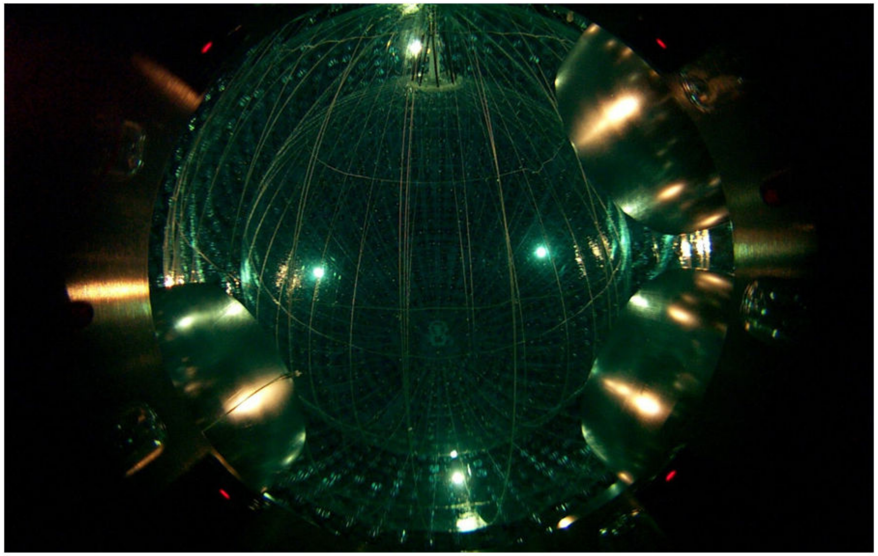
Water Purification in Borexino

Marco G. Giammarchi
Istituto Nazionale di Fisica Nucleare - Via Celoria 16 – 20133 Milano (Italy)
marco.giammarchi@mi.infn.it http://pcgiammarchi.mi.infn.it/giammarchi/
On behalf of the

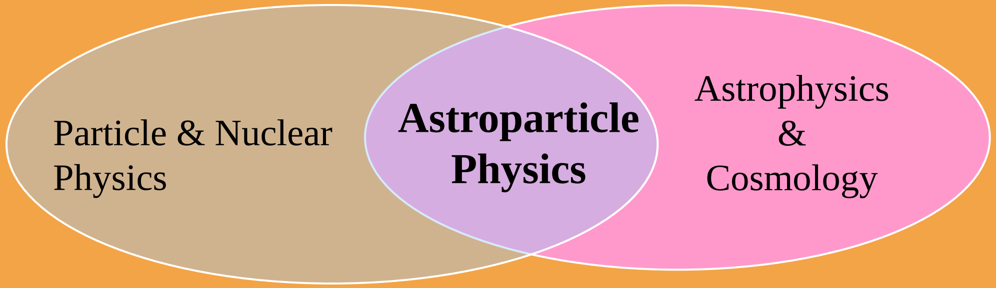
Borexino Water Working Group :
• M.G. Giammarchi, L. Miramonti (Infn and Università di Milano)
• M. Balata, L. Ioannucci, S. Nisi (Laboratorio Nazionale del Gran Sasso)
• A. Goretti, A. Ianni (Princeton University)

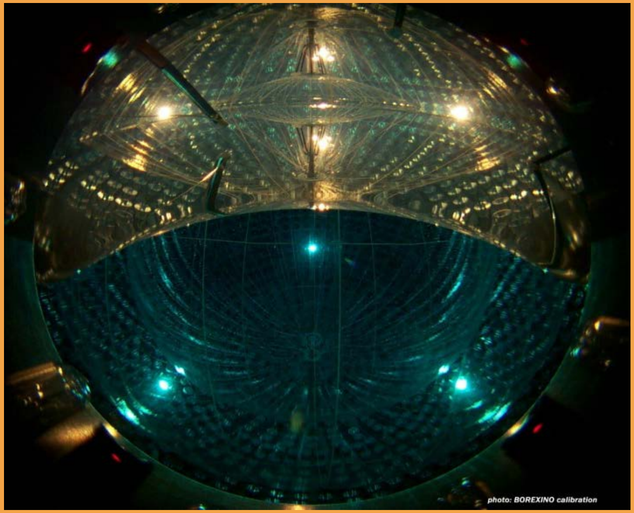
- Low Radioactivity Experiments
- Water as a Radiopure Shielding
- Water Purification in Borexino
- Results and Perspectives



Borexino Detector Filling in 2007

Low Radioactivity Experiments





Research topics:

- Solar Neutrinos
- Double Beta Decay
- Proton Stability
- Geoneutrinos
- Supernovae detection
- ….

Impact on fundamental physics (Weak Interactions, Neutrino Oscillation, Standard Model)

Physics experiments in which the signal searched for in swamped in a very high (dominant) background

Laboratori Nazionali del Gran Sasso

1700 m of rock to shield against cosmic rays

3 Experimental Halls, each the size of a football field

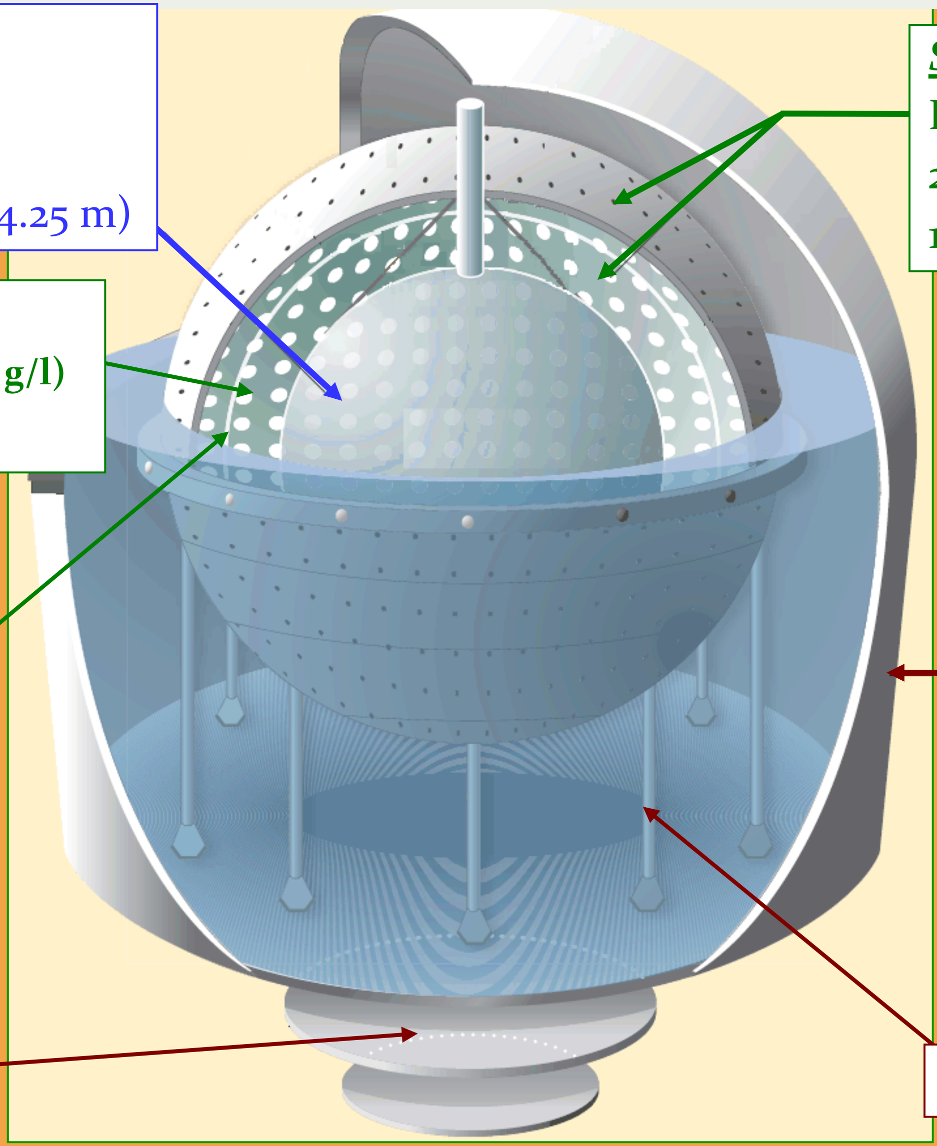
Borexino Detector

Scintillator:
270 t PC+PPO (1.5 g/l)
in a 150 µm thick
inner nylon vessel (R = 4.25 m)

Buffer region:
PC+DMP quencher (5 g/l)
4.25 m < R < 6.75 m

Outer nylon vessel:
R = 5.50 m
(^{222}Rn barrier)

Carbon steel plates



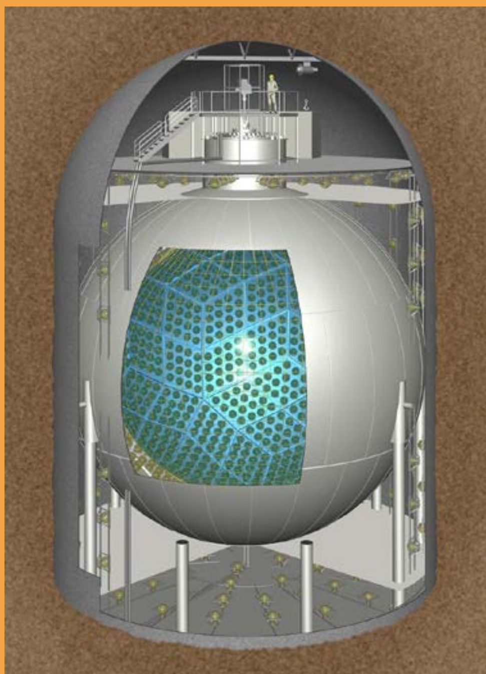
Stainless Steel Sphere:
R = 6.75 m
2212 PMTs
1350 m^3

Water Tank:
γ and n shield
µ water Č detector
208 PMTs in water
2100 m^3

20 steel legs

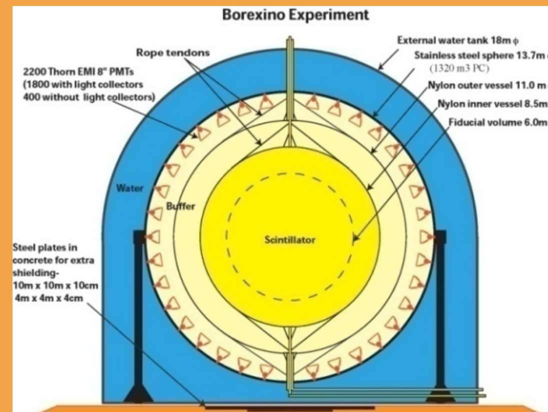
Detectors using water as a shielding or as a detecting medium

KamLAND



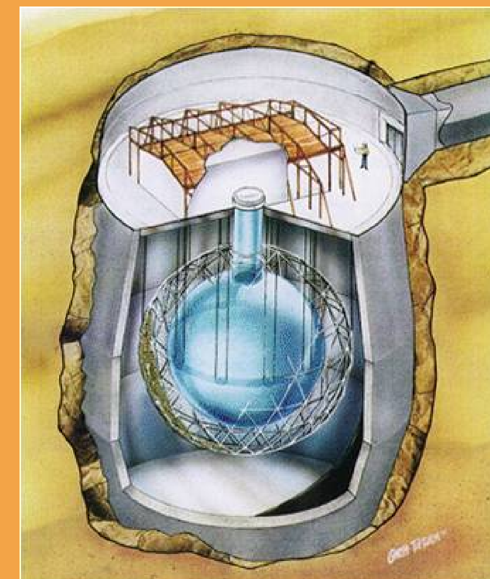
1000t
Running since 2002.

Borexino

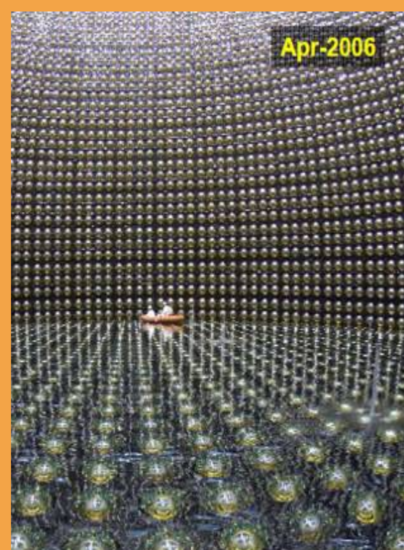


300t
Running since 2007.

SNO+



1000t
Starting in 2012



Super-Kamiokande

20000 t
Running since 1996.

What is the matter with a Low Background Experiment?

SIGNAL

- 50 events/day in 300 tonnes of liquid scintillator in Borexino (Be-7 signal)

BACKGROUNDS

- Cosmic Rays (even undeground!) will need to be reduced by a factor ≈ 10^3
- Radioactivity of Materials. For U,Th, K normal concentrations, say as an example, 10^{-11} g/g of ^{238}U

$$300\,t \times 10^{-11}\, gU238/g = 3\,mg\,U238$$

$$\frac{dN(U238)}{dt} = \frac{0.693}{T_{1/2}} N = \frac{0.693}{1.64\times10^{12}\,d} \frac{3\times10^{-3}\,g\times6\times10^{23}}{238g} = 3\times10^{6}/d$$

Signal to Noise ratio can be as low aso 50 / 3×10^6 !!

Water as a Radiopure Shielding (e.g. in Borexino)

Widely used in Low Radioactivity Experiments:

- Cheap
- Widely available
- Flexible shielding
- Can be purified
- Can be used for cleaning

→ Purification processes to reach the lowest level of contamination possible

$4 \times 10^{-13} \quad g\,^{238}U / g$

Requirements for the Water Shield in (CTF) Borexino: 5 x 10^{-6} Bq/kg

Impurities in the Water

- Inorganic salts

$Ba^{++}, Ca^{++}, Fe^{++}, H^{+}, K^{+},$

$Mg^{++}, Na^{+}, OH^{-}, Br^{-}, Cl^{-} ......$

Usually present in underground water at a TDS (Totally Dissolved Solids) of $10^2 - 10^3$ mg/l.
They are responsible for a total conductivity of about 150 μS/cm at LNGS

- Organic matter

Bacteria, Silica,

Hydrocarbons...

Does not contribute to conductivity but can introduce radio-impurities and spoil transparency. Measured by TOC and Bacterial tests.

- Dissolved gases

CO_2, Kr, Ar, Rn

Significant radioactivity problem mainly because of Rn-222 of the U chain, highly soluble in water.
Does not contribute to conductivity except for CO_2 dissolution

Water Conductivity

$$J = \sigma E = \sum_i n_i q_i v_i E = \sum_i \Lambda_i \left\{ \mu^-(-e) + \mu^+(+e) \right\}$$

Perhaps the most important single parameter, besides direct counting

Ions contributing to conductivity

Units (conductivity, resistivity):

$$[\sigma] = Siemens/cm = S/cm \qquad S = \Omega^{-1}$$

Equilibrium Constant of water → self-ionization

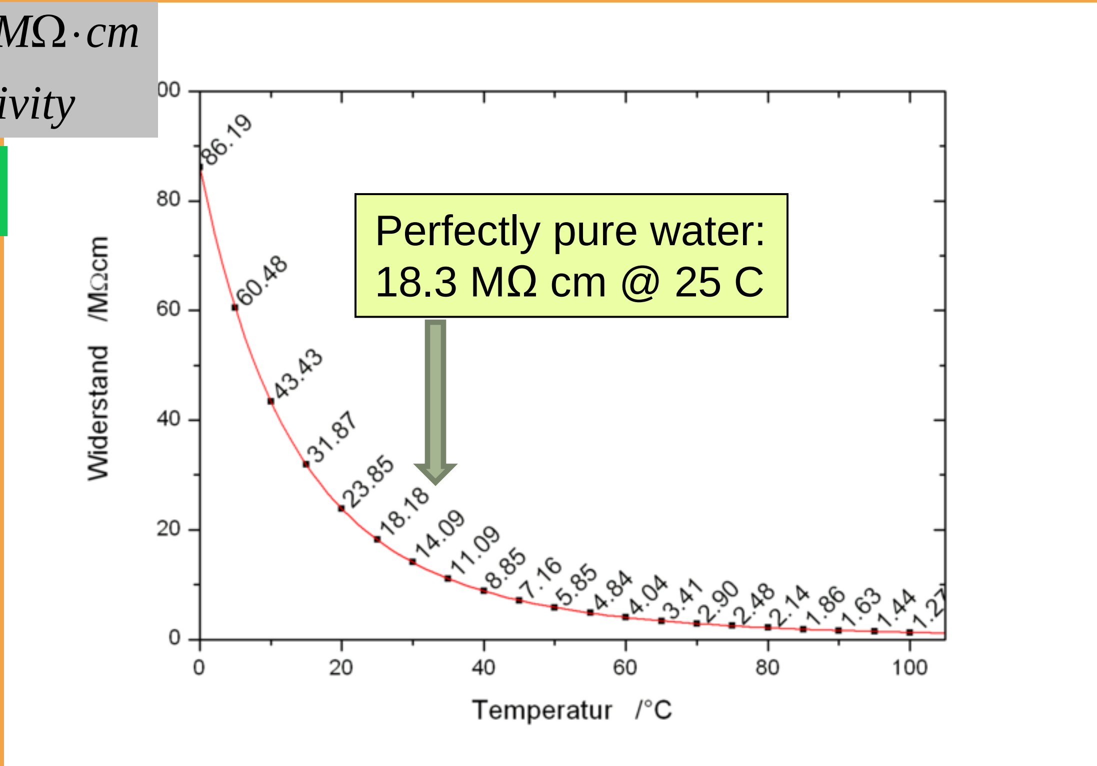
$[\rho] = M\Omega \cdot cm$

Resistivity

$$H_2O + H_2O \Leftrightarrow H_3O^+ + OH^-$$

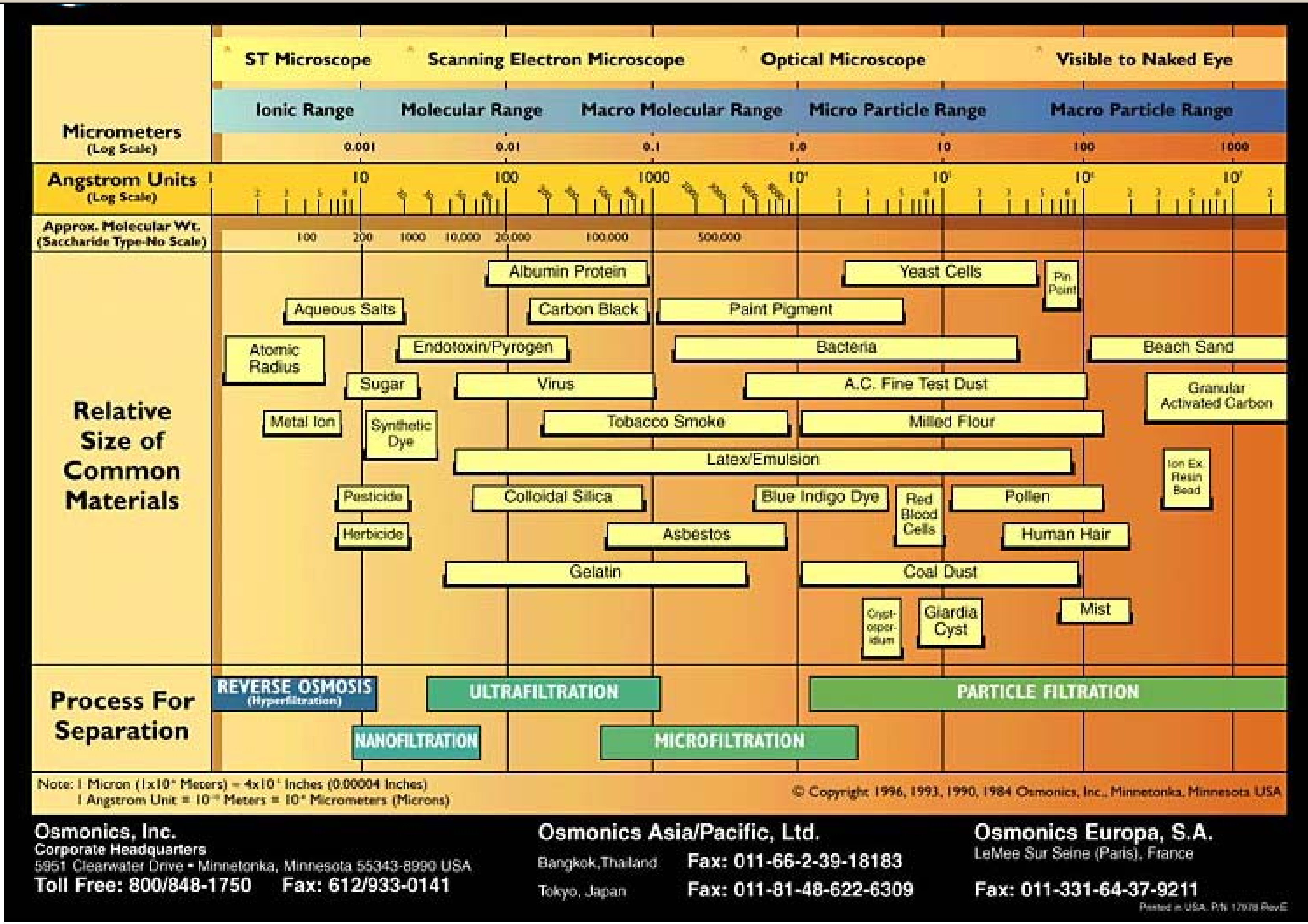
Water molecules dissociate into H_3O^+ and OH^-. Concentrations are 1.00×10^{-7} mol·dm^{-3} at 25 °C

$$\rho \leq 18.3\ M\,\Omega \cdot cm \quad @\ 25\ ^0C$$



Perfectly pure water: 18.3 MΩ cm @ 25 C

A synopsis of Water Purification Techniques



Reverse osmosis (RO):

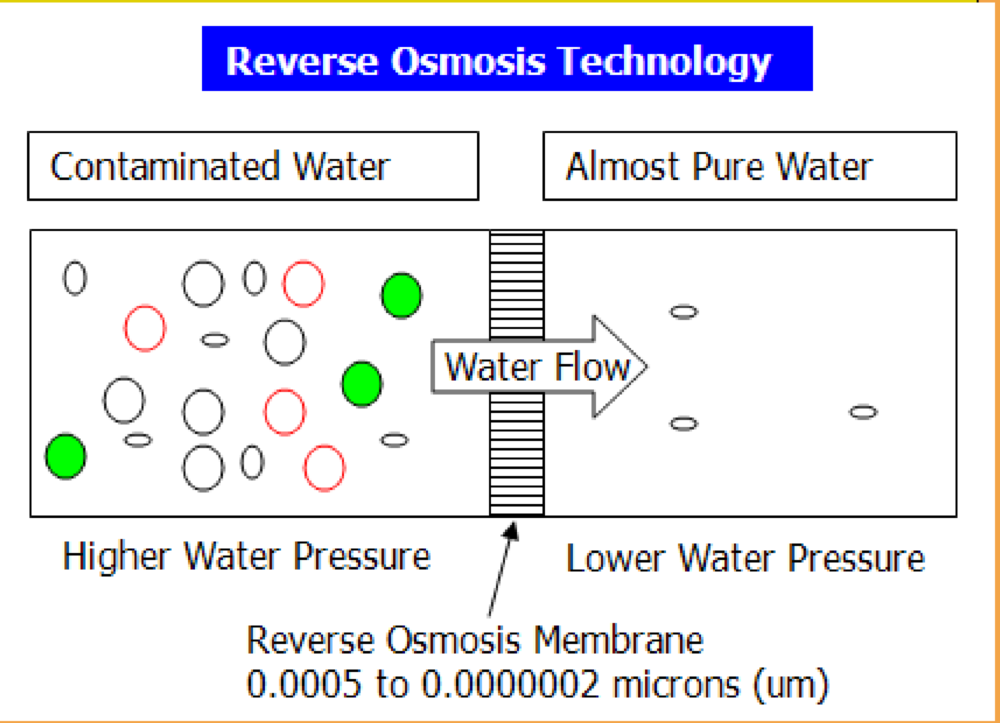
- A membrane-technology filtration method
- Pressure applied to a solution when it is on one side of a selective membrane
- The solute is retained on the pressurized side of the membrane
- The pure solvent is allowed to pass to the other side

- The membrane (Thin Film Composite) does not allow large molecules or ions to pass through the pores

Reverse Osmisos efficiently removes large molecules and ions . It is a very broadly used purification technique

Membrane grade porosity down to 10 MW. Typically will bring water up to :

$$\rho \approx 1\ M\Omega \cdot cm \quad @\, 25\ ^{0}C$$



Continuous Deionization:

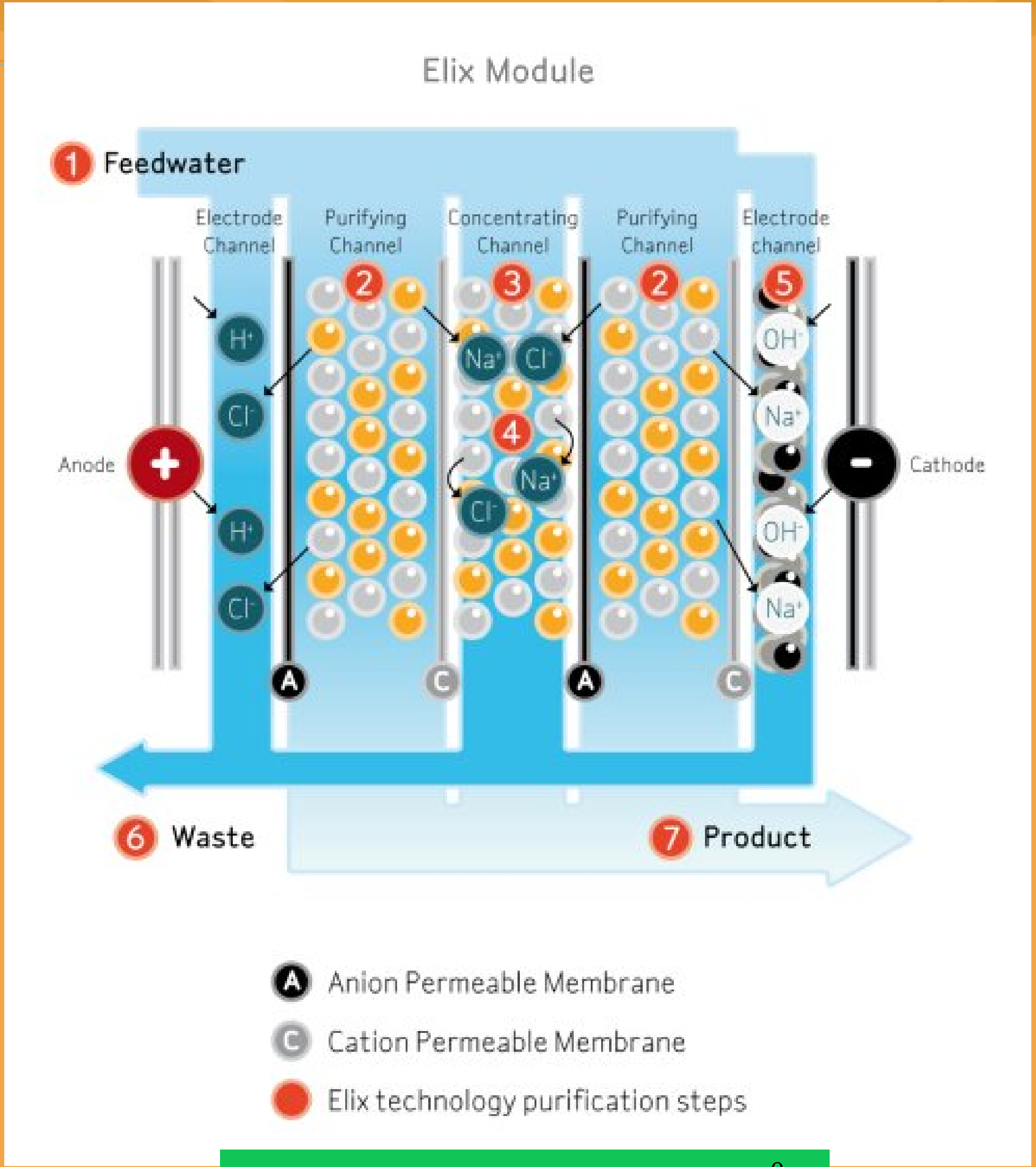
• Based on the Ion Exchange capability of Mixed Beds and their transport capability in an electric field.

• Anions and cations are removed by the Mixed Bed.

• Selective membranes are used to concentrate ions or cations.

• The applied electric field helps removing ions effectively.

• The electric field regenerates the Mixed Bed



$$\rho \rightarrow 18.3 \ M\Omega\cdot cm \ \ @\, 25\ ^{0}C$$

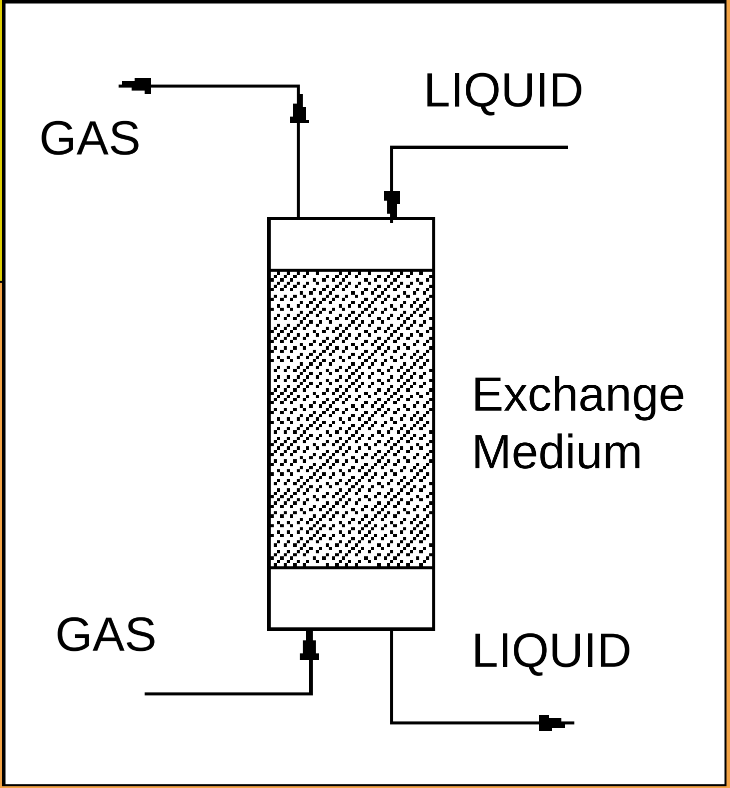
Gas Stripping:

- A physical separation process where some componentes are removed from a liquid stream by a vapour stream.

- Can be in gas mode or vacuum mode (gas is absent but a vacuum is pulled)

- Can have co-current or countercurrent mode

- Can be carried out in a packed column to enhance the the interface area between the liquid and the gas phase



Rn-222 in underground water can be as high as 10 Bq/kg

Requirements for the Water Shield in (CTF) Borexino: 5 x 10^{-6} Bq/kg

Water Purification in Borexino

Requirements: produce high purity water for:

- Counting Test Facility (now hosting DarkSide) filling
- Borexino Filling
- Purification Processes (e.g. Water Extraction of Scintillator)
- Cleaning

- Built in 1993 (for CTF) to treat raw LNGS water
- Reduce U,Th from 10^{-10} g/g
- Reduce Rn-222 from 10,000 Bq/m^3 = 10 Bq/kg

→

U,Th down to 10^{-14} g/g

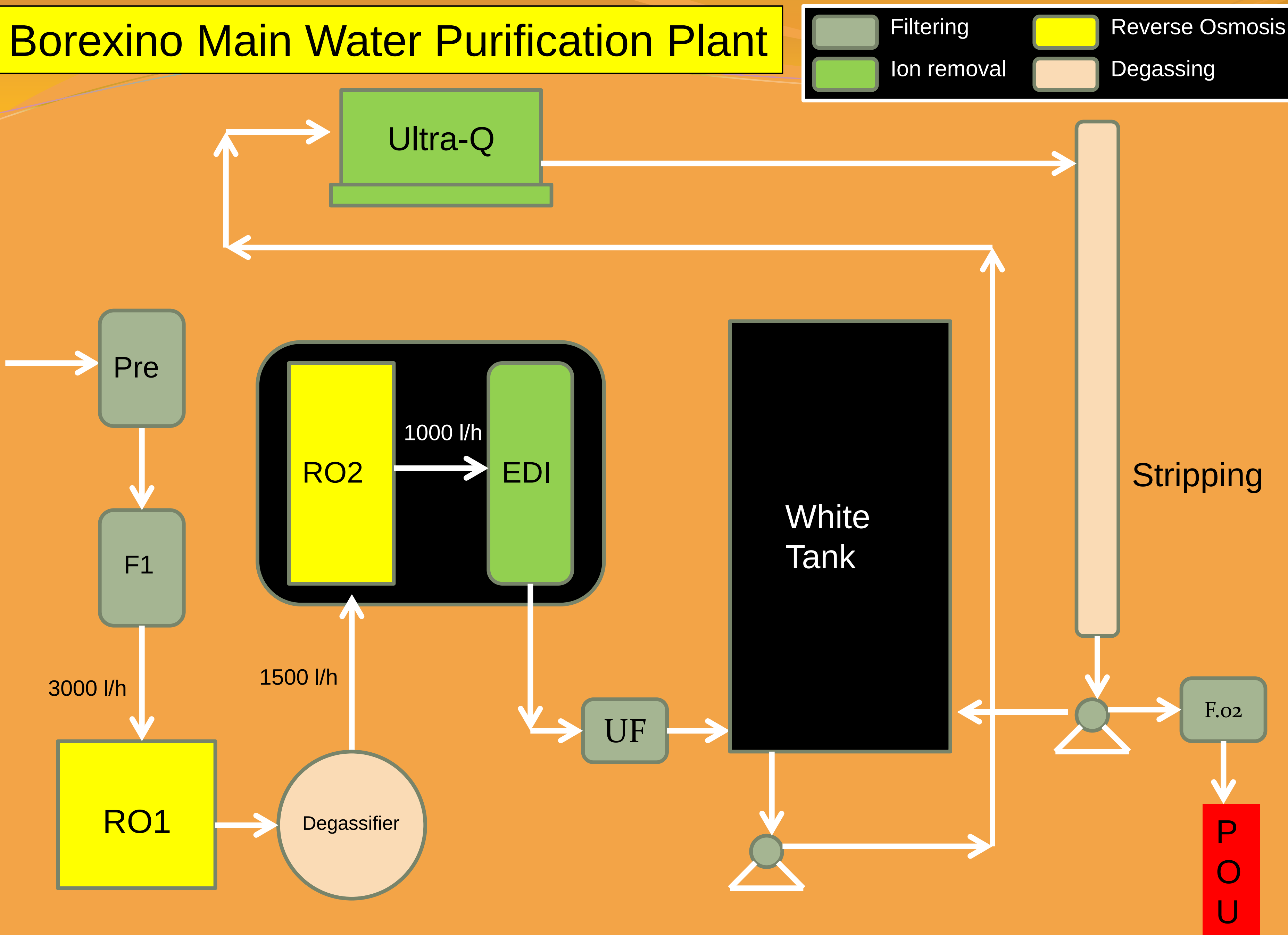
^{222}Rn < 3.4×10^{-6} Bq/kg

^{226}Ra < 1×10^{-6} Bq/kg

The Borexino Water System is operational since 1994

- *M. Balata et al., Nuclear Instruments & Methods A 370 (1996) 605.*
- *M.G. Giammarchi et al., Ultrapure Water 13 (1996) 59.*
- *M.G. Giammarchi, Ultrapure Water 16 (1999) 76.*

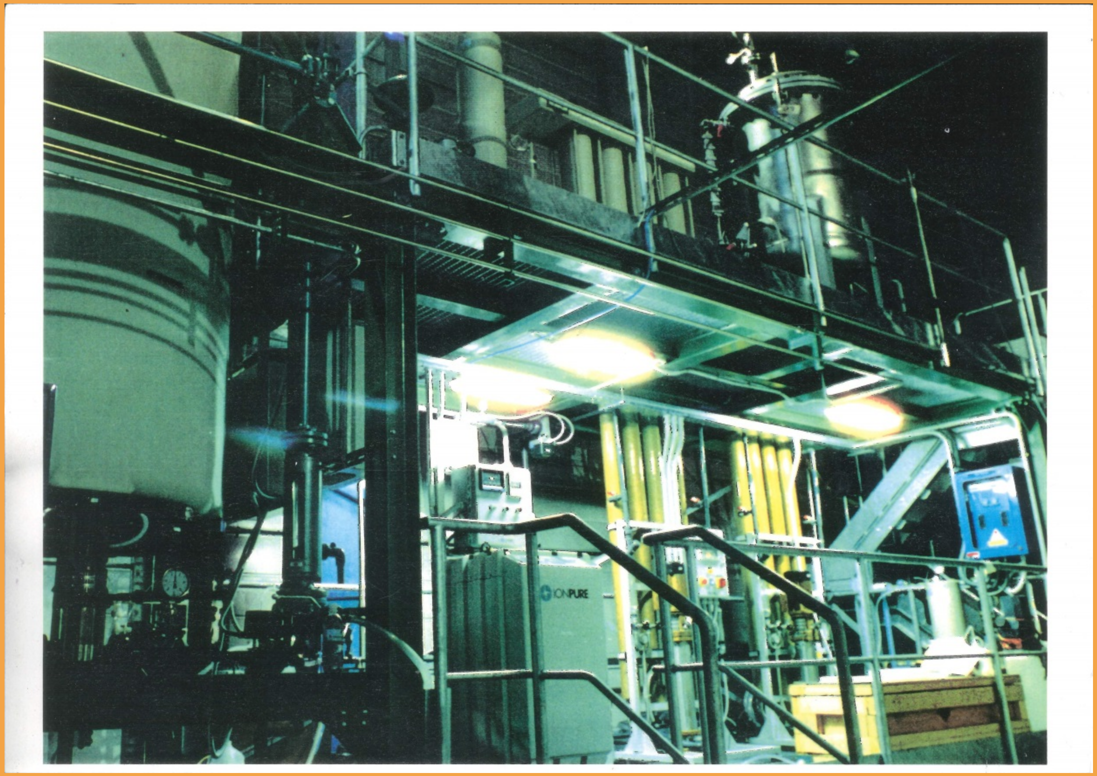
Borexino Main Water Purification Plant



Borexino Main Water Purification Plant

Hall C of LNGS

Operational group for the system:
M. Balata, L. Ioannucci, S. Nisi, A. Ianni, A. Goretti



Measurement techniques:

- High resolution mass spectrometry (ICPMS)
- Neutron Activation
- Low background counting for Ra/Rn (H. Simgen et al, Nuclear Instruments & Methods A 497 (2003) 407)

Summary of the Water Purification System performance (Bq/kg)		
	Water in	Water out
U-238	$\sim 10^{-3}$	3×10^{-7}
Ra-226	~ 0.3	$< 1 \times 10^{-6}$
Rn-222	~ 10	$< 3.4 \times 10^{-6}$
Th-232	$\sim 10^{-3}$	3×10^{-7}
K-40	$\sim 10^{-3}$	$< 1.6 \times 10^{-6}$

Unfortunately, no real clue on Pb or Po isotopes
Pb-208 measured as a tracer with hi-resolution mass spectrometry

Conclusions

- Water Purification: an established technology in low background experiments (Superkamiokande, SNO, Kamland)
- Borexino features a reliable water plant (about 20 years of operation)
- More to understand in the future: Po,Pb
- The water plans has been recently refurbished
- To become a facility for LNGS experiments in general !

Thank you for your attention

Backup slides

Some water does not really need to be purified

Strontium-selective resins → also sensitive to Pb
A. Musilek et al., 2° International Conference on Po and Radioactive Pb Isotopes

EDTA technique to remove metals

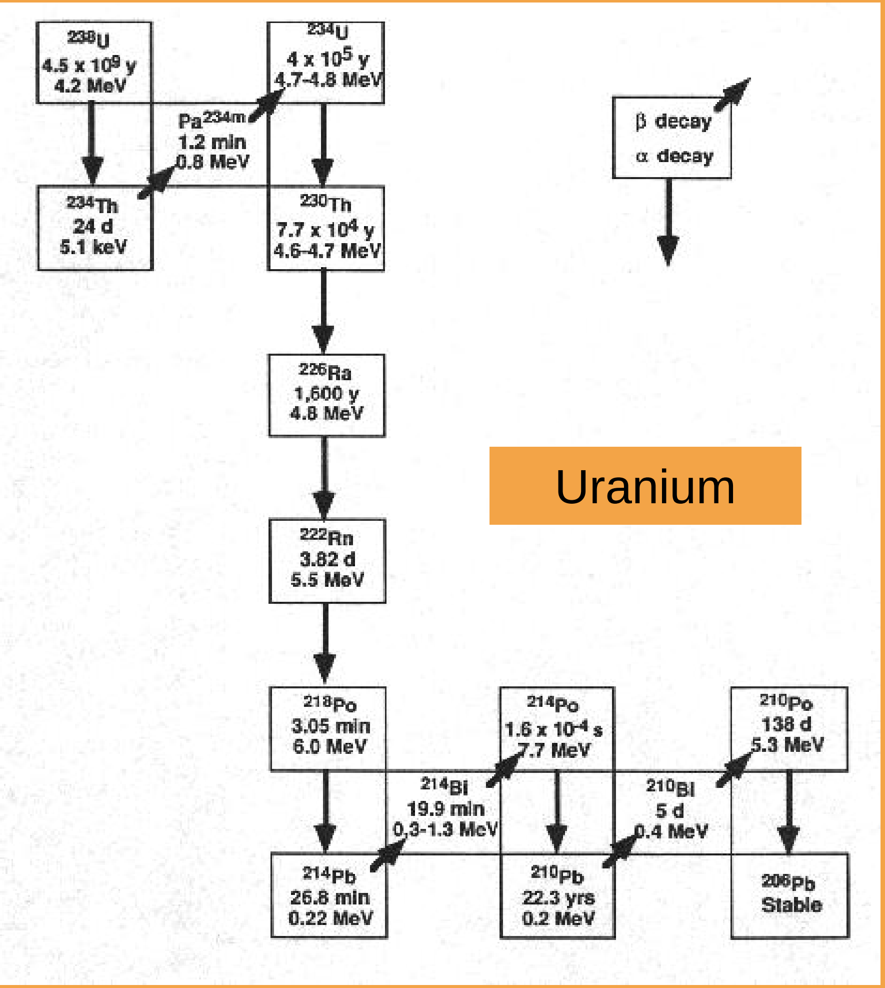
Seeded Ultrafiltration Technique, microfileters coated with HTiO,DTio (Th,Ra,Pb)

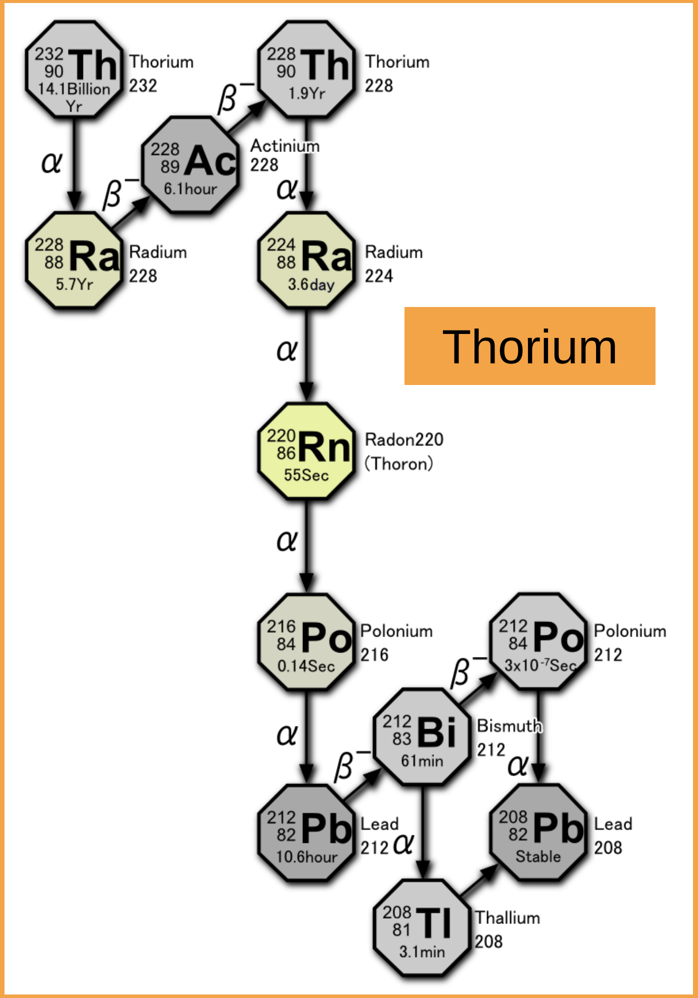
Acrylic beads coated with MnOx (Ra)

Silver deposition for Po determination

Po and Pb RadioIsotopes

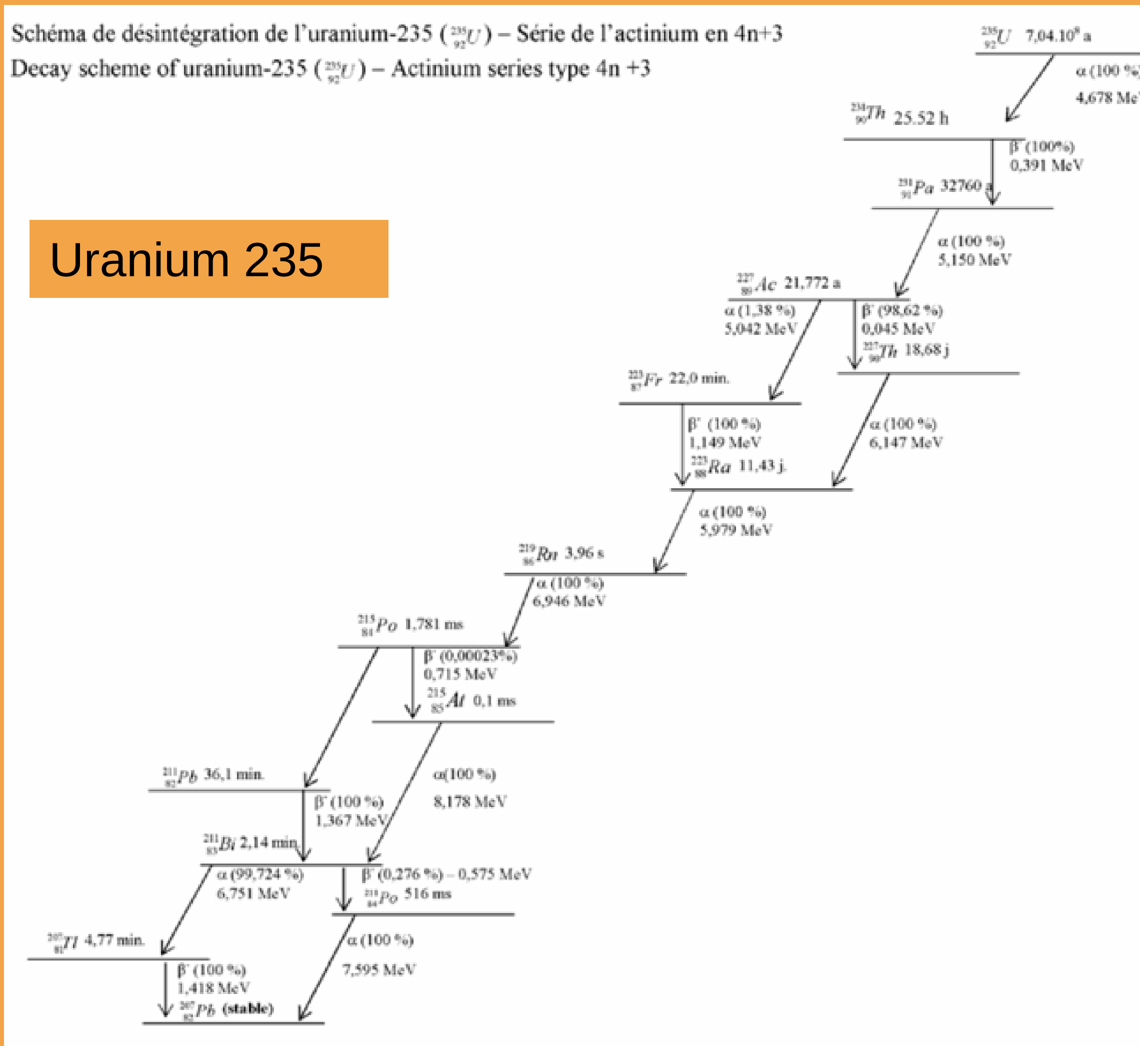
They are located at the end of U,Th radioactive chains



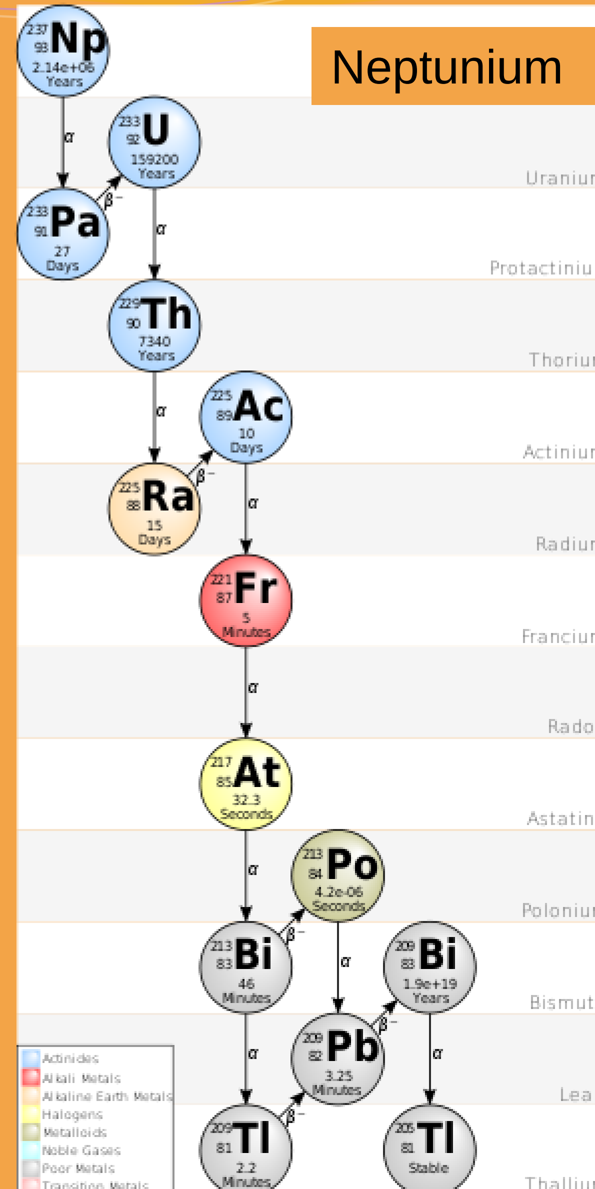


The Actinium and Neptunium series
(a less important role in experiments)

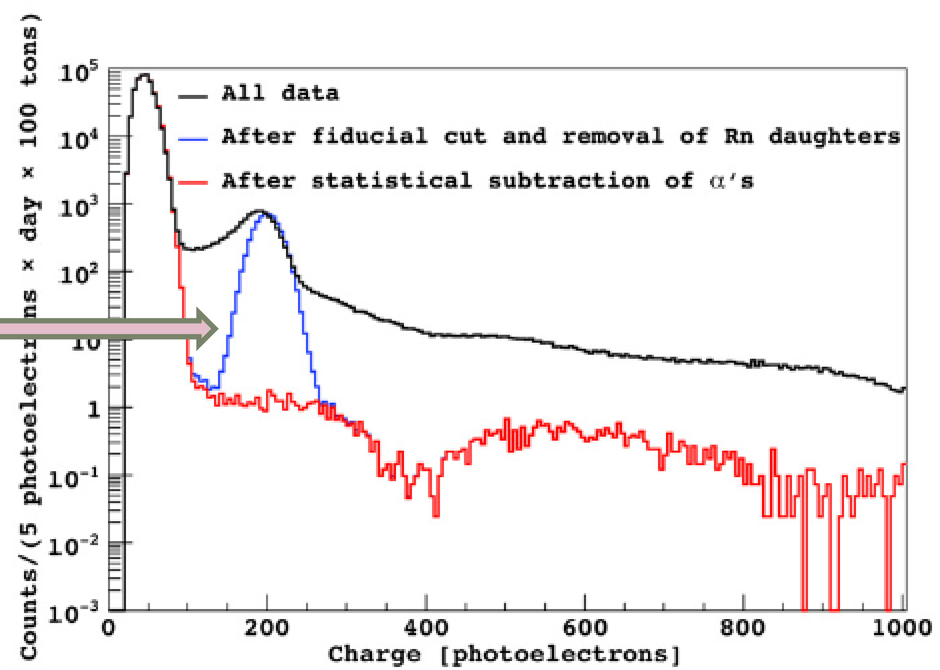
Uranium 235



Neptunium



Borexino single photoelectron spectrum to search for Solar Neutrinos



Po-210 alpha decay

Not in equilibrium with Rn-222

Fig. 4. The raw photoelectron charge spectrum after the basic selection cuts (i)–(ii) (black), the spectrum after the subtraction of Rn daughters and muon-correlated activity, and after the application of the fiducial cut (iii)–(v) (blue), and with full α/β statistical subtraction of the ^{210}Po α peak (red). All curves scaled to the exposure of 100 d t. Cuts are described in the text.

Concentration of Po-210 in our scintillator before the analysis cuts

$$N = \frac{T_{1/2}}{0.693}\frac{dN}{dt} = \frac{138.4}{0.693} d \frac{50{,}000}{d} = 10^6$$

$$P(Po210) = 10^6 \times 210 \times 1.6 \times 10^{-24} g = 3 \times 10^{-16} g$$

$$\frac{3 \times 10^{-16} g}{3 \times 10^{8} g} = 10^{-24}$$

Pb-210 and Bi-210 background

Bi-210 decays

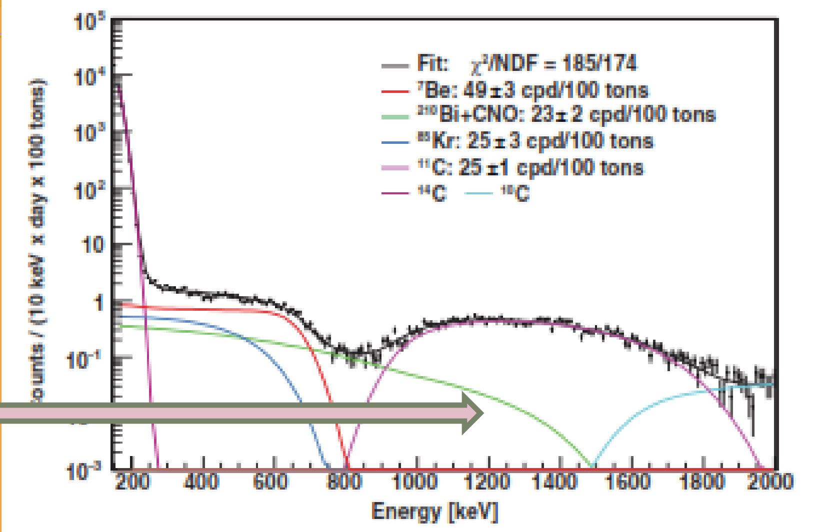


FIG. 2 (color). Spectral fit in the energy region 160–2000 keV. Contributions from ^{214}Pb, *pp*, and *pep* neutrinos, not shown, are almost negligible with respect to those in the figure.

Concentration of Pb-210 in our scintillator

$$N = \frac{T_{1/2}}{0.693}\frac{dN}{dt} = \frac{22.3}{0.693}yr\,\frac{23}{d} = 500 \;\; atoms$$

Cannot measure by analytic methods.
Can measure by counting.
But in doing this we face all radioactivity components