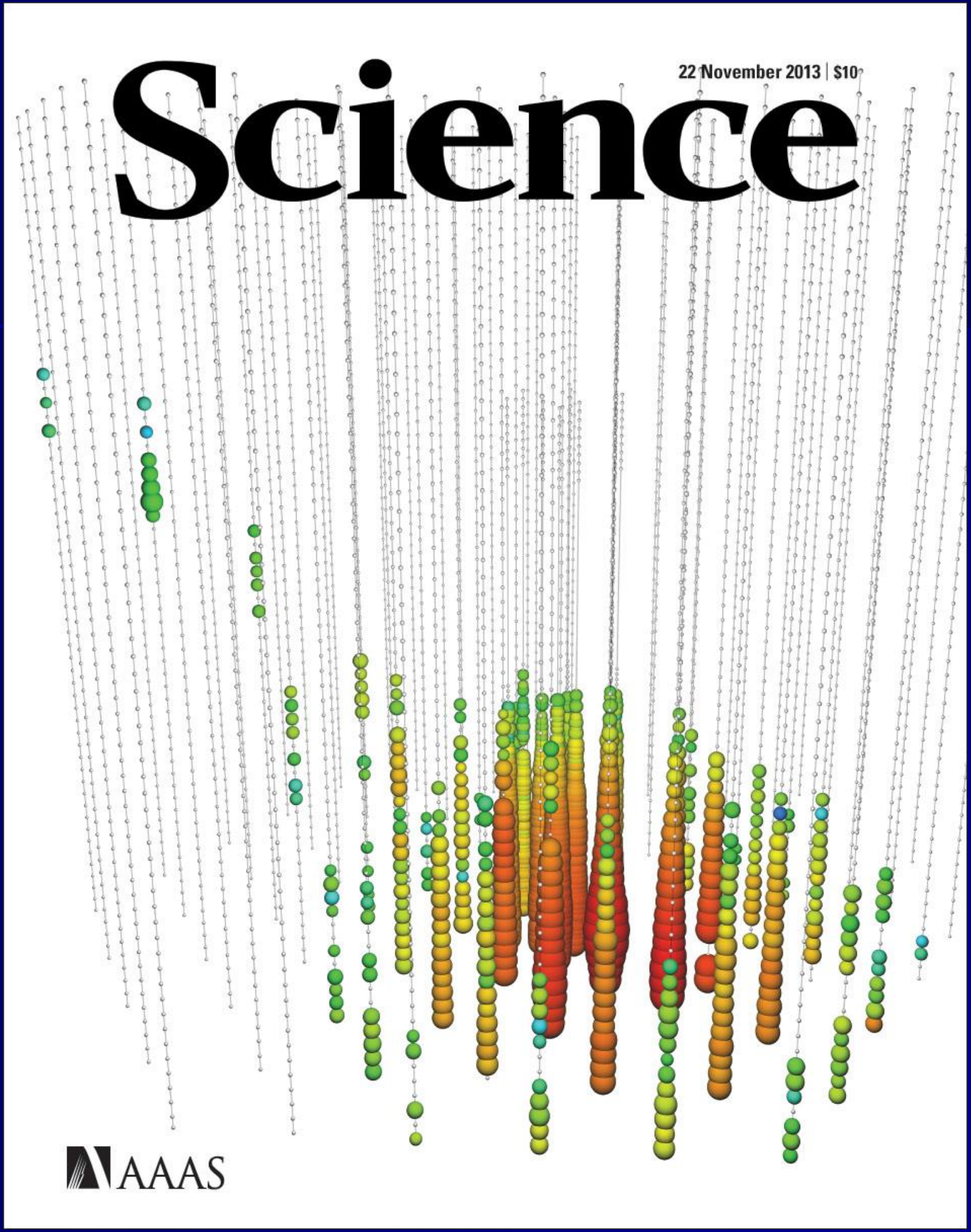
IceCube: Results and Status

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

Ali R. Fazely for the IceCube Collaboratrion.
icecube.wisc.edu

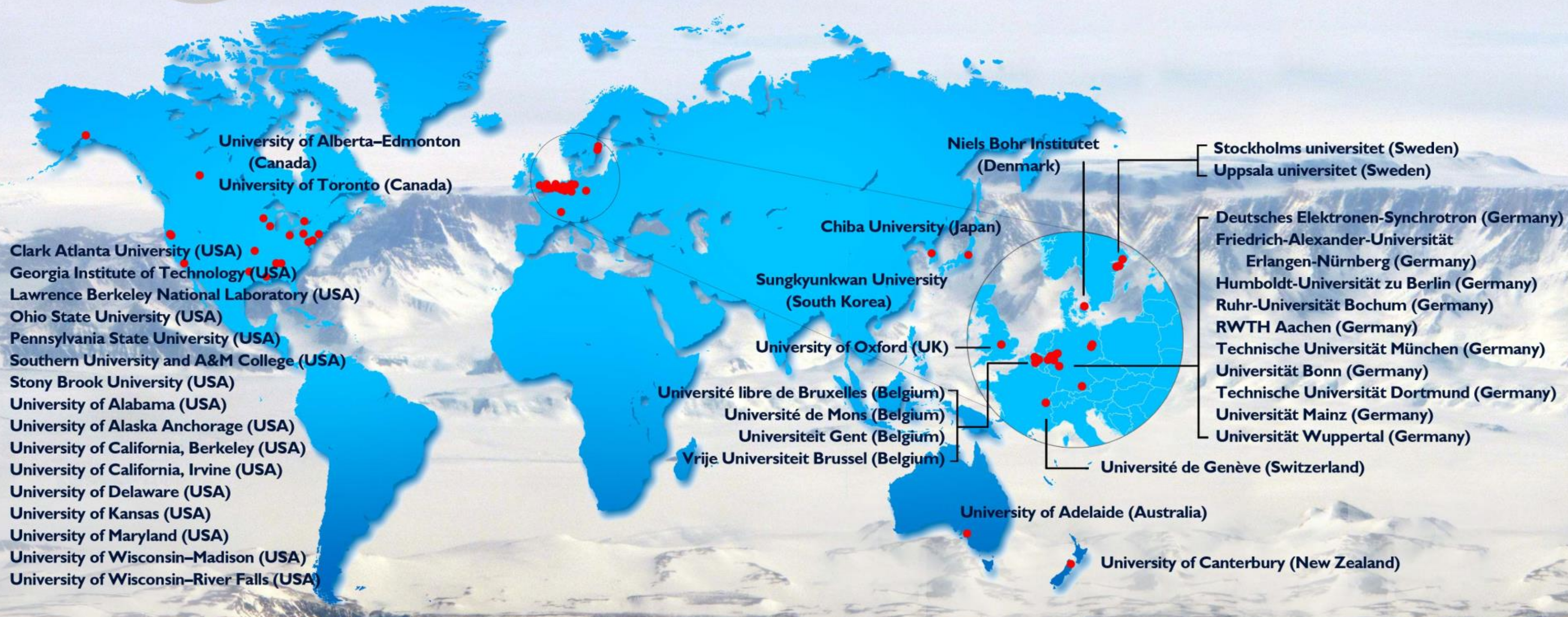
IceCube


Science
22 November 2013 | $10
AAAS

What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies
- We are in our 10th 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 just opened up the neutrino window to the cosmos and has ushered in the dawn of Neutrino Astronomy. Science Cover Article November 22nd 2013.
- http://icecube.wisc.edu/

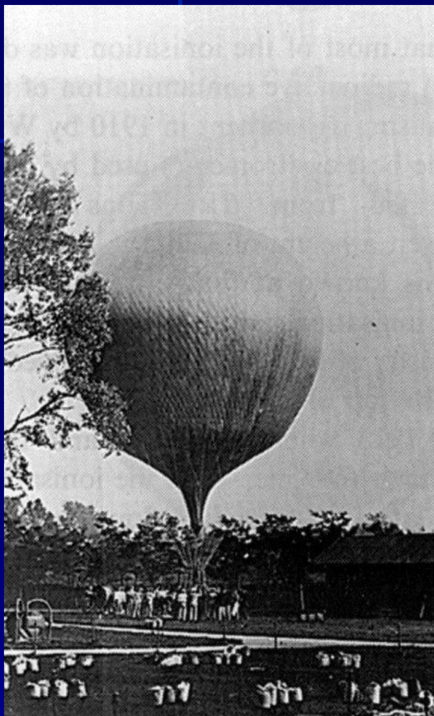
The IceCube Collaboration



International Funding Agencies

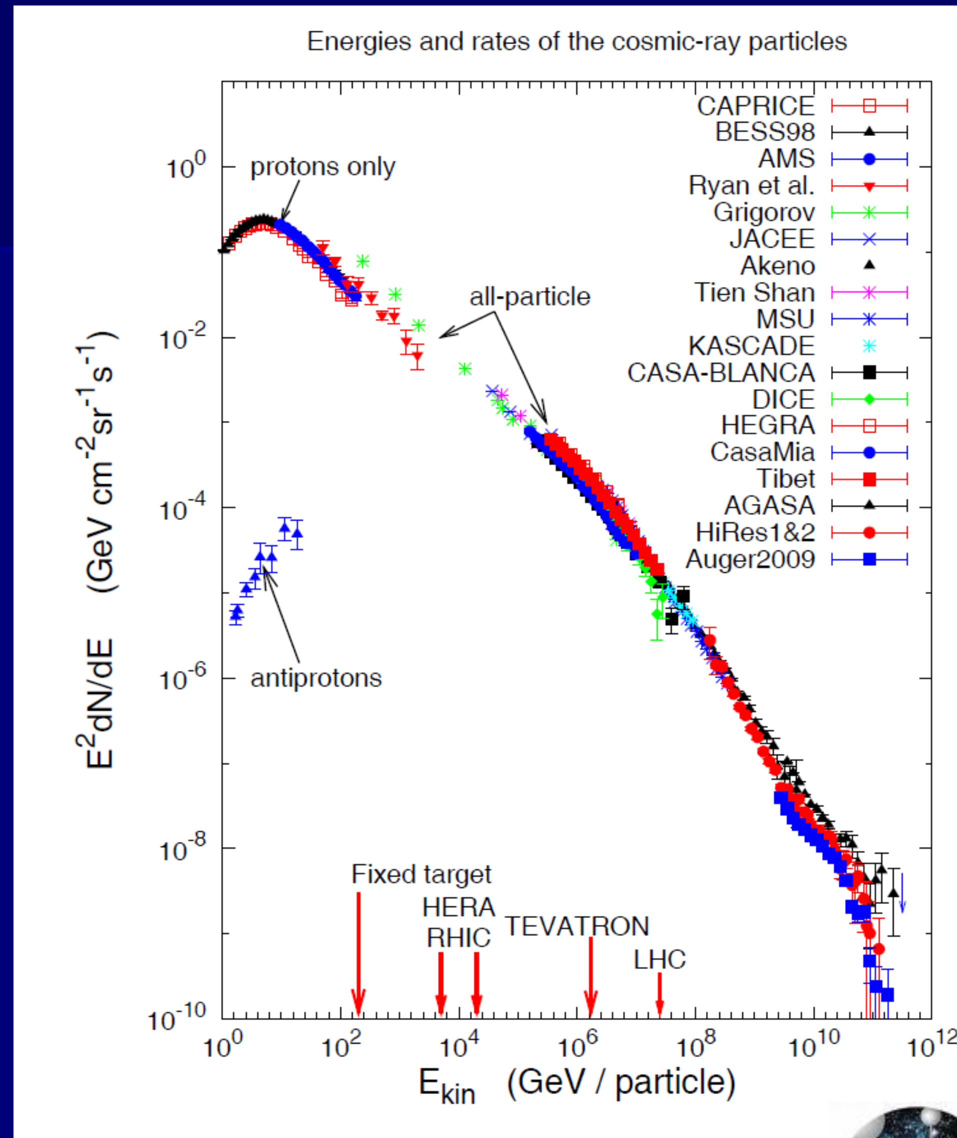
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
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

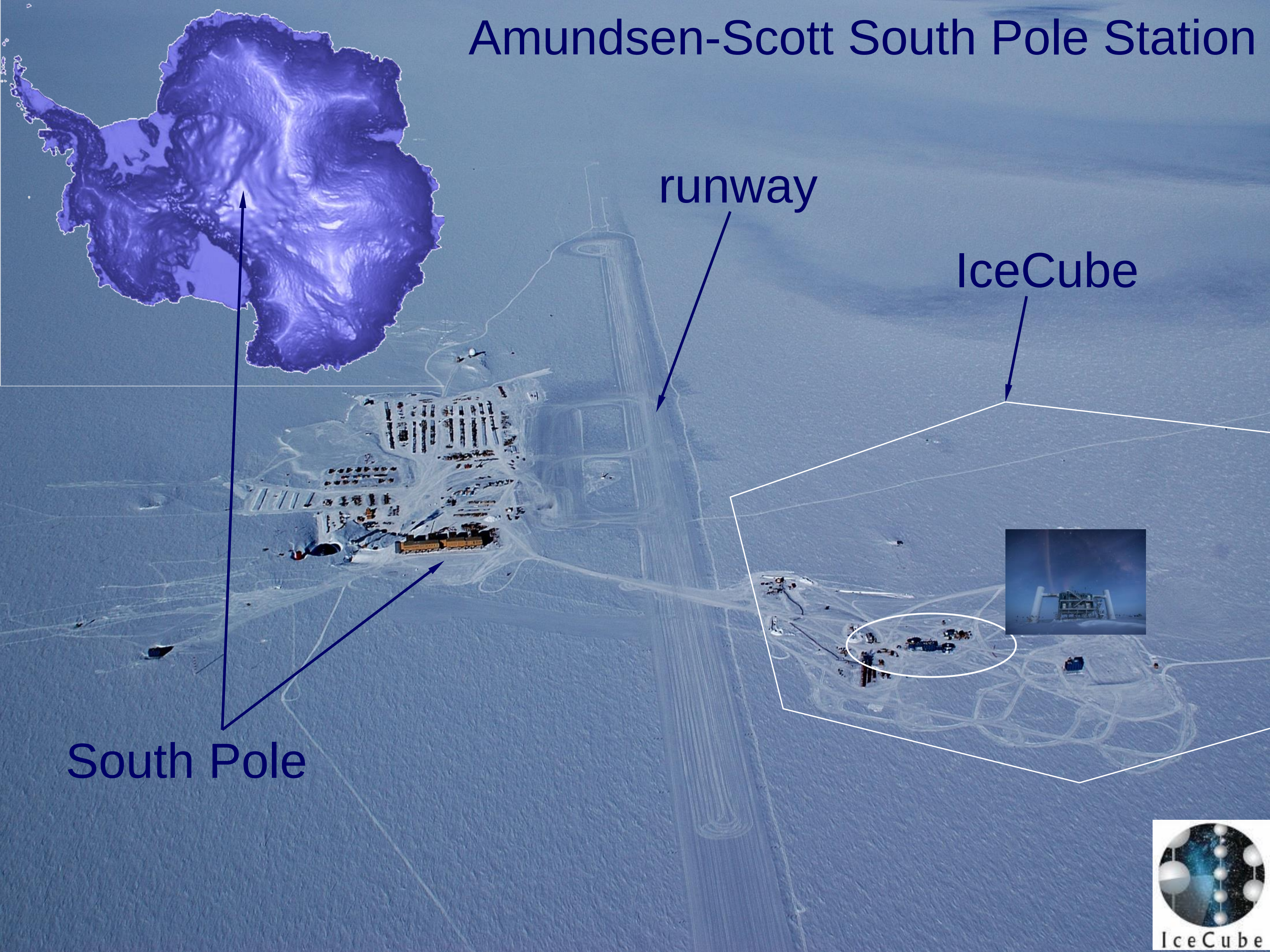


Balloon flights
1911-1913

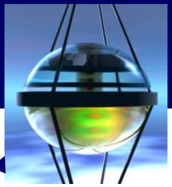
Victor Hess
Nobel Prize
1936

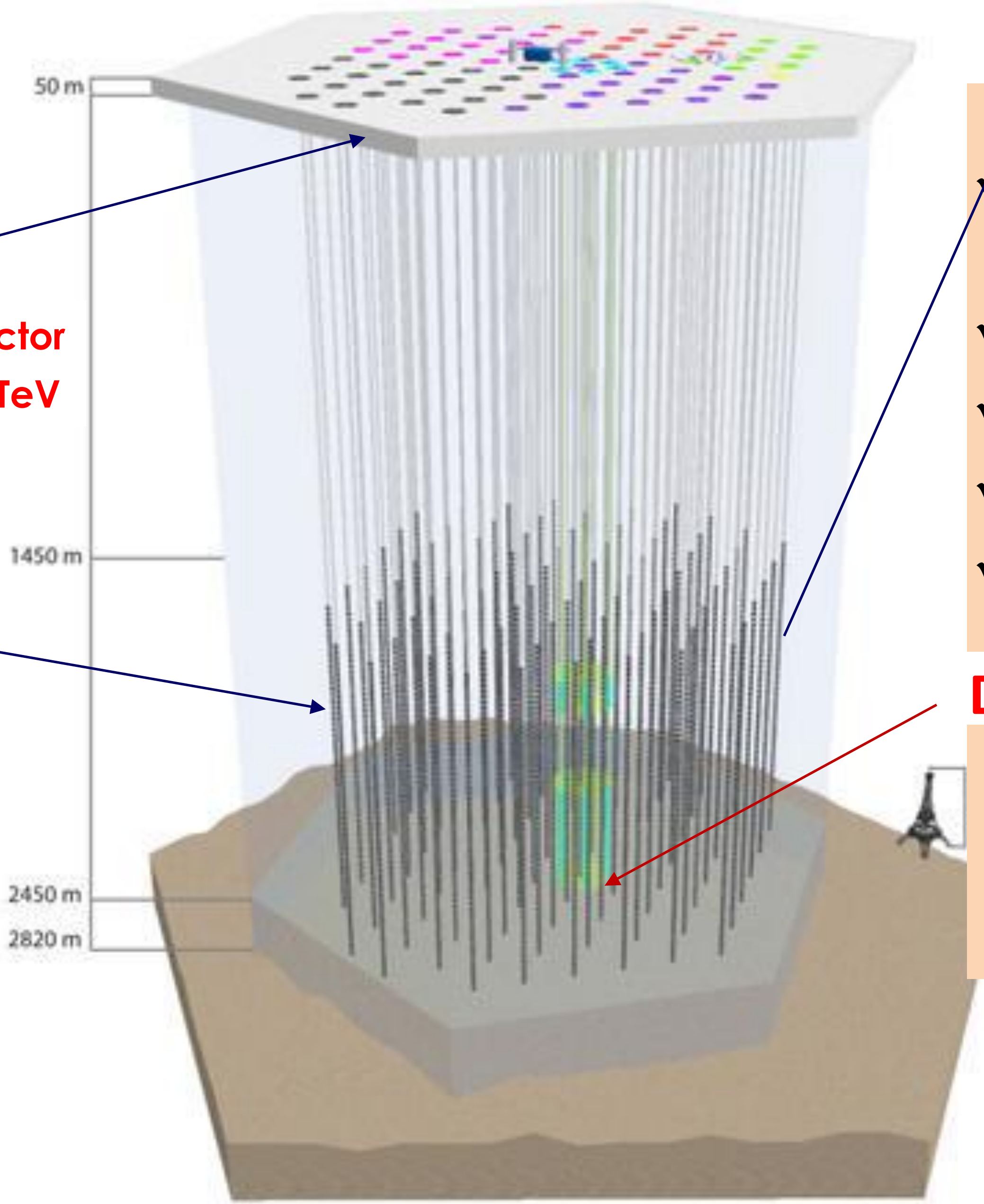


- Power law over many decades
- Origin Uncertain


Amundsen-Scott South Pole Station
runway
IceCube
South Pole

The IceCube Detector





IceTop

Air shower detector threshold ~ 300 TeV

InIce

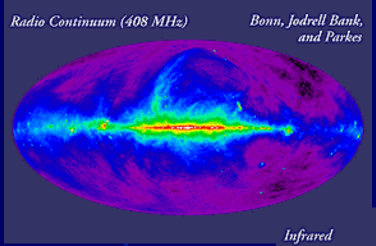
86 Strings, 60 Optical Modules per String

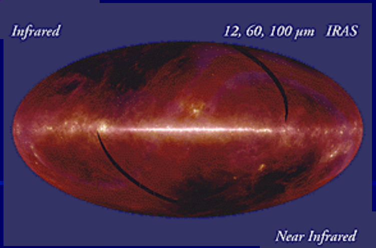
- ✓Completion: December 2010
- ✓86 strings
- ✓2010: 79 Strings
- ✓2009: 59 Strings
- ✓2008: 40 Strings

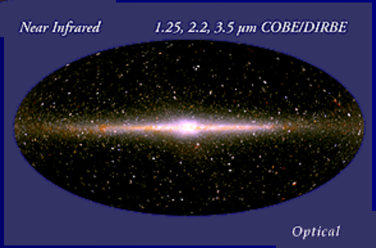
Deep Core

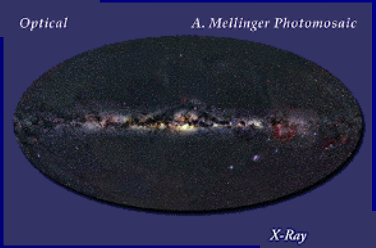
IceCube

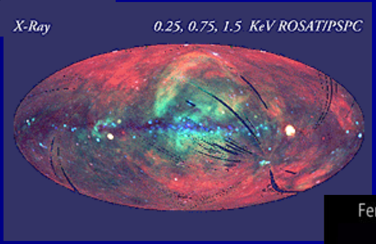
Observing the Universe

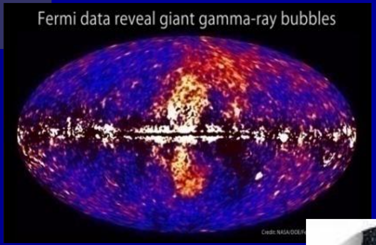


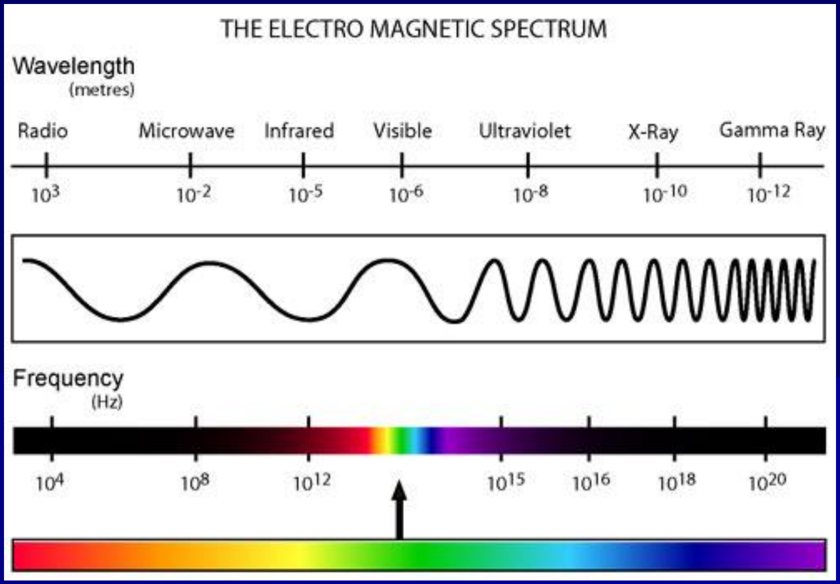






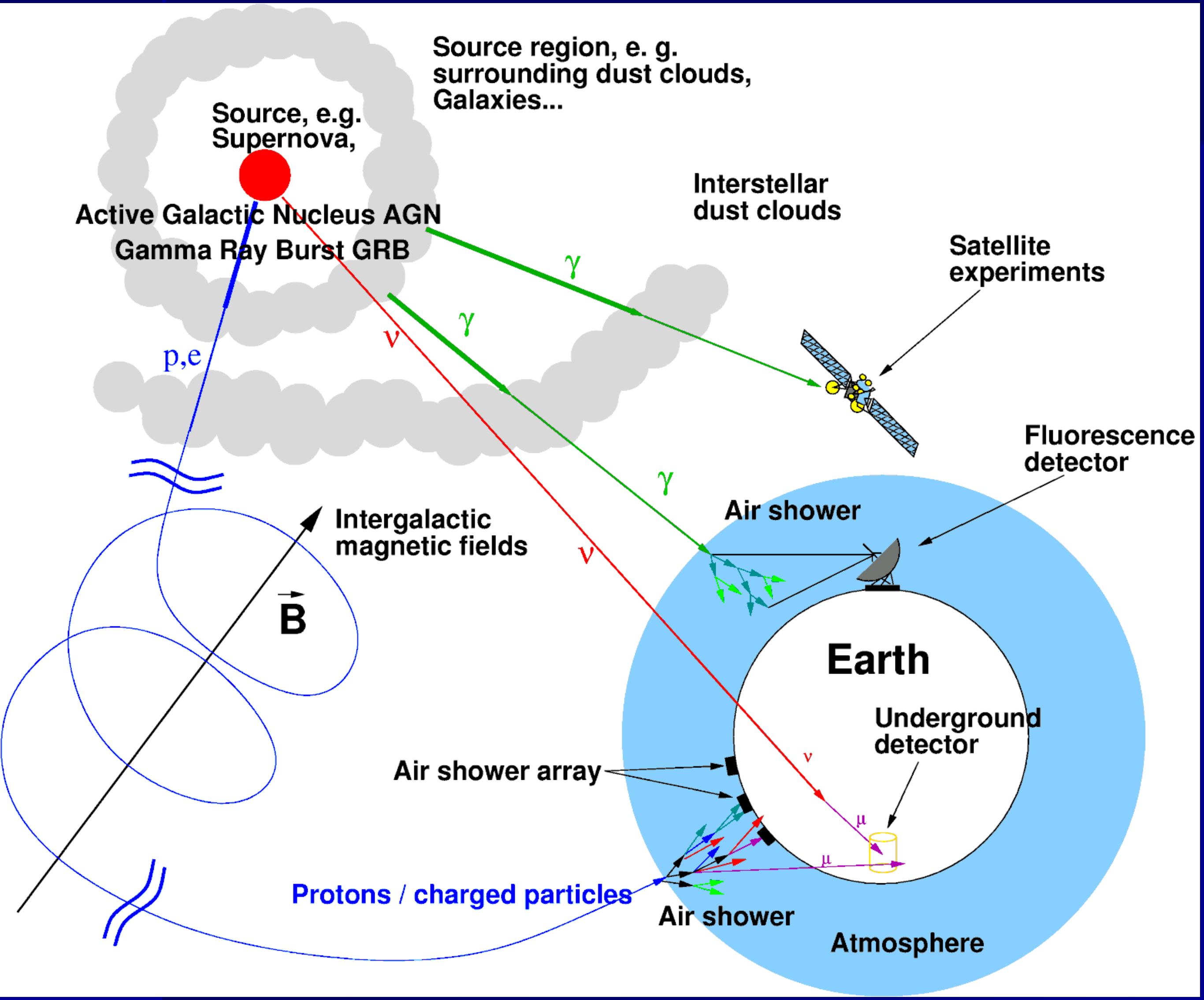






http://mwmw.gsfc.nasa.gov/mmw_allsky.html

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.

Slow History of Neutrinos!

1930 Pauli proposes Neutrinos

1956, Reines and Cowan discovery of neutrinos

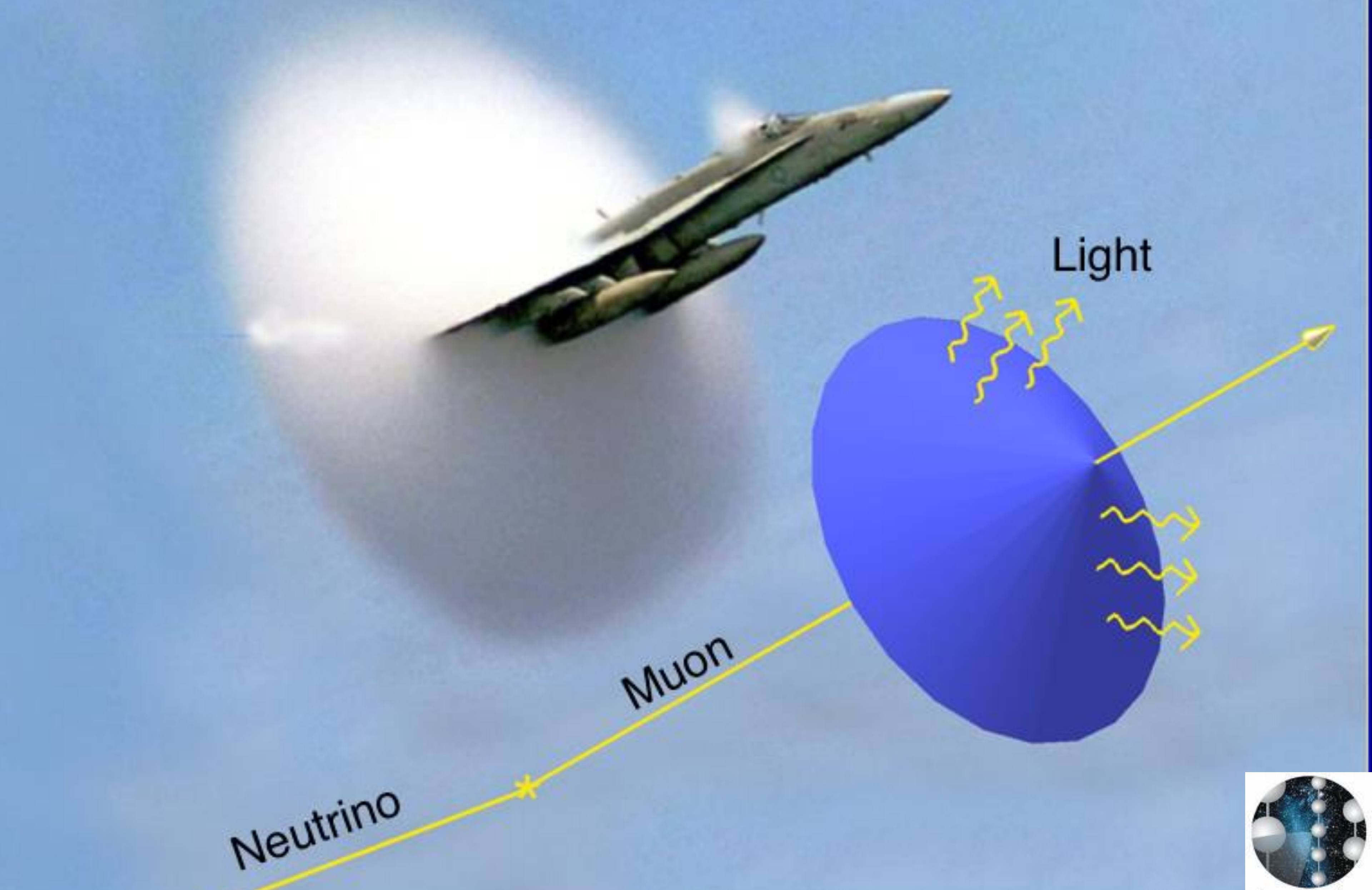
1967, Davis Solar Neutrinos and their deficits

1987 Supernova IMB, Kamioka

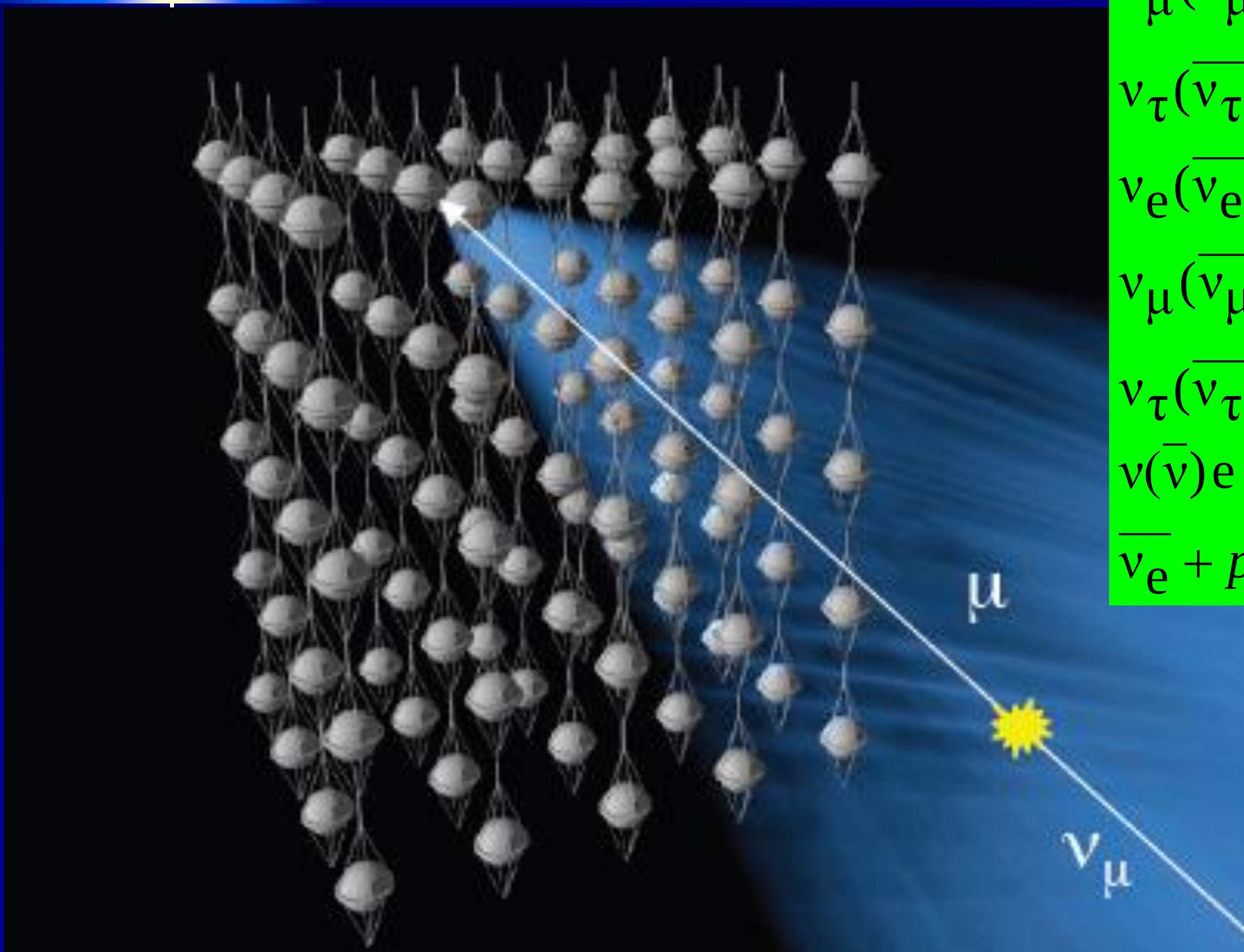
1998 Neutrino Oscillations, Super-K

2013 Dawn of Neutrino Astronomy

Cerenkov Radiation - the electromagnetic "sonic boom"



Neutrino interactions



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

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

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

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

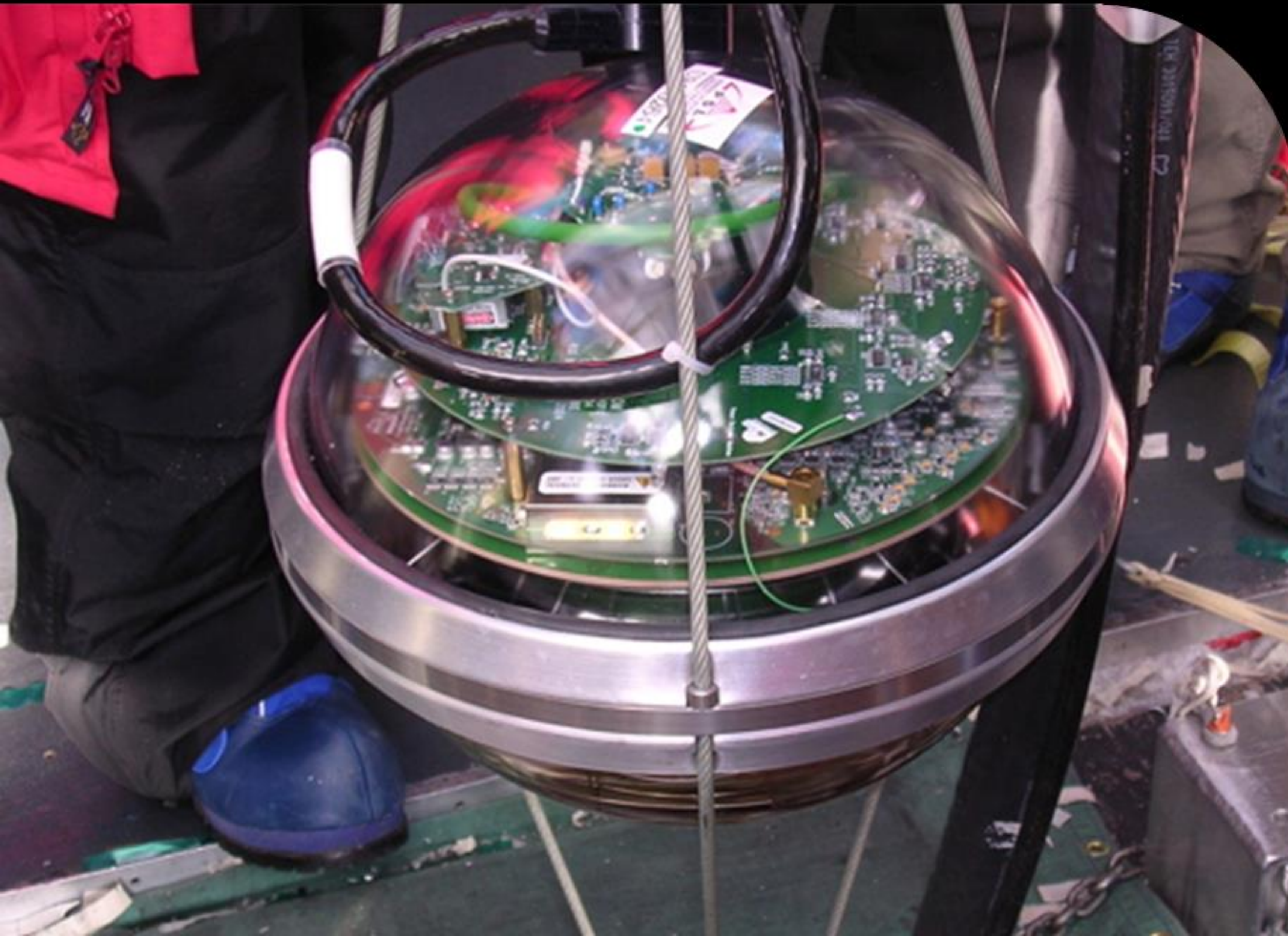
$$\nu_\mu(\overline{\nu_\mu}) + {}^{16}\mathrm{O} \rightarrow \nu_\mu(\overline{\nu_\mu}) + \mathrm{X} \quad (\mathrm{NC})$$

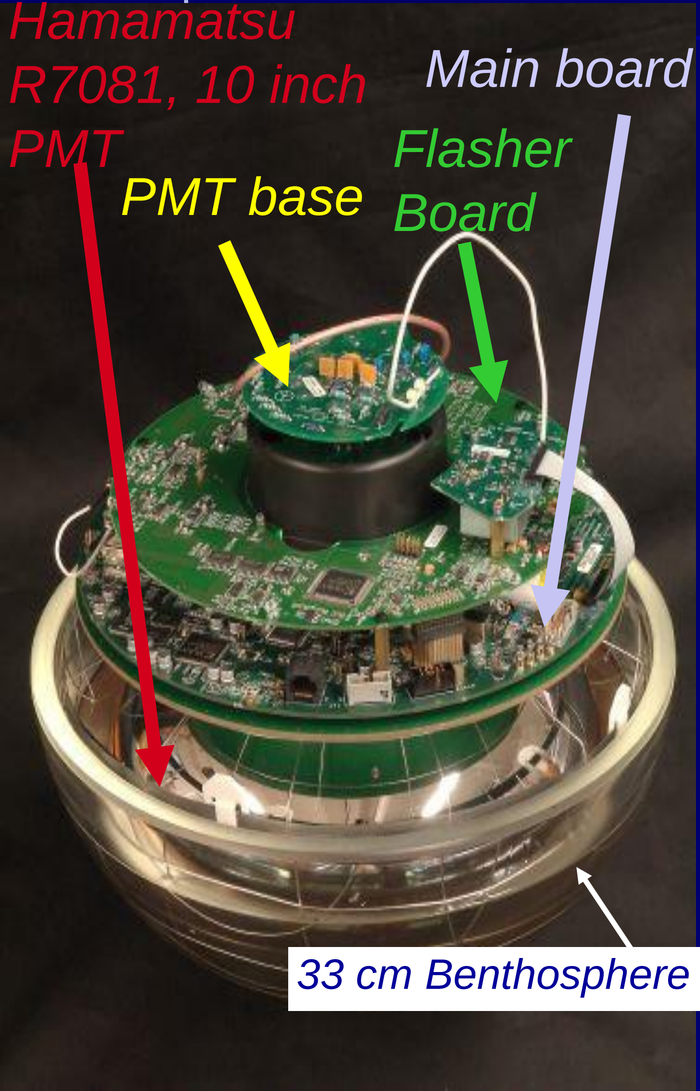
$$\nu_\tau(\overline{\nu_\tau}) + {}^{16}\mathrm{O} \rightarrow \nu_\tau(\overline{\nu_\tau}) + \mathrm{X} \quad (\mathrm{NC})$$

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

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

Digital Optical Module





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

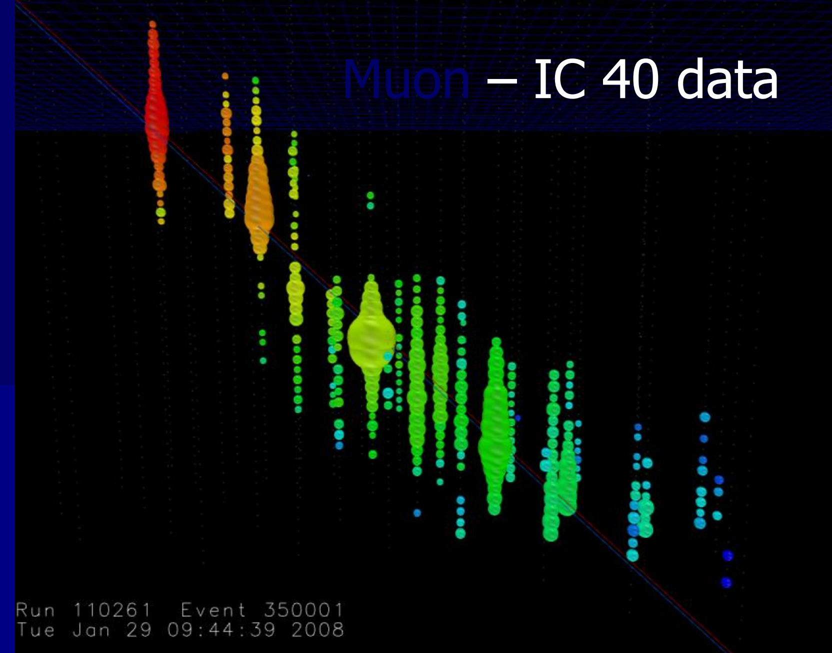
Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized periodically to precision of O(2 nsec)

IceCube

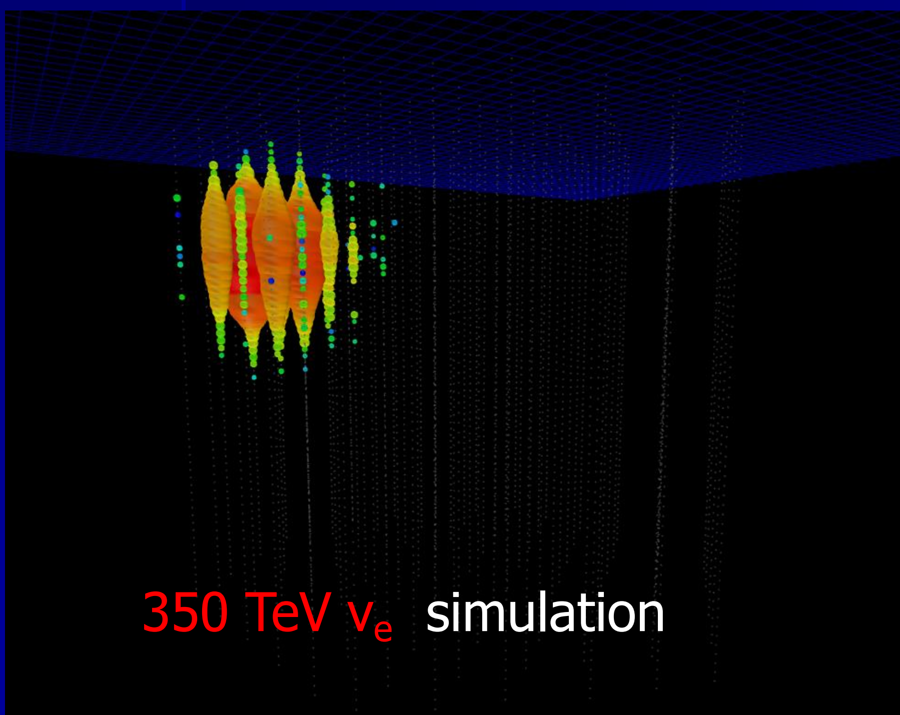
IceCube Construction

Event Topologies

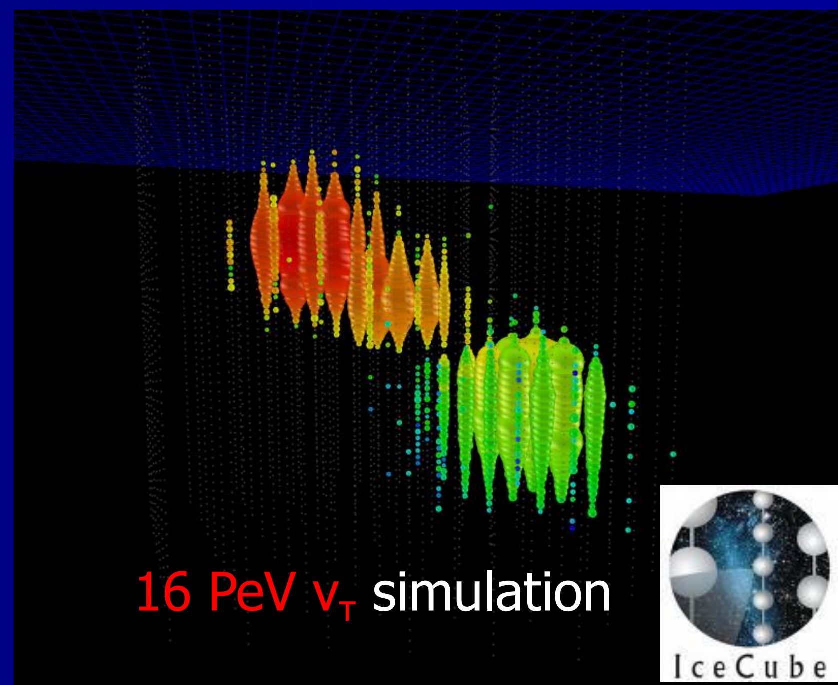
- ν_μ produce μ tracks
  - Angular Res ~ 0.7^0
  - Eres log(E) ~ 0.3
- ν_e CC, ν_x NC create showers
  - ~ point sources, 'cascades'
  - Eres log(E)=0.1-0.2
- ν_τ double bang events, others



Muon – IC 40 data

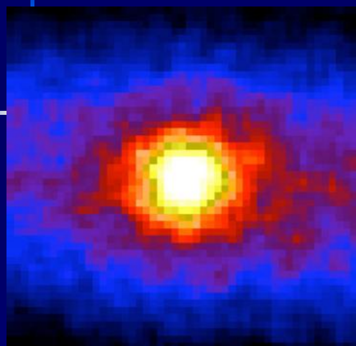


350 TeV ν_e simulation

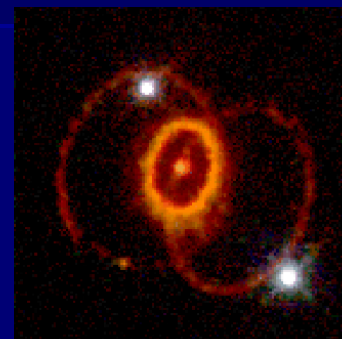


16 PeV ν_τ simulation

Real and Possible ET Neutrino Sources

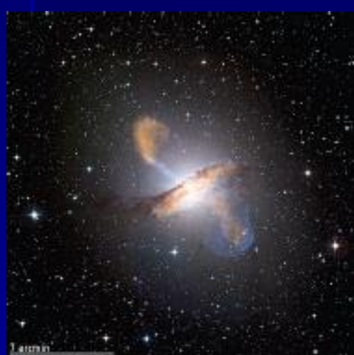


Solar Neutrinos



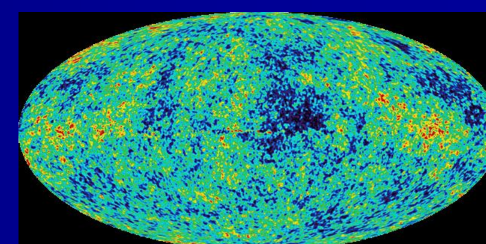
Supernova 1987A

Dark Matter?



Active Galactic Nuclei

Gamma Ray Bursts

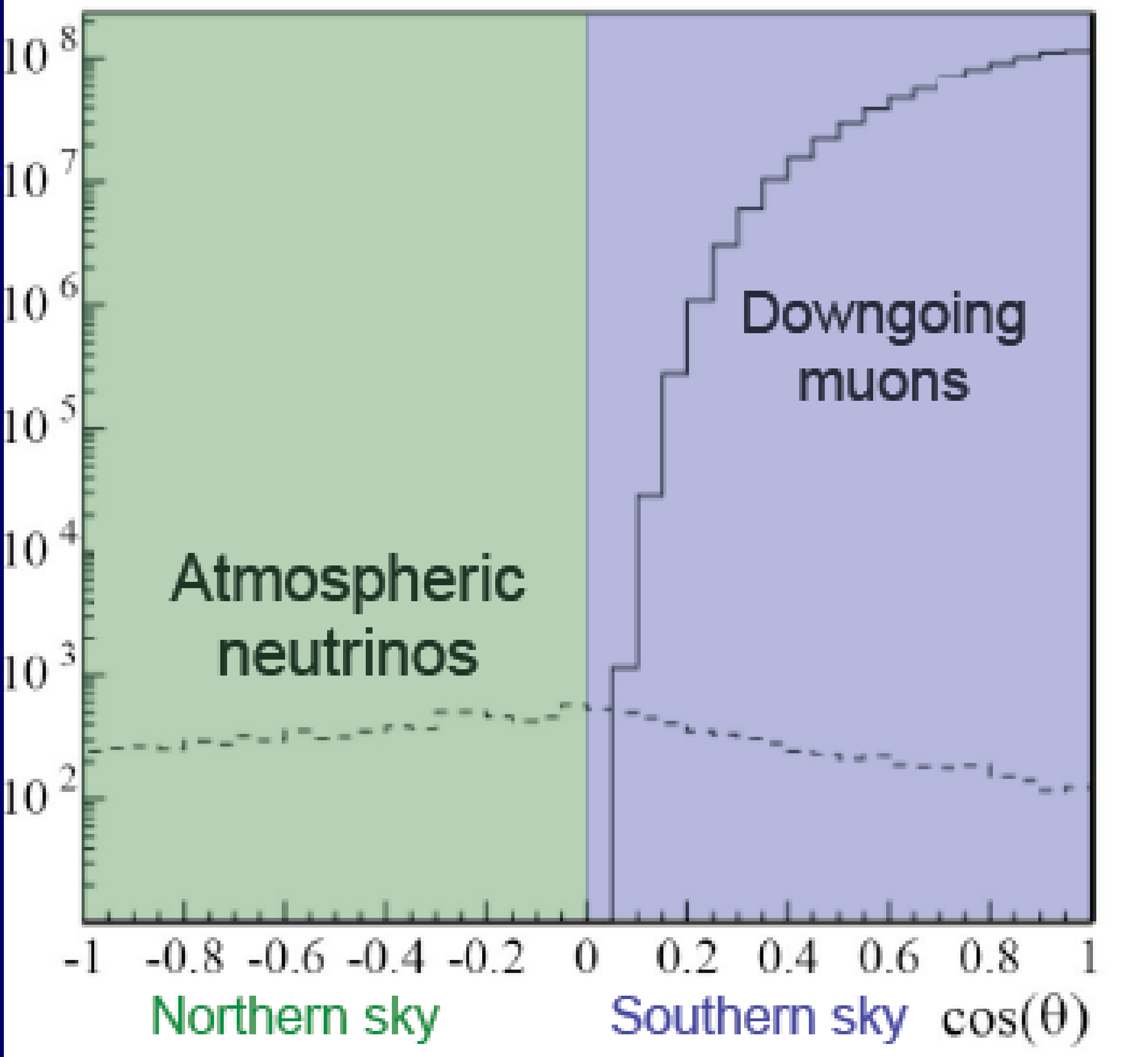


Cosmogenic Neutrinos

Backgrounds

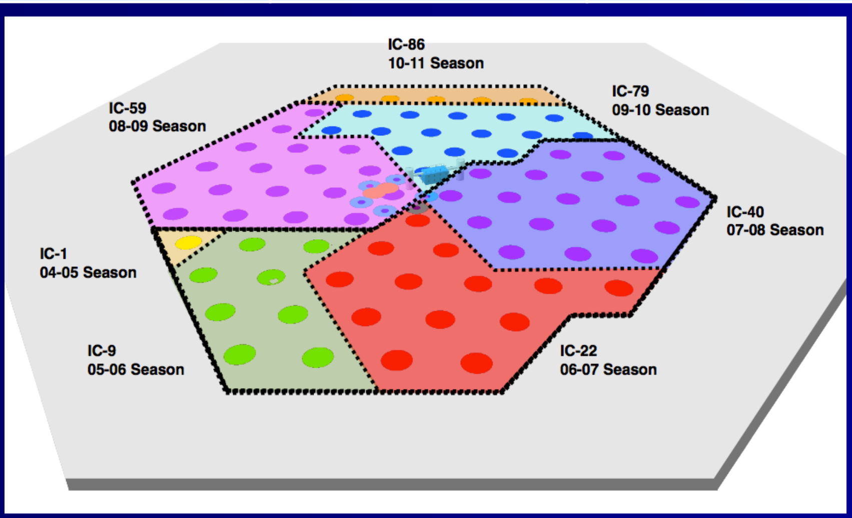
The majority of triggers in IceCube are from atmospheric muons

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

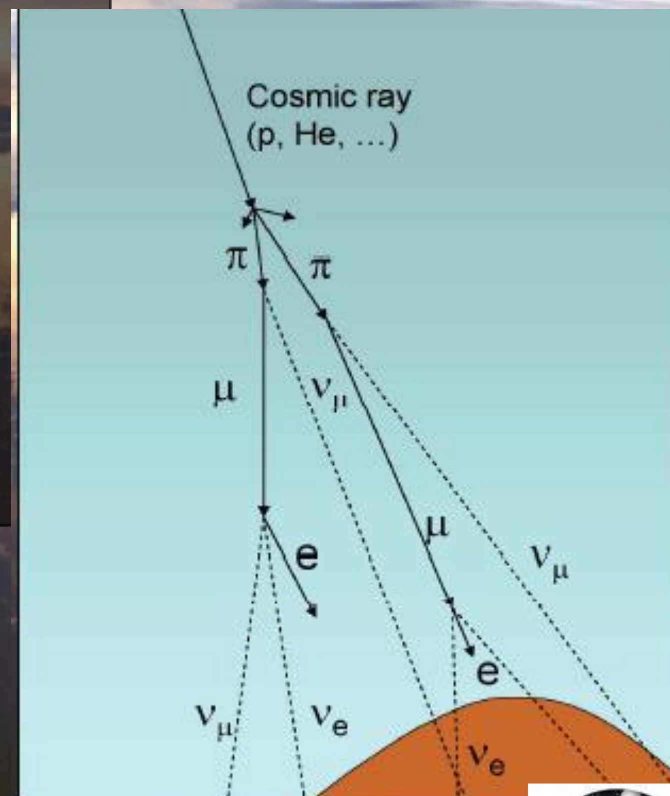
$E_\nu \sim$ 1-100 GeV

- 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

$$p + {}^{16}\text{O} \rightarrow \pi^+, K^+, D^+, \text{etc.}$$

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

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

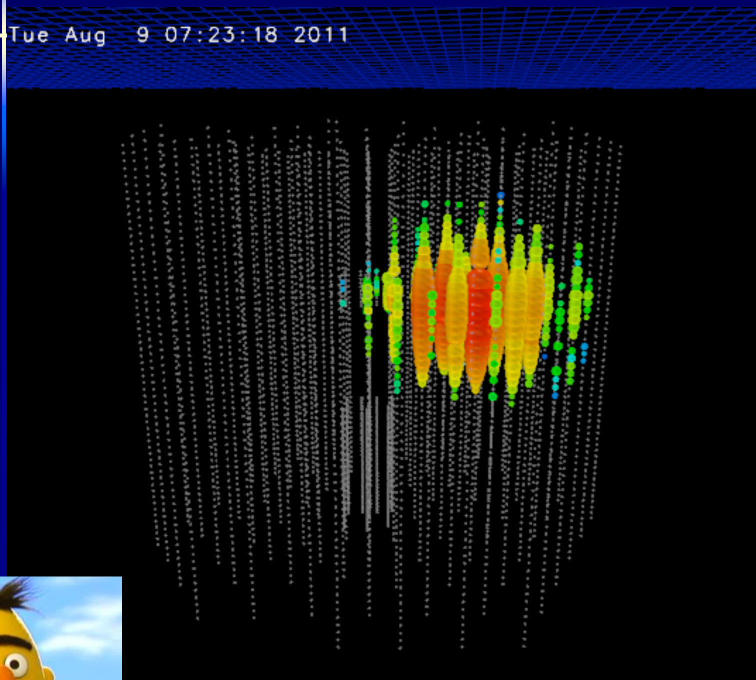


IceCube

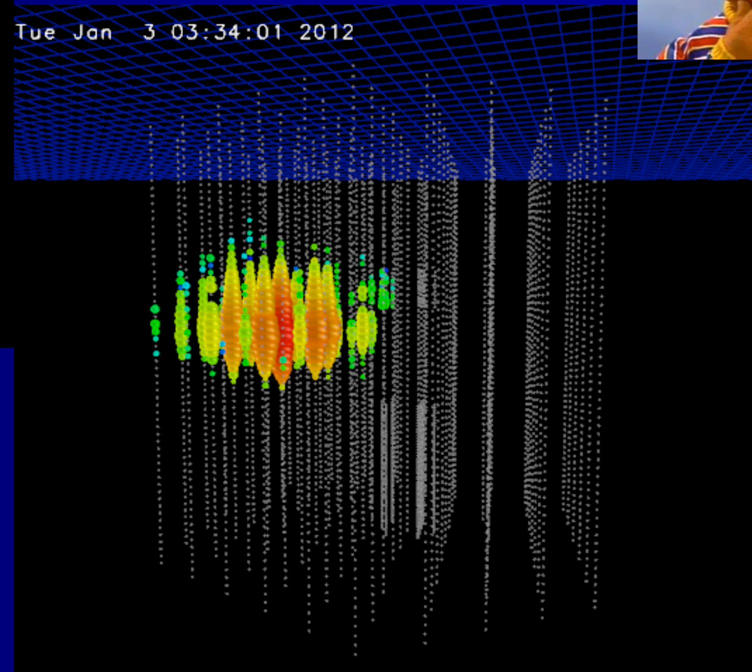
Observation of Highest Energy Neutrinos Dubbed "Bert & Ernie". (PRL 111 021103 2013)

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

Angular resolution on cascade events at these energies ~10°



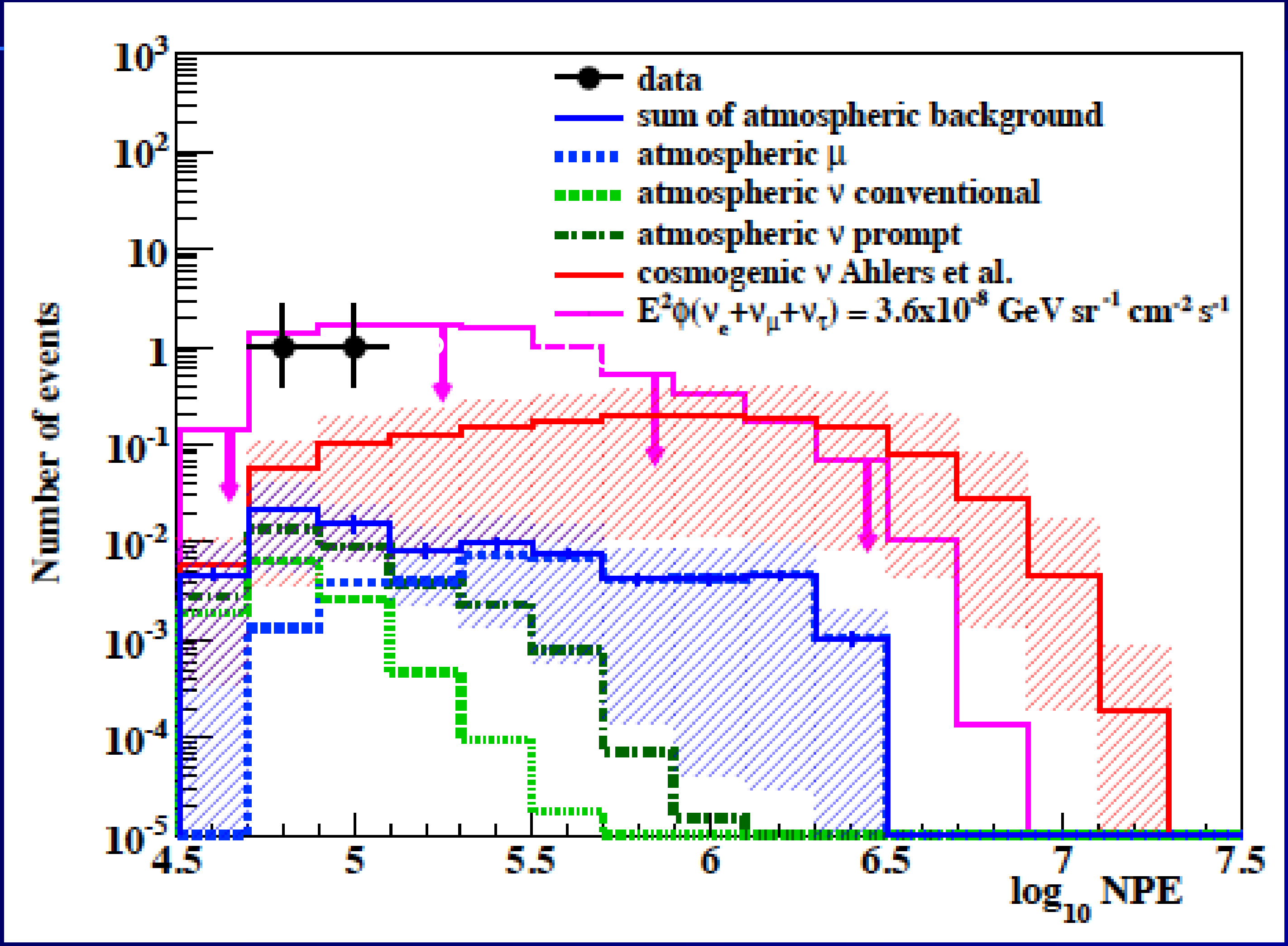
Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6 x 10^4
NDOM: 312
1.14±0.17 PeV



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

NPE Distributions

(PRL 111 021103 2013)



IceCube

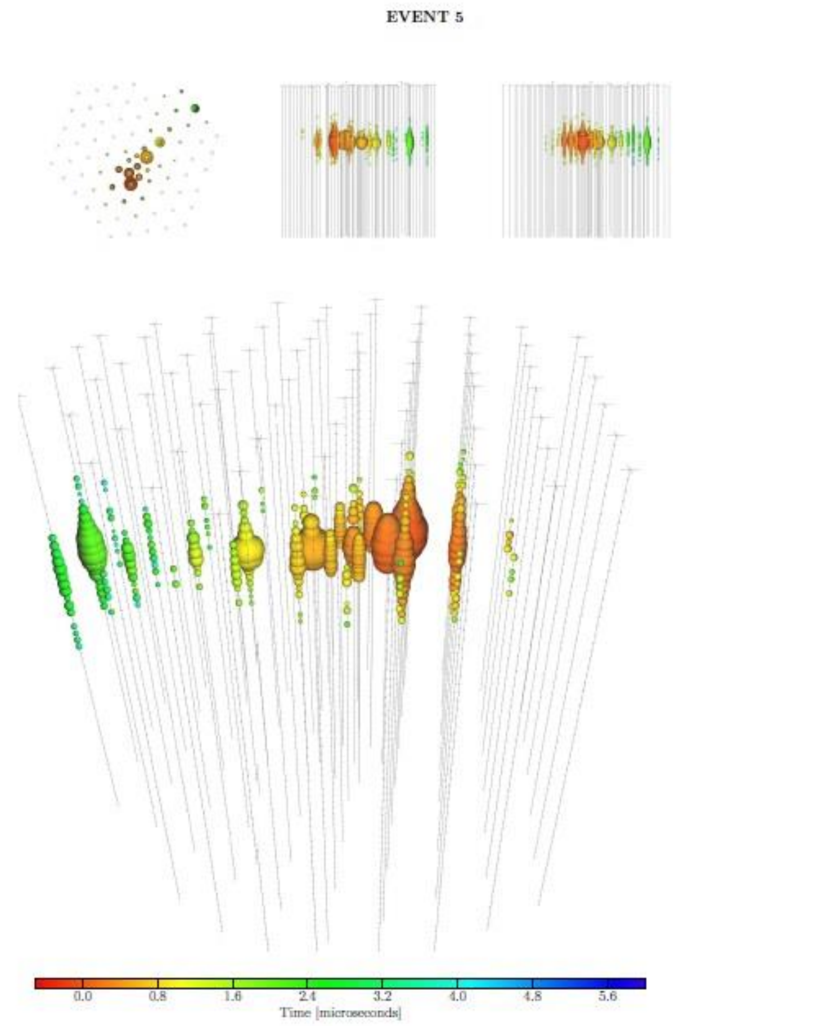
Backgrounds for "Bert & Ernie"

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

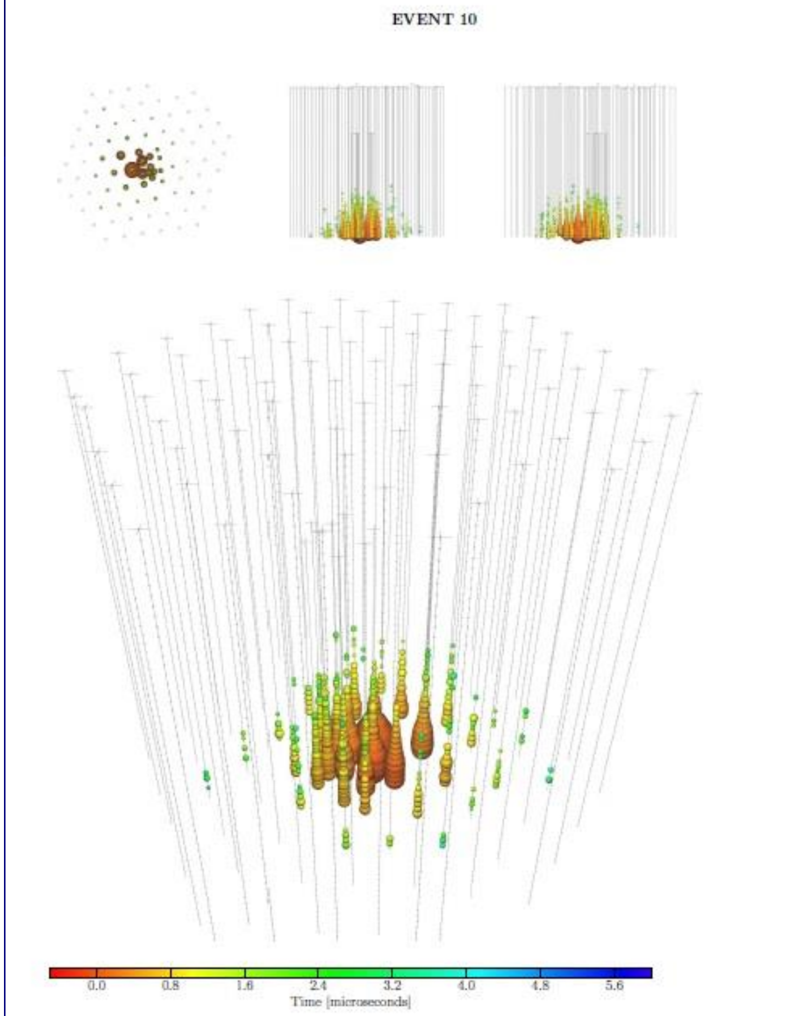
* R. Enberg, et al., PRD078 043005 (2008)

Significance = 2.8σ

Results



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

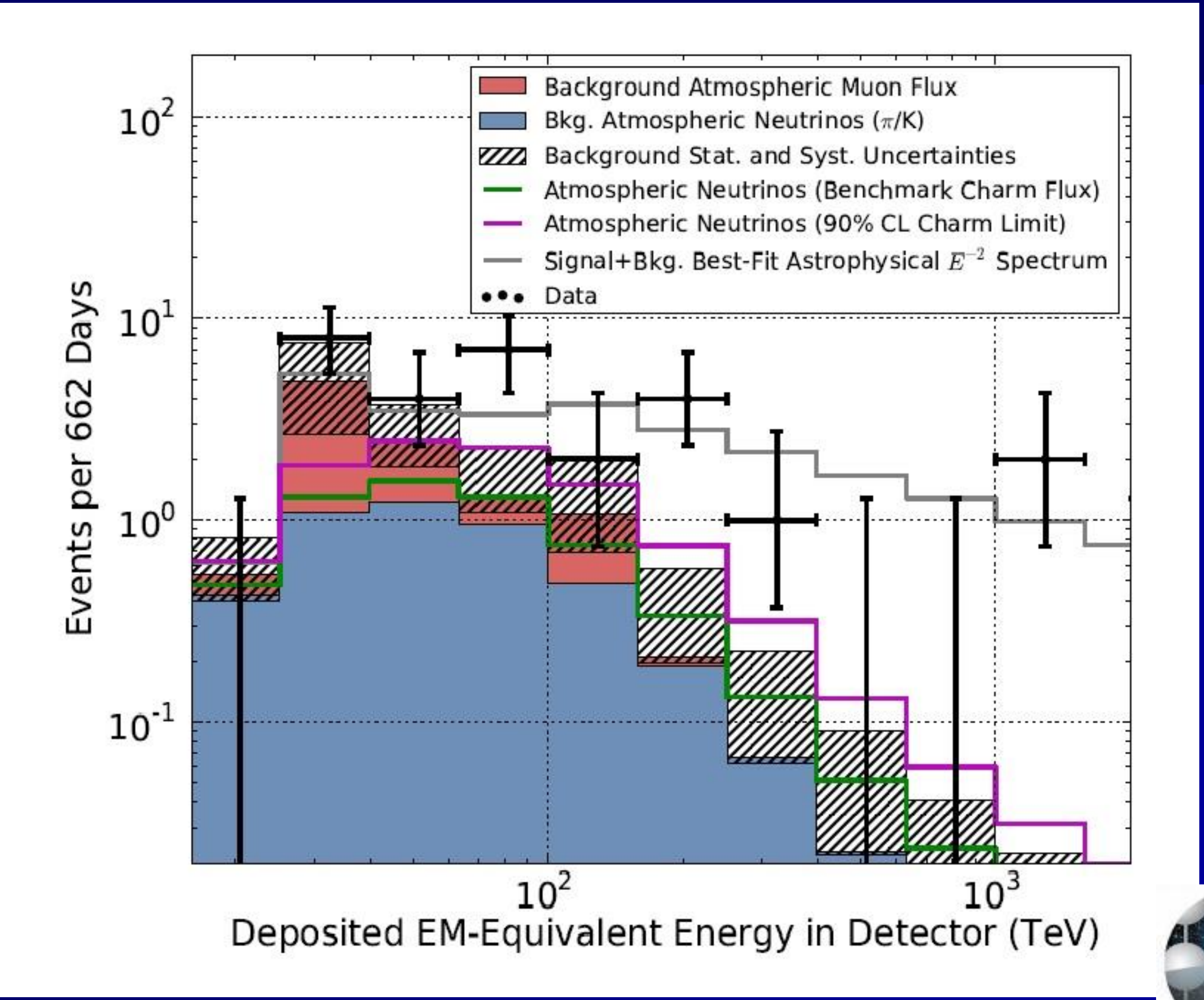


Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$97.2^{+10.4}_{-12.4}$	55695.2730442	−29.4	5.0	8.1	Shower

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

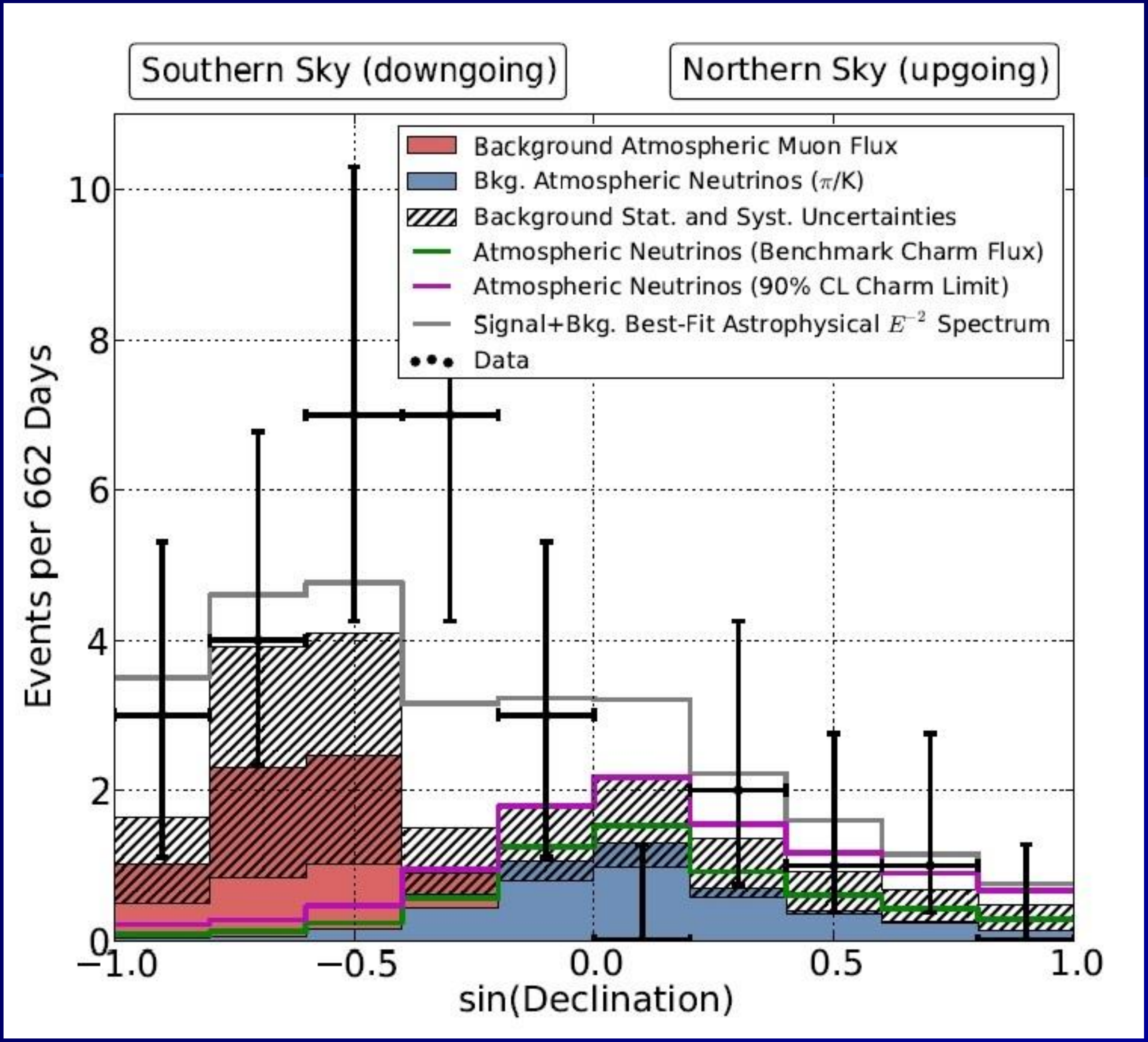
28 events, including Bert & Ernie, (7 tracked, 21 cascades) observed. Background from known atmospheric neutrinos is $10.6^{+5.0}_{-3.6}$

Significance = 4.1 σ

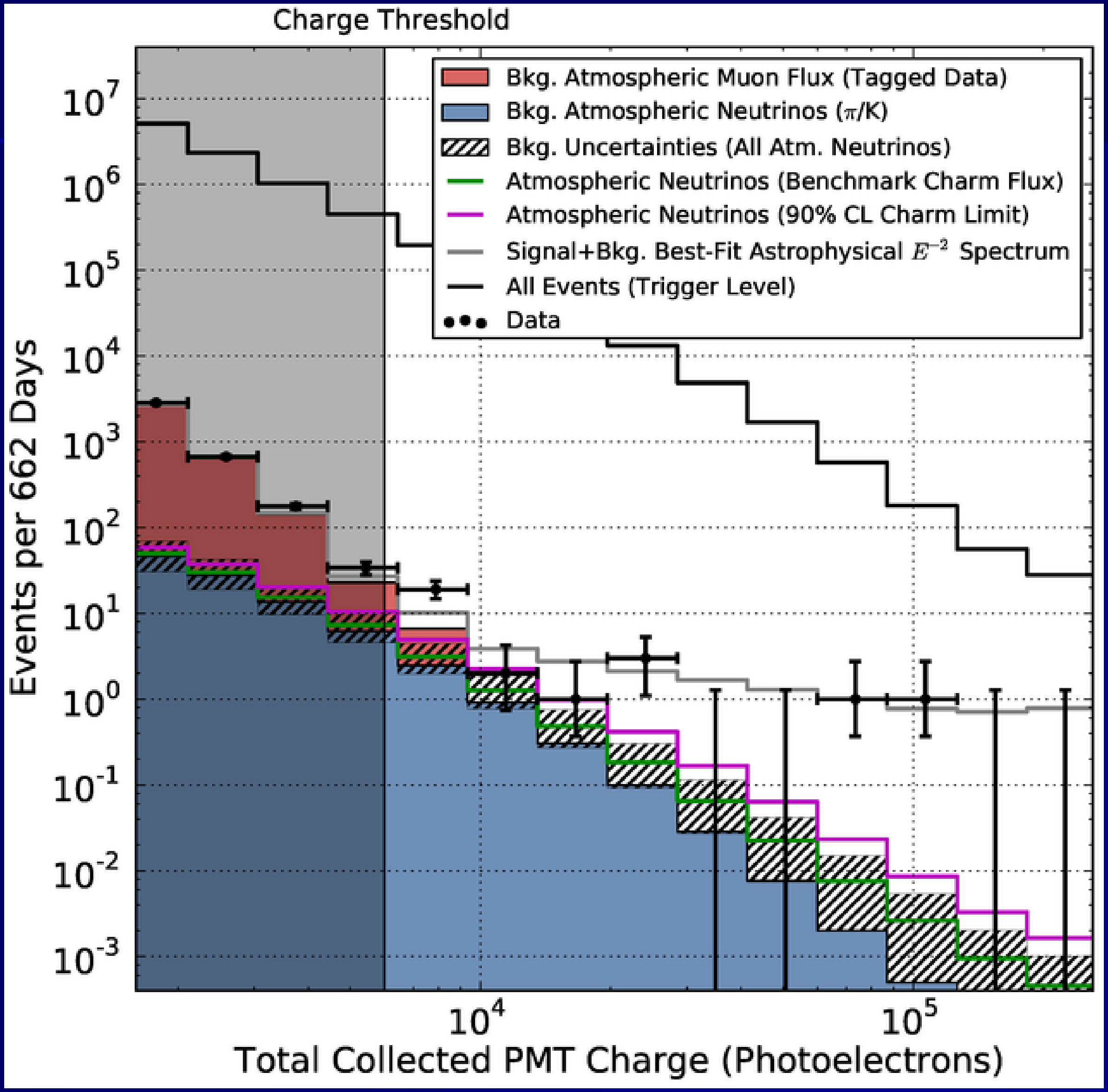


IceCube

Results, Declination



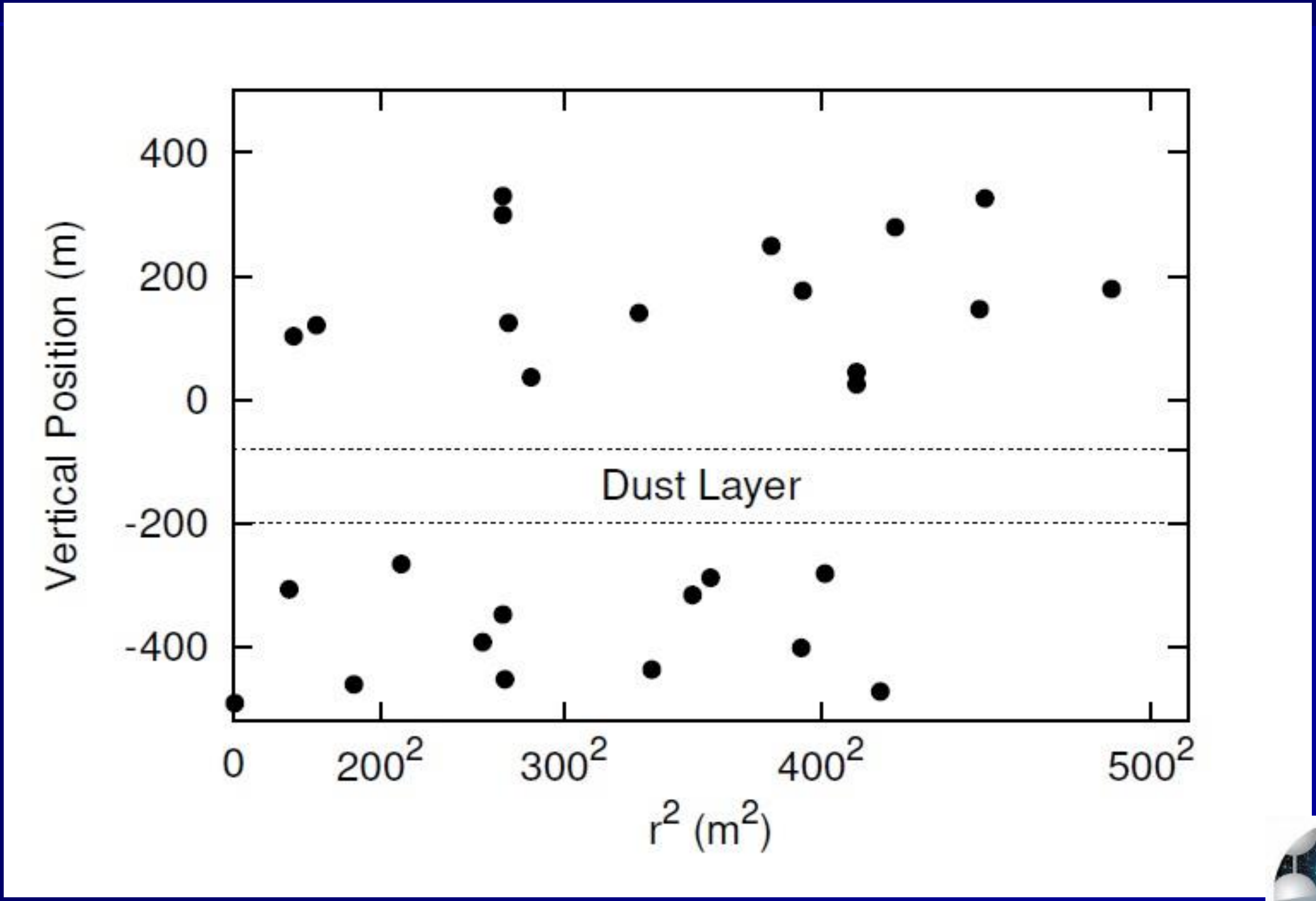
Results, Charge Threshold



IceCube

Coordinates of the First Detected Light

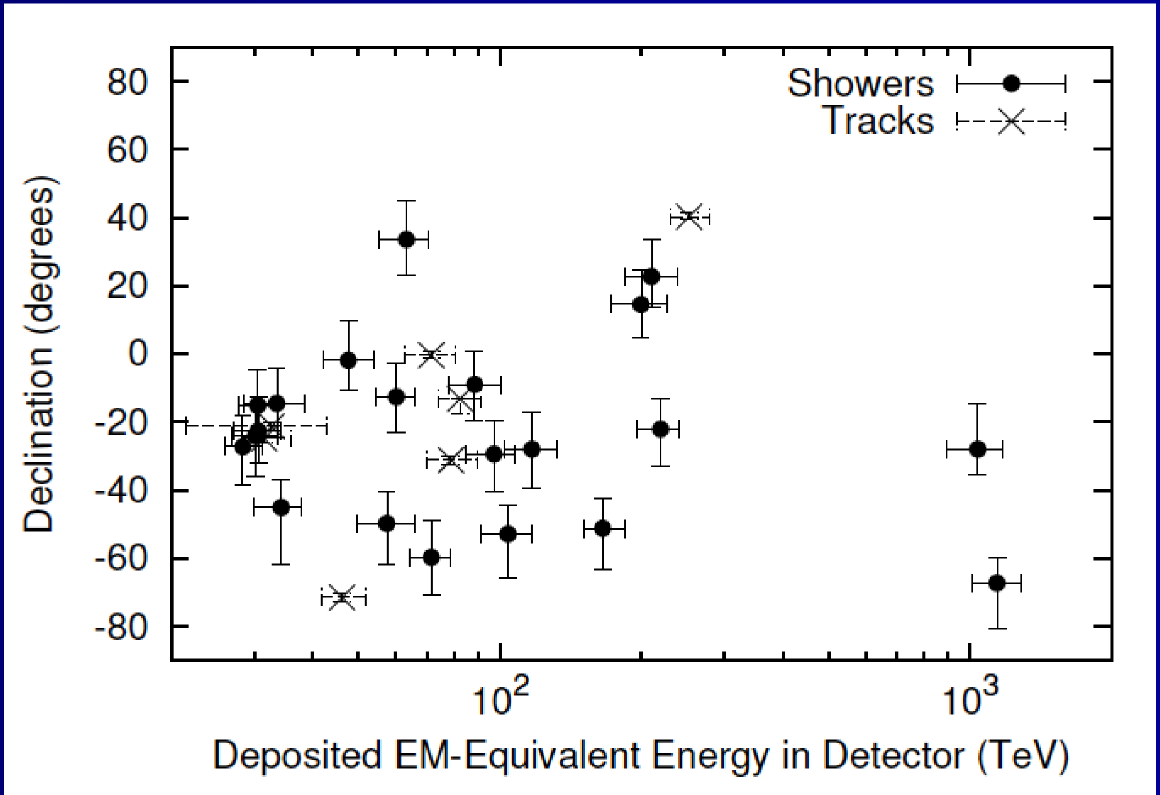
First light from atmospheric μ interacting on the top and to the right of the plot are vetoed. ν interactions are uniform throughout the detector.



Declination vs. deposited energy

A few observations.

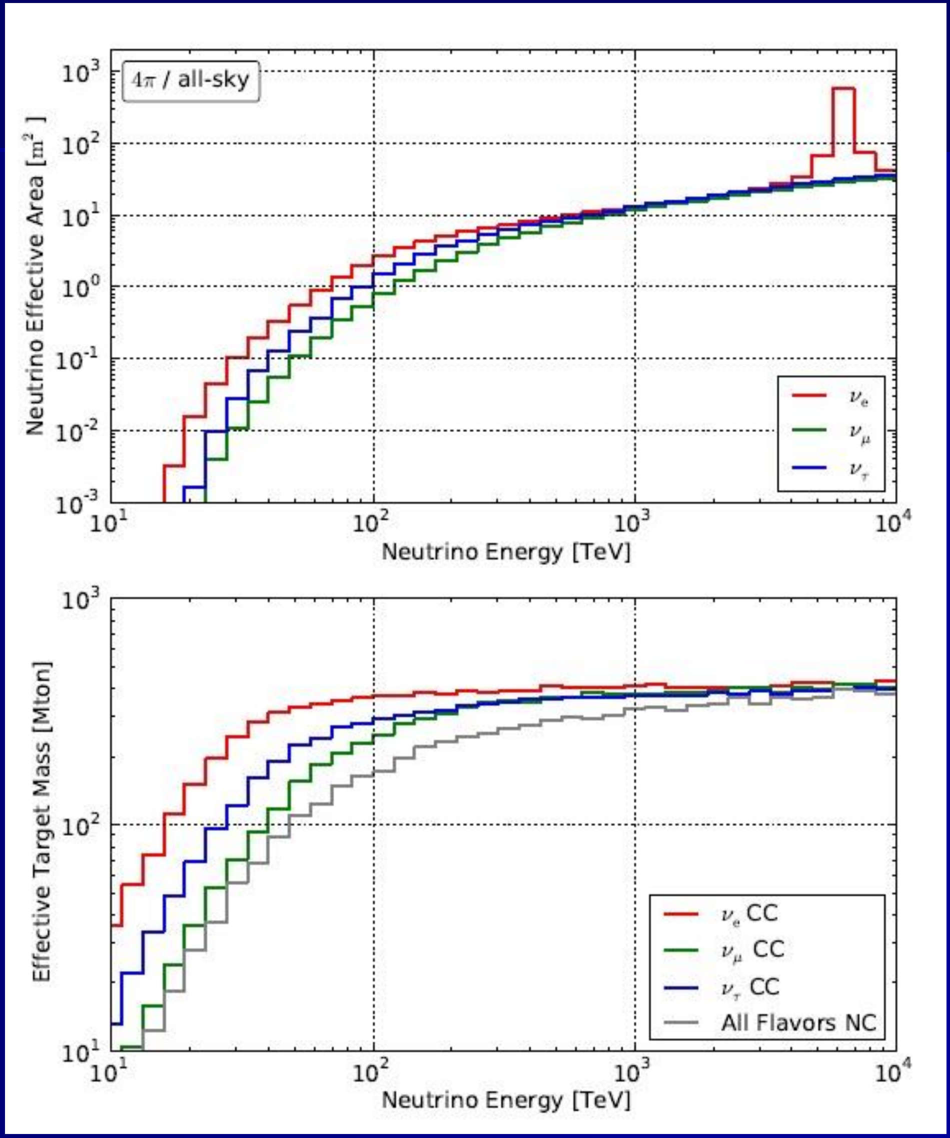
- Signal contains 21 cascades and 7 tracks
- Atmospheric neutrinos: track/cascade = 2
- Most events originate from southern sky because most HE neutrinos from northern sky are absorbed by the Earth
- Excess from the southern sky is not due to atmospheric ν_μ because they are reduced in the south by μ rejection.



IceCube

Neutrino Effective Area/Volume

Neutrino effective area and volume. Event rates are obtained by multiplying the effective areas by 4π, by the sum of neutrino and antineutrino fluxes, and by the live-time of 662 days.
Neutrino effective areas for each flavor assuming equal fluxes of neutrinos and antineutrinos are averaged over all incident angles. At 6.3 PeV, resonant W production on atomic electrons increases sensitivity to electron antineutrinos.



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

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

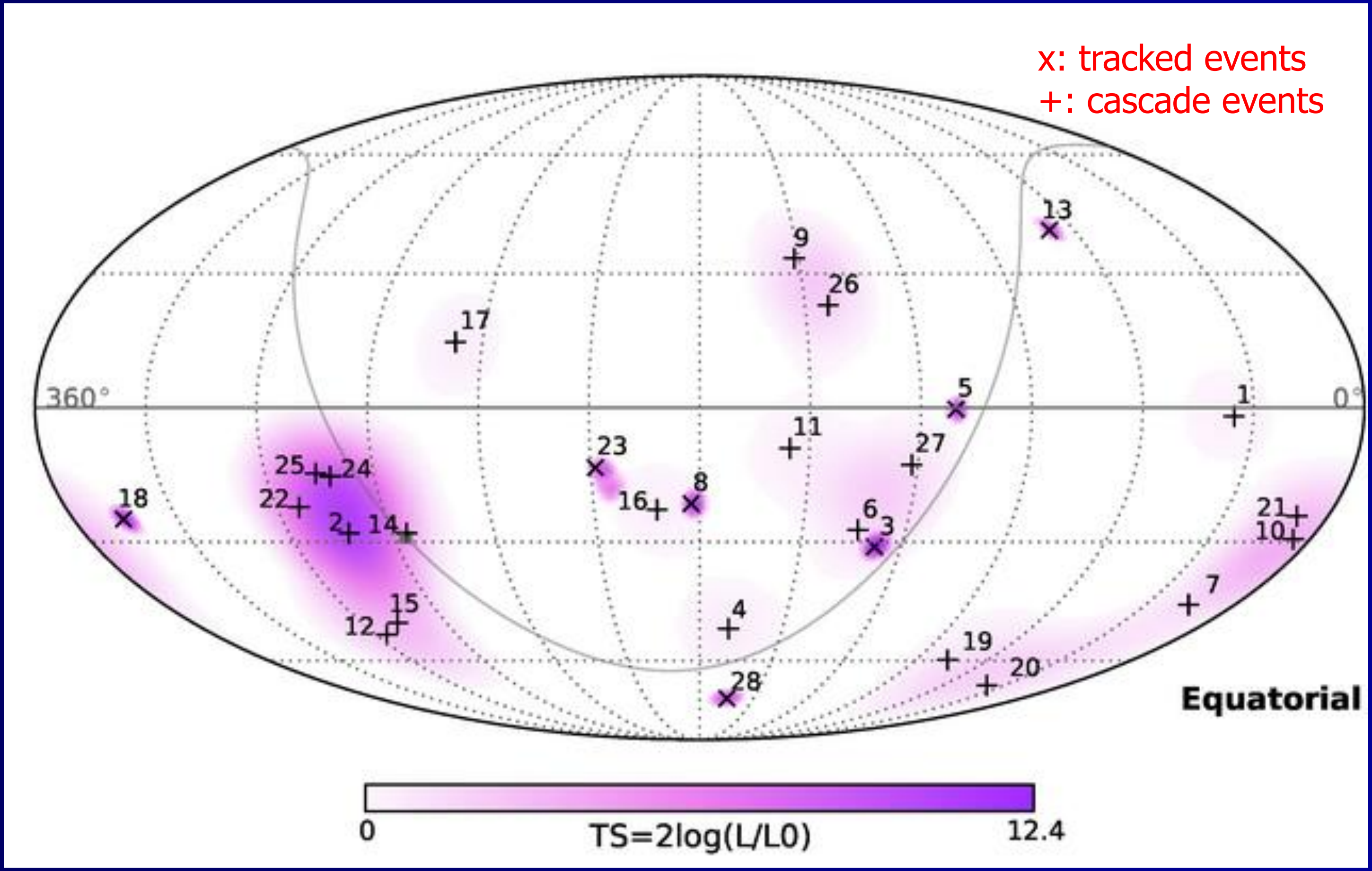
where $L_0 = L(x, n_s = 0)$

IceCube

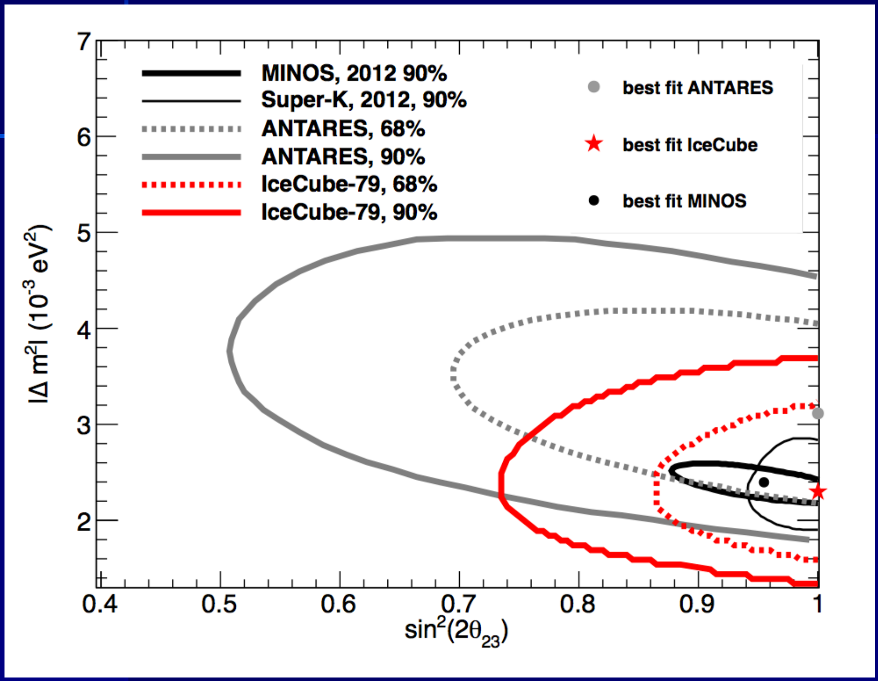
Point Source Analysis

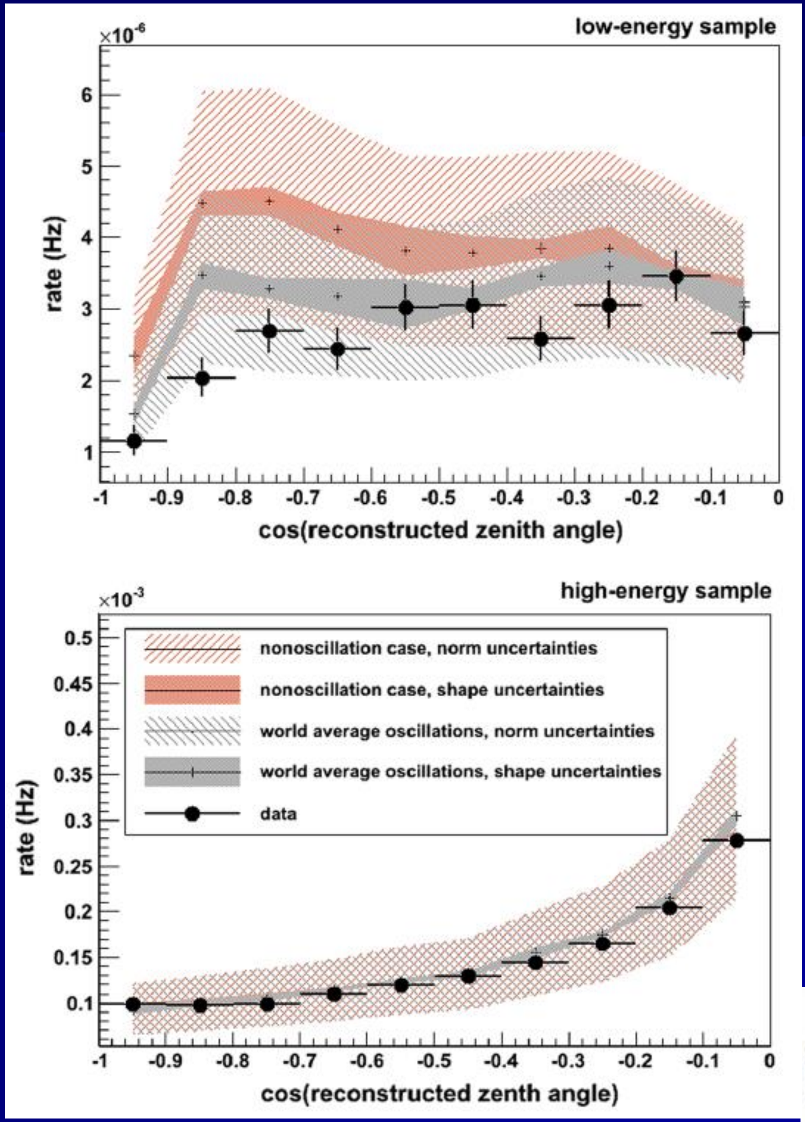
Test null hypothesis vs. most likely
L0: null hypothesis
L: maximized likelihood

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



Atmospheric ν Oscillations



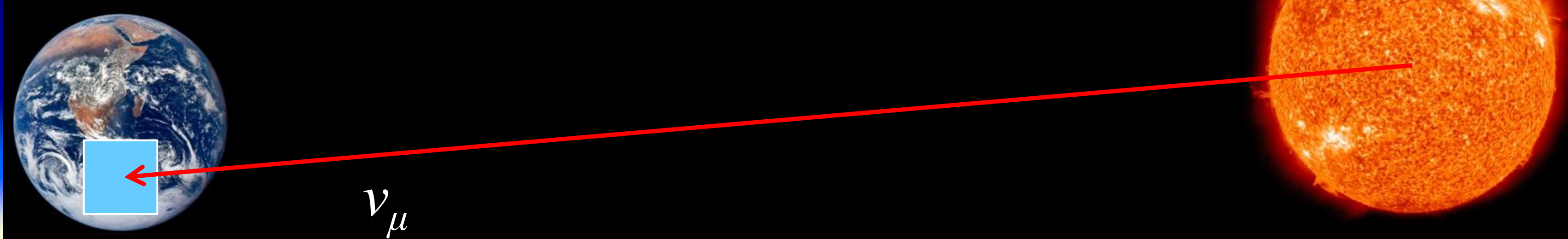


Data from IC-79 (319 days)
$\Delta m_{32}^2 = 2.3^{+0.6}_{-0.5} \times 10^{-3}\ eV^2$
sin2 ($2\theta_{23}$) > 0.93 (68% *C.L.*)

PRL, 111, 081801 (2013)

IceCube

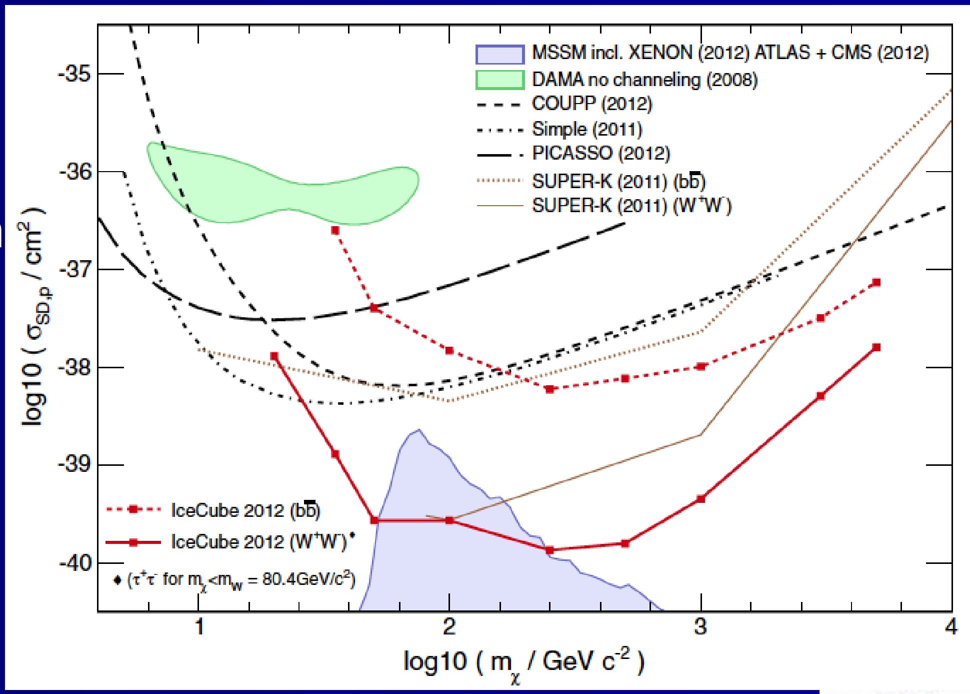
Dark Matter Search from the Sun



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

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.

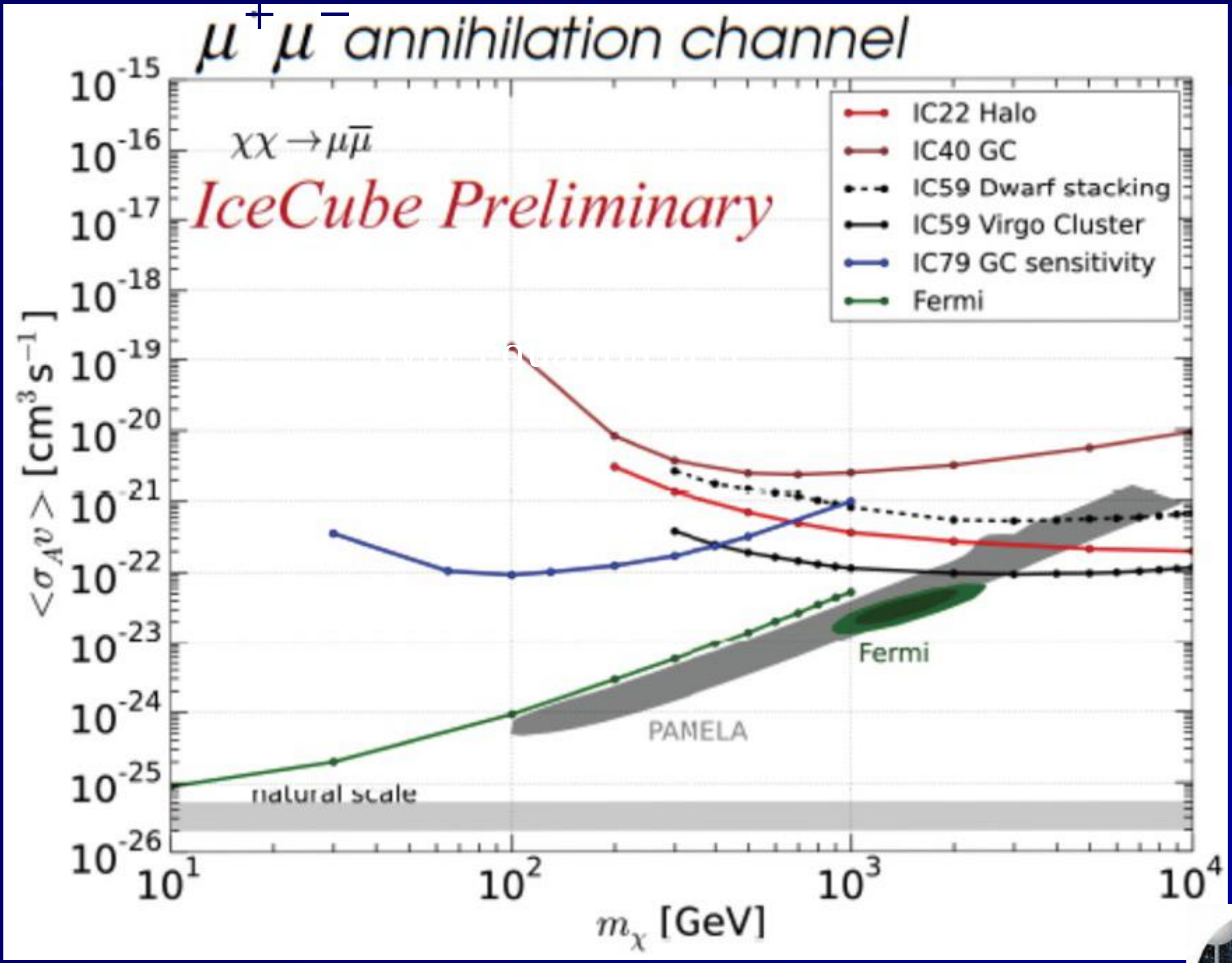
Data from IC-79 (317 days)
PRL110, 131302 (2013)



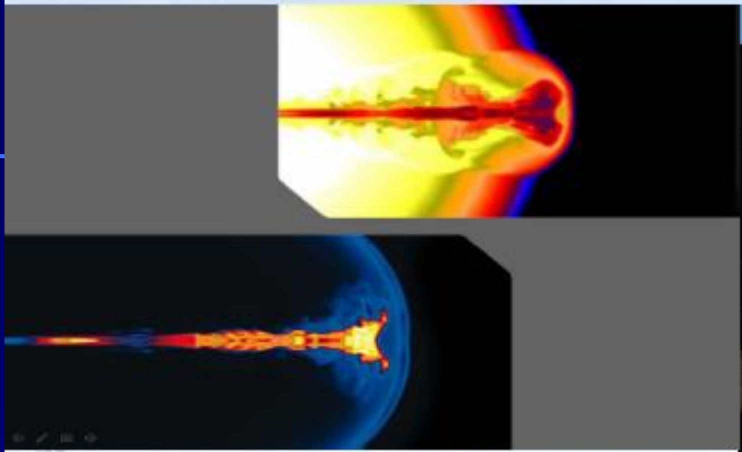
Dark Matter Search in the Milky Way

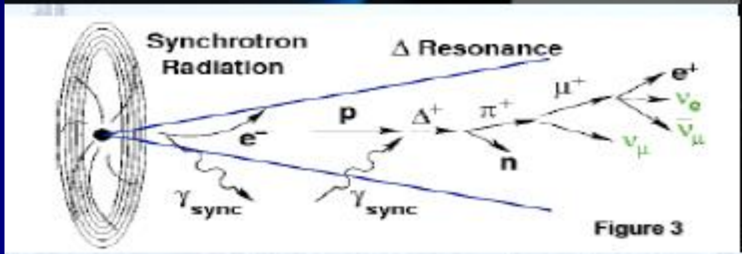
IC-79 (320 days)
No excess found

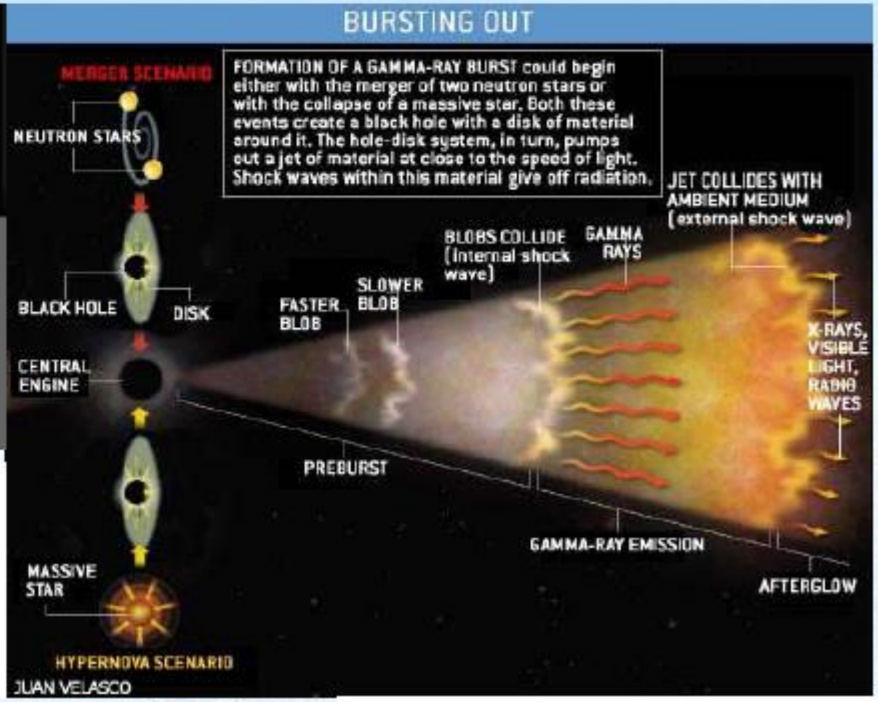
IceCube is sensitive to a minimum WIMP mass of 30 GeV.



Gamma-Ray Bursts

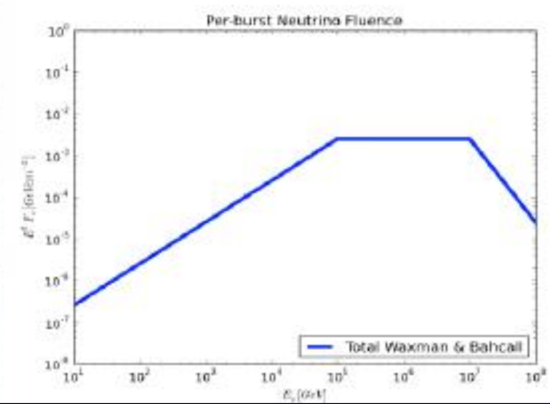




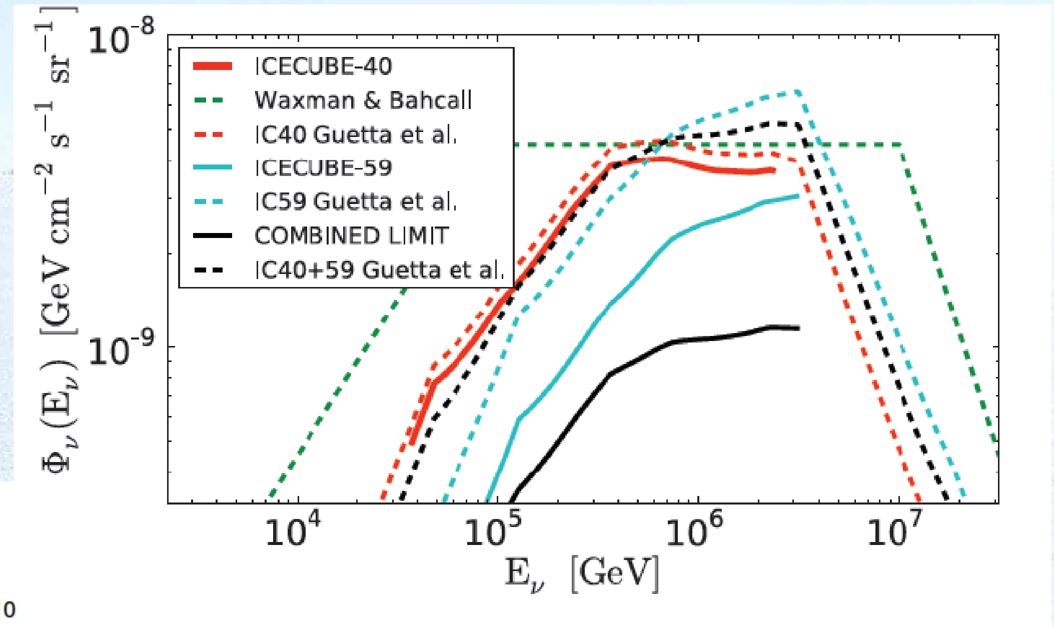


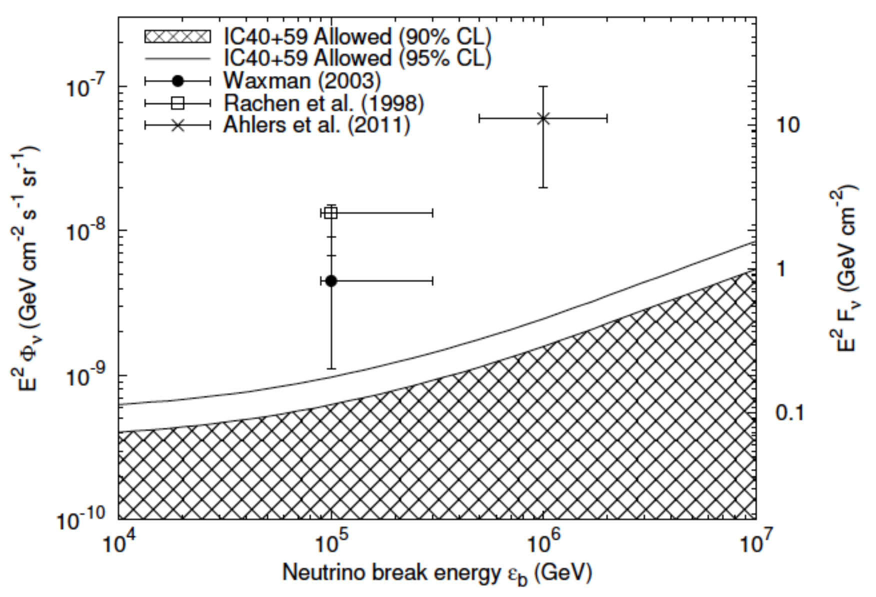
Fireball model:

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



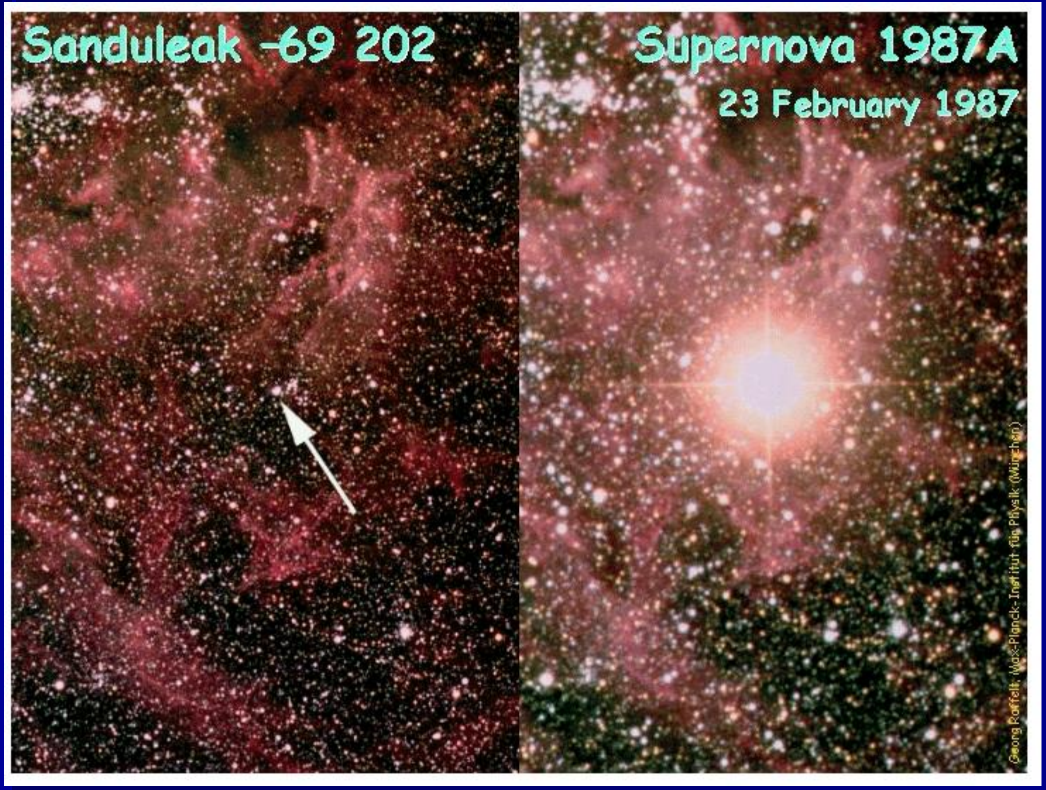
IC40 data **2008-2009** (117 GRBs in northern sky) and **IC59** data **2009-2010** (98 GRBs in the northern sky and 85 from the southern sky) analyzed. **No coincidence found. Note, analysis has very low background because both direction and timing coincidence are applied.**

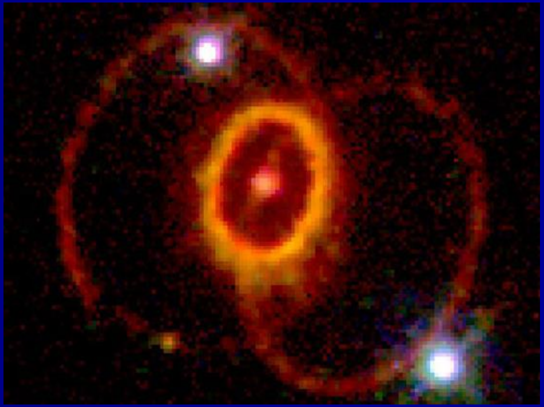




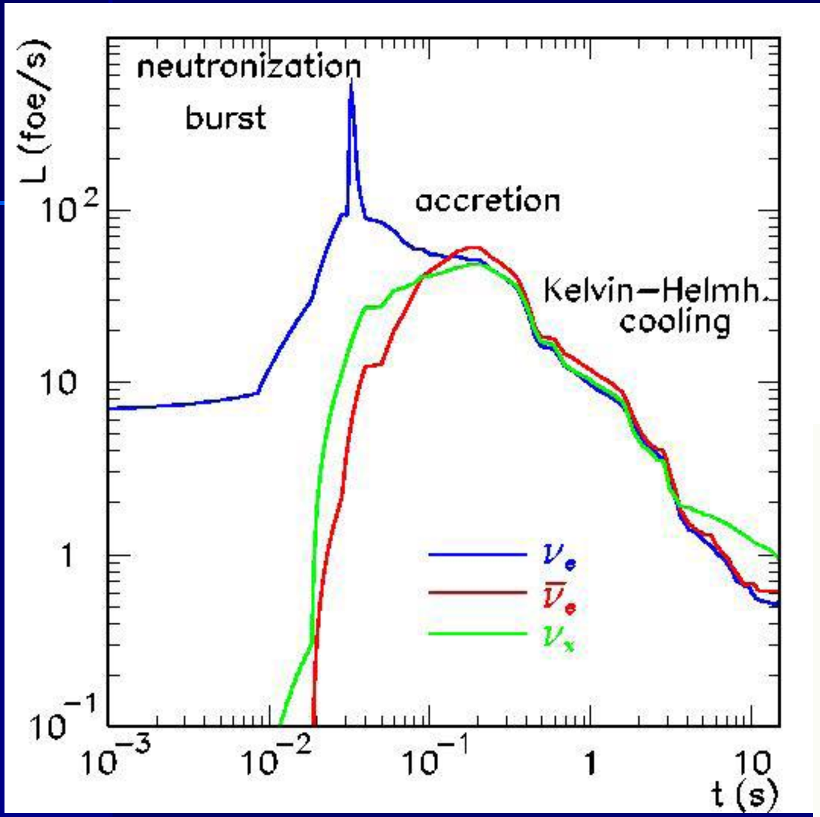
IceCube Collaboration - Nature Vol 484, 351 (2012)

IceCube: A Supernova Detector



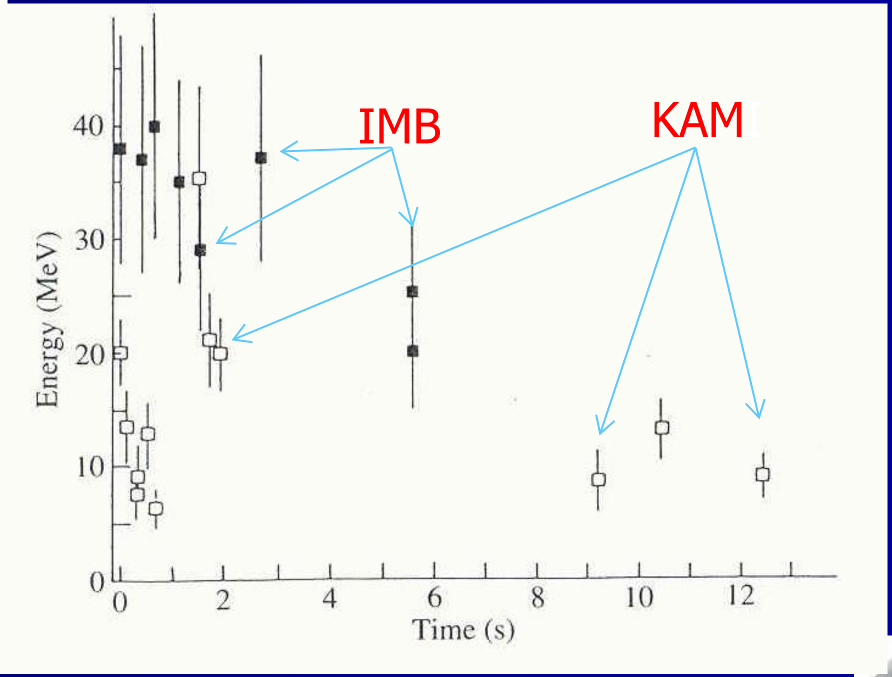


Neutrino Spectra from SN

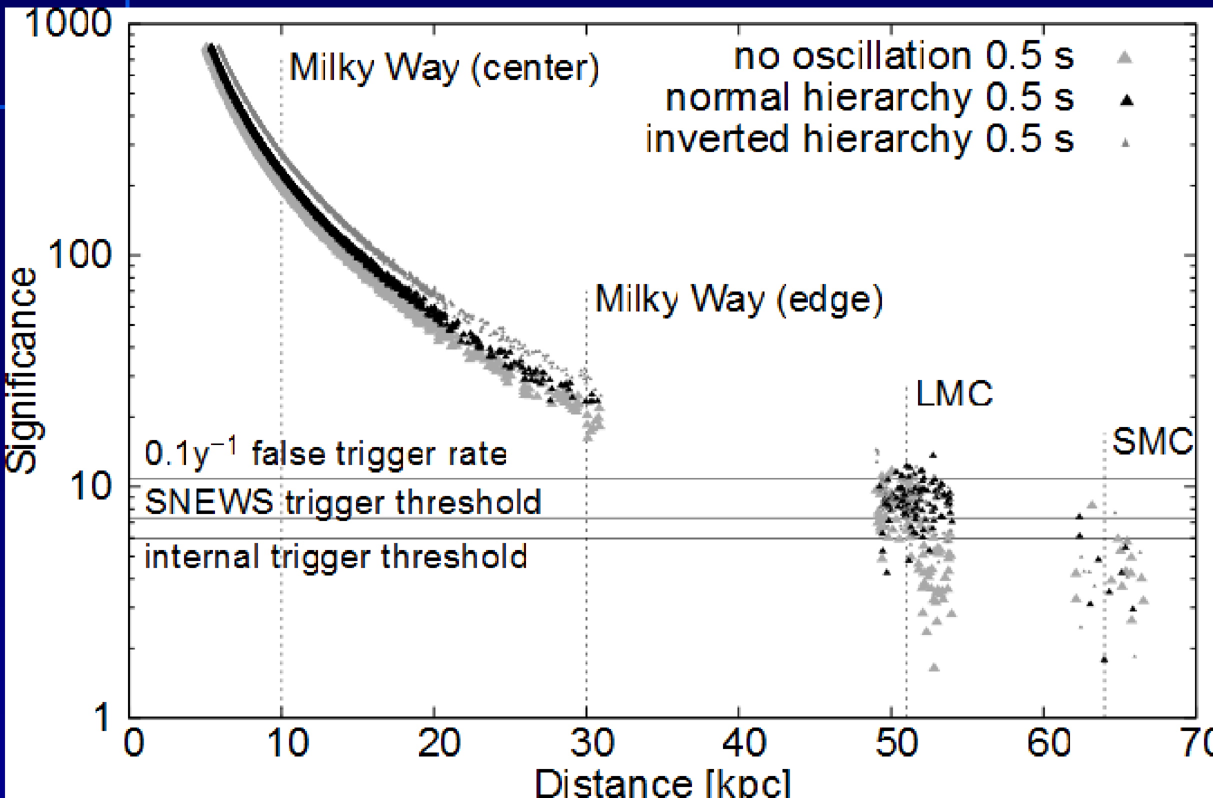


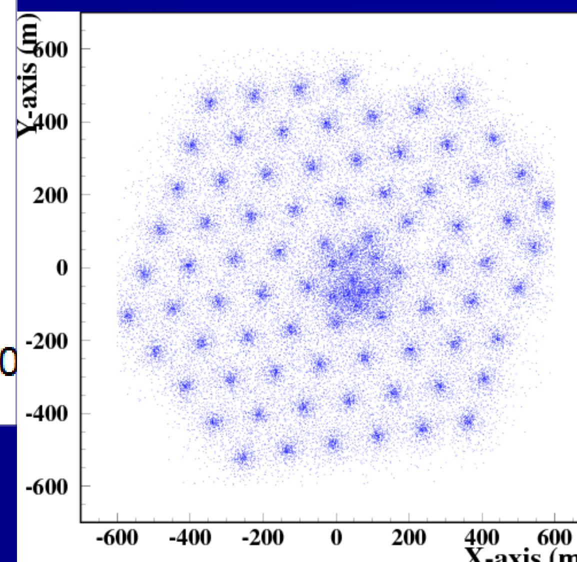
Totani et al., (1998)

SN87A Events
IMB & Kamioka



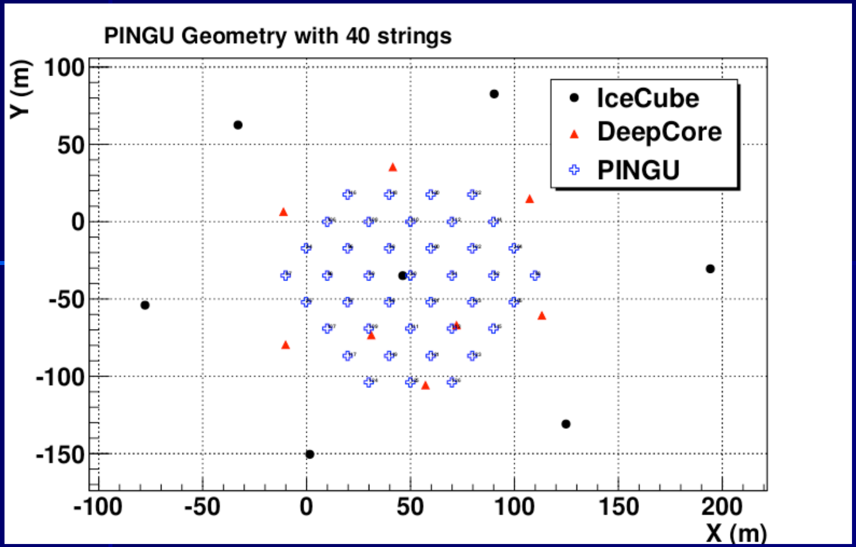
IceCube Sensitivity to SN Explosions





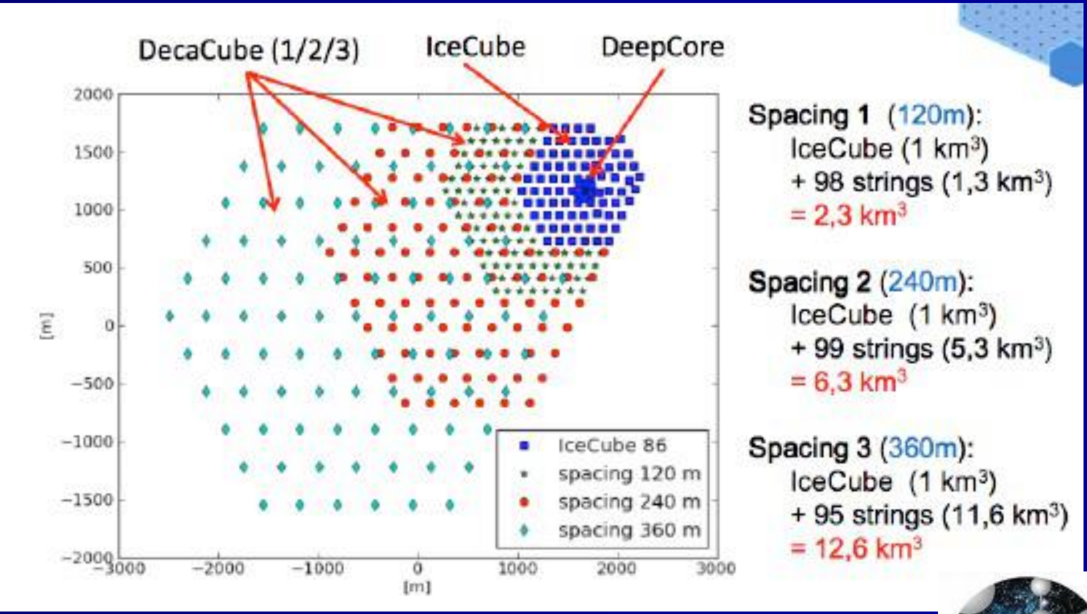
A&A 535, A109 (2011)

Future Plans



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.

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.



IceCube

Overall Conclusions

- IceCube has Evidence for High Energy Astrophysical Neutrinos and has achieved its main goal of opening an era for 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: PINGU dense array for Neutrino Mass Hierarchy … IceCube Extensions for Higher Energies …