Metody eksperymentalne w fizyce wysokich energii

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Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład VII

- Eksperymenty neutrinowe
- Eksperyment Pierre Auger

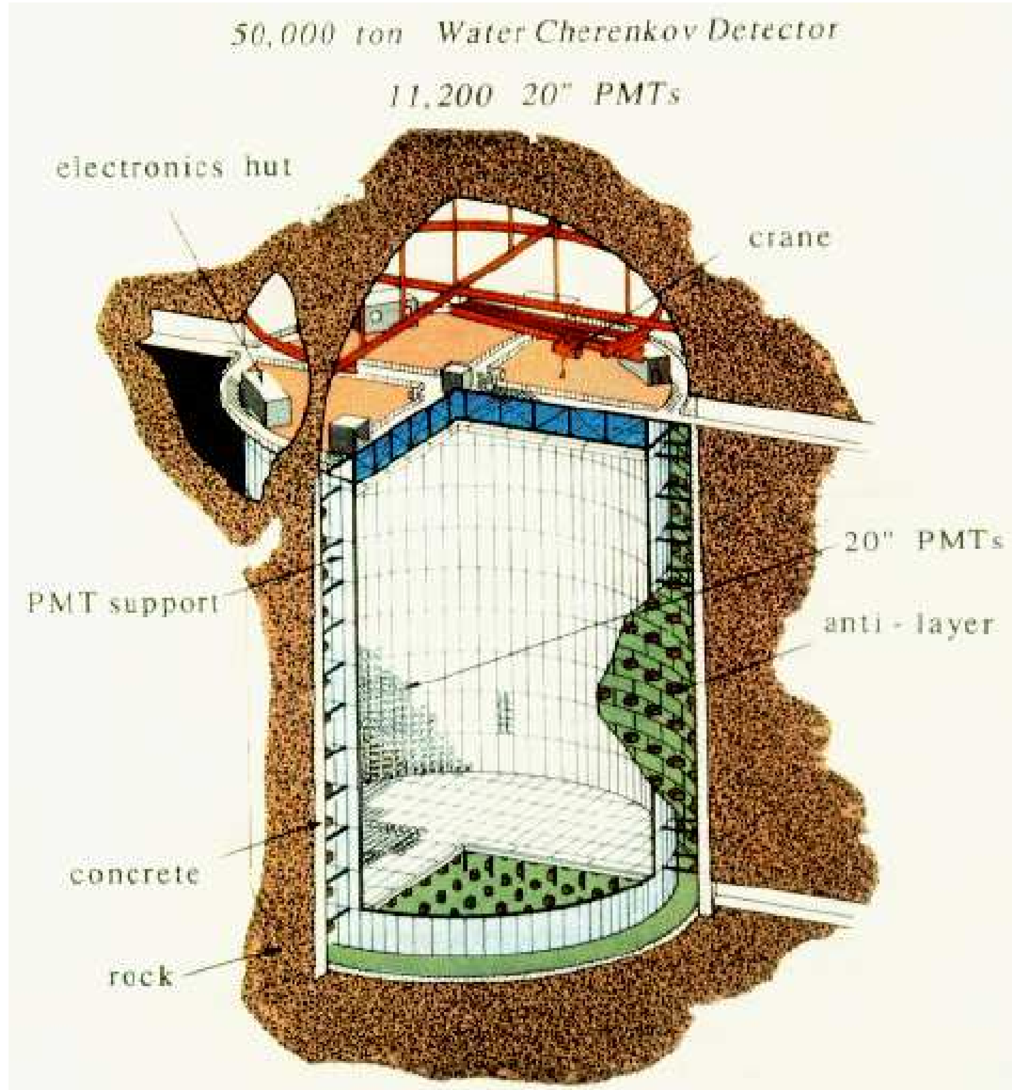
Neutrina atmosferyczne

Eksperyment Super-Kamiokande

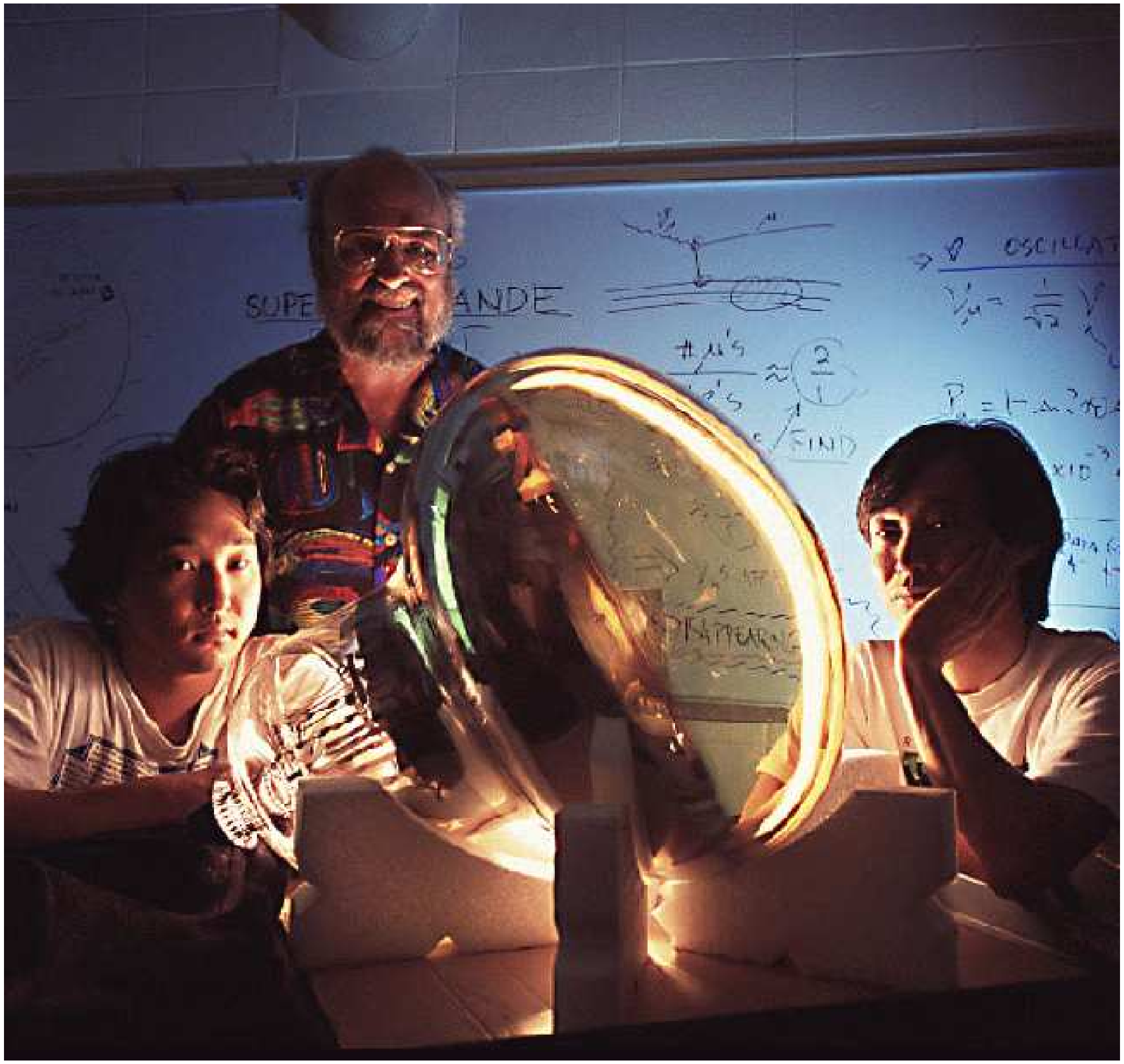
Japonia, w starej kopalni, 1 km pod górą Kamioka, komora o wysokości 40 m i średnicy 40 m, wypełniona wodą

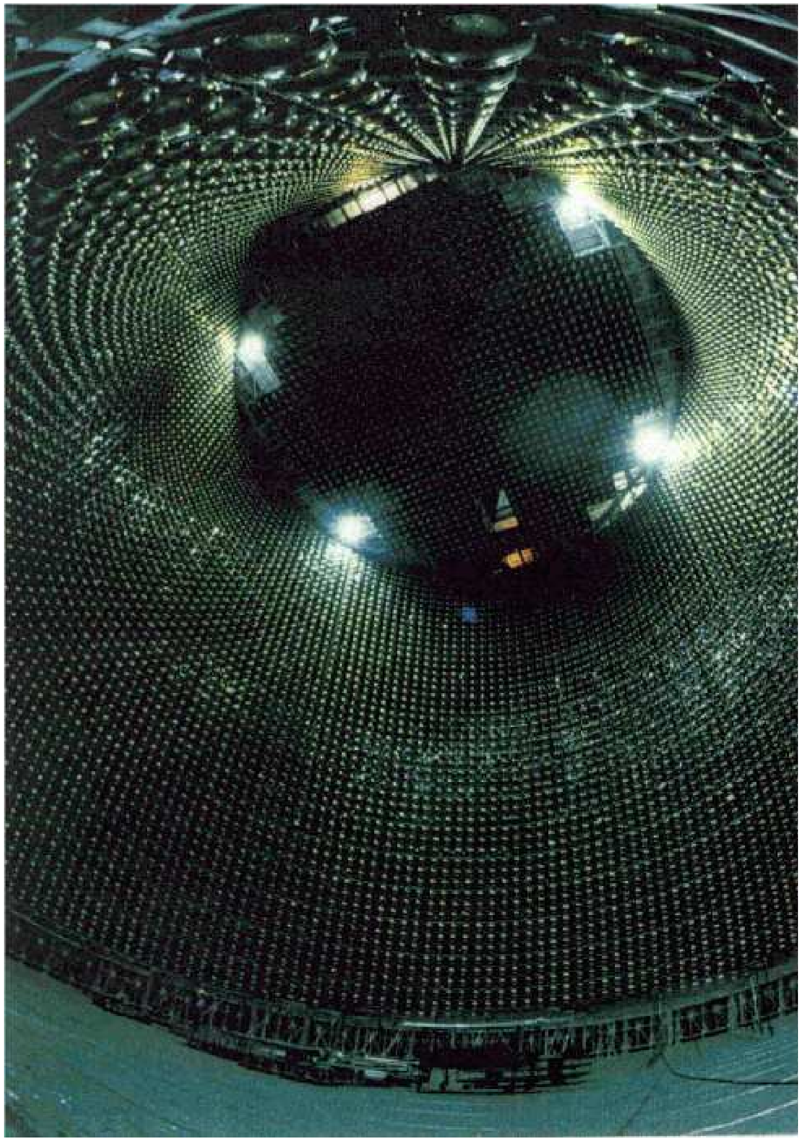
11’000 fotopowielaczy (50 cm średnicy!) rejestruje przechodzące cząstki

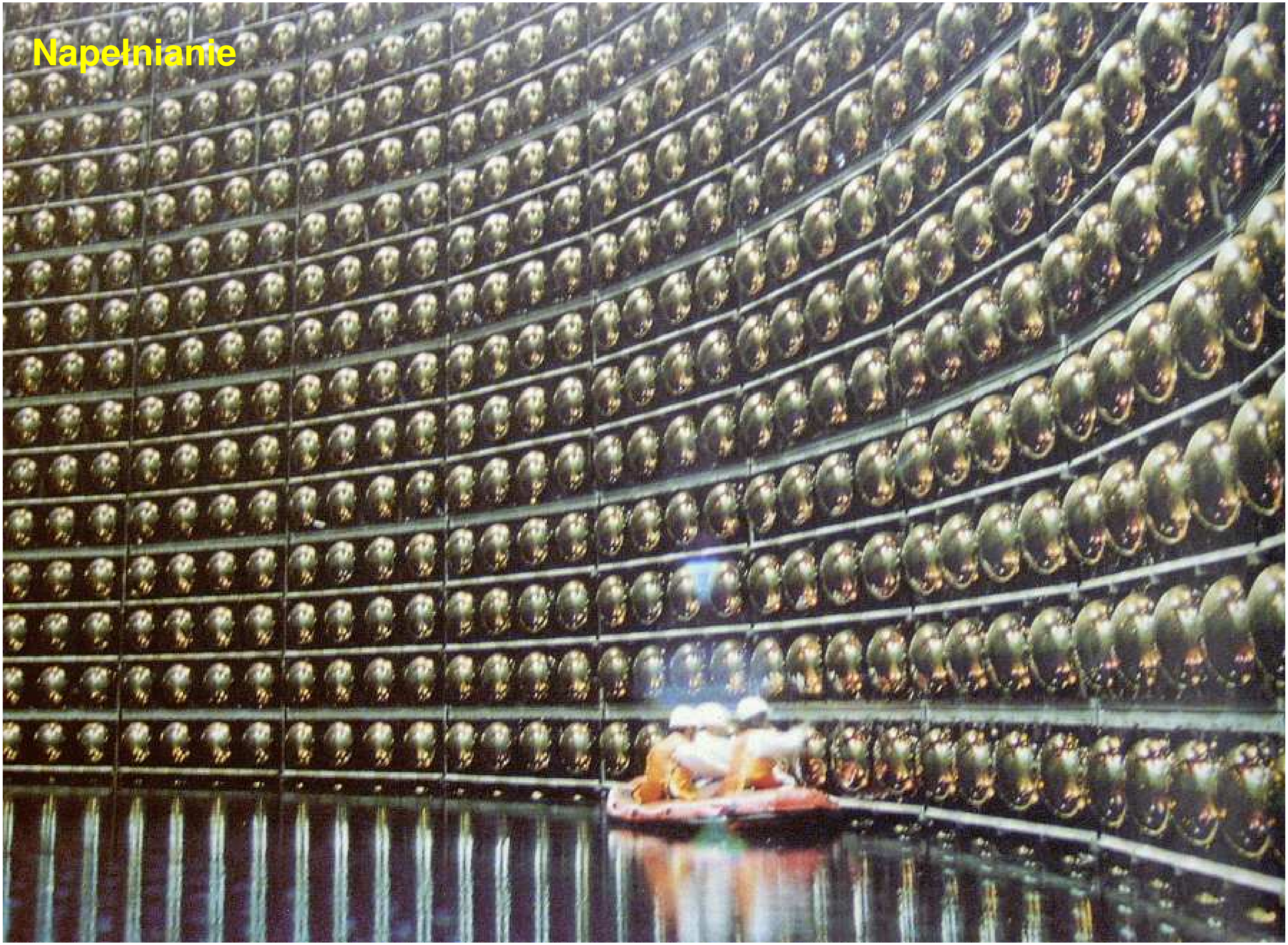
rejestrowane jest
promieniowanie Czerenkowa
emitowane w kierunku ruchu przez cząstki poruszające się z prędkością większą od prędkości światła (w wodzie)



Super-Kamiokande





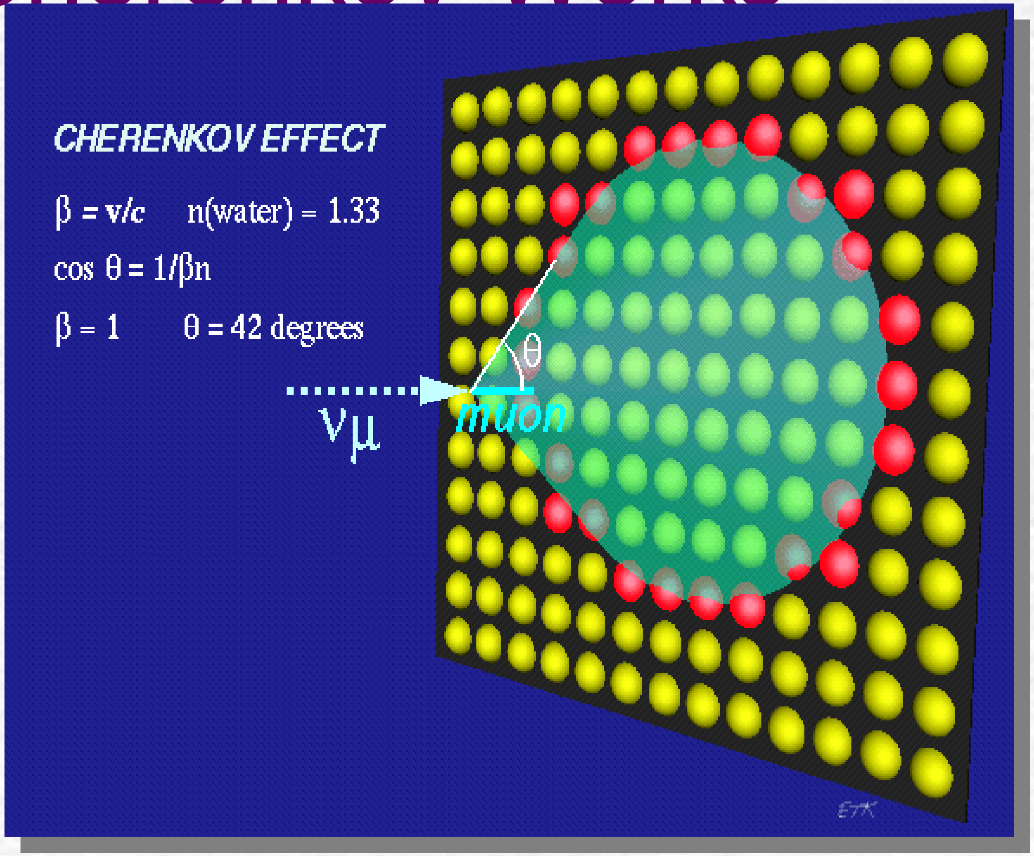

Napełnianie

Super-Kamiokande Milestones

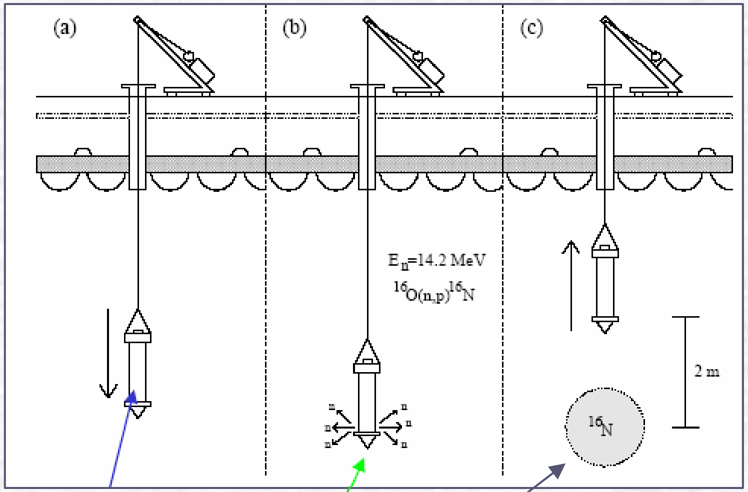
- April 1996: Data-taking begins
- June 1998: Evidence for atmospheric oscillation announced
- Spring 1999: K2K long-baseline experiment begins
- June 2001: Detector shutdown for PMT maintenance
- August 2001: Refilling of detector begins
- November 2001: Implosion disaster; end of SK-I
- December 2002: SK-II phase begins with half PMT coverage and acrylic housings
- Summer 2005: K2K long-baseline experiment ends
- Fall 2005: Restoration of full PMT coverage (SK-III) begins
- 2008?: Start of T2K long-baseline experiment

How Water Cherenkov Works

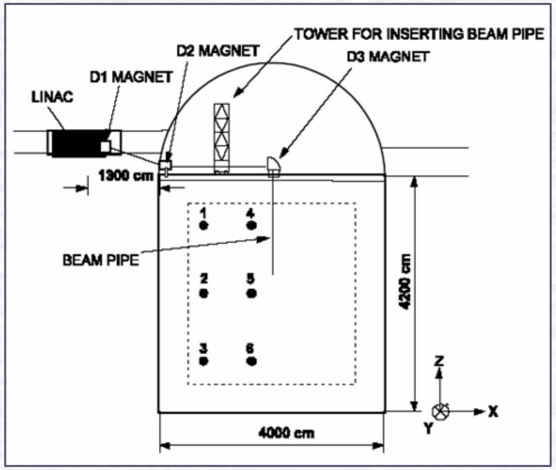
- Cheap target material
- Surface instrumentation
- Vertex from PMT timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and delayed muon decay signature
- Cherenkov threshold:
  - $\beta > 1/n \sim 0.75$



Low Energy Calibrations



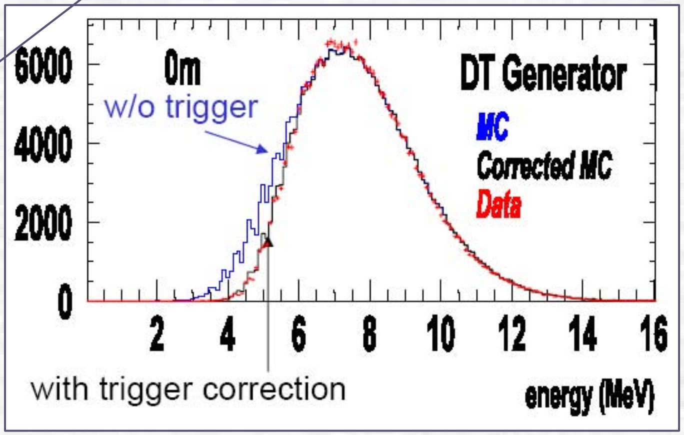
- At low-energy, SK is calibrated using:
  - lasers,
  - radioactive sources,
  - a “DT” generator,
  - and its own LINAC

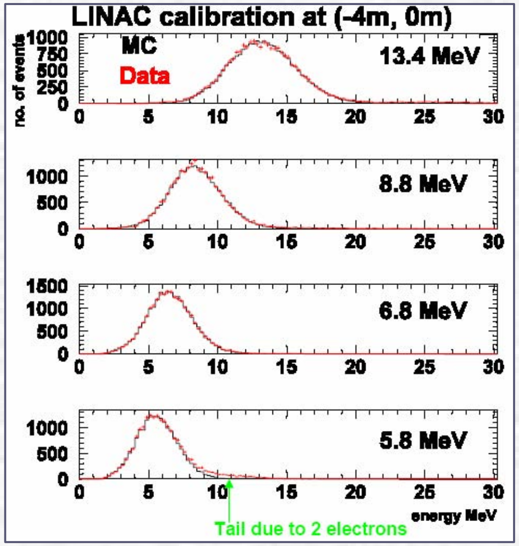


$D+T \rightarrow He + n$

$n + {}^{16}O \rightarrow p + {}^{16}N$

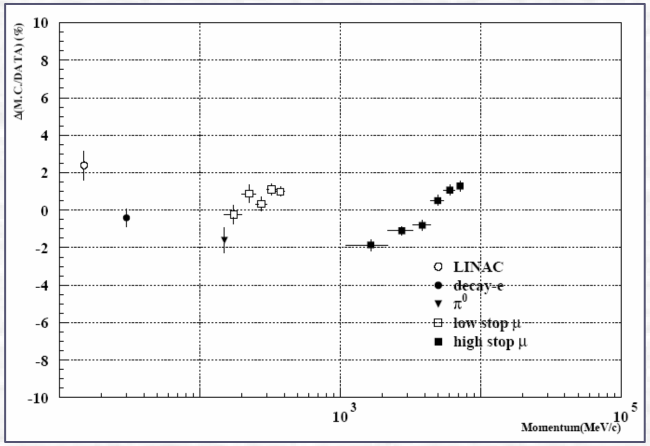
${}^{16}N \rightarrow {}^{16}O + e^{-} + \nu$

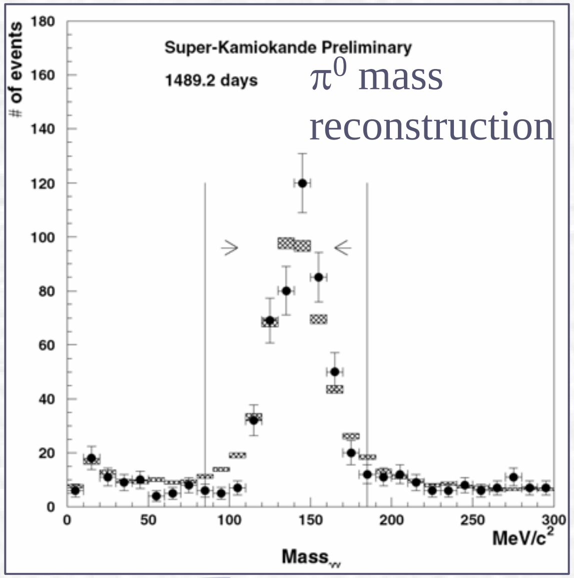




High-Energy Calibration

- For high-energy events, the energy scale is calibrated using:
  - Through-going cosmic-ray muons
  - Stopping cosmic-ray muons
  - Electrons from muon decay
  - Reconstructed π^0 from neutral-current interactions
- The energy scale for all types of events agrees to within about 2%





Super-Kamiokande

Klasyfikacja przypadków

Przypadki które rozpoznajemy jako oddziaływania neutrin:

FC: Fully Contained

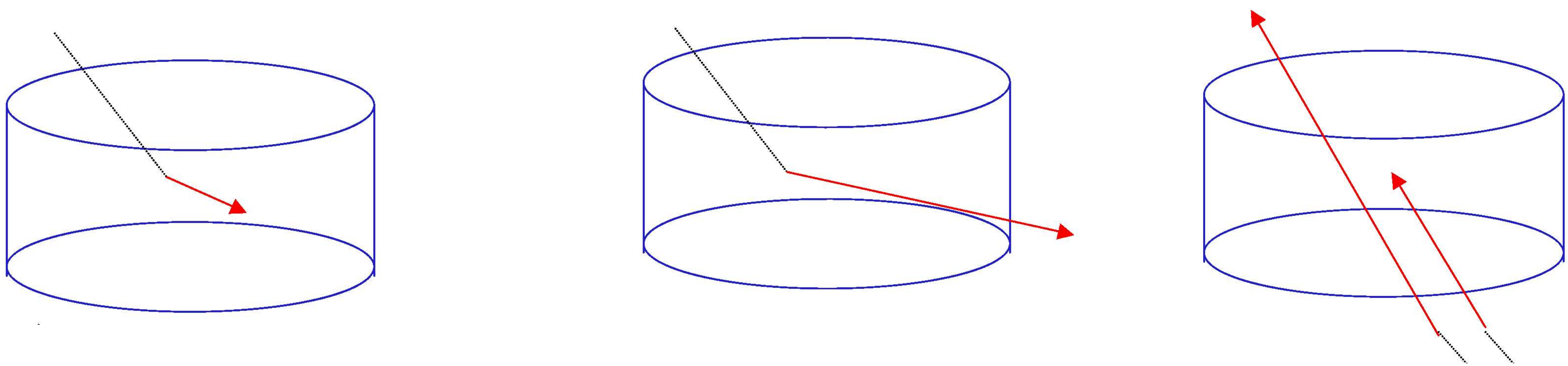
Elektron lub niskoenergetyczny mion wyprodukowany w detektorze zatrzymuje się w nim

PC: Partially Contained

Wysokoenergetyczny mion wyprodukowany w środku ucieka z detektora

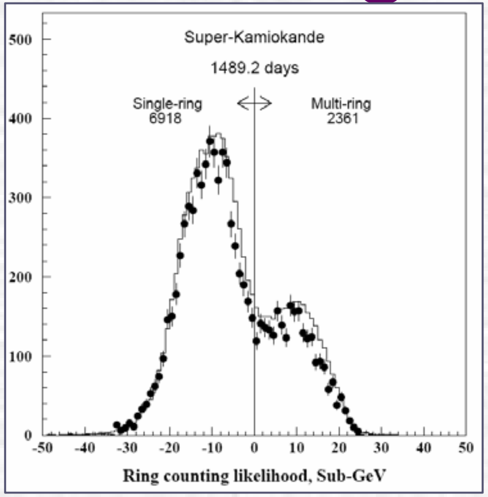
Upward

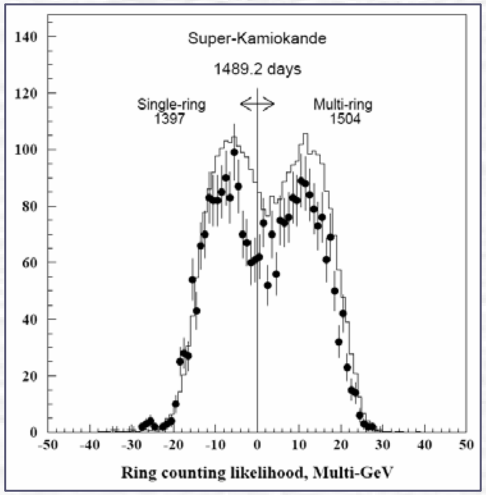
Miony wpadające do detektora od dołu



Data Reduction and Ring Counting

- Fully-contained events are selected by requiring no activity in the outer detector
- Partially-contained and upward-muon events are selected by reconstructing the vertex and direction
- Contained events are required to originate at least 2m from the walls
  - Vertex resolution is about 25 cm
- A maximum likelihood algorithm automatically identifies Cherenkov rings



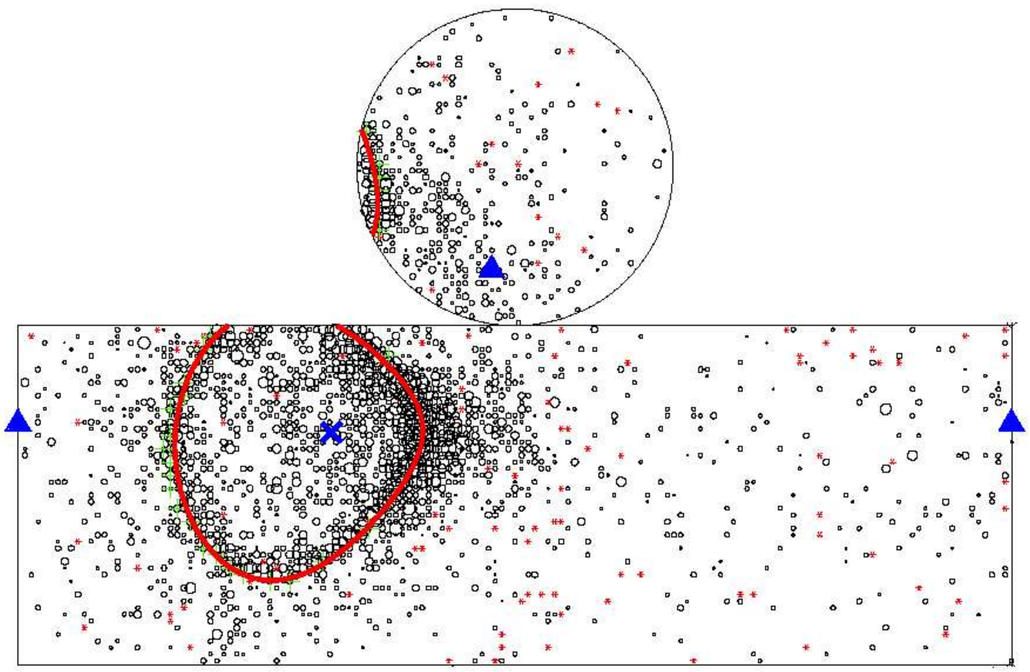


Super-Kamiokande

Neutrino elektronowe

Przypadek $\nu_e \, n \to e^- p$

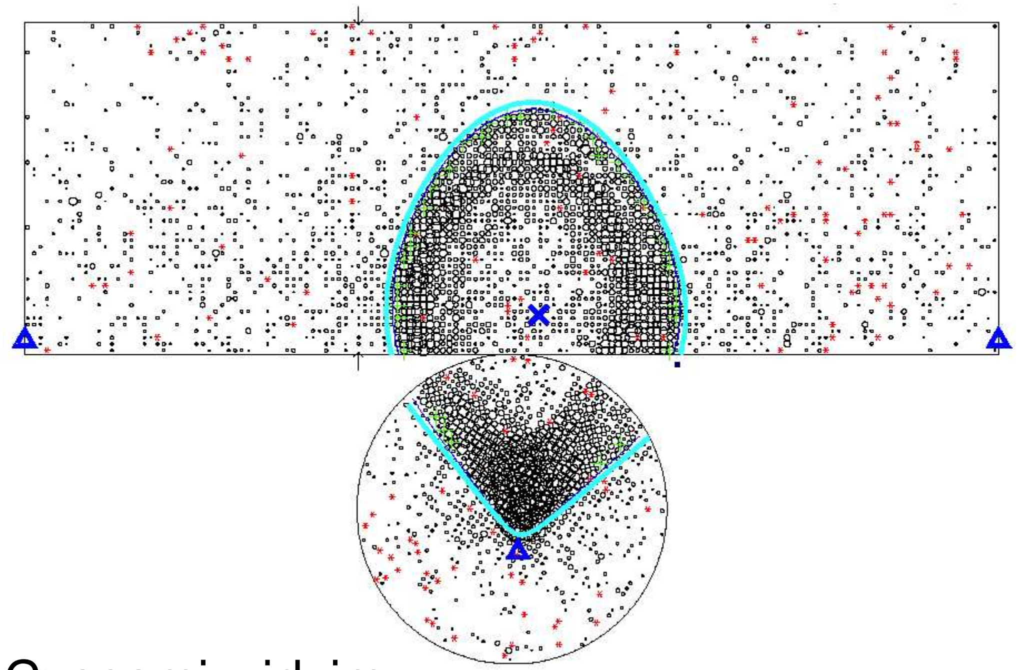
Krótki zasięg elektronu - “cienki” pierścień



Neutrino mionowe

Przypadek $\nu_\mu \, n \to \mu^- p$

Długa droga w wodzie - “gruby” pierścień.

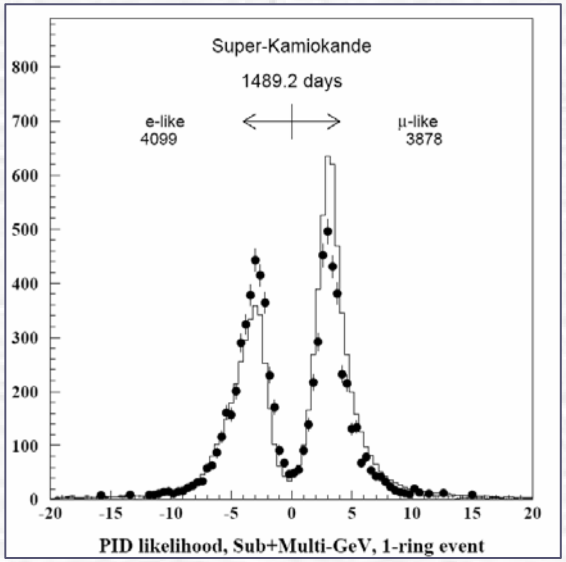


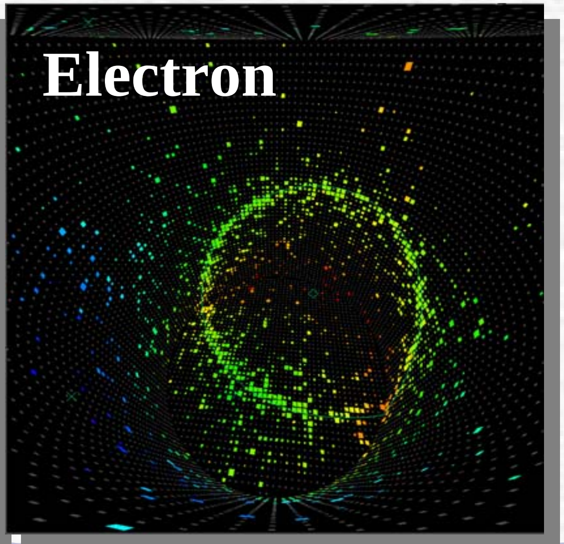
Czasami widzimy

też opóźniony sygnał e^- z rozpadu μ^-.

Particle Identification

- Single-ring events are identified as e-like or μ-like, based on the geometry of the Cherenkov cone
  - e-like events shower
  - μ-like events have a sharp ring edge

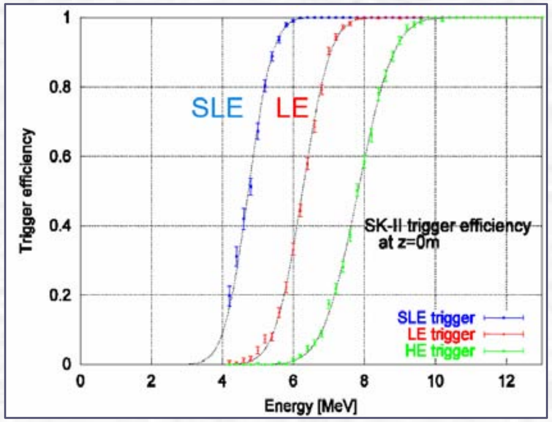




- Particle ID perfomance can be tested on cosmic-ray muons, muon-decay electrons, π^0. It has also been verified in a test beam

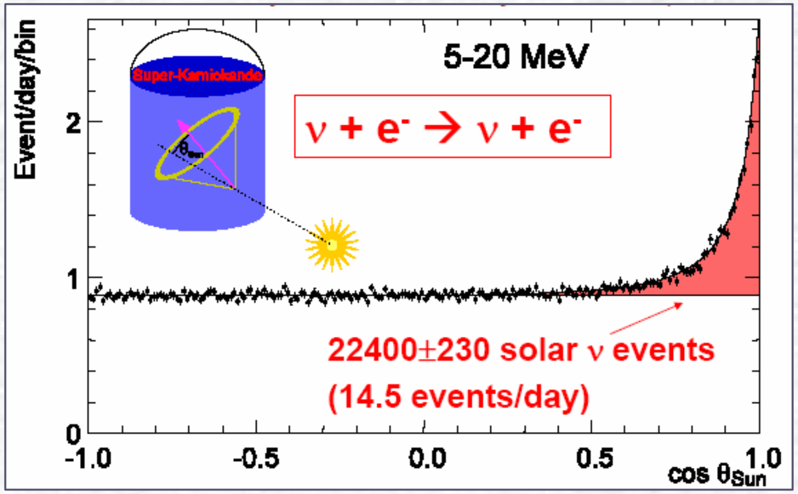
Solar Neutrino Rate

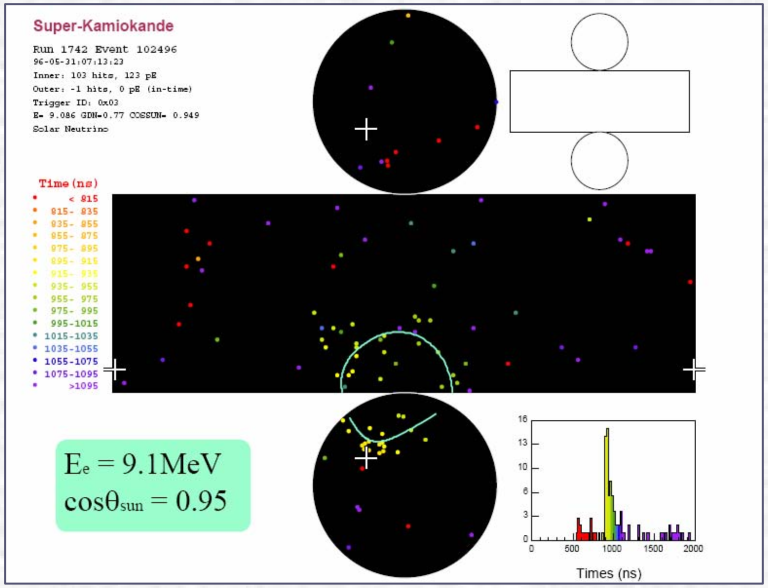
- SK observes a clear excess of electrons pointing from the direction of the Sun
- Principal solar neutrino backgrounds come from Radon, spallation products, and radioactivity
- Only about 40% of the expected interaction rate is observed:



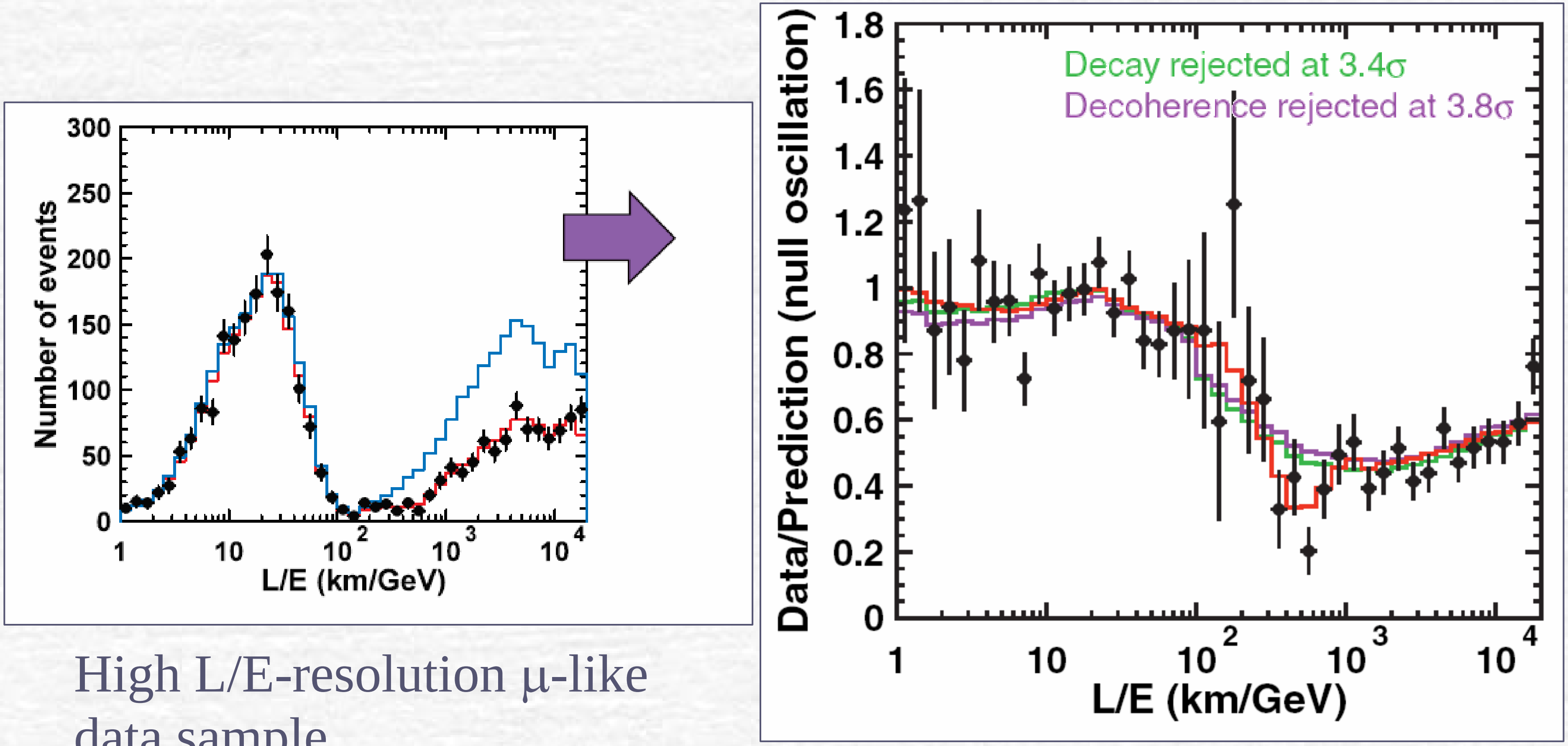
^{8}B flux = 2.35 ± 0.02 ± 0.08 [x10^{6}/cm^{2}/s]

Data / SSM_{BP2004} = 0.406 ±0.004(stat.) +0.014 -0.013 (syst.)



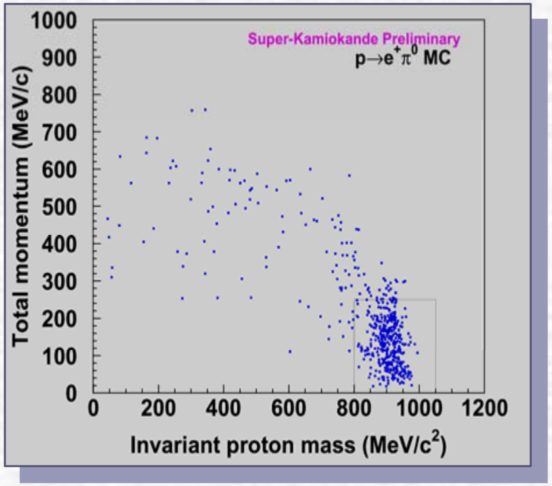


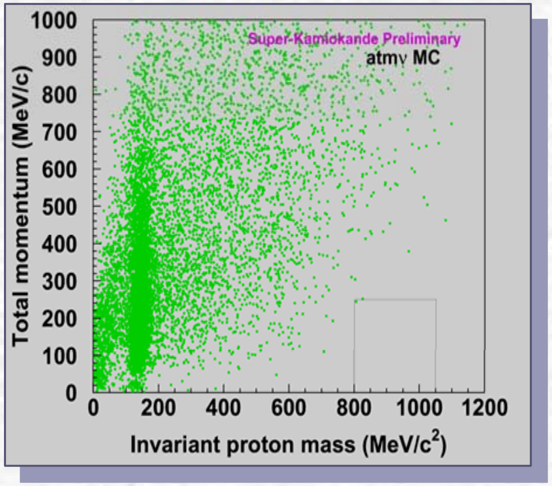
“Direct” Evidence for Oscillation

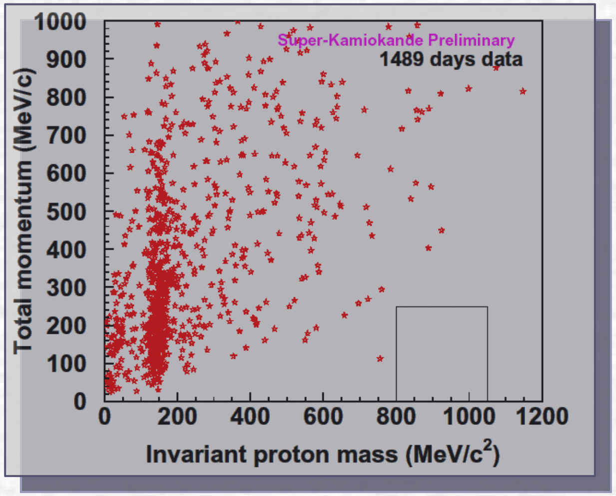


High L/E-resolution μ-like data sample

SuperK I: $p \rightarrow e^+\pi^0$ Results







- Require 2-3 showering rings, 0 $\mu \rightarrow e$
- π^0 mass cut if 3 rings
- Overall Detection Efficiency: 43%
- No candidates
- $\tau/\beta > 5.7 \times 10^{33}$ yrs (90% CL)

SuperK I:
1489 days = 0.091 Mty

AMANDA

Antarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray

AMANDA

(Antarctic Muon And Neutrino Detector Array)

677 modułów na 19 “strunach”,
1500–2000 m pod lodem (biegun południowy)

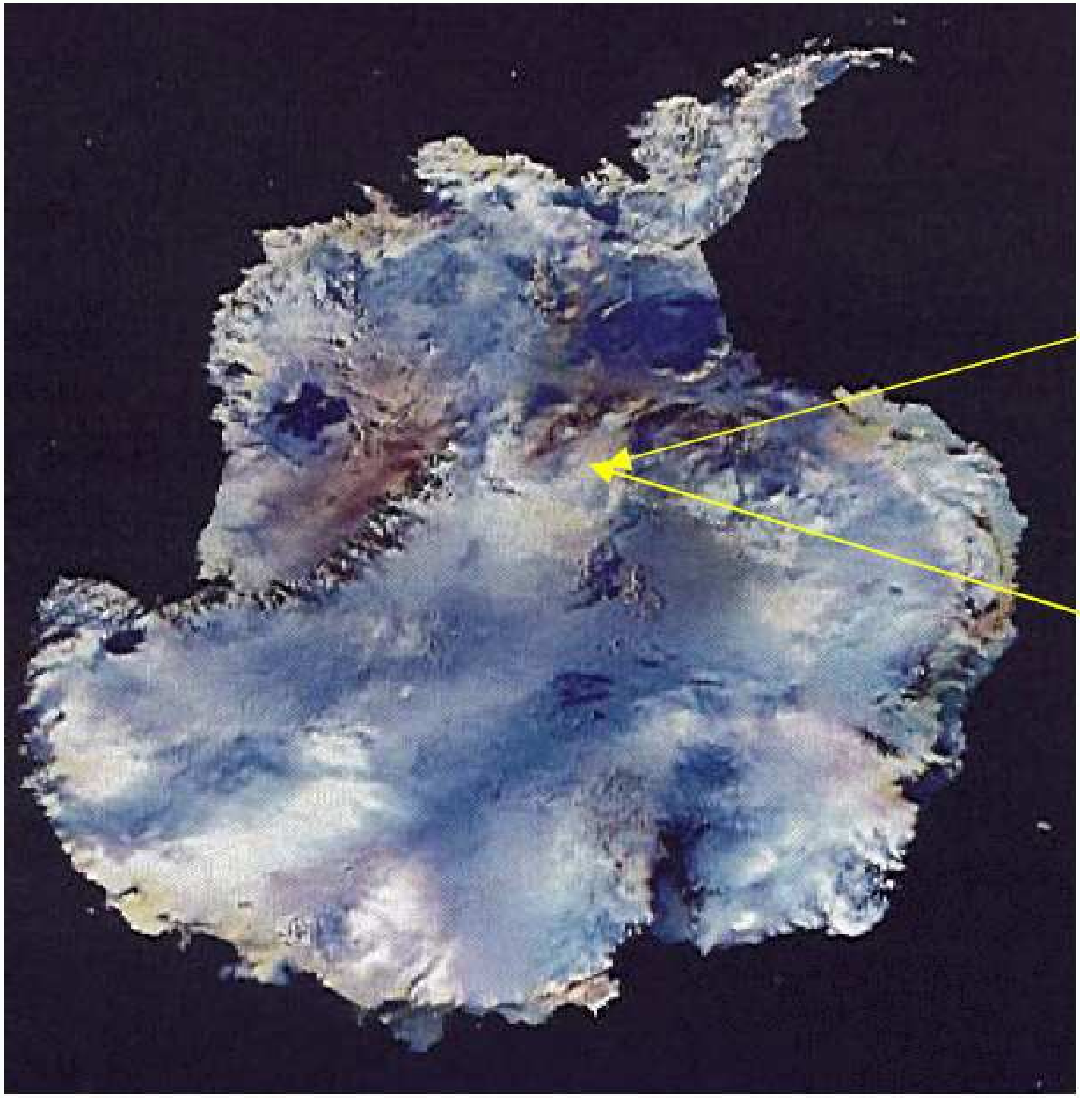
promieniowanie Czerenkowa mierzone przez skierowane do dołu fotopowielacze

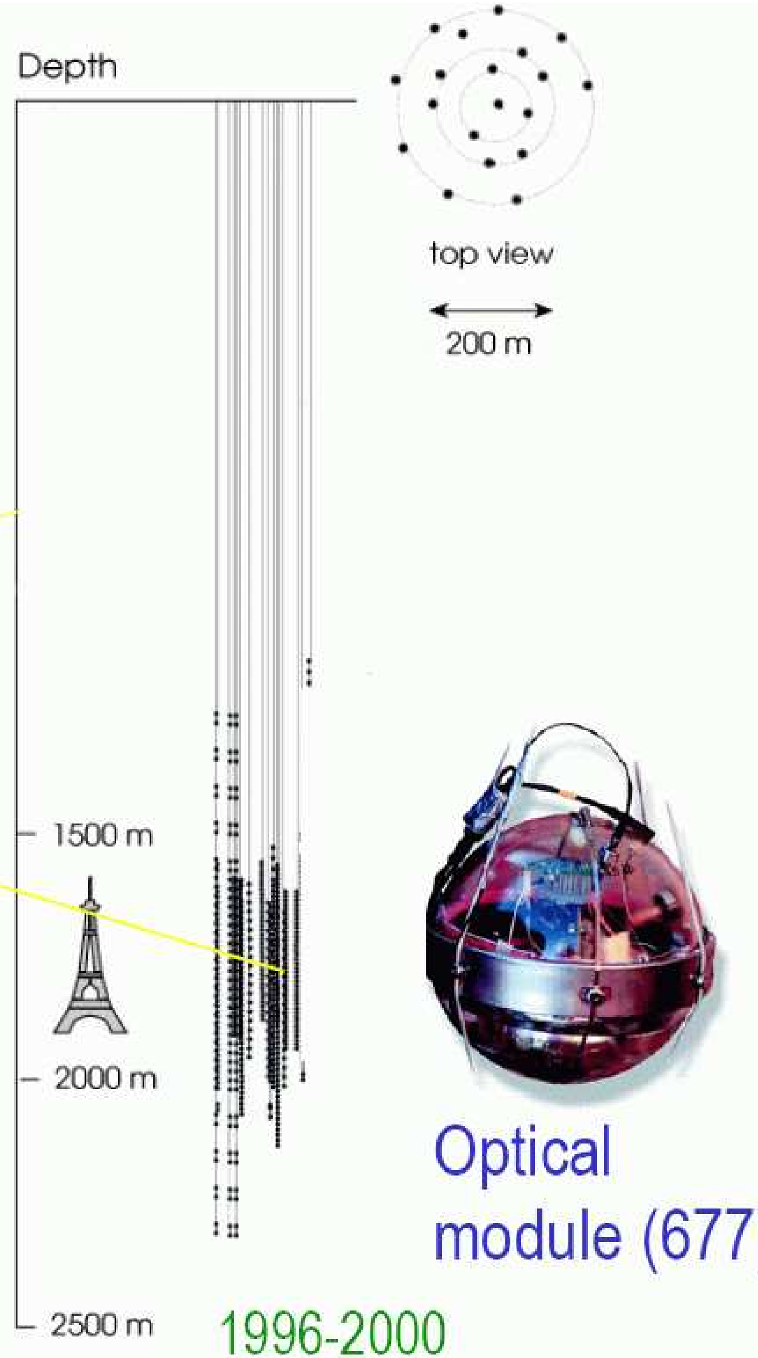
Obszar aktywny: ok. 40 mln. ton lodu (!)

Rejestracja mionów o energiach $\geq$50 GeV.

Eksperyment AMANDA w

Amundsen-Scott Station South Pole

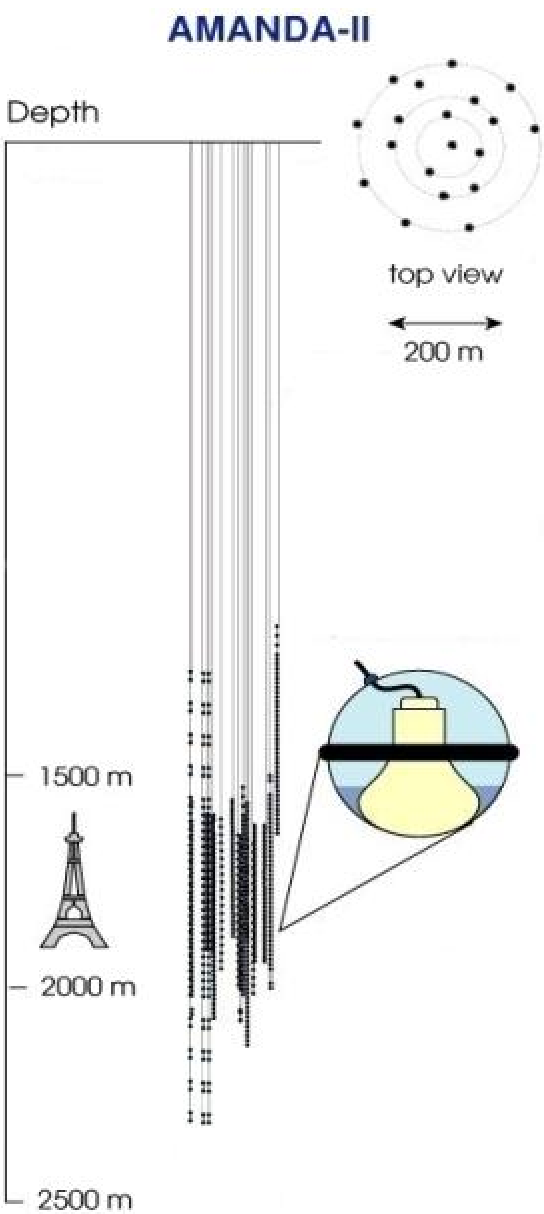


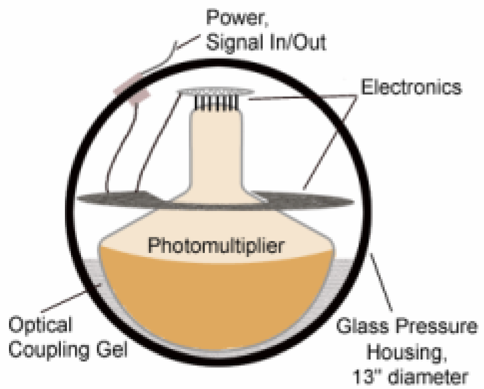


AMANDA

South Pole

AMANDA

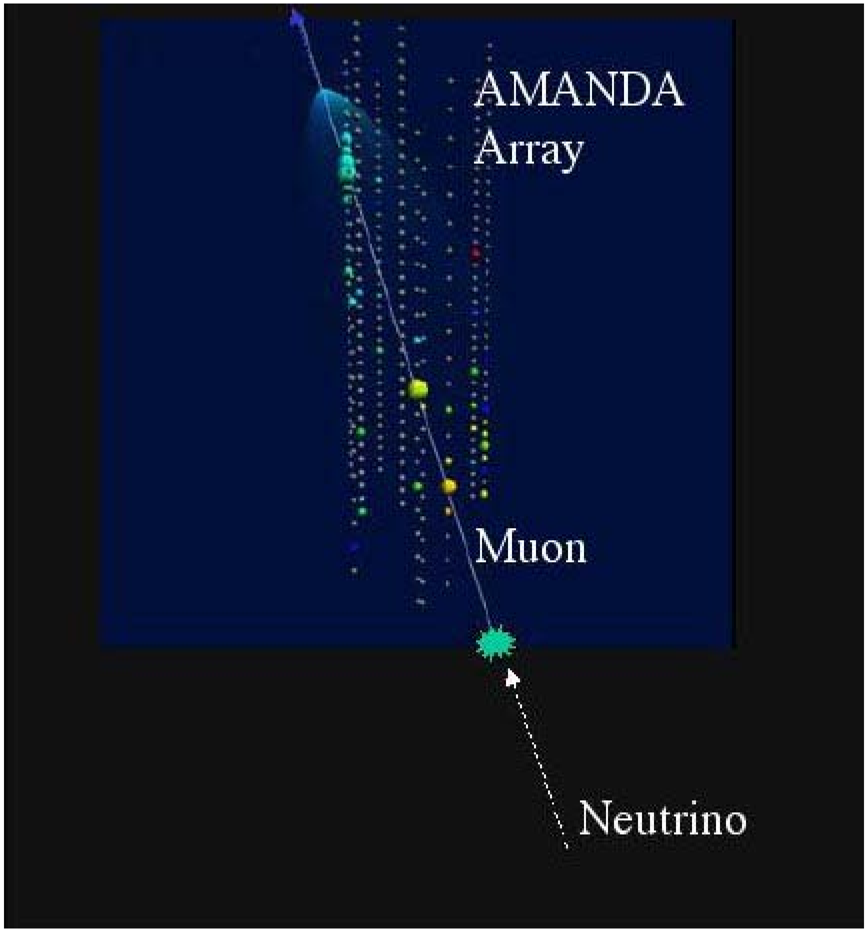

AMANDA-II
Depth
top view
200 m
1500 m
2000 m
2500 m


Power,
Signal In/Out
Electronics
Photomultiplier
Optical
Coupling Gel
Glass Pressure
Housing,
13" diameter

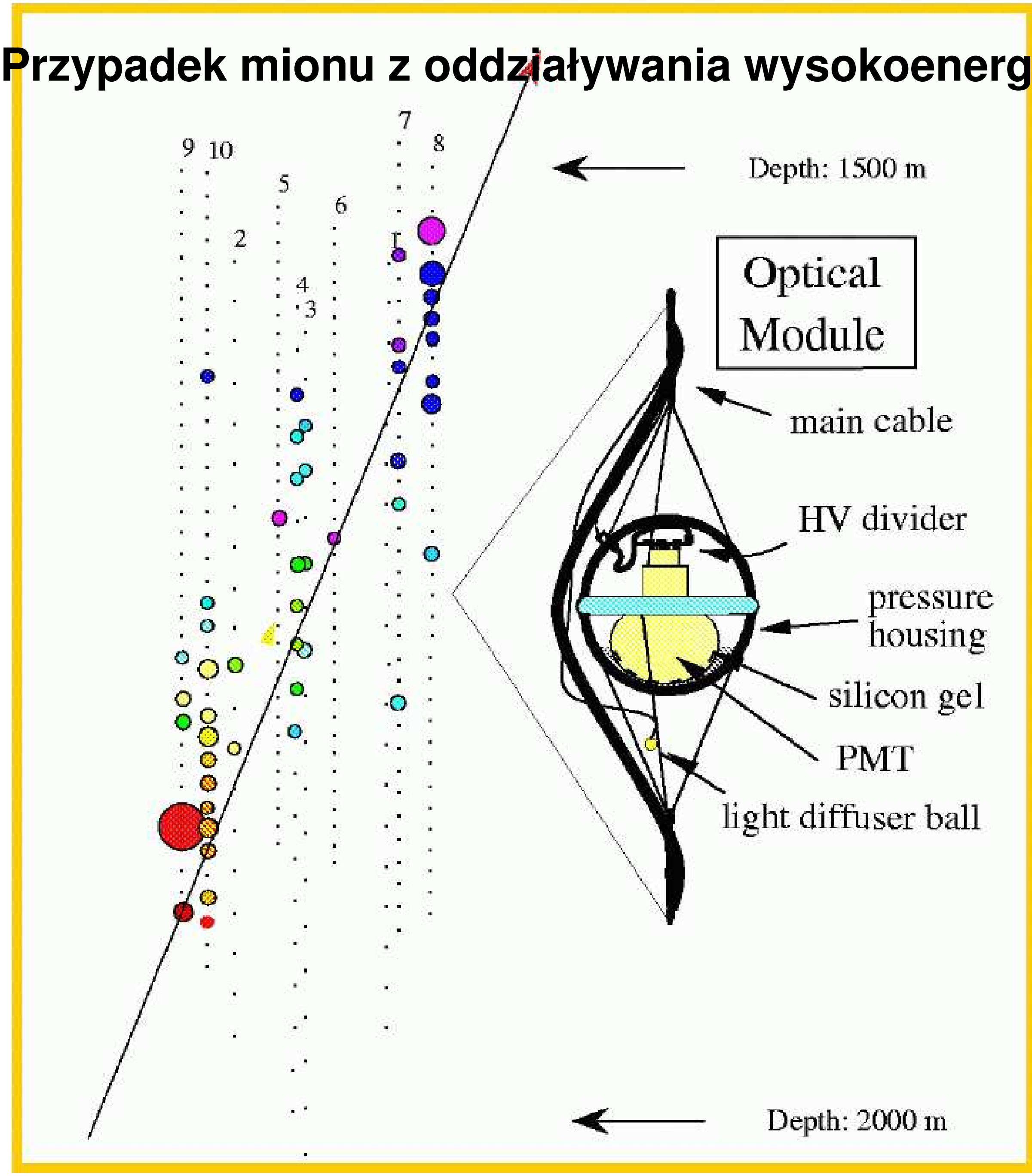
AMANDA

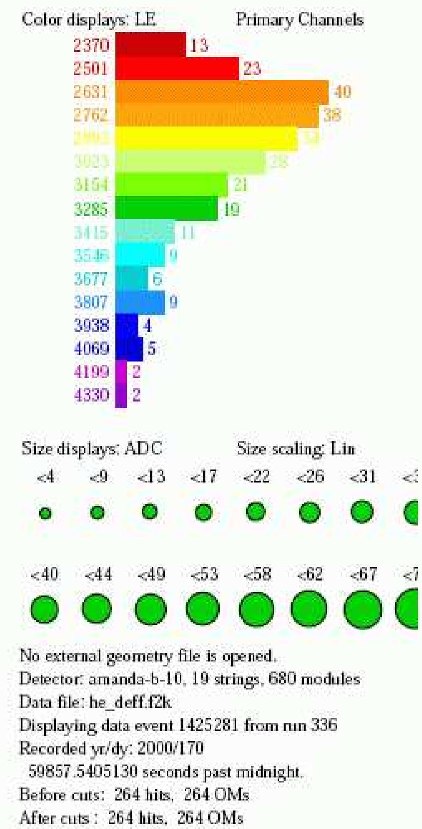
Look for upwards going Muons from Neutrino Interactions.
Cherekov Light propagating through the ice.

→ Find neutrino point sources in the universe !



Przypadek mionu z oddziaływania wysokoenergetycznego neutrina





200 TeV ν_e candidate

AMANDA

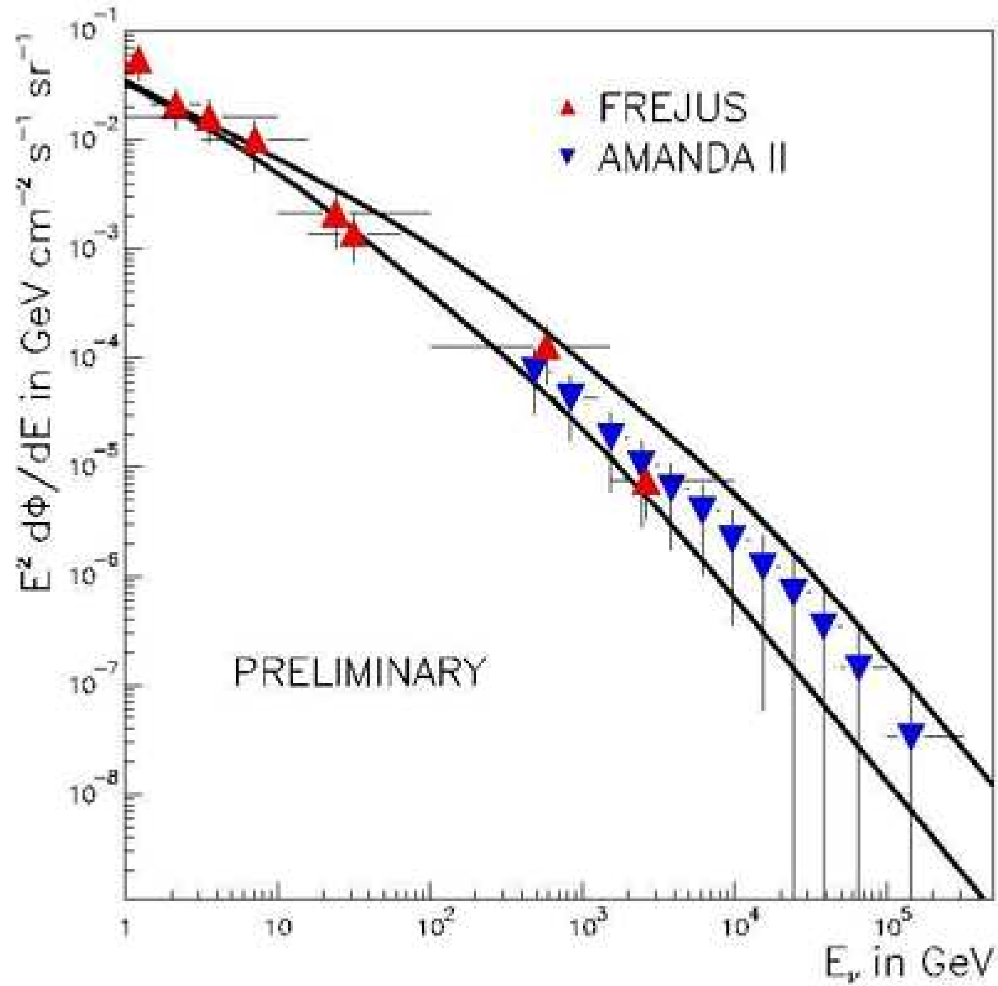
Badania

Duże odległości między licznikami powodują, że detektor czuły jest tylko na neutrina o bardzo wysokiej energii - wyprodukowane w ich oddziaływaniach cząstki muszą mieć zasięg porównywalny z rozmiarami detektora.

Poszukiwanie neutrin stowarzyszonych z:

- wybuchami supernowych
- błyskami gamma (GRB)
- gwiazdami neutronowymi
- ...

Mierzony rozkład energii neutrin

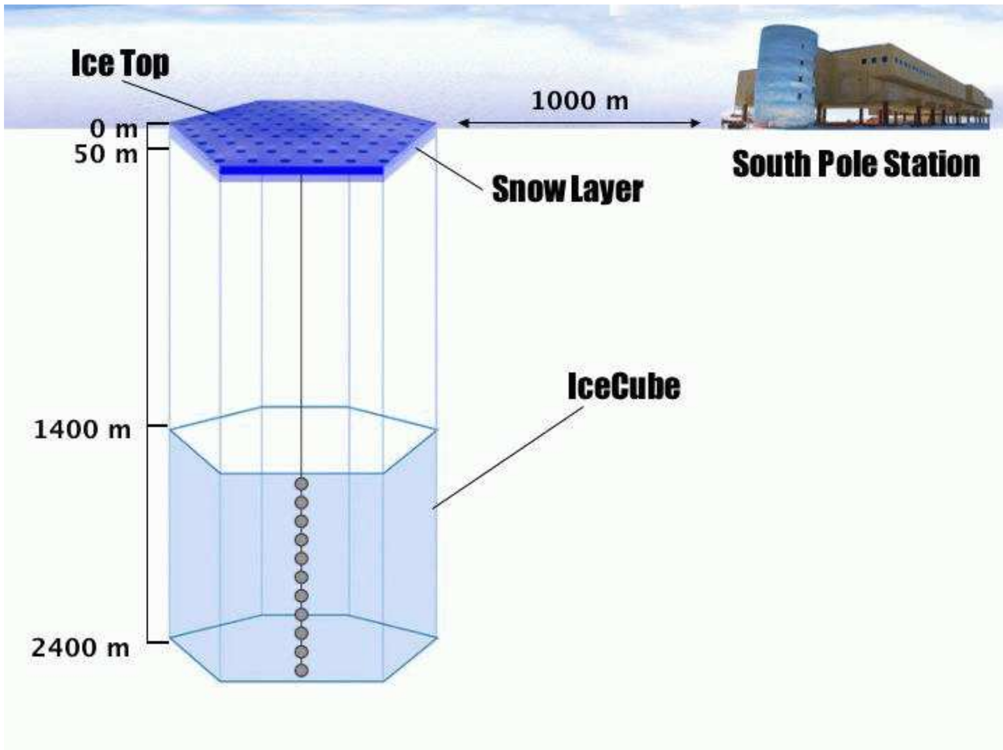


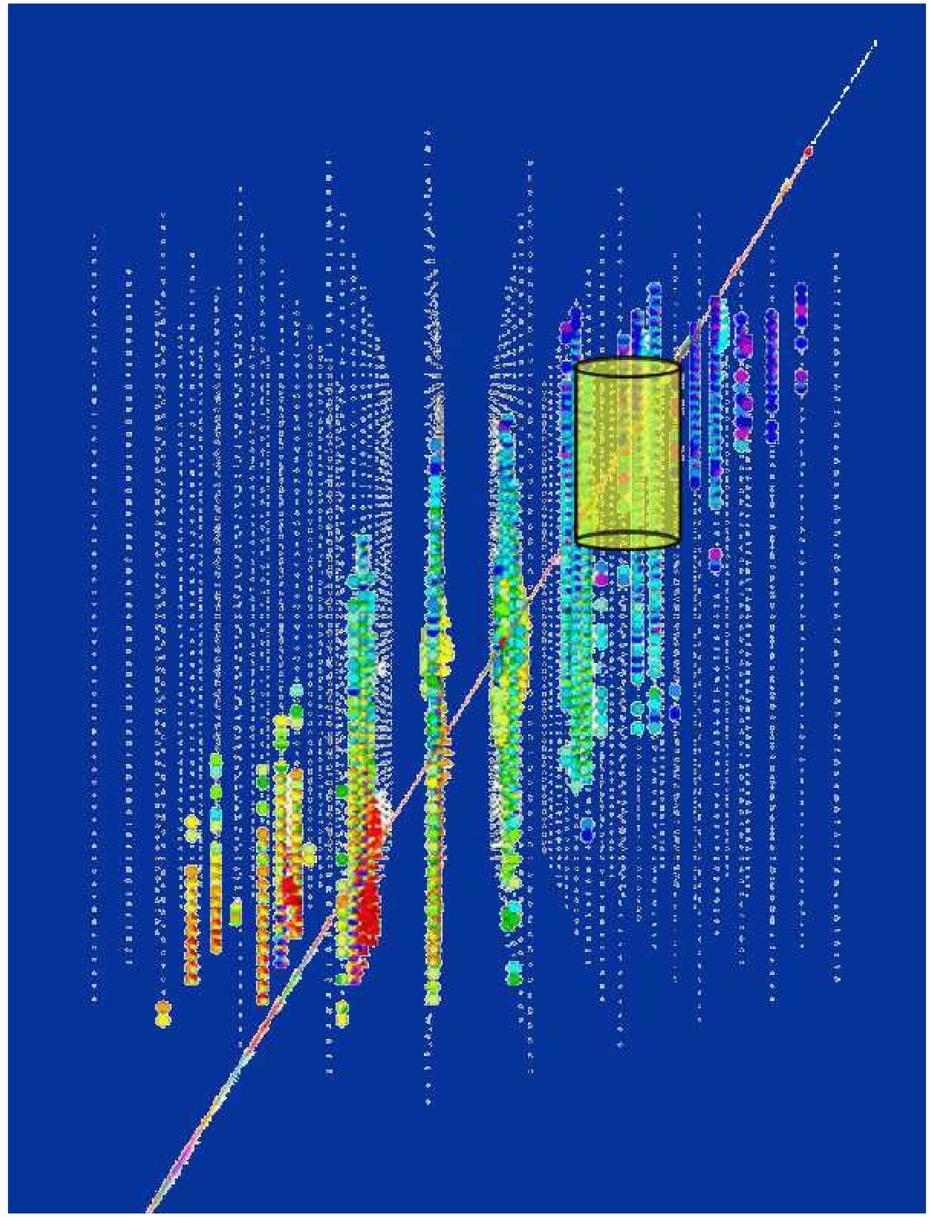
IceCube

"Następca" AMANDY

Sensory mają wypełnić obszar 1 km^3 lodu

$\Rightarrow$ 1 gigatonowy detektor





The detector, at the South Pole

Very large scale hybrid observatory

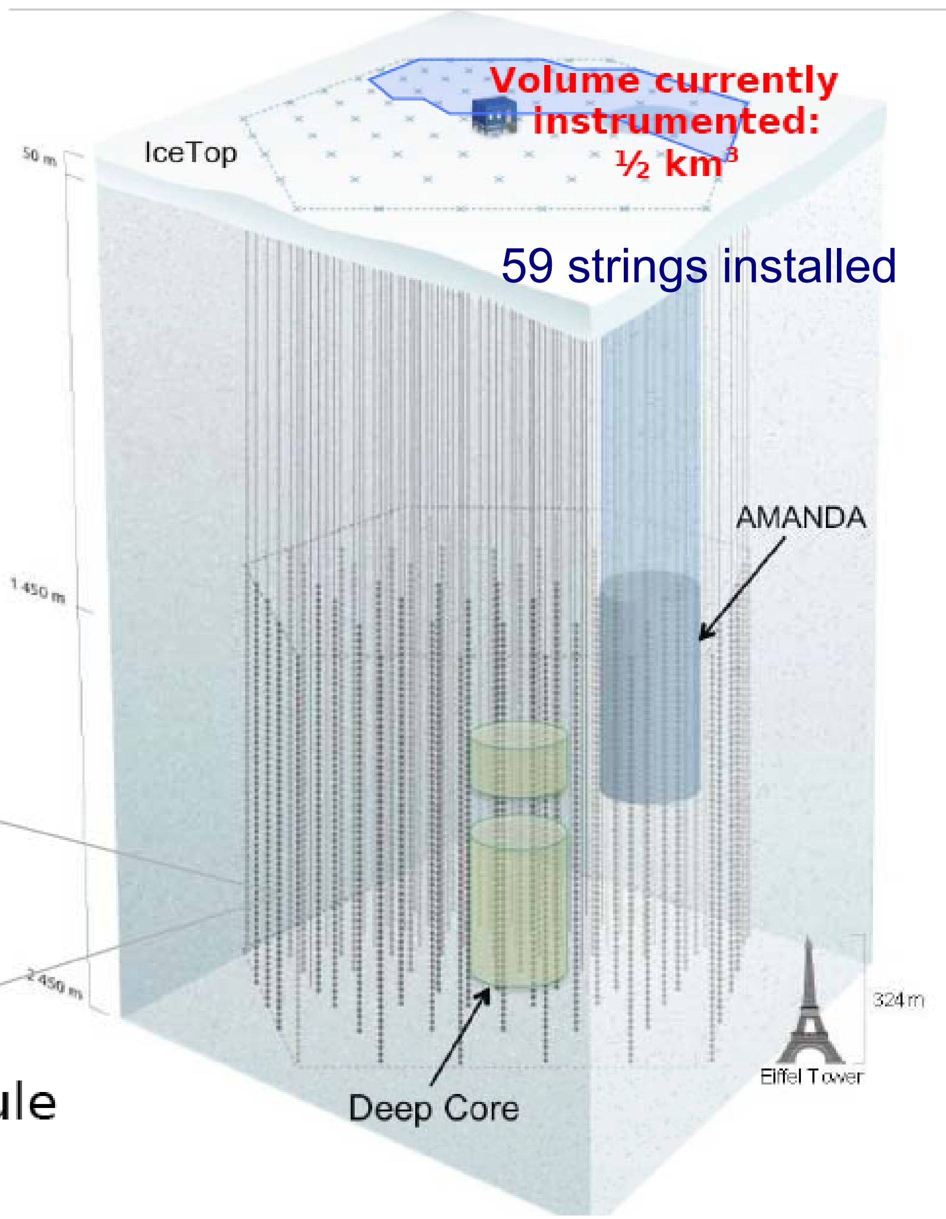
- 1km approximate diameter

<u>IceTop</u>

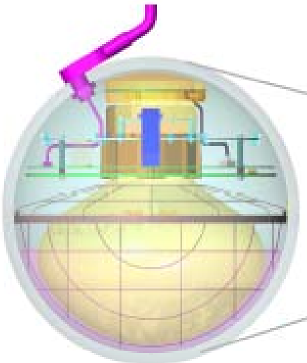
- Surface Air-Shower detector array
- Approximate threshold: 300 TeV

<u>IceCube</u>:

- 80 strings with 60 Digital OM's per string
- 125m interstring spacing, 17m DOM spacing



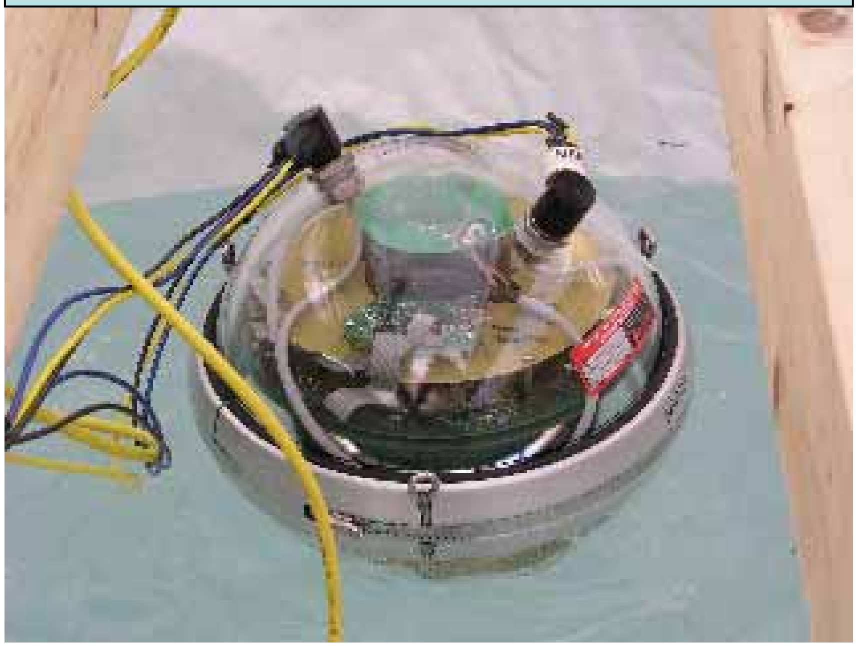
- 5^{th} drilling season starting.
- IC40 taking data
- Plan to deploy 16 IceCube strings



Digital Optical Module (DOM)

The first DOMs have been frozen into IceTop test tanks.

IceTop-DOM freezing into place, January 2004



Picture by John Kelly / NSF

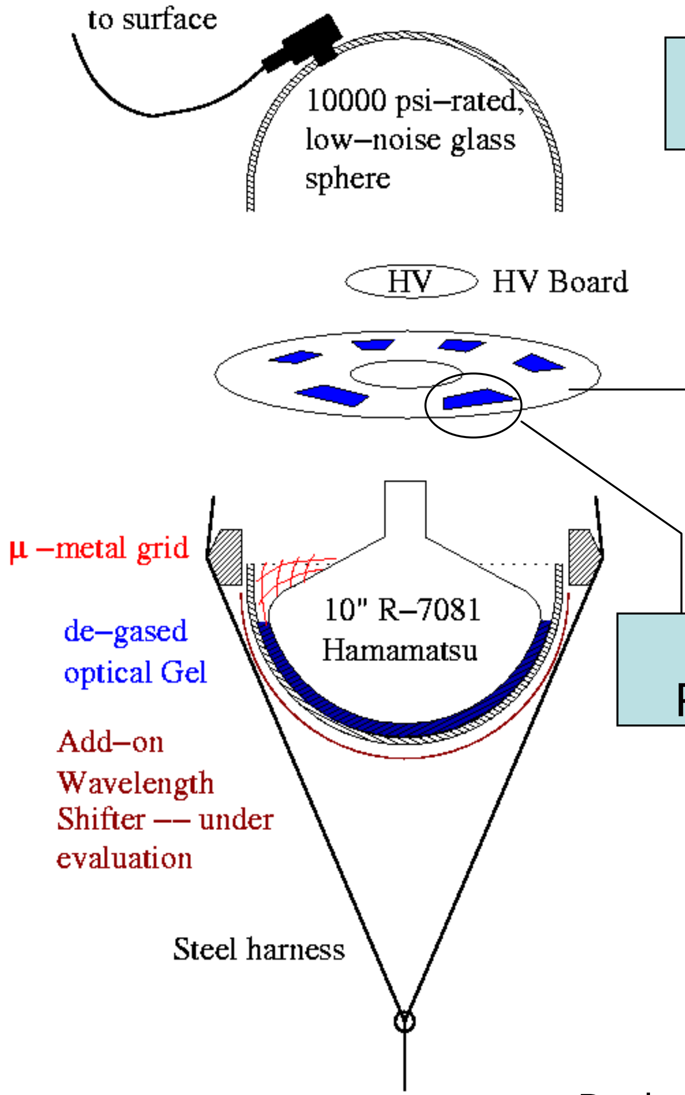
Proof of principle for IceTop

Muon telescope mounted on top of tank, UTC time stamps

- DOMs collect UTC time-stamped waveforms
- match-up nicely shows a muon peak from DOM data

… passed!

Digital optical modules (DOMs) are the IceCube building blocks.



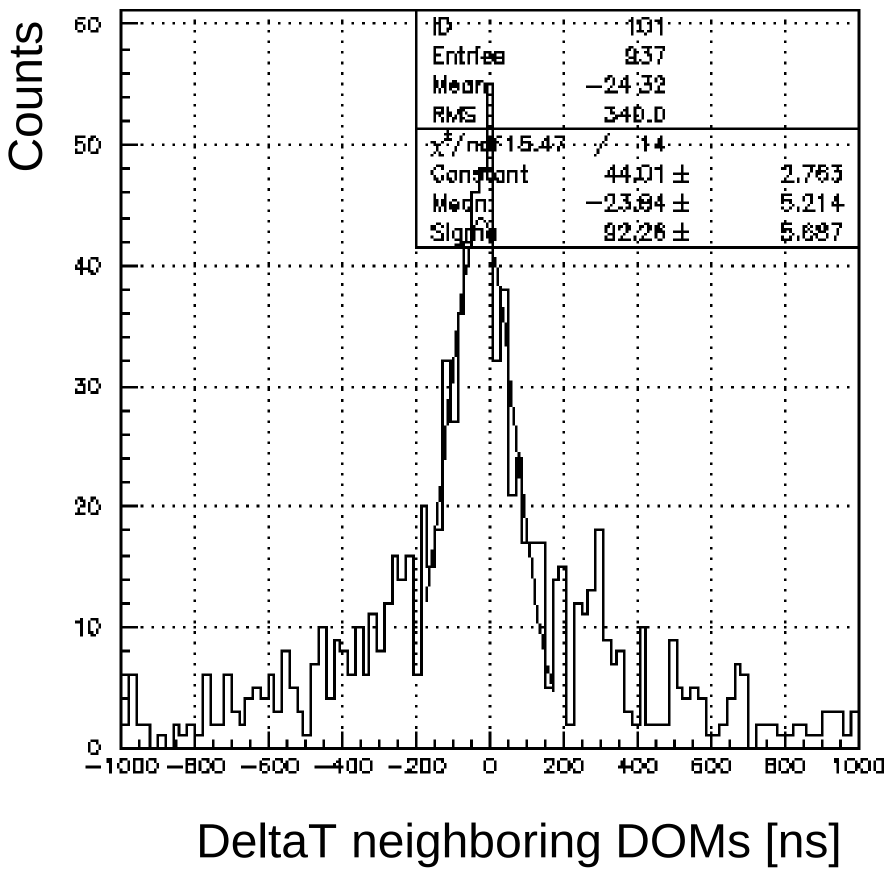
MainBoard

- **CPU/memory** self-test mode, data taking mode
- **logic chips** fast, programmable
- **clock** and other electronic gadgets
- **digitizers** (see below)
- **single-photo-electron LED**

6 LED Flasher Board

- **405nm LEDs,** up to 200m range in Antarctic ice
- study **IceCube geometry**
- study **ice properties**
- simulate **neutrino signals**

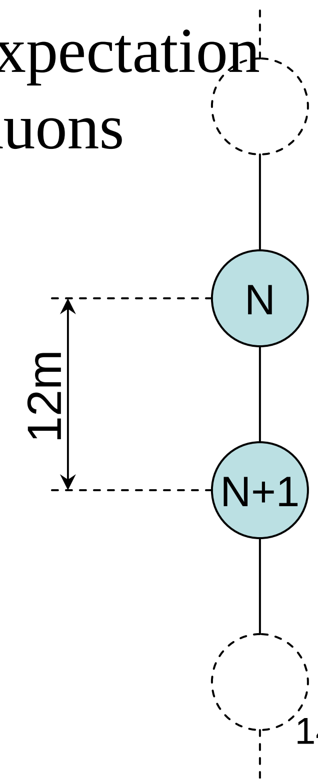
In AMANDA, String 18, timing has been checked with muons.



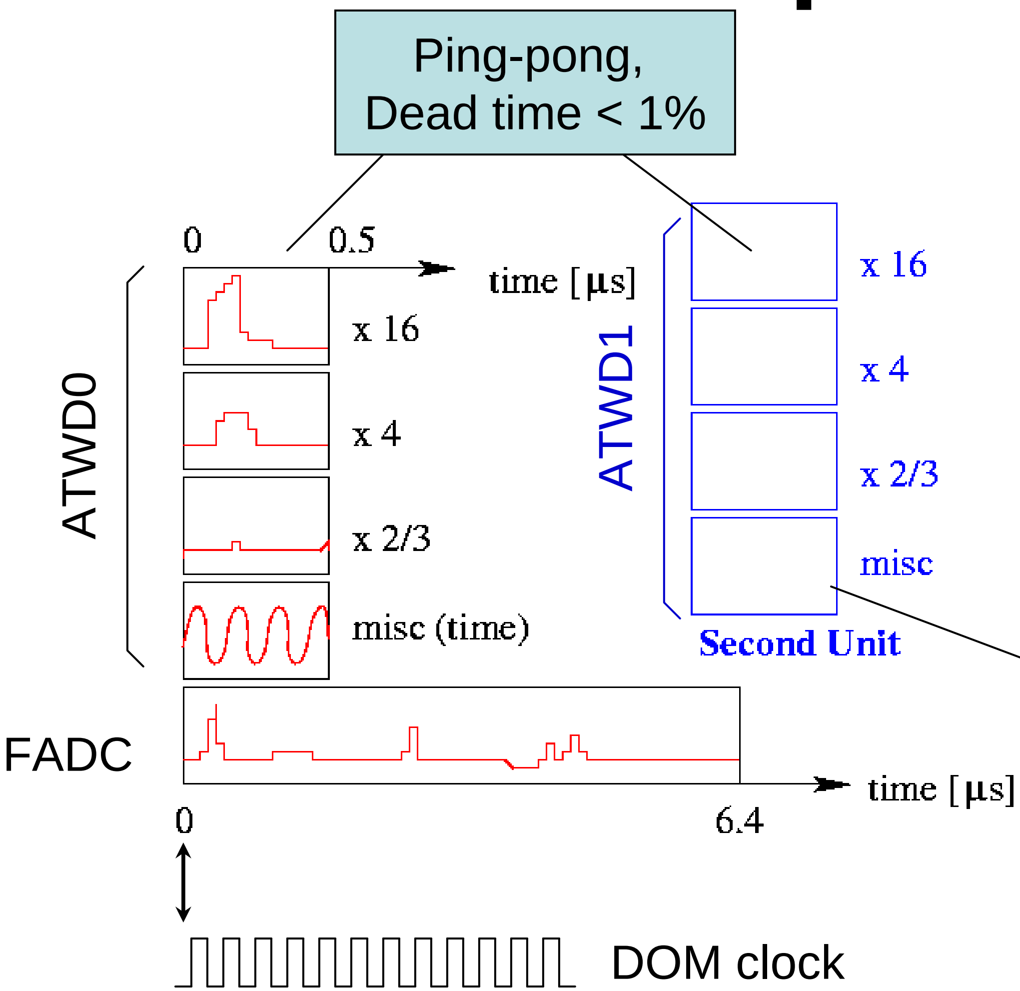
DeltaT = T (DOM N) - T (DOM N+1)

Zoom around [-1,+1] μsec :

- Mean at ~ -24 nsec
- Consistent with expectation for downgoing muons with v ~ c



DOMs trigger on, digitize, and time-stamp PMT signals.



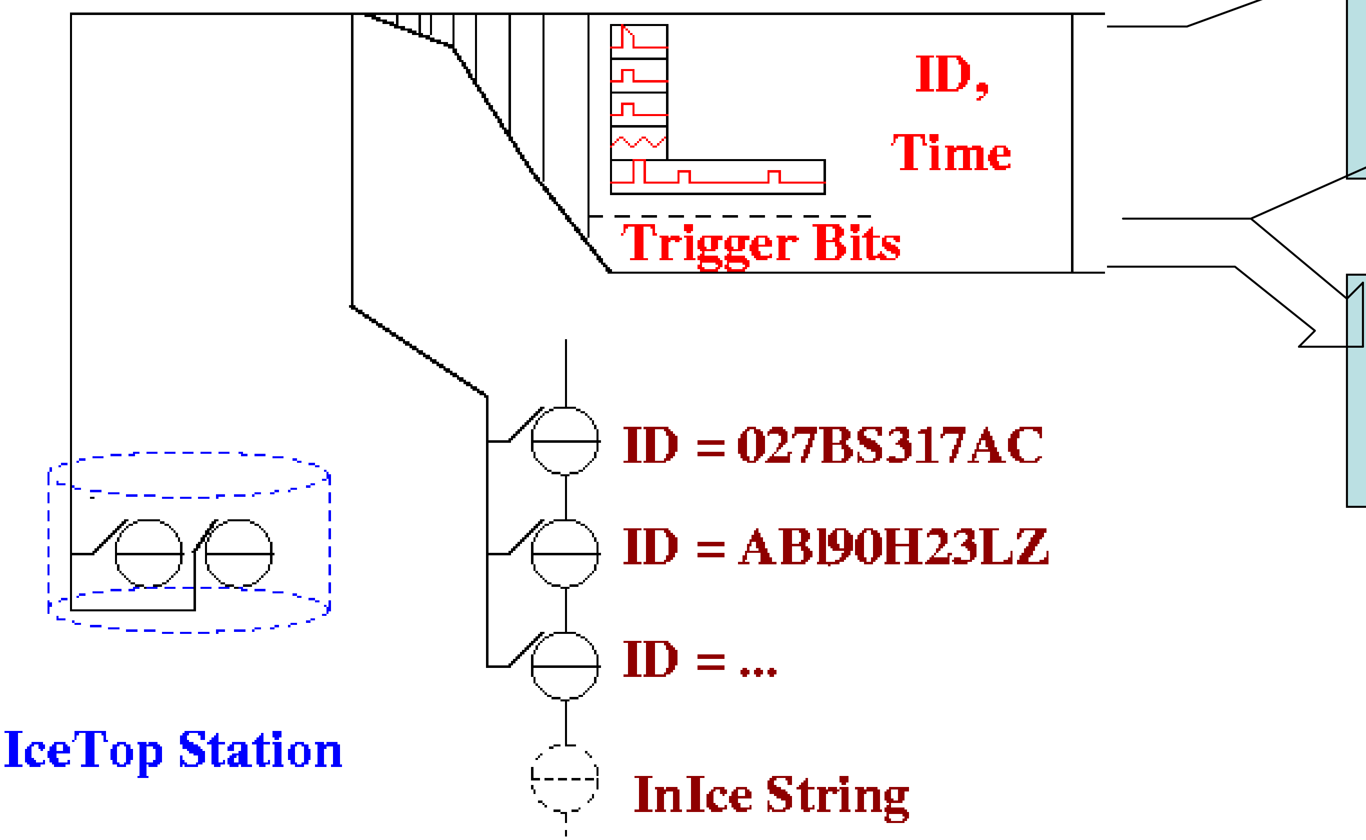
< 5ns RMS time resolution

Sampling with
330MHz for ~0.5µs
40MHz for ~6µs

Resolution
>200 pe / 15ns
>2000pe / 5µs

Selectably feed:
DOM clock, LED currents, many more input possibilities

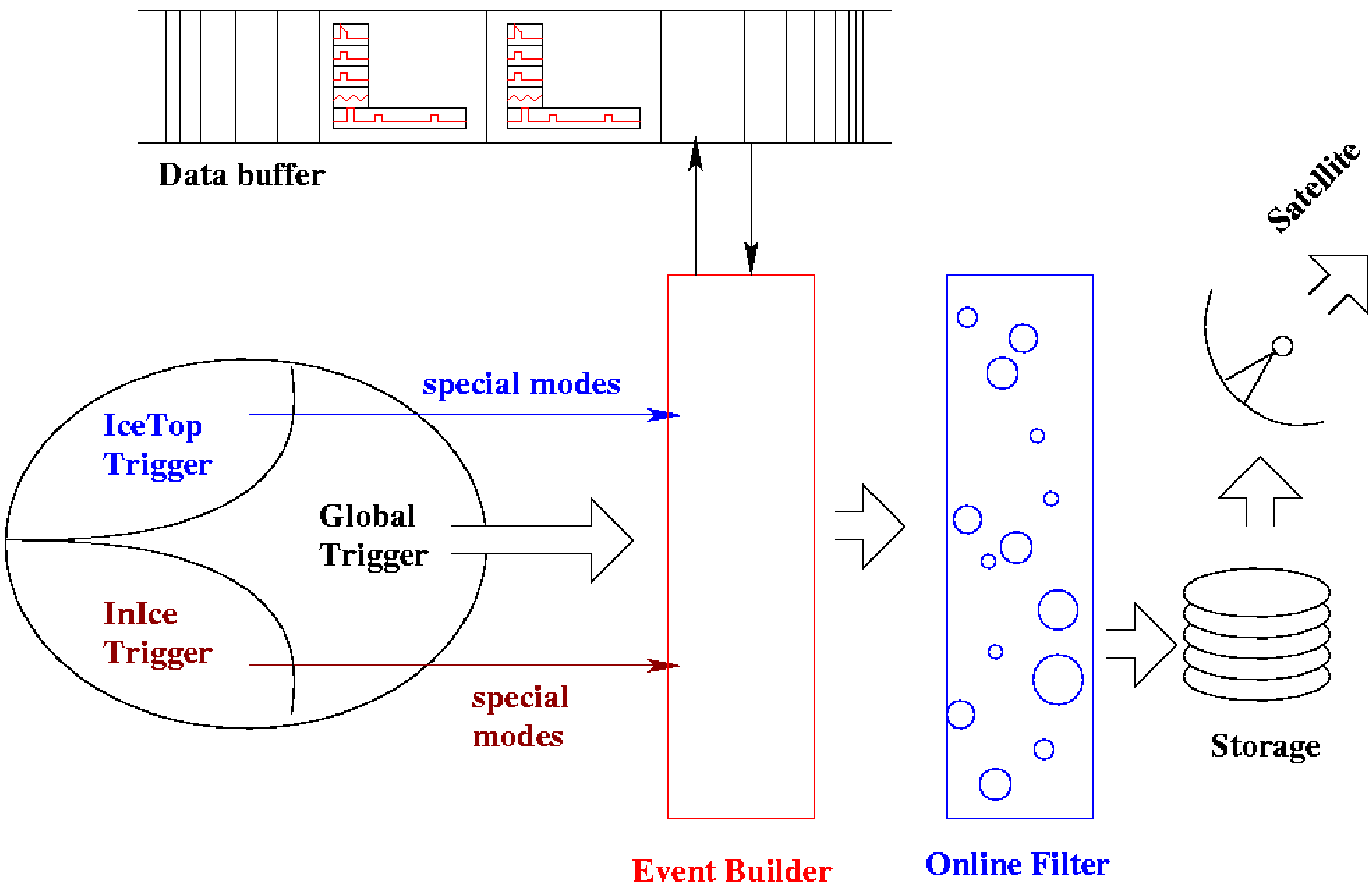
Waveforms get buffered while the trigger is formed.



to minute-deep **buffer** for later event building

to **IceTop Trigger** resp. **InIce Trigger**

InIce- and IceTop-triggers form an IceCube trigger.



CERN Neutrino Gran Sasso

(CNGS)

CNGS Project

CNGS (CERN Neutrino Gran Sasso)

- **A long base-line neutrino beam facility (732km)**
- **send ν_μ beam produced at CERN**
- **detect ν_τ appearance in OPERA experiment at Gran Sasso**

➔ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

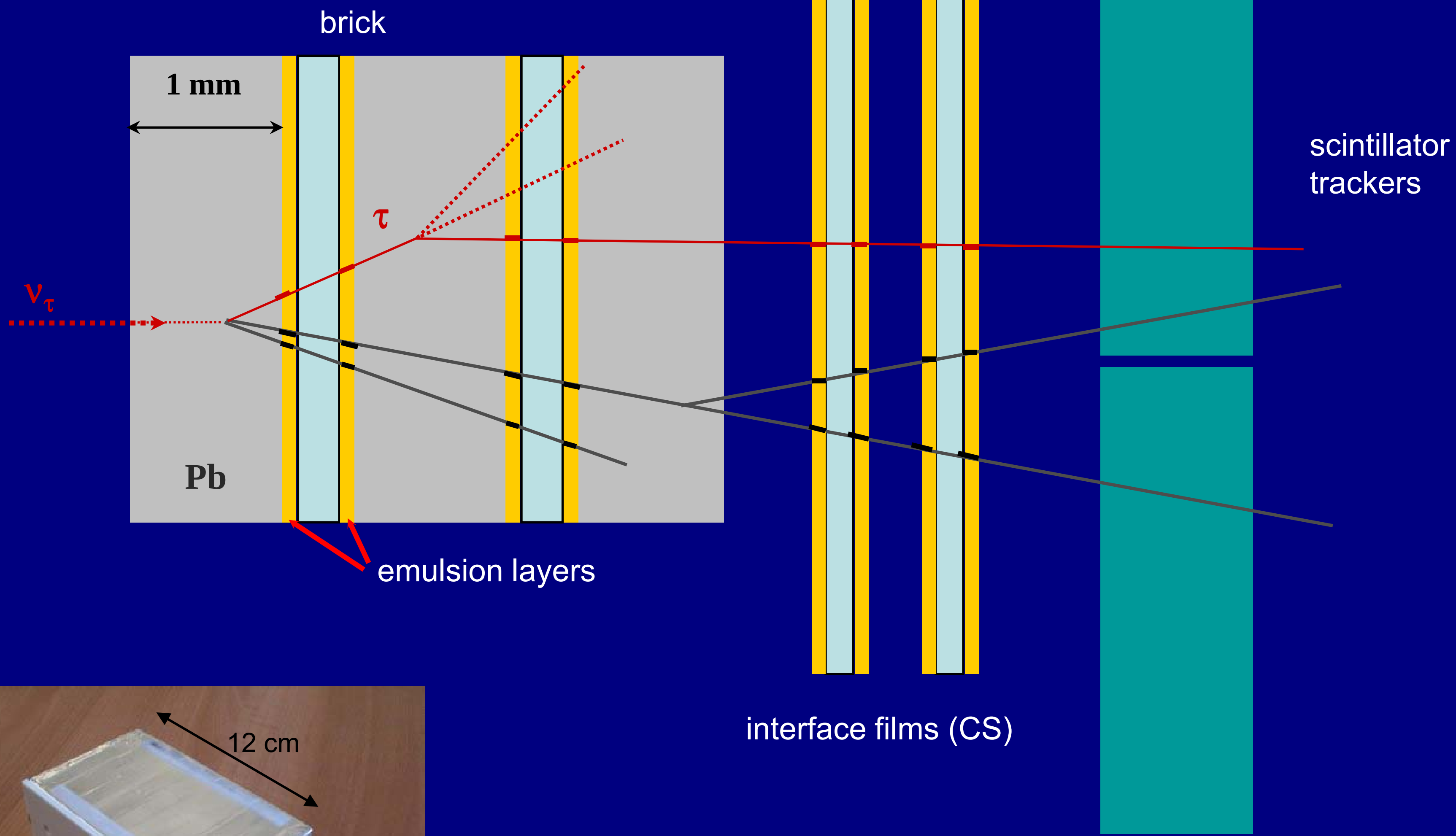
Neutrinos at CNGS: Some Numbers

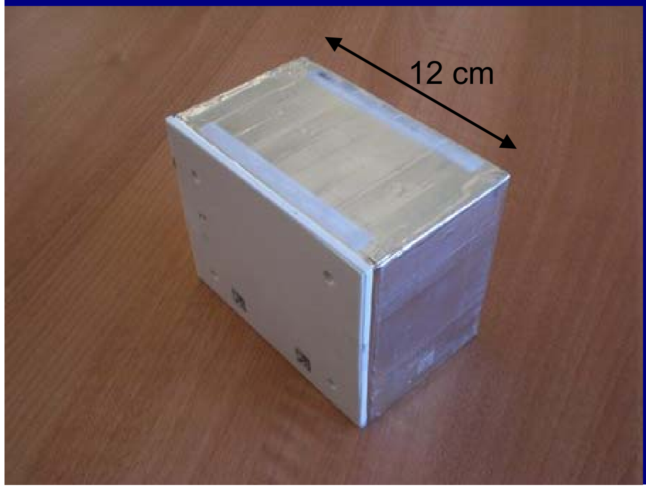
For 1 day of CNGS operation, we expect:

protons on target	**2 x 10^{17}**
pions / kaons at entrance to decay tunnel	**3 x 10^{17}**
ν_μ **in direction of Gran Sasso**	**10^{17}**
ν_μ **in 100 m^2 at Gran Sasso**	**3 x 10^{12}**

ν_μ events per day in OPERA	≈ 25 per day
ν_τ events (from oscillation)	≈ 2 per year

OPERA detector concept

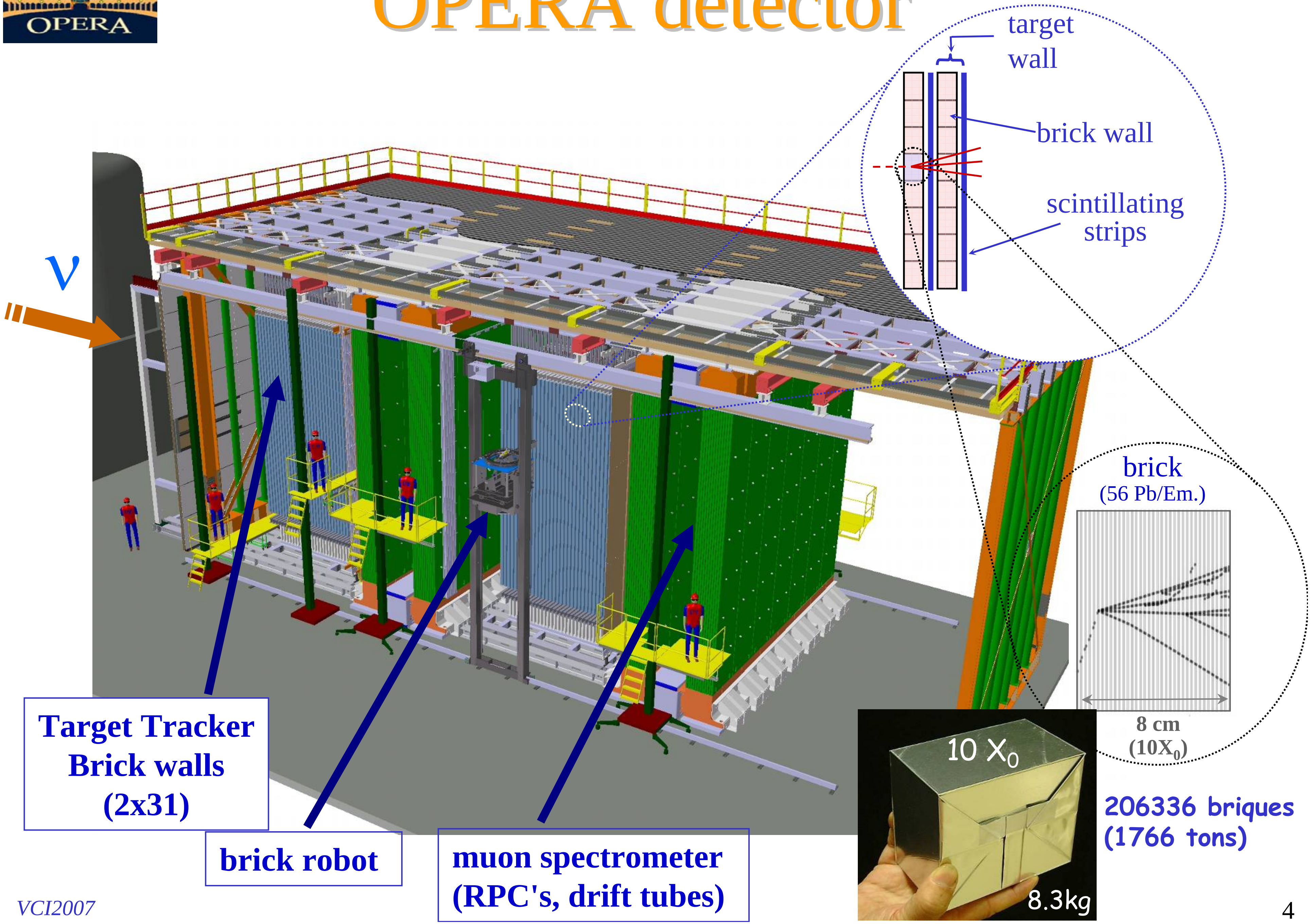




Neutrino target: 150000 bricks

57+2 emulsion films and 57 1mm lead plates per brick
For a total of 105000 m^2 of lead surface
and 111000 m^2 of film surface (~ 8.9 million films)

OPERA detector

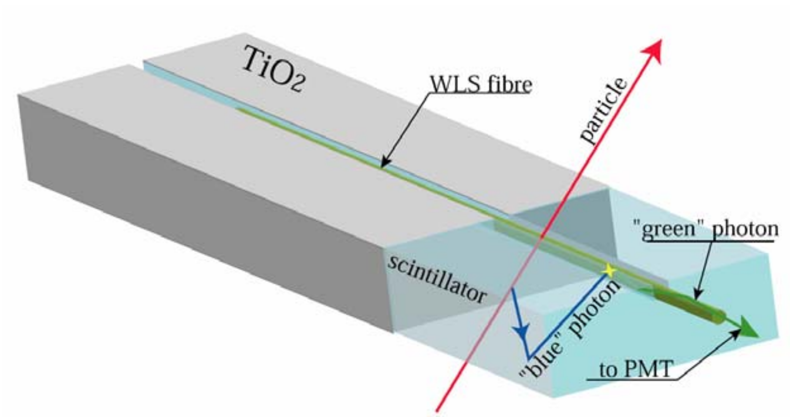


206336 briques
(1766 tons)

M. Dracos

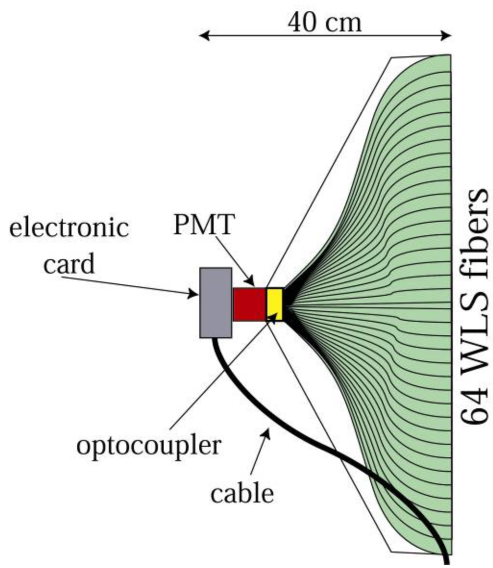
Target Tracker

(Bern, Brussels, Dubna, Neuchâtel, Orsay, Strasbourg)

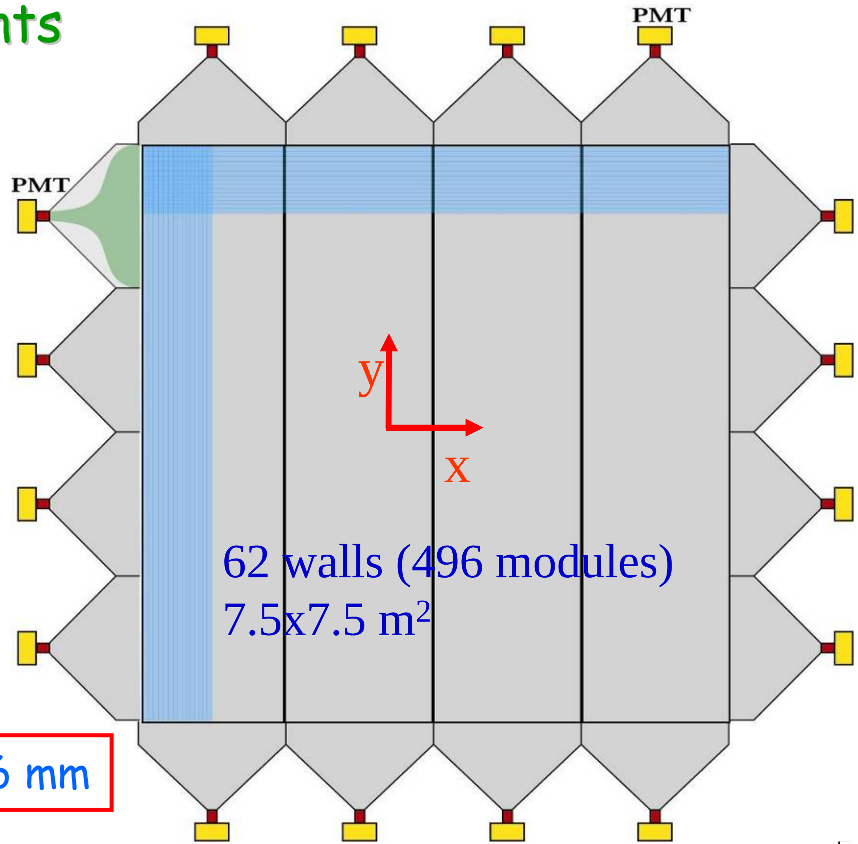


- detection technique: polystyrene scintillating strips (plastic)
- role:
  - find the "good" Pb/emulsion brick
  - calorimetric information on neutrino events

Hamamatsu MA-PMT (64 channels) 3x3 cm^2



TT wall thickness<36 mm

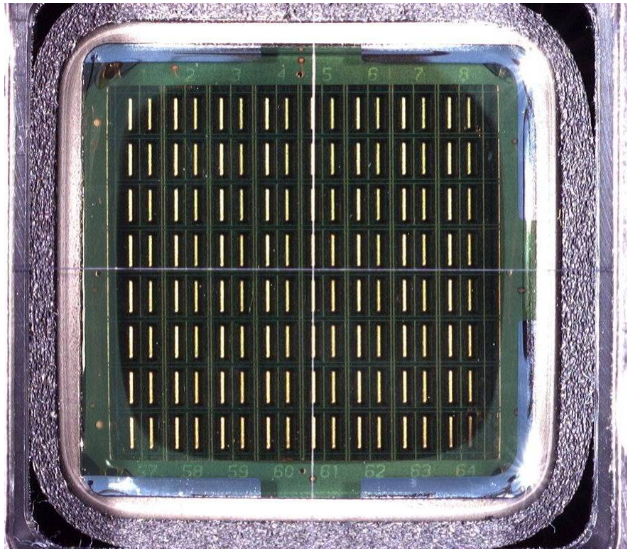


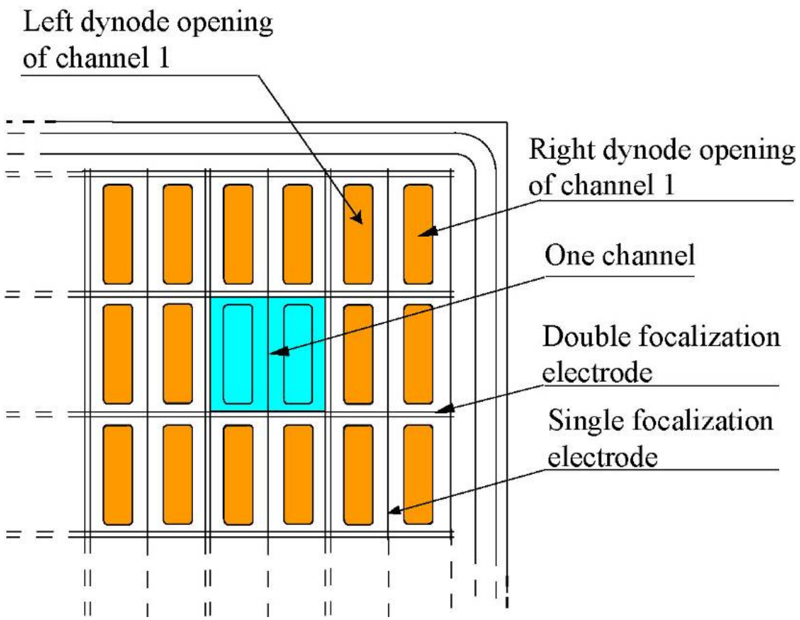
M. Dracos

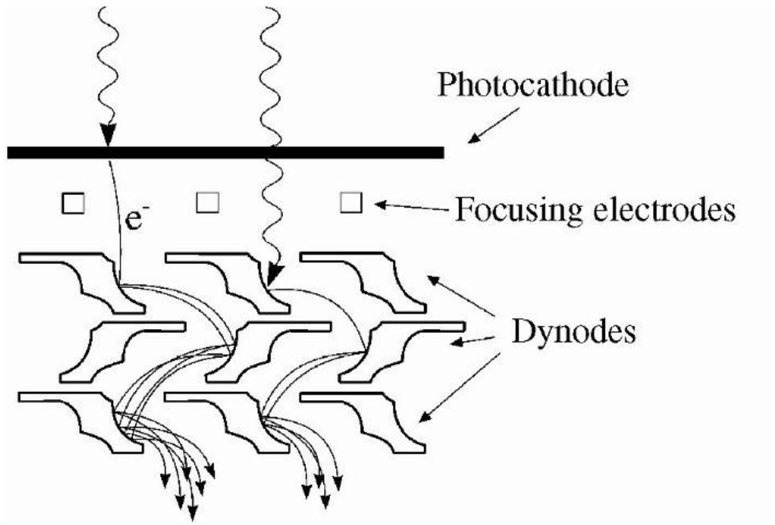
Photomultipliers

H8804MOD-1 (OPERA)

- Hamamatsu multianode photomultipliers
- 8x8 cannels
- Quantity: 1040
- Suitable for OPERA dimensions

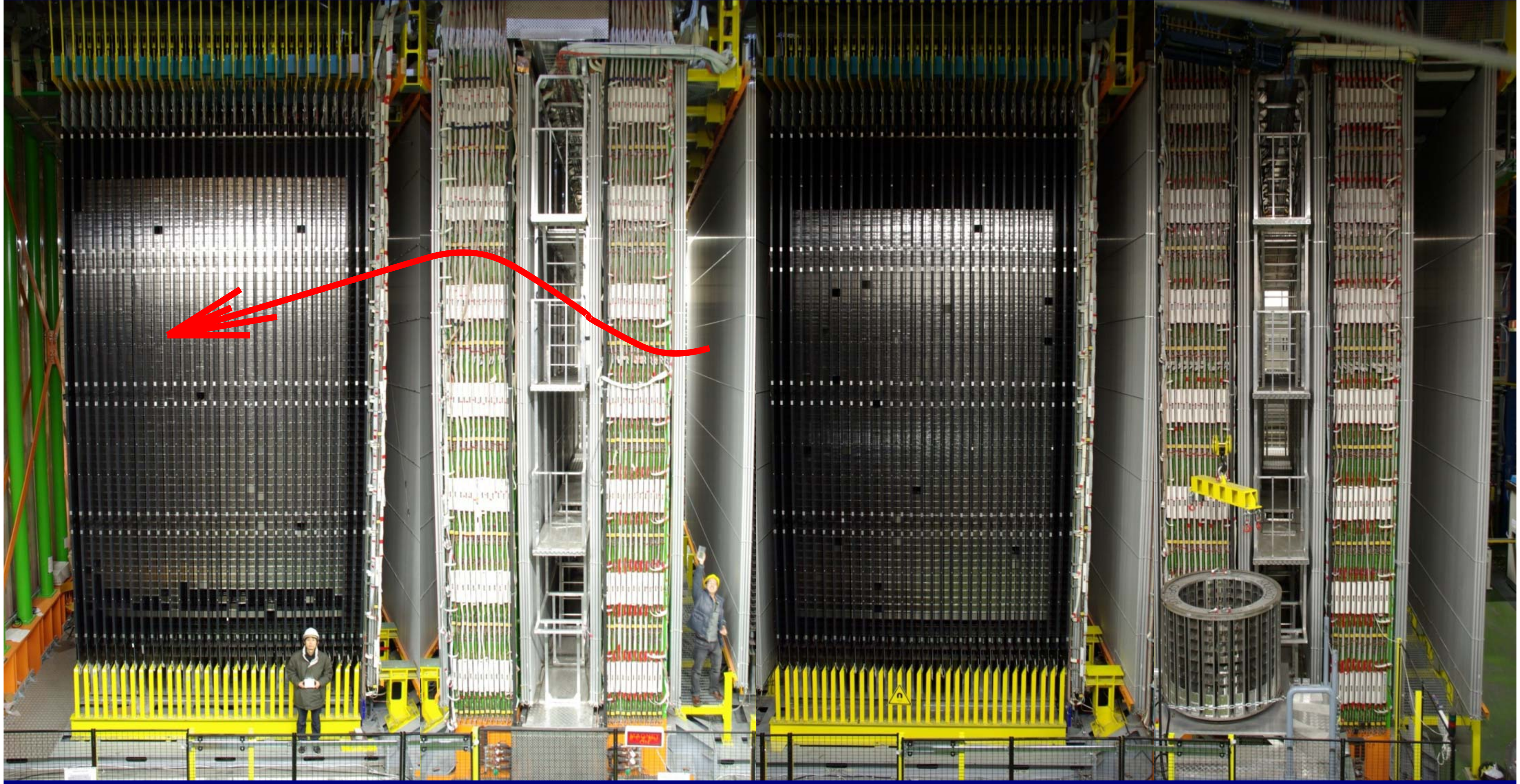




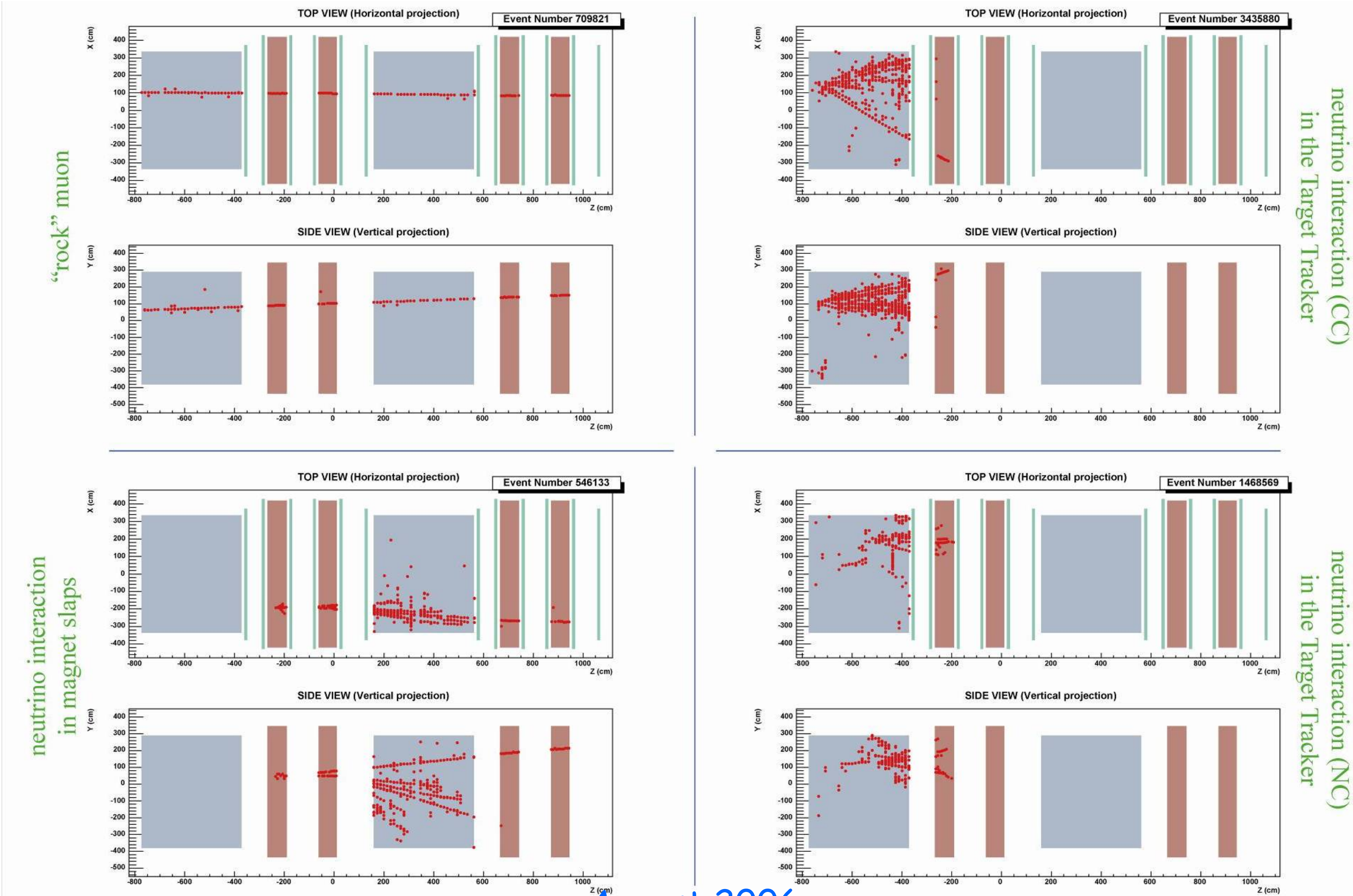


M. Dracos

Detector installation



CNGS events



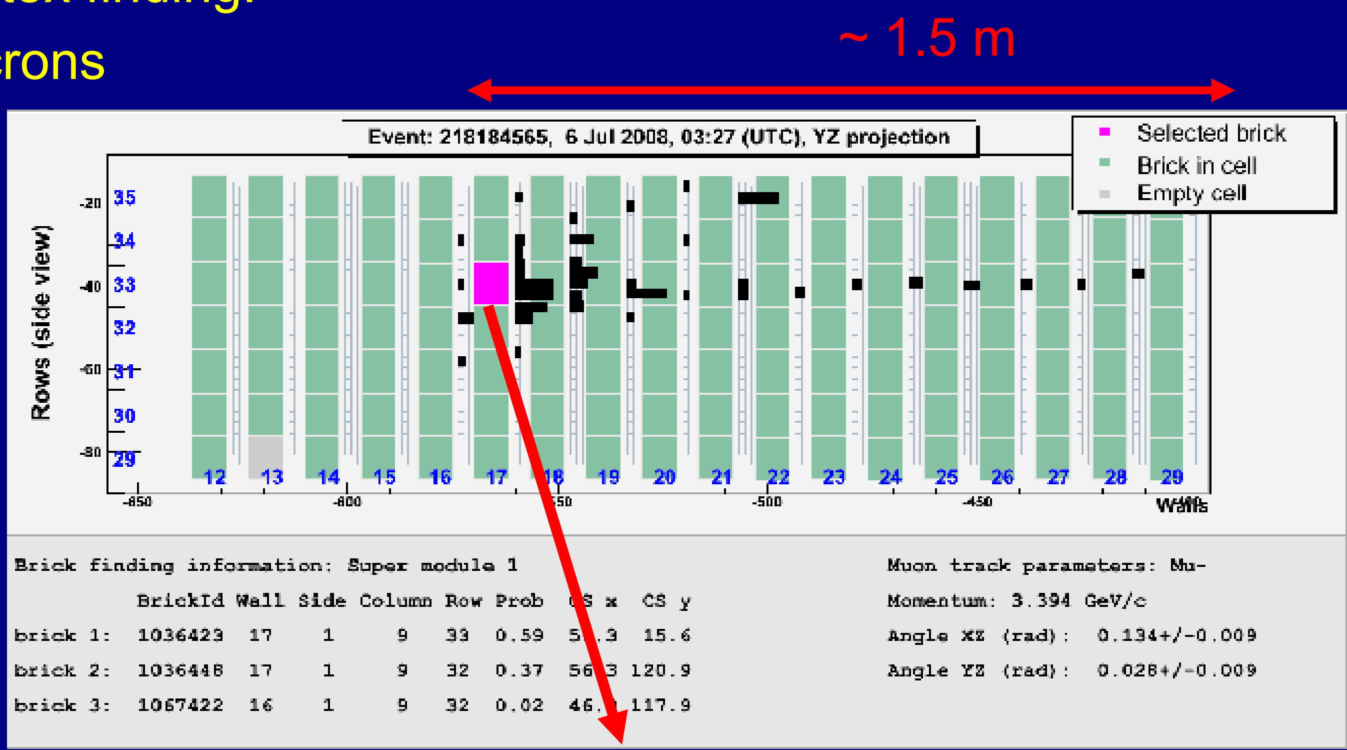
August 2006

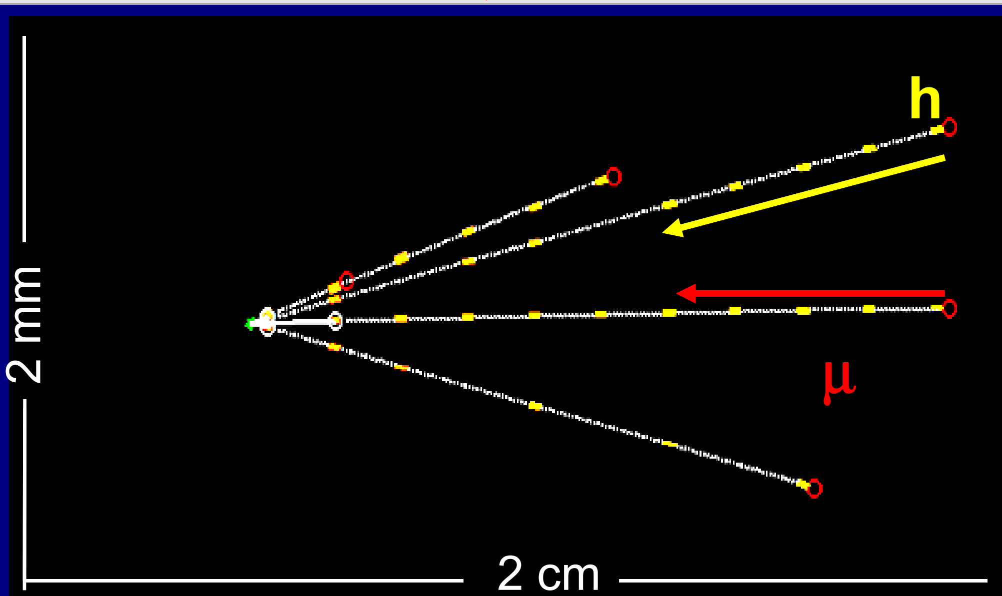
Automatic high-speed microscopes (~ 40 in the collaboration)

LHEP Bern: Swiss Scanning Station with 5 microscopes. ~10 physicist from Bern and ETHZ involved. Largest european laboratory

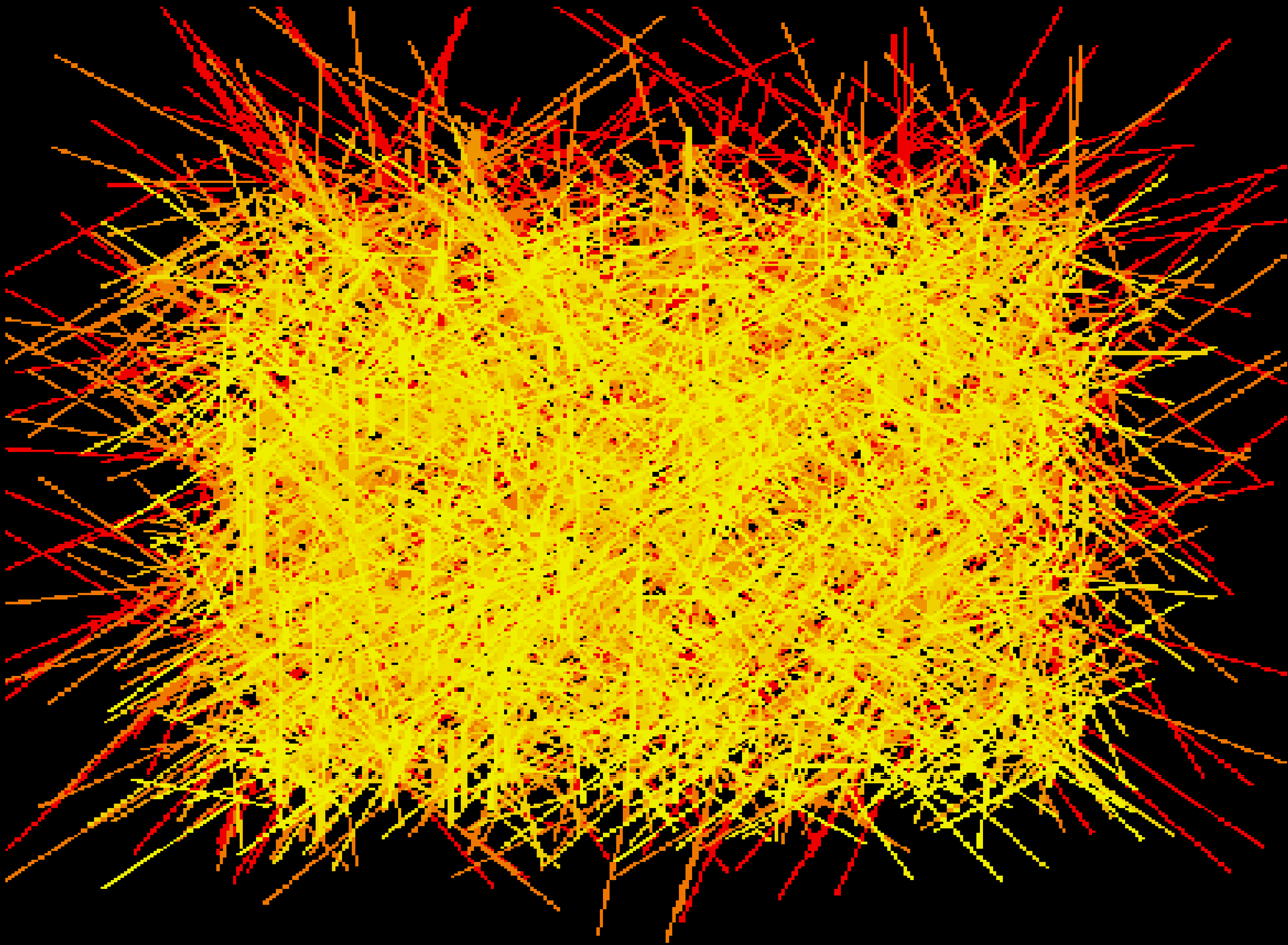
Goal: analyze ~ 20% of the total OPERA brick statistics (up to1000 brick/year).

From trigger to vertex finding: from meters to microns

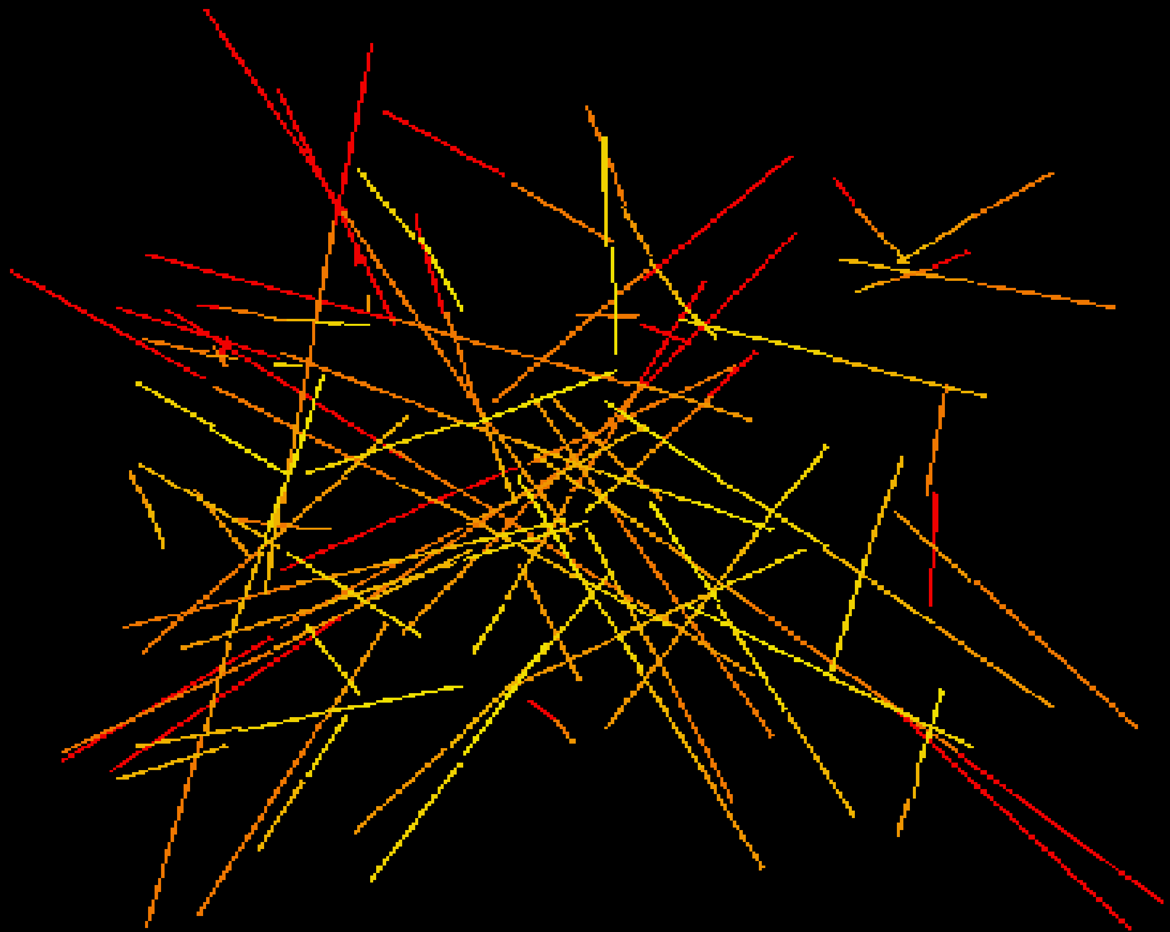




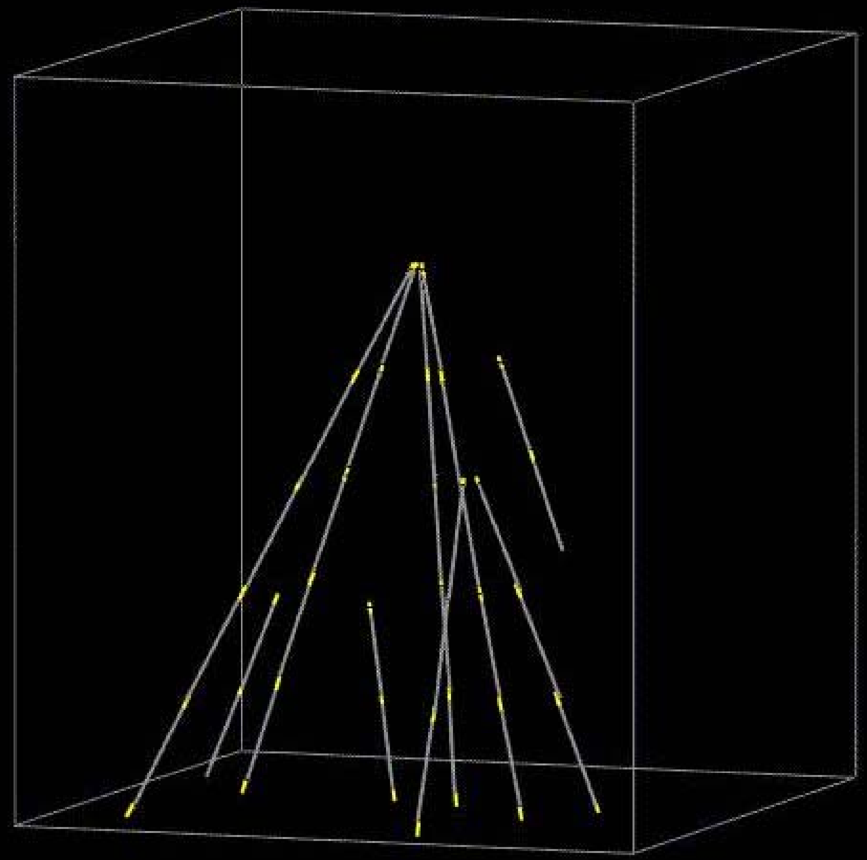
3D-track segments found in 8 consecutive films



Passing-through and low momentum tracks rejection



Vertex reconstruction



OPERA recent history

May 2006: electronic detector commissioning

Aug 2006: technical run, **0.76×10^{18} pot** collected

319 interactions in the rock, mechanical structure and iron of the spectrometer

Oct 2006: start of brick production

Oct 2007: pilot physics run (~40% target) **0.82×10^{18} pot**

first **38** neutrino events in the lead/emulsion target

Jun 2008: OPERA detector filled with brick and fully commissioned

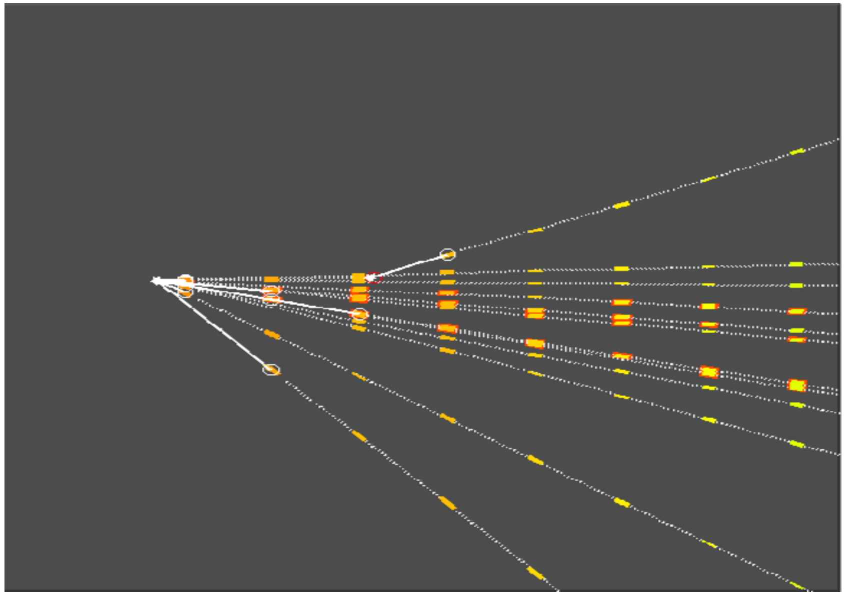
Jun 2008: Start first OPERA production run

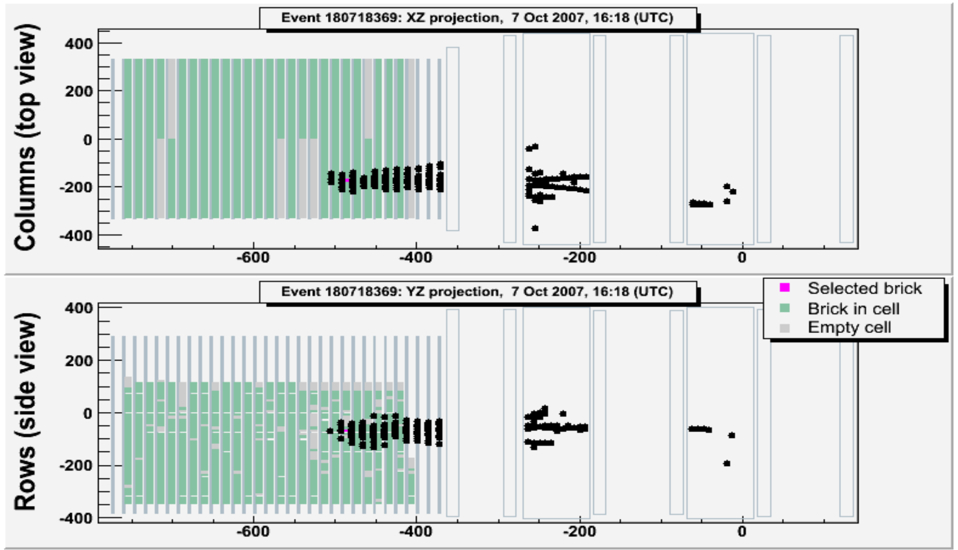
Nov 2008: **18×10^{18} pot** and **~1700** neutrino events in the target:

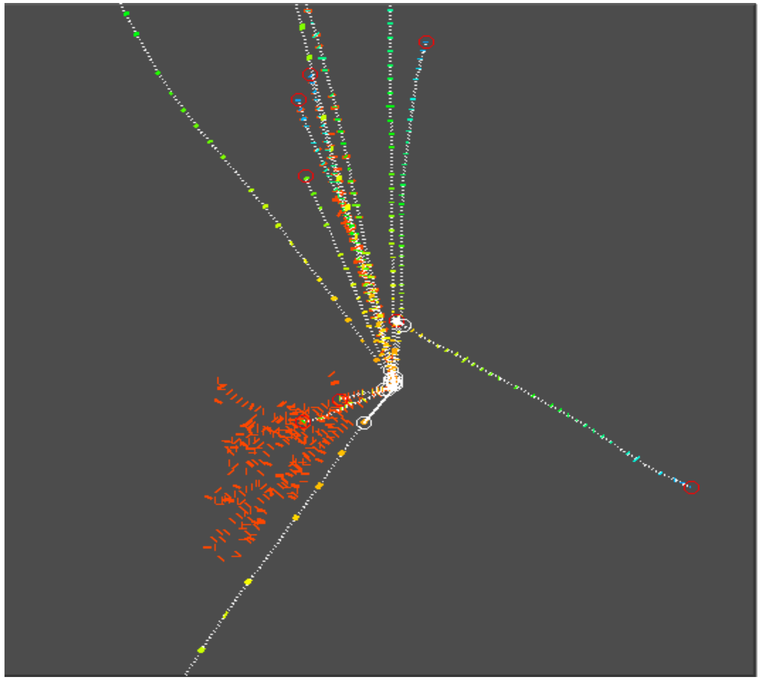
54 charm events, …0.6 τ

2009 run: 35×10^{18} pot expected. Secure "some" tau candidates ?

A charm decay candidate







Clear kink topology
Two EM showers pointing to the vertex

Flight length	3247.2 μm
θ_{kink}	0.204 rad
$P_{daughter}$	3.9 (+1.7 -0.9) GeV
P_T	796 MeV

4×10^{-4} probability for a hadron re-interaction to have a P_T > 600 MeV

Pierre Auger Cosmic Ray Observatory

Obserwatorium Pierre Auger

Badanie promieni kosmicznych w zakresie najwyższych obserwowanych energii, E > 10 EeV ($>10^{19}$ eV):

skład
: lekkie czy ciężkie jądra, fotony, neutrina, ??

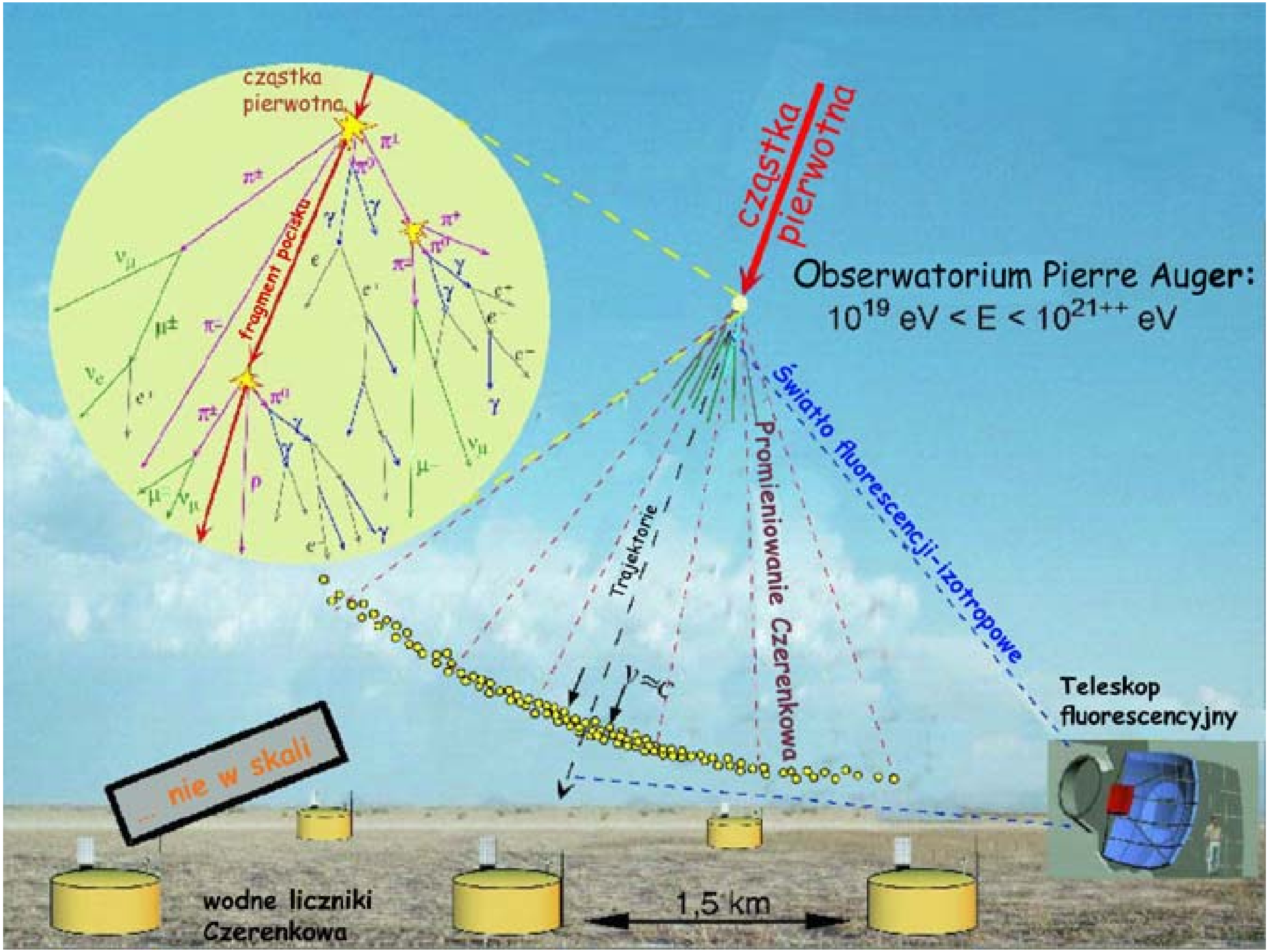
widmo energii
: kształt widma w zakresie efektu GZK

rozkład kierunkowy
: anizotropia, źródła punktowe

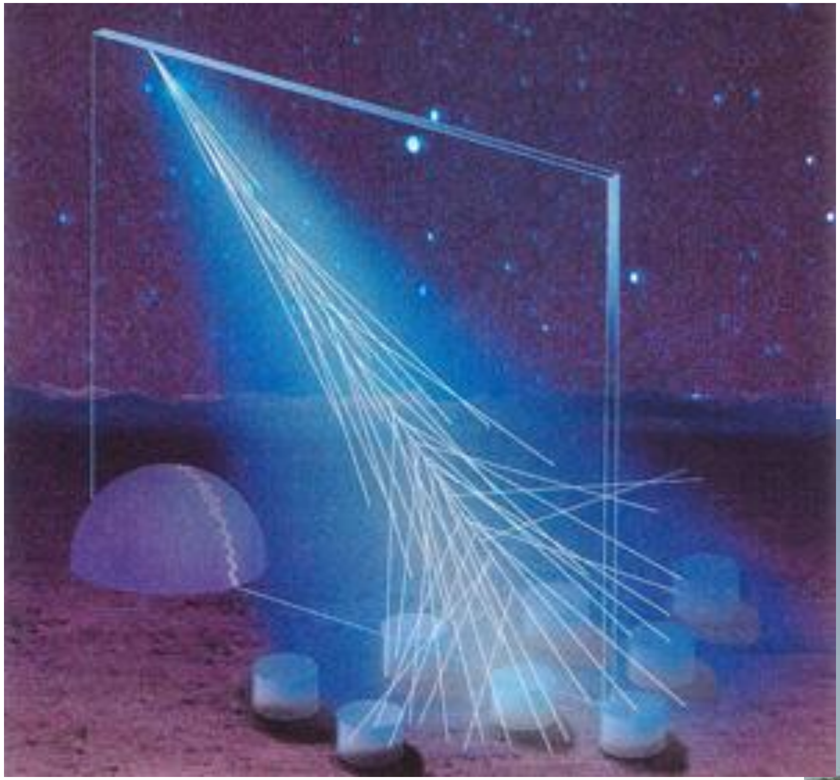
$\rightarrow$ wyjaśnienie ich pochodzenia ???

- obserwacja całego nieba – detektory w Argentynie i w USA
- 2 * 3000 km^2 $\rightarrow$ duża statystyka danych
- hybrydowa detekcja wielkich pęków: dwa układy detektorów

Wielki pęk atmosferyczny



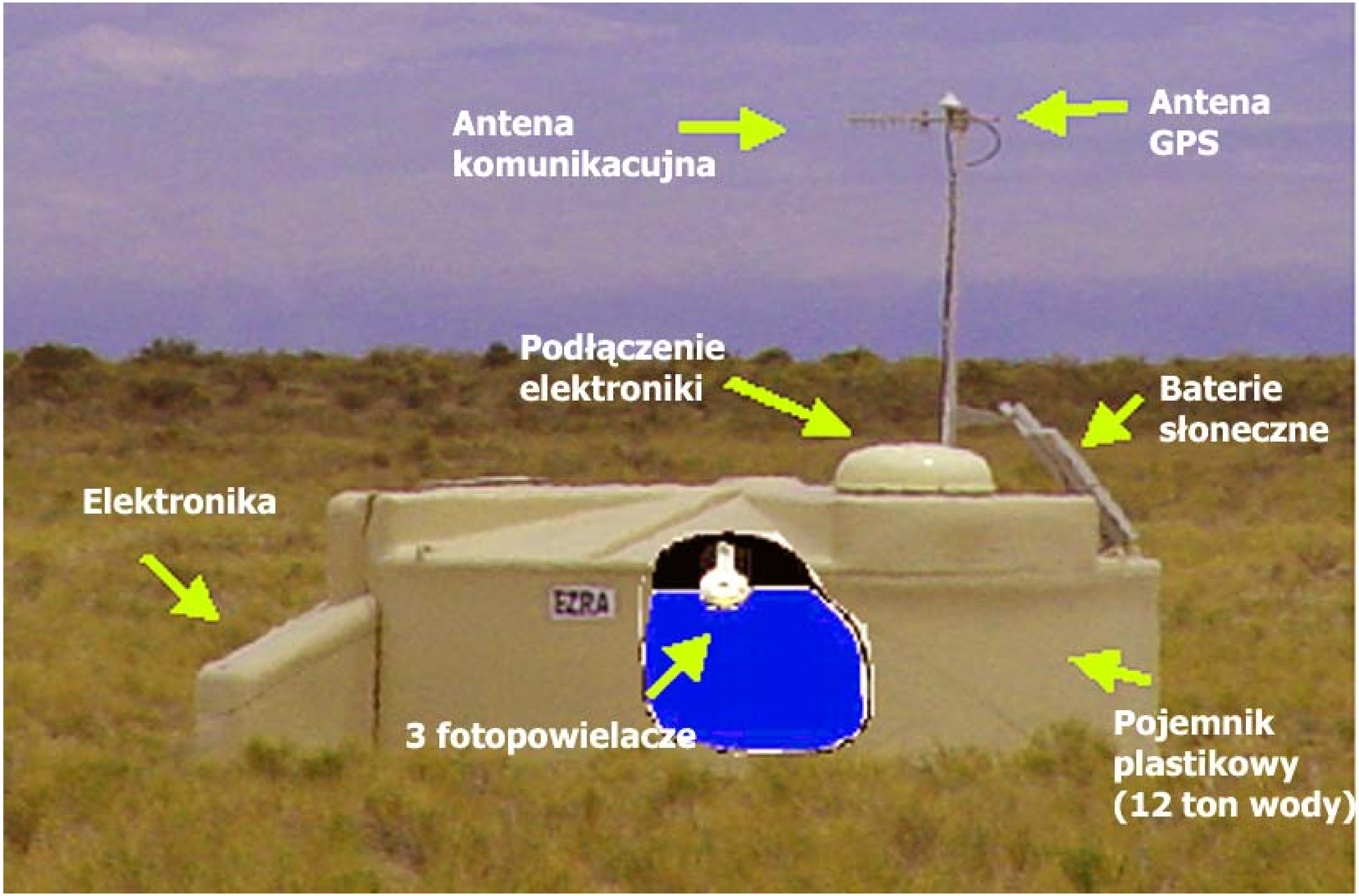
Pierre Auger Cosmic Ray Observatory



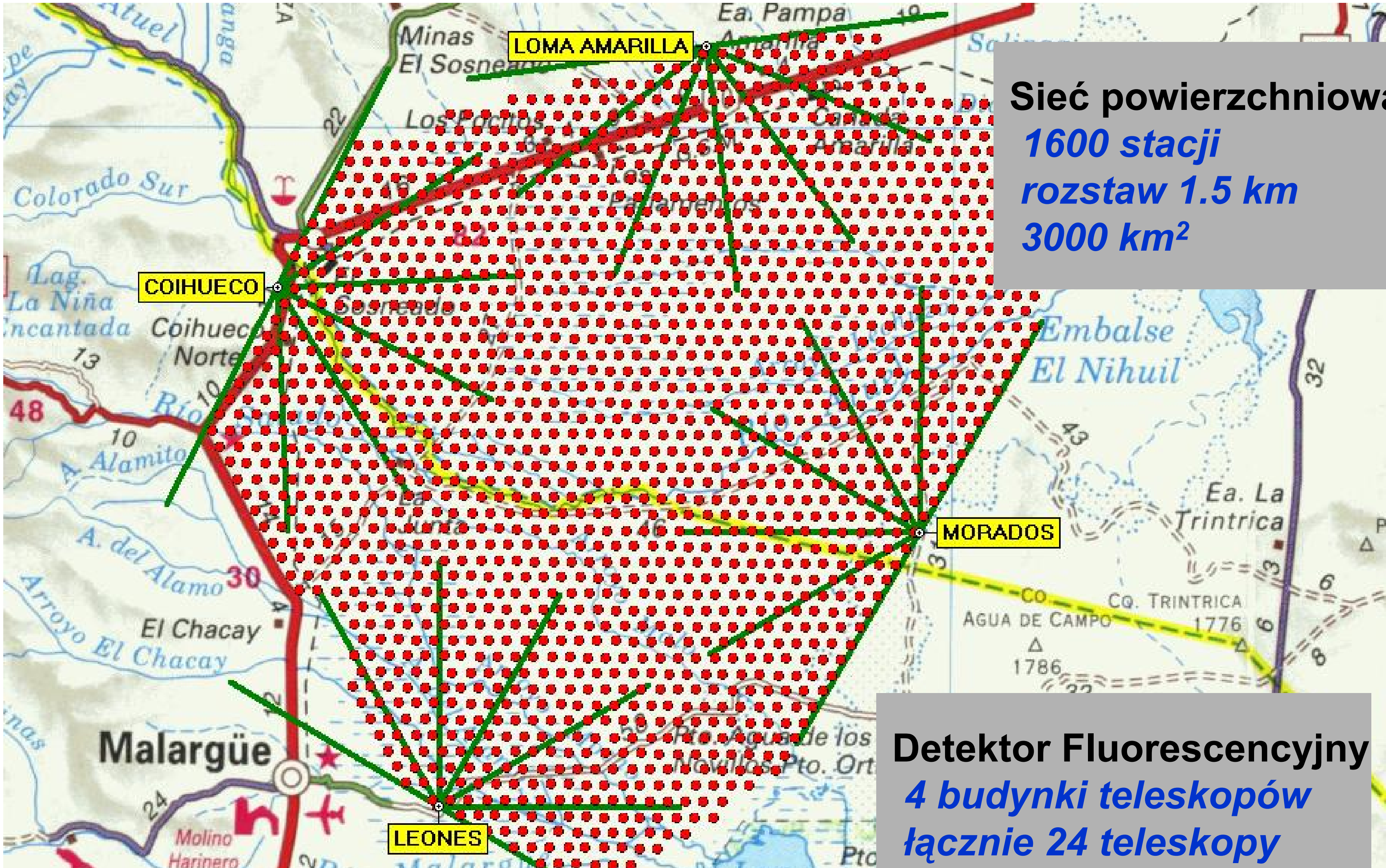
Use earth's atmosphere as a calorimeter. 1600 water Cherenkov detectors with 1.5km distance.

Placed in the Pampa Amarilla in western Argentina.

Detektor naziemny



Obserwatorium Pierre Auger



Sieć powierzchniowa

1600 stacji

rozstaw 1.5 km

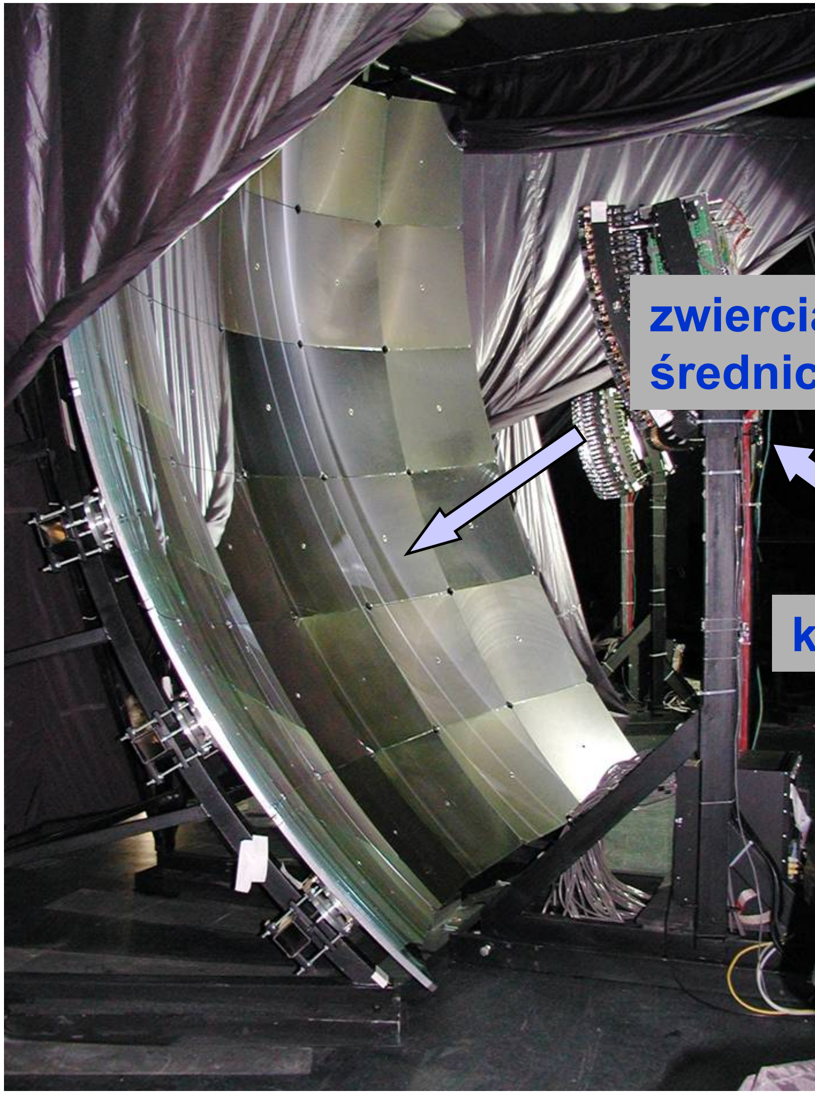
3000 km²

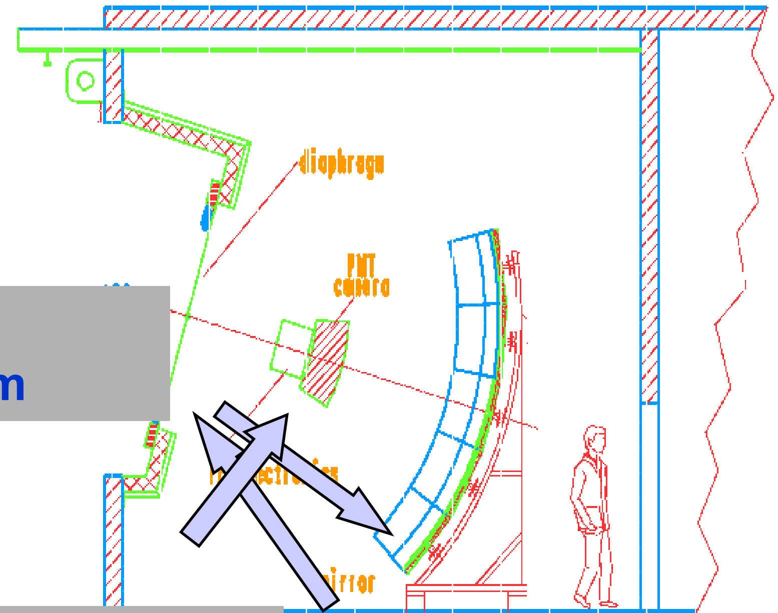
Detektor Fluorescencyjny

4 budynki teleskopów

łącznie 24 teleskopy

Detektor Fluorescencyjny



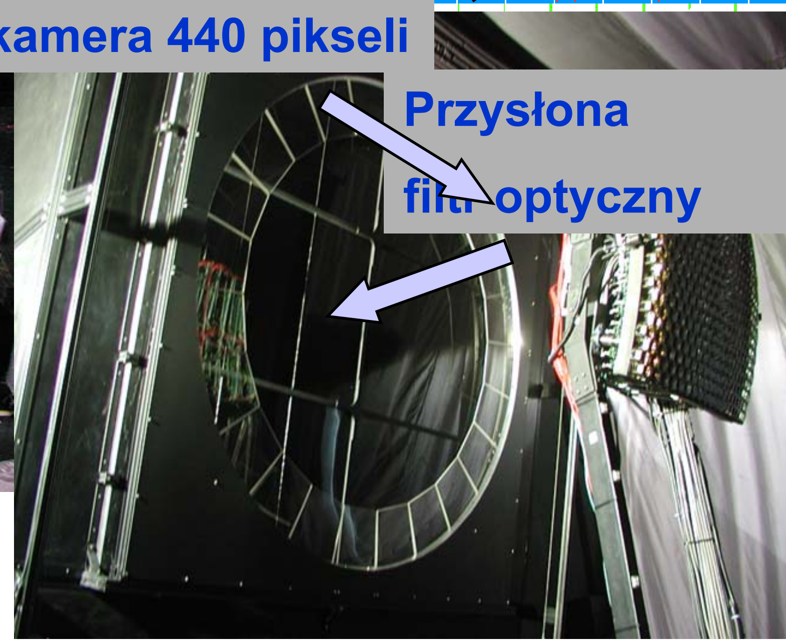


zwierciadło
średnicy 3.4 m

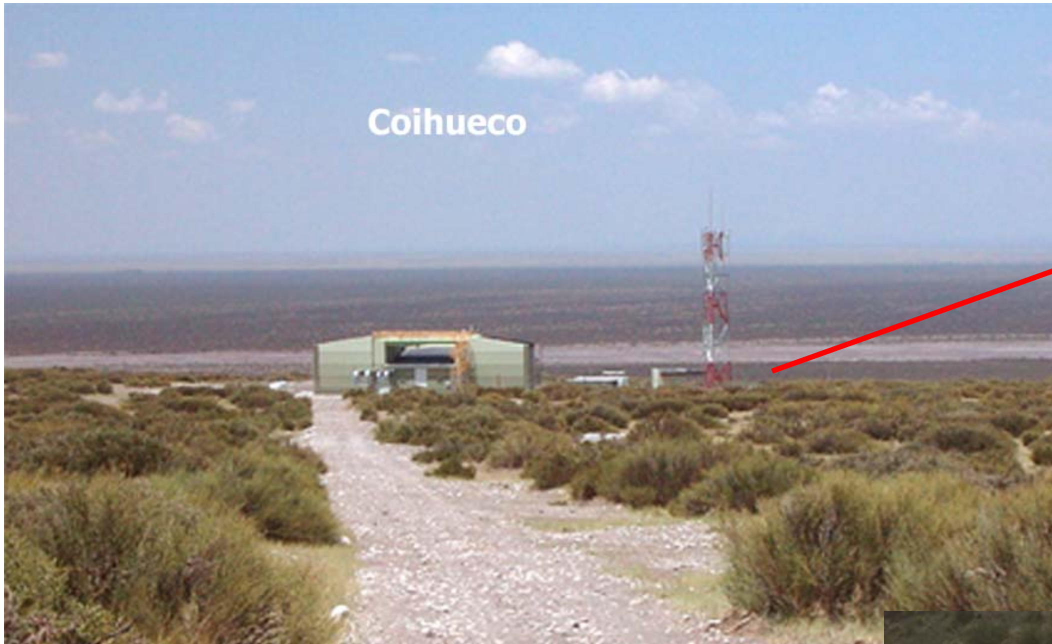
kamera 440 pikseli

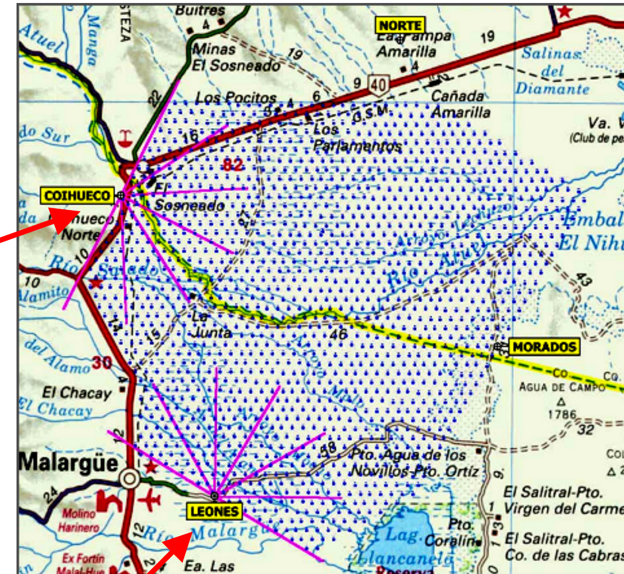
Przysłona

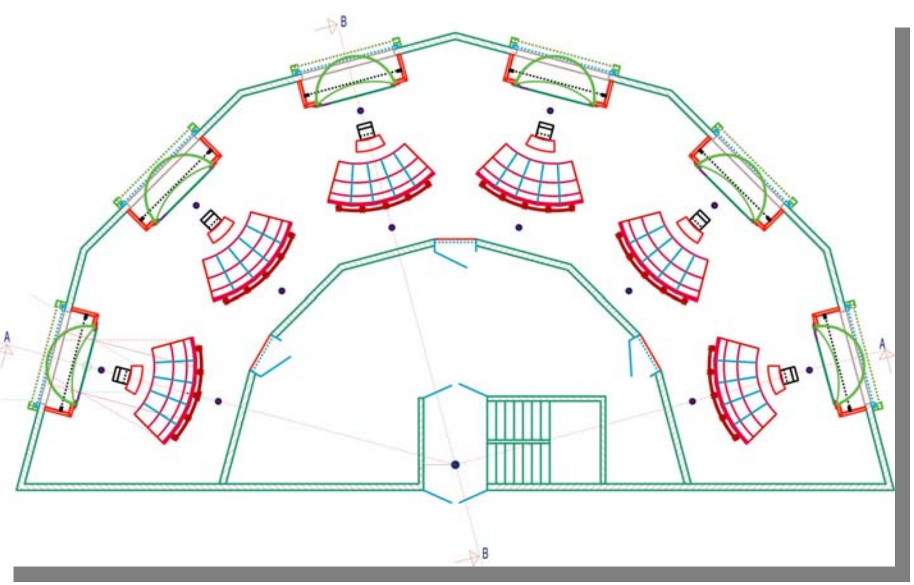
filtr optyczny

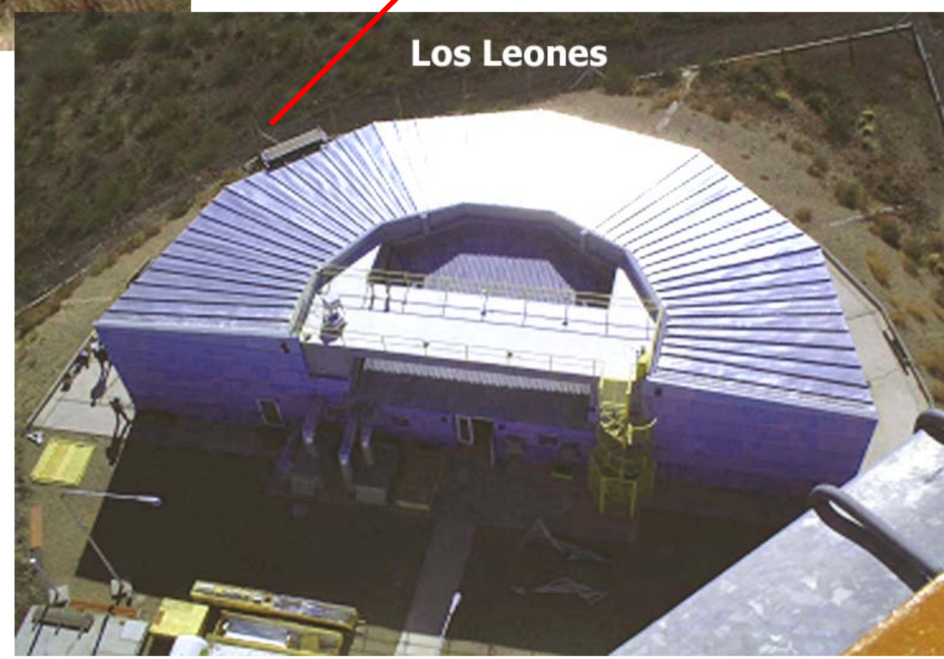


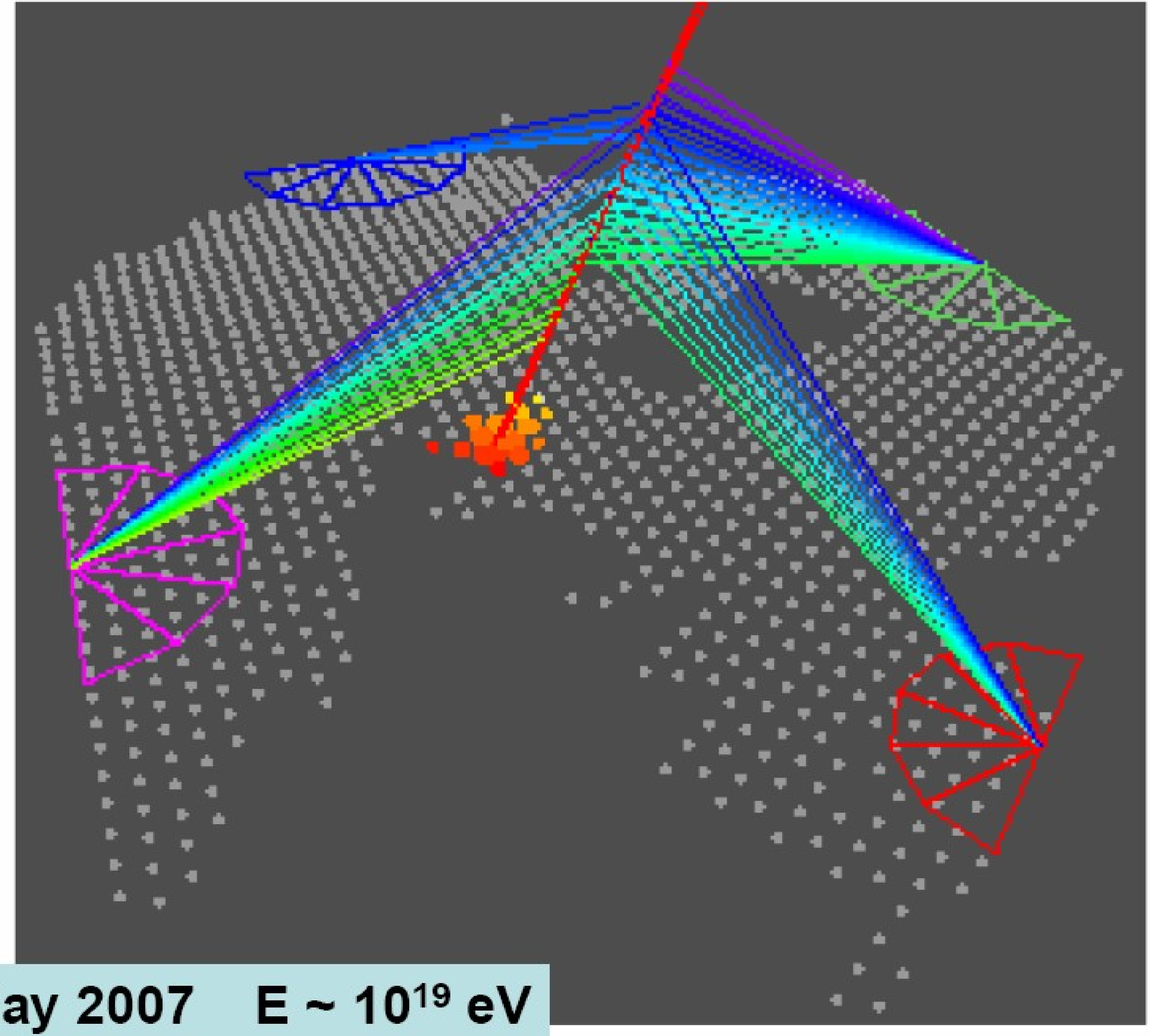
Detektory fluorescencyjne







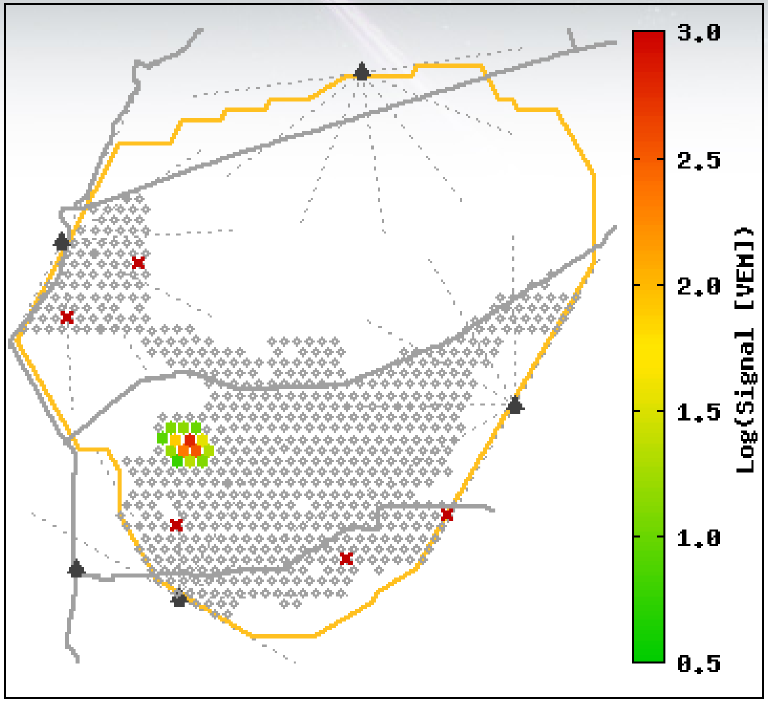




20 May 2007 E ~ 10^{19} eV

Event 1234800

See CR incoming direction | See individual station data

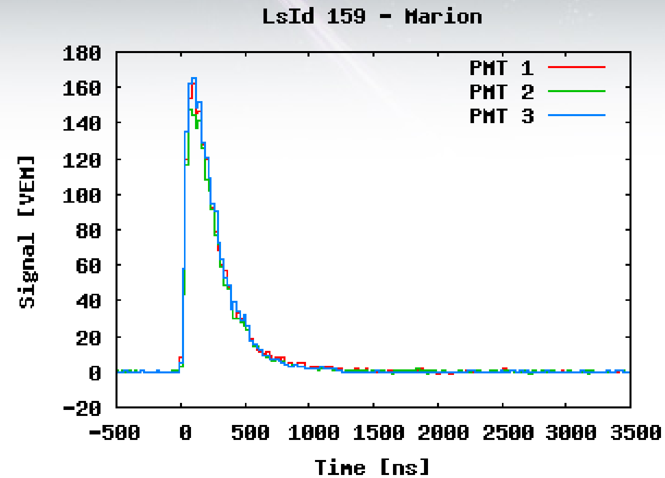


37 EeV = Exa Electron Volt = 37 x 10^{18} eV

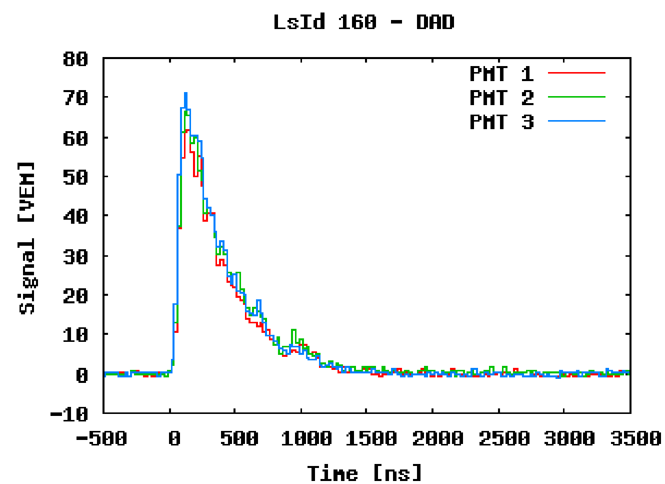
Generic Information	
Id	1234800
Date	Sat Mar 5 15:54:48 2005
Nb Station	14
Energy	37.4 ± 1.2 EeV
Theta	43.4 ± 0.1 deg
Phi	-27.3 ± 0.2 deg
Curvature	15.8 ± 0.8 km
Core Easting	460206 ± 20 m
Core Northing	6089924 ± 11 m
Reduced Chi^2	2.30

Event 1234800

See event reconstruction data | See CR incoming direction



Signal in VEM for the 3 PMTs of station 159 (Marion) as a function of time

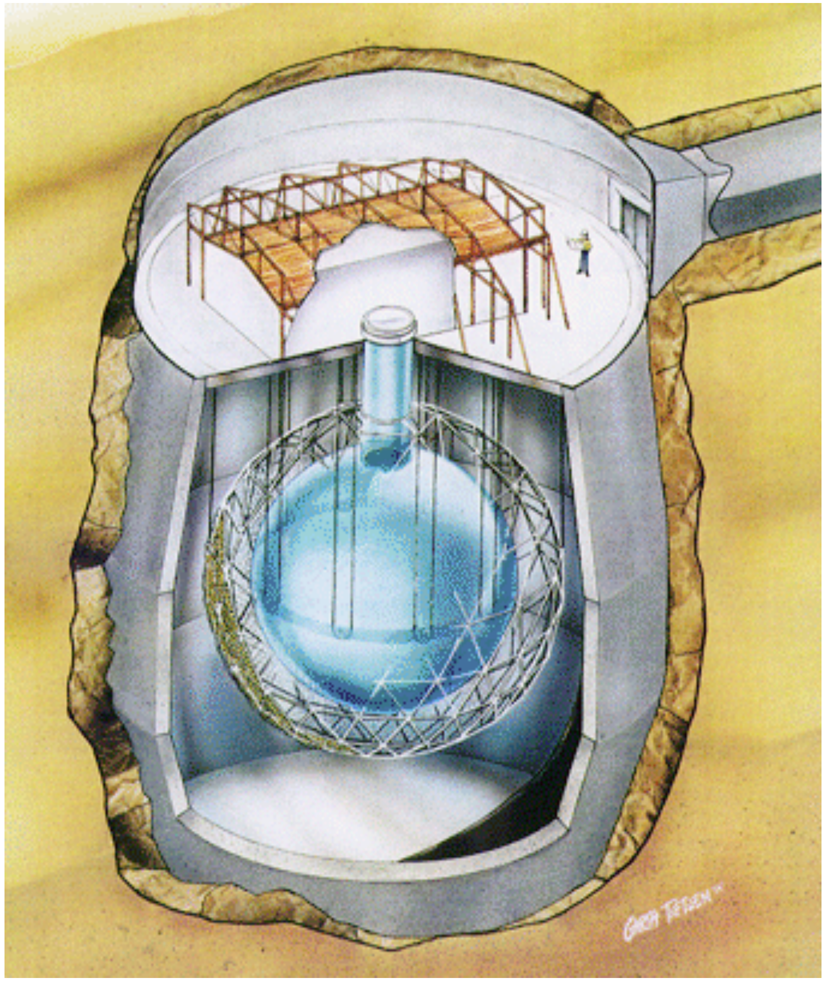


Signal in VEM for the 3 PMTs of station 160 (DAD) as a function of time

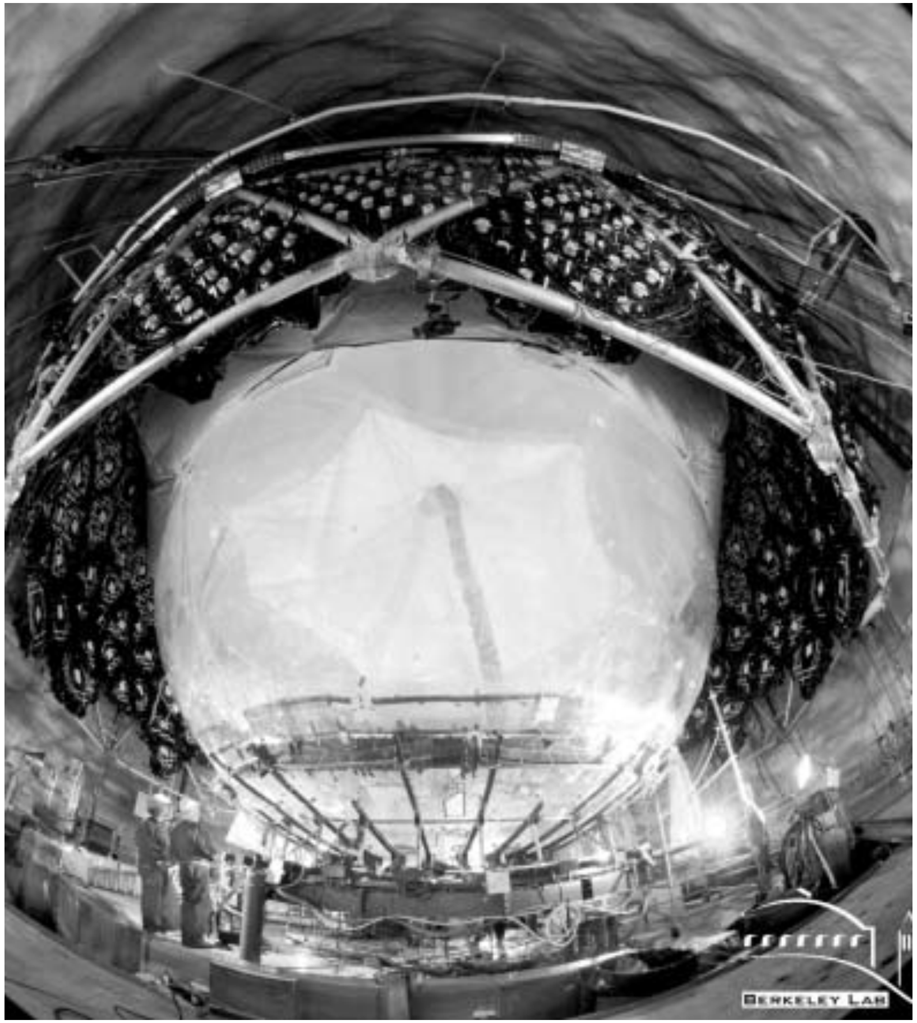
SNO
(Sudbury Neutrino Observatory)

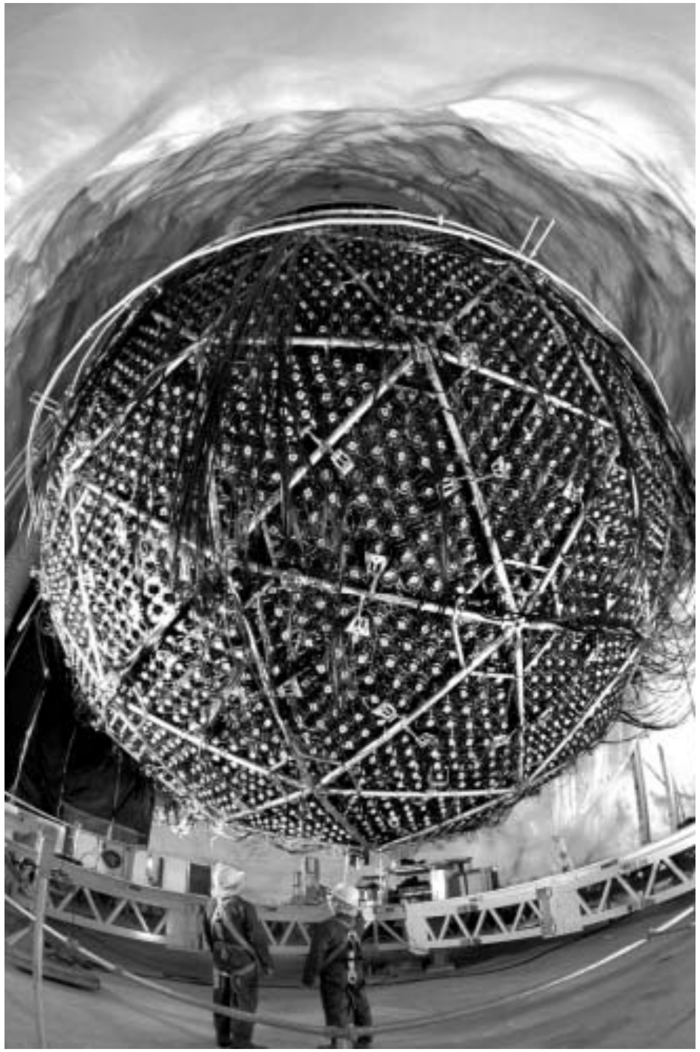
Water detector with a difference:

- **2 km underground**
- **1000 tonnes D_2O**
- **10^4 - 8" PMTs**
- **6500 tons H_2O**

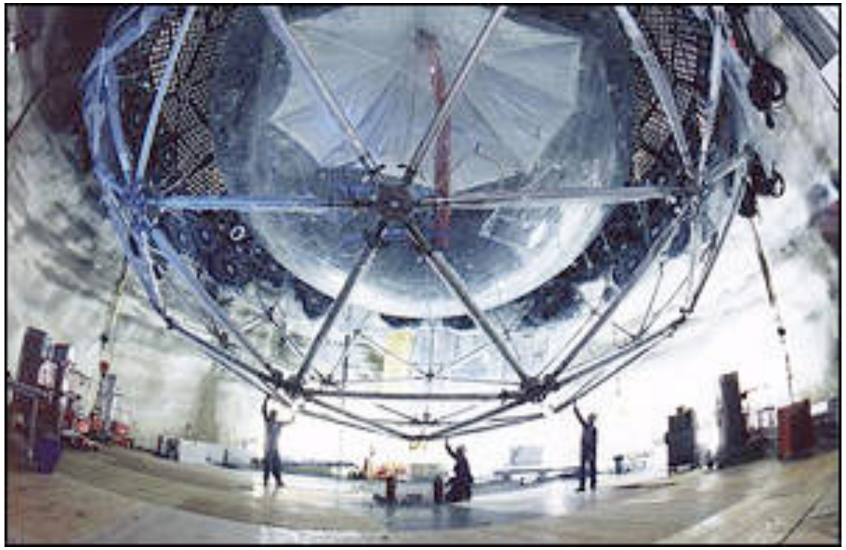


SNO under construction





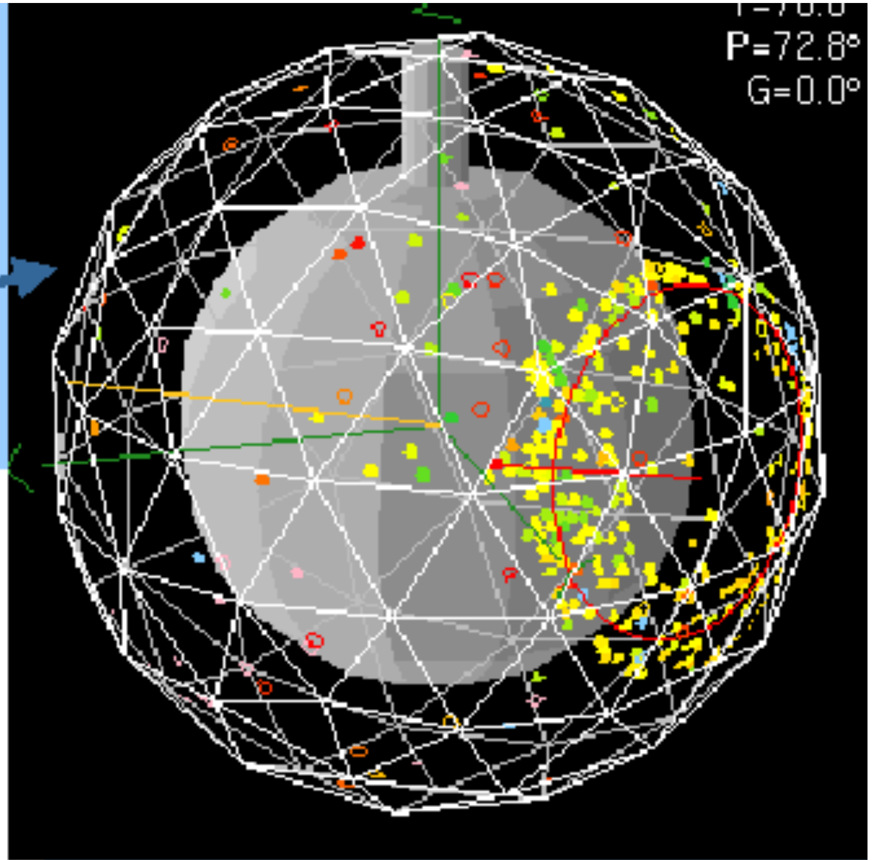
SNO

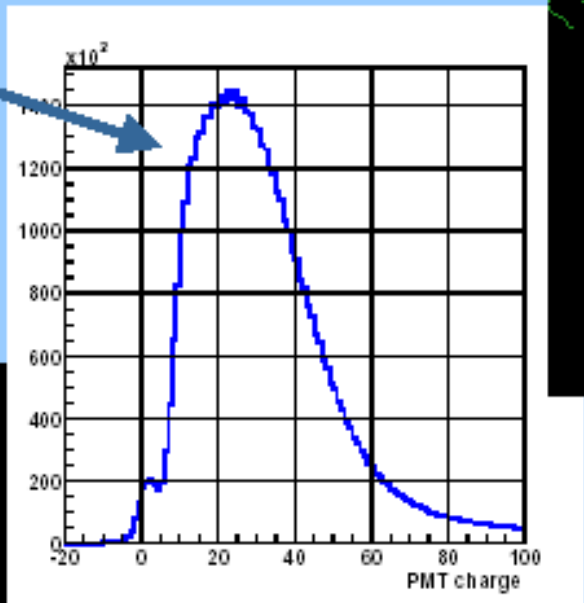


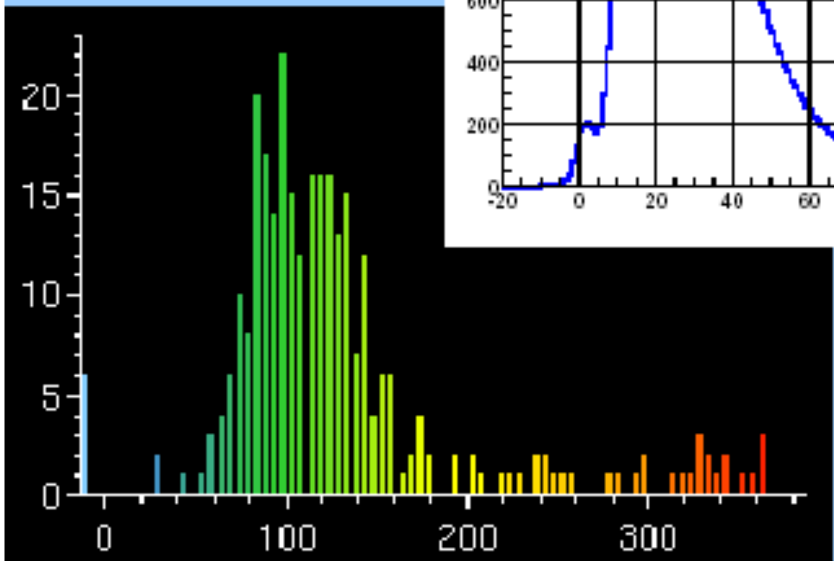
What We Measure

PMT Measurements

-position
-charge
-time







Reconstructed Event

-event vertex
-event direction
-energy
-isotropy

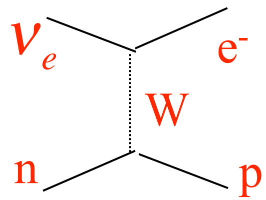
Neutrino reactions in heavy water (SNO)

Charged Current Reaction:

$$\nu_e + d \rightarrow e^- + p + p \qquad E_{thresh} = 1.4 \text{ MeV}$$

CC

- 6-9 events per day
- ν_e flux and energy spectrum
- Some directional sensitivity $(1 - 1/3\cos(\vartheta_e))$

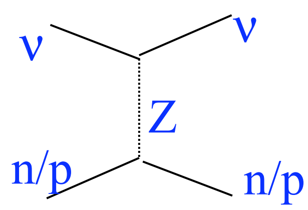


Neutral Current Reaction:

$$\nu_x + d \rightarrow \nu_x + p + n \qquad E_{thresh} = 2.2 \text{ MeV}$$

NC

- 1-2 or 6-8 events per day
- (different detection mechanisms)
- Total solar ^{8}B active neutrino flux

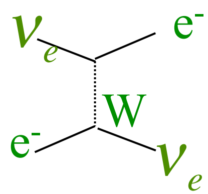


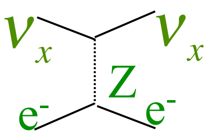
Elastic Scattering Reaction:

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad E_{thresh} = 0 \text{ MeV}$$

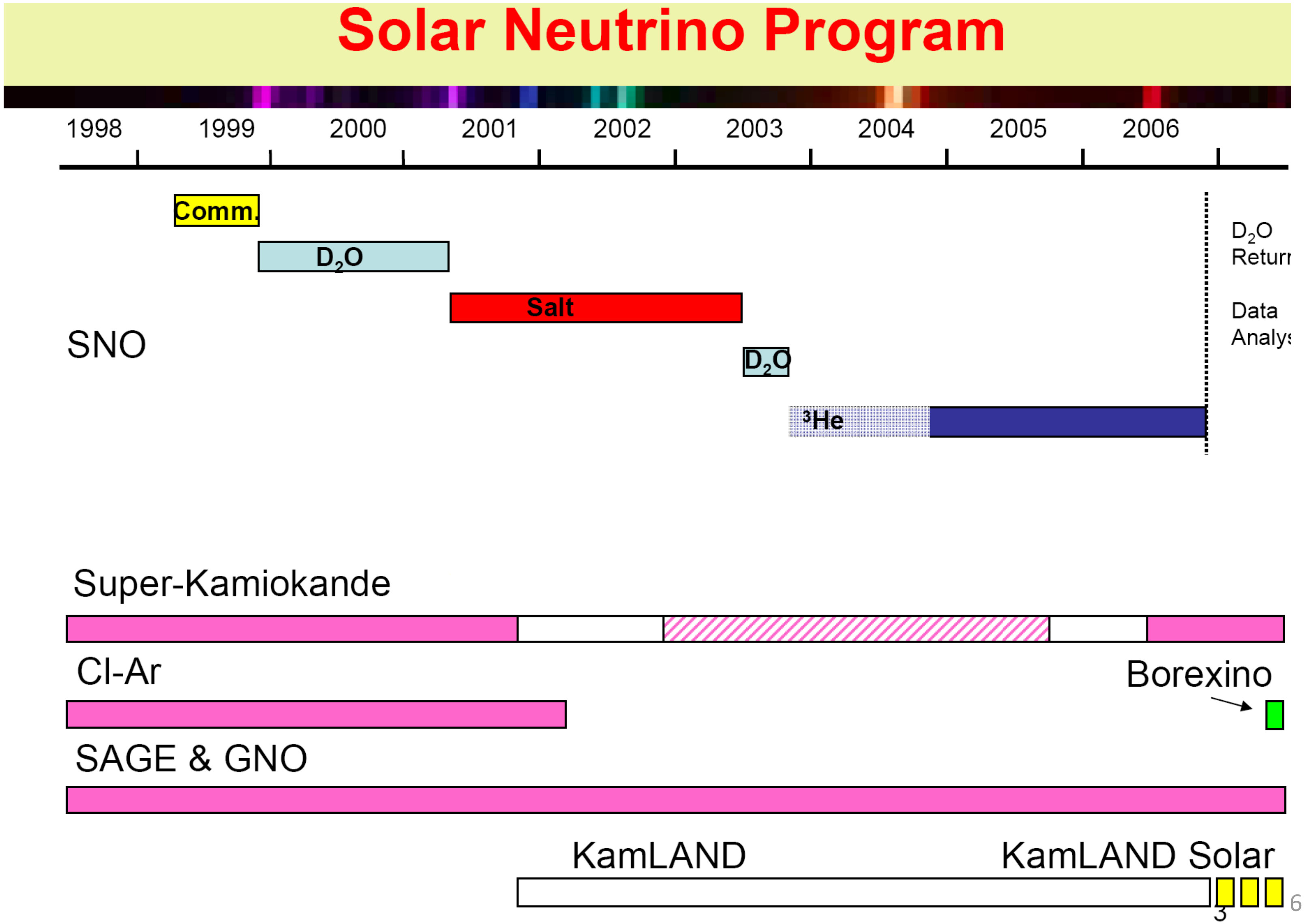
ES

- 1-2.5 events per day
- Directional sensitivity (very forward peaked)

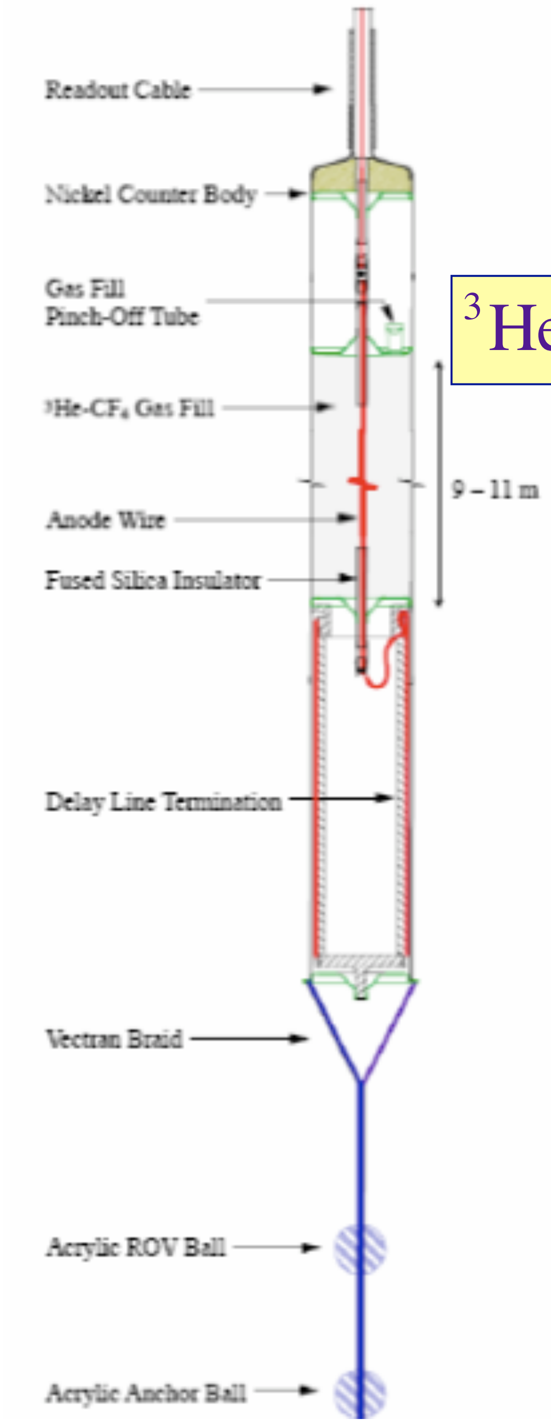




Completing the oscillation picture at small dm^2 (solar)

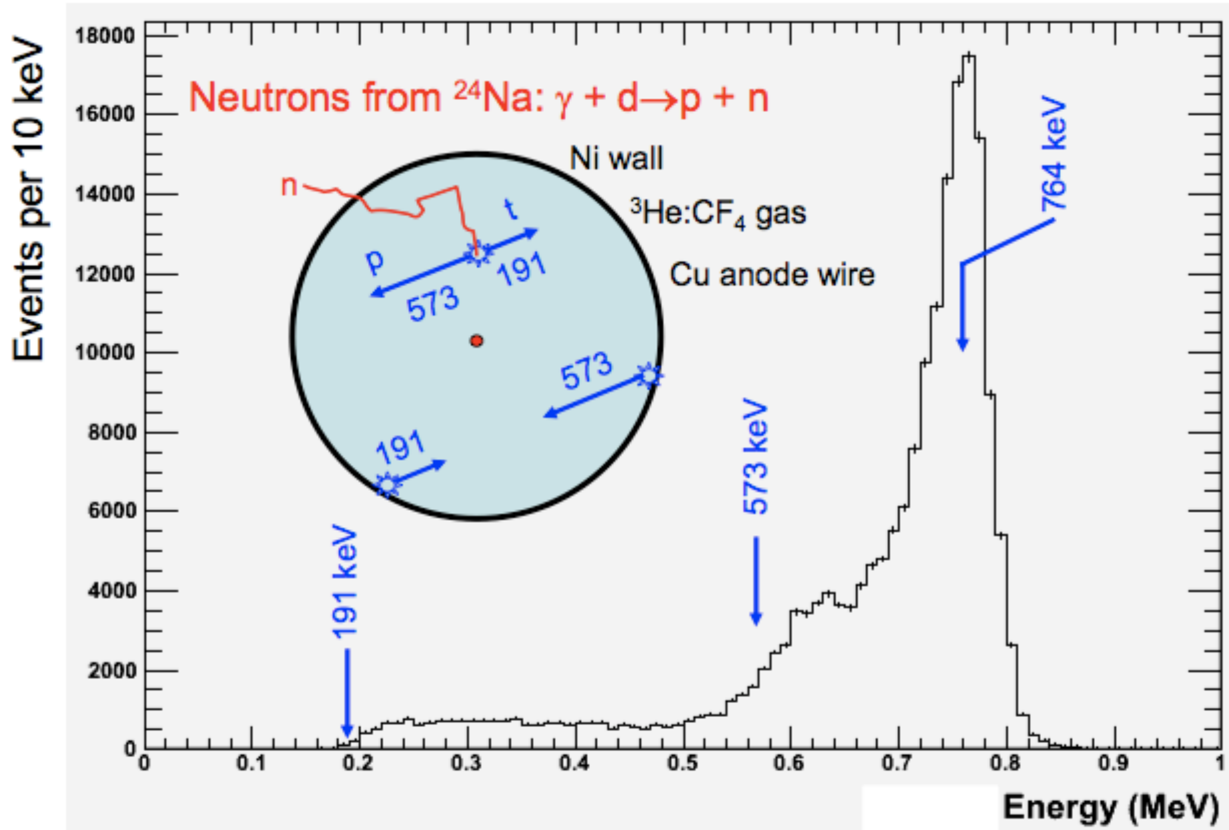


Neutron counters in SNO



$^{3}\mathrm{He}(n,p)\mathrm{t}$

Counters 2-3 m long.
36 strings on 1x1 m grid



Neutron counters

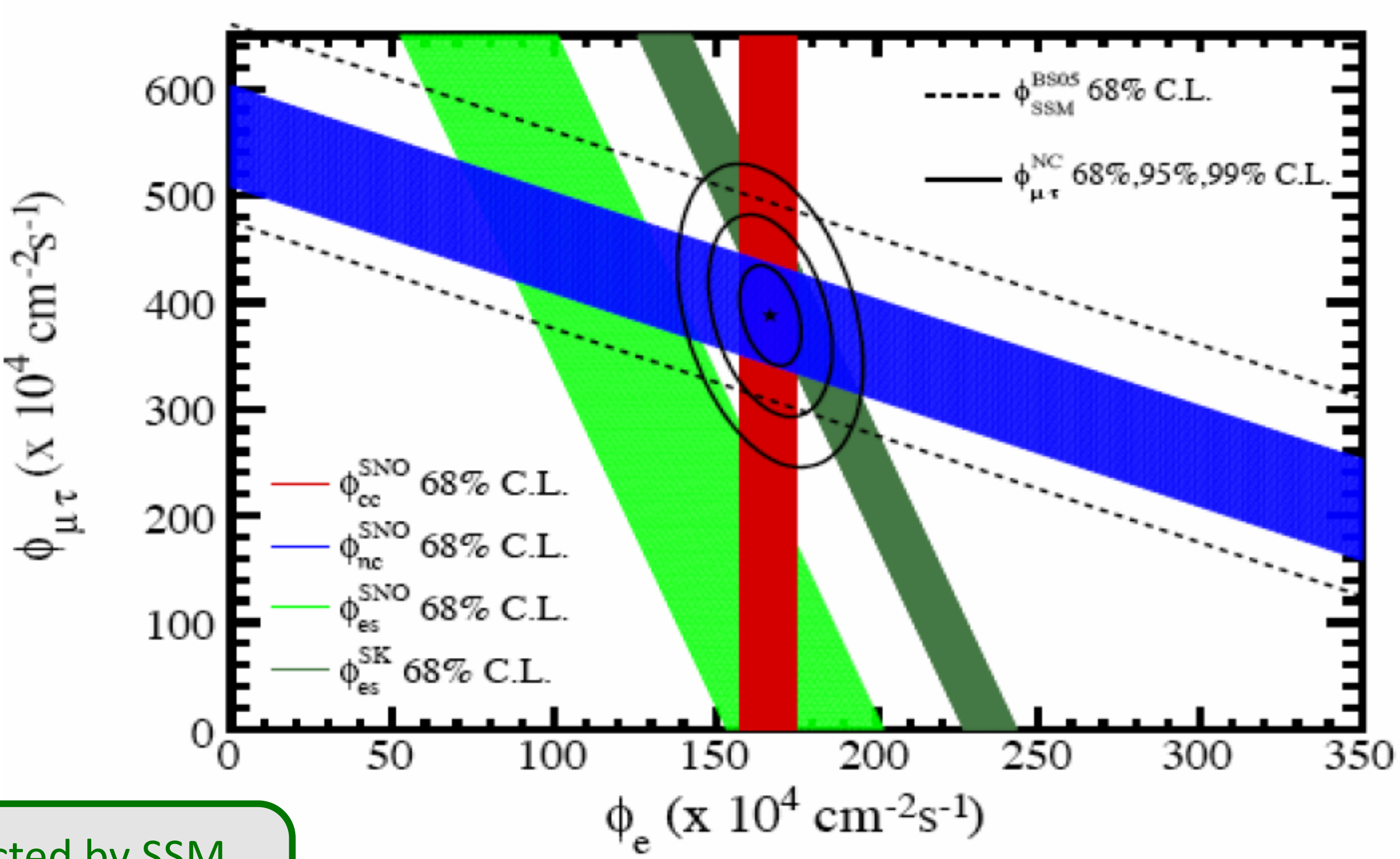
Results from SNO NCD Phase & Super-K

Preliminary

Fluxes

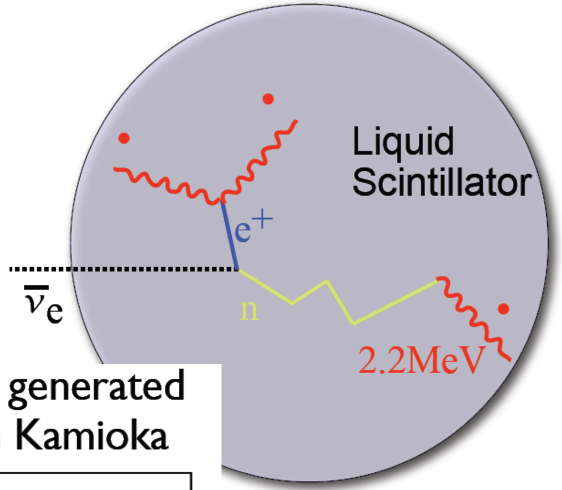
(10^4 cm^{-2} s^{-1})

ν_e:	167(9)
ν_{ES}:	177(26)
ν_{total}:	554(48)
ν_{SSM}:	569(91)

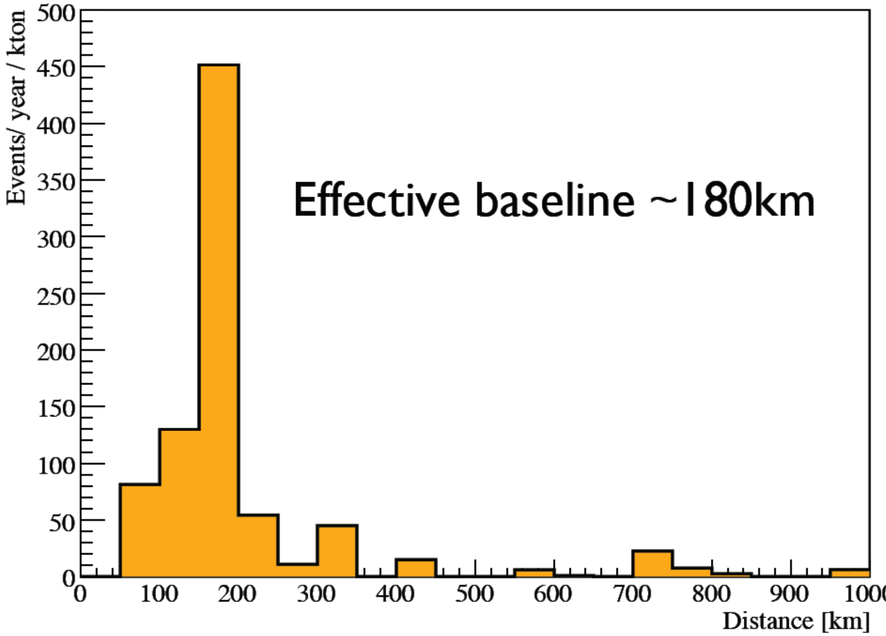


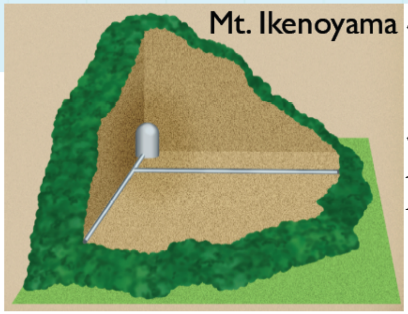
All the neutrinos predicted by SSM have been observed by NC reaction

Kamland – recent results



70 GW (7% of world total) is generated at 130-220 km distance from Kamioka



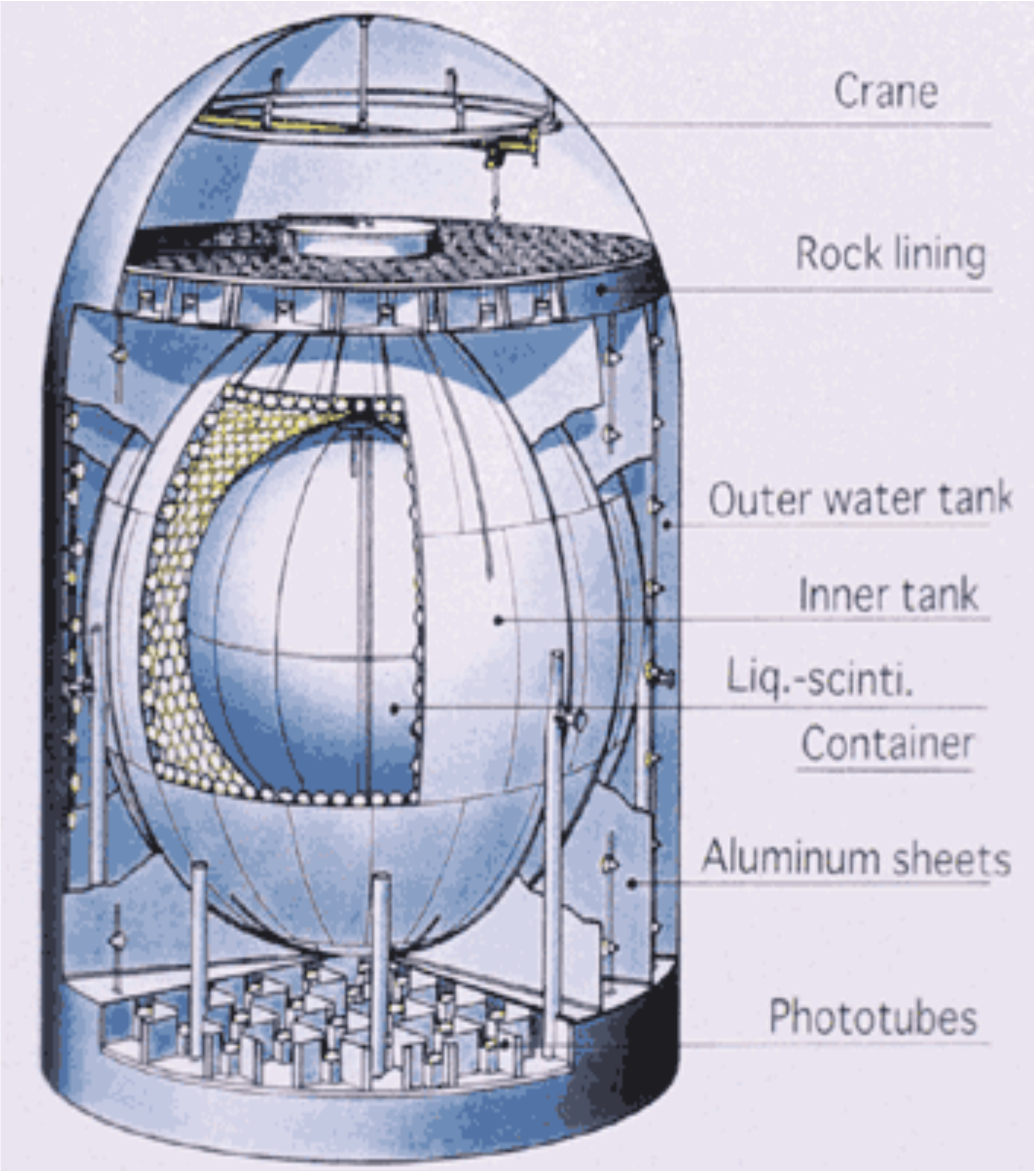


1000m rock
= 2700 mwe

long. 137° 18'43.495"
lat. 36° 25'35.562"
alt. 358 m

Reactor neutrino flux:
~6×10^6 $cm^{-2}s^{-1}$

KamLAND detector



- external container filled with 3.2 ktons of water
- inner spherical container filled with 2 ktons of mineral oil
- inside a transparent baloon filled with **1 kt of liquid scintillator**
- 2100 photomultipliers to measure scintillation light
- located in Kamioka mine at **depth of 1 km**

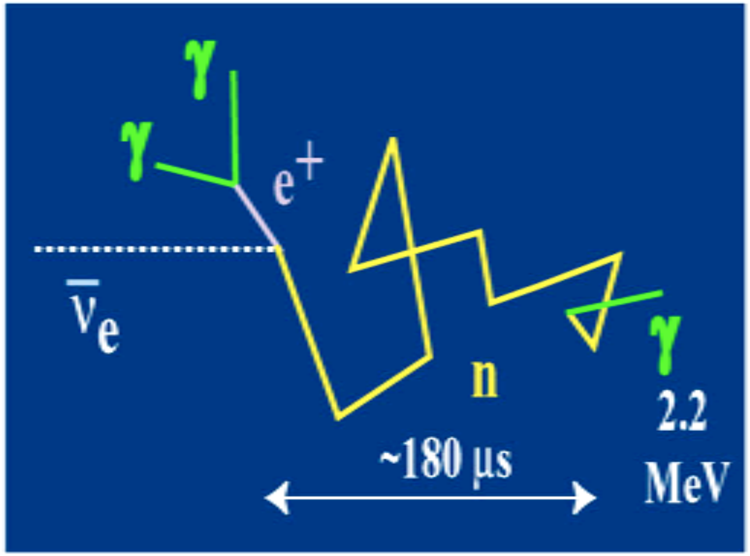
ources, DK&ER,

Detection of reactor antineutrinos

reaction process : inverse- β decay ($\bar{\nu}_e + p \longrightarrow e^+ + n$)

$+ p \longrightarrow d + \gamma$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- prompt part : e^+

  $\bar{\nu}_e$ energy measurement

  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

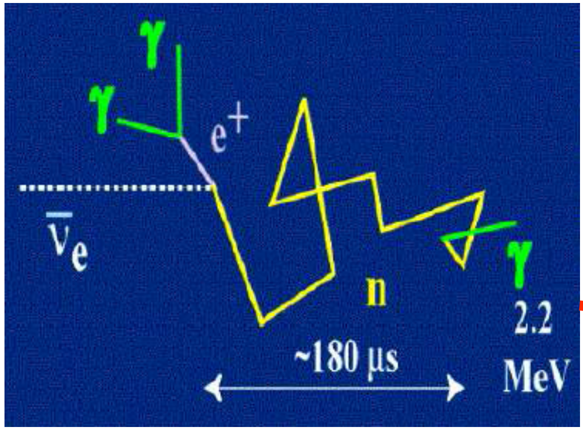
  $$\Delta = M_n - M_p$$

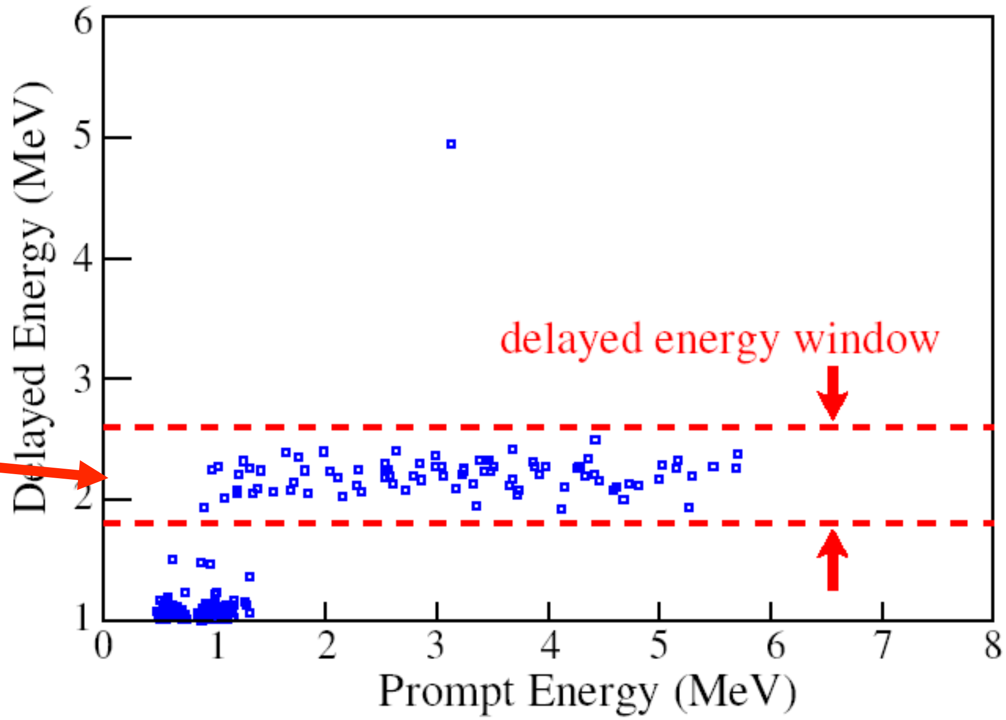
- delayed part : γ (2.2 MeV)

- tagging : correlation of time, position and energy between prompt and delayed signal

KamLAND results

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

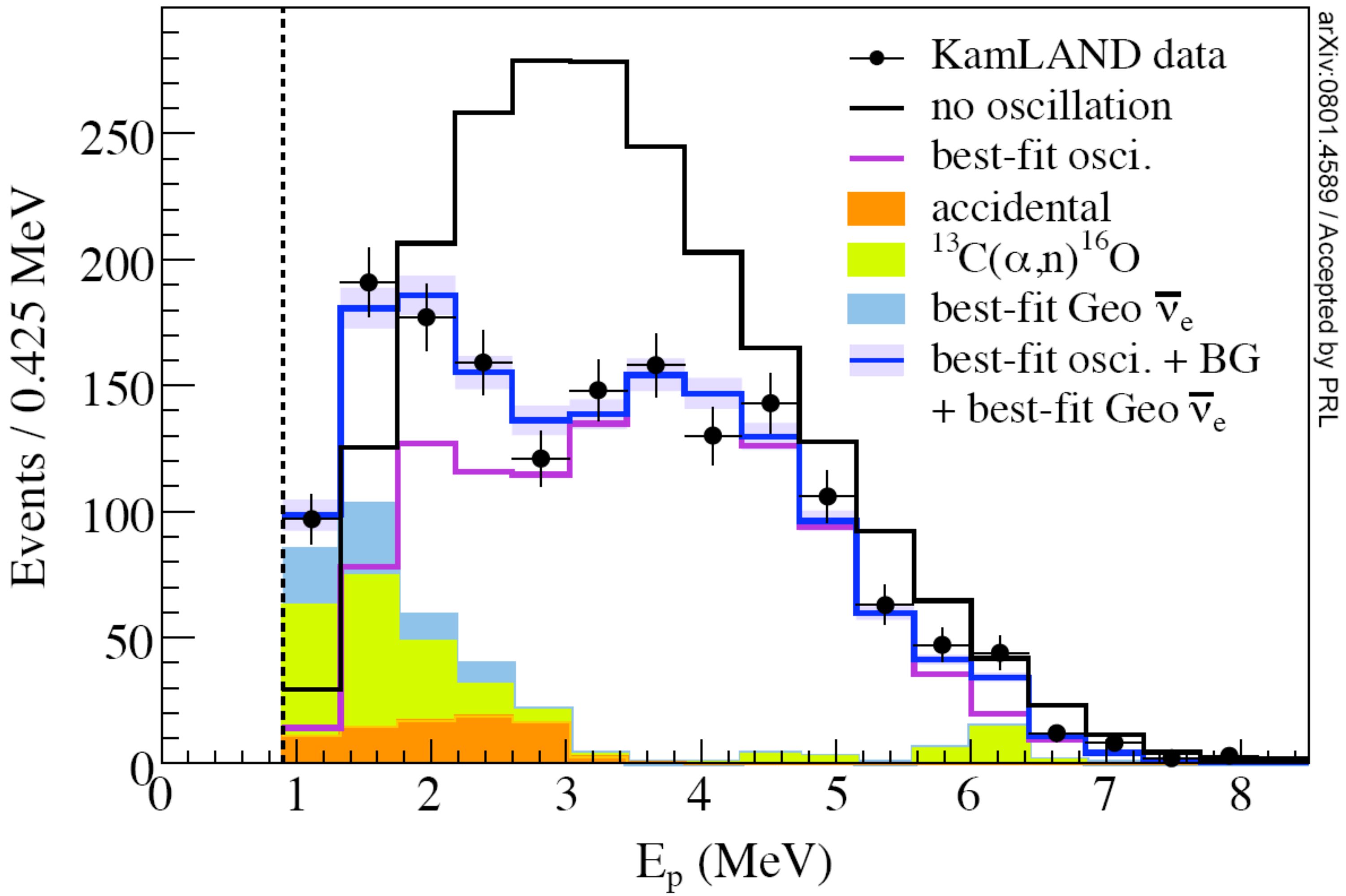


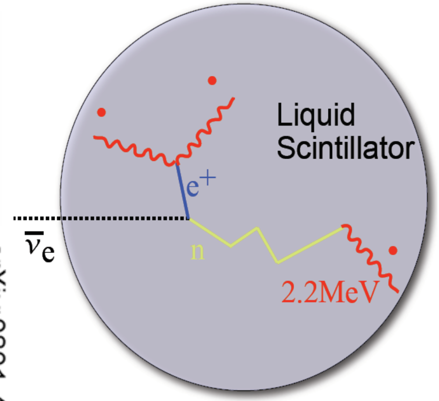


„Prompt energy" is equal to positron energy, which gives the antineutrino energy (when corrected for mass differences).

Very good signal separation from background.

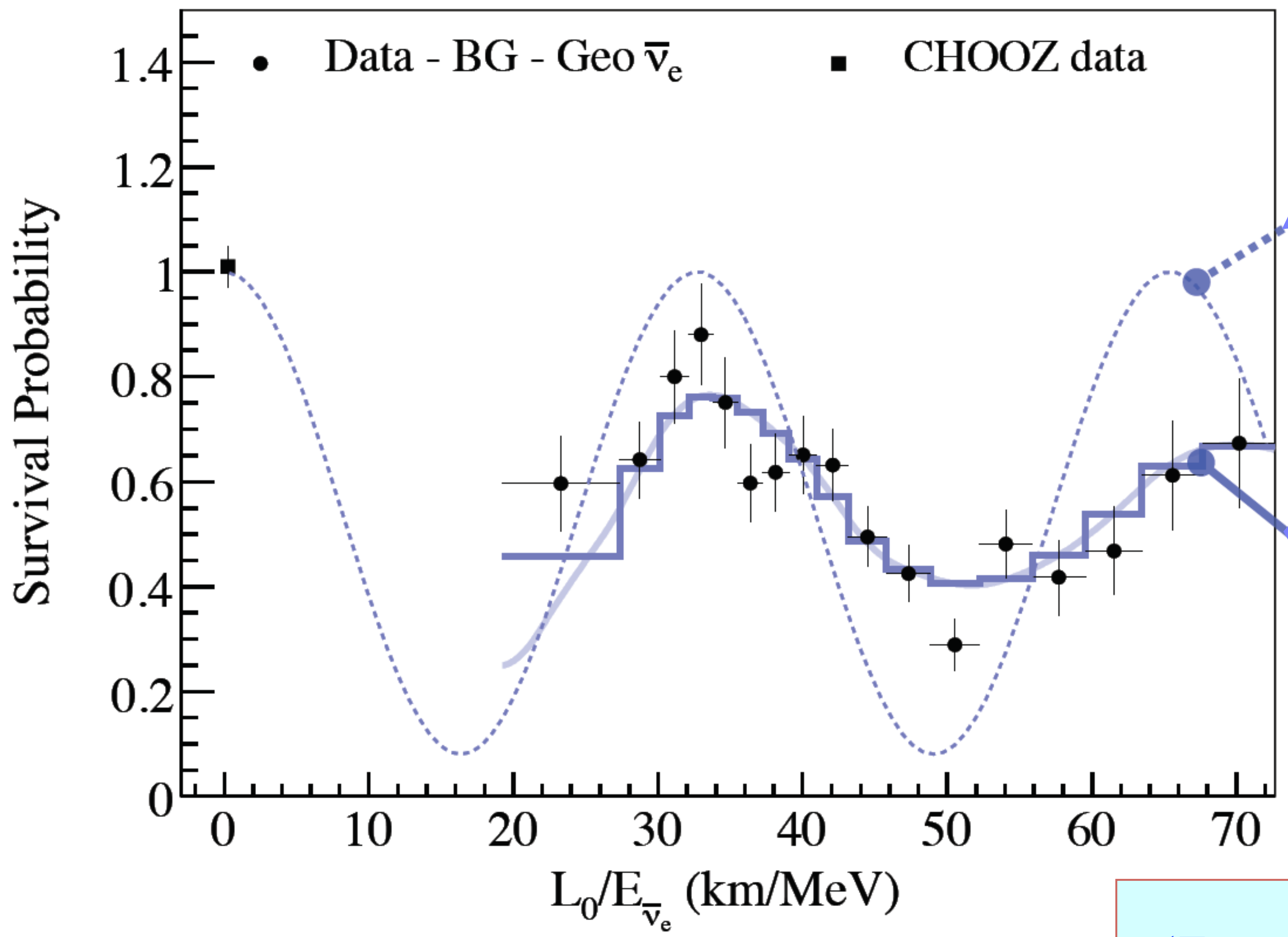
Kamland - Energy spectrum





Fit to scaled no-oscillation spectrum excluded at 5.1σ

Kamland – oscillation signature



Oscillation pattern for mono-energetic, at one baseline

Best-fit oscillation accounting for energy spectrum and reactor distribution

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sin^2 2\vartheta \sin^2 \frac{1,27\delta m^2 L}{E_\nu}$$