Detecting high energetic cosmic neutrinos

- The IceCube Experiment -

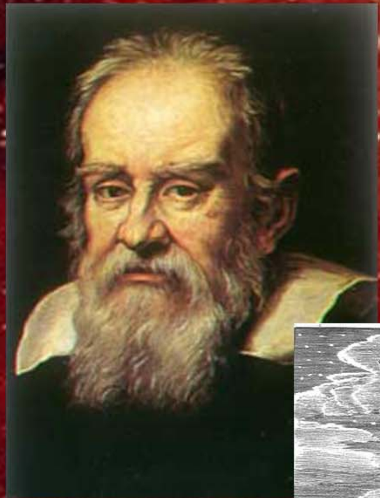
Rolf Nahnhauer

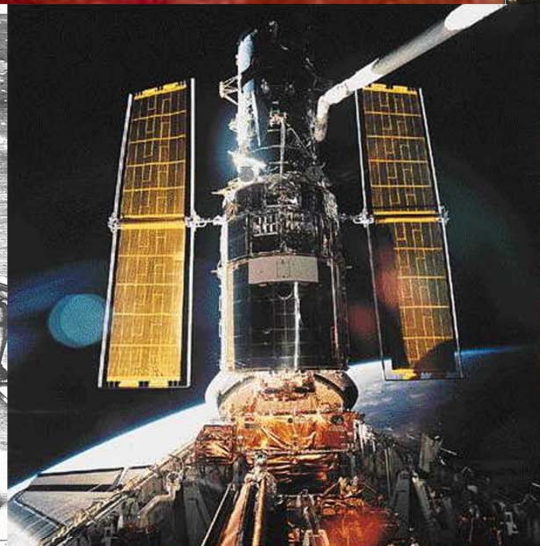
DESY Zeuthen

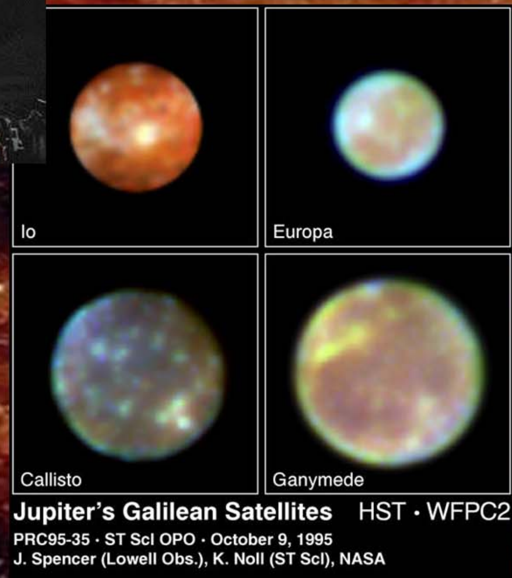
How do we get our information about the universe ?

Light - See - Think

From Galilei to HST







New Windows for „Invisible“ Light

Arecibo (Radio)

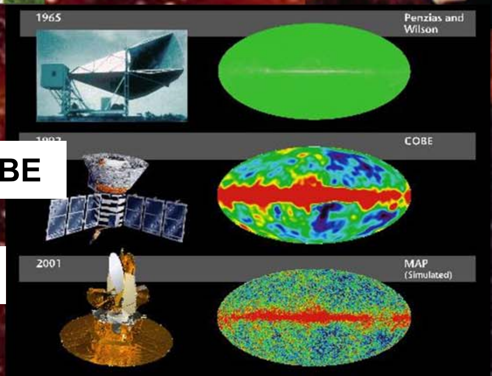
Spitzer (IR)

Suzaku (X-rays)

VERITAS (Gamma-rays)

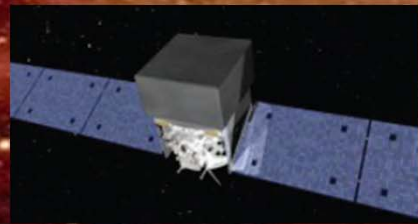
COBE

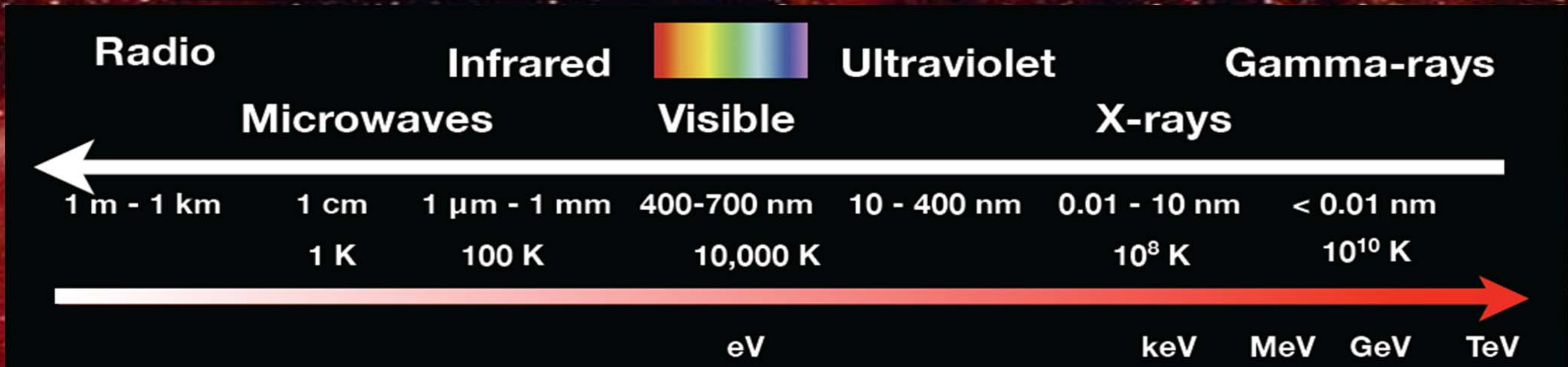
WMAP



VLT (Optical)

Fermi (Gamma-rays)





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

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

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

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

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

σ : cross section

N_{TD} : particles in detector

Φ_{ν} : neutrino flux

N_{av} : Avogadros-number

ρ : density

λ_I : interaction length

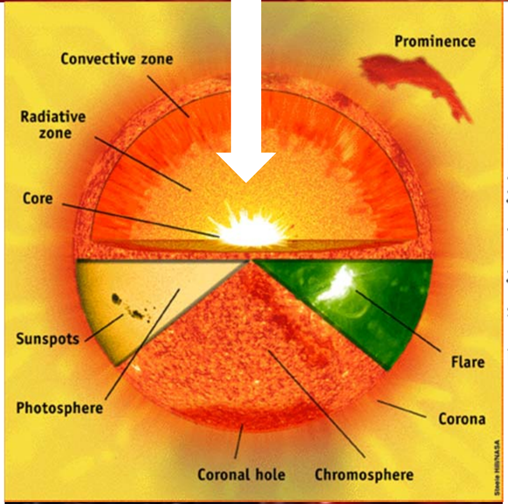
S=Sun, D=Earth : $\lambda_I = 1.9 \cdot 10^{13}$ km ≅ 2 light years ≅ 1.6 billion Earth-balls

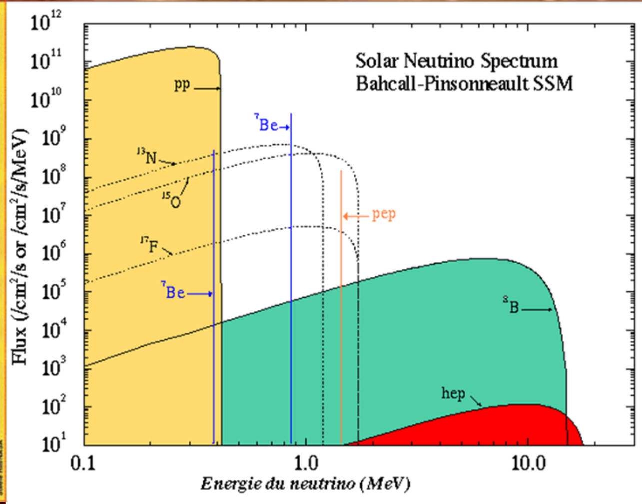
ννννννννννννννννννννννννννννννννννννννννννννννννννννννννννννννννννν➔

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	$\rightarrow$	$^8Be^* + e^+ + \nu_e$	
$^8Be^*$	$\rightarrow$	$2\,{^4He}$	

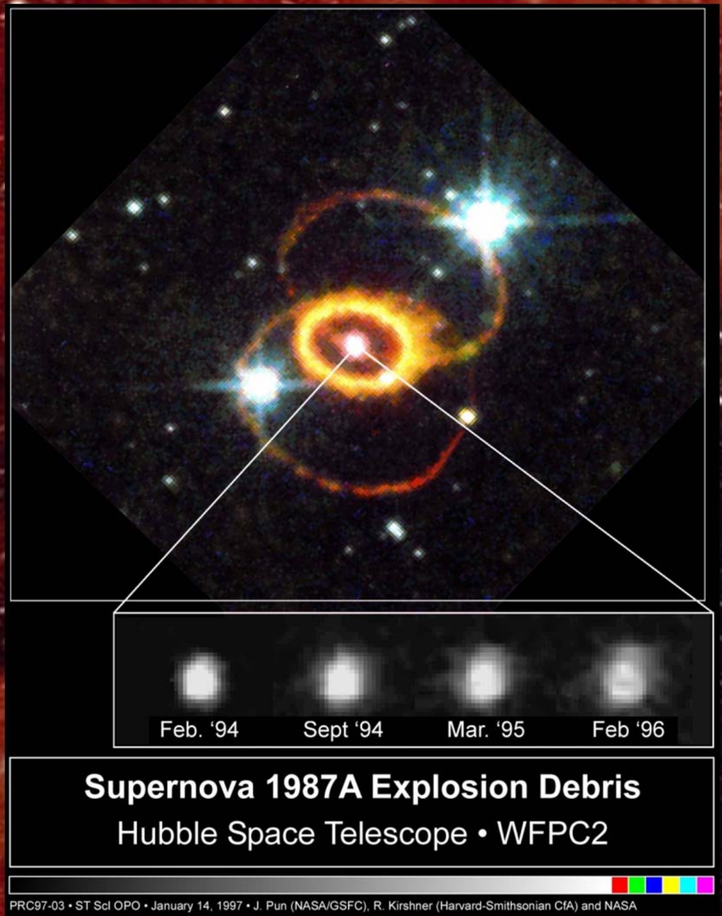




Produced: $2{*}10^{38}$ ν's/sec

Arriving after ~ 7.5 min at the earth surface : $40{*}10^{9}$ ν's/cm²sec

The Supernova 1987A :



Optical observation :

23.2.1987 10:37

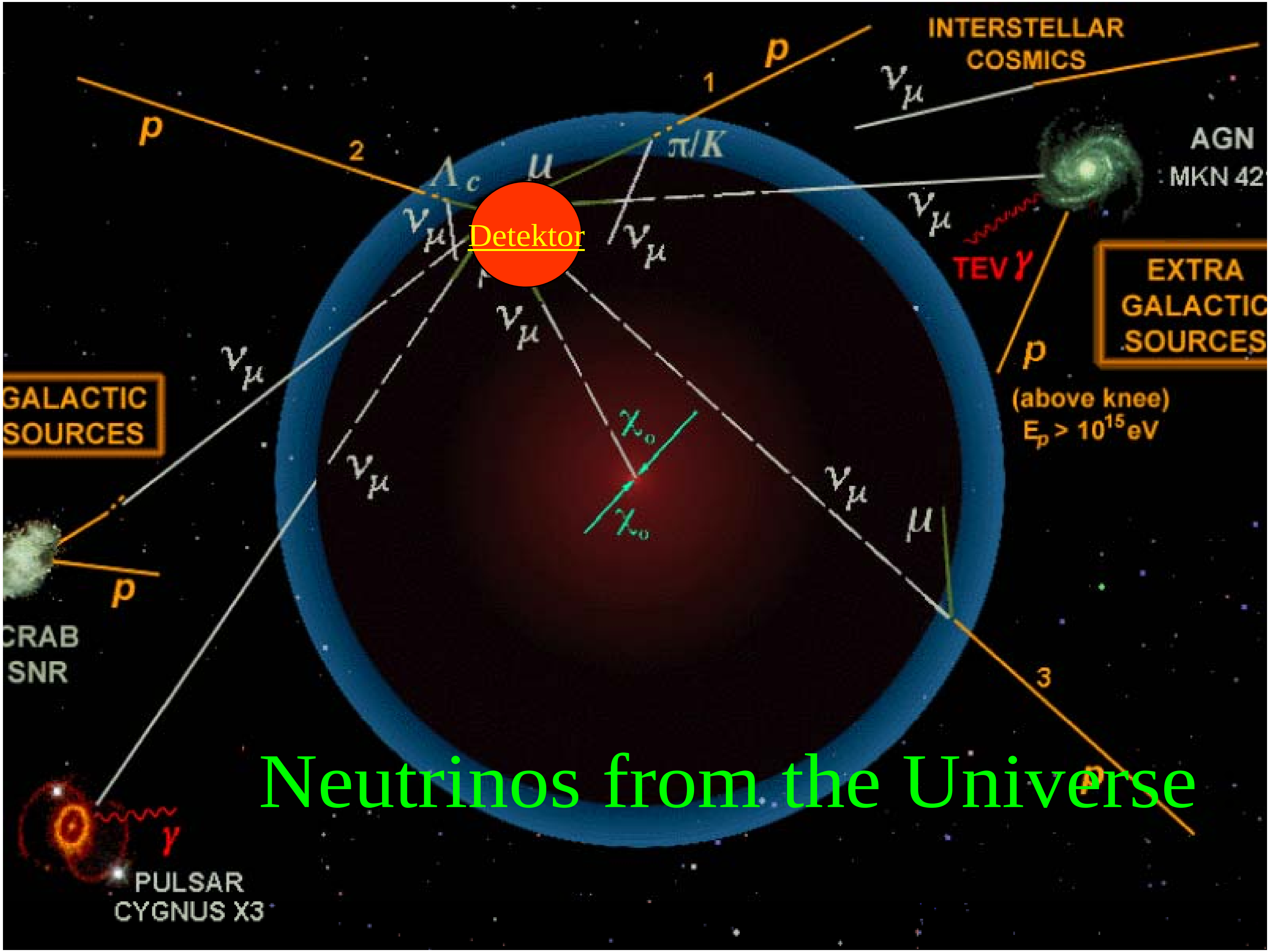
Australia

Neutrino observation

23.2.1987 7:25 + ...

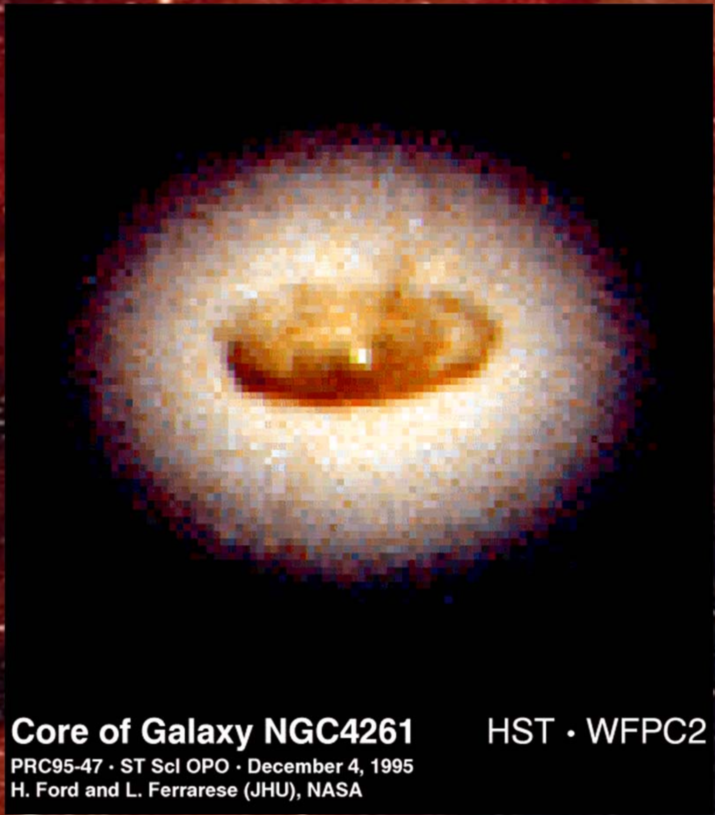
KAMIOKANDE, IMB, BAKSAN, Mt.BLANC

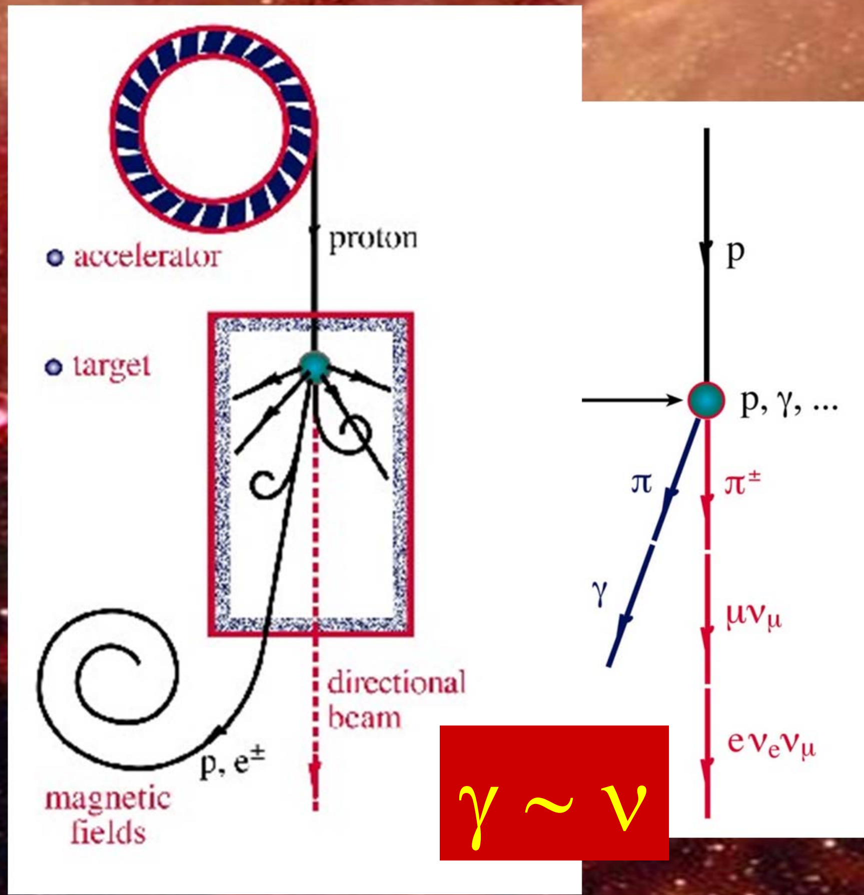
~ 25 events



Neutrinos from the Universe

Cosmic Particle Accelerators





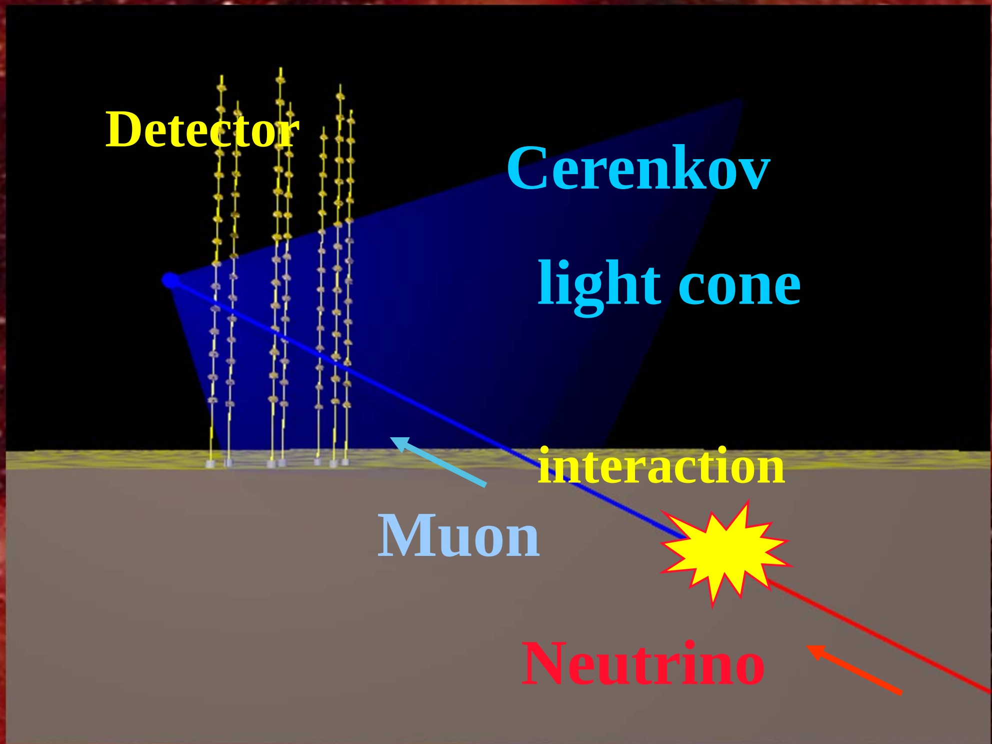
- **Only a few events per km^2 per year**
- **Need giantic telescopes**

Cherenkov Neutrino Telescope Projects

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

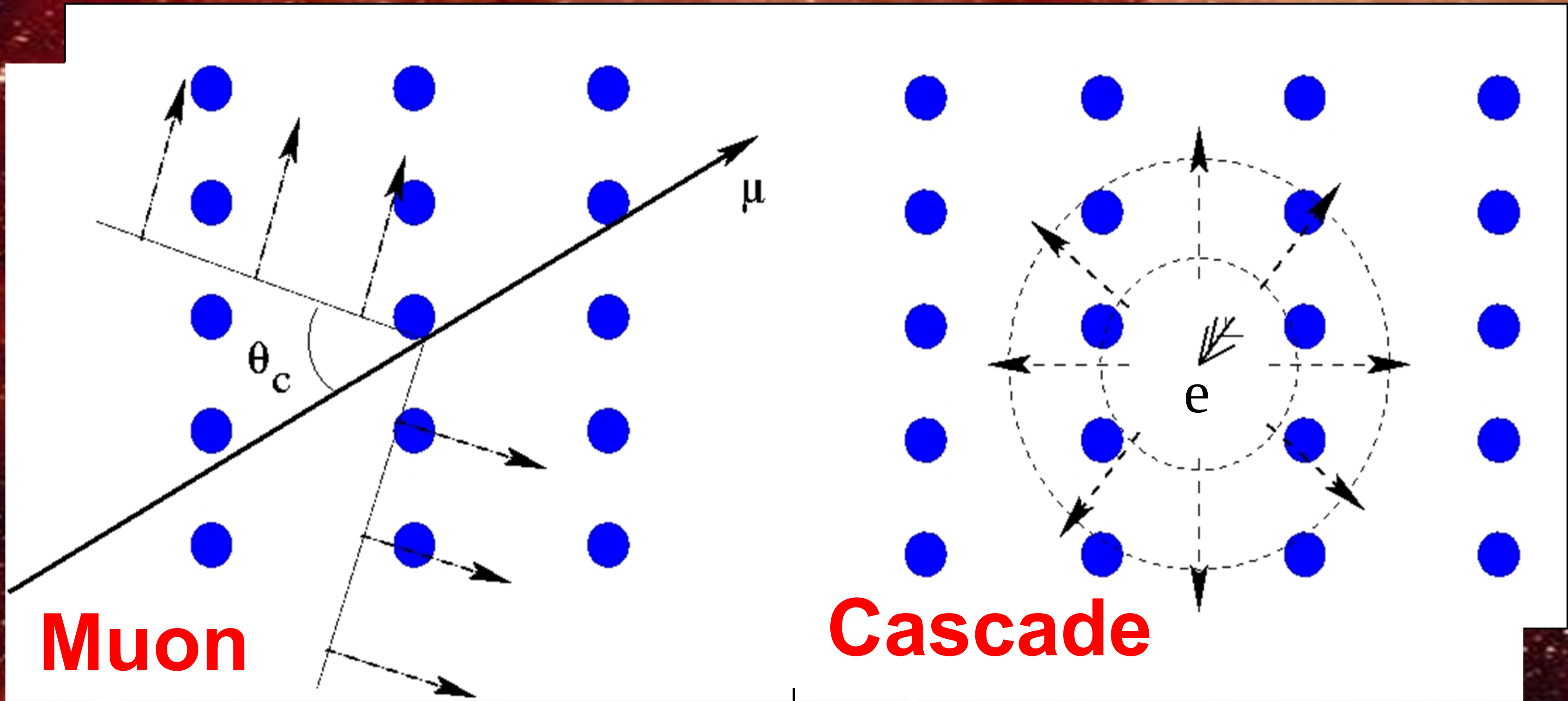
absorption length large:

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

scattering length small:

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

Detector Signals



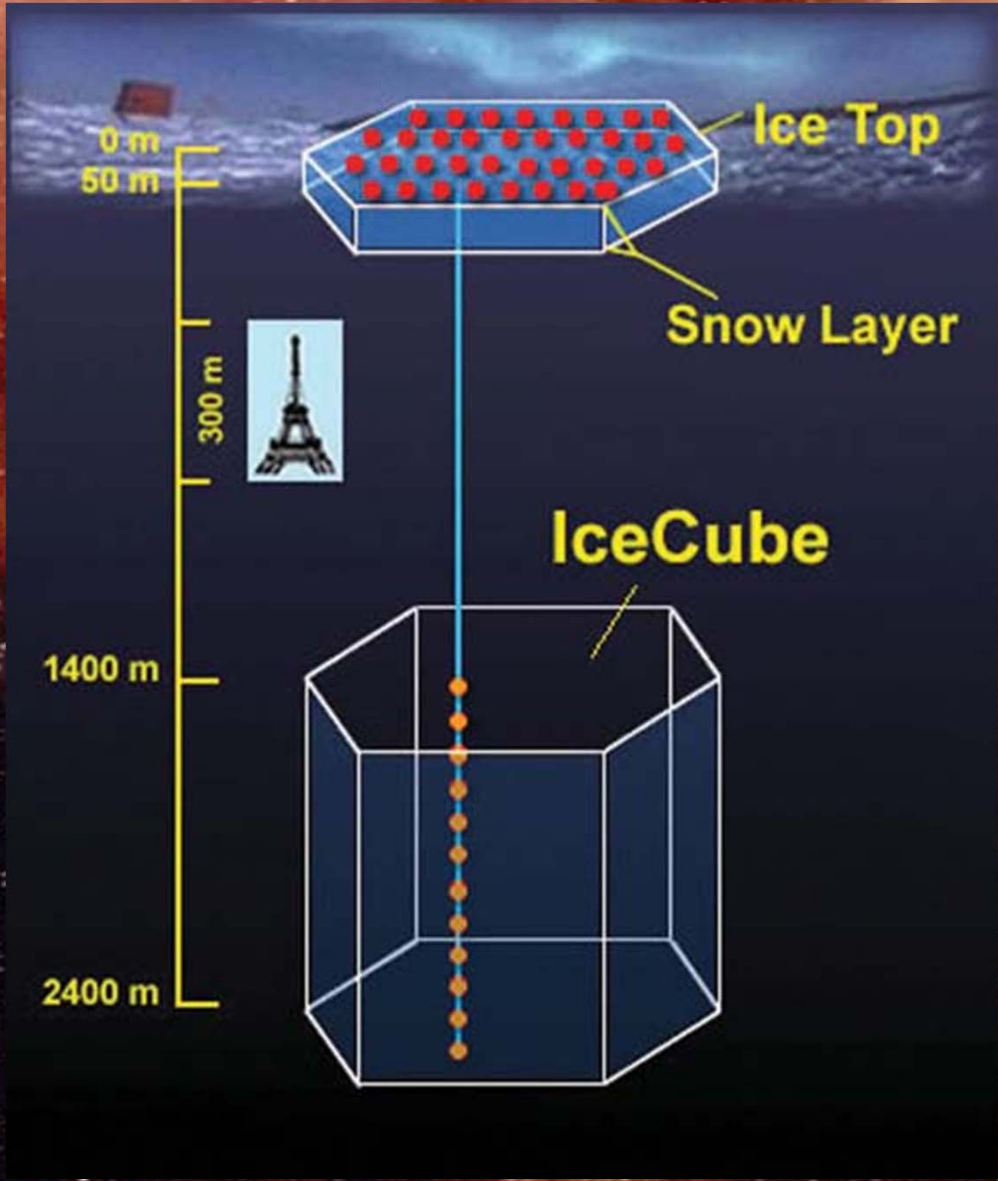
information: which photosensors see how much light at which time ?

reconstruction: type, direction, energy of event

The largest detector today: IceCube

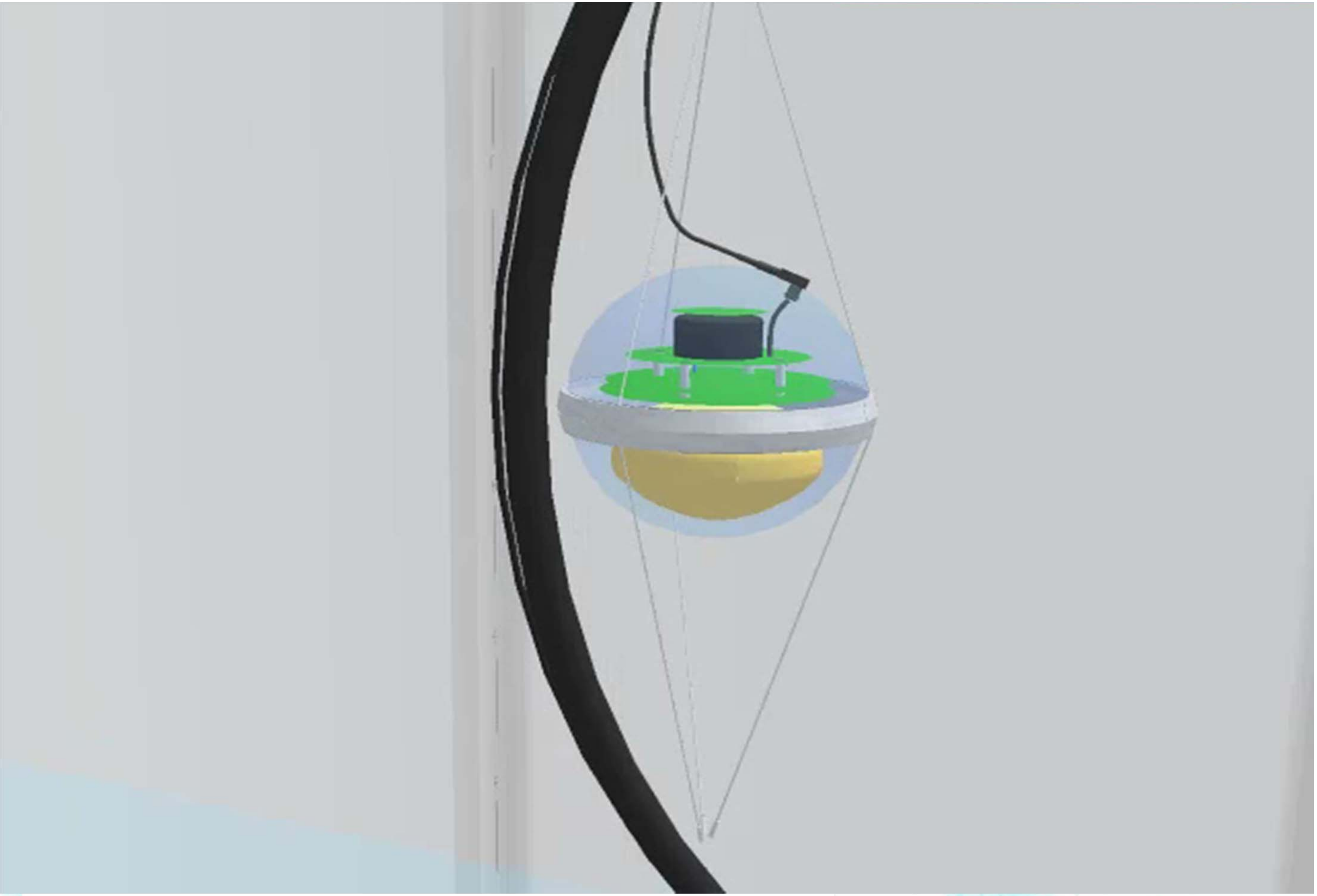
- 86 Strings } end 2010
- 5120 PMT } end 2010
- Instrumented volume: 1 km^3
- Installation: 2004-2010

~ 80.000 atm.ν per year



the IceCube Collaboration

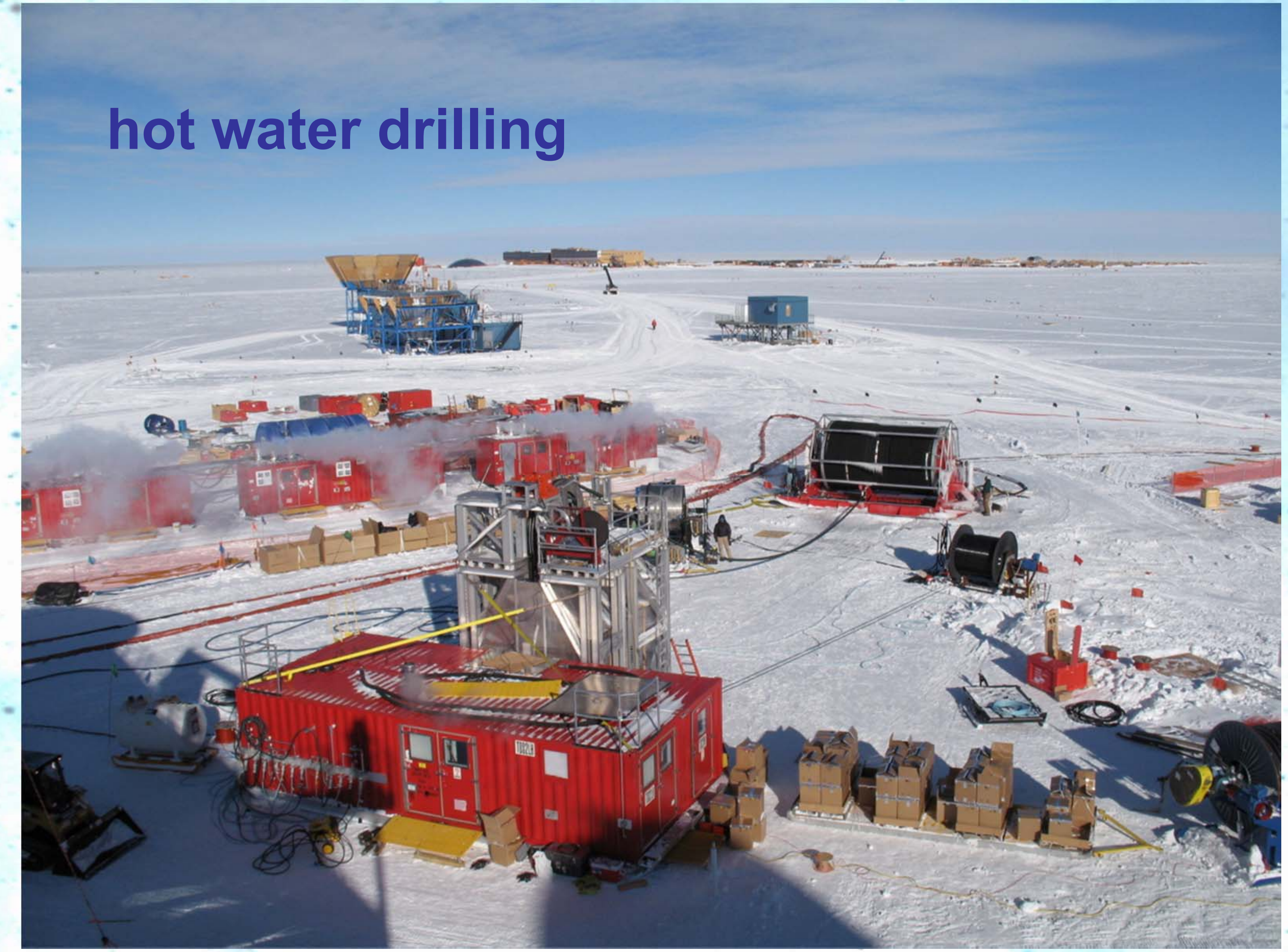
34 institutions in 4 continents

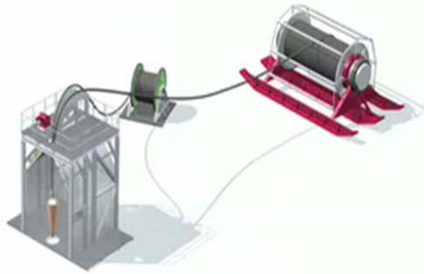


Schedule & Logistics

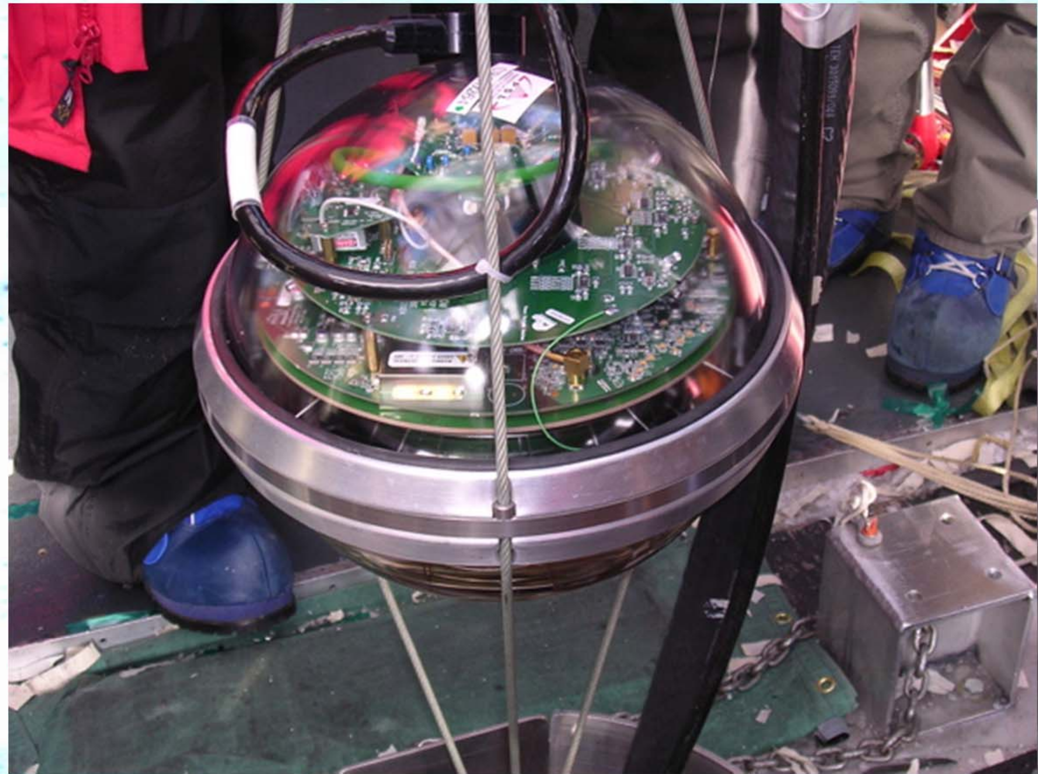
- Can work November → mid-February
- New South Pole Station
- Logistics - icebreakers, planes on skies,
  - planes only from McMurdo to Pole

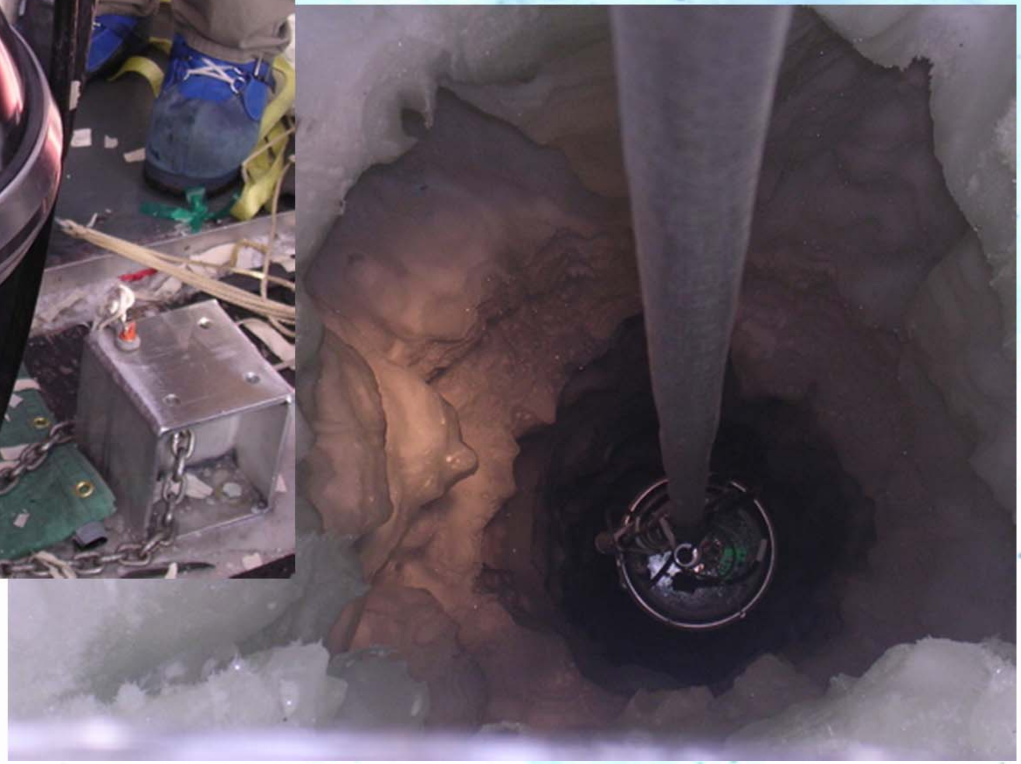
IceCube Drilling and Deployment





First string installation





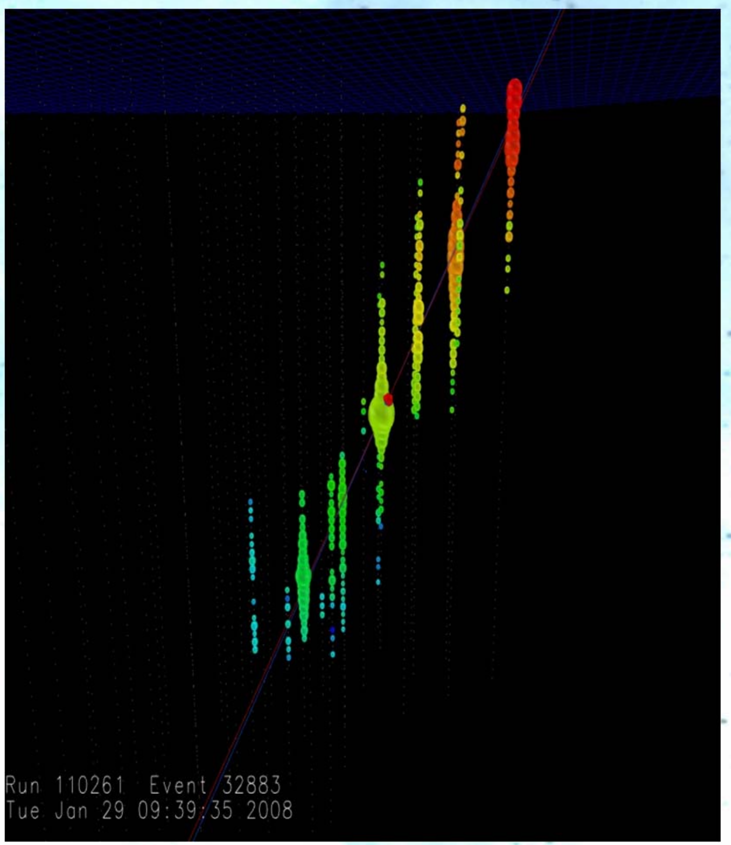
IceCube Laboratory

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

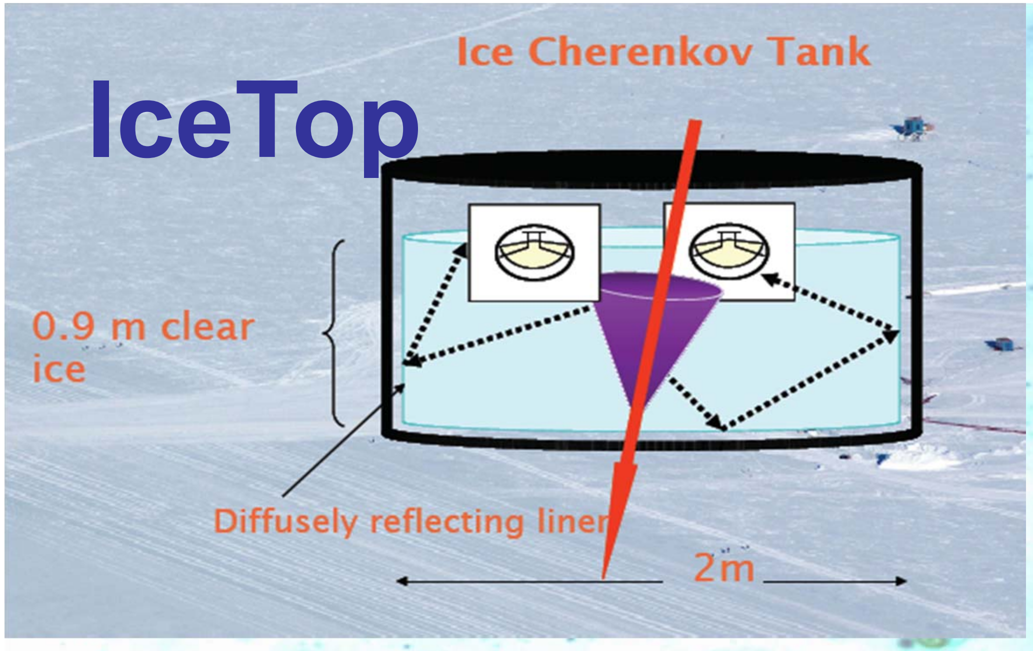
IceCube Events

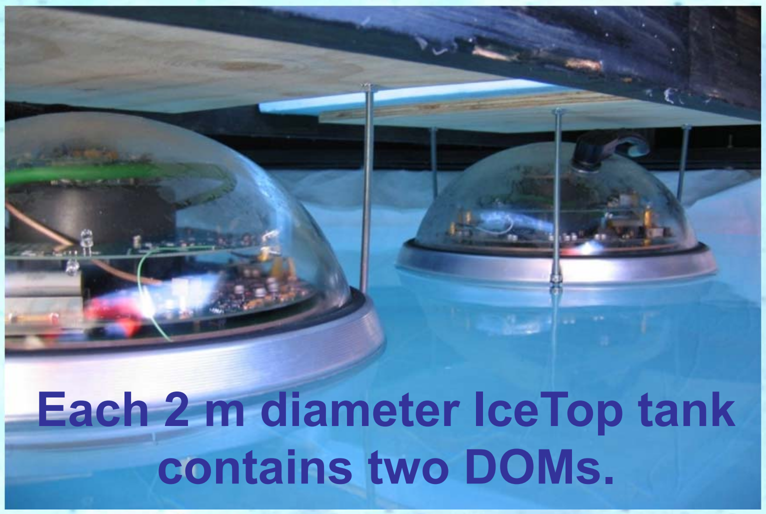
Neutrino Simulation

Neutrino Event

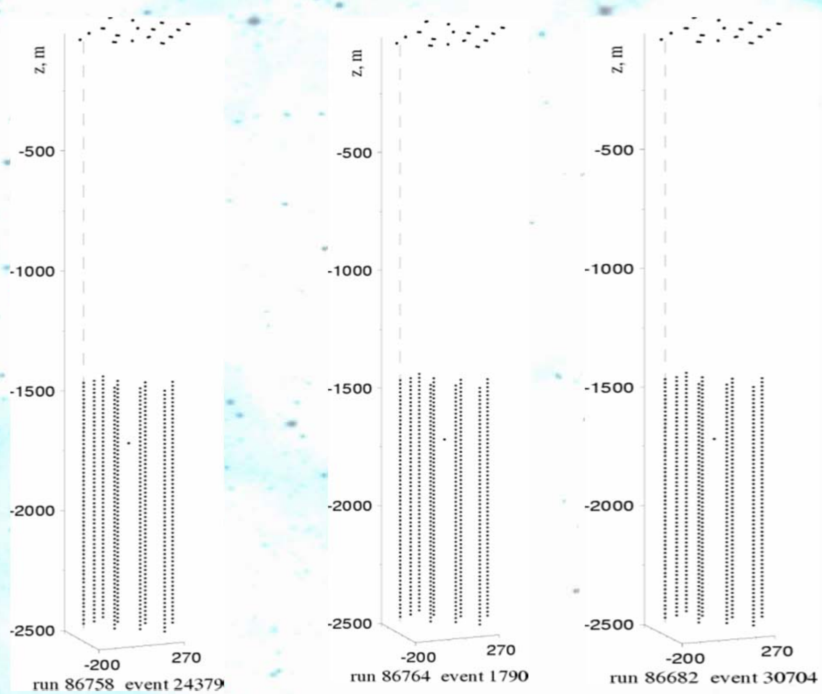


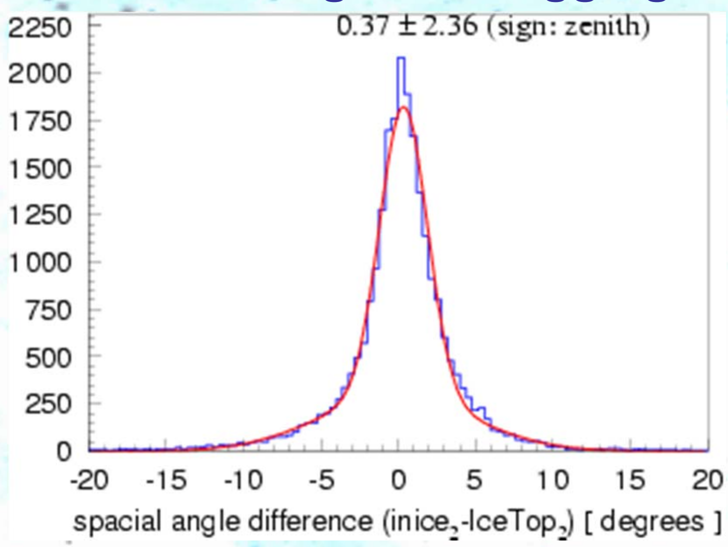
IceTop





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

- <u>Quality data</u>, 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

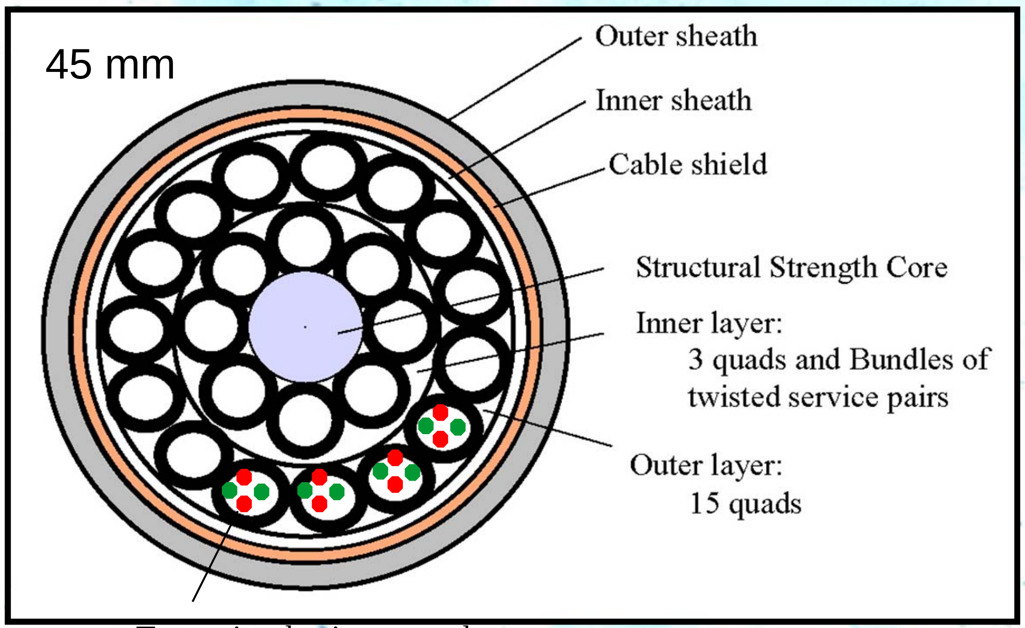
‘Environmental’ Requirements

- 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

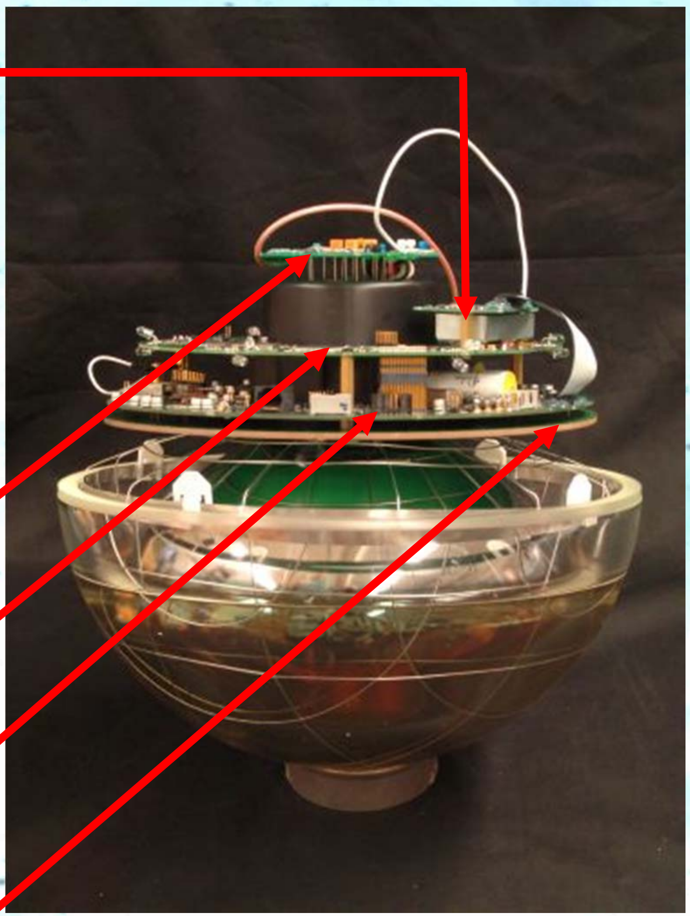
- > 50 db suppression near end cross talk
- > 30 db suppression far end cross talk
- Requires careful mechanical construction



Two twisted pair per quad

The Digital Optical Module

HV generator



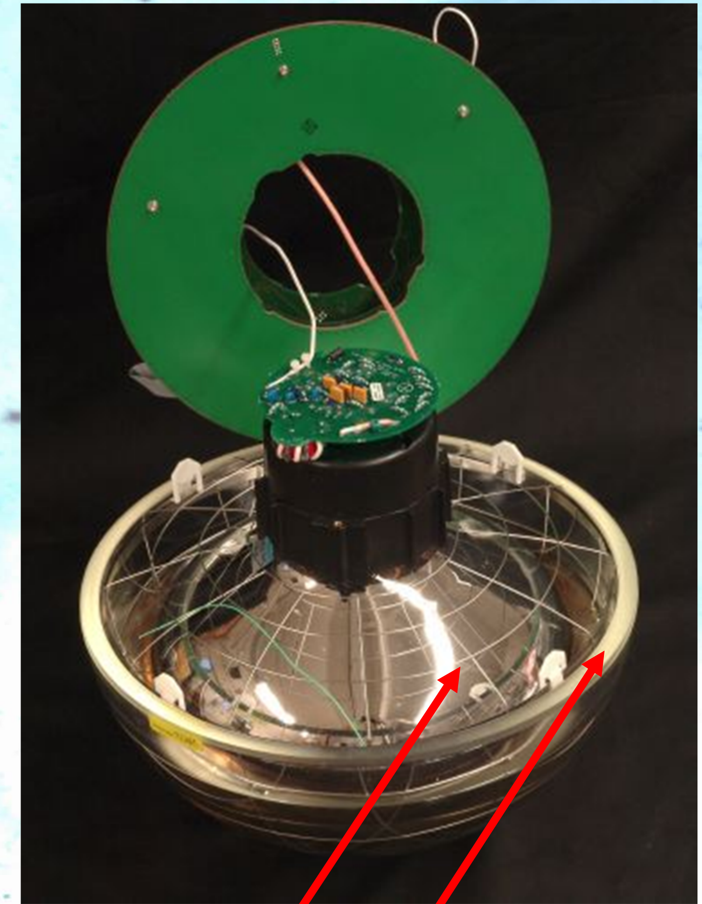
HV PMT base

LED
flasher

board

main board

75 ns delay board

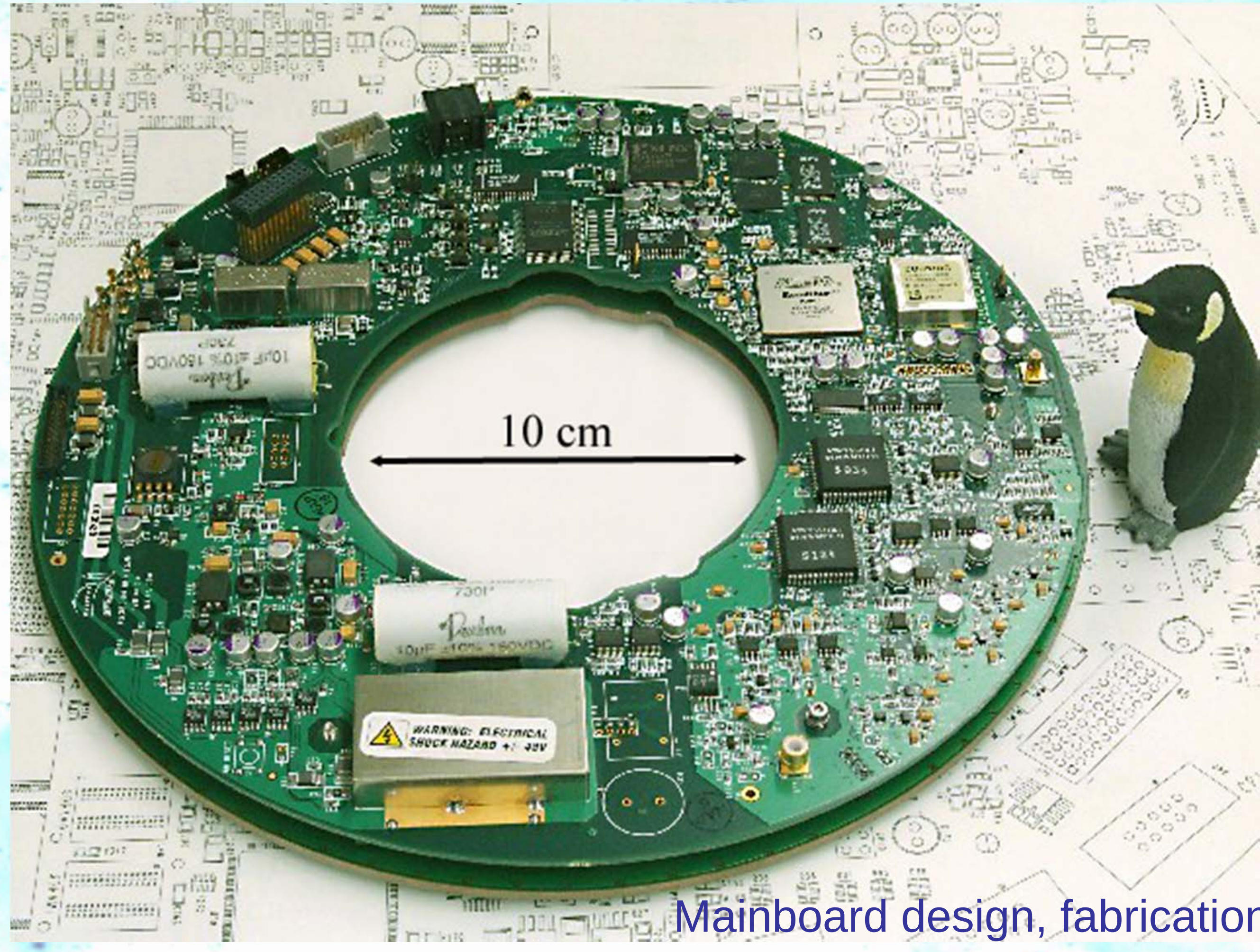


25 cm PMT

33 cm Benthosphere

4W

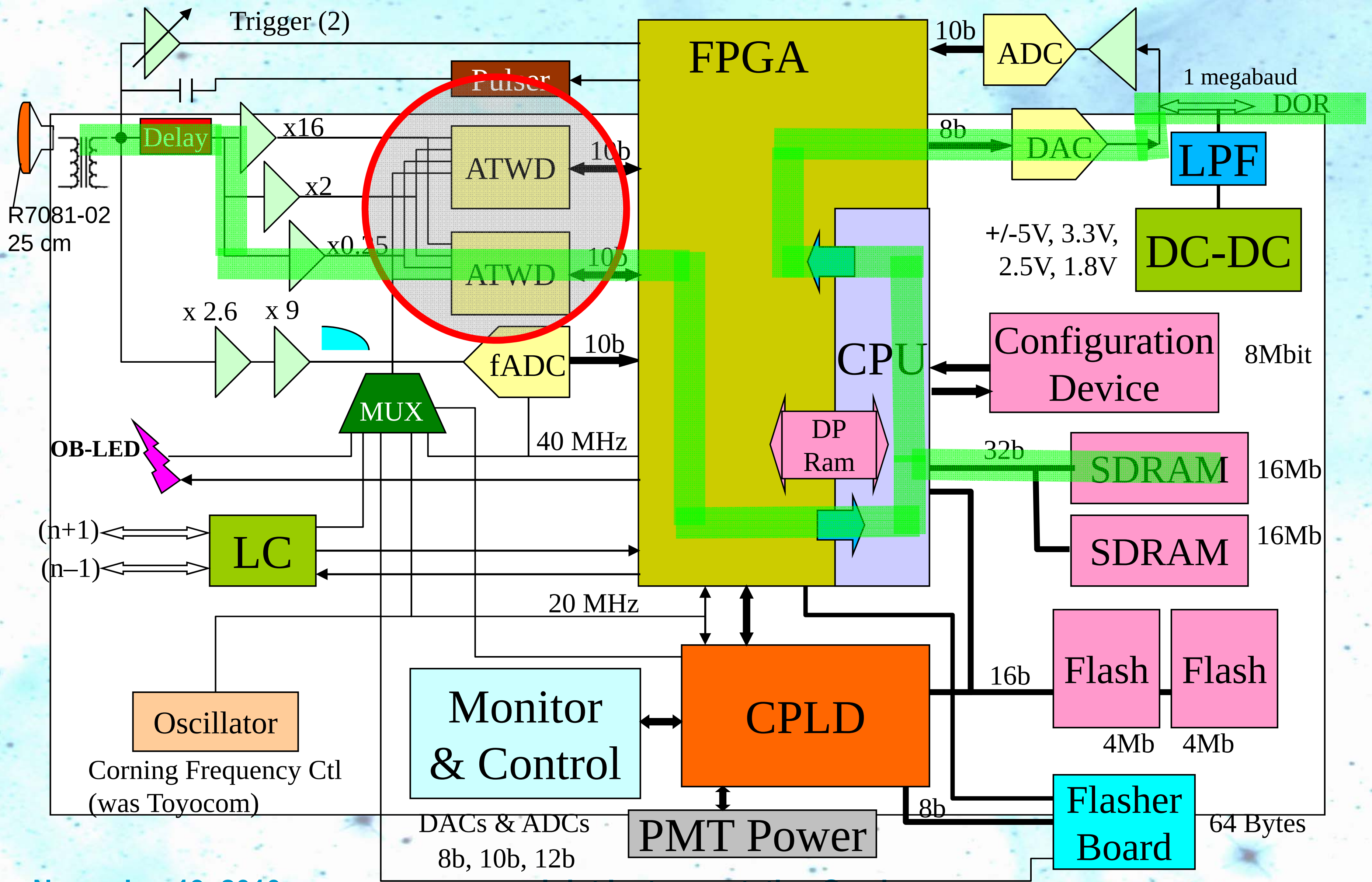
The DOM - Mainboard



Mainboard design, fabrication and testing by

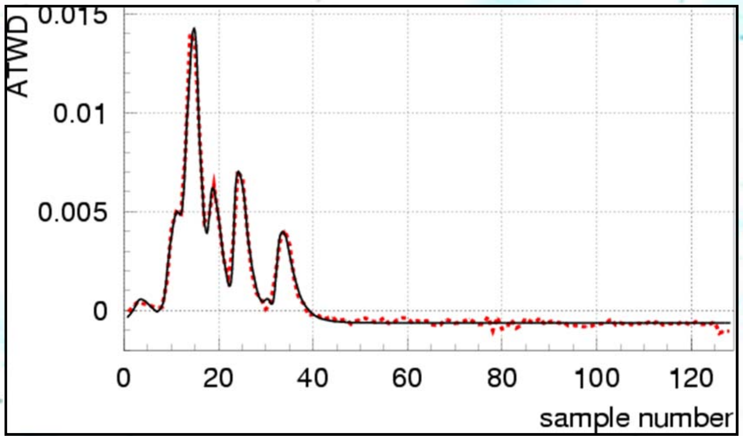
Lawrence Berkeley National Laboratory

DOM MB Block diagram



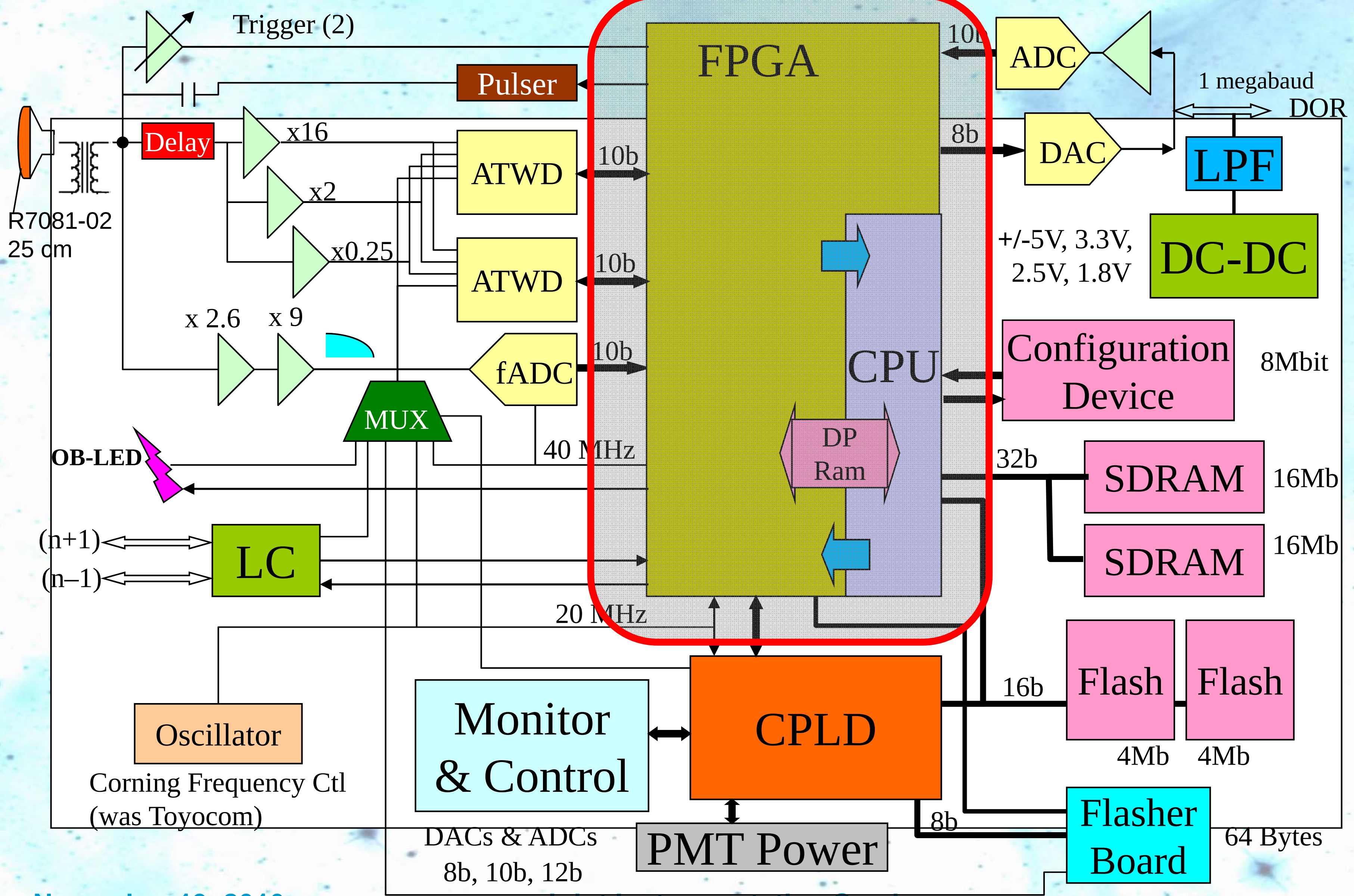
The Analog Transient Waveform Digitizer

- 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



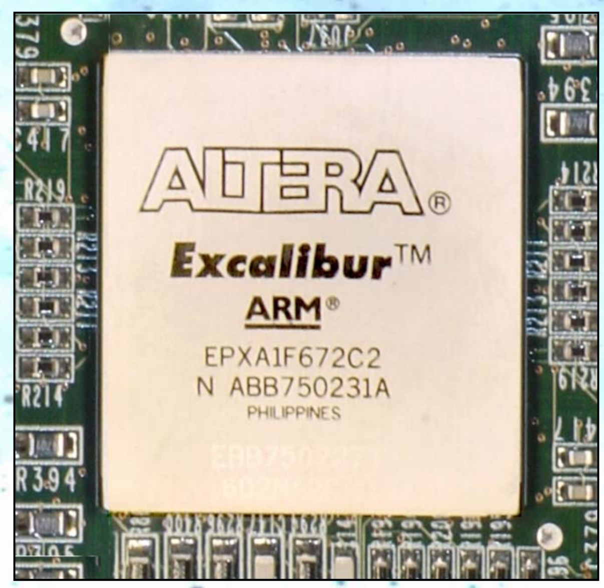
2 ATWD/DOM: 0.25 W

DOM MB Block diagram



FPGA + CPU

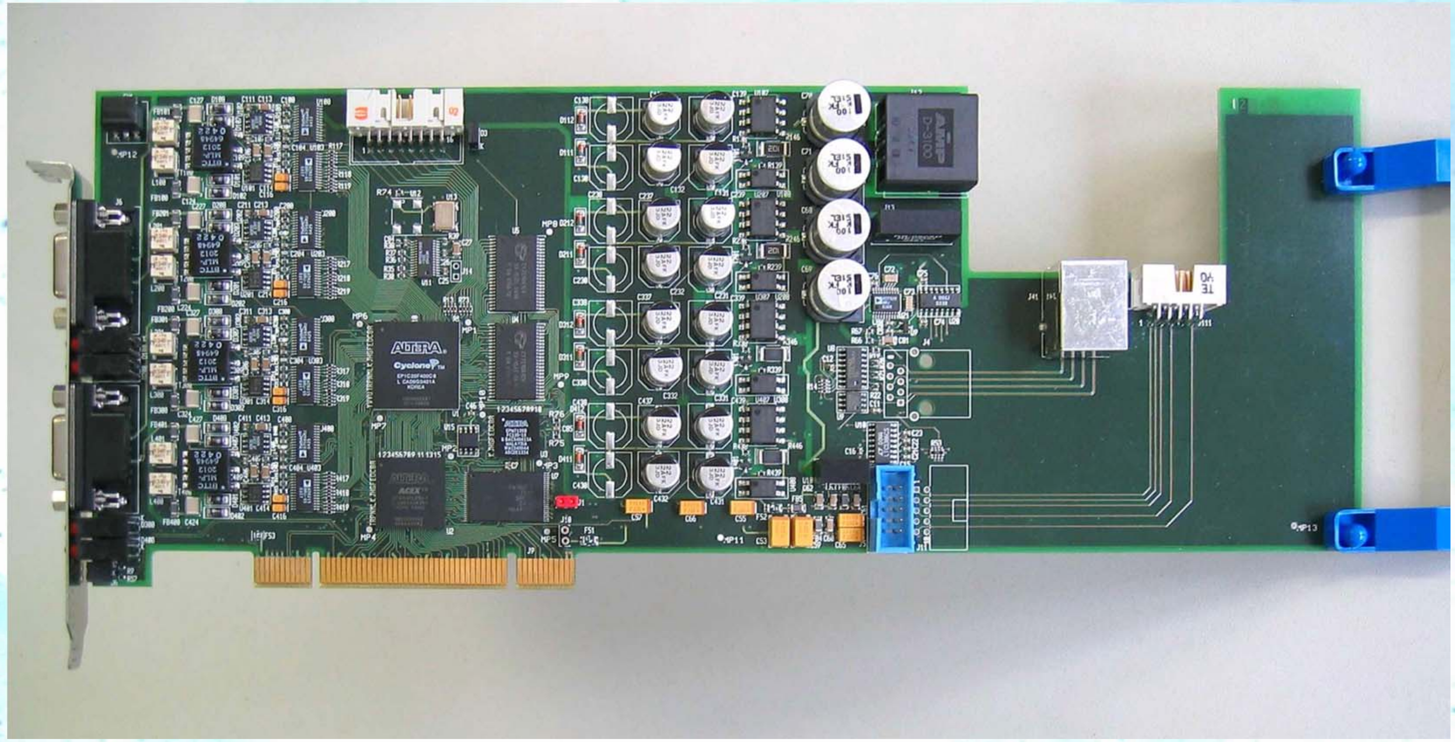
- Altera EPXA 4
- System On a Programmable Chip
  - FPGA
    - 400,000 gates
    - 20, 40 MHz
  - CPU
    - ARM922T 32-bit processor
    - Single Port SRAM 128 Kbytes
    - Dual Port SRAM 64 Kbytes
    - 80 MHz
- Power consumption 0.5 - 0.7 W



Supports: control, communications, ATWD readout, data compression, calibration, …..

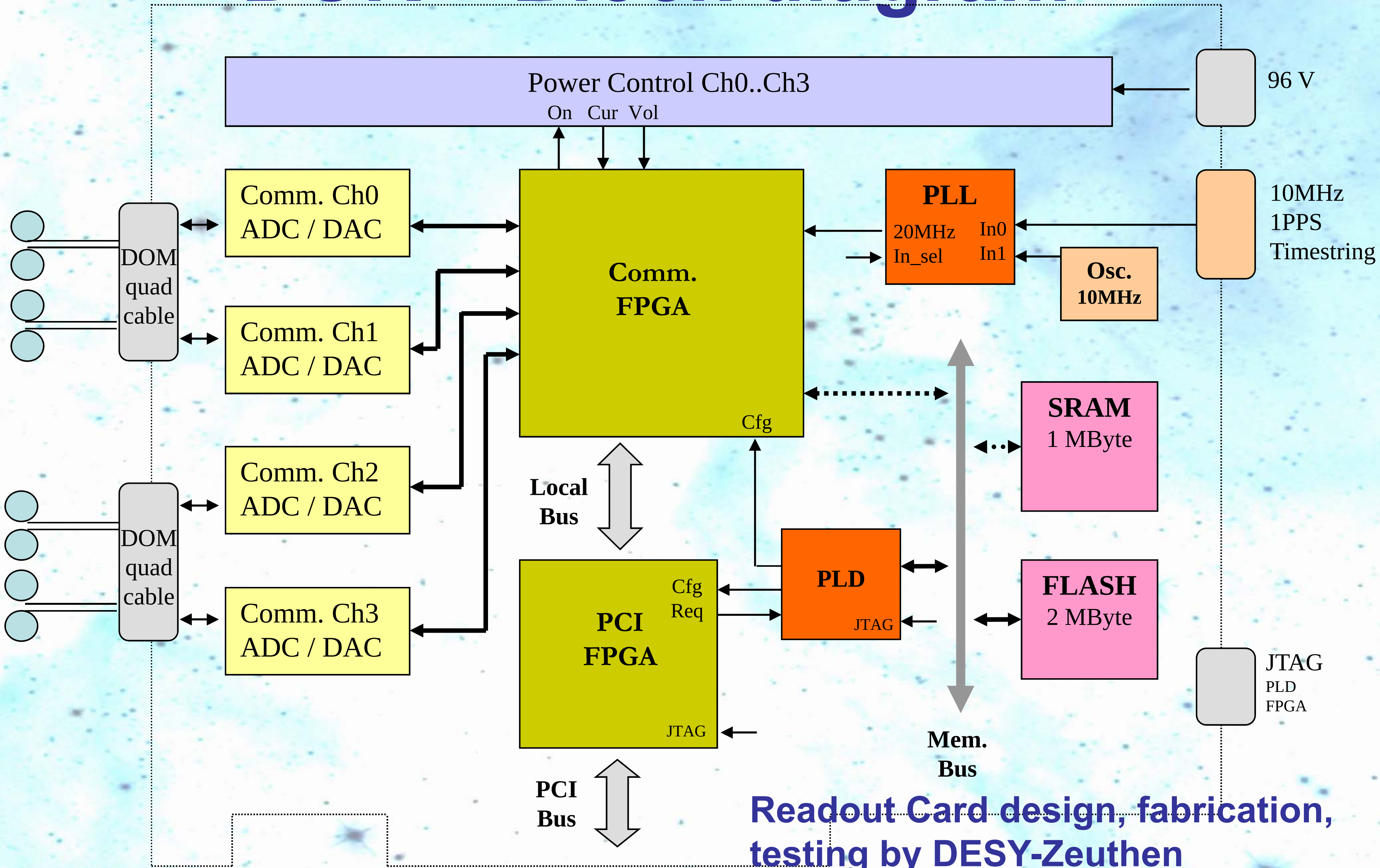
Digital Optical module Readout

Surface front-end readout card



0.7 W/DOM

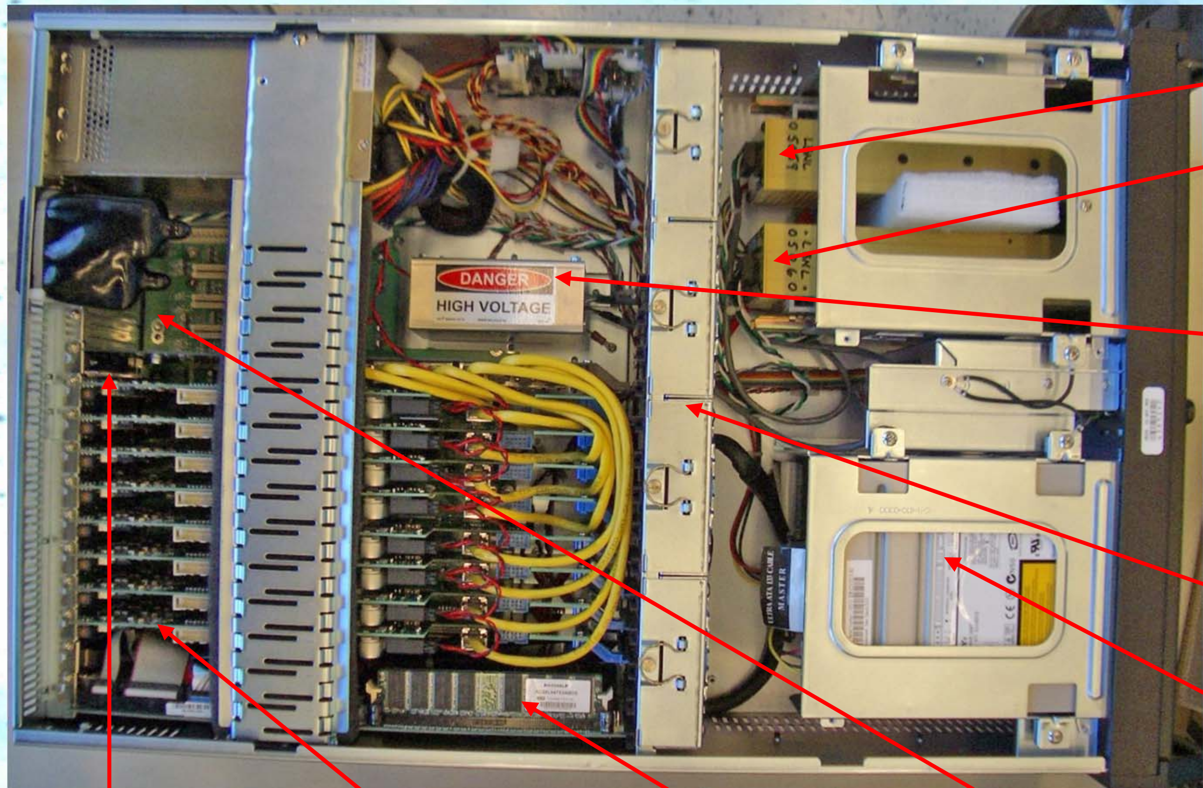
DOR – Block diagram



Readout Card design, fabrication, testing by DESY-Zeuthen

DOM Hub

services 1 String = 60 DOMs



DOM Power Supplies

Power Distr. Card

Chassis Fans

Hard Drive

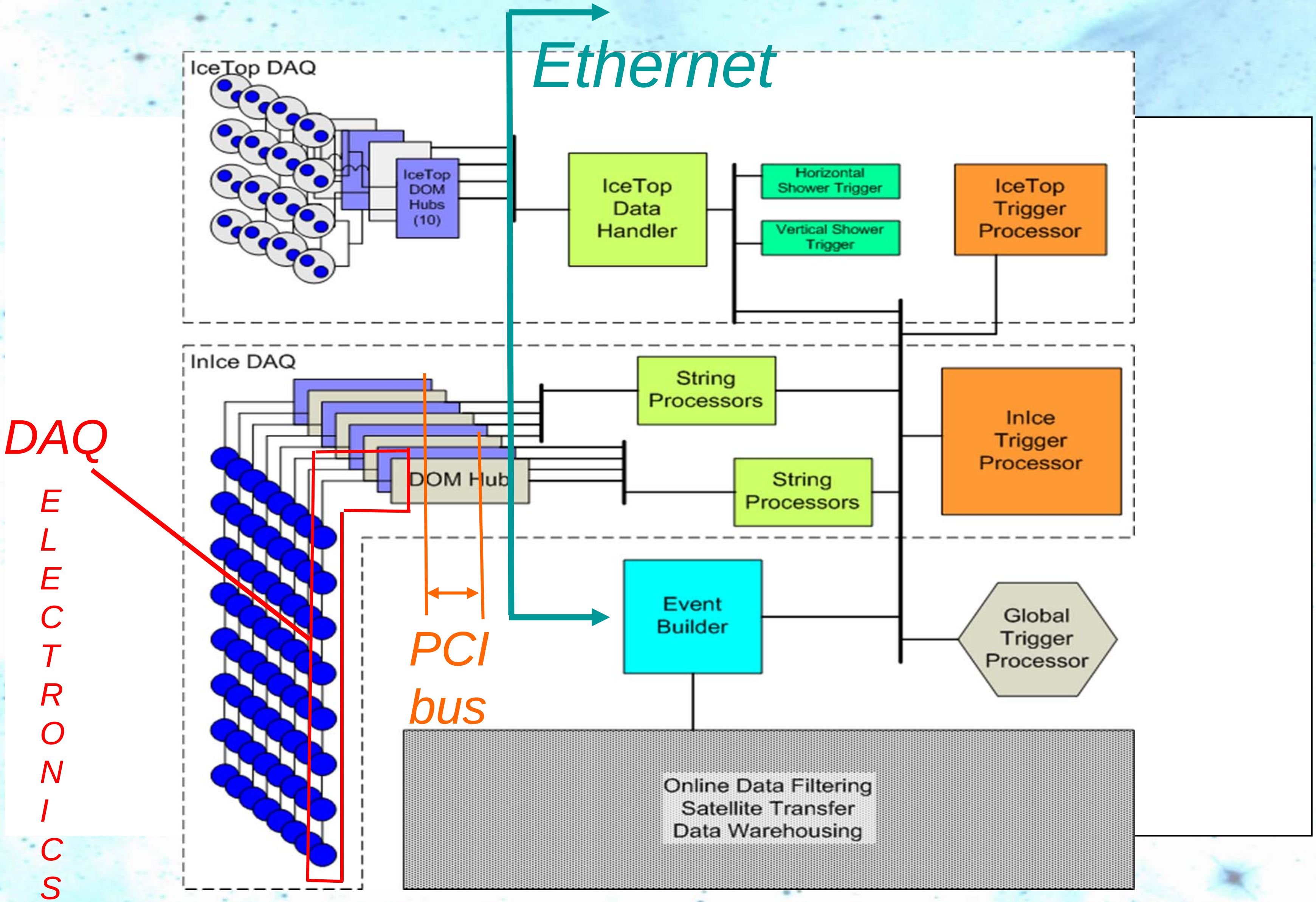
8 DOR Cards

CPU

GPS distr.

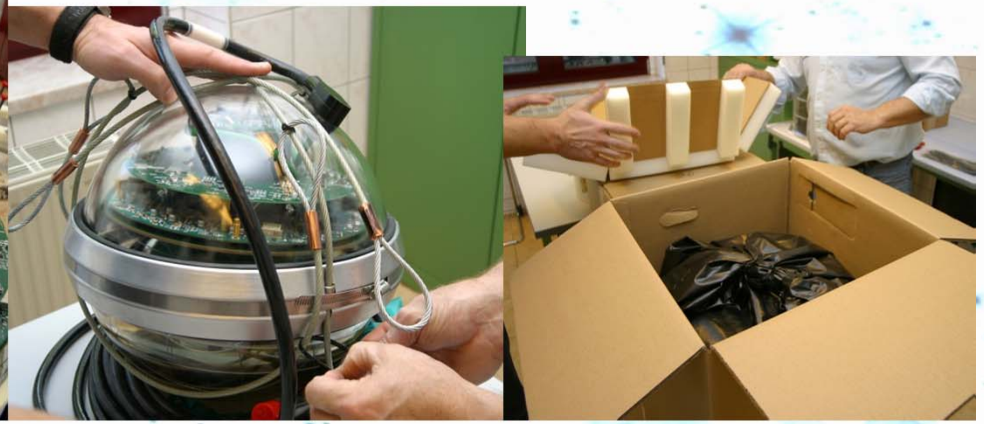
~300 W running 60 DOMs

IceCube DAQ Block Diagram



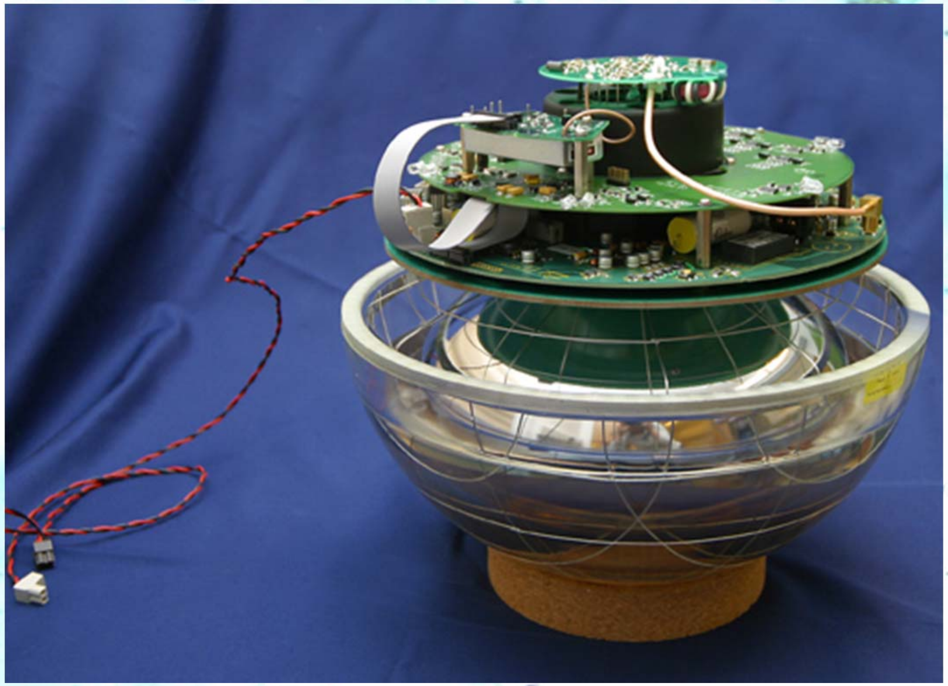
DOM PRODUCTION at DESY

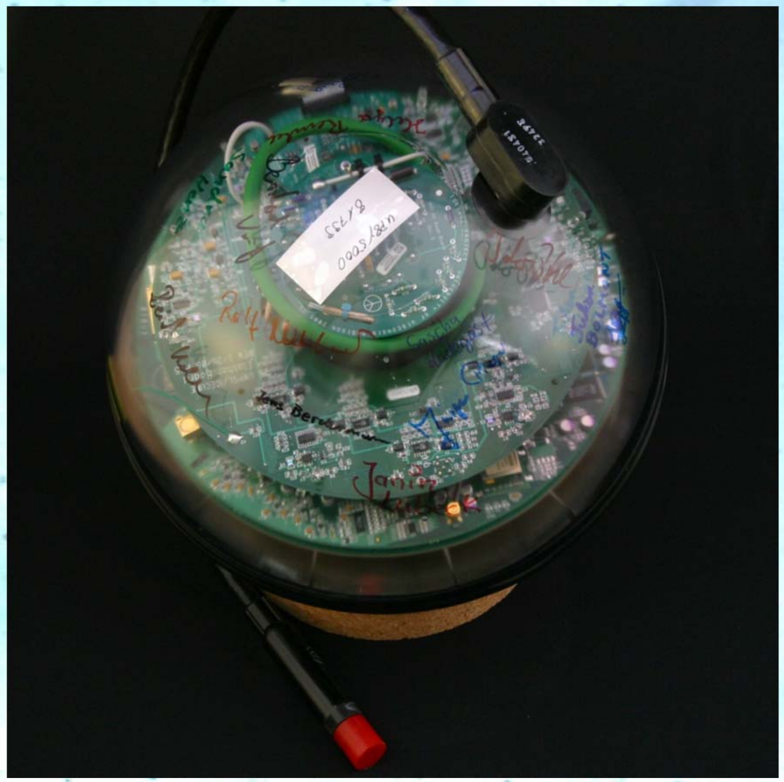
- Production of up to 1168 Optical Modules until mid 2008
- Production comprises:
- Gel mixing, filling and potting PMTs
- Collar mounting and assembly of electronics
- Sealing of DOMs at low pressure
- Harness DOM with suspension
- Finally pack DOMs and ship to the pole



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

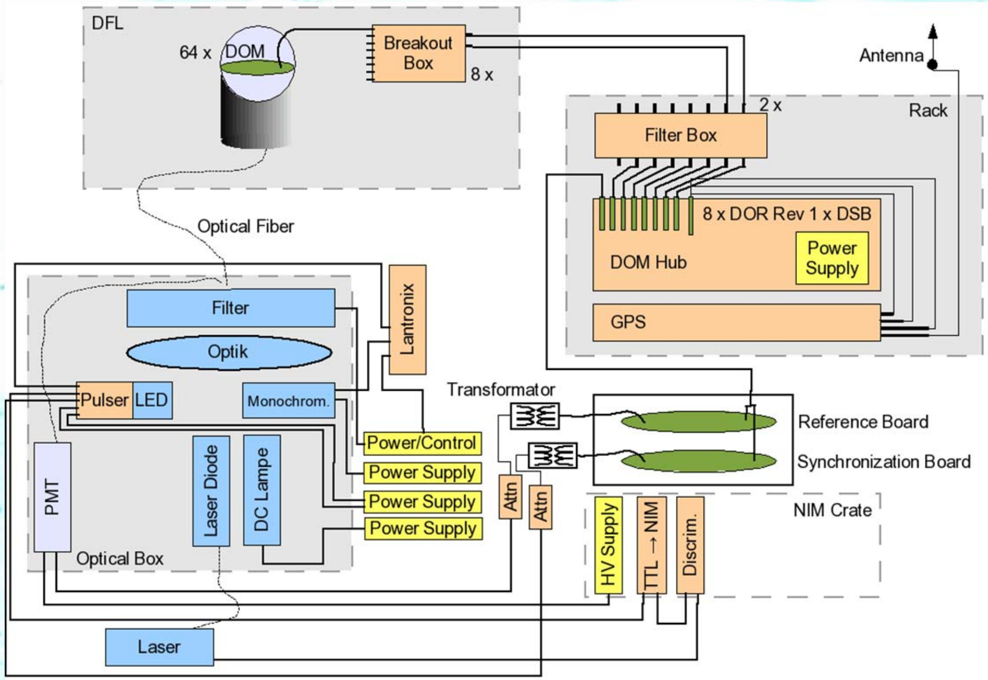
Same DAQ and wiring as for the South Pole system

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

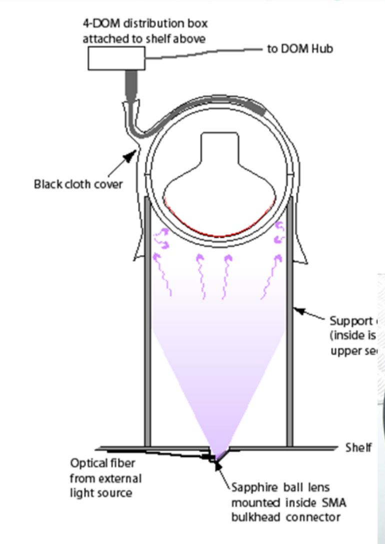


Different light sources:

- 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)

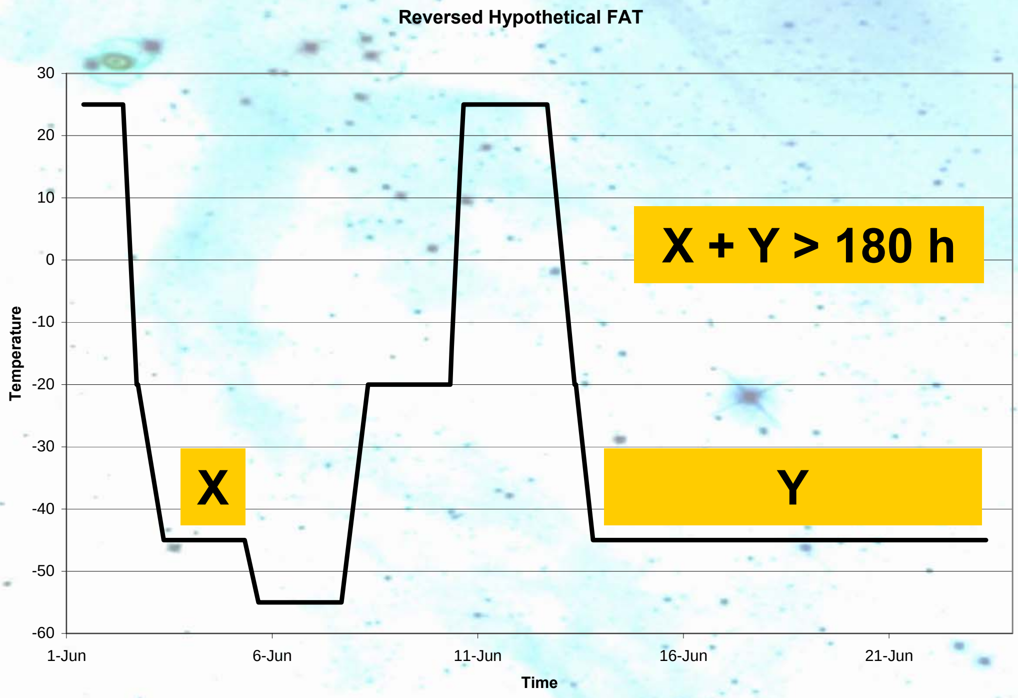
PMT high voltage calibration

Rate monitoring while DOMs are illuminated with light of different wavelength

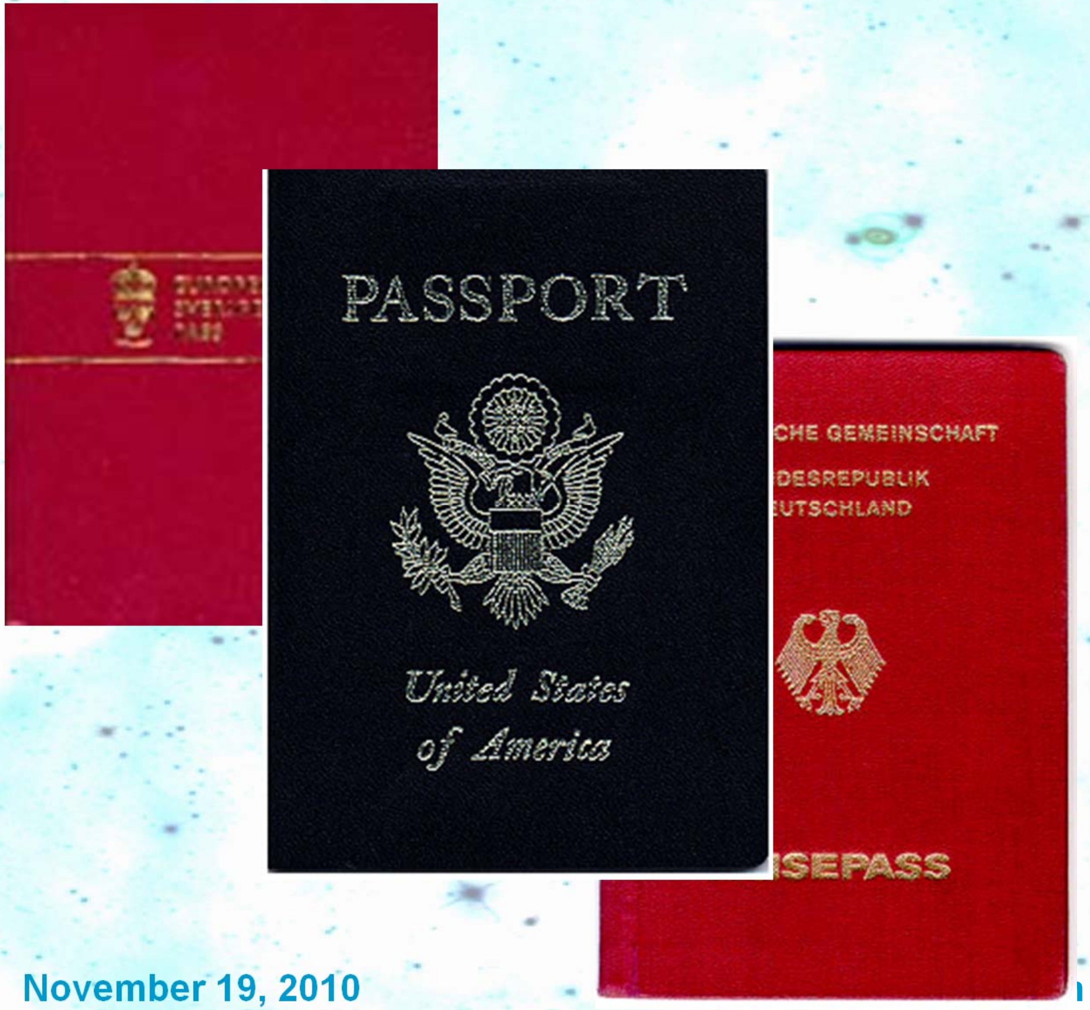
Dark rate monitoring

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)

DOM summary sheet

TP7Y4835	Crataegus_Cuneata	f99ccca88814

Status: passed | **Ship:** Y | **code:**

	mean	width	spike	HV diff	P/T	gain 2kv	Time res sigma (ns)	HV for 10^7	Optical effi at 400
+25A	2428	125.402	0	3	0.1695				30.14
-45A	2706	230.380	0	3	0.1584	3.18E+08	2.71	1237	31.79
-55	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant
-20	2249	190.134	0	3	0.1600	2.63E+08	2.76	1265	30.58
+25B	2240	130.223	0	4	0.1675				29.89
-45B	2751	236.479	0	4	0.1600	2.67E+08	2.60	1273	31.63
5E7	3019	258.209	0	4	0.1581				not relevant

Comment:

STF	Pressure	testdaq	Dark noise	reboot	gain	Other
P	P	P	P	P	P	P

Failed STF

ADC	atwd baseline	atwd clock1x forced	atwd_ped.	atwd ped. Noise	atwd ped.sweep forced	atwd pulser spe	disc scan	fadc base

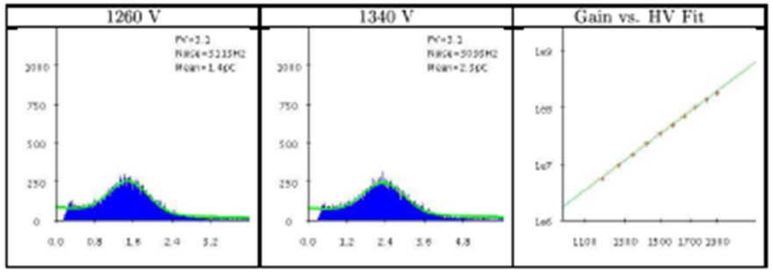
fadc fe pulser	flasher brightness	flasher clock	flasher width	memory	pmt hv ramp	pmt hv stability	temp.

Test si DESY - FAT26 **Date:** 13-Mar-08 **Reporter:** Rolf Nahnhauer

DOMCal Summary page for FAT26
CrataegusCuneata - TP7Y4835

f99ccca88814

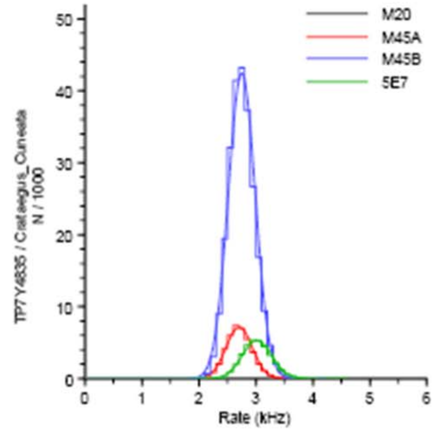
Date	Temperature	Slope	Intercept	Gain@2kV	HV@1e7
2008-02-21	32.0101	7.055	-14.93	2.28e8	1283V
2008-02-23	-35.1775	7.196	-15.252	3.17e8	1236V
2008-02-26	-10.49	7.133	-15.127	2.62e8	1264V
2008-02-28	31.1351	6.986	-14.794	1.84e8	1317V
2008-02-29	-32.24	7.266	-15.559	2.66e8	1272V

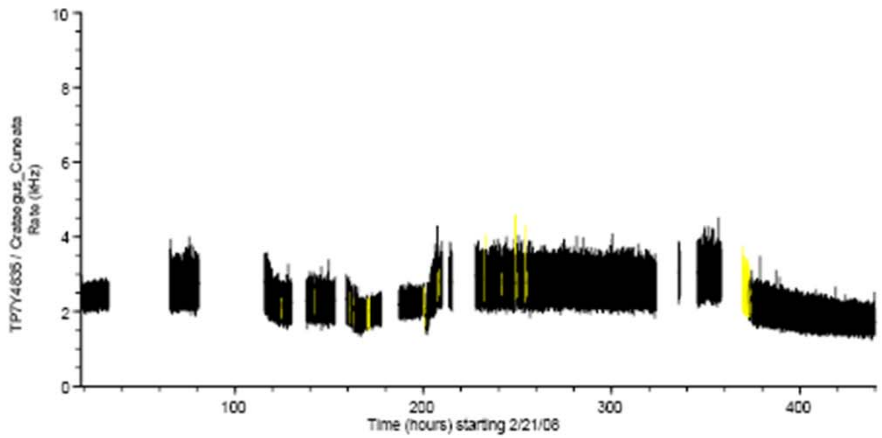


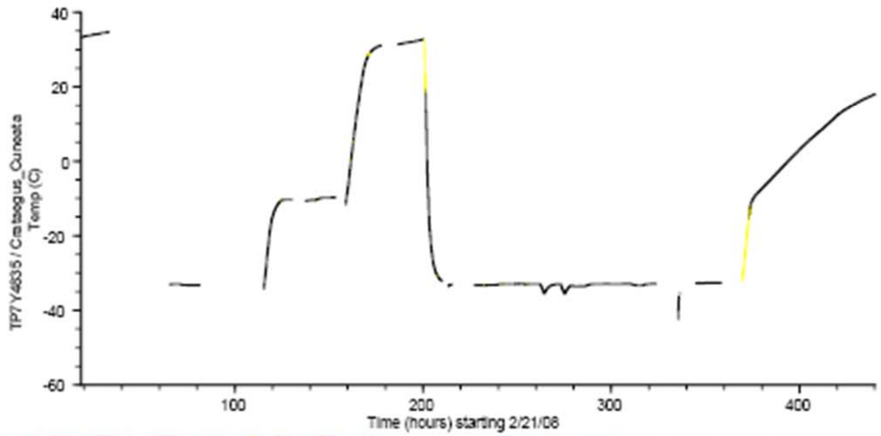
TP7Y4835 / Crataegus_Cuneata

Monitoring summary (cleaned)

		M20	M45A	M45B	5E7	
Duration	net		10.1	61.8	8.5	hrs
Temp	min		-33.3	-35.6	-32.8	°C
	max		-32.9	-32.8	-32.6	°C
	avg		-33.1	-33.2	-32.7	°C
Rate	min		1.89	1.83	2.11	kHz
	max		3.98	4.07	4.50	kHz
	avg		2.71	2.75	3.02	kHz
	width		0.23	0.24	0.26	kHz
	spikes		0	0	0	
HV	min		2463	2534	3165	volts
	max		2466	2538	3169	volts
	avg		2464	2536	3166	volts
Current	min		91.0	91.0	93.0	mA
	max		93.0	93.0	95.0	mA
	avg		92.1	92.0	94.0	mA
P/T	avg		0.158	0.158	0.158	kPa/°K



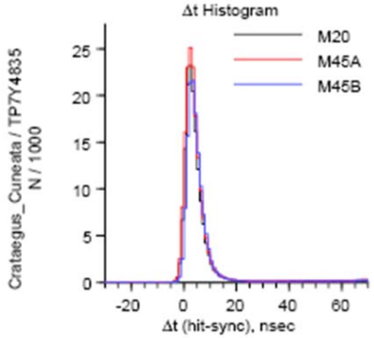


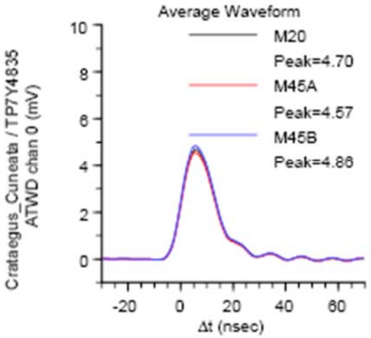


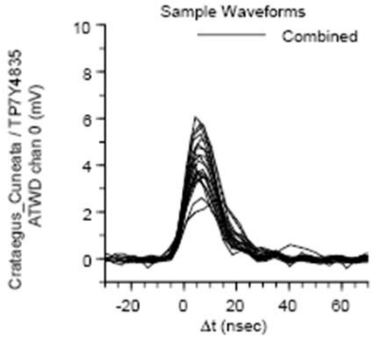
TP7Y4835 / Crataegus_Cuneata

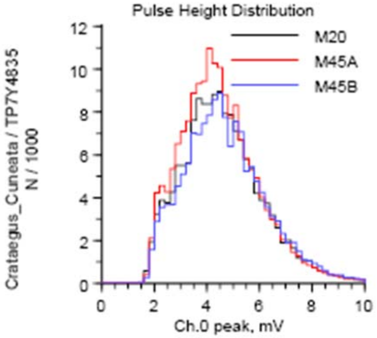
SPE Time Resolution

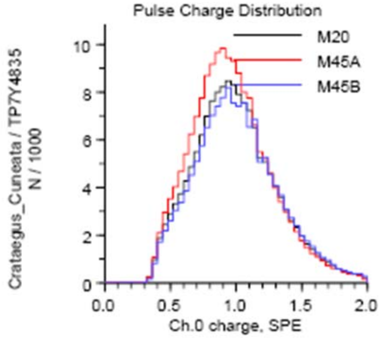
		M20	M45A	M45B	
events		155857	173441	145724	
Δt	mean	2.9	2.9	3.5	nsec
	sigma	2.8	2.7	2.6	nsec
	>15 ns	2.7	2.7	2.8	%
rise time		5.0	5.0	5.0	nsec
fwhm		13.5	13.6	13.6	nsec







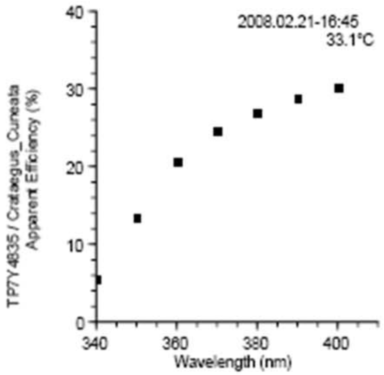


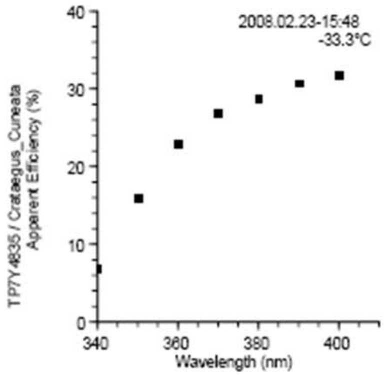


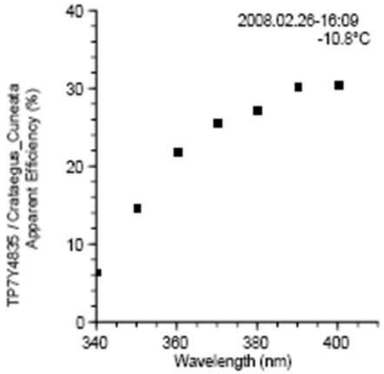
TP7Y4835 / Crataegus_Cuneata

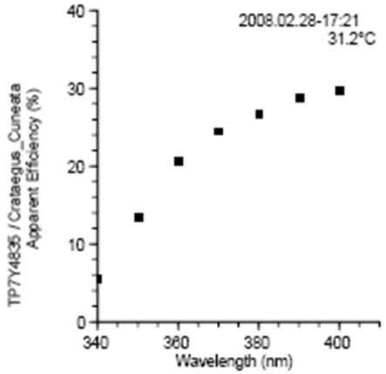
Optical Sensitivity

Temp (°C)	Date/Time	Test Station	Apparent efficiency, % 340nm	360nm	380nm	400nm	λ (½), nm
33.1	2008.02.21-16:45	16	5.5	20.5	27.0	30.1	352.2
-33.3	2008.02.23-15:48	16	7.0	23.0	28.7	31.8	350.0
-10.8	2008.02.26-16:09	16	6.4	21.9	27.3	30.6	350.8
31.2	2008.02.28-17:21	16	5.6	20.7	26.7	29.9	352.0
-33.0	2008.03.05-13:24	16	6.9	23.3	28.8	31.6	350.0









DESY DOM-Production 2004-2008

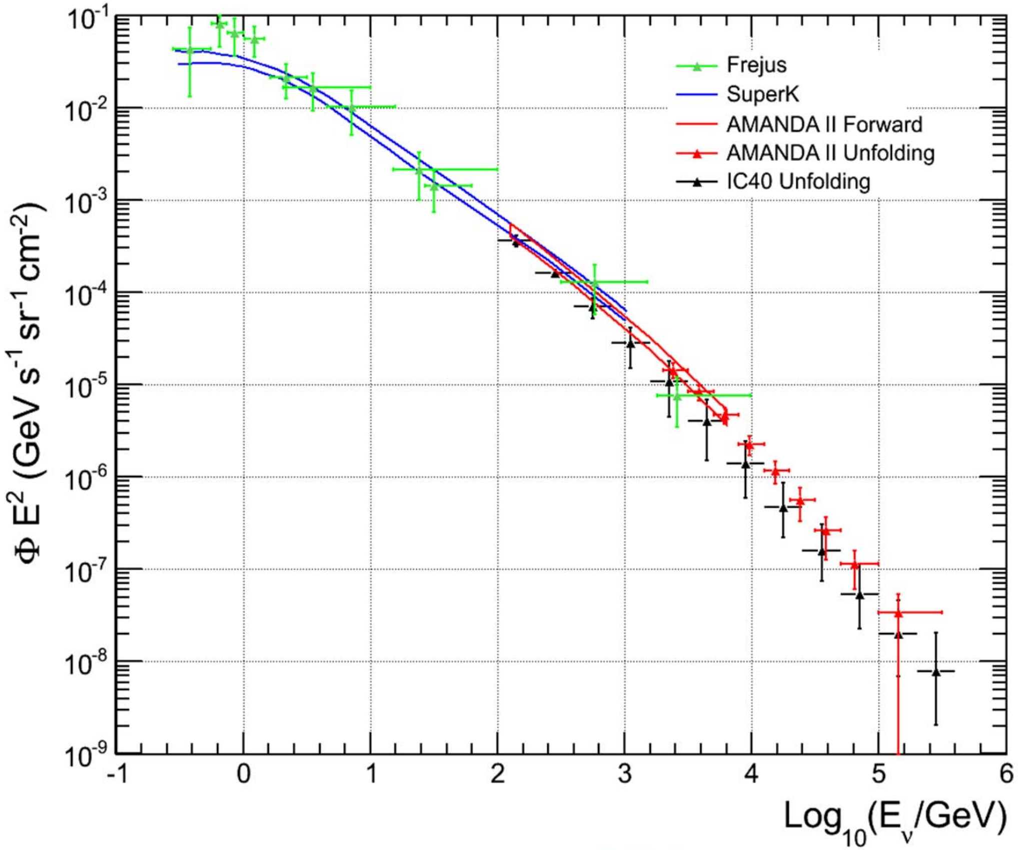
Year	DOMs produced	DOMs ok	ε_{final}	DOMs shipped
2004	60	45	0.75	28
2005	160	159	0.99	160
2006	257	255	0.99	224
2007	480	477	0.99	480
2008	233	232	0.99	276
$\sum$	1190	1168	0.98	1168

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

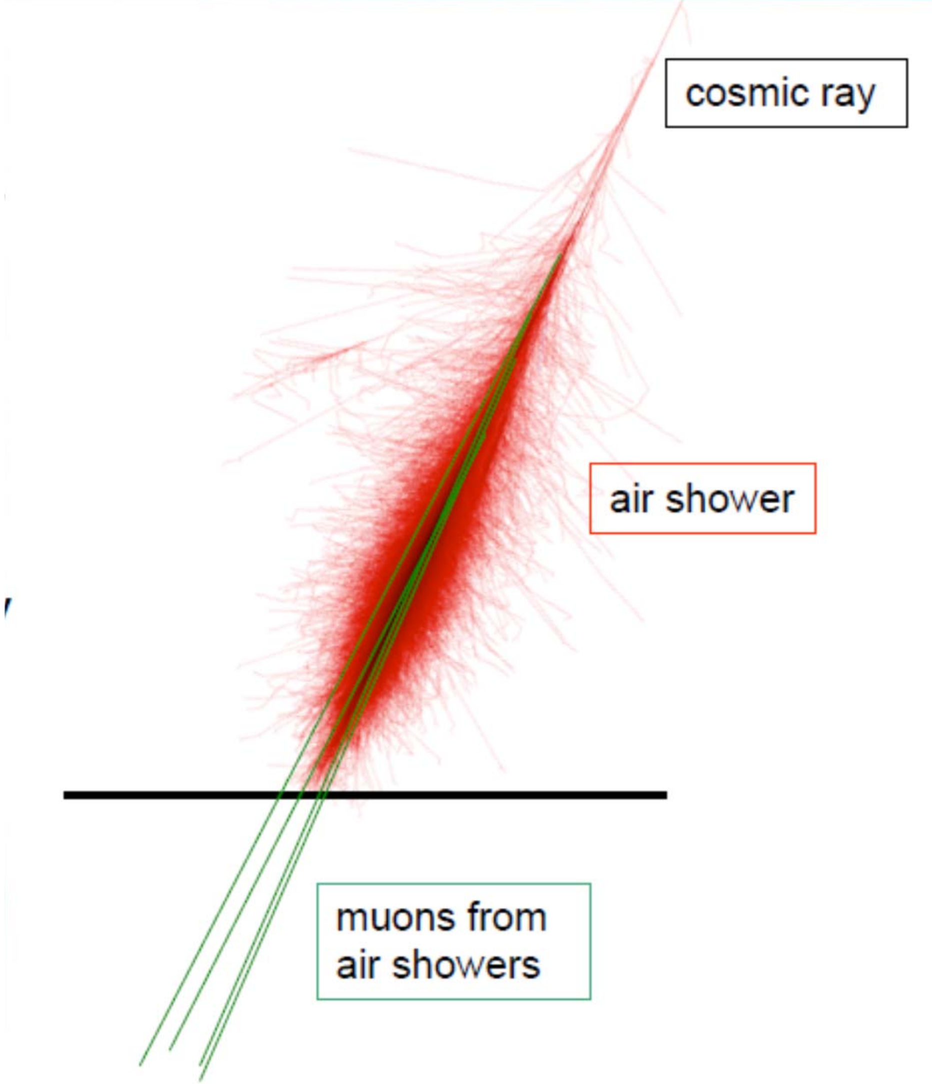
Early IceCube Results
(a few examples)

Atmospheric Neutrinos

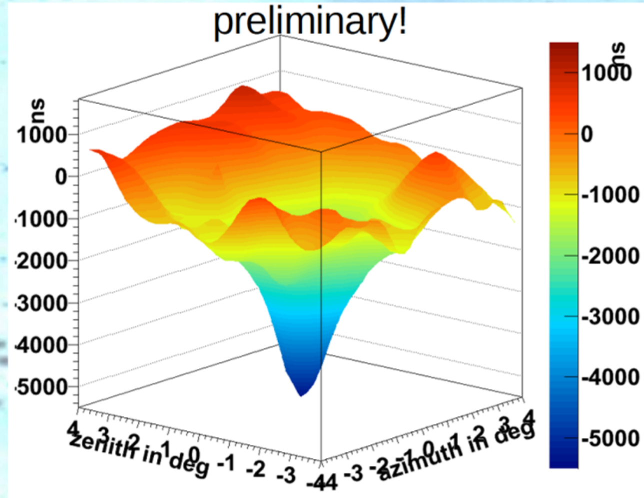
- **IC-40**
- **~18000 ν_μ CC events**
- **θ= 180°-97°**
- **Compatible with Bartol/Honda predictions**
- **Close to constrain estimates for prompt neutrinos**



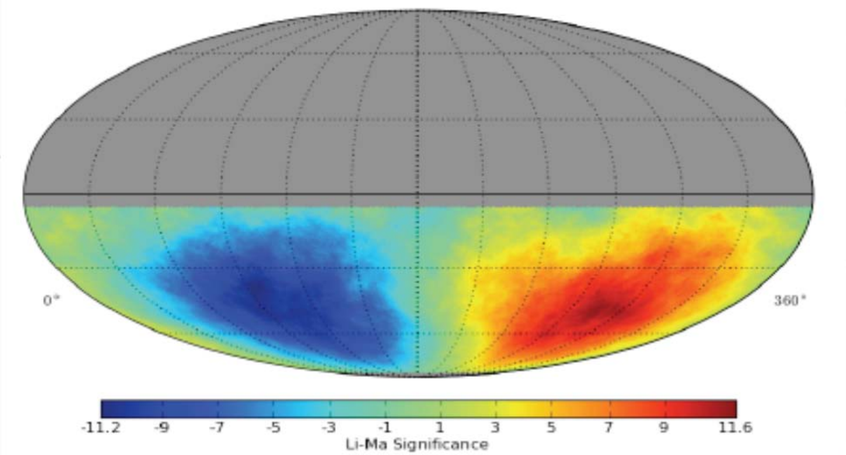
Muon astronomy I



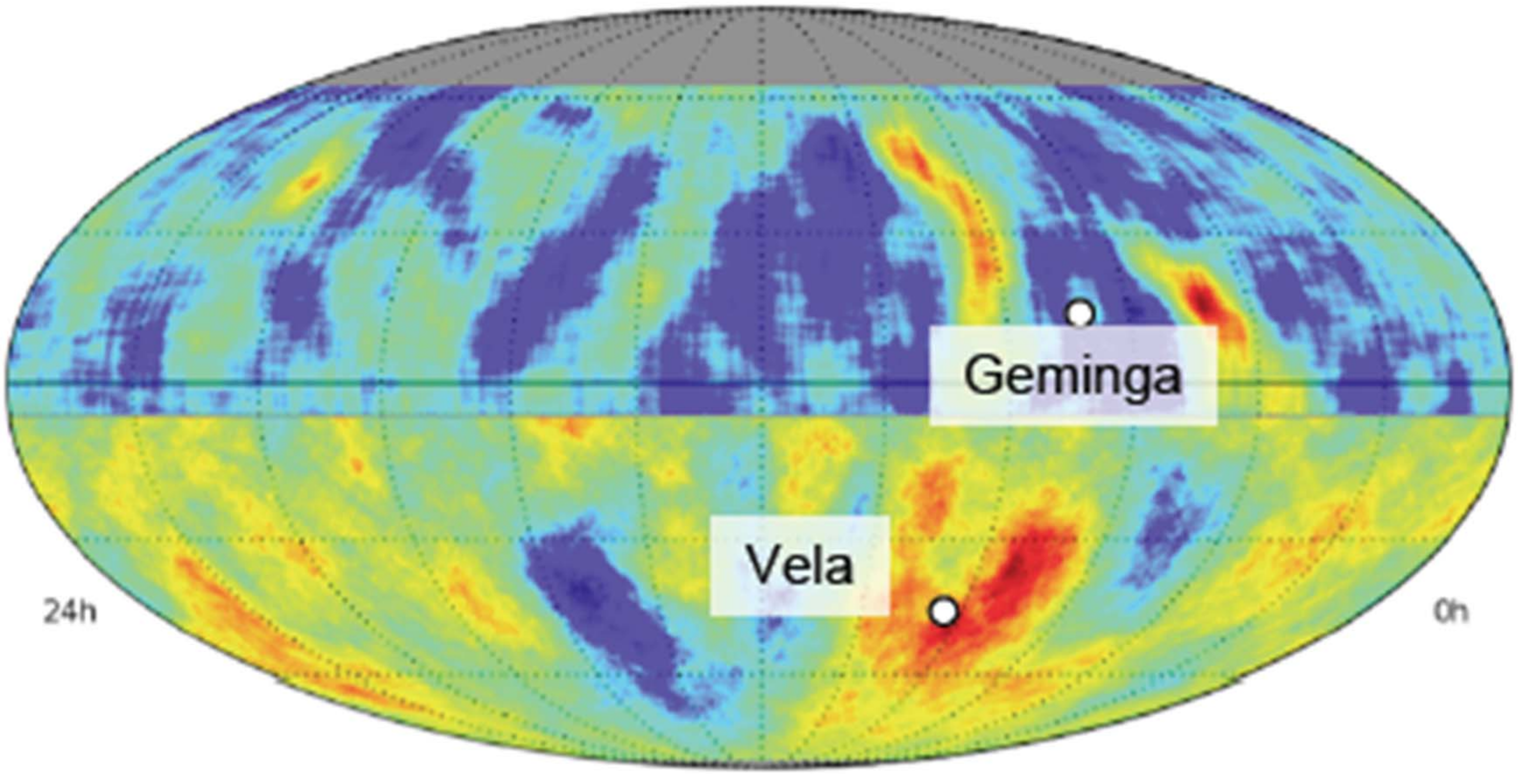
Shadow of the moon: **it works!**



Motion of the Earth around the Sun (siderial coordinates): **dipole, as expected**



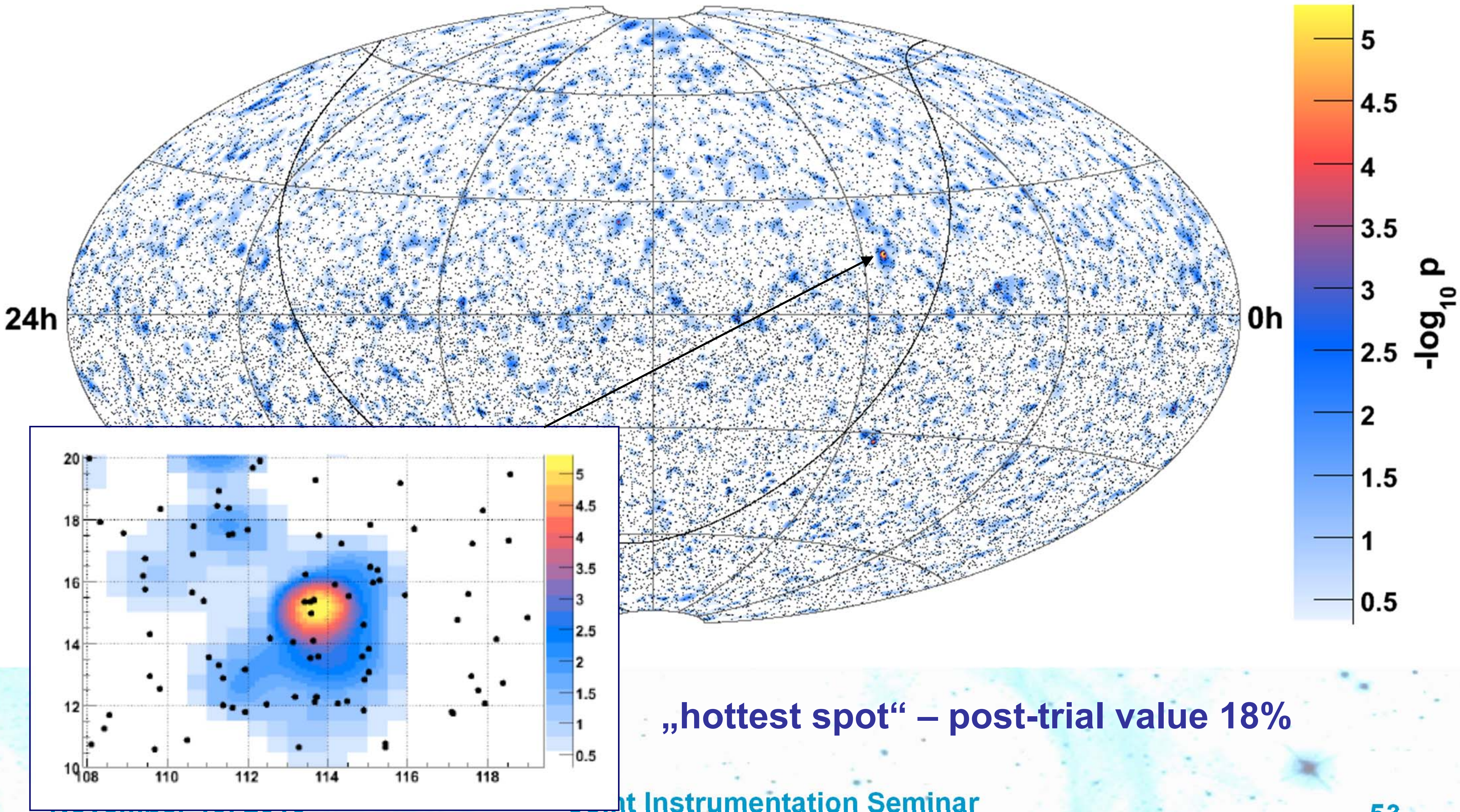
Muon astronomy II



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.

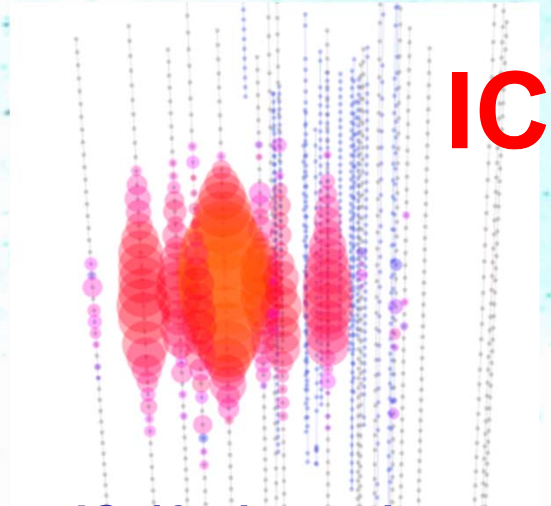
IC-40 sky map

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

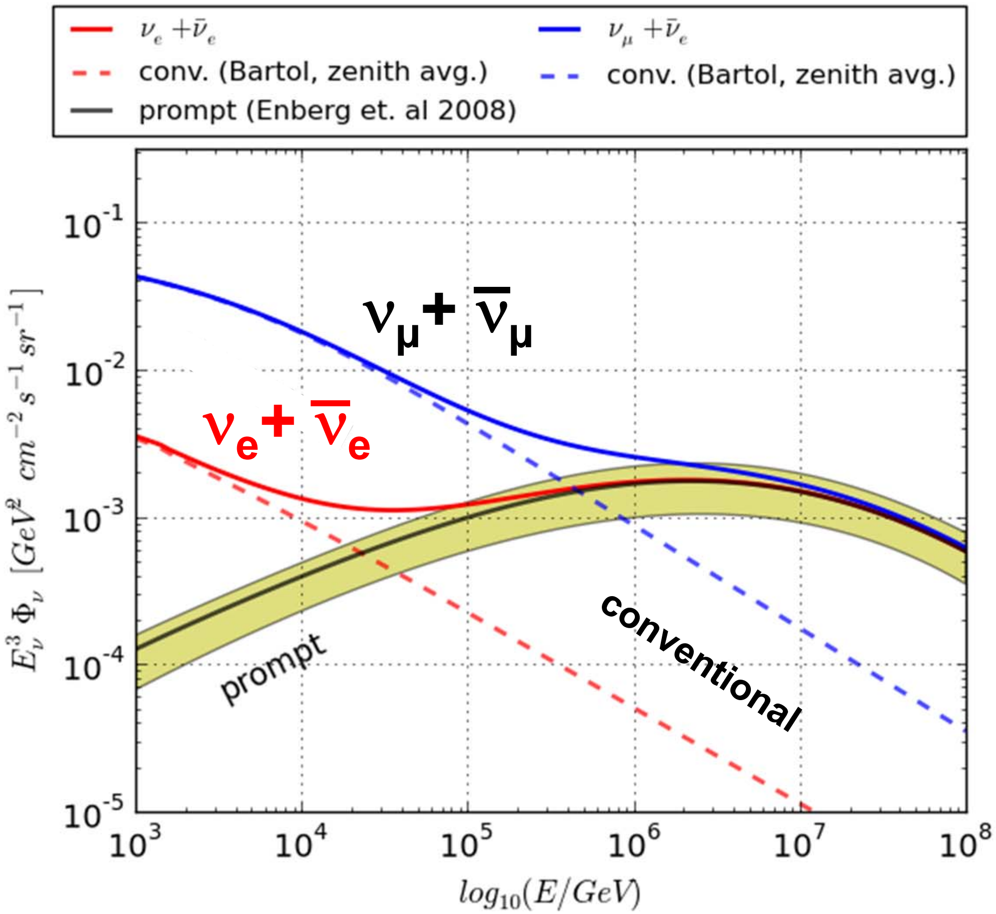


„hottest spot“ – post-trial value 18%

Cascades in IceCube

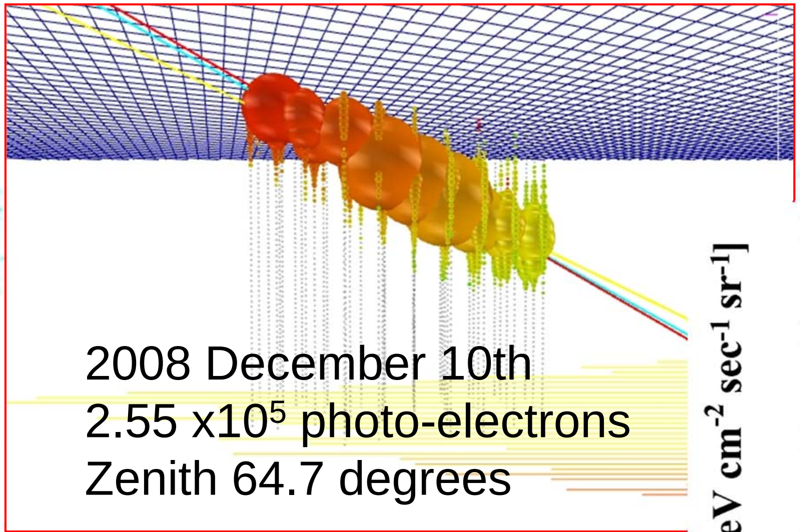


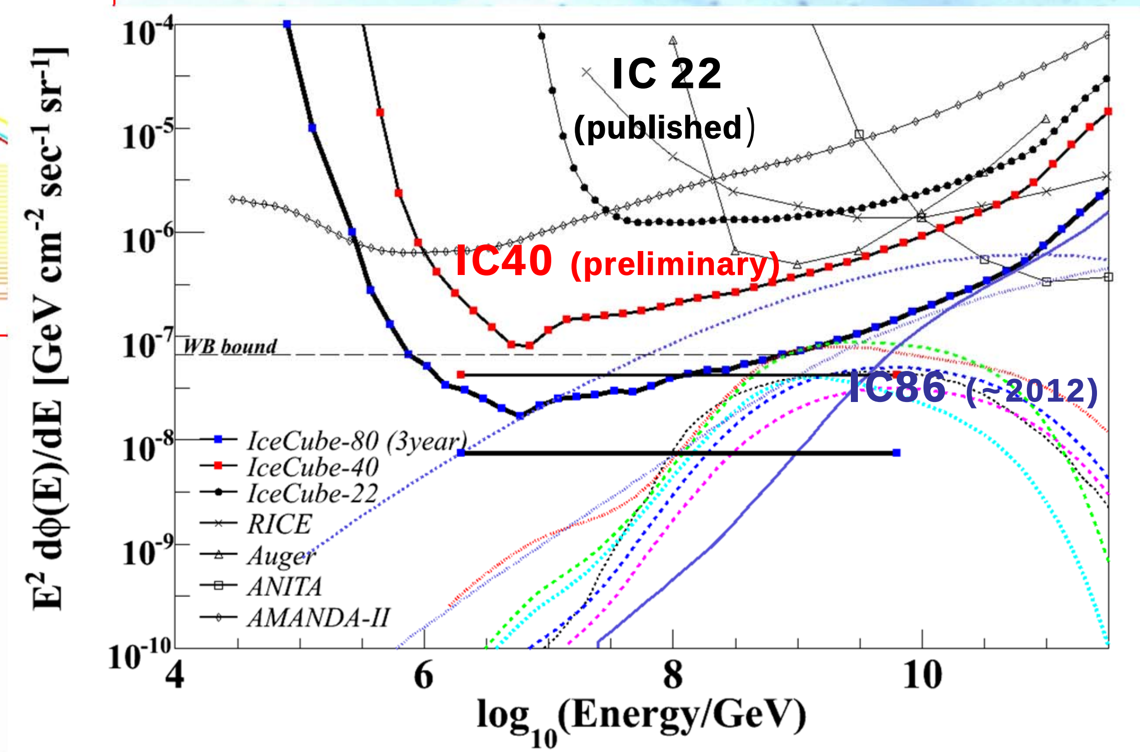
- IC-40: dramatic step compared to Amanda and IC-22 w.r.t. cascade identification
- Expect first clear identification of cascades from atm. neutrinos and spectrum
- Sensitivity to extraterr. E^{-2} flux $\sim 10^{-7}$ E^2 cm^{-2} s^{-1} sr^{-1}



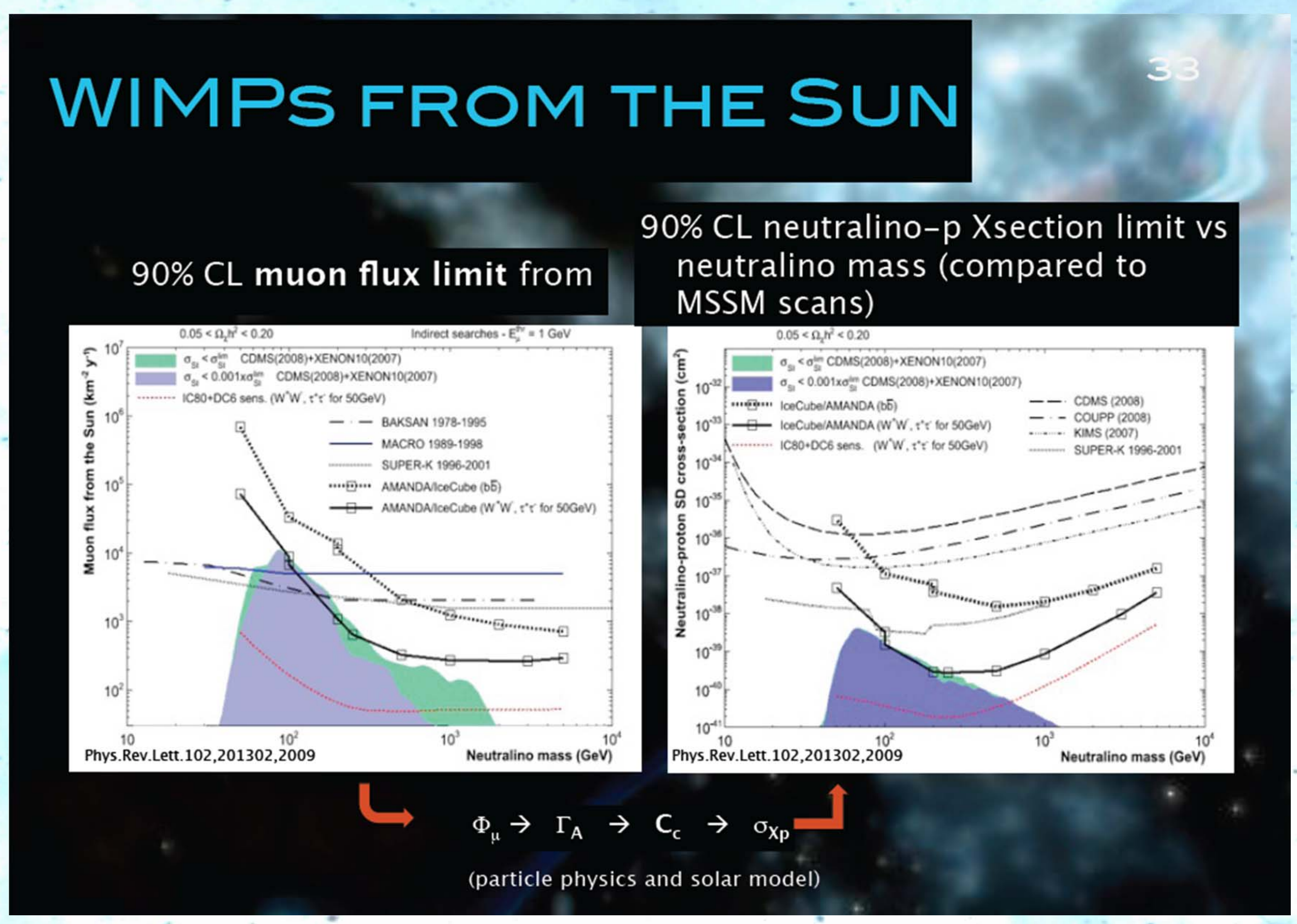
Ultra-High Energy Events

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





Indirect Dark Matter Search



Summary

- IceCube will be completed end of this year
- Excellent operational performance
- Many results using half of the final detector size are close to publication
- Hope for first neutrino signals until 2012 ...

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