XVII International Workshop on Neutrino Telescopes

13-17 March 2017 Venezia, Palazzo Franchetti - Istituto Veneto di Scienze, Lettere ed Arti

The SOX experiment

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on behalf of the SOX collaboration

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European Research Council
Project N. 320873
P.I. M. Pallavicini

European Research Council
StG N. 307184.
P.I. T. Lasserre

INFN

Scientific motivations

The Standard Model of neutrino oscillations

$$\Delta m^2_{32} \approx \Delta m^2_{31} = 2.4 \cdot 10^{-3}\ eV^2$$
$$\Delta m^2_{12} = 8 \cdot 10^{-5}\ eV^2$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

The anomalies

- LSND — $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ — 30 m
- MiniBoone — $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and $P(\nu_\mu \to \nu_e)$ — 540 m
- GalleX, SAGE — ^{51}Cr - ^{37}Ar — 1.9 m - 0.6 m
- Reactors — $\bar{\nu}$ flux — 10 -100 m

Appearance (LSND, MiniBoone)

Deficit (GalleX, SAGE, Reactors)

cannot be explained by the same matrix

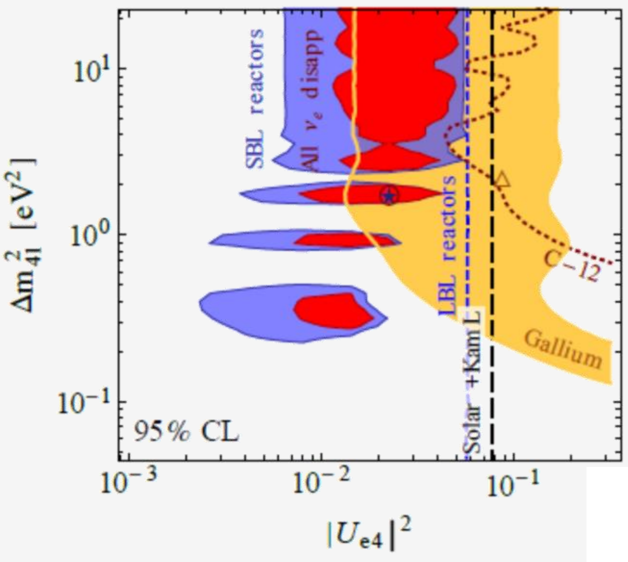
All of these hint to $\Delta m^2 \approx$1-10 eV^2 mass scale

The hypotesis of the sterile neutrinos

Sterile neutrino properties

- no SM interactions
- no coupling with Z boson (LEP)
- mixing with active ν's

Combined analysis: 3+1 scenario



Kopp et al.
arXiv: 1303:3011

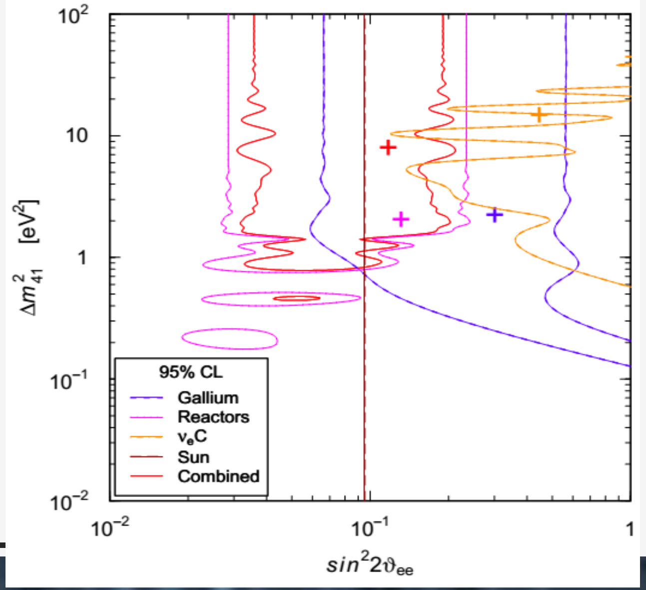
$$P_{ee} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m^2_{41}L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

0.01-0.2

E=1-10 MeV → L=E/ Δm² =1-10 m

$$L_{osc}(m) = \frac{E(MeV)}{1.27\Delta m^2(eV^2)}$$

Giunti et al. (2013)



Experimental requirements:

→ Precision on L (vertex recontruction and compact source dimension)

→ High sensitivity (low background, large scale detector)

Hunt the sterile neutrino

- **With accelerators** to test the MiniBooNE and LSND signal

  T2K and MicroBooNE

  MINOS-DayaBay ν_μ disappearance $\Delta m^2_{14} < 0.8\ eV^2$ Arxiv:1607.01177 (2016)

- **With artificial source** to test the Gallium anomaly

  RICOCHET **^{37}Ar** ν_e

  SNO+ **^{51}Cr (EC)** ν_e

  BOREXINO-SOX **^{144}Ce-^{144}Pr** $\bar{\nu}_e$ **in 2018!**

- **Others**

  ICeCube: from sterile neutrino induced matter effect in atmospheric neutrino

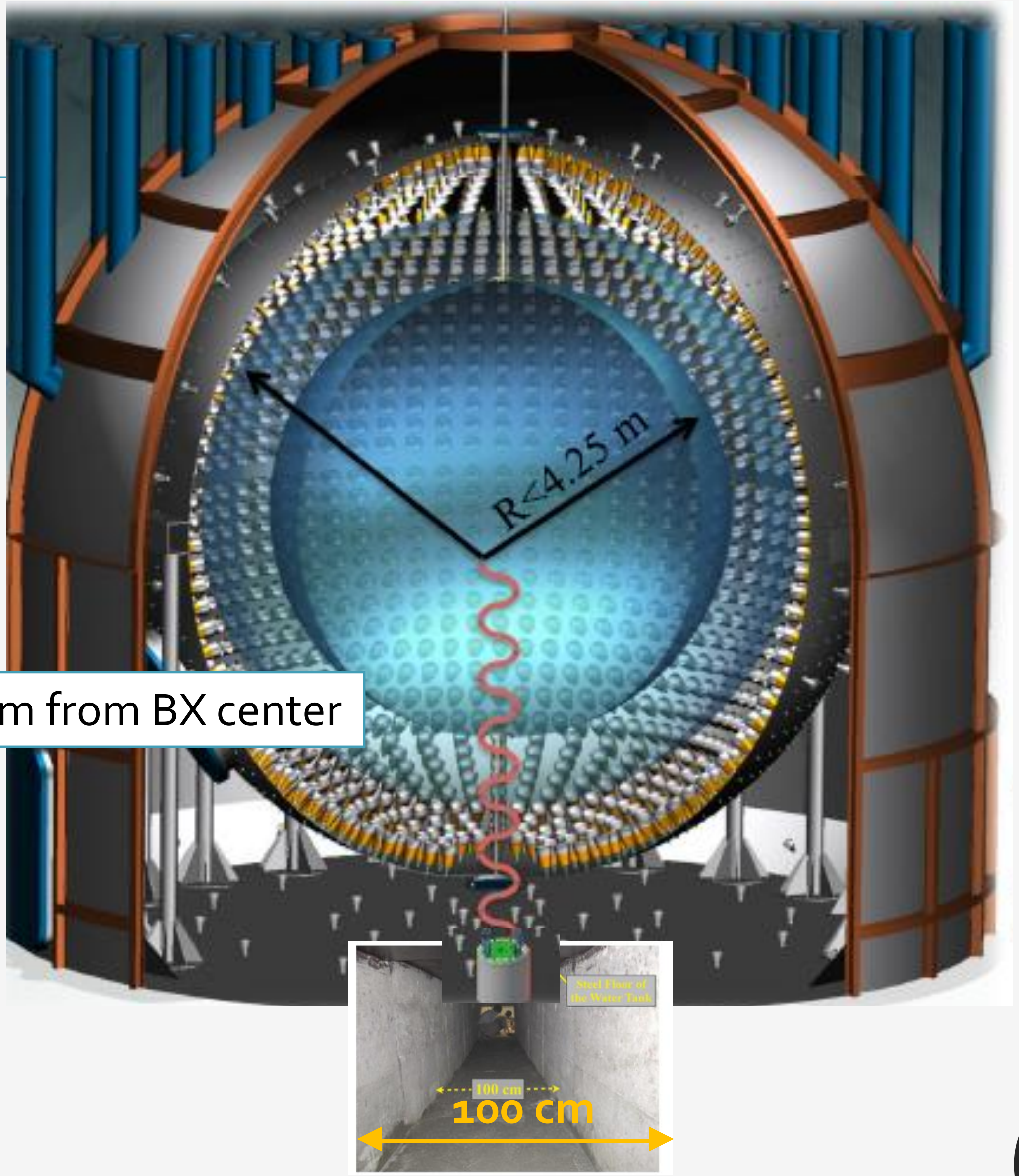
  IceCube 1605.01990 (2016)

The SOX idea

Short neutrino Oscillation with BoreXino

A **^{144}Ce-^{144}Pr** $\bar{\nu}_e$ source (**100-150 kCi**)

under the **Borexino** detector at LNGS Laboratory



Signature signal of new sterile neutrinos:

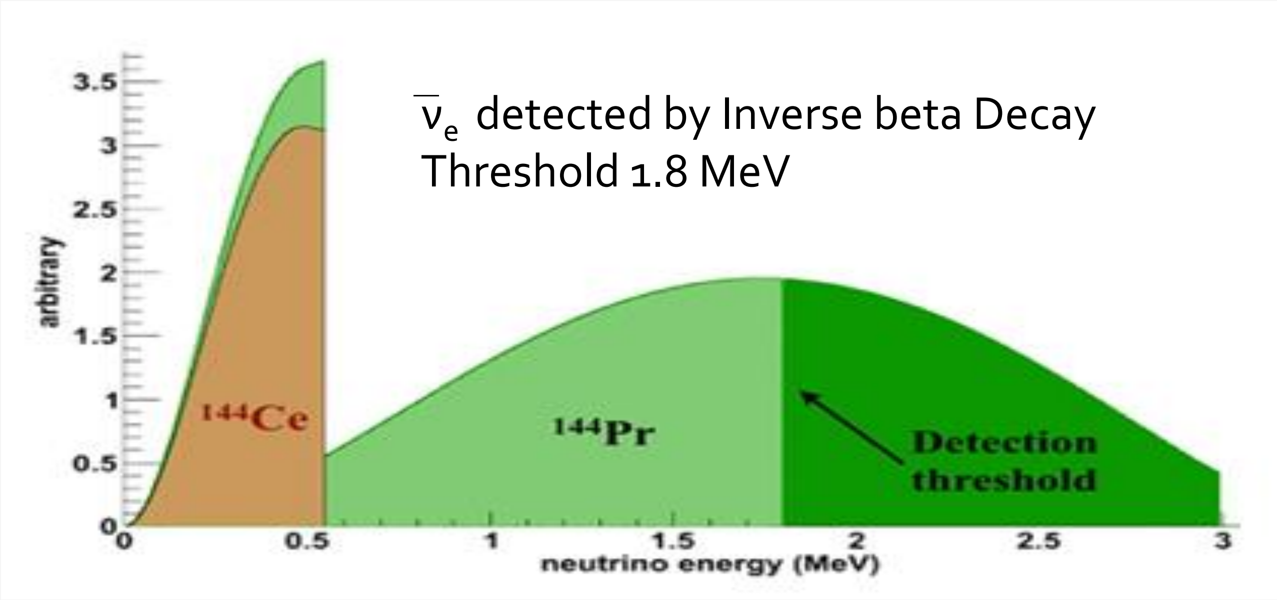
- Deviation from $1/r^2$ behavior of count rates **("disappearance technique")**
- Direct observation of oscillation pattern **("waves")**

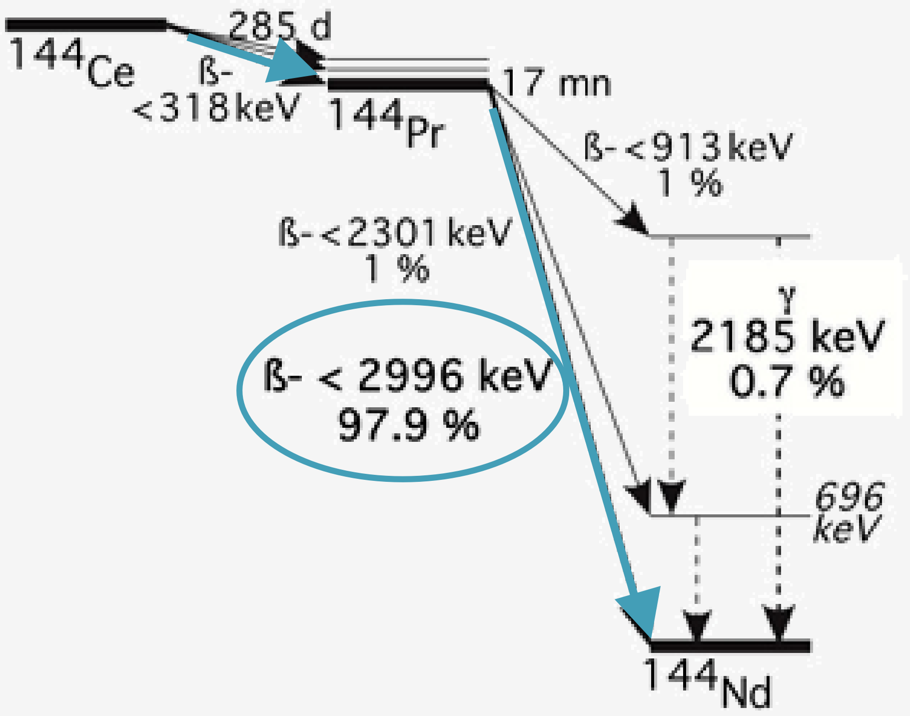
The radioactive source

$^{144}Ce \rightarrow {}^{144}Pr + e^- + \bar{\nu}_e$ long lived with low Q

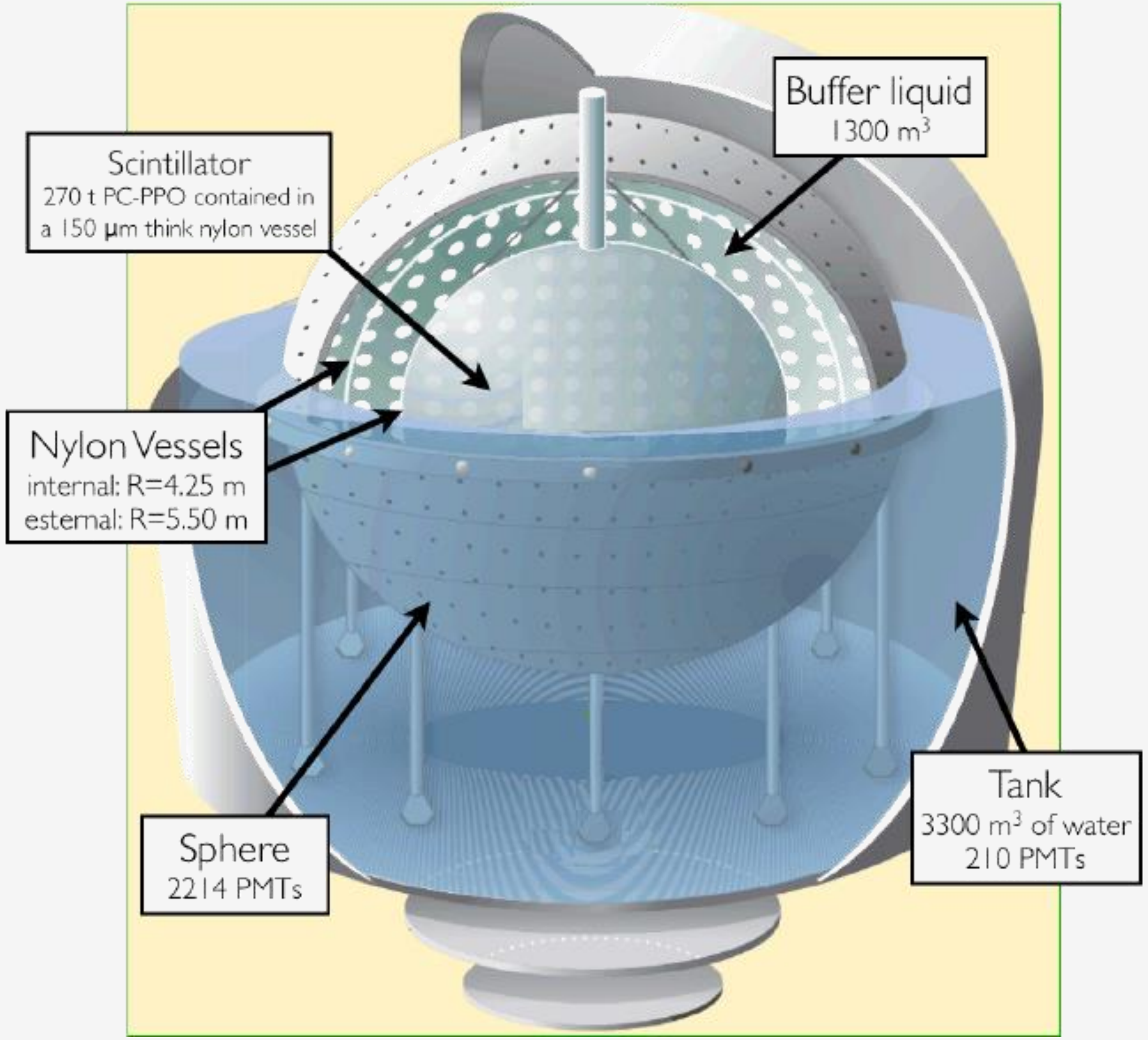
$^{144}Pr \rightarrow {}^{144}Nd + e^- + \bar{\nu}_e$ short lived with high Q above the IBD threshold

Activity : 100 -150 kCi **$T_{1/2}$=285 days**





The Borexino detector



Built mainly, for solar neutrino:

ν + e- → ν + e-

in an organic liquid scintillator

Ultra-low radioactive background

- **Spatial resolution: 12 cm @ 2 MeV**
- **Energy resolution: ~3.5% @ 2 MeV**

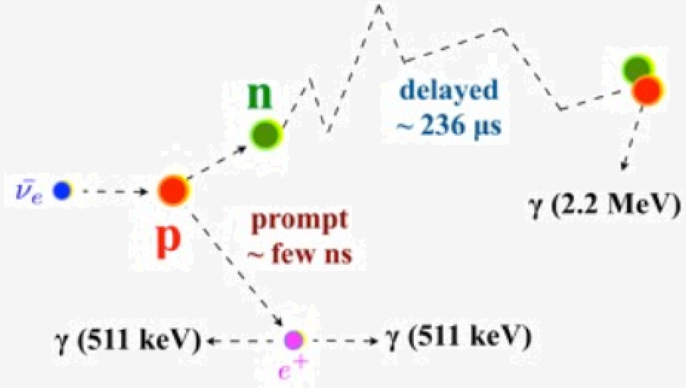
Fiducial volume estimation: 0.7% for ^{7}Be

See G. Bellini's talk

The Borexino detector

The anti-neutrino detection by a coincidence measurement

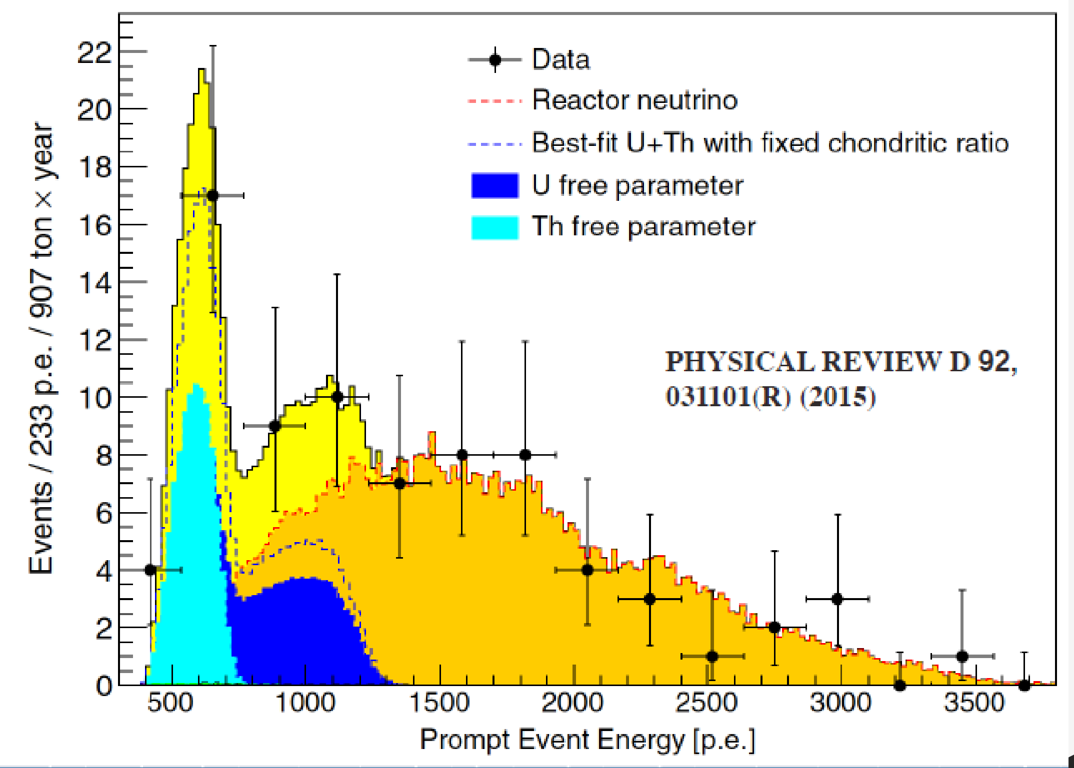
$\overline{\nu}$ + p → n + e+



- **geo-ν**: ~5 ev/y in 300 t
- distant **reactors**: ~10 ev/y in 300 t
- accidental **background**: << 1 ev/y

Ultra-low radioactive background

- **Spatial resolution: 12 cm @ 2 MeV**
- **Energy resolution: ~3,5% @ 2 MeV**



SOX is background free

expected signal: **> 10⁴ events in 1.5 y**

New calibration with many radioactive sources (next October)

Two types of analysis

The rate analysis

We look for a deviation from $1/r^2$ behaviour

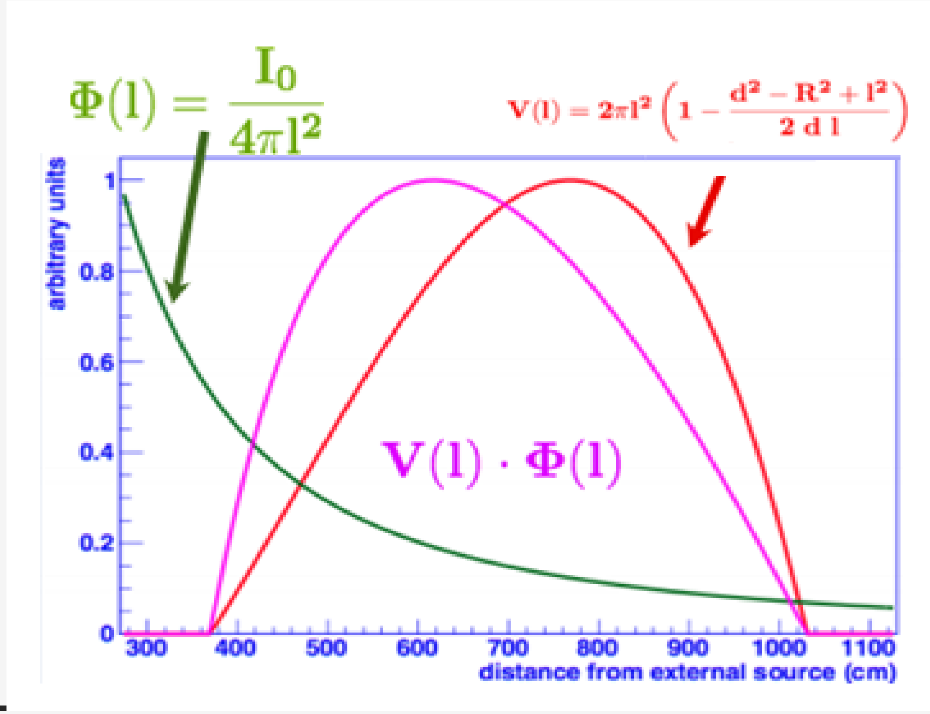
It depends mainly of θ_{ee}
the amplitude of the oscillation

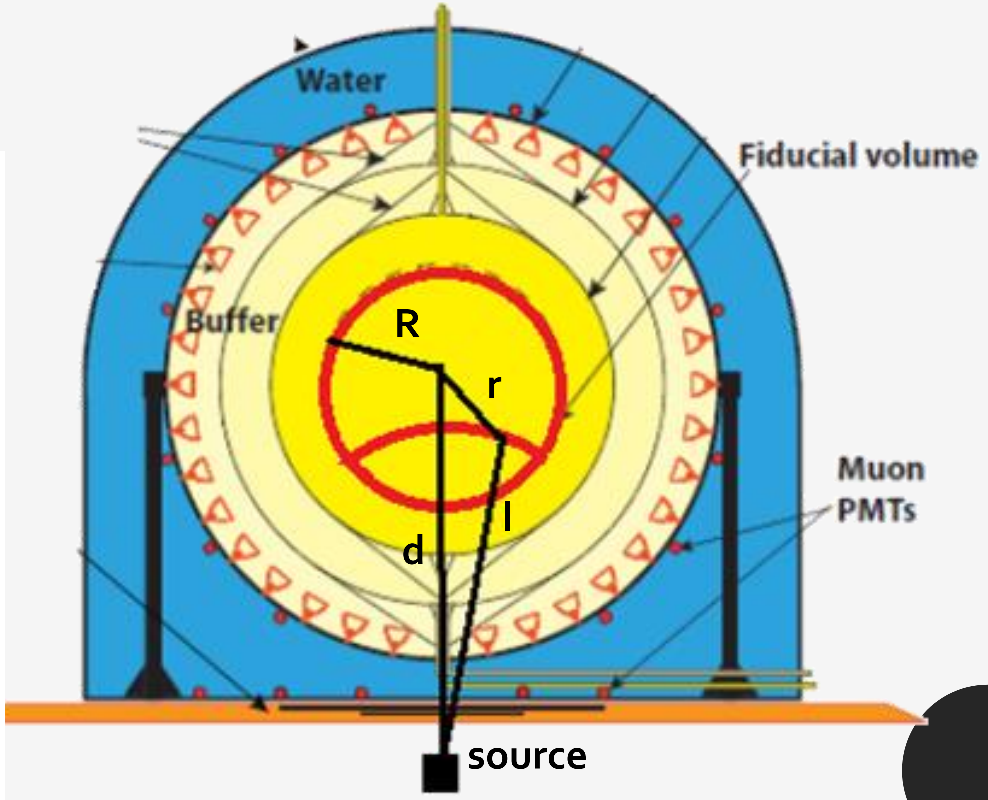
$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$N_0(l, T_1, T_2) = n_e \; \Phi(l) \; V(l) \; P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E, T)}{dT} dT$$

The **sensitivity** depends on:

- Error on source activity
- Error on $\overline{\nu}$e spectrum
- FV determination





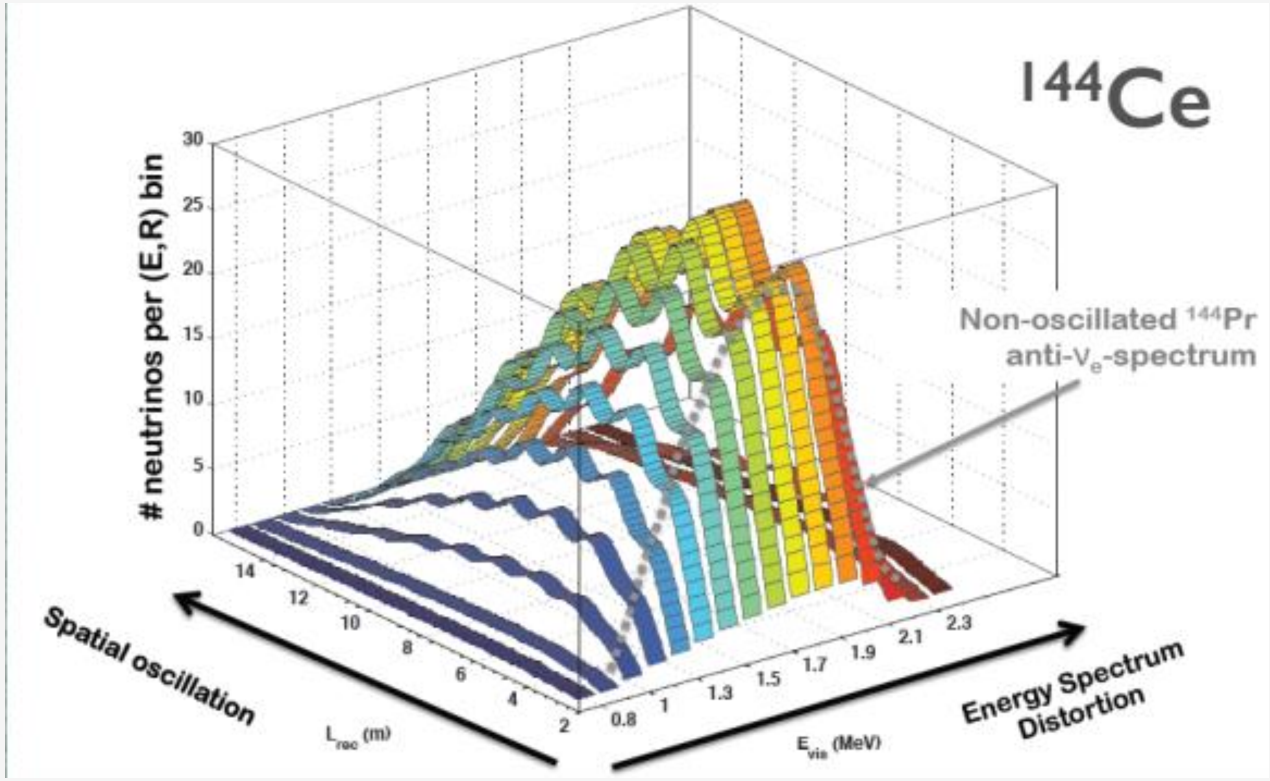
Both the oscillation parameters can be extracted independently

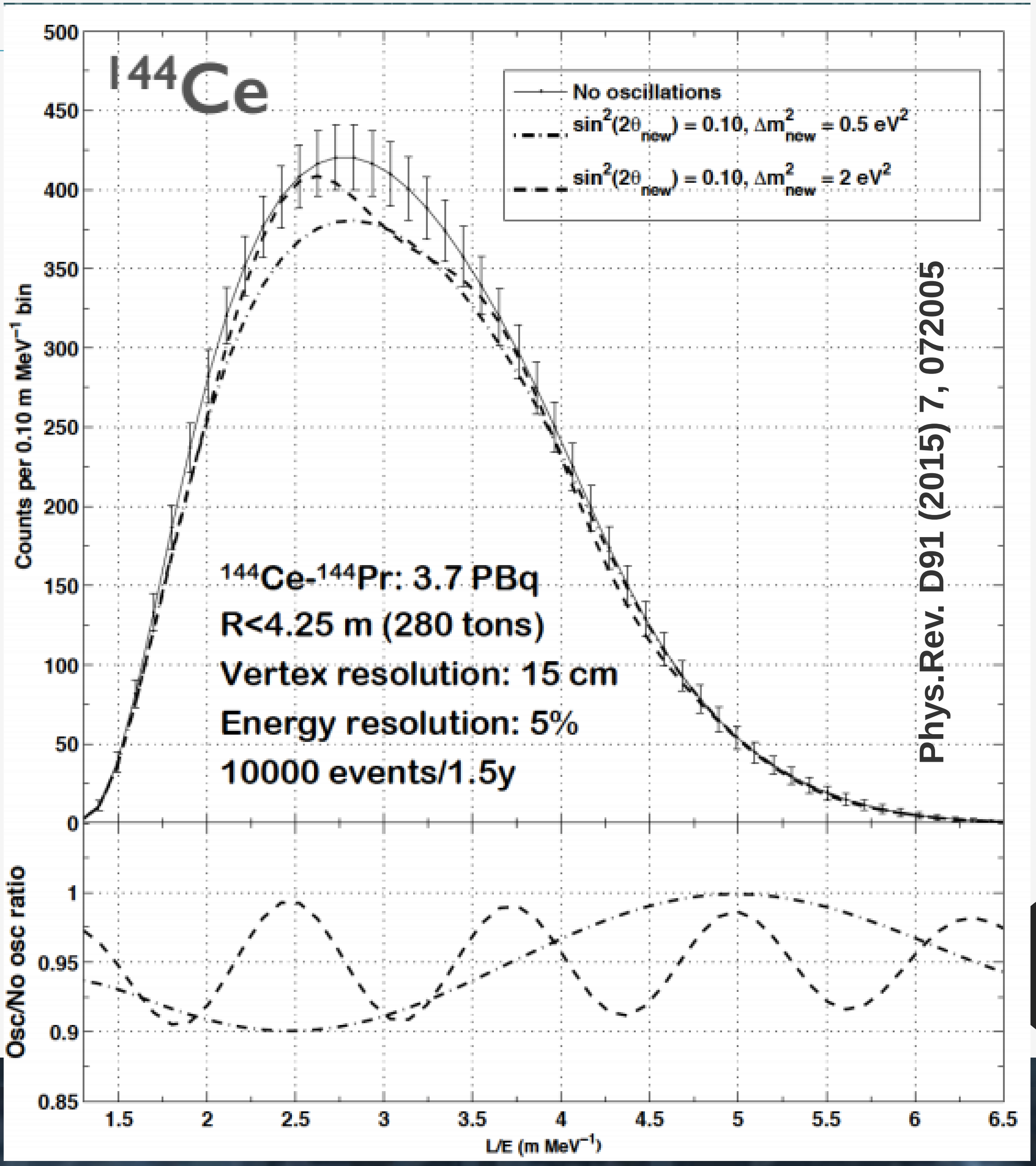
Two types of analysis

The shape analysis

The «waves» might be seen!

It does not depend on the activity measurements





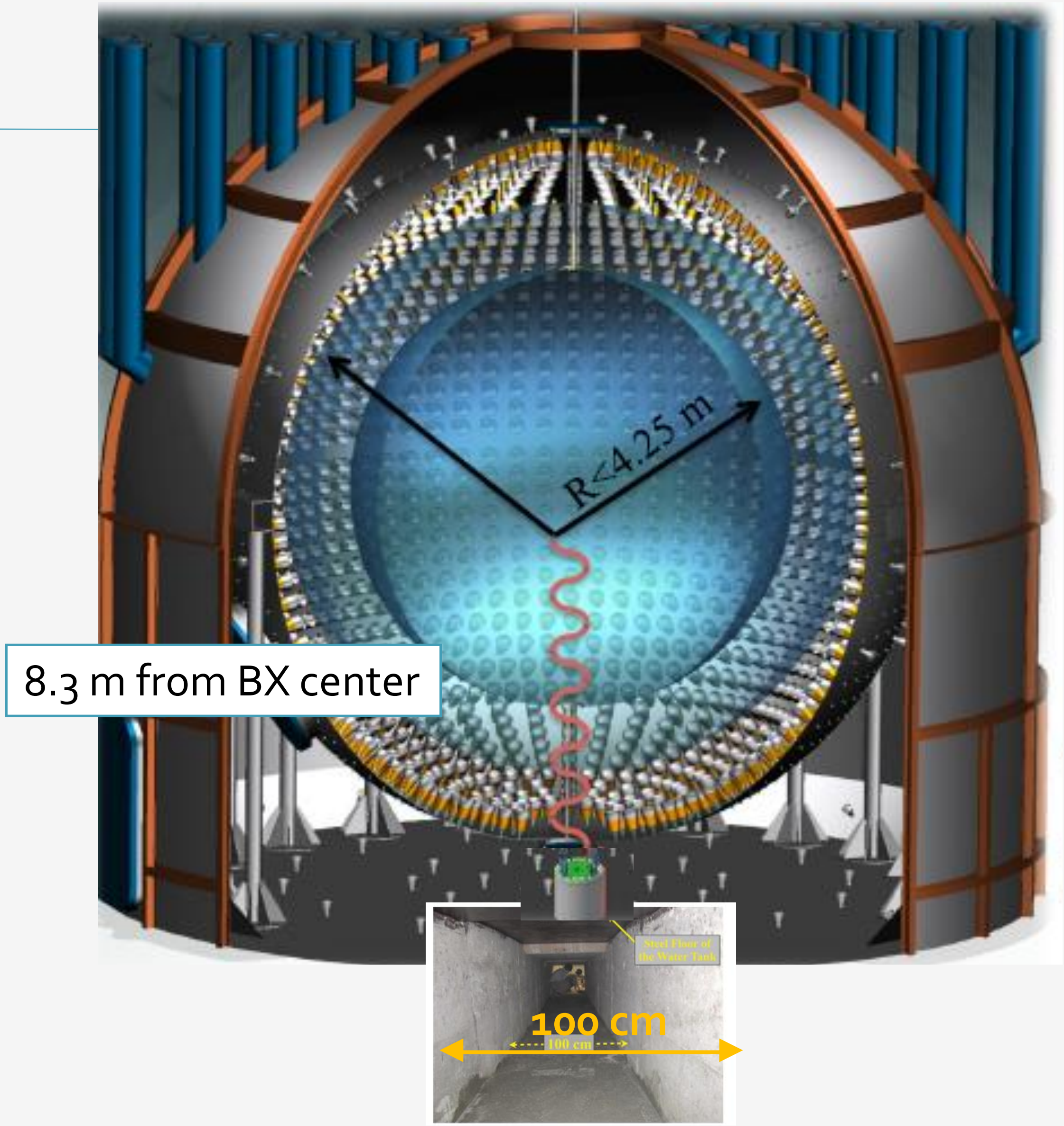
The SOX project

What we **need**:

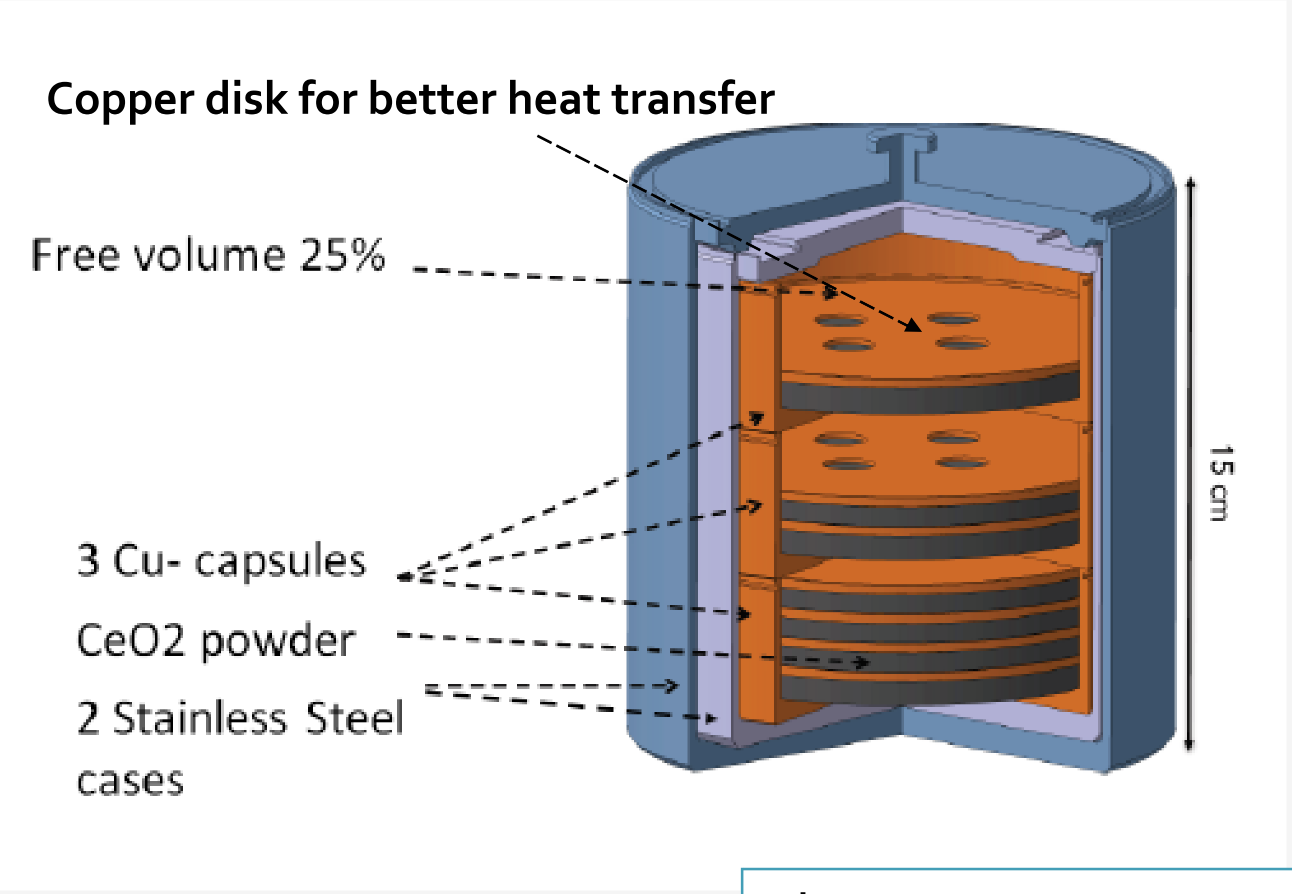
- The source production /authorizations
- The activity measurement (1%) by two calorimeters
- The $\bar{\nu}_e$ spectrum measurement

The **final sensitivity** will depends on:

- source activity (100-150 kCi)
- precision level of activity and spectrum measurements
- fiducial volume estimation



The source production process



At Mayak in Russia

From **spent nuclear fuel** from Research Reactor

purification
calcination
separation processes

CeO_2 powder

Pressed up to density of 3 -5 g/cm^3

Put inside the copper capsule

inside the two welded containers

Inserted in the byological shield

The contract was signed last December!!

Source constrains

- **Radioactivity**

It must be very PURE!

→ **γ** emitter activity **< 10^{-3} Bq/Bq** with respect to ^{144}Ce

→ **neutron** rate: ^{244}Cm activity **< 10^{-5}Bq/Bq**

with respect to ^{144}Ce **(max 10^{5}n/s)**

→ A limit is put on several nuclides measured at Mayak spectroscopy before the delivery

→ Power from impurities **10^{-3} W/W** with respect to ^{144}Ce

^{22}Na, ^{44}Ti-^{44}Sc, ^{49}V, ^{54}Mn, ^{55}Fe, ^{57}Co, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{68}Ge-^{68}Ga, ^{90}Sr-^{90}Y, ^{91}Nb, ^{93m}Nb, ^{106}Ru-^{106}Rh, ^{101}Rh, ^{102}Rh, ^{102m}Rh, ^{108m}Ag, ^{110m}Ag, ^{109}Cd, ^{113m}Cd, ^{119m}Sn, ^{121m}Sn, ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{133}Ba, ^{143}Pm, ^{144}Pm, ^{145}Pm, ^{146}Pm, ^{147}Pm, ^{145}Sm, ^{151}Sm, ^{150}Eu, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{148}Gd, ^{153}Gd, ^{157}Tb, ^{158}Tb, ^{171}Tm, ^{173}Lu, ^{174}Lu, ^{172}Hf-^{172}Lu, ^{179}Ta, ^{178m}Hf, ^{194}Os-^{194}Ir, ^{192m}Ir, ^{193}Pt, ^{195}Au, ^{194}Hg-^{194}Au, ^{204}Tl, $^{210}Pb \rightarrow ^{206}Pb$, ^{207}Bi, ^{208}Po, ^{209}Po, $^{228}Ra \rightarrow ^{208}Pb$, $^{227}Ac \rightarrow ^{207}Pb$, $^{228}Th \rightarrow ^{208}Pb$, $^{232}U \rightarrow ^{208}Pb$, ^{235}Np, ^{236}Pu-^{232}U, $^{238}Pu \rightarrow ^{230}Th$, ^{239}Pu, ^{240}Pu, ^{241}Pu-^{241}Am, ^{241}Am, ^{242m}Am-^{230}Th, $^{243}Cm \rightarrow ^{235}U$, ^{244}Cm, ^{248}Bk-^{244}Am, ^{249}Bk-^{249}Cf, ^{248}Cf, ^{249}Cf, ^{250}Cf, ^{252}Cf, ^{252}Es, ^{254}Es-^{250}Bk.

Tungsten alloy shield

W-Ni-Fe alloy for mechanical properties

95% Tungsten (high density shield)

Dosimetry issue

→ Gamma dose:

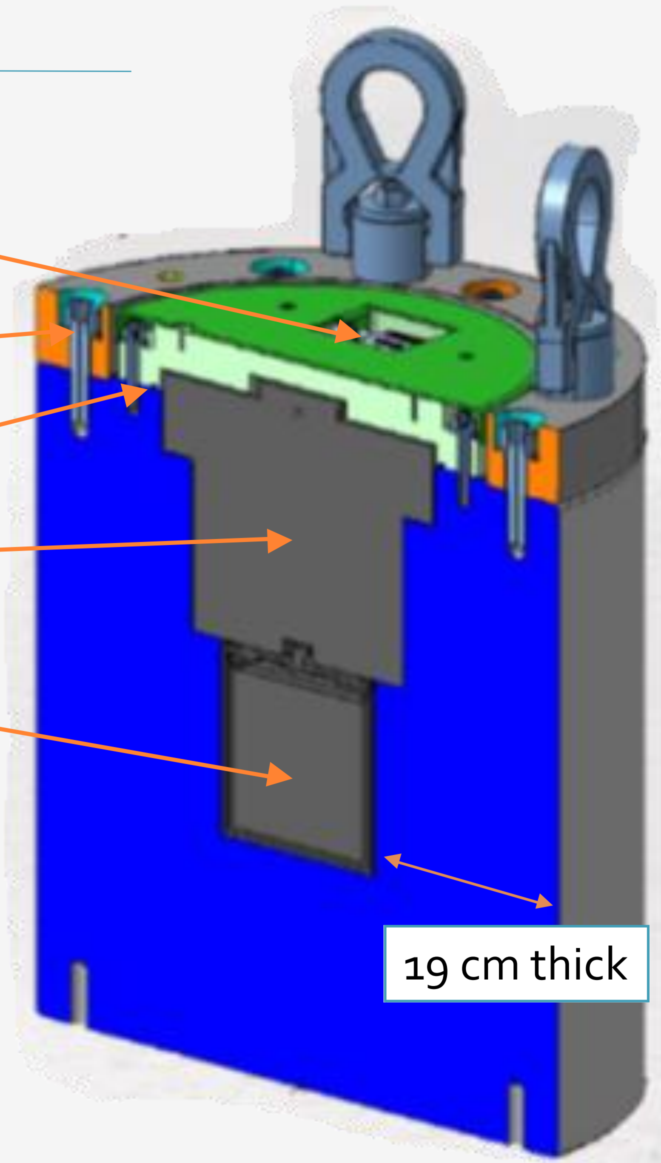
8 μSv/h at 1 m

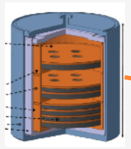
from Pr decay (gamma of 2.2 MeV)

→ Neutron dose:

5 nSv/h at 1m

Weight: 2.2 ton





Built in Xiamen Ltd, China

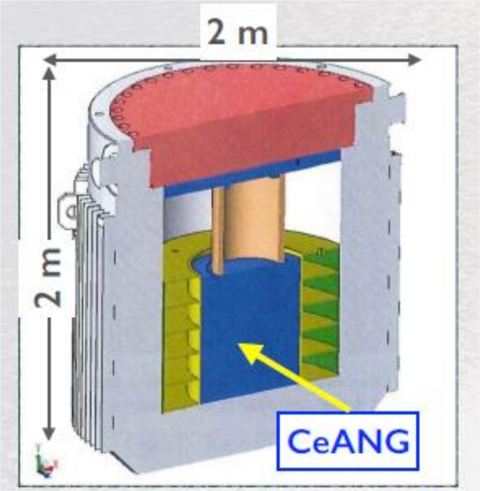
The logistic

A journey to minimize borders:

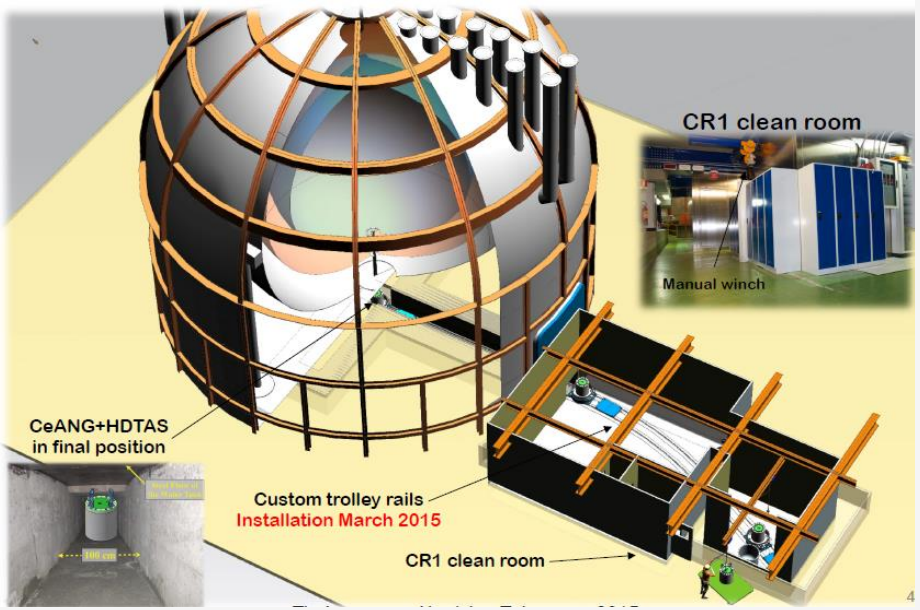
- Mayak → St. Petersburg — by train
- St. Petersburg → Le Havre — by boat
- Le Havre → Saclay → LNGS — by truck

Container: TN MTR

- **24 t** container for nuclear fuel (CEA)



Transportation from Mayak to Hall C	1 month
In the clean room for the activiy measurement:	2 weeks
In the pit for data taking	1.5 year



The activity measurement

$$P = \dot{m}[h(T_{out}, \bar{p}) - h(T_{in}, \bar{p})]$$

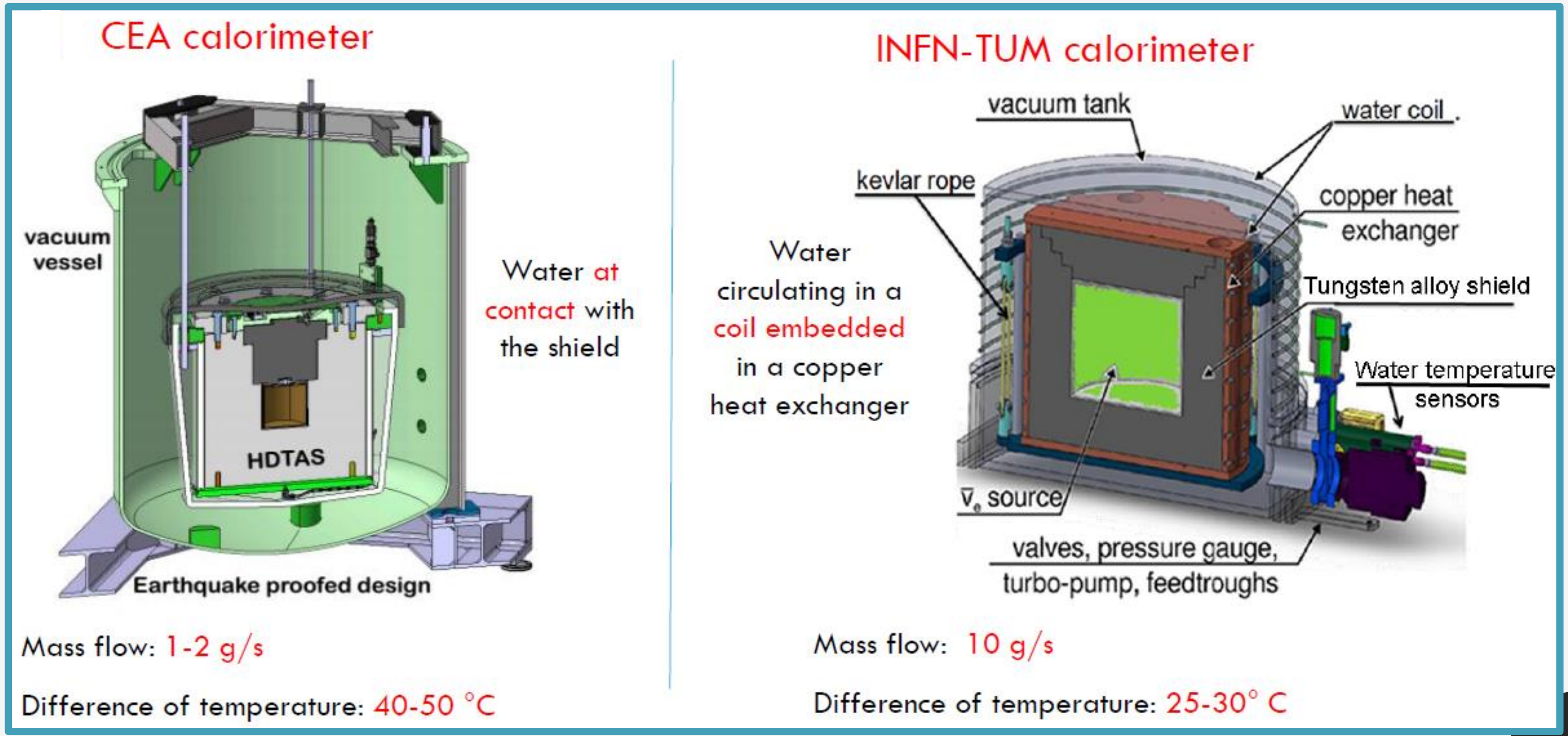
The activity is measured by knowing the heat released inside the shield and absorbed by a water flow

150 kCi →1200 W

$T_{1/2}$=285 days

Final precision due to:

- Heat losses (systematic)
- Massflow measurement (0.05 % accuracy)
- Temperature sensors (mK accuracy!!)
- **Entalphy** function (0.1% IAPWS)



- Estimation of the system **time constant**

The goal was 1 %...but we are going to do better!!

INFN/TUM calorimeter

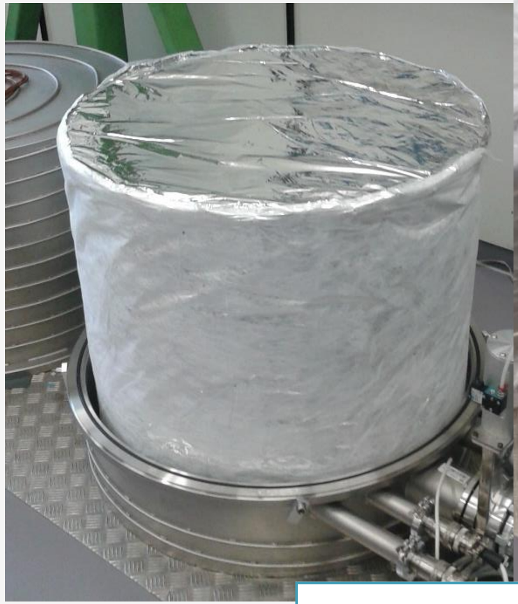
CONVECTION

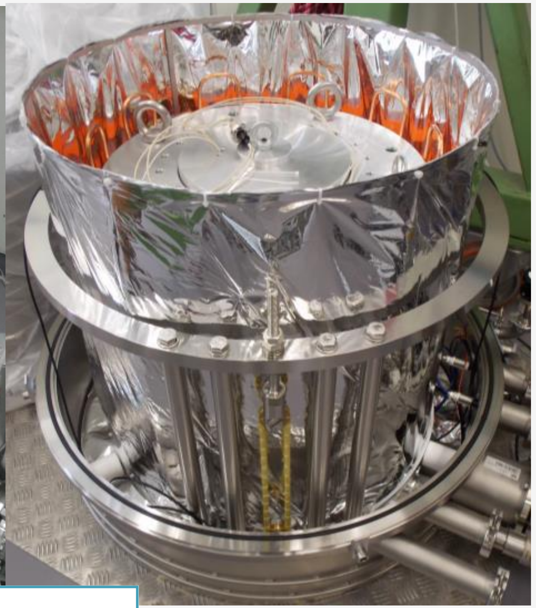
Vacuum system
Scroll pump
Turbo molecular pump
$P < 5 \cdot 10^{-5}$ mbar

$P_{loss} \approx 0$ W

RADIATION

2 stages of superinsulator (10 layers each one)
Thermalization of the external chamber by hot water

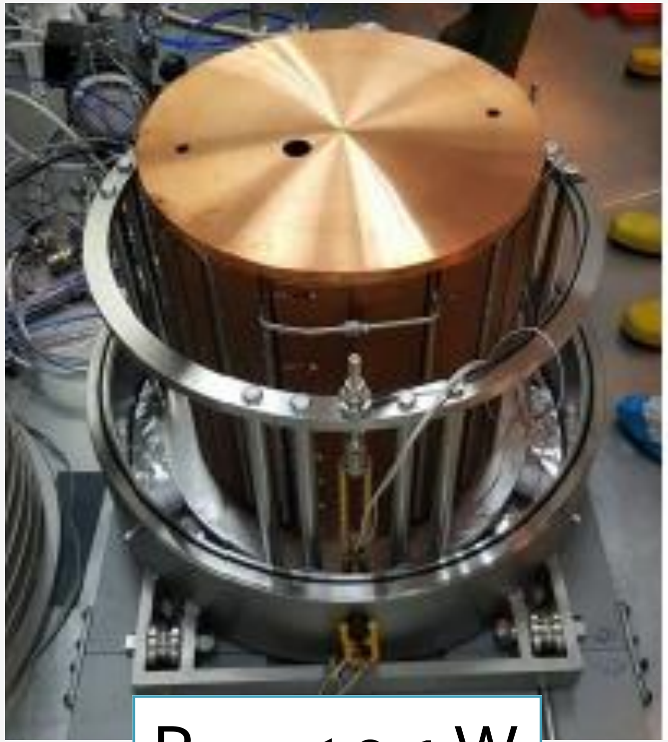




$P_{loss} < 1$ W

CONDUCTION

System suspended by 3 kevlar ropes

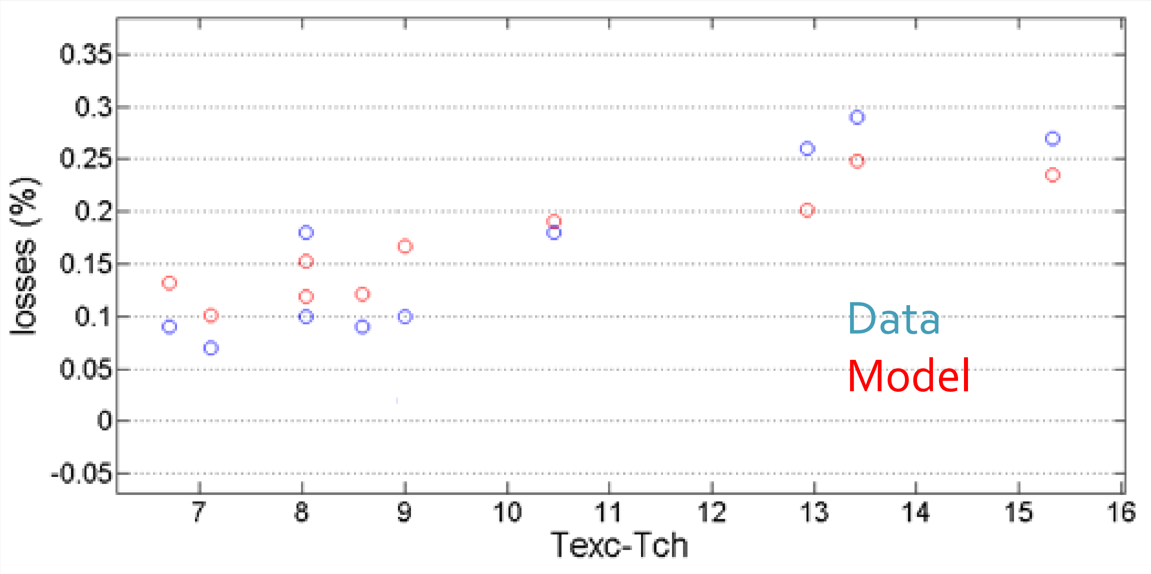


$P_{loss} < 0.1$ W

Results from the electrical source calibration

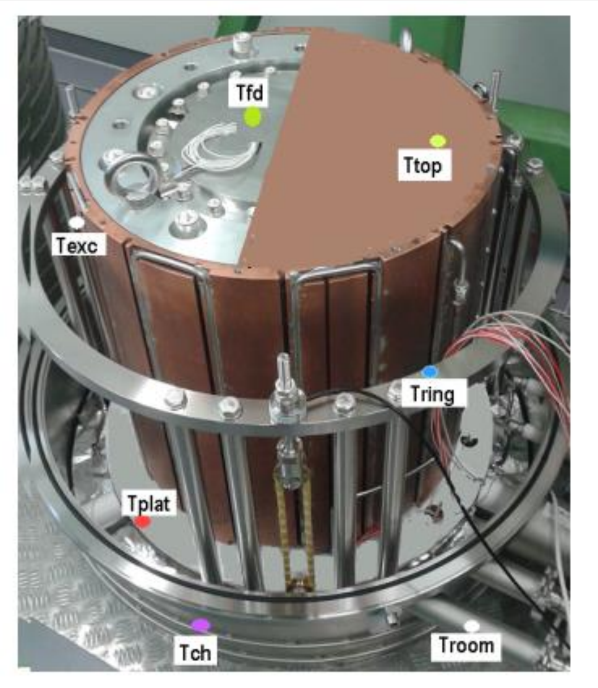
Steady state: a constant power was applied

The temperature distribution in the system was studied as a function of the setting parameters inorder to estimate the losses



Parameters:

- massflow value
- entering temperature value
- temperature of the external vacuum chamber



In the best condition of measurement the losses result negligible!

Blind measurement:

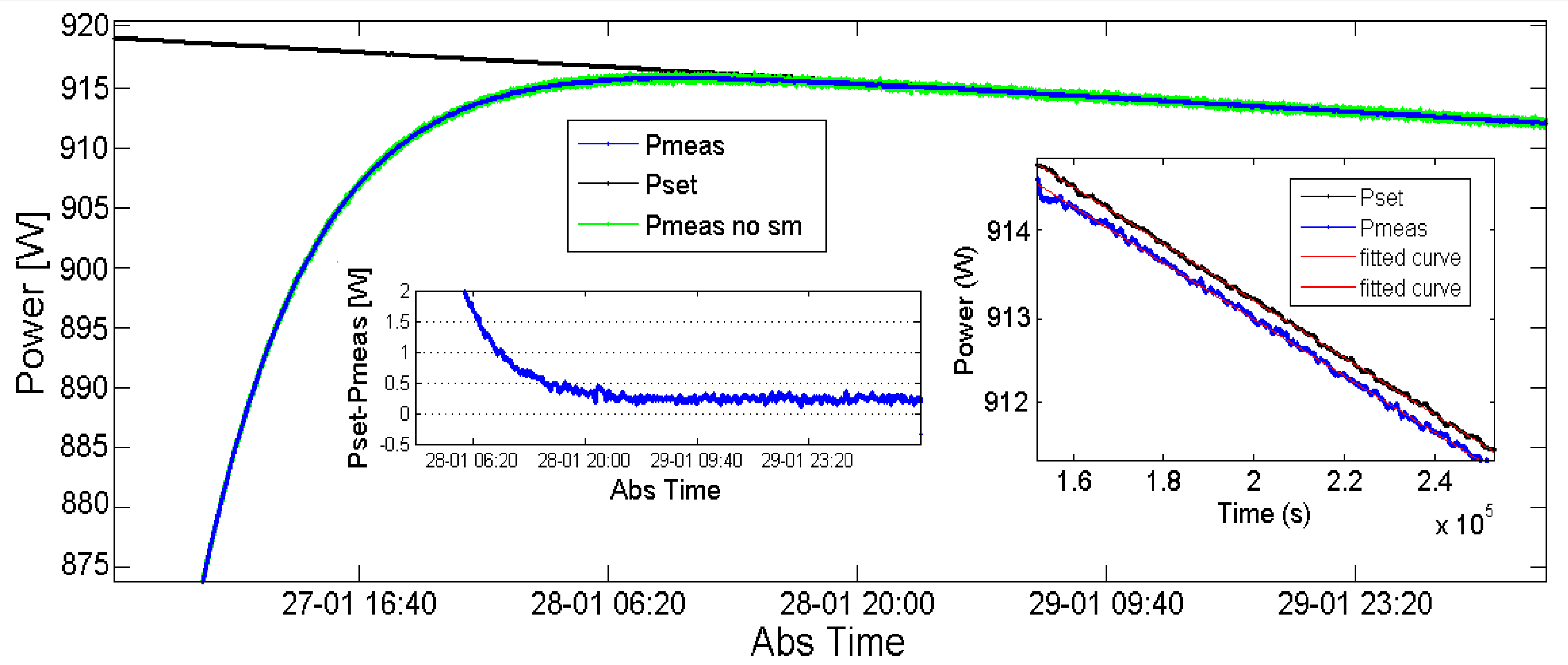
Measured P =927.8 ± 1.3 W Set Power=929 W

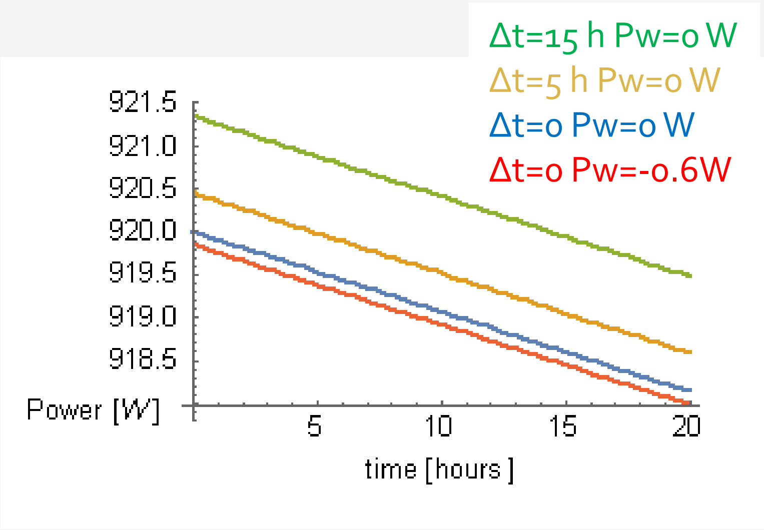
0.3 % precision!!

Results from calibration

Time dependent power, like the exponential decay

The time constant of the system is estimated for the final measurement





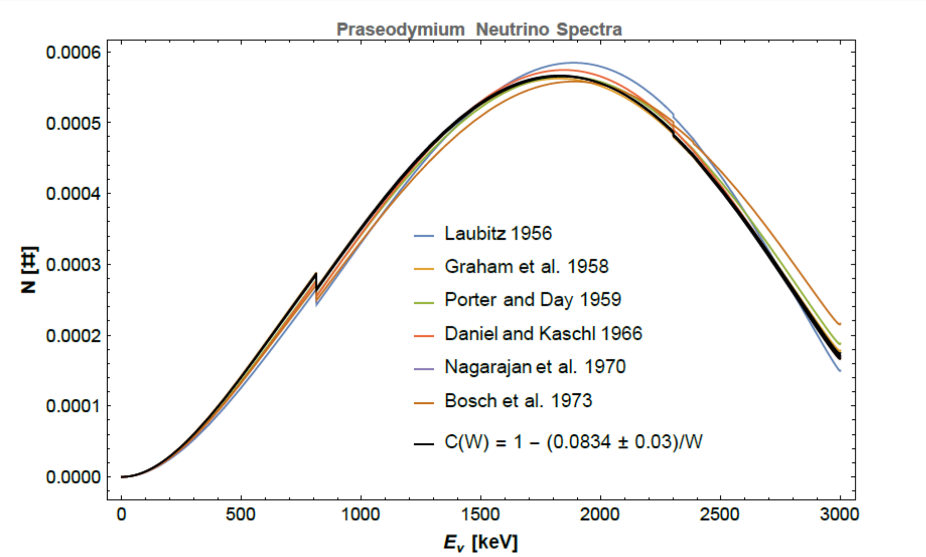
Heat propagation time

$$P(t) = P_0 e^{-\frac{t-\Delta t}{\tau}} + P_w$$

Lost power < 1 W

We are ready for the final measurement!

The beta spectrum measurement



It influences:

the source heat power (source-activity conversion)

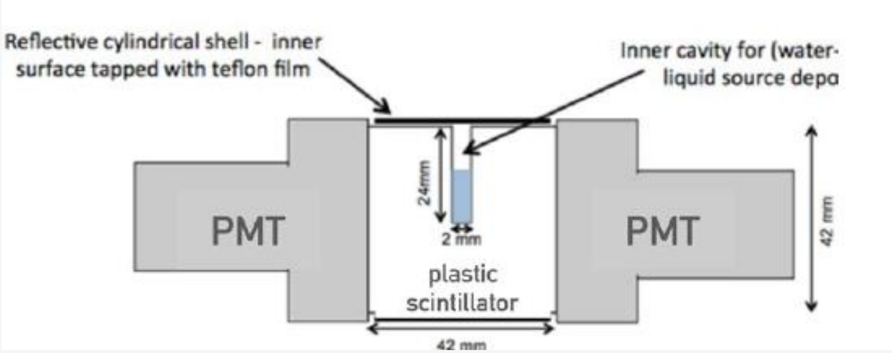
expected IBD interaction rate in Borexino

^{144}Ce and ^{144}Pr beta spectra both present **non-unique forbidden transitions**

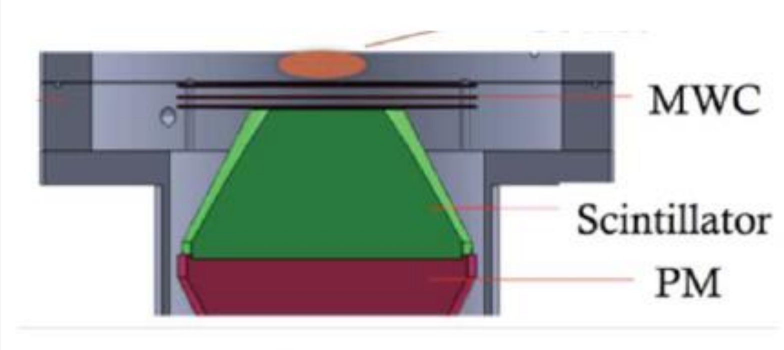
for which spectral shape is uncertain at the **few % level**

Some apparatus are under development:

at CEA in Paris



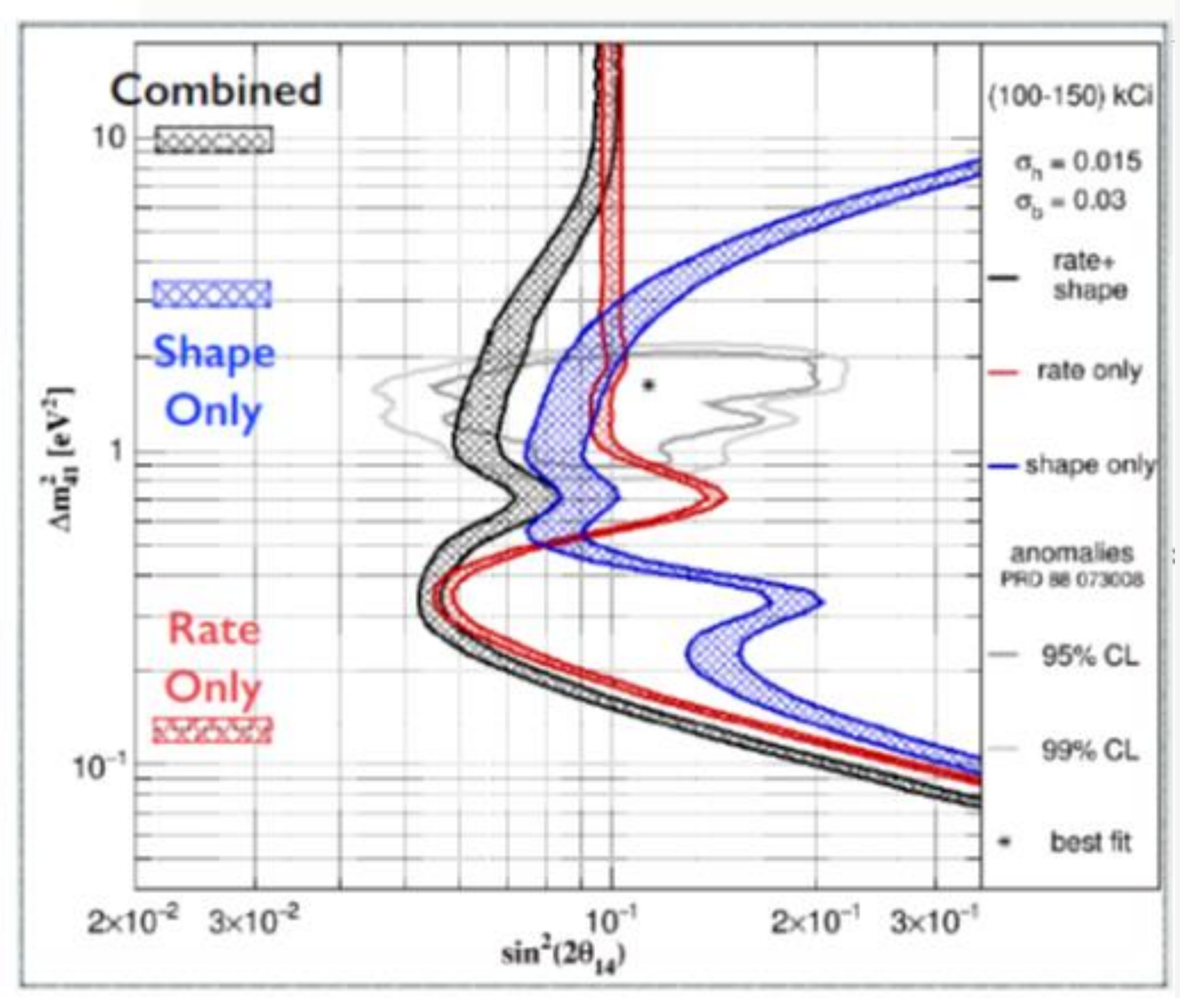
at TUM in Munich



A proposal is submitted for using **PERKEO III** spectrometer at Munich

The SOX sensitivity

Assuming
σ=0.015 activity meas
σ=0.03 spectrum meas



Thanks to both the analysis the puzzle of 1 eV sterile neutrino might be closed!!

Thanks