

Experimental methods in Neutrino Search

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Summary of the topics

- Neutrino detection overview
- Scintillation methods
- Cerenkov approach
- Radiochemical methodology
- Low background implications in low energy neutrino search

A many facets problematic: sources

The neutrino detection techniques encompasses several different methodology of widespread use in the general field of particles detection.

The multiplicity of the detection methods is enhanced by the plurality of experimental needs posed by the different neutrino sources of experimental interest:

- solar neutrinos
- atmospheric neutrinos
- reactor neutrinos
- accelerator neutrinos
- supernova neutrinos
- ultra high energy neutrinos from astrophysical sources

A many facets problematic: experimental methods

The richness of the neutrino physics field finds almost naturally its counterpart in the variety of techniques applied or proposed by the experimentalists to cover this broad range of applications:

- ❖ Radiochemical methods
- ❖ Water cerenkov detectors
- ❖ Heavy water detectors
- ❖ Scintillation techniques
- ❖ Long string, large Water Cerenkov Detectors
- ❖ Time projection chambers
- ❖ Nuclear emulsions

Focus of this presentation

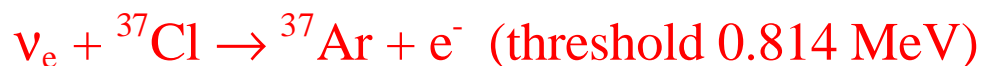
- a) **Radiochemical methods** vastly applied in the solar neutrino search
- b) **Water cerenkov detectors, included the heavy water version**, which provided epochal results in the atmospheric neutrino detection, and in the assessment of neutrino oscillations
- c) **The scintillation detectors** which are the choice for most of the reactor and accelerator experiments, as well as promising instruments for the challenging real time detection of low energy solar neutrinos.
- d) **Low background issues** connected to the low energy neutrino measurements

Radiochemical methods

The radiochemical technique exploits a detection target which, upon absorption of a neutrino, is converted into a radioactive element whose decay is afterwards counted.

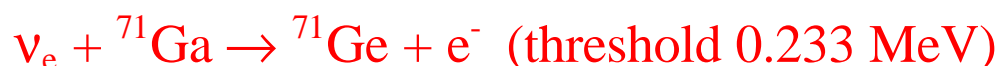
Experiments of this kind: [Homestake](#), [Gallium Detectors \(Gallex/GNO, SAGE\)](#)

The pioneering Homestake experiment was based on the inverse beta reaction



(method proposed by Pontecorvo (1946) and later independently by Alvarez (1949))

The Gallium experiments are based on the reaction:



(proposed by Kuzmin in 1965)

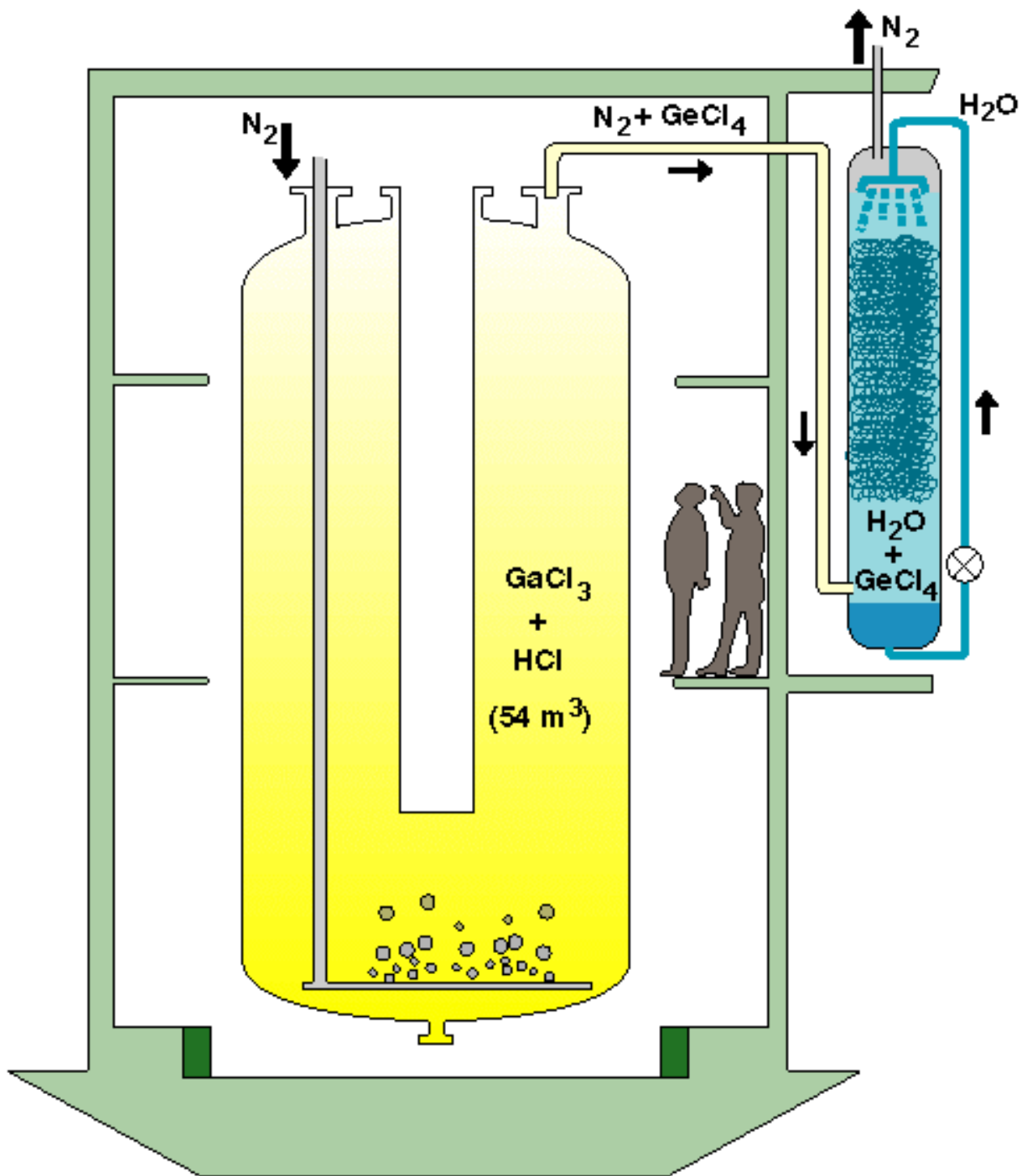
Example of radiochemical methods: The Gallium solar Neutrino Observatory (GNO) at Laboratori Nazionali del Gran Sasso

The detector is sensitive mainly to pp-neutrinos (53 % of the interaction rate according to the standard solar model), with smaller contributions from ${}^7\text{Be}$ ν (27%), ${}^8\text{B}$ ν (12 %), and CNO ν (8%).

The target consists of 101 tons of a GaCl_3 solution in water and HCl, containing 30.3 tons of natural gallium; this amount corresponds to $\sim 10^{29}$, ${}^{71}\text{Ga}$ nuclei. The solution is contained in a large tank.

${}^{71}\text{Ge}$ produced by neutrinos is radioactive, and decays back by electron capture into ${}^{71}\text{Ga}$. The mean life of a ${}^{71}\text{Ge}$ nucleus is about 16 days: thus the ${}^{71}\text{Ge}$ accumulates in the solution, reaching equilibrium when the number of ${}^{71}\text{Ge}$ atoms produced by neutrino interactions is just the same as the number of the decaying ones. When this equilibrium condition is reached, about a dozen ${}^{71}\text{Ge}$ atoms are present inside the 103 tons gallium chloride solution (containing $\sim 10^{29}$ Ga nuclei)

GNO/Gallex Tank



GNO/Gallex experimental procedure

The solar neutrino flux above threshold is deduced from the number of ^{71}Ge atoms produced using the theoretically calculated cross sections

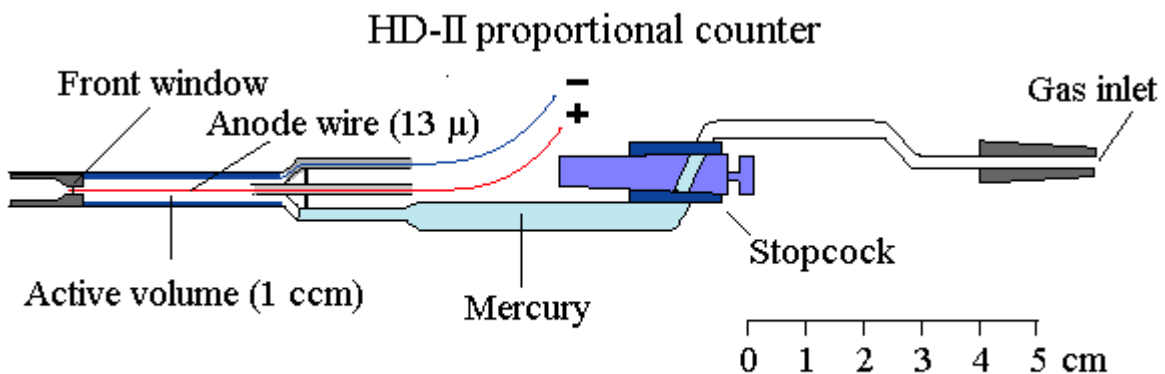
The ^{71}Ge are identified through their decay after chemical separation from the target

In summary the methodology for the measurement of the solar neutrino flux contemplates the following steps:

- The solution is exposed to solar neutrinos for about 4 weeks; at the end of this time ~ 10 ^{71}Ge nuclei are present in the solution, due to solar neutrino interactions on ^{71}Ga .
- ^{71}Ge , present in the solution as volatile GeCl_4 , is chemically extracted into water by pumping ~ 3000 m^3 of Nitrogen through the solution.

GNO/Gallex experimental procedure (cont'd)

- The extracted ^{71}Ge is converted into GeH_4 (Germane gas), and introduced into miniaturized proportional counters mixed with Xenon as counting gas. At the end $\sim 95\text{-}98\%$ of the ^{71}Ge present in the solution at the time of the extraction is in the counter; extraction and conversion efficiencies are under constant control using non radioactive germanium isotopes as carriers



- Decays and interactions in the counter, including ^{71}Ge e-capture (meanlife 16.5 days) $^{71}\text{Ge}(e^-, \nu)^{71}\text{Ga}$, are observed for a period of 6 months, allowing the complete decay of ^{71}Ge and a good determination of the counter background. The charge pulses produced in the counters by decays are recorded by means of fast transient digitizer operating at 0.2 ns/chan for a depth of 400 ns.

GNO/Gallex experimental procedure (cont'd)

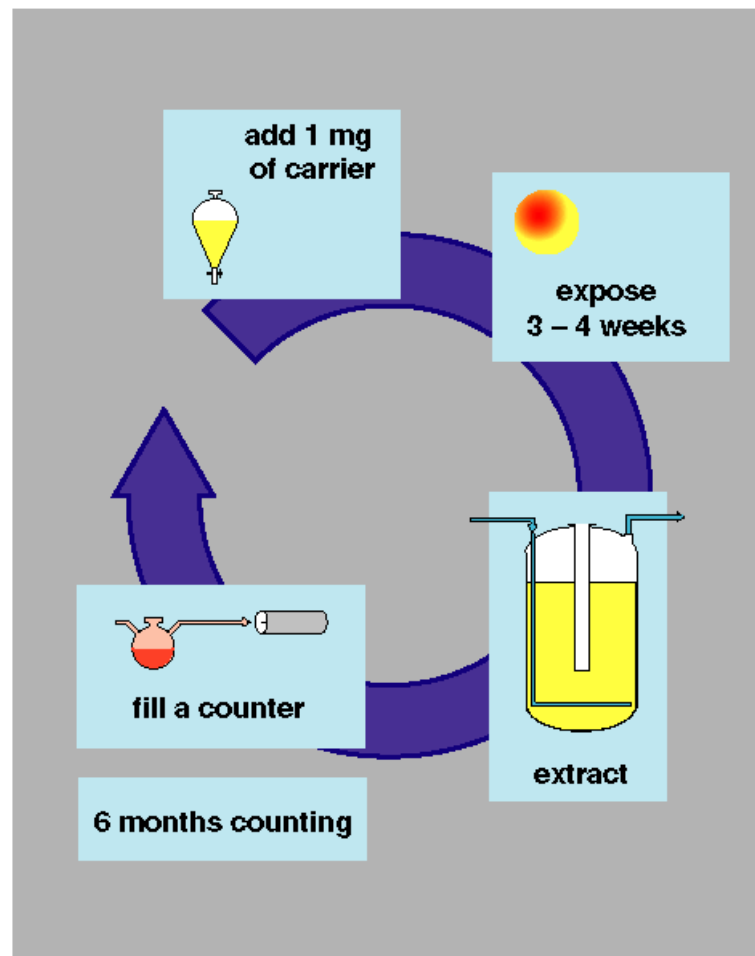
- Data are analyzed to obtain the most probable number of ^{71}Ge introduced in the counter.

Key issue - backgrounds minimization:

- rigorous application of low-level-radioactivity technology in counter design and construction.
- Rejection of the residual background through application of amplitude and shape analysis on the recorded pulses: K (10.4 keV) and L (1.2 keV) energy windows identification and rise time selection the ionization produced by the decay is point-like, so that the pulses are fast compared with most of the natural radioactivity background (producing diffuse ionization and 'slow' pulses)).
- Counters are calibrated by an external Gd/Ce X-ray source, for amplitude and pulse shape cuts efficiency determination for each measurement. The event amplitude and shape selection reduces the mean background rate to less than 0.1 counts per day. Calibration is repeated 5 times during the 6 month counting time, to check the stability of the gain and of the resolution.

GNO/Gallex experimental procedure (cont'd)

- The final Ge production rate is obtained by a suitable maximum likelihood determination applied on the data sample after the cuts application.
- Final corrections to take into account the production rate due to so called "side reactions", i.e. interactions in the solution generated by high energy muons from cosmic rays and by natural radioactivity.



Class of detectors based on the Cerenkov methodology

-Multi purpose detectors

-Solar neutrinos

Kamiokande/Superkamiokande
SNO (Heavy water version)

- Atmospheric neutrinos

(Kamiokande/Superkamiokande)

- Accelerator neutrinos

(Kamiokande/Superkamiokande)

- String detectors for UHE neutrinos

AMANDA

Baikal

Čerenkov radiation

In a material with refractive index n , a charged particle emits photons if its velocity is greater than the local phase velocity of light.

The charged particle polarizes the atoms along its trajectory.

These time dependent dipoles emit electromagnetic radiations.

If $v < c/n$ the dipole distribution is symmetric around the particle position, and the sum of all dipoles vanishes.

If $v > c/n$ the distribution is asymmetric and the total time dependent dipole is non nul, thus radiates.

mechanism of the Čerenkov radiation [Gruppen96].

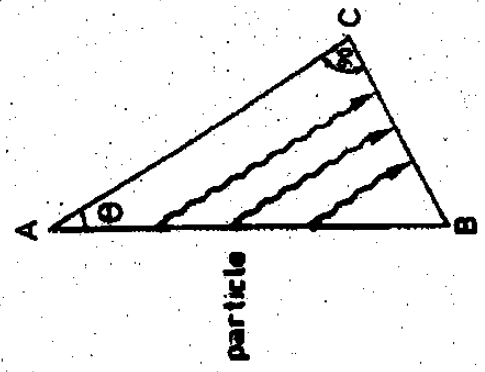
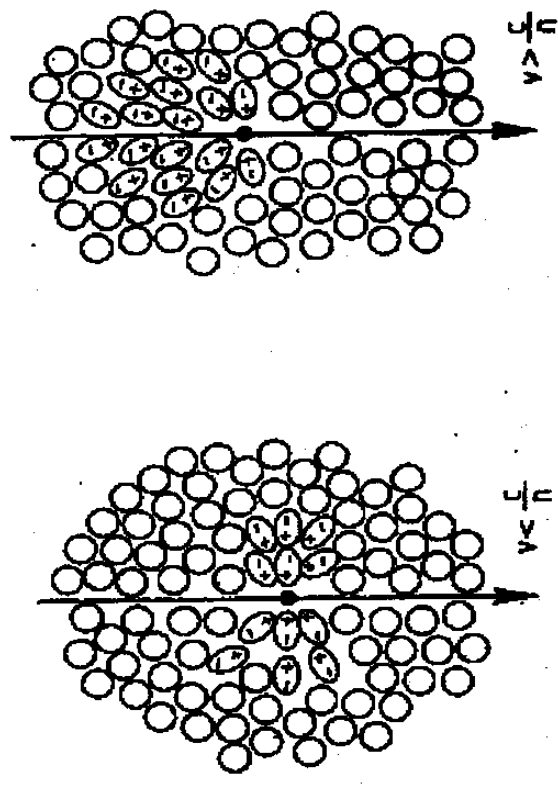


Fig. 6.7. Illustration of the Čerenkov effect [68].

$$\cos \vartheta = \frac{1}{\beta n} \quad I \propto \frac{1}{\lambda^2}$$

The Huyghens construction gives immediately :

$$\cos \theta = \frac{1}{\beta n}$$

Thus :

$$\frac{1}{n} \leq \beta < 1 \implies 0 \leq \theta < \arccos \frac{1}{n}$$

The number of photons produced per unit path length and per energy interval of the photons is

$$\frac{d^2 N}{d\epsilon dx} = \frac{\alpha z^2}{\hbar c} \sin^2 \theta = \frac{(\alpha z)^2}{r_e m c^2} \left[1 - \frac{1}{\beta^2 n^2(\epsilon)} \right]$$

in which

$$\beta n(\epsilon) > 1$$

In the X-ray region $n(\epsilon) \approx 1$. There is no X-ray Čerenkov emission.

Cerenkov/Heavy water approach: SNO

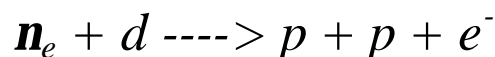
Basic idea: independent measurements of **a)** the flux of electron neutrinos (\mathbf{n}_e) and **b)** the cumulative flux of mu- and tau-neutrinos (\mathbf{n}_μ and \mathbf{n}_τ) from the Sun.

Heavy water makes this possible, allowing to determine

$$F(\mathbf{n}_\mu \text{ and } \mathbf{n}_\tau) = F(\mathbf{n}_x) - F(\mathbf{n}_e)$$

SNO can measure these fluxes via the different ways in which neutrinos will interact with the heavy water:

i. *Charged Current Reaction*



As the neutrino approaches the deuterium nucleus, a W boson is exchanged, changing the neutron in deuterium to a proton, and the neutrino to an electron.

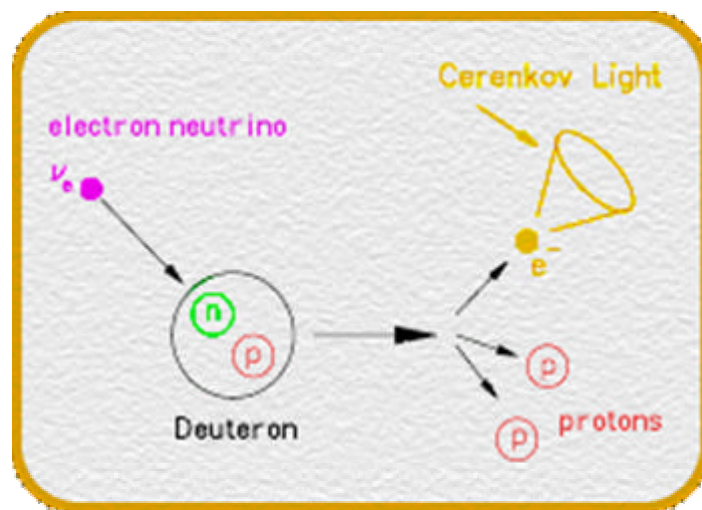
Essentially all the neutrino energy is transferred to the electron.

Cerenkov/Heavy water approach: charge current reaction in SNO

Due to the large energy of the incident neutrinos, the electron will be so energetic that it will be ejected at light speed, which is actually faster than the speed of light in water. This causes the optical equivalent of a "sonic boom", where a "shock wave of light" is emitted as the electron slows down. This light flash, called **Cherenkov radiation**, is detected by the photomultiplier tubes (**PMT's**); the amount of light is proportional to the incident neutrino energy.

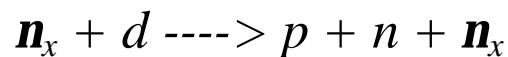
From the PMT hit patterns the energies of the neutrinos can be determined and an angular distribution measured. The spectrum of neutrino energies will show a distortion from the theoretical shape if neutrino oscillations are occurring.

(The Standard Solar Model predicts about 30 charged current events per day in SNO)



Cerenkov/Heavy water approach: neutral current reaction in SNO

ii. *Neutral Current Reaction*



In this reaction a neutral Z boson is exchanged (hence the name "neutral current reaction"). The net effect is just to break apart the deuterium nucleus; the liberated neutron is then thermalized in the heavy water as it scatters around.

The reaction can eventually be observed due to gamma rays which are emitted when the neutron is finally captured by another nucleus. The gamma rays will scatter electrons, which produce detectable light via the Cherenkov process, as discussed before.

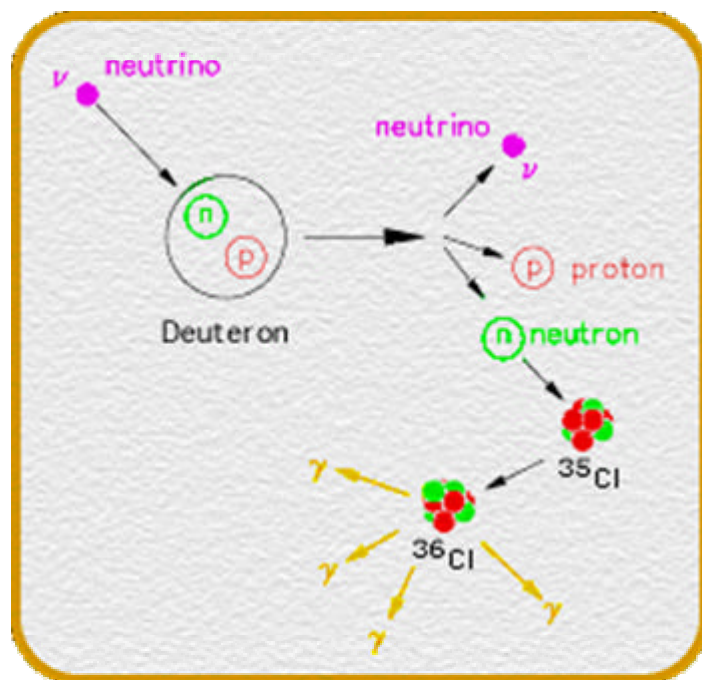
Cerenkov/Heavy water approach: neutral current reaction in SNO

The neutral current reaction is equally sensitive to all three neutrino types; the detection efficiency depends on the neutron capture efficiency and the resulting gamma cascade.

Neutrons can be captured directly on deuterium, but this is not very efficient and clearly distinguishing the spectra would be challenging.

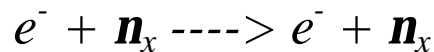
For this reason SNO is developing two separate neutral current systems to enhance the neutral current detection. The diagram below shows capture on ^{35}Cl , which will be added to the heavy water in the form of NaCl during the second phase of detector operation.

(The Standard Solar Model predicts about 30 neutrons per day in SNO)



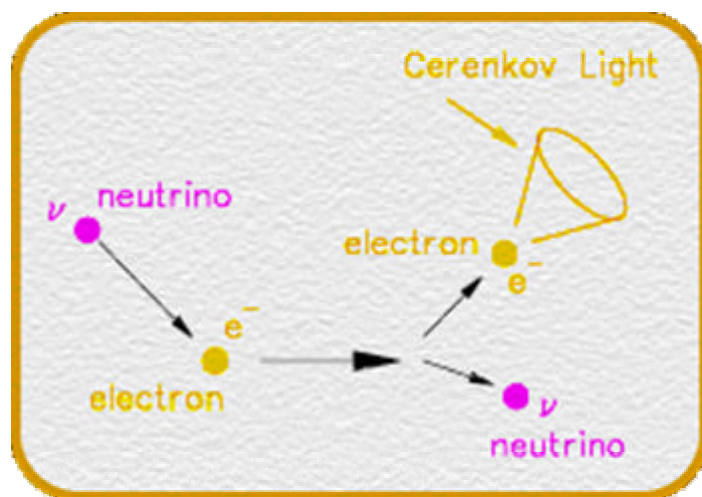
Cerenkov/Heavy water approach: Electron scattering reaction

iii. *Electron Scattering*

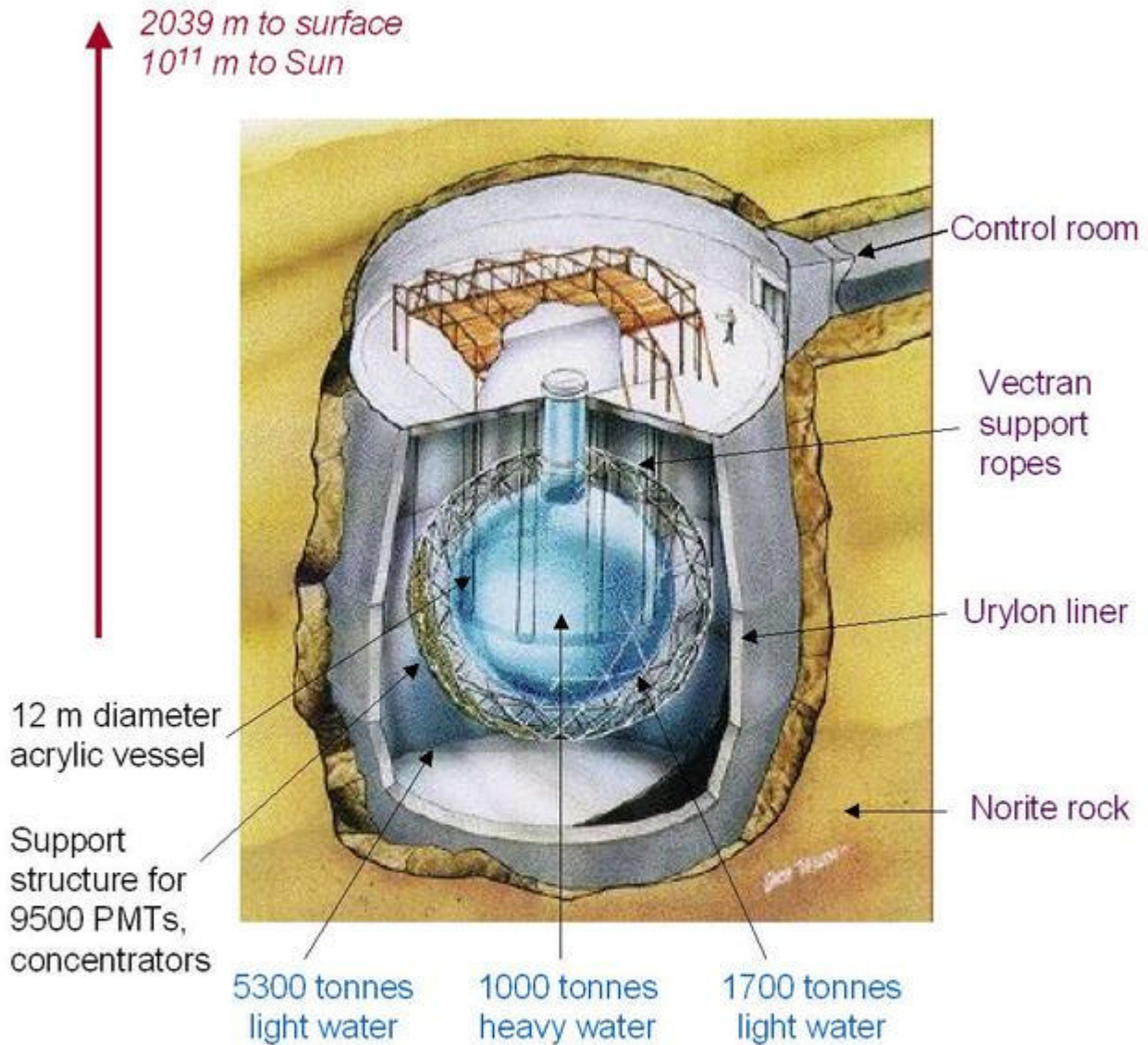


This reaction is not unique to heavy water and it is the primary mechanism in other light water detectors ([Kamiokande/Super-Kamiokande](#)). Although the reaction is sensitive to all neutrino flavours, the electron-neutrino dominates by a factor of six. The final state energy is shared between the electron and the neutrino, thus there is very little spectral information from this reaction. Good directional information is obtained.

(The Standard Solar Model predicts about 3 electron scattering events per day in SNO.)



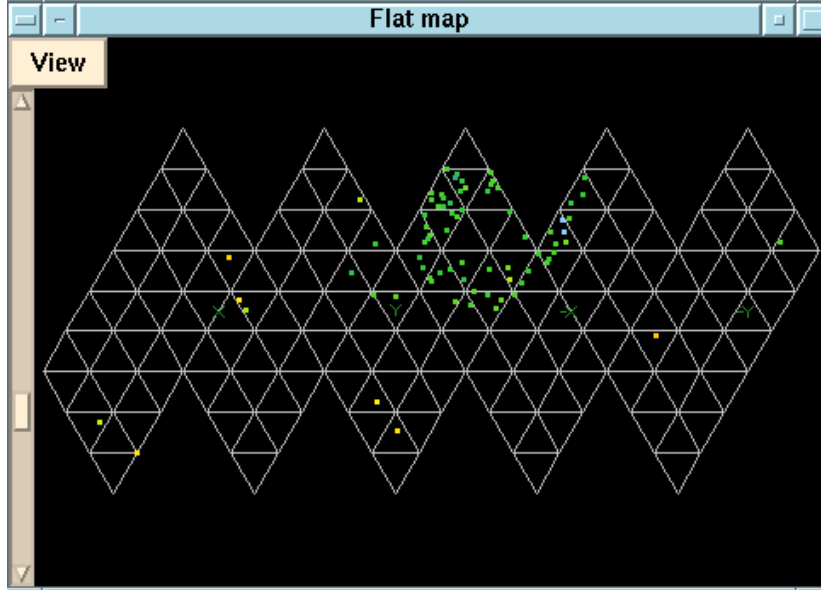
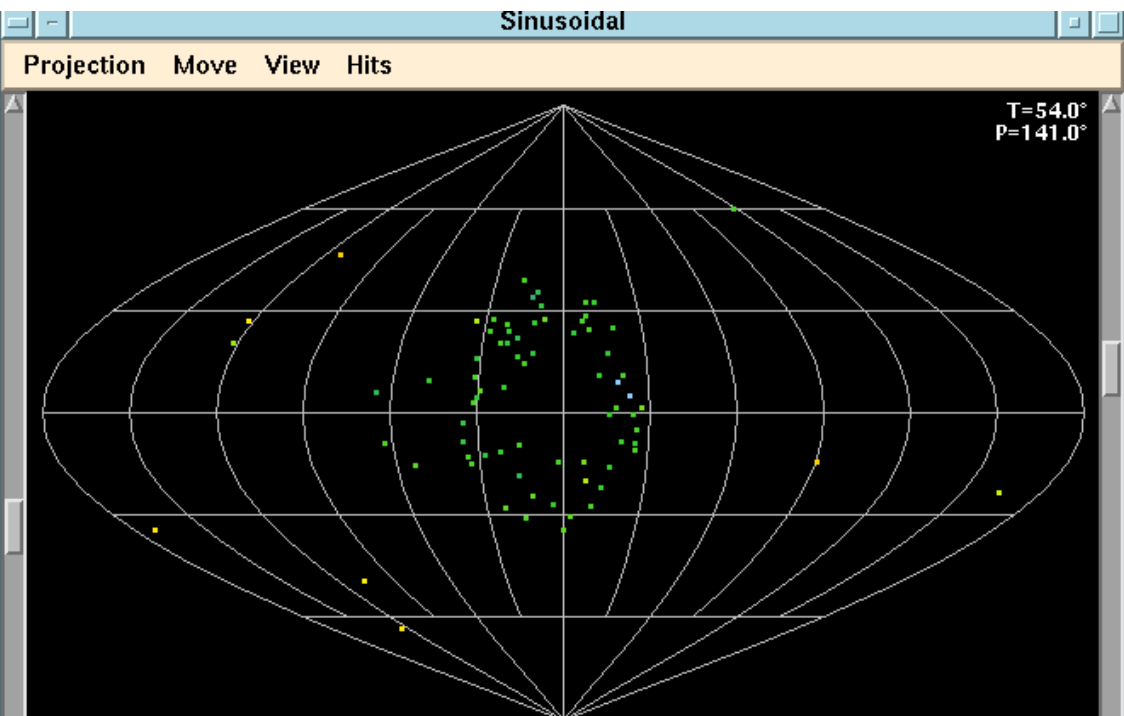
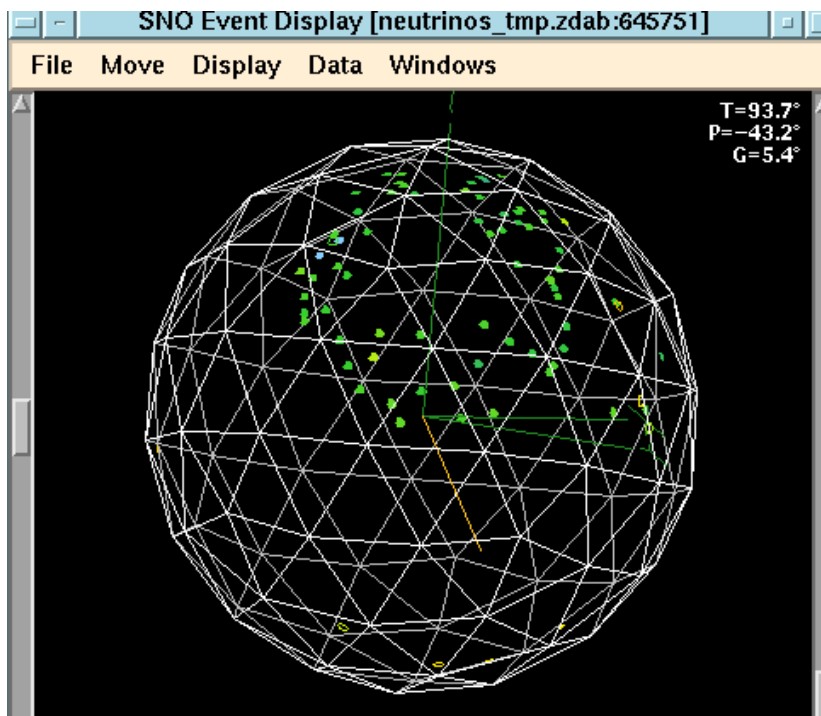
The SNO Detector



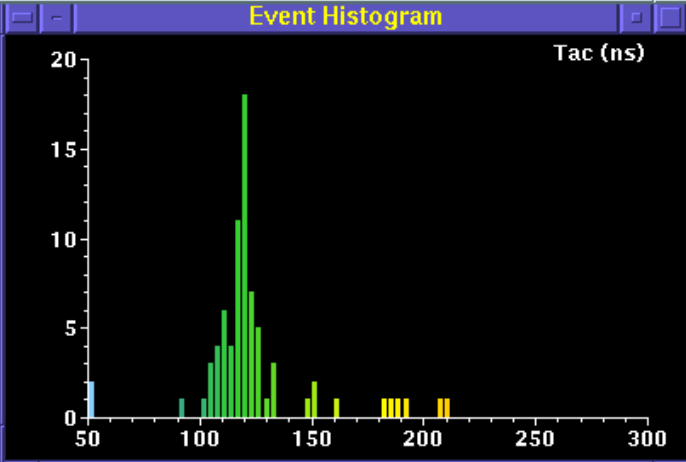
- **Location:** 6800 ft. level of INCO's Creighton mine near Sudbury, ON, Canada (~70 muons / day)

- **SNO Detector:** 9438_{inward} + 91_{outward} Hamamatsu 8" PMTs + concentrators = 64% coverage

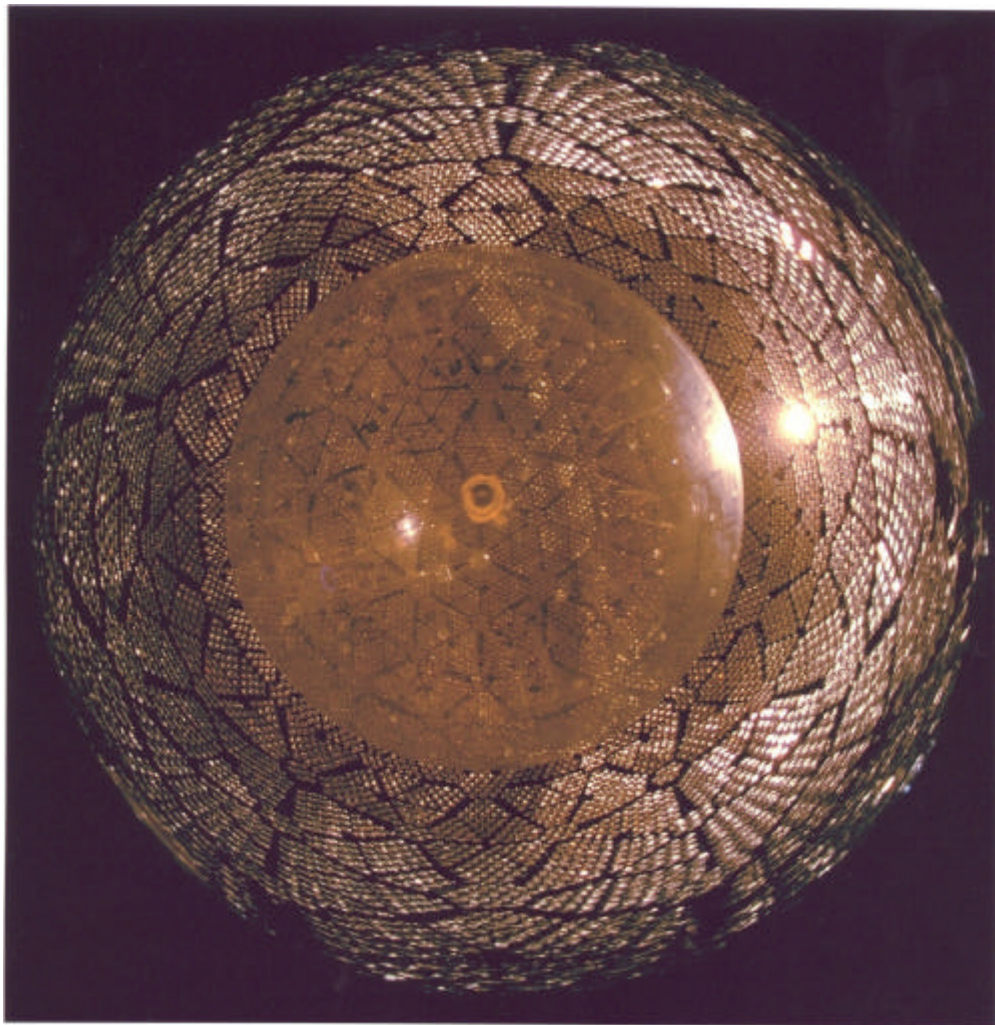




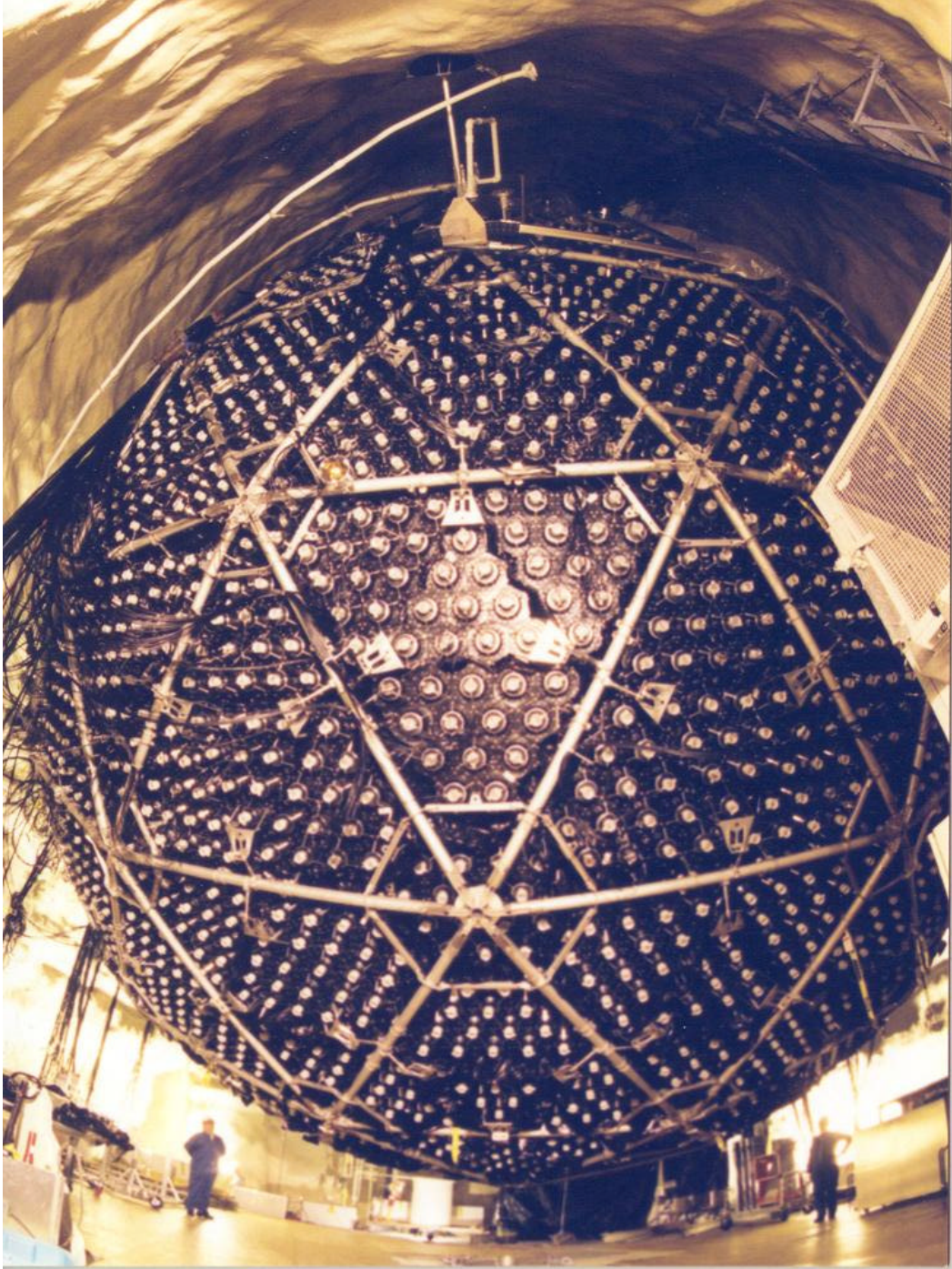
GTID: 645751
 Evt Num: 646705
 Run Num: 5463
 Date: 10/09/1999
 Time: 04:42:26.0497823
 Prev/Next: 141 ms / 789 ms
 Trigger: 20LB,20,100H,100M,100L
 Pk/Int/Dif: 12 / 120 / 0



Phototubes plus concentrators



PMT's sphere (external view)



SNO Calibration

• Optical

- Phototube timing, threshold, occupancy.
- Optical properties of: D₂O, H₂O, Acrylic as a function of wavelength.
- Sources:
 - * Laserball

• Energy and Event Characteristics

- Absolute energy scale (Nhits/MeV).
- Energy response as a function of event position and direction.
- Angular resolution.
- Sources:
 - * ¹⁶N — 6.131 MeV γ
 - * p-t source — 20 MeV γ
 - * ²⁴Na — 2.8 and 1.4 MeV γ
 - * ⁸Li — 14 MeV end point β

• Neutral Current

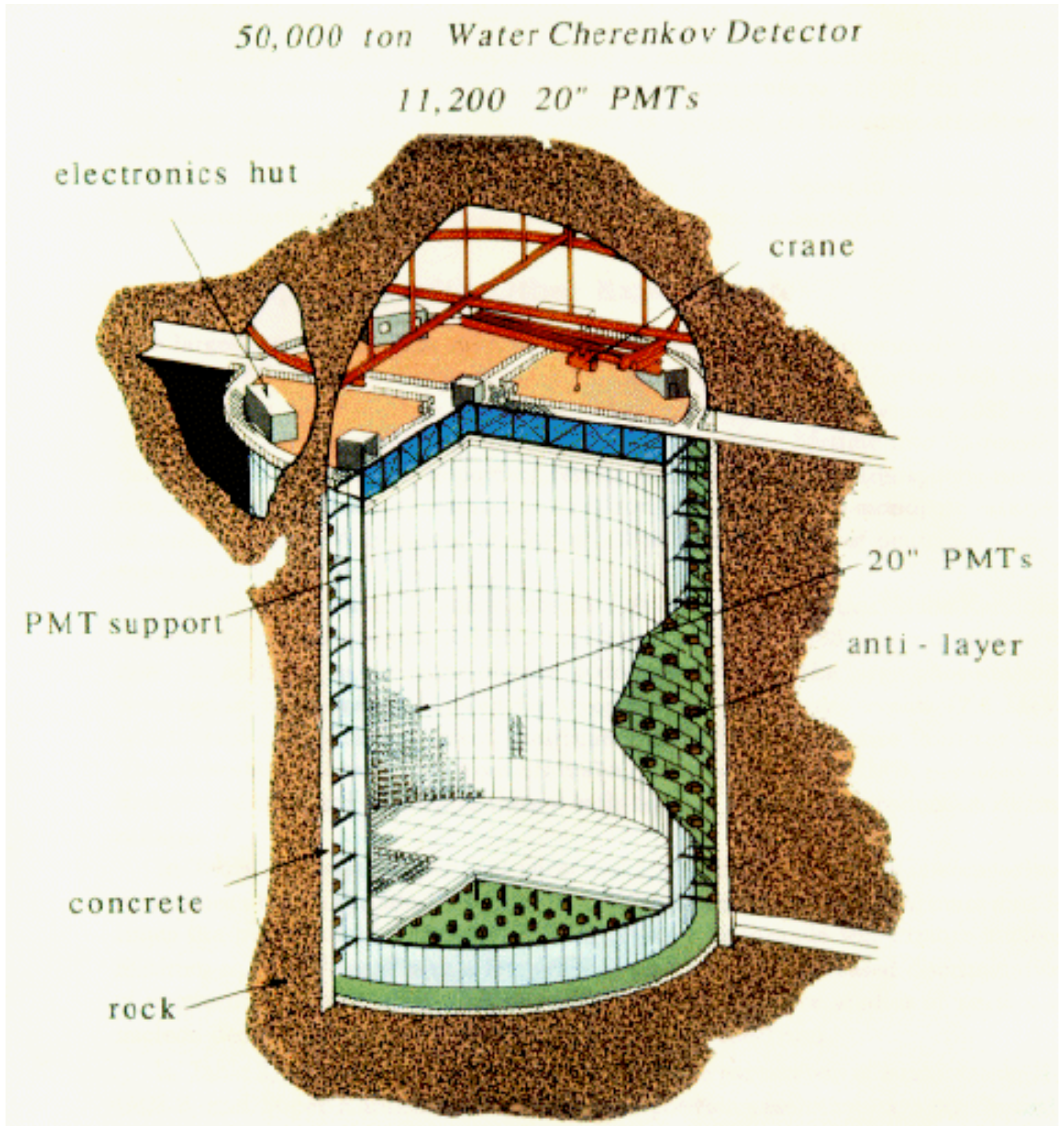
- Neutron capture efficiency (function of event position in D₂O)
- Sources:
 - * ²⁵²Cf
 - * ¹⁷N

• Backgrounds

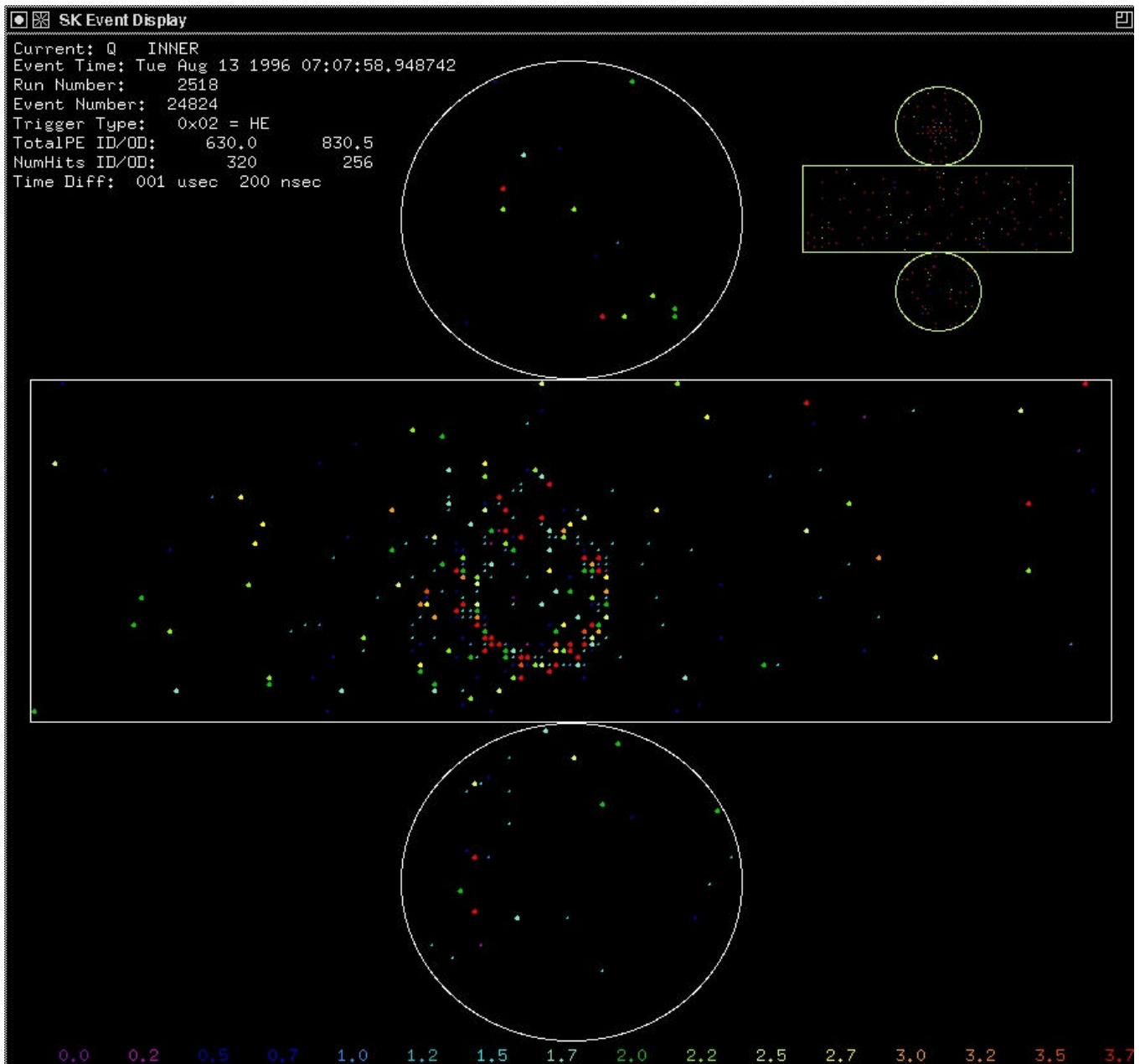
- U and Th decay products
- Sources:
 - * Proportional Counter U and Th Source

Source in Red have been deployed

Superkamiokande artistic view

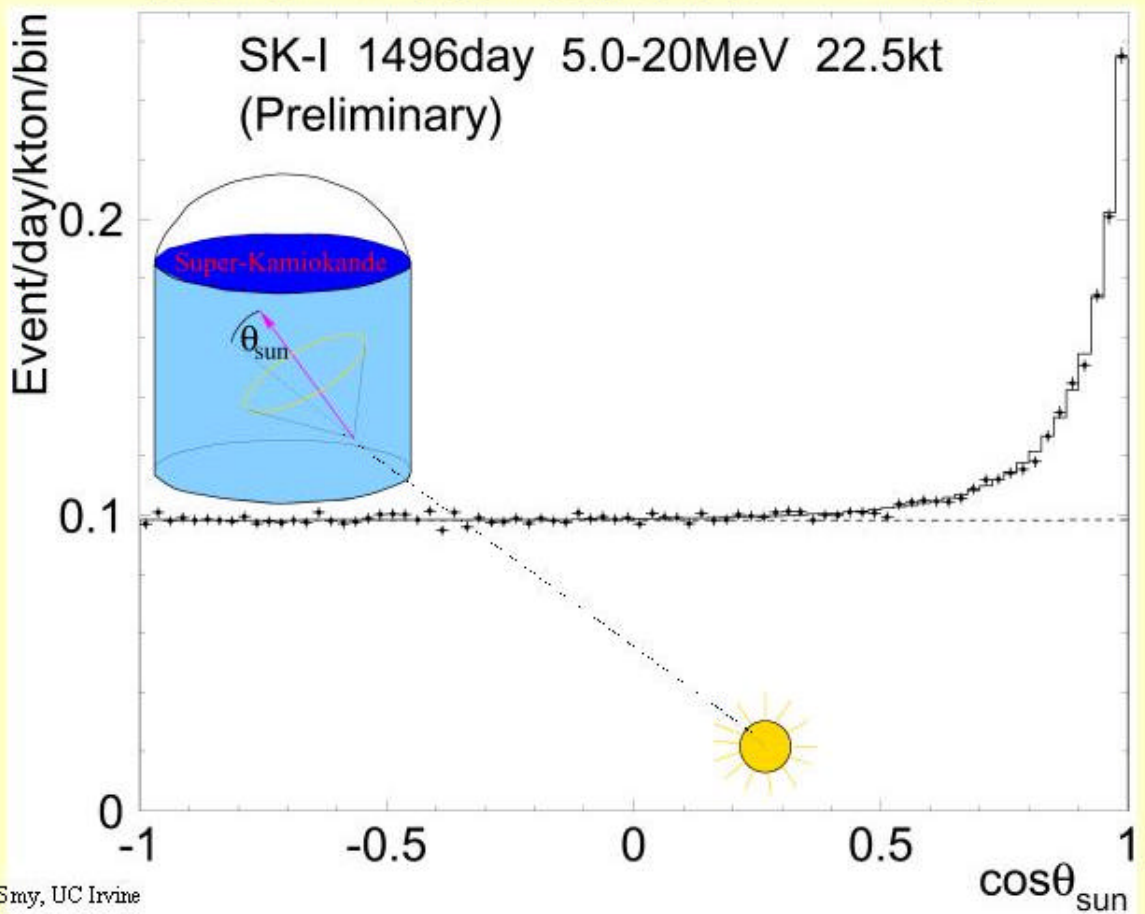


Example of Cerenkov ring



How to exploit the Cerenkov light directionality

Solar Peak above 5 MeV



Michael Smy, UC Irvine

Cerenkov based string detectors as neutrino telescope for UHE neutrinos

Instrumentation of a large volume of water in a deep ocean trench or deep in the polar ice allow UHE neutrino astronomy via the detection of the cerenkov light from the (upward going) neutrino induced muons.

The deep under water or under ice locations shield the detector from cosmic ray muons.

Dumand (feasibility study)

Amanda (existing detector at south pole, being upgraded)

BAIKAL (lake Baikal detector, being upgraded)

Future experiment toward the ambitious km^3 goal

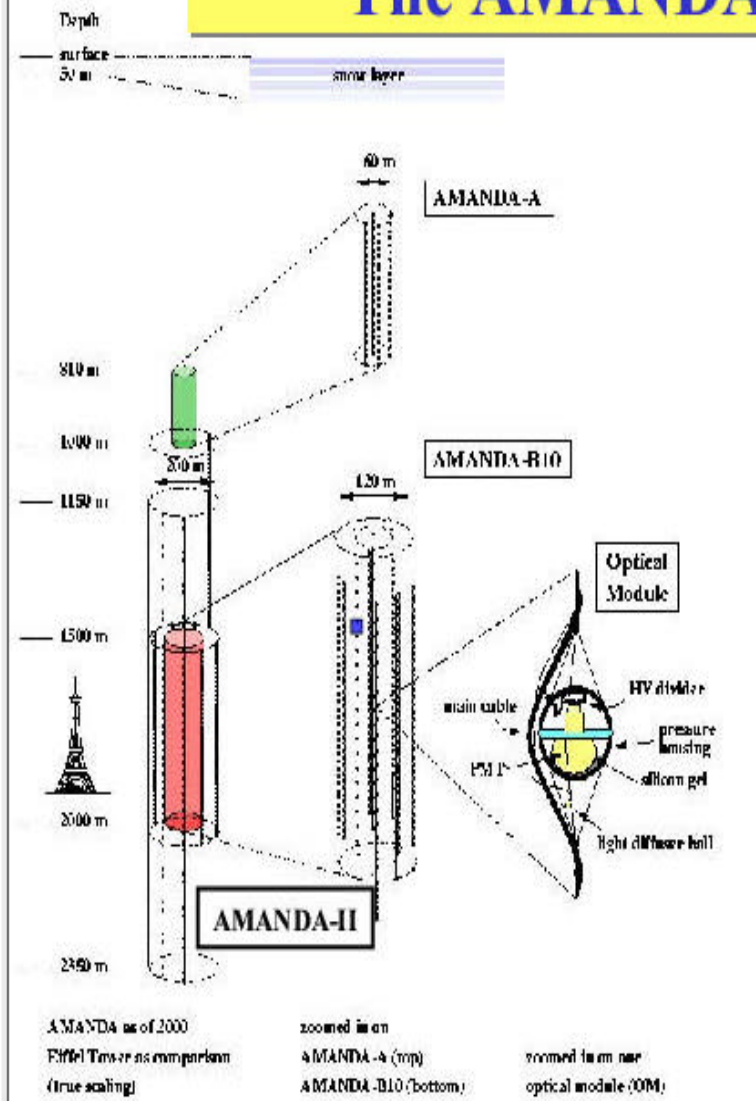
Icecube

Antares

Nestor

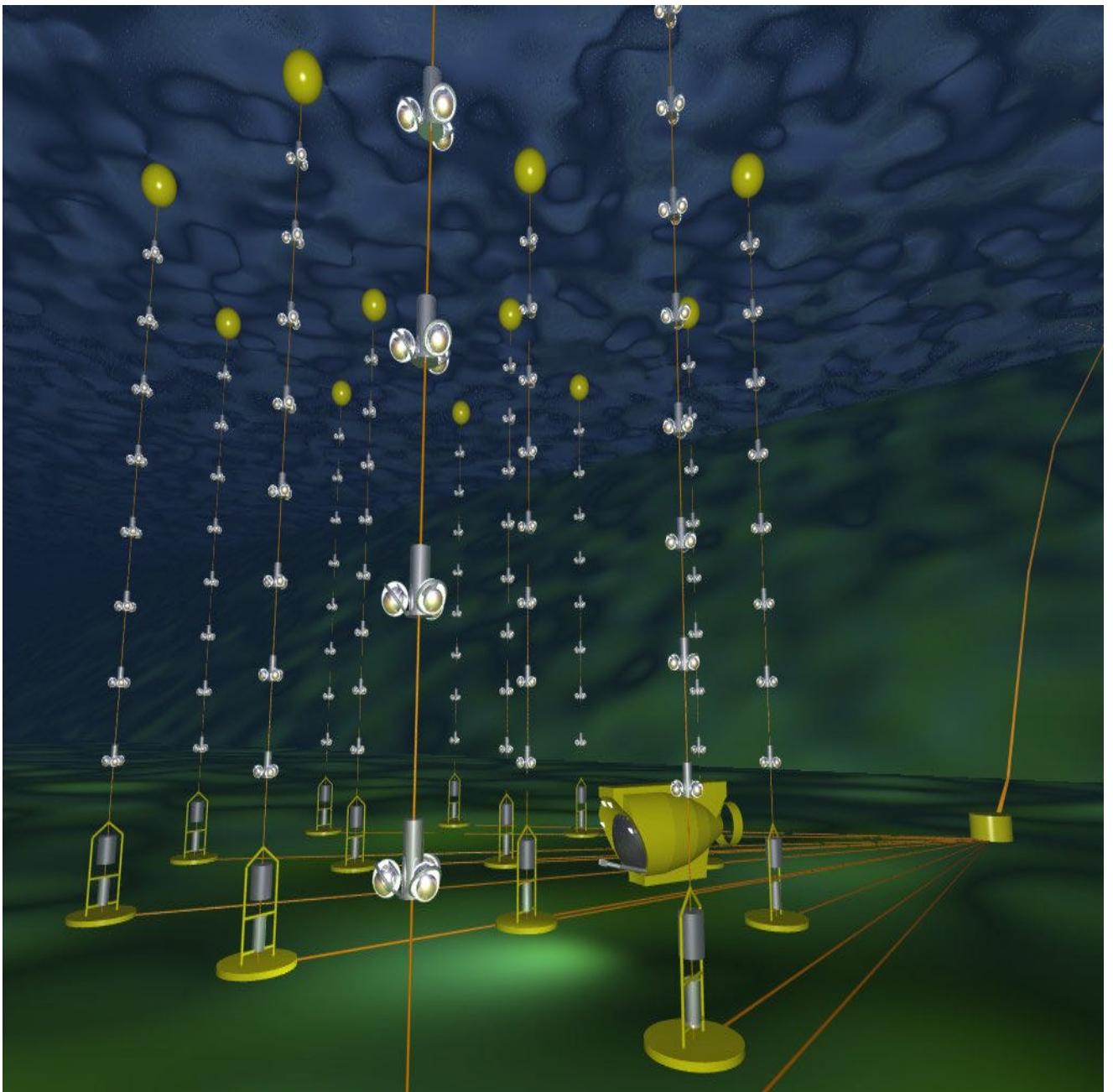
Nemo

The AMANDA Detector



- **Hot-water-drill 2km-deep holes & insert strings of PMTs in pressure vessels.**
 - AMANDA-B10: 302 PMTs, completed in 1997
 - Old & new A-B10 results presented
 - AMANDA-II: 677 PMTs, completed in 2000
 - Prelimin. results presented
- **AMANDA challenges:**
 - **Natural medium!**
 - Blame Mother Nature
 - **Remote location!**
 - Blame Scott & Amundsen who made it look too hard to get there
 - **Unfettered bkgd. source!**
 - We'd all like to know exactly who to blame...
 - **Prototype detector!**
 - Can you blame us for trying to improve things?

Antares artistic view

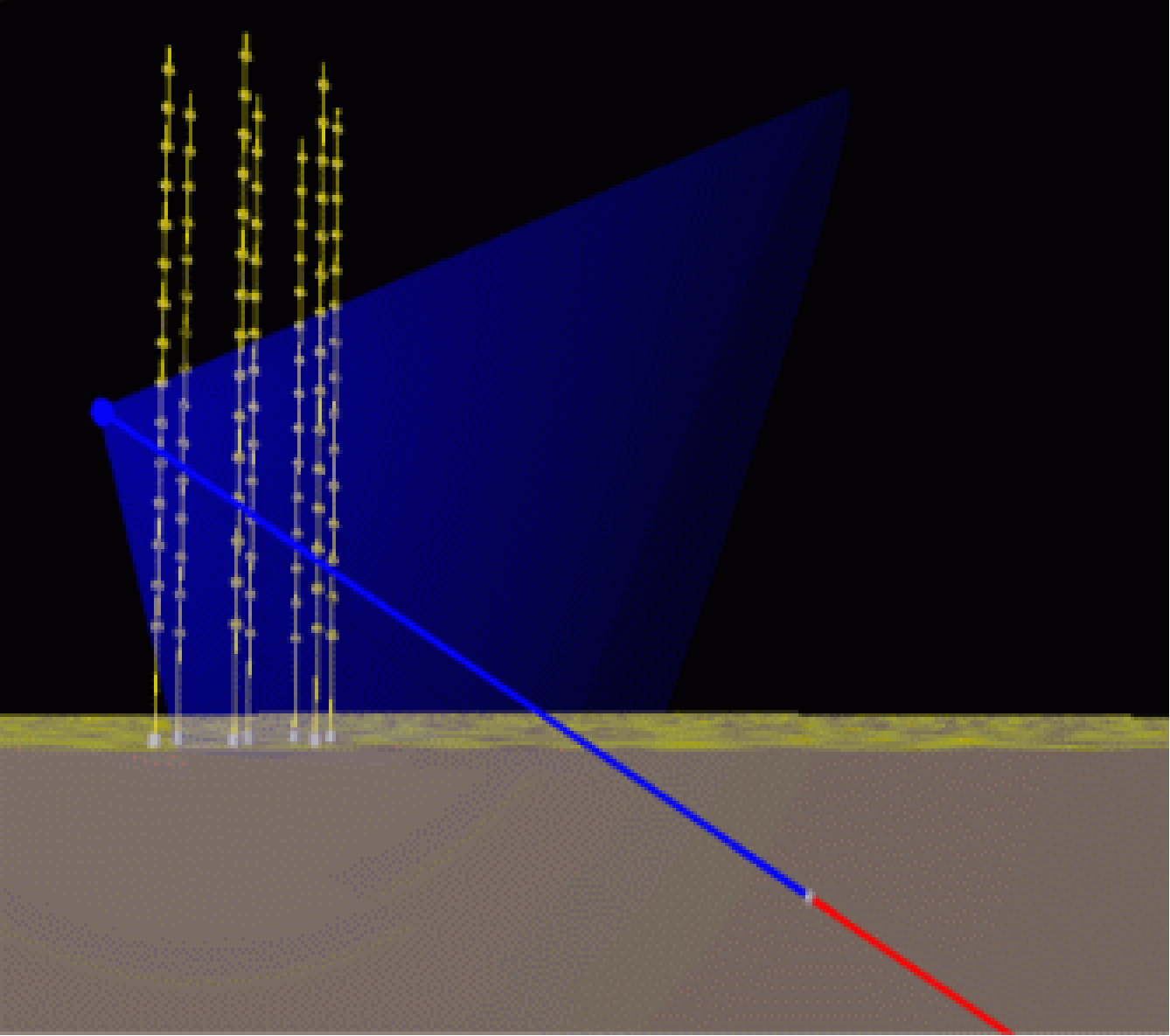




An opened optical module



Cerenkov light detection in a string detector



Scintillation technique

The scintillation technique is suited to build massive experiments devoted to the detection of low energy rare events

In particular in the neutrino field this kind of technique has been exploited fruitfully for the

a) reactor neutrino experiments

Gosgen

Bugey

Chooz

Palo Verde

Kamland

b) accelerator based experiments

LSND

Karmen

c) supernova neutrino experiment

LVD

d) and they are planned for low energy solar neutrino detection

Borexino

LENS

KamLAND

Scintillation

Detection of ionising radiation through the scintillation light induced in special organic or inorganic materials.

Fundamental properties for a good scintillating material:

1. High scintillation efficiency
2. Linear dependence between energy deposit and produced light
3. Limited self absorption
4. Short decay time of the scintillation light (fast pulses generation)
5. Suited to be easily shaped in various forms and dimensions
6. Refractive index similar to the glass (phototube matching)

Light emission process

1. **Fluorescence**: prompt emission of visible radiation after original the material excitation
2. **Phosphorence**: emission of visible radiation of longer wavelength than fluorescence, with longer decay time
3. **Delayed fluorescence**: production of emission light of wavelength equal to that of fluorescence emission, but with emisson time substantially longer

Scintillating materials of common use

1. **Plastics, liquids and some crystals** realized with aromatic polycyclic hydrocarbons with one or more benzene rings (organics)

2. **Alkali Halide Crystals** (inorganic materials)

Organic scintillators: fast response but less emitted light

Suited for beta spectroscopy and fast neutron detection

Inorganic scintillators: better light yield and linearity, but

longer time response. Particularly good for gamma

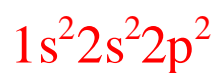
spectroscopy (high Z and density)

Scintillation mechanism in organic materials

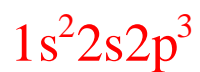
The fluorescence process takes place in transition between the energetic levels of the single molecule, independently from its physical state.

In the so called polycyclic aromatic hydrocarbons the molecular level involved in the process are the so called electronic level p which stem from the trigonal hybridisation (sp^2) of the four valence electrons of the carbon atoms at the vertex of the hexagonal planar molecule C_6H_6 (benzene ring)

Electron configuration of the carbon atom in the ground state



Configuration of the carbon atom ready for the chemical binding



Possible hybridisation of the 4 valence electron orbitals

1. **Tetraedric or sp^3** : 4 equivalent orbital spatially directed according to the vertex of a tetraedric, angle $109^\circ 28'$

(diamond, methane). Non luminescent materials.

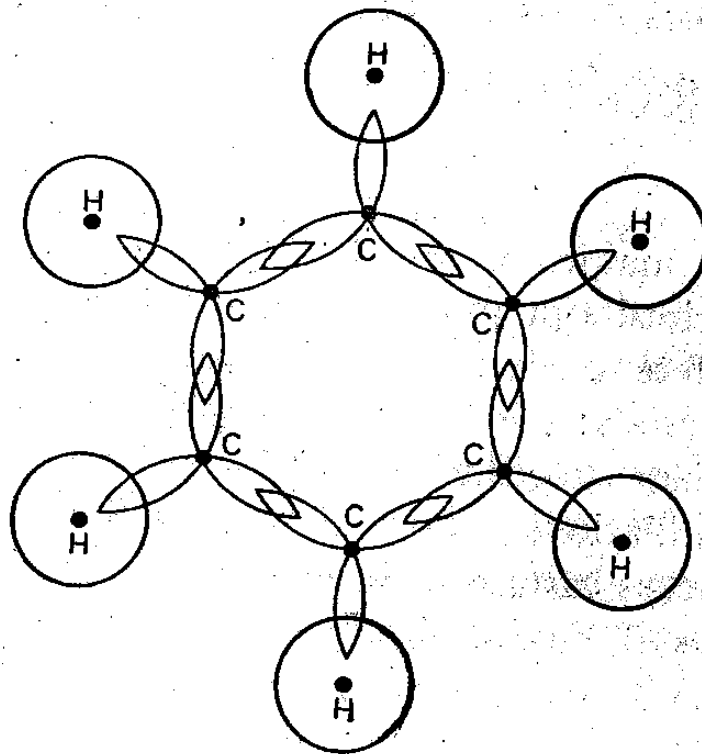
2. **Trigonal or sp^2** : an unaltered p orbital (π) and three equivalent orbital (σ), coplanar and at 120° degree. This is the typical hybridisation of the aromatic polycyclic hydrocarbons (planar and luminescent molecules). The s orbital is symmetric with respect to the plane of the σ bounds (molecular plane)

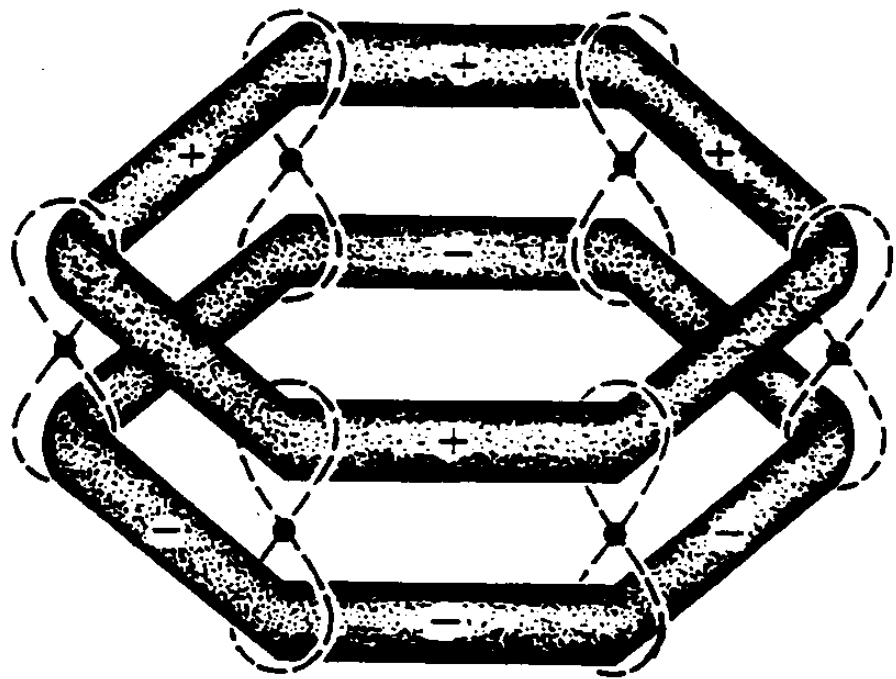
3. **Digonal or sp** : two unaltered p orbitals and two equivalent orbitals at 180° degree. Linear molecules as acetylene.

Benzene

In Benzene the σ orbitals interact as shown in the figure giving rise to localized σ bonds C-C and C-H

The six atomic orbital π interact originating molecular orbitals π completely delocalised whose excited states cause the molecular luminescence





Energetic levels of the molecular orbitals π

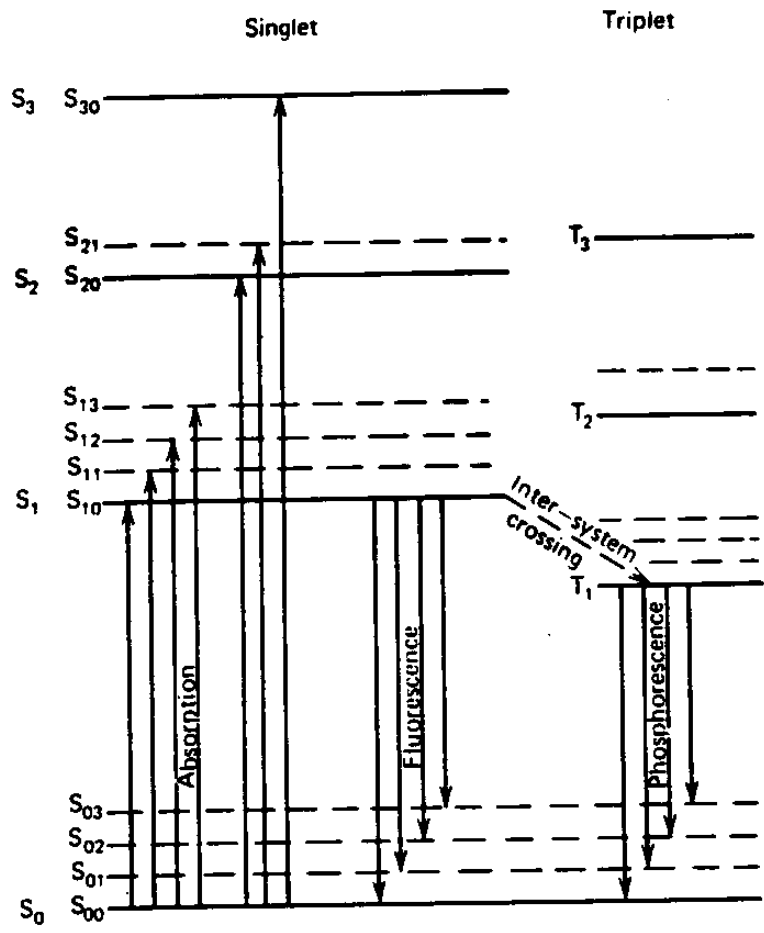
S0, S1, S2 spin 0 levels (singlet level)

T0, T1, T2.... Spin 1 levels (triplet levels)

The dashed sublevels (spacing around 0.15 eV) are vibrational molecular levels

S0 - S1 gap $\sim 3 - 4$ eV

The highest excited states de-excite to S1 through non radiative internal conversion in time interval of ps. Also the vibrational levels S11, S12.... go rapidly to S10.



Fluorescence

Transition between S_{10} and one of the levels S_0 :

fluorescence (main component of the scintillation light)

Fluorescence Decay time of the S_{10} level : τ

Time profile of the fluorescence light intensity: $I=I_0e^{-t/\tau}$

τ ~ few nanoseconds in the majority of the organic
scintillators

Phosphorescence

Populating T_1

1. Non radiative transition $S_1 - T_1$ (intersystem crossing)
2. Direct ion recombination to T_1

Phosphorescence light originated in the (highly inhibited) transition T_1-S_1 . Wavelength longer than in the fluorescence case since T_1 is below S_1

T_1 lifetime : $10^{-3} - 10^{-4}$ s

Delayed fluorescence

Inverse transition $T_1 - S_1$ followed by a normal fluorescence decay. The transition takes place according to the so called triplet annihilation reaction



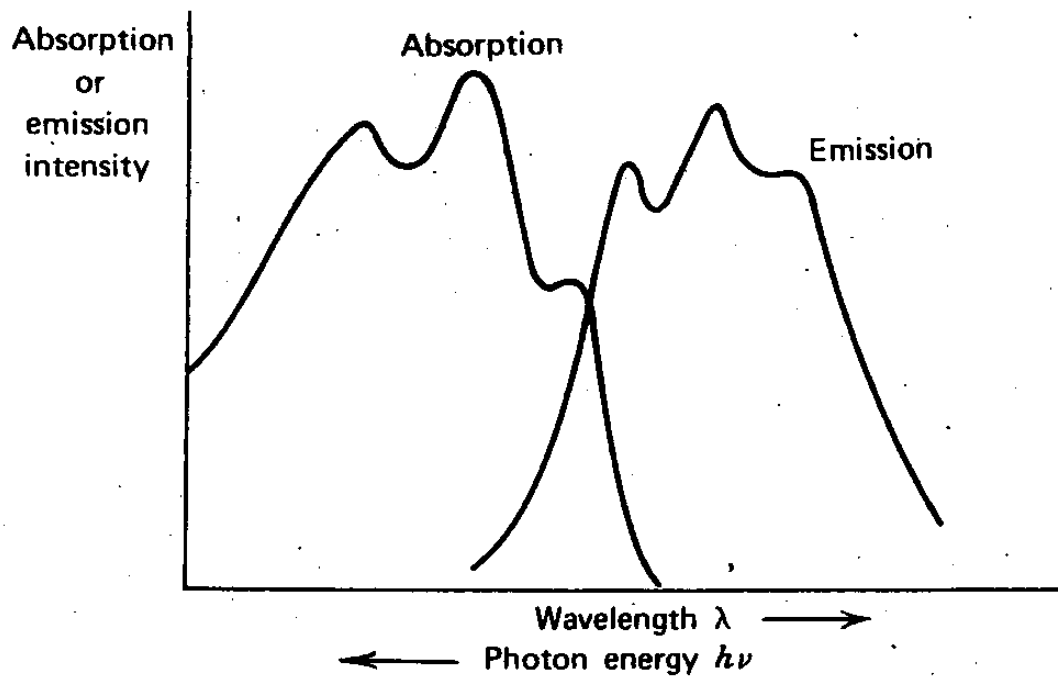
Emission and absorption spectra

The transparency of an organic scintillator to its own light is measured by the relative displacements of the two spectra (Stokes shift).

Since the excitation transitions require photons of energy higher than those resulting from the de-excitation the emission spectrum is shifted towards the right with respect to the absorption one.

The overlapping region corresponds to the de-excitation

$S_{10}-S_{00}$



Scintillation efficiency

Fraction of the energy of the incoming particle converted into visible light.

Competing non radiative de-excitation modes limit the energy available for light production (quenching, heat production).

The oxygen dissolved in the liquid scintillator is an important additional quenching factor, which has to be removed.

By exploiting the energy migration process typical of the hydrocarbon solvent through the addition of a small quantity of an high efficiency solute the overall efficiency is highly enhanced:

Binary plastic or liquid scintillators

Pulse shape discrimination

The fast fluorescence component is followed by the slow component due to the phosphorescence and delayed fluorescence whose origin is connected to the presence of the so called triplet state T_1 (typical time of hundreds of nanoseconds).

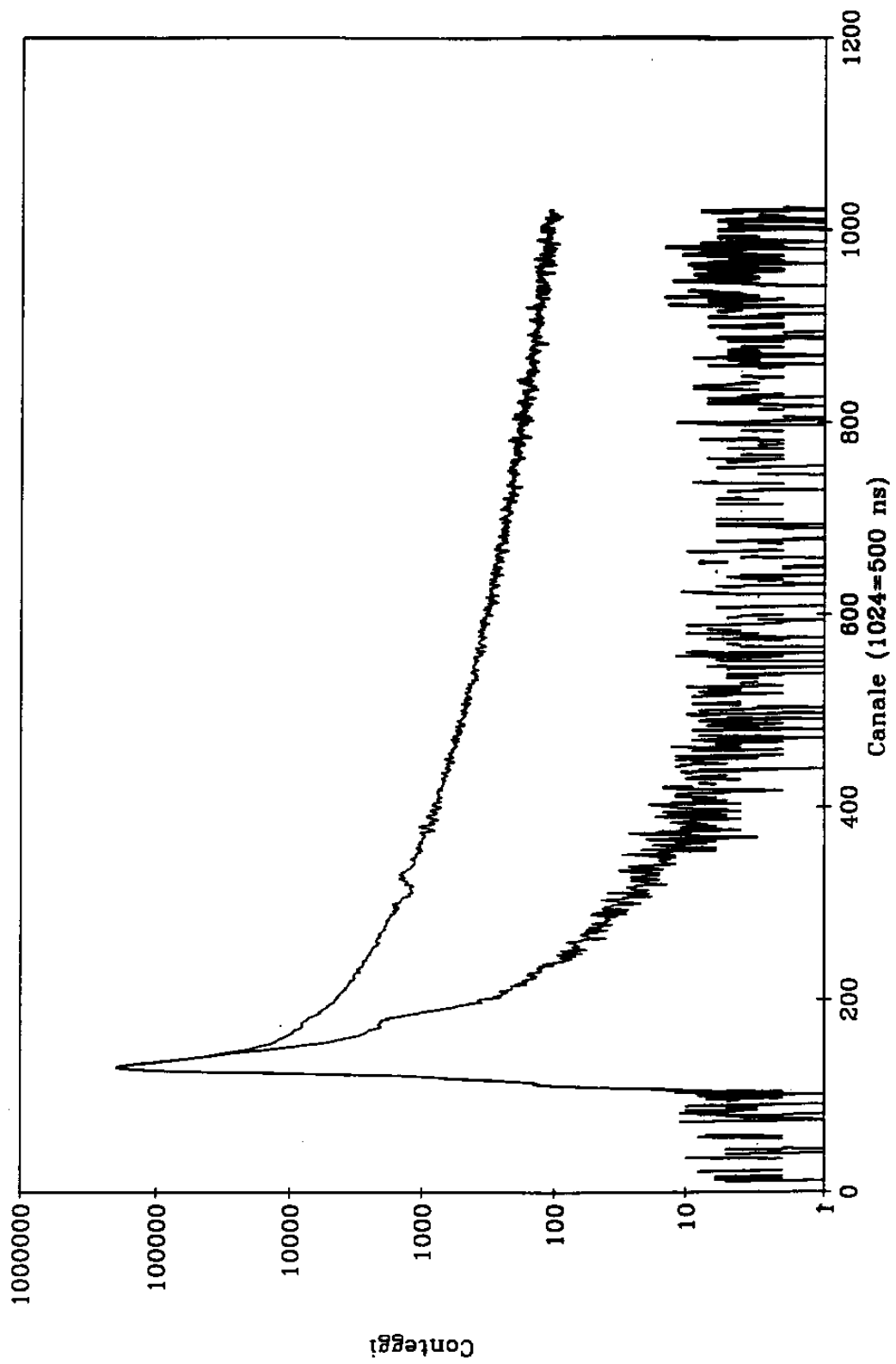
The light fraction which is comprised in the slow component depends upon the particle type

Discrimination of particle types

The density of the triplet states increases as function of the specific loss (dE/dx) of the incident particle

Tail more pronounced for heavily ionising particles

Pc+pmp (6.6 g/l)



Time evolution of the fluorescence light

Unitary scintillator: monoexponential decay

Taking into account the population process of the optical levels:

$$I = I_0 (e^{-t/\tau} - e^{-t/\tau_1})$$

τ_1 : time constant for the population of the optical levels

τ : time decay constant of the optical levels

For a fast scintillator $\tau \sim 3 - 4 \tau_1$

Binary or ternary scintillators: one or two more exponential terms

Some examples of scintillator based neutrino detectors

Borexino (low energy solar neutrino detector)

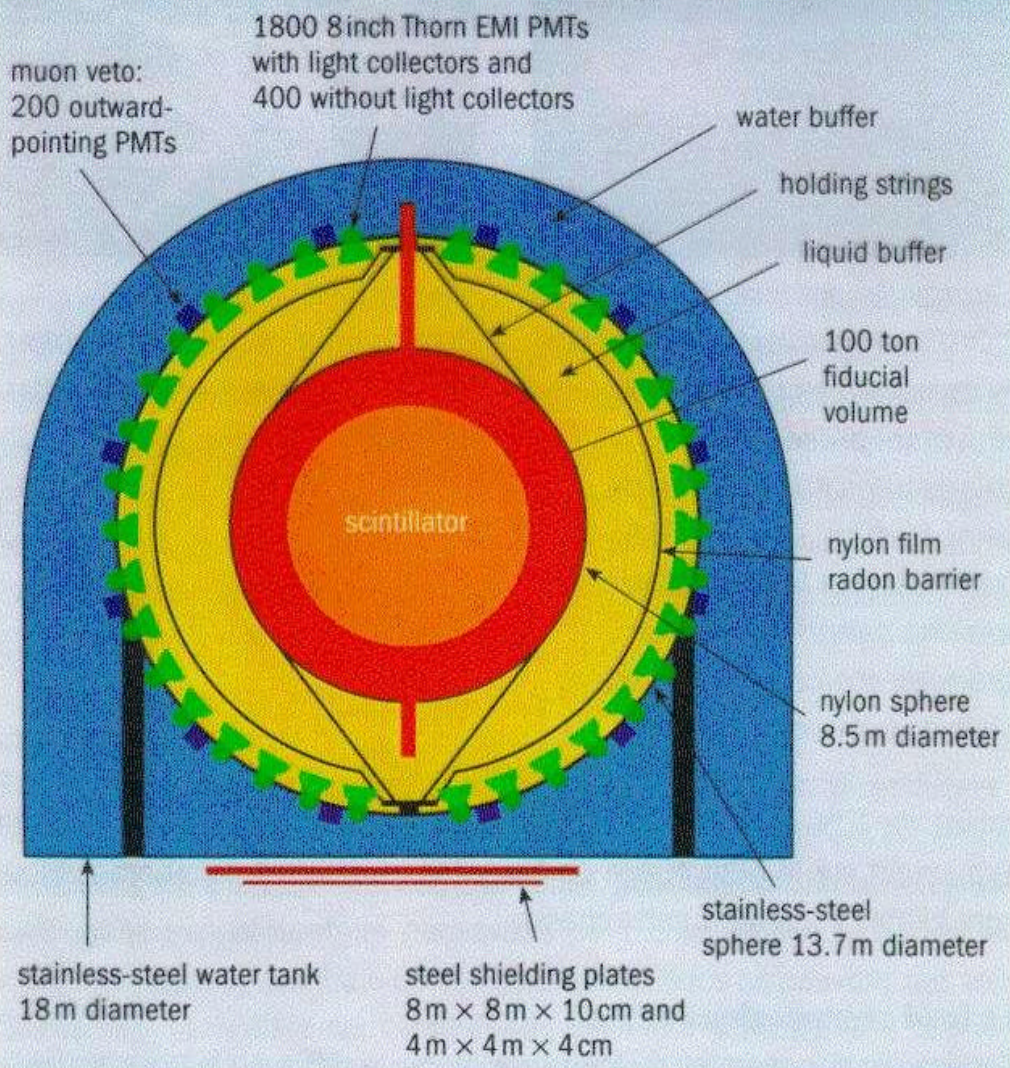
Chooz (reactor neutrino experiment)

Kamland (reactor neutrino experiment and solar neutrino detector)

Borexino

A real time, calorimetric, scintillation detector, for low energy solar neutrinos, under installation at the Gran Sasso underground Laboratory, aimed at the detection of the monoenergetic ${}^7\text{Be}$ neutrinos, through scattering off the electrons of the scintillator

Expérience Borexino



Main Components: Detector

Scintillator

Nylon (Inner and Outer) Vessels

Buffer Liquid

Stainless Steel Sphere

support of PMT's

containment of the buffer (zero

buoyancy for the nylon vessels)

PMT's

Concentrators

Muon veto

Calibration equipments

Water Tank

Electronics and DAQ

Main components: Plants

Storage Vessels

Scintillator Purification systems

Water extraction

Distillation

Column purification

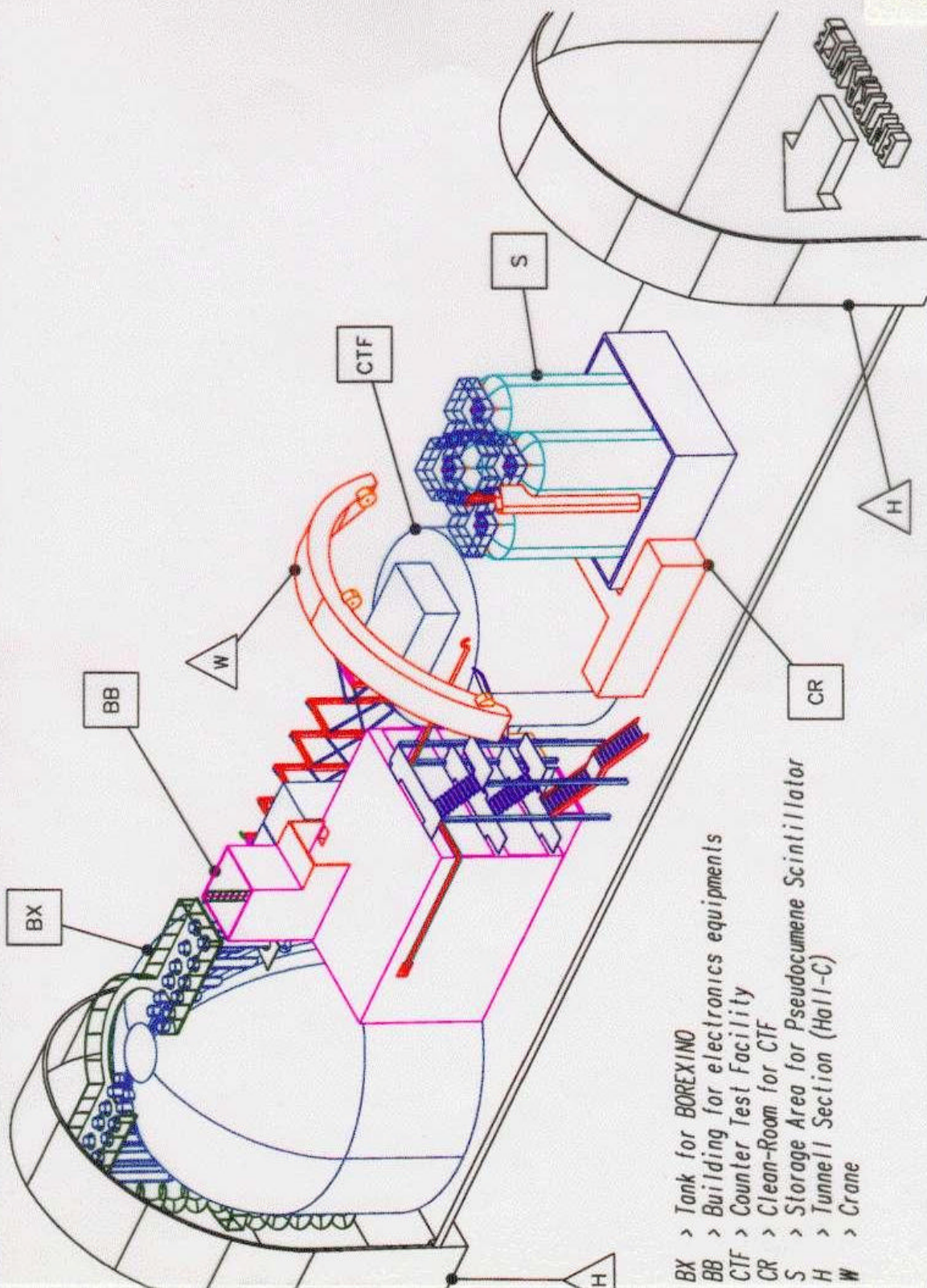
Nitrogen sparging

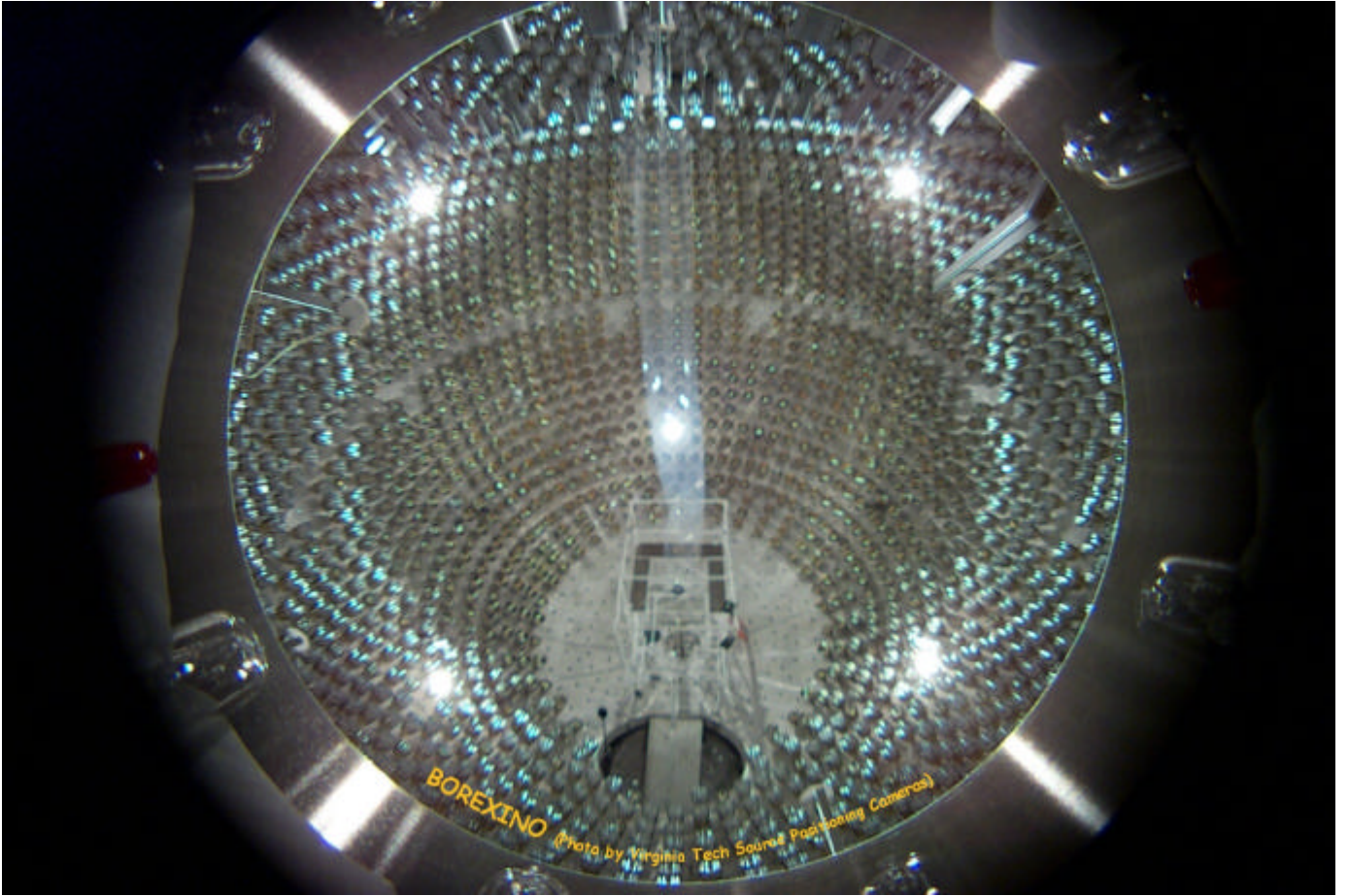
N₂ PLANT

Fluid Handling System

Water Purification System

Clean room





BOREXINO (Photo by Virginia Tech Source Positioning Cameras)



Scintillator

Solvent : Pseudocumene

Solute: PPO (1.5 g/l)

Light yield: 11000 ph/MeV

Att. Length (@420): 30 m

Scatt. length (@420 nm): 7 m

Decay Time (fast component) : 3.5 ns

Good α / β properties

Photomultipliers

8" Electron Tubes Limited 9351 type

P/V : 2.5

Transit Time Spread: 1 ns

Dark Count rate: 1kHz

Afterpulsing < 3%

Low radioactive glass and internal parts

Light Concentrators

Truncated string cone design

Optimized to collect the light from the inner vessel and 20 cm beyond it

Material: anodized aluminum

Mesured quantities

The electronics measures and provides for each triggered event :

- the photomultipliers pulse height
 - ⇒ energy measurement
- the photoelectrons arrival time (0.3 ns resolution)
 - ⇒ location identification
- the absolute time of the event

Expected detector performances

Effective Coverage: 30%

Photoelectron yield: 400 pe/MeV

Energy resolution (@ 1MeV): 5 %

Position resolution (@ 1 MeV): 10 cm

Calibrations

A variety of calibration and monitoring systems are planned:

✓ Laser pulses distributed to all PMT's with a fiber optics splitting system

- timing calibration
- gain adjustment via detection of the single photoelectron peak

✓ External sources (Th) located in the S.S.S close to the light cones

- check of the stability in time of the overall detector response

✓ Internal sources inside the scintillator

- position calibration
- energy calibration
- α/β PSD determination

Calibrations

✓ Laser beams with different wavelengths through the buffer and laser excitation of the scintillator

- stability monitoring of optical properties

✓ Blue LEDs on the external tank for the outer muon veto detector

✓ Active tags of trace impurities in the scintillator

- cross check of the absolute energy scale determination

- additional stability monitor

✓ Calibration of the overall detector response via a sub-MeV ν -source (^{51}Cr)

Neutrino Detection in Borexino

Detection through the scattering reaction



off the electrons of the scintillator

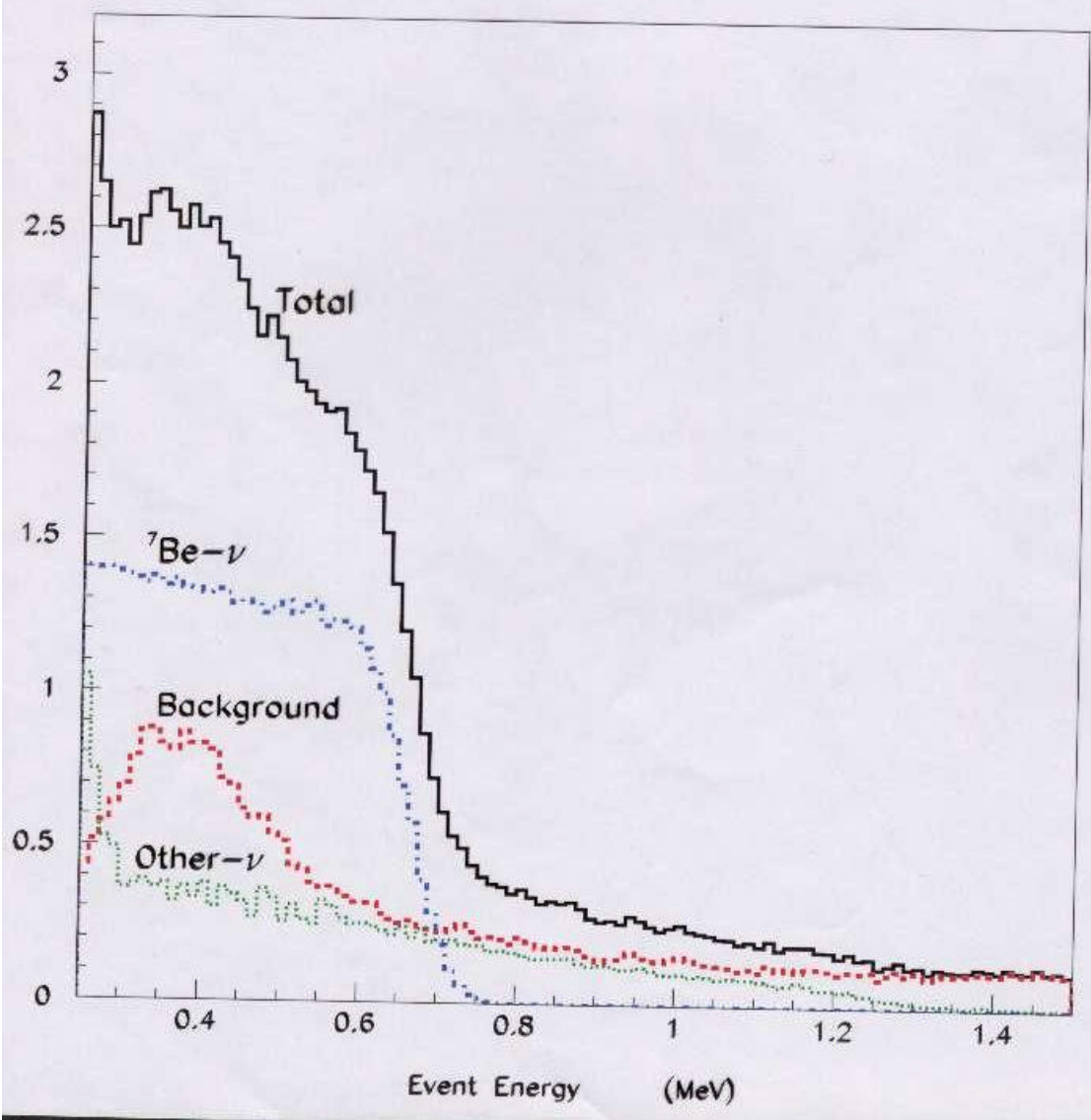
The **high luminosity** and **high radiopurity**

of the scintillator lead to a low detection threshold: **250 keV**.

It is possible to detect the recoil electrons produced by the monoenergetic (**0.861 MeV**) ${}^7\text{Be}$ ν .

Maximum recoil energy: **0.66 MeV**

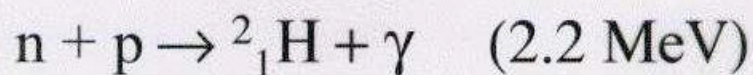
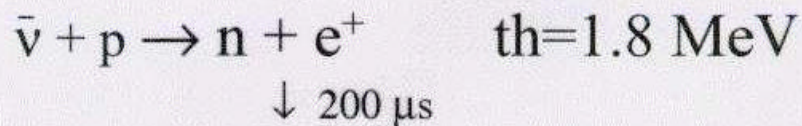
SSM prediction: **55 ev/d for 100 T.F. V**



Other capabilities

⇒ ^8B spectrum in the unique energy window 1.5-5 MeV

⇒ Antineutrino Science



Search for solar $\bar{\nu}_e$

Geophysical $\bar{\nu}_e$ from the Earth

$\bar{\nu}_e$ from Type II Supernovae

Long-baseline $\bar{\nu}_e$ from European reactors

Radiopurity of the scintillator

Main issue for the feasibility of the experiment

Purity requirements for ^{238}U and ^{232}Th in the range of 10^{-16} g/g

Laboratory measurements on small samples: $2-3 \times 10^{-15}$ g/g
mainly limited by impurities leached from the wall of the vessels

Needed a direct measurement on some tons of scintillator with a sensitivity level at least 5×10^{-16} g/g \rightarrow CTF

Further high sensitivity measurements performed with **Neutron Activation Analysis**

Achievements of CTF

1 - Demonstration of unprecedented purity levels

$$^{14}\text{C}/^{12}\text{C} = (1.94 \pm 0.09) \times 10^{-18}$$

$$^{232}\text{Th} < (4.4 \pm 1.5) \times 10^{-16}$$

$$^{238}\text{U} < (3.5 \pm 1.3) \times 10^{-16}$$

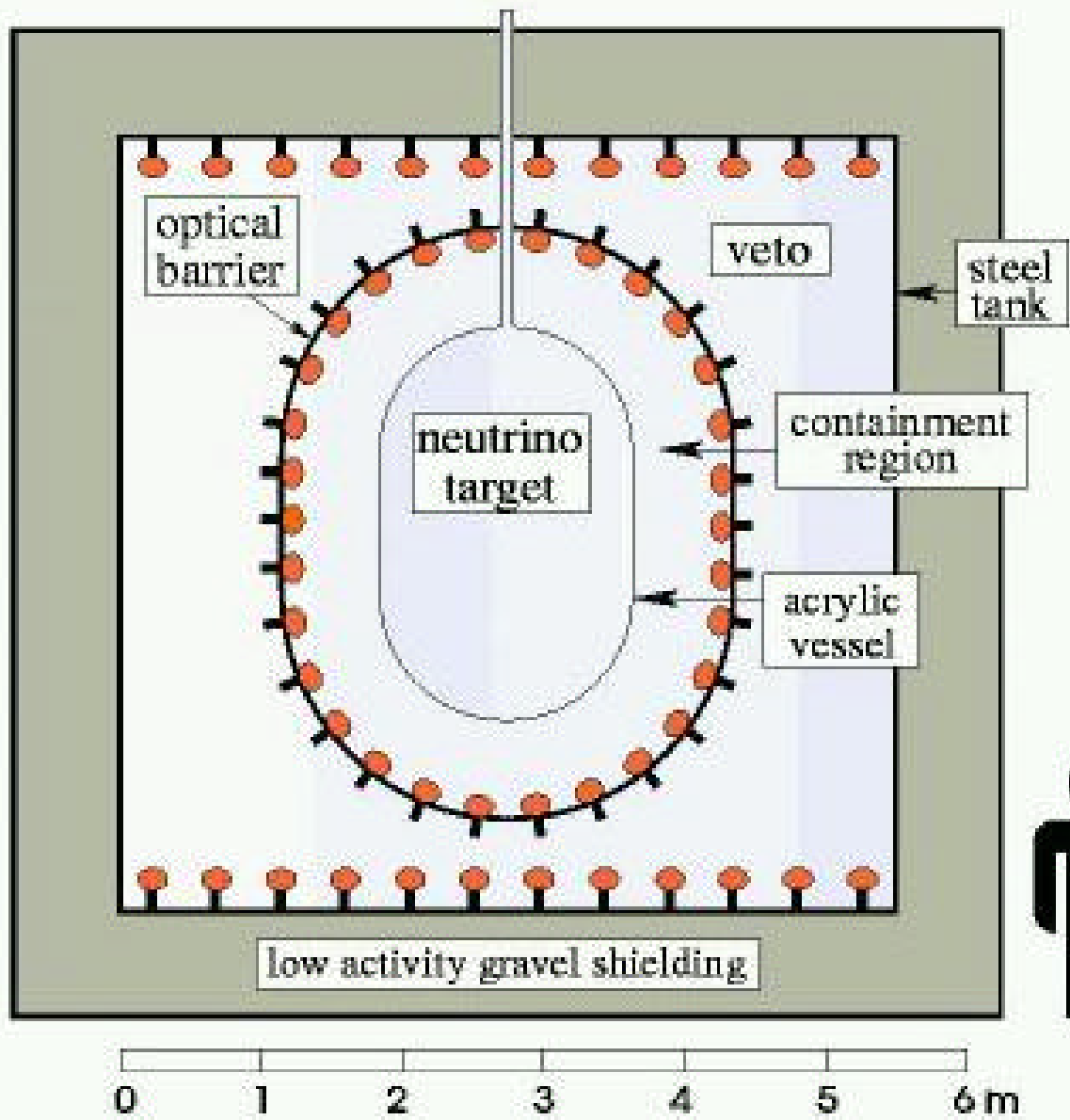
2 - Demonstration of the effectiveness of the planned purification methods for Borexino

Purity levels confirmed with Neutron Activation Analysis

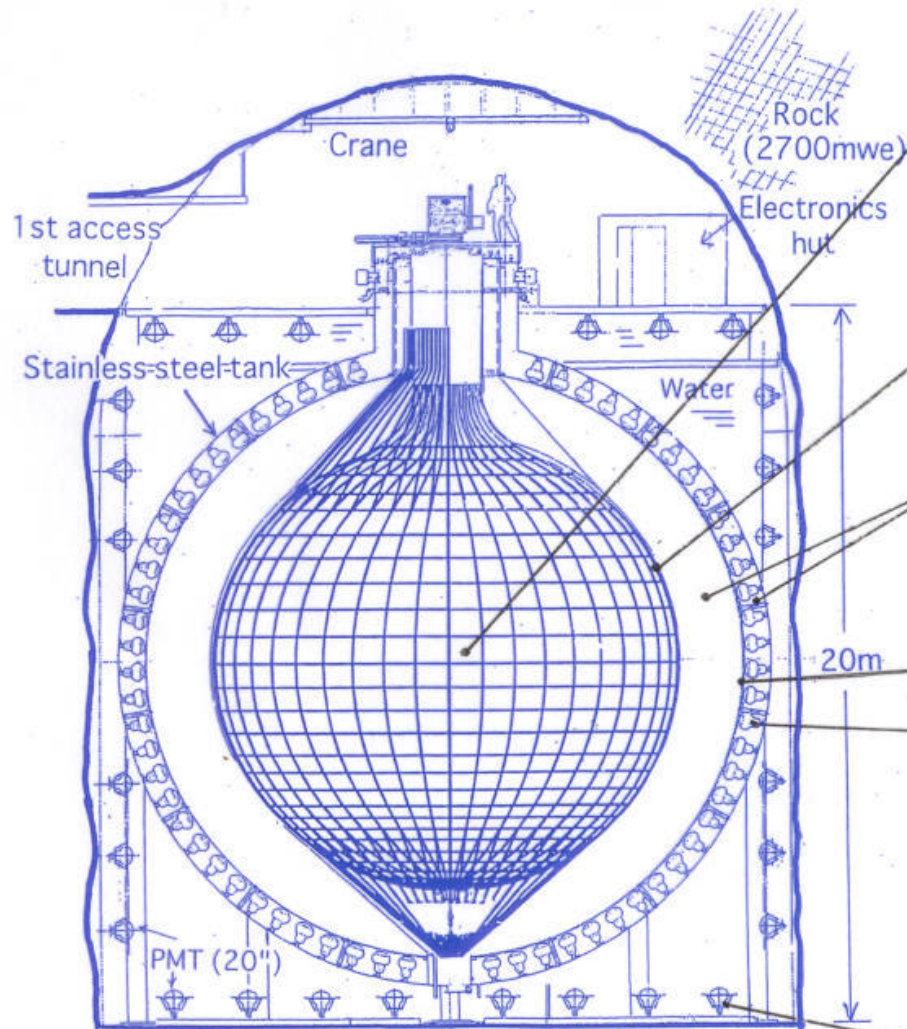
$$^{238}\text{U} < 2 \times 10^{-16}$$

CTF has been recently reinstalled for quality control of the scintillator prior to detector filling

Chooz



KamLAND Detector



Liquid scintillator (1000ton)

Dodecane(80%)
+Pseudocumene(20%)+PPO(1.5g/l)

Balloon+Kevlar ropes

13m ϕ , EVOH/3Ny/EVOH, 135 μ m

Buffer Oil (inner+outer)

Dodecane(50%)+Isoparaffin (50%)

$$\rho_{LS}/\rho_{BO}=1.003$$

Acrylic plate (3mm)

PMT 17"($\sigma\sim 1$ ns) $\times 1325$ + 20"($\sigma\sim 5$ ns) $\times 554$

$$\Omega=35\% \text{ of } 4\pi$$

440pe/MeV, $\sigma/E=5\%/\sqrt{E}$,

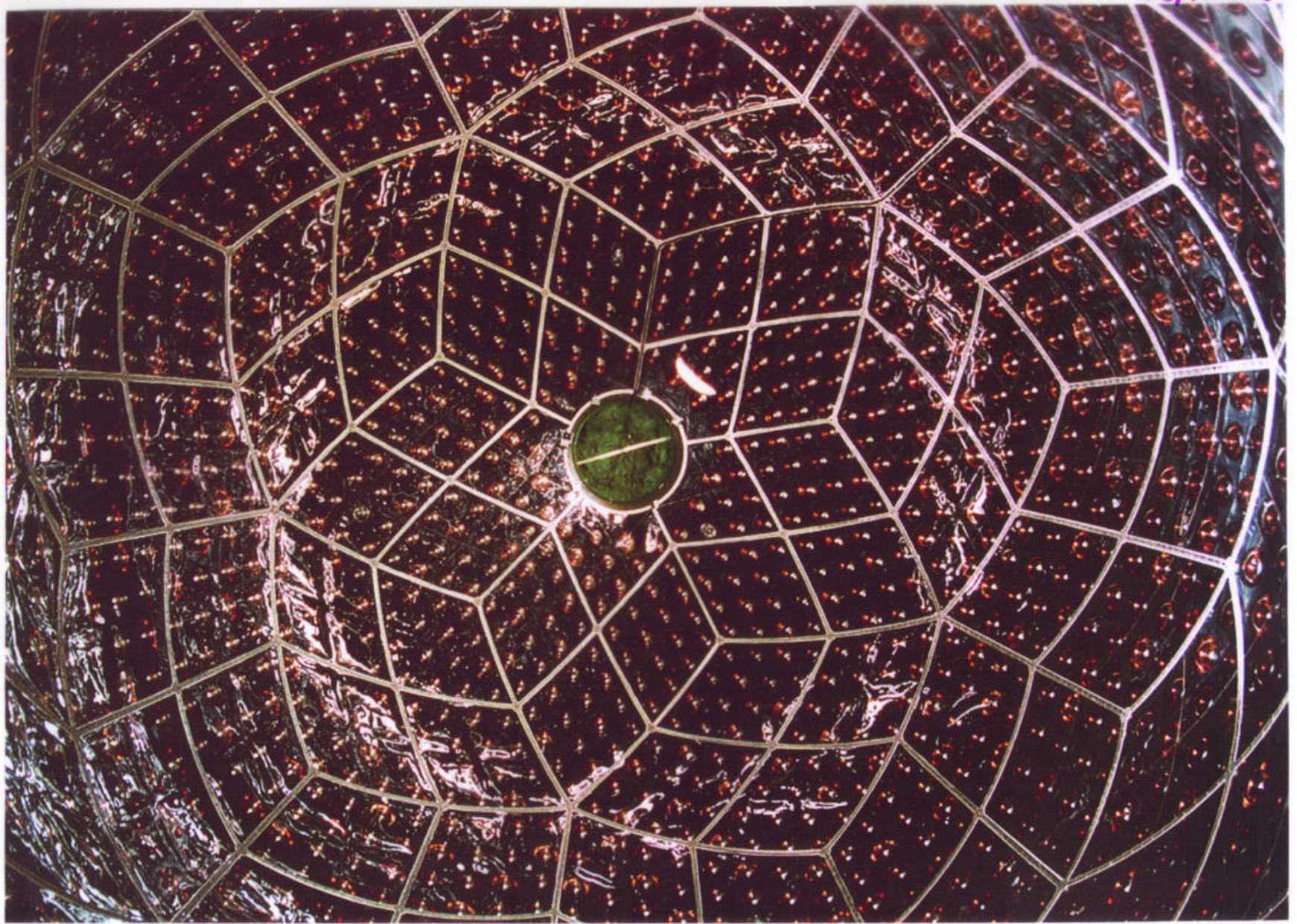
$\sigma_{vtx}\sim 10$ cm (@1MeV)

Outer Detector *Water \checkmark*

PMT 20" $\times 225$ in purified water

13m
18m

Sep. 2000



Reactor $\bar{\nu}_e$ experiment

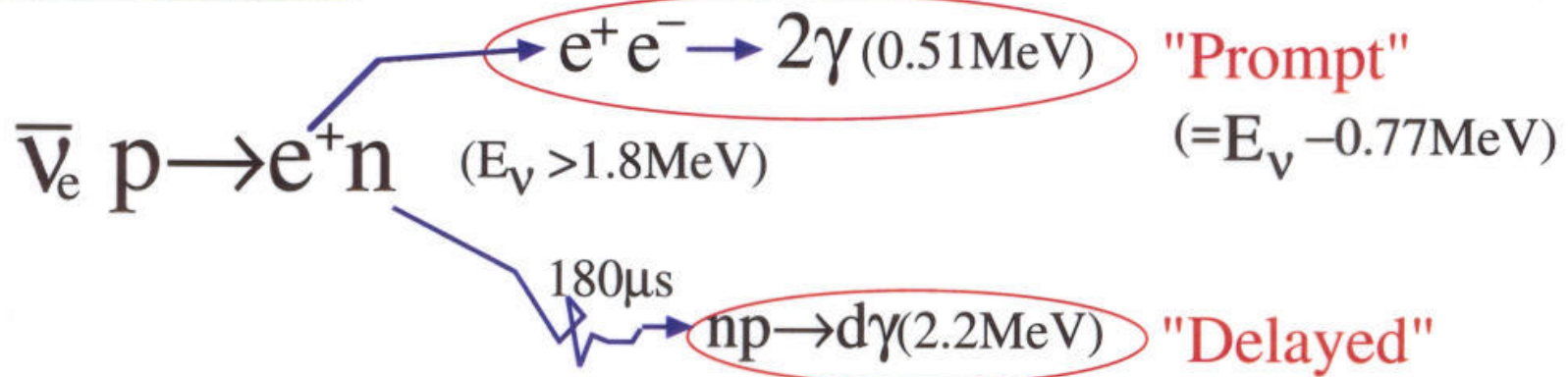
- Pure $\bar{\nu}_e$ flux
 - Flux is well known ($\sim 1\%$)
 - Low energy ($< \text{several MeV}$)
- \rightarrow Front detector is not necessary.
 \rightarrow Disappearance exp., Large L/E

$$N_{\text{ev}} = \sum_i^{\text{reactors}} \frac{1}{4\pi L_i^2} \Phi_i (1 - \sin^2 2\theta \sin^2 \frac{\Delta M^2 L_i}{4E_\nu}) \sigma_{(\bar{\nu}_p \rightarrow e^+ n)} N_p$$

KamLAND

Powerful (70GW) reactors @ $L \sim 175 \pm 35 \text{ km}$
 $\rightarrow 1.3 \times 10^6 \bar{\nu}_e / \text{s/cm}^2$ (21.8 MeV)
 $\rightarrow \Delta M^2 = \sim 6 \times 10^{-6} \text{ eV}^2$ (@ $\sin^2 \theta \sim 1$)
 1000ton LS (CH_2)
 $\rightarrow 10^{32}$ free protons
 $\rightarrow 550 / \text{yr}$ (No oscill., Fid. vol. 600 ton, Reactor eff. 80%)
Covers LMA !!

$\bar{\nu}_e$ Detection



- $\bar{\nu}_e$ only (CC)
- Reject BG (delayed signal ← timing, distance, energy)
- σ is large ($\sim 100\sigma(\nu e \rightarrow \nu e)$) and well known.
- E_ν is measured by prompt energy.

● KamLAND Liquid Scintillator

Large light yield, High purity, Pulse shape discrimination (n/γ , α/γ)
Fast response, cheap, safe

Background issues in low energy neutrino detection

This field gained over the past decade much interest in view of the possible real time detection of sub MeV solar neutrinos.

The major challenge posed by this measurements is the removal of the otherwise overwhelming natural background

Similar problems have been faced also in the Cerenkov detectors (SNO and Supekamiokande) but with less demanding background requiremenst due to the higher energy regime of interest.

Major background category:

- a) natural radioactivity (U, Th, K)
- b) cosmogenic induced isotope
- c) metallic impurities
- d) radioactive isotopes of noble gases
- e) C^{14}



Beta spectrum

End point 0.156 MeV

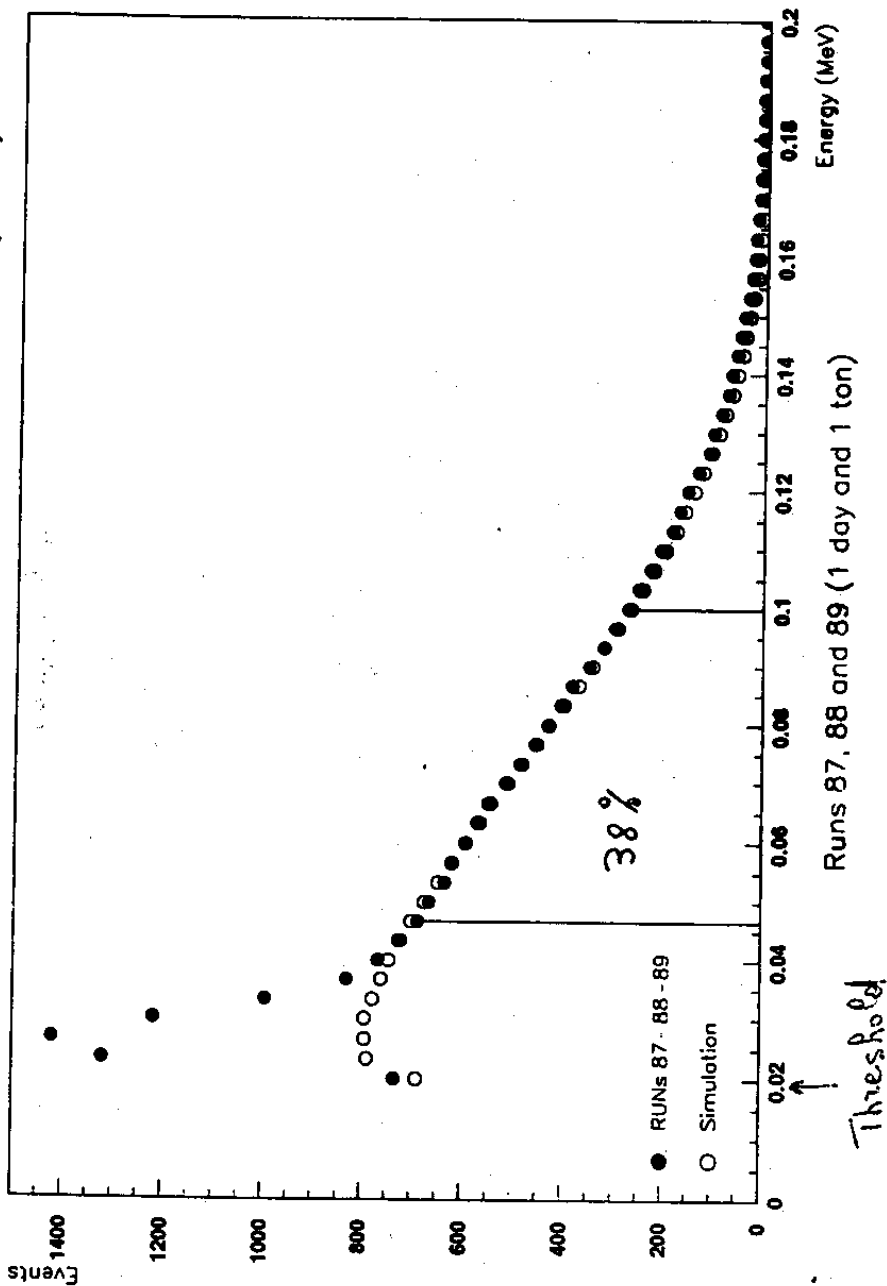
Half life 5620 years

Unremovable background -> it has to be directly tested in the scintillator

Problems that can poses: tail in the useful energy window, pile up

Acceptable limit in the range of $10^{-18} \text{C}^{14}/\text{C}^{12}$

¹⁴C β-spectrum (simulated and corrected measured spectra)



Radioactive noble gases

Rn^{222}

Originated by the ubiquitous naturally occurring U^{238}

Average concentration in air $20\text{Bq}/\text{m}^3$

underground $80\text{-}100\text{ Bq}/\text{m}^3$

requirement in the scintillator: few $\mu\text{Bq}/\text{m}^3$

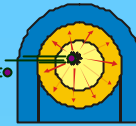
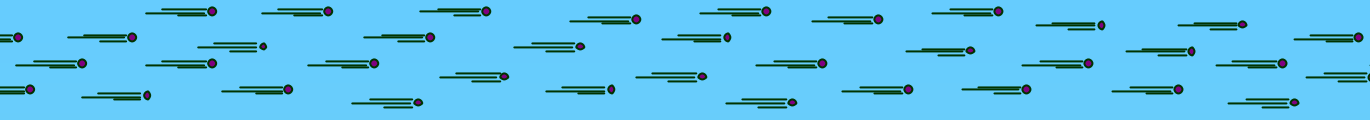
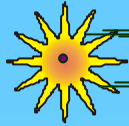
Kr^{85}

average concentration in the atmosphere $1\text{ Bq}/\text{m}^3$, half life
11 years

requirement in the scintillator:

Ar^{39}

β end point 565 KeV , half life 266 years



Radioactive noble gases in nature

Radon

- Natural decay chains (^{235}U , ^{238}U , ^{232}Th)
- ^{222}Rn dominant P **10-100 Bq/m³ in air**

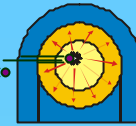
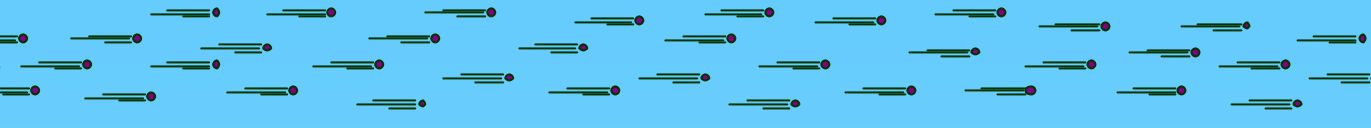
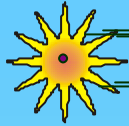
Krypton

- Anthropogenic origin (nuclear fuel reprocessing)
- ^{85}Kr P **1 Bq/m³ in air**

Argon

- Cosmogenic production
- ^{39}Ar : **1.2 Bq/m³ Ar P 11 mBq/m³ in air**





Decay modes and detection techniques

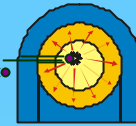
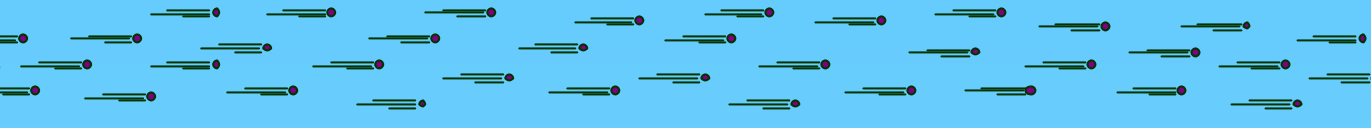
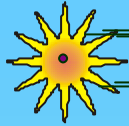
Krypton (^{85}Kr)

- Beta emitter: $E_{\text{max}} = 687 \text{ keV}$
- Half-life: 10.8 years
- b- g- coincidence (BR: 0.43 %), $E_g = 514 \text{ keV}$, life-time: 1 ms

Argon (^{39}Ar)

- Beta emitter: $E_{\text{max}} = 565 \text{ keV}$, no gamma!
- Half-life: 269 years
- Mass spectrometry (detection of stable Ar-isotopes)



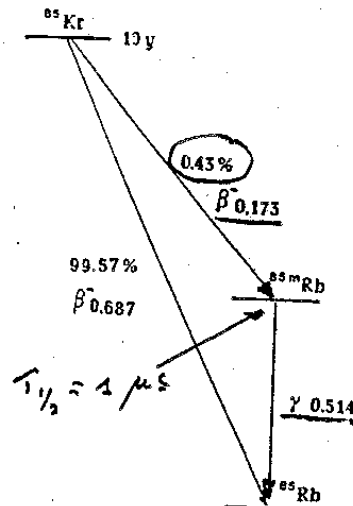
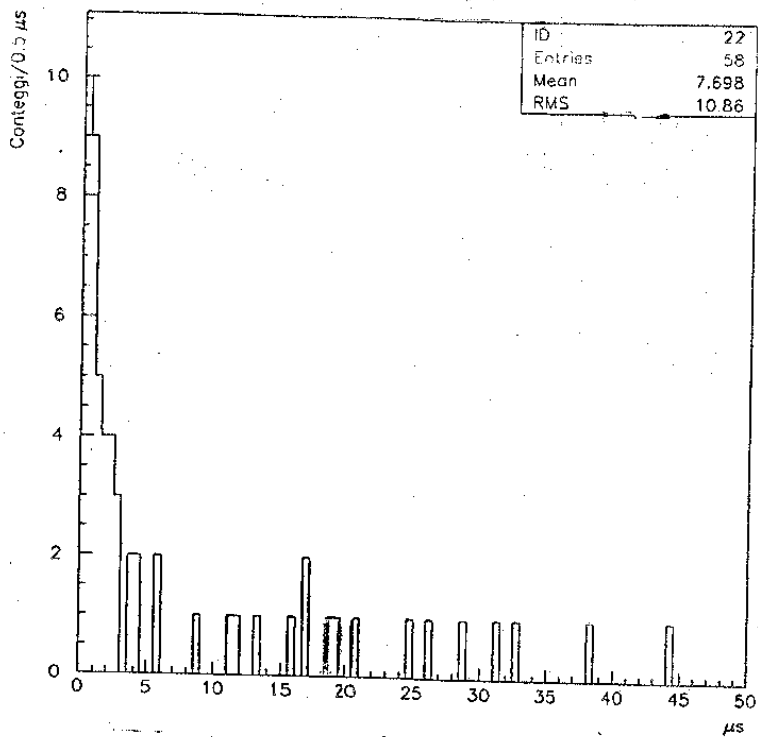


Decay modes and detection techniques

Radon

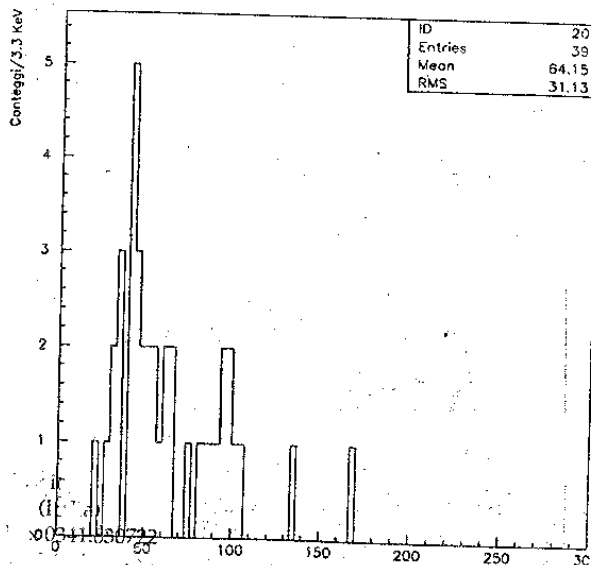
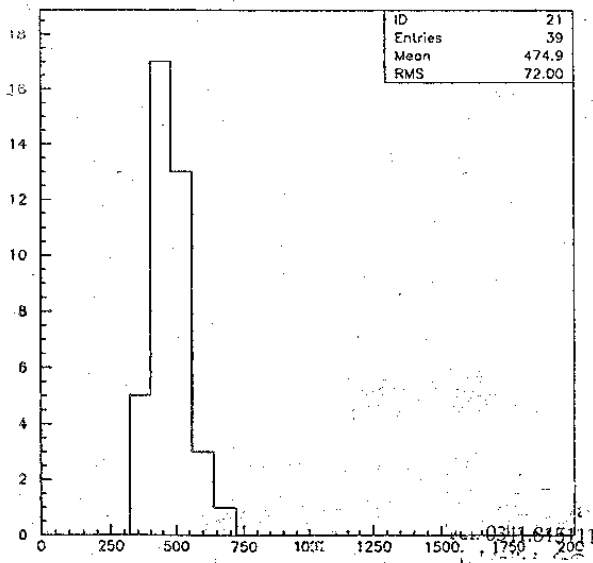
- Alpha-, beta- and gamma-detection
 - Radon and radon-progenies
- Delayed coincidences
 - ^{222}Rn : ^{214}Bi - ^{214}Po b- a- coincidence (164 ms)
 - ^{220}Rn : ^{212}Bi - ^{212}Po b- a- coincidence (300 ns)





Apr. 21 - May 27: 1.3 ± 0.3 c/d for the coincidence
 $\sim 300 \pm 70$ c/d for ^{85}Kr

Sept. 20 - Oct. 20: 0.2 ± 0.15 c/d for the coincidence
 $\sim 50 \pm 35$ c/d for ^{85}Kr



How to overcome the noble gases background (work in progress...)

1) Stripping with N₂ to remove all the gases

but the nitrogen itself has to be Rn, Kr, and Ar free

Rn suppression

a) Boil - off technique

b) via charcoal purification in liquid phase : 0.5
μBq/m³

Ar and Kr still an outstanding problem. Good chance from some industrial suppliers working in a strictly controlled, atmosphere free, environment

2)

- ❖ Air tight installations and plants for the detector, the scintillator handling and the purification systems (tightness requirement 10⁻⁸ mbar.l/sec)
- ❖ Control and reduction of possible Rn emanation sources (bulk, surface)
- ❖ Impermeability to the Rn diffusion- anti diffusive membranes if possible

Natural radioactivity

- ^{40}K and ^{238}U , ^{232}Th secular chains

Reduction methodologies

I - Preliminary precautions

-removal of dust and particulates

-suitable surface treatment of all the components in contact with the scintillator (electropolishing pickling and passivation)

II - Purification

Water extraction + sub-micron filtration (0.05 μm)
Suited for Ionisable species such as metals

Distillation

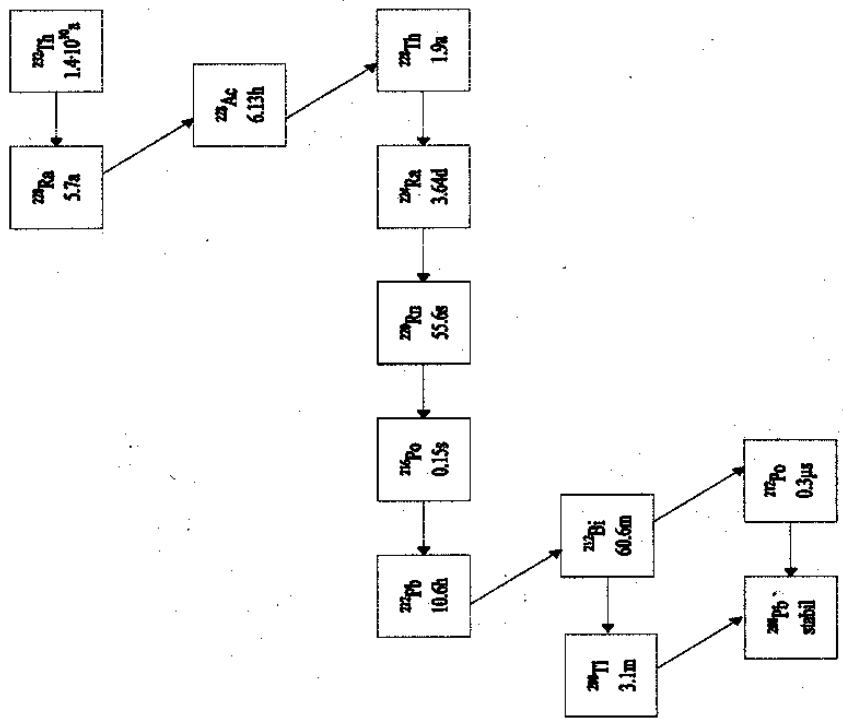
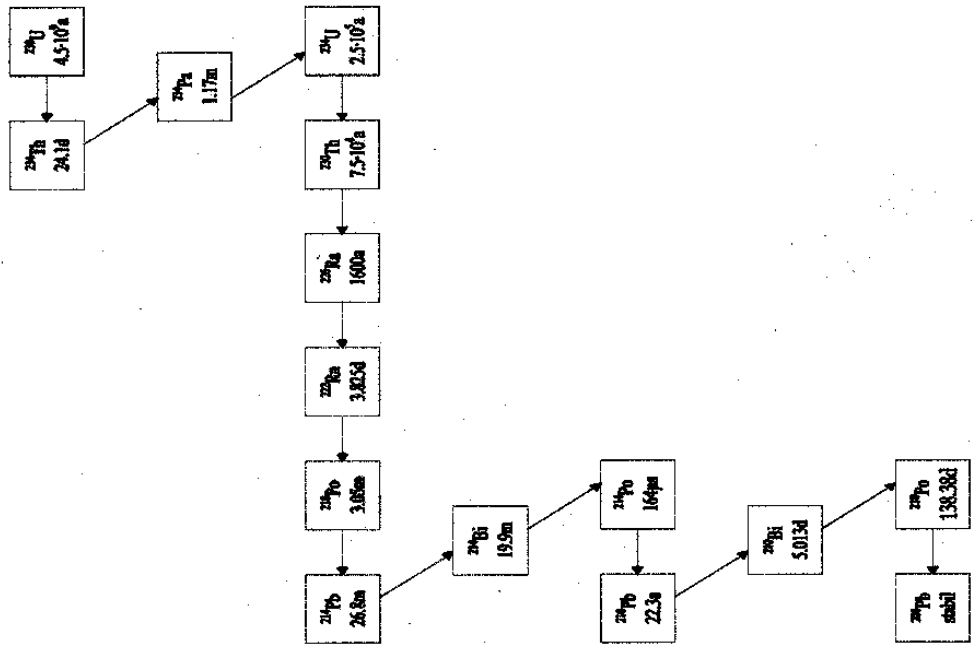
Vacuum distillation (falling film evaporator/condenser unit)
Suited for low volatile components (metal and dust particles)

Solid column (SiO_2)

High affinity of impurities for the column material in dry and wet form

III

- ❖ Selection of the construction materials
- ❖ Selection and purification of the shielding materials
 - Measurements of bulk activities
 - Water: reverse osmosis + deionisation units+N₂ stripping +ultrafiltration (0.1μm)
- ❖ All installations performed in clean rooms (class 10 - 1000)



Assay methods for low radioactive levels

-Ge gamma ray spectrometry

- ❖ operated underground to suppress the cosmic ray flux
- ❖ at Gran Sasso attenuation of the μ flux of 10^6 (3500 m.w.e.)
- ❖ shielding with Pb, Cu, and continuous N_2 flushing
- ❖ sensitivity U, Th 10^{-10} g/g

-Rn

in gas $\mu\text{Bq}/\text{m}^3$

in liquid mBq/m^3

Assay methods for low radioactive levels (cont'd)

-ICPMS -Inductive coupled mass spectrometer

- ❖ Water, other liquid (organics)

- ❖ Solid (ex Nylon) via "digestion" process

- ❖ Sensitivity

 - Water $\sim 10^{-14}$ g/g in U, Th

 - Nylon $\sim 10^{-13}$ g/g in U, Th

-For higher sensitivity : neutron activation analysis

-Direct measurements with large scale prototypes: CTF

Muon Induced background

-Underground strong flux suppression (@Gran Sasso 1 $\mu/m^2/h$)

1. μ or prompt secondaries

- ❖ very high light pulse in the scintillator
- ❖ pattern of the hit PMT's in the shielding liquid (Cherenkov light)
- ❖ μ veto
- ❖ track reconstruction

2. γ from cosmogenic neutrons

- ❖ path to reach thermal energies
- ❖ p capture and emission of 2.2 MeV γ 's

3. μ induced radioactivity

- ❖ β^- emitters: ^8Li , ^9Li , ^{11}Be , ^{12}B half life (0.1 - 10 s)
- ❖ β^+ emitters: ^8B , ^9C , ^{11}C

→ μ position - software cut

Conclusions

The neutrino detection technology has reached a mature stage, where different techniques coexist to cope with the multiple experimental challenges posed by the different neutrino sources to be investigated.

In particular Cerenkov, Scintillator and Radiochemical methods have proved to be essential in the long quest towards the recently achieved assessment of neutrino oscillations.

Scintillation and Cerenkov techniques have also promising perspectives in the next experimental frontiers: telescopes for high energy neutrinos and detector for sub-MeV solar neutrinos.

In this interesting future, the achievement of ultra low background levels will be more and more of paramount importance.