Search for sterile neutrinos at reactors

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1. Introduction

2. Sterile neutrino oscillations at reactors

3. Summary

Based on OY, arXiv:1107.4766 [hep-ph]

1. Introduction

1.1 ν oscillation

Mass eigenstates

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}=\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$E_j\equiv\sqrt{\vec{p}^2+m_j^2}$$

Flavor eigenstates

$$\begin{pmatrix}\nu_\mu\\ \nu_\tau\end{pmatrix}=U\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$U\equiv\begin{pmatrix}U_{\mu1} & U_{\mu2}\\ U_{\tau1} & U_{\tau2}\end{pmatrix}$$

Probability of flavor conversion

$$P(\nu_\mu\to\nu_\tau)=\sin^2 2\theta\,\sin^2\left(\frac{\Delta E\,L}{2}\right)$$

$$\Delta E=E_2-E_1\cong\frac{m_2^2-m_1^2}{2E}=\frac{\Delta m^2}{2E}$$

1.2 Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

1.3 Information we have obtained so far

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8 \times 10^{-5} \mathrm{eV}^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} \mathrm{eV}^2$

CHOOZ (reactor)
+T2K+MINOS+others → $\theta_{13} \cong 0.14^{+0.02}_{-0.03}$

1.4 Beyond the three flavor scenario

- **accelerator ν anomaly LSND (1993-98, LANL)**

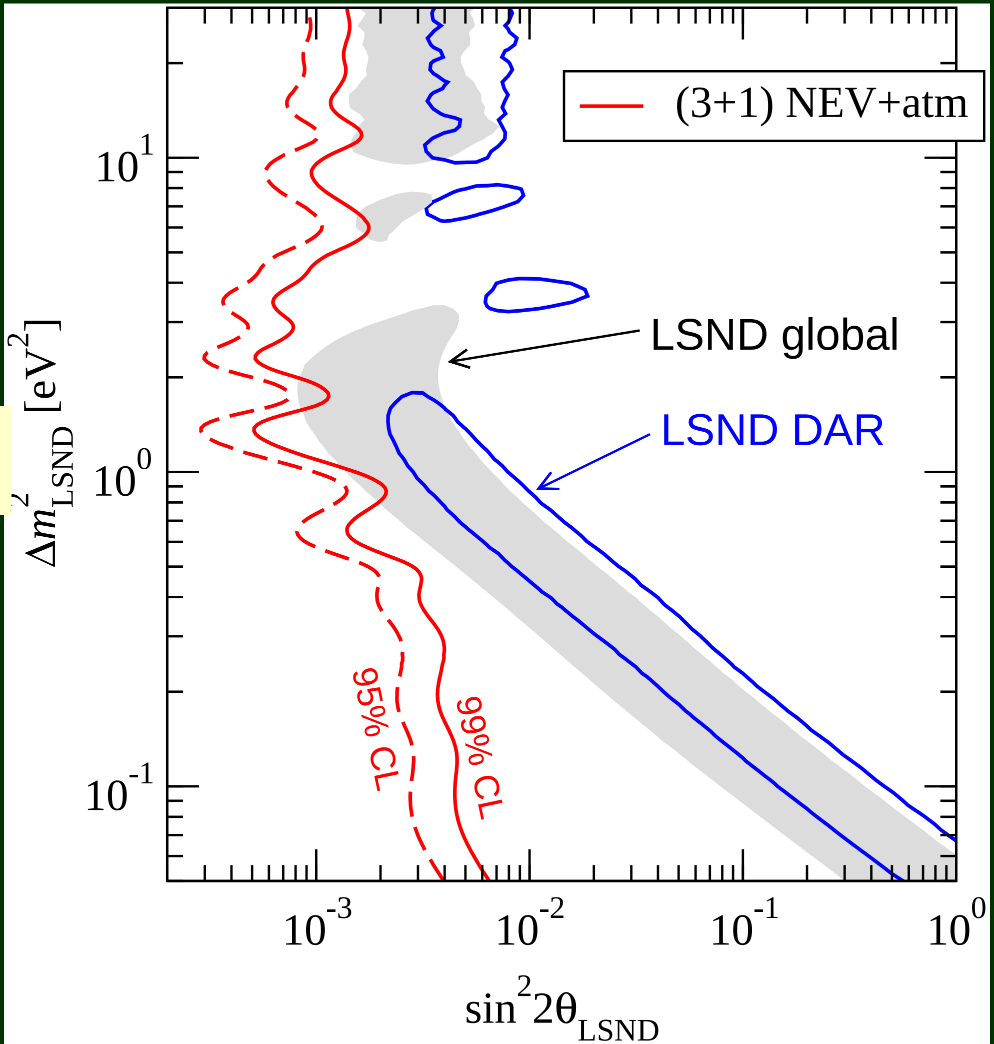
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$E_\nu \cong 50\text{MeV}$

$L \cong 30\text{m}$

$\Delta m^2 \cong O(1)\text{eV}^2$
$\sin^2 2\theta \cong O(10^{-2})$ **??**

Maltoni et al., hep-ph/0405172



MiniBooNE (2002-, FNAL)

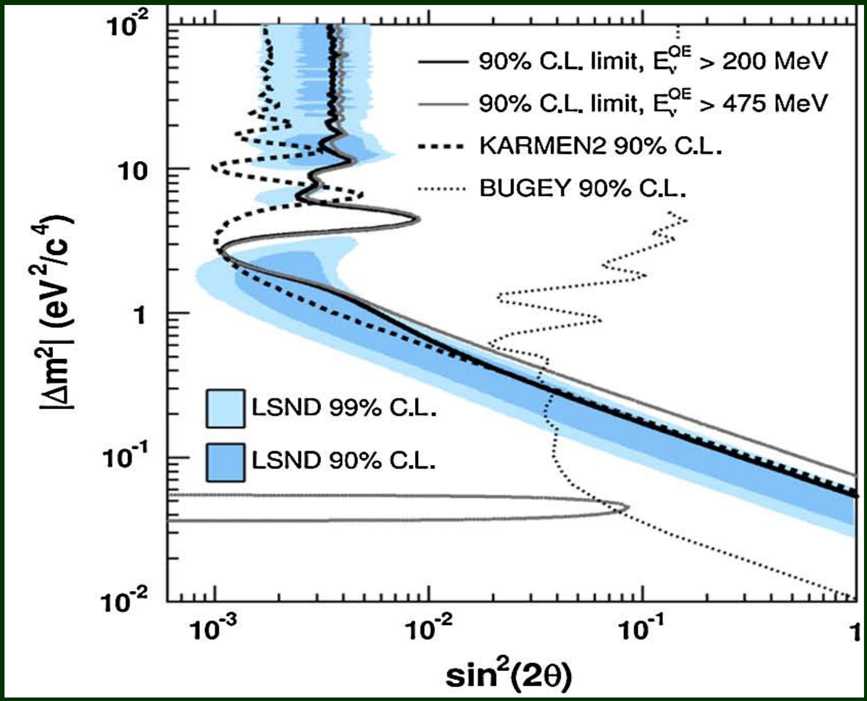
$E \sim 1$GeV, $L \sim 1$km,
$(L/E)_{MB} = (L/E)_{LSND}$
The purpose of MB: to check LSND

In both cases, depending on energy ($E > 475$ MeV or $E > 200$ MeV), the conclusion changes

ν mode(nagative)

$\nu_\mu \to \nu_e$

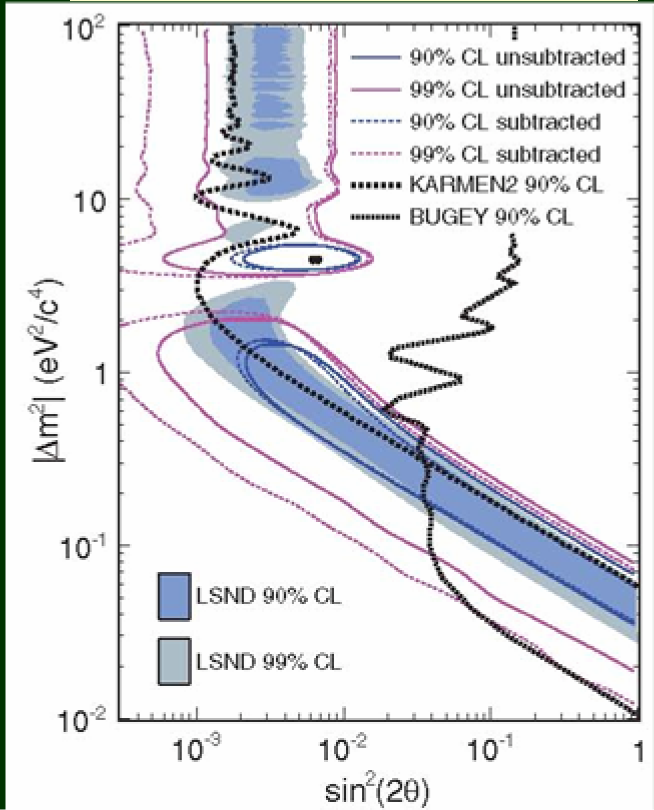
Aguilar-Arevalo et al., PRL 103, 111801 (2009)



anti-ν mode(affirmative; No. of events is small)

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

Aguilar-Arevalo et al., PRL 105, 181801 (2010)



MiniBooNE's summary

R. Van der Water@Neutrino2010

→ The data is still confusing

mode	E<475MeV	E>475MeV
$\nu_\mu \to \nu_e$	An unexplained 3σ electron excess	Inconsistent w/ LSND @ 90%CL
$\bar{\nu}_\mu \to \bar{\nu}_e$	A small 1.3σ electron excess	Consistent w/ LSND @ 99.4%CL

1.5 N_ν=4 schemes

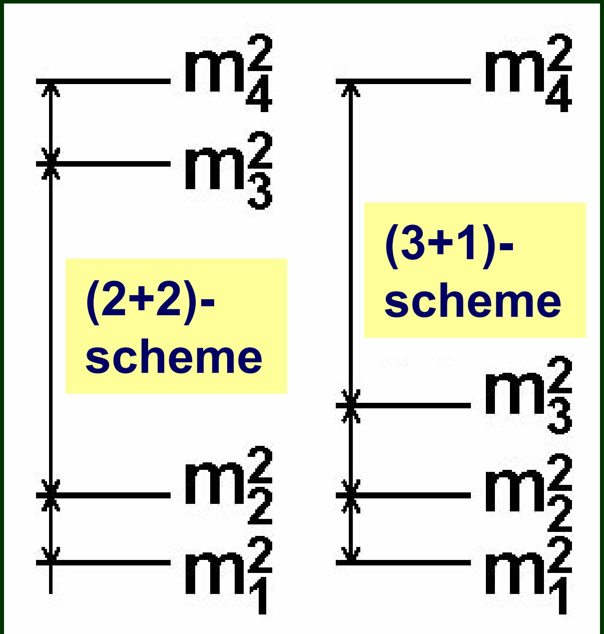
Because of the hierarchy: $\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{LSND}$

N_ν=3 schemes can't explain LSND.

N_ν=4 schemes may be able to explain all.

$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}, \Delta m^2_{43} = \Delta m^2_{LSND}$

LEP ➡ 4th ν has to be sterile



(2+2)-scheme is excluded by solar + atmospheric ν

➡ (3+1)-scheme will be discussed

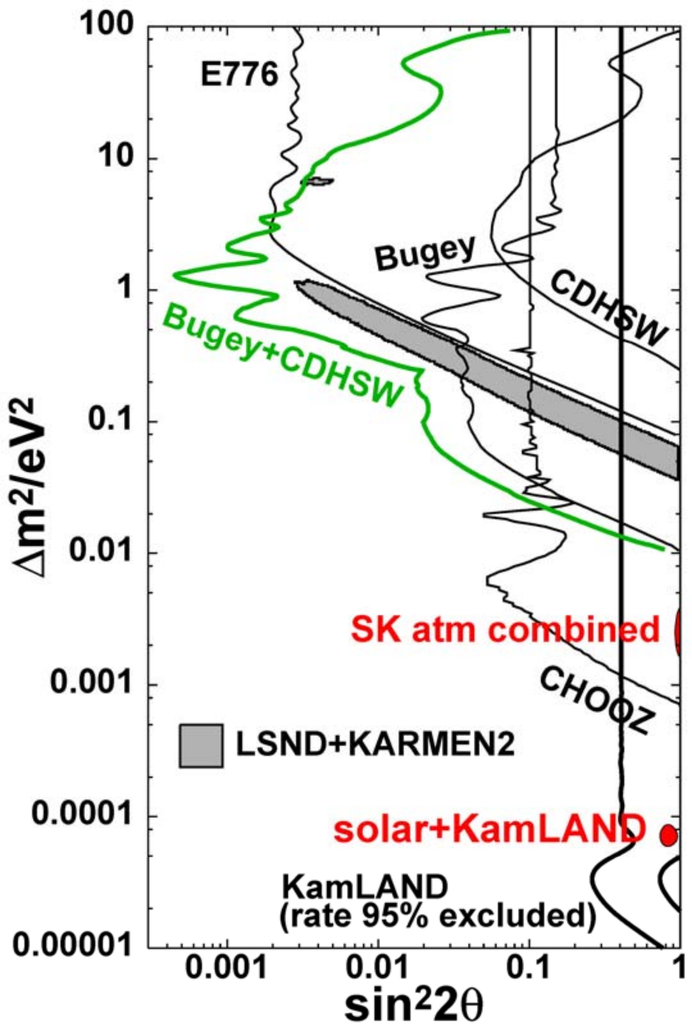
(3+1)-scheme

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2(\Delta m_{41}^2 L/4E)$$
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2(\Delta m_{41}^2 L/4E)$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu 4}|^2\sin^2(\Delta m_{41}^2 L/4E)$$

$$\sin^2 2\theta_{\mathrm{Bugey}} > 4|U_{e4}|^2(1 - |U_{e4}|^2) \cong 4|U_{e4}|^2$$

$$\sin^2 2\theta_{\mathrm{CDHSW}} > 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \cong 4|U_{\mu 4}|^2$$

$$\sin^2 2\theta_{\mathrm{LSND}} = 4|U_{e4}|^2|U_{\mu 4}|^2$$



$U_{\alpha 4}$: an element of 4x4 mxing matrix

$$\sin^2 2\theta_{\mathrm{LSND}}(\Delta m^2) < \frac{1}{4}\sin^2 2\theta_{\mathrm{Bugey}}(\Delta m^2)\sin^2 2\theta_{\mathrm{CDHSW}}(\Delta m^2)$$

must be satisfied (Okada-OY,'97; Bilenky-Giunti-Grimus, '98)

But there is no overlap between LSND and left side of Bugey+CDHSW

1.6 Reactor Anti-neutrino Anomaly

New prediction of the reactor ν flux

T. A. Mueller et al., PRC83, 054615 (2011)

→ **About +3% normalization shift with respect to old ν spectrum**

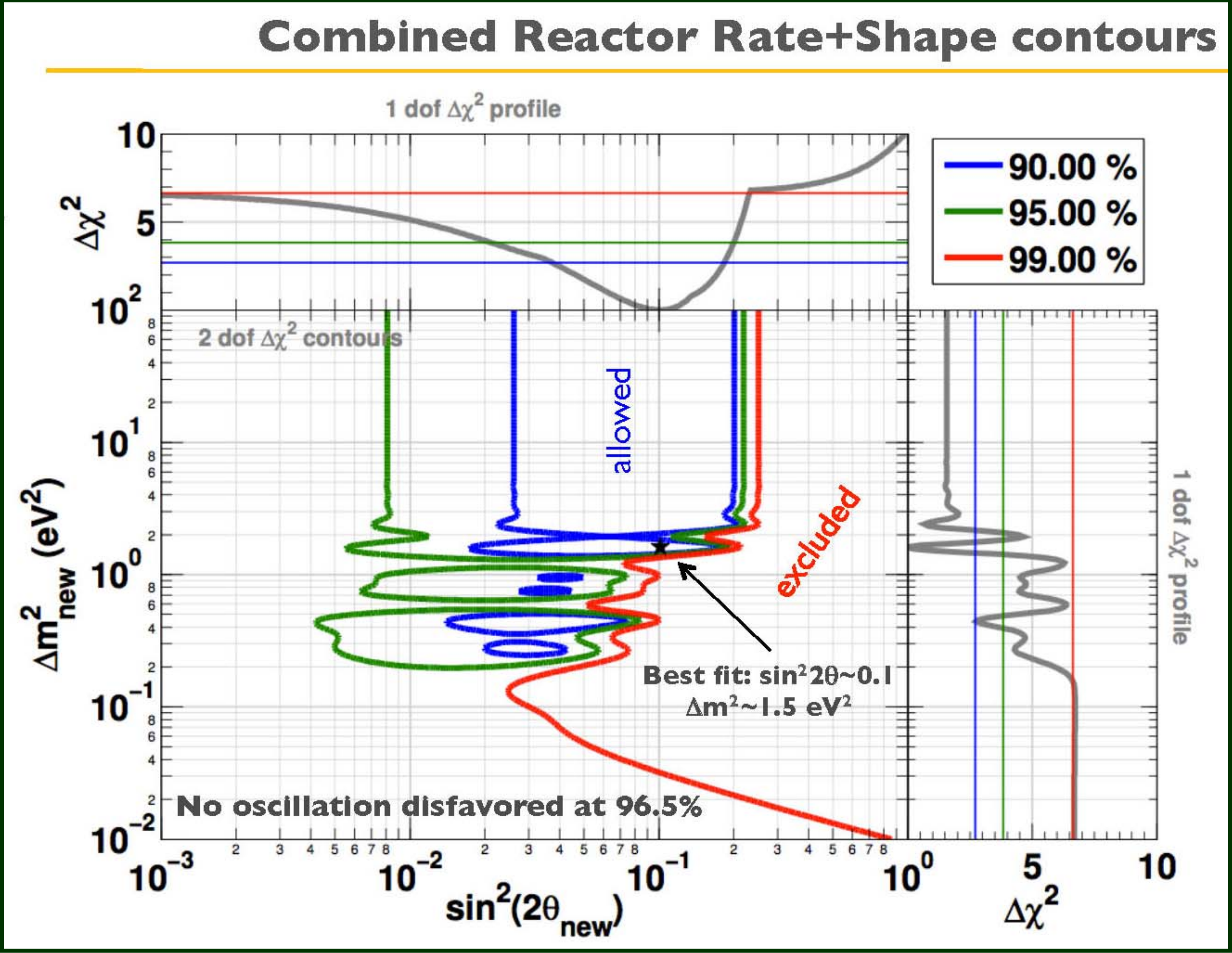
19 Experimental Results (L<100m) reexamined (ILL, Goesgen, Rovno, Krasnoyarsk, Bugey, Savannah River)

G. Mention et al, PRD83, 073006 (2011)

→ **An affirmative result for ν oscillation at $\Delta m^2 > 1 eV^2$**

Allowed region with the new ν flux prediction

G. Mention et al,PRD83, 073006 (2011)



New prediction of the reactor ν flux

→ (3+1)-scheme may fit to the data (LSND+MB+other short baseline expts.) better with new flux than before (with old flux).

→ It is important to confirm sterile ν oscillations

- A ten kilocurie scale anti-ν source (^{144}Ce, ^{106}Ru) $\bar{\nu}_e \rightarrow \bar{\nu}_e$
  M. Cribier et al., arXiv:1107.2335
- A proposal for a β-beam $\nu_e \rightarrow \nu_e$

  Agarwalla-Huber-Link, JHEP 1001:071,2010
- ν oscillation experiments at a reactor with a small core → Present work arXiv:1107.4766 [hep-ph] $\bar{\nu}_e \rightarrow \bar{\nu}_e$

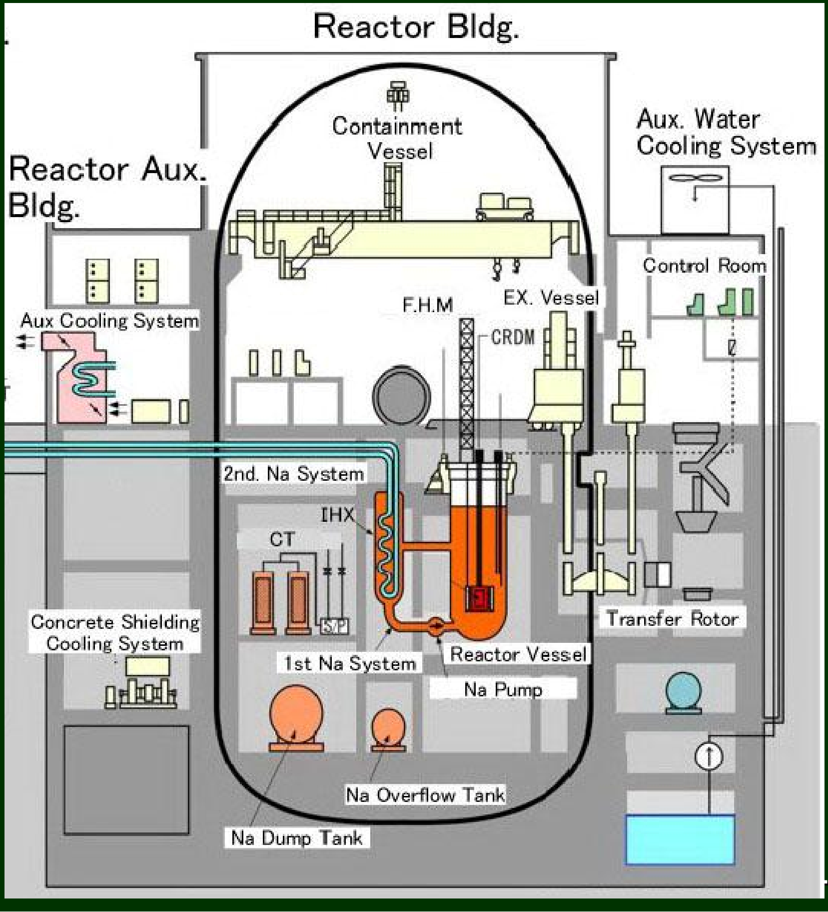
1.7 Thermal Neutron Reactors vs Fast Neutron Reactors

Fuels must be distant ⇨ the volume must be larger

	Kinetic energy of neutron	Moderator	Coolant	Power density
Thermal Neutron Reactor (w/ H_2O)	~0.02eV	H_2O	H_2O	~O(10MW/m^3)
Fast Neutron Reactor	~2MeV	None	Na	~O(100MW/m^3)

Fuels can be closer ⇨ the volume can be smaller

Joyo Fast Research Reactor



Operated by JAEA
P_{th}=140MW
Frequent On/Off

2. Analysis of a reactor neutrino oscillation experiment with one reactor & two detectors

$$\chi^2 = \min_{\alpha's}\left\{ \sum_{A=N,F}\sum_{i=1}^{n}\frac{1}{(t_i^A\sigma_i^A)^2}\left[m_i^A - t_i^A(1+\alpha+\alpha^A+\alpha_i) - \alpha_{\rm cal}^A t_i^A v_i^A\right]^2 + \sum_{A=N,F}\left[\left(\frac{\alpha^A}{\sigma_{\rm dB}}\right)^2 + \left(\frac{\alpha_{\rm cal}^A}{\sigma_{\rm cal}}\right)^2\right] + \sum_{i=1}^{n}\left(\frac{\alpha_i}{\sigma_{\rm Db}}\right)^2 + \left(\frac{\alpha}{\sigma_{\rm DB}}\right)^2 \right\}.$$

n=#(bin)=32

OY, arXiv: 1107.4766 [hep-ph]

m^A_i : Measured numbers of events

t^A_i : Theoretical prediction

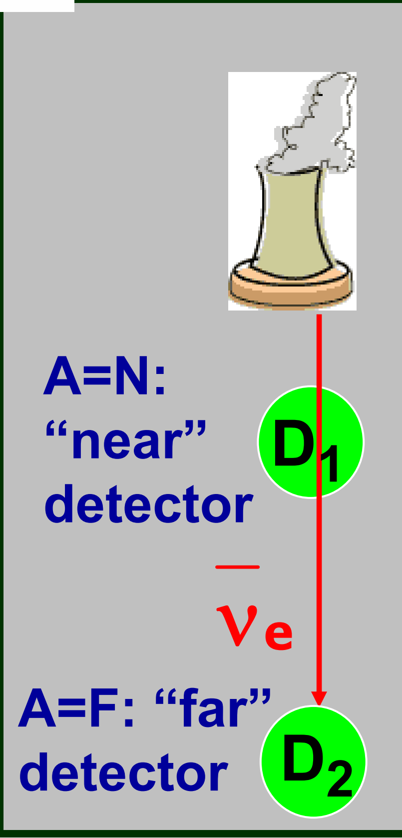
v^A_i : Variation due to energy calibration error

$$(t_i^A\sigma_i^A)^2 = t_i^A + \left(t_i^A\sigma_{\rm db}^A\right)^2$$

statistical errors

systematic errors

In the present case $\sigma_{stat} > \sigma_{sys}$:
statistical errors are more important



Assumed systematic errors

σ_{DB}: correlated wrt detectors, correlated wrt bins = 3%

σ_{Db} :correlated wrt detectors, uncorrelated wrt bins = 2%

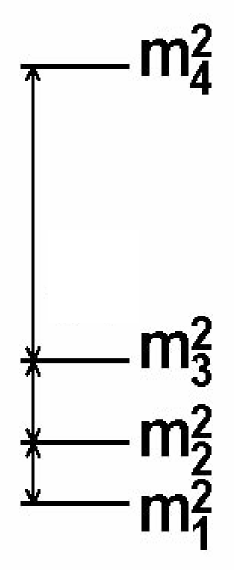
σ_{dB} :uncorrelated wrt detectors, correlated wrt bins = 0.5%

σ_{db} :uncorrelated wrt detectors, uncorrelated wrt bins = 0.5%

σ_{cal} :energy calibration error for each bin = 0.6%

Formula for oscillation probability

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{14}\, \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

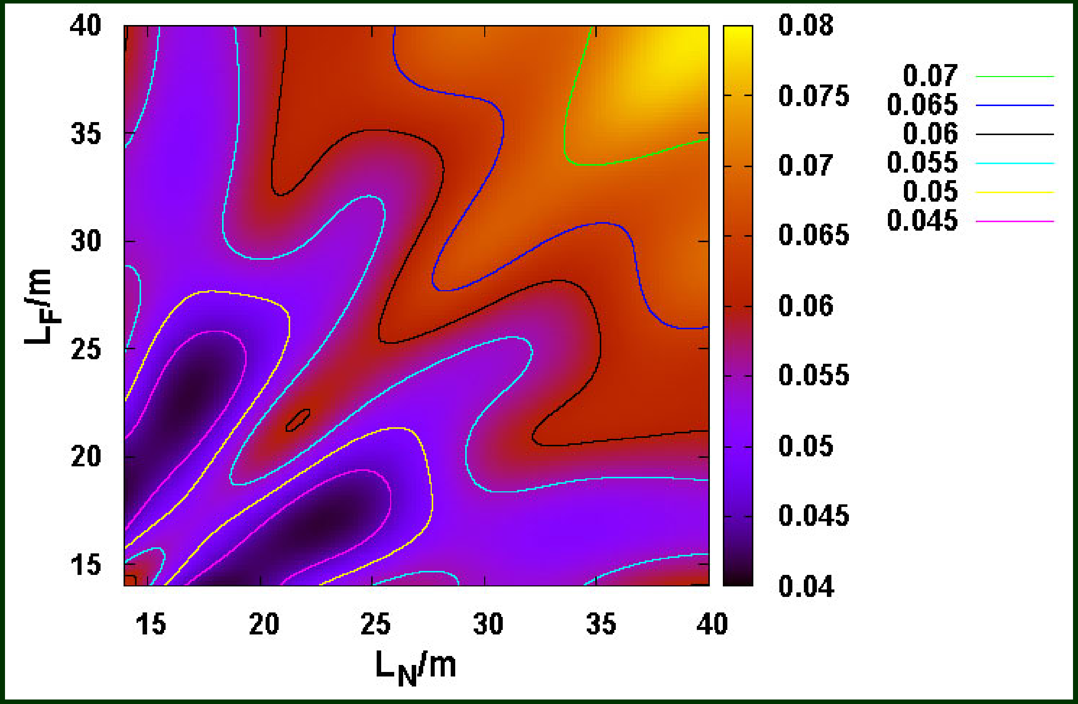


(1) Conventional reactors (thermal neutron reactors)

Assumed parameters (a la Bugey)

- Power: 2.8 GW
- Size of the core: Diameter=4m, Height=4m

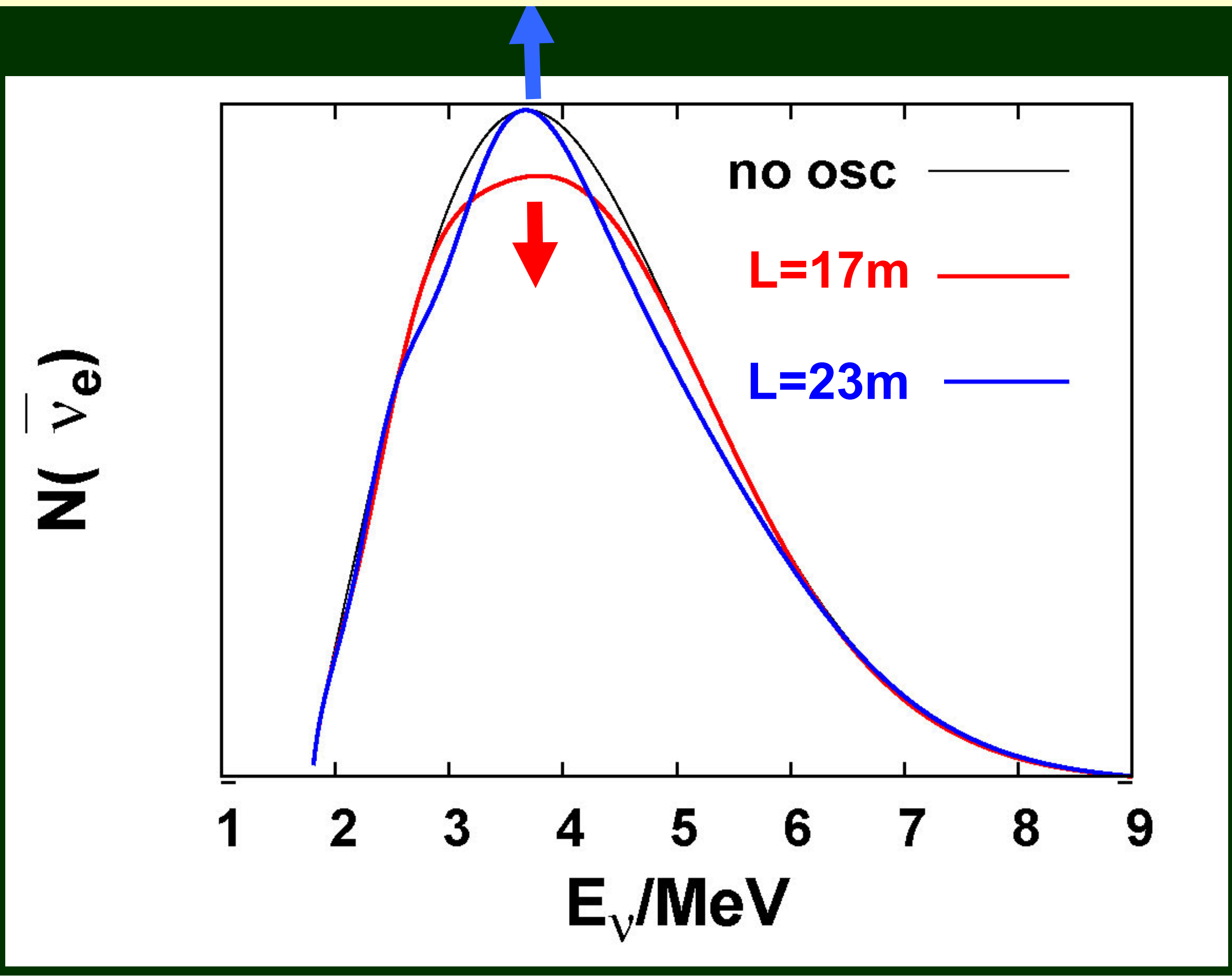
Optimization w.r.t. baseline lengths L_N, L_F for Δm^2=1eV^2



Optimized baseline lengths: L_N,=17m, L_F=23m

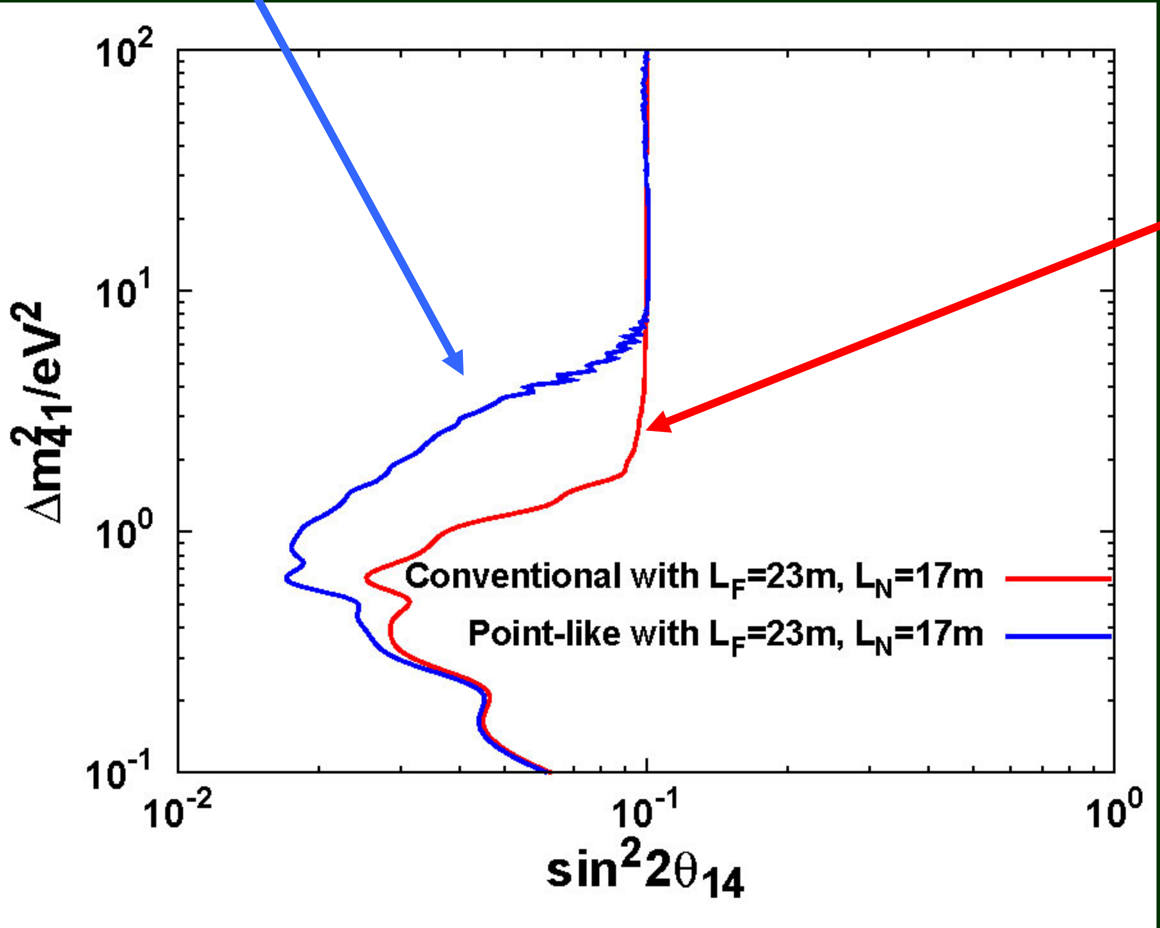
The role of a “near” detecor in the energy spectrum analysis for Δm^2=1eV^2

The difference at <E> ~ 4MeV is most significant for $L_{N,}$=17m L_F=23m



Sensitivity of Conventional reactors to $\sin^2 2\theta_{14}$ at L_N,=17m L_F=23m

The case of a hypothetical reactor with a point-like core → better sensitivity



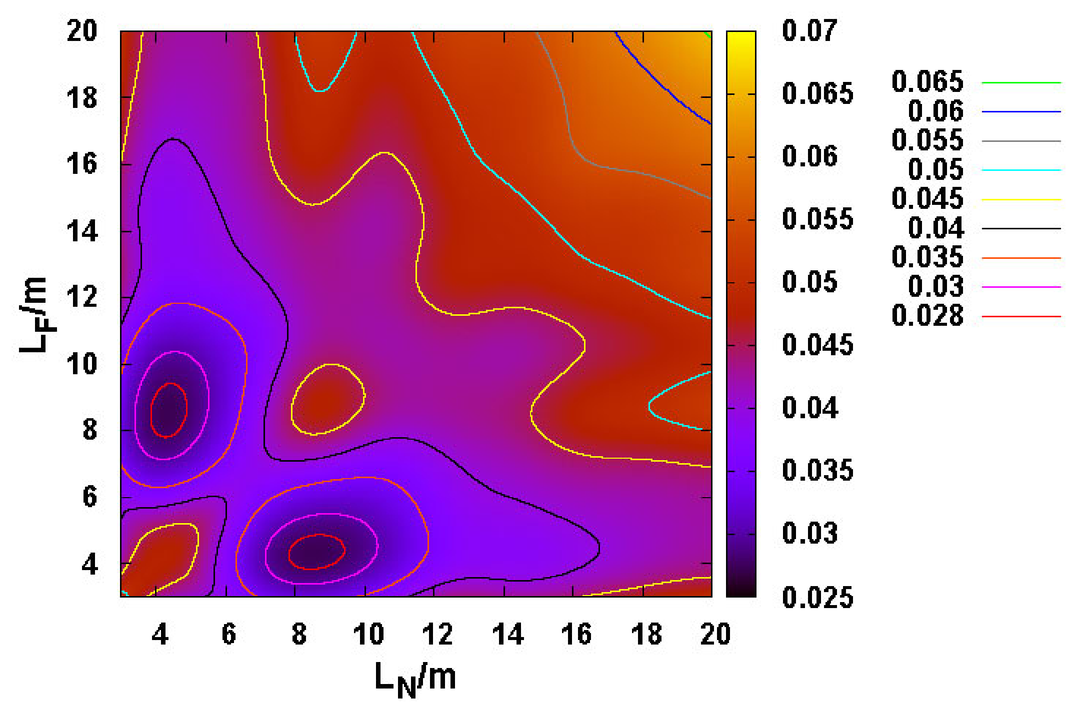
Finite size effect of a core → poor sensitivity for $\Delta m^2 \sim 2eV^2$

(2) A fast neutron reactor

Assumed parameters

- Power: 0.14 GW
- Size of the core: Diameter=0.8m, Height=0.5m

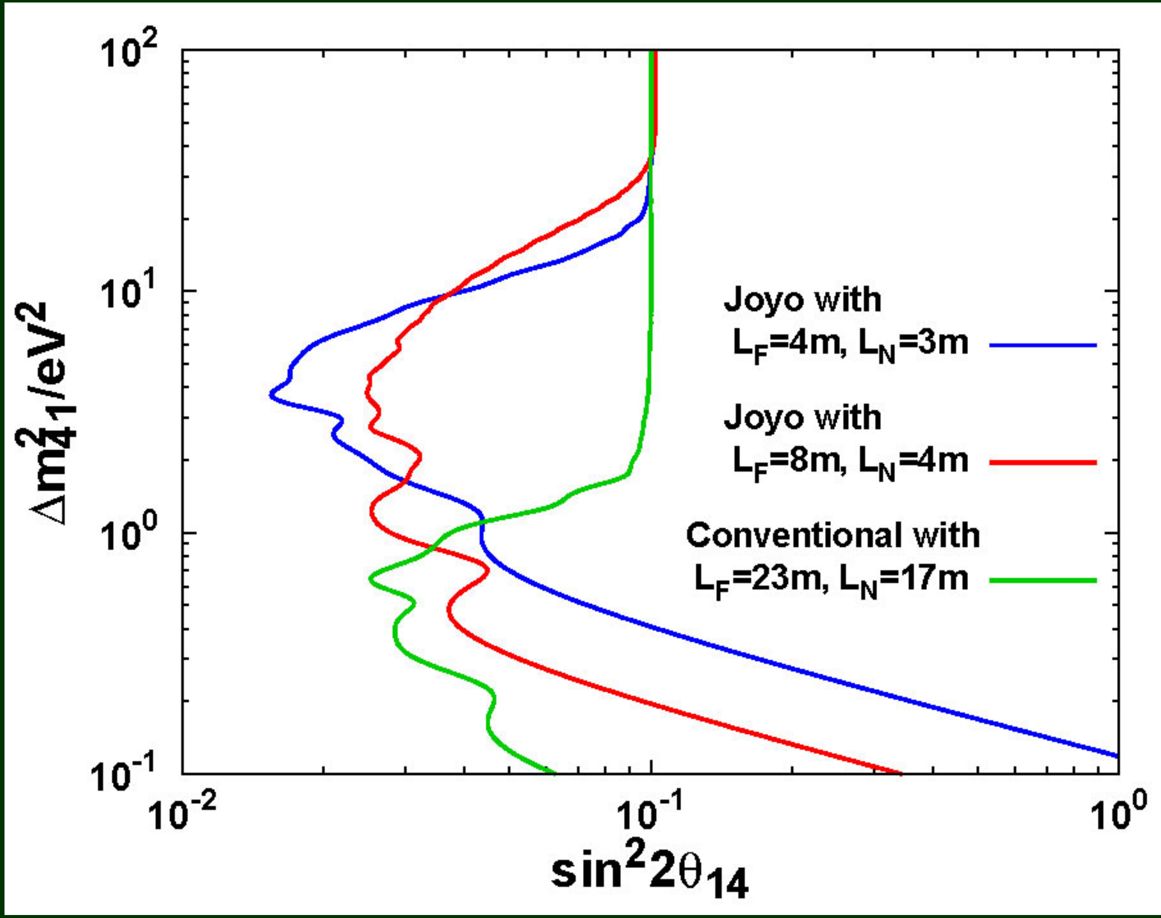
Optimization w.r.t. baseline lengths L_N, L_F for Δm^2=1eV^2



Optimized baseline lengths:
L_N,=4m
L_F=8m

Sensitivity of Joyo to $\sin^2 2\theta_{14}$ at L_N,=4m, L_F=8m

- Less power is compensated by closer distance
- A reactor with a small core prevents smearing effect



A Study of Reactor ν Monitoring at Experimental Fast Reactor JOYO

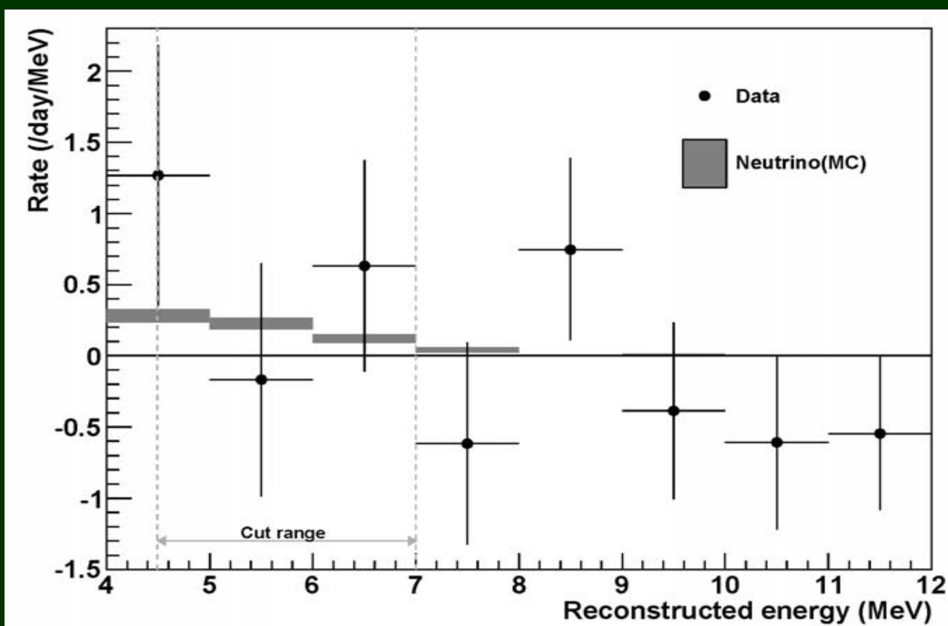
H.Furuta et al., arXiv:1108.2910v1 [hep-ex]

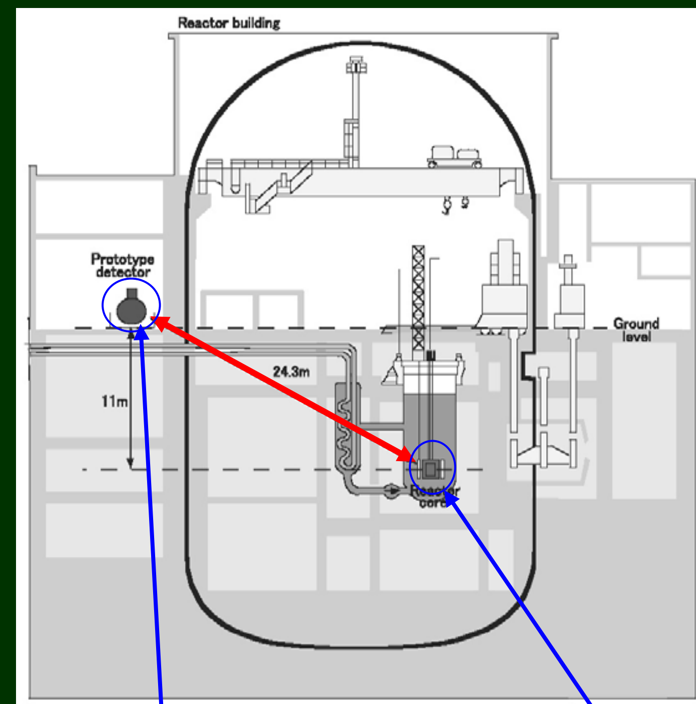
L=24.3m; about 150 νp → e^+n reactions/day

The measured ν event rate from reactor on-off comparison was 1.11±1.24(stat.)±0.46(syst.) events/day.

The statistical significance of the measurement was not enough.

Their motivation: to detect ν from a fast reactor (not motivated by ν_s)





Prototype detector

Reactor core

3. Summary (1)

- Because of the recent re-evaluation of the reactor ν flux, scenarios of sterile ν oscillations with $\Delta m^2 \sim O(1eV^2)$ are reviving.

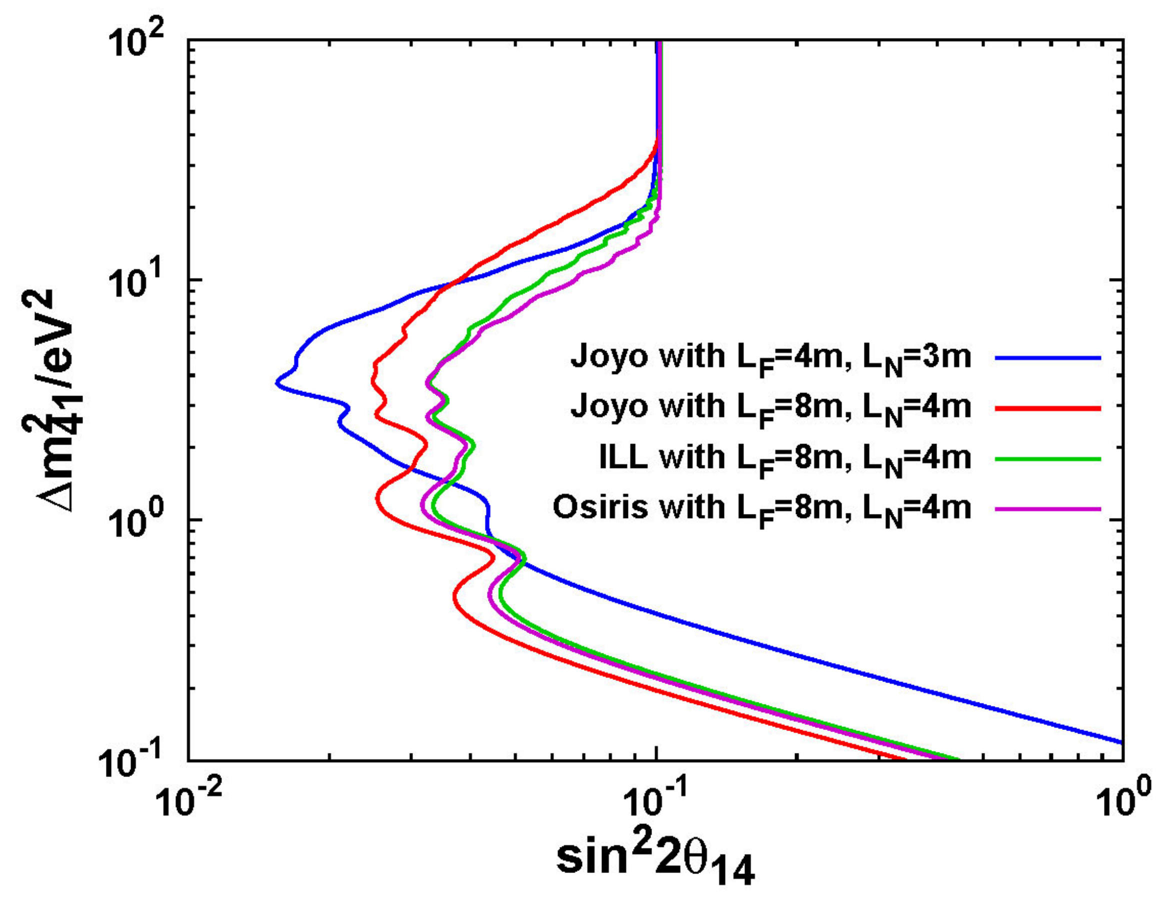
- To get a useful information from the spectrum analysis of reactor ν for $\Delta m^2 > 1eV^2$, a reactor with a small core is necessary to avoid the smearing effect.

- Fast neutron reactors have a small core in general, and measurements of ν from a fast neutron reactor Joyo may be able to offer a test of LSND/MiniBooNE.

- A preliminary experiment to measure ν from Joyo has been performed, but not sufficient significance of the signals was obtained. → More developments are needed.

3. Summary (2)

- There exist in France a couple of experimental thermal neutron reactors with a small core. → **Nucifer project**



ILL (Institut Laue-Langevin near Grenoble) research reactor
Power=58 MW,
Diameter=40cm,
Height=80cm

Osiris (in the French Atomic Energy Commission (CEA) centre at Saclay)
Power=70 MW,
Size=57cmx57cmx60cm

Great if the detectors are placed very closed to a reactor!

Backup slides

(2+2)-scheme

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 0$$

$$\nu_{atm} : \nu_\mu \to \nu_s (100\%)$$

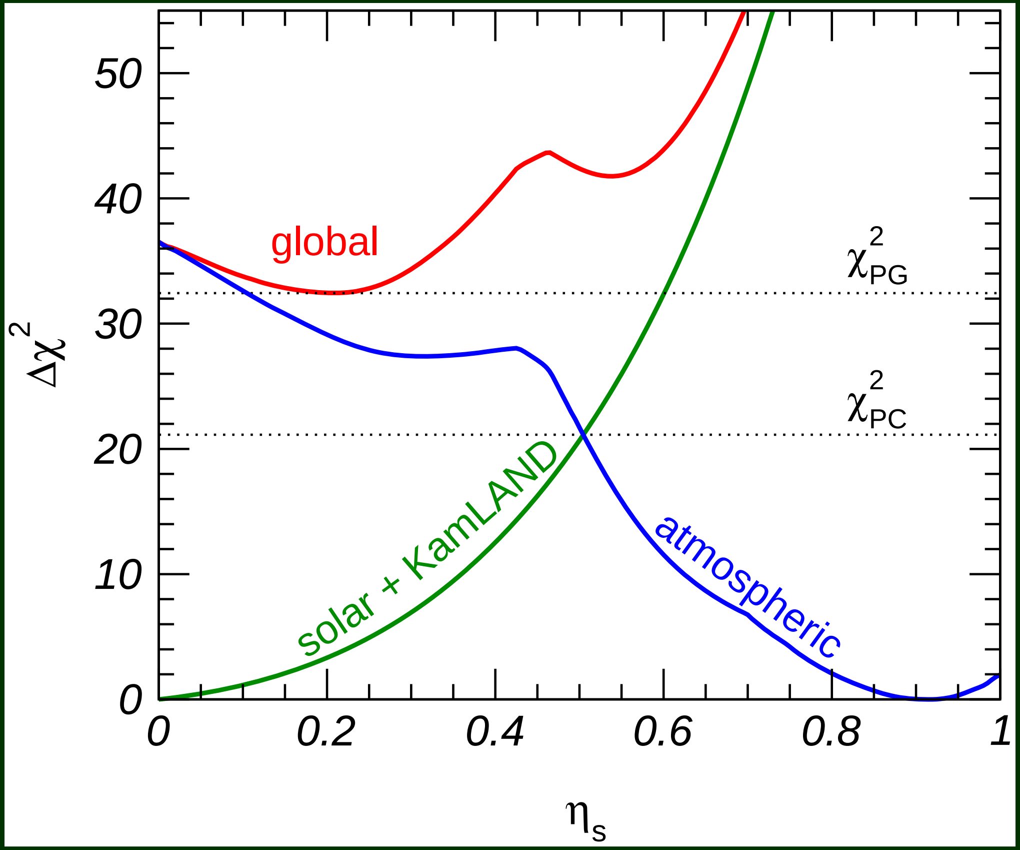
Strongly disfavored by SK ν_{atm} data

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 1$$

$$\nu_{sol} : \nu_e \to \nu_s (100\%)$$

Strongly disfavored by SNO ν_{sol} data

Maltoni et al., hep-ph/0405172



PC: parameter consistency test
PG: parameter goodness-of-fit test

For any value of $|U_{s1}|^2 + |U_{s2}|^2$, fit to sol+atm data is bad.

(3+2)-scheme

LSND($\bar{\nu}_\mu \to \bar{\nu}_e$): affirmative

MiniBOONE($\nu_\mu \to \nu_e$): negative

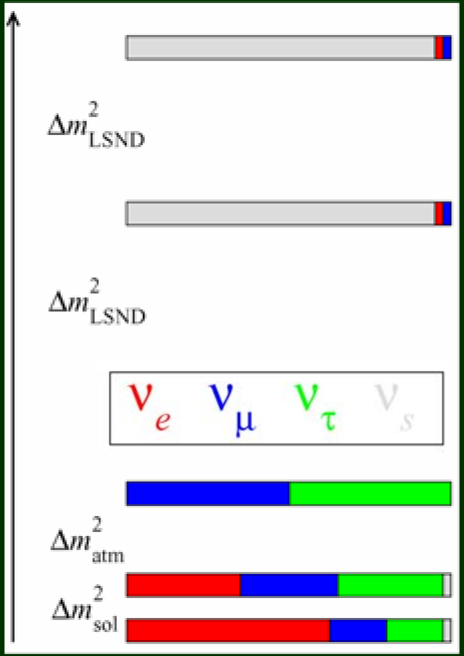
difference between ν & anti-ν may offer a promising fit

(3+2)-scheme w/ CP phase δ

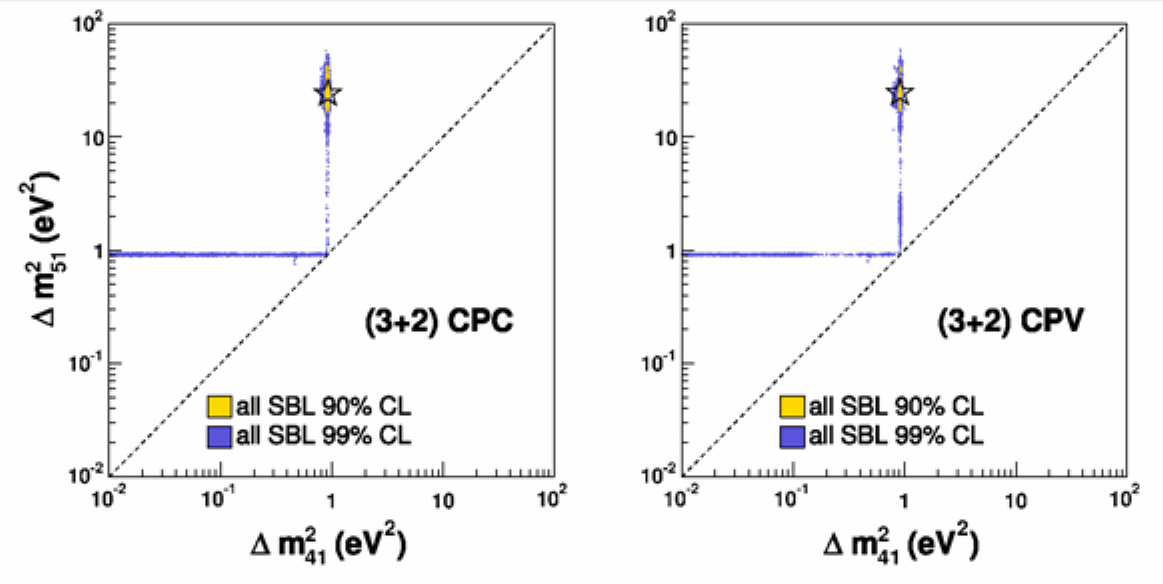
$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \\ &+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}, \qquad \delta \equiv \arg \left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5} \right).$$



(3+2)-scheme gives slightly better fit than (3+1) between MB & LSND



Karagiorgi, Djurcic, Conrad, Shaevitz, Sorel, Phys.Rev.D80:073001,2009.

Data Sets	PG (%)
APP vs. DIS	0.26
APP (no BNB-MB(ν)) vs. DIS (no CDHS + ATM)	36.4
APP (no BNB-MB(ν)) vs. DIS (no CDHS)	0.58
APP (no BNB-MB(ν)) vs. DIS (no ATM)	0.82
APP (no BNB-MB(ν)) vs. DIS	0.10
APP vs. DIS (no CDHS + ATM)	15.7
APP vs. DIS (no CDHS)	0.76
APP vs. DIS (no ATM)	1.4

TABLE VII: Comparison of compatibility between appearance (APP) and disappearance (DIS) experiments, within a (3+2) CP-violating scenario. The BNB-MB(ν) data set, CDHS data set, and atmospheric constraints (ATM) are removed from the fits as specified in order to establish the source of tension between appearance and disappearance experiments. See text for more details.

But tension also exists between (3+2)-scheme and disappearance data

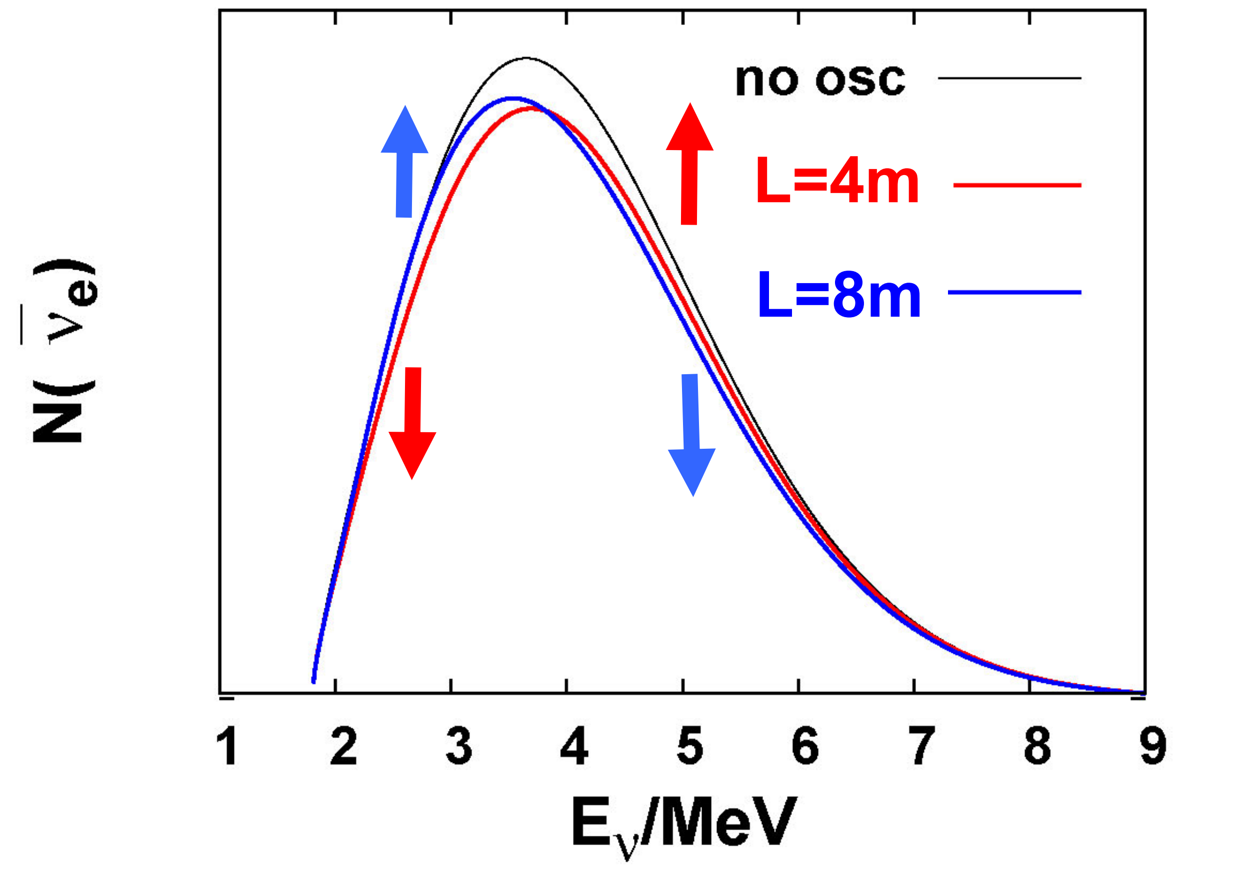
$$v_i^A = \lim_{\alpha_{\rm cal}^A \to 0} \frac{1}{\alpha_{\rm cal}^A t_i^A} \left[\frac{N_p T}{4\pi L_A^2} \int dE \int_{(1+\alpha_{\rm cal}^A)E_i}^{(1+\alpha_{\rm cal}^A)E_{i+1}} dE' \, R(E_e, E') \epsilon(E) F(E) \sigma(E) - t_i^A \right]$$

$$t_i^A \equiv \frac{N_p T}{4\pi L_A^2} \int dE \int_{E_i}^{E_{i+1}} dE' \, R(E_e, E') \epsilon(E) F(E) \sigma(E)$$

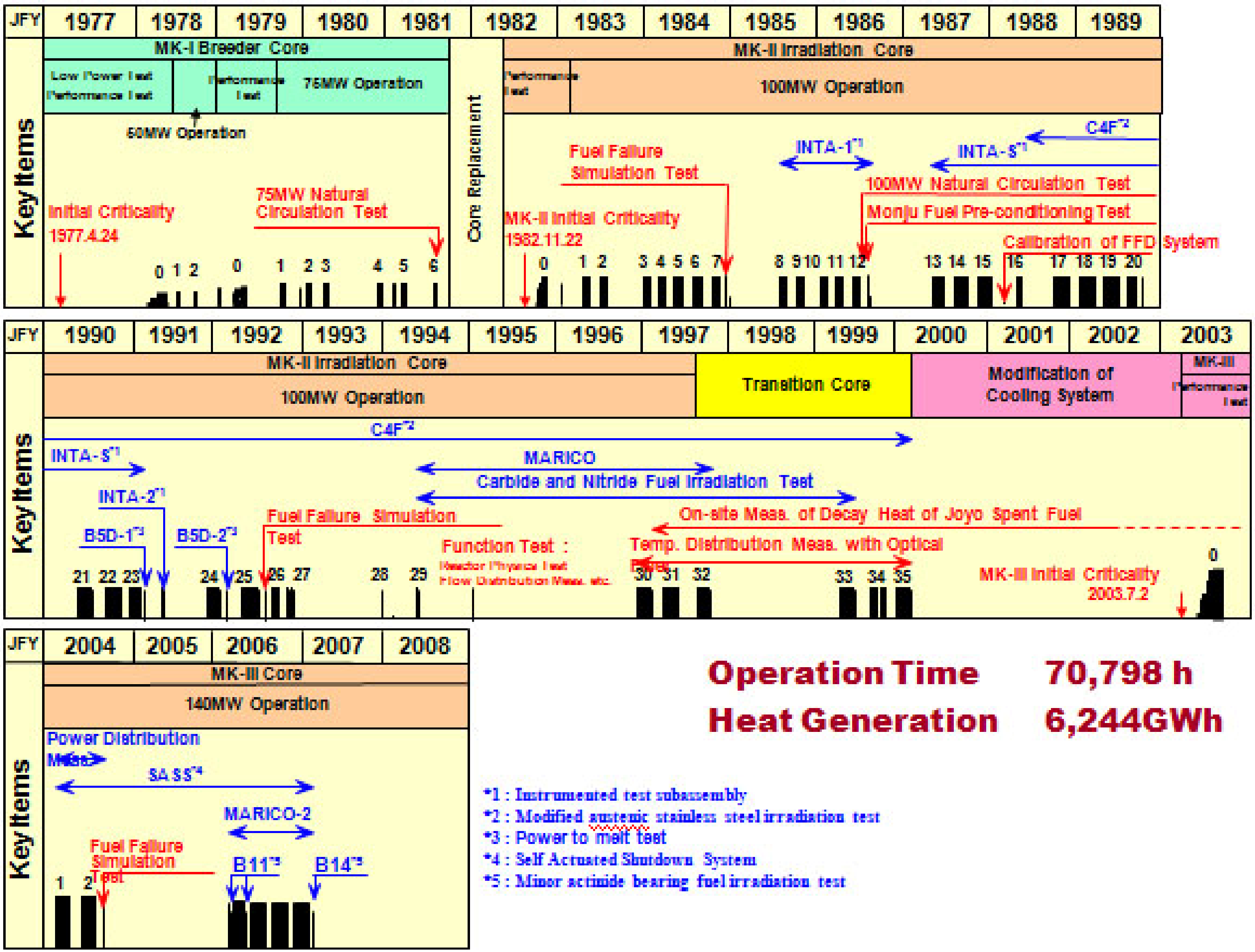
In Eqs. (4) and (5), N_p is the number of target protons in the detector, T denotes the exposure time, L_A is the baseline for the detector A, $F(E)$ is the flux of $\bar{\nu}_e$, and $\sigma(E)$ is the cross section of the inverse β decay $\bar{\nu}_e + p \to n + e^+$. E is the energy of the incident $\bar{\nu}_e$ and it is related to the positron energy E_e and the masses m_n, m_p of a neutron and a proton by $E = E_e + m_n - m_p = E_e + 1.3$ MeV. E' is the measured positron energy and we will assume that the energy resolution is given by $8\%/\sqrt{E}$, i.e., $R(E_e, E') = R(E - m_n + m_p, E')$ is a Gaussian function which describes the energy resolution and is given by $R(E_e, E') = (1/\sqrt{2\pi}\sigma) \exp[-(E_e - E')^2/2\sigma^2]$, where $\sigma = 0.08\sqrt{(E_e + m_e)/\text{MeV}} = 0.08\sqrt{(E - 0.8/\text{MeV})/\text{MeV}}$. Our strategy is to *assume no*

The role of a "near" detecor in the energy spectrum analysis for Δm^2=1eV^2

Asymmetry at <E> ~ (4∓1)MeV is most significant for L_N,=4m L_F=8m



Operation history of Joyo



Operation Time 70,798 h

Heat Generation 6,244GWh

*1 : Instrumented test subassembly
*2 : Modified austenic stainless steel irradiation test
*3 : Power to melt test
*4 : Self Actuated Shutdown System
*5 : Minor actinide bearing fuel irradiation test

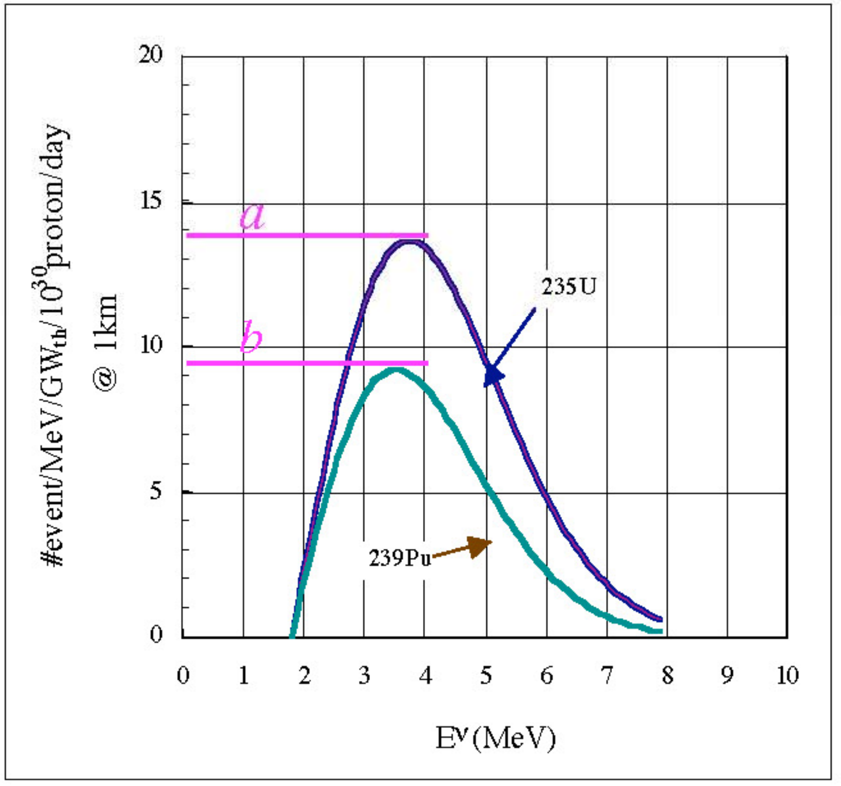
How to measure Pu/U ratio by ν

(simplified discussion)

$$\begin{cases} P_{th} = q(n_U + n_{Pu}) \\ N_\nu = a n_U + b n_{Pu} \end{cases}$$

$$\frac{n_{Pu}}{n_U} = \frac{1 - ar}{br - 1}; \quad r = \frac{P_{th}}{q N_\nu}$$

- n_U, n_{Pu}: Fission rate of U and Pu
- q: Energy release per fission (~200MeV)
- P_{th}: Thermal power
- N_ν: # of ν
- a, b: # of ν generation per U, Pu fission (a/b~1.5)



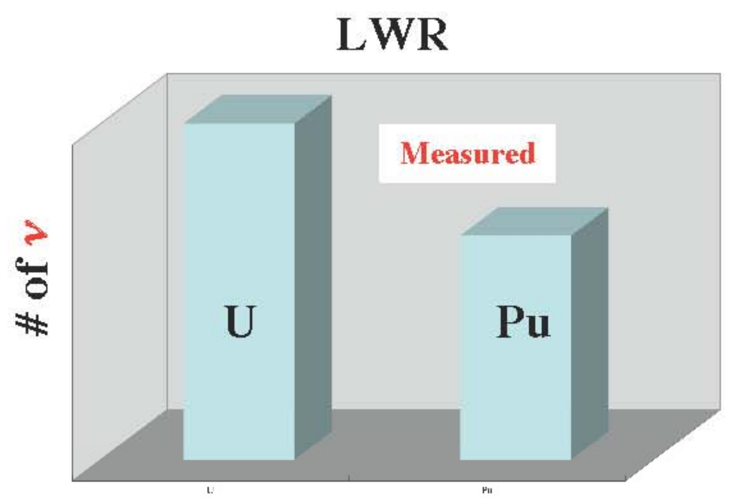
Why Joyo?

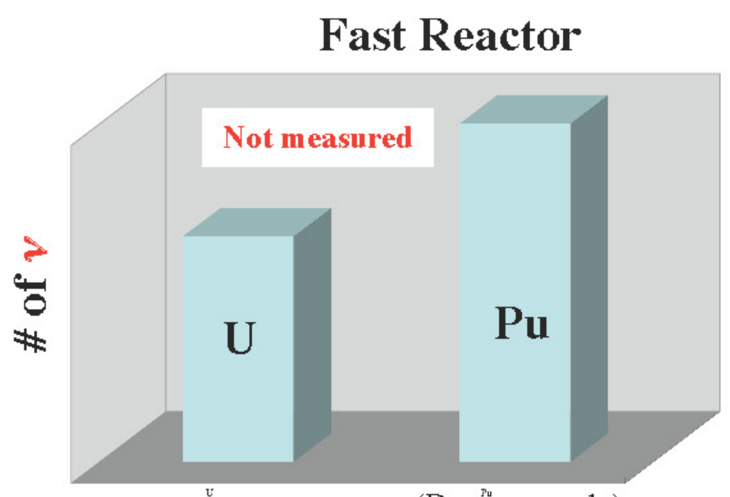
* Practical Reason:
Research Reactor is easier to access.

* Scientific Interest:
ν from fast reactor has not been measured.

* Technological Interest
ν spectum from U and Pu can be measured separately by combining with the data from Light Water Reactor

However, the thermal power is small (1/20 of San-Onofre) and it is challenging to detect ν at Joyo.

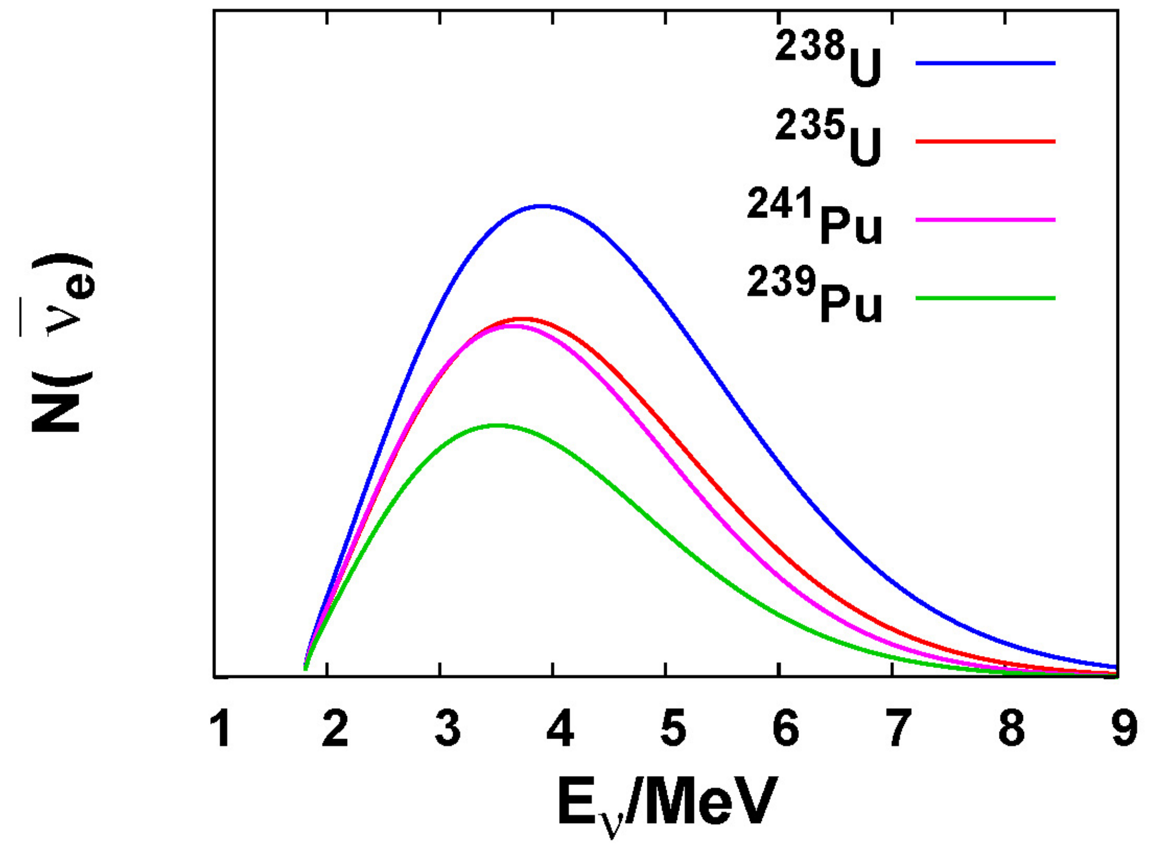




(Does not scale)

Composition of Thermal Neutron Reactor & Fast Neutron Reactor

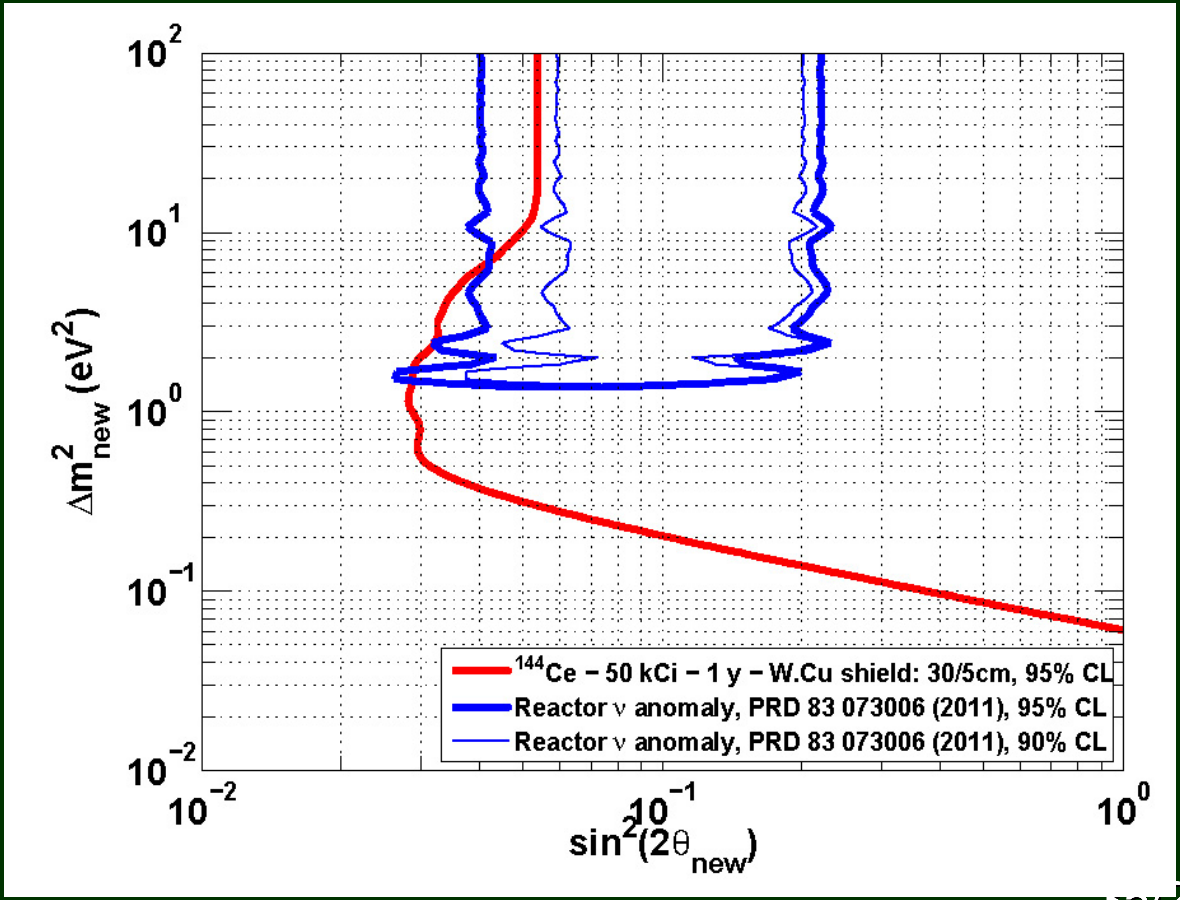
	^{235}U	^{239}Pu	^{238}U	^{241}Pu
Thermal Neutron Reactor (w/ H_2O)	53.8%	32.8%	7.8%	5.6%
Fast Neutron Reactor	37.1%	51.3%	7.3%	4.3%



A ten kilocurie scale anti-ν source (^{144}Ce, ^{106}Ru)

Cribier et al., arXiv:1107.2335v1 [hep-ex]

anti-ν source placed in a liquid scintillator detector (e.g., KamLAND)



Proposal of a β-beam

Agarwalla-Huber-Link,
JHEP 1001:071,2010