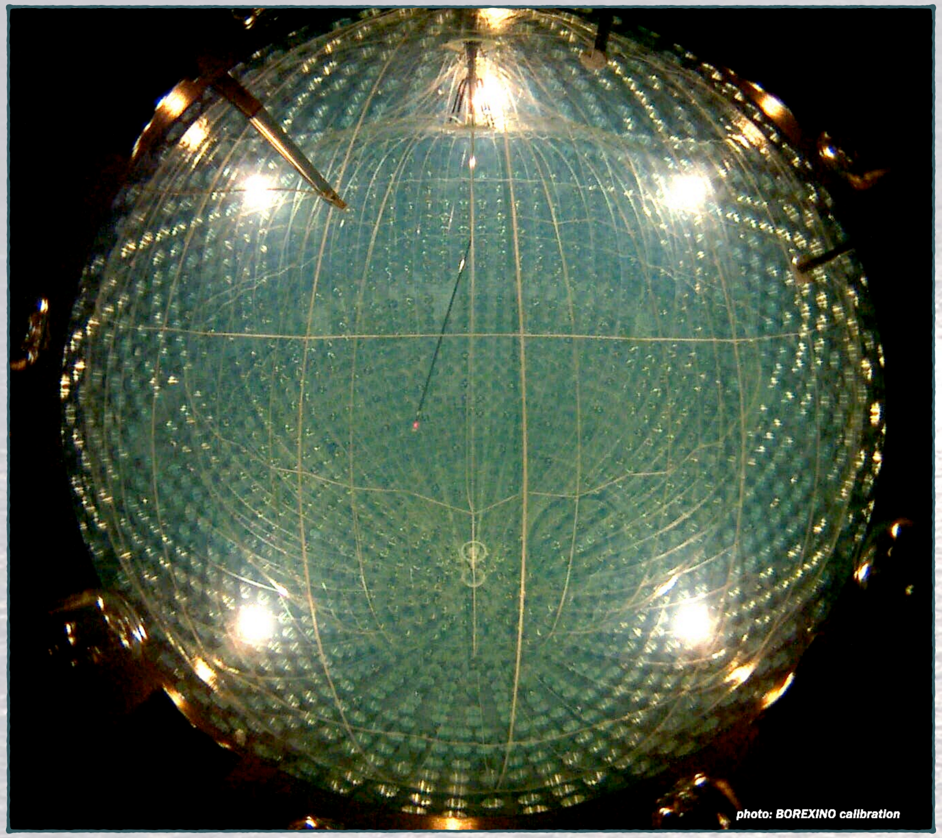
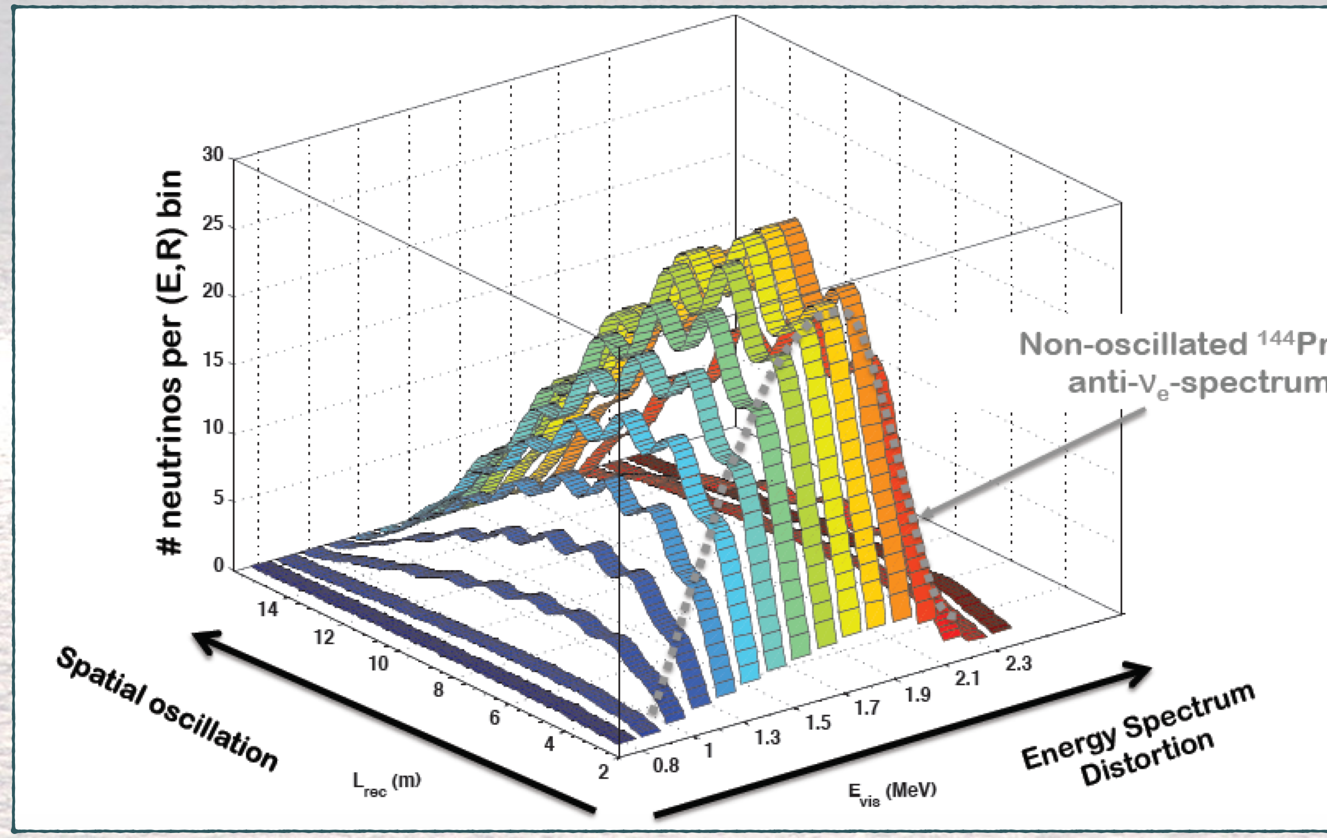




# STERILE NEUTRINO SEARCH WITH THE SOX PROJECT

Project N. 320873

**Marco Pallavicini**
**(on behalf of BOREXINO-SOX Collaboration)**
**Università di Genova and INFN**

## Standard model neutrinos work well

- 3 mixing angles, 2 mass splittings ($\Delta m^2$=2.4 $10^{-3}$ $eV^2$, $\delta m^2$=8.$10^{-5}$ $eV^2$)
  - Unknown absolute mass scale and neutrino mass ordering ("hierarchy")
  - Unknown CP phase(s) and nature of neutrino mass term
- No more than 3 neutrinos coupled to $Z_0$

## BUT

- Weak couplings are poorly measured: **room for small corrections**
- Physics beyond standard model is called for by neutrino masses
  - Either right-handed neutrinos for Dirac mass terms or Majorana fields to build Majorana mass terms and possibly explain small mass through See-Saw

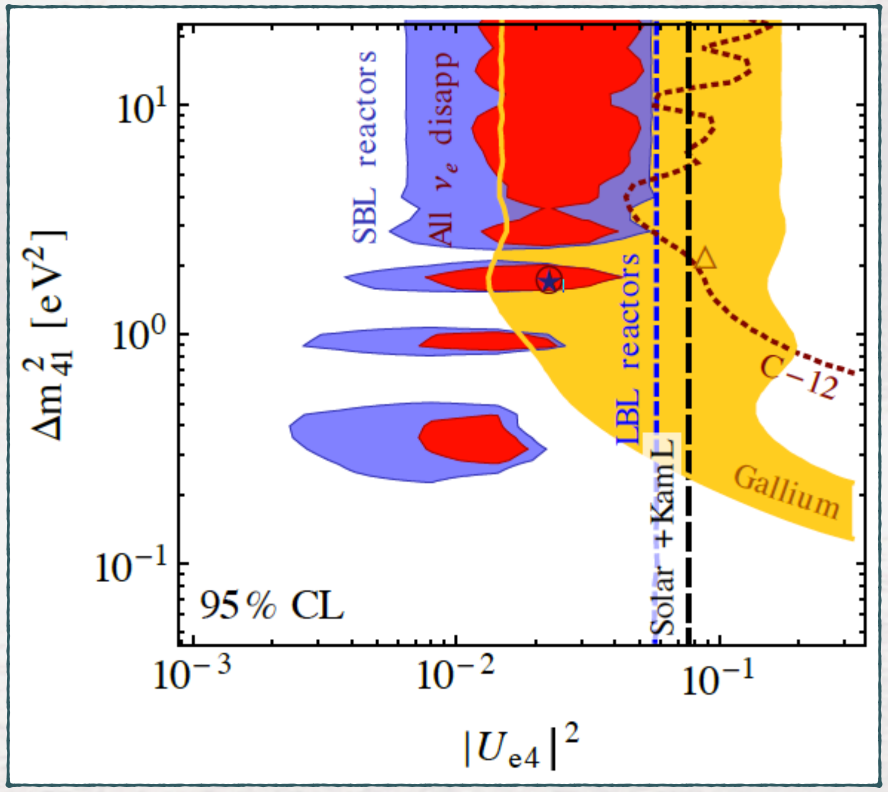
## AND

- **A few experimental results sing out of tune**

# SCIENTIFIC MOTIVATIONS

A few long standing **anomalies at small L/E** may be interpreted as **mixing of one or more sterile neutrinos with known states**

- In a short schematic list:
  - LSND/MiniBoone $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and $P(\nu_\mu \to \nu_e)$ (long standing)
  - Reactors at 5-100 m ("reactor anomaly")
  - $^{51}Cr$ and $^{37}Ar$ sources with Gallium solar ν detectors ("Gallium anomaly")




J. Kopp et al., arXiv:1303.3011

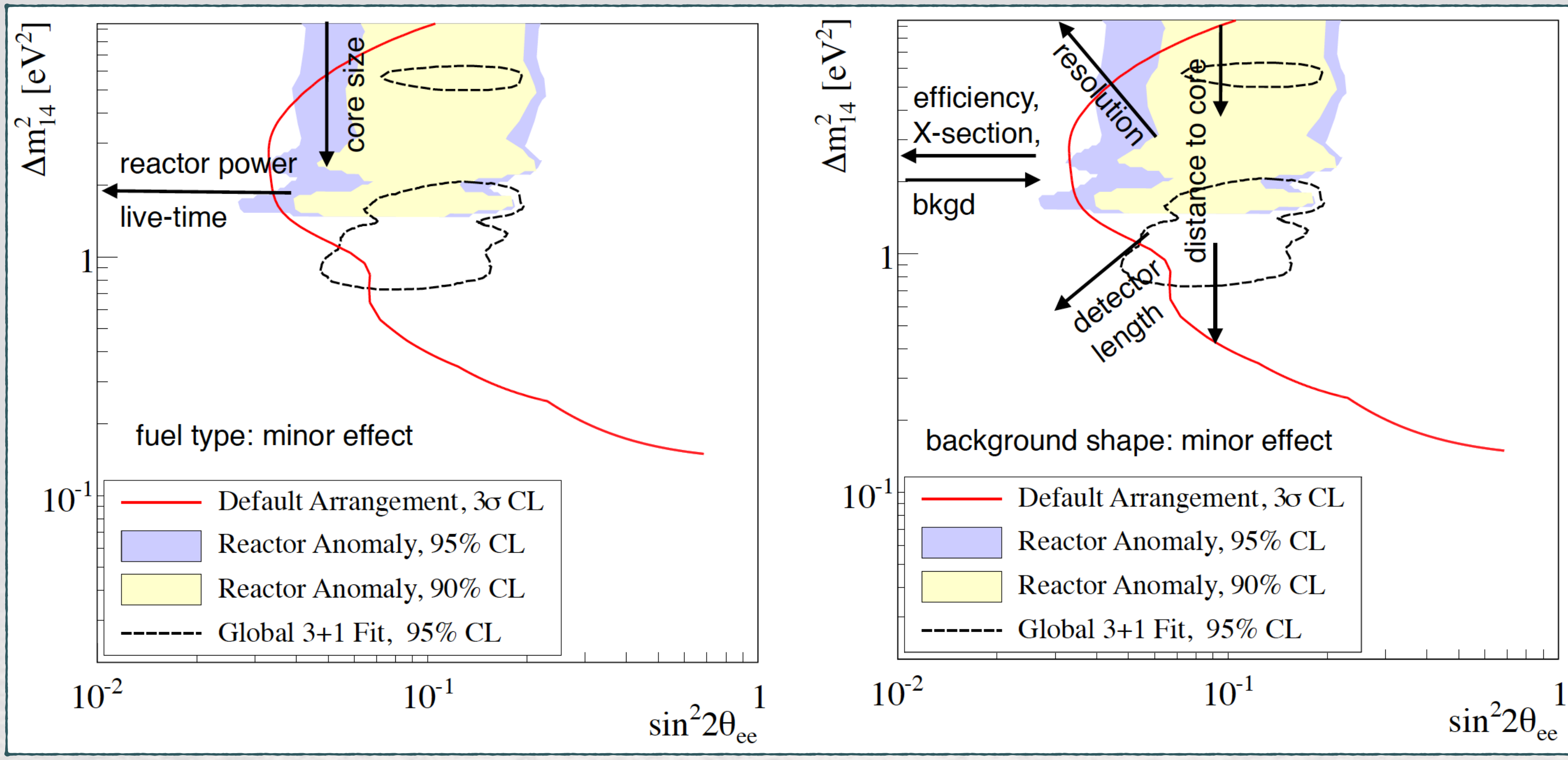
- It is **intriguing that all anomalies point to ~1 eV mass scale**
  - Although some results (e.g. IceCube 1605.01990) disfavour simple explanations

A **large ultra-pure solar neutrino detector** such as **Borexino** can help clarify this (unclear indeed) scenario

- *If confirmed*, there will be maybe **a long way to go** to understand its origin

# CRUCIAL PARAMETERS

**Arxiv 1212.2182v1**



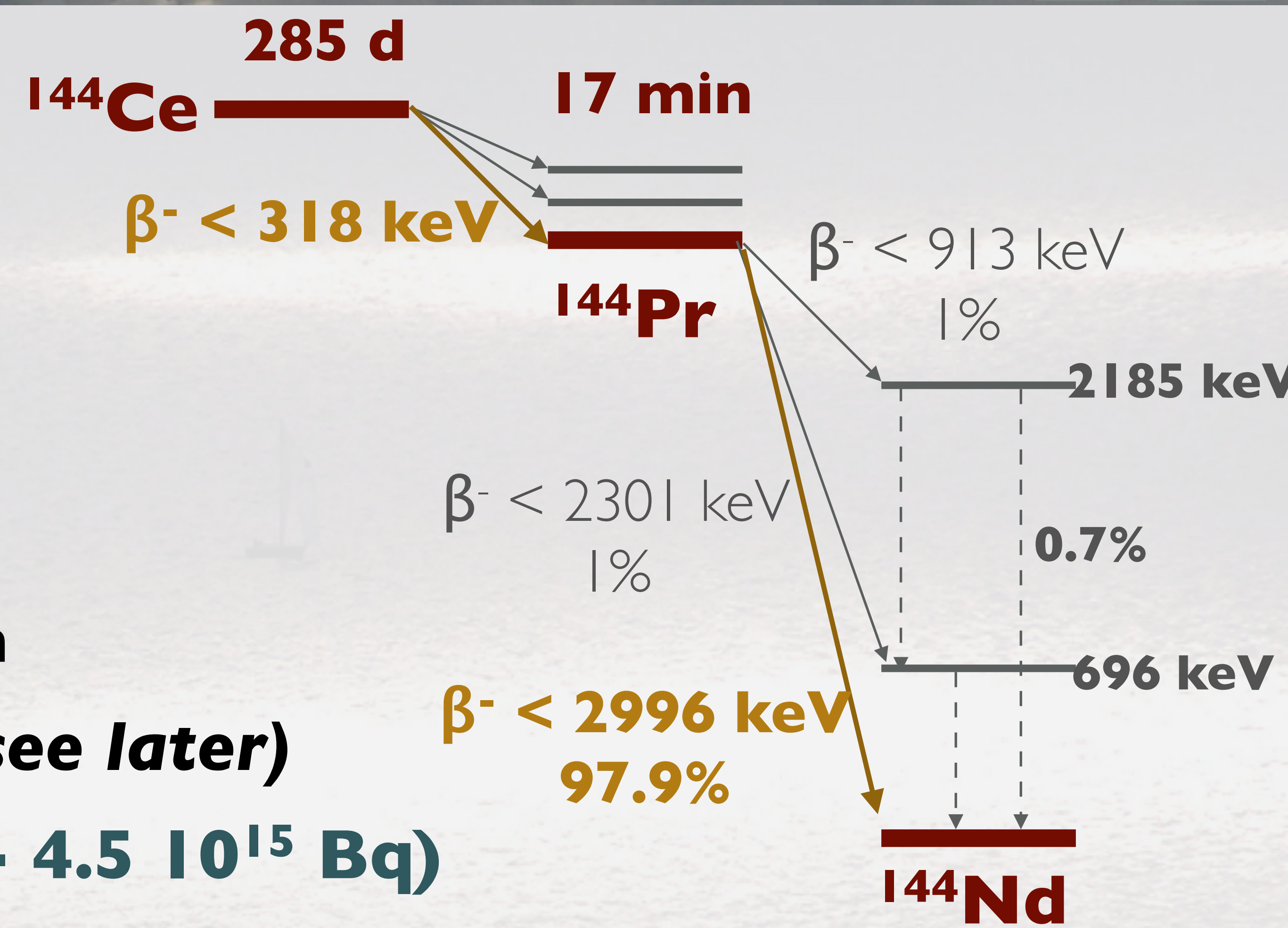

## SOURCE PRO

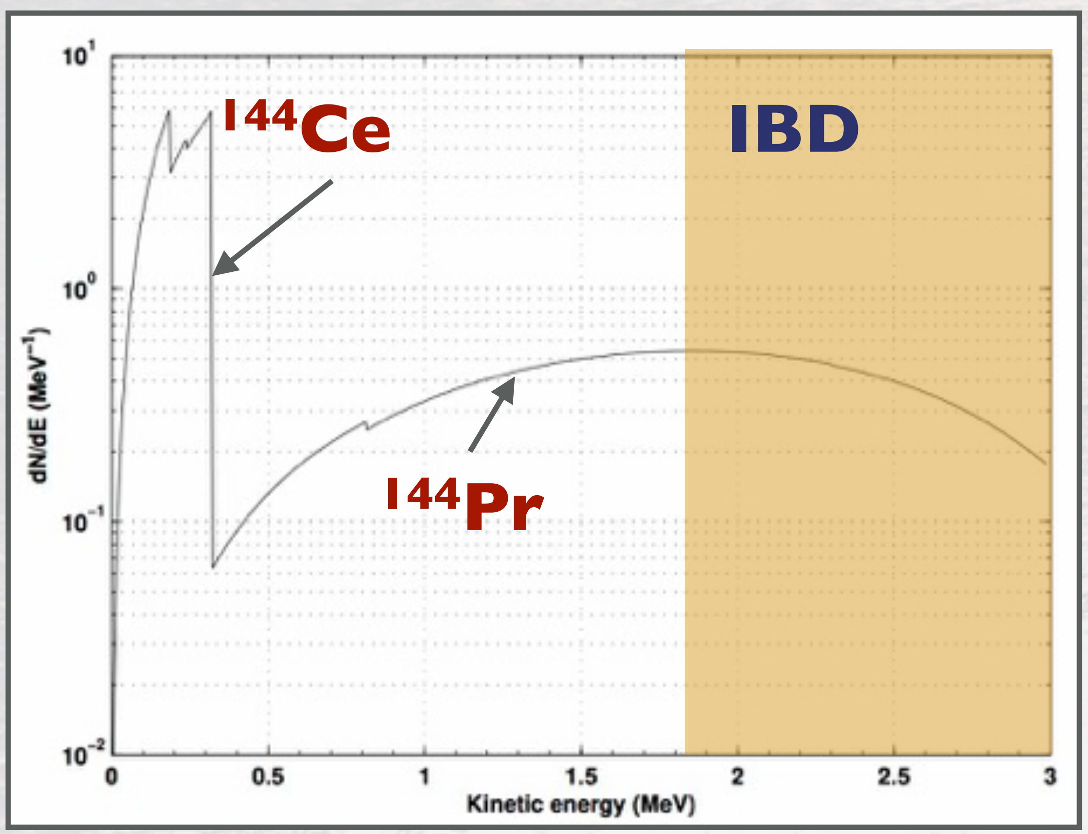
- **Small size** (~one litre). Better for small $\Delta m^2$
- **No source background** if well shielded
- Deep underground: **no μ-induced background**
- **Known $\nu_e$ spectrum** (reactors are difficult!)
  - (well…. if you measure it well!)
- **Can go very close** (min. distance in SOX **~4 m**)

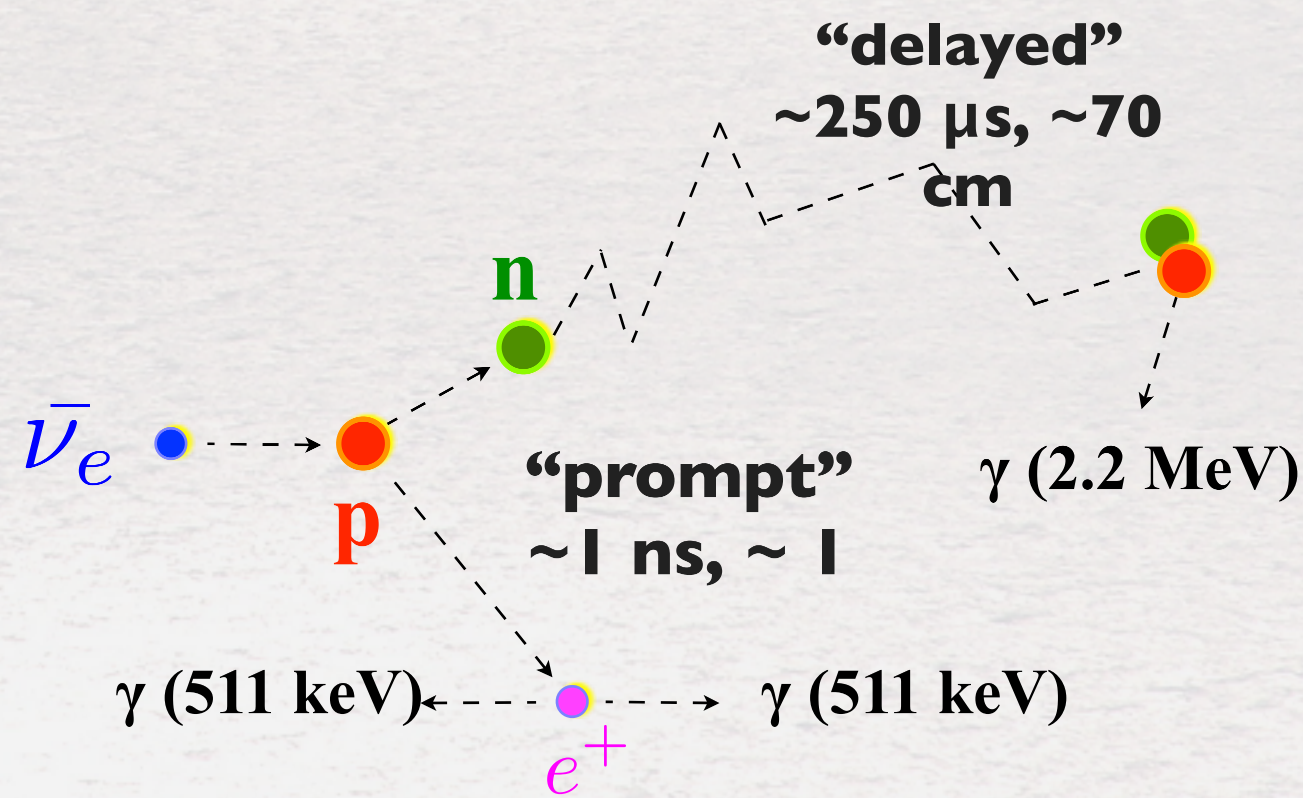
## SOURCE CONS

- Can take data for **limited time** (it decays)
- **Flux** cannot reach reactors' values
  - 150 kCi max because of heat, mainly
- **Hard (damn hard…) to:**
  - Make, Authorise, Transport, Use, Dispose

- $\beta^-$ $\bar{\nu}_e$ up to 3 MeV from $^{144}$Pr
  - $^{144}$Ce $T_{1/2}$= 285 days
- Extracted from spent nuclear fuel
- Detection via IBD:
  - Threshold: 1.8 MeV
  - ~250 μs coincidence between $e^+$ & n
  - ***Background free in Borexino*** ***(see later)***
  - **Activity: ≈ 100-150 kCi (≈ 3 - 4.5 $10^{15}$ Bq)**



The idea of making a neutrino or anti-neutrino source experiment with BoreXino dates back to the birth of the project (1991)

N.G. Basov, V. B. Rozanov, JETP 42 (1985)
**Borexino proposal, 1991 (Sr90)**
J.N.Bahcall,P.I.Krastev,E.Lisi, Phys.Lett.B348:121-123,1995
N.Ferrari,G.Fiorentini,B.Ricci, Phys. Lett B 387, 1996 (Cr51)
I.R.Barabanov et al., Astrop. Phys. 8 (1997)
Gallex coll. PL B 420 (1998) 114 **Done** (Cr51)
A.Ianni,D.Montanino, Astrop. Phys. 10, 1999 (Cr51 and Sr90)
A.Ianni,D.Montanino,G.Scioscia, Eur. Phys. J C8, 1999 (Cr51 and Sr90)
SAGE coll. PRC 59 (1999) 2246 **Done** (Cr51 and Ar37)
SAGE coll. PRC 73 (2006) 045805
C.Grieb,J.Link,R.S.Raghavan, Phys.Rev.D75:093006,2007
V.N.Gravrin et al., arXiv: nucl-ex:1006.2103
C.Giunti,M.Laveder, Phys.Rev.D82:113009,2010
C.Giunti,M.Laveder, arXiv:1012.4356

**SOX** Proposal European Research Council 320873 - Feb. 2012 - (P.I. M.Pallavicini)

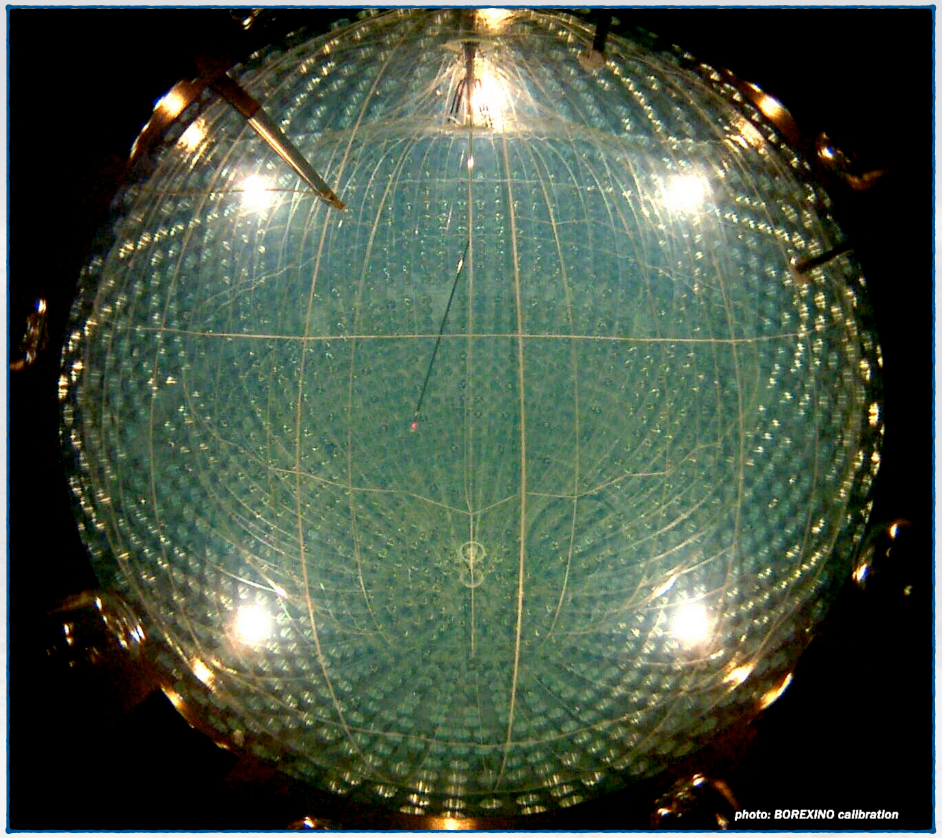
- Original SOX proposal: $^{51}$Cr neutrino source OR $^{144}$Ce anti-neutrino source

**Jan. 2014: agreement between CEA and INFN** and Borexino Collaboration to merge the CELAND proposal with SOX

- CeSOX using the Ce-144 source proposed and developed by the CEA group (based on another ERC project, P.I. T. Lasserre)

Mainly, a solar neutrino experiment:

- $\nu + e^- \rightarrow \nu + e^-$ in an organic liquid scintillator
  - **Ultra-low radioactive background** obtained via **selection, shielding, and purifications**
  - **Spatial resolution: 12 cm @ 2 MeV**
  - **Energy resolution: ~3.5% @ 2 MeV**

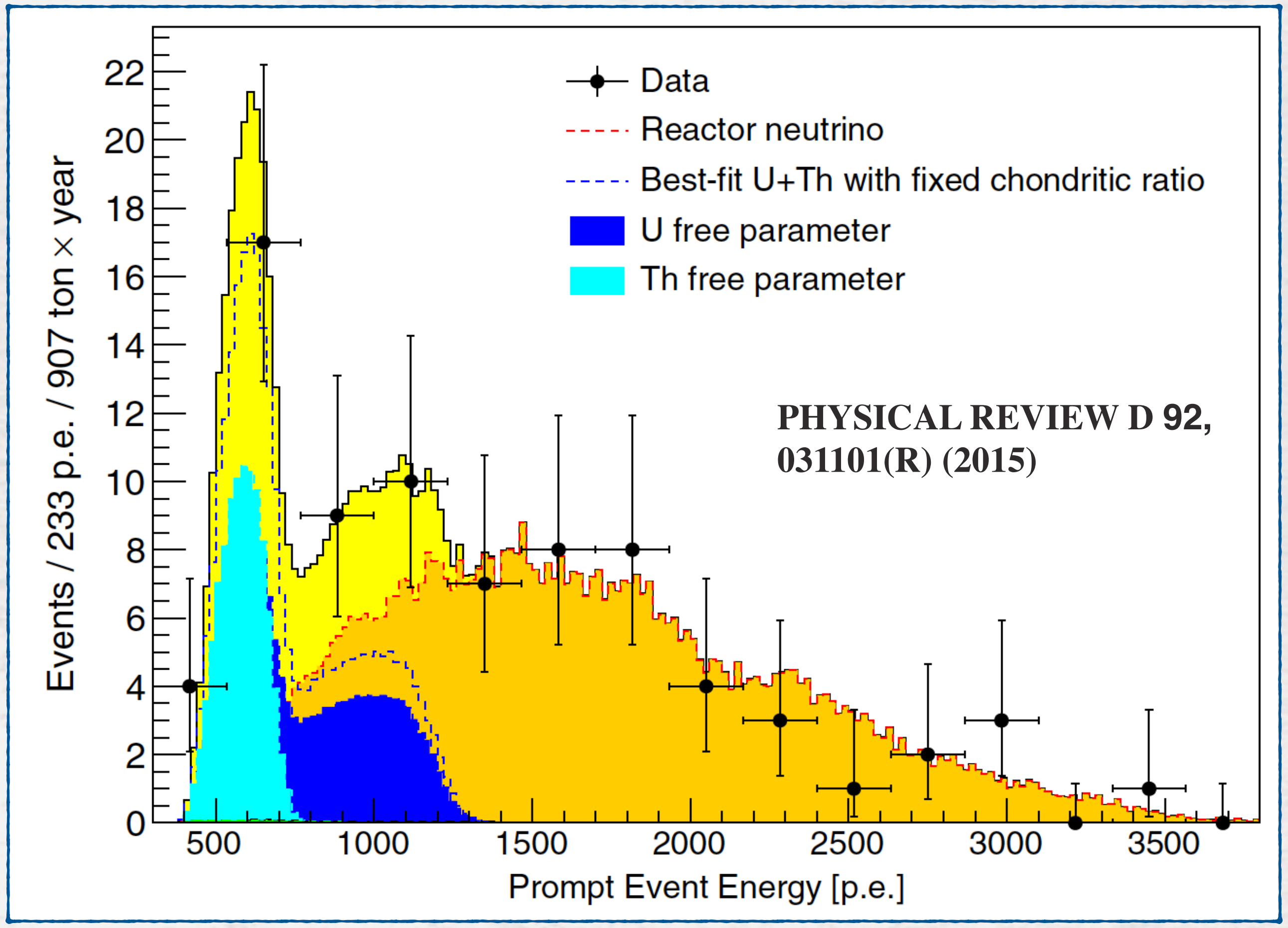


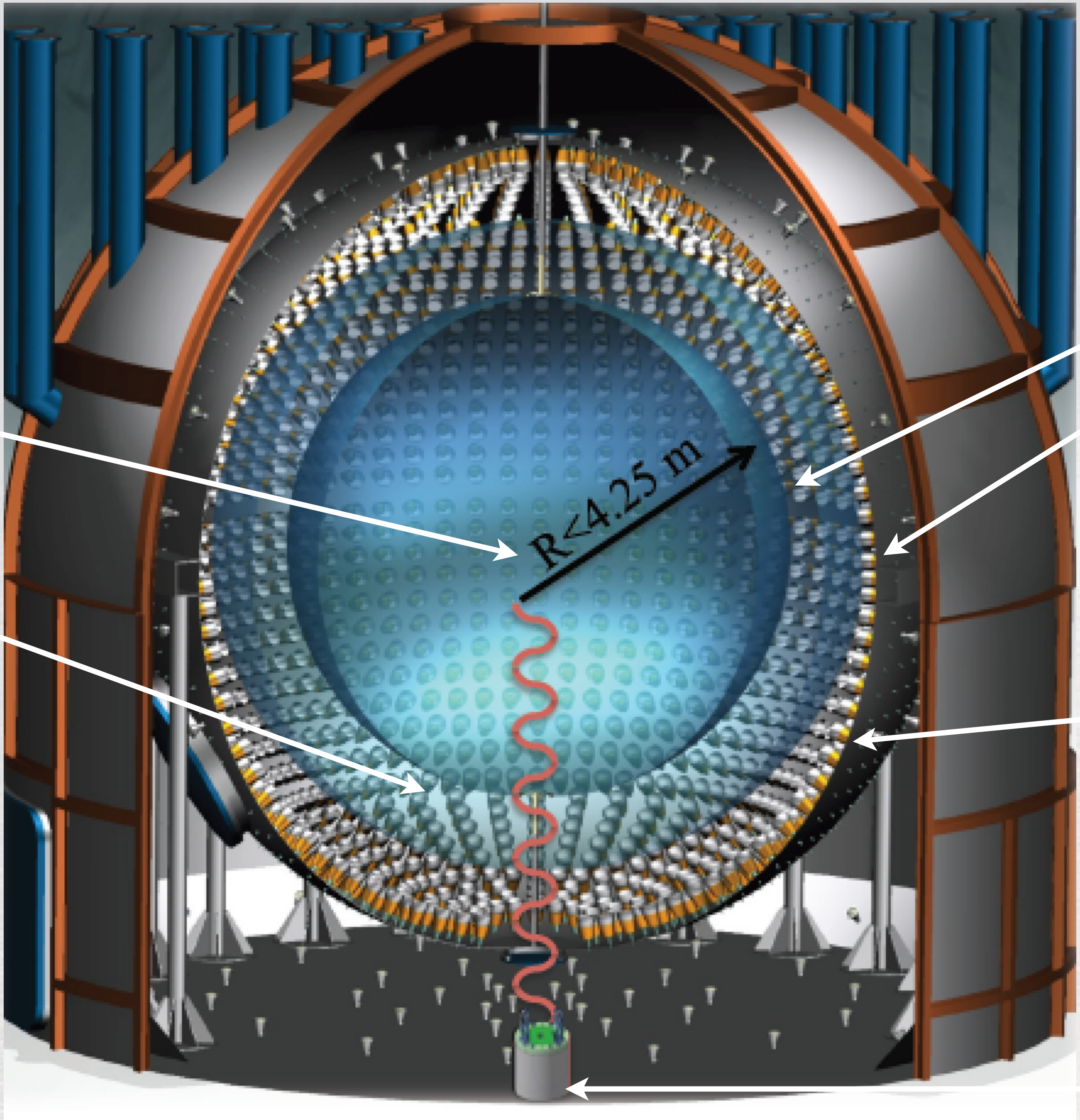

**Anti-Neutrino detection capability demonstrated by geo-ν detection**

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

**SOX experiment is background free**

- Expected signal: **> $10^4$ events in 1.5 y**





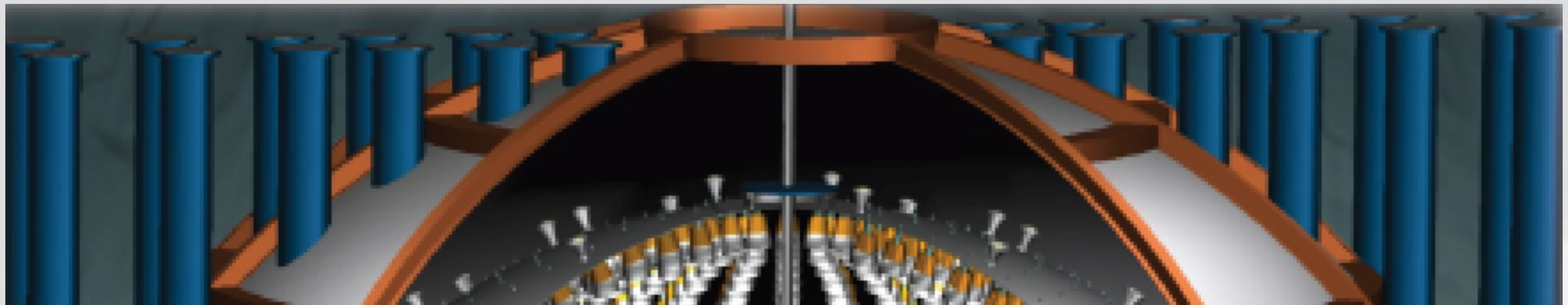

Scintillator
270 t PC-PPO

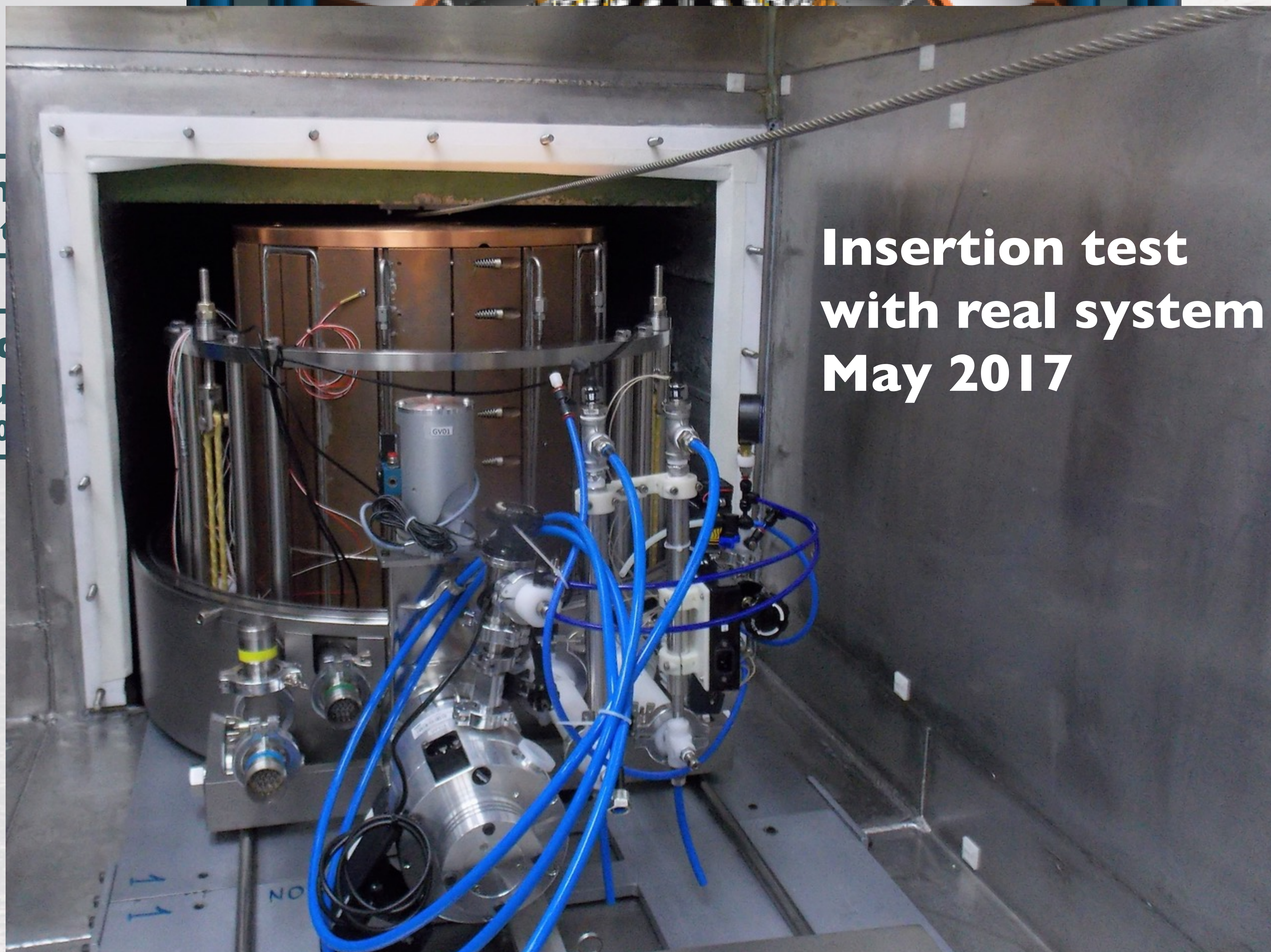
Liquid Buffer
~1000 t PC

Nylon vessels
150 μm thick

PMTs

Source Under the Floor






Scin
270 t

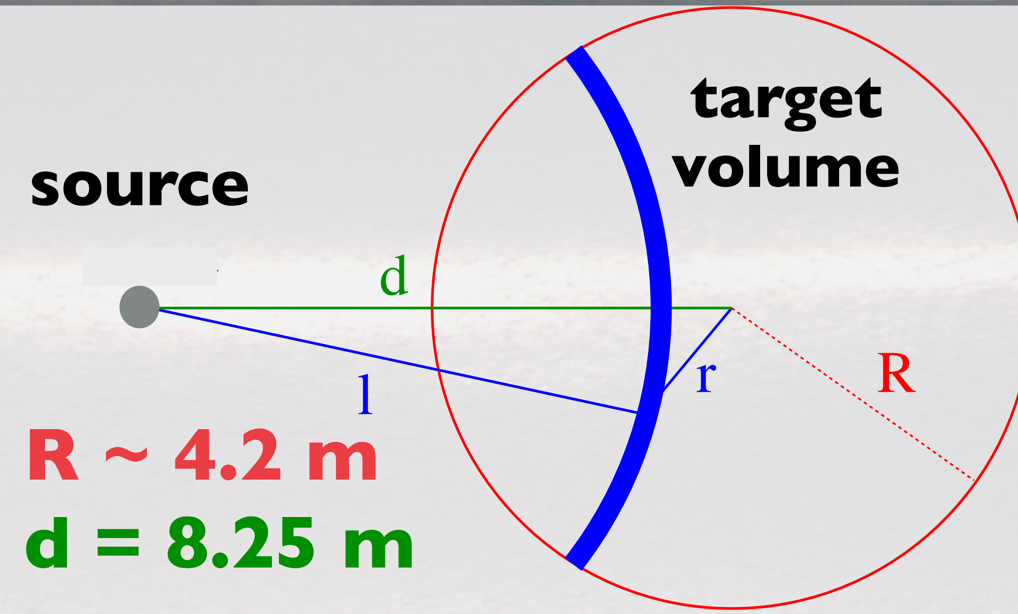
Lic
Bu
~100

**Nylon vessels**
150 µm thick

**PMTs**

**Source Under the Floor**

*Two different techniques*:



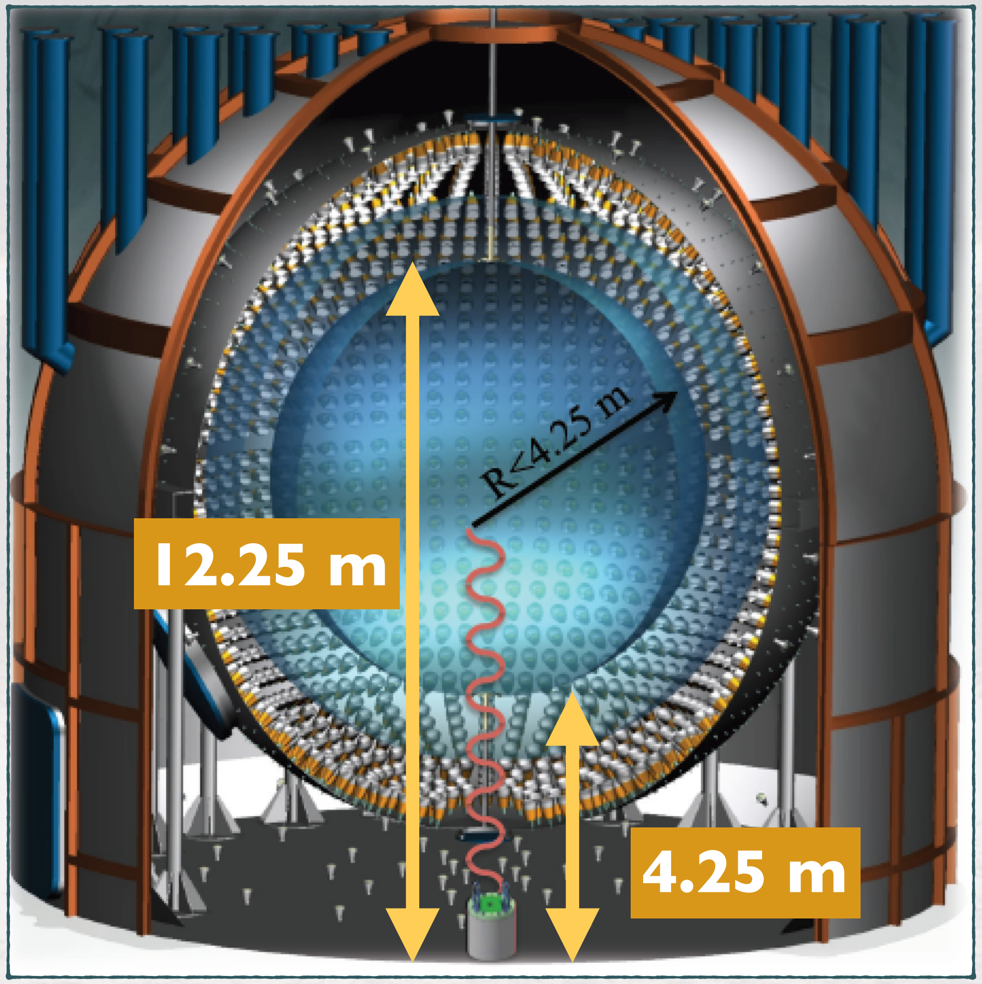

**R ~ 4.2 m**
**d = 8.25 m**

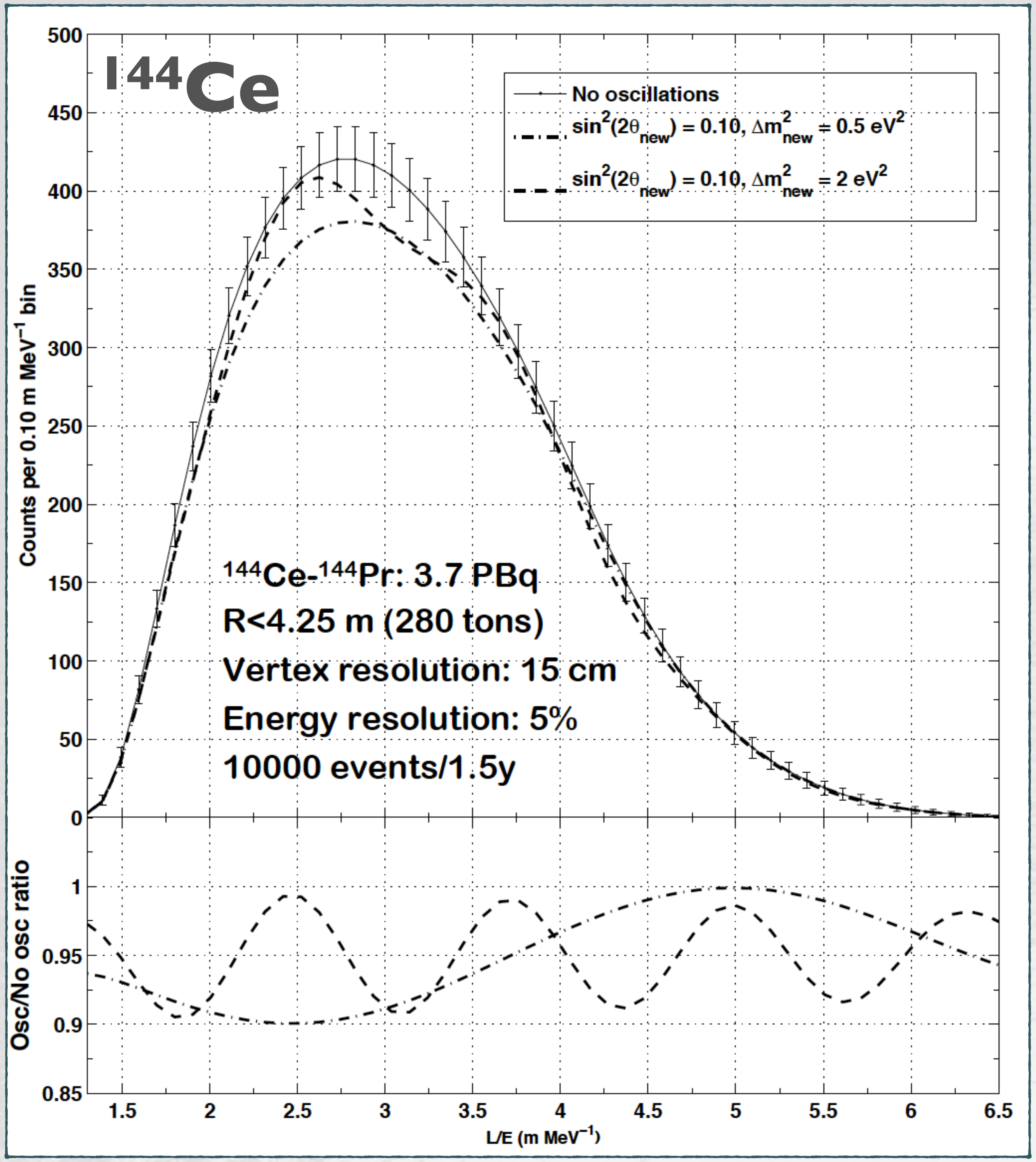
$$\mathbf{V(l) = 2\pi l^2 \left(1 - \frac{d^2 - R^2 + l^2}{2\ d\ l}\right)}$$

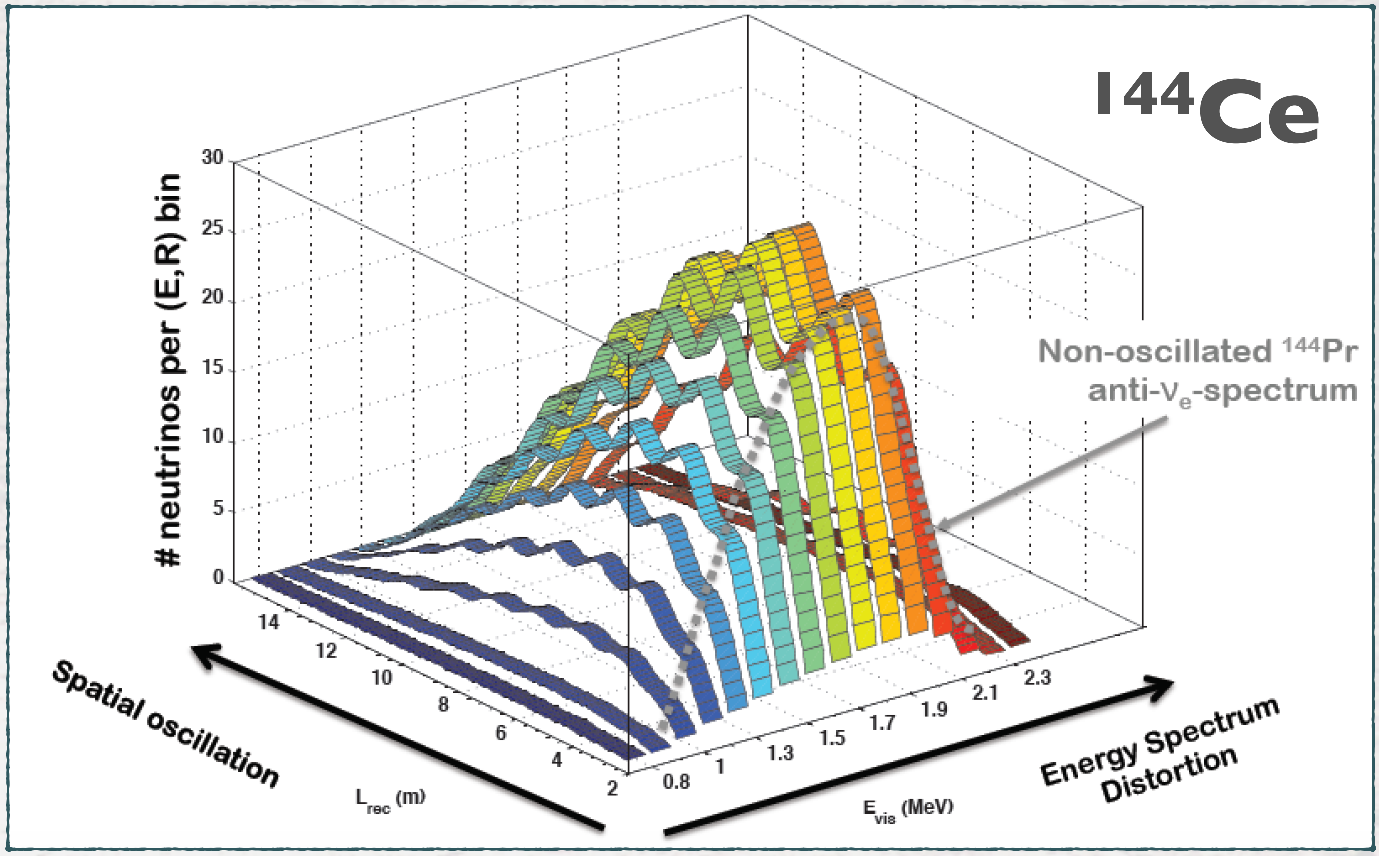
- **Standard disappearance**
  - Rate depends on $\theta_s$ and (weekly) on $\Delta m^2$
  - Sensitivity depends on:
    - Source activity (statistics)
    - Error on source activity and $\nu_e$ spectrum
    - FV determination $$\mathbf{N_0(l, T_1, T_2) = n_e\ \Phi(l)\ V(l)\ P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E,T)}{dT} dT}$$

- **Spatial waves.** [C.. Grieb et al., Phys. Rev. D75: 093006 (2007)]
  - For $\Delta m^2 \sim 1\ eV^2$, oscillation wavelength is smaller than detector size (~ 7 m), but larger that the spatial resolution (~ 15 cm)
    - **The distribution of the event distance from the source shows oscillations**
    - **Direct measurement of $\Delta m^2$ and $\theta_s$ independently**
    - **Does not depend neither on source activity nor on FV determination**

**SOX** is at the same time a **disappearance experiment** and an **oscillometry one**



The making of a **100-150 kCi $^{144}$Ce** source is not a trivial business

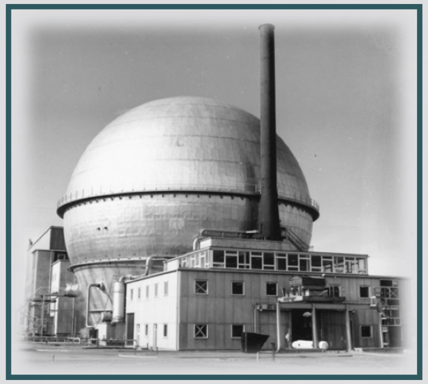
- Essentially a unique vendor (Mayak, Russia)
- Humongous amount of paperwork for **authorisations** (Russia, France, Italy)
- Many technical problems to be solved for:
  - CeANG **production** and **transportation**
  - Usage and insertion beneath Borexino
  - High precision measurement of the **activity** and of the $\bar{\nu}_e$ **spectrum**

Synergy between CEA, INFN and Borexino Collaboration

- CEA/INFN: source production and transportation
- INFN: site preparation, shield, and Borexino detector preparation (new trigger)
- CEA/INFN/TUM: High precision calorimetry
- Borexino Collaboration: detector, high precision MC, data analysis, calibrations

# THE MAKING OF THE $\overline{\nu}_e$ SOURCE

**Fuel from Research Reactor (higher $^{235}U$)**

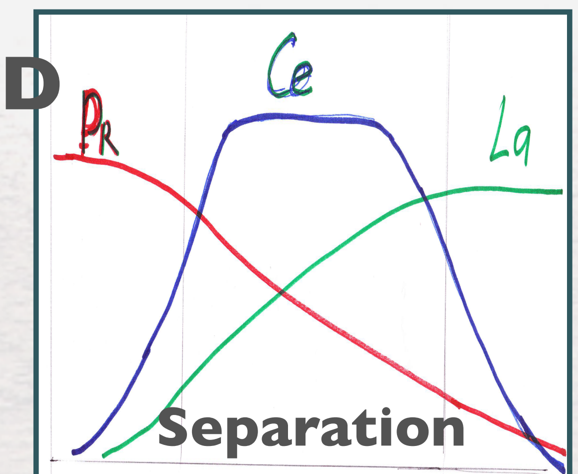


**Cutting, digestion (Purex process)**


**Lanthanide and Actinides concentrate**

**Rare Earths Precipitation**

**Displacement Chromatography**

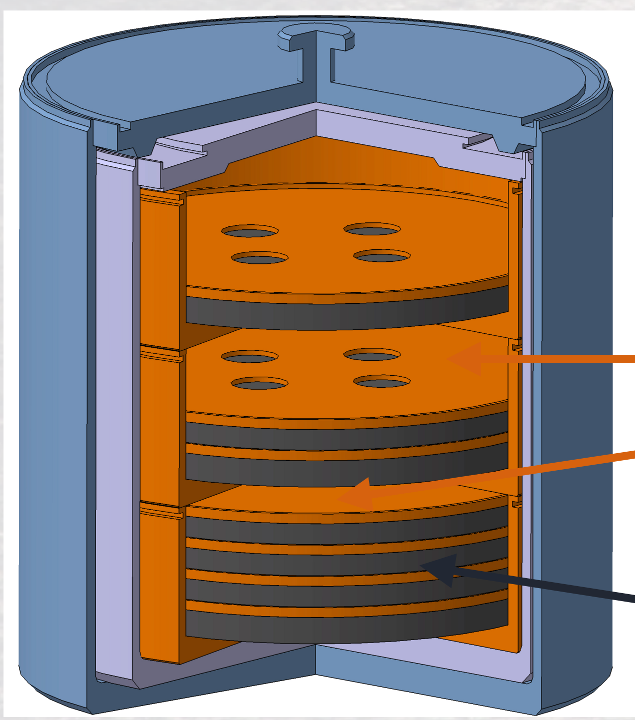




**Calcination**

**At the END**

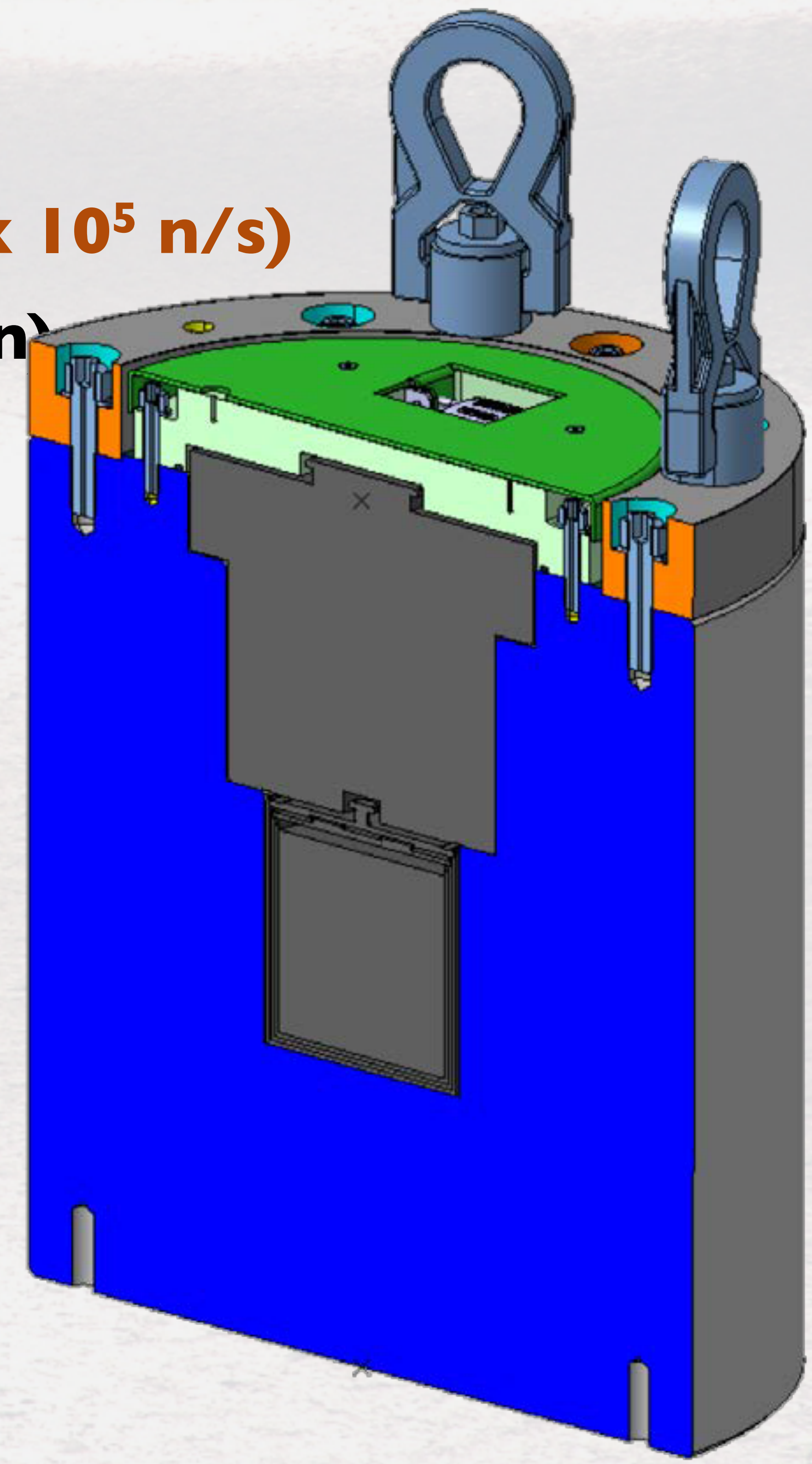
**THE CAPSULE (few litres)**




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

## The $CeO_2$ powder must be quite pure

- **Radio-protection,** relation between **heat and activity,** strict LNGS **requirements on n flux**
  - Rare Earths: **$\gamma$ rate < $10^{-3}$ Bq/Bq** w.r.t. $^{144}$Ce
  - Pu and actinides: **< $10^{-5}$ Bq/Bq** w.r.t. $^{144}$Ce **(max $10^5$ n/s)**
  - **A long list of nuclei to check! ($\gamma$,$\alpha$,ICPMS,n)**
  - $^{22}$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, $^{93}$mNb, $^{106}$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$^{206}$Pb, $^{207}$Bi, $^{208}$Po, $^{209}$Po, $^{228}$Ra$^{208}$Pb, $^{227}$Ac$^{207}$Pb, $^{228}$Th$^{208}$Pb, $^{232}$U$^{208}$Pb, $^{235}$Np, $^{236}$Pu-$^{232}$U, $^{238}$Pu$^{230}$Th, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu-$^{241}$Am, $^{241}$Am, $^{242m}$Am-$^{230}$Th, $^{241}$Am, $^{244}$Cm-$^{243}$Cm, $^{243}$Cm$^{235}$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

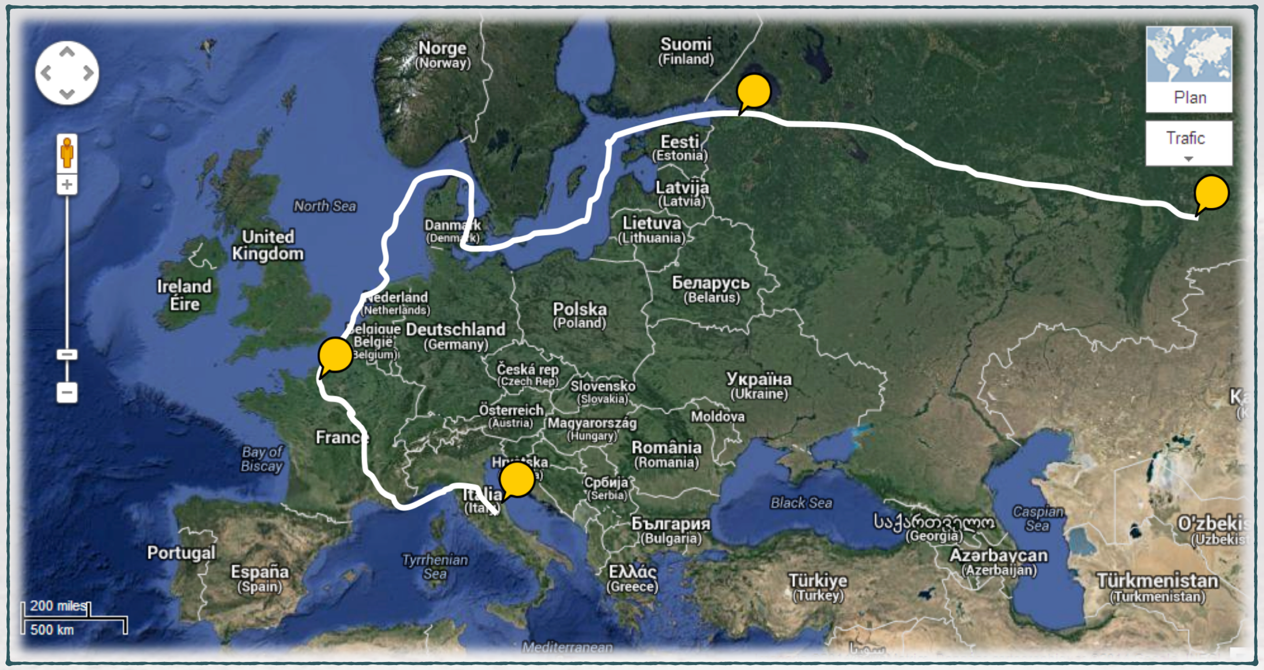


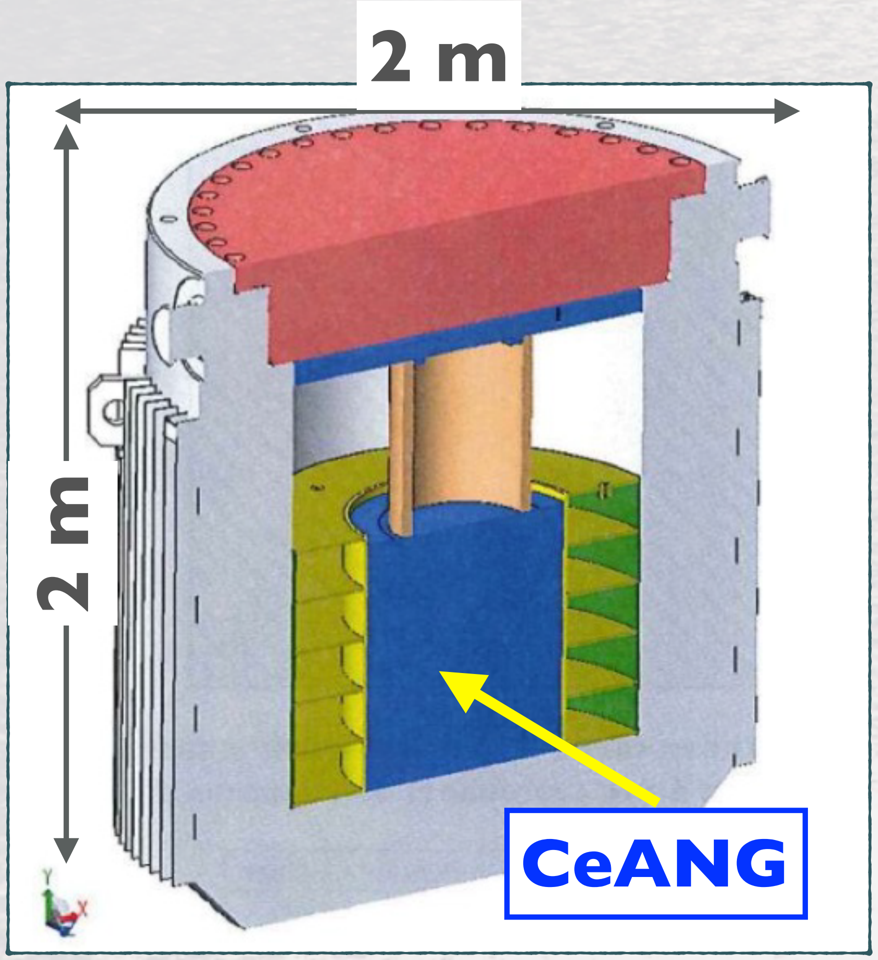
## $\gamma$ radiation must be fully shielded

- Container inserted into a **19 cm thick W shield**
- Being Built at Xiamen Ltd, China
  - > 2.2 ton weight
  - Made with W-Ni-Fe alloy for mechanical properties
    - W ~ 95%

**A long journey to minimise borders:**

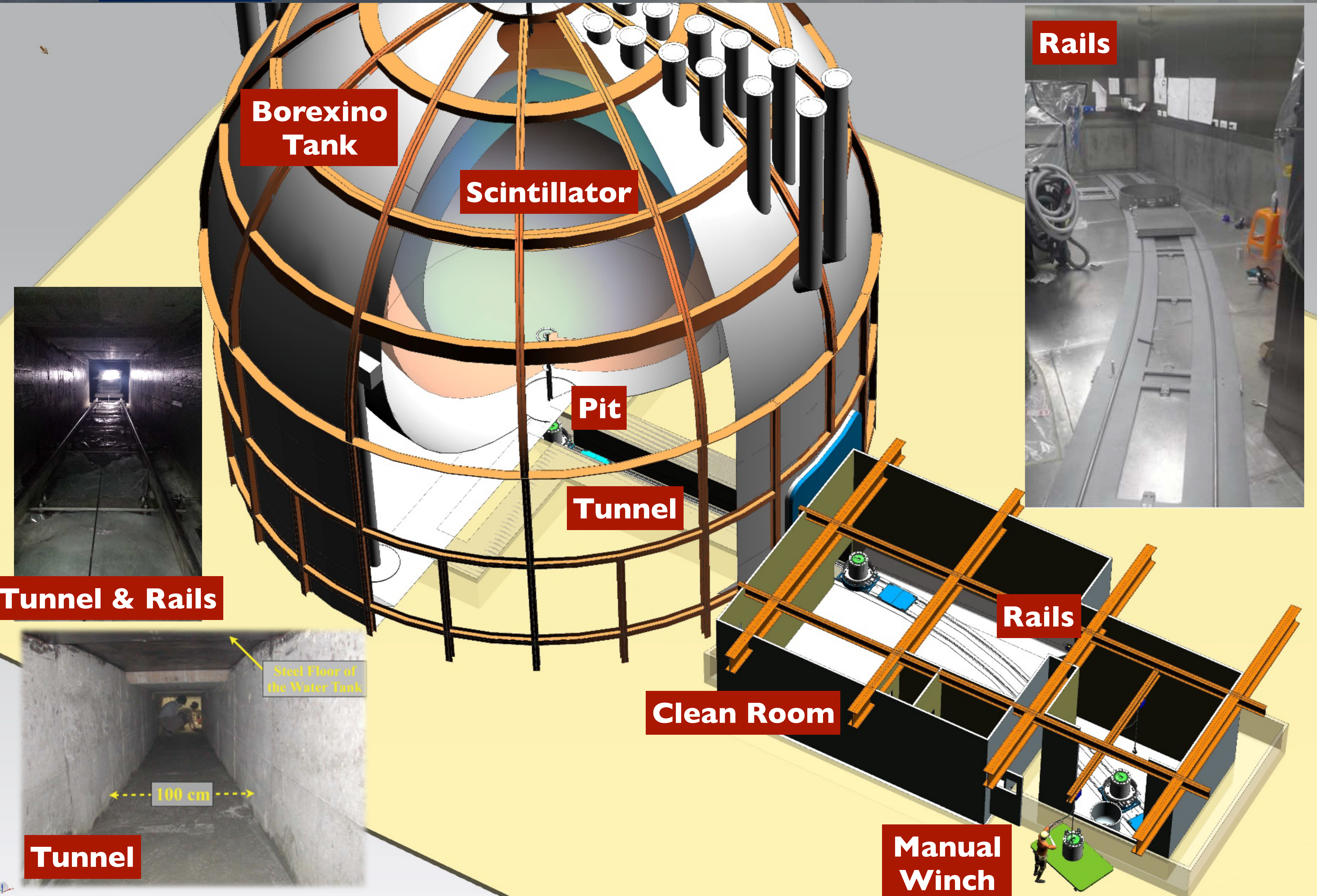
- Mayak → St. Petersburg by **train**
- St. Petersburg → Le Havre by **boat**
- Le Havre → Saclay → LNGS by **truck**
- Container: TN MTR
  - **24 t** container for nuclear fuel (CEA)
- Three companies (in Russia, France and Italy) likely involved (tender in progress)



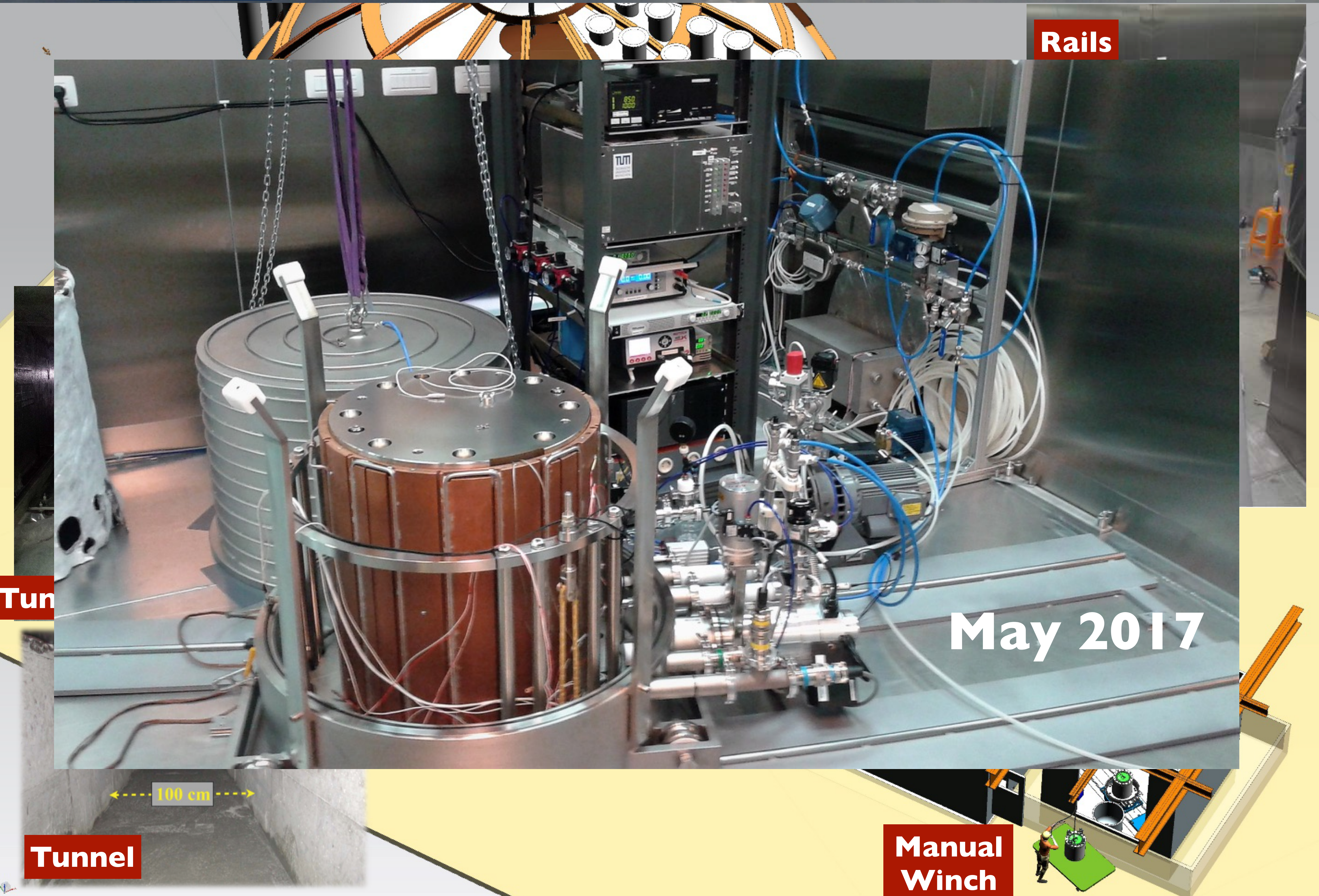



**Unloading of the truck in Hall C**

# LOCATION OF THE SOURCE @ LNGS



# LOCATION OF THE SOURCE @ LNGS

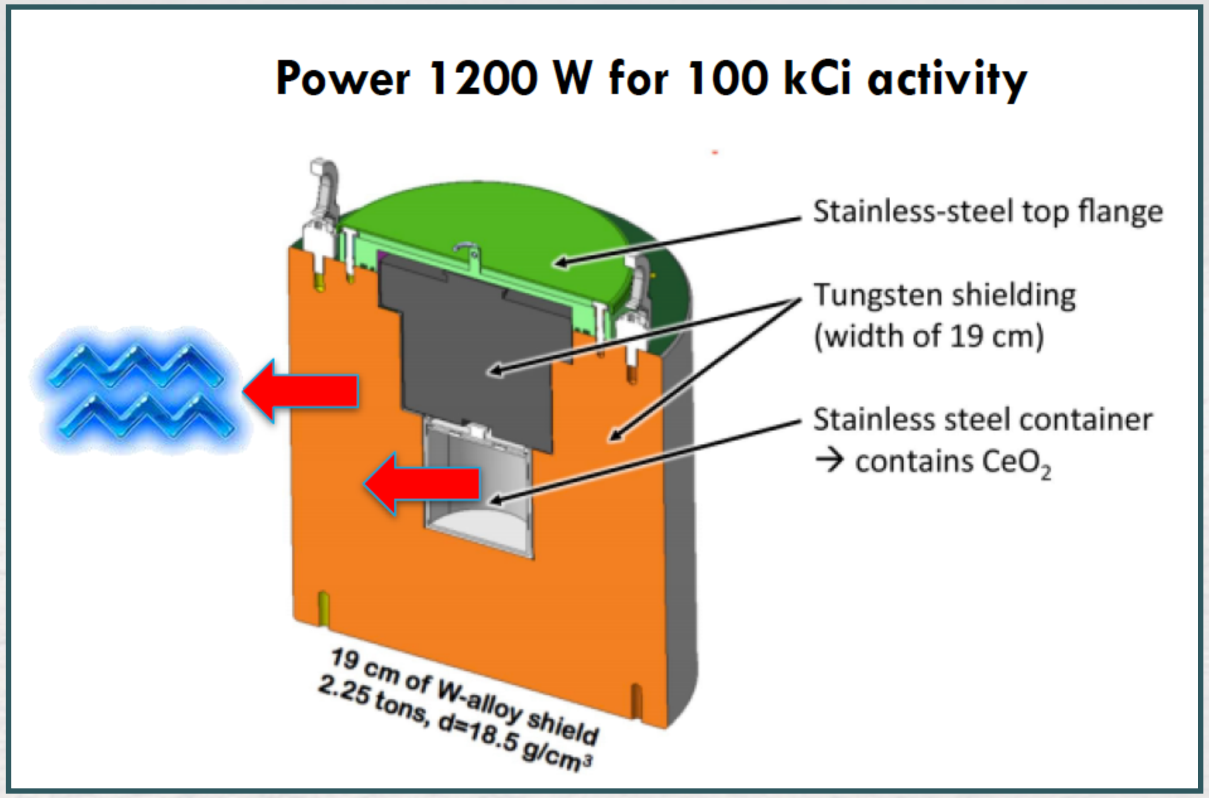


The **activity** is obtained by measuring the **heat released inside the shield and absorbed by a water flow**

- In principle, an easy measurement:

$$P = \int_{T_{in}}^{T_{out}} c_p(T)\, \dot{m}\, dT$$

power: $P$; water heat capacitance: $c_p(T)$; mass flow: $\dot{m}$



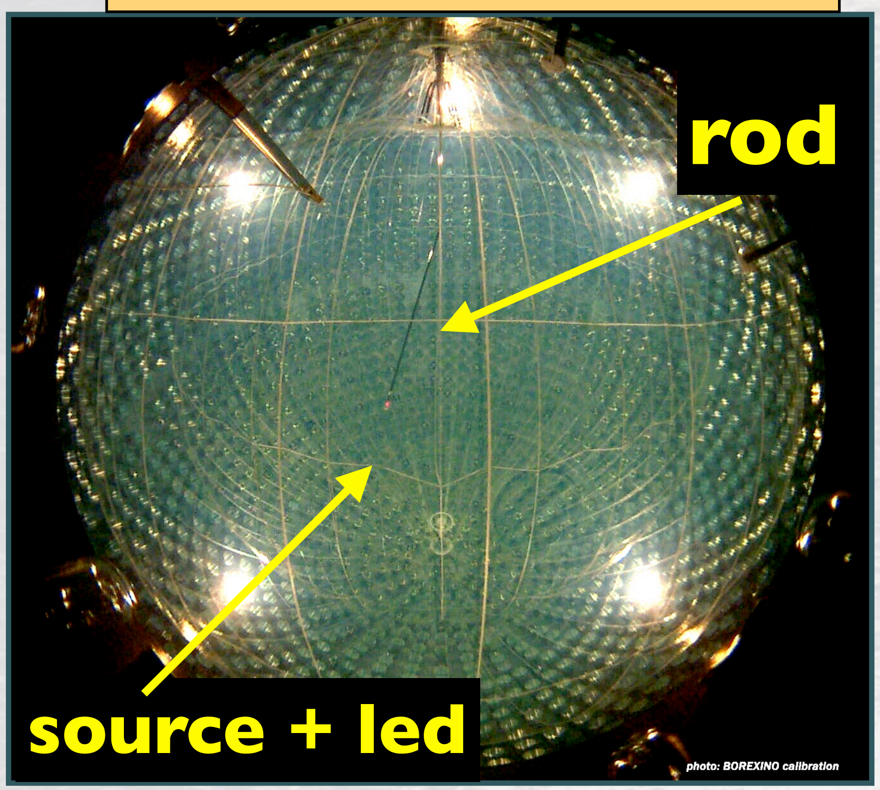

- **Systematics** are the crucial point:
  - **Heat losses**
    - Gas convection
    - Conduction through contacts
    - Radiation
  - **Relation between power and flux (anti-neutrino beta spectrum)**

# GETTING SUFFICIENT PRECISION

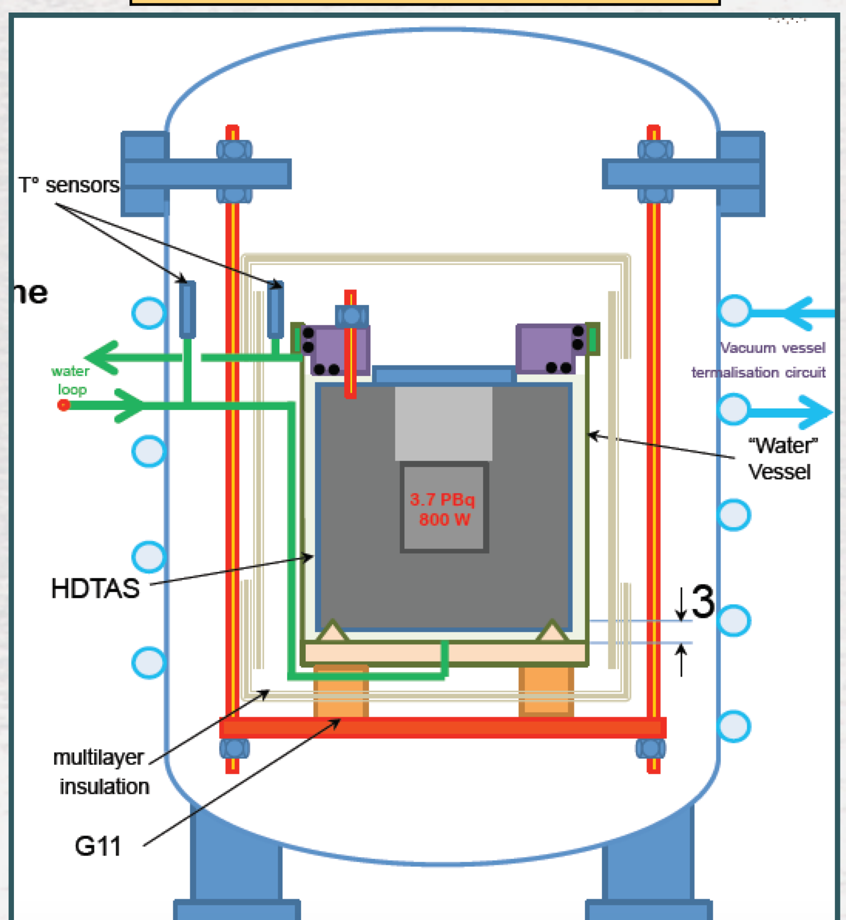
As **disappearance experiment, sensitivity** depends on: (**waves detection does not!**):

- **Activity:** Calorimetric measurement will reach 1% precision (two measurements with independent calorimeters)
- **Fiducial volume** (Calibration program in early 2017, 0.7% achieved for Be-7)
- **Detector response:** well known from Borexino data
- Measurements of $^{144}$**Ce β spectrum,** above 1.8 MeV

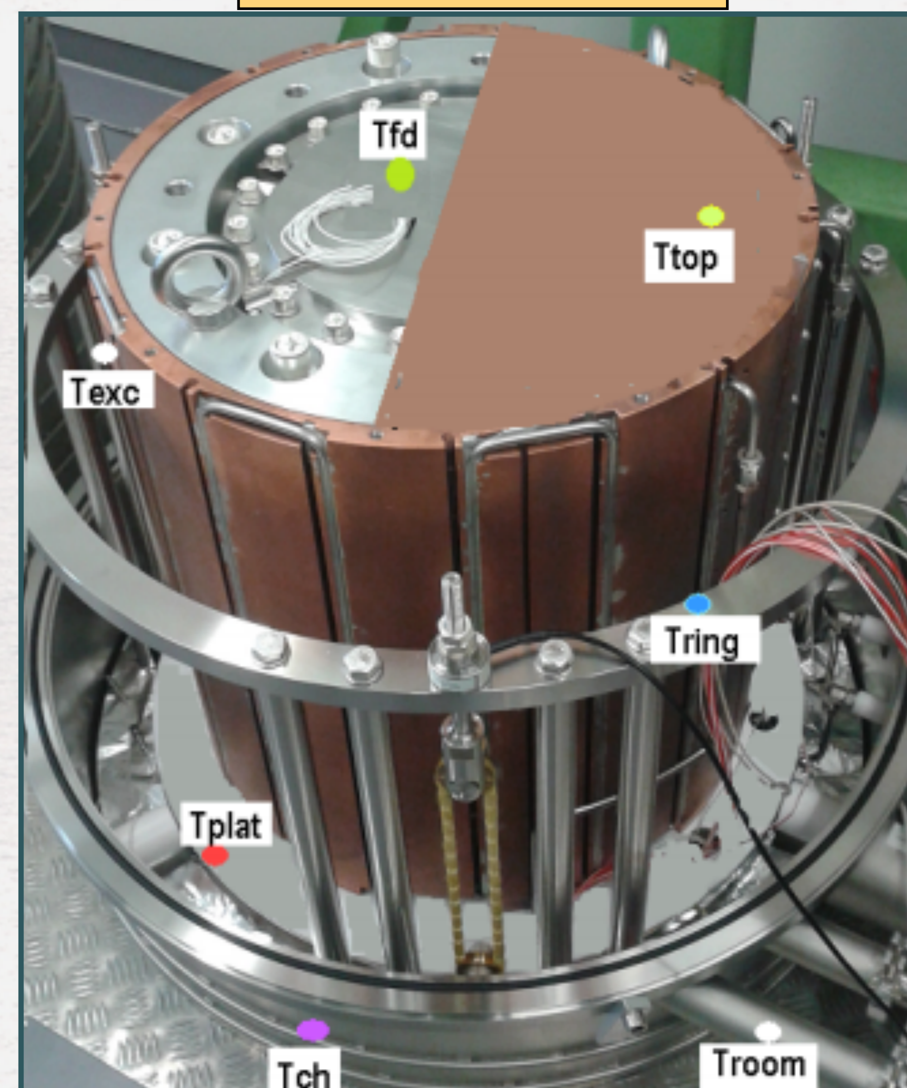
**Borexino Calibration**




**CEA calorimeter**




**Genova/TUM**



## Convection

Vacuum system
Turbo molecular pump
skroll pump

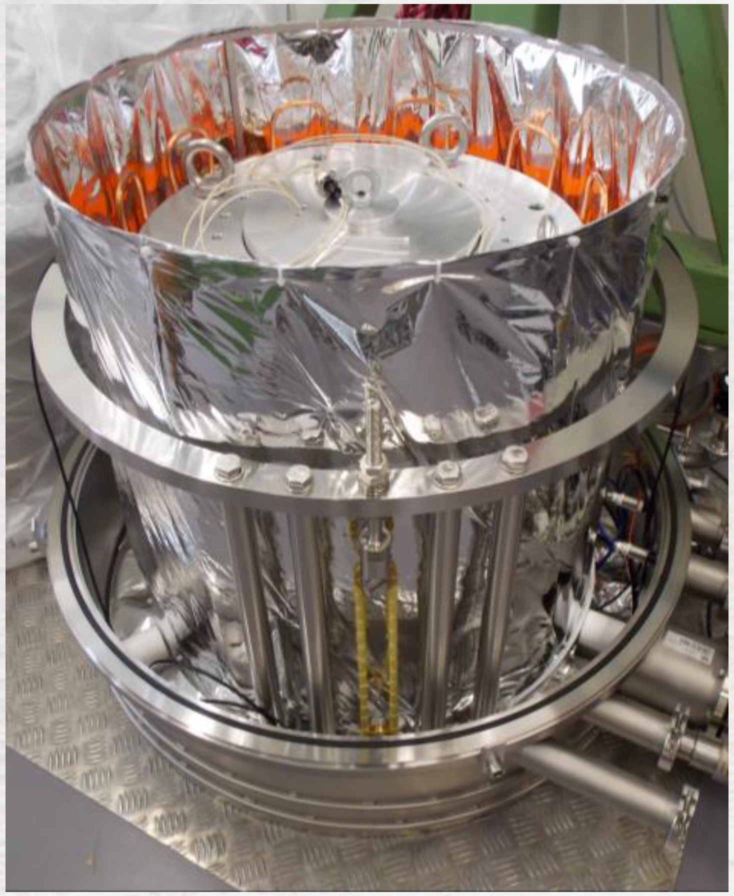
**$P < 5 \cdot 10^{-5}$ mbar**

**P ≈ 0 W**

## Radiation

2 stages of super insulator
(10 foils each)

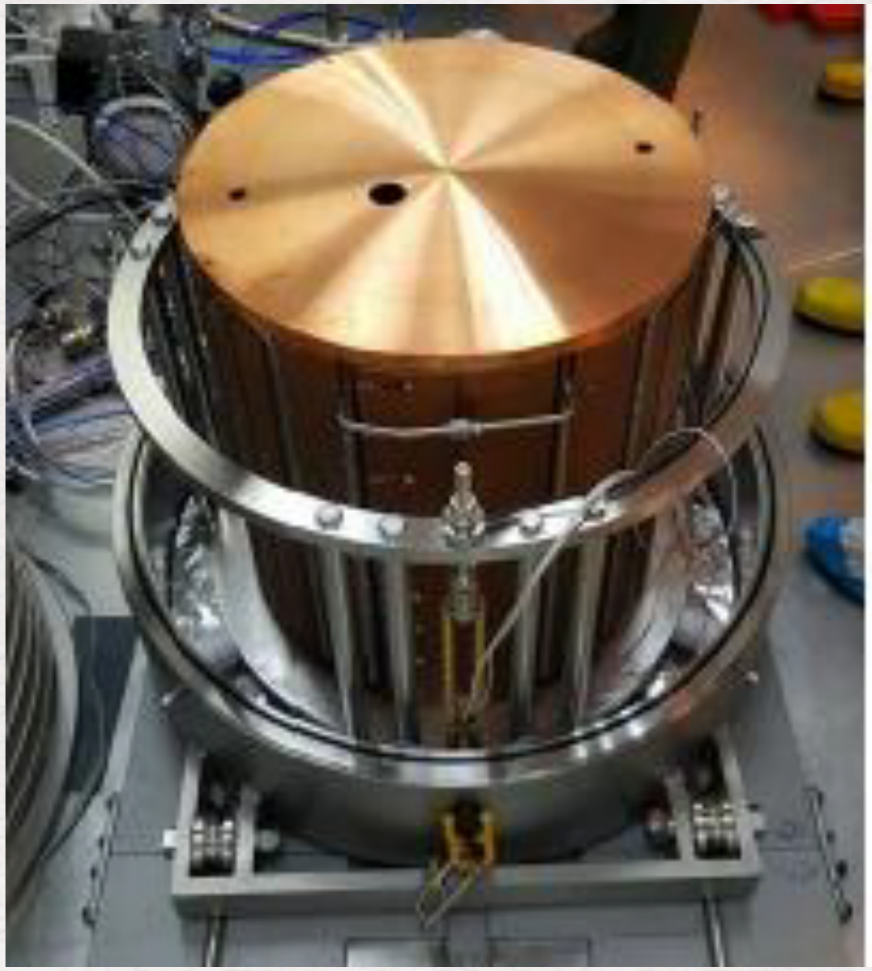
Thermalisation of the external chamber by hot water flow



**P < 1 W**

## Conduction

Hanging platform suspended by three kevlar ropes

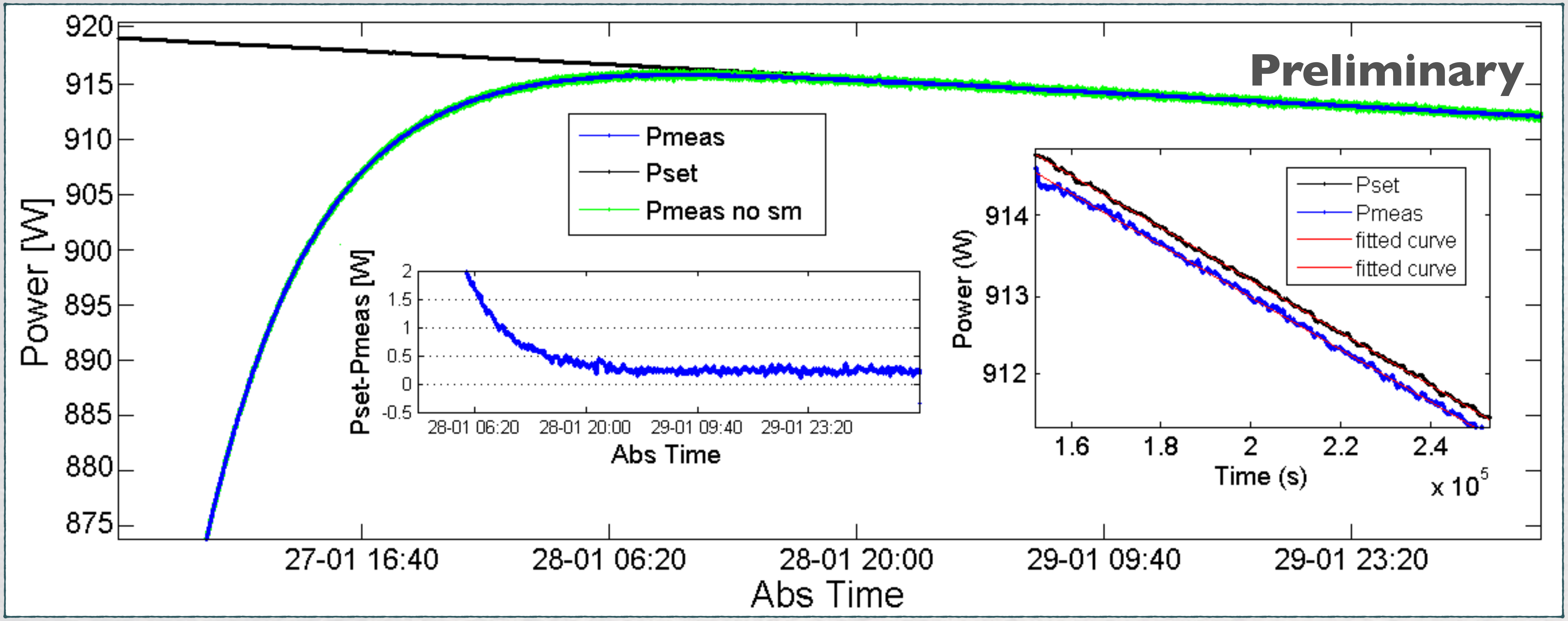


**P < 0.1 W**

Preliminary results from calorimeter calibrations

- Close to **0.1 % precision** in heat measurement

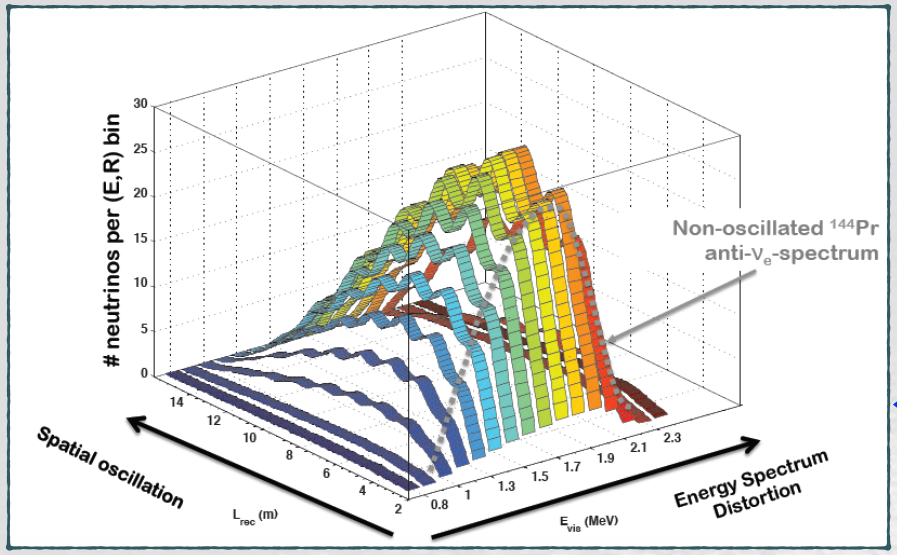
$$P(t) = P_0 e^{-\frac{t-\Delta t}{\tau}} + P_w$$

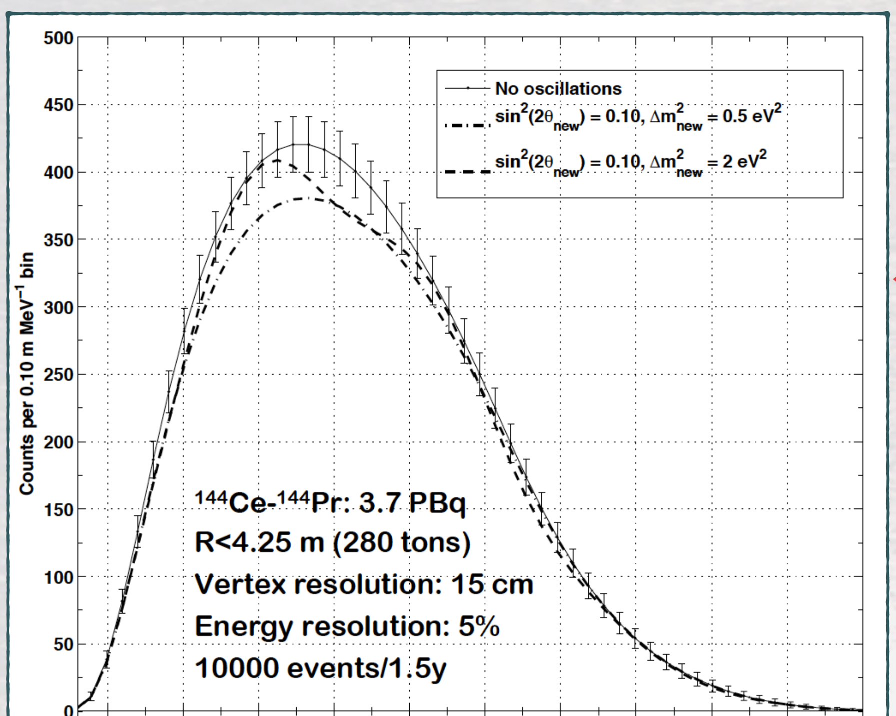


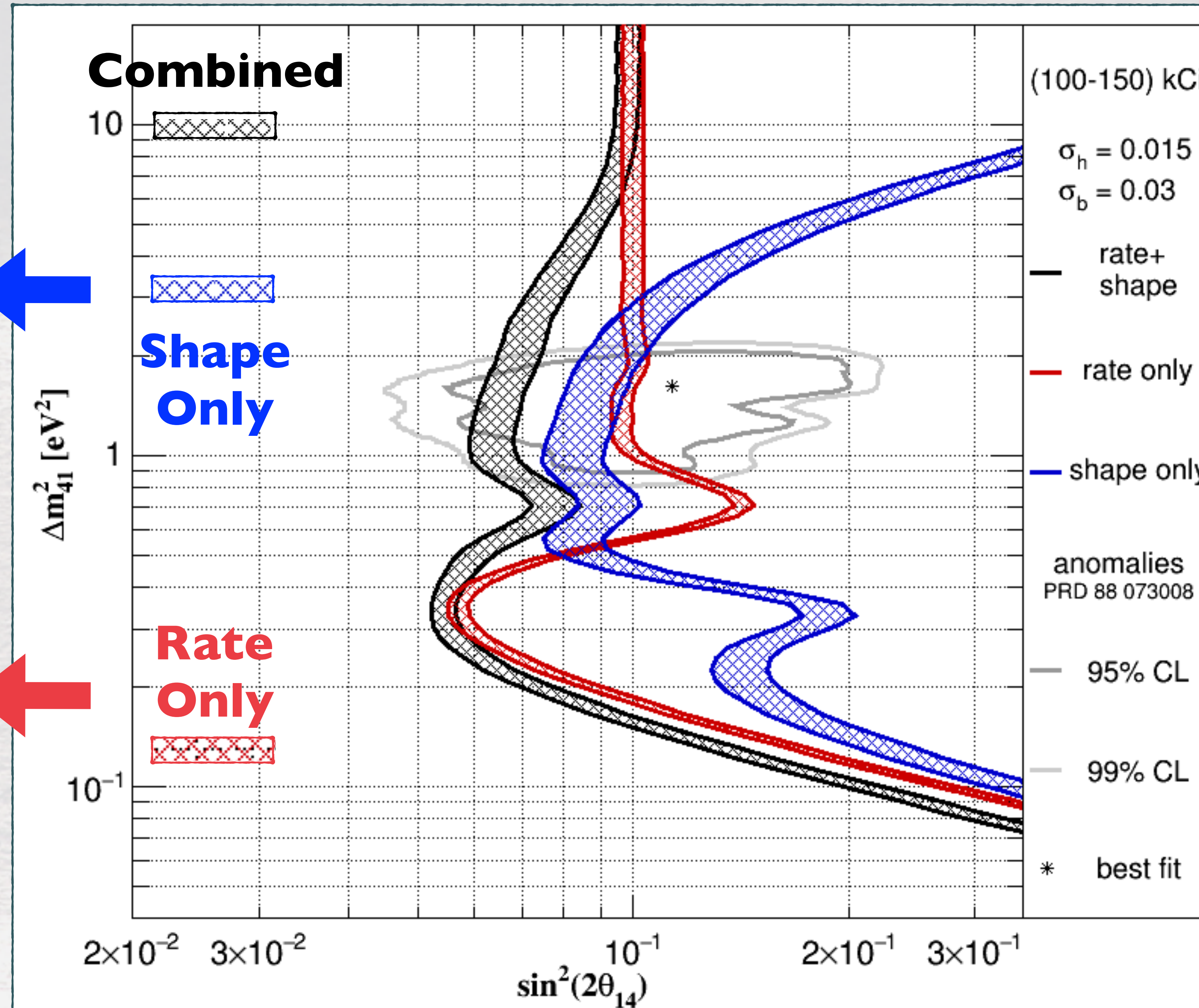

- Note: translation of the heat measurement to **neutrino flux requires precise knowledge of Ce-144 - Pr-144 spectra**
  - Work in progress

$^{144}$Ce source @ 8.2 m from the center. **1.5% calibration.** **100-150 kCi bands.**

- *Under the assumption that a single sterile dominates*



✔ Construction of the shield done

✔ Work at LNGS site and authorisation done

Construction of the source in progress

- Delivery expected no later than **March 31st, 2018** in St. Petersburg

Delivery to LNGS

- April 2018

Physics

- 18 months of data taking



EPS
EUROPEAN PHYSICAL SOCIETY
HEP2017
EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

# Many Thanks