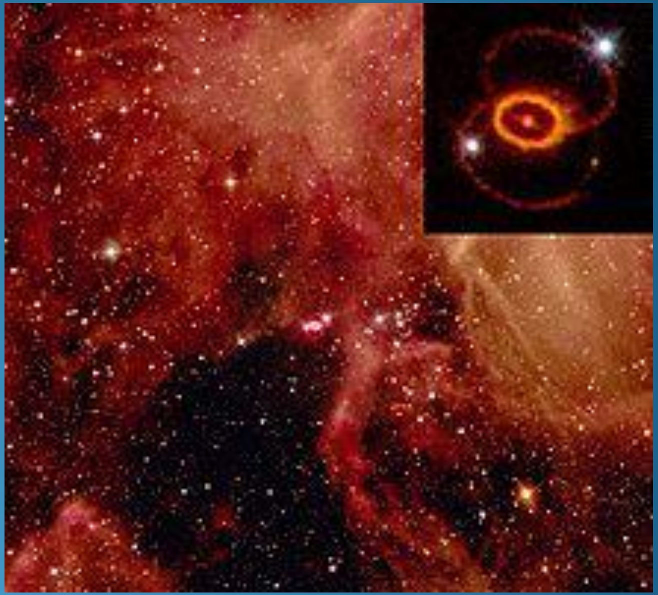
Supernova Detection with IceCube

Miami Conference

December 15-20, 2011

Fort Lauderdale, FL



A.R. Fazely

Southern University, Baton Rouge, LA

What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies
- We are in our 8th project year and data taking with the full detector (86 strings) began in May 2011
- IceCube is the largest Neutrino Telescope in operation
- The project has just begun to produce exciting physics.
- http://icecube.wisc.edu/

IceCube

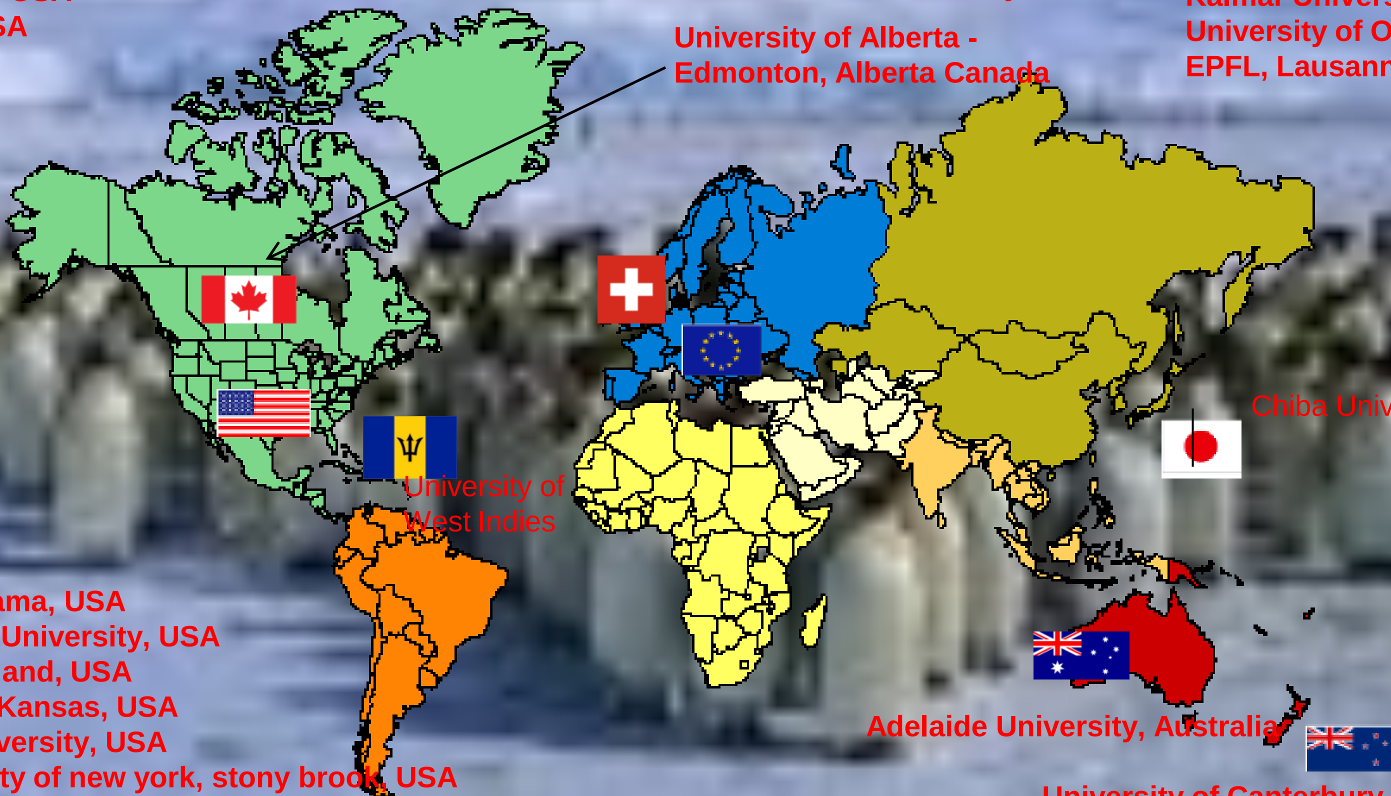
The IceCube Collaboration

- Bartol Research Inst, Univ of Delaware, USA
- Pennsylvania State University, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- UC Berkeley, USA
- UC Irvine, USA

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany

Humboldt Universität, Germany
MPI, Heidelberg, Germany
Ruhr-Universität, Bochum, Germany
Bonn Universität, Germany
RWTH Aachen, Germany
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
University of Oxford, UK
EPFL, Lausanne, Switzerland

University of Alberta - Edmonton, Alberta Canada



University of West Indies

Chiba University, Japan

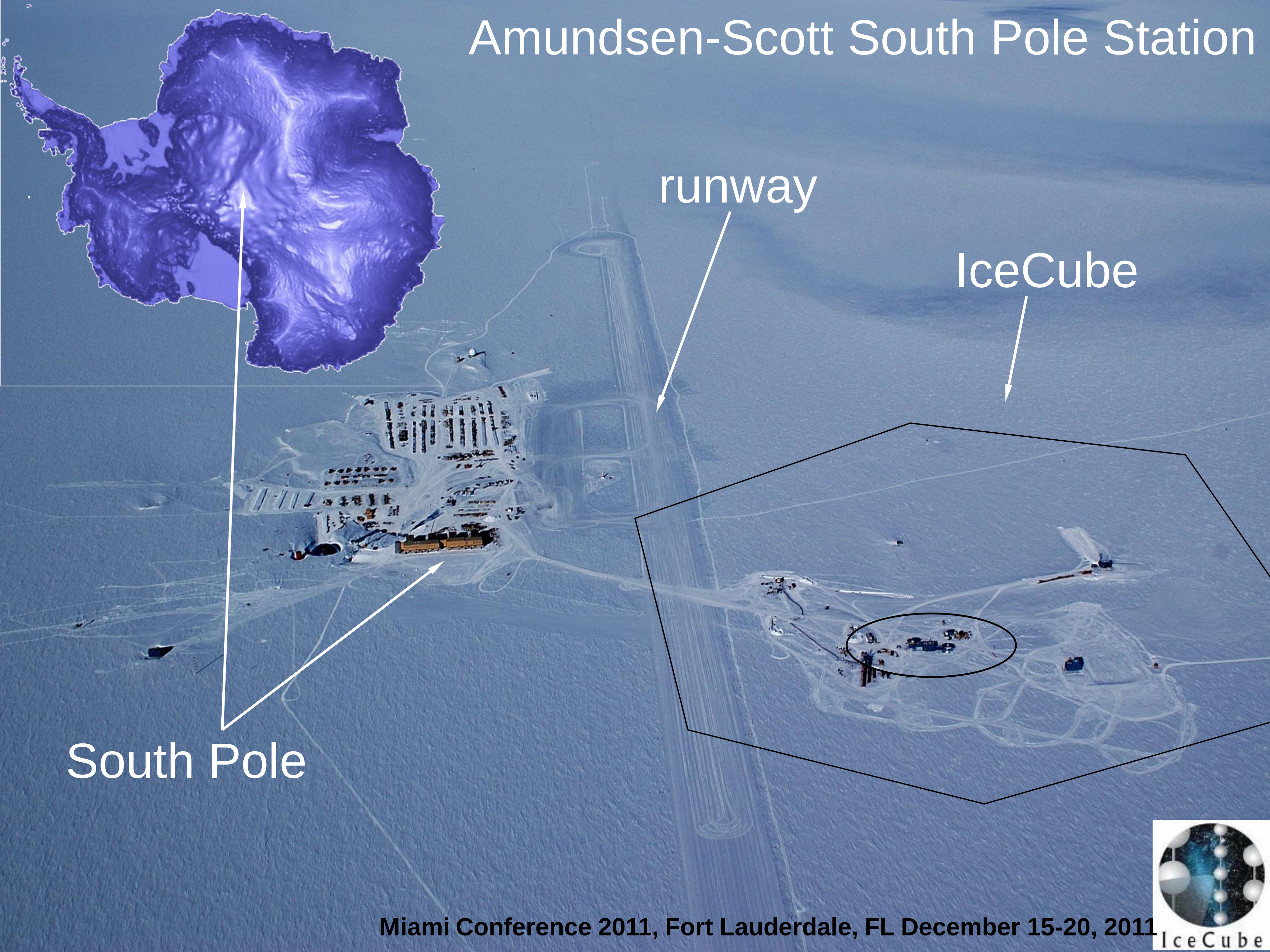
Adelaide University, Australia

University of Canterbury, Christchurch, New Zealand

Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern University, USA
state university of new york, stony brook, USA
University of Alaska, Anchorage, USA
Georgia Tech, USA
Ohio State, USA

36 collaborating institutions

Amundsen-Scott South Pole Station



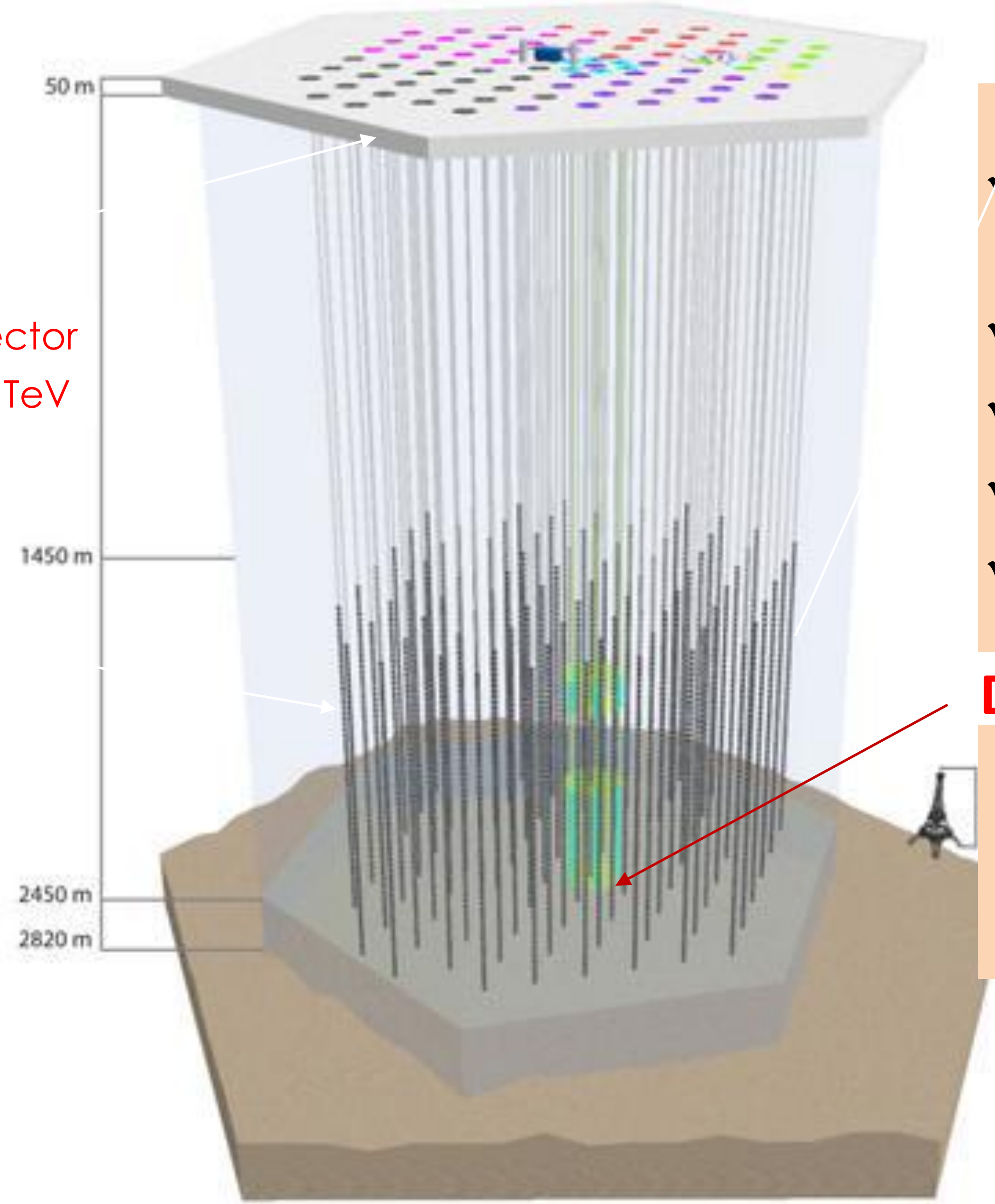
The IceCube Detector

IceTop

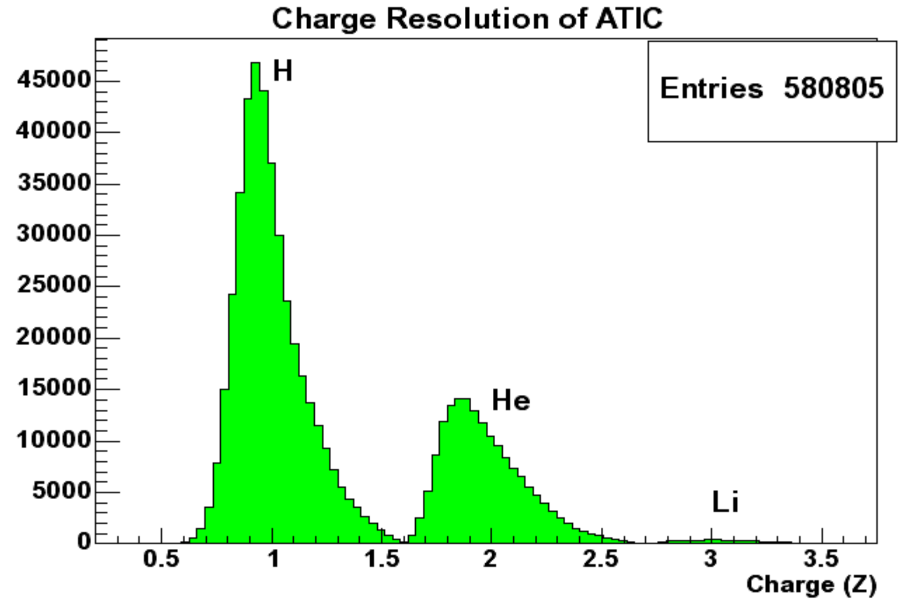
Air shower detector threshold ~ 300 TeV

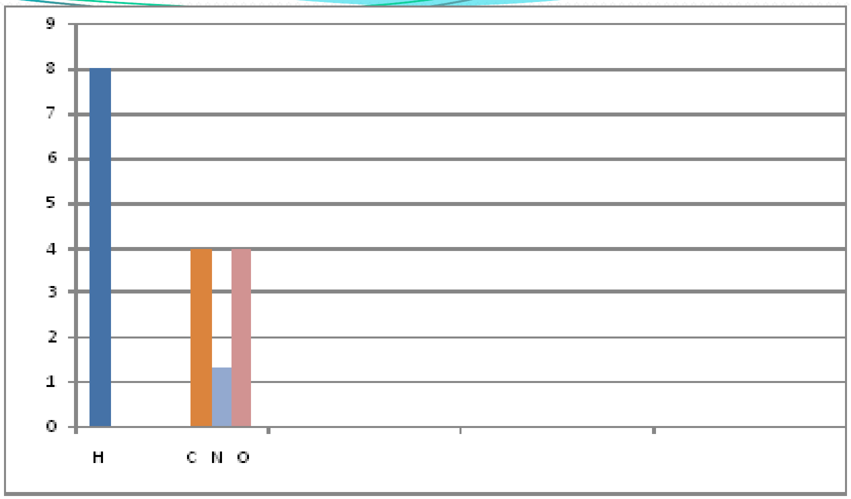
InIce

86 Strings, 60 Optical Modules per String



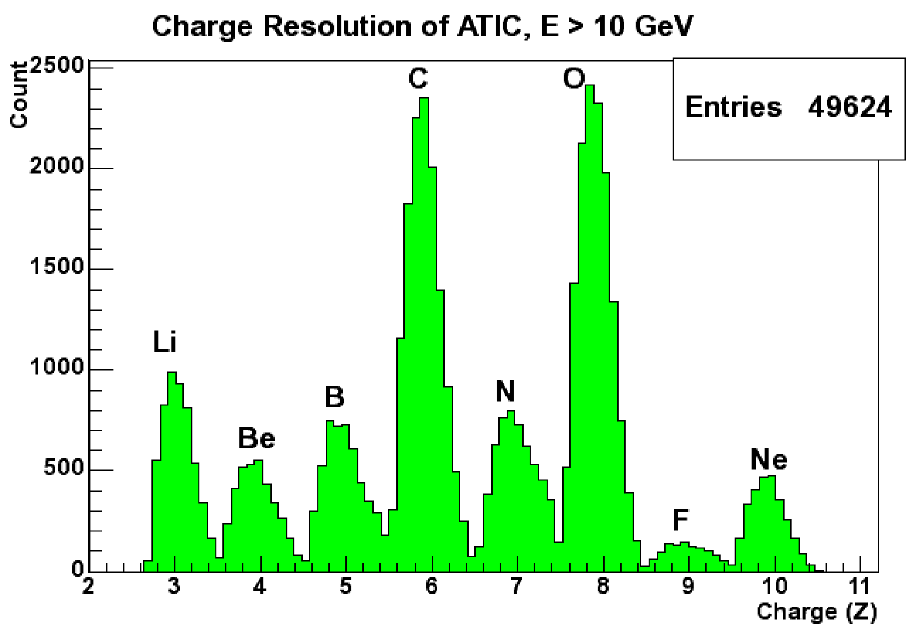
- ✓Completion: December 2010
- ✓86 strings
- ✓2008: 40 Strings
- ✓2009: 59 Strings
- ✓2010: 79 Strings





Chemical composition of plants

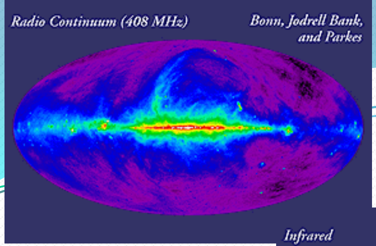
Nuclei are easy to detect with balloon and satellites. Lack directional information and limited to sub-PeV energies.

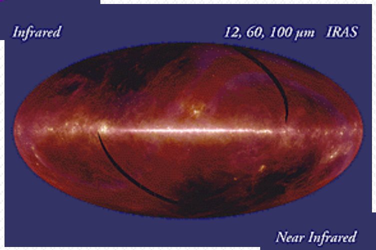


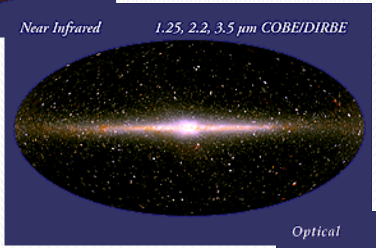
A.R. Fazely, et al.,
28th International Cosmic Ray Conference, Tsukuba, Japan (2003)

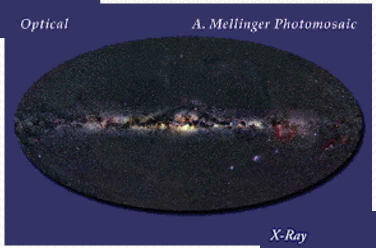
IceCube

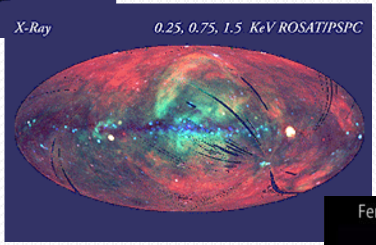
Observing the Universe

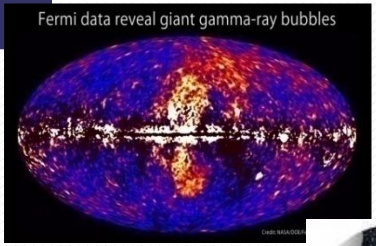


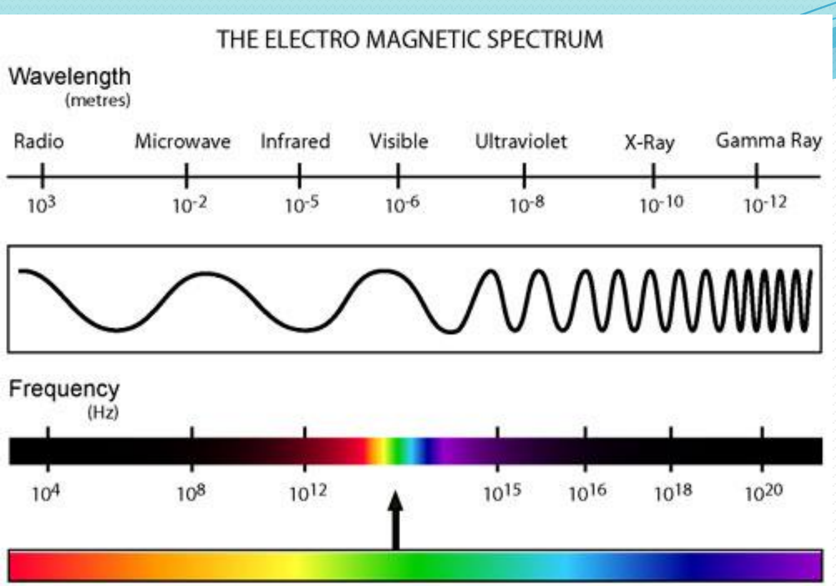








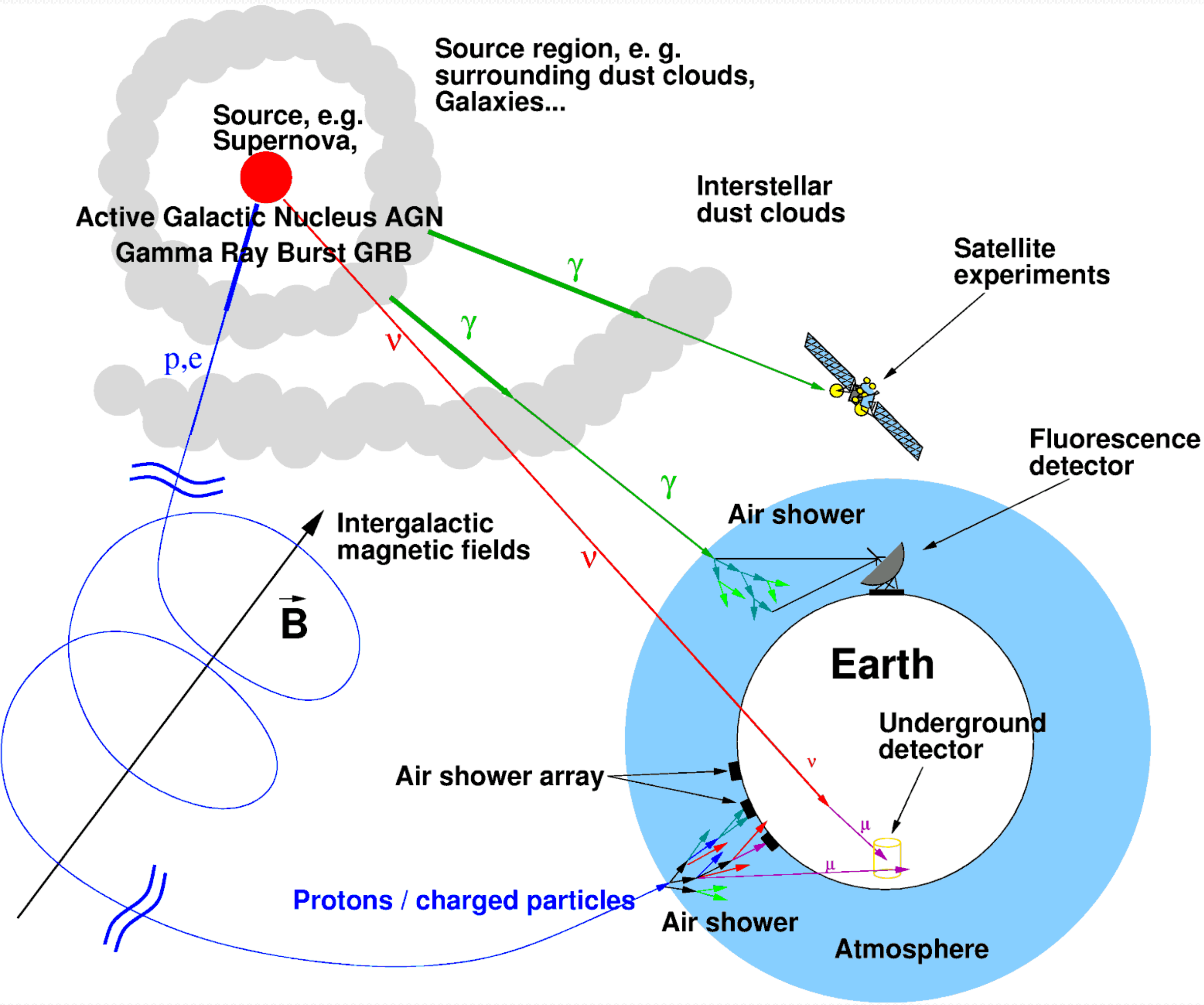




http://mwmw.gsfc.nasa.gov/mmw_allsky.html

IceCube

Neutrinos as Cosmic Messengers

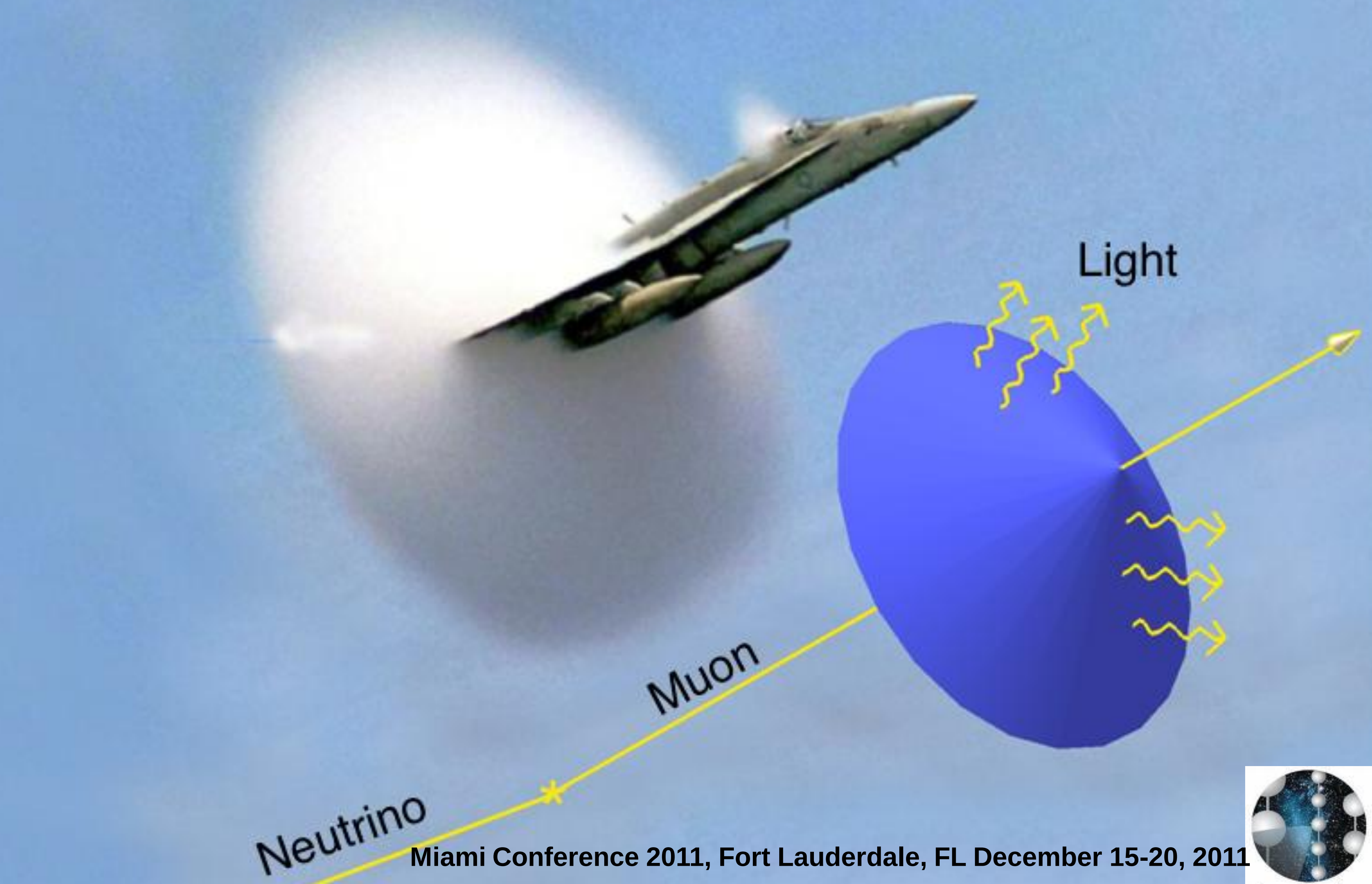


p ***Protons:*** **deflected by magnetic fields.**

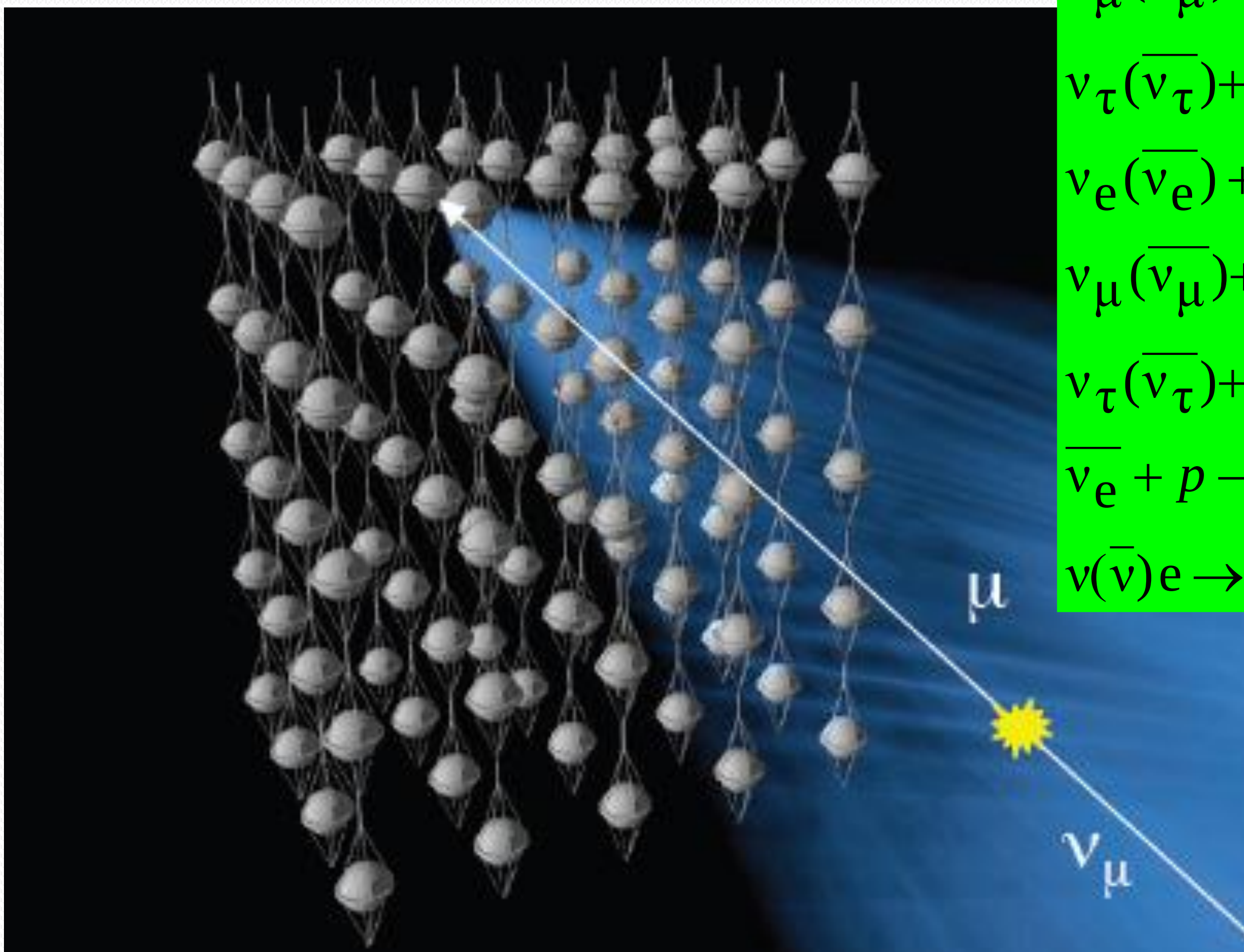
γ ***Photons:*** **easily absorbed by CMB backgrounds.**

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

Cerenkov Radiation - the electromagnetic "sonic boom"



Neutrino interactions



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

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

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

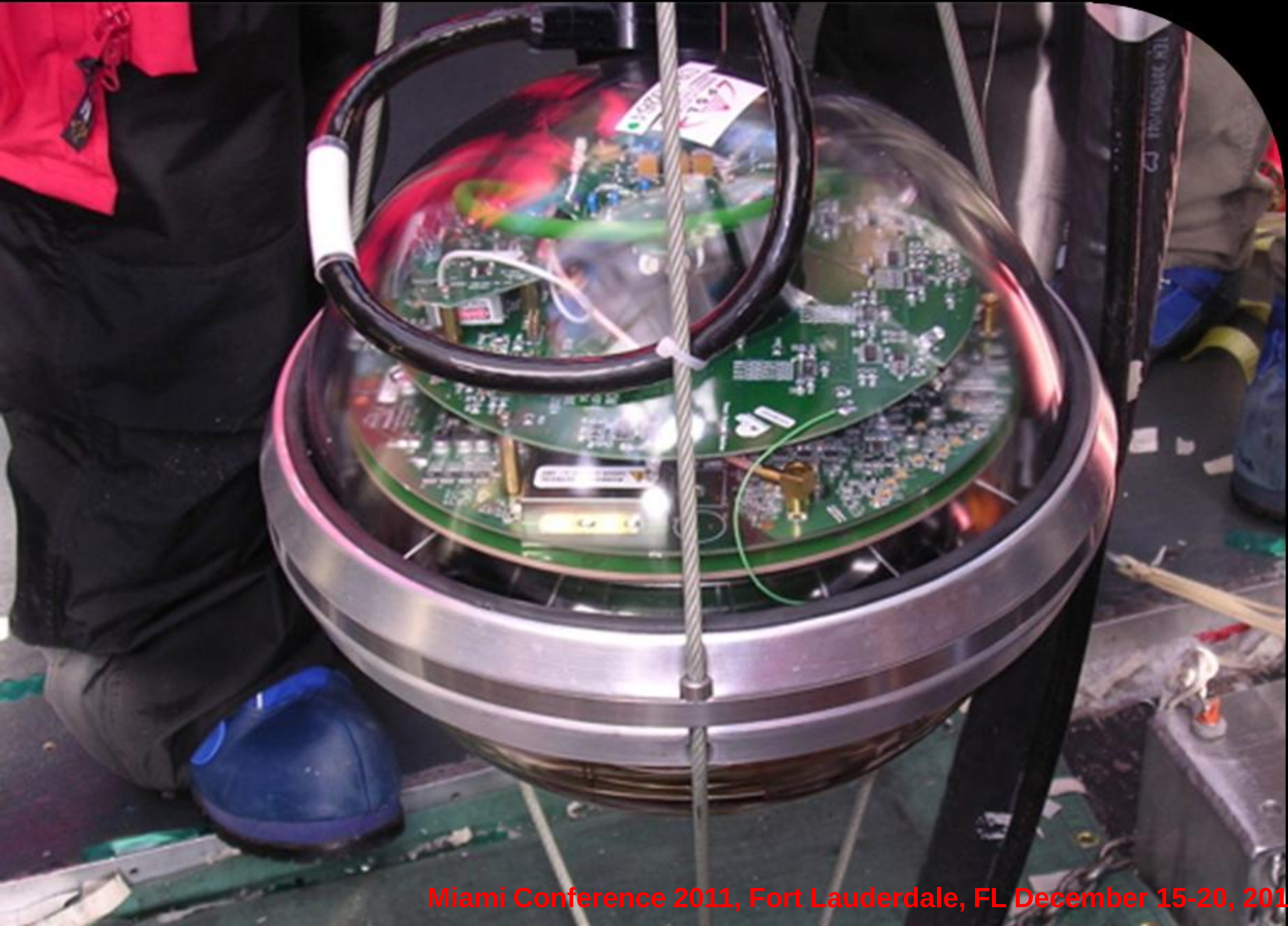
$$\nu_e(\overline{\nu_e}) + {}^{16}\mathrm{O} \rightarrow \nu_e(\overline{\nu_e}) + X \quad (NC)$$

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

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

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

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

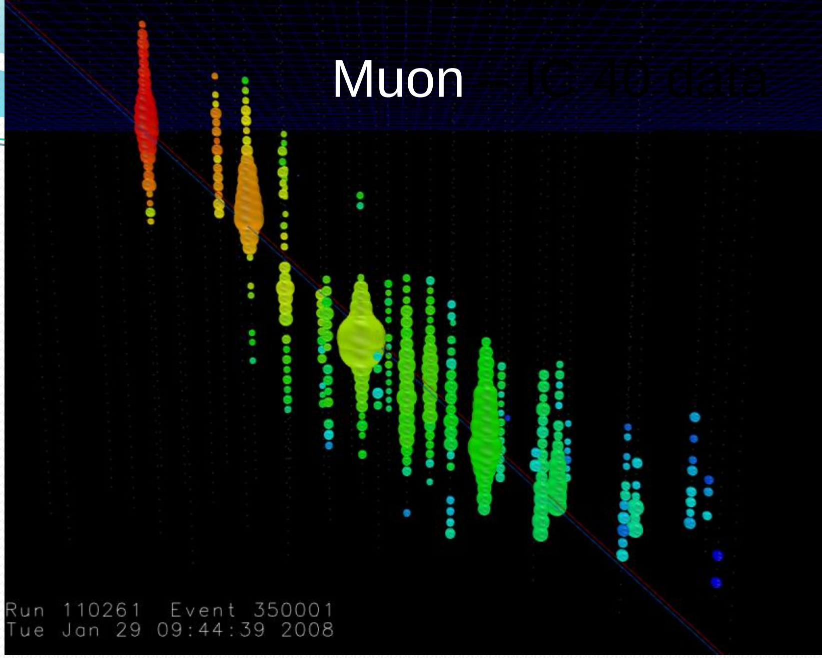


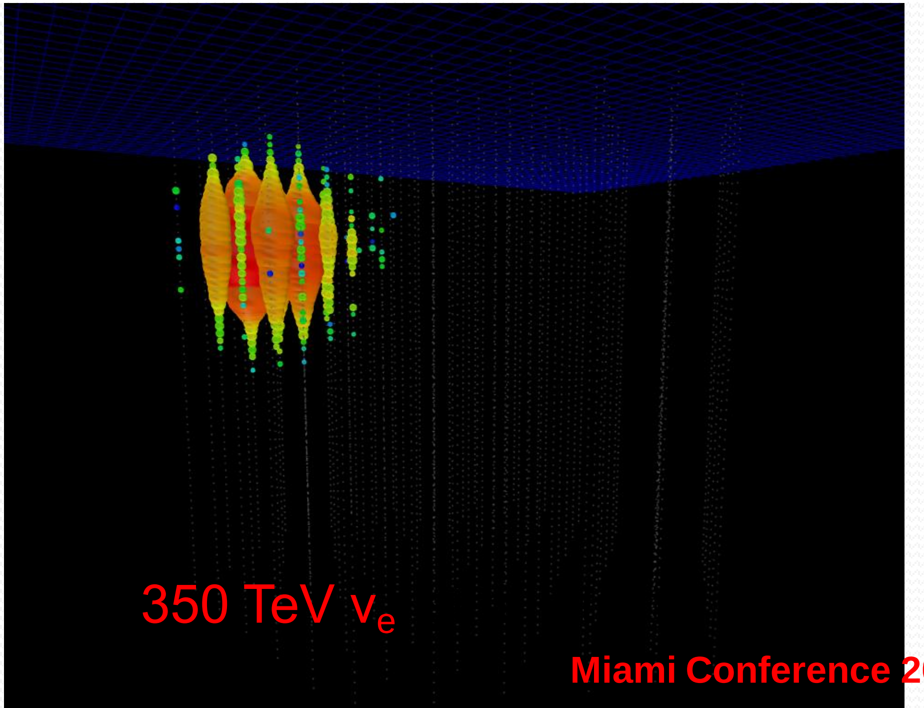
IceCube

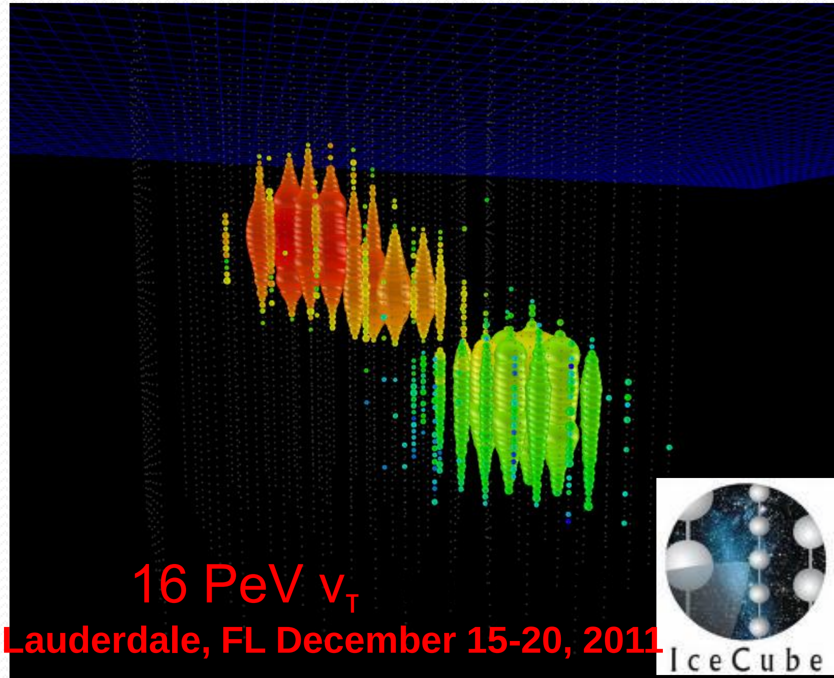
IceCube Construction

Event Topologies

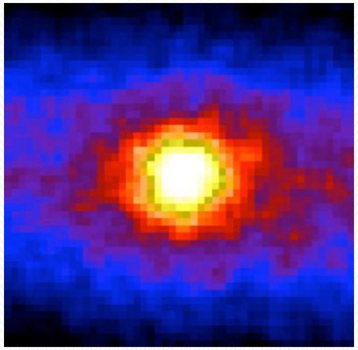
- ν_μ produce μ tracks
  - Angular Res ~ 0.7°
  - Eres log(E) ~ 0.3
- ν_e CC, ν_x NC create showers
  - ~ point sources, 'cascades'
  - Eres log(E)=0.1-0.2
- ν_τ double bang events, others





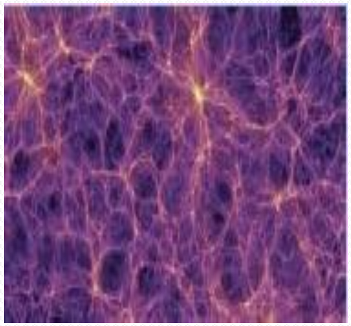


Real and Possible ET Neutrino Sources

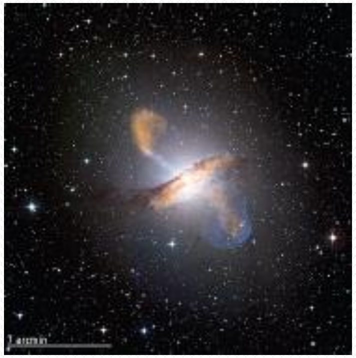


The sun

Supernova 1987A

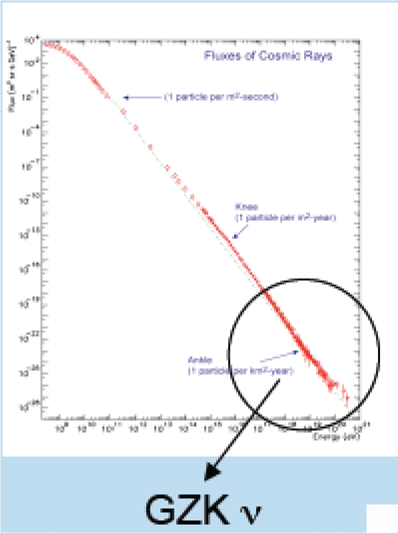


Dark Matter?



Active Galactic Nuclei

Gamma Ray Bursts



Plethora of Physics

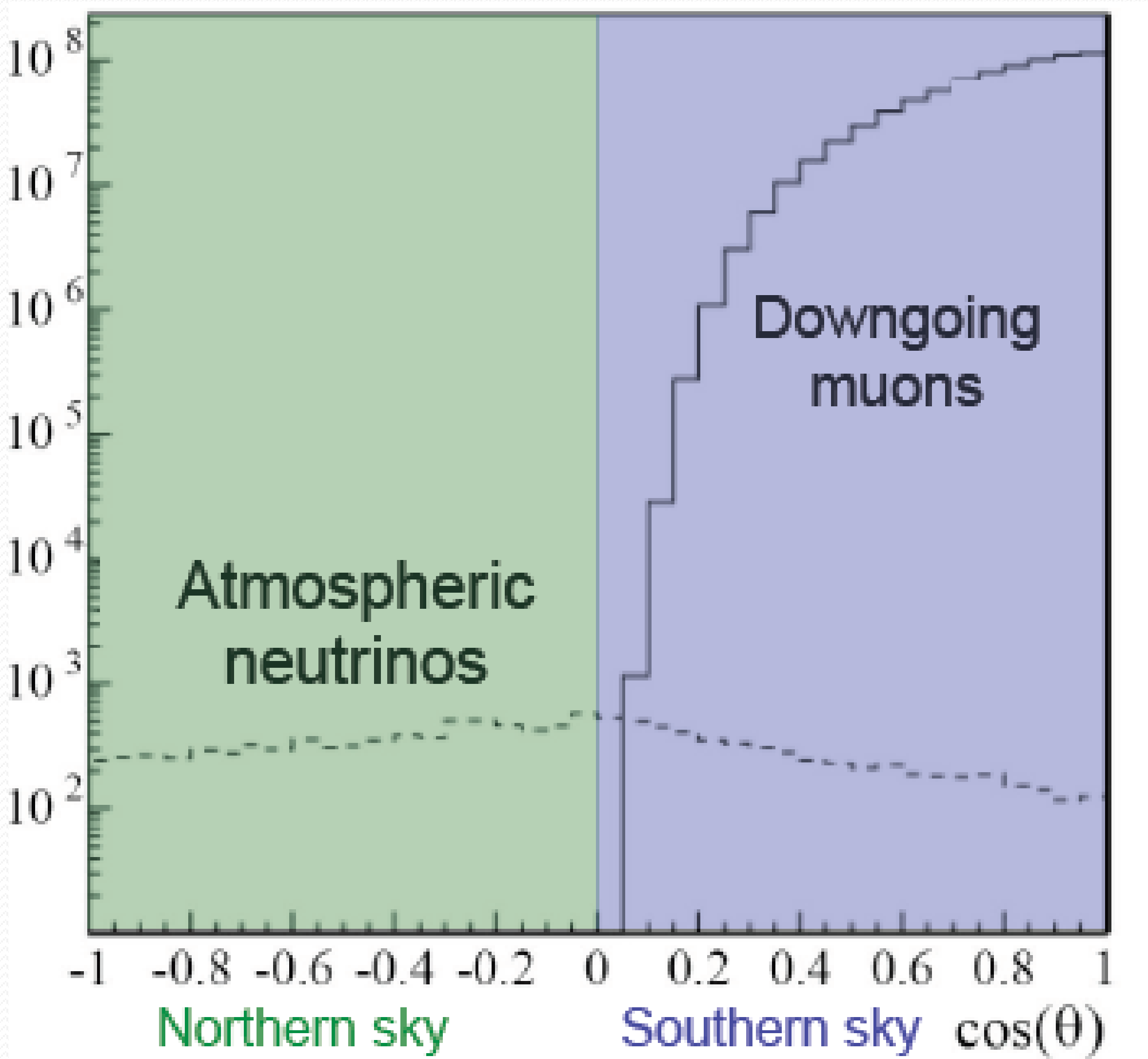
- Low energy neutrinos from the sun and SN1987A have been observed
- IceCube can search for SN event with high sensitivity.
- We want to search for higher energy neutrinos and open up a new window to the universe.
- Searches also can be done for neutrino oscillations, wimps, magnetic monopoles….

IceCube

Backgrounds

The majority of triggers in IceCube are from amospheric muons

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



Supernova Search with IceCube

Recent IceCube publication

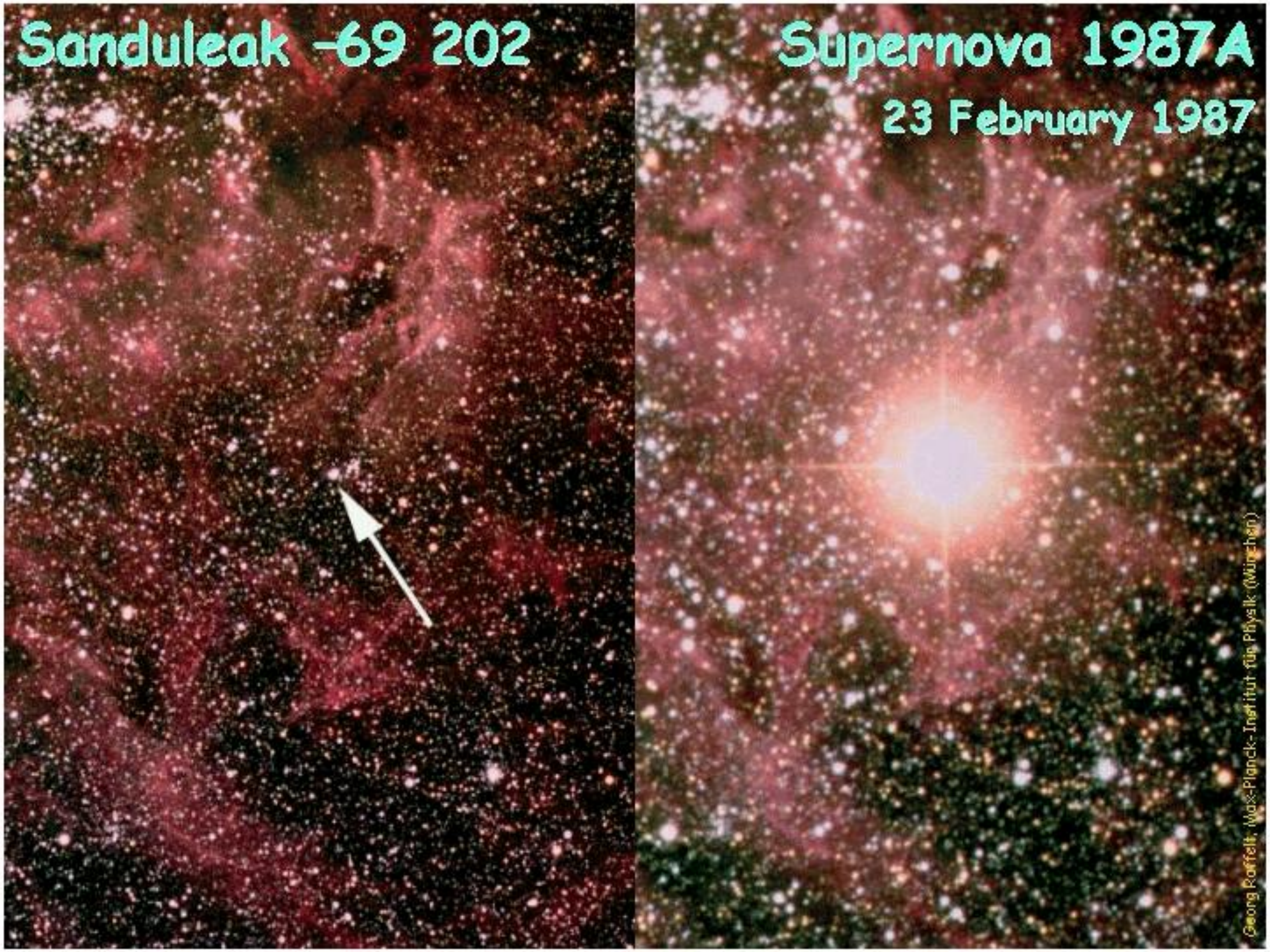
"IceCube sensitivity for low-energy neutrinos from nearby supernovae"

The IceCube Collaboration, R. Abbasi eta al.,

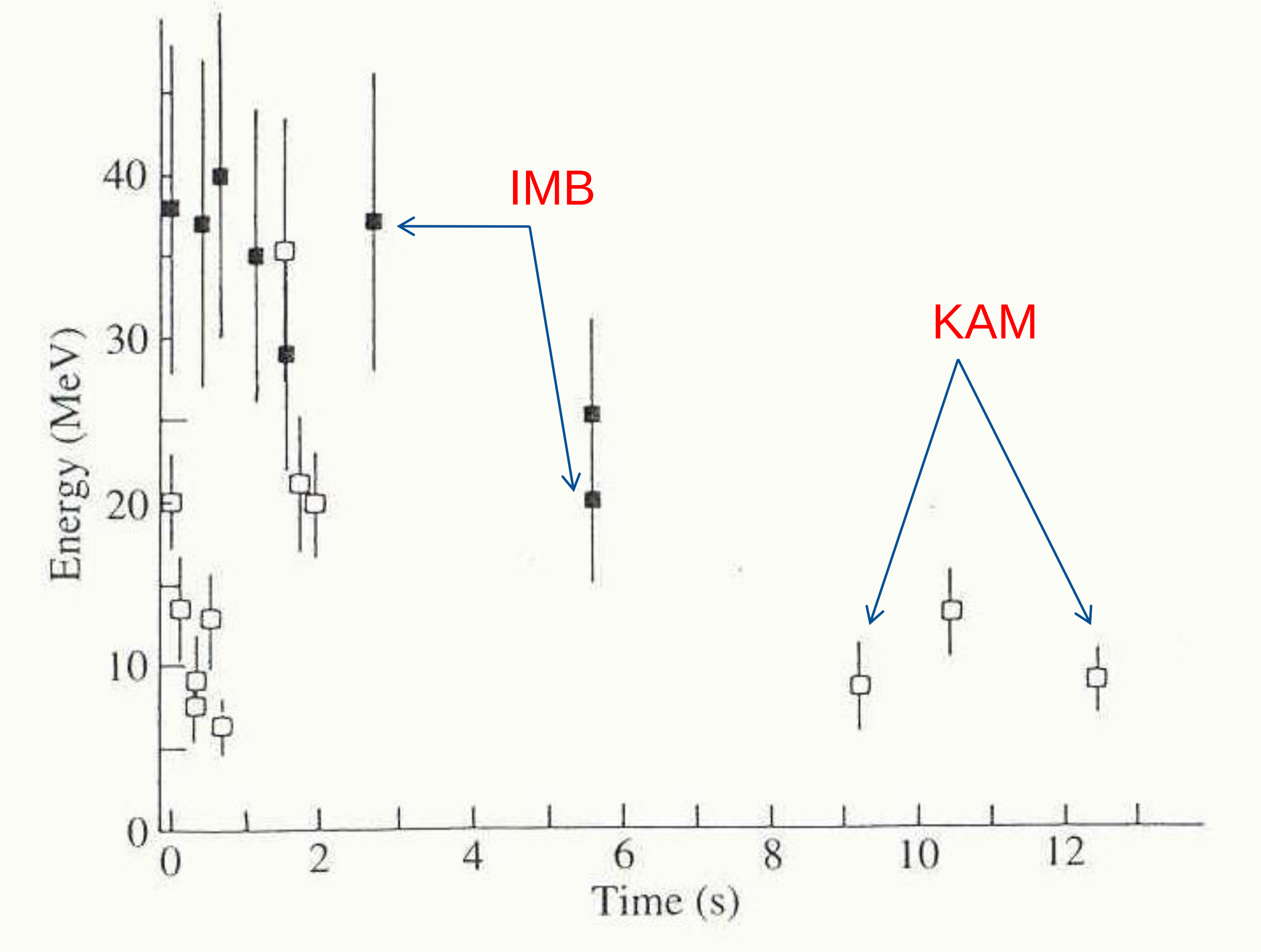
Astronomy &Astrophysics, 535 (2011) A109

DOI: http://dx.doi.org/10.1051/0004-6361/2011/7810

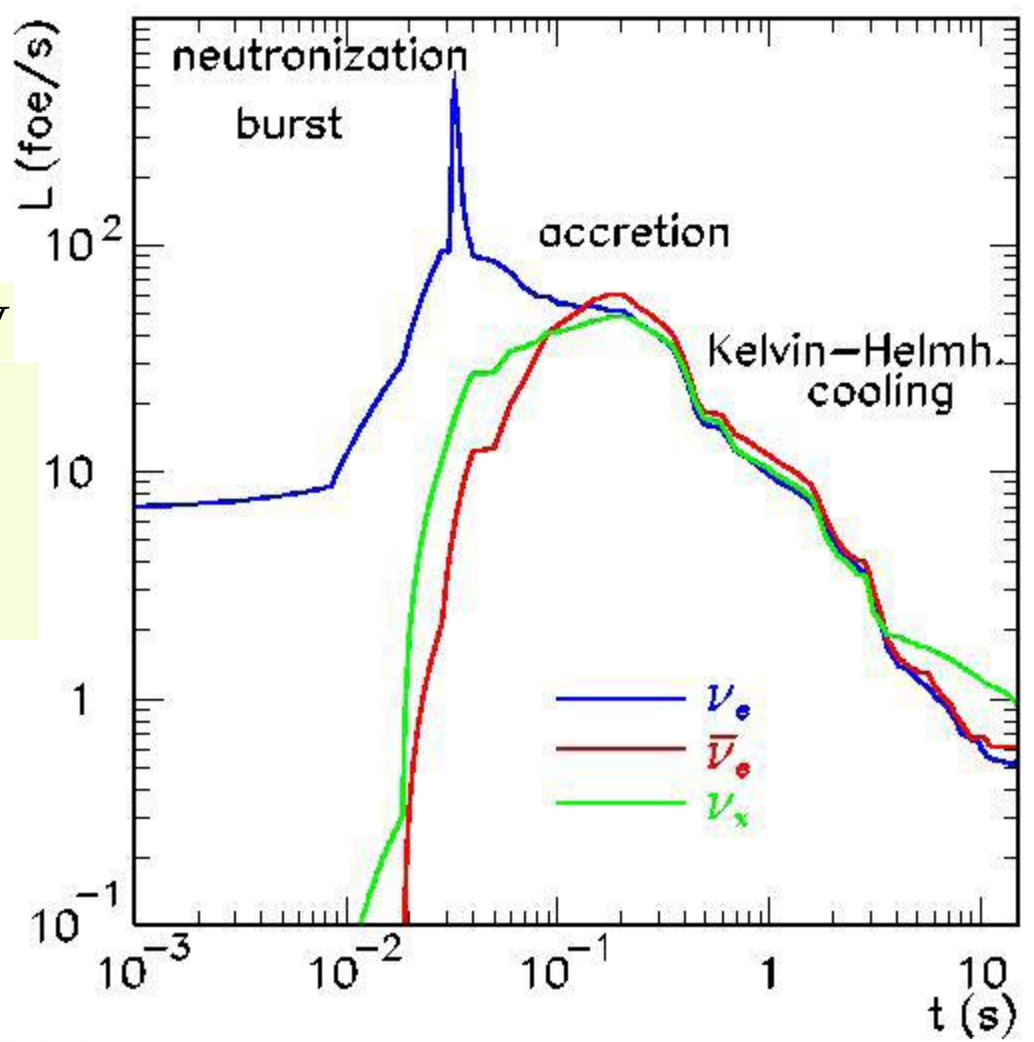
Supernova 1987a



SN87A Events: IMB & Kamioka



Neutrino time spectrum from Supernovae



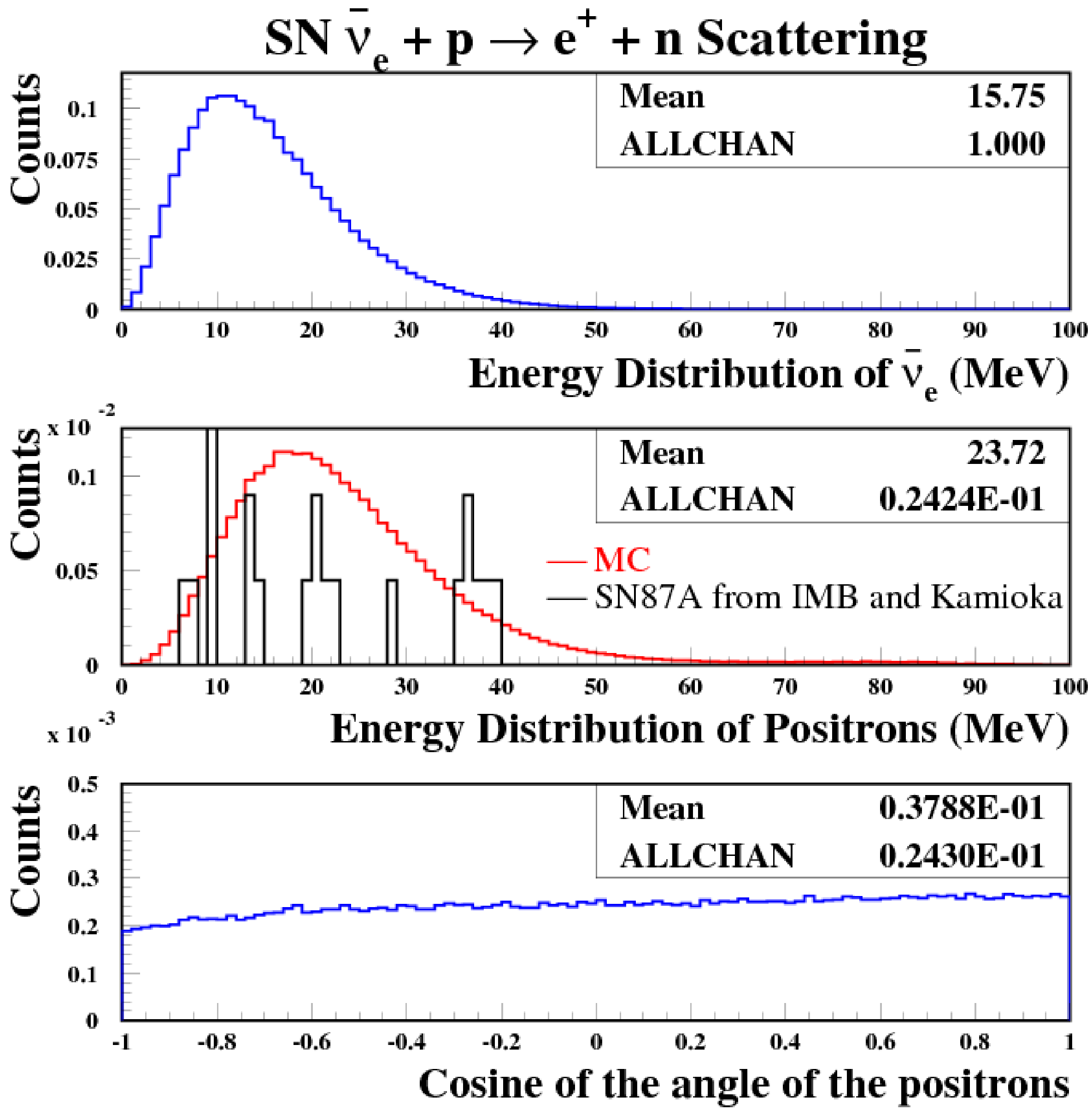
$E \approx 10^{59}\,\mathrm{MeV}$

This energy is approximately divided equally amoung all 6 neutrino flavors.

Totani et al., (1998)

Electron anti-neutrino spectrum

- $n(E_\nu) = (1/F(\alpha)T^3)(E_\nu^3/\exp(E_\nu/T - \alpha) + 1)$
  We assume T = 5 MeV and $\alpha = 0$.
- $F(\alpha)$ normalizes the spectrum to unit flux
- This yields an average neutrino energy of ~16 MeV.


SN $\bar{\nu}_e + p \rightarrow e^+ + n$ Scattering
Counts
Mean 15.75
ALLCHAN 1.000
Energy Distribution of $\bar{\nu}_e$ (MeV)
x 10^-2
Counts
Mean 23.72
ALLCHAN 0.2424E-01
MC
SN87A from IMB and Kamioka
Energy Distribution of Positrons (MeV)
x 10^-3
Counts
Mean 0.3788E-01
ALLCHAN 0.2430E-01
Cosine of the angle of the positrons

IceCube SN Trigger

The IceCube SN trigger is designed based on an increase in scalar counts above the dark rates of the PMTs.

There are 5160 PMTs in the IceCube and the average noise rate, including the atmospheric muons, is about 280 Hz per PMT. This would introduce a fluctuation of approximately ± 1200.

Three different trigger gates: 0.5 s, 4.0 s and 10.0 s

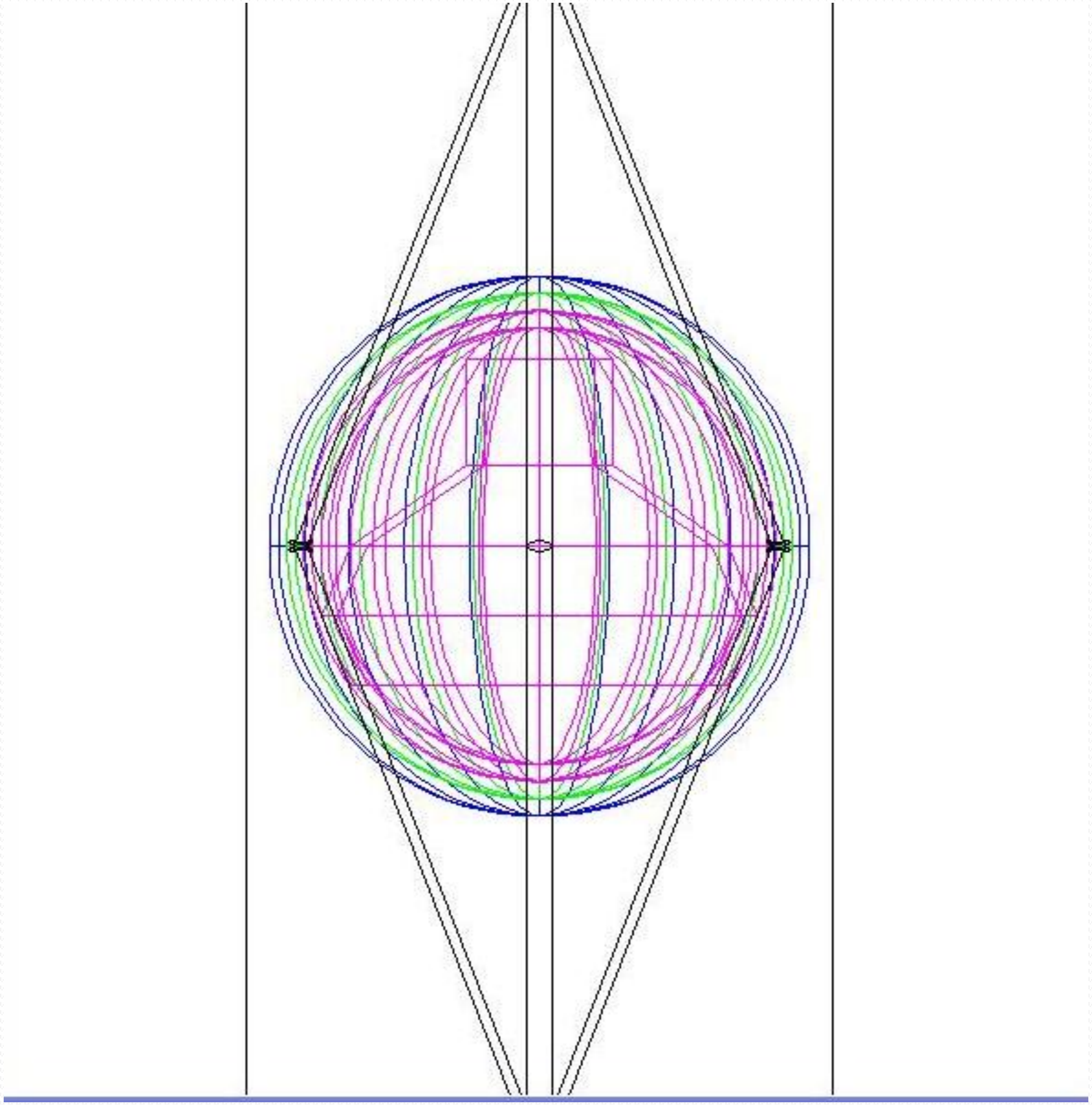
IceCube on-line alerts are only $\geq 6\sigma$.

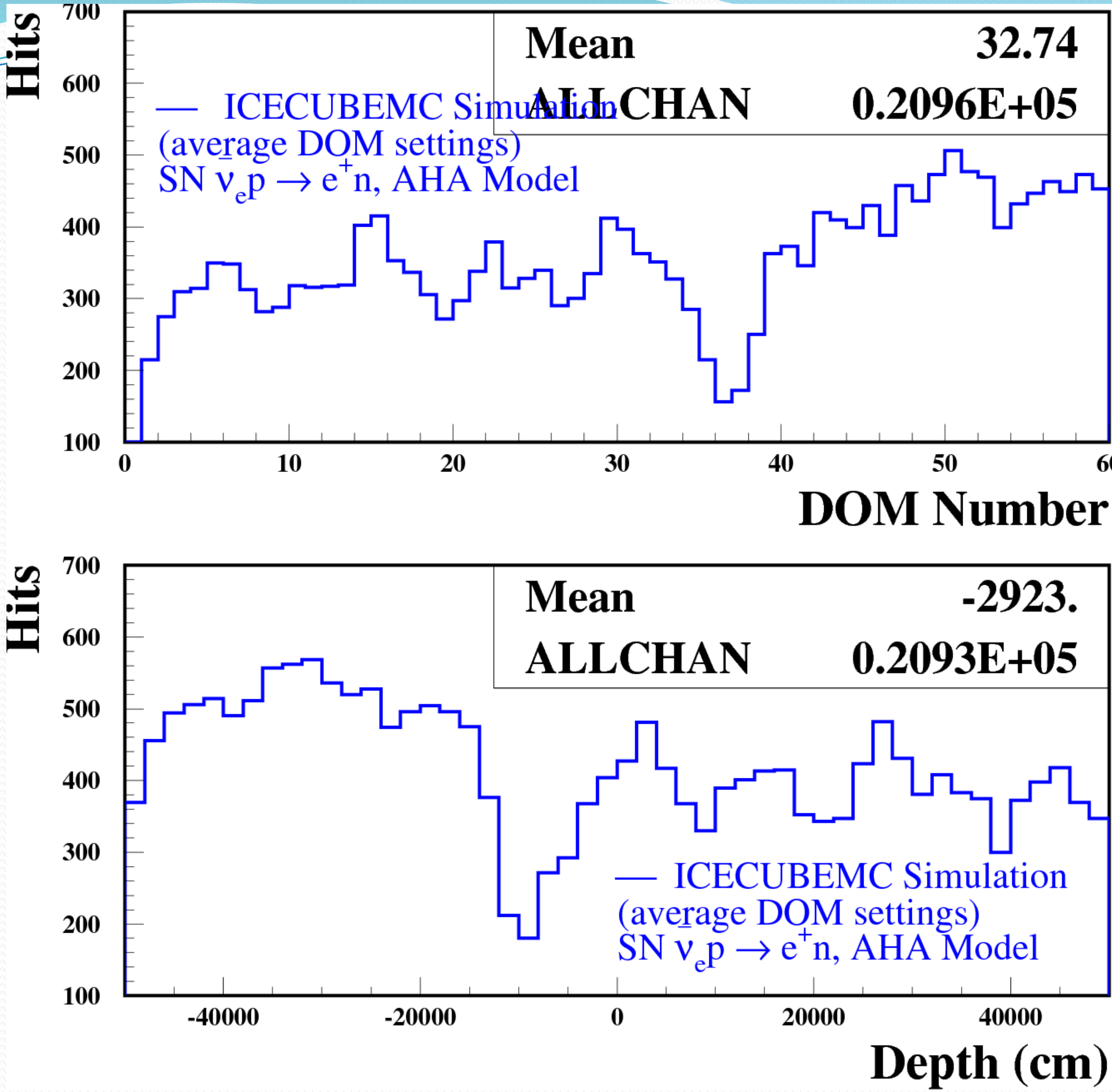
IceCube is a member of SNEWS and alerts $\geq 7.1\ \sigma$ (published) are reported to SNEWS. Now, $\geq 7.3\ \sigma$

Simulation Process

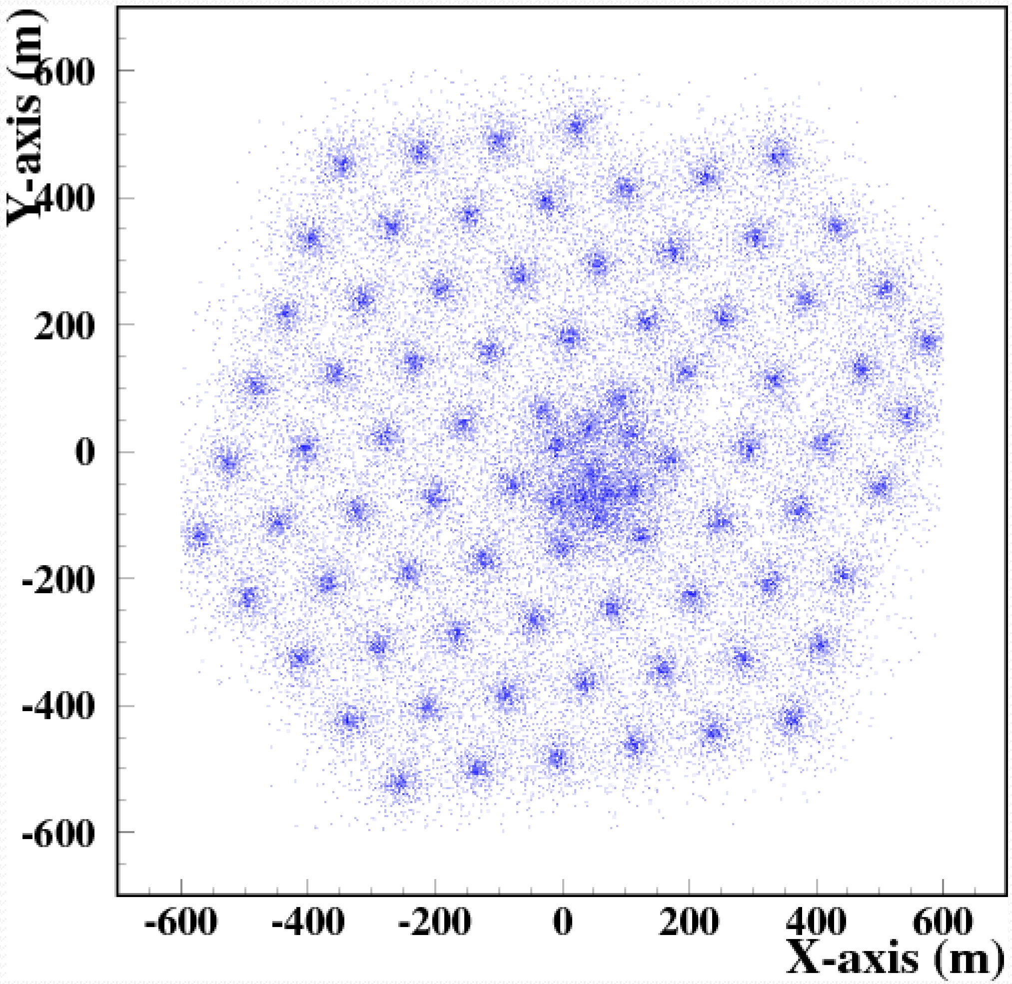
- Geant/GCALOR
- Full IceCube geometry (IC-86)
- SN neutrino or other neutrino generators
- Layered ice included
- Scattering, Absorption included
- DOM simulator, photon transport using Geant Cherenkov codes
- Dead/problem DOMs excluded
- DOM noise included
- Cable shadow included
- Neutrino Capture and positron annihilation included
- Hard local coincidence included
- Output – root tree files fully compatible with data

DOM Geometry

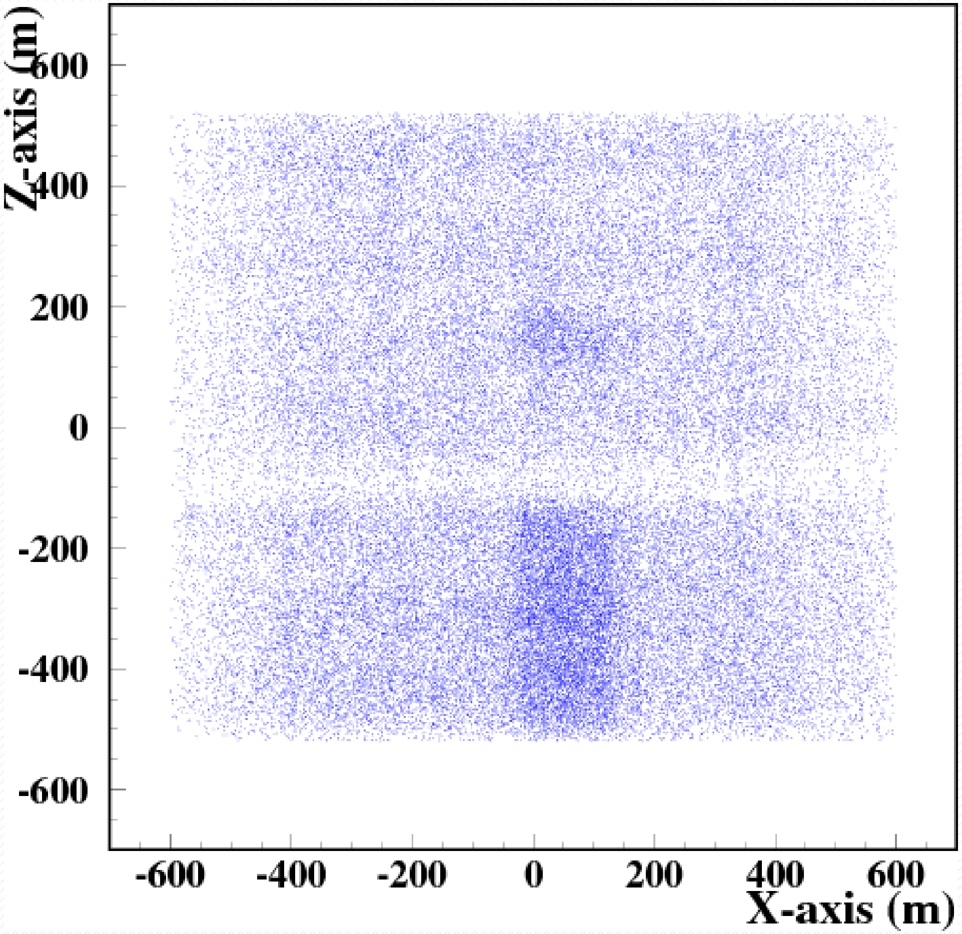


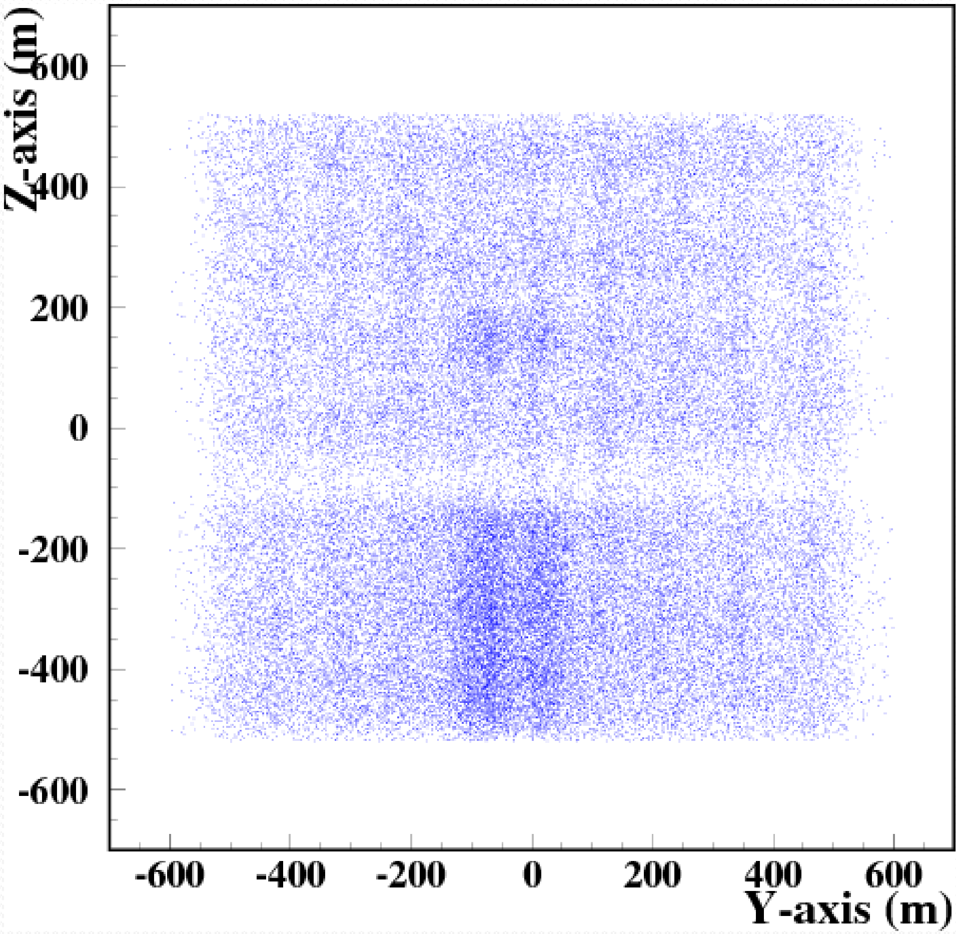

Hits
Mean 32.74
ALLCHAN 0.2096E+05
— ICECUBEMC Simulation
(average DOM settings)
SN $\nu_e p \rightarrow e^+ n$, AHA Model
DOM Number
Hits
Mean -2923.
ALLCHAN 0.2093E+05
— ICECUBEMC Simulation
(average DOM settings)
SN $\nu_e p \rightarrow e^+ n$, AHA Model
Depth (cm)

XY Hit distribution for SN positrons, i3geant , Average DOM QE, 35% higher for DeepCore (AHA Ice Model, M. Ackermann, et al., J. Geophys. Res. 111, (2006) D13203.)



ZX and ZY Hit distributions for SN positrons, I3geant , Average DOM QE, 35% higher for DeepCore (AHA Ice Model)





Number of Different Isotopes and Electrons in the IceCube

Isotope	% Nat. Abund.	# of Atoms
^{1}H	99.9885	6.13E+37
^{16}O	99.762	3.06E+37
^{17}O	0.038	1.16E+34
^{18}O	0.200	6.13E+34
e		3.06E+38

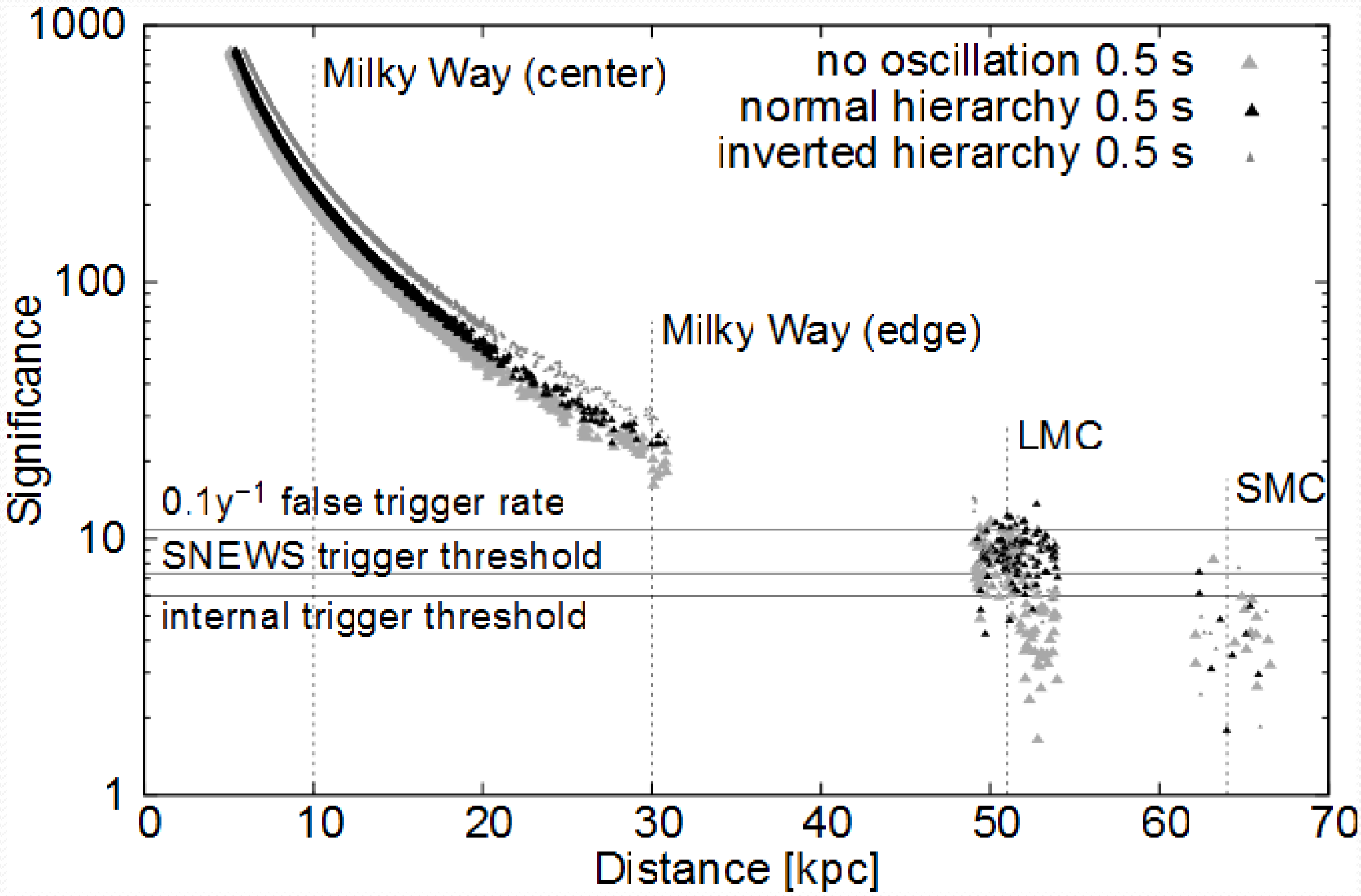
Reaction Cross Sections for Various SN ν Interactions in the IceCube

Reaction	Flux-averaged σ(cm^2)
$\bar{\nu}_e p \rightarrow n\ e^+$	0.24×10^{-40}
$\nu_e\,^{16}O \rightarrow\ ^{16}F\ e^-$ $\nu\,^{16}O \rightarrow \nu\ \gamma\,^{16}O$	0.22×10^{-41} 0.03×10^{-40}
$\nu_e\,^{17}O \rightarrow\ ^{17}F\ e^-$	0.63×10^{-40}
$\nu_e\,^{18}O \rightarrow\ ^{18}F\ e^-$	1.26×10^{-40}
$\nu_e e^- \rightarrow \nu_e e^-$	1.05×10^{-43}
$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$	0.72×10^{-43}
$\nu_\mu\ (\nu_\tau) e^- \rightarrow \nu_\mu (\nu_\tau) e^-$	0.34×10^{-43}
$\bar{\nu}_\mu\ (\bar{\nu}_\tau) e^- \rightarrow \bar{\nu}_\mu (\bar{\nu}_\tau)\ e^-$	0.24×10^{-43}

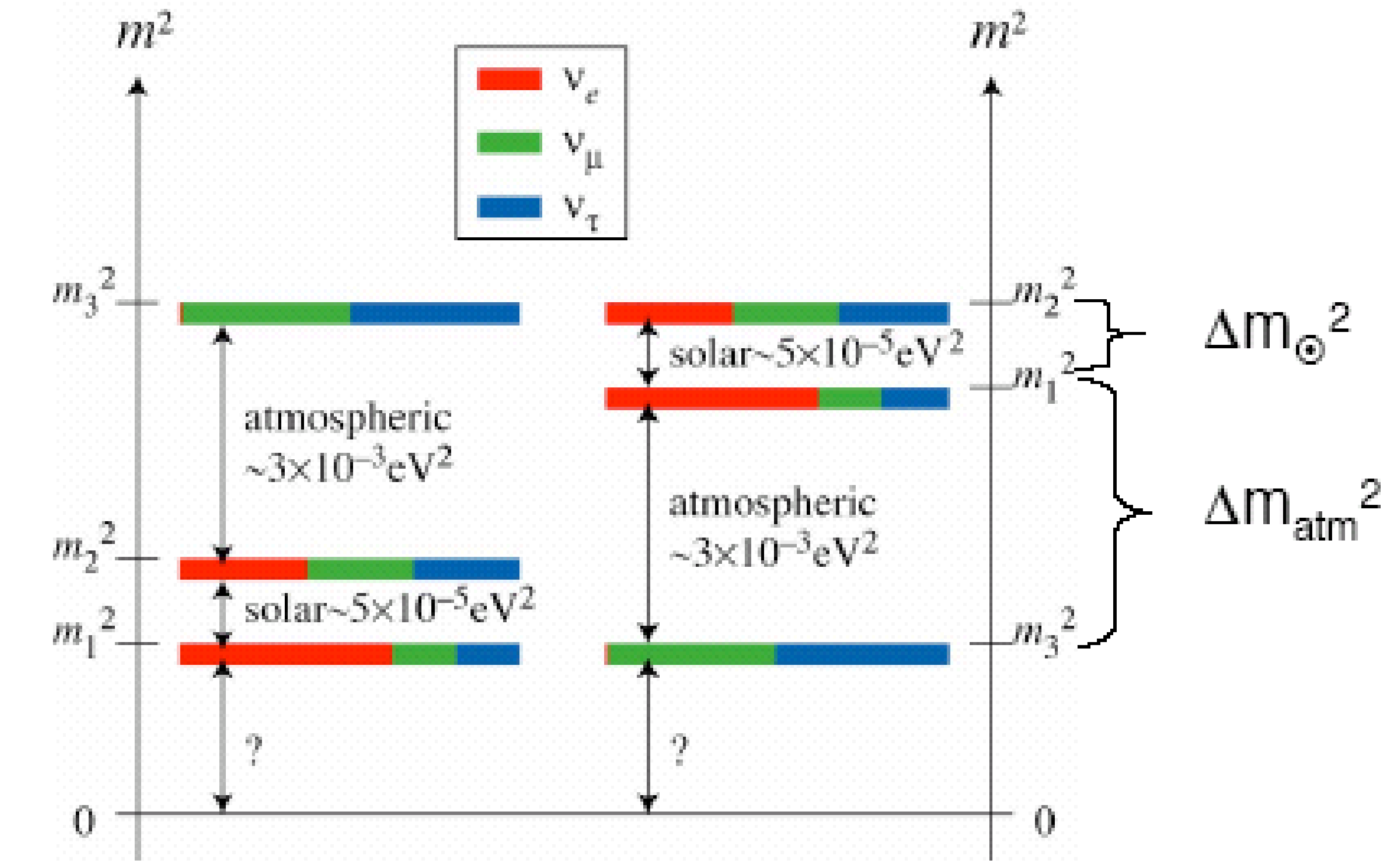
Number of events in Icecube due to a Galactic $10M_\odot$-SN at 10 kpc, T= 5 MeV, no Oscillations

Reaction	# of single hits
$\bar{\nu}_e p \rightarrow n\, e^+$	1,000,000
$\nu_e(\bar{\nu}_e)^{16}O \rightarrow {}^{16}F({}^{16}N)e^-(e^+)$	10,000
$\nu\, {}^{16}O \rightarrow \nu\, {}^{16}O\, \gamma$	70,000
$\nu_e\, {}^{18}O \rightarrow {}^{18}F\, e^-$	2,500
$\nu e^- \rightarrow \nu e^-$	30,000

IceCube Sensitvity to SN Explosions

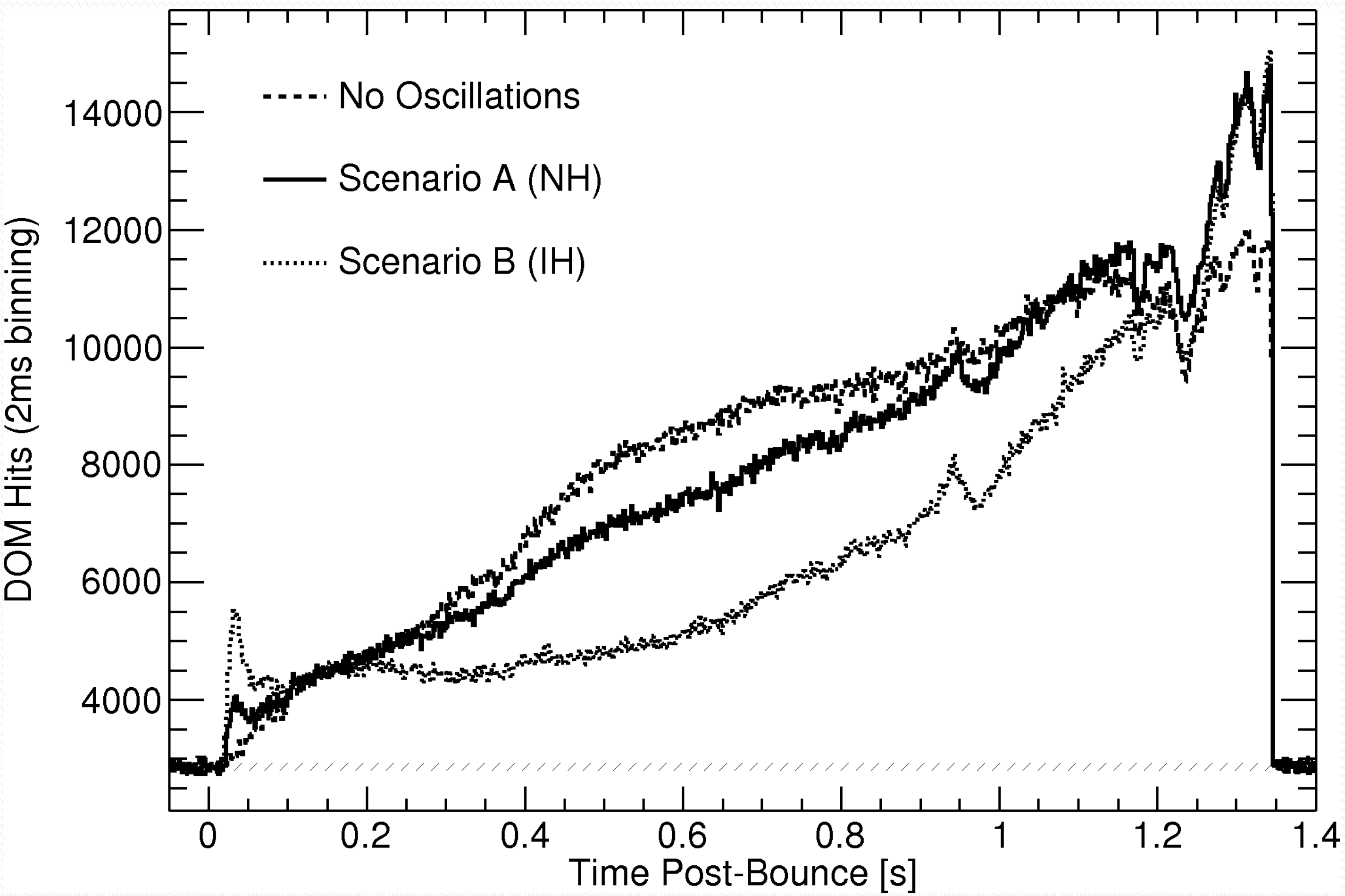


Normal and Inverted Neutrino Mass Hierarchy

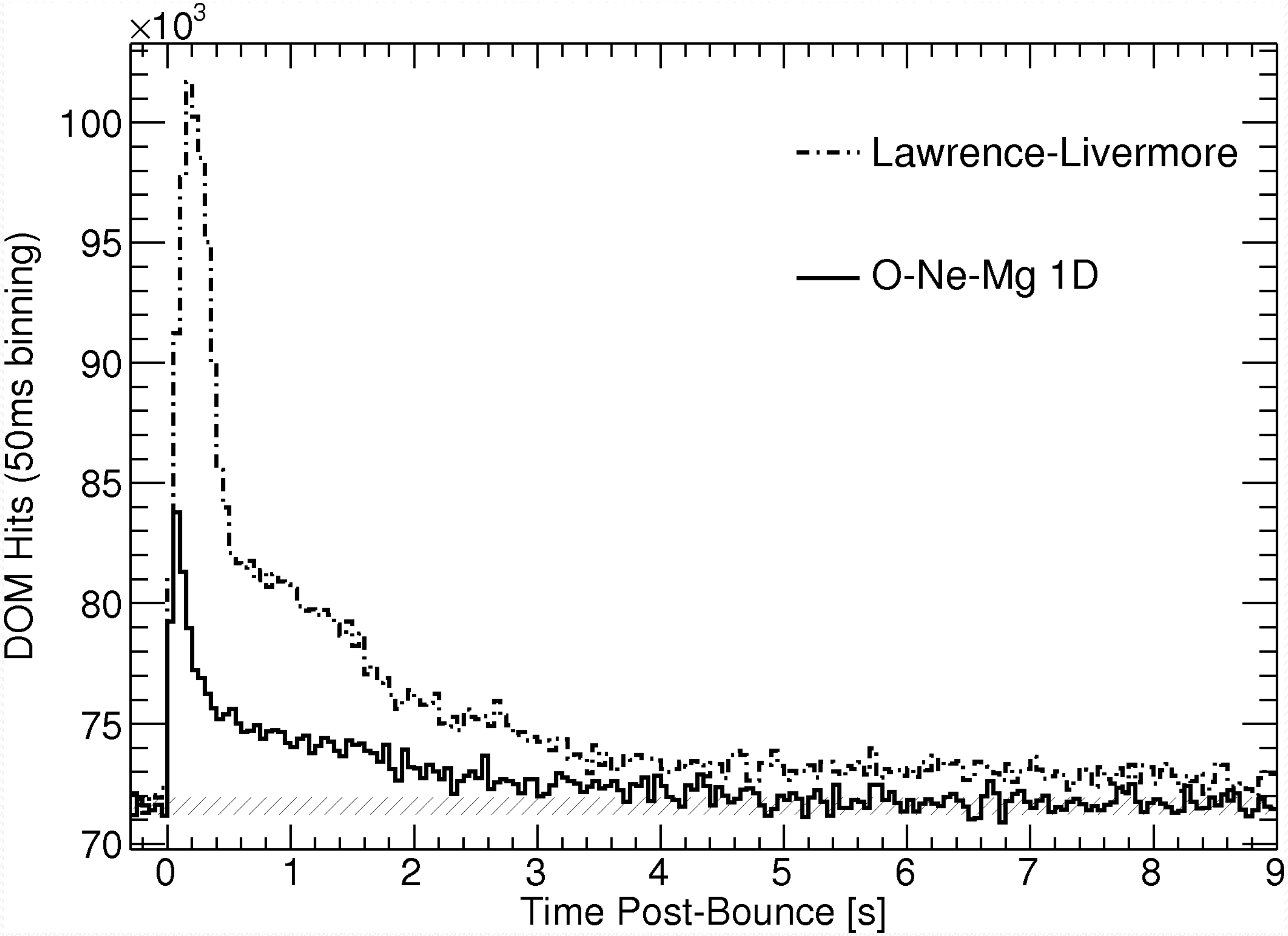


From a talk by: Sergio Palomares-Ruiz
Topical Workshop on Physics at Henderson DUSEL
Fort Collins, CO, November 18-19, 2005

Expected neutrino signal from the gravitational collapse of a non rotating massive star of 40 solar masses into a black hole at 10 kpc distance for a hard equation of state (Shen 1998) following Sumiyoshi et al. (2007). The 1σ-band corresponding to detector noise (hatched area) has a width of about ±70 counts.



- **Expected rate distribution at 10 kpc distance for the Lawrence-Livermore model (dashed line) and O-Ne-Mg model by Hüdepohl et al.(2010) with the full set of neutrino opacities (solid line). The 1σ-band corresponding to measured detector noise (hatched area) has a width of ± 330 counts**



Number of events in Icecube due to a 10$M_\odot$-SN from Andromeda, 778 kpc

Neutrino Spectrum	# of single hits
T = 5 MeV	181
T= 6.5 MeV	331

For usual SNs, this trigger will not be possible without higher PMT coverage.

Conclusions

- **The physics on the of SN, on the IceCube end, is very important.**
- **It is possible to design a trigger and add more DOMs to increase range sensitivity of IceCube to SN in the local group and beyond!!**
- **Frequency of SN explosion in the local group is every 5 years!**
- **This slightly varies with neutrino direction ($\nu e^- \rightarrow \nu e^-$).**
- **With galactic SN, neutrino properties can be investigated, oscillations, i.e. normal or inverted hierarchy, θ_{13}, mass, magnetic moment, neutrino velocity, and ....**