Liquid Scintillator and Water Cherenkov Detectors

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Why Liquid Scintillator and Water Cherenkov detectors in the context of Underground Physics

-Spanning a broad range of applications for underground (anti-)neutrino detection (also under-water and under-ice) from natural and artificial sources

-Exploited in several experimental set-ups of medium and large dimensions throughout the most important worldwide underground Laboratories

-Pivotal in the demonstration of the neutrino oscillation phenomenon -> neutrino mass and mixing -> first and, so far, only firm indication of physics beyond standard model

-Crucial role in the next generation huge experiments for precise and complete determination of the neutrino oscillation mixing parameters

-Well suited to amass large quantities of material which can be purified to achieve the ultra-low radioactive background implied by neutrino detection

-LS in this framework are organic hydrocarbon compounds - cryogenic noble liquids not included in this category

-Underground locations to suppress the cosmic background which would overwhelm the feeble and rare neutrino signals

Neutrino detection: a multipronged approach

Neutrino detection techniques encompass several different methodologies of widespread use in the general field of particle detection

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

- ✓ Solar neutrinos
- ✓ Atmospheric neutrinos
- ✓ Geo-neutrinos
- ✓ Supernova neutrinos
- ✓ Ultra high energy neutrinos from astrophysical sources

Natural sources

- ❖ Reactor neutrinos
- ❖ Accelerator neutrinos

Artificial sources

Remark – Approaches for neutrinoless double beta decay and neutrino mass represent different classes of experiments

A many facets issue – experimental methods

The richness of the neutrino physics field finds almost naturally its counterpart in the plurality of techniques applied by the experimentalists for this broad range of applications

Radiochemical methods

Water Cherenkov detectors
Heavy water detectors
Long string, large under-water/under-ice Cherenkov detectors

Cherenkov class

Liquid Scintillation technique

Time projection chambers
Nuclear emulsions

Focus of this presentation

Water Cherenkov detectors, included the heavy water version, which provided crucial results both in the atmospheric and solar neutrino sectors, leading to the assessment of neutrino oscillations - 2015 Nobel Prize

The scintillation detectors which are the choice for the reactor experiments, and proved also to be extremely effective for the challenging real time detection of low energy solar neutrinos

Liquid scintillation technique

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

In the neutrino field this kind of method has been exploited for (with different level of overburden)

a) Reactor neutrino experiments

Savannah River (first antineutrino detection), Gosgen, Bugey, Chooz, Palo Verde, KamLAND, Daya Bay, Reno, Doble Chooz etc… (many others not listed here)

b) Accelerator based experiments

LSND, Karmen, Nova

c) Supernova neutrinos

LVD (Borexino and KamLAND as ancillary capability)

d) Solar neutrino experiments and detection of other low energy neutrino fluxes like geoneutrinos Borexino, SNO+ (also double beta decay exp.) KamLAND

LVD, SNO+, KamLAND - in a version for $0\nu\beta\beta$ decay - Nova and Reno are those in operation (several small set-ups not listed here)

The baton soon will be taken by JUNO (gigantic multipurpose experiment for reactor and other neutrino fluxes of natural origin)

Scintillation

Detection of ionizing 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 like the glass (phototube matching)

G. Knoll Radiation detection and measurements
J.B. Birks The theory and practice of scintillation counting

Light emission processes

1. Fluorescence: prompt emission of visible radiation after the material excitation

2. Phosphorescence: 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 emission time substantially longer

Scintillating materials of common use

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

2. Alkali Halide crystal (inorganic materials)

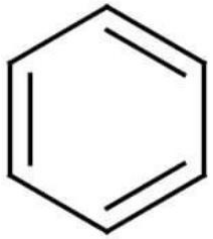
Organic scintillators: fast response, but less emitted light, suited for beta spectroscopy and neutron detection

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 transitions between the energetic levels of the single molecule independently from its physical state

In the so called polycyclic aromatic hydrocarbons the molecular levels involved in the process are the so-called electronic levels p which stem from the trigonal hybridization - sp^2 - of the four valence electrons of the carbon atoms at the vertex of the hexagonal planar molecule C_6H_6 - **Benzene ring**



Schematic benzene symbol

Hybridization

Electron configuration of the carbon atom in the ground state

$1s^2 2s^2 2p^2$

Configuration of the carbon atom ready for the chemical binding

$1s^2 2s 2p^3$

Possible hybridizations of the 4 valence electron orbitals

Tetrahedric or sp^3: 4 equivalent orbitals spatially directed according to the vertex of a tetrahedron, angle 109°28' (diamond , methane). Non luminescent materials

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

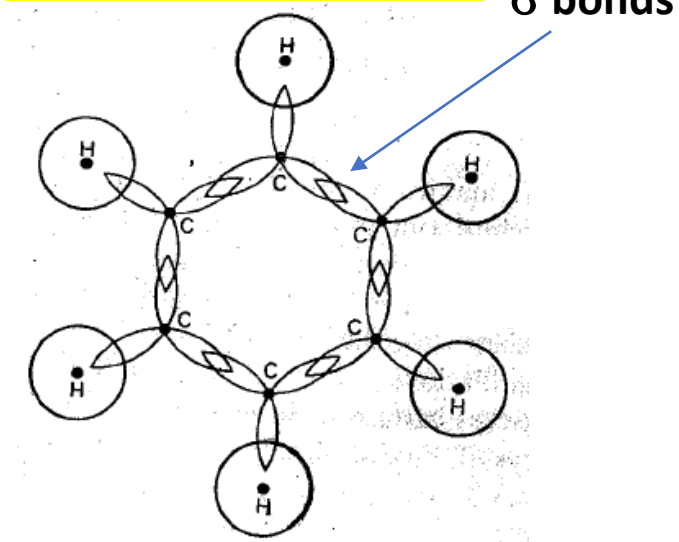
Digonal or sp: two unaltered p orbitals and two equivalent orbitals at 180 degree. Linear molecules as acetylene

Benzene

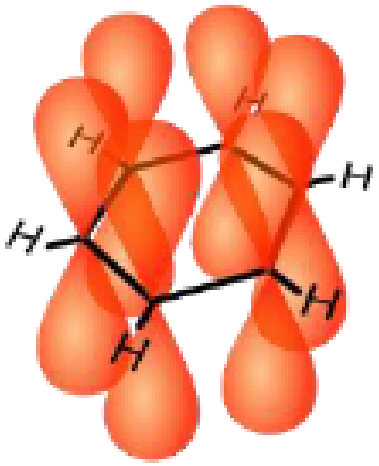
In benzene the σ orbitals interact as shown in the figure giving rise to localized σ bonds C-C and C-H

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

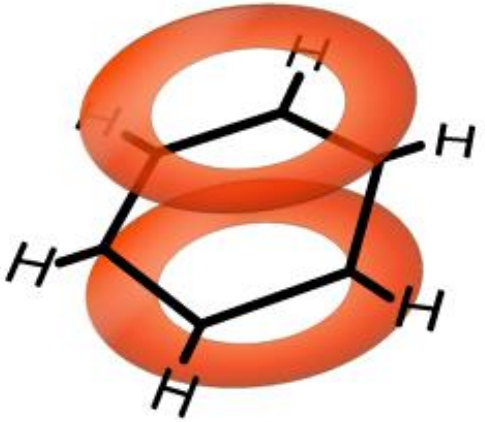
Planar configuration of the molecule



π Atomic orbitals before molecule



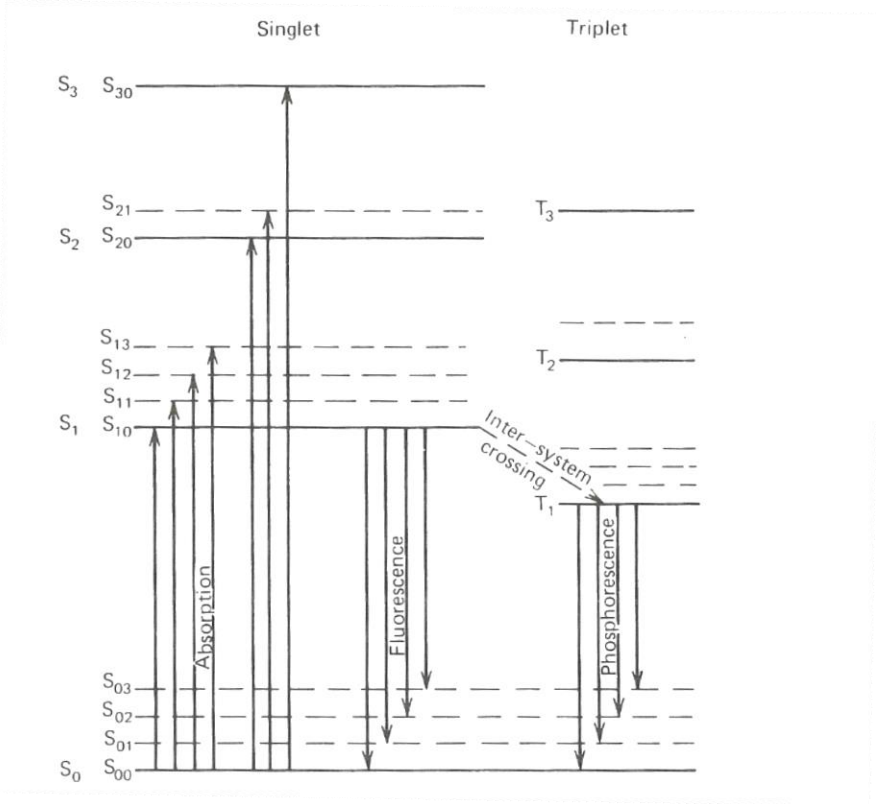
Delocalized π molecular orbital



Energetic levels of the molecular orbitals π

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

T1 T2 T3 …. Spin 1 levels (triplet levels)



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

S0 - S1 gap ~3 - 4 eV → Visible to near UV region

The highest excited states de-excite to S1 through non radiative internal conversion in time interval of ps. Also thee 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: $I=I_0e^{-t/\tau}$

$\tau \sim$ 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

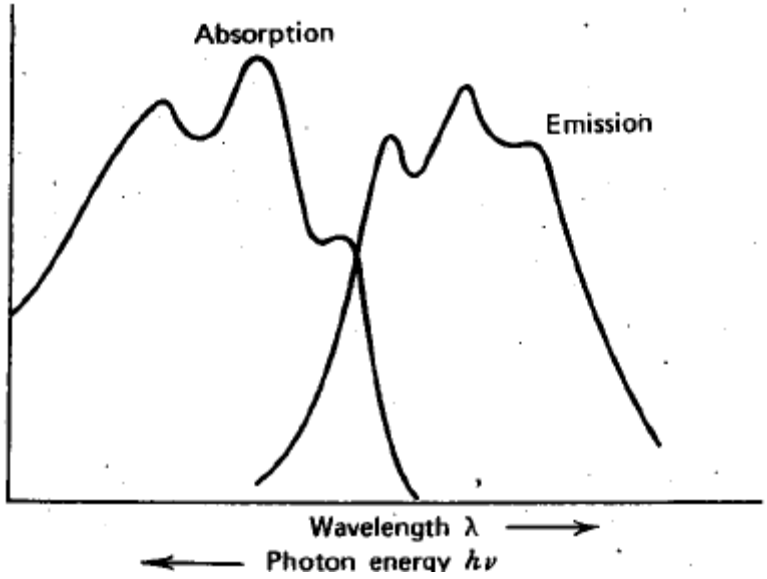
Delayed fluorescence

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

$$T_1 + T_1 \rightarrow S_1 + S_0 + \text{phonons}$$

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 that 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}

Excitation and subsequent emission triggered also by photoexcitation – very effective with ultraviolet light

Scintillation efficiency

Fraction of the energy of the incoming particle converted into visible light typically 3-4 % (higher in solid inorganic **N_aI** 12-13%)

Competing non radiative de-excitation modes limit the energy available for light production – ionization quenching, heat production

The oxygen dissolved in the liquid scintillator is an important additional quenching factor, which must be removed -> nitrogen purging

By exploiting the energy migration process (energy transfer from molecule to molecule of the solvent) typical of the hydrocarbon solvent through the addition of a small quantity of a high efficiency solute the overall efficiency is highly enhanced

$\rightarrow$ binary plastic or liquid scintillators

Possible addition of a third fluor as wavelength shifter to match the phototube response **ternary scintillator – not essential**

Summary of the energy transfer and scintillation steps

A

Energy deposit in base material ➛ **excitation and energy migration from molecule to molecule**

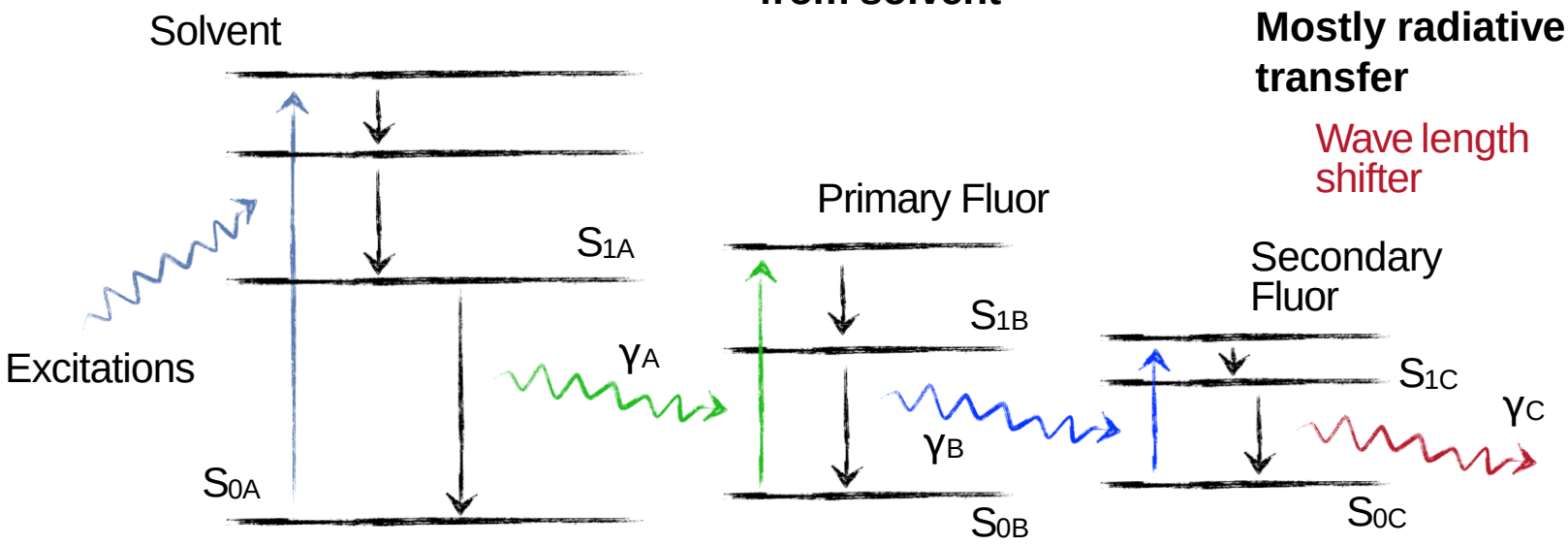
Primary fluorescent
- Good light yield ...
- Radiative and **mostly non radiative transfer from solvent**

B

Secondary fluorescent **Mostly radiative transfer**

C

Wave length shifter

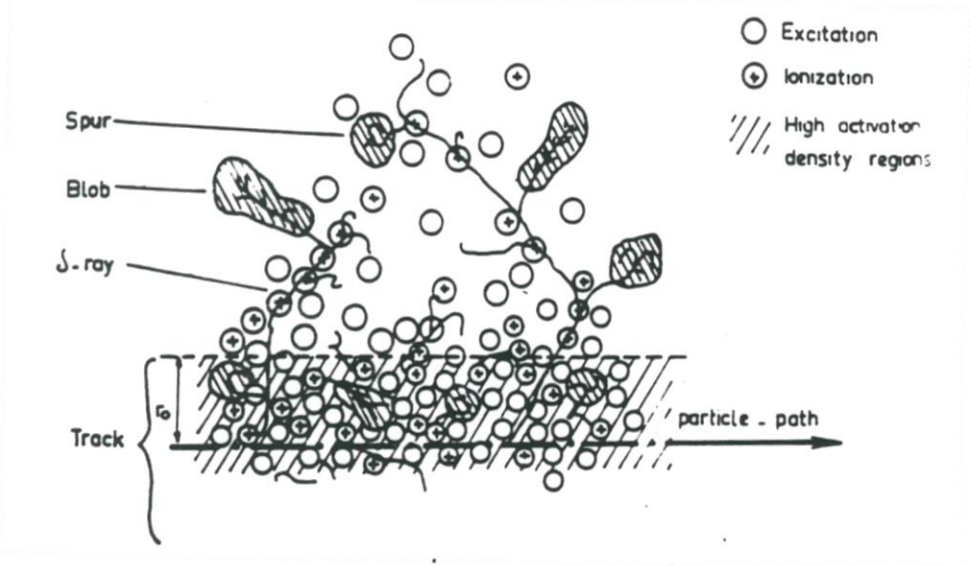


Eff. 3-4%

Efficiency of the last 2 steps very high between 90 and 100%

Ionization quenching

Many aspects of the output of the scintillation process depends on the energy loss dE/dr of the incident particle



Heavily ionizing particle (high dE/dr) -> high density of excited and ionized molecule -> high probability of non radiative decay to ground state through their interaction and hence less energy converted into light - ionization quenching

Particle at ionization minimum -> low density track like the delta rays in the picture and hence more light production

This effect is phenomenologically captured by the **Birks' formula**

Birks' Rule

For an ideal scintillator and low ionization density

$$\text{Luminescence} \propto \text{Energy dissipated in scintillator}$$

$$L = SE$$

or, in differential form

$$\frac{dL}{dr} = S\frac{dE}{dr}$$

The specific density of ionized and excited molecules along the particle track is

$$B\frac{dE}{dr}$$

Assume that a portion of the primary excitation is lost at high ionization density (ionization quenching) and introduce a quenching parameter k. Then

$$\frac{dL}{dr} = \frac{S\frac{dE}{dr}}{1 + kB\frac{dE}{dr}}$$

Simplest and more used formulation of the rule, other more complex formulation with additional parameters sometimes adopted

For small dE/dr this yields the luminescence yield postulated above.

For large dE/dr the specific luminescence saturates, as indicated by the data.

$$\frac{dL}{dr} = \frac{S}{kB} = const$$

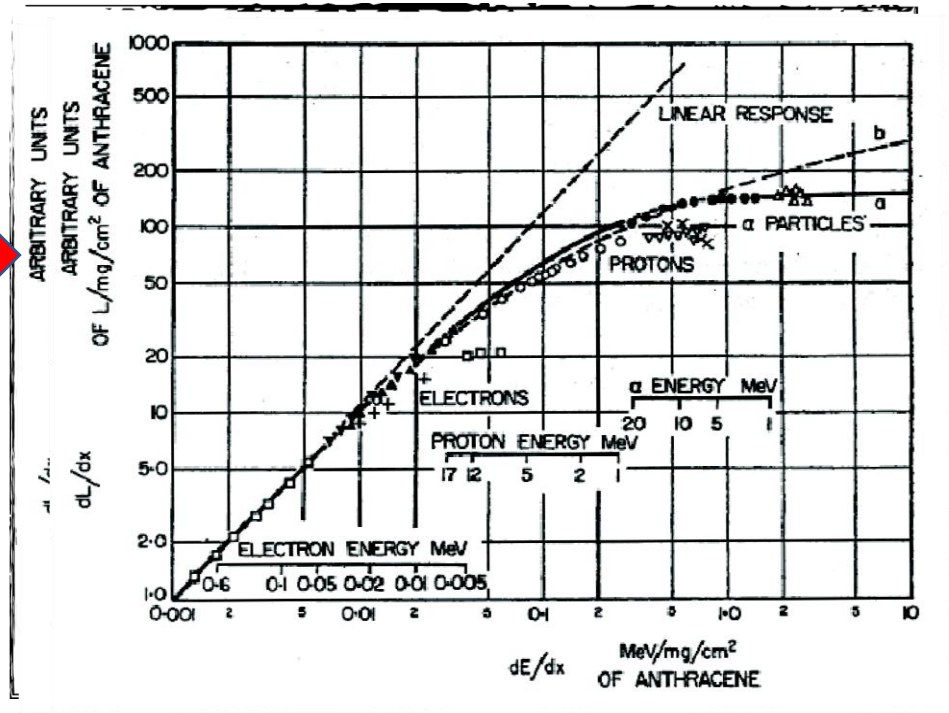
Several aspects of scintillation linked to ionization quenching and Birks' formula

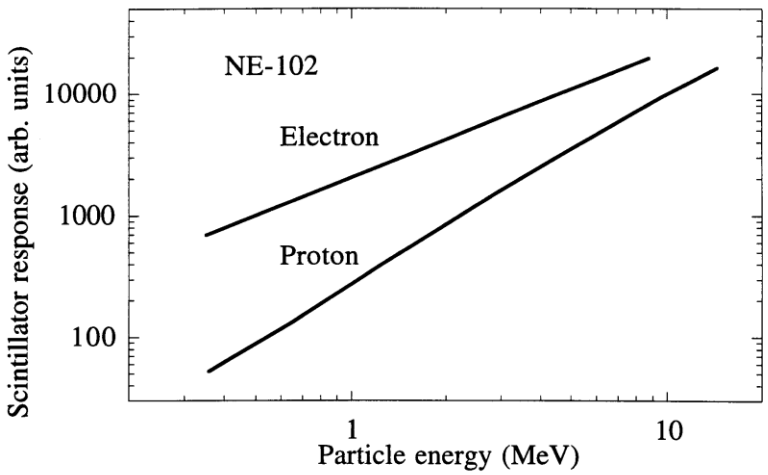
Linearity

only minimum ionizing particles display a linear relation between energy and light yield

In the energy region of interest above about 50 keV electrons are in this condition

α particles and protons are not yet at minimum in the energy region of interest for most application and thus exhibit highly nonlinear response





Also the total light yield is affected

Higher for particles at minimum

Ionization quenching and scintillation timing

Remind that the fast fluorescent component is followed by the slow component due to phosphorescence and delayed fluorescence whose origin is connected to the so-called triplet states T_1 (typical lifetime microseconds to milliseconds)

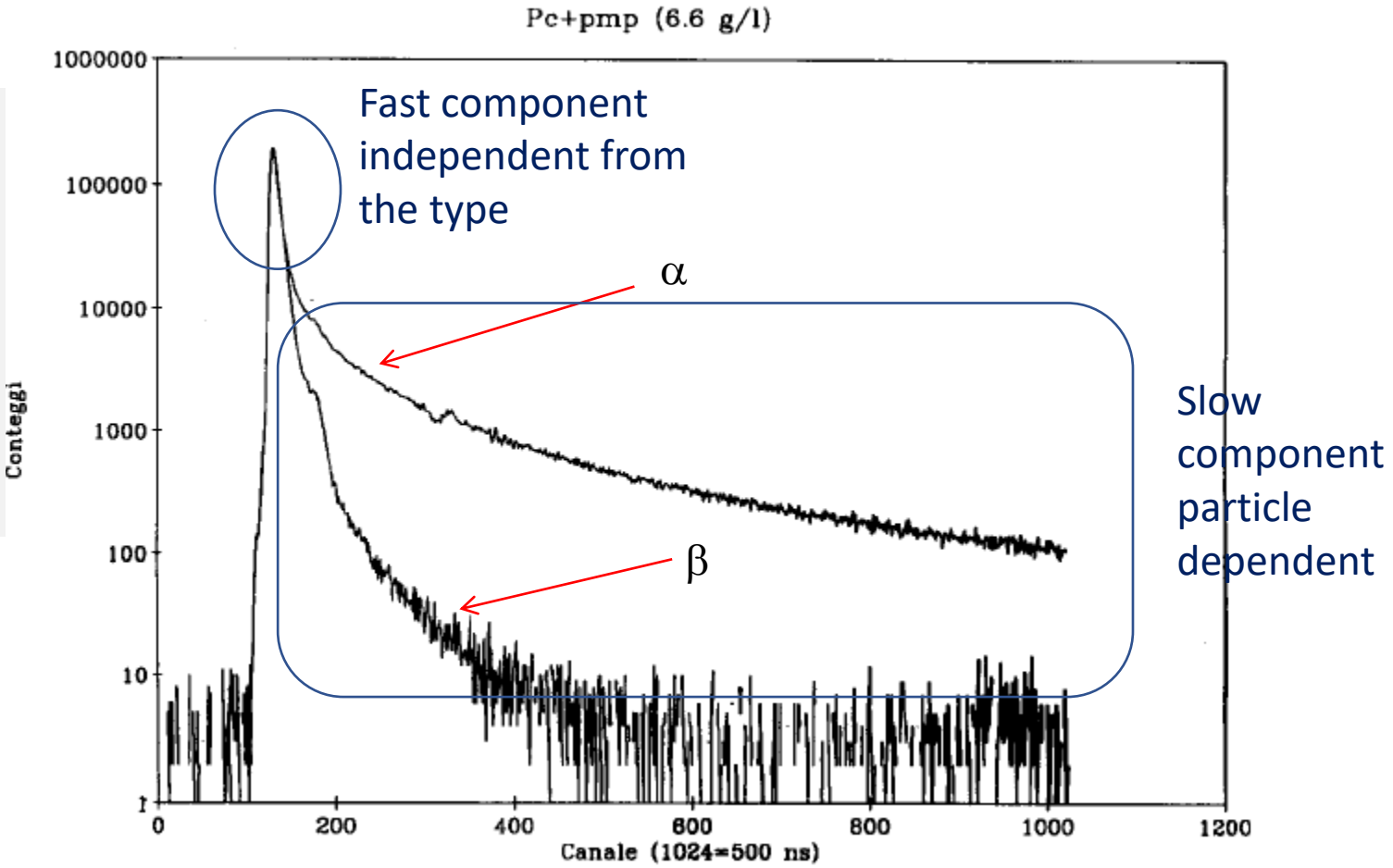
The more heavily ionizing is the particle the larger the presence of T_1 states $\rightarrow$ longer tailed is the resulting light pulse

By inspecting the tail is possible to distinguish the type of interacting particle

Origin of the **Particle Shape Discrimination** capability of liquid scintillators

Difference in time pulse shape under different particle irradiation

Time scale of the tail from tens of ns up to about 1 μs stopped to 500 ns in this example



Frequently exploited as n-γ discrimination

Neutrons scatter off protons in the scintillator – tailed proton-induced pulses

γ's scatter off electrons – less tailed electron-induced pulses

Timing of the fluorescent (fast) component of the scintillation pulse

a) non-radiative transfer of energy from vibrational states to fluorescent state

typical time: 0.2 – 0.4 ns

b) decay of fluorescent state

typical time: 1 – 3 ns

$\Rightarrow$ rise with time constant τ_r

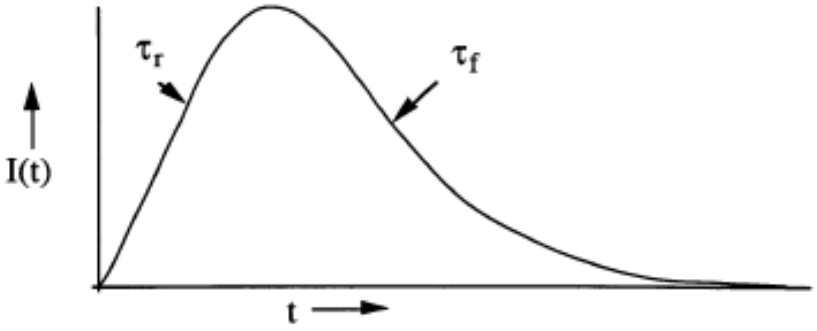
$$I(t) \propto 1 - e^{-t/\tau_r}$$

fall with time constant τ_f

$$I(t) \propto e^{-t/\tau_f}$$

total pulse shape

$$I(t) = I_0(e^{-t/\tau_f} - e^{-t/\tau_r})$$



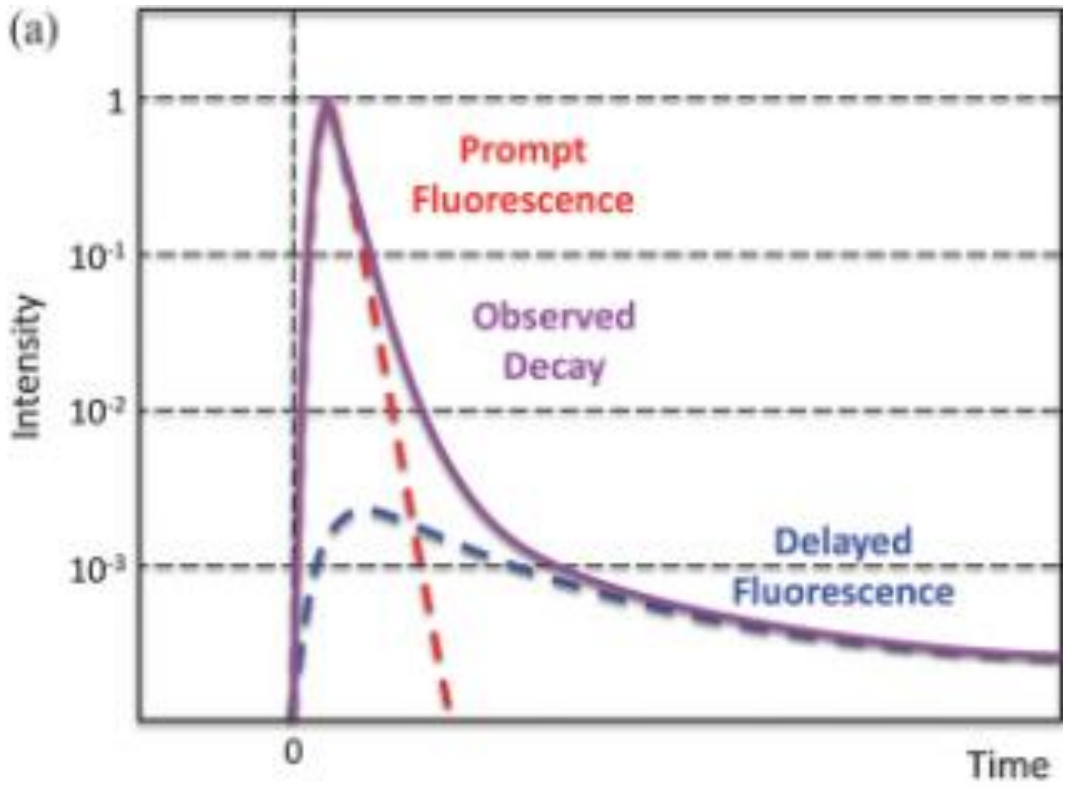
In case of binary scintillators τ_f is that of the solute

In case of ternary scintillators it stems by the interplay of the first solute and the wavelength shifter

For a fast scintillator $\tau_f \sim$ 4-8 τ_r

Very often the rise time is blurred by the resolution of the measurement system and therefore not actually measurable

Description of the delayed fluorescence (slow) component

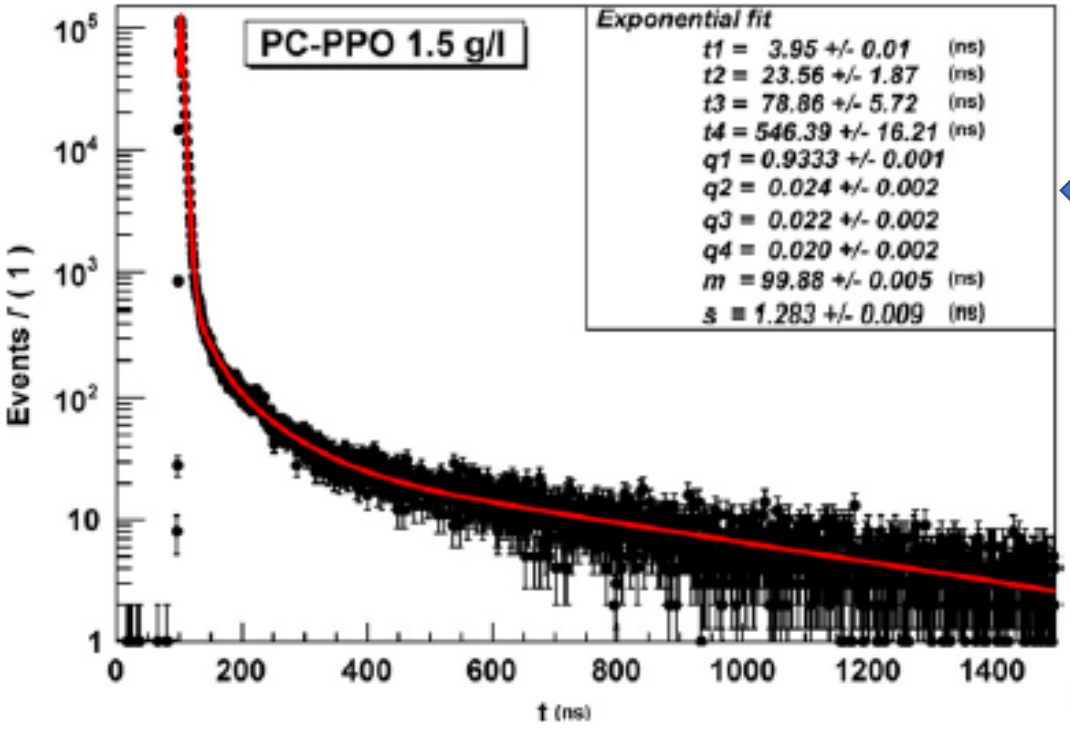


The molecular kinetic associated with the generation of the delayed fluorescence from the triplet states and triplet triplet annihilation can originate a mathematical description of the evolution in time of the slow component

However due to the inherent mathematical difficulties this is rarely done

Effective description with multiexponential fit

Electron irradiation

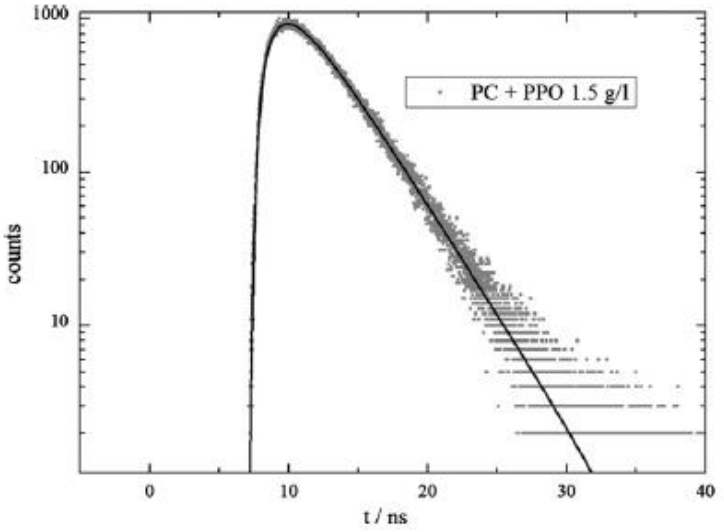


t1-> fast component - reflects rather faithfully the fluorescent time

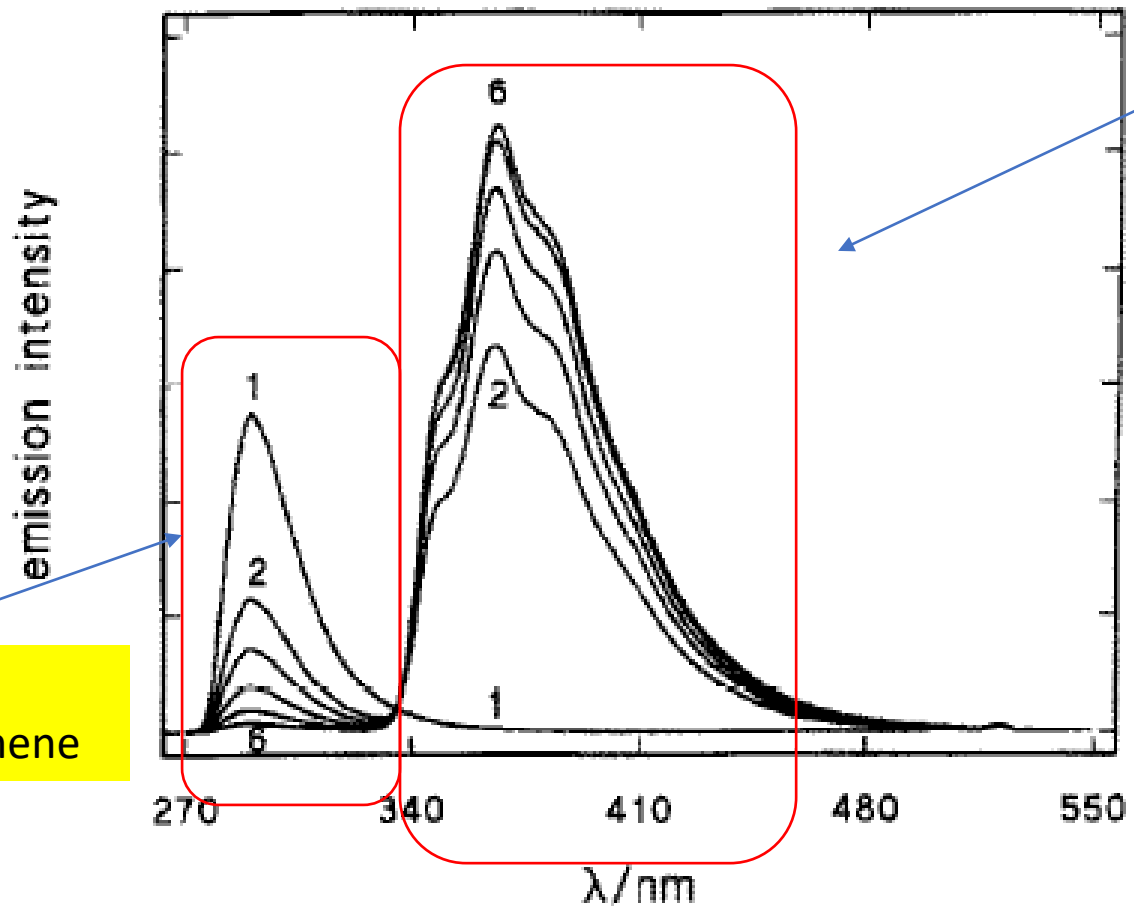
t2, t3, t4 -> effective slow component description
Limited but existing also with electron excitation

- Cross check with photoexcitation - UV light
- Essentially no long tail – very similar to electron excitation
- Scintillation decay time as t_1 above – confirmed that it is due to fluorescence

UV irradiation



Emission spectra



Primary solute
PPO

Solvent
Pseudocumene

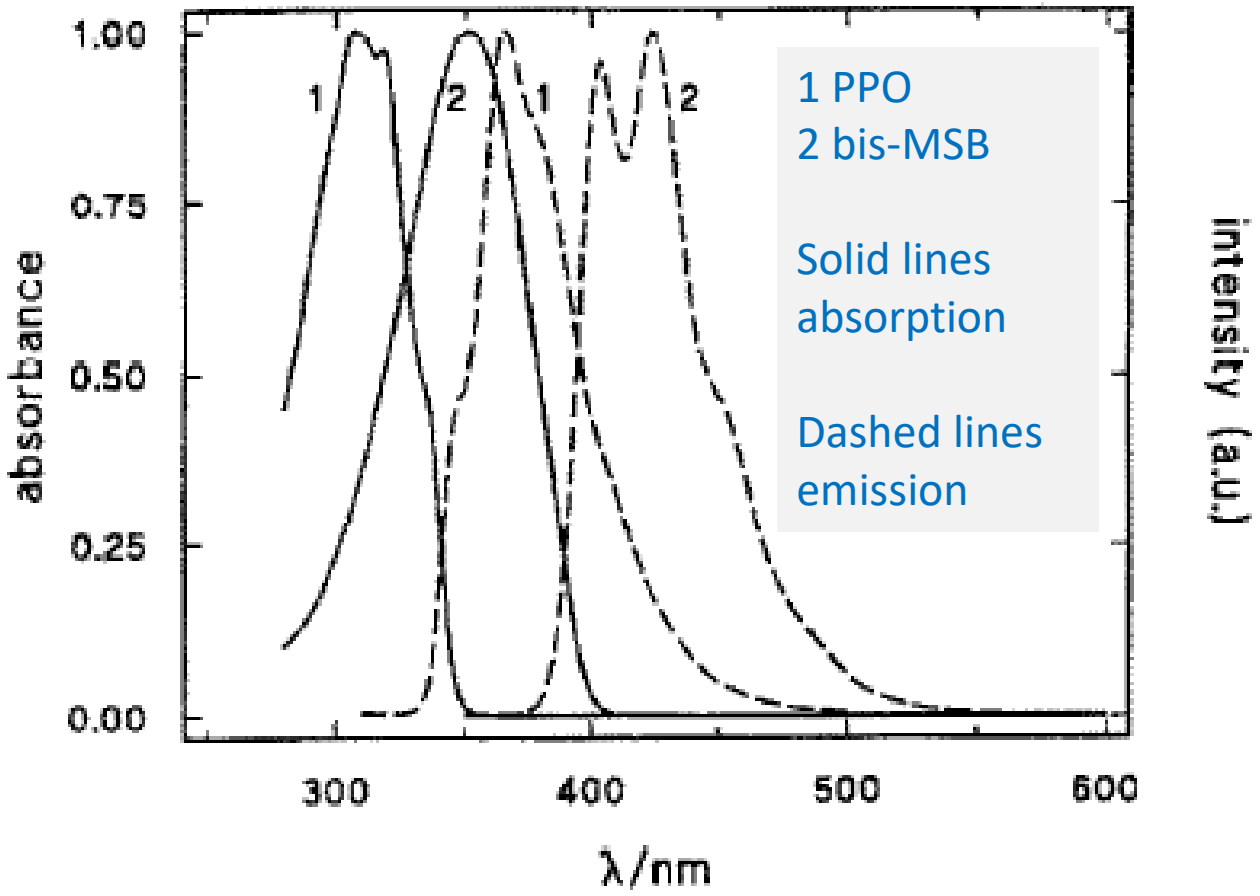
Studies conveniently performed through UV excitation @ 267 nm

Labels correspond to different PPO concentrations
1 no PPO

Pseudocumene alone emits in a not convenient for phototubes near UV region

PPO in addition to increase the scintillation efficiency ensures a better match with the phototubes' response

Absorption and emission spectra of first solute and wavelength shifter



Good overlap between the PPO emission and bis-MSB absorption – radiative transfer
Remind: the transfer from PC to PPO is essentially non radiative
The bis-MSB should match better the photocathode response – with modern photocathodes often this is not always needed

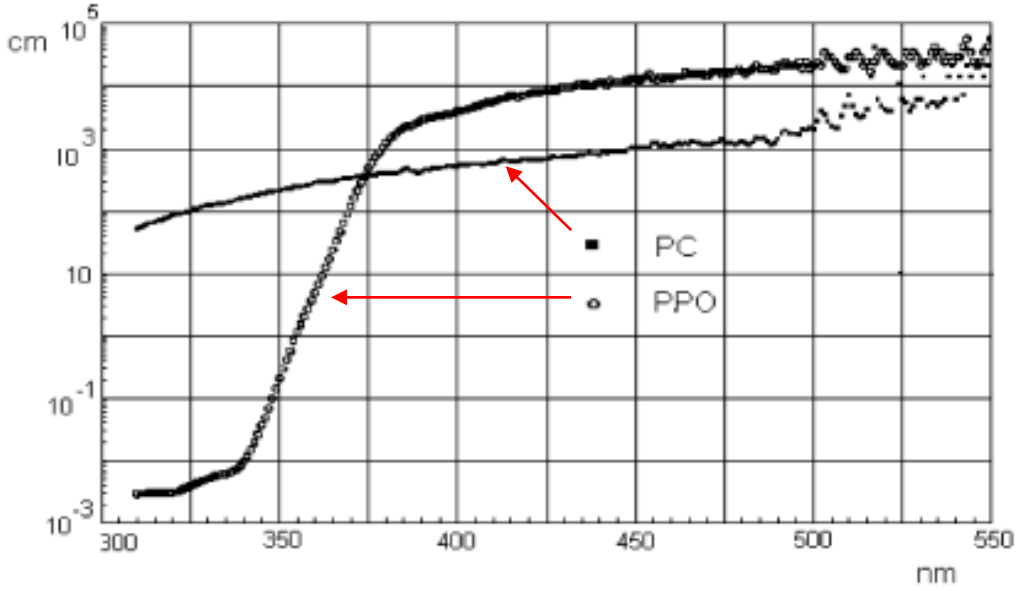
Attenuation length

- ✓ Important parameter in large set-ups thus crucial in the underground applications where the detectors are huge
- ✓ It measures the decrease of intensity of a light beam
- ✓ It is due to two effects : absorption and Rayleigh scattering $1/\lambda_{att} = 1/\lambda_{abs} + 1/\lambda_{scatt}$
- ✓ Absorption is self-absorption and absorption from impurities $\rightarrow$ purification to reduce them
- ✓ In a linear arrangement, a long tube filled with scintillator and a phototube at the extreme, absorbed and scattered photons are lost
- ✓ The self-absorbed photons are subsequently re-emitted and the scattered photons are removed from the beam, but simply to change direction $\rightarrow$ both recovered and detected in a spherical set up
- ✓ What is crucial for a spherical detector is thus the purification to remove the impurities which trap definitively the photons

A practical case of a binary scintillator

Pseudocumene + PPO

Att. length



Used in Borexino

Attenuation@ conventional 420 nm 7 m

Already Rayleigh dominated

Key points

- The attenuation length is wavelength dependent
- At longer wavelengths the solvent dominates - at shorter wavelengths the solute
- It can be shown that at long wavelengths the Rayleigh scattering takes over – $l_{att} \propto \lambda^4$

Considerations on light yield and calibration

Initial number of photons originated by the intrinsic scintillation mechanism distributed over the wavelength of the last solute

Determination of the precise absolute light yield rather difficult – ab initio calculation impossible

Practical characterization via comparison with a same standard – Anthracene crystal

Anthracene is a solid organic scintillator and is known to be the organic scintillator with highest yield – in the literature quoted between 16000 and 18000 ph/MeV

Example of a table reporting the main properties

	scintillator	light output	peak λ	decay constant	attenuation length	index of refraction	density [g/cm^3]
Plastic scint	BC-400	65%	423 nm	2.4 ns	250 cm	1.58	1.032
	BC-404	68%	408 nm	1.8 ns	160 cm	1.58	1.032
	BC-416	38%	434 nm	3.3 ns	400 cm	1.58	1.032
	BC-428	36%	480 nm	12.5 ns	150 cm	1.58	1.032
LS	PC-based liquid	80%	425 nm	2.5 ns		1.505	0.877
	30% PC diluted in mineral oil	60%	425 nm	3 ns	>500 cm	1.48	0.86
	LAB-based	75%	425 nm	3.5 ns		1.47	0.87

To overcome the difficulty of a precise knowledge of the yield in practical applications – both small and large setups – the scintillator response is calibrated in situ with the aid of calibration radioactive sources

The widespread role of calibration

- kB and response non-linearity
- Light yield in linear regime
- Quenched light yield for heavily ionizing particles
- Pulse shape discrimination

Can be quantitively assessed via extensive calibration with several calibration sources

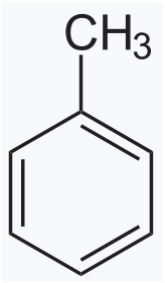
In addition in large detectors also the light propagation effects – absorption scattering re-emission - can be unveiled through appropriate calibrations

Large detectors -> multiple calibration locations

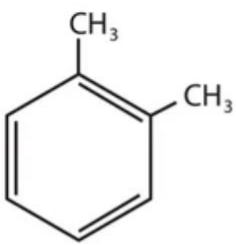
Complete and precise quantitative description of detectors obtained by comparing a MC incorporating the effects described so far with the calibration results

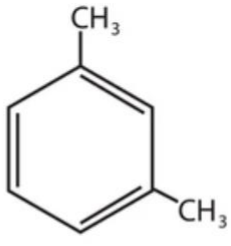
Commonly used solvents

Toluene
C_7H_8



Xylene
C_8H_{10}



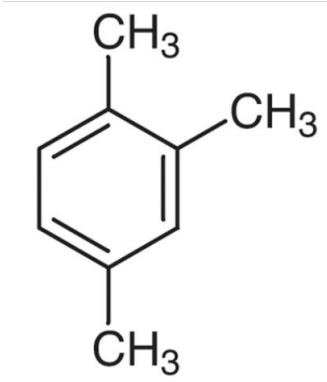


Mixed isomers

First generation solvents – beginning of ‘50s

Hazardous flammable and threat to environment though less than benzene

Pseudocumene
(1,2,4-trimethylbenzene)
C_9H_{12}



Second generation solvent – middle of ‘70s

Less Hazardous and less threat to environment though not with zero harm - flammable

Borexino and its prototype CTF

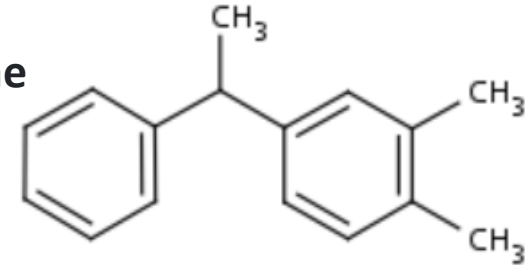
Modern solvents

At the turn of the century introduced a new generation of solvents with the following characteristics:

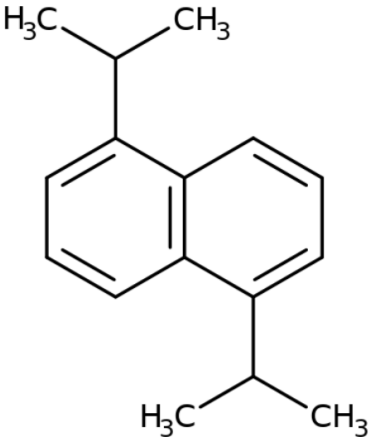
- High Flash point (no flammable)
- Low vapor pressure
- odor lessness
- Low toxicity and irritancy
- Biodegradability

No hazard for operators and environment

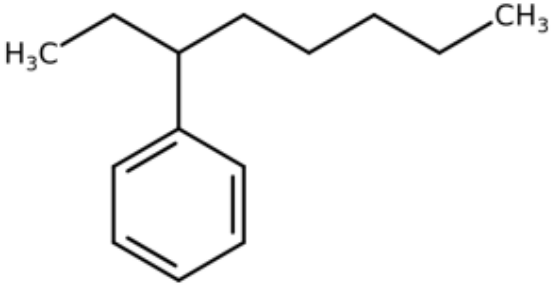
Phenyl xylyl ethane
PXE
$C_{16}H_{18}$



Diisopropylnaphthalene
DIN (mixture of isomers)
$C_{16}H_{20}$



Linear alkylbenzene
LAB
precursor of biodegradable detergents large availability and low cost

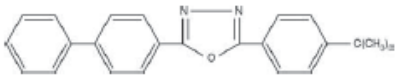
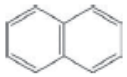
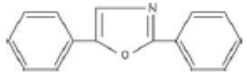


Linear chain of length between 10 and 13
Each vertex CH2
(mixture of isomers)
$C_6H_5CnH_2n+1$

Widespread modern choice

Solutes

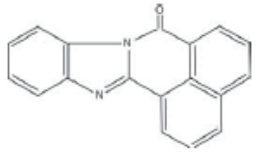
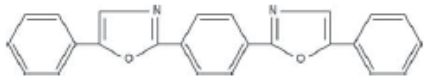
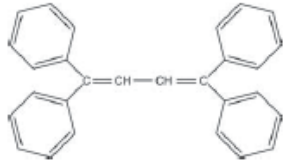
Primary Scintillators

Scintillator	Structure	Emission Wavelength
Butyl PBD 2-[4-biphenylyl]-5-[4-*tert*-butyl-phenyl]-1,3,4-oxadiazole) **Order No. SFC-20**		363nm
Naphthalene **Order No. SFC-40**		322nm
PPO 2,5-diphenyloxazole **Order No. SFC-10**		357nm
p-Terphenyl **Order No. SFC-50**		340nm

Among primary solutes PPO is the most used typically few g/l

Among secondary solutes bis MSB is the most used typically few mg/l

Secondary Scintillators

BBQ (7H-benzimidazo[2,1-a]benz [de]isoquinoline-7-one) **Order No. SFC-13**		477nm
Bis-MSB (1,4-bis[2-methylstyryl]-benzene) **Order No. SFC-90**		420nm
POPOP (1,4-bis[5-phenyloxazol-2-yl]benzene) **Order No. SFC-60**		410nm
TPB (1,1,4,4-tetraphenyl-1,3-butadiene) **Order No. SFC-15**		455nm

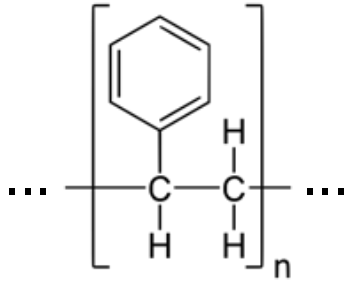
A remark on plastic organic scintillators

"Solution" of scintillation solutes in a monomer base solvent which can then be subsequently polymerized into a solid plastic element

The solutes are the same used for the organic liquid scintillators

Among monomers suited for polymerization there are

- Styrene
- Vinyltoluene
- Vinylbenzene



Polystyrene

Main advantage is the ease with which they can be produced and shaped in any suitable useful arrangement

Beta spectroscopy and neutron detection

Liquid scintillators are extremely well suited for beta spectroscopy by direct dissolution of the specimen → the electron can deposit inside the liquid its total energy along its very short track (mm)

For the same reason the alpha particles are very well observed in LS

Fast neutrons impart their energy to the protons of the scintillator which in turn produce scintillation - moreover upon thermalization are captured with gamma ray productions -> very effective way to detect neutrons

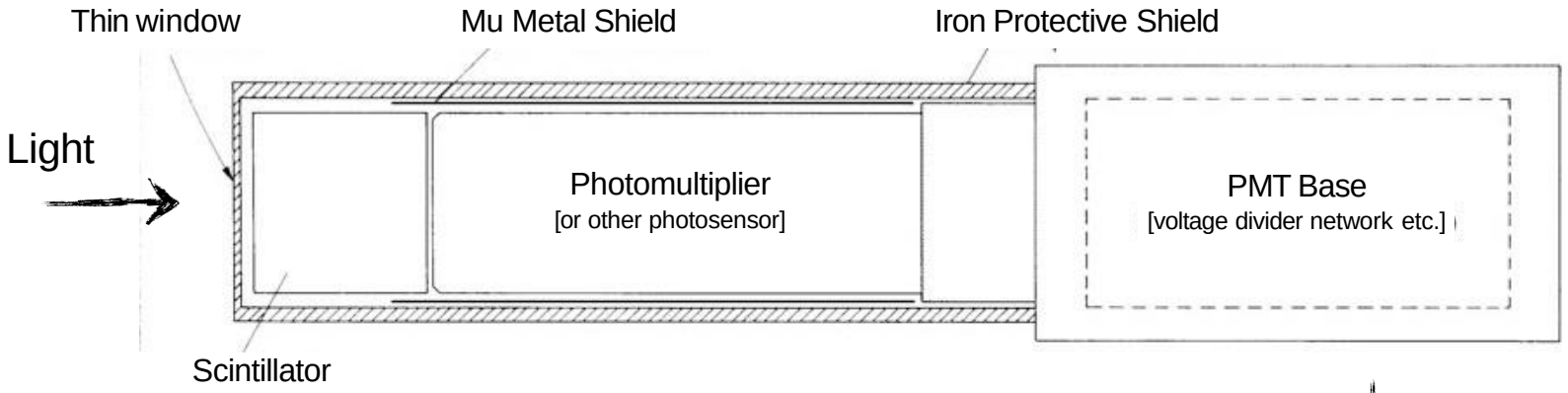
Pulse shape discrimination dependent upon dE/dr helps distinguishing among them

What does this imply for the application of neutrino detection?

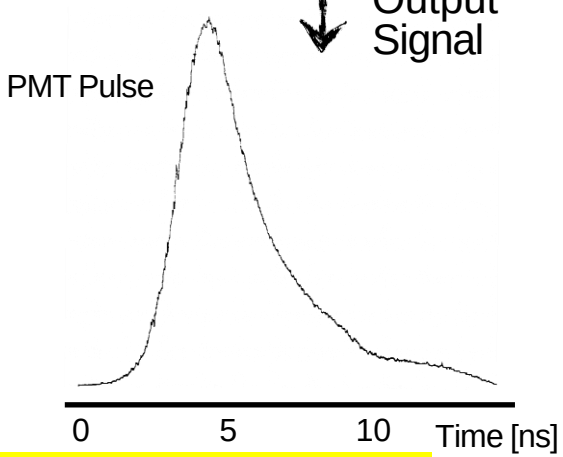
Neutrinos scatter off electrons of the scintillator → beta detection

Anti-neutrinos are detected via the inverse beta detection a la Cowan Reines implying neutron production and subsequent observation (more details later)

Scintillators – Basic Counter Setup



Output Signal



Scintillator Types:

Photosensors

Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photo Multipliers

Organic Scintillators
Inorganic Crystals
Gases

Ingredients for LS applications

Photon Detection

Purpose : Convert light into a detectable electronic signal

Principle : Use photo-electric effect to convert photons to photo-electrons (p.e.)

Main Requirements :

Quantum Efficiency; Q.E. = $N_{p.e.}/N_{photons}$

And

High Photon Detection Efficiency (PDE)
includes the photoelectron collection probability

Photomultipliers

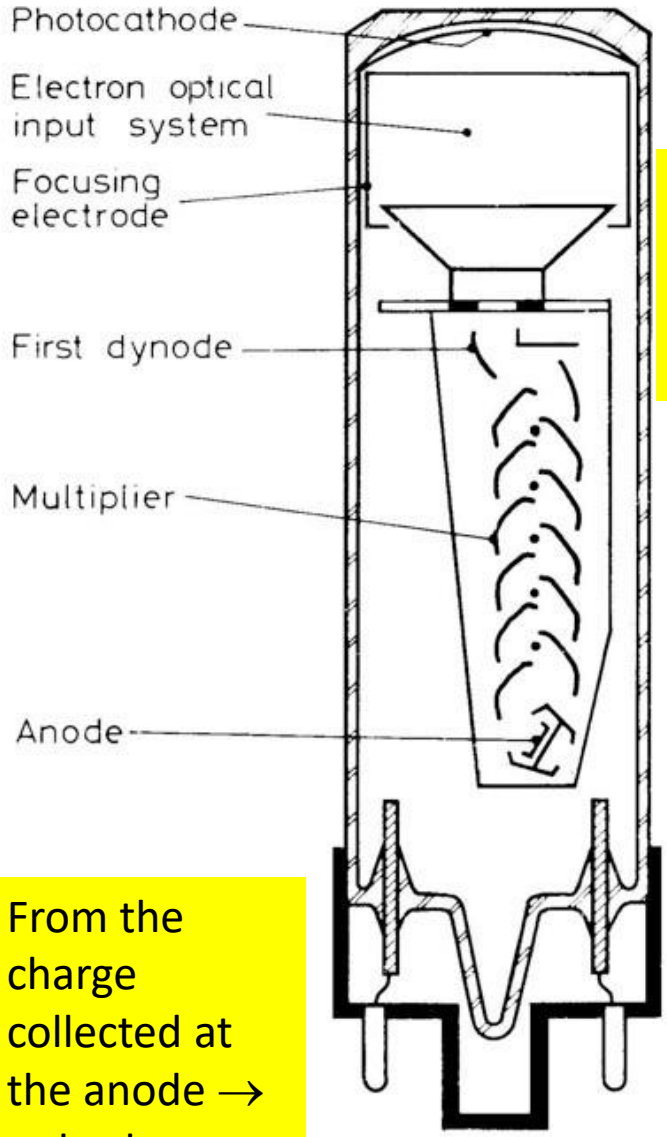
Principle:

Electron emission
from photo cathode

Secondary emission
from dynodes; dynode gain can span a large interval 3-50 depending upon the incident energy

Typical PMT Gain: > 10^6
[PMT can see single photons ...]

Best practical approximation of an ideal current amplifier



Glass envelope Vacuum inside

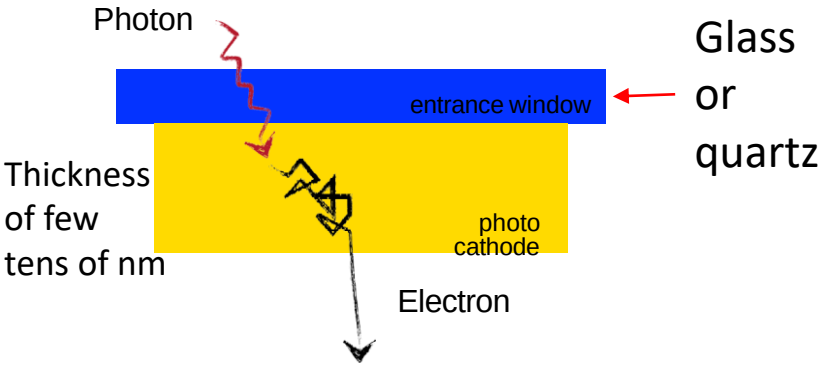
From the charge collected at the anode → output current pulse

Photomultipliers – Photocathode

Caveat: thermionic spontaneous emission → dark rate

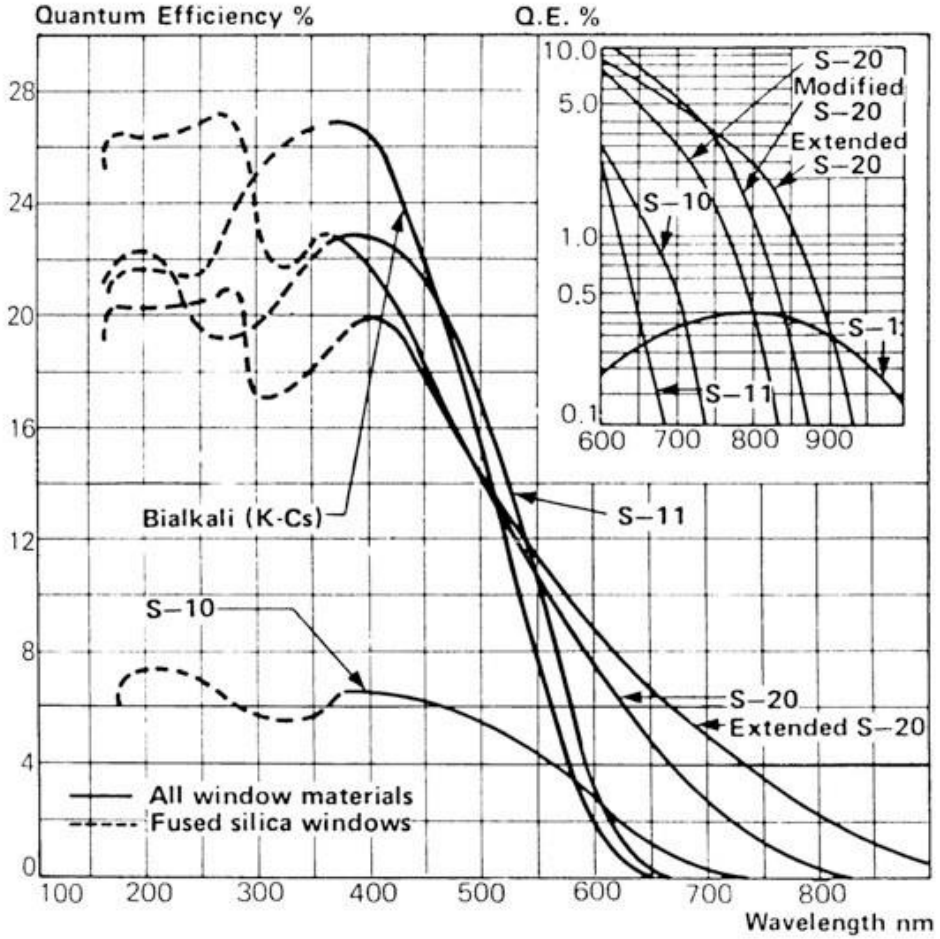
light-conversion

via photoelectric effect in a semiconducting layer with proper band gap ~ 3 eV



3-step process:

1-Absorption and transfer of energy to an electron
2-Propagation through cathode
3-Escape of electron into vacuum → enough energy to overcome the surface potential barrier (work function or electron affinity)

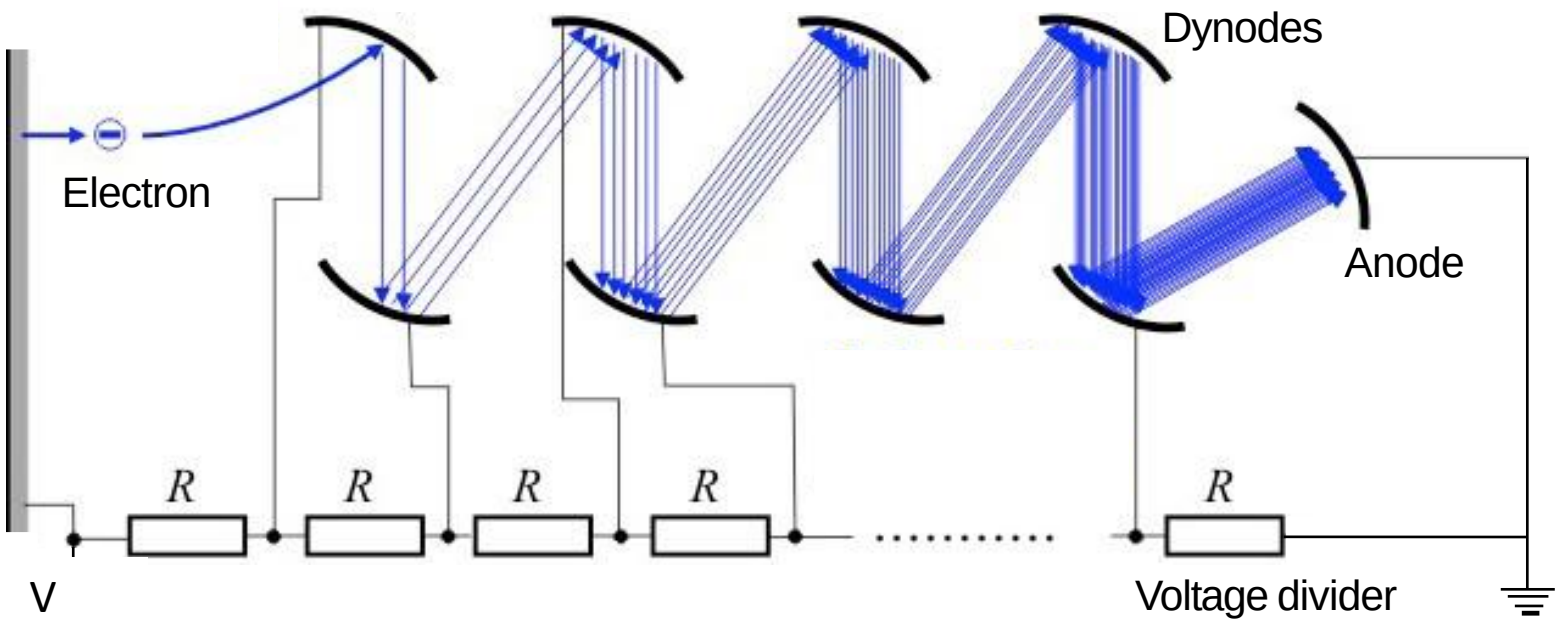


Different type of photocathode materials according to the applications

Bialkali photocathode (K-Cs + Sb) optimum choice for LS application : good spectral matching with the LS light further improved by the wavelength shifter

Q.E. ≈ 20-30% @ wavelength peak value

Photomultipliers – Dynode Chain



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:

δ = #(e^- produced)/#(e^- incoming)
Dependent upon the interdynode voltage
n number of dynodes

Typical values: $\delta = 2 - 10$, $n = 8 - 15$ ➛ Total gain $G = \delta^n = 10^6 - 10^8$

In reality $G = a\,\delta^n$ (**a** practical collection effects) and also proportional to V^n

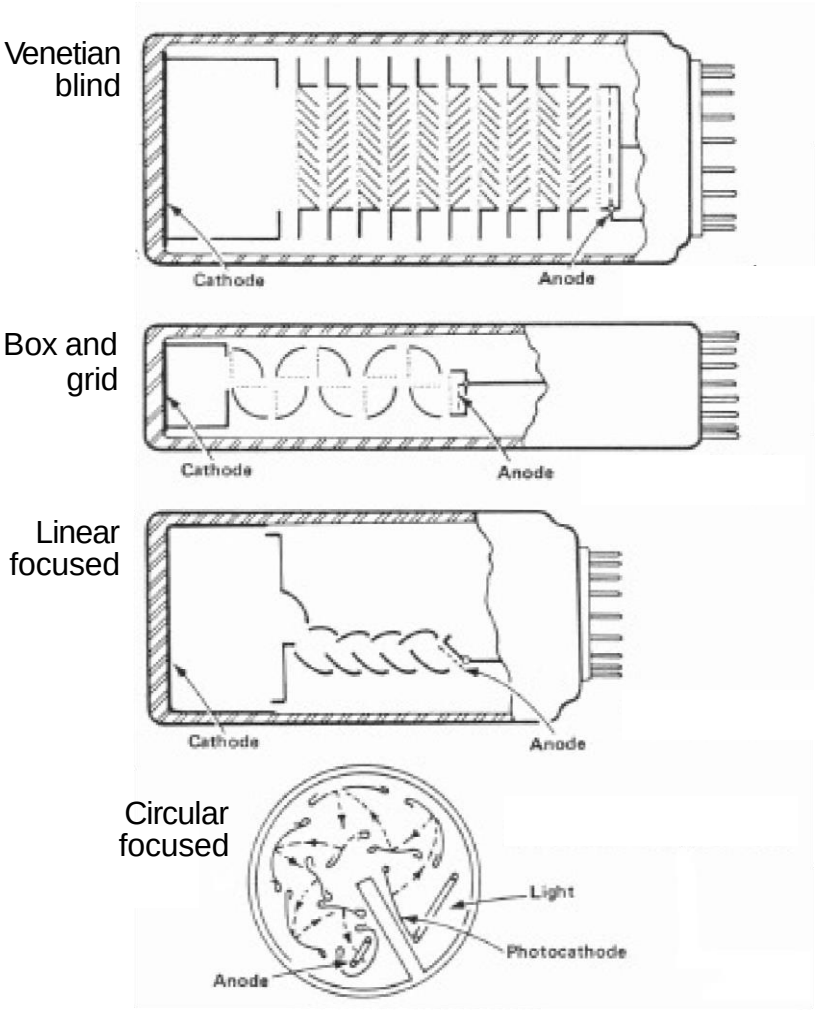
Photomultipliers – Geometries of Dynode Chain

Optimization of

Gain
Linearity
Transit time dispersion
Magnetic field dependence

PMT's are in general very sensitive to magnetic fields !

Even to Earth's field (around 50 μT) - μ-metal shielding required – particularly important for underground applications with large PMT's



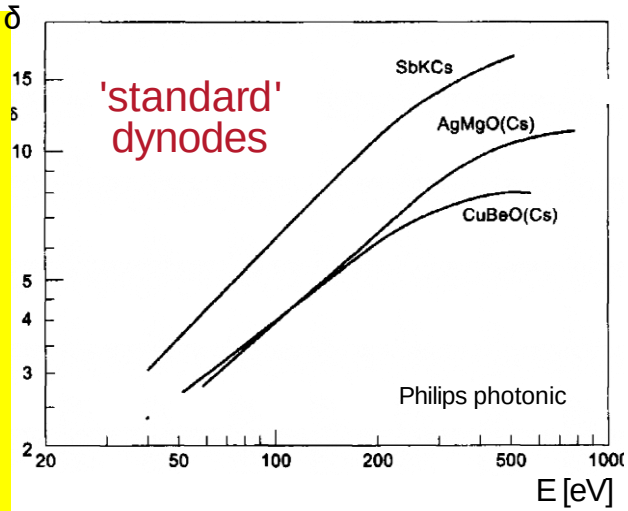
Photomultipliers – Amplitude Resolution

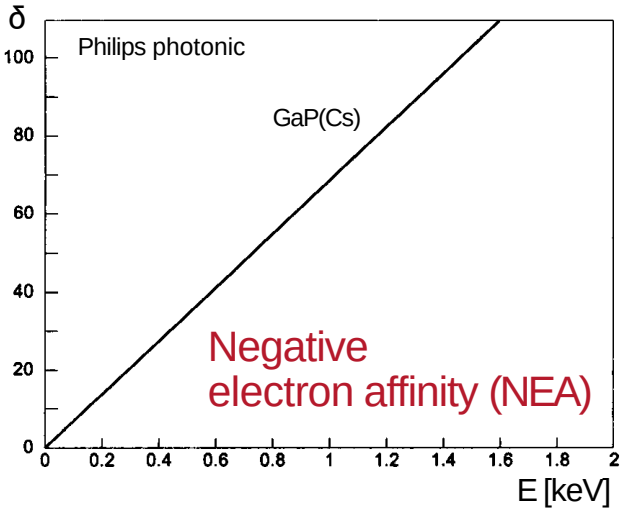
In high light pulses regime → PMT effect on global resolution negligible
In low light pulses regime typical for underground application→ single photoelectron response important

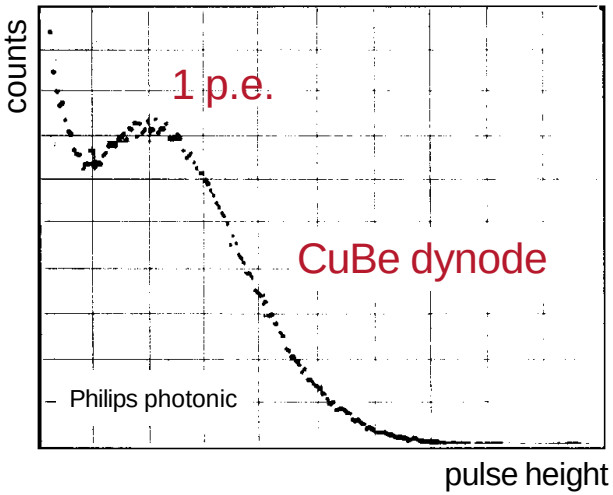
The resolution depends upon the gain of the dydnodes, in particular the first
relative variance =1/(δ-1)
The higher δ the better the resolution

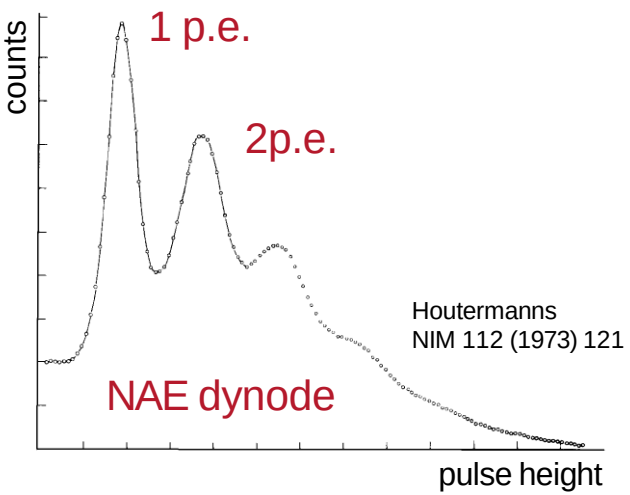
The standard materials have a lower gain whose increase with voltage saturates

The special negative electron affinity materials – no surface barrier for electrons to escape – have higher gain which does not saturate









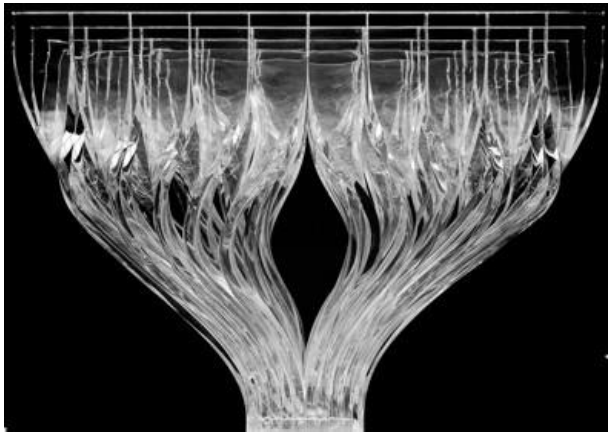
How the PMT's for underground LS and Water Cherenkov Detectors look like

Large dimensions to avoid the proliferation of the acquisition channels

Photocathode dimensions between 20 and 50 cm

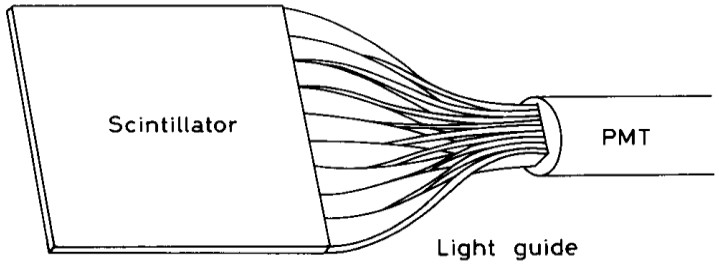
Light guides and optical concentrators

In the case of large set-up with organic plastic scintillators adopted to guide conveniently the light to the PMT's especially in case of systems with complex mechanical arrangement



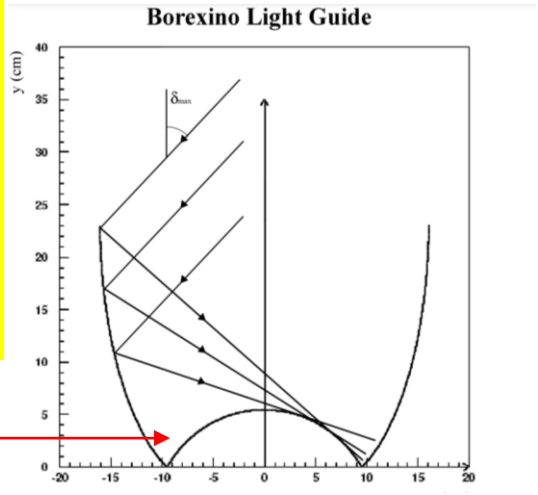
Typical examples

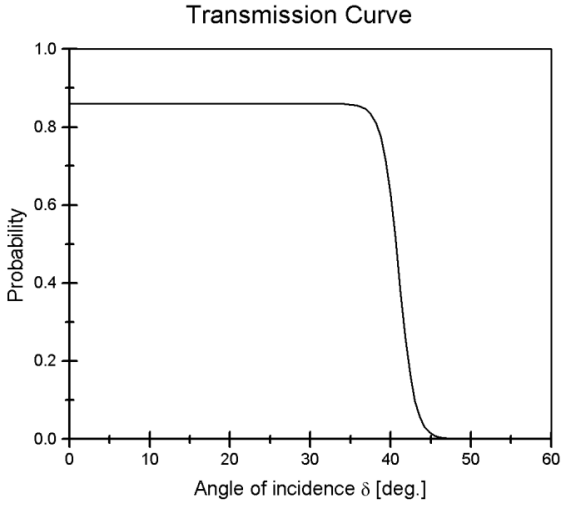
Light transfer by
total internal reflection



Concept adapted to the LS case with the development of optical concentrators→ Winston Cones

PMT surface





Practical cases of liquid scintillator underground detectors

Concluded experiments

- Borexino (low energy solar neutrino detector) and its prototype Counting Test Facility

Future experiment under installation

- JUNO

Borexino

A real time calorimetric scintillation detector for low energy solar neutrinos installed at the Gran Sasso underground laboratory, aimed at detecting solar neutrinos through the scattering off the electrons of the scintillator $\nu + e^- \rightarrow \nu + e^-$

Moreover geo-neutrinos

Designed for

<u>good performance as instrument</u>

precision in

-energy measurement

-position measurement

needs of calibration and Monte Carlo tuning

Optimum large-scale implementation of the technique described so far

<u>low background</u>

-choice of construction materials

-assay of materials during the assembly

-special precautions for installation procedures (clean room, cleanliness of the surfaces)

-accurate strategy for liquid manipulation and purification

-special issue : particular care for the nitrogen purity

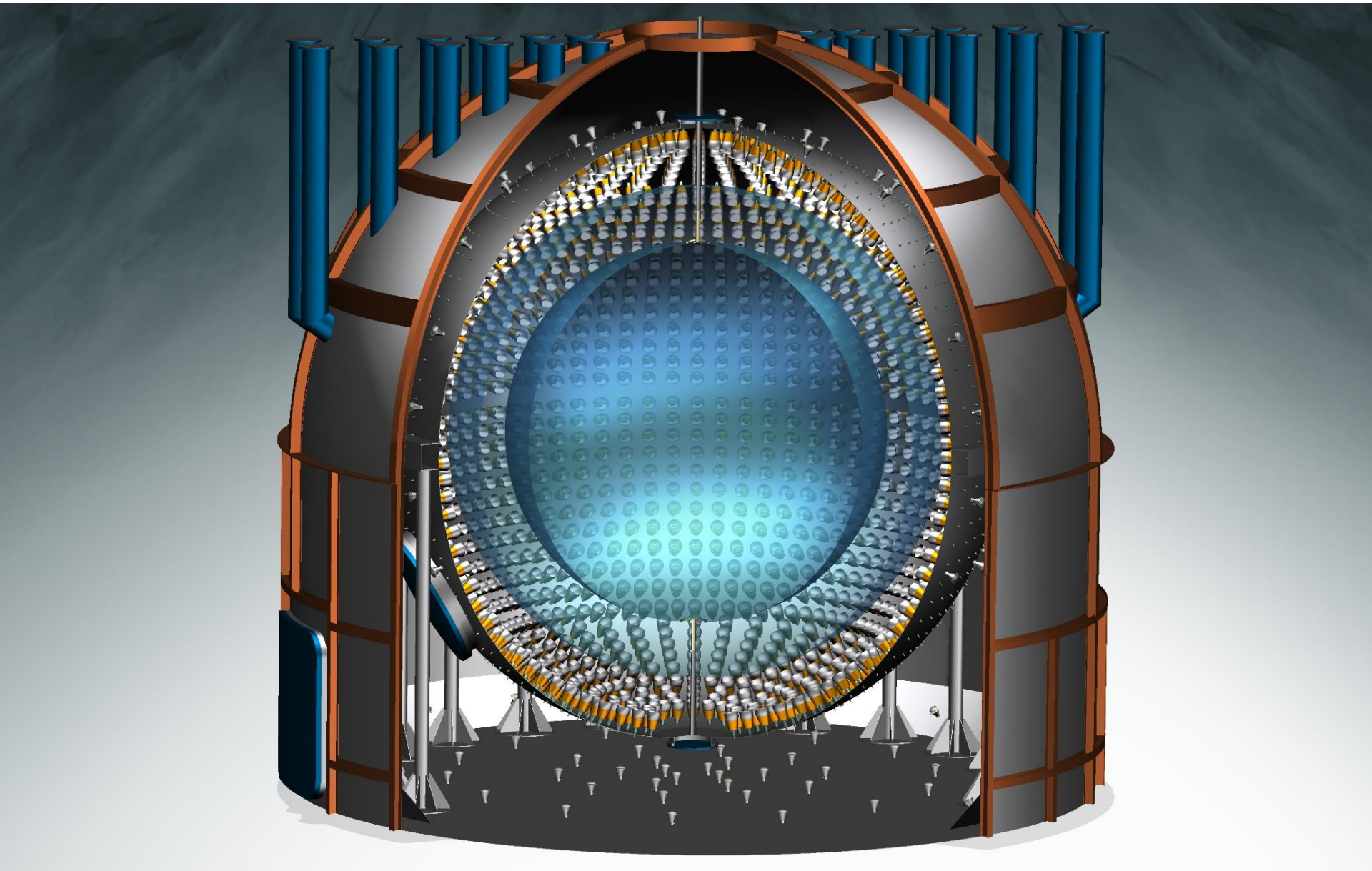
-strategy against the cosmic muon: underground location, muon veto, tagging of the residual cosmogenic products

The great challenge of the underground detectors for rare events detection

Main problematic isotopes: ^{238}**U** ^{232}**Th** and their chains in secular equilibrium, plus ^{40}**K** (altogether natural radioactivity),^{210}**Bi** and ^{210}**Po** out of equilibrium from U chain

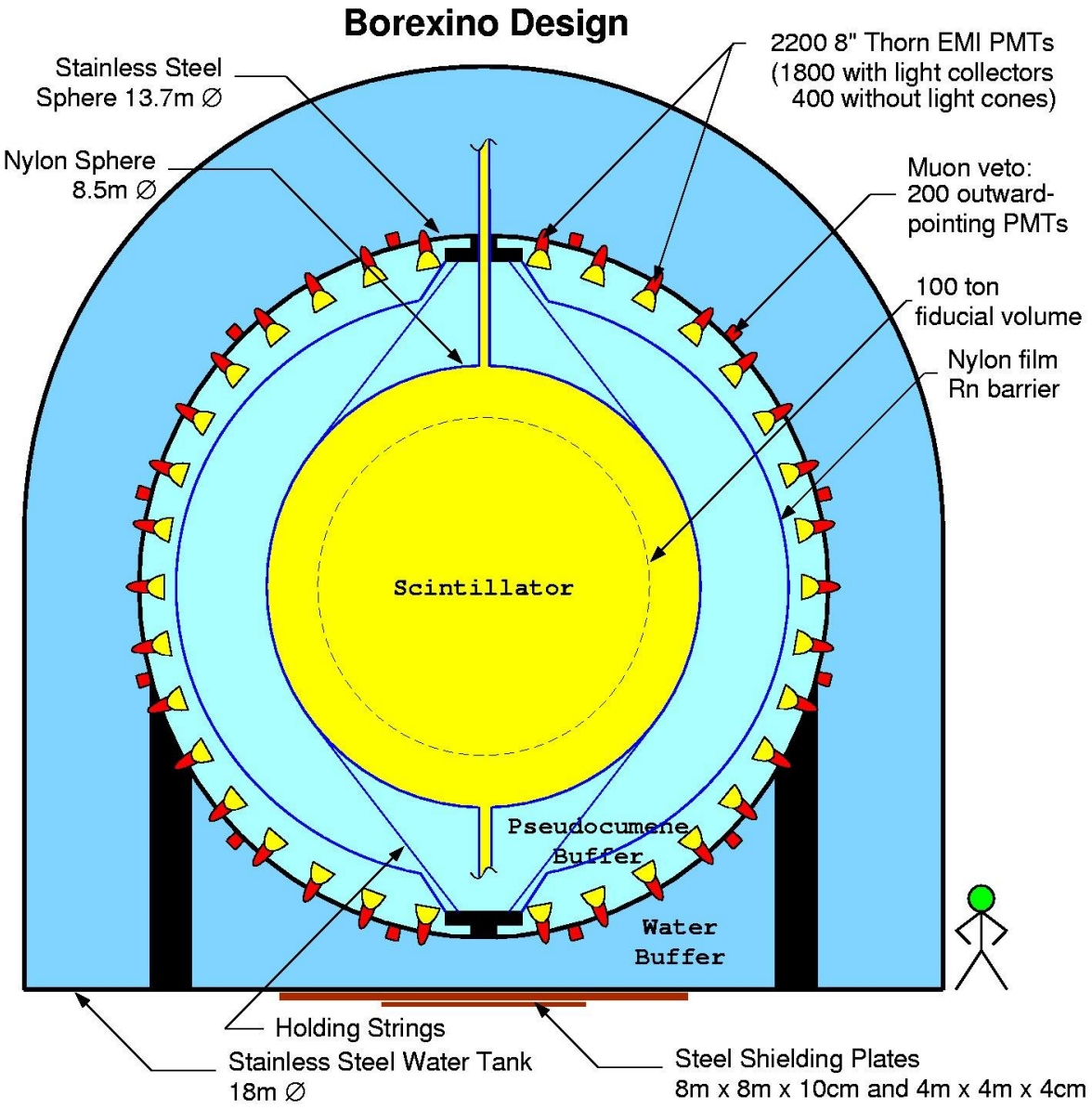
Gaseous radioactive isotopes: ^{222}**Rn** (from U chain often out of equilibrium), ^{39}**Ar** (cosmogenic), ^{85}**Kr** (man made through nuclear explosions)

Artistic view of the detector



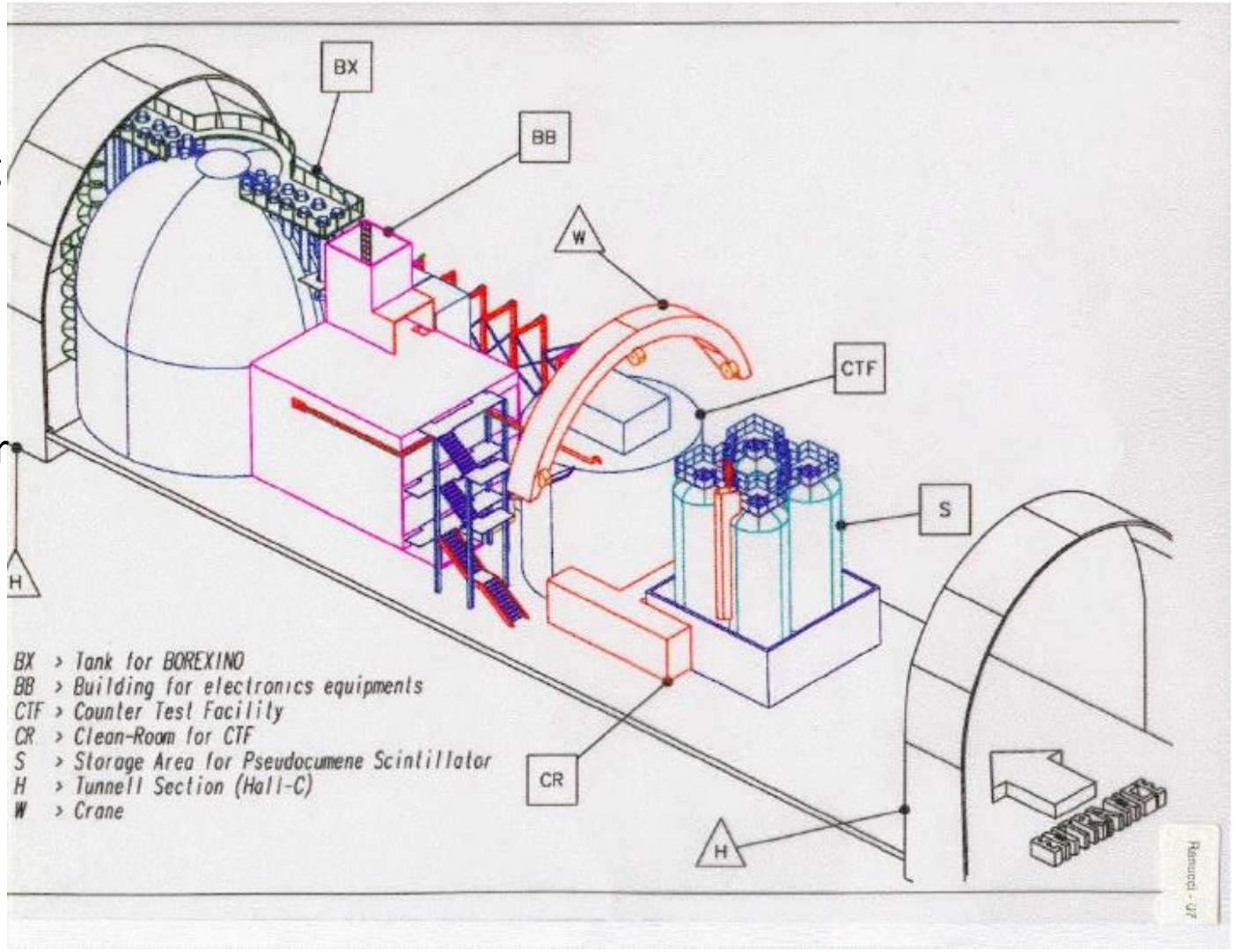
Main components

- Scintillator
- Nylon (inner and outer) vessels
- Buffer liquids
- 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



Ancillary Plants

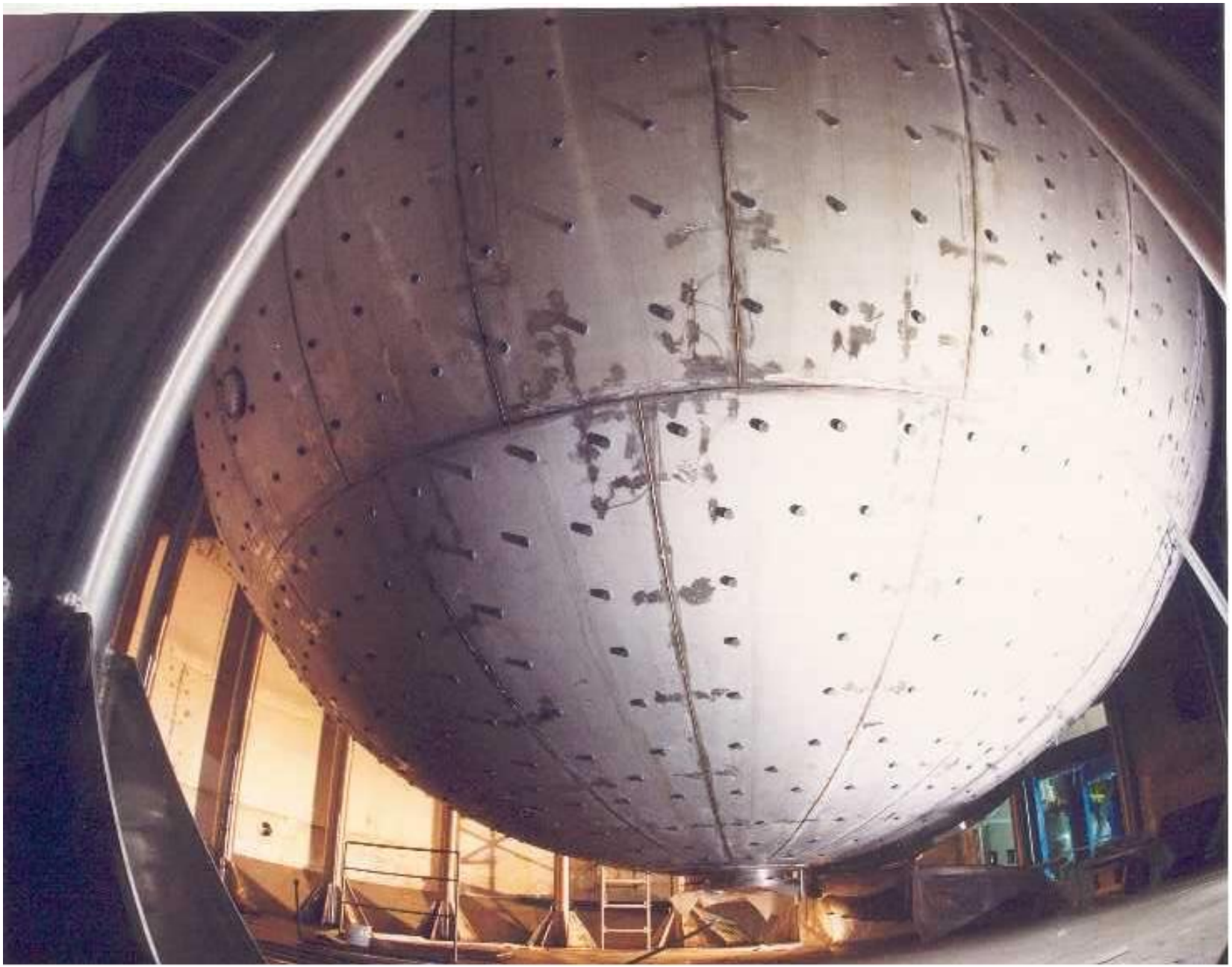
- Storage vessels
- Scintillator purification systems
  - Water extraction
  - Distillation
  - Nitrogen sparging
  - PPO (solute) distillation
- Normal nitrogen
- High purity nitrogen purified in ^{39}Ar and ^{85}Kr
- Fluid handling system
- Water purification
- Clean room
- CTF, the initial prototype



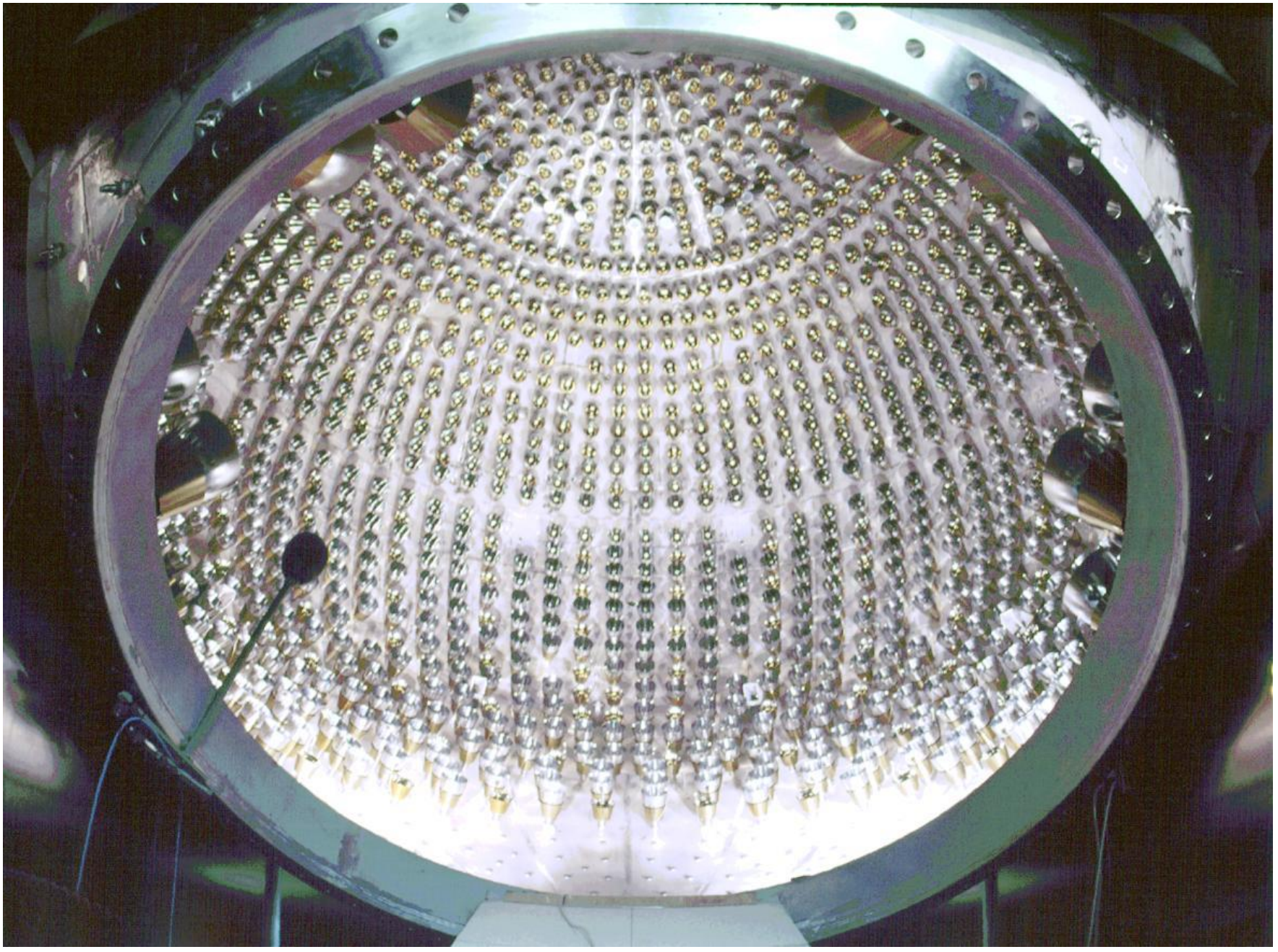
Water Tank

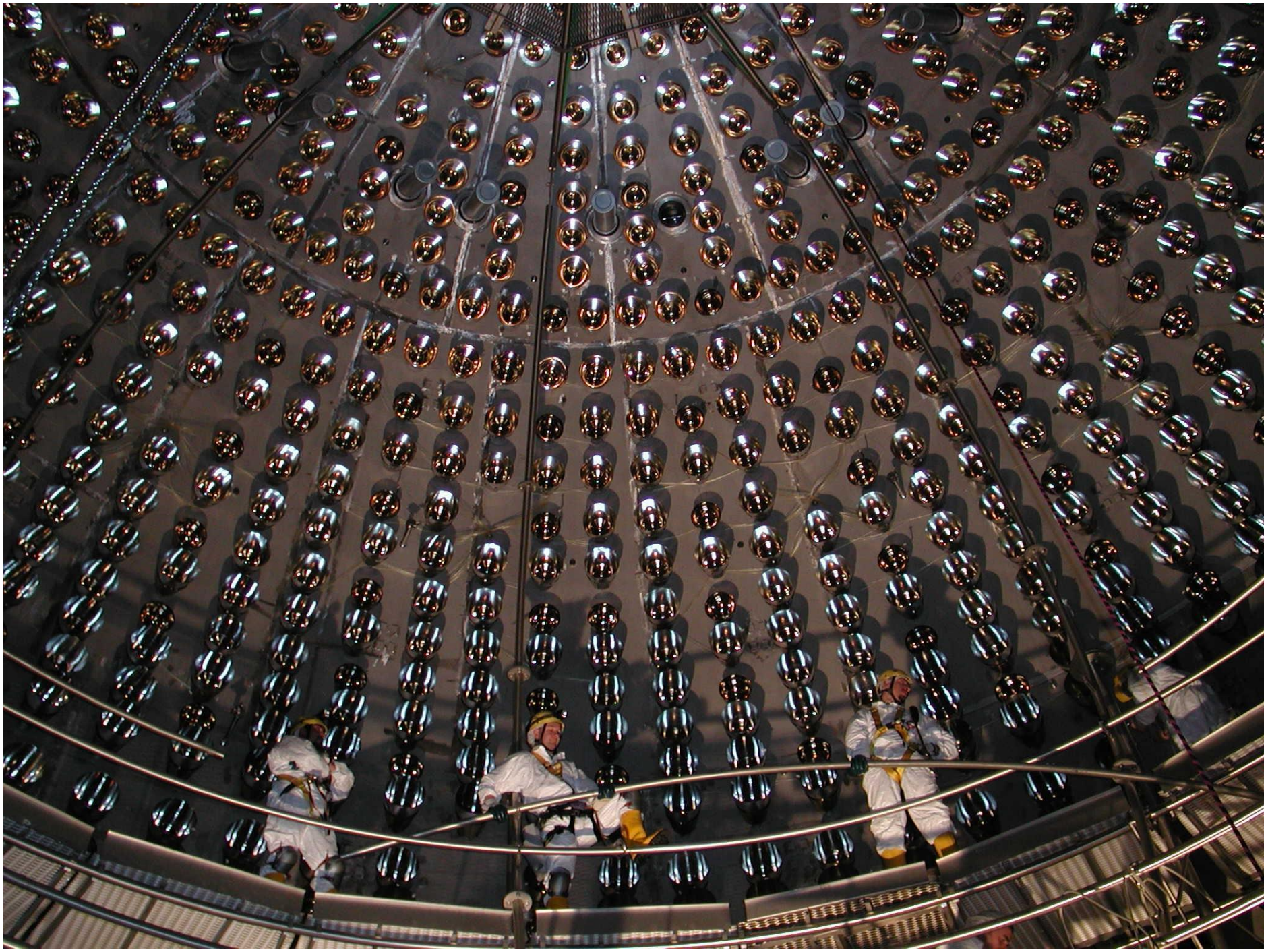
Later wrapped with insulation material for thermal stabilization

Stainless steel sphere



PMT's on the sphere surface



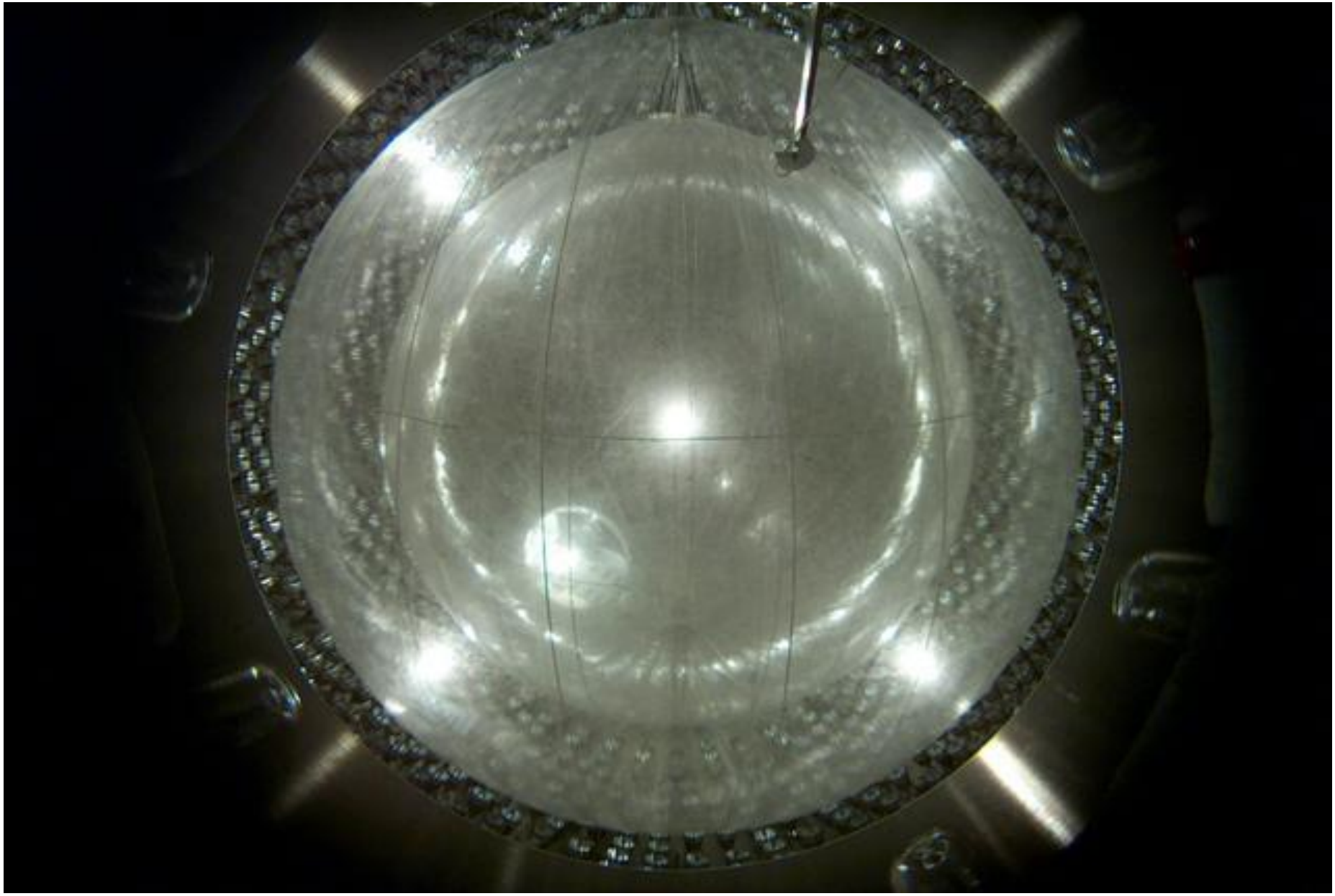


Prototype of the containment double vessel

The second barrier acts to prevent the radon diffusion towards the inner core of the scintillator

Vessel before inflation (viewed by CCD cameras)

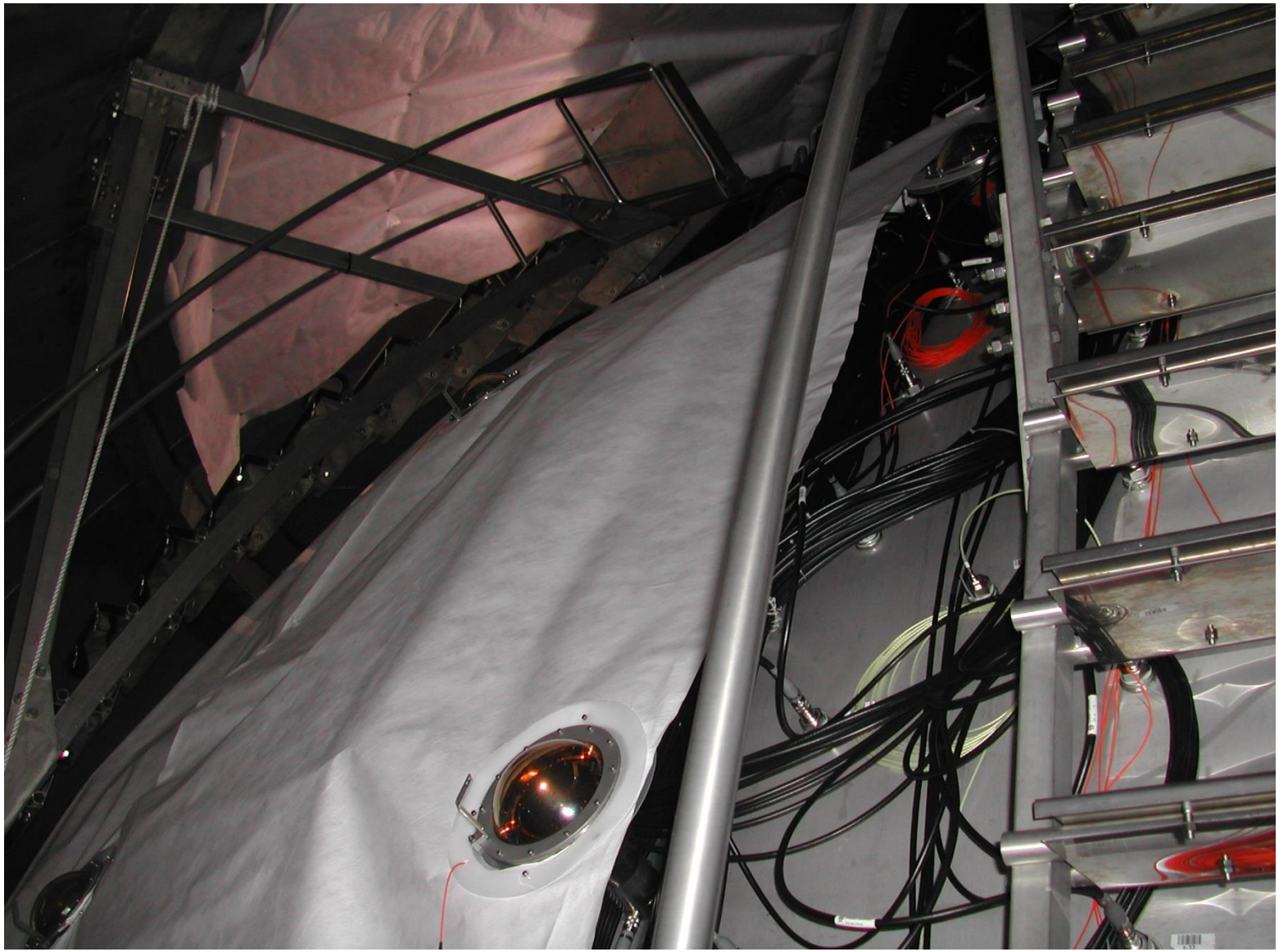
Vessel after inflation (viewed by CCD cameras)



Detail of the south end-cap of the vessel and of the last mounted PMT's on the 3 m door of the sphere

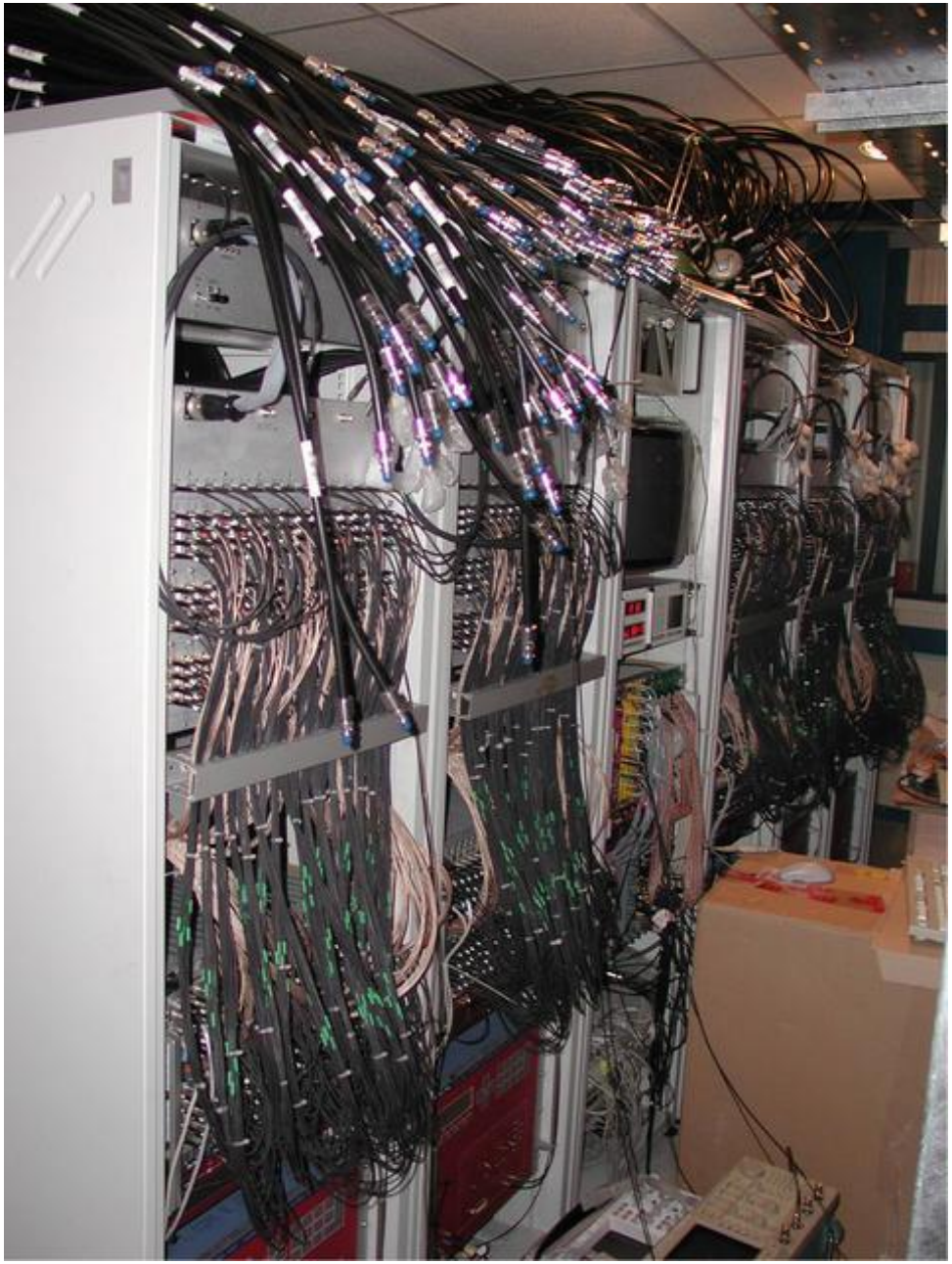
Muon veto: tyvek (diffusive panels) and phototubes on the external sphere surface

The diffusive panels increase the collected light



Tyvek on the surface of the Water Tank dome

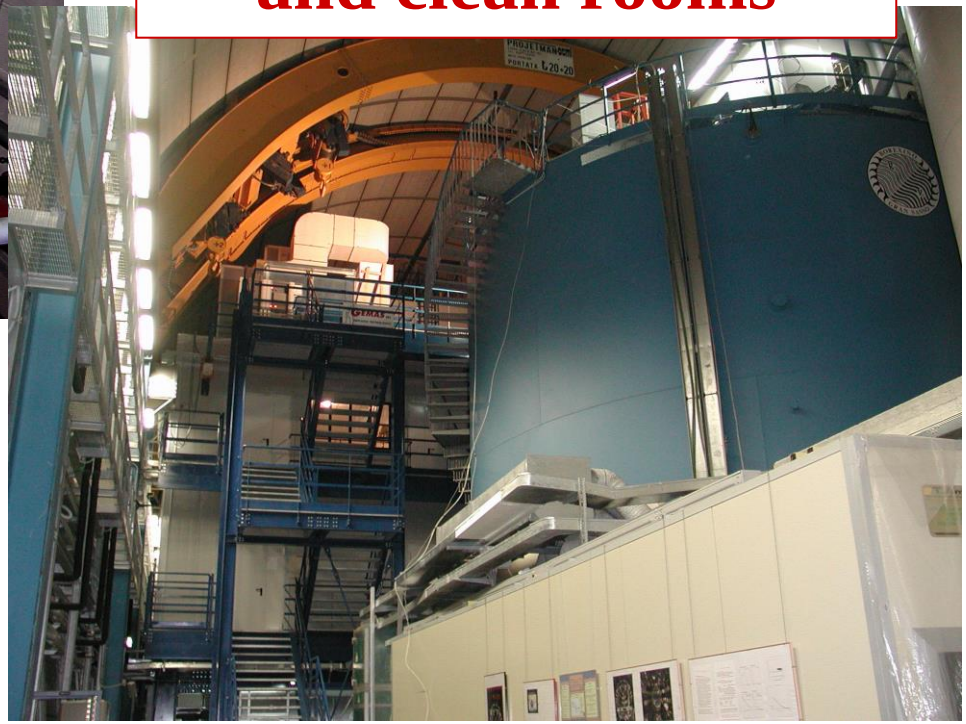
Electronic racks (cables length more than 50 meters)



Storage Vessels and the skeleton of other auxiliary plants on the right

Water Plant

Counting room - CTF and clean rooms



Background framework

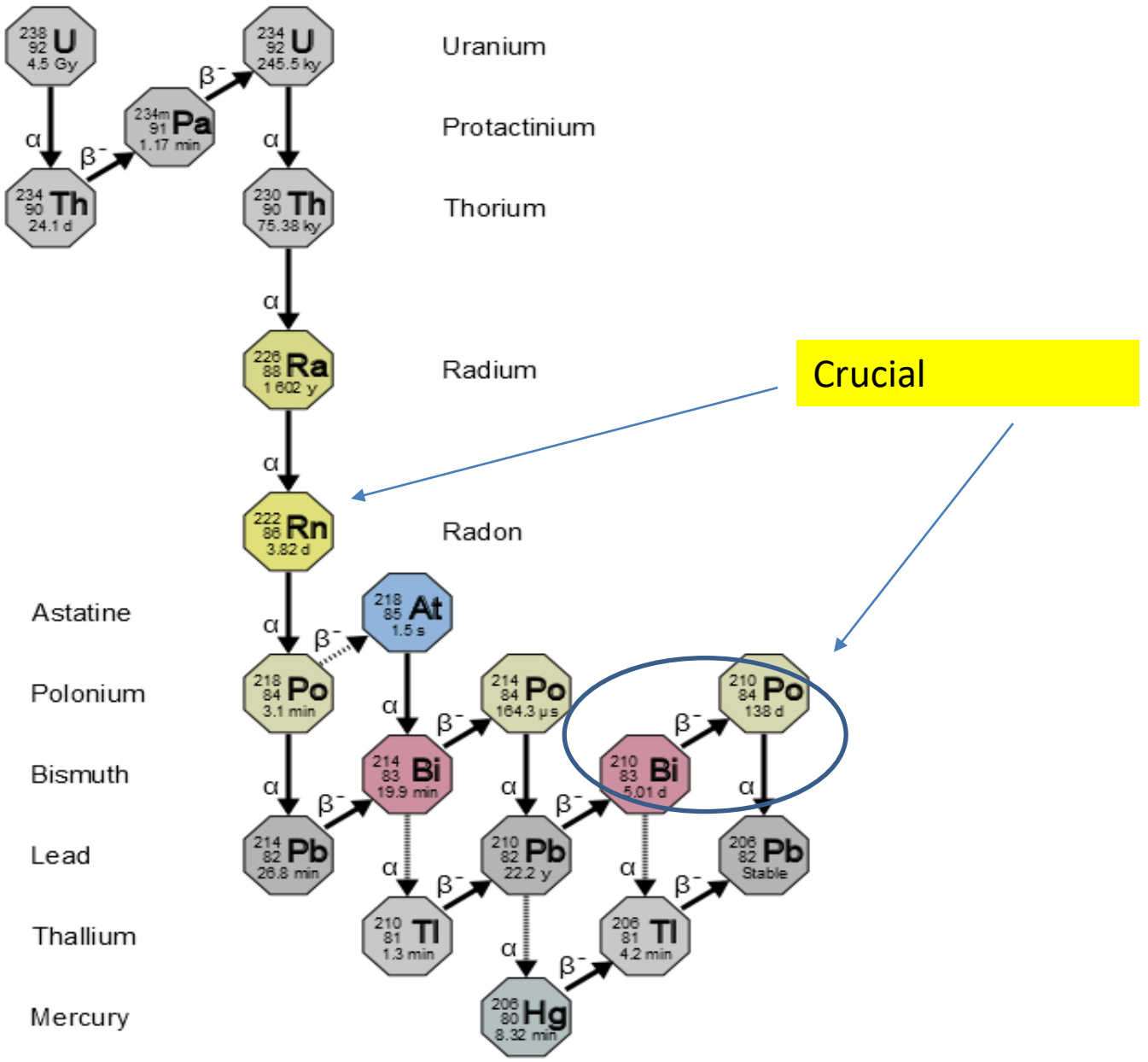
Initial Requirements

^{238}U and ^{232}Th 10^{-16} g/g

^{40}K 10^{-18} g/g

Measurement methodologies and approaches

- Gamma spectroscopy with low background germanium
- Mass spectroscopy for water
- CTF for the scintillator


238 92 U 4.5 Gy
234 92 U 245.5 ky
234m 91 Pa 1.17 min
234 90 Th 24.1 d
230 90 Th 75.38 ky
226 88 Ra 1 602 y
222 86 Rn 3.82 d
218 85 At 1.5 s
218 84 Po 3.1 min
214 84 Po 164.3 µs
210 84 Po 138 d
214 83 Bi 19.9 min
210 83 Bi 5.01 d
214 82 Pb 26.8 min
210 82 Pb 22.2 y
206 82 Pb Stable
210 81 Tl 1.3 min
206 81 Tl 4.2 min
206 80 Hg 8.32 min
α
β-
Uranium
Protactinium
Thorium
Radium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Mercury
Crucial

Radiopurity construction precautions

- **Detector and plants materials**
  - Low intrinsic radioactivity
  - Low radon emanation
  - Chemical compatibility with PC
  - Special 316 L stainless steel
- **Pipes, vessels and drums**
  - Electropolished
  - Cleaned with filtered detergents (Detergent-8, EDTA)
  - Pickled and passivated with acids
  - Rinsing with ultrapure water (class 20 – 50 MIL STD 1246)
- **Nylon vessel**
  - Good chemical and mechanical strength (small buoyancy)
  - Low radioactivity (Rn contribution < 1 count/day/100 tons of scintillator)
  - Construction in low ^{222}Rn clean room
  - High purity nitrogen storage
- **ETL photomultipliers 8'**
  - Low radioactivity Schott borosilicate glass (type 8246)
  - Dynode material carefully screened, in particular ceramics, as well as divider components
  - Screened aluminum for light concentrators
  - Screened mu-metal material for the individual shields against the Earth's magnetic field
- **Leak tightness**
  - Leak rate < 10^{-8} atm cc /s
  - Nitrogen blanketing on critical elements like pumps, valves, big flanges
  - Double seal metal gaskets
- **Clean rooms**
  - Mounting room in class 100
  - Inner detector in class 1.000
  - Outer detector in class 100.000

Scintillator

Solvent: Pseudocumene

Solute: PPO (1.5 g/l)

Light yield: ~11000 ph/MeV (approximate estimate)

Absorption length (@ 420 nm): 30 m

Scattering length (@420 nm): 7 m

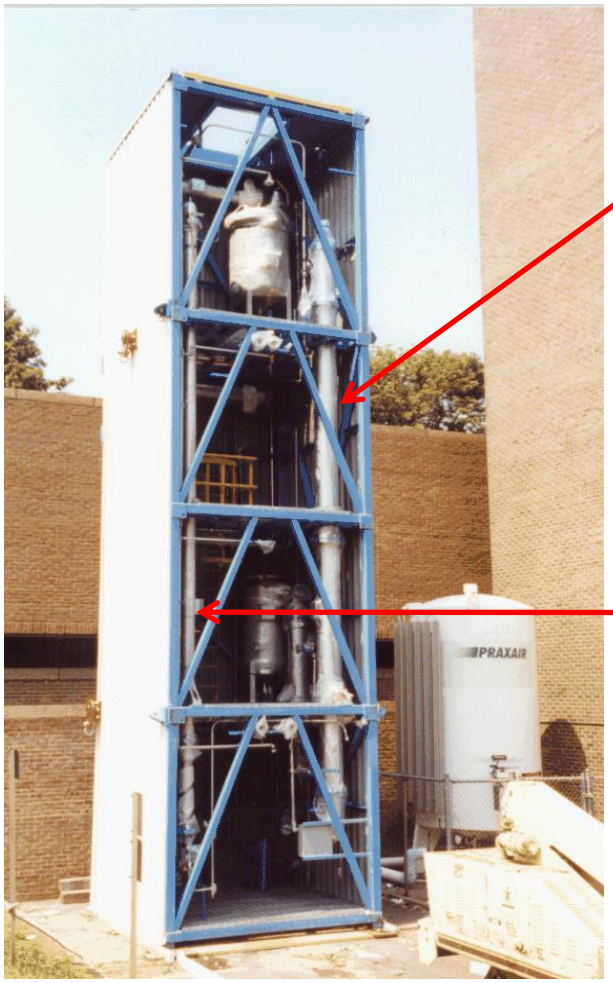
Decay time (fast component): 3.5 ns

Good α/β properties

Purification Procedures

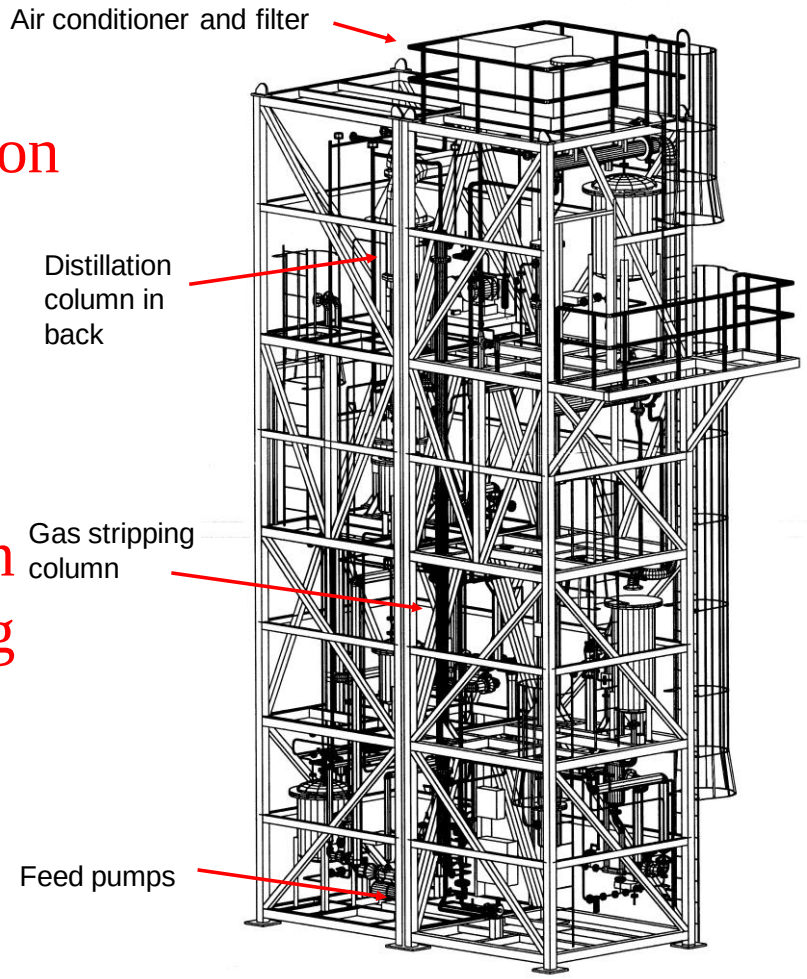
- **Filtration** - 0.05 μm teflon filters for removing particulate material.
- **Water Extraction** - Counter current contacting of scintillator with distilled water for removal of metal and ionic impurities.
- **Distillation** - Vacuum distillation of pseudocumene solvent for removal of low volatility species. Removes metal impurities and is the only proven procedure for improving optical clarity
- **Nitrogen stripping** - Counter current contacting of scintillator with nitrogen gas to remove dissolved water and gaseous impurities (e.g. Rn and Kr).
- **Fluor pre-purification** - Water extraction of concentrated solutions of PPO in pseudocumene for K removal.

Purification Skids

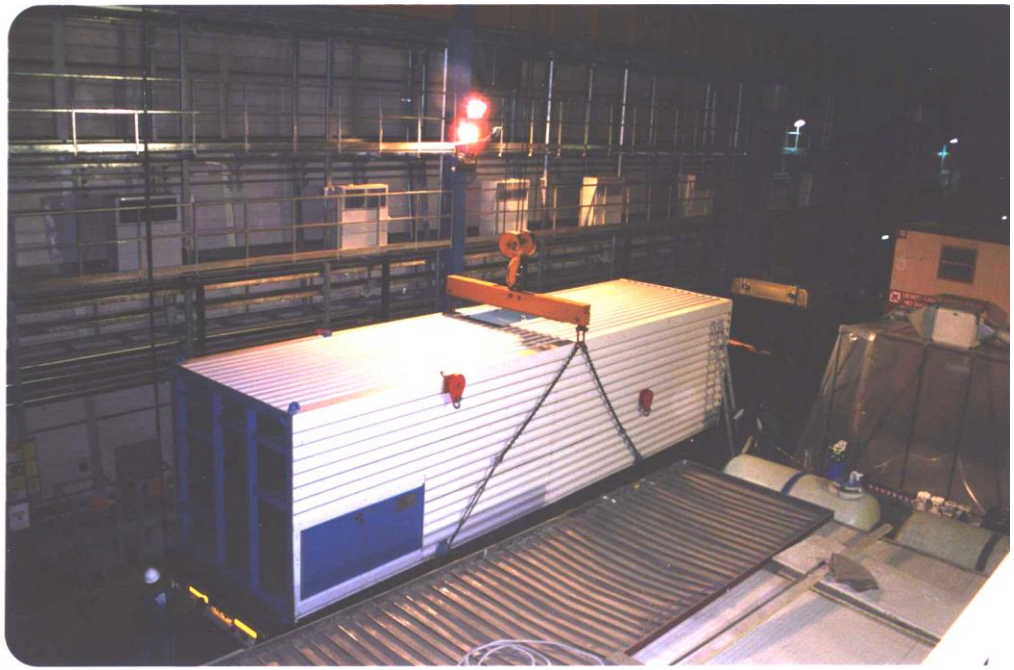


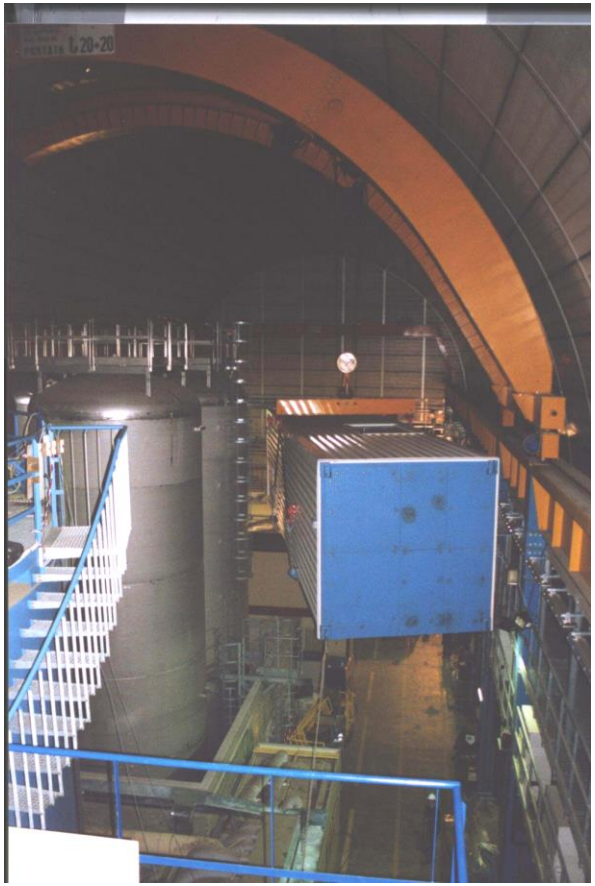
Water extraction column

Nitrogen stripping column



Installing Purification Skids in Hall C

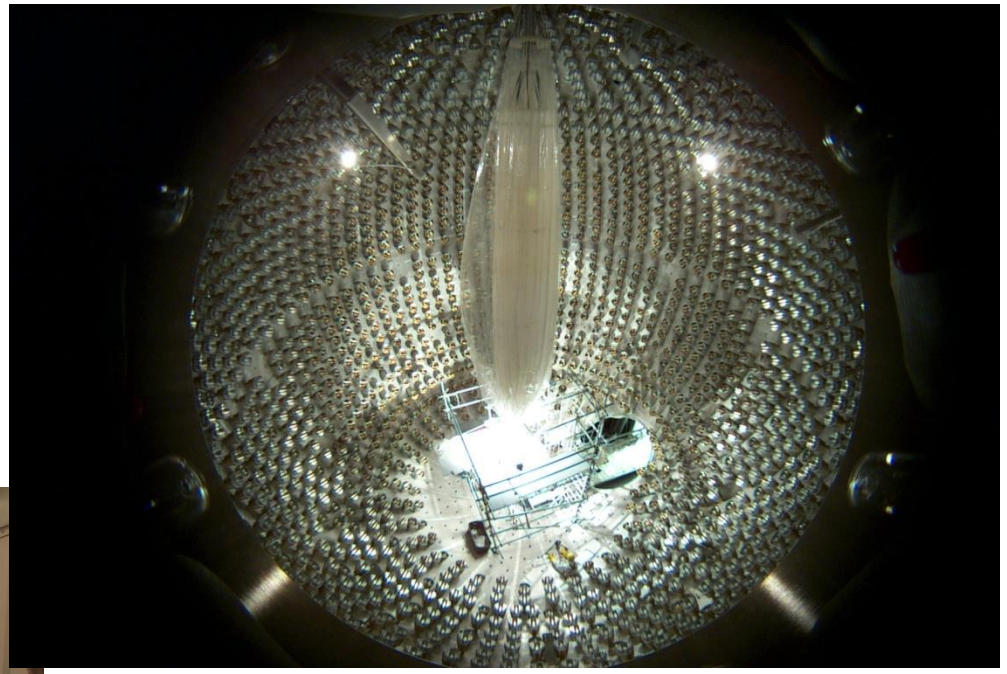




Skids were lifted and moved around storage vessels

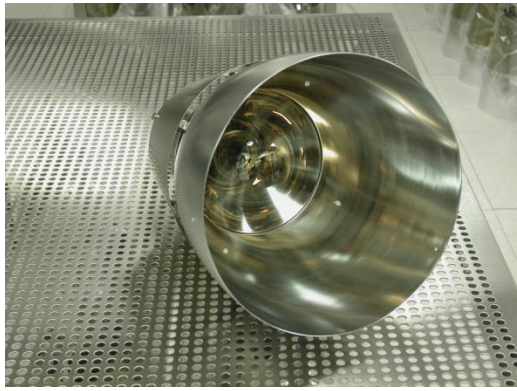
Nylon vessels

- **Requirements:**
  - Chemical compatibility with water and scintillator
  - Mechanical strength (20MPa – 5° ΔT)
  - Optical transparency (350-450 nm)
  - Low intrinsic radioactivity (U, Th, K)
  - Clean fabrication (<3 mg dust)
  - Low permeability ti Rn
  - Leak tightness



- **Solutions and results:**
  - Sniamid Nylon-6 film
  - 125 μm thick film
  - Index of refract. = 1.53 with >90% transmittance
  - U, Th less than 2 ppt (Rn < 1 count/day/100 tons
  - Humidification to decrease the T_g glass transition temperature (brittle state)

Photomultipliers



8” Electron Tubes Limited (ETL) 9351 type
P/V : 2.5 (measure of the single electron resolution)
Transit Time Spread: 1ns (σ)
Dark Count Rate: 1kHz (typical rate at 20 °C)
Afterpulsing < 5% (for single electron pulses)
Low radioactive glass and internal parts (main contributors to the external background)

Light concentrators

Truncated string cone design
Optimized to collect the light uniformly from the inner vessel and 20 cm beyond it while rejecting photons from outside
Material: anodized aluminum selected for low radioactivity
384 PMTs with no cones for muon identification in the buffer region

Electronics

ADC and TDC circuits
Good single electron resolution
Time resolution better than 0.5 ns

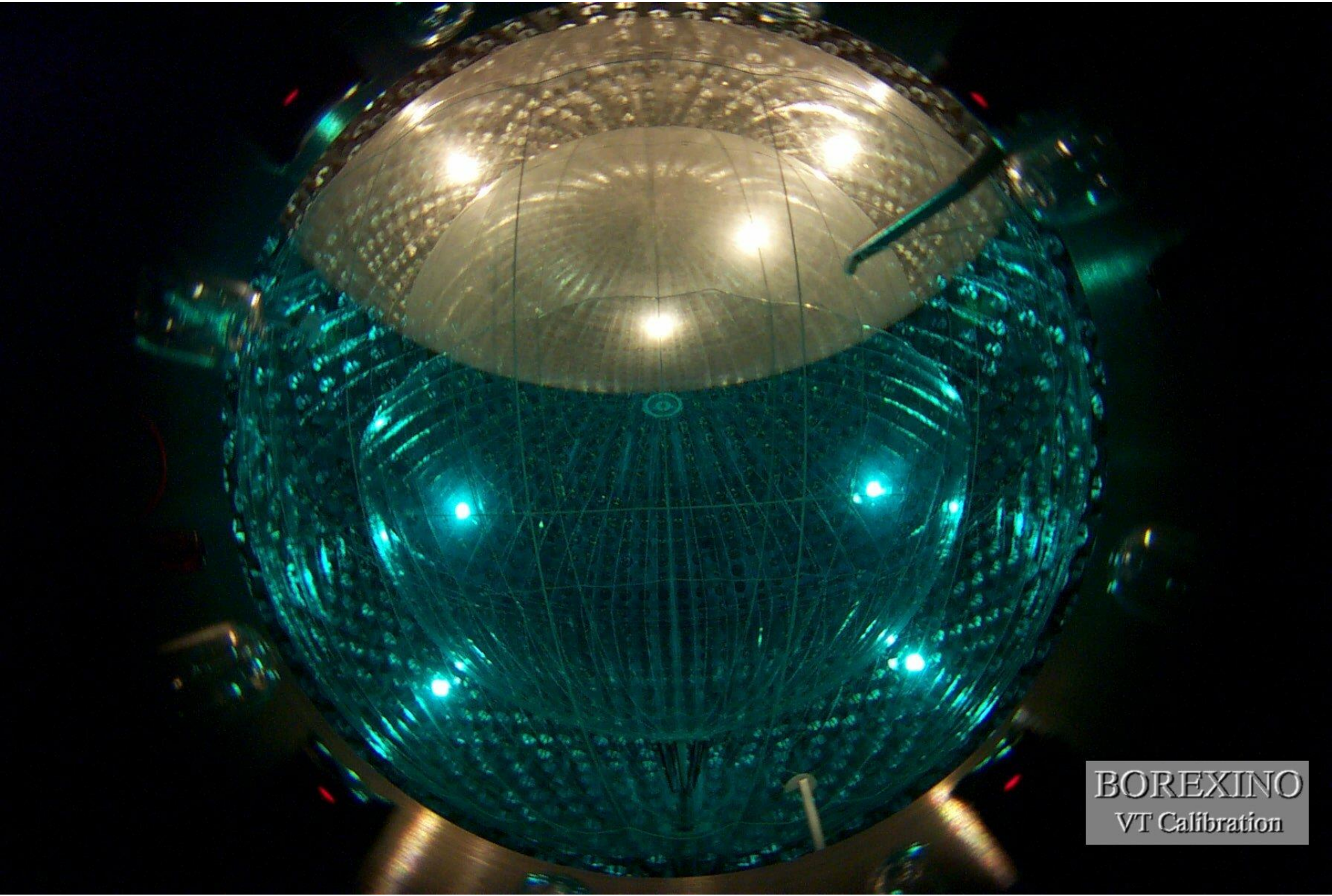
Nowadays the full waveform is recorded

Borexino Fluid Handling Operations

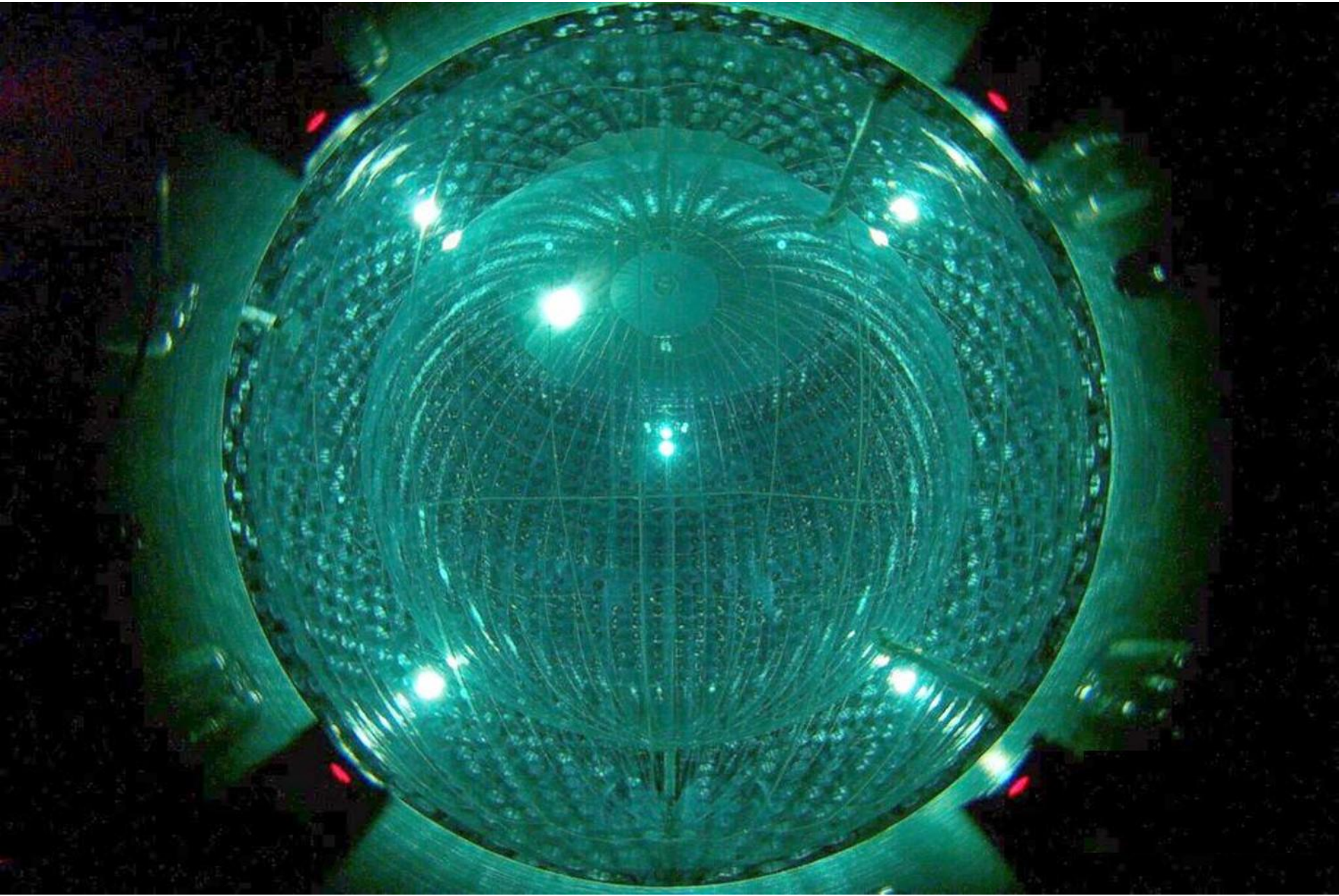
- Receiving scintillator components
  - Pseudocumene loaded at Sarroch into special transport Isotank
- Scintillator Preparation and Testing
- Borexino Detector Filling
  - Water filling
  - Scintillator filling
- On-line fluid level and pressure control
- Material Recovery and shutdown (ongoing now)


22T6
22T6
22T6
22T6

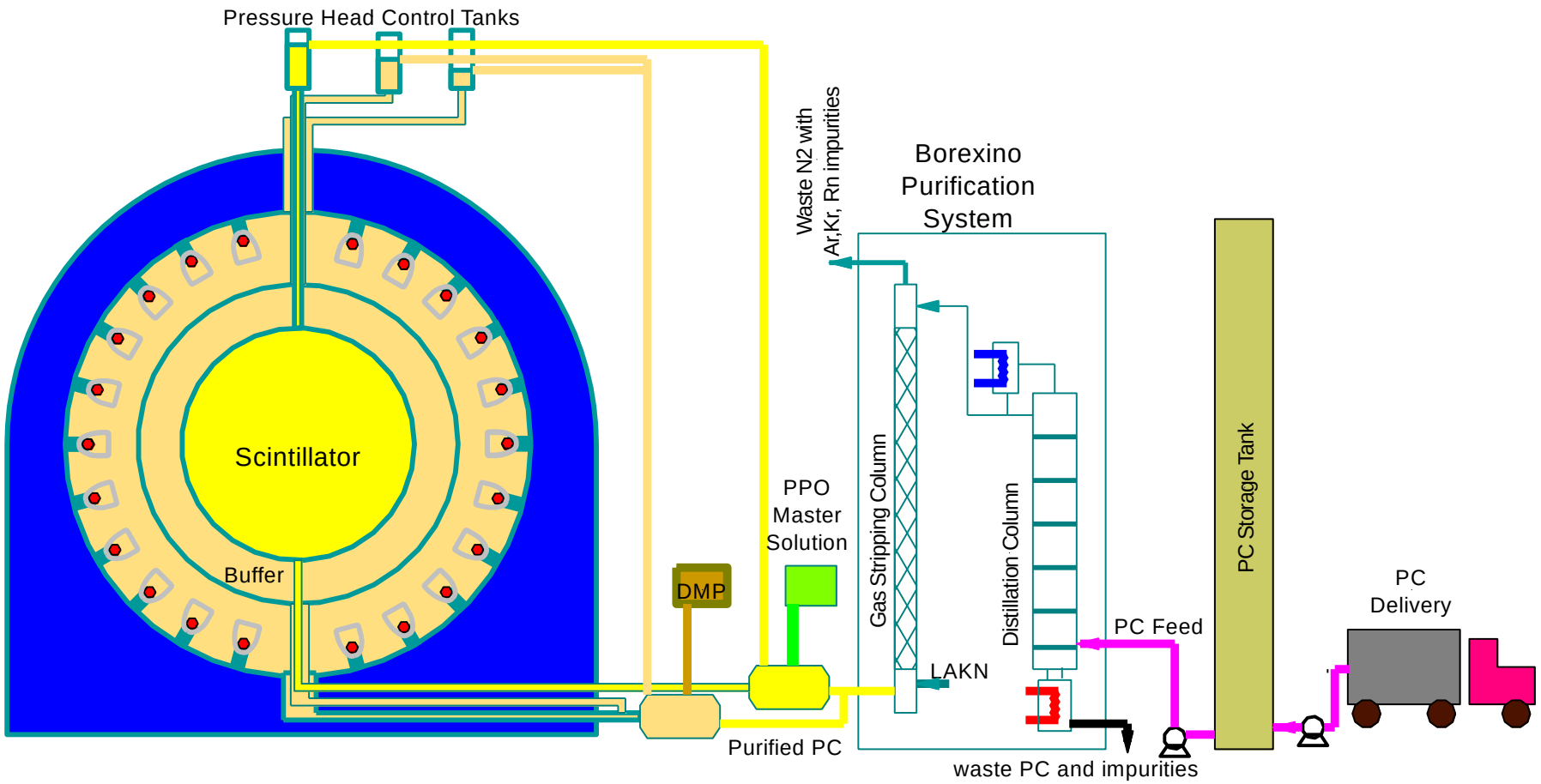
Preliminary water fill



Vessel completely full with water

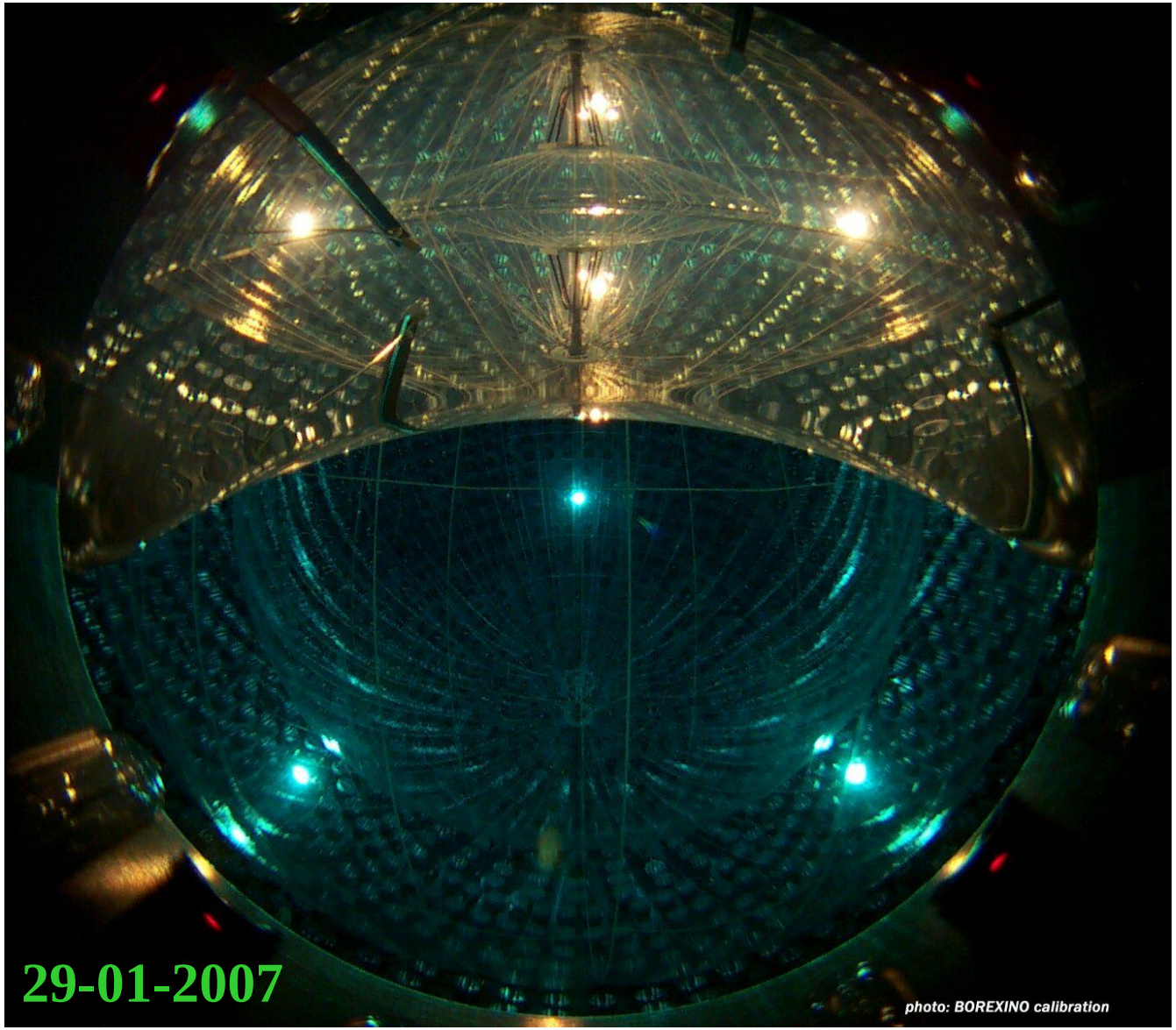


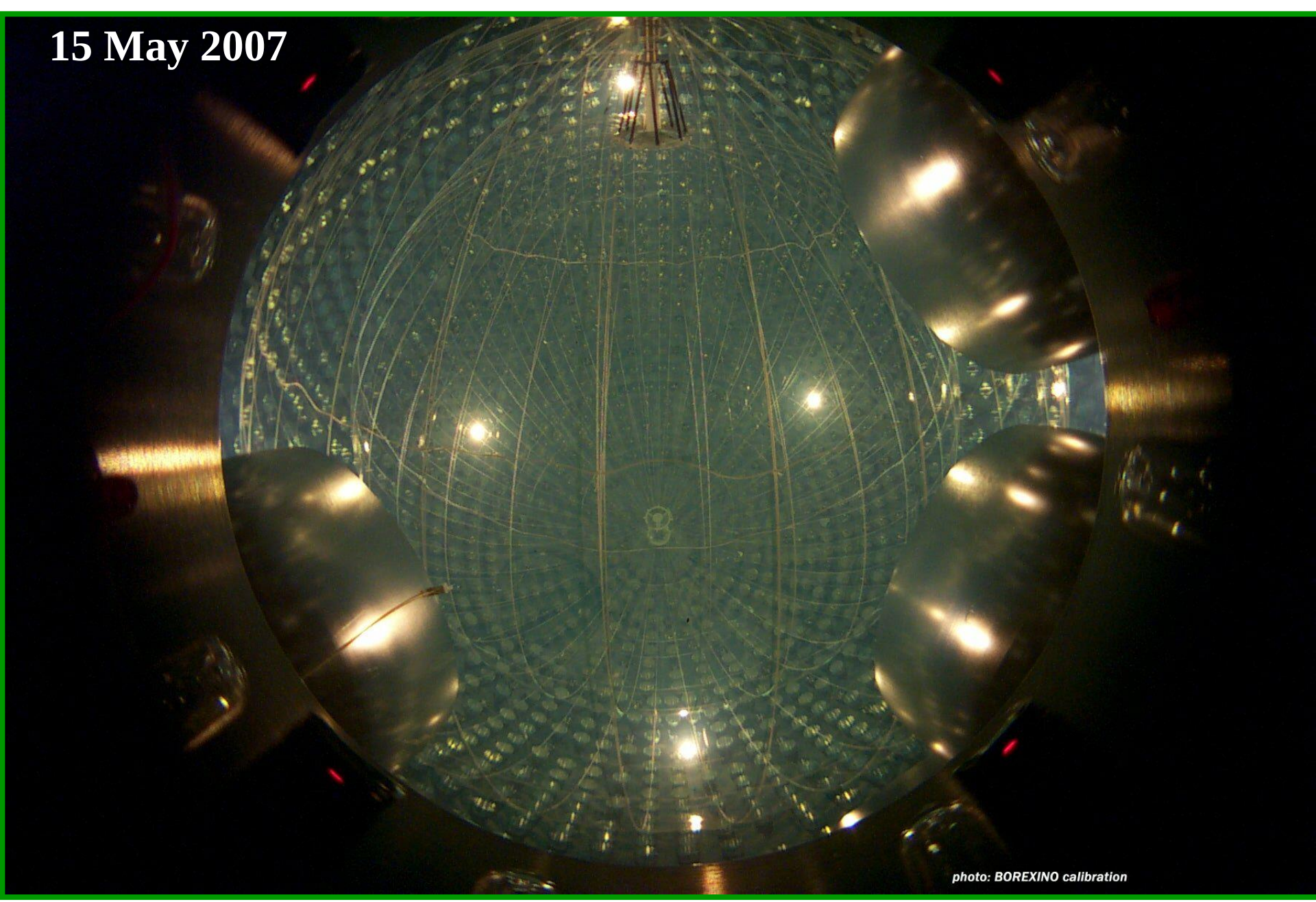
Scheme of detector scintillator fill with pseudocumene



Unloading of PC from isotank

PC nella SSS




15 May 2007
photo: BOREXINO calibration

Performances

Two categories

- Background -> residual internal/external radioactivity and muon rejection efficiency

- Measurement capabilities as extended scintillation counter
  - ❖ Light yield i.e. how many photons/MeV per deposit energy – threshold
  - ❖ Position resolution to locate the events within the active volume – definition of a fiducial volume
  - ❖ Energy resolution and linearity for adequate spectroscopy of the signal
  - ❖ α/β discrimination capability to suppress the residual alpha background

Output of the quest for the ultimate purity

Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final in phase I
Name	Source	Typical	Required	Hardware	Software	
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	$<10^{-10} s^{-1} m^{-2}$	underground water detector	Cerenkov PS analysis	$< 10^{-10}$ eff. > 0.99992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	$\sim 10^{-12}$ g/g	$\sim 10^{-18}$ g/g	selection	threshold	2.7×10^{-18} $^{14}C/^{12}C$
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	$<10^{-16}$ g/g	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	$5.35 \pm 0.5 \times 10^{-18}$ $3.8 \pm 0.8 \times 10^{-18}$ g/g
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	$<10^{-6}$ Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	$<10^{-18}$ g/g	distillation, W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		<1 c/d/t	distillation, W.E., filtration, cleanliness	fit	May '07: 70 c/d/t Jan '10: ~1 c/d/t
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	<10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	<1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	30 ± 5 cpd/100 t

May 2007 to May 2010

Threshold

20 times better than the design value

Bismuth-210 41.0±1.5±2.3 c/d/100t

U Th and K ok

Issue -> out of equilibrium ^{210}Bi and ^{210}Po , plus gaseous ^{85}Kr

Determined through the observation of the features of the scintillator signals

What it does mean to determine a background through the observation of the features of the scintillator signals

Example: ^{238}U content

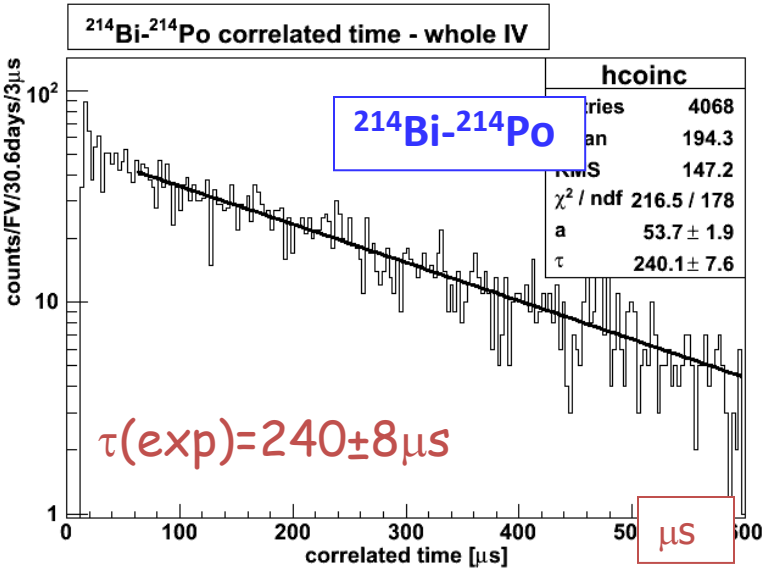
Assuming secular equilibrium, **^{238}U** is measured with the delayed concidence:

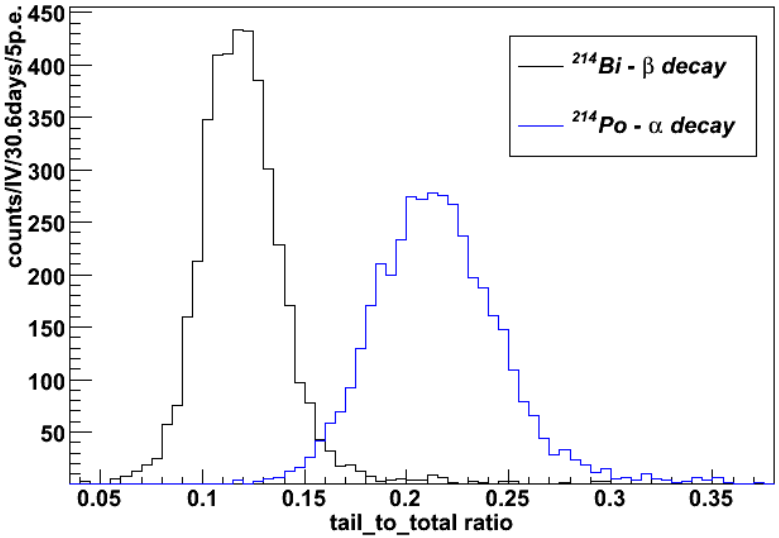
τ = 236 μs

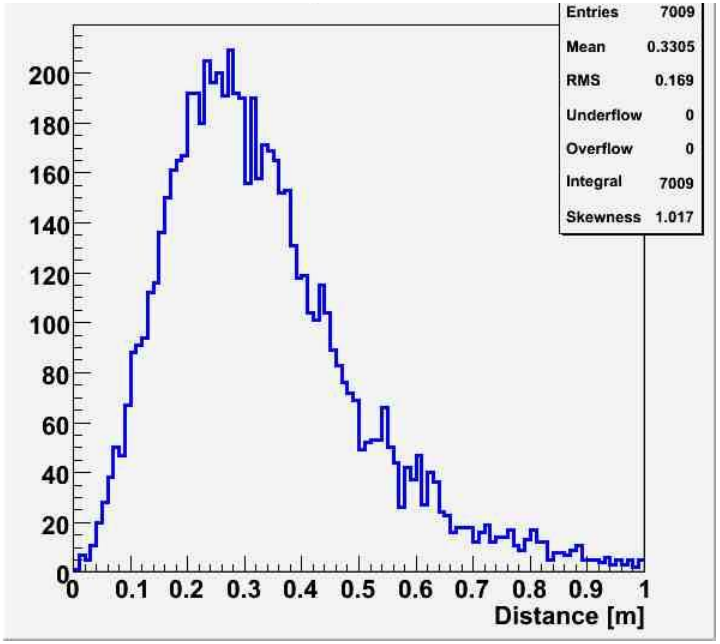
^{214}Bi $\xrightarrow{\beta}$ ^{214}Po $\xrightarrow{\alpha}$ ^{210}Pb

3.2 MeV

~700 KeV eq.







Purification after phase I – August 2010 to December 2011

Further data taking with improved **backgrounds** after the **online purification**

Th< **5.7 10^{-19}** g/g 95% C.L.
U < **9.4 10^{-20}** g/g 95% C.L.
Kr< 7.1 cpd/100 tons 95% C.L.

Purification (water extraction and nitrogen stripping) astonishingly effective in further reducing the already ultralow background Evaluated through the delayed coincidence tag

Only sizable residual backgrounds:

^{210}Po factor 100 less than at the beginning of data taking

^{210}Bismuth (**the most relevant)** factor 2 less than in phase I

Just after the purification - later ^{210}Po further decreased as effect of **decay (200 d τ)** and of the subsequent thermal stabilization which stopped the recontamination from the vessel **surface**

General validity for these kind of detectors: ^{210}Bi-^{210}Po out of equilibrium always present and may limit the sensitivity in the sub-MeV region

^{210}Po is an alpha emitter -> removable with PSD in a liquid scintillator
Because of its intrinsic high mobility ubiquitous present in rare events set ups especially on the surfaces

Takeaway from the Borexino experience about radiopurity of large underground liquid scintillator detectors

- U Th and K can be well beyond the specifications and further removed with purification
- Transient out of equilibrium ^{222}Rn gas a concern, but manageable
- Gaseous ^{85}Kr removable with nitrogen selection and stripping
- Low energy sub-MeV limit mainly from residual ^{210}Bi, ^{210}Po not a real concern because PSD (**important: this may not be true for other techniques**)
- Intrinsic ^{14}C dictates the low energy limit for physics measurements abut 120 keV
- Surface treatments and cleanliness of the construction environment crucial

All in all, a thorough strategy encompassing

- Selection of materials including nitrogen
- Cleanliness of surfaces
- Purification of the scintillator and of water
- and a fill procedure that does not spoil the key elements above

$\rightarrow$can result in a very ultra pure environment in the inner core of the detector

Measured quantities

The electronics measures and provides for each triggered event:

- The photomultipliers pulse height

→ energy measurement

- The photoelectrons arrival times (better than 0.5 ns precision)

→ position identification

- The absolute time of the event

Expected detector perfomances

Effective coverage 30% (by design, it depends upon the concentrator)

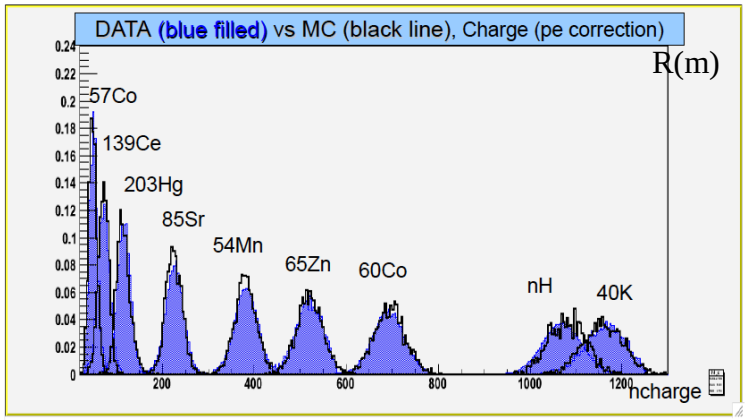
Photoelectron yield 500 pe/MeV

Energy resolution @ 1 MeV 5% mainly driven by the Poisson statistics of the detected photoelectrons - relative resolution $\propto 1/\sqrt{N}$

Position resolution @ 1 MeV 10 cm

How to cross check: calibration

Very convenient and easy to use→ γ sources
Self made radon sources → radon in a scintillator vial
AmBe as neutron source



Energy scale-Resolution

$\frac{5\%}{\sqrt{E}}$ from 200 keV to 2 MeV

Beyond 2 MeV: γ from n capture on C and H

@ MC tuned on γ source results

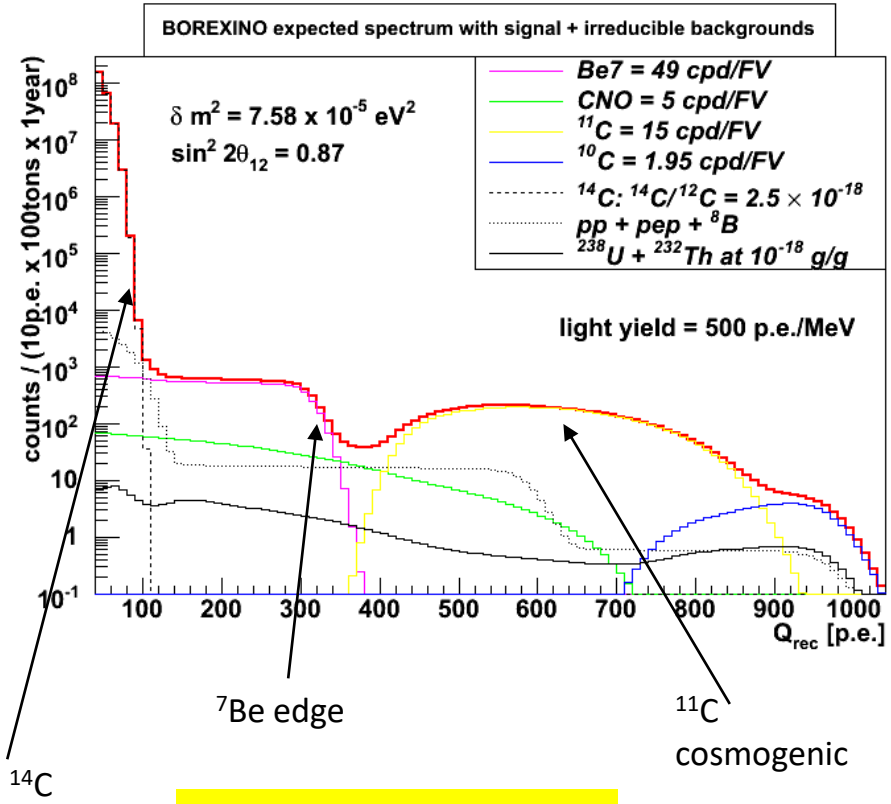
@ Determination of Light yield and of the Birks parameter k_B
L.Y. → obtained from the γ calibration sources with MC: **~ 500 p.e./MeV**
→ left as free parameter in the total fit in the analytical approach

@ Precision of the energy scale global determination: max deviation **1.5%**

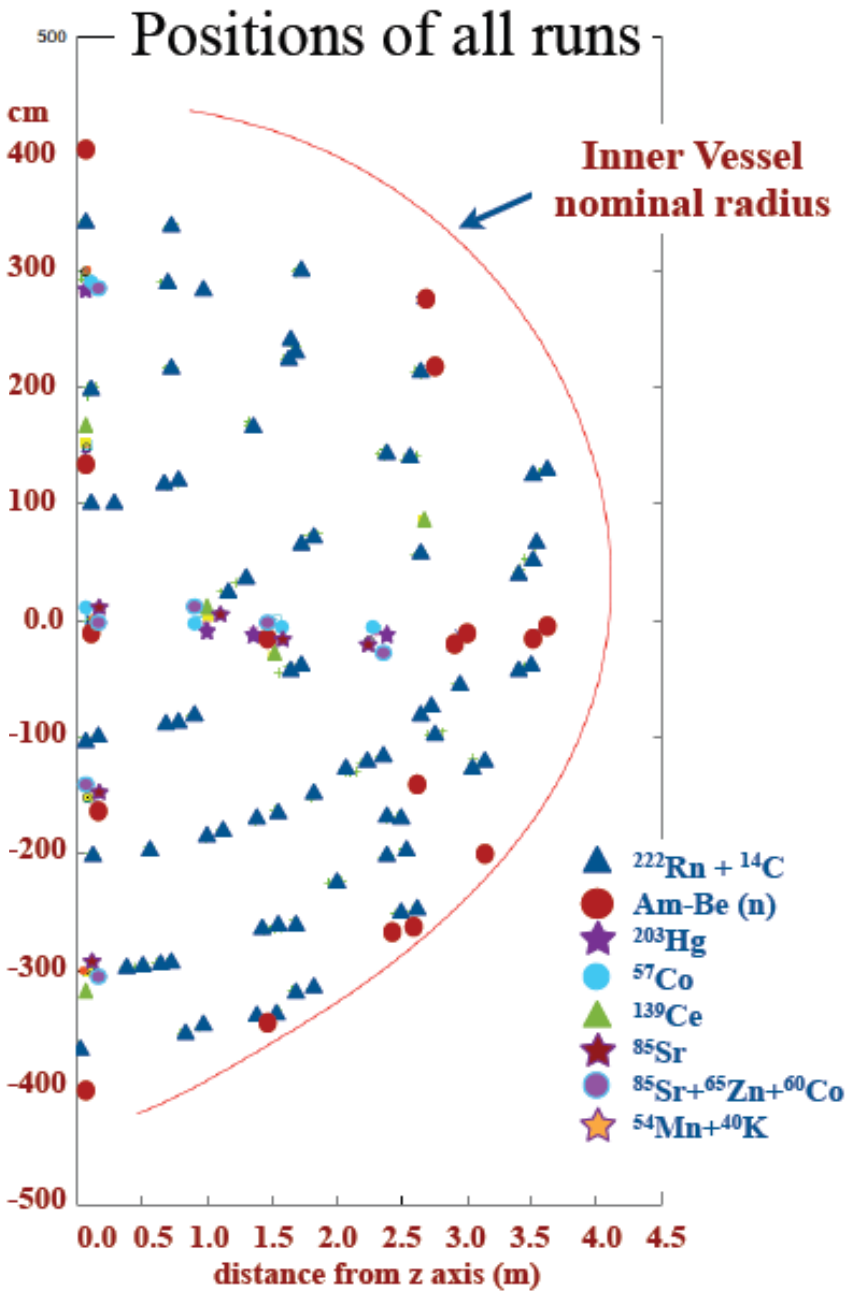
@ Fiducial volume uncertainty: $^{+0.5}_{-1.3}\,\%$ (1 σ) (radon sources)

Optimum agreement with the expectations

MC prediction of signal + intrinsic Background



Main visible features

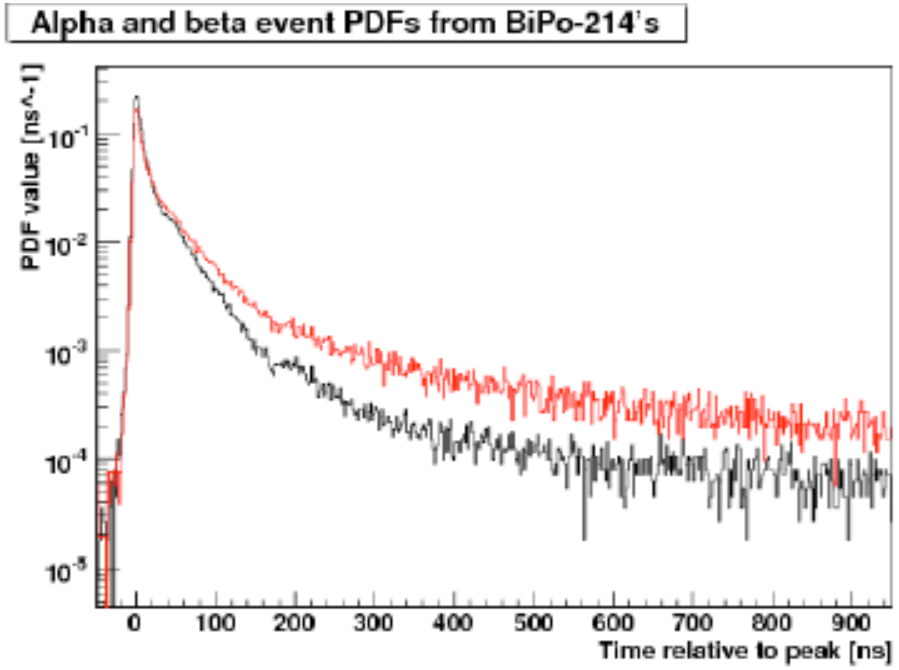


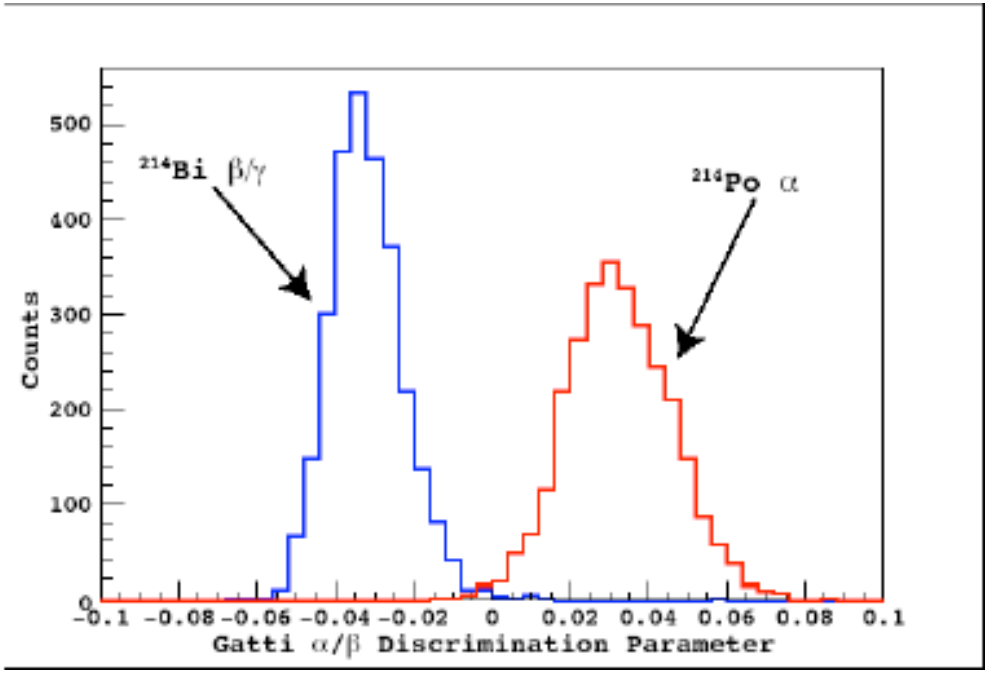
α/β Discrimination Calibration

Different discrimination methods
Tail-to-total linear processing via so called Gatti method neural network like approach

Calibrated with intrinsic radon and following daughters especially ^{214}Bi and ^{214}Po

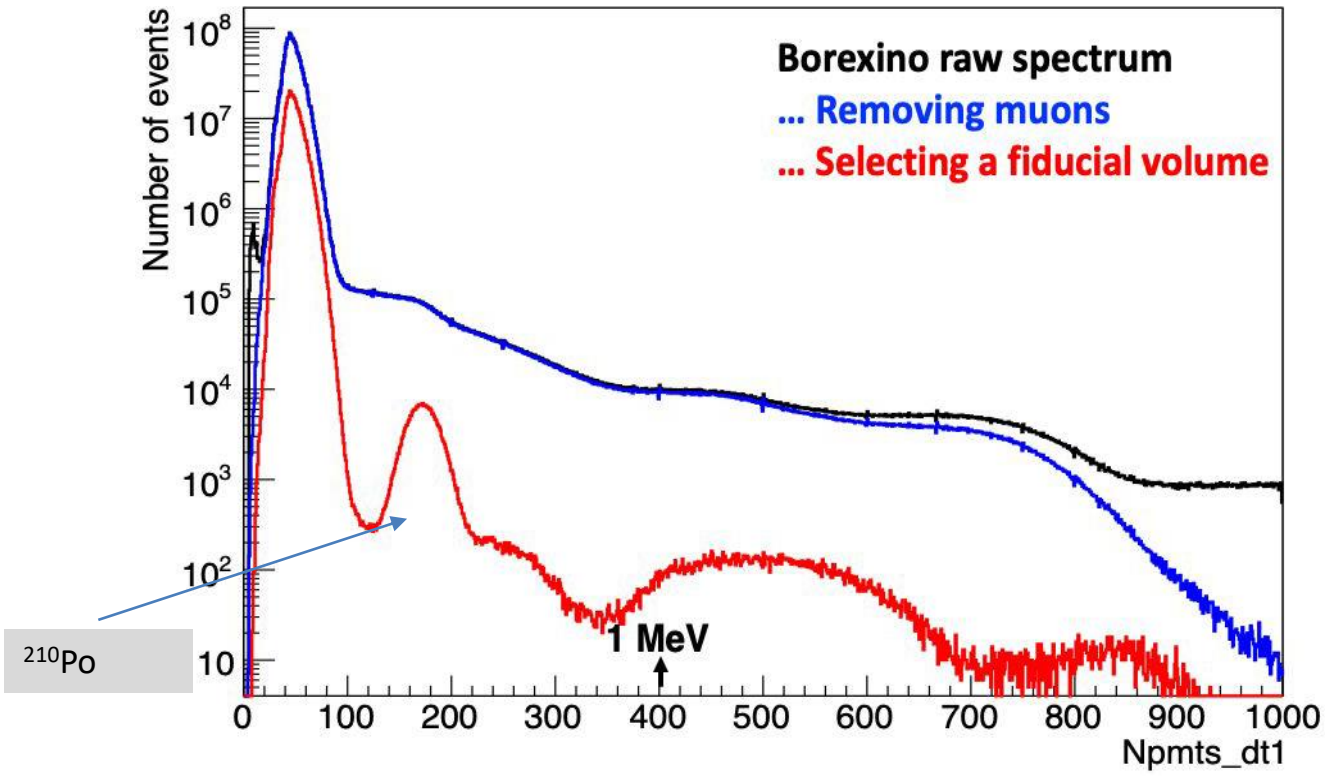
Efficiency energy dependent and MC modeled - about 95% for ^{214}Po alpha @ 7.8 MeV





This analysis for the reference curves has been done during the filling period, when ^{222}Rn was present

Actual data histogram



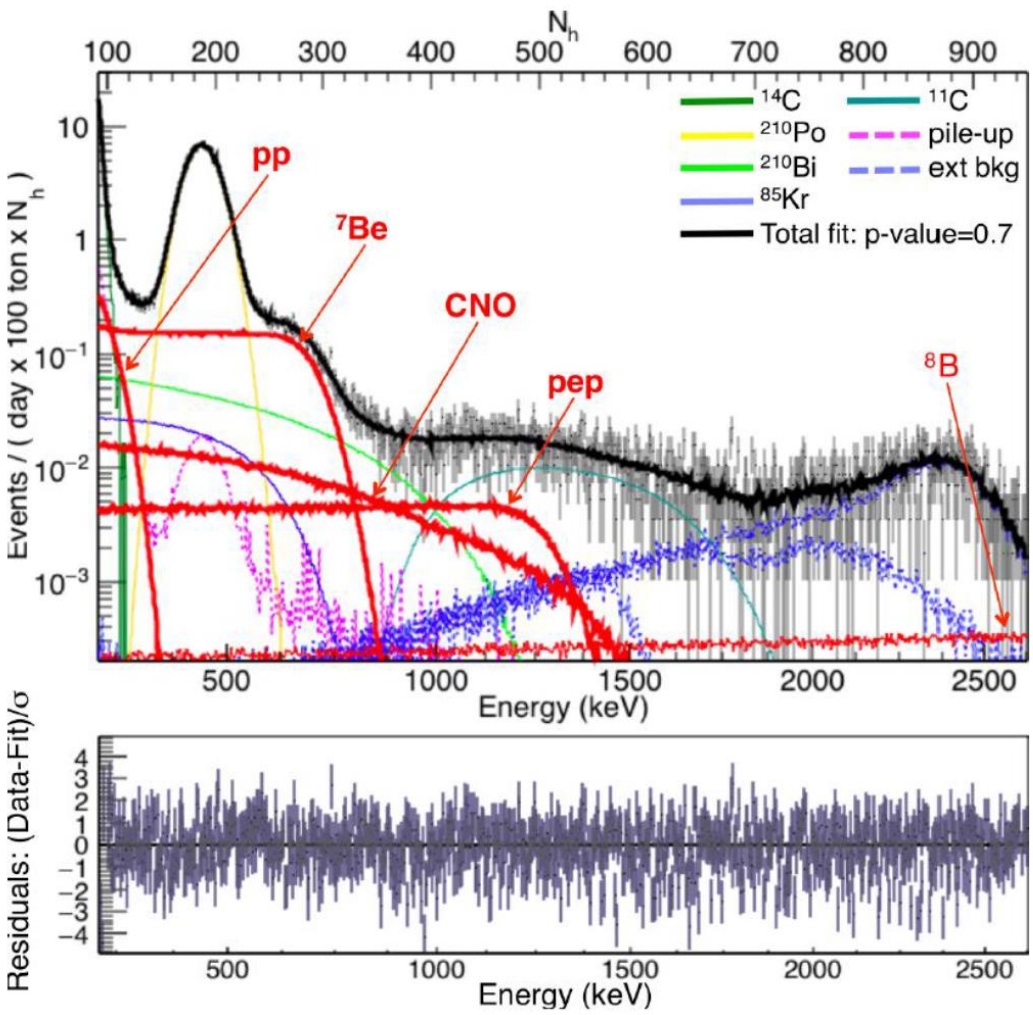
The same features noted in the MC spectrum plus the ^{210}Po out of equilibrium peak

This agreement indicates the very good job done with the Mc modeling and the calibrations

Even at the Borexino very high radiopurity conditions, we still have background events contaminating our solar neutrino signal and we need to apply software cuts to data, in order to remove as much background as possible. Furthermore, we need a powerful tool to separate the signal from the residual background components -> **fit to a signal + background model**

Phase II data simultaneous low energy spectroscopy data-to-model fit

Nature, Volume 562, pp. 505-510 (2018) and Physical Review D, Volume 100, Issue 8, id.082004 (2019)

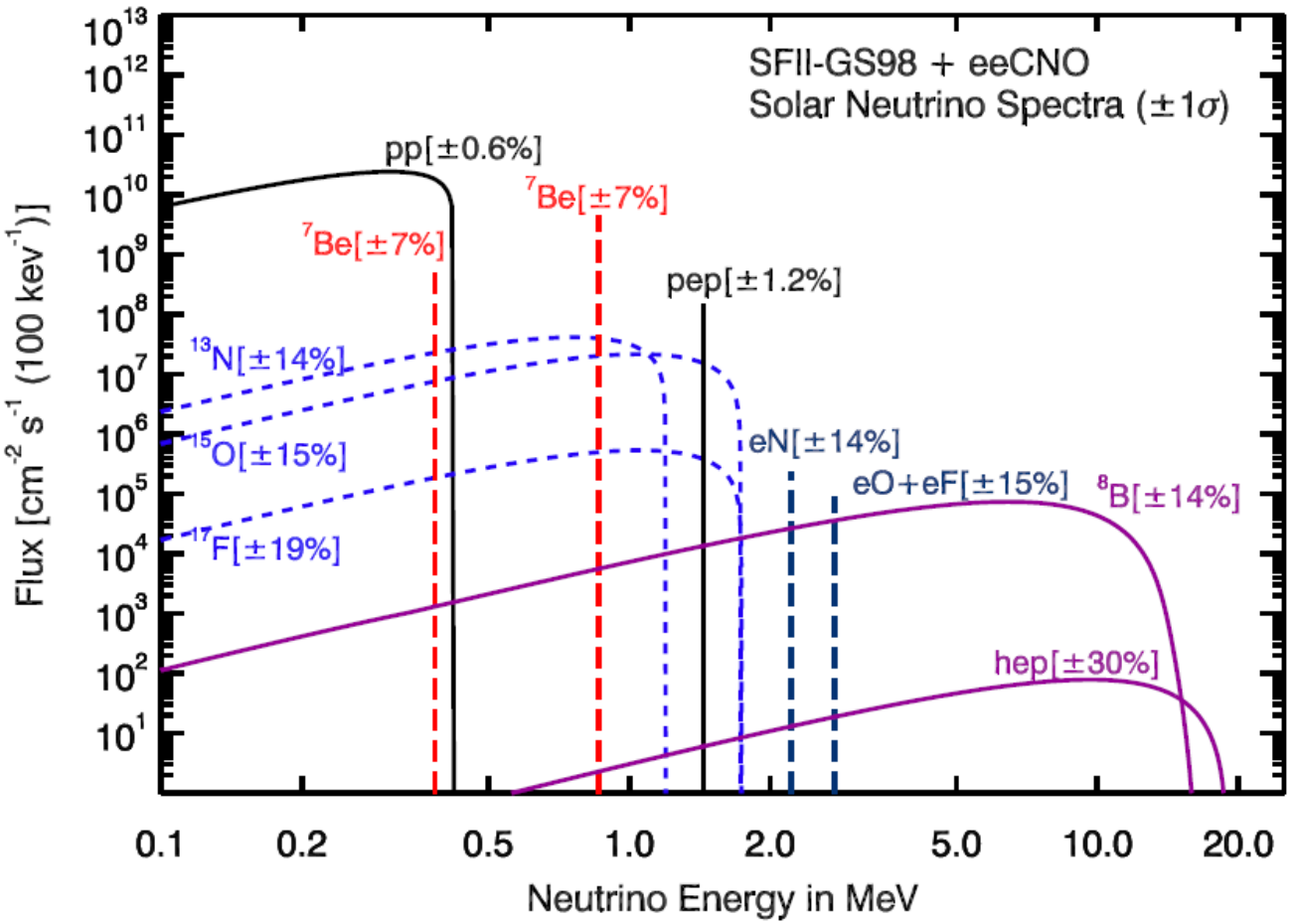


Example of how the amplitude distribution of the scattered electron signals is fit to a signal + background model in Borexino - similar approach in any large scintillator detector – the model can be MC or analytical

From the fit the flux rate of each component is inferred

The background model is obtained through the extensive studies outlined before

Signal model – theoretical input



Predicted neutrino spectra from a **Standard Solar Model**

Used for the electron signal model in the detector response via the quantification of the scattering process off the electrons of the scintillator

Two sequences of reactions postulated in the Sun

pp chain

CNO cycle

Main achievements of Borexino

Astroparticle physics

Full spectroscopy of the neutrinos coming from the two sequences of nuclear reactions occurring in the core of the Sun

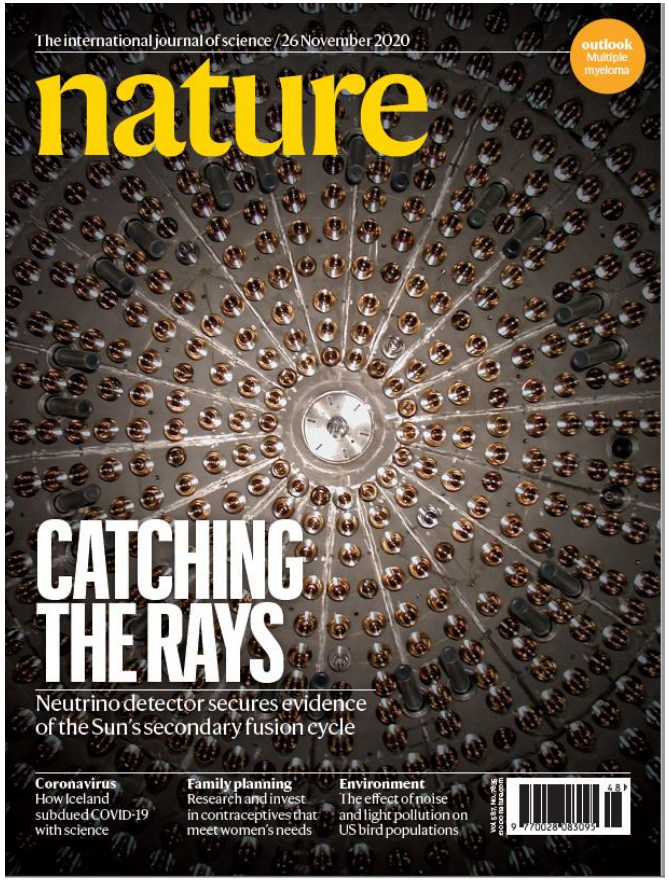
- **pp chain** – first detection ever of the separated low energy components
- **CNO cycle** – first detection ever of this flux

Particle physics – neutrino oscillations

Confirmation of the energy dependent neutrino oscillation phenomenon via the so called MSW (Mikheyev, Smirnov and Wolfenstein) effect - vacuum flavor conversion altered by the interaction of neutrinos with the matter's electrons / Sun and Earth

Moreover

Geoneutrinos – antineutrinos from Earth via IBD reaction (see later and Francesco talk) less demanding for background



For reference: Compendium of Borexino results

New pp, ^{7}Be, pep results of the analysis of Phase II data

	Borexino results cpd/100t	expected HZ cpd/100t	expected LZ cpd/100t
pp	$134 \pm 10^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.4
^{7}Be(862+384 KeV)	$48.3 \pm 1.1^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05

	Borexino results Flux ($cm^{-2}s^{-1}$)	expected HZ Flux ($cm^{-2}s^{-1}$)	expected LZ Flux ($cm^{-2}s^{-1}$)
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \, 10^{10}$	$5.98 \, (1\pm 0.006) \, 10^{10}$	$6.03 \, (1\pm 0.005) \, 10^{10}$
^{7}Be(862+384 KeV)	$(4.99 \pm 0.13^{+0.07}_{-0.10}) \, 10^{9}$	$4.93 \, (1\pm 0.06) \, 10^{9}$	$4.50 \, (1\pm 0.06) \, 10^{9}$
pep (HZ)	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \, 10^{8}$	$1.44 \, (1\pm 0.009) \, 10^{8}$	$1.46 \, (1\pm 0.009) \, 10^{8}$
pep (LZ)	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \, 10^{8}$	$1.44 \, (1\pm 0.009) \, 10^{8}$	$1.46 \, (1\pm 0.009) \, 10^{8}$

Phys. Rev. D **101**, 012009 – 2020
Geo-neutrinos

Nature, Volume 562, pp. 505-510 (2018) and Physical Review D, Volume 100, Issue 8, id.082004 (2019)

Beginning of the precision era in the study of low energy solar neutrinos
^{7}Be precision 2.7%

$^{8}B = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)$ cpd/100 t.

Expected 0.211 ±0.025 cpd/100t

^{8}B flux =2.55 ±0.18±0.07 x10^{6} cm^{-2} sec^{-1}

PHYSICAL REVIEW D 101, 062001 (2020)

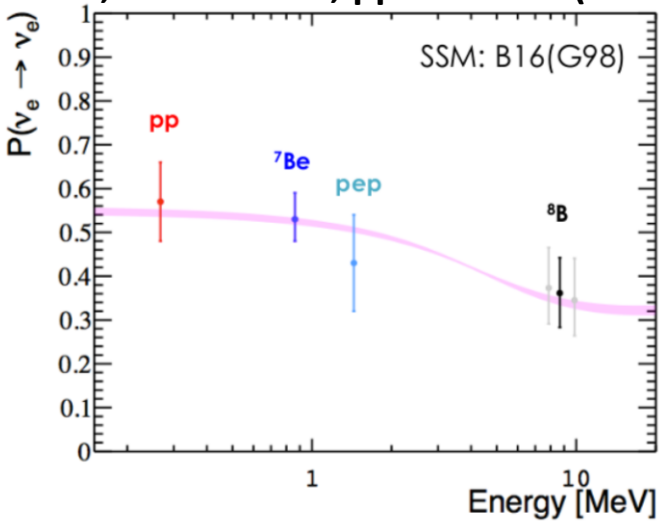
CNO = 6.7 $^{+2.0}_{-0.8}$ cpd/100t

CNO flux 6.6 $+^{2.0}_{-0.9}$ ×10^{8} cm^{-2} s^{-1}

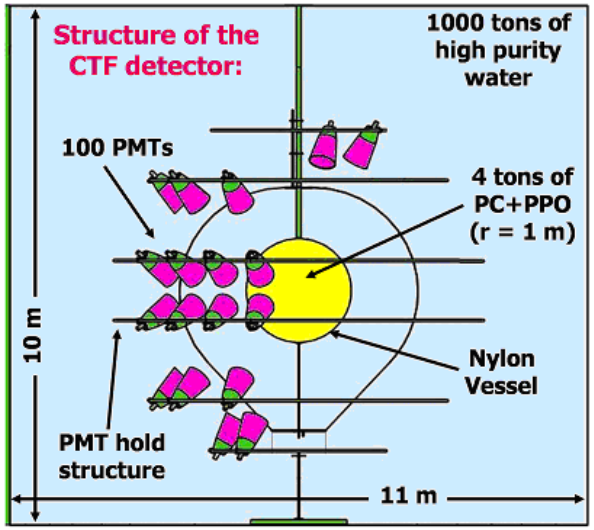
arXiv:2205.15975

MSW proof

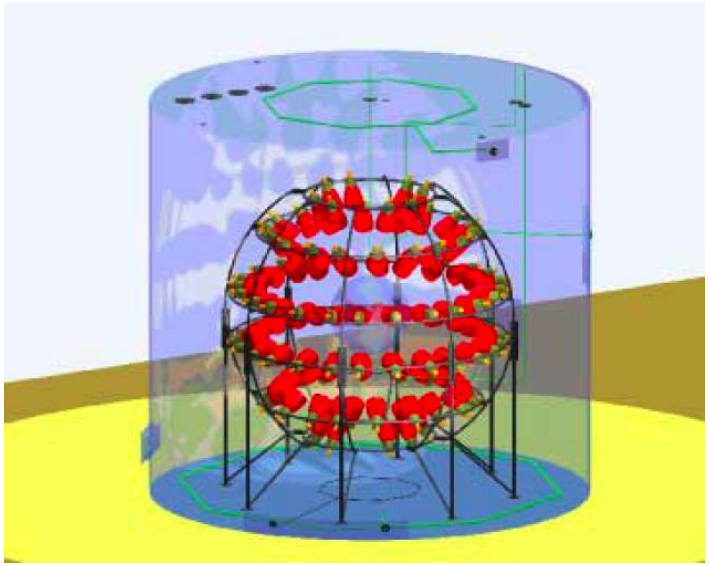
Nature, Volume 562, pp. 505-510 (2018)



Sometimes a prototype detector to test the technologies and prove the feasibility – this was the role of CTF for Borexino



The concept

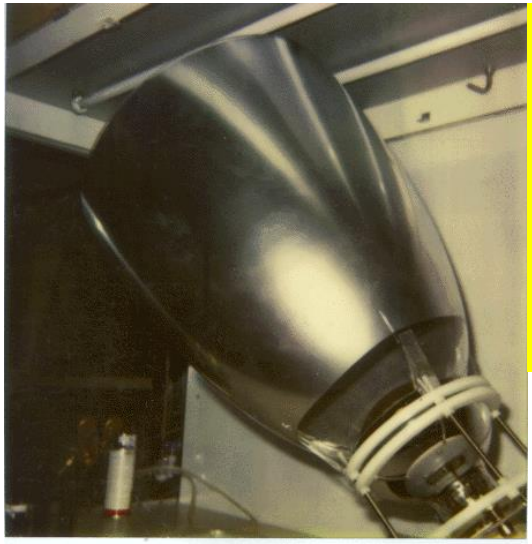


The implementation

You may recognize the similarity with the SOUP image……

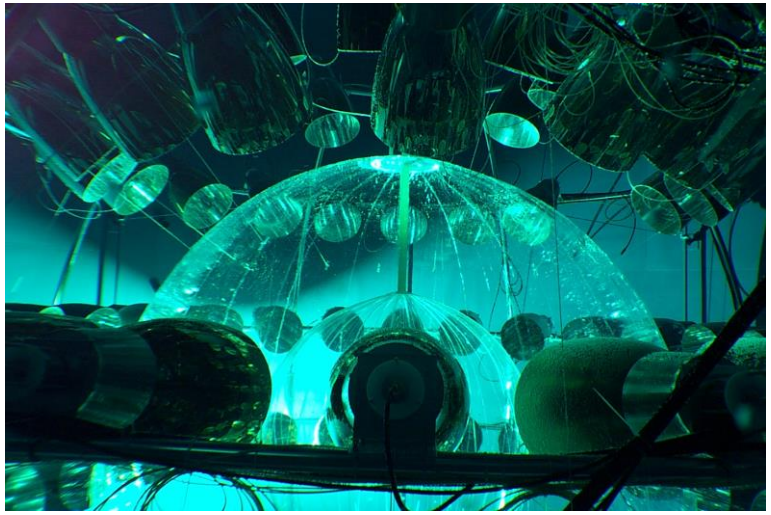
Other equipment

The tank in Hall C – still there surrounded by the Borexino equipment



A CTF concentrator note the difference with that of Borexino

Second vessel with outer barrier



The steel structure now !

CTF: most important results and activities

- **First measurement in a liquid scintillator of ^{238}U, ^{232}Th e ^{14}C radiopurity level; at that time a real *"breakthrough"* in the field of ultra pure material;**

- **Identification of the specific background issues of ^{85}Kr and ^{210}Po;**

- **Investigation of removal and purification techniques : water extraction, nitrogen stripping, distillation, alpha-beta discrimination;**

- **Large scale quality check of optics and radiopurity of the scintillator to be used for the Borexino fill;**

- **check of the operational properties and of the compliance to the specifications of the filling stations and of the purification set-ups: distillation and water extraction plants.**

Pilot fish of Borexino!

The next frontier of large LS underground detectors - JUNO

- **LS large volume: ➔ for statistics**
- **High Light(PE) ➔ for energy resolution 1200 pe/MeV**

Both crucial for the physics capabilities

Steel Truss to support the acrylic and hold PMTs

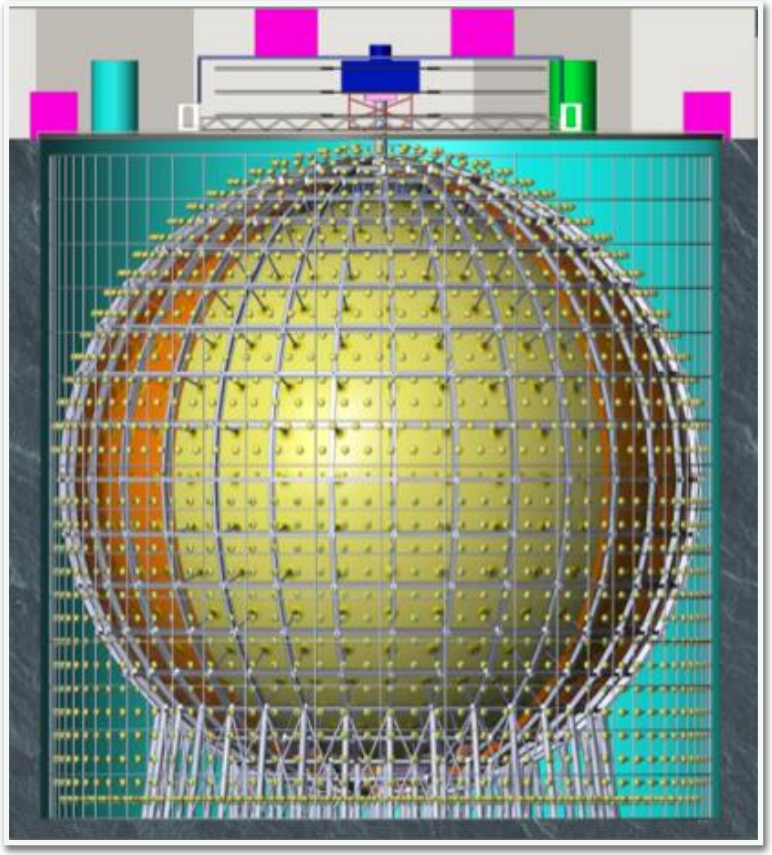
~20000 x 20”

18000 Inner

2000 veto

~25000 x 3”

Acrylic Sphere filled with 20 kt LS



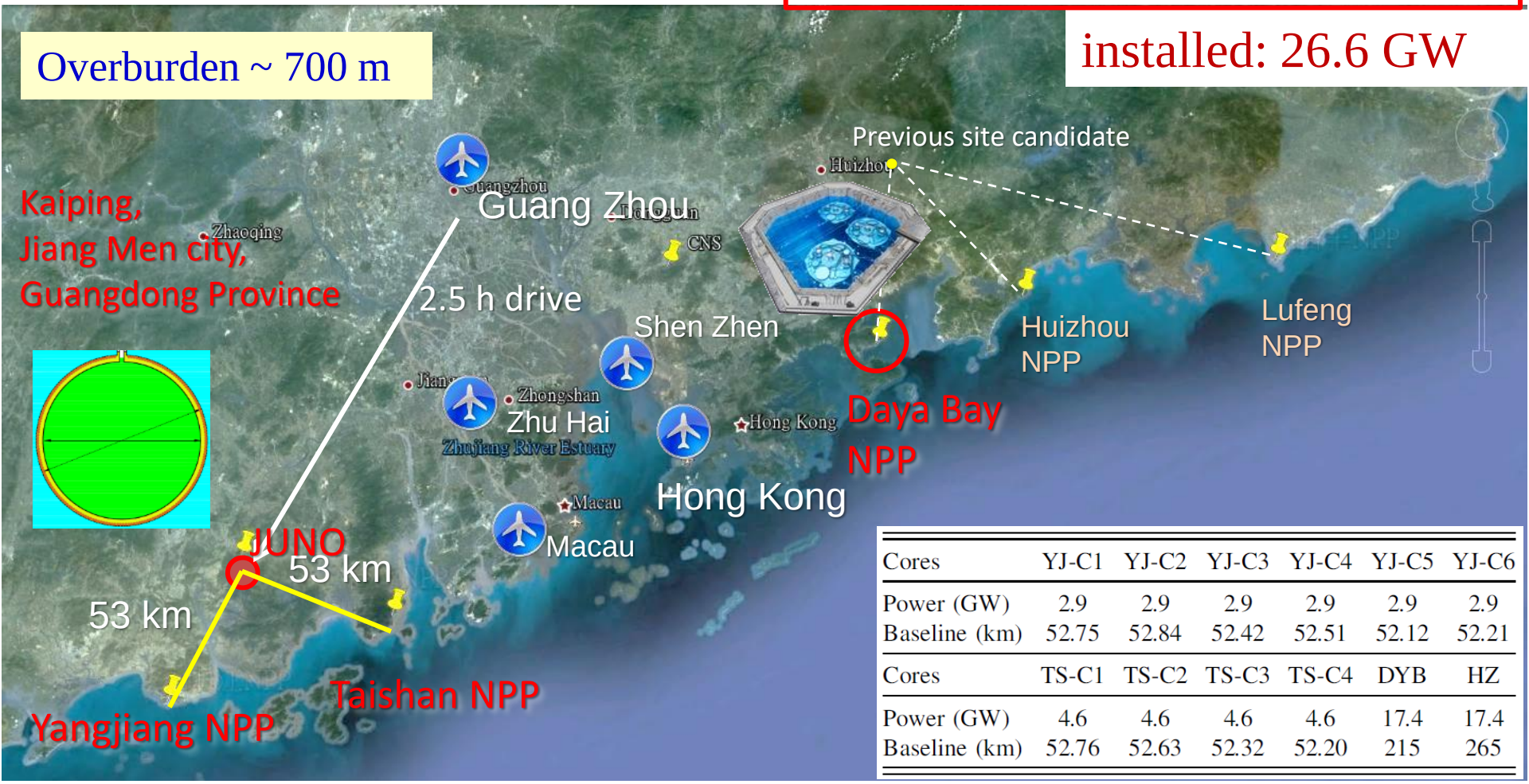
JUNO has been approved in China in Feb. 2013 – under construction

Participation and contributions from several other countries:

- **Armenia**
- **Belgium**
- **Brazil**
- **Chile**
- **Czechia**
- **Finland**
- **France**
- **Germany**
- **Italy**
- **Latvia**
- **Pakistan**
- **Russia**
- **Slovakia**
- **Taiwan**
- **Thailand**
- **USA**

Antineutrino beams from reactors at medium distance

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	6 built	2 built + 2 future
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



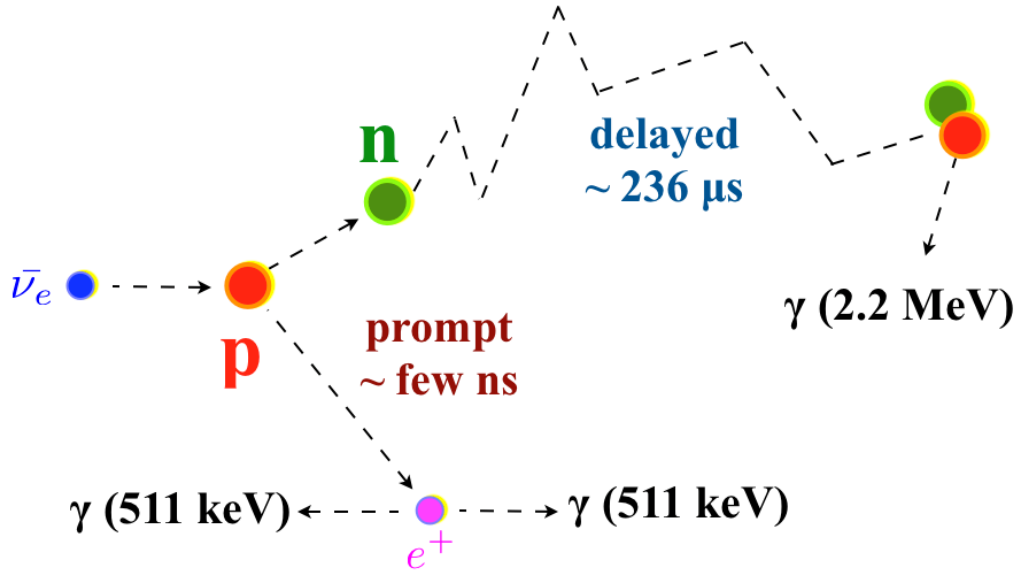
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Antineutrino detection

Detection through the classical inverse beta decay reaction

Reaction used by Cowan and Reines for the first (anti)neutrino observation at the Savannah River experiment

$$\bar{\nu} + p \rightarrow n + e^{+}$$ E_ν>1.8 MeV



The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The "observable" for the antineutrino studies is the positron spectrum
It results that $E_{vis}(e^+)=E(\nu)-0.8$ MeV

Physics of JUNO

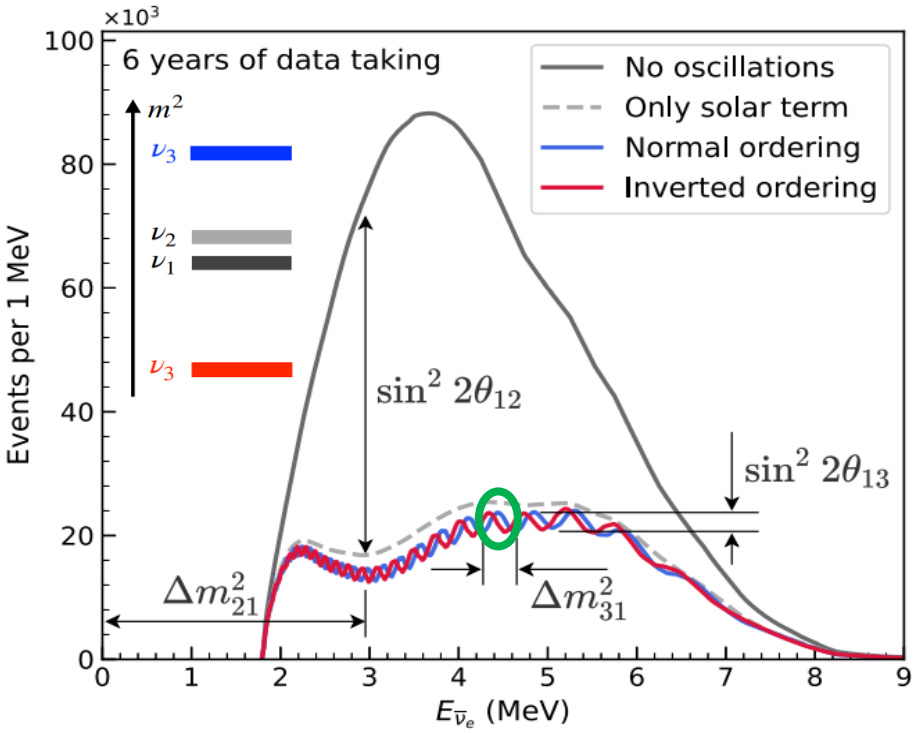
- Determination of the neutrino mass hierarchy with a large mass liquid scintillation detector located at medium distance – 53 km – from a set of high power nuclear complexes
- Precise measurements of neutrino oscillation parameters

IBD

- Vast astroparticle program
  - Solar neutrinos
  - Atmospheric neutrinos
  - Supernova neutrinos
  - Relic neutrinos from past supernovae
  - geoneutrinos

IBD and νe scattering

Physics from the observed spectrum



The oscillation phenomenon depends upon three mixing angles θ_{12}, θ_{13} **and** θ_{23} and three mass differences (only two independent) Δm^2_{21} Δm^2_{31} Δm^2_{32}

Summary of how JUNO will extract the information on neutrino oscillation – mass hierarchy and oscillation parameters – from the features of the observed spectrum

Goals

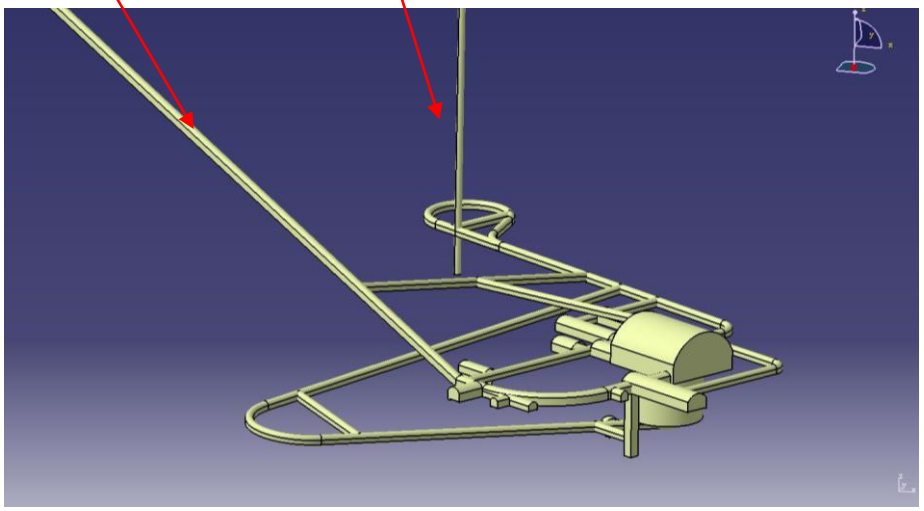
Sub percent precision on the parameters

3σ discrimination of hierarchy

Layout of the site

Slope tunnel

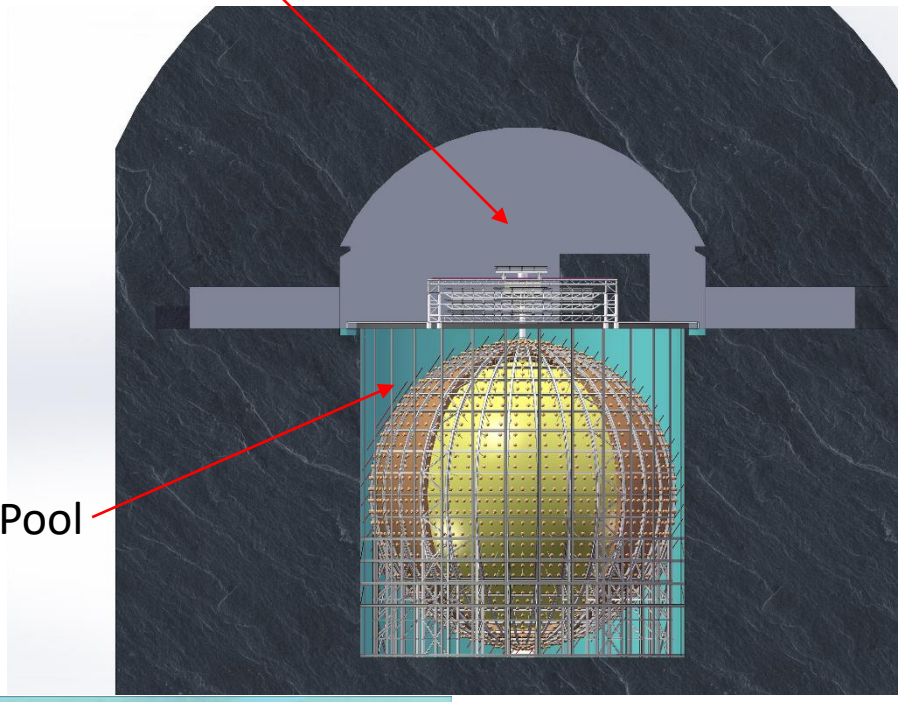
Vertical shaft



overburden ~ 700 m

Experimental Hall

Pool



Surface buildings

Detector’s layout

Central detector

- Acrylic sphere with 20k t liquid scintillator
- PMTs in water buffer on a stainless steel truss - 18k 20” and 25k 3”
- 78% PMT coverage

Water Cherenkov muon veto

- 2000 20” PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 Bq/m^3

Compensation coils

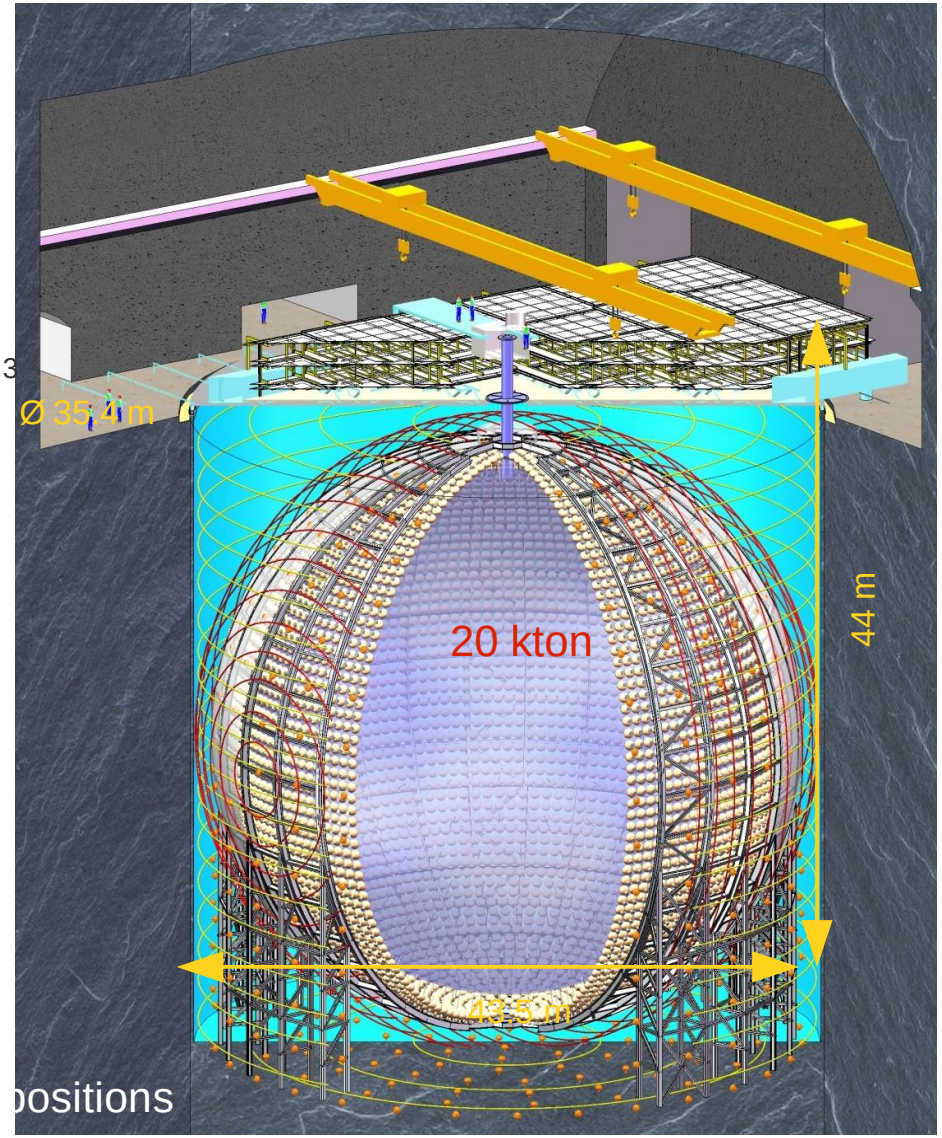
- Earth‘s magnetic field <10%
- Necessary for 20” PMTs

Top tracker

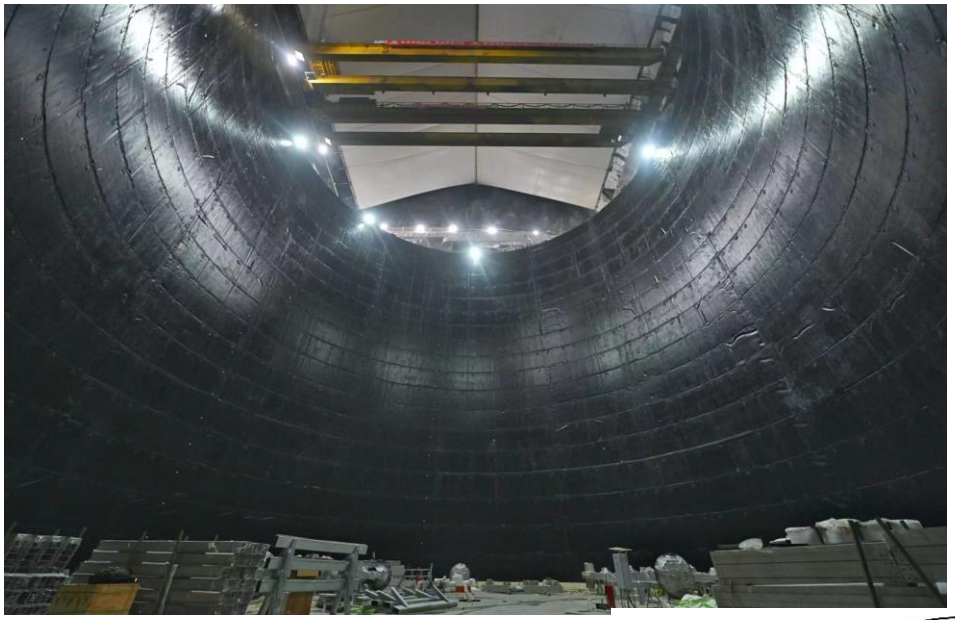
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

Calibration System

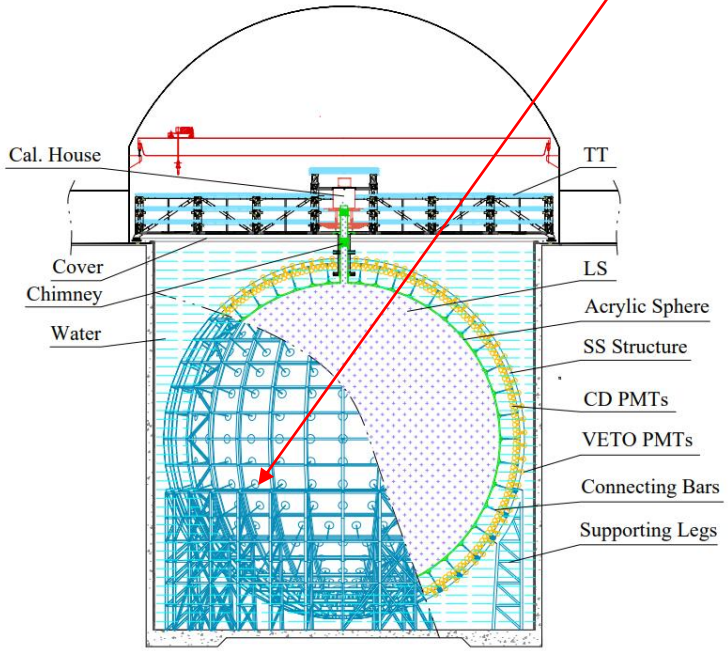
- 4 complementary sub-systems
- various particle types, ranges and positions



Status of the installation

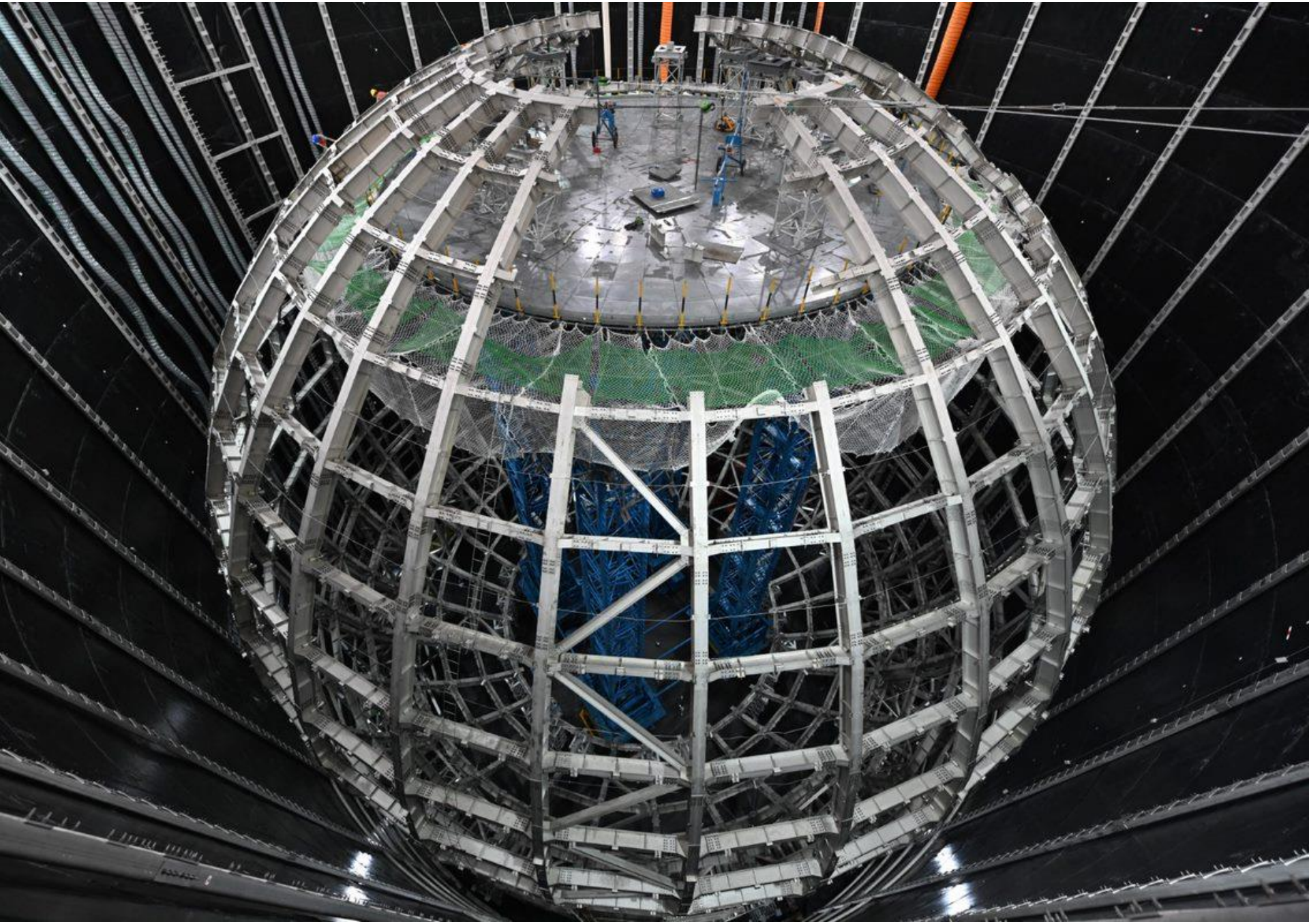


Experimental pool with the liner just before the installation startup



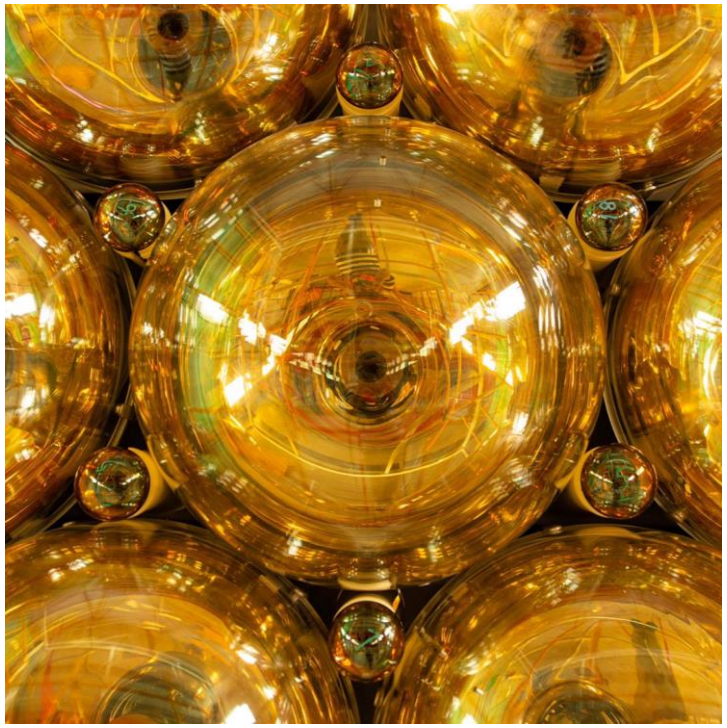
Platform ready for acrylic vessel installation

Assembly in clean room environment class 1000-10000



Photomultipliers

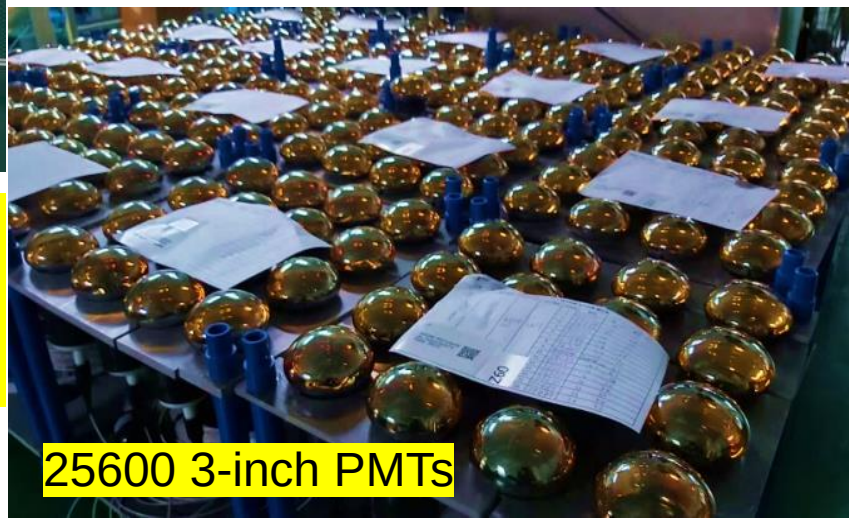
Synergy between large and small PMTs



Acrylic cover against implosion

Preparation

17612 (CD) + 2400 (Veto) 20-inch PMTs



25600 3-inch PMTs

Purification of the scintillator

Methods inherited from the Borexino experience

Distillation to remove radioactive impurities

Distillation

Water extraction

Water extraction to remove radioactive impurities in ionic form

Gas stripping to remove Rn and O_2

Stripping

JUNO has inherited also the thorough strategy of background control of Borexino: materials, cleanliness, filling strategy

Linear alkyl benzene chosen as base of the scintillator

In conclusions the scintillator technology

- Very mature and reliable
- Well rooted in past experiences
- Crucial for many achievements in neutrino physics
- With a bright future ahead to complete the unveiling of the neutrino properties