



CesoX

JJC
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Outline

- Neutrino reminder
- Sterile neutrino
 - Pour new wine into old bottles: ν anomalies
 - The fourth ν hypothesis
- CeSOX(Cerium for Short distance ν Oscillations with boreXino)
 - Summary
 - Cerium ν source: CeANG
 - Borexino detector
 - Source handling
- CeANG characterization (my work)
 - Source purity
 - β spectroscopy
 - Activity measurement
- Outlook

Neutrino reminder

- First inferred by Pauli in 1930 to explain β decay missing energy
- ν_e discovered in 1956 with nuclear reactor (Reines & Cowan)
- Weakly interacting particle
 - ➡ Very low interaction cross-section
 - ➡ Very hard to detect
- ν_μ discovered in 1962 (Lederman, Schwarz & Steinberger)
- ν_τ discovered in 2000 (DONUT collaboration)
- At first glance they seem massless

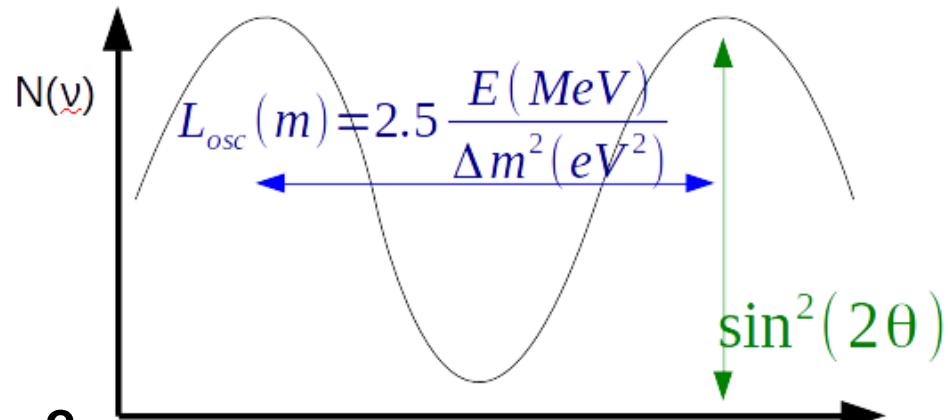


Disturbing particle

- Standard model was perfectly happy with 3 massless neutrinos

But...

- Solar neutrinos (seen as soon as 1968) and atmospheric neutrinos deficits lead to oscillations discovery (SuperK 1998)
→ Neutrinos have a mass

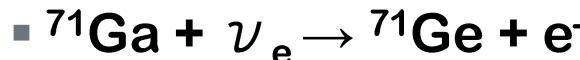


Some open questions right now:

- Possible Majorana particles ?
- Explanation for the low ν masses ?
- Mass hierarchy ?
- C_p violation in lepton sector ?
- Some ν anomalies are yet unexplained...

The Gallium Anomaly

- Test of solar neutrino radiochemical detectors **GALLEX** and **SAGE**



- 4 calibration runs with 20-60 PBq Electron Capture ν_e emitters

- Gallex, $\langle L \rangle = 1.9$ m

- ^{51}Cr , 750 keV

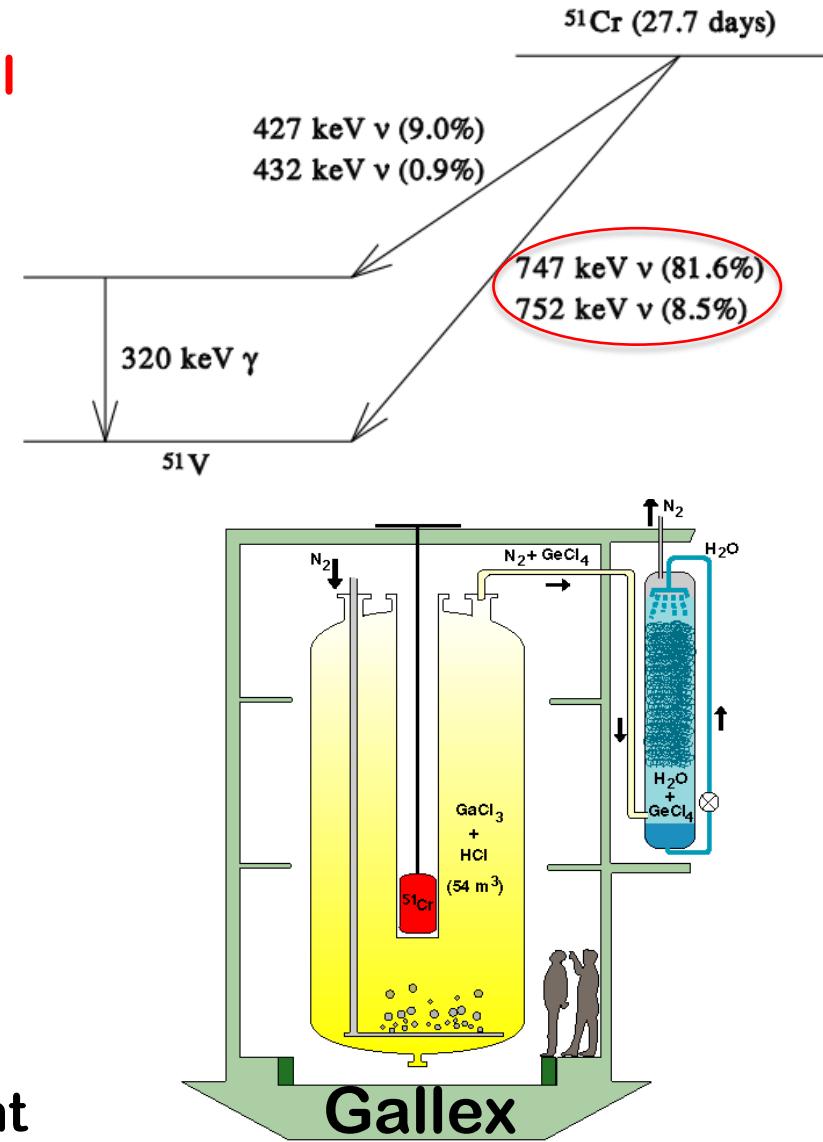
- Sage, $\langle L \rangle = 0.6$ m

- ^{51}Cr & ^{37}Ar (810 keV)

- Deficit observed

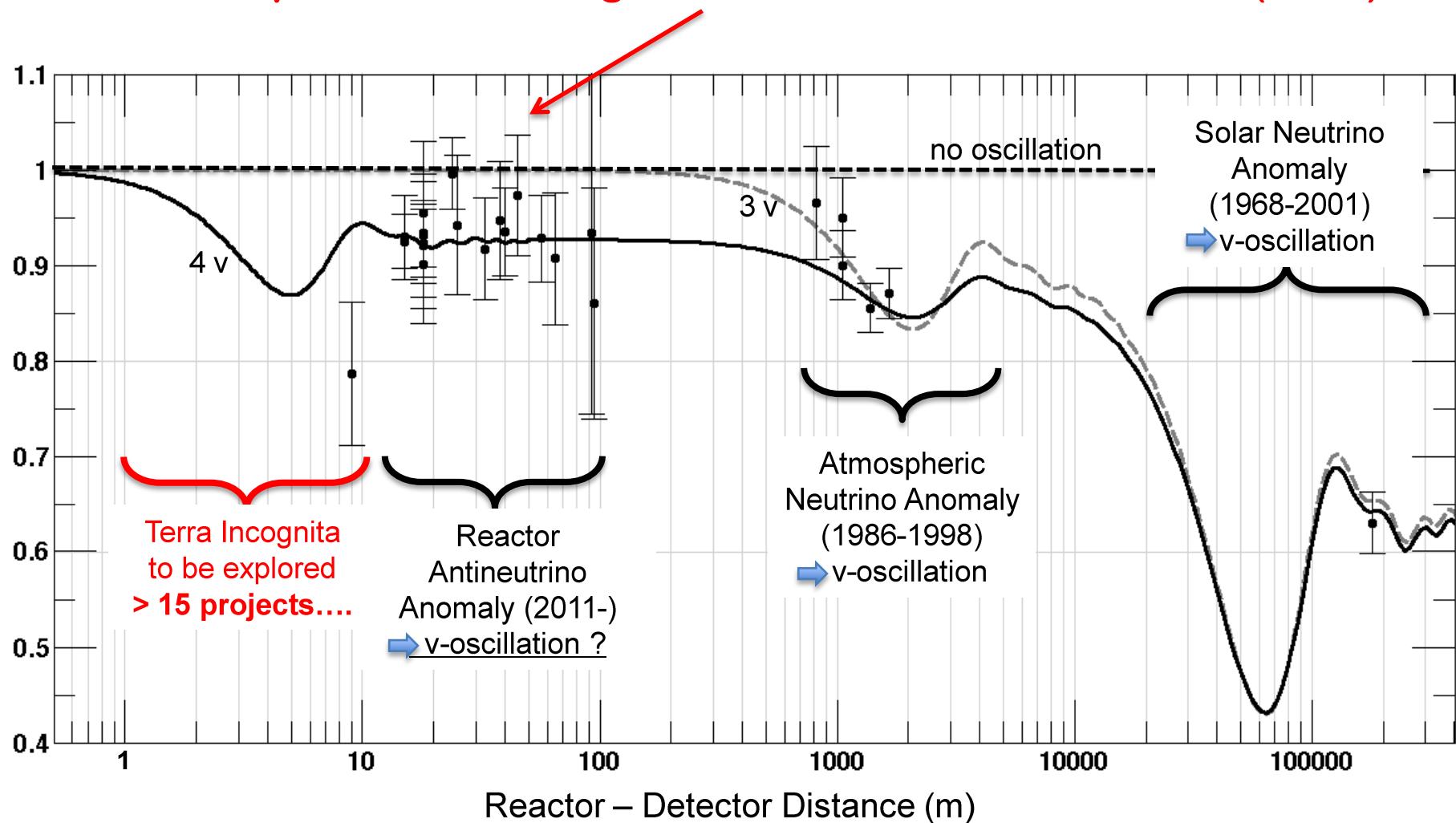
- 3σ anomaly

- Supported by new ^{71}Ga ($^3\text{He}, ^3\text{H}$) ^{71}Ge cross section measurement



The Reactor Anomaly

- Observed/predicted averaged event ratio: $R=0.938\pm0.023$ (2.7σ)



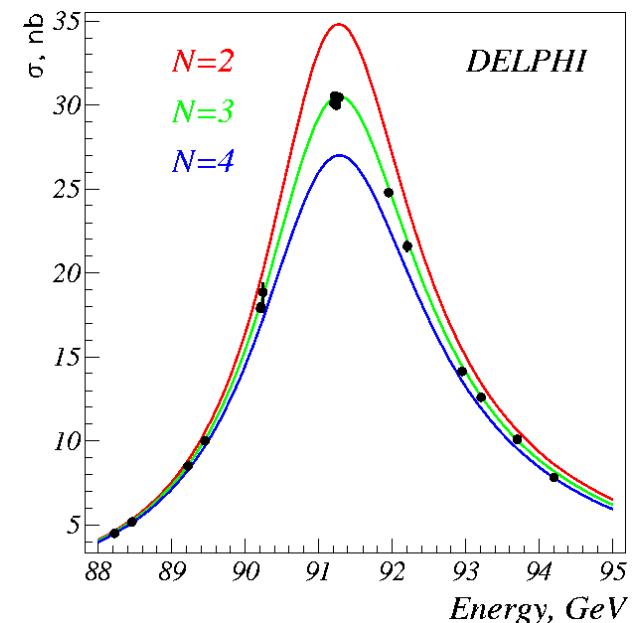
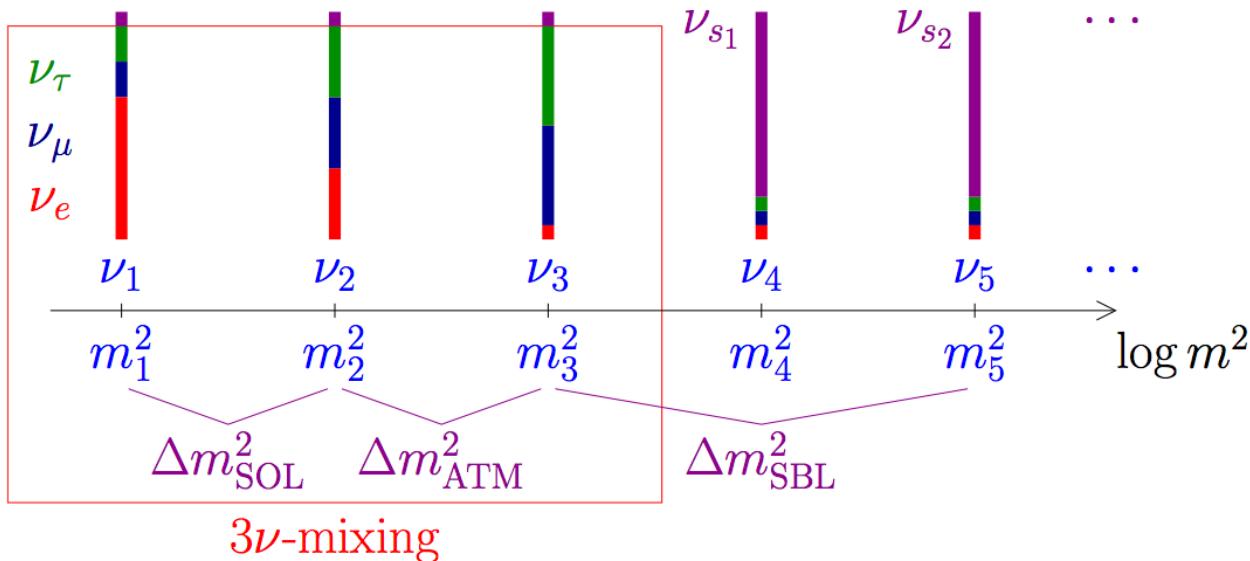
The Three Little Neutrinos

And how many big bad sterile ones ?

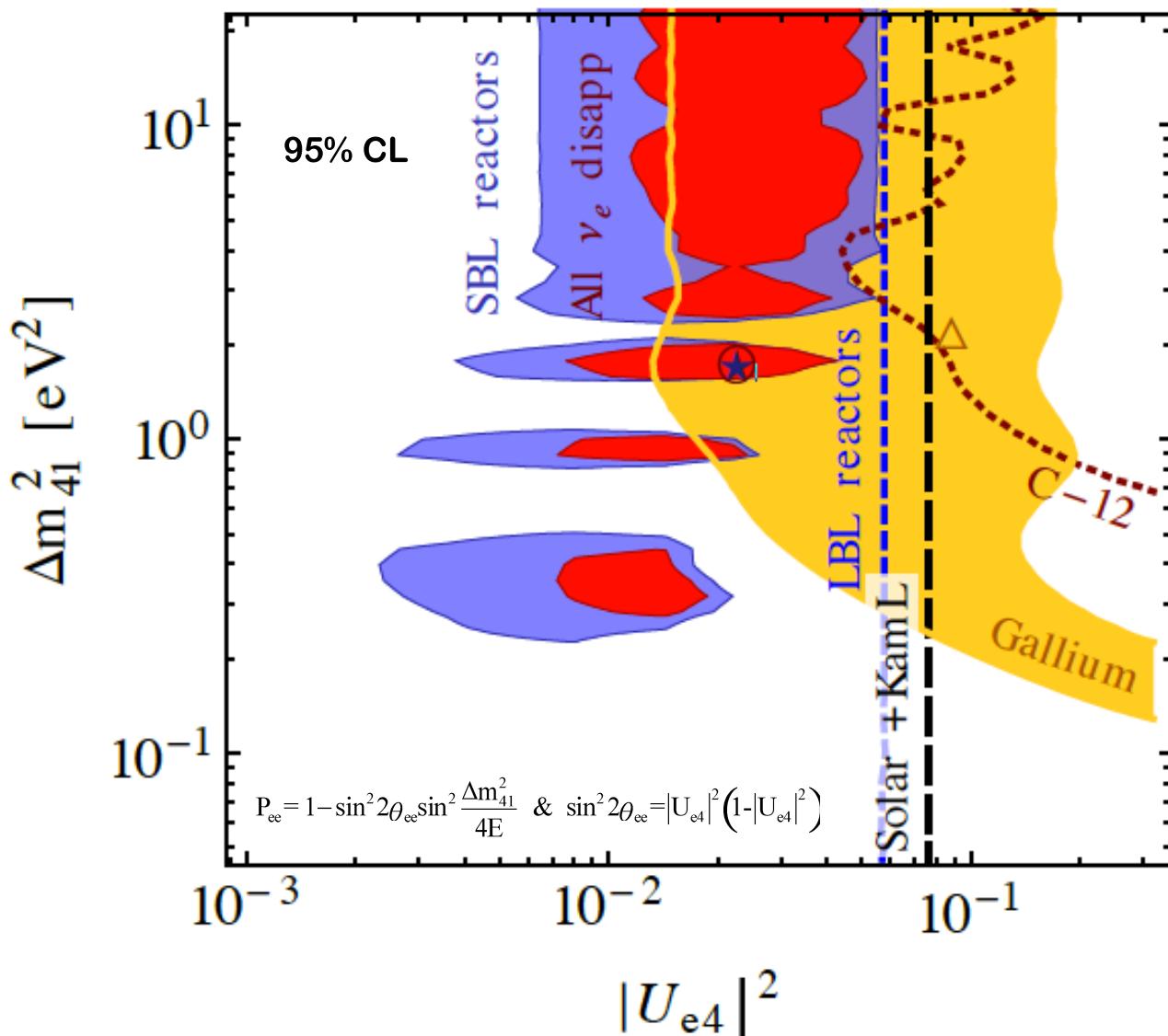
- We know only 3ν couple to Z boson: DELPHI

→ new ν must be sterile

- Explain the anomalies by mixing and oscillations
- You can add as many of them as you want (as soon as they are discreet enough)



A 3+1 hypothesis



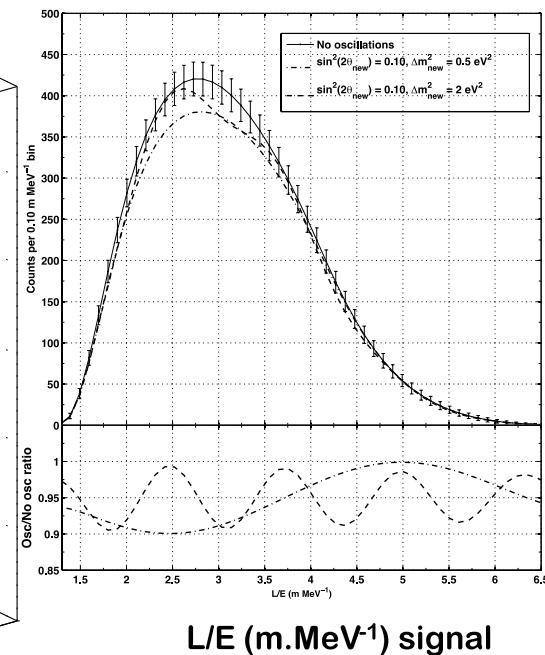
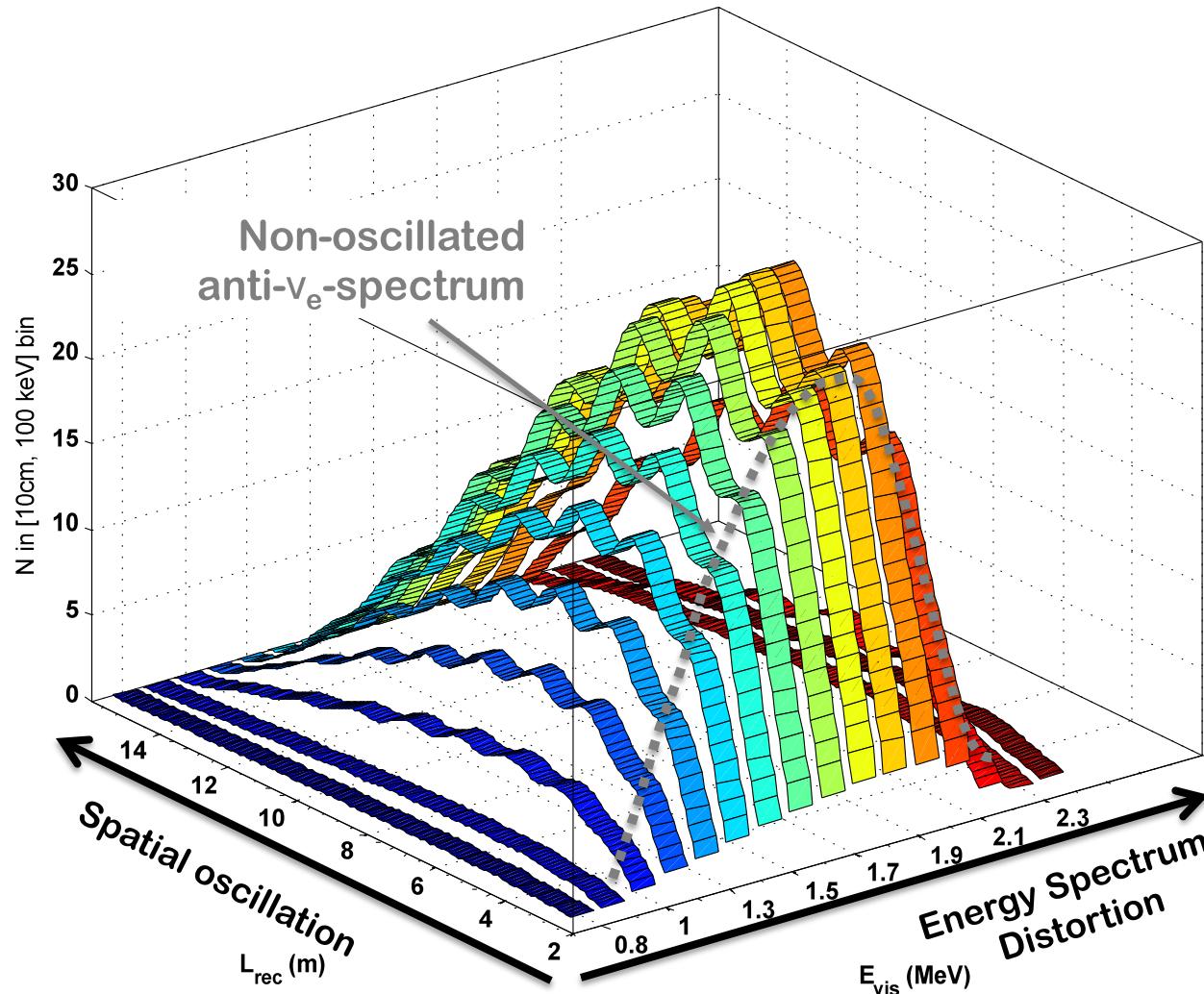
Testing $\bar{\nu}_e$ disappearance anomalies

- For the anomalies: comparison between data and event prediction
 - Search for L, E, L/E pattern (shape only)
 - Complement with a rate analysis
- Input from Sterile Neutrino Fits
 - $\Delta m^2 \approx 0.1\text{--}10 \text{ eV}^2 \rightarrow L_{\text{osc}}(m) = 2.5 \frac{E(\text{MeV})}{\Delta m^2(\text{eV}^2)} \approx 1\text{--}10 \text{ m}$
 - $\sin^2(2\theta_{\text{new}}) \approx 0.01\text{--}0.2$
- Experimental Specifications
 - $\Delta m^2 \approx \text{eV}^2$: compact source $\ll 1\text{m}$ & vertex resolution $\ll 1\text{m}$
 - $\sin^2(2\theta_{\text{new}})$: experiment with few % stat. syst. uncertainties

Expected $\nu_e \rightarrow \nu_s$ Oscillation Signal

$$\frac{d^2 N(R, E_\nu)}{dR dE_\nu} = \mathcal{A}_0 \cdot n \cdot \sigma(E_\nu) \cdot \mathcal{S}(E_\nu) \cdot \mathcal{P}(R, E_\nu) \int_0^{t_e} e^{-t/\tau} dt,$$

2-D reconstructed spectrum for $U_{e4} = 0.25$ and $\Delta m_{41}^2 = 3.0 \text{ eV}^2$

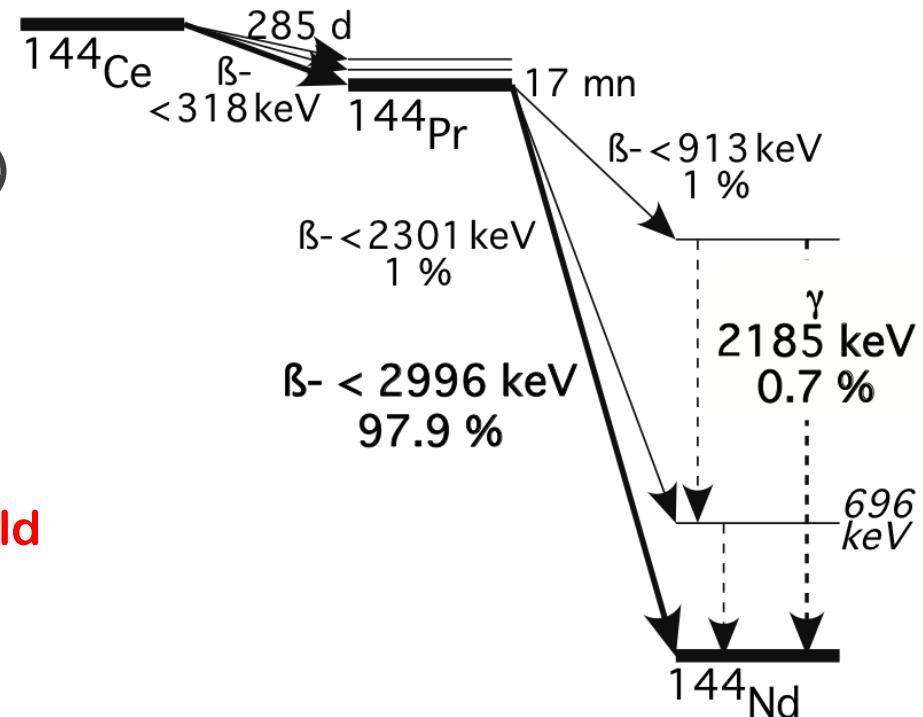


Antineutrino Source: ^{144}Ce - ^{144}Pr

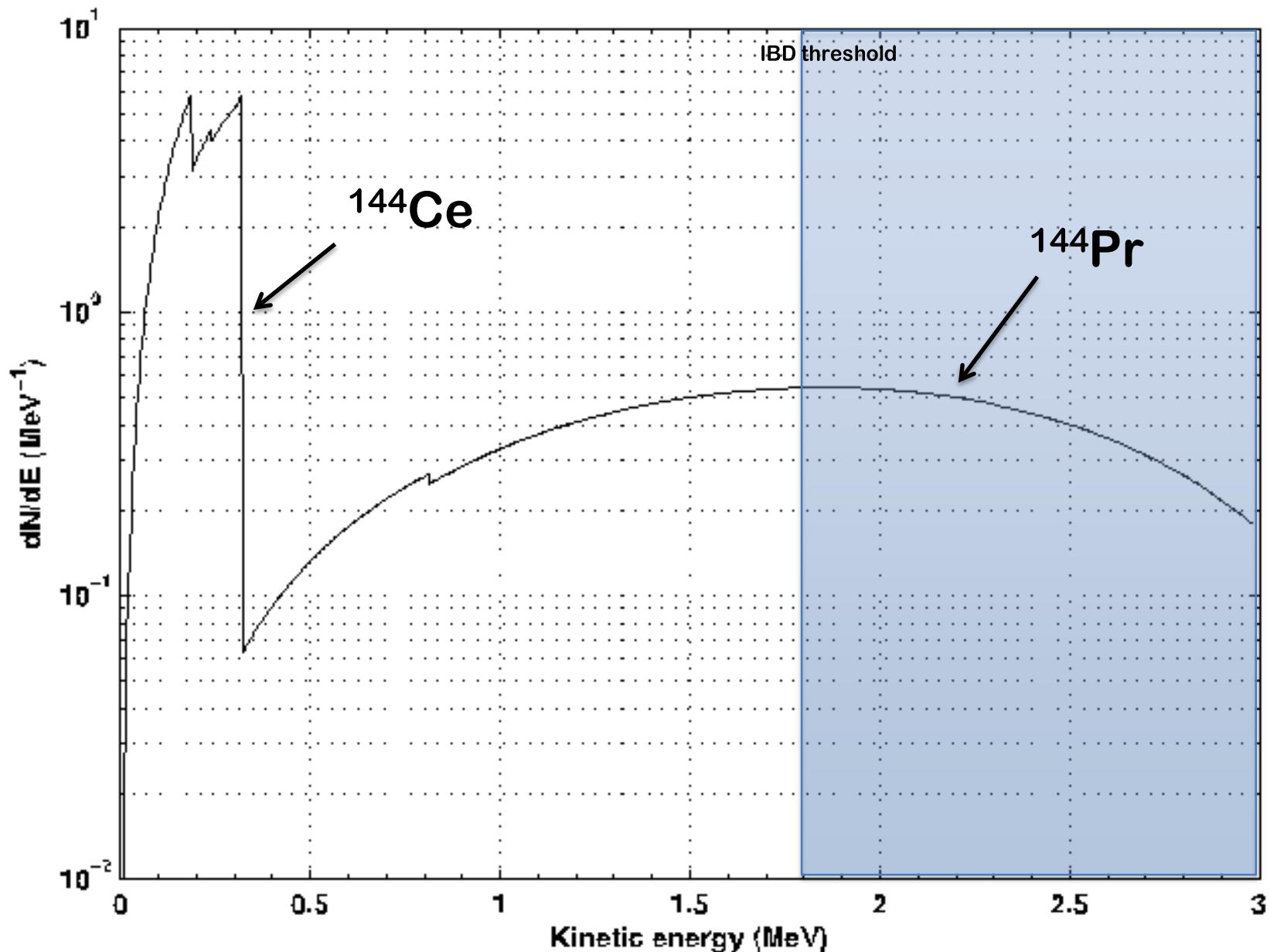
(ITEP N°90 1994, PRL 107, 201801, 2011)



- $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ ($Q=1.8 \text{ MeV}$)
 - High IBD cross section $\rightarrow > 3 \text{ PBq activity}$
 - (e^+, n) detected in coincidence \rightarrow low backgrounds
- ^{144}Ce - ^{144}Pr
 - Abundant fission product (5%)
 - ^{144}Ce : long-lived & low- Q_β
Enough time to produce, transport and use
 - ^{144}Pr : short-lived & high- Q_β
 $\bar{\nu}_e$ -emitter above IBD threshold

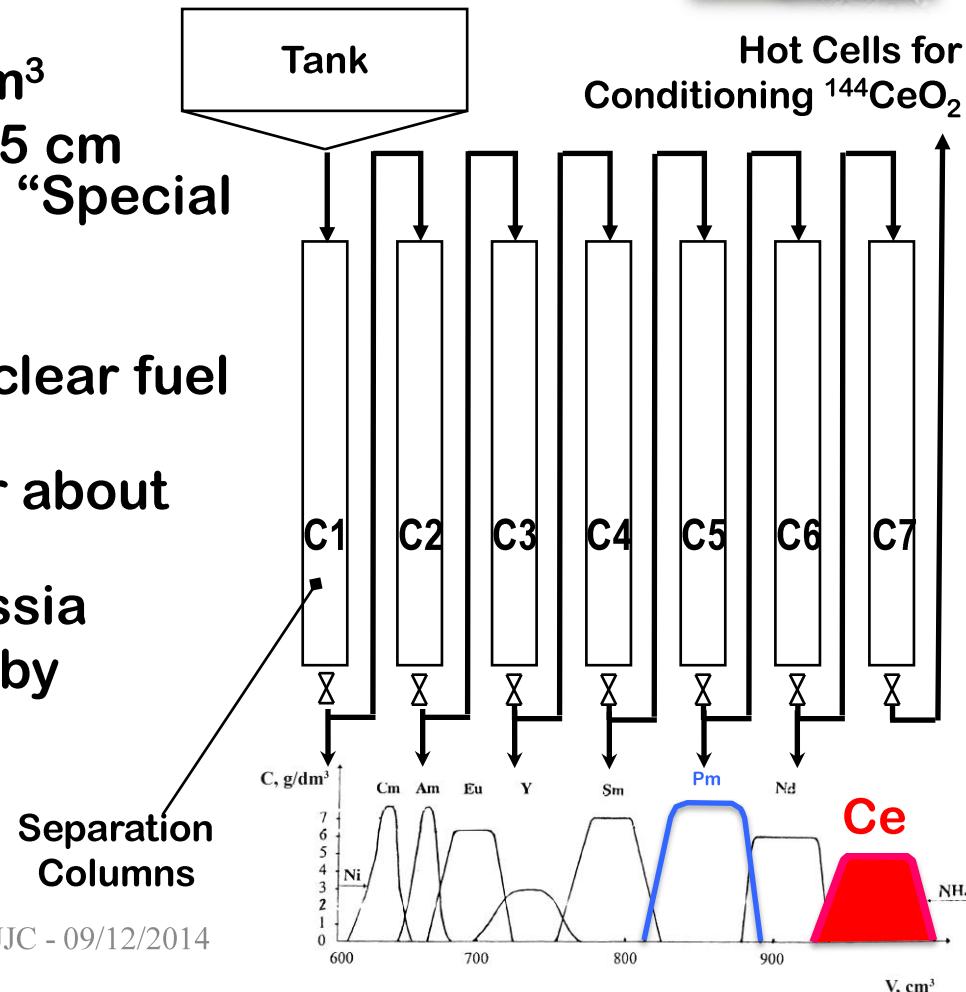


^{144}Ce - $^{144}\text{Pr} \nu$ Spectra



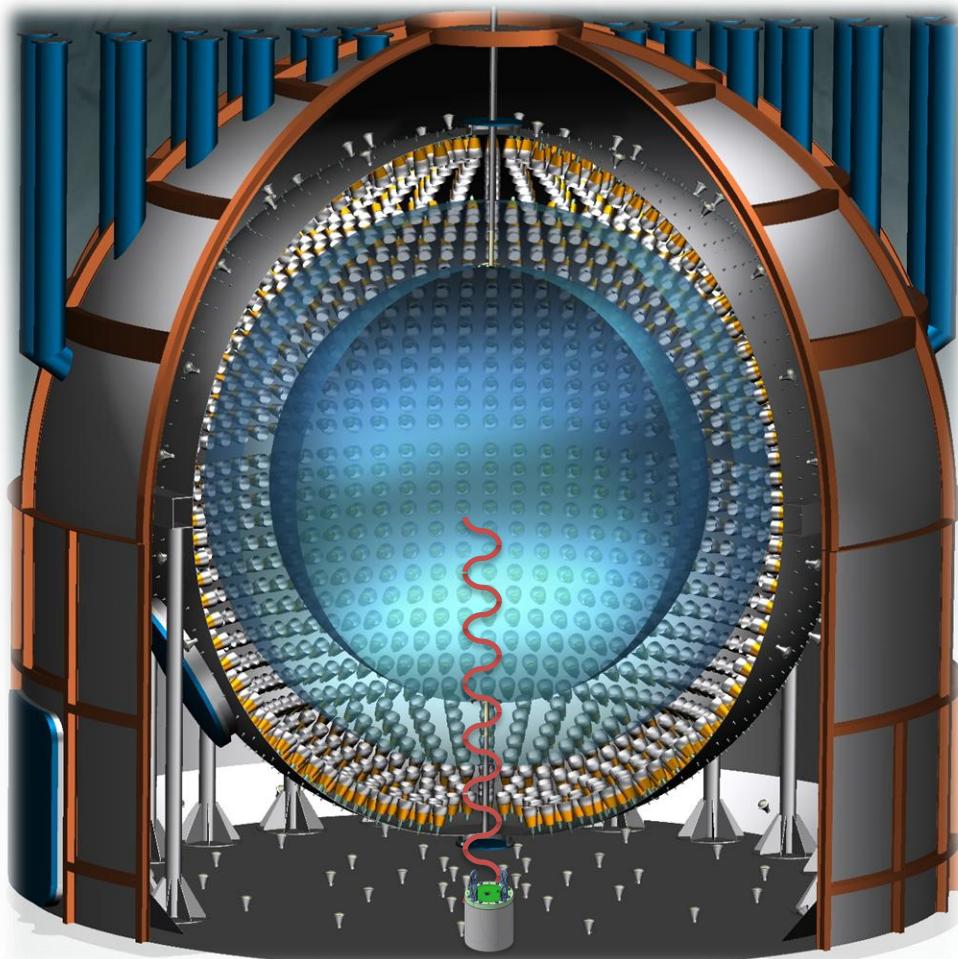
^{144}Ce - ^{144}Pr Antineutrino Generator

- β activity driven by ^{144}Ce between 3.7 and 5.5 PBq
- Chemical form : cerium oxyde CeO_2 compressed powder
- Density : between 4 and 6 g/cm³
 - Must fit inside a D:H=15:15 cm steel double capsule of “Special Form of Radioactive Material”
- Extracted from fresh spent nuclear fuel (<2 years)
 - 10 t of fuel reprocessed for about 30g of ^{144}Ce
 - Produced at PA Mayak, Russia
 - Rare earths are separated by column chromatography
 - 8 months



Oscillometry in BOREXINO

Search for an oscillation pattern inside LS target
Compare observed to expected ν rate



Experimental layout

- Radioactive ν source in tunnel below the detector ($d=8.43$ m)

Detector Specifications (1 MeV)

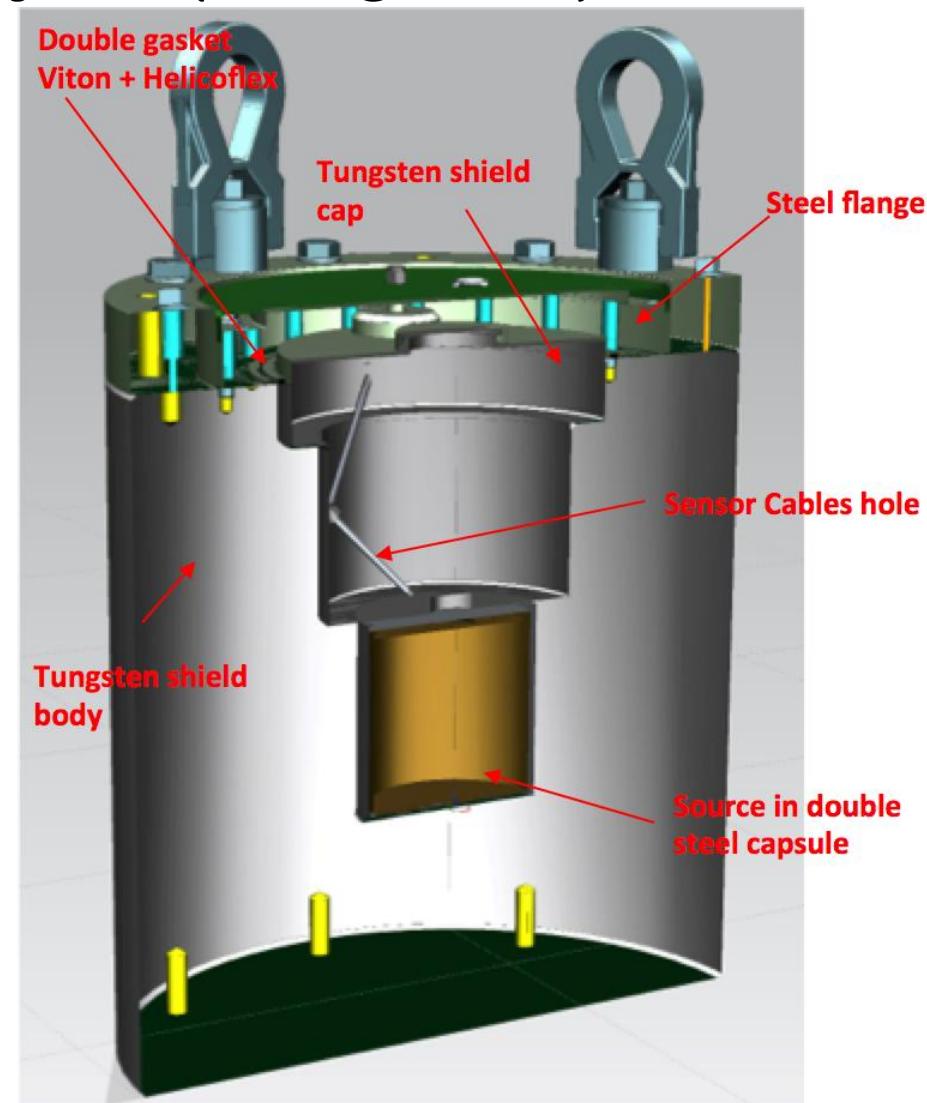
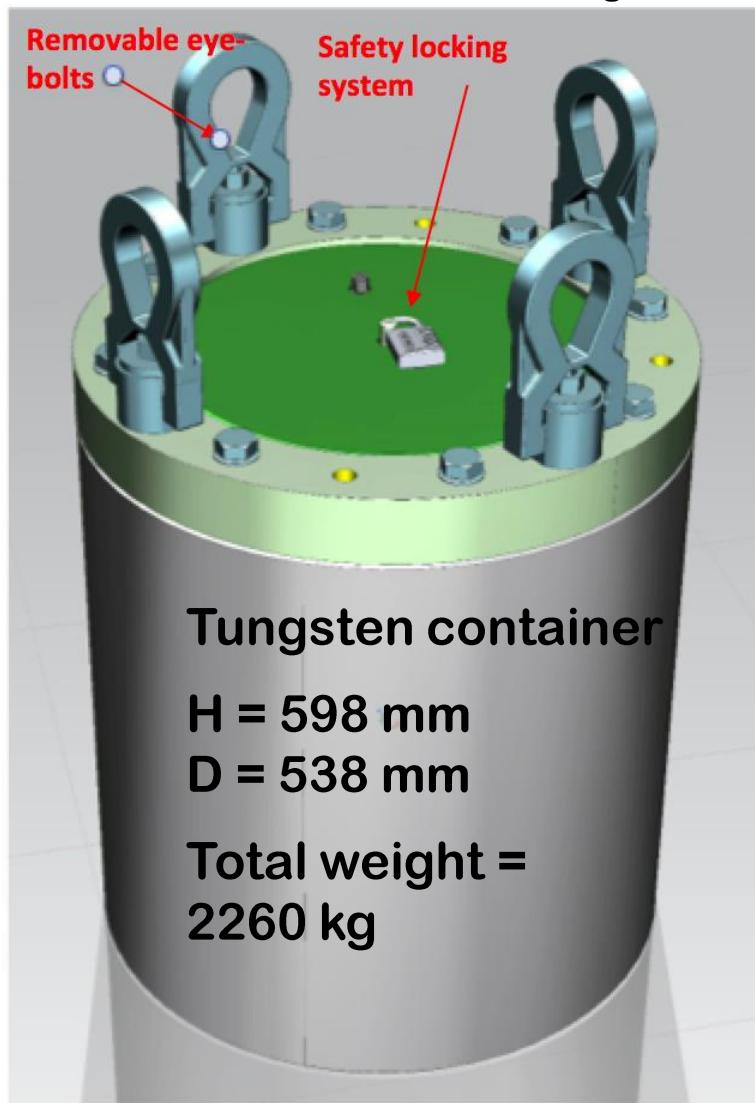
- Energy resolution: 5%
- Vertex resolution: 15 cm
- Fiducial mass: 280 tons
- #H: $1.7 \cdot 10^{31}$
- R < 4.25 m

Antineutrino Generator

- ${}^{144}\text{Ce}/\text{Pr} \beta^- E_\nu < 3 \text{ MeV}$
- ${}^{144}\text{Ce}-{}^{144}\text{Pr} > 3.7 \text{ PBq}$
- Exposure: 1.5 yrs
- Events (1.5yrs) $\sim 10^4$

High-Density Tungsten Alloy Shielding

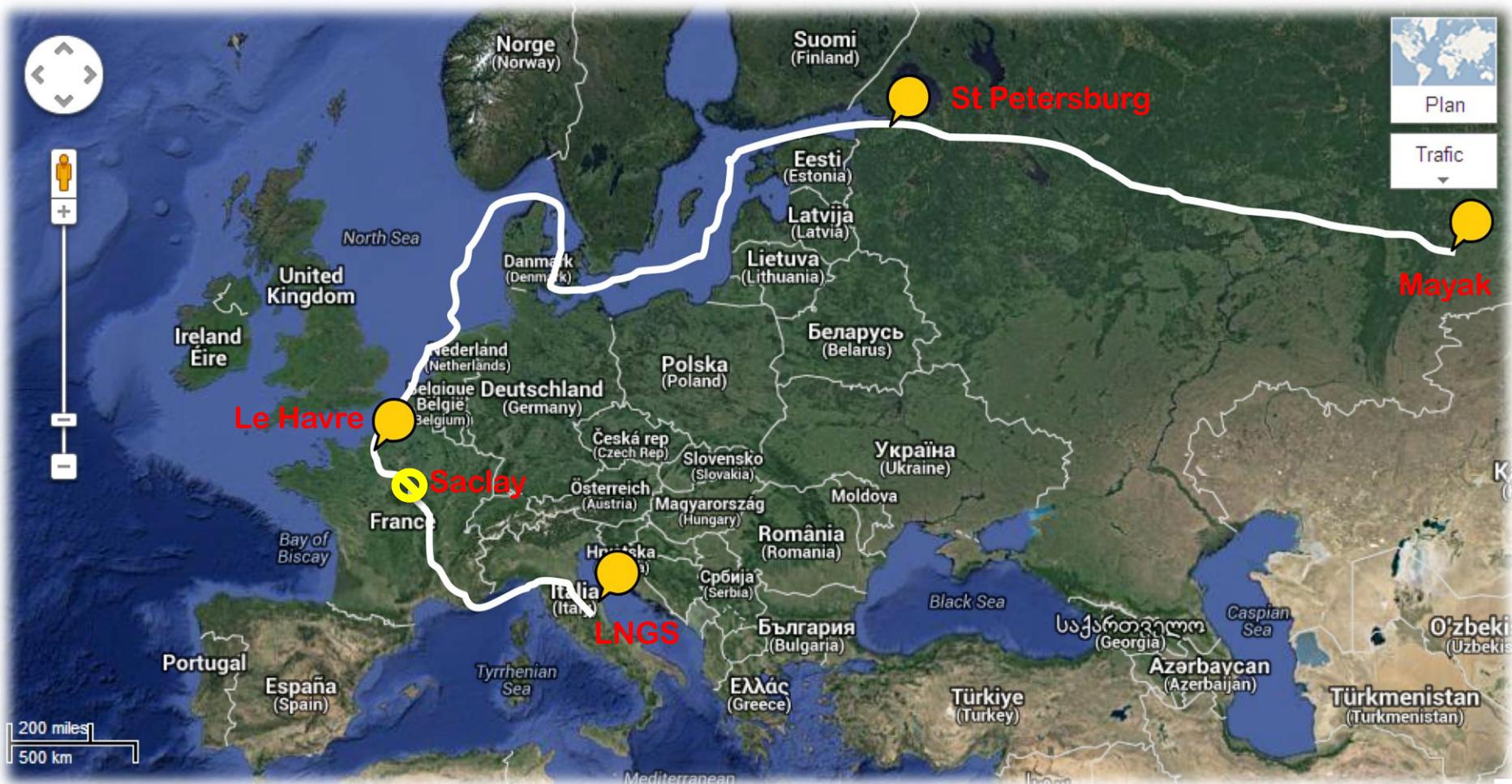
For safety and physics (background)



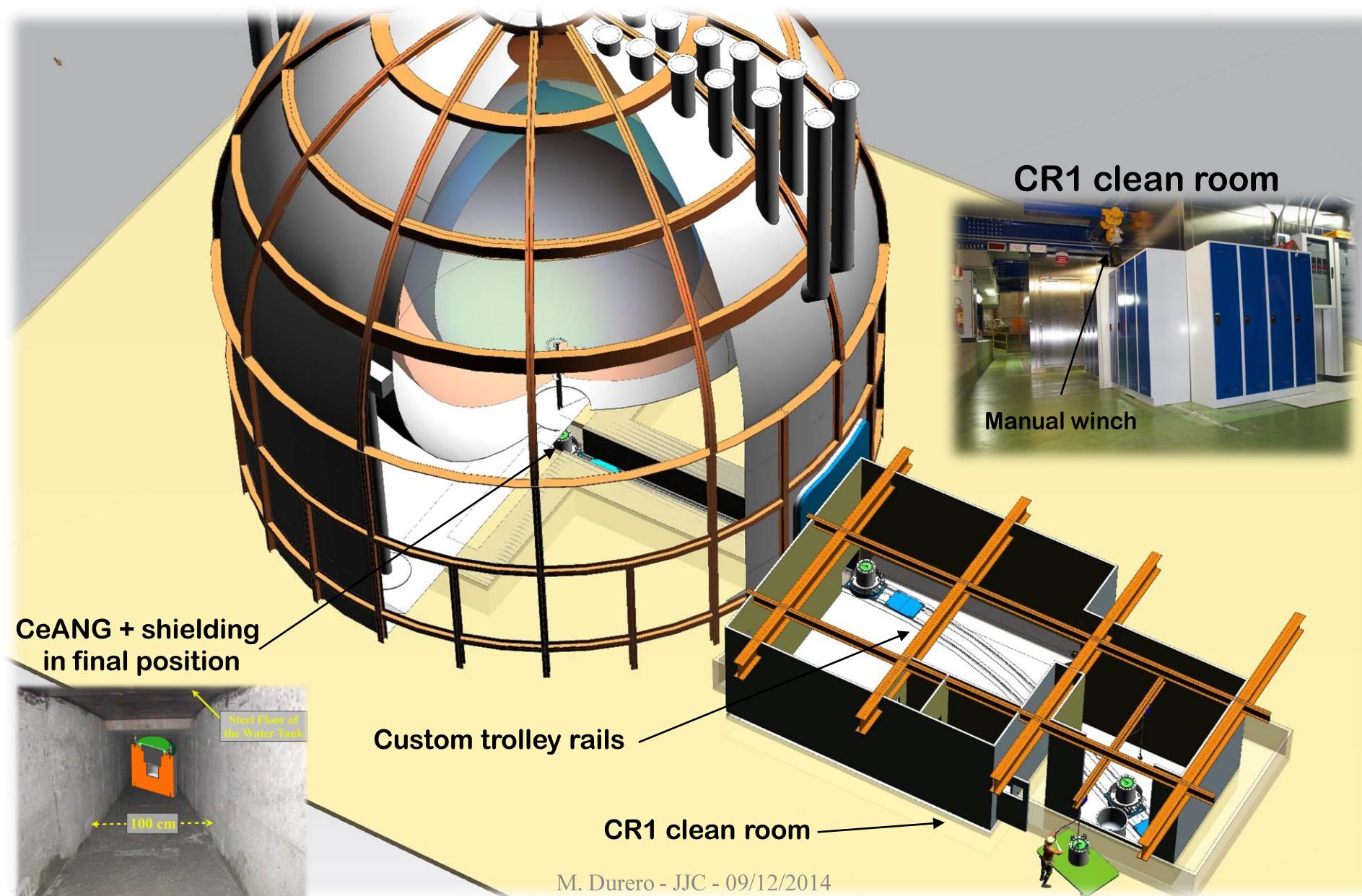
Transport Route to LNGS



- In Areva-TNI spent nuclear fuel container TN-MTR
- IAEA Regulations for the Safe Transport of Radioactive Material
- Train / Dedicated vessel / Truck : AAPC published on 15/10/2014



Inserting the CeANG beneath BX



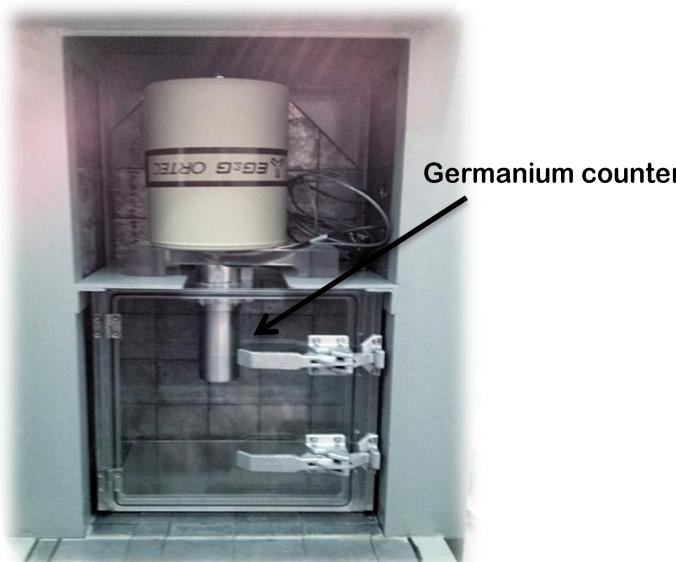
Sensitivity to CeANG parameters

- **^{144}Ce - $^{144}\text{Pr} \beta/\nu$ spectra needed with % level precision**
 - Power-to-activity conversion factor: $216.0 \pm 1.2 \text{ W/PBq}$
 - Prediction of the IBD rate depends on the ^{144}Pr spectral shape
- **Major backgrounds come from the source itself**
 - Neutrons from minor actinides (reminder: ^{144}Ce is extracted from spent nuclear fuel)

- Mass spectroscopy &
 γ spectroscopy
- \rightarrow Characterization of
impurity content

- spectrum modeling
- Fermi theory + corrections
- QED, finite size, finite mass, screening...

- β spectroscopy
- \neq measurements for
- \neq pros & cons:
- Si counter, plastic...



- Characterization of β & ν emission of the whole spectrum.
- Using ^{144}Ce - ^{144}Pr and ^{144}Pr alone
- Assess the mean β energy at 0.5 %
- Assess the expected number of interactions at 1 %
- Safeguard against spectrum shape distortions

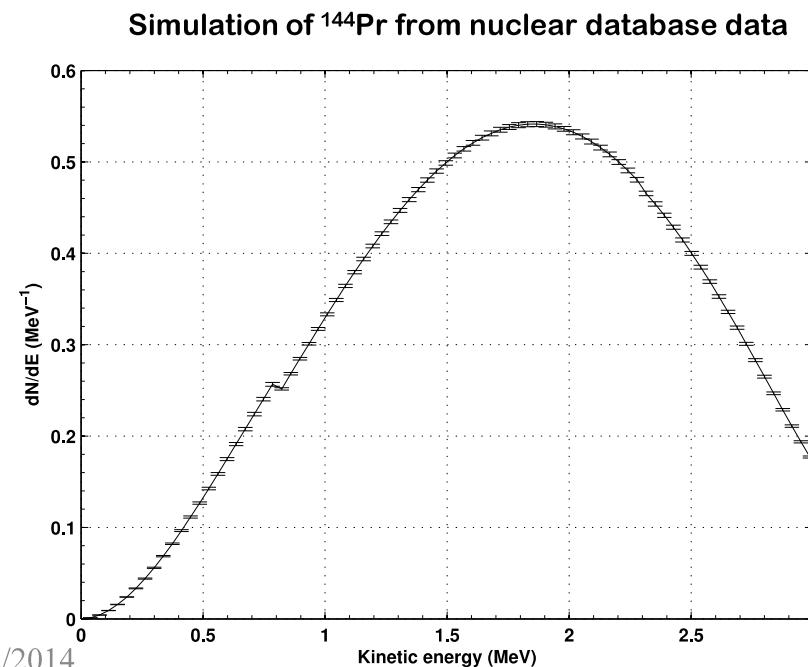
Antineutrino spectra modeling

- Fermi's Theory spectrum: $N(W) = K_p W (W - W_0)^2 F(Z, W) C(Z, W)$
 - $W = E/m_e$: Reduced electron energy $W_0 = Q/m_e + 1$: maximal energy
 - F : Fermi function: influence of Coulomb field from point-like nucleus
 - C : Shape factor from nature of the transition (phase space factor) and various small corrections (1% order of magnitude).
- β^- transitions behavior differs according to:
 - Change in nucleus quantum numbers & parity
 - Ratio between weak axial and vector currents

	Branching ratio	Q_β (keV)	Transition type
^{144}Ce	76.5 %	318.7	1 st non-unique forbidden
	3.9 %	238.6	1 st non-unique forbidden
	19.6 %	185.2	1 st non-unique forbidden

	Branching ratio	Q_β (keV)	Transition type
^{144}Pr	97.9%	2997.5	1 st non-unique forbidden
	1.04%	2301.0	1 st unique forbidden
	1.05%	818.8	Allowed

- Non-unique forbidden β^- -branches
- Vague knowledge of shape factor
- need for a measurement



β spectroscopy on source samples



- $3 \times 10 \text{ cm}^3 \text{ Ce}(\text{NO}_3)_3$ - 59 kBq in ^{144}Ce each
- Secular equilibrium between ^{144}Ce and ^{144}Pr
 - ➡ Low energy is dominated by ^{144}Ce
 - ➡ Study of chemical separation for ^{144}Pr



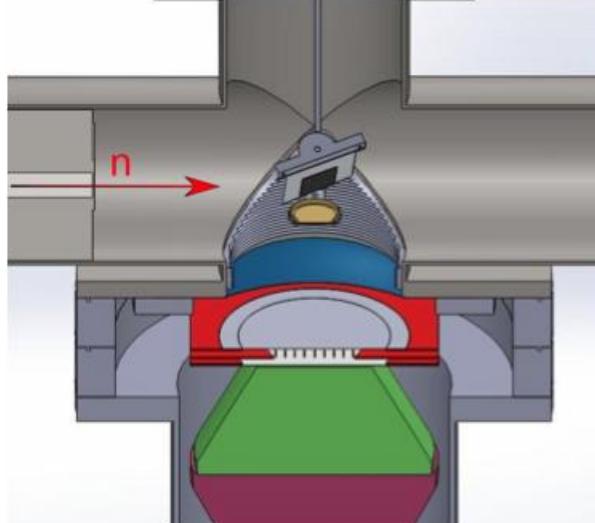
With ^{144}Pr only:

- Mean life time: 17 min
 - Spectrometers set up close to the chemical lab
 - Some setup can't be used (readying is too slow)
- Detection methods:
 - ^{144}Pr solution in liquid scintillator + PMTs
 - ^{144}Pr solid deposit in PS + PMTs
 - ^{144}Pr solid deposit onto silicon detector (study ongoing)
- Complementing each others:
 - ≠ sensitivity to backscattering
 - ≠ measuring range
 - ≠ simulation flaws

β spectroscopy current setups

TUM spectrometer: (cf. PRL. 112, 122501)

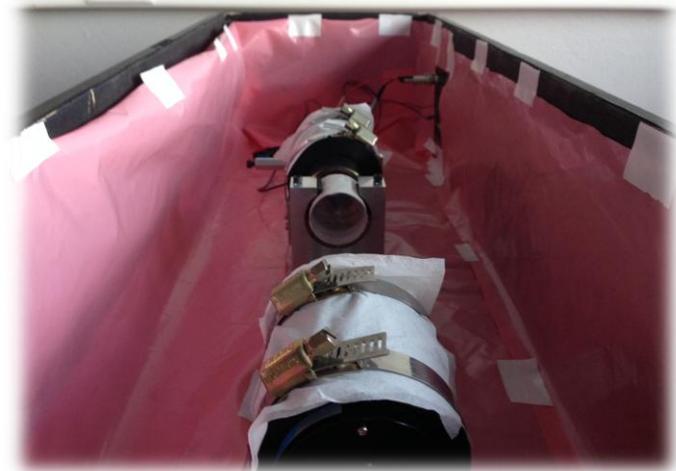
- Multiwire chamber as a γ veto:
 - Density low enough to not be sensitive to γ
- Plastic scintillator +1 photomultiplier for main detection
- Need vacuum to operate



IRFU-LNHB new setup:

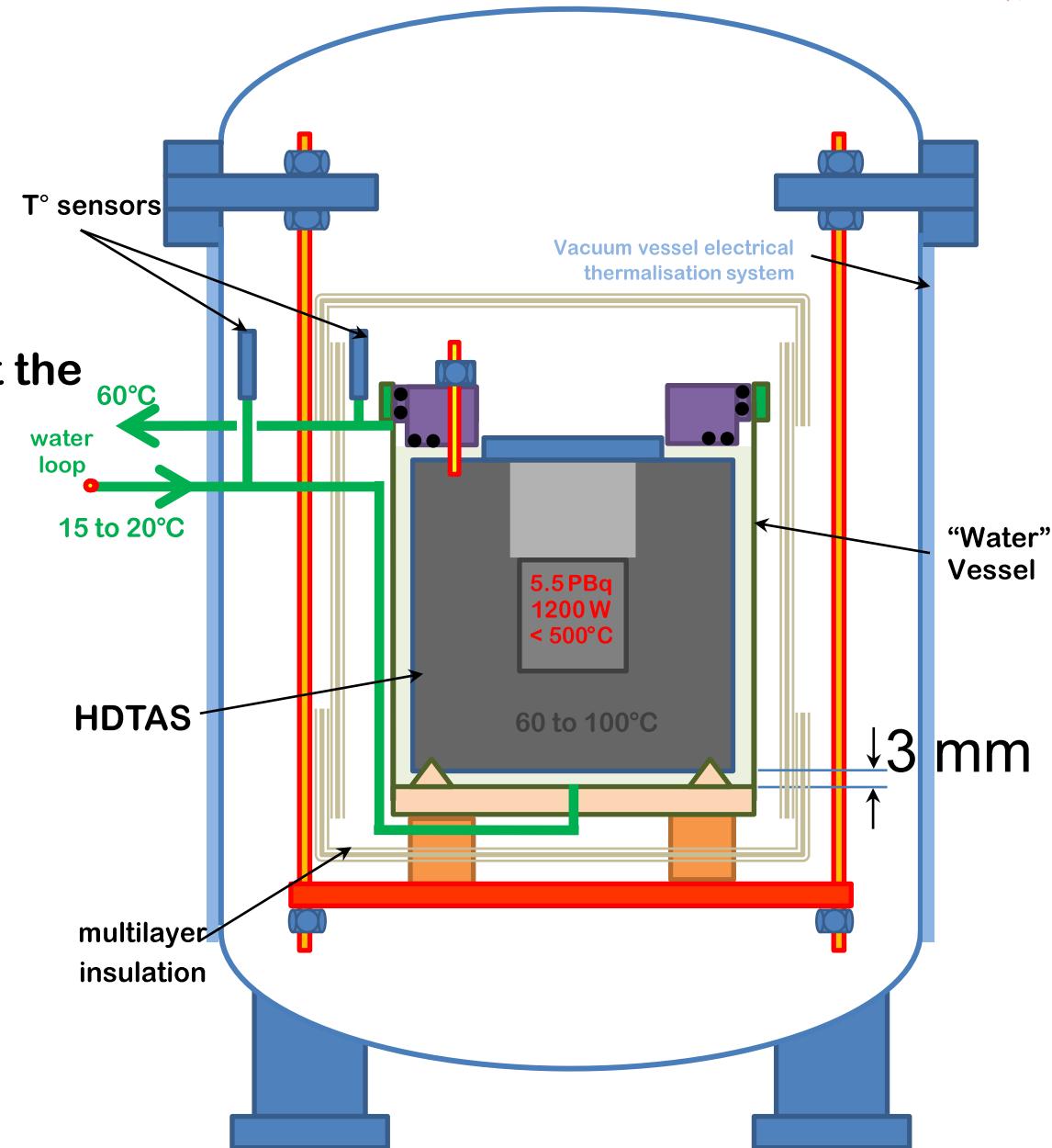
- Plastic scintillator cylinder
- 2*High quantum efficiency PMTs
- Optical coupling
- Source will be sealed in plastic
- High low energy statistics but no γ rejection
- High energy β not fully confined

CEA spectrometer



Activity measurement

- Measure CeANG Heat with a $\approx 1.5\%$ precision
- Method: calorimetry
- Mesure water flow and T° at the in/outlets: $\dot{Q} = \dot{m}C(T_{in}-T_{out})$
- Preventing heat leaks
 - Conduction
 - Suspension platform
 - Insulation
 - Convection
 - Vacuum vessel
 - Radiation
 - Multilayer insulation
 - Vessel thermalization
- Calibration with a dummy electrical source



- SOX will test reactor antineutrino anomaly with a characteristic energy and baseline dependent signal
- Cerium Antineutrino Generator: big steps are settled
 - >3.7 PBq ^{144}Ce - ^{144}Pr , production in 2015 from spent nuclear fuel
 - Settled transport plan
 - Shielding ordered
- To be deployed in Borexino detector by the end of November 2015.
- Serious challenge for now: accurate CeANG characterization
 - Multiple cross-checked measurements
 - Wish to obtain the new state of the art ^{144}Pr spectrum
 - Dedicated apparatuses for subpercent spectrum & activity measurements

Thanks for your attention !



More information on the CeLAND proposal, arXiv:1312.0896, the SOX proposal, arXiv:1304.7721, and the article arXiv:1411.6694 to be published.