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], 1110.2579 [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

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

$$U\equiv\begin{pmatrix}U_{\mu 1} & U_{\mu 2}\\ U_{\tau 1} & U_{\tau 2}\end{pmatrix}$$

Probability of flavor conversion

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

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

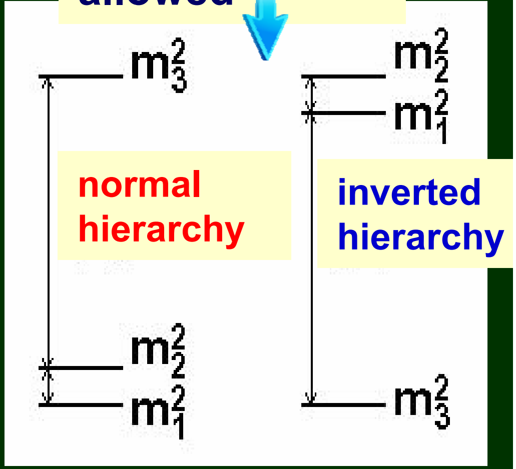
1.2 Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

Both hierarchy patterns are allowed



1.3 Information we have obtained so far

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

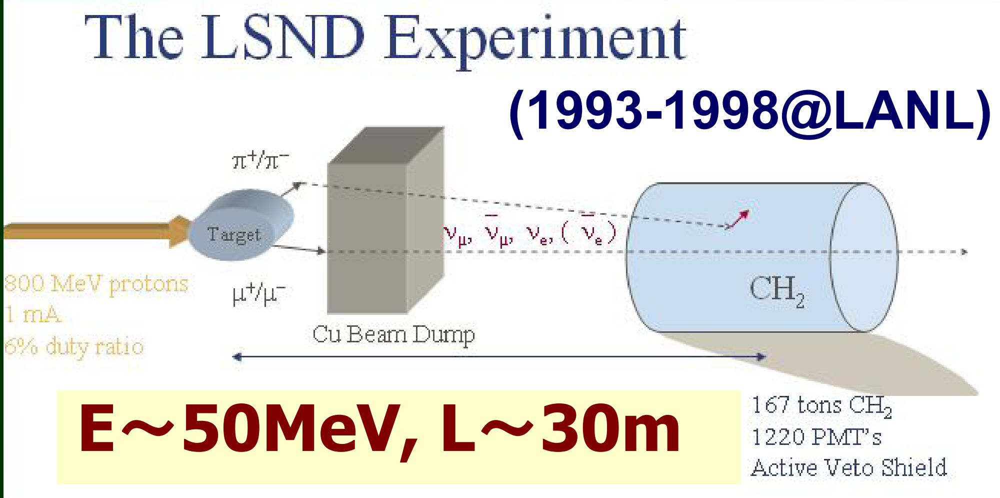
ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3}\,\mathrm{eV}^2$

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

New!!

1.4 Hints for beyond N_ν=3 oscillation

● **LNSD experiment** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



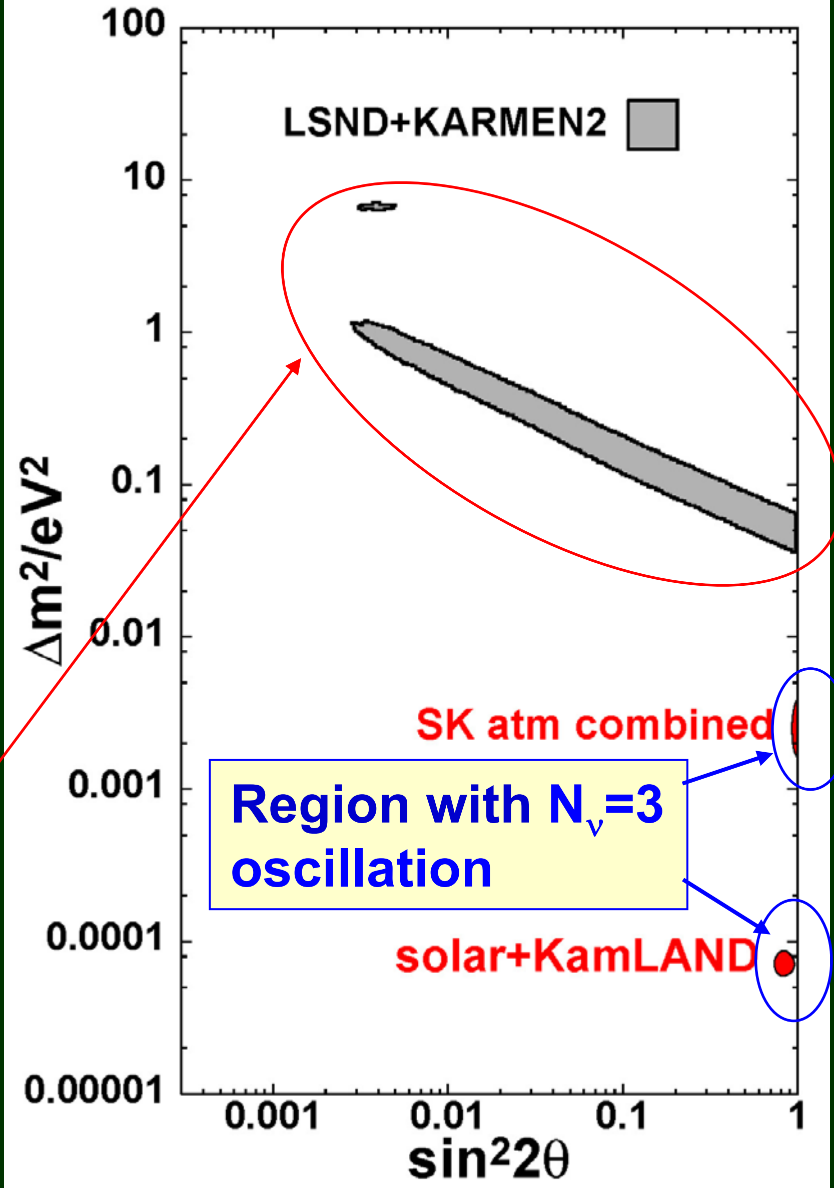
(1993-1998@LANL)

E～50MeV, L～30m

$$\Delta m^2 \cong O(1)eV^2 \quad ??$$

$$\sin^2 2\theta \cong O(10^{-2})$$

This region cannot be explained by N_ν=3 oscillation

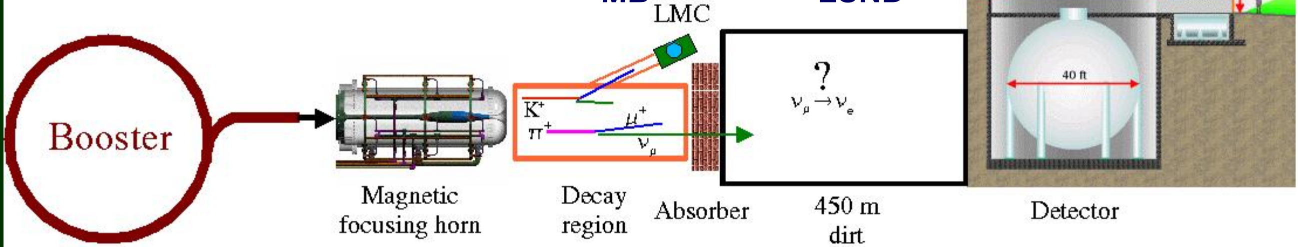


Region with N_ν=3 oscillation

● MiniBooNE (2002-, FNAL)

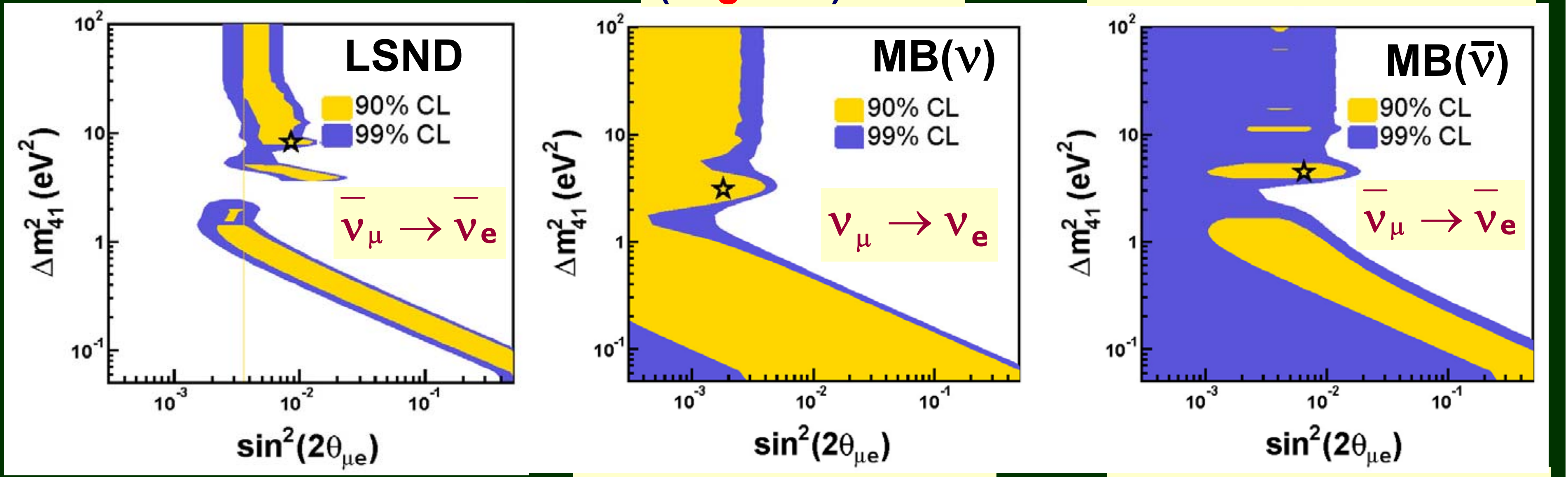
Check of the LSND data

E∼1GeV, L∼1km, $(L/E)_{MB}=(L/E)_{LSND}$



ν mode(2007)
(negative)

anti-ν mode(2010)
(affirmative)



1995
Is LSND correct？

2007
LSND was wrong!

2010
LSND was correct?

Note the time dependence of reputation of ν_s scenarios!

● Reactor ν anomaly

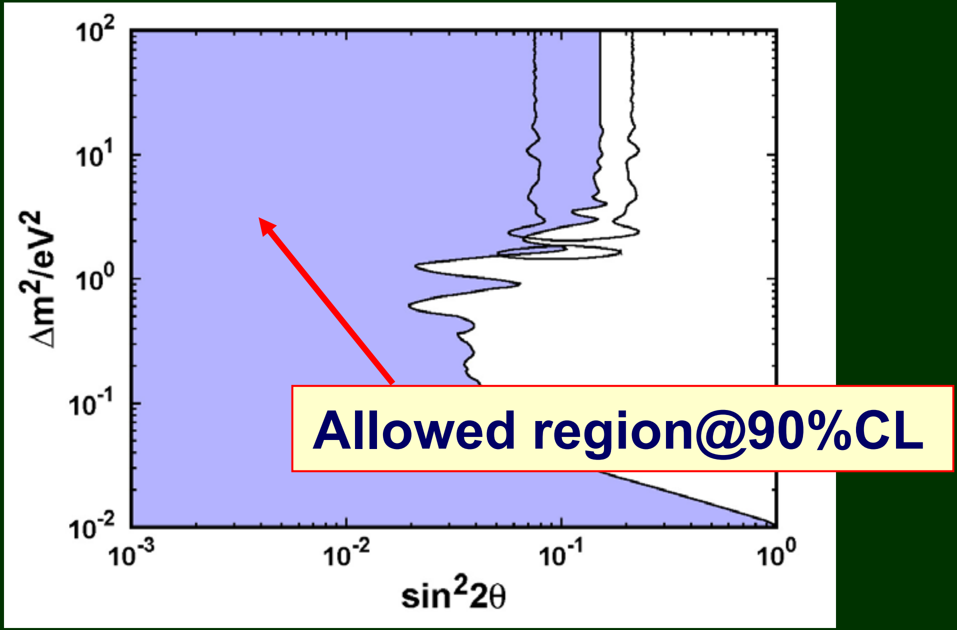
Mention et al, 2011

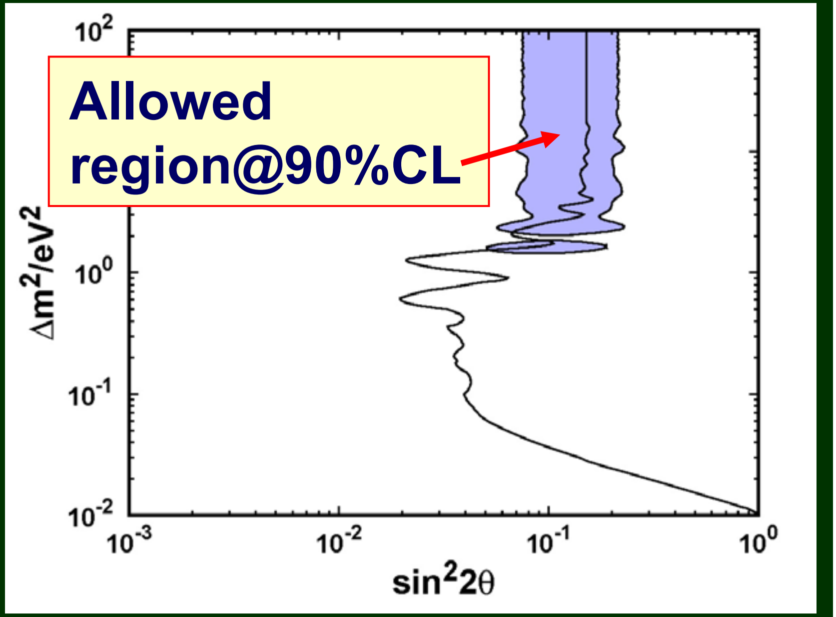
Recent reevaluation of reactor ν flux suggests affirmative interpretation of $\bar{\nu}_e \to \bar{\nu}_e$ oscillation

(new flux)= (old flux) x 1.03

Bugey(reactor $\bar{\nu}_e \to \bar{\nu}_e$):
Negative w/ old flux

Bugey(reactor)+etc:
Affirmative w/ new flux?



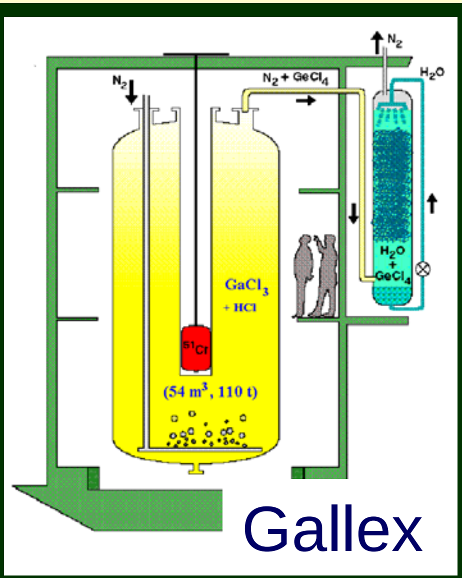


No ν oscillation for $\Delta m^2_{41} = O(1)\,\mathrm{eV}^2$

ν oscillation may exist for $\Delta m^2_{41} = O(1)\,\mathrm{eV}^2$

Gallium anomaly

Gallium radioactive source experiments

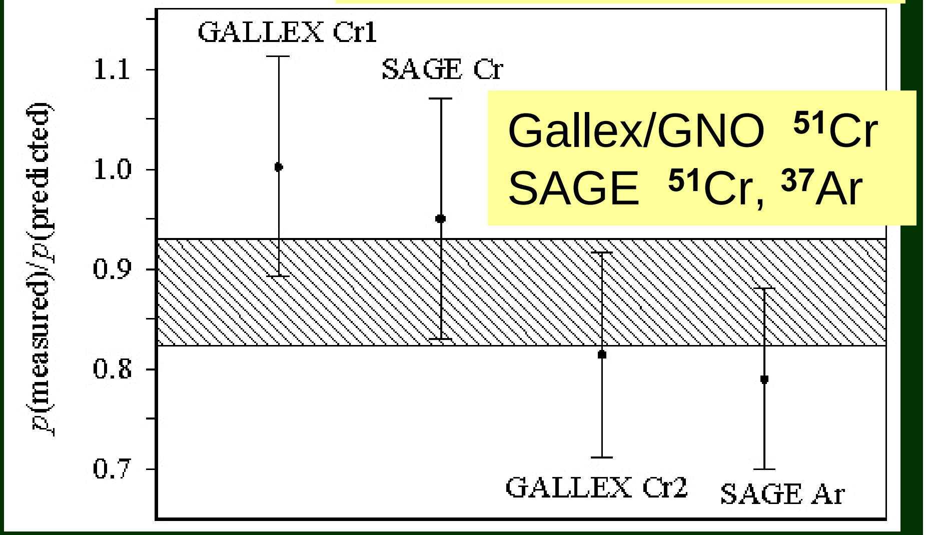


$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.88 \pm 0.05(1\sigma)$$

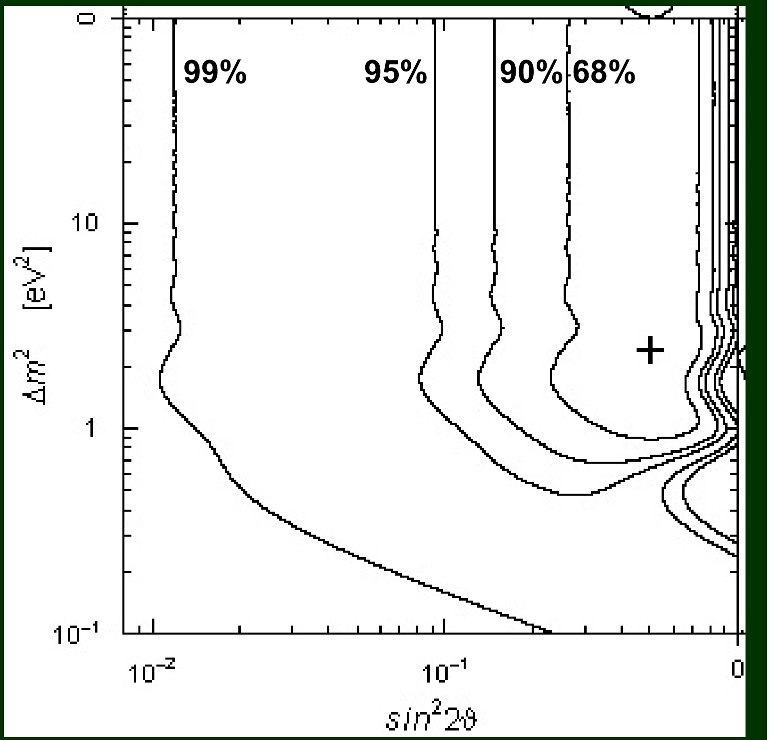
Giunti-Laveder, 1006.3244v3 [hep-ph]

Results of the Ga radioactive source calibration experiments may be interpreted as an indication of the disappearance of ν_e due to active-sterile oscillations.

SAGE, nucl-ex/0512041



Gallex/GNO ^{51}Cr
SAGE ^{51}Cr, ^{37}Ar



1.5 N_ν=4 schemes

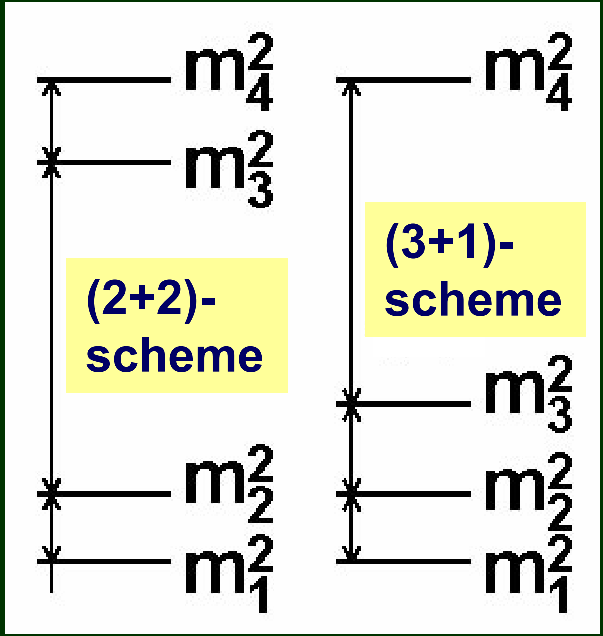
Because of the hierarchy: $\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{LSND}$

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

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

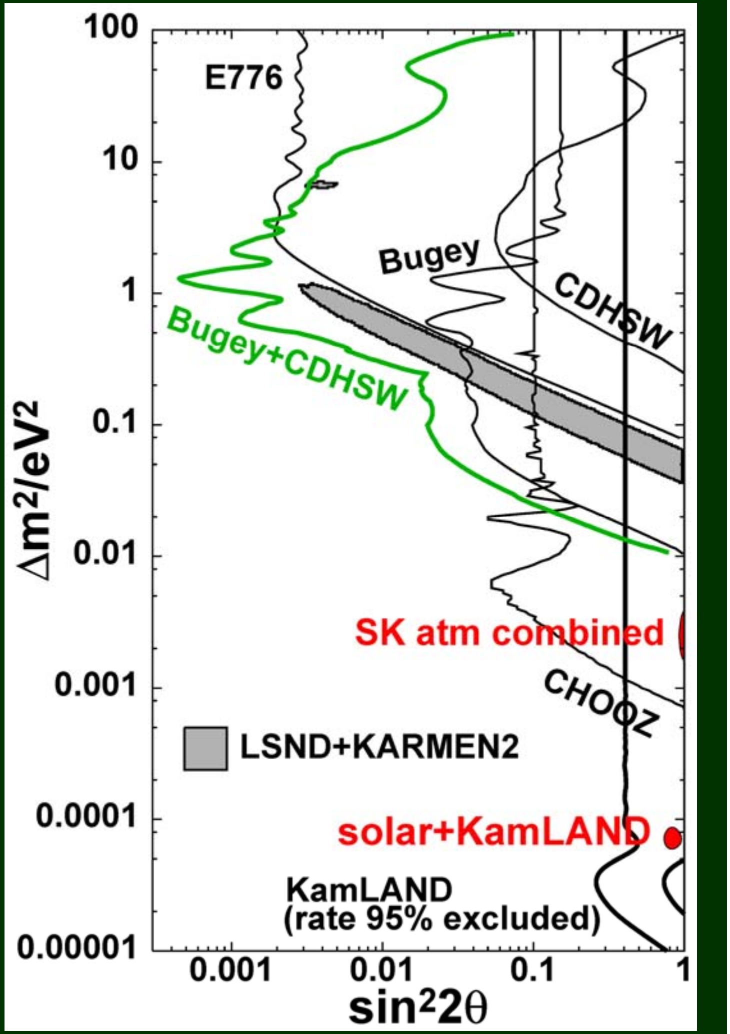
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$

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

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

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

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



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

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

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

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

reactor ν anomaly + gallium anomaly

→ (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] $\bar{\nu}_e \rightarrow \bar{\nu}_e$

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

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

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

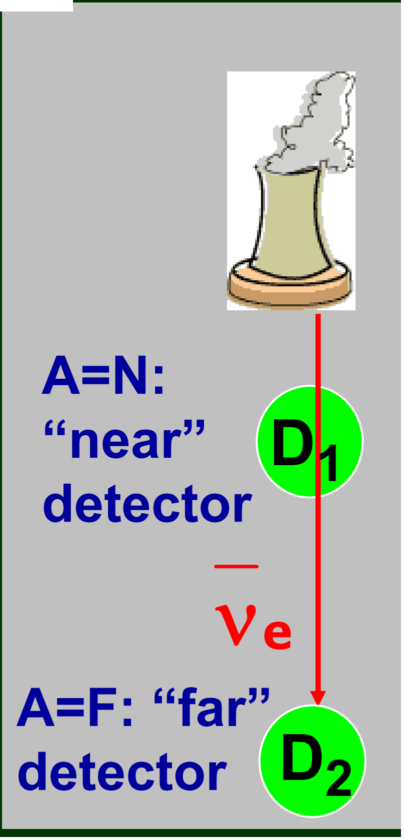
$$(t_i^A \sigma_i^A)^2 = \boxed{t_i^A} + \boxed{\left(t_i^A \sigma_{\rm db}^A \right)^2}$$

statistical errors

systematic errors

In the present case $\sigma_{\rm stat} > \sigma_{\rm sys}$:

statistical errors are more important



A=N: “near” detector

D$_1$

$\bar{\nu}_e$

A=F: “far” detector

D$_2$

Assumed systematic errors: those of Bugey experiment

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

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

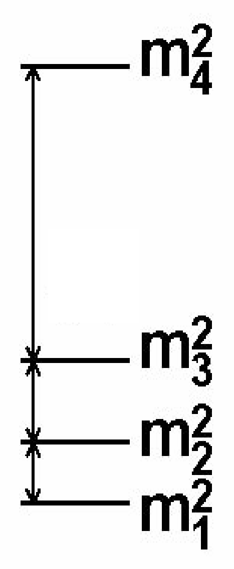
σ_{dB} :uncorrelated wrt detectors, correlated wrt bins = 0.5%

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

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

Formula for oscillation probability

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



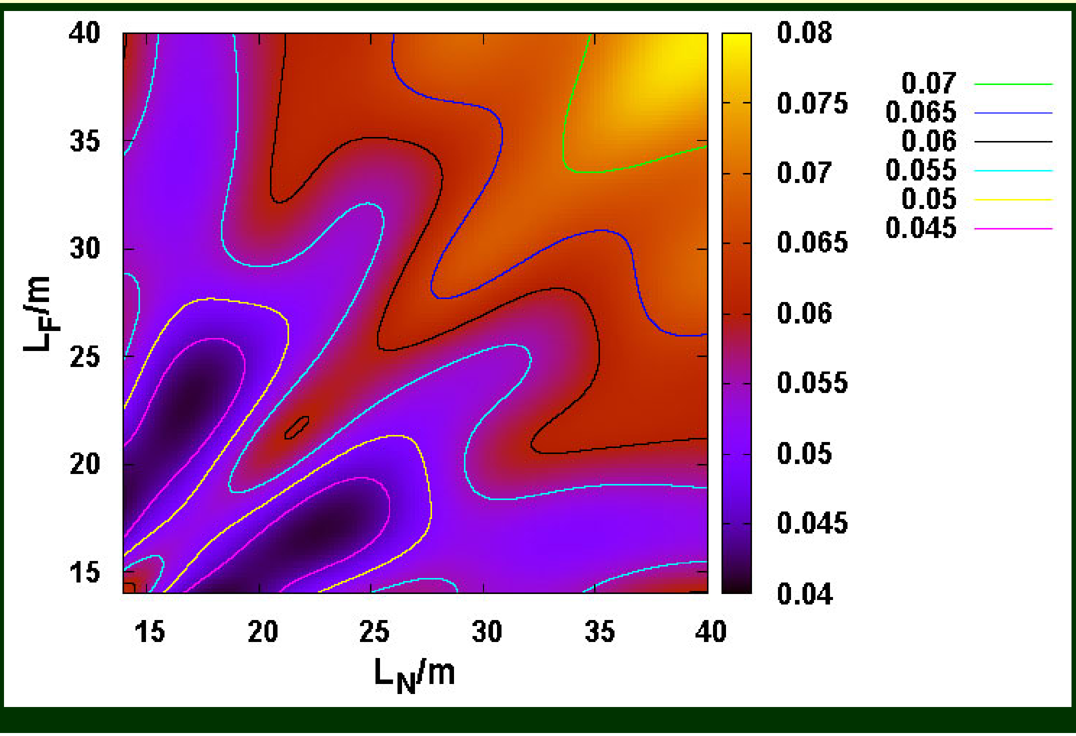
(1) Commercial reactors

Assumed parameters (a la Bugey)

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

Power density~50MW/m^3

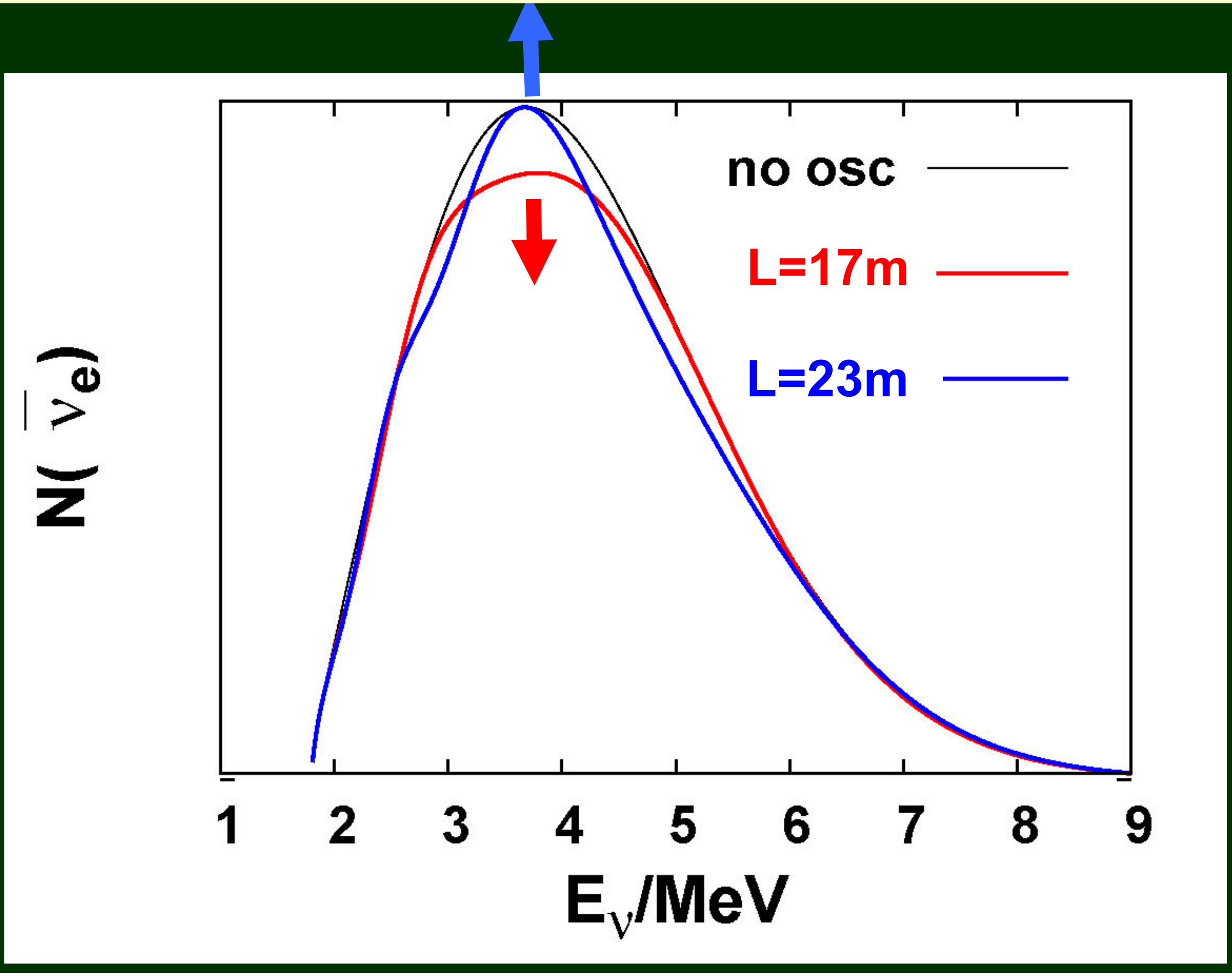
Optimization w.r.t. baseline lengths L_N, L_F for Δm^2=1eV^2



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

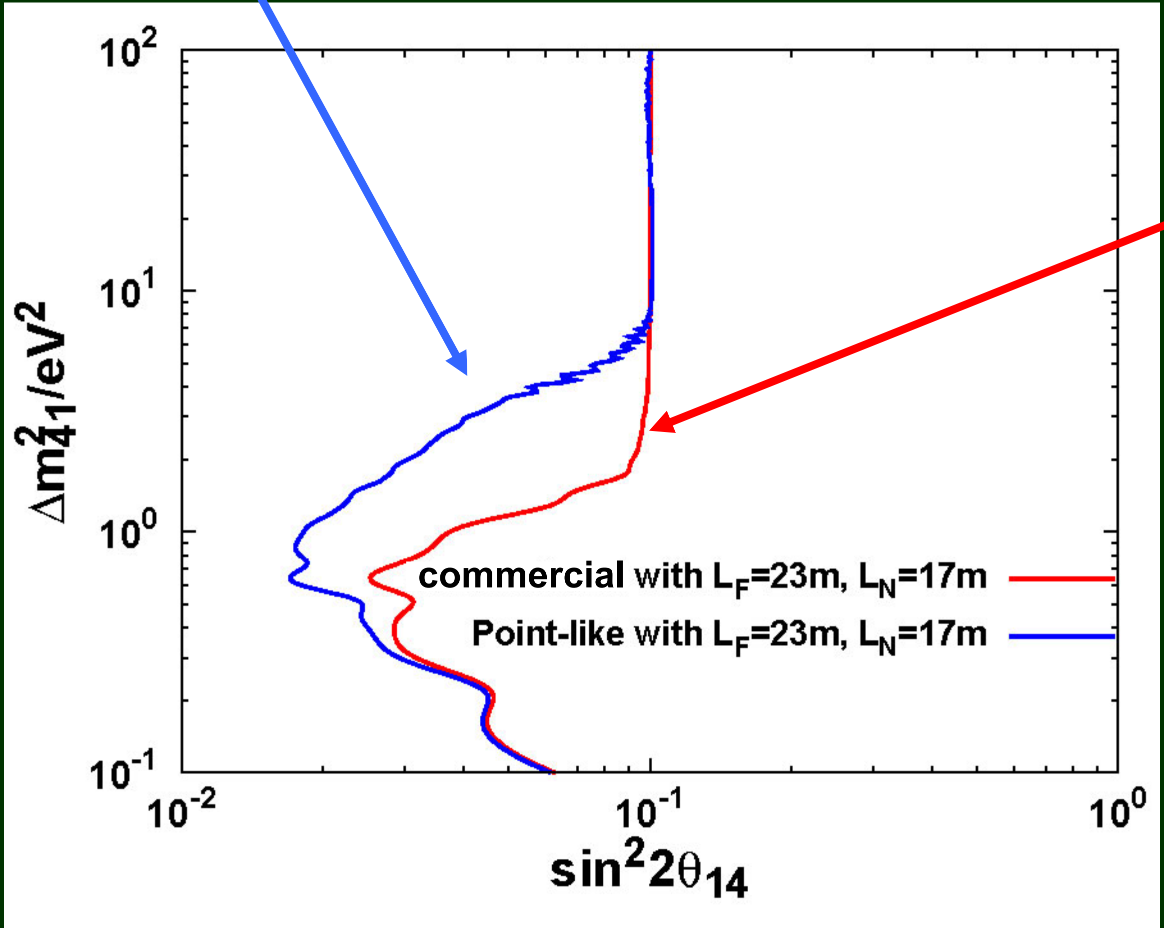
The role of a “near” detecor in the energy spectrum analysis for Δm^2=1eV^2

The difference at <E> ~ 4MeV is most significant for L_N,=17m L_F=23m



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

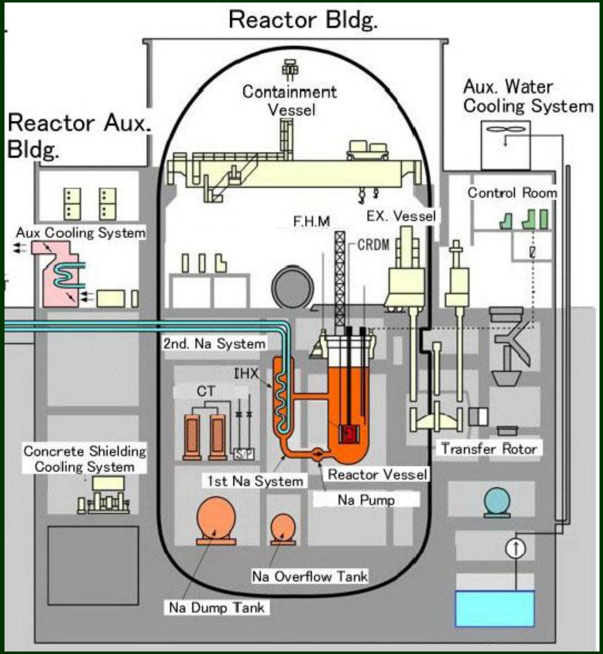
The case of a hypothetical reactor with a **point-like** core → better sensitivity



Finite size effect of a core → poor sensitivity for Δm^2~2eV^2

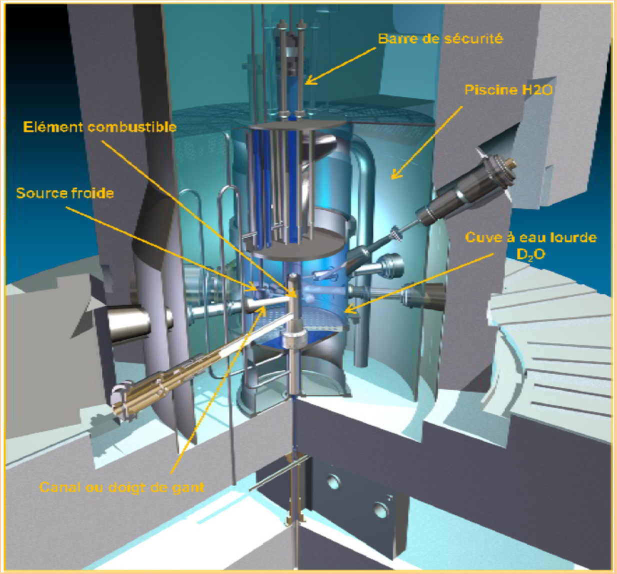
(2) Research Reactors with a small core

● **Joyo (Ibaraki, Japan): D=0.8m, h=0.5m, P_{th}=140MW**

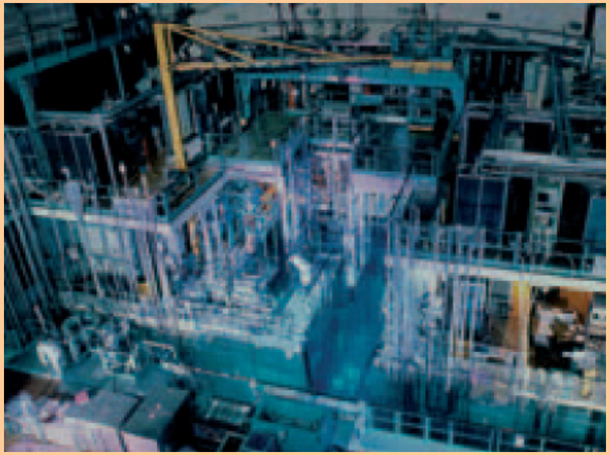


Nucifer project

●**ILL reactor (Grenoble, France):D=0.4m, h=0.8m, P_{th}=58MW**



●**Osiris reactor (Saclay, France): 0.57m×0.57m×0.6m, P_{th}=70MW**



Power density~500MW/m^3

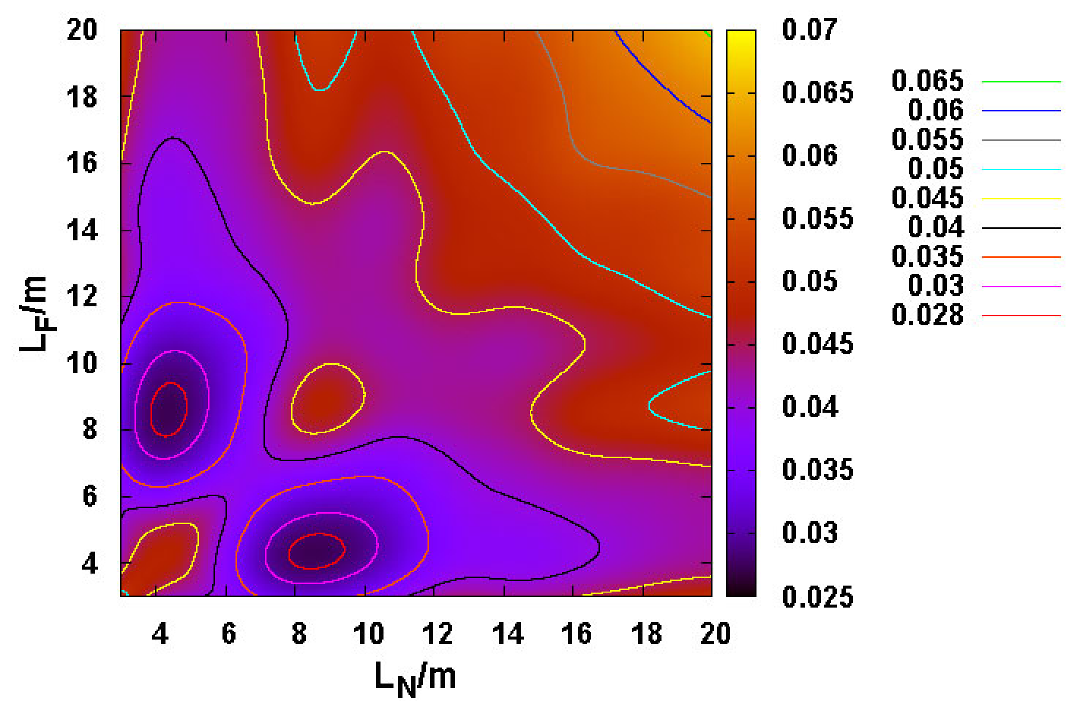
cf. ~50MW/m^3 for commercial reactors

● Joyo (A fast neutron reactor)

Assumed parameters

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

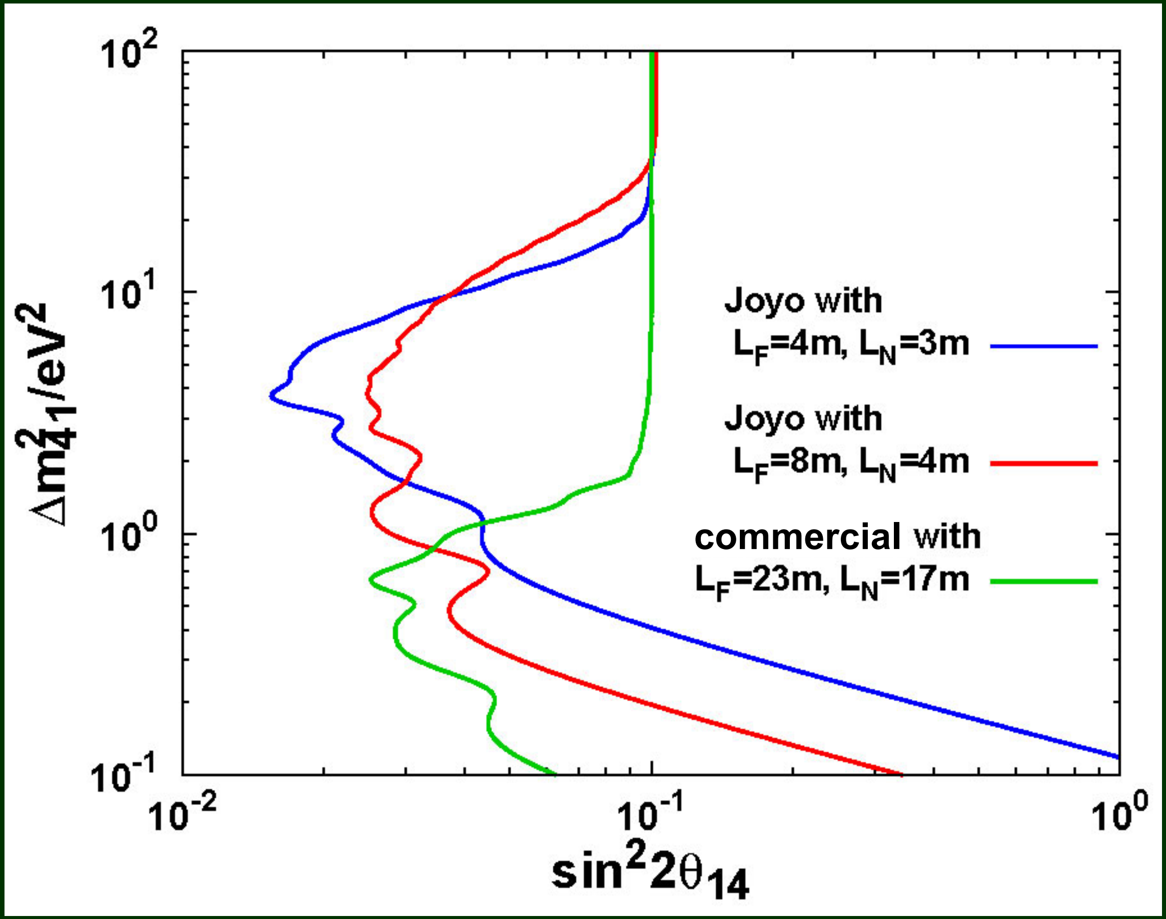
Optimization w.r.t. baseline lengths L_N, L_F for Δm^2=1eV^2



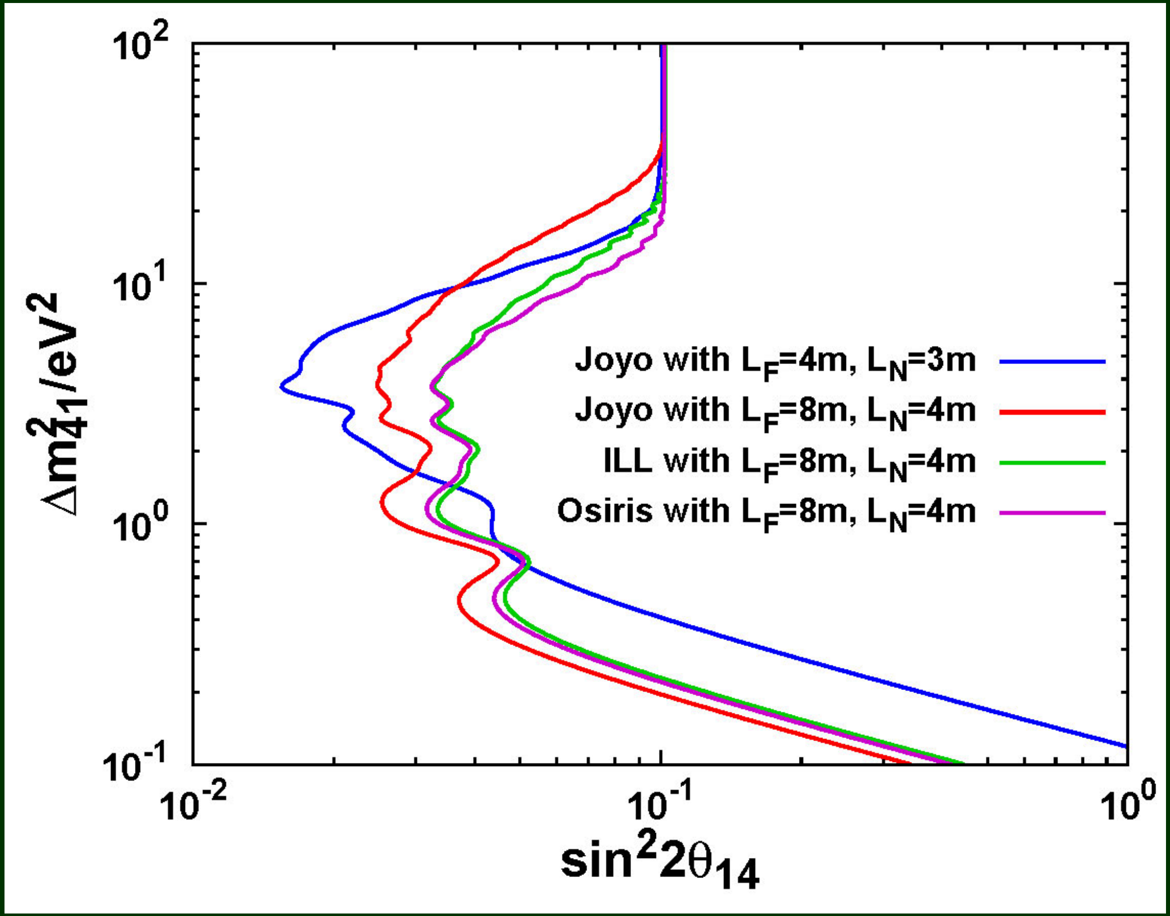
Optimized baseline lengths:
L_N,=4m
L_F=8m

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



(2-2) ILL & Osiris



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

In the nucifer project, optimization w.r.t baselines is not planned. → Great if the detectors are placed very close to a reactor!

3. Summary

- Because of the recent re-evaluation of the reactor ν flux, scenarios of sterile ν oscillations with Δm^2~O(1eV^2) are reviving.

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

- Research reactors have a small core in general, and measurements of ν from those may be able to offer a test of LSND/MiniBooNE.

Backup slides

(2+2)-scheme

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

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

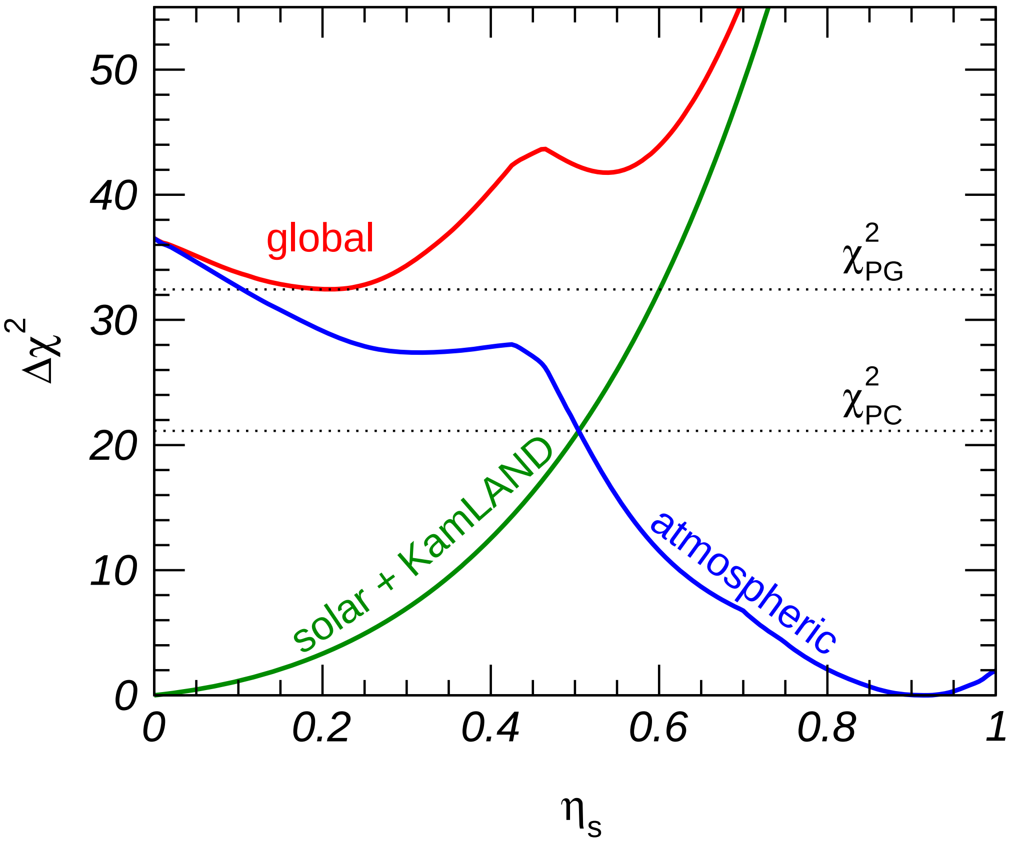
Strongly disfavored by SK ν_{atm} data

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

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

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.

MiniBooNE's summary

→ The data is still confusing

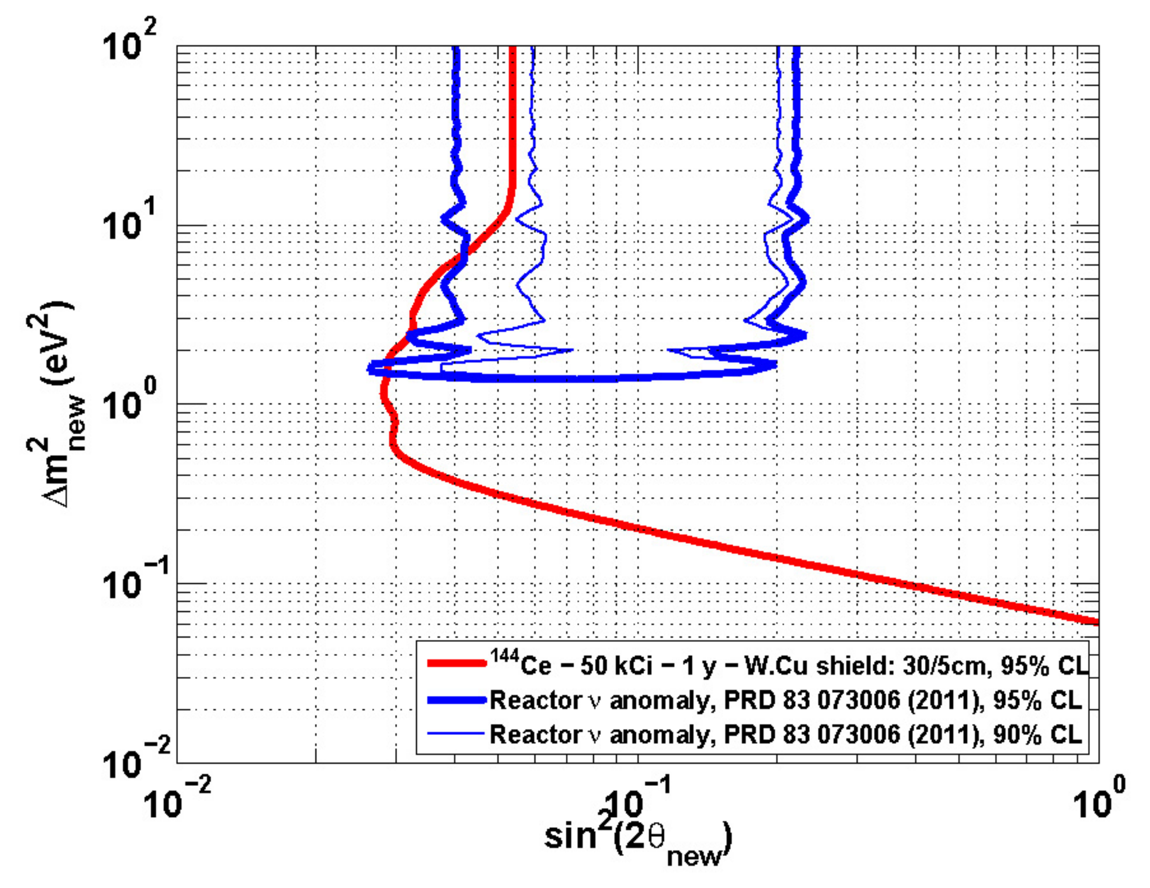
R. Van der Water@Neutrino2010

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

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

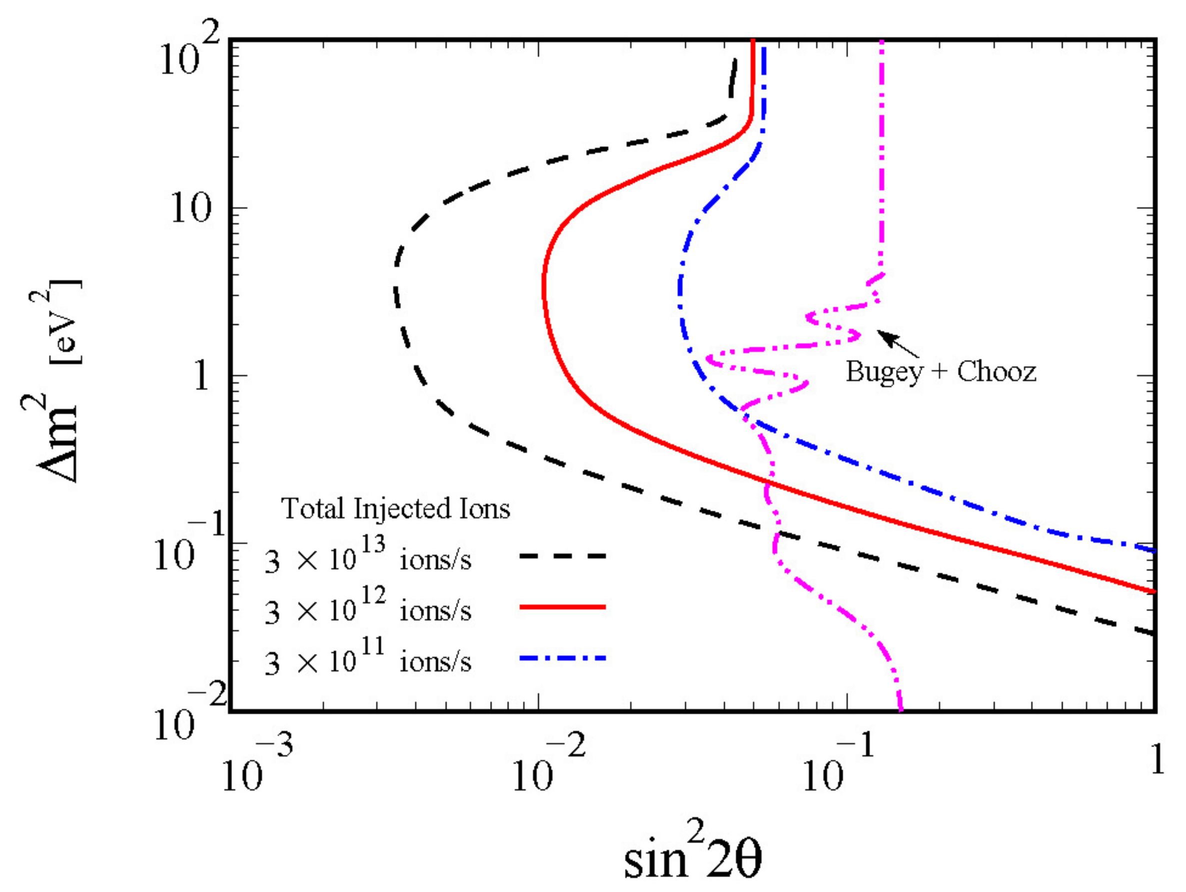
Cribier et al., arXiv:1107.2335v1 [hep-ex]

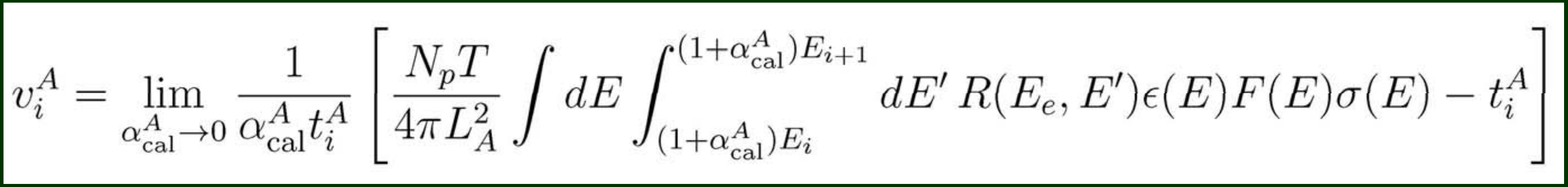
anti-ν source placed in a liquid scintillator detector (e.g., KamLAND)



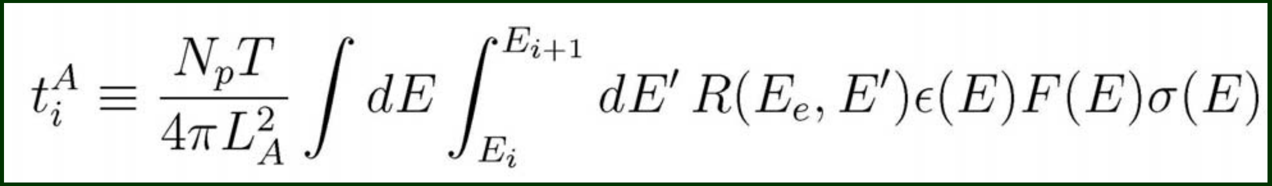
Proposal of a β-beam

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

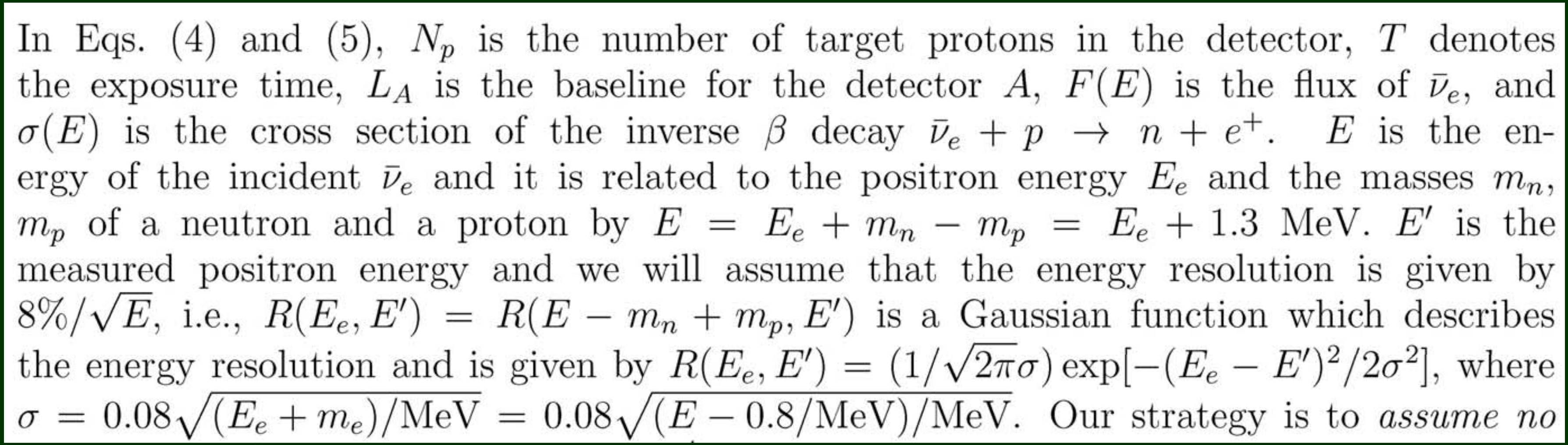




$$v_i^A = \lim_{\alpha_{\rm cal}^A \to 0} \frac{1}{\alpha_{\rm cal}^A t_i^A} \left[\frac{N_p T}{4\pi L_A^2} \int dE \int_{(1+\alpha_{\rm cal}^A)E_i}^{(1+\alpha_{\rm cal}^A)E_{i+1}} dE' \, R(E_e, E') \epsilon(E) F(E) \sigma(E) - t_i^A \right]$$



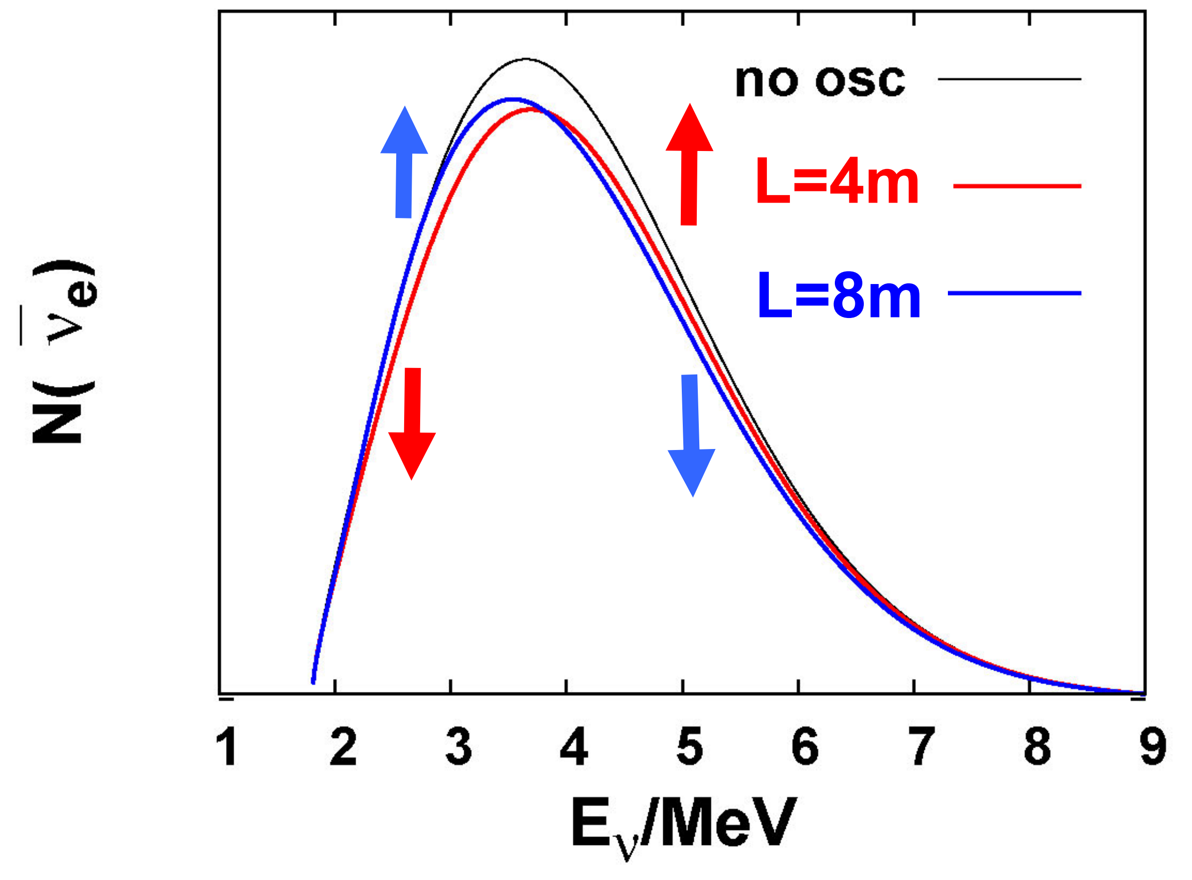
$$t_i^A \equiv \frac{N_p T}{4\pi L_A^2} \int dE \int_{E_i}^{E_{i+1}} dE' \, R(E_e, E') \epsilon(E) F(E) \sigma(E)$$



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



1.7 Thermal Neutron Reactors vs Fast Neutron Reactors

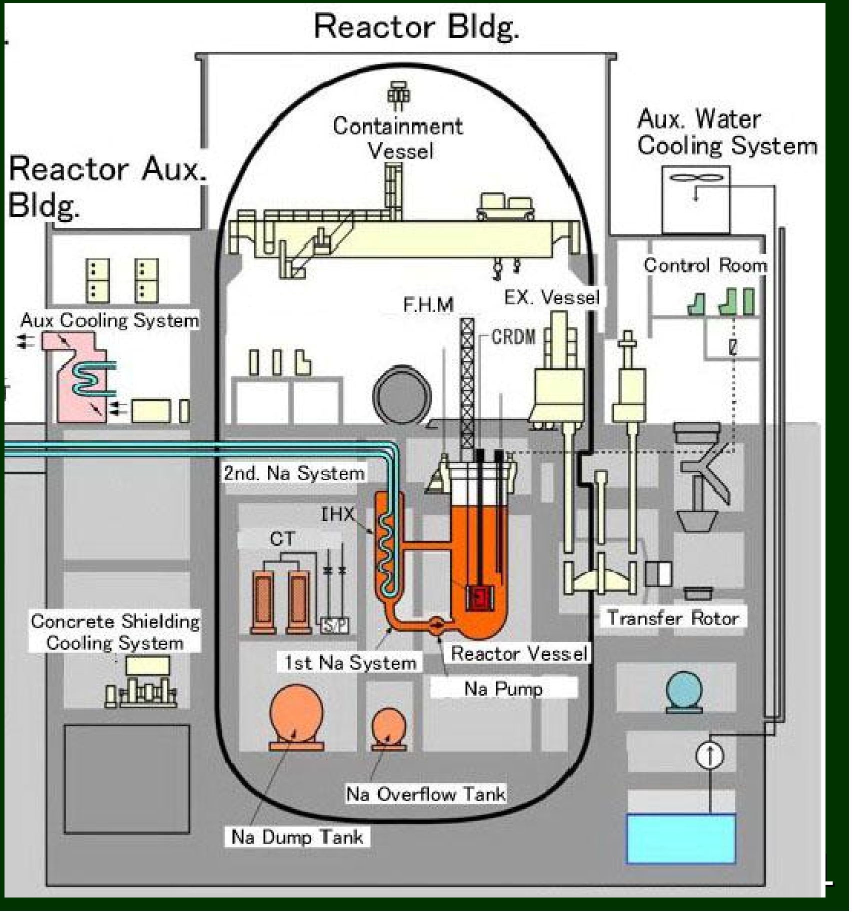
Fuels must be distant ⇨ the volume must be larger

	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

Oarai, Ibaraki



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

A Study of Reactor ν Monitoring at Experimental Fast Reactor JOYO

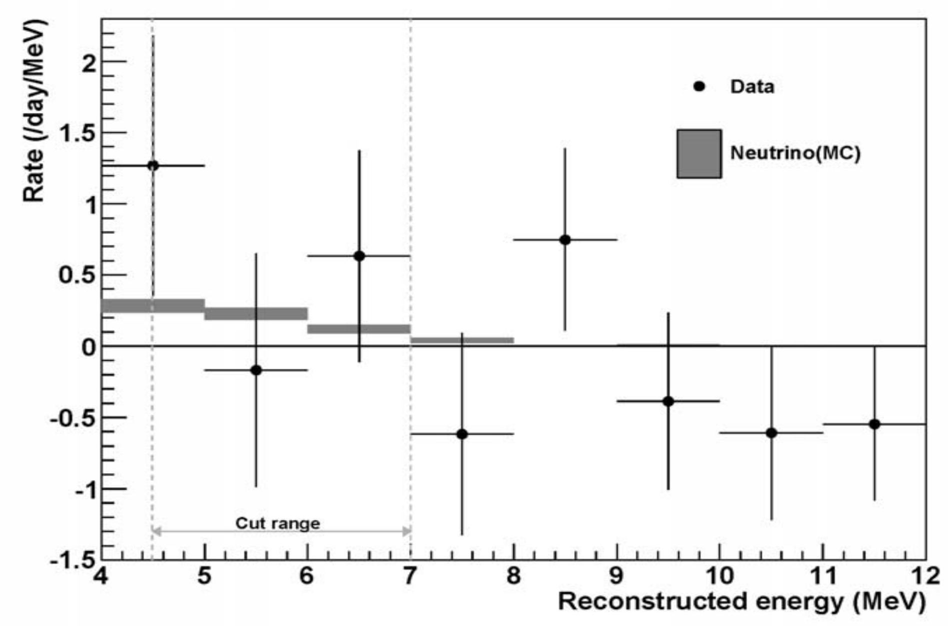
H.Furuta et al., arXiv:1108.2910v1 [hep-ex]

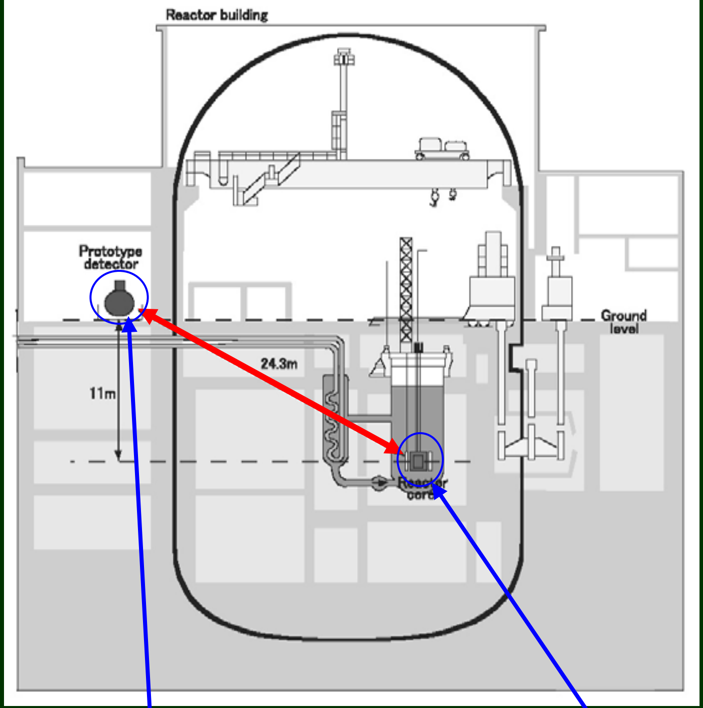
L=24.3m; about 150 $\nu p \rightarrow e^{+}n$ reactions/day

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)

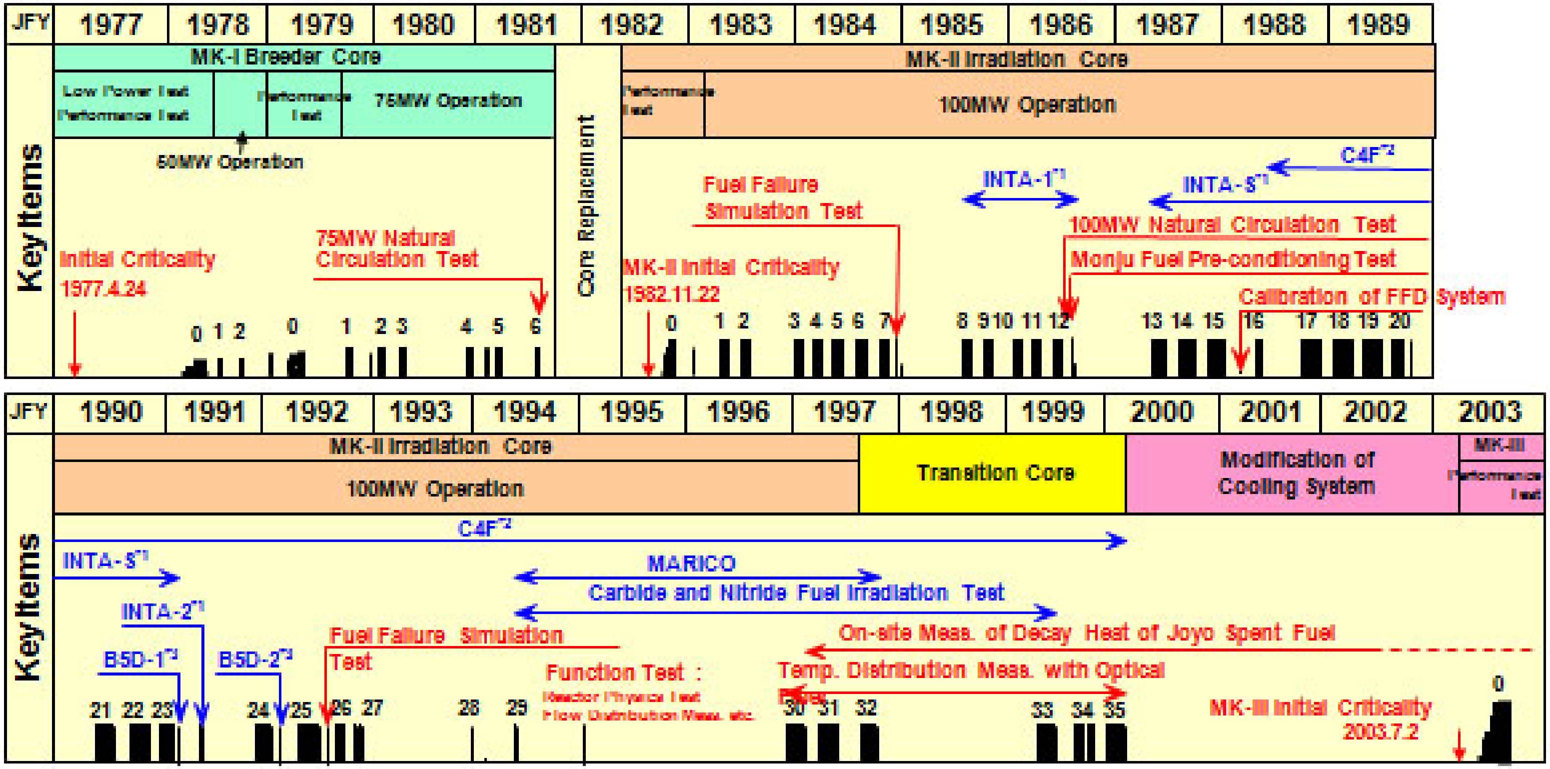


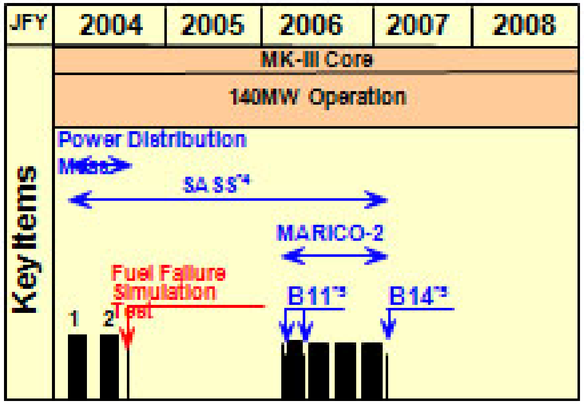


Prototype detector

Reactor core

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

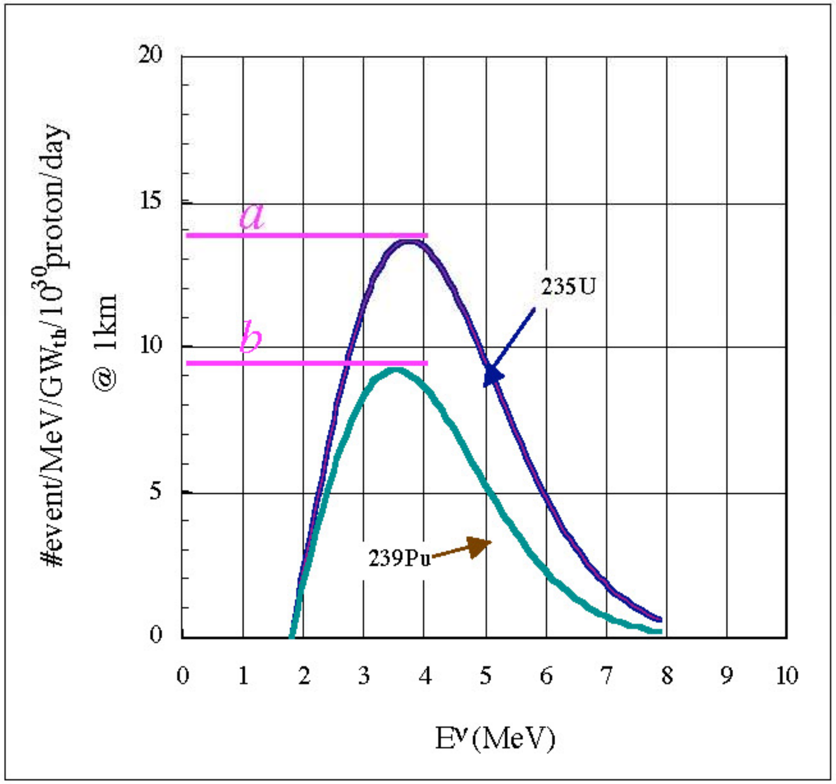
How to measure Pu/U ratio by ν

(simplified discussion)

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

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

- 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?

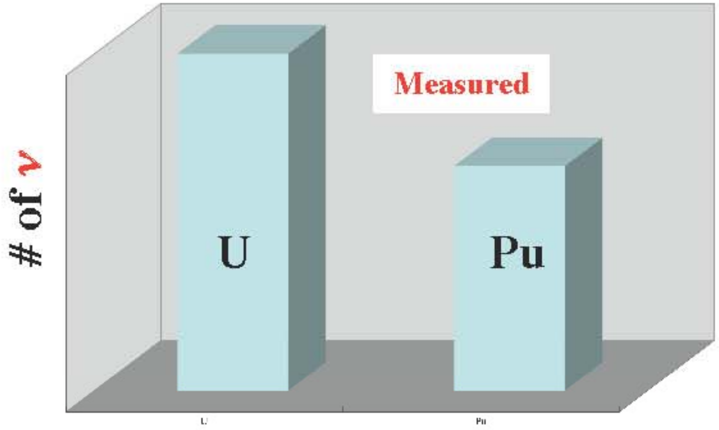
* Practical Reason:
Research Reactor is easier to access.

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

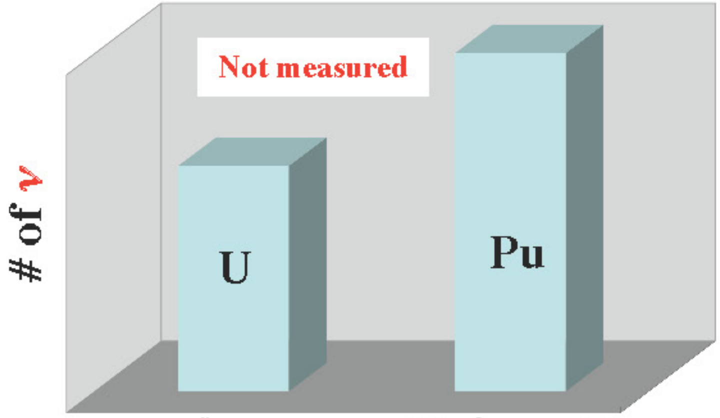
* Technological Interest
ν spectum from U and Pu can be measured separately by combining with the data from Light Water Reactor

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

LWR



Fast Reactor



(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%