Status of eV Mass Scale Sterile Neutrino Searches

Marco Pallavicini
Università di Genova and INFN

Project N. 320873

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

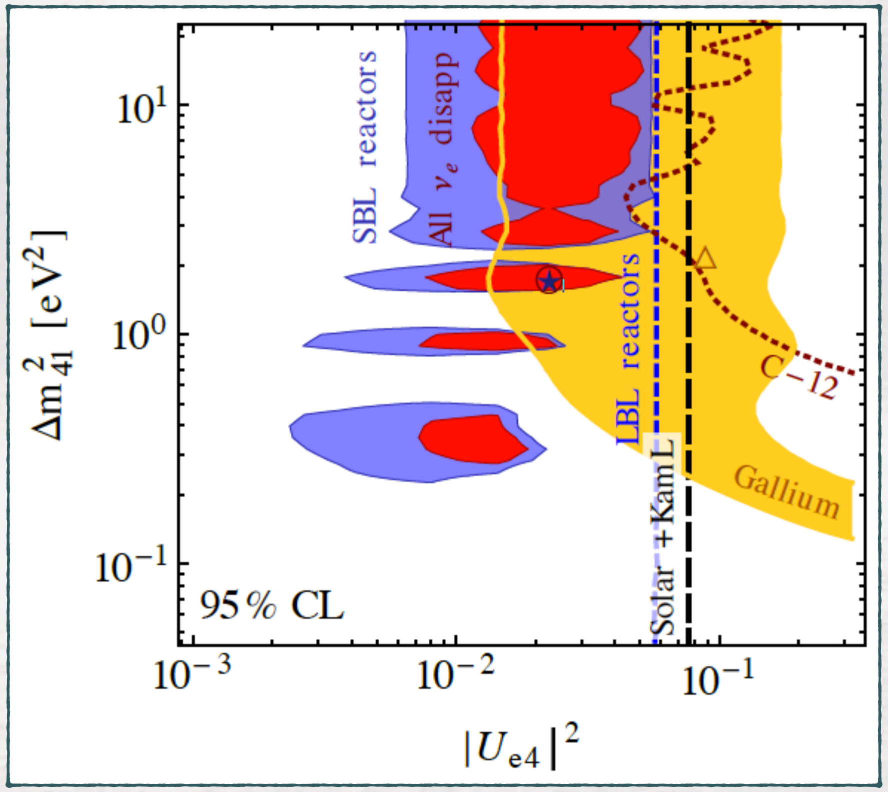
- Weak couplings are poorly measured: **room for small corrections**
- Physics beyond standard model is called for by neutrino masses
  - Either right-handed neutrinos for Dirac mass terms or Majorana fields to build Majorana mass terms and possibly explain small mass through See-Saw

AND

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

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 and recent reactor experiments narrow parameter space

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

SOURCE AND REACTOR EXPERIMENTS

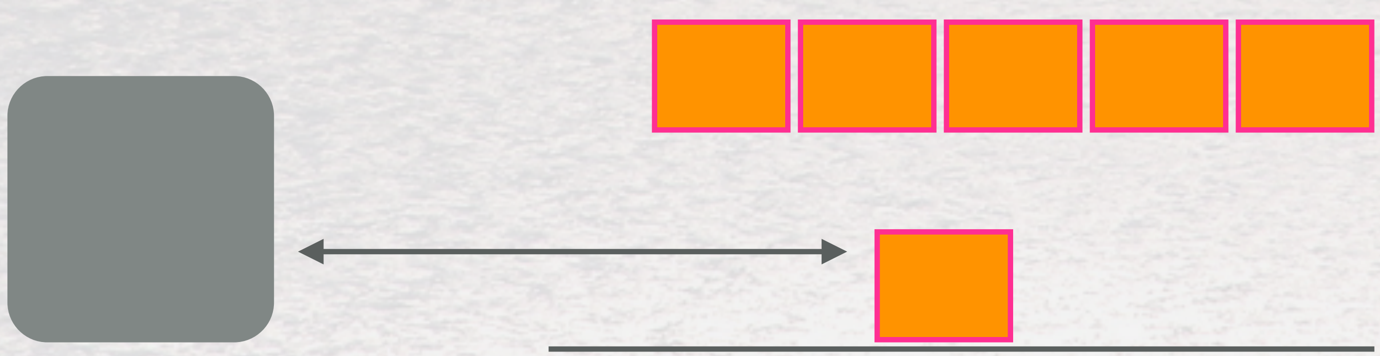
Two main elements:

- **A pure source of (1-10 MeV) ν_e or $\bar{\nu}_e$**
  - A **reactor** ($\bar{\nu}_e$ only) or a **powerful radioactive source** ($\bar{\nu}_e$ and ν_e)
- **The capability to measure the interaction rate as a function of the distance from the source**
  - Option 1: **movable** detector from a few up to ~20 m from the source
  - Option 2: the detector is large and it is either **segmented** or has the capability to **reconstruct efficiently the neutrino interaction point**

Signatures:

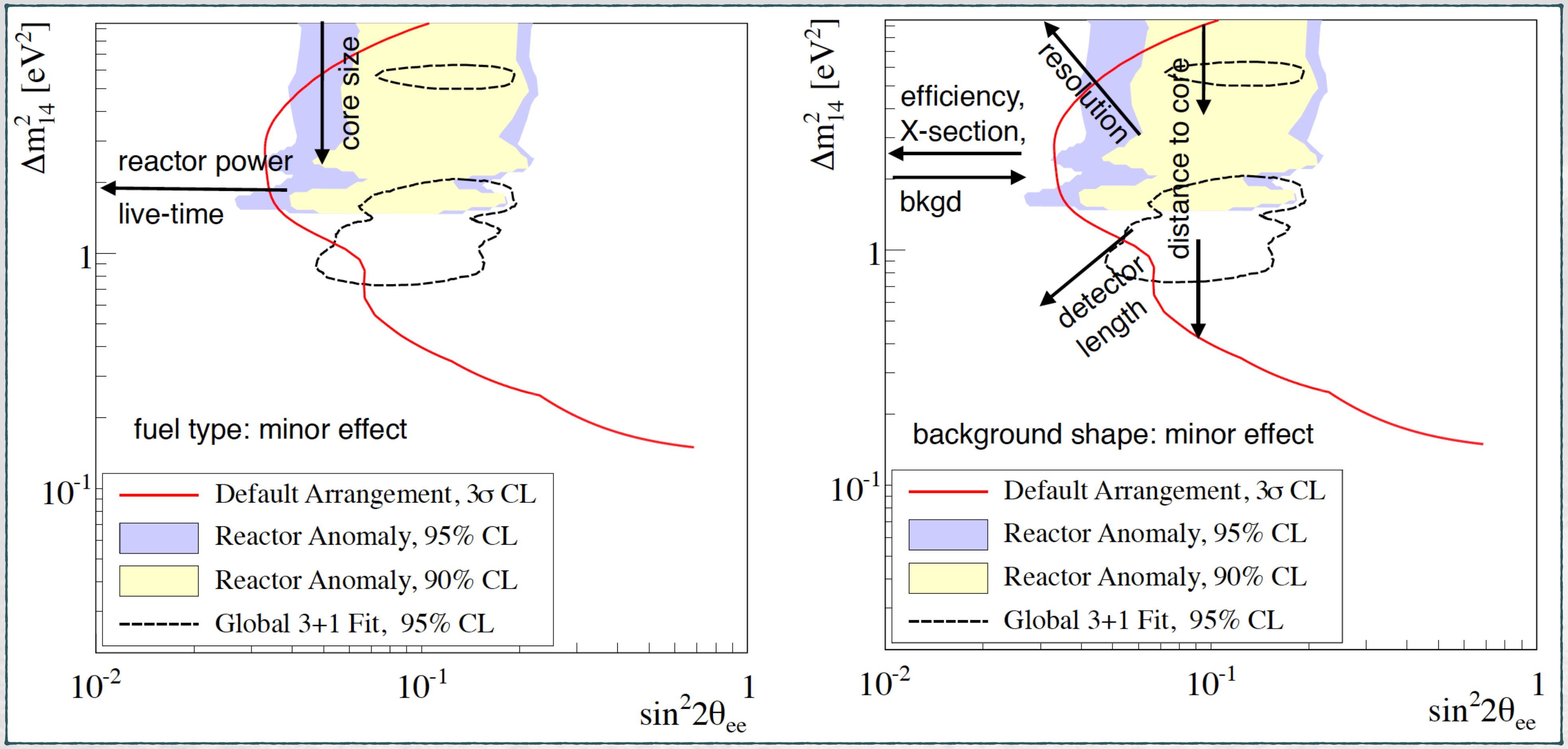
- Deviation from $1/R^2$ behaviour for movable detectors (Option 1)
- Direct observation of oscillation pattern for Option 2

N.B. A source could be placed inside a detector



CRUCIAL PARAMETERS

Arxiv 1212.2182v1



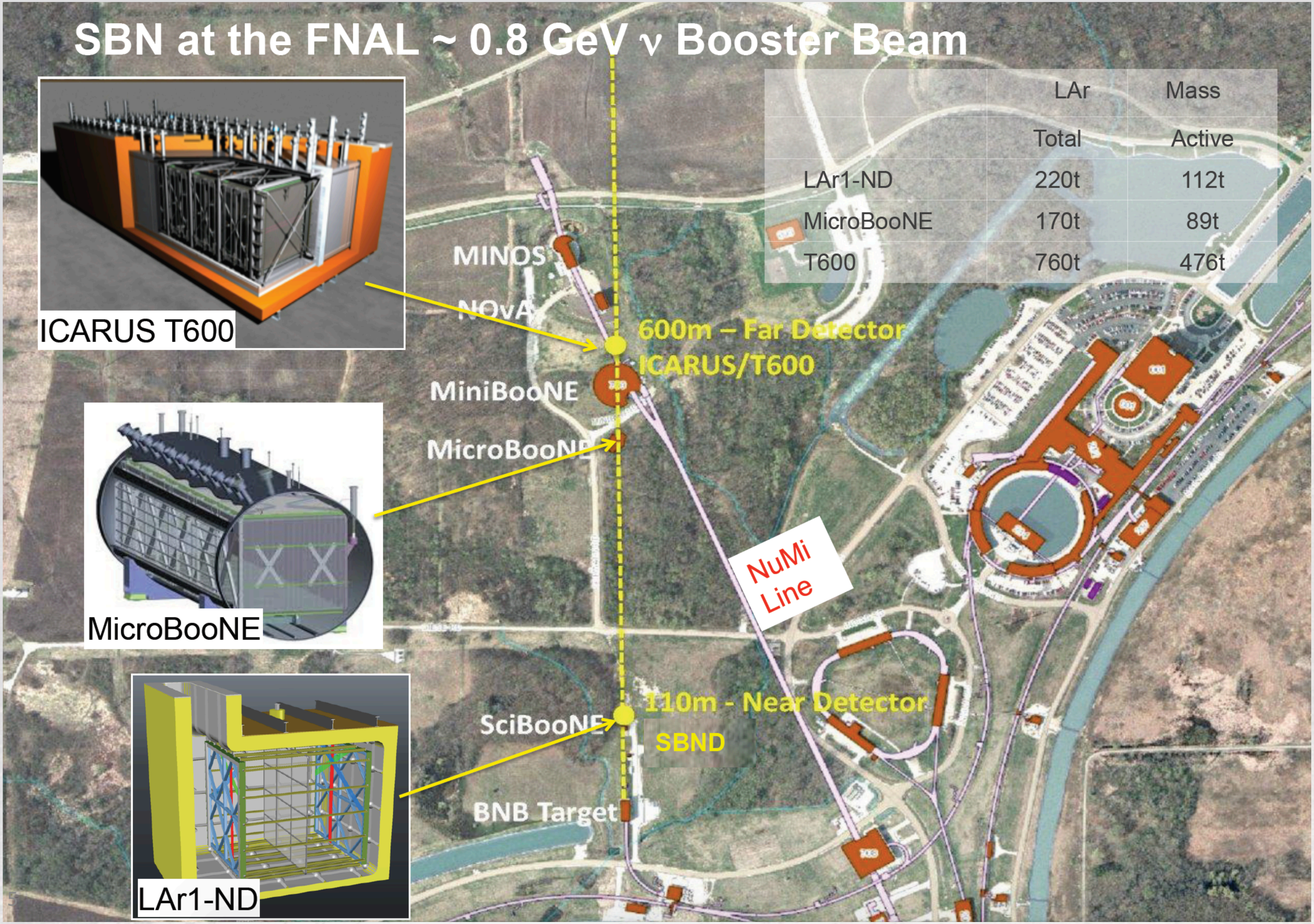
SOURCE PRO

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

SOURCE CONS

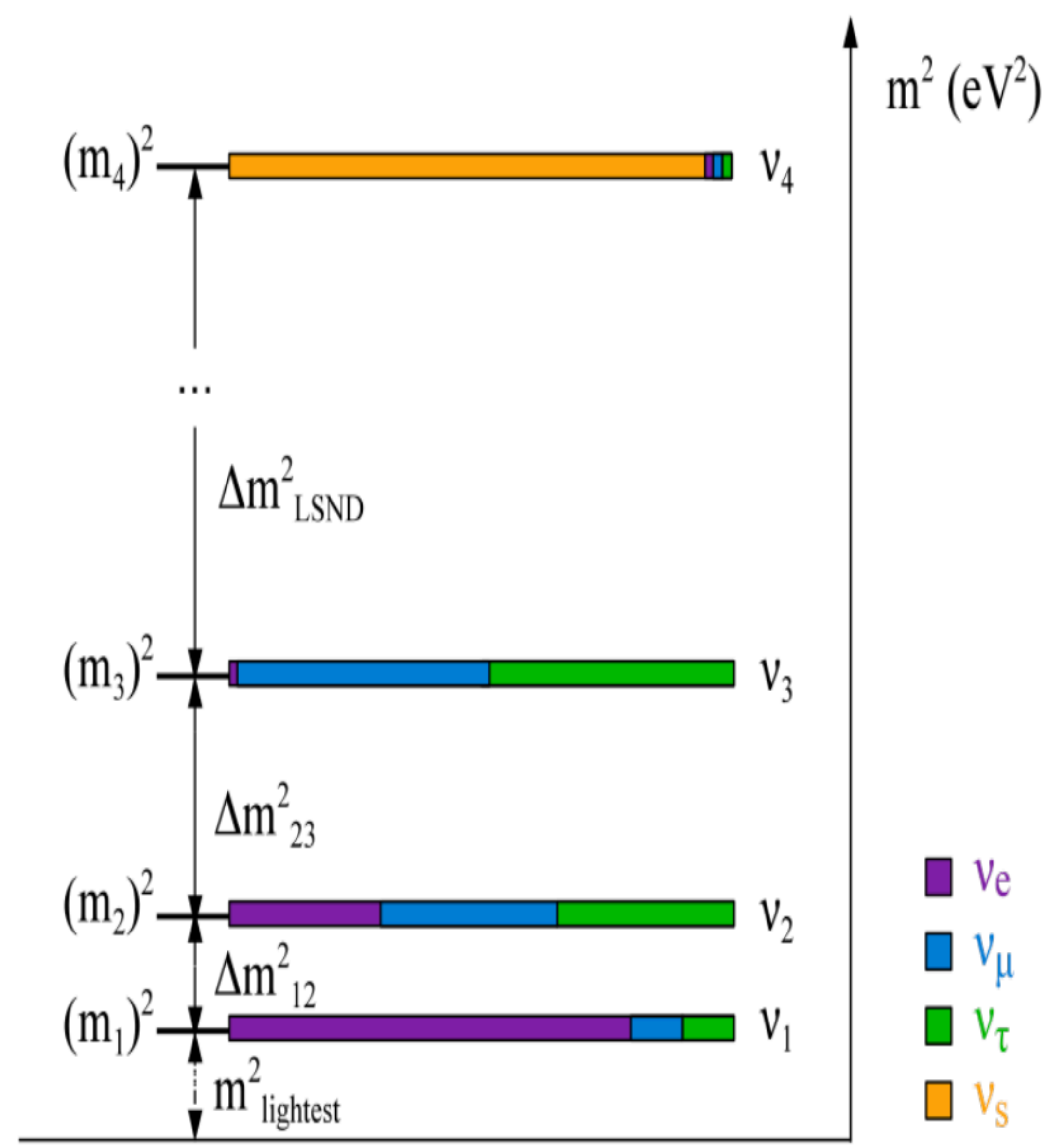
- Can take data for **limited time** (it decays)
- **Flux** cannot reach reactors' values
  - 150 kCi max because of heat, mainly
- **Hard (damn hard…) to:**
  - Make, Authorise, Transport, Use, Dispose

SBN at the FNAL ~ 0.8 GeV ν Booster Beam



	LAr	Mass
	Total	Active
LAr1-ND	220t	112t
MicroBooNE	170t	89t
T600	760t	476t

- A Multi-detector program will address the unexplained anomalies which together could be hinting at new physics (steriles?)
  - *MicroBooNE will address MiniBooNE low energy excess but is not designed to explore the complete sterile neutrino oscillation parameter space on its own*
  - *Plans to have all 3 detectors in operation in 2018 (LOI submitted in 2014, proposal submitted in January 2015)*

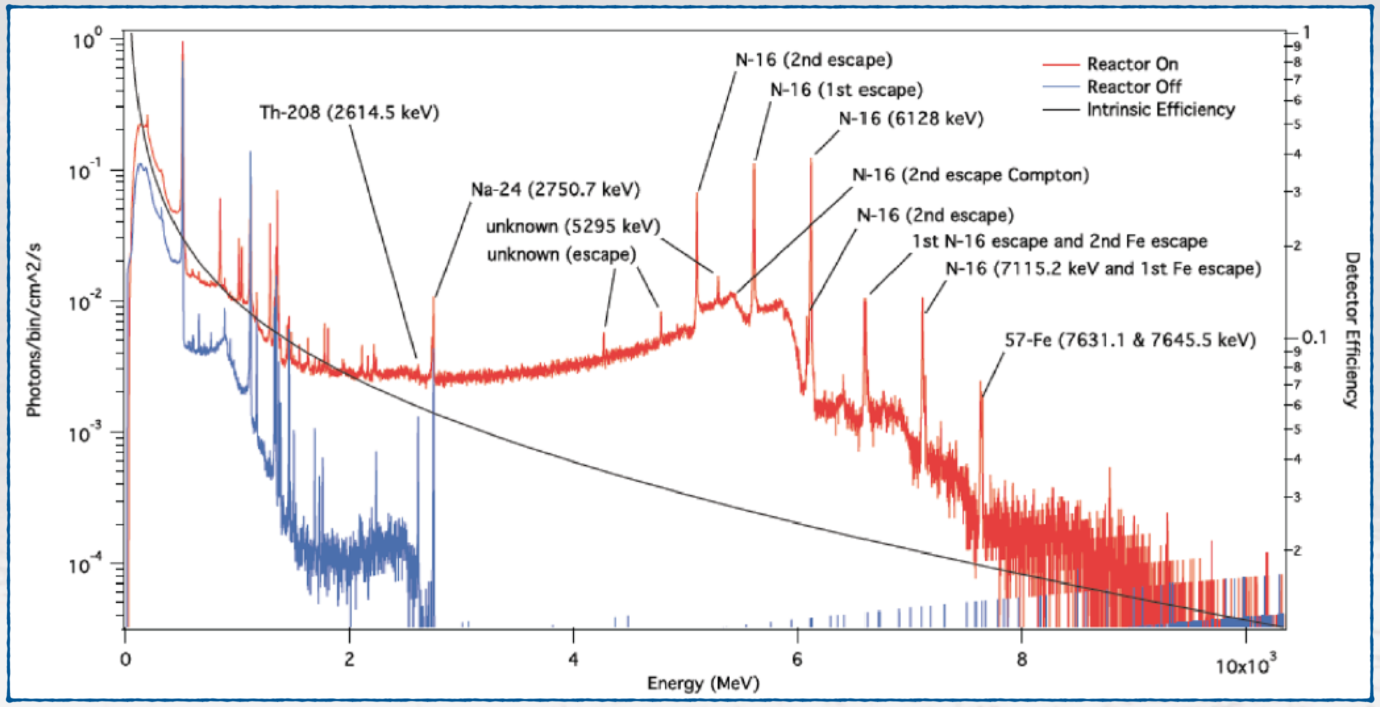


Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv: 1204.5379 [hep-ph], (2012)

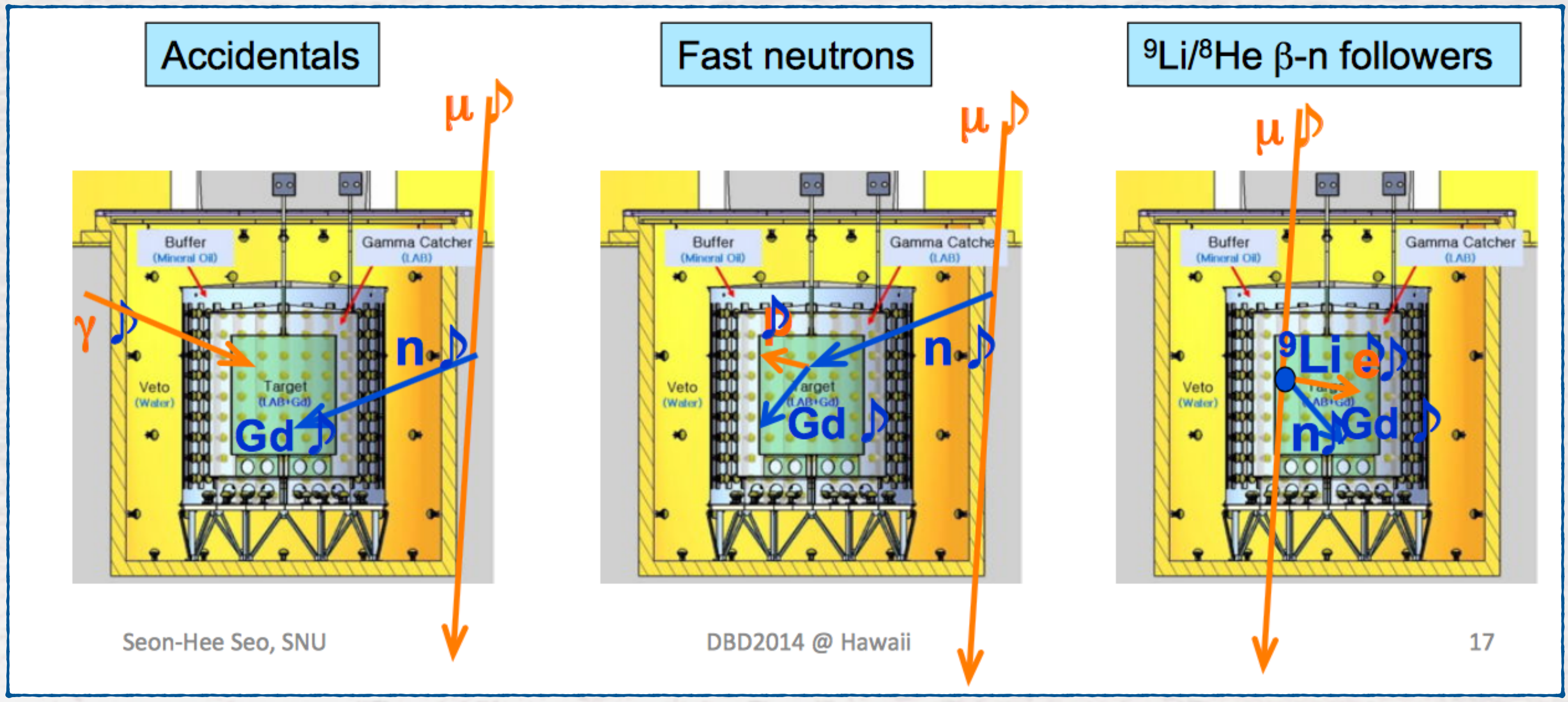
Fast neutrons (reactors only)

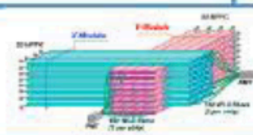
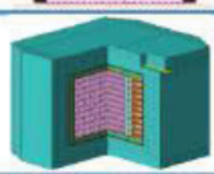
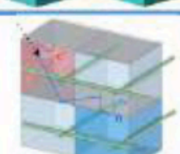
- Fast neutrons mimic prompt-delayed coincidences when:
  - Are produced by muon spallation
  - Directly come from reactor (therm.+capture)
- Rejection strategies
  - Shield; muon tagging; PSD to identify positrons; subtraction using "off" states of reactor



Accidentals (surface only)

- Reactor γ + thermal n coincidence
  - Very high energy γ are produced by neutron capture on passive materials (e.g. Fe)
- Rejection strategies
  - Shielding is crucial; Subtraction using "off" states of reactor



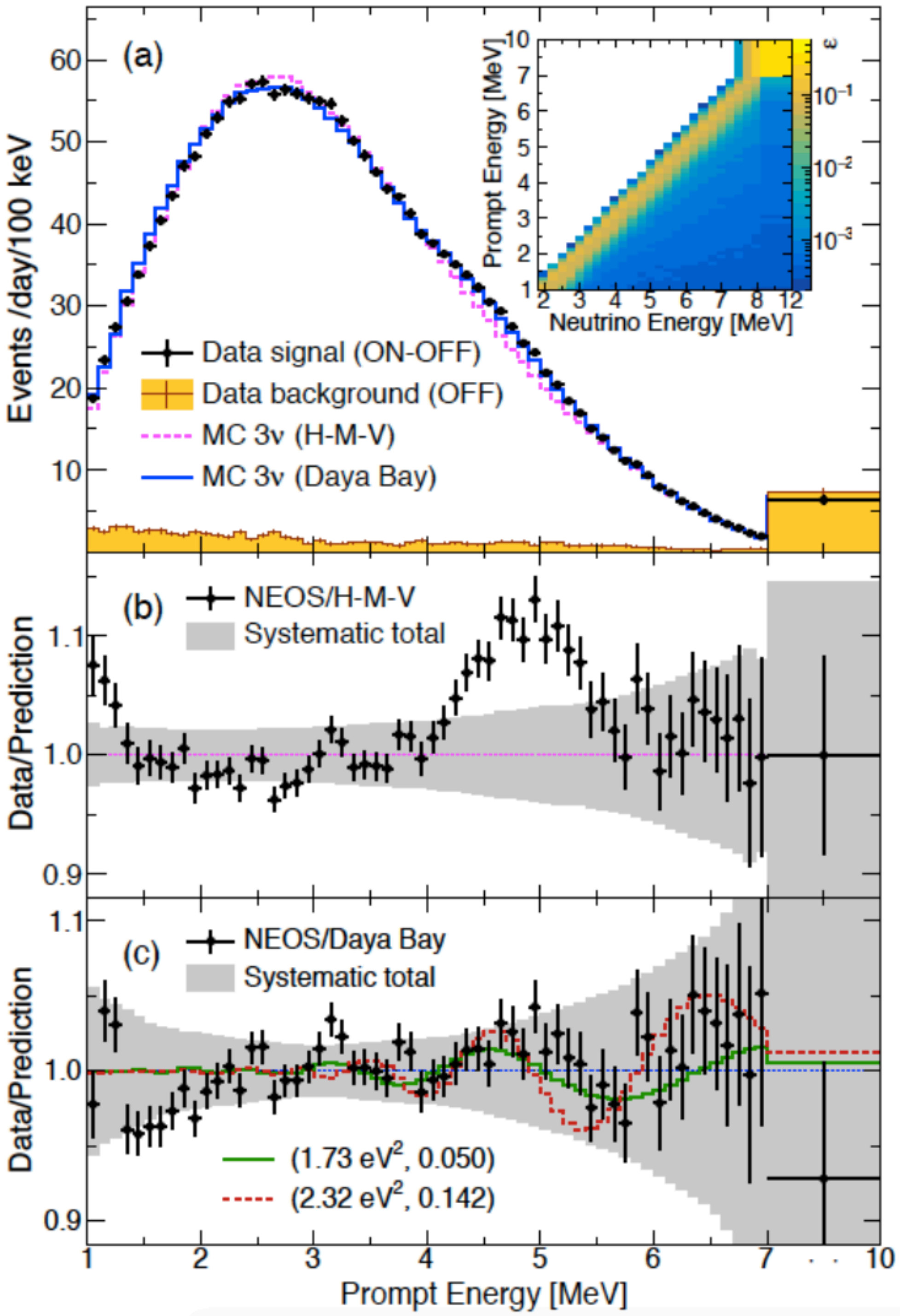
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

N. Bowden AAP 2016

Credit: S. Schönert

NEOS @ Hanbit (Korea)

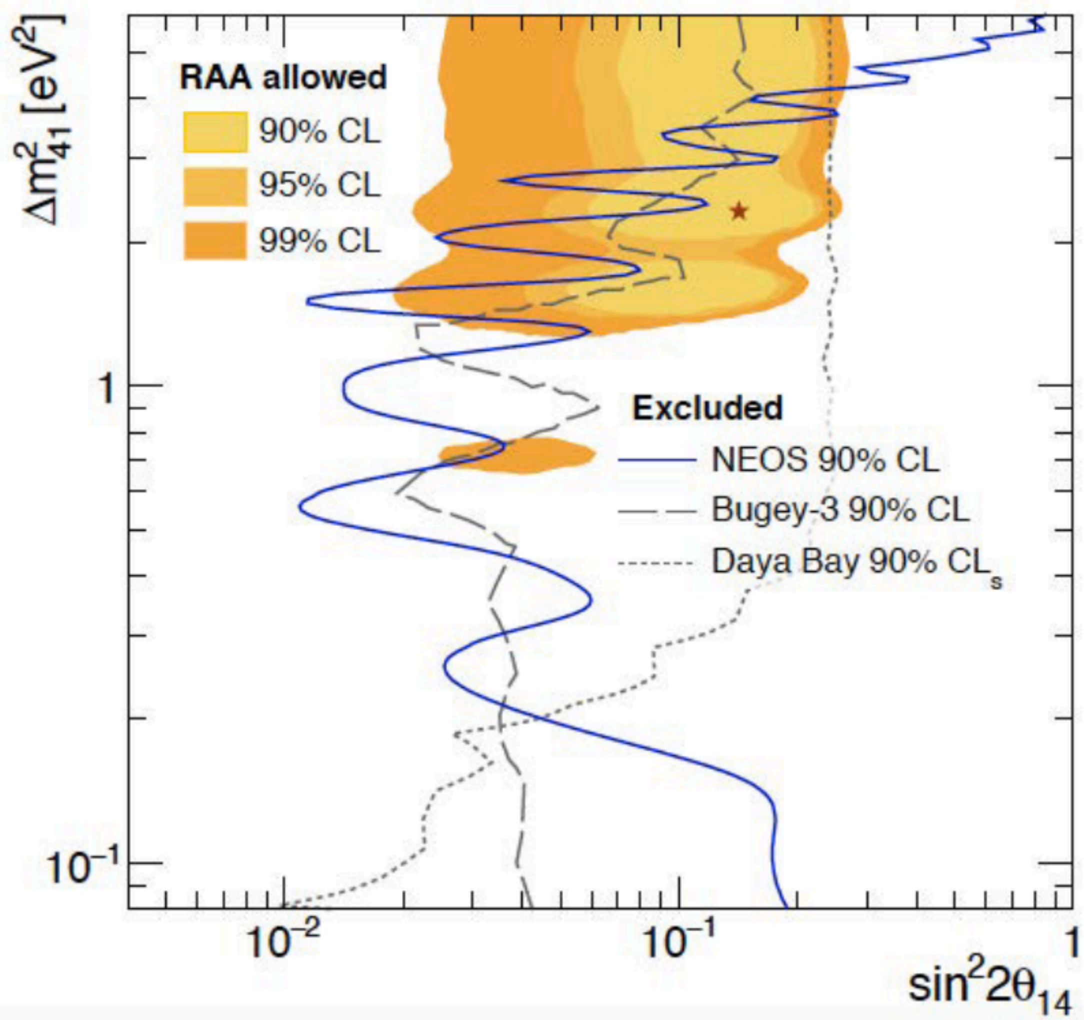
arXiv:1610.05134v4 [hep-ex] 21 Mar 2017



Single detector / single distance

Analysis done with Daya Bay spectrum as reference

Relies on 5 MeV bumb!

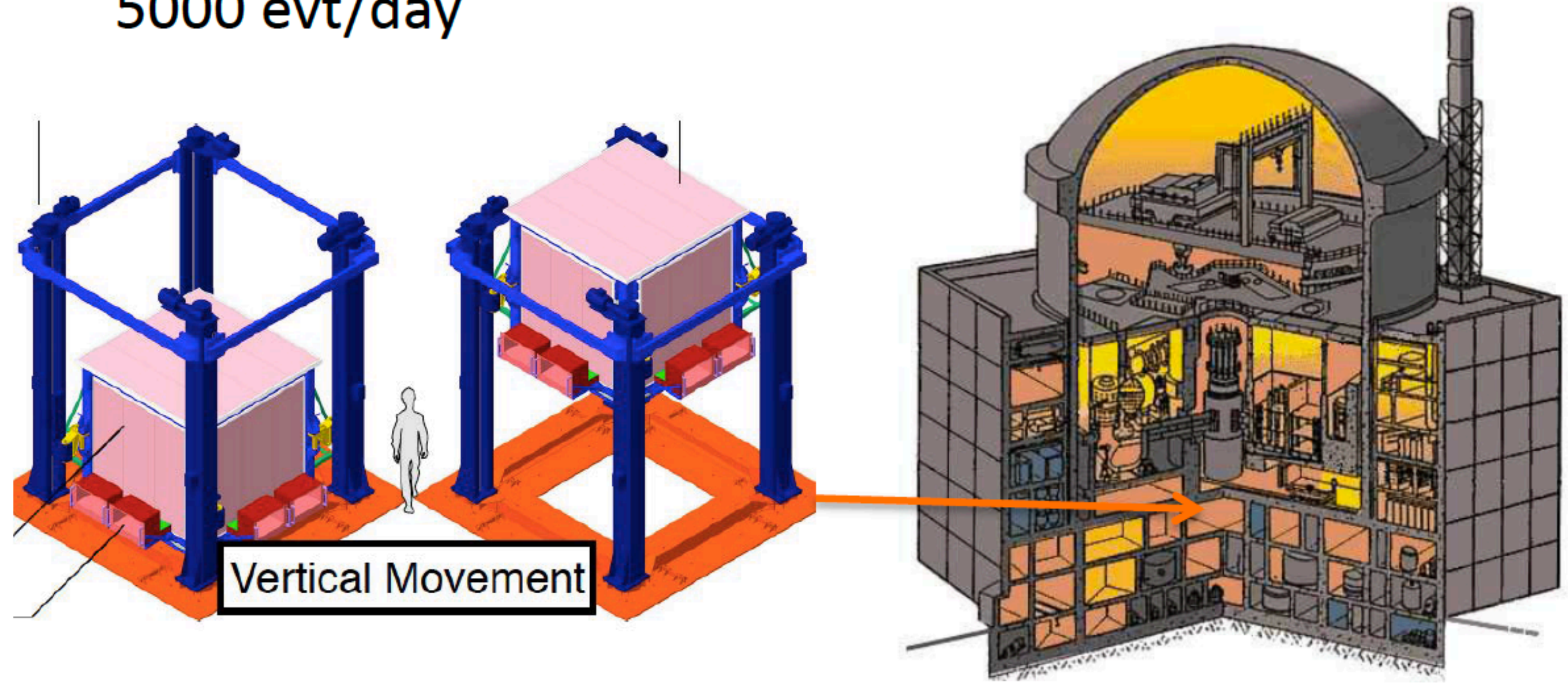


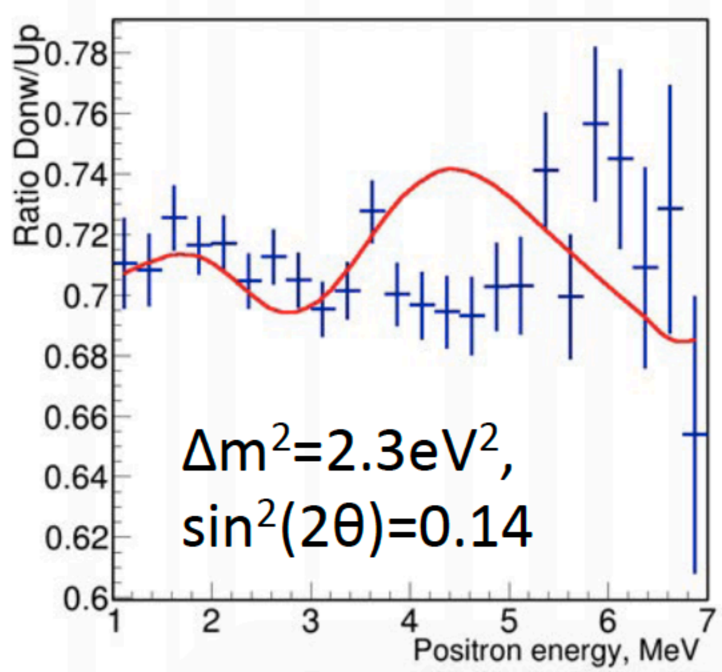
S. Schönert | TUM | Sterile neutrinos

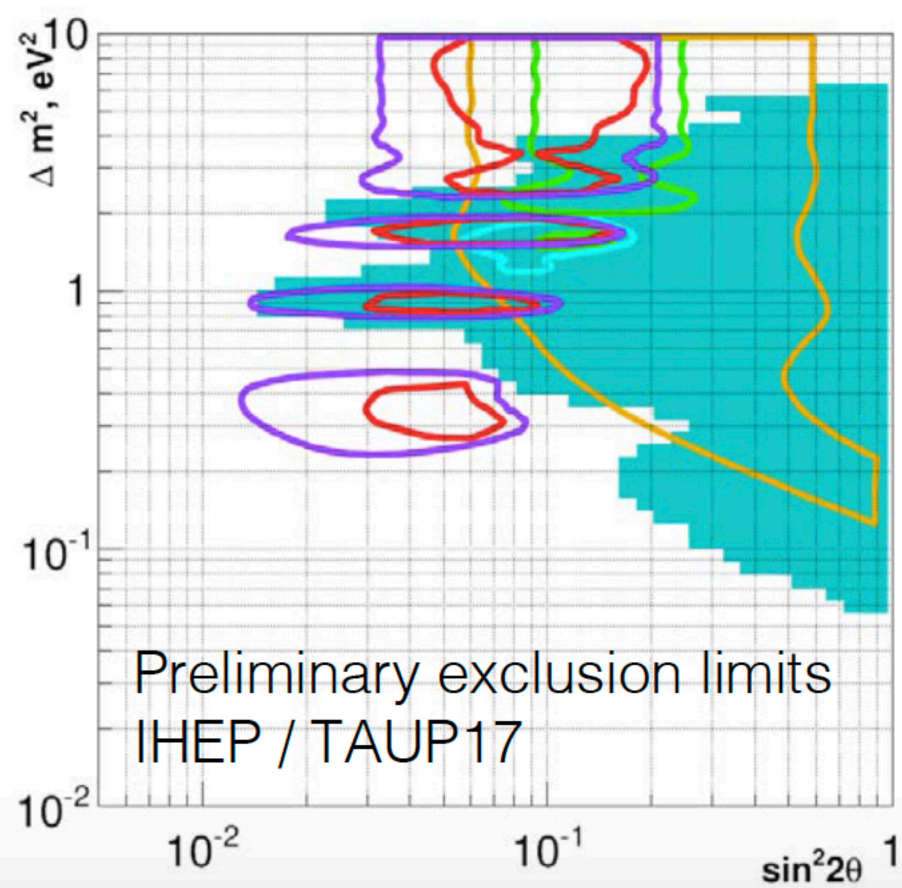
DANSS @ Kalinin

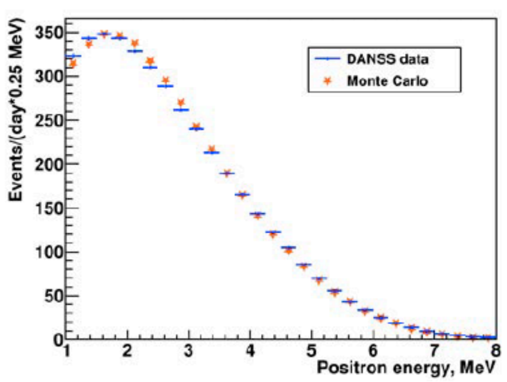
- 3 GW extended core (5000 ev/day)
- Plastic strips with Gd-loaded interlayer, WLS fibers
- Vertical motion of the detector (9.7-12.2 m)
- Independent of burn-up or spectral feature

5000 evt/day



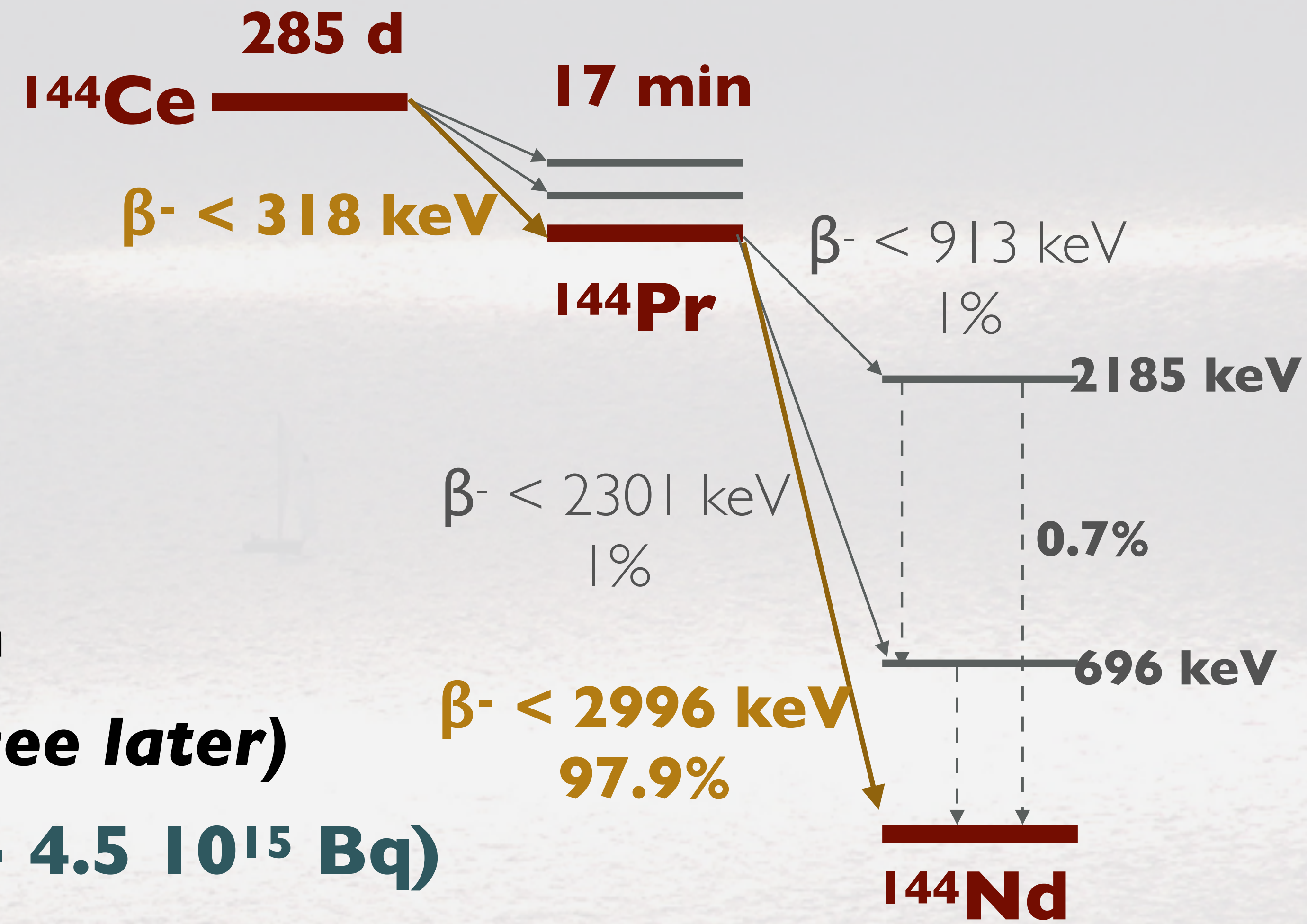


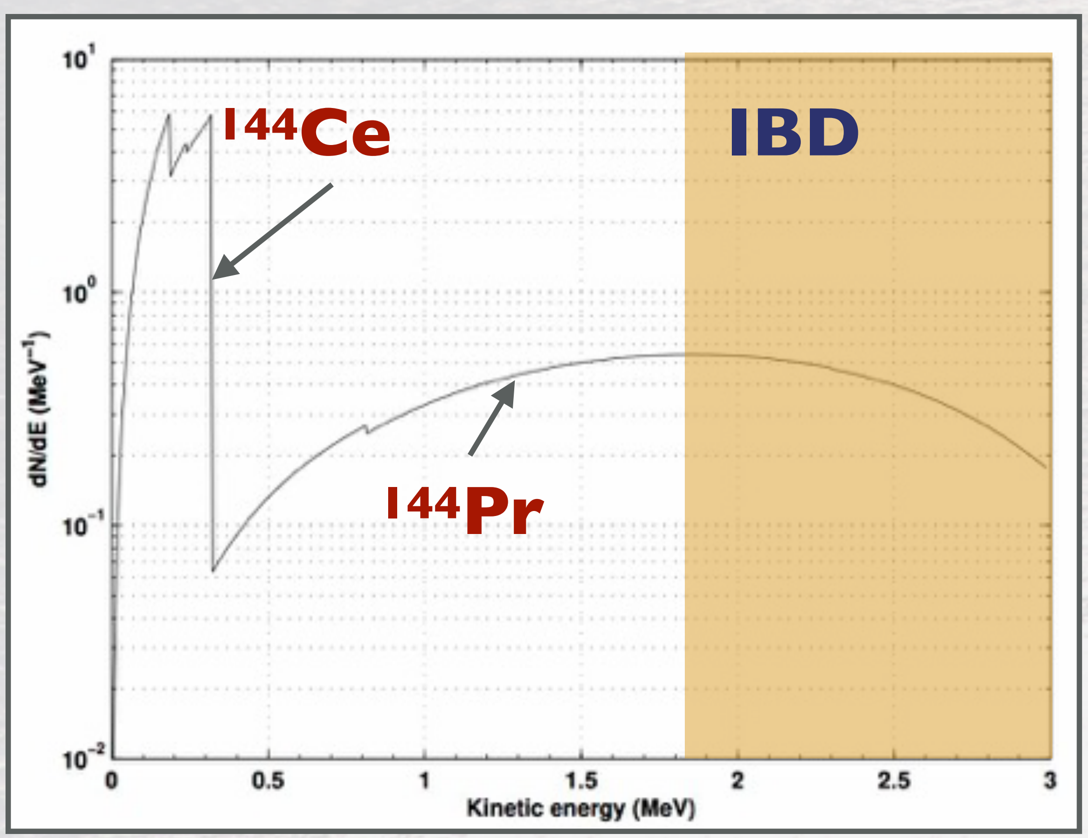


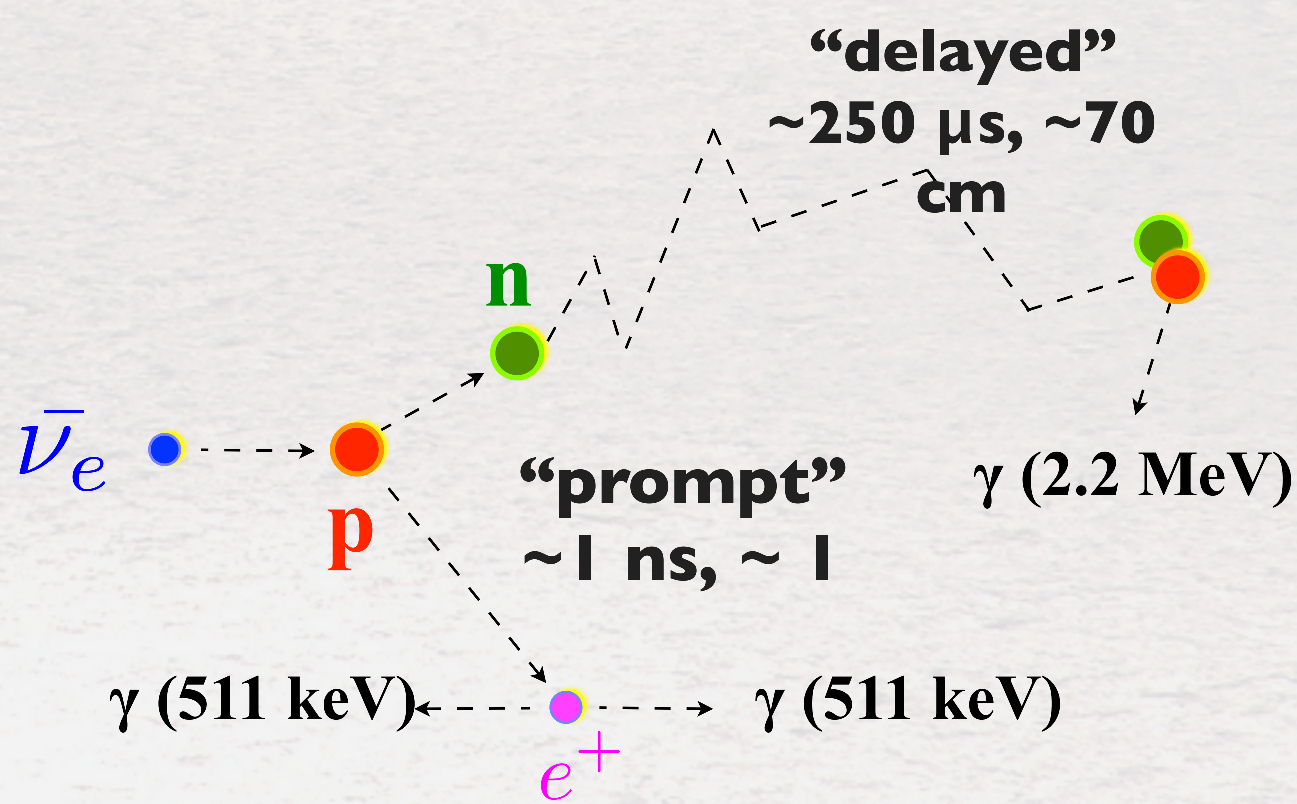


No 5 MeV bump

- **β- $\bar{\nu}_e$ 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)

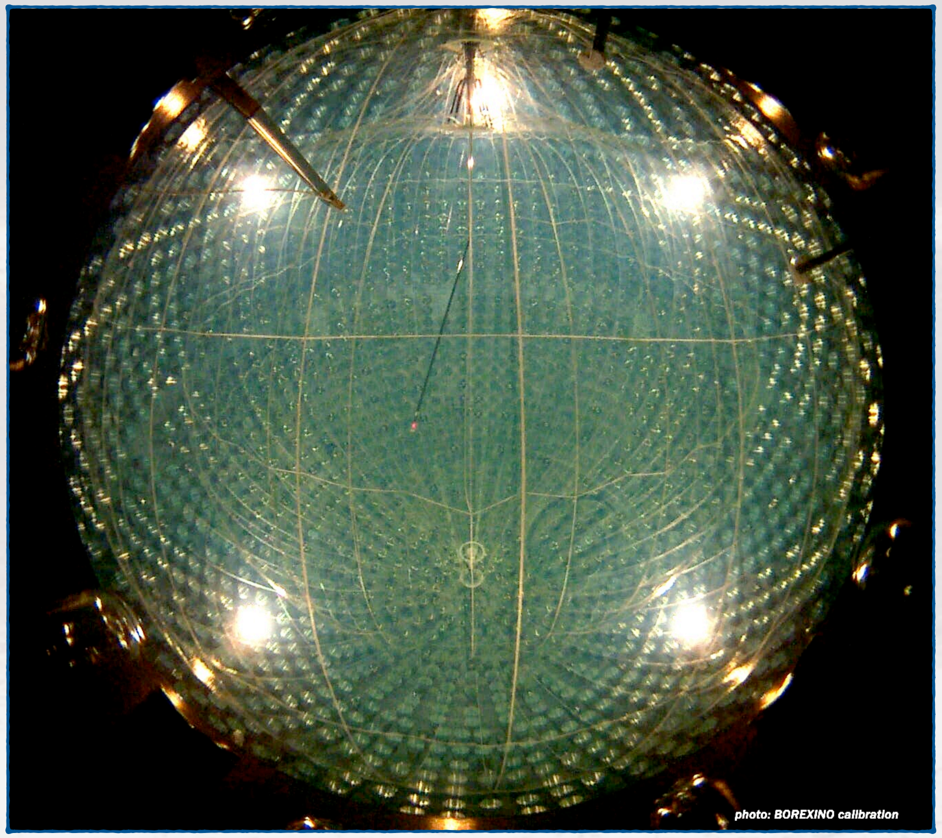
- Original SOX proposal: ^{51}Cr neutrino source OR ^{144}Ce anti-neutrino source

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)

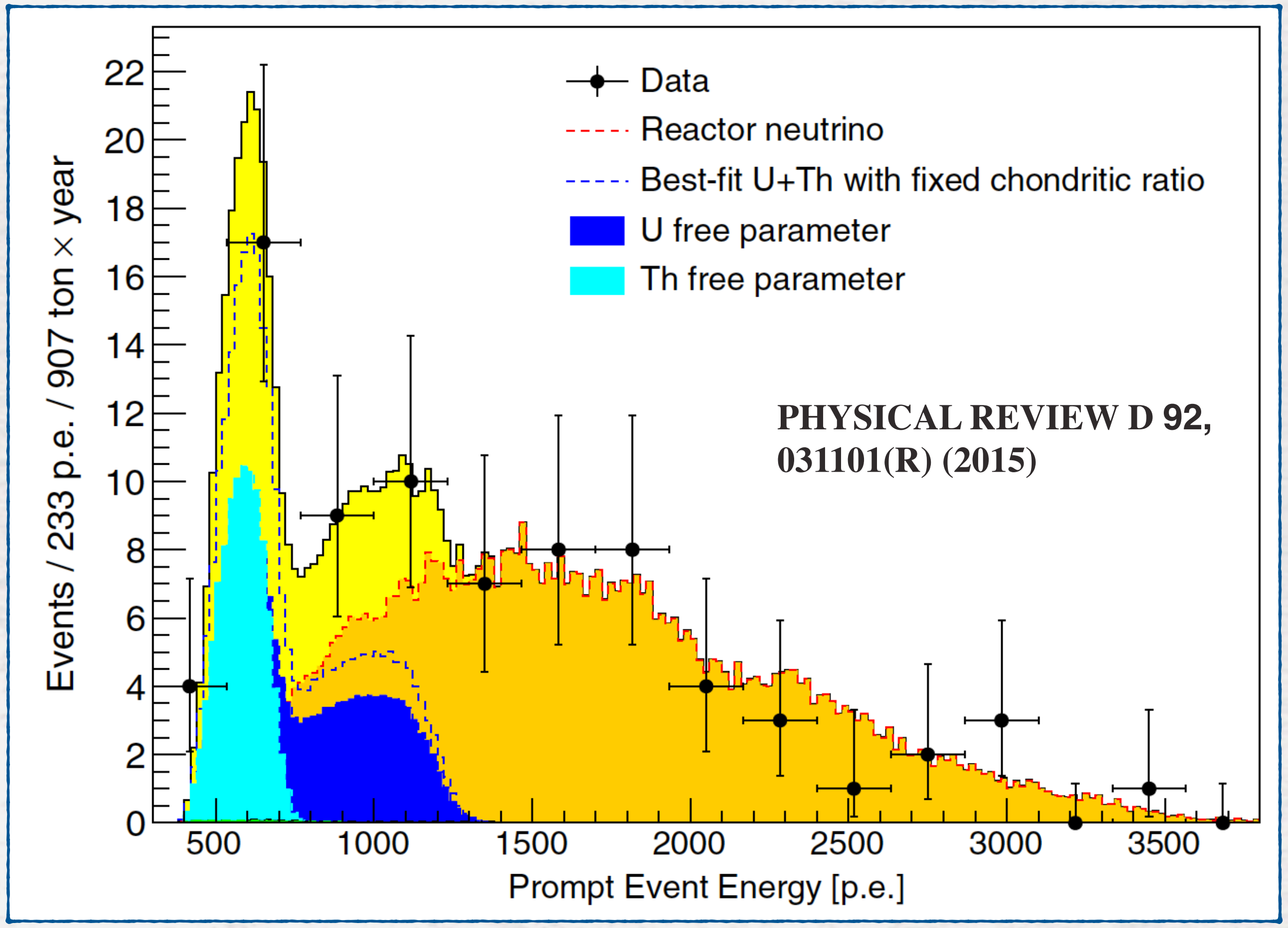
Mainly, a solar neutrino experiment:

- $\nu + e^- \rightarrow \nu + e^-$ 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**

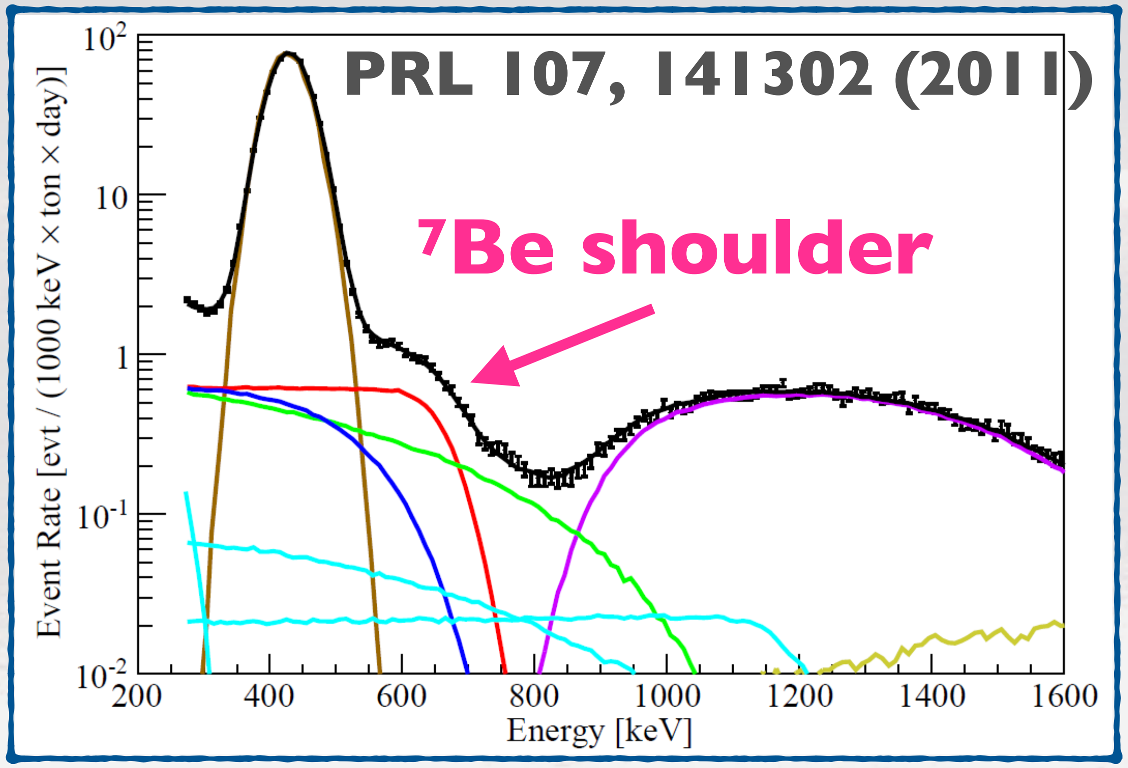


SOX experiment is background free

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

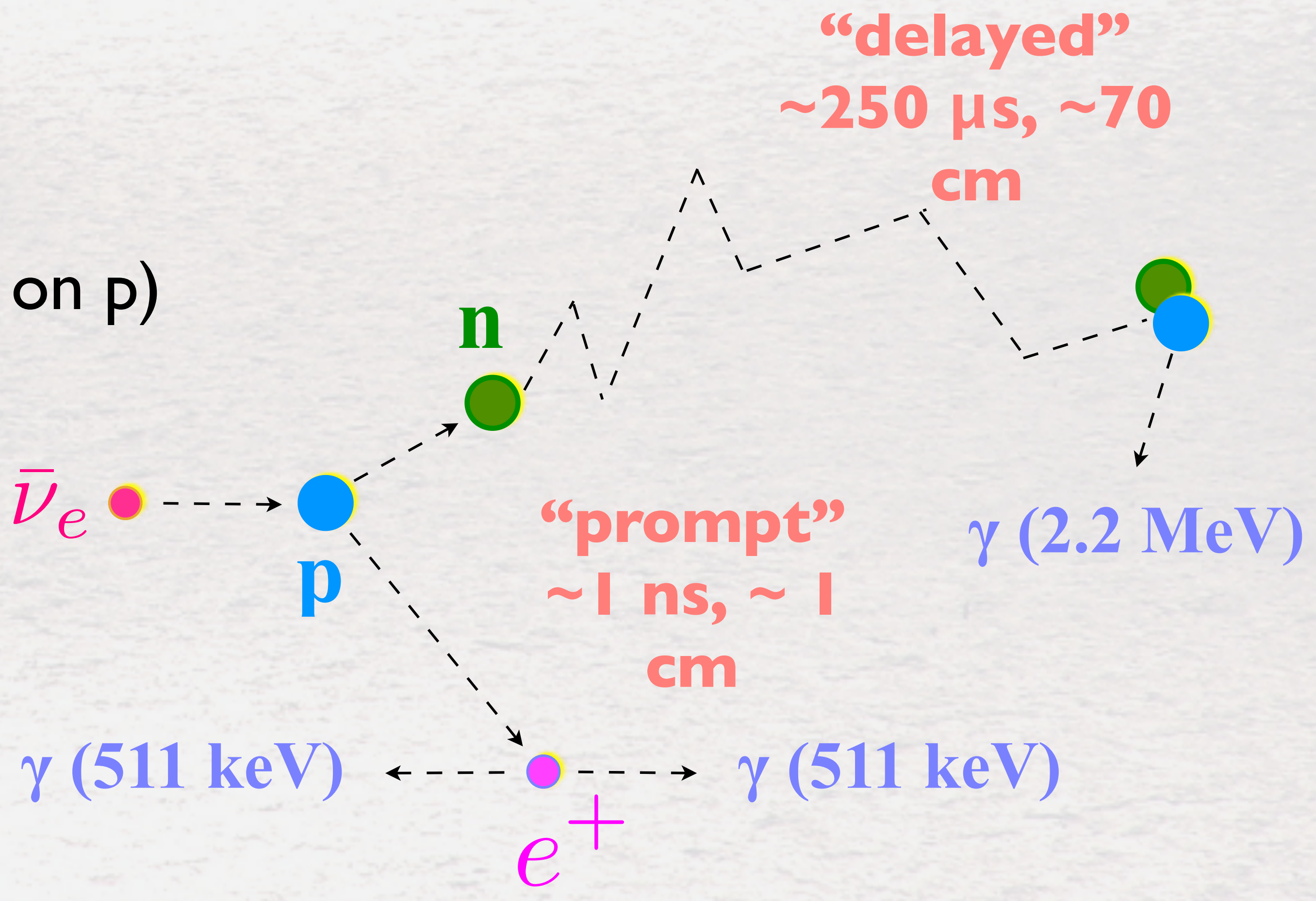
Neutrinos

- Compton-like on electrons :
  - $\nu + e^- \rightarrow \nu + e^-$
- Mono-energetic ν_e produce the characteristic shoulder
- Main background: ^{7}Be solar ν_e !
  - **~ 45 cpd 100 t target**

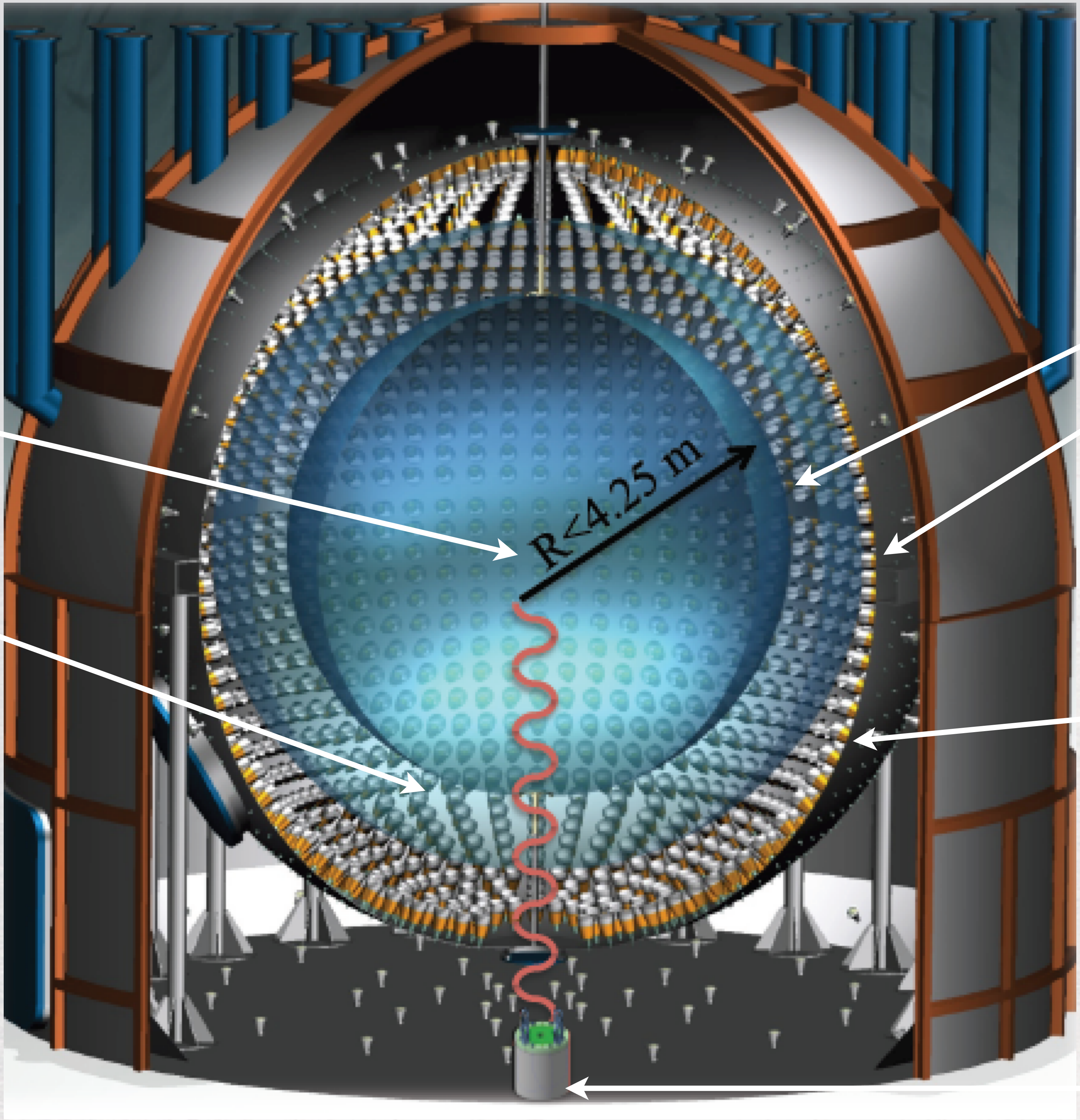


Electron anti-neutrinos

- Standard Reines-Cowan delayed coincidence technique (inverse β decay on p)
- Extremely small background:
  - **4 geo-neutrinos** ev/y in 300 t
  - **9 reactor**
  - **0.4 random coincidences**



THE BOREXINO DETECTOR AND SOX



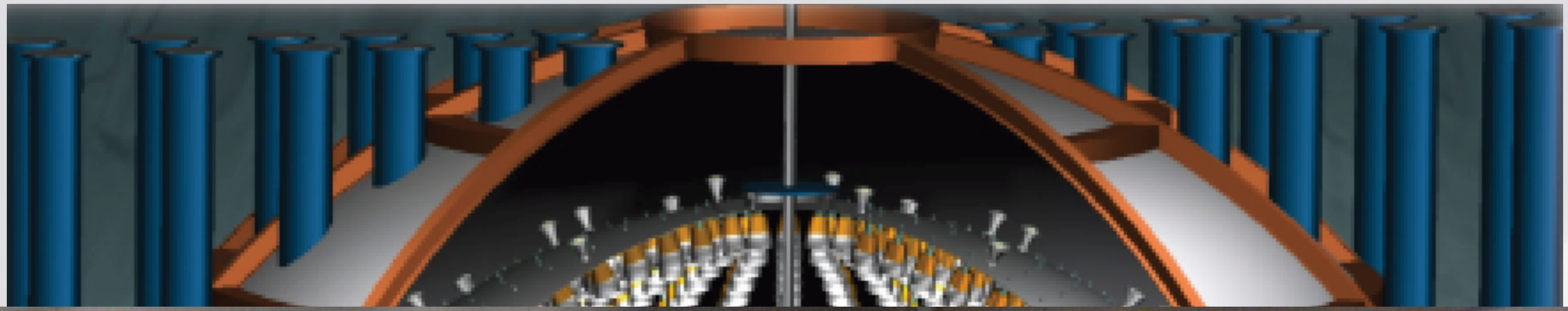
Scintillator
270 t PC-PPO

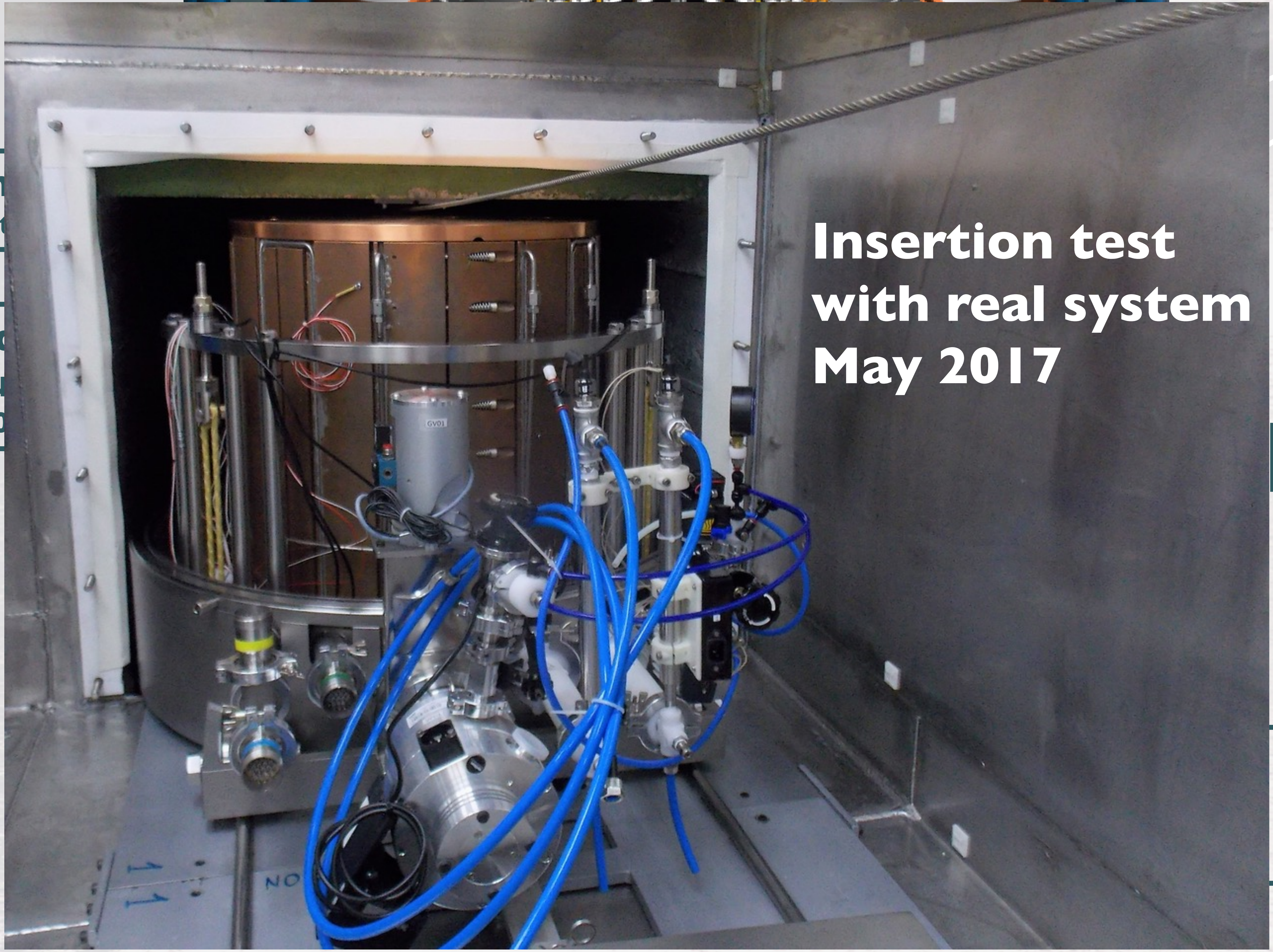
Liquid Buffer
~1000 t PC

Nylon vessels
150 µm thick

PMTs

Source Under the Floor





Scin
270 t

Lic
Bu
~100

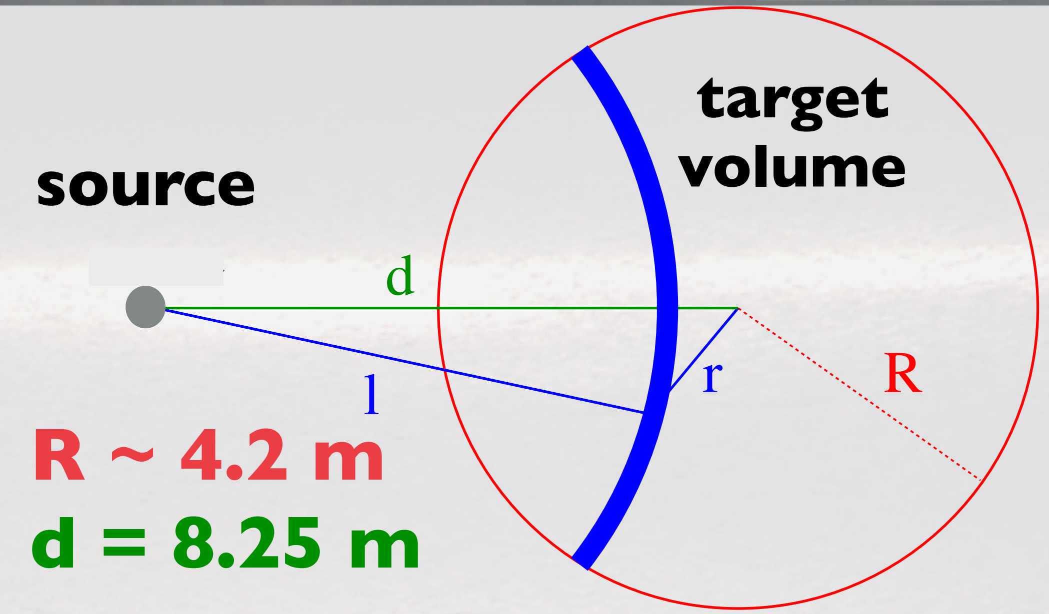
Insertion test with real system May 2017

Nylon vessels
150 μm thick

PMTs

Source Under the Floor

Two different techniques:



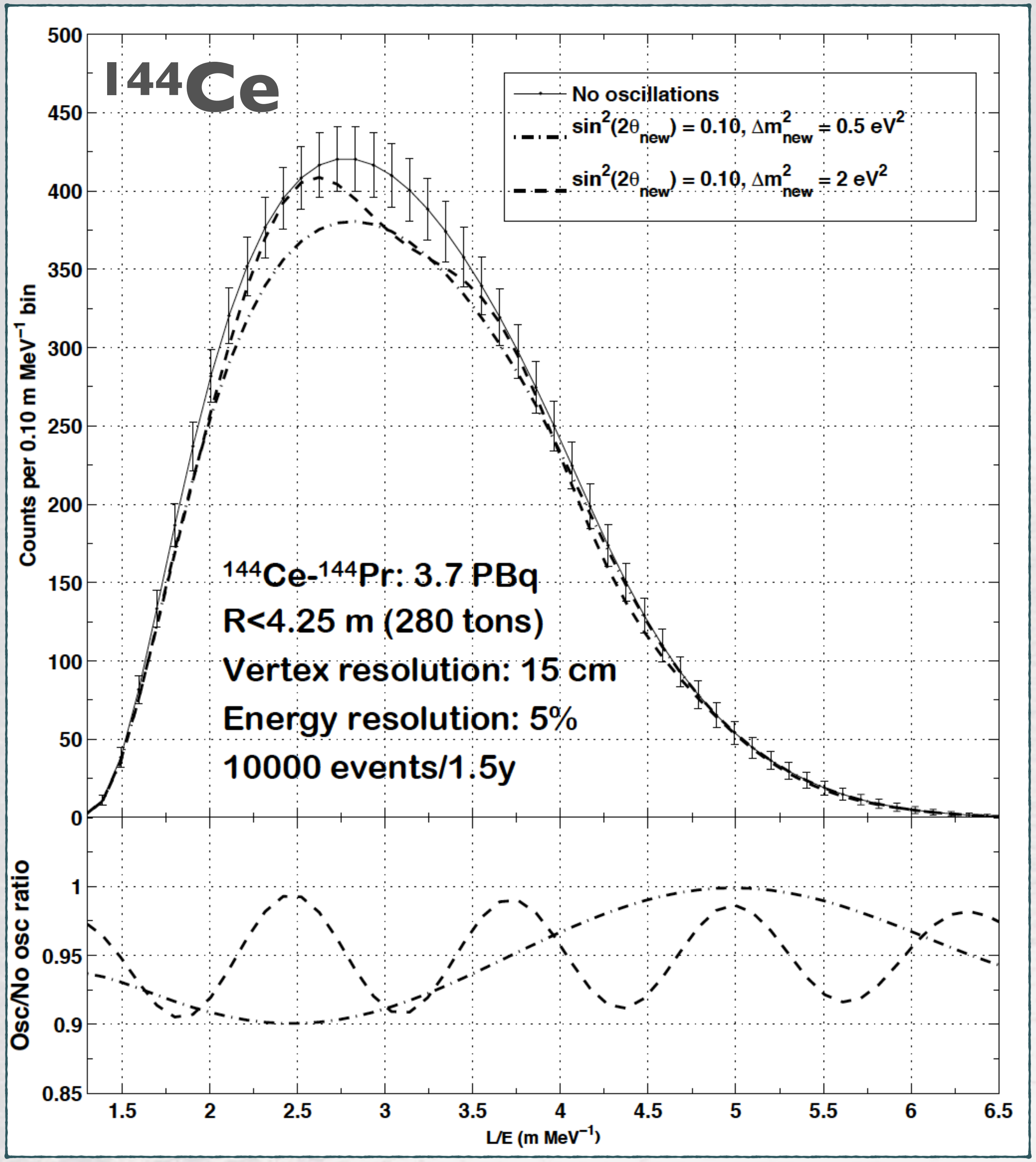
R ~ 4.2 m
d = 8.25 m

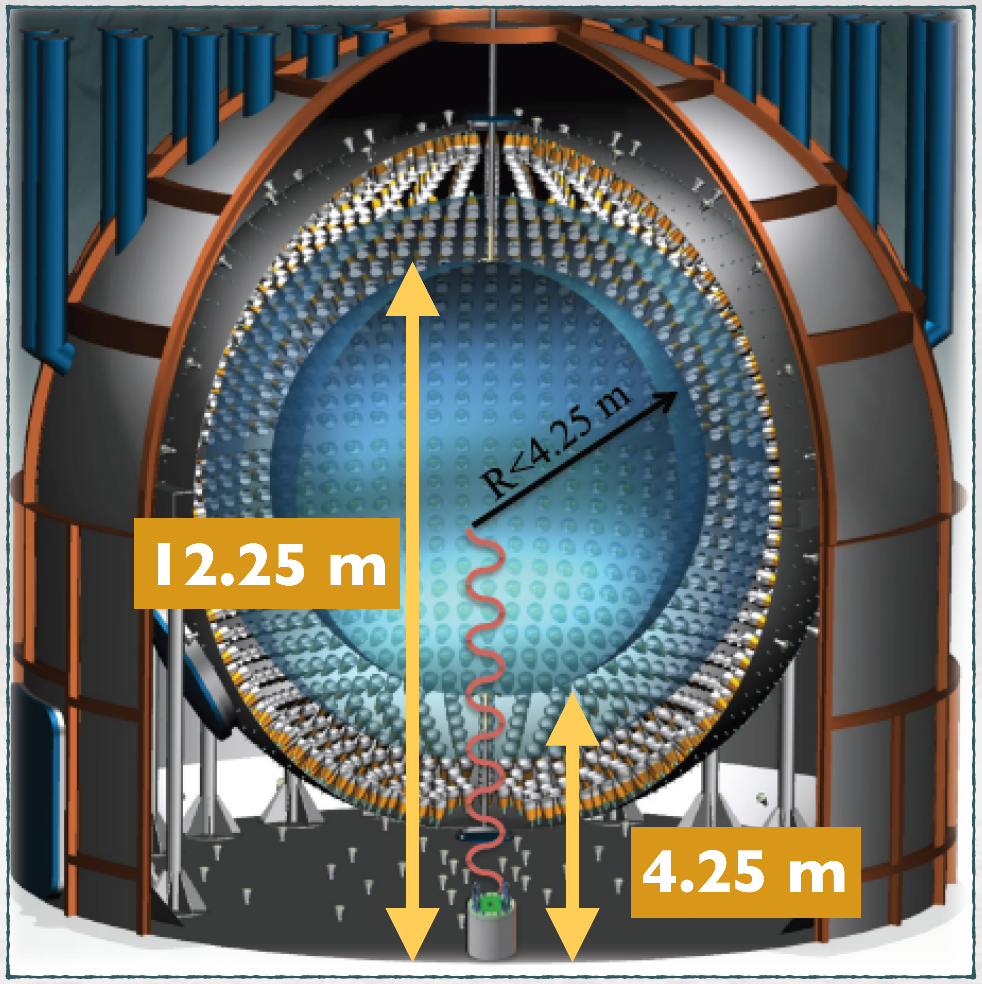
$$\mathbf{V(l) = 2\pi l^2 \left(1 - \frac{d^2 - R^2 + l^2}{2\ d\ l}\right)}$$

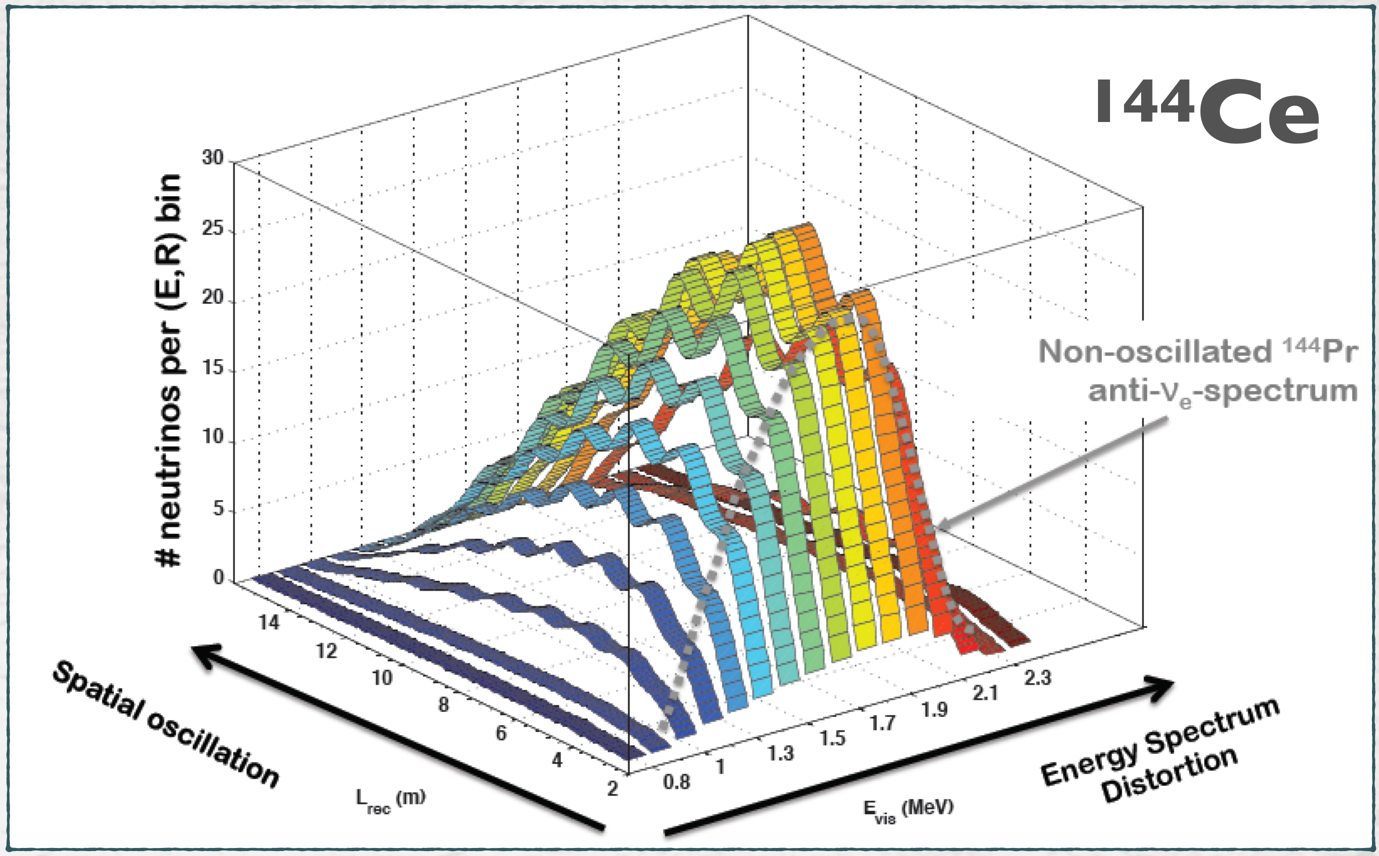
- **Standard disappearance**
  - Rate depends on θ_s and (weekly) on Δm^2
  - Sensitivity depends on:
    - Source activity (statistics)
    - Error on source activity and ν_e spectrum
    - FV determination $$\mathbf{N_0(l, T_1, T_2) = n_e\ \Phi(l)\ V(l)\ P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E,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

- **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 Δm^2 and θ_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

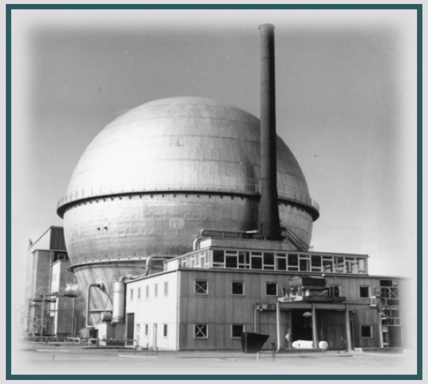
- Essentially a unique vendor (Mayak, Russia)
- Humongous amount of paperwork for **authorisations** (Russia, France, Italy)
- Many technical problems to be solved for:
  - CeANG **production** and **transportation**
  - Usage and insertion beneath Borexino
  - High precision measurement of the **activity**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



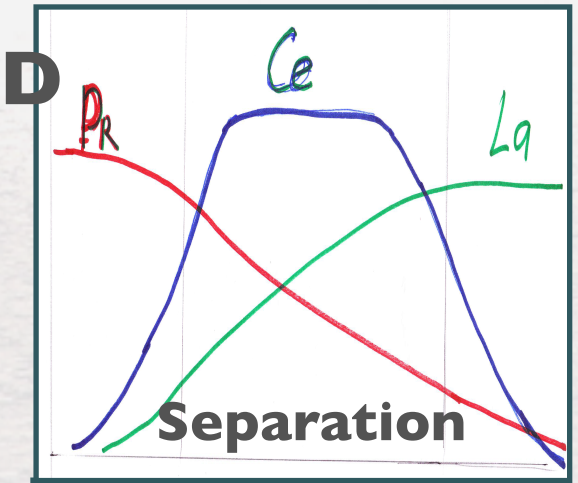
Cutting, digestion (Purex process)

Lanthanide and Actinides concentrate

Rare Earths Precipitation

Displacement Chromatography

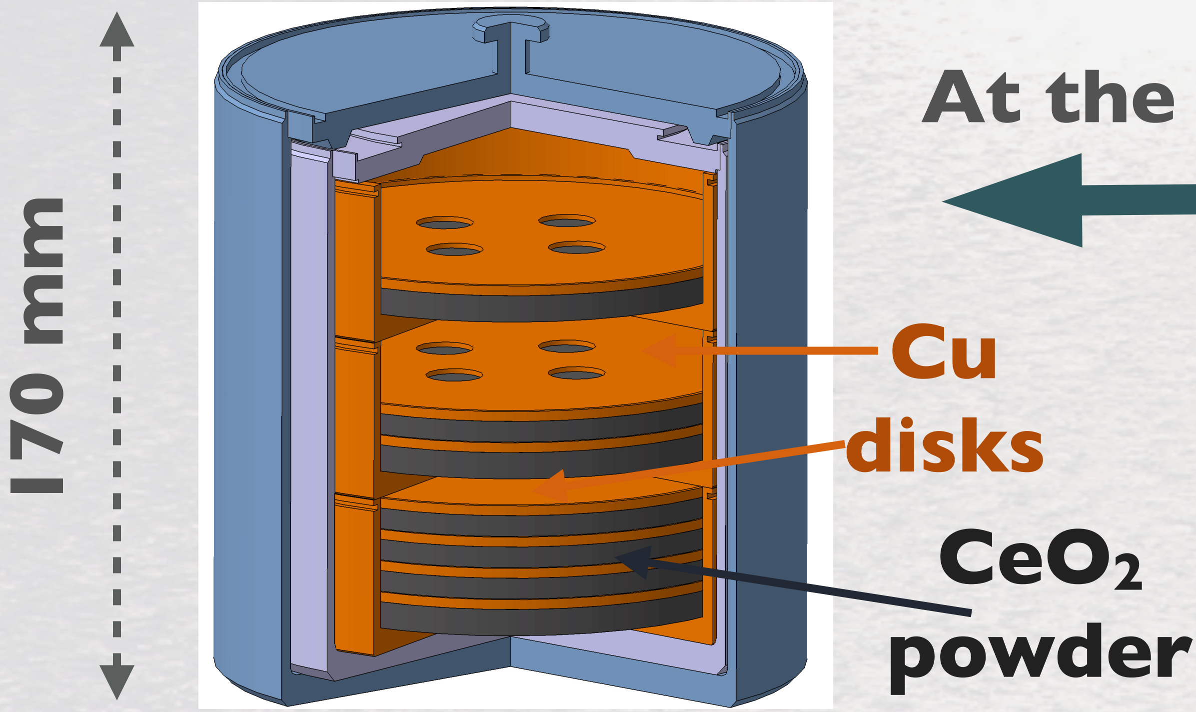
Separation



Calcination

At the END

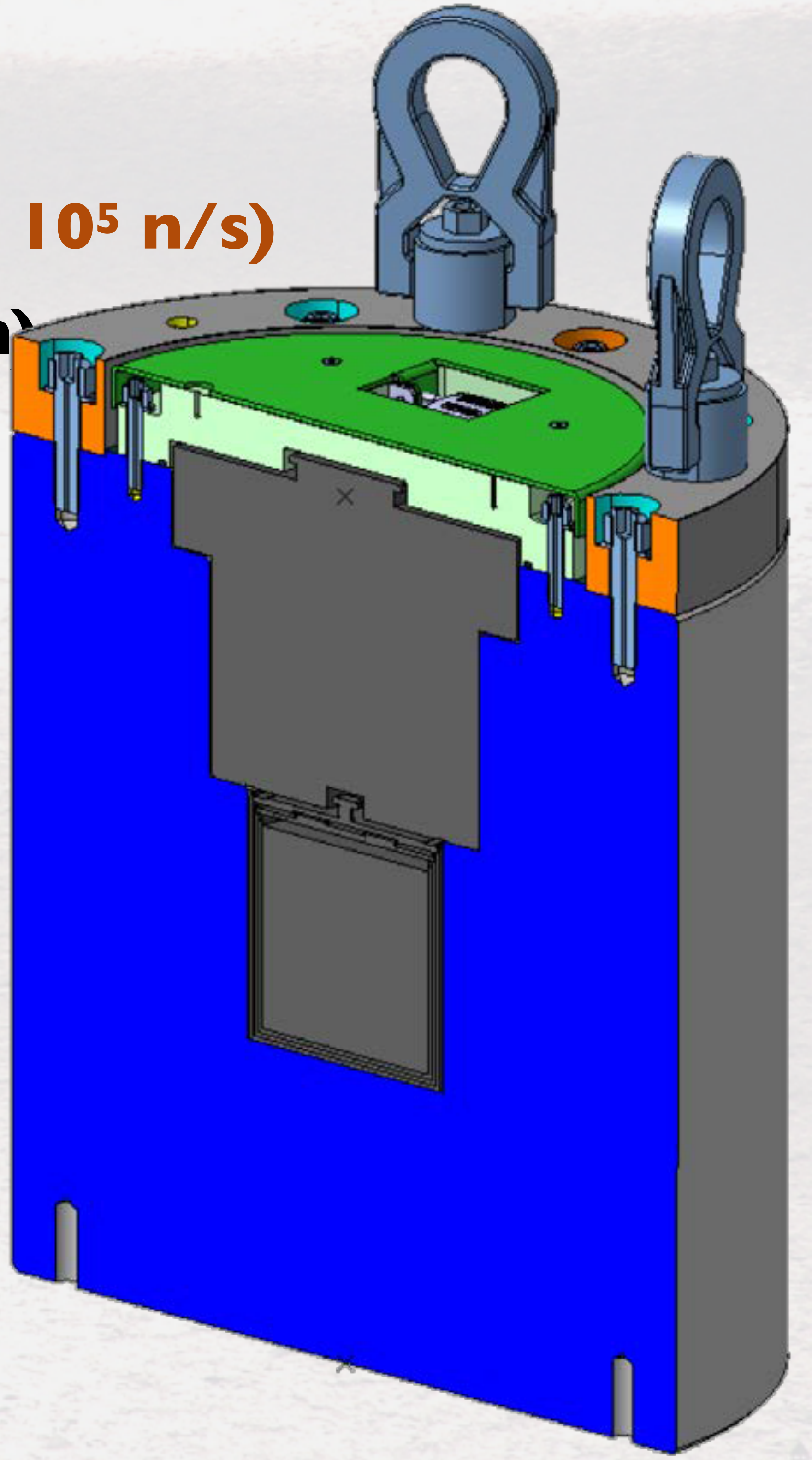
THE CAPSULE (few litres)



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

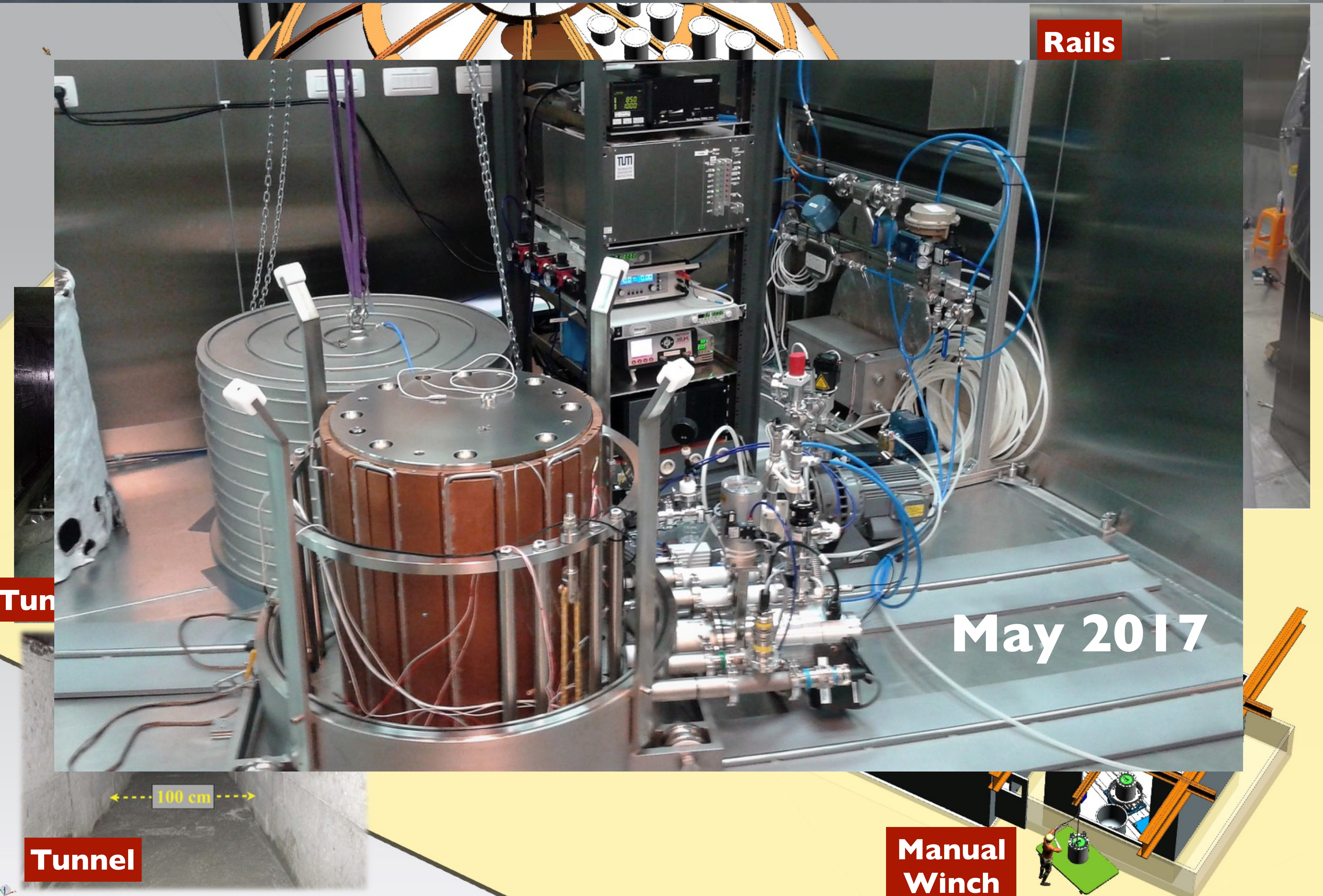
The CeO_2 powder must be quite pure

- **Radio-protection,** relation between **heat and activity,** strict LNGS **requirements on n flux**
  - Rare Earths: **γ 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! (γ,α,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



γ 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%

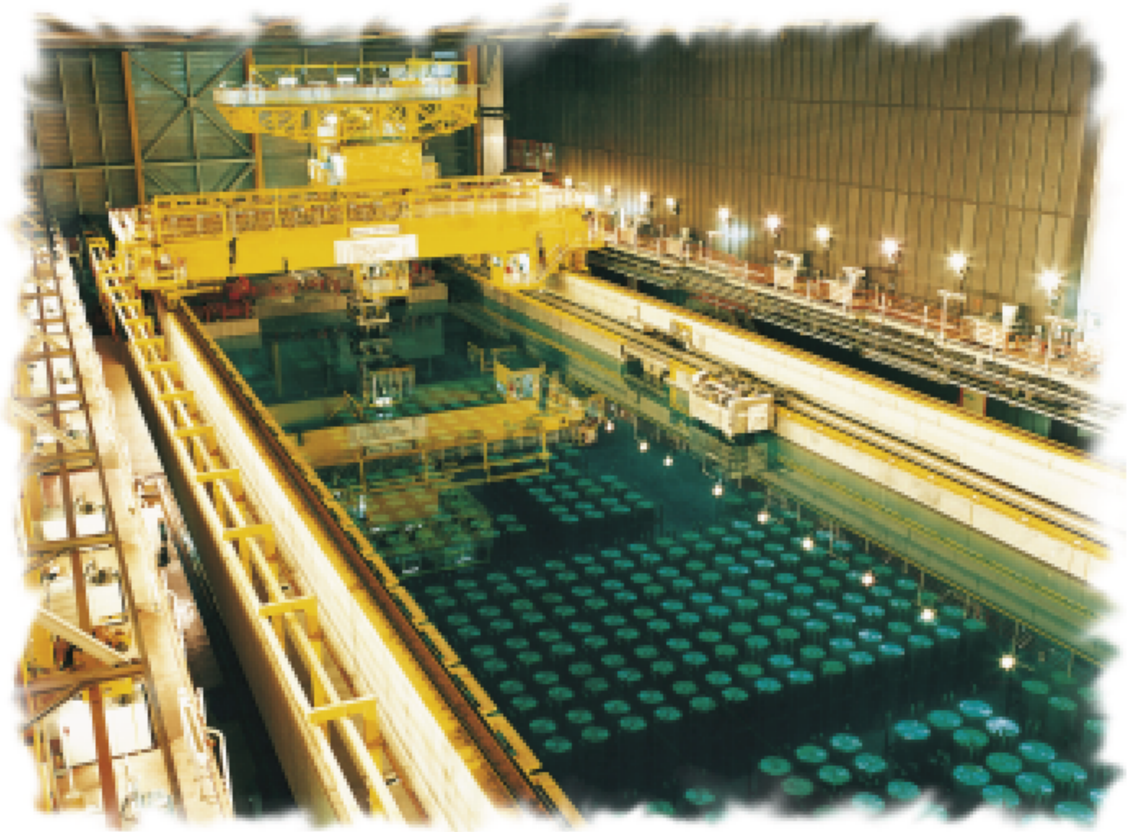

Rails
Tun
May 2017
100 cm
Tunnel
Manual
Winch

Radiochemical plant

- Standard process (PUREX) used to treat spent nuclear fuel
- Production of and separation of CeO_2
- Encapsulation of powder
- Activity measurement

Radioisotope Plant

- Source fabrication
- Certification ISO 9978
- Loading into W shield
- Loading into transportation cask



CE-144 PURIFICATION

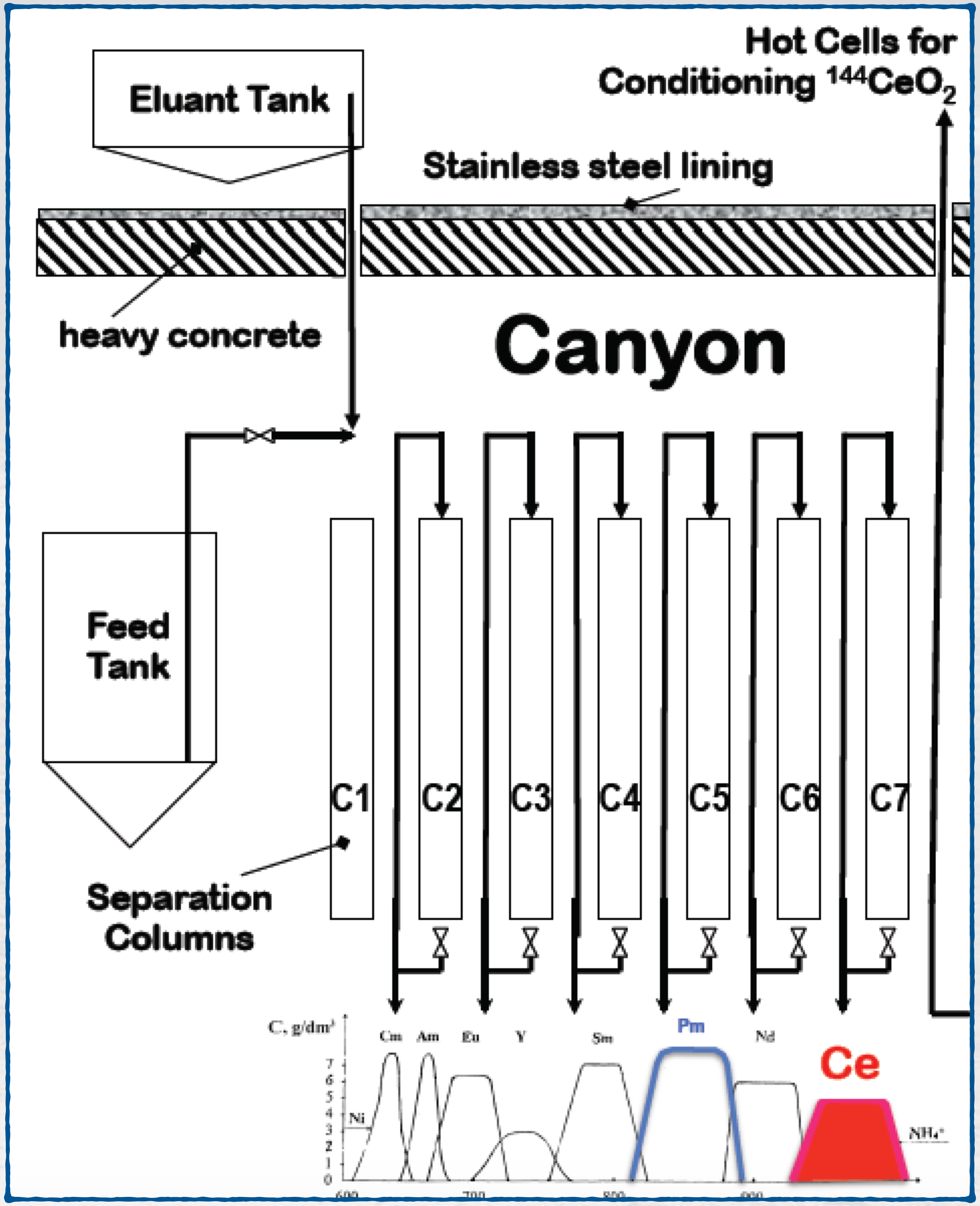
Complexing agent displacement chromatography for Rare Earths Elements(REE)

Spent Nuclear Fuel

- Mayak: 100 t PUREX / year
- 1 ton SNF
  - 13 kg REE (22 g Ce-144 (3y, 70 kCi))

Production

- Start now
- Delivery Aug.-Oct 2016
  S. Petersburg harbour
- @LNGS end of 2016

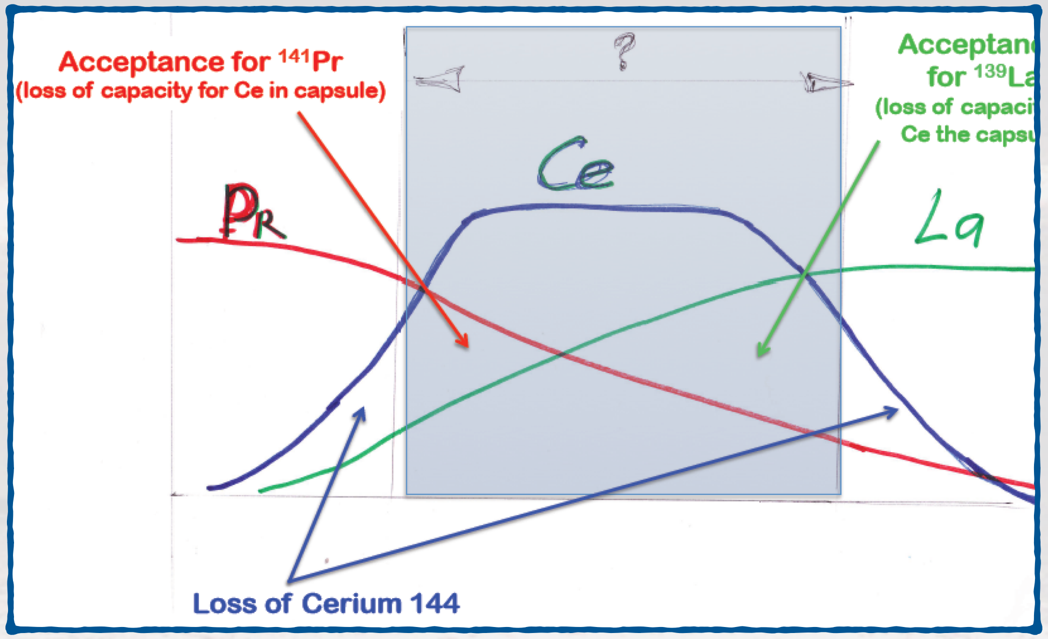


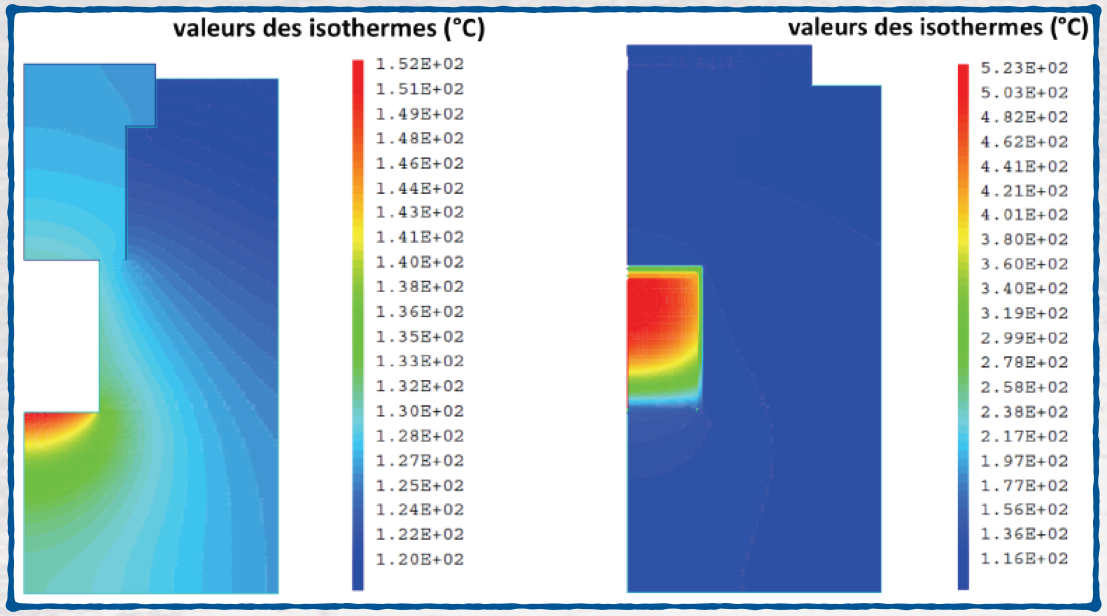
A VERY LONG STORY MADE SHORT: CeANG

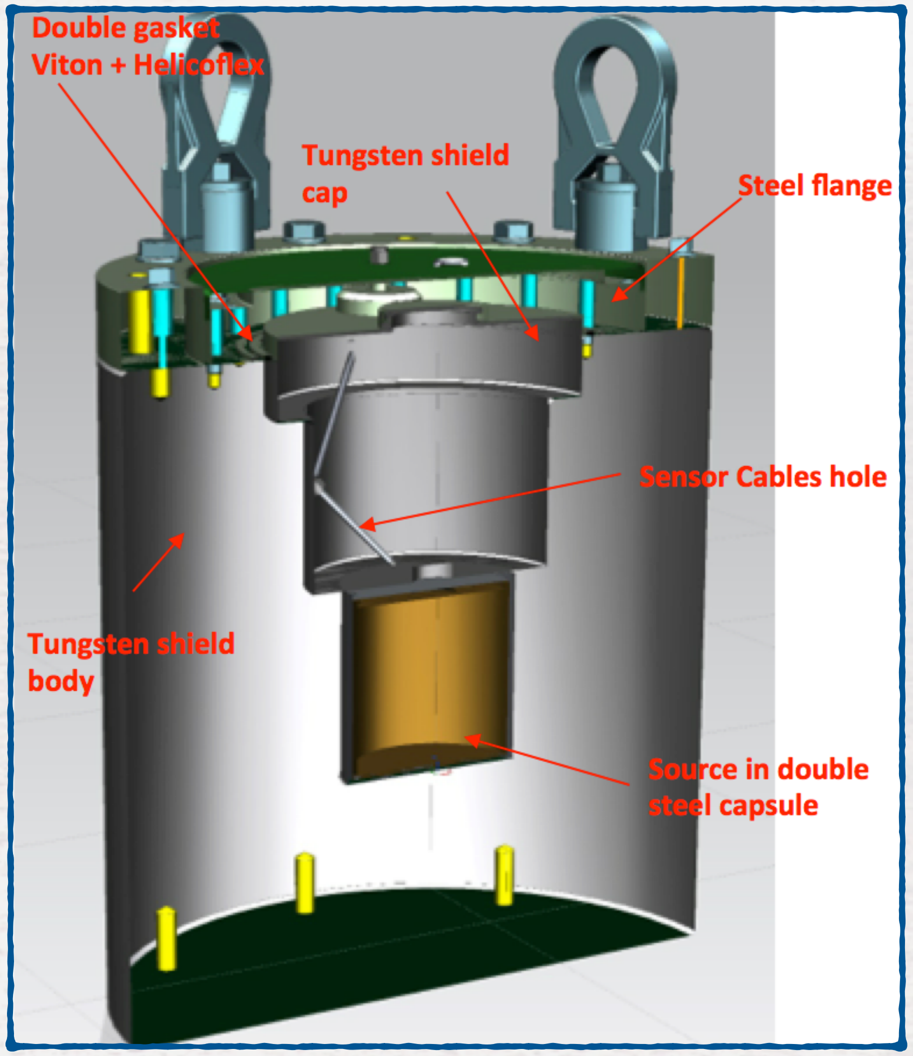
for more details on CeANG see e.g.
T. Lasserre talk at Venice 2015

Specs

- >3.7 PBq (^{144}Ce only); powder 4-6 g cm^{-3} density
- CeO_2 with Ce from fresh spent fuel (<2 y old)
- Purity
  - Rare Earth: γ 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)
- Production
  - Key: separation of Ce from other REE with chromatography
  - CeO_2 powder sealed in a container
  - Container inserted into a 19 cm thick W shield
  - Internal T ~ 500 °C; surface T @ 20:°C ~ 80 °C



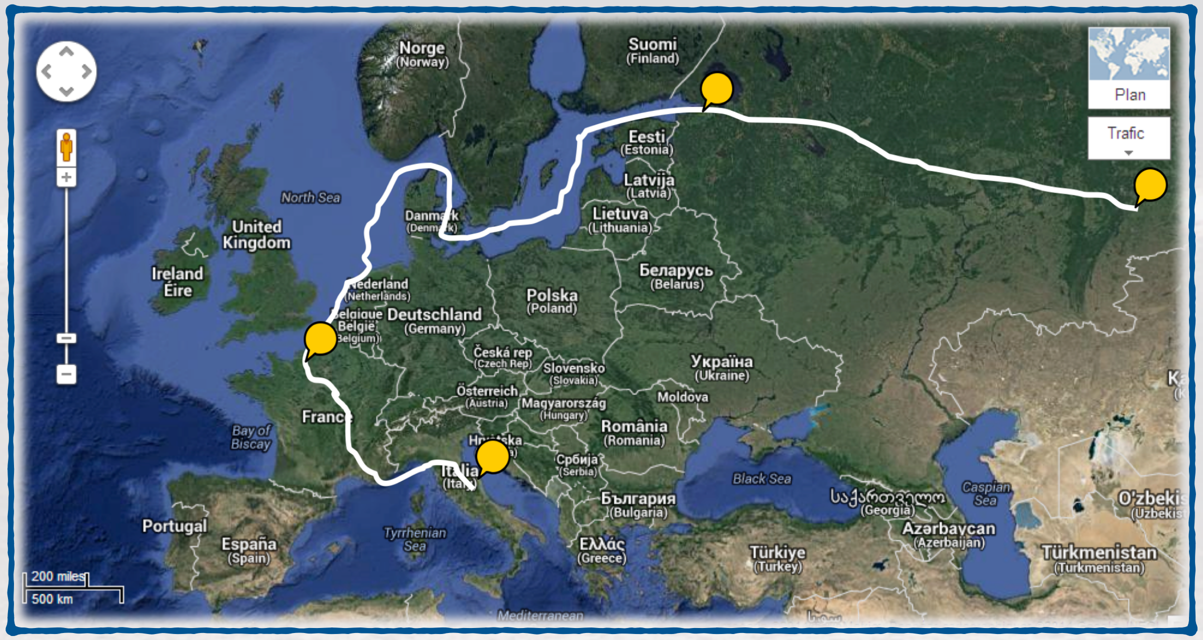


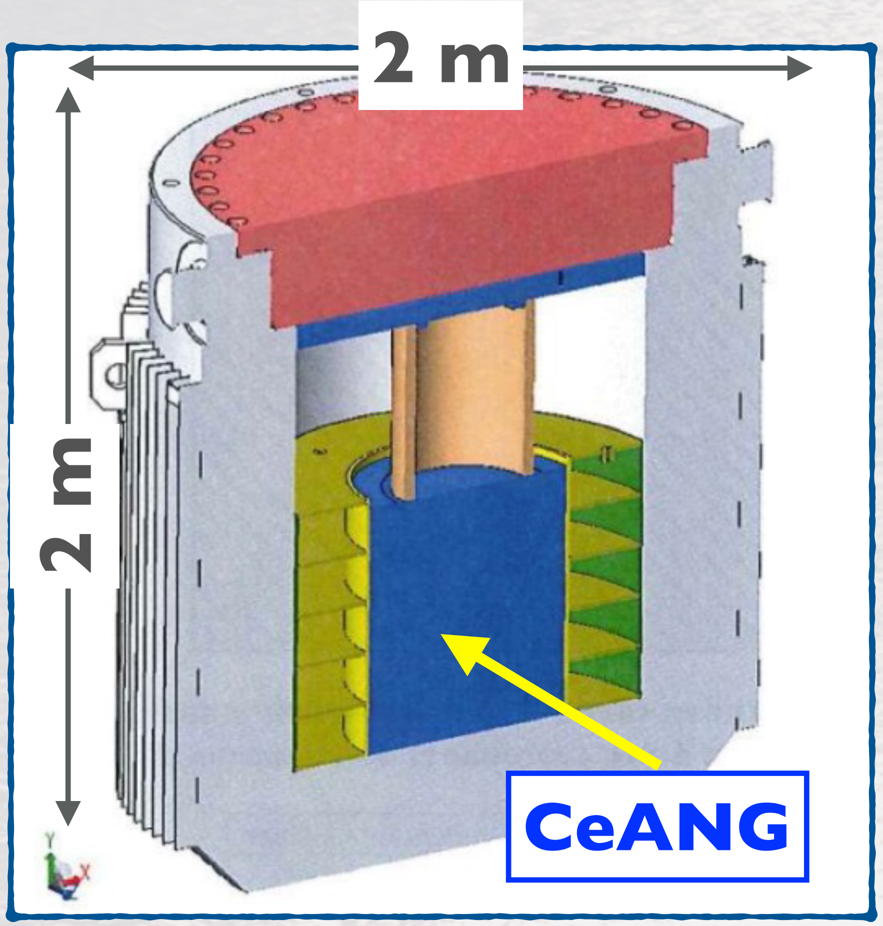


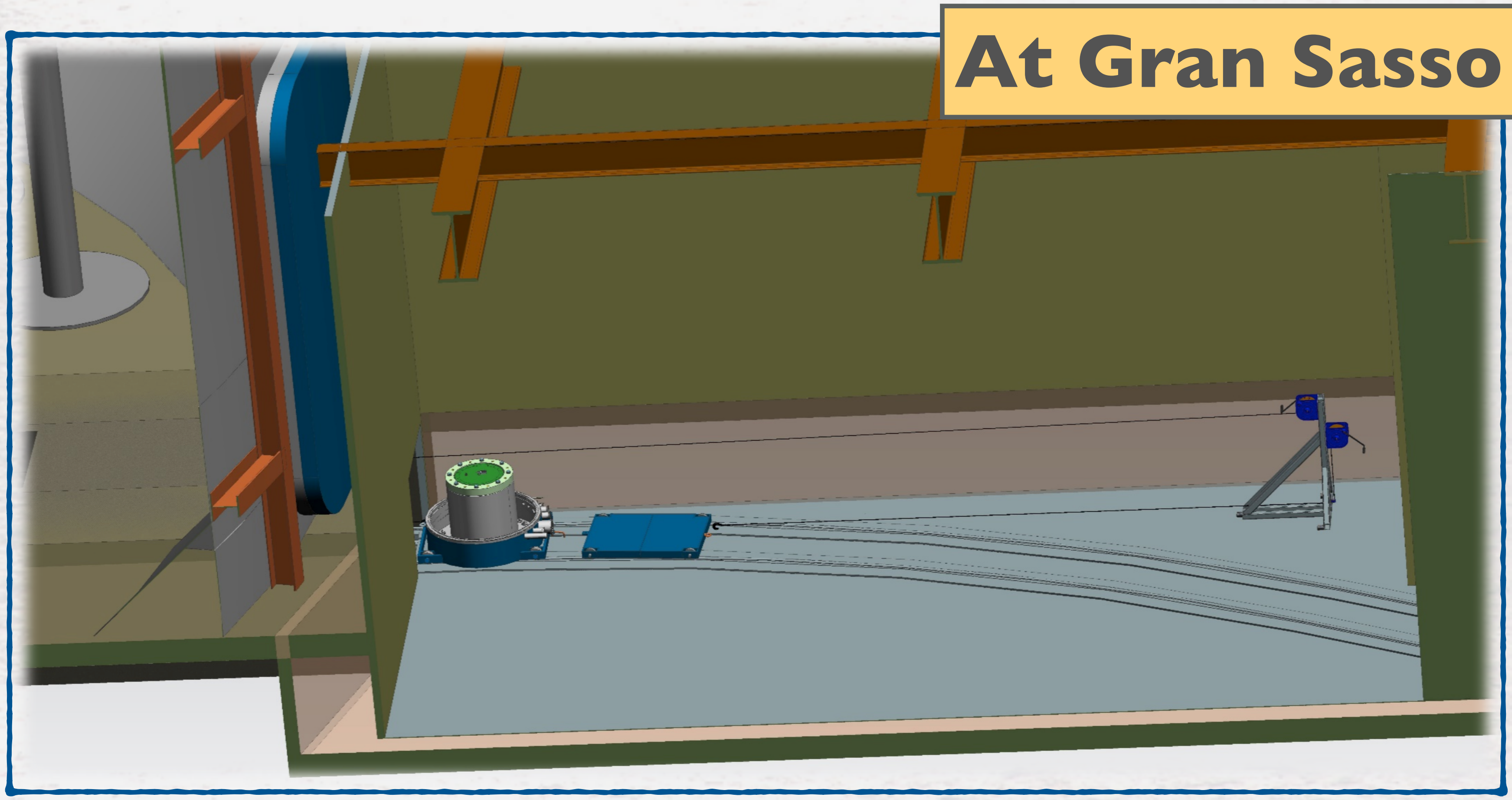
for more details on CeANG see e.g.
T. Lasserre talk at Venice 2015

A long way (~1-2 months):

- 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)
- IZOTOP (Russia), AREVA (Main contractor, France) + MIT (Italy) will handle the long journey







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

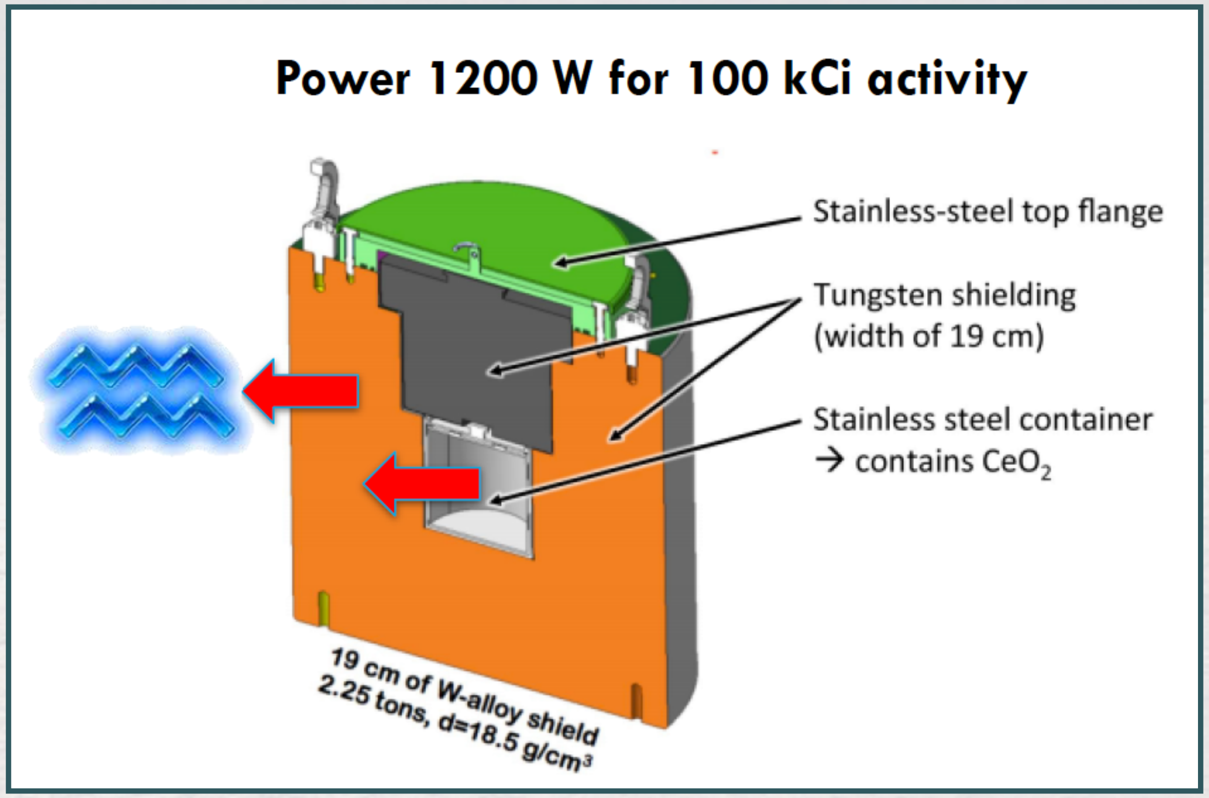
- In principle, an easy measurement:

power

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

water heat capacitance ($c_p(T)$)

mass flow ($\dot{m}$)

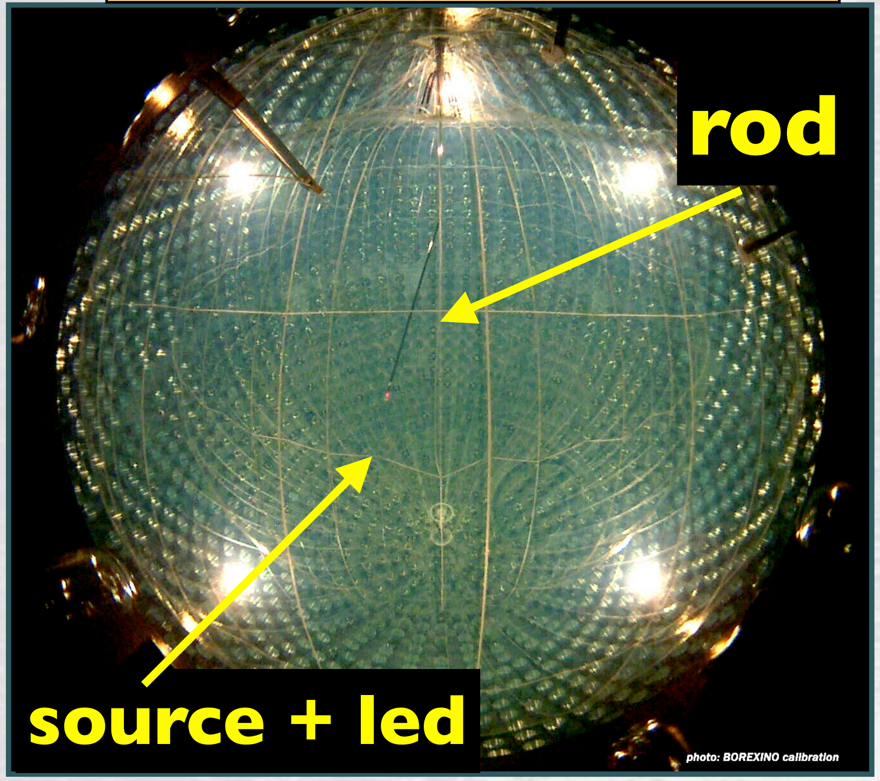


- **Systematics** are the crucial point:
  - **Heat losses**
    - Gas convection
    - Conduction through contacts
    - Radiation
  - **Relation between power and flux (anti-neutrino beta spectrum)**

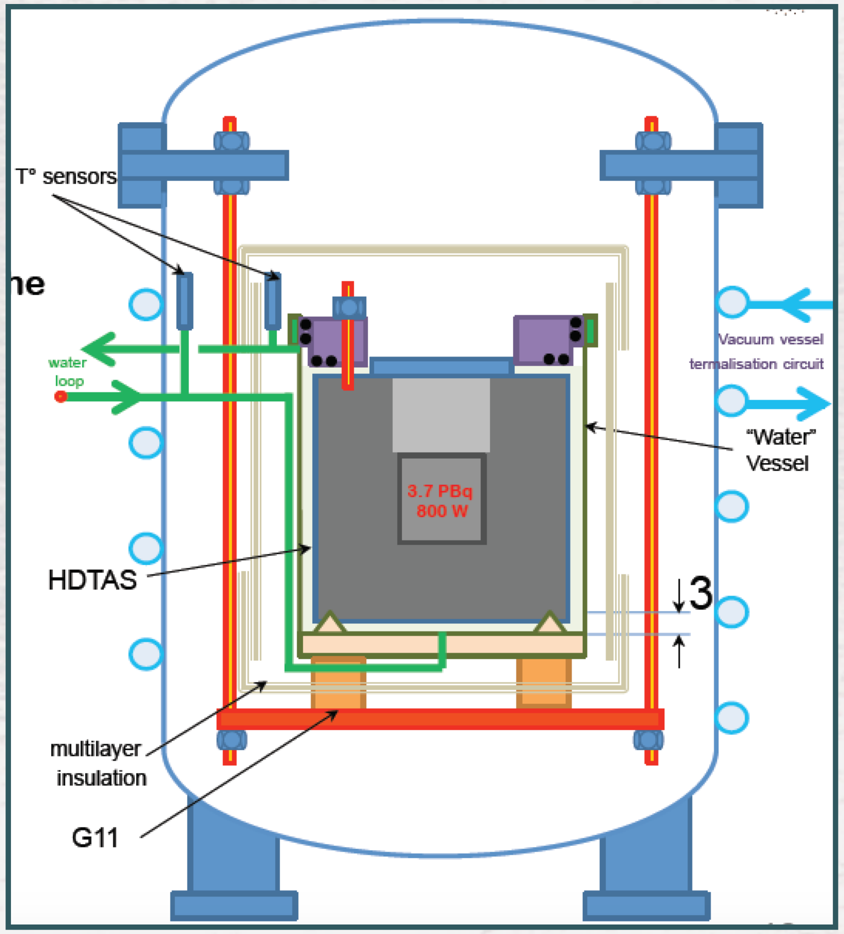
As **disappearance experiment, sensitivity** depends on: (**<u>waves detection does not!</u>**):

- **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

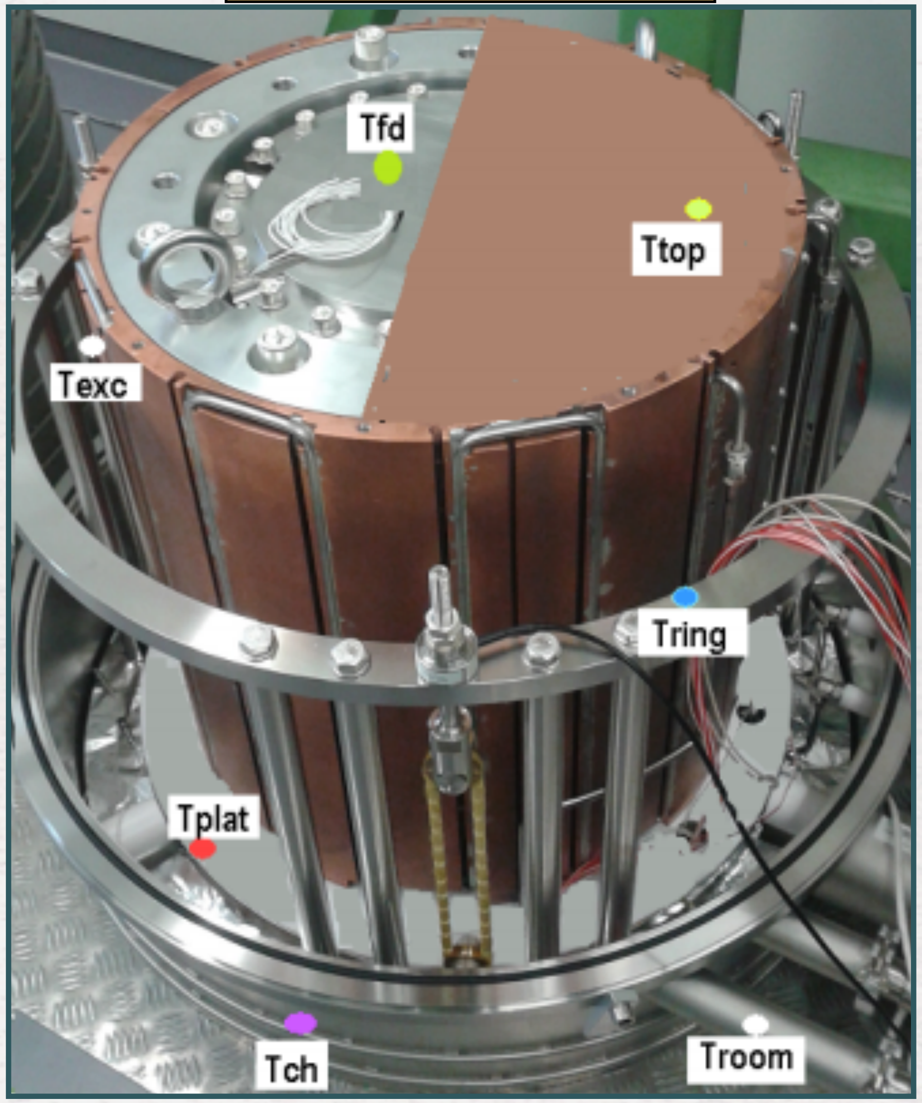
Borexino Calibration



CEA calorimeter



Genova/TUM



Convection

Vacuum system
Turbo molecular pump
skroll pump

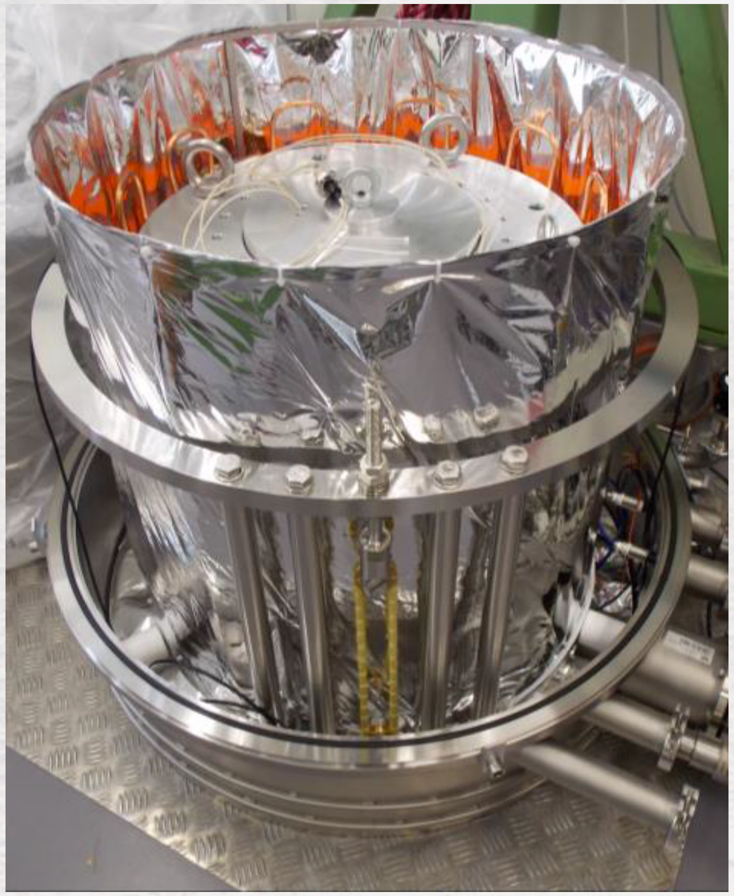
P < 5·10^{-5} mbar

P ≈ 0 W

Radiation

2 stages of super insulator
(10 foils each)

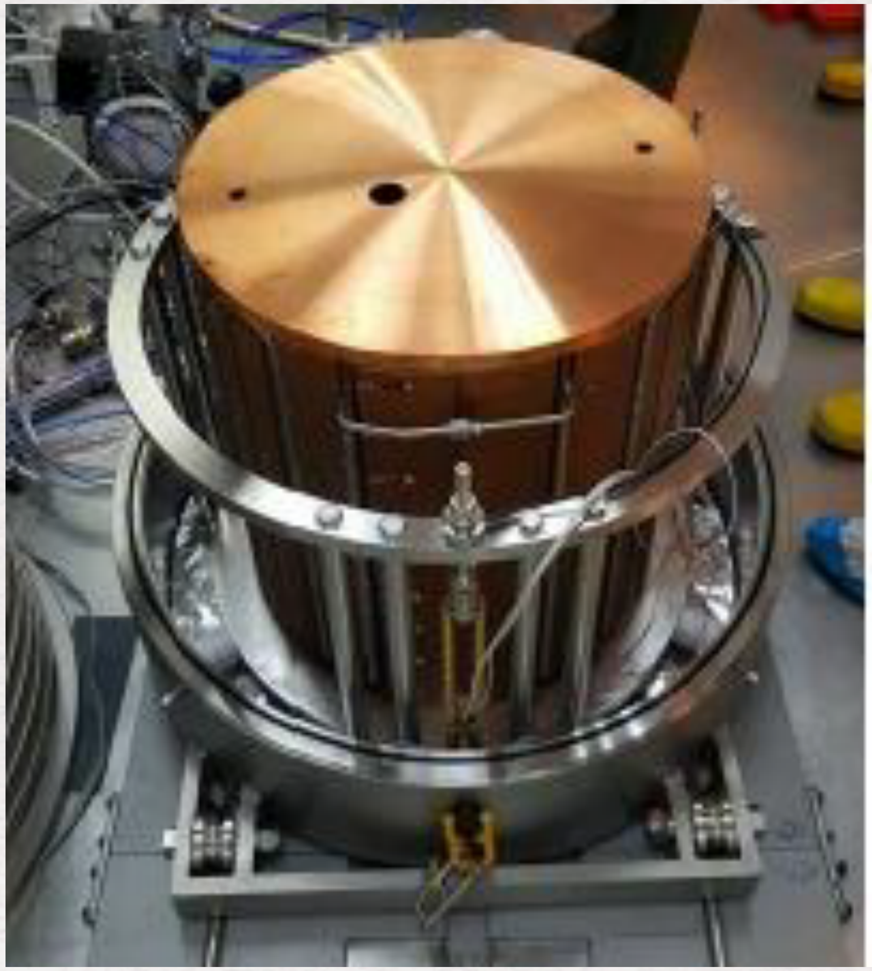
Thermalisation of the external chamber by hot water flow



P < 1 W

Conduction

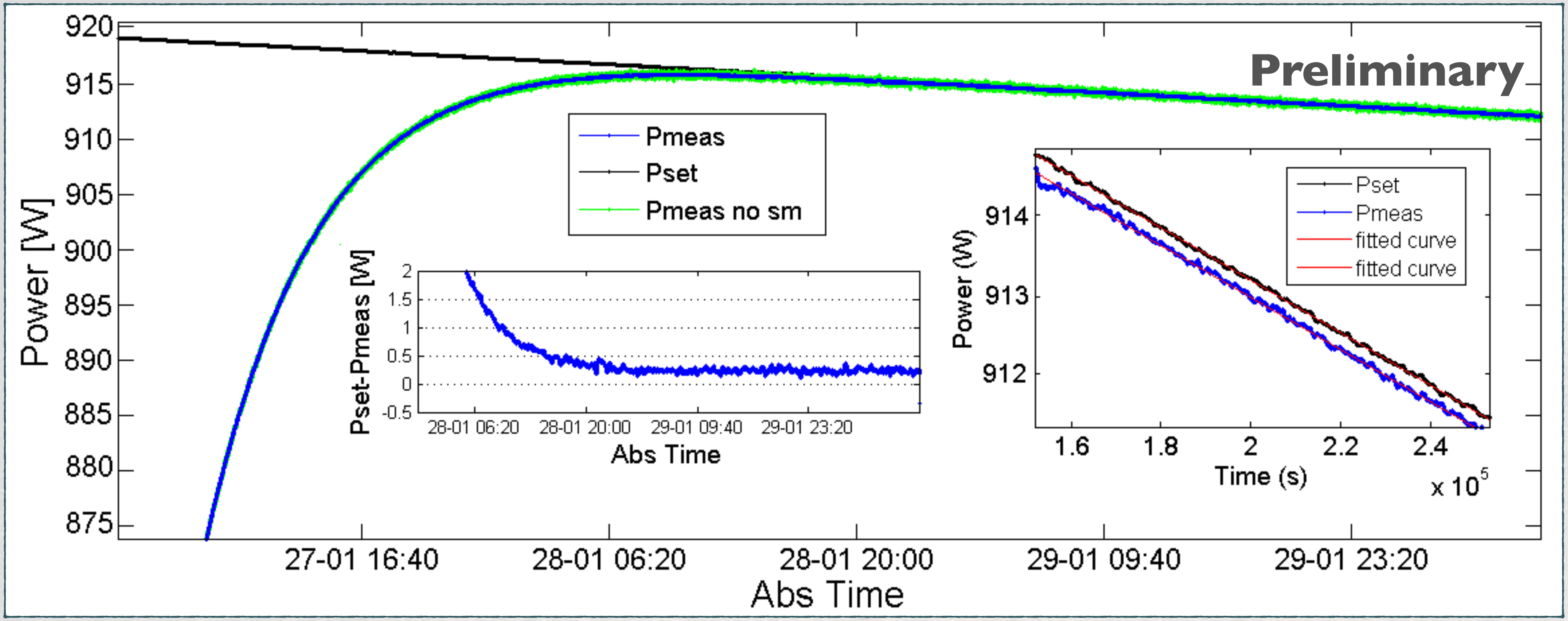
Hanging platform suspended by three kevlar ropes



P < 0.1 W

Preliminary results from calorimeter calibrations

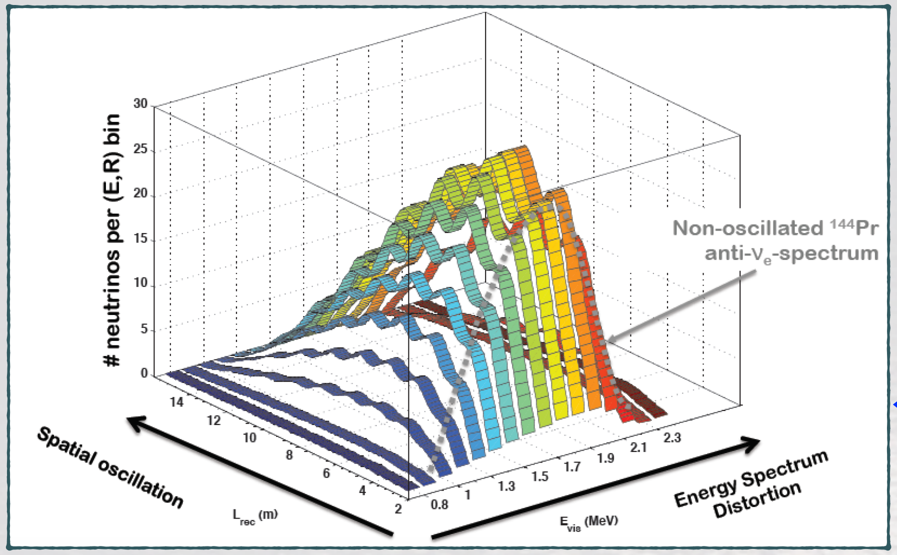
- Close to **0.1 % precision** in heat measurement $P(t) = P_0 e^{-\frac{t-\Delta t}{\tau}} + P_w$

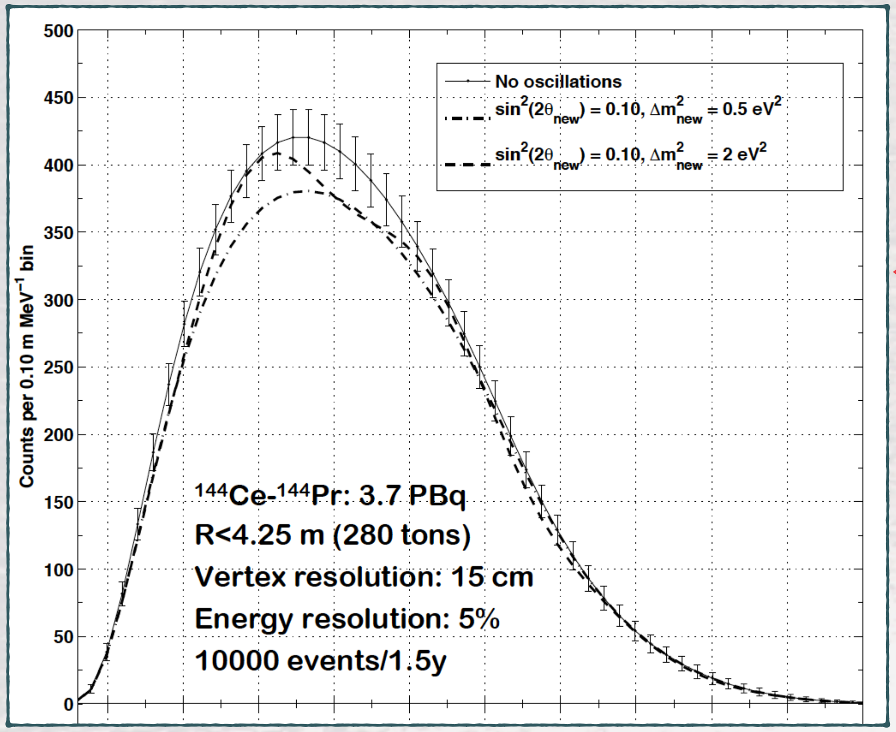


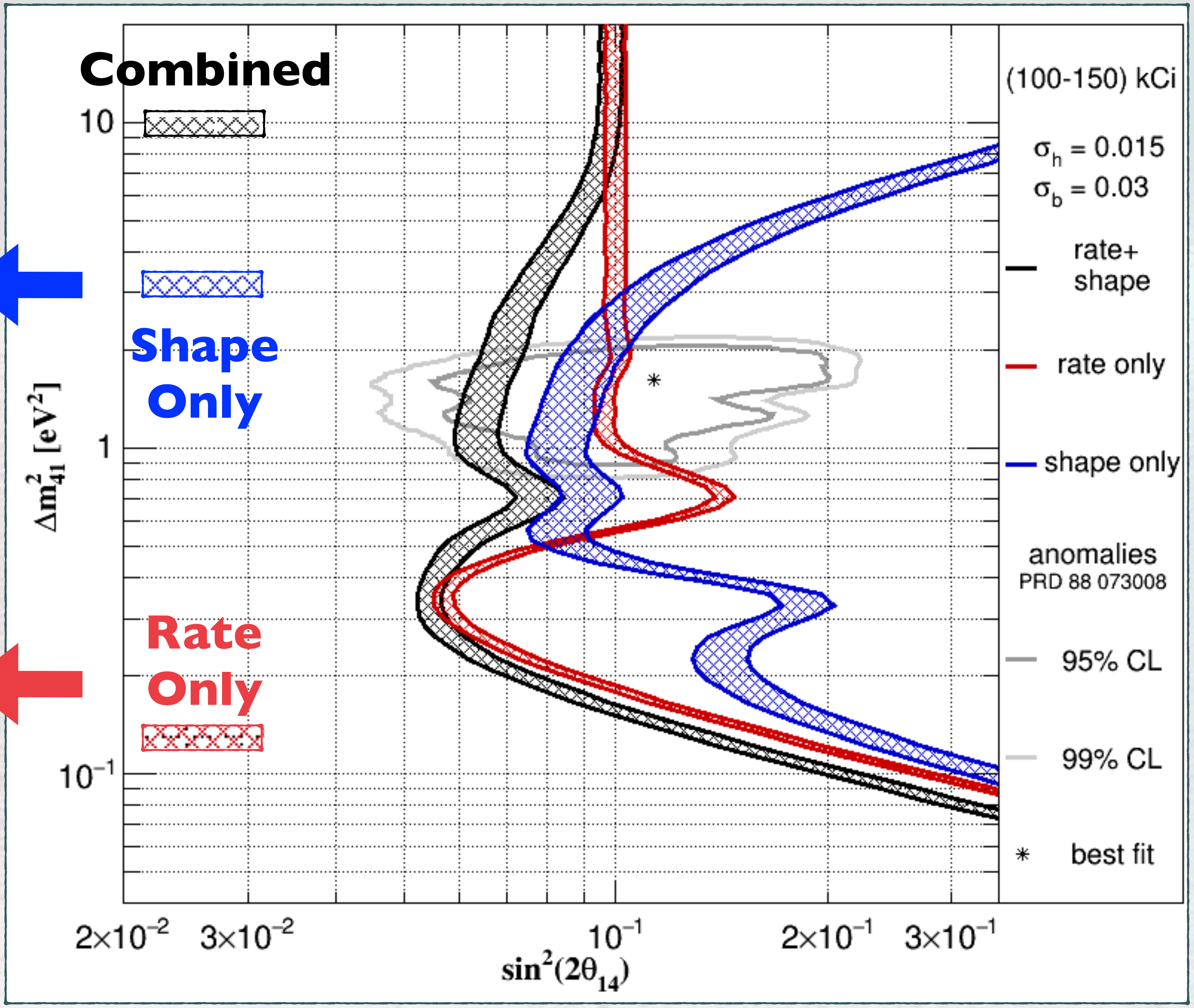
- Note: translation of the heat measurement to **neutrino flux requires precise knowledge of Ce-144 - Pr-144 spectra**
  - Work in progress

^{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

- Spring 2018

Physics

- 18 months of data taking

Thanks