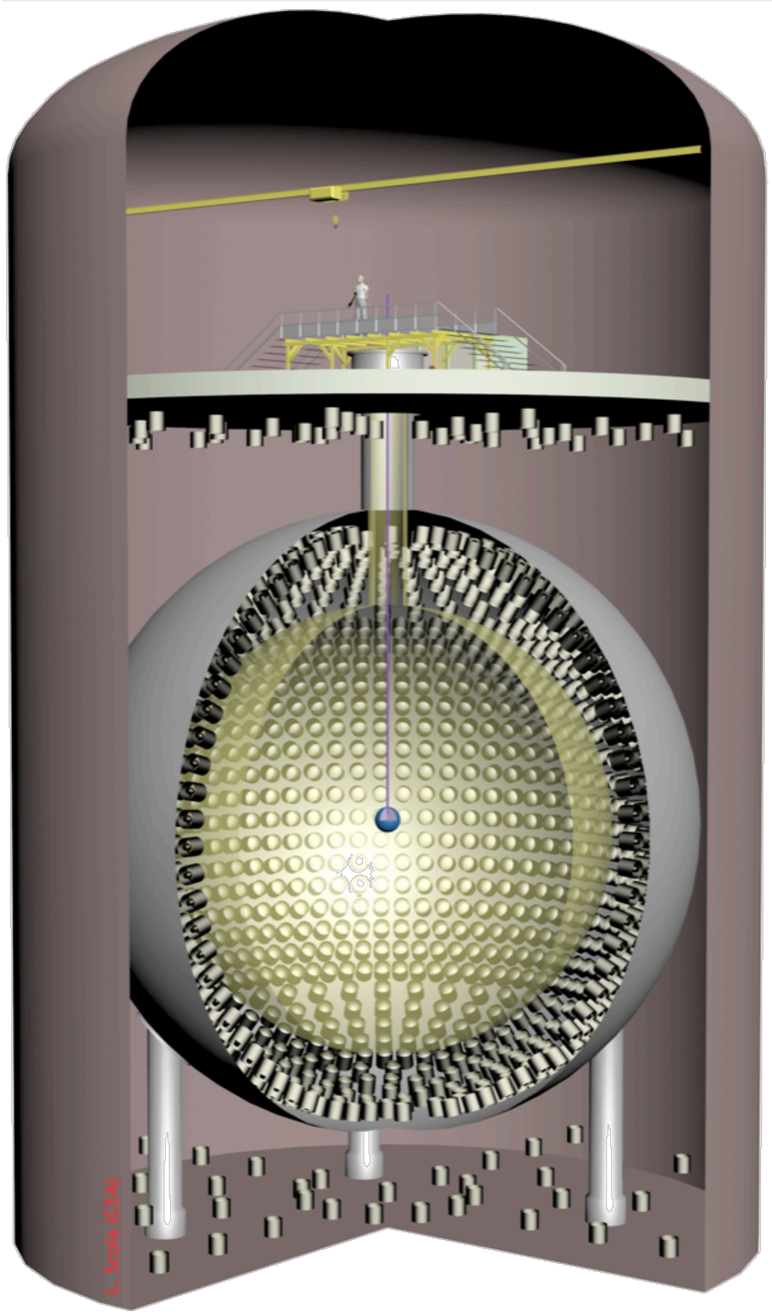


Search for a 4^{th} neutrino type with intense antineutrino emitters

Virginia Tech 31/10/2012

Th. Lasserre
(CEA-Saclay, Irfu)

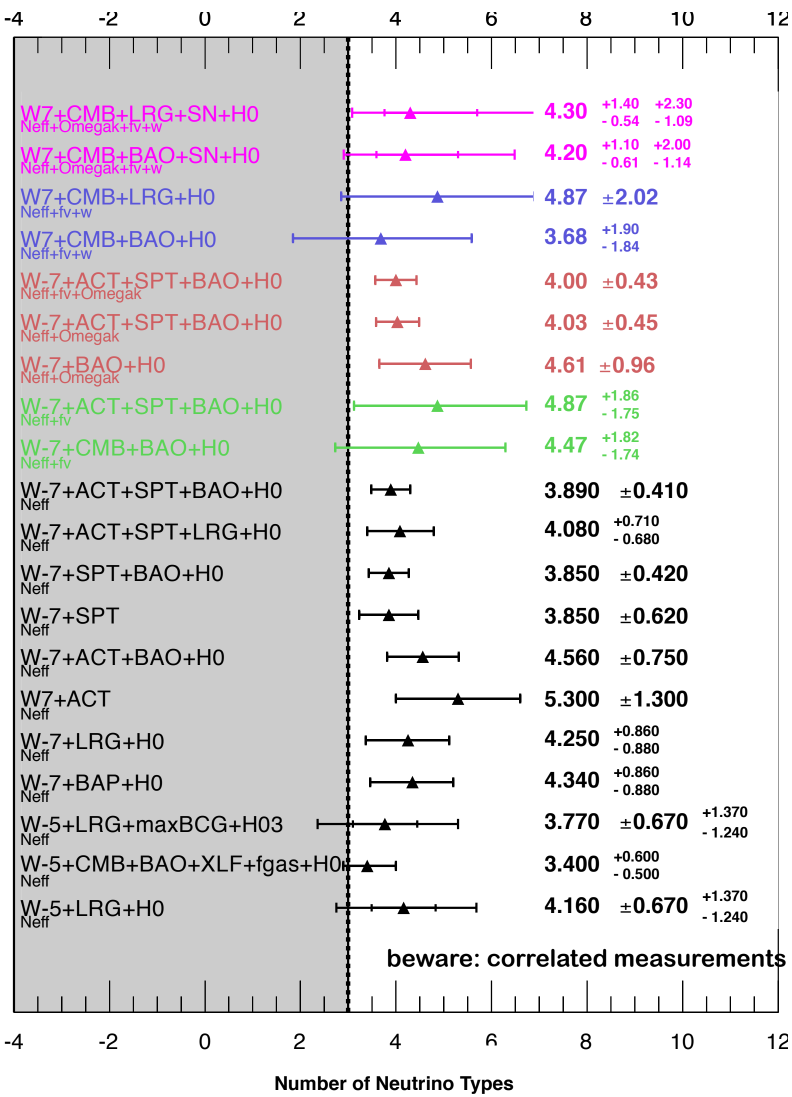
Neutrino Anomalies & 4th Neutrino

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	3.0 σ
Cosmology	Big-Bang	All	Number of ν, N_{eff}	CC	≈2 σ

→ **could be interpreted by an existing eV^2 4th neutrino state…**

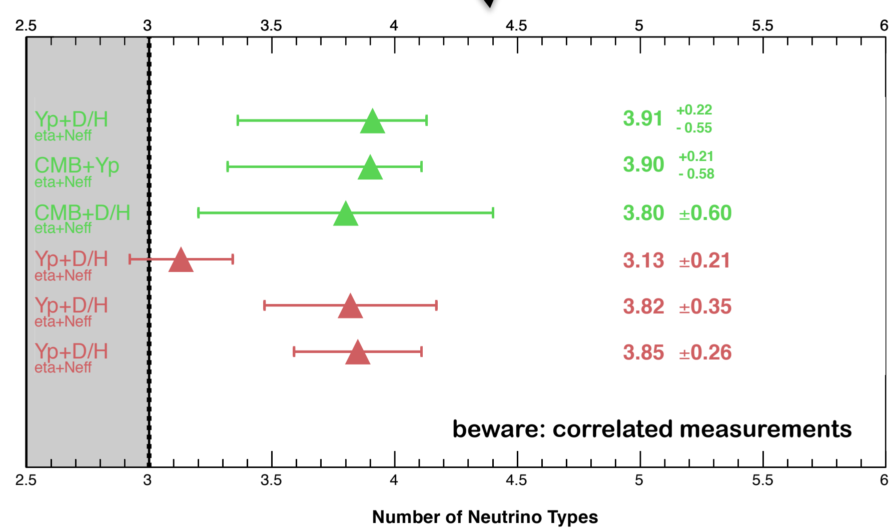
Number of ν's From Cosmology

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



Cosmic Microwave Background and Large Scale Structures

Big Bang Nucleosynthesis

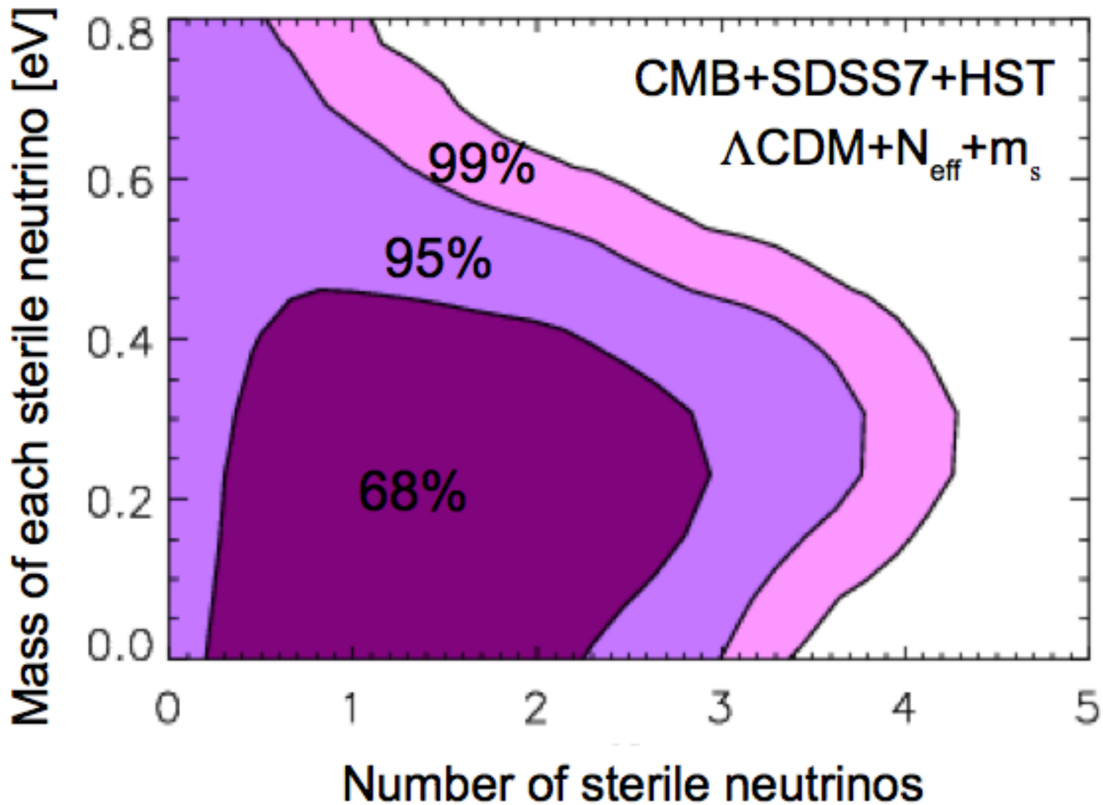


→ a 4[th] dof (ν?) favored (2σ)

Th. Lasserre

Neutrino Mass From Cosmology

- **Constraint on ν mass and Number from flat ΛCDM**



- **$m_{heavier}$ < ≈1 eV → <u>tension with terrestrial neutrino data</u>**

The Reactor Antineutrino Anomaly

G. Mention, M. Fechner, T. Lasserre,
M. Cribier, Th. Mueller D. Lhuillier, A. Letourneau,

CEA / Irfu

Phys. Rev. D 83, 073006 (2011), arXiv:1101.2755
based on Phys. Rev. C83 054615 (2011)

Reactor Neutrino Exp. Overview

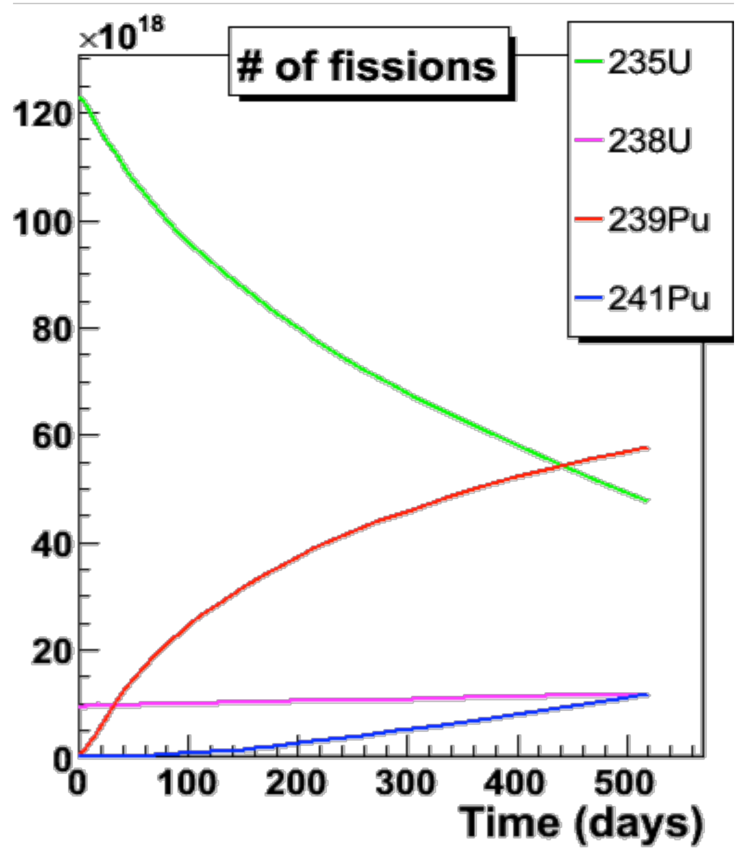
- **Electron antineutrinos emitted through Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**
- **Nuclear reactors** : $1\ \mathrm{GW_{th}} \Leftrightarrow 2\ 10^{20}\ \bar{\nu}/\mathrm{s}$
- **Neutrino Luminosity** : $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$

  γ: reactor constant
  k : fuel evolution correction (<10%)

- **Common Detection Principle**
  - Inverse Beta-Decay reaction ($\sigma_{\text{V-A}}$)

    $$\bar{\nu}_e + p \longrightarrow e^+ + n$$

  - Threshold 1.8 MeV. E_ν extend to 10 MeV



- **Measure anti-ν_e of interaction rate**

$$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\mathrm{th}}}{\langle E_f\rangle}N_p\varepsilon\sigma_f \longrightarrow \sigma_f^{\mathrm{meas.}} = \frac{4\pi R^2 n_\nu^{\mathrm{meas.}}}{N_p\varepsilon}\frac{\langle E_f\rangle}{P_{\mathrm{th}}}$$

$\updownarrow$

  - Comparison of σ_f to prediction

$$\sigma_f^{\mathrm{pred.}} = \int_0^\infty \phi_f^{\mathrm{pred.}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu$$

New Reactor Antineutrino Spectra

- **Accurate e^- measurements, ILL reactor (1980-89):**
  - Irradiation of ^{235}U, ^{239}Pu, ^{241}Pu foils in intense n_{th} flux at the ILL core
  - High resolution magn. spectrometer, normalization uncertainty of 1.8%

- **Thousands of β-branches involved…**

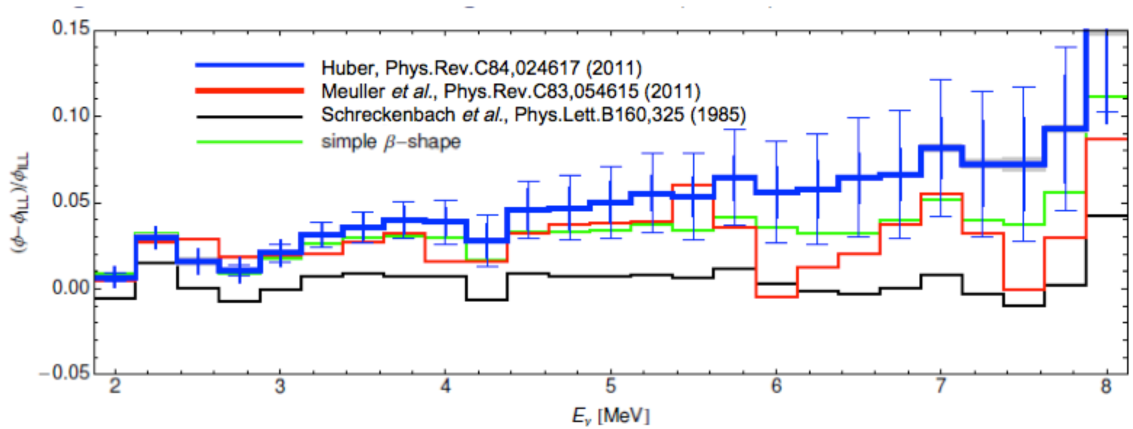
- **From electron to neutrino spectra: need a conversion**

  - **Old Method:**
    - Fit integral e^- spectrum with a sum of 30 effective β-branches
    - Conversion of the effective branches to ν spectra
    - Effective correction on the ν-spectra ($A_{C,W}$)

  - **New Method (Phys. Rev. C83, 054615, 2011)**
    - Conversion with "true" distribution of β-branches reproducing >90% of ILL e^- data + five effective branches to the remaining 10%
    - Net 3% upward shift in energy-averaged neutrino fluxes with respect to old ν-spectrum for ^{235}U, ^{239}Pu, ^{241}Pu
    - Confirmed and improved by Phys. Rev. C 84, 024617 (2011)

The Reactor Antineutrino Anomaly

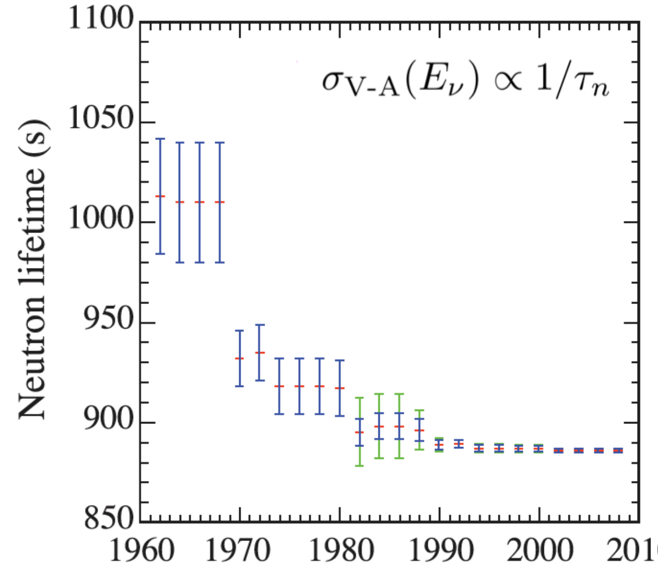
i) **$\nu_{emission}$: Improved reactor neutrino spectra → +3.5%**



PRC83, 054615 (2011)

PRC84, 024617 (2011)

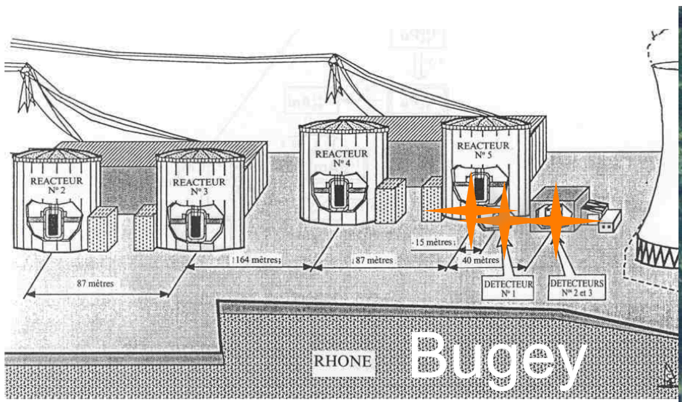
ii) **$\nu_{detection}$: Reevaluation of σ_{IBD} → +1%**
Evolution of the neutron life time

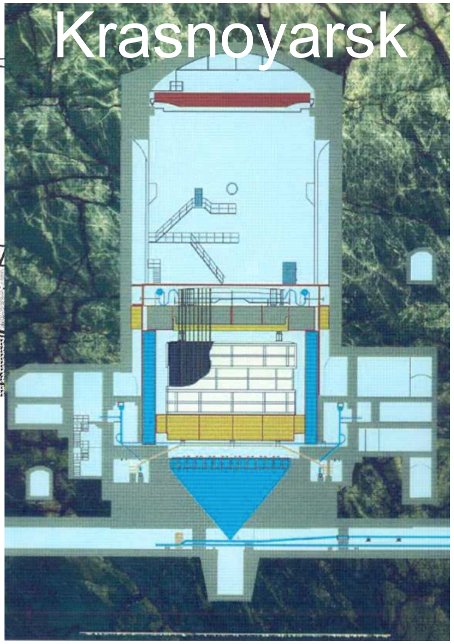


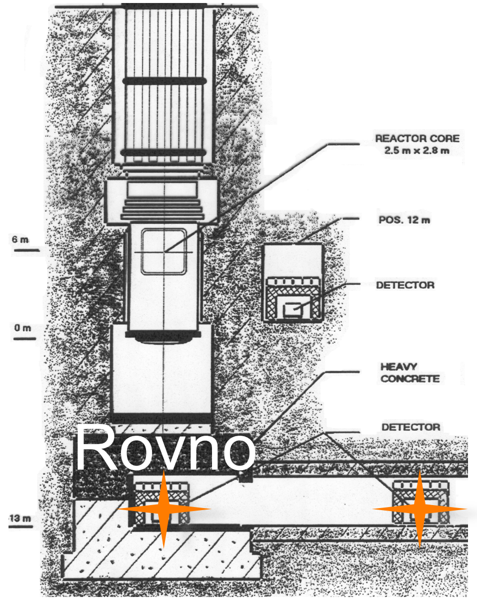
iii) **$\nu_{detection}$: Accounting for long-lived isotopes accumulating in reactors → +1%**

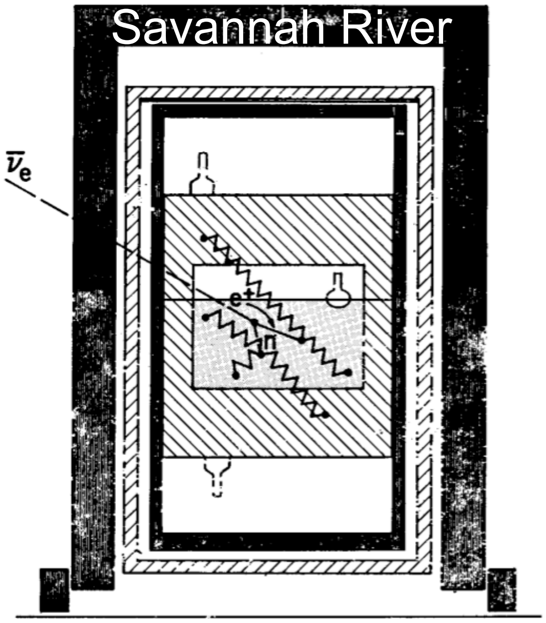
Th. Lasserre

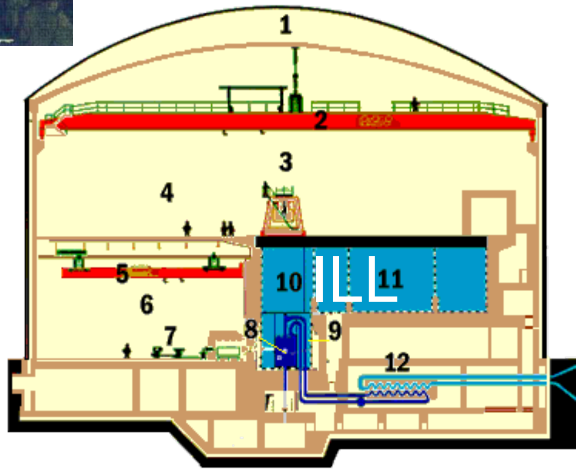
19 Experimental Results below 100m











Measured cross sections are taken at their face values

The Reactor Antineutrino Anomaly

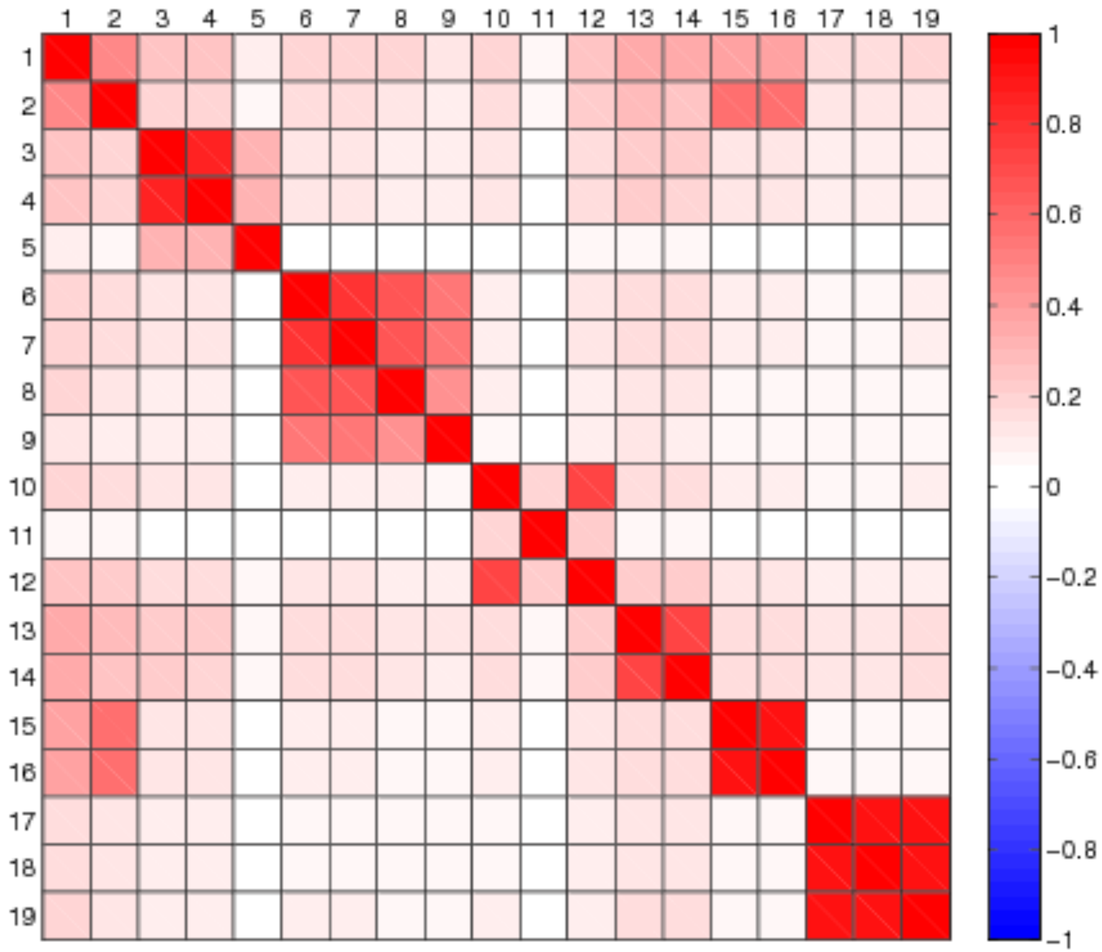
Reanalysis of Short Baseline Experiments Results (PRD83, 073006, 2011)

result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
Bugey-4	^{3}He+H_2O	888.7	0.538	0.328	0.078	0.056	0.987	0.926	3.0	3.0	15
ROVNO91	^{3}He+H_2O	888.6	0.614	0.274	0.074	0.038	0.985	0.924	3.9	3.0	18
Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.930	4.8	4.8	15
Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.936	4.9	4.8	40
Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.861	14.1	4.8	95
Goesgen-I	^{3}He+LS	897	0.620	0.274	0.074	0.042	1.018	0.949	6.5	6.0	38
Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.975	6.5	6.0	45
Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.909	7.6	6.0	65
ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.7882	9.5	6.0	9
Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.920	5.8	4.9	33
Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.937	20.3	4.9	92
Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.931	4.9	4.9	57
SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.936	3.7	3.7	18
SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.001	3.8	3.7	24
ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.901	6.9	6.9	18
ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.932	6.9	6.9	18
ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.955	7.8	7.2	18
ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.943	7.8	7.2	25
ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.922	7.2	7.2	18

But 19 correlated results…

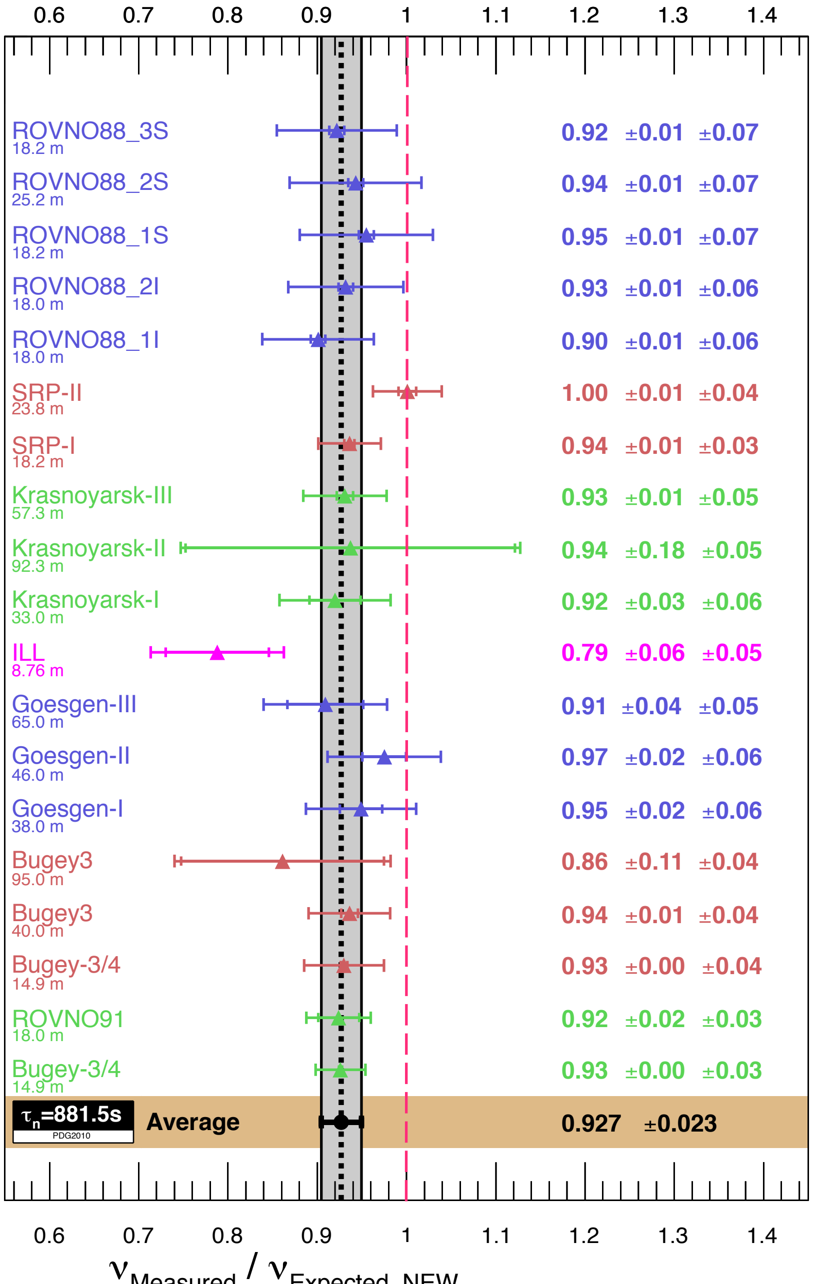
$\overrightarrow{R}$	$\Sigma_{tot.}$ (in %)	$\Sigma_{cor.}$ (in %)
Bugey-4 15m	3.0	3.0
Rovno91 18m	3.9	3.0
Bugey-3 15m	5.0	5.0
Bugey-3 40m	5.1	5.0
Bugey-3 92m	14.1	5.0
Goesgen 38m	6.5	6.0
Goesgen 45m	7.6	6.0
Goesgen 65m	9.5	6.0
ILL 9m	5.1	4.1
Krasno 33m	5.1	4.1
Krasno 92m	20.3	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7	3.7
SRP II 25m	3.8	3.7
Rovno88 1I 18m	6.9	6.9
Rovno88 2I 18m	6.9	6.9
Rovno88 1S 18m	7.8	7.2
Rovno88 2S 25m	7.8	7.2
Rovno88 3S 18m	7.2	7.2

C (correlation matrix on Ratios)



- Main pink color comes from the 1.8% systematic on ILL β-spectra normalization uncertainty
- The experiment block correlations come from identical detector, technology or neutrino source

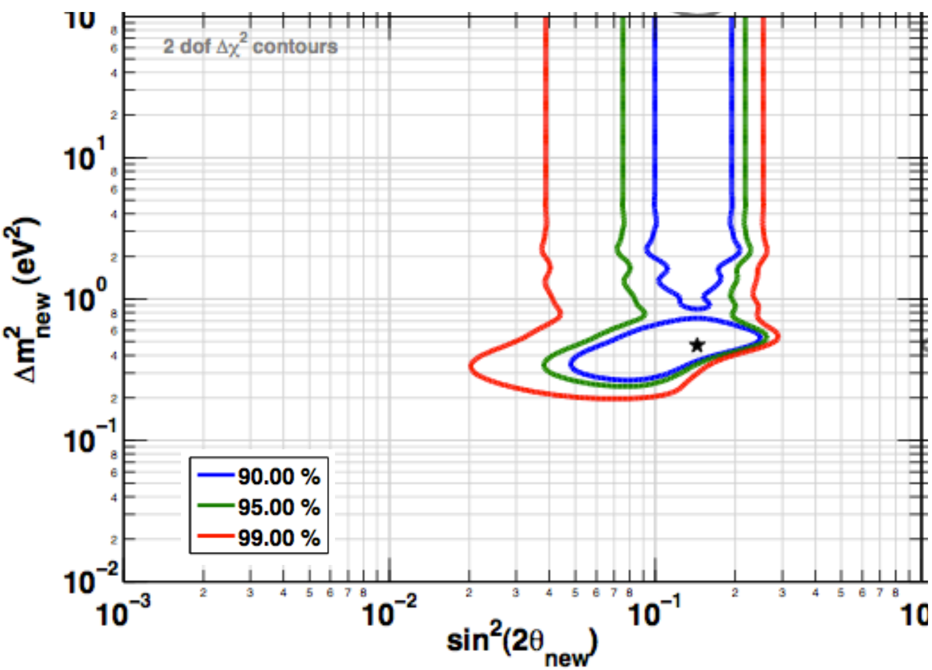
The reactor anomaly



- **Fit:** $\chi^2 = \left(r - \vec{R}\right)^T W^{-1} \left(r - \vec{R}\right)$
- **Best fit for N_{obs}/N_{exp}: μ = 0.927**
- **Uncertainty : 0.023 (syst.)**
- **7% deficit wrt the new prediction**
  - **≈3%: reevaluation of emitted flux**
  - **≈3%: reevaluation of**
    - **IDB cross section parameters**
    - **Neutron lifetime**
    - **Accounting for off eq. effect**
- **99.7 % C.L. deviation from unity**
- **THE question:**
  - **Artifact or new physics?**

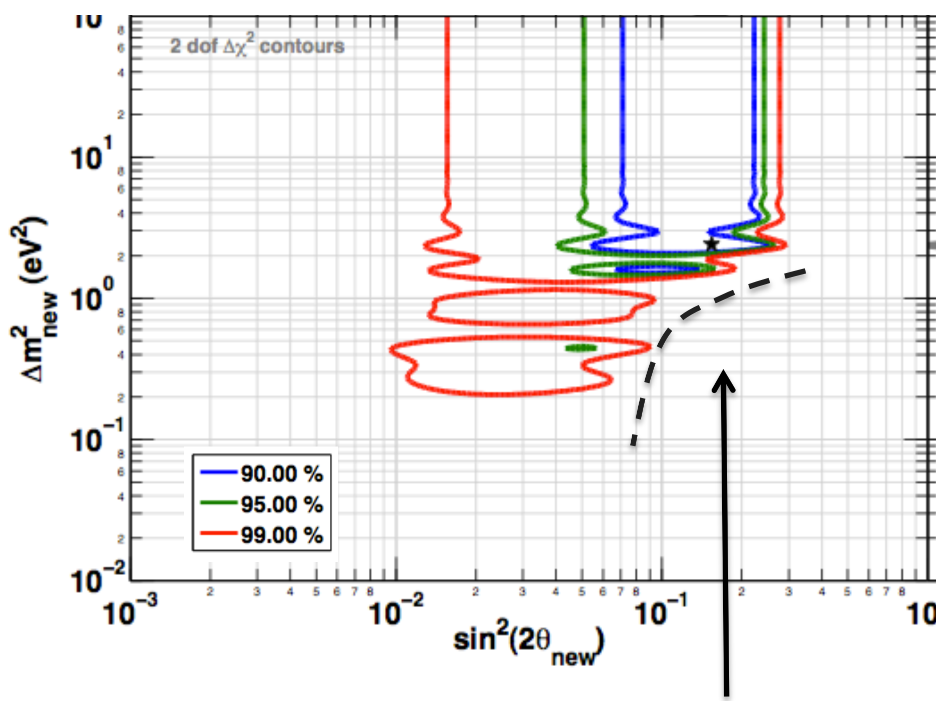
The 4th neutrino hypothesis

Rate Only Analysis



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

Rate + Shape Analysis

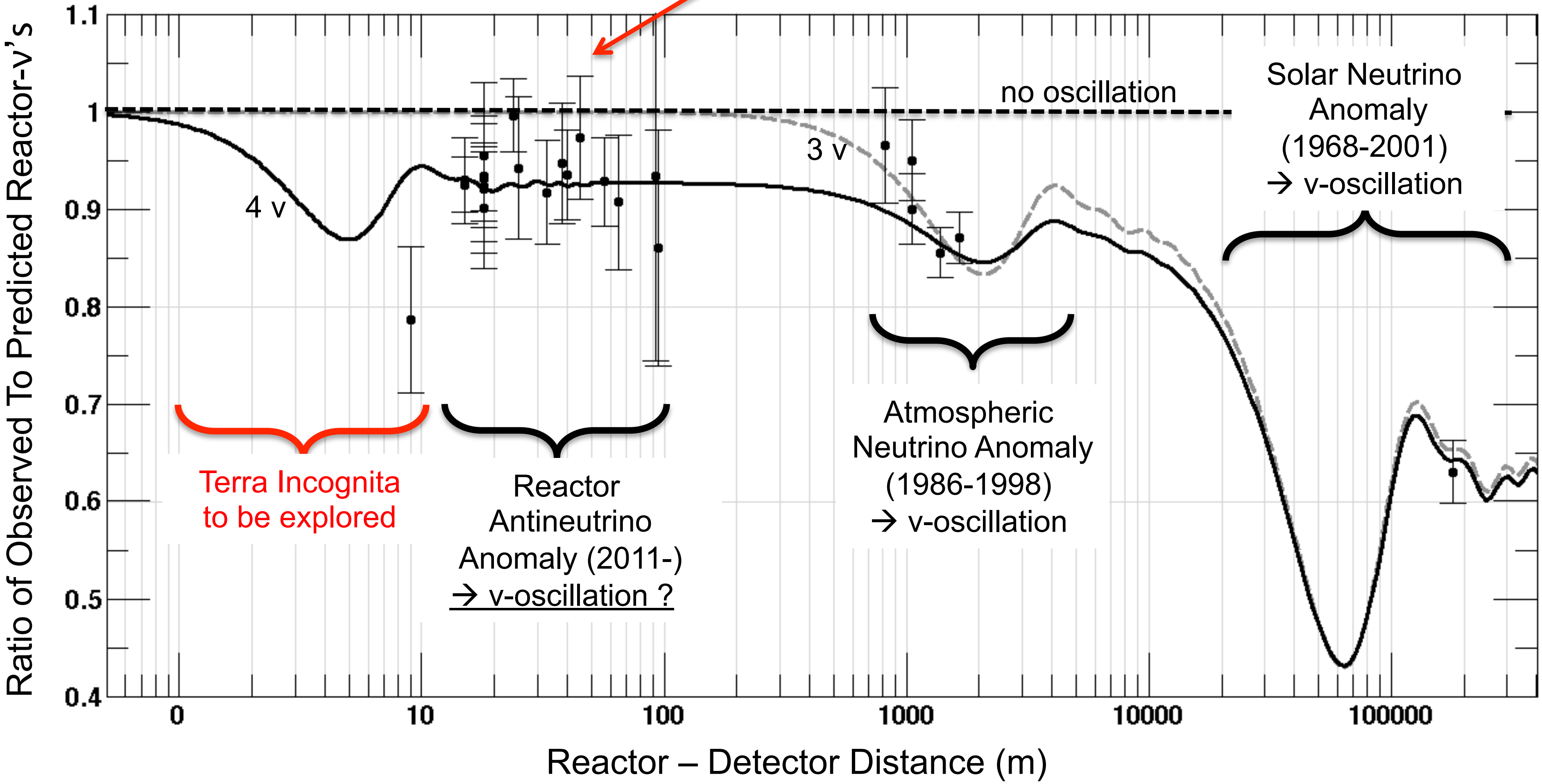


- Bugey-3 40m/15m $E_{spectrum}$ ratio
→ No energy spectrum distortion
→ large PWR core extension

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

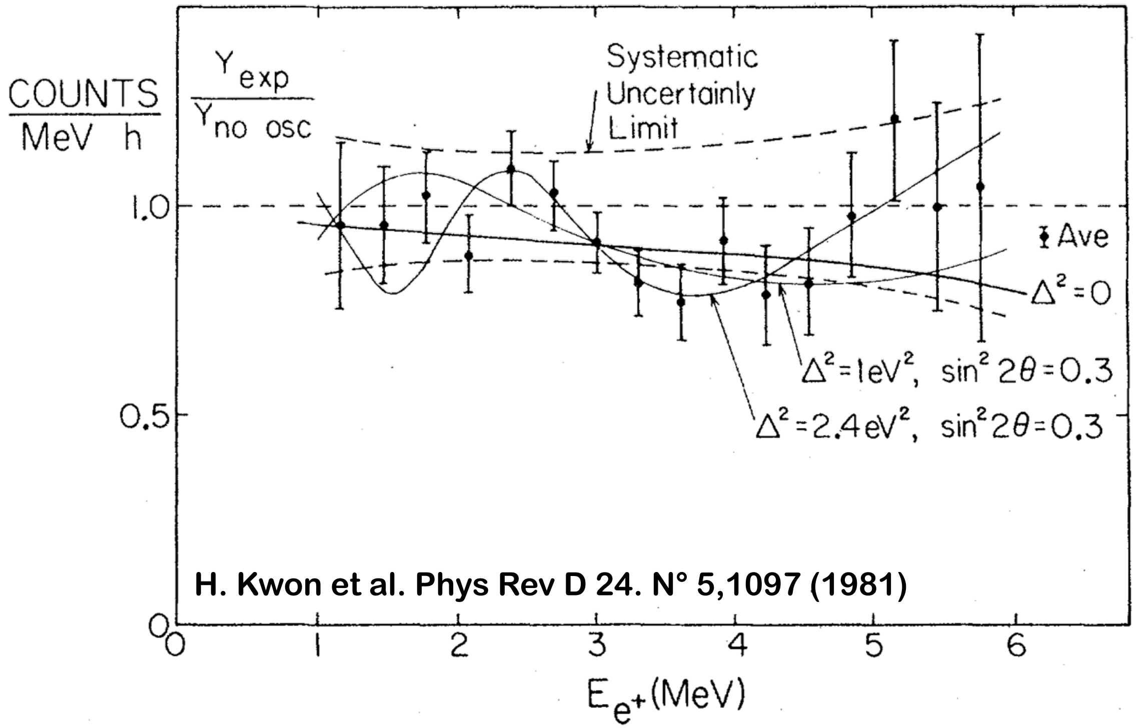
The Reactor Antineutrino Anomaly

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



Puzzling 1981 ILL ν-experiment

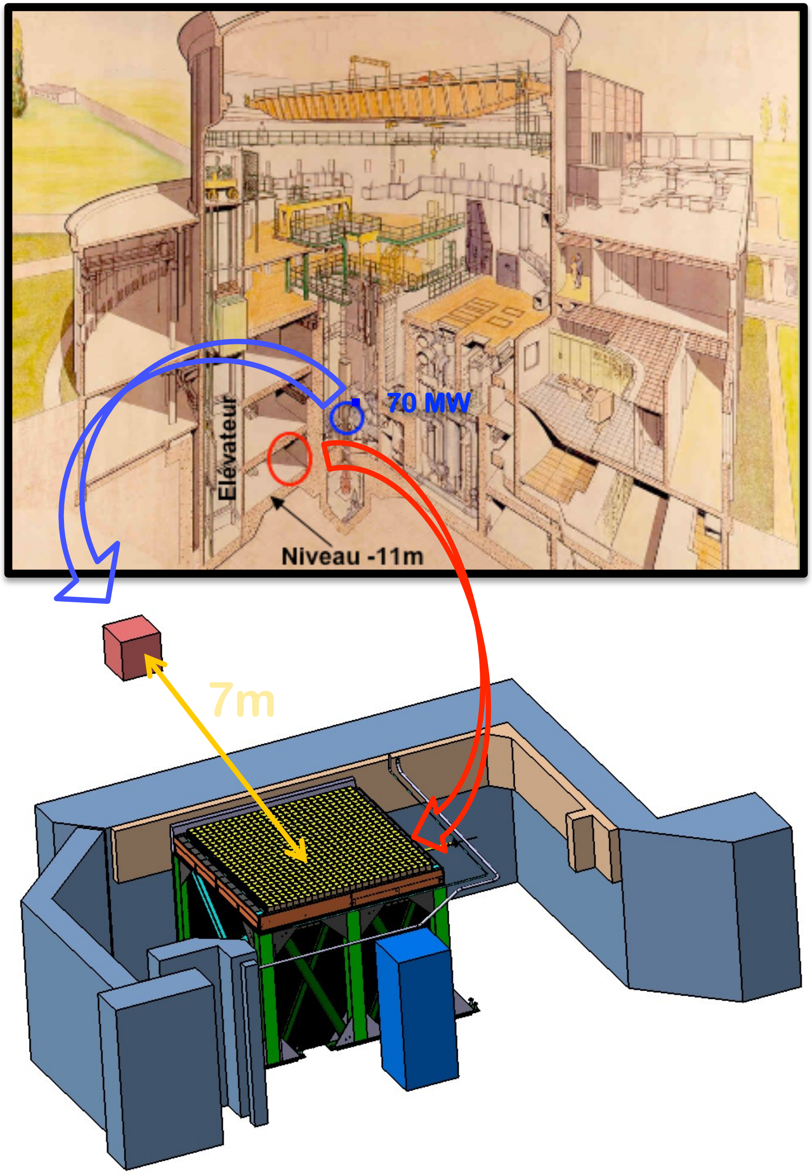
- Reactor at ILL with **almost pure** ^{235}U, with **compact core**
- **Detector 8.8 m from a COMPACT core**
- Reanalysis in 1995 to account for overestimation of flux at ILL reactor by 10%... Affects the rate only but 20% deficit!



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

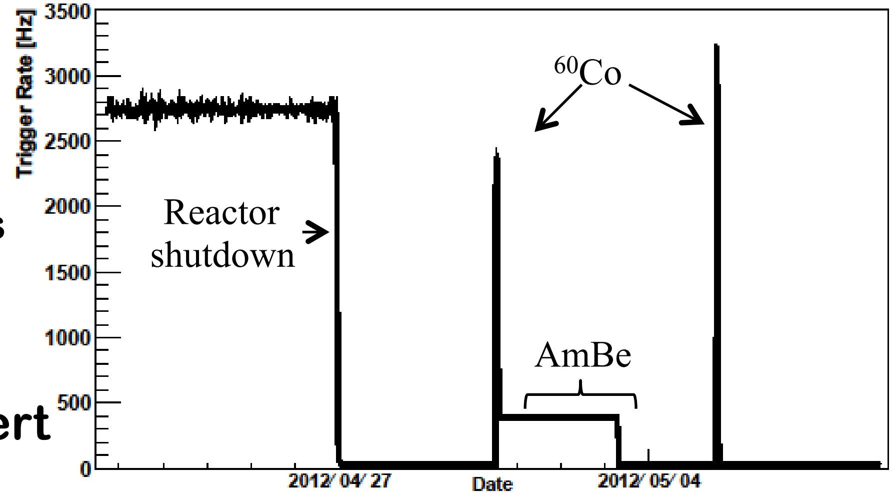
Nucifer experiment

- Osiris research reactor
  - At Saclay, France
  - 70 MW, 20%
  - Compact: 61x61x63 cm^3
- Detector designed for reactor monitoring studies
  - 850 kg Gd-loaded liquid scintillator
  - 400 neutrinos expected / day
- But oscillation detection abilities:
  - Short baseline: only 7 m (center to center)
  - Target: h = 70 cm, Φ = 1.2 m



Commissioning and data taking

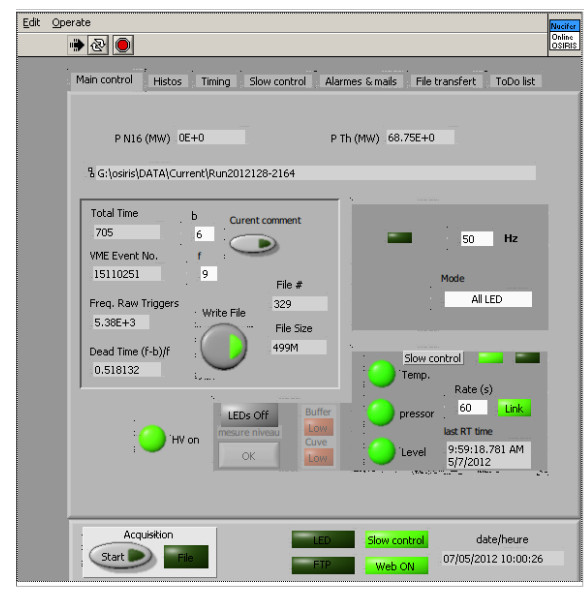
- Data taking since 4/2012
  - Agreement from French National Security Agency (ASN)
  - No safety issue reported in 6 months



- Remote control & monitoring

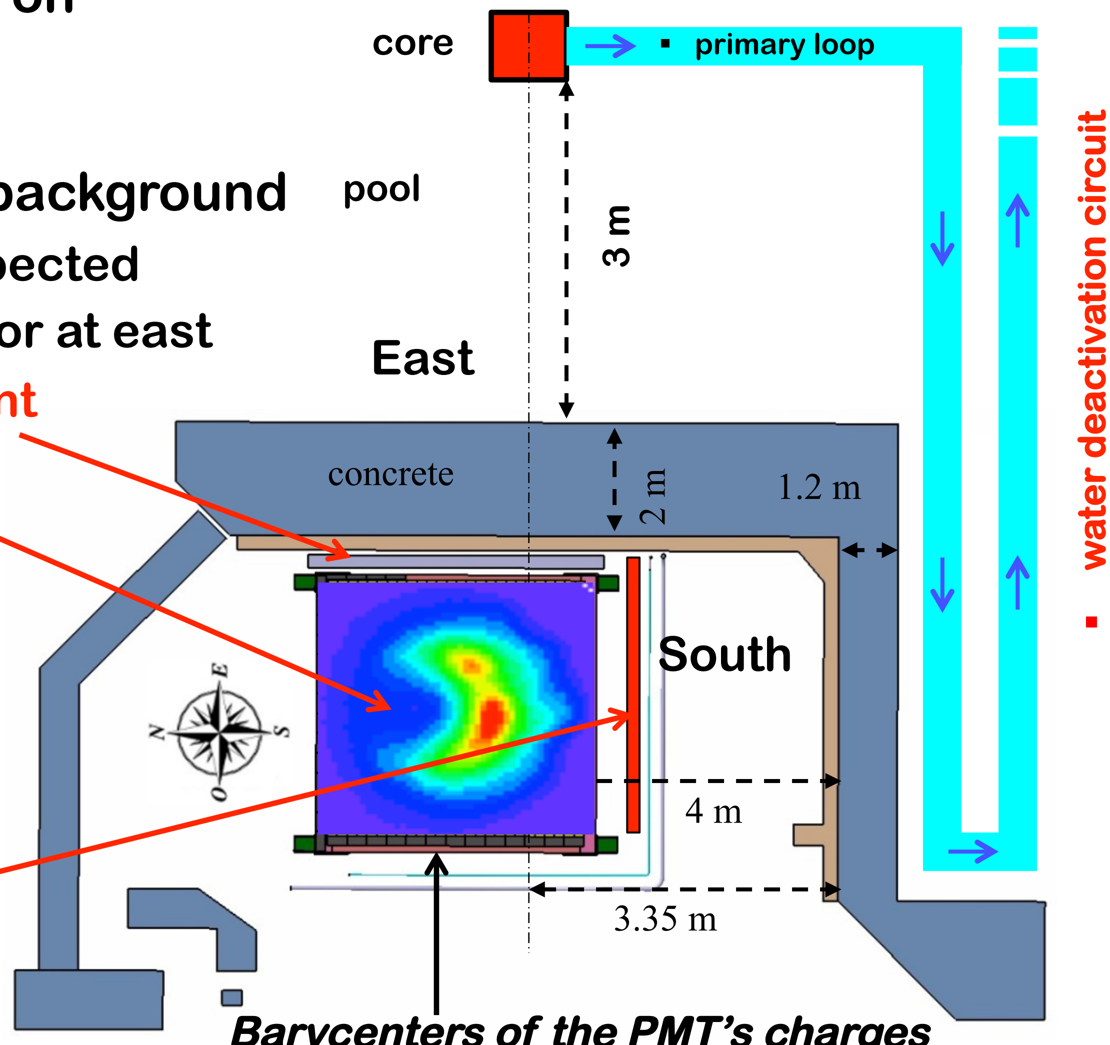
  +Automatic operation & data transfert

- Detector works well (but see bkg…)



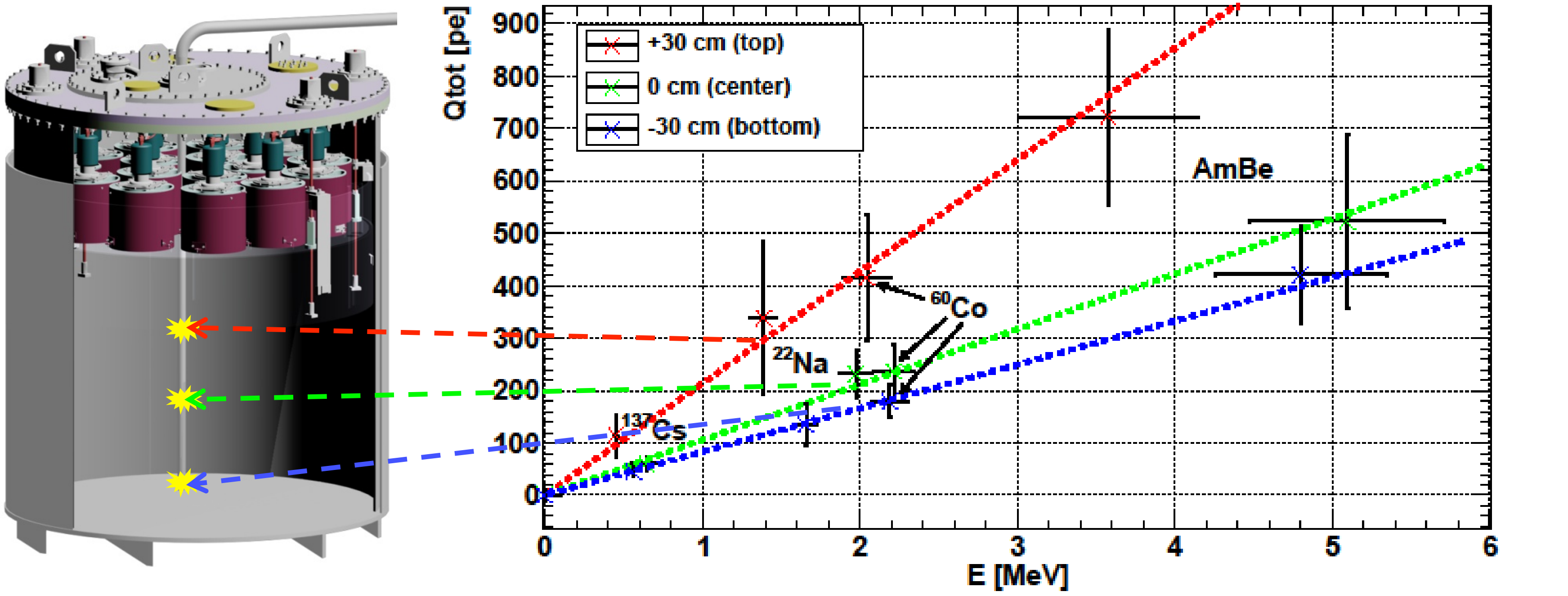
Accidental background

- Reactor OFF background on expectation
- Unexpected reactor ON background
  - 10 times higher than expected
  - Point to south, but reactor at east
  - Lead front wall is efficient
  - Expected level at north
- Primary loop water activation
  - High energy γ leakage from ^{16}N
- New south lead wall
  - Lead already acquired
  - Installation end 2012



Liquid scintillator upgrade

- Liquid scintillator shows unexpected short attenuation length 1m
  - Vertex dependent energy reconstruction: degradation of energy resolution
  - Time resolution not affected: preliminary studies of correlated background (40/day, energy cut dependent), veto muon efficiency (97 %)…
- New liquid based on Double-Chooz R&D to be provided this fall

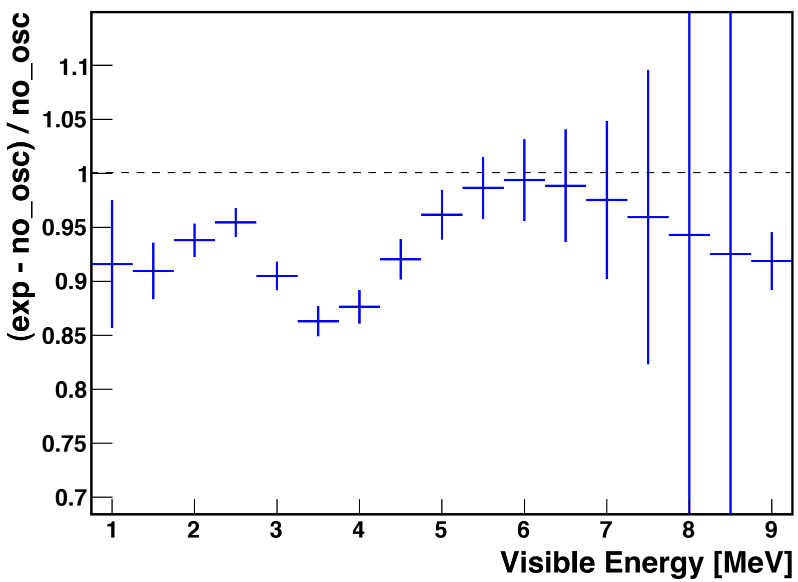


Expected sensitivity after upgrades

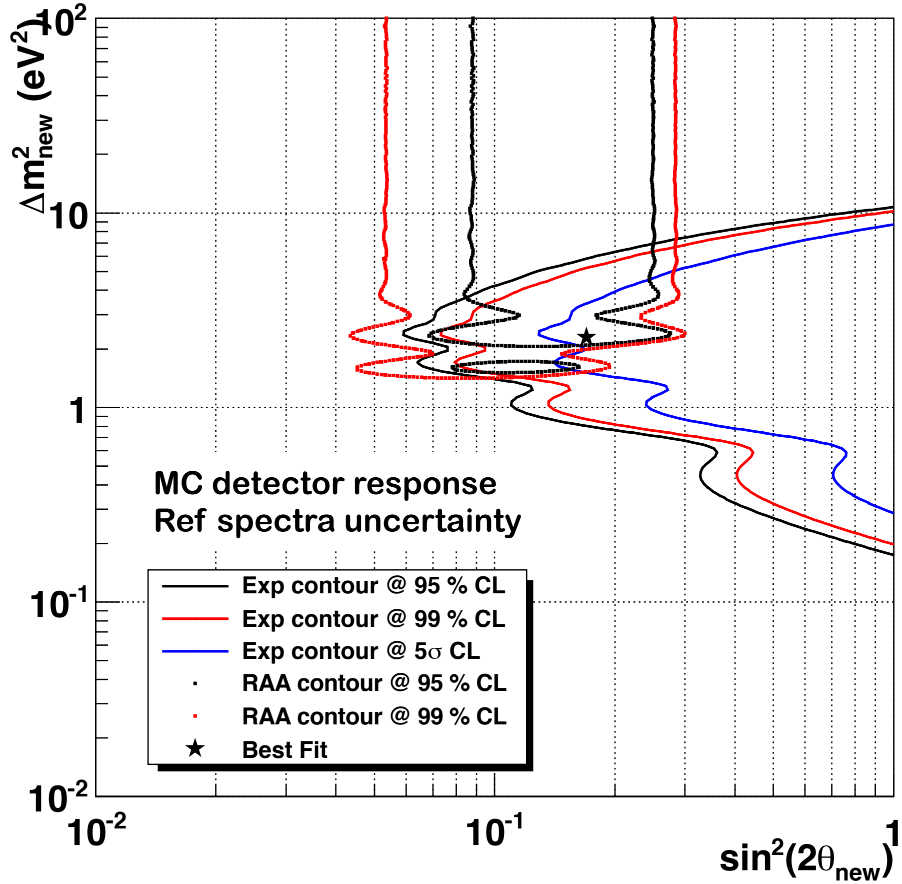
- Upgrades planned to be finished early 2013

- With upgrades →

300 days @ Osiris



Expected spectrum distortion
- Error stat only -

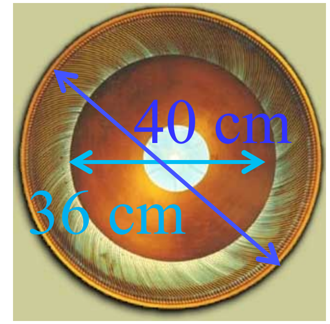


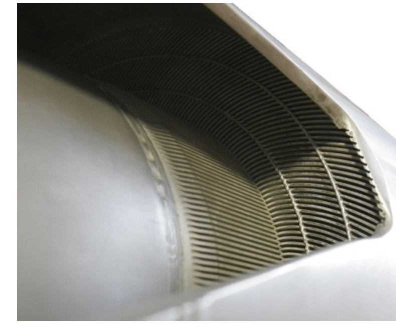
- If present, sterile hint possible

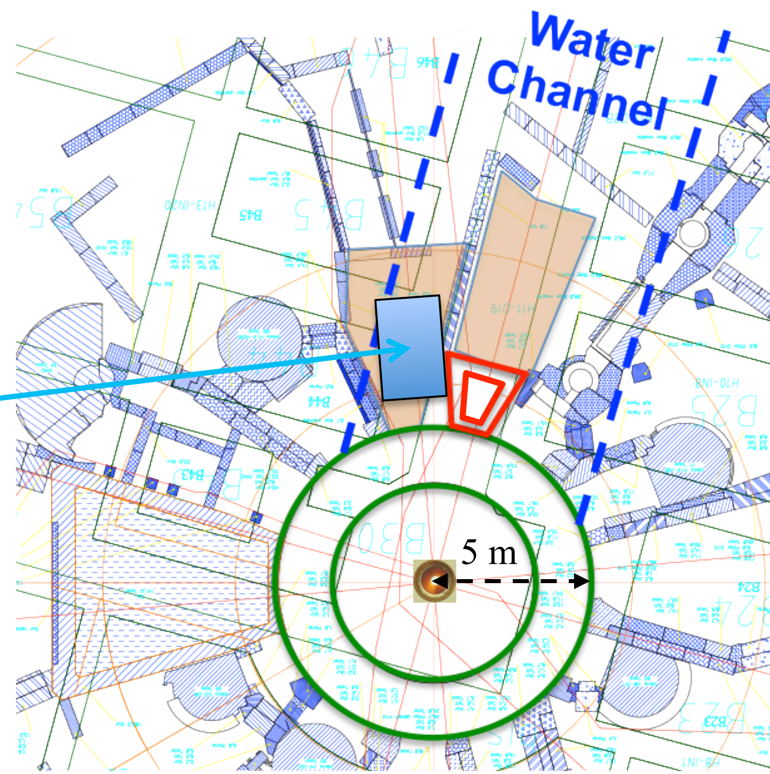
STEREO project

Contact: D. Lhuillier

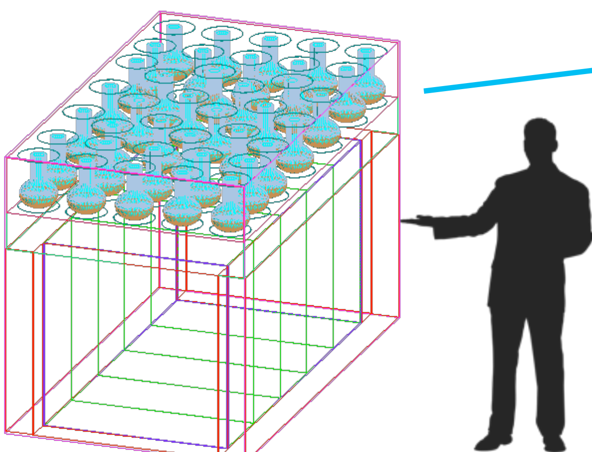
- French and German project
- ILL research reactor (Grenoble):
  - 57 MW, highly enriched U
  - Compact: h = 80 cm, Φ = 40 cm
- Dedicated detector:
  - 5 segments: L and E oscillation
  - Active outer layer: high efficiency+veto
  - Muon flux divided by 4, thick CH_2 and Pb walls (70 t)







Target:
Gd-doped
liquid
scintillator



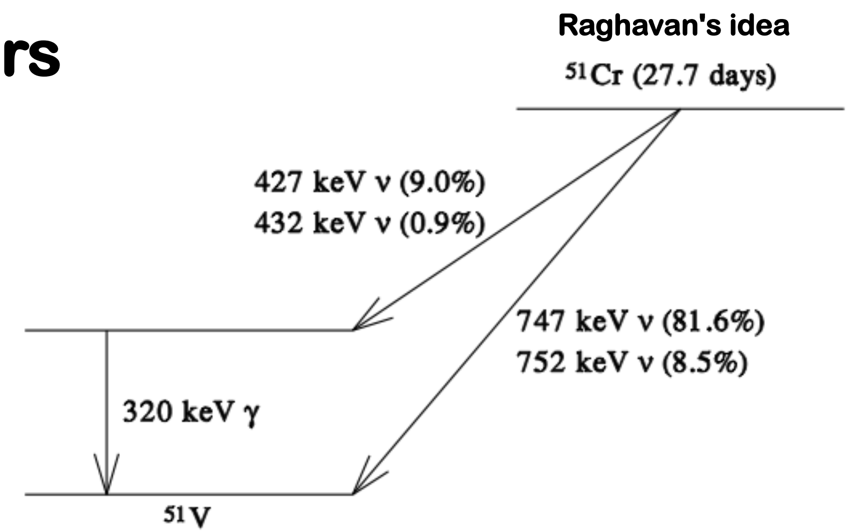
The Gallium Neutrino Anomaly

Based on PRD82 053005 (2010), C. Giunti & M. Laveder

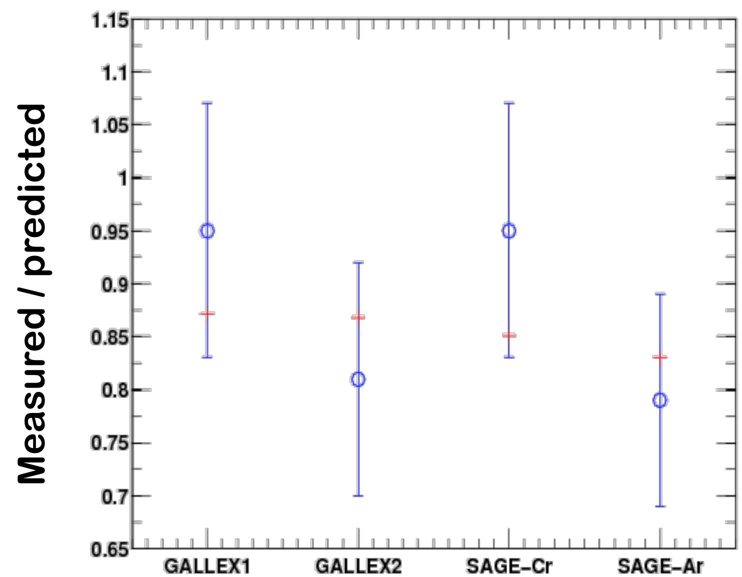
Recent update: C. Giunti et al., arXiv:1210.5715 (not included here)

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 MCi EC ν_e emitters**
  - Gallex
    - ^{51}Cr source (750 keV)
  - Sage
    - ^{51}Cr & ^{37}Ar (810 keV)



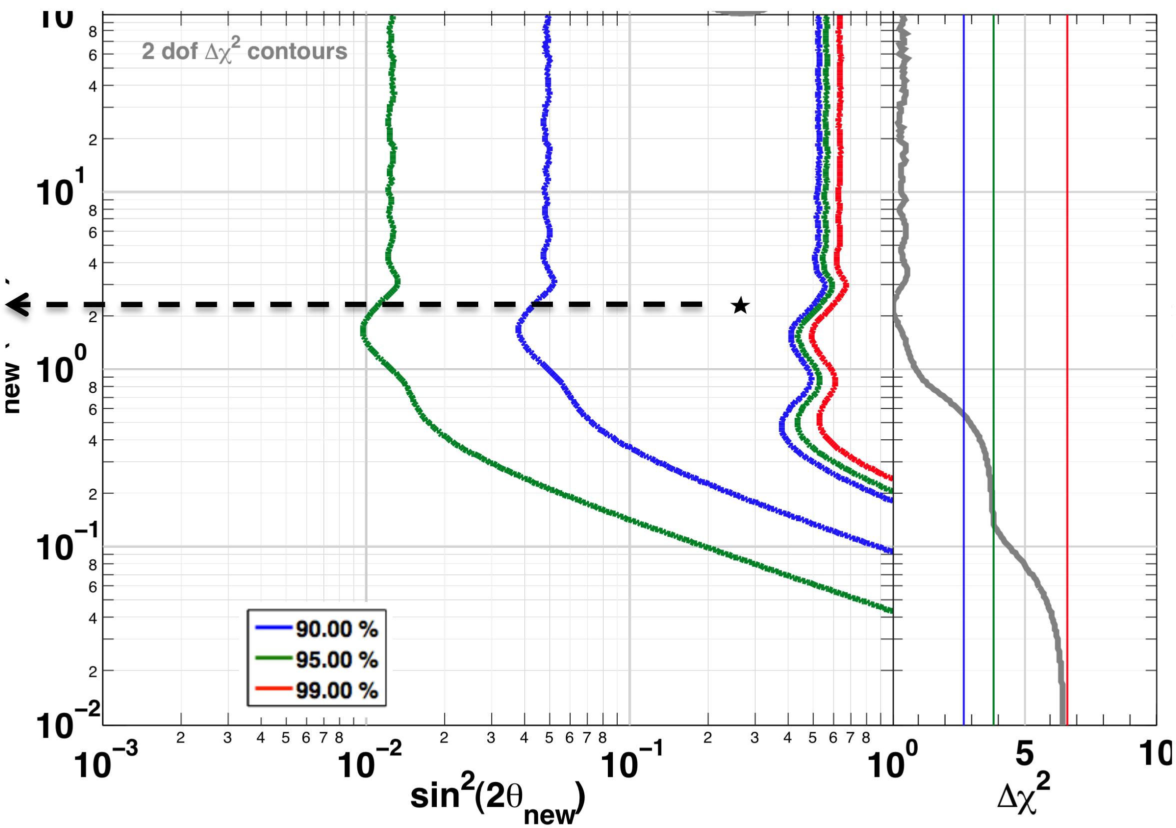
- **Deficit observed**
  - $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
  - $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})

The Gallium Neutrino Anomaly

Fit to ν_e disappearance hypothesis (3+1)

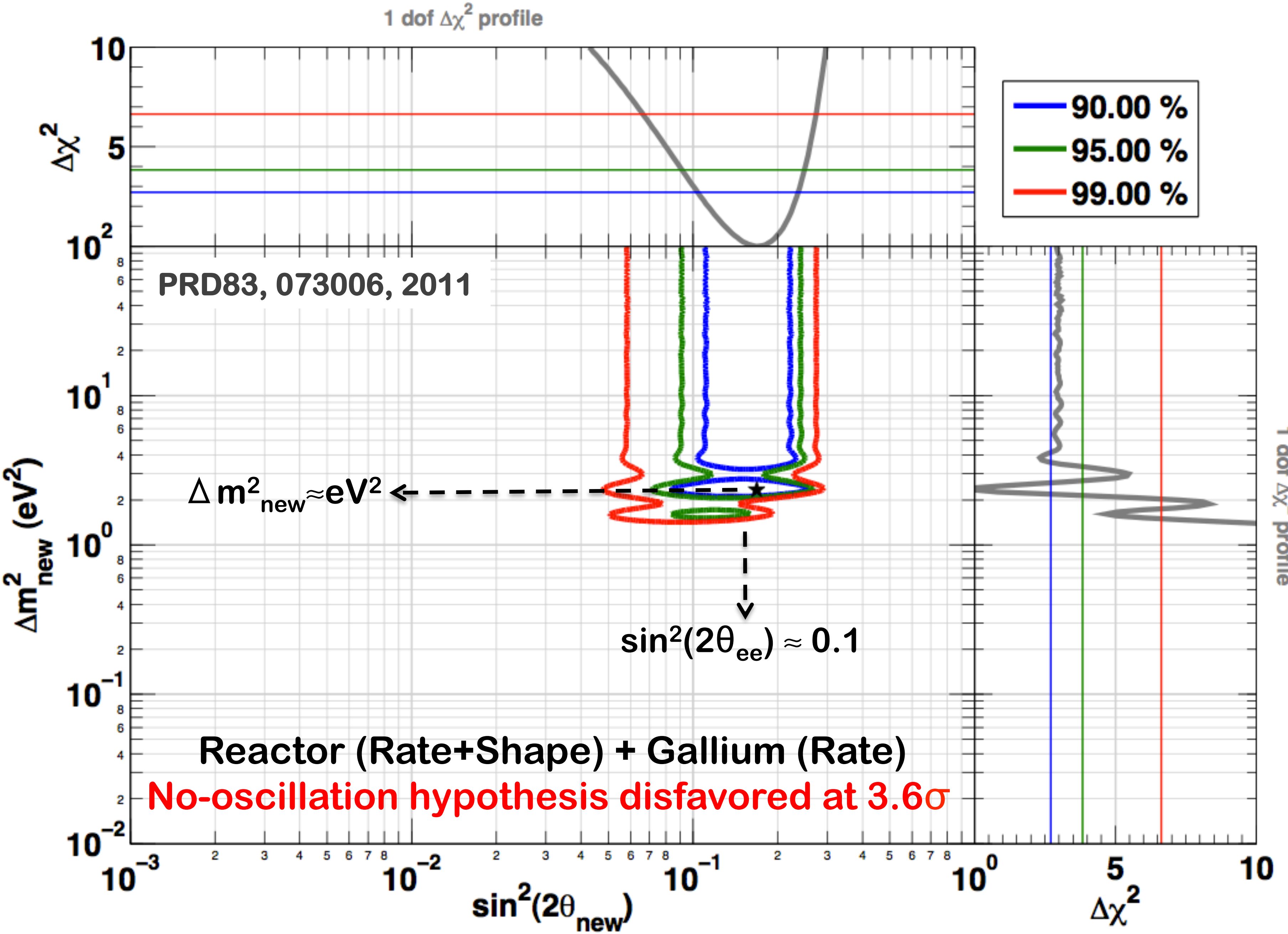
$$\begin{pmatrix}\nu_e\\ \nu_s\end{pmatrix} = \begin{pmatrix}\cos\theta_{new} & \sin\theta_{new}\\ -\sin\theta_{new} & \cos\theta_{new}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_{new}\end{pmatrix},\quad P_{ee} = 1 - \sin^2(2\theta_{new})\sin^2\left(\frac{\Delta m^2_{new} L}{E}\right)$$

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



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

Combining Gallium & Reactor Anomalies



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**
  - **$\Delta m^2 \approx$ 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**

Oscillometry inside a ν-detector

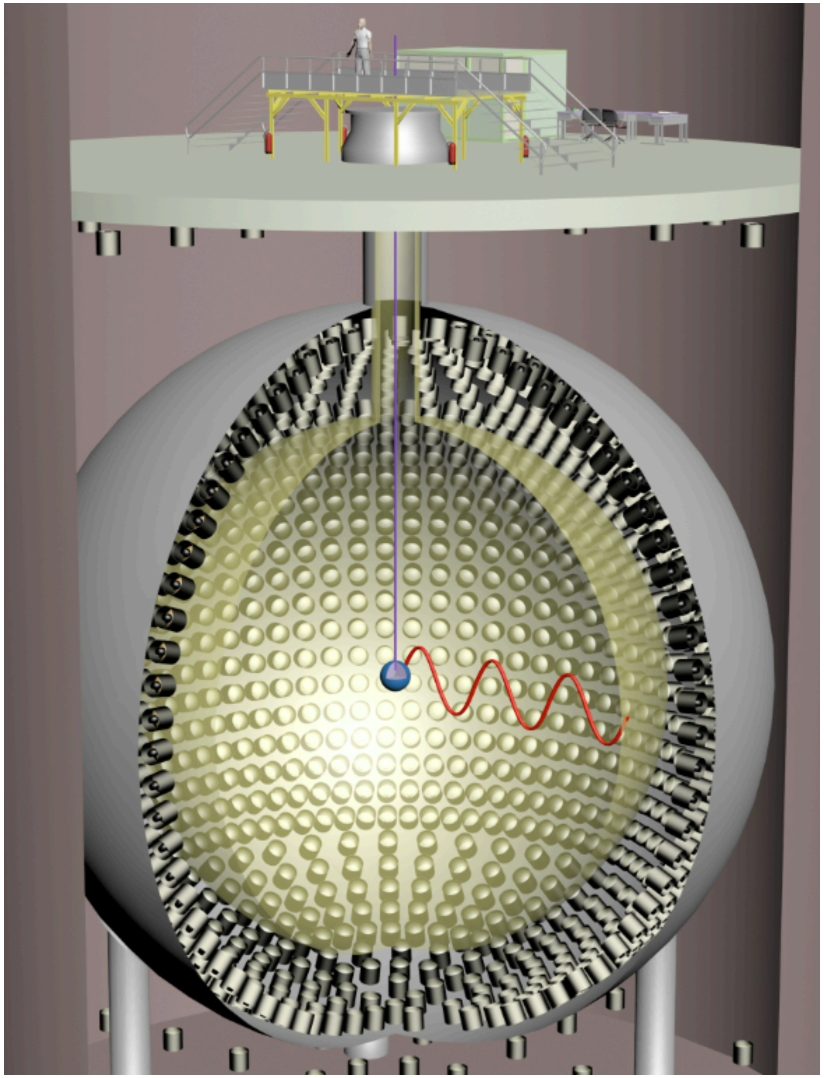
- **Place the ν-emitter inside or close to existing detectors**
  - **Very short Baseline (few m)**
  - **Low Background**

i) ν-source at center

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

ii) ν-source Outside LS

- **Specific oscillation pattern analytically computable**



ν-source Proposal Overview

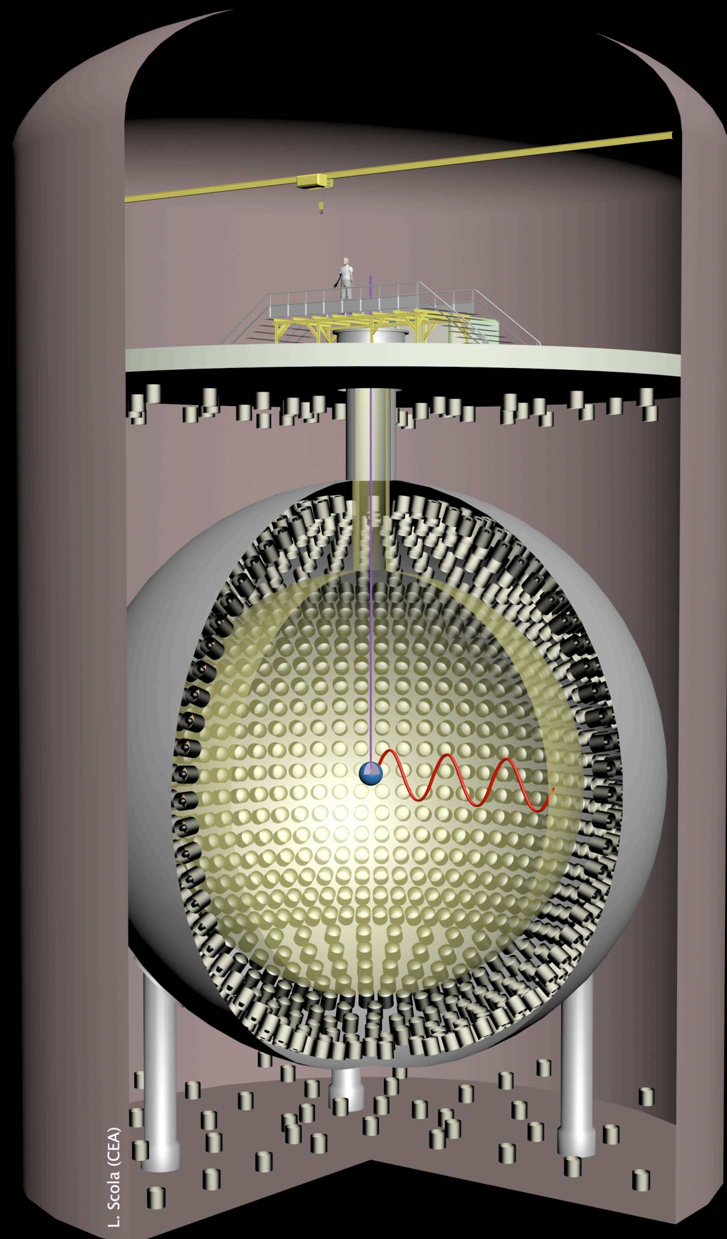
Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	Radiochemical $\nu_e\, e \rightarrow \nu_e\, e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solarν (irreducible) ν-Source (OUT ok but IN ?)	**^{51}Cr** 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Baksan 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}	reactorν& ν-Source → Background free!	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	in	0.005-0.05	CeLAND SOX
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

CeLAND: A proposed search for a fourth neutrino with a PBq anti-neutrino source

M. Cribier, M. Fechner, T. Lasserre,
D. Lhuillier, A. Letourneau, G. Mention
D. Franco, S. Schoenert, V. Kornoukhov

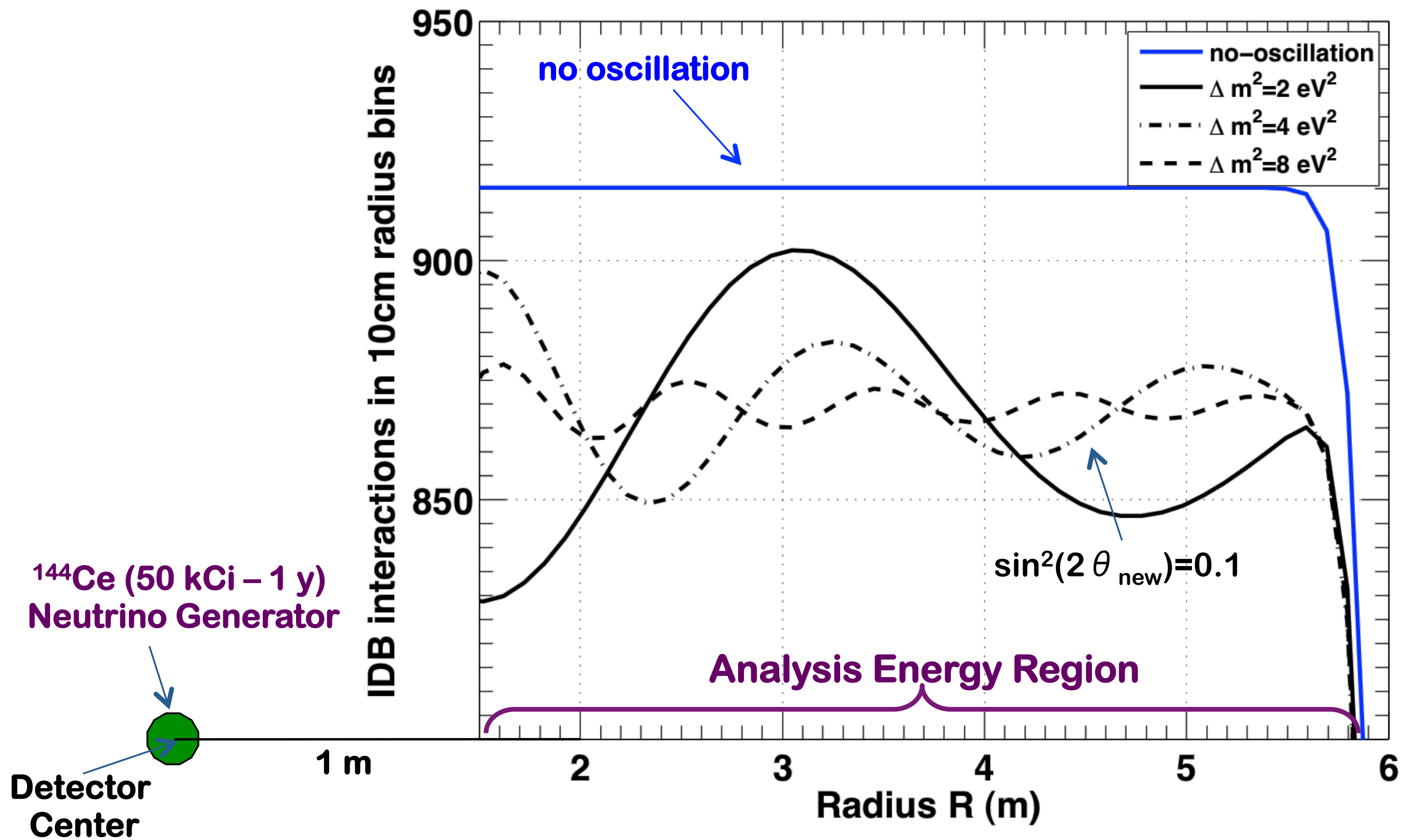
Phys. Rev. Lett. 107, 201801 (2011)
arXiv:1107.2335

The Concept



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

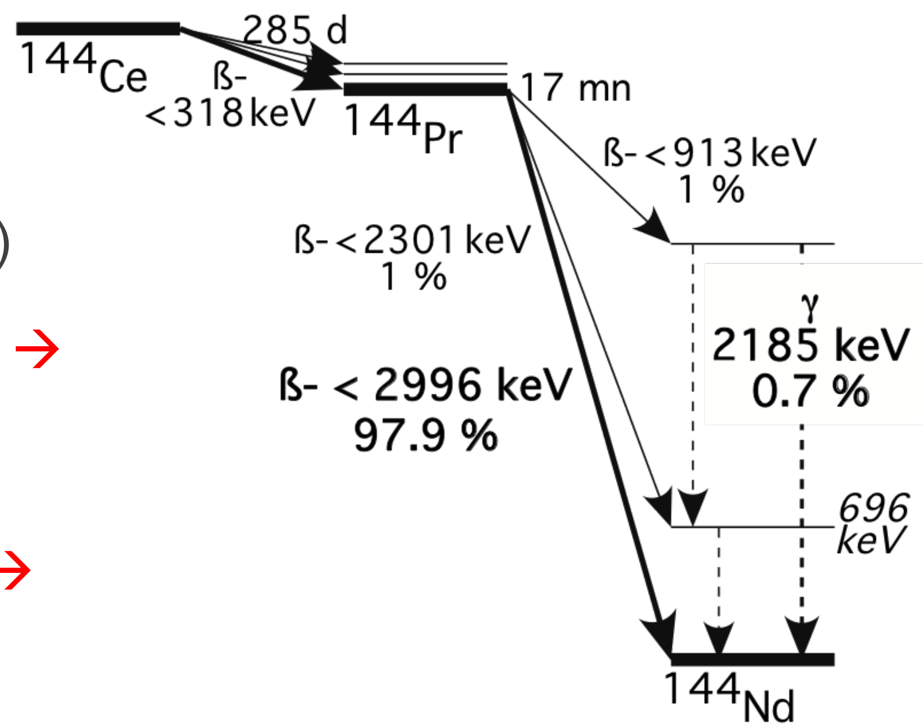
$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{\cancel{4\pi R^2}} \times \langle\sigma\rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E\rangle}\right)$$



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 → kCi activity**
  - **(e^+,n) detected in coincidence → Background free**

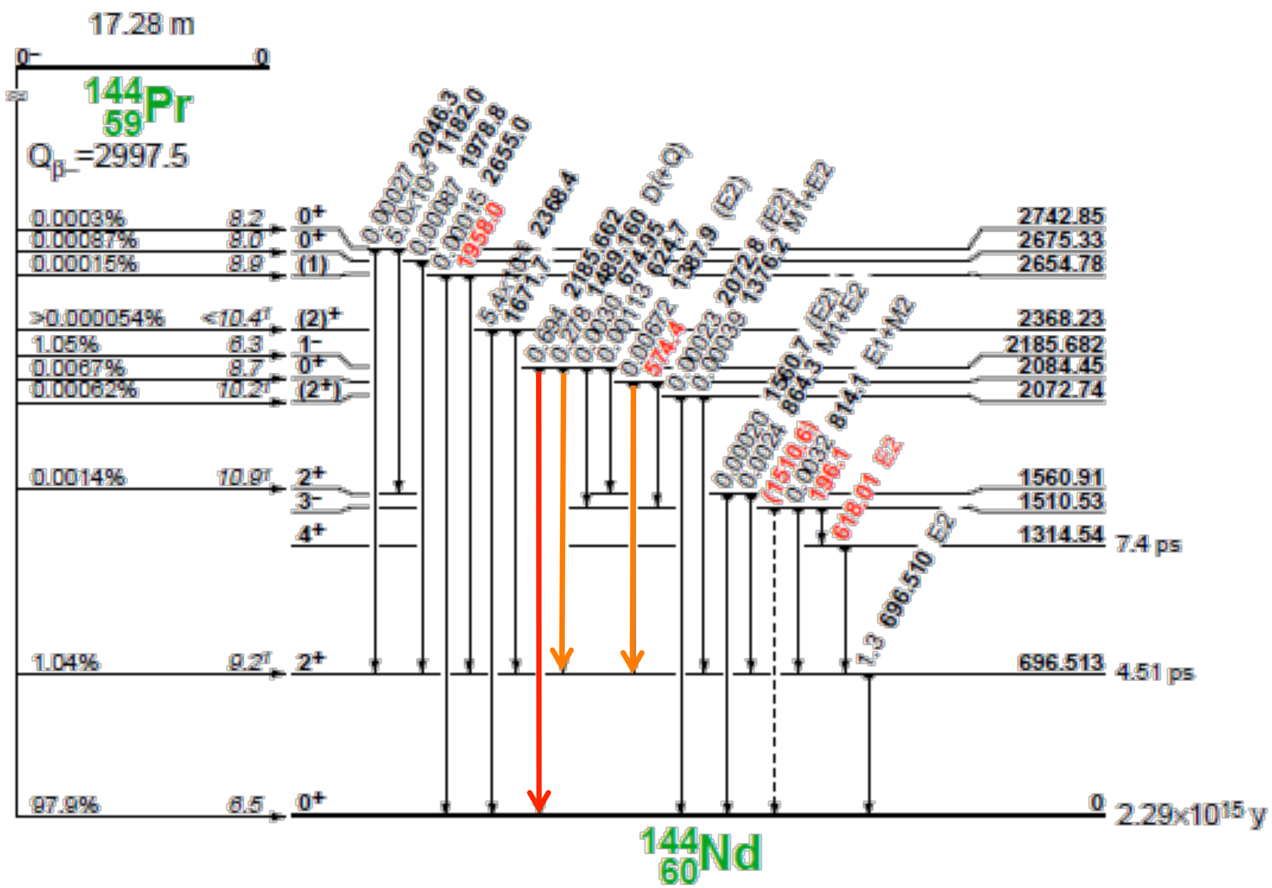


- 2nd Trick: **^{144}Ce-^{144}Pr**
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β → Enough time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β → ν_e-emitter above threshold

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

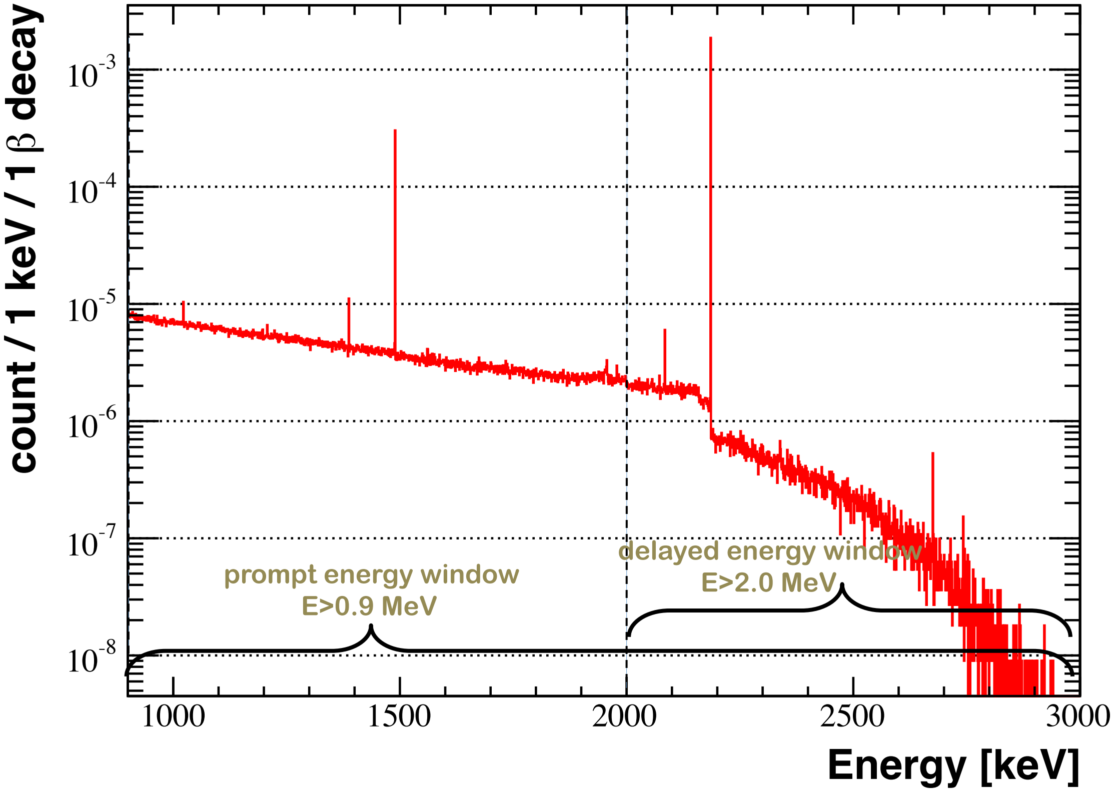
- γ rays produced by the decay through excited states of ^{144}Pr
  - Intensity γ >1 MeV
    - 1380 keV – 0.007 %
    - 1489 keV – 0.3 %
  - Intensity γ >2 MeV
    - 2185 keV – 0.7 %

      (10^{10} γ /sec for 50 kCi)



Bremsstrahlung Background

- ^{144}Ce Electron – Nucleus Bremsstrahlung in the cerium
→emission of gamma rays till Q-value



- Bremsstrahlung modelization in thick Cerium Target
  - GEANT4 Simulation
  - #photons escaping the Ce

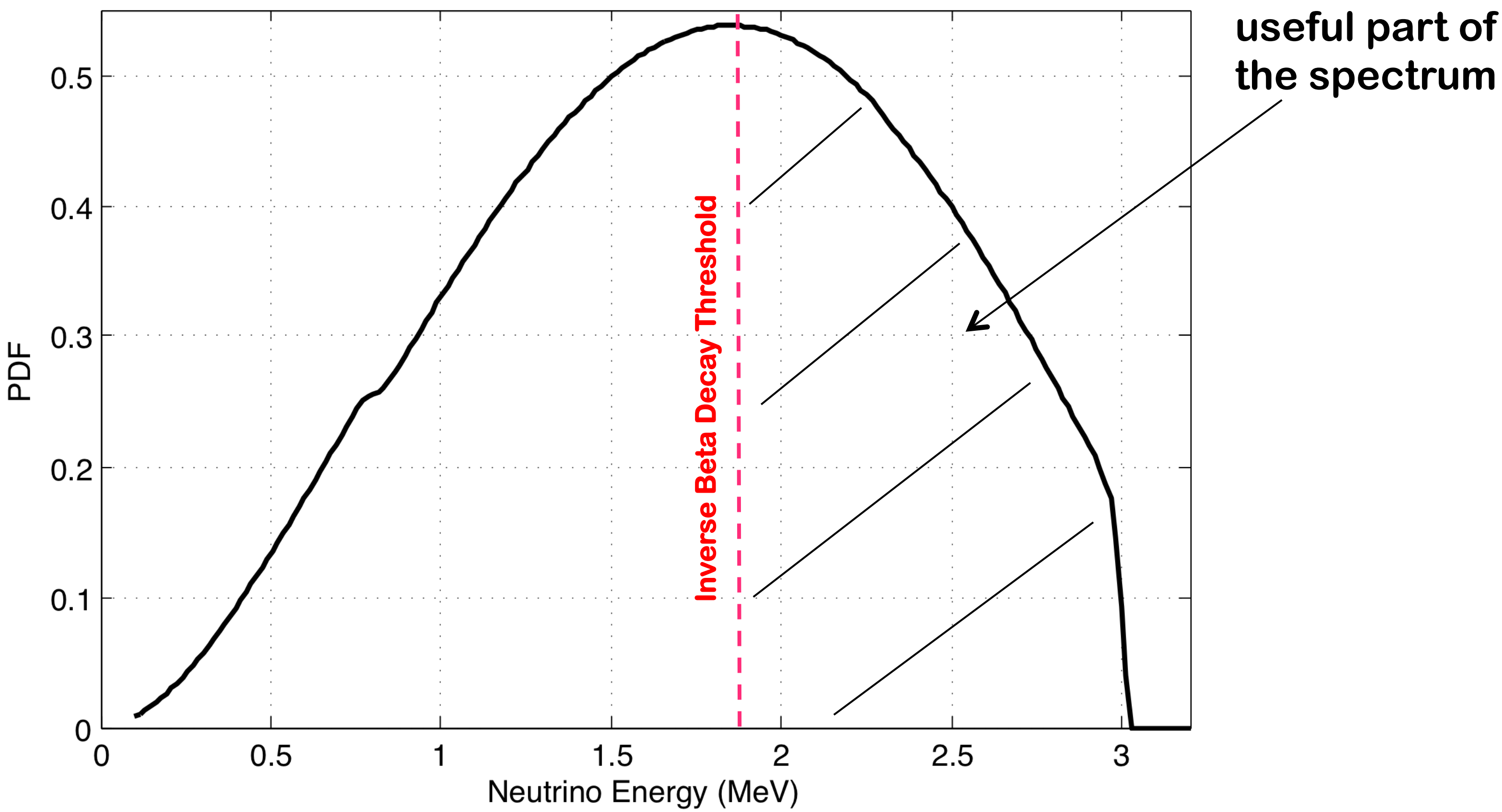
-E>0.9 MeV: <6.5 10^{-3}/decay

-E>2.0 MeV: <10^{-4}/decay

- Background less Critical with respect to γ rays produced by the decay through excited states of ^{144}Pr

Neutrino Signal of ^{144}Pr

- Relevant Antineutrino emitter : ^{144}Pr (Half-life : 0.78 y)
- 48.7 % of antineutrinos emitted above IBD threshold



The Cerium Compact Source

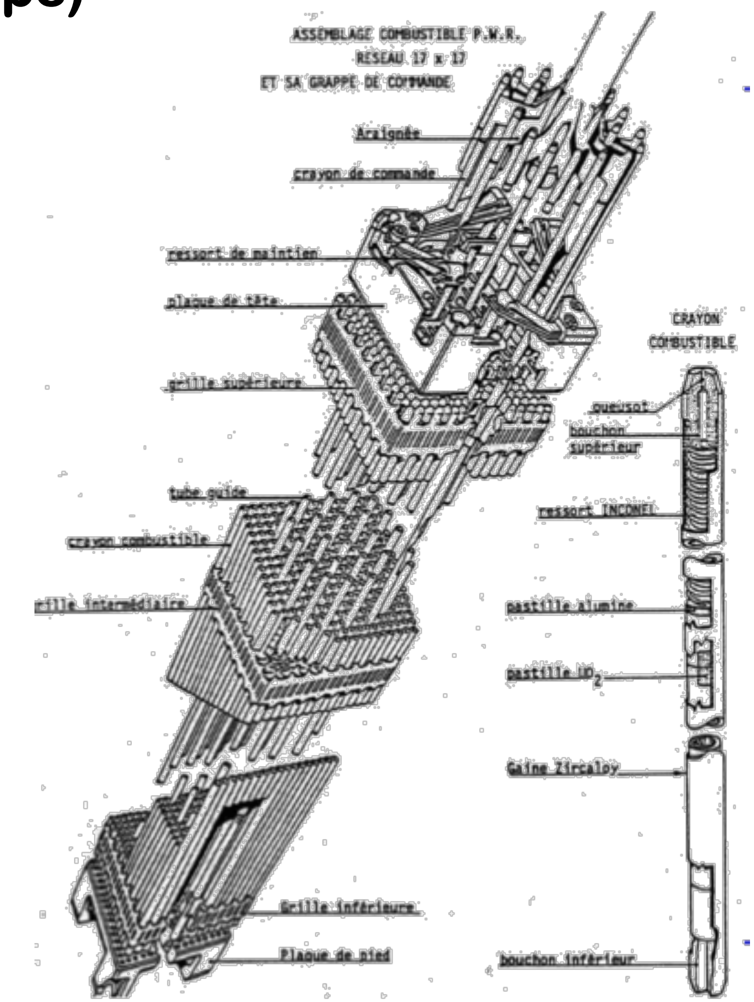
- 50 kCi source (1.85 PBq)
- Assuming a spent fuel cooling time of 3 years
  - Composition (material in form of CeO_2)
    - $^{144}Ce:Ce = 1/130$
  - $\rho(CeO_2) = 4\ g/cm^3 \rightarrow R_{source} = 5$ cm (if spherical)
  - 15 g $^{144}Ce \rightarrow \approx 3$ kg of CeO_2
  - Initial Heat release = 380 Watt (comparable to PMTs → passive cooling foreseen)

Nuclear Spent Fuel Elements

- **Fuel in N4-reactors (EDF N4-Type)**
  - 120 tons of UO_2
  - $^{235}U \approx 3.45\%$: 3.60 tons

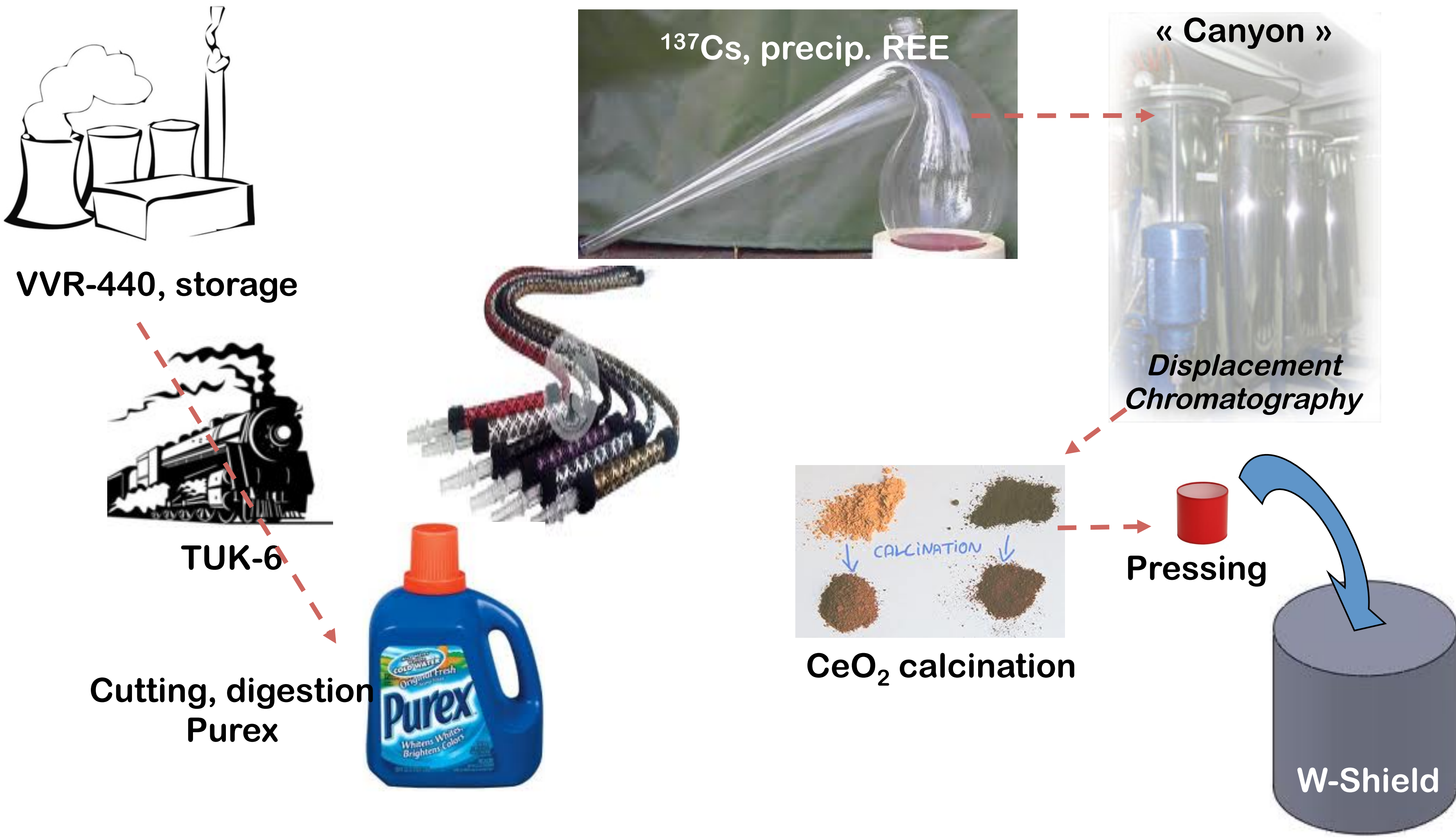
- **205 fuel assembly**
  - 264 rods per assembly
  - 272 "pellets" per rods

- **1 ton of VVR-440 spent fuel**
  - Burnup of 40 GW*days/t
  - Fission Products: 44 kg
  - 13 kg of Rare Earth (RE)
    - Ce≈22% → ≈3 kg
  - **22 g of ^{144}Ce (60 kCi)**



- **Must account for recovery efficiency**
  - **Estimation: ≈10 tons needed (80 fuel rods)**

Scheme of production



^{144}Ce-^{144}Pr Production Data

- **Technology & Productivity:**
  - Complexing agent displacement chromatography
  - ≈10 kg of Rare Earth per cycle
  - Content of Ce element 25% → ≈2.5 kg of Ce /cycle
- Ratio of ^{144}Ce/Ce element is strongly depended on:
  - Fuel burning
  - Cooling time
  - ^{144}Ce:Ce ≈ 1:130 for 3 years old fuel -
- **Purity data from ^{147}Pm production line (TBC for ^{144}Ce)**
  - Content of any others RE (γ-*emitters*) in *Ce* ≤ 10^{-9} Ci/Ci
  - Content of Pu and TPE (*n emitters*) in Ce ≤ 10^{-10} Ci/Ci

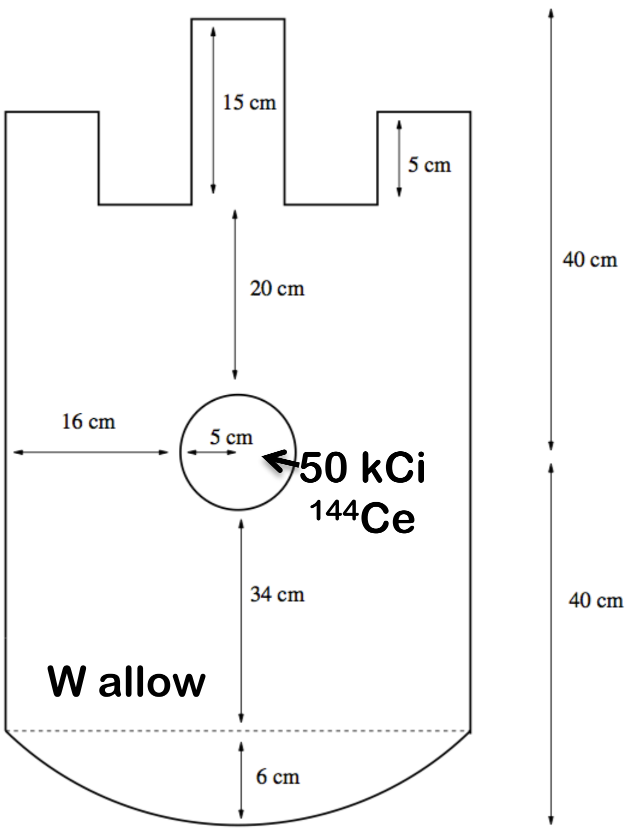
Existing Chromatography Facility (Mayak)

General requirements on shielding

- **Two separate goals**
  - Usual biological protection
    - Could be achieved with ≈ 15 cm of W-alloy
  - Minimisation of accidental bkg during the experiment
    - Need an extra 20 cm of W-alloy or equivalent
- **Important constraints to fulfill**
  - The size of the hole (chimney) of the neutrino detector
  - Cleanliness - Radiopurity
- **Several solutions under study**
  - Internal ^{144}Ce : An « orange-like » shielding
  - Internal ^{144}Ce : A central W-shield inside a balloon filled with heavy liquid
  - External ^{144}Ce : another dedicated W-shield

Radioprotection Shielding

- A first shield around the source just after production
- Designed to physicists/engineers to operate the source
- Preliminary design based on dose calculation using γ cross-section and attenuation in W-alloy (GEANT4)
  - 16 cm W allow (18.5 g/cm^3)
  - Attenuation of 10^{-12}
  - Dose @contact: 145 μ Sv/h
  - Dose @1m: 4.5 μ Sv/h (Regulation limit 2 mSv/h @1m)
- Cross check by radioprotection authority done (40% difference)



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

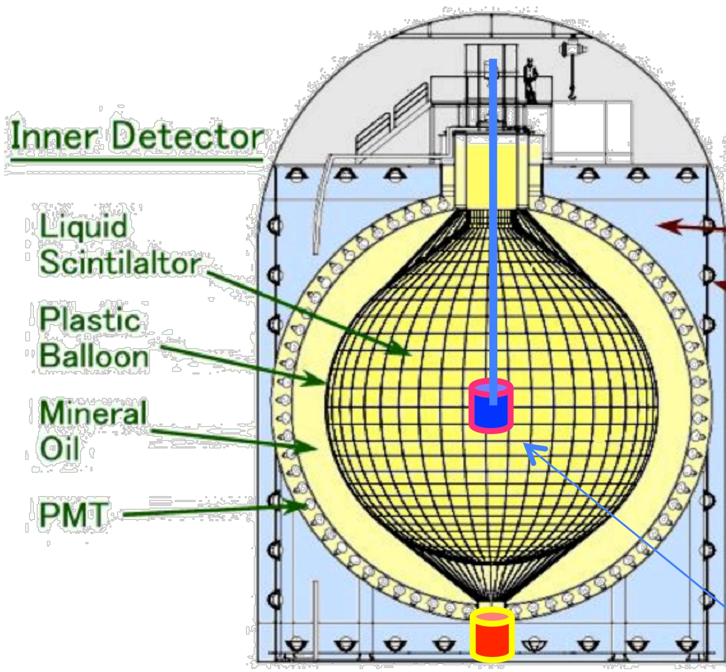
Final product

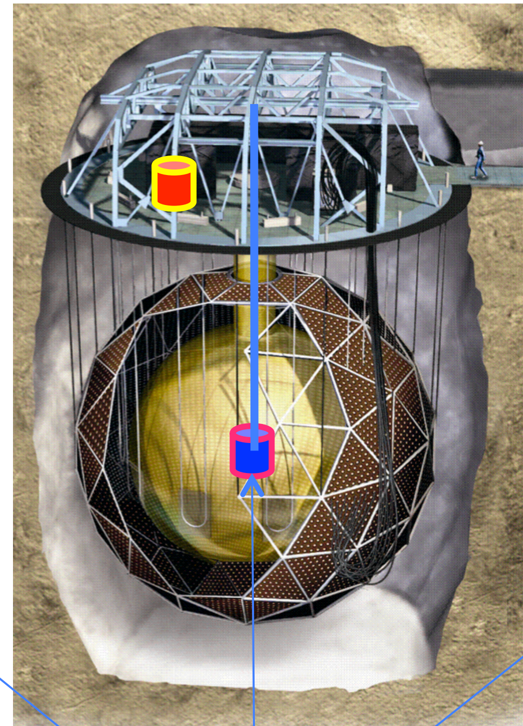
- ^{144}Ce 15g, 3 kg CeO_2
- Mainly a ß emitters → heat deposition localised only (99%) in the CeO_2 or in the 1st few mm of shielding.
- $\langle P_{50kCi} \rangle$ = 380 W → 150 W after 1 year (500 W from PMTs)

- **Activity Measurement**
  - Differential calorimetric measurement in hot cells @ Mayak.
    - Routinely 3 % accuracy (certified by Lloyd's…).
    - Enough for physicists, but effort to improve to <2%
  - Ge Spectroscopy Cross check
    - Sampling, huge dilution and counting (accuracy?)

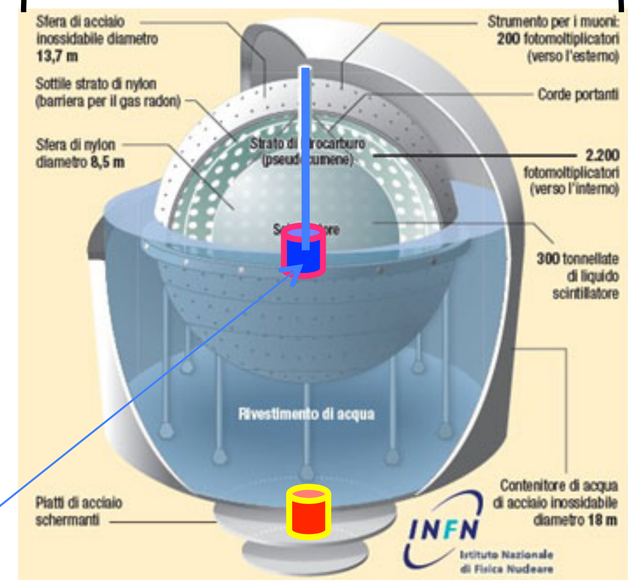
^{144}Ce-^{144}Pr Projects

3 Suitable Detectors for internal / external deployments





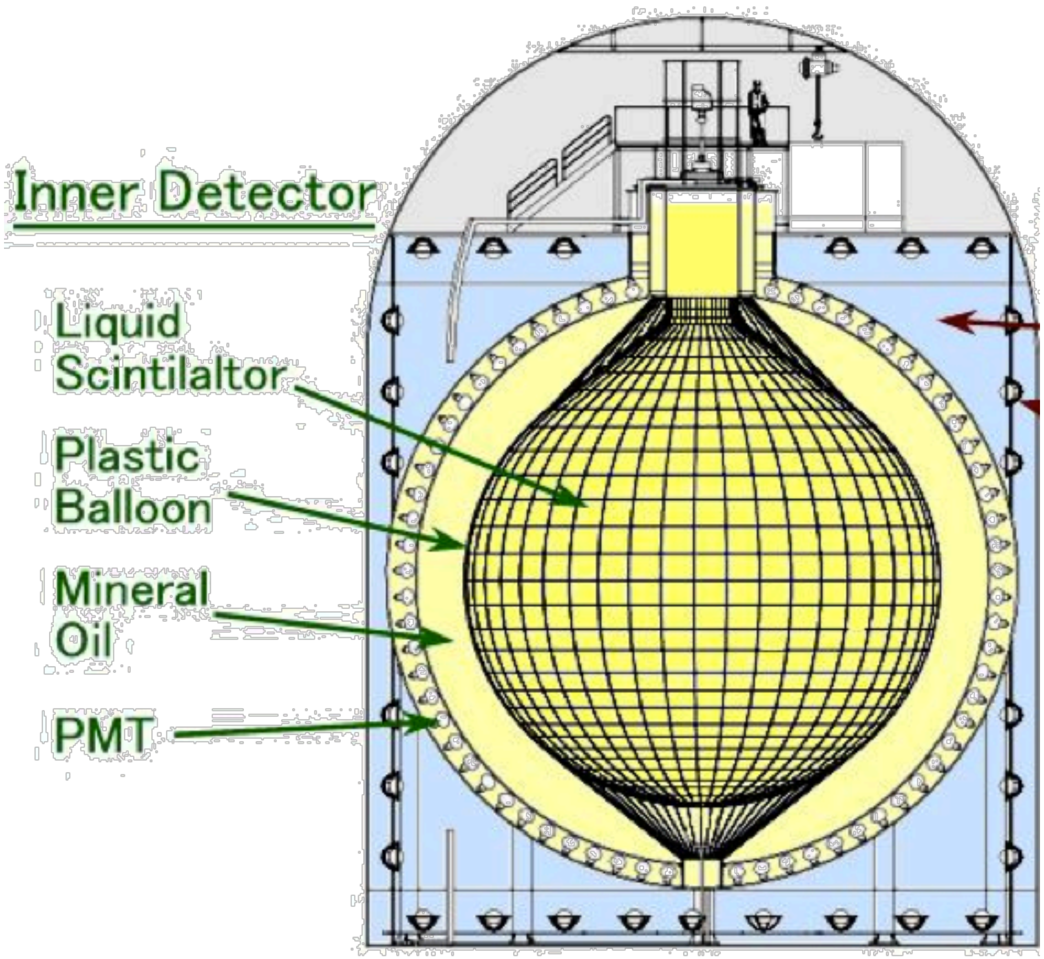
Comparable initiative
by Borexino Collaboration



a 50 kCi ^{144}Ce-^{144}Pr source

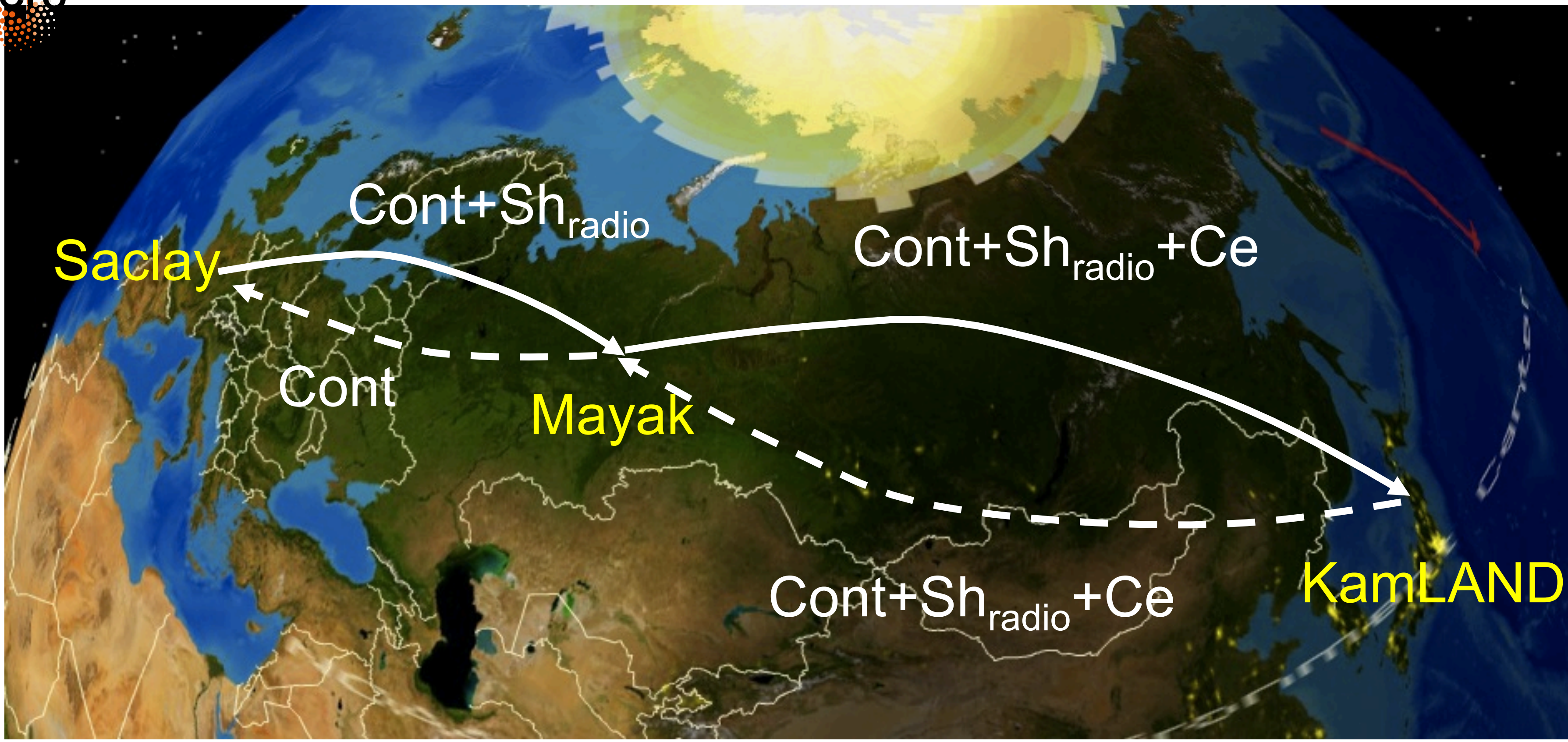
Another proposal : a 500 kCi ^{144}Ce-^{144}Pr source in Daya Bay
(D.A. Dwyer et al., http://arxiv.org/pdf/1109.6036)

KamLAND



- A great existing underground detector
- But several constraints
  - Full of an extra pure mineral oil
  - Avoid contaminations
- The entrance hole
  - 55 cm in diameter
  - Complex operations to insert the source
- Hanging suspension
  - A rather limited space above the detector
  - $\approx$ 15 m long
- Dismounting the source

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



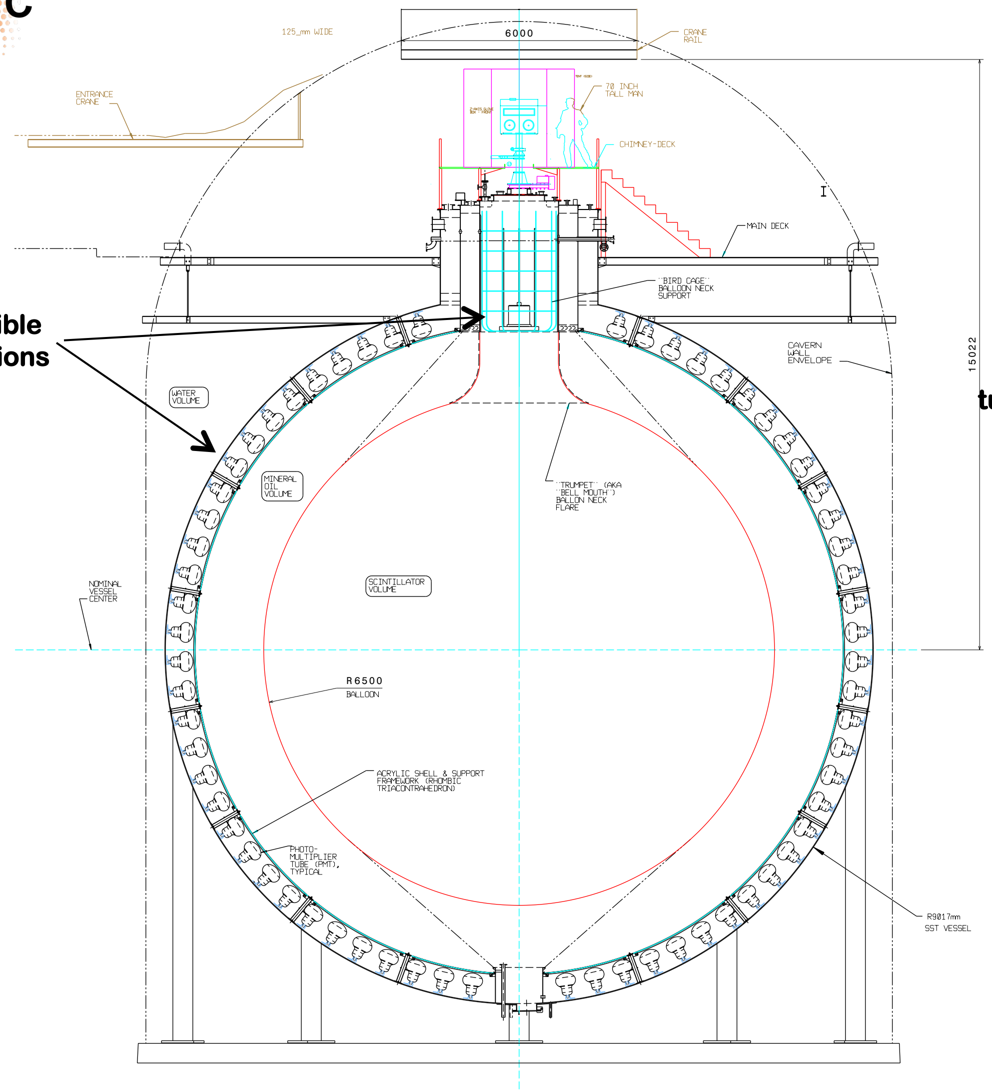
- **Ship radioprotection shield (Sh_{radio}) to PA Mayak**
- **Fit the ^{144}Ce source (Ce) inside first Sh_{radio} at Mayak**
- **Use certified container for further transportation (Conta)**

CeLAND Stage 1:

Internal Antineutrino ^{144}Ce-^{144}Pr Emitter

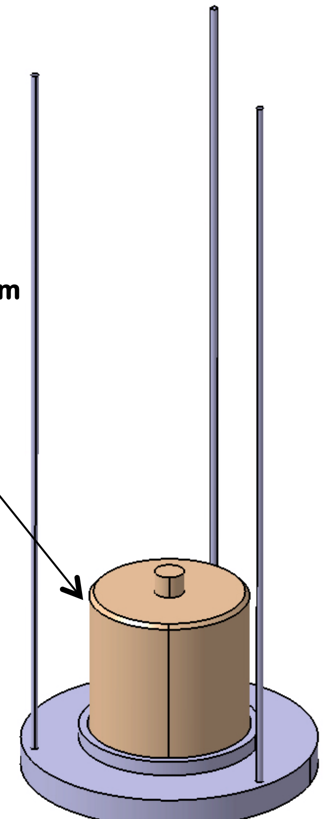
^{144}Ce Source @external + 35 cm W-alloy

Possible locations



Source @2.5-3.5 m from LS
75 kCi & 6 months of data taking

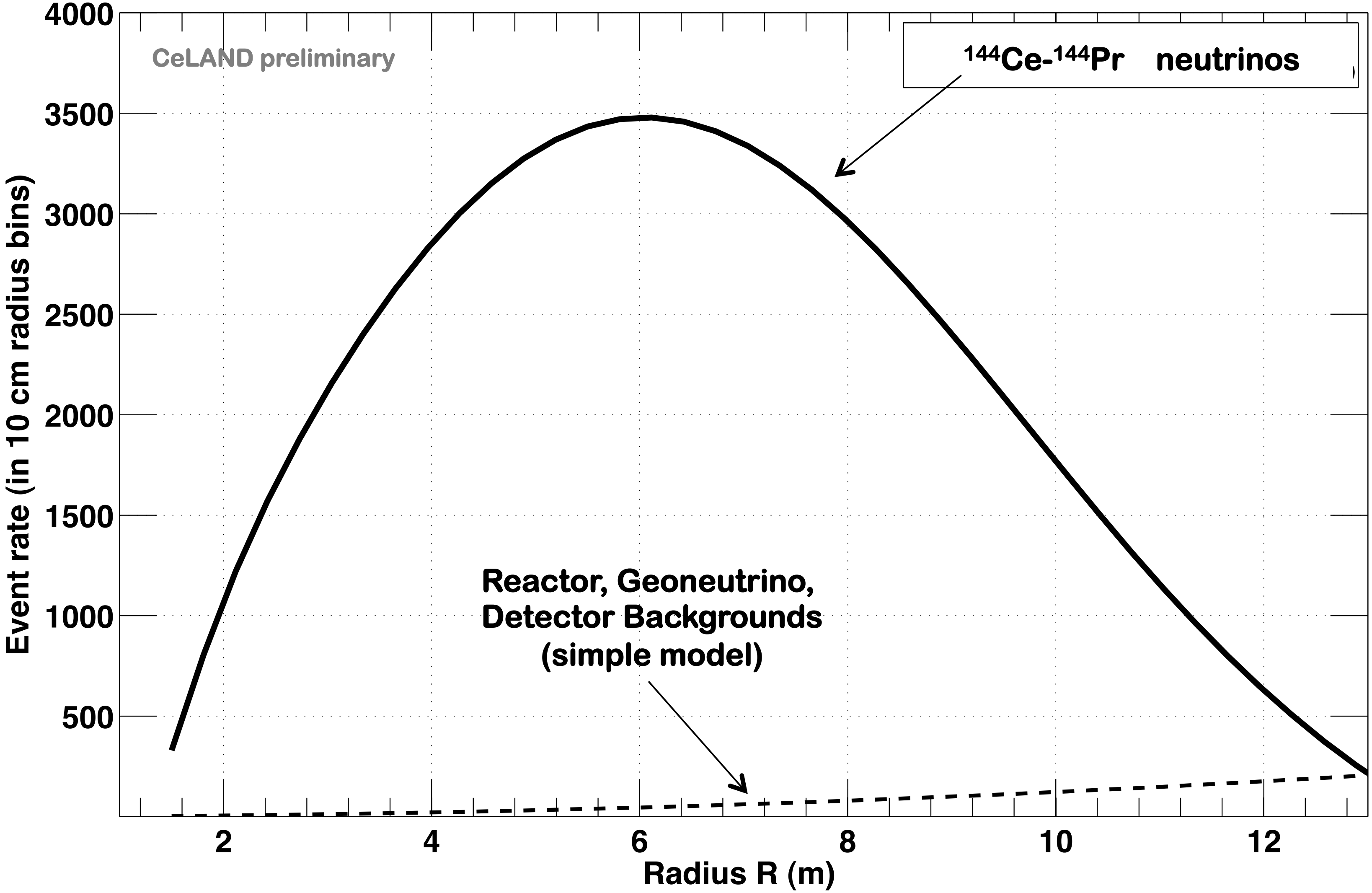
tungsten allow, 54 cm
d=18.5 g/cm^3



Bottom shield plateau
d=18.5 g/cm^3

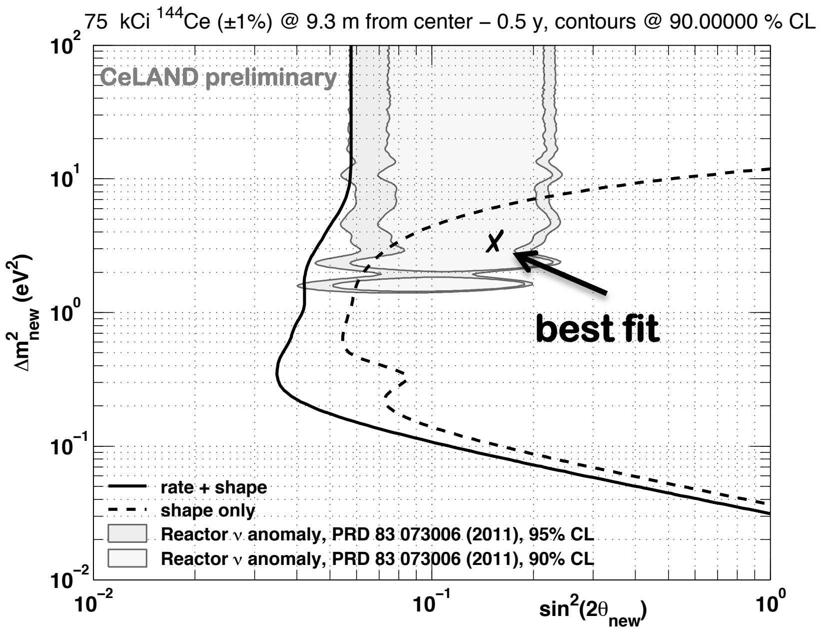
CeLAND-External Signal/background

75 kCi ^{144}Ce-^{144}Pr – 2 year of data (30 kevts)



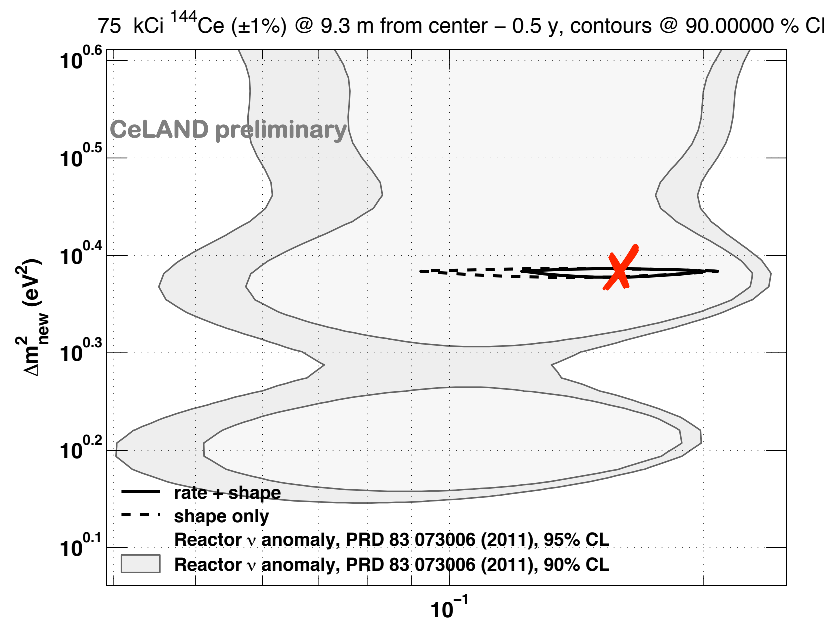
CeLAND-External Sensitivity

75 kCi ^{144}Ce-^{144}Pr – 0.5 year of data (9.3m from center 13 kevts)



90% C.L. exclusion

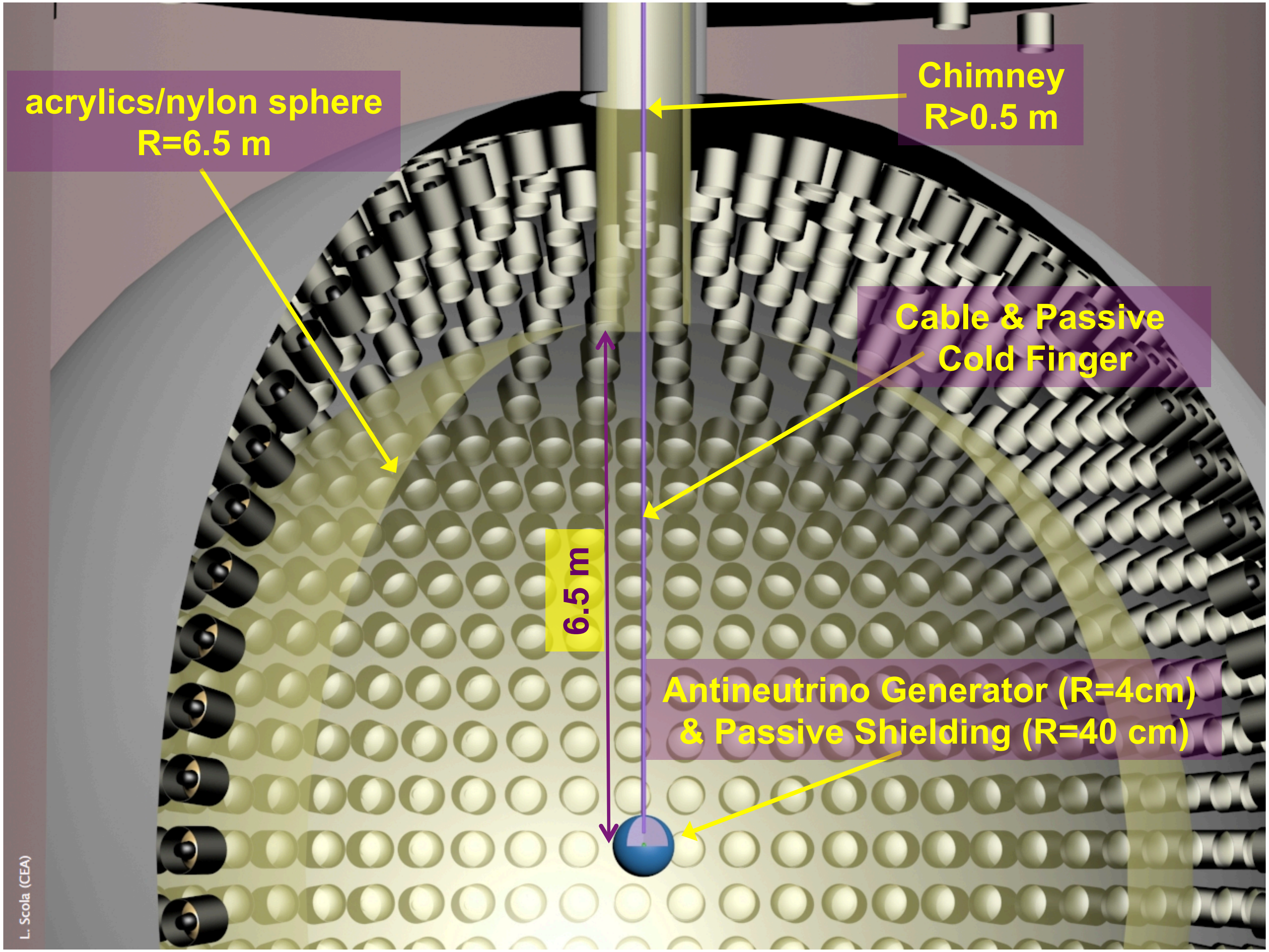
90% measurement



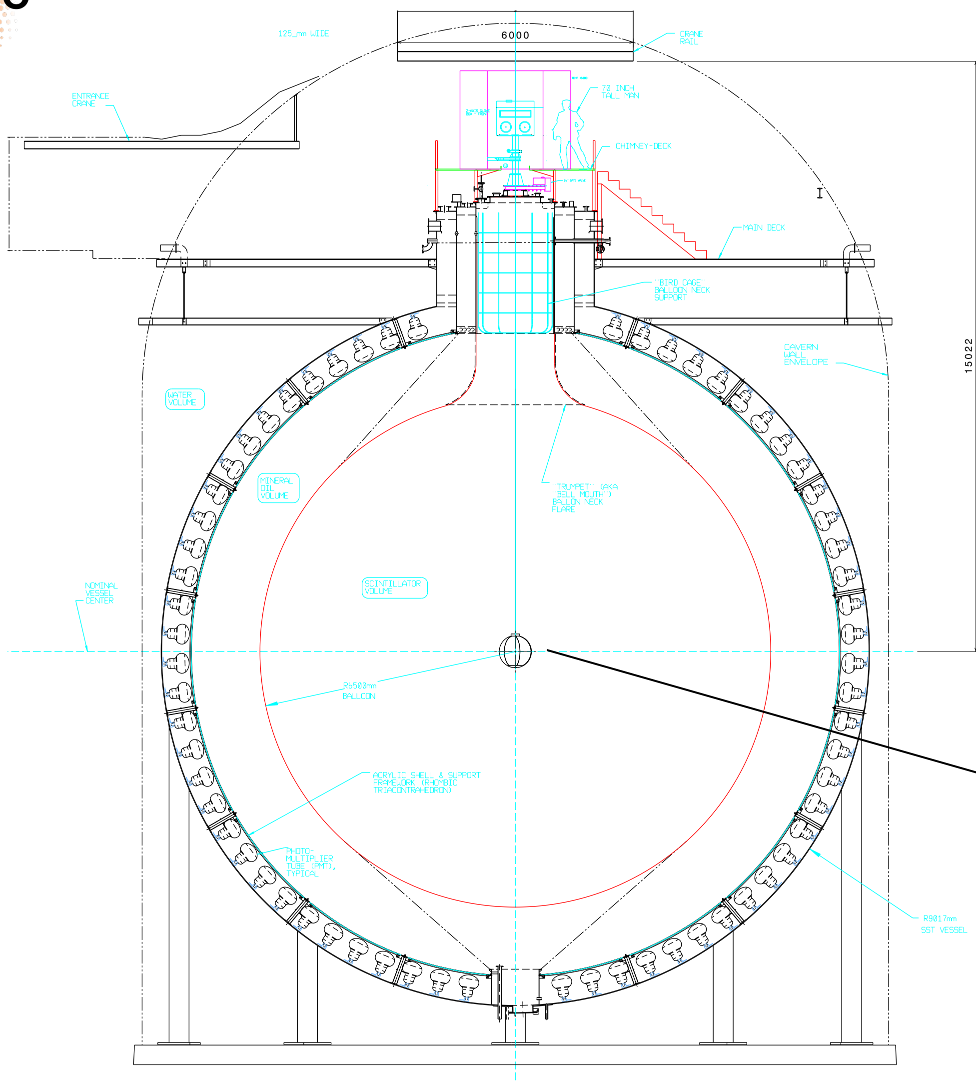
CeLAND Stage 2:

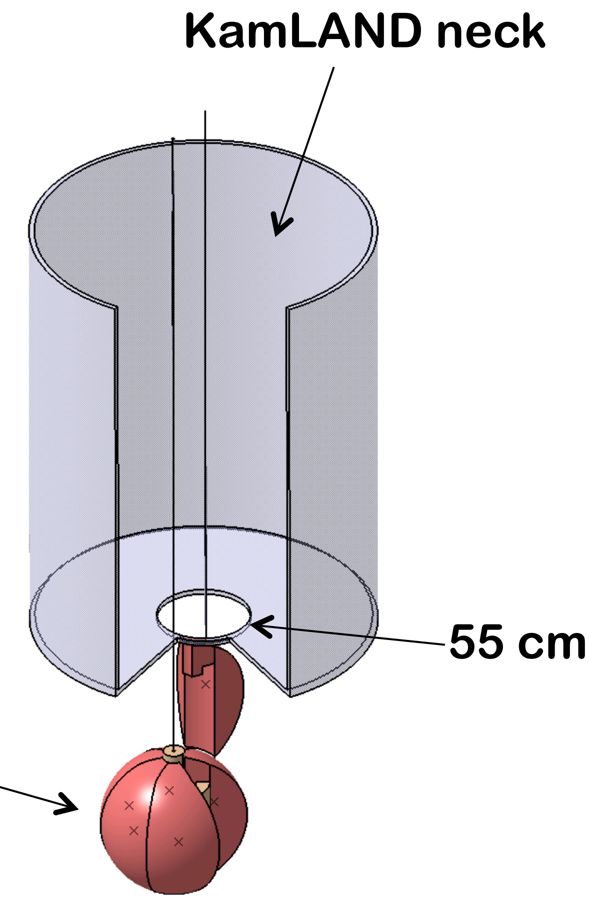
Internal Antineutrino ^{144}Ce-^{144}Pr Emitter

The Concept


acrylics/nylon sphere
R=6.5 m
Chimney
R>0.5 m
Cable & Passive
Cold Finger
6.5 m
Antineutrino Generator (R=4cm)
& Passive Shielding (R=40 cm)
L. Scola (CEA)

^{144}Ce @center + 35 cm tungsten alloy





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

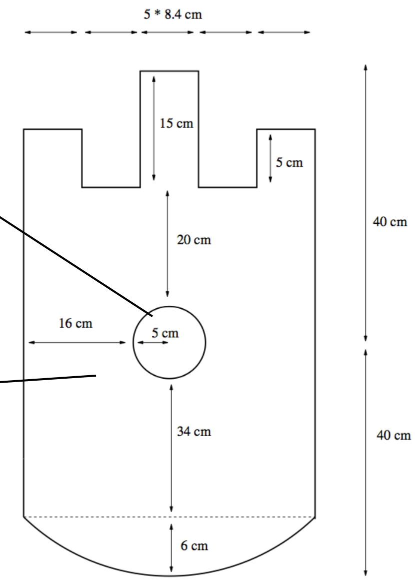
γ-attenuation (2 MeV) : 10^{-12}

Shielding For Gamma Ray Attenuation

- GEANT4 preliminary simulation (50 kCi Ce source + W-shielding)

(courtesy D. Franco)

Name	Radius	Material	Density
Source	R < 4 cm	CeO_2 ^{144}Ce: 0.010% ^{142}Ce: 49.995% ^{140}Ce: 49.995%	7.65 g/cm³
Densimet	4 cm < R < 37 cm	W: 98.50% Fe: 0.75% Ni: 0.75%	18.8 g/cm³ (λ_D = 1.24 cm for 2.185 MeV γ)
Copper	37 cm < R < 39 cm	Cu	8.94 g/cm³
Scintillator	39 cm < R < 300 cm	C_9H_{12}	0.882 g/cm³



- γ suppression factor S for one ^{144}Pr beta decay:
  33 cm Densimet : S_D=2.10^{-13} & 2 cm Copper : S_C=0.66

- Single rate in LS (E>900 keV): 160 Hz, 3 Hz after 1 m
- Acc. rate (1m LS): R_{promt}=3 Hz, $R_{delayed}$=0.6 Hz, $R_{accident}$=1 mHz
  - S/B≈1 @1m from the shield
  - +3 cm W-alloy → B/10

W-Shielding Intrinsic Background

- Background induced by intrinsic contamination in Densimet (Plansee Company W-alloy, d=18.5 g/cm^3)

- Contamination is measured by the GERDA collaboration:
  - ^{238}U: 180±20 mBq/kg ^{232}Th: 70±20 mBq/kg
  - ^{60}Co: 7±2 mBq/kg ^{40}K: <57mBq/kg

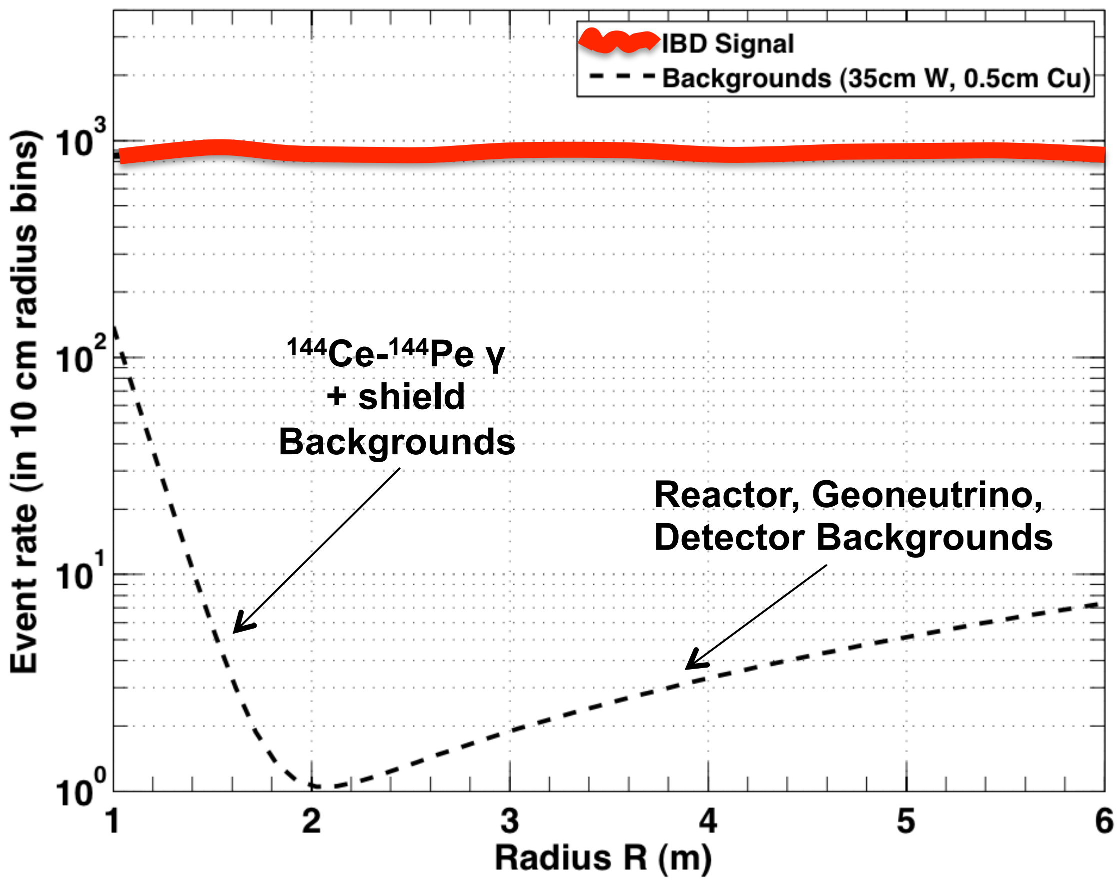
- GEANT4 simulation: Isotopes generated uniformly in the W-volume

(D. Franco)

Isotope	Rate [Hz]	Rate E > 900 keV [Hz]	Rate E > 900 Hz R > 139 cm [Hz]
^{238}U	12.6 ± 2.1	5.3 ± 0.9	(7.4 ± 1.2)x10^{-2}
^{232}Th	6.2 ± 1.8	2.6 ± 0.7	(6.0 ± 1.7)x10^{-2}
^{60}Co	0.8 ± 0.2	0.4 ± 0.1	(3.3 ± 0.9)x10^{-3}
^{40}K	< 0.44	< 0.23	< 2.5x10^{-3}
^{137}Cs	< 0.01	0	0
Total	**19.6 ± 2.8**	**8.3 ± 1.2**	**(13.7 ± 2.1)x10^{-2}**

>1 order magnitude less than the ^{144}Pr induced background
But a real concern for material selection

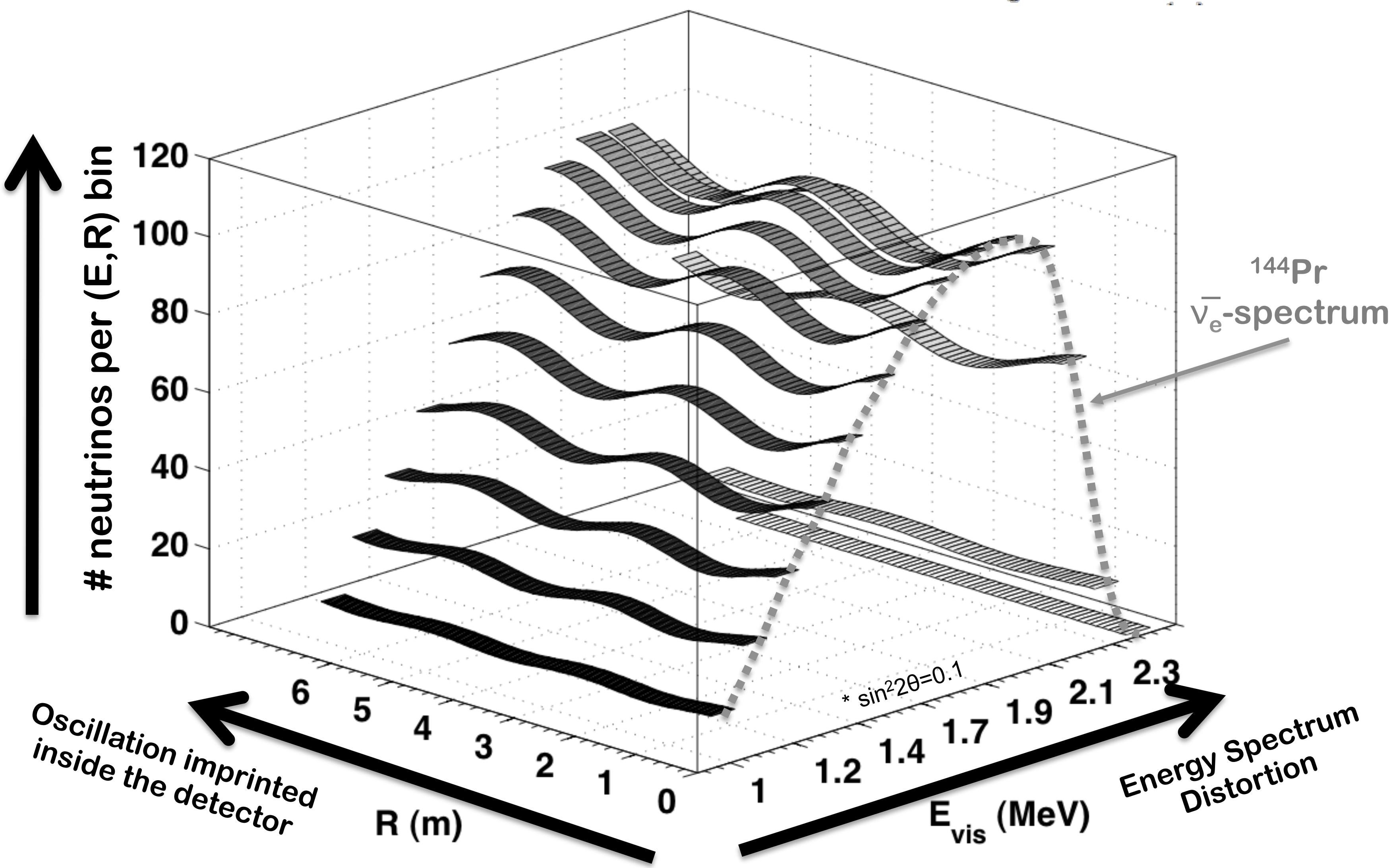
CeLAND Signal & Background



- Signal: 50 kCi ^{144}Ce-^{144}Pr
  - 40000/8 months
  - about 1 mHz
- Backgrounds:
  - Detector backgrounds negligible
  - Gammas from the source can be attenuated with enough high-Z shield material
  - Shielding material should be radiopure
    - 10-100 mBq/kg

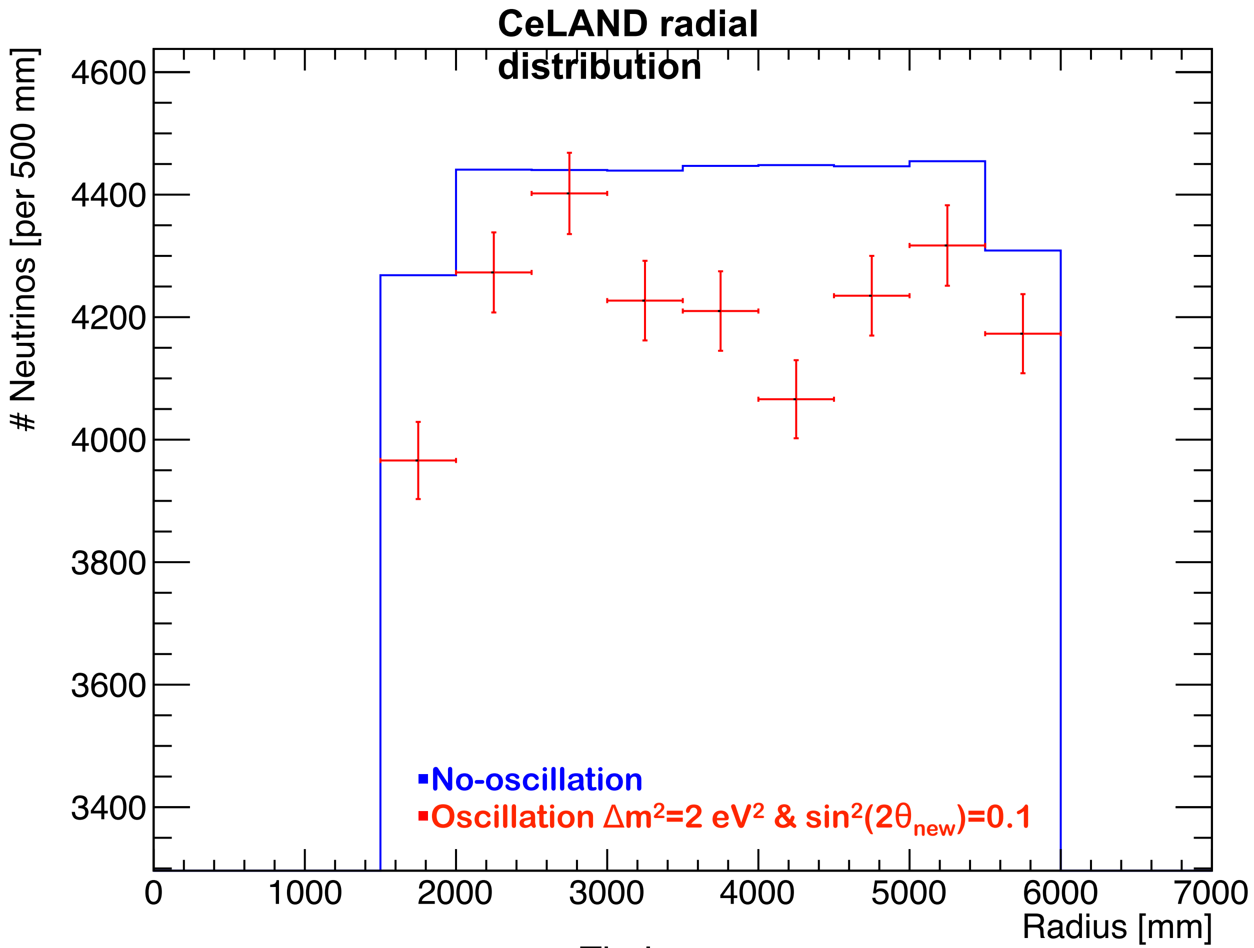
CeLAND Expected Signal (Oscillation)

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



CeLAND R-oscillating Pattern

- **Geant4 simulation of a CeLAND realization:**
  - **50 kCi ^{144}Ce-^{144}Pr source running for 8 months in KamLAND**
  - **No-oscillation: 40000 events**
  - **Oscillation Δm^2=2 eV^2 & $\sin^2(2\theta_{new})$=0.1: 38000 events**



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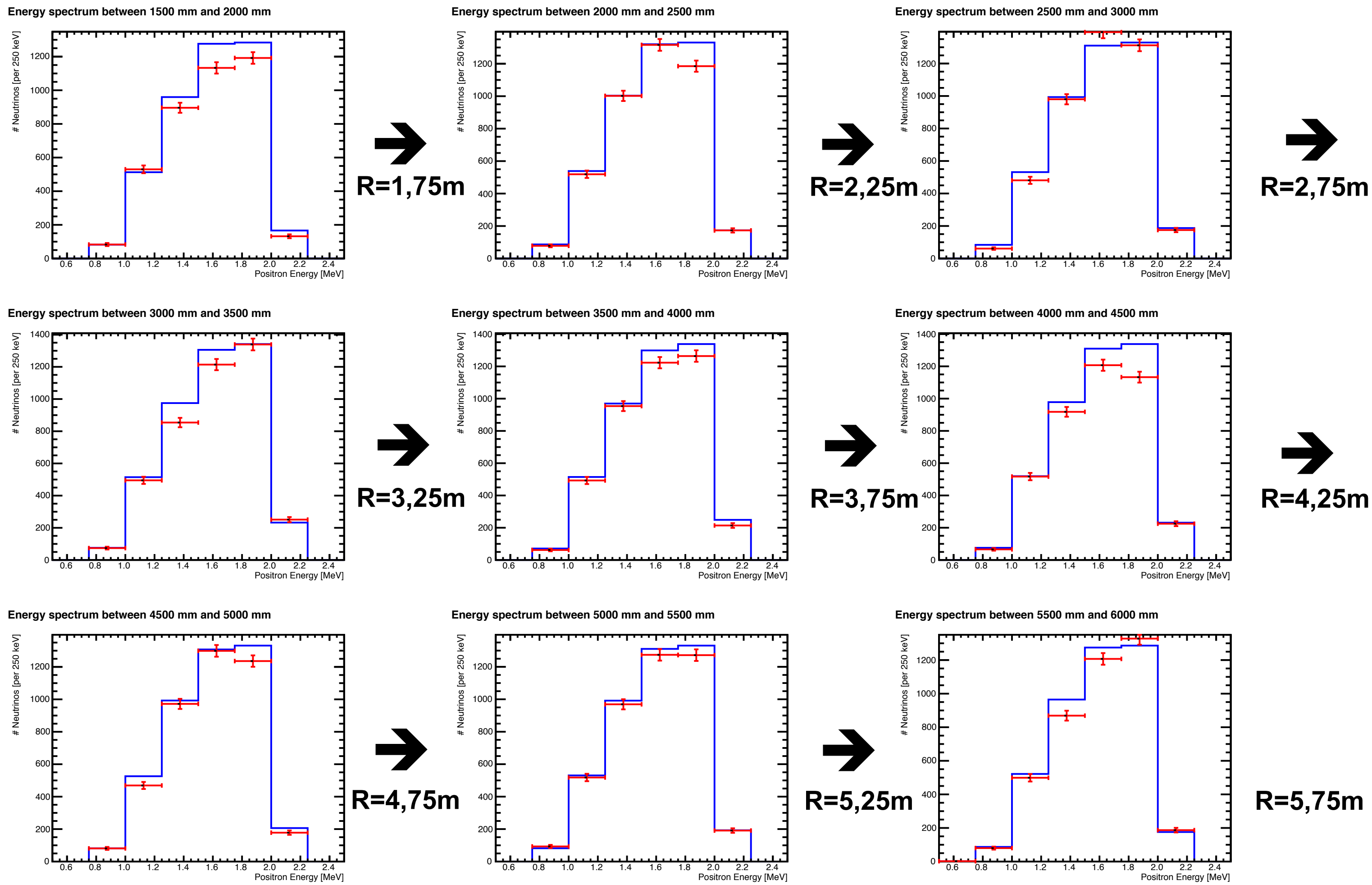
CeLAND E-oscillating Pattern

- **Geant4 simulation of a CeLAND realization:**
  - **50 kCi ^{144}Ce-^{144}Pr source running for 8 months in KamLAND**
  - **No-oscillation: 40000 events**
  - **Oscillation $\Delta m^2=2\ eV^2$ & $\sin^2(2\theta_{new})=0.1$: 38000 events**



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Expected Sensitivity

- **Inputs:**
  - 50 kCi ^{144}Ce-^{144}Pr source running for 1 yr
    (decrease in the source activity over 1 year : 66%)
  - 35 cm W-alloy
  - Using events between 1.5 and 6 m → background free

- **Detector Parameters:**
  - 15 cm vertex resolution & 5% energy resolution

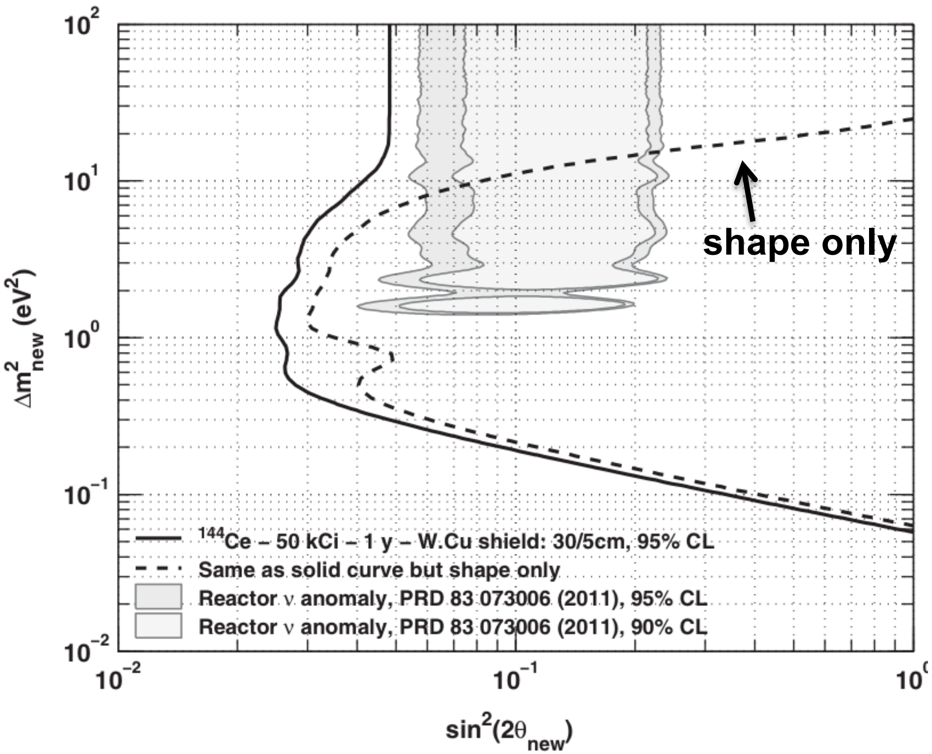
- **χ^2 analysis using R (i) & E (j) information:**

$$\chi^2 = \sum_i \sum_j \frac{[N_{\text{obs}}^{i,j} - (1+\alpha)N_{\text{exp}}^{i,j}]^2}{N_{\text{exp}}^{i,j}(1+\sigma_b^2 N_{\text{exp}}^{i,j})} + \left(\frac{\alpha}{\sigma_N}\right)^2$$

  - σ_N : Normalization error of 1% for the source activity uncertainty
  - σ_b : Fully uncorrelated systematic error of 2% for:
    - fiducial volume uncertainty (1%) in a calibrated detector
    - analysis detection efficiencies uncertainties (sub-%)

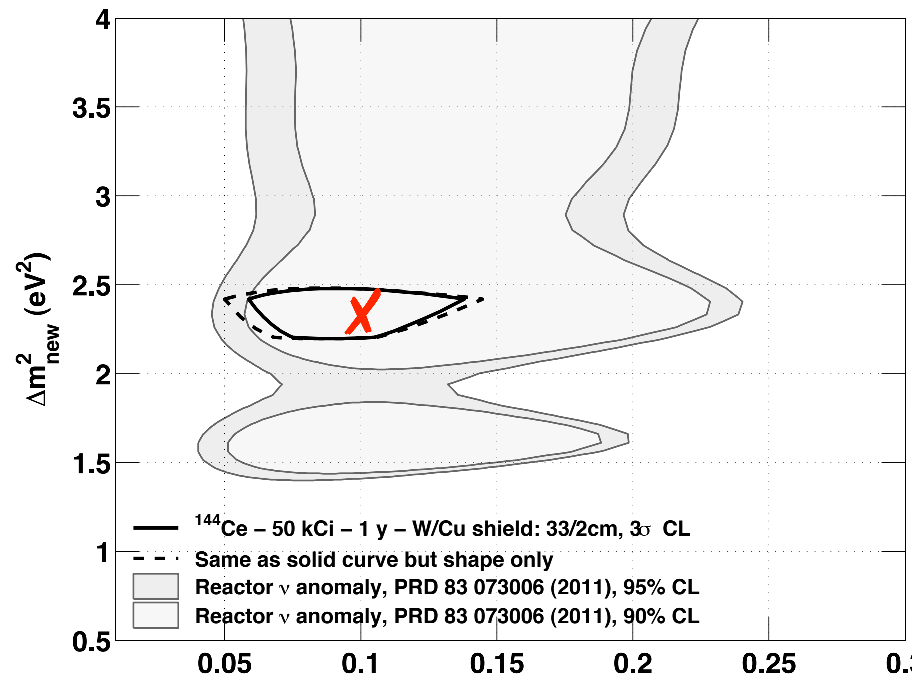
CeLAND-Inside Sensitivity

50 kCi ^{144}Ce-^{144}Pr – 1 year of data (55 kevts)

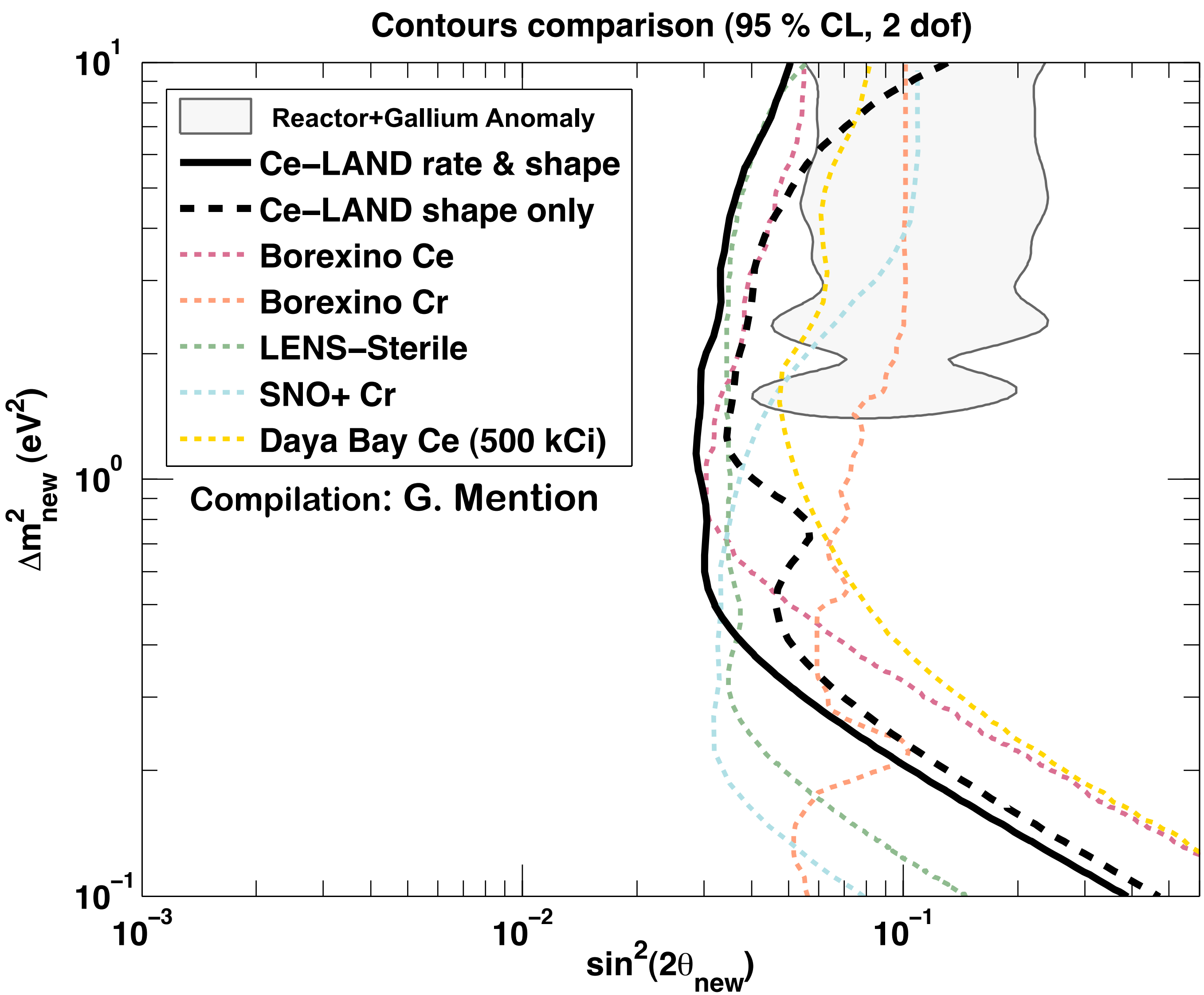


95% C.L. exclusion

3 σ measurement contours



Comparison of proposal sensitivities



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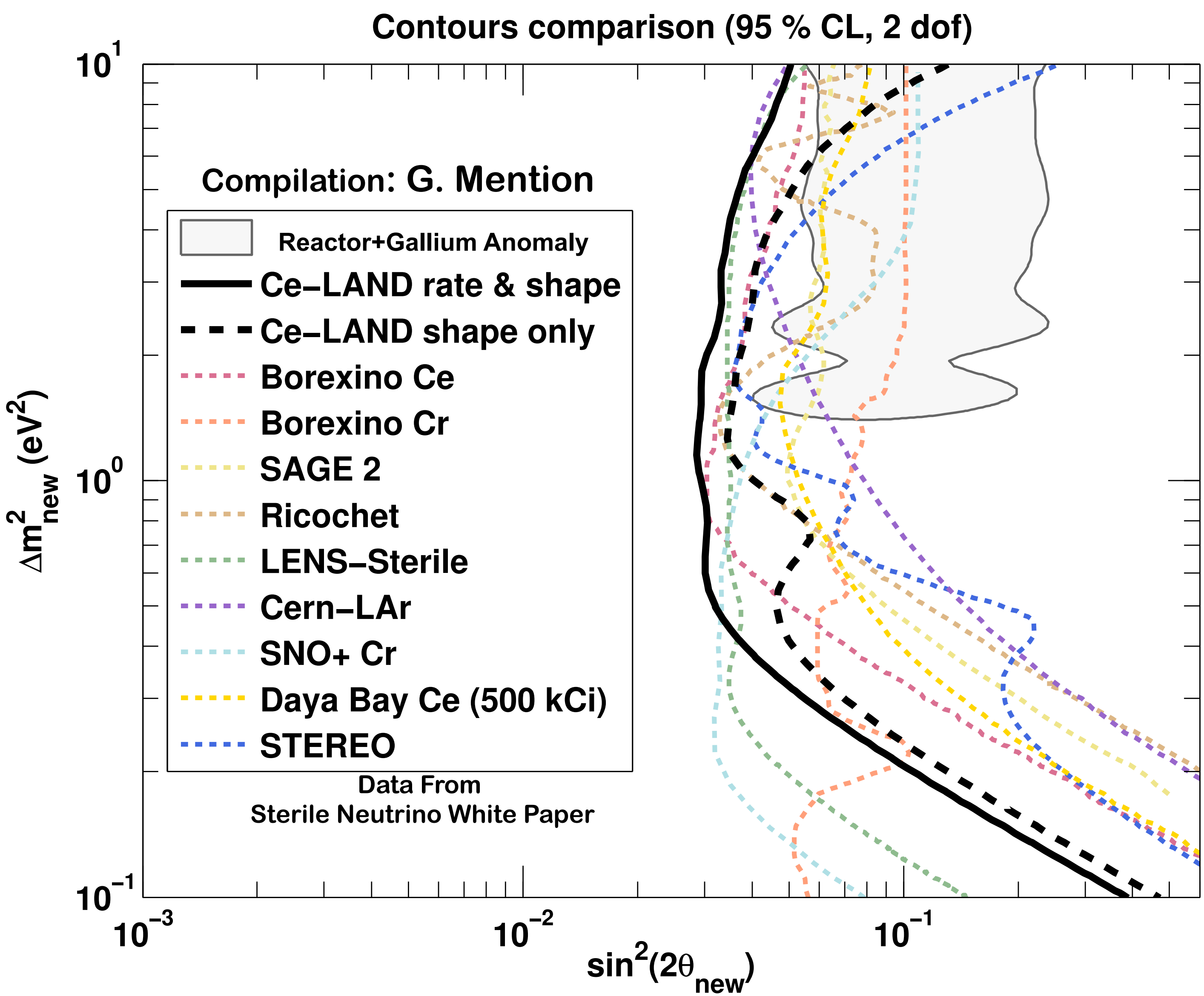
Comparison of proposal sensitivities



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Conclusion & Outlook

- **Test of Reactor & Gallium Anomalies calls for Energy and baseline-dependent signatures for an unambiguous resolution**

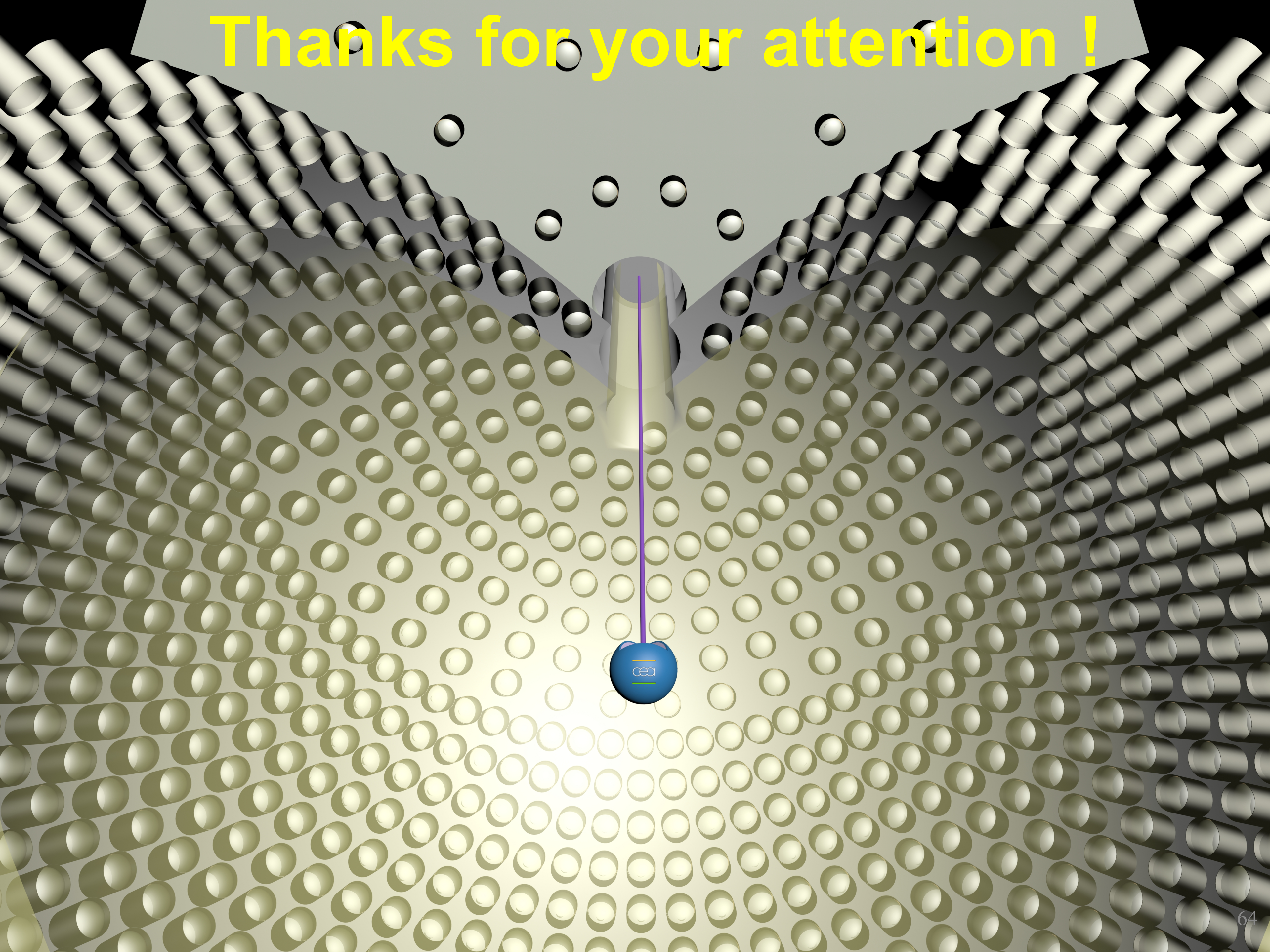
- **Physics case: Sterile Neutrino White Paper arXiv:1204.5379**
  - Thanks to VT effort (editors, Patrick & John)

- **CeLAND: an appealing approach testing RAA+GAA**
  - **^{144}Ce-^{144}Pr, 50 kCi, in/next to KamLAND**

- **50 kCi scale ^{144}Ce + High-Z shielding feasible (&funded)**
  - **CEA-Saclay / PA Mayak Collaboration**
  - **Time scale : 1 y development & 1 year production (2014?)**

- **KamLAND is a suitable detector**
  - **Joint CEA-KamLAND effort towards realization ongoing**

Thanks for your attention !



The Daya Bay Proposal

- **D. Dwyer et al. Arxiv:1109.6036**
- **Proposal based on M. Cribier et al., Arxiv:1107.2335**
- **500 kCi ^{144}Ce-^{144}Pr source in the Daya Bay FD Pool**