Neutrini sterili

Ubaldo Dore March 2015

INTRODUCTION

The 3-neutrino mixing scheme is:

$$|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$$

with l = e, μ, τ and i = 1,2,3 (mass eigenstates)
U is the Pontecorvo-Maki-Nagakawa-Sakata mixing matrix
After the determination of the third mixing angle θ_{13} all the mixing angles of the 3-neutrino scheme are known. The phase δ responsible of CP violation is still not known.

With two neutrino species only, the simplified oscillation probability is:

$$P(\nu_1 \rightarrow \nu_2) = sen^2(\theta_{12})\, sen^2(1.27\, \Delta m_{12}^2\ L/E)$$

(L = distance from source, E = neutrino energy)

Still open problems are:

1) CP violation
2) Absolute value of masses
3) Mass hierarchy
4) Neutrino nature: Majorana or Dirac

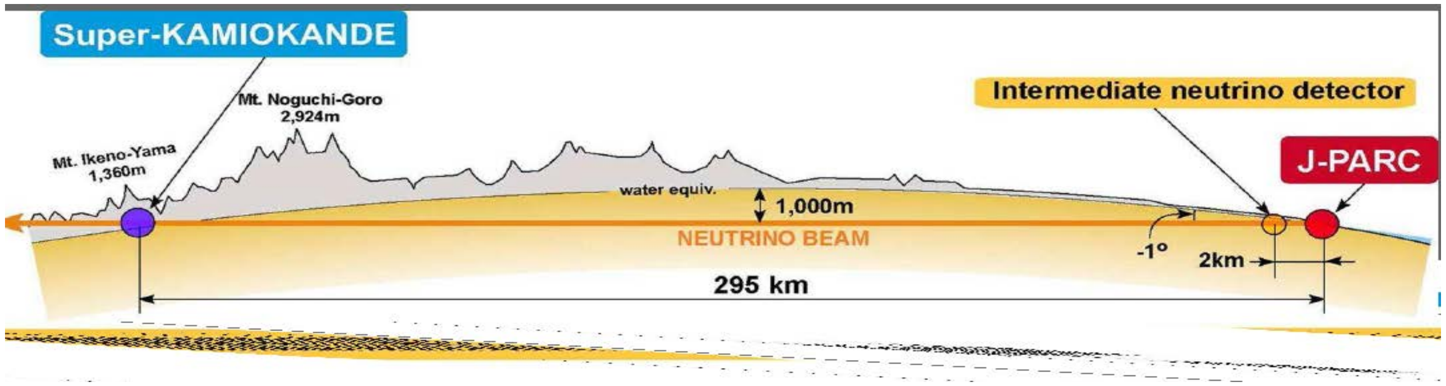
5) Do sterile neutrinos exist?

The last question will be discussed in this seminar

CP violation

Mixing matrix contains a CP violating phase δ
Oscillation $\nu_\mu \rightarrow \nu_e$ contains δ
According to T2K ($\sin^2(2\theta_{13}) = 0.104 \pm 0.060$))
$\delta = -\pi/2$ is favored (conference Neutrino 2014)

T2K

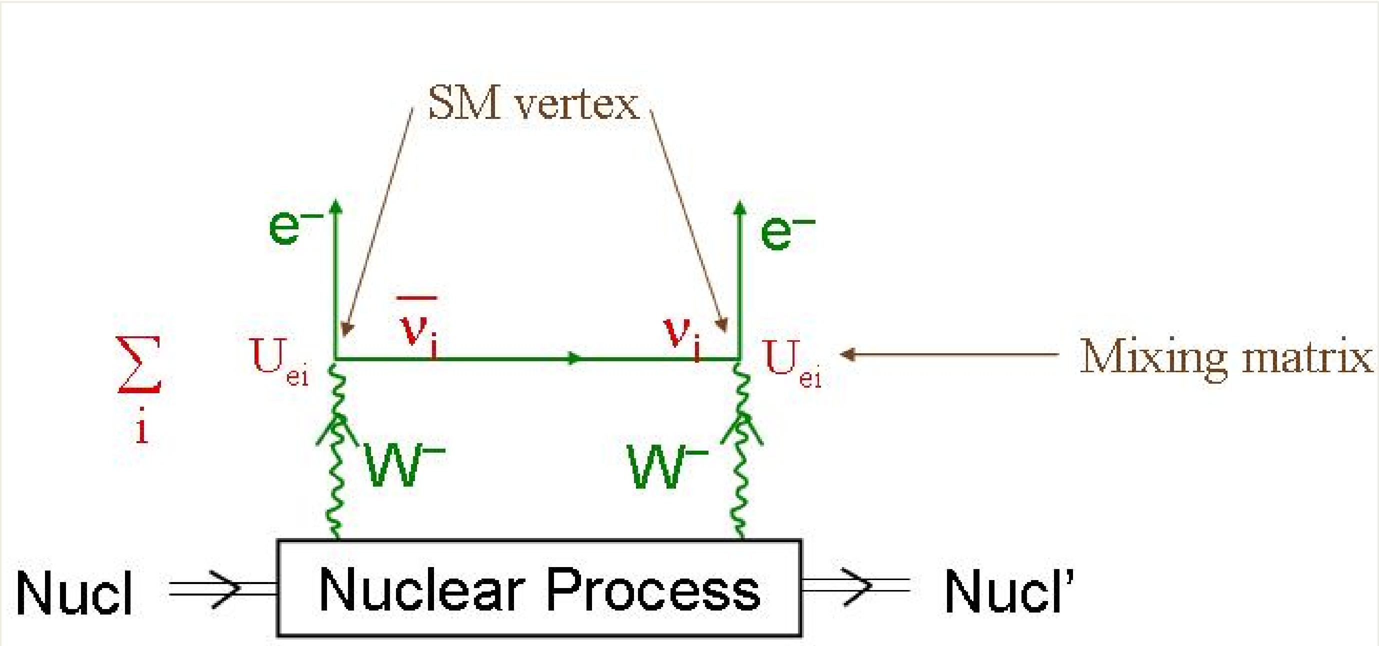


T2K - Neutrinos (E=0.7 GeV) produced at J-PARC accelerator are observed in a close detector and in SuperKamiokande detector at 730 km
$\rightarrow$ $(L/E)^*\Delta m^2_{atmosf} \cong 1$

Majorana or Dirac nature of neutrinos

Majorana - one neutrino → coincident with its antiparticle
Dirac - one neutrino and one antineutrino
Majorana $\nu = \bar{\nu}$ Dirac $\nu \neq \bar{\nu}$

Neutrinoless double beta decay can solve problem
Process is permitted for Majorana, forbidden for Dirac

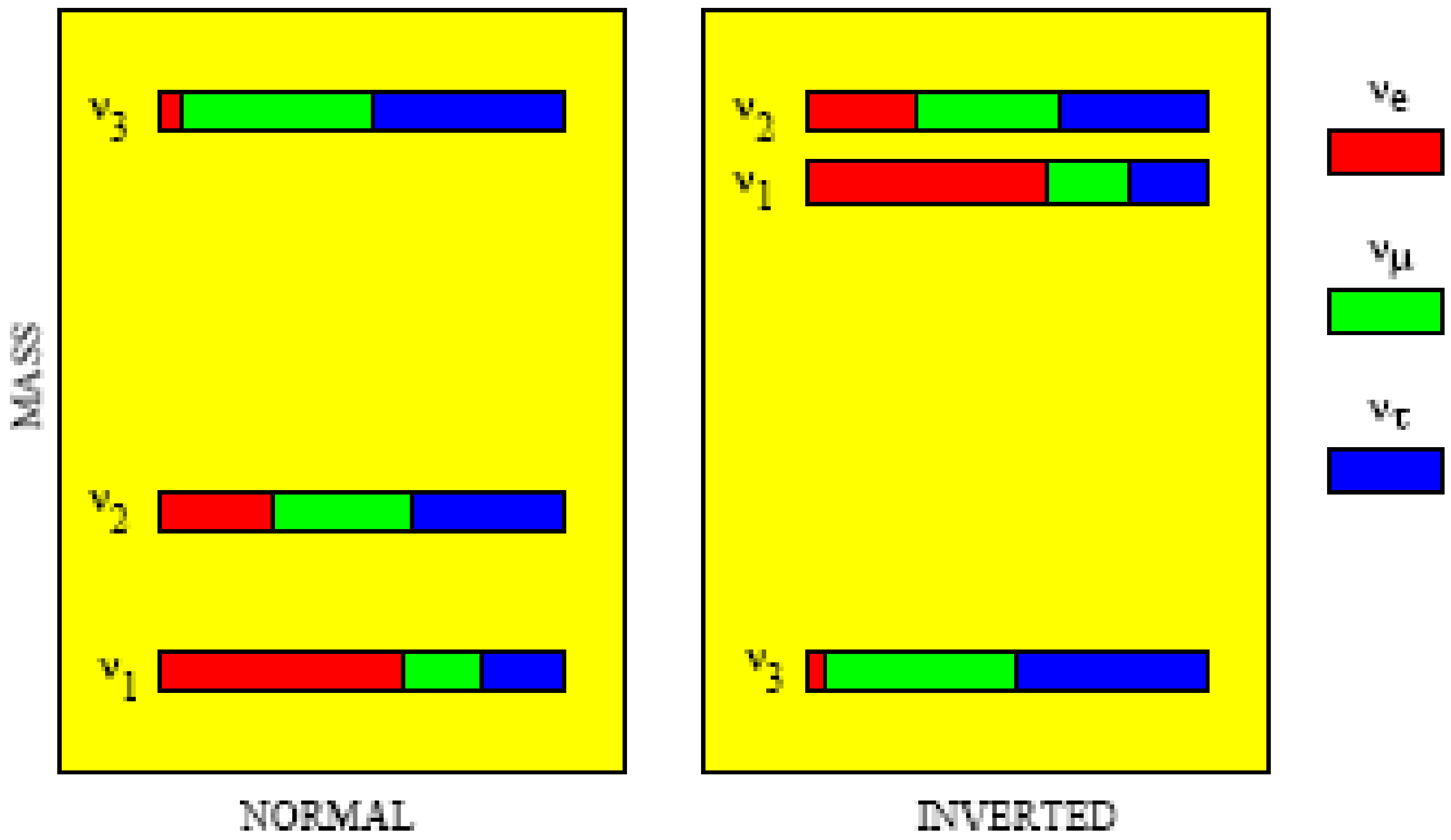


From oscillations → only mass differences
(absolute value of m not measured)

$\Delta m^2_{12} = 7.9\ 10^{-5}\ eV^2$

$\Delta m^2_{23} = 2.4\ 10^{-3}\ eV^2$

Mass hierarchy



The seminar will present the situation in the field of sterile neutrinos

Sterile neutrino: A neutral lepton with no ordinary weak interaction, except those induced by mixing

All neutrino conferences have presentations on sterile neutrinos

For example

J.Kopp - Theory and phenomenology of sterile neutrinos

Neutrino 2014 - Boston

His comment:

if sterile neutrinos exist they would be the discovery of the decade

A complete description can be found in:

Light Sterile Neutrinos - A White Paper

K.N. Abazajian et al.

ArXiv:1204.5379

Hints for a sterile neutrino:

1) Oscillation signal at a mass of $1eV^2$ by the LSND and MiniBooNE experiments

2) Deficit of neutrinos from radioactive sources in the calibration of solar neutrino experiments

3) Deficit of antineutrinos from reactors

Just hints, no firm result

After discussing these effects,
we will present the projects planned to clarify the situation

Hint 1 – LSND Los Alamos

The detector consisted of a tank of 168 tons of liquid scintillator looked by 1280 photomultipliers

The intense proton beam with E = 789 MeV produced a large number of pions, mainly π^+ which then decay:

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

The $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation was observed via the detection of the reaction:

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

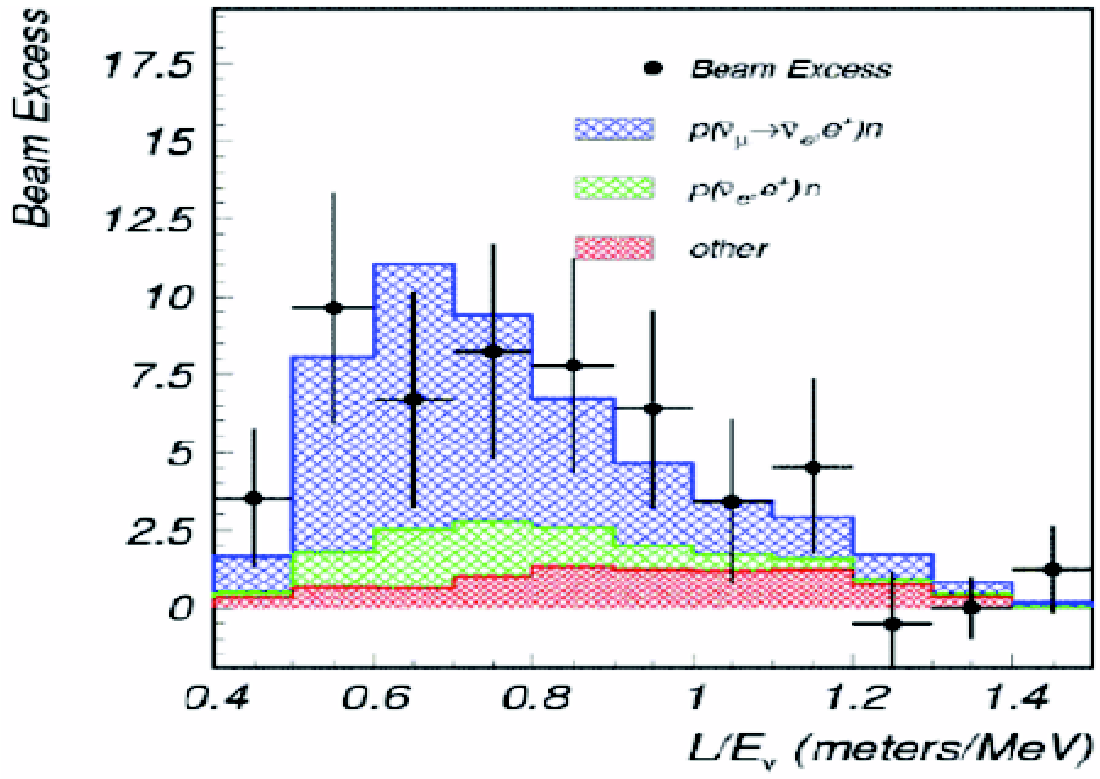
The detection was based on the delayed coincidence of a prompt signal from the positron, followed by a gamma signal from the absorption of the thermalized neutron

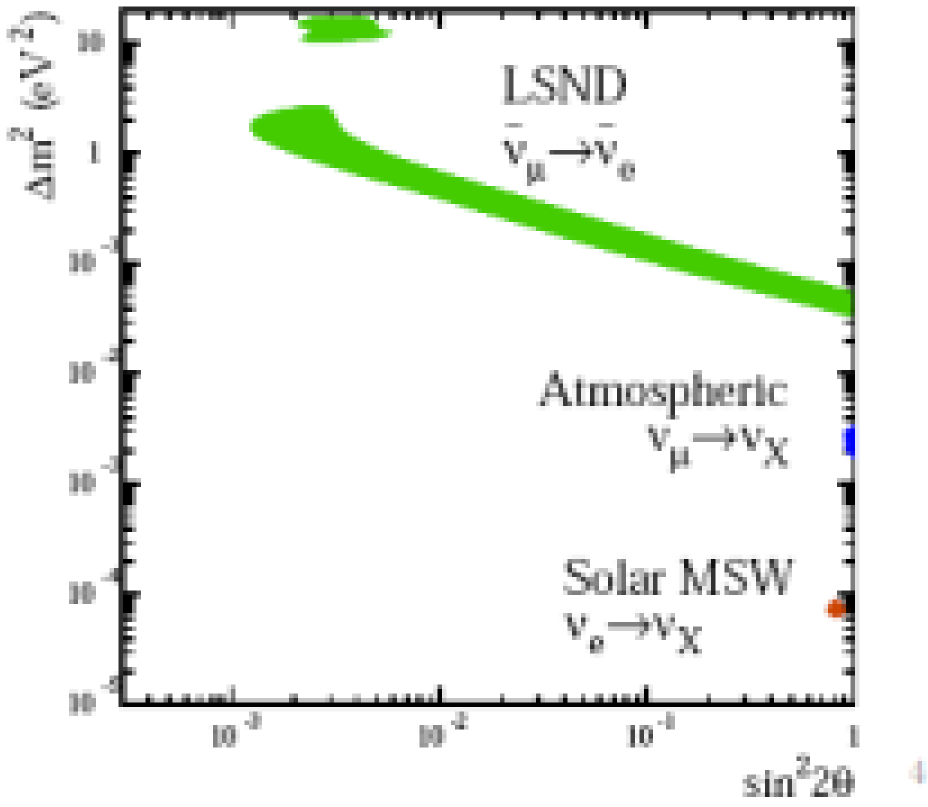
(the ν_e flux was small because the π^- are absorbed)

The LSND signal

(PRD64 (2001) 112007)

An excess of positron events has been observed in the muon antineutrino beam.
Interpreted in terms of oscillations it requires a Δm^2 of the order of 1 eV^2.





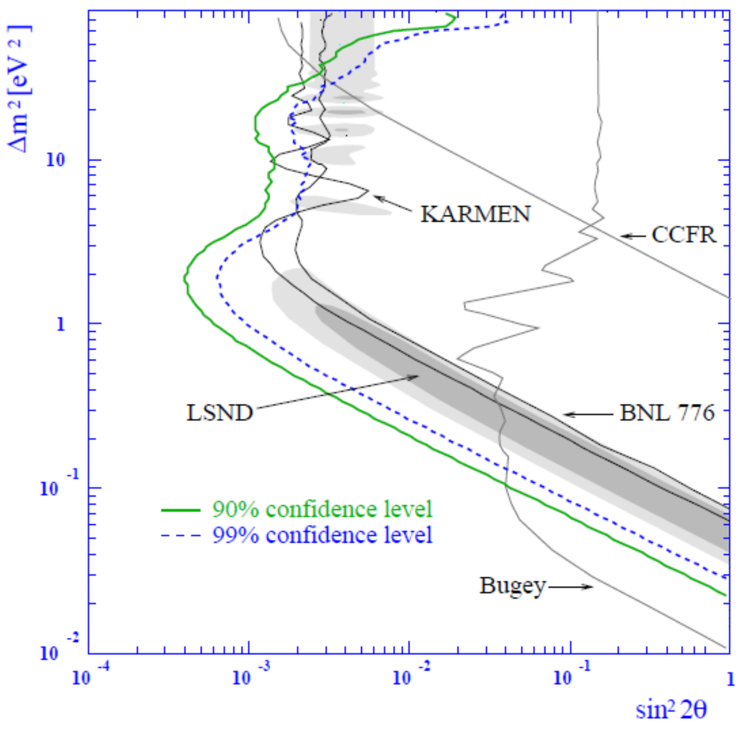
The presence of a third mass difference ($\Delta m^2 \sim 1$ eV^2) would require a new neutrino, that has to be sterile because of the number of active neutrinos measured at LEP.

At that time the interest of the scientific community was not very high.

In fact a proposal at CERN was rejected:

Search for $\nu_\mu \rightarrow \nu_e$ *oscillation at the CERN PS*

I216 – SPSC/P311 (1999)



MiniBooNE

Improved Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

Phys.Rev.Lett.110 (2013) 161801 arXiv:1303.2588

Test LSND signal with low energy ν_μ and $\bar{\nu}_\mu$ beams

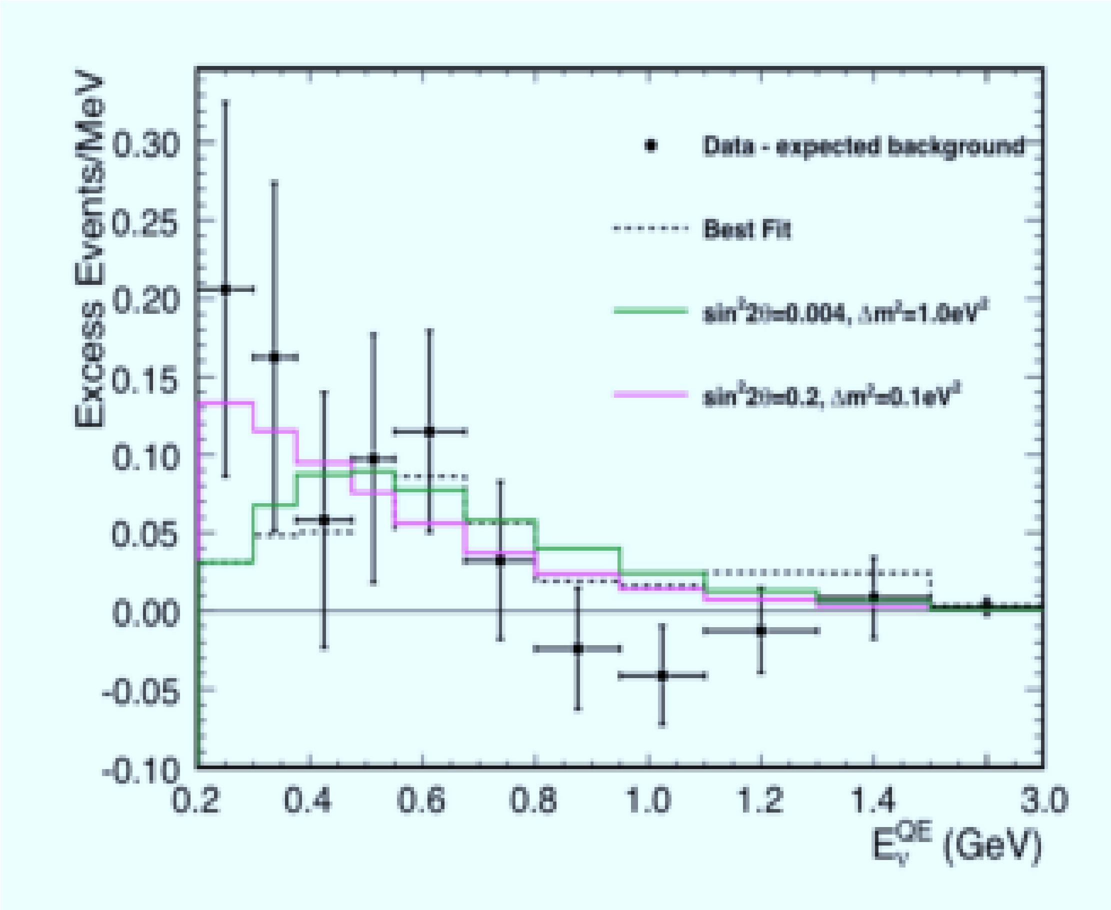
Antineutrinos - show an excess in the LSND region

Neutrinos - no excess in the LSND region
- small excess at low energy

The authors: expanded models, with several sterile neutrinos, can reduce the incompatibility between ν and $\bar{\nu}$

MiniBooNE

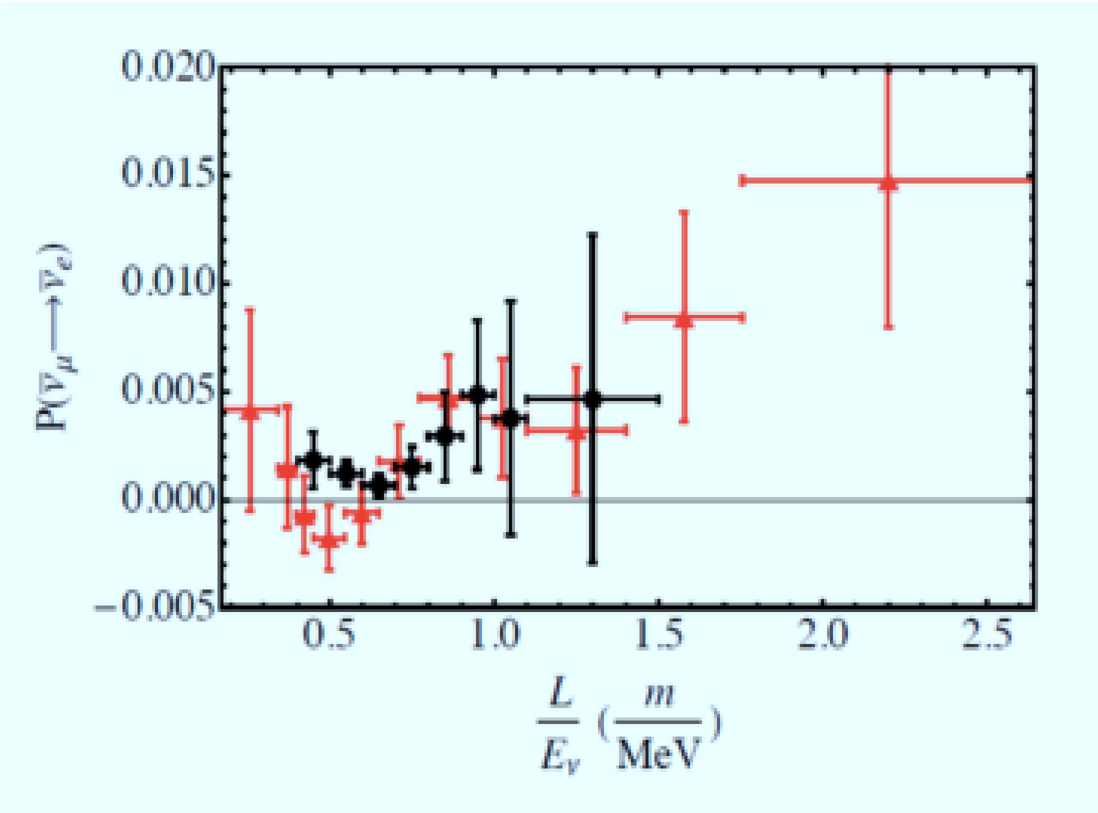
$\bar{\nu}_e$ energy spectrum



Compare L / E_ν

MiniBooNE(red)-LSND (black)

Good agreement



Hint 2 - Gallium anomaly: deficit of electron neutrinos in the calibration of the solar neutrinos detectors

(arXiv:1006.3244)

Calibrations of the GALLEX and SAGE detectors have been made using strong radioactive chromium and argon sources of ν_e

They measure R, ratio of measured over predicted germanium events

(normalization via the cross-section of $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$)

R_G1= GALLEX ^{51}Cr exposure 1 = 0.953 ± 0.11
R_G2= GALLEX ^{51}Cr exposure 2 = 0.812 ± 0.10
R_S1= SAGE ^{51}Cr exposure = 0.95 ± 0.12
R_S2= SAGE ^{37}Ar exposure = 0.791 ± 0.08

R < 1 → possible disappearance of ν_e via oscillation

Combining GALLEX and SAGE *(C.Giunti and M.Laveder arXiv:1006.3244)*

$R = 0.76 \pm 0.09 \pm 0.16 \pm 0.24$ (1,2,3 σ errors respectively)

i.e. ~ 3σ deficit of ν_e

In terms of oscillations (ν_e disappearance)

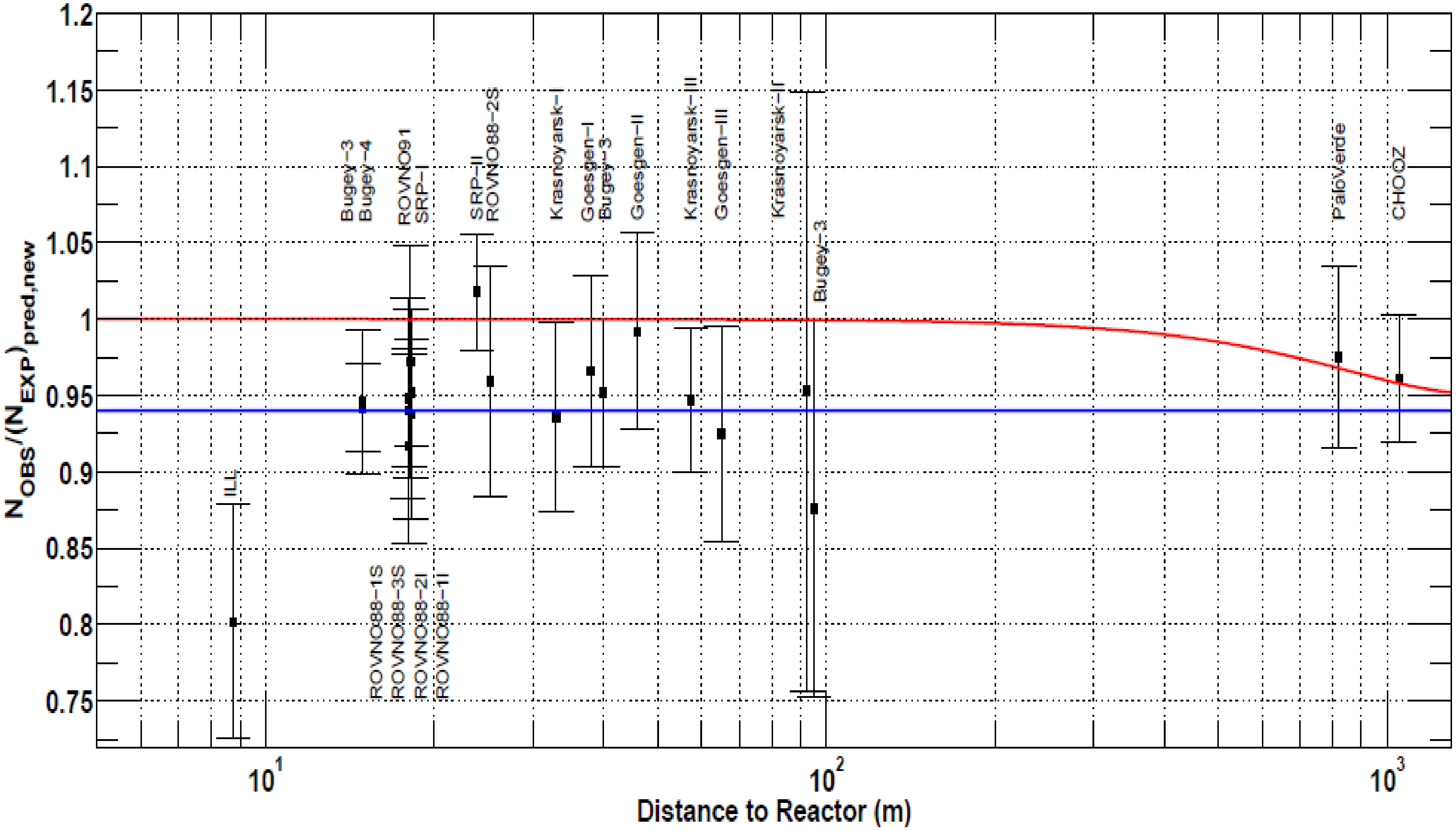
$\Delta m^2 > 0.35\ eV^2$ and $\sin^2(2\theta) > 0.07$

Hint 3 - REACTOR ANOMALY

Calculations of $\bar{\nu}_e$ flux from reactor recently revised → ~ 3% increase → corresponds to a deficit of $\bar{\nu}_e$ in measurements at near locations

Global analysis by G.Mention et al.
(Phys.Rev. D83 (2011) 073006)

R(measured/predicted) = 0.943±0.023



Reactors data

Red line = standard 3 ν oscillations, $\sin^2(\theta_{13}) = 0.12$

Blue line = sterile neutrino with $\Delta m^2 >> 1 eV^2$ $\sin^2(2\theta_{new}) = 0.12$

Combining with MiniBooNE+Gallium

→ $|\Delta m^2_{new}| > 1.5 \text{ eV}^2$ $\sin^2(2\theta_{new}) = 0.14 \pm 0.08$

Summary of “hints”

anomaly		source		type	Sensitivity		channel		signifi cance
LSND		decay at rest		$\nu\mu \rightarrow \nu e$	Total rate, energy		cc		3.8 σ
MiniBooNE		short baseline		$\nu\mu \rightarrow \nu e$	Total rate energy		cc		3 σ
Gallium		electron capture		νe disapp	Total rate		cc		2.7 σ
reactors		beta decay		νe disapp	Total rate energy		cc		3 σ

No 5 sigmas effect

Recent searches for sterile neutrinos in the large Δm^2 region → all give negative results

1) T2K - J. Caracas at NuFact 2014

Search for sterile neutrinos in the close detector

Part of the LSND allowed region has been excluded

2) SuperKamiokande - Limits on sterile neutrinos in atmospheric neutrinos

Arxiv:1410.2006

Results $U_{\mu 4}$ smaller 0.18 and $\Delta m^2 > 0.8$ eV^2

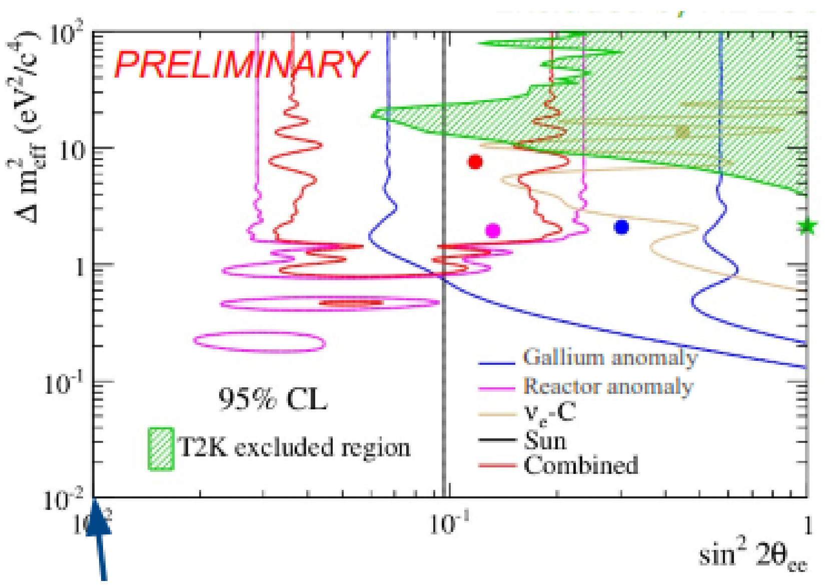
3) Daya Baya

Search for sterile neutrinos

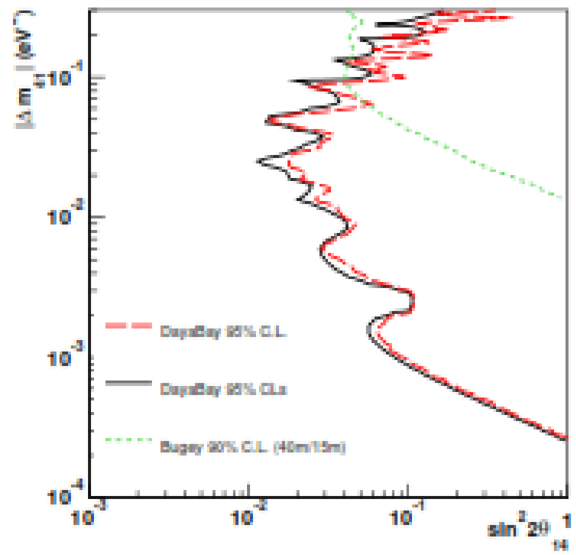
Arxiv.:1407.7259v2

Limits for $\Delta m^2 < 0.1$ eV^2

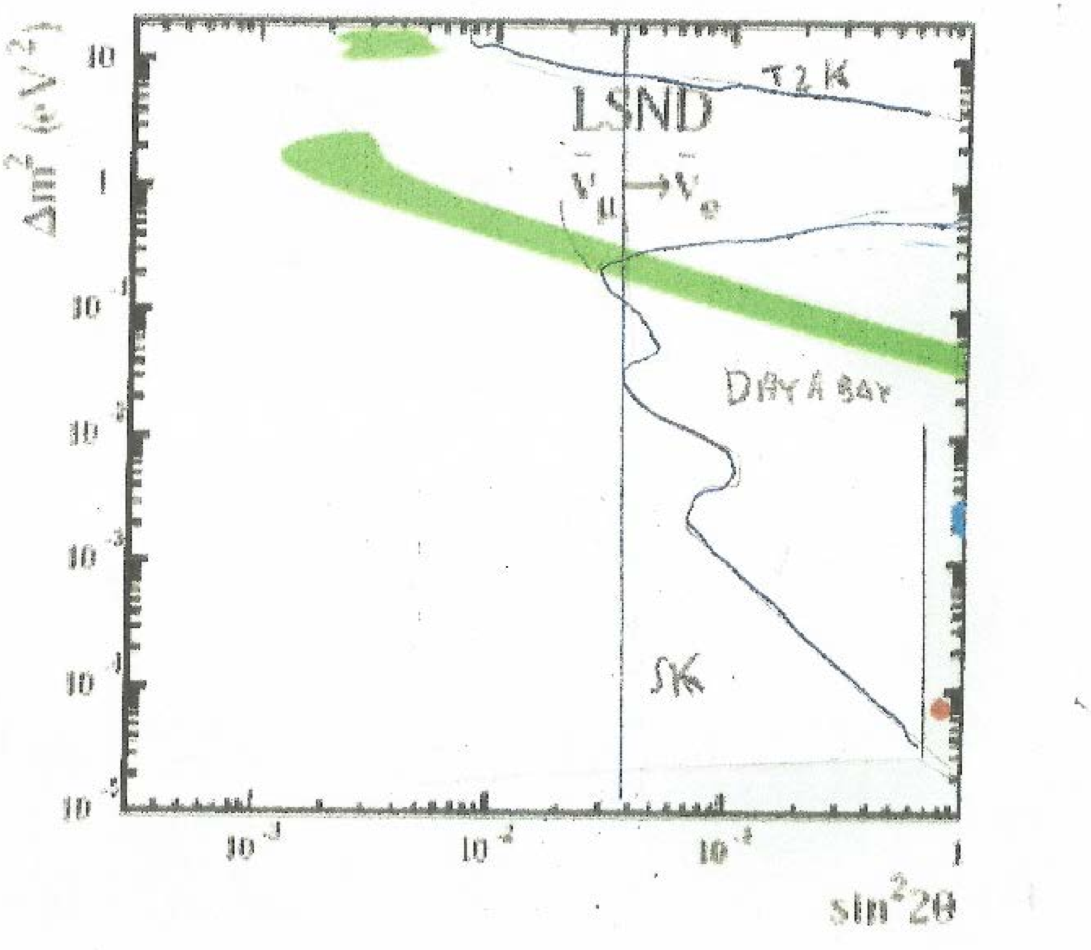
T2K



Daya Bay



The 3 results compared to LSND



SuperKamiokande

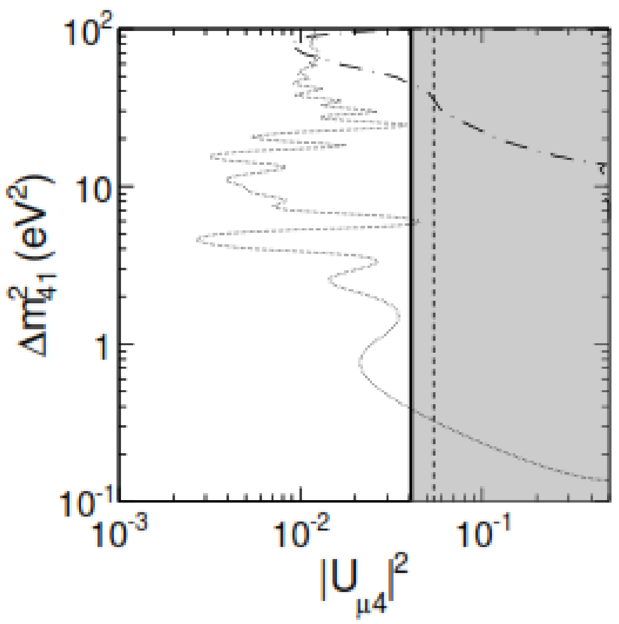


FIG. 7. The 90% and 99% upper limits on $|U_{\mu 4}|^2$ from the

Older results

1) Search of oscillation in the region Δm^2 15-1000 eV^2
   CCFR Z.Phys. C27 53 1985
   No indication of oscillations

2) Dual baseline search for antineutrino disappearance
   MiniBooNE-SciBooNE PRD D86 052009 2012
   No oscillations seen in the region 0.1- 100 eV^2

Comment - Null observations are a problem in fitting signals with a single sterile neutrino
See for example: *T. Schwetz Nucl Phys Proc Suppl 235 229 2013*
Reasonable fits can be obtained in a 3+2 or better 3+3 model
J. Conrad et al arxiv:1207.4755

FUTURE

Proposed or in building stage experiments

1) Searches with radioactive sources
2) Searches at small core reactors
3) Short baseline accelerator searches
4) Neutrinos from K^+ decays at rest
5) New idea: muon storage ring

Present and future experiments

Experiment(s)	Source	Type	Sensitivity to Oscillations	Channel
LSND†	Decay-at-rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total Rate, Energy	CC
MiniBooNE†	Short baseline	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total Rate, Energy	CC
Reactor measurements†	Reactor	$\bar{\nu}_e$ dis.	Total Rate	CC
Gallium Anomaly†	EC Source	ν_e dis.	Total Rate	CC
Future Decay-at-Rest				
(*OscSNS, Super-K*)	Decay-at-rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total Rate, Energy	CC
		ν dis.	Total Rate	NC
Future Short Baseline				
(*μBooNE, BooNE, NESSiE, LArLAr*)	Short baseline	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	Total Rate, Energy	CC
		$\overset{(-)}{\nu}_\mu$ dis.	Total Rate, Energy	CC
(*VLENF*)	Short baseline	$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$	Total Rate, Energy	CC
		$\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu$ dis.	Total Rate, Energy	CC, NC
Future Reactor Measurements				
(*Nucifer, SCRAAM, Stereo*)	Reactor	$\bar{\nu}_e$ dis.	Total Rate, Length	CC
Future Source Experiments				
(*Borexino, Ce-LAND, Daya Bay*)	β^- Source	$\bar{\nu}_e$ dis.	Total Rate, Length	CC
(*Borexino, SNO+Cr*)	EC Source	ν_e dis.	Total Rate, Length	ES
(*LENS, Baksan*)	EC Source	ν_e dis.	Total Rate, Length	CC
(*RICOCHET*)	EC Source	ν_e dis.	Total Rate, Length	NC

1) – Searches with radioactive sources

SOX: Short distance neutrino Oscillations with BoreXino
arXiv:1304.7721

BoreXino is a high purity liquid scintillator detector

Recall:
- measurement of pp solar neutrinos
- measurement of geoneutrinos

Now they propose a search for sterile neutrinos *(SOX)*

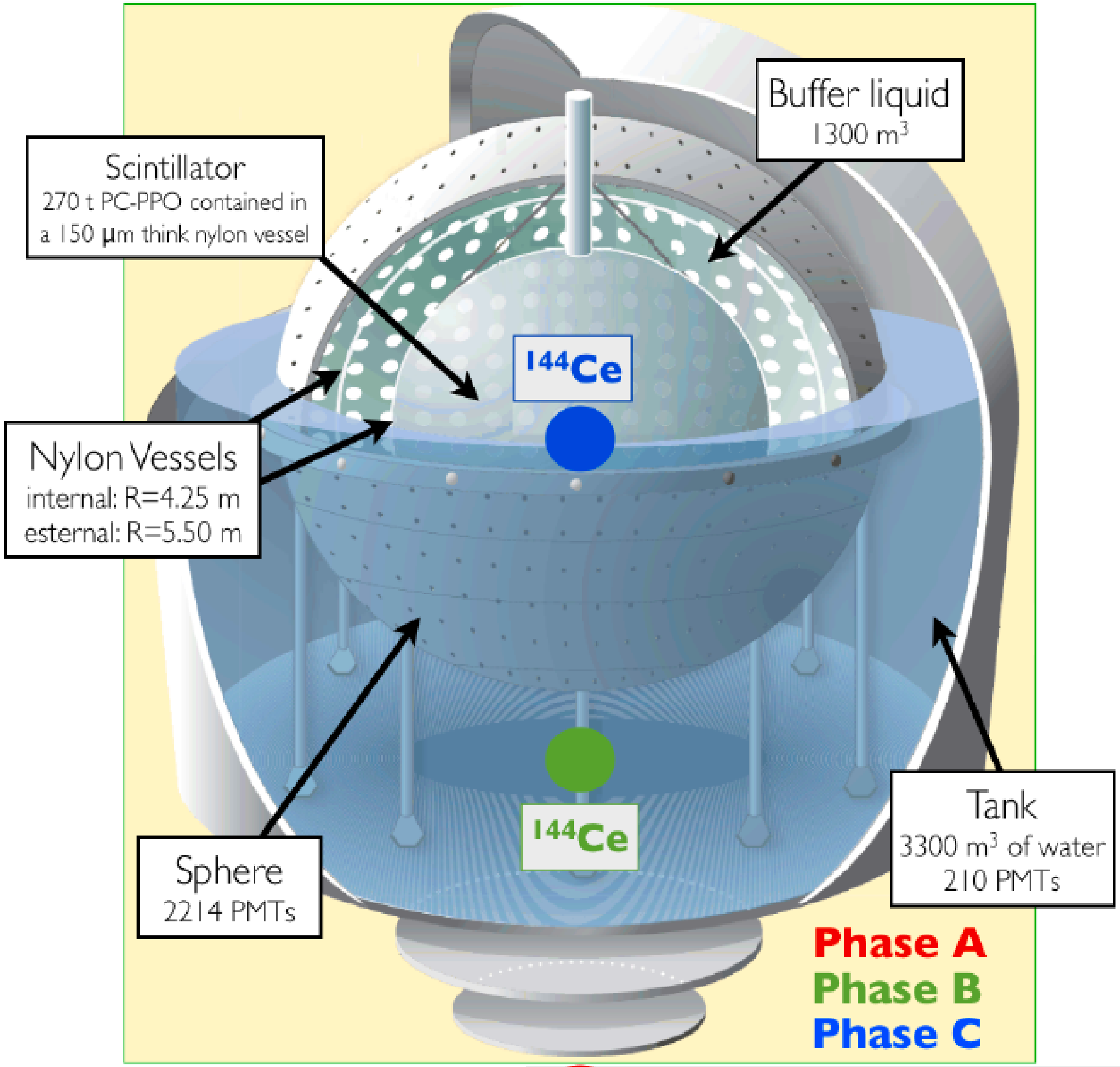
Three phases:

Phase A ^{51}Cr ν_e source, 8.25m from detector centre
Phase B ^{144}Ce-^{144}Pr Aν_e source, 7.15m from detector centre
Phase C ^{144}Ce-^{144}Pr Aν_e source, centre of detector

A+B → can be made during solar neutrino program
Phase C (most attractive) only after finishing solar (end of 2015)

Neutrinos → detected via scattered electrons
Antineutrinos → by means of inverse beta decay on protons
Energy measurement obtained using scintillation light

BoreXino - SOX



^{51}Cr tunnel beneath detector

Borexino-SOX sensitivity

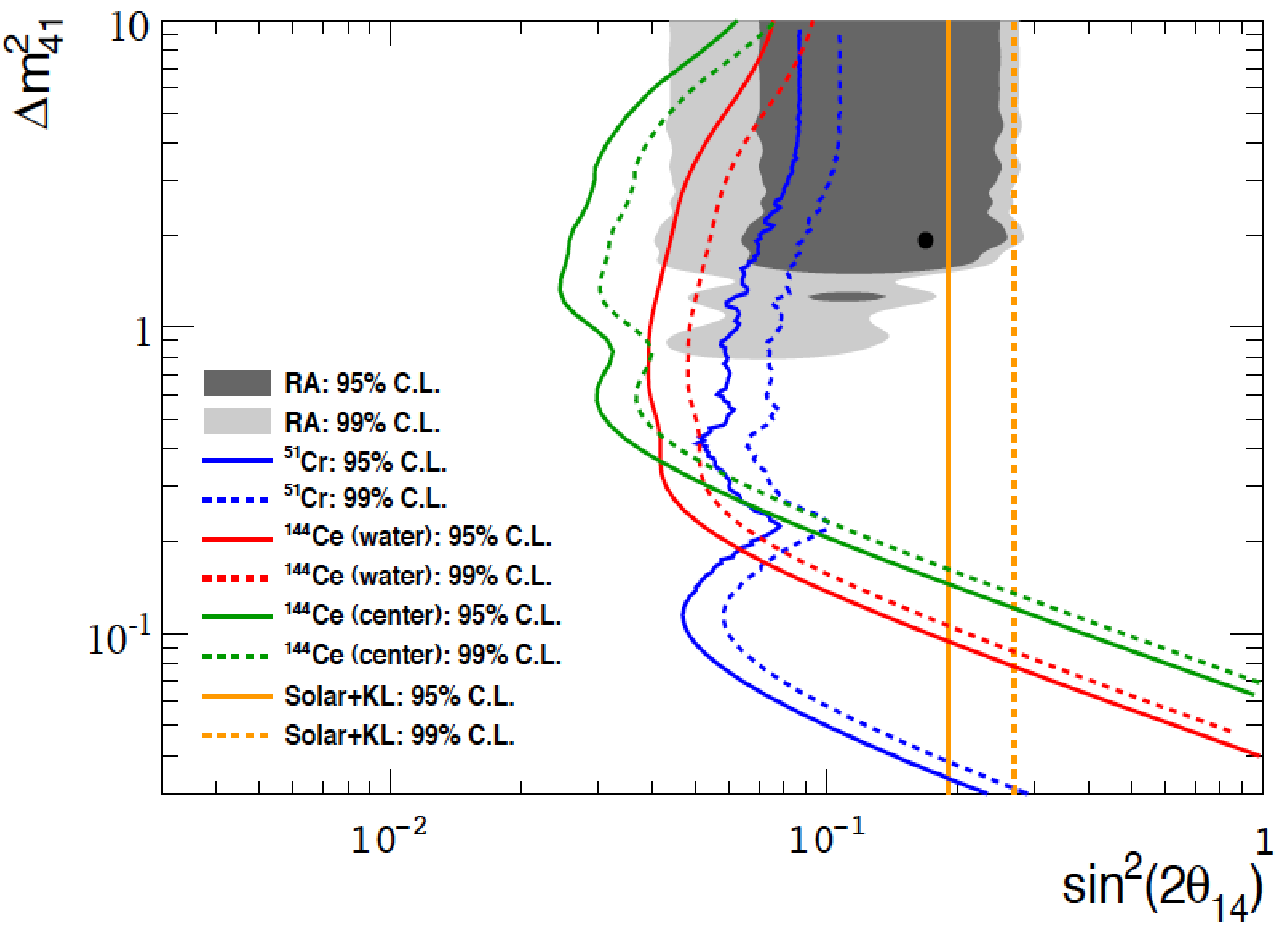


Figure 4. Sensitivity of the Phase A (^{51}Cr external, blue), of Phase B (^{144}Ce–^{144}Pr external, red) and Phase C (^{144}Ce–^{144}Pr center, green). The grey area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95% and 99% C.L. are shown for all cases. The yellow line indicates the region already excluded in [40].

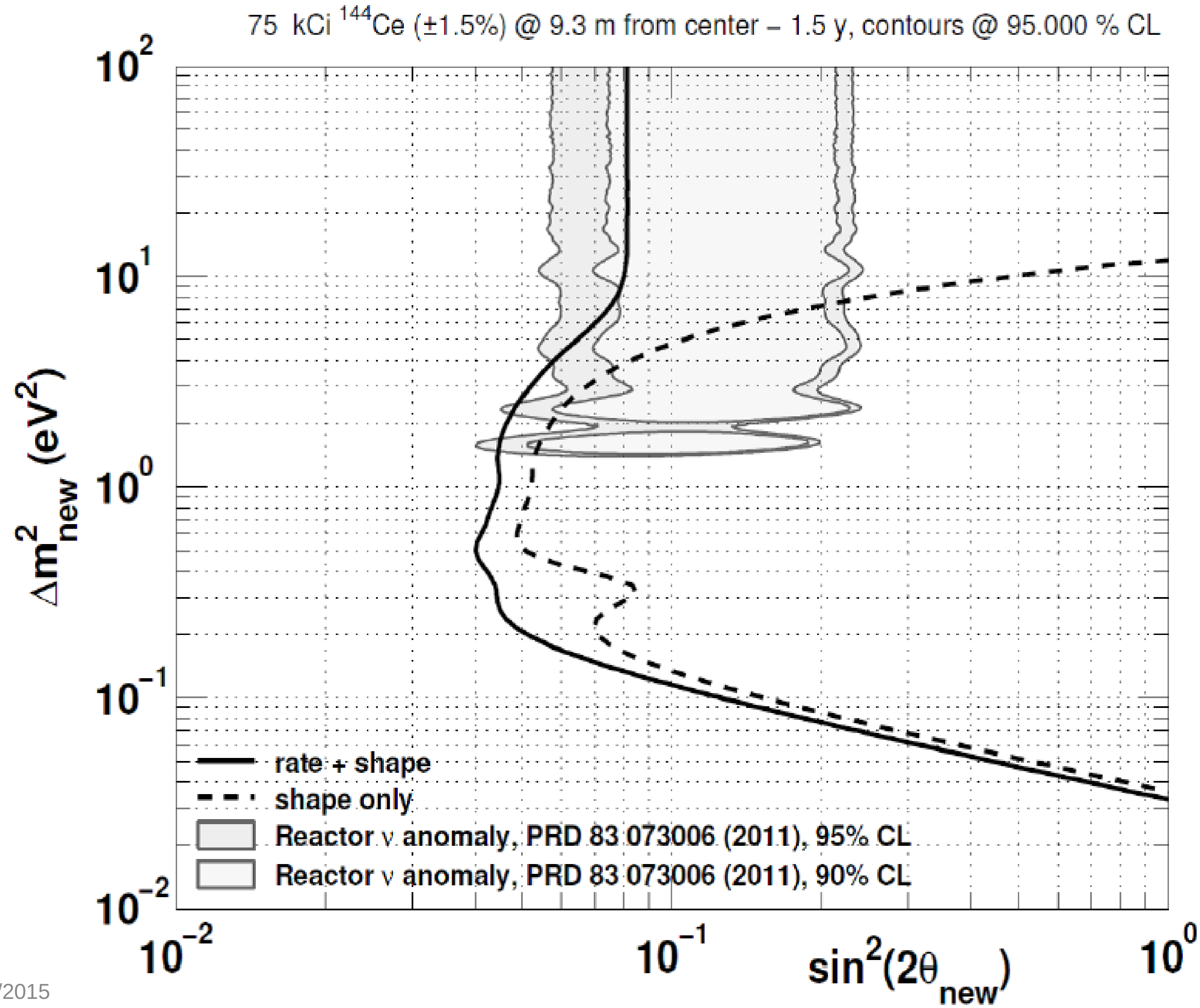
CeLAND – Radioactive source in KamLAND
arXiv:1309.6805 - White Paper - October 2013

Intense ^{144}Ce-^{144}Pr antineutrino source
at 9.3 m from detector centre

(Detector: KamLAND
Kamioka Liquid scintillator Antineutrino Detector)

Oscillation pattern can be observed on 10m baseline
in 1.5 years of data taking

CeLAND – sensitivity 1.5 years



LENS

arXiv:0705.2769 - LENS as a probe of sterile neutrino mediated oscillations

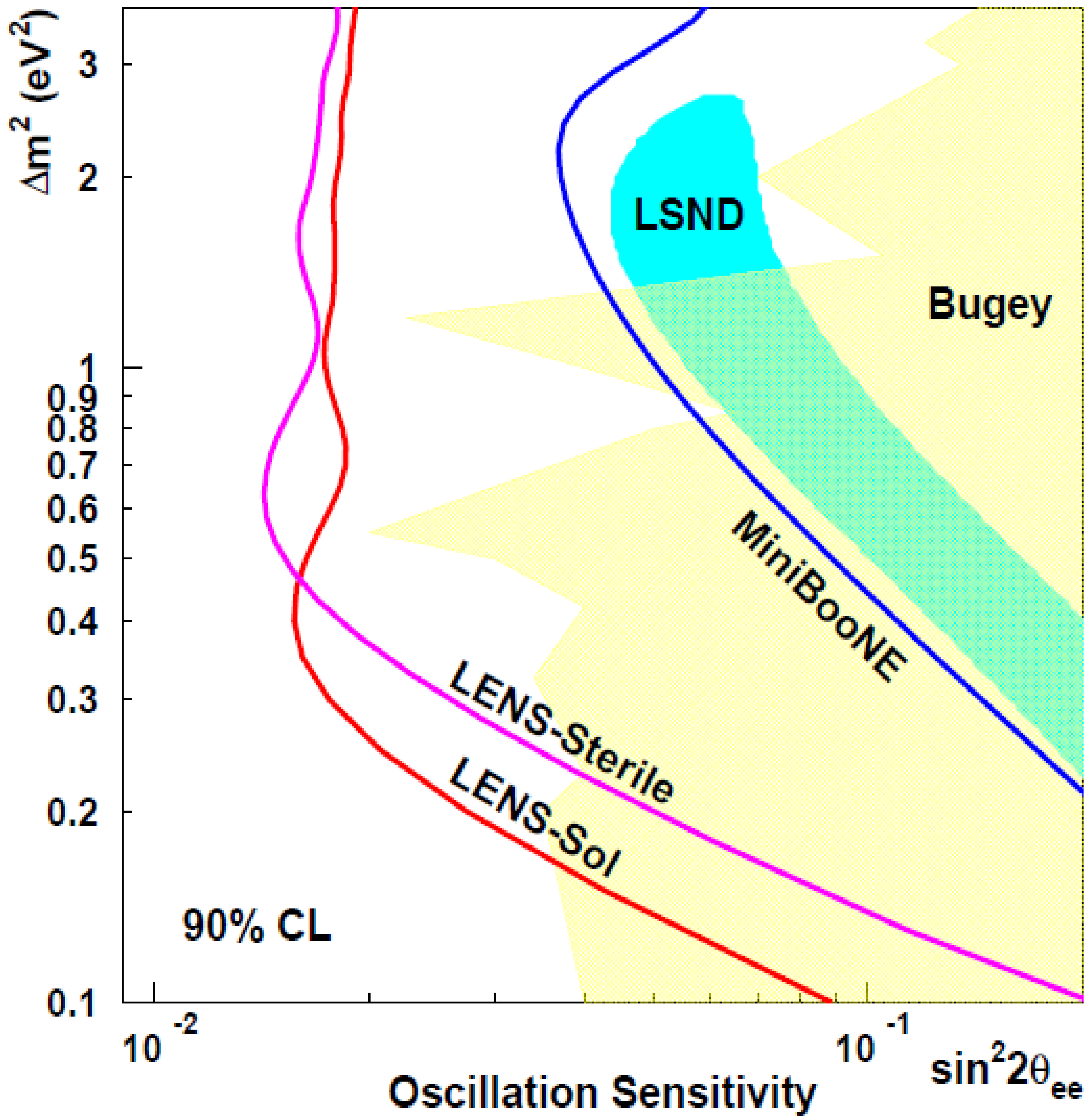
Detector:
Indium loaded liquid scintillator
sub-MeV ν_e detected via

$$\nu_e + {}^{115}\mathrm{In}(95.6\%) \rightarrow {}^{115}\mathrm{Sn}^* + e^-$$
$$\hookrightarrow {}^{115}\mathrm{Sn} + 2\gamma$$

(^{115}Sn lifetime = 4.75 μs)*

Coincidence electron+2 gammas → clear identification of the process

LENS sensitivities



Gallium proposal *(GALLEX,SAGE)*

(Gallium experiments with artificial neutrino sources as a tool for investigation of transition to sterile states *V.N.Gavrin et al.,arXiv:1006.2103*)

^{51}Cr intense source in centre of 50 tons gallium detector divided in two zones
Search for differences in the capture rate in the two zones

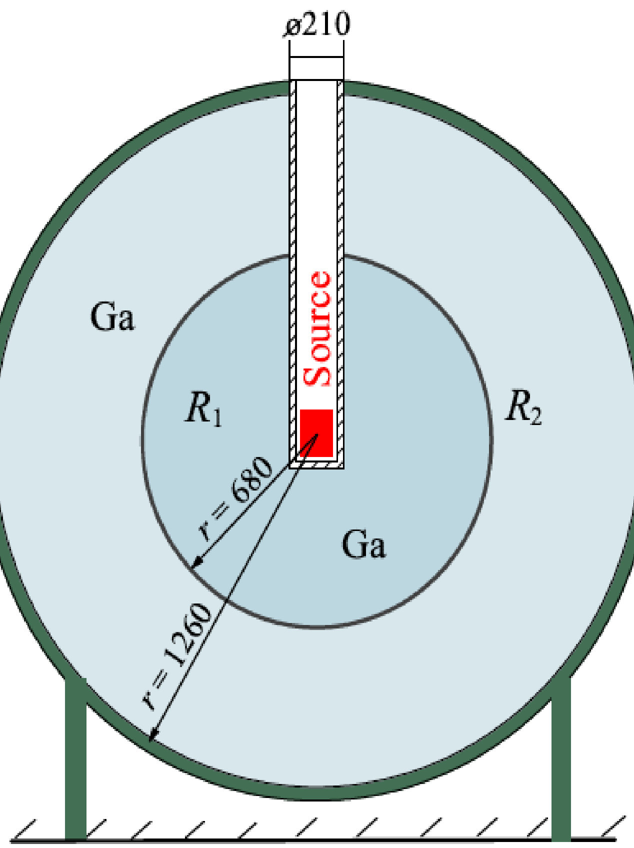


Figure 94. Schematic drawing of proposed neutrino source experiment. R_1 and R_2 are the ratios of measured capture rate to predicted rate in the absence of oscillations in the inner and outer zones, respectively. Outer radii r of the two zones and diameter ϕ of source reentrant tube are given in mm.

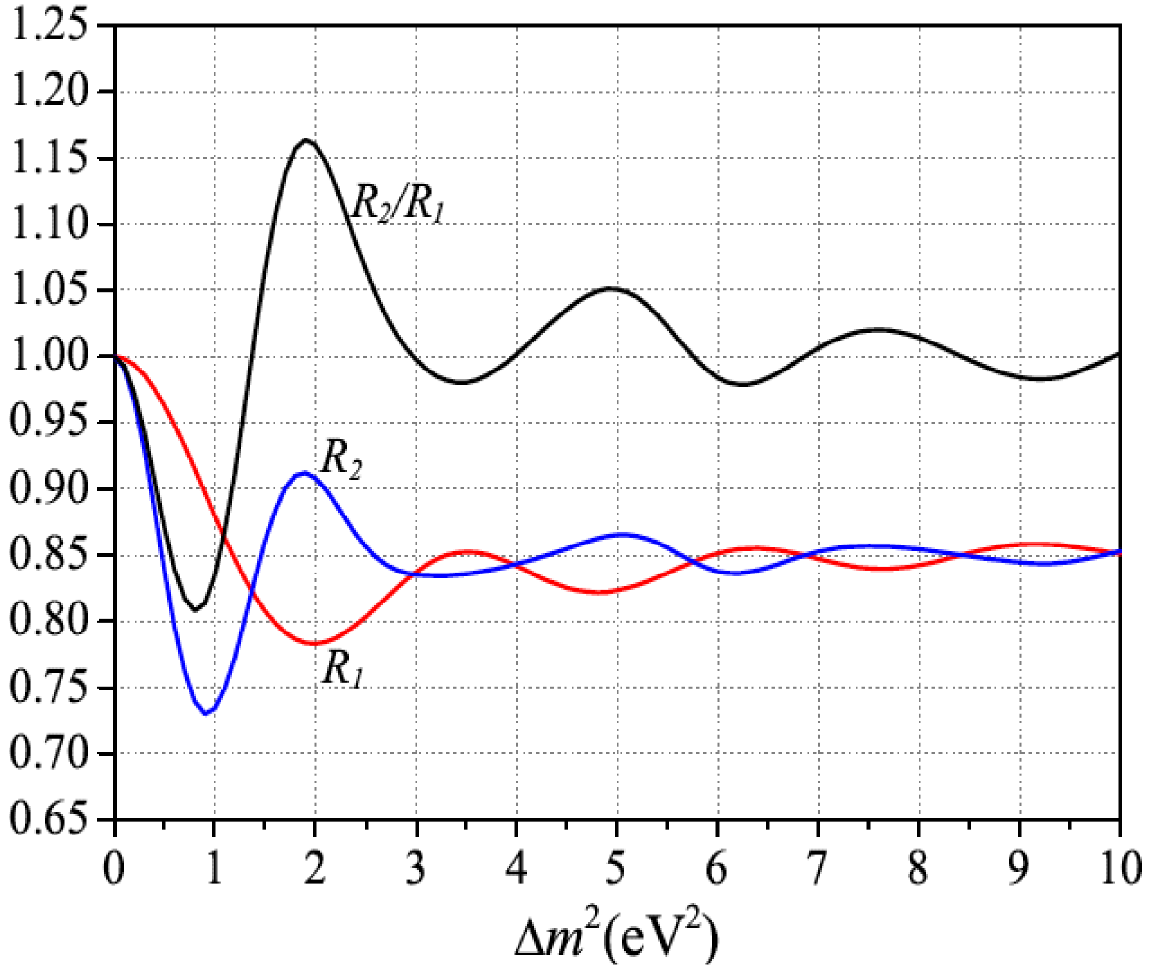
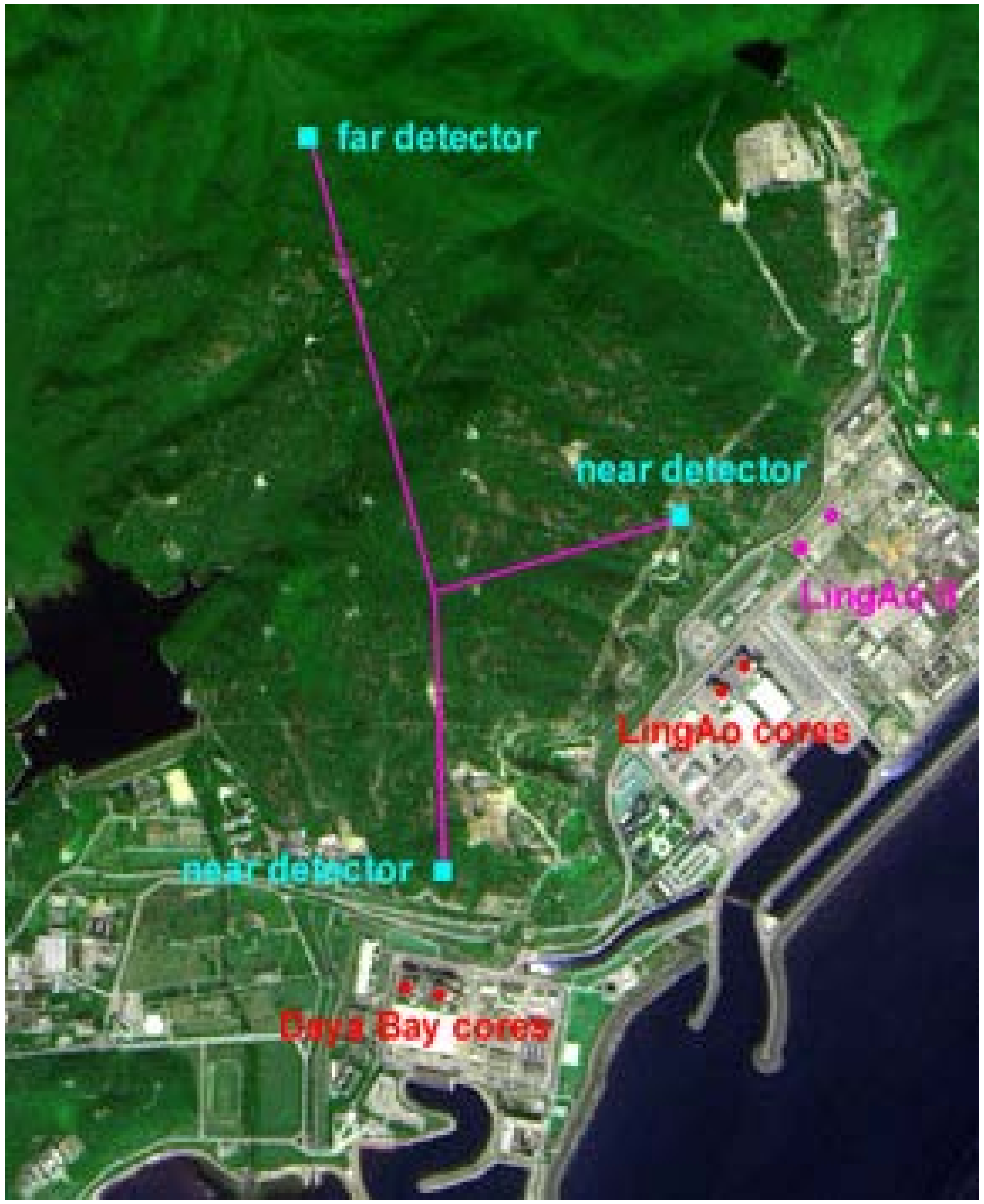


Figure 95. Ratio of measured capture rate to predicted rate in inner zone (R_1), in outer zone (R_2), and their ratio R_2/R_1 as a function of Δm^2 for the case of $\sin^2 2\theta = 0.3$. The outer shell of the outer zone is assumed to be a cylinder, not a sphere.

Daya Bay – proposal

D.A.Dwyer et al. Search fo sterile Neutrinos with a Radioactive Source at Daya Bay
arXiv:1109.6036



Use the four 20 tons neutrino detectors at the far site

Antineutrinos from ^{144}Ce-^{144}Pr β-decay source

Flexible source placement

Daya Bay - sensitivity

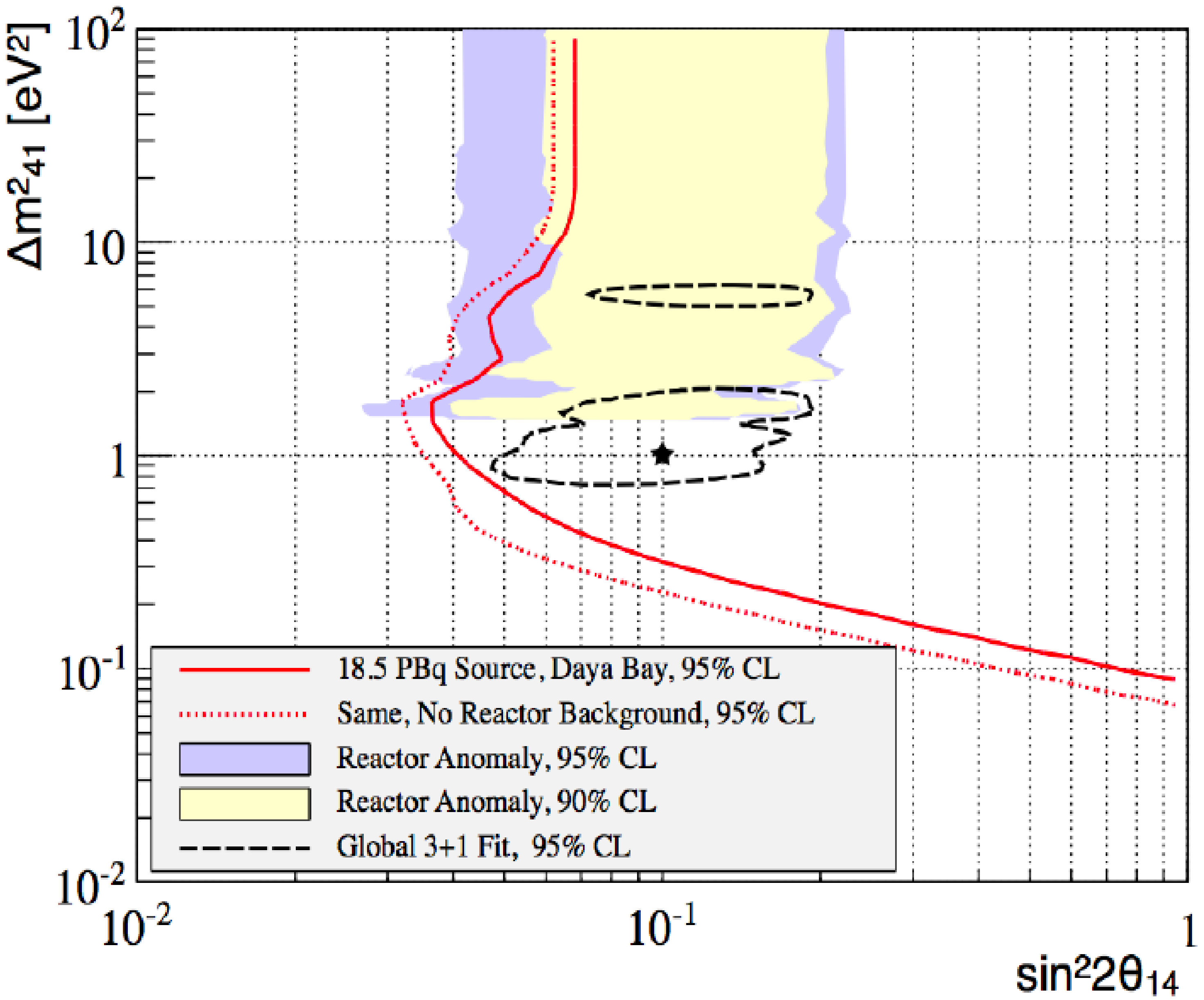


FIG. 6: Sensitivity of a $\overline{\nu}_e$ search at Daya Bay to the oscillation parameters Δm^2_{41} and $\sin^2 2\theta_{14}$ assuming a 500 kCi ^{144}Ce source at position B in the Daya Bay Far Hall. We show the 95% C.L. sensitivity of the Daya Bay source experiment with reactor background (red solid) and without (red dashed), the 90% and 95% C.L. preferred regions of the reactor anomaly (shaded yellow and blue) [3], and the 95% best-fit region from a 3+1 global fit to all neutrino data (dashed black) [2]. The parameter space to the left and above the Daya Bay sensitivity curve will be excluded at 95% C.L. The star indicates the oscillation parameters Δm^2_{41} and $\sin^2 2\theta_{14}$ used in Figures 4 and 5 for the study in this paper.

2) Searches with ν from small core reactors

O. Yasuda *arXiv:1110.2579*

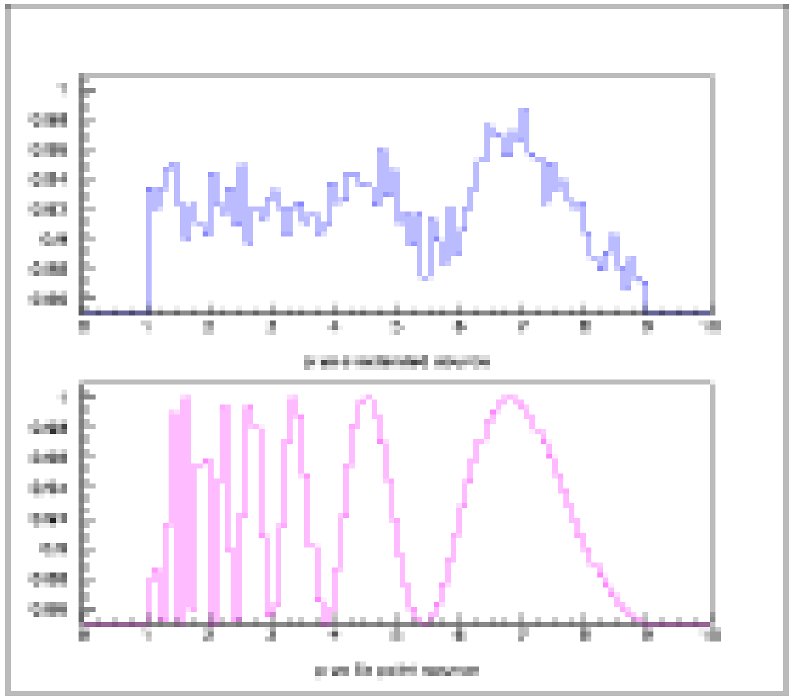
Suggestion:

Commercial reactors: size about 4 m → sensitivity lost for $\Delta m^2 > 1$ eV^2

Better sensitivity:

special small core reactors (size ~ 0.5 m): JOYO, ILL, Osiris

Example: $\Delta m^2 = 2.4$ eV^2 $\sin^2 2\theta = 0.15$



Blue -- extended source (reactor size: 3m)

Pink -- point source

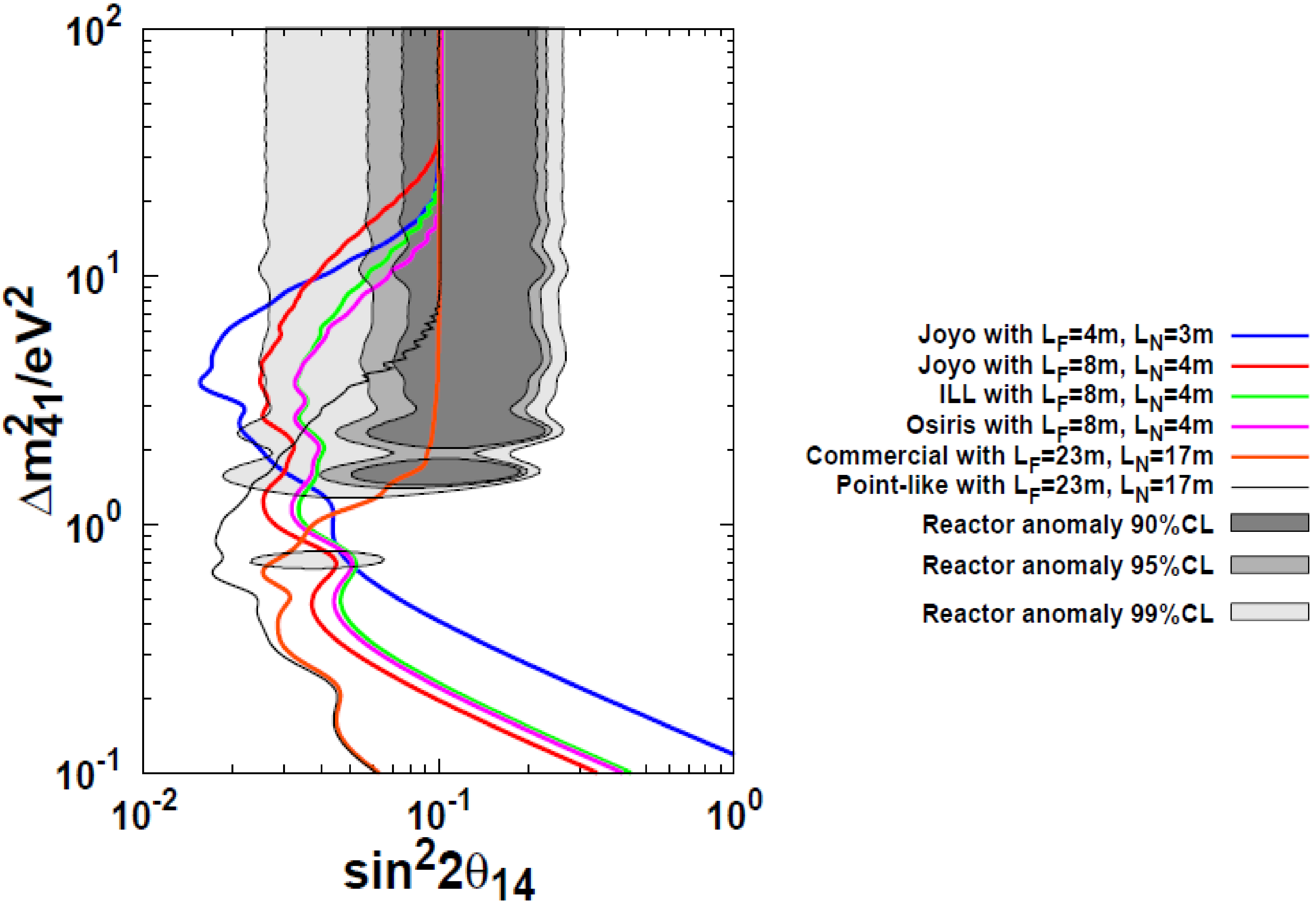


Fig. 2. The sensitivity to $\sin^2 2\theta_{14}$ of each reactor with the two detectors at its optimum baseline lengths. Also shown as a shaded area is the region given in Ref. [9] from the combination of the reactor neutrino experiments, Gallex and Sage calibration sources experiments, the MiniBooNE reanalysis of Ref. [10], and the ILL energy spectrum distortion.

3) Short baseline accelerator searches

MicroBooNE

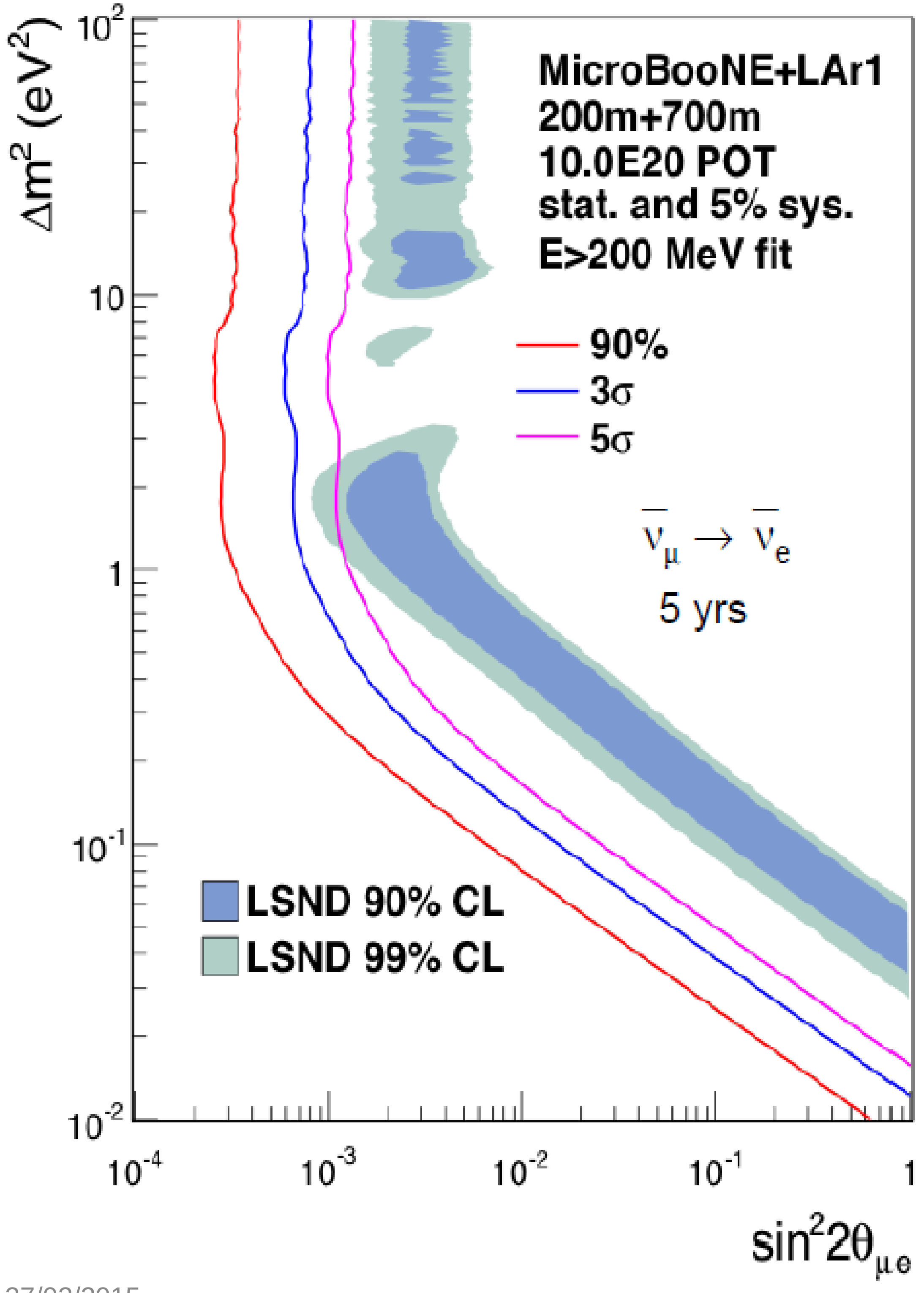
Designed to investigate low energy excess observed by MiniBooNE

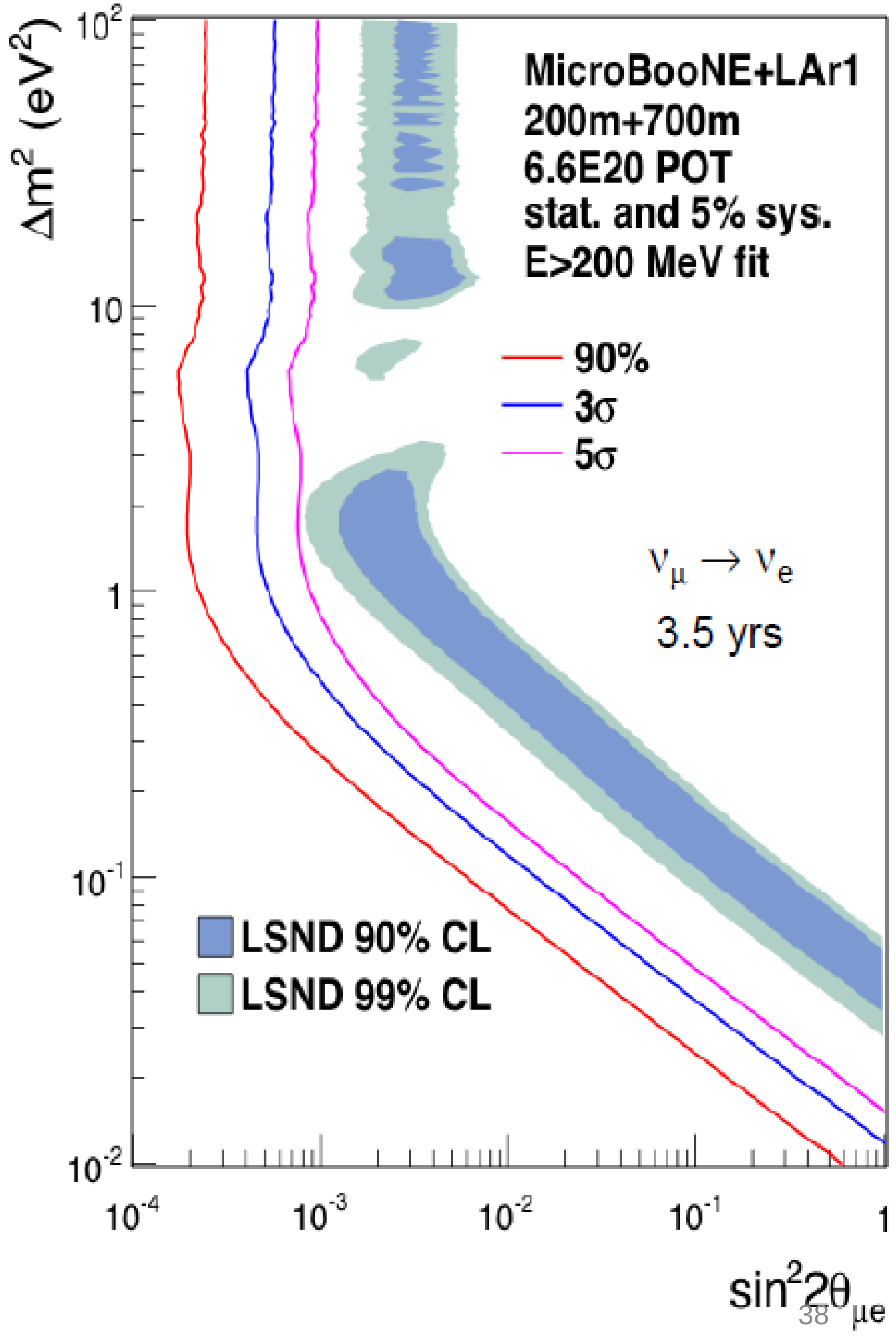
Detector: 170-ton liquid Argon TPC at L= 200 m
(allows electron/gamma discrimination)

Installation → started in 2013

Future plans → 1 kton detector (LAr1) at L=700 m_

LAr1kton Sensitivity





Short baseline accelerator searches
ICARUS + NESSiE *arXiv:1208.0862*

The ICARUS-NESSiE experiment will probably not run. No neutrino physics is planned at CERN

With a double detector configuration, as the old I216 one, the confirmation or disproving of LSND would have been possible

A similar experiment has been proposed at Fermilab
Prospect for ν_μ *disappearance at the Fermilab booster ArXiv: 1404.2521*

I will anyway present the CERN experiment

Short baseline accelerator searches
ICARUS + NESSiE *arXiv:1208.0862*

ICARUS - LAr TPC – 600 ton (from LNGS)
NESSiE - spectrometer – magnetized iron + air core magnet

ICARUS → $\nu_\mu - \nu_e$ appearance
NESSiE → ν_μ disappearance

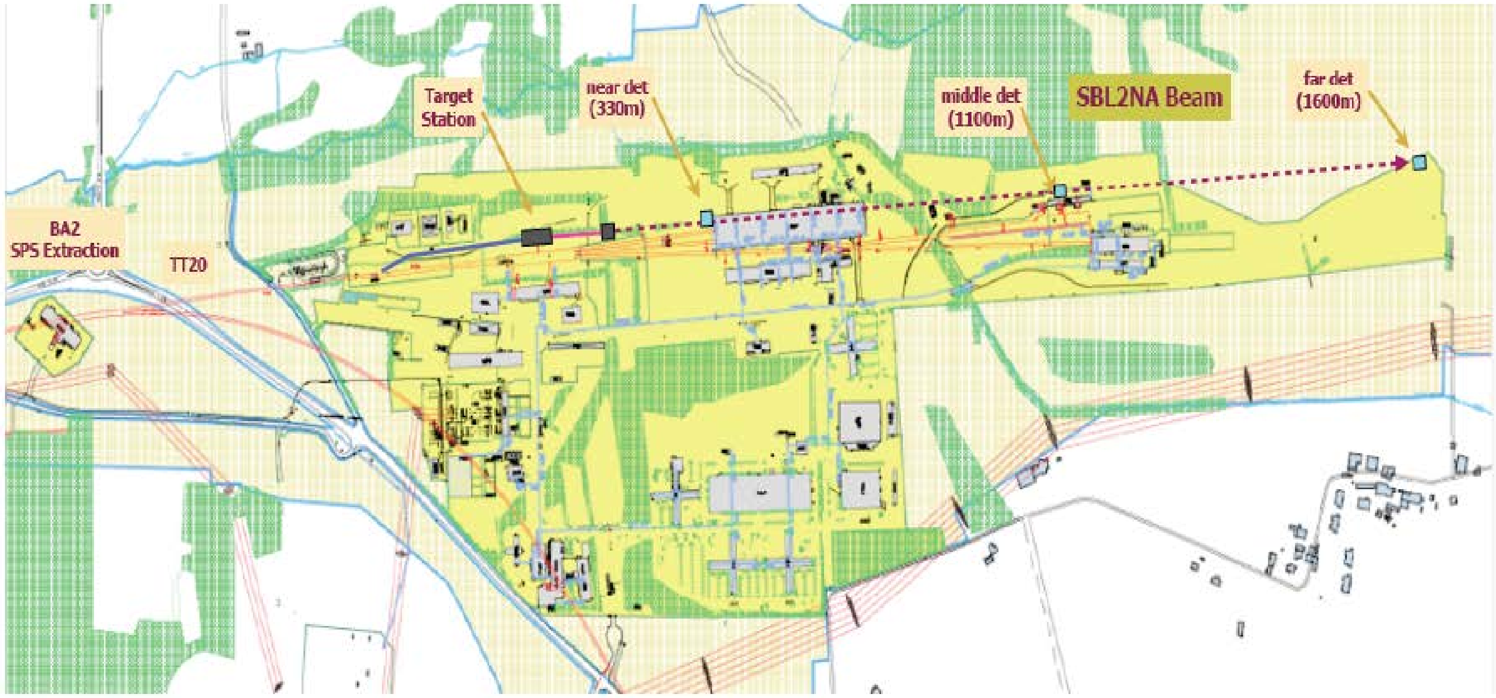


Figure 1: *The new SPS North Area neutrino beam layout. Main parameters are: primary beam: 100 GeV; fast extracted from SPS; target station next to TCC2, ~11 m underground; decay pipe: 100 m, 3 m diameter; beam dump : 15 m of Fe with graphite core, followed by muon stations; neutrino beam angle: pointing upwards; at ~3 m in the far detector ~5 mrad slope.*

ICARUS/NESSiE detector layout at the far site (L = 1600 m)

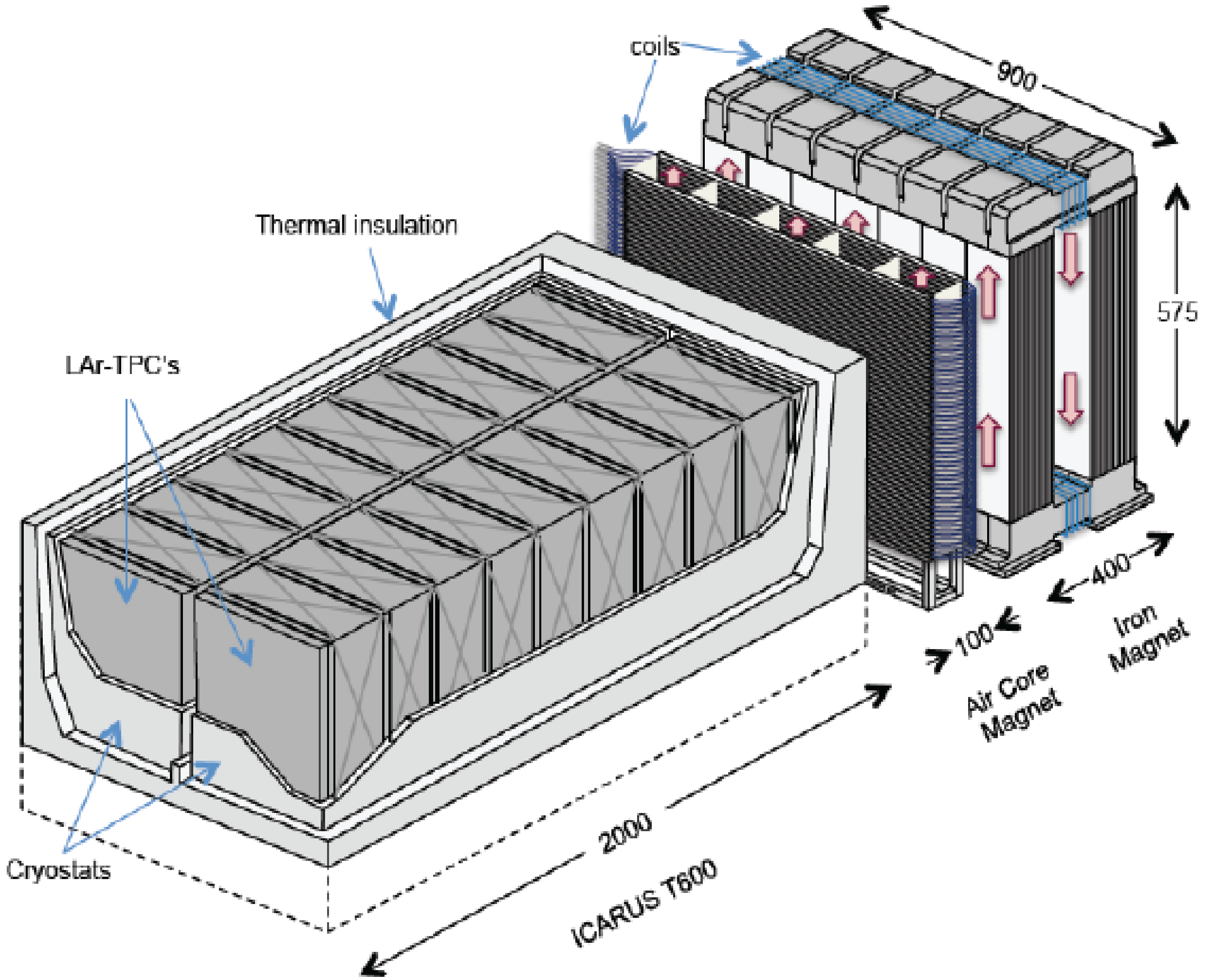
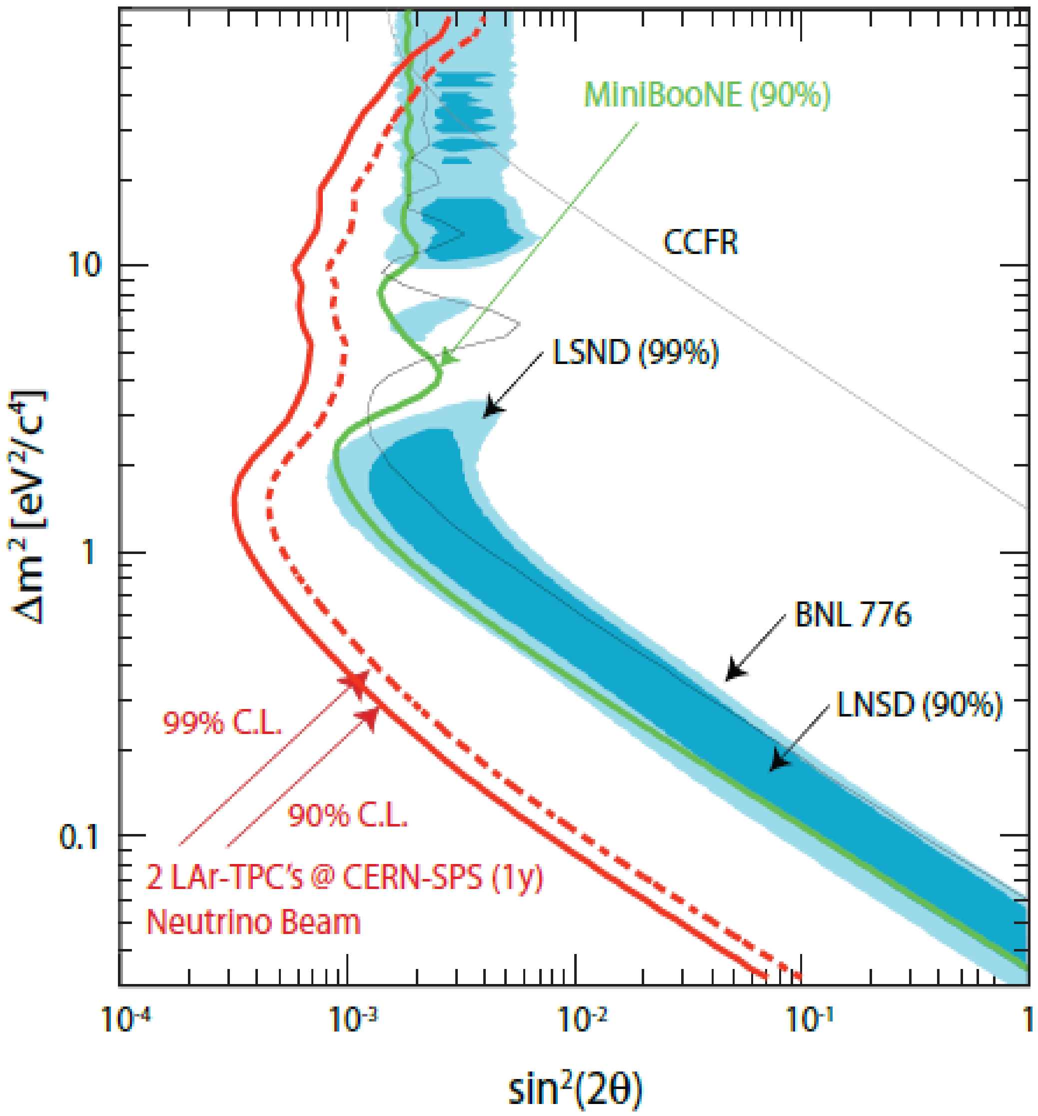
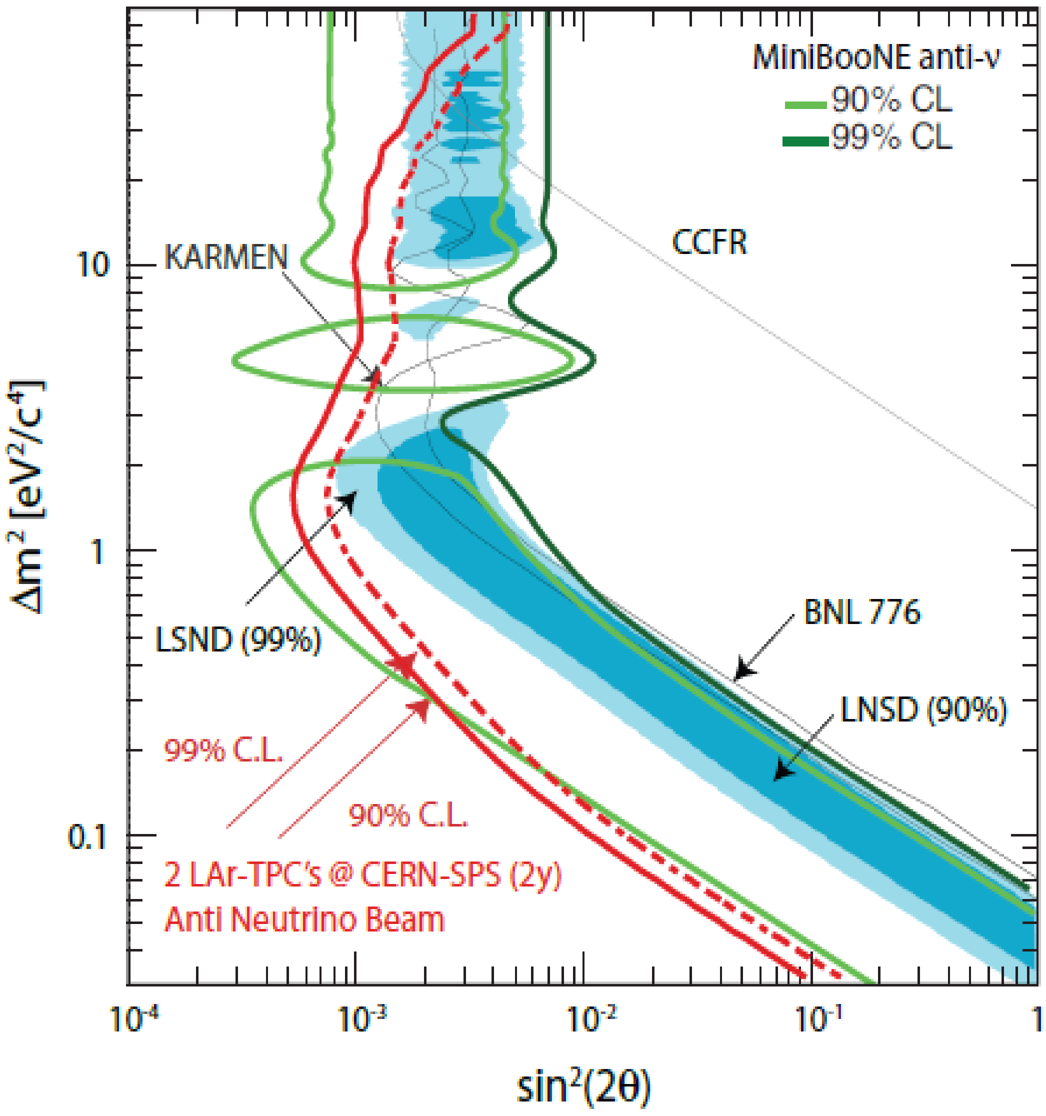


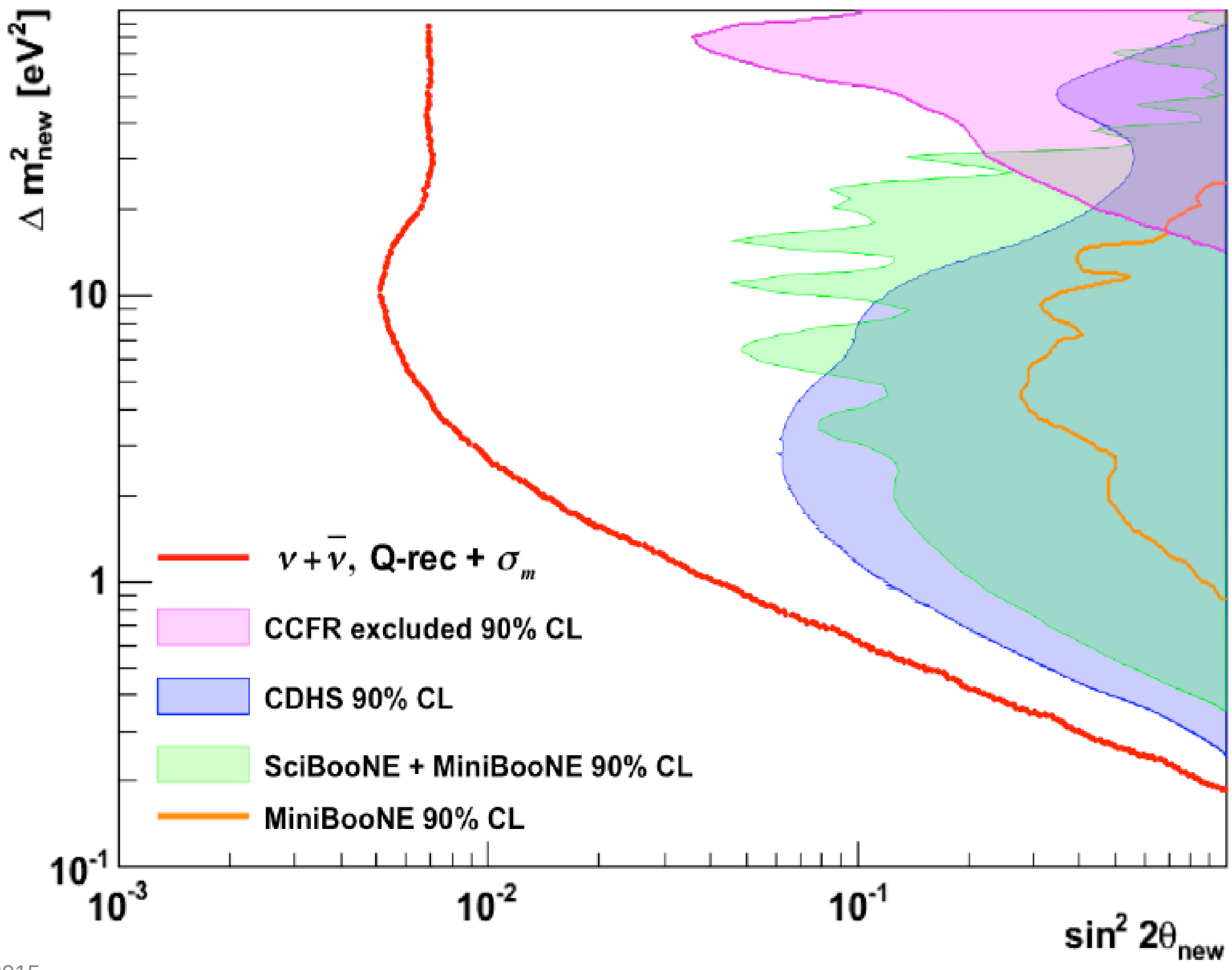
Figure 2: *3D sketch of the ICARUS/NESSiE detector layout at the far site.*

ICARUS - electron appearance - sensitivity





ν_μ disappearance - sensitivity



4) Monocromatic ν_μ from K^+ decay at rest *J.Spitz-arXiv:1203.6050*

K^+ from intense proton facilities
Search for ν_e appearance in 235.5 MeV ν_μ from $K^+ \rightarrow \mu^+ \nu_\mu$ at rest
Sensitivity estimate → use LAr TPC ~ 2kton at 100 m

$E_{electron}$ bckg + oscillation signal

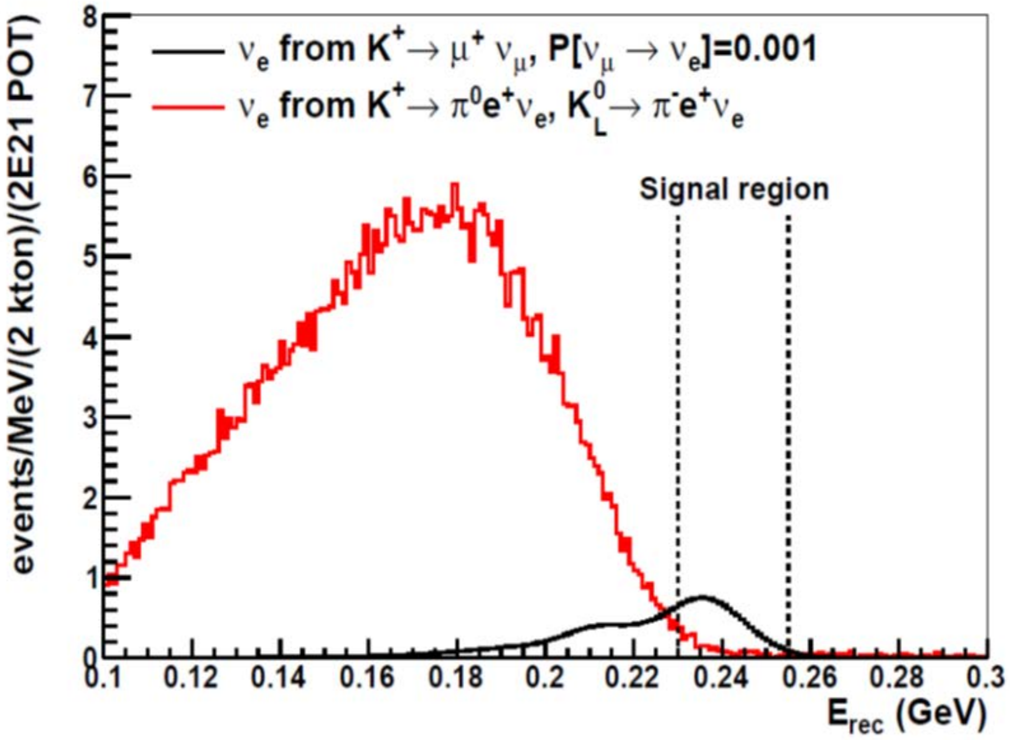


FIG. 5. Electron neutrino rate with detector resolution and nuclear effects included. The vertical lines designate the signal region.

$K^+ \to \mu^+ \nu_\mu$ at rest

$\nu_\mu \to \nu_e$ appearance

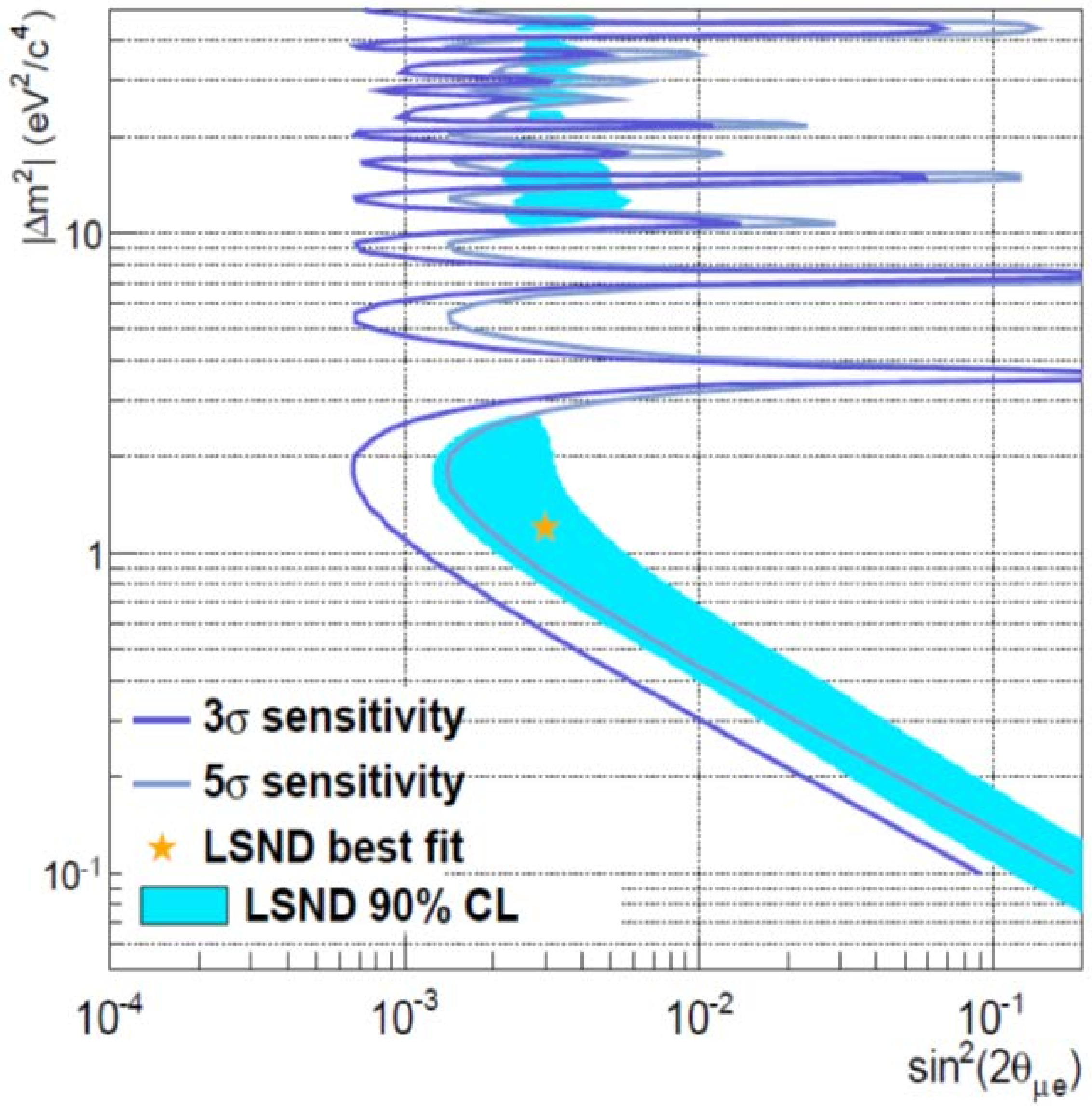


FIG. 6. The sensitivity to the LSND allowed region achievable with a kaon decay-at-rest source in combination with a large LArTPC.

5) Muon storage ring nuSTORM
Proposal at Fermilab *arXiv:1308.6892 (September 2013)*

Store 3.8 GeV muons
Neutrino beams from muon decays in straight sections

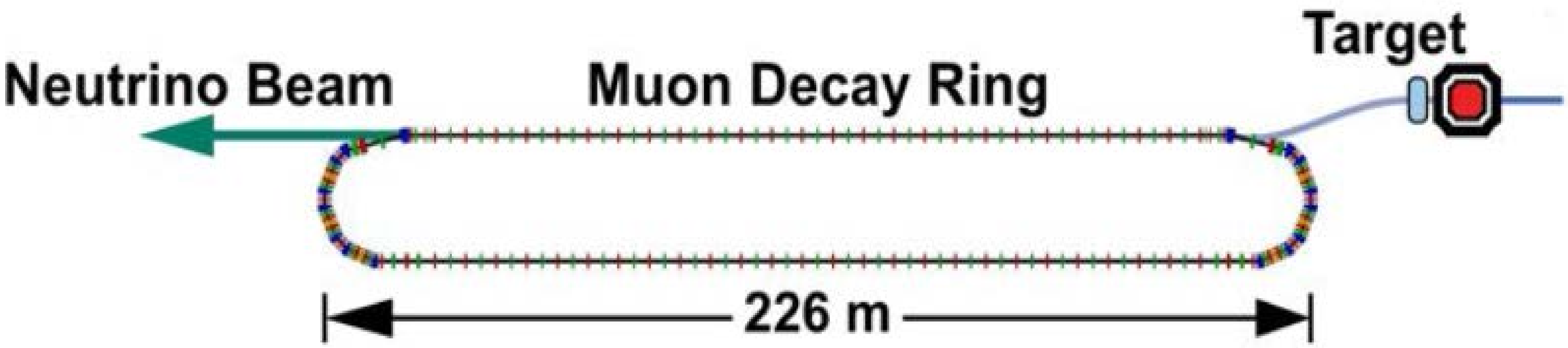


Figure 2. Schematic of the facility

wrong sign muon events for $\nu_e \rightarrow \nu_\mu$ appearance

e.g.

stored μ^+ give $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

ν_μ appearance $\rightarrow$ detect wrong sign muon (μ^-) events

Disappearence of electron neutrinos with a detector at 50 m

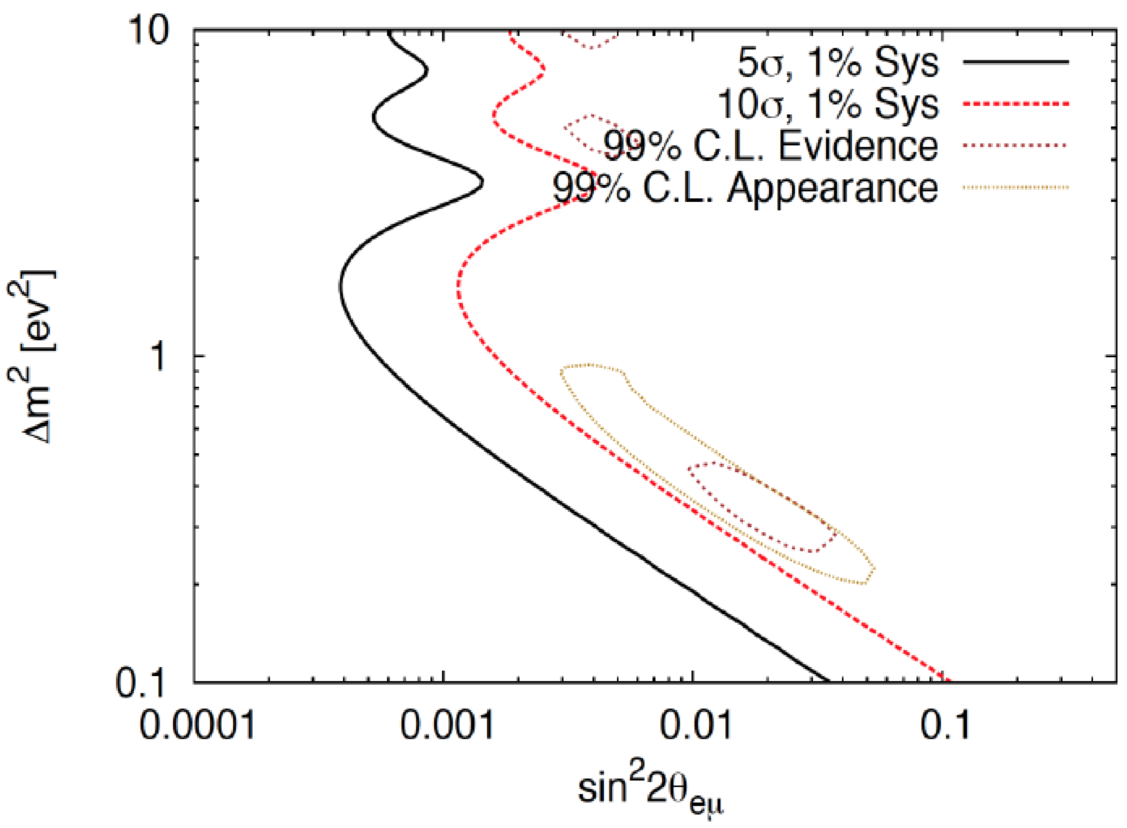


Figure 1. Contours of the χ^2 deviation from the no-sterile neutrino hypothesis corresponding to 5σ and 10σ variations with 1% systematic uncertainties. The 99% confidence level contours from a global fit to all experiments showing evidence for unknown signals (appear + reactor + Gallium) and the contours derived from the accumulated data from all applicable neutrino appearance experiments [14] are also shown.

Cosmological information on number of neutrinos

PLANCK results on number of neutrinos

$N(\nu) = 3.13 \pm 0.32$

J. Lesgourgues - *PLANCK Collaboration 2014*

→ little room for sterile neutrinos.

In past years results with 4 neutrinos have been proposed.

See for example

- *Melchiorri Journal of Physics 485 012085 2014*

  $N(\nu) = 4.08 + 0.71 - 0.08$

- *T. Lasserre at Neutrino 2014*

Neutrino Anomalies & 4^{th} Neutrino

Anomaly	Source	Type	Sensitivity to Oscillation	Channel	Significance
LSND	Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBoone	Short baseline	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3 σ
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	2.7 σ
Reactor	Beta-decay	$\bar{\nu}_e$ dis.	Total Rate, Energy	CC	3.0 σ
Cosmology	Big-Bang	All	Number of ν, N_{eff}	CC	$\approx$2 σ

→ could be interpreted by an existing eV-scale 4^{th} neutrino state…

Conclusions

Hints for anomalies (1 eV sterile neutrino ?)

somewhat weak (2-3 σ) and partially inconsistent
but numerous

Many different ideas for testing → situation should be clarified in a few years

Back up slides

A sterile neutrino is a neutral lepton with no ordinary weak interaction except those induced by mixing

The oscillation between normal neutrinos will be given for example by:

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad (\alpha \neq \beta),$$

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right),$$

for $\alpha, \beta = e, \mu, \tau, s$, with the transition amplitudes

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha4}|^2 |U_{\beta4}|^2,$$

$$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha4}|^2 \left(1 - |U_{\alpha4}|^2\right).$$

$U_{\alpha4}$ are elements of a 4x4 mixing matrix

Nuova presentazione di nustorm
Arxiv:1402.525

TABLE I. Expected rates for neutrino oscillation channels observed at a 1.3 kt detector, 2 km away from a muon storage ring with an exposure of 10^{21} POT.

Channel	Oscillation	$N_{osc.}$	N_{null}
ν_μ Appearance	$\nu_e \to \nu_\mu$ CC	332	0
$\bar{\nu}_\mu$ Disappearance	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433
ν_e Disappearance	$\nu_e \to \nu_e$ CC	216657	230766
NC Disappearance	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073
NC Disappearance	$\nu_e \to \nu_e$ NC	73941	78805