Ultra-sensitive analysis of U, Th and K in the liquid scintillator of the JUNO experiment

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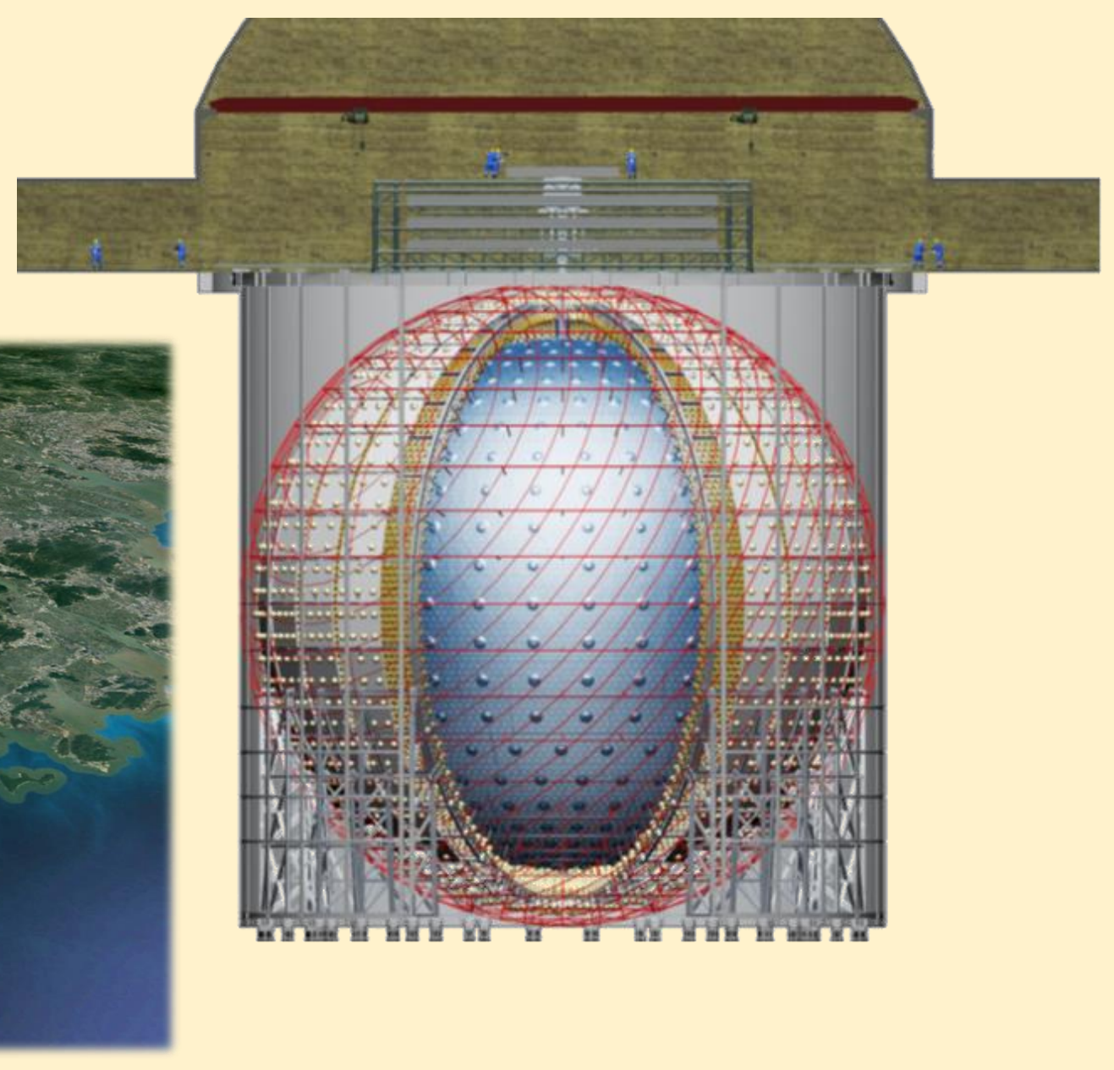
* speakers

1 The JUNO experiment

- **Main JUNO physics goals :**
  - **3σ measurement of the neutrino mass ordering with reactor antineutrinos in ~6 years**
  - **Measuring oscillation parameter with a precision < 0.5 %** $(sin^2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31})$
- Reactor $\bar{\nu}$ detected by Inverse Beta Decay on free protons
- Large scintillator detector (20 ktons)
- Largest PMT coverage ever built (78%) with < 3% energy resolution at 1 MeV
- Broad physics program: mass ordering, precision measurement of oscillation parameters, solar and supernova neutrinos, atmospheric neutrinos, geo-neutrinos, proton decay...



2 JUNO background

Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$

- Prompt signal from positron ionization and annihilation
- Delayed signal from neutron capture on ^{1}H (2.2 MeV γ)

Criteria for IBD identification:

- Prompt signal: 0.7 < Ep < 12 MeV
- Delayed signal: 1.9 < Ed < 2.5 MeV
- Time coincidence < 1 ms
- Prompt-delay signal vertexes distance < 1.5 m

Single trigger count rate from natural radioactivity in materials must be below 10 Hz in the liquid scintillator fiducial volume (R < 17.2 m).
Careful material selection, surface cleanliness, radon emanation and dust control are mandatory.

Main background sources for IBDs

- ***Natural radioactivity***
- Cosmogenic nuclei (^{9}Li/^{8}He)
- Fast neutrons and (α,n) reactions
- Geo-neutrinos
- Cosmic muons

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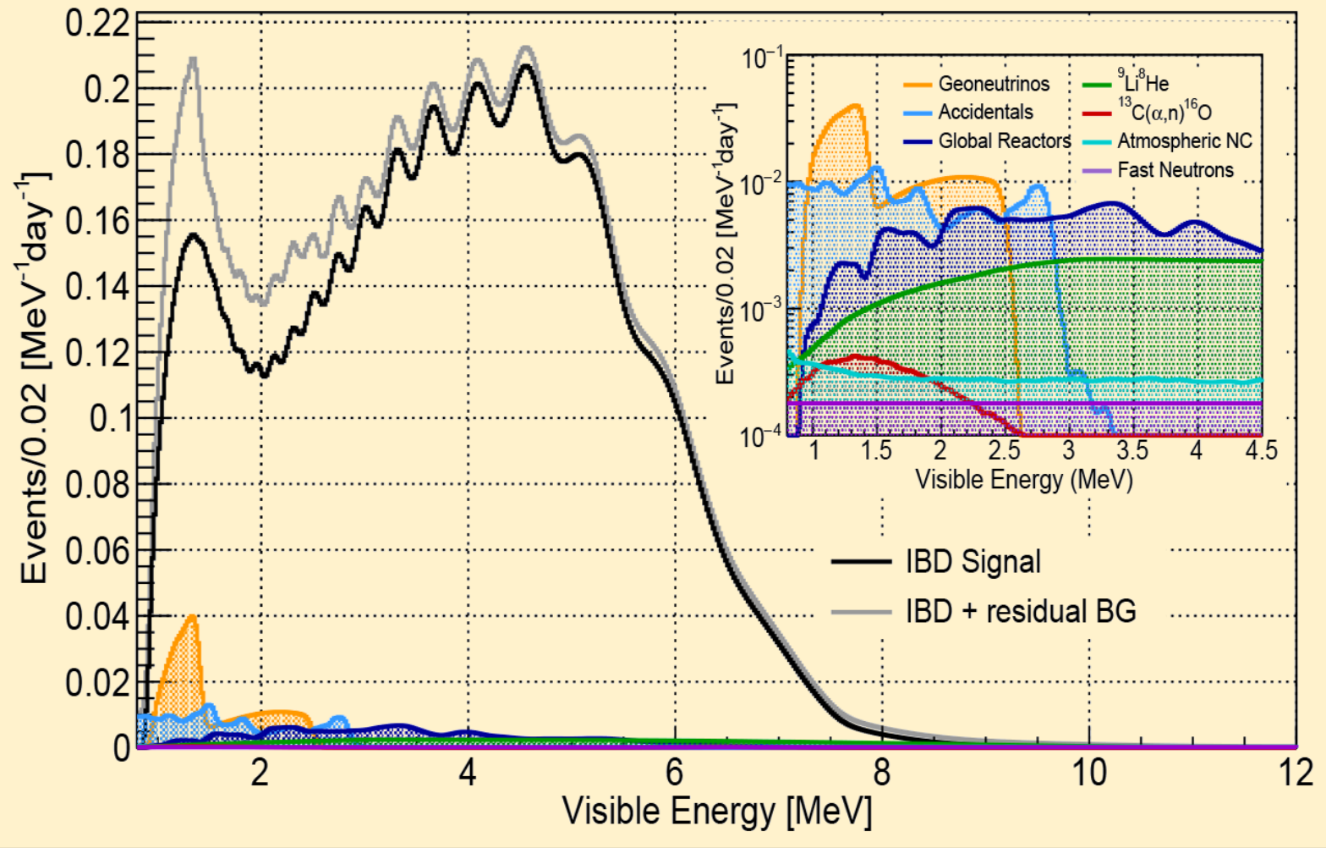
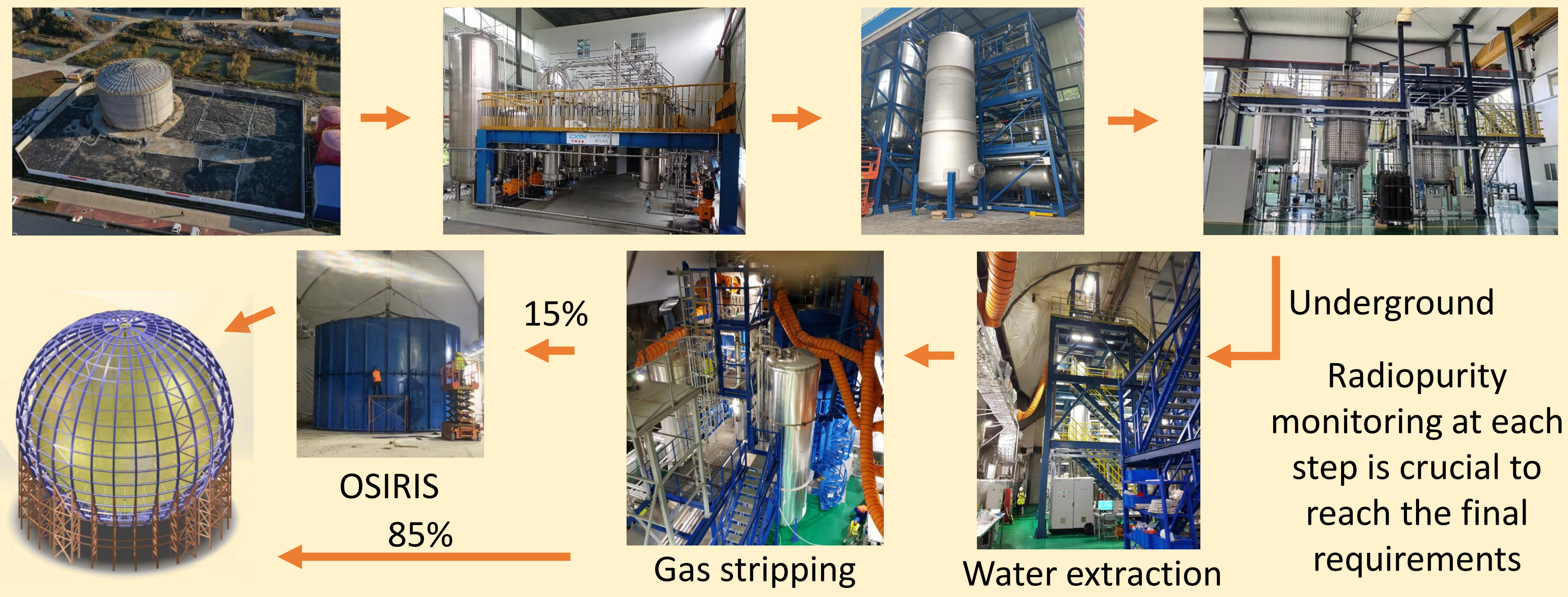


3 JUNO liquid scintillator production

The Liquid Scintillator (LS) is the most critical component for the radiopurity:
minimum requirements: **^{238}U and ^{232}Th < 10^{-15} g/g and ^{40}K < 10^{-16} g/g**

LS: Linear Alkyl Benzene (LAB) added with fluor (PPO) and wavelength shifter (bis-MSB).
Custom purification plants are exploited for the JUNO liquid scintillator:



Radiopurity monitoring at each step is crucial to reach the final requirements

4 High sensitivity techniques for ^{238}U, ^{232}Th and ^{40}K measurement in LS

Our approach for U and Th measurement combines neutron activation analysis (NAA), radiochemical treatments and high sensitivity measurements by a novel β-γ low background detector

Chemical treatments → **Sample irradiation** → **Radiochemical separation** → **β-γ measurements**

Chemical treatments	Sample irradiation	Radiochemical separation	β-γ measurements
Remove interferences **Concentrate** sample	**Activates** elements of interest	**Separation** of activated elements	**High sensitivity** measurements

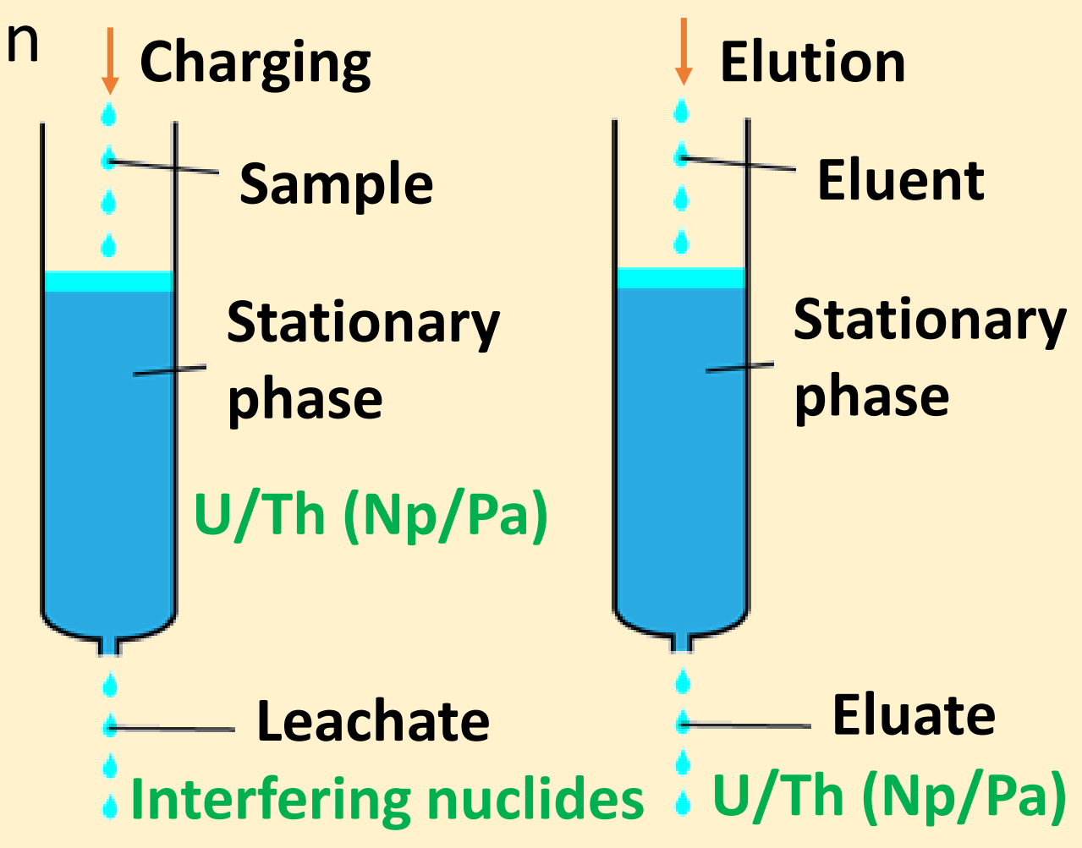
For K we exploit **the direct irradiation of the LS** followed by gamma spectroscopy measurement of the irradiated sample, due to high contamination risk during pre-irradiation treatments

5 Radiochemical treatments

Treatments before irradiation

- Clean room to reduce the sample contamination risk
- Development of a dedicated cleaning protocol for tools
- Use PFA containers for extremely low contaminations
- Use reagents with the highest purity available (“ultra pure”)

1. **Liquid-liquid extraction:** U and Th transfer from LS to an acid aqueous solution.
2. **Extraction chromatography (UTEVA resin):** U and Th separation from the other nuclides and to reduce the sample volume.



Treatments after irradiation

1. **Extraction chromatography (TEVA resin)** Np and Pa separation from interfering nuclides produced during the activation.

Overall efficiency of the process:
(86 ± 12) % for U and (43 ± 10) % for Th

6 Neutron activation analysis

The neutron activation process consists in the production of unstable isotopes through neutrons absorption by the nuclei of interest in the sample

$$^{238}_{92}U + n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np$$
$$^{232}_{90}Th + n \rightarrow ^{233}_{90}Th \rightarrow ^{233}_{91}Pa$$
$$^{41}_{19}K + n \rightarrow ^{42}_{19}K$$

Sample and standard are exposed to a **neutron flux** → **Extraction** of the irradiated sample and **measurement** of induced γ radioactivity → **Calculation** of the **quantity of precursor** element

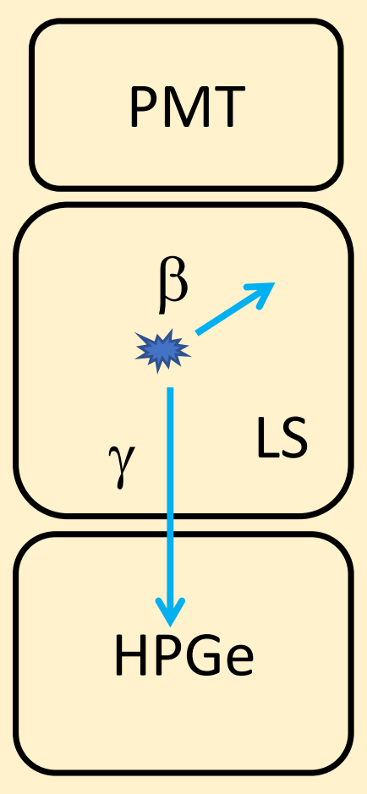
Irradiation channels:

- Rotating facility around the reactor core (ϕ~10^{12} cm^{-2}s^{-1}) → multiple samples
- Channel at the center of the reactor core (ϕ~10^{13} cm^{-2}s^{-1}) → two samples

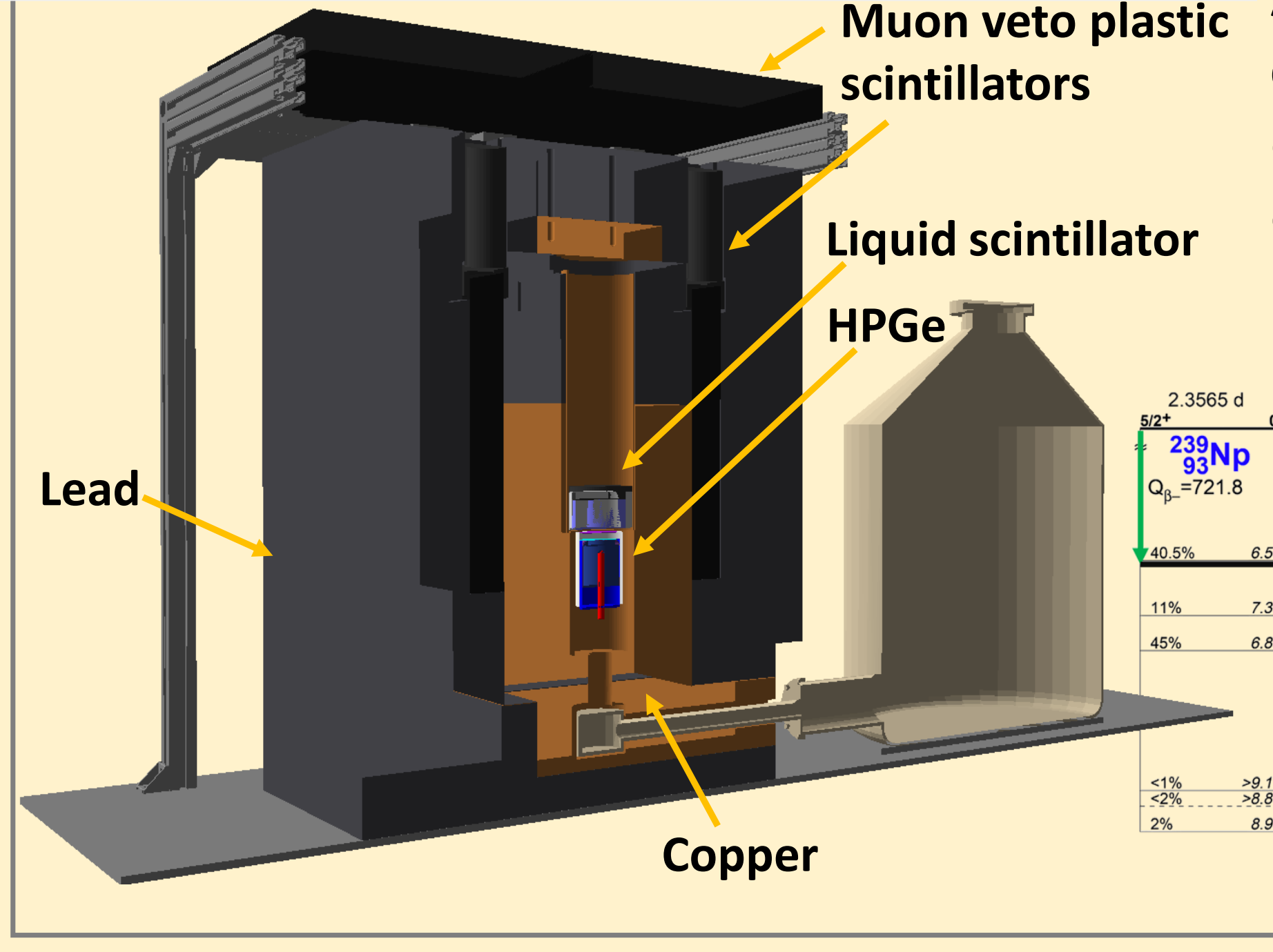
TRIGA Mark II Research reactor (250 kWth) - Pavia, Italy

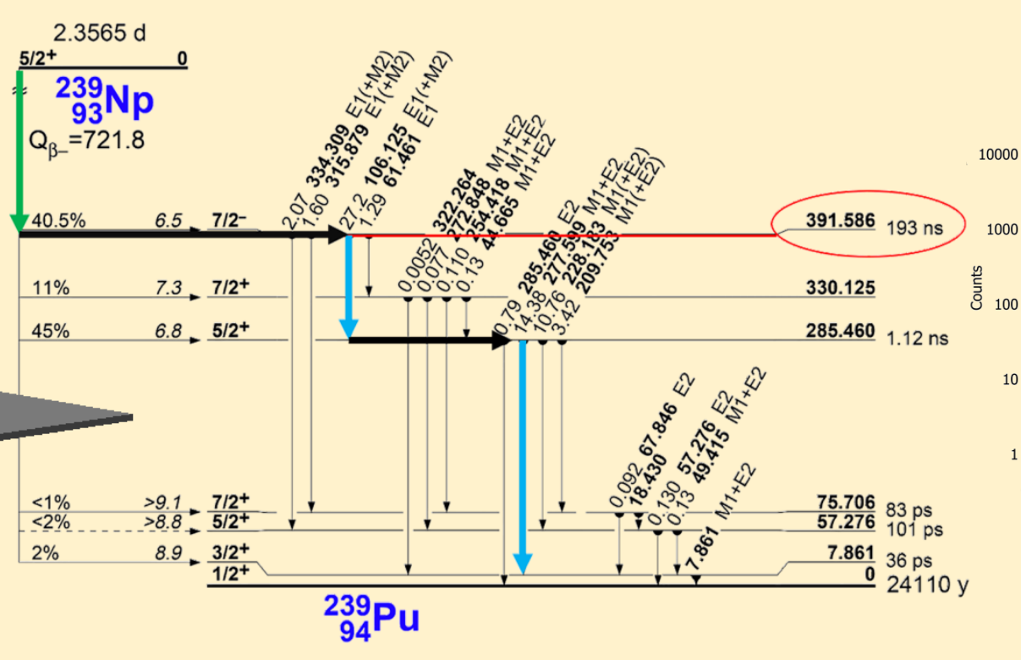
7 β–γ coincidence measurements

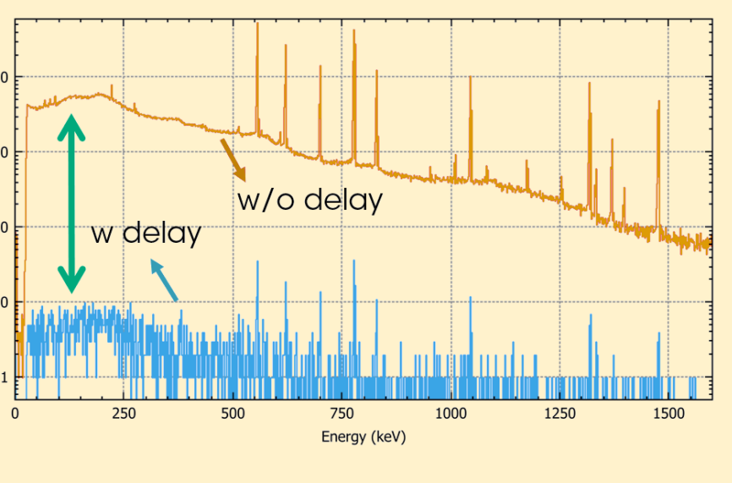
The detector is made of a liquid scintillator and a High Purity Germanium (HPGe) detectors operating in time coincidence. The irradiated sample is mixed with fresh liquid scintillator. → This measurement system is able to detect well-defined time correlated events allowing a **strong reduction of background**



An innovative **triple delayed coincidence techniques** has been developed for U measurements, exploiting a metastable nuclear level in ^{239}Pu, decay product of ^{239}Np.







8 Sensitivity and radiopurity results on JUNO LS during plant commissioning

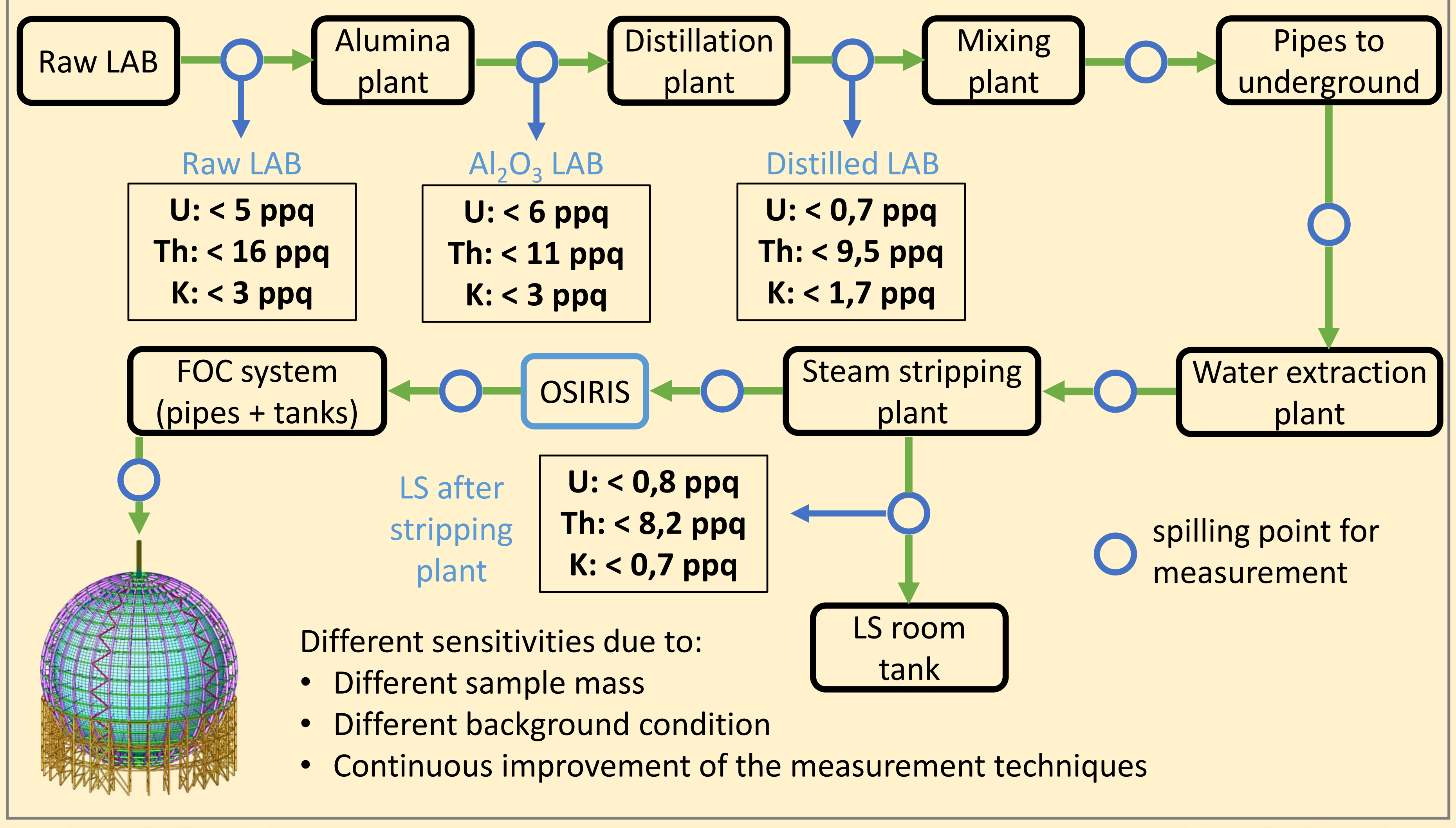
Blank measurements and **clean real sample** allowed to evaluate the **sensitivity** of the developed technique →

Nuclide	Sensitivity @ 95 %
^{238}U	< 0,7 ppq @ 500 mL < 0,4 ppq @ 1 L
^{232}Th	< 8 ppq @ 1 L < 1,9 ppq @ 1 L using central channel
^{40}K	< 0,7 ppq @ 126 g

Limits to sensitivity:

- **Uranium**: residual uranium released by the resin in the pre-irradiation treatment, sample mass.
- **Thorium**: lower activation cross section and higher measurement background, sample mass.
- **Potassium**: sample mass and random contamination of the samples

Results from samples took during the commissioning of the JUNO purification plants



Raw LAB	Al$_2$O$_3$ LAB	Distilled LAB	LS after stripping plant
U: < 5 ppq	**U: < 6 ppq**	**U: < 0,7 ppq**	**U: < 0,8 ppq**
Th: < 16 ppq	**Th: < 11 ppq**	**Th: < 9,5 ppq**	**Th: < 8,2 ppq**
K: < 3 ppq	**K: < 3 ppq**	**K: < 1,7 ppq**	**K: < 0,7 ppq**

Different sensitivities due to:

- Different sample mass
- Different background condition
- Continuous improvement of the measurement techniques

9 Future plans and improvements

- The beginning of the JUNO detector filling with LS is currently foreseen at the end of the 2024
- Before and during the filling phase new measurement campaigns will be performed to monitor the radiopurity of the liquid scintillator

- Th and K sensitivity improvements by exploiting the reactor central channel
- Post-irradiation radiochemical treatment is under study to improve the K sensitivity

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