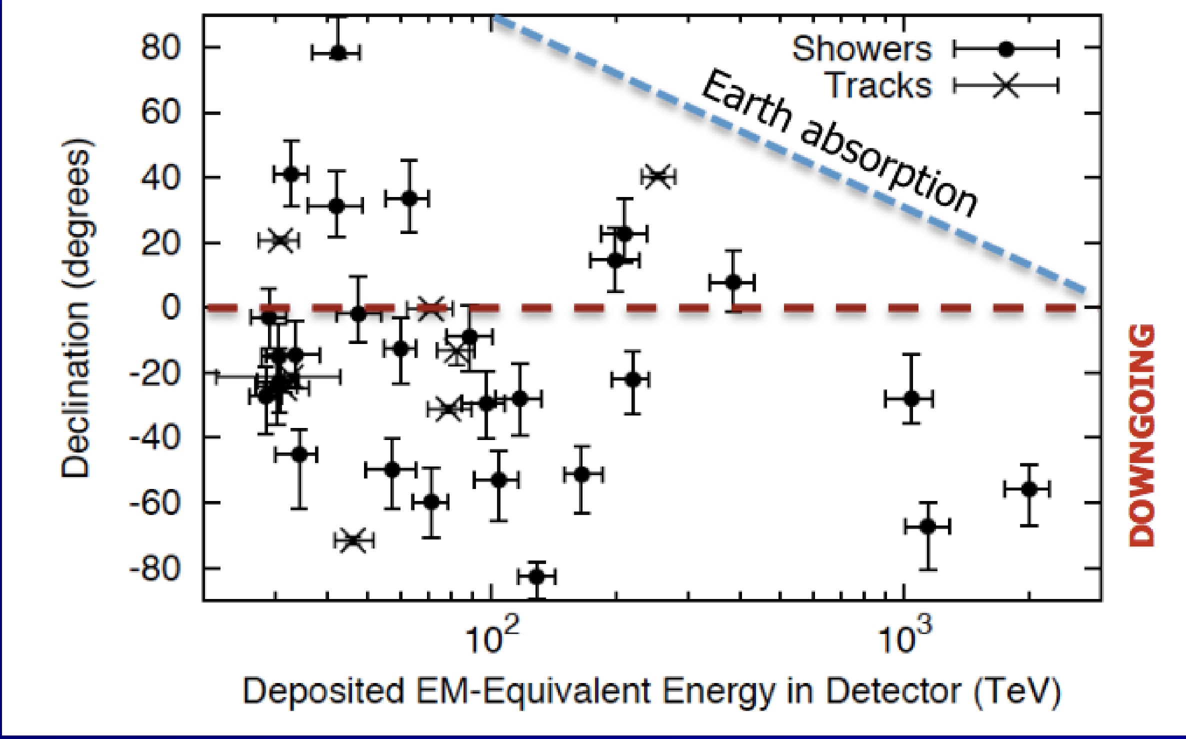
PRL 113 (2014) 101101



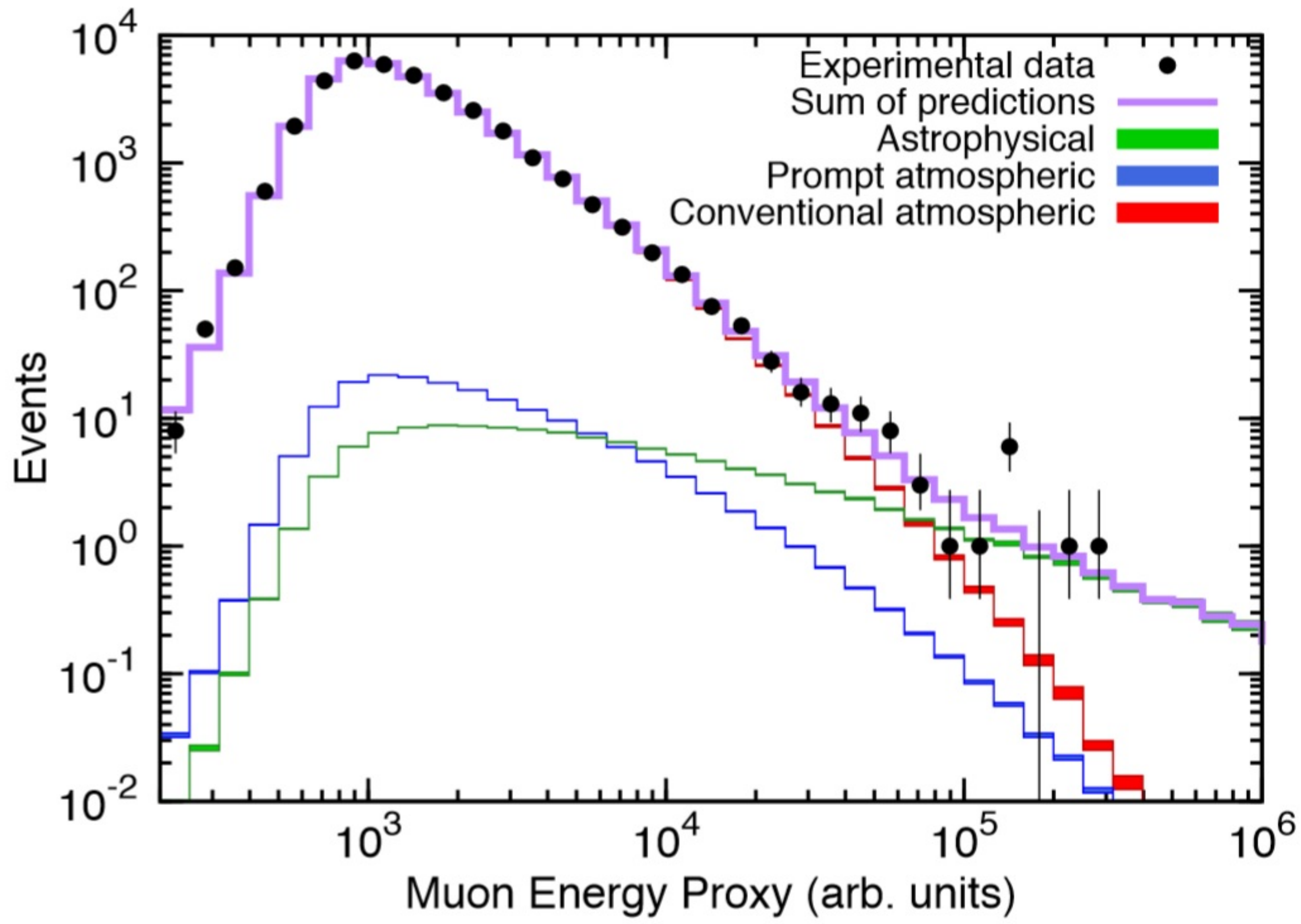
Declination vs. deposited energy

A few observations.

- Signal contains 28 cascades and 9 tracks
- Atmospheric neutrinos: track/cascade = 2
- Most events originate from southern sky because most HE neutrinos from northern sky are absorbed by the Earth
- Excess from the southern sky is not due to atmospheric ν_μ because they are reduced in the south by μ rejection.



Astrophysical Muon Neutrinos Northern Sky

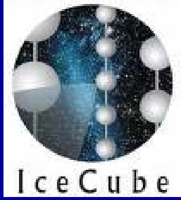


The distribution of reconstructed muon energy proxy for events sample, compared to the expected distributions for an E^{-2} flux. Significance = 3.7σ

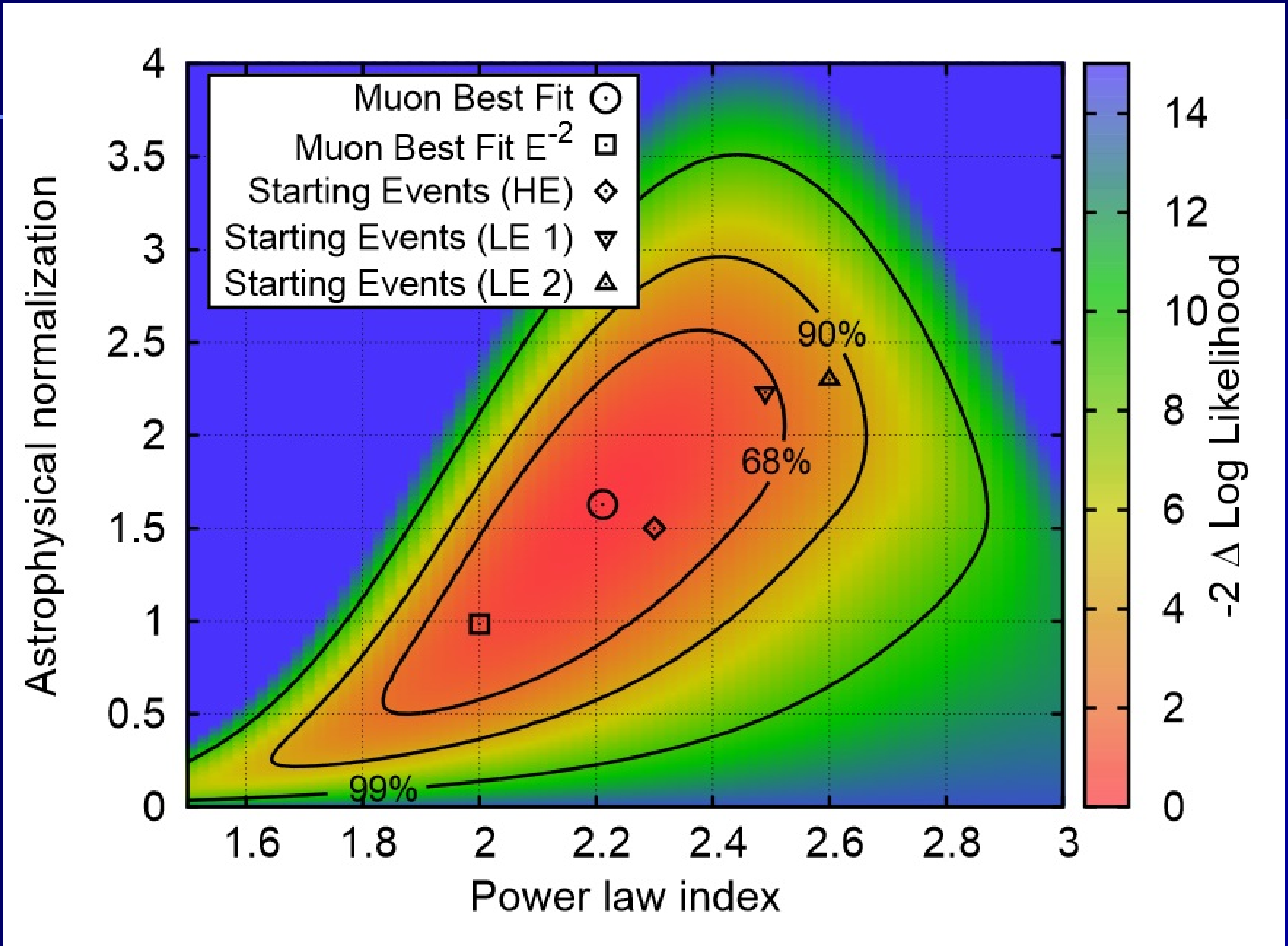
330 TeV<E<1.4 PeV

PRL 115, 081102 (2015)

$$\Phi(E_\nu) = 9.9^{+3.9}_{-3.4} \times 10^{-19}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-2}$$



Astrophysical Muon Neutrinos



Likelihood Search for a Point Source
- Test Statistic (TS) Calculation -

Maximize the likelihood L at every point in the sky x

Total # of events = 28

# of events from source
Varied to maximize L

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Reconstruction map
value at position x
from event i

Uniform value
for each event
at every position

** Events' energies not used in the likelihood*

TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left(L(x) \big/ L_0(x) \right)$$

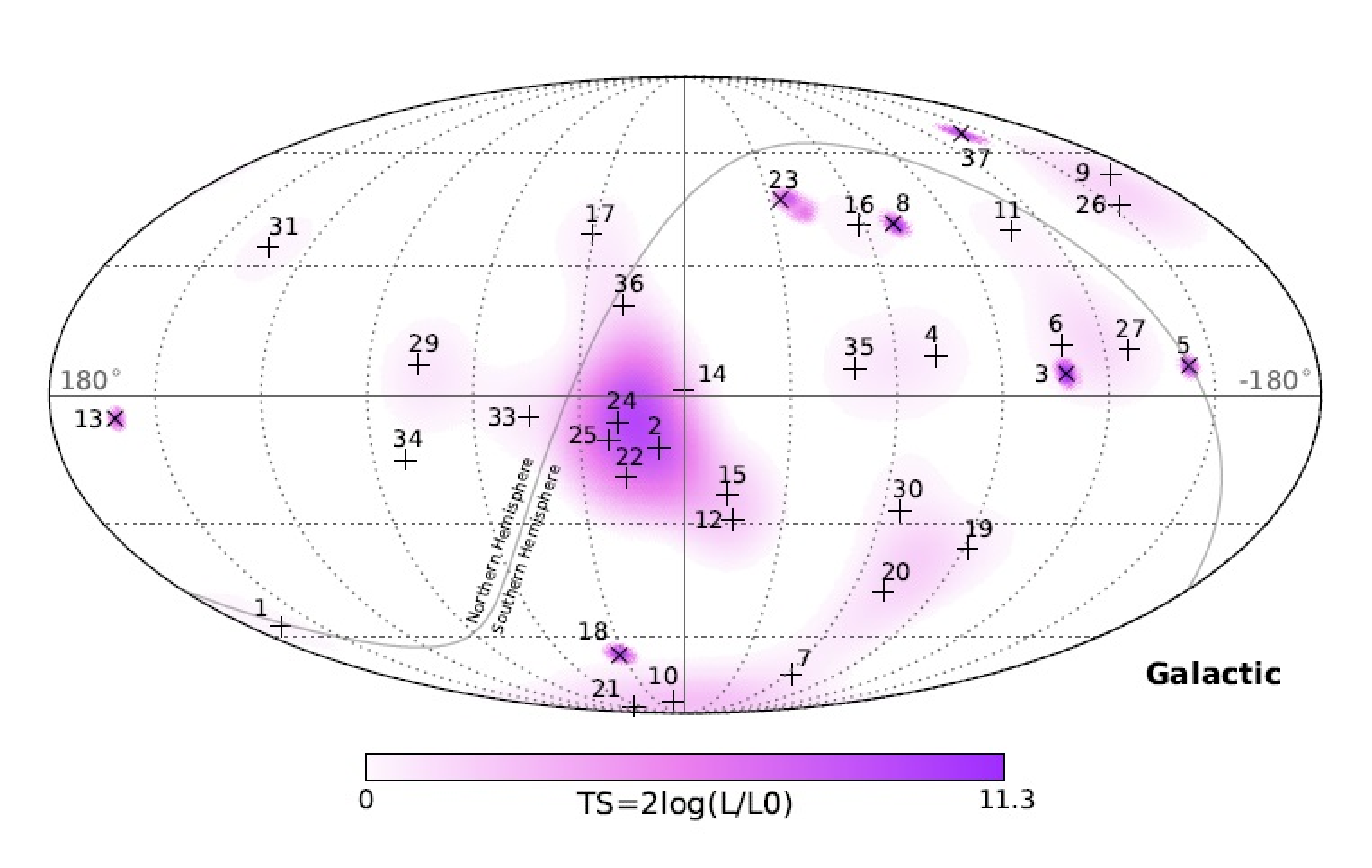
where $L_0 = L(x, n_s = 0)$

Point Source Analysis

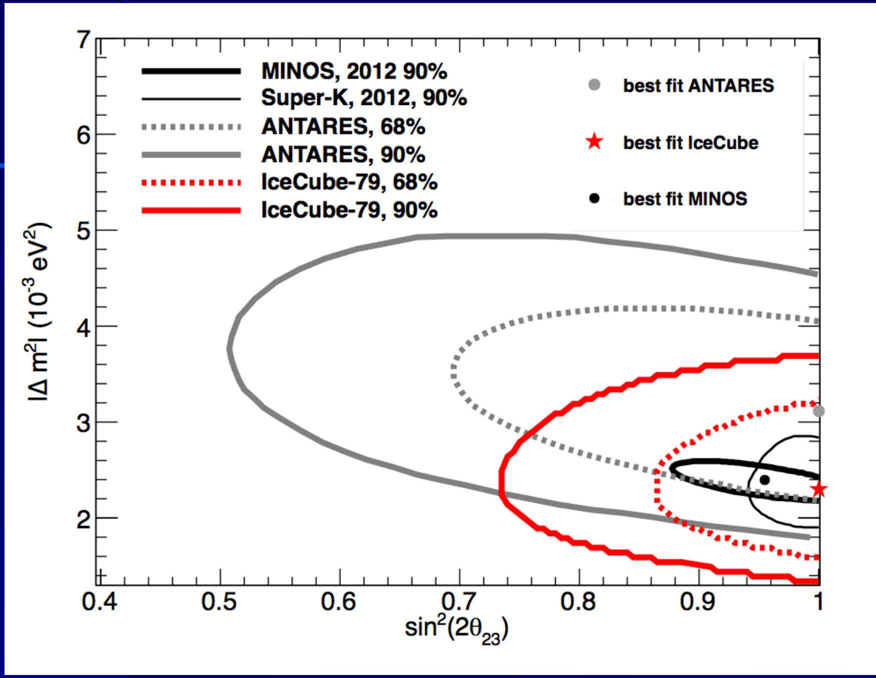
Test null hypothesis vs. most likely
L0: null hypothesis
L: maximized likelihood

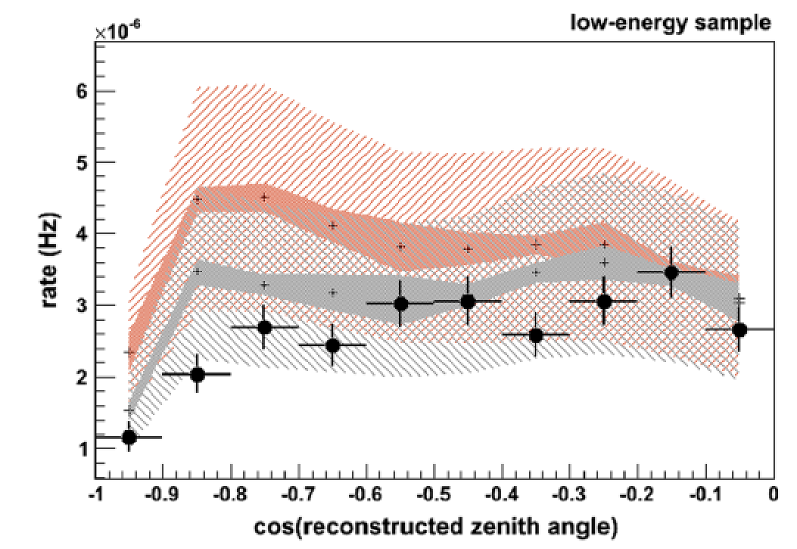
x: tracked events
+: cascade events

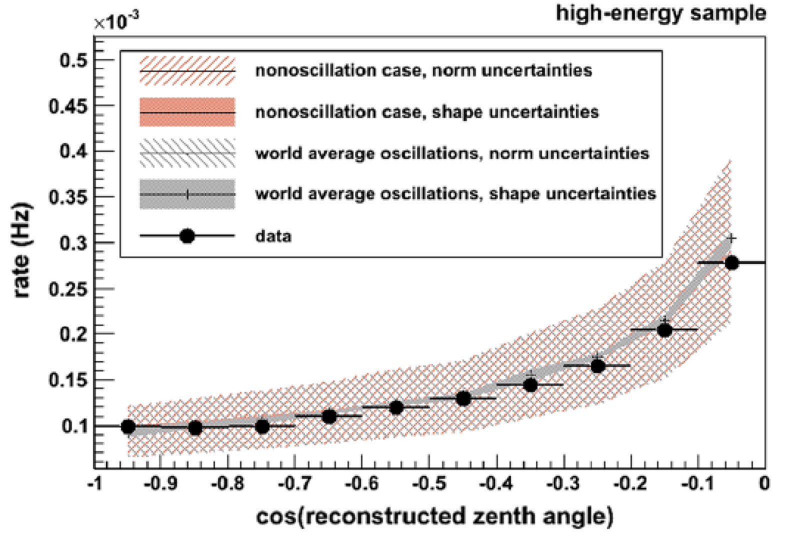
All event p-value = 80%
Cascade events p-value = 8%



Atmospheric ν Oscillations







Data from IC-79 (319 days)

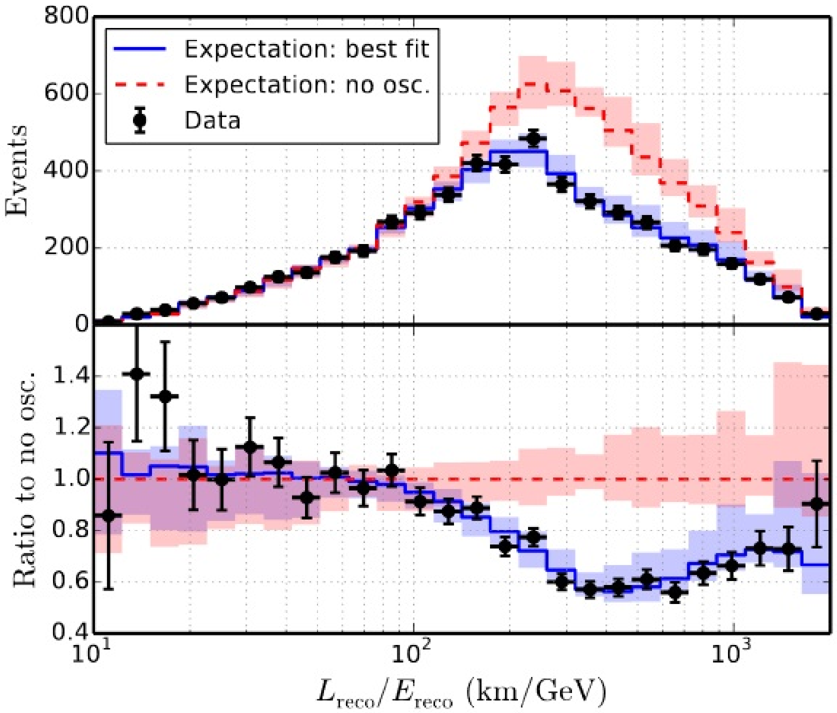
$\Delta m_{32}^{2} = 2.3^{+0.6}_{-0.5} \times 10^{-3}\ eV^{2}$

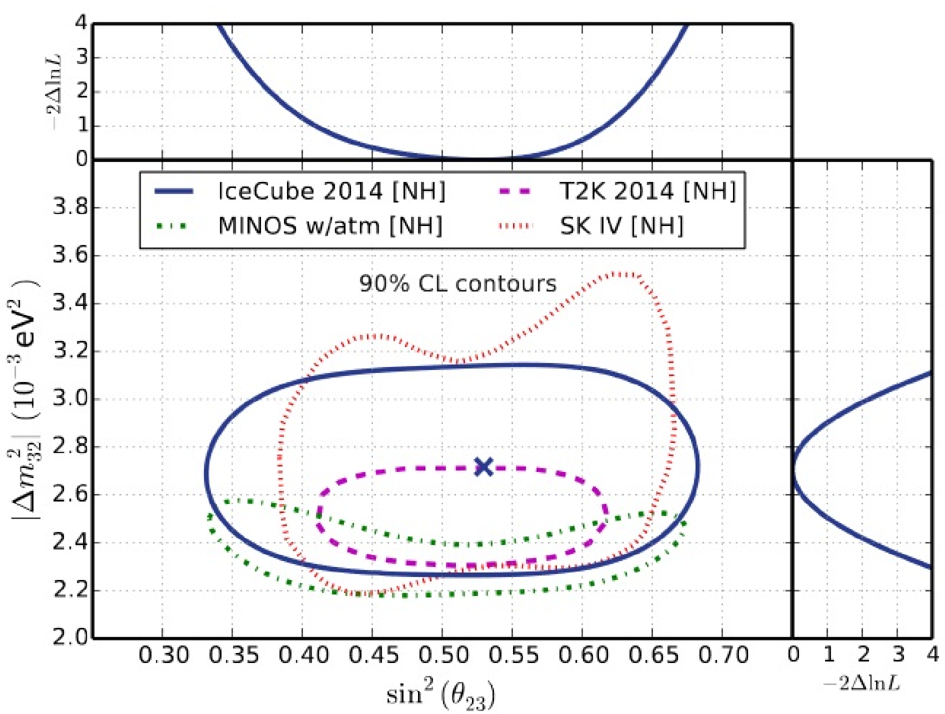
sin2 $(2\theta_{23}) > 0.93$ (68% $C.L.$)

PRL, 111, 081801 (2013)

Atmospheric ν Oscillations

Phys. Rev. D 91, 072004, 2015
3 year data 2011-2014

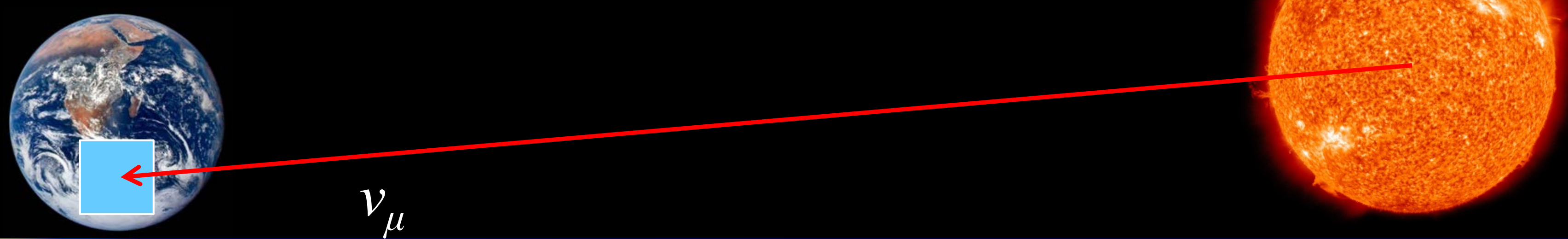




Normal mass hierarchy, 90 % CL

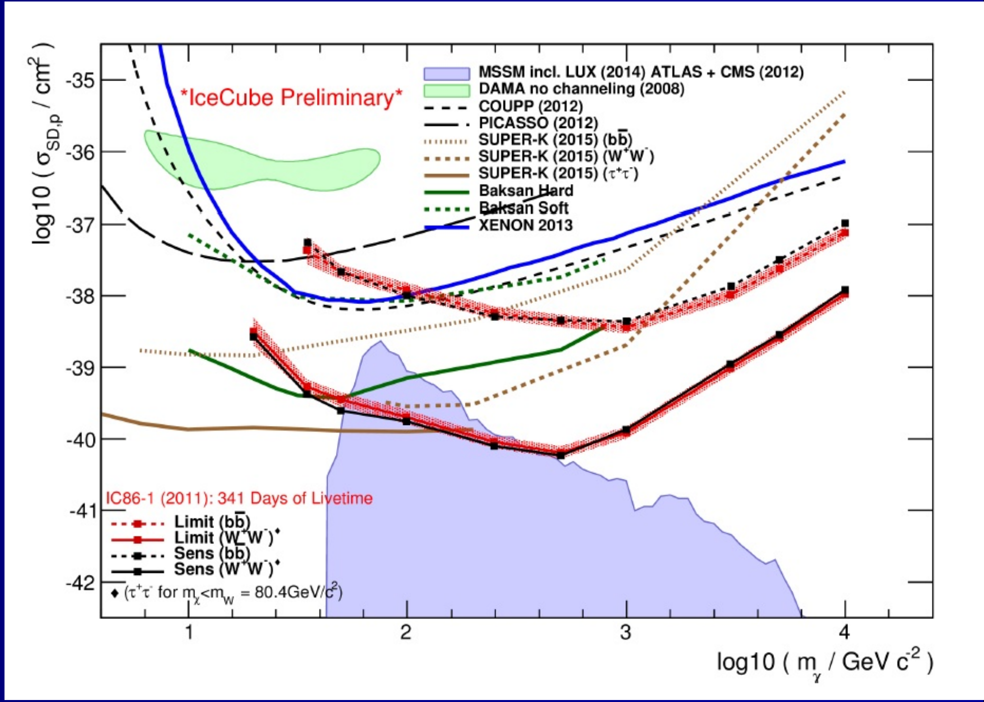
$$\Delta m^2_{32} = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2 \text{ and } \sin^2\theta_{23} = 0.53^{+0.09}_{-0.12}$$

Dark Matter Search from the Sun



$$\chi^0\chi^0 \longrightarrow W^+W^-, \; W \longrightarrow \mu\nu_\mu$$

Neutralinos scatter inside the Sun, get trapped in its gravity field, and annihilate producing W's and other SM particles decaying into μ neutrinos that interact inside IceCube and produce μ tracks which can be pointed back to the Sun.

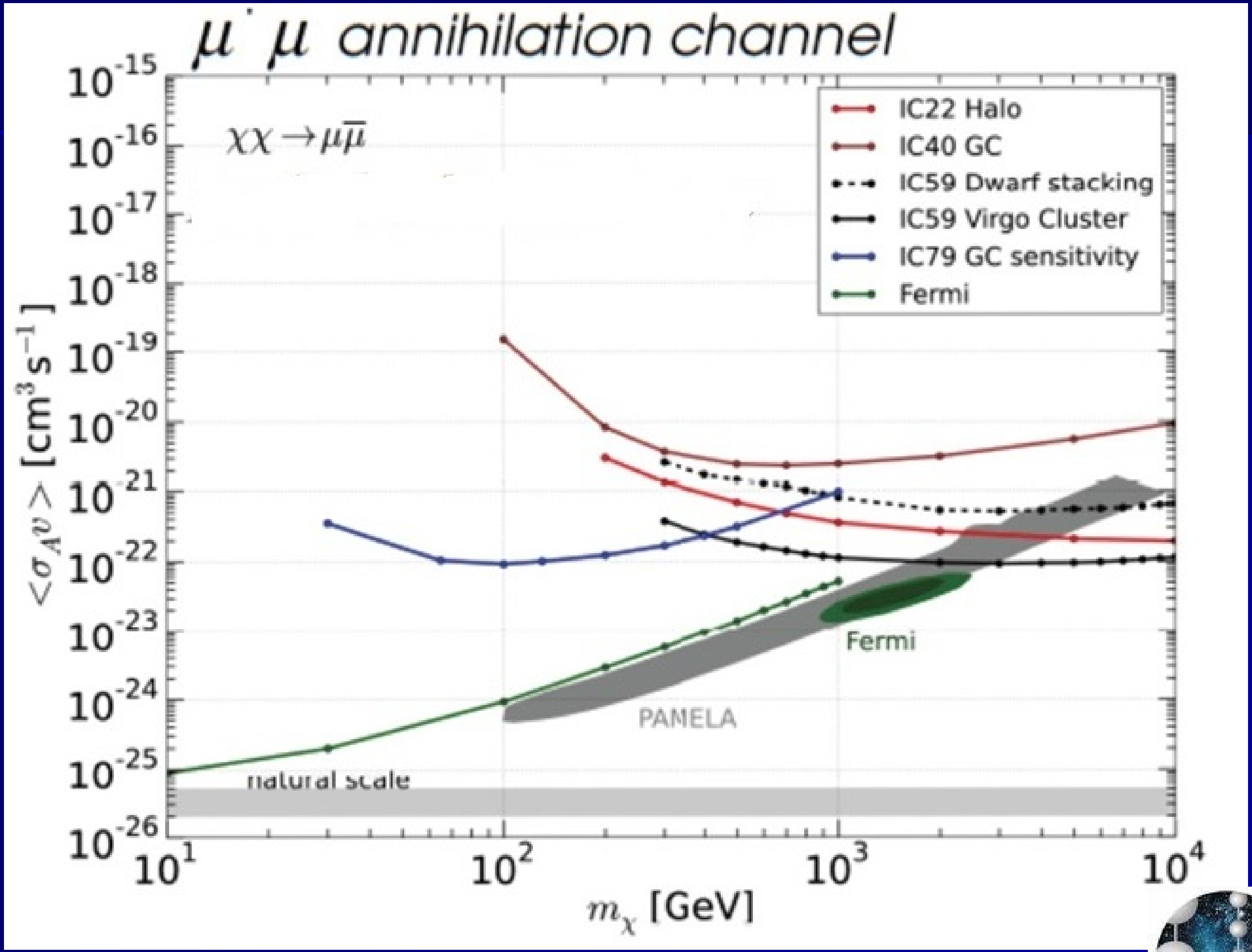


IceCube Collaboration, M. Rameez, T. Montaruli, S. Vallecorsa for the IceCube Collaboration The 34th International Cosmic Ray Conference, 30 July- 6 August, 2015, The Hague, The Netherlands

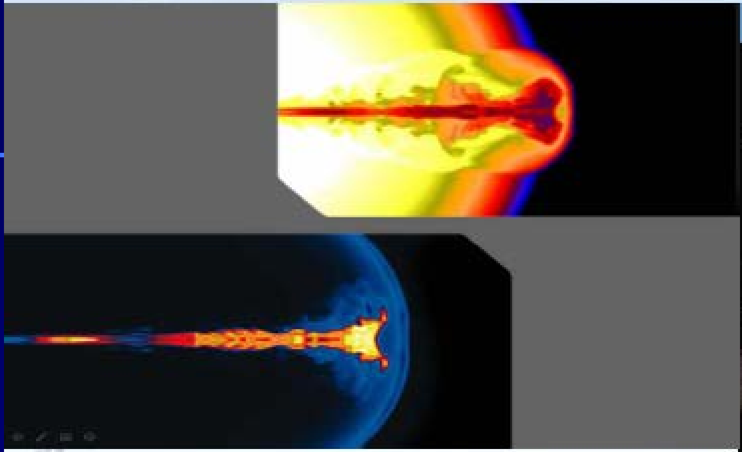
Dark Matter Search in the Milky Way

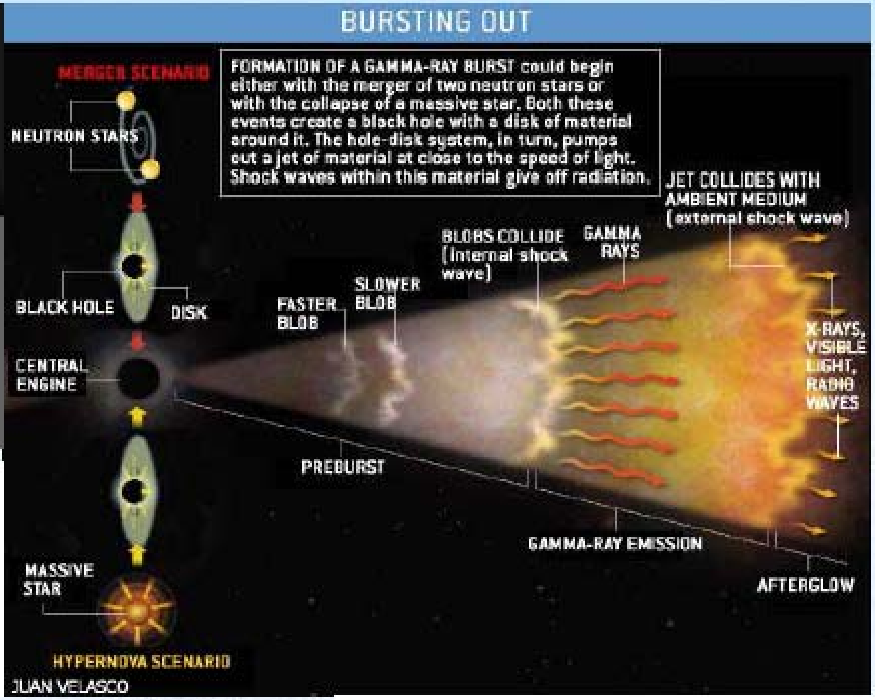
IC-79 (320 days)
No excess found

IceCube is sensitive to a minimum WIMP mass of 30 GeV.



Gamma-Ray Bursts





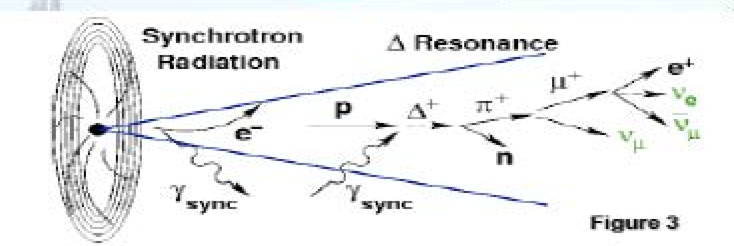
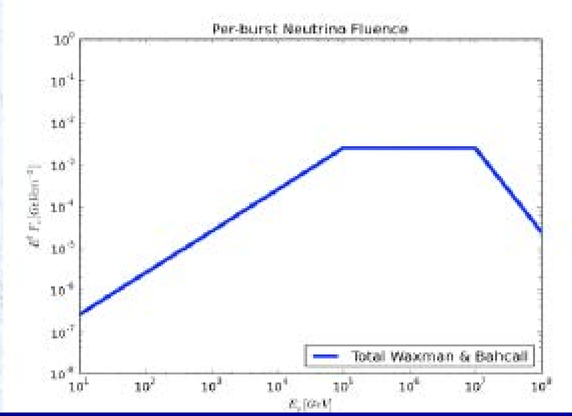


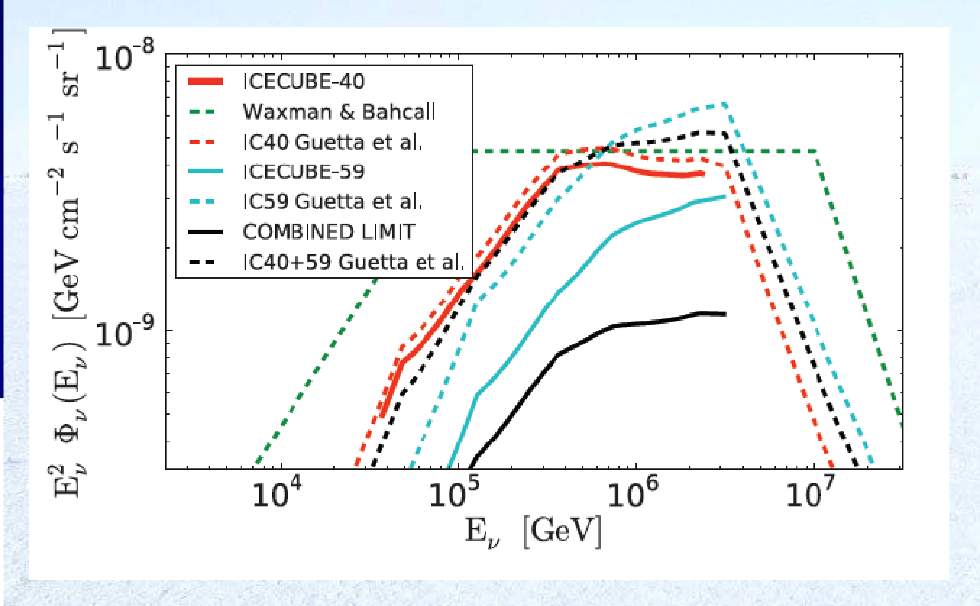
Figure 3

Fireball model:

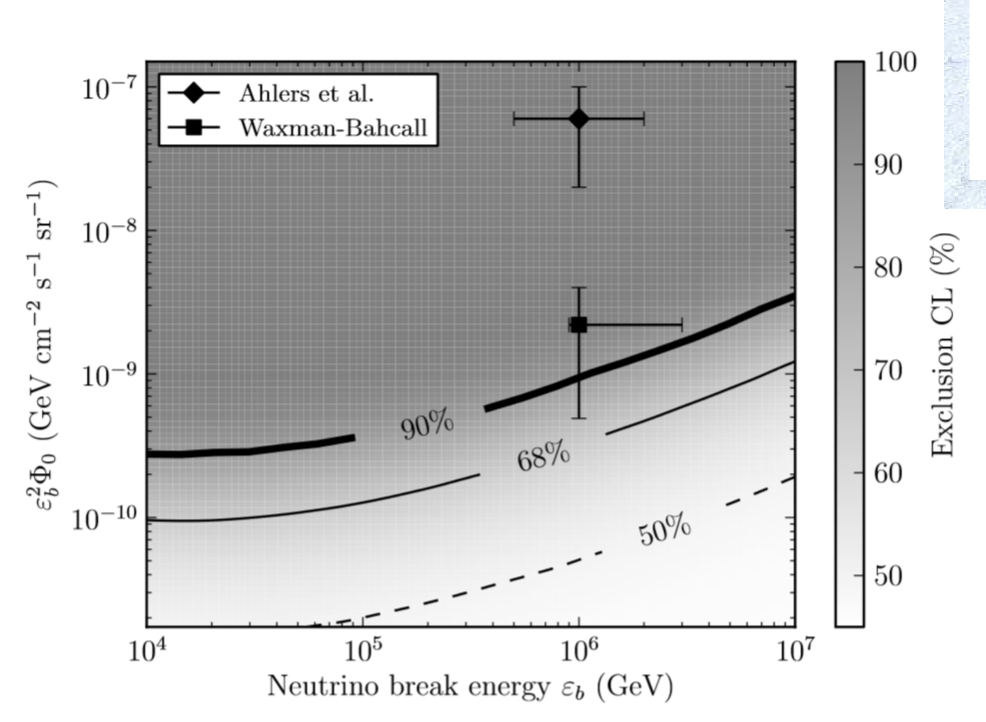
- Internal shocks in GRBs → acceleration for UHECRs.
- Neutrino production in γ-hadron interactions in fireball



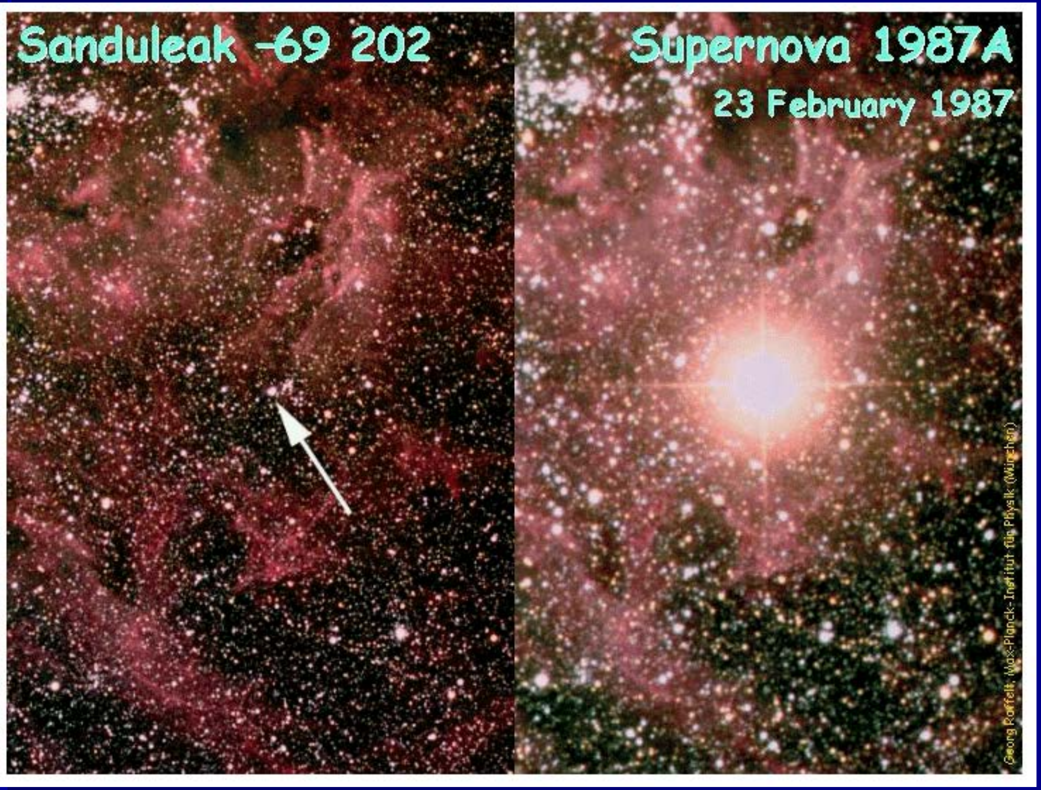
IC40 data **2008-2012** (508 GRBs in northern sky). **No coincidence found. Note, analysis has very low background because both direction and timing coincidence are applied.**

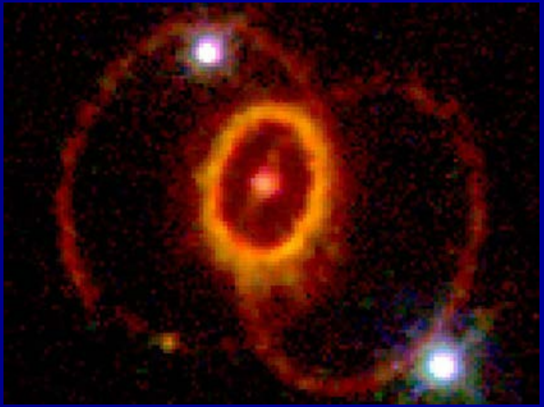


APJ, Letter 805 1 , 2015
4 years of data, we found 1 neutrino event correlated with A GRB with p = 0.46



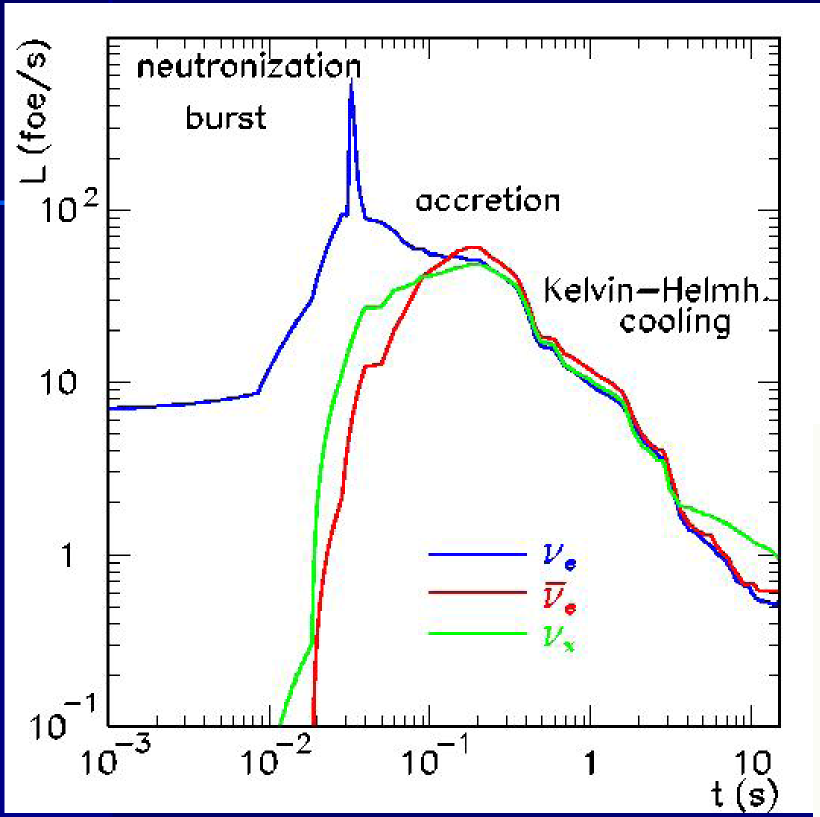
IceCube: A Supernova Detector





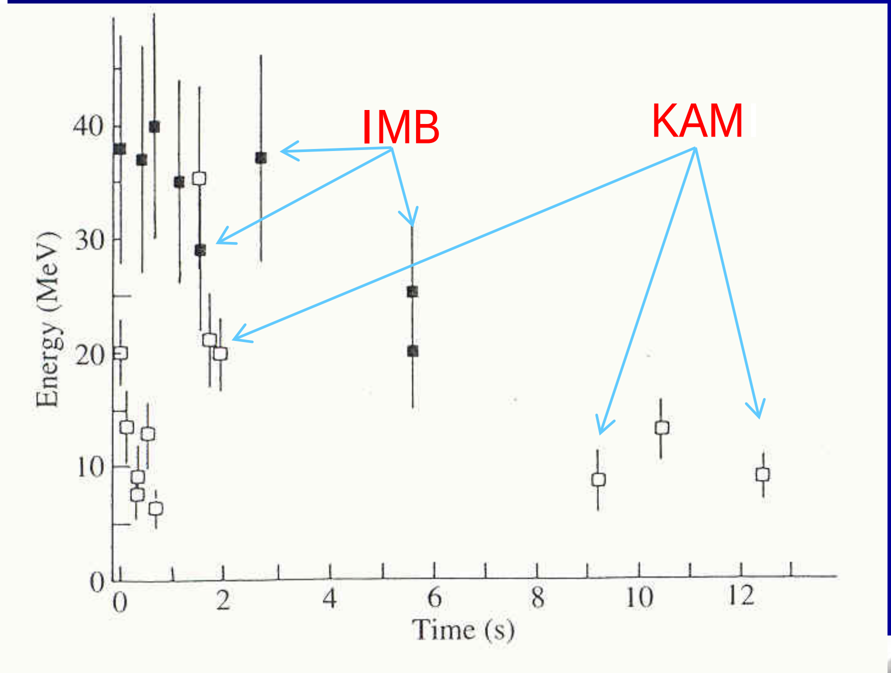
Ali R. Fazely, Miami Conference, December 16 -22, 2015

Neutrino Spectra from SN

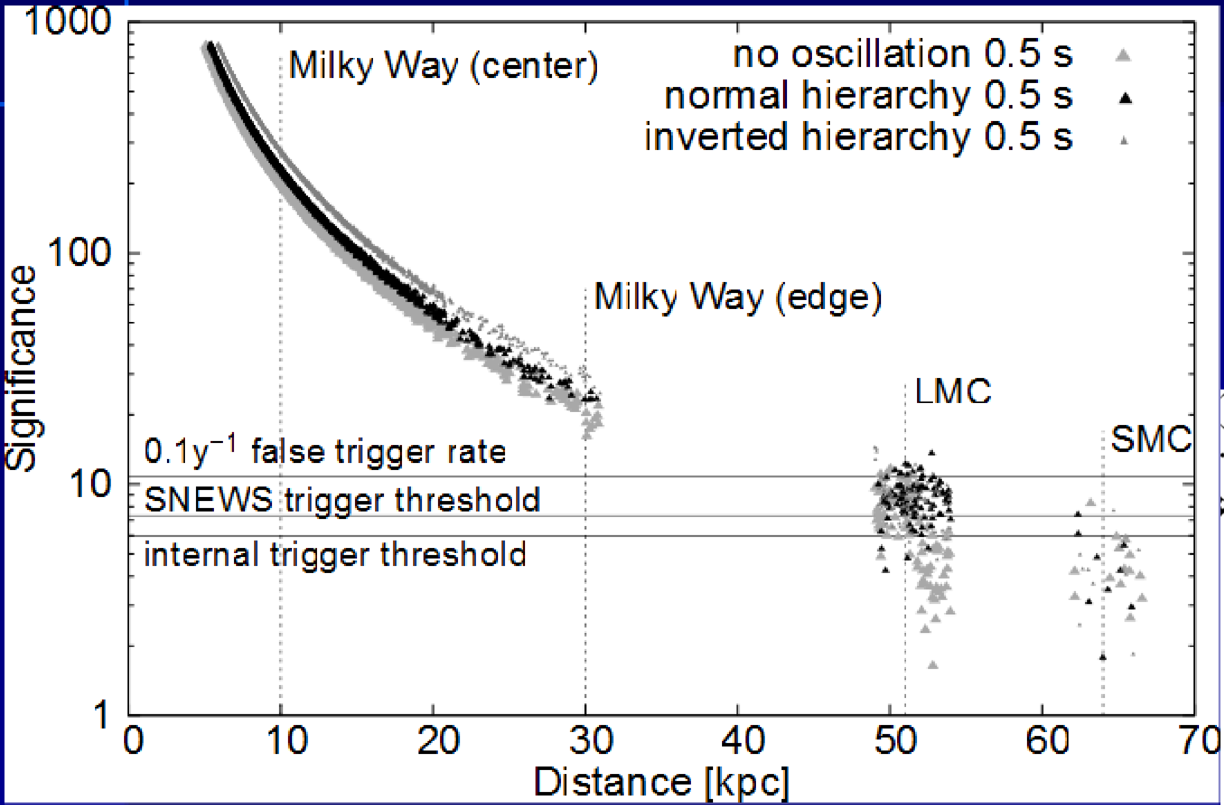


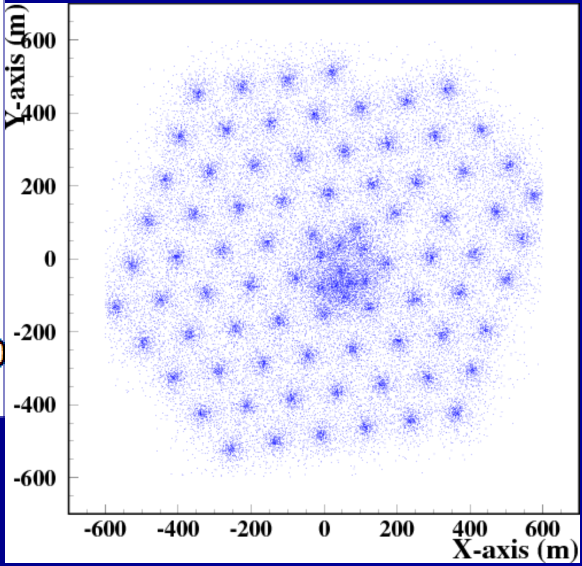
Totani et al., (1998)

SN87A Events
IMB & Kamioka



IceCube Sensitivity to SN Explosions





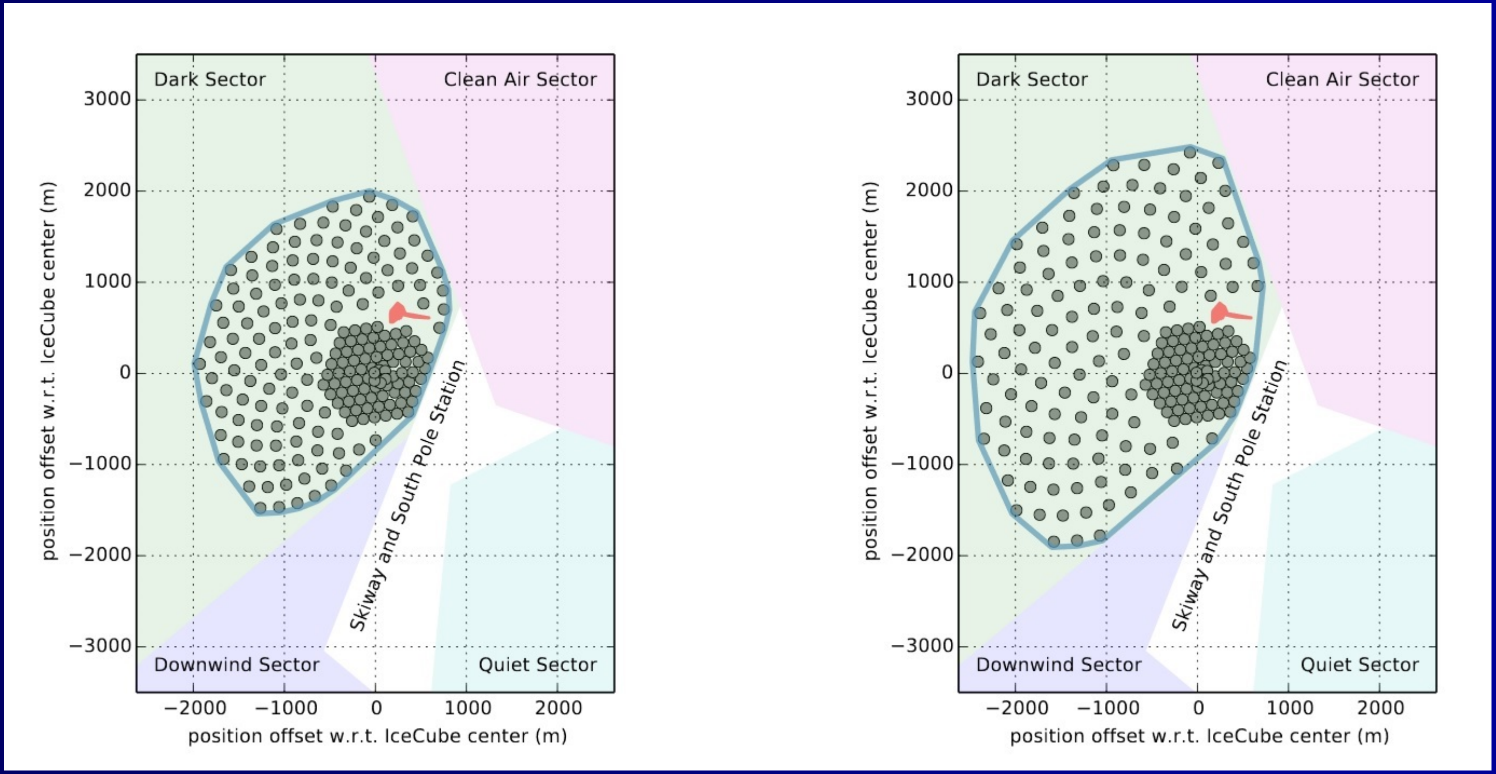
A&A 535, A109 (2011)

Future Plans, IceCube-Gen2

Larger IceCubes, up to more than an order of magnitude in mass/volume. Much higher statistics in the PeV region, much higher energy neutrino acceptance, a deeper view of the cosmos and source ID of high energy neutrino production.

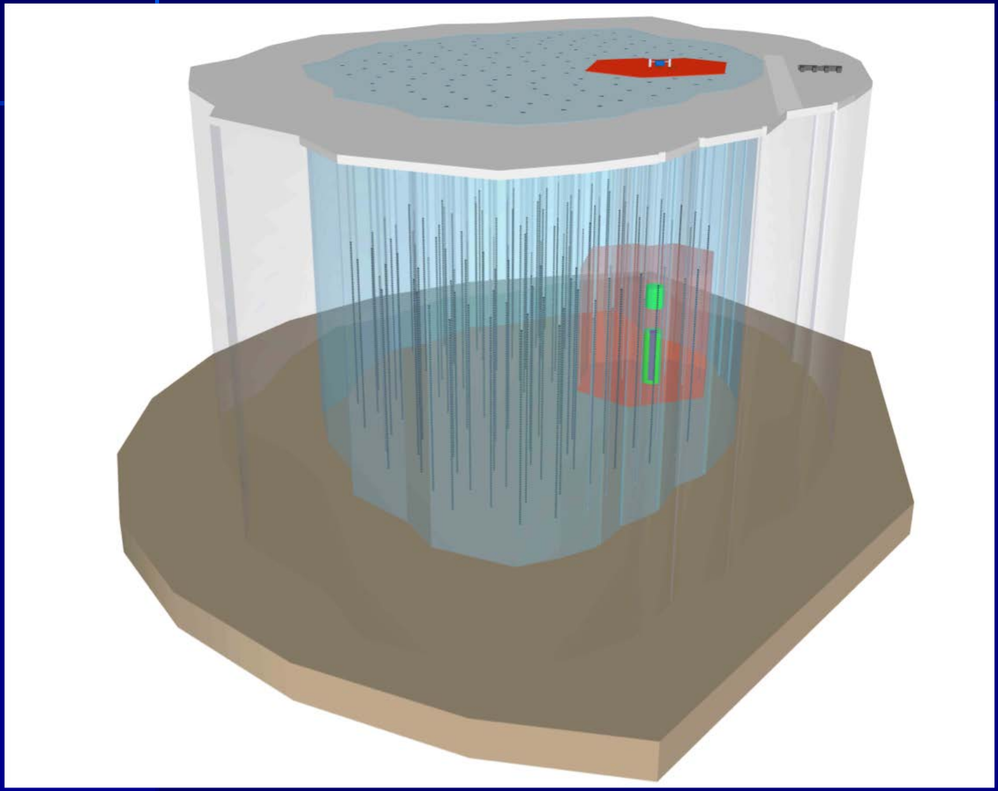
PINGU, acronym for Precision IceCube Next Generation Upgrade, is a proposed dense array and has physics goals such as precision measurements of neutrino oscillations (mass hierarchy, …) and other physics such as test of low mass dark matter models. arXiv:1412.5106

240 m Spacing

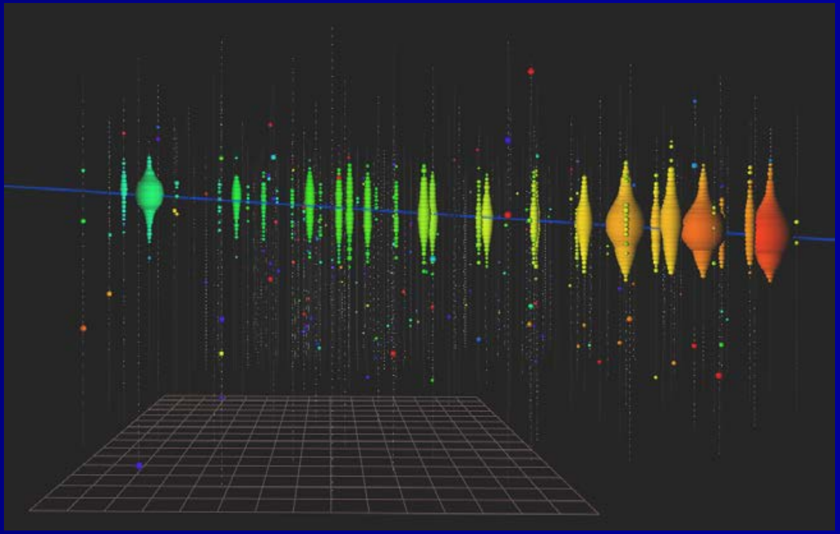


300 m spacing

Future Plans, IceCube-Gen2



A simulated 60-PeV horizontal muon



Overall Conclusions

- IceCube has observed High Energy Astrophysical Neutrinos and has achieved its main goal of opening the era of neutrino astronomy.
- Further question: what is the origin of the high energy neutrinos?
- IceCube is in it for the long haul and more data is yet to come.
- Future plans: IceCube Extensions for Higher Energies and PINGU dense array for Neutrino Mass Hierarchy ... ...

IceCube