Detecting high energetic cosmic neutrinos

- The IceCube Experiment -

Rolf Nahnhauer

DESY Zeuthen

How do we get our information about the universe ?

Light - See - Think


From Galilei to HST
Galaxy Cluster Abell 1689
HST • ACS
Io
Europa
Callisto
Ganymede
Jupiter's Galilean Satellites HST • WFPC2
PRC95-35 · ST ScI OPO · October 9, 1995
J. Spencer (Lowell Obs.), K. Noll (ST ScI), NASA
February 15, 2011
Technical Seminar Zeuthen
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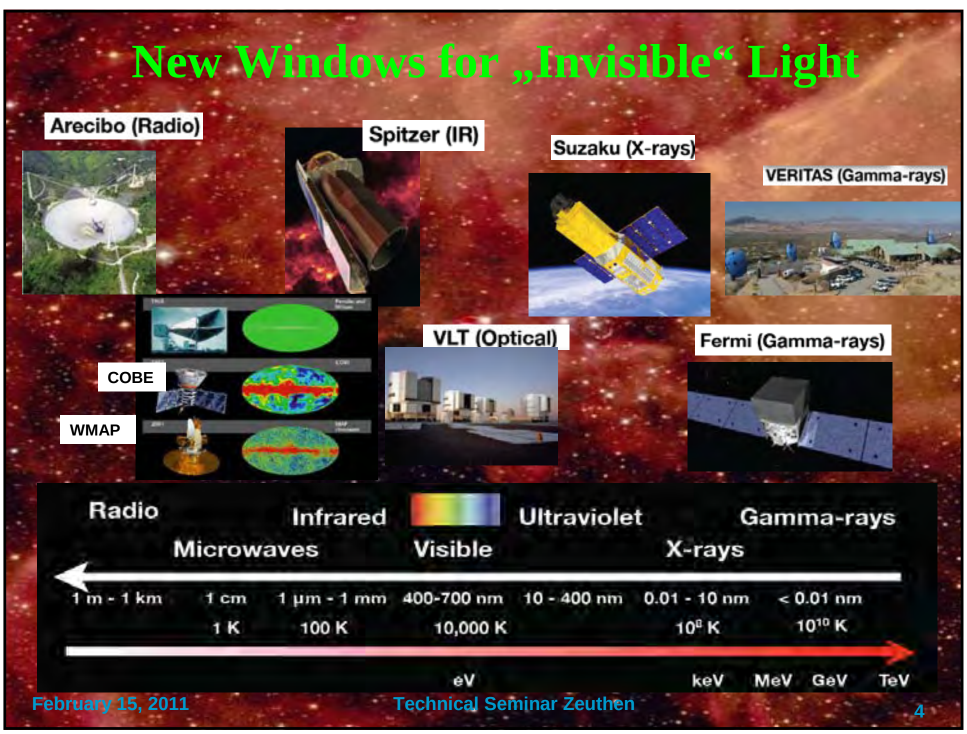
New Windows for „Invisible“ Light
Arecibo (Radio)
Spitzer (IR)
Suzaku (X-rays)
VERITAS (Gamma-rays)
COBE
WMAP
VLT (Optical)
Fermi (Gamma-rays)
Radio
Infrared
Ultraviolet
Gamma-rays
Microwaves
Visible
X-rays
1 m - 1 km
1 cm
1 µm - 1 mm
400-700 nm
10 - 400 nm
0.01 - 10 nm
< 0.01 nm
1 K
100 K
10,000 K
10⁸ K
10¹⁰ K
eV
keV
MeV
GeV
TeV
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Three carrier of information at high energies:
protons, gamma-rays, neutrinos

p: TeV – 100 EeV
- point back to sources only at highest energies
- observable range limited
- signals observed
- sources still unidentified

γ: GeV – 10 TeV
- point always back to sources
- observable range limited
- signals observed
- many sources identified

ν: 1TeV – 100 EeV
- point always back to sources, - observable range "unlimited", - no signals observed yet

Neutrinos – New messengers from the universe

ν

NEUTRINOS FROM THE BIRTHDAY OF THE WORLD :

each cm^3 of space still contains~330 neutrinos from the Big Bang 10-15 billion years ago

INVISIBLE NEUTRINO RAIN :

every human beeing is crossed by ~400000 billion neutrinos per second from the Sun

NEUTRINOS – CONNECTION TO WORLD´s LAST DAYS :

every human beeing produceses ~4000 Neutrinos per second which are irradiated in the universe

Neutrino – Only Weak Interactions

$N_{beob} = \sigma N_{TD} \Phi_{\nu}$

$\lambda_I = 1/N_{av} \rho \sigma$

$\sigma(\nu n \to p e^-) \rightarrow 6.4 \cdot 10^{-44} (E/MeV)^2 cm^2$

$\sigma(\nu N \to \mu^- X) \rightarrow 0.7 \cdot 10^{-38} (E/GeV) cm^2$

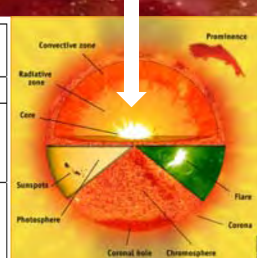
σ : cross section
N_{TD} : particles in detector
Φ_{ν} : neutrino flux
N_{av} : Avogadros-number
ρ : density
λ_I : interaction length

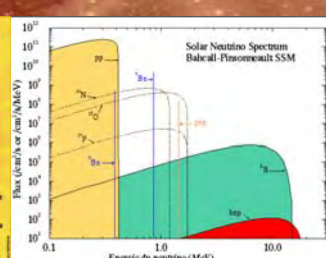
S=Sun, D=Earth : $\lambda_I = 1.9 \cdot 10^{13}$ km ≅ 2 light years ≅ 1.6 billion Earth-balls

Neutrinos from the Center of the Sun

- Nuclear fusion in the center of the Sun at 15 million K

pp	$\rightarrow$	$^2H + e^+ + \nu_e$	
$^2H + p$	$\rightarrow$	$^3He + \gamma$	
$^3He + {}^3He$	$\rightarrow$	$^4He + 2p$	85%
$^3He + {}^4He$	$\rightarrow$	$^7Be + \gamma$	15%
$e^- + {}^7Be$	$\rightarrow$	$^7Li + \nu_e$	
$^7Li + p$	$\rightarrow$	$2\,{}^4He$	
$p + {}^7Be$	$\rightarrow$	$^8B + \gamma$	0.02%
^8B	$\rightarrow$	$^8Be^* + e^+ + \nu_e$	
$^8Be^*$	$\rightarrow$	$2\,{}^4He$	





Produced: $2 \cdot 10^{38}$ ν's/sec

Arriving after ~ 7.5 min

at the earth surface : $40 \cdot 10^9$ ν's/cm²sec

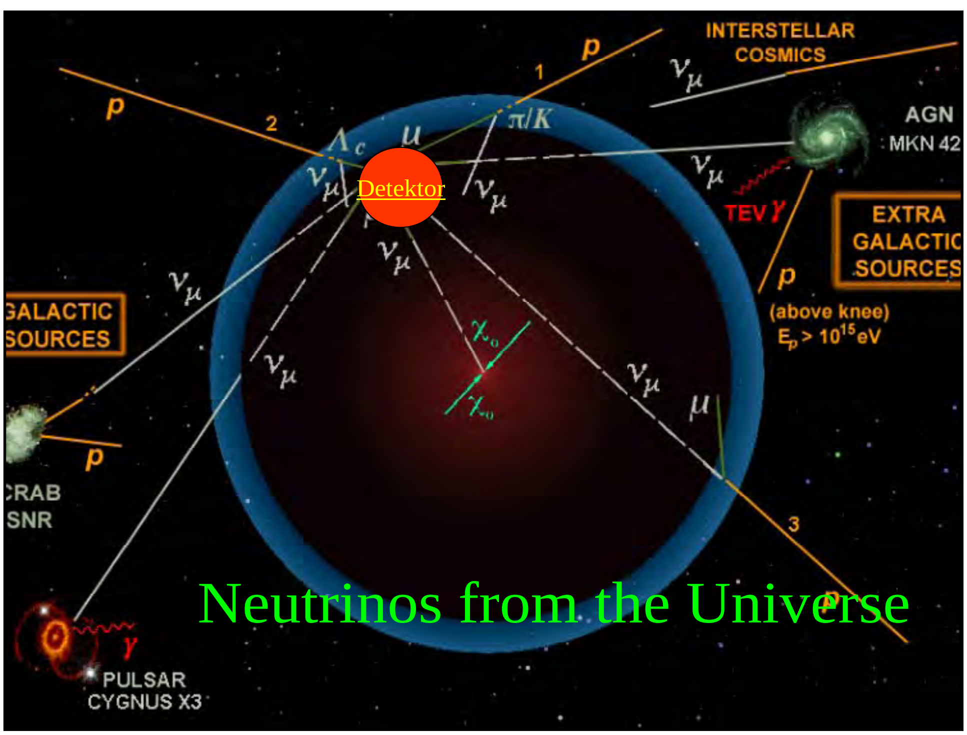
The Supernova 1987A :

Optical observation :
23.2.1987 10:37
Australia

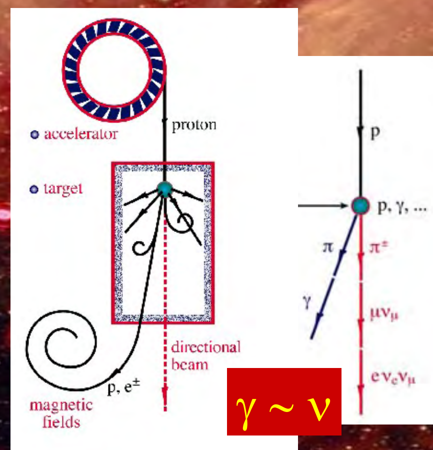
Neutrino observation
23.2.1987 7:25 + ...
KAMIOKANDE, IMB,
BAKSAN, Mt.BLANC

~ 25 events

Neutrinos from the Universe



Cosmic Particle Accelerators

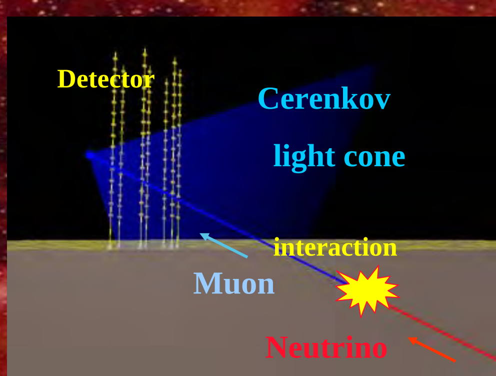


- Only a few events per km^2 per year
- Need giantic telescopes

Cherenkov Light

condition:

$\cos \Theta = c_{medium} / v_{particle} < 1.$



H_2O, Ice:

$\Theta \approx 40°$

good transparency for sensitive wavelengths

$\lambda = 200 - 600$ nm

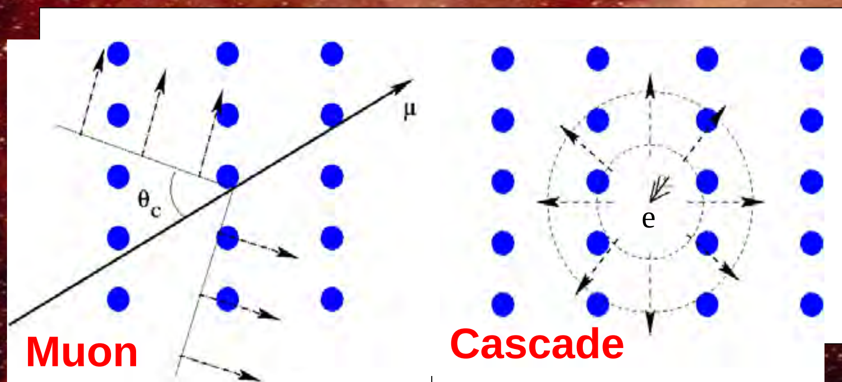
absorption length large:

$\lambda_{abs} = 20 - 120$ m

scattering length small:

$\lambda_{sc} = 2\text{-}20$ m

Detectors: Arrays Instead of Containers



information: which photosensors see how much light at which time ?

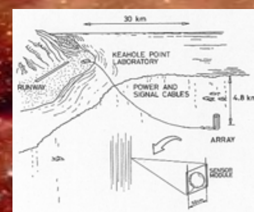
reconstruction: type, direction, energy of event

Cherenkov Neutrino Telescope Projects

The First Big Project : DUMAND

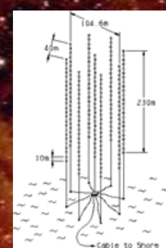
Hawai 1975 - 1995

Collaboration
USA, Japan, Deutschland, Schweiz



DUMAND I 1983-1988
prototype 70 m string with 7 moduls
readout from ship

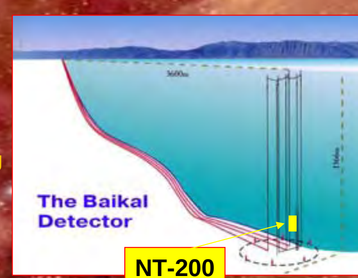
DUMAND II 1988 – 1995
2 *10^6 t $H_2$0

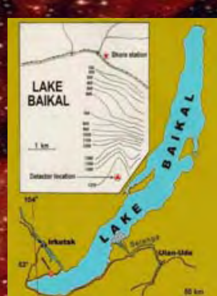


cable to shore
1 complete string
live time: only
a few hours

The First Successful Project: Lake Baikal

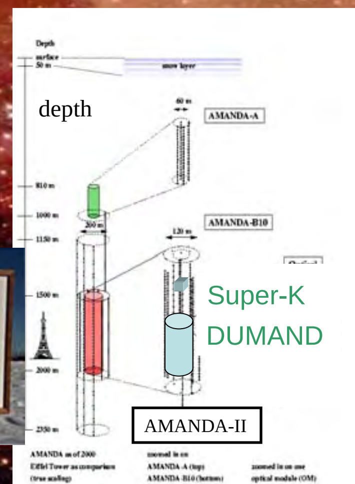
Institute of Nuclear Research, Moscow
Irkutsk State University, Irkutsk
DESY Zeuthen, Zeuthen
Moscow State University, Moscow
Nishni Novgorod State Technical University
State Marine Technical University, St.Petersburg
Kurchatov Institute, Moscow
JINR, Dubna





The First Detector in Ice : AMANDA

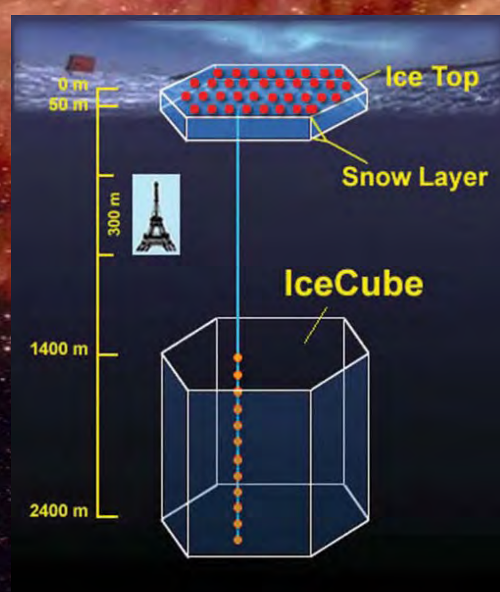
Collaboration:
Belgium, Germany, Netherlands, Sweden,United Kingdom, USA, Venezuela

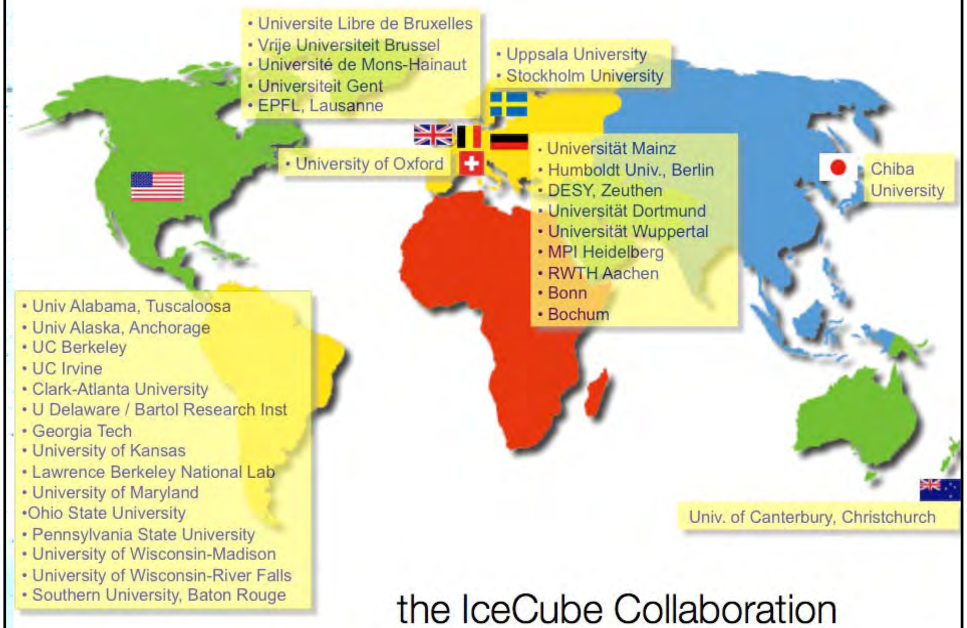


The largest detector today: IceCube

- 86 Strings } end 2010
- 5120 PMT
- Instrumented volume: 1 km³
- Installation: 2004-2010

~ 80.000 atm.ν per year

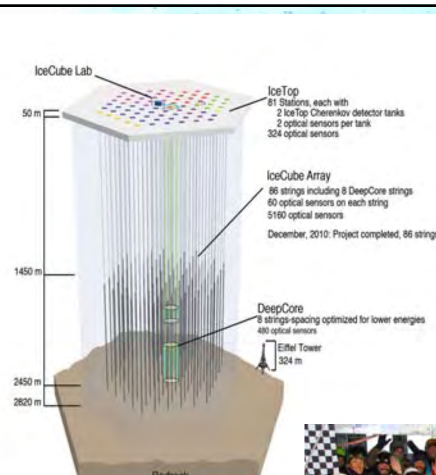




the IceCube Collaboration

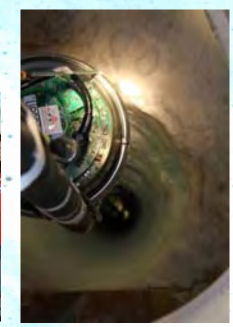
34 institutions in 4 continents

Detector completed



Final string deployed December 18, 2010

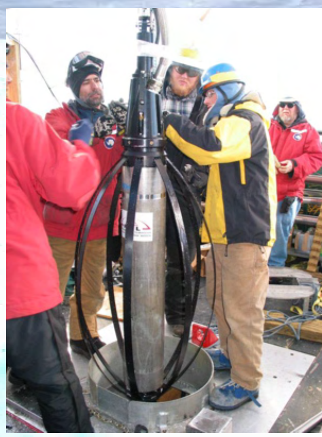


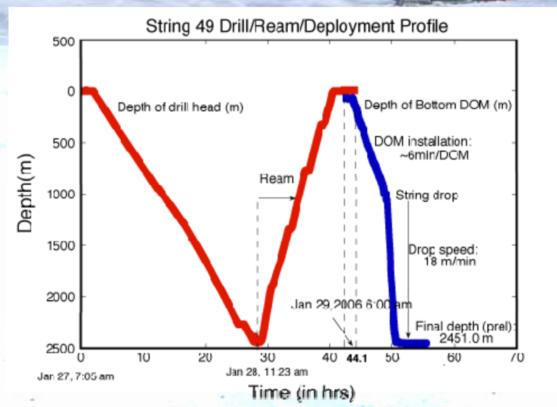


Schedule & Logistics

- Can work November → mid-February
- New South Pole Station
- Logistics - icebreakers, planes on skies,
  - planes only from McMurdo to Pole

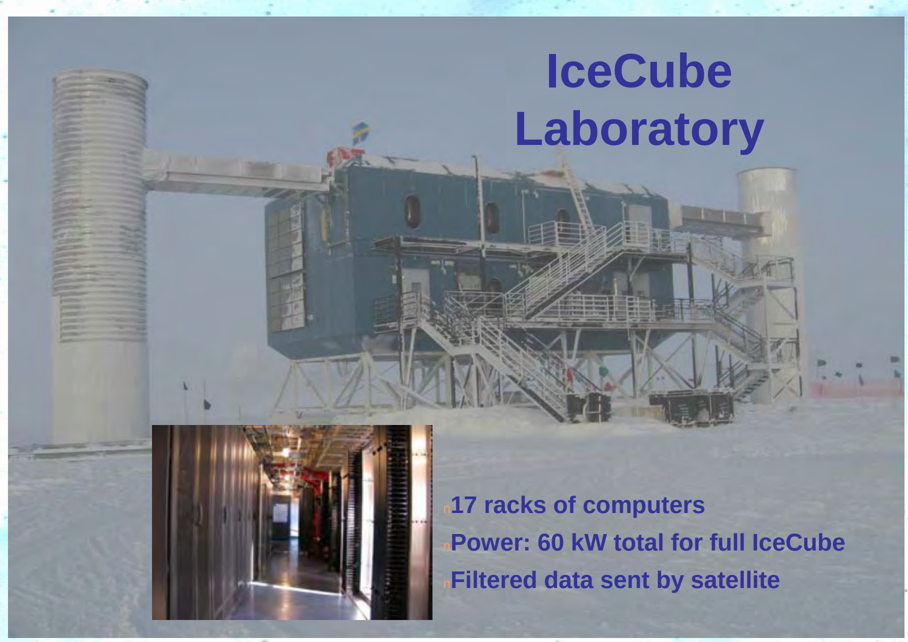
IceCube Drilling and Deployment





drilling (2450m) 40 hrs, deployment: 10 hours

5MW x 30 hrs = 0.56 TJ!



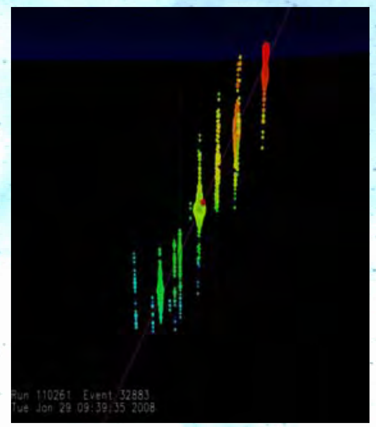
IceCube Laboratory

- **17 racks of computers**
- **Power: 60 kW total for full IceCube**
- **Filtered data sent by satellite**

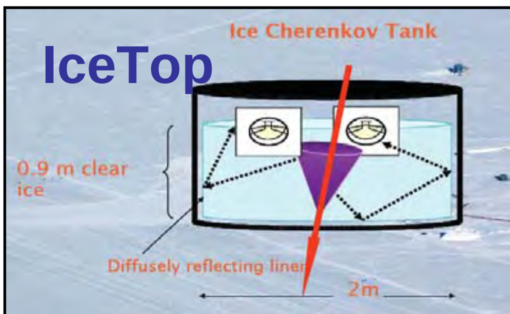
IceCube Events

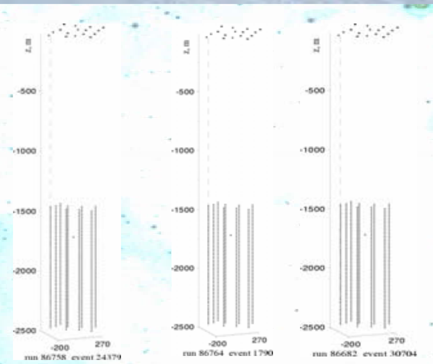
Neutrino Simulation

Neutrino Event

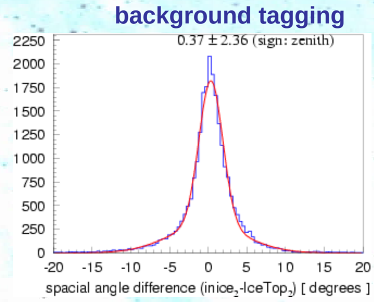


IceTop





IceTop: cosmic-ray physics
IceCube: calibration, background tagging



Ice Drives the Design

- Surface temperatures -20°C ↔ –70°C
- At-depth temperatures -35°C ↔ –10°C
- Freeze-in subjects cables, connectors, optical modules to high stress
- Inaccessibility requires reliability, remote operation

- Once modules are deployed, have stable environment
- No radioactivity in ice ⇒ PMT rate < 1kHz
- Optical scattering relaxes timing requirements

'Electronic' Requirements

- Quality data, maximum information, high information/noise (identify, analyze rare events)
  - Timing (ability to reconstruct tracks, locate vertices)
    <7ns rms *3 ns*
  - Waveform capture (all photons carry information)
    300 MHz (for 400 ns), 40 MHz (for 6.4 μsec)
  - Charge dynamic range (energy resolution)
    >200PE/15ns *~500 PE/15 ns*
  - Onboard calibration devices
    LEDs for int. & ext. calibration. Electronic pulser
  - Hardware local coincidence in the ice
    Nearest and next-nearest neighbor
  - Communications signaling rate to surface
    1 Mbaud/twisted pair

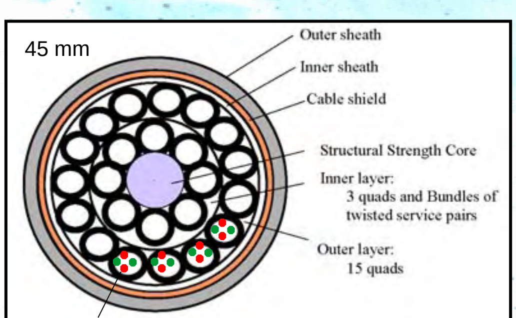
‘Environmental’ Requirements

- Robust equipment for a harsh environment
  copper cable, rugged connectors
- Effective operation (reduce manpower at S. Pole)
  automatic, self-calibration; remote commissioning
- Low power (fuel expensive at S. Pole)
  ≤ 5 W/DOM
- Insensitivity to interference from other experiments at S. Pole: VLF, Radar
  Common mode rejection
- Long life time > 10 years after completion
  Design for reliability
- Minimize cost
  Two DOMs per twisted pair

The IceCube Cable

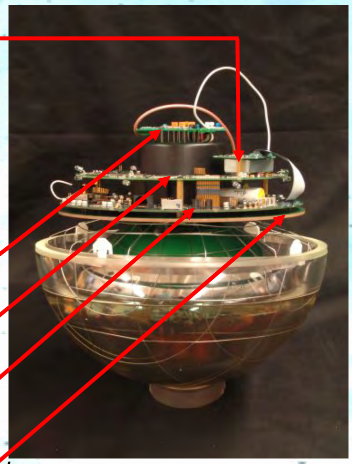
- Length: 3 km
- 0.9 mm copper wire
  twisted quad configuration
- 145 Ohm impedance
  DC resistance < 140 Ohm/2.5km (cold)
- low cross talk between twisted pairs is essential

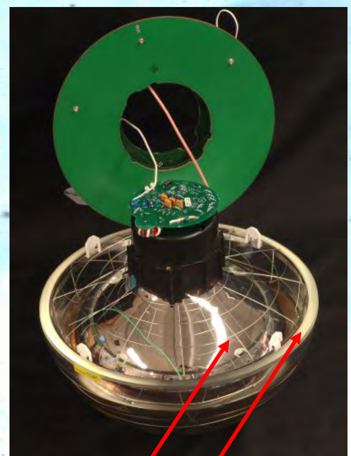
- > 50 db suppression near end cross talk
- > 30 db suppression far end cross talk
- Requires careful mechanical construction



Two twisted pair per quad

The Digital Optical Module





HV generator

HV PMT base

LED flasher board

main board

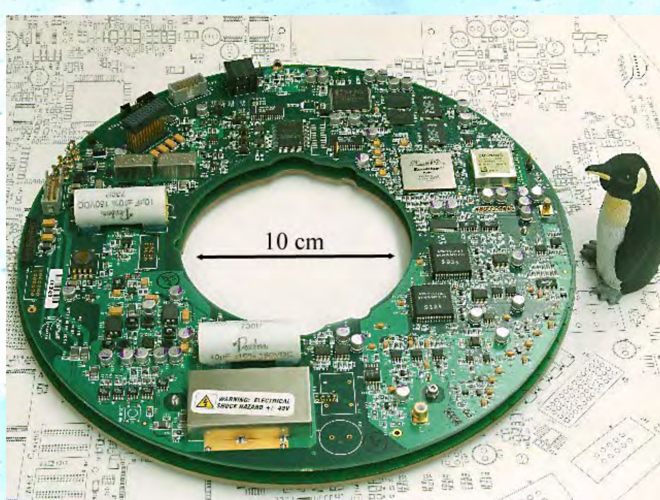
75 ns delay board

25 cm PMT

33 cm Benthosphere

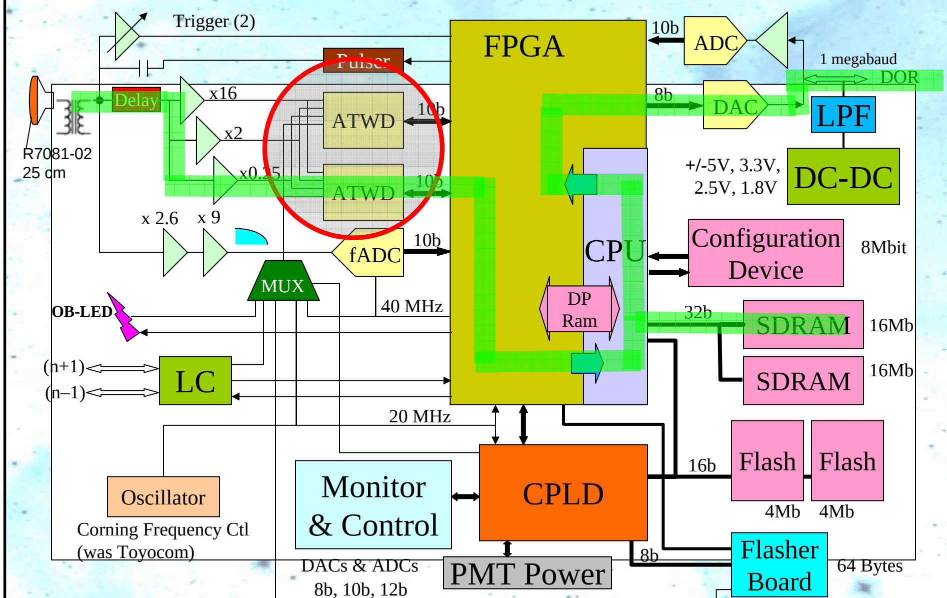
4W

The DOM - Mainboard



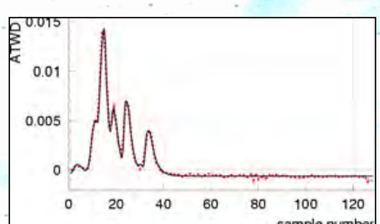
Mainboard design, fabrication and testing by Lawrence Berkeley National Laboratory

DOM MB Block diagram



The Analog Transient Waveform Digitizer

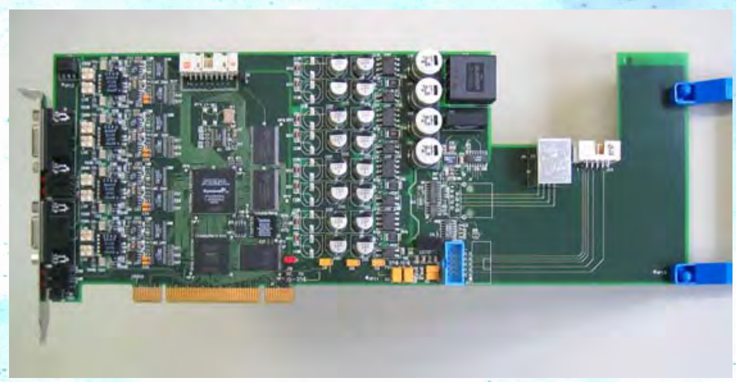
- Custom ASIC having high speed and low power consumption
- Switched capacitor array
- 4 channels x 128 samples deep, acquisition on launch
- Digitization: 10 bit, 30 µs /channel
- Variable sampling speed: 250 - 800 MHz
- Power consumption 125 mW
- Design - S. Kleinfelder ~1996 (also used in KamLAND, NESTOR



2 ATWD/DOM: 0.25 W

Digital Optical module Readout

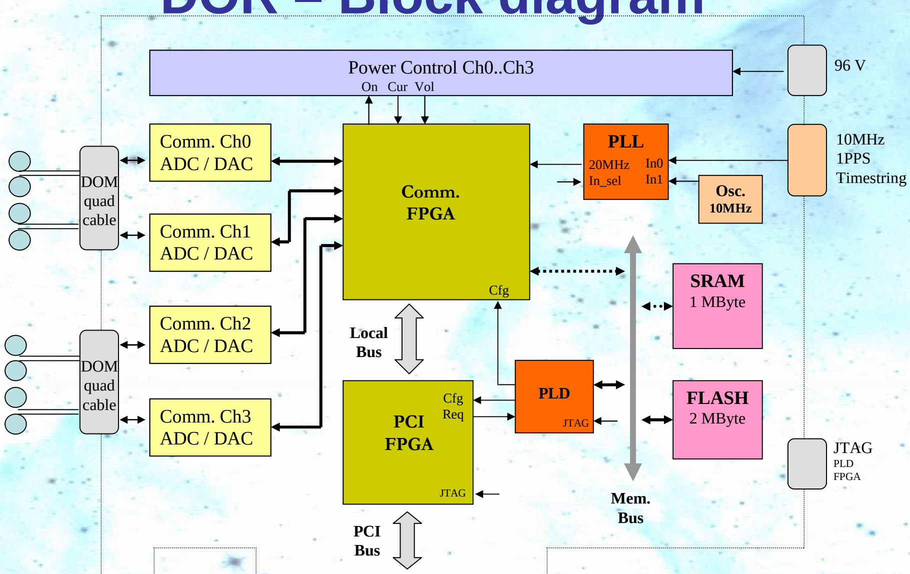
Surface front-end readout card



Readout Card design, fabrication, testing by DESY-Zeuthen

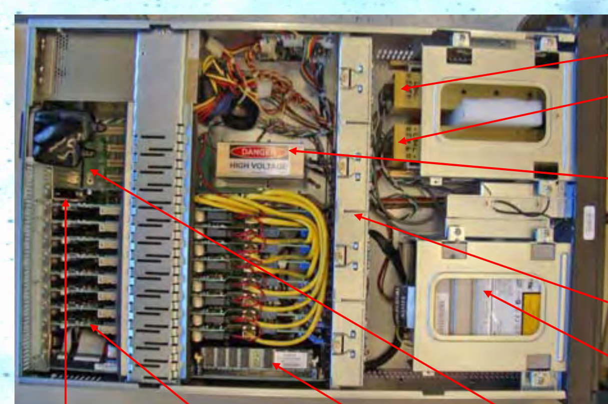
0.7 W/DOM

DOR – Block diagram



DOM Hub

services 1 String = 60 DOMs



DOM Power Supplies

Power Distr. Card

Chassis Fans

Hard Drive

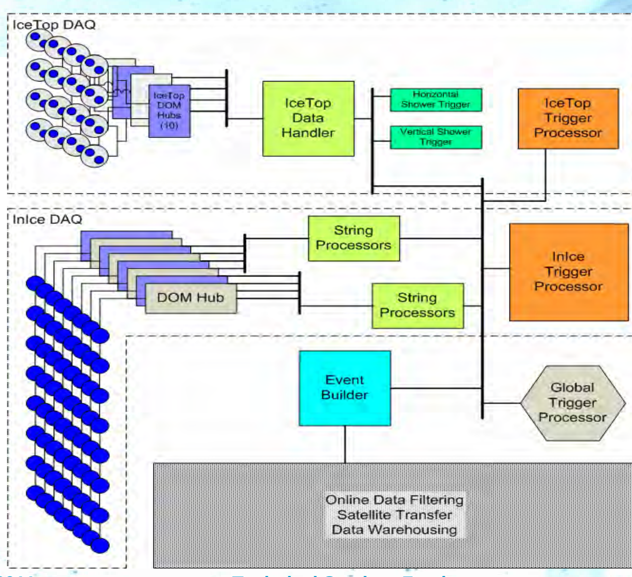
8 DOR Cards

CPU

GPS distr.

~300 W running 60 DOMs

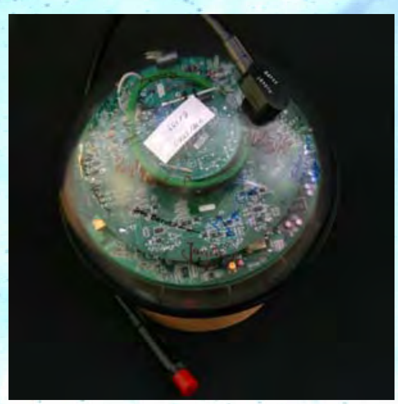
IceCube DAQ Block Diagram



DOM PRODUCTION at DESY

- Production of ~1200 Optical Modules from 2004 to 2008
- Production comprises:
- Gel mixing, filling and potting PMTs
- Collar mounting and assembly of electronics
- Sealing of DOMs at low pressure
- Harness DOM with suspension
- Finally pack DOMs and ship to the pole

1.3.2004 :
First DOM produced at DESY



1000^{th} DOM finished in March 2008

DOM TESTING

- Electronic and optical requirements
  - Reboot- and communication over a wide temperature range from +20°C to -45°C
  - Single photo electron detection
  - Wide dynamic signal range – capable to handle large light pulses with up to several 1000 photo electrons per microsecond
  - Time resolution better than 5ns for single photo electron pulses
  - High voltage calibration of the PMT better than 5%
  - Optical sensitivity within low variations for different DOMs
  - Dark noise rates less than 1kHz in ice
- Mechanical requirements
  - Vibration and pressure fluctuation during transport
  - Rapid temperature variations from +20°C to -45°C
  - Very high environment pressure up to 650 bar

TEST ENVIRONMENT SETUP

Dark Freezer Lab (DFL) with 64 test stations

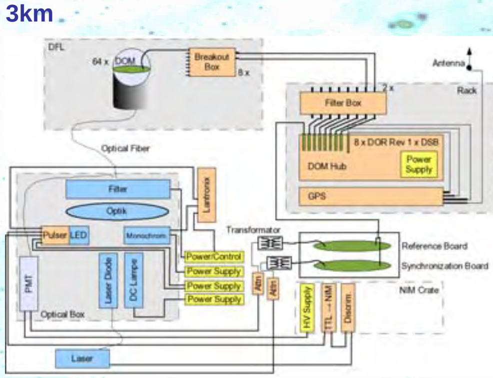
Same DAQ and wiring as for the South Pole system

Simulated cable length up to 3km

Light is distributed equally to the DOM stations via optical fibers

Time synchronization of multiple domhubs with a global GPS clock

Light system allows event simulation

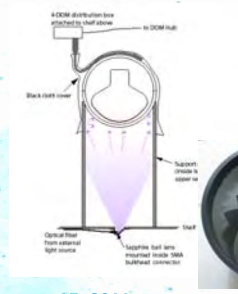


Different light sources:

- Laser for time calibration,
- pulsed LED for linearity test,
- DC lamp with monochromator for optical sensitivity test

DARK FREEZER LAB

- Large cooling chamber (4 x 6 x 2 m)
- Temperature control with cooling aggregate and heaters
- Minimal temperature for test cycle is -45°C (in the US -55°C for IceTop DOMs)
- Optical fibers and mirror system installed on each test station



DOMs sit on top of cylindric cans

Cans are taped with aluminum foil to distribute the light

DOMs are covered with black plastic bags to keep them as dark as possible
for the measurements

DOM FINAL ACCEPTANCE TEST

A full set of different tests is performed for defined temperatures

Test of the electronics (mainly running diagnostic programs, checking the hardware components)

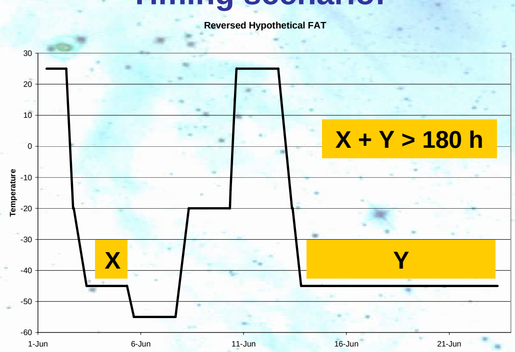
PMT high voltage calibration

Rate monitoring while DOMs are illuminated with light of different wavelength

Dark rate monitoring

Data taking with a DAQ system similar to the final low level south pole DAQ (Linearity and time resolution tests)

Timing scenario:



DOM - Passport

Decision June 2005:

use formalized
DOM-passport
for characterization
and qualification of
DOM's
(ready early 2006)

DESY DOM-Production 2004-2008

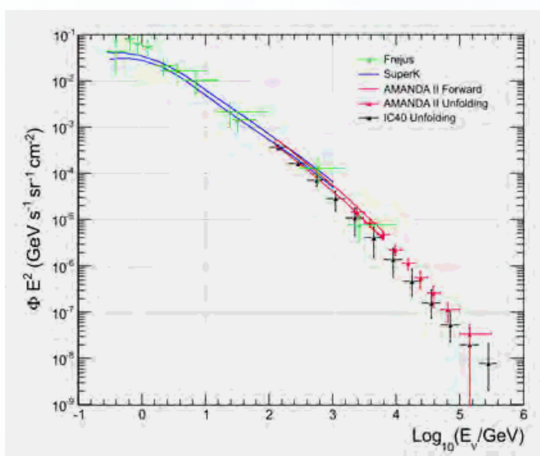
Year	DOMs produced	DOMs ok	ε_{final}	DOMs shipped
2004	60	45	0.75	28
2005	160	159	0.99	160
2006	257	255	0.99	224
2007	480	477	0.99	480
2008	233	232	0.99	276
$\sum$	1190	1168	0.98	1168

only ~1% of DOMs are cannibalized – goal was 5% or better
good components are used in next years production

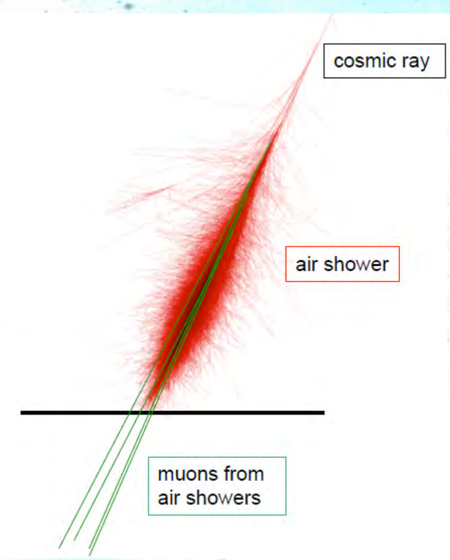
Early IceCube Results (a few examples)

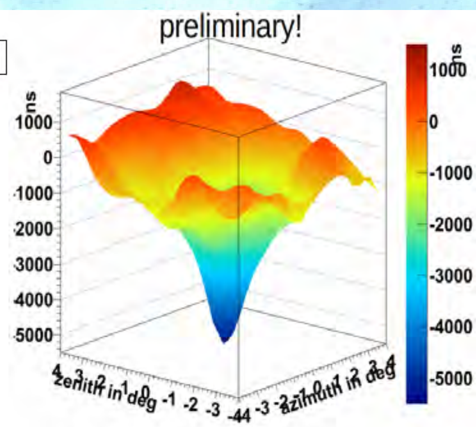
Atmospheric Neutrinos

- IC-40
- ~18000 ν_μ CC events
- θ= 180°-97°
- Compatible with Bartol/Honda predictions
- Close to constrain estimates for prompt neutrinos



Muon astronomy I



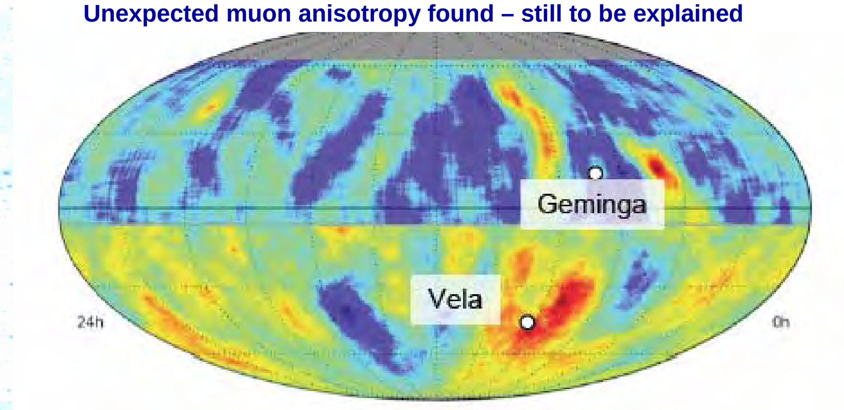


Shadow of the moon:

it works!

Muon astronomy II

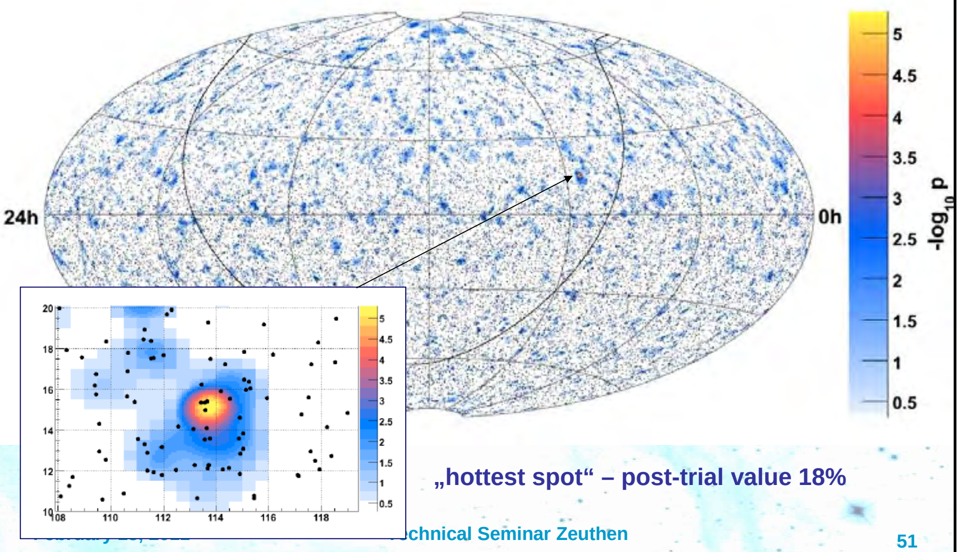
Unexpected muon anisotropy found – still to be explained



Energy range: 10-100 TeV scale
Protons in excess of 20 TeV have gyro radius < 0.1 pc.
Vela (strongest gamma source) is 300 pc away.

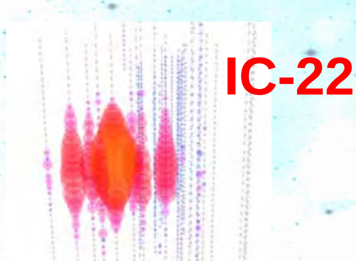
IC-40 sky map

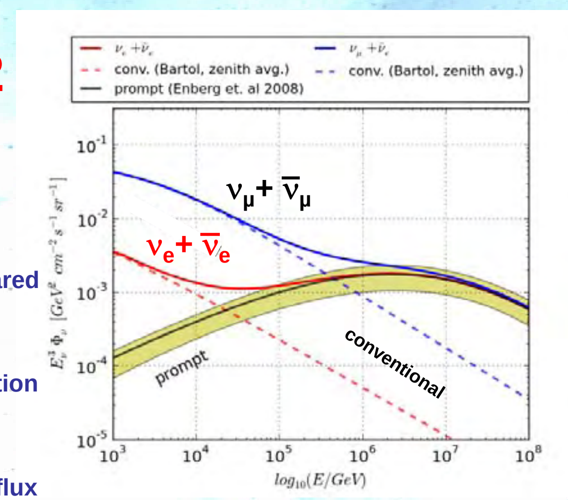
Live time 375 days, 14121 upgoing events, 22779 downgoing events



„hottest spot" – post-trial value 18%

Cascades in IceCube

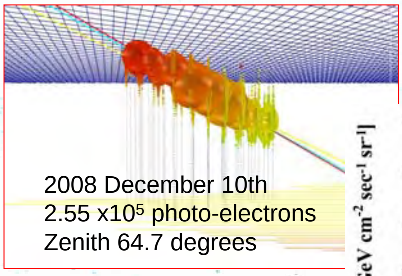


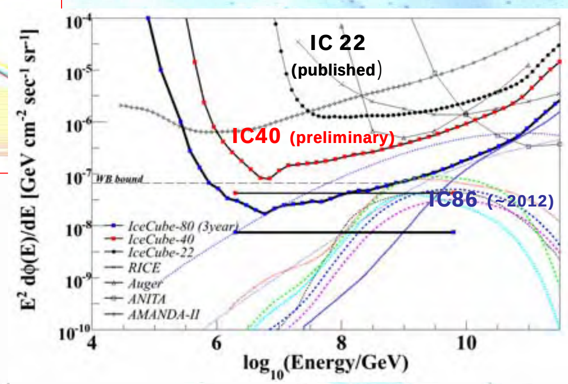


- IC-40: dramatic step compared to Amanda and IC-22 w.r.t. cascade identification
- Expect first clear identification of cascades from atm. neutrinos and spectrum
- Sensitivity to extraterr. E^{-2} flux ~10^{-7} E^2 cm^{-2} s^{-1} sr^{-1}

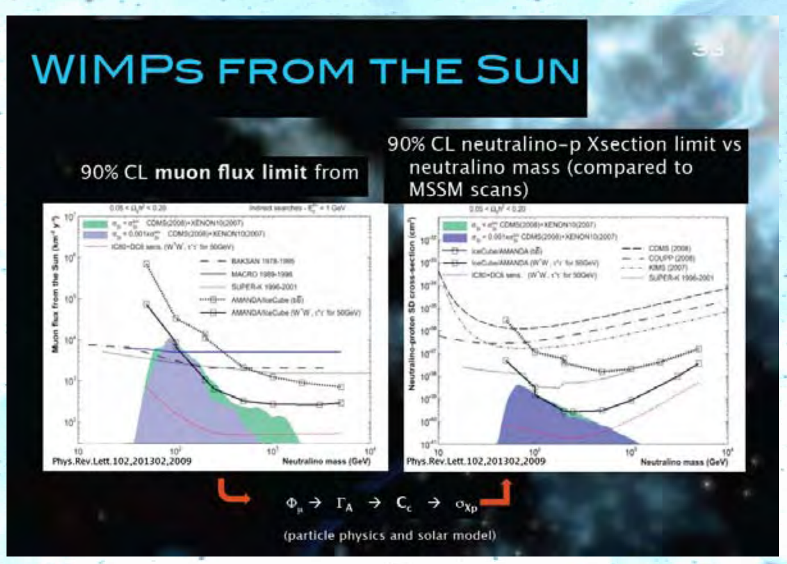
Ultra-High Energy Events

Look for extremely bright events from close to or above horizon IC-22 (2007/08, 242 days)



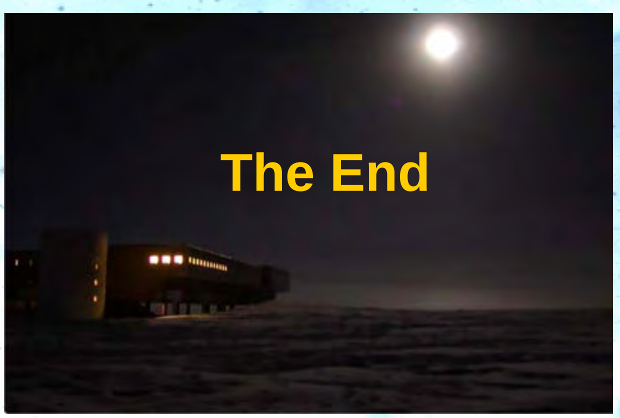


Indirect Dark Matter Search



Summary

- IceCube is now completed
- It has excellent operational performance
- Many results using half of the final detector size are published or close to publication
- Hope for cosmic neutrino signals until 2012 ...
- IC+DC promizes lot of interesting particle physics results



Acknowledgement:
I profited a lot by using material form talks given by A.Karle, G. Meyer, E. Resconi, C, Spiering, R. Stockstadt and K. Sulanke and discussions with my IceCube colleagues