Short distance neutrino Oscillations with boreXino: SOX

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile, March 6th –March 11th 2017

Barbara Caccianiga-INFN Milano

(on behalf of the Borexino/SOX collaboration)

Borexino and SOX Collaborations

BOREXINO GRAN SASSO

UNIVERSITÀ DEGLI STUDI DI MILANO

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Outline of the talk

- Why sterile neutrino? Experimental hints;
- How can we search for sterile ν?;
- SOX: Short Distance neutrino Oscillations with boreXino;

Why sterile neutrinos? Experimental hints

ν_e, anti-ν_e DISAPPEARANCE

ν_e, anti-ν_e APPEARANCE

Reactor anomaly ~2.5σ

Re-analisys of data on anti-neutrino flux from reactor short-baseline (L~10-100 m) shows a small deficit of R=0.943 ±0.023

G.Mention et al, Phys.Rev.D83, 073006 (2011) , A.Mueller et al. Phys.Rev.C **83**, 054615 (2011)*;*

Gallex/SAGE anomaly ~3σ

Deficit observed by Gallex in neutrinos coming from a ^{51}Cr and ^{37}Ar sources

$$R = 0.76^{+0.09}_{-0.08}$$

C. Giunti and M. Laveder, Phys.Rev. C83, 065504 (2011), arXiv:1006.3244 [hep-ph].

Accelerator anomaly ~3.8σ

Appearance of anti-ν_e in a anti-ν_μ beam (LSND). *A.Aguilar et al. LSND Collaboration Phys.Rev.D 64 112007 (2001).*

Confirmed by miniBooNE (which also sees appearance of ν_e in a ν_μ beam) *A.Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)*

These experimental results are inconsistent with oscillations in the 3 neutrino scenario;
In fact they would require a value of Δm^2 ~ 1 eV^2, much larger than Δm_{12}^2, Δm_{13}^2

Need to introduce one (or more) neutrino(s): the sterile neutrino

Why sterile neutrinos? Experimental hints

In the (3+1) scenario,

$$\Delta m_{41}^2, \quad \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

$$\Delta m_{21}^2 << \Delta m_{31}^2 << \Delta m_{41}^2$$

$$|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 << 1 \quad |U_{s4}|^2 \cong 1$$

Why sterile neutrinos? Experimental hints

In the (3+1) scenario,

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$$\boxed{\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta \mathrm{m}_{41}^2 L}{4E}\right) \\ P(\nu_\alpha \to \nu_\alpha) &= 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta \mathrm{m}_{41}^2 L}{4E}\right) \end{aligned}}$$

Why sterile neutrinos? Experimental hints

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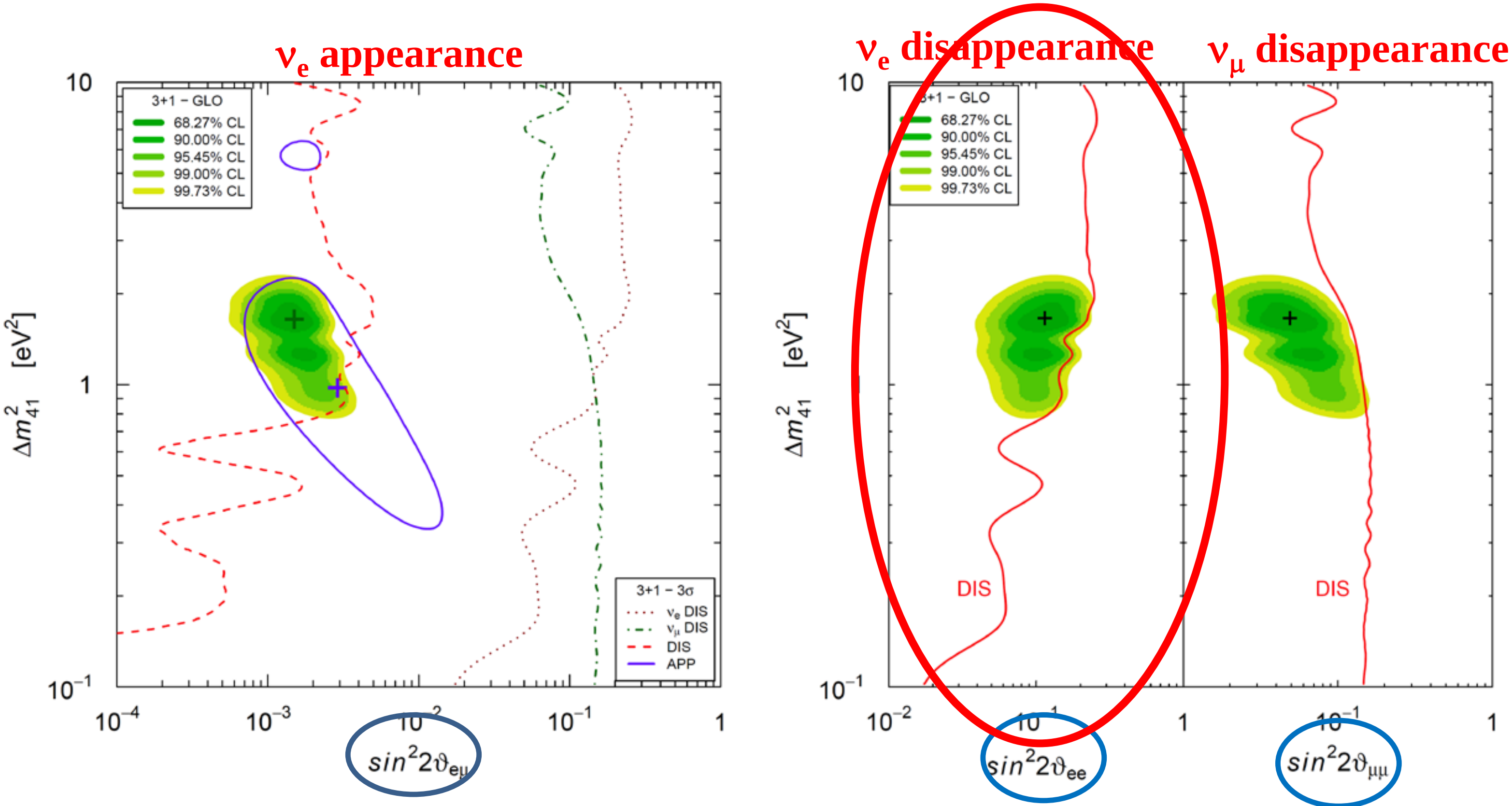
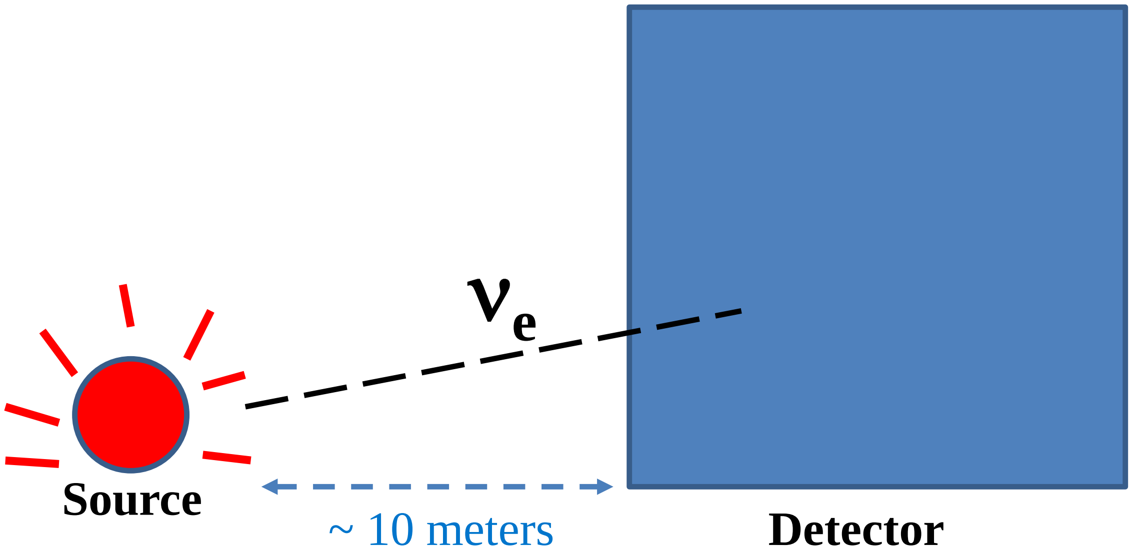
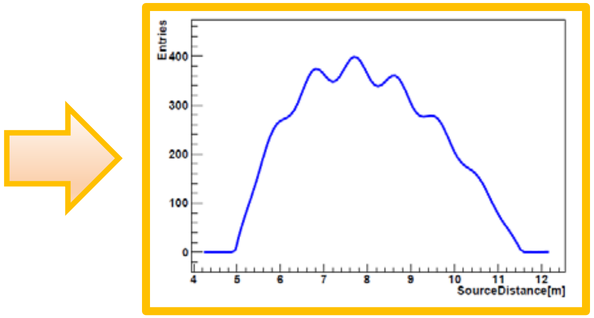


How can we search for sterile neutrinos?

These experimental anomalies deserve indipendent confirmation or disproval





1) **Look for disappearance of ν_e emitted by the source;**

2) **Look for oscillation waves within the detector volume (oscillometry);**

In order to be sensitive to $\Delta m^2 \sim 1$ eV^2

- **Need a source with E ~ 1- 10 MeV**
- **Located at a distance L ~ 1-10 m**

How can we search for sterile neutrinos?

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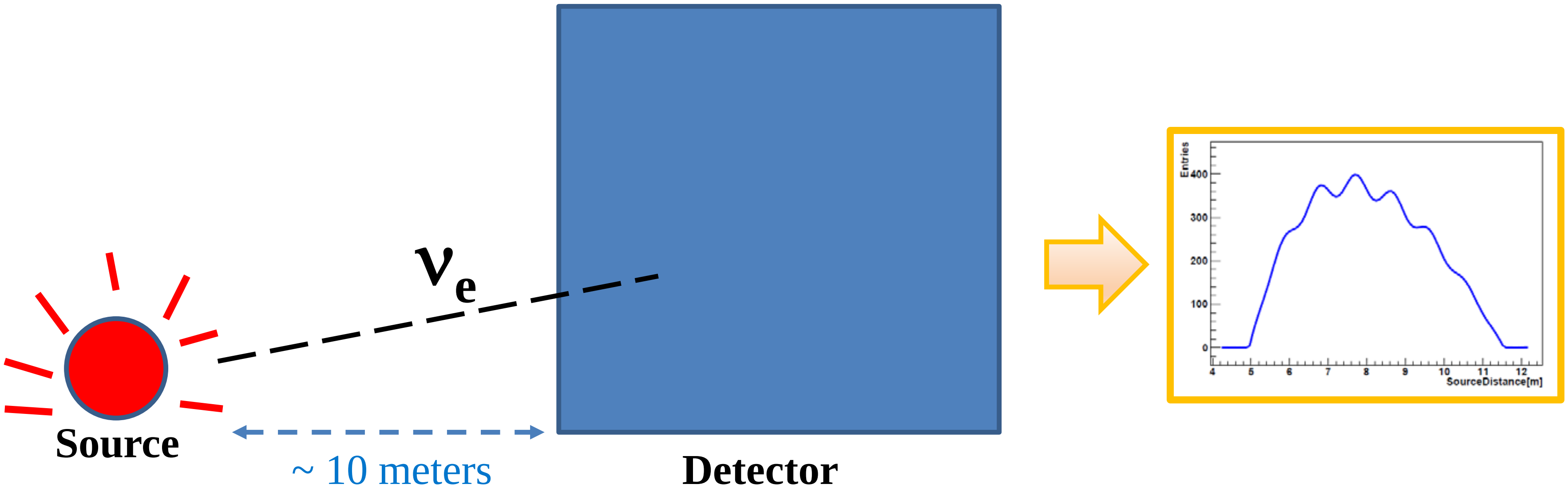
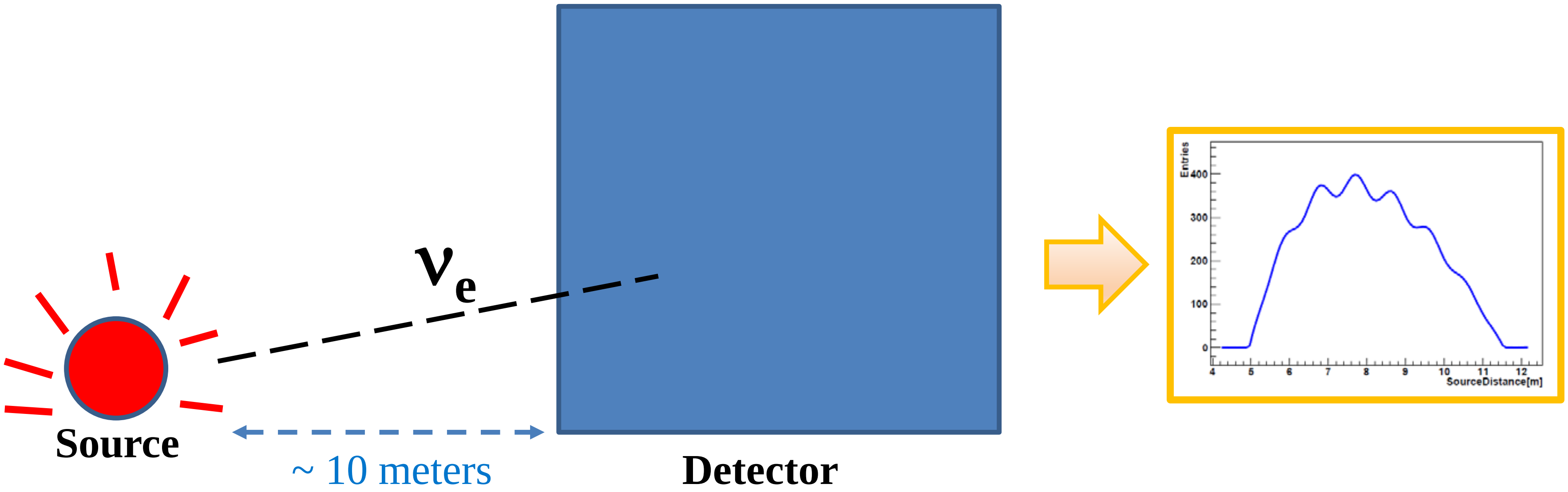


Advantages (compared to reactors or accelerator experiments)

- Intrinsecly pure ν_e (or anti- ν_e) beam;
- Neutrino spectrum can in general be measured more precisely than in reactors or accelerators;
- Neutrino cross-sections in the ~MeV region known more precisely than at ~ GeV;
- Neutrino flux known with high precision (at ~% level);

How can we search for sterile neutrinos?

These experimental anomalies deserve indipendent confirmation or disproval



Disadvantages (compared to reactors or accelerator experiments)

- **Sources decay! Limited data-taking time..**
- **Smaller neutrino flux;**
- **Both a technical and burocratical challenge: need authorizations for transportation, importation, handling, usage, storage, disposal;**

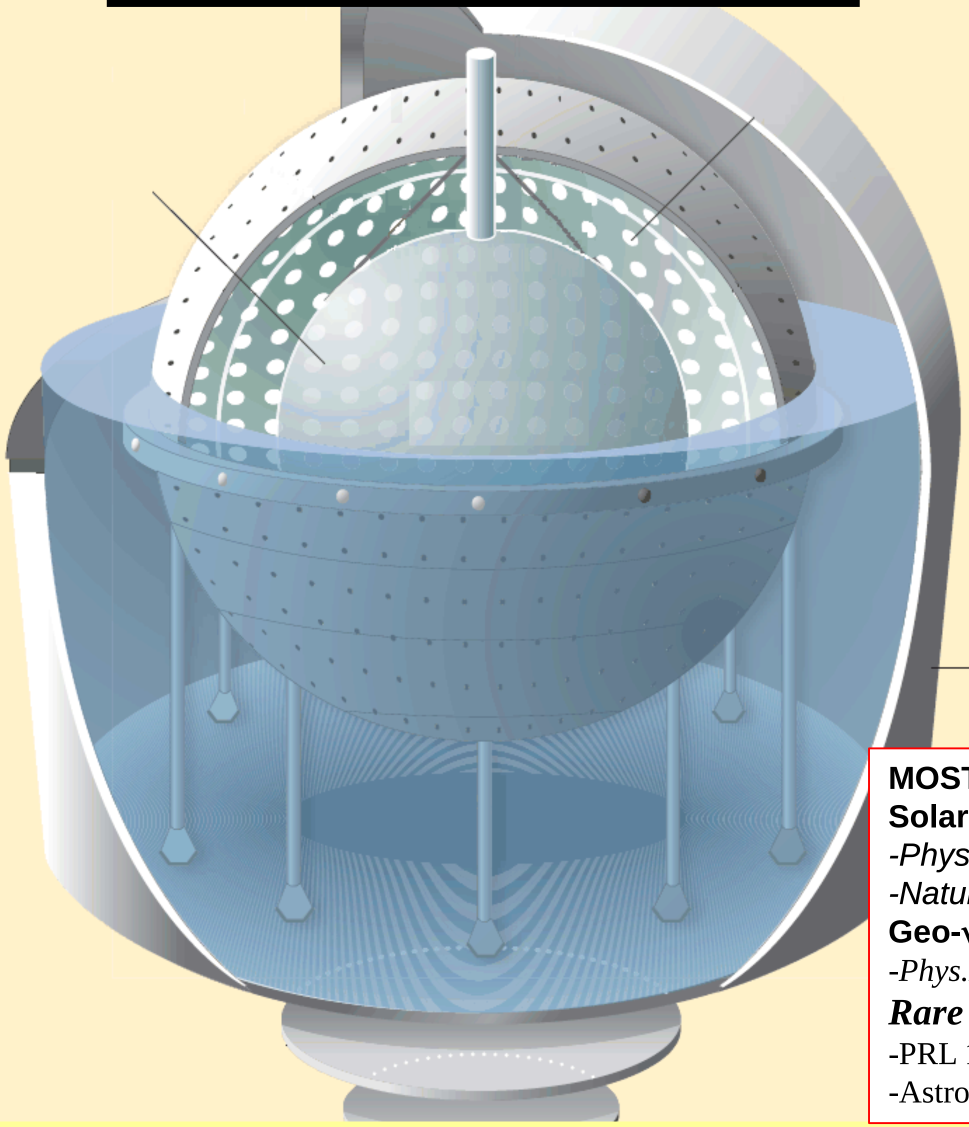
The SOX idea

SOX: Short distance ν_e Oscillations with boreXino

Borexino in a nut-shell

- It is located at the Laboratori Nazionali del Gran Sasso;
- It was conceived to study solar neutrinos;
- Started taking data in 2007;
- Still taking data for solar ν;

The Borexino detector



Borexino results

- BX has performed a complete study of the solar neutrino spectrum
- geo-neutrinos;
- Limits on rare processes;

MOST RECENT BX RESULTS ON

Solar ν

-Phys.Rev. D 89, 112007 (2014),

-Nature 512 (2014) 383-386;

Geo-ν

-Phys.Rev. D 92, 031101(R) (2015)

Rare processes

-PRL 115, 231802 (2015)

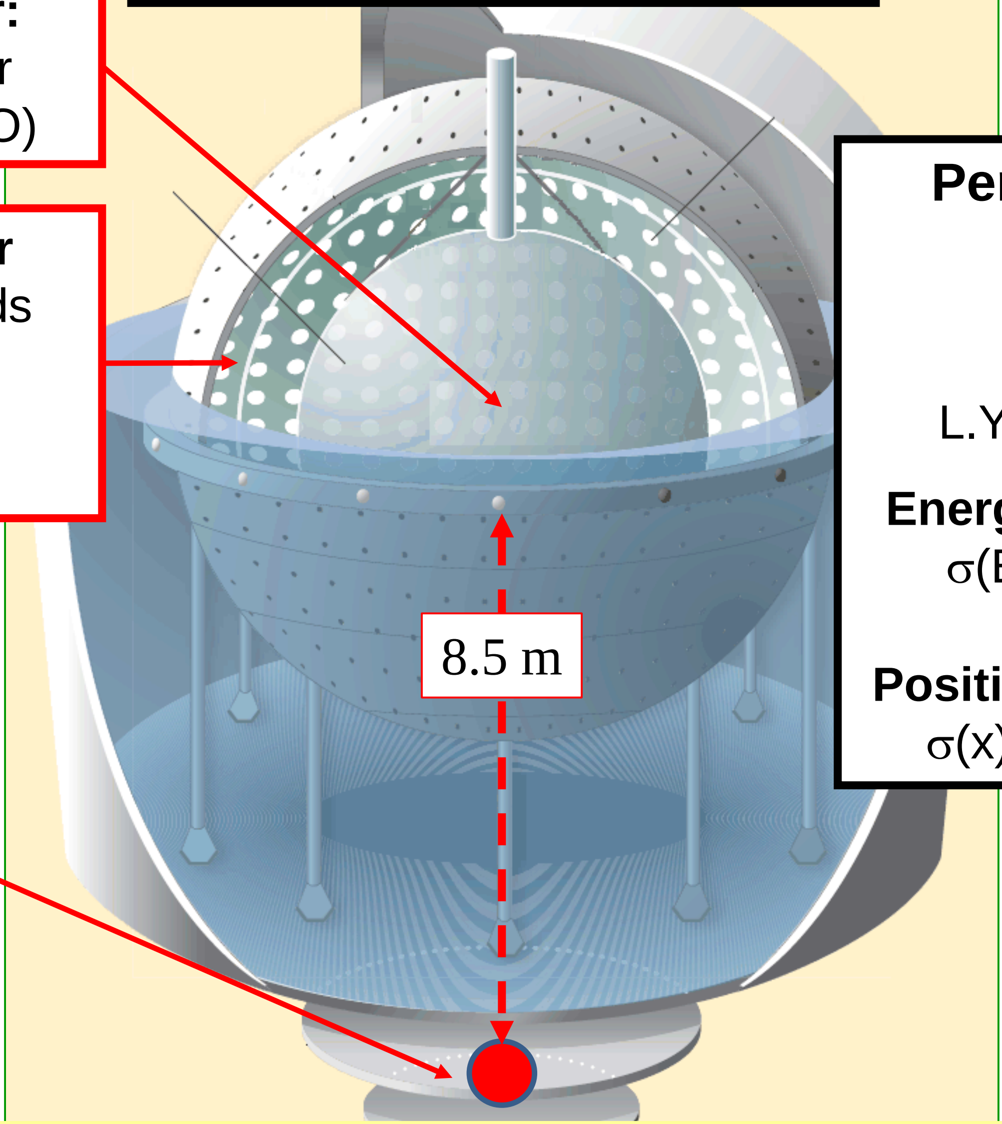
-Astrop. Phys. 86 (2017) 11–17

SOX: Short distance ν_e Oscillations with boreXino

The Borexino detector

Core of the detector:
300 tons of scintillator
(pseudocumene+PPO)

2212 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;



PIT under the detector where the source will be located.

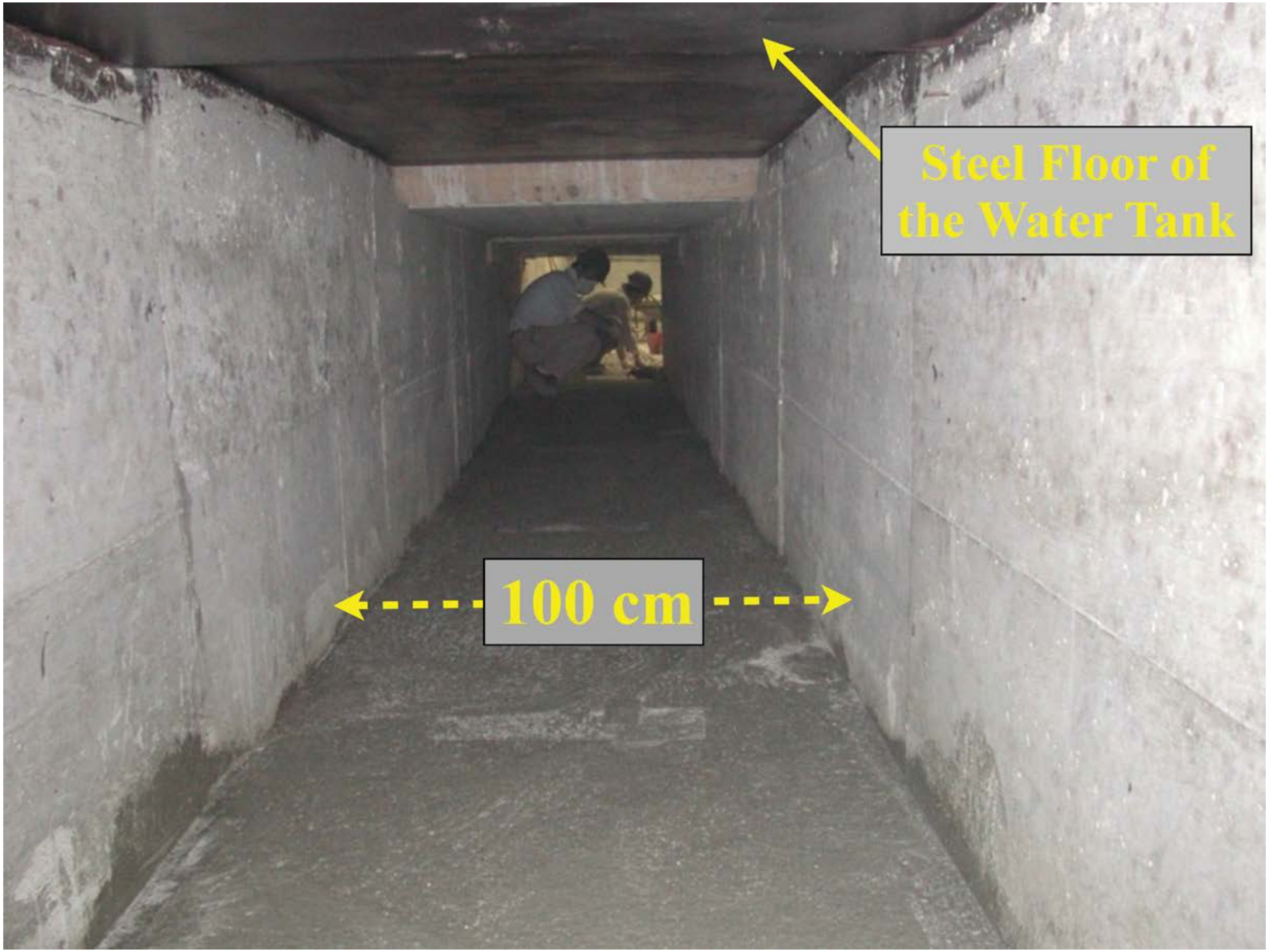
Performances of Borexino

Light Yield
L.Y.~ 500 p.e./MeV

Energy reco capability
σ(E)= 5% @1MeV

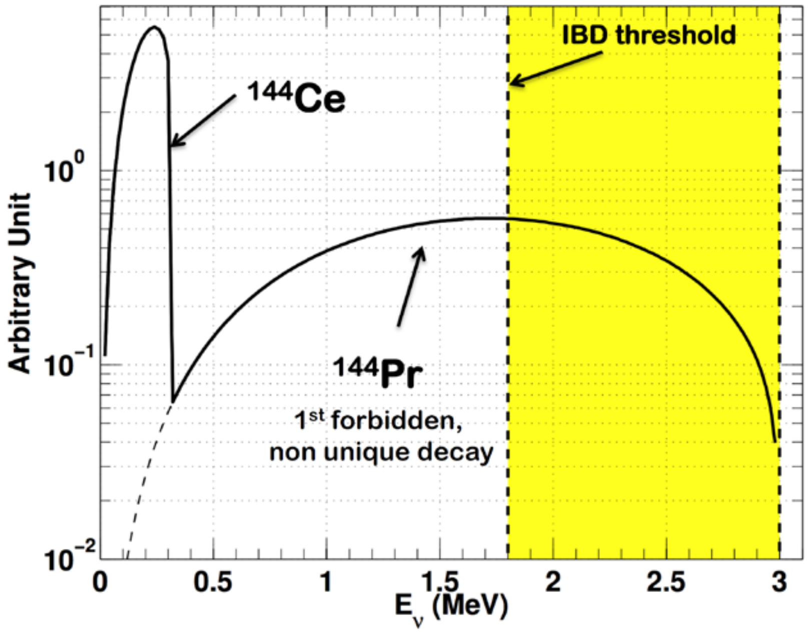
Position reco capability
σ(x)=10 cm @1MeV

SOX: the tunnel under the detector



SOX: the ^{144}Ce-^{144}Pr anti-ν source (see *PRL 107, 201801 (2011)*)

Source characteristics: anti-ν source, E_ν <2.99 MeV τ=411 d



Required source activity

~100 kCi (3.7 x 10^{15} ν/sec)

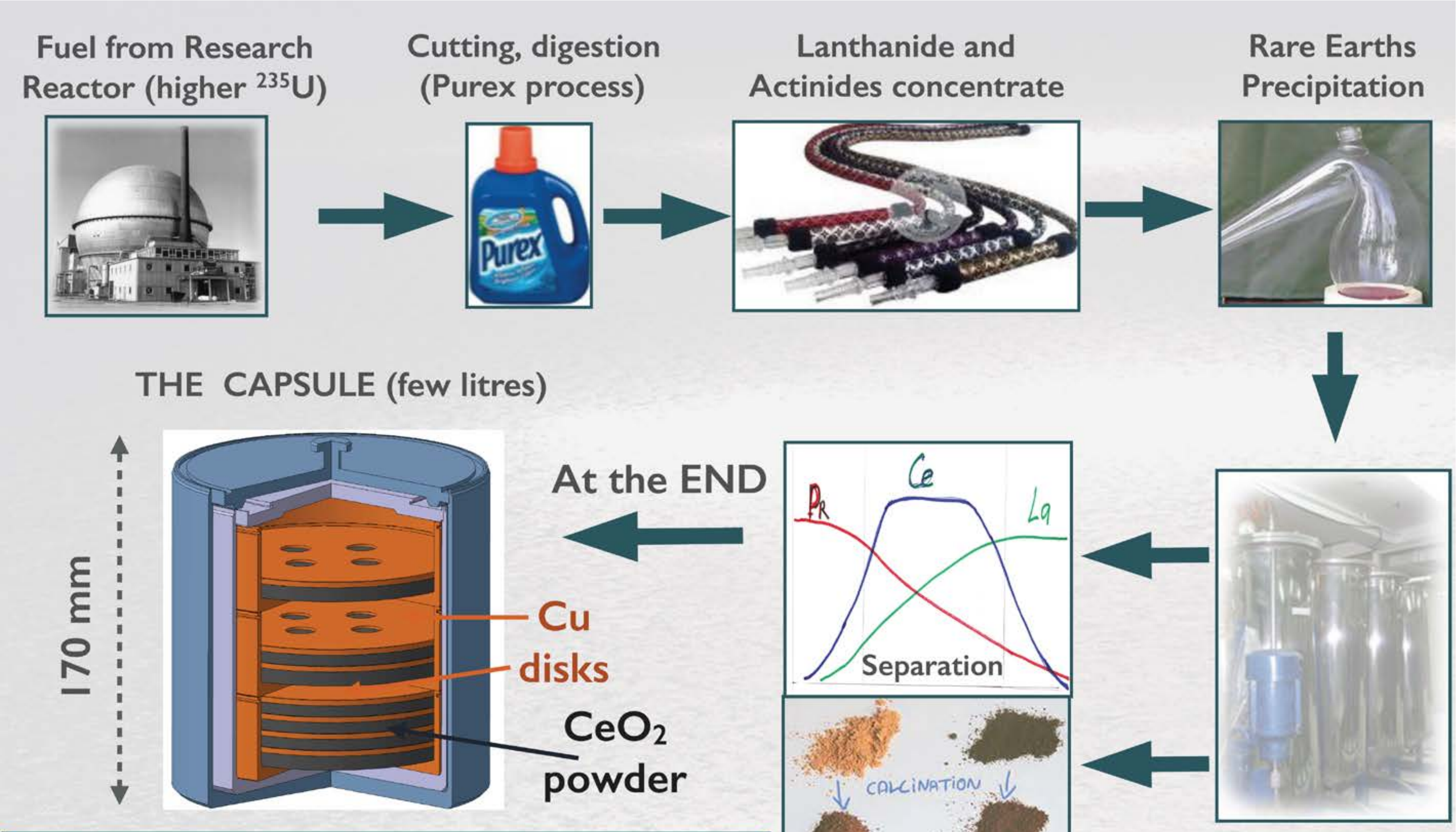
ADVANTAGES

- detecting reaction is $\bar{\nu}$+ p → n + e^+ very little background;
- Long lifetime;

DISADVANTAGES

- high energy γ_s (E=2.2 MeV) emitted by the source are difficult to handle;

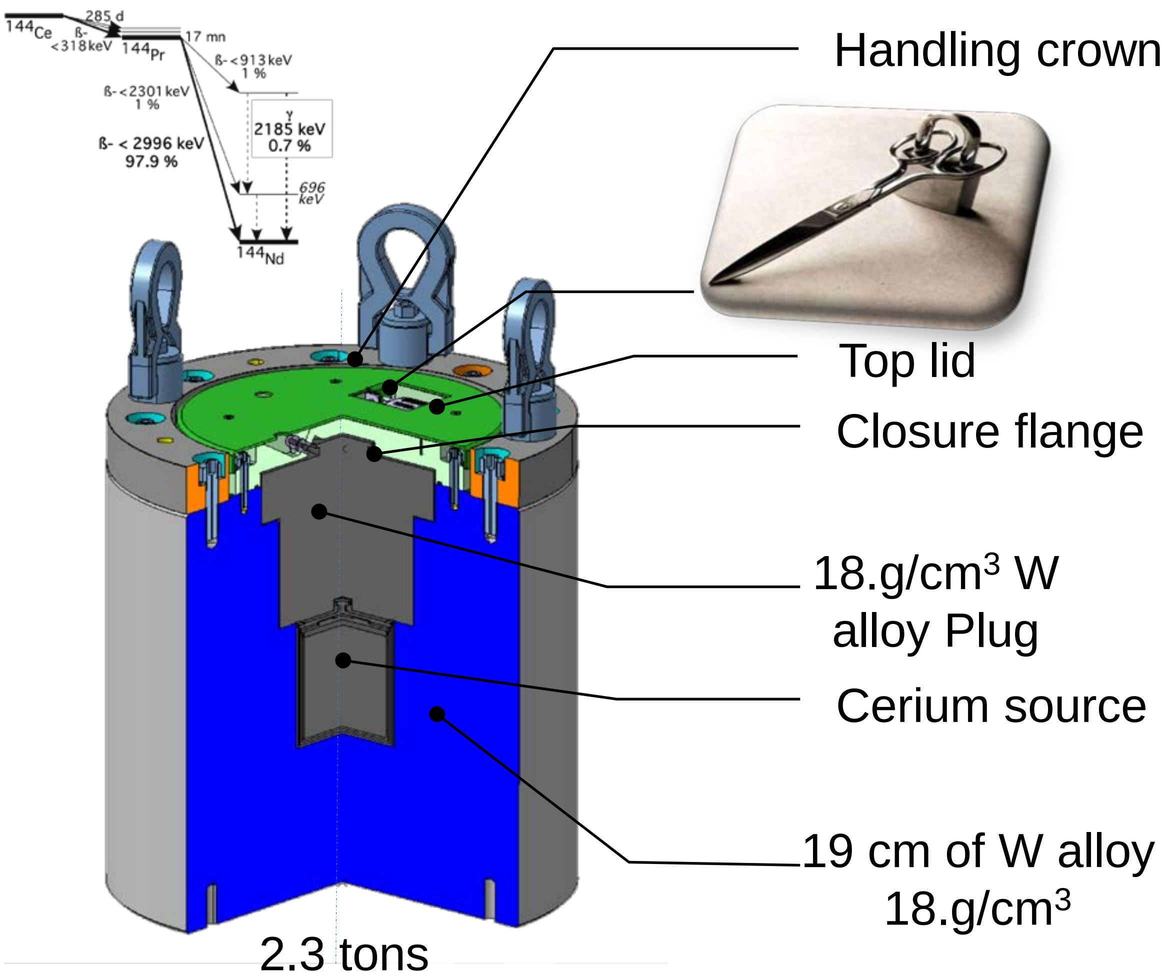
SOX: source production in Mayak



CeO_2 powder pressed in a sealed stainless steel capsule with copper disks for better heat transfer and internal free space for pressure control

SOX: source shielding

The source capsule must be contained in a tungsten shielding to stop gamma-rays



Already in Gran Sasso

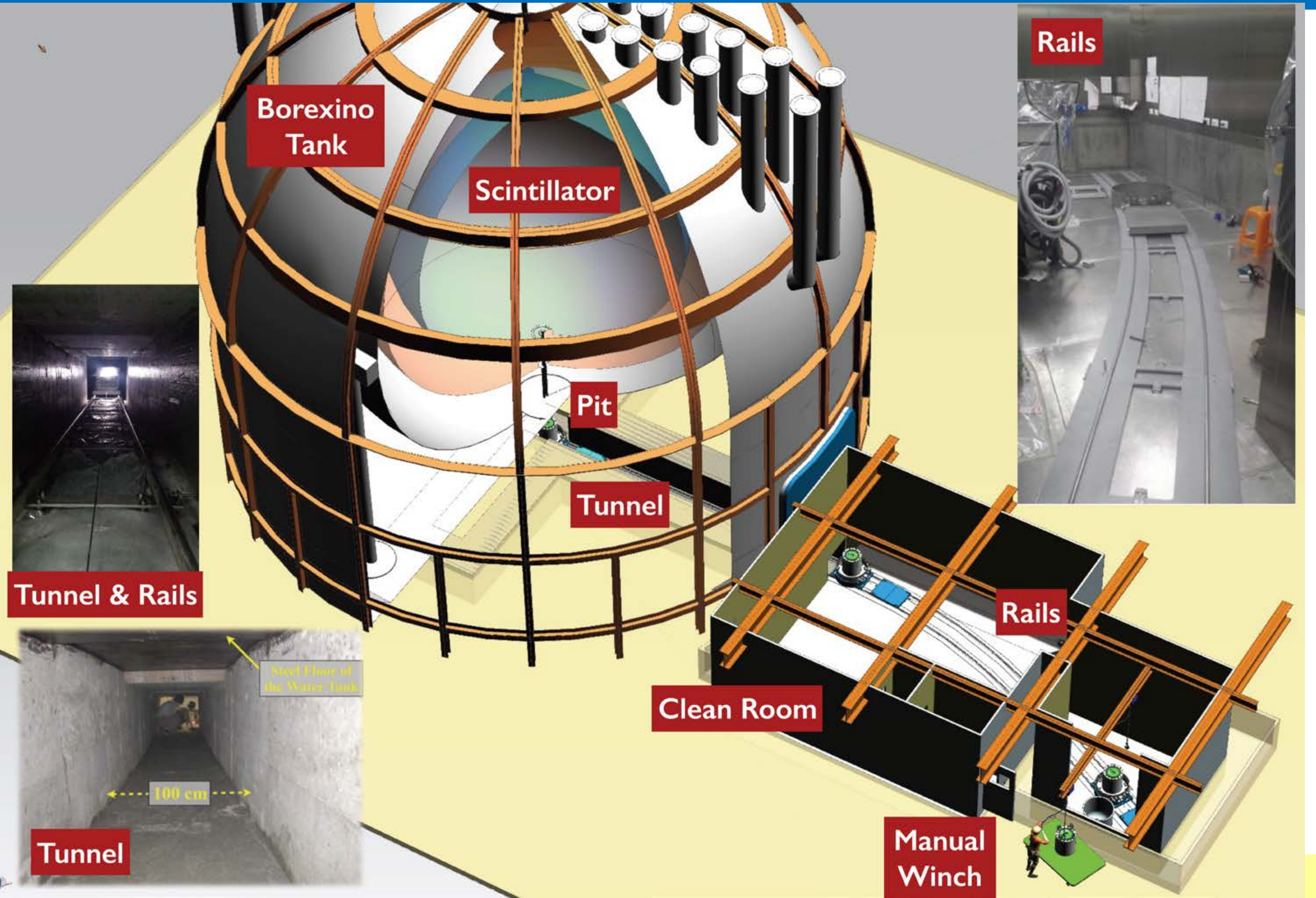
SOX: source trasportation

Complicated transportation logistic in order to comply with safety regulations for transport of radioactive material:

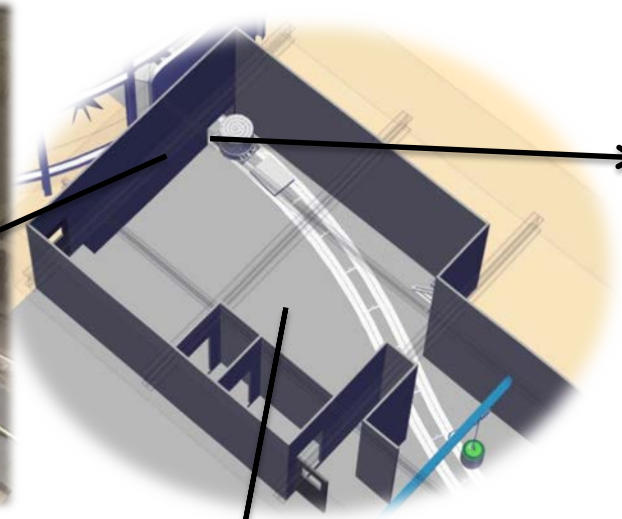
- **Container**: TN MTR 24t container for nuclear fuel;
- **Transportation:** Train + dedicated boat+ truck
- **Time**~ 3 weeks
- **Loss of activity**~ 5%

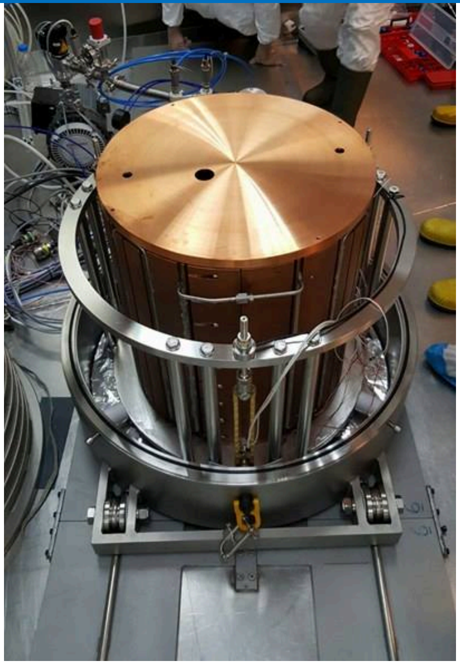
- ^{144}Ce source ready for shipment to Gran Sasso between Jan and March 2018;
- **Transportation to Gran sasso by April 2018;**

SOX: logistic in Gran Sasso



SOX: logistic in Gran Sasso





The physics with SOX

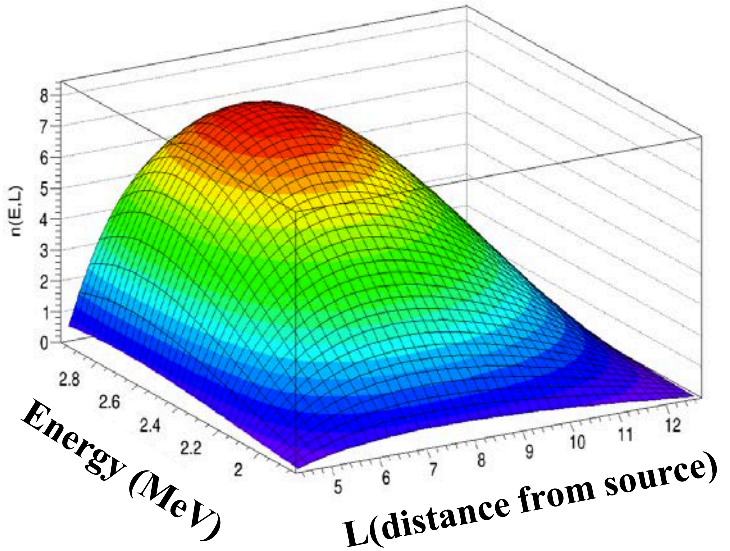
SOX: sensitivity to sterile neutrinos

Two types of analysis

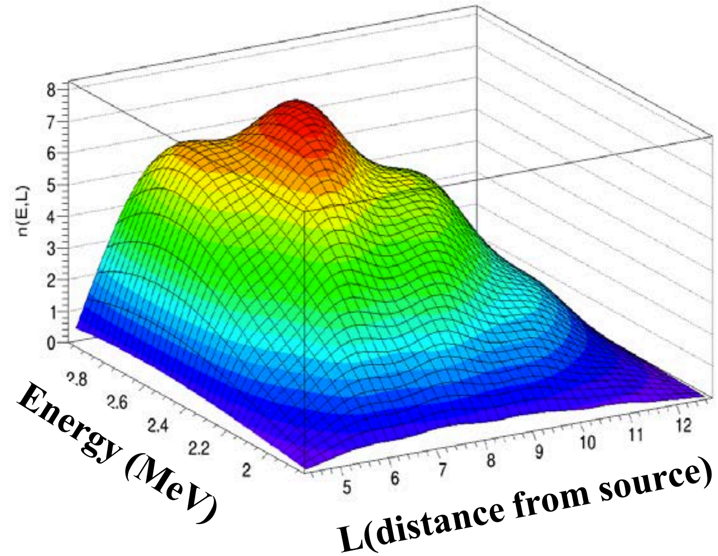
- **Rate analysis**: look for a deficit in the total anti-neutrino number (the activity of the source must be known very precisely!)
- **Shape analysis**: look for anomaly in the distribution of events as a function of E and L (distance from the source)

$$P(\nu_e \to \nu_s) = \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{14} L}{4E}\right)$$

NO Oscillations



Oscillations (Δm^2=2.5 eV^2, $\sin^2(2\theta)$=0.14)



SOX: sensitivity to sterile neutrinos

The sensitivity depends on some critical parameters of the experiment:

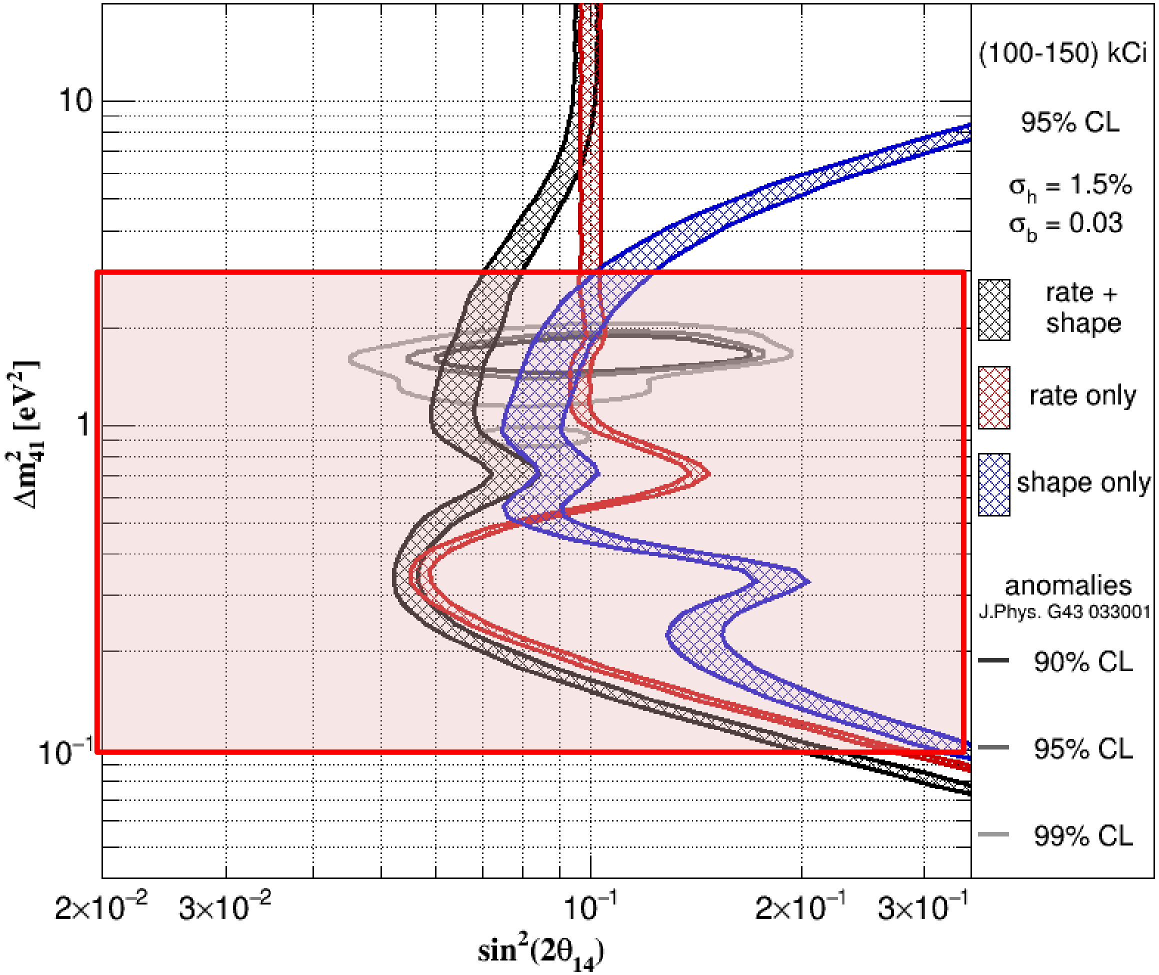
- **a**: activity of the source (the higher the better);
- **t**: time of data-taking (it is constrained by the source lifetime);
- $\boldsymbol{\sigma_E}$ and $\boldsymbol{\sigma_L}$**:** capability to reconstruct energy E and position L of events;
- $\boldsymbol{\sigma_A}$**:** precision on determining the source activity (two calorimeters);
- Precise knowledge of the source Ce-Pr electron/neutrino spectrum;
- Precise knowledge of detector efficiency;

Nominal conditions of SOX

- **a =100kCi - 150 kCi (contract with Mayak)**
- **t = 1.5 years;**
- $\boldsymbol{\sigma_E}$**=5% (@ 1MeV)** $\boldsymbol{\sigma_L}$**=10 cm (@1MeV)**
- $\boldsymbol{\sigma_A}$**=1%**

SOX: sensitivity to sterile neutrinos

In the hypothesis of ''null result'', SOX will be able of excluding a region in the oscillation parameter space;



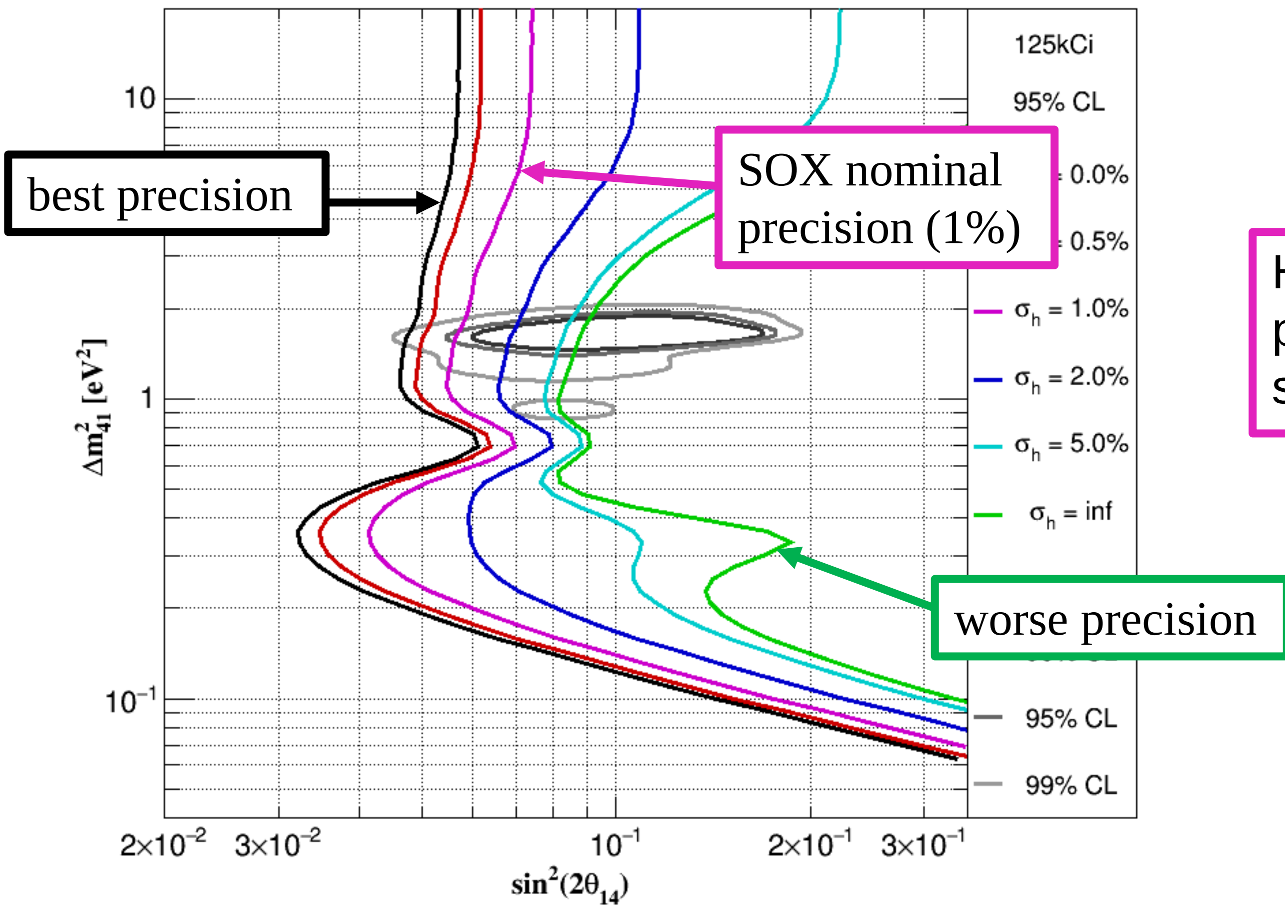
$$L_{osc}(m) = \frac{E(MeV)}{1.27\Delta m^2(eV^2)}$$

- Δm^2 >5 eV^2 $L_{osc} << \sigma_x$ P~1/2sin$^2 2\theta$;
- Δm^2 <0.1 eV^2 L_{osc} >> detector dimensions P~ $\Delta m^2 \sin^2 2\theta$;
- **0.1 <Δm^2 <5 eV^2 best sensitivity window;**

SOX will be able of excluding the region currently allowed by the anomalies

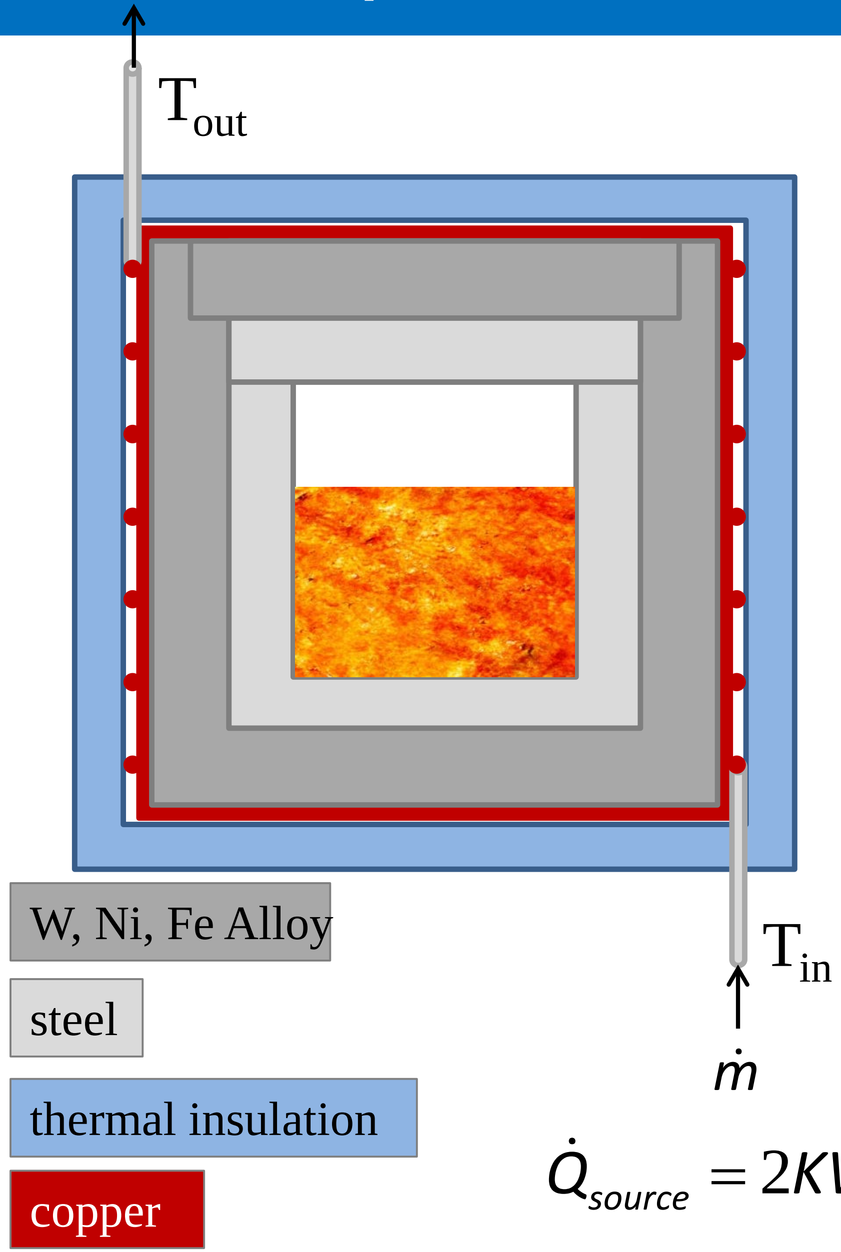
SOX: the importance of knowing the source activity

- Knowing precisely the source activity is crucial for the ''rate-only'' analysis;
- **The source activity will be measured with a calorimetric method: the precision of the measurent will be 1% or better;**



How can SOX reach a precision of 1% on the source activity?

SOX: the importance of knowing the source activity



SOX Calorimeters

$$\frac{\Delta\dot{Q}}{\dot{Q}} \leq 0.01$$

Steady state equation

$$\dot{Q}_{source} = \dot{m}C\left(T_{in} - T_{ext}\right) + \dot{Q}_{cond}$$

- T measured with Calibrated Platinum Thermometers (accuracy < 10^{-3});
- C for pure water known better than 10^{-4} ;
- Water mass flow measured with Coriolis flowmeters (accuracy $\pm 10^{-3}$);
- Heat losses due to conduction, radiation and convection must be minimized

$$\dot{Q}_{source} = 2KW; \quad \dot{m}_{water} = 0.01Kg/s \;\rightarrow\; \Delta T = 48°C$$

SOX: the importance of knowing the source activity

Two calorimeters to have independent measurements of the source activity:

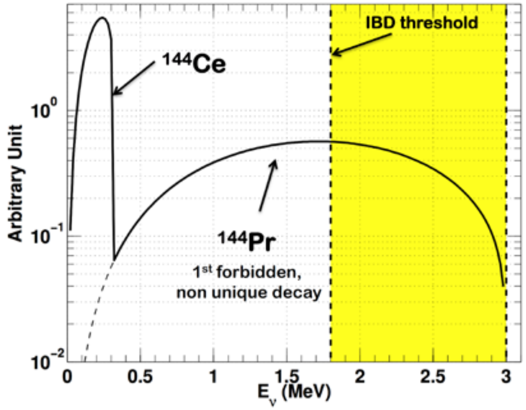
- Preliminary tests with a source mockup have shown that the design precision of 1% (or even better) is reachable;
- One of the two calorimeters already @LNGS; the other will arrive in April 2017;

TUM/Genova calorimeter

CEA calorimeter

SOX: the importance of knowing the source spectrum

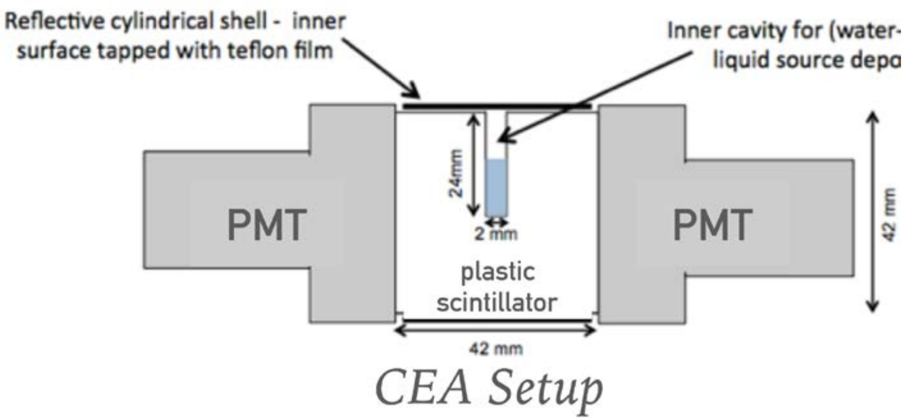
- This measurement is crucial for different reasons:
  1. conversion Q → activity;
  2. conversion activity → number of ν above threshold;
  3. oscillometric analysis



Two setups to independently measure the spectrum

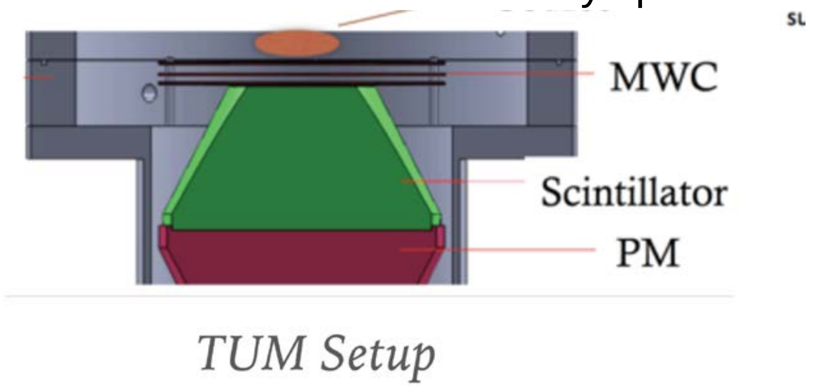
CEA β-spectrometer

- ^{144}Pr beta decay spectrum only



TUM β-spectrometer installed in Saclay:

- ^{144}Ce and the ^{144}Pr beta decay spectra



A DFG-ANR proposal is being submitted to use Perkeo III instrument

Conclusions

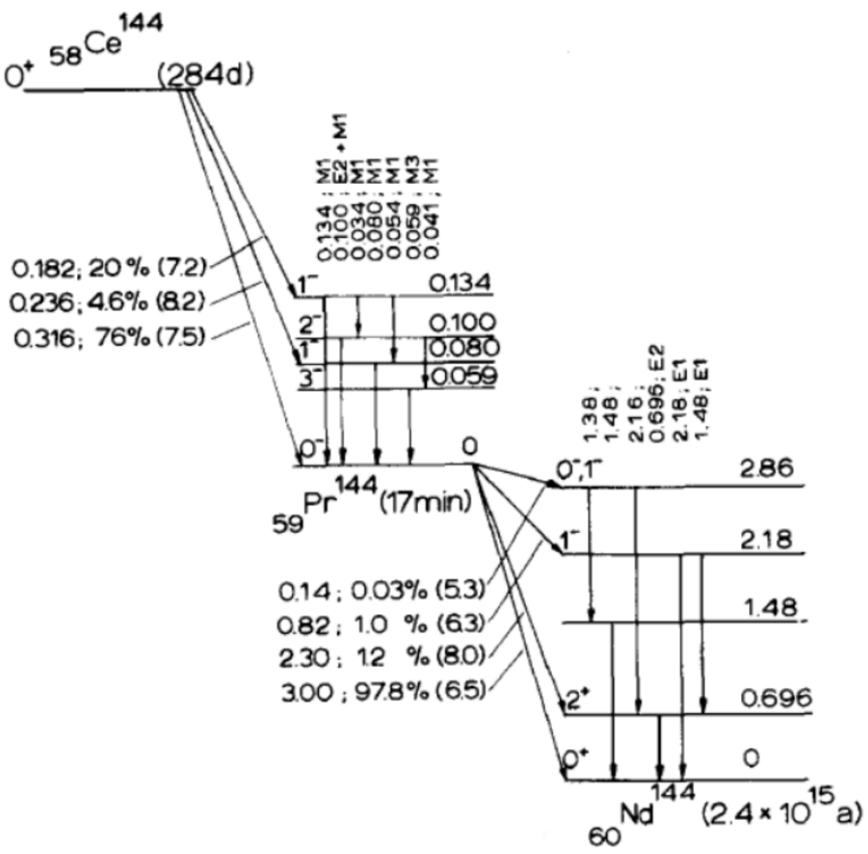
Conclusions

- **SOX is getting ready to start data-taking:**
  - The contract with Mayak for the source production has been signed;
  - The site is ready (Borexino detector, Clean Room..);
  - The tungsten shield has been produced and delivered to Gran Sasso to perform some tests;
  - The two calorimeters are under commissioning;
  - A complete test of the procedures for the installation of the source underneath the detector is planned for this summer (with a source mockup);

- SOX will start taking data in spring 2018 and will be able of covering most of the currently allowed region in the oscillation parameter space;

Backup slides

SOX: the importance of knowing the source spectrum



Main ^{144}Pr branch: ground state $0^- \to 0^+$ first non-unique forbidden transition.

Shape of energy spectra:

$$S_\beta \propto \underbrace{W \cdot p \cdot (W - W_0)^2}_{\text{statistical shape}} \cdot \underbrace{F(W, Z)}_{\text{Fermi func}} \cdot \underbrace{C(W)}_{\text{shape factor}}$$

- W: total energy of electron
- W_0: end point
- p: electron momentum
- $\mathbf{C(W) = 1 + a \cdot W + b/W + c \cdot W^2}$