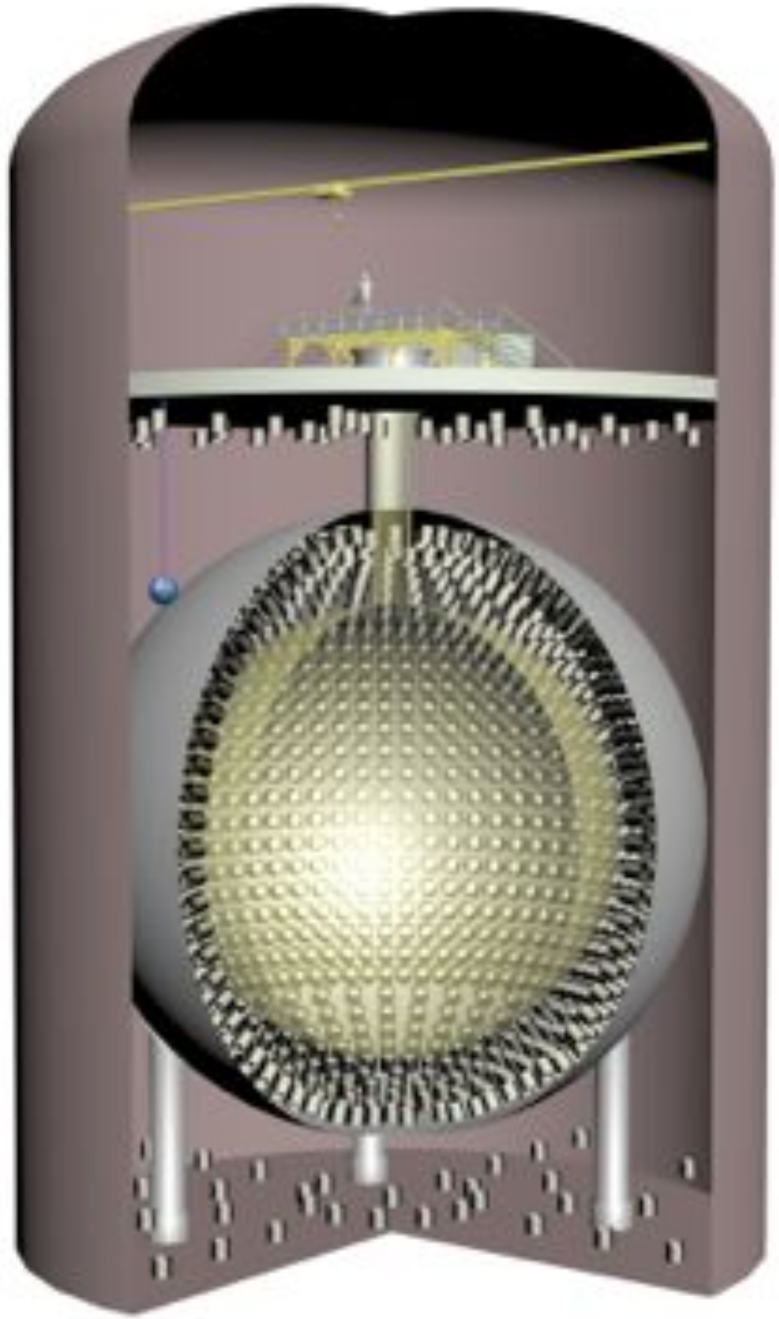
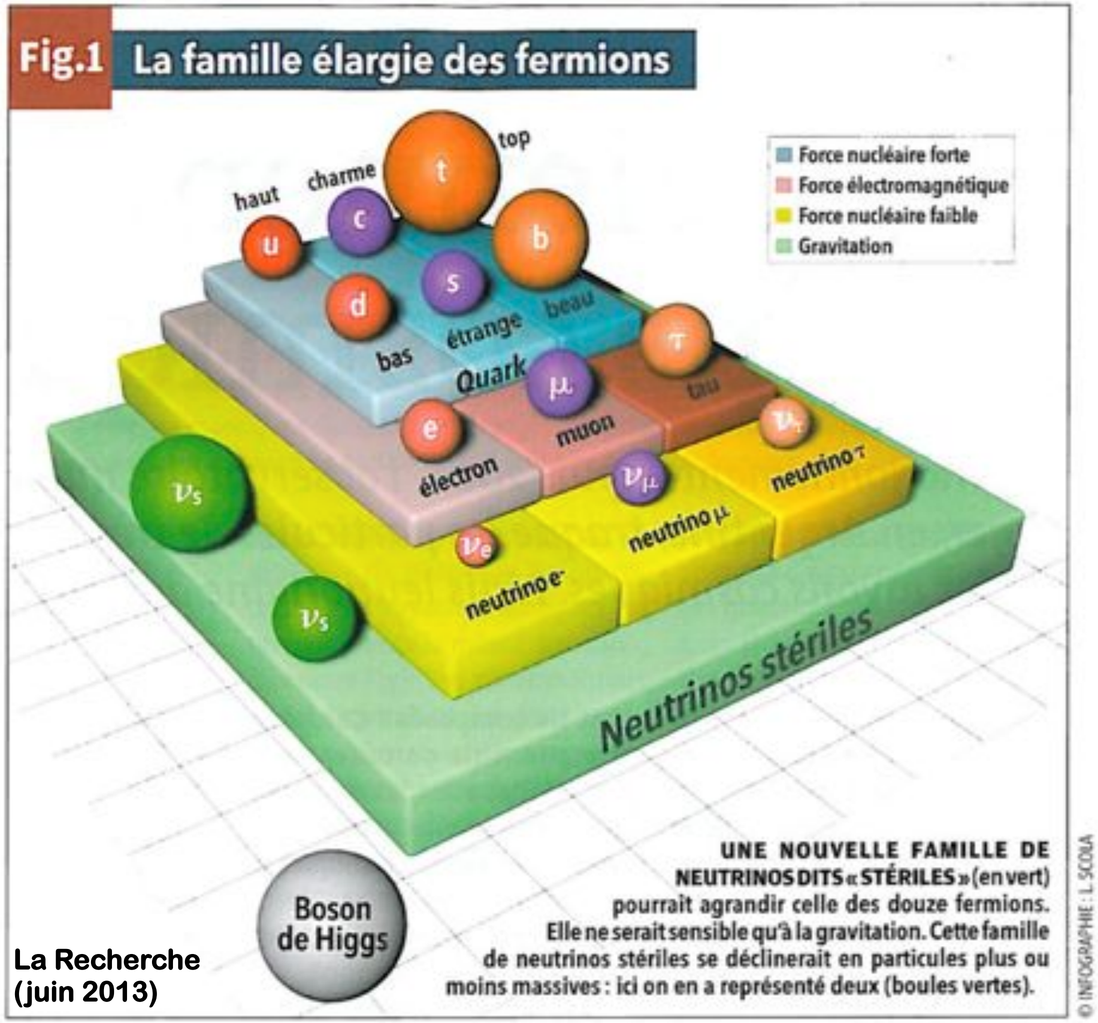


CeLAND

CSTS
June 17th 2013

Th. Lasserre, M. Cribier,
M. Durero, V. Fischer,
J. Gaffiot, L. Scola,
D. Lhuillier, A. letourneau,
G. Mention, Ch. Veyssière,
M. Vivier, (CEA Irfu & APC)

Physics Case



La Recherche (juin 2013)

Double Chooz By-Product

PHYSICAL REVIEW C **83**, 054615 (2011) → **138 citations**

Improved predictions of reactor antineutrino spectra

Th. A. Mueller,[1] D. Lhuillier,[1,*] M. Fallot,[2] A. Letourneau,[1] S. Cormon,[2] M. Fechner,[3] L. Giot,[2] T. Lasserre,[3] J. Martino,[2] G. Mention,[3] A. Porta,[2] and F. Yermia[2]
[1]*Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Centre de Saclay, IRFU/SPhN, FR-91191 Gif-sur-Yvette, France*
[2]*Laboratoire SUBATECH, École des Mines de Nantes, Université de Nantes, CNRS/IN2P3, 4 rue Alfred Kastler, FR-44307 Nantes Cedex 3, France*
[3]*Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Centre de Saclay, IRFU/SPP, FR-91191 Gif-sur-Yvette, France*
(Received 14 December 2010; revised manuscript received 9 March 2011; published 23 May 2011)

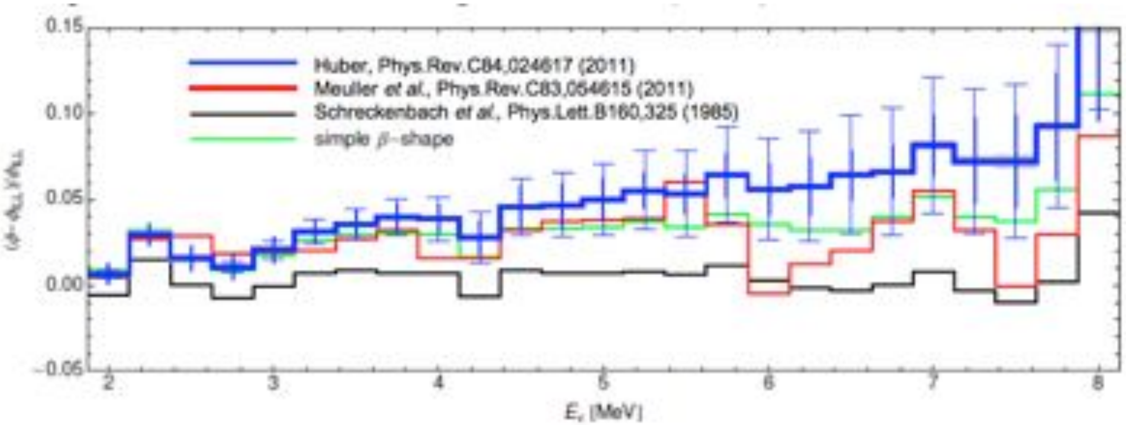
PHYSICAL REVIEW D **83**, 073006 (2011) → **201 citations**

Reactor antineutrino anomaly

G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]
[1]*CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
[2]*Astroparticule et Cosmologie APC, 10 rue Alice Domon et Léonie Duquet, 75205 Paris cedex 13, France*
[3]*CEA, Irfu, SPhN, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
(Received 14 January 2011; published 29 April 2011)

The Reactor Anomaly

i) $\nu_{emission}$: **Improved reactor neutrino spectra → <u>+4%</u>**

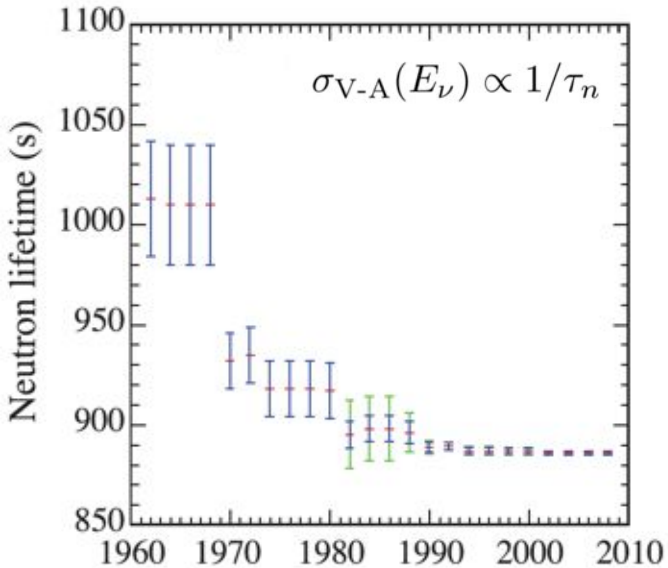


PRC83, 054615 (2011)

PRC84, 024617 (2011)

ii) $\nu_{detection}$: **Reevaluation of σ_{IBD} → <u>+1.5%</u>**
Evolution of the neutron life time

PRD 83, 073006 (2011)



iii) $\nu_{detection}$: **Accounting for long-lived isotopes in reactors → <u>+1%</u>**

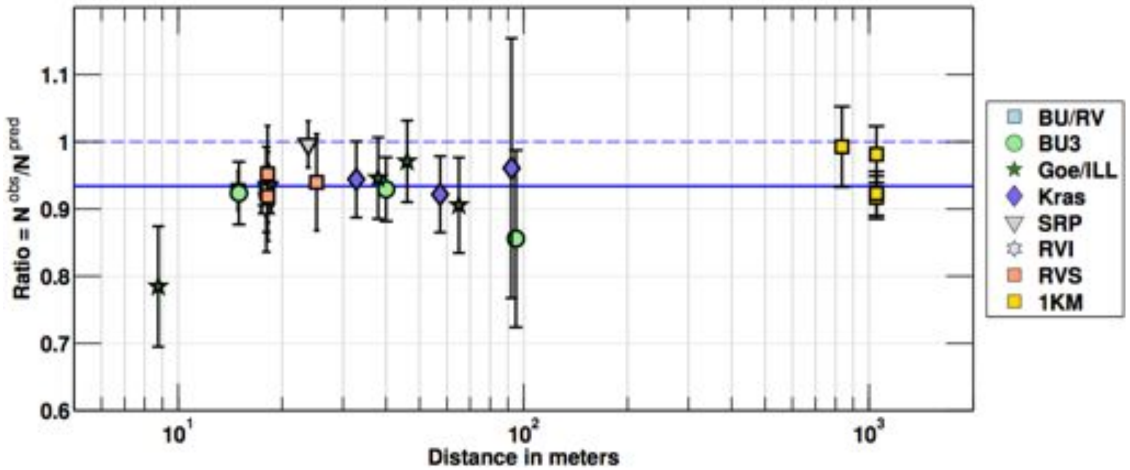
PRD 83, 073006 (2011)

The Reactor Anomaly: Update

The reactor antineutrino anomaly in the light of latest oscillation results

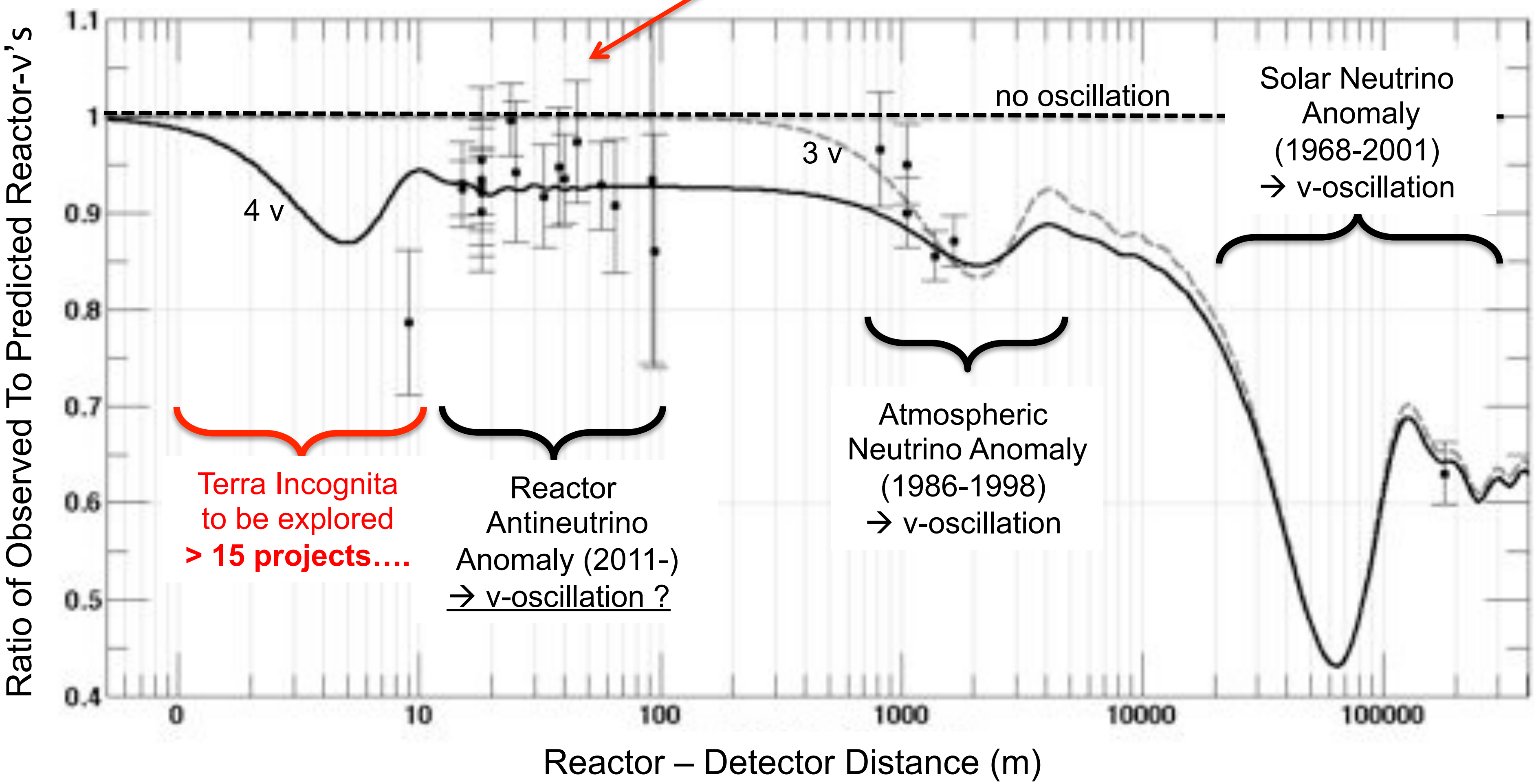
G. Mention[1], T. Lasserre[1,2], M. Cribier[1,2], V. Fischer[1], J. Gaffiot[1,2],
A. Letourneau[1], D. Lhuillier[1], M. Vivier[1] and others
[1] *Commissariat à l'énergie atomique et aux énergies alternatives, Centre de Saclay, IRFU, 91191 Gif-sur-Yvette, France* and
[2] *Astroparticules et Cosmologie, 10 rue Alice Domon et Léonie Duquet, 75205 Paris cedex 13, France*

We provide a re-evaluation of the analysis of short and middle baseline reactor neutrino experiments, leading to an update of the reactor antineutrino anomaly [1]. We use the most recent reactor antineutrino spectra [2] and inverse beta decay (IBD) cross section, as well as current best knowledge of the θ_{13} mixing angle independent from reactor flux normalization to include reactor experiments with a kilometer baseline. The synthesis of published experiments at reactor-detector distances below 100 m leads to a ratio of observed to predicted event rate of 0.938 ± 0.012 (IBD) ± 0.022 (Spectra). Independently, experiments performed with a baseline around 1 km, Palo Verde, Chooz, and Double Chooz, yield a consistant average ratio of 0.934 ± 0.017 (IBD) ± 0.021 (Spectra). Combining both results provide an overall ratio of 0.934 ± 0.009 (IBD) ± 0.021 (Spectra). The reactor antineutrino anomaly significance is therefore unaffected by inclusion of 1 km-scale baseline reactor neutrino experiments. The updated significance of the reactor anomaly using all relevant data is now $2.8\,\sigma$, based on a rate-only analysis. **→ To be submitted to PRD**



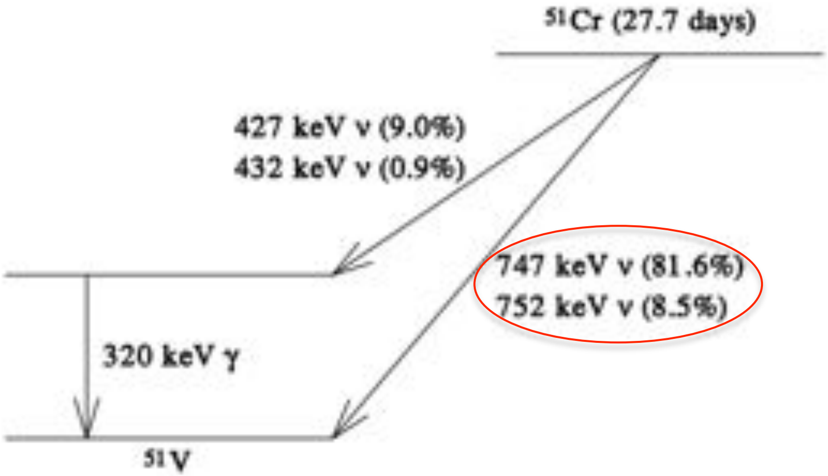
The Reactor Anomaly

- **Observed/predicted averaged event ratio: R=0.934±0.023 (2.8 σ)**



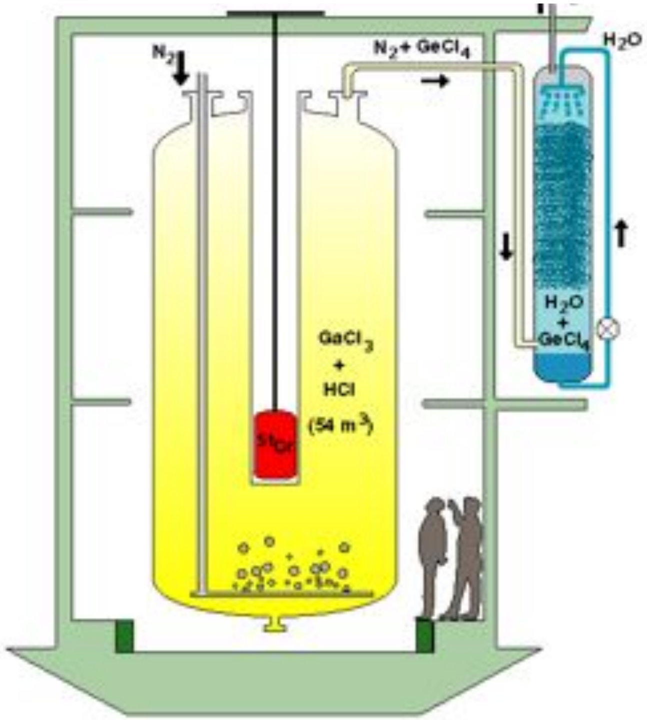
The Gallium Neutrino Anomaly

- **Test of solar neutrino detectors GALLEX and SAGE (ν_e's)**
  - E ≈ MeV, Baseline range ≈ few m



- **4 calibration runs ≈1-2 MCi EC ν_e emitters**
  - Gallex
    - ^{51}Cr source (750 keV)
  - Sage
    - ^{51}Cr & ^{37}Ar (810 keV)

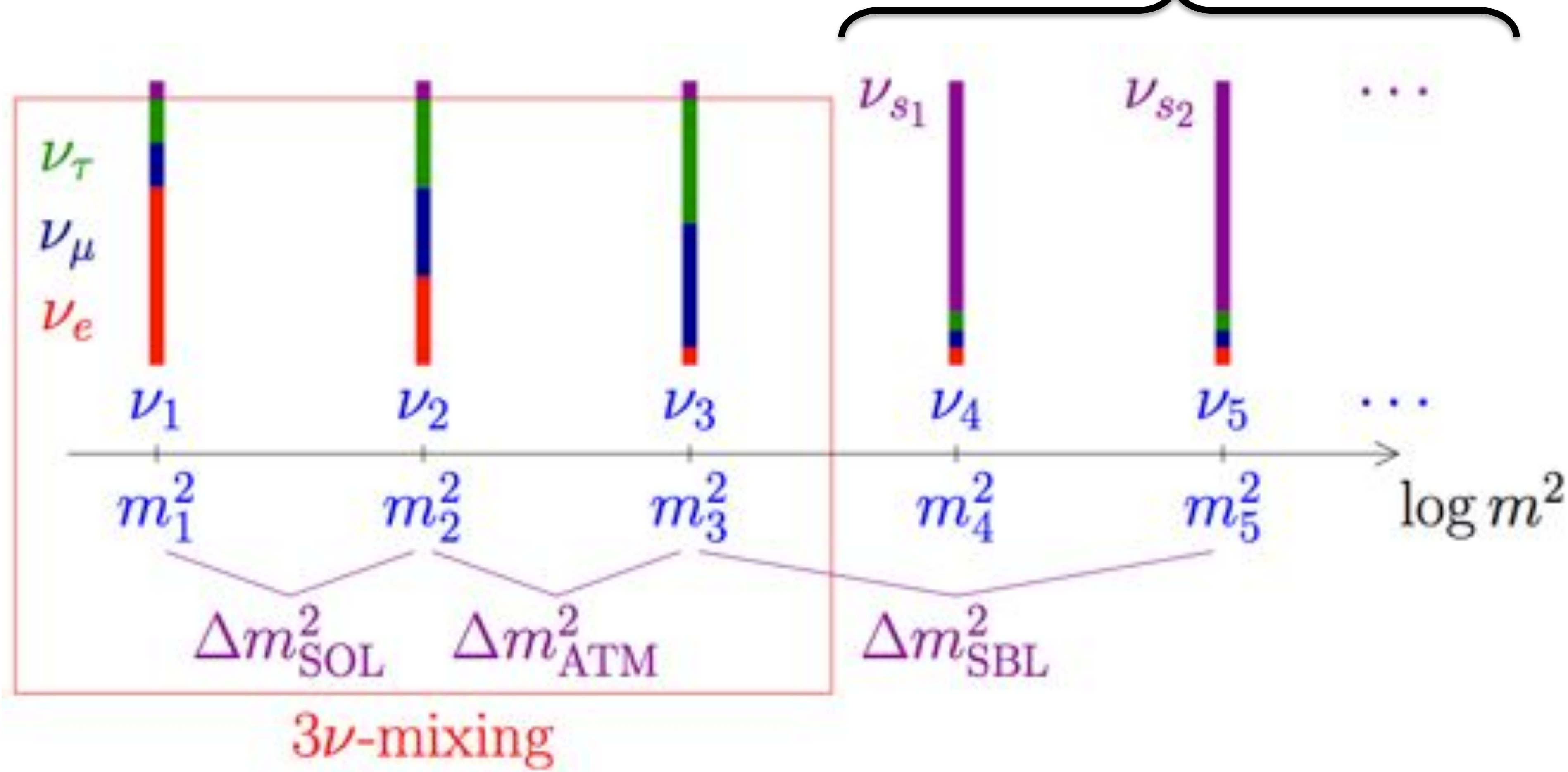
- **Deficit observed**
  - $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
  - $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})



Adding Sterile Neutrinos

Introduce a light ν_R in SM, No SM interactions mixing with active ν' s

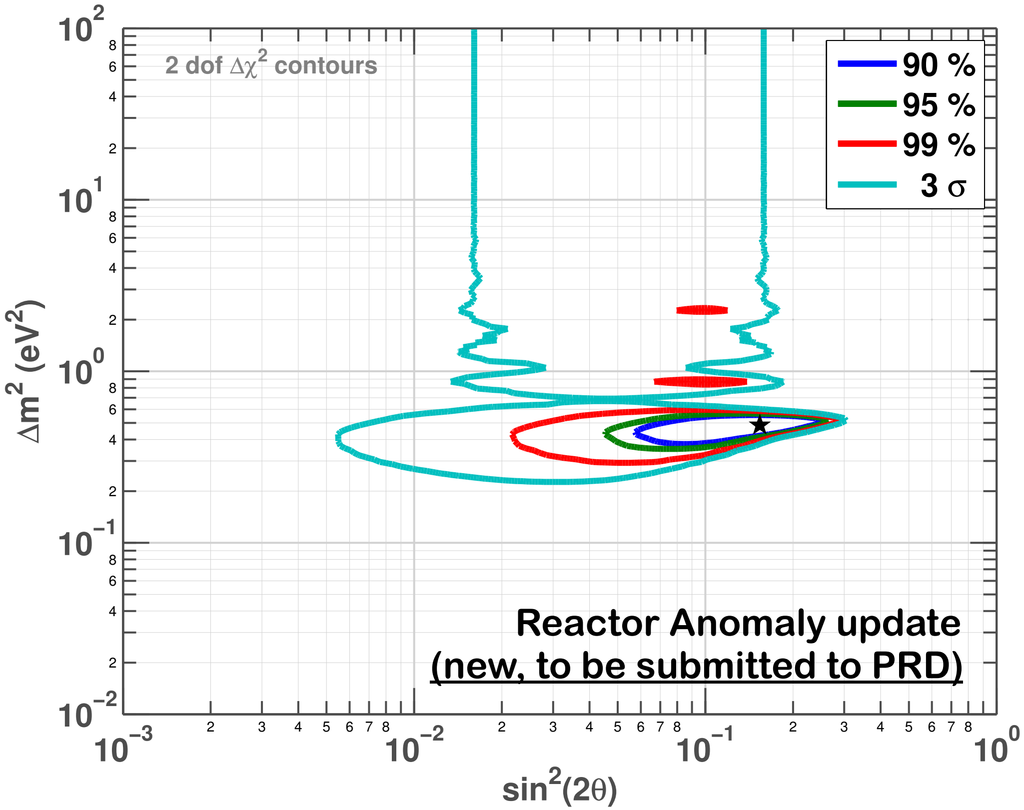
No coupling with Z boson (LEP)

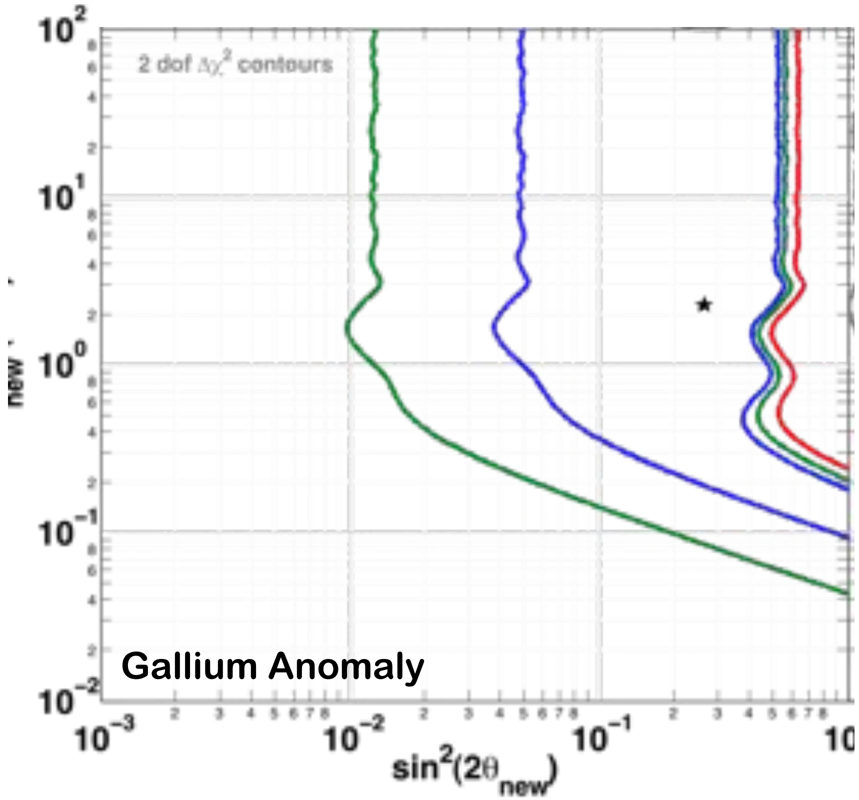


The 4th neutrino hypothesis

Fit to ν_e disappearance hypothesis (3+1)

$$\begin{pmatrix}\nu_e\\ \nu_s\end{pmatrix}=\begin{pmatrix}\cos\theta_{new} & \sin\theta_{new}\\ -\sin\theta_{new} & \cos\theta_{new}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_{new}\end{pmatrix}, P_{ee}=1-\sin^2(2\theta_{new})\sin^2\left(\frac{\Delta m^2_{new}L}{E}\right)$$





No-oscillation hypothesis disfavored at 99.9% C.L. (PRD 83, 073006, 2011)

Anomalies & 4th Neutrino

Anomaly	**Source**	**Type**	**Sensitivity to Oscillation**	**Channel**	**Significance**
LSND	Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBoone	Short baseline	$\nu_\mu \rightarrow \nu_e$	Total Rate, Energy	CC	3.8 σ
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	2.7 σ
Reactor	Beta-decay	$\bar{\nu}_e$ dis.	Total Rate, Energy	CC	**2.8 σ (new)**
Cosmology	Big-Bang	All	Number of ν, N_{eff}	N_{eff} = 3 or 4 allowed	

Could be interpreted with a 4th neutrino state?

CeLAND: Concept

^{144}Ce-^{144}Pr to search for a 4th ν

PRL 107, 201801 (2011) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2011

Proposed Search for a Fourth Neutrino with a PBq Antineutrino Source

Michel Cribier,[1,2] Maximilien Fechner,[1] Thierry Lasserre,[1,2,*] Alain Letourneau,[1] David Lhuillier,[1] Guillaume Mention,[1] Davide Franco,[2] Vasily Kornoukhov,[3] and Stefan Schönert[4]

[1]*Commissariat à l'Energie Atomique et aux Energies Alternatives, Centre de Saclay, IRFU, 91191 Gif-sur-Yvette, France*
[2]*Astroparticule et Cosmologie APC, 10 rue Alice Domon et Léonie Duquet, 75205 Paris cedex 13, France*
[3]*ITEP, ulica Bolshaya Cheremushkinskaya, 25, 117218 Moscow, Russia*
[4]*Physik Department, Technische Universität München, 85747 Garching, Germany*

(Received 12 July 2011; published 7 November 2011)

Several observed anomalies in neutrino oscillation data can be explained by a hypothetical fourth neutrino separated from the three standard neutrinos by a squared mass difference of a few eV^2. We show that this hypothesis can be tested with a PBq (ten kilocurie scale) ^{144}Ce or ^{106}Ru antineutrino beta source deployed at the center of a large low background liquid scintillator detector. In particular, the compact size of such a source could yield an energy-dependent oscillating pattern in event spatial distribution that would unambiguously determine neutrino mass differences and mixing angles.

DOI: 10.1103/PhysRevLett.107.201801 PACS numbers: 14.60.Lm, 14.60.Pq, 14.60.St

→ **Funding through** ERC-2012-StG 307184-4th-Nu-Avenue

Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- GA & RAA arise from comparisons between data and event prediction → Need a conclusive technique
- Input from Sterile Neutrino Fits
  - $\Delta m^2 \approx$ 0.1-10 eV² → $L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2 (eV^2)} \approx 2-10$ m
  - $\sin^2(2\theta_{new}) \approx 0.1$
- Experimental Specifications
  - Search for L, E, L/E pattern (shape only)
  - Complement with a rate analysis (direct test of RAA+GA)
  - $\Delta m^2 \approx eV^2$: compact source <1m & good vertex resolution (<1m)
  - $\sin^2(2\theta_{new})$: experiment with few % stat. syst. uncertainties

ν generator proposals

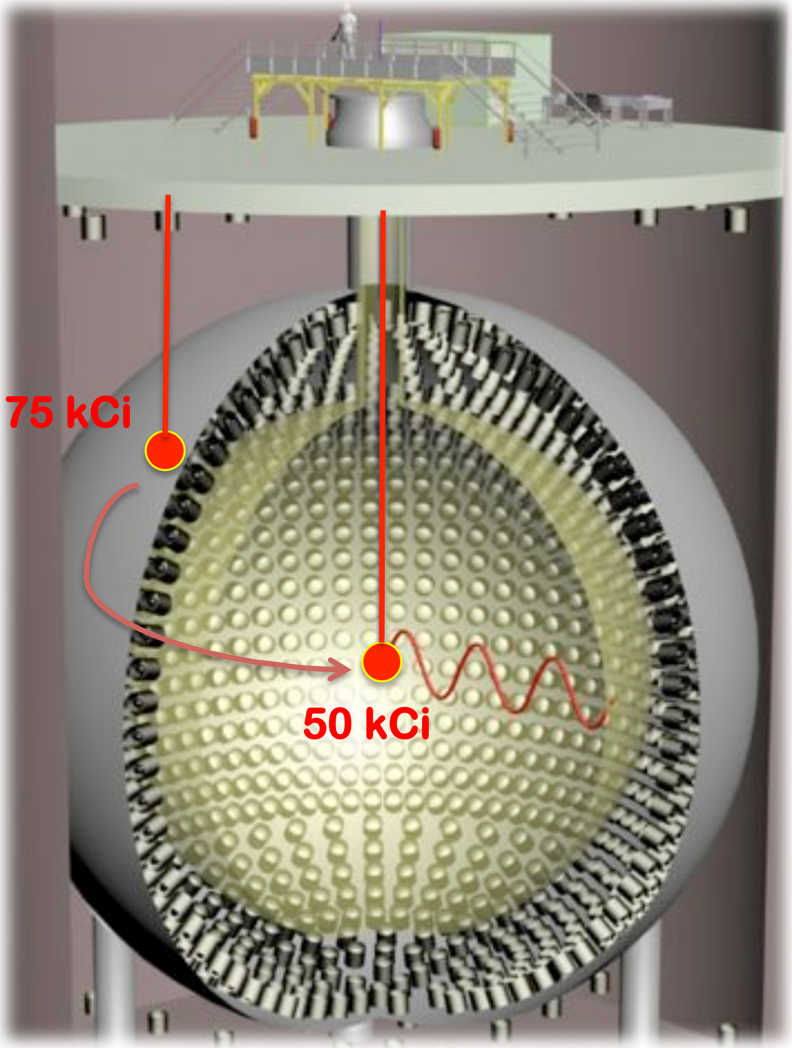
Type	Detection	Background	Source Type	Production	Activity (MCi)		Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	>10	SOX* SNO+
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
					out	5	Ricochet (NC)
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ E_{th}=1.8 MeV (e^+,n) coincidence 5% E_{res} 15cm R_{res}	reactor ν, geo ν, ν-Source → Background free Expt !	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + REE extraction	In/out	0.075	CeLAND* SOX
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

Oscillometry inside a ν-detector

- **Test ν anomalies**
- **Place the ν-emitter inside or close to existing detectors**
  - **High-Activity compact source**
  - **Very short baseline (few m)**
  - **Low Background**
- **Phase 1: 2015**

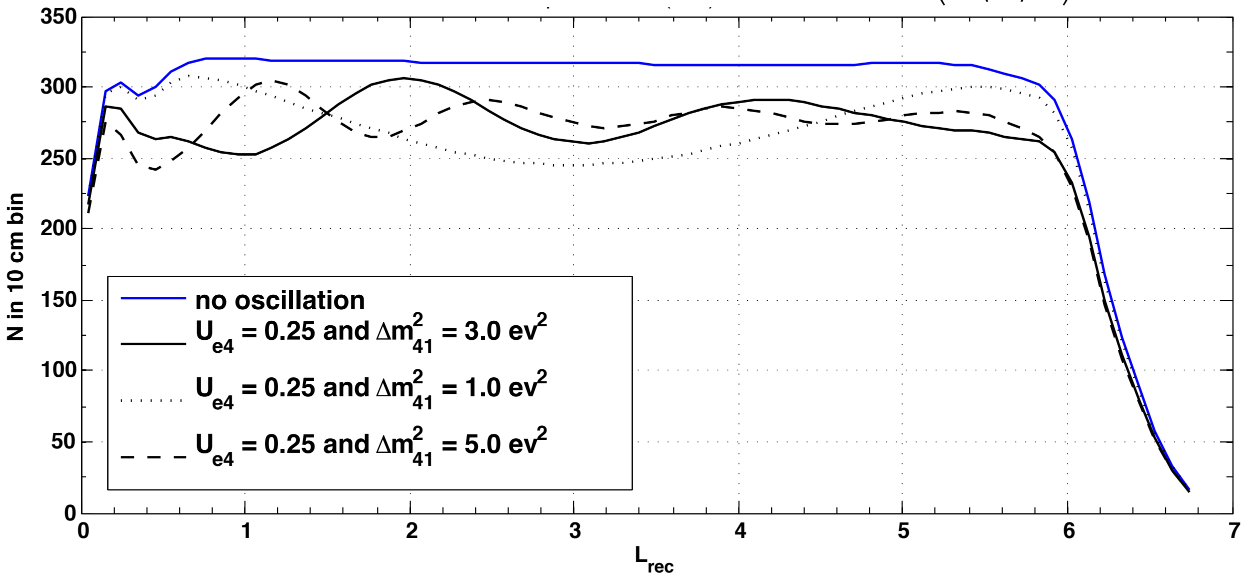
  75 kCi ν-source in KamLAND OD
- **Phase 2: 2016/7 <u>if feasible</u>**

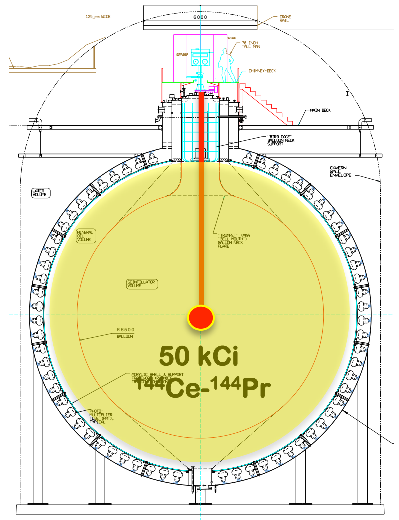
  50 kCi ν-source at center of LS

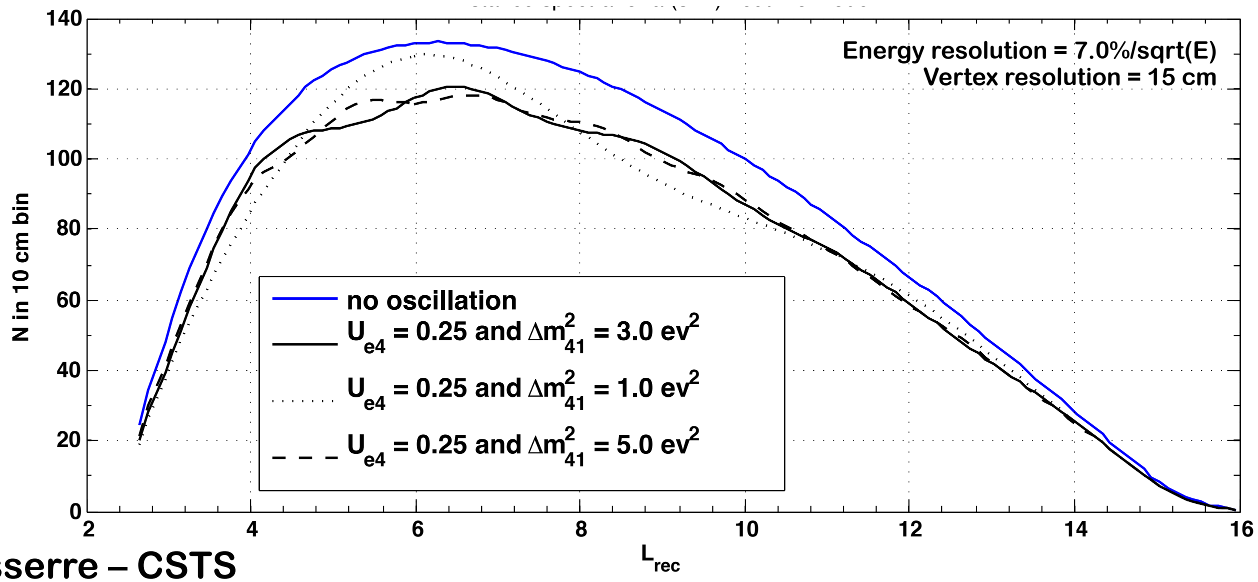


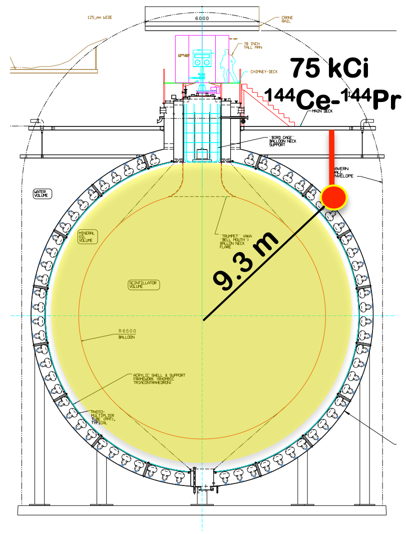
Unambiguous Proof of $\nu_e \rightarrow \nu_s$ Oscillation

$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{\cancel{4\pi R^2}} \times \langle \sigma \rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E \rangle}\right)$$







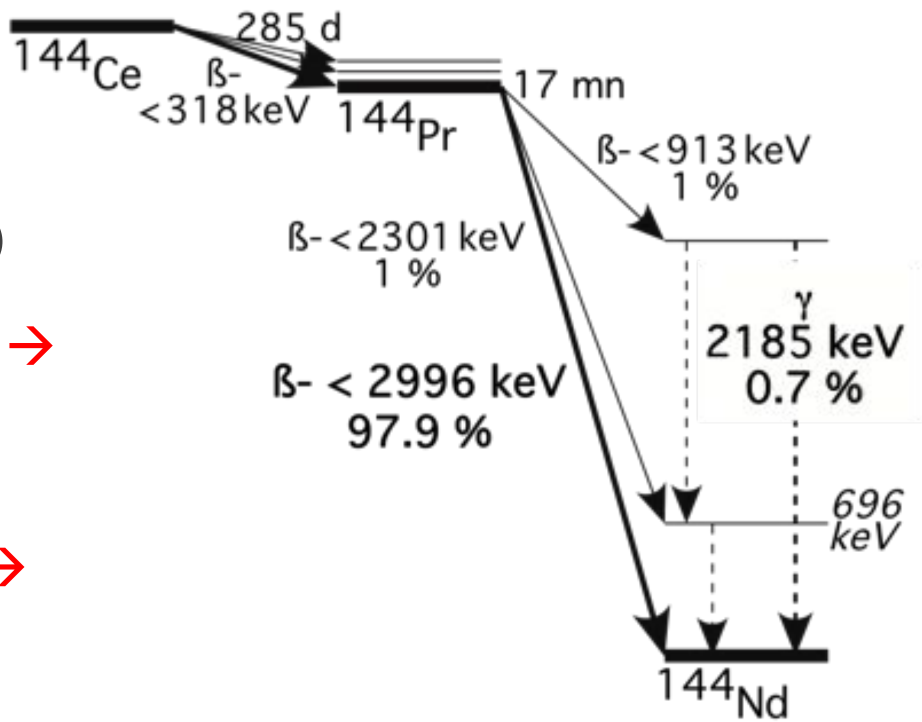


Antineutrino Source: ^{144}Ce-^{144}Pr

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

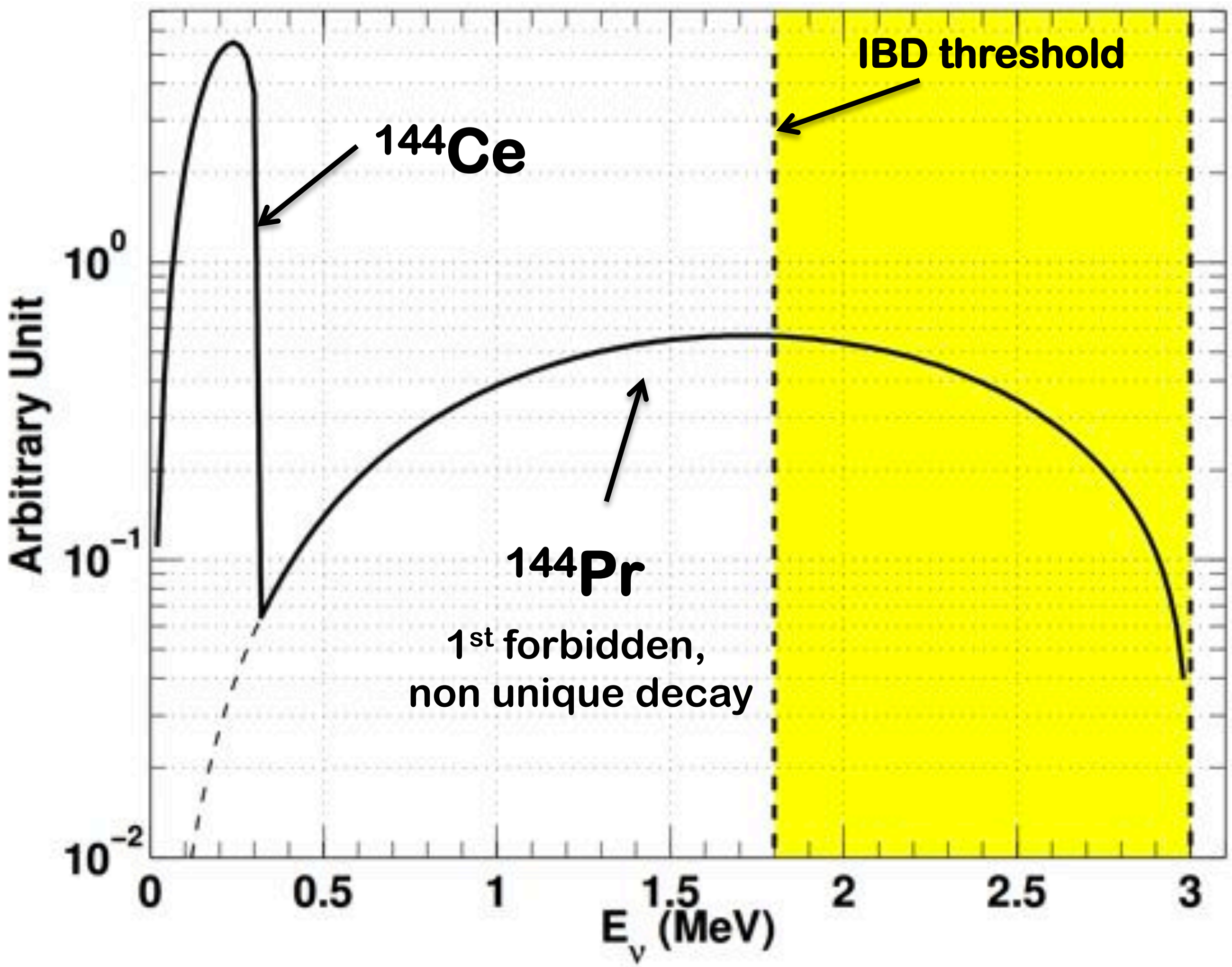
- **1st Trick: $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)**
  - **High IBD cross section → 10-100 kCi activity**
  - **(e^+,n) detected in coincidence → Background free**

- 2nd Trick: **^{144}Ce-^{144}Pr**
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β → Enough time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β → $\bar{\nu}_e$-emitter above threshold



^{144}Ce-^{144}Pr ν Spectra (Irfu / LNHB)

- **Theoretical computation of neutrino spectra ongoing**
- **Measurement in sept. 2013 with LNHB**

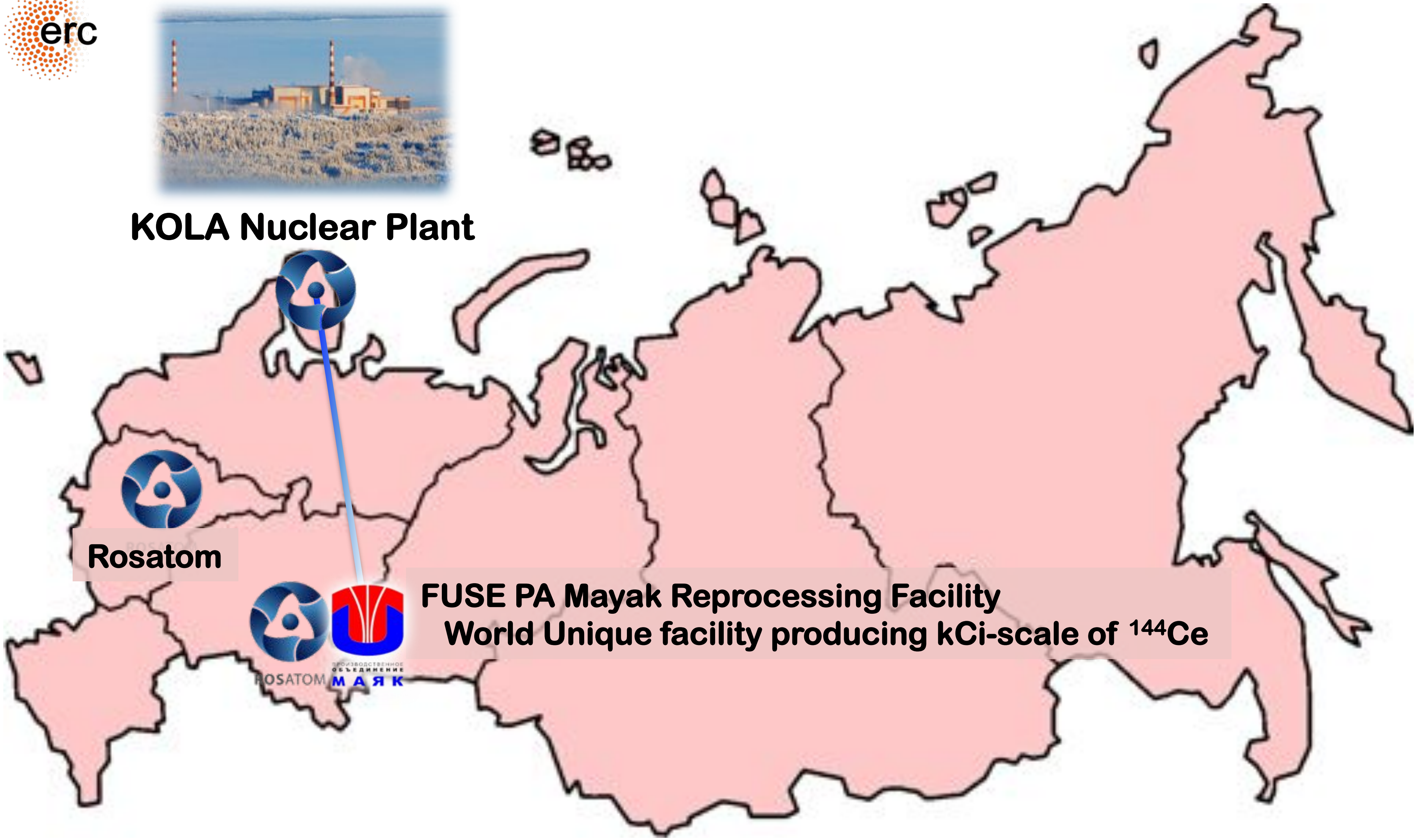


^{144}Ce-^{144}Pr Antineutrino Generator Production

^{144}Ce-^{144}Pr 75 kCi: Specifications

- ß activity at delivery
  - Between 75 kCi and 100 kCi
- Chemical form : cerium oxyde CeO_2
- Density : between 4 and 5 g/cm^3
- Fitting inside a D:H=18 cm : 18 cm cylinder
  - Fuel less than 4 y old at the end of the production
- Insertion of source inside a high-Z shield at Mayak
- Purity data from ^{147}Pm production line (TBC for ^{144}Ce)
  - Content of any others RE (γ*-emitters*) in *Ce* $\leq 10^{-9}$ Ci/Ci
  - Content of Pu and TPE (*n emitters*) in Ce $\leq 10^{-10}$ Ci/Ci

Russian Institutions & Facilities



Technico-financial issues being discussed with Rosatom & PA Mayak

Spent Nuclear Fuel (Mayak / Irfu / Mephi)

- Cerium : 5.5% / 3.7% in the fission products of U / Pu
- ^{144}Ce decays with a half-life of 411 days. 3 years after last irradiation m(^{144}Ce)/m(Ce) = 1 / 128
- Selection of SNFE in Cola NPP
- Delivery of SNF from Cola NPP to FSUE "Mayak" PA (3000 km)
  - TUK-6 container →
- PA Mayak made preliminary arrangement to receive fresh fuel for ^{144}Ce prod. early 2014

Overview of the process (Mayak / Irfu)

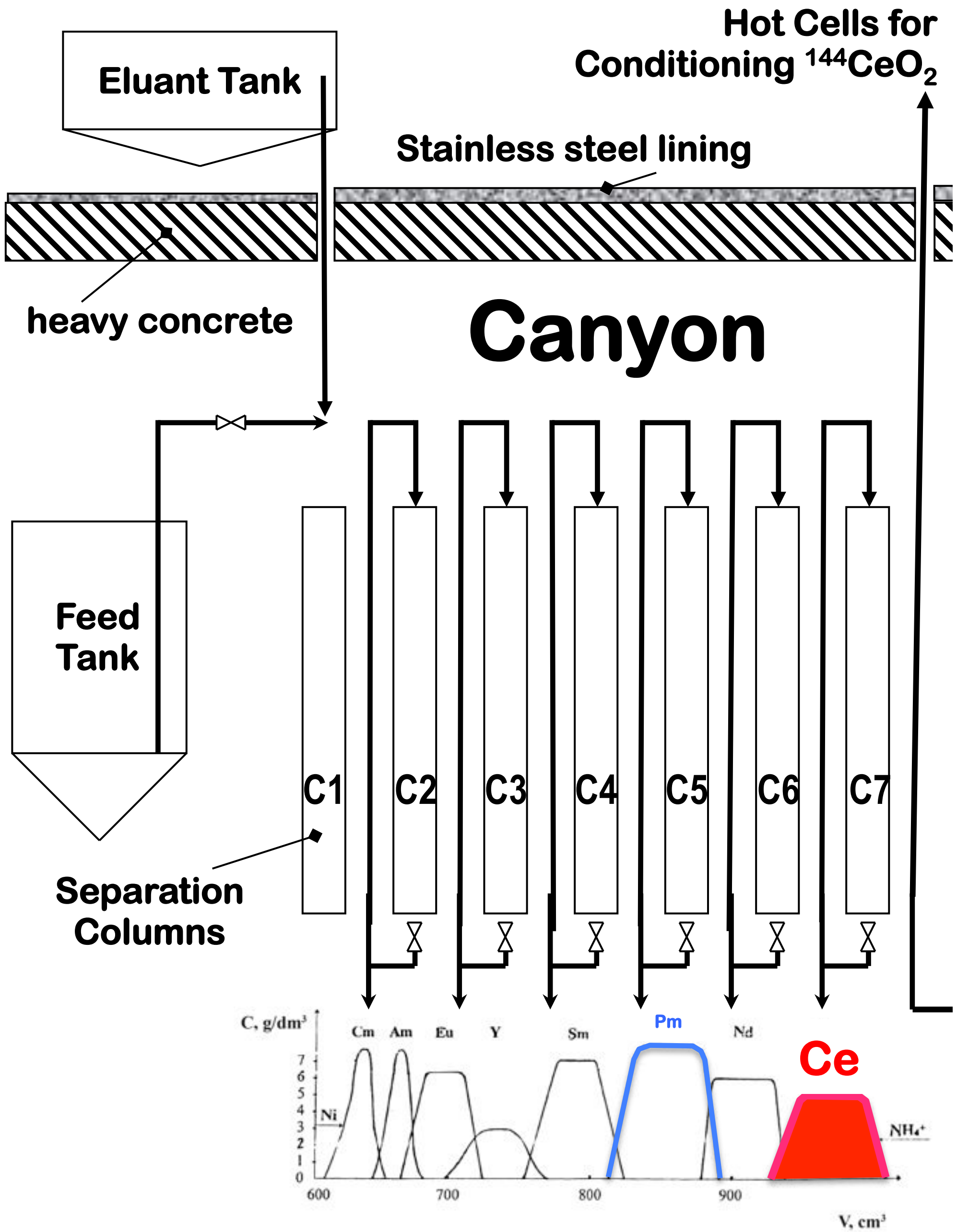
- Radiochemical Plant
  - Standard radiochemical re-processing of SNF
  - Separation of CeO_2
  - Primary encapsulation
  - Activity measurement (3%)

- Radioisotope Plant
  - Source manufacture
  - Certification ISO 9978
  - Loading into W-shield
  - Loading into container

- Dedicated upgrade of Mayak facilities for Ce prod. defined

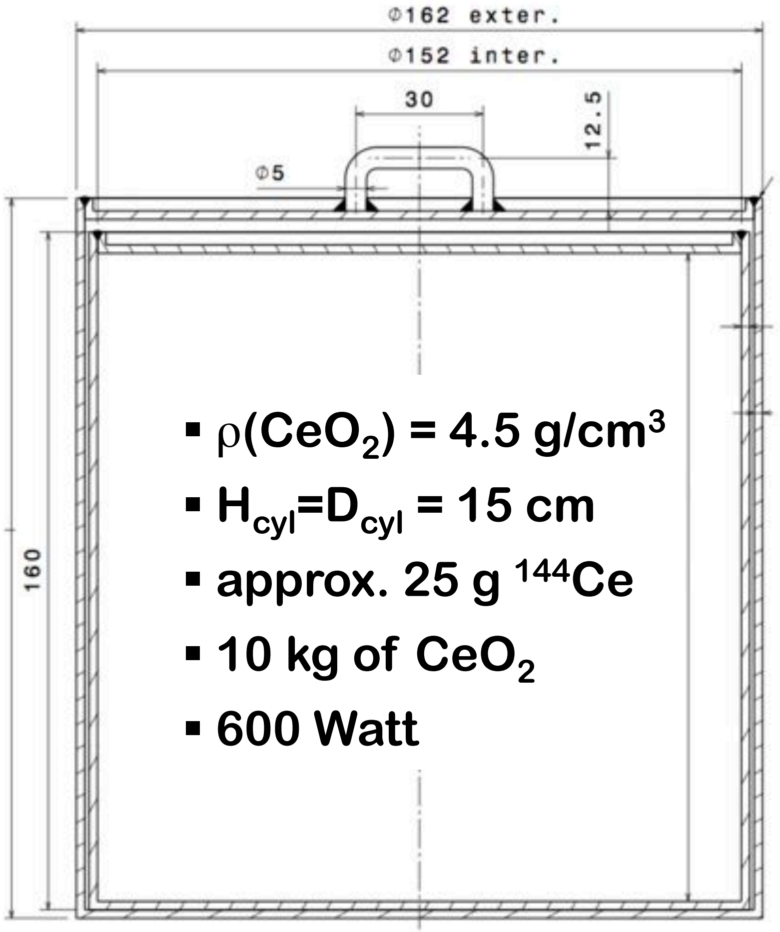
Extraction of Cerium Solution

- Complexing agent displacement chromatography for Reare Earth elements (REE)
- VVR-440 Spent Nuclear Fuel:
  - PA Mayak: 100 t SNF/y
  - 1 ton SNF:
    - 13 kg REE
    - 22 g ^{144}Ce (3 y, 70 kCi)
- Production (3-4 y old SNF)
  - <3 tons of SNF needed
  - But 10 ton special production for Ce & Pm
  - 4-6 months (mid-2014)



^{144}Ce-^{144}Pr: capsule (Irfu / X / Mayak)

Mechanical design

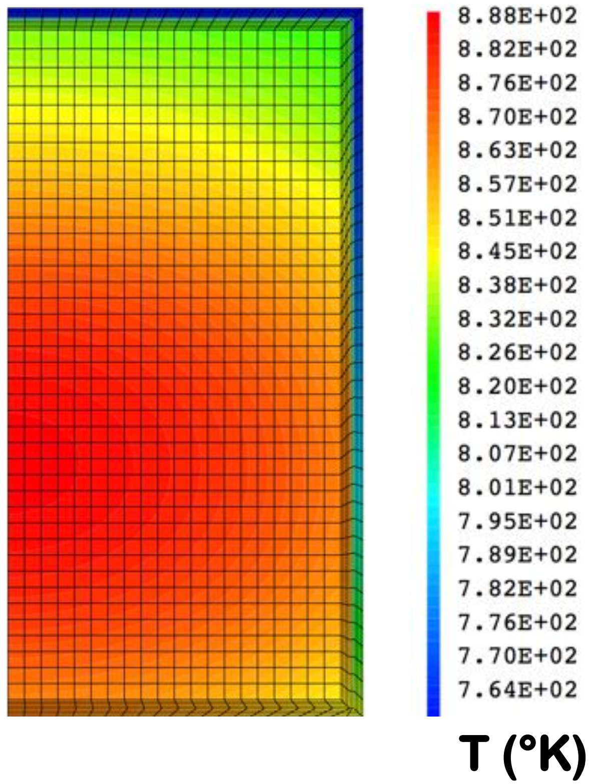


- $\rho(CeO_2)$ = 4.5 g/cm^3
- $H_{cyl}=D_{cyl}$ = 15 cm
- approx. 25 g ^{144}Ce
- 10 kg of CeO_2
- 600 Watt

Final capsule designed by PA Mayak as special form of radioactive material (ISO 9978)

Thermal study

Conduction + Convection
No radiation loss



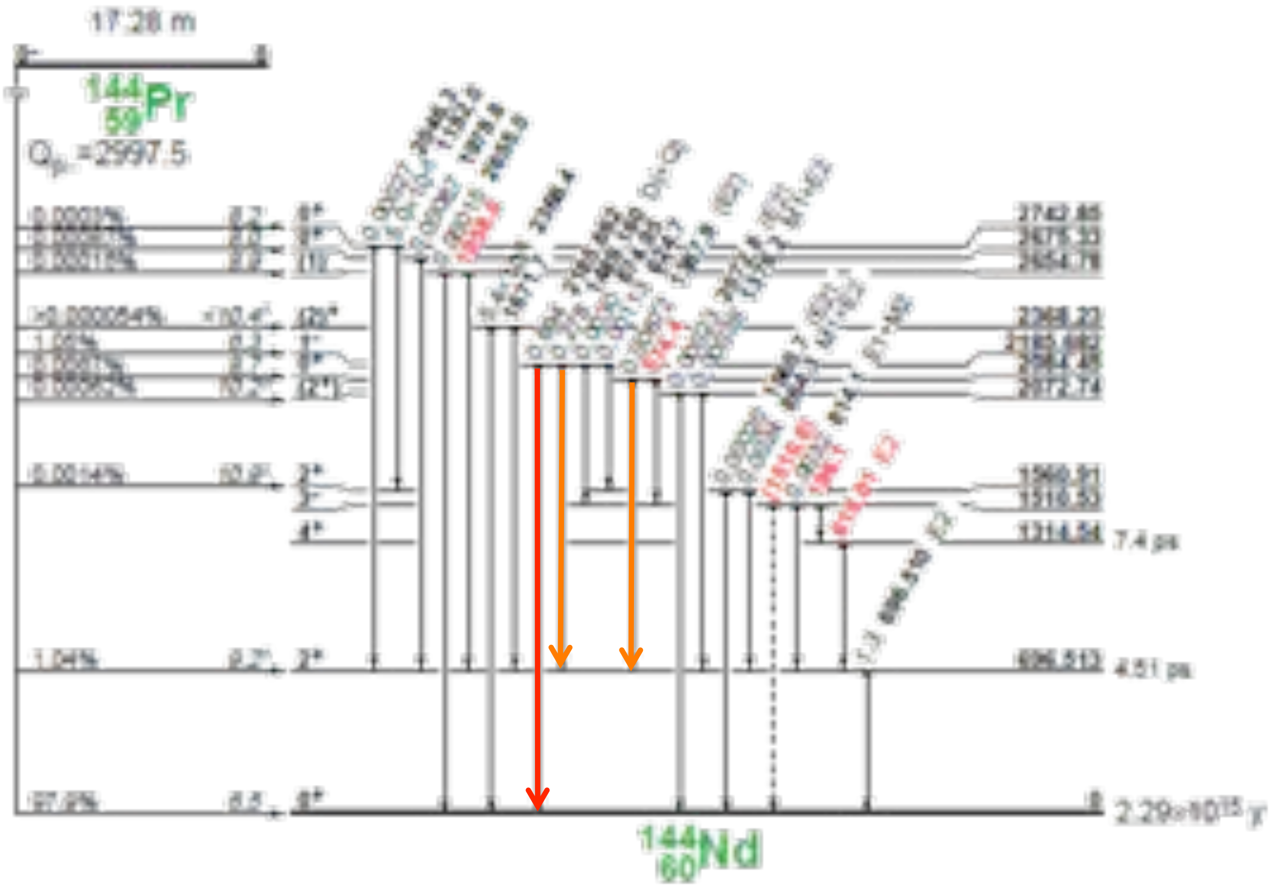
600 °C
550 °C
500 °C

Stainess Steel suitable

High-Z Shielding

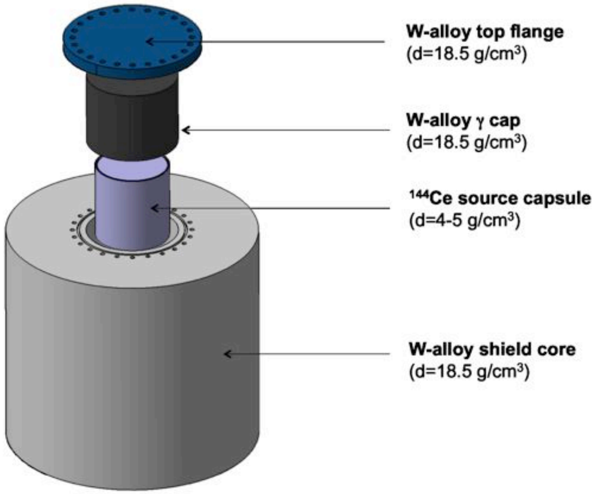
Gamma Backgrounds of ^{144}Ce-^{144}Pr

- γ rays produced by the decay through excited states of ^{144}Pr
  - Intensity γ >1 MeV
    - 1380 keV – 0.007 %
    - 1489 keV – 0.3 %
  - Intensity γ >2 MeV
    - 2185 keV – 0.7 %
      (10^{10} γ/sec for 50 kCi)



CeLAND: high-Z Shielding

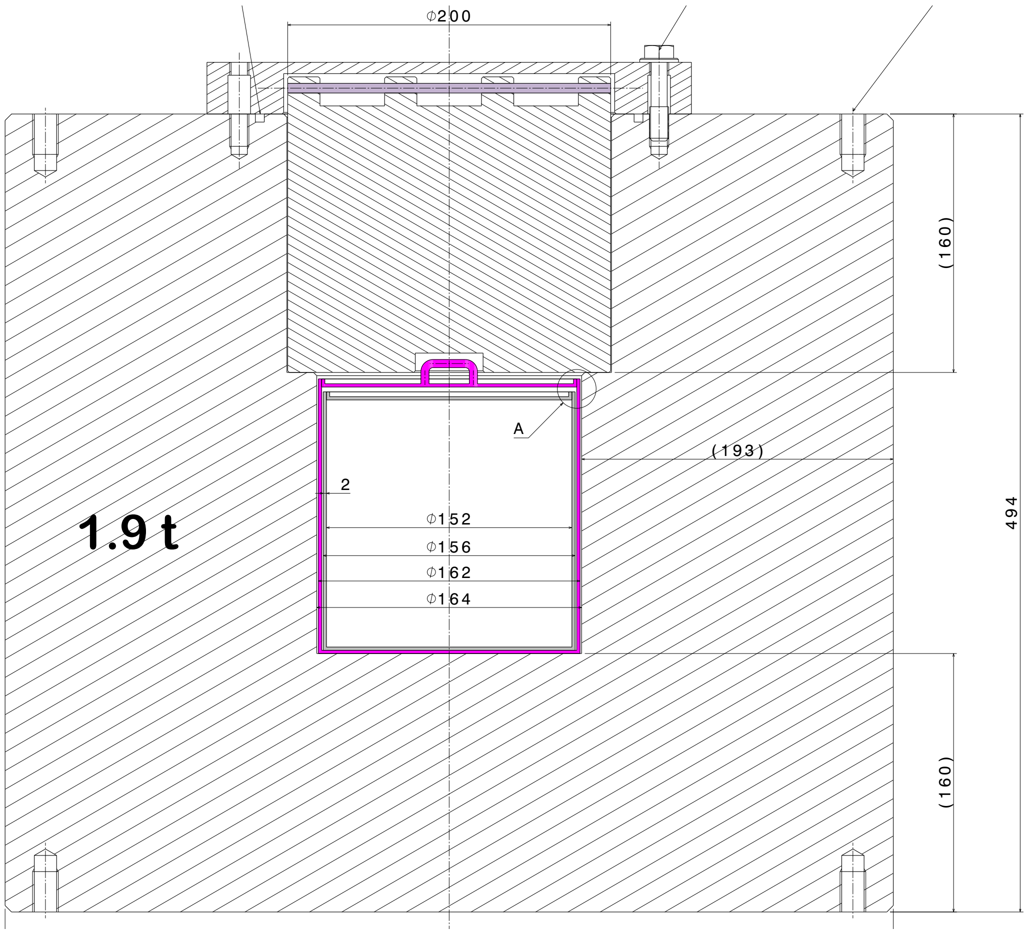
- **Absorption of the 2.18 MeV γ's**
  - Suitable for the transportation
    - Few cm of tungsten-alloy
  - Usual biological protection
    - ≈ 15 cm of tungsten-alloy
  - Suitable fordeployment in KamLAND
    - ≈ 20 cm of tungsten-alloy towards the detector solid angle



- **Material selected**
  - Tungsten alloy (18.5 g/cm³ for machining)
  - 4 companies identified (Plansee, Polema, Starck, Xiamen)
    - Price quotation available
    - Manufacturing time: few months
  - Radiopurity measurement campaign ongoing

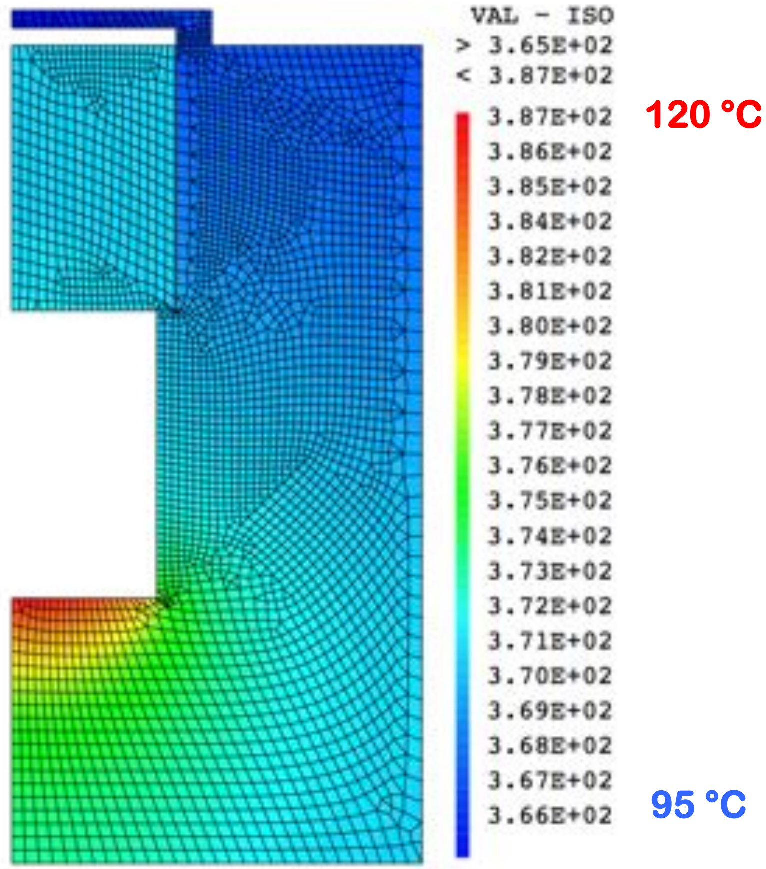
W-Shielding (Irfu / X / DEN / SPR)

Mechanical design (for handling in hot cell)



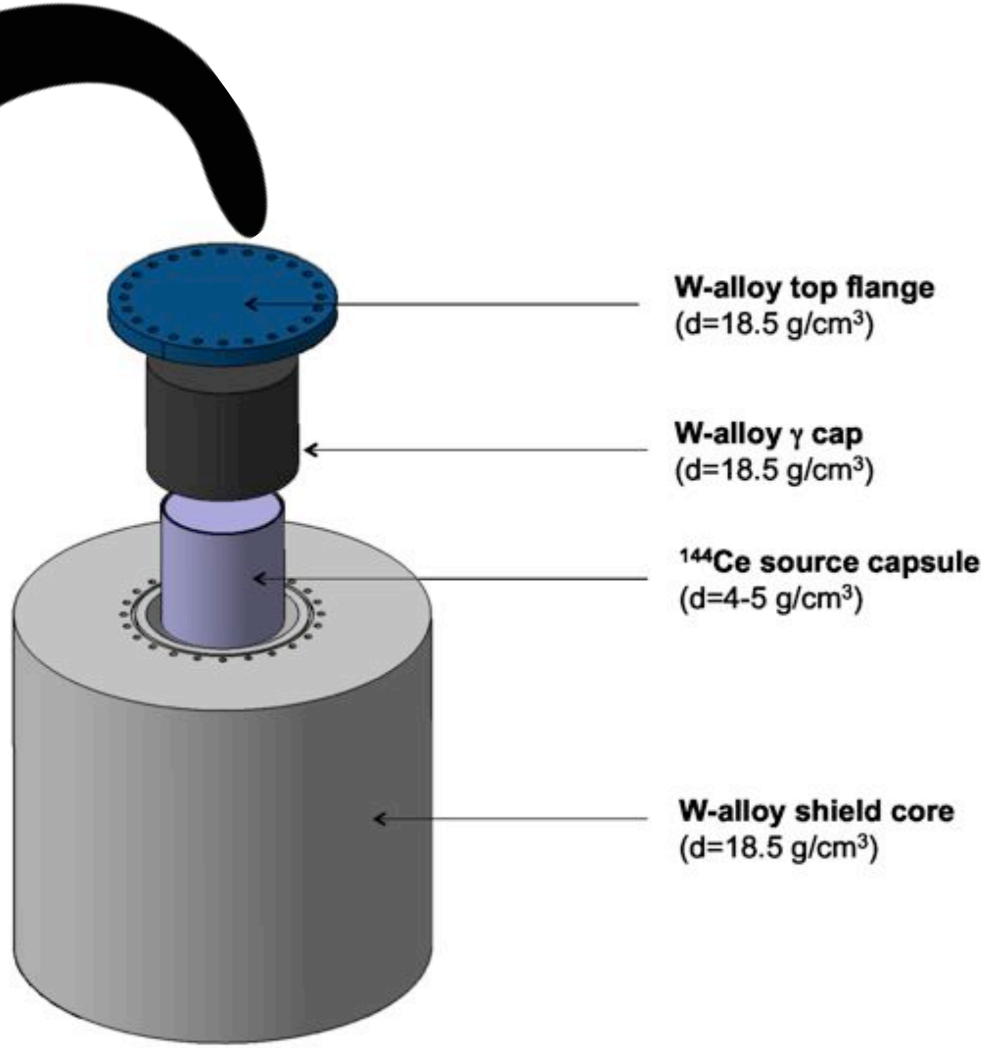
CEA-SPR (MCNP) & GEANT4 - 16 cm W
Radiation dose @1m: 50 μ Sv/h

Thermal study



$T_{shield\ ext} = T_{ext}$ (38°C) + 60 °C

Source insertion into W-shield

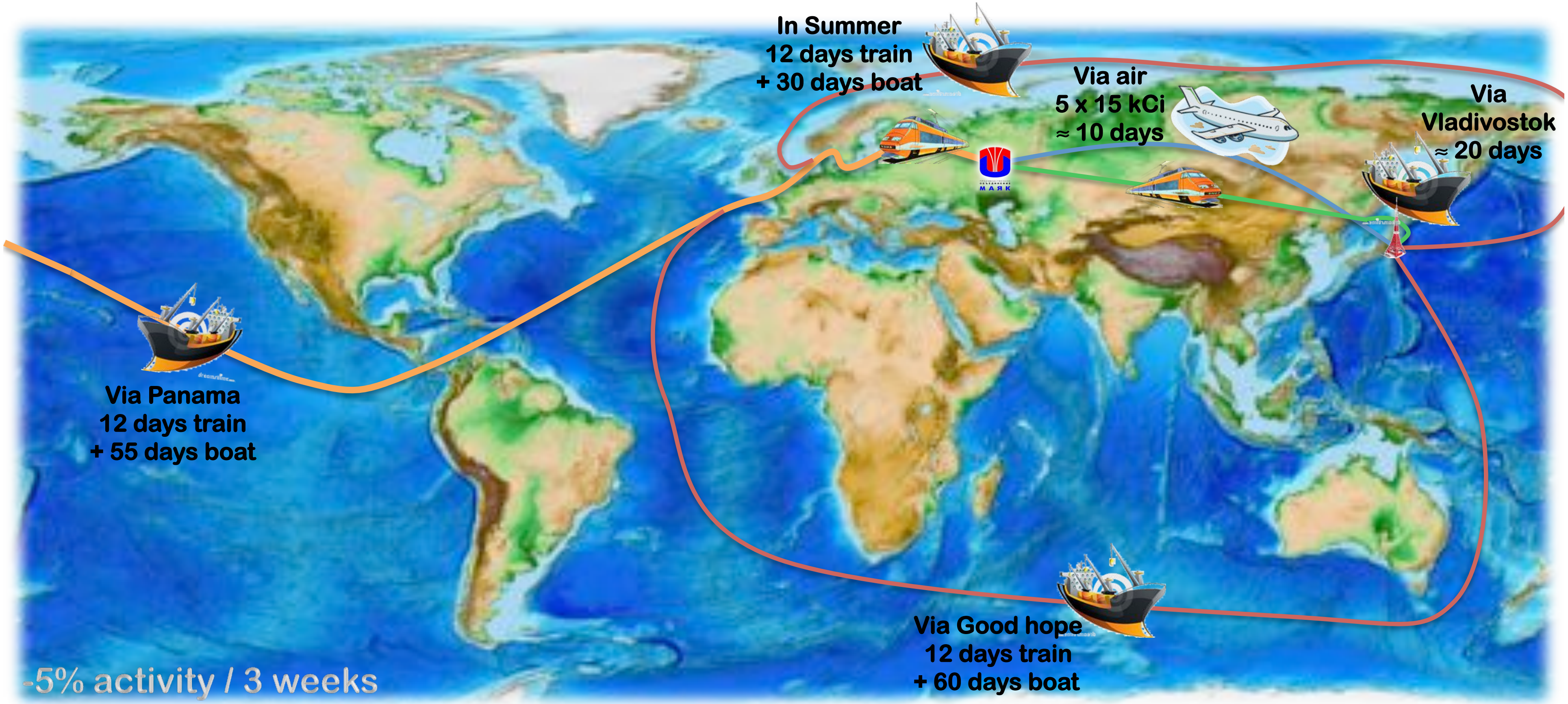


To handle inside hot cell at Mayak
Need prevent risk of contamination

^{144}Ce-^{144}Pr Antineutrino generator transportation

Transport Routes (Irfu / Areva / DOE)

IAEA Regulations for the Safe Transport of Radioactive Material
Pre-study conducted together with Areva & DOE/Oakridge



Option 1) 1 x 75 kCi – train to Russian East coast – days boast – 3 weeks
Option 2) 5 x 15 kCi – plane to japan – 10 days
Option 3) 1 x 75 kCi – train to St Petersburg – Boat via Panama – 10 weeks

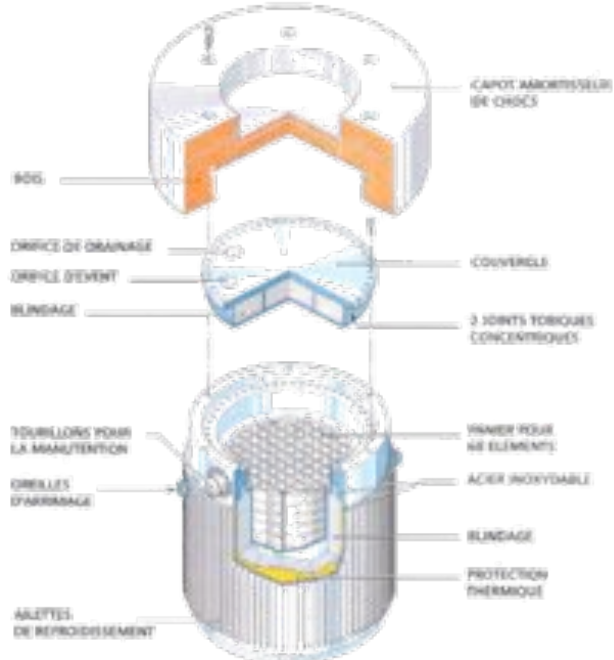
Transport Route to KamLAND

From Japanese harbor to Atotsu mine by truck

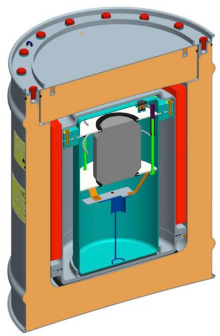
Notify Prefectual Public Safety Commission

Transport Container

- Type: B(U)
  - Train/Boat/Truck: 1 x 75 kCi
  - Plane : 5 x 15 kCi
- Need certification in
  - Japan
  - Russia (Europe)
- Need to design/certify the basket holding the source
- To be handled in Atsotu mine
- Contacts:
  - CEA/DEN
  - Areva / TNI
  - Atox (Japan)
  - DOE (Oakridge)
- No suitable solution yet



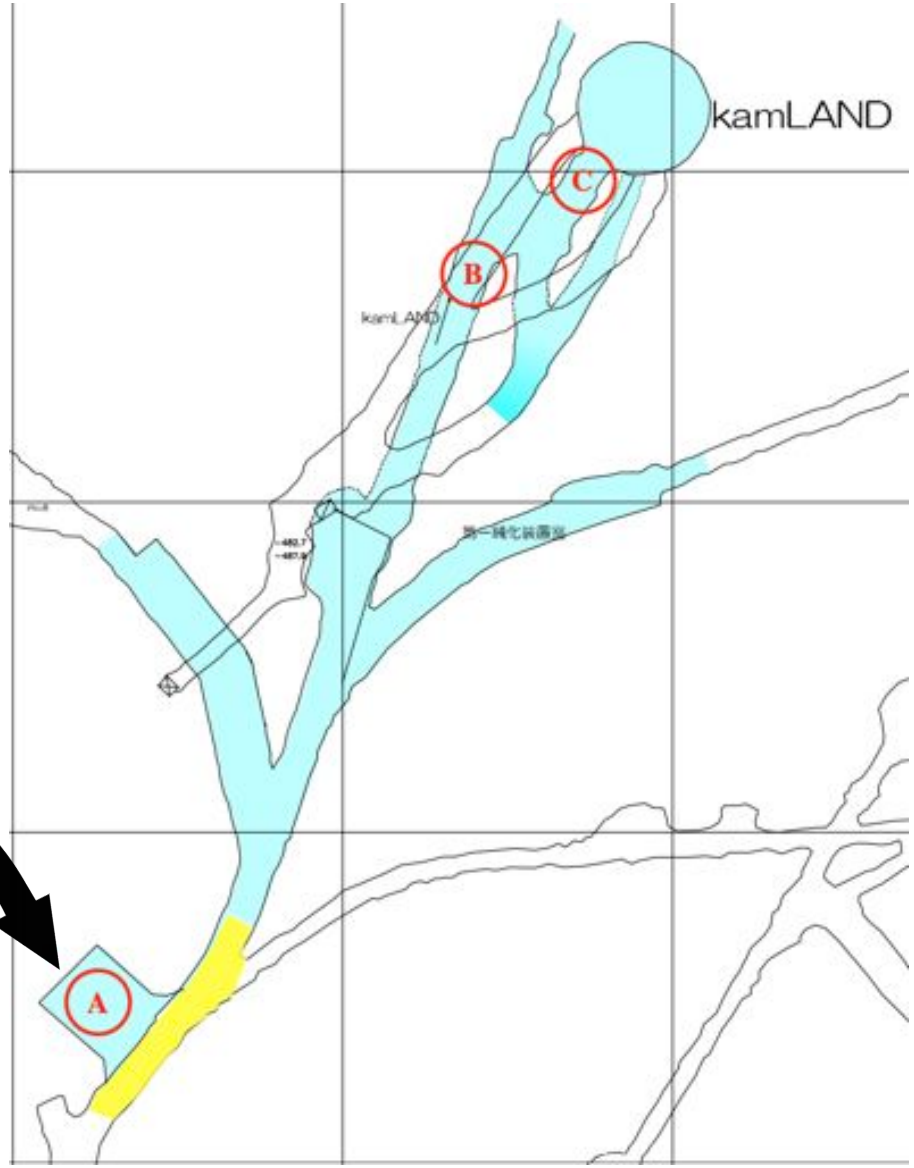
TN – TM – MTR – 23 t (EU / US)


MD-2 – 1 t (US)

JMS – 18 t (JP / Europe / US)

Unloading & handling in KamLAND

- Unloading area found (A)
- Definition of a temporary radiation controlled area
- Handling: Nippon Express
- Measurement of Activity

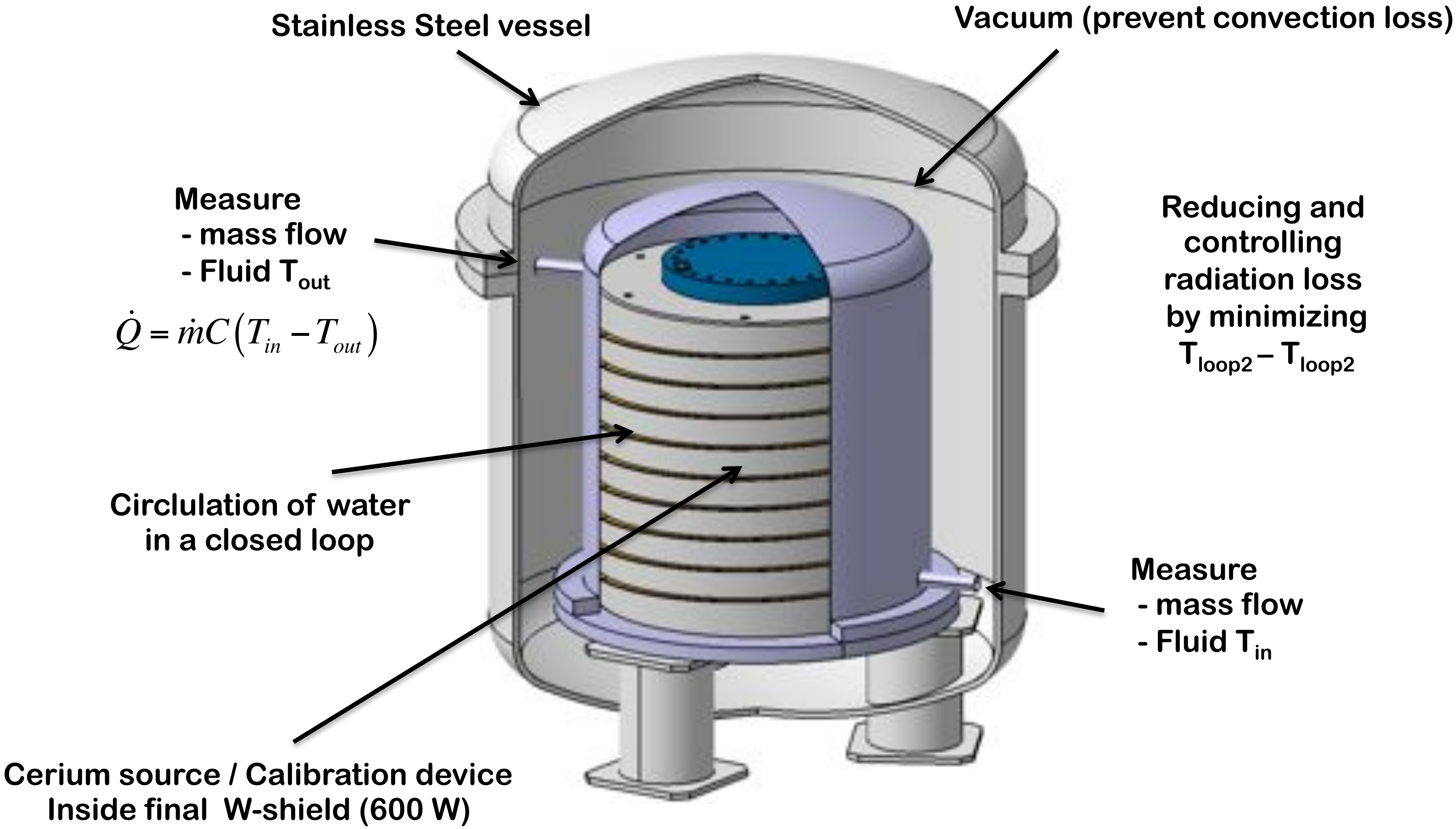


Neutrino Activity Measurement

^{144}Ce-^{144}Pr Source Calorimetry

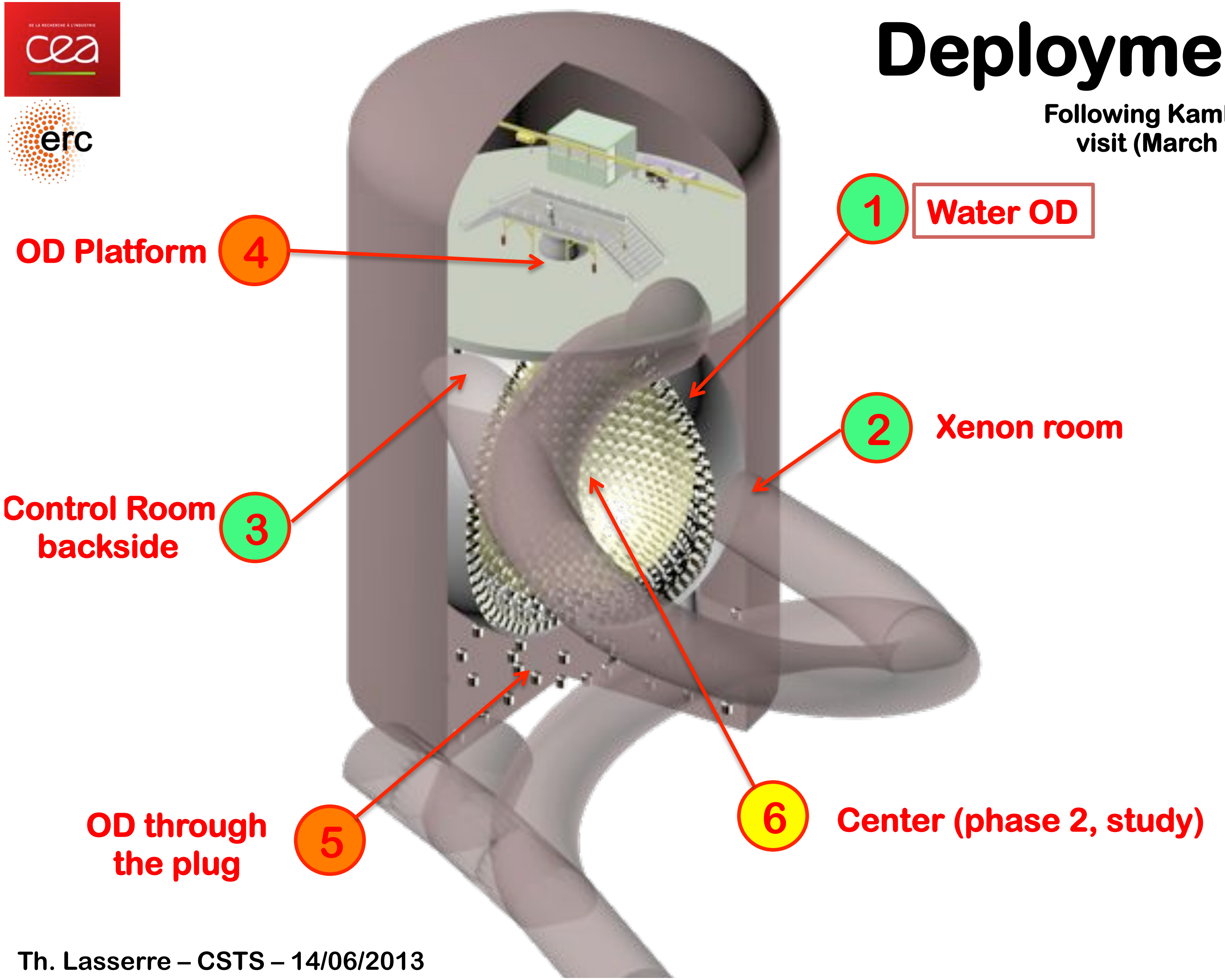
- **Source Heat Release**
  - **96% from β-decays - 75 kCi → 600 W released**
- **Specification**
  - **Few days measurement**
  - **Precision <1.5% (Achieved for Gallex & Sage)**
  - **Realization of a calorimeter (Irfu / DEN / APC? / SOX ERC?)**
- **Concept**
  - **Calibration phase in Saclay (2014)**
    - **With final W-shielding, fake-source (known elec. Power)**
  - **Measurement in the Atsotu mine**
    - **Before (600 W) and after the deployment (100 W)**

Calorimeter (Irfu / DEN / X)



Deployment

Following KamLAND
visit (March 2013)



Deployment in KamLAND Phase 1

Deployment - phase 1

- **1) Deployment in OD through the platform man-hole (9.3 m)**
  - **Hanged from a new supporting crane using existing anchors**
  - **Engineering by Mitsui Company ongoing (KamLAND Tank builder)**
- **2) Deployment in Xenon storage room (12.0 m)**

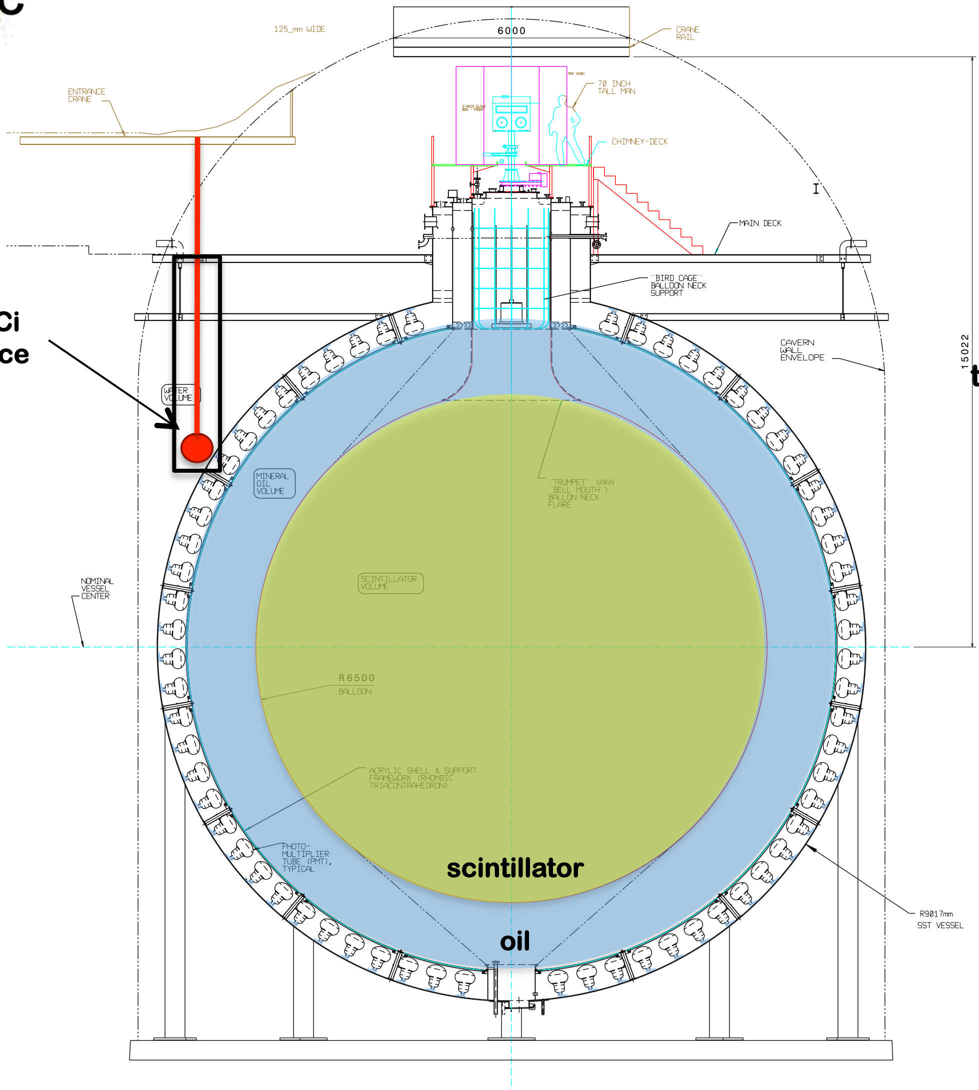
20 000 events in 1.5 y

14 000 events in 1.5 y

In both cases, run in parallel with KamLAND-Zen ($\beta\beta0\nu$)

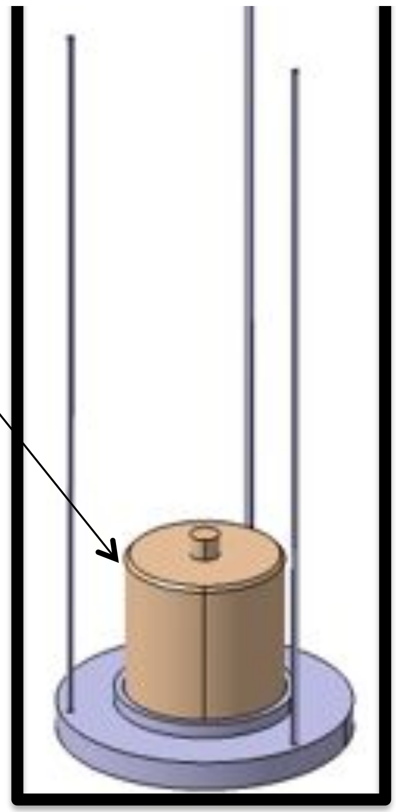
CELAND Phase 1 (goal: 2015)

75 kCi
Source



Source @2.5 m away from LS
75 kCi & 6-18 months of data taking

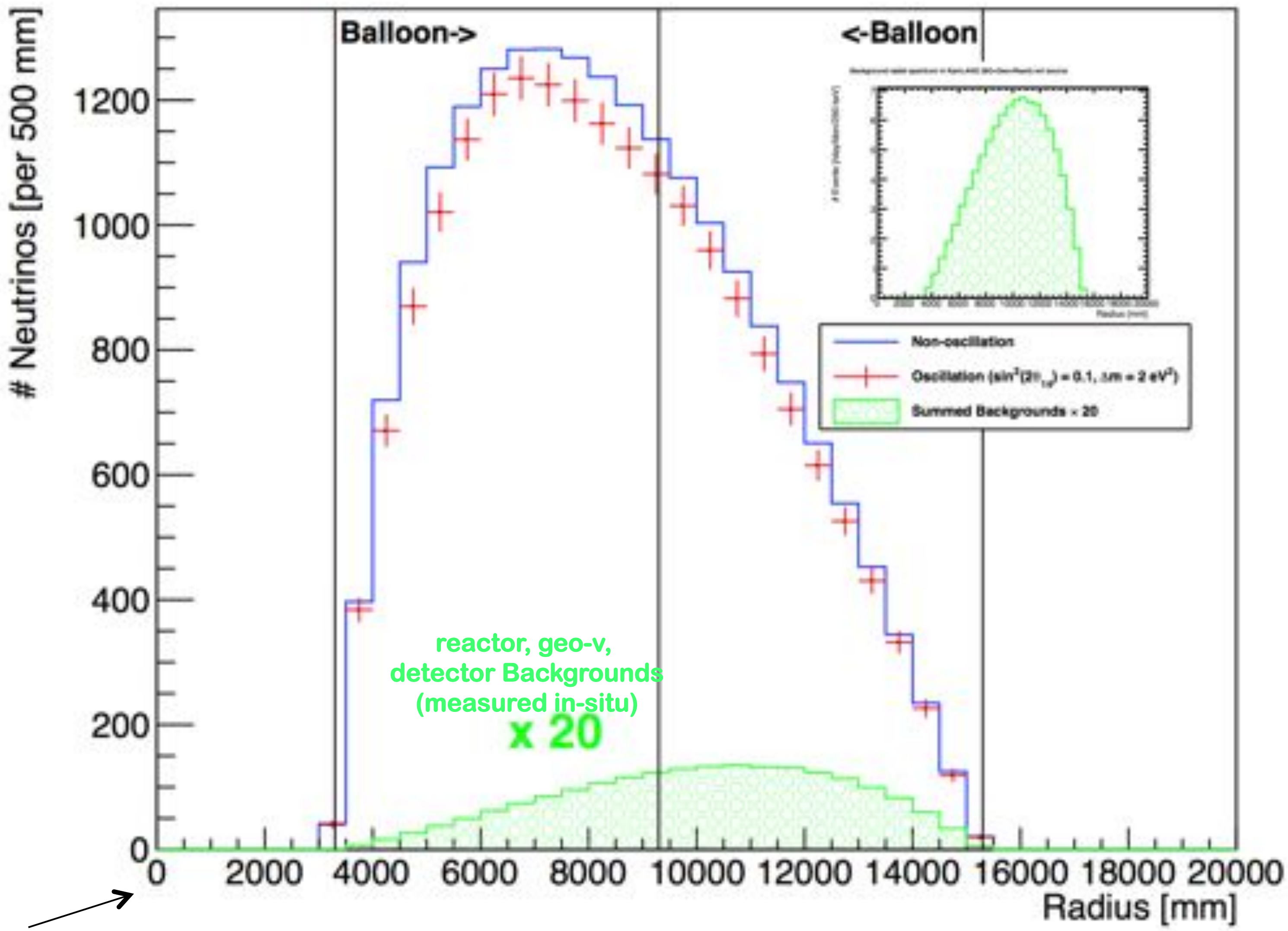
tungsten alloy,
54 cm
d=18.5 g/cm^3



- **SS basket to isolate the source from the OD Water (no contamination risk)**

CeLAND phase 1: signal & background

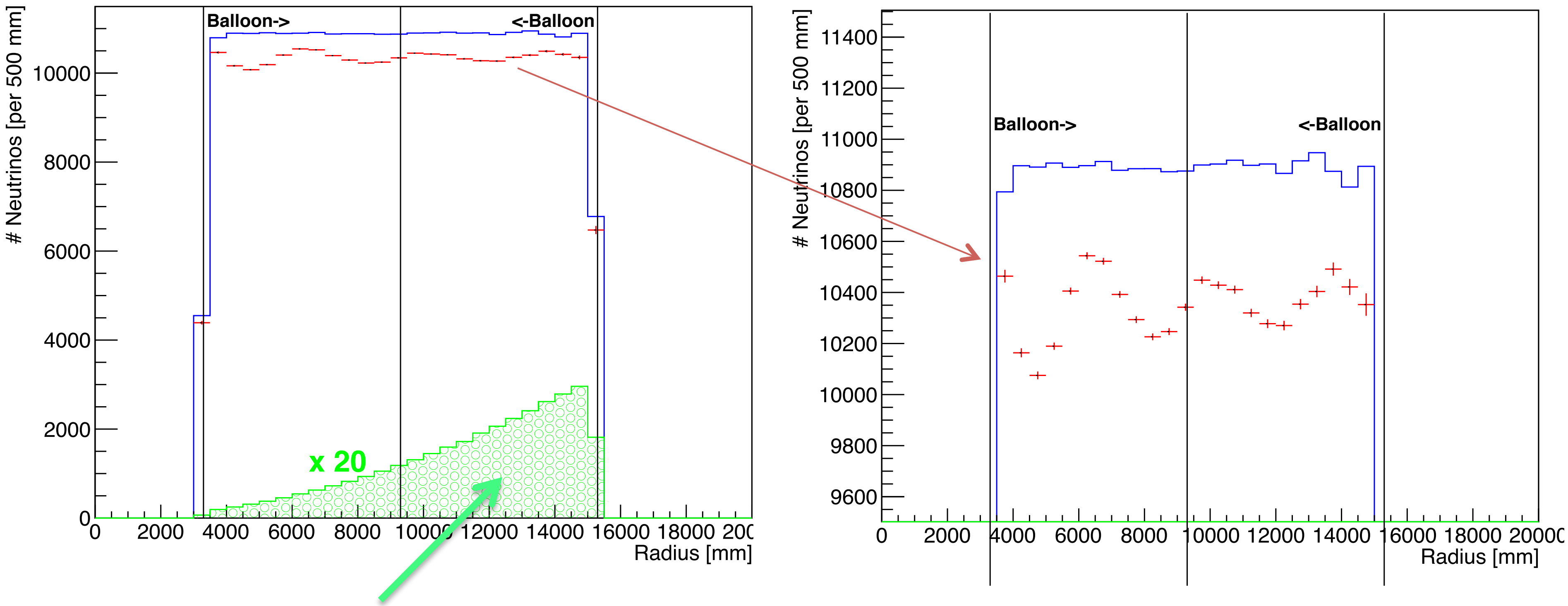
1.5 y - 20 000 interactions – full KamLAND Geant4 simulation



75 kCi ^{144}Ce-^{144}Pr antineutrino generator

CeLAND phase 1: R-oscillation

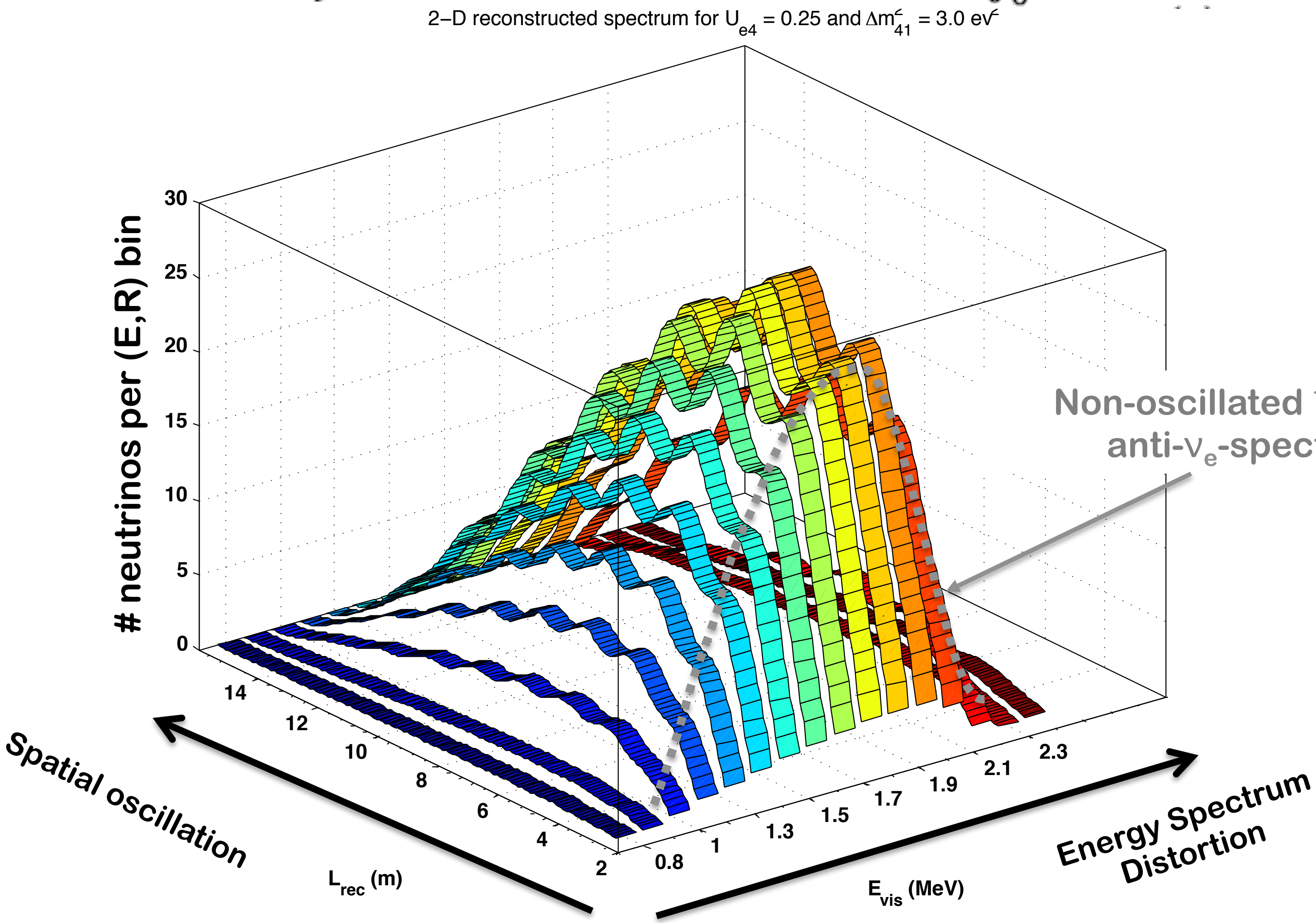
- **Geant4 simulation of a source in Water Veto:**
  - 75 kCi ^{144}Ce-^{144}Pr source running for 12 months in KamLAND
  - No-oscillation: 20 000 evts
  - Oscillation $\Delta m^2=2\ eV^2$ & $\sin^2(2\theta_{new})=0.1$



KamLAND detector backgrounds

CeLAND phase 1 : R & L signals

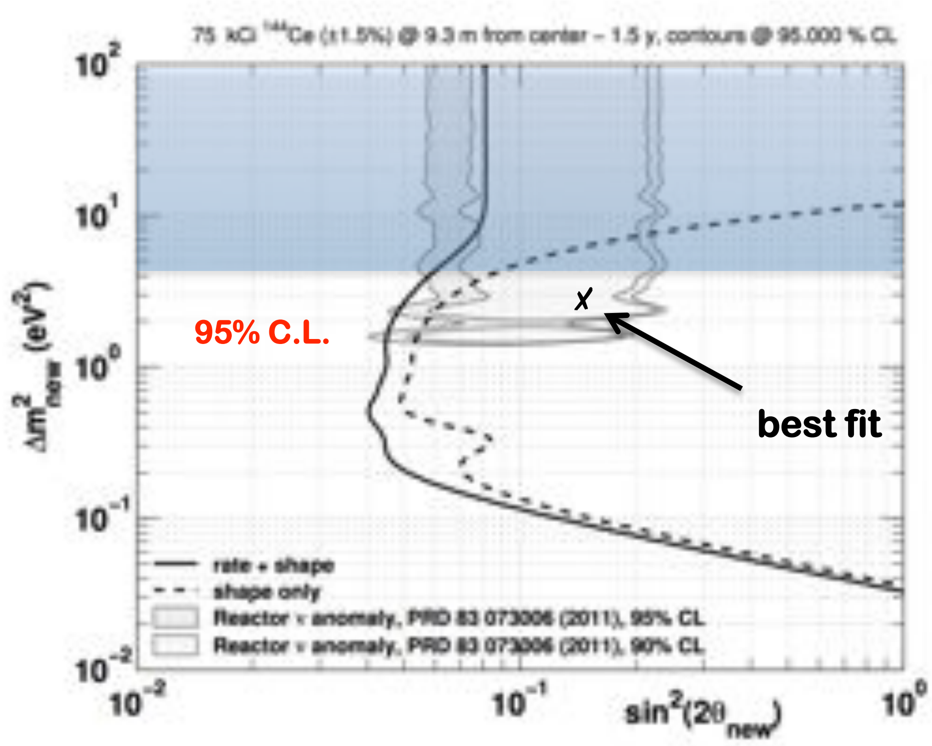
$$\frac{d^2N(R,E_\nu)}{dRdE_\nu} = \mathcal{A}_0 \cdot n \cdot \sigma(E_\nu) \cdot \mathcal{S}(E_\nu) \cdot \mathcal{P}(R,E_\nu) \int_0^{t_e} e^{-t/\tau} dt,$$



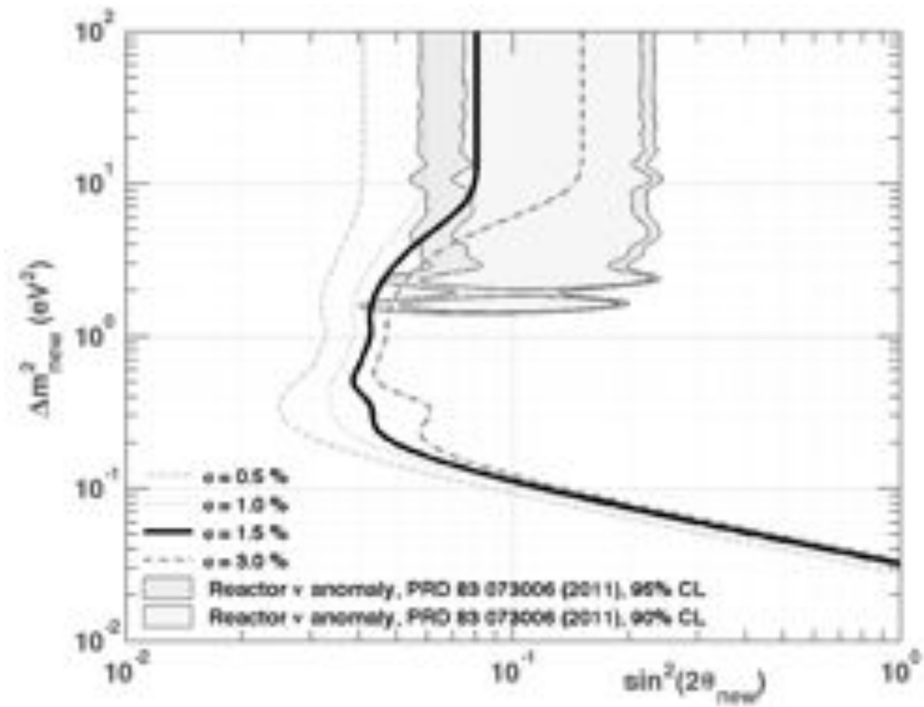
CeLAND phase 1 : sensitivity

75 kCi ^{144}Ce-^{144}Pr – 9.3 m from detector center

1.5 year of data



Impact of Activity calibration

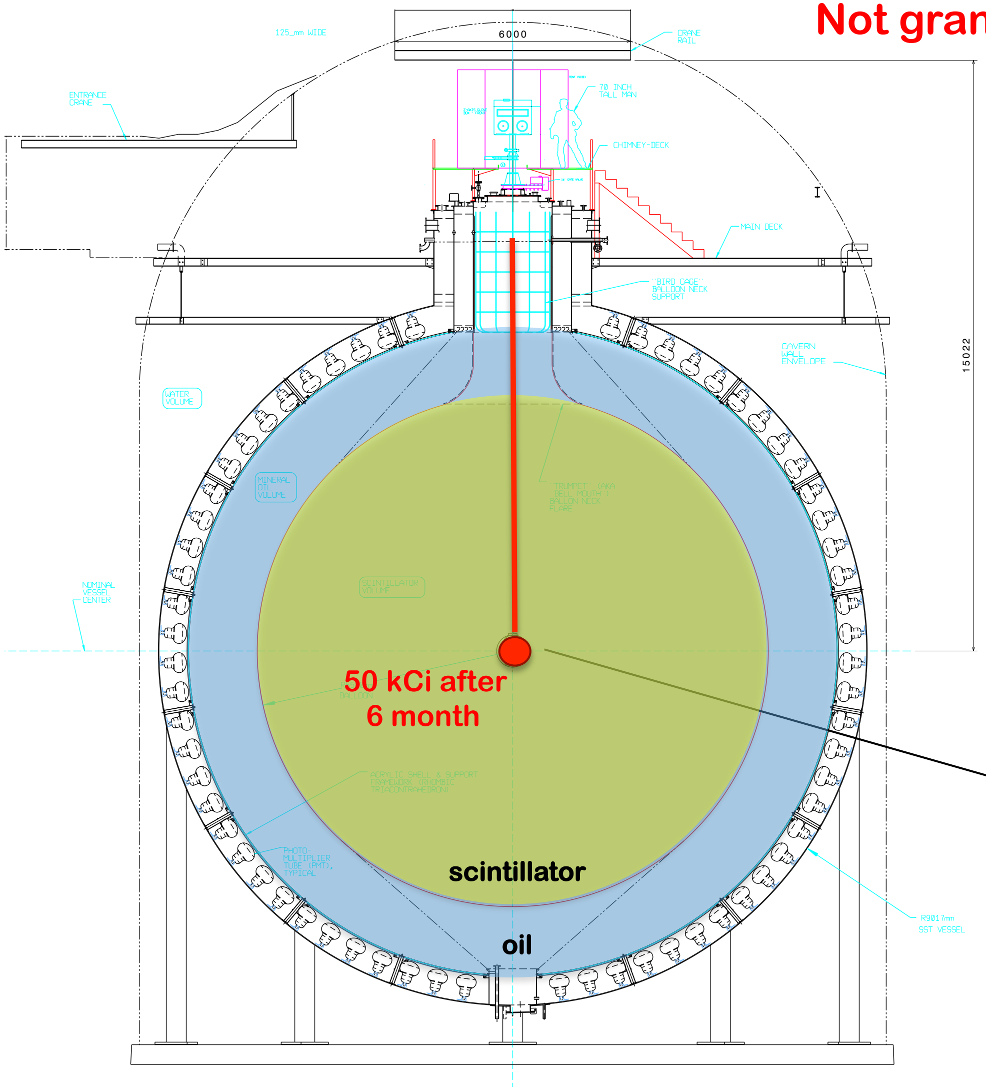


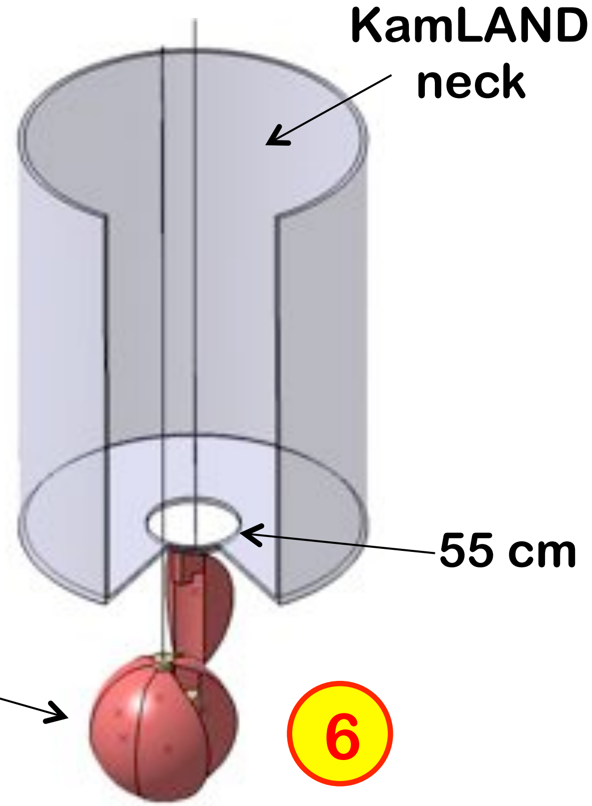
Deployment in KamLAND
Phase 2

CELAND Phase 2: 2016 (under study)

If hint of oscillation: relocate the 75 kCi source after 6 months

Not granted! Technically challenging



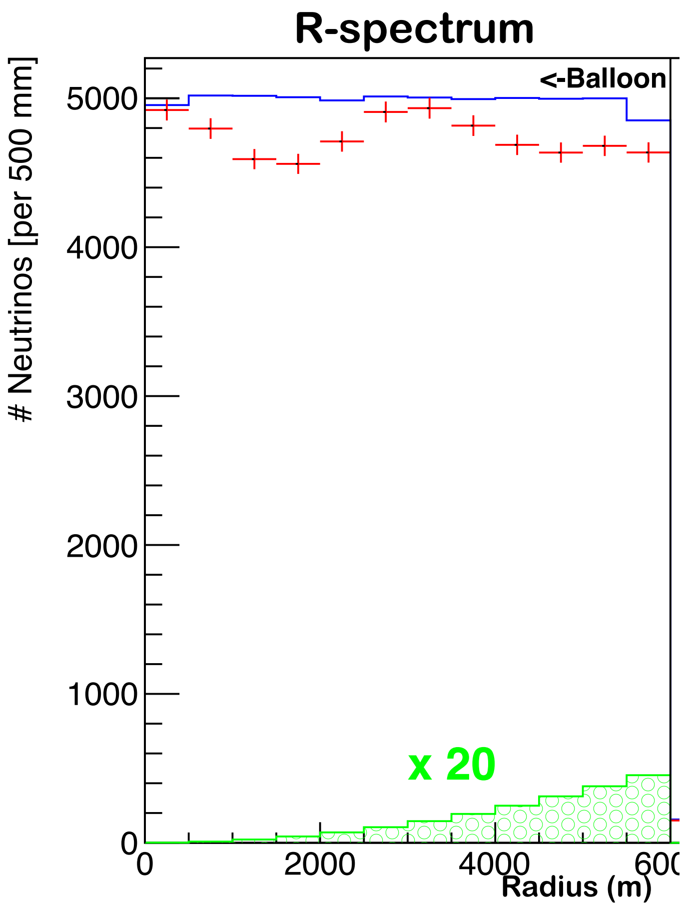


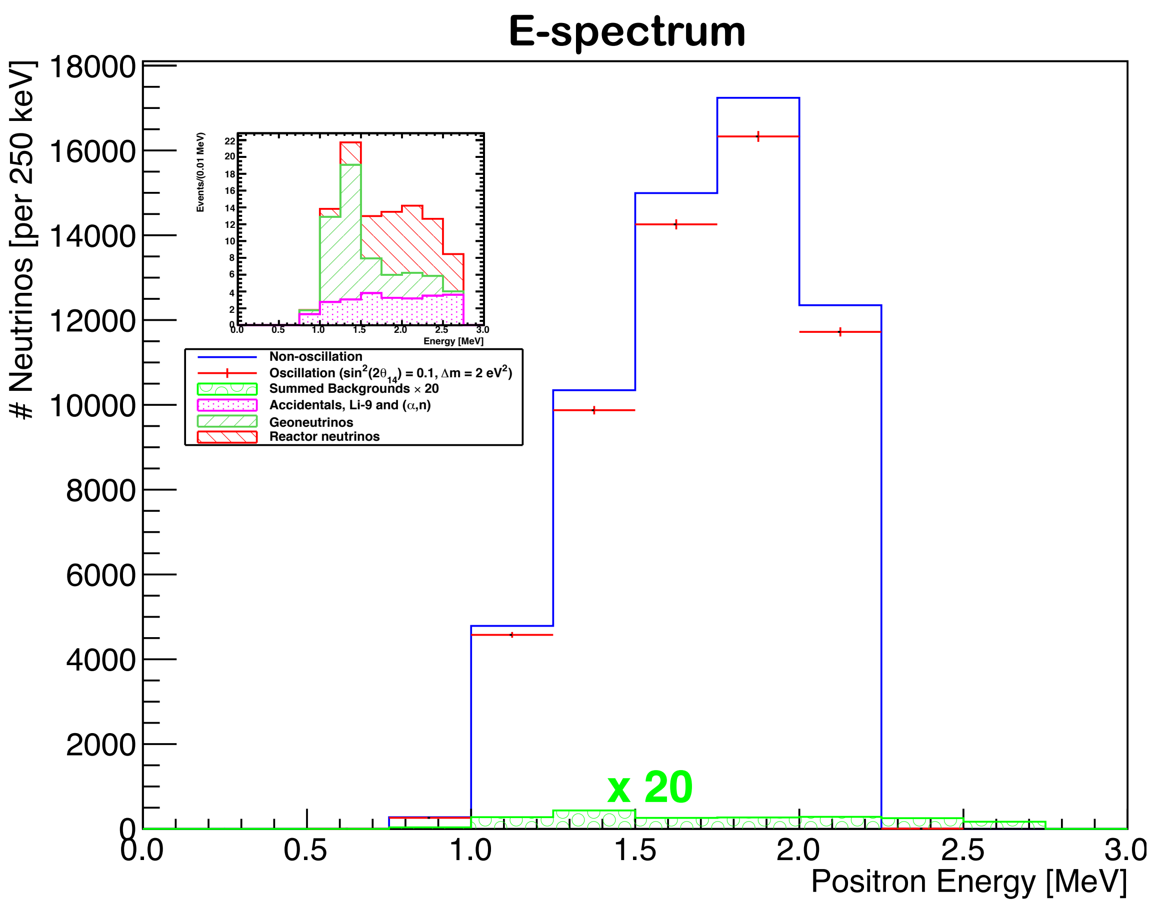
40 cm W-alloy, d=18.5 g/cm^3

γ-attenuation (2 MeV) : 10^{-13}

CeLAND Phase 2 Signal

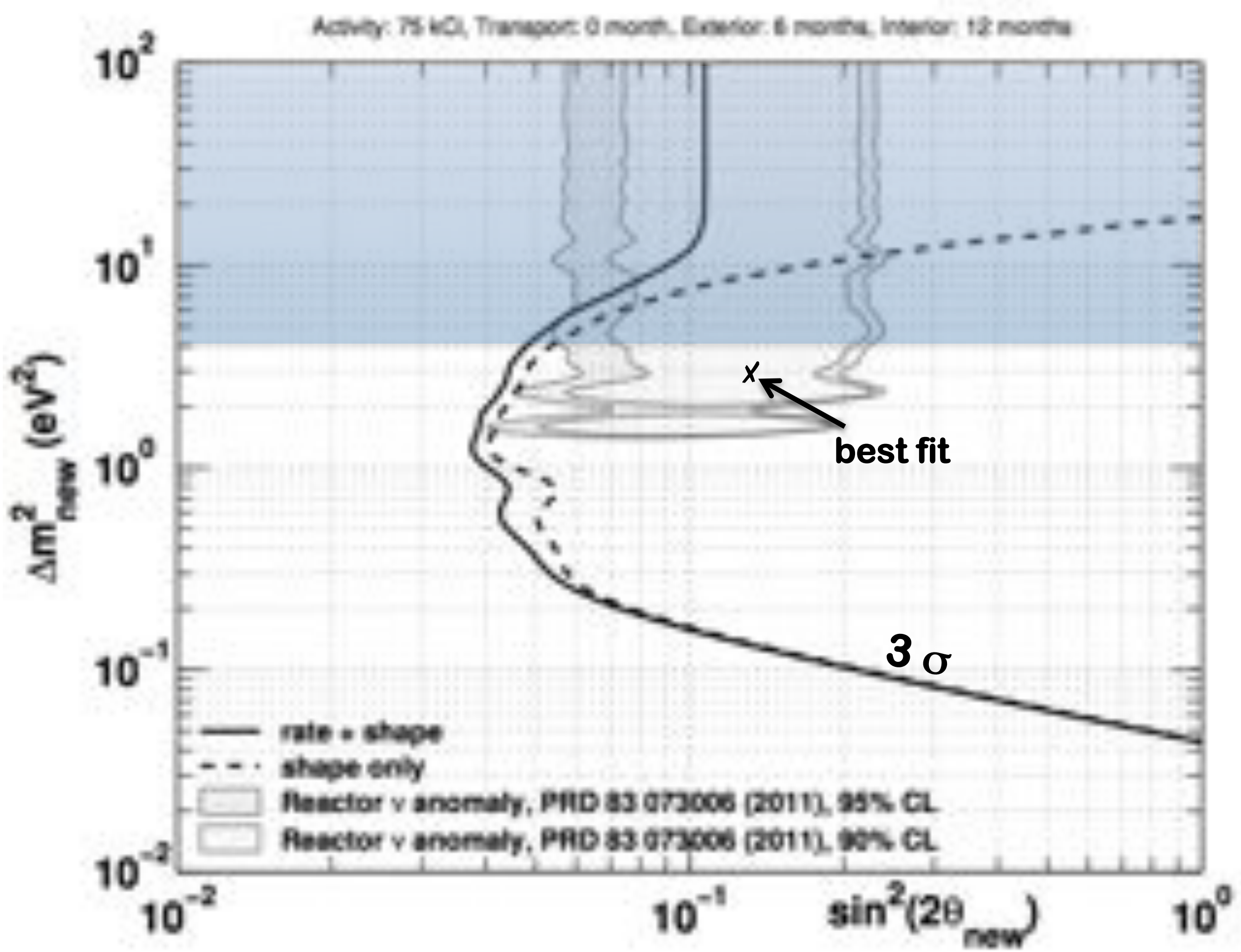
Need enlarged W-shield → technical challenge
Severe radiopurity constraint → material selection ongoing





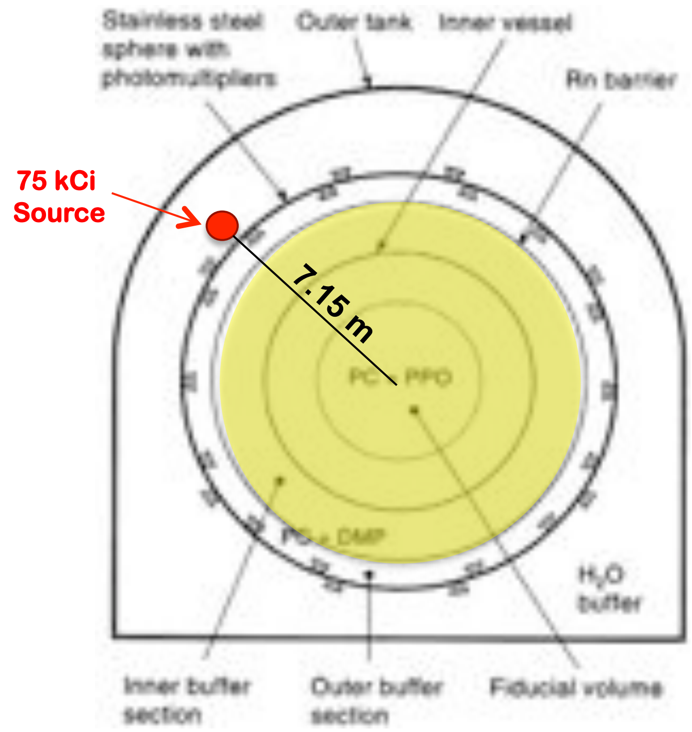
CeLAND Phase 1 + Phase 2

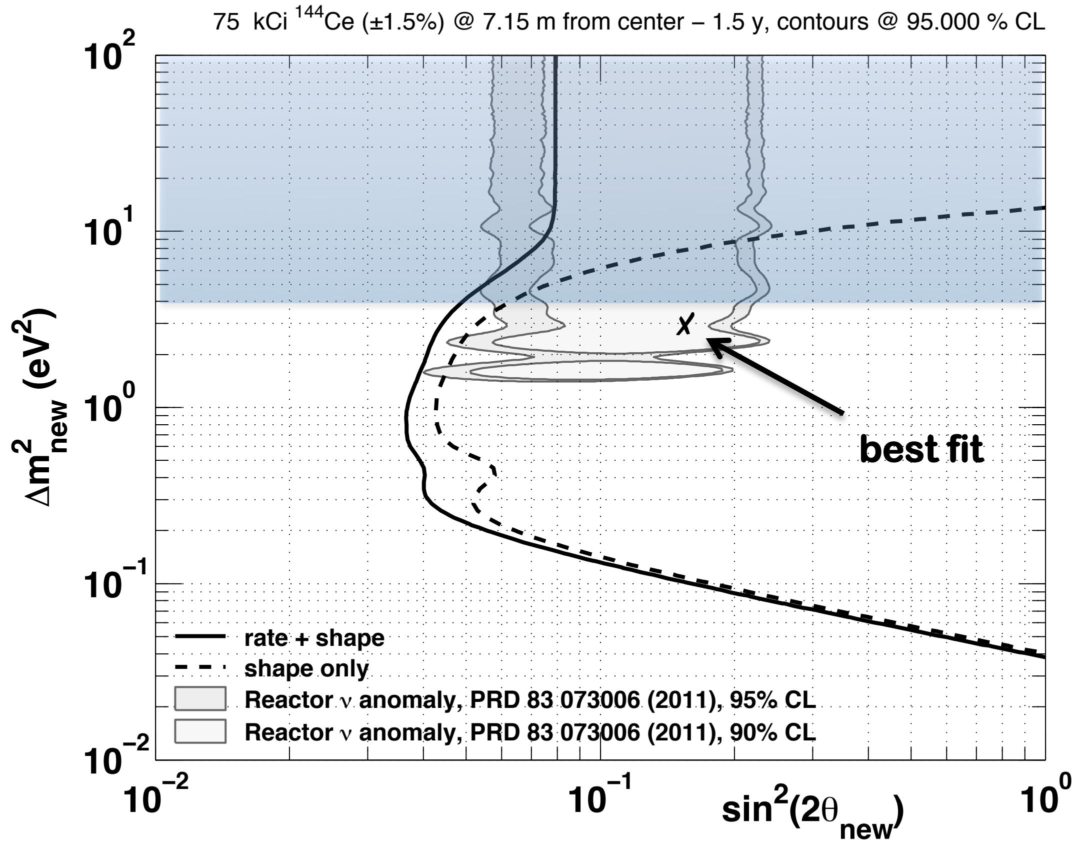
75 kCi 6 months + 50 kCi 1 year (10+50 kevts)



Ce-SOX 613 tons - 75 kCi - 1.5y

- **Borexino priority: deployment of 10 MCi ^{51}Cr**
- **Study of ^{144}Ce deployment in Borexino**
- **Necessitate enlarging fiducial volume from 300 t to 600 t**





R_{max} = 5.5 m
N_{evt} = 21800 / 1.5 y

Conclusion

- **Cerium Antineutrino Generator**
  - **75 kCi ^{144}Ce-^{144}Pr production in 2014: OK – Negotiation ongoing**
  - **Delivery of 75 kCi ^{144}Ce in Jan. 2015**
- **Shielding: Design for phase 1 – cost/schedule: OK**
- **Logistic: No solution secured for transportation**
- **Activity Calibration: Calorimeter design ongoing**
- **Host Detector Deployment: KamLAND: OK**
- **CeLAND Collaboration**
  - **CEA: DSM-Irfu / DEN / SPR / LNHB / DRI**
  - **KamLAND Japanese Collaboration, Irfu (ERC), Hawaii U. (DOE funding), LBNL/UCB, Russia (Mephi), IN2P3-APC?**
- **Goal: Start Data Taking Middle 2015**