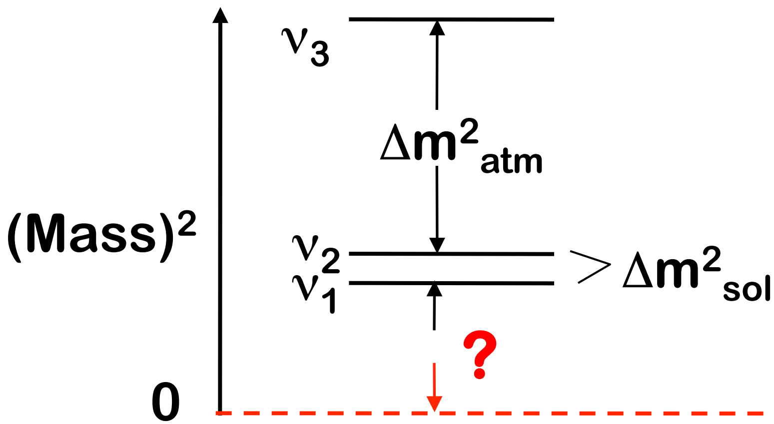
Sterile Neutrinos

Thierry Lasserre - CEA

CPPM, May 13th 2013

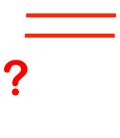
Open questions

- What are the masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, $\beta\beta 0\nu$ decay, cosmology

- Is the spectral pattern  or ?  ν behavior in matter, $\beta\beta 0\nu$, osc.

- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? $\beta\beta 0\nu$

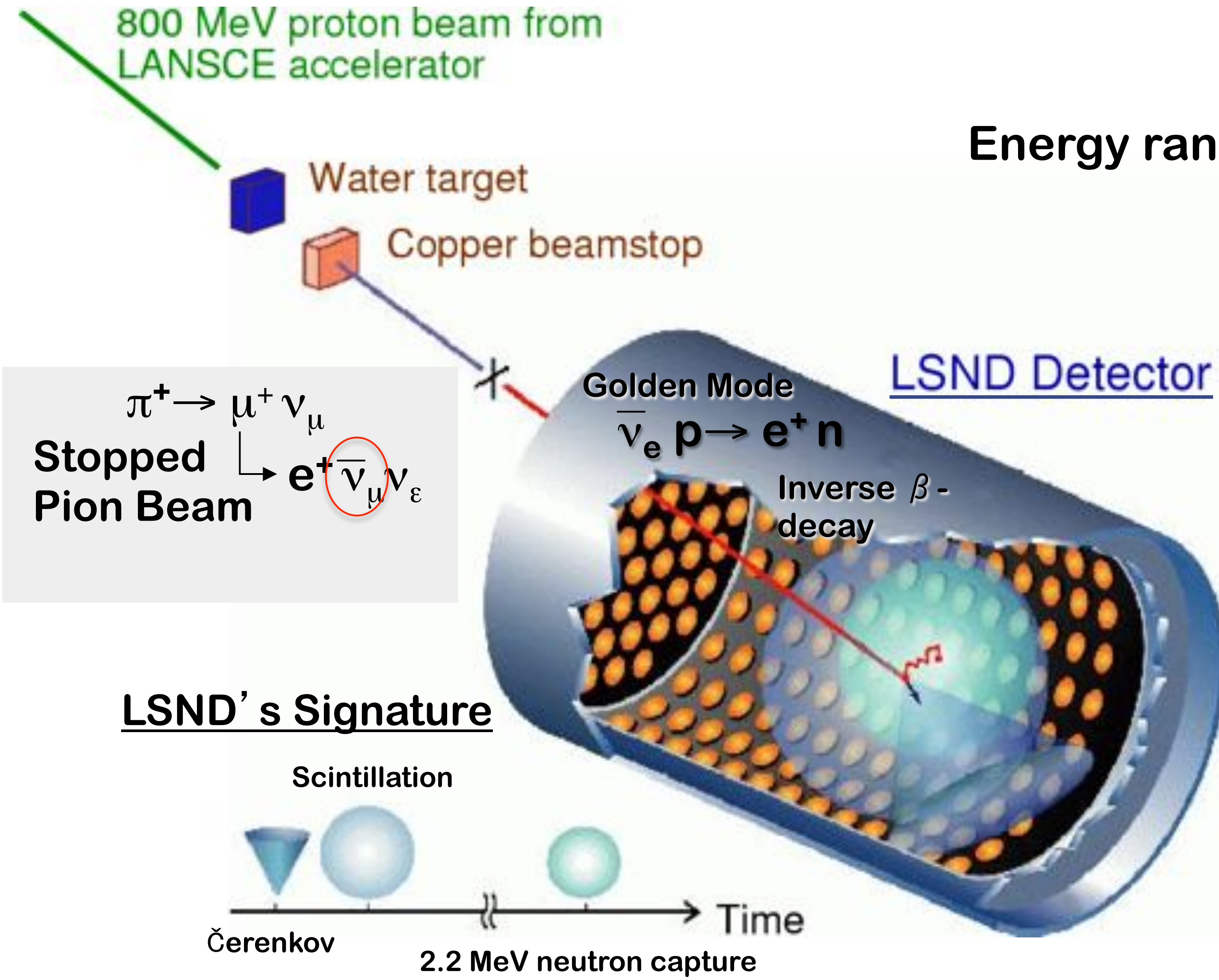
- Precise measurements of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic ~~CP~~ responsible for the matter-antimatter asymmetry?

} ν flavor change

- **Are there additional (sterile) neutrino states** ν flavor change, Cosmology

A bunch of Neutrino Anomalies

LSND (Los Alamos, 1993-98)



Baseline of 30 m

Energy range of 20 to 55 MeV

$L/E \approx 1$ m / MeV

$\downarrow$

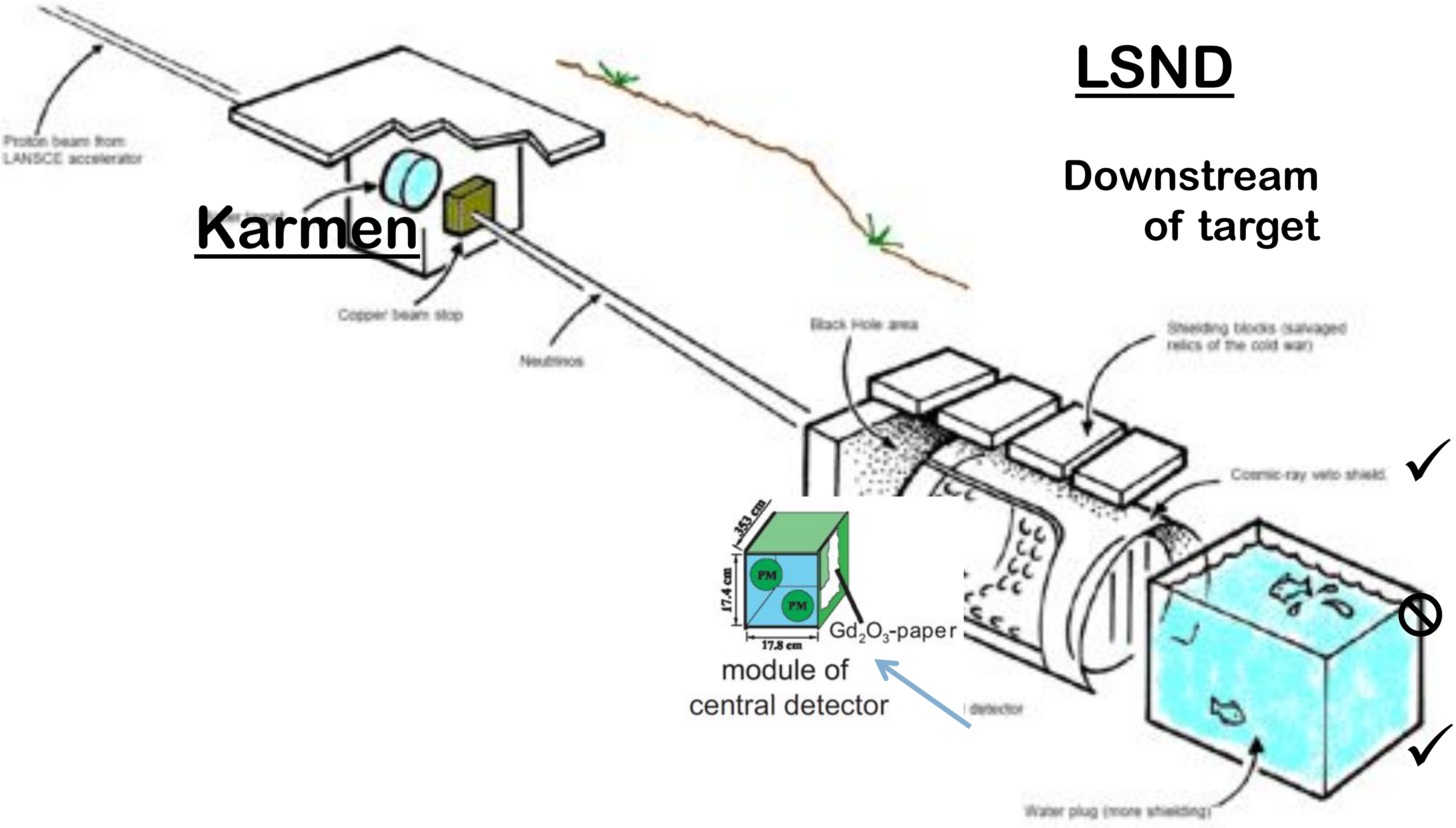
$\Delta m^2 \approx 1\ eV^2$

Detection :

$\bar{\nu}_e + {}^1H \rightarrow e^+ + n$

Karmen (stopped π^+ beam)

Oscillation not confirmed – exclude part of LSND



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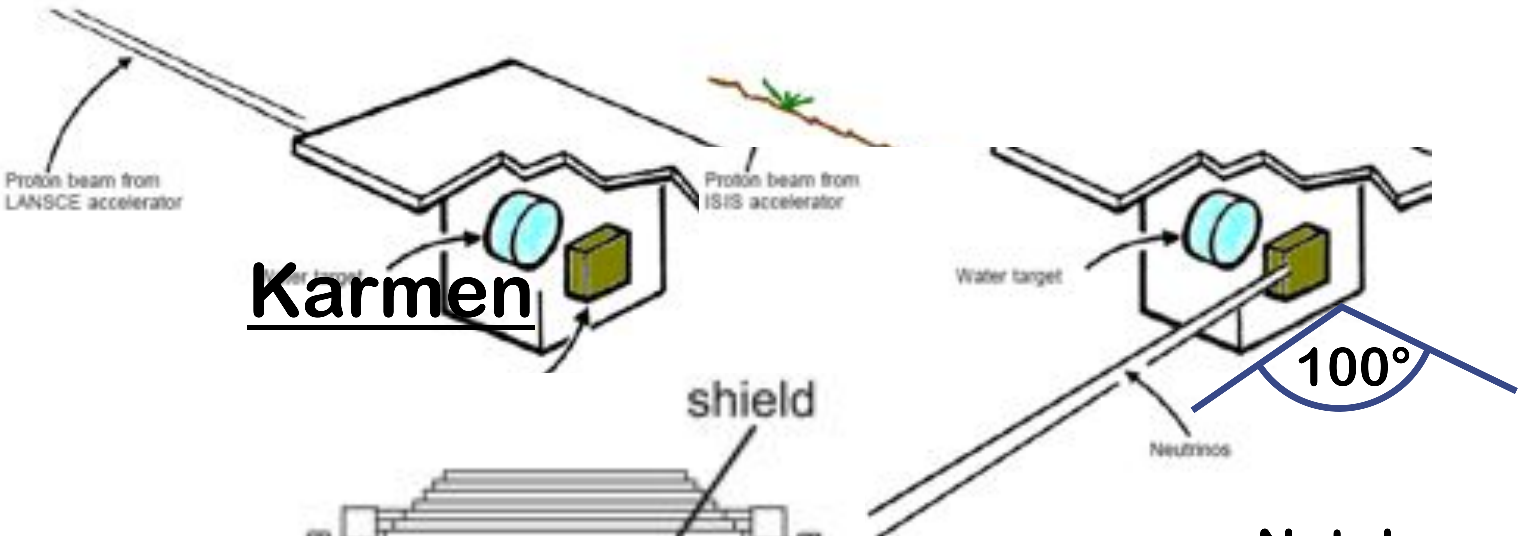
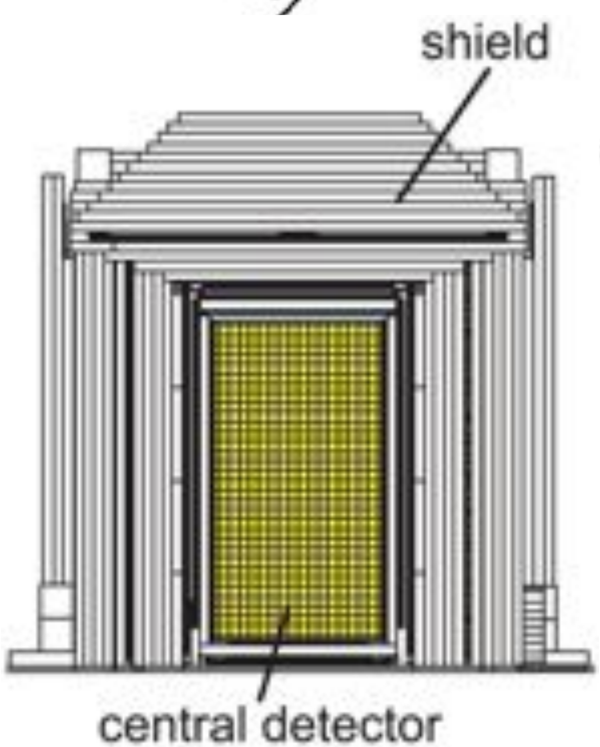
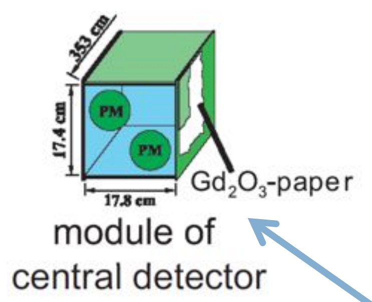


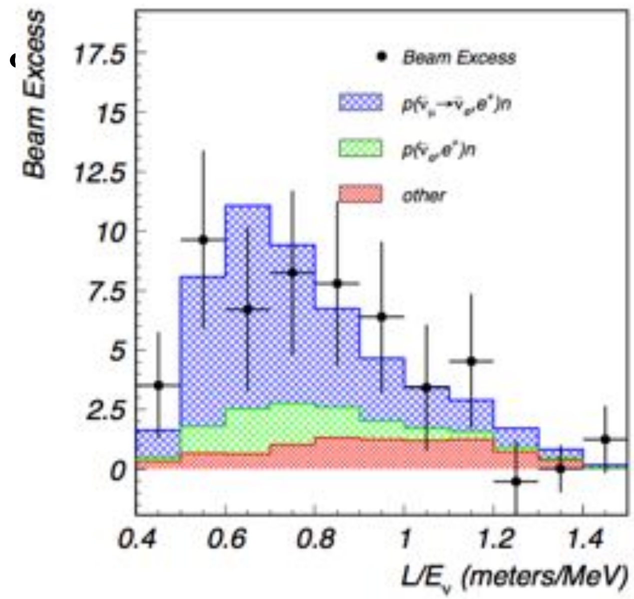


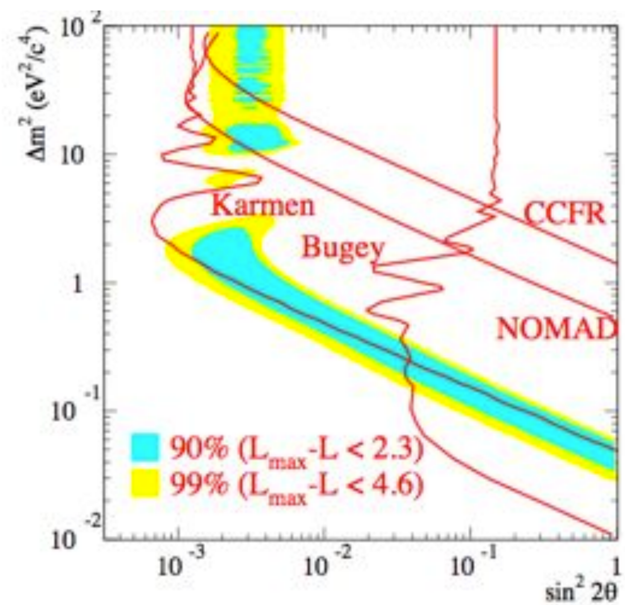


- Not downstream of the target ✓
- Only 18 meters baseline ⦸
- Gadolinium for neutron capture ✓

LSND

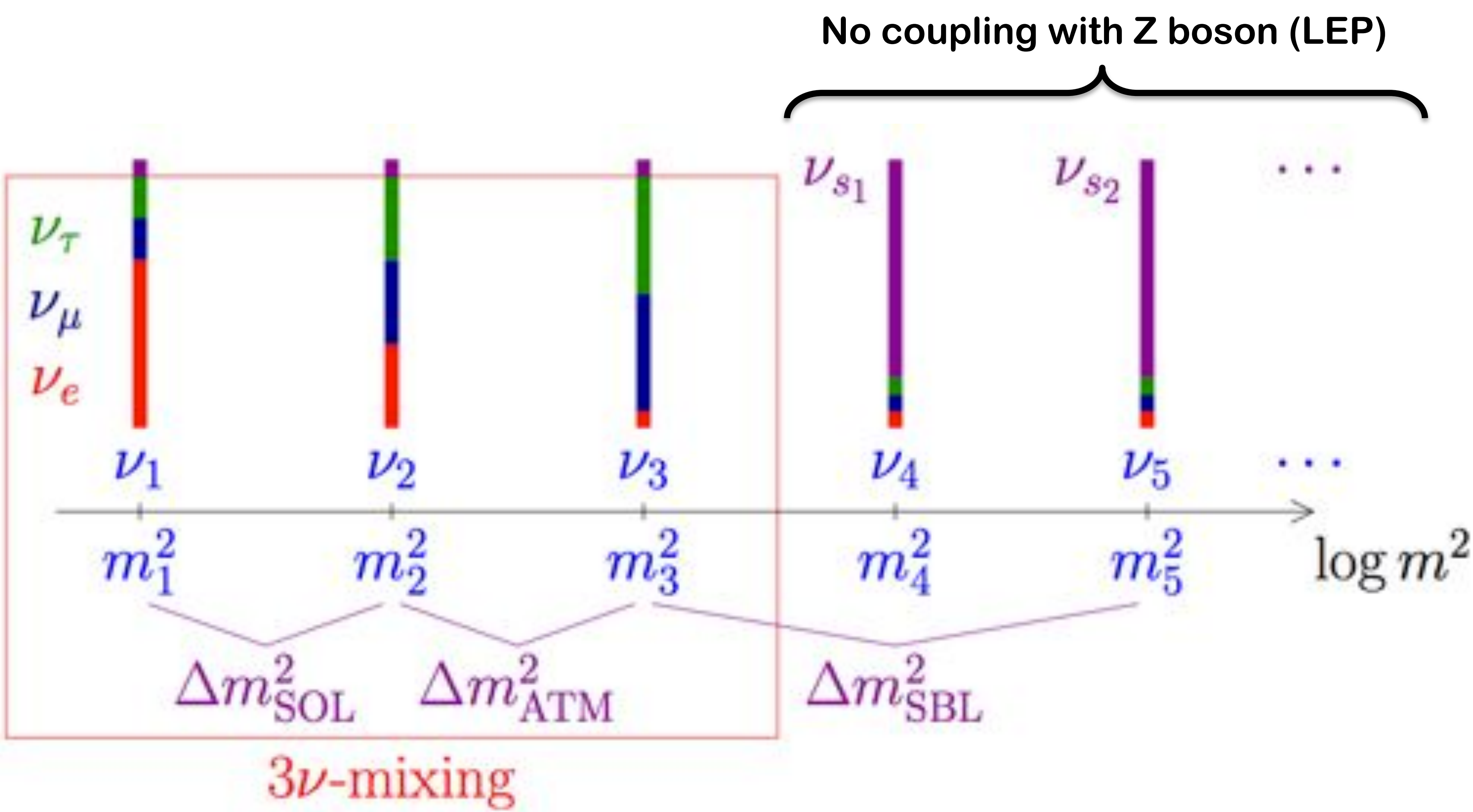
- 1^{st} results published in PRL 75 (1995)
- **Channel:** anti-ν_μ → anti-ν_e
- **Detection :** anti-ν_e + ^1H → e^+ + n
- **Baseline:** 30 m
- **Energy:** 20 < E (MeV) < 200
- **Status:**
  - anti-ν_e excess observed → 32.2 ± 9.4 ± 2.3 (3.8σ)
  - not confirmed by Karmen
- **Oscillation parameters:**
  - $\Delta m^2 >> 0.2\ eV^2 >> \Delta m_{atm}^2$
  - Require a 4^{th} neutrino state





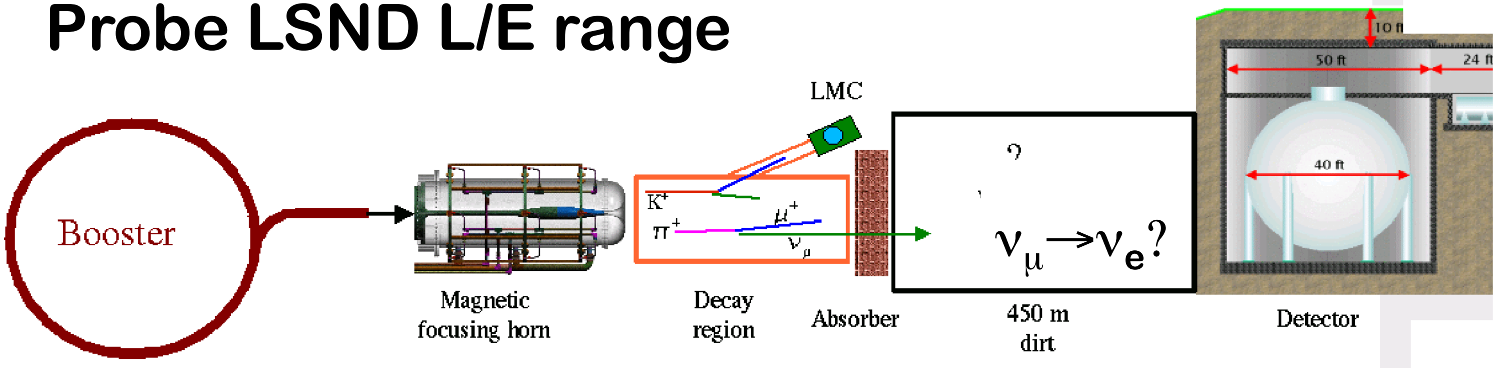
Adding Sterile Neutrinos

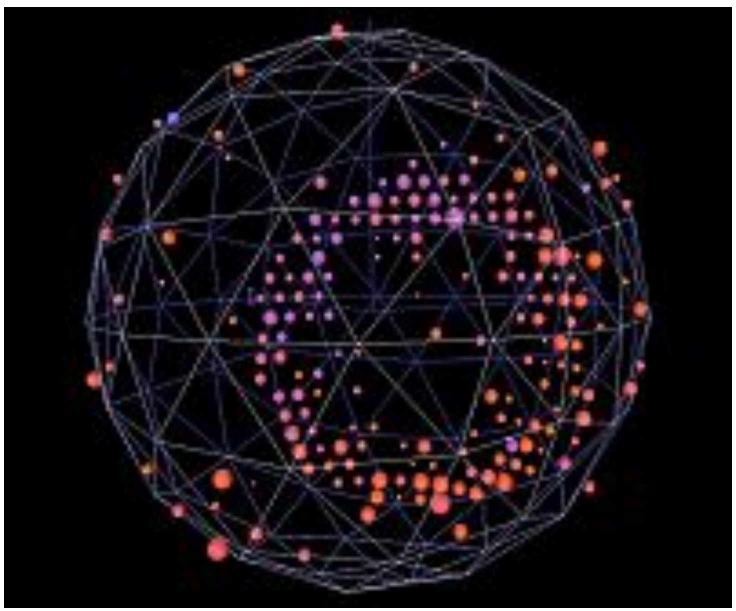
Introduce a light ν_R in SM, No SM interactions mixing with active ν' s



The MiniBooNE Experiment

Primary goal: look for ν_e appearance in a ν_μ beam
Probe LSND L/E range

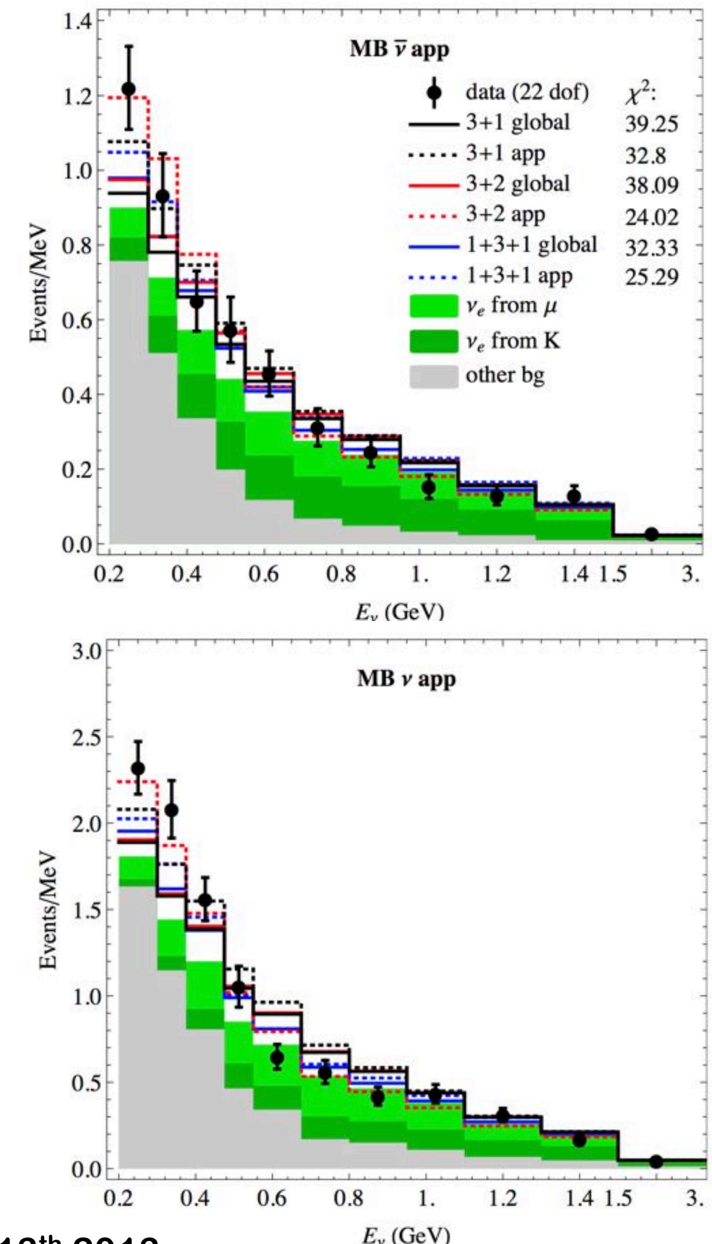




- Cherenkov + scintillation
- π^+ (π^-) decay in flight beam
- L/E $\approx$1 m / MeV
  - Baseline: 500 m
  - <E> 500 MeV
- Started in 2002

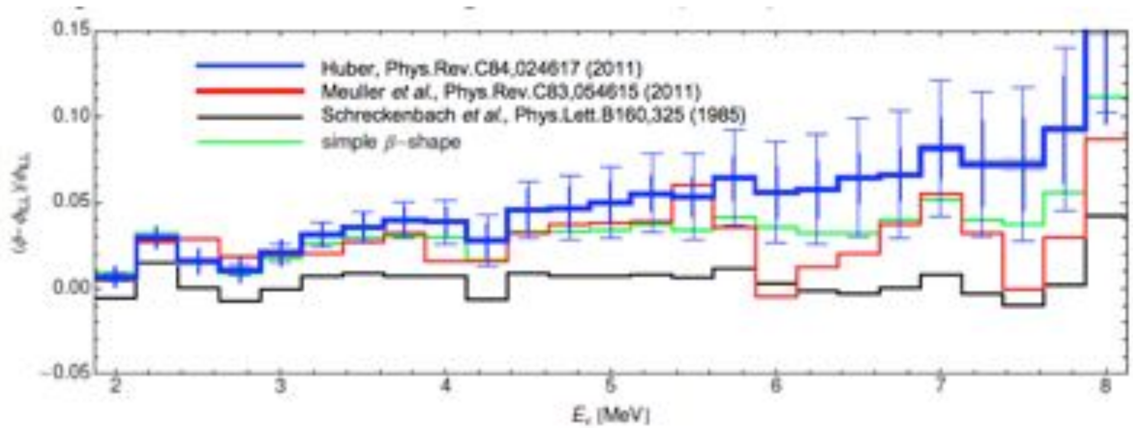
Miniboone Results (FNAL)

- Results published from 20107-12
- **Channel:** (anti-)ν_μ → (anti-) ν_e
- **Detection:** ν_e (p)n → e p (CCQE)
- **Baseline:** 541 m
- **Energy:**
  - 200 < E (MeV) < 3000
- **Status:**
  - Excess of event at low energy
    - 3.8 σ
    - 4th neutrino?
    - Backgrounds issue?



The Reactor Anomaly

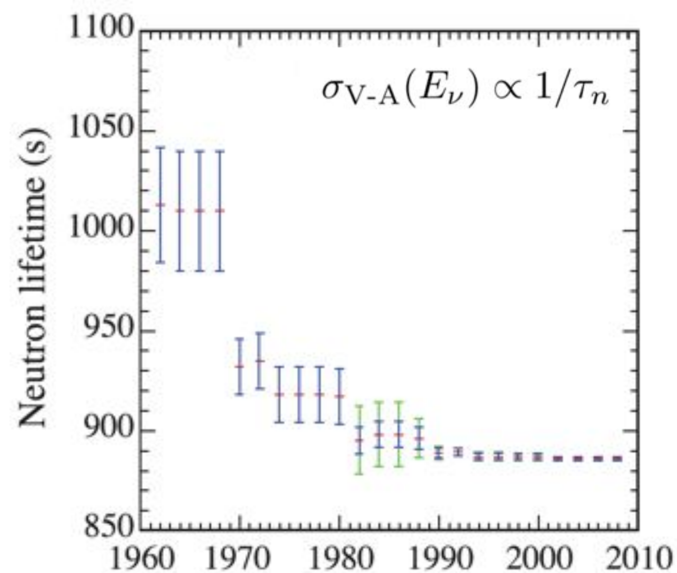
i) $\nu_{emission}$: **Improved reactor neutrino spectra → <u>+3.5%</u>**



PRC83, 054615 (2011)

PRC84, 024617 (2011)

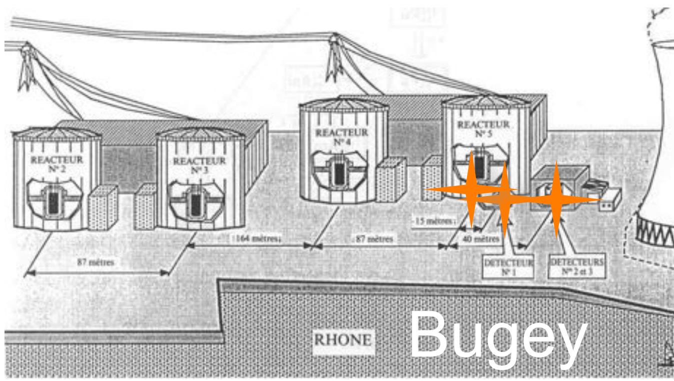
ii) $\nu_{detection}$: **Reevaluation of σ_{IBD} → <u>+1%</u>**
Evolution of the neutron life time

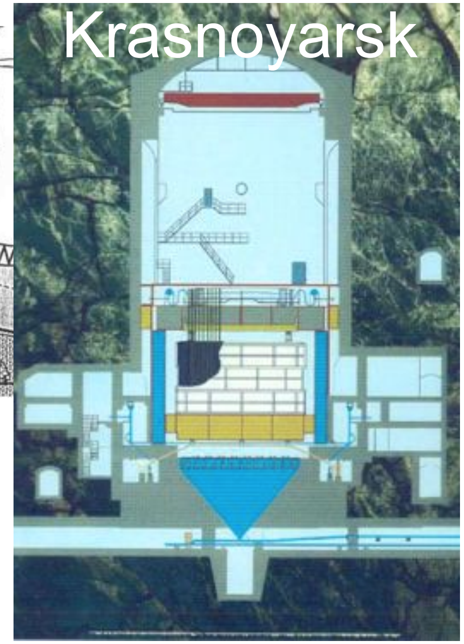


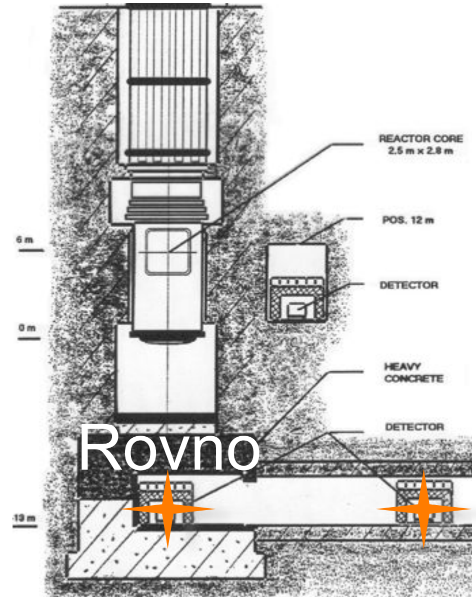
iii) $\nu_{detection}$: **Accounting for long-lived isotopes accumulating in reactors → <u>+1%</u>**

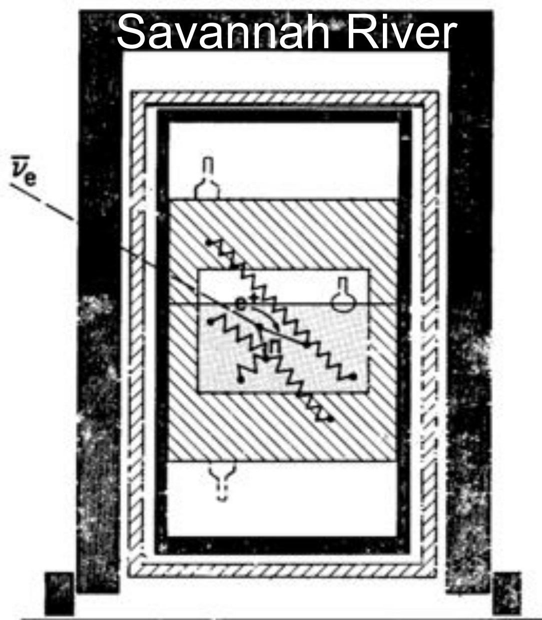
PRD 83, 073006 (2011)

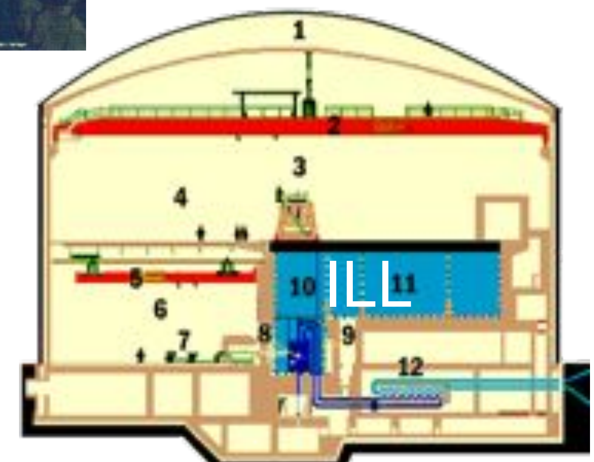
19 Experimental Results below 100m





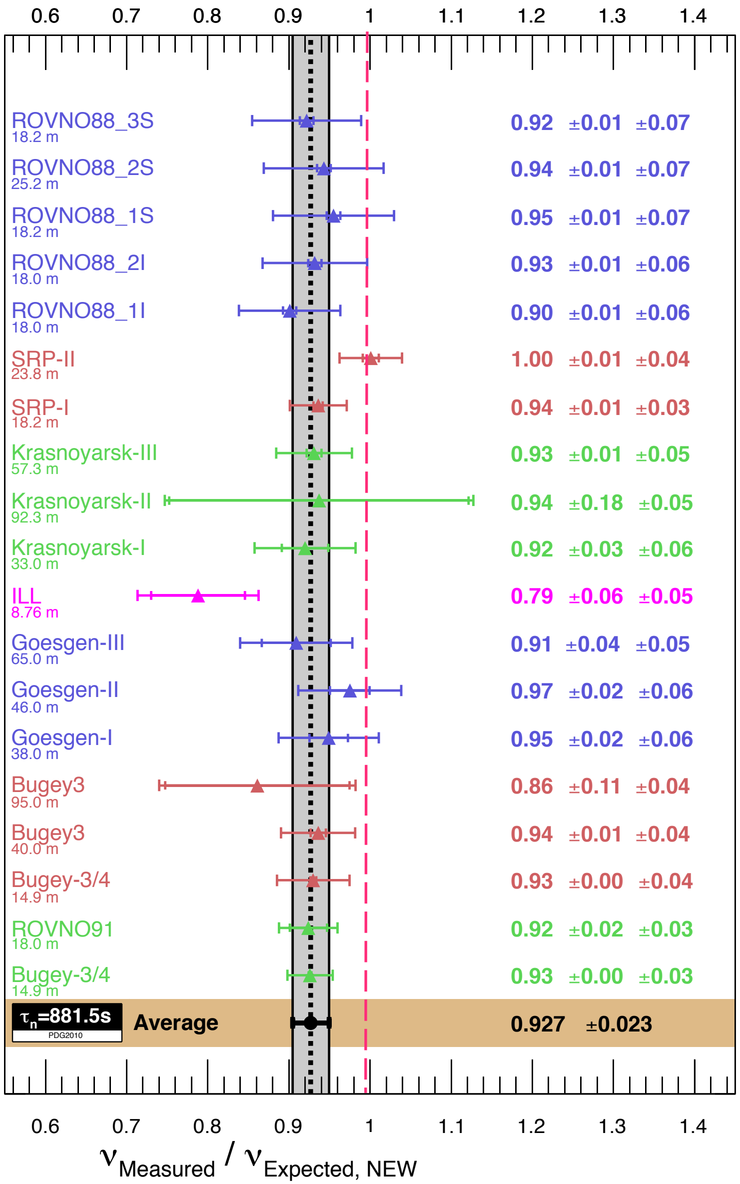






Measured cross sections / fission taken at their face values

The reactor anomaly

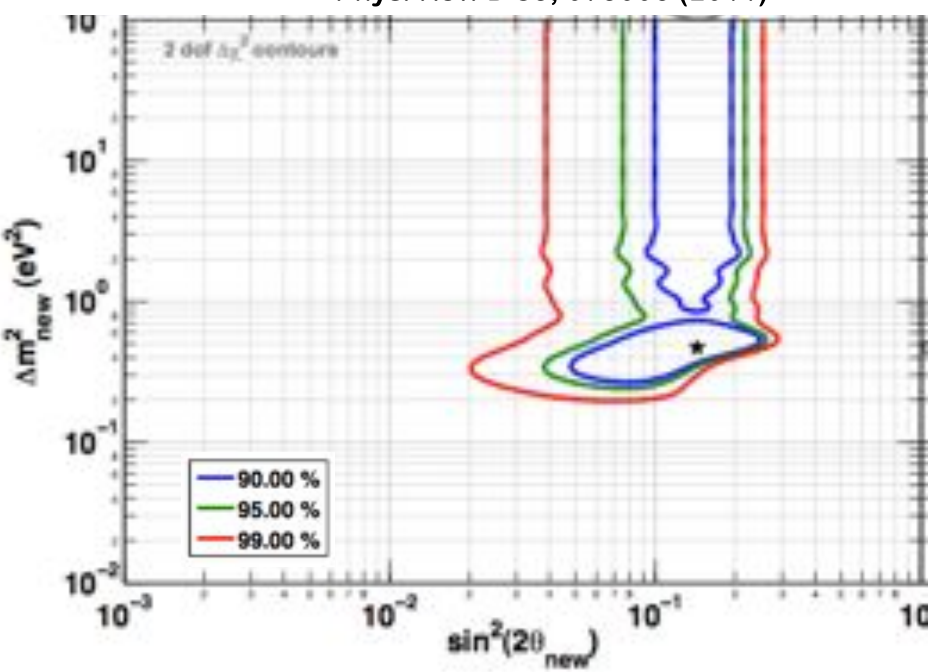


- 19 experiments reanalyzed PRD 83, 073006 (2011)
- 7% deficit wrt the new prediction
  - ≈3%: reevaluation of emitted flux
  - ≈3%: reevaluation of
    - IDB cross section revision
    - Accounting for off eq. effect
- 99.7 % C.L. deviation from unity
- Artifact or new physics?

The 4th neutrino hypothesis

Rate Only Analysis

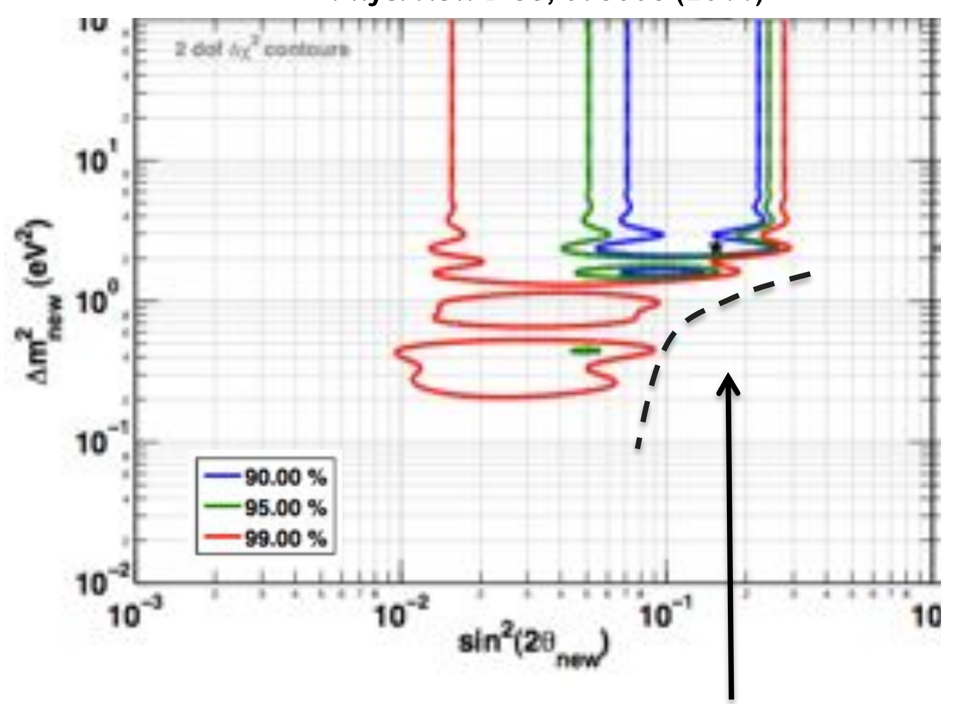
Phys. Rev. D 83, 073006 (2011)



- Best Fit at $\Delta m^2_{new} \approx$ few 0.1 eV^2

Rate + Shape Analysis

Phys. Rev. D 83, 073006 (2011)

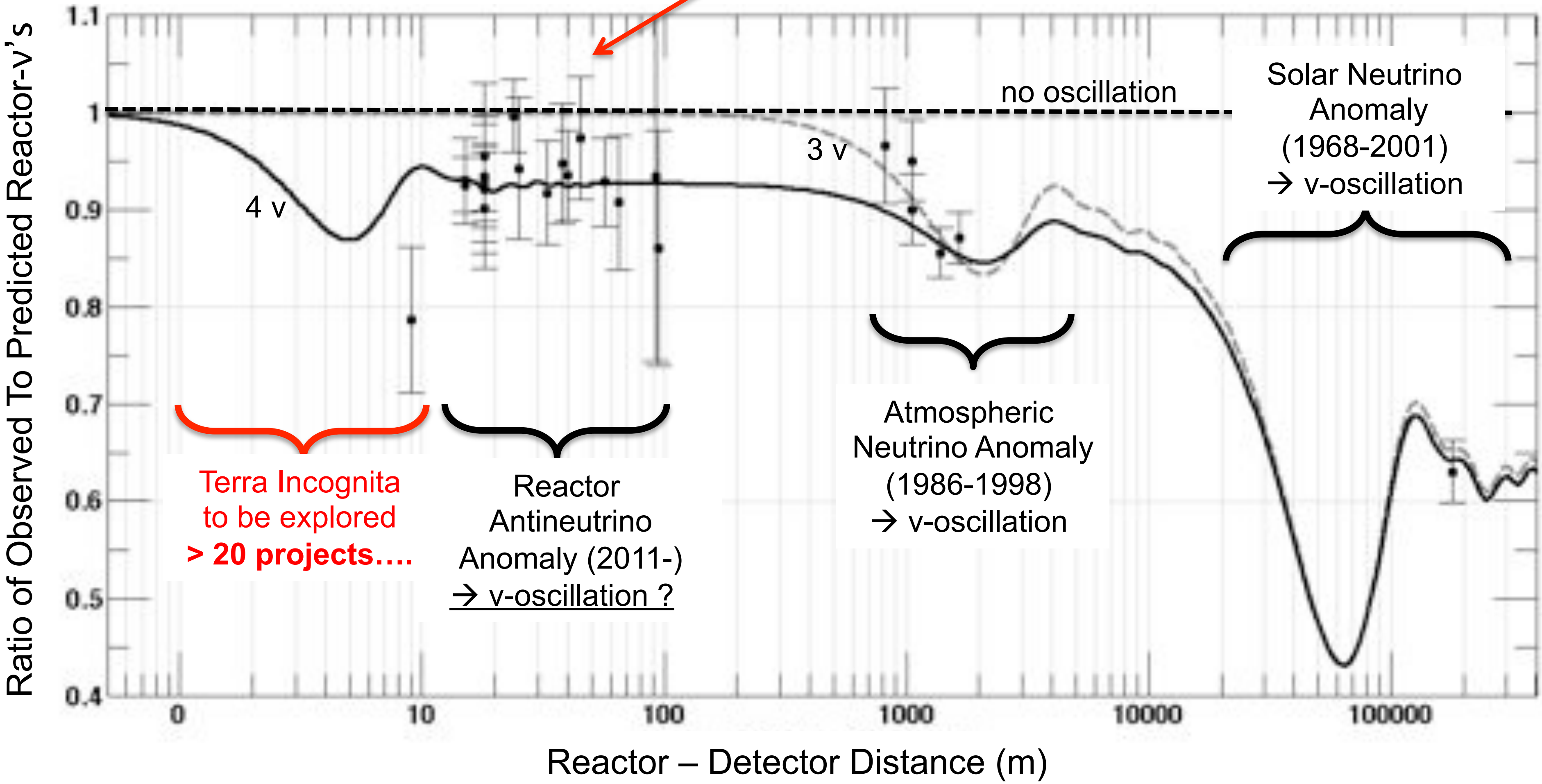


- Bugey-3 40m/15m $E_{spectrum}$ ratio
→ No energy spectrum distortion
→ large PWR core extension

- Best Fit at $\Delta m^2_{new} > 1$ eV^2

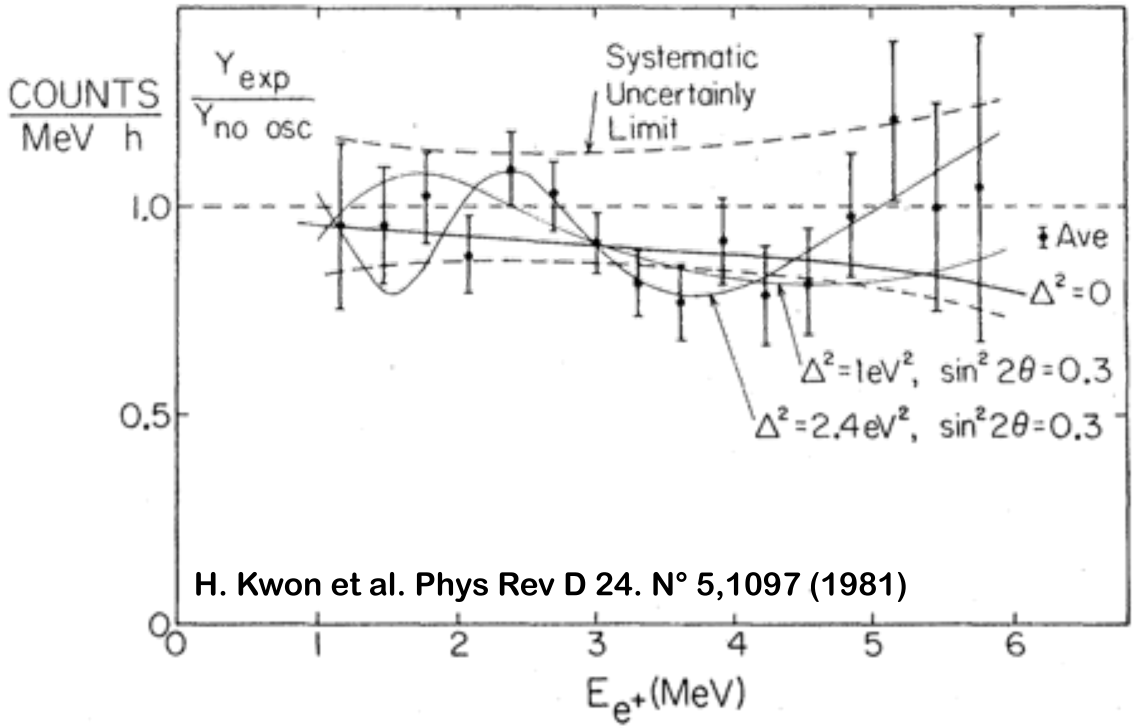
The Reactor Anomaly

- **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**



Puzzling 1981 ILL ν-experiment

- Reactor at ILL with **almost pure** ^{235}U, with **compact core**
- Detector 8.8 m from a COMPACT core
- Reanalysis in 1995 to account for overestimation of flux at ILL reactor by 10%... Affects the rate only but 20% deficit!

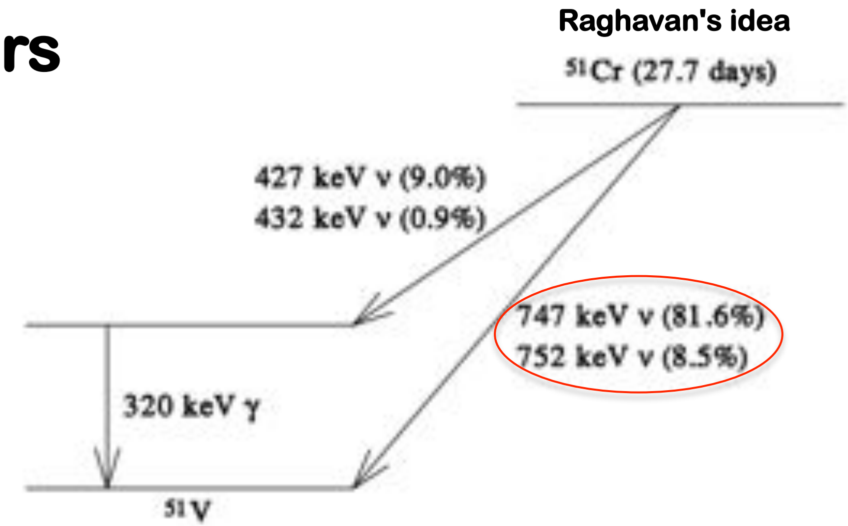


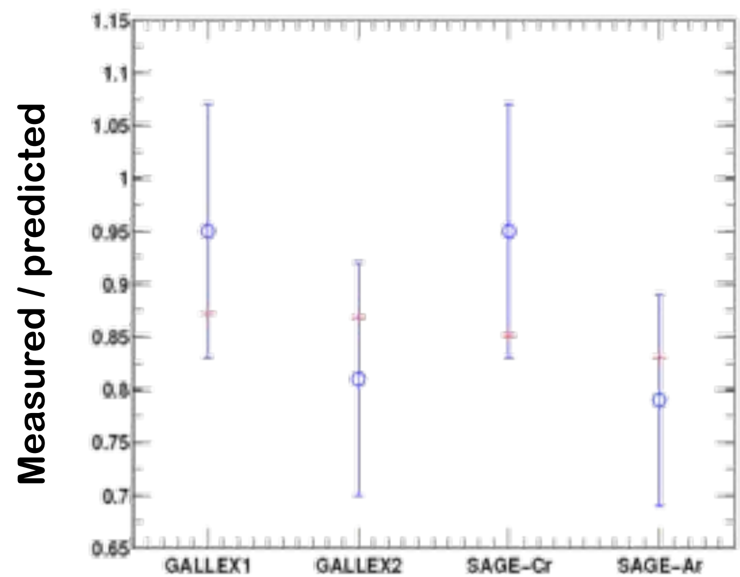
H. Kwon et al. Phys Rev D 24. N° 5,1097 (1981)

- Large errors, but a striking pattern is seen by eye ?

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)





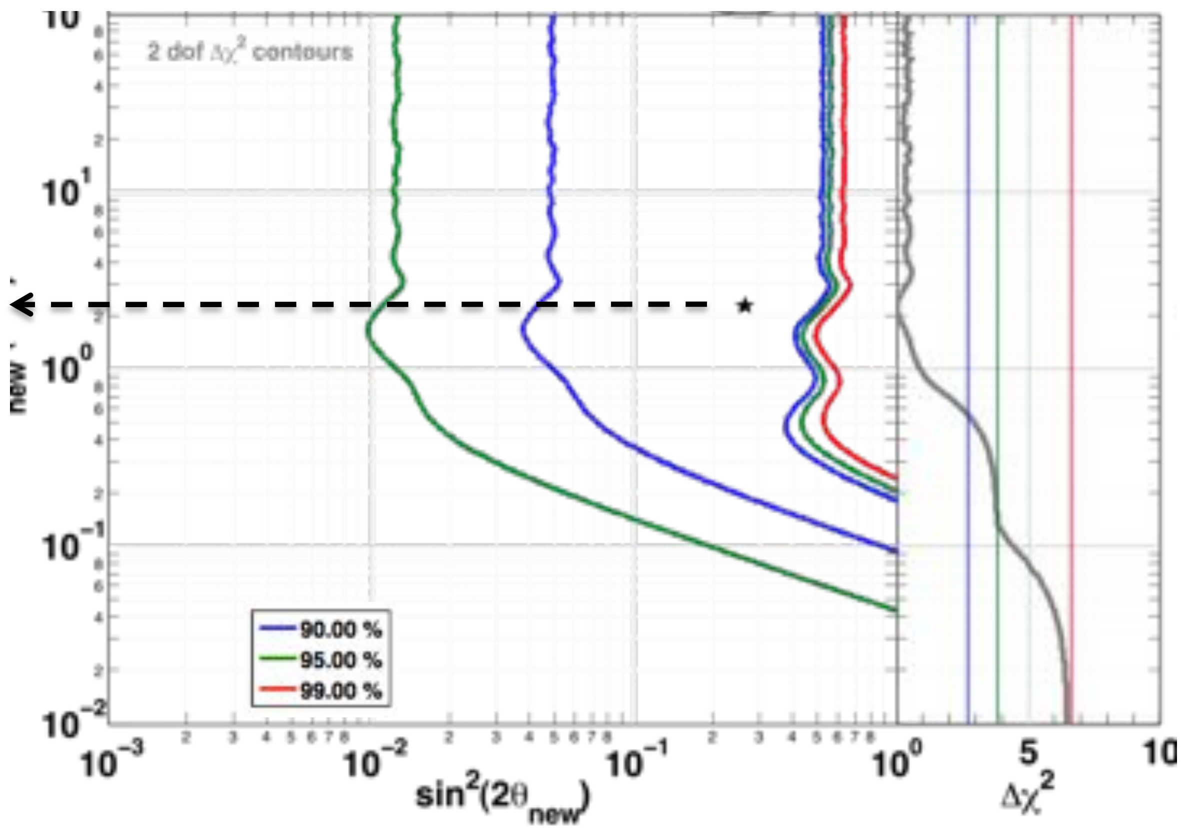
- **Deficit observed**
  - $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
  - $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})

The Gallium Neutrino Anomaly

Fit to ν_e disappearance hypothesis (3+1)

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

$\Delta m^2_{new} \approx eV^2$

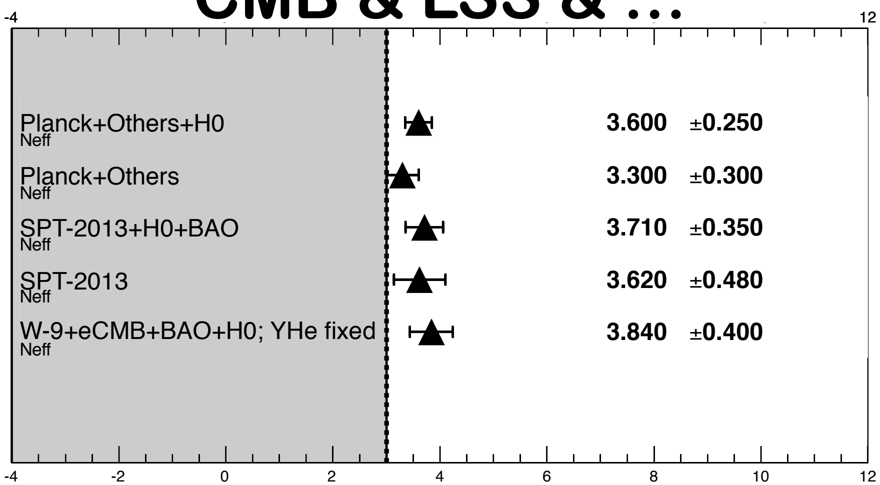


No-oscillation hypothesis disfavored at 2.7σ (PRC 83 065504,2011)

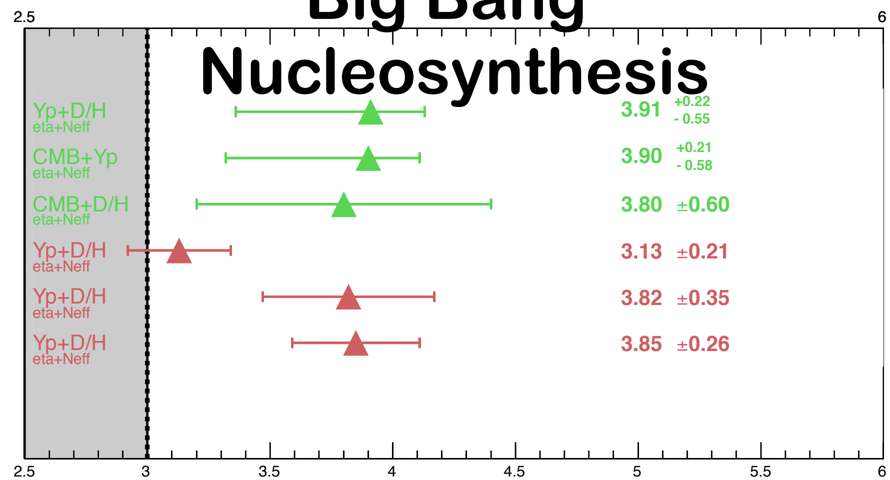
Number of ν's From Cosmology

Universe Expansion Rate $H^2 \approx (\rho_\gamma+\rho_\nu)$ - ρ_γ given by CMB data

CMB & LSS & …



Big Bang Nucleosynthesis



- **WMAP + other observables consistent with 3 and 4**
- **Planck favors 3.3, but consistent with 4**
- **Strong cosmological bounds, but model dependent**

Anomalies & 4^{th} Neutrino

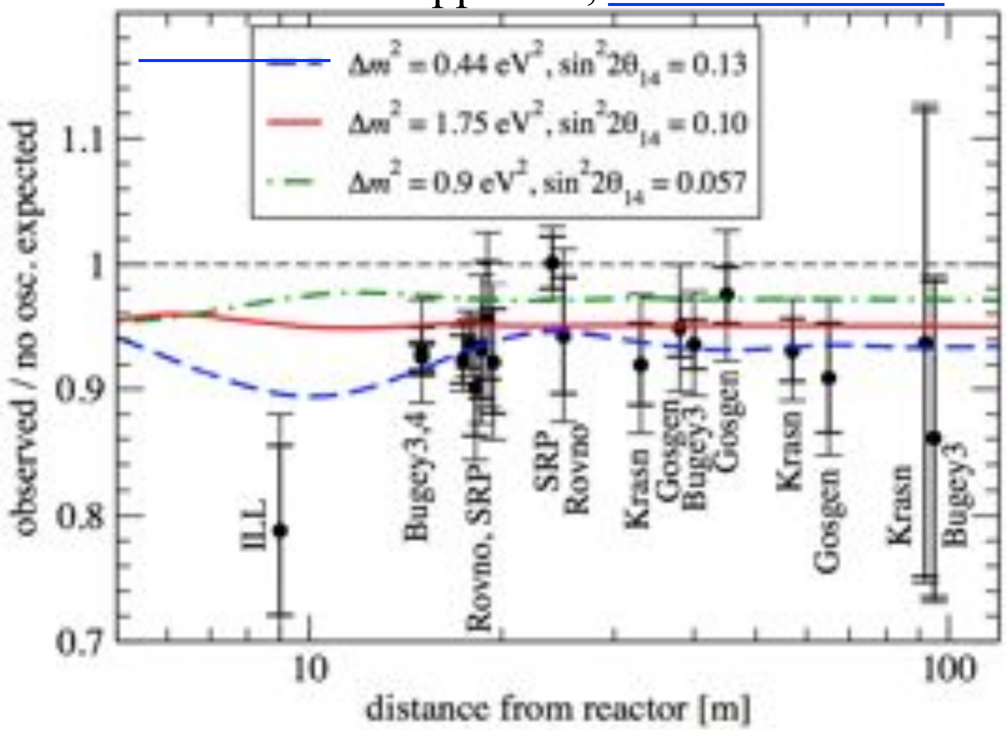
Anomaly	Source	Type	Sensitivity to Oscillation	Channel	Significance
LSND	Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBoone	Short baseline	$\nu_\mu \rightarrow \nu_e$	Total Rate, Energy	CC	3.8 σ
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	2.7 σ
Reactor	Beta-decay	$\bar{\nu}_e$ dis.	Total Rate, Energy	CC	3.0 σ
Cosmology	Big-Bang	All	Number of ν, N_{eff}	N_{eff} = 3 or 4 allowed	

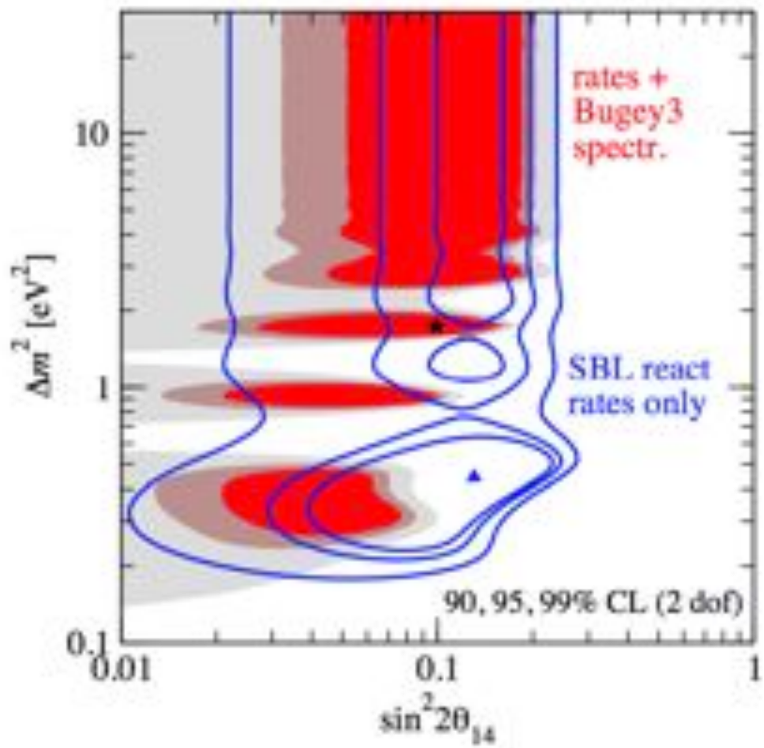
could be interpreted by an existing eV^2 4^{th} neutrino state?

Global Picture

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

J. Kopp et al., arXiv:1303.3011





	$\sin^2 2\theta_{14}$	$\Delta m^2_{41}\ [eV^2]$	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{no\ osc}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)

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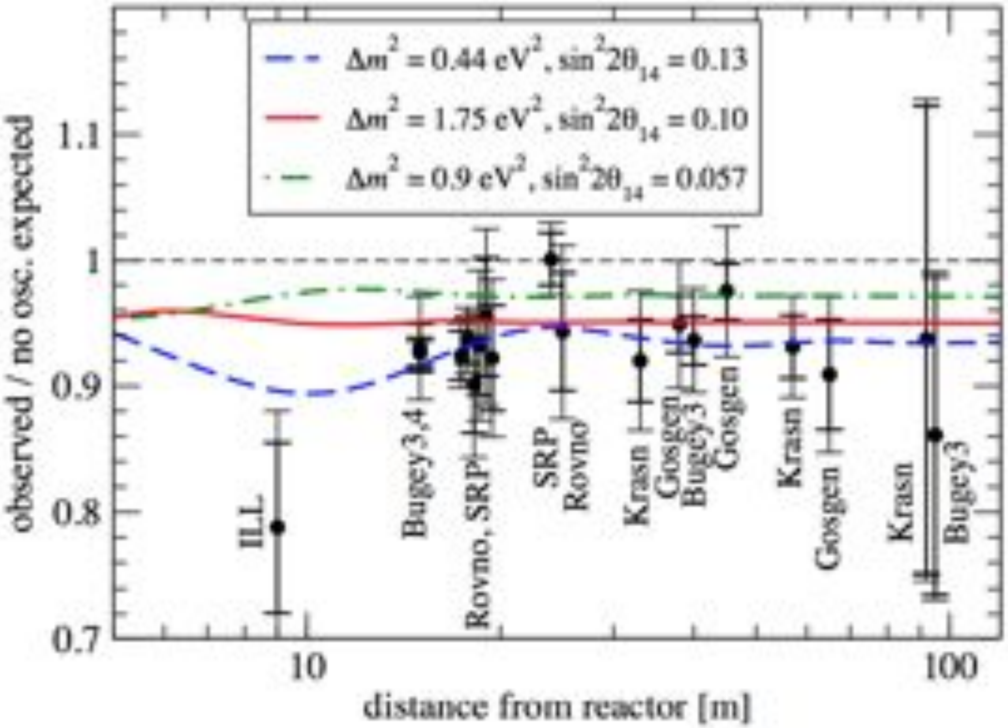

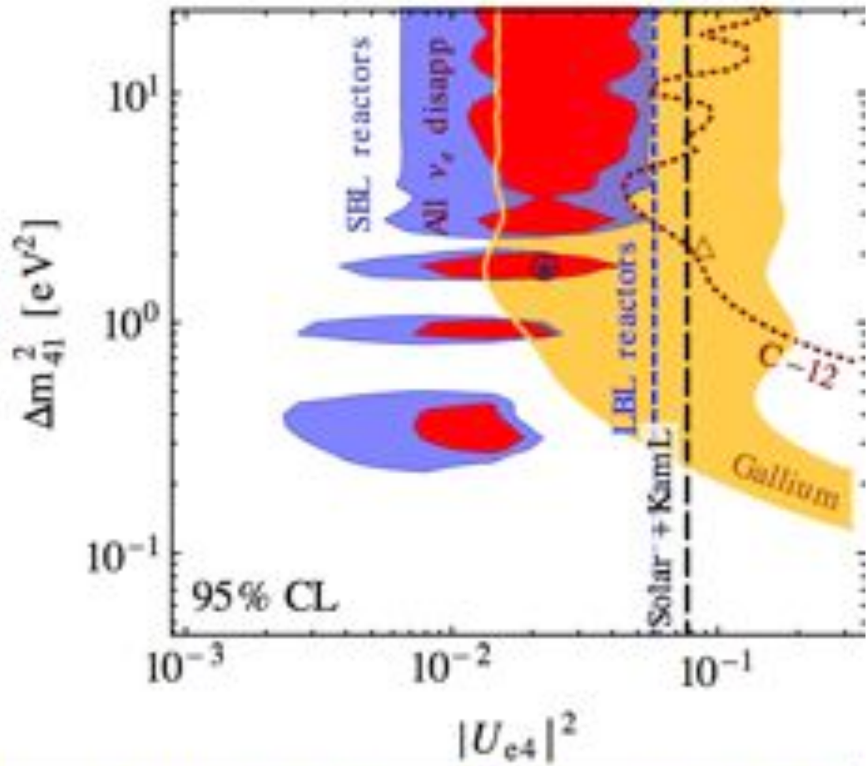

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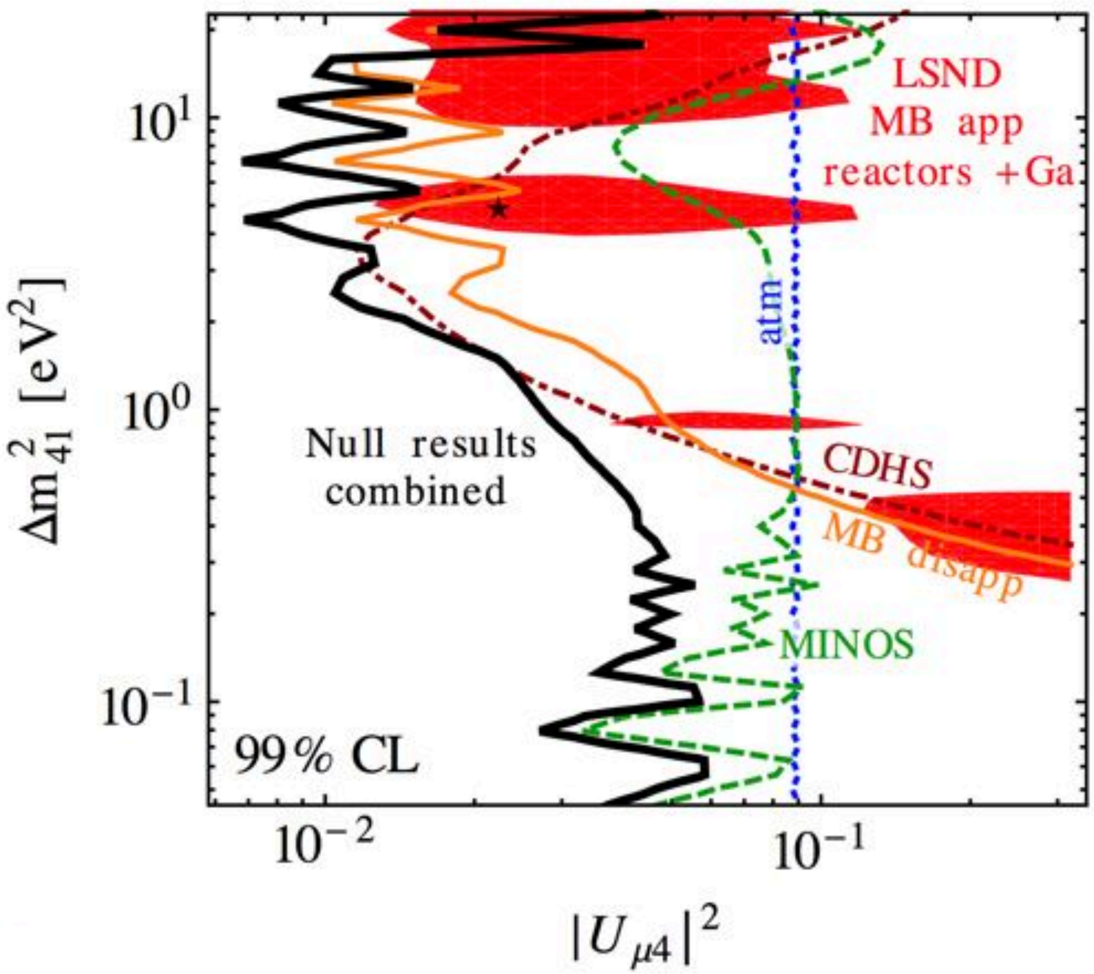
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

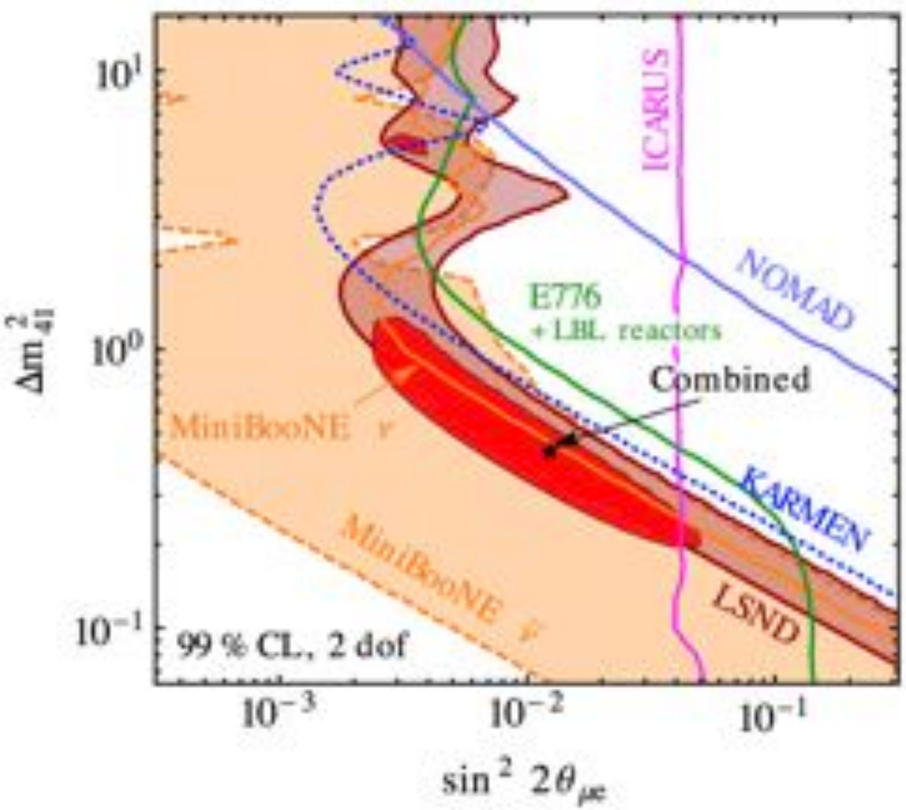
$\overset{(-)}{\nu}_\mu$ disappearance (3+1 scenario)

No evidence for disappearance



J. Kopp et al., arXiv:1303.3011

$\overset{(-)}{\nu}_e$ appearance (3+1, 3+2 scenarios)



J. Kopp et al., arXiv:1303.3011

	χ^2_{3+1}/dof	χ^2_{3+2}/dof	χ^2_{1+3+1}/dof
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/66	72.7/63	74.6/63

- **Global fit to all appearance data is consistent**
- **Improvement of the fit by adding 2 sterile neutrinos**

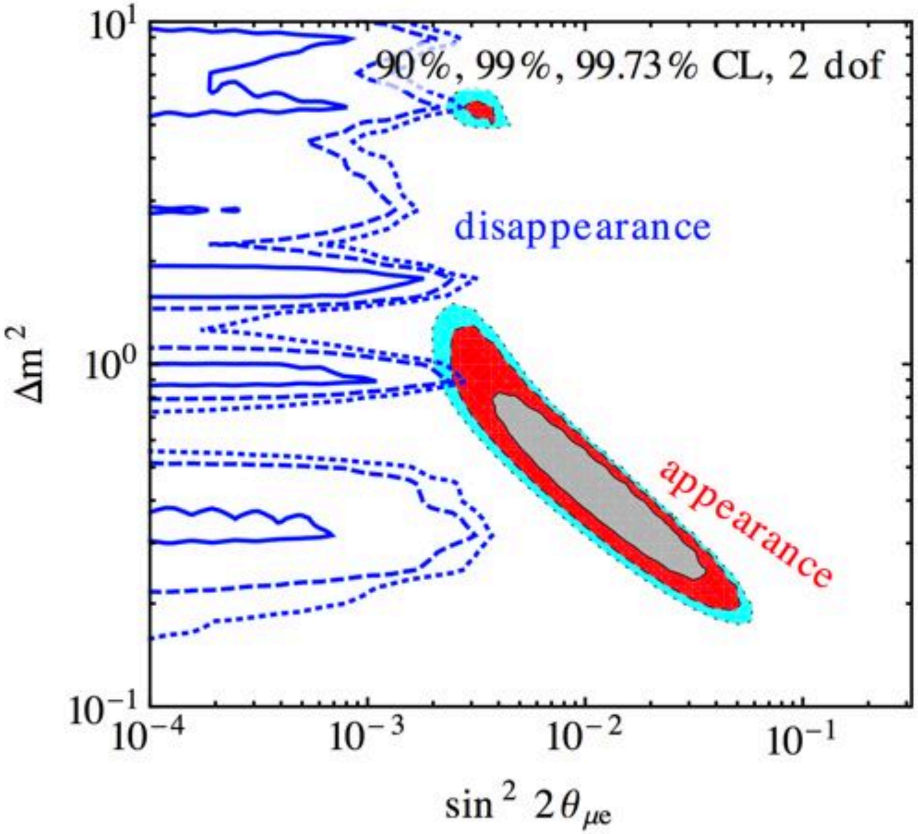
Appearance / Disappearance Coupling

- **Electron disappearance channel**
  - $P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E}$ & $\sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$
- **Muon disappearance channel**
  - $P_{\mu\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41}}{4E}$ & $\sin^2 2\theta_{\mu\mu} = |U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$
- **Electron appearance channel**
  - $P_{\mu e} = 4 \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41}}{4E}$ & $\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$

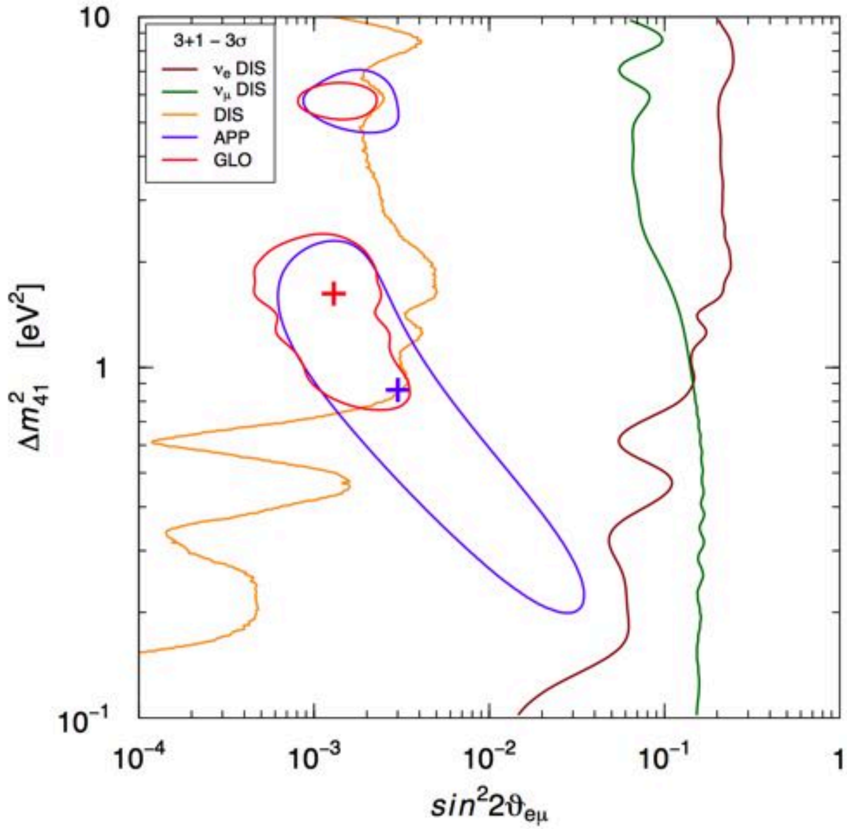
$\nu_\mu \rightarrow \nu_e$ appearance required both ν_μ & ν_e disappearance

Appearance / disappearance tension

J. Kopp et al., **arXiv:1303.3011**



C. Giunti et al., **arXiv:1302.6720**



Testing the eV-scale Sterile Neutrino Hypothesis

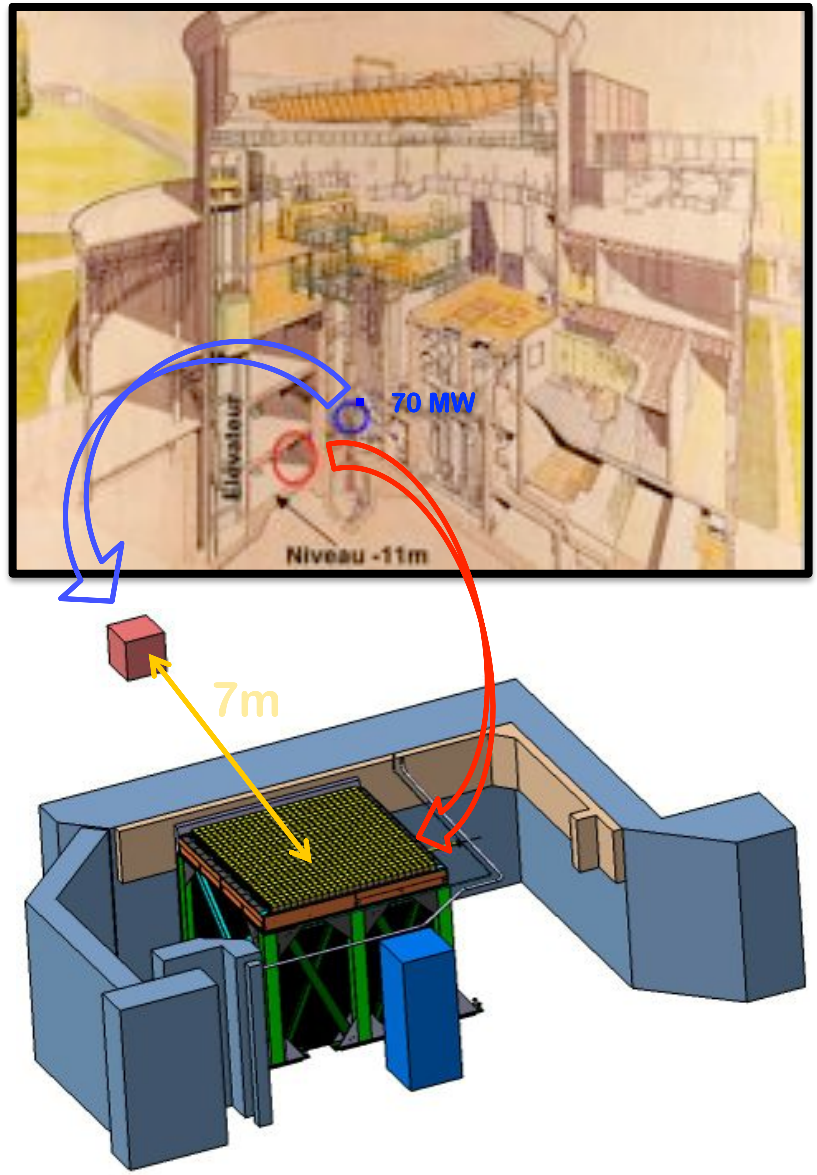
Th. Lasserre – CPPM May 13th 2013

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)
  - $\Delta m^2 \approx$ eV² : compact source <1m & good vertex resolution (<1m)
  - $\sin^2(2\theta_{new})$: experiment with few % stat. syst. uncertainties

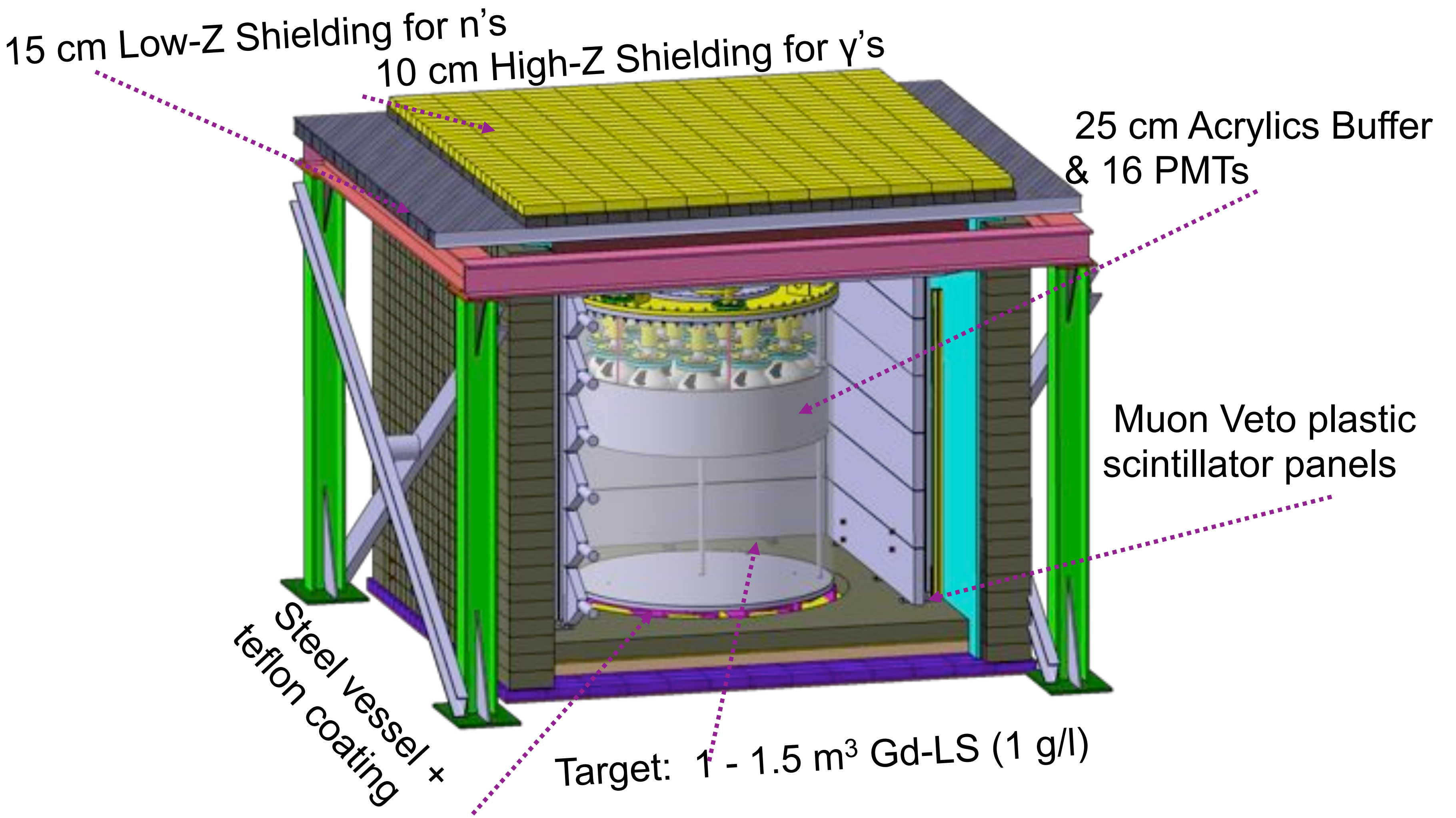
Nucifer

- Osiris research reactor
  - At Saclay, France
  - 70 MW, 20% ^{235}U
  - Compact: 60x60x60 cm^3
- Detector designed for reactor monitoring studies
  - 850 kg Gd-loaded liquid scintillator
  - 350 int. expected / day
- But modest oscillation detection capabilities:
  - Short baseline: only 7 m
  - Target: h = 70 cm, Φ = 1.2 m



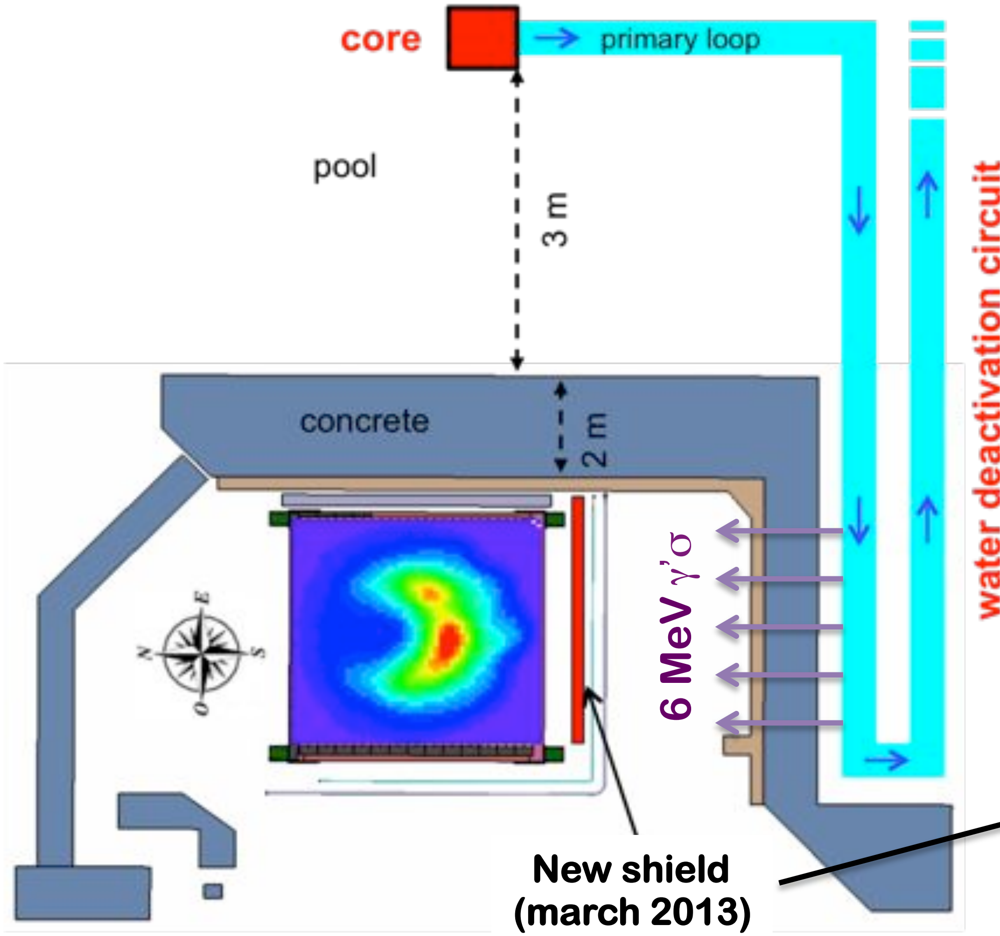
Nucifer Detector

▪ **Design accounting for IAEA constraints : A simple monolithic Gd-LS detector with PMTs reading from the top** (Nitrogen sealed, small, safe, robust, non intrusive)



Nucifer Upgrade

First run in 2012 indicated a unexpected background from primary loop circuit



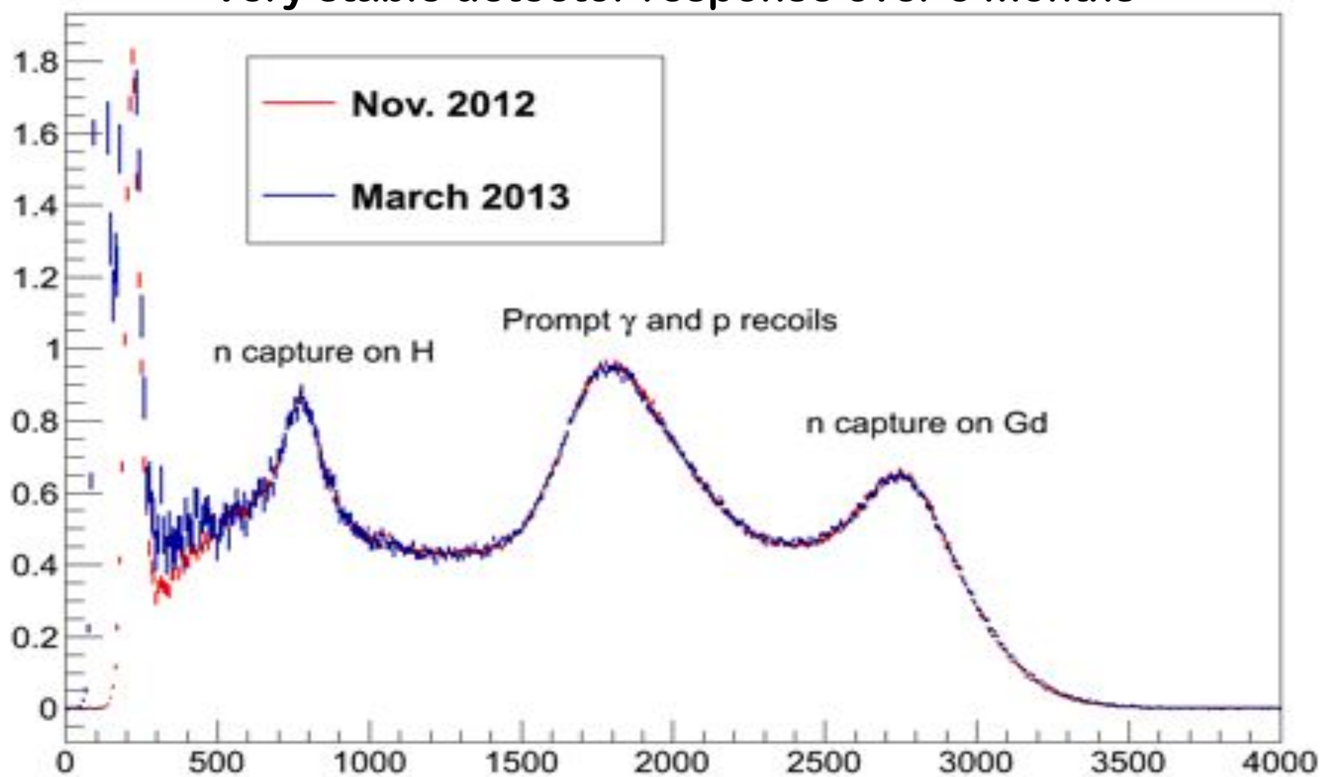
New lead wall erected early 2013

Accidental background has been reduced by a factor 500

Detector Operation

- **Detector is working as designed**
- Detector is running smoothly. Detector response is stable
- Nucifer has been operated remotely for several months.
- No safety incident has been reported

Very stable detector response over 5 months

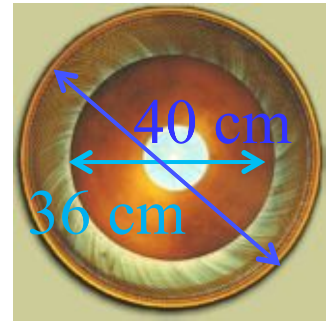


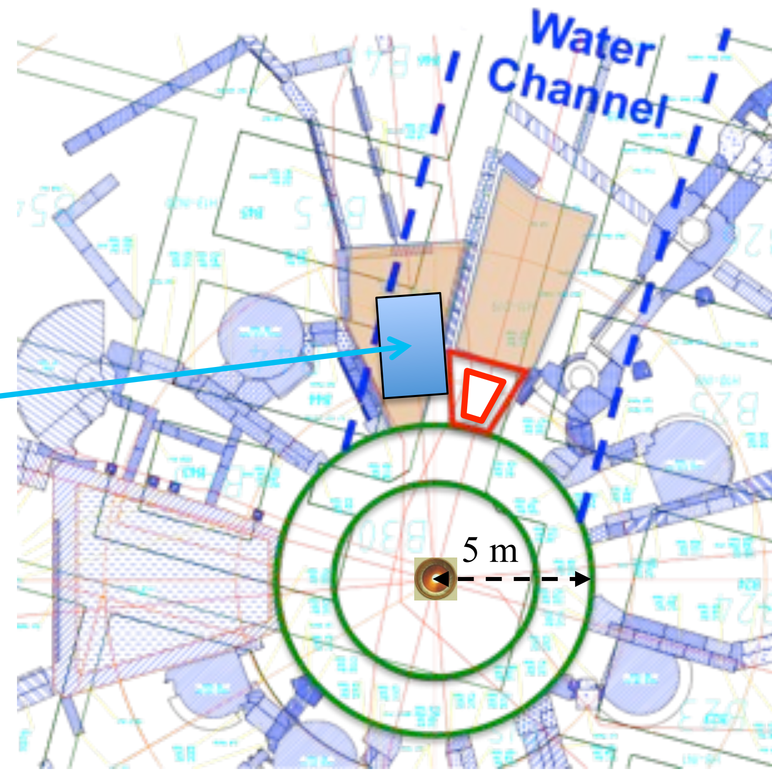
(Energy – 1 MeV = 340 photoelectrons)

STEREO project

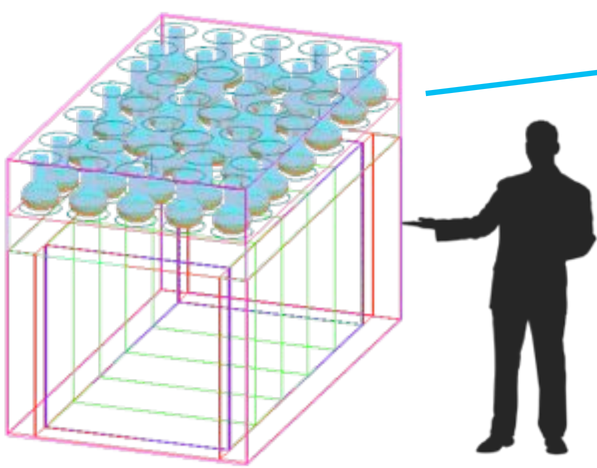
Contact: D. Lhuillier

- **ILL research reactor (Grenoble):**
  - **57 MW, highly enriched U**
  - **Compact: h = 80 cm, Φ = 40 cm**
- **Dedicated detector:**
  - **5 segments: L and E oscillation**
  - **Active outer layer: high eff.+veto**
  - **Muon flux divided by 4,**
    thick CH_2 and Pb walls (70 t)





Target:
Gd-doped
liquid
scintillator



Oscillometry inside a ν-detector

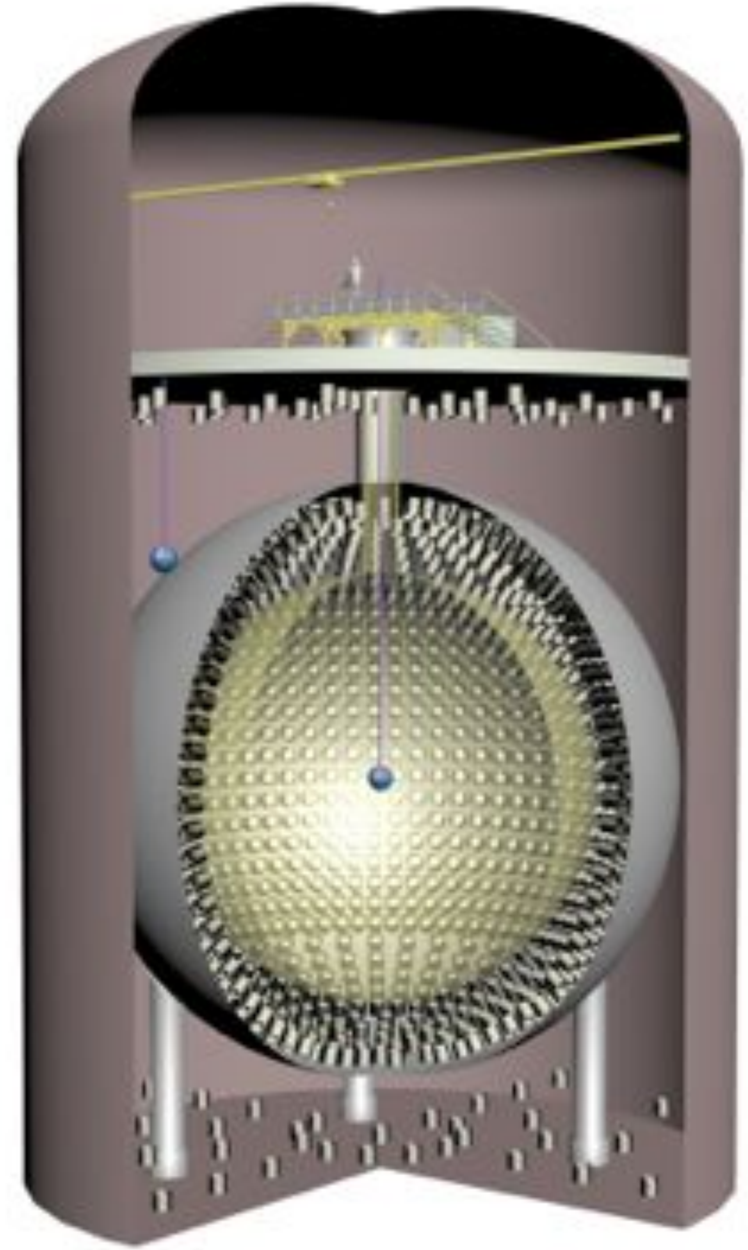
- **Place the ν-emitter inside or close to existing detectors**
  - **Very short Baseline (few m)**
  - **Low Background**

i) ν-source at center

- $$\frac{dN_\nu}{dR} \propto \left[1 - \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 R}{\langle E \rangle}\right)\right]$$

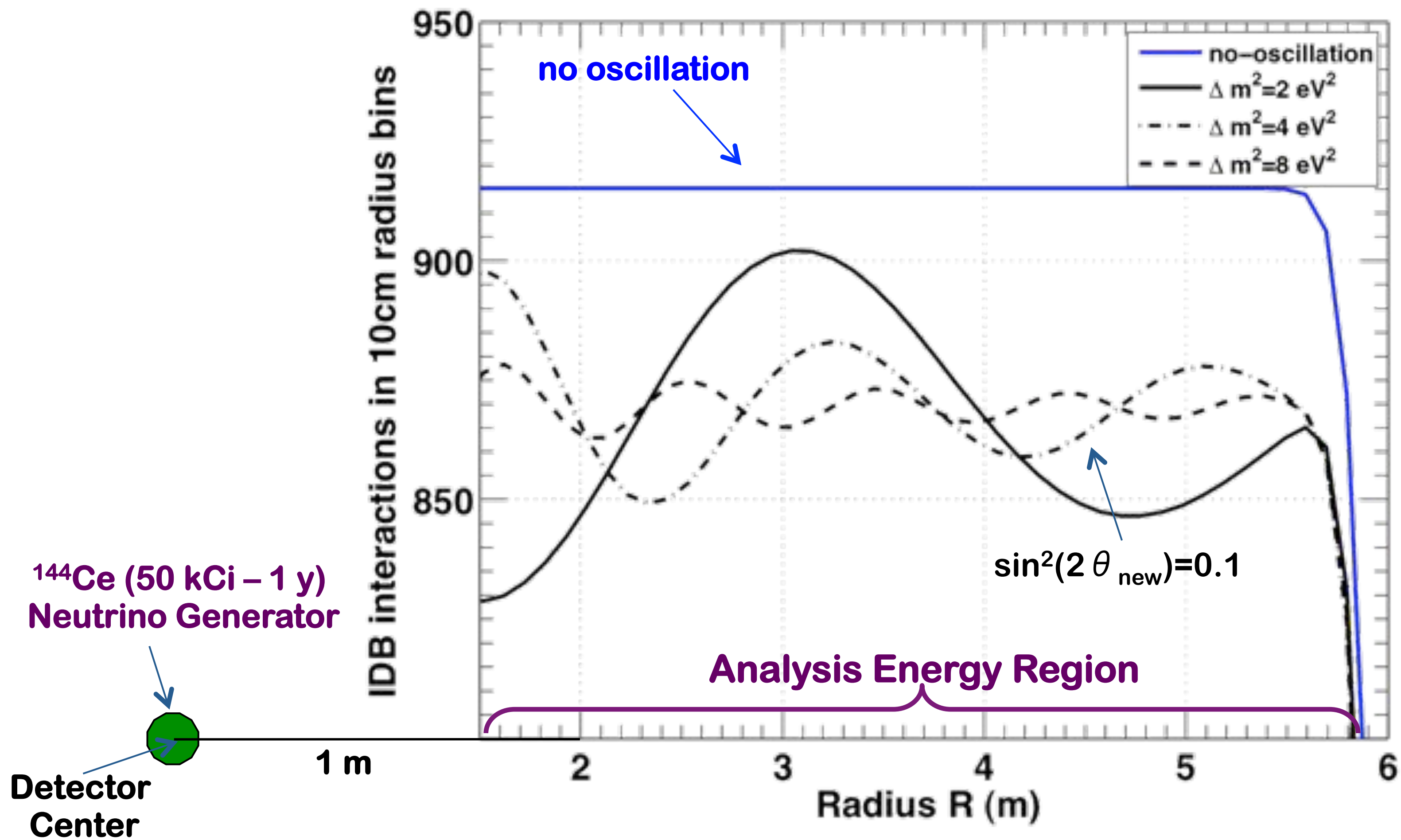
ii) ν-source Outside LS

  - **Specific oscillation pattern analytically computable**



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

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



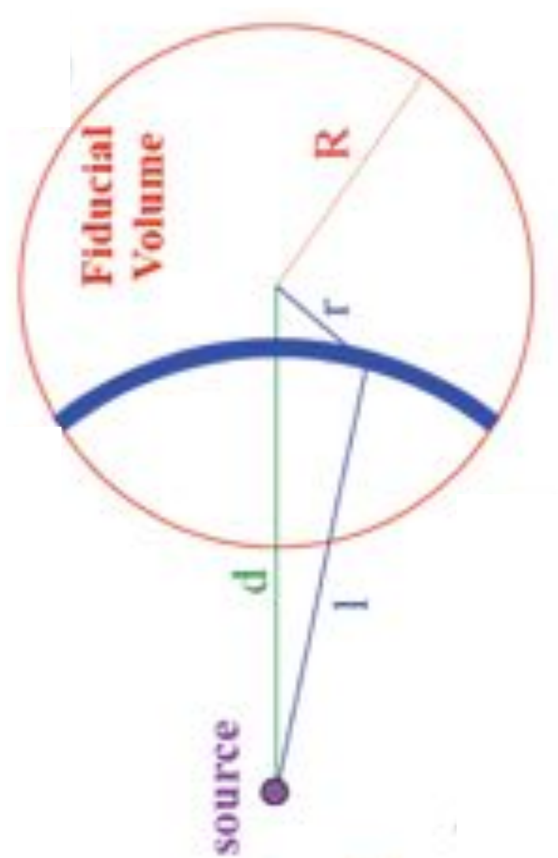
ν generator proposals

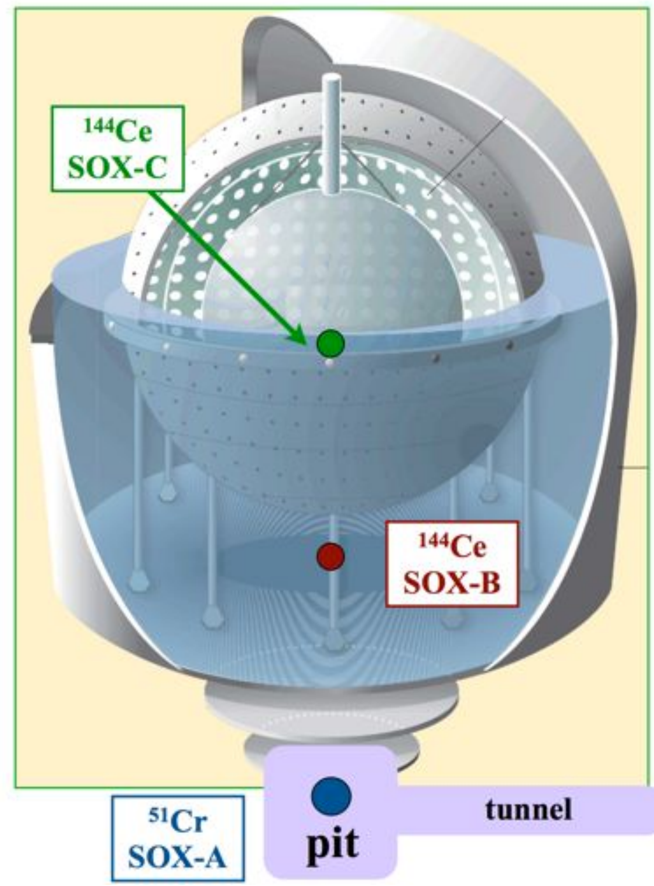
Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	$\nu_e e \rightarrow \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν -Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	>10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

$^{51}Cr/^{144}Ce$ Source in Borexino (SOX)

- **Existing Tunnel → source at 8.25 m from the LS target**

Eur. Phys. J C8, 1999

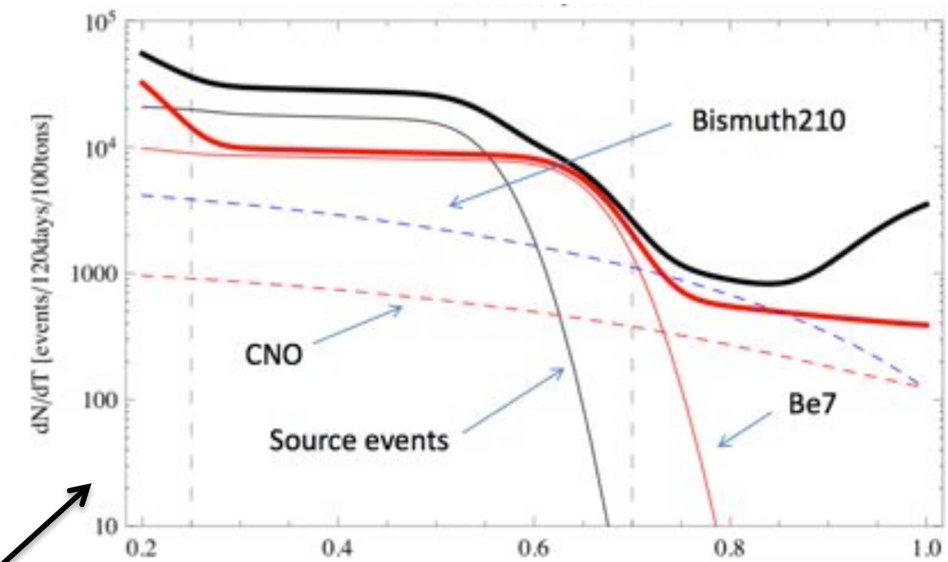


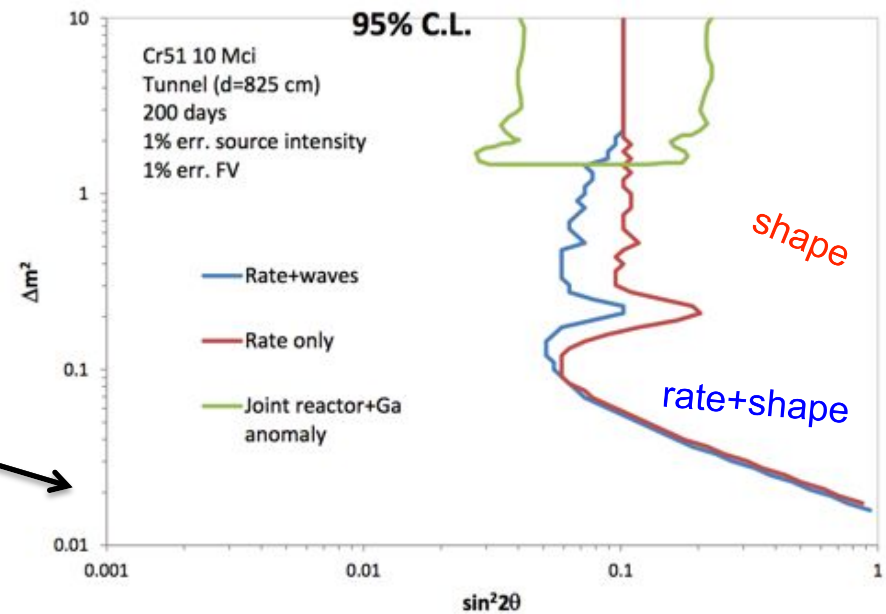


- **Observable: ν_e events as a function of distance (l)**

^{51}Cr Source underneath Borexino

- **10 MCi ^{51}Cr**
  - Re-use Gallex 36 kg of enriched chromium (38%)
  - But need add. enriched ^{50}Cr
- **Reactors (Petten, Ludmila, US)**
  - $n_{th} \approx 10^{15}$ n/cm^2/sec
  - Space to accommodate ^{50}Cr
- **Detection as ^7Be solar ν**
  - Well known background in 0.25-0.7 MeV: solar ν's & ^{210}Bi
  - 1% fiducial volume error
- **R+S Oscillometry analysis**
- **ERC Funding**





CeLAND: 75 kCi ^{144}Ce-^{144}Pr in KamLAND

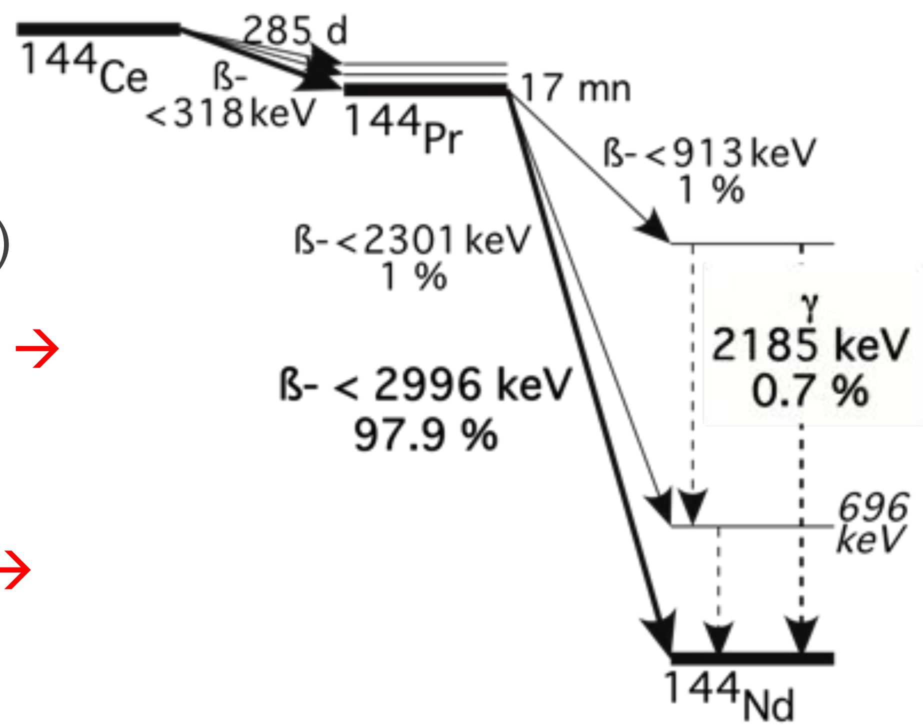
Phys. Rev. Lett. 107, 201801 (2011)

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

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

- 1^{st} 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

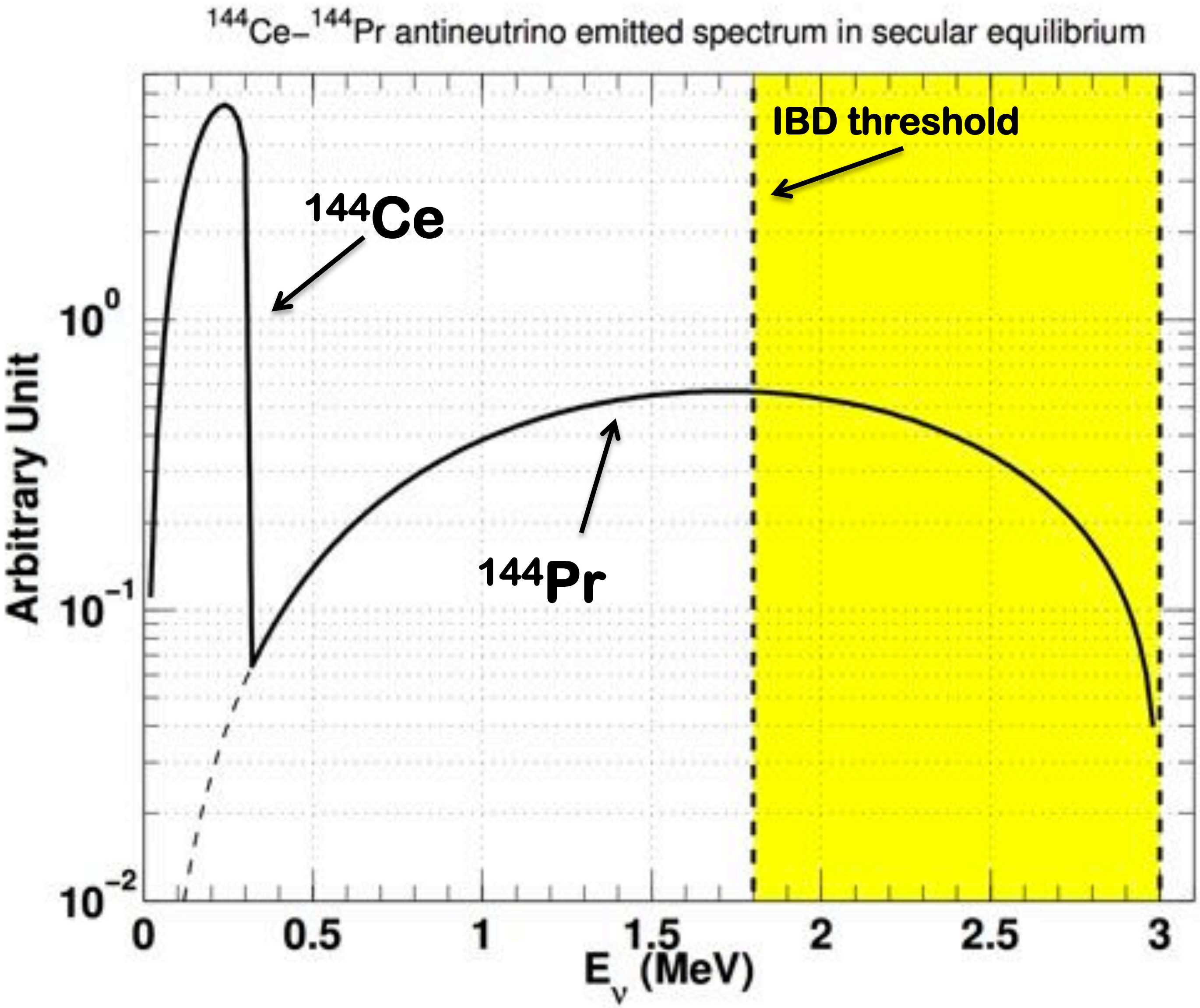
- 2^{nd} Trick: ^{144}Ce-^{144}Pr
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β → Enough time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β → $\bar{\nu}_e$-emitter above threshold



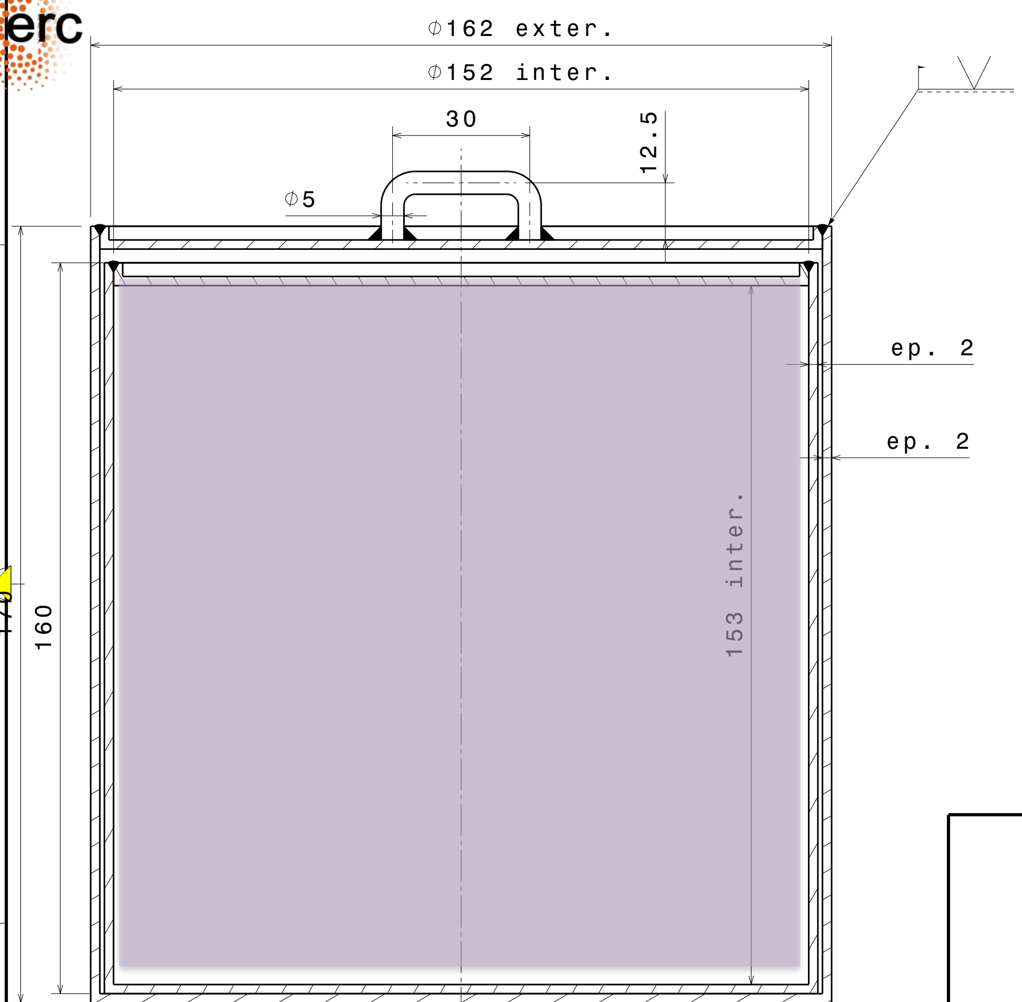
^{144}Ce Production at PA Mayak: 2014

75 kCi (2.77 PBq), 4 kg of Ce0$_2$ (ρ= 4 g/cm^3), 600 W

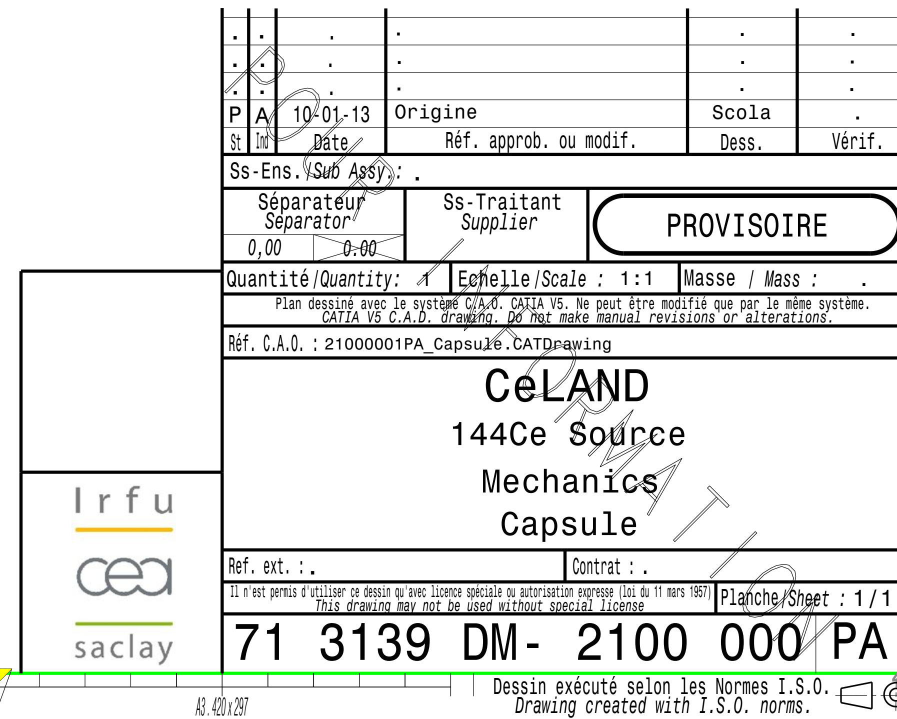
^{144}Ce-^{144}Pr Antineutrino Spectra



75 kCi (2.78 PBq) ^{144}Ce-^{144}Pr Source

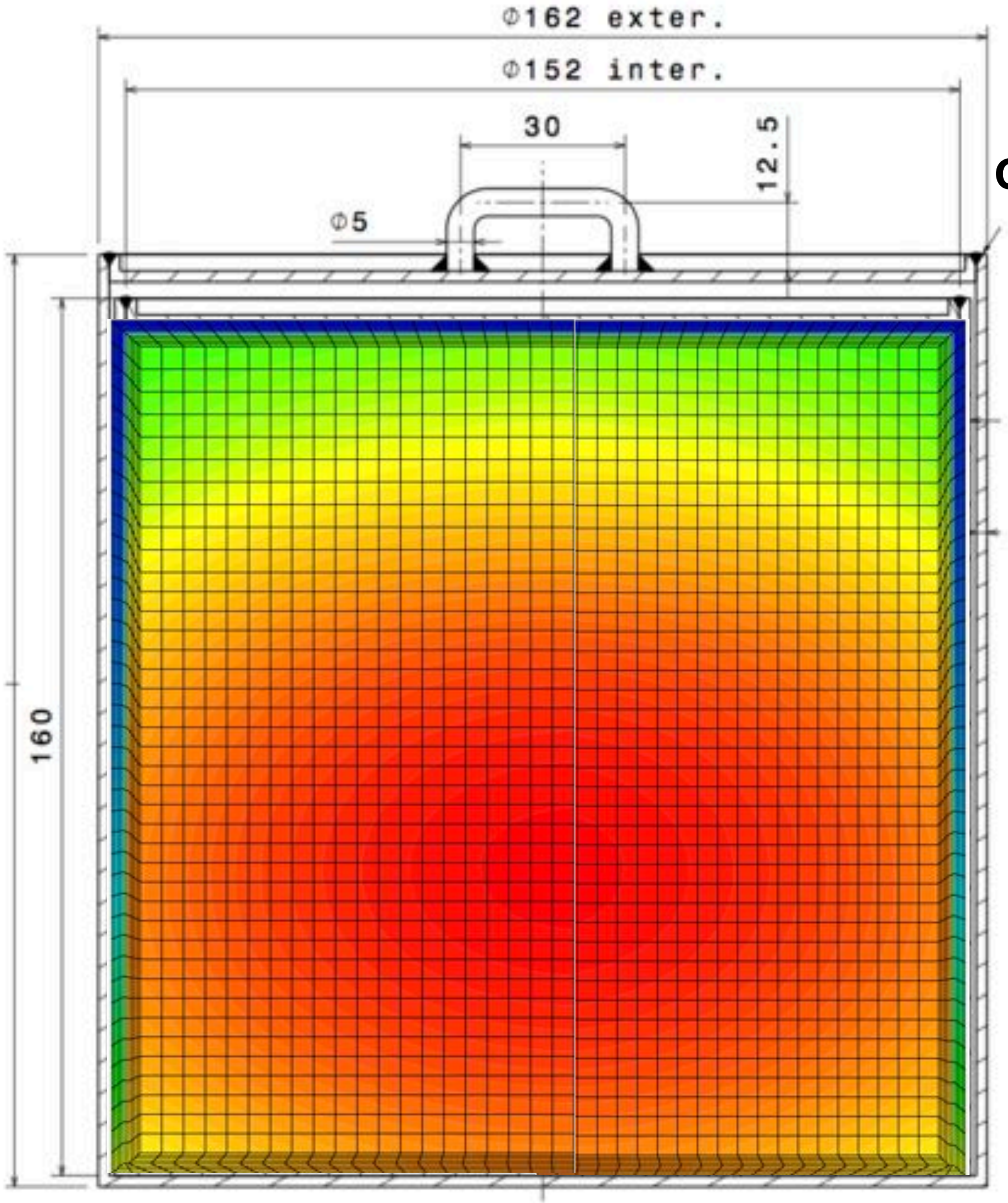


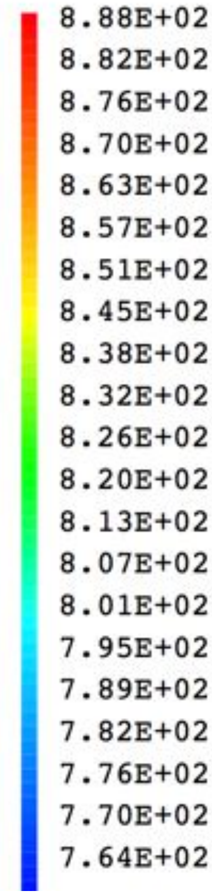
- $\rho(CeO_2) = 4\ g/cm^3$
- $H_{cyl}=D_{cyl} = 15$ cm
- 23 g ^{144}Ce
- 10 kg of CeO_2
- 600 Watt



Source capsule sketch

^{144}Ce-^{144}Pr Capsule Temperature





T (°K)

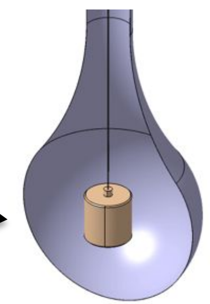
Conduction + Convection
No radiation loss

Steel OK

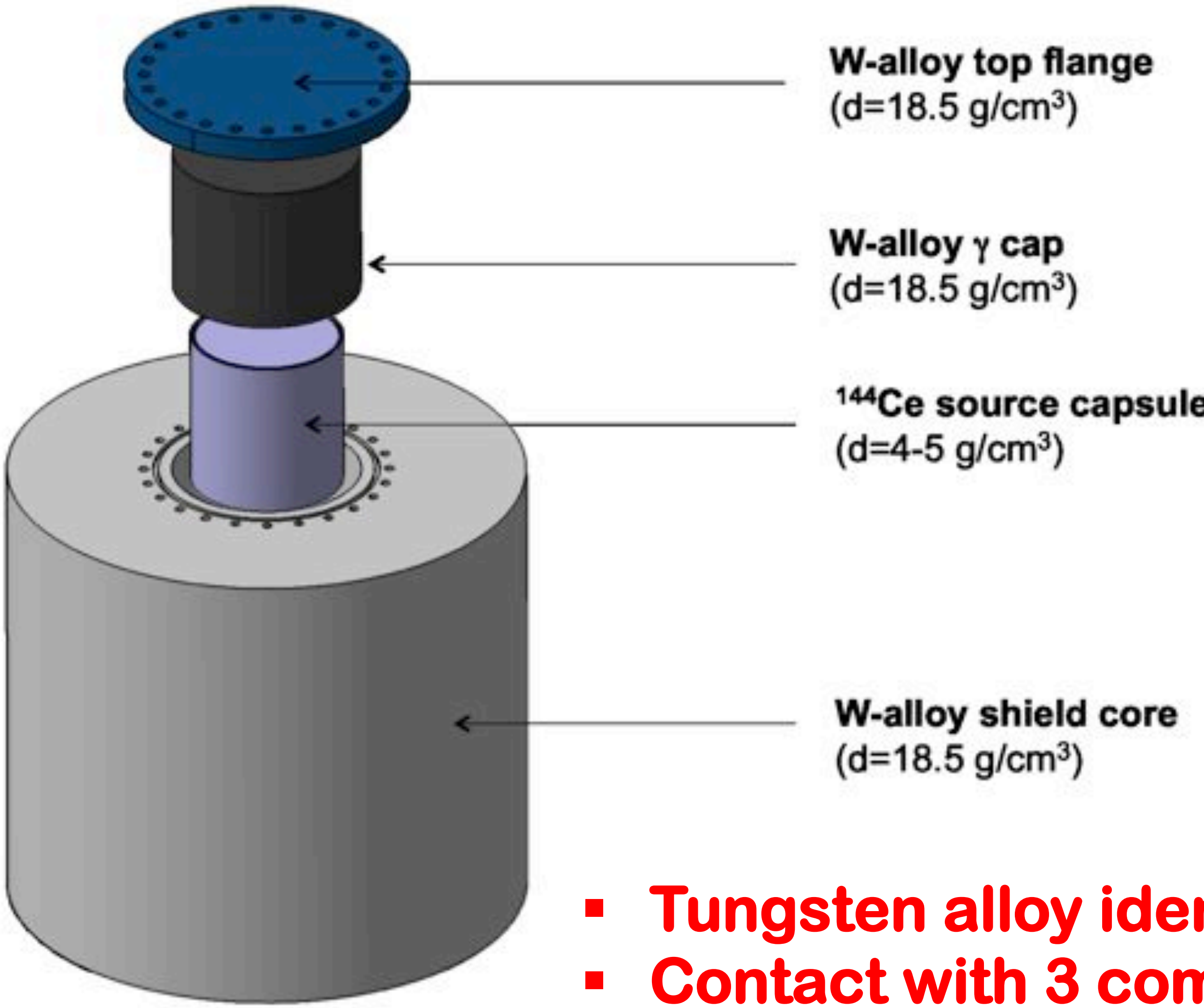
High-Z Shielding

- Two separate goals
  - Usual biological protection
    - Can be achieved with ≈ 16 cm of W-alloy
  - Absorption of the 2.18 MeV γ' s

- Deployment scenario in KamLAND
  - 2015: deployment in Water Veto (OD) - Feasible
    - 6 months data taking
    - 20 cm W-alloy shield
  - 2016: deployment in Liquid Scintillator (ID) - Study
    - 1 year data taking
    - Need additional shielding
      - 35 cm W-alloy
      - Heavy liquid balloon (NaWO3, Hg)



Biological & Phase 1 Shield

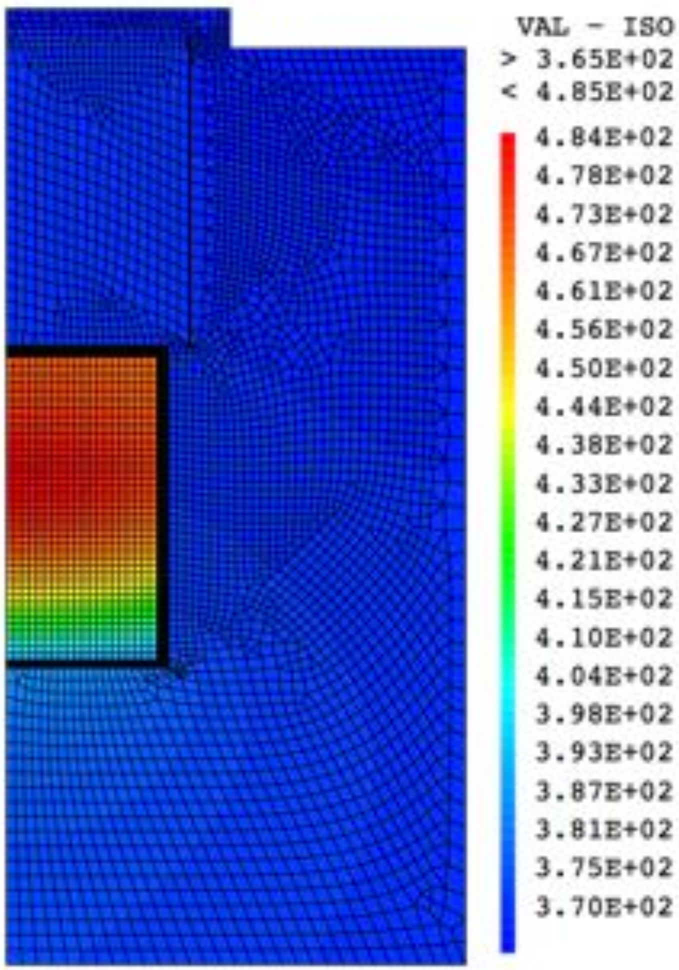


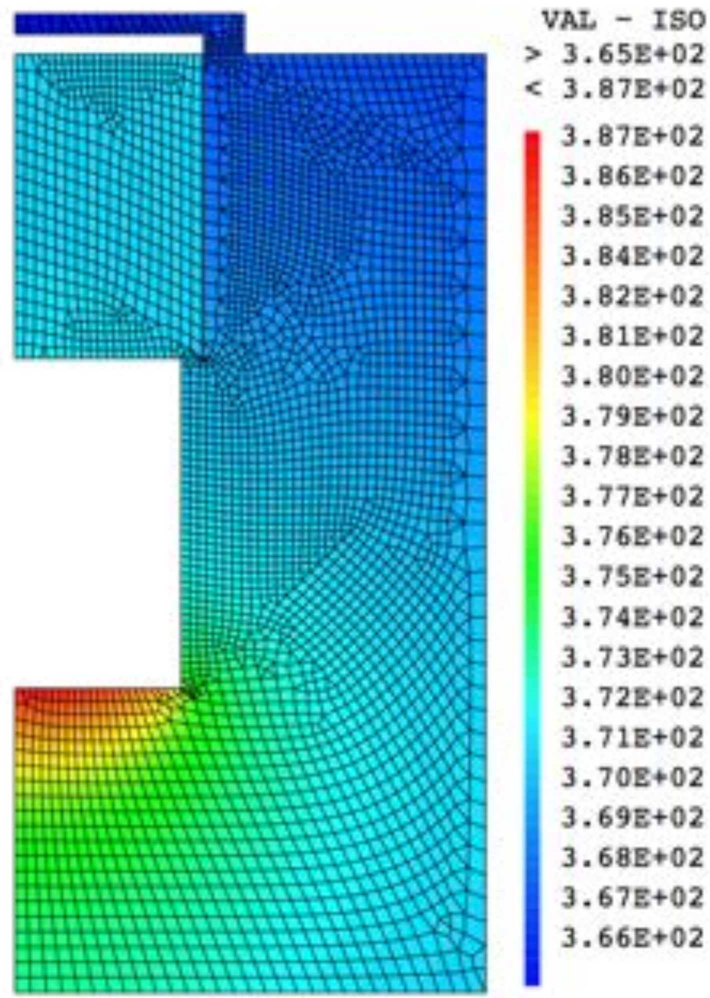
Radiopurity measurements ongoing

- **Tungsten alloy identified (D185)**
- **Contact with 3 companies in Europe, Russia, China**

Shielding Temperature

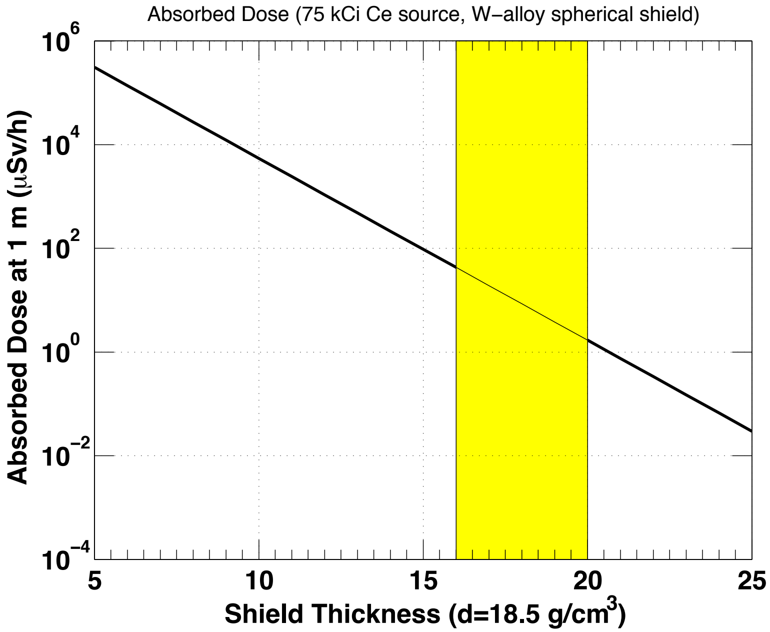
Shielding external temperature: T_{ext} (38°K) + 60°K

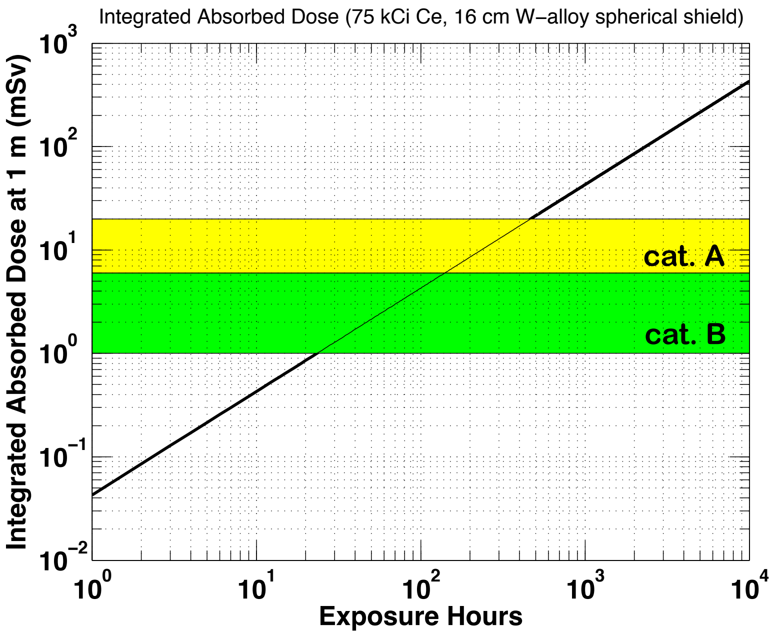




Biological Protection 16 cm D185

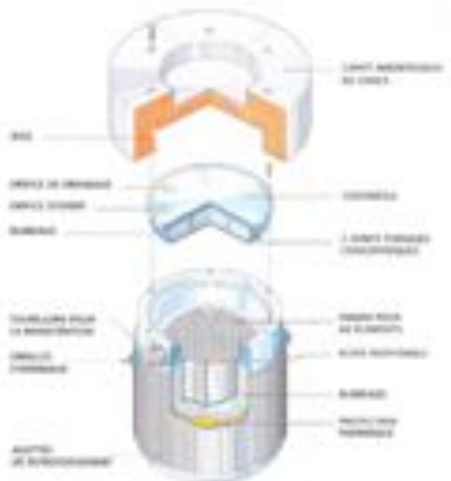
- Back of the envelope dose @1m: 14 μ Sv/h
- GEANT4 dose @1m: 28 μ Sv/h
- <u>CEA-SPR</u> computation dose with MCNP @1m: 42 μ Sv/h
  - Regulation limit 2 mSv/h @1m? <u>Applicable in Kamioka?</u>

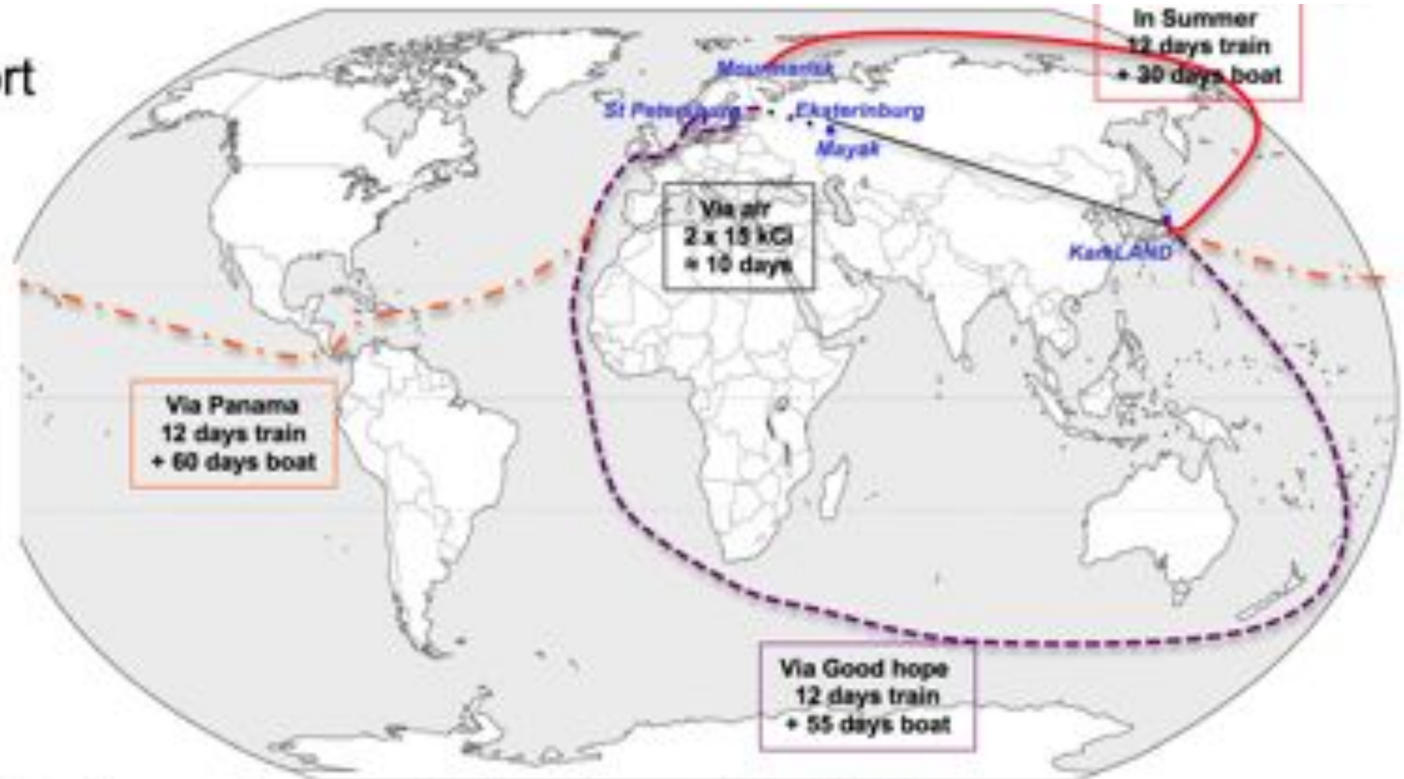




^{144}Ce Source Transportation: 2014/15

- Certified transport container
  - 23 tons !





- Severe constraints based on regulation issued by IAEA
  - nothing impossible, but long, bureaucratic and costly
  - by air limit for each radioisotope : 16.2 kCi for ^{144}Ce, 2.4 MCi for ^{51}Cr
  - by boat : only limited number of harbours agreed for radioactive materials

Transport Route to KamLAND

- Transportation from Tokyo/Yokoyama harbor by truck (ok)
- Several difficulties to be solved for the final lab access

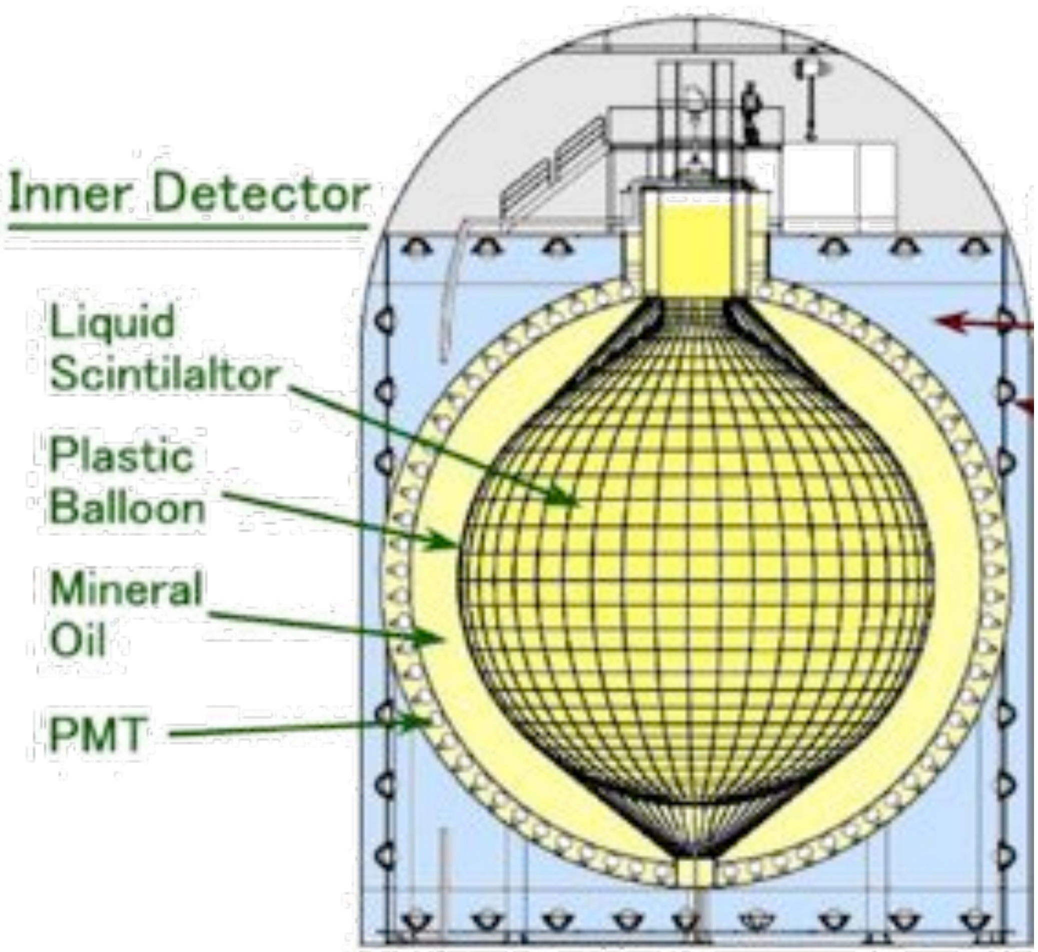
^{144}Ce-^{144}Pr Source Calorimetry

- **Source Heat Release (75 kCi, 600 W, 96% β)**

Time (months)	0	6	12	18	24	36	48	60	120
Activity (kCi)	75.0	48.1	30.8	19.8	12.7	5.2	2.1	0.9	0.01
Activity (PBq)	2.78	1.78	1.14	0.73	0.47	0.19	0.08	0.03	0.0004
Heat (W)	592.5	379.9	243.5	156.1	100.1	41.1	16.9	6.9	0.08

- **Calorimetry**
  - **Precision requested for the activity : <1.5%**
    - **Achieved for Gallex / Sage**
  - **Realization of a calorimeter (2013/14)**
  - **Measurement at the KamLAND site just before deployment, for few days**

CeLAND: ^{144}Ce in KamLAND

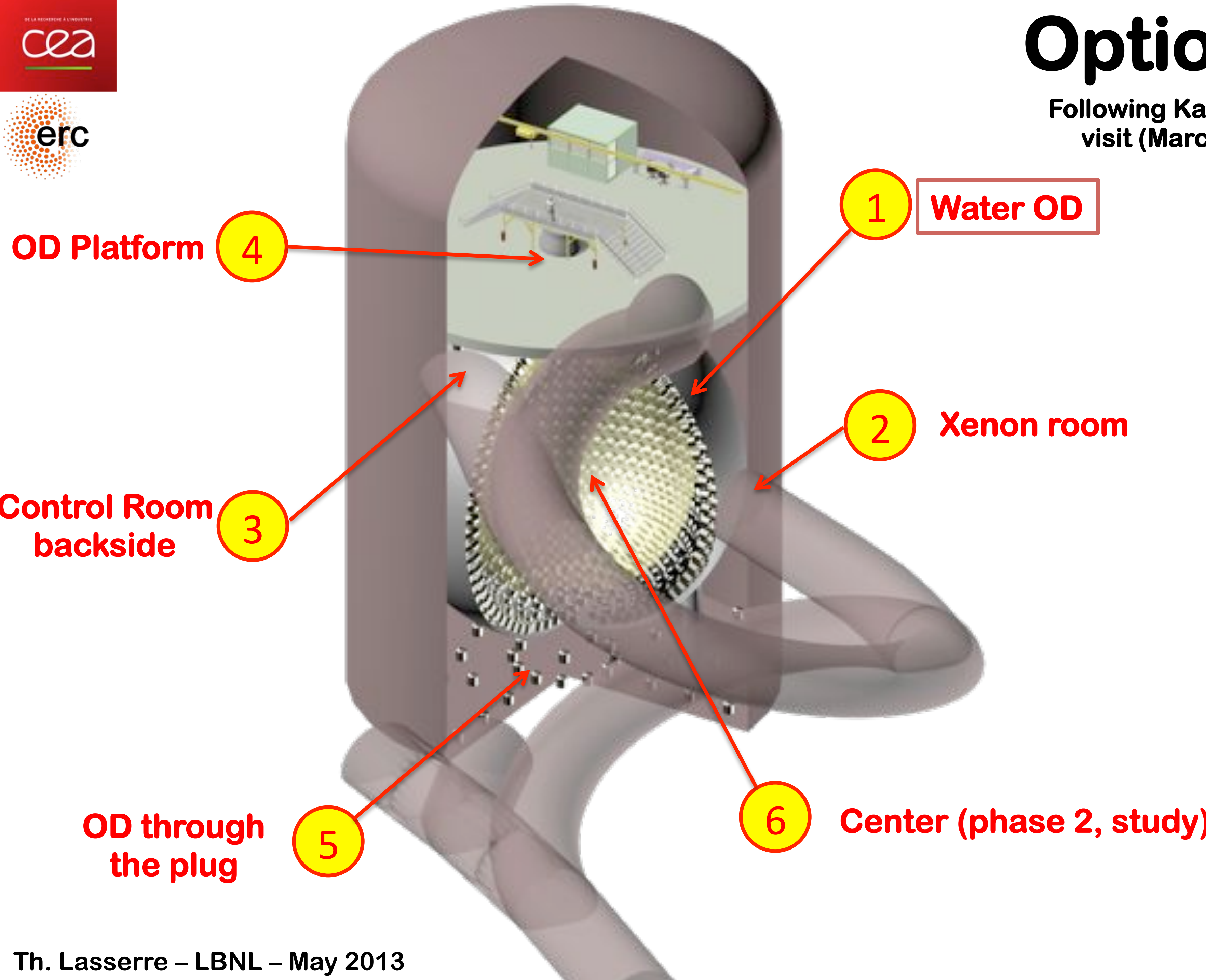


- **A great existing underground detector**

  1000 tons of PC +mineral oil
- **But several constraints**
  - Full of extra pure mineral oil
  - Avoid contaminations
- **The entrance hole**
  - 55 cm in diameter
  - Complex operations to insert the source
- **Hanging suspension**
  - **Phase 1: OD Water**
  - **Phase 2: ID Oil**

Options

Following KamLAND visit (March 2013)

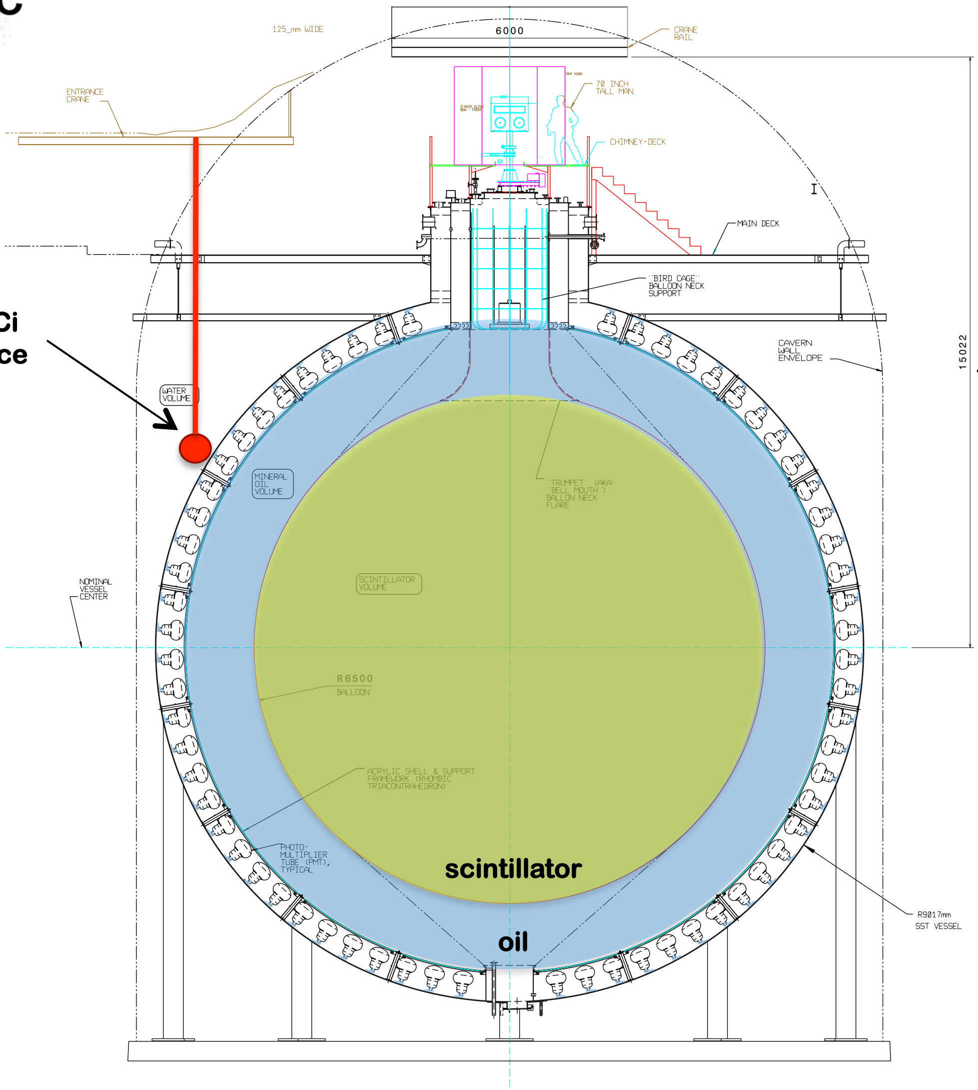


Deployment in Water OD

- Deployment in Water OD through the platform man-hole
- Hanged from a new supporting crane using existing anchors
- Run in parallel with KamLAND-Zen

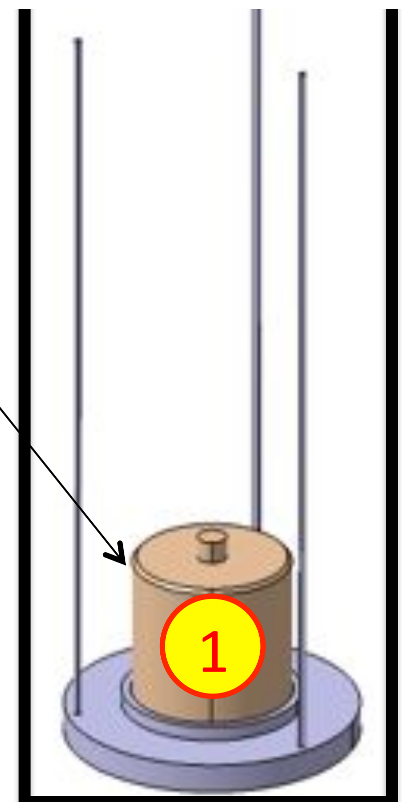
CELAND Phase 1: 2015 in KamLAND

75 kCi
Source



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

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

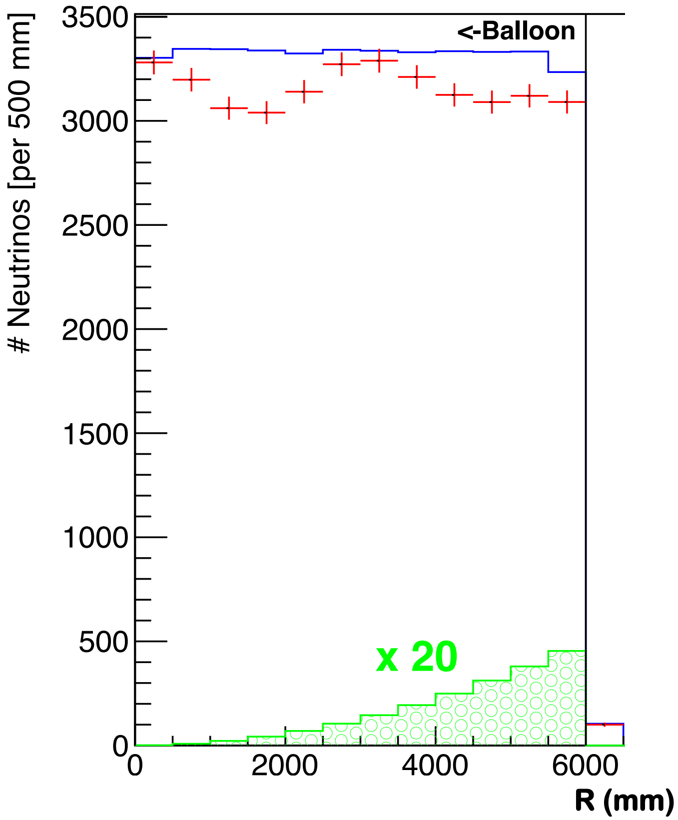


SS structure to isolate the source from
the OD Water (no contamination risk)

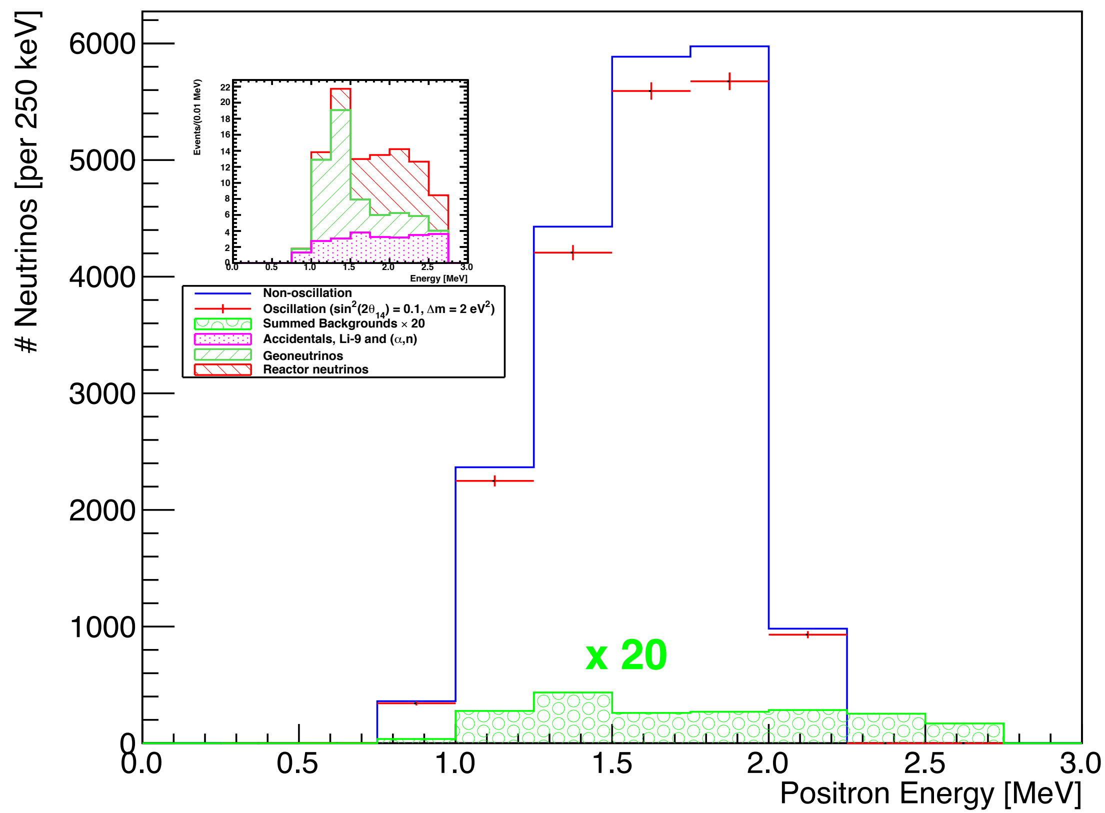
Phase 1: signal/backgrounds

75 kCi Source @2.5 m away from LS
9.3 m from the detector center

Spatial event distribution



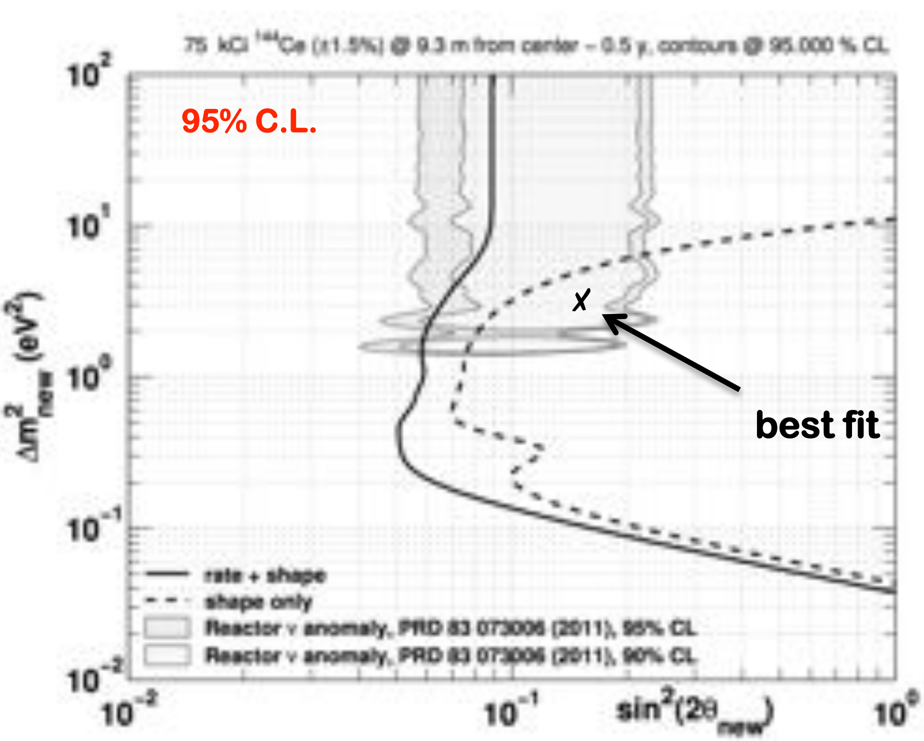
Energy Spectrum



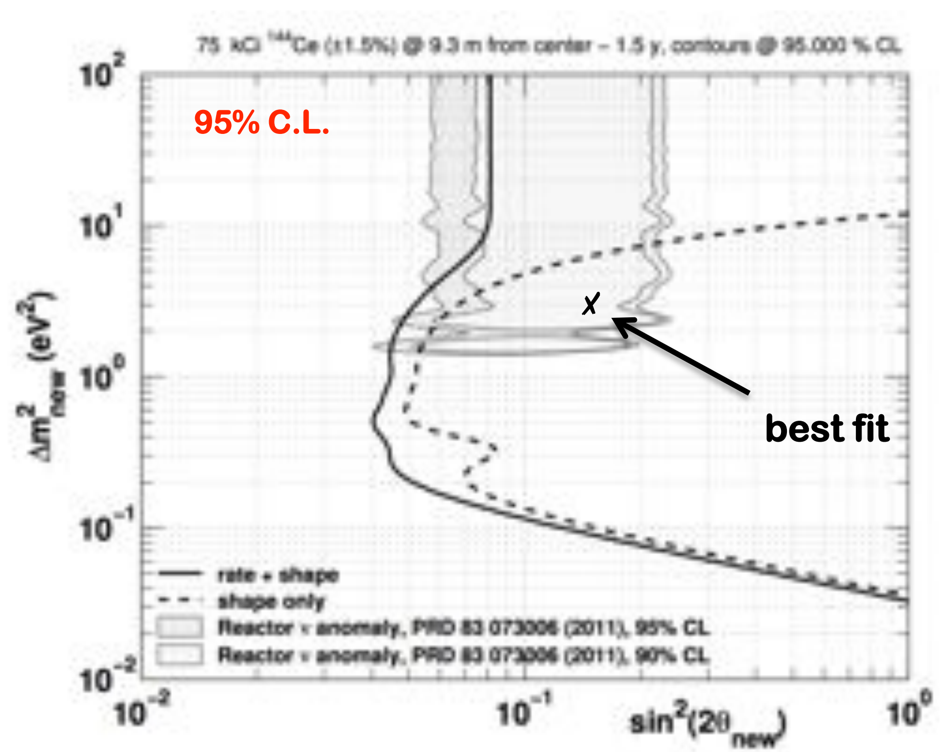
CeLAND phase 1 sensitivity

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

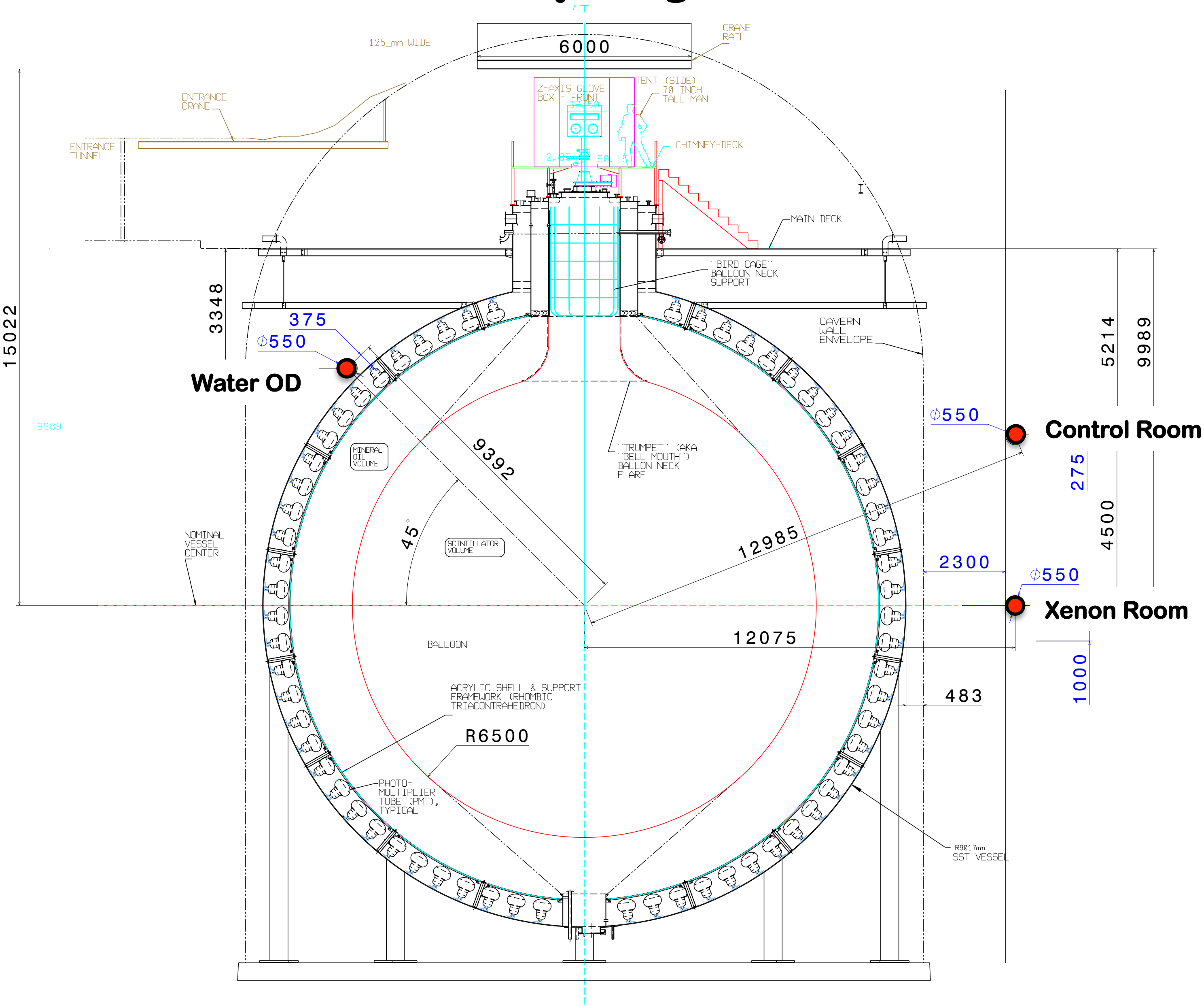
0.5 year of data (10 kevts)



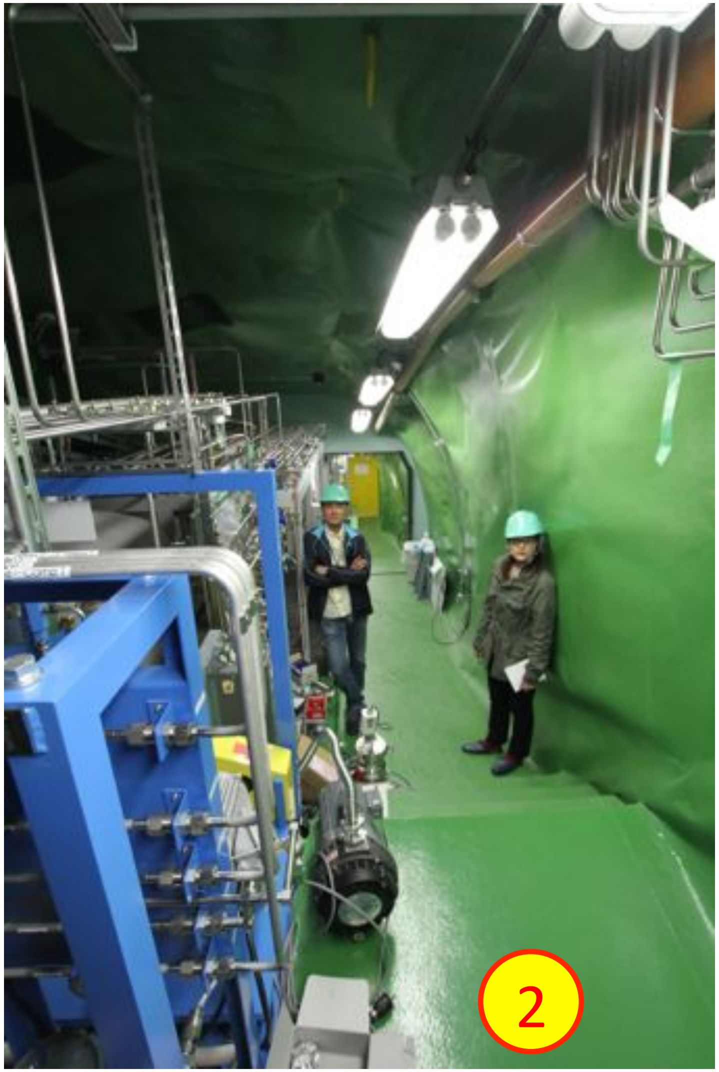
1.5 year of data (20 kevts)



Alternative Deployment Locations



CeLAND phase 1 : Xenon Room

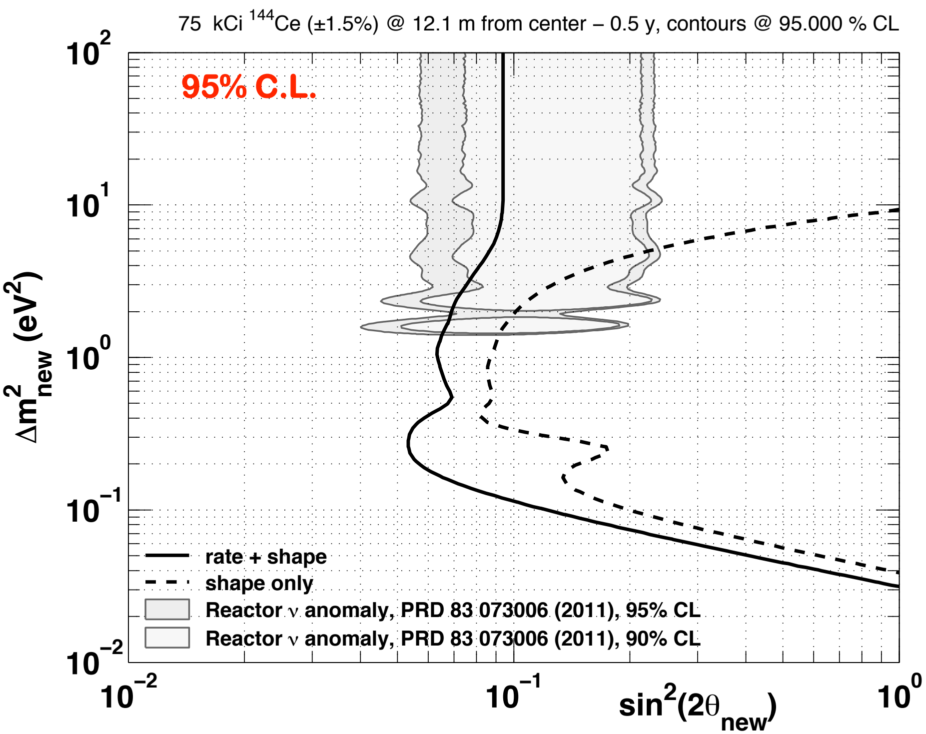


- **Configuration:**
  - **75 kCi ^{144}Ce-^{144}Pr**
  - **12 m from detector center**
  - **14 kevt/1.5 y**
- **Pros:**
  - **Space available**
  - **Easier integration**
  - **Simultaneous calorimetry**
- **Cons:**
  - **Farther from LS**
  - **Worst shape-only sensitivity**

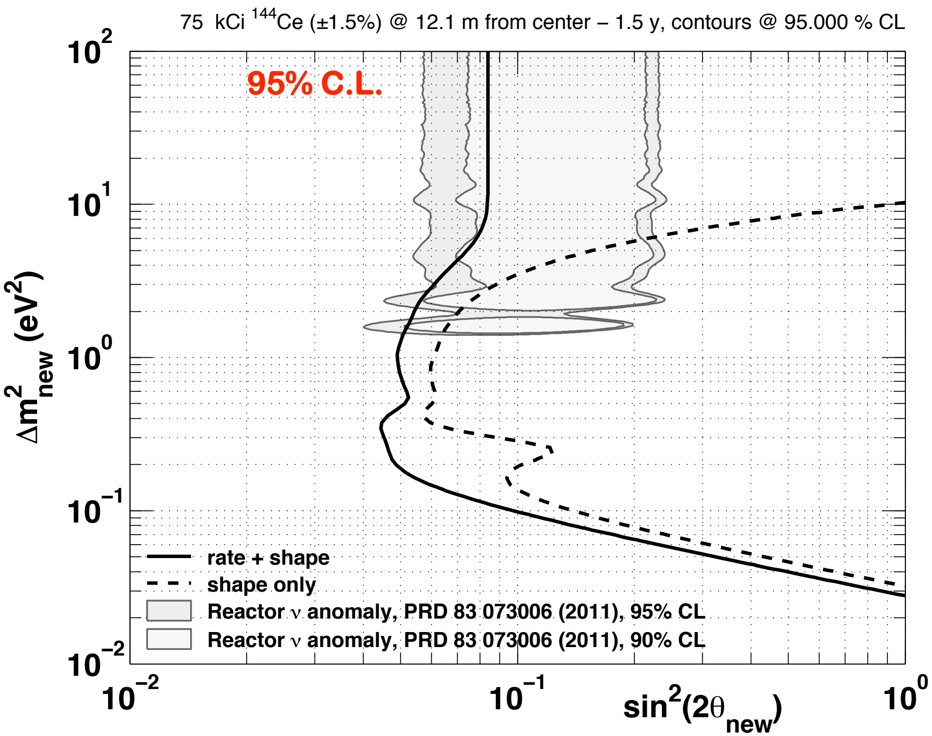
^{144}Ce-^{144}Pr in Xenon room

75 kCi ^{144}Ce-^{144}Pr – 12.1 m from detector center
Fiducial volume considered from 0 to 6.5 m

0.5 year of data (7 kevts)

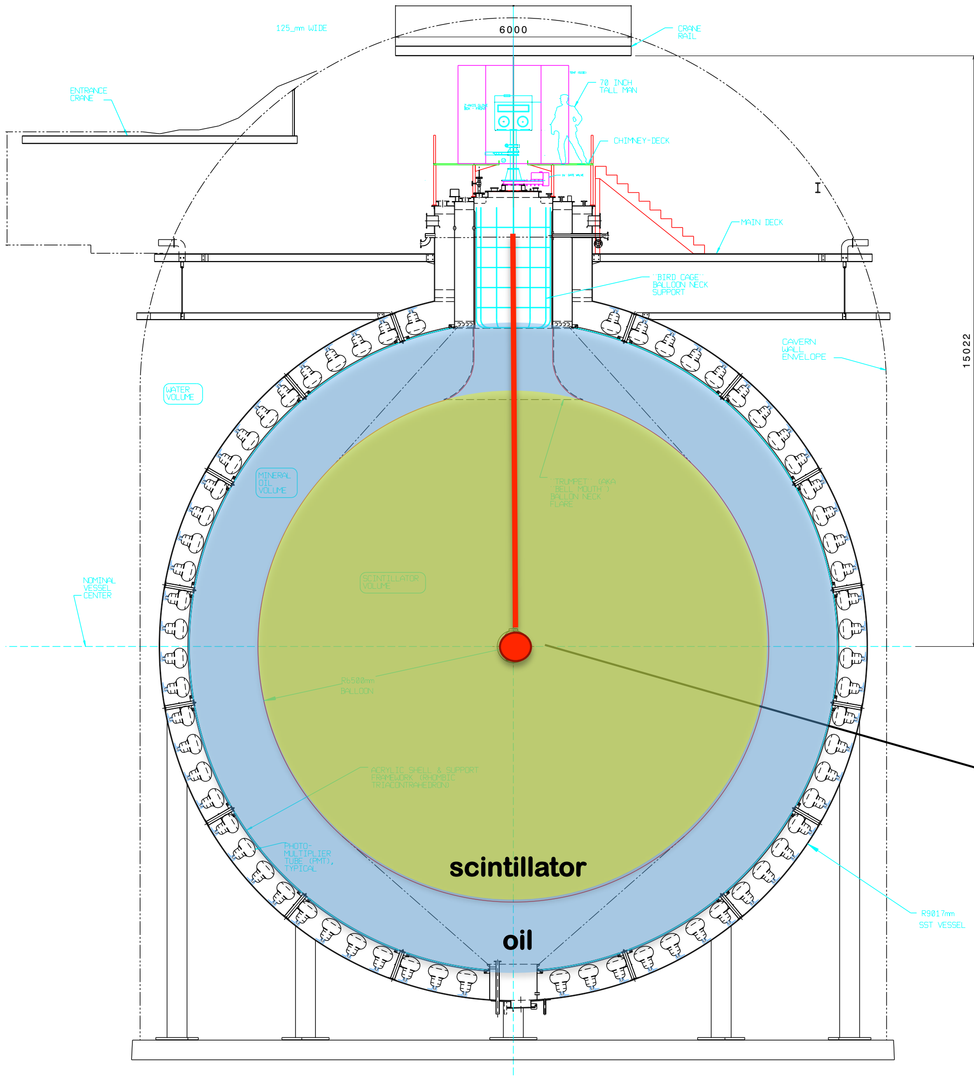


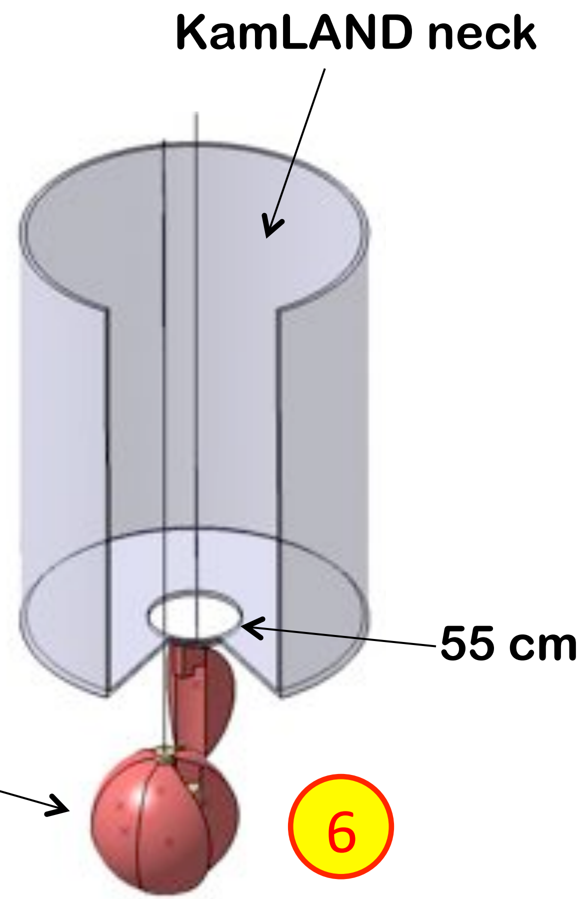
1.5 year of data (14.3 kevts)



CELAND Phase 2: 2016

Relocate the ^{144}Ce source: 75 kCi leads to 50 kCi after 6 months

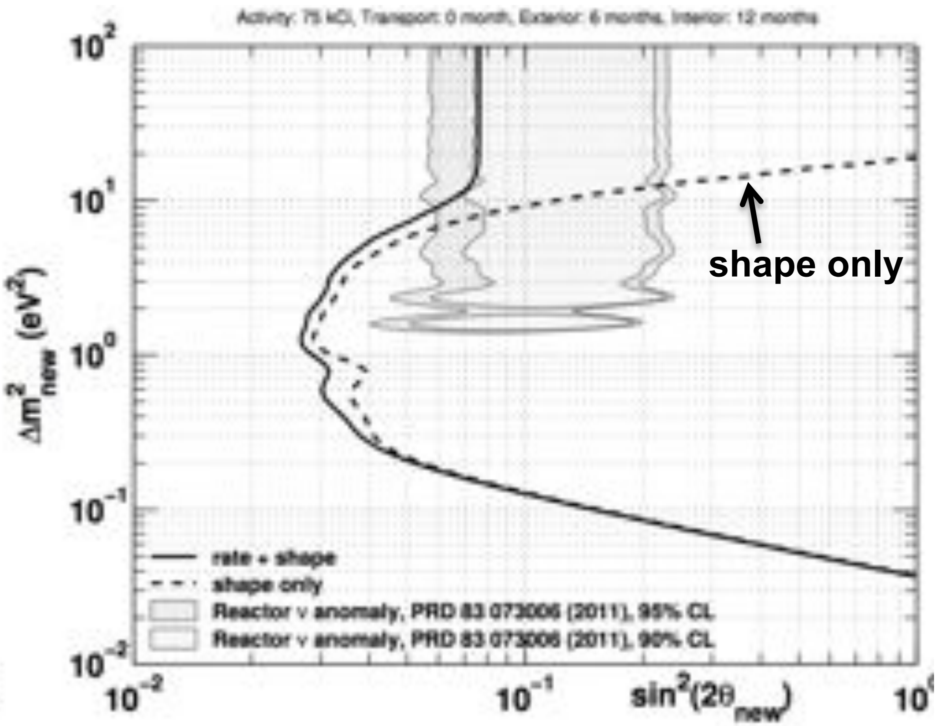




40 cm W-alloy, d=18.5 g/cm^3
γ-attenuation (2 MeV) : 10^{-13}

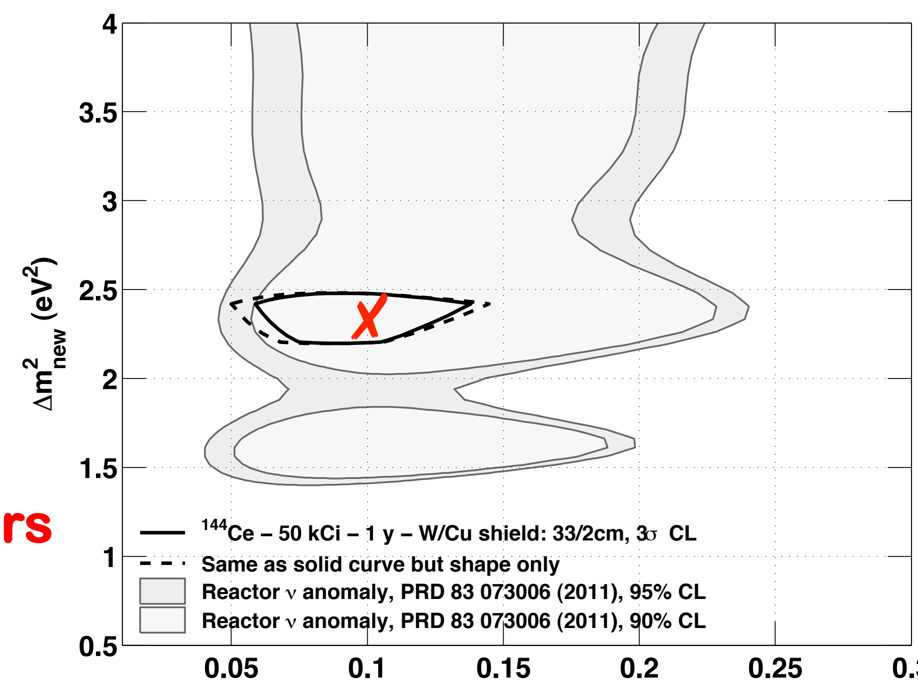
CELAND Phase 2: Sensitivity

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



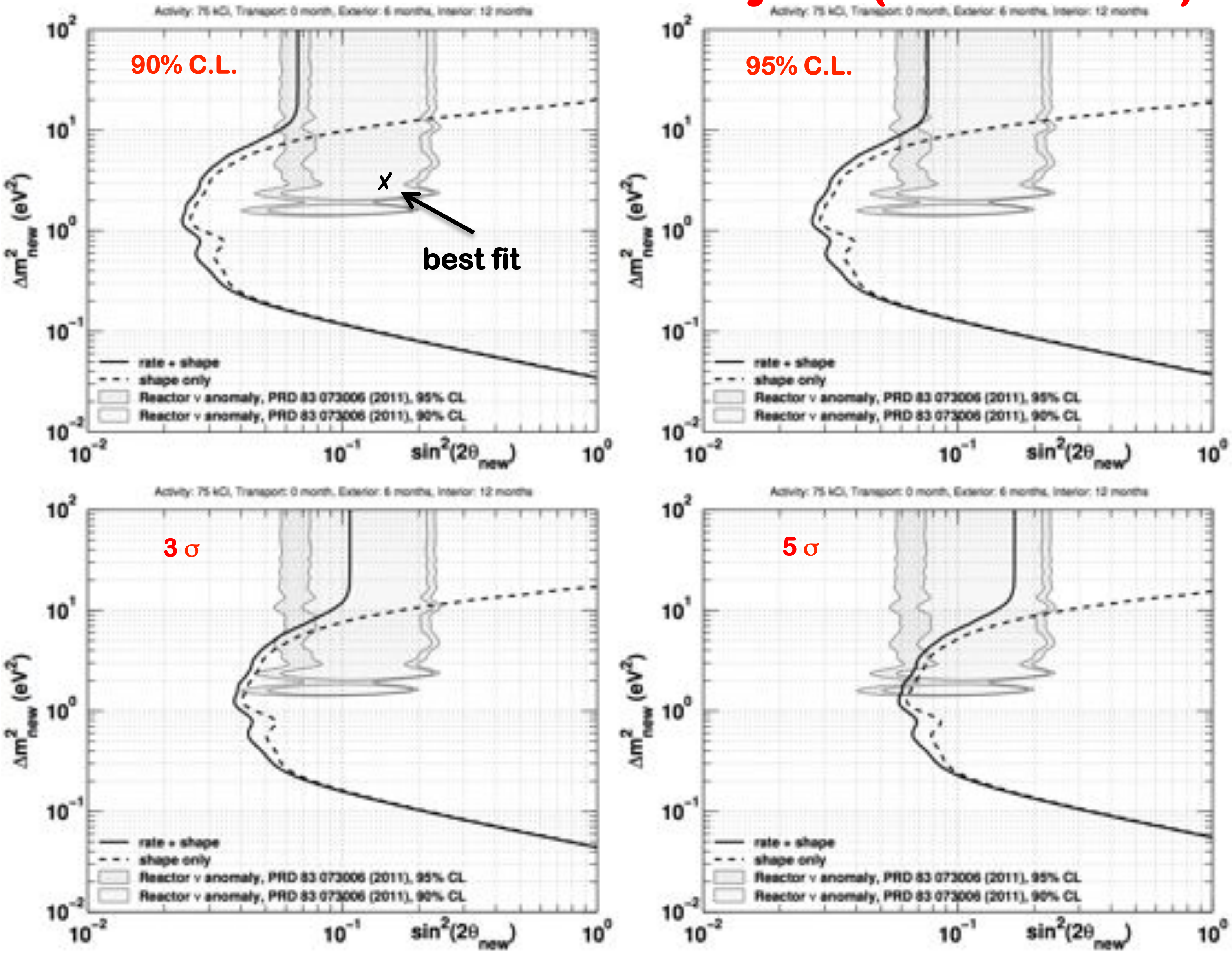
95% C.L. exclusion

3 σ measurement contours

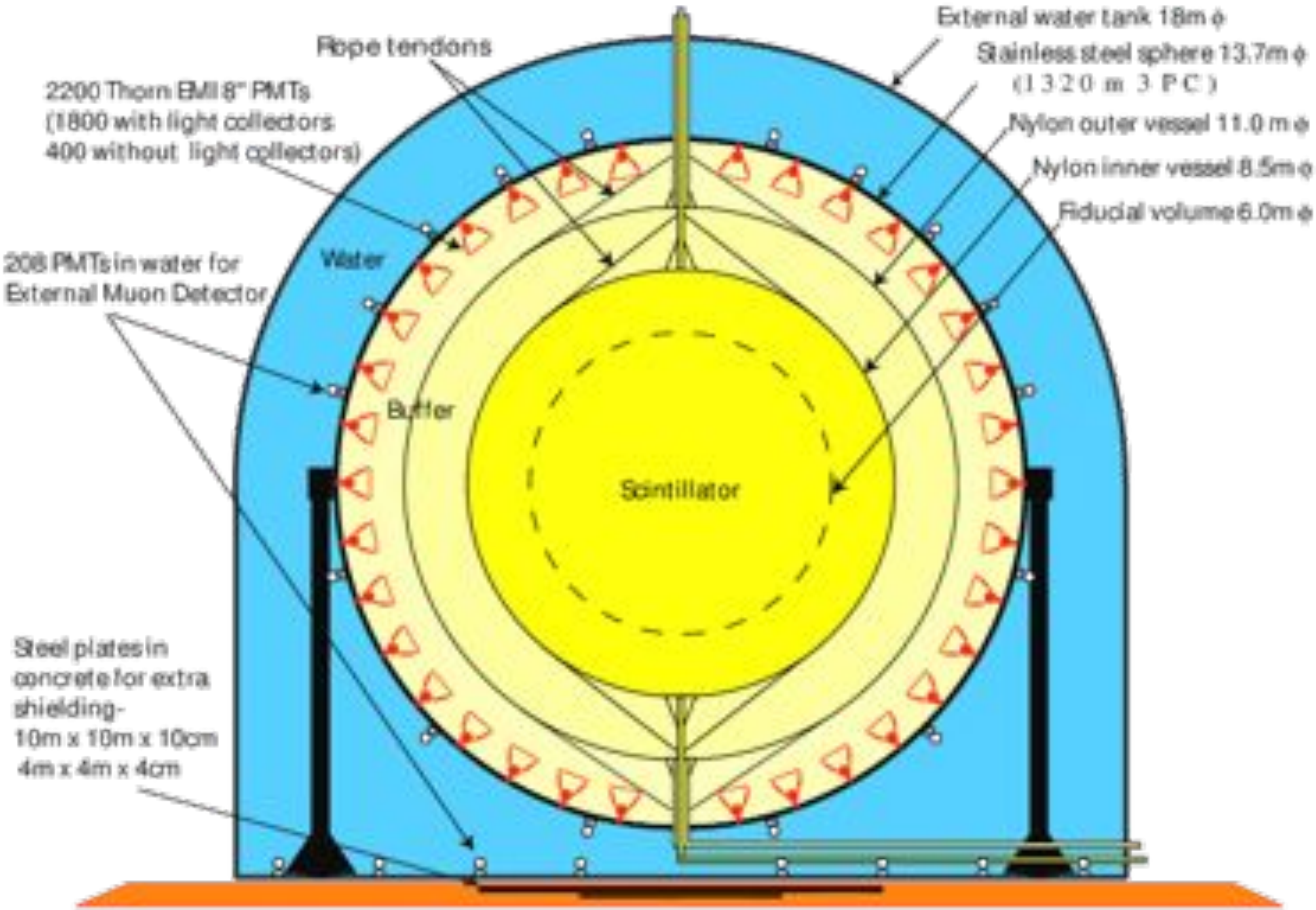


CeLAND Phase 1 + Phase 2

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



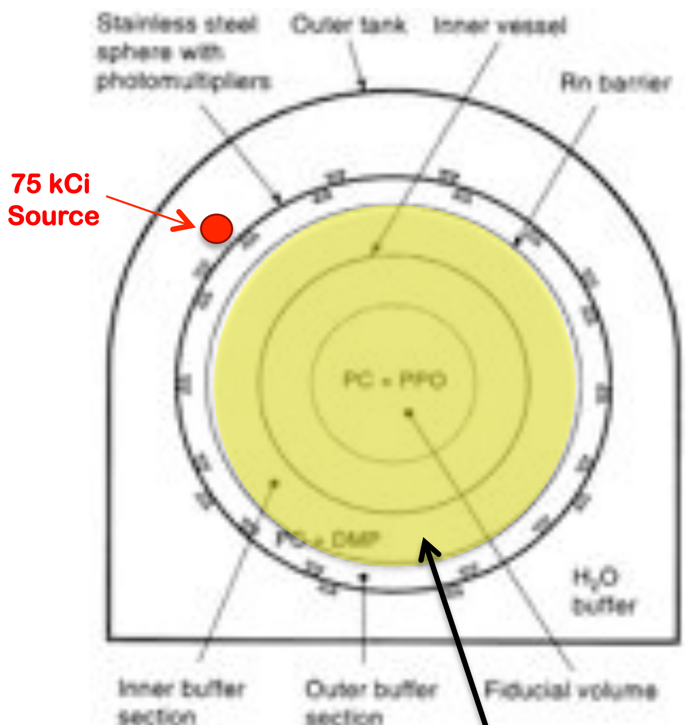
Borexino

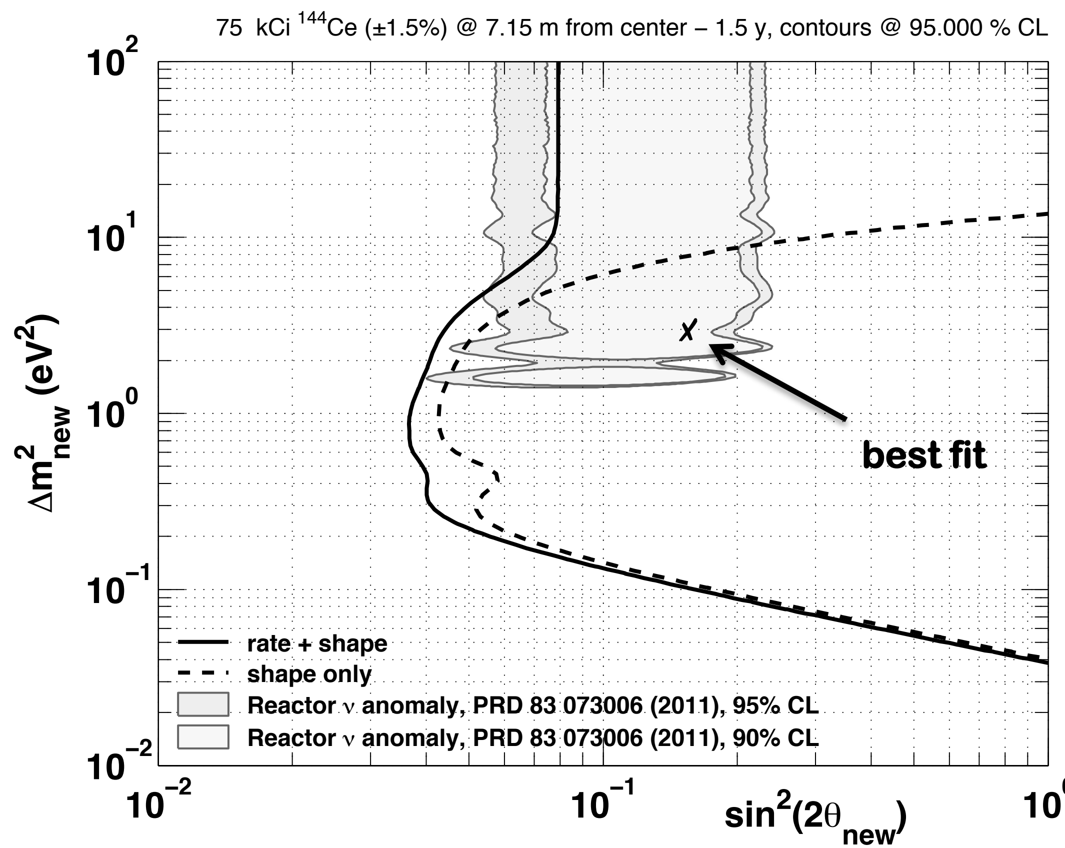


External water tank 18m ϕ
Stainless steel sphere 13.7m ϕ
(1320 m 3 PC)
Nylon outer vessel 11.0 m ϕ
Nylon inner vessel 8.5m ϕ
Fiducial volume 6.0m ϕ
Rope tendons
2200 Thorn EMI 8" PMTs
(1800 with light collectors
400 without light collectors)
208 PMTs in water for
External Muon Detector
Water
Buffer
Scintillator
Steel plates in
concrete for extra
shielding-
10m x 10m x 10cm
4m x 4m x 4cm

CeSOX 613 tons - 75 kCi - 1.5y

Distance from center: 7.15 m





R_{max} = 5.5 m
N_{evt} = 21800

Need liquid scintillator modification
as well as detector draining

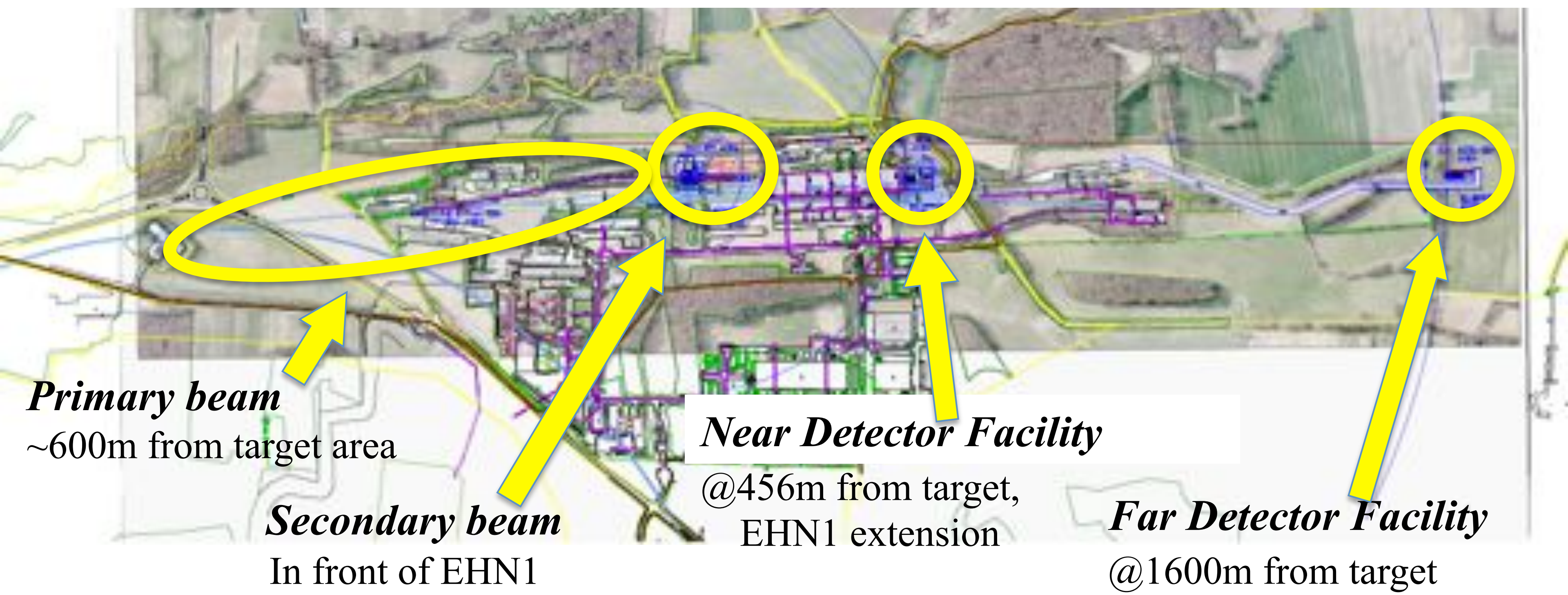
Th. Lasserre – 17/01/2013

Many Projects: Overview

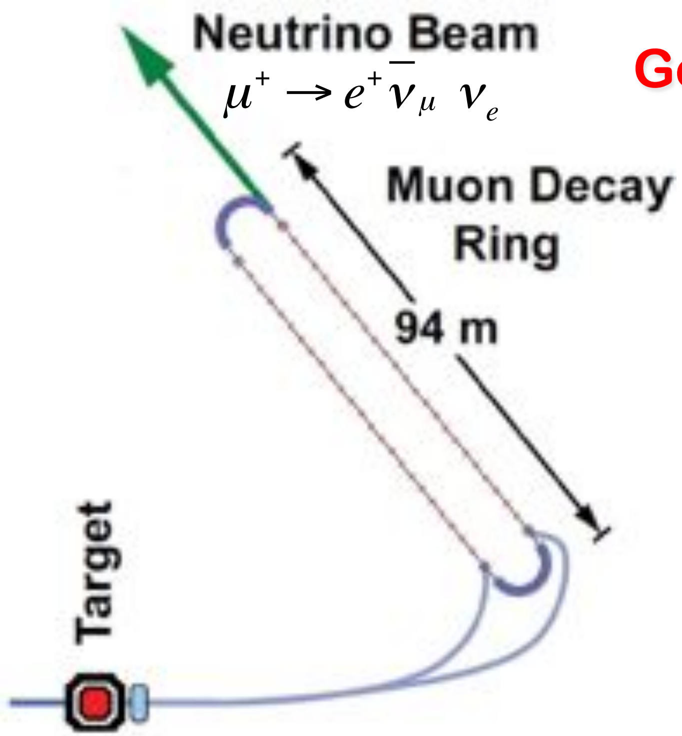
Experiment Type	Appearance / Disappearance	Oscillation Channel	Projects
Reactor	Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stéréo, Scraam, Neutrino-4, DANSS, Poséidon, MARS, …
Radioactive Source	Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$ $\nu_e \to \nu_e$	CeLAND, SOX (Cr & Ce), Sage2, SNO+, LENS-s
Cyclotron	Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest	Apparition & Disappearance	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Pion Decay-in-Flight (Beam)	Appearance & Disappearance	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$ $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN
Low-E Neutrino Factory	Appearance & Disappearance	$\nu_e \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_e$	νSTORM@Fermilab

Icarus-Nessie at CERN

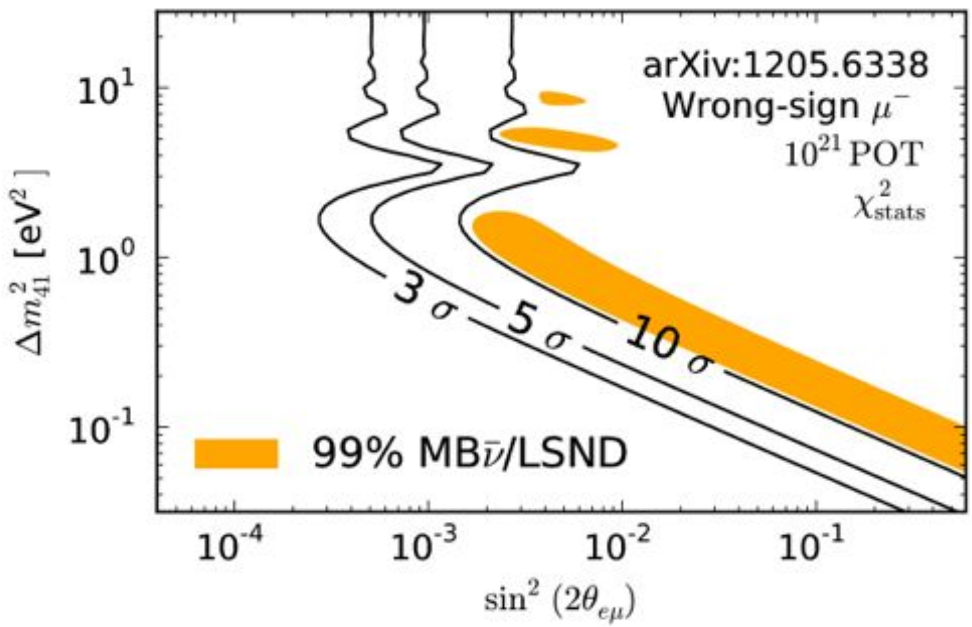
- Concept (L/E≈ km/GeV → eV-scale 4th ν)
  - Move T600 (2 x 300 tons) from LNGS to CERN, 2013/14
  - New T150 (150 tons)
  - New magnetized muon spectrometers (Opera's techno)
  - New neutrino beam on the SPS (on-axis, few GeV, fast extraction, 4.5 10^{19} pot/y, neutrinos & antineutrino runs, start 2016/7?, under review)



Decay in Flight Beams: ν-STORM



Golden Mode: $\overset{(-)}{\nu}_\mu$ appearance in a $\overset{(-)}{\nu}_e$ beam



- Beam+Detector: manageable extrapolation from known techno
- Capable of definitive sterile ν search in appearance and disappearance channels with : ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$.
- Source of GeV $\overset{(-)}{\nu}_e$ for studies of cross sections (HK, LBNO/E).
- First step to Neutrino Factory / Muon Collider (LOI @FNAL/CERN)

Conclusions

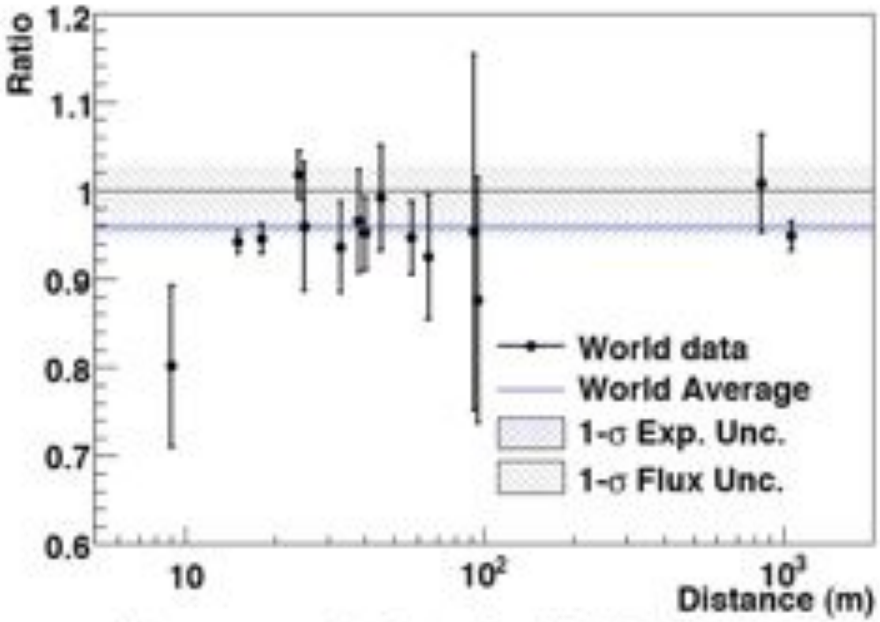
- A bunch of anomalies calling for clarification:
  - LSND (ν_S, $\Delta m^2 \approx eV^2$) & Miniboone ?
  - Gallium Anomaly (ν_S, $\Delta m^2 \approx eV^2$)
  - Reactor Anomaly (ν_S, $\Delta m^2 \approx eV^2$)
  - Cosmological bounds do not exclude a 4th ν
  - But:
    - No deficit in muon channel
    - Significant tensions in global fits

→Bunch of 2 to 4 σ effects → NEED for new CONCLUSIVE short baseline experiments, >20 projects under consideration

- Need to Test the Beam related anomalies (LSND, MiniBoone)
- Need to Test the Gallium and Reactor Anomalies

Thanks for your attention !

C. Zhang, X. Qian & P. Vogel
RAA Reanalysis (arXiv:1303.0900v1)



- New reanalysis of old 19 reactors antineutrinos experiments adding :
  - *$\sin^2(2\theta_{13})$ = 0.089±0.011*
  - allow to use Chooz, Palo Verde, Double Chooz (Gd & Hyd. datas)
  - *=> R = 0.959±0.009(stat.) ±0.027(react.flux) : 1.4 σ effect*

- First quick comments from Saclay's group
  - which IBD cross-section used ?
  - wrong error used by authors in RAA
    - 0.027 instead of 0.023
    - taken wrongly as fully correlated
    - only ILL data is fully correlated
  - Saclay preliminary similar reanalysis :
    ≈ **0.94+- 0.023** **(confirmed by Arxiv:1303.3011)**
  - short written answer in preparation