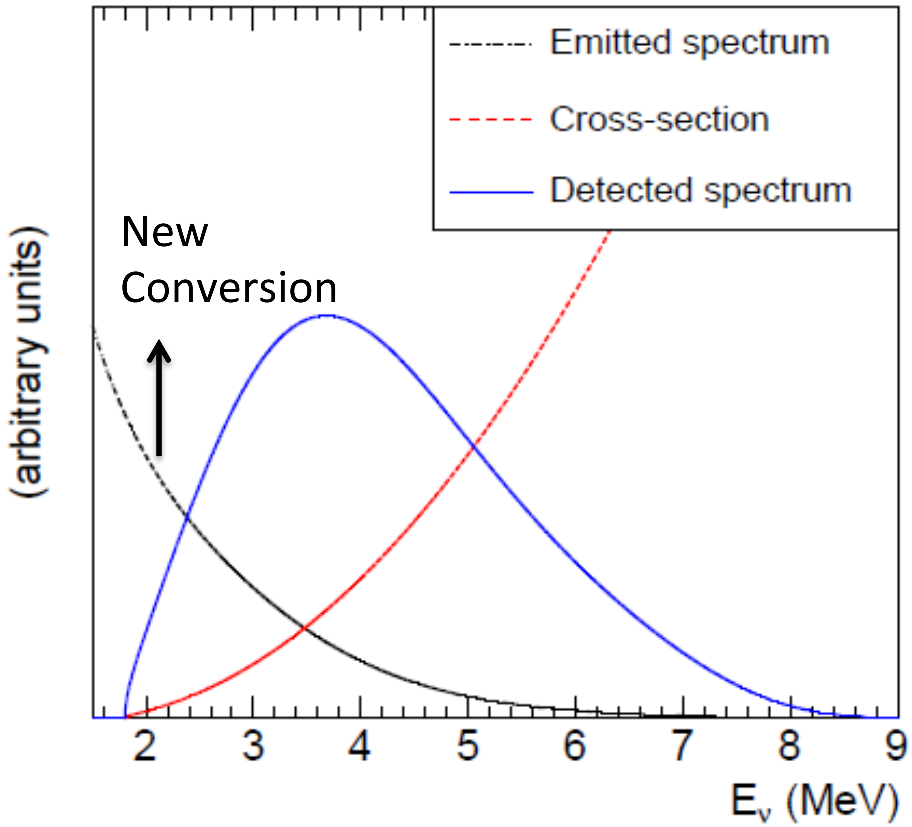
Experimental review of sterile neutrino searches with very short baselines

David Lhuillier – CEA Saclay

Outline

- Reactor anomaly
- Testing the 4^{th} ν hypothesis
- Short baseline reactor experiments
- Source experiments

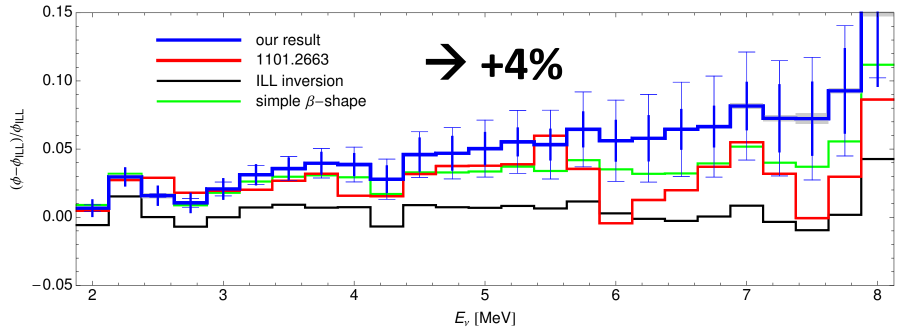
The Reactor $\bar{\nu}_e$ Anomaly

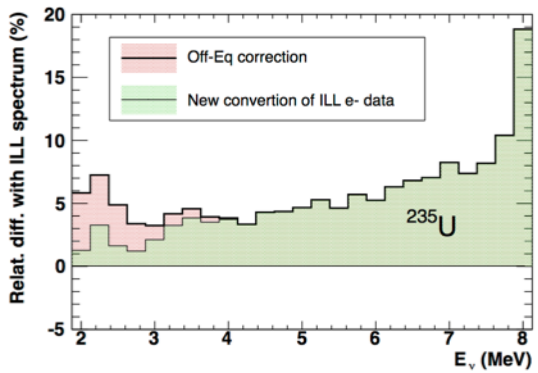


New conversion of ILL beta spectra

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

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

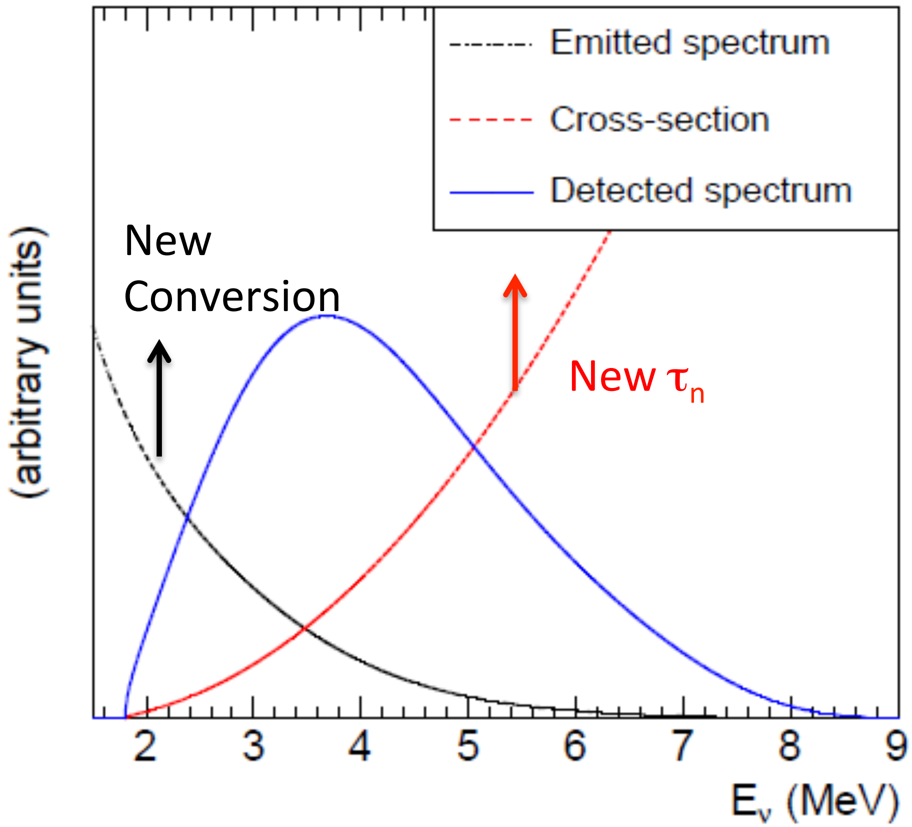




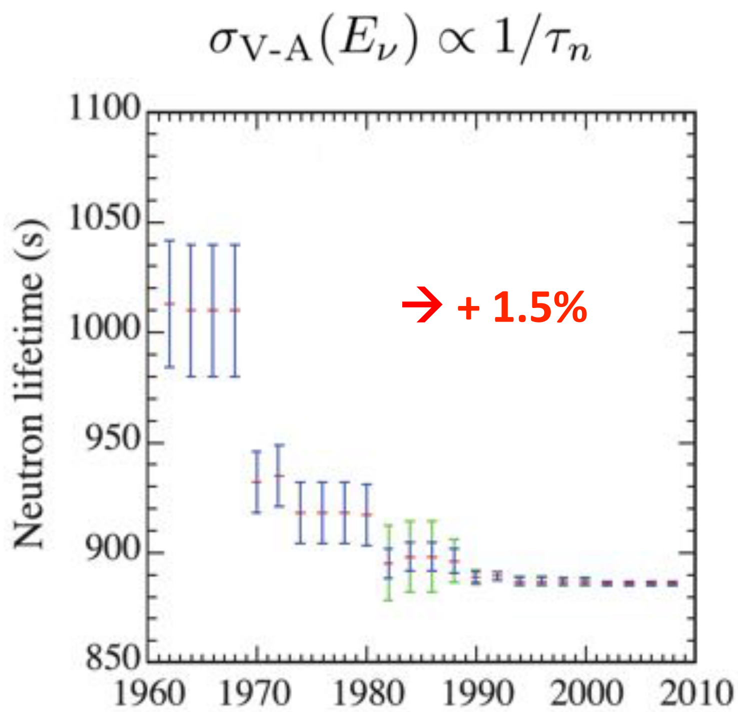
Accumulation of long lived isotopes

→ +1%

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

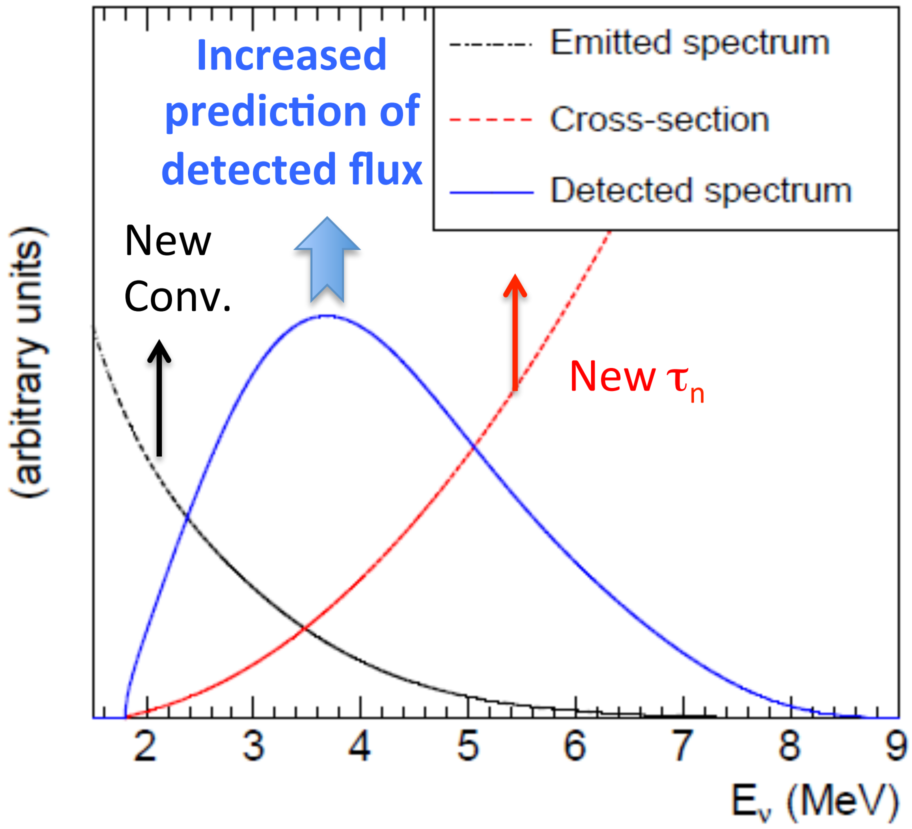


Reevaluation of $\sigma_{interaction}$



PRD 83, 073006 (2011)

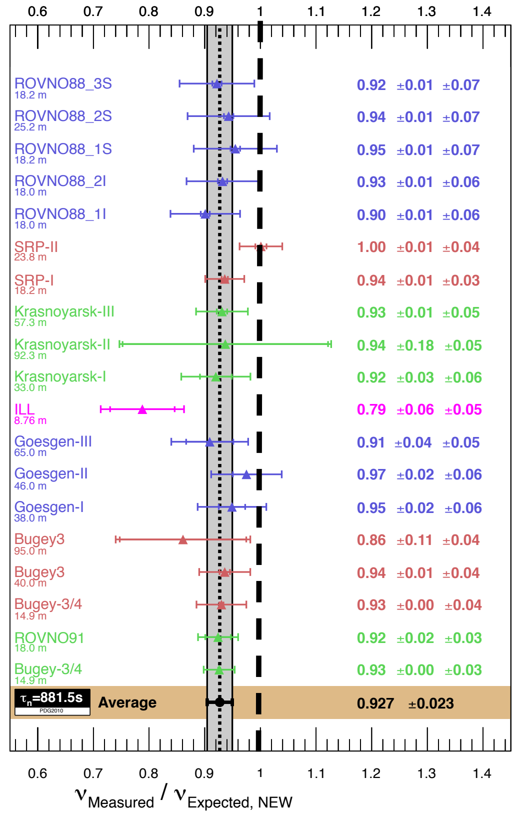
The Reactor $\overline{\nu}_e$ Anomaly



Significant increase of the prediction by 6.5%

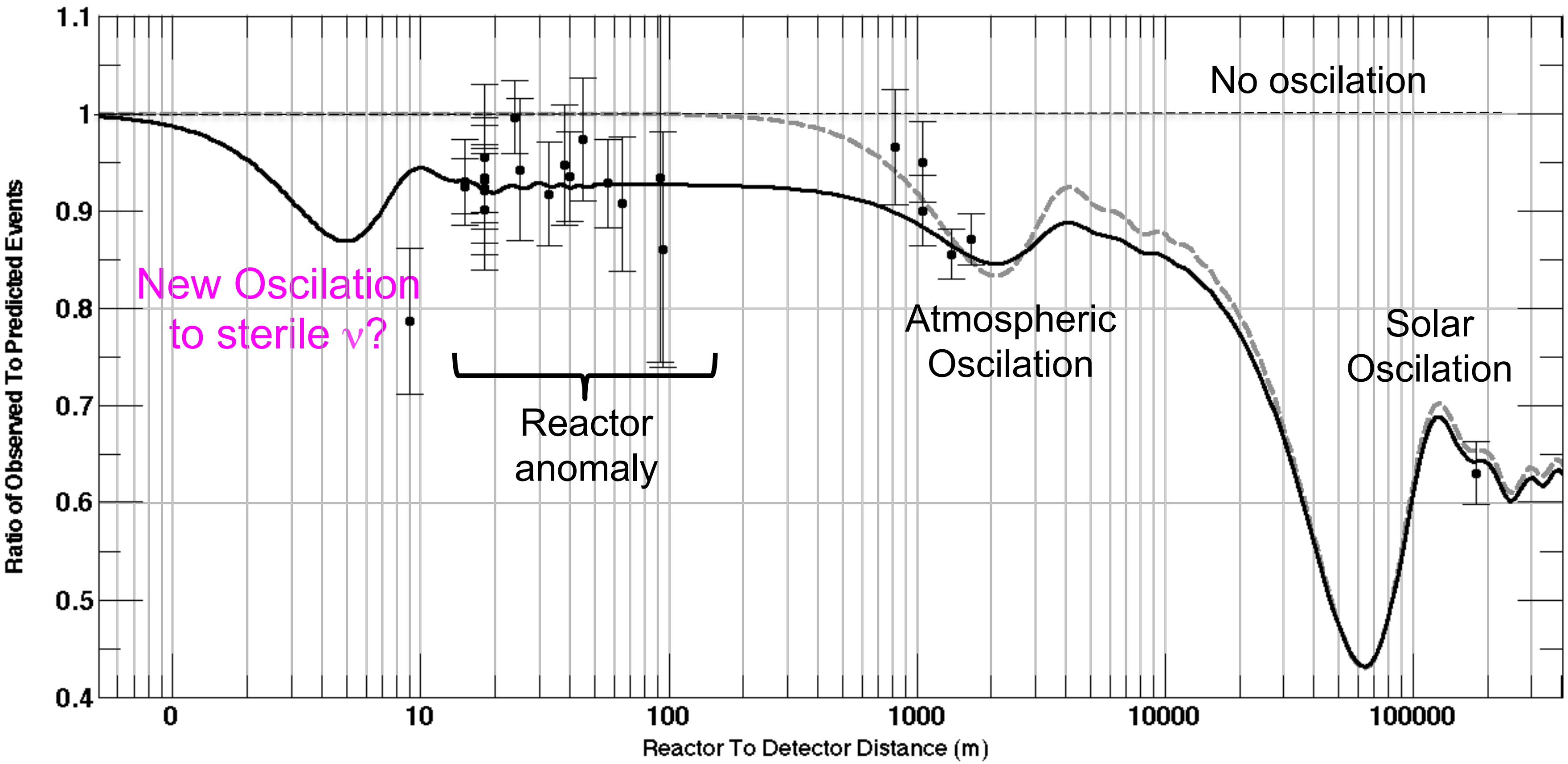
Reanalysis of reactor short baselines experiments

G. Mention et al., Phys. Rev. D83, 073006 (2011)



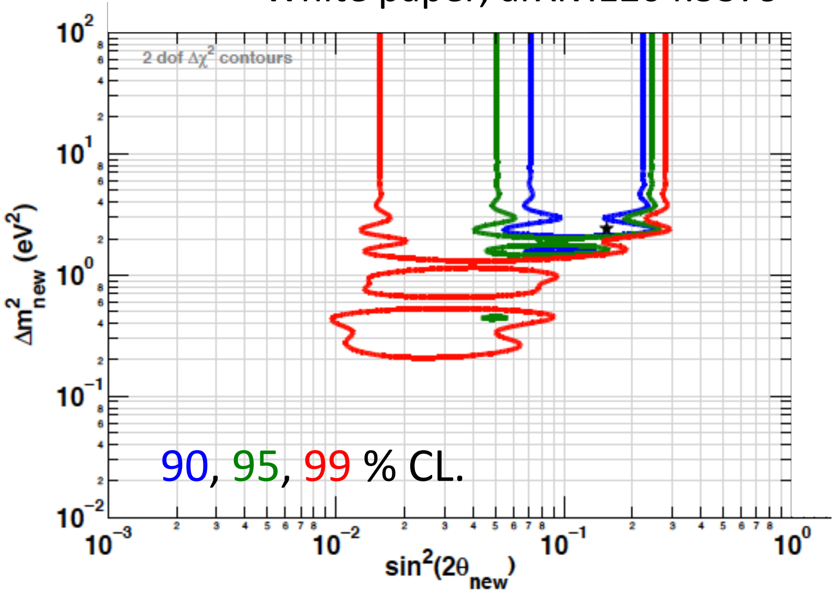
The Reactor $\bar{\nu}_e$ Anomaly

Observed/predicted averaged event ratio: R=0.935±0.024 (2.7 σ)

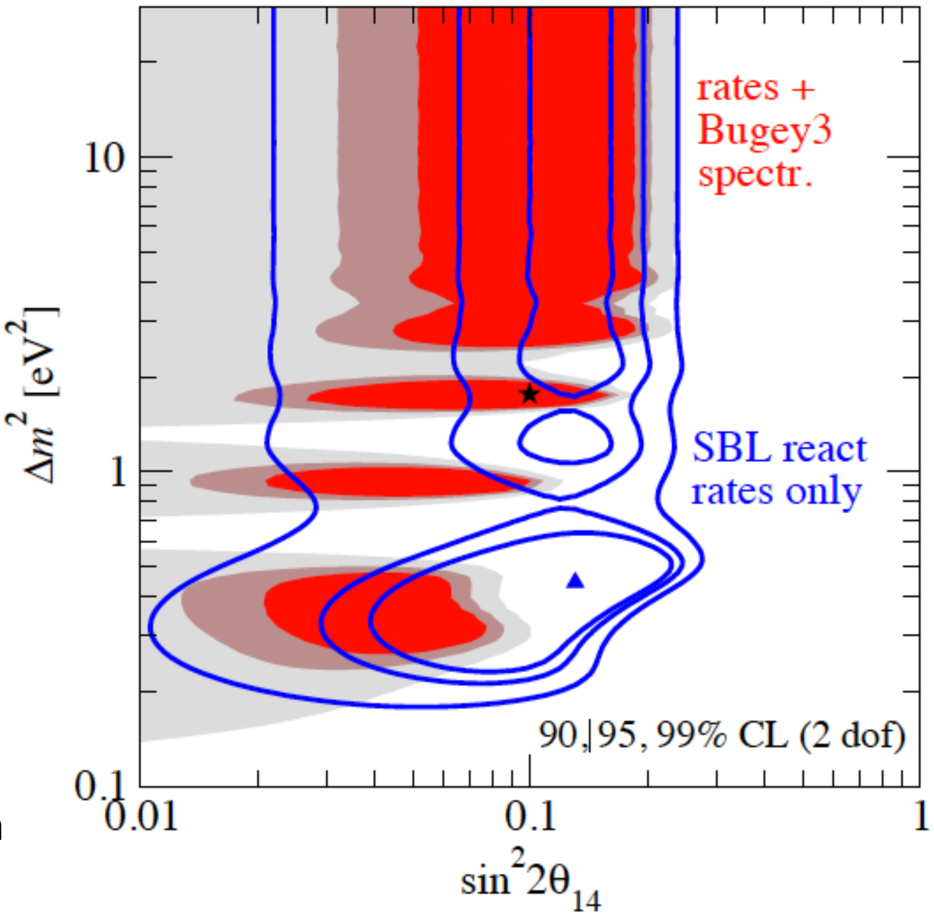


The Sterile Neutrino Hypothesis

White paper, arXiv:1204.5379



J. Kopp et al., hep/ph:1303.3011

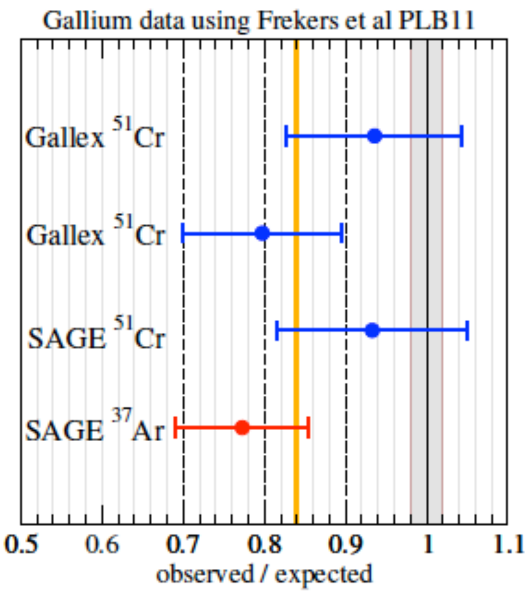


- Δm^2=0.2- 1 eV2 region very sensitive to the treatment of correlations.
- Lowest Δm^2 spot driven by the lever arm of ILL and SRP points.

Consistent Picture in $\overline{\nu}_e$ disappearance

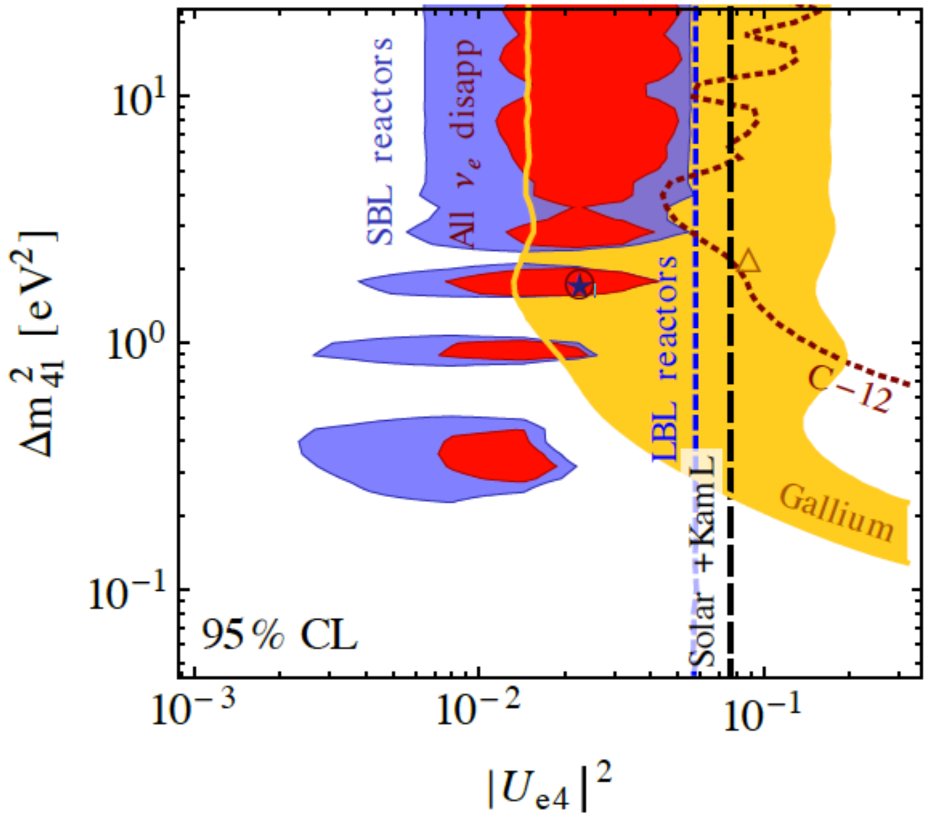
Compatible with ν_e deficits observed in Gallium experiments

- Gallex: 51Cr source (750 keV)
- Sage: 51Cr & 37Ar (810 keV)



$R_{obs/pred} = 0.86 \pm 0.05$ ($\sigma_{Bahcall}$)
$R_{obs/pred} = 0.76 \pm 0.085$ (σ_{Haxton})

J. Kopp et al., hep/ph:1303.3011



- Non-oscill hypothesis disfavored at 3.3 σ level.
- Cancellation of the anomaly by a single syst effect requires a ≥4σ deviation from expectation

Testing $\bar{\nu}_e$ disappearance anomalies

Experimental Strategy

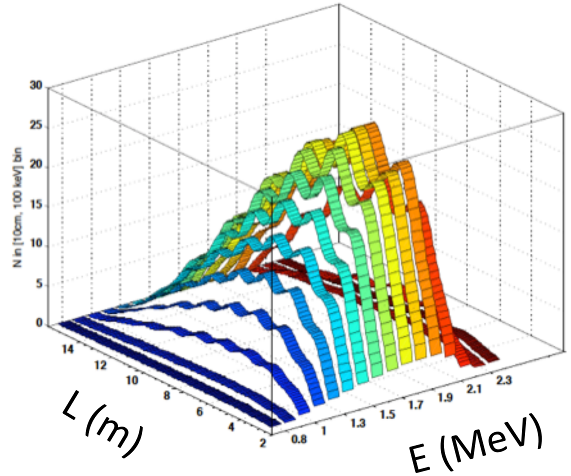
- **Goal**: **direct test**, beyond the current mean deviation from predicted rate

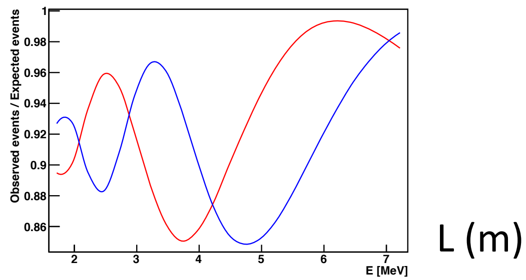
→ **Search for a new oscillation pattern in E & L**

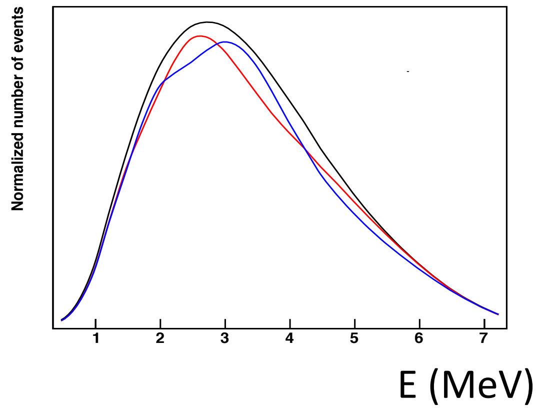
- Sensitivity to few m scale oscillations:
  - Compact source
  - Good position and energy resolutions
  - High statistics

- Few % stat + syst measurements to cover the anomaly contour

→ **Measurement of relative shape distortion**, completed by norm information.



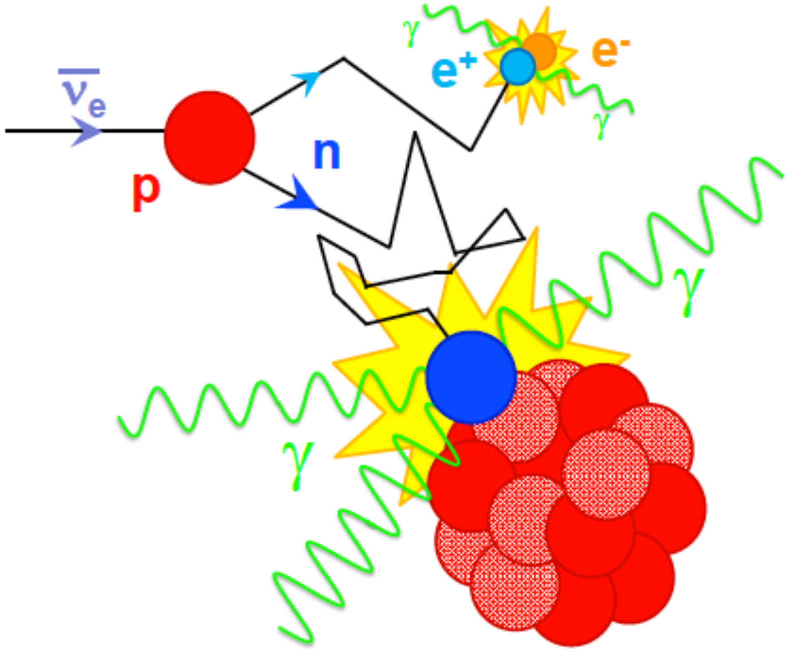




Neutrino Interaction

Inverse Beta Decay

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



Selective coinc

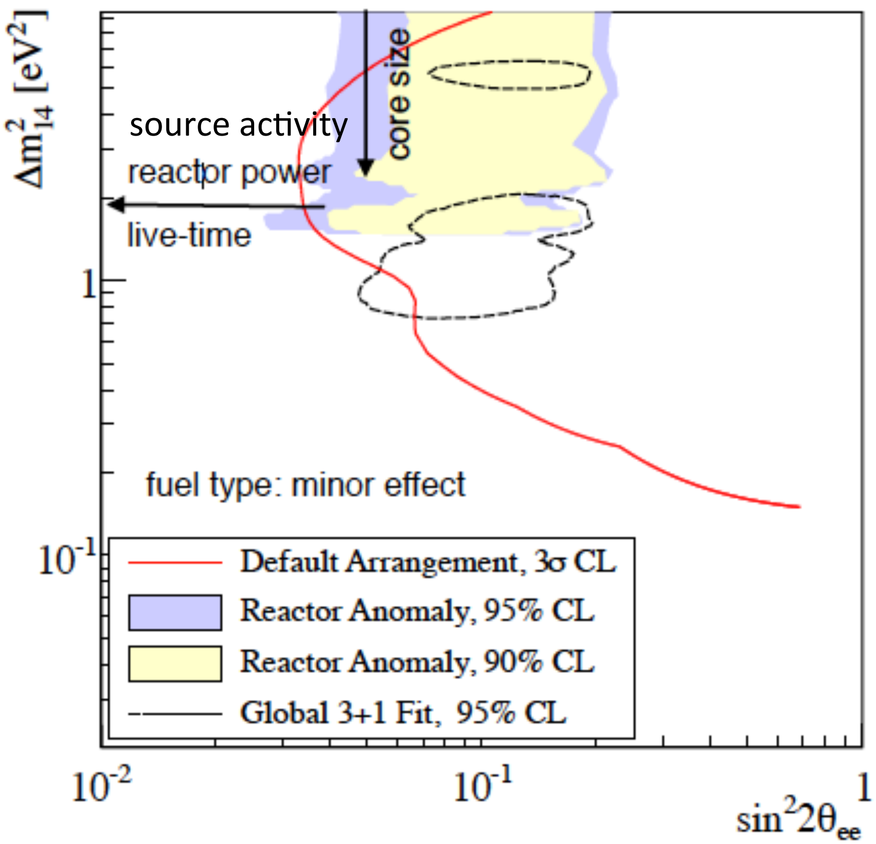
e^+ prompt signal & n-capture

Background rejection

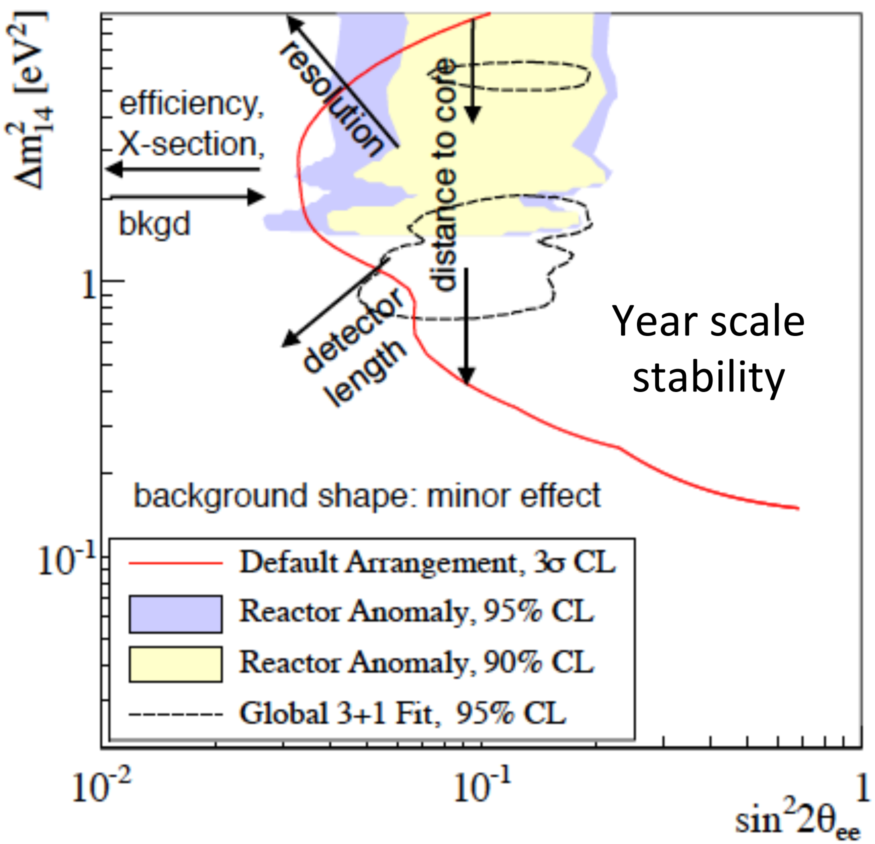
- Accidental γ-neutron coincidence
  - Shielding
  - Segmentation
  - Neutron discrimination
  - R&D on positron discrimination
- Fast-n correlated background
  - Rejection of recoil protons with PSD
  - Cosmic rays induced:
    Reactor OFF
    Overburden
  - Reactor induced: must be negligible.

Specifications

Source



Detector



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

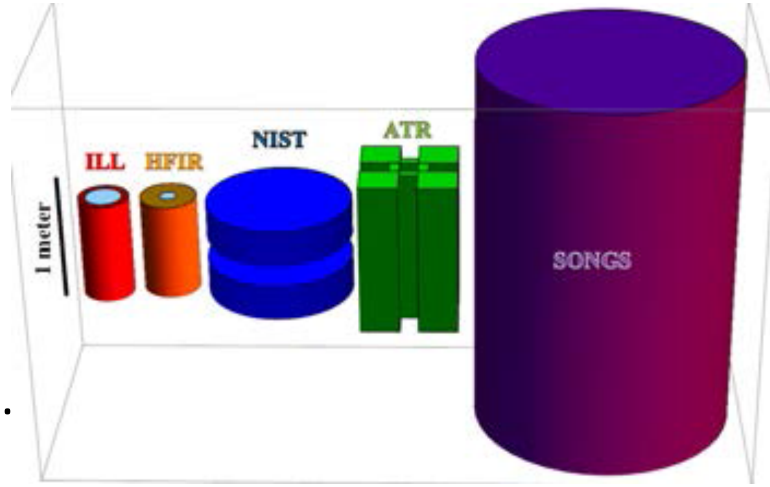
Short Baseline
Reactor Experiments

Research Reactors

- Compact sources → no oscill. smearing.

- Intense source and very short baselines available

→ high statistics, typically few 100 evts/day/t.



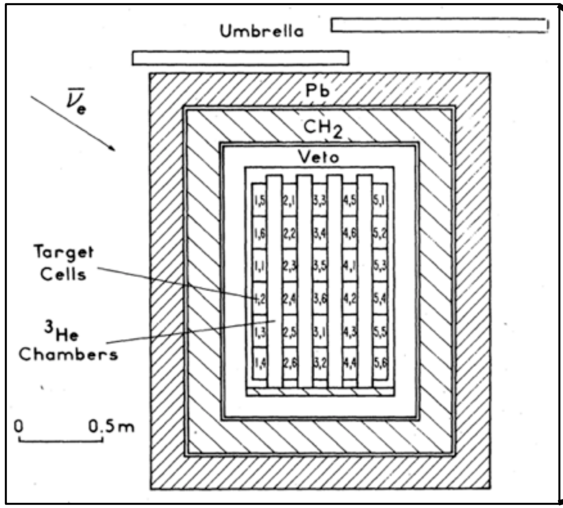
- Short cycles with typical 30% reactor-off time → moderate overburden compensated by accurate measurement of the cosmogenic component.

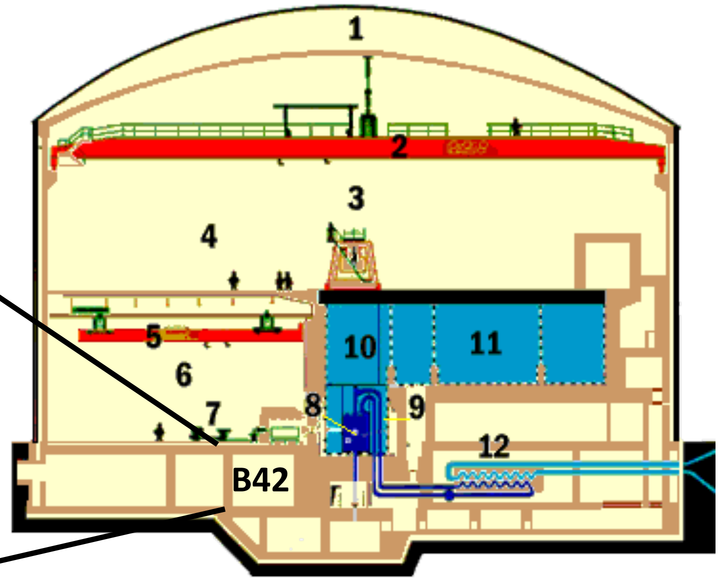
- Challenging reactor-induced backgrounds (γ and n) , depending on sites.

- Highly enriched fuel → well known ^{235}U fisison spectrum.

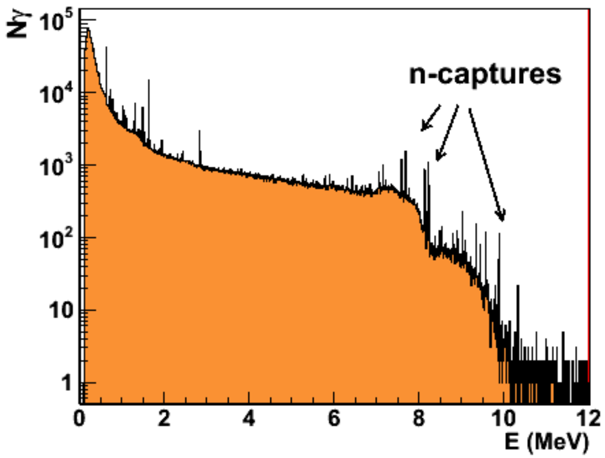
Benchmark of ILL experiment

20 cm lead shielding
30 cm neutron shielding



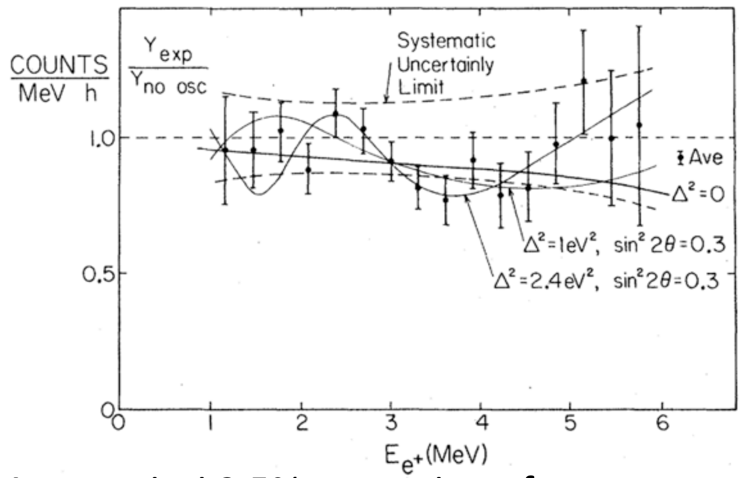


- 377 l Liquid Scintillator target + ^{3}He tubes
- 9 m away from the reactor core
- ~38 ν/d, 4890 ν total.

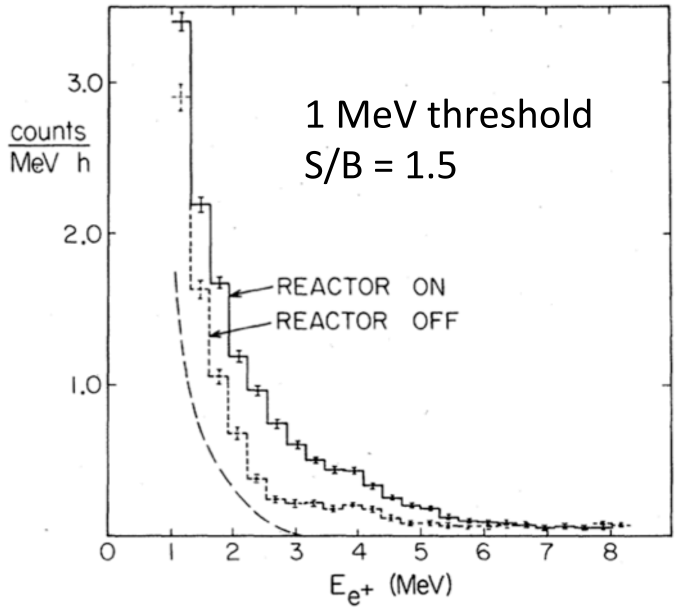


- High energy γ's from n-captures on metals

Benchmark of ILL experiment



A posteriori 9.5% correction of reactor power.
A. Hoummada et al., Appl. Radiat. Isot. 46 (1995)



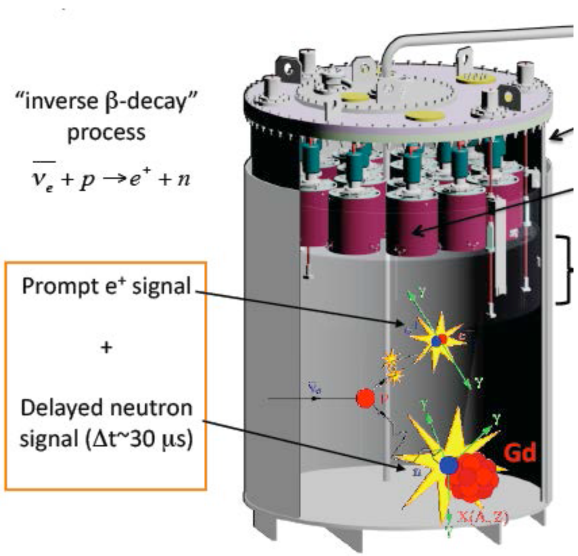
- No measurable reactor induced background in the prompt and delayed rates.

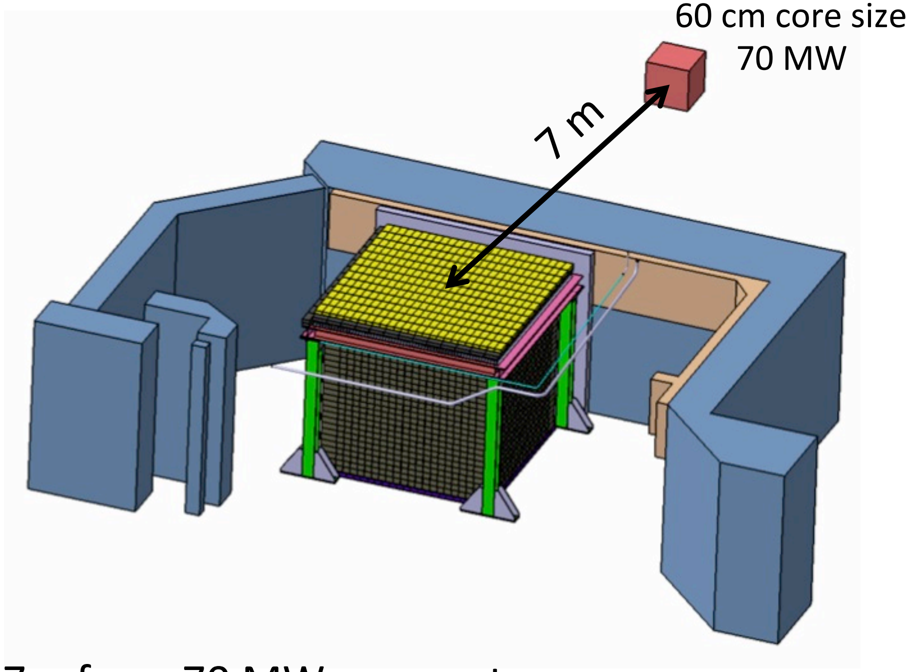
Reactor status	Count rates (s^{-1}) 30 target cells [a]	4 ^{3}He counters [b]	6 veto tanks [a]	4 umbrellas [a]
Off	216.3	0.422	256.8	440
On	216.7	0.427	258.6	5384

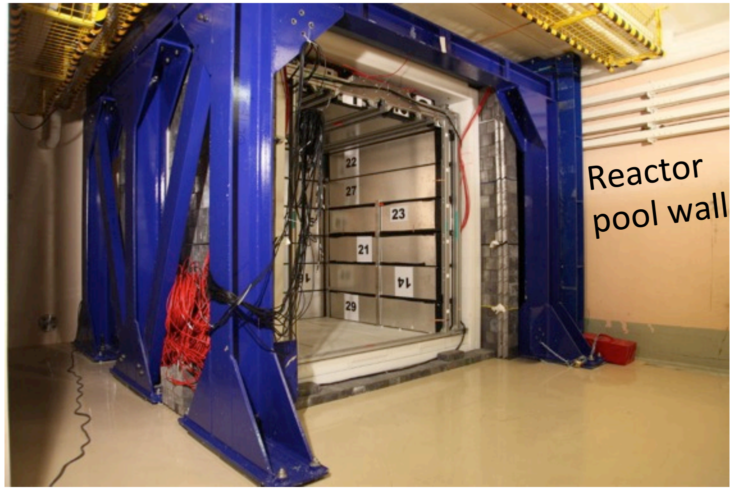
- Stat. and cosmic background limited.

Synergy with Reactor Monitoring Experiments

Nucifer @ OSIRIS





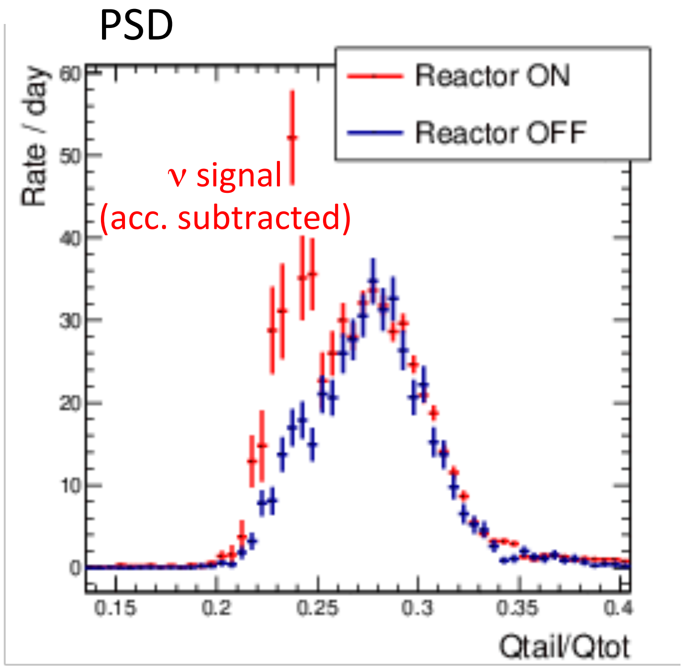


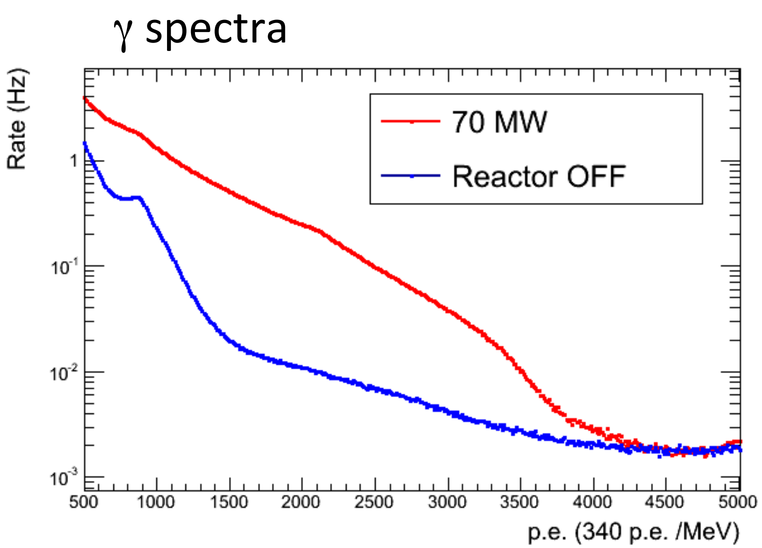
- 7m from 70 MW compact core
- Very simple design based on **Gd-loaded LS** (Double Chooz R&D, see C. Buck's talk)
- High-E γ background (~1 MHz/m^2 above 2 MeV)
- Heavy passive shielding 20 cm of lead in front main γ sources+ active μ-veto.

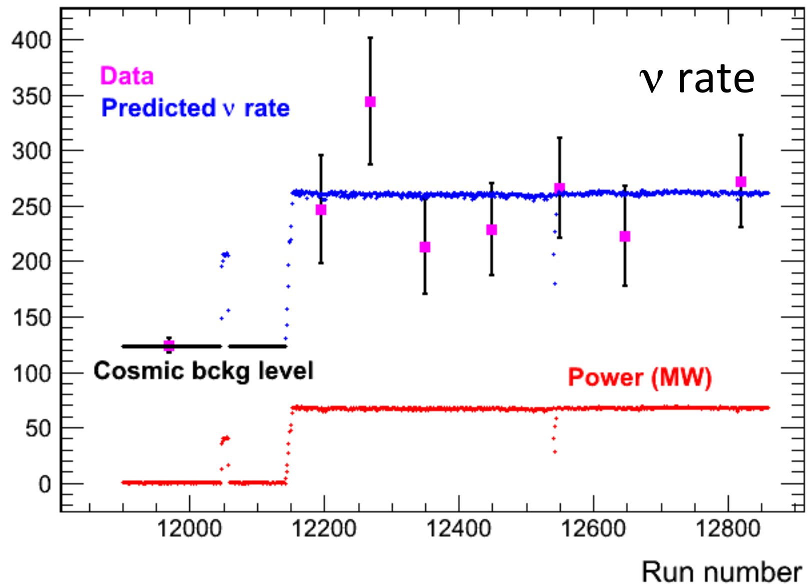
Contact: T. Lasserre, CEA-Saclay

Nucifer @ OSIRIS

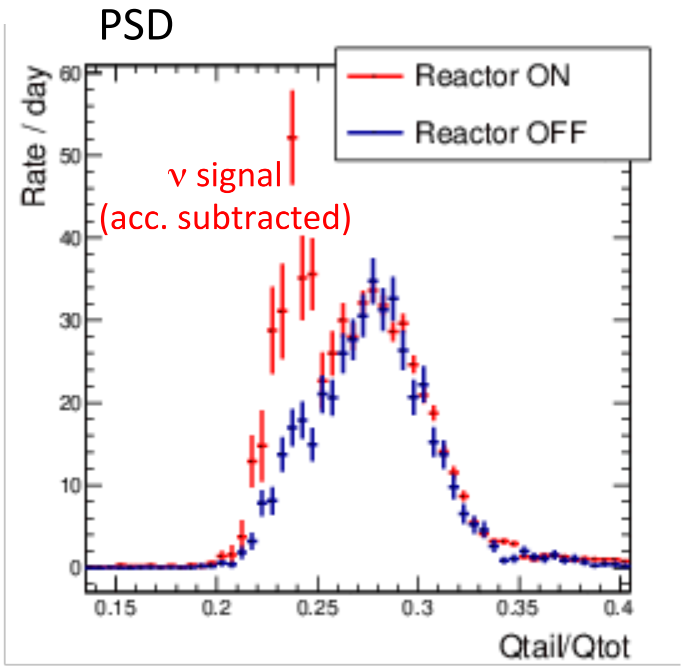
- No reactor induced fast n.
- Efficient rejection of cosmic background.
- Need further γ attenuation to reach S/B~1. Extra 3.75 cm of lead to be implemented this fall.







Nucifer @ OSIRIS



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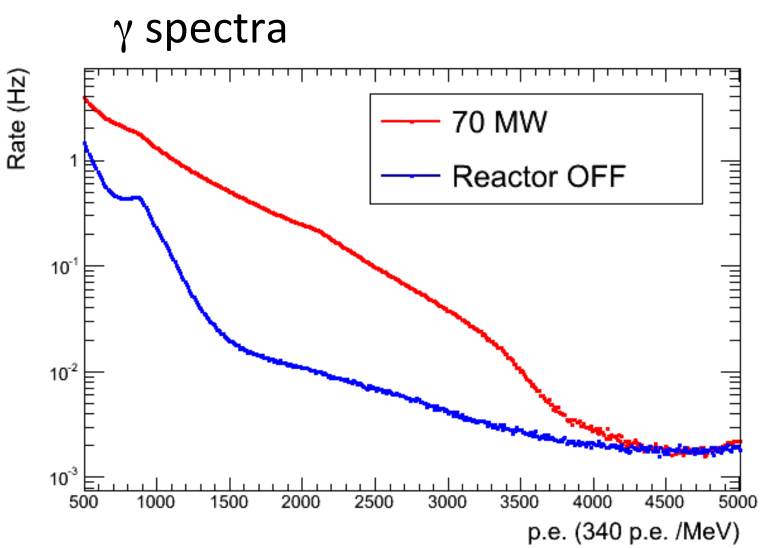
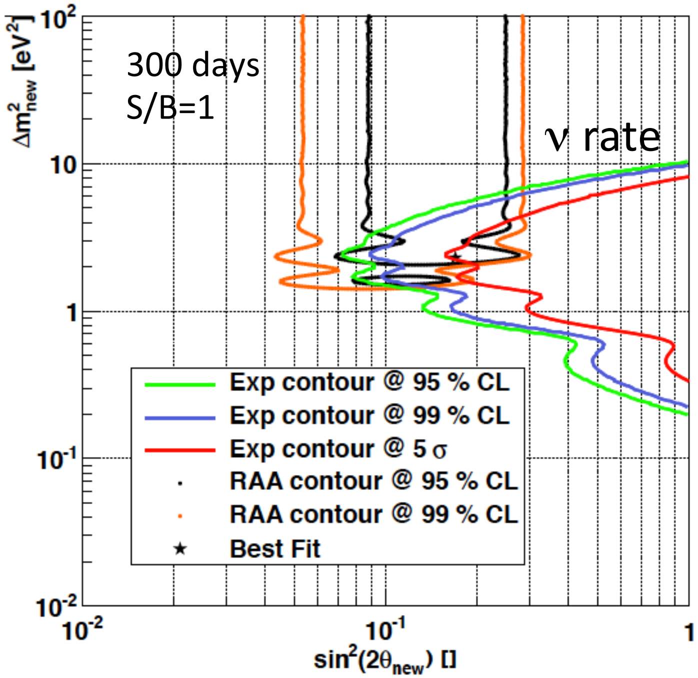
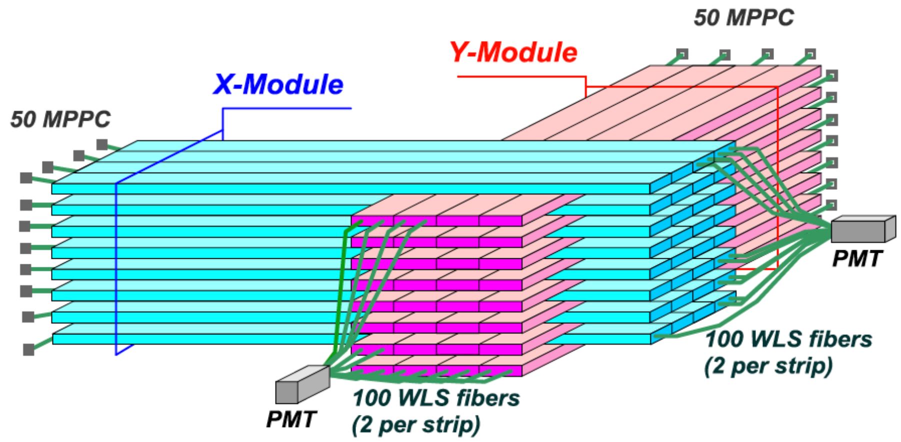


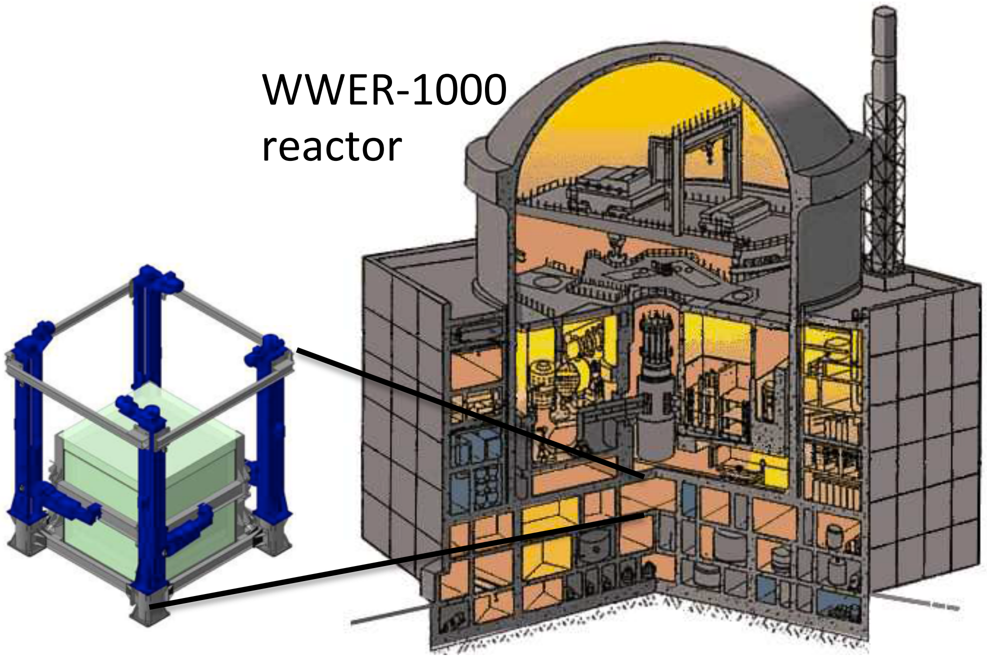


See M. Danilov's talk

DANSS @ KNPP

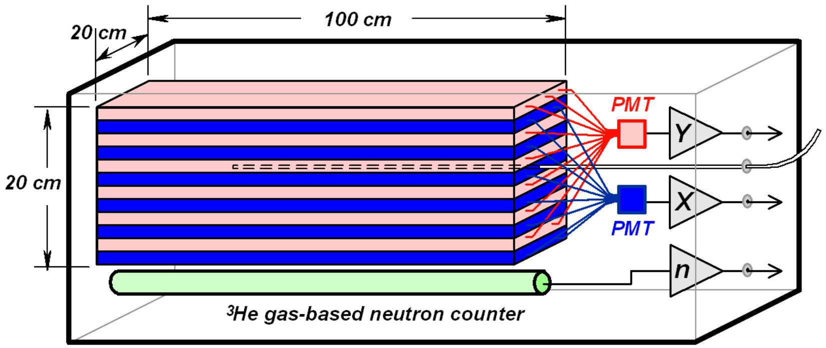
- Highly segmented detector for better background reduction.
- Plastic strips with Gd-loaded interlayer, read out by WLS fibers.
- E resol ~20% at 1 MeV.
- Vertical motion of the detector from 9.7 to 12.2 m baseline.
- 10^4 evt/day expected at 11m.
- Good overburden from core structure. Extended source.





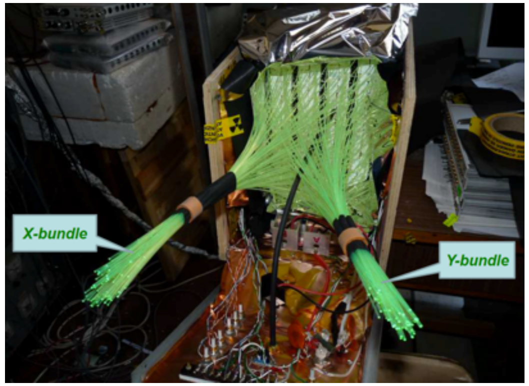
DANSSINO Prototype

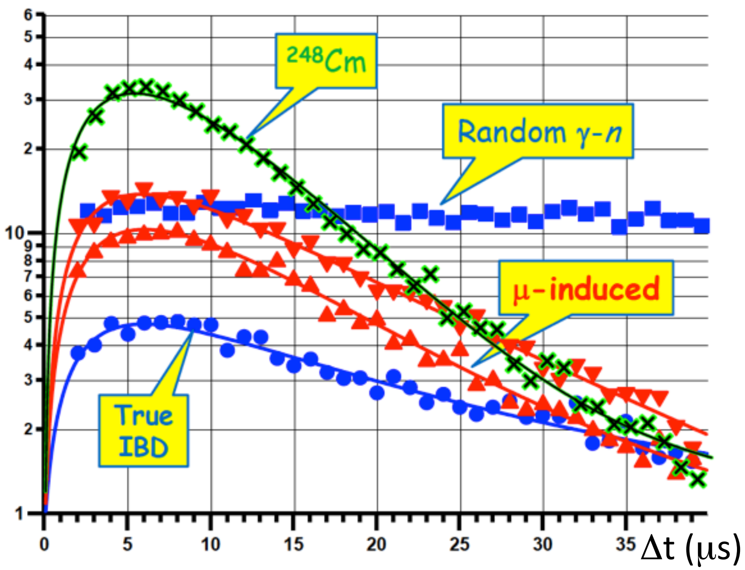
1/25th of DANSS

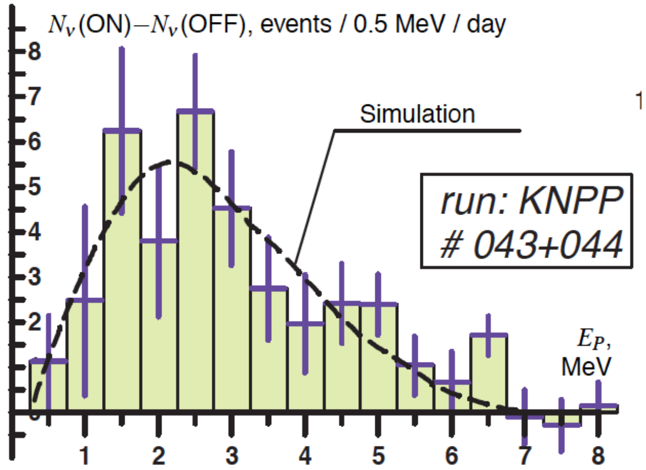


10 cm Cu-Lead + 10 cm CH_2 shelding

Tested for ~20 days @ KNPP



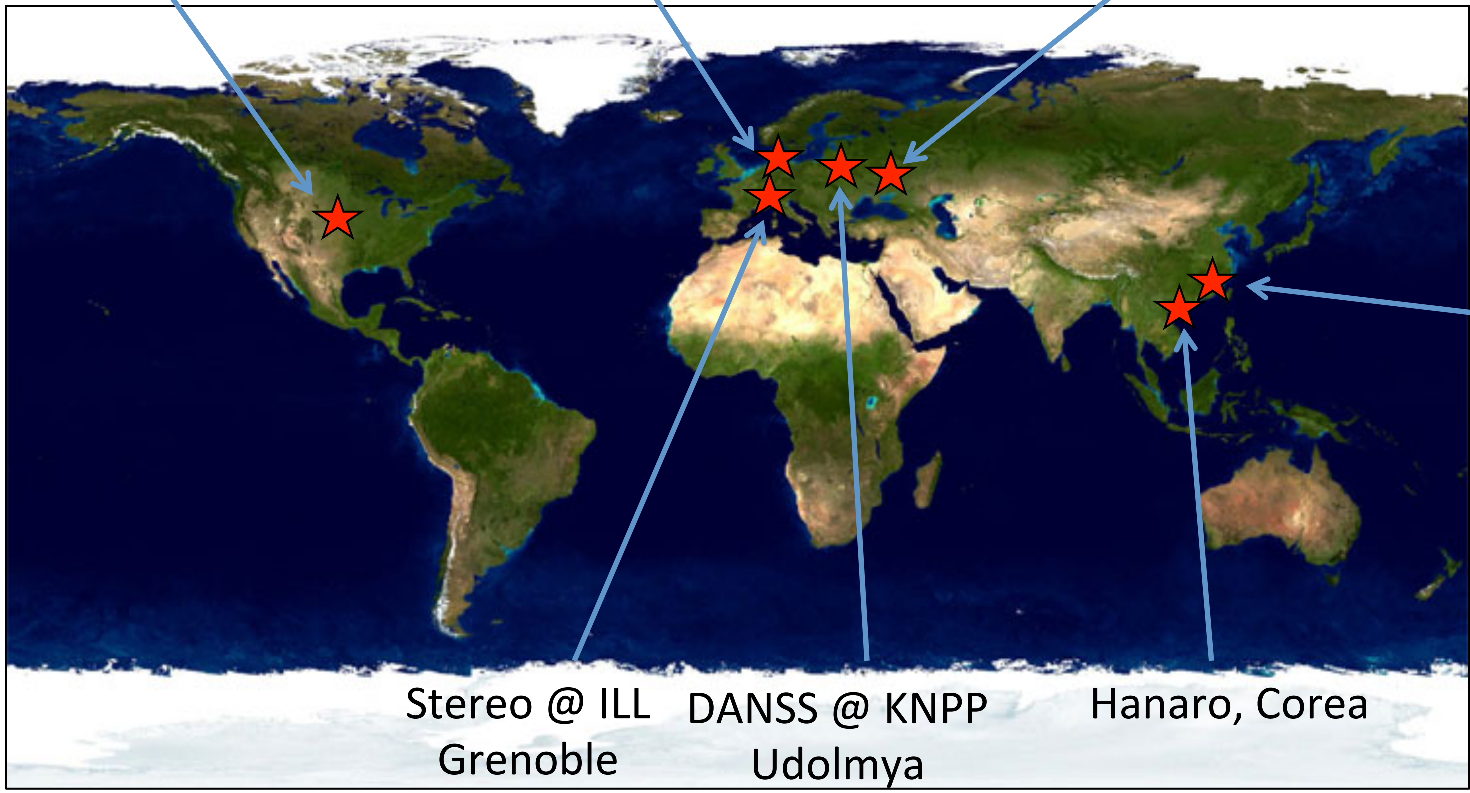




- Accidentals well suppressed
- S/B~1, limited by cosmic fast neutrons.

New Short Baseline Reactor Experiments

New Short Baseline Reactor Experiments



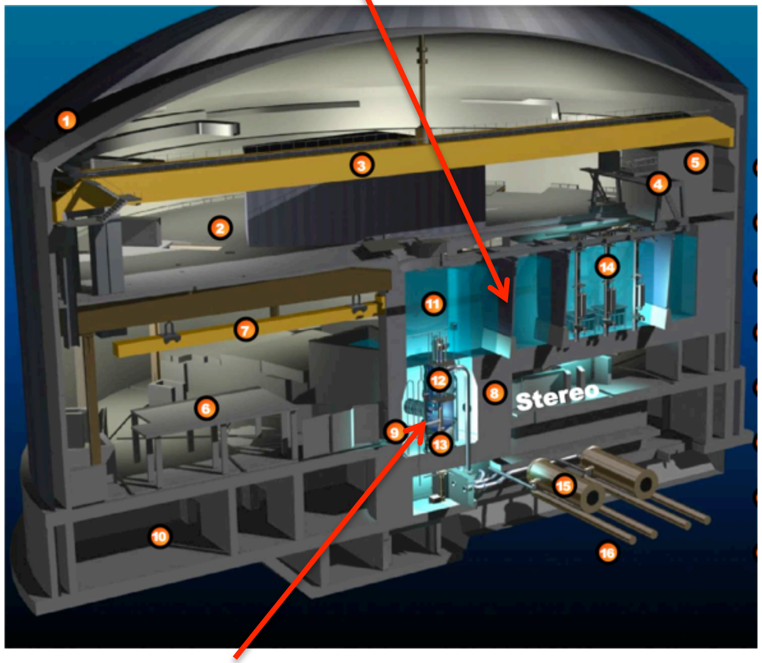
New Short Baseline Reactor Experiments

Segmented Liquid Scintillator Target

Stereo @ ILL

Contact: D. Lhuillier, CEA-Saclay

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

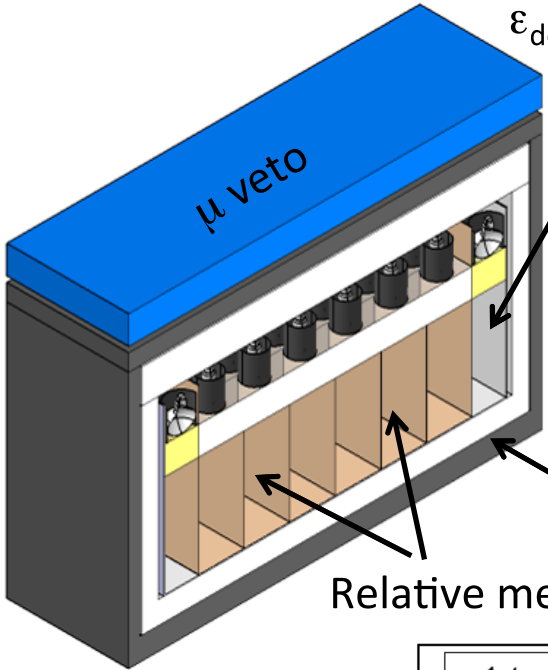


50 MW core
h=80cm, Φ=40cm

[8.5-11] m baseline range

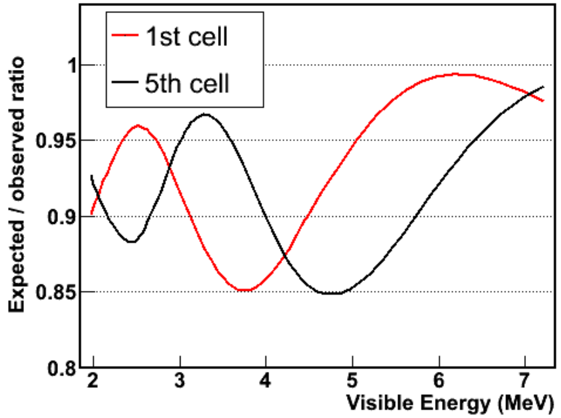
Detector based on Double Chooz and Nucifer developments.

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

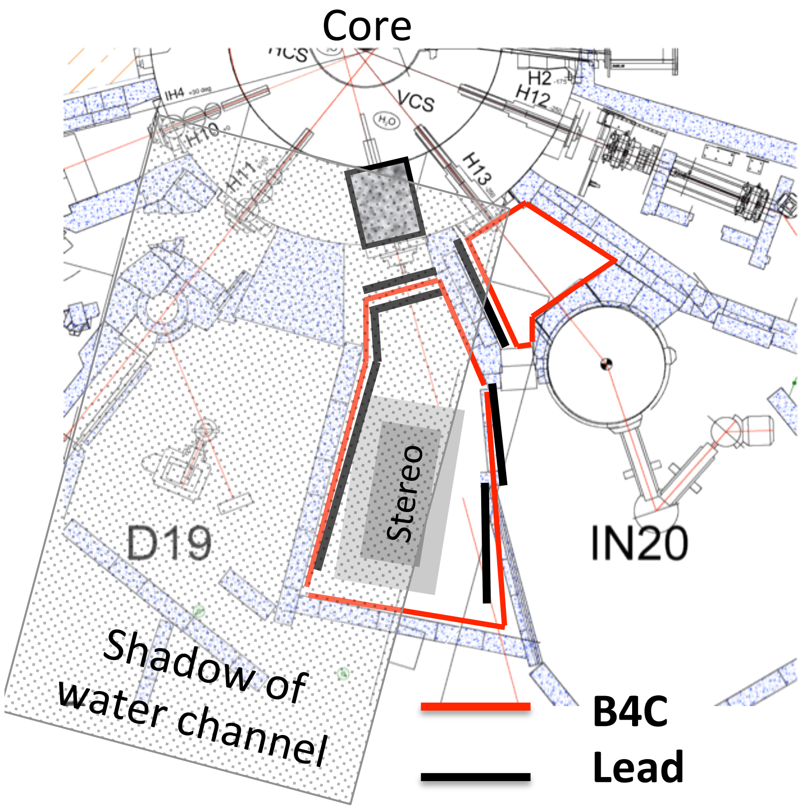


γ and n shielding

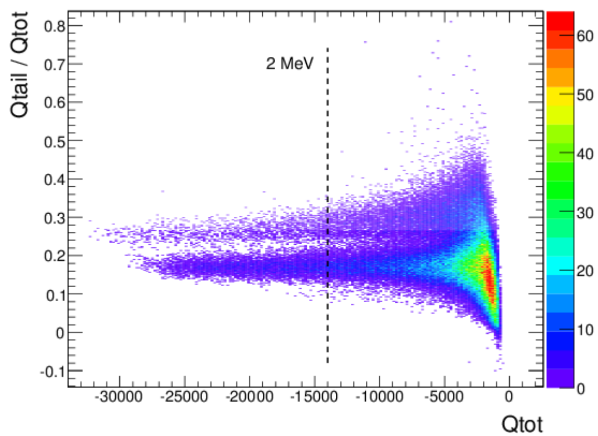
Relative measurement in 6 cells



Background Rejection

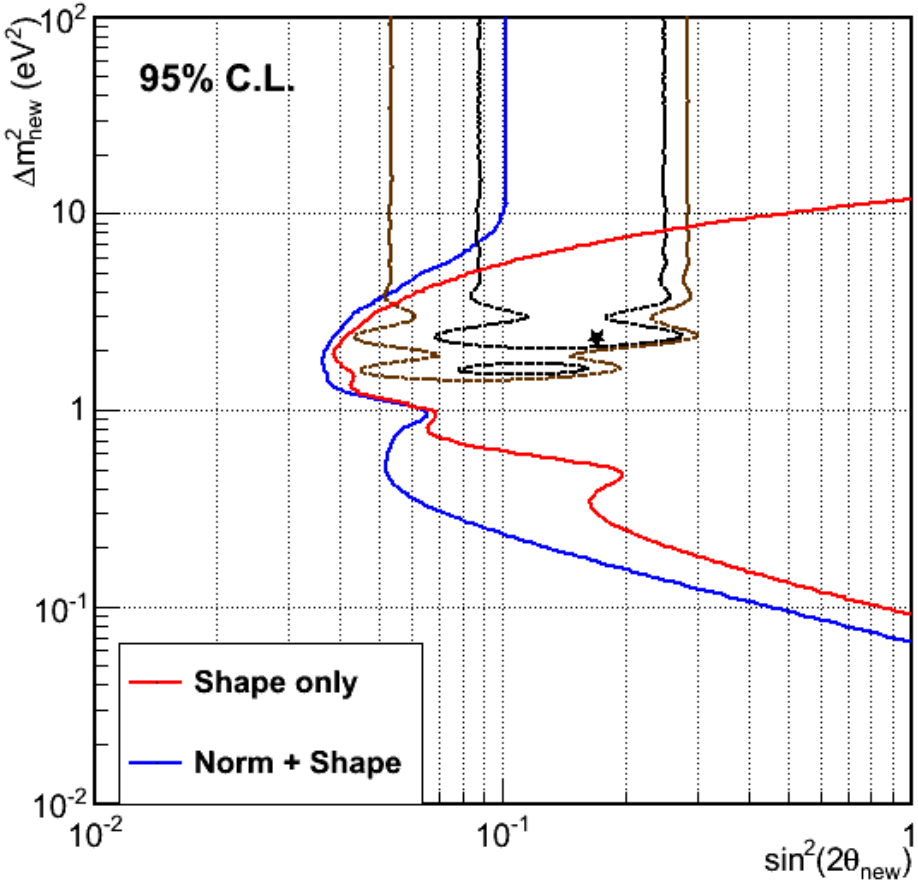


- Extensive on site measurements of muon, thermal n, fast n and γ background
- Massive deployment of shielding during the upcoming long reactor shutdown. 30 cm of lead in front hot γ spots + hermetic B4C coating.
- Dedicated plug of the neutron line already designed.



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

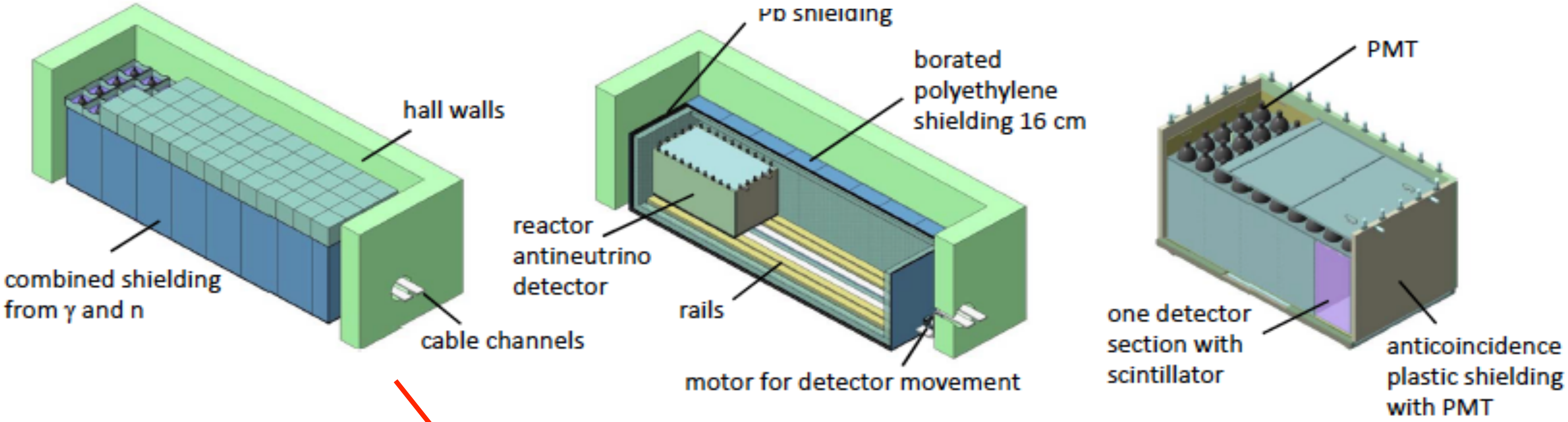
- Funded by ANR grant

- Time schedule:
  2013-2014: design and construction
  Mid-late 2014: installation
  2015-2016: data taking

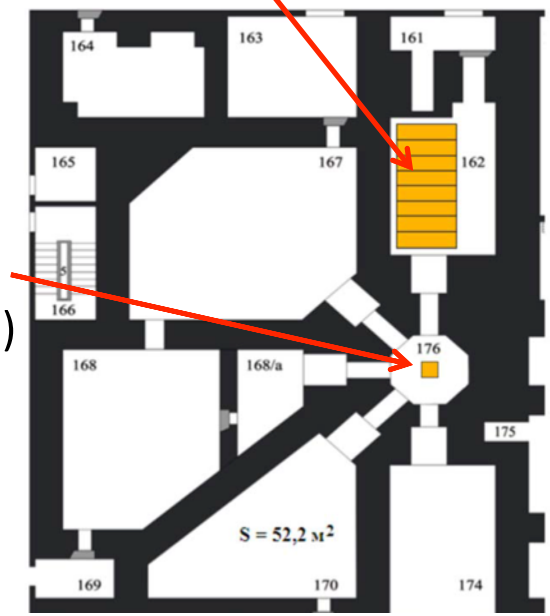
Neutrino-4 @ SM3

Contact: A. Sereborv, Gatchina

5 section movable detector [6-12] m, 2.5 m^3 target

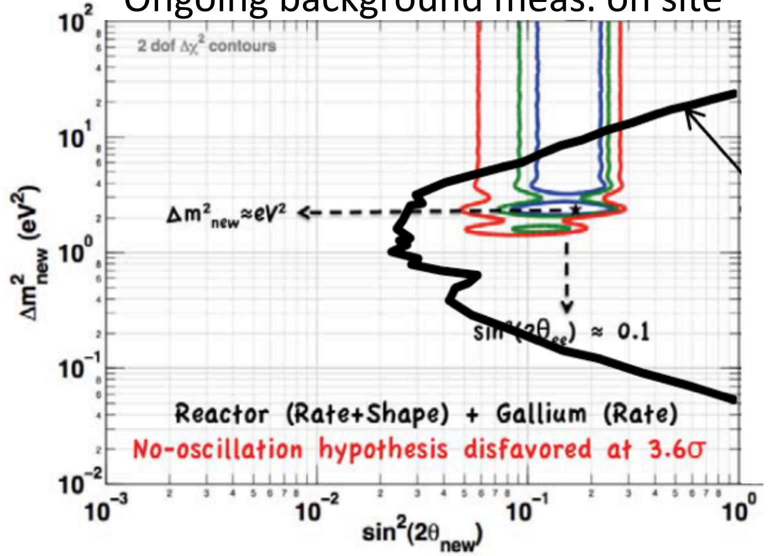


100 MW compact core (35x42x42 cm^3)

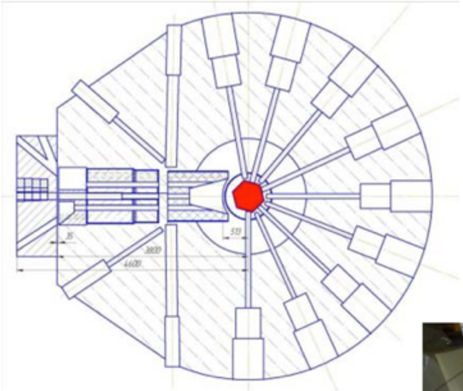


E_{prompt}>2.2 MeV, No background

Ongoing background meas. on site

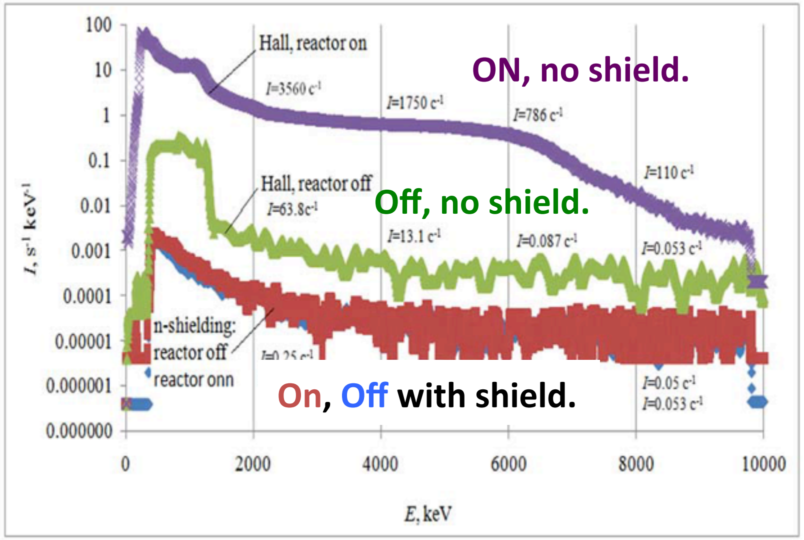


Neutrino-4 Prototype

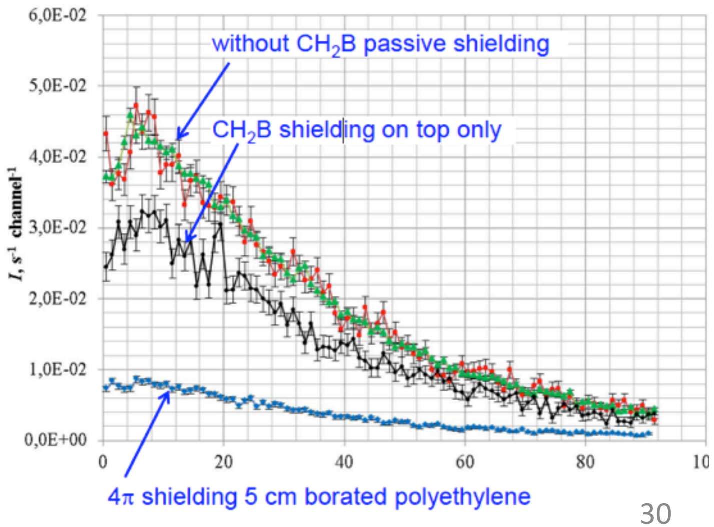


Validation of a prototype detector at the WWR-M 17 MW reactor (Gatchina)

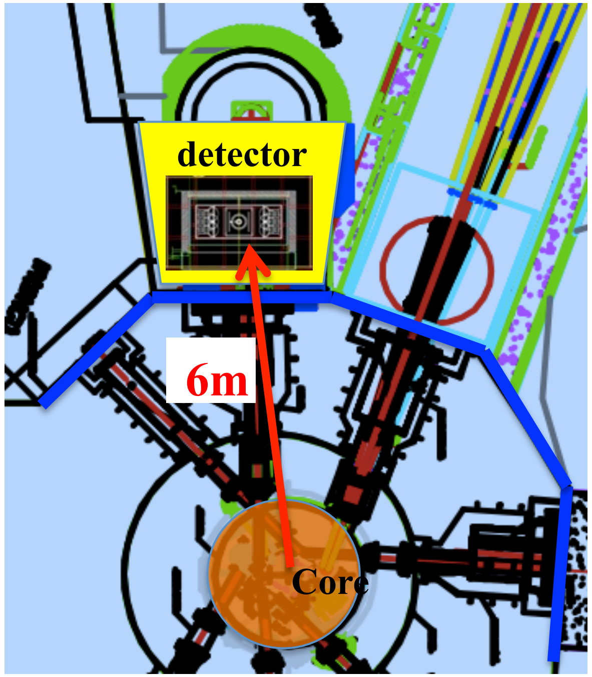
- Good suppression of γ background



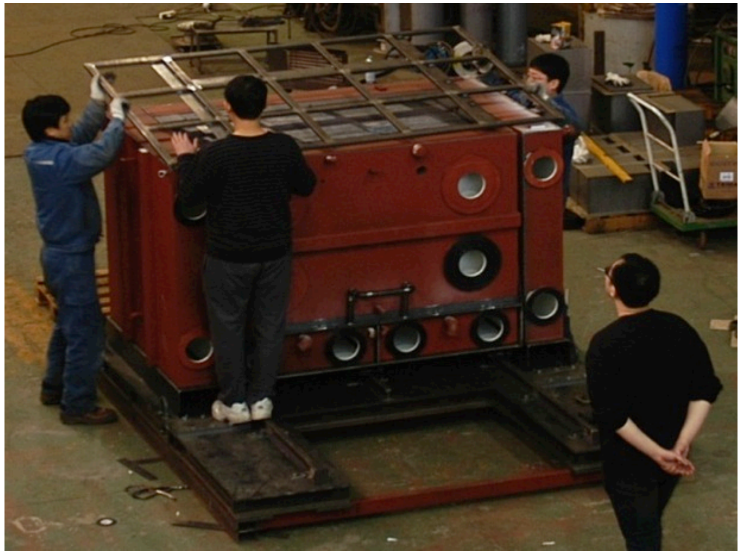
- Neutrino detection currently limited by cosmic rays induced fast neutrons.
- Installation of shielding at the SM-3 site foreseen this fall.



Hanaro, Korea



- 30MW research Reactor
- Compact core ~ 20x40x60cm
- Modest overburden
- 500L Main Detector → ~ 100 events /day.

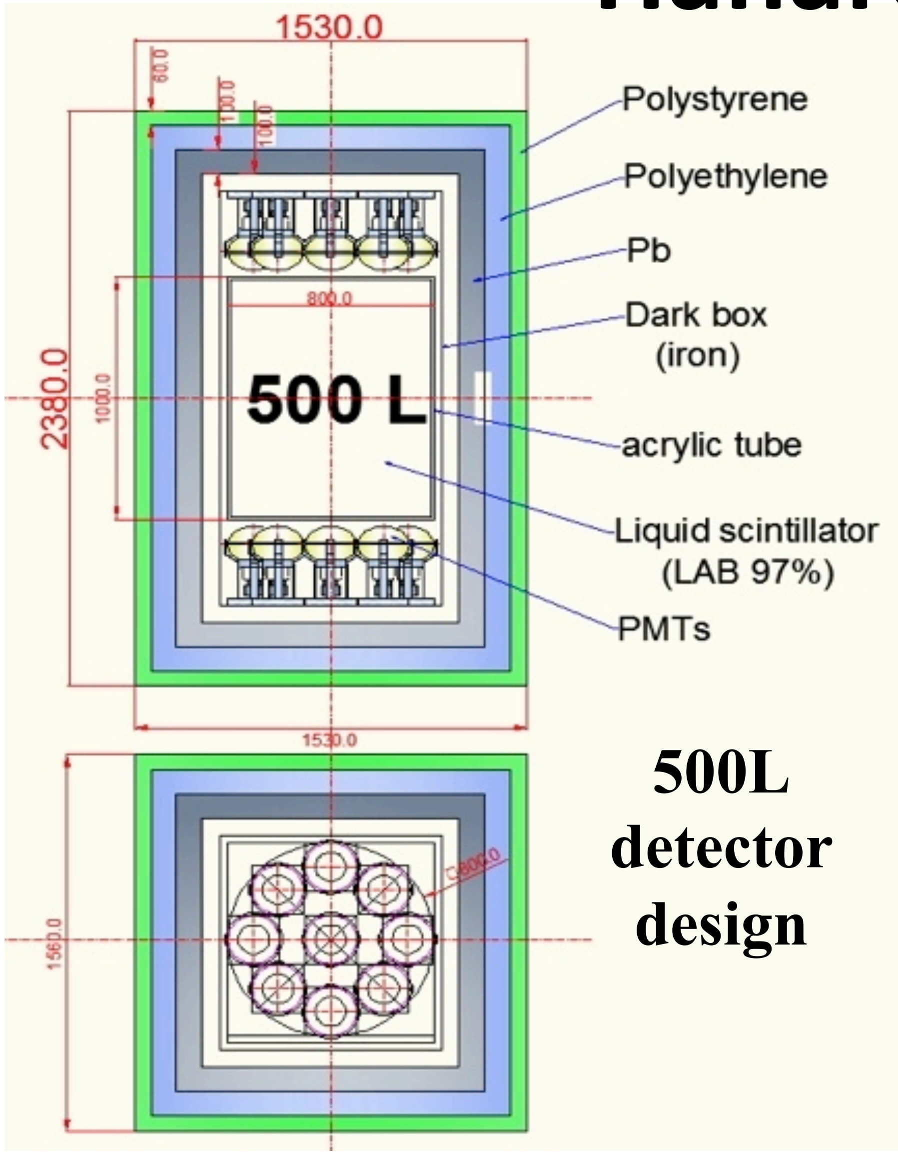


- 50L Prototype Detector built (2013)
- Background study @ surface
- Test of ^{6}Li-loaded LS with segmentation

→ good n discrimination but low $E_{visible}$

Contact: K. Yeongduk, Sejong Univ.

Hanaro, Korea



500L detector design

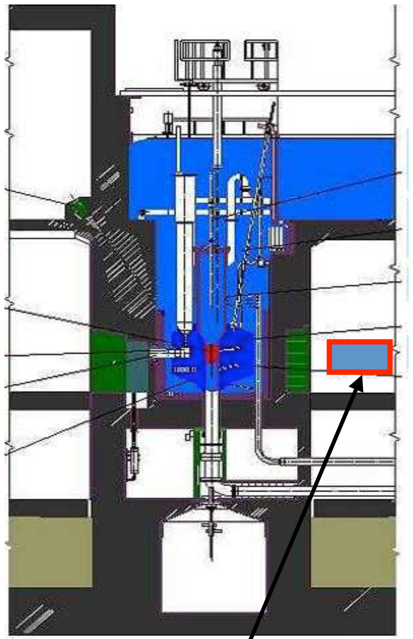
- Simulations about backgrounds
  - ✓ Cosmic muon induced
  - ✓ Cosmic neutron induced
  - ✓ Accidentals
  - ✓ Detector optimization.

- Physics Run @ two places (2015)
  1. 30MW research reactor.
  2. Tendon Gallery run @ 3GW commercial reactor.

- Detector optimization :
  - ✓ Include Gamma Catcher ?
  - ✓ Include Pb shielding inside PE shielding ?

Poseidon

Position-**Se**nsitive **D**etector **Of** **N**eutrino



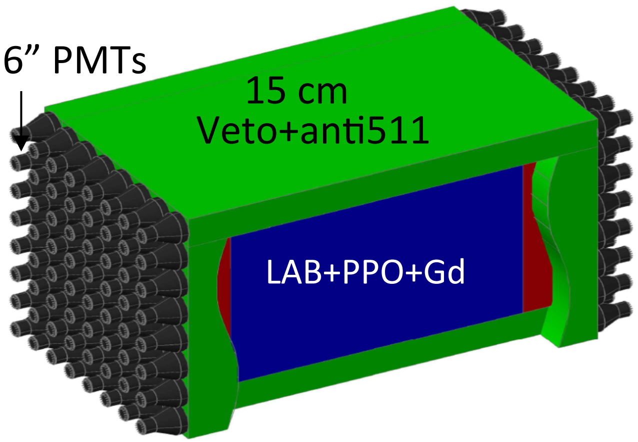
Detector can be placed at 5-8 m

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

100 MW research **Reactor PIK**
is being built in Gatchina, (~2014 y)

Compact core: h=50 cm, d=39 cm

64 6” PMTs



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

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

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

Contact: A. Derbin, pnpi-Gatchina

New Short Baseline Reactor Experiments

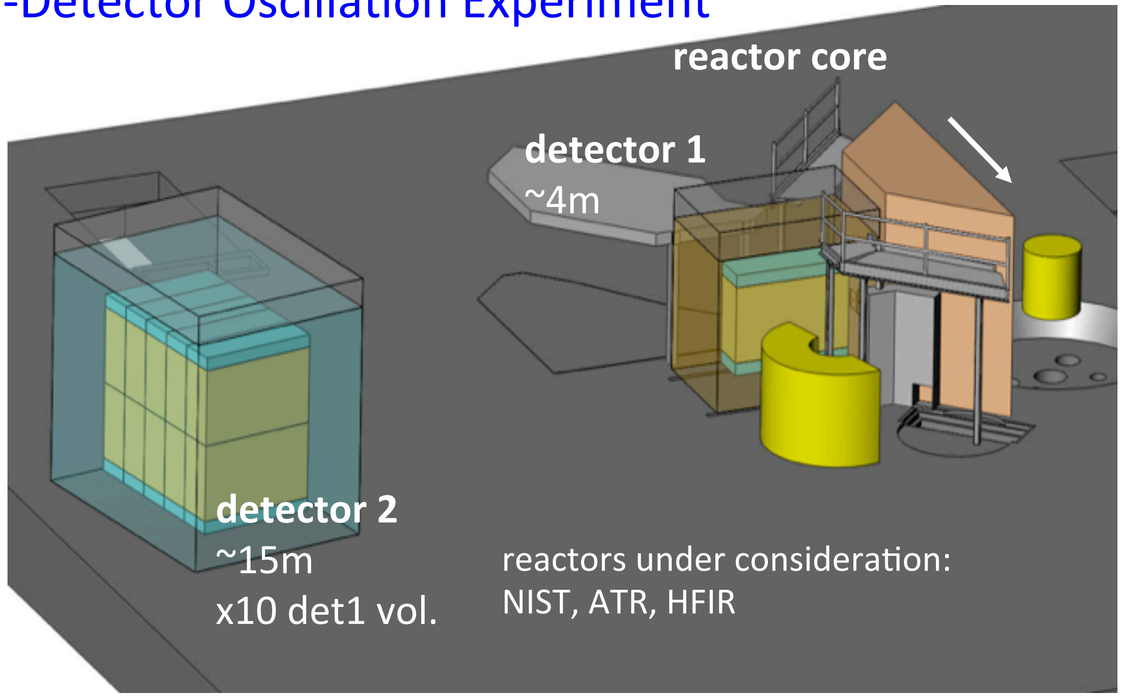
Near/Far Detector Concept

US Short-Baseline Reactor Experiment

Objectives

- short-baseline neutrino **oscillation search with high sensitivity**, probe of new physics
- test of the oscillation region suggested by reactor anomaly and $\bar{\nu}_e$ disappearance channel
- **precision measurement of reactor $\bar{\nu}_e$ spectrum** for physics and safeguards
- develop antineutrino-based **reactor monitoring technology for safeguards**

2-Detector Oscillation Experiment

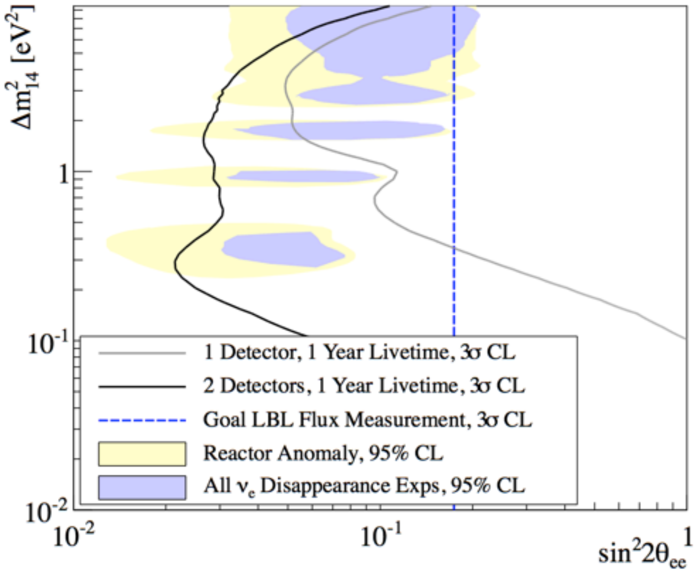


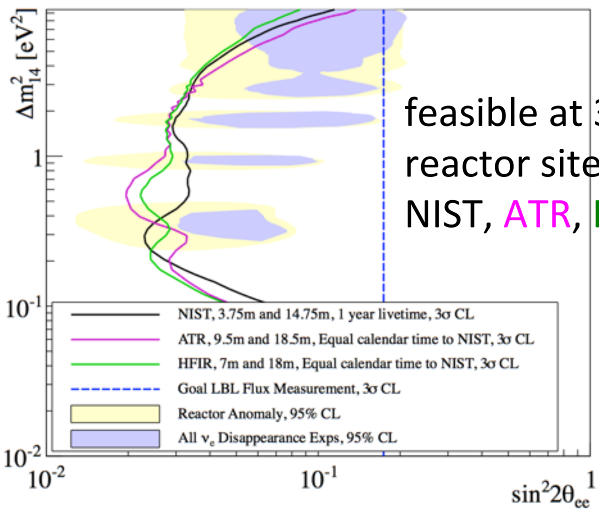
Technically Limited Schedule:

- FY13-14 - R&D
- FY14-15 - design&construction
- FY 2016 - first data?

Contact: K.M. Heeger, Yale

A 2-Detector Oscillation Experiment

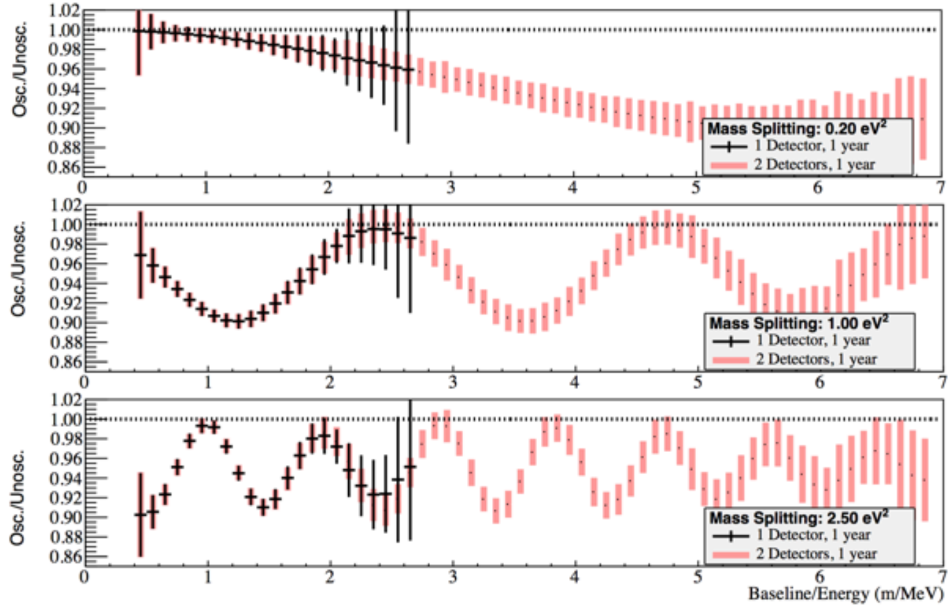




feasible at 3 US reactor sites
NIST, ATR, HFIR

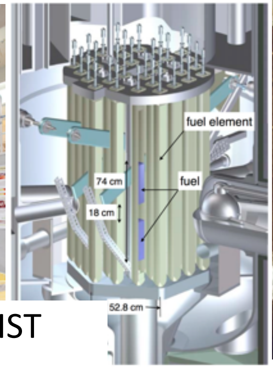
Discovery Potential

3σ in 1 year
5σ in 3 years

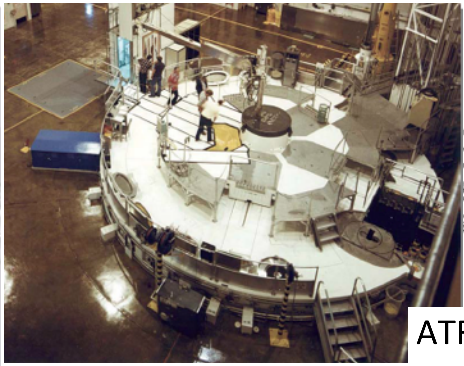


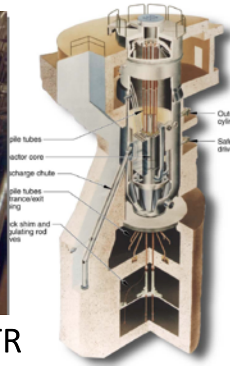
Mumm, Littlejohn, K.M.Heeger, arXiv:1307.2859 (2013)

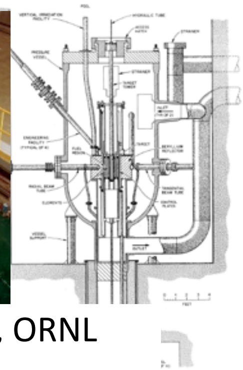
US Research Reactors

NBSR, NIST


ATR



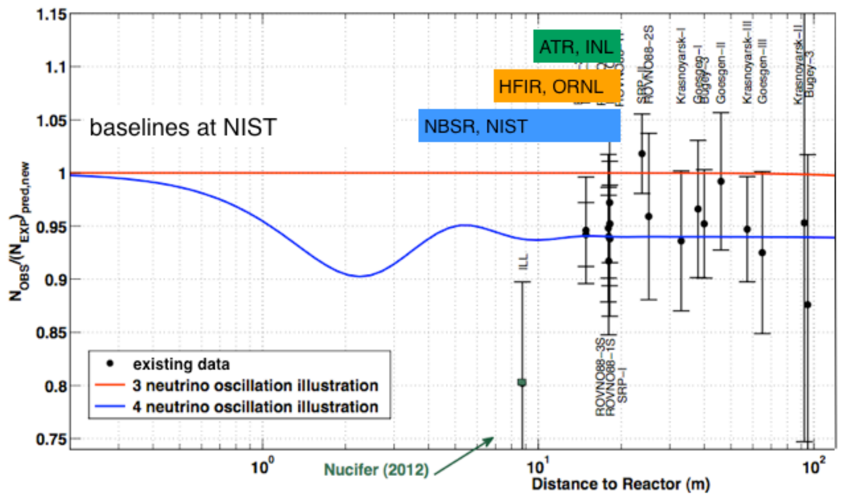

HFIR, ORNL

Site	Power	Duty Cycle	Near Detector Baseline	Average $\bar{\nu}$ Flux (Near)	Far Detector Baseline	Average $\bar{\nu}$ Flux (Far)
NIST	20 MW_{th}	68%	3.9m	1	15.5	1
HFIR	85 MW_{th}	41%	6.7m	0.96	18	1.93
ATR	120 MW_{th}	68%	9.5m	1.31	18.5	4.30

Ongoing site characterization

Adapted from Lasserre et al 2012


NBSR, NIST



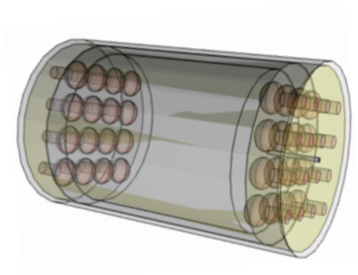
China Advanced Research Reactor

China Advanced Research Reactor

CARR:

- @CIAE in Beijing
- Nearly operational
- 60 MW_{th}
- 5 m shielding wall

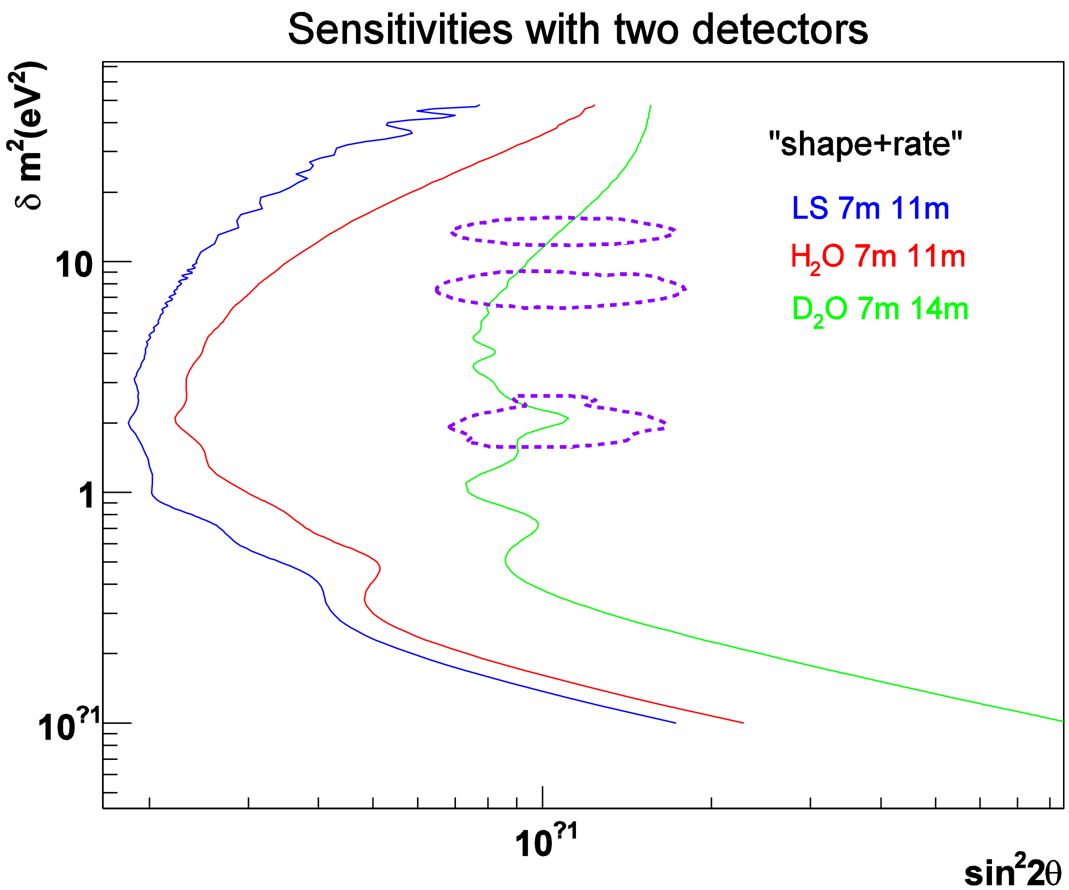
Detector concept:



- GdLS (Daya Bay)
- 1-ton target/detector module
- Teflon reflector on the inner wall
- Two identical detector modules for relative measurement (rate+shape). Near detector @ 7 m, far flexible
- Passive gamma/neutron shield + outer detector with liquid scintillator (anti-compton, fast neutron/muon veto).

Contact: J. Liu, Shangai Univ.

Sensitivity Study



G. Guo et al., arXiv:1313.0607

- Near/far configuration
- $60MW_{th} \times 1$ year $\times$ near/far 1 ton $\times$ 100% efficiency
- Detector-related systematics included
- **No background**
- Challenge: reactor-on background suppression

New Short Baseline Reactor Experiments

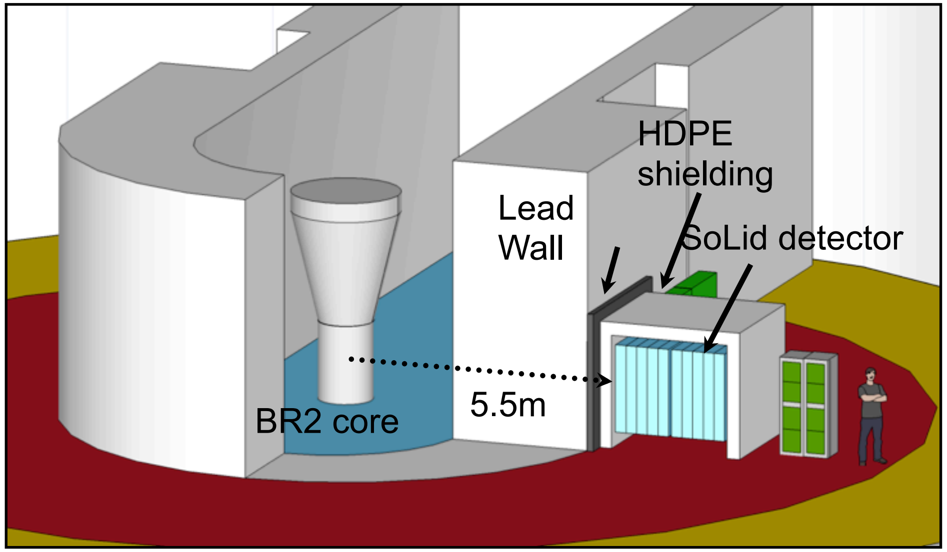
Highly Segmented Plastic Scintillators

SoLid

Search for Oscillations with ^{6}Li Detector

Imperial College London

UNIVERSITY OF OXFORD



BR2 REACTOR, Mol, Belgium

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

DETECTOR

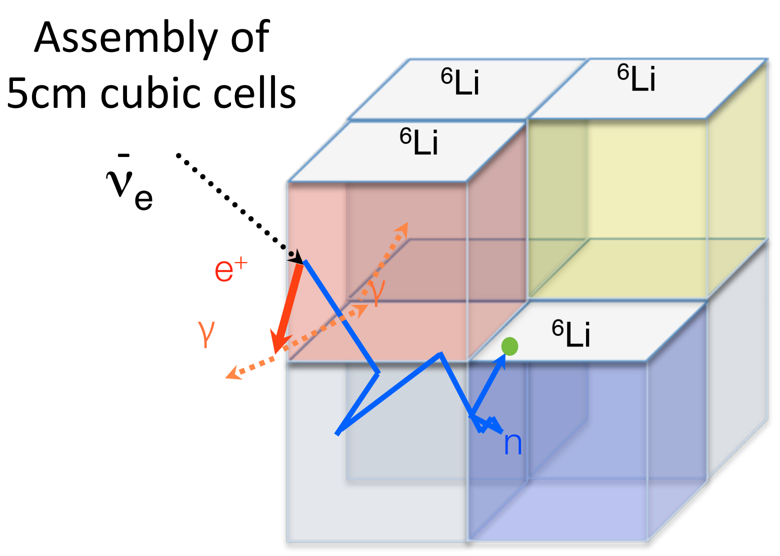
- 2.88t fiducial volume
- Novel type of composite solid scintillator detector (PVT + 6LiF:ZnS)
- 2x 20 planes 1.2m x 1.2m x 1m with 576 5cm x 5cm x 5cm cubes
- Read out by WLS fibres and Geiger-mode APDs (MPPC), 1920 channels total

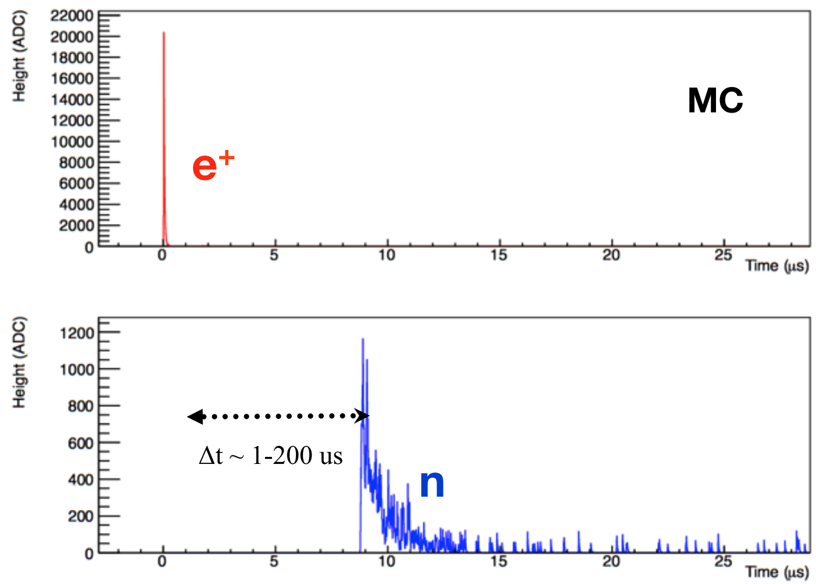
HIGH SIGNAL TO BACKGROUND RATIO : S/B ~ 6

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

contact : antonin.vacheret@physics.ox.ac.uk

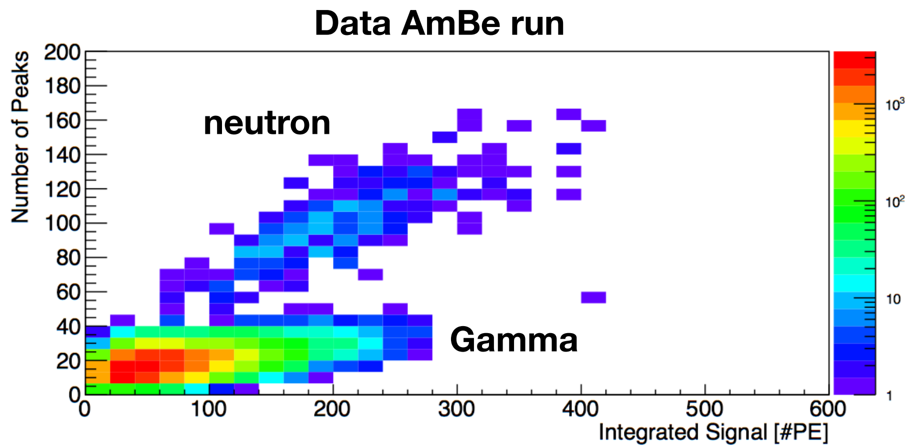
SoLiд Antineutrino detection



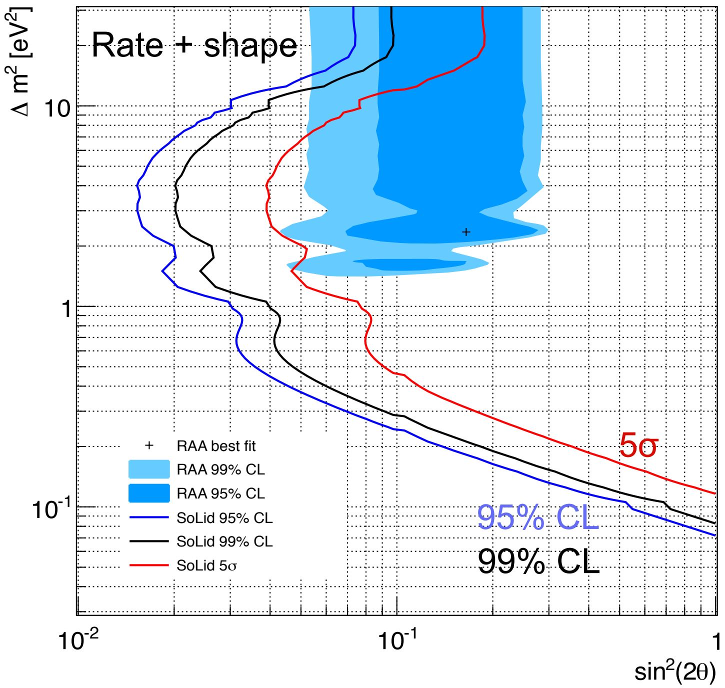


$$^6_3\text{Li} + \text{n} \rightarrow ^2_4 \text{He (2.05 MeV)} + ^1_3 \text{T (2.75 MeV)}$$

- 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.**
- High light yield and good energy resolution (~17% at 1 MeV)

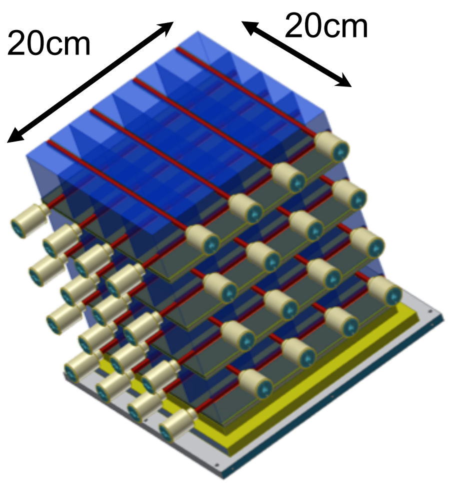


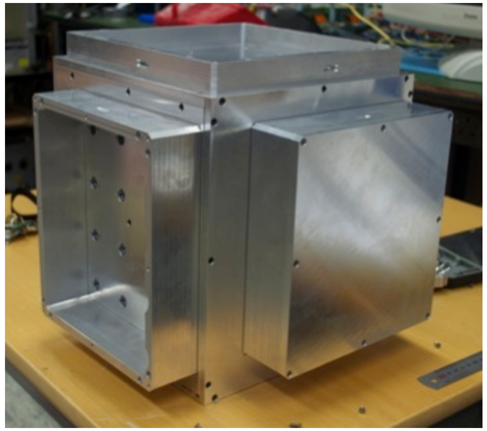
SoLi∂ Sensitivity & status

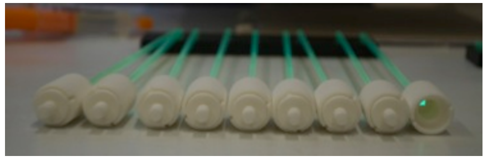


- <Baseline>=6.8m, 2.88t fiducial mass
- 300 days (~ two years running)
- 45% IBD efficiency, 1200 n/day expected
- L binning of 20 cm
- Systematics : norm 4.1%, total ~5%
- Physics run scheduled for start of 2016

8kg Fiducial mass







- Prototype under commissioning at Oxford
- Deployment at BR2 for August 2013 reactor cycle (~25-30 days)
  - study of background conditions
  - antineutrinos measurement trial at 5m from reactor core
  - expect 6 evts/day, S:B ~ 1:5

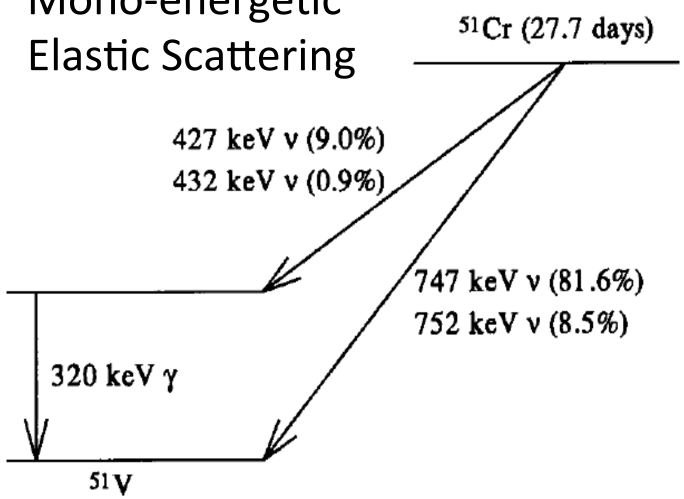
Source Experiments

General Idea

- Place an intense (0.5-10 MCi) source inside or close to a **large size**, already **existing** and **well known** neutrino detector.
- The sources are very compact and can be accurately calibrated (~1%)

Neutrino source ^{51}Cr

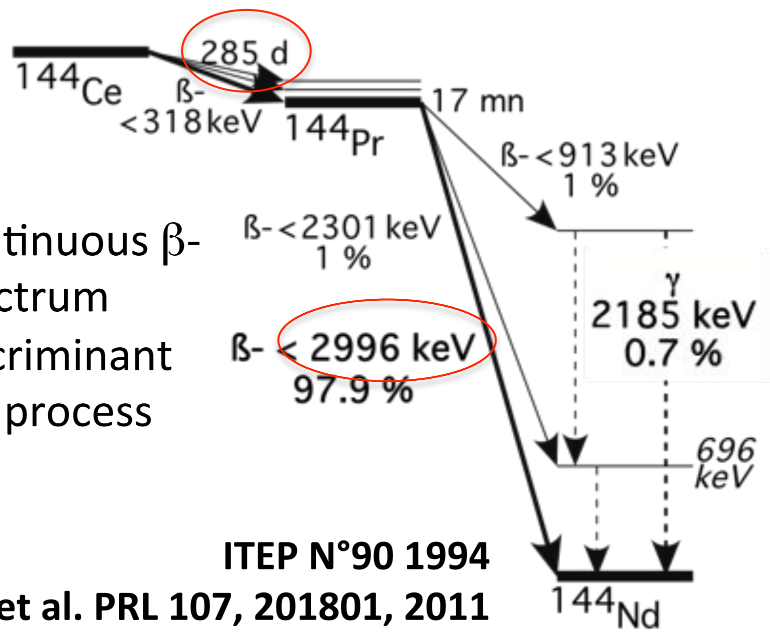
- Mono-energetic
- Elastic Scattering



Proposed by Raghavan
Produced for Gallium experiments

Antineutrino source ^{144}Ce

- Continuous β- spectrum
- Discriminant IBD process



ITEP N°90 1994
M. Cribier et al. PRL 107, 201801, 2011

CeLand Project

^{144}Ce Source @ the KamLAND detector

IBD: Eth = 1.8 MeV - (e+,n) coincidence

Virtually background free experiment!

Resolutions: 7.0%/√E - 15 cm

Funded by ERC and DOE grants.

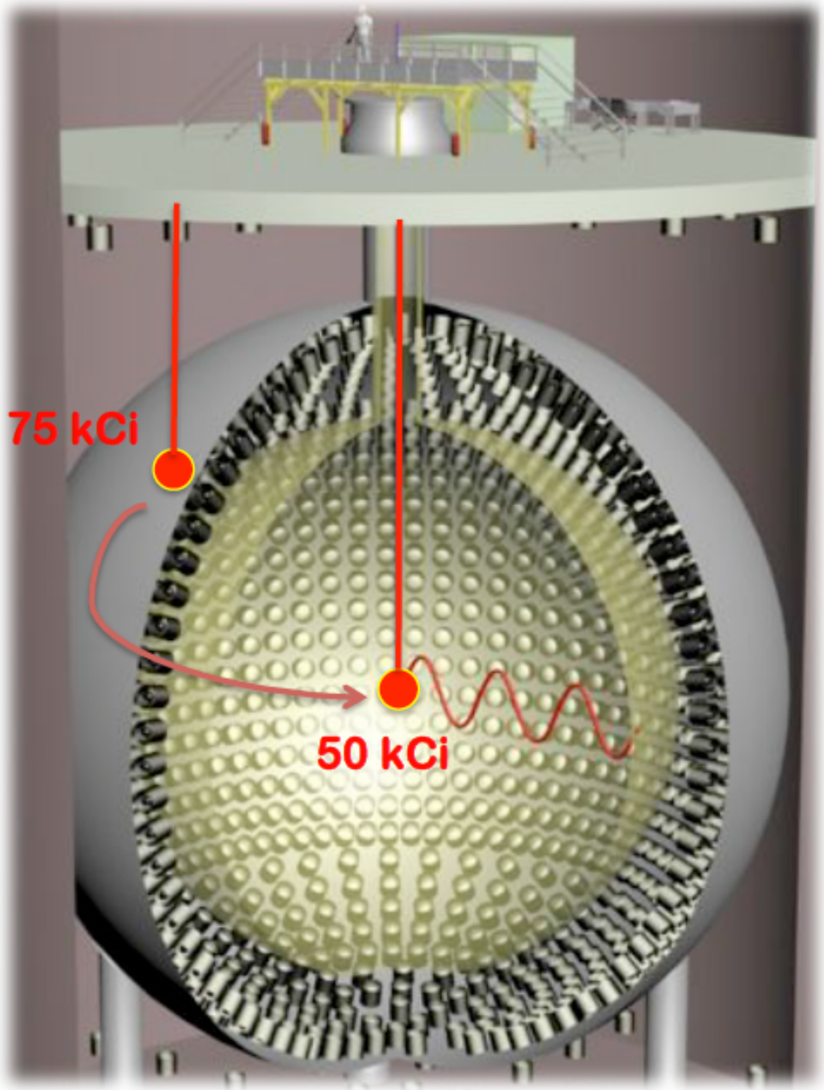
- Phase 1: 2015
  75 kCi source in outer detector

- Phase 2: 2016 (if feasible)
  50 kCi source at center of LS

CeLAND Collaboration:

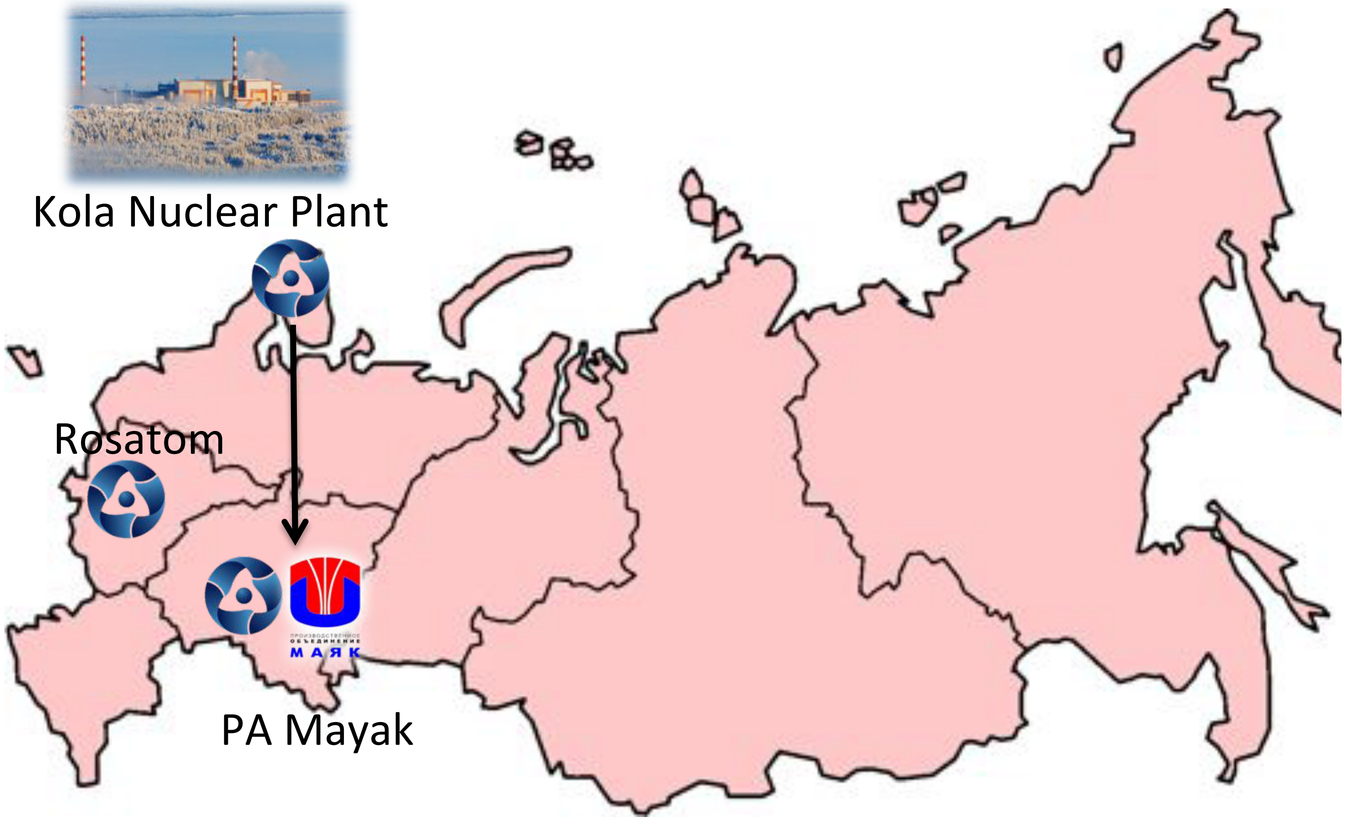
• CEA: DSM-Irfu / DEN / SPR / LNHB / DRI

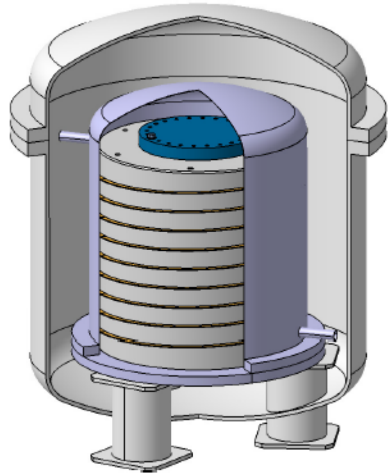
• KamLAND Japanese Collaboration, Irfu (ERC), Hawaii U. (DOE funding), LBNL/UCB, Russia (Mephi)



Contact: T. Lasserre, CEA-Saclay

Source Production

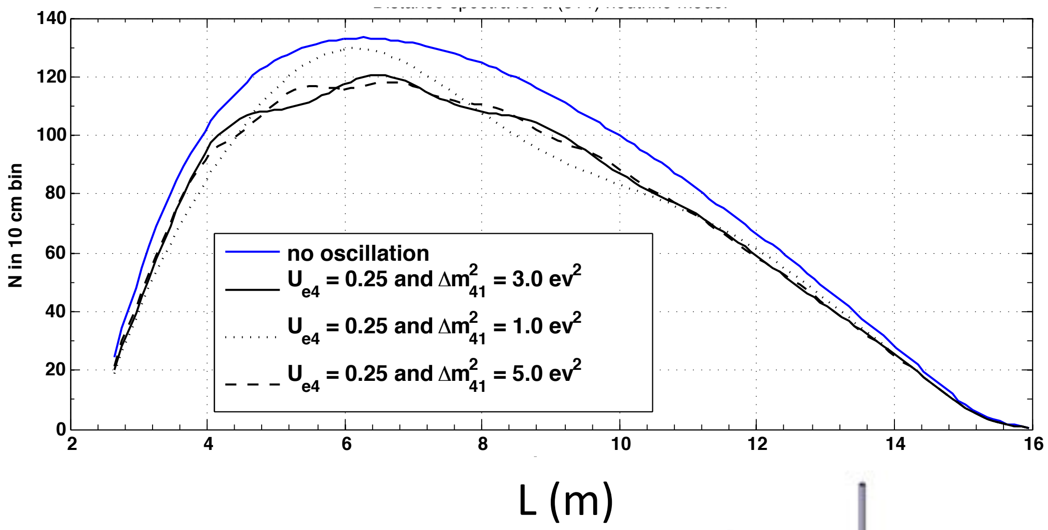




Common SOX/CeLAND development for a 1% calorimeter at ~1kW thermal power.

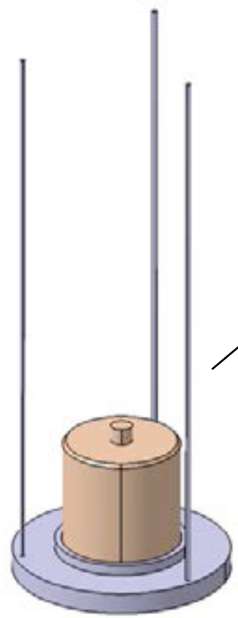
- Reprocessing of few tons of spent nuclear fuel from the Kola reactor at the Mayak facility. Clean separation from other rare earth element by chromatography.
- Samples to be delivered soon at CEA-Saclay
- Final 75 kCi source to be delivered early 2015.
- Transport issues under discussion.

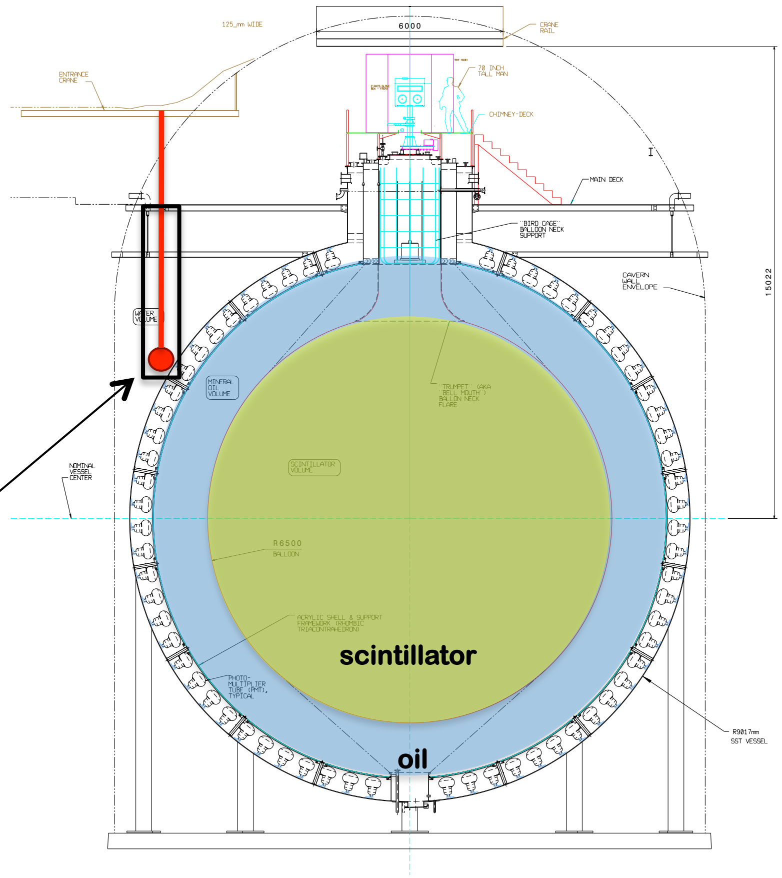
CeLand Phase 1



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

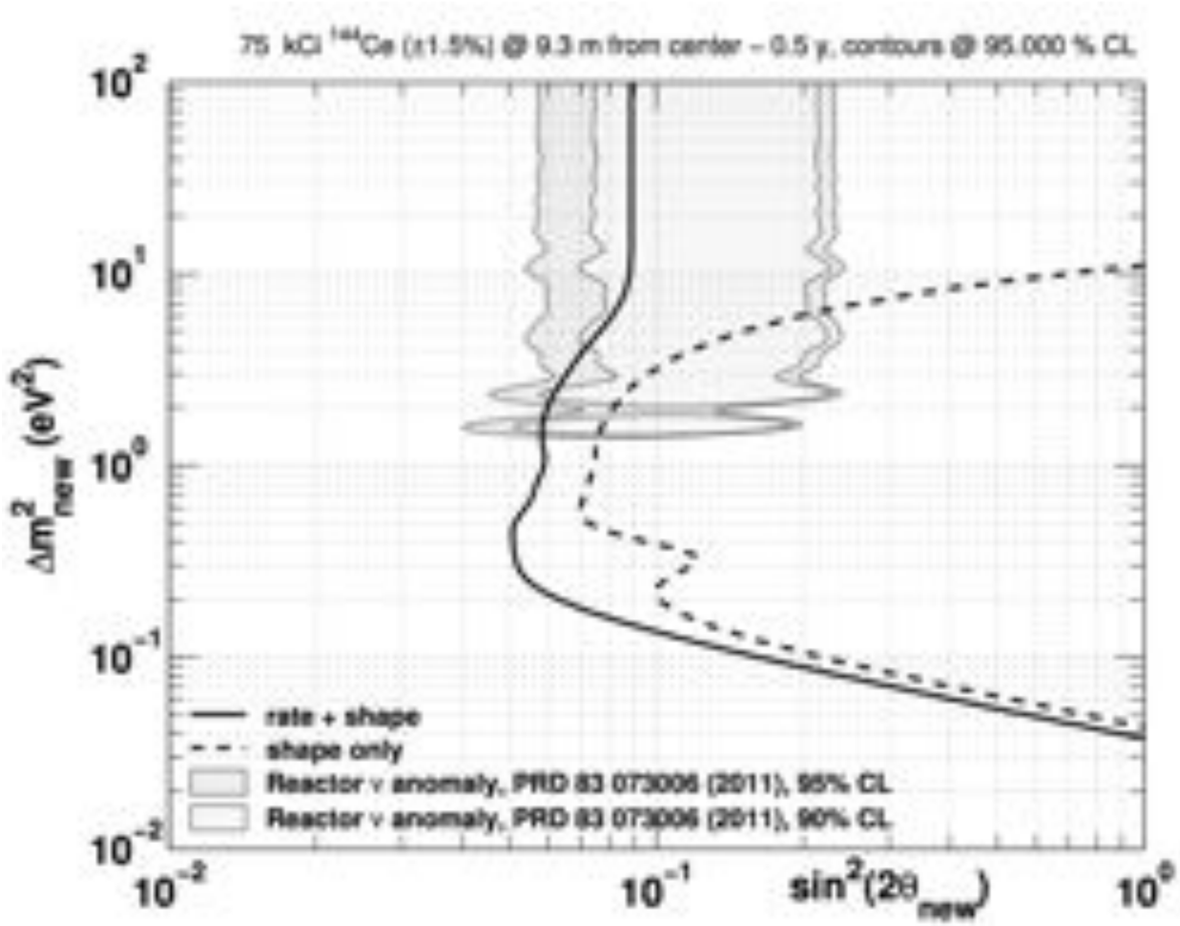
- Shielding tungsten alloy
  47 cm diameter
  16 cm thickness
  ρ=18.5 g/cm^3





CeLand Phase 1

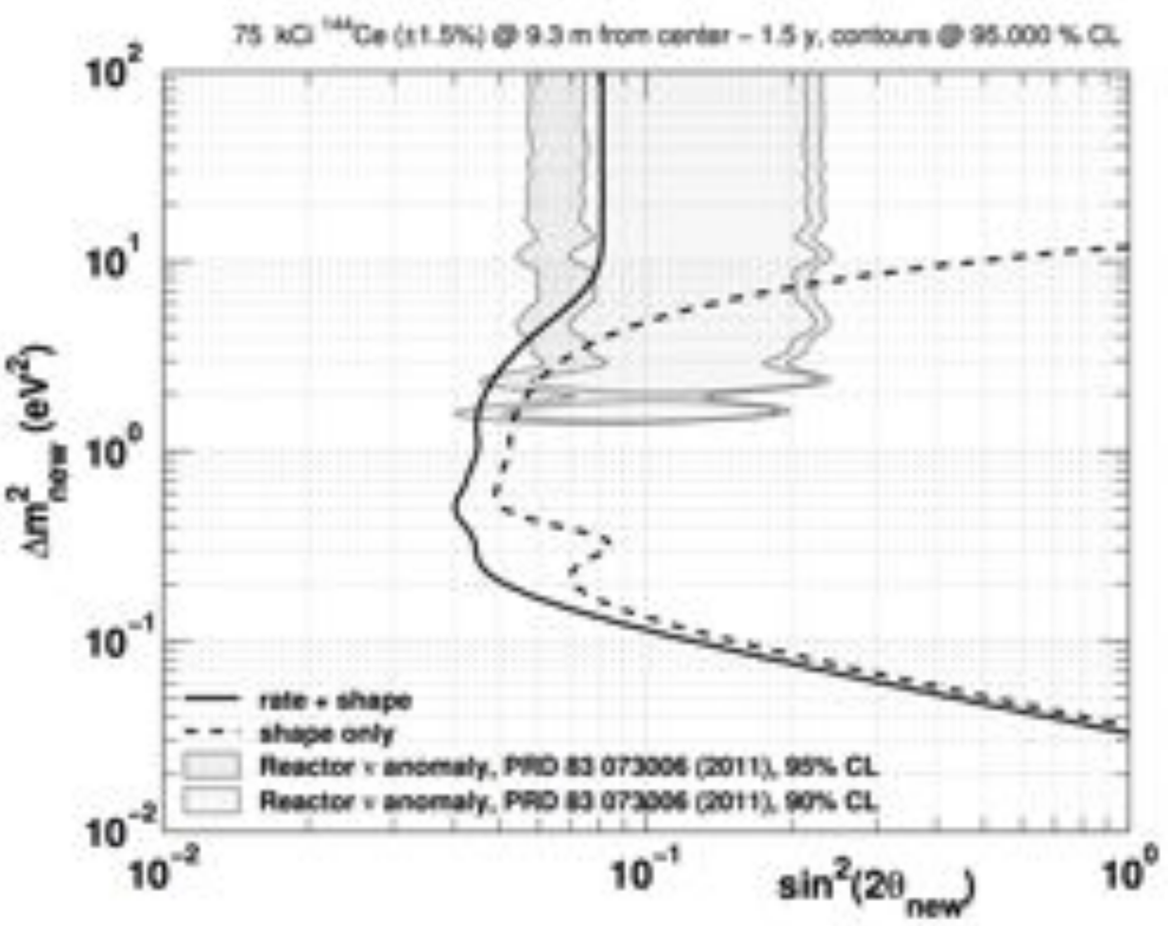
0.5 year exposure



95% C.L.

CeLand Phase 1

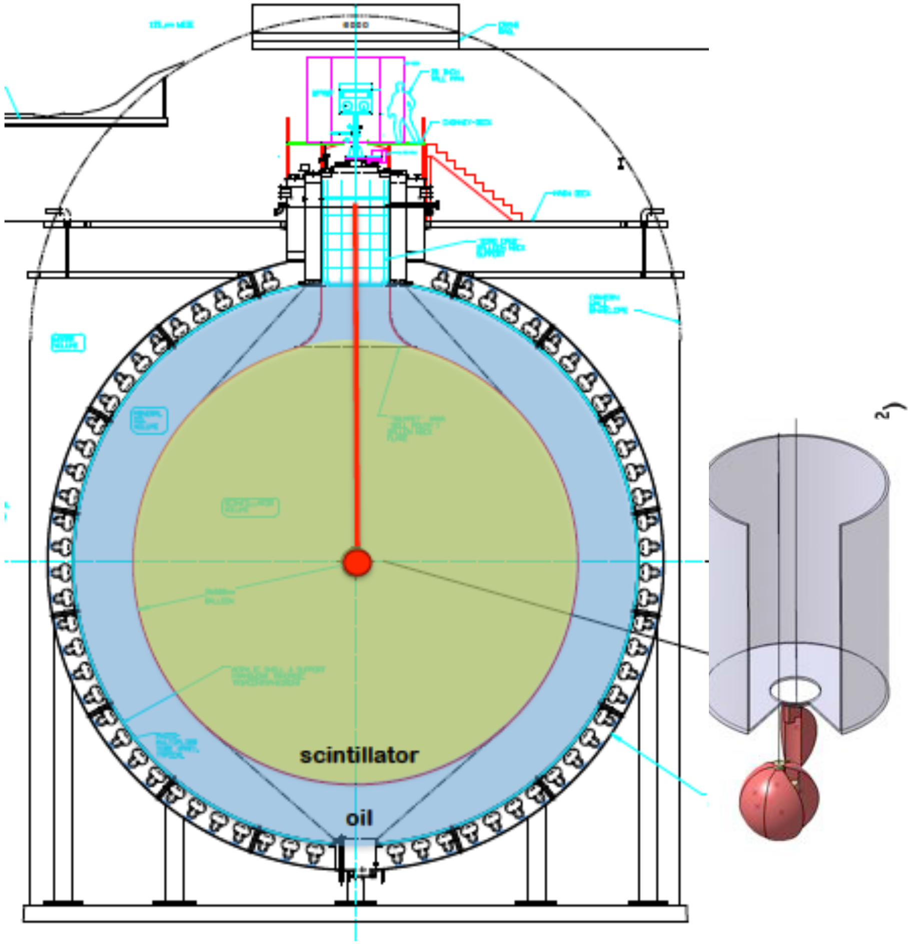
1.5 year exposure

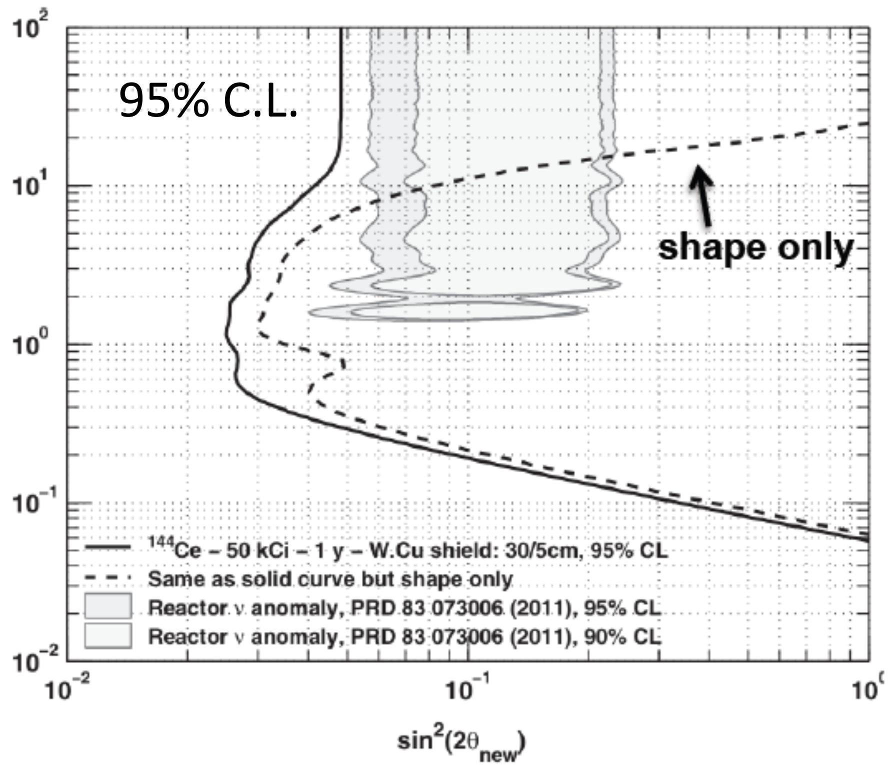


95% C.L.

CeLand Phase 2

Relocate the 144Ce source at the center of KAmLAND
75 kCi leads to 50 kCi after 6 months



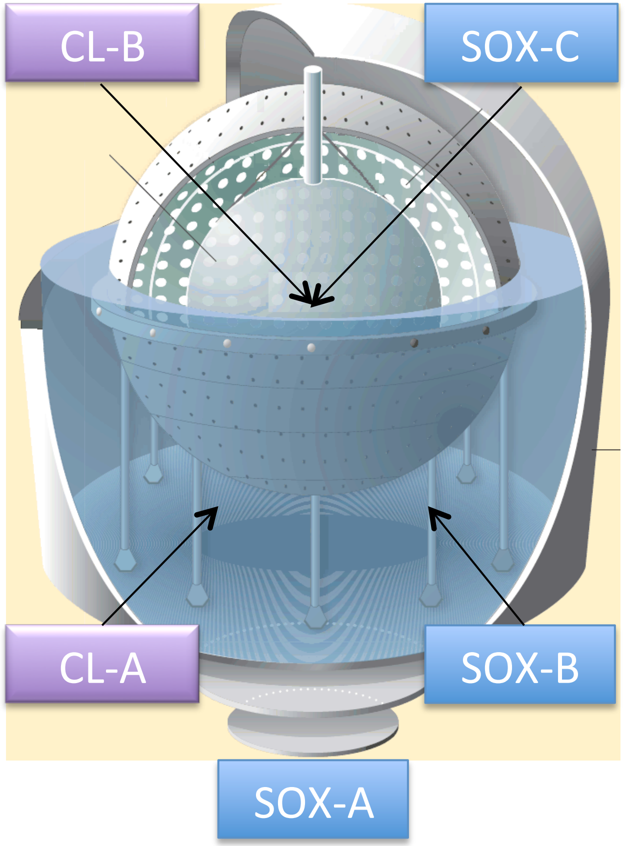


SOX Source Deployment in Borexino

CL-A (2015)
75 kCi ^{144}Ce in the WT
6 months of data taking

CL-B (2016/2017)
50 kCi ^{144}Ce source in the center
1.5 y of data taking

Funded by ERC grant.



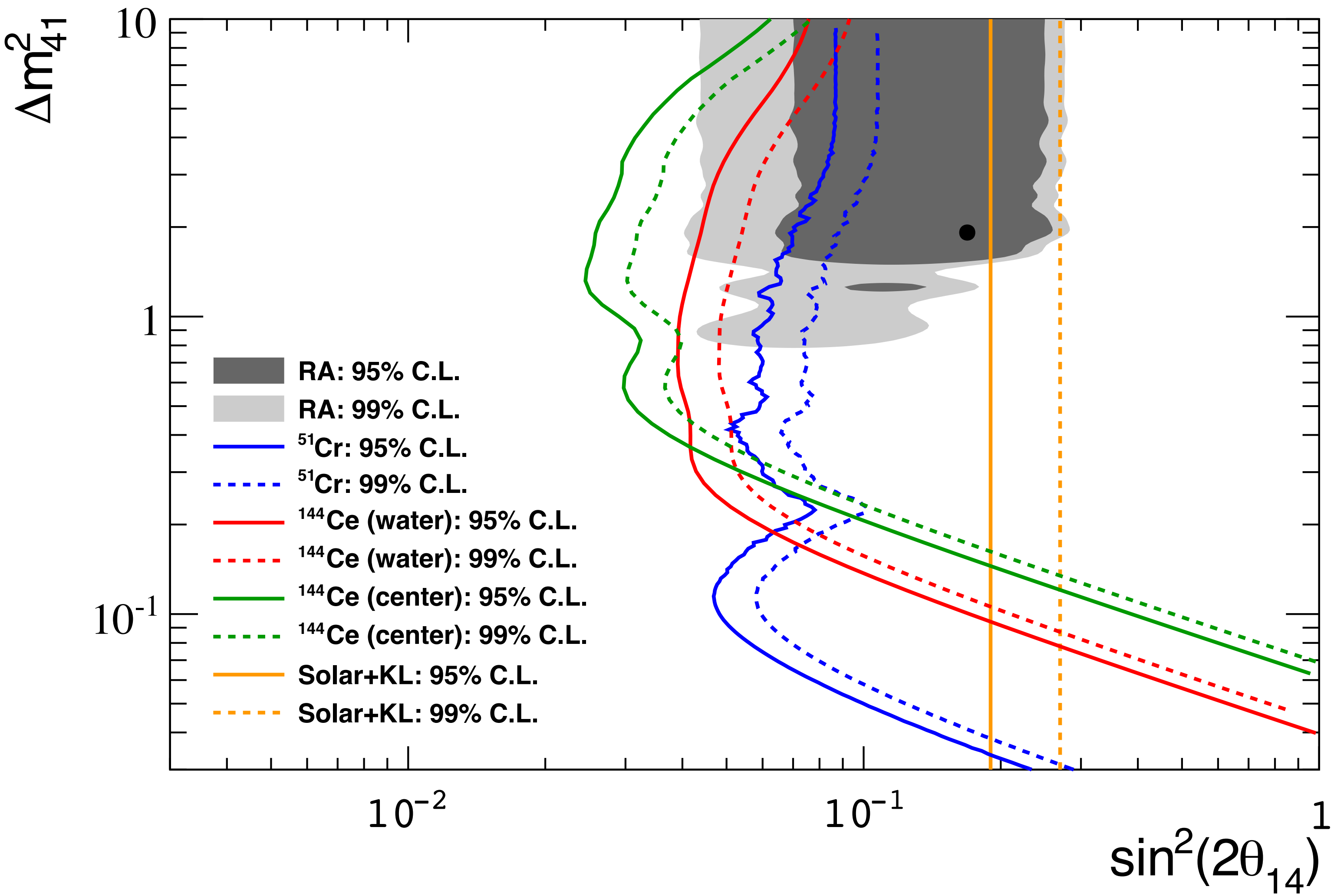
SOX-A (2015)
10MCi ^{51}Cr in Icarus pit
8.25 m from the center
3 months of data taking

SOX-B (end 2015)
75 kCi ^{144}Ce source in W.T.. PPO everywhere to enhance sensitivity

SOX-C (2016/2017)
50 kCi ^{144}Ce source in the center. Only after the end of solar program

See next talk by G. Ranucci

SOX sensitivities



Conclusions

- Reactor and source experiments offer direct tests of the 4th neutrino hypothesis.

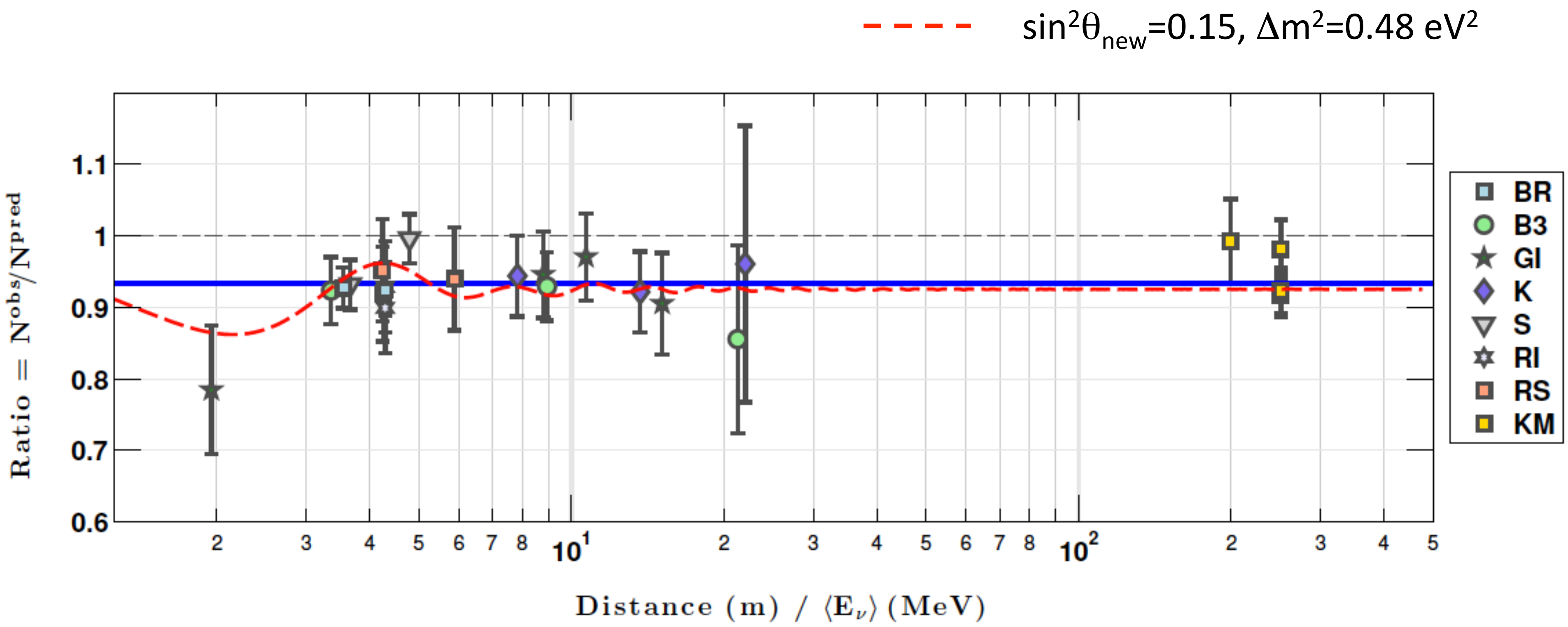
- Sensitivities nicely cover the anomaly contour with complementary E and L coverage →unique discovery potential within the next 5 years.

- High statistics experiments searching for few % deviations. The final sensitivity will be driven by detector systematics and background suppression

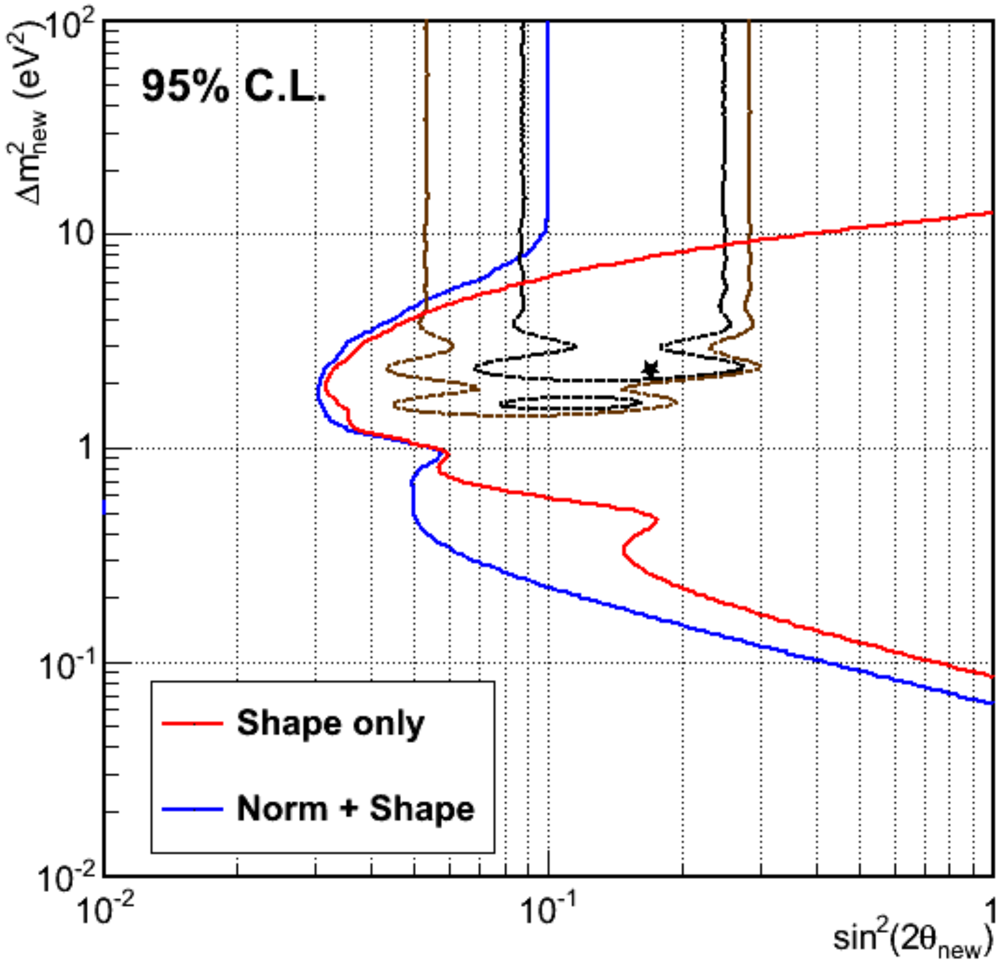
- Reactors:
  - Background mitigation is challenging. Site characterization is crucial.
  - Nice combination of mature and new technologies; Synergies with reactor monitoring efforts.
- Sources:
  - Low background measurements using state of the art detectors.
  - Challenge of the production and transportation of intense source

Backup Slides

Low Δm^2 Solution

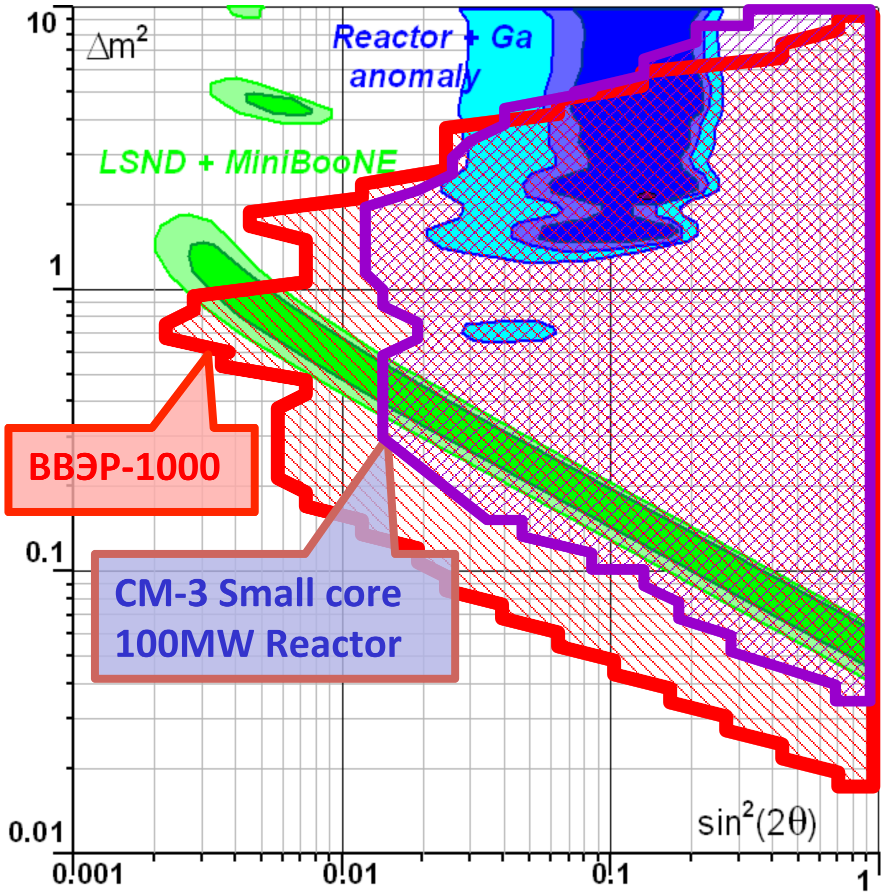


Stereo

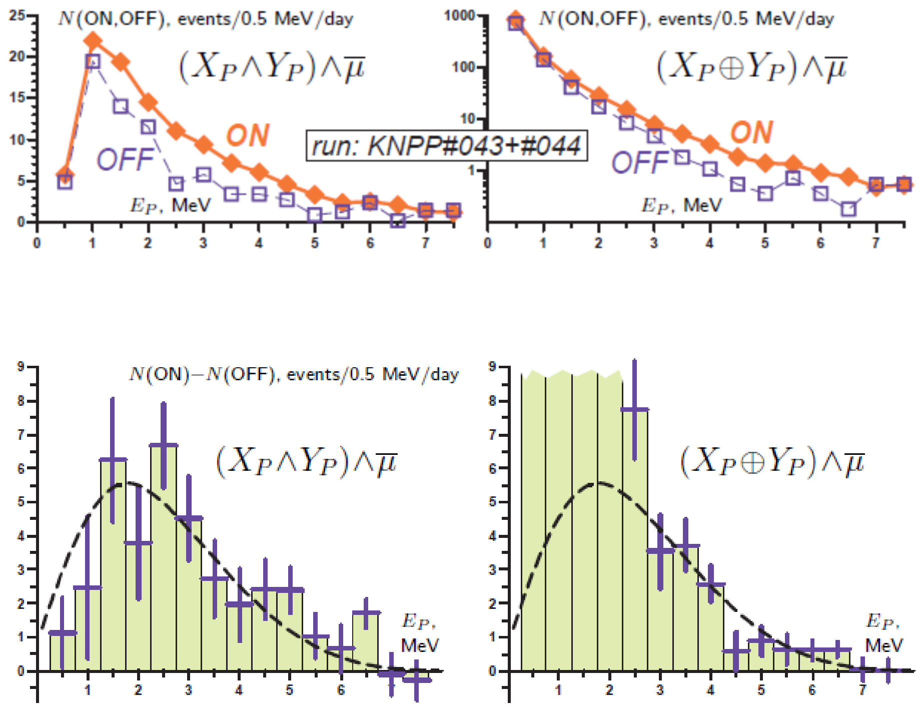


10 reactor cycles
2 years data taking

DANSS

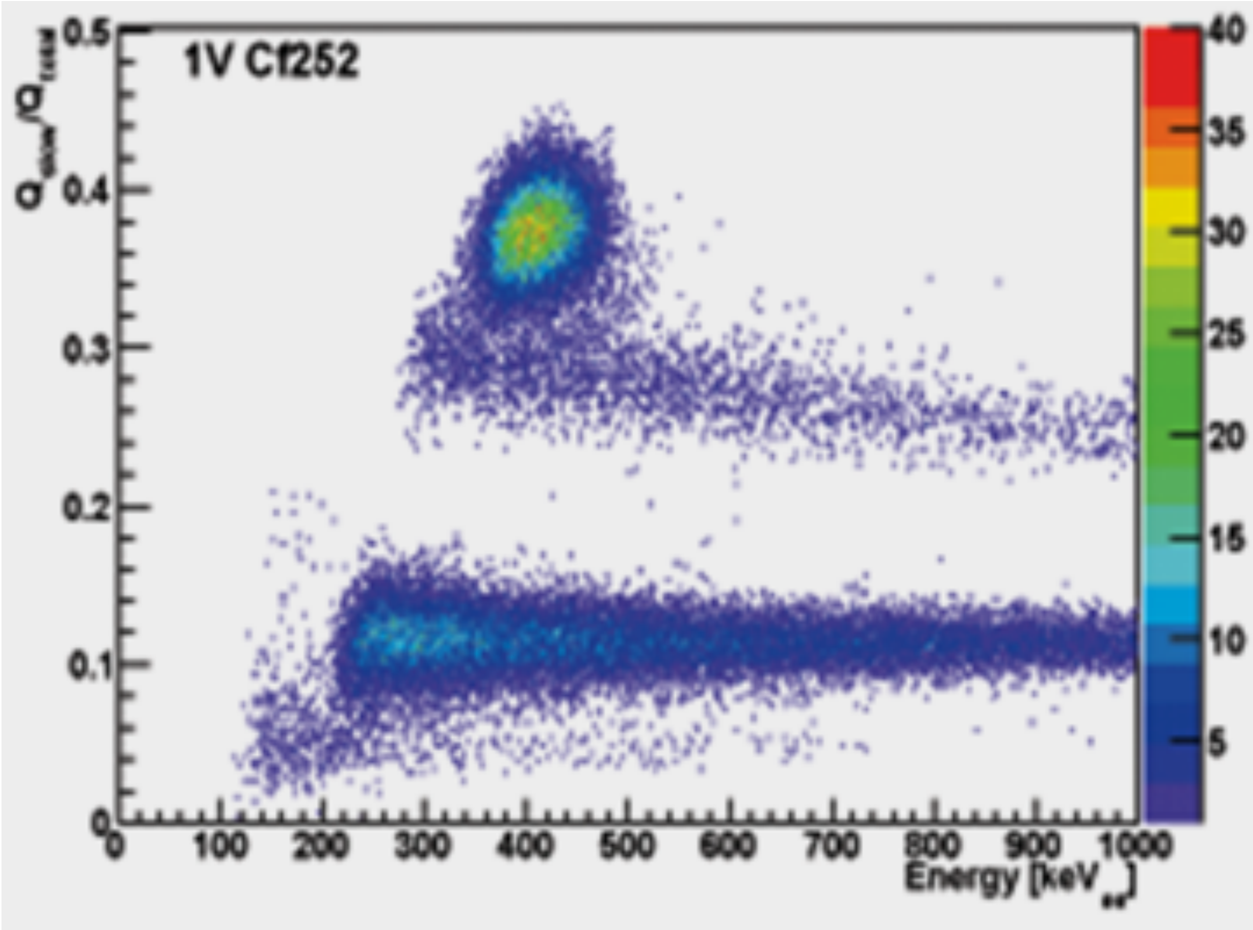


Δm²
Reactor + Ga anomaly
LSND + MiniBooNE
ВВЭР-1000
CM-3 Small core
100MW Reactor
sin²(2θ)



N(ON,OFF), events/0.5 MeV/day
ON
OFF
run: KNPP#043+#044
N(ON)−N(OFF), events/0.5 MeV/day

Li6-Doped Scintillator



N. Bowden, NANPino conference 2013.

SoLiϑ

Search for Oscillations with ^{6}Li Detector

contact : antonin.vacheret@physics.ox.ac.uk

RESEARCH REACTOR

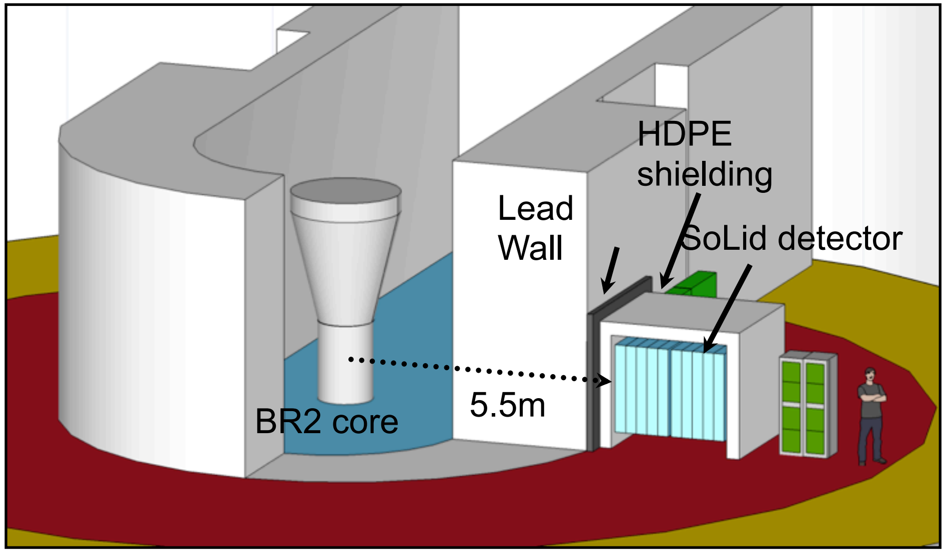
- **SCK•CEN BR2 Mol, Belgium**
- **Core: 45-80 MW, ~ 50cm diameter**

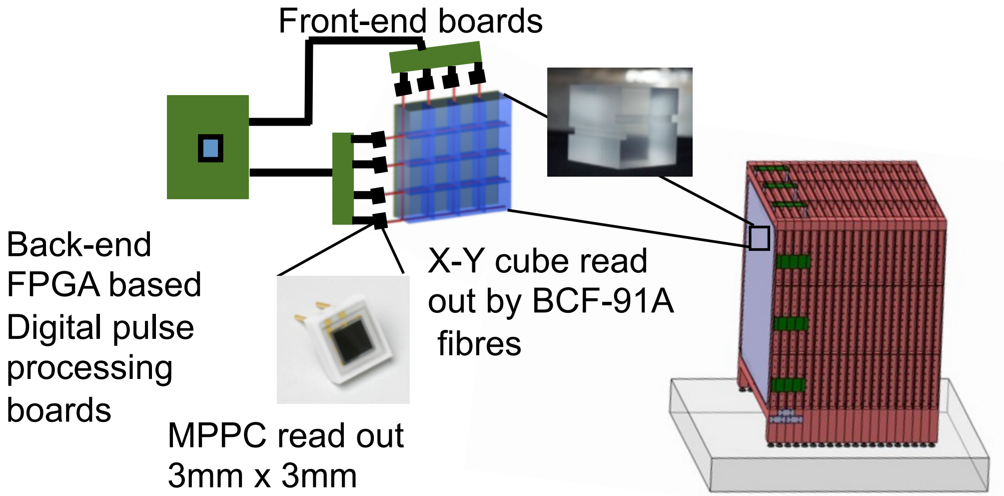
DETECTOR

- **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**
- **65MS/S dead timeless electronics**

BACKGROUND

- **High signal to background ratio : S/B ~ 6**
- **Soft Gamma-rays (< 3 MeV)**
- **No reactor neutrons**
- **Overburden ~10 m.w.e**

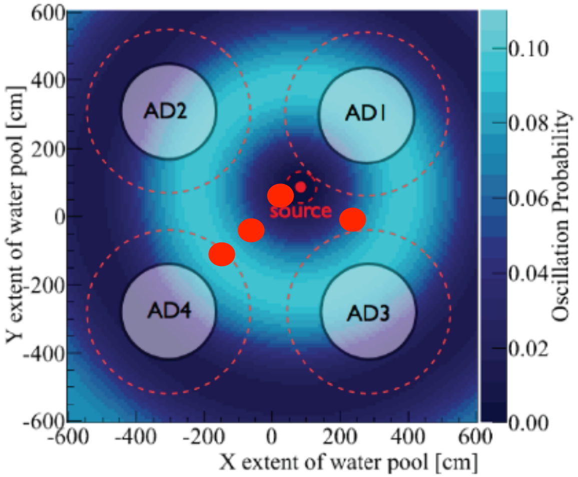


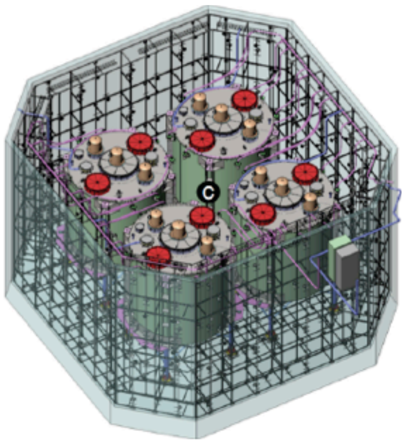


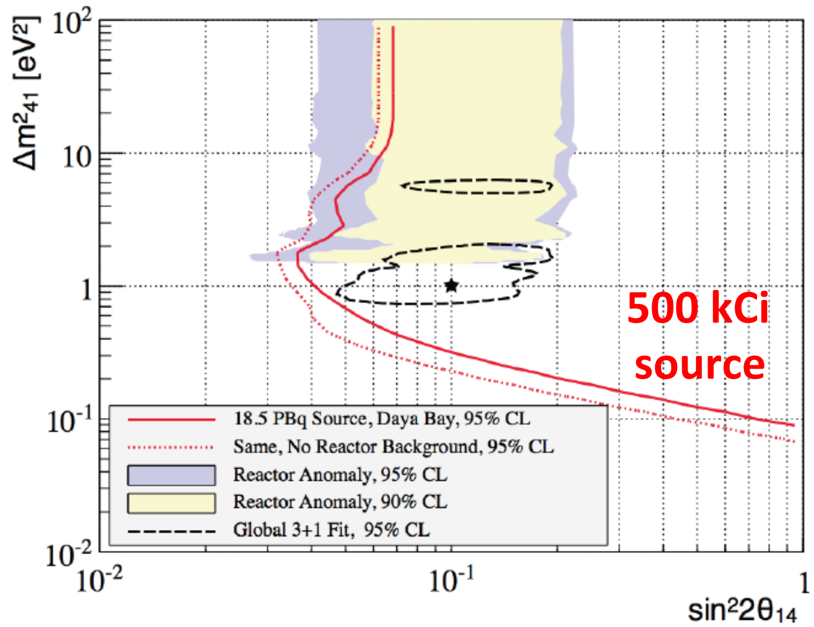
Source @ Daya Bay

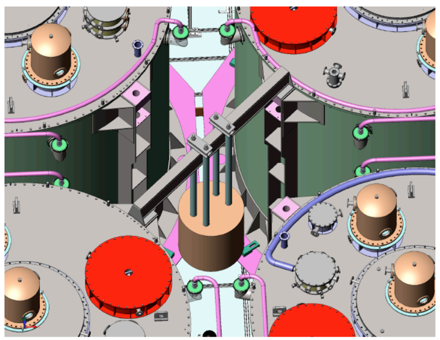
^{144}Ce-^{144}Pr source can Probe baselines from 1.5-8 m with an source in the water pool of the Daya Bay Far Hall

- Advantageous to place source outside detectors in water pool.
- Multiple detectors allow for control of systematics.





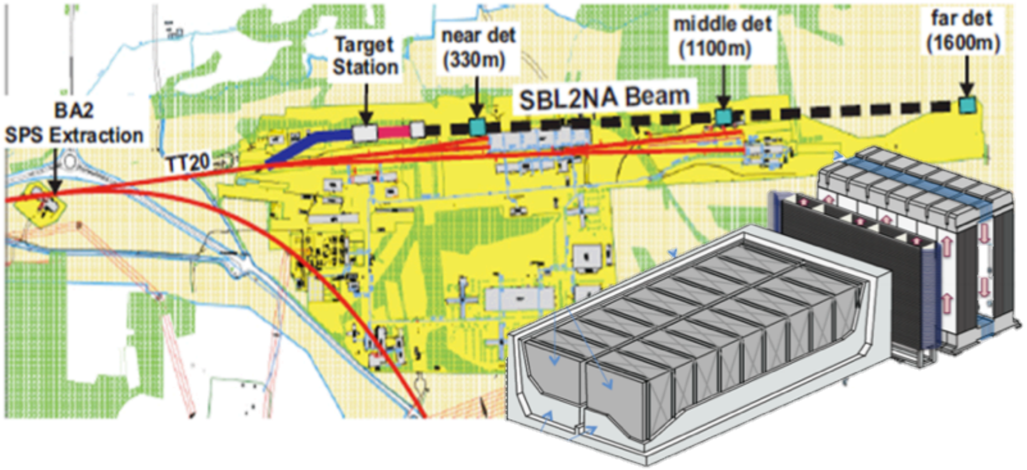




source experiment feasible in Far Hall of the Daya Bay experiment after θ_{13} measurement.

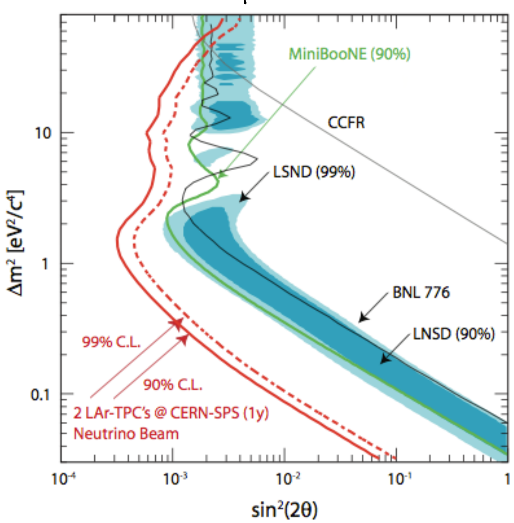
Phys. Rev. D 87, 093002 (2013), Dwyer, Littlejohn, Vogel, Heeger

Icarus-Nessie @ CERN

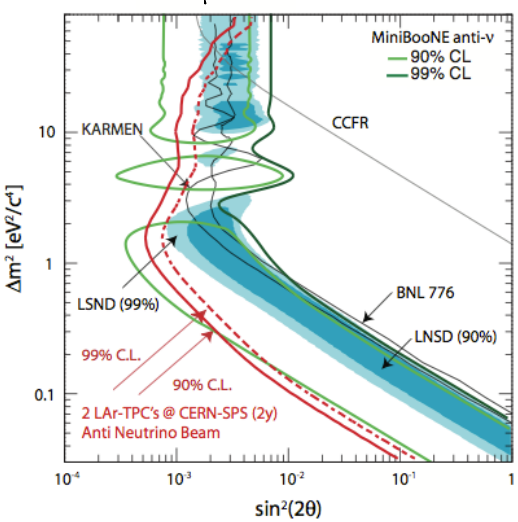


- Using CERN-SPS new **ν**μ beam (E**ν** ~ 2 GeV)
- 2 LAr-TPC (from ICARUS): near: 150 t, far: 600 t
- +magnetic spectrometers for charge determination
- Should start (both beam and detector data taking by end of 2015).

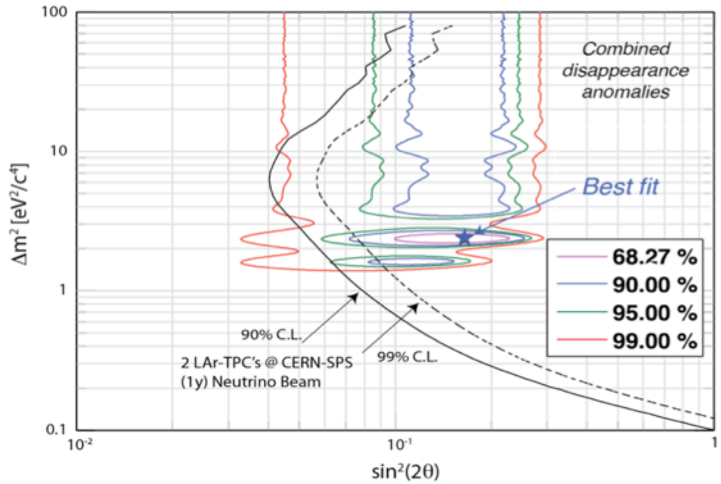
ν_μ to ν_e



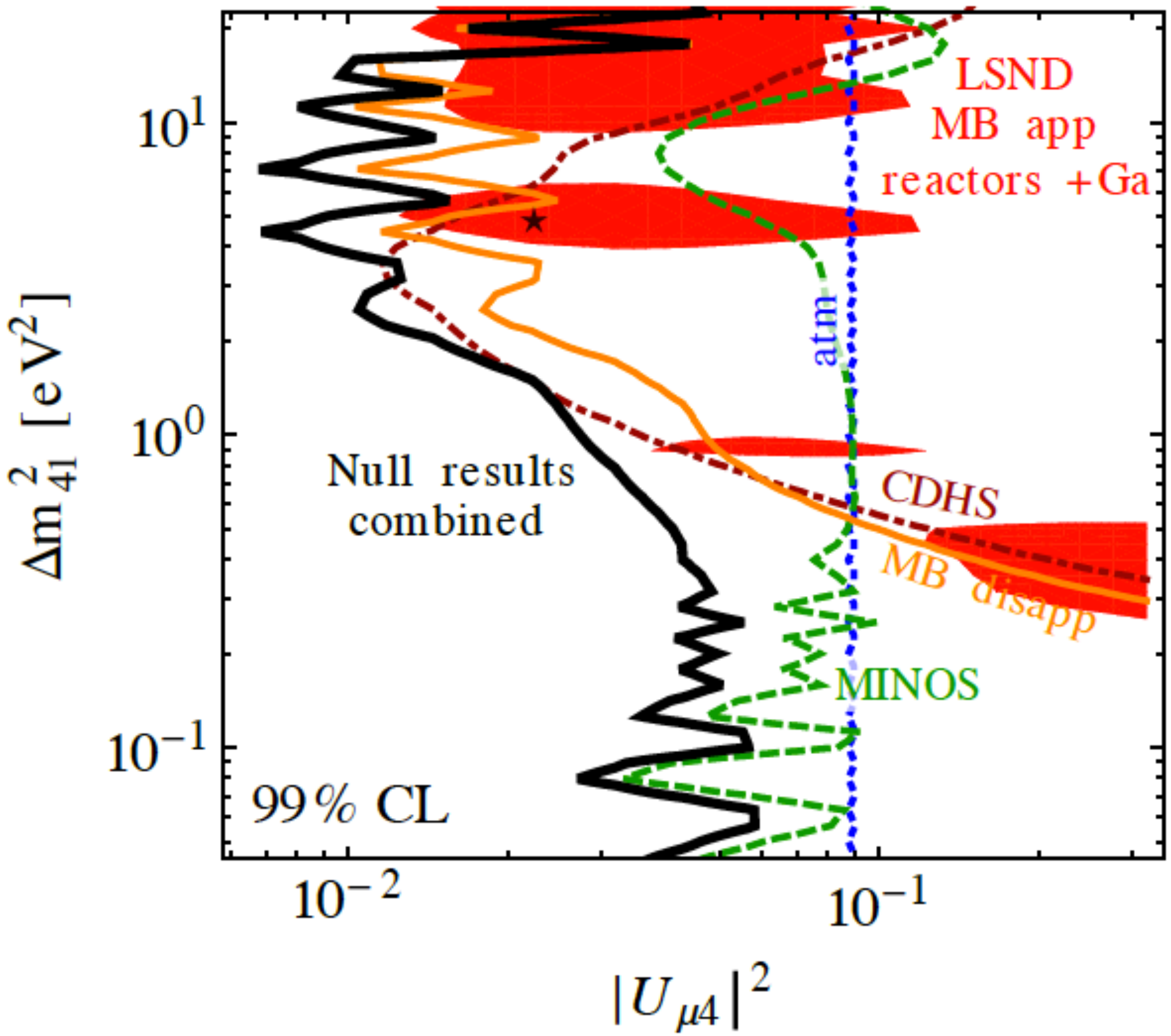
$\bar{\nu}_\mu$ to $\bar{\nu}_e$



ν_e to ν_e



ν_μ Sector



LSND
MB app
reactors +Ga
atm
CDHS
MB disapp
MINOS
Null results
combined
99% CL
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
Δm^2_{41} [eV^2]
$|U_{\mu 4}|^2$