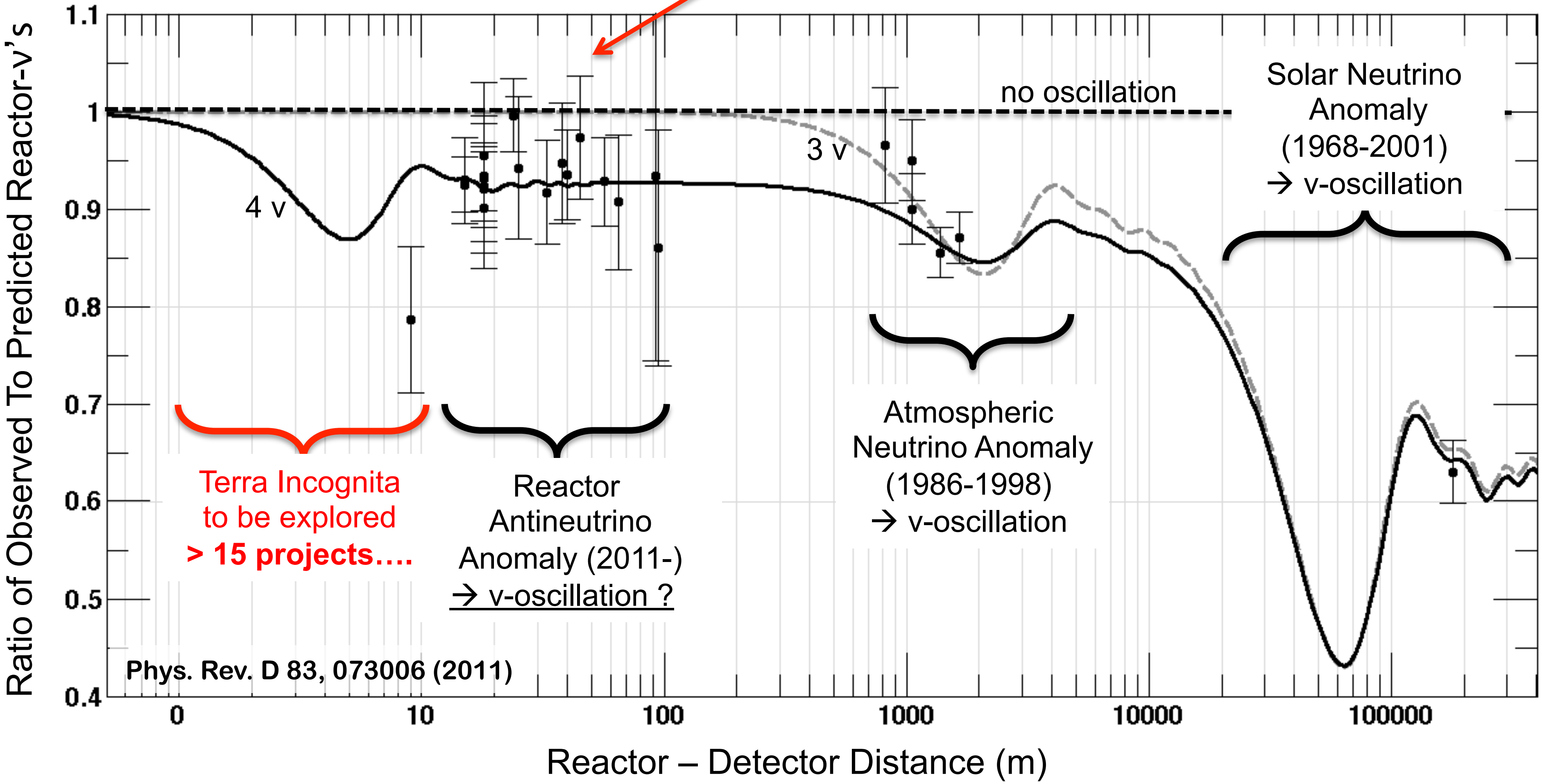

SOX
Neutrino Telescope
2015
Th. Lasserre
CEA Irfu
SPP - APC

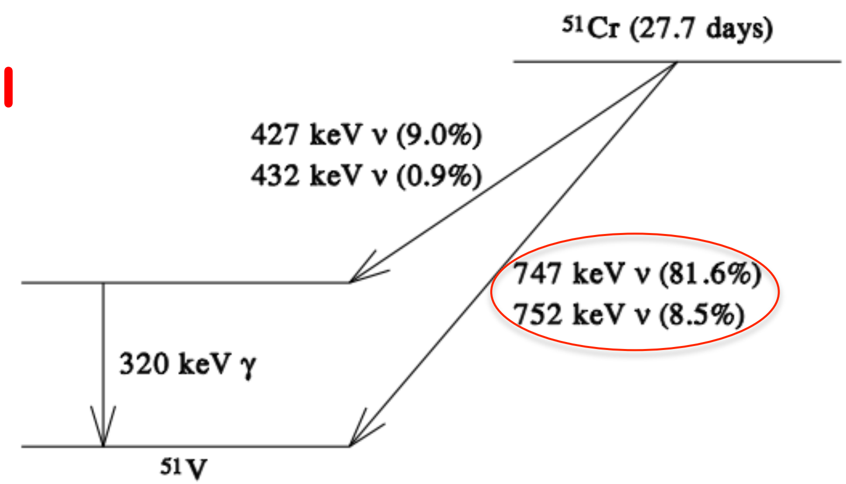
The Reactor Anomaly

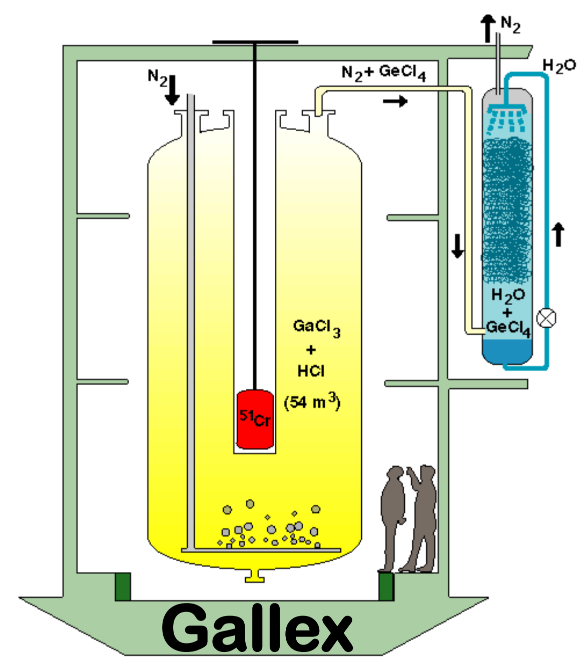
- **Observed/predicted averaged event ratio: R=0.938±0.023 (2.7 σ)**



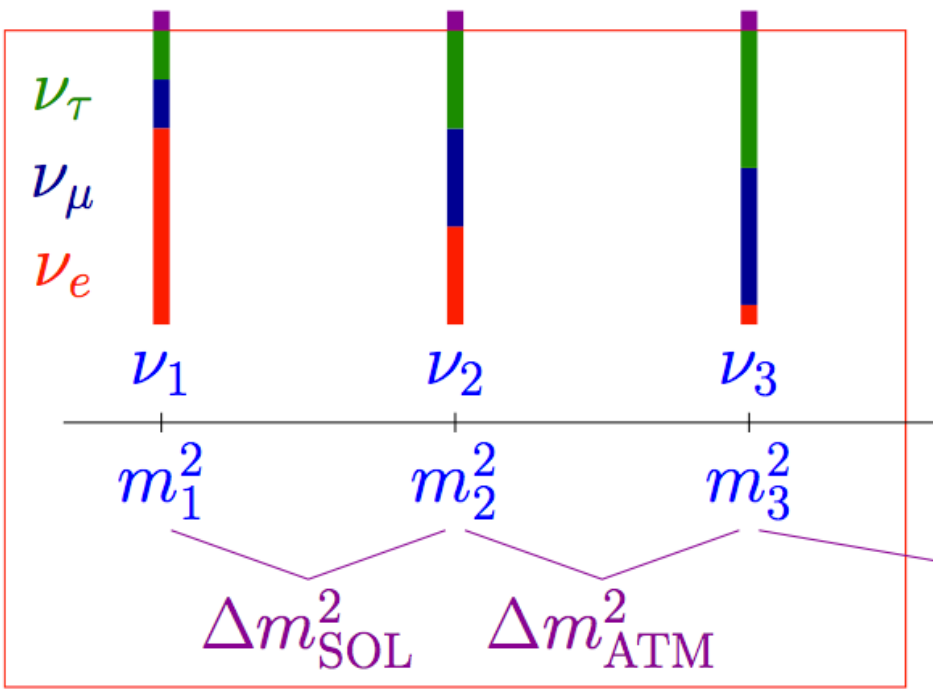
The Gallium Anomaly

- **Test of solar neutrino radiochemical detectors GALLEX and SAGE**
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- **4 calibration runs with 20-60 PBq Electron Capture ν_e emitters**
  - Gallex, <L>=1.9 m
    - ^{51}Cr, 750 keV
  - Sage, <L>=0.6 m
    - ^{51}Cr & ^{37}Ar (810 keV)
- **Deficit observed**
  - 3σ anomaly
  - Supported by new ^{71}Ga (^3He,^3H) ^{71}Ge cross section measurement



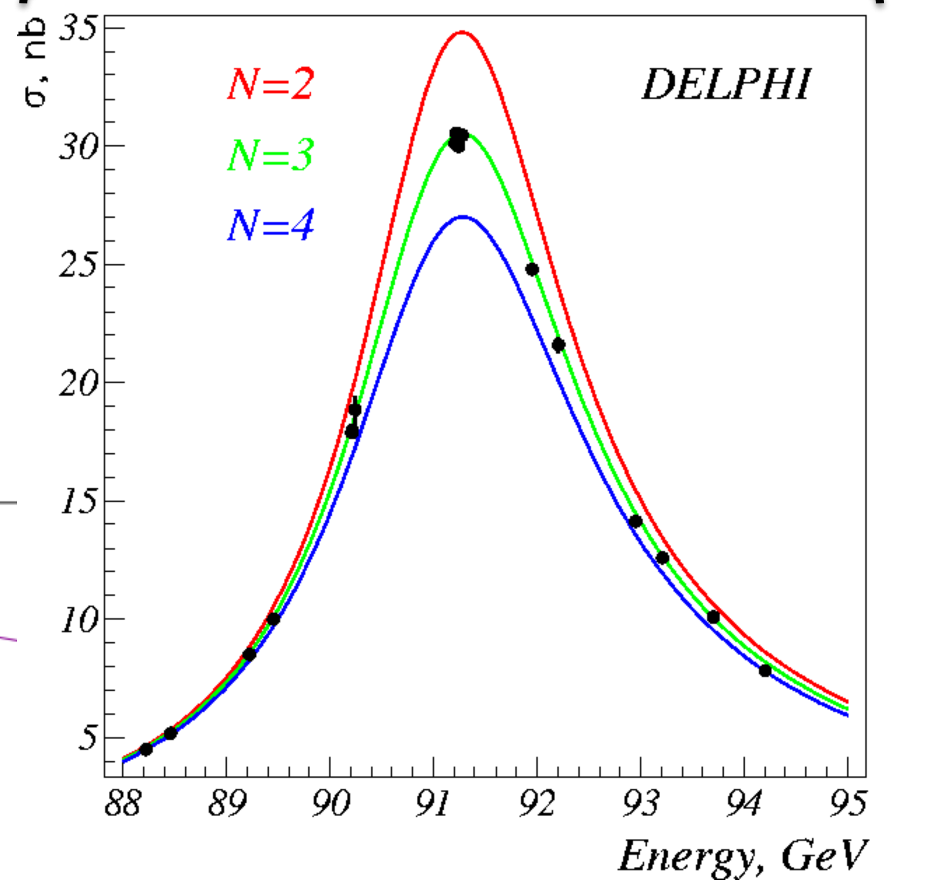


Active Neutrinos



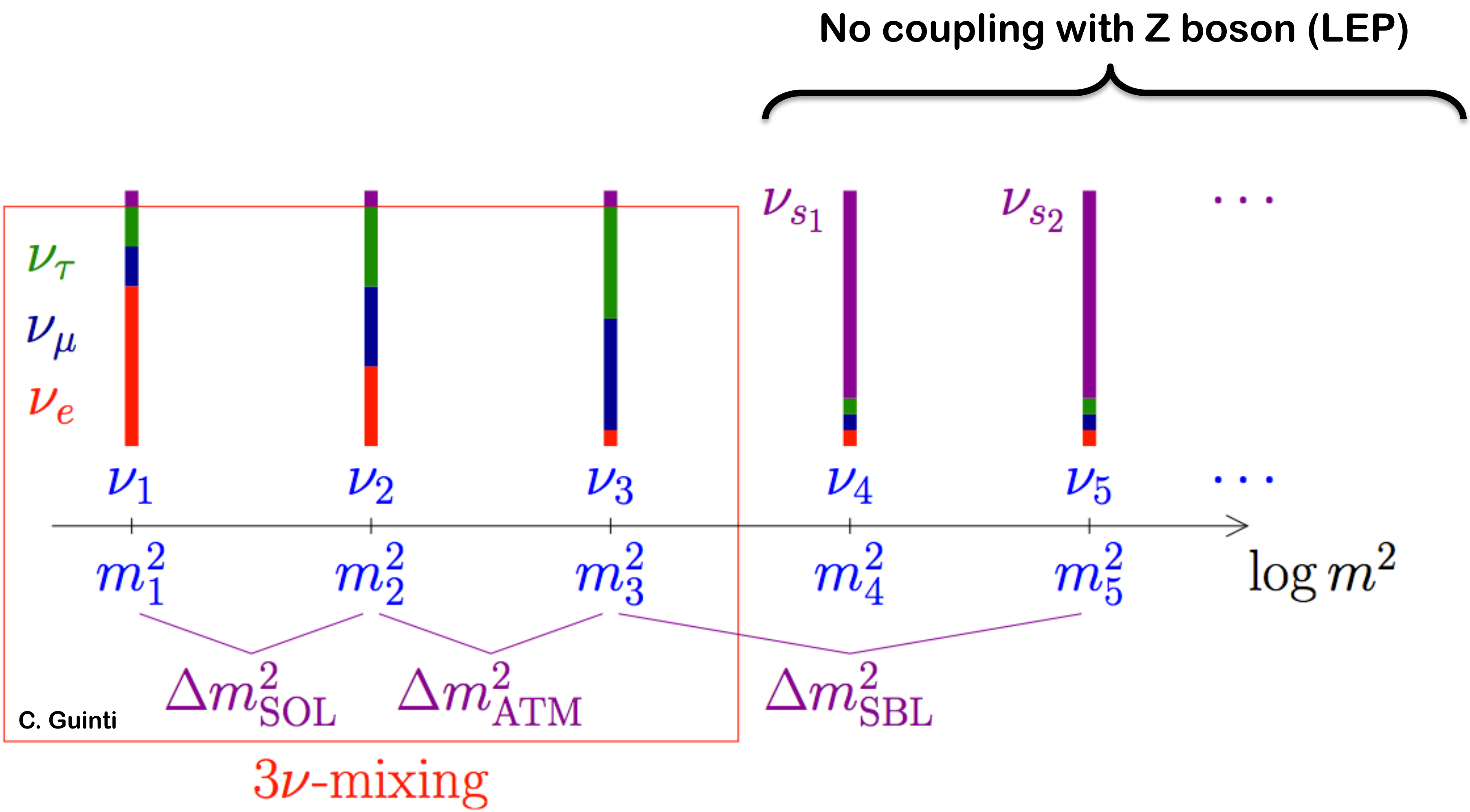
3ν-mixing

Only 3 light ν's coupling to Z boson



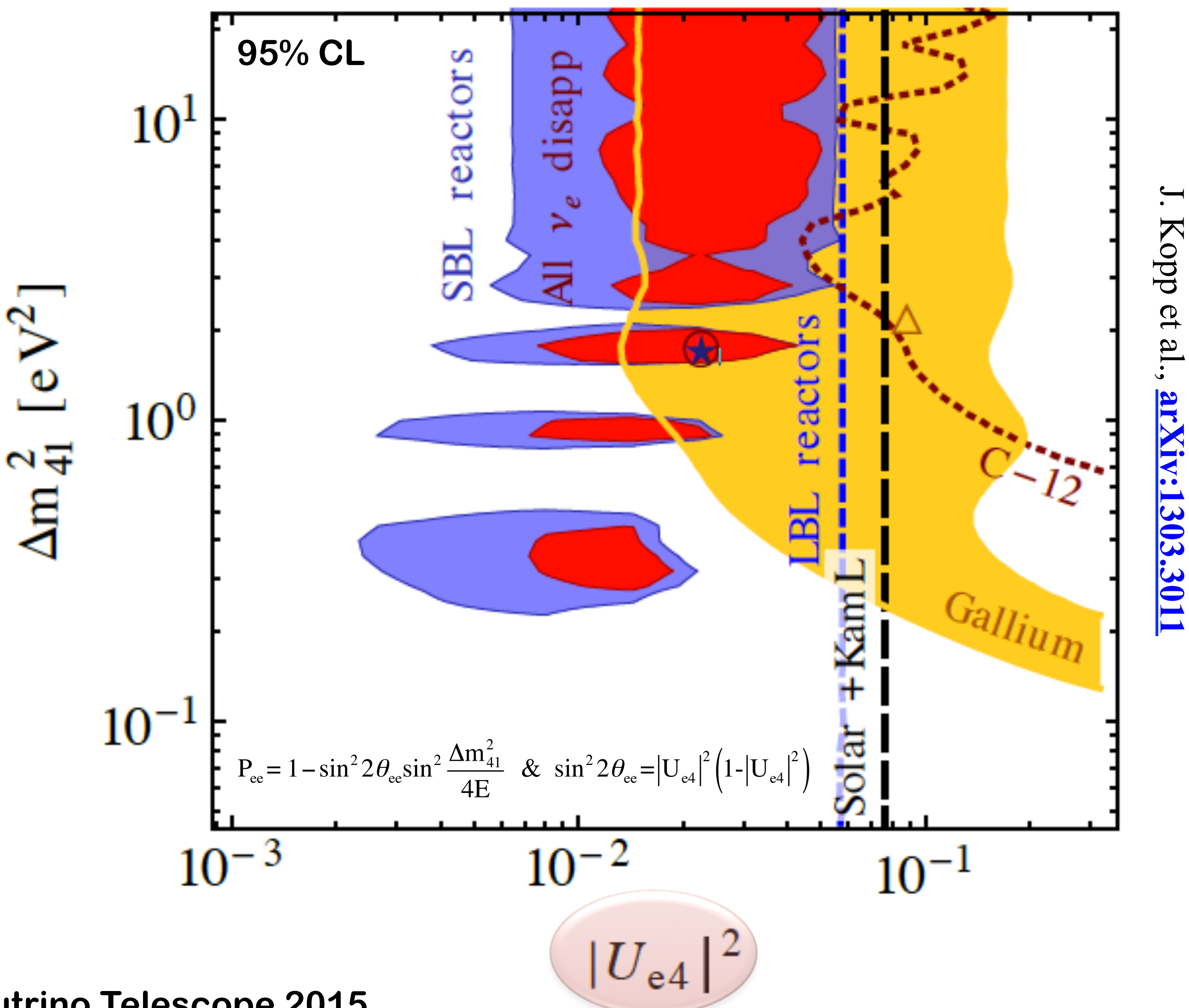
Adding Sterile Neutrinos

But maybe light ν_R? No SM interactions. Mixing with active ν' s



$\overset{(-)}{\nu}_e$ disappearance (3+1)

Data consistent with $\overset{(-)}{\nu}_e$ disappearance at L/E≈1 m/MeV



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

- **GA & RAA : comparison between data and event prediction**
  - Search for L, E, L/E pattern (shape only)
  - Complement with a rate analysis – need for an absolute calibration

- **Input from sterile neutrino global fits**
  - $\Delta m_{new}^2 \approx 0.1\text{-}10\ eV^2 \rightarrow L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2 (eV^2)} \approx 1-10\ m$
  - $\sin^2(2\theta_{new}) \approx 0.01 - 0.2$

- **Experimental specifications**
  - $\Delta m_{new}^2 \approx eV^2$: compact source < 1m & vertex resolution << 1m
  - $\sin^2(2\theta_{new})$: experiment with few % stat. & syst. uncertainties

ν Generator Proposals

Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>110 PBq	Sage LENS
					>370 PBq	CrSOX (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>37 PBq	-
					185 PBq	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ E_{th}=1.8 MeV (e^+,n) 5% E_{res} 15cm R_{res}	reactor ν , geo ν , ν generator impurities	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + Single isotope extraction	3.7-5 PBq	CeLAND CeSOX
					18.5 PBq	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^3H \rightarrow He\ e^-\ \bar{\nu}_e$ EC/β-decay	Kink search	^3H E<18 keV	Irradiation in reactors	110 GBq	KATRIN (Mare/Echo)

CeSOX:

^{144}Ce-^{144}Pr next to Borexino

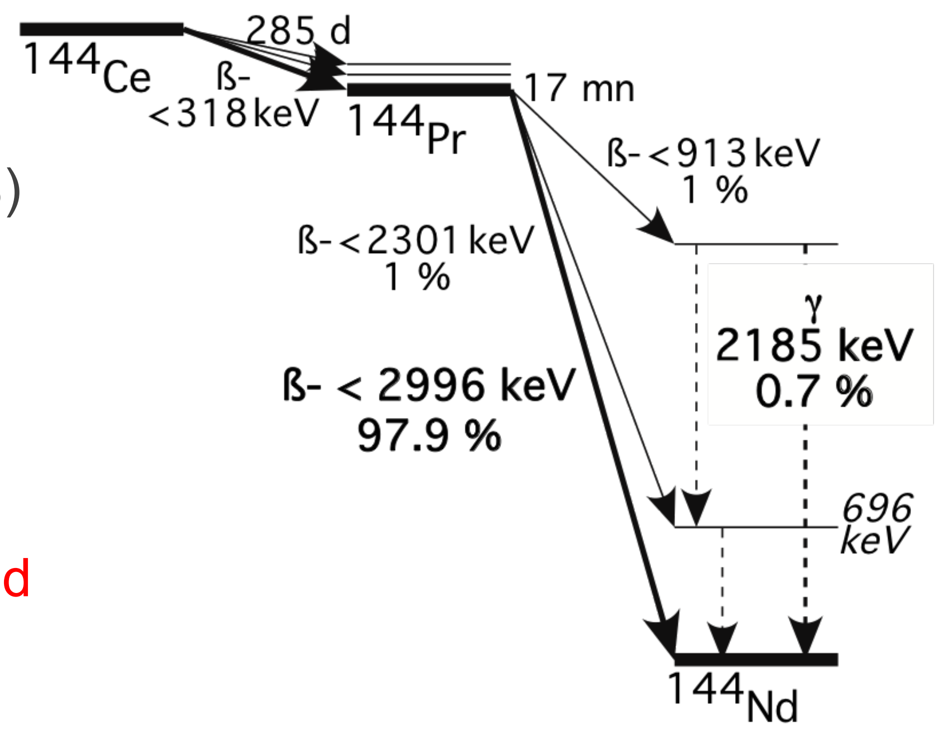
(Borexino Coll. + CEA)

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

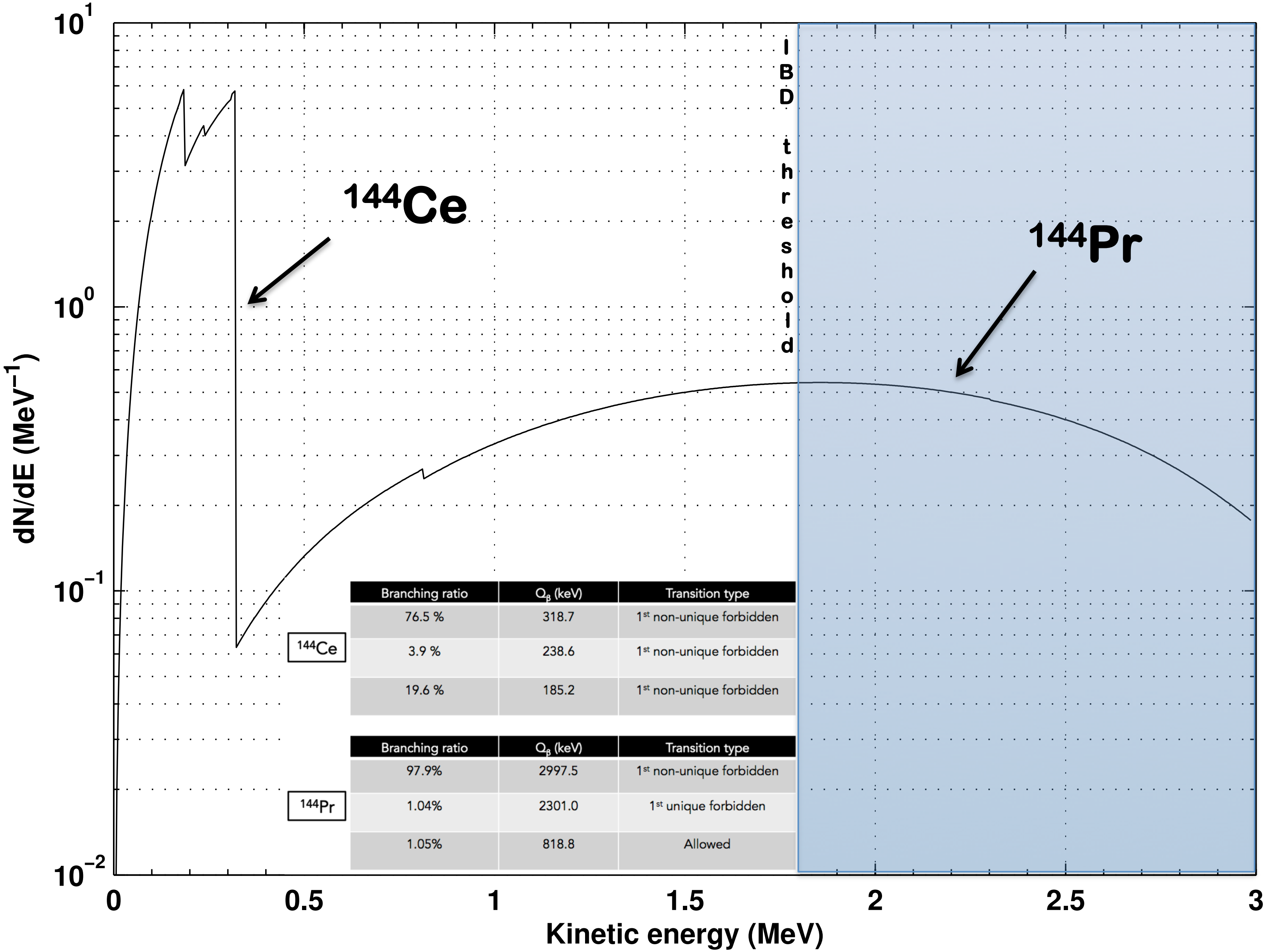
(ITEP N°90 1994, PRL 107, 201801, 2011)

- $\bar{\nu}_e$ **detection:** $\bar{\nu}_e + p \rightarrow e^+ + n$ **(Q≈1.8 MeV)**
  - **large IBD cross section → 3.7 PBq activity**
  - **(e^+,n) detected in coincidence → mitigate backgrounds**

- **^{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 IBD threshold



^{144}Ce-^{144}Pr ν-spectra



^{144}Ce

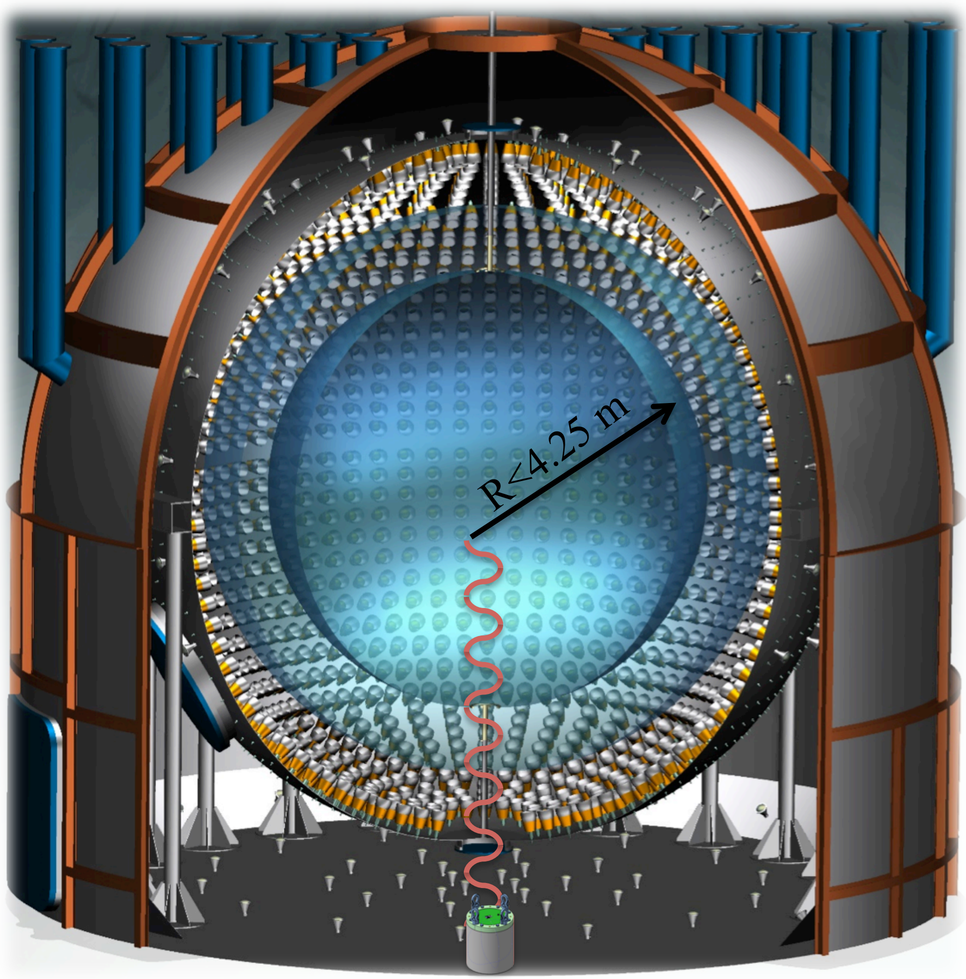
Branching ratio	Q_β (keV)	Transition type
76.5 %	318.7	1st non-unique forbidden
3.9 %	238.6	1st non-unique forbidden
19.6 %	185.2	1st non-unique forbidden

^{144}Pr

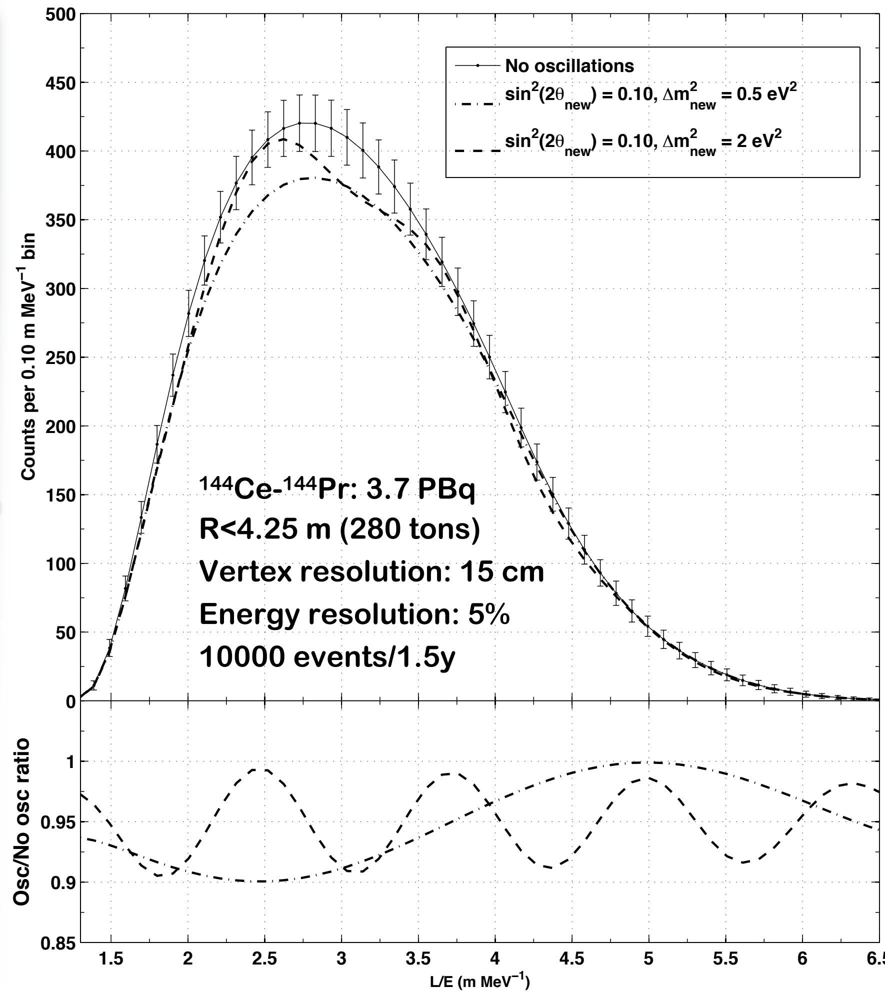
Branching ratio	Q_β (keV)	Transition type
97.9%	2997.5	1st non-unique forbidden
1.04%	2301.0	1st unique forbidden
1.05%	818.8	Allowed

Oscillometry in BOREXINO

Search for an L/E oscillation pattern inside LS target
Compare observed to expected ν rate (no oscillation)



8.3 m from Bx Center



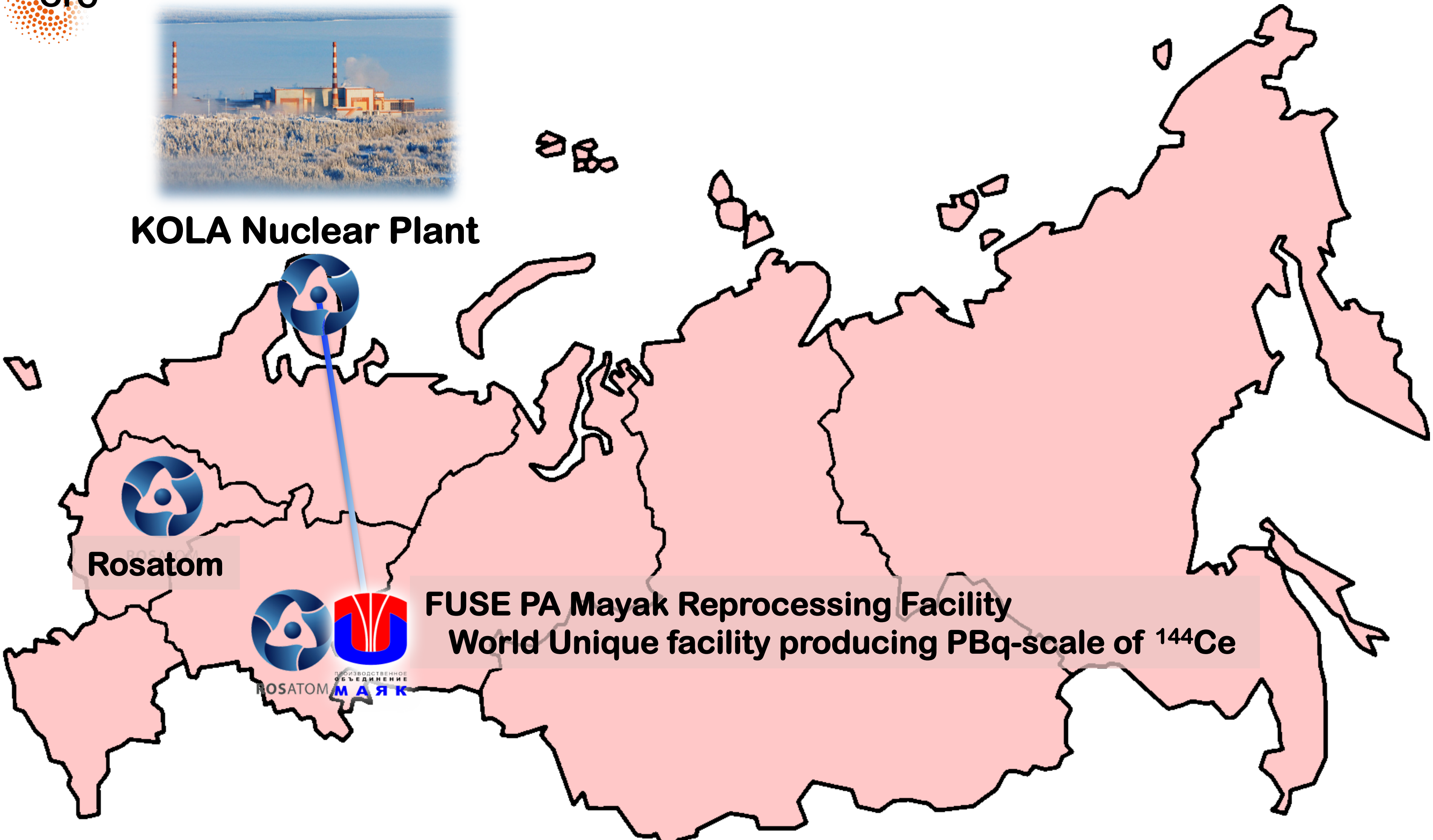
3.7 PBq ^{144}Ce-^{144}Pr Antineutrino Generator (CeANG) Production

CeANG: Specifications

- ß activity (in ^{144}Ce)
  - 3.7 PBq
- Extracted from fresh spent nuclear fuel (<2 years cooling)
- Chemical form : CeO_2
- Density : between 4 and 6 g/cm^3

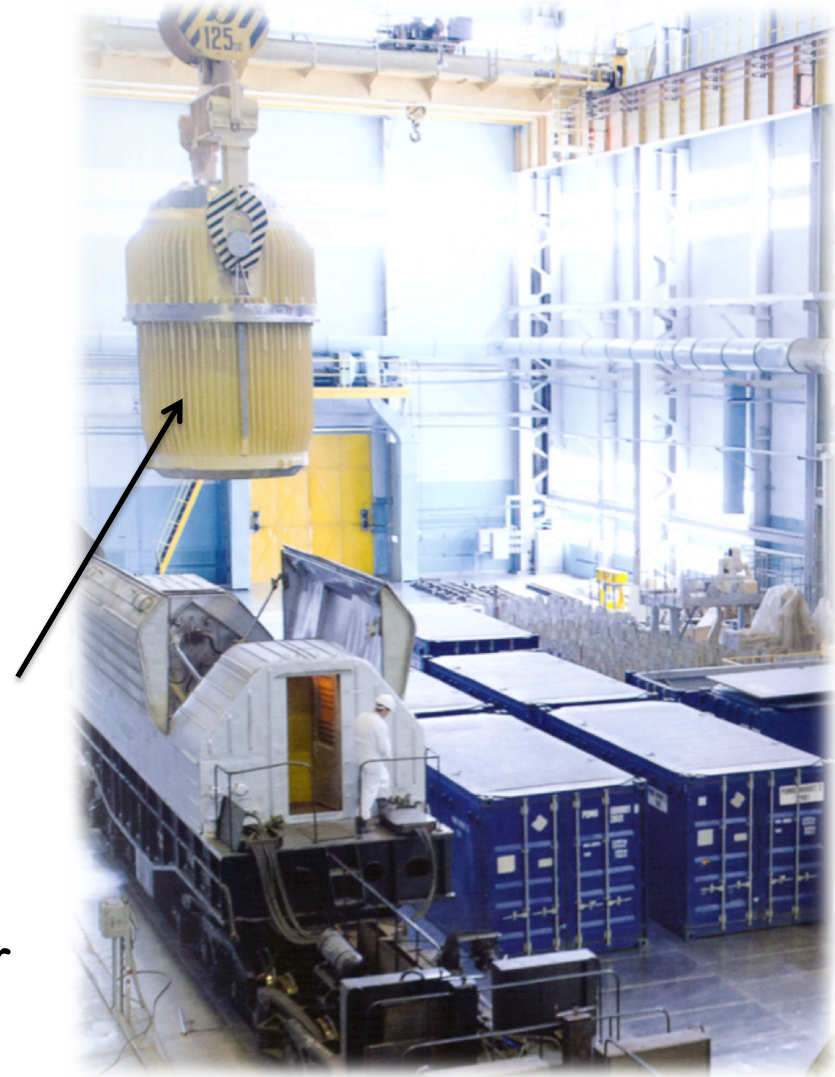
- Fitting inside a D:H=15:15 cm double capsule of Special Form of Radioactive Material (ISO 9978 - IAEA regulation)
- Purity requirements
  - Content of any others REE (γ*-emitters*) $\leq 10^{-3}$ Bq / Bq of ^{144}Ce
  - Content of Pu and TPE (*actinides*) $\leq 10^{-5}$ Bq / Bq of ^{144}Ce

CeANG production in Russia



Dedicated Spent Nuclear Fuel

- ^{144}Ce:
  - Produced in nuclear reactor core
    - 5.5% in fission prod. of U
    - 3.7% in fission prod. of Pu
  - Then decay 411 d mean-life.
- Selection of best SNF at Cola NPP
  - Shortest cooling time
    - <2 years
  - Highest burnup in last irr. cycle
- Delivery of SNF from Kola NPP to FSUE Mayak PA (3000 km)
  - TUK-6 container
- PA Mayak will receive fresh fuel for CeSOX prod. in March 2015

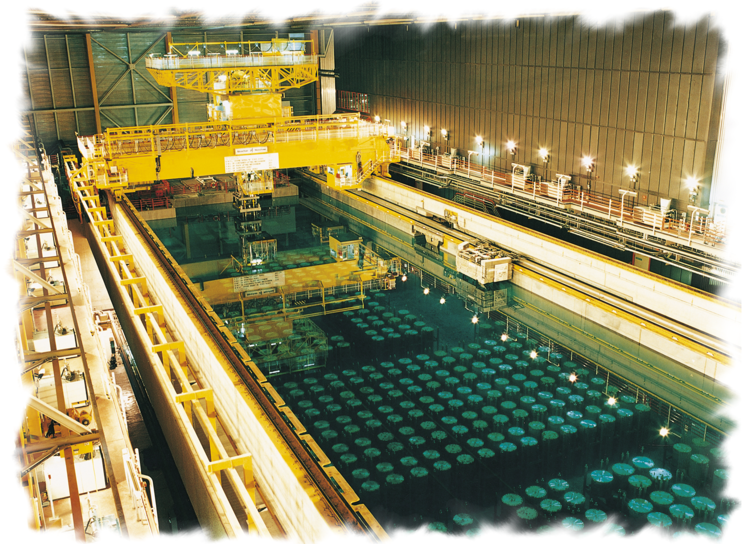


Overview of the process

- **Radiochemical Plant**
  - Standard radiochemical re-processing of SNF (Purex)
  - Separation of CeO_2
  - Primary encapsulation
  - Activity measurement (≈5%)

- **Radioisotope Plant**
  - Source manufacture
  - Certification ISO 9978
  - Loading into W-shield
  - Loading into transport cask

- R&D and upgrade of PA Mayak facilities for CeANG production ongoing since 2012

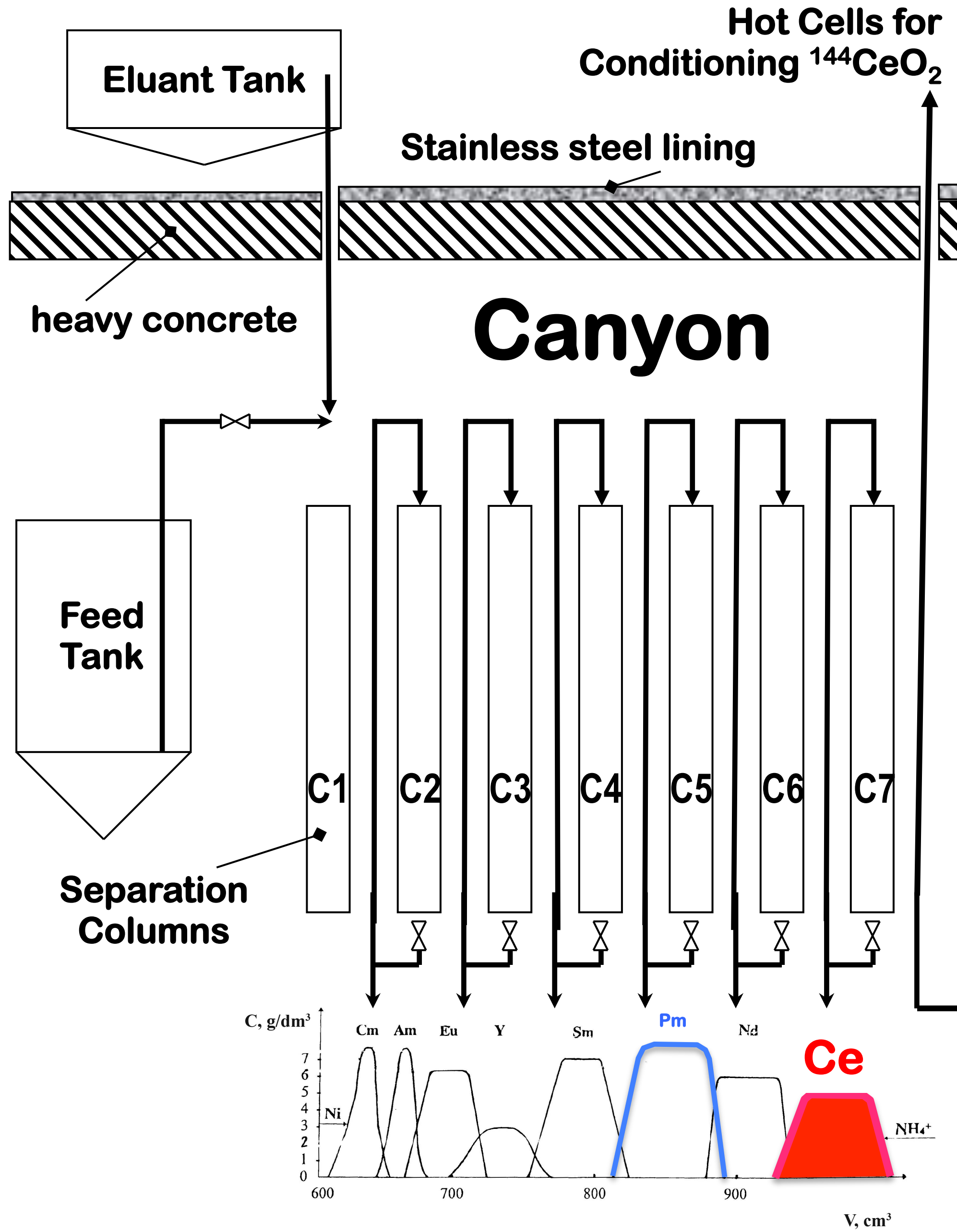


Extraction of Cerium Solution

- Complexing agent displacement chromatography for Rare Earth elements (REE)

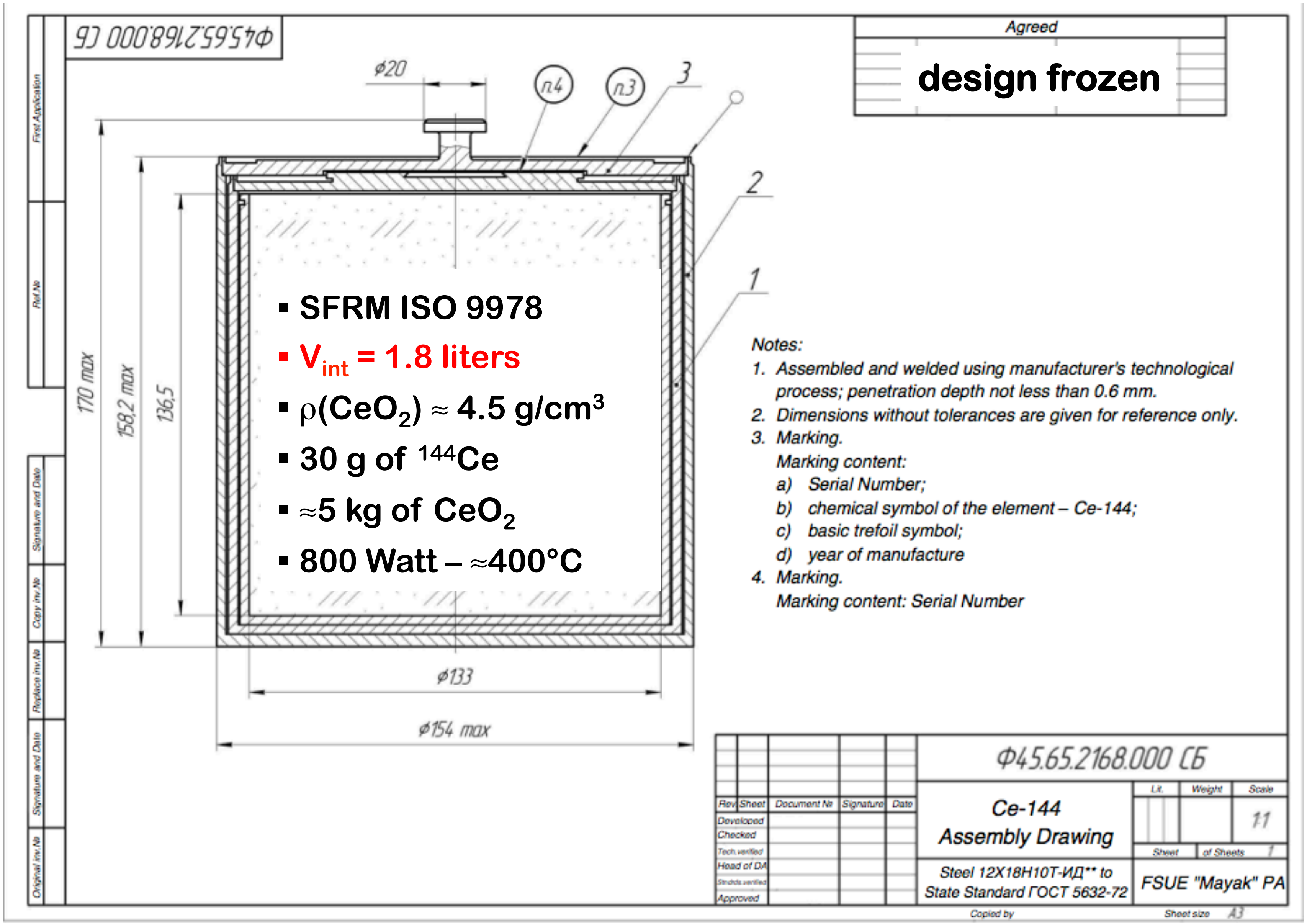
- Reactor Spent Nuclear Fuel:
  - PA Mayak: 100 t SNF/y
  - 1 ton SNF:
    - 13 kg REE
    - 22 g ^{144}Ce (3 y, 70 kCi)

- Production
  - Start Ce-extraction in 2015
  - Ce extraction: 9-12 months
  - Delivery June-August 2016 (saint Petersburg harbor)

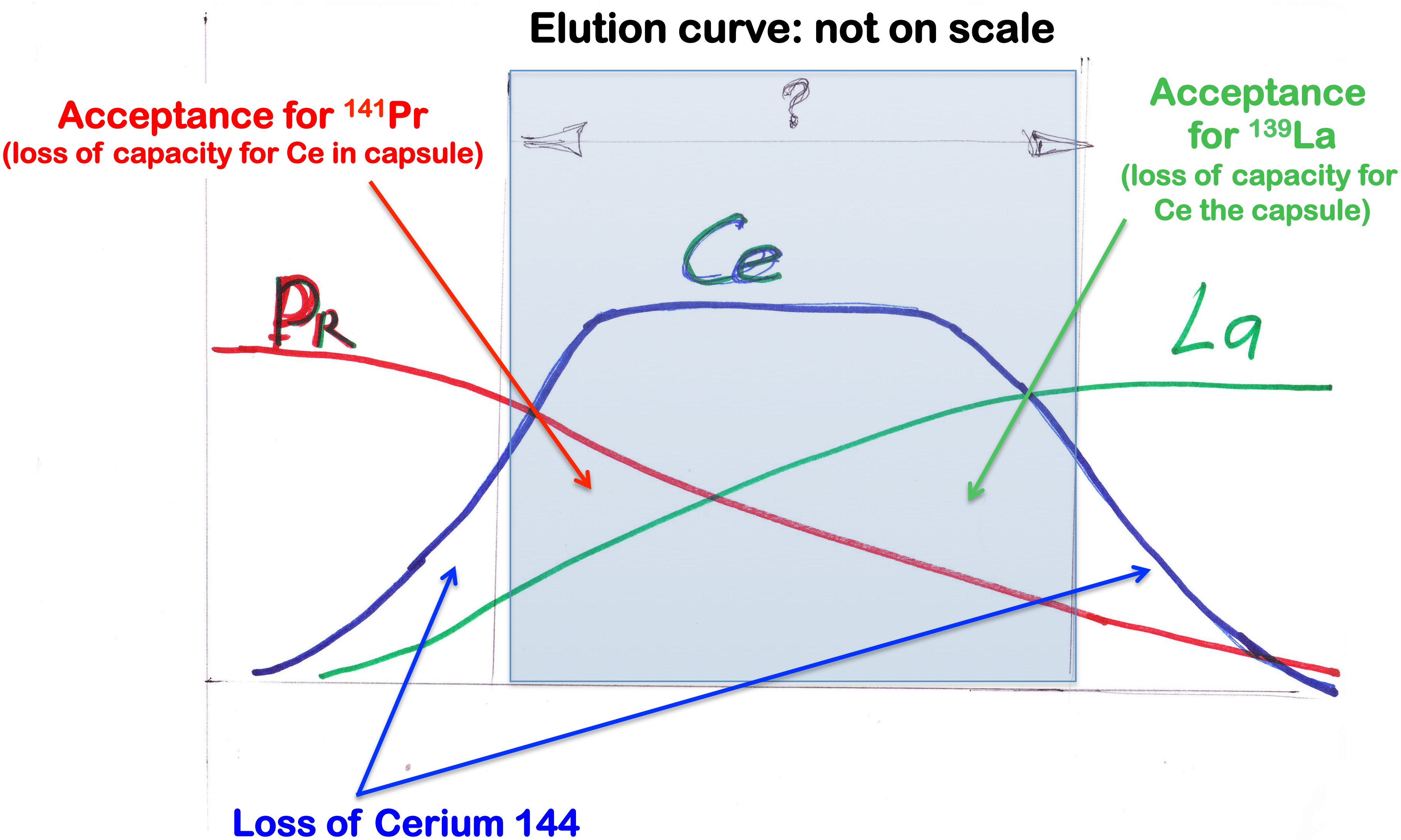


^{144}Ce-^{144}Pr SFRM capsule

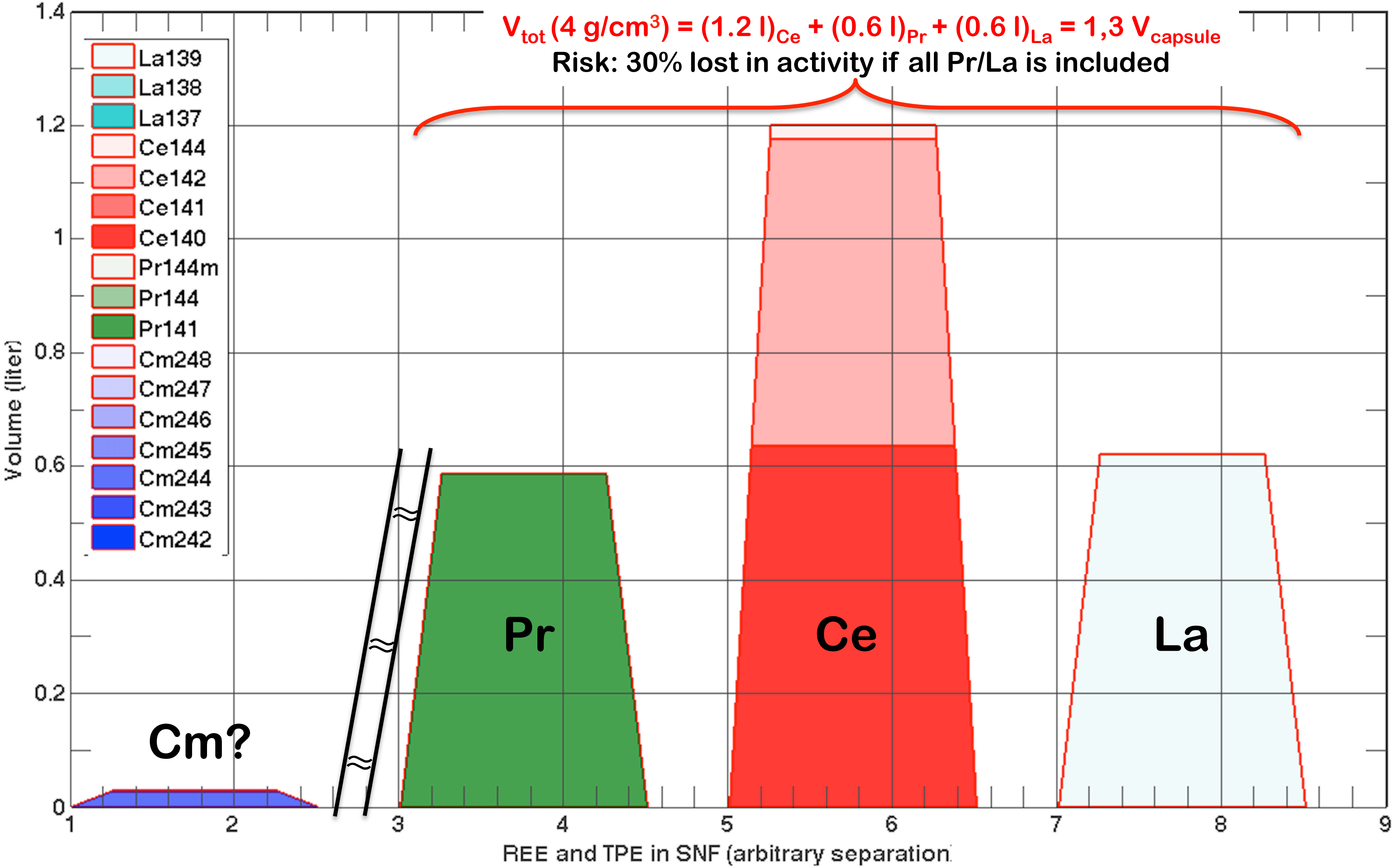
- SFRM ISO 9978
- V_{int} = 1.8 liters
- $\rho(CeO_2) \approx 4.5$ g/cm^3
- 30 g of ^{144}Ce
- $\approx$5 kg of CeO_2
- 800 Watt – $\approx$400°C



1st challenge: Ce-only recovery

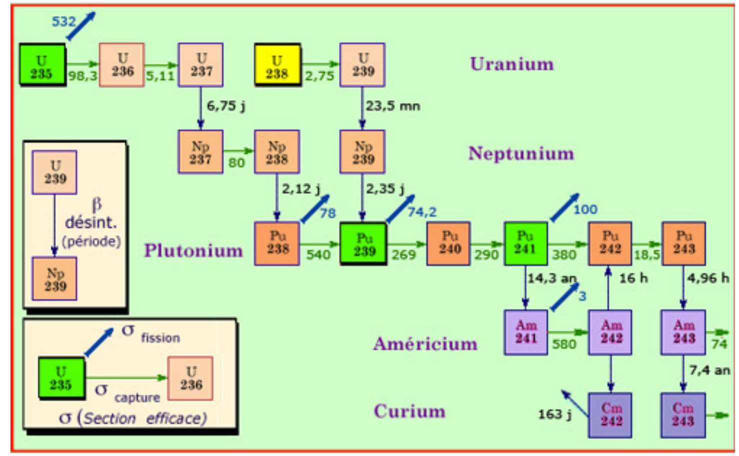


Extracting Cerium (only...)



2nd challenge: ^{244}Cm

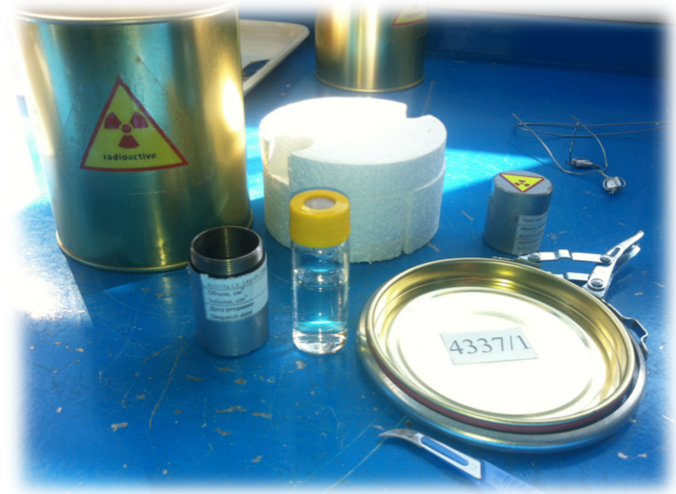
- **Traces of minor actinides**
  - Am, Cm, Bk, Cf,…
  - Spontaneous fission (SF→ neutrons)
  - (α,n) reaction (about 10^{-2} of SF)
- **Most hazardous: ^{244}Cm**
  - ^{244}Cm ~ all Cm after 3 years
  - T =18,1 y ; $I_{SF} = 1.4.10^{-6}$; 2,7 n/SF
  - Heavier minor actinides
    - Higher branching ratio to SF
    - Much less produced in reactor
- **CeSOX specification**
  - ^{244}Cm/^{144}Ce < 10^{-5} Bq/Bq (Driven by LNGS regulation)
  - Factor 1/1000 rejection needed during the chromatography
- **Requires dedicated purification step**



Isotope	Half-life	I_{SF} (%)	Specific neutron activity (n/g)
^{241}Am	432.2 y	$4.0\ 10^{-10}$	1.2
^{242m}Am	141 y	$4.7\ 10^{-9}$	46
^{243}Am	7370 y	$3.7\ 10^{-9}$	0.72
^{243}Cm	29.1 y	$5.3\ 10^{-9}$	$2.6\ 10^{2}$
^{244}Cm	18.10 y	$1.4\ 10^{-4}$	$1.6\ 10^{7}$
^{245}Cm	$8.5\ 10^{3}$ y	$6.1\ 10^{-7}$	$1.1\ 10^{2}$
^{246}Cm	$4.73\ 10^{3}$ y	$3.0\ 10^{-2}$	$1.0\ 10^{7}$
^{248}Cm	$3.40\ 10^{5}$ y	8.39	$4.2\ 10^{7}$

^{144}Ce-^{144}Pr Antineutrino Generator (CeANG) Characterization

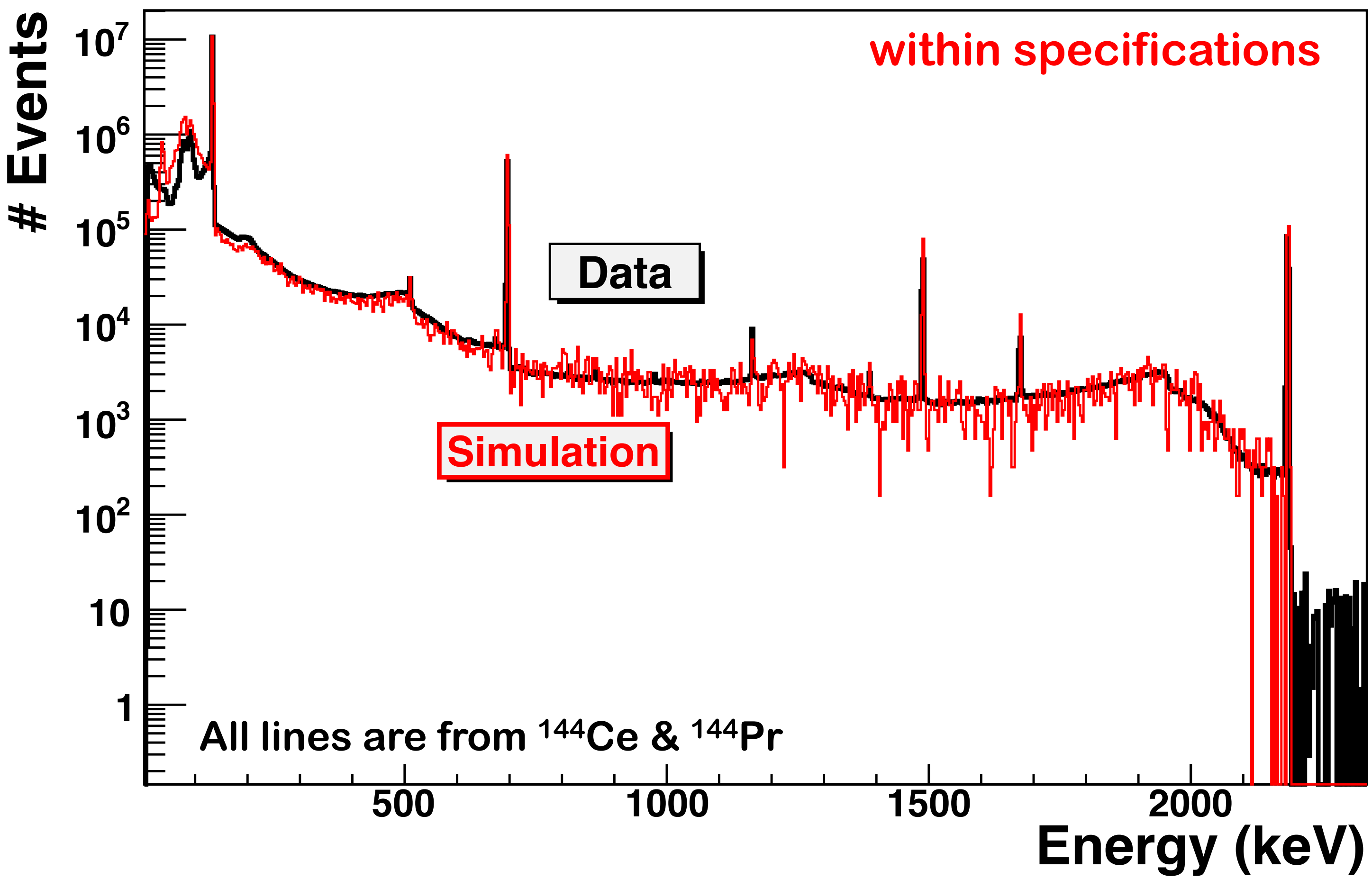
^{144}Ce-^{144}Pr samples from Mayak



- **Pilot production phase in Mayak (2013)**
  - **PBq scale – 6 y old fuel**
  - **3x 10 cm^3 $Ce(NO_3)_3$ samples – 59 kBq/^{144}Ce**
- **γ−spectroscopy**
  - **Characterization of β/γ impurity content**
- **β−spectroscopy**
  - **Measure ^{144}Ce & ^{144}Pr β−spectra: Heat/Activity conversion**
  - **Predict the ^{144}Pr ν−spectrum: expected ν−rate**
  - **Realization of two β−spectrometers**
- **ICP-MS & EAS and α-spectroscopy**
  - **Characterization of neutron impurity content**

$Ce(NO_3)_3$ samples: γ spectroscopy

- Absence of impurities emitting γ's
  - <10^{-4} Bq/Bq of ^{144}Ce for E>500 keV
  - <10^{-3} Bq/Bq of ^{144}Ce for E<500 keV
- Activity
  - 01/10/2014
  - 58,9 (2.5) kBq in ^{144}Ce

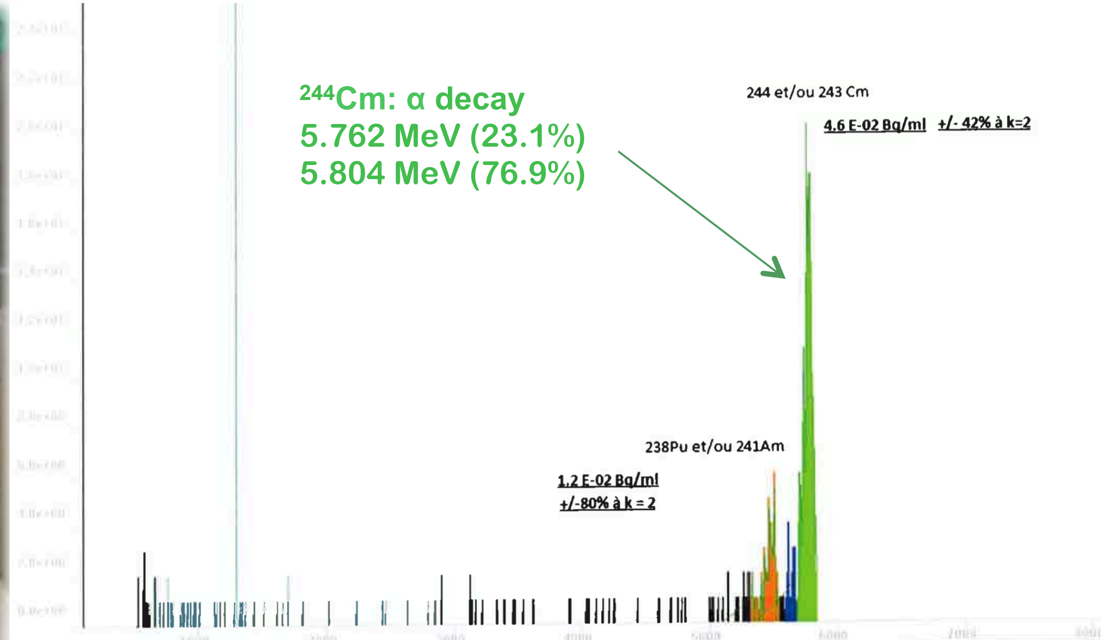


$Ce(NO_3)_3$ samples: α spectroscopy

Deposition and evaporation of 250 µl of $Ce(NO_3)_3$ solution

CANBERRA type IN 114, ionization chamber, 100% in 2π st. $\sigma_E = 40$ keV at CEA/LASE

α-spectrometry (12 hours)
Gridded ionization chamber



$^{244}Cm / ^{144}Ce = 8(3)\ 10^{-6}$ Bq/Bq

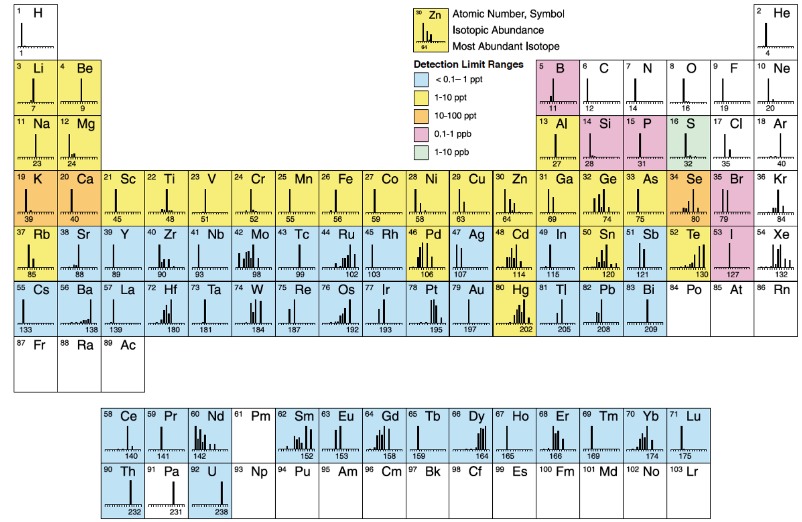
- 65000 n/s/3.7 PBq → within specifications

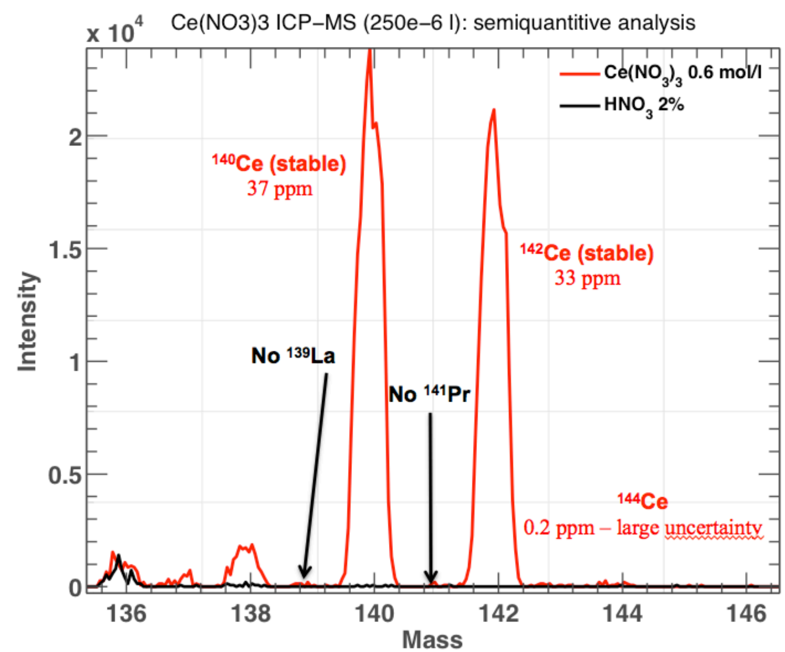
$^{241}Am / ^{144}Ce = 2(2)\ 10^{-6}$ Bq/Bq

- 330 n/s/3.7 PBq → within specifications

$Ce(NO_3)_3$ samples: ICP-MS/AES

- Measurements by CEA/LASE
- 0.25 ml sample $Ce(NO_3)_3$ diluted 100 times
- Semi-quantitative analysis → 50% uncertainty
- **ICP-MS/AES**:
  - Cerium – 30 ppm
  - ½ ^{140}Ce (stable) as expected
  - ½ ^{142}Ce (stable) as expected
  - Traces of ^{144}Ce as expected consistent with 6 y old fuel
  - No ^{139}La & No ^{141}Pr Good recovery process
  - No significant impurities





But samples not fully representative of 3.7 PBq CeANG → first step

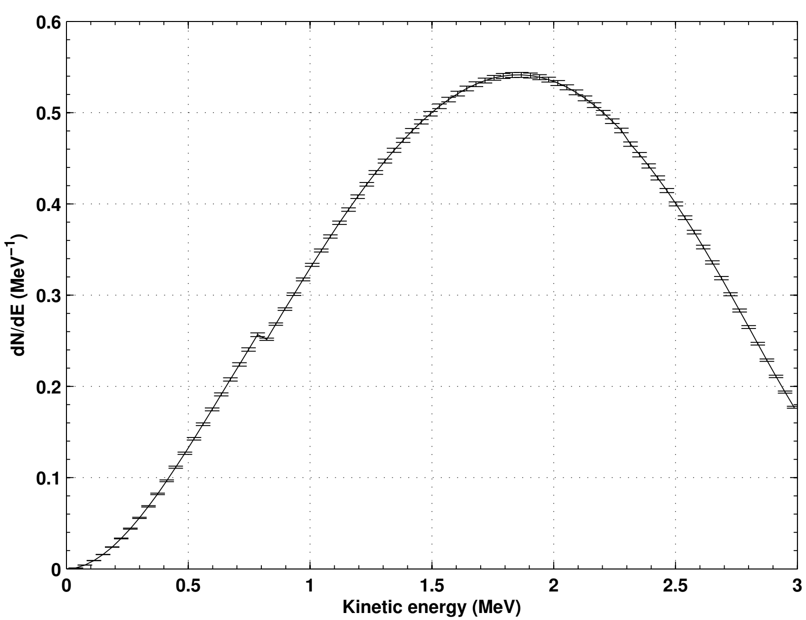
^{144}Pr Antineutrino Spectrum

- ^{144}Ce-^{144}Pr β/ν spectra needed with % level precision
  - Power-to-activity conversion factor: 216.0 ± 1.2 W/PBq
  - Prediction of the IBD rate depends on the ^{144}Pr spectral shape

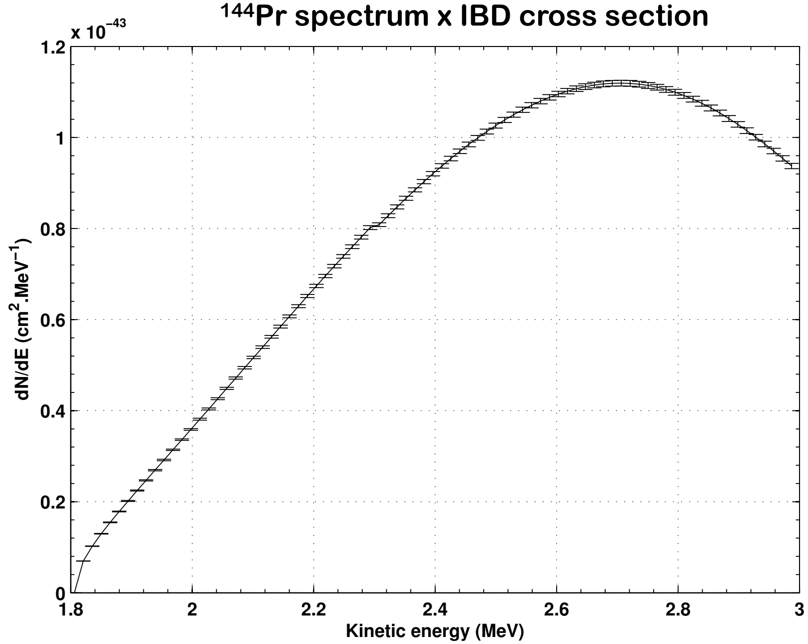
- Modeling of the ^{144}Ce-^{144}Pr β/ν spectra
  - Fermi theory + nucleus finite-size effects + screening + QED corrections + weak magnetism + recoils and mass effects → 1% uncertainty (theory)

- But forbidden β-branches→ need for a measurement (shape factor, 10%)

Simulation of ^{144}Pr from nuclear database data



^{144}Pr spectrum x IBD cross section



^{144}Ce-^{144}Pr samples: β spectroscopy

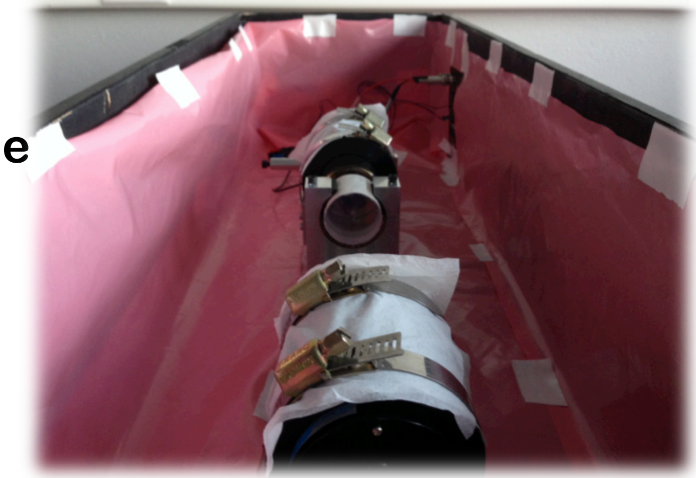
erc

- ^{144}Ce-^{144}Pr
  - Plastic spectrometers (+wire chamber)
  - But low energy β's from ^{144}Ce pollute the determination of the ^{144}Pr-ν spectrum

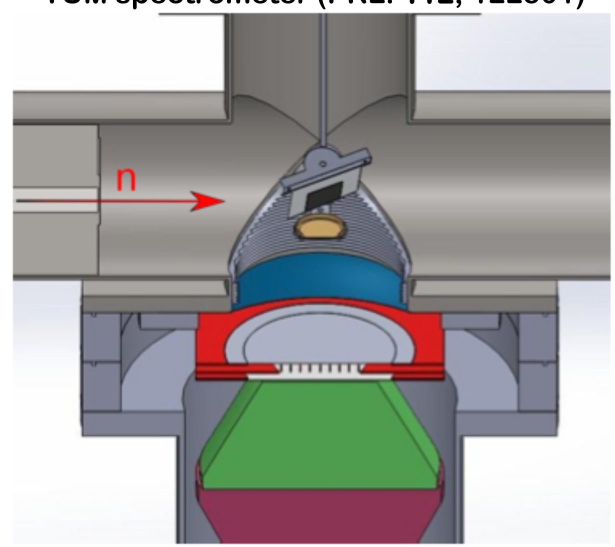
- ^{144}Pr only
  - Need chemical separation of ^{144}Pr from ^{144}Ce (CEA/LNHB)
  - But ^{144}Pr mean life time is only 17 min
  - So need to be fast…
  - Detection methods:
    - $(^{144}Pr)_s$ in PS + PMTs
    - $(^{144}Pr)_s$ onto Si-detector

- Ongoing measurements. Needed by 2016

CEA spectrometer (under construction)



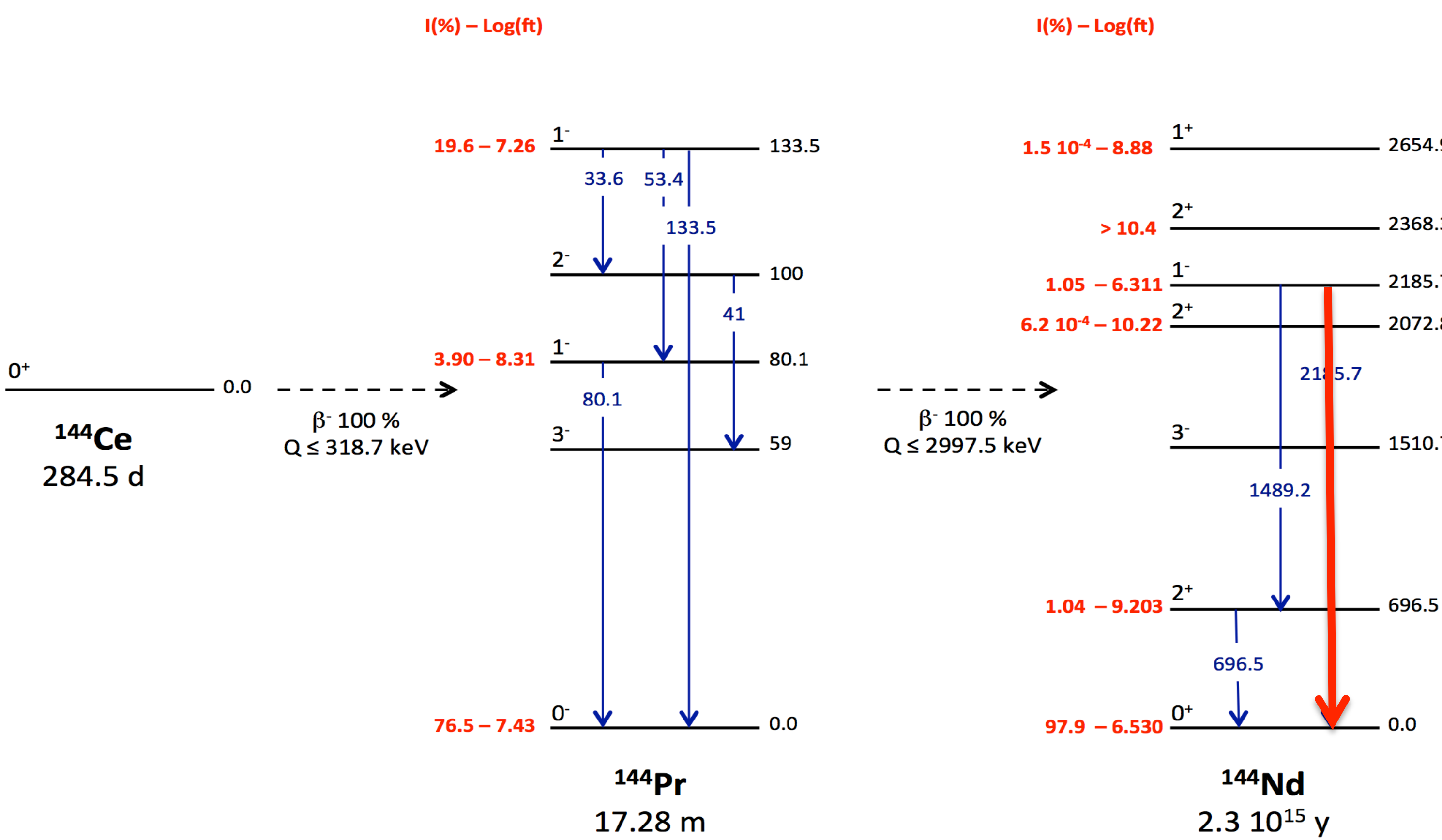
TUM spectrometer (PRL. **112**, 122501)



High-Density Tungsten Alloy Shielding (HDTAS)

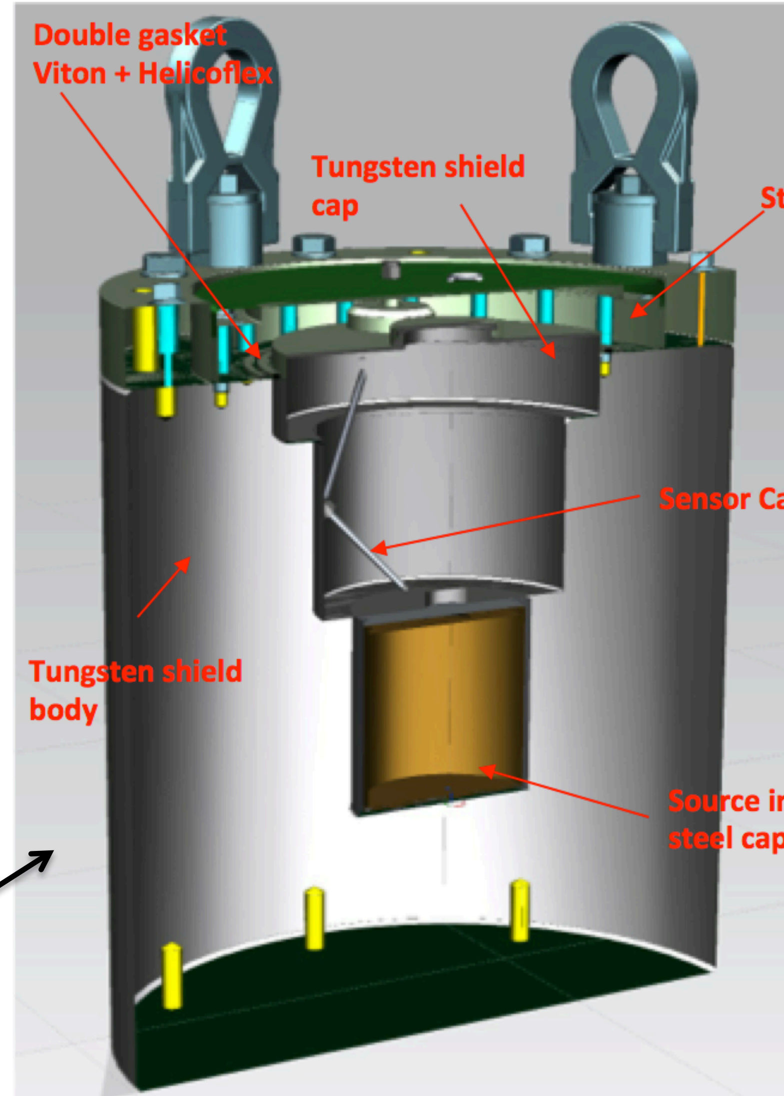
Gamma Backgrounds of ^{144}Ce-^{144}Pr

- 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 % (2.10^{10} γ /sec for 3.7 PBq)



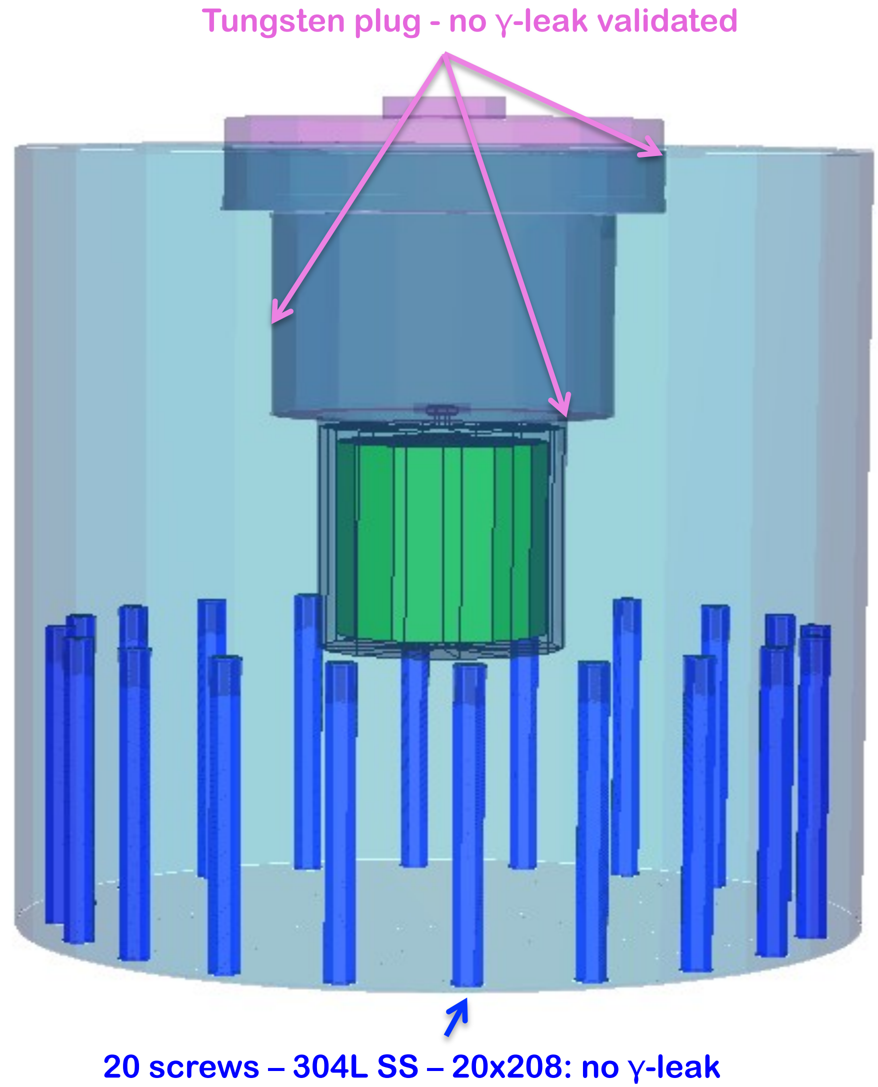
HDTAS: Mechanics

Mockup at TU München



HDTAS: Radiation Dose

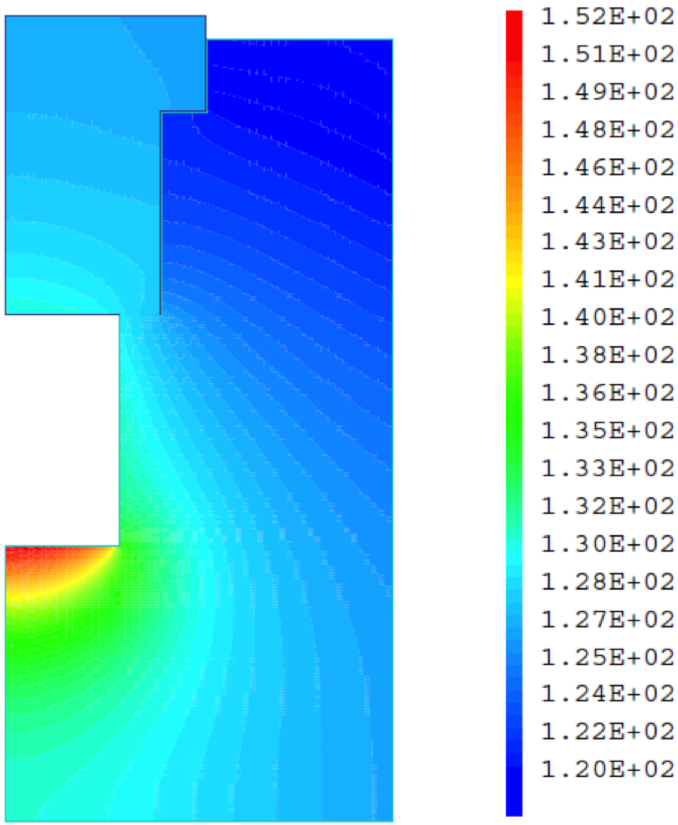
- **Computation by CEA/SPR**
  - Code Mercurad v1.10
  - Code MCNPX v2.7.0
- **Hypothesis**
  - 5.5 PBq in ^{144}Ce
  - γ-emitters in Ce < 10^{-3} Bq/Bq
  - n emitters in Ce < 10^{-5} Bq/Bq
- **Gamma Radiation dose**
  - at contact <120 μSv/h
  - at 1 m <7 μSv/h
  - Source: ^{144}Pr de-excitation
- **Neutron Radiation dose**
  - 'at contact' <100 nSv/h
  - at 1 m <4 nSv/h
  - Source: ^{244}Cm SF (<10^5 n/s)



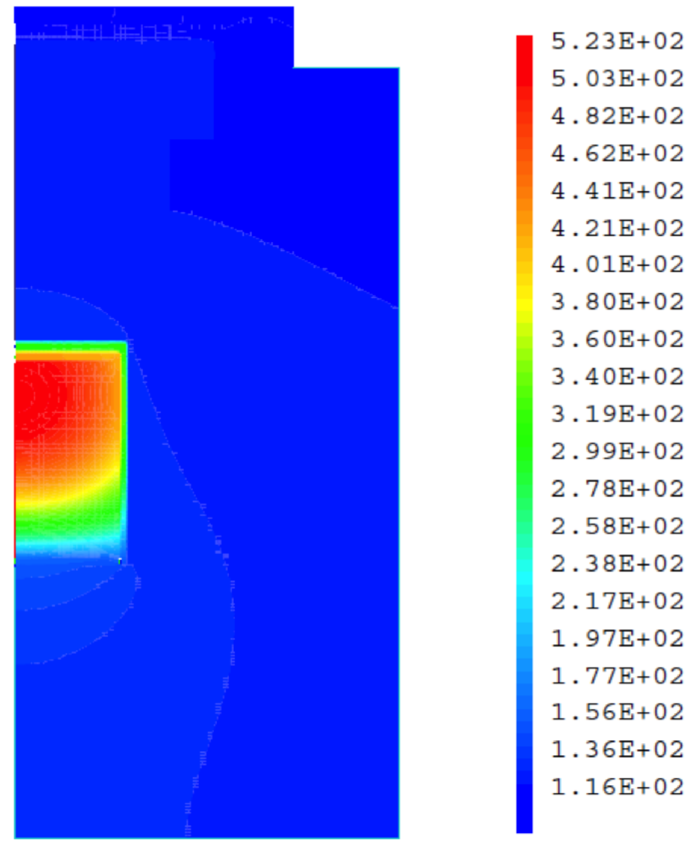
HDTAS: Thermal Features

4.6 PBq (CeANG)-W temperature distribution alone in air at 38°C. Assuming a temperature of 20°C. The temperature of the shield surface will be 80°C.

valeurs des isothermes (°C)



valeurs des isothermes (°C)



HDTAS

HDTAS + Capsule

T°C max in Cerium	HDTAS Averaged T°C in cerium	T°C max of inner capsule	T°C max of external capsule	T°C max of HDTAS	External HDTAS T°C
526	398	434	338	153	119

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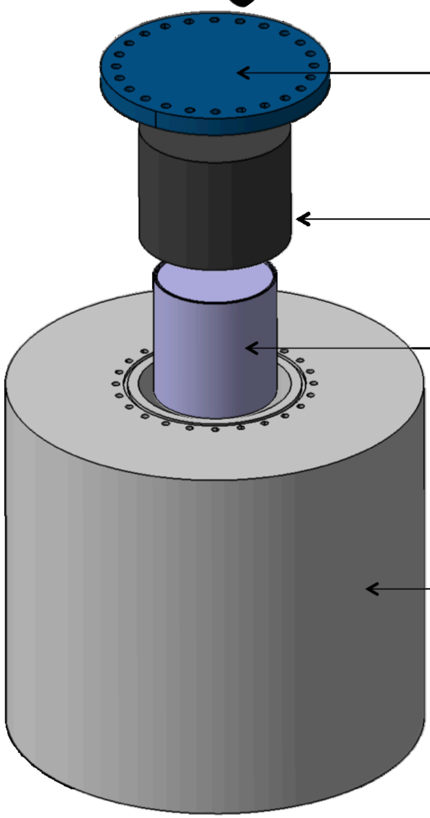
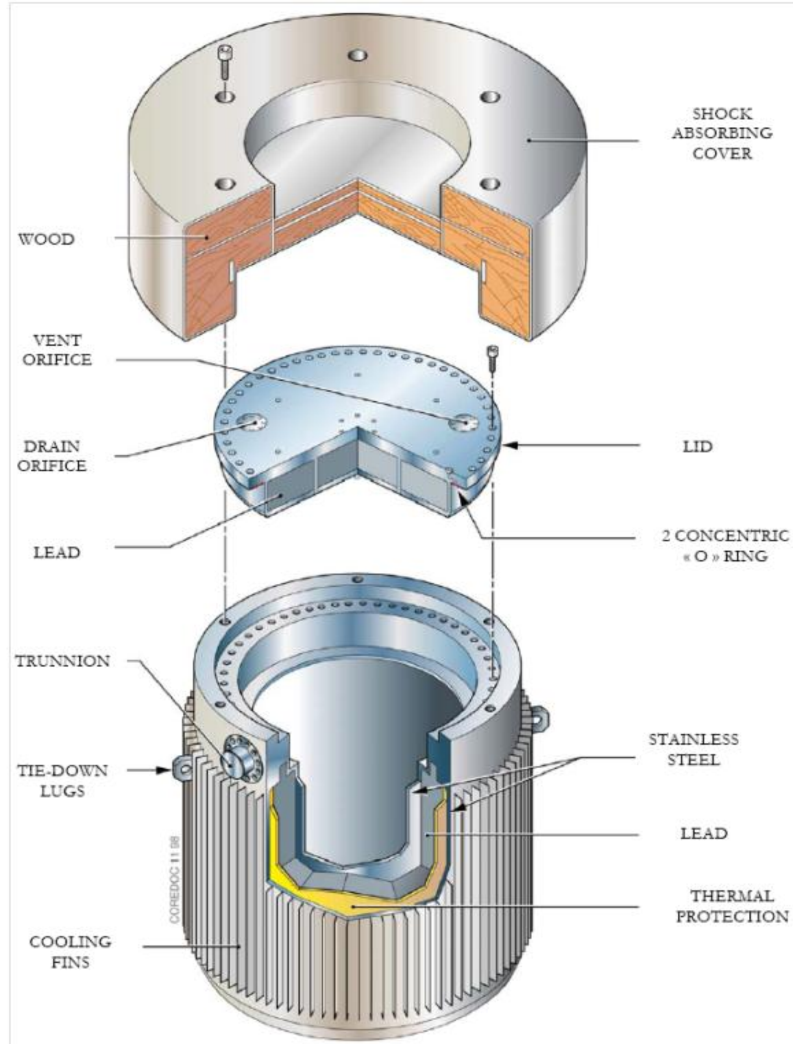
CeANG insertion into HDTAS



Handling inside hot cell at Mayak

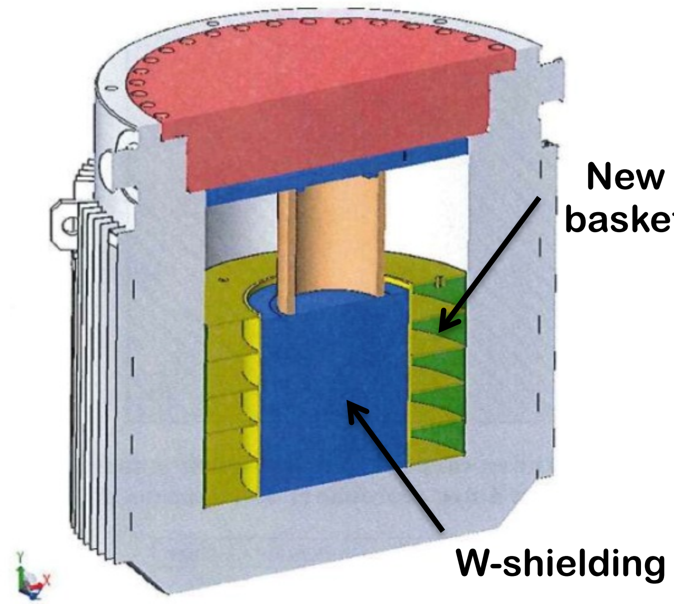
^{144}Ce-^{144}Pr Antineutrino generator transportation

TN MTR Transport Cask



TN MTR Certification for CeSOX

- **TN MTR**
  - Suitable container for Nuclear Fuel
  - 2 m ⃠ x 2 m height – M_{max} = 24 ton (30g ^{144}Ce…)
  - Large internal cavity (1 m ⃠ x 1 m height)
  - 4 existing casks (3 for AREVA TN, 1 for CEA)
  - Packed into a 20' ISO-container

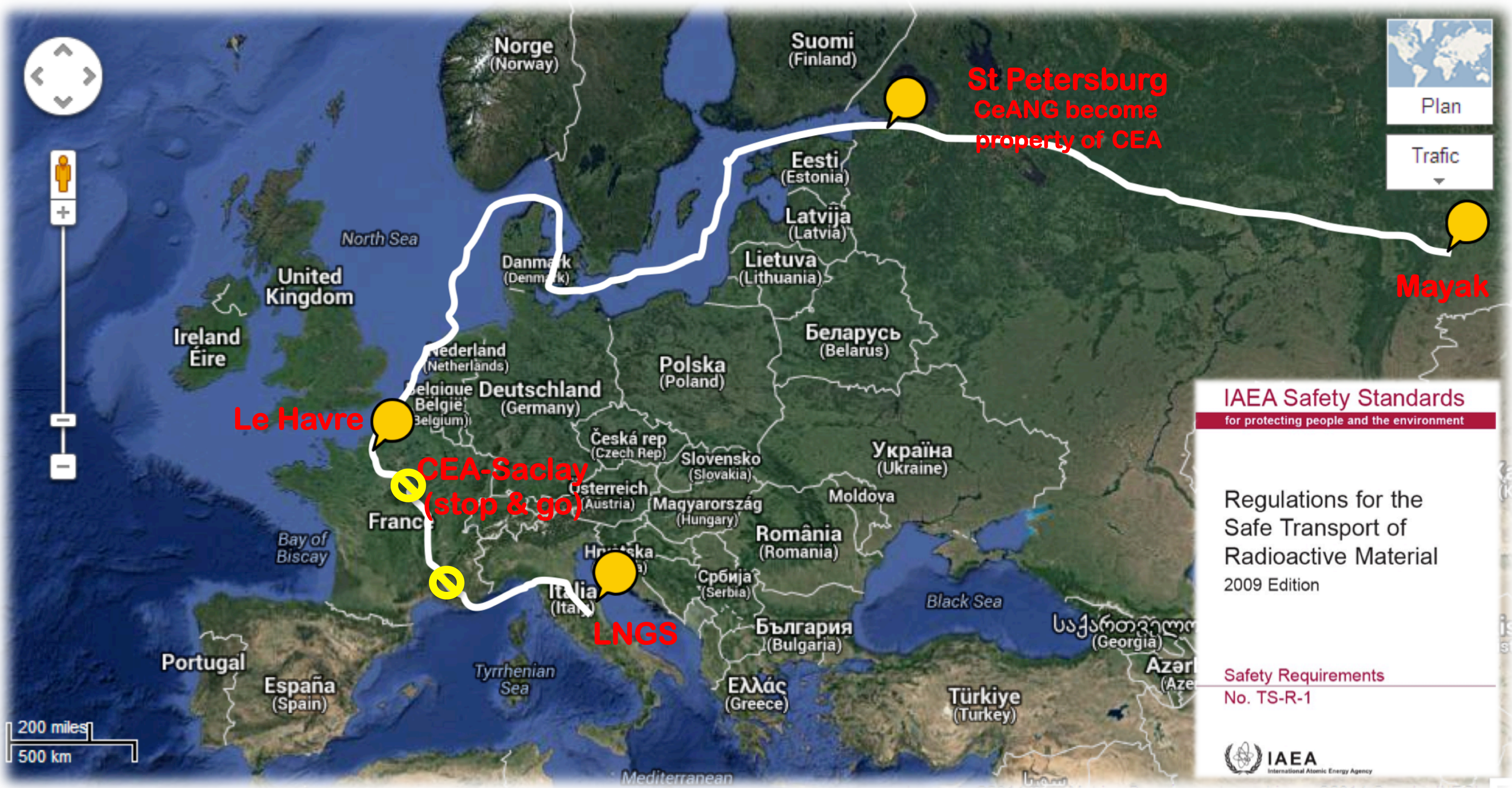


- **CeSOX package certification**
  - Engineering by AREVA TN & CEA
  - Thermal & Radioprotection studies
  - Need dedicated basket to hold the W-shield

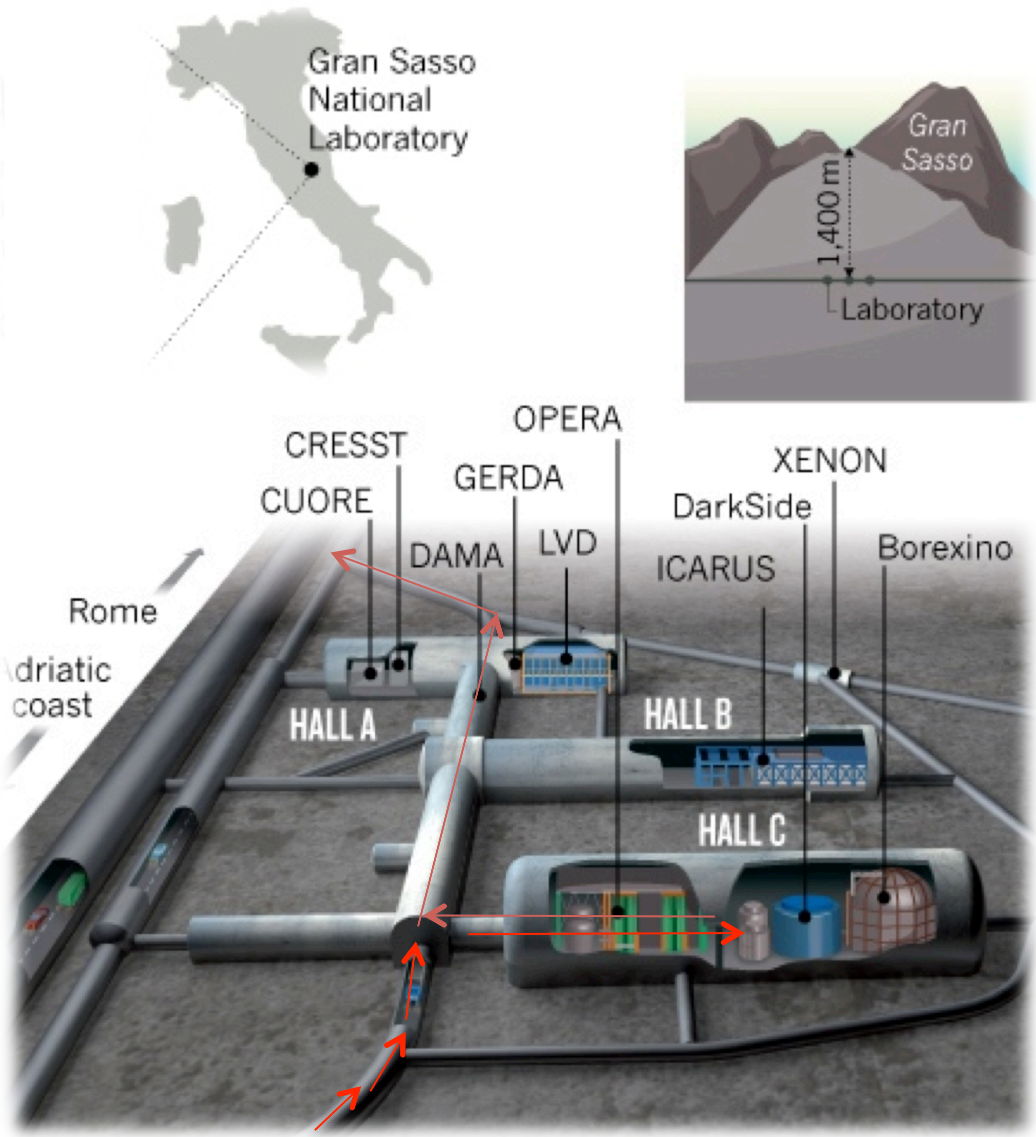
- **Status**
  - Request submitted to French authority (11/2014)
  - Validation expected by April 2015
  - Then need a validation in Italy (+4 months)

Transport Routes & Logistics

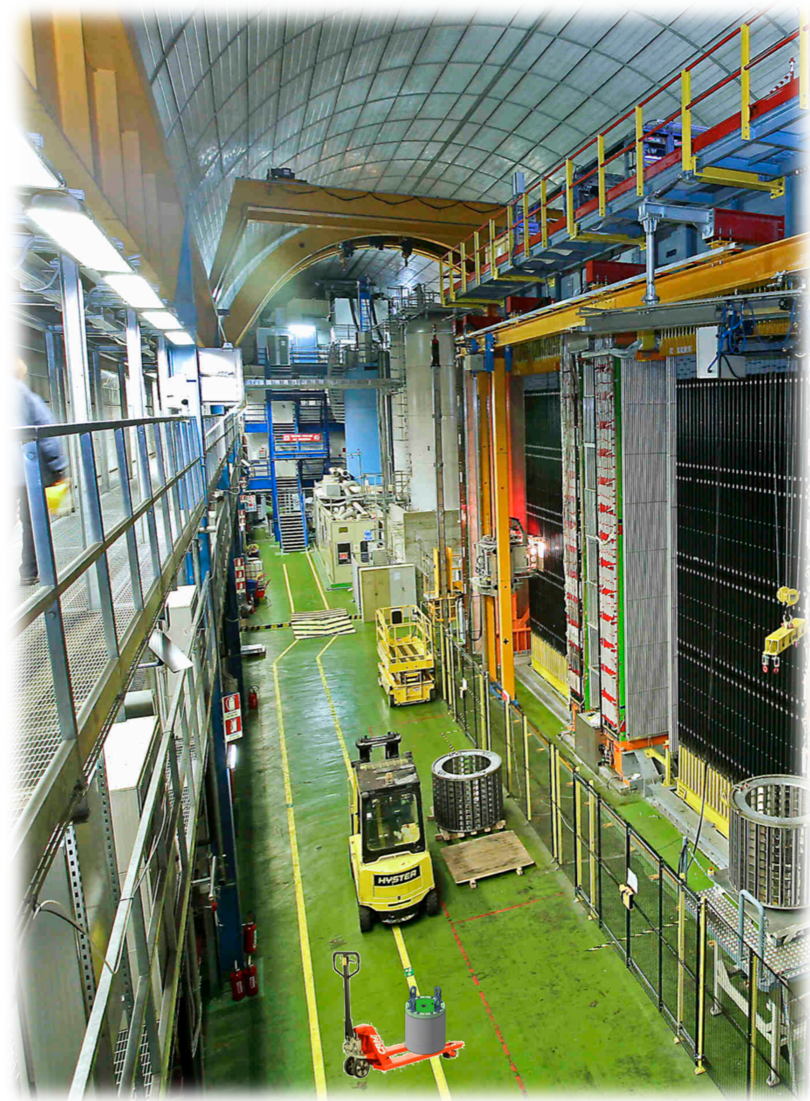
- IAEA Regulations for the Safe Transport of Radioactive Material
- Train / Dedicated Boat/ Truck: 3 weeks (5% activity loss)



Arrival of the CeANG at LNGS

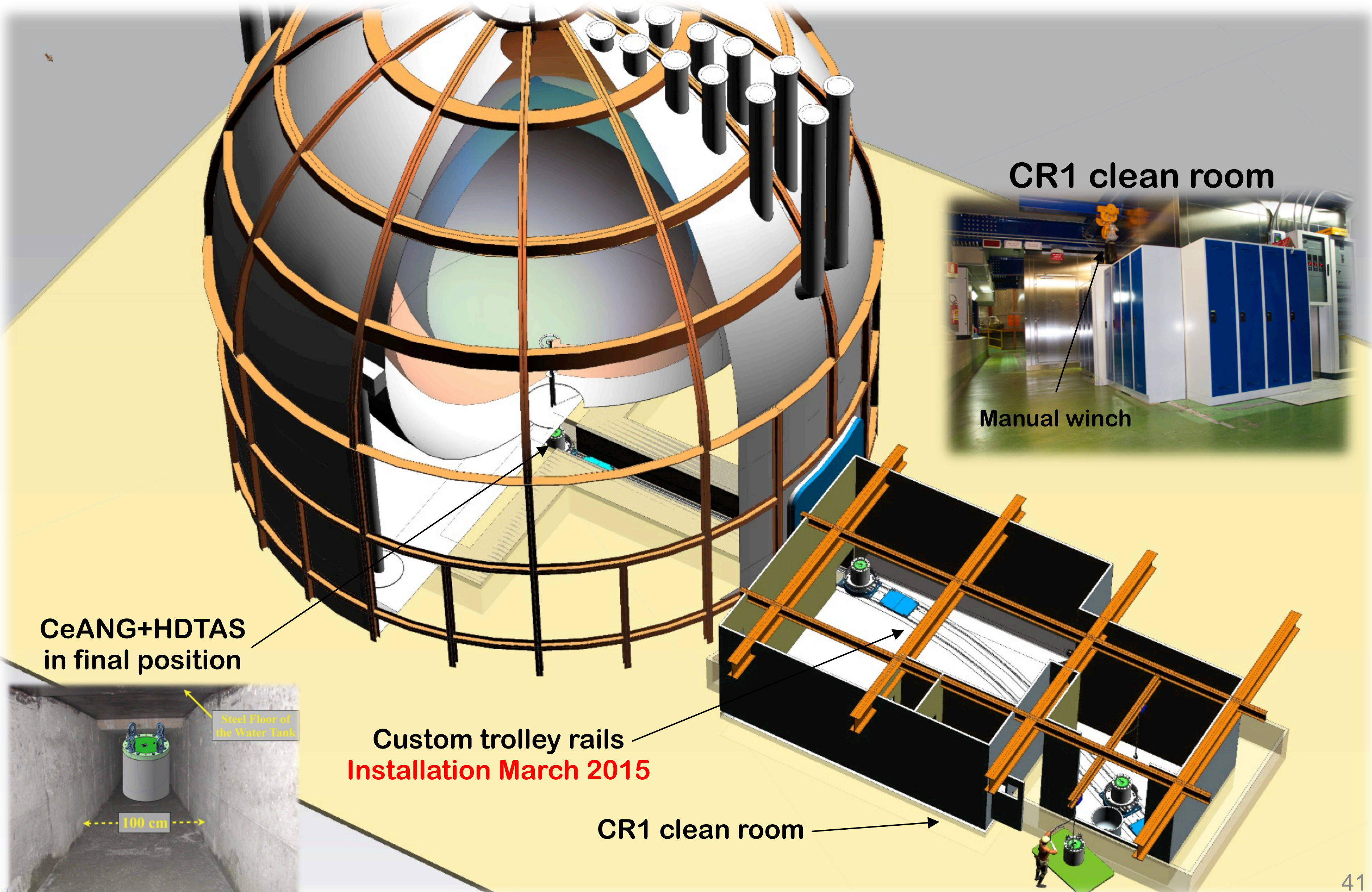


Gran Sasso National Laboratory



Hall C (Opera / Borexino)

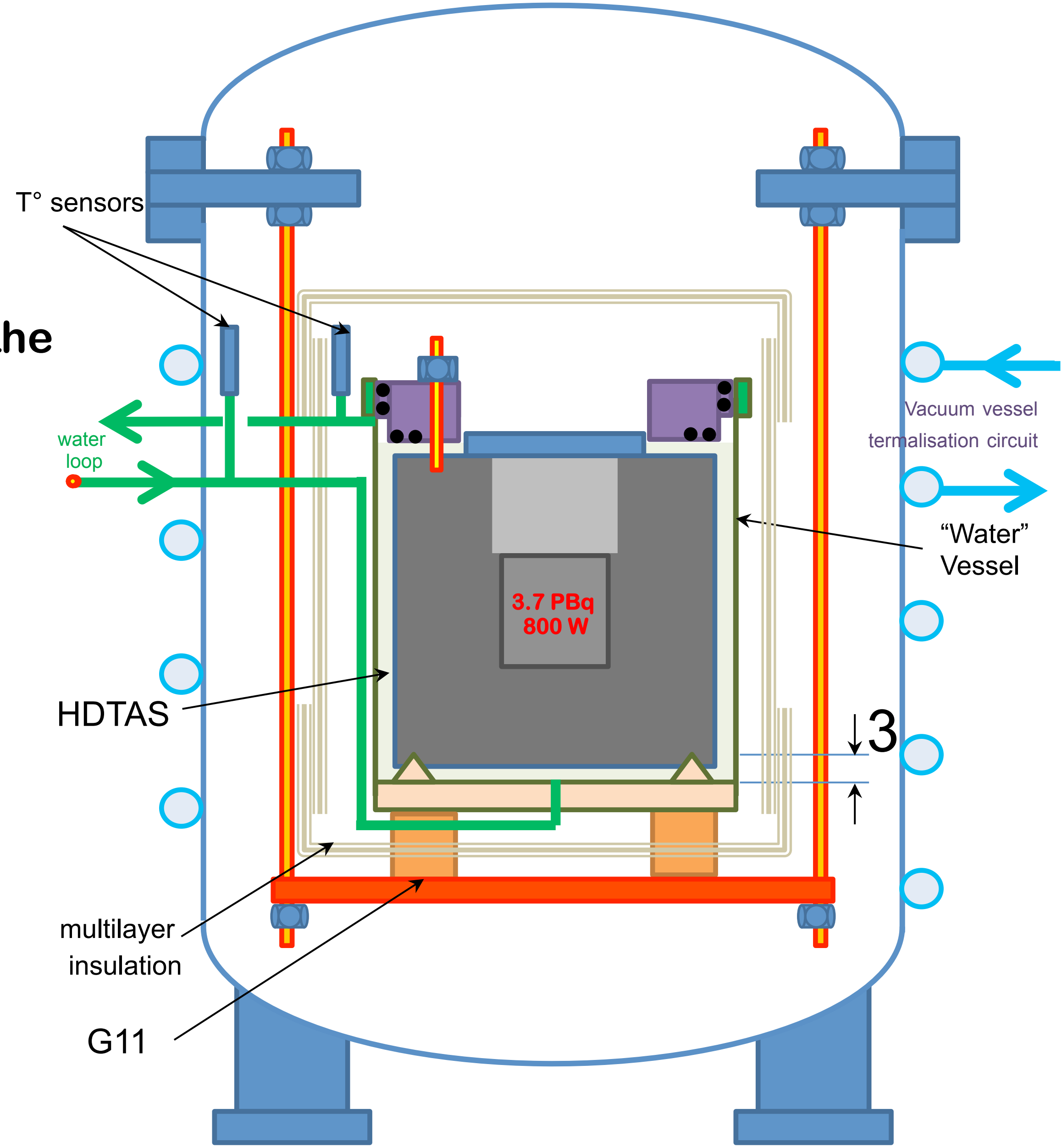
Inserting the CeANG beneath BX



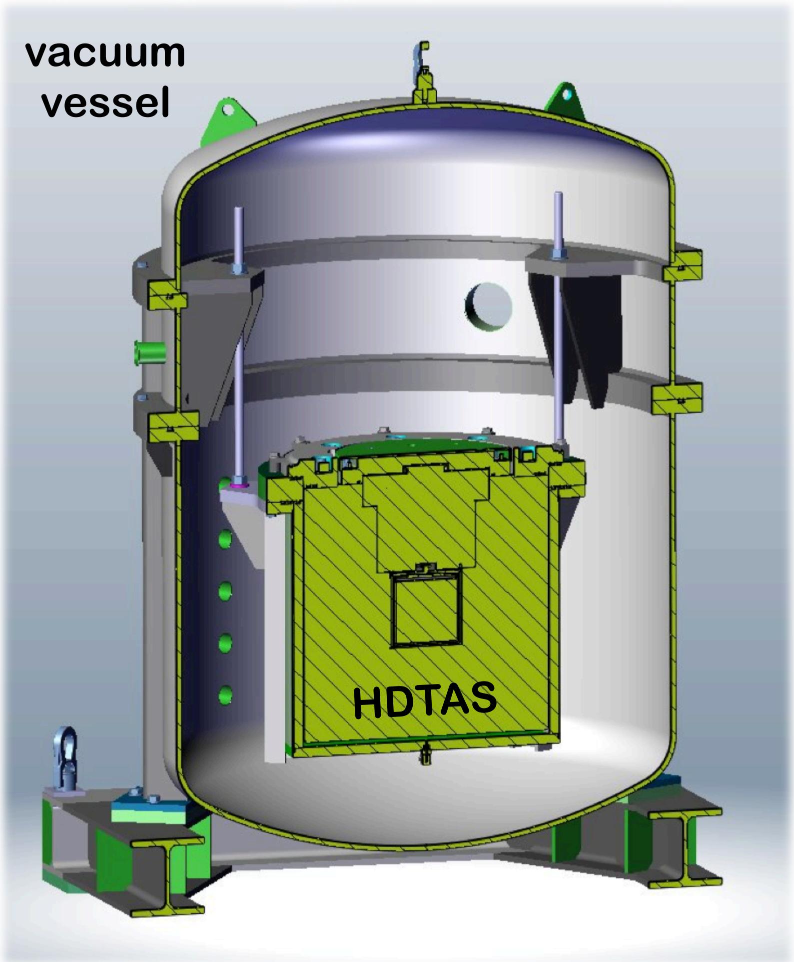
Neutrino Activity Measurement

Calorimetric measurement

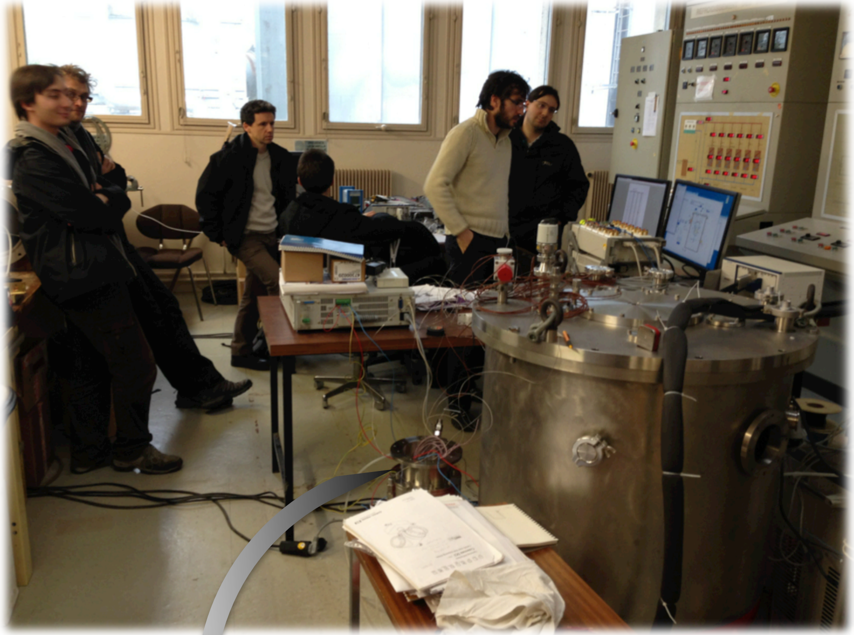
- **Measure CeANG Heat with a < 1.5% precision**
- **Mesure water flow and T° at the in/outlets:** $\dot{Q} = \dot{m}C\left(T_{in} - T_{out}\right)$
- **Preventing heat leaks**
  - **Conduction**
    - Suspension platform
    - insulation
  - **Convection**
    - Vacuum vessel
  - **Radiation**
    - Multilayer insulation
    - Vessel thermalization
- **Calibration with a dummy electrical source**

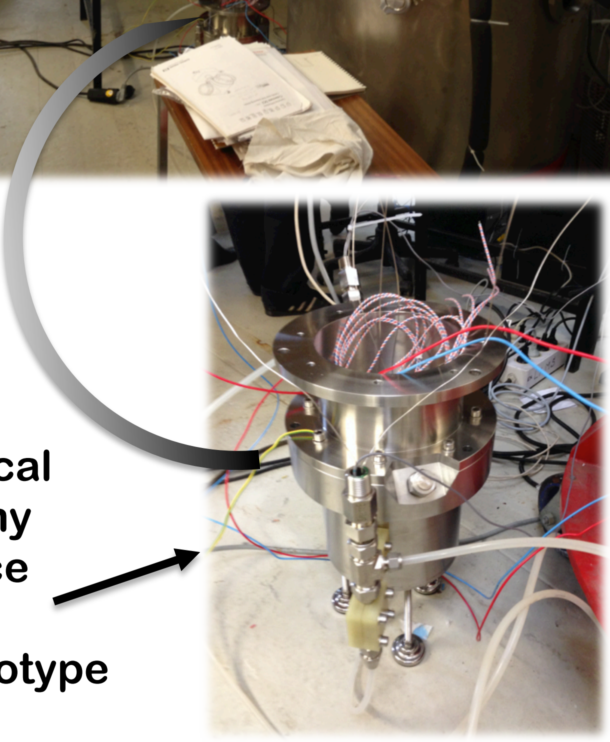


CEA Calorimeter



Earthquake proofed design

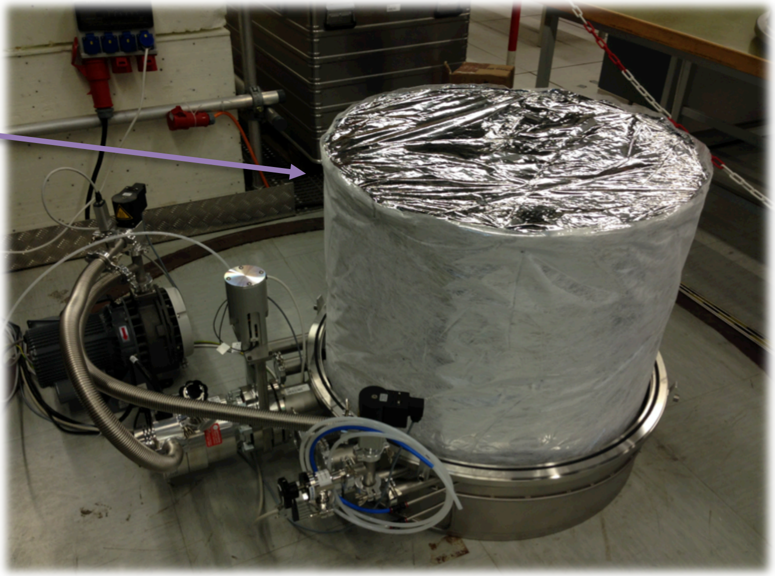


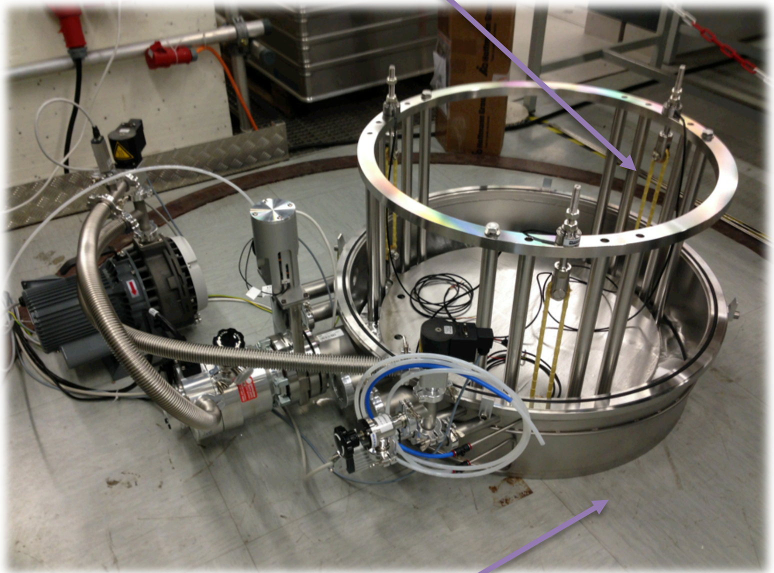


electrical dummy Source + Calo prototype

TUM/Genova Calorimeter

- Super-insulator (radiation)
- Isolating structure (conduction)

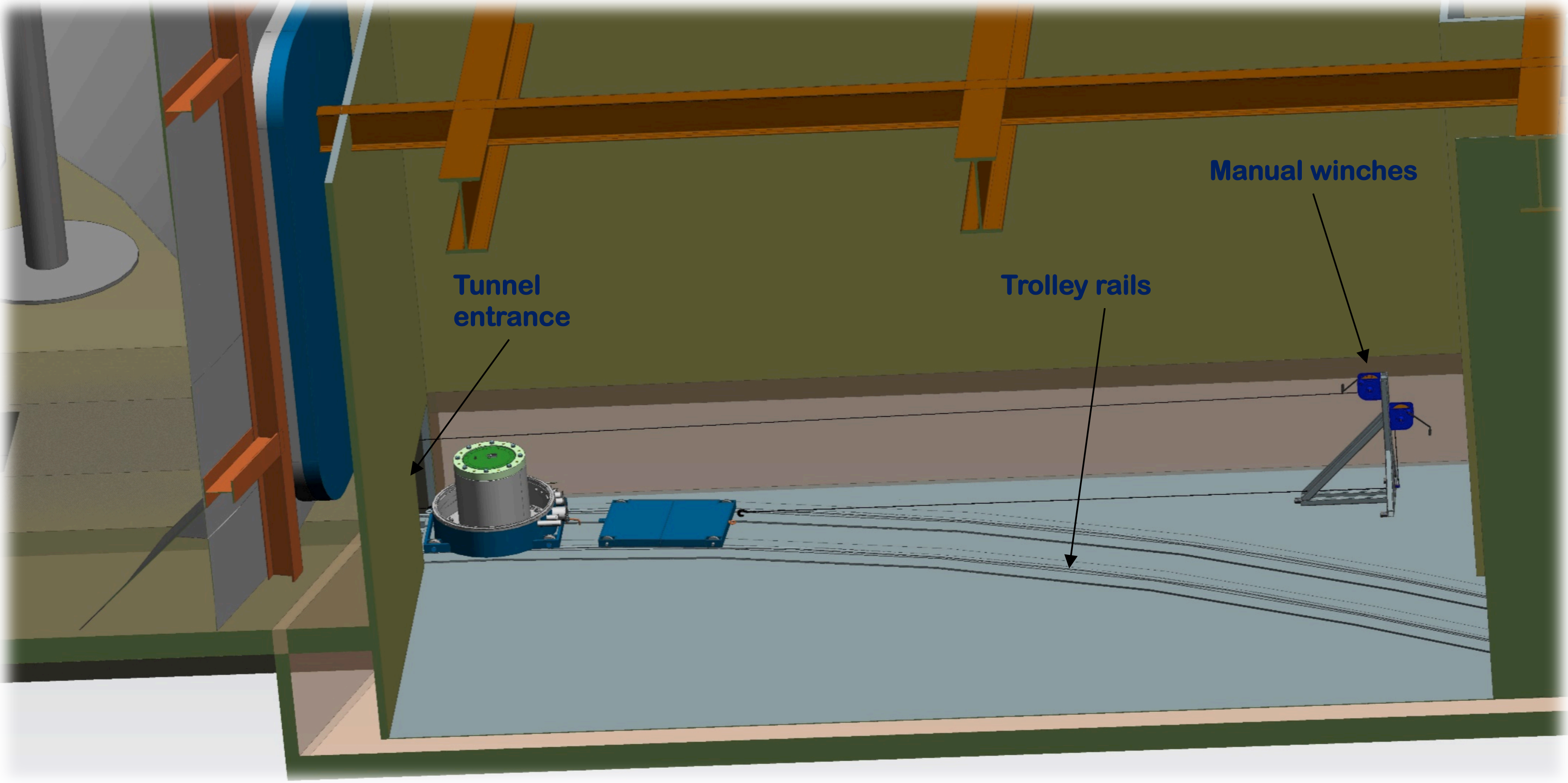




- Base supporting the HDTAS
- Vacuum chamber & Cooling

CeANG inside SOX pit @ LNGS

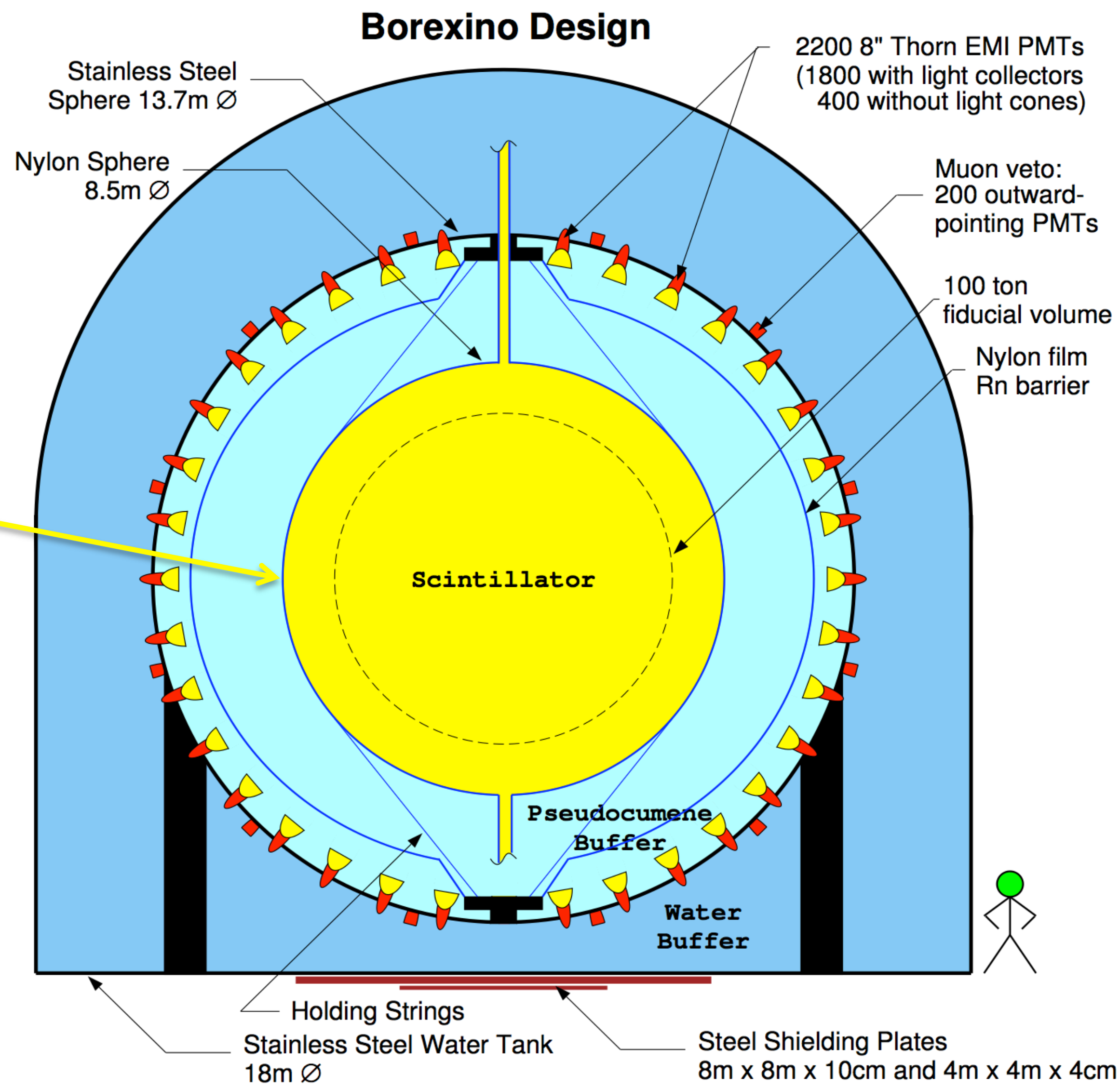
- Use based of TUM/Genova-Calo as trolley & cooling device
- Slide the CeANG into the pit – Radiation dose controls (0.5 y)



Deployment

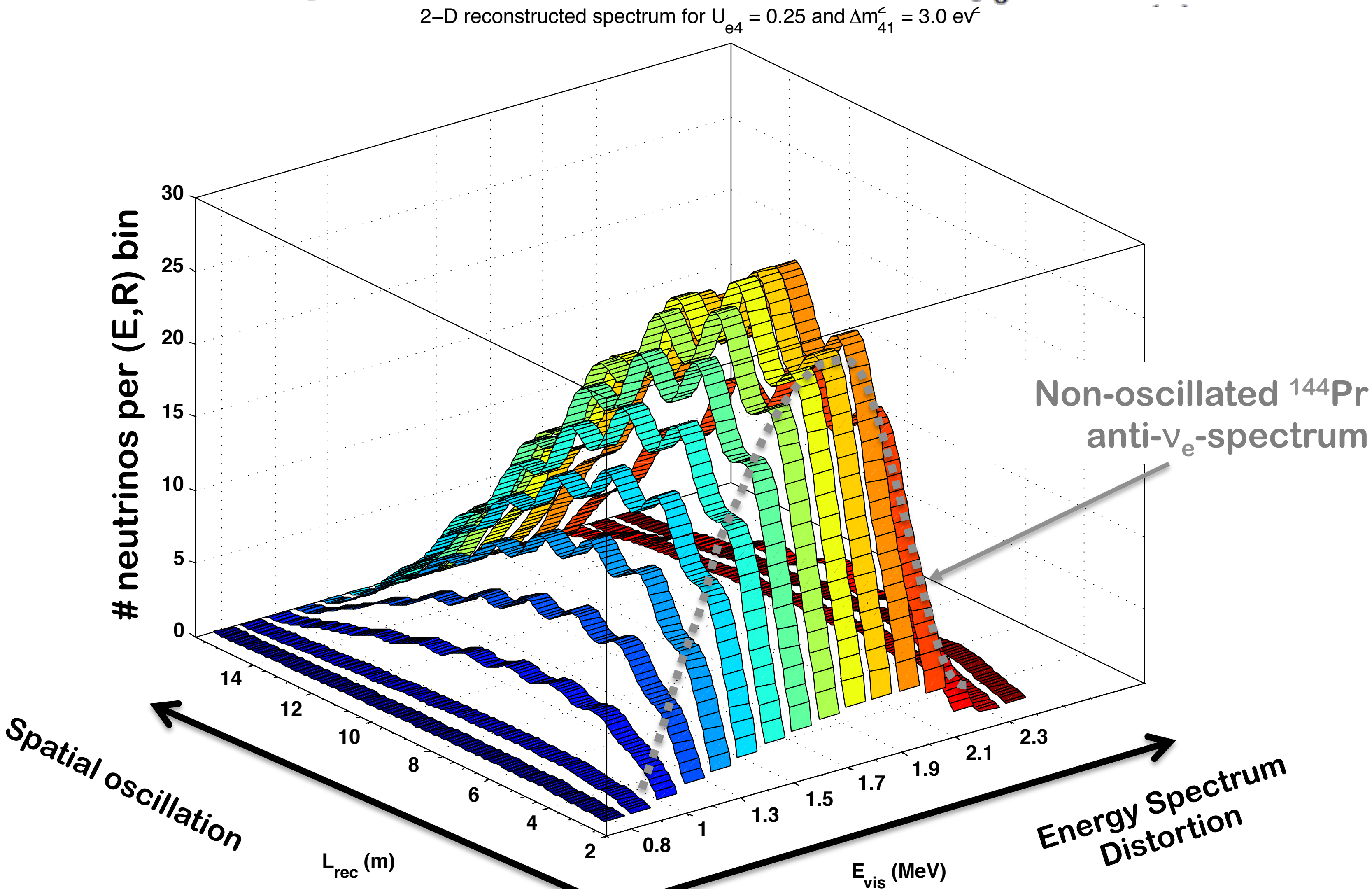
CeSOX target

- R < 4.25 m
- 280 tons
- C_6H_{12}
- #H: 1.7 10^{31}



Expected Signal if Oscillation

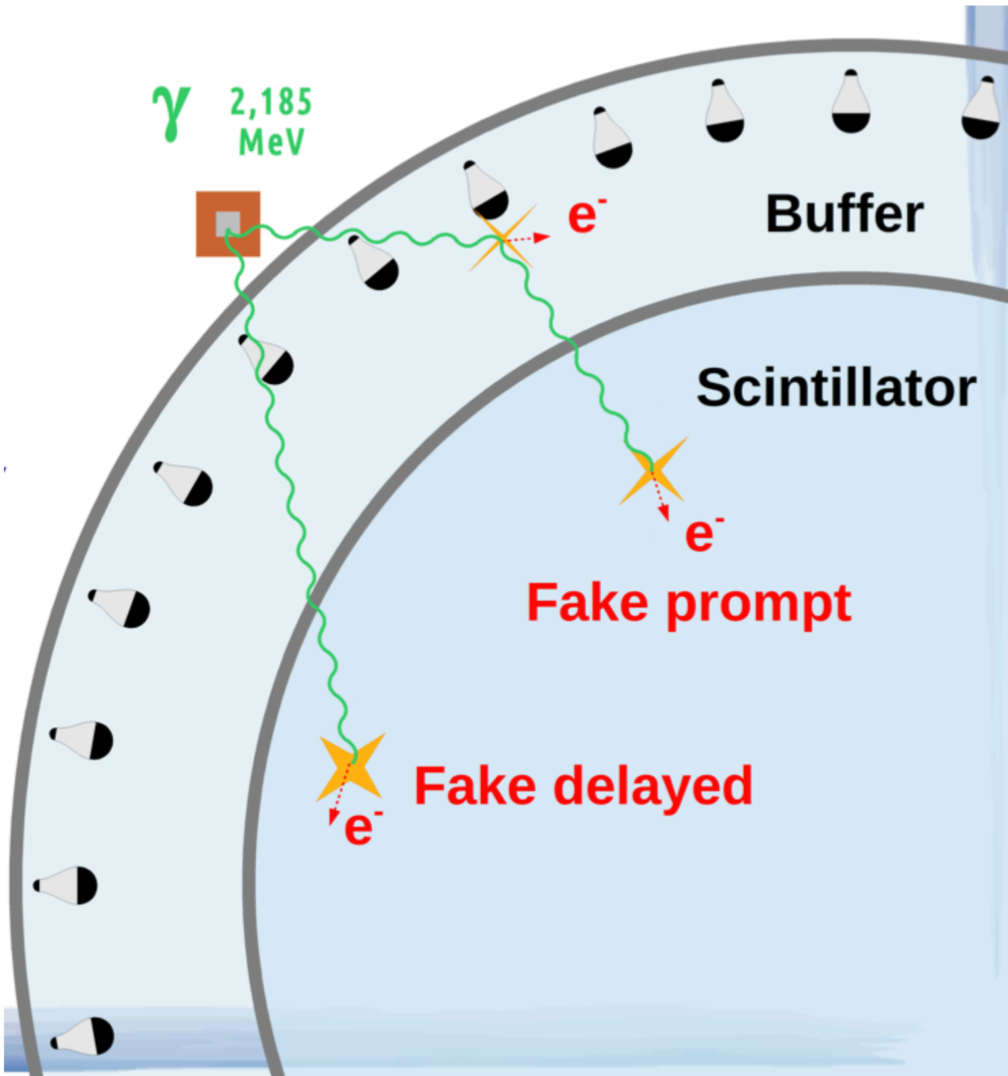
$$\frac{d^2N(R,E_\nu)}{dRdE_\nu} = \mathcal{A}_0 \cdot n \cdot \sigma(E_\nu) \cdot \mathcal{S}(E_\nu) \cdot \mathcal{P}(R,E_\nu) \int_0^{t_e} e^{-t/\tau} dt,$$



Th. Lasserre - Neutrino Telescope 2015

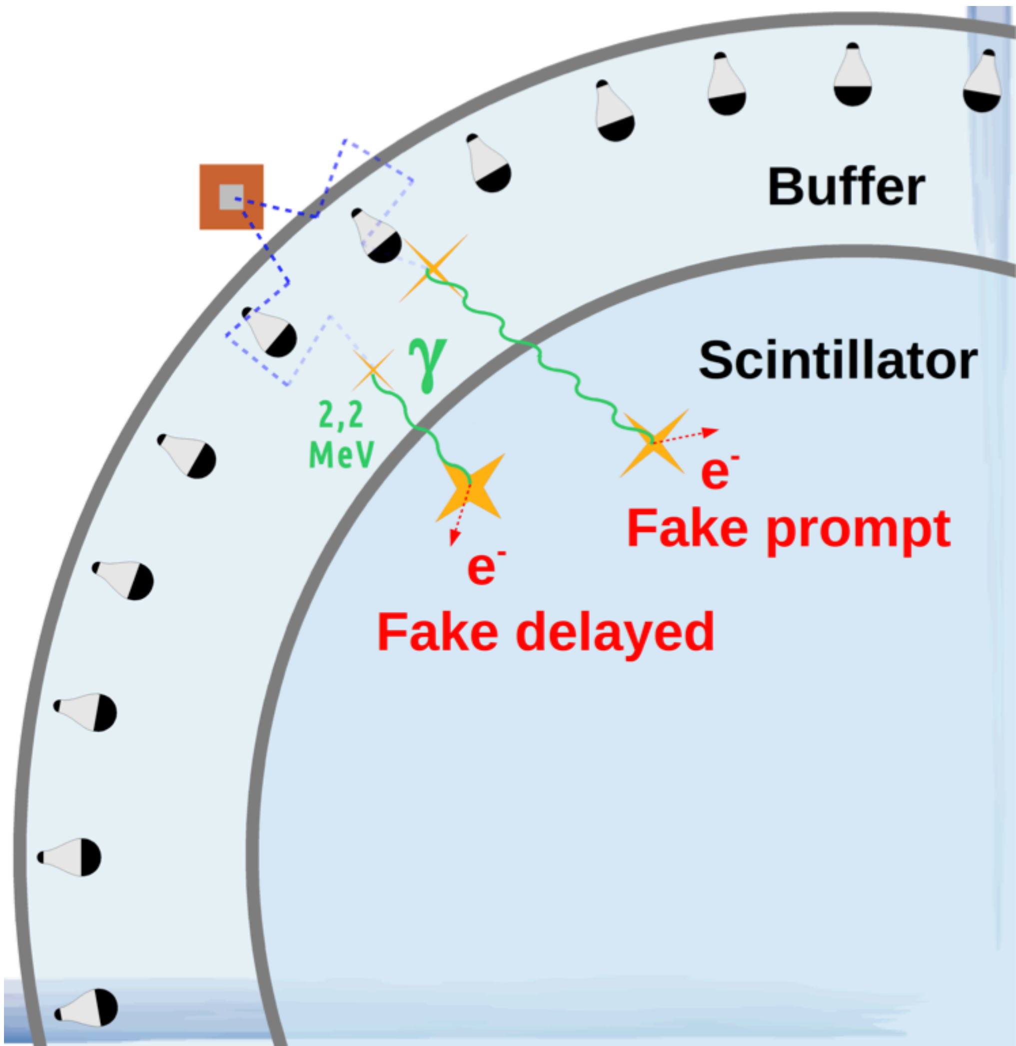
Gamma Background

- **Random coincidence between two γ's from CeANG**
- **IDB-like event:**
  - Prompt: $E_\gamma > 1$ MeV
  - Delayed: E_d in [2 – 2.4] MeV
  - Time window: 1 ms (3 τ)
- **Simulations**
  - GEANT4 (limited)
  - TRIPOLI-4
- **Results:**
  - 2 10^{-4} event/day (w/o E cut)
  - O(10^{-5}) event/day (w E cut)
  - 50% uncertainty
  - Negligible (HDTAS design)



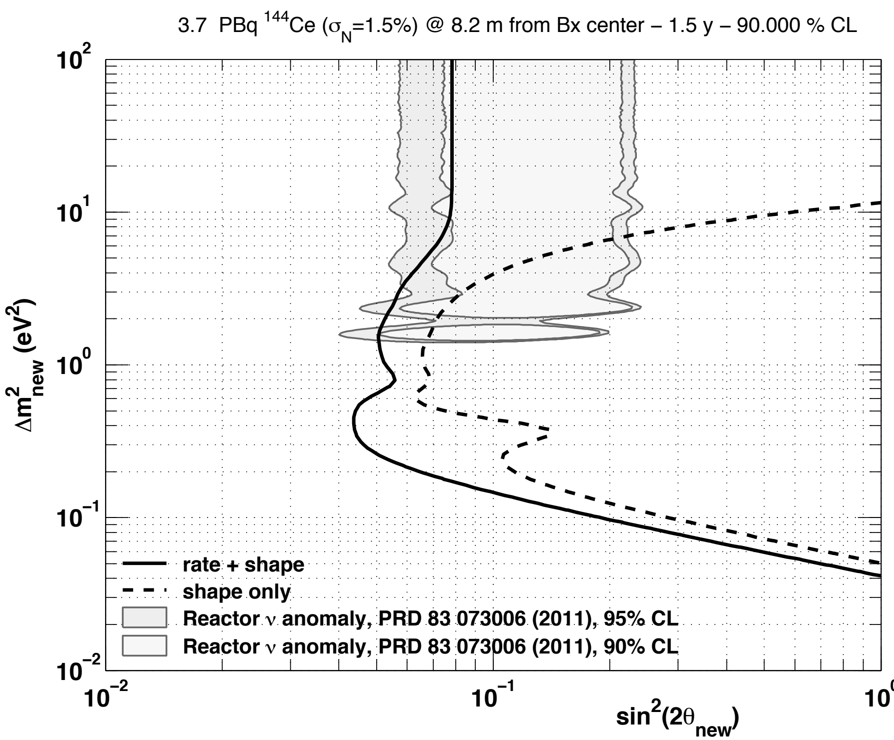
Neutron Background

- **Minor actinides SF fission**
  - 10^{-5} Bq ^{244}Cm / Bq ^{144}Ce
- **2 neutrons captured in BX releasing 2 γ's**
- **IDB-like event:**
  - Prompt: $E_\gamma > 1$ MeV
  - Delayed: E_d in [2 – 2.4] MeV
  - Time window: 1 ms (3 τ)
- **Simulations**
  - TRIPOLI-4
- **Results:**
  - < $O(10^{-2})$ event/day
  - 50% uncertainty

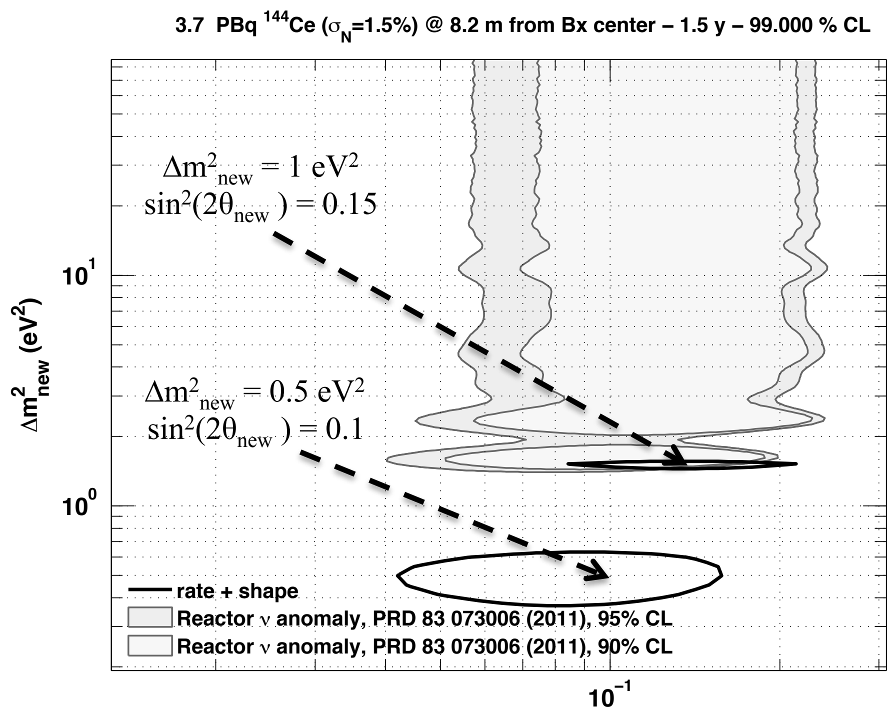


Sensitivity Studies

3.7 PBq (100 kCi) - 1.5 year of data taking
Activity measurement uncertainty: 1.5%
Shape only analysis (- - -) & Rate + Shape analysis (---)



Exclusion contour (90% CL)



Discovery potential (99% CL)

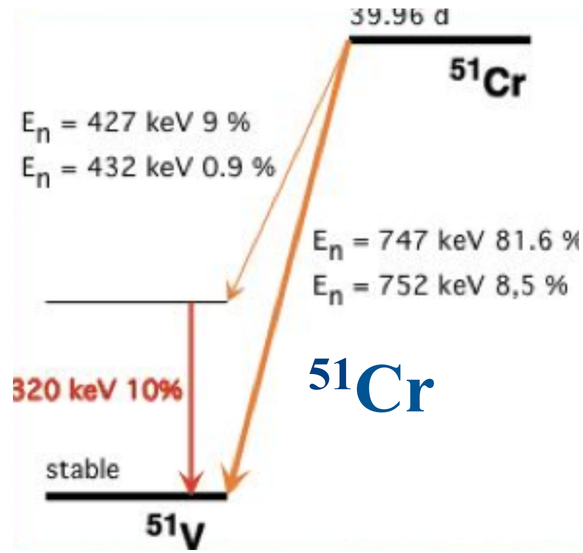
CrSOX:

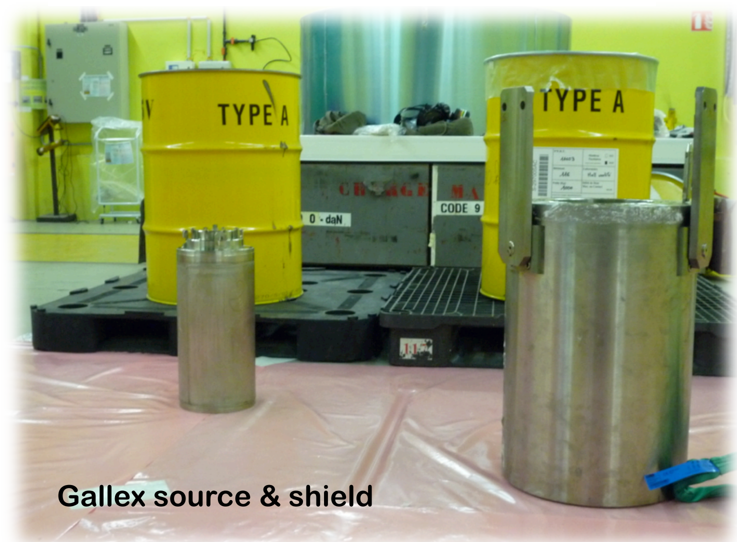
^{51}Cr next to Borexino

(Borexino Collaboration)

^{51}CrSOX overview

- ^{51}Cr (EC decay)
  - E = 0.75 MeV
  - $t_{1/2}$ = 26 days
- Production through n_{th} irradiation of enriched ^{50}Cr in a nuclear reactor
- Need: 370 PBq ^{51}Cr
  - 62 PBq in Gallex/Sage
- Detection:
  - ν scattering off electrons
- Status:
  - R&D phase
  - To be deployed after CeSOX

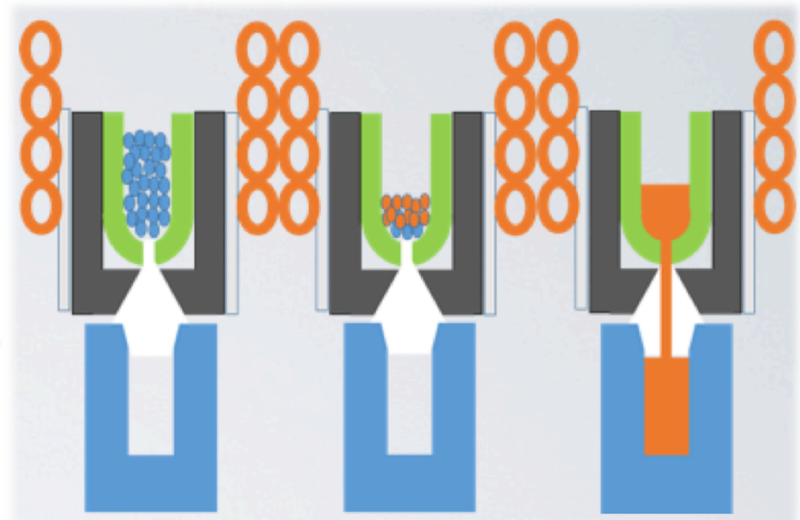




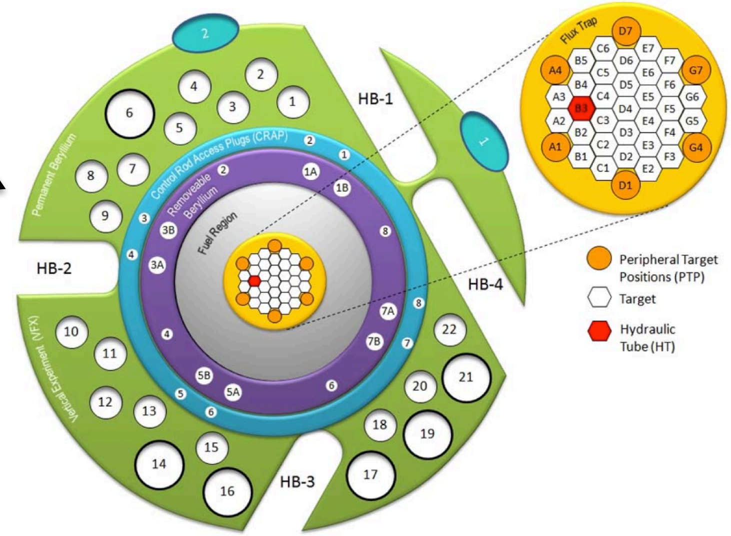
Gallex source & shield

^{51}Cr source production

- **Re-use Gallex 36 kg ^{50}Cr**
  - enriched ^{50}Cr (38.6%)
  - depleted in ^{53}Cr (0.7%)
- **Transform the Cr chips into 650 metal rods**
  - Induction melting
  - Impurities?



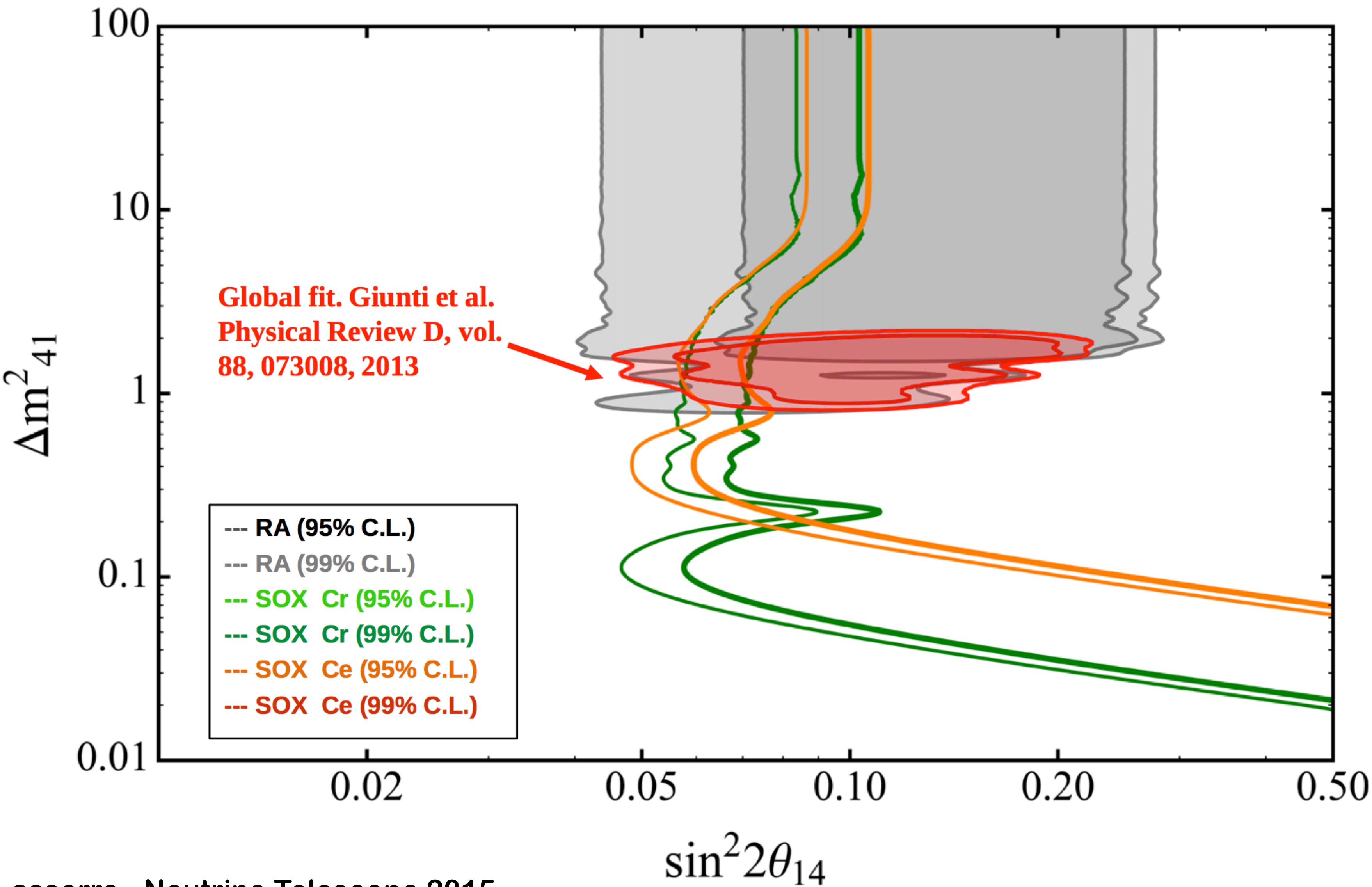
- **Irradiation at Oak Ridge HFIR**
  - 1 or 2 40 days cycle(s)
  - 180 PBq could be reached



- **After irradiation**
  - Insertion in a custom made capsule in hot cell
  - Quick flight to Italy
- **Repeat operations to reach 10 MCi**

CrSOX sensitivity

370 PBq ^{51}Cr source in 1 shot. Continuous activity measurement



Conclusion & Outlook

- **CeSOX**
  - **CeANG:** 3.7 PBq to be delivered in June-August 2016
  - **Shielding:** Ordered to Xiamen (China)
  - **Logistic**: Engineering design completed. TN-MTR licensing ongoing.
  - **Activity Calibration**: 2 calorimeters being realized
  - **Borexino Upgrade:** Rail system installation in 03/2015
  - **Risk:** legal authorizations - schedule

- **CrSOX**
  - **CrNG:** Feasibility study for producing 2 x 180 PBq at Oak Ridge
  - **Deployment**: after CeSOX