Future Short-Baseline Sterile Neutrino Searches with Reactors

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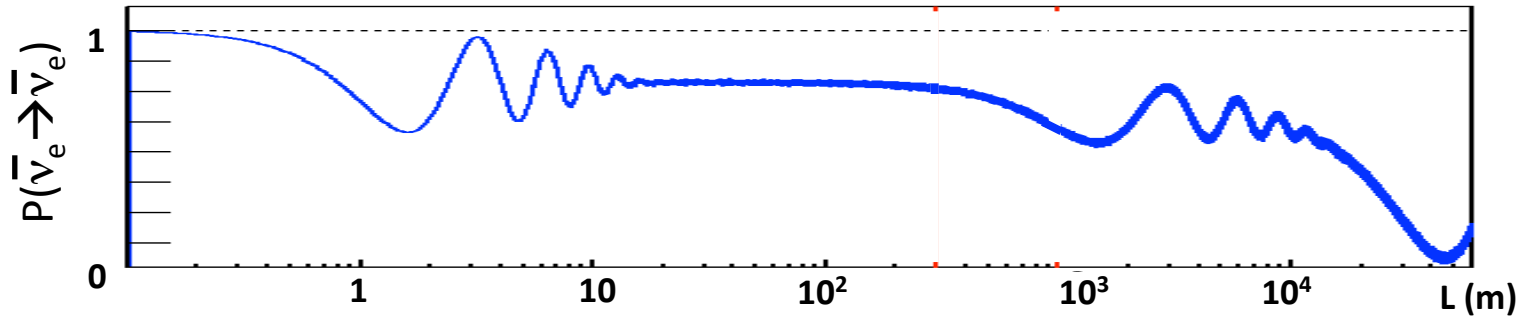
CEA - Saclay

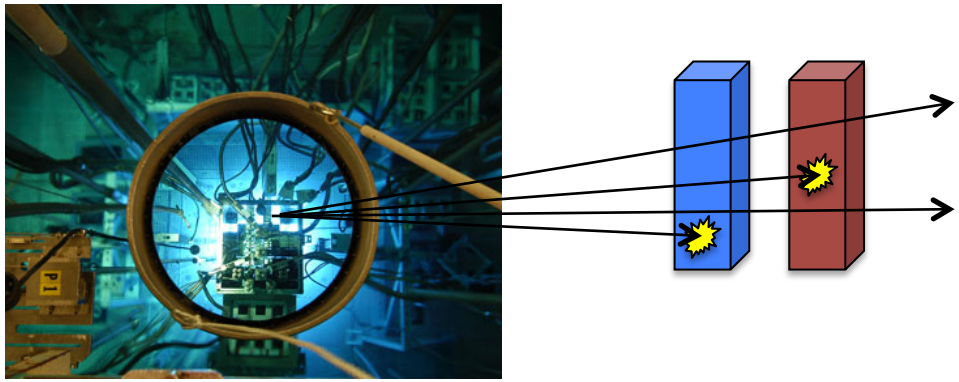
Neutrino 2014 - Boston

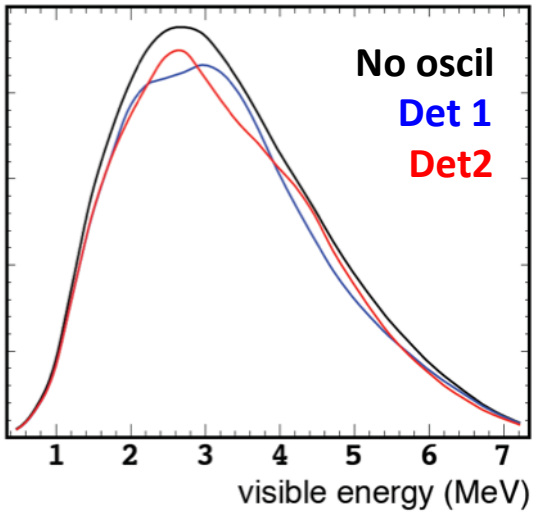
Testing the New Oscillation Hypothesis

Direct test of a new oscillation pattern in E & L

$\Delta m^2 > 0.1$, $\sin^2 2\theta > 0.05$ → L_{osc} = [1-10] m

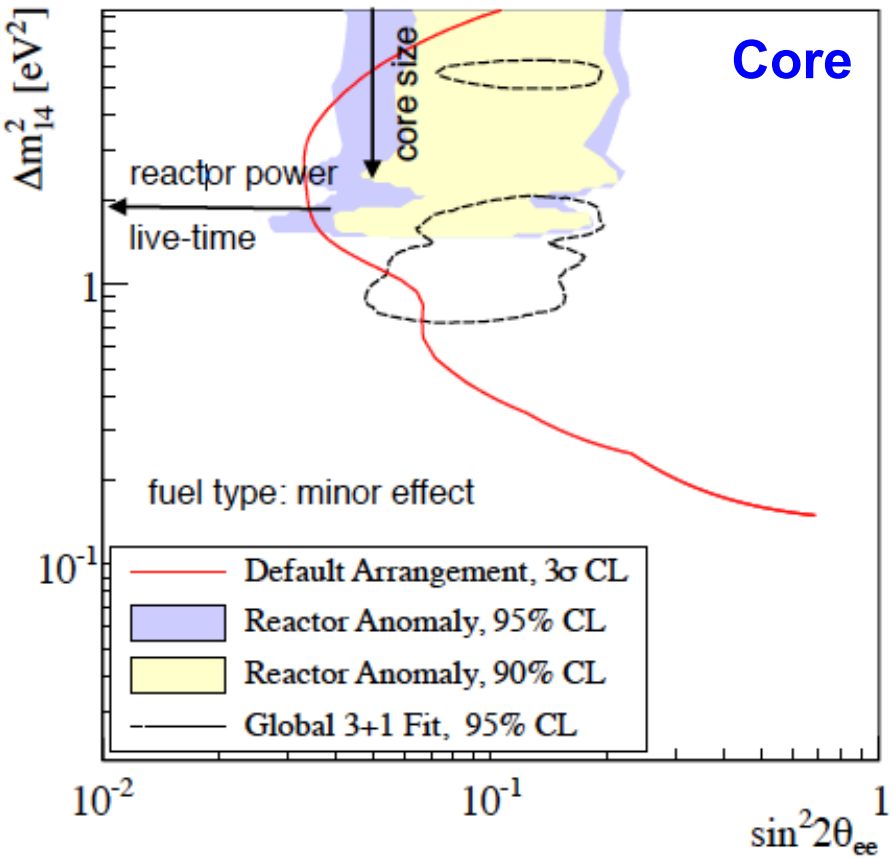


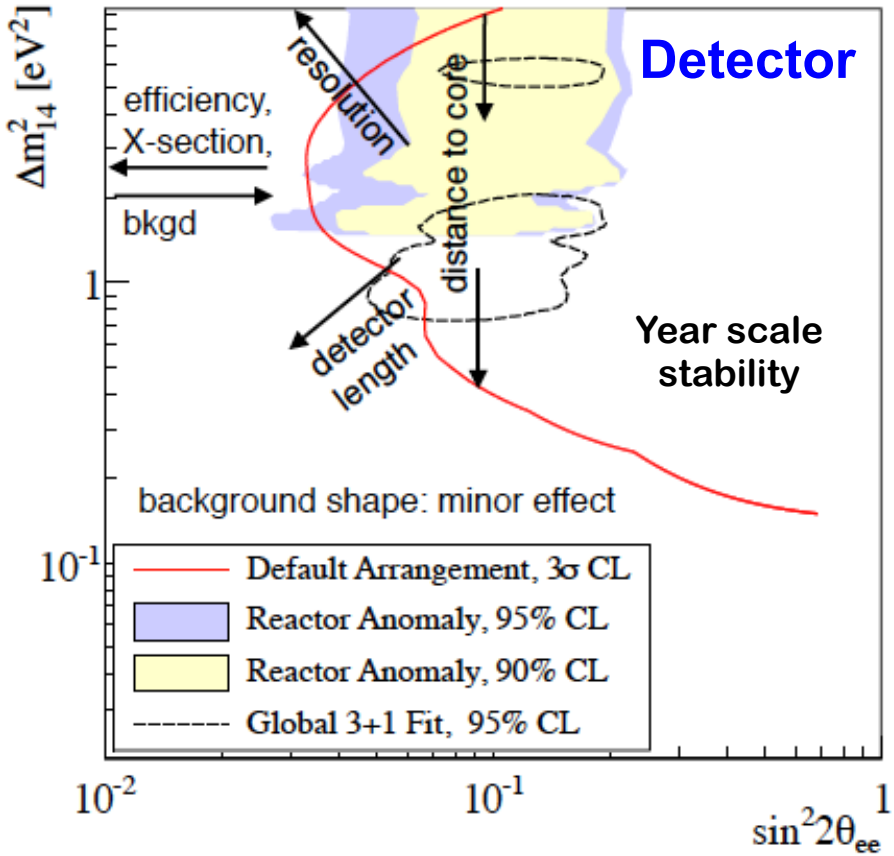




- <u>Relative</u> shape distortion in identical detector modules
- Complemented by rate info.

Key Experimental Parameters





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

Few % Accuracy @ Reactors

- **High statistics**
  - Intense source
  - Very short baselines available

- **Variety of reactor sites**
  - Compact sources at research reactors vs powerful commercial reactors
  - Large range of E (1-8 MeV) and L (5-20 m) covered
  - 93% to 4% enriched nuclear fuel

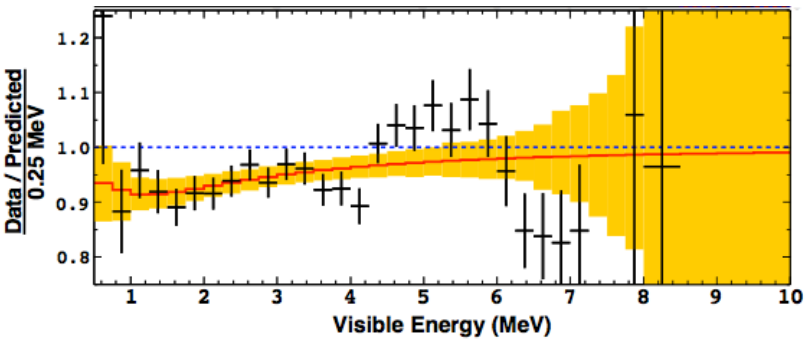
- **Predicted reactor spectrum**
  - What shape?

- **Challenging background mitigation at shallow depths and very short baselines**

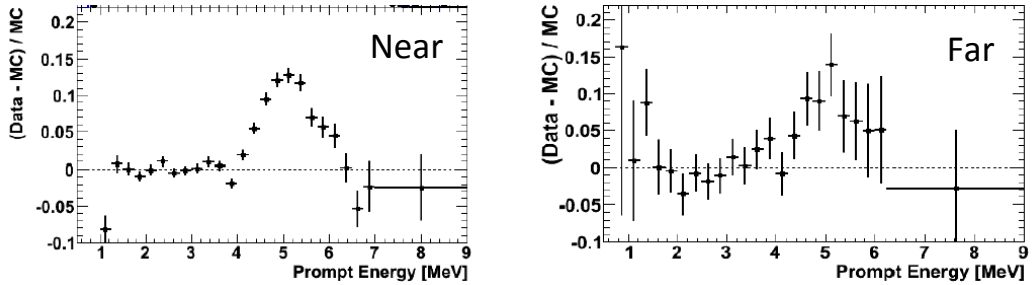
  → Review the detection technics of current projects

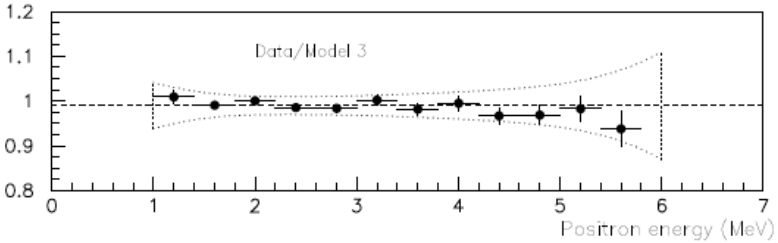
Convergent Signs of ν Excess at 5 MeV

Double Chooz, this conference

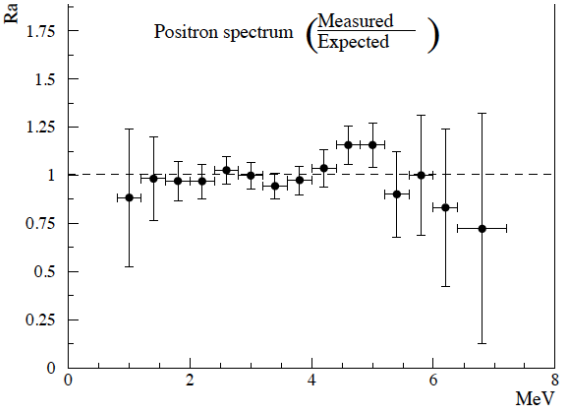


RENO, this conference

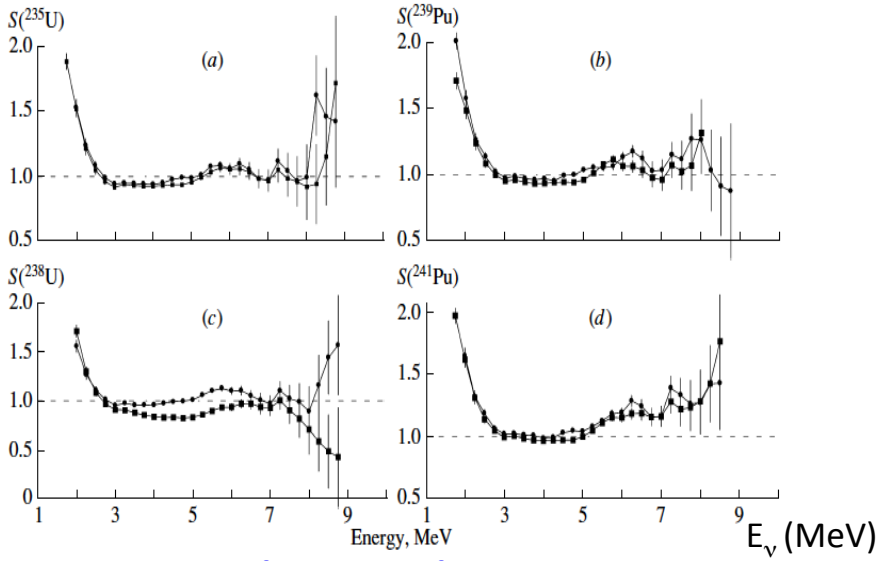




Bugey, Phys.Lett. B374 (1996) 243-248



CHOOZ,
Phys.Lett. B466 (1999) 415-430



Rovno, V. Sinev, arXiv:1207.6956

Neutrino Excess at 5 MeV

- Upcoming release of **Daya Bay** spectrum shape → high significance of combined results (?)

- **Origin of the excess to be understood:**
  - Bias in the conversion procedure? Difficult to induce a localized excess with distortion of (forbidden) beta-decay branches.
  - Bias in the reference electron-ILL data? Well beyond the currently known systematics.
  - New neutrino interaction?

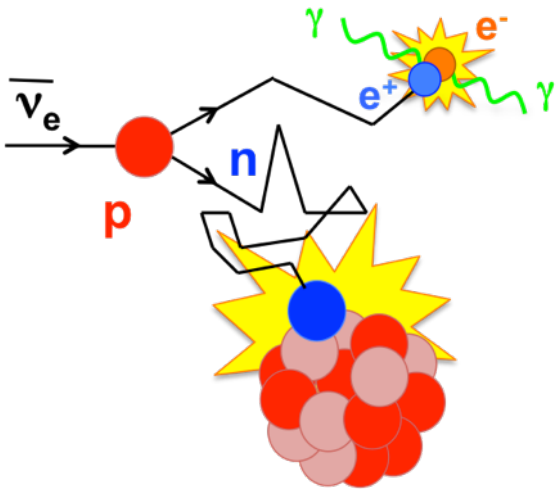
- **Input for short baseline reactor experiments**:
  - The combined analysis of high precision data from DC, DB and Reno may surpass the accuracy of current predictions.
  - **All projects are based on relative shape (+norm) distortions** in identical detectors at different baselines and are therefore little sensitive to a fixed spectrum distortion (as demonstrated by accurate θ_{13} measurements).

Background mitigation of very short baseline and shallow depth experiments

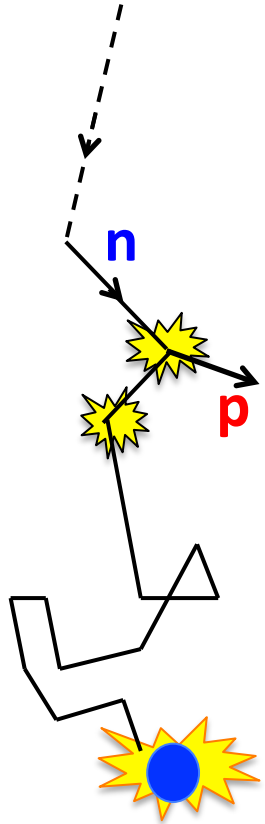
Detection Process and Backgrounds

Inverse Beta Decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



Selective prompt-delayed signal sequence



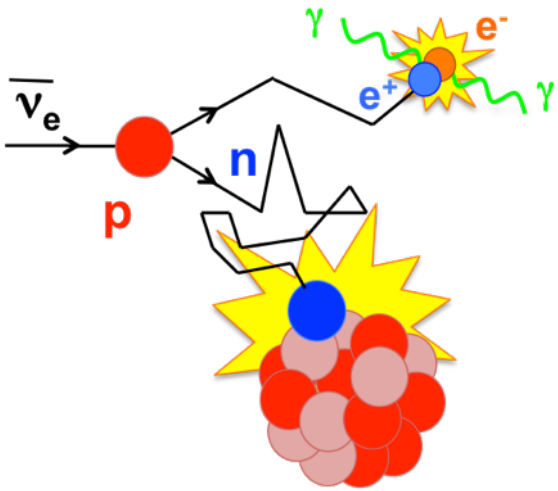
Correlated background from fast n

- Cosmic rays - induced
- Fast n from reactor is a killer
- **Online rejection:**
  - Minimal overburden
  - Active μ veto around target
  - PSD
- **Offline**:
  - Subtraction of reactor OFF data

Detection Process and Backgrounds

Inverse Beta Decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



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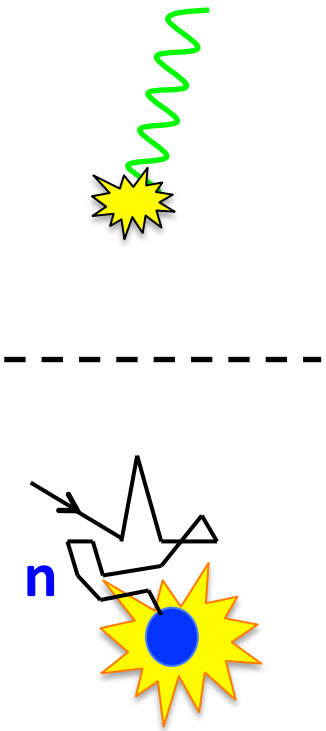
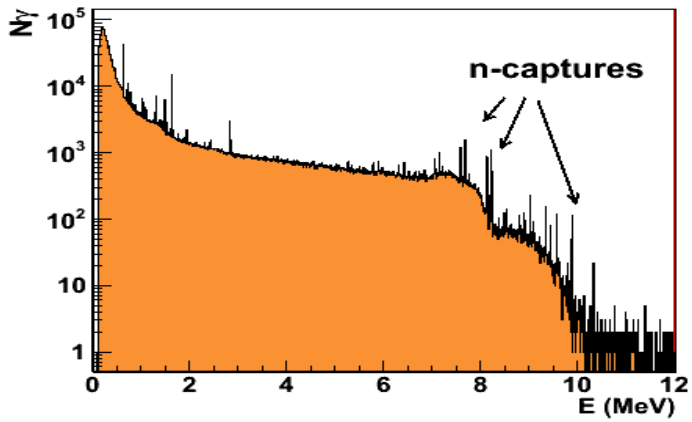


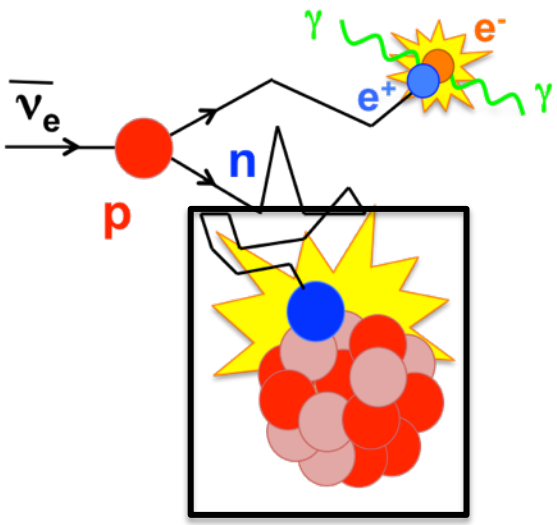
Accidental [γ-n_{th}] coinc

- Reactor dominated
- n_{th} leakage
- High E γ's from n-capture on metals, ^{16}N production in primary circuit, …



→
- On site measurements + heavy shielding design
- Online measurement and subtraction

Neutron Discrimination



Gd-loaded LS

$$n + Gd \rightarrow Gd + \gamma's\ (8\,MeV)$$

- Mature technology with few years scale stability
- Short capture time
- PSD capability

But

- Sensitivity to high-E γ's
- Inefficiency from detector edge effects

n-capture on ^{6}Li

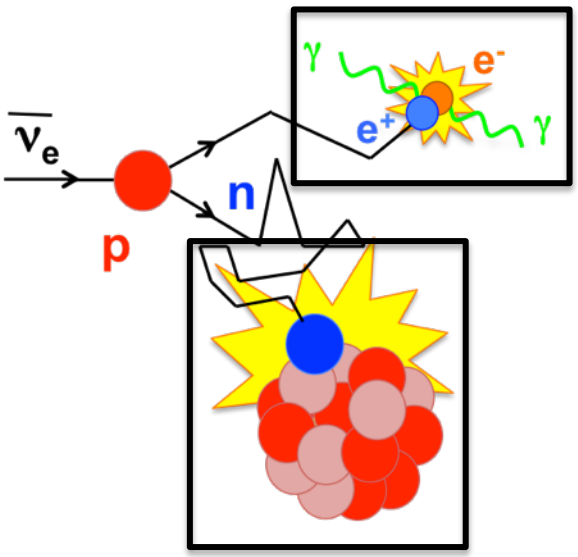
$$n + {}^6Li \rightarrow \alpha + t$$

- Very discriminant final state for online rejection of electromagn background
- High efficiency from localized E deposition
- Short capture time achievable

But

- Low energy signal in LS
- R&D for large target volume

Event Topology



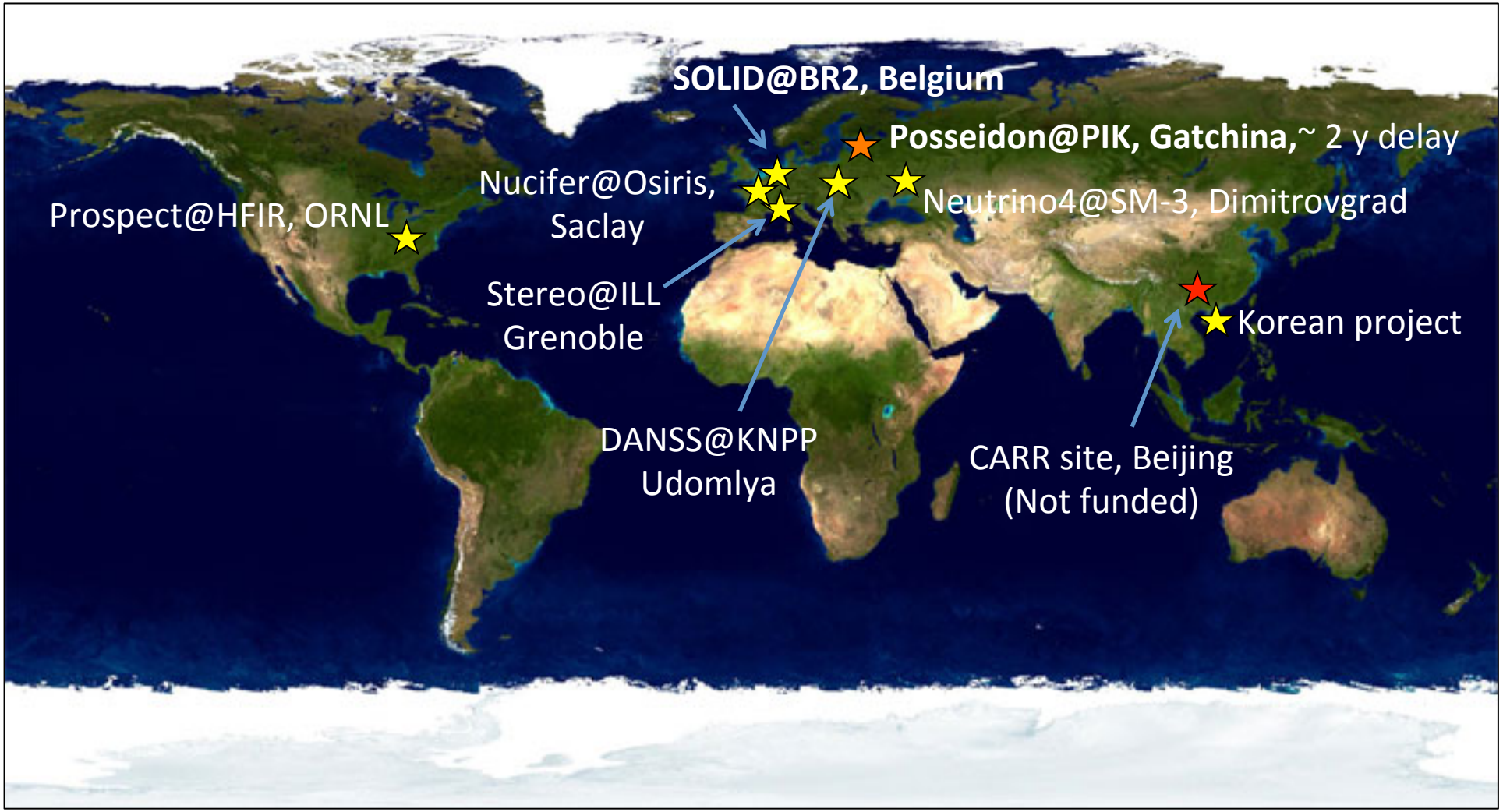
Highly segmented detector (10 cm scale) can help tagging the specific pattern of E deposition of the IBD process

- E depositions of e^+:
  e+ → compact track
  + annihilation γ's → longer int. length

- Space correlation between prompt and delayed vertices linked to n capture time.

Limitations: dead layer of the cell walls, light output, intercalibration

Worldwide Overview



Reactor Proposals

	Gd	^{6}Li	Highly Segmented	Moving detector	2 det.
Nucifer (FRA)	■				
Poseidon (RU)	■				
Stéréo (FRA)	■			■	
Neutrino 4 (RU)	■			■	
Hanaro (KO)	◣	◥	■	■	
DANSS (RU)	■		■		
Prospect (USA)	◣	◥	■		■
SoLid (UK)		■	■		

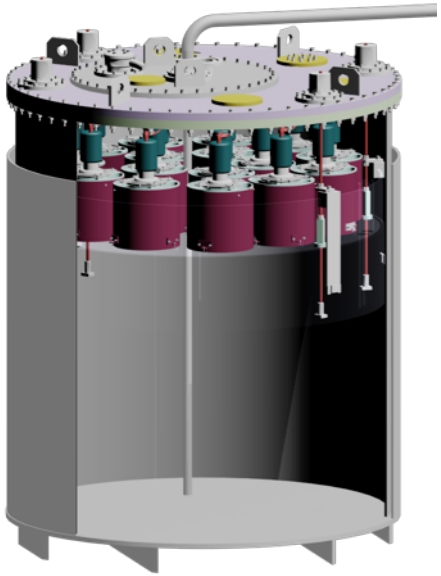
Reactor Proposals

	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
Nucifer (FRA)	70	0.8	7	13
Poseidon (RU)	100	~ 3	5-8	~ 15
Stéréo (FRA)	57	1.75	8.8-11.2	18
Neutrino 4 (RU)	100	1.5	6-12	~ 10
Hanaro (KO)	30-2800	~ 1	6	few
DANSS (RU)	3000	0.9	9.7-12.2	50
Prospect (USA)	85	1 & 10	7-18	few
SoLid (UK)	45-80	2.9	6-8	10

Gd-Loaded Liquid Scintillators

Nucifer @ OSIRIS

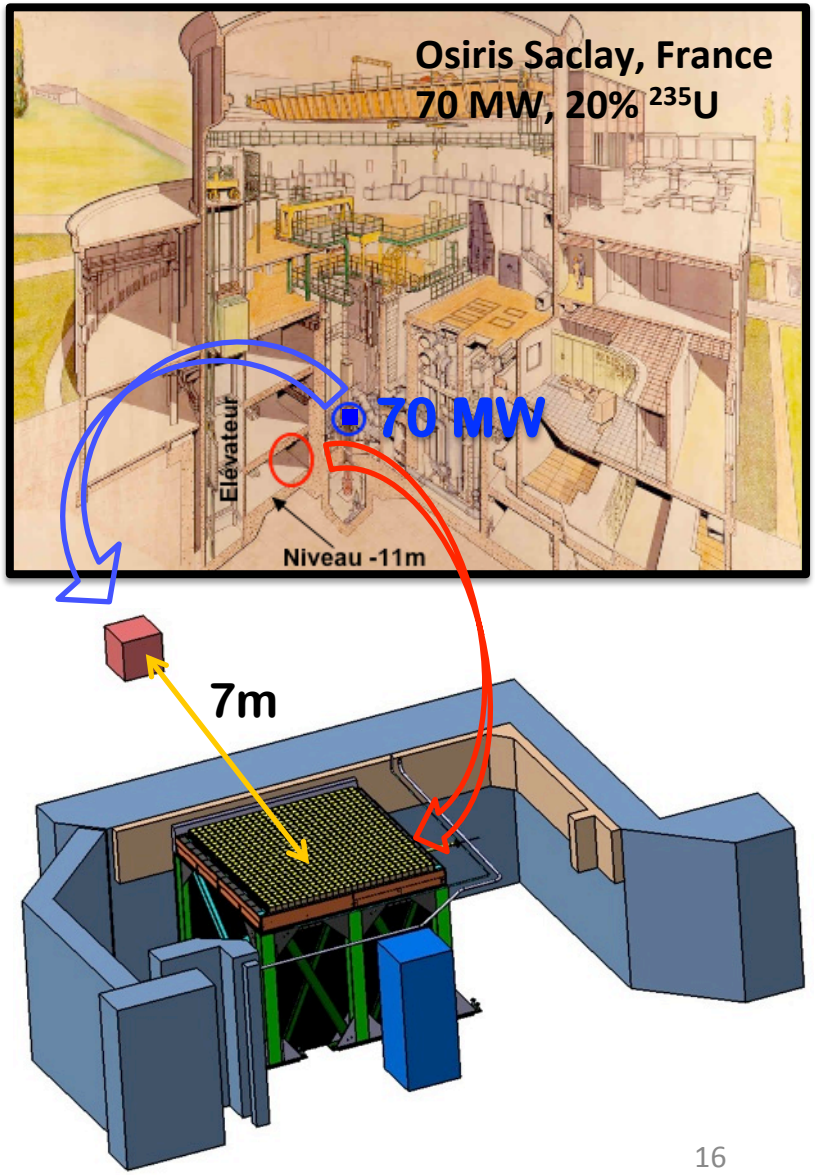
Simple design for reactor monitoring studies



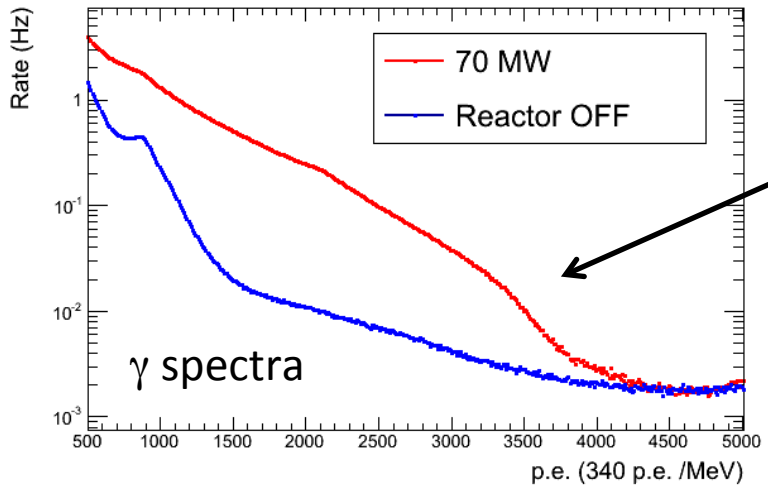
- 850 l Gd-loaded LS
- Compact core (60x60x60 cm^3)
- Short baseline: 7m
- 10 mwe overburden
- ~300 detected ν/day expected

→ Some sensitivity to Sterile ν

But challenging reactor background

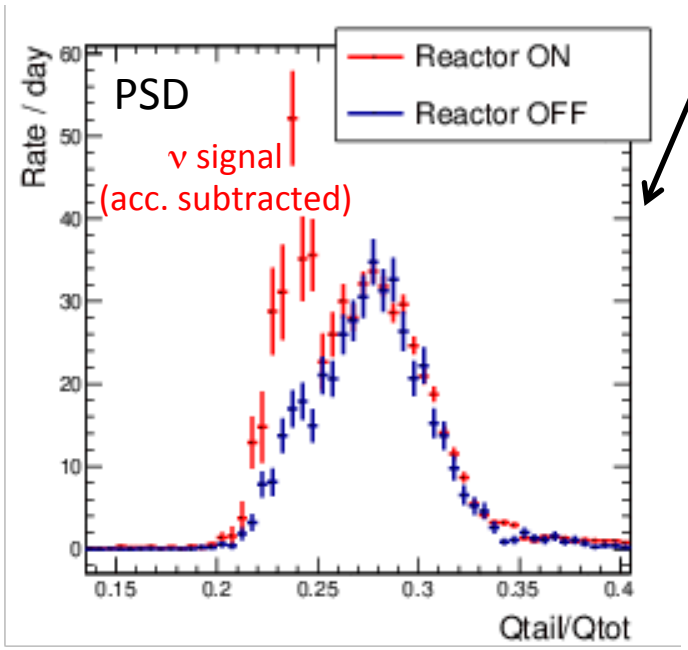


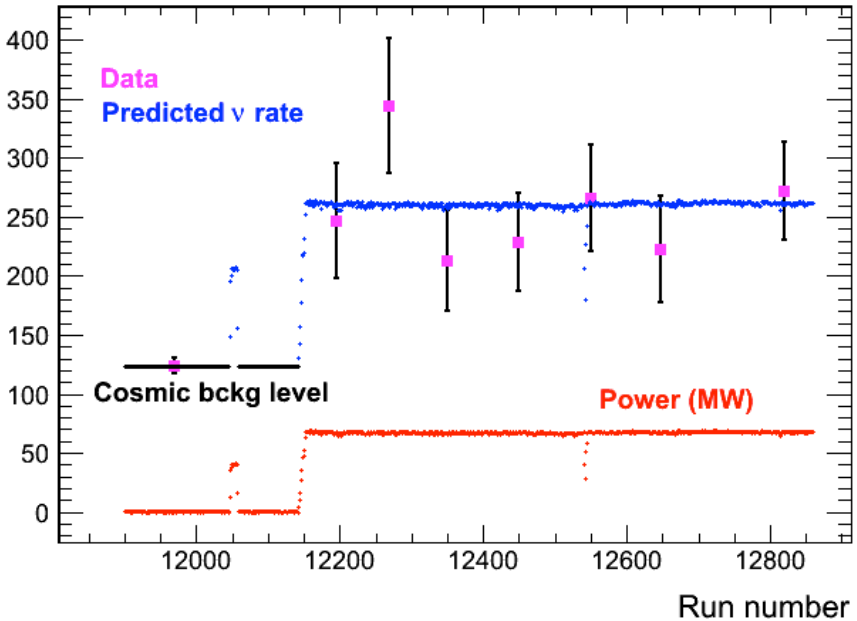
Nucifer @ OSIRIS



- Need further γ attenuation to reach ν/Acc ~ 1. New data taking next week with extra 4 cm of lead on reactor side.

- Rejection of cosmic background with PSD
  No reactor induced fast n @ 7m from core.





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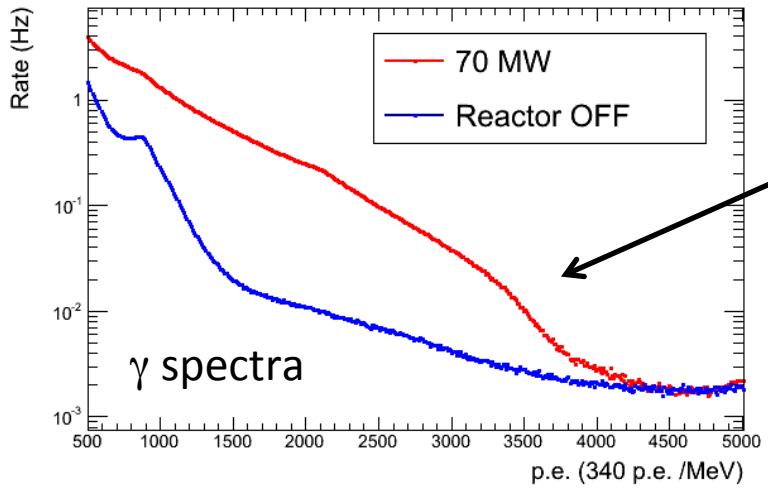

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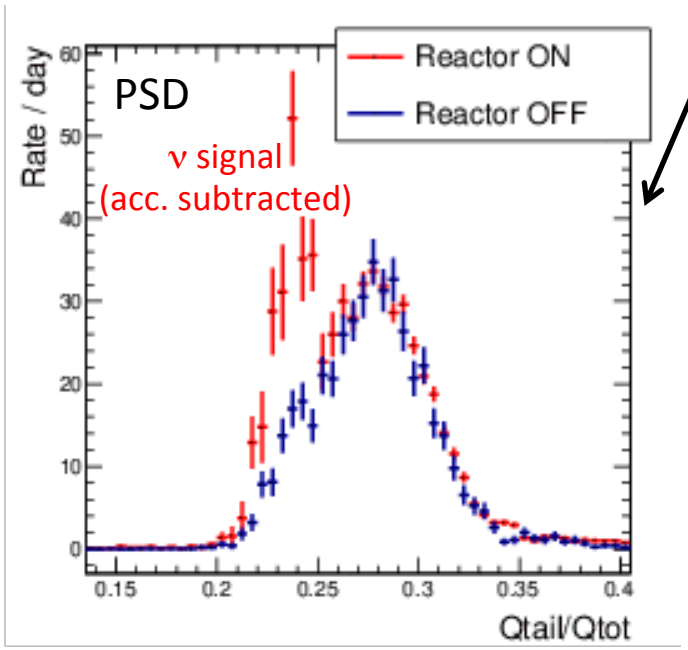
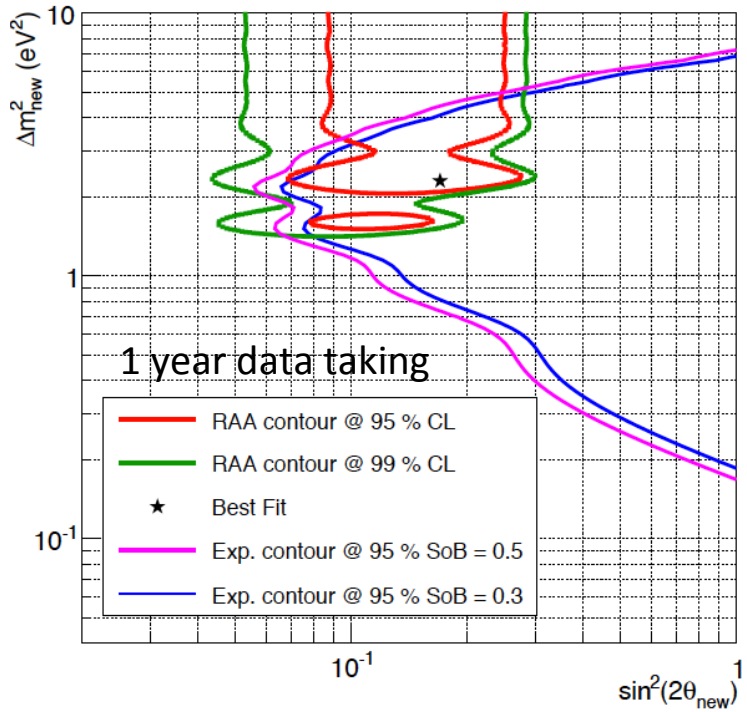
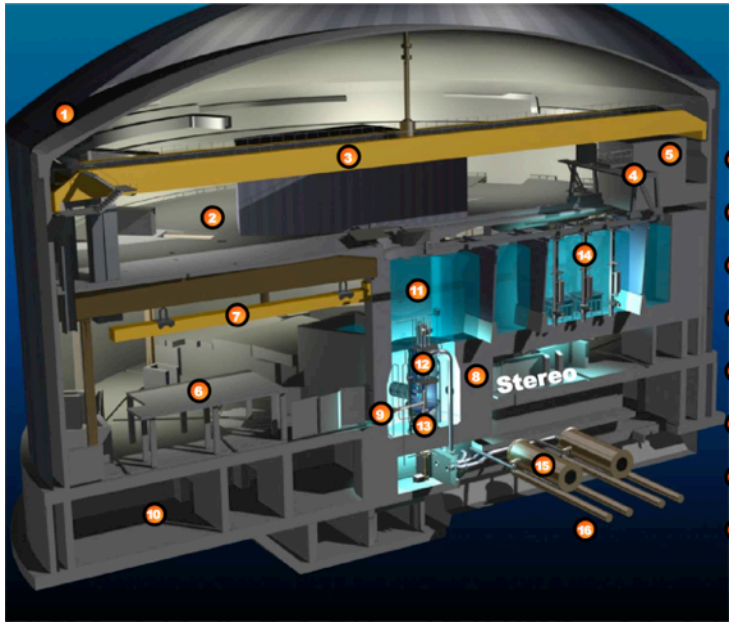
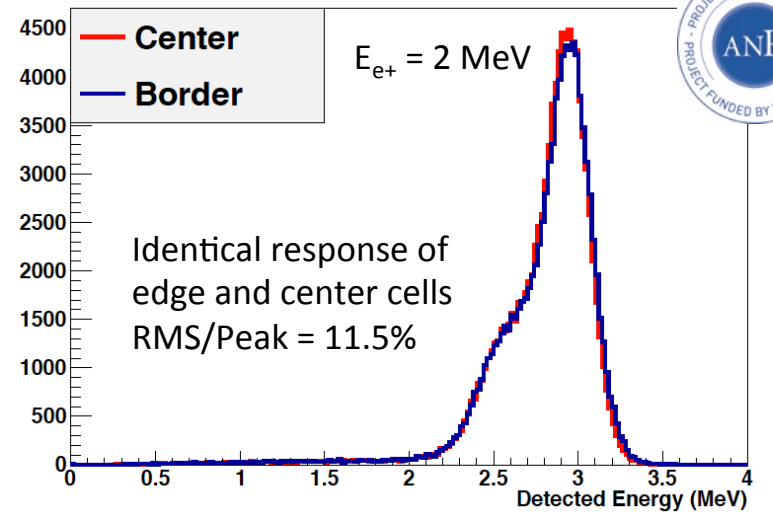
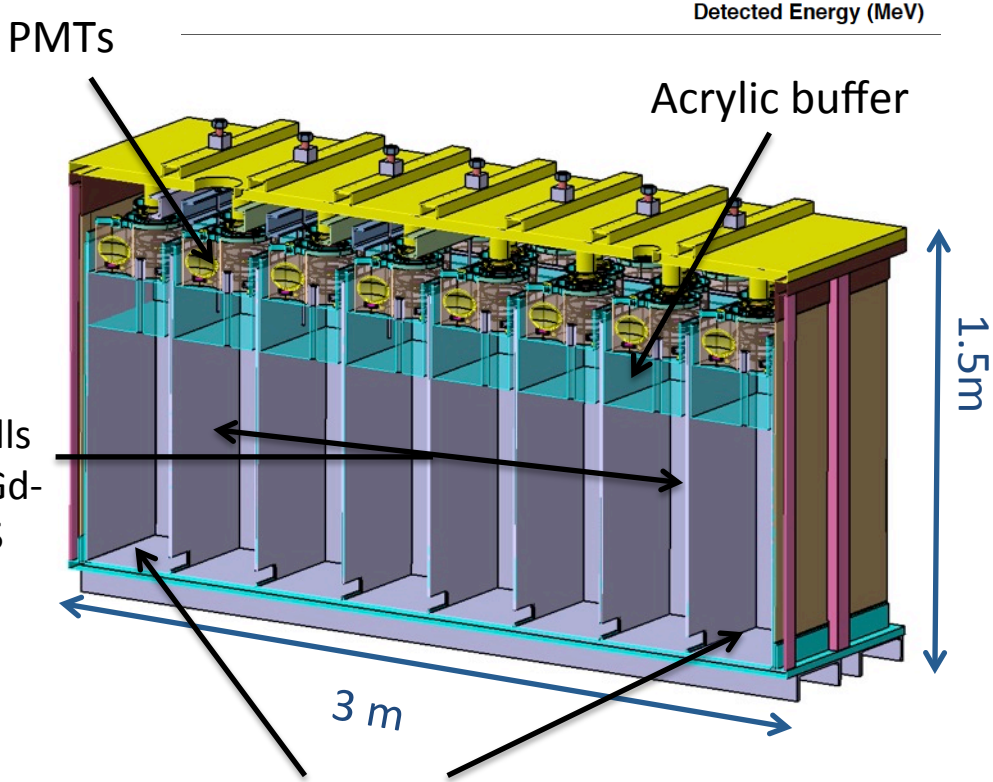




STEREO @ ILL





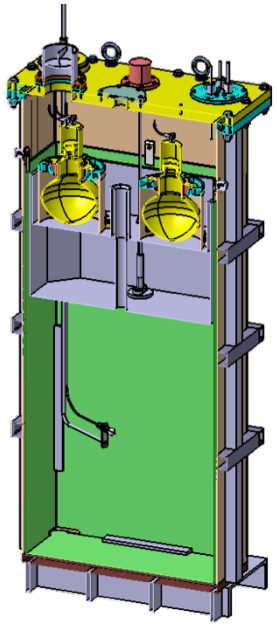


ILL site:

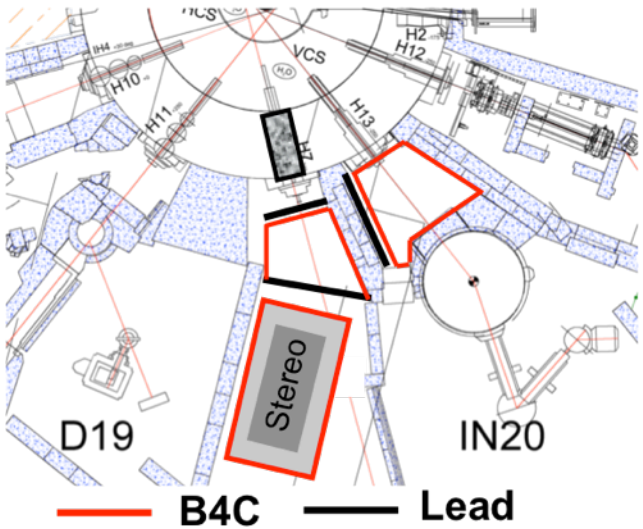
- 57 MW, compact core < 1m
- [8.9–11.1] m from core, possible extension to 12.3 m.
- 15 mwe overburden
- High level of reactor background

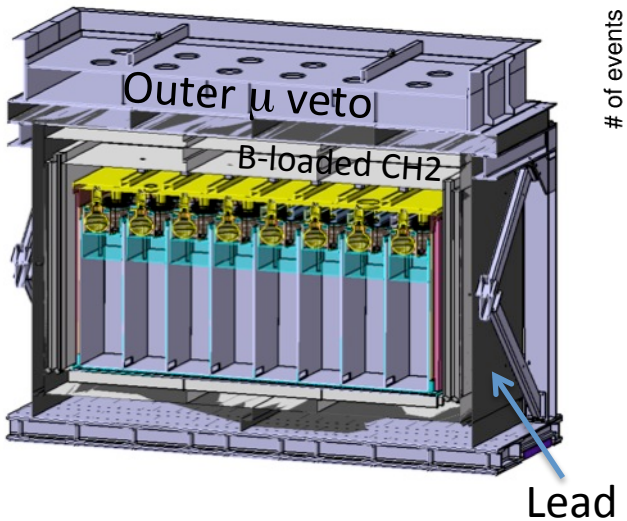
Background rejection

- Comprehensive on site measurements performed last year: μ, n and γ backgrounds.
- Sequential installation/validation of external shielding before detector installation early 2015.
- Muon induced:
  - Overburden
  - Active outer-crown and μ-veto
  - PSD capability of the liquid scintillator

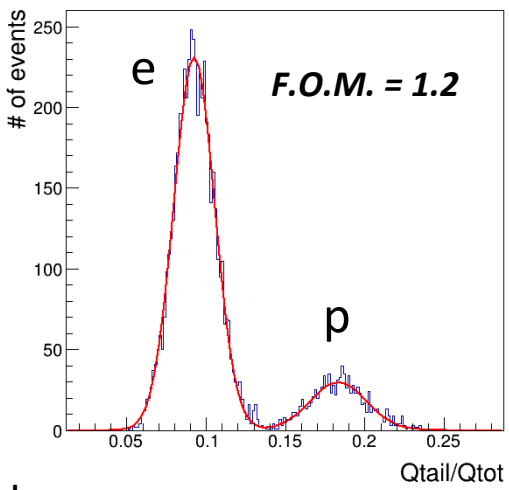


Test of cell prototype next month to validate the detector response

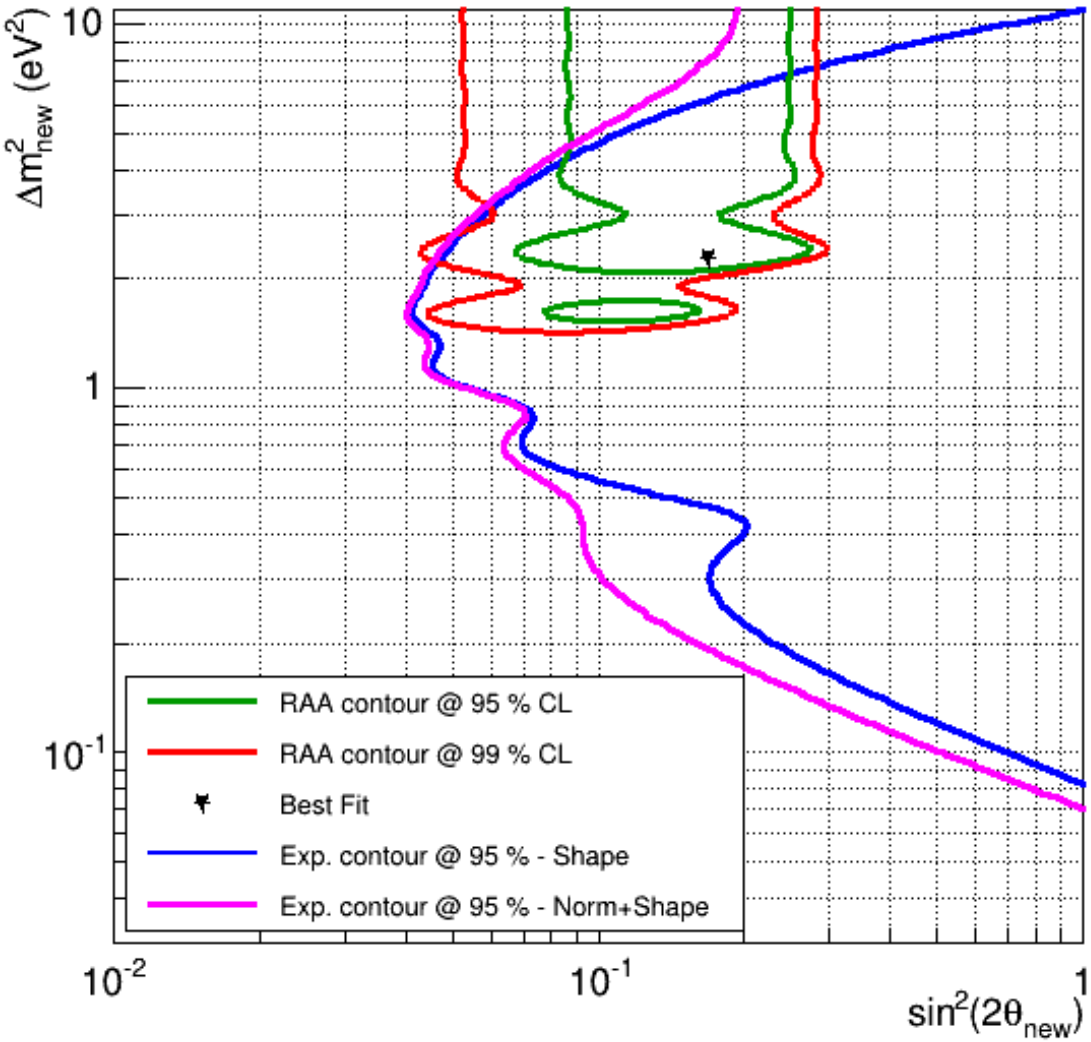




PSD in small cell

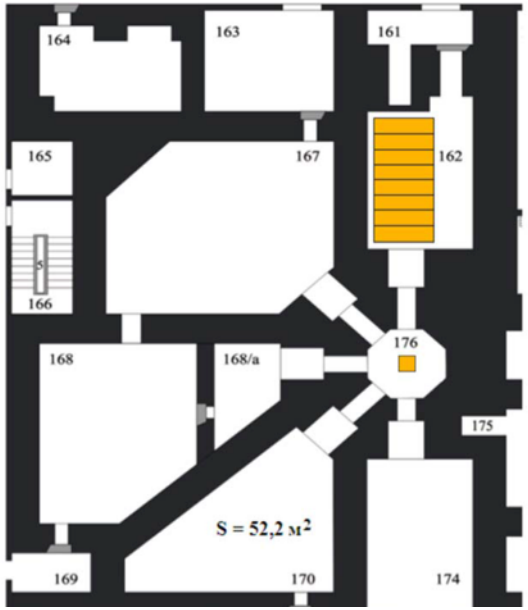


STEREO Sensitivity



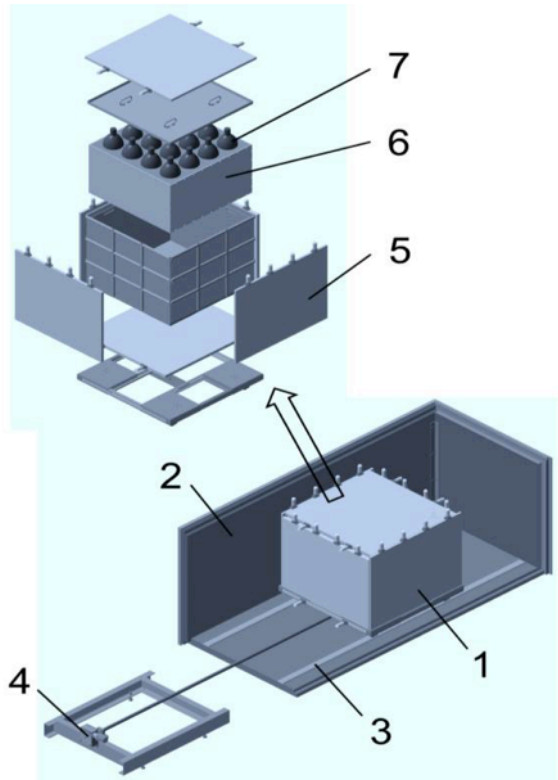
- 300 days, L_0 = 10 m
- E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
- ~410ν_e/day
- δE_{scale} = 2%
- All syst. of predicted spectra
- S/B = 1.5, 1/E+flat model
- Norm 4%
- Start data taking in 2015

NEUTRINO-4 @ SM3



- Compact core
- 100 MW
- Few mwe

60 t shielding



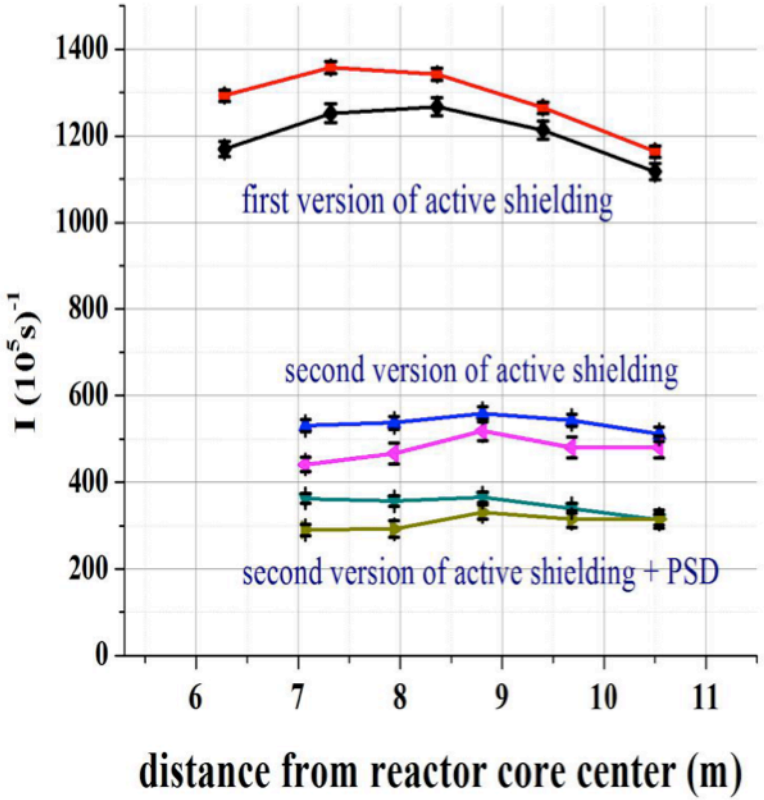
Prototype module

1 –detector module
2 –passive shielding
3 –rail
4 –motion system,
5 –muon veto,
6 –400 l Gd-loaded LS,
7 –Detector PMTs.

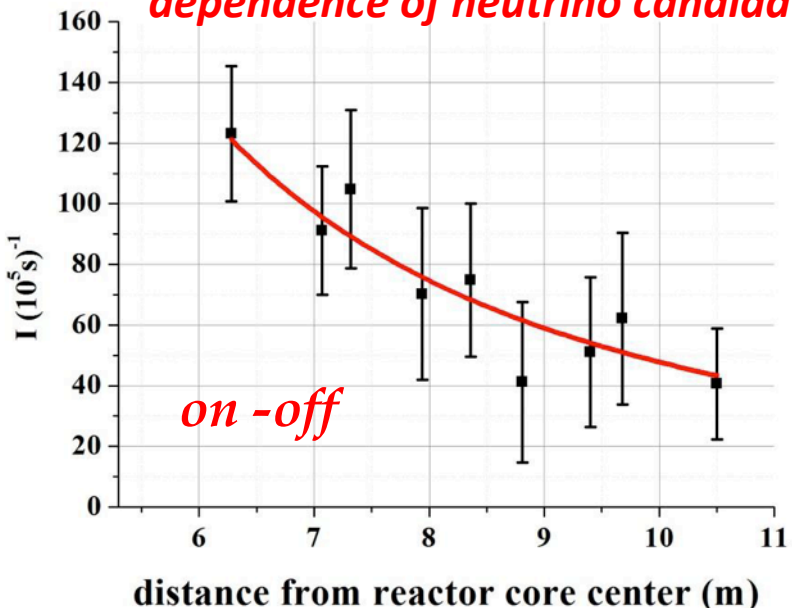
Movable det module
6-12 m baseline range

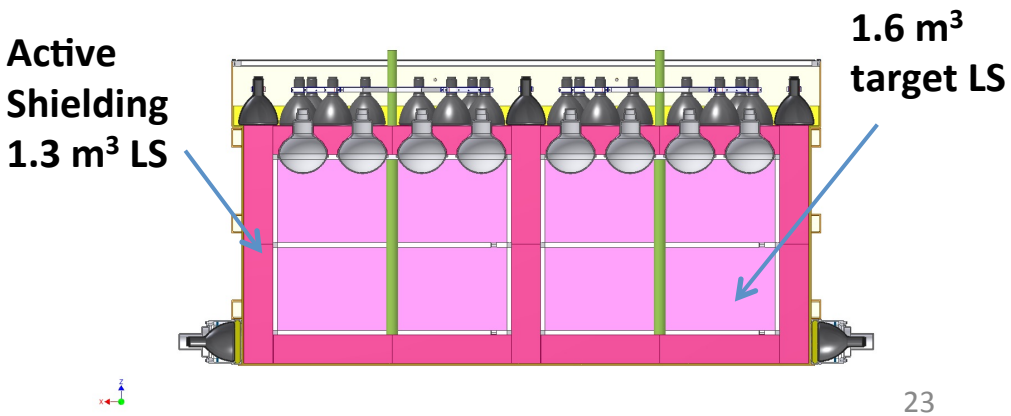
NEUTRINO-4 @ SM3

Cosmic background suppression



First measurement of 1/ R^2 dependence of neutrino candidates





- Production of the full-scale NEUTRINO-4 detector
- Data taking in 2015.

Highly Segmented Detectors

Korean Experiment

Reactor candidates

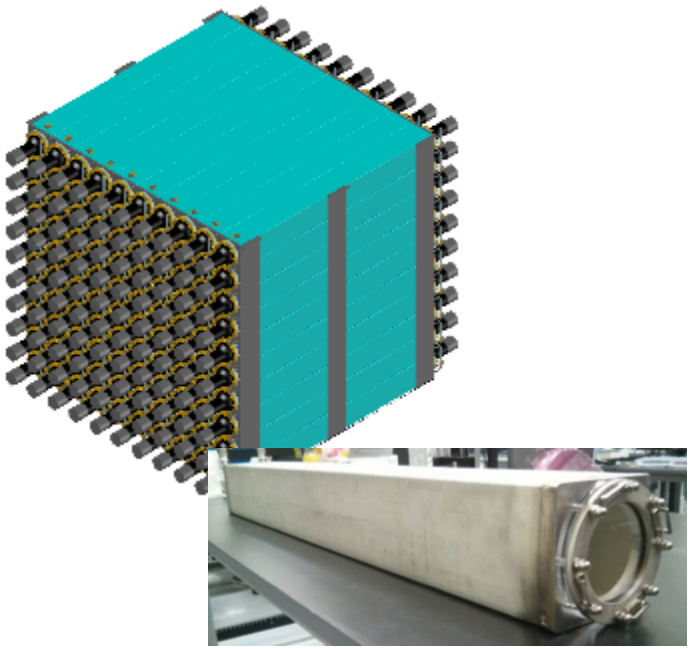
Reactor	Baseline [m]	Thermal Power [GW]	ν events / day	Overburden [m.w.e.]
Hanaro	6	0.03	179	-
Younggwang	24	2.8	1052	~ 10
Kijang (2017)	5	0.015	129	~ 20

Hanaro

Younggwang

Segmented detector

- 11x11x100 cm^3 cells
- Gd (or 6Li)-loaded LS
- 3” PMT
- 10x10 cells (~1 ton target)

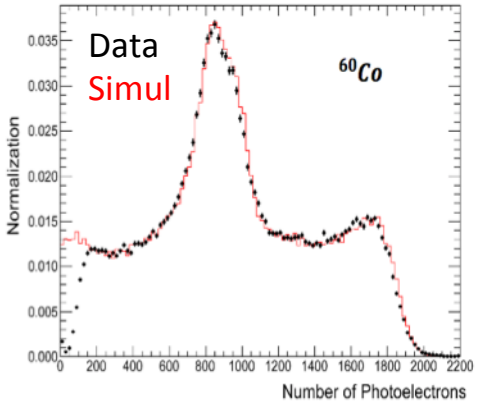


Korean Experiment

Prototype detector

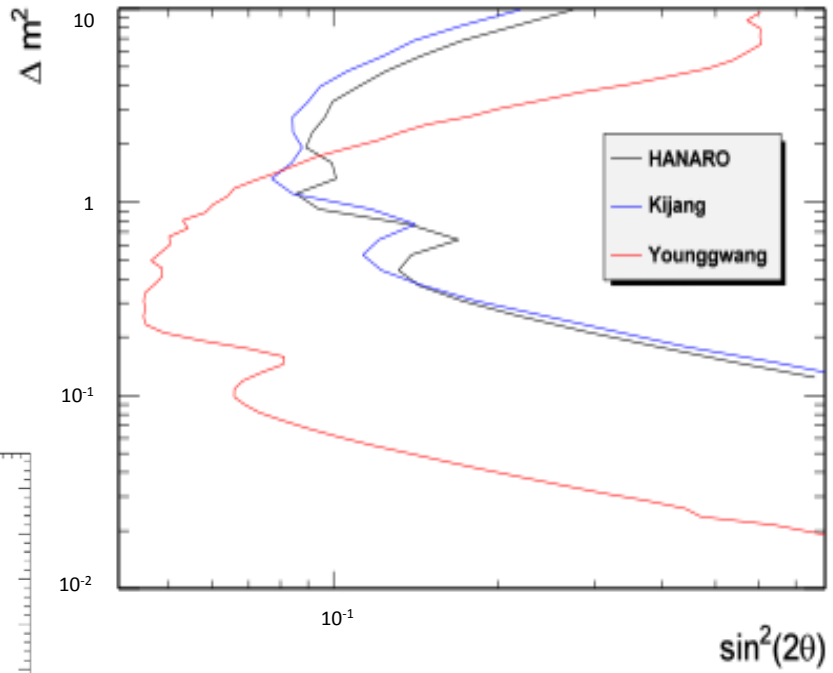
- 50 l of Gd-LS inTarget, 6 PMTs (8”)
- 10 cm Thickness lead for passive shield
- 4π muon detector with liquid scintillator
- 670 pe/MeV

- R&D on ^{6}Li-loaded LS and PSD capability



Final installation and data taking in spring 2015

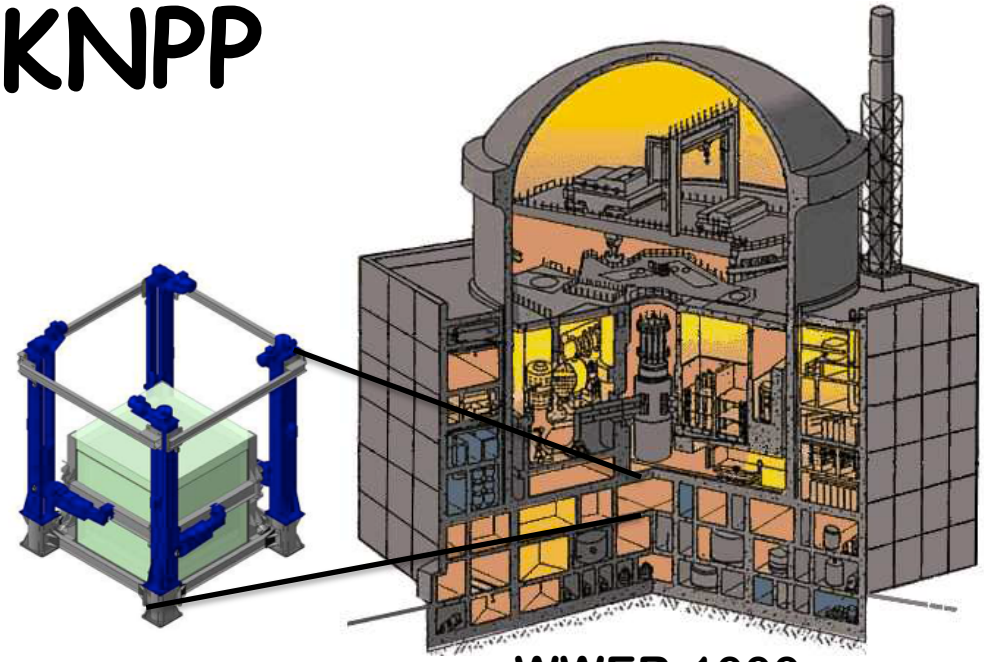
Sensitivity



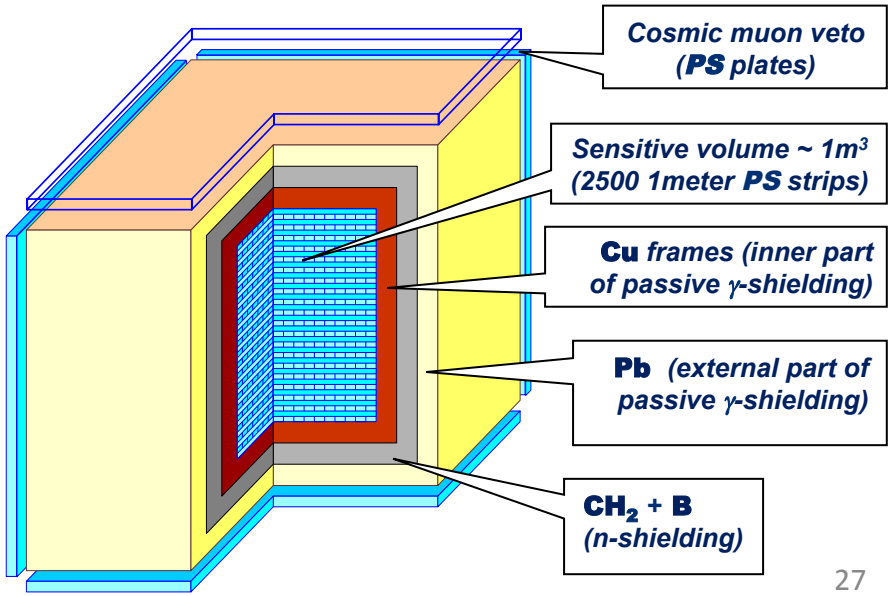
- **500 L of target**
- **1 year data taking**
- **S/B ~ 1: 1 @ Hanaro**
- **Detection and spectrum syst. included**

DANSS @ KNPP

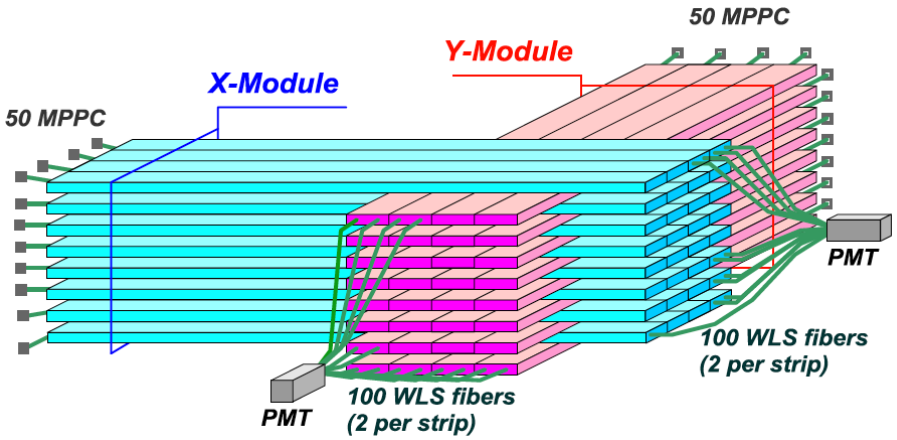
- 1 GW extended core
- Good overburden, underneath the reactor.
- High statistics, ~ 10^4 evt/ day expected
- Vertical motion of the detector (9.7-12.2 m)
- Highly segmented detector
  → background rejection



WWER-1000

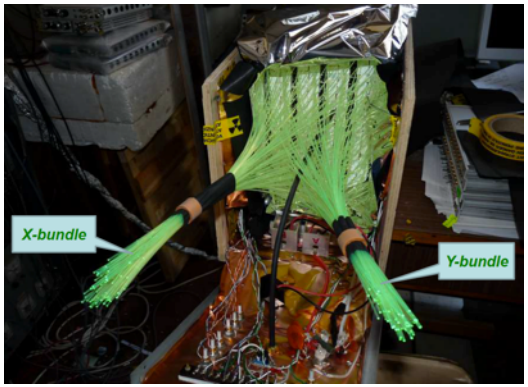


Detector Structure

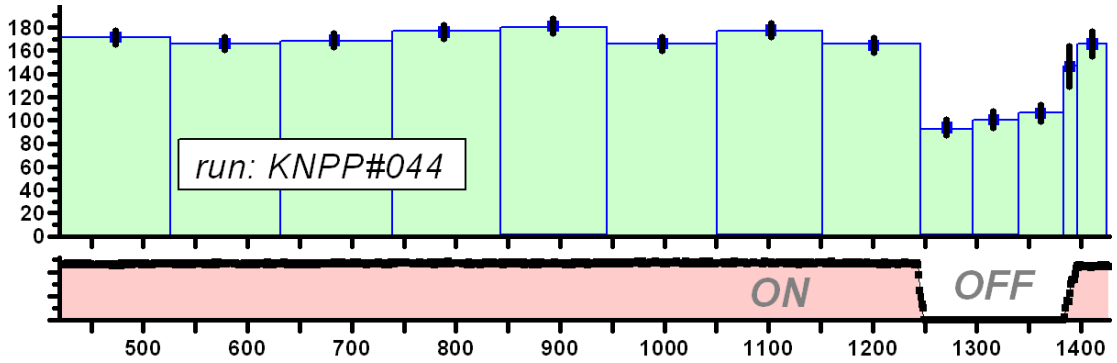


Plastic strips with Gd-loaded interlayer, WLS fibers readout, 15 pe/MeV expected.

1/25th prototype tested for 20 days @ KNPP



- First validation of the detector concept with the DANSSino prototype
- Antineutrino signal reported with S/B~1
- Final detector in2015.



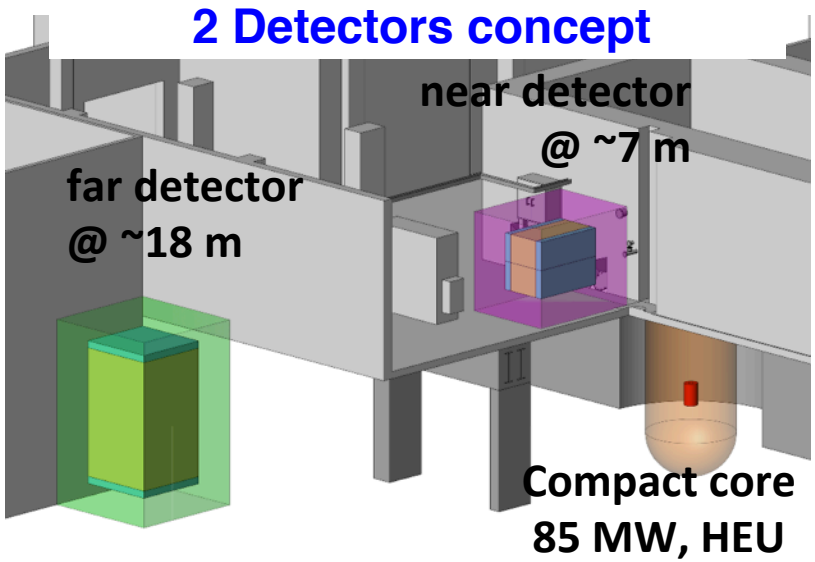
arXiv:1304.3696v2

Highly Segmented Detectors
+
^{6}Li-loaded Scintillators

PROSPECT

A Precision Reactor Neutrino Oscillation and Spectrum Experiment

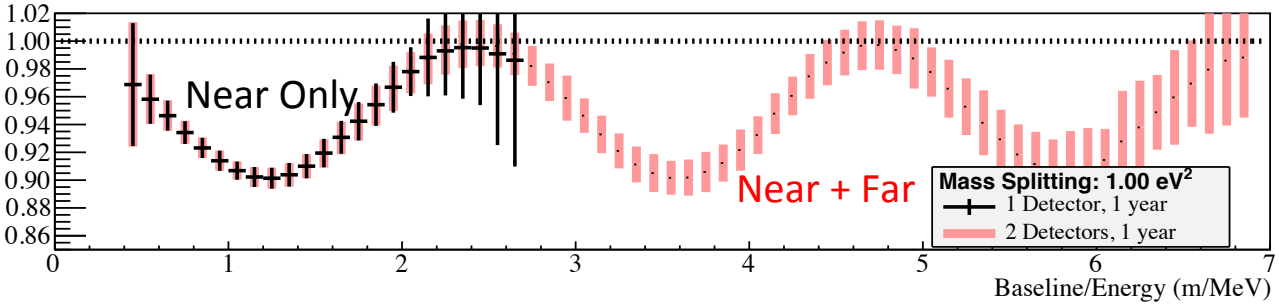
2 Detectors concept



Physics Goals

- Search for sterile ν_e oscillations at short-baseline.
- Probe and resolve "reactor anomaly".
- Precision measurement of reactor ν_e spectrum for physics and safeguards.

Map out L/E Oscillations

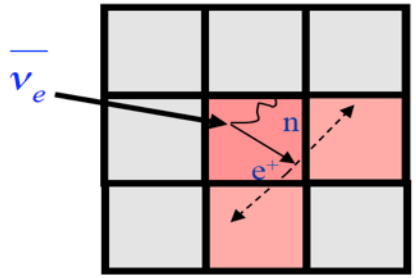


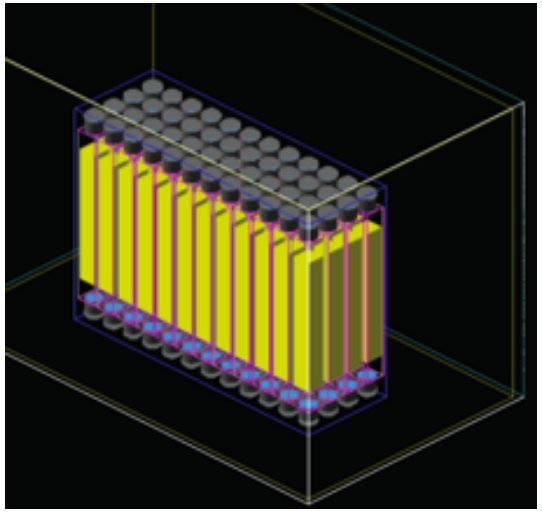
PROSPECT – Design, Concept, Sensitivity

Detector Concept

Segmented detector

- position resolution for oscillation search
- background rejection via topology
- low inactive mass and uniform response for good energy resolution





Target Materials

^{6}Li liquid scintillator – localized neutron capture, capture and neutron recoil ID possible via PSD, or

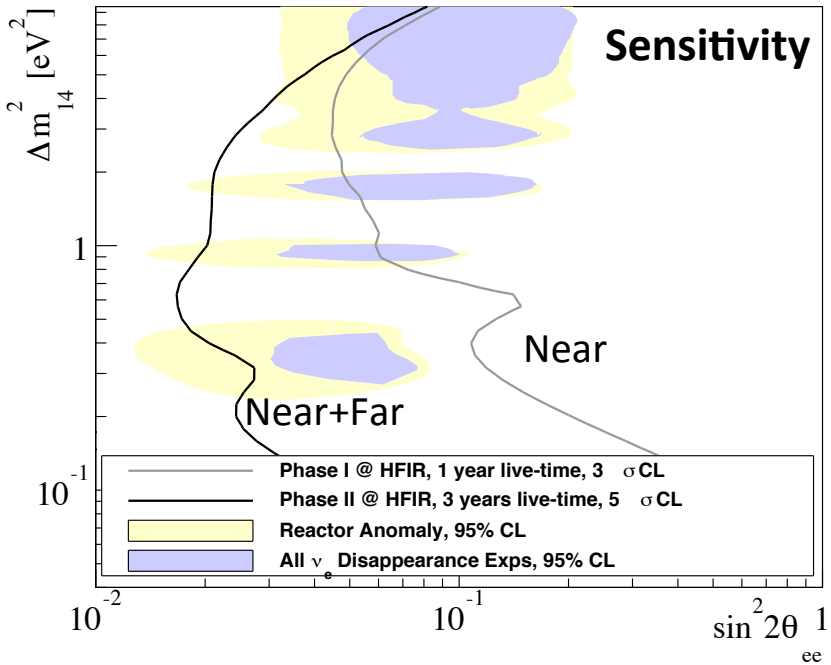
Gd liquid scintillator – proven technology, proton recoil ID possible via PSD

Sensitivity

Near detector: 3σ in 1 year

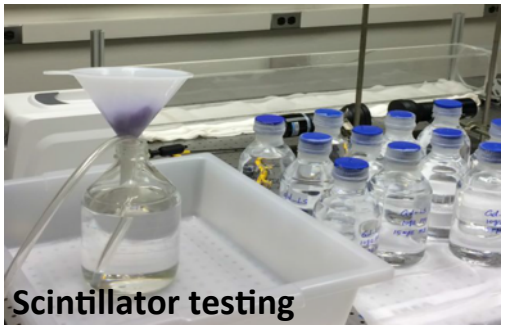
Near + far detectors: 5σ in 3 years

White paper: arXiv:1309.7647

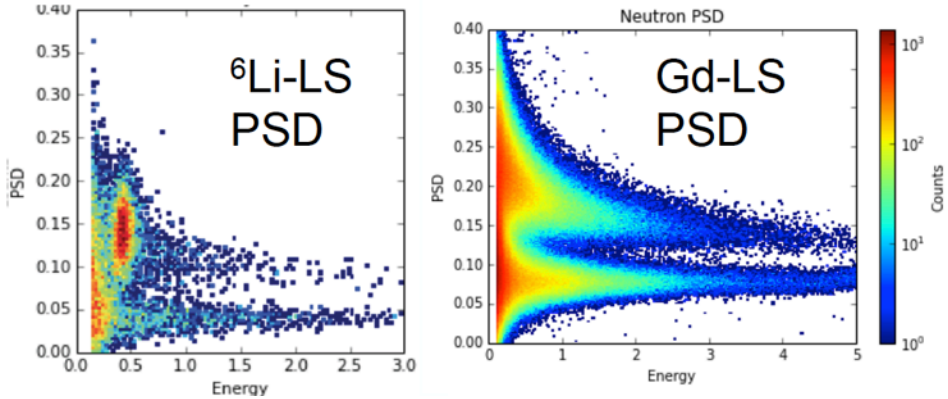


PROSPECT – Development and R&D

Scintillator Development

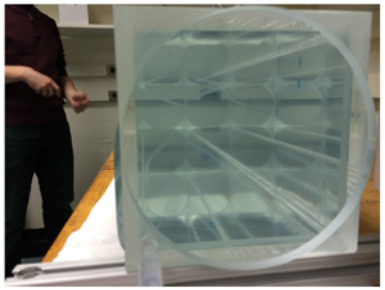


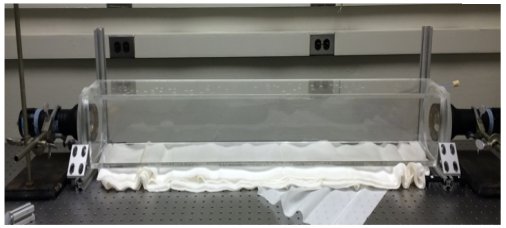
LS development



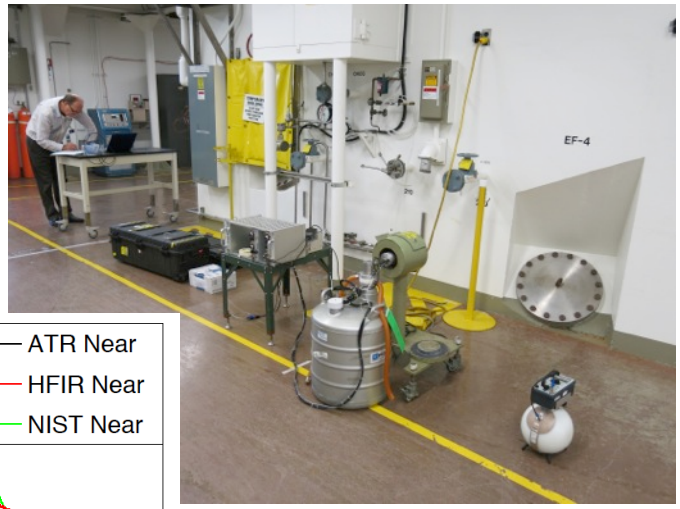
Prototype Detector Development

Large Cell PSD tests



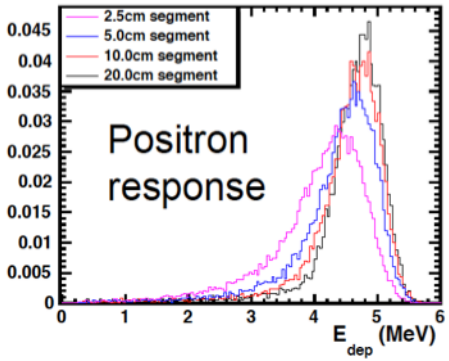


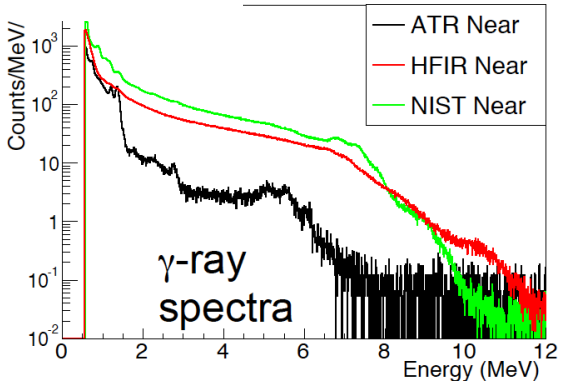
Background Measurements at Reactor



Few mwe overburden

Detector and Background Simulations





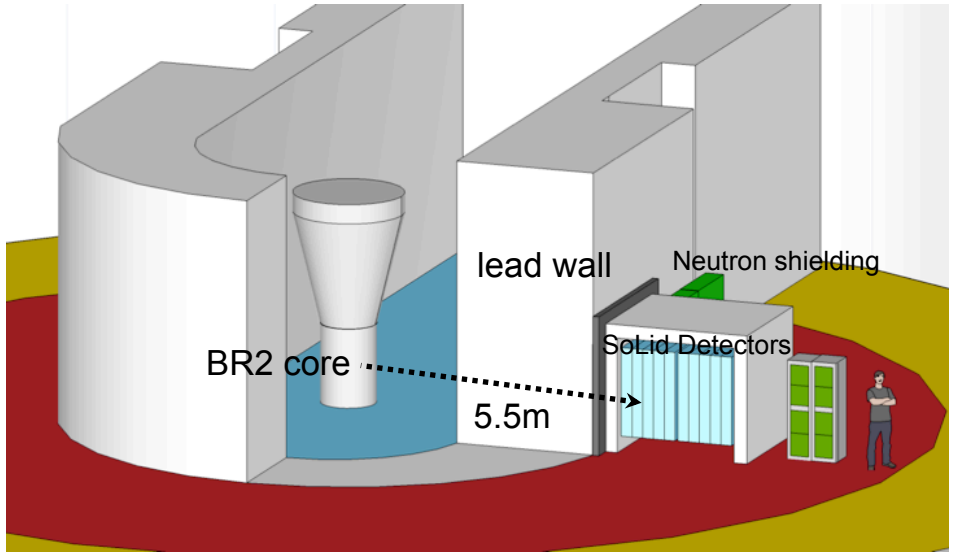
SoLid

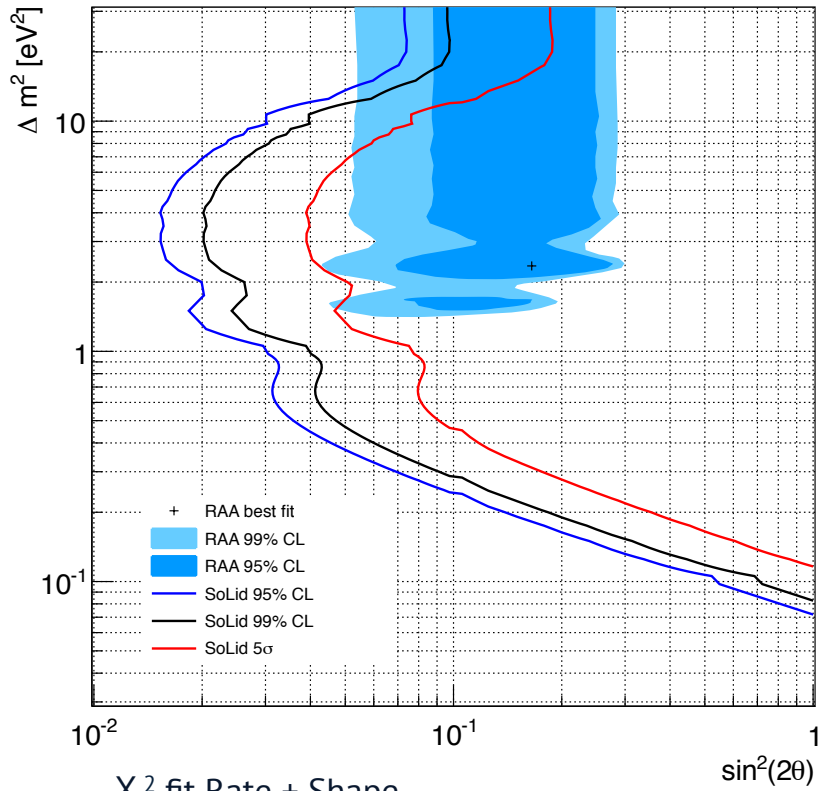
BR2 REACTOR, Mol, Belgium

- Core: 45-80 MW, HEU fuel
- Favorable reactor background level

DETECTOR

- **Novel type of composite solid scintillator detector** (PVT + ^{6}LiF:ZnS)
- 2.88t fiducial volume, highly segmented.





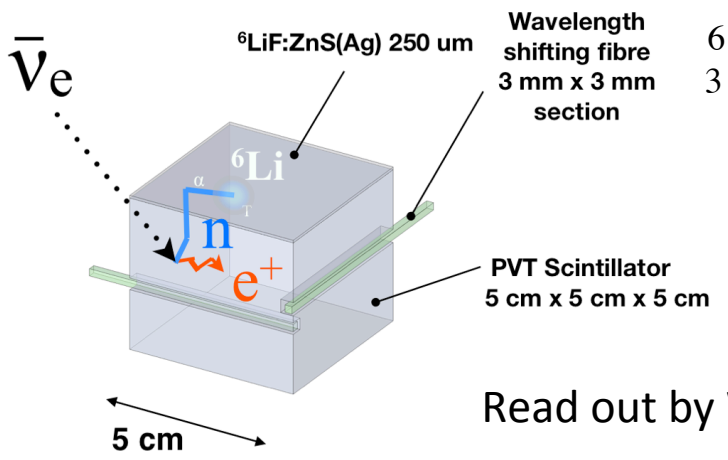
χ^2 fit Rate + Shape

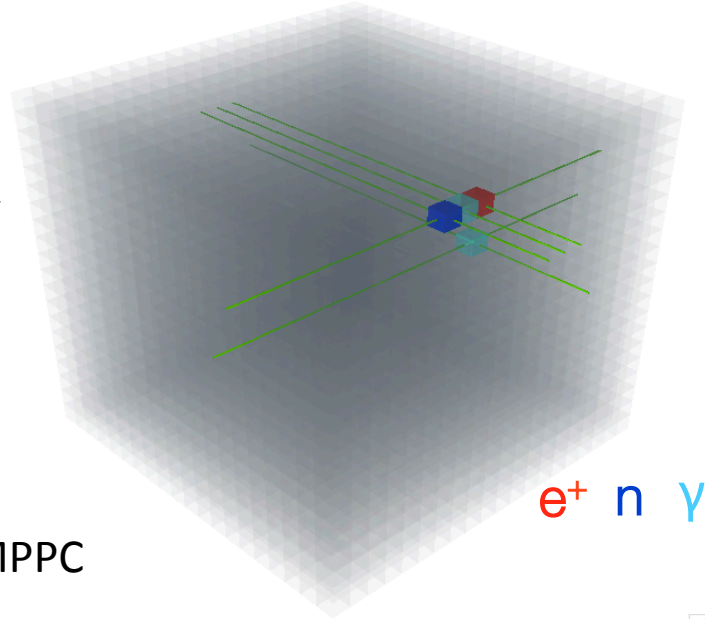
- IBD efficiency 41% (416nu/day/tonne)
- 300 days running at 6.8m baseline
- S/B ~ 6
- include flux normalisation (4.1%), detector efficiency (2%) systematics and backgrounds
- large bins to account for energy smearing effects

SoLid Detection Principle

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

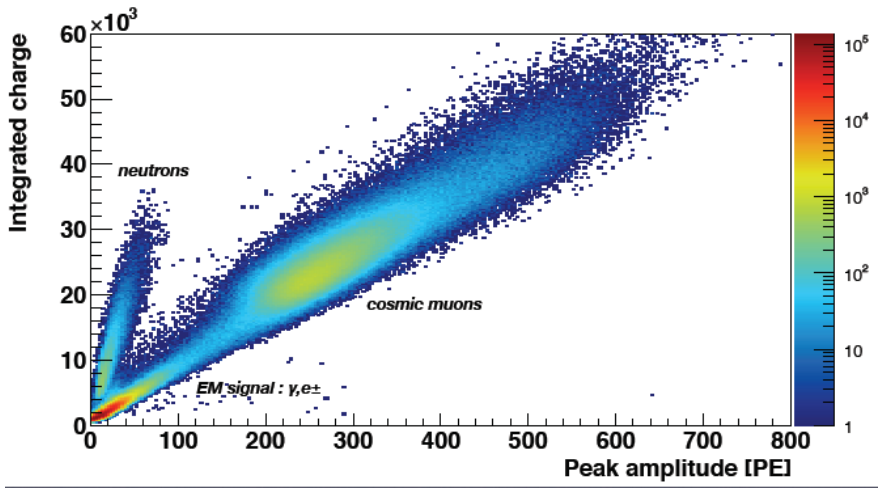
$$^{6}_{3}Li + n \rightarrow \alpha + t$$





Read out by WLS fibers and MPPC

- 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.**

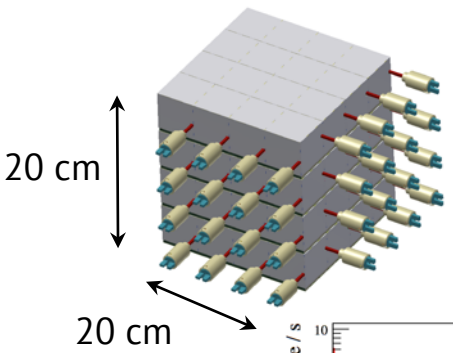


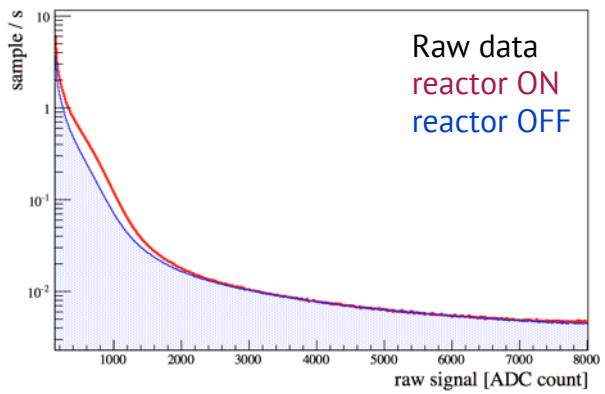
Status of experiment

NEMENIX prototype tested at BR2

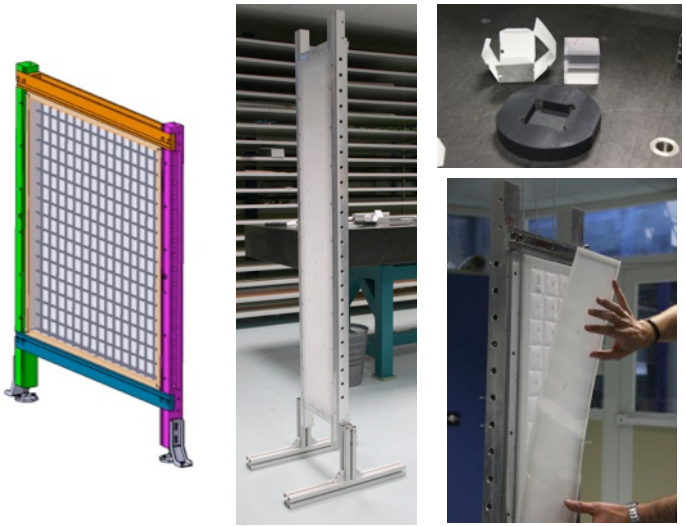
- New DAQ + muon veto
- Demonstrate expected response
- Study background rate and IBD analysis.
- Analysis of mars-may 2014 cycles in progess

8 kg, 64x cubes

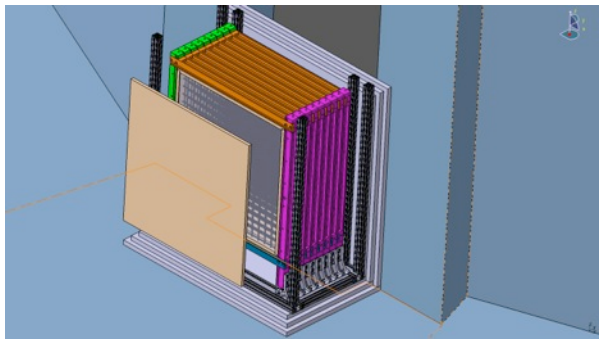




Larger scale prototype



- 288 kg module (2304 cubes) deployment planned before end of year 2014 at BR2.
- **Data taking with full det early 2016.**



Summary

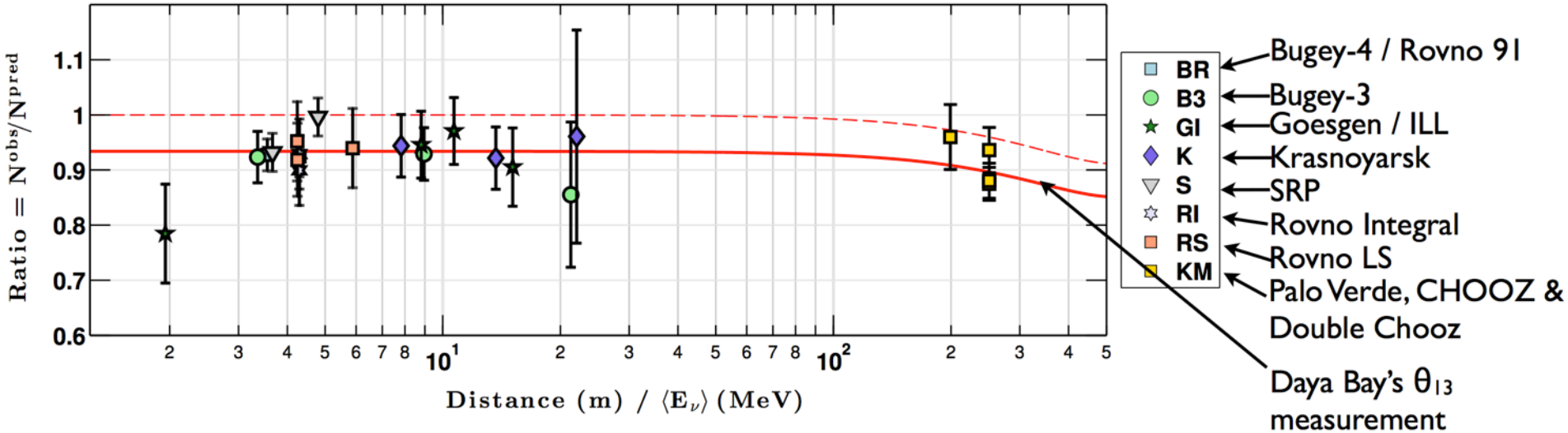
- **Antineutrino spectra**
  - Need to understand the 5 MeV excess → update shape and norm of prediction. Limited impact on relative distortion search.
  - Pure ^{235}U to standard commercial cores to be measured.
  - New input on reactor monitoring.
- **Detection at very short baseline and shallow depth**
  - Challenging n and γ backgrounds near reactors and at shallow depth.
  - Large panel of detection technics: Liquid vs Plastic, segmentation, R&D for enhanced discrimination of IBD.
  - Ultimate background induced by comic rays: reactor off period, PSD capability.
- **Sterile neutrino search**
  - Unique signature of new oscillation pattern with large range in E and L.
  - Good sensitivity to the reactor anomaly, prommissing Neutrino 2016 conf.

- ***Thanks to M. Danilov, A. Derbin, K. Heeger, Y. Kim, J. Lee, J. Liu, A. Serebrov, A. Vacheret et al. for slides and material.***

Posters

Abstract #	Presenter	Title
114	A. Vacheret	SoLid: Search for Oscillations with Li6 Detector at the BR2 reactor
122	N. Ryder	First measurements with the SoLid experiment's prototype antineutrino detector
319	A. Collin	The Stereo Project
349	K. Heeger	PROSPECT: A Precision Reactor Neutrino Oscillation and Spectrum Experiment
359	N. Bowden	Bckground Assessment for the PROSPECT Short-Baseline Reactor Experiment
360	T. Langford	Development of novel Scintillator for the PROSPECT Short-Baseline Neutrino Experiment

Reactor Anomaly



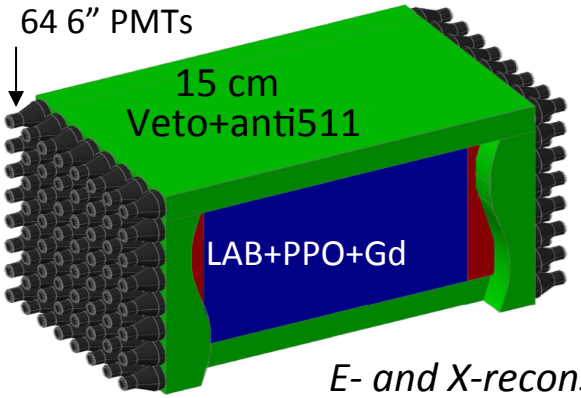
Updated result including :

- Km baseline results
- Corrected statistical bias (1% shift)
- Neutron mean life (τ_n = 881.5 s)
- Refined treatment of experimental uncertainties and parameters

- 2013 result: $\mu = 0.936 \pm 0.024$, 2.7σ deviation from unity

POSEIDON -Liquid scintillation **po**sition-**se**nsitive **d**etector **o**f **n**eutrino

Petersburg Nuclear Physics Inst., NRC Kurchatov Inst. (project arXiv:1204.2449)

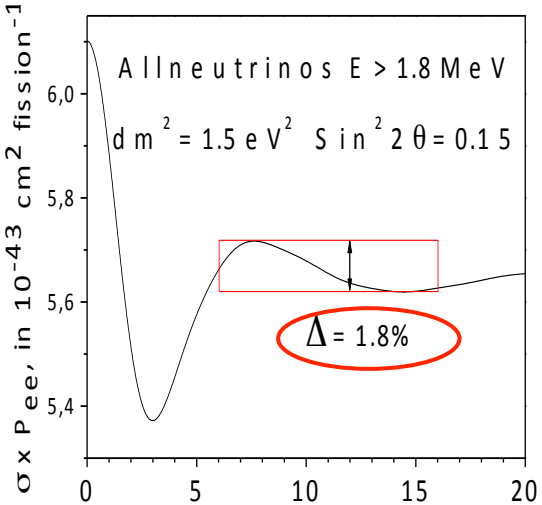


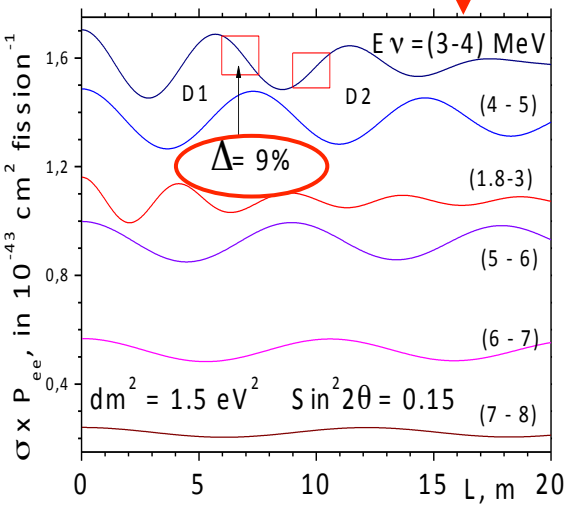
LS(Gd) **Detector**
2.1x1.3x1.3 m^3
MC simulation:
Energy resolution
σ = 7% at 1 MeV
Spatial resolution
σ_x = 15 cm at 1 MeV

E- and X-reconstruction of event is based on the charges collecting by PMTs

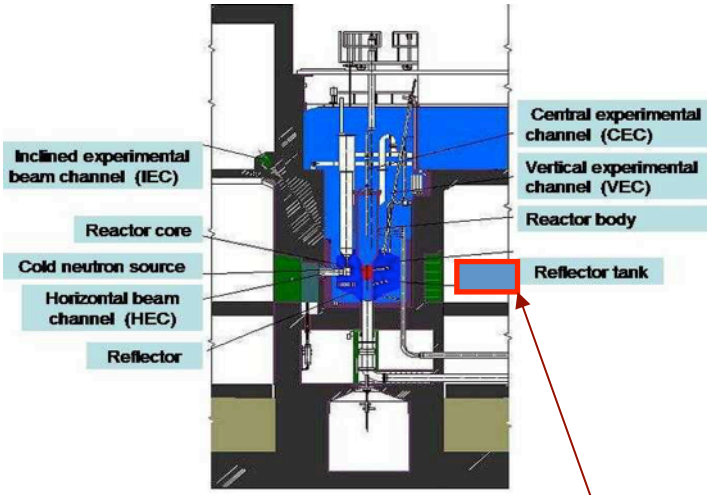
100 MW research **Reactor PIK** is being built in Gatchina, (~2016 y)

Energy and spatial resolution should allow to observe the oscillation curves for different E_ν





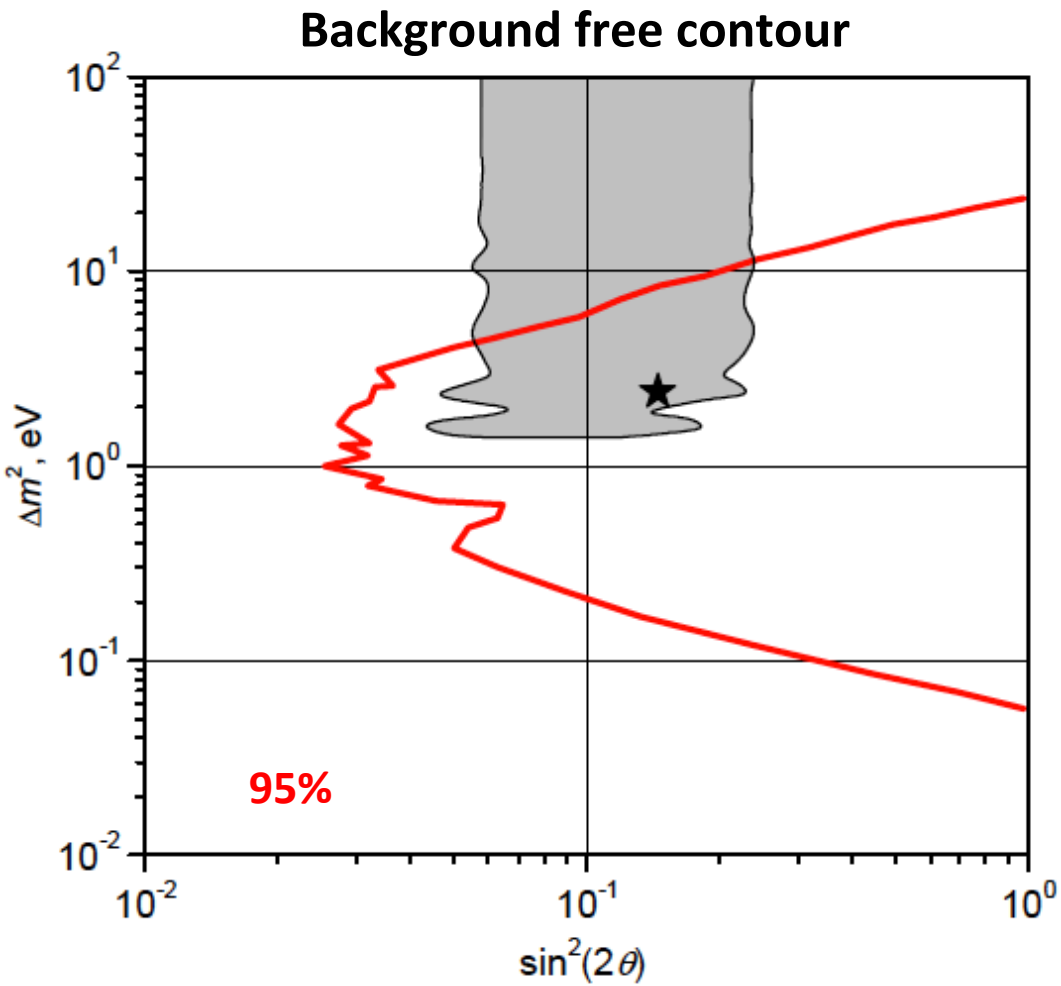
Small zone: h=50 cm, d=39 cm



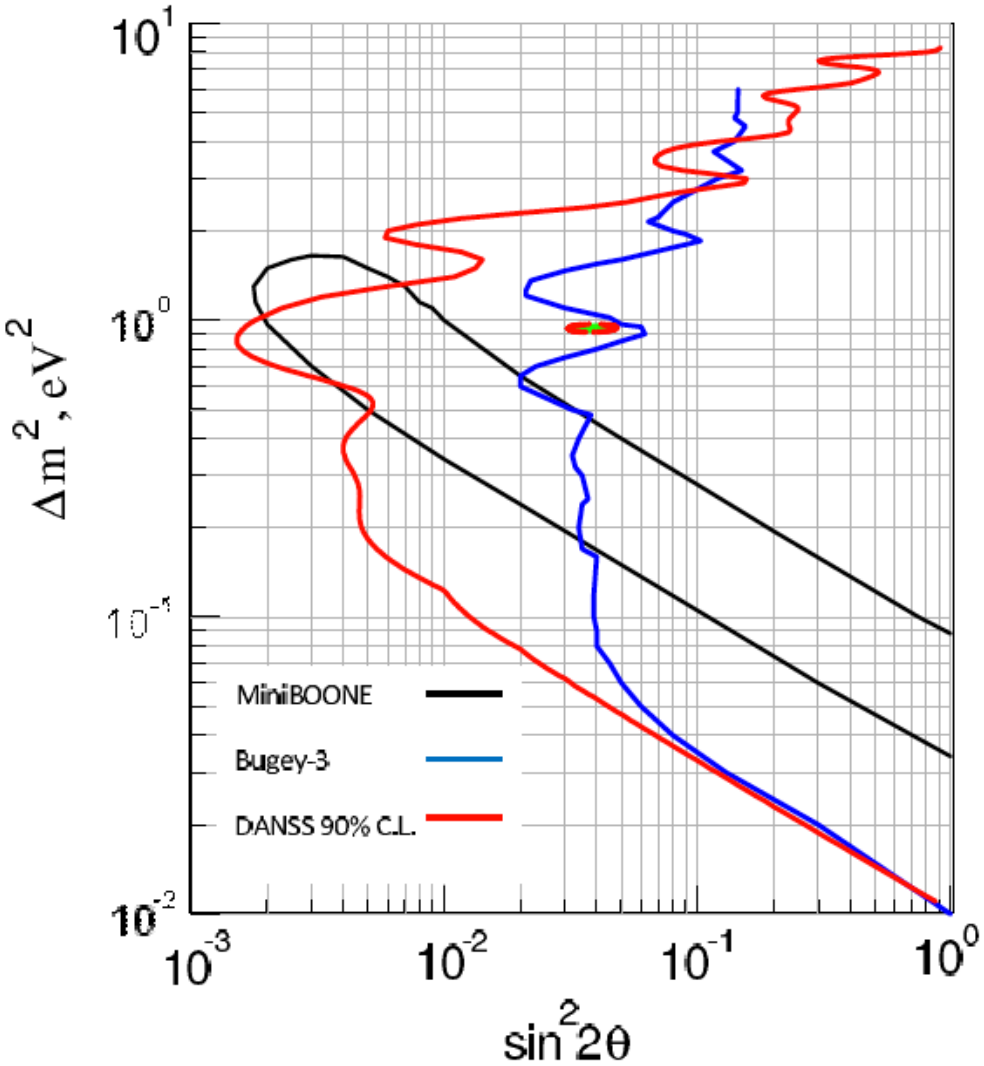
The region of sensitivity:
δm^2 = (0.3 - 6) eV^2 and $Sin^2(2\vartheta) \geq 0.01$

Detector can be placed at 5-8 m

Neutrino-4 Sensitivity



DANSS Sensitivity



Systematic errors not included yet