The reactor anomaly and its testing with high intensity neutrino generators

16th LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

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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	**2.7 σ**
Cosmology	Big-Bang	All	Number of ν, N_{eff}	N_{eff} = 3 or 4 allowed	

Could be interpreted with a 4th light neutrino state
But no satisfactory scenario describing all data together

Reactor Antineutrino Anomaly

PHYSICAL REVIEW C **83**, 054615 (2011) → Talk of D. Lhuillier

Improved predictions of reactor antineutrino spectra

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(Received 14 December 2010; revised manuscript received 9 March 2011; published 23 May 2011)

PHYSICAL REVIEW D **83,** 073006 (2011) → This talk

Reactor antineutrino anomaly

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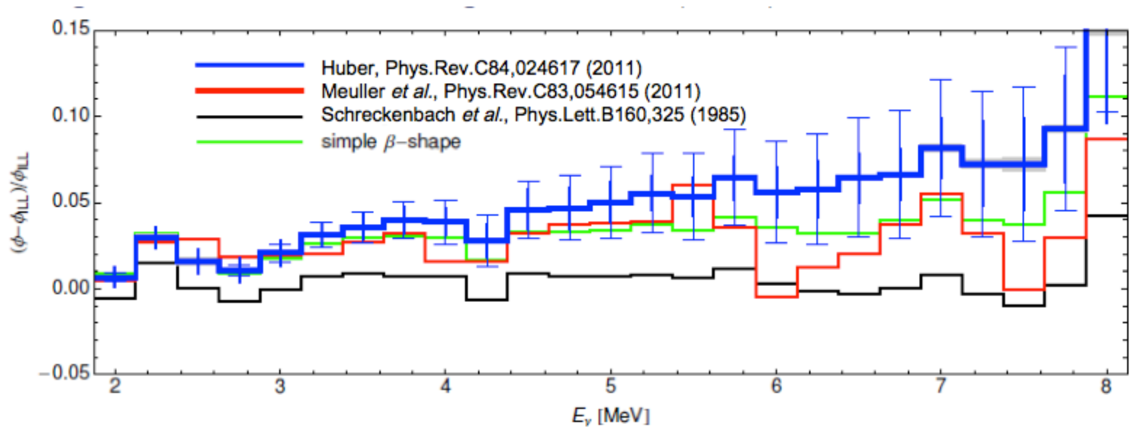
(Received 14 January 2011; published 29 April 2011)

Breakthroughs

i) $\nu_{emission}$: **Improved reactor neutrino spectra → <u>+3.5%</u>**

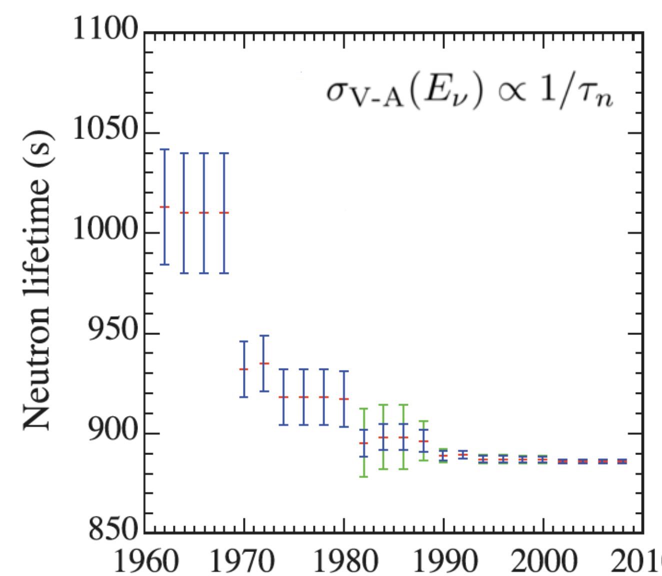


PRC83, 054615 (2011)

PRC84, 024617 (2011)

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

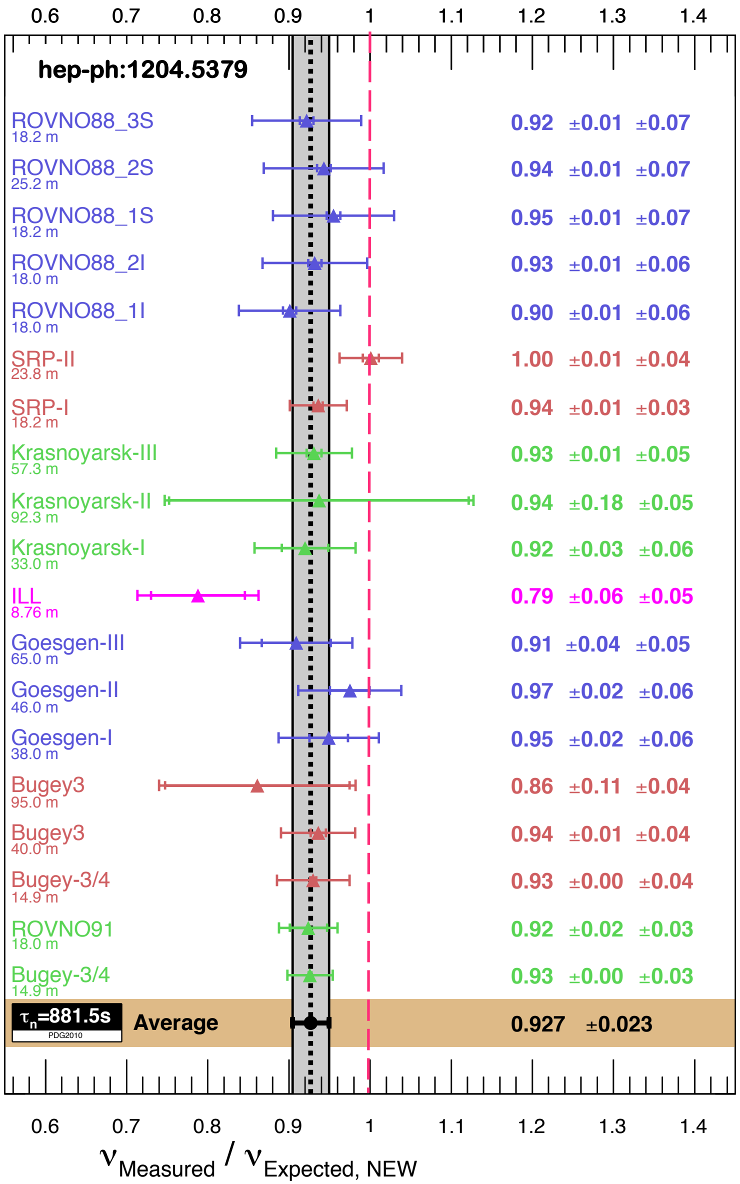
PRD 83, 073006 (2011)



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

PRD 83, 073006 (2011)

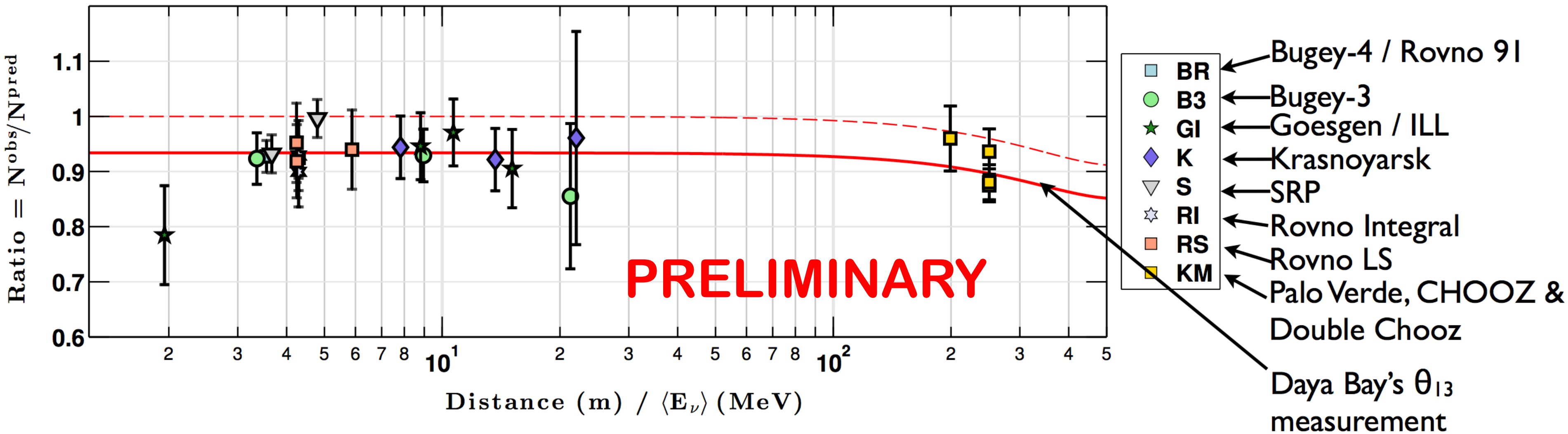
Implication for SBL experiments



- 19 ratios R of observed event rate to predicted rate of events (L<100m)
- 2011 results (PRD 83, 073006, 2011)
  - μ = 0.943 ± 0.023
  - 98.6 % C.L. deviation from unity
- 2012 results (hep-ph:1204.5379, WP)
  - μ = 0.927 ± 0.023
  - 99.7 % C.L. deviation from unity
- 2013: update to be submitted soon

Update with km-scale experiments

Update of 2011 reactor anomaly pub. [PRD83, 073006] to be submitted soon

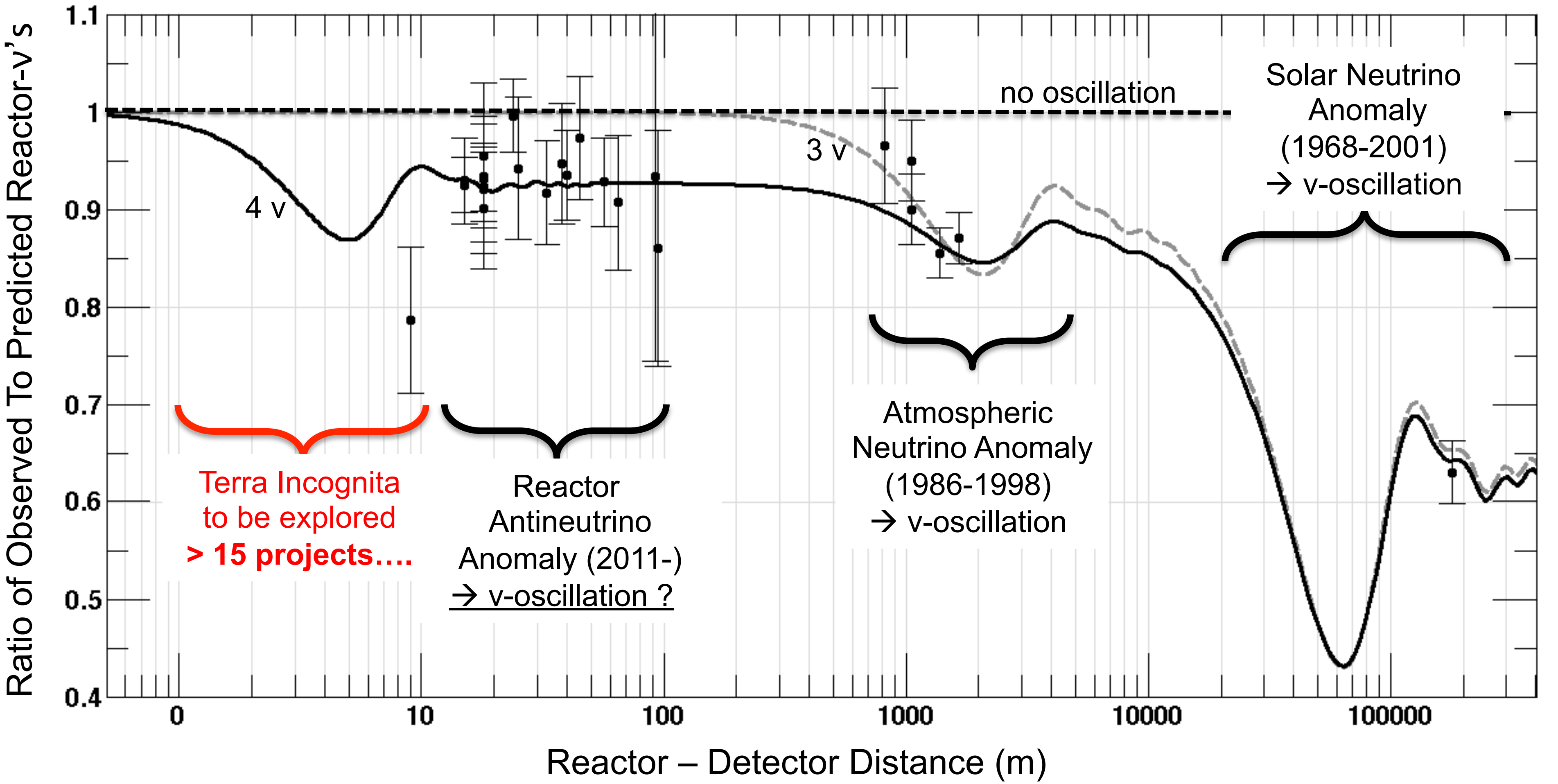


- Refined treatment of correlations (measurements vs predictions)
- Includes all known nuclear corrections to β - ν spectra.
  - combining: PRC83, 054615 & PRC 84, 024617
- Corrected for a statistical bias in the previous method (1% shift)
- Includes the latest updated neutron mean life (τ_n = 881.5 s).
- Includes km-scale baselines (Chooz, DC, PV)
  - correcting for θ_{13} deficit from Daya Bay's measured value
- 2013 result: μ = 0.936 ± 0.024, 98.6 % C.L. deviation from unity (2.7σ)

Current Experimental Status

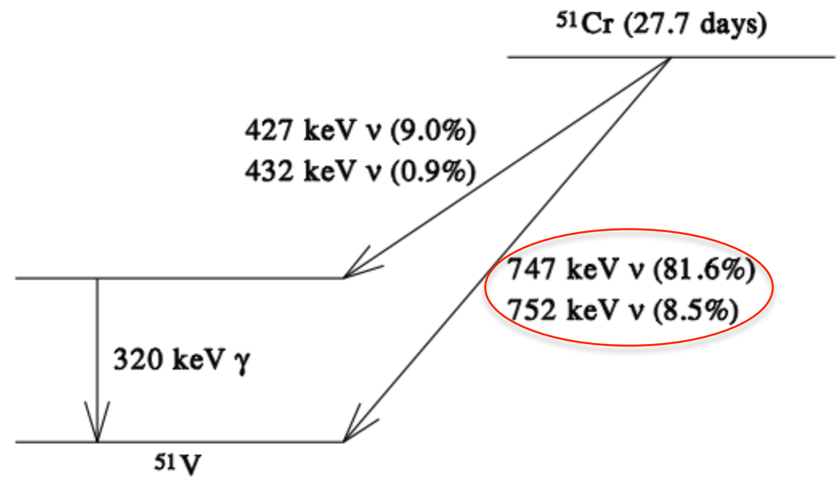
Do we face a real physical effect or an experimental artifact?

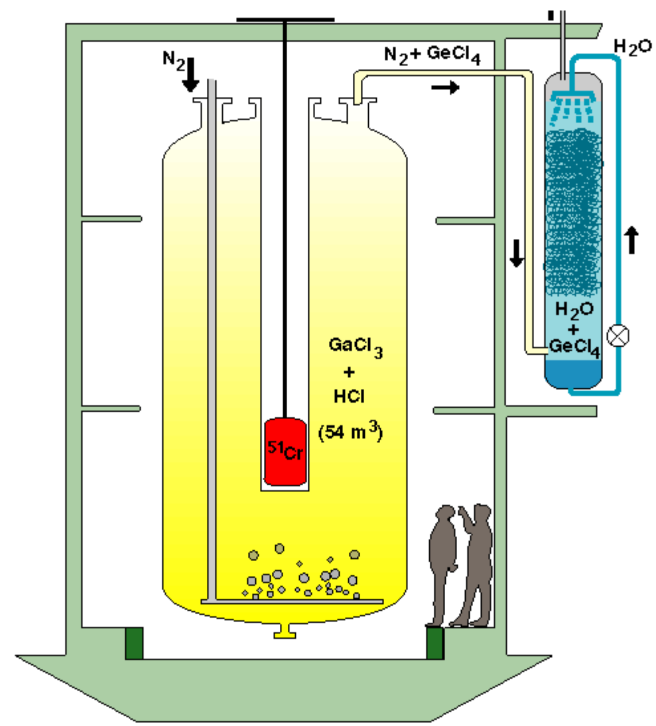
→ New experimental inputs are needed



The Gallium Neutrino Anomaly

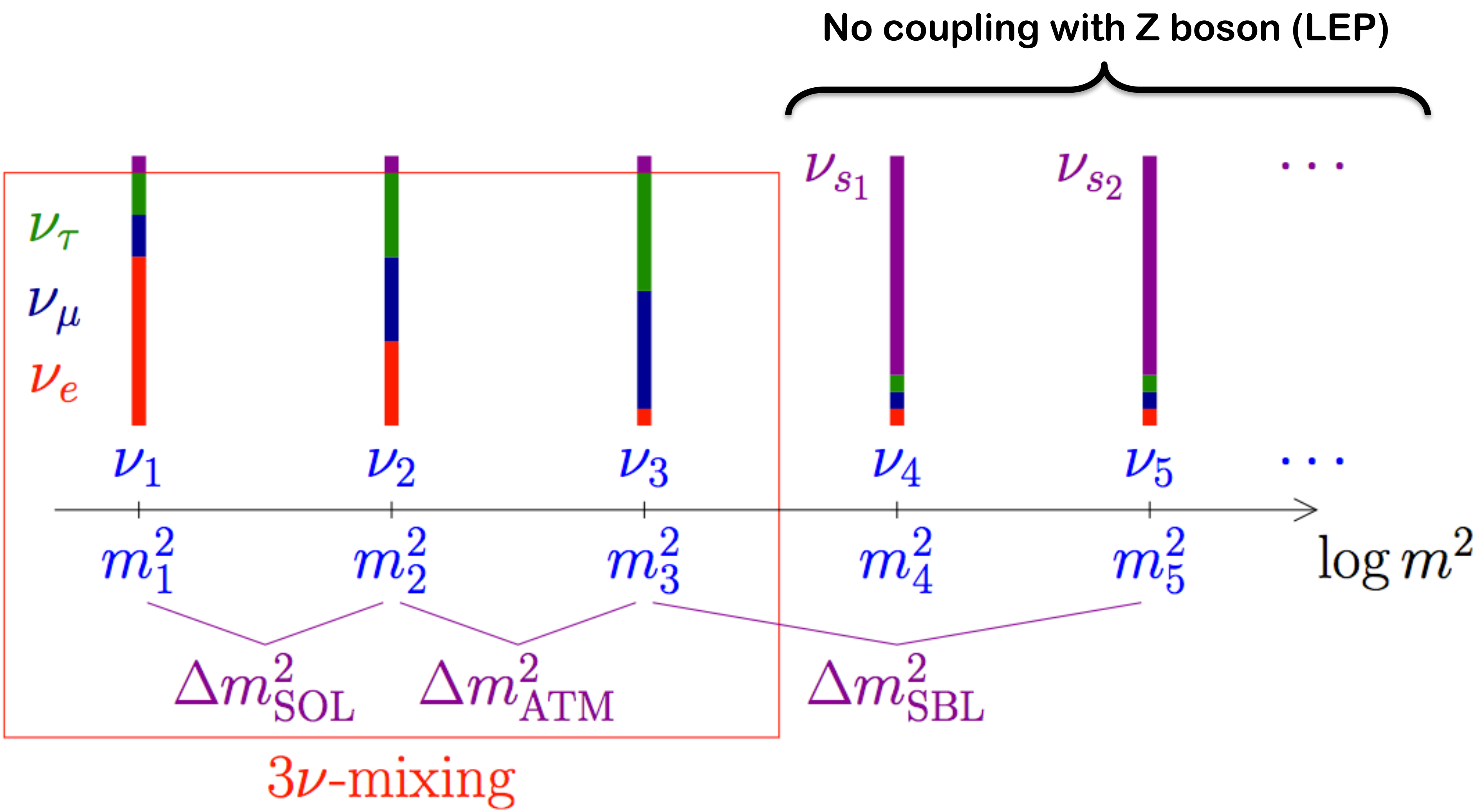
- **Test of solar neutrino detectors GALLEX and SAGE (ν_e's)**
  - **E ≈ MeV, baseline ≈ few m**
- **4 calibration runs ≈1-2 MCi EC ν_e emitters**
  - Gallex
    - ^{51}Cr source (750 keV)
  - Sage
    - ^{51}Cr & ^{37}Ar (810 keV)
- **Deficit observed**
  - $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
  - $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})





The (light) sterile neutrino hypothesis

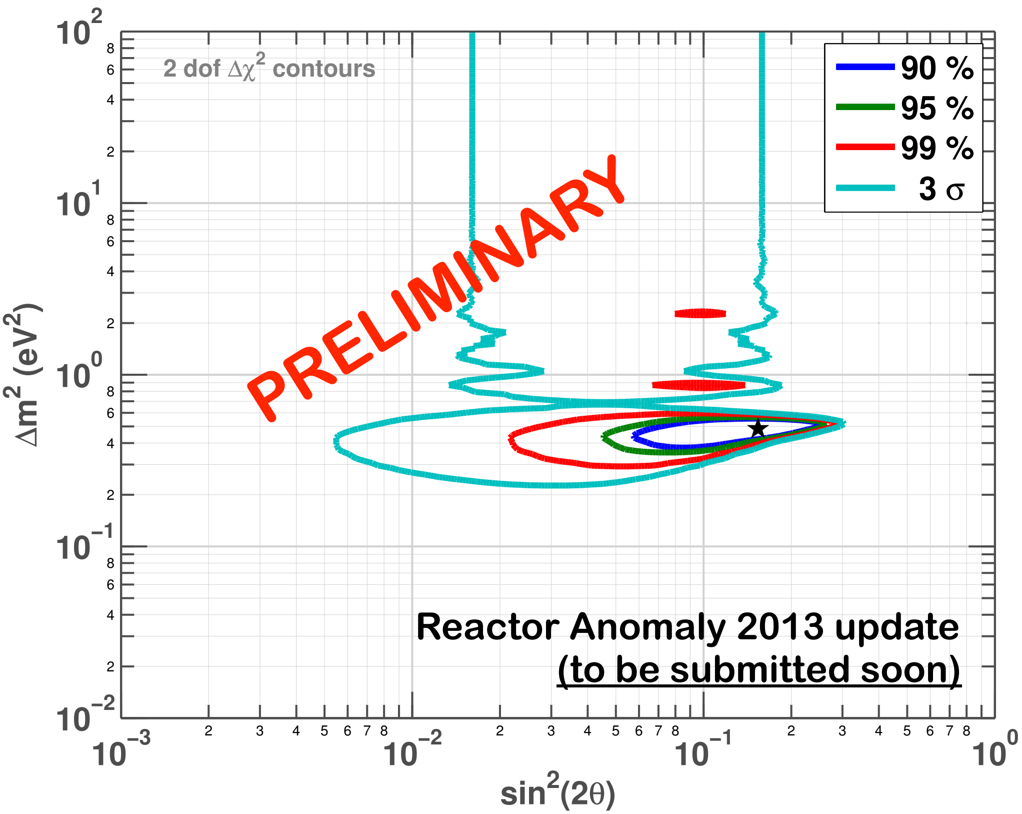
add a light ν_R to SM, no SM interaction but mixing with active ν' s

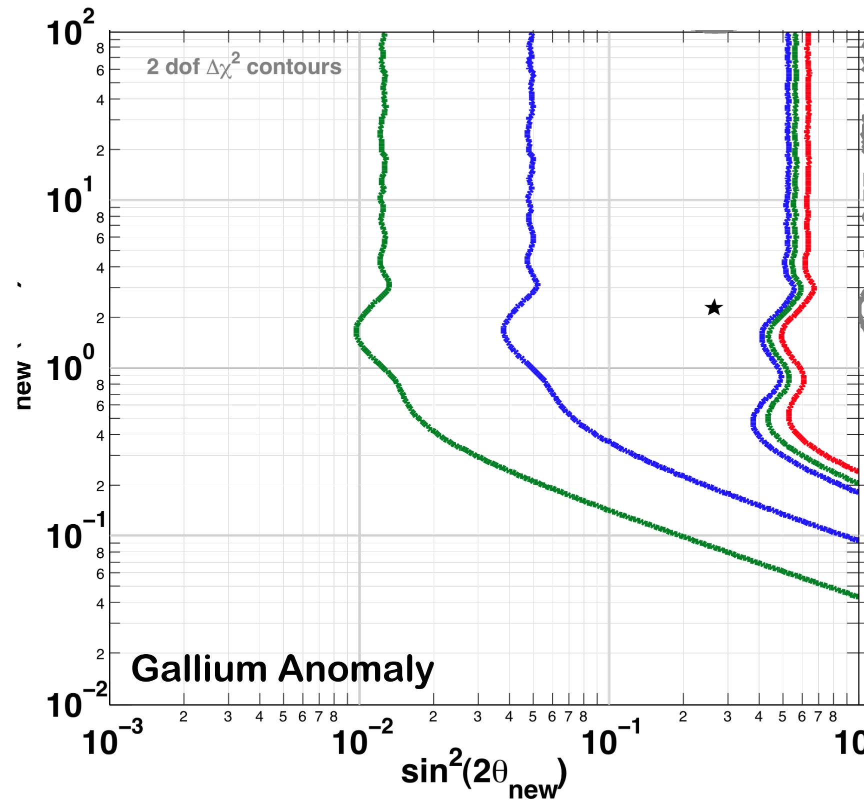


The 4th neutrino hypothesis

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)

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

- GA & RAA arise from comparisons between data and event rate prediction → Need a conclusive technique
- Input from sterile neutrino fits
  - $\Delta m^2 \approx 0.1\text{-}10\ eV^2$ → $L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2(eV^2)} \approx 2-10\ m$
  - $\sin^2(2\theta_{new}) \approx 0.1$
- 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

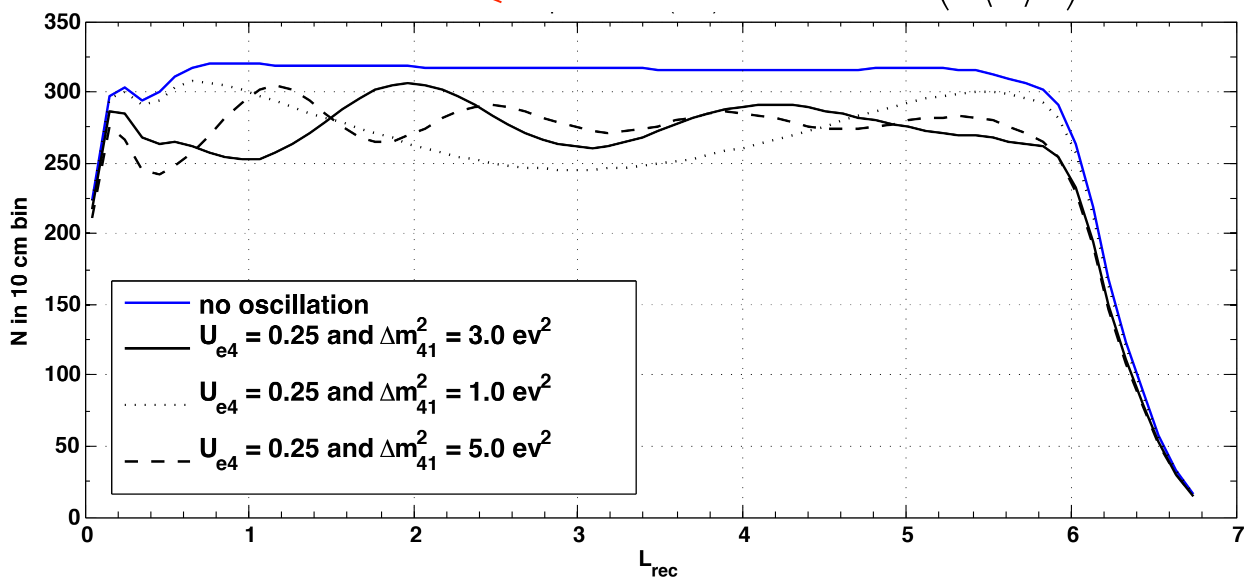
Test with high intensity (anti-)neutrino generators

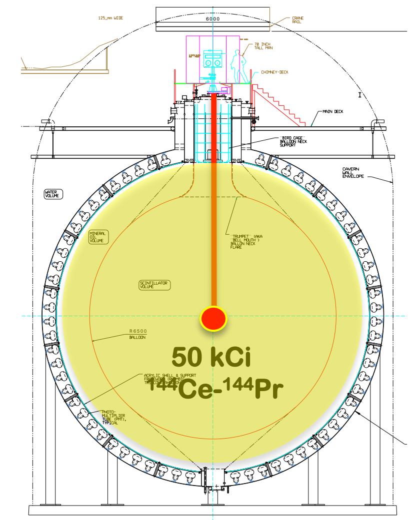
ν generator proposals

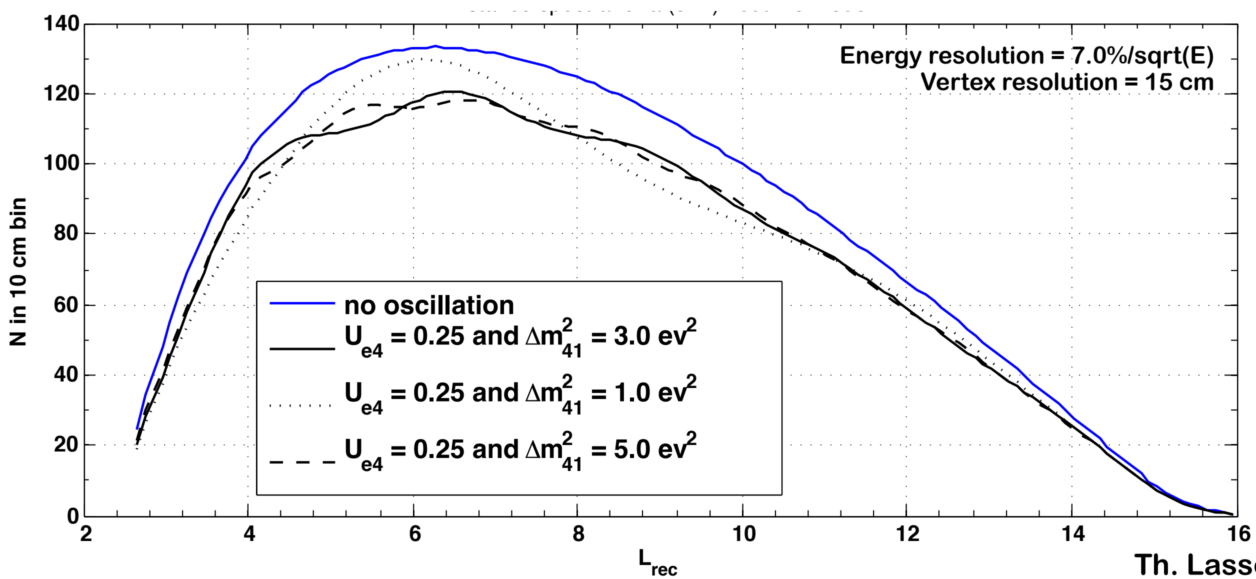
Type	Detection	Background	Source Type	Production	Activity (MCi)		Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (not inside)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	>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	^{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		-	-	-
			Tritium	Irradiation in reactors	out	3e-6	KATRIN

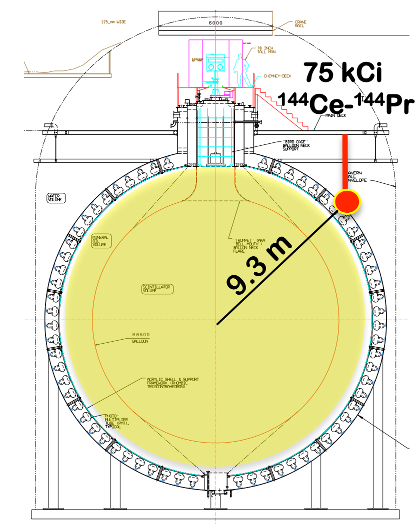
Rate-only search for $\nu_e \rightarrow \nu_s$

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









^{51}Cr

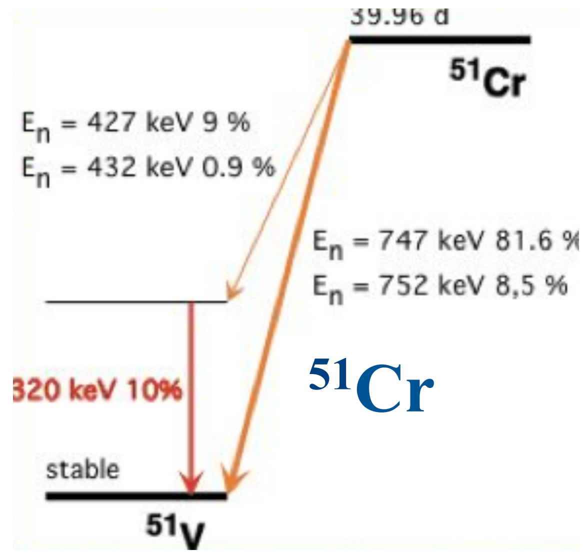
^{51}Cr neutrino generator

- ^{51}Cr EC
  - E = 0.75 MeV
  - $t_{1/2}$ = 26 days

- Produced through n_{th} irradiation of enriched ^{50}Cr in a nuclear reactor

- Need 10 MCi ^{51}Cr
  - 2 MCi in Gallex/Sage

- Detection:
  - ν scattering off electrons
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$



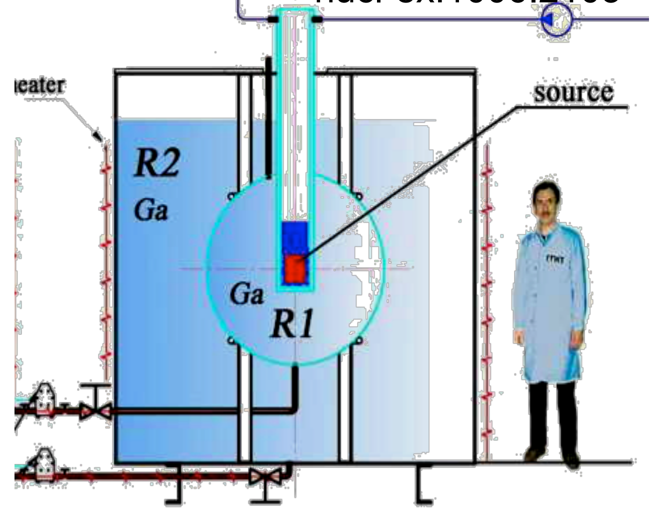
SAGE 2-Zone (INR)

- ^{51}Cr Source:
  - Enrichment of 3.5 kg ^{50}Cr (97%, 2014)
  - Irradiation to reach 3 MCi (2015?) at research reactor SM-3

- 2-layer detector in Baksan
  - Inside a new dual Metallic Ga Target
  - Zone 1: 8t - Zone 2: 42 t metal Ga
  - SAGE procedures well understood
  - Not sensitive to γ-ray background

- Observable
  - Ratio of ν_e capture rates to predicted rate in inner (R1) and outer zone (R2)
  - Ratio R_2/R_1

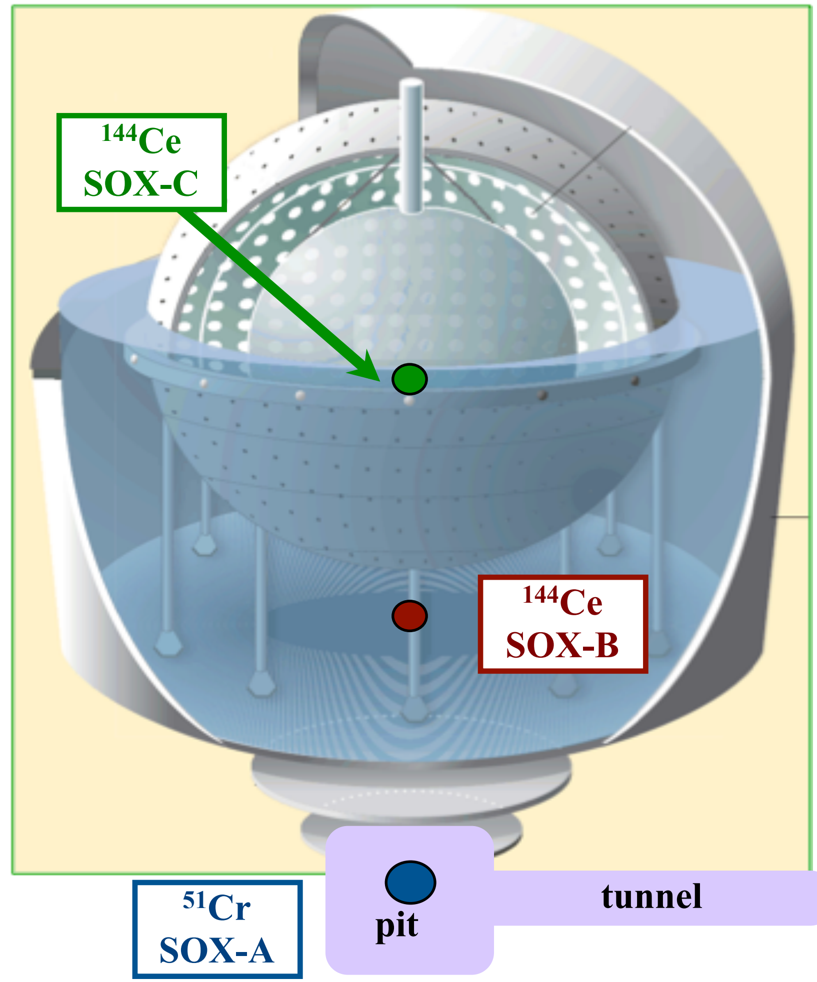
nucl-ex:1006.2103



65 Ge atoms/day expected

SOX (dedicated talk by I. Machulin)

- Re-use Gallex 36 kg of enriched chromium
- Production reactors:
  - Oak Ridge (US)
  - Ludmila (Ru)
- Source **8.25 m** from center **[2015/2016]**
- Detection as ^{7}Be solar ν
  - Well known background
- Oscillometry analysis
- ERC funding (M. Pallavicini)



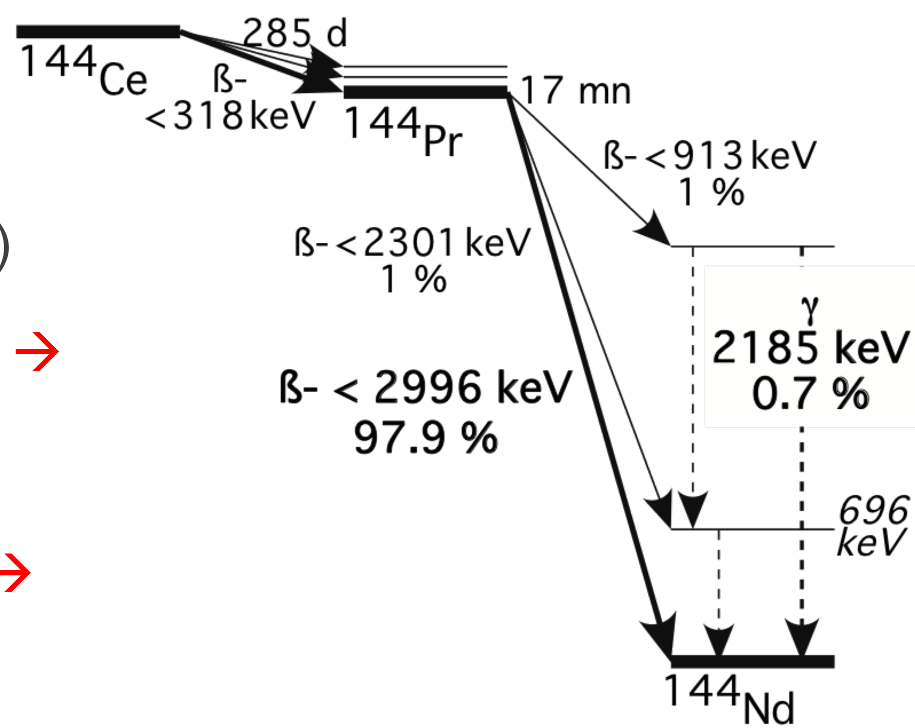
^{144}Ce-^{144}Pr

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

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

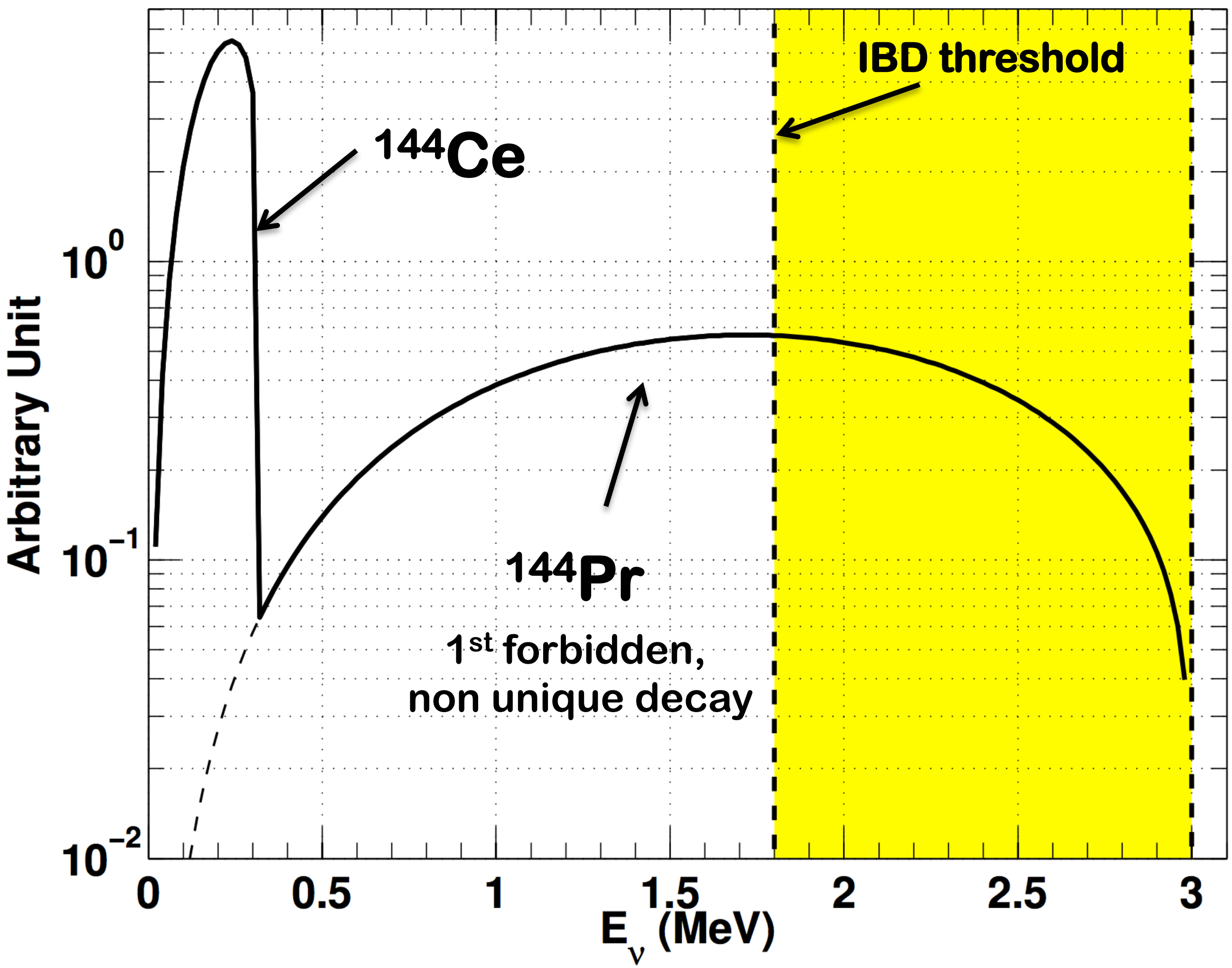
- **1st Trick: $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)**
  - **High IBD cross section → 75-100 kCi activity**
  - **(e^+,n) detected in coincidence → Background free**

- 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

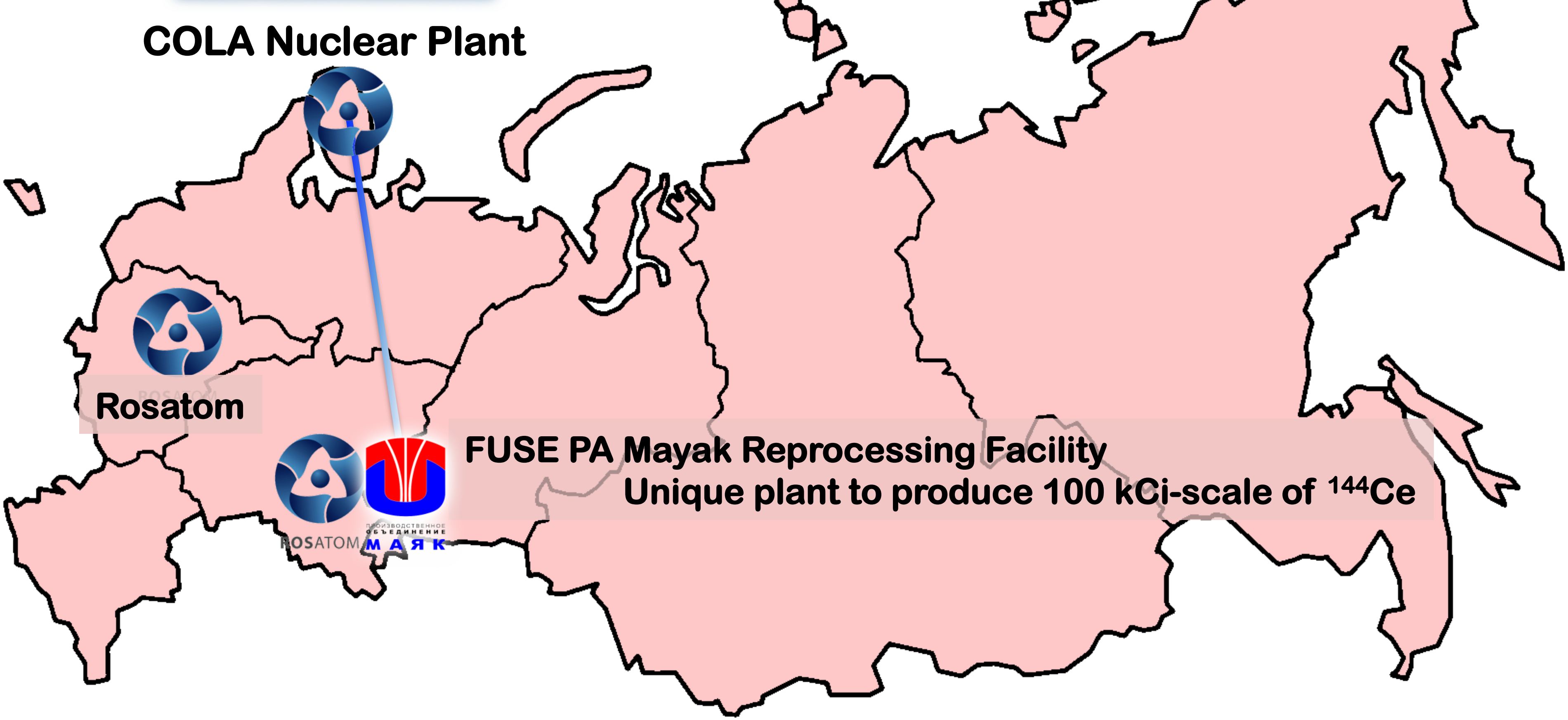
- Theoretical computation of neutrino spectra ongoing
- Spetrum shape measurement onoing base on samples



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

- ß activity at delivery
  - **Between 75 kCi and 100 kCi**
- Chemical form : cerium oxyde CeO_2
- Density : 4.0 ± 1.0 g/cm^3
- Fitting inside a D:H=15 cm:15 cm cylinder (ext.)
  - 2-3 y old fuel at the start of the production
- **Purity data from ^{147}Pm production line (TBC for ^{144}Ce)**
  - Content of any others RE (γ*-emitters*) in *Ce* $\leq 10^{-3}$ Ci/Ci
  - Content of Pu and TPE (*n emitters*) in Ce $\leq 10^{-6}$ Ci/Ci

Production Facility: FUSE PA Mayak



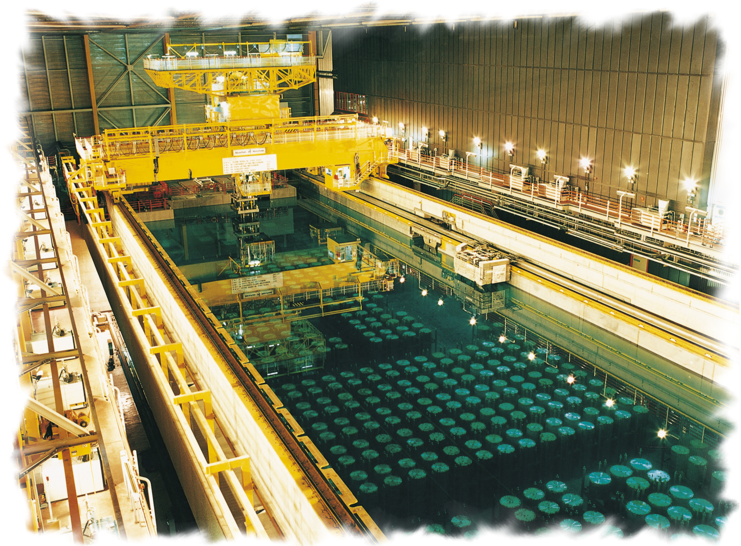
Spent Nuclear Fuel

- Cerium : 5.5% / 3.7% in the fission products of U / Pu
- ^{144}Ce decays with $t_{1/2}$=286 d
- 3 years after last irradiation m(^{144}Ce)/m(Ce) = 0.5-0.7%
- Delivery of selected SNF from Cola NPP to FSUE "Mayak" PA
  TUK-6 container →

- Preliminary arrangement to receive fresh fuel for ^{144}Ce production Feb. 2014

Overview of the production (1 year)

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

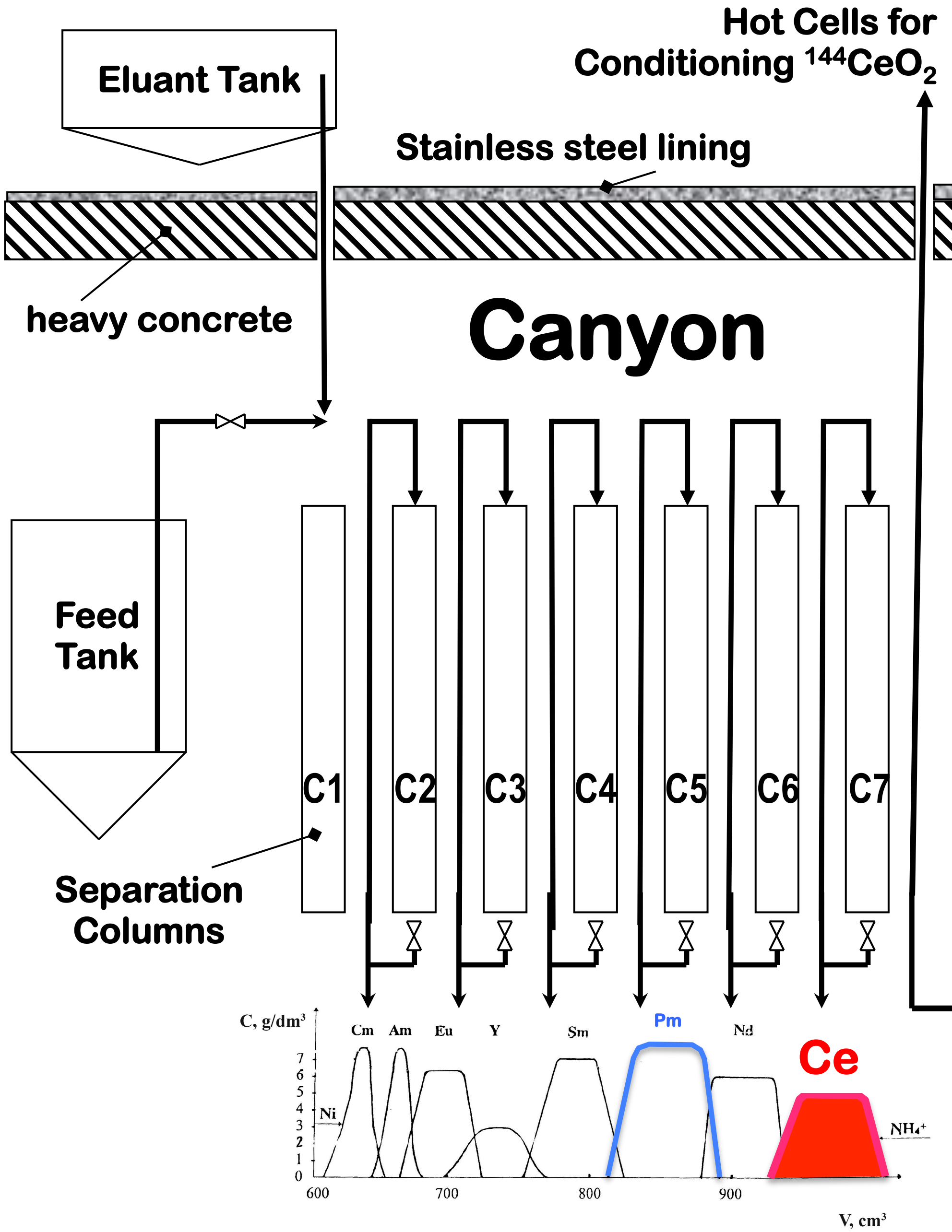


- Radioisotope Plant
  - Source manufacture
  - Certification ISO 9978
  - Loading into W-shield
  - Loading into container

- Dedicated upgrade of Mayak facilities for Ce prod. defined

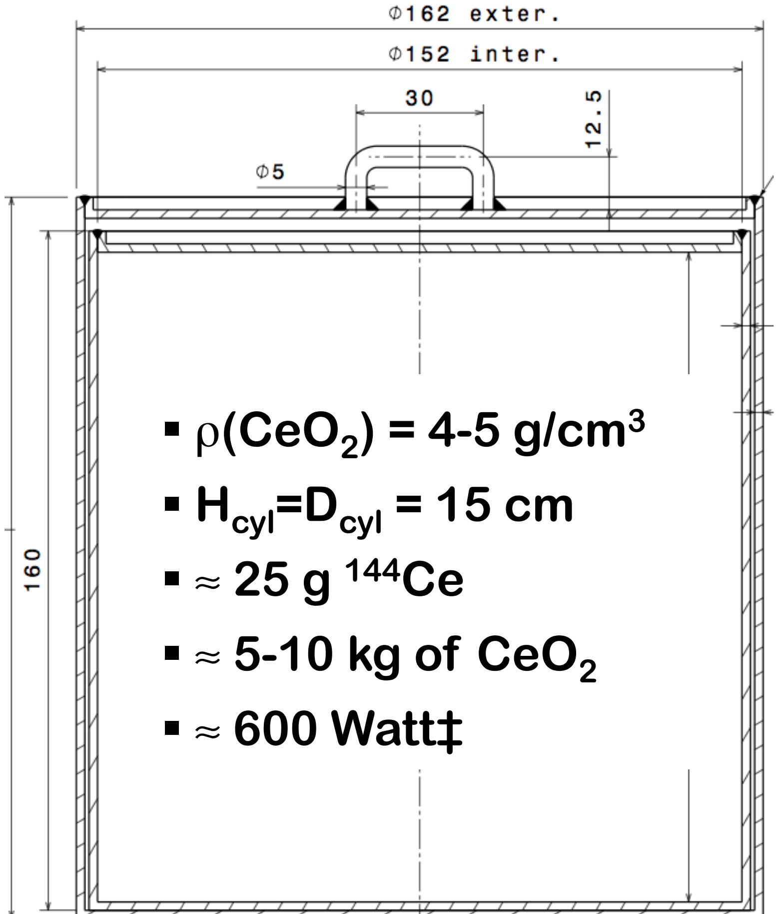
Extraction of Cerium Solution

- Complexing agent displacement chromatography for Rare Earth Elements (REE)
- VVR-440 Spent Nuclear Fuel:
  - PA Mayak: 100 t SNF/y
  - 1 ton SNF:
    - 13 kg REE
    - 25 g ^{144}Ce (3 y, 70 kCi)
- Production (2-3 y old SNF)
  - 10 tons of SNF needed for industrial reasons
  - 4-6 months



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

Mechanical design

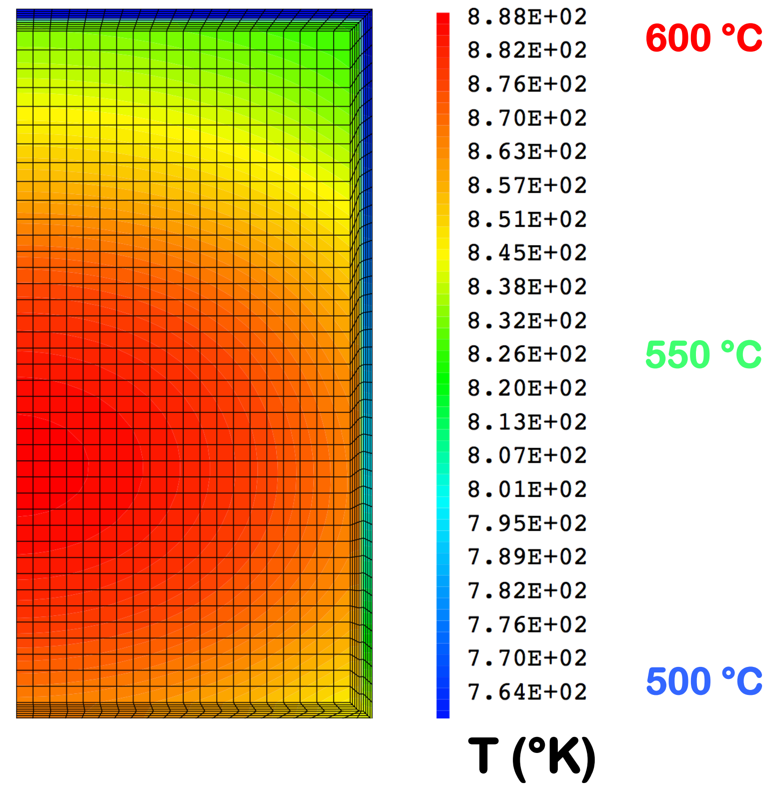


- $\rho(CeO_2)$ = 4-5 g/cm^3
- H_{cyl}=D_{cyl} = 15 cm
- ≈ 25 g ^{144}Ce
- ≈ 5-10 kg of CeO_2
- ≈ 600 Watt‡

Designed as special form of radioactive material (ISO 9978)

Thermal constaints

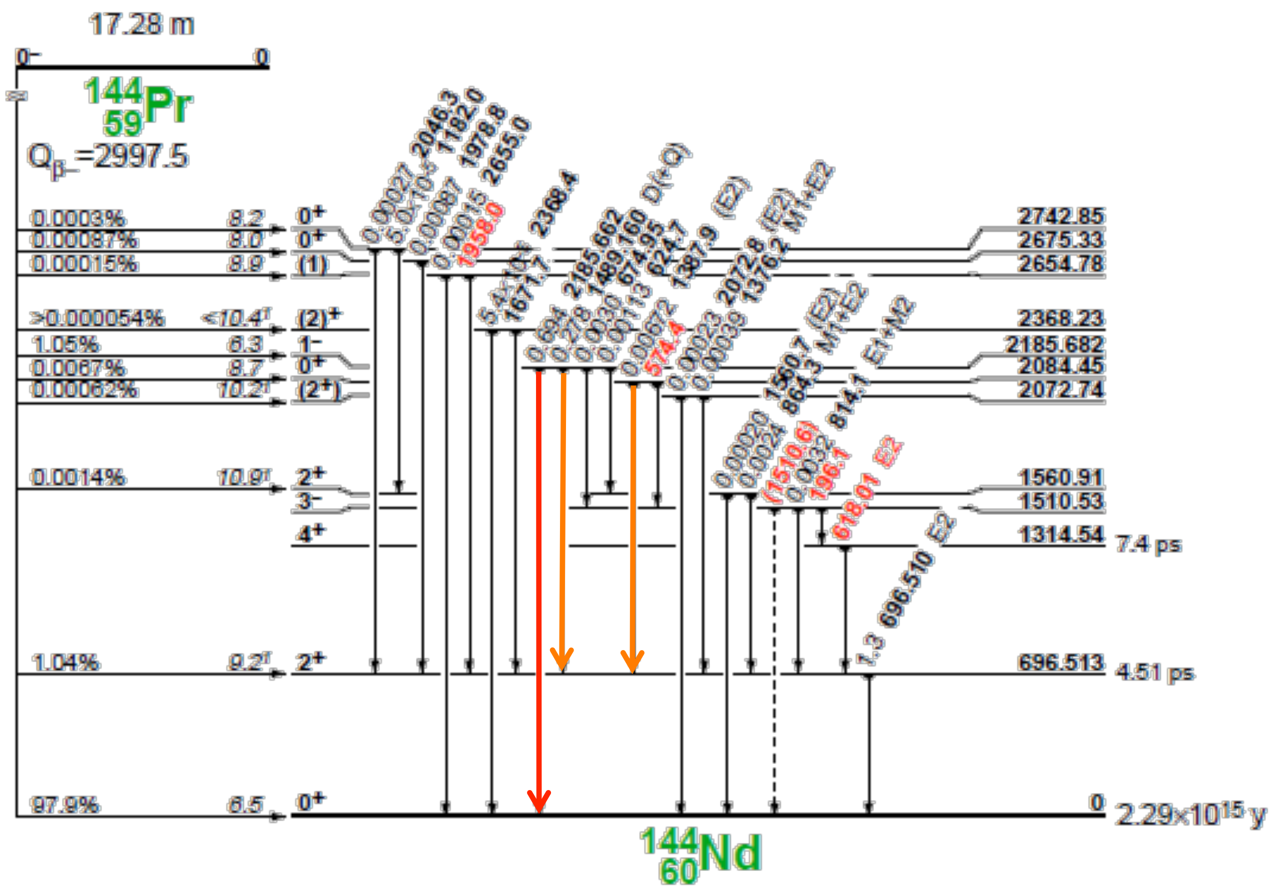
Conduction + Convection
No radiation loss



^{144}Ce-^{144}Pr: γ–emission

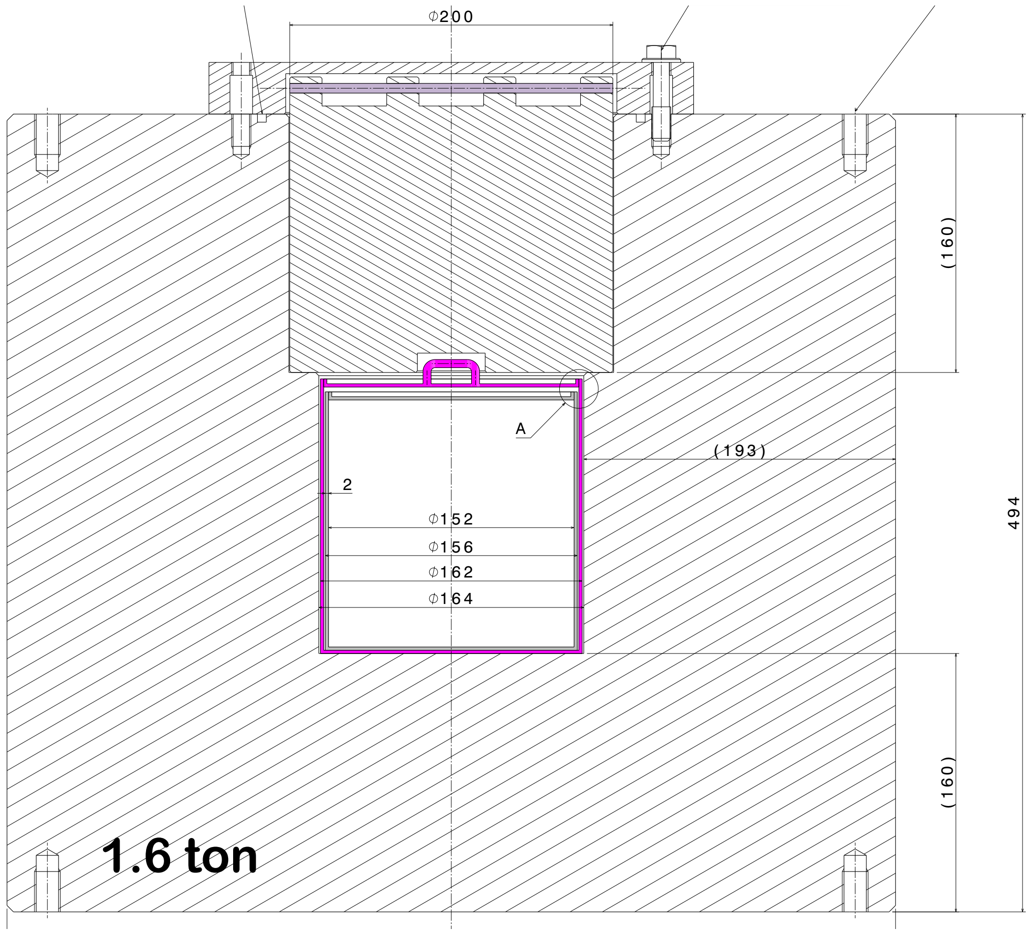
- γ rays produced by the decay through excited states of ^{144}Pr
  - Intensity γ >1 MeV
    - 1380 keV – 0.007 %
    - 1489 keV – 0.3 %
  - Intensity γ >2 MeV
    - 2185 keV – 0.7 %

      (10^{10} γ /sec for 50 kCi)



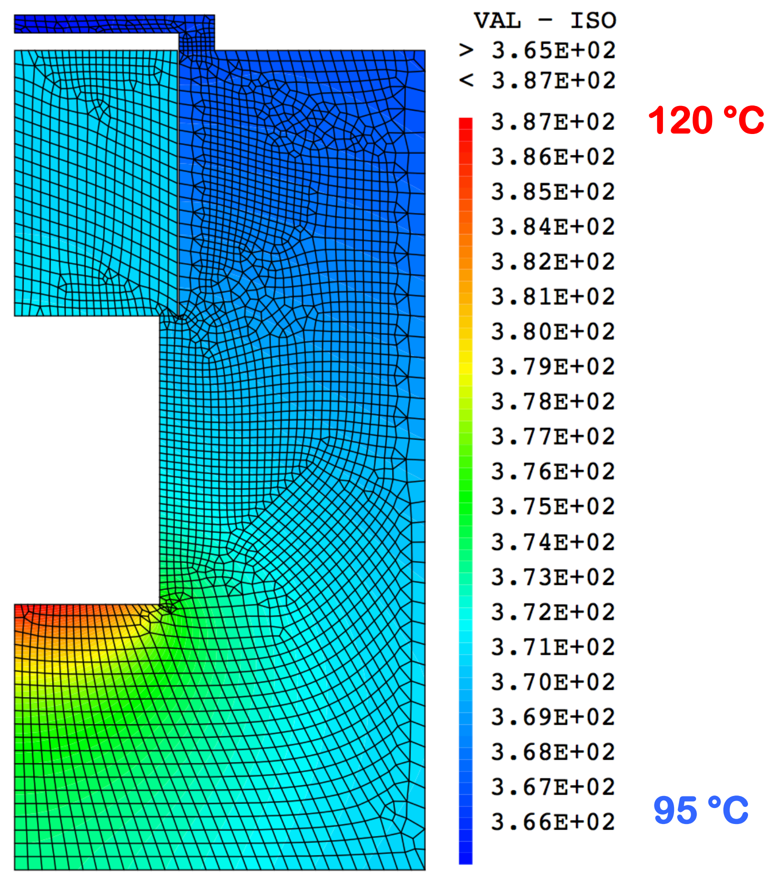
High-Z Tungsten Shielding

Mechanical design (for handling in hot cell)



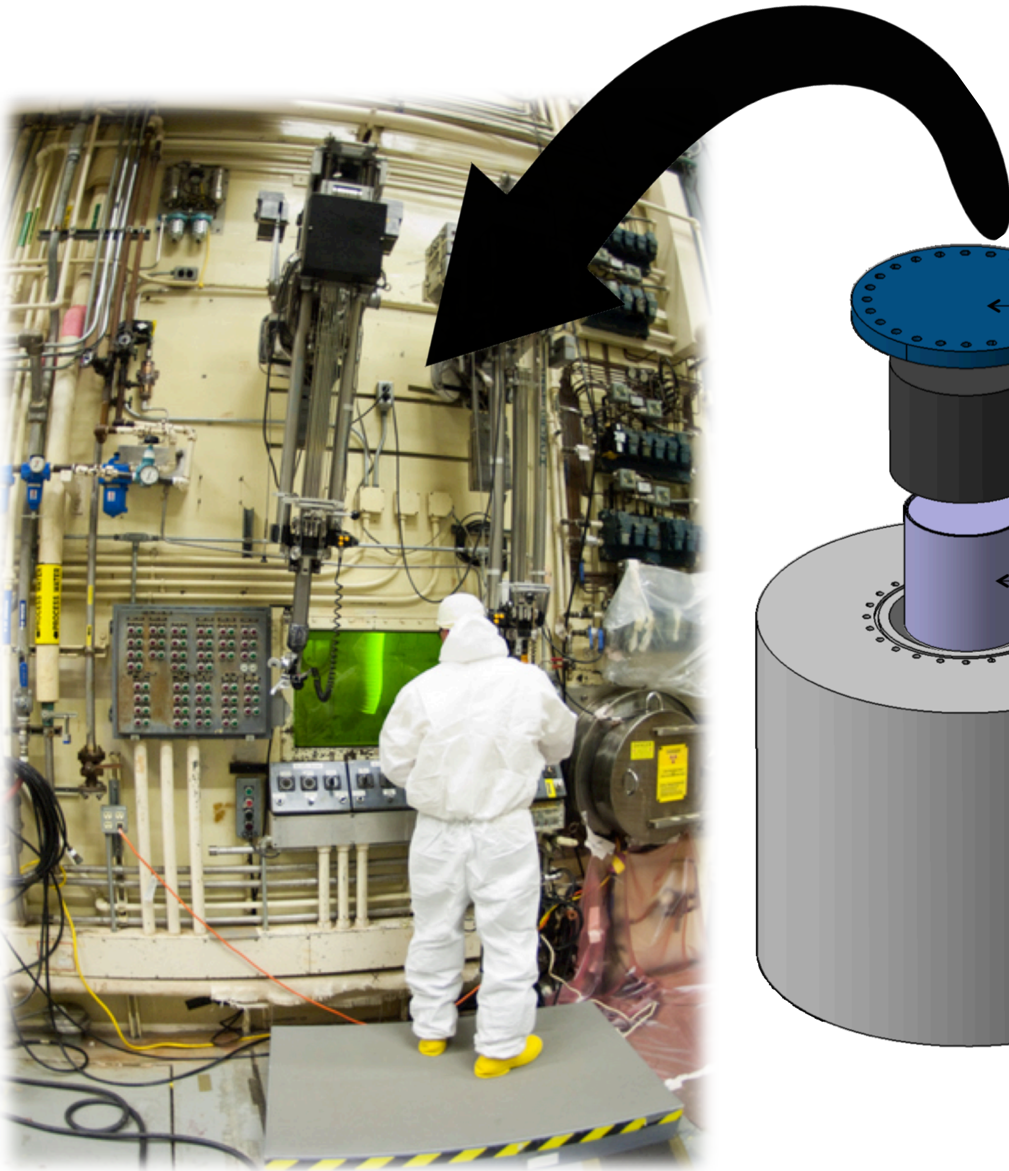
CEA-SPR (MCNP) & GEANT4 - 16 cm W
Radiation dose @1m: 50 μ Sv/h

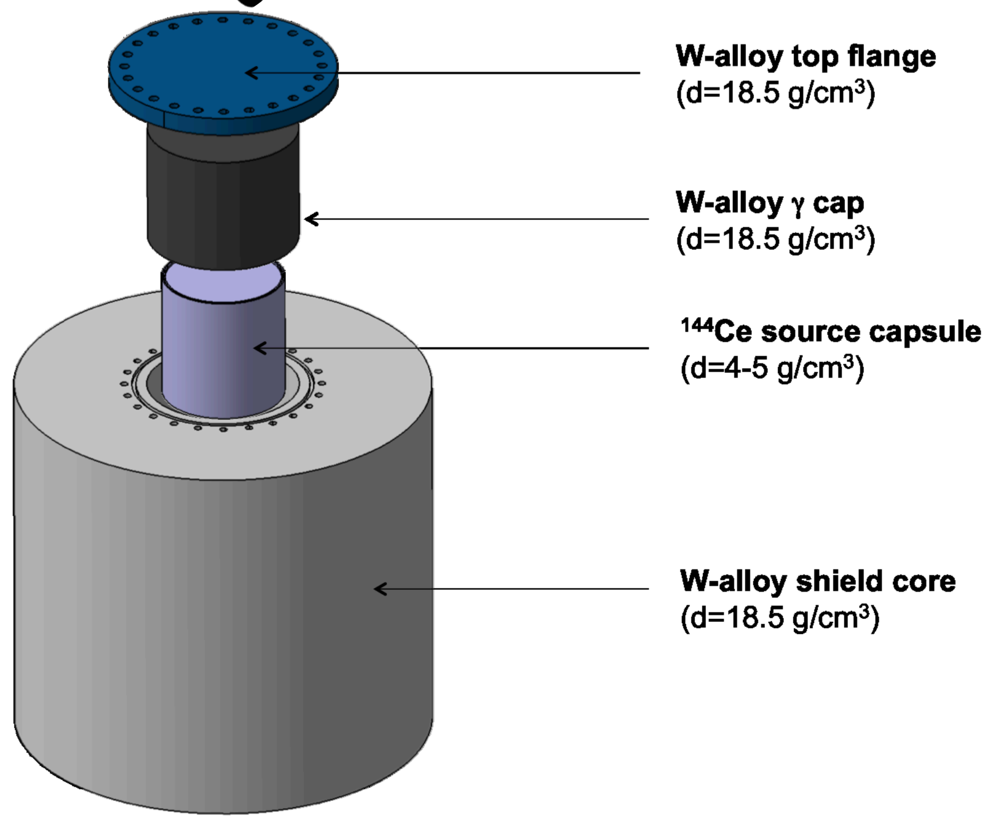
Thermal study



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

Source insertion into W-shield



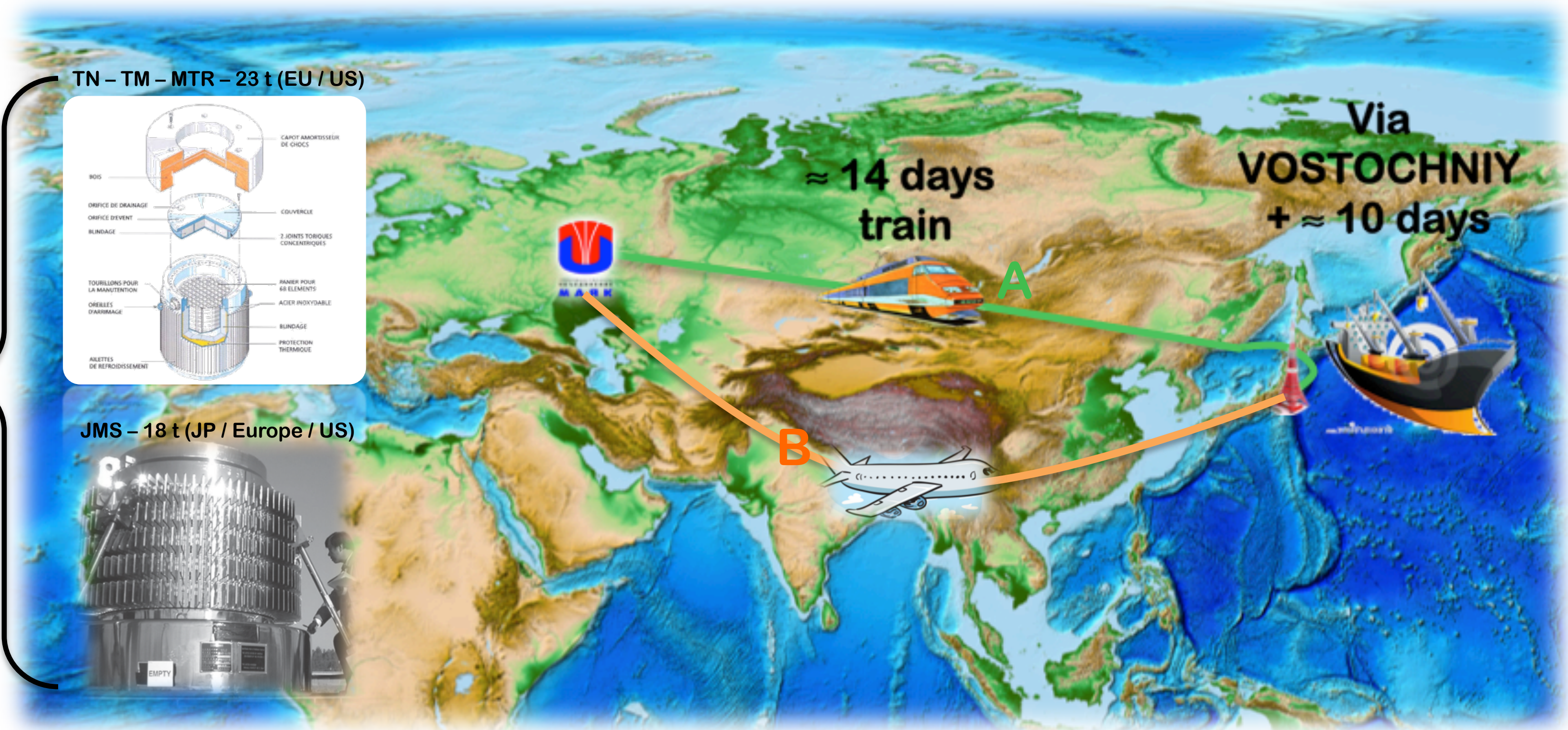


Transport from Russia to Japan

Option A) approx. 4 weeks

- train to Russian east coast (Vostochniy harbor)
- dedicated boat to Tokyo / Yokoyama + truck to KamLAND

2 suitable B(U) casks identified



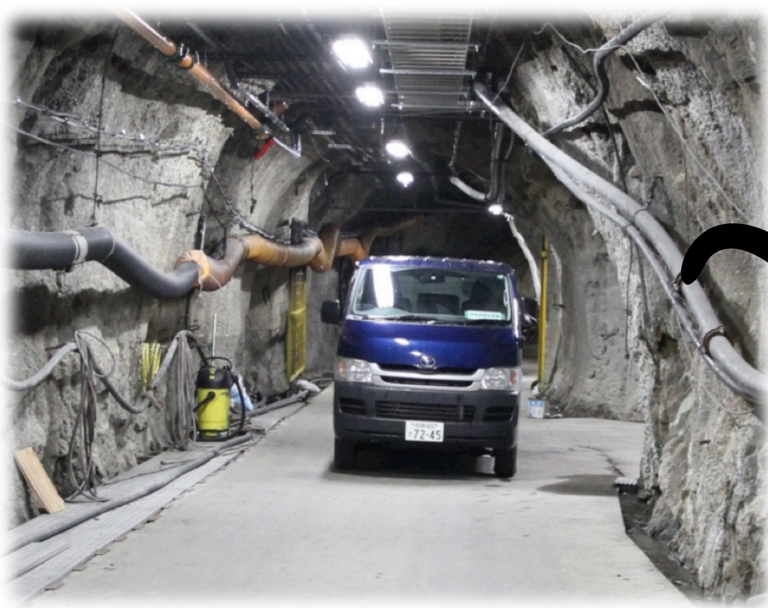
Option B) approx. 2 weeks

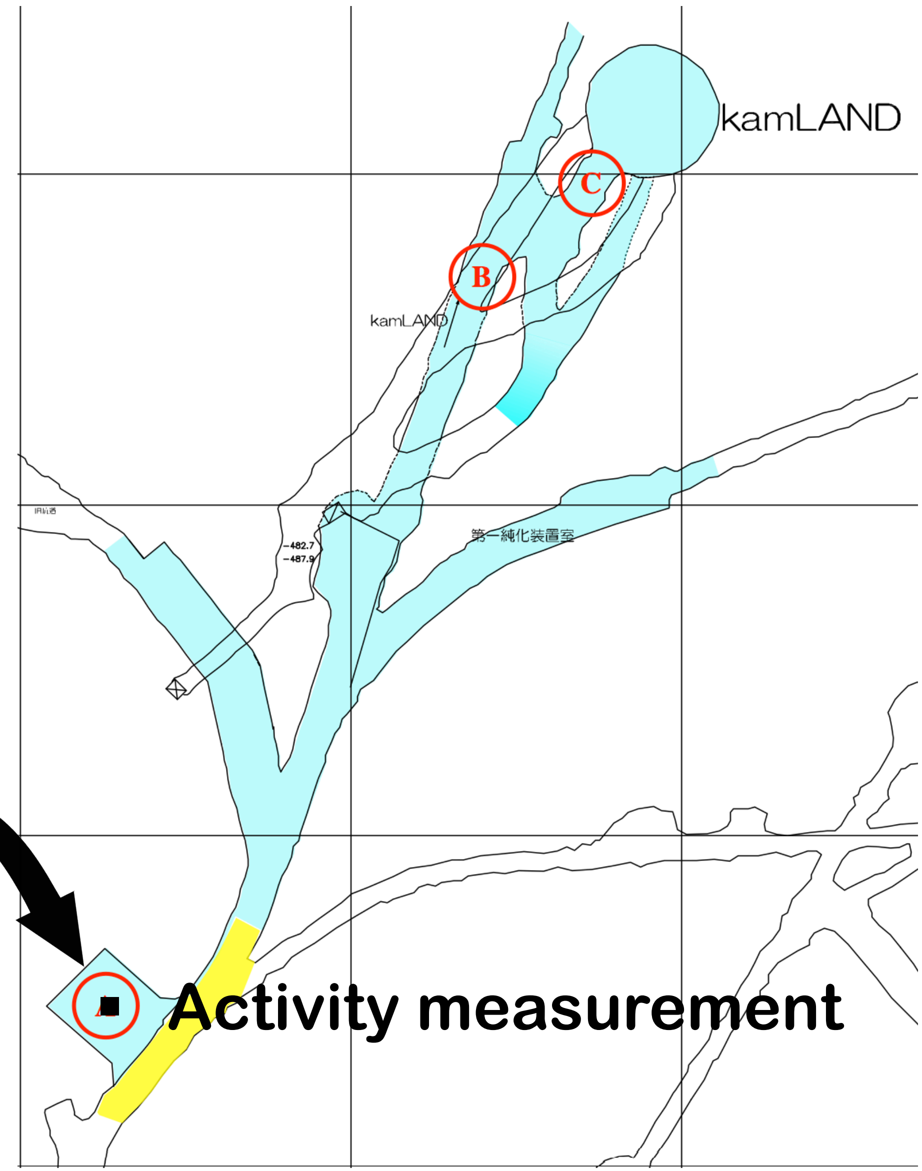
- flight from Russia to Japan + truck towards KamLAND
- special arrangement to be agreed between Japan/Russia

Unloading & handling in KamLAND

- Process for certifying KamLAND as a radiation facility to receive 75 kCi of ^{144}Ce-^{144}Pr ongoing with Japanese Nuclear Regulation Authority

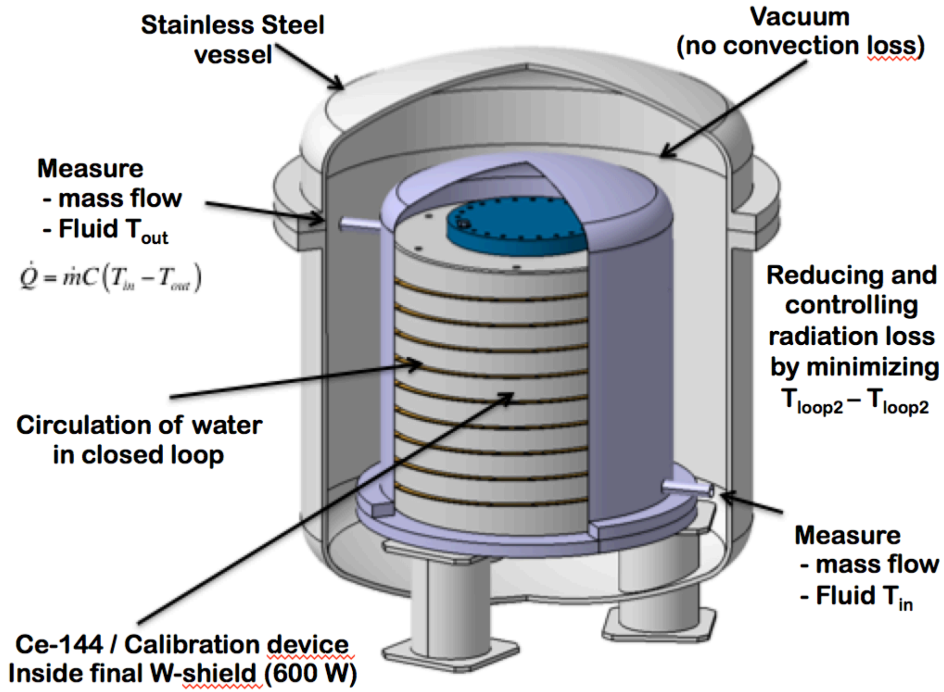
- Definition of a temporary radiation controlled area



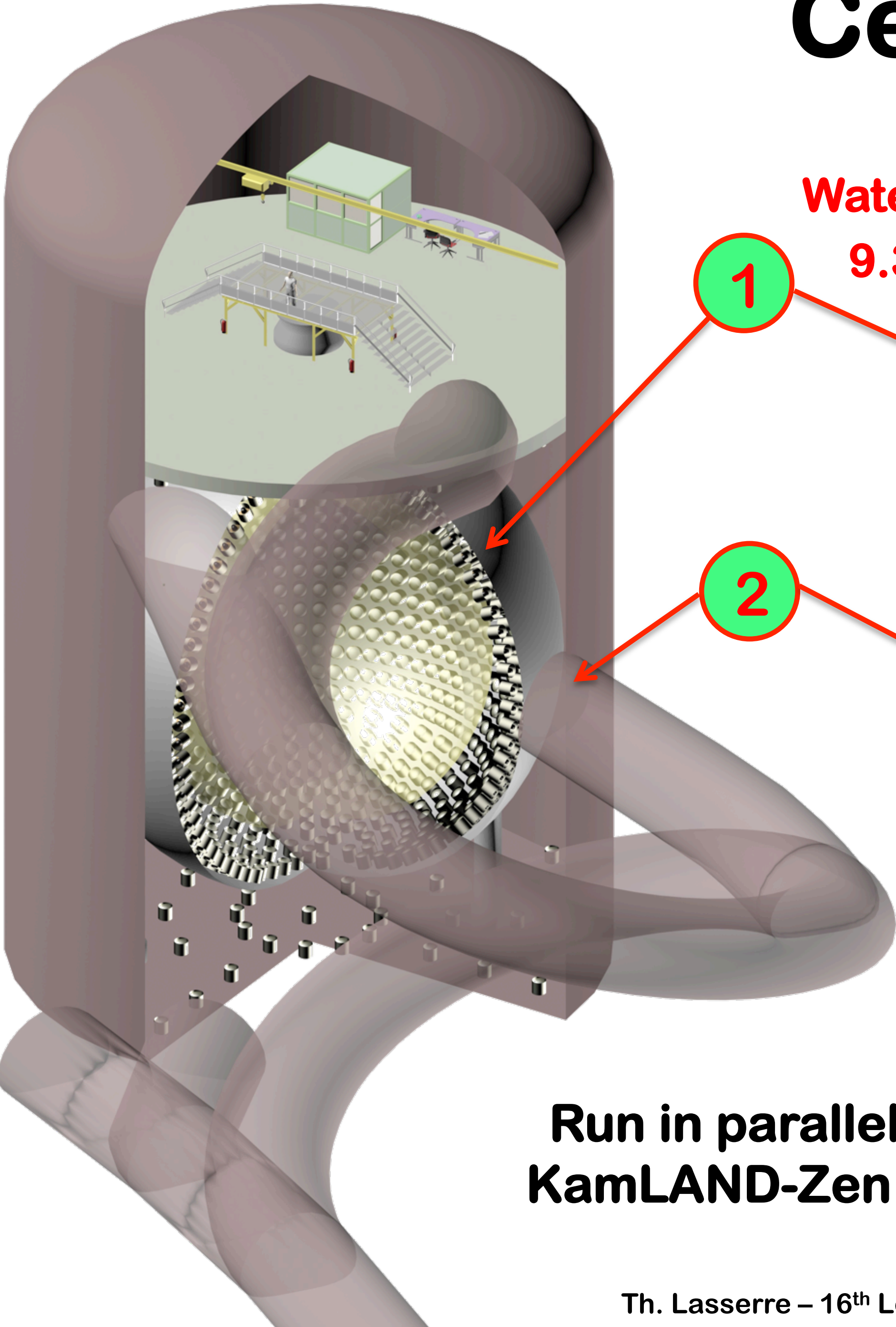


Activity through Calorimetry

- **Source Heat Release**
  - **96% from β-decays –**
  - **75 kCi → 600 W released**
- **Calorimeter**
  - **Few days measurement**
  - **Precision <1.5%**
- **Concept (CeLAND/Sox Coll.)**
  - **Calibration (2014)**
    - **final W-shielding,**
    - **fake-source (known elec. power)**
  - **Measurement at Kamioka**
    - **before (600 W) and after deployment (100 W)**



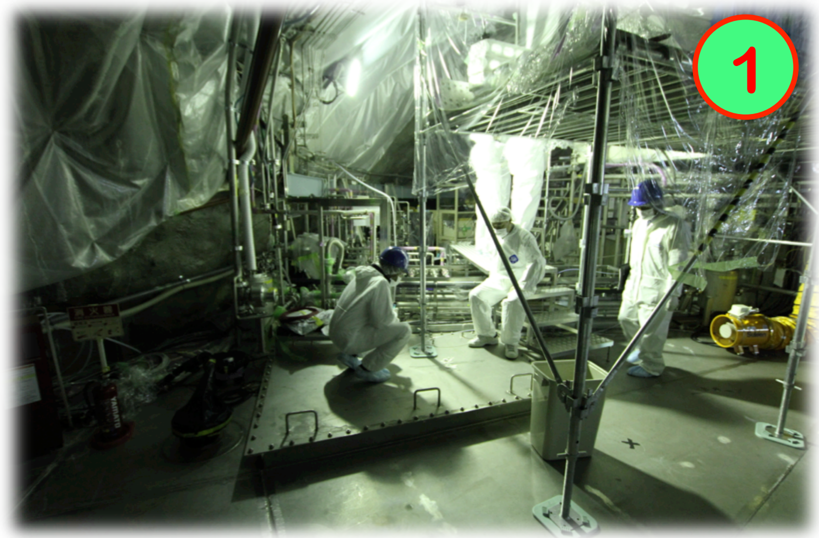
CeLAND deployment



Water OD
9.3 m

1

2

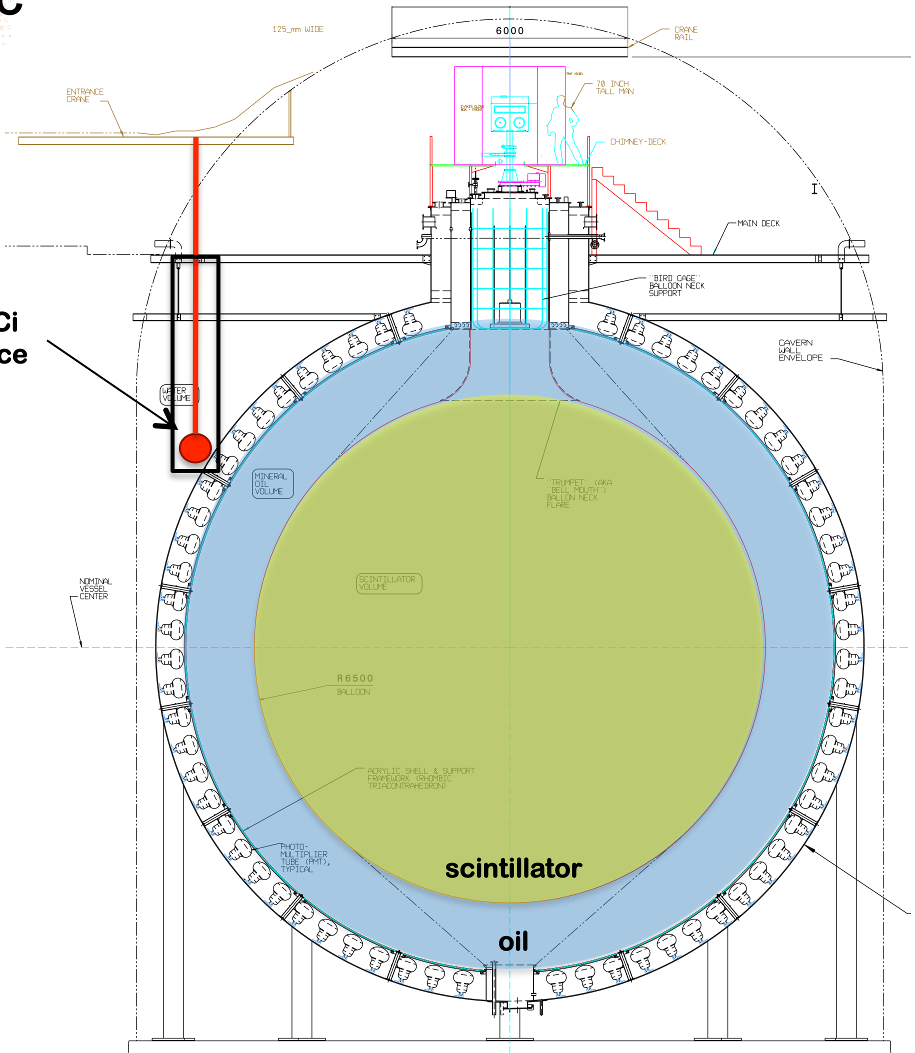


Xenon
room
12.0 m

Run in parallel with KamLAND-Zen ($\beta\beta0\nu$)

CELAND Phase 1 (goal: 2015/6)

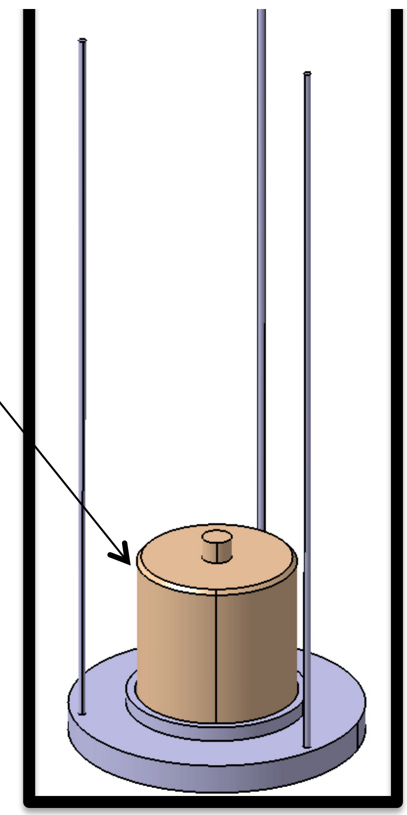
75 kCi Source



20 000 events in 1.5 y

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

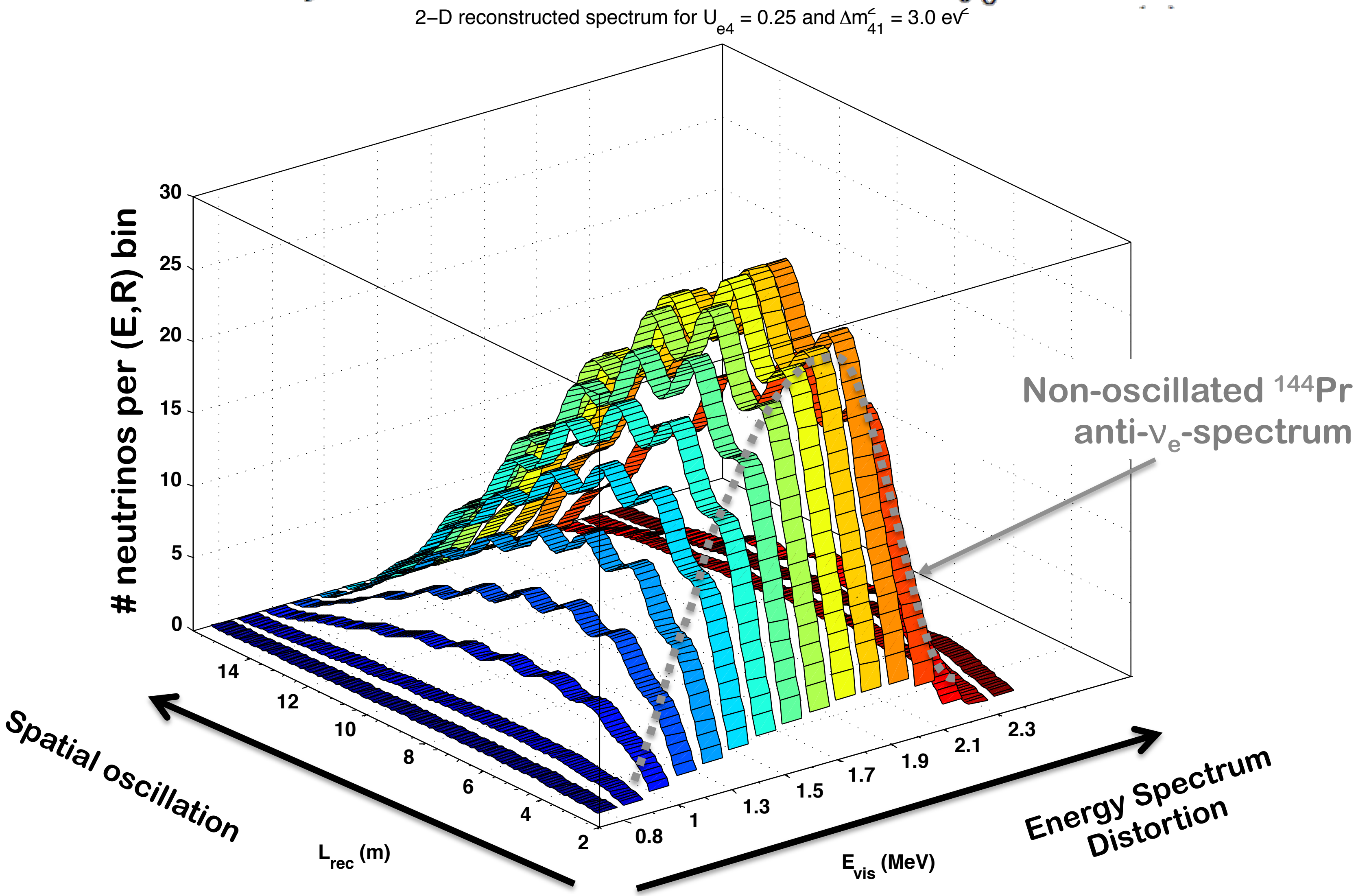
tungsten alloy, 54 cm $d=18.5\ g/cm^3$



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

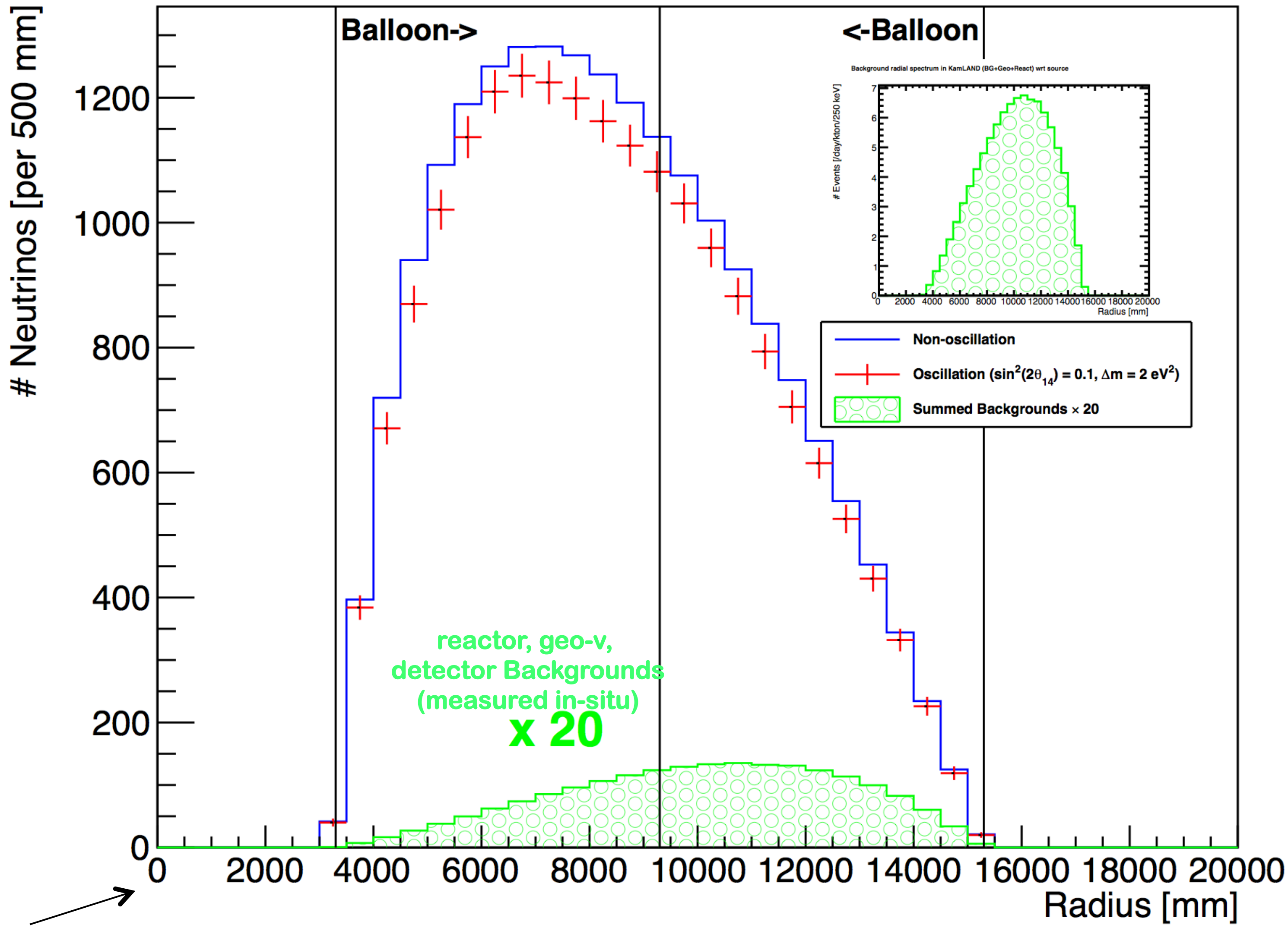
CeLAND phase 1 : R & L signals

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



CeLAND phase 1: signal & background

1.5 y - 20 000 interactions – full KamLAND Geant4 simulation

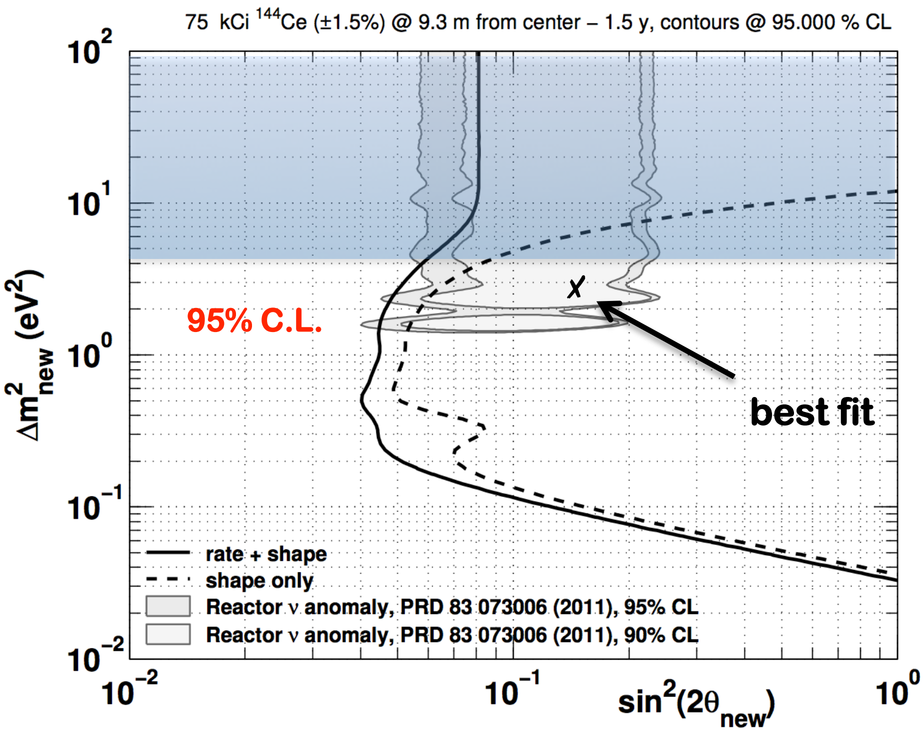


75 kCi ^{144}Ce-^{144}Pr antineutrino generator

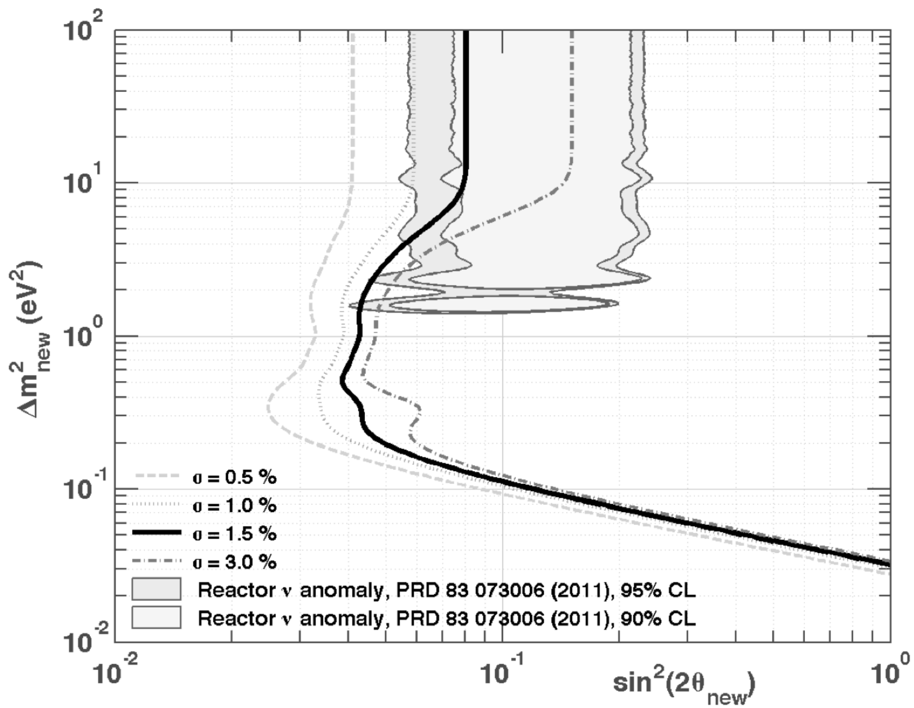
CeLAND phase 1 : sensitivity

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

1.5 year of data



Impact of Activity calibration



Goal: data taking from middle of 2015

Tritium

KATRIN

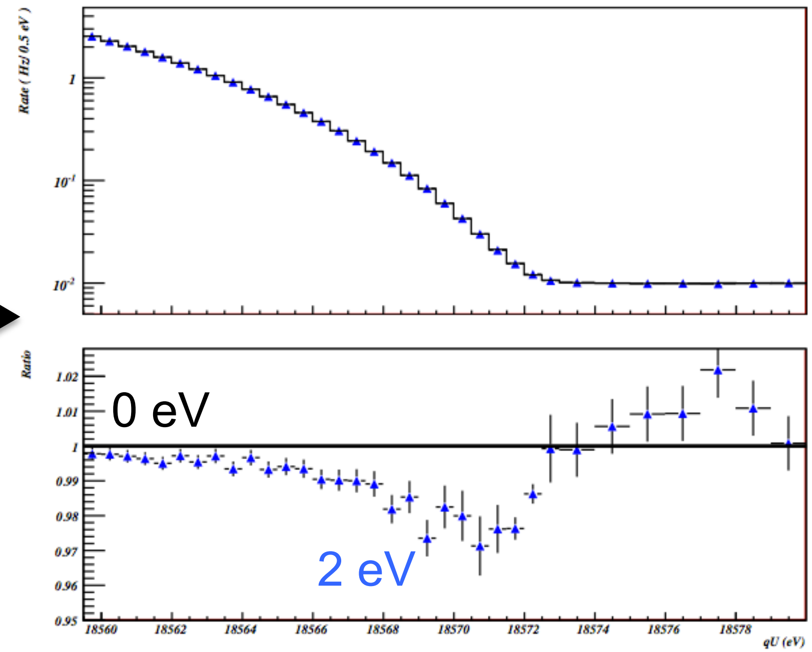
- Source: $^{3}_{1}\mathrm{H} \rightarrow \ ^{3}_{2}\mathrm{He} + e^{-} + \overline{\nu}_{e}$
- β decay e-spectrum near end point **depends** on:

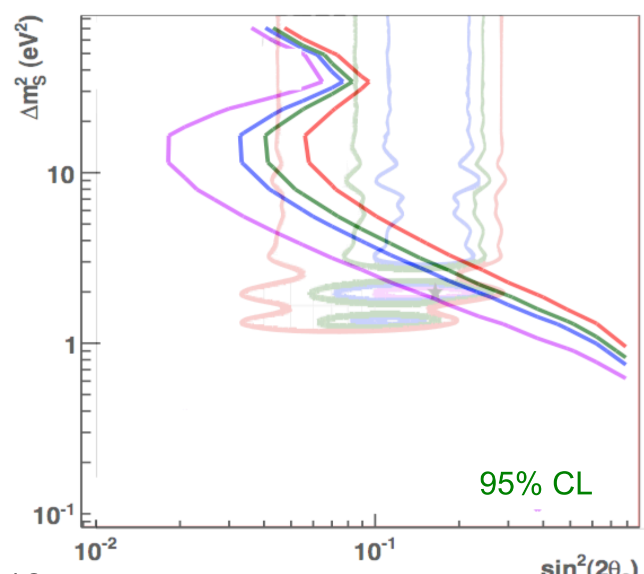
$$\langle m_{\beta} \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^{2} m_{i}^{2}}$$

- 4^{th} Neutrino contribution

$$\langle m_{\beta} \rangle_{4} = |U_{e4}| \sqrt{\Delta m^{2}_{41}}$$

- KATRIN –as designed– will be sensitive to an eV-scale 4^{th} neutrino state





Outlook

- **Reactor & Gallium Anomalies must be tested**
  - **Need energy or/and baseline-dependent signatures**

- **Complementary approaches with ≠ systematics**
  - Accelerator based short baseline
  - <15 m from compact nuclear reactor (D. Lhuillier's talk)
  - High intensity (anti-)neutrino emitters

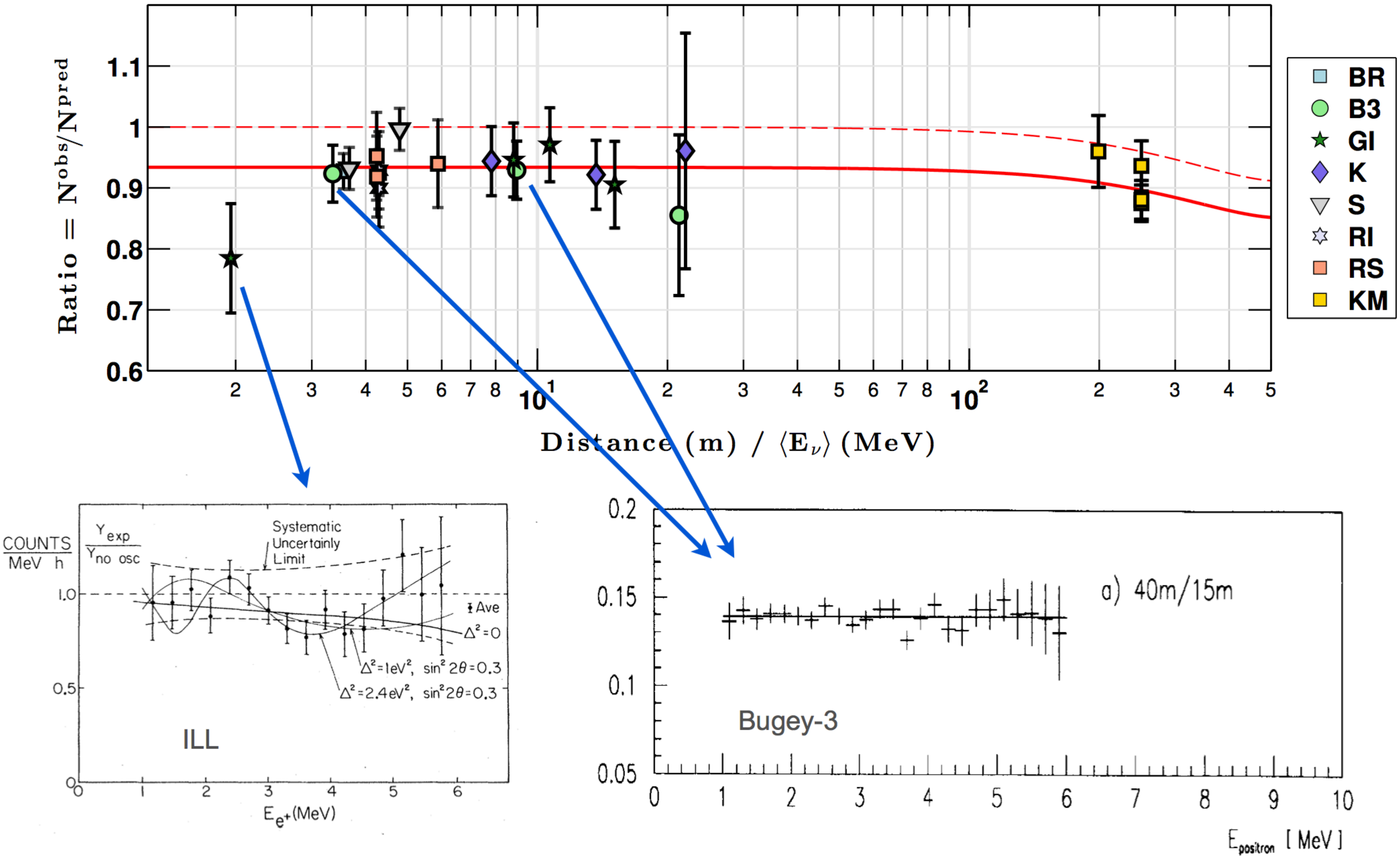
    - **^{51}Cr neutrino generator (10 Mci)**
      - Baksan, SOX (2015/6)

    - **^{144}Ce-^{144}Pr antineutrino generator (75 kCi)**
      - CeLAND (2015/6), SOX (2017), Daya Bay?

    - **Tritium antineutrino generator**
      - **KATRIN (2015)**

BACKUP SLIDES

Input from energy spectra



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

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

Proposed Search for a Fourth Neutrino with a PBq Antineutrino Source

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(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.

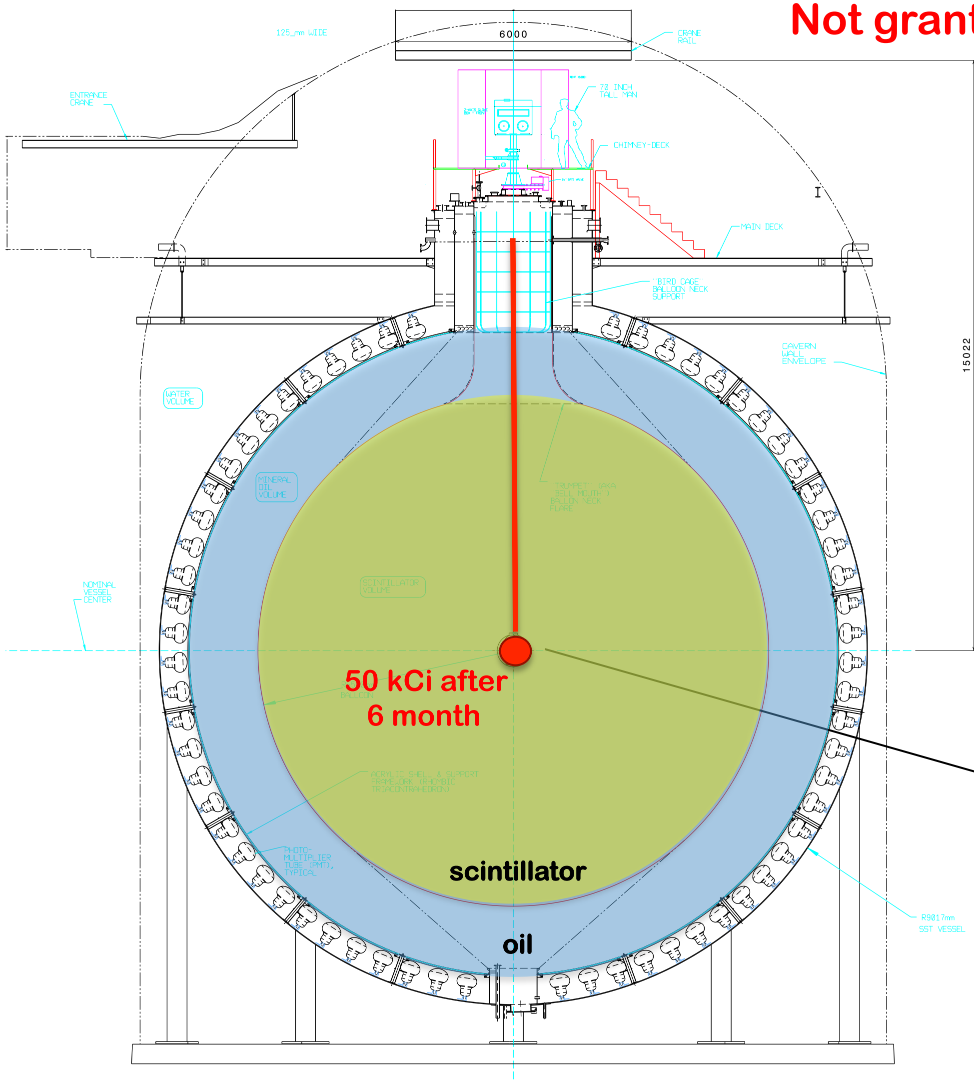
DOI: 10.1103/PhysRevLett.107.201801 PACS numbers: 14.60.Lm, 14.60.Pq, 14.60.St

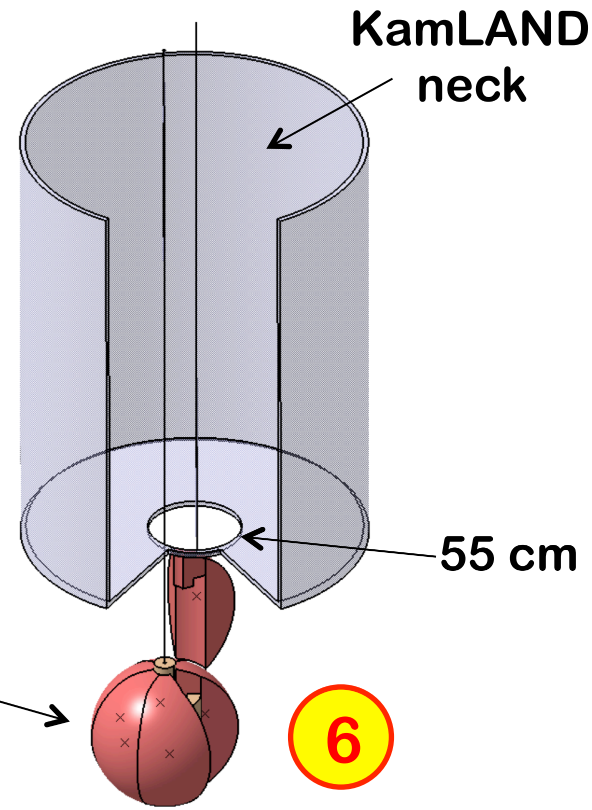
→ Funding through ERC-2012-StG 307184-4th-Nu-Avenue

CELAND Phase 2: 2016/7 (under study)

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

Not granted! Technically very challenging

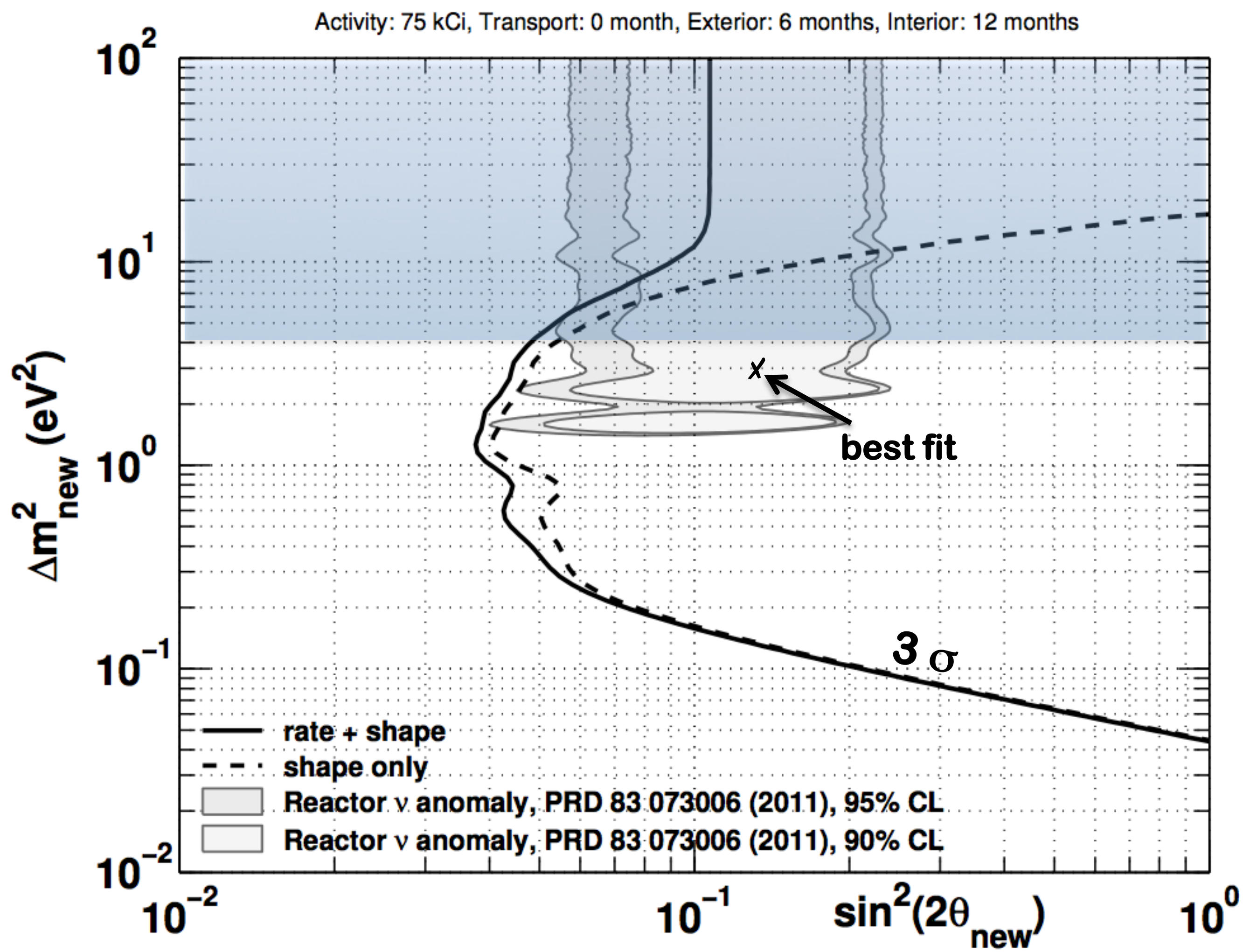




40 cm W-alloy, d=18.5 g/cm^3
γ-attenuation (2 MeV) : 10^{-13}

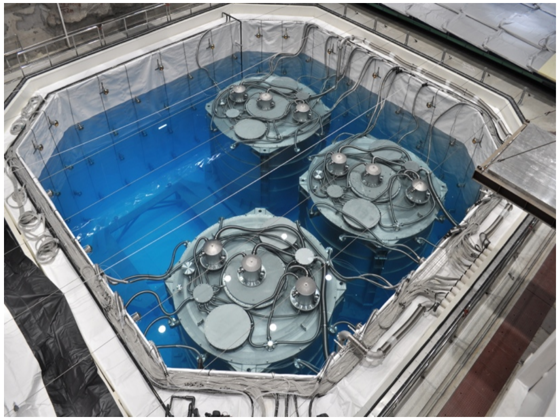
CeLAND Phase 1 + Phase 2

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



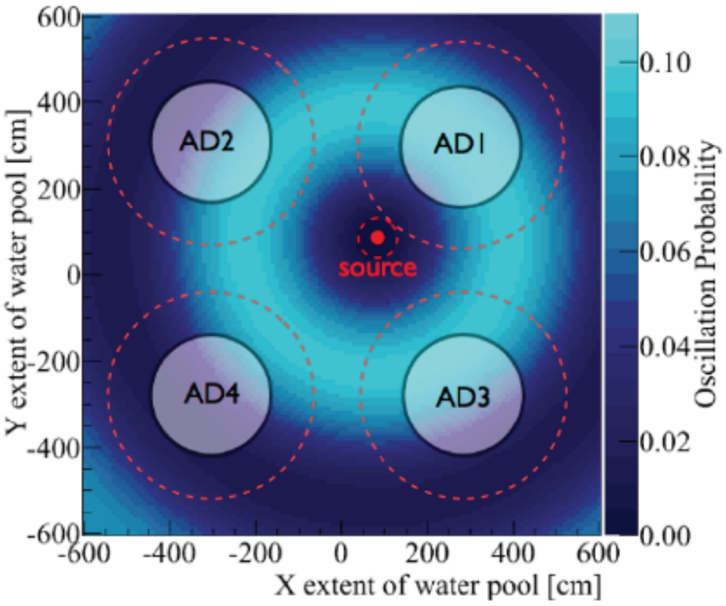
500 kCi ^{144}Ce-^{144}Pr in Daya Bay

- 500 kCi of ^{144}Ce in the water pool of the Daya Bay far hall
  - Baseline range: 1.5 - 8 m
  - Energy range: 1.8 - 3 MeV
  - 35 000 IBD events/per year
  - ‘Easy’ to deploy



- Ongoing discussion for ^{144}Ce recovery with LLNL

- Multiple source location to probe sterile oscillations



500 kCi ^{144}Ce-^{144}Pr in Daya Bay

- Specific oscillation pattern through simulation

- Water + 50 cm W-shielding
  - γ's attenuation

- Must subtract reactor neutrino 'background'
  - well-known to <1% from near detectors

- Sterile neutrino oscillations with mass >1eV can be tested