Reactor anomaly
&
Sterile Neutrino Searches with Very Short Baselines

DE LA RECHERCHE À L'INDUSTRIE
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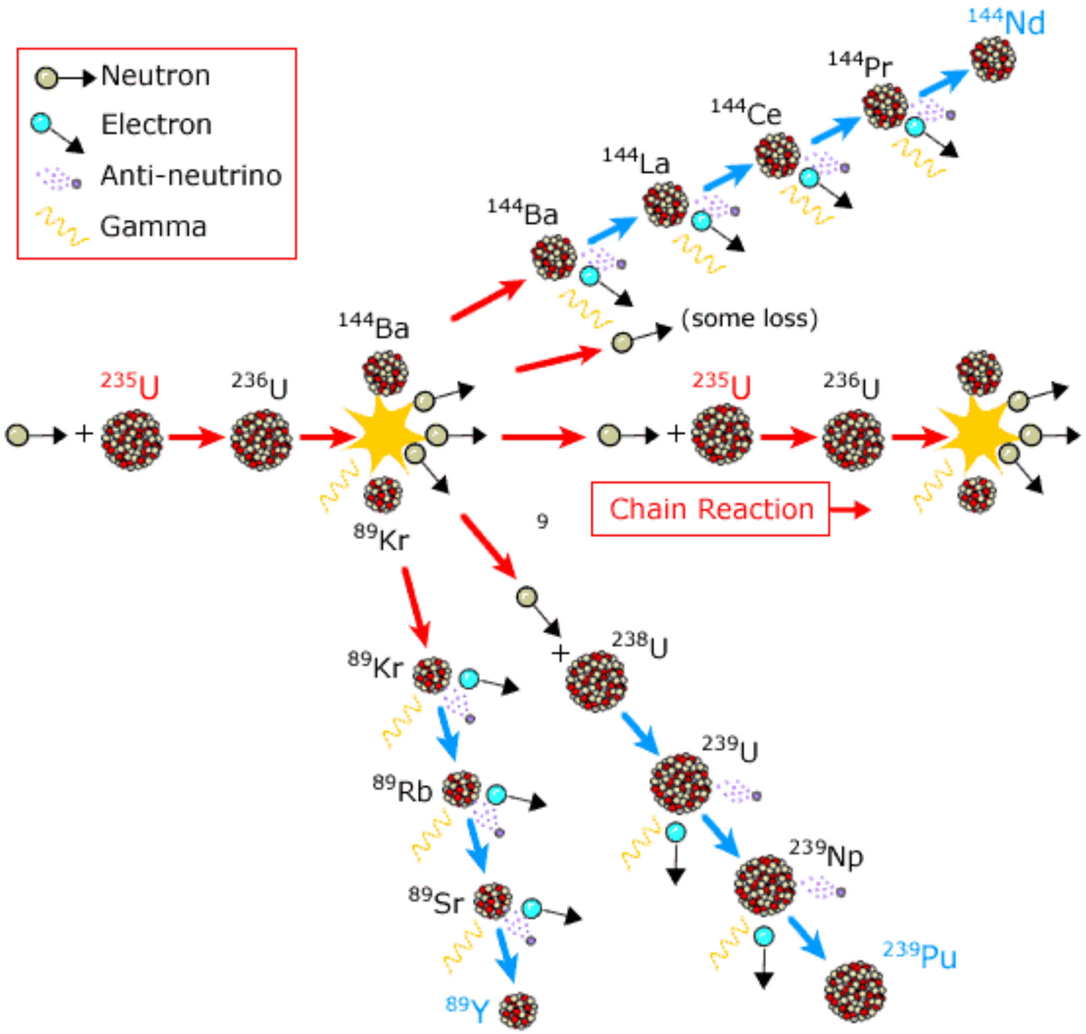
Outline

- Reactor neutrinos
- The 4th ν hypothesis:
  - Status of the reactor anomaly
  - General context of neutrino anomalies

- Testing new $\overline{\nu}_e$ disappearance at short distance from compact sources:
  - Reactor experiments
  - Source experiments

Reactor Antineutrinos



- Reactor are intense and pure sources of electron antineutrinos from β^- decay of fission products

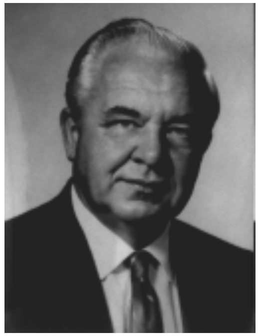
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e $$

- [0;8] MeV energy range
- $2.10^{20}\ \nu_e$ /s/GW$_{th}$
- Compensate for tiny interaction probability

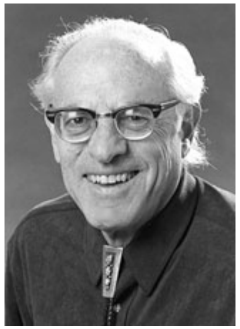
History

- 1^{st} neutrino detection - 1956

Cowan



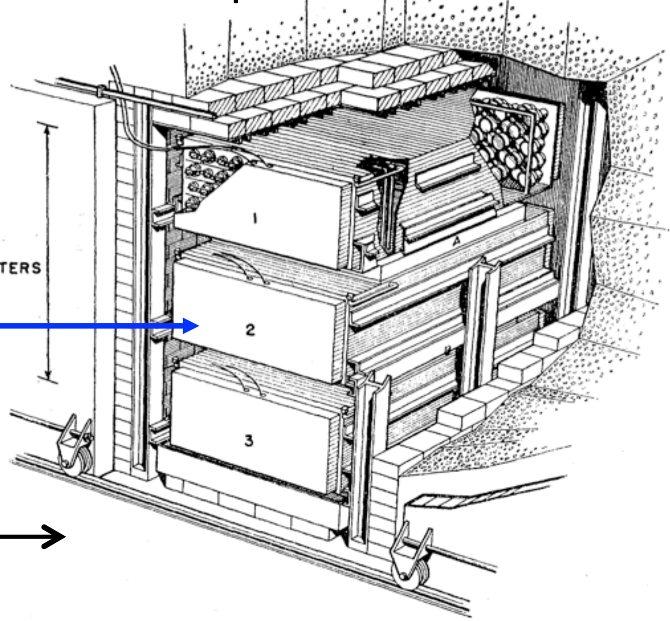
Reines



Nobel 1995

3 GWth reactor
Savannah River

1 m^3 liquid scintillator



ν

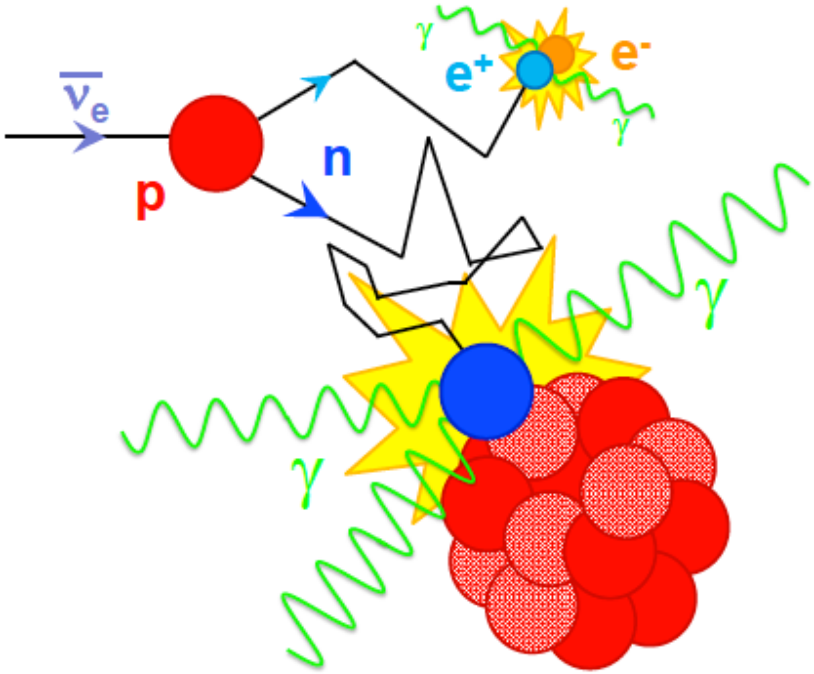
25 m

~3 ν/h

Golden Detection Process

Inverse Beta Decay

$$\overline{\nu_e} + p \rightarrow e^+ + n$$



Selective signal sequence:

e^+ prompt signal

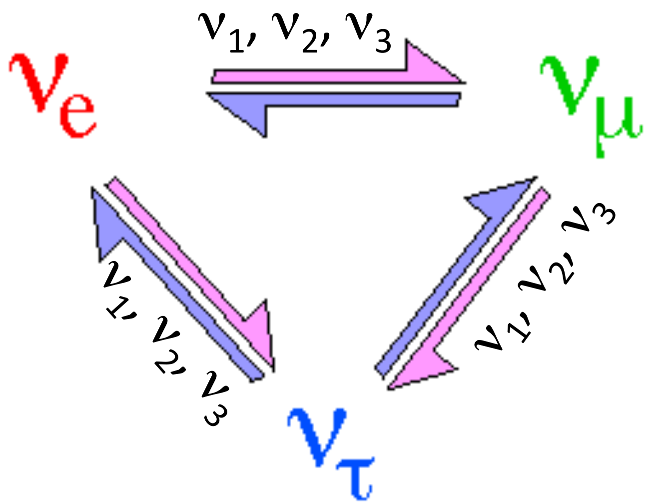
\+

n-capture few 10 μs later

Backgrounds

- Accidental: [γ-n_{th}] coinc
- Correlated: fast n
- Not sensitive to solar ν_e.

Neutrino Oscillations



Mixing:
$\theta_{12}, \theta_{23}, \theta_{13}$

Propagation:
$\Delta m^2_{21}, \Delta m^2_{31}$

L_{osc}=80 km L_{osc}= 2 km

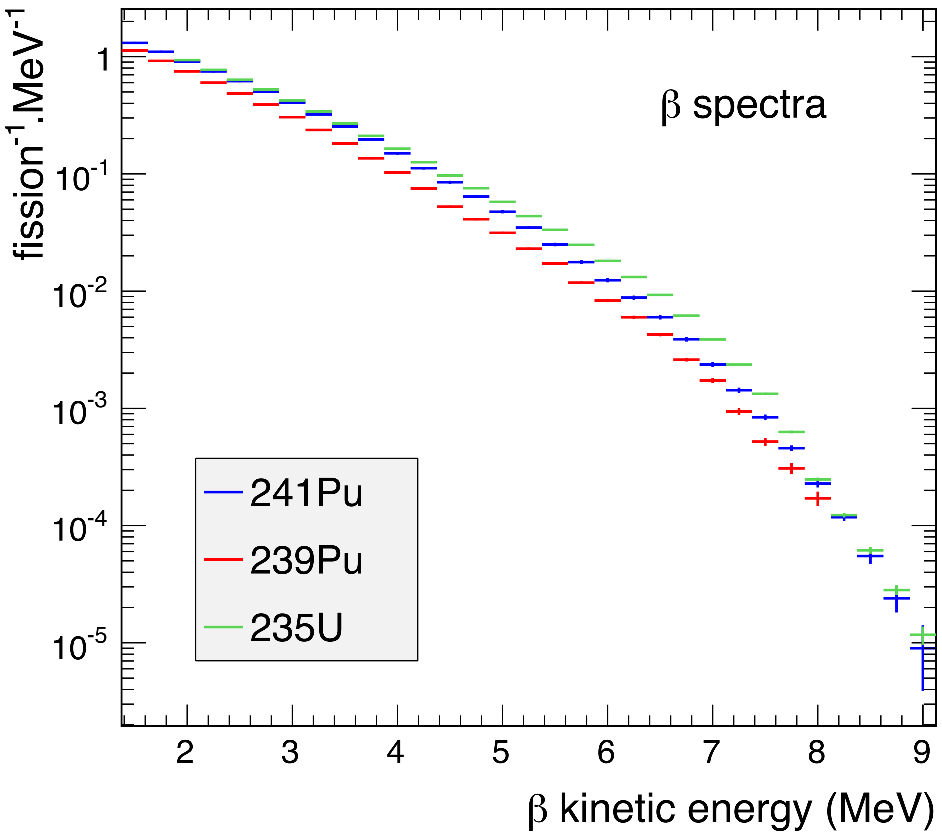
B. Pontecorvo

If reactor neutrinos oscillate, one should observe a periodic disappearance of the detected ν_e rate with a L/E dependence :

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{ij}) \sin^2(\Delta m^2_{ij} L/4E)$$

Prediction of Reactor ν Spectra

Reference fission β spectra of 3 isotopes measured at the ILL reactor

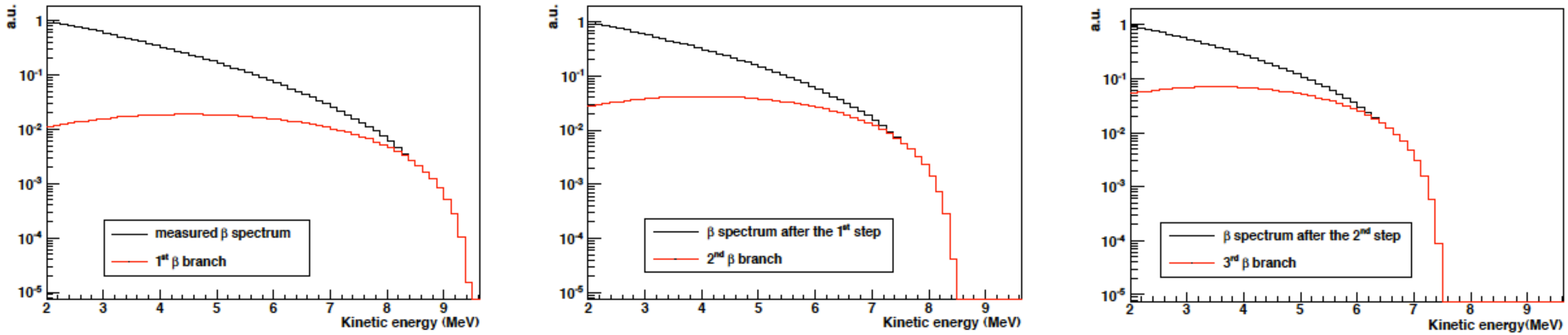


K. Schreckenbach et al., Phys. Lett. 99B, 251 (1981)

- Accurate reference of total fission β-spectra
- Key input for searches of oscillations at reactors

Conversion of reference e^- spectra

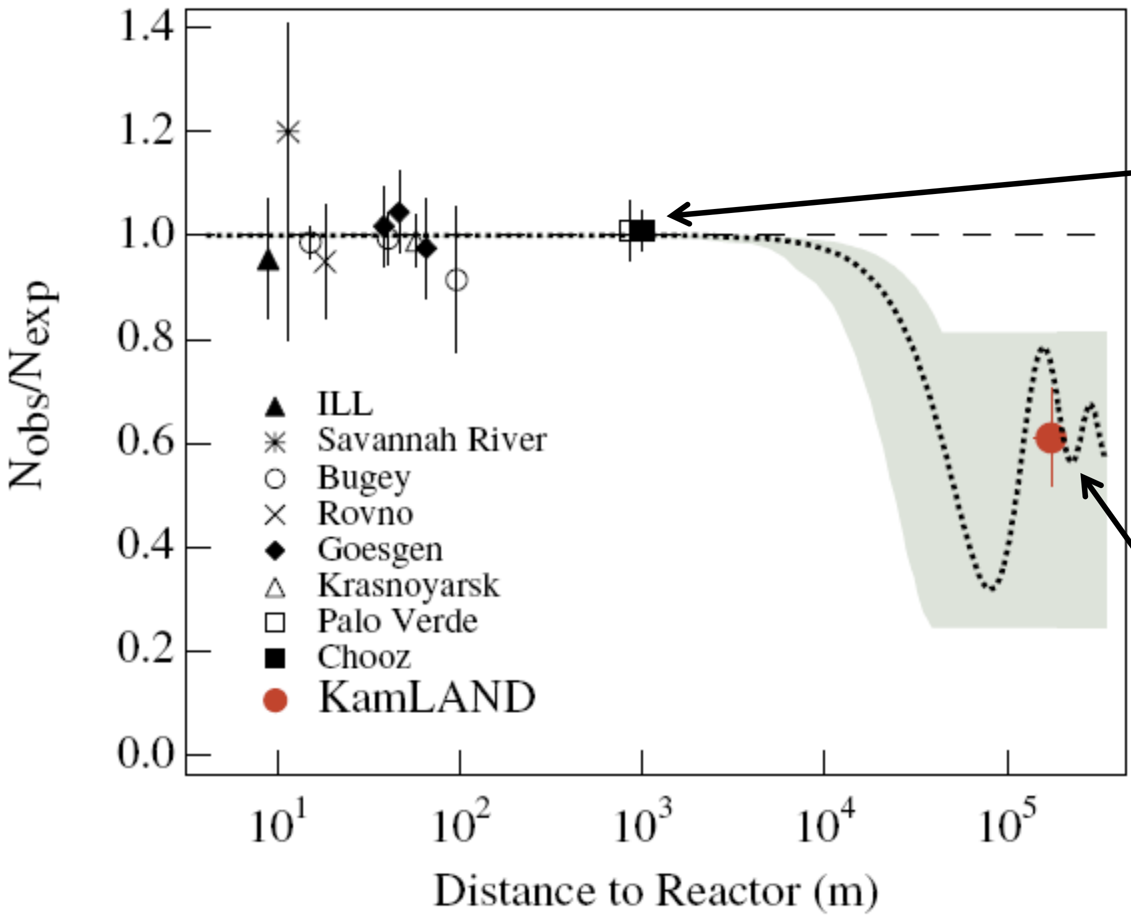
1- Fit total e^- spectrum with a sum of 30 effective β branches determined by iterative method (instead of ~10,000 real branches)
2- Convert each effective e^- branches to ν branches
3- Sum all converted ν branches to get total ν spectrum



→ **Reference neutrino spectra to be coupled to a reactor simulation. Dramatic improvement with respect to *ab-initio* calculation, limited by the knowledge of nuclear data.**

Reactor Neutrino Oscillations

Experimental status in early 2000's



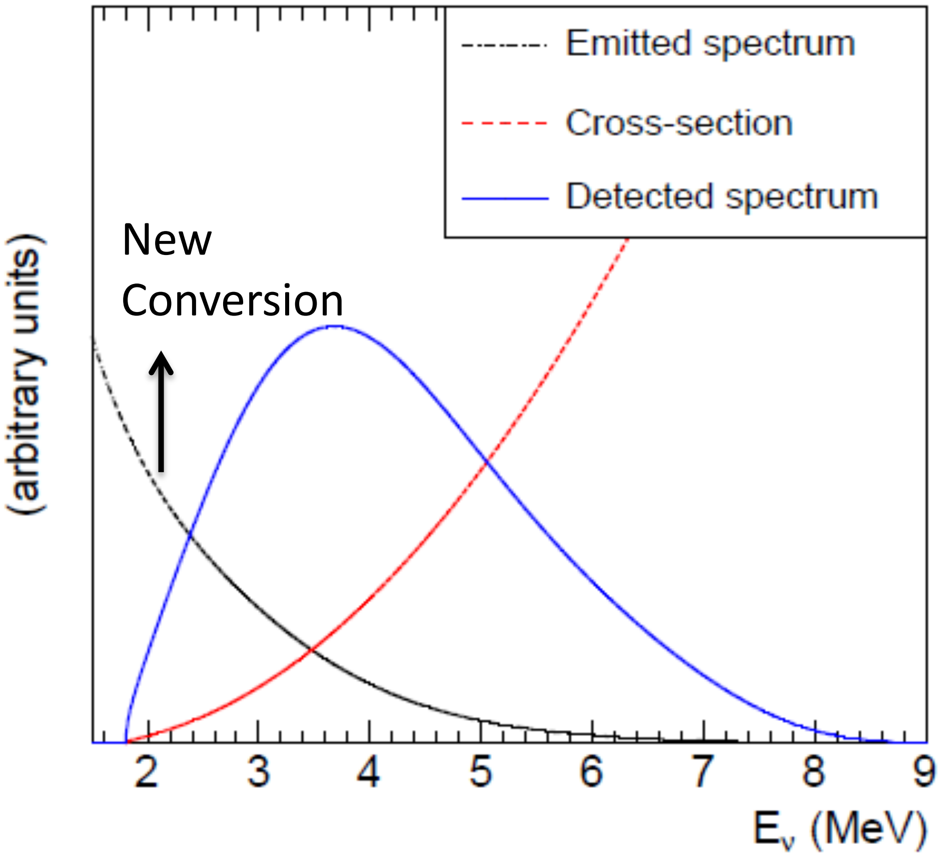
Expected oscillation from θ_{13} angle. Is $\theta_{13} \neq 0$?

Large θ_{12} confirmed by KamLAND exp. 180 km away from Japanese reactors

The Reactor Anomaly

Re-evaluation of Reactor ν Spectra

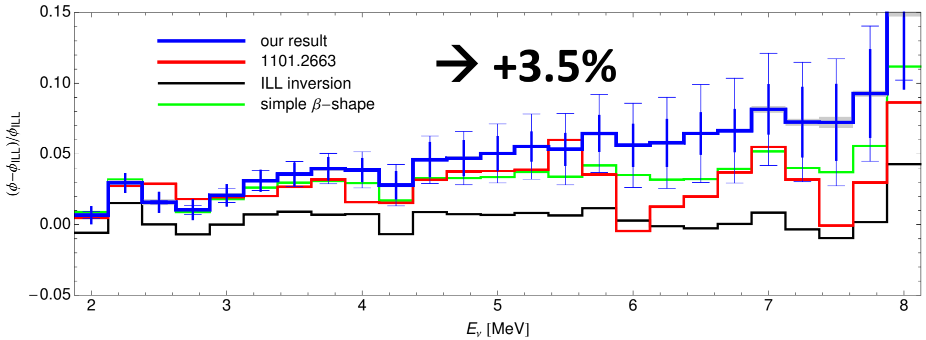
Work triggered at CEA-Irfu by the need of accurate predictions for the Double Chooz experiment

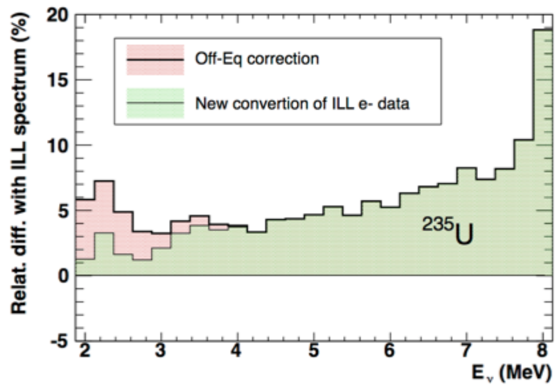


Improved conversion of ILL beta spectra

Th. Mueller et al, Phys. Rev. C83,054615 (2011)

P. Huber, Phys. Rev. C84, 024617(2011)

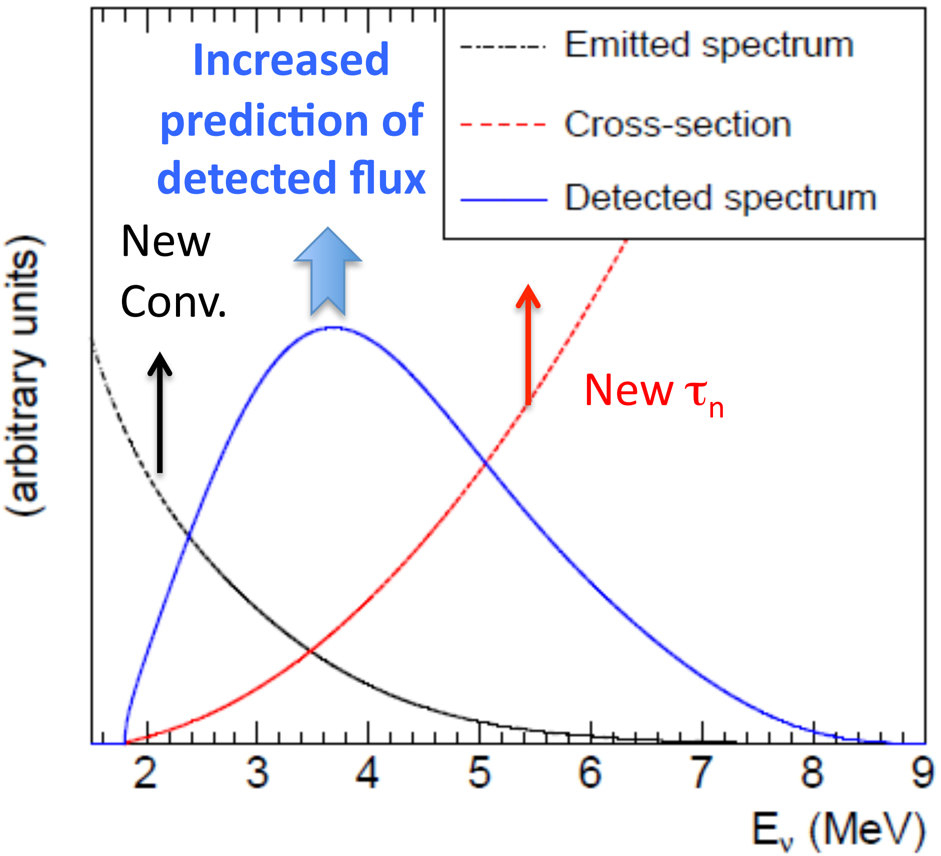




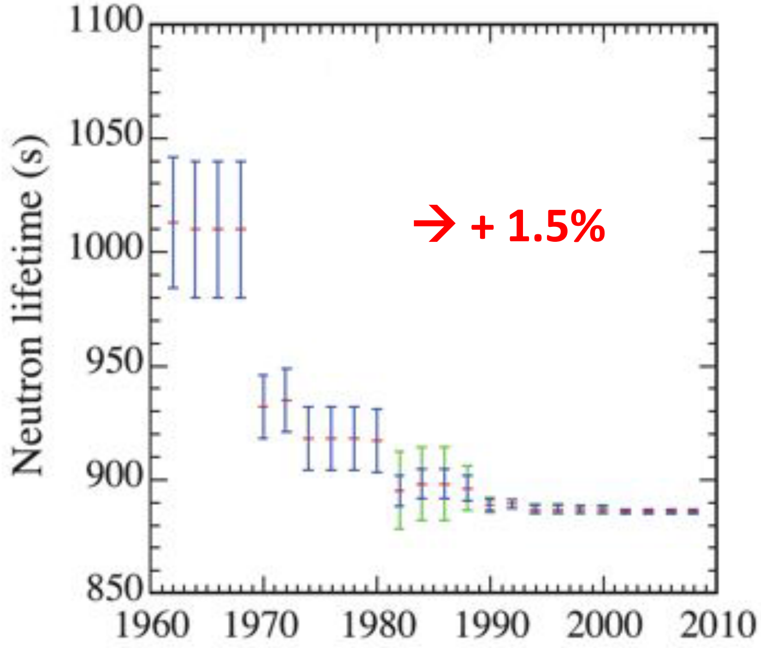
Accumulation of long lived isotopes

→ +1%

Re-evaluation of Detected Spectra

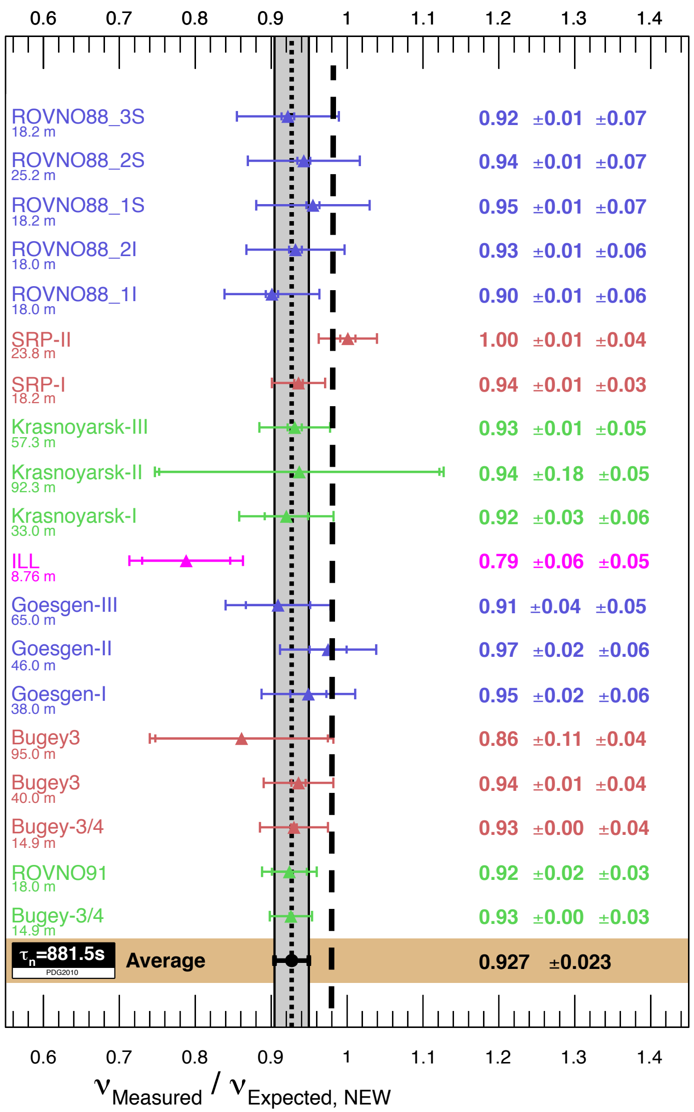


$$\sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n$$



PRD 83, 073006 (2011)

The Reactor $\bar{\nu}_e$ Anomaly

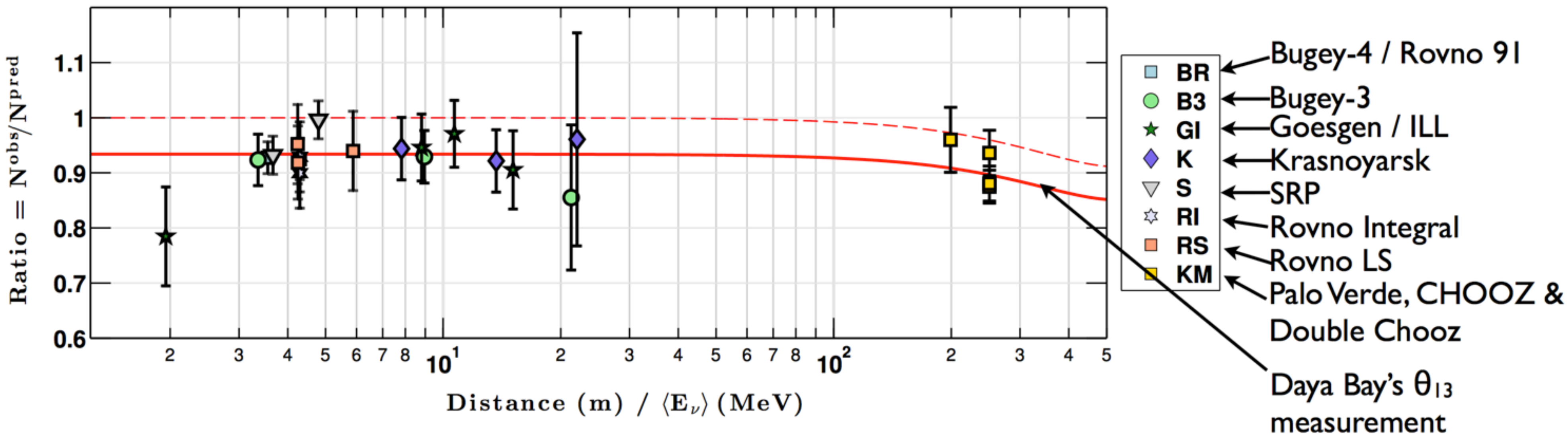


- Re-analysis of 19 Short Baseline Experiments (L<100m)
- Observables: ratios of observed event rate to predicted rate of events

- 2011 results *Phys. Rev. D83, 073006 (2011)*
  - Average: $\mu = 0.943 \pm 0.023$
  - 98.6 % C.L. deviation from $\mu = 1$

- 2012 update *White paper, hep-ph:1204.5379*
  - Average $\mu = 0.927 \pm 0.023$
  - 99.7 % C.L. deviation from $\mu = 1$

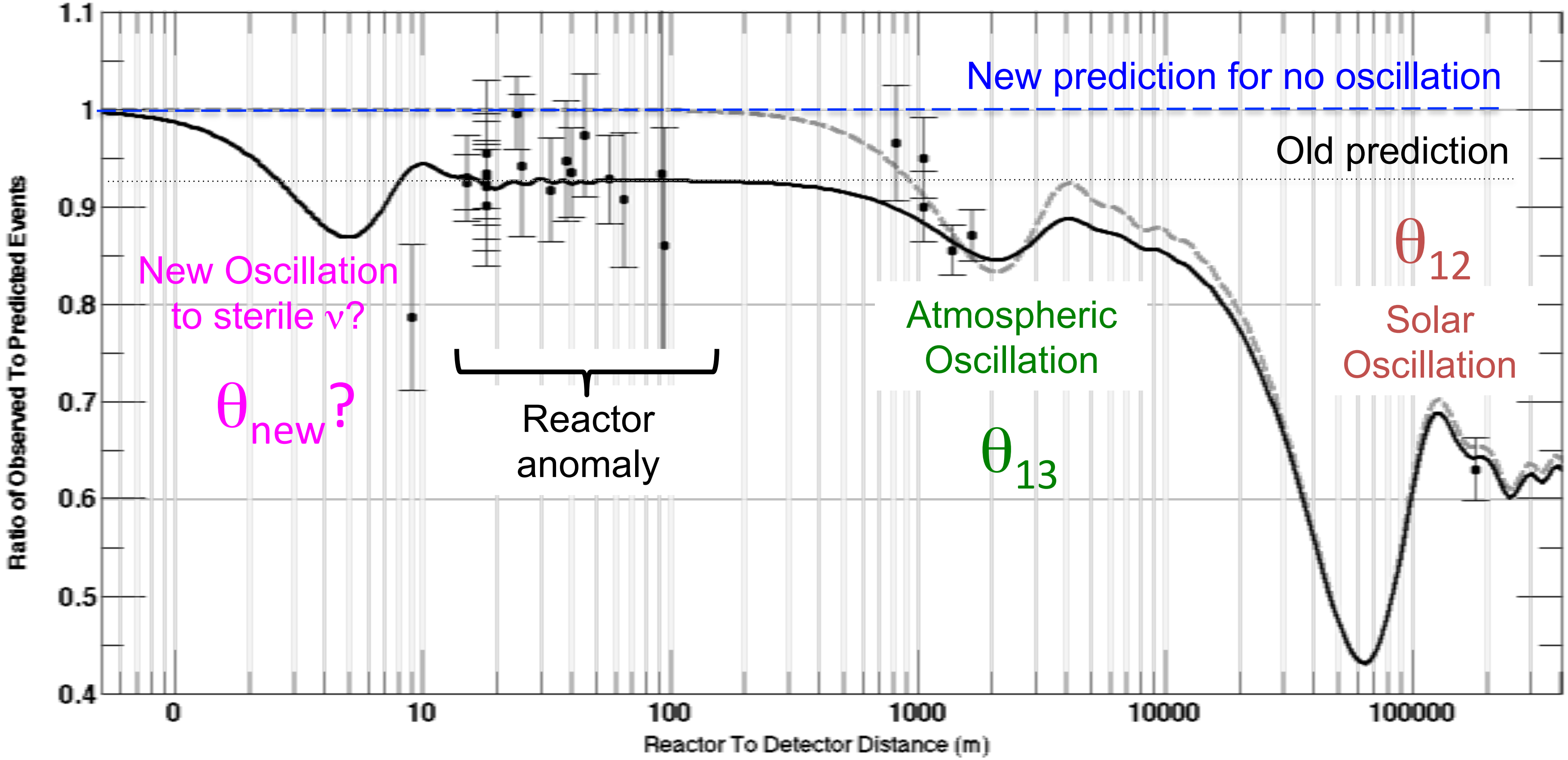
Including km-scale Experiments



- Refined treatment of experimental correlations
- Latest updated neutron mean life (τ_n = 881.5 s).
- Corrects for a statistical bias (1% shift)
- km-scale baselines (Chooz, Double Chooz, Palo Verde)
  - θ_{13} deficit corrected from Daya Bay's independent measurement
- 2013 result: $\mu = 0.936 \pm 0.024$, 2.7σ deviation from unity

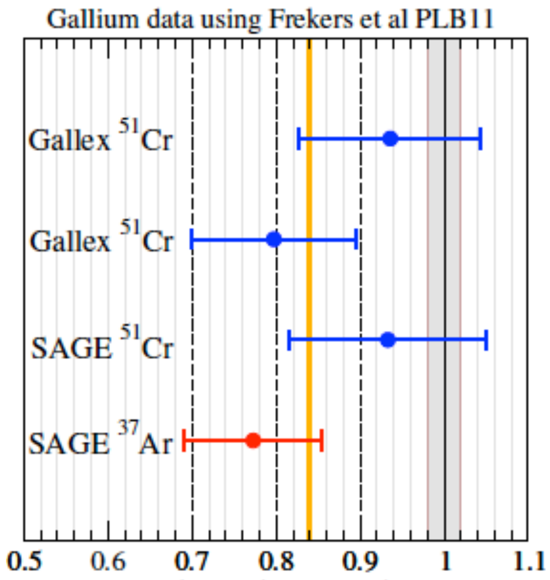
The Sterile Neutrino Hypothesis

A 4th neutrino ?

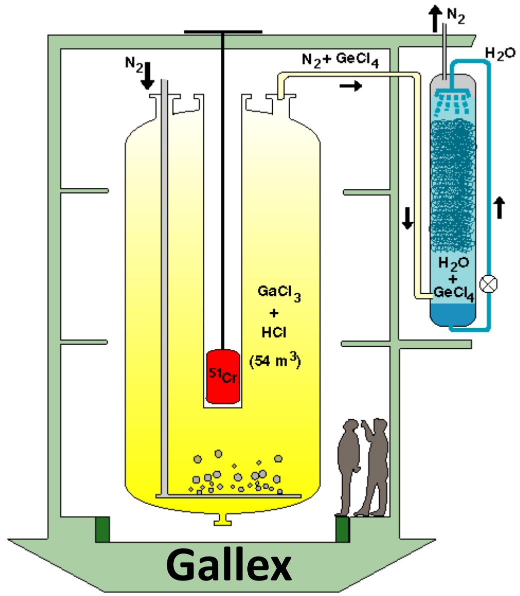


The Gallium Neutrino Anomaly

- **Calibration of solar neutrino detectors with MCi e-capture ν_e emitters**
  - $^{71}Ga/^{37}Ar + \nu_e \rightarrow {}^{71}Ge/^{37}Cl + e^-$
  - Gallex, <L>=1.9 m
    - ^{51}Cr, 750 keV
  - Sage, <L>=0.6 m
    - ^{51}Cr & ^{37}Ar (810 keV)

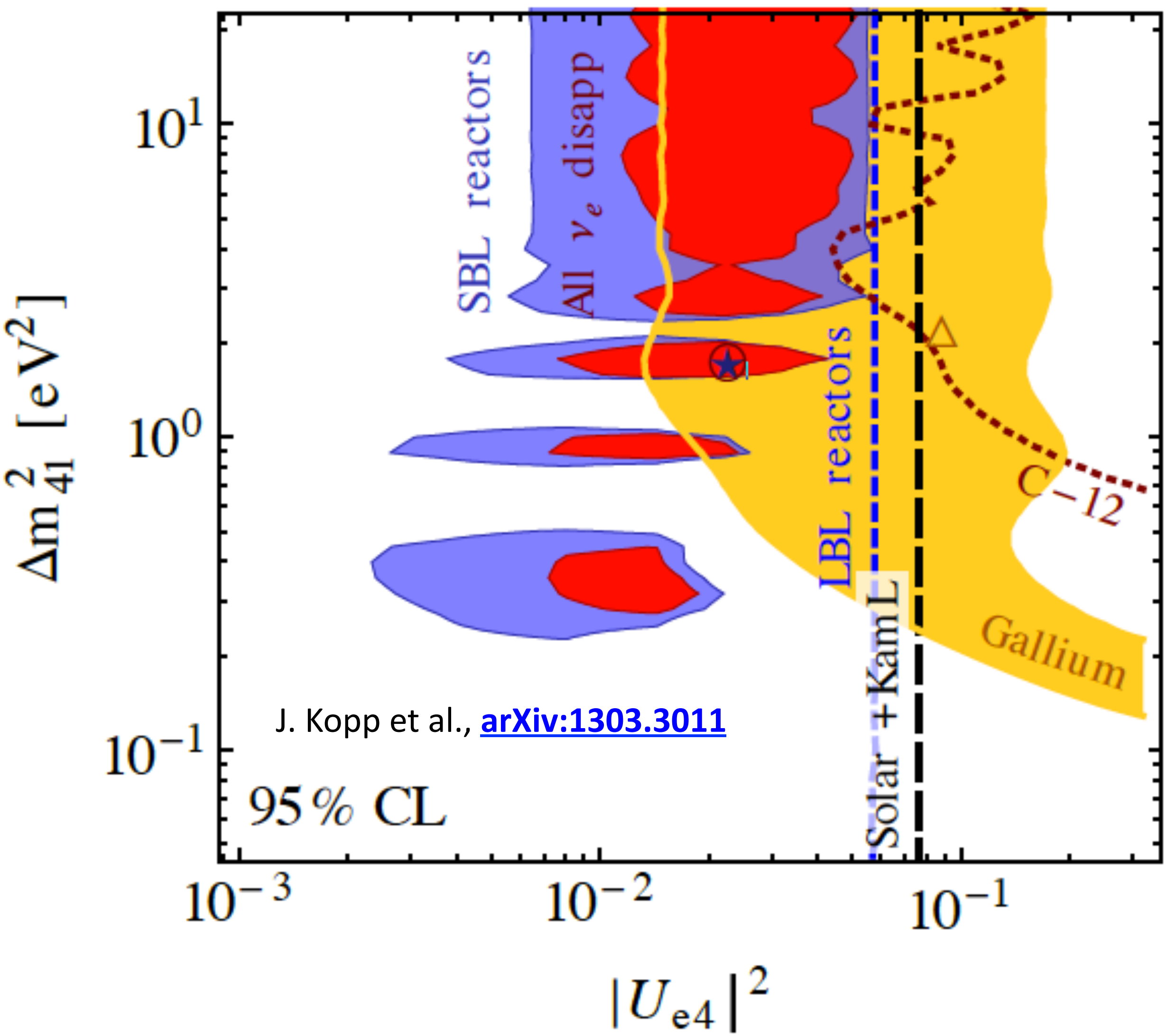


- **Deficit observed**
  - 2.8 - 3 σ anomaly
  - Supported by new $^{71}Ga(^3He,^3H)^{71}Ge$ cross section meas.



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

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



$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E}$$

$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)$$

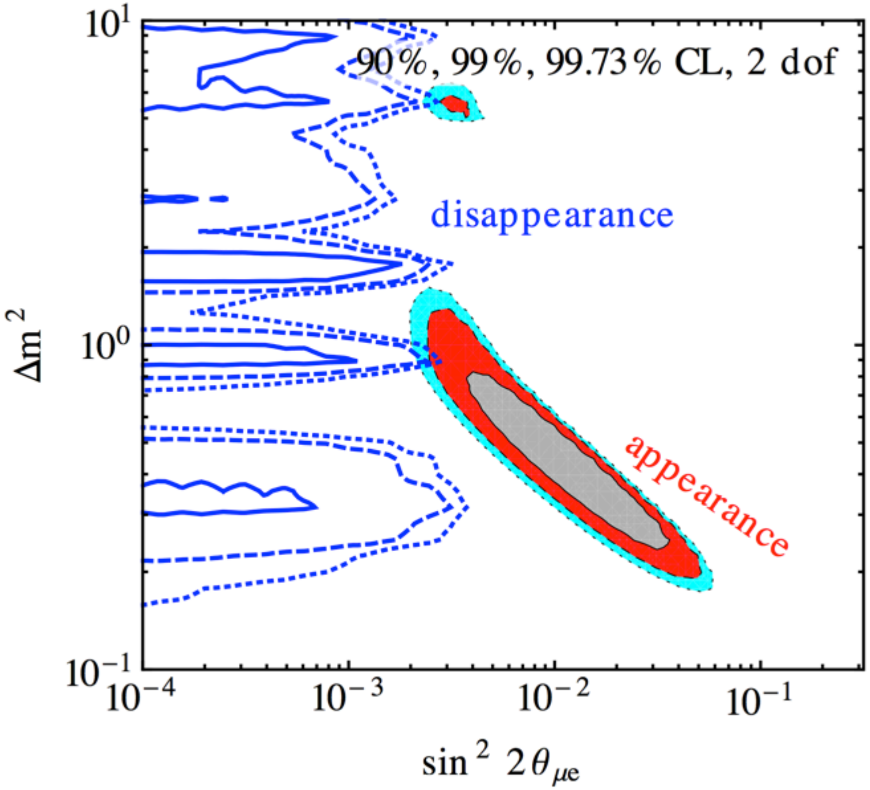
Anomalous & Regular Results

Anomalous	Source	Type	Signal	Channel	Significance
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	2.7-3.0 σ
Reactor	Beta-decay	ν_e dis.	Total Rate, Energy	CC	2.7 σ
LSND	Meson Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBooNE	Meson Decay-in-Flight	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ

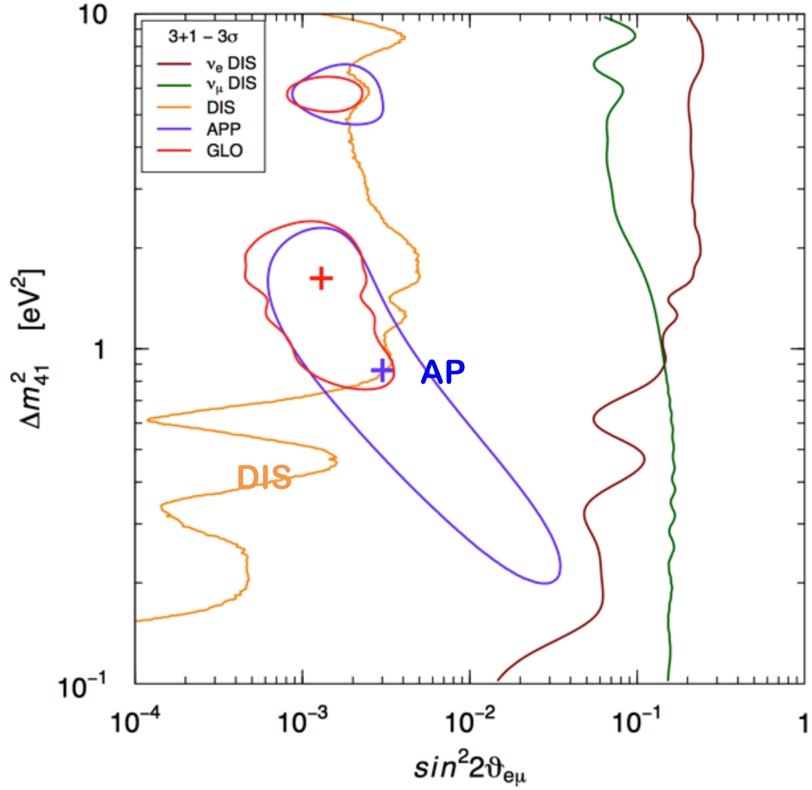
Regular	Source	Type	Signal	Channel
KARMEN Icarus/Opera	Meson Decay - at-Rest & Flight	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC
CDHS/ MiniBooNE	Meson Decay-in-Flight	$\nu_\mu \rightarrow \nu_\mu$	Total Rate, Energy	CC
Minos	Meson Decay-in-Flight	$\nu_\mu \rightarrow \nu_s$	Total Rate	CC

Appearance VS Disappearance

J. Kopp et al., arXiv:1303.3011



C. Giunti et al., arXiv:1302.6720



$$P_{\mu e} = 4\sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41}}{4E} \qquad \sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

Hard to reconcile $\bar{\nu}_e/\nu_e$ appearance/disappearance with $\bar{\nu}_\mu/\nu_\mu$ disappearance (3+1 & 3+2 models)

Testing new $\overline{\nu}_e$ disappearance at short distance from compact sources

Experimental Strategy

- **Need direct test, beyond the current mean deviation from predicted rate**

- **Input from sterile neutrino fits**
  - **$\Delta m^2 \approx$ 0.1-10 eV^2 →**
  - **$\sin^2(2\theta_{ee}) \approx$ 0.01-0.15**

$$L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2 (eV^2)} \approx 2-10 \text{ m}$$

- **Experimental specifications:**
  - Compact source
  - Good vertex and energy resolutions
  - High statistics, few % stat. uncertainty
  - Few % syst measurements to cover the anomaly contour

→ **Search for a new oscillation pattern in E & L**
Measurement of relative shape distortion, completed by norm information.

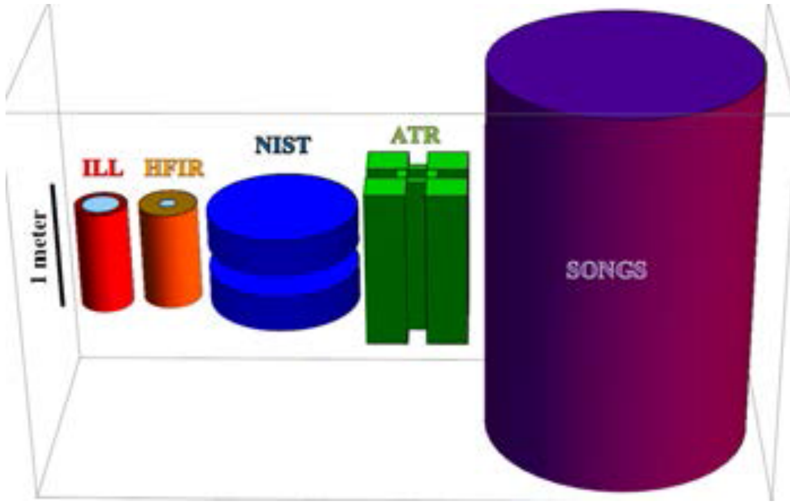
Reactor Experiments

Research Reactors

- **Compact sources**
  - No oscill. smearing.
- **High statistics, typically few 100 evts/day/t**
  - Intense source
  - Very short baselines available (5-50 m)
- **Alternation of reactor ON/OFF periods**
  - moderate overburden compensated by accurate measurement of the cosmogenic component.
- **Highly enriched fuel**
  - Well known ^{235}U fisison spectrum.
- **But challenging reactor-induced backgrounds (γ and n)**

→ Requires comprehensive site characterization.

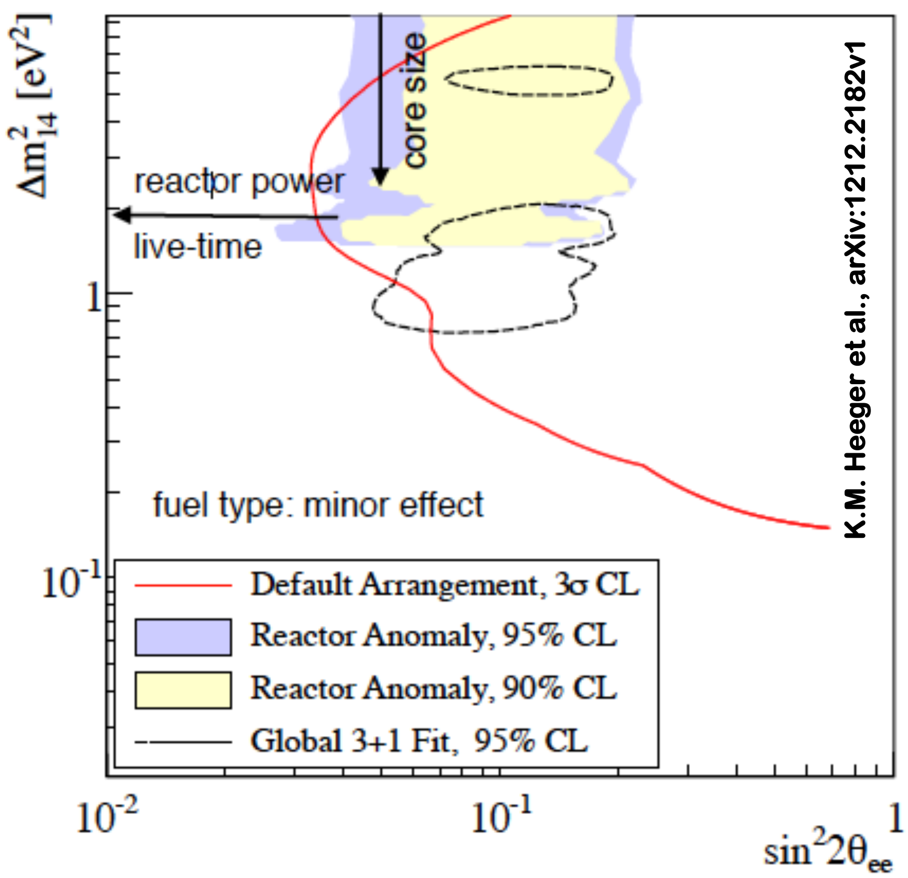
Typical reactor core sizes



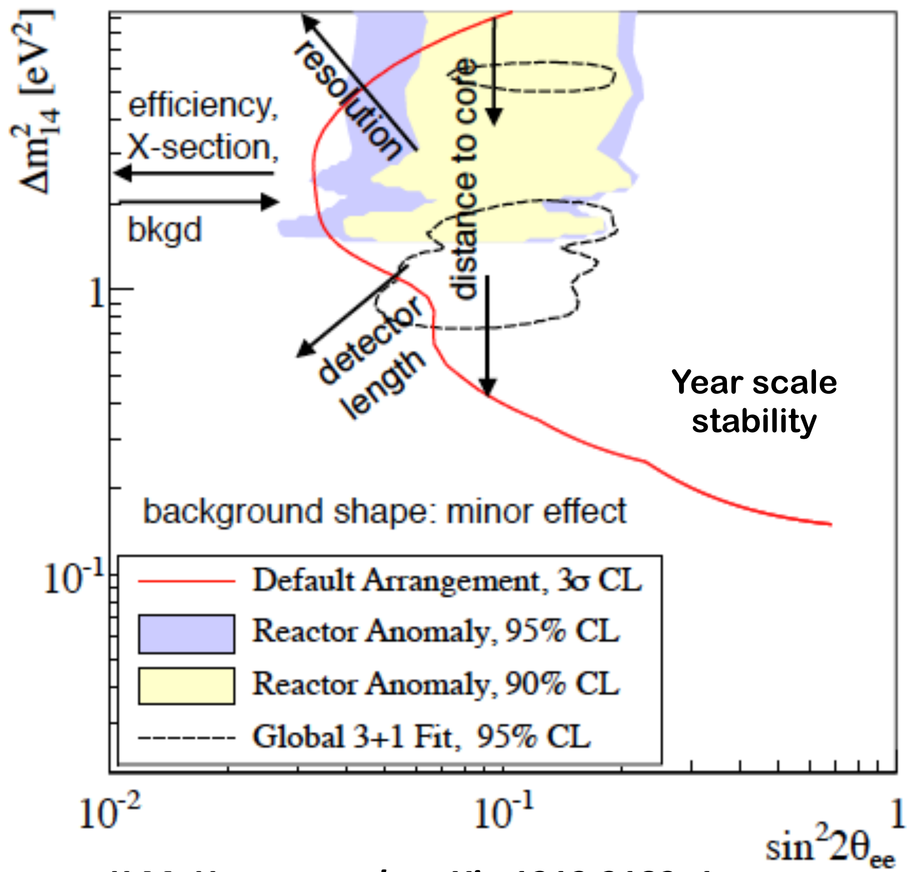
Main Experimental Parameters

All current projects have the sensitivity to test the reactor anomaly space of parameters, $\Delta m^2>0.1$, $\sin^2 2\theta>0.05$

Source



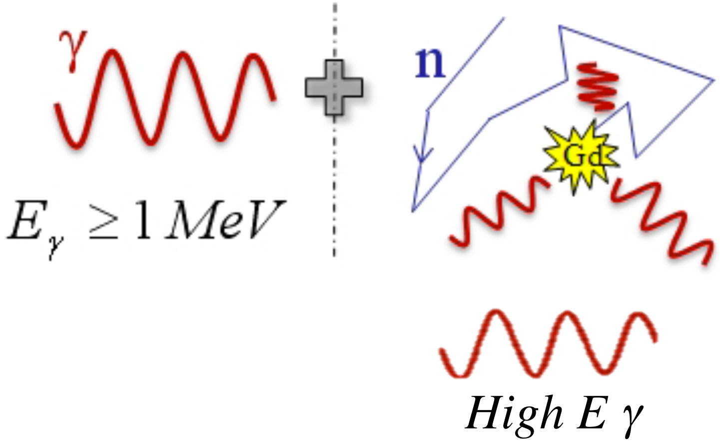
Detector



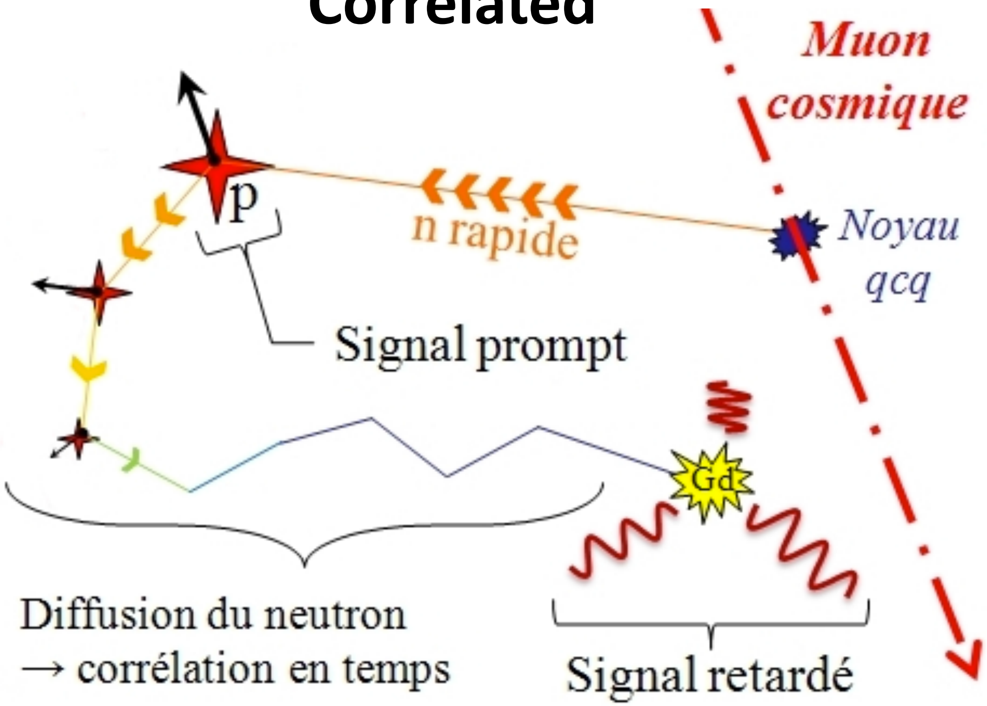
K.M. Heeger et al., arXiv:1212.2182v1

Backgrounds

Accidental



Correlated

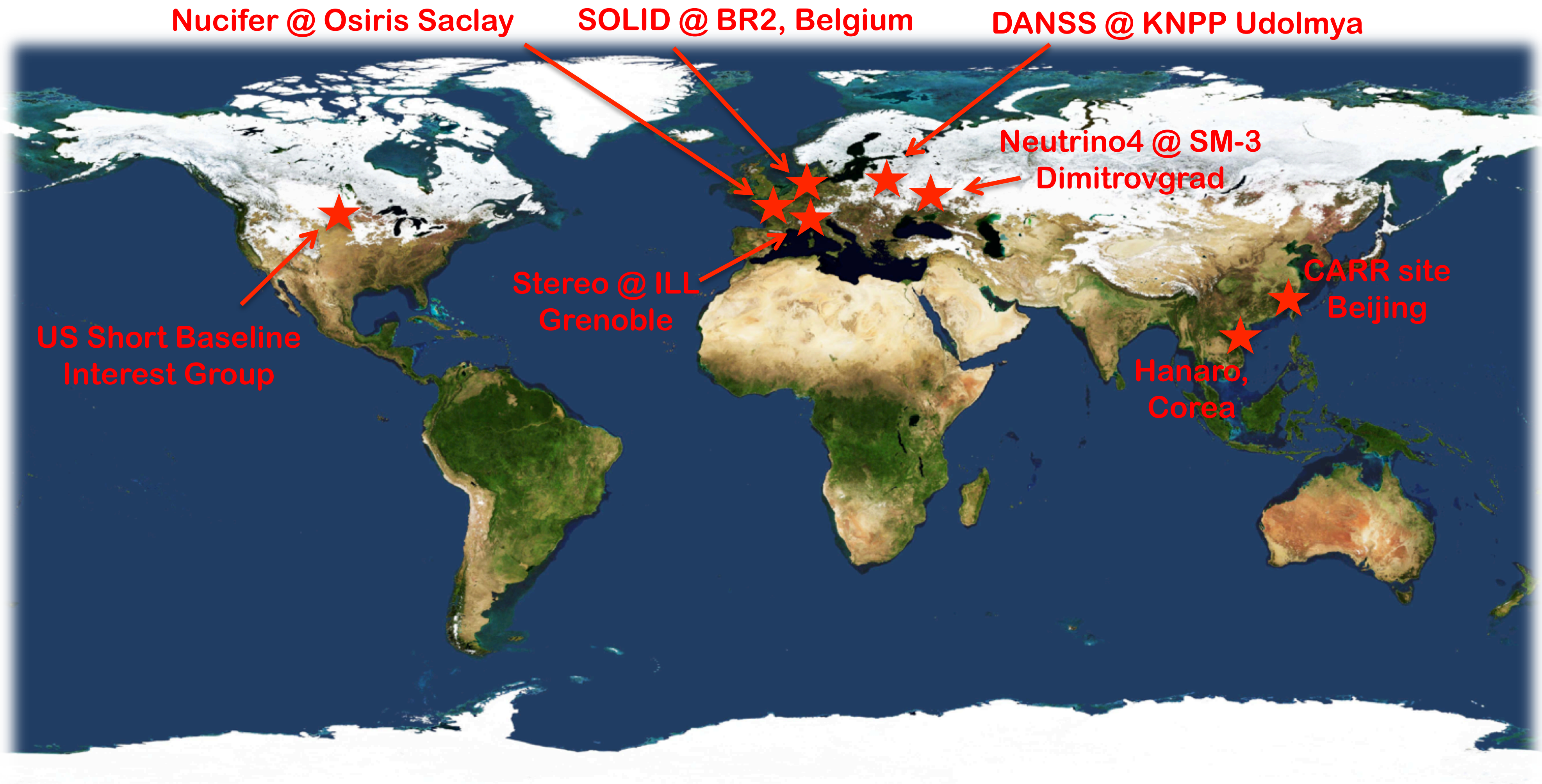


- Random coinc of independent evts
- Accurately measured online using duplicated off-time windows
  → Statistical limitation only

- Online reduction: overburden, μ-veto, PSD of recoiling proton
- Measured reactor OFF and subtracted

$$N_\nu = N_{corr}^{ON} - N_{acc}^{ON} - (N_{corr}^{OFF} - N_{acc}^{OFF})$$

Worldwide Experimental Program



Detection of Reactor ν

Experiment Type	Experimental Strategy
Mature Gd-doped LS detector Technology	- High E signature of n-capture (8 MeV γ-cascade) - High light yield → fast n background rejection by PSD - But sensitive to high-E γ's → need large passive shielding
Highly segmented detector for background reduction	- Vertex correlation between prompt and delayed - Topology of E depositions: e+ → compact track + annihilation γ's γ → longer interaction length
Enhanced neutron Tagging	- Unique signature of neutron capture with Li-doped LS/PS $^6Li + n \rightarrow \alpha + t$
2 detector complex or Moving detector	- Better sensitivity to lower Δm^2 - But Need larger volume and/or longer running time

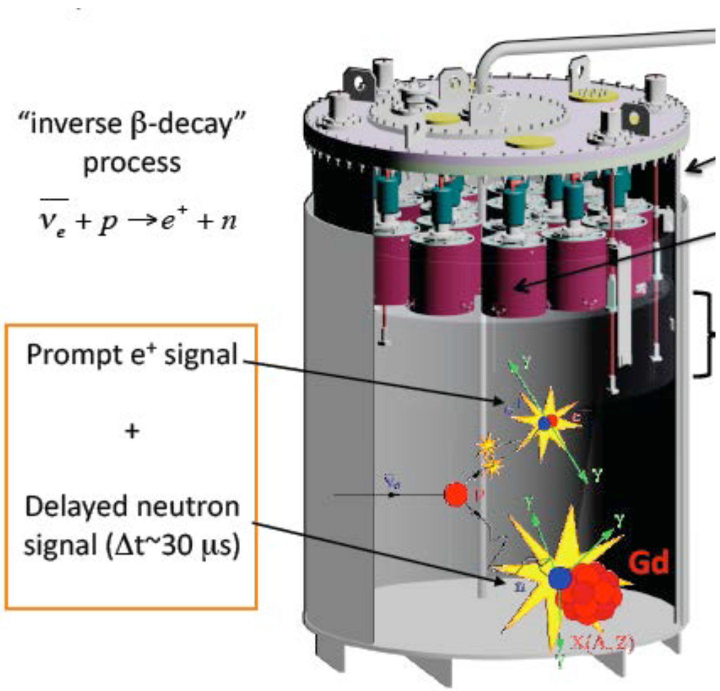
Reactor ν Proposals

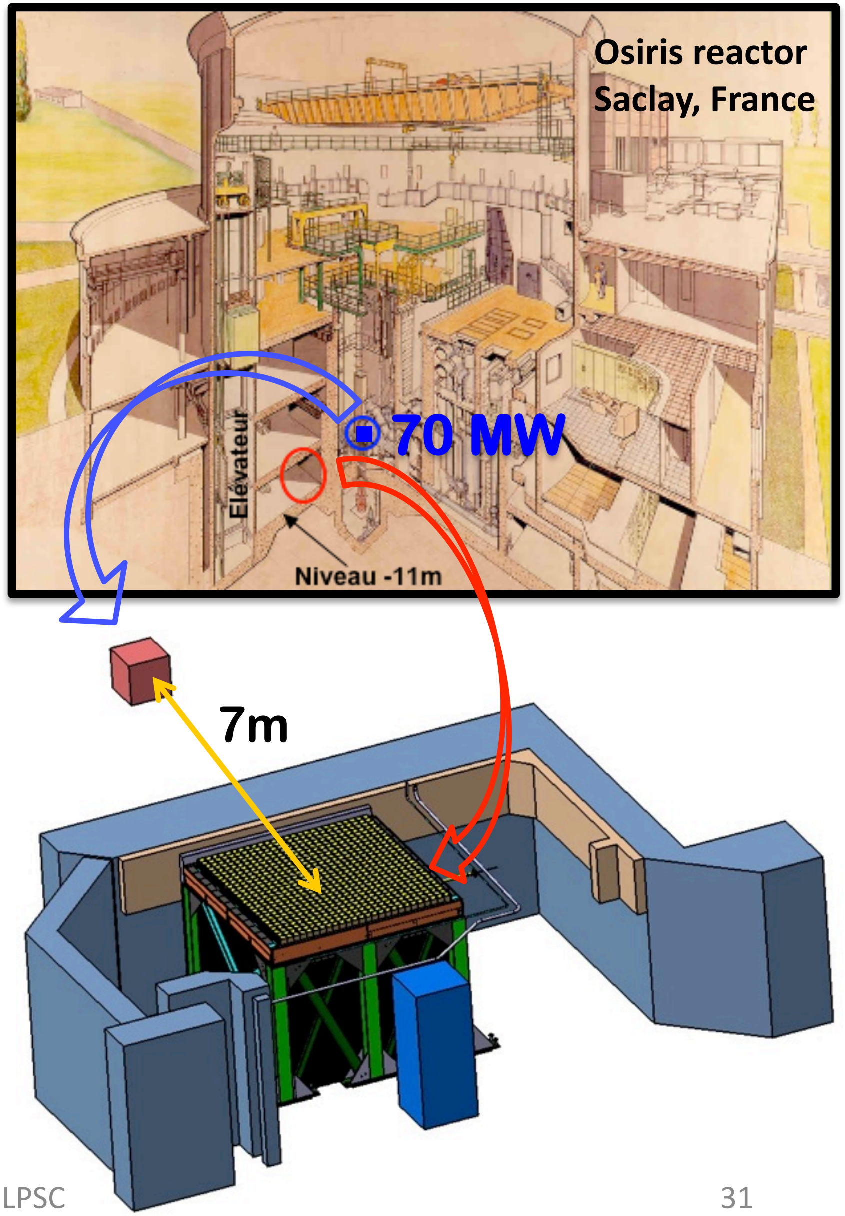
Experiment Type	Projects	P_{Th}	M_{det}	L	Depth
Mature Gd-doped LS detector Technology	Nucifer (FRA)	70 MW	0.7 tons	7 m	Few mwe
	Stéréo (FRA)	50 MW	2 tons	[8-11] m	10 mwe
	Neutrino 4 (RU)	100 MW	2 tons	[6-12] m	Surf.
Highly segmented detector for background reduction	DANSS (RU)	1 GW	1 ton	[10-12] m	50 mwe
Highly segmented detector for background reduction / Enhanced neutron Tagging	SoLid (UK)	45-80 MW	3 tons	8 m	10 mwe
Enhanced neutron Tagging	Hanaro (KO)	30 MW	0.5 t	6 m	Few mwe
2 detector complex or Moving detector	US project	20-120 MW	-	4m & 15m	Surf.
	China project	-			
	DANSS/Neutrino4	Movable detector			

Gd-Loaded Liquid Scintillators

Nucifer @ Osiris

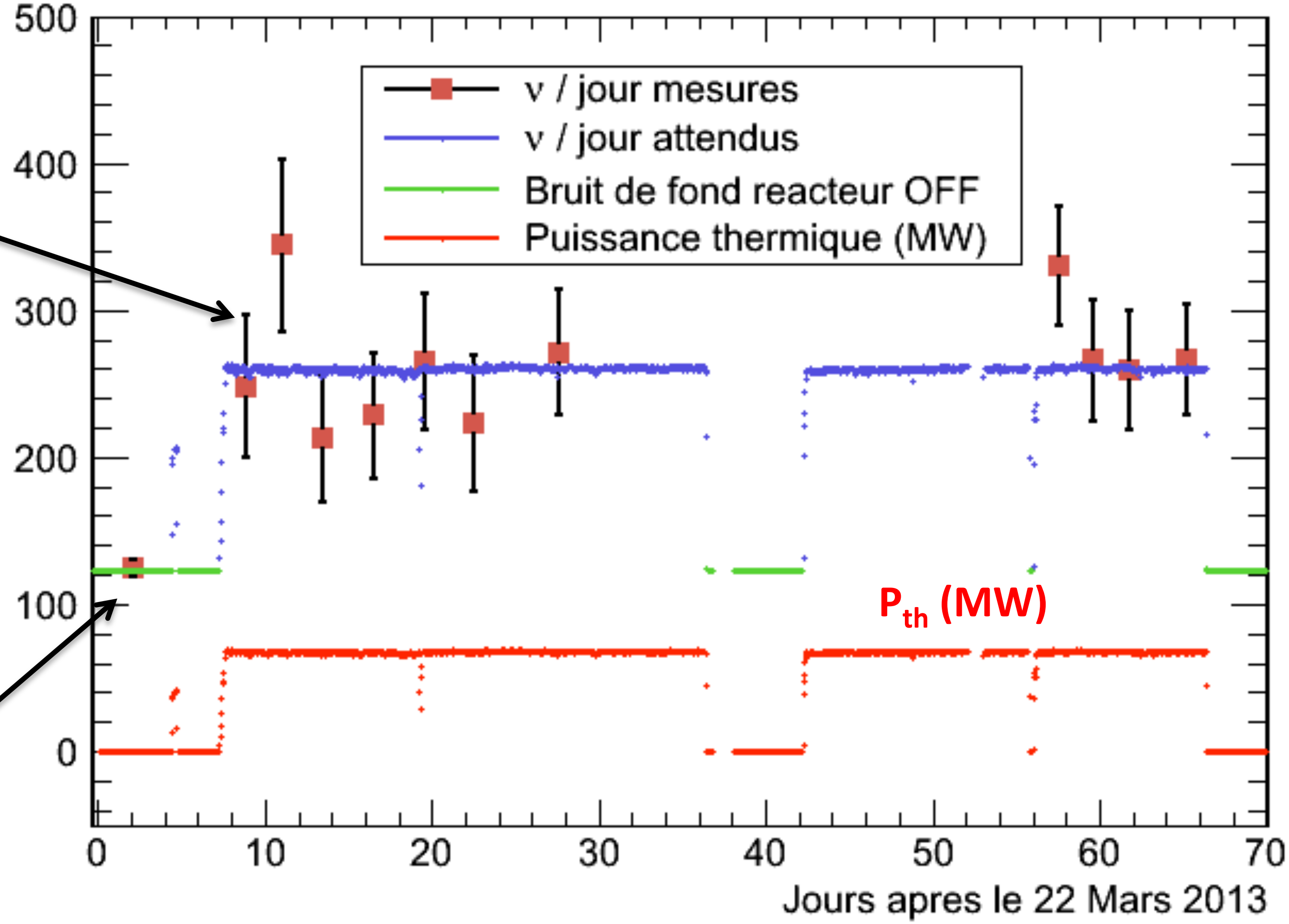
- **Detector designed for reactor monitoring studies**
  - 850 kg Gd-loaded LS
  - ~1000 int. expected / day
  - Shallow depth (few mwe)





Nucifer: First Neutrinos

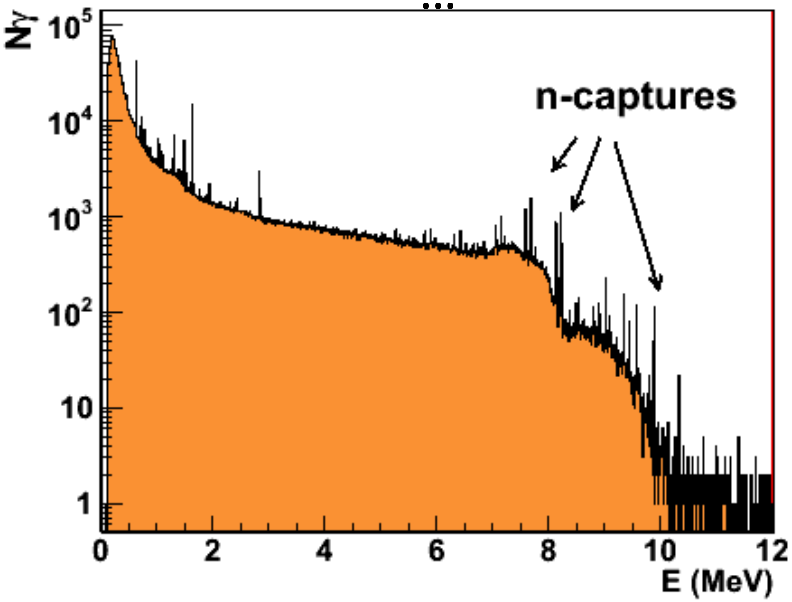
Detection efficiency and statistical accuracy limited by excessive accidental background



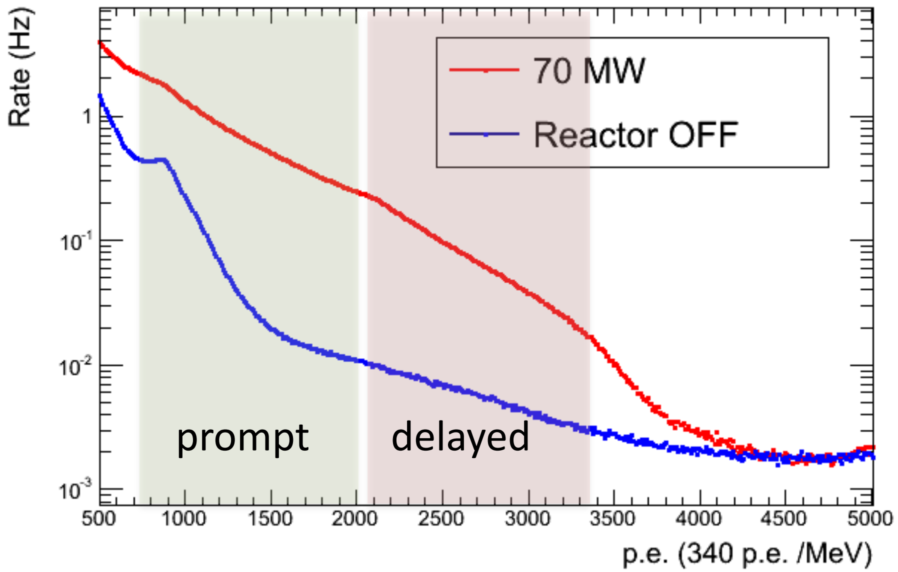
Shallow depth but cosmic bkg is kept below the ν signal.

Nucifer: Accidentals

External γ background: high E rays from n-capture on Fe, Al, Ni, …



Nucifer singles

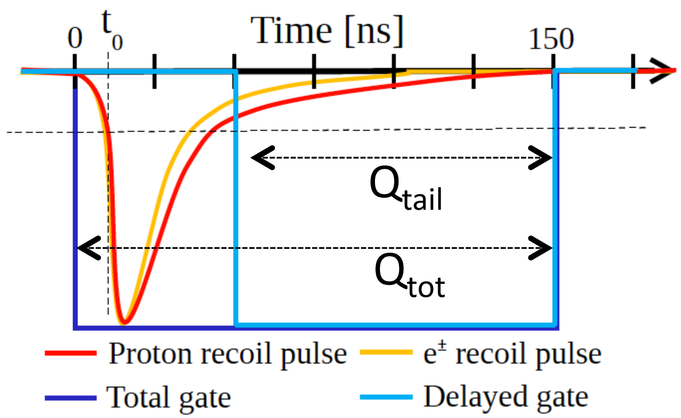


- Total rate above 2 MeV = 200 Hz, on specification
- But high energy tail, spoiling the n-capture signal around 8 MeV

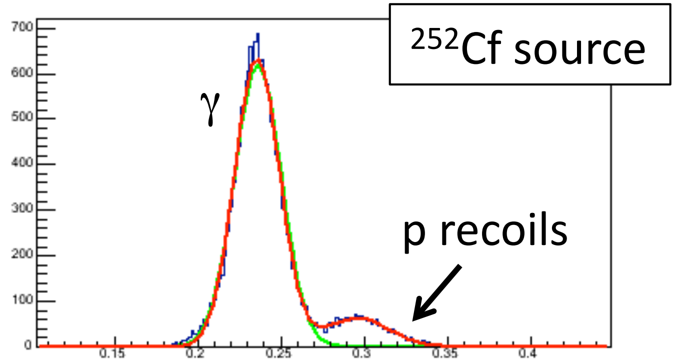
→ Need 4cm extra lead shielding, to be installed soon.

Nucifer: Fast n Background

Pulse Shape Discrimination

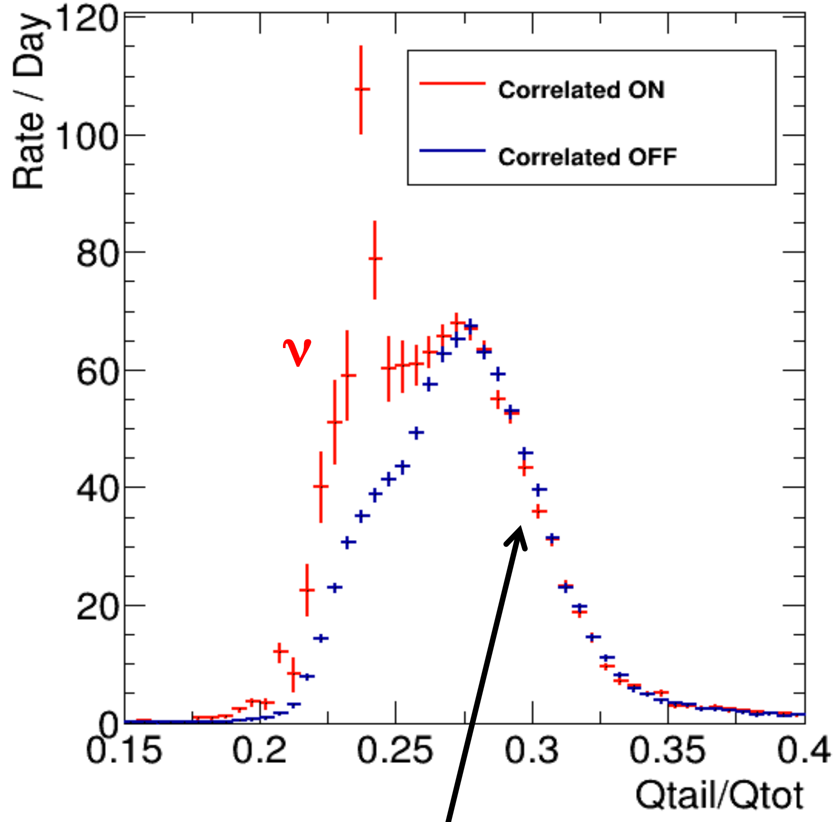


Nucifer liquid : 50% PXE, 50% dodecane



$$FoM = \Delta Mean / \Sigma(FWHM) \approx 0.8$$

PSD plot of Osiris data taking



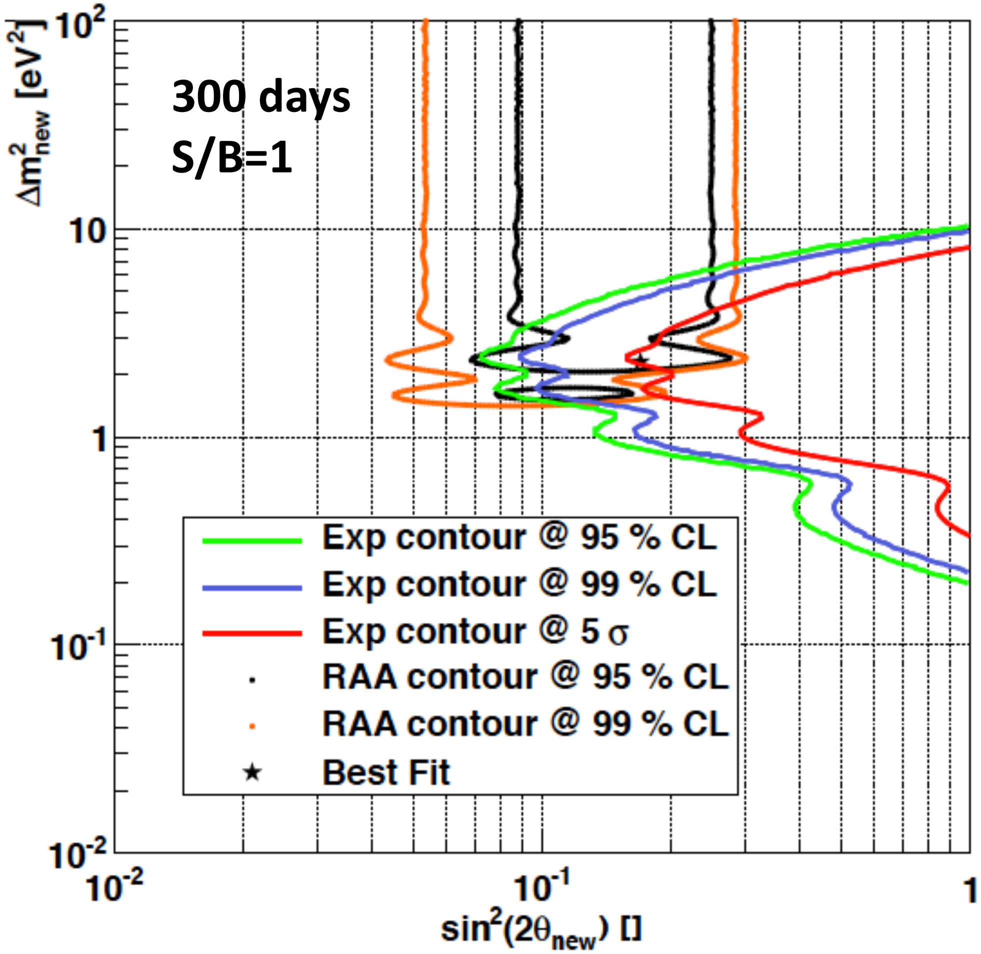
Perfect match of p recoils after acc subtraction

→ No fast neutrons from reactor

Nucifer: Sensitivity to Sterile ν

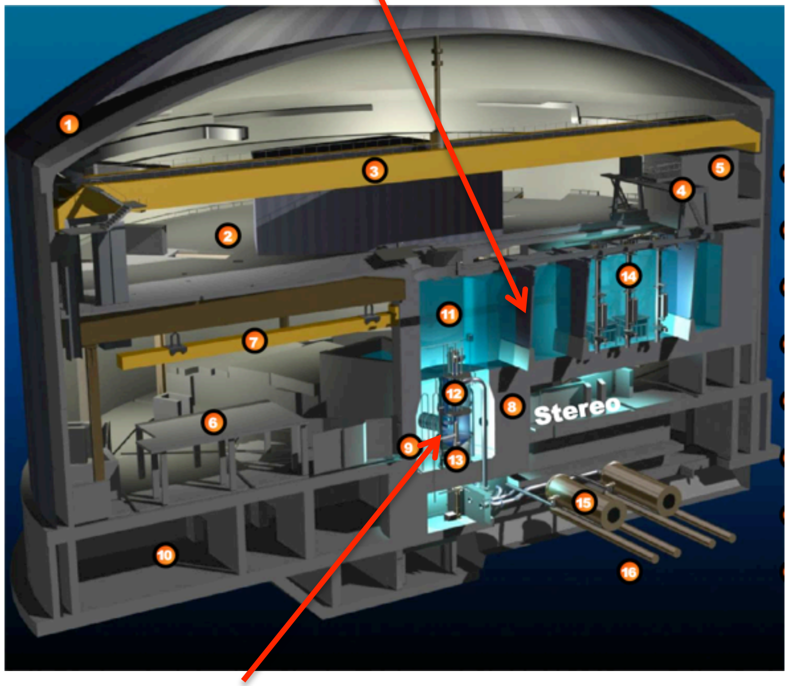
- Modest sensitivity to Sterile-ν:
  - Compact core: 60x60x60 cm^3
  - Short baseline: only 7 m
  - Simple design
  - One single baseline
  - Challenging Reactor bkg

- 1 year data taking in 2014 after final shielding upgrade



Stereo @ ILL

Good overburden from water channel, factor 4 attenuation of vertical flux

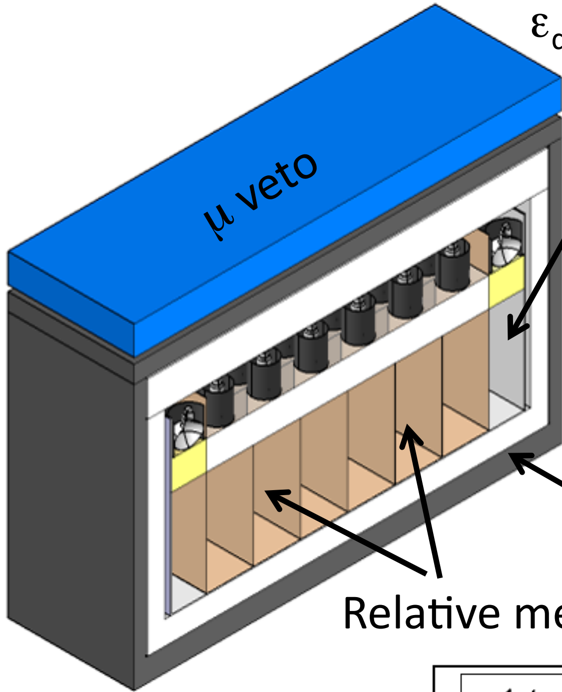


50 MW core

h=80cm, Φ=40cm

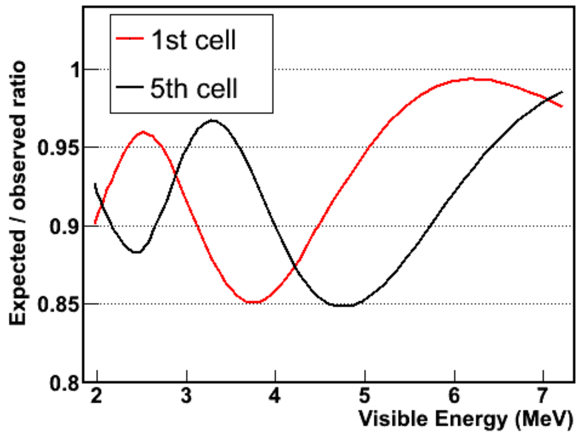
[8.5-11] m baseline range

Outer crown for improved ε_{det} and veto of external background



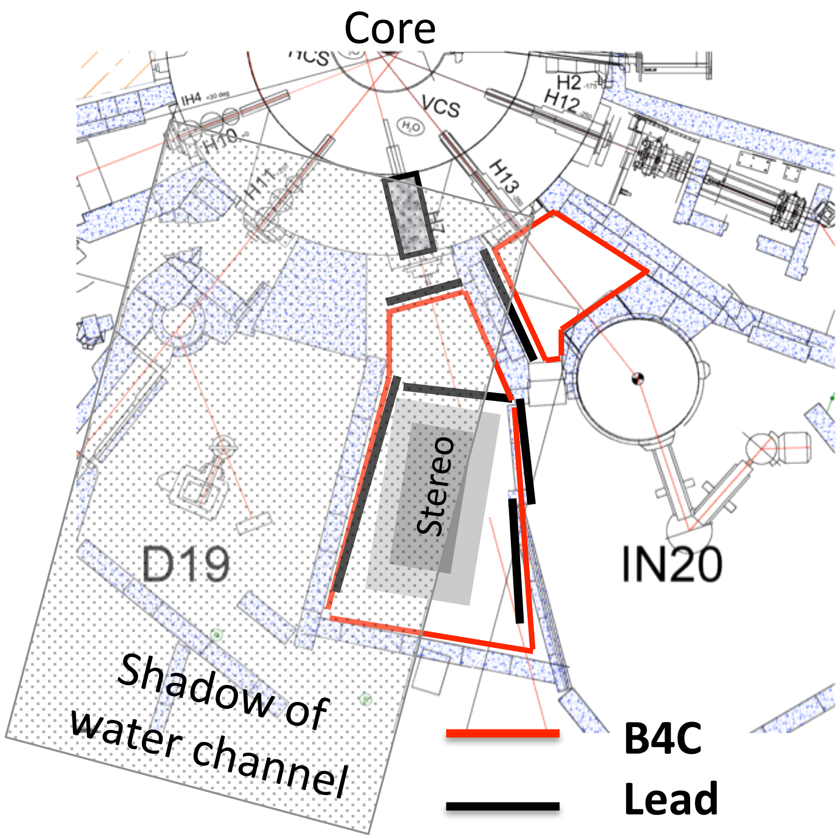
γ and n shielding

Relative measurement in 6 cells



Detector based on Double Chooz and Nucifer developments.

Stereo: Background Rejection



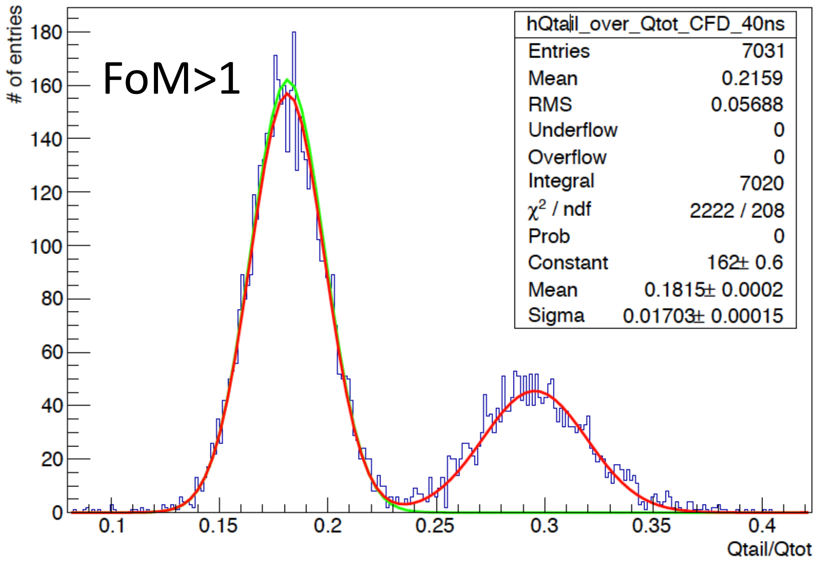
Reduction of accidentals

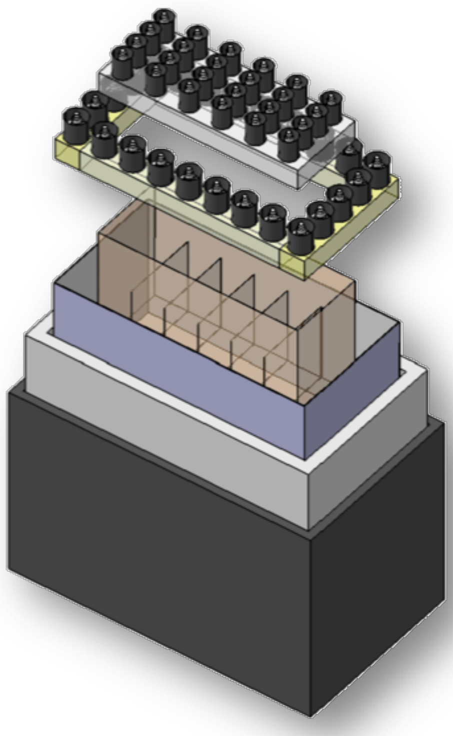
- Comprehensive on site measurements of muon, thermal n, fast n and γ backgrounds.
- Massive deployment of shielding during the upcoming long reactor shutdown. 30 cm of lead in front hot γ spots + hermetic B4C coating.
- Dedicated plug of the neutron line.

Stereo: Background Rejection

Rejection of fast neutrons

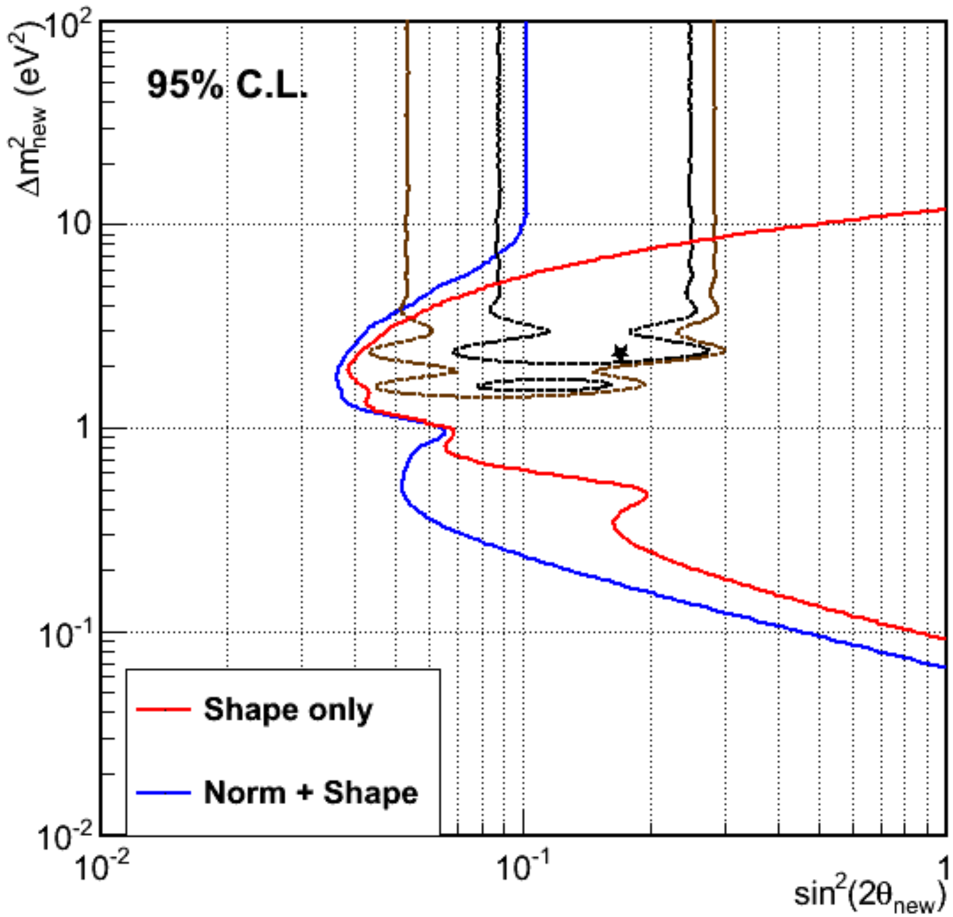
100 ml test sample





- Overburden
- μ-veto and top passive shielding
- Active outer-crown
- Kinematics and liquid quenching factor → E_n > 5 MeV
- Liquid R&D for optimal light yield and PSD

Stereo Sensitivity



- 6 ILL cycles (1.5 year running)
- L_0 = 9.8 m
- S/B = 1.5
- E_{vis}>2 MeV, Neutron cut = 5 MeV
- Complete det response
- δL=20 cm, δE/E~10%@ 1MeV
- δEscale = 2%
- All syst. of ^{235}U spectrum
- 3.5% total norm error
- 480 ν/day expected

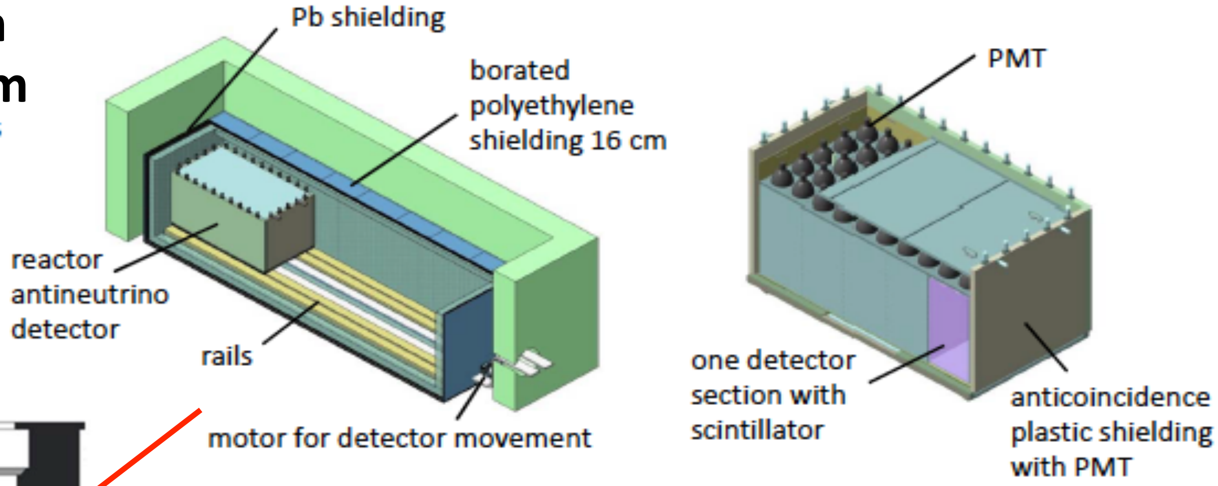
- **Funded by ANR grant**

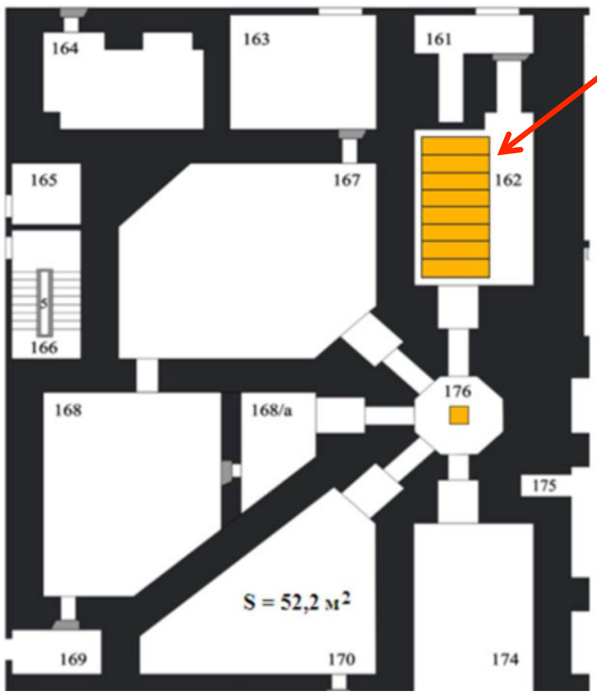
- **Time schedule:**
  2013-2014: design and construction
  2015-2016: data taking

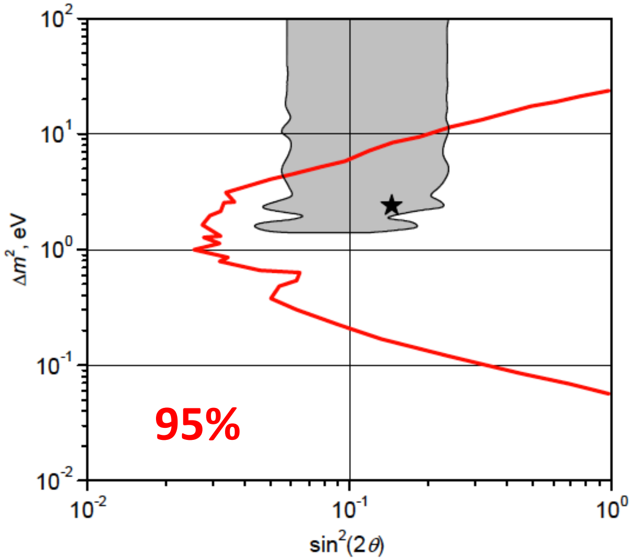
Neutrino-4 @ SM3

Courtesy of A. Serebrov

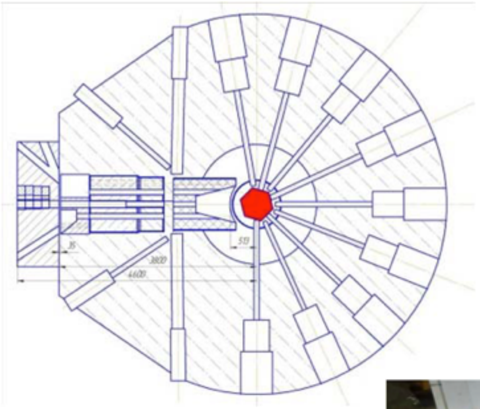
- 2.5 m³ LS target, 5 section movable detector [6-12] m
- 100 MW compact core
- Detector at Surface



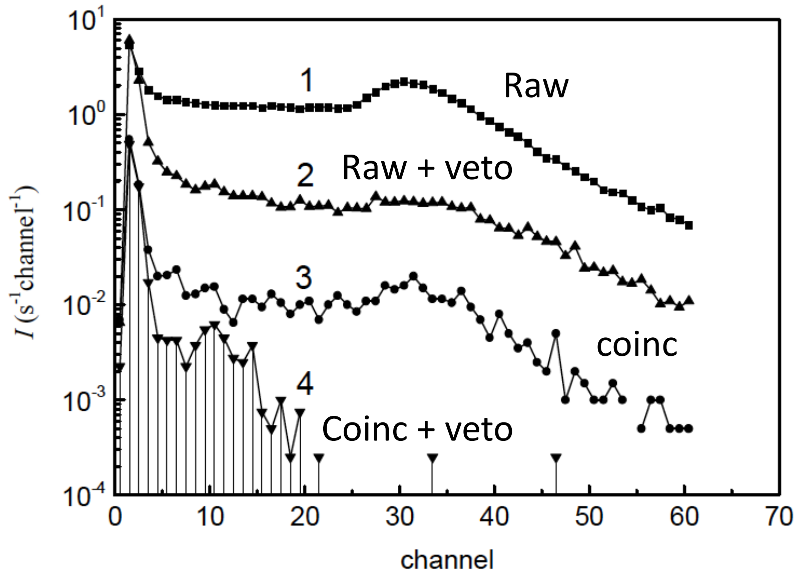




Neutrino-4 Prototype



Validation of a prototype detector at the WWR-M 17 MW reactor (Gatchina)



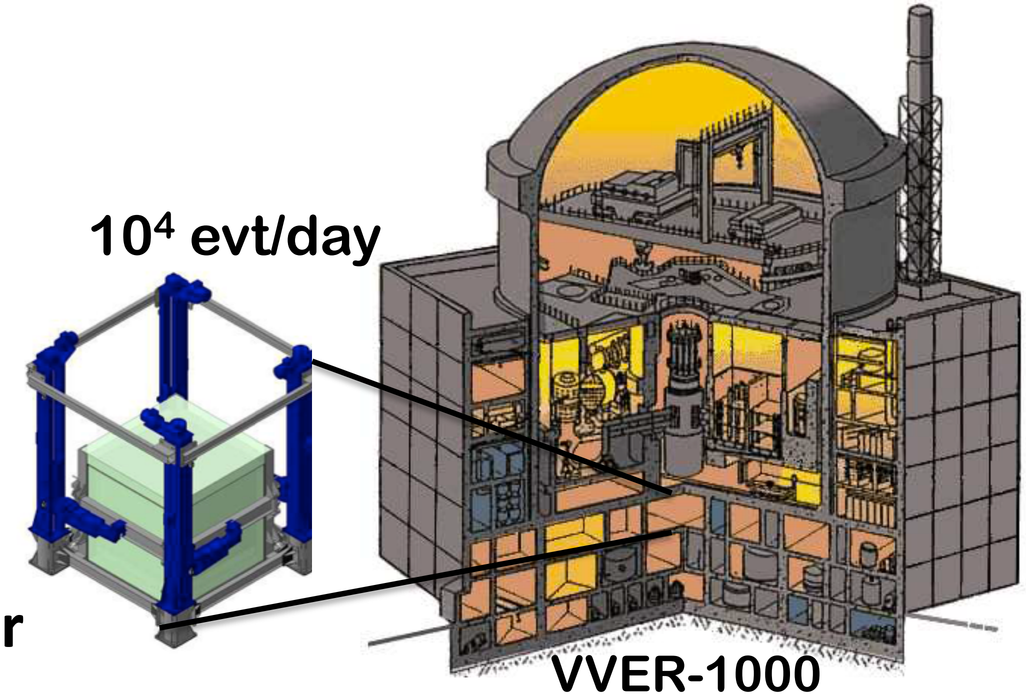
- Neutrino detection currently limited by cosmic rays induced fast neutrons.
- Lead + CH2 detector shielding integrated at the SM-3 site.
- Data taking in 2015

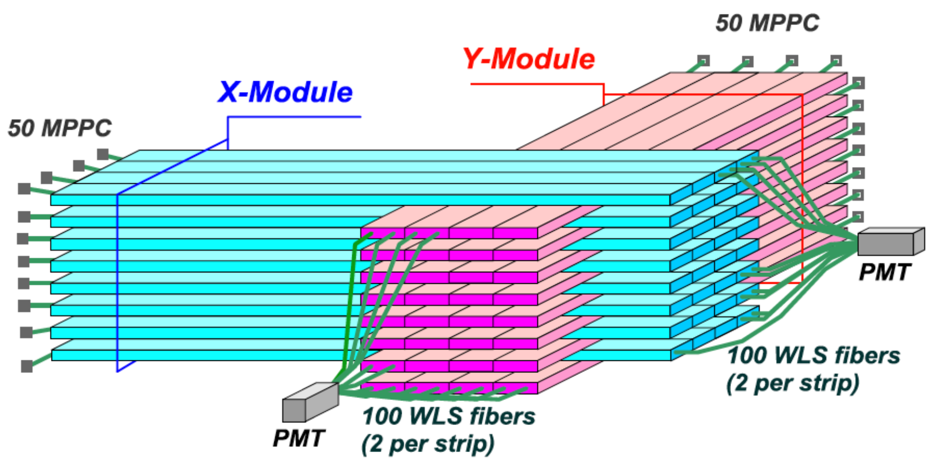
arXiv:1310.5521

Highly Segmented Detectors

DANSS @ KNPP

- 1 GW extended core
- Good overburden
- Vertical motion of the detector (9.7-12.2 m)
- Highly segmented detector → background rejection
- Plastic strips with Gd-loaded interlayer, WLS fibers readout, $\delta E/E$~20%
- Start in 2014/15

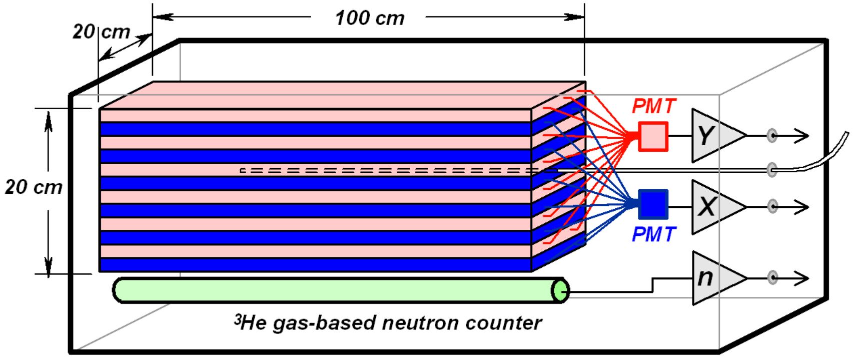




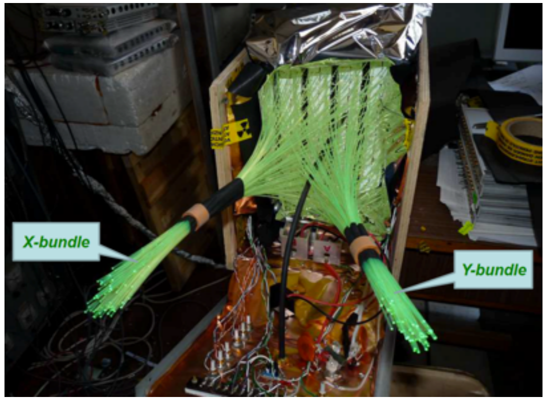
DANSSINO Prototype

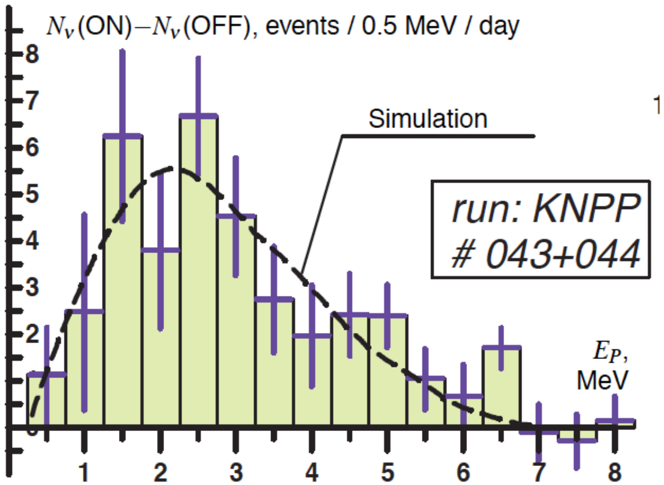
Tested for ~20 days @ KNPP

1/25th of DANSS



10 cm Cu-Lead + 10 cm CH_2 shelding





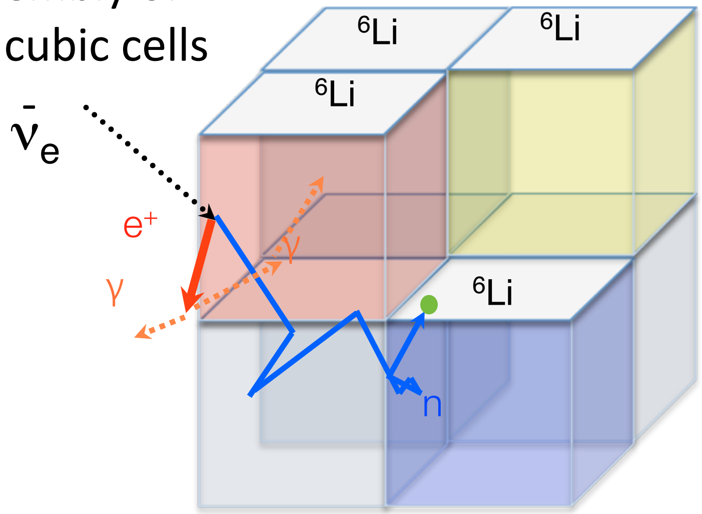
- Accidentals well suppressed
- S/B~1, limited by cosmic fast neutrons.

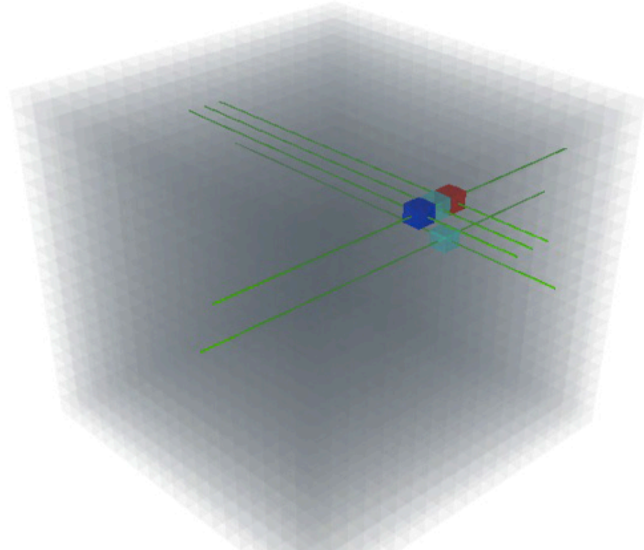
arXiv:1304.3696v2

Highly Segmented
&
Enhanced Neutron Discrimination

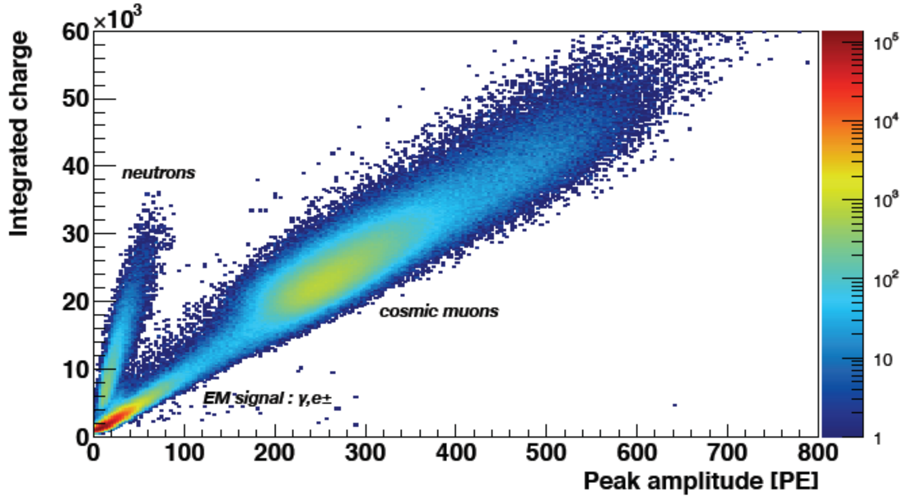
SoLid Antineutrino detection

Assembly of
5cm cubic cells





$$^6_3\mathrm{Li} + \mathrm{n} \rightarrow ^2_4 \mathrm{He}\ (2.05\ \mathrm{MeV}) + ^1_3 \mathrm{T}\ (2.75\ \mathrm{MeV})$$



- Very **discriminant neutron signal** in ^{6}LiF:ZnS. High neutron-γ rejection factor
- 3D reconstruction close to interaction point : **high background rejection capability using topological information of IBD.**
- δE/E ~ 17% at 1 MeV

Courtesy of A. Vacheret

SoLi∂

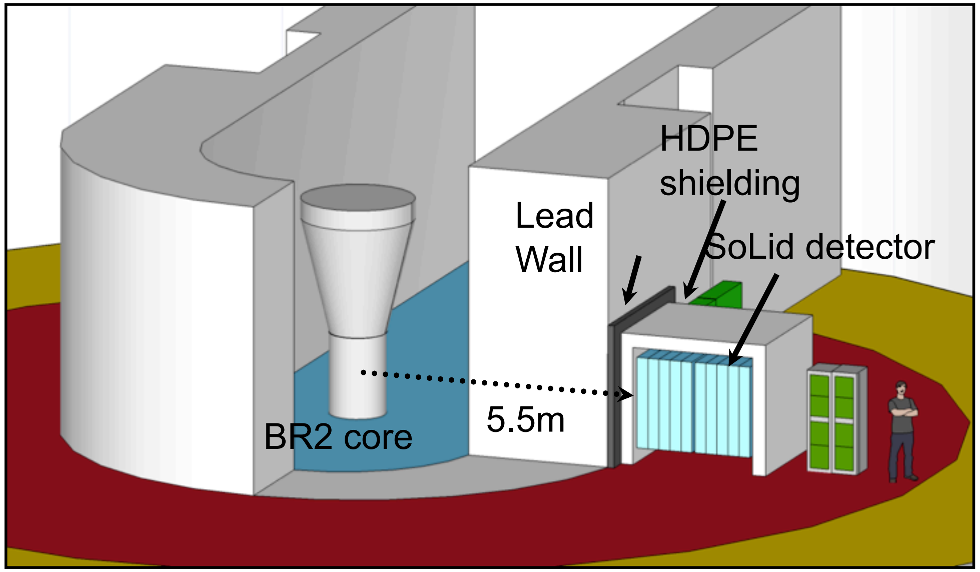
Search for Oscillations with ^{6}Li Detector

BR2 REACTOR, Mol, Belgium

- **Core: 45-80 MW, ~ 50cm diameter**

DETECTOR

- **2.88t fiducial volume**
- **Novel type of composite solid scintillator detector (PVT + 6LiF:ZnS)**
- **2x 20 planes 1.2m x 1.2m x 1m with 576 5cm x 5cm x 5cm cubes**
- **Read out by WLS fibres and Geiger-mode APDs (MPPC), 1920 channels total**



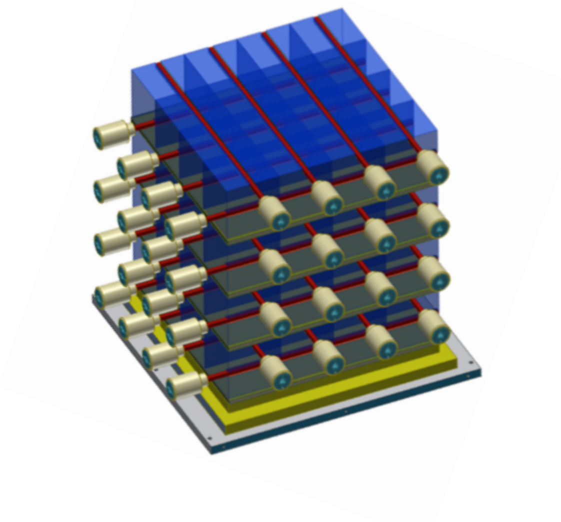
HIGH SIGNAL TO BACKGROUND RATIO : S/B ~ 6

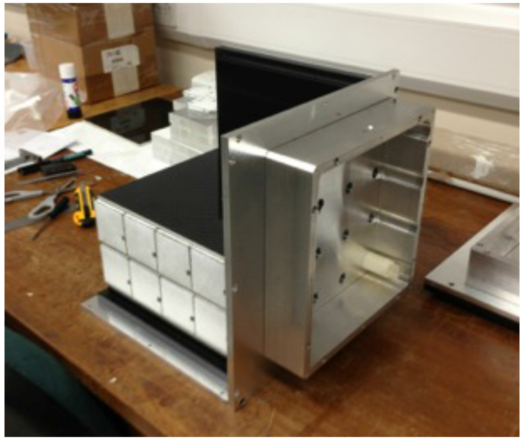
- **Soft Gamma-rays (< 3 MeV)**
- **No reactor neutrons**
- **Overburden ~10 m.w.e**

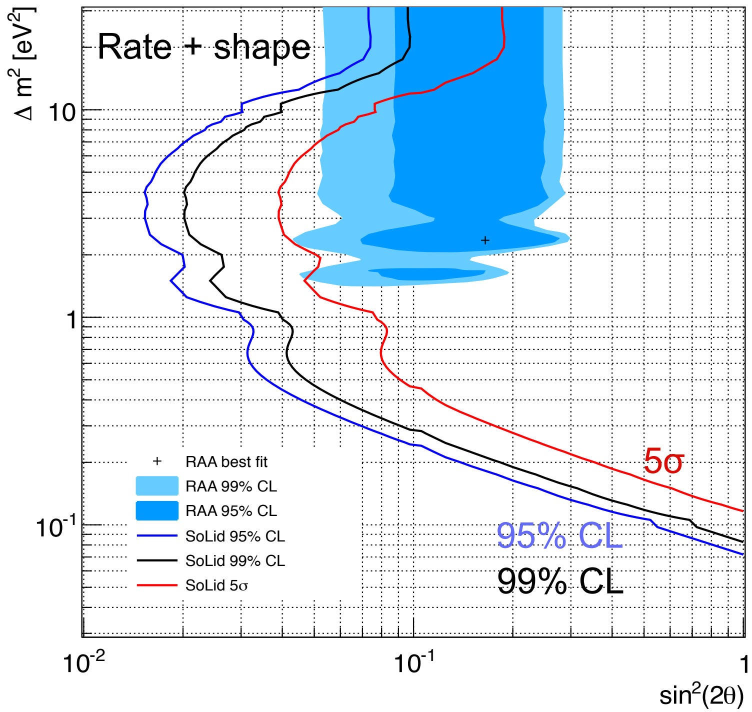
SoLid Sensitivity & status

NEMENIX prototype under test at BR2

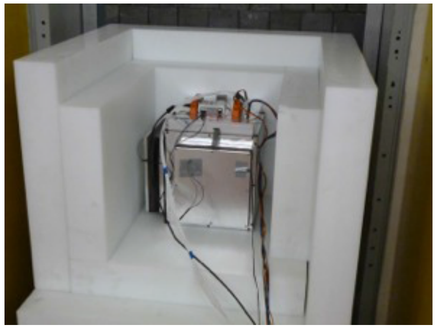
8kg Fiducial mass







Analysis in progress

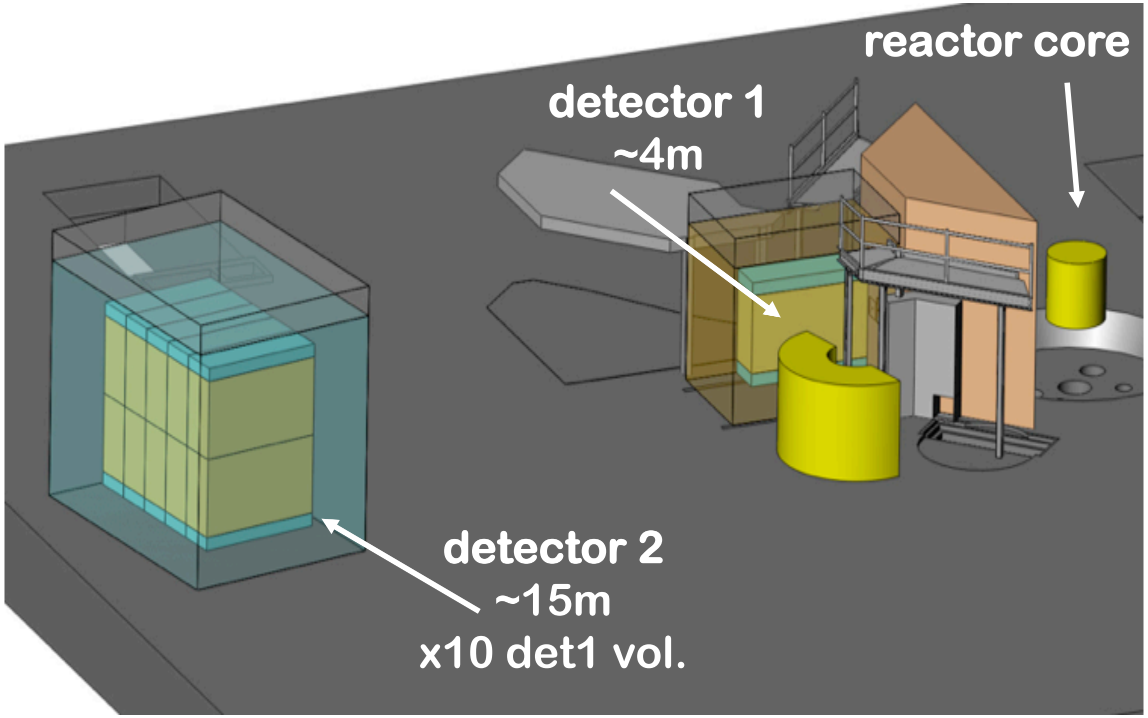


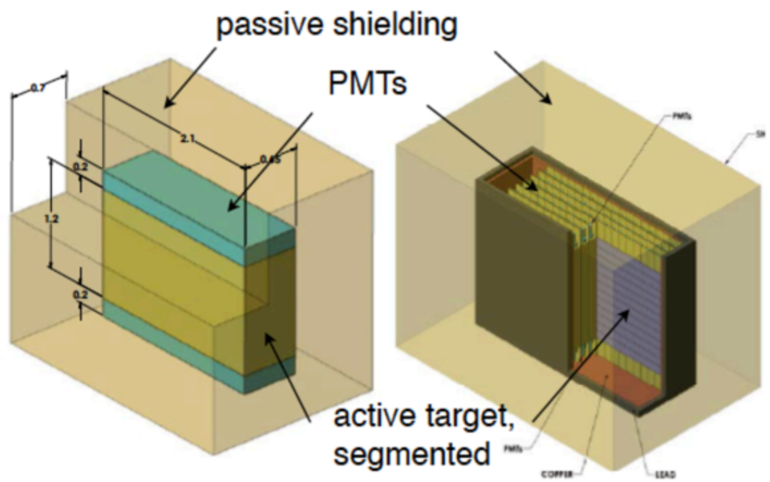
- <Baseline>=6.8m, 2.88t fiducial mass
- 300 days (~ two years running)
- 45% IBD efficiency, 1200 n/day expected
- L binning of 20 cm
- Systematics : norm 4.1%, total ~5%
- Physics run scheduled for start of 2016

2 Detector Concept

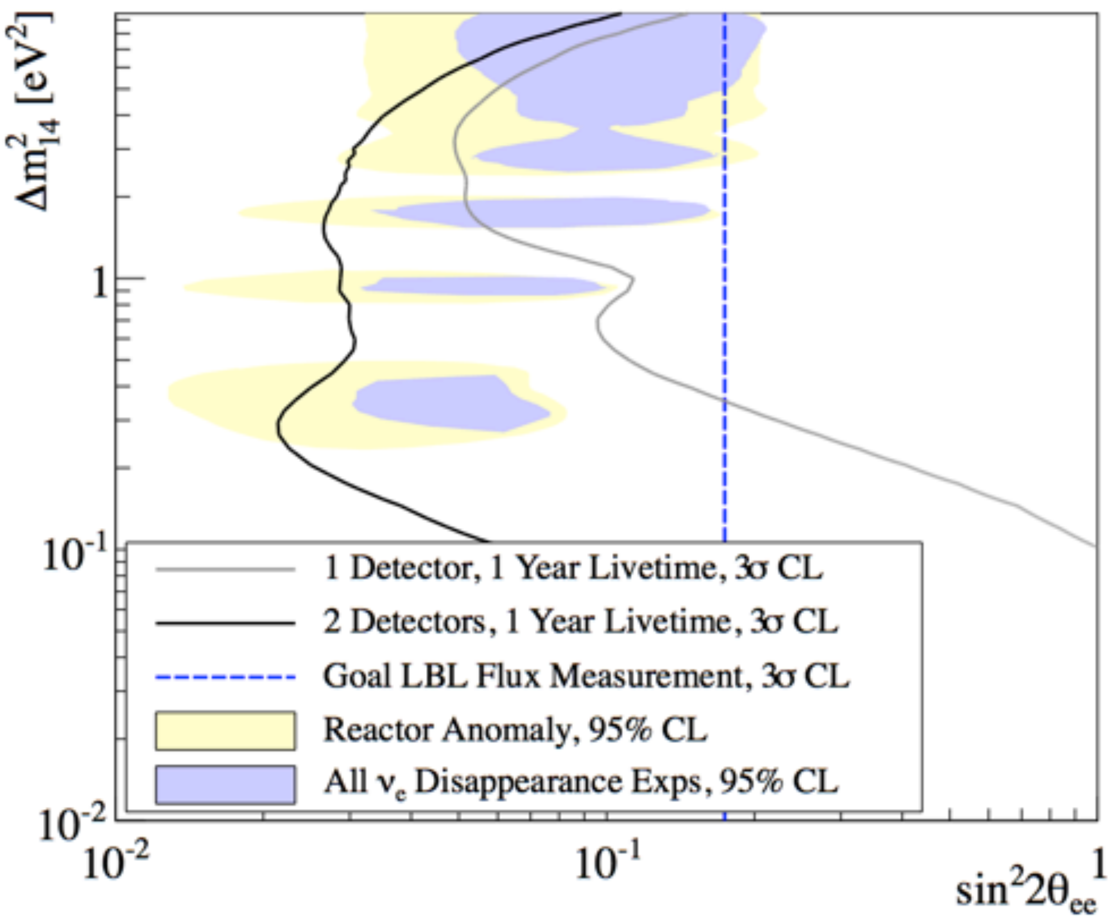
US Effort

- Segmented, LS target based technology
- 3 reactor sites
  - NIST – 20 MW
  - ATR – 85 MW
  - HFIR – 120 MW
- Surface location
- 2-detector concept
- Status:
  - Site characterization ongoing
  - Start 2016?





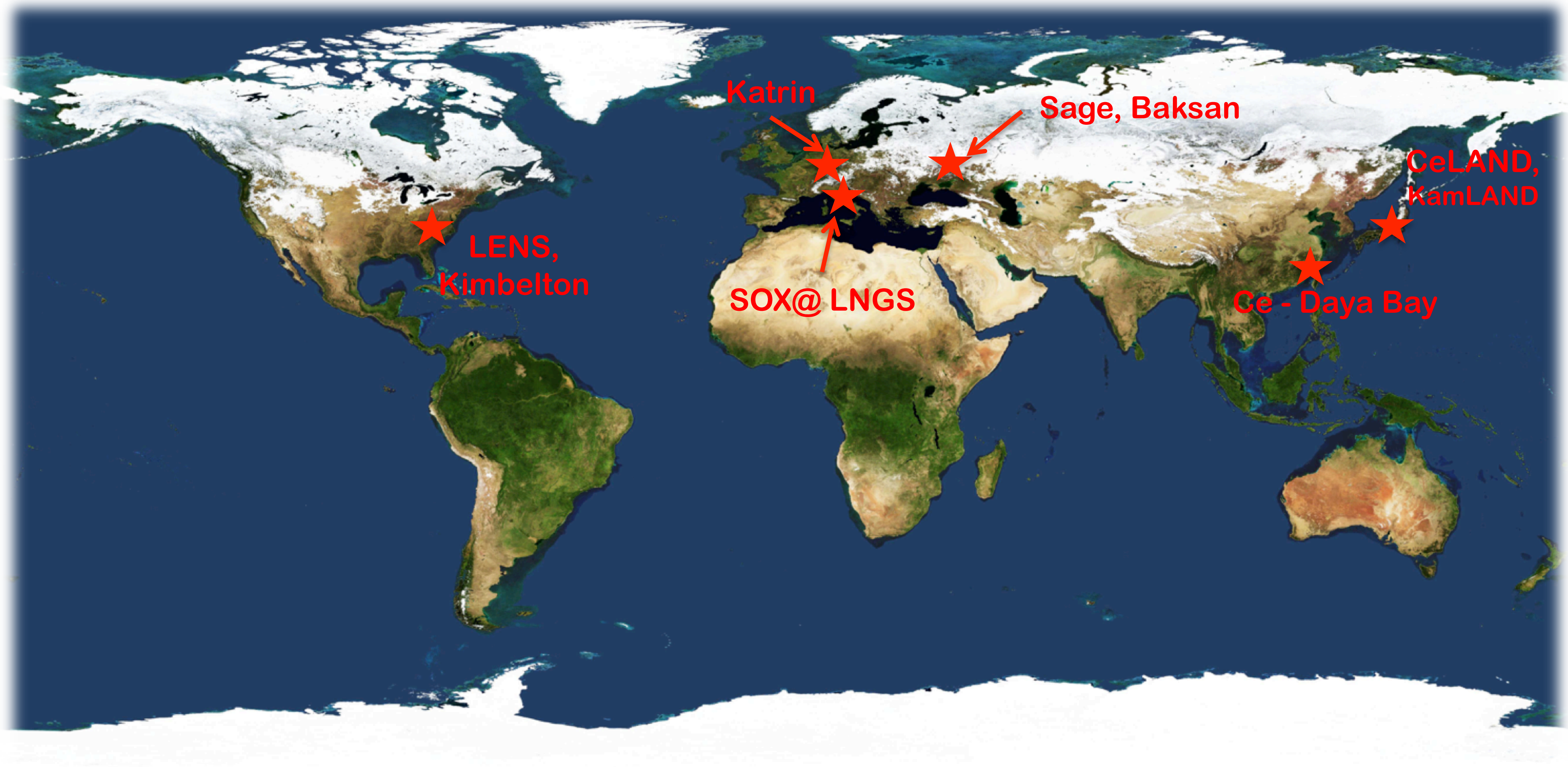
2 Detector Sensitivity



- Extends sensitvity to lower Δm^2
- Possible discrimination between 3+1 and 3+2 scenarios

Source Experiments

Worldwide Experimental Program

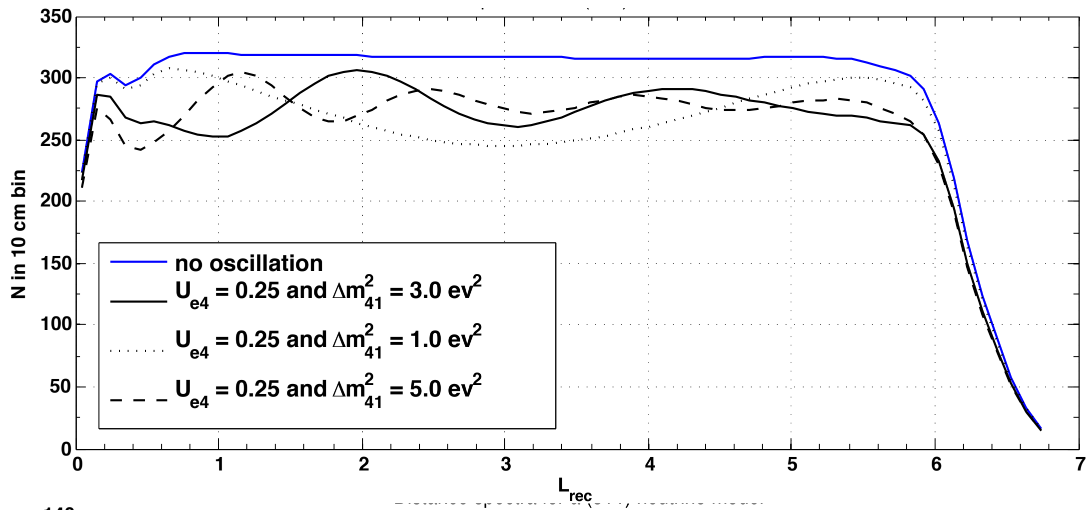


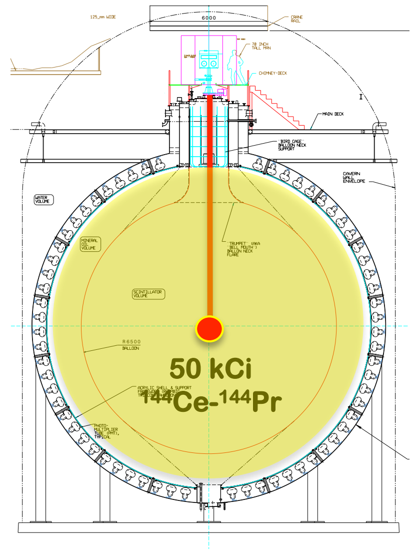
ν Generator Proposals

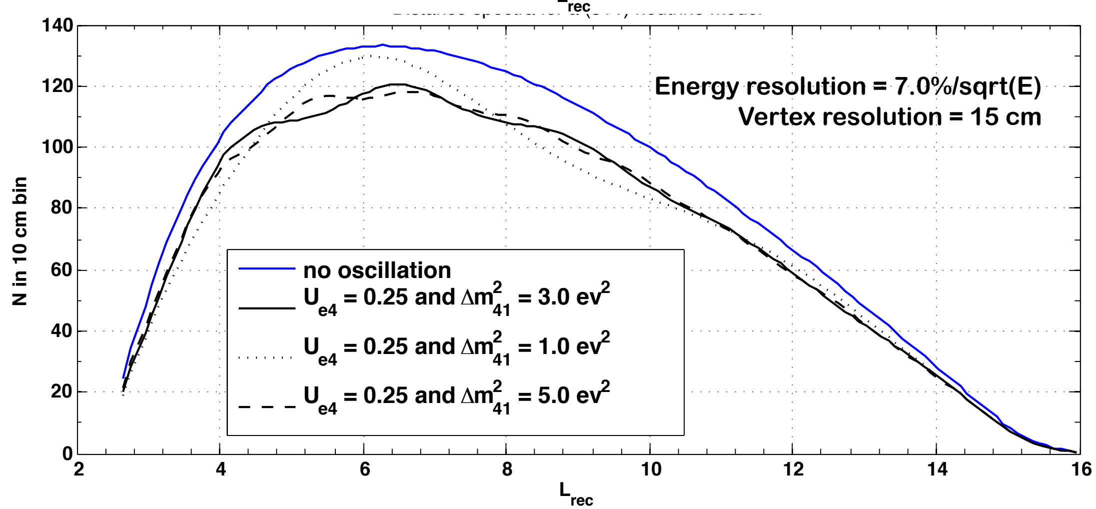
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \to \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
					>10 MCi	SOX (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>1 MCi	-
					5 MCi	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \to e^+ n$ E_{th}=1.8 MeV (e^+,n) 5% E_{res} 15cm R_{res}	reactor ν, geo ν, ν generator impurities	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + REE extraction	75 kCi	CeLAND SOX
					500 kCi	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^3H \to He\ e^-\ \bar{\nu}_e$ EC/β-decay	Kink search	^3H E<18 keV	Irradiation in reactors	3 Ci	KATRIN (Mare/Echo)

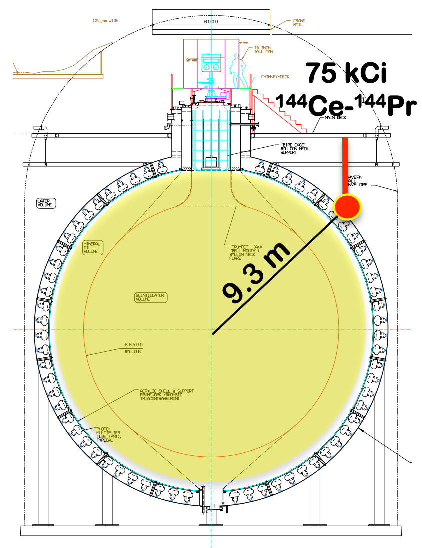
Oscillations from Point-like Source

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









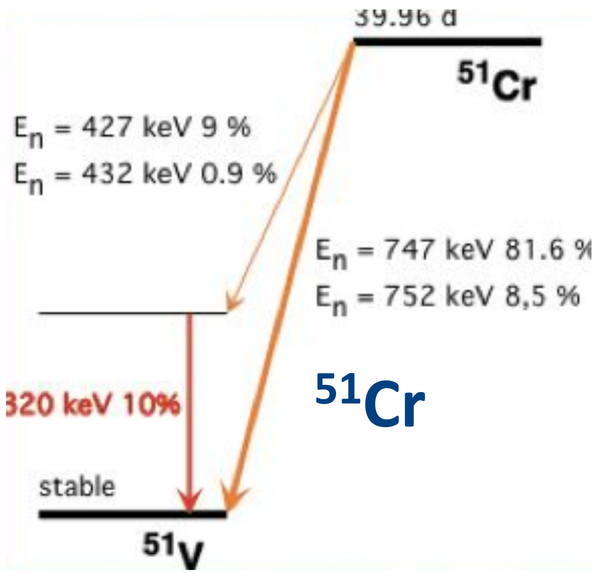
^{51}Cr Neutrino Generator

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

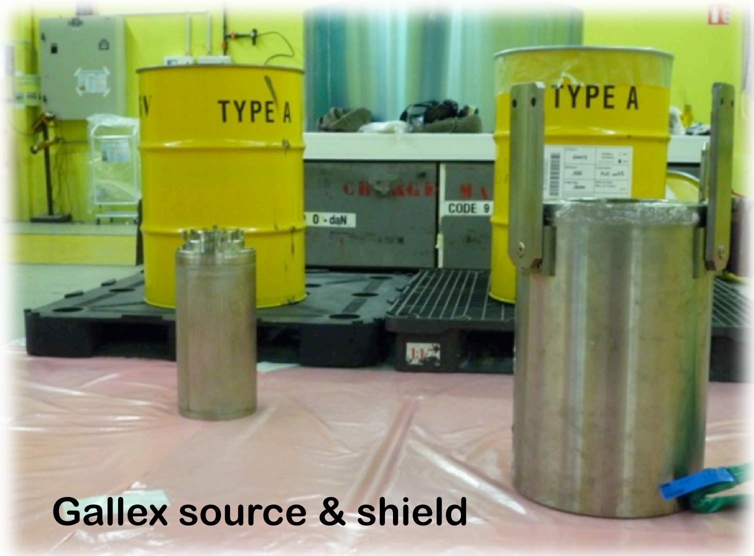
- Production through n_{th} irradiation of enriched ^{50}Cr in a nuclear reactor

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

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



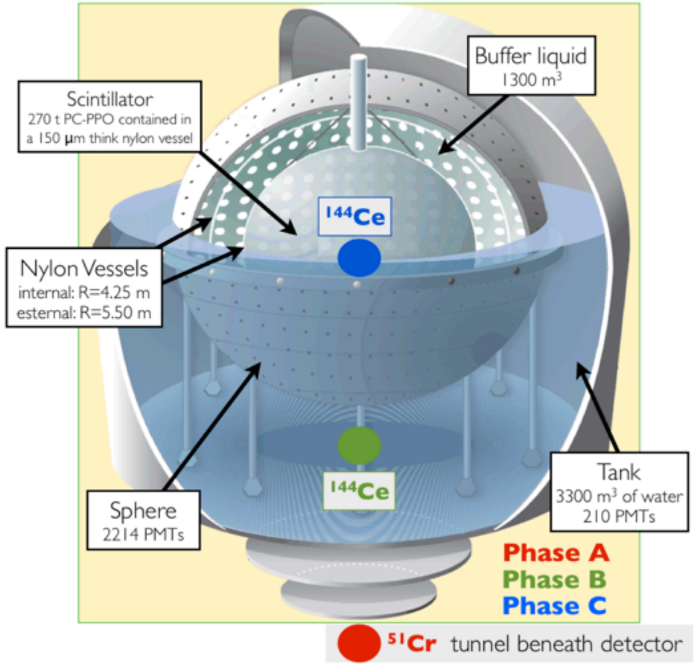
51Cr

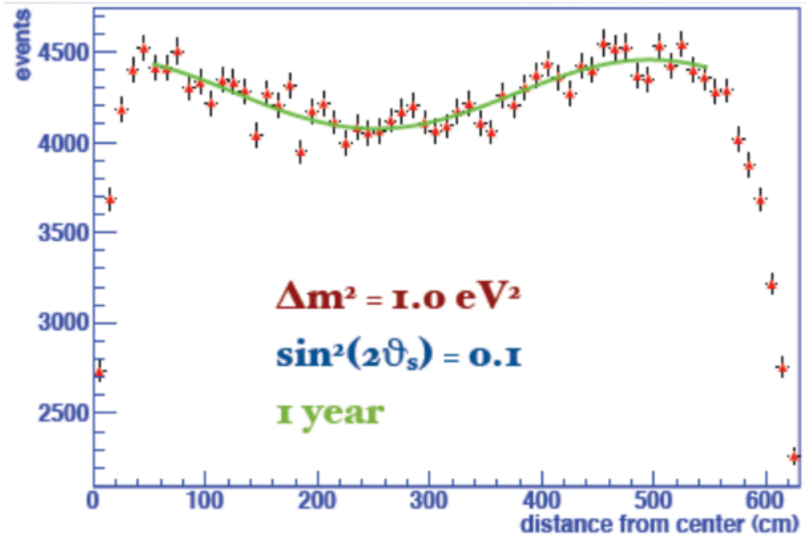


Gallex source & shield

51Cr- SOX (Borexino)

- Re-use Gallex 36 kg of enriched chromium
- Production reactors
  - Oak Ridge (US)
  - Ludmila (Ru)
- Source 8.25 m from center
- Detection as for ^{7}Be solar ν
  - Well known background
- Status:
  - Preparation for irradiation and transportation (10 Mci)
- Staged approach: ^{51}Cr & ^{144}Ce

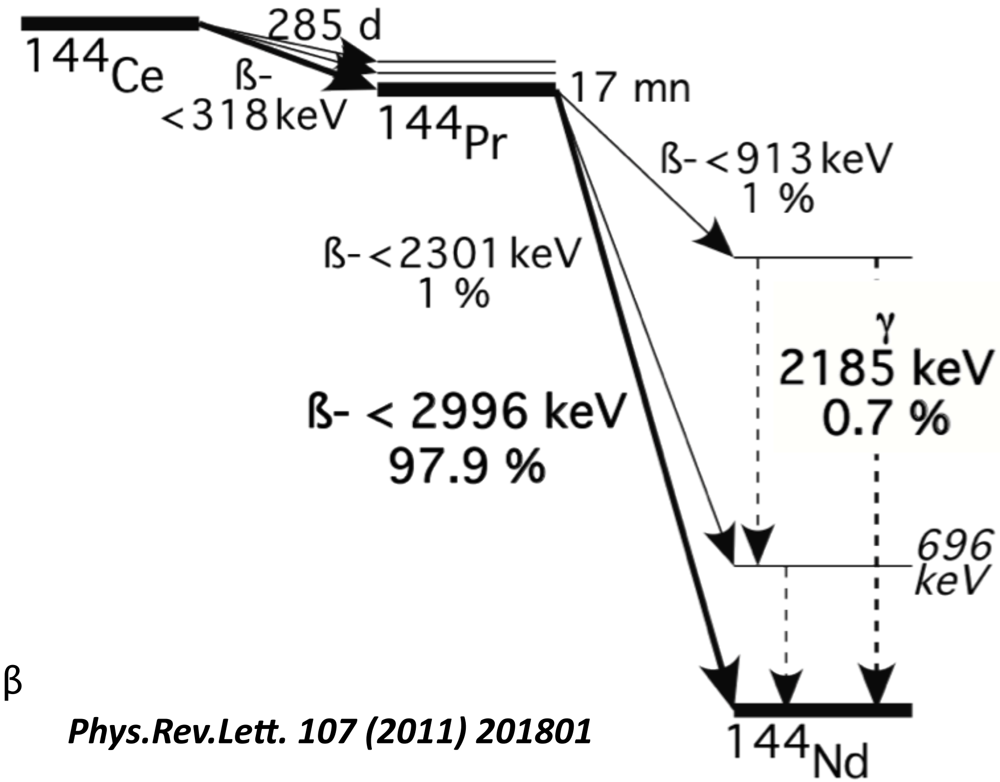




^{144}Ce-^{144}Pr ν generator

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

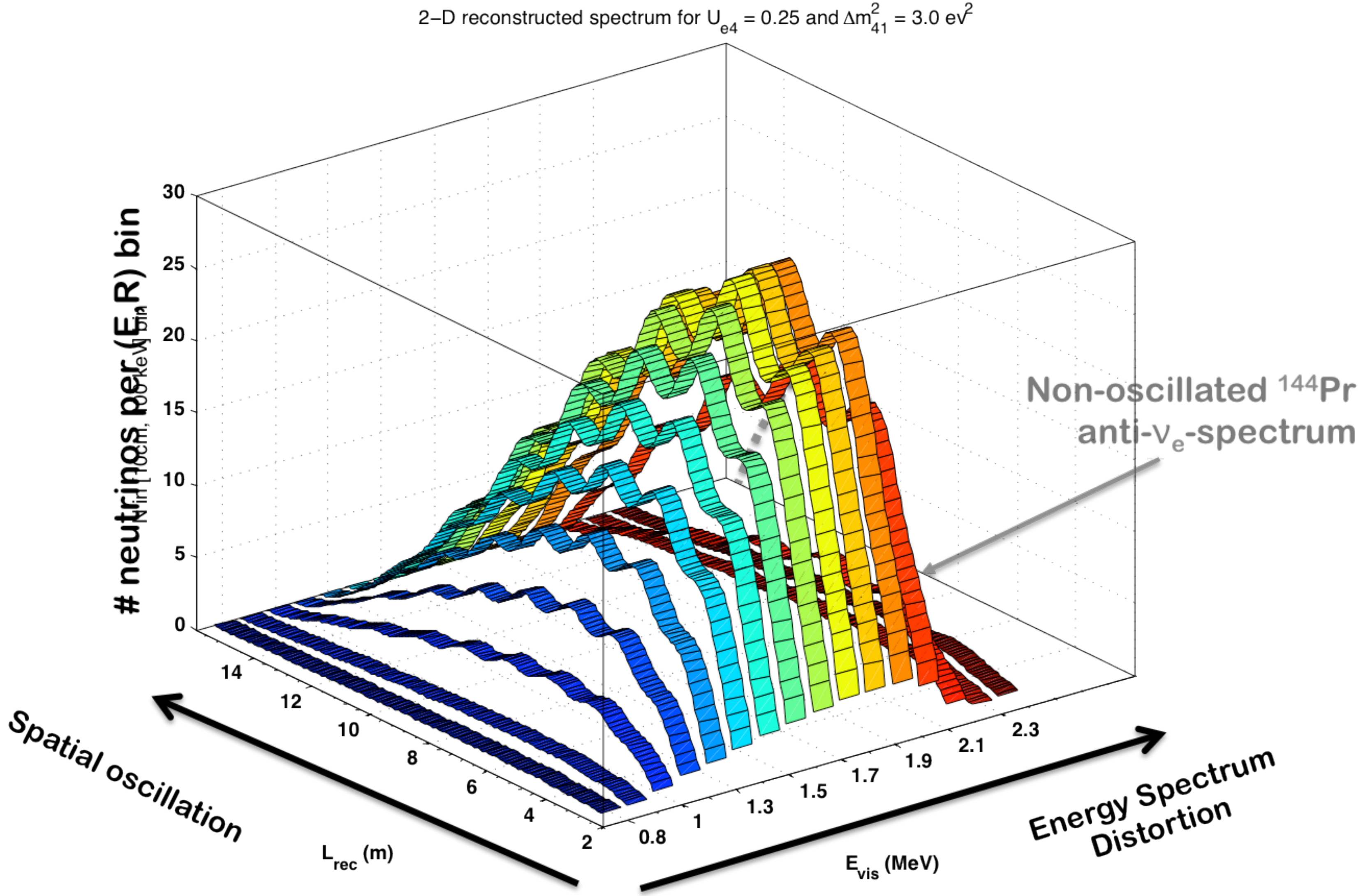
- 2nd Trick: ^{144}Ce-^{144}Pr
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β
    Enough time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β
    $\bar{\nu}_e$-emitter above threshold



Phys.Rev.Lett. 107 (2011) 201801

^{144}Ce-^{144}Pr Signal

75 kCi ^{144}Ce-^{144}Pr – 9.3 m from detector center – 1.5 year



CeLAND

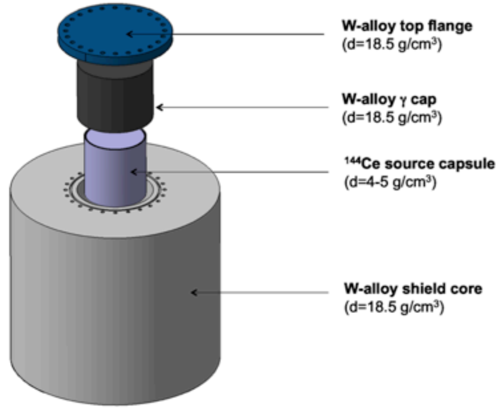
- 75 kCi of ^{144}Ce-^{144}Pr (CeO_2)

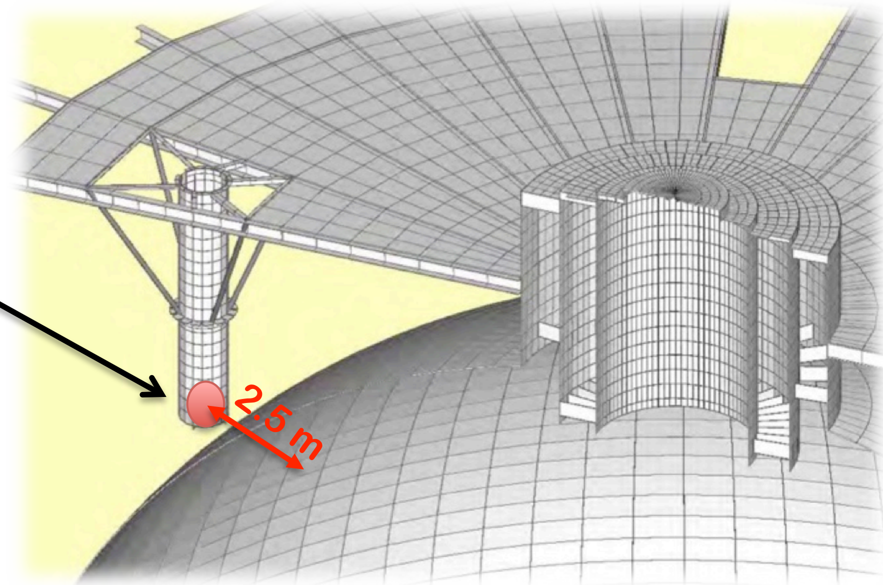
- **Production feasible at Mayak Facility (RU) in 2014 (1 y)**
  - Standard SNF reprocessing
  - Ce extraction through displacement chromatography

- **Need 16 cm tungsten-shield**

- **KamLAND being prepared**
  - Deployment
    - in water veto (3-16 m)
    - In Xenon Room (5-18 m)
  - Run in // with KamLAND-zen

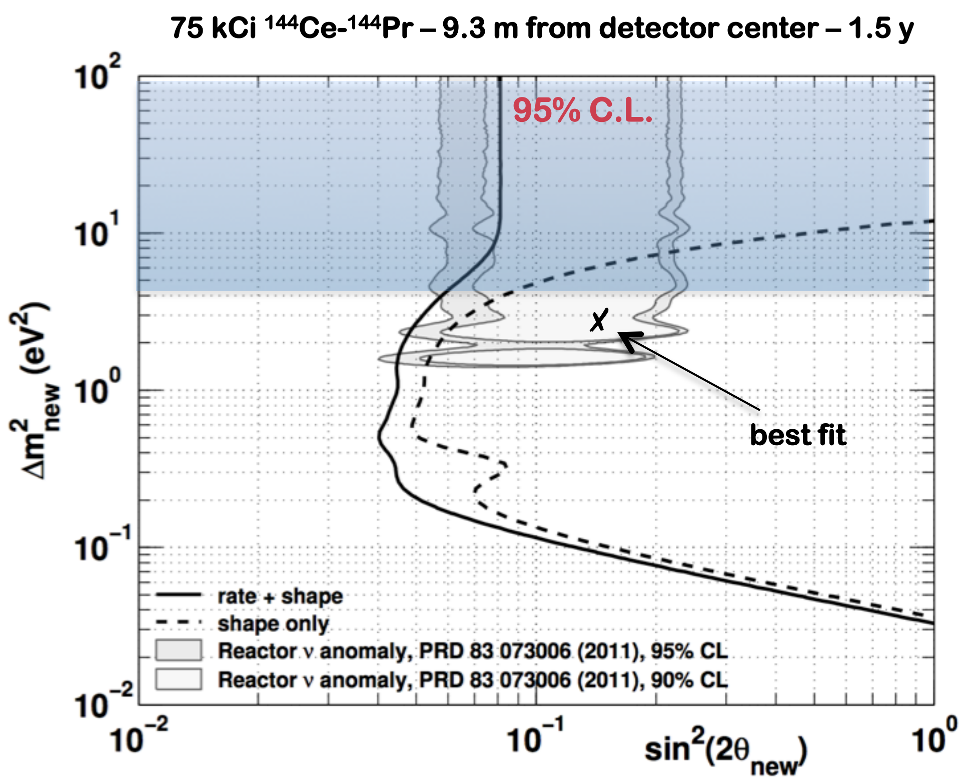
- Deployment in 2015





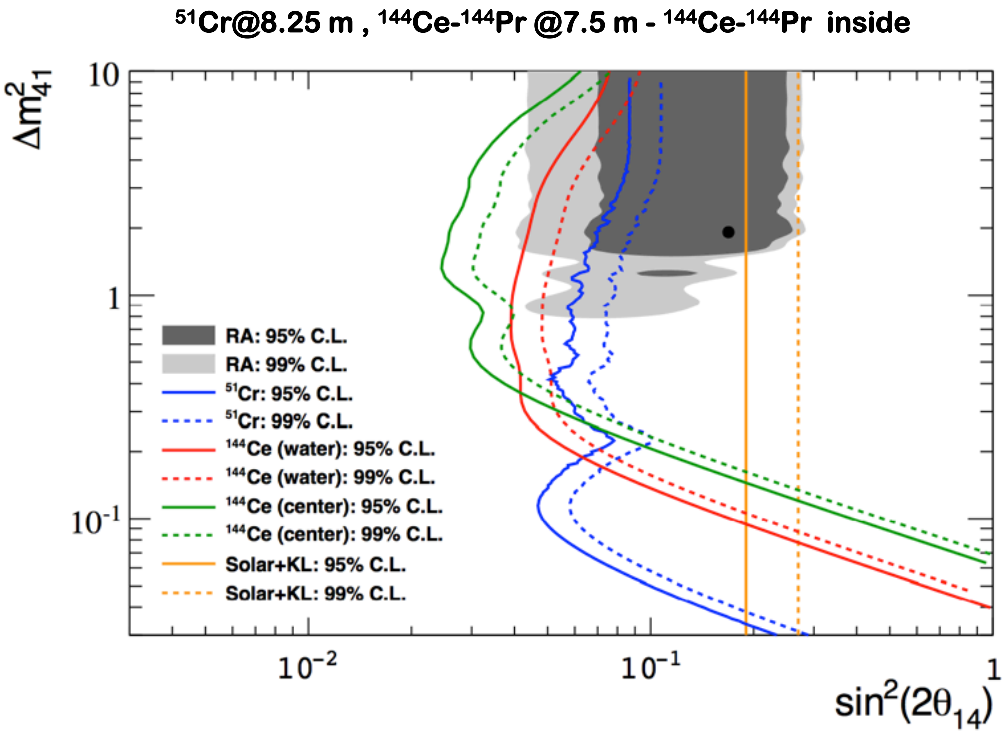
Sensitivities

CeLAND (KamLAND)



^{144}Ce-^{144}Pr in 2015

SOX (Borexino)



^{51}Cr in 2015

^{144}Ce-^{144}Pr in 2016/7

Conclusion

- **Anomalies calling for clarification**
  - Compatible Reactor and Gallium anomalies (ν_e disappearance)
  - Tension in global fit (appearance vs disappearance results)
  - → $\Delta m^2 \approx eV^2$ Sterile Neutrino? Or Experimental Artifacts?

- **Establishing the existence of sterile neutrinos would be a major result for physics .** Many proposals with capabilities to unambiguously test L/E≈1 m/MeV oscillatory behavior within short time scale (5 years) and modest cost.

- **Reactor experiments:** combination of mature technologies and R&D. Background mitigation is challenging.

- **Source experiments**: low background and state of the art detector. Challenging source production and transportation.