Exploring the high-energy universe with the AMANDA and IceCube detectors

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Caltech, January 13, 2004

LIGO-G040558-00-R

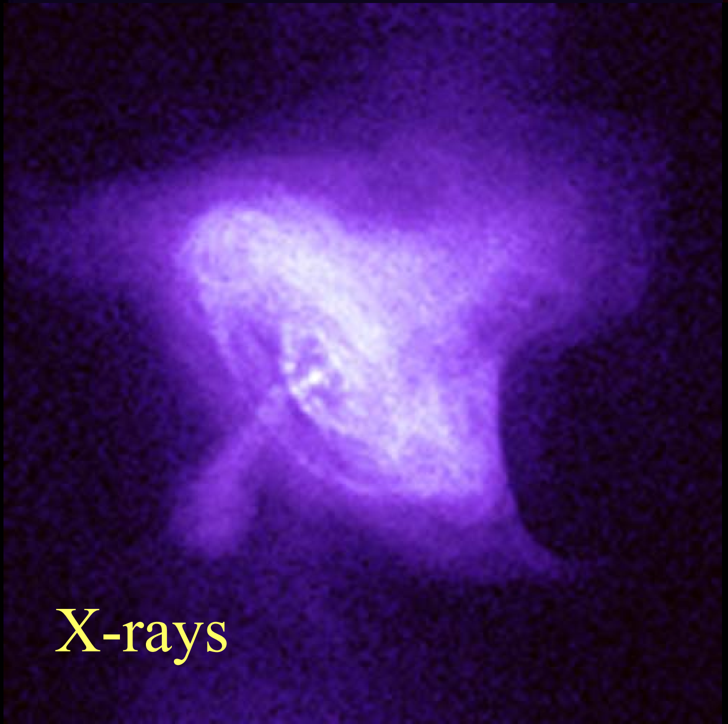
Why neutrinos?

Why the South Pole?

Why high energies?

What will we learn?

Questions to be answered



?

Neutrinos

IceCube

- ν's can escape from high-density, energetic environments (photons can't)
- ν's have no charge, so they do not get deflected by magnetic fields (cosmic rays do)
- ν's are not absorbed/scattered by matter along the way (photons are)

IceCube

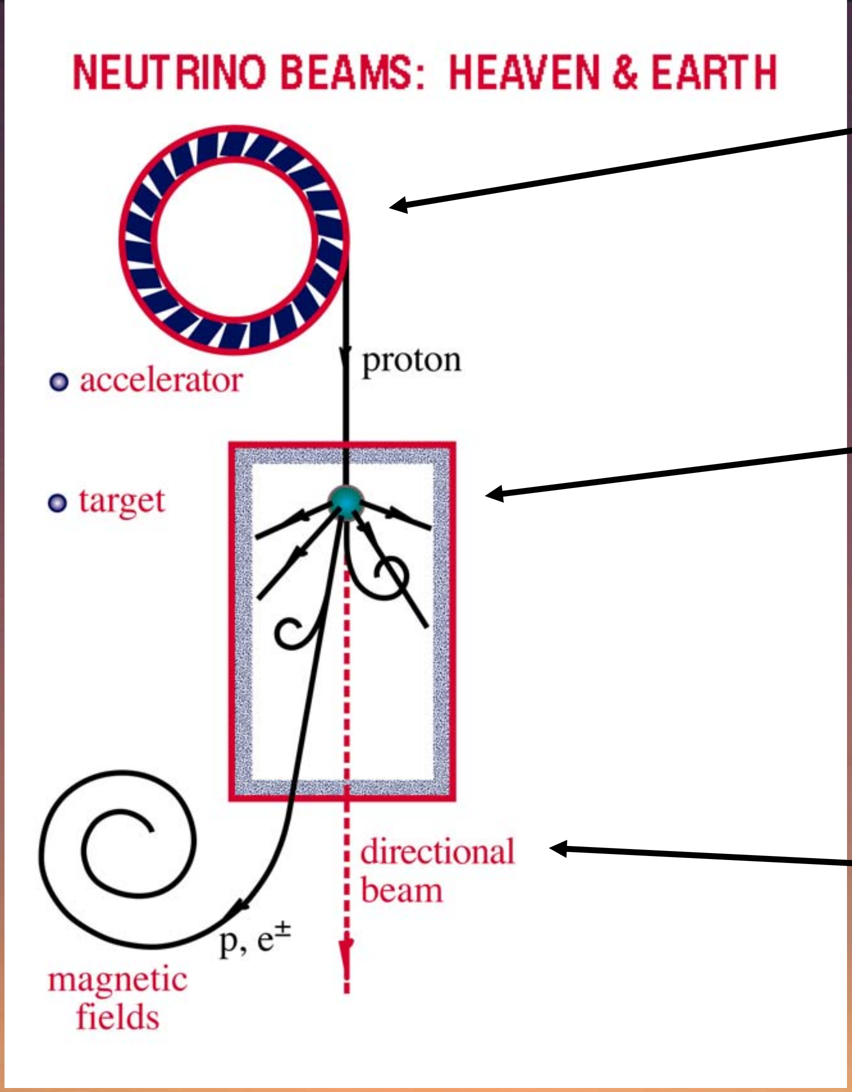
Why neutrinos?

- At very high energies, photons do not make it to Earth because they're likely to interact with the Cosmic Microwave Background:

$$\gamma + \gamma_{CMB} \longrightarrow e^{+} + e^{-}$$

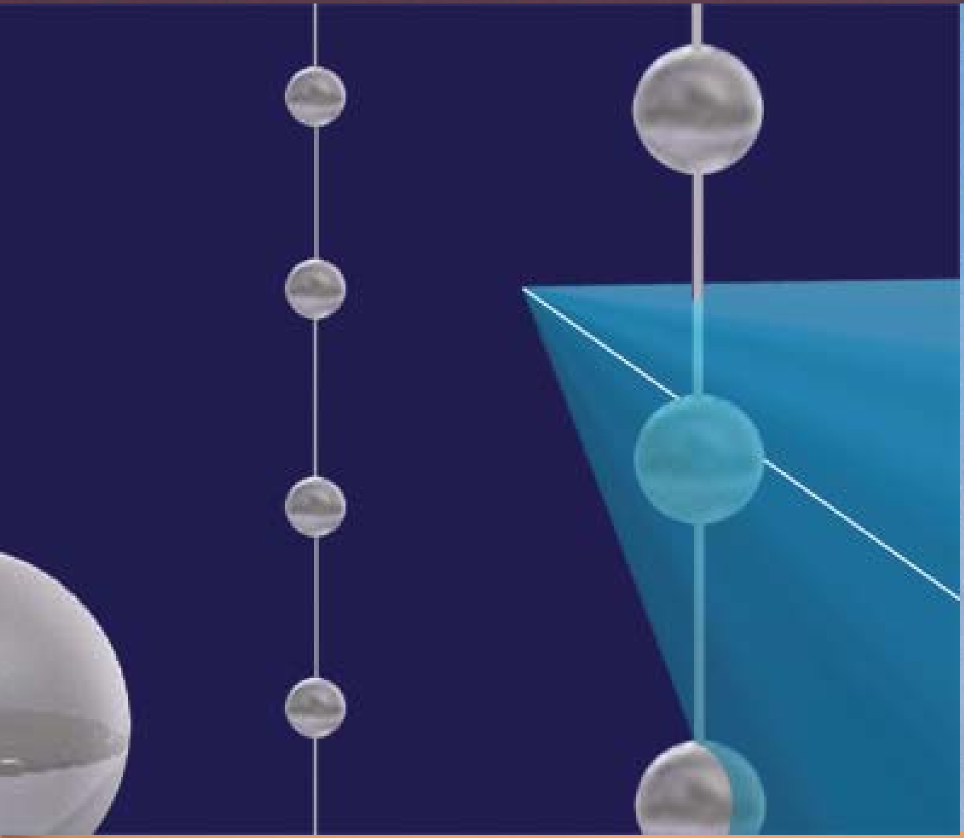
Why neutrinos?

Why neutrinos?



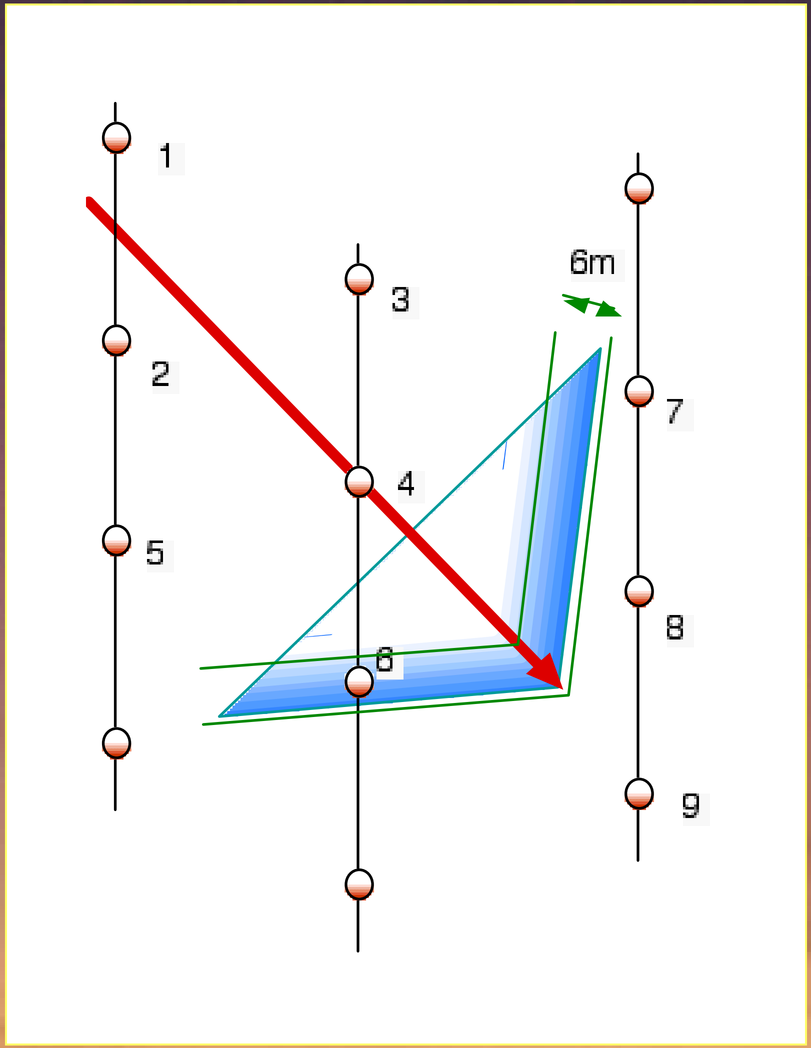
- Accelerator (could be a blazar jet, or supernova shock)
- Target (could be external radiation field, or molecular cloud)
- Neutrinos emerge undeflected

- Use the phenomenon of Cherenkov light



How to build a ν detector

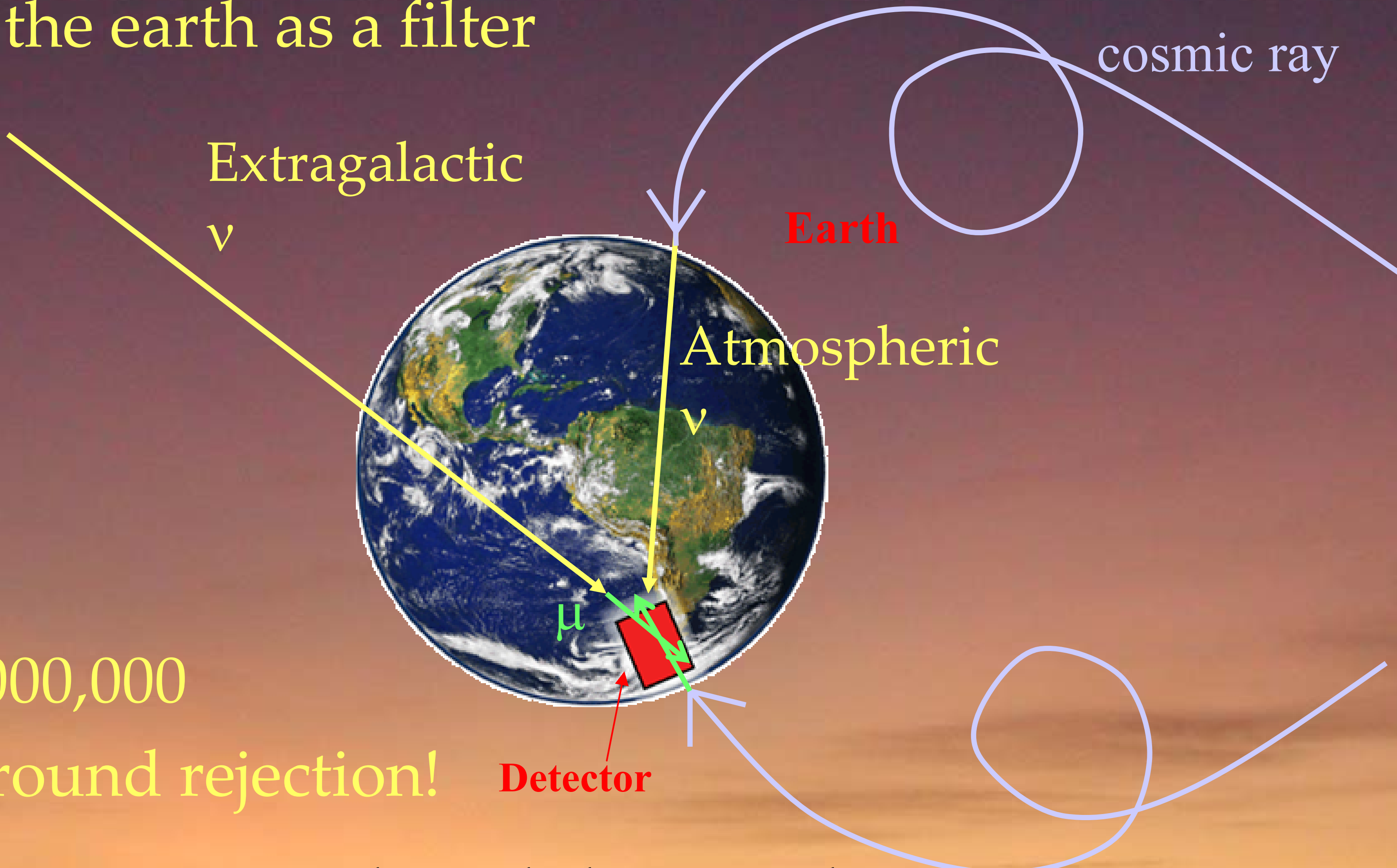
- Detect the Cherenkov light with an array of sensors
- Reconstruct the particle's direction
- Infer the direction of the original neutrino (unavoidable error of ~ 1 degree)



How to build a ν detector

How to build a ν detector

- Look for the neutrino's interaction product (e,μ,τ)
- Use the earth as a filter



- 1:1,000,000 background rejection!

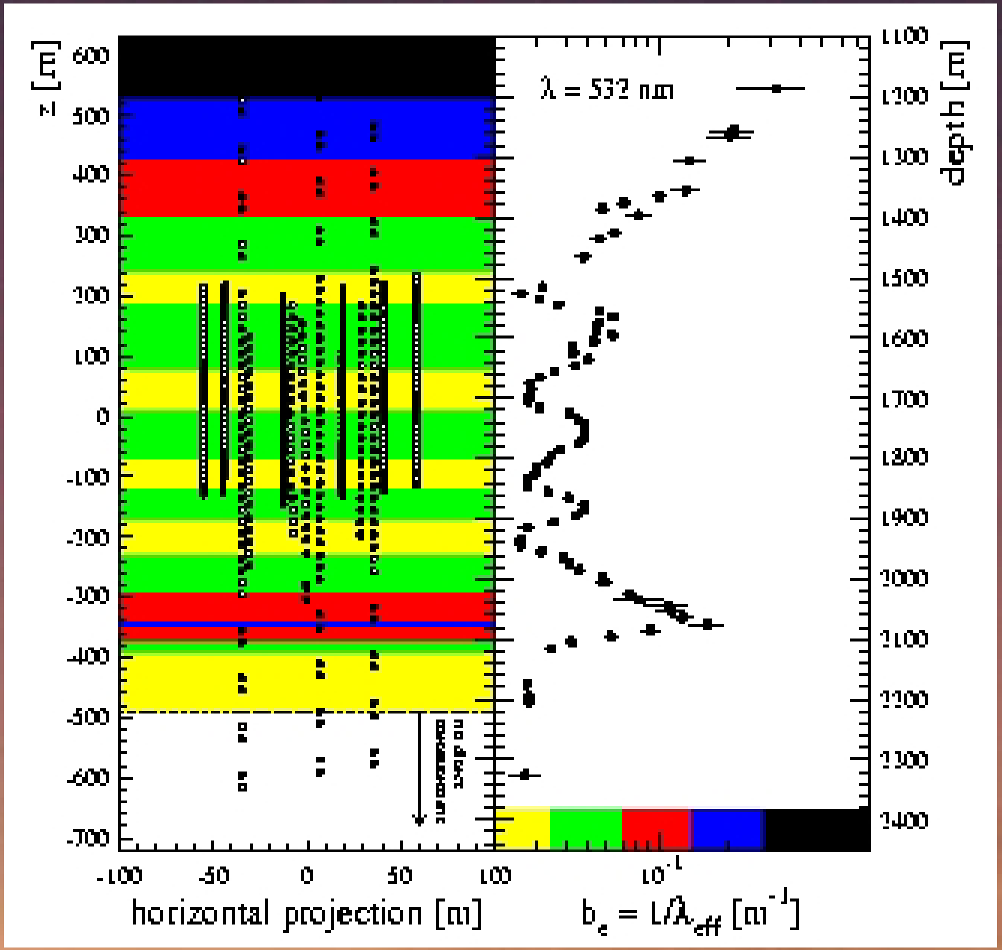
Why the South Pole?

- We need something transparent (water or ice)
- We need a large volume of it
- We need electricity, food, airplanes, and other infrastructure

South Pole

Why the South Pole?

- Absorption length >100 meters
- Scattering length ~25 meters
- Radioactivity negligible (only what we put down: ^{40}K in glass)
- Properties mapped with *in-situ* lasers/LED's

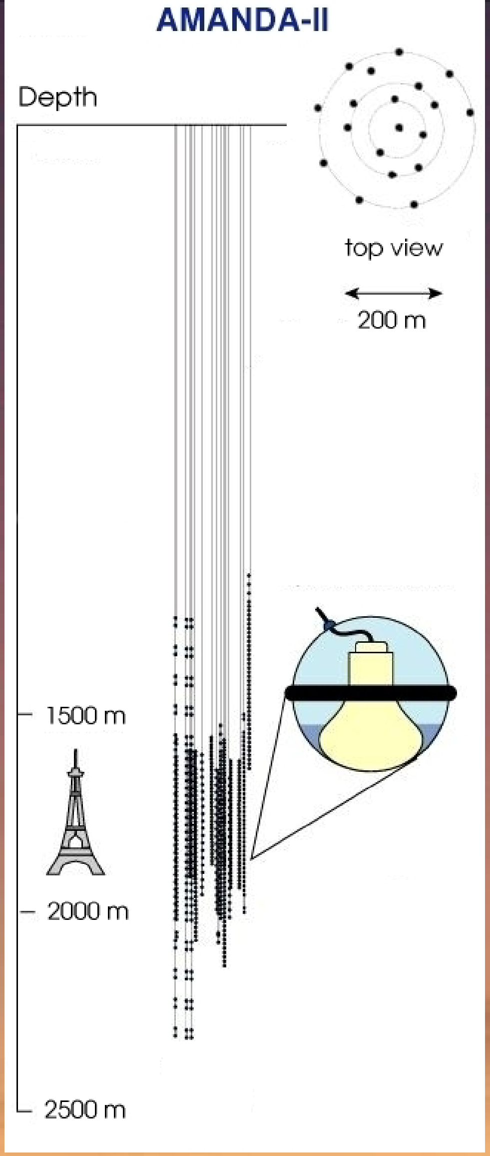


Water vs. Ice?

Water:	Ice:
Long scattering length	Short scattering length
Short absorption length	Long absorption length
^{40}K radioactivity	Pure, no radioactivity
Bioluminescence	No critters
Biofouling	No movement/currents
Access to ships difficult	Stable platform
Access year-round	Summer operations only
Repairable	Not repairable

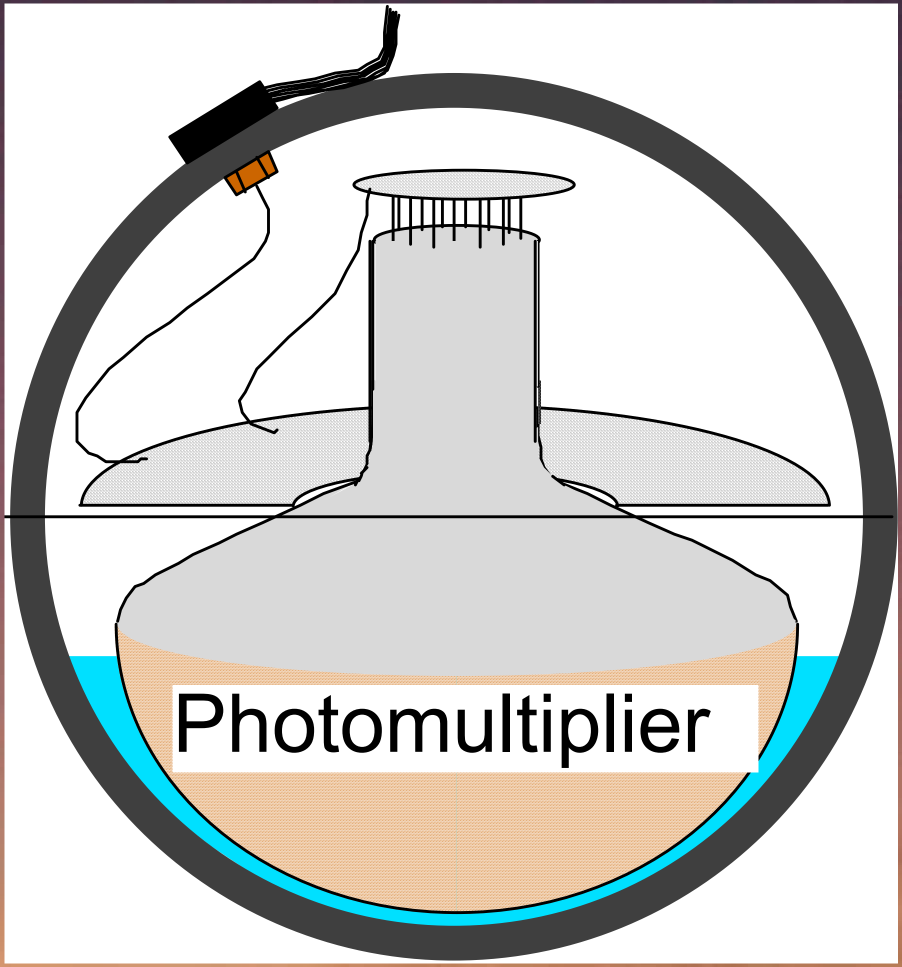
IceCube

- Construction began in 1995 (4 strings)
- AMANDA-II completed in 2000 (19 strings total)
- 677 optical modules
- 200 m across
- ~500 m tall (most densely instrumented volume)



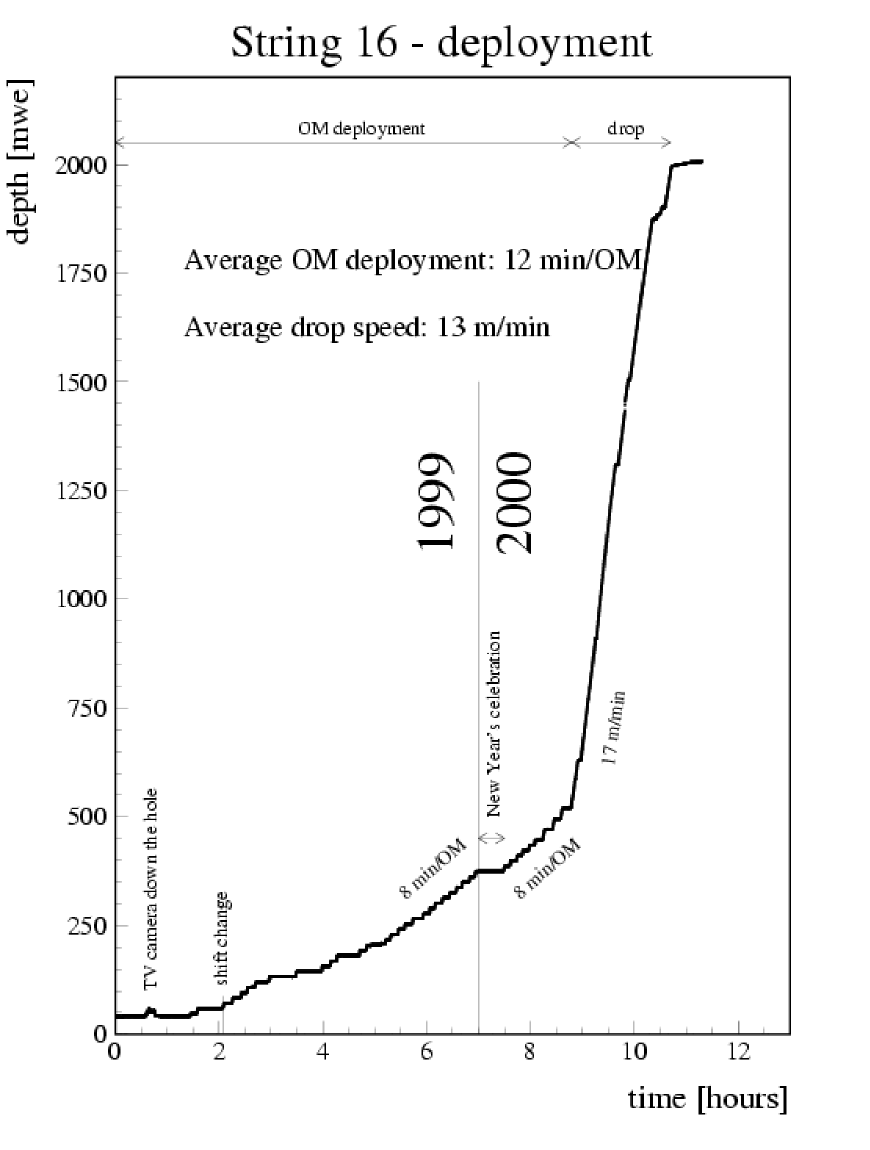
The AMANDA detector

- Glass pressure housing protects PMT from forces of the ice
- Gel provides optical coupling between glass and PMT photocathode



Optical Module

Optical Module deployment



Optical Module deployment

SCIENTIFIC AMERICAN

Seven Wonders of Modern Astronomy

The Sharpest

The Biggest

The Farthest Flung

The Most Extensive

The Swiftest

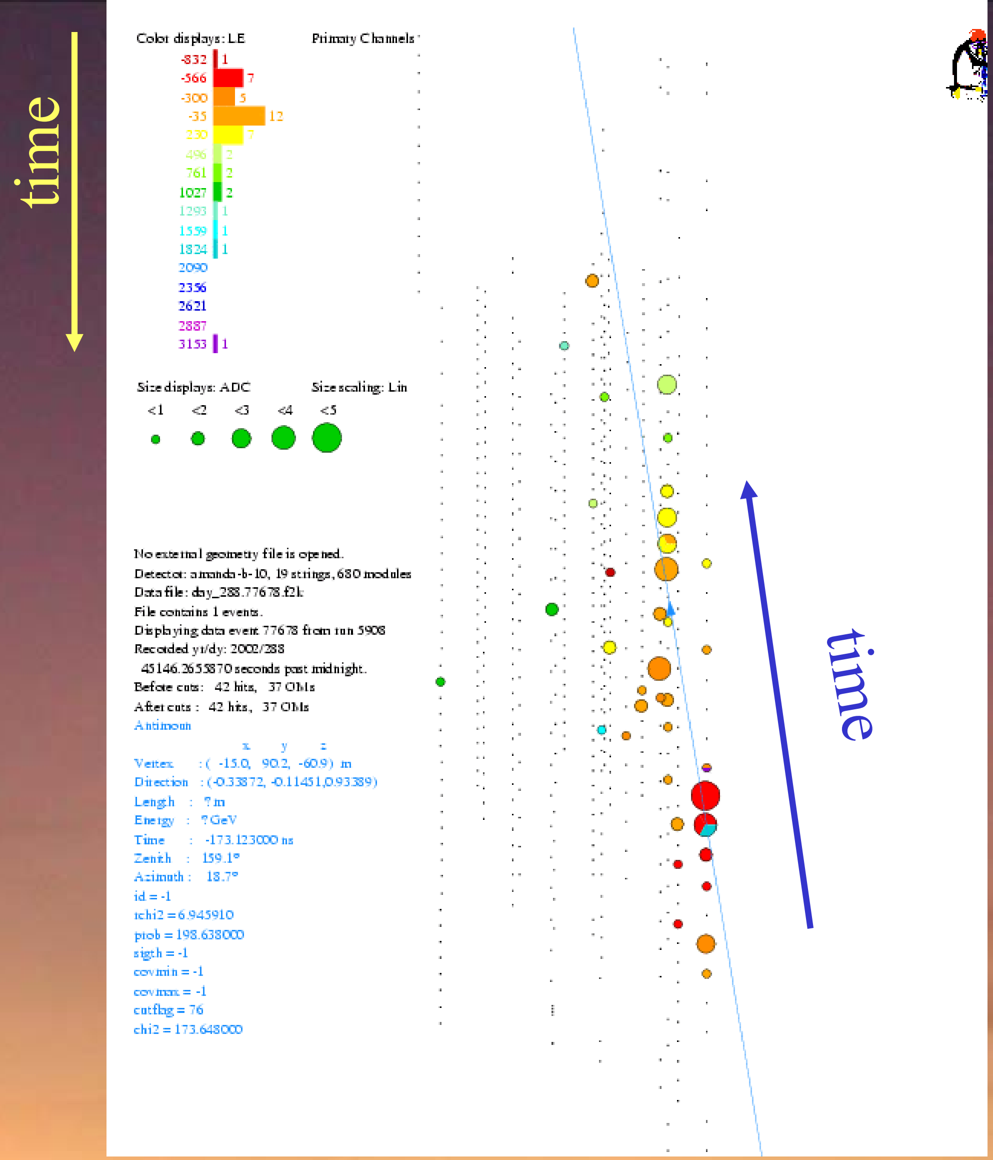
The Deadliest

The Wierdest

www.sciam.com/1999/1299engineering/1299musser.html

IceCube

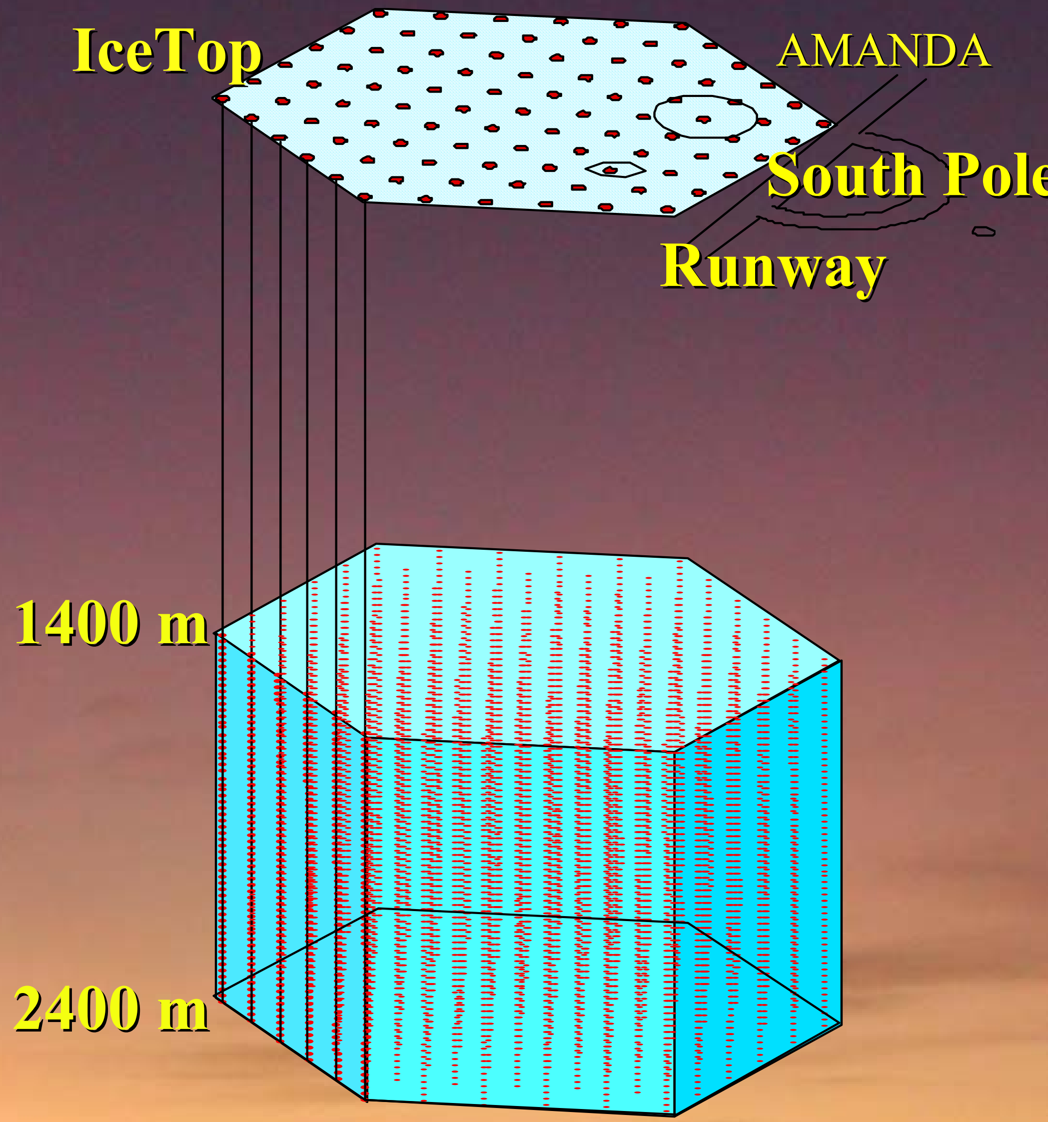
- Realtime filtering is performed at the Pole (sorry, it's summertime now!)

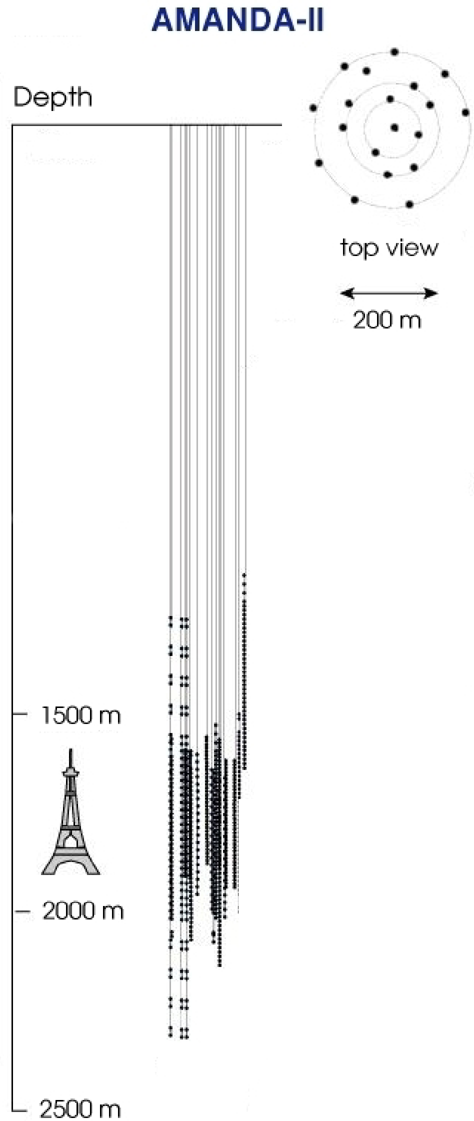


A real event in AMANDA

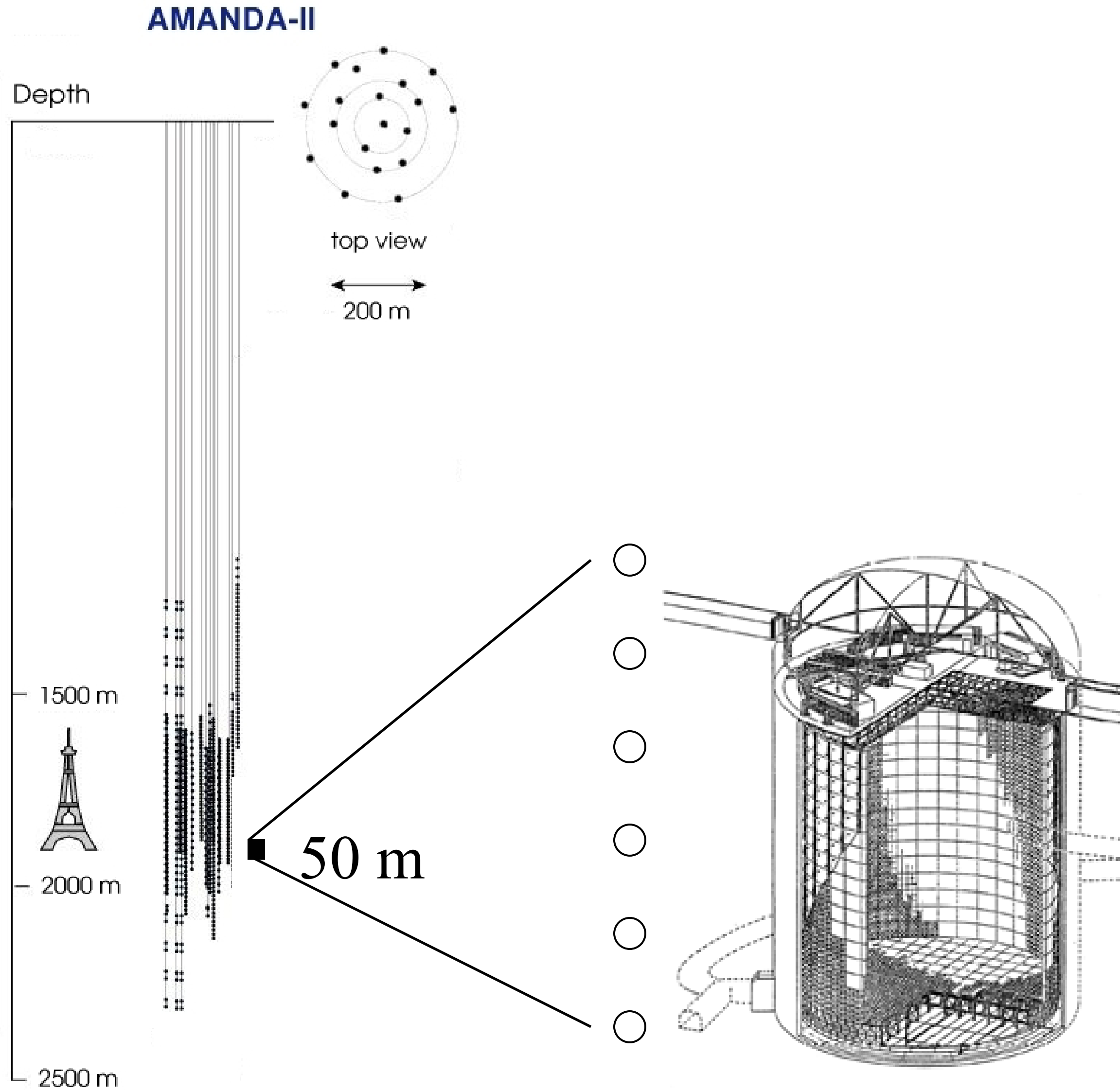
The IceCube observatory

- 80 strings
- 4800 optical modules
- 1 km^3 volume
- First strings to be deployed in Dec. 2004
- AMANDA contained within IceCube

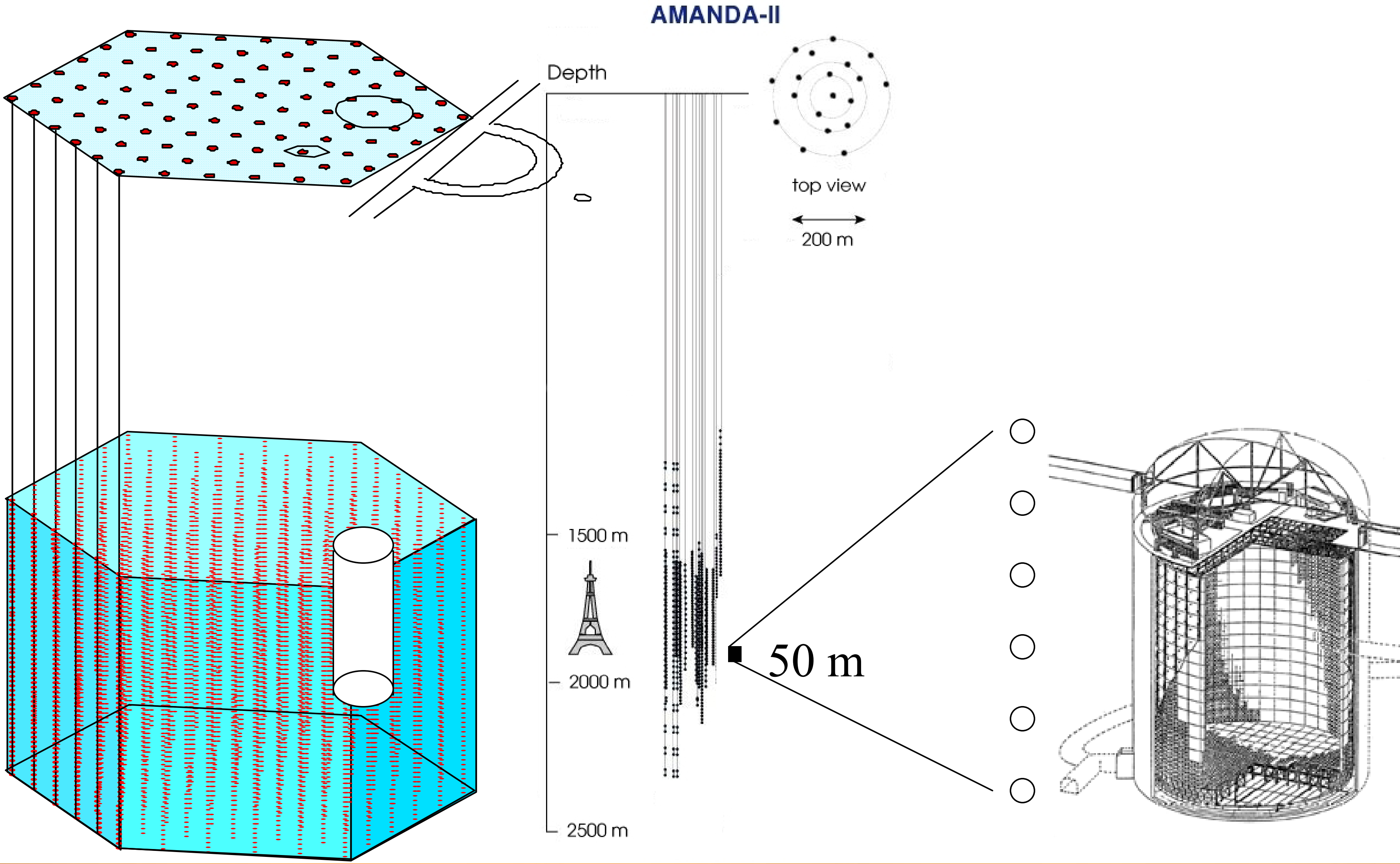




Size perspective



Size perspective

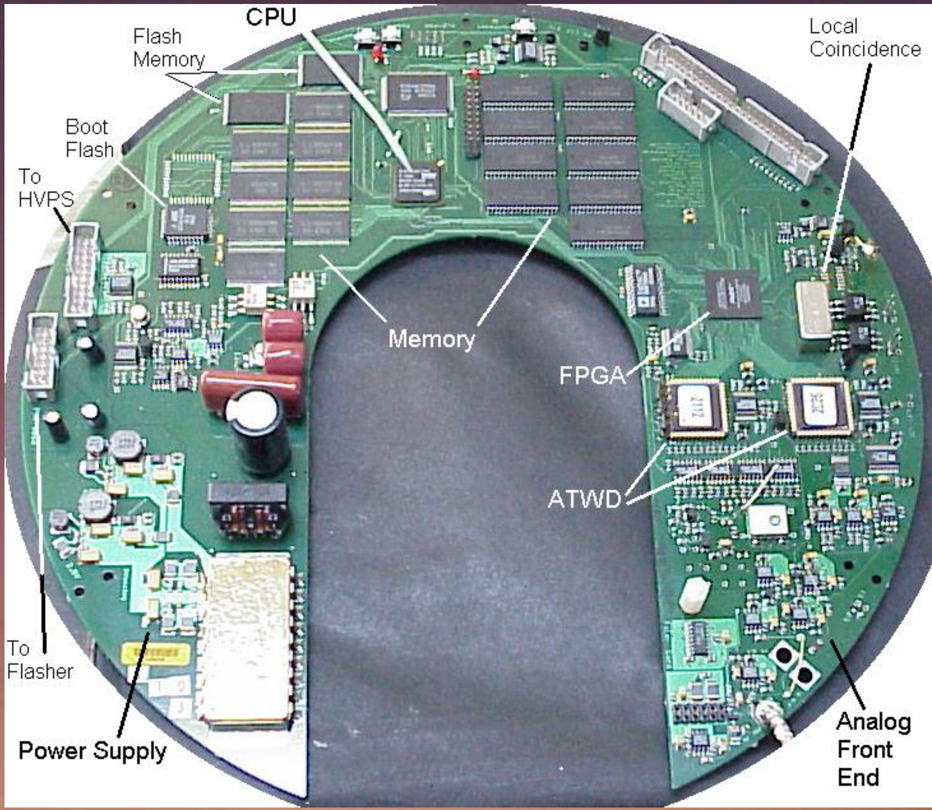


Size perspective

The IceCube hose reel

Digital Optical Module

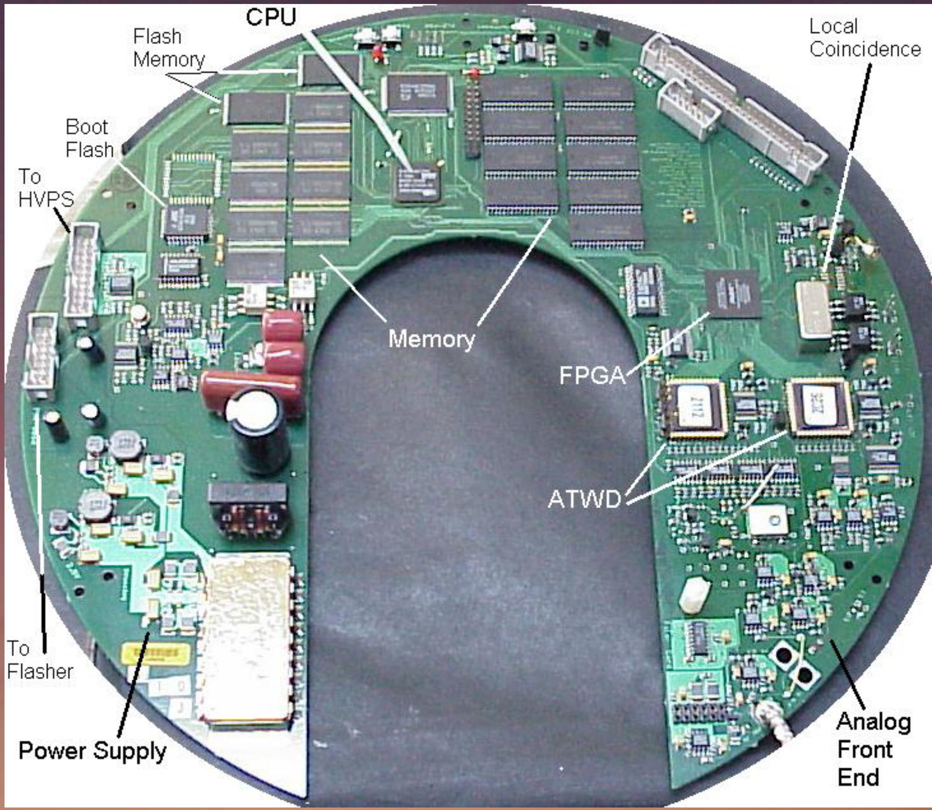
- Self-triggers on each pulse
- Captures waveforms
- Time-stamps each pulse
- Digitizes waveforms
- Performs feature extraction
- Buffers data
- Responds to Surface DAQ
- Set PMT HV, threshold, *etc*



Digital Optical Module

Design parameters:

- Time resolution: < 5 ns rms
- Waveform capture:
  >250 MHz for first 500 ns
  ~ 40 MHz for 5000 ns
- Dynamic Range:
  > 200 PE / 15 ns
  > 2000 PE / 5000 ns
- Dead-time: < 1%
- OM noise rate: < 500 Hz (^{40}K in glass sphere)



- MeV energies: neutrinos from the sun, supernovae
- GeV energies: neutrinos from the atmosphere (cosmic ray showers)
- TeV and PeV energies: neutrinos from AGN, cosmic ray accelerators, and more!

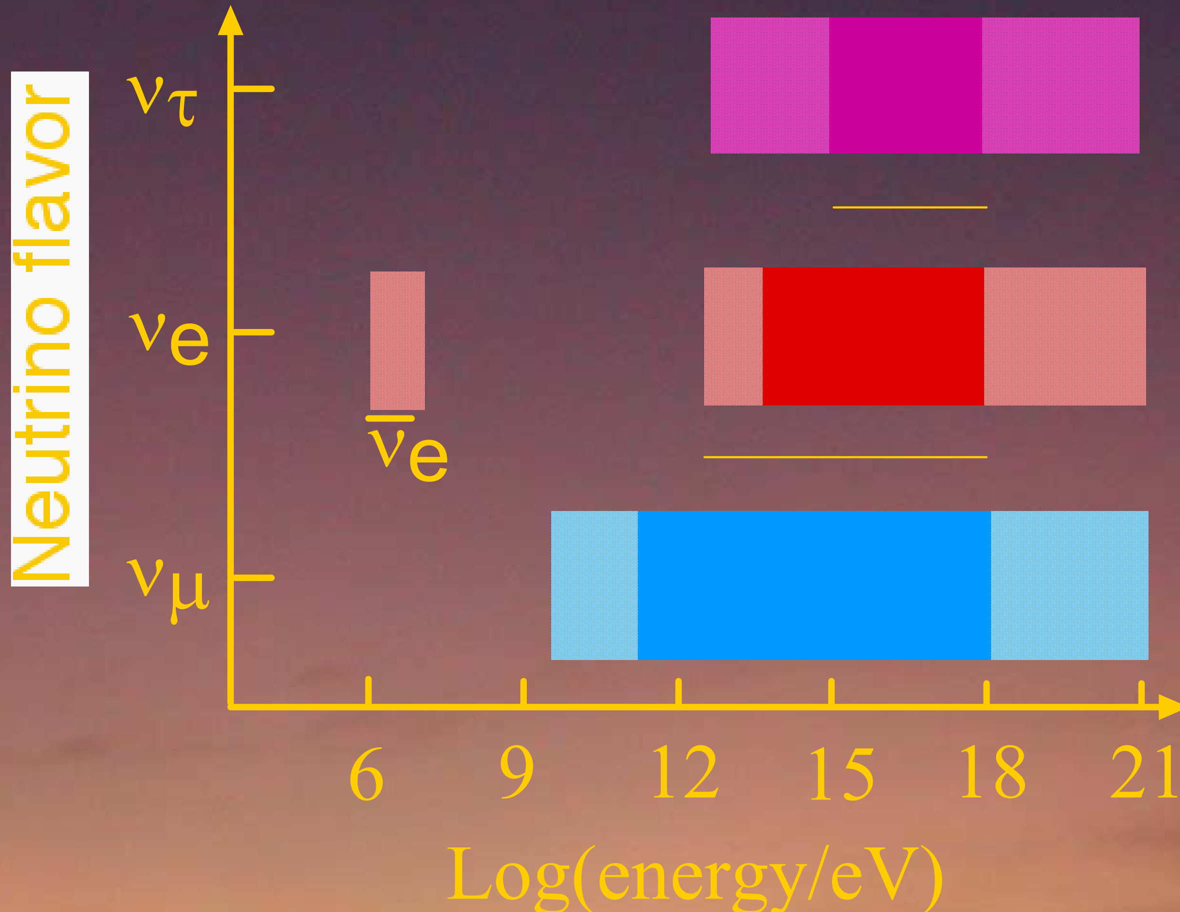
Why high energies?

Science goals and results

- Neutrino flavor identification
- Supernova search
- Neutrino point sources
- Diffuse extragalactic neutrinos
- GRB search
- WIMP search
- Cosmic ray composition

IceCube

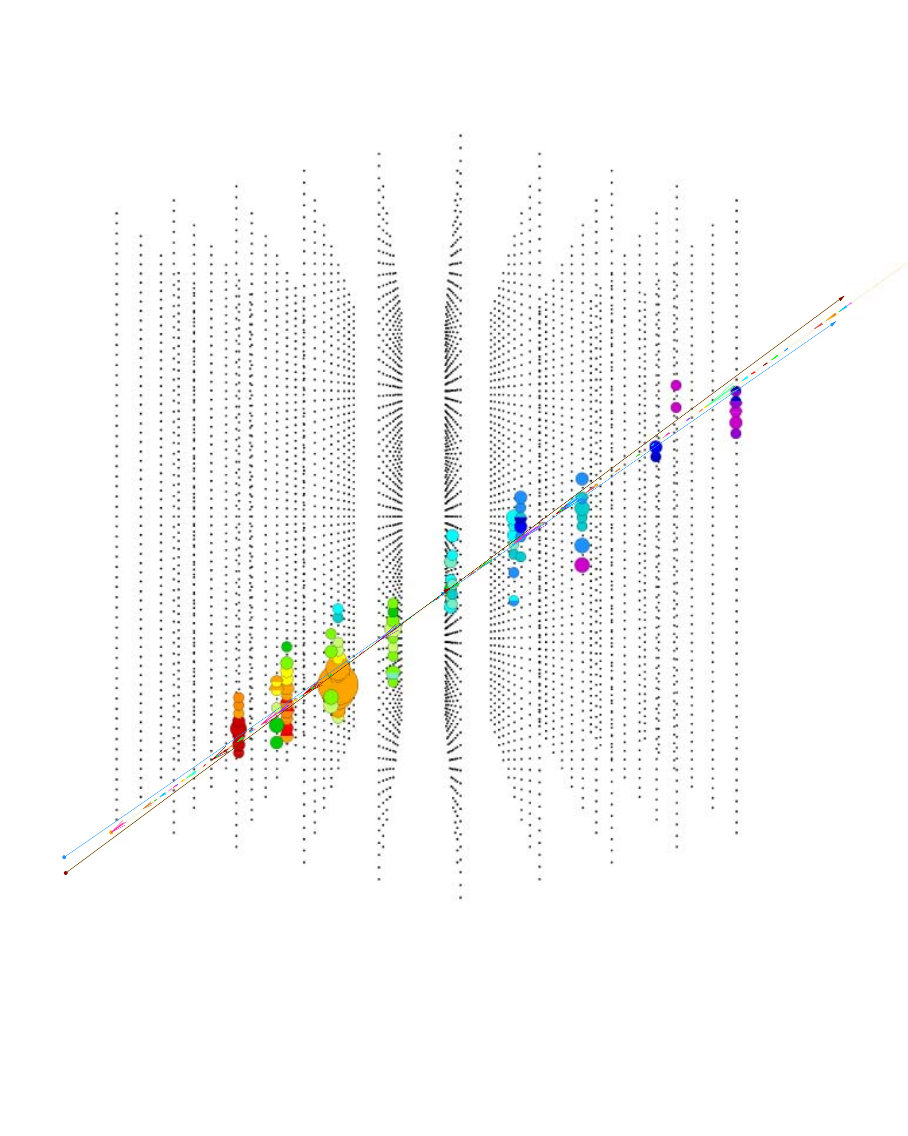
- Solid: particle ID, direction, and energy
- Shaded: energy only



Particle identification

- Long "track-like" light pattern
- CC interaction:

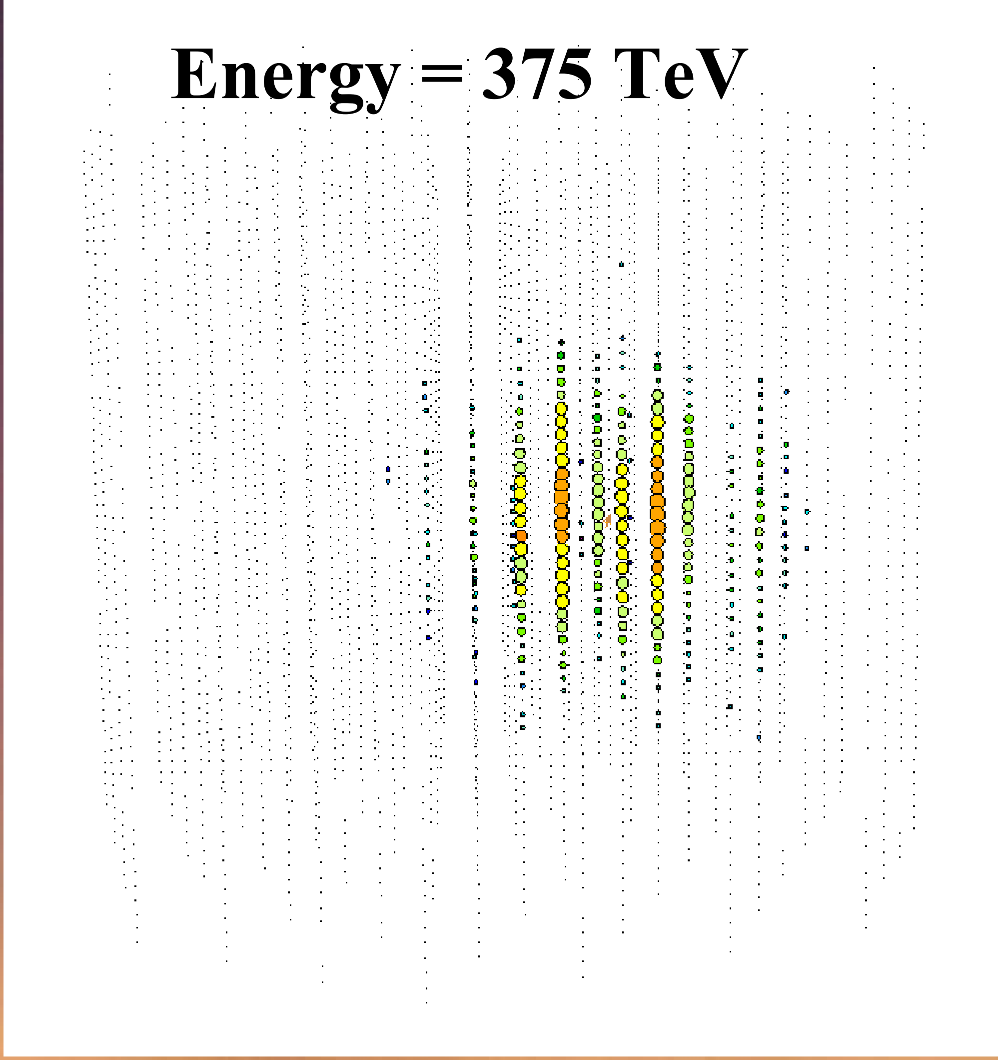
$$\nu_\mu + N \rightarrow \mu + X$$



μ neutrinos

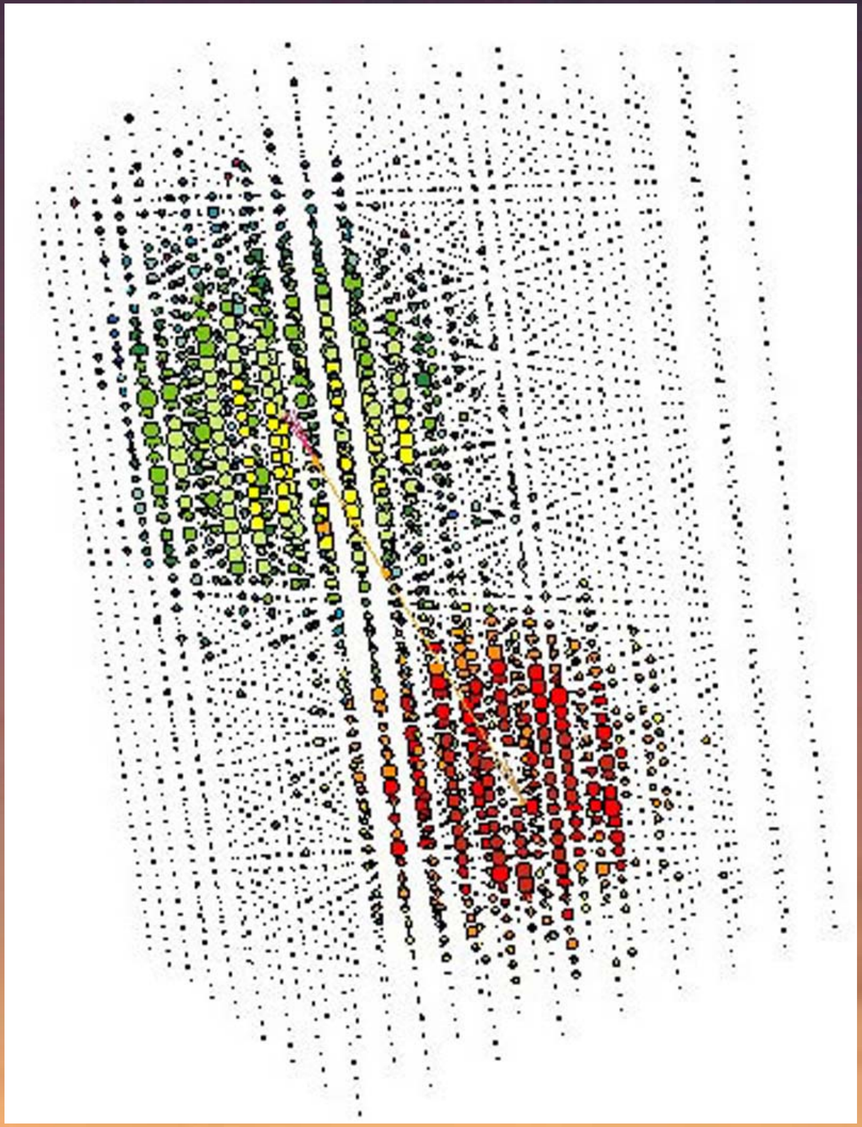
e neutrinos

- Length of the cascade is small compared to the spacing of sensors.
- Roughly spherical density distribution of light.

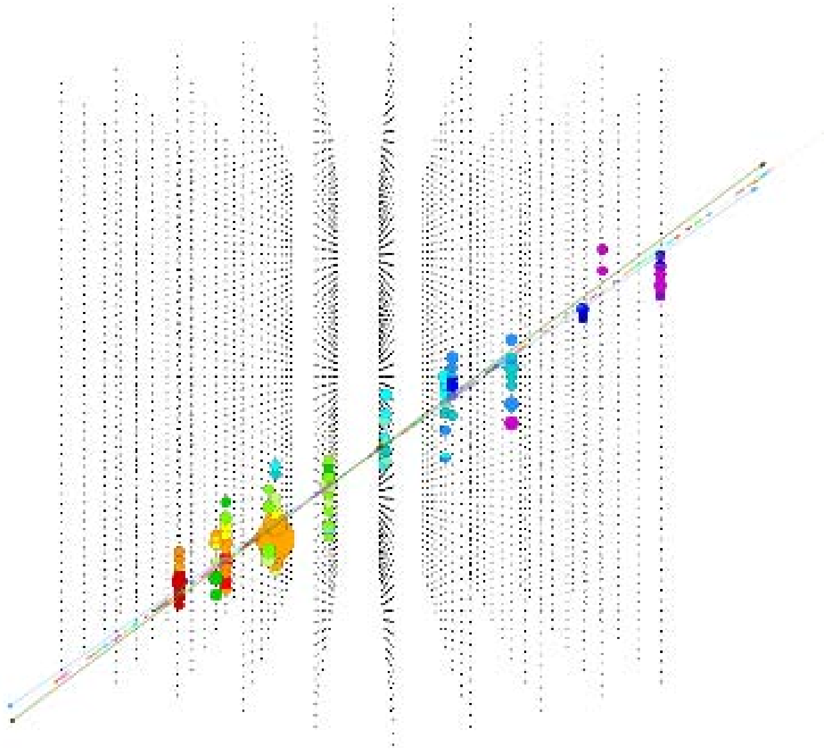


τ neutrinos

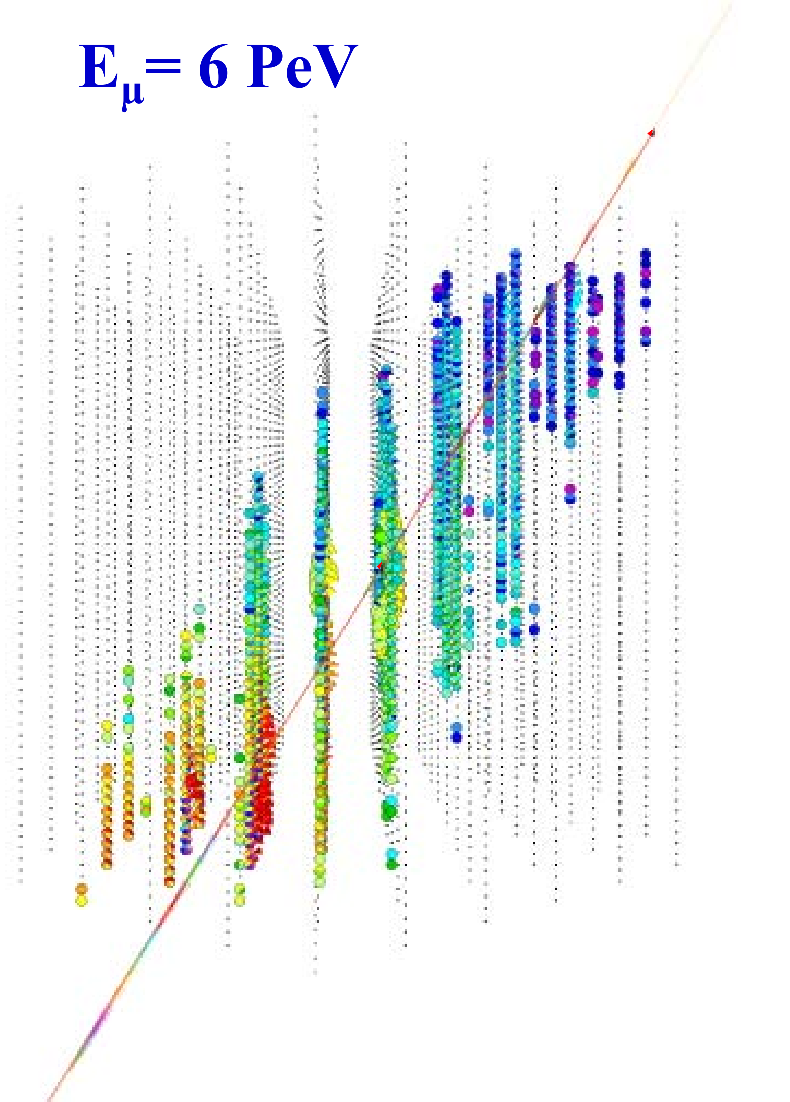
- "Double-bang" signature (one cascade from the ν interaction, the other from the τ decay)
- Two "bangs" are hundreds of meters apart for a PeV τ neutrino.
- Expected from astrophysical sources because of oscillations



E_{μ}= 10 TeV



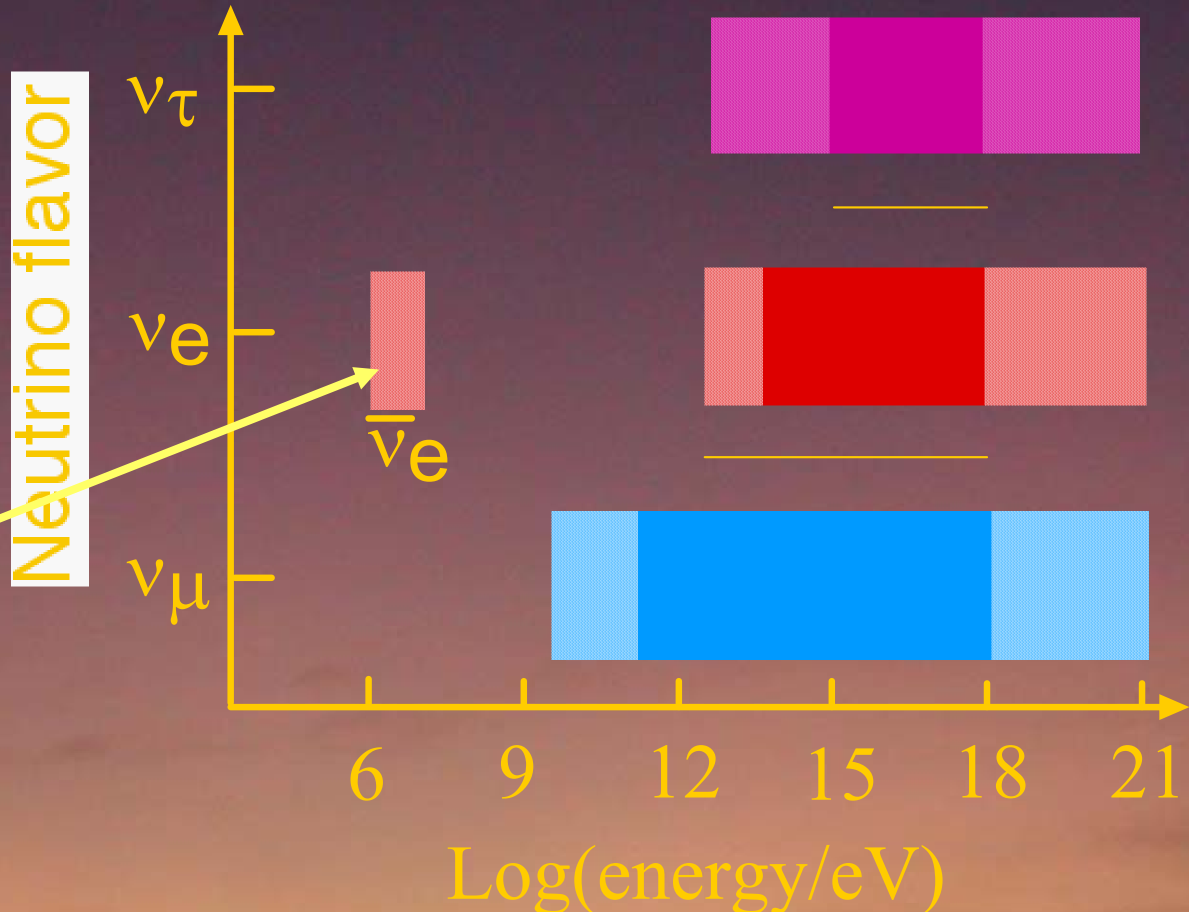
E_{μ}= 6 PeV



Energy measurement

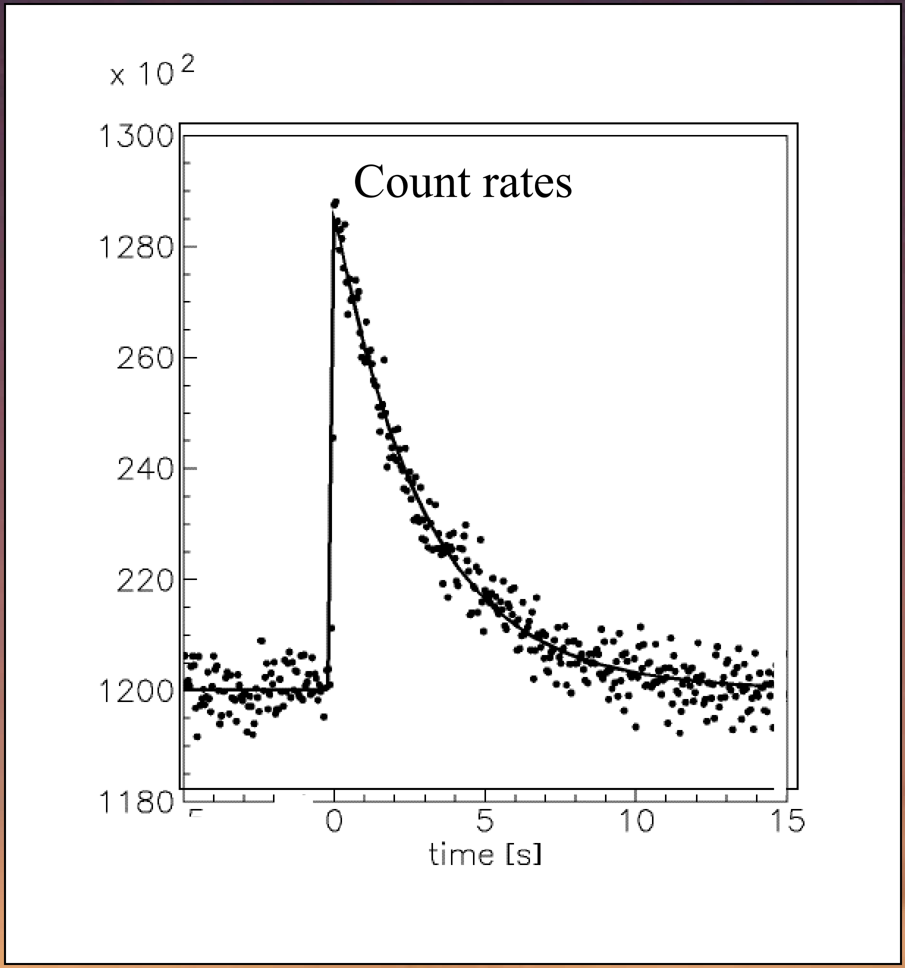
Particle identification

- Supernova detection



Supernova detection

- Neutrinos from a supernova are too low-energy to be detected individually by IceCube
- However, a flood of MeV neutrinos would result in an increase of the darknoise rate in all OM’s

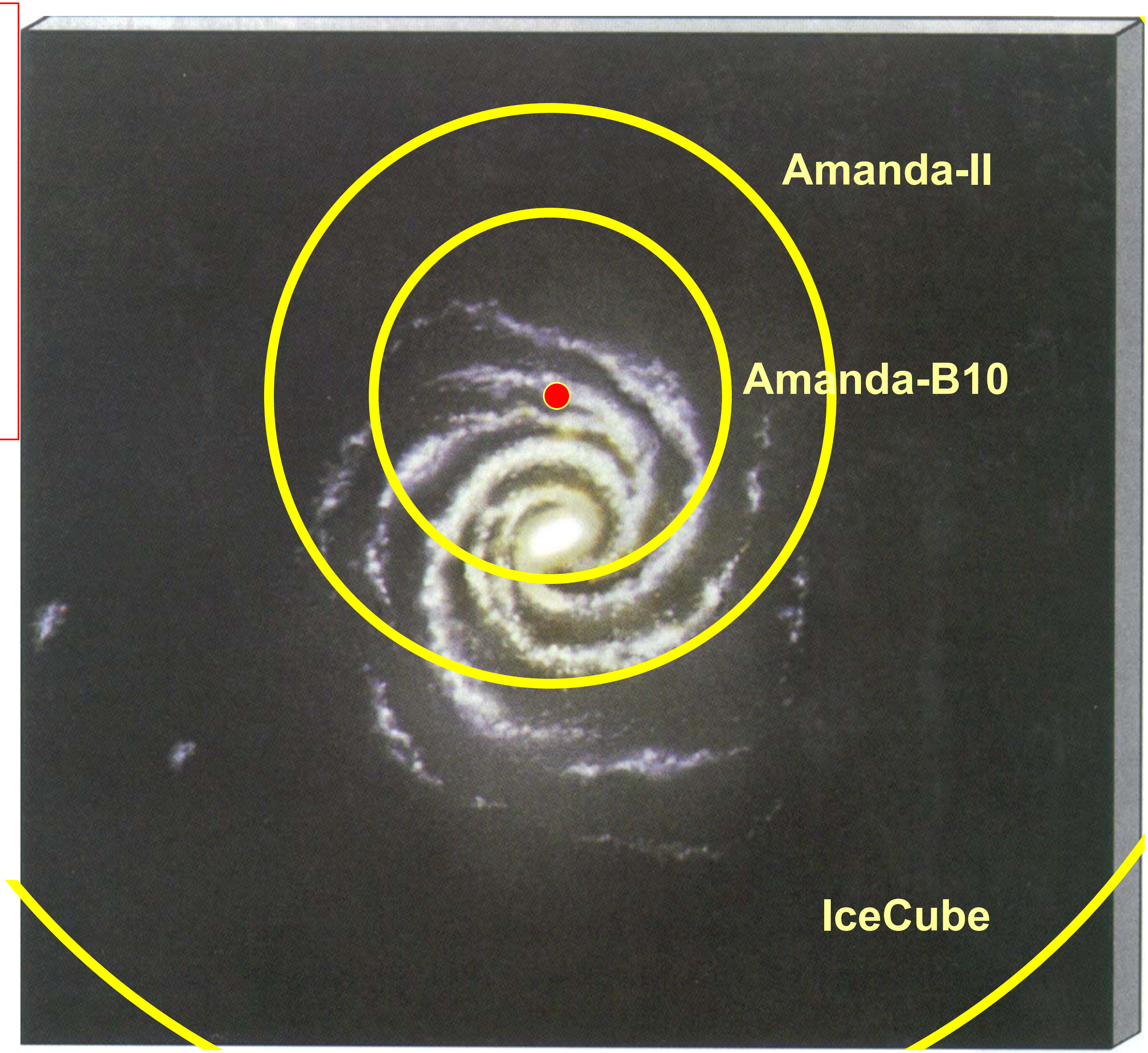


IceCube

B10:
60% of Galaxy

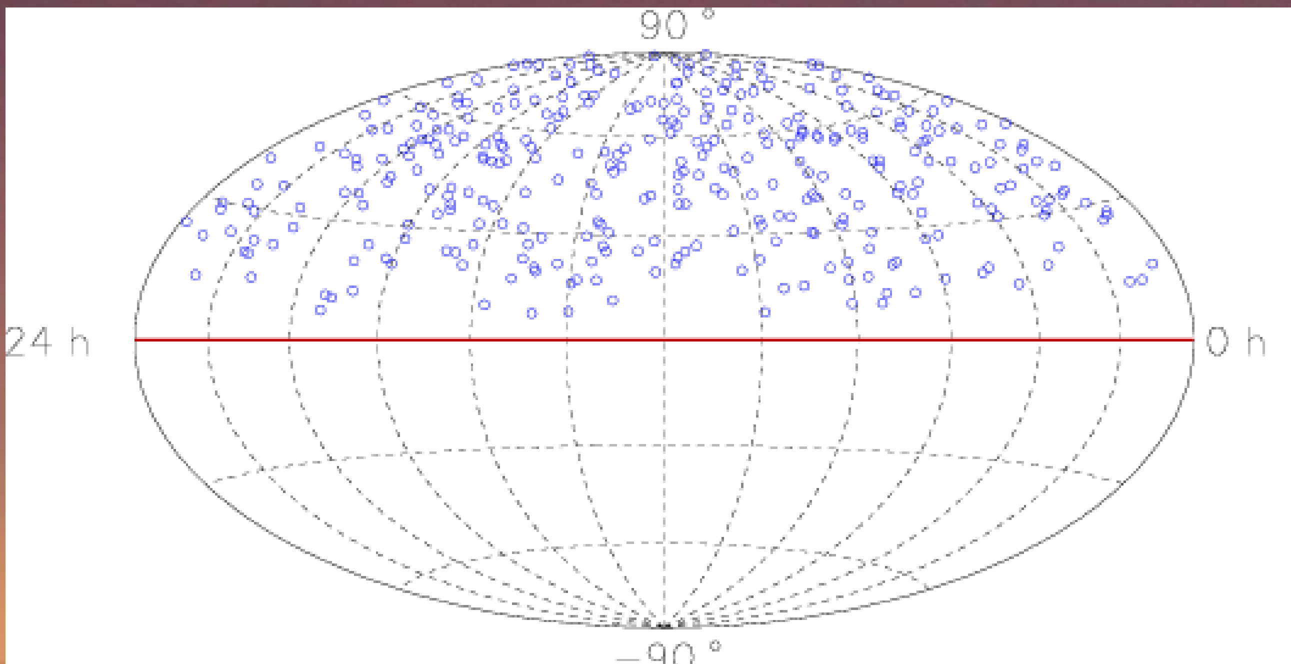
A-II:
95% of Galaxy

IceCube:
up to LMC

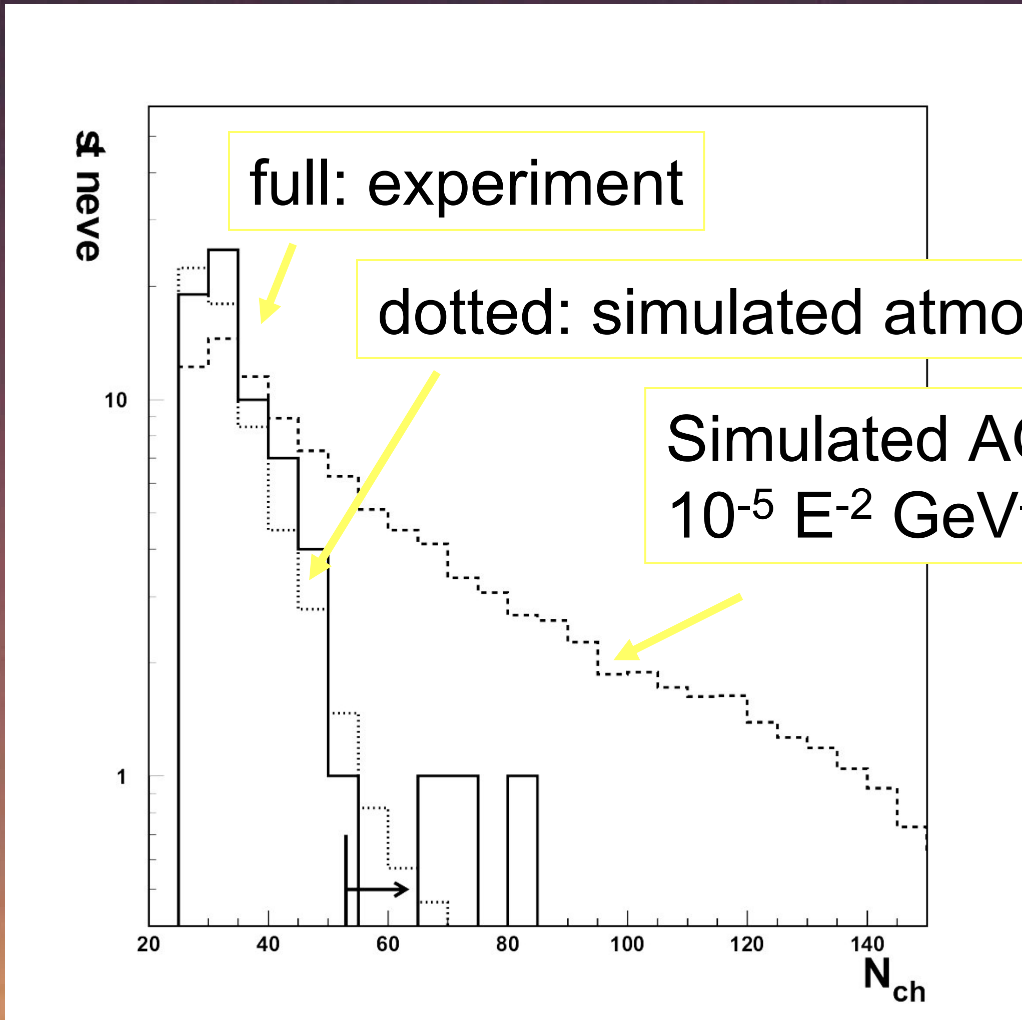


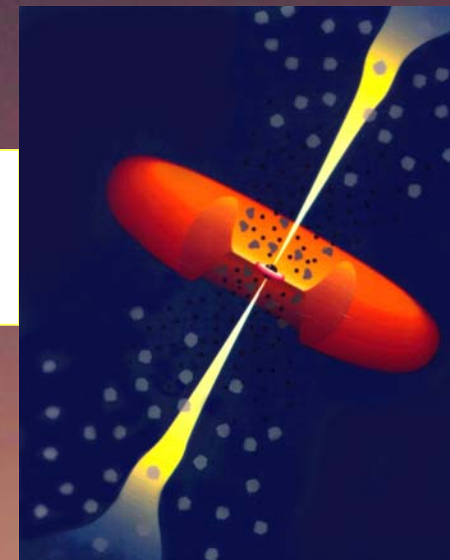
Atmospheric neutrinos

- AMANDA-B10: ~300 per year
- AMANDA-II: ~4 per day (real-time!)
- IceCube: ~300 per day



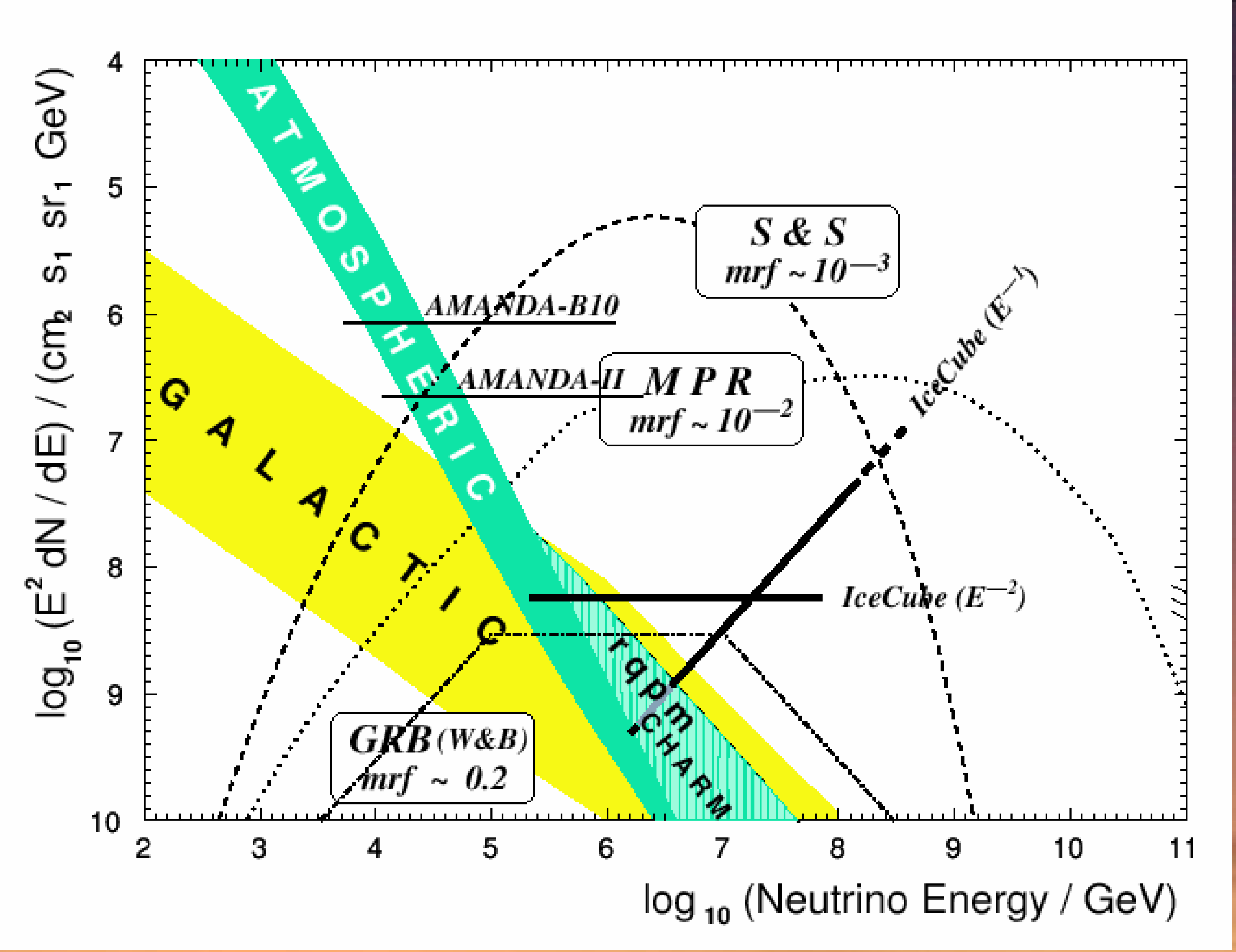
1997 data:
Contamination by cosmic ray muons: <10%





$E^2\ \Phi$
$< 0.84 \times 10^{-6}\ GeV\ cm^{-2}\ s^{-1}\ sr^{-1}$

Diffuse search

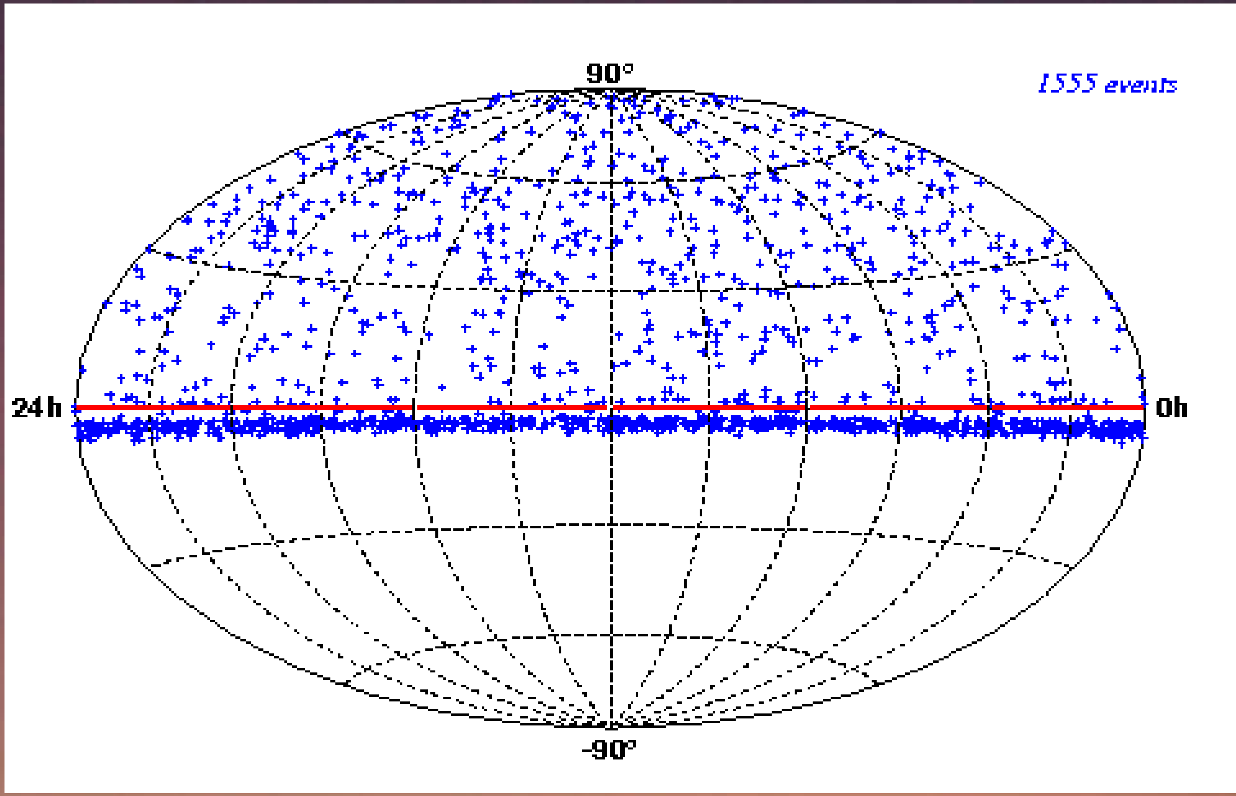


Diffuse search

Point source search

AMANDA-II

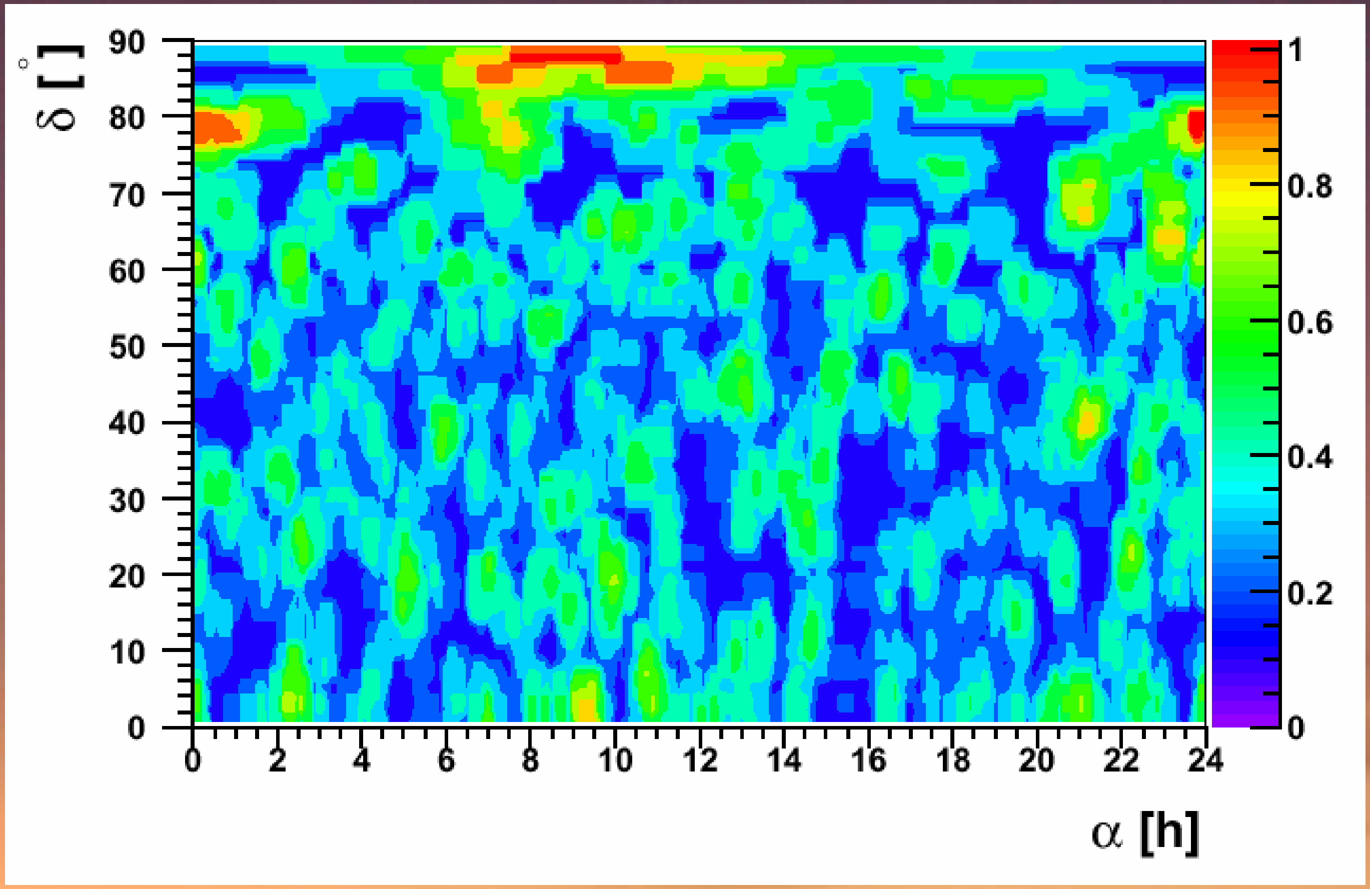
- Cuts optimized for each declination band
- Analysis developed with azimuth-scrambled data for blindness



2000 data:
Contamination by cosmic ray muons: <10% (above 110 degrees)

- A sky full of upper limits

(integrated above 10 GeV, units: 10^{-7} cm^{-2} s^{-1})



Point source search

- Preliminary results for individual sources

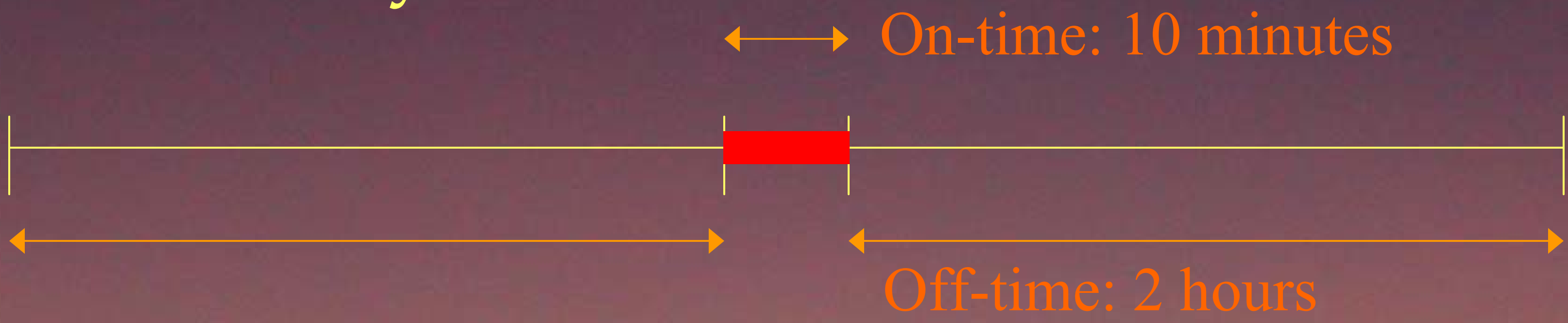
Source	Dec	1997	2000
		$E^2\Phi_\nu$ (10^{-8} $cm^{-2}s^{-1}$)	
Crab	22	4.2	2.4
Mkn421	38.2	11.2	3.5
Mkn501	39.8	9.5	1.8
Cygnus X-3	41.5	4.9	3.5
Cass. A	58.8	9.8	1.2

IceCube

Point source search

GRB search

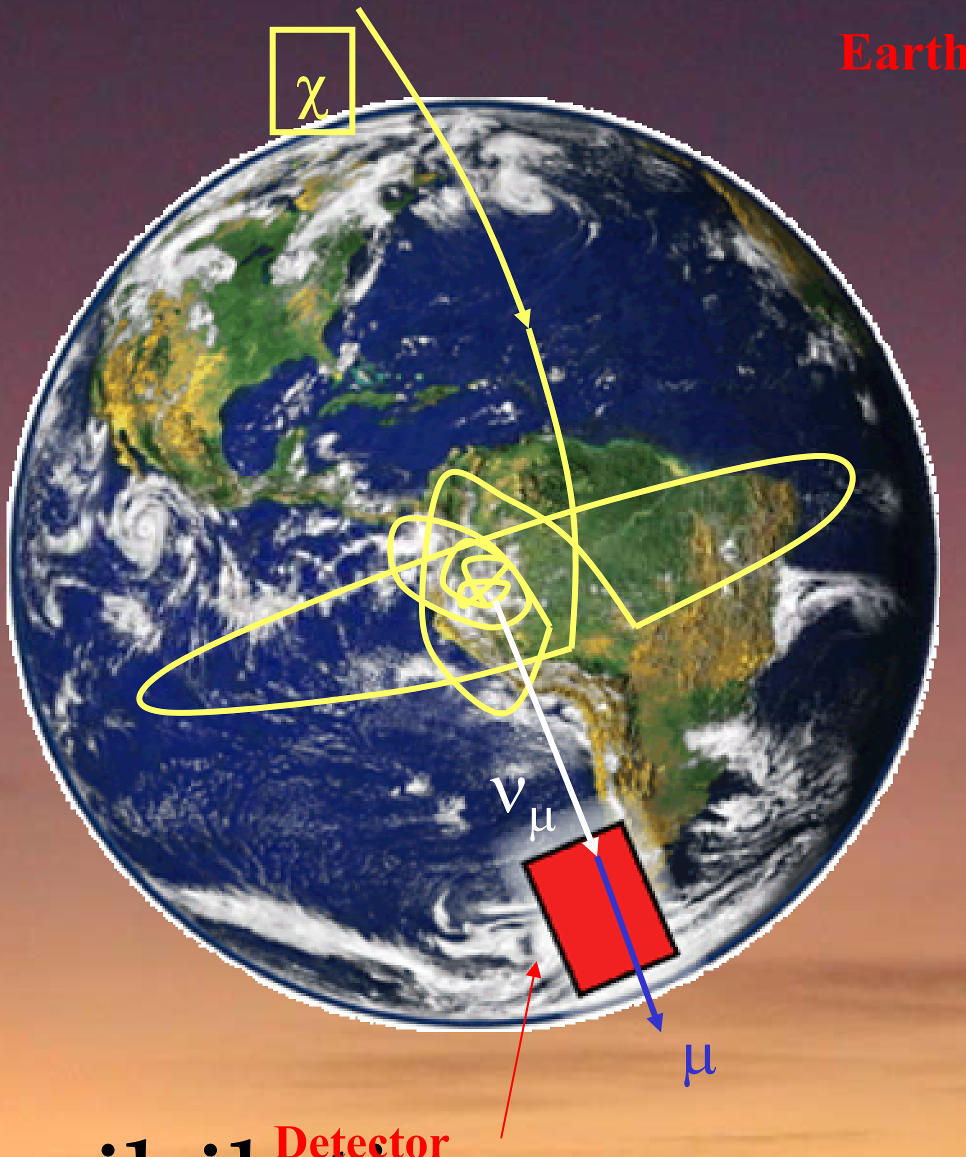
- By using GRB *time* as a cut, other cuts can be loosened, giving a high signal efficiency



- How many do we expect? About 1 per 100 bursts per km^2

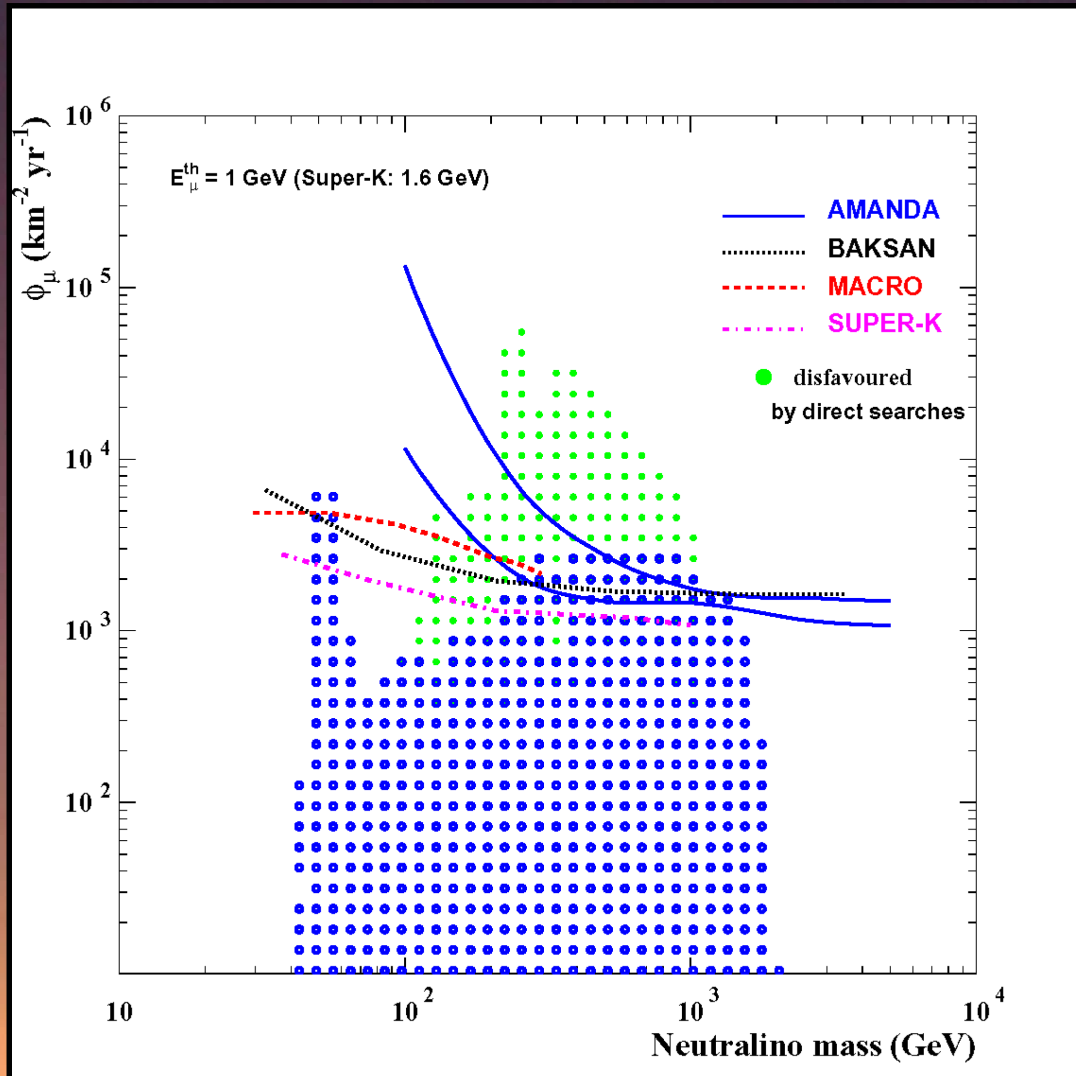
So far? From 317 BATSE bursts from 1997-2000, no coincident neutrinos observed with AMANDA

$$\chi\chi \longrightarrow \begin{matrix} q\bar{q} \\ l\bar{l} \\ WW \\ ZZ, \\ Higgs\ldots \end{matrix} \longrightarrow \nu_\mu$$



WIMP annihilation

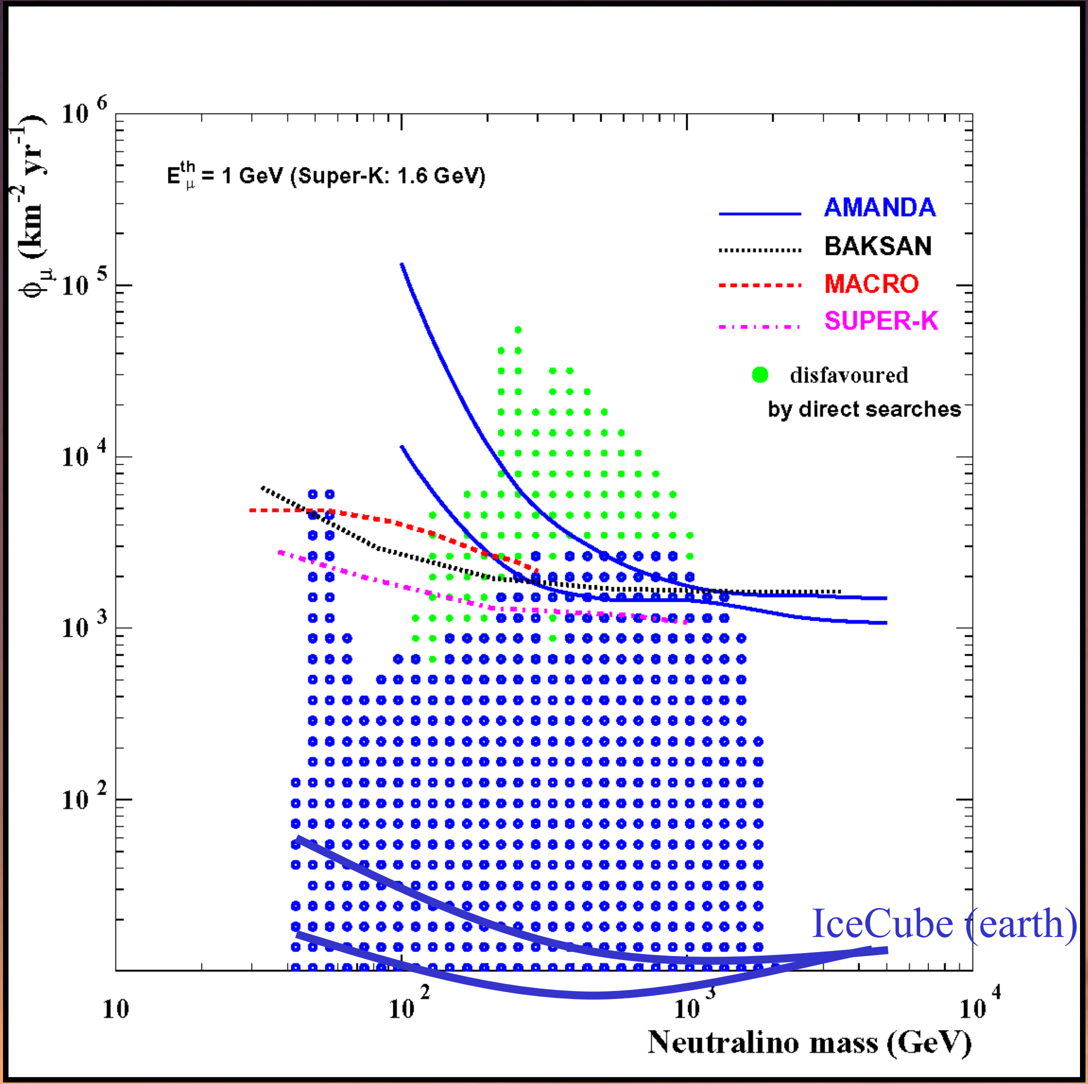
WIMP annihilation at Earth's center



WIMP annihilation

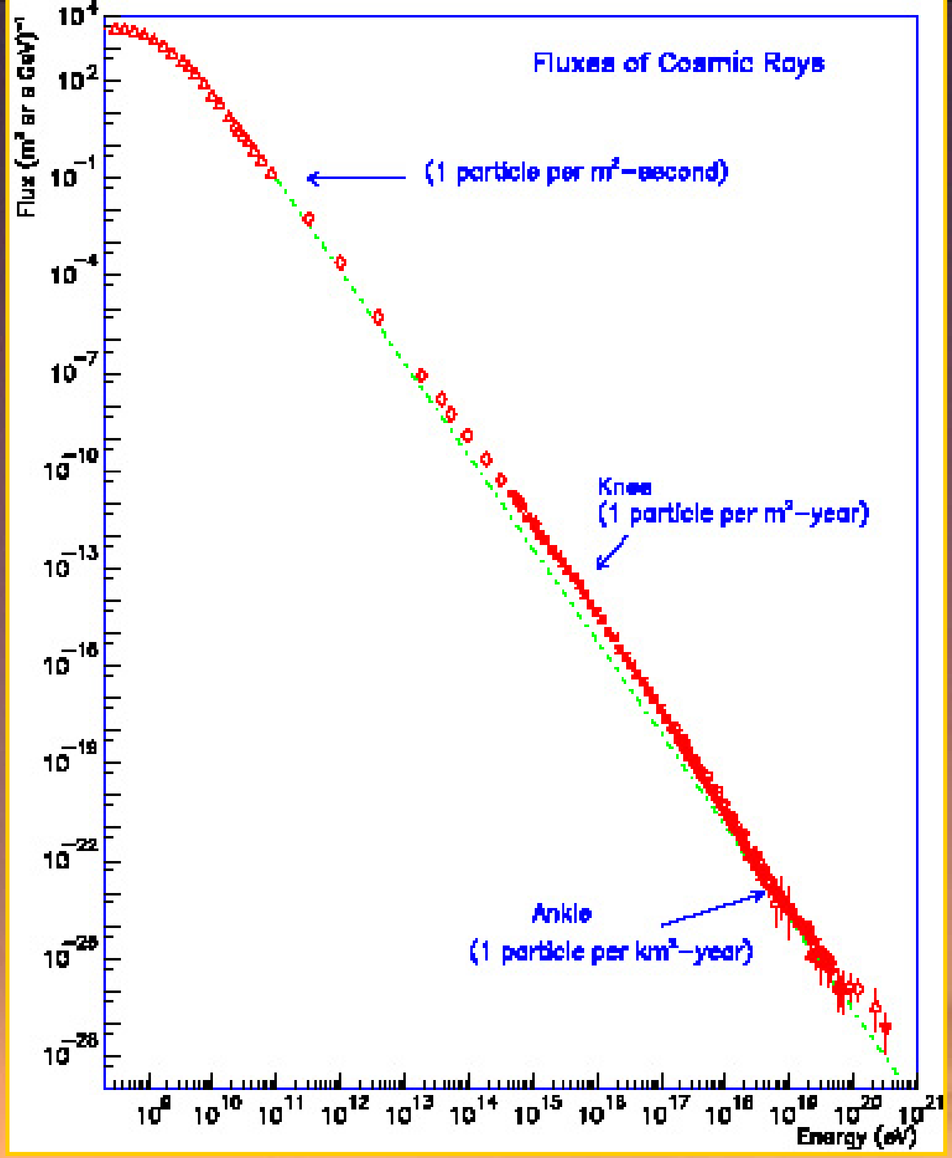
WIMP annihilation

at Earth's center



IceCube

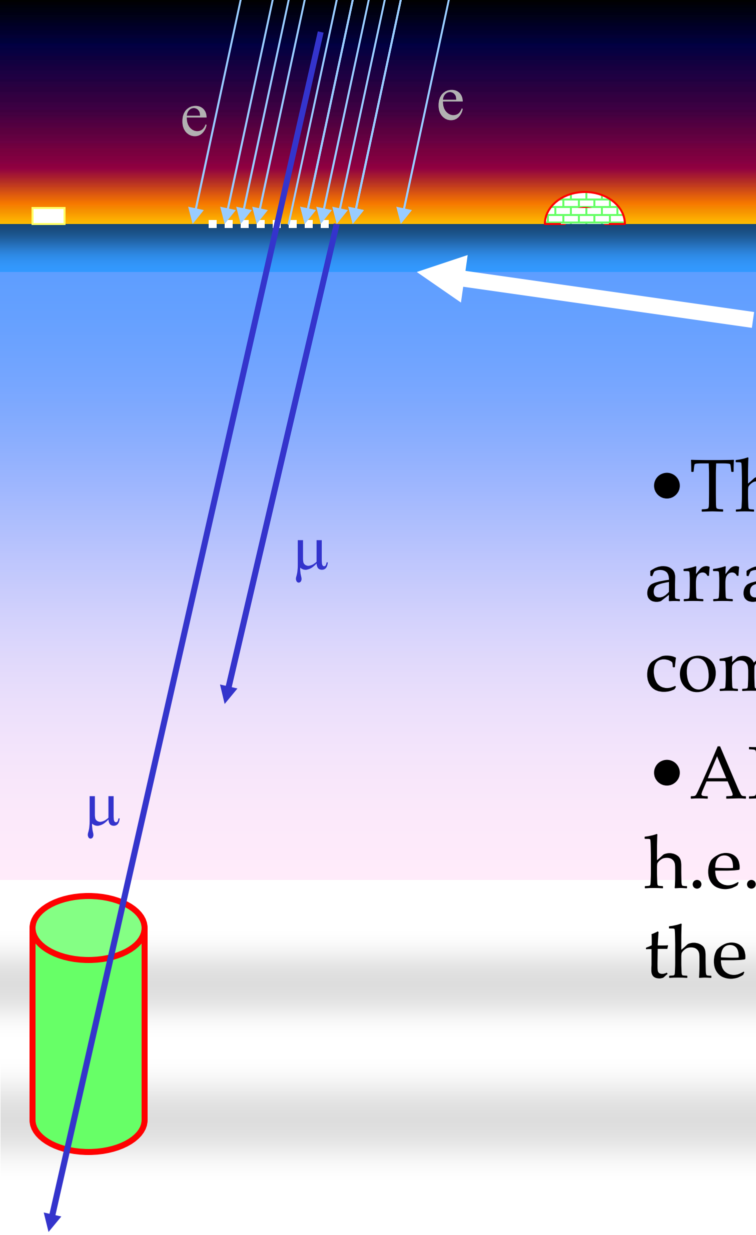
WIMP annihilation



Cosmic ray composition

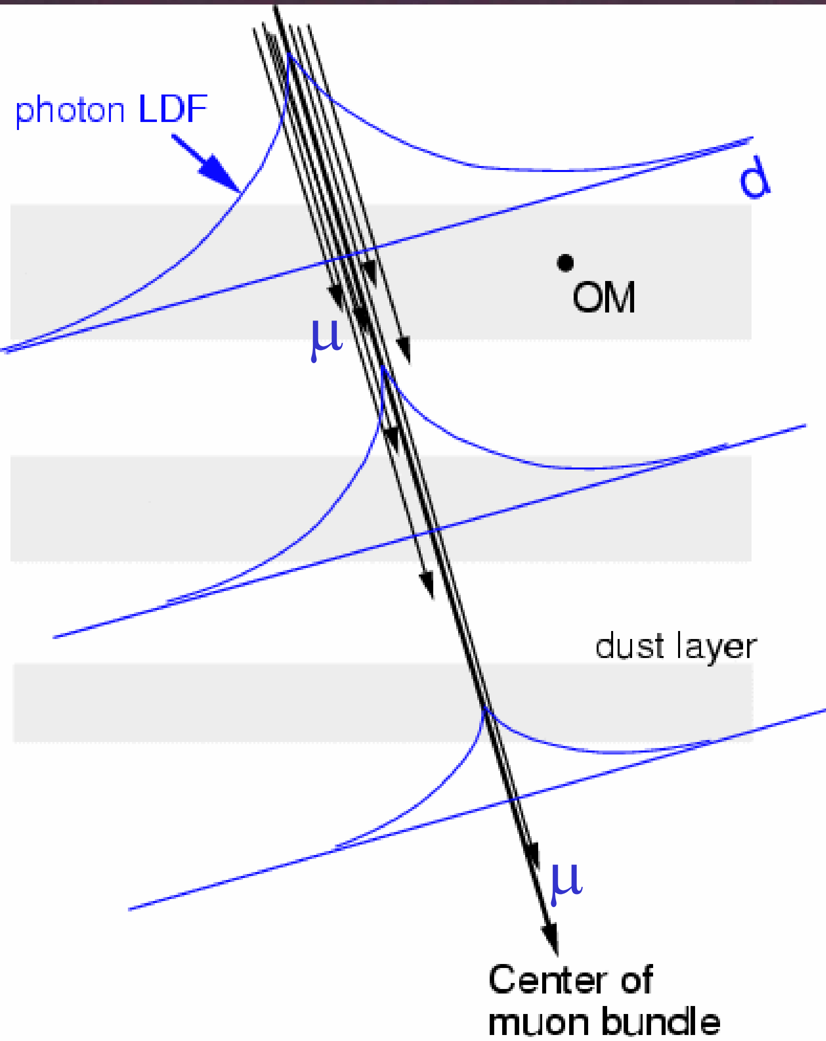
IceCube

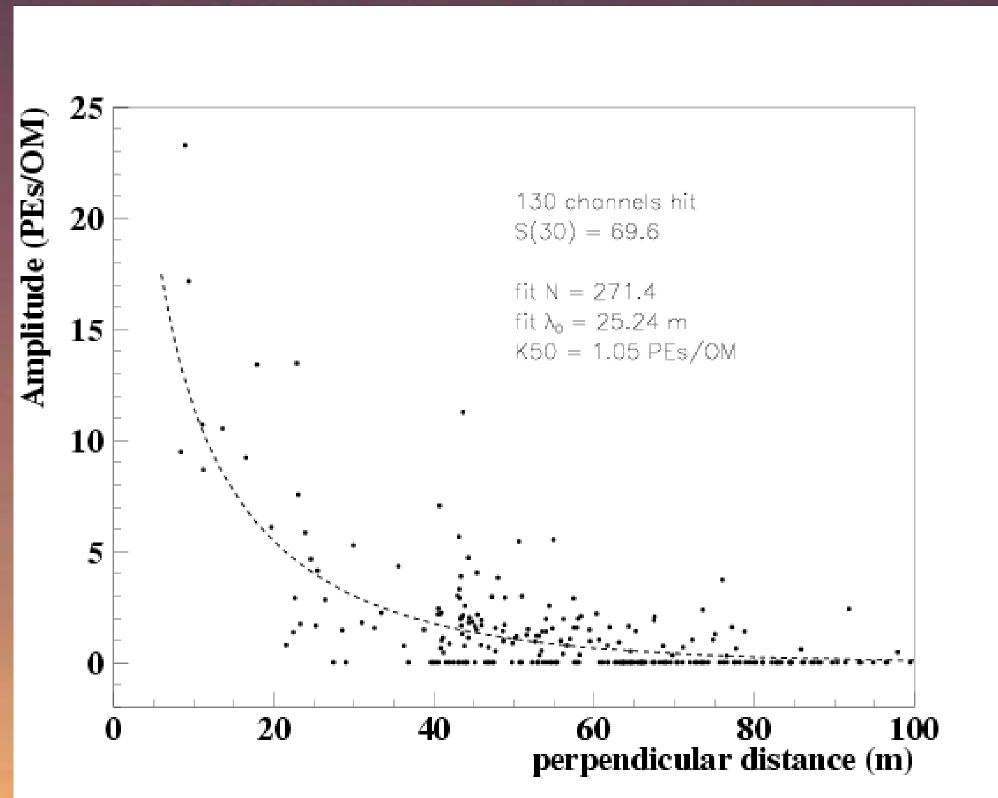
Cosmic ray composition



- The SPASE air shower array measures electron component of the shower
- AMANDA measures the h.e. muon component of the shower

- Muon properties measured using photon LDF, sampled by detector over large distances

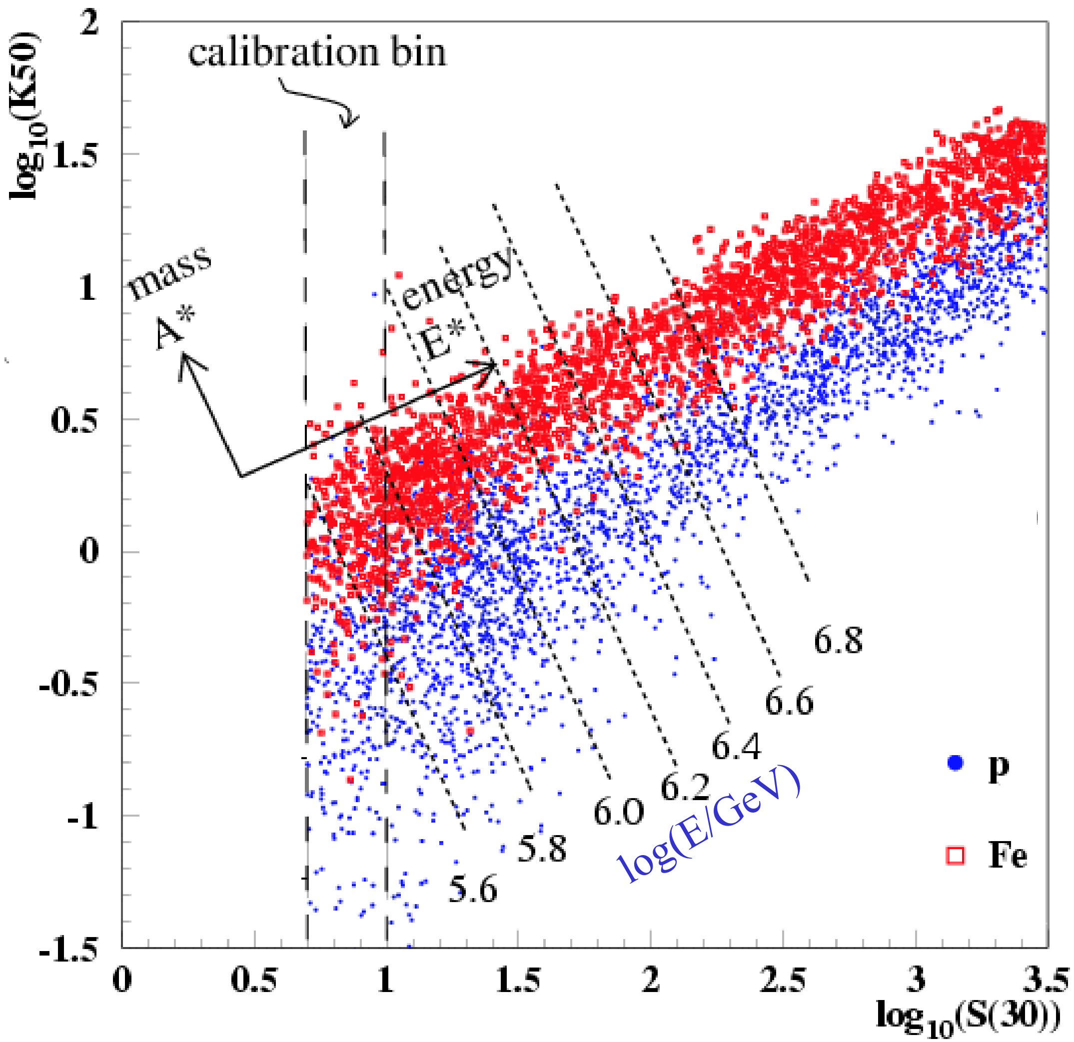




Cosmic ray composition

Cosmic ray composition

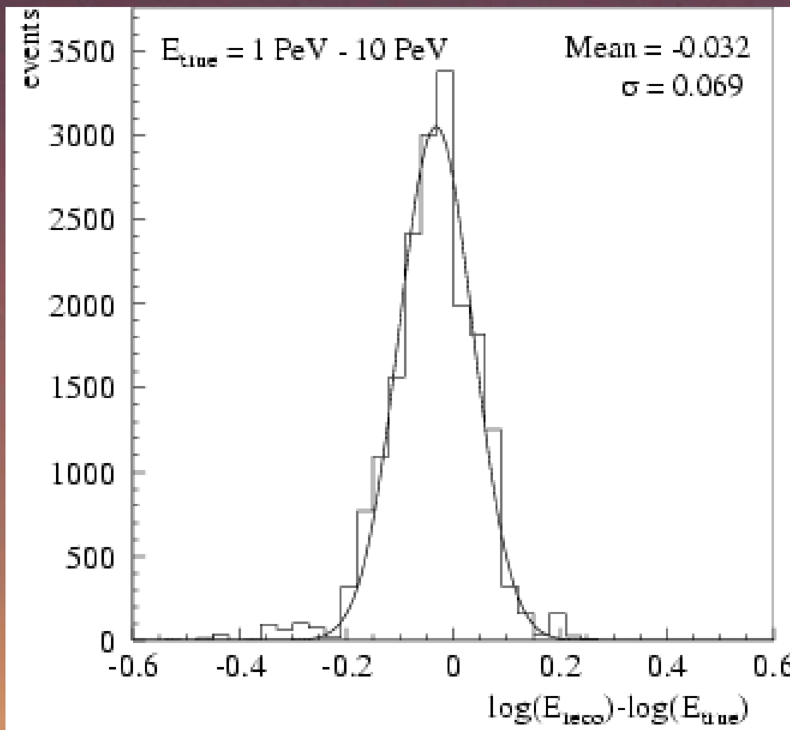
- Plot muons vs. electrons
- Transformed axes correspond to mass and energy

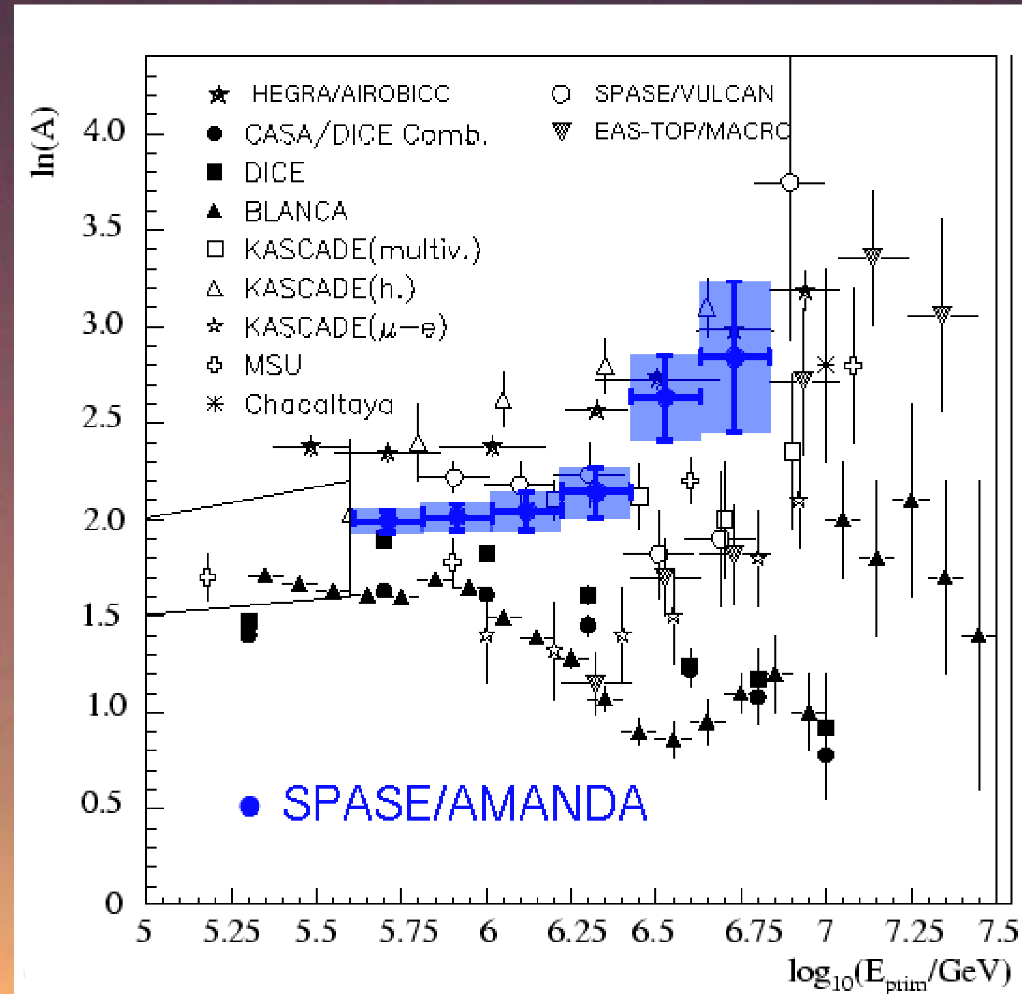


IceCube

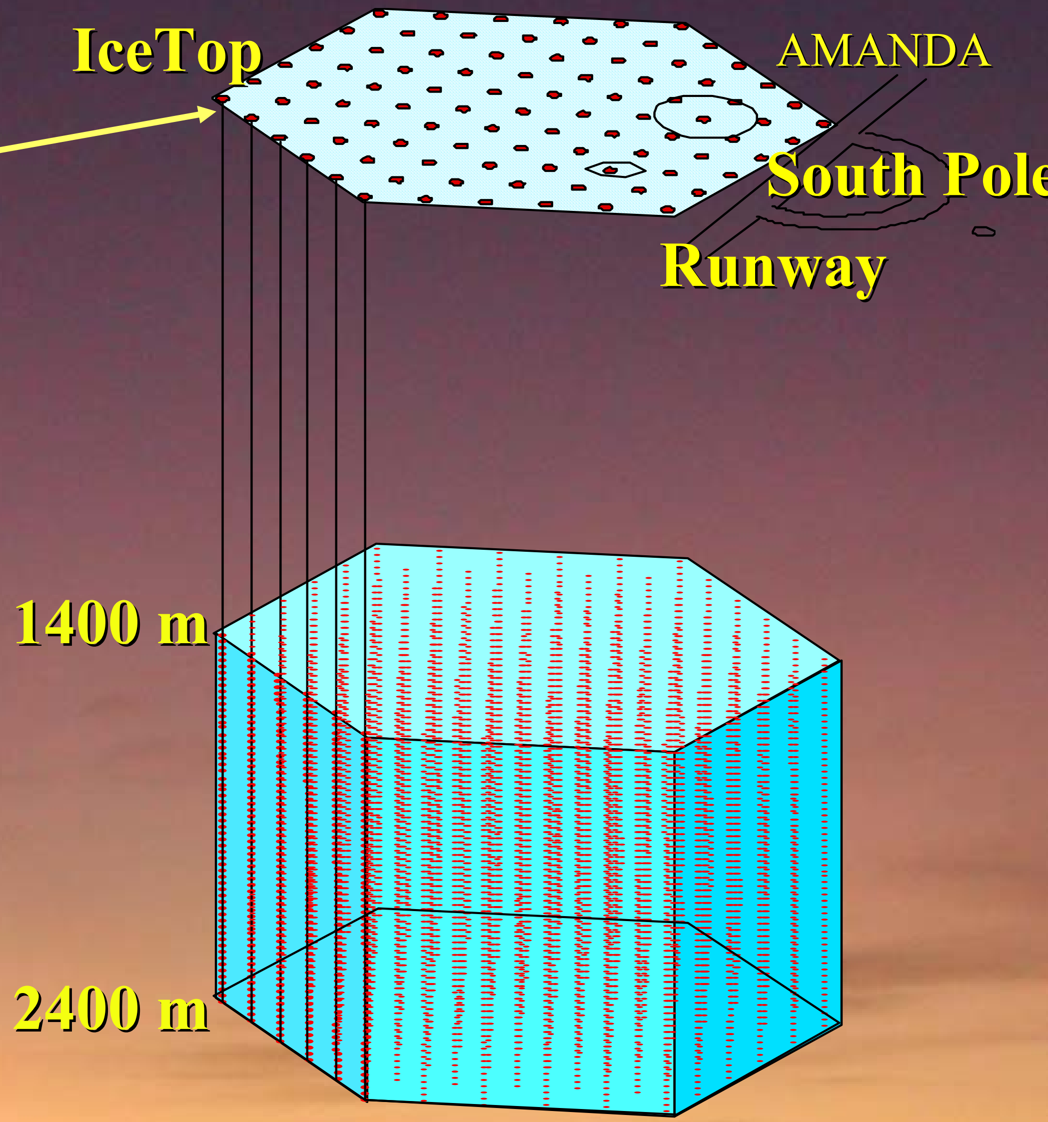
Cosmic ray composition

- Data show increasing average mass
- Good energy resolution





- Surface array composed of frozen water tanks
- Air shower threshold: ~1 PeV
- Will serve as:
  - calibration source
  - UHE veto
  - cosmic ray composition beyond the knee

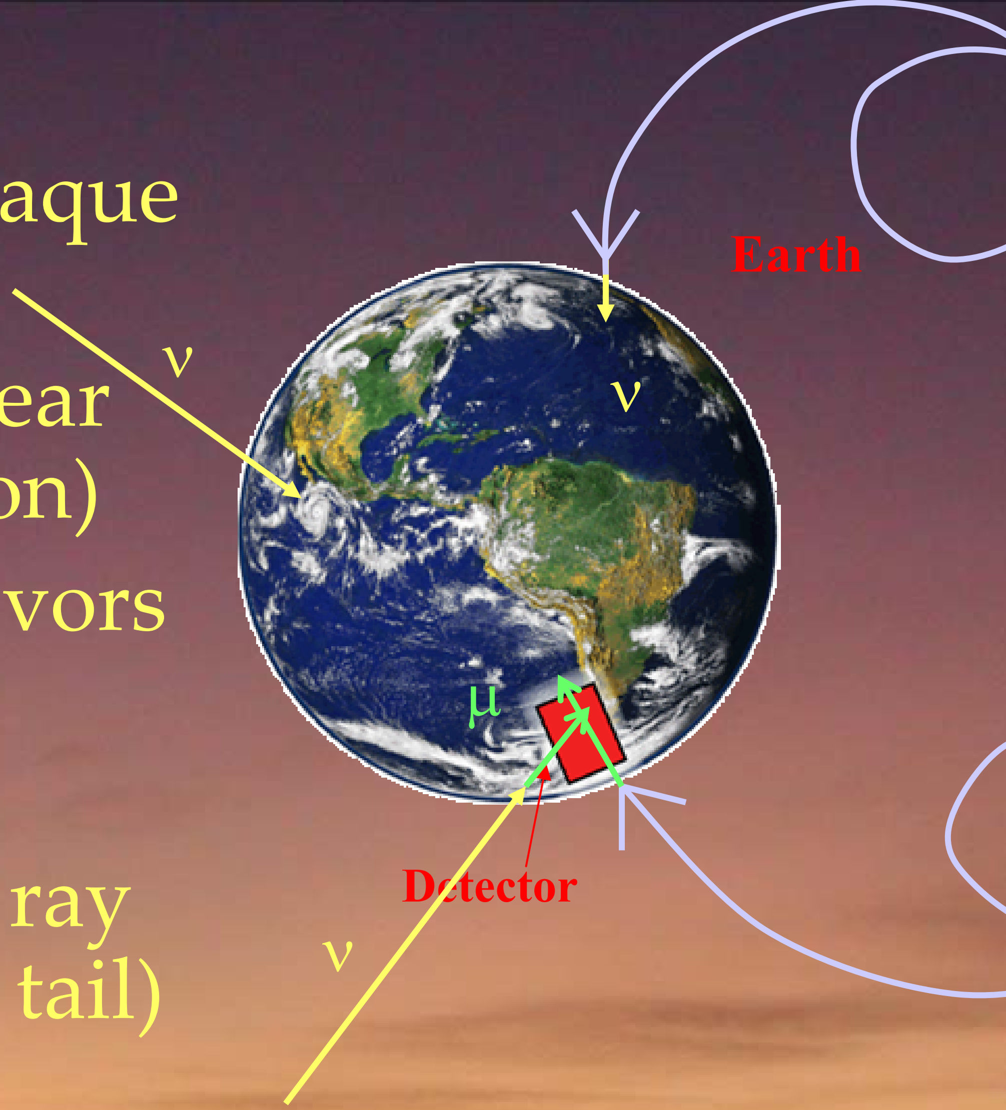


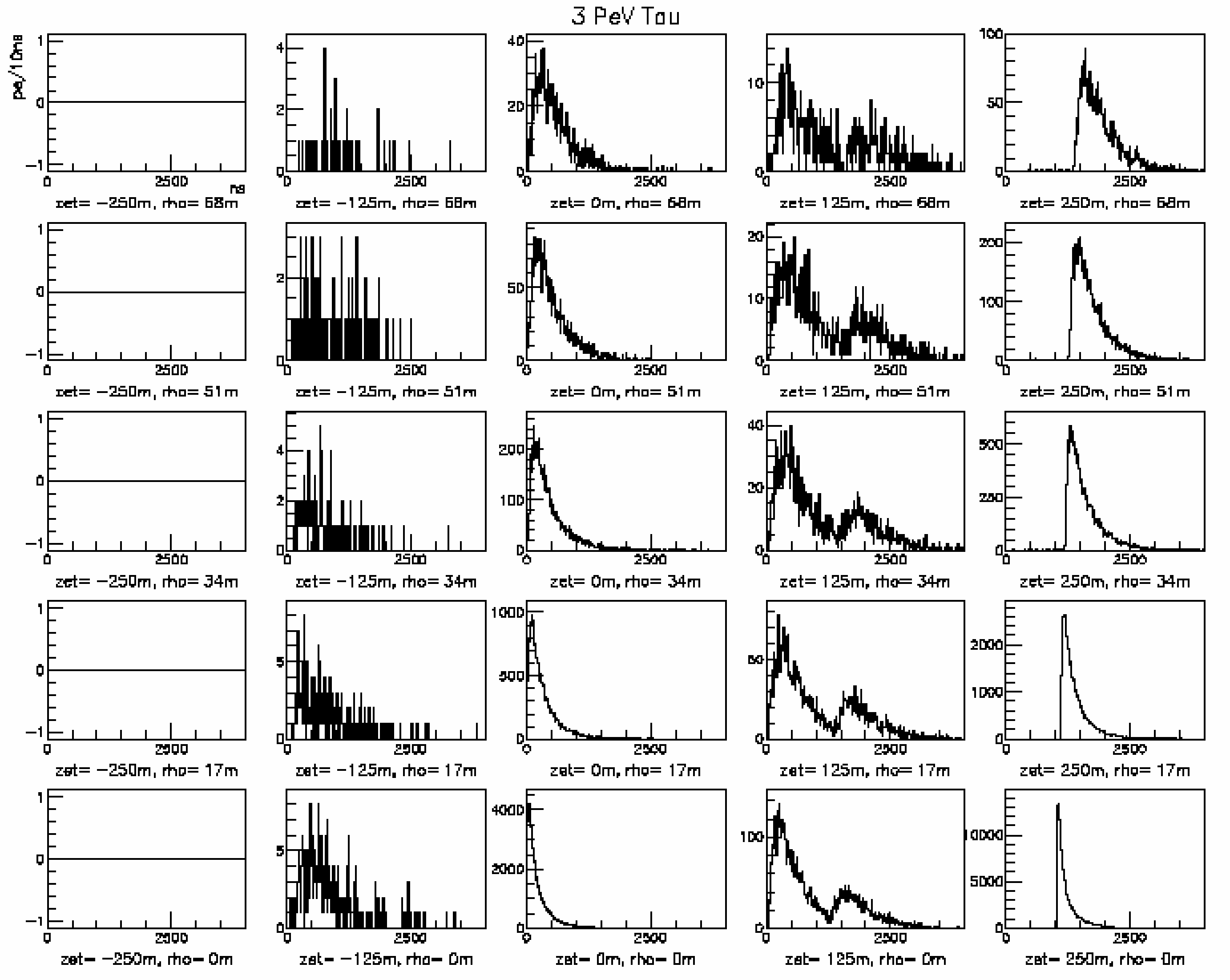
IceTop

IceTop tanks

New techniques at UHE

- Past 1 PeV, the earth begins to become opaque to neutrinos
- τ neutrinos still appear upgoing (regeneration)
- Can search for all flavors in the downgoing direction
- Background: cosmic ray muons (high-energy tail)





IceCube

Tau neutrinos

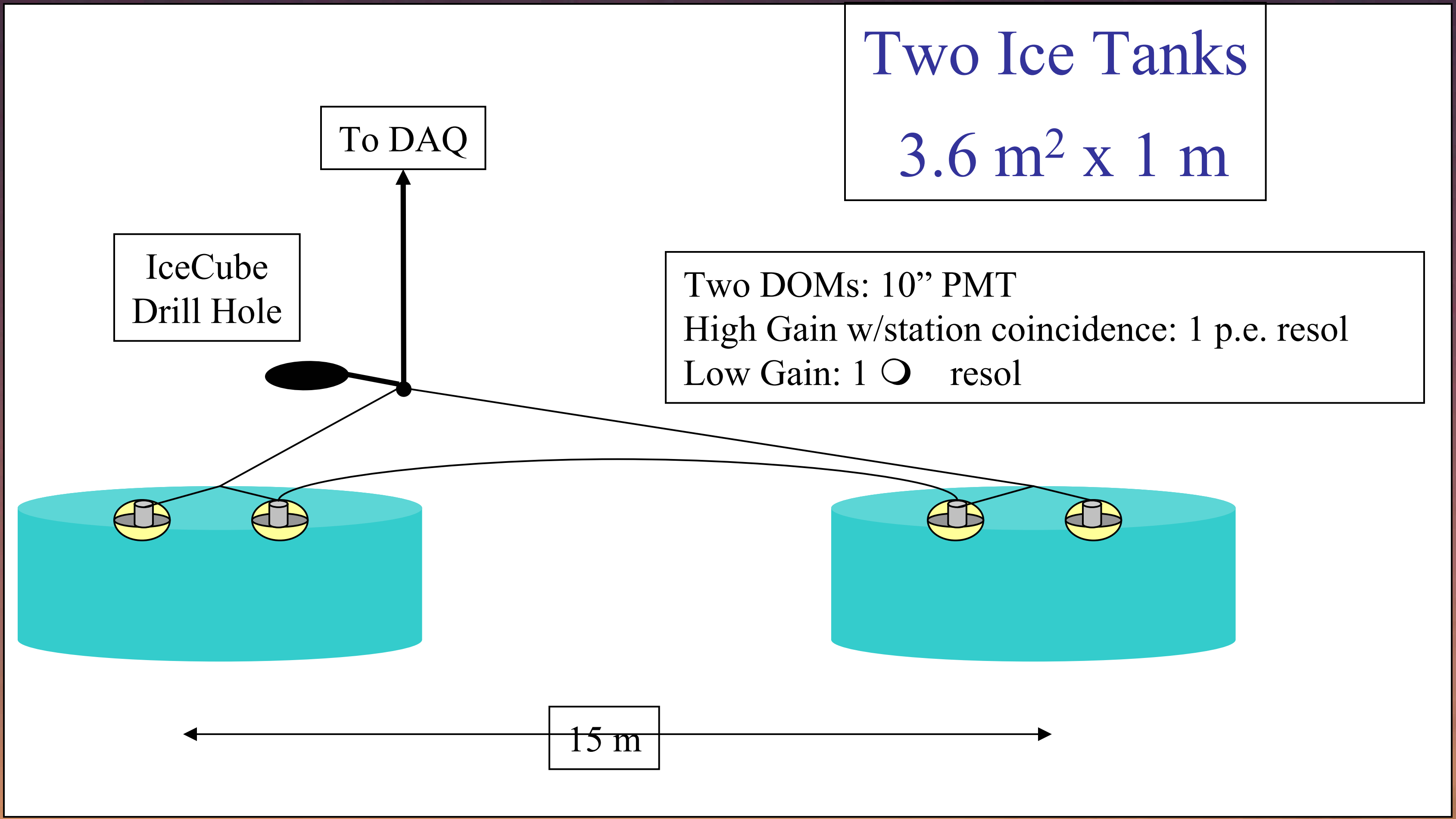
Conclusions

- AMANDA, currently operating, is running well and exploring a variety of physics topics.
- IceCube will be a powerful instrument for exploring the universe in neutrinos:
  - All three flavors
  - TeV, PeV and above (and below!)
  - Construction has begun!

The IceCube collaboration

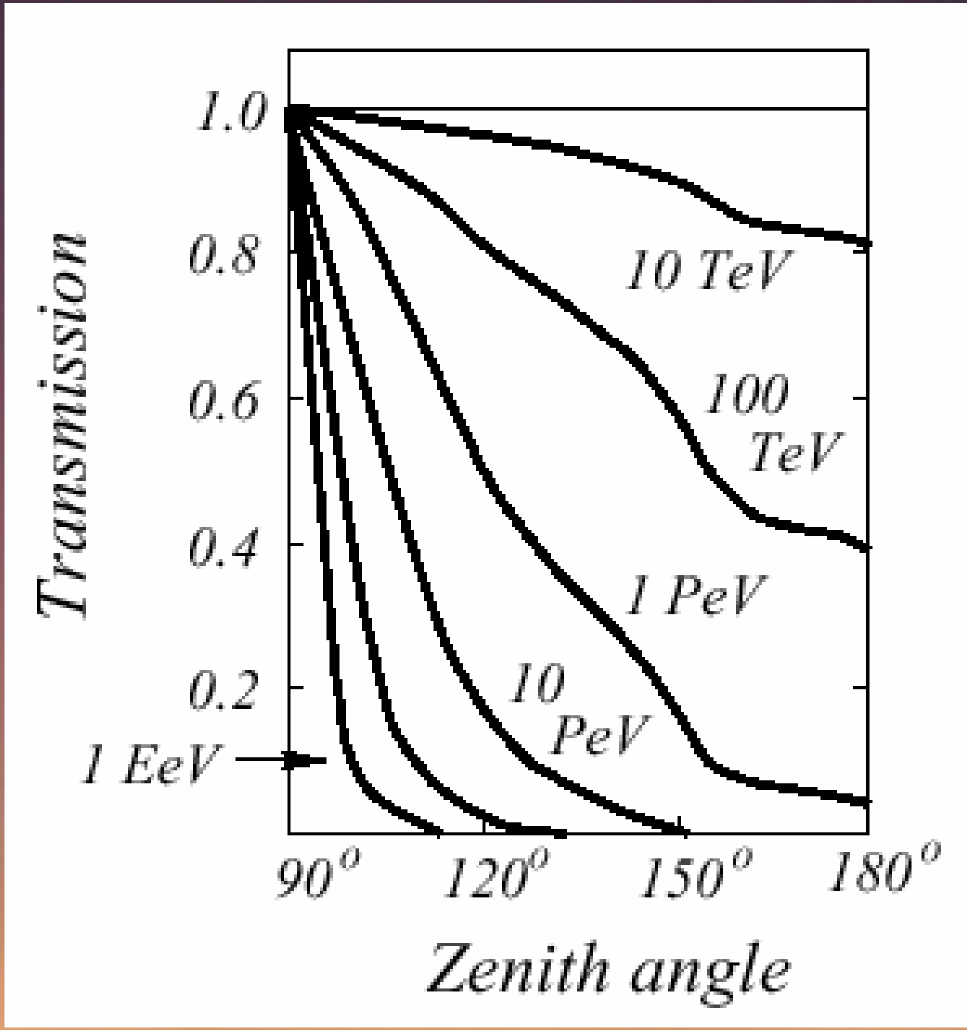
- Chiba University, Chiba, Japan
- Clark Atlanta University, Atlanta, GA
- DESY-Zeuthen, Zeuthen, Germany
- Imperial College, UK
- Institute for Advanced Study, Princeton, NJ
- Lawrence Berkeley National Laboratory, Berkeley, CA
- Pennsylvania State University, Philadelphia, PA
- South Pole Station, Antarctica
- Southern University and A & M College, Baton Rouge, LA
- Stockholm Universitet, Stockholm, Sweden
- Universität Mainz, Mainz, Germany
- Universität Wuppertal, Wuppertal, Germany
- Université Libre de Bruxelles, Bruxelles, Belgium
- Université de Mons-Hainaut, Mons, Belgium
- University of Alabama, Tuscaloosa, AL
- University of California-Berkeley, Berkeley, CA
- University of Delaware, Newark, DE
- University of Kansas, Lawrence, KS
- University of Maryland, College Park, MD
- University of Wisconsin-Madison, Madison, WI
- University of Wisconsin-River Falls, River Falls, WI
- Universidad Simon Bolivar, Caracas, Venezuela
- Uppsala Universitet, Uppsala, Sweden
- Vrije Universiteit Brussel, Brussels, Belgium

Backup slides

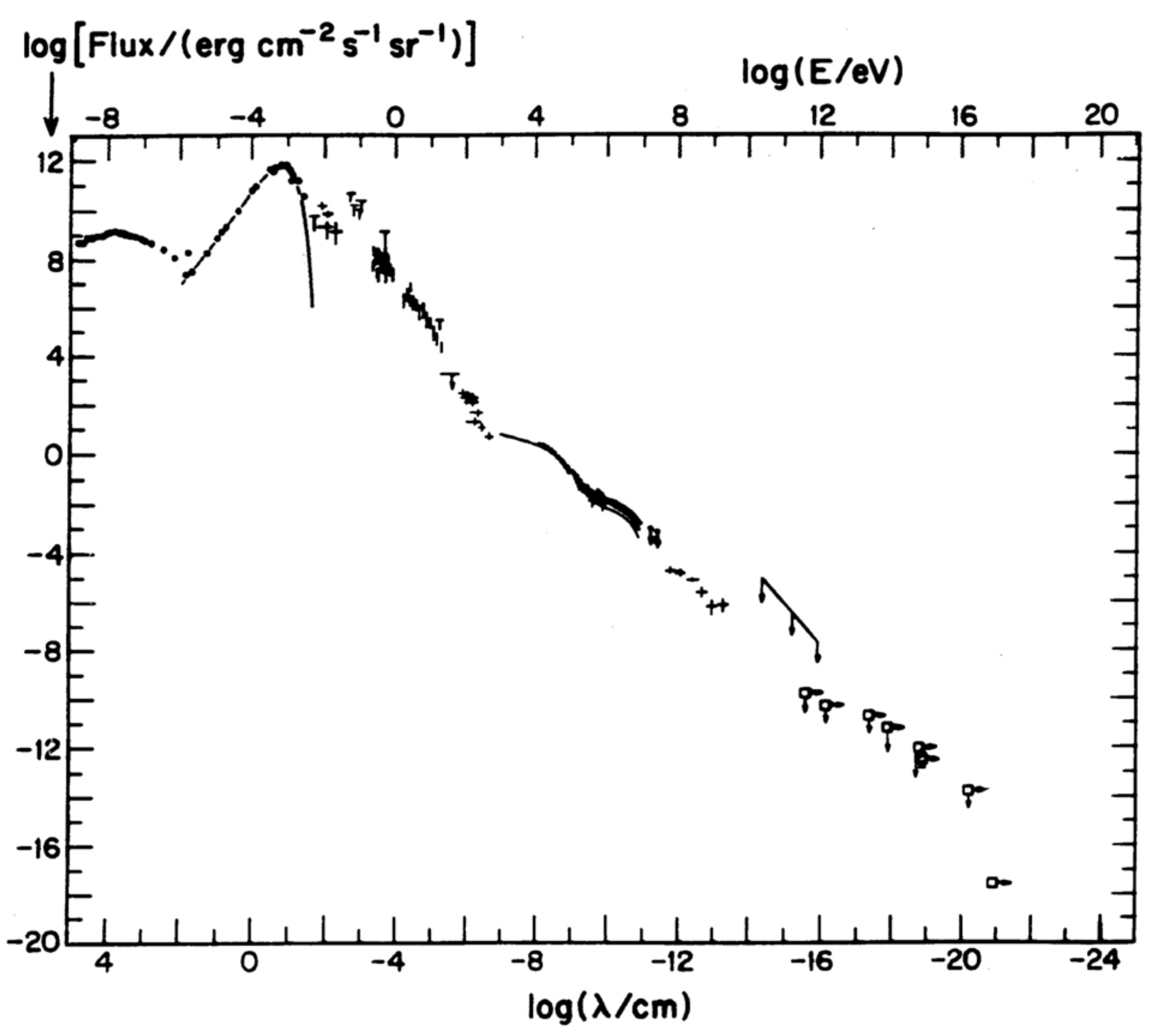


IceTop tanks

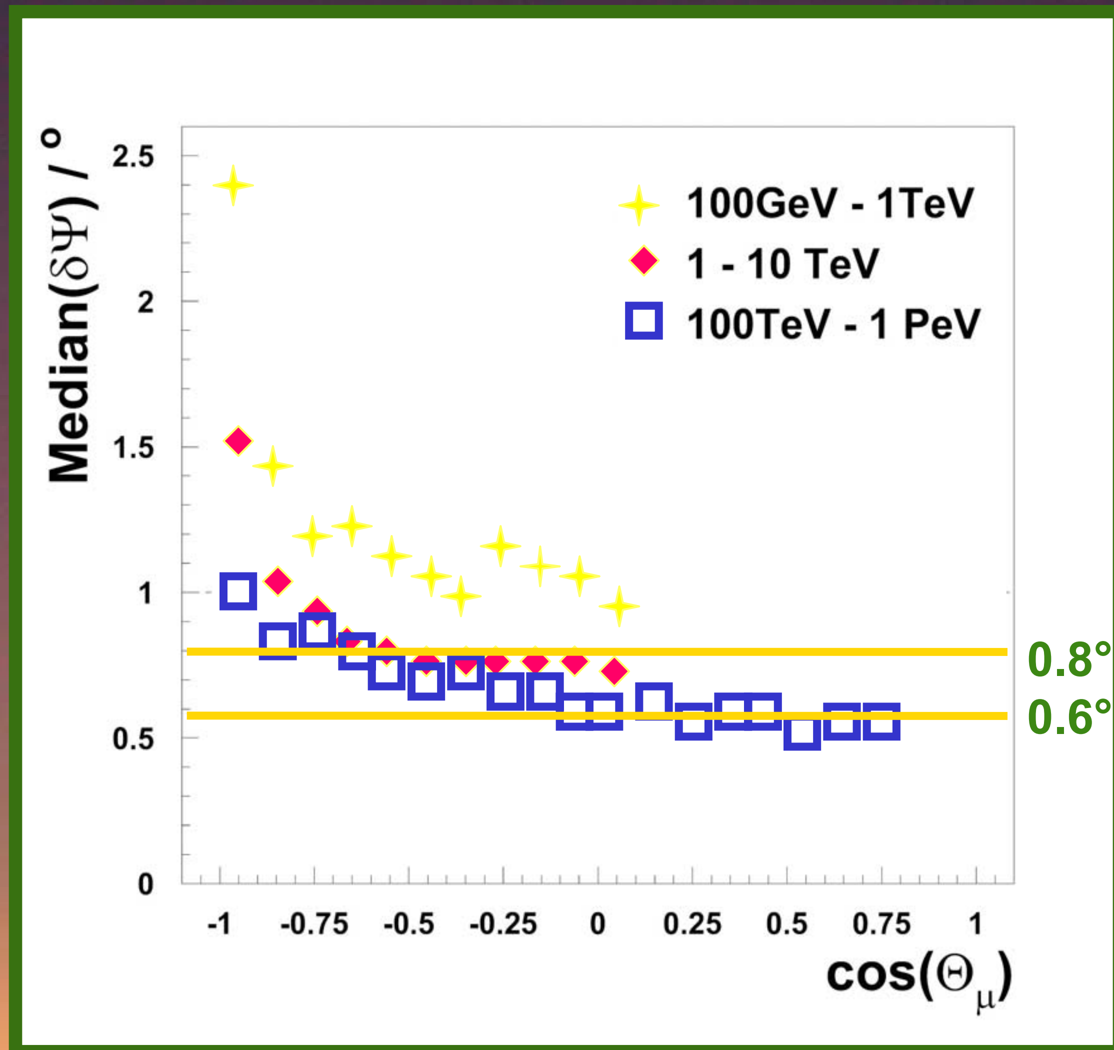
- At high energies, the earth becomes opaque to neutrinos



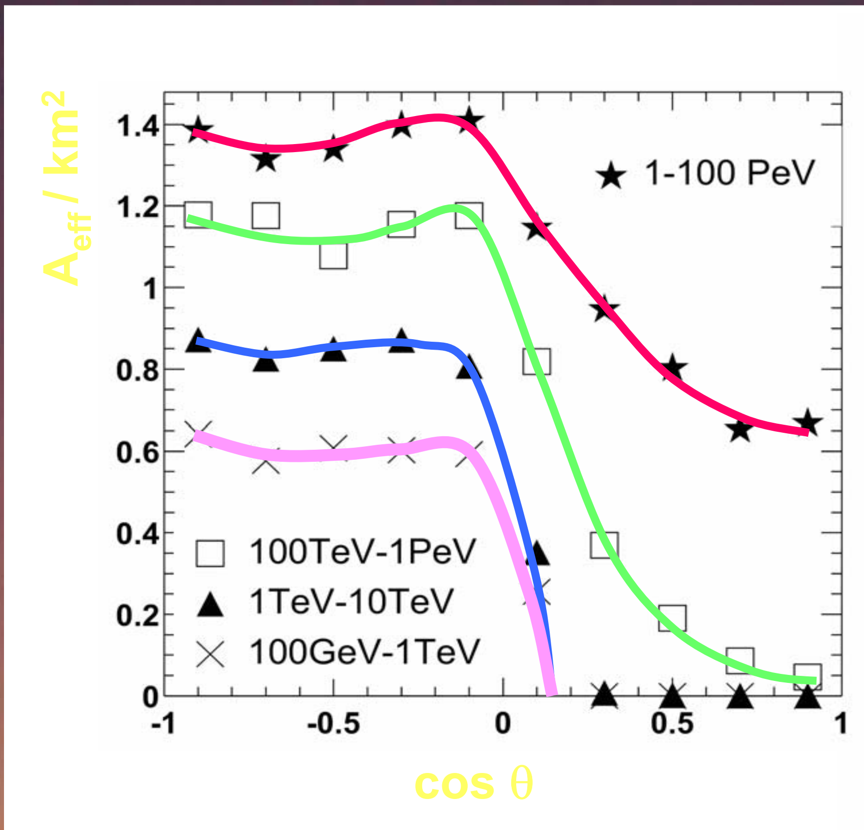
New techniques at UHE

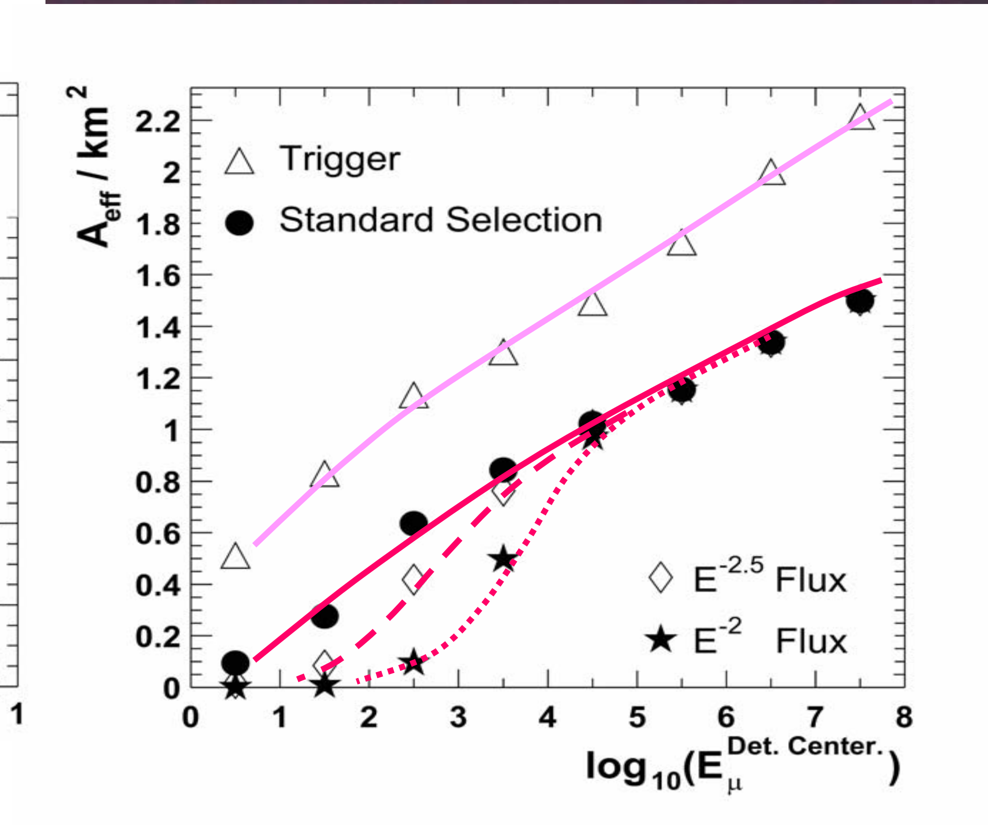


What we can learn from light



Angular resolution of IceCube





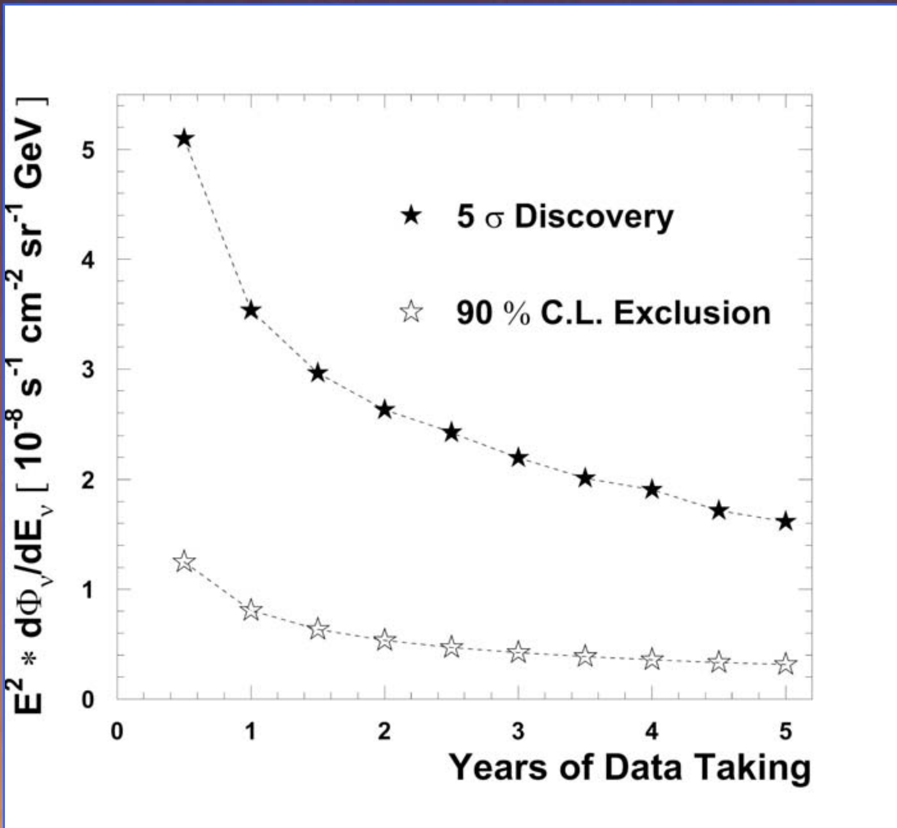
Effective area vs. zenith angle (downgoing muons rejected)

Effective area vs. muon energy (trigger, atm μ, pointing cuts)

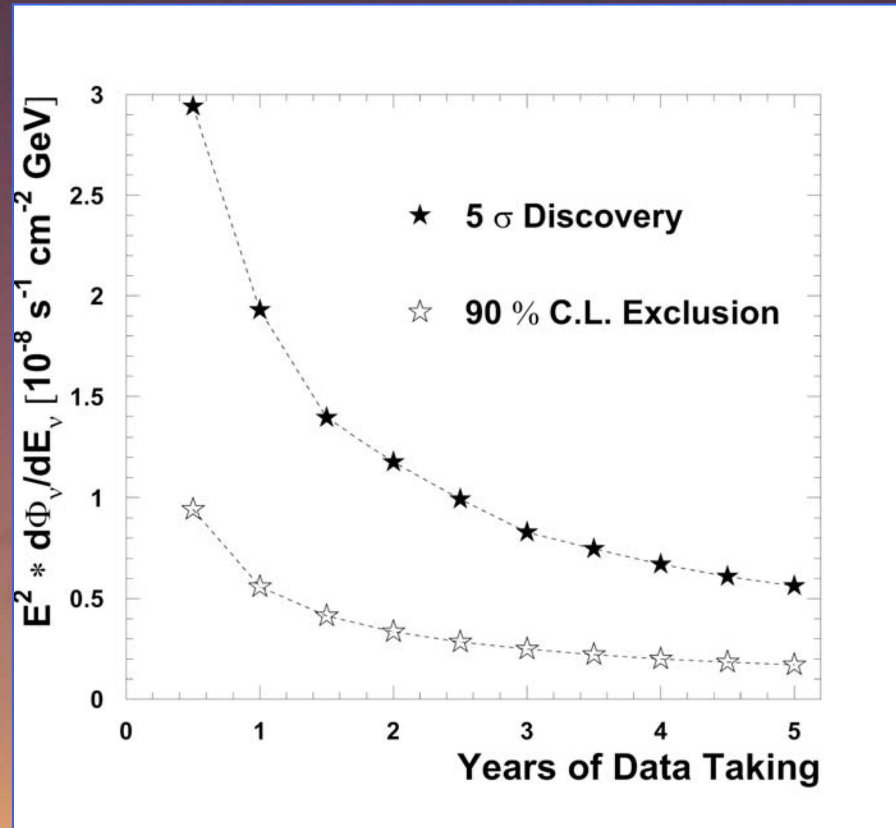
Effective area of IceCube

IceCube

Diffuse Fluxes

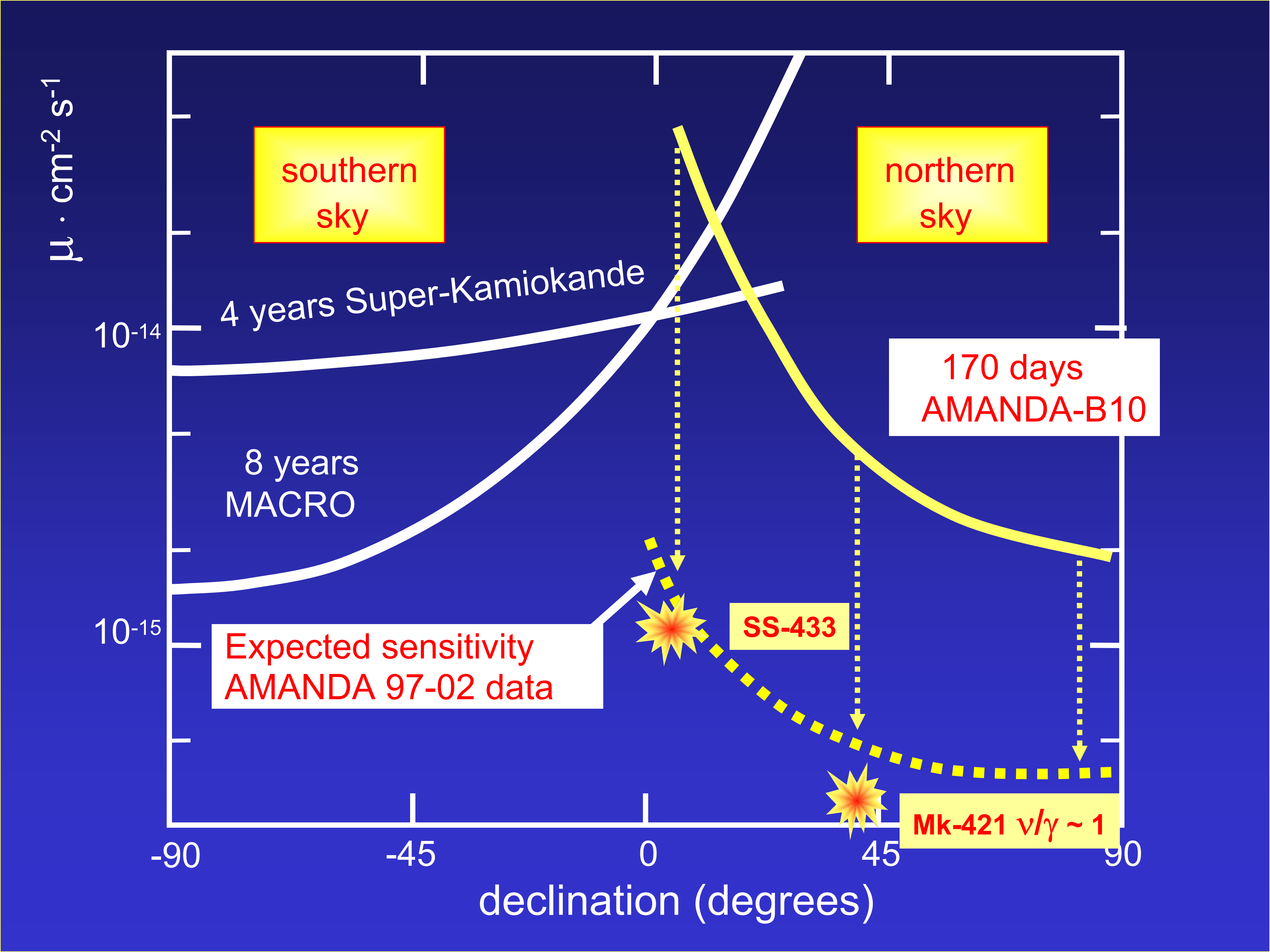


Point Sources

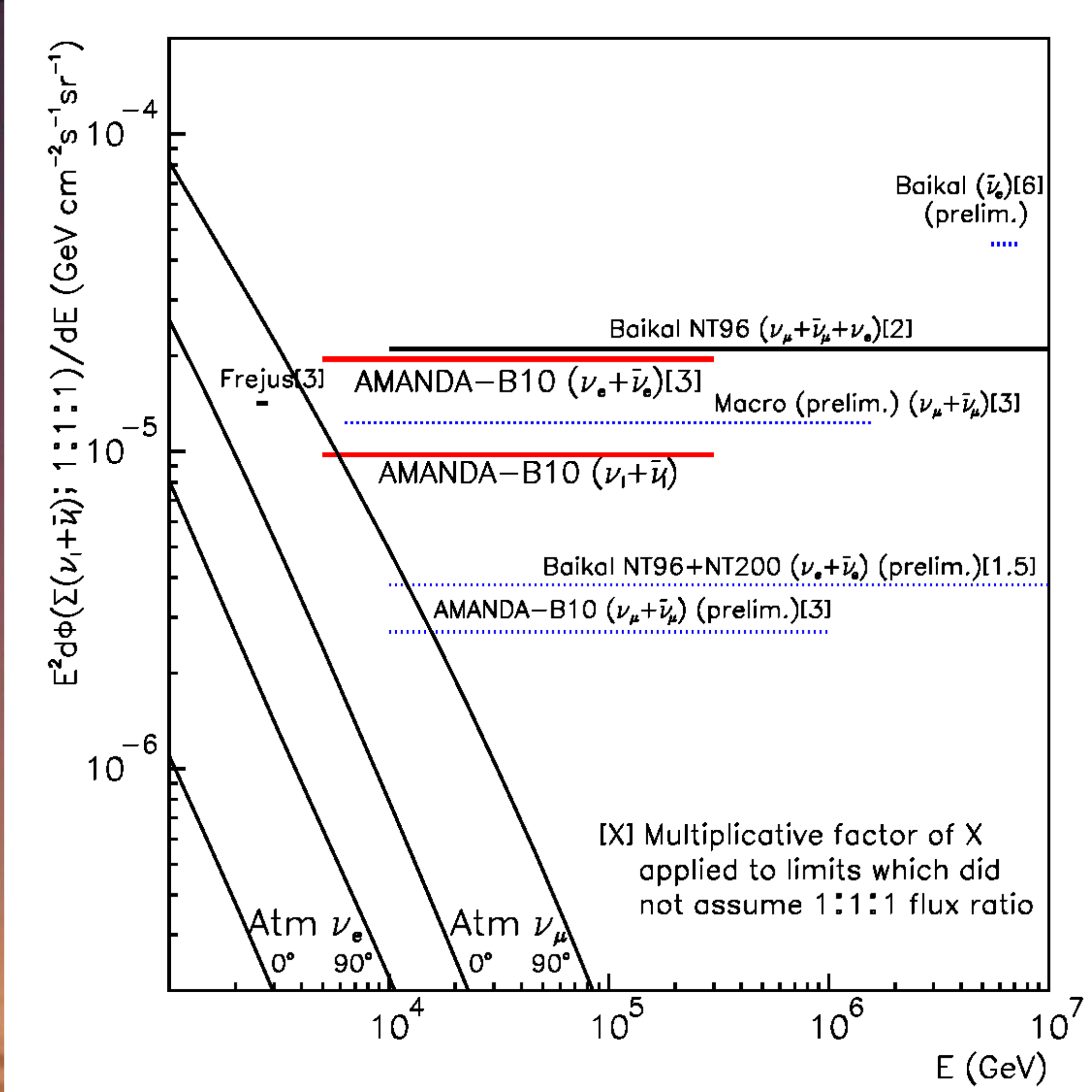


Sensitivity of IceCube

IceCube



μ · cm-2 s-1
southern sky
northern sky
4 years Super-Kamiokande
8 years MACRO
170 days AMANDA-B10
Expected sensitivity AMANDA 97-02 data
SS-433
Mk-421 ν/γ ~ 1
10-14
10-15
-90
-45
0
45
90
declination (degrees)



Cascade limits

Astrophysical ν's	*Predicted events* in 100% of 2000 data
$\Phi_{\nu_e+\nu_e} = 10^{-6} E^{-2}$ GeV cm^{-2} s^{-1}	5.5
$\Phi_{\nu_\tau+\nu_\tau} = 10^{-6} E^{-2}$ GeV cm^{-2} s^{-1}	3.2
Atmospheric ν's	***Predicted events*** **in 100% of 2000 data**
ν_e (CC), $\nu_e+\nu_\mu$ (NC)	0.15
Prompt charm (RQPM)	0.50

90% C.L. limit

$\nu_\mu+\nu_e+\nu_\tau$ (130 days):

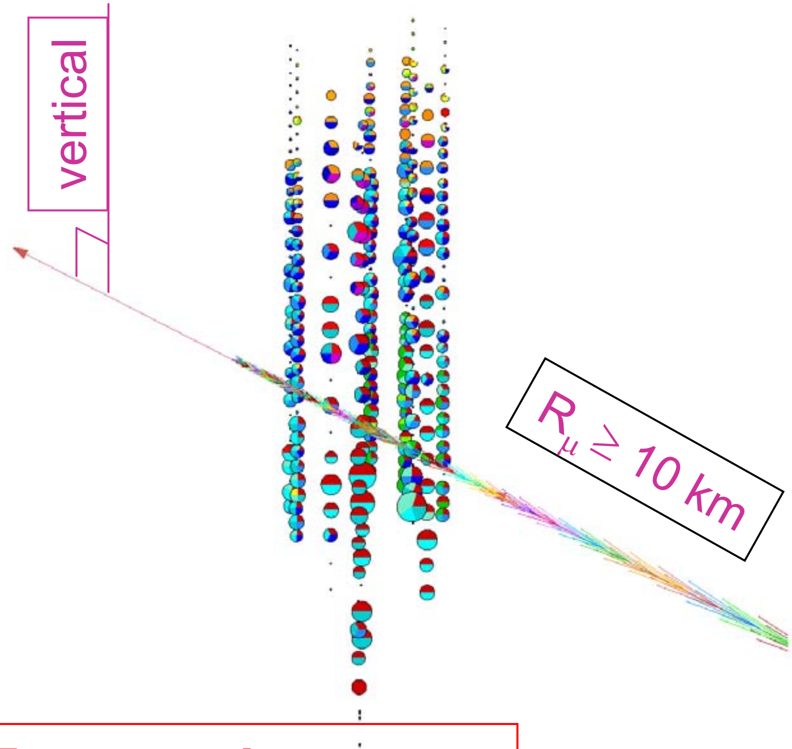
E^2Î(E) < 9.8 ·10 $^{-6}$

GeV cm^{-2} s^{-1} sr^{-1}

Cascade search

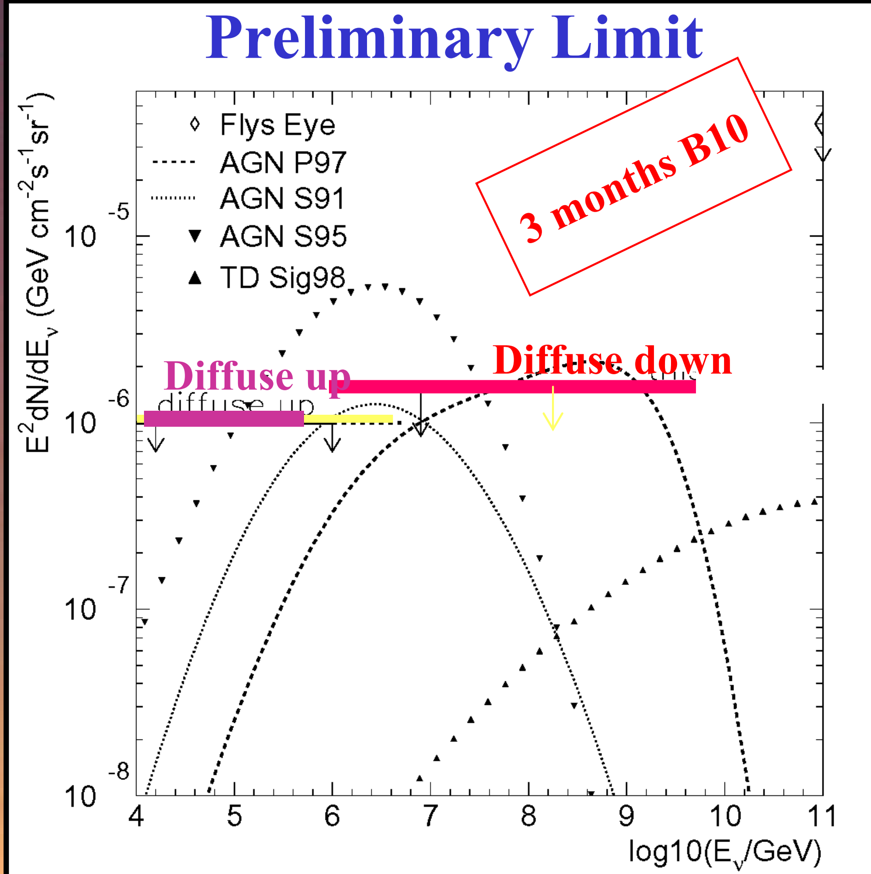
IceCube

EHE events very bright; many PMTs detect multiple photons

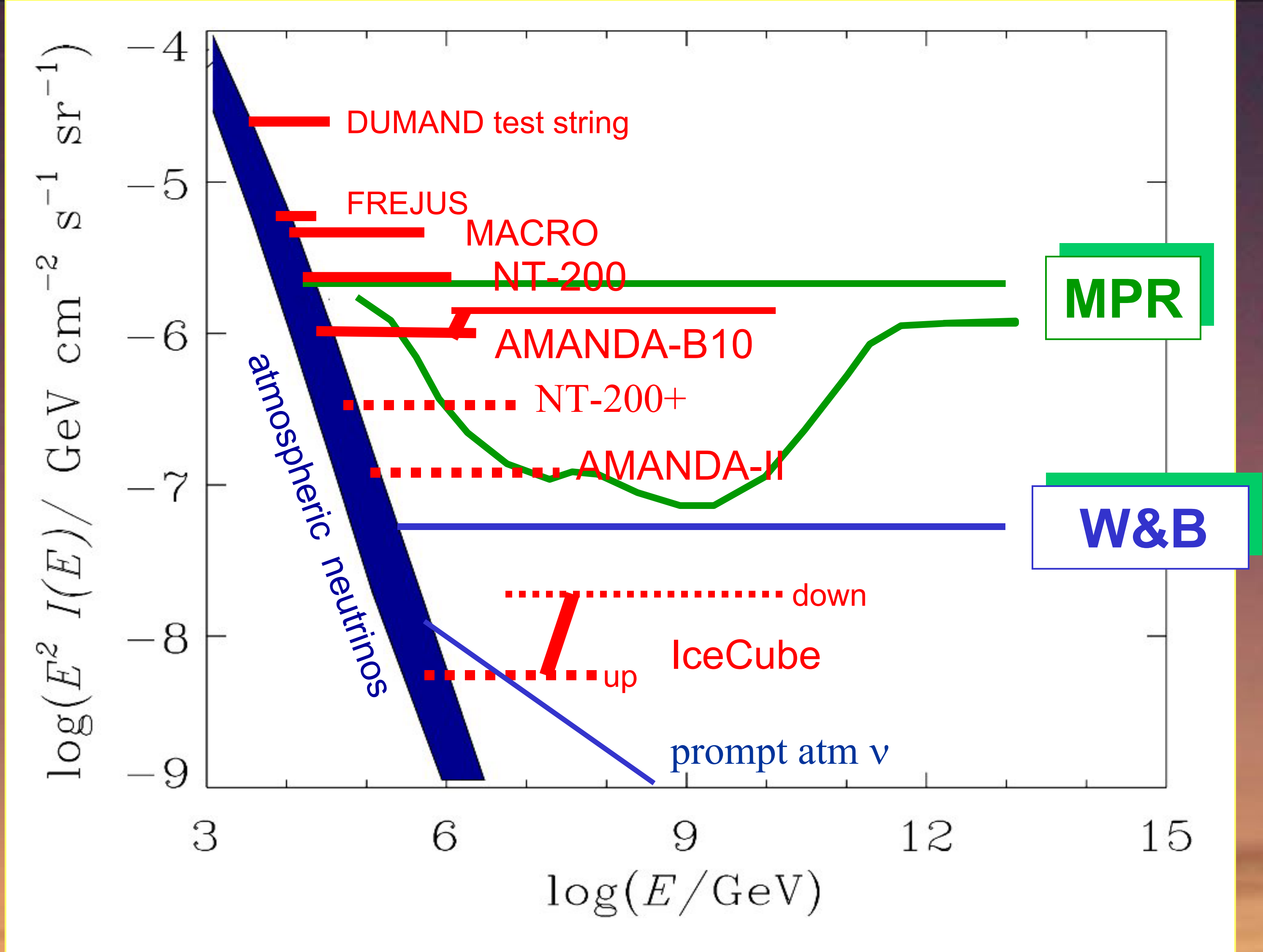


Expect only events near horizon

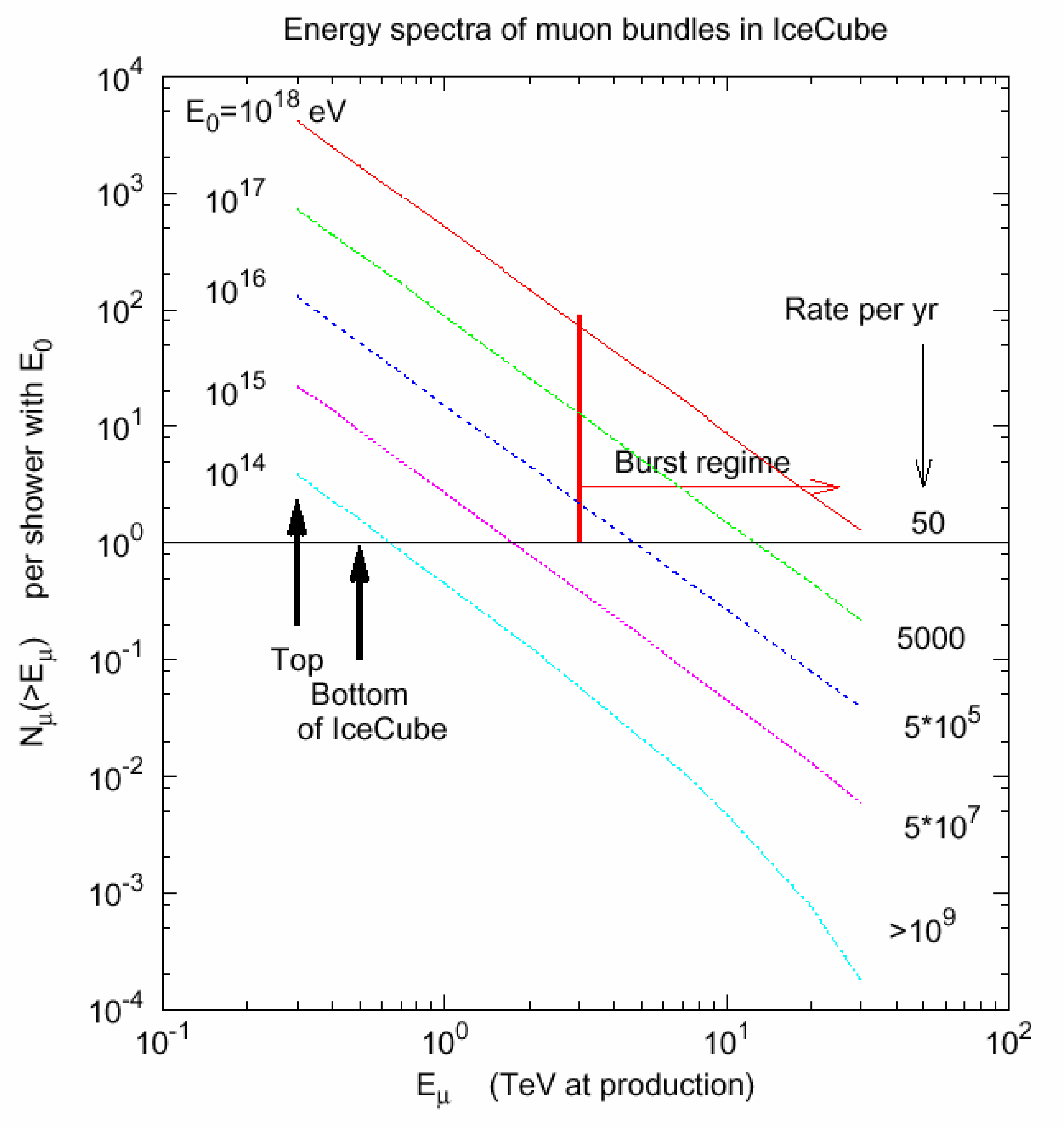
Main background: muon “bundles”
Comparable N_{PMT} but less photons



EHE search



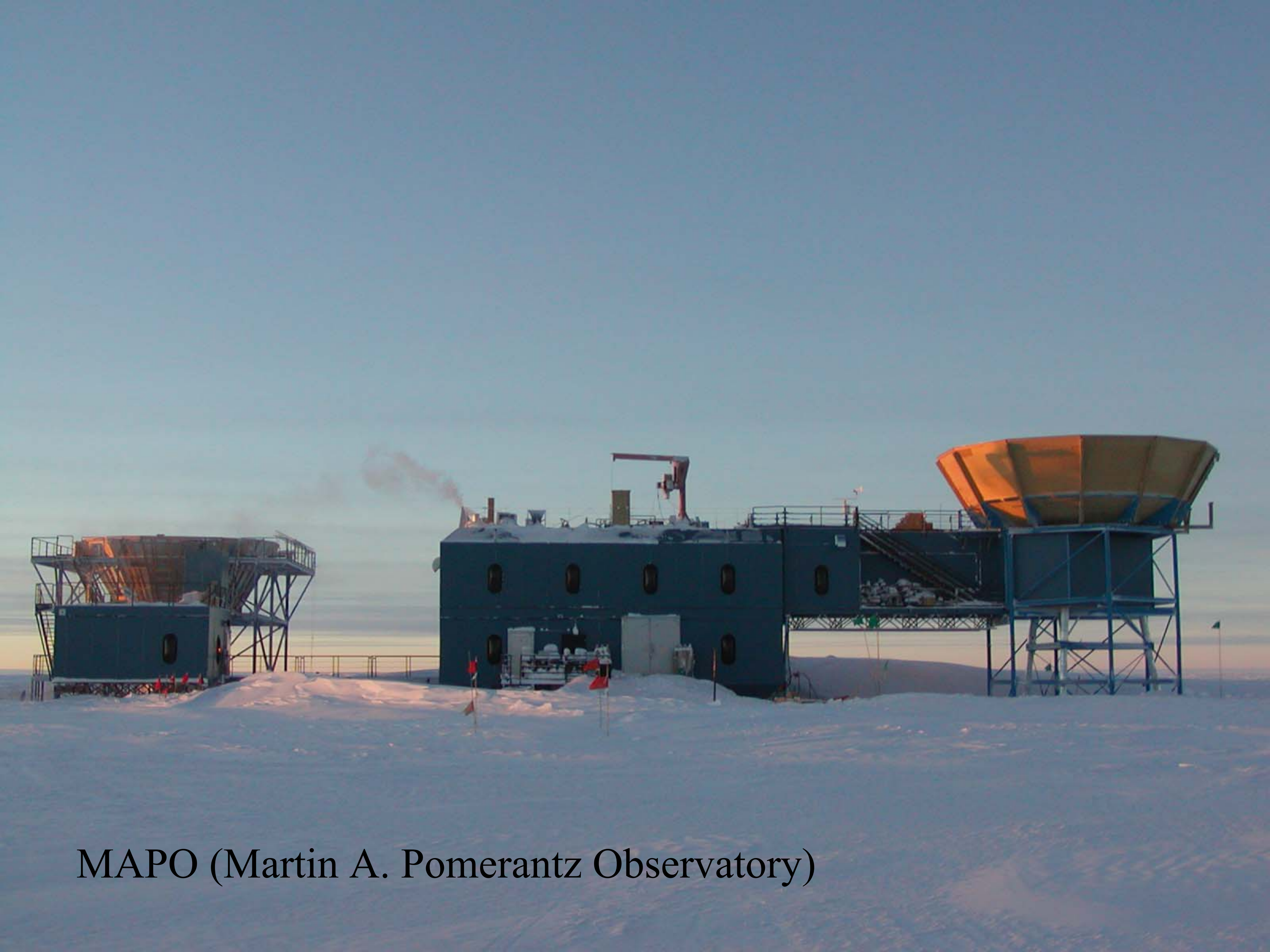
Diffuse search



IceTop rates

Pictures


The new station
The Dome



MAPO (Martin A. Pomerantz Observatory)

LC-130 Hercules

Halos

Sunset


THE UNITED STATES OF AMERICA
WELCOMES YOU TO
AMUNDSEN – SCOTT SOUTH POLE STATION
Me


Aurora Australis

Nighttime


Sunrise