Neutrinos from the Sun : Observation

The fourth COE Symposium
Jun. 30, 2006
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Solar Neutrinos : Prediction and Measurement

Prediction

SSM (Standard Solar Model)

high energy ↑	$^8B\ \nu$	0.01%
	CNO ν	1.6%
	pep ν	0.2%
	$^7Be\ \nu$	7%
low energy ↓	pp ν	91%

Measurement

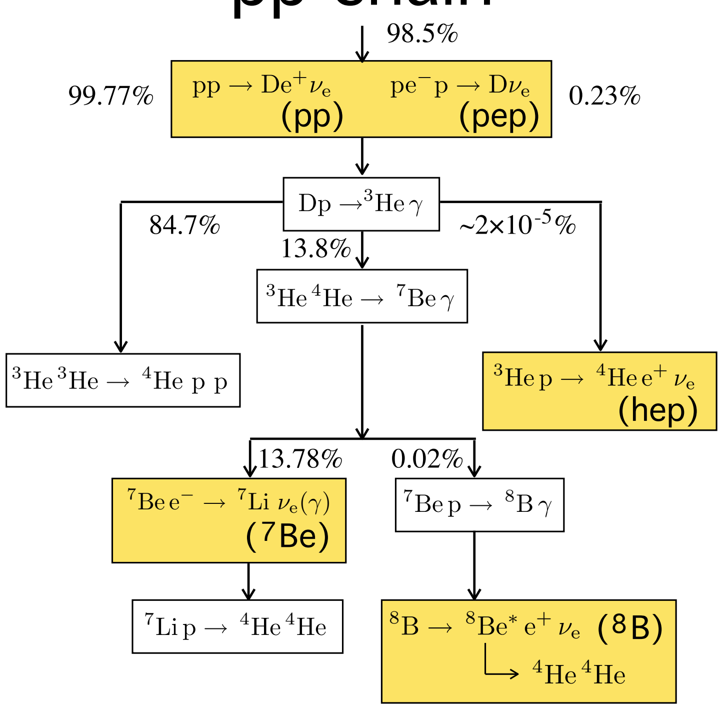
Super-Kamiokande, SNO

NC/CC discrimination

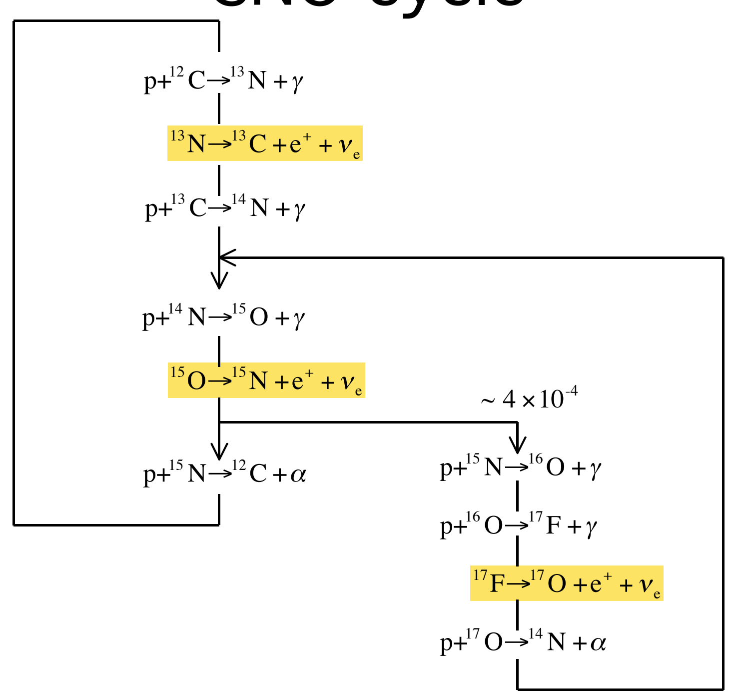
Cl (Homestake)

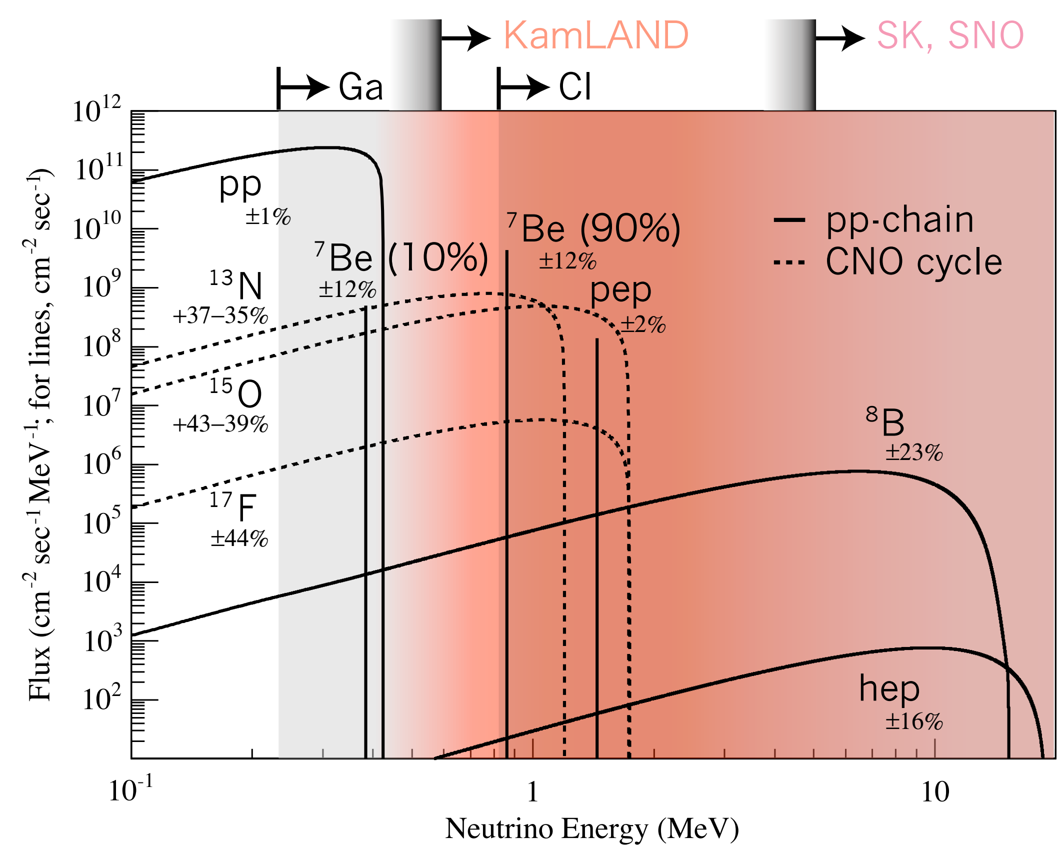
Ga (Gallex/GNO, SAGE)

pp chain



CNO cycle

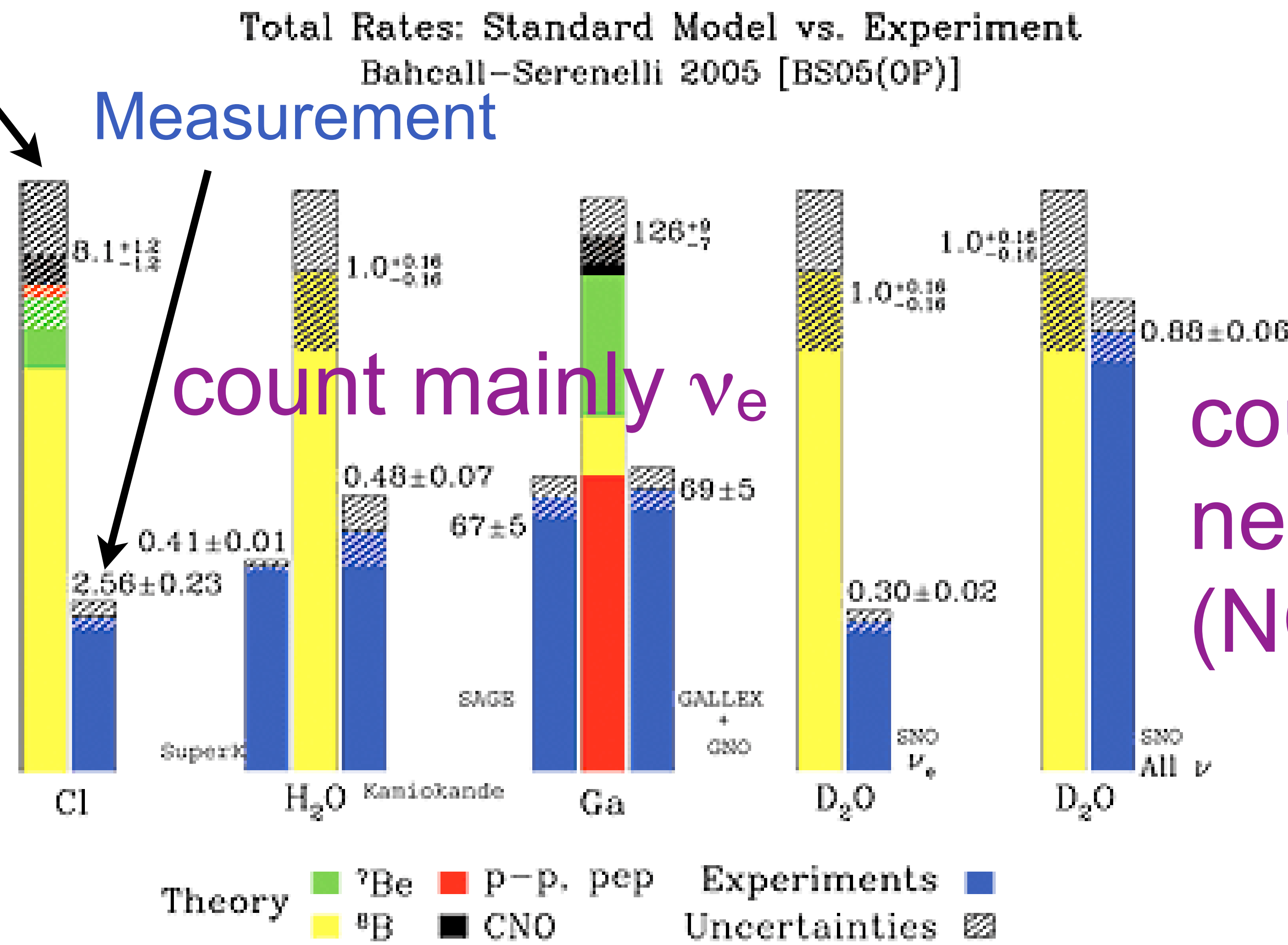




Solar Neutrino Problem

Prediction

Measurement



count mainly ν_e

count all neutrino types (NC)

Measurement / Prediction — mainly ν_e — 1 / 2 ~ 1 / 3

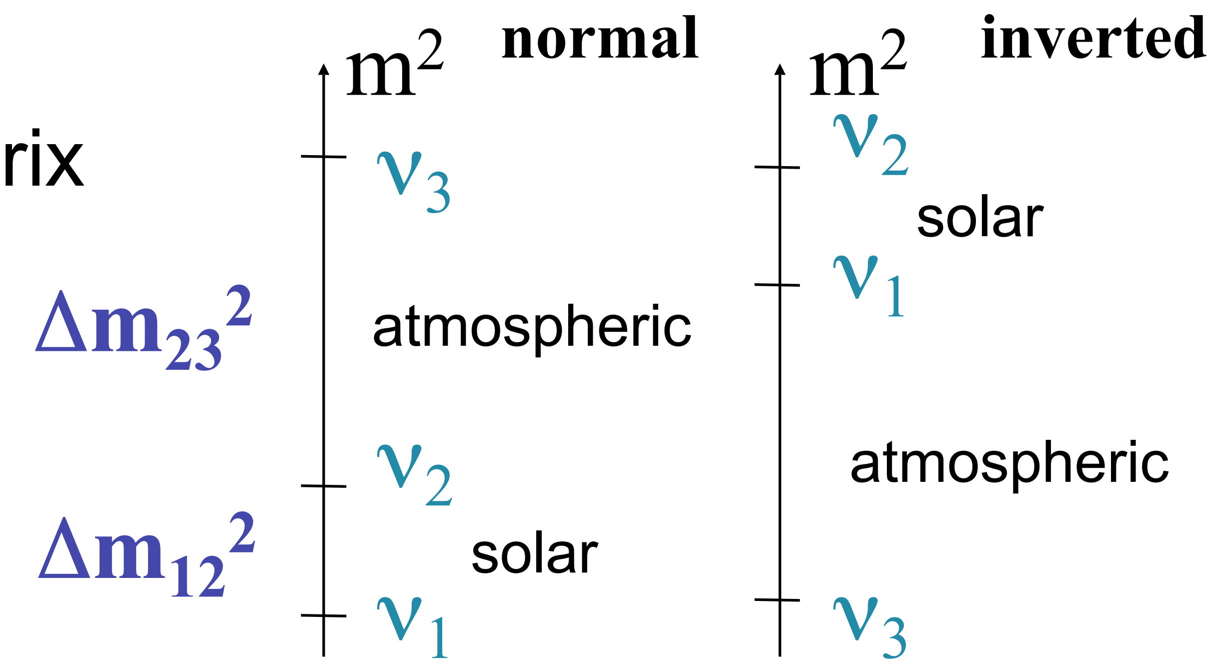
all neutrino type — ~ 1

Measurements show significant ν_e deficit from the sun

Neutrino Oscillation

MNS (Maki-Nakagawa-Sakata) Matrix

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



θ_{23} θ_{13}, CP phase θ_{12} Majorana phase

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

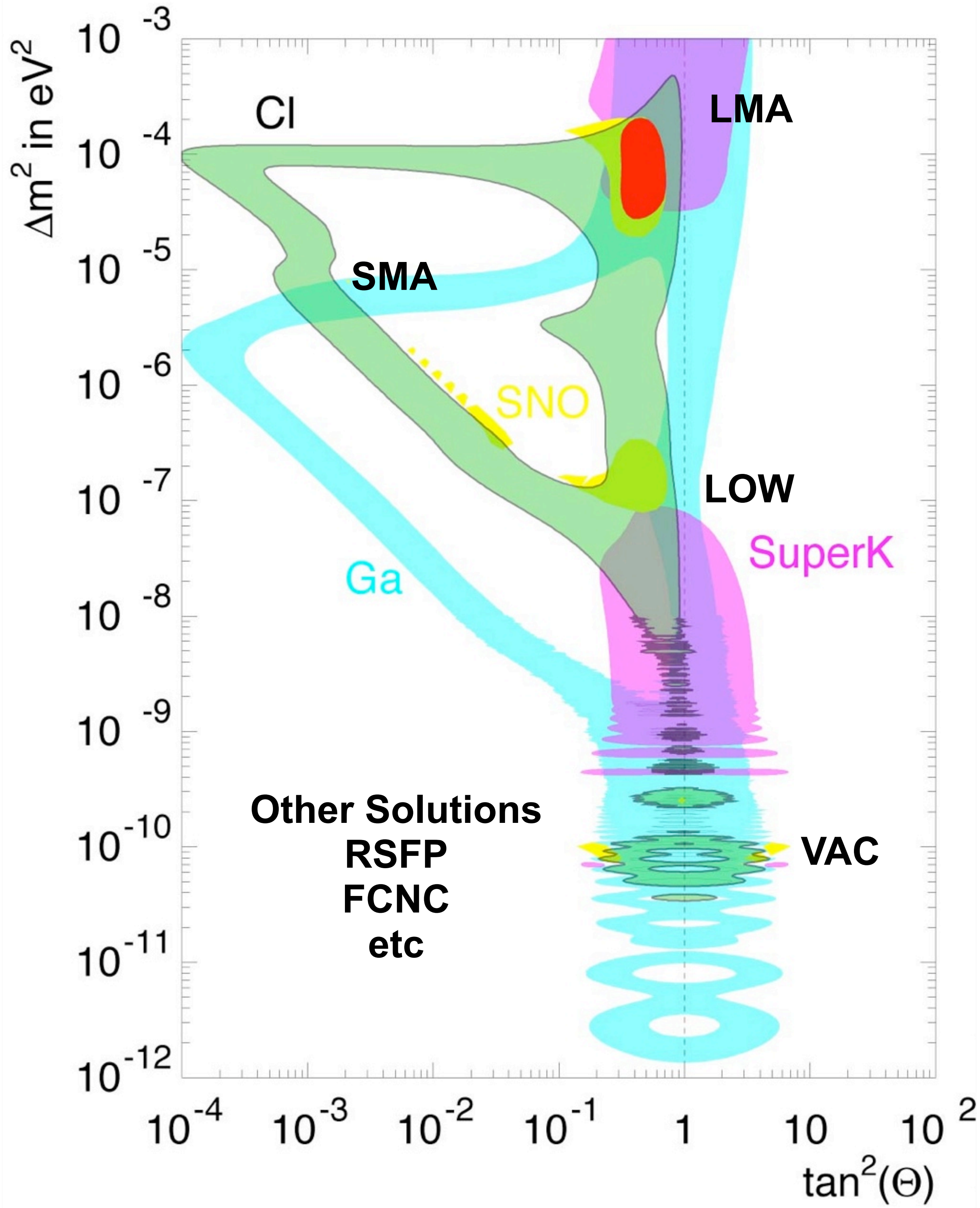
atmospheric solar

6 parameters : 3 mixing angle, 2 mass difference, 1 CP phase

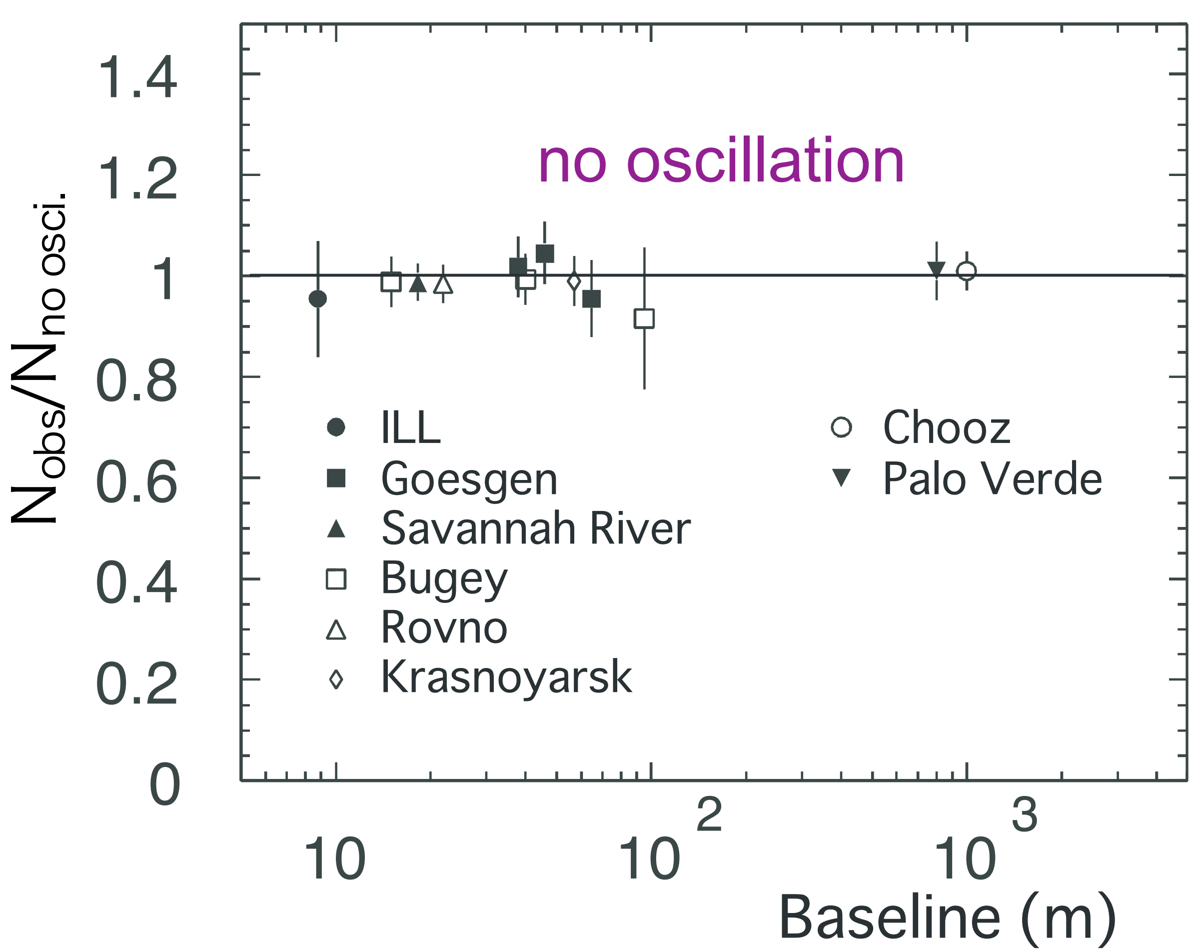
+ 2 Majorana phase

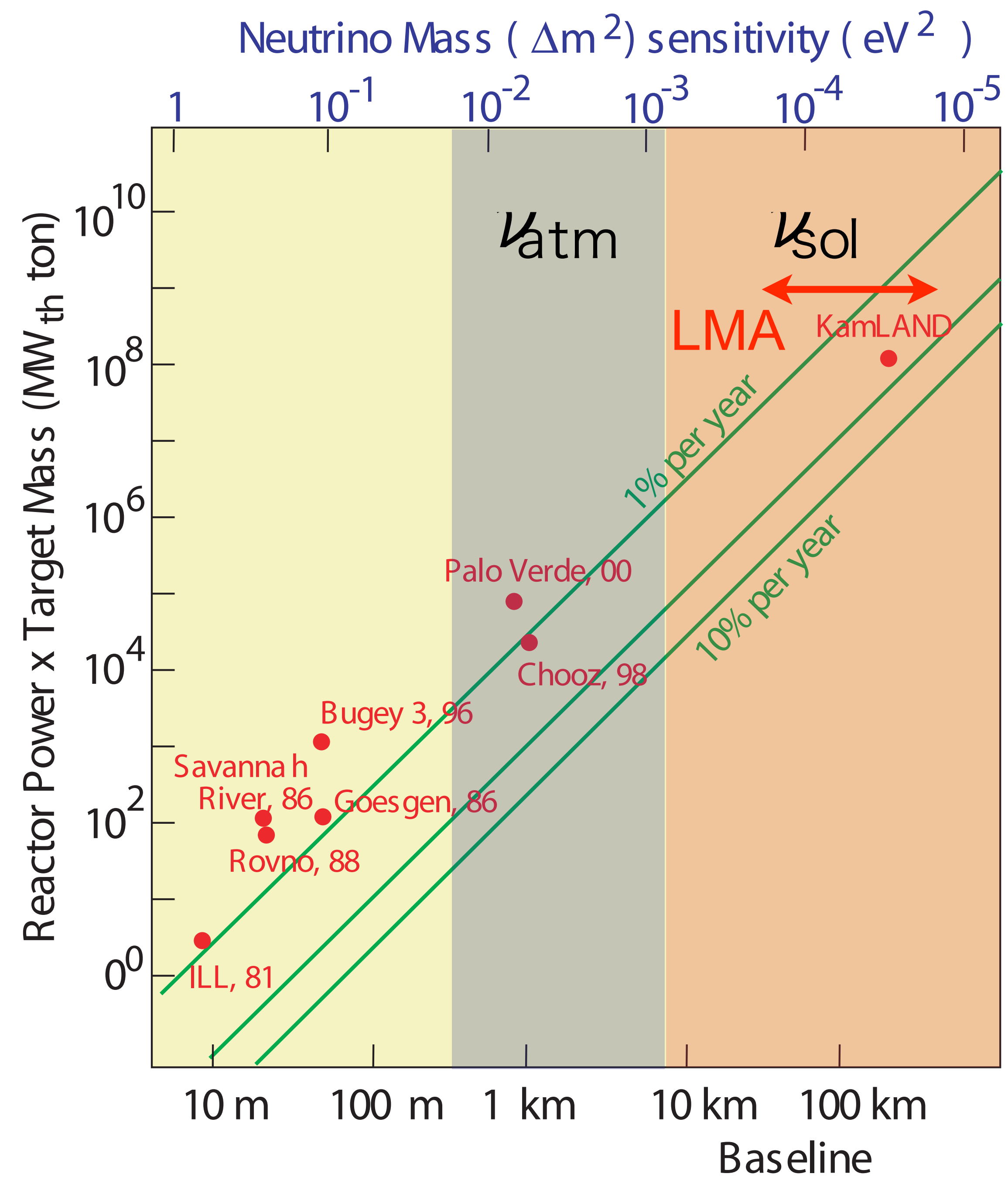
Measured by neutrino oscillation experiments
(solar, atmospheric, accelerator and reactor neutrinos)

Neutrino Oscillation Parameter which Reconcile all Experiments



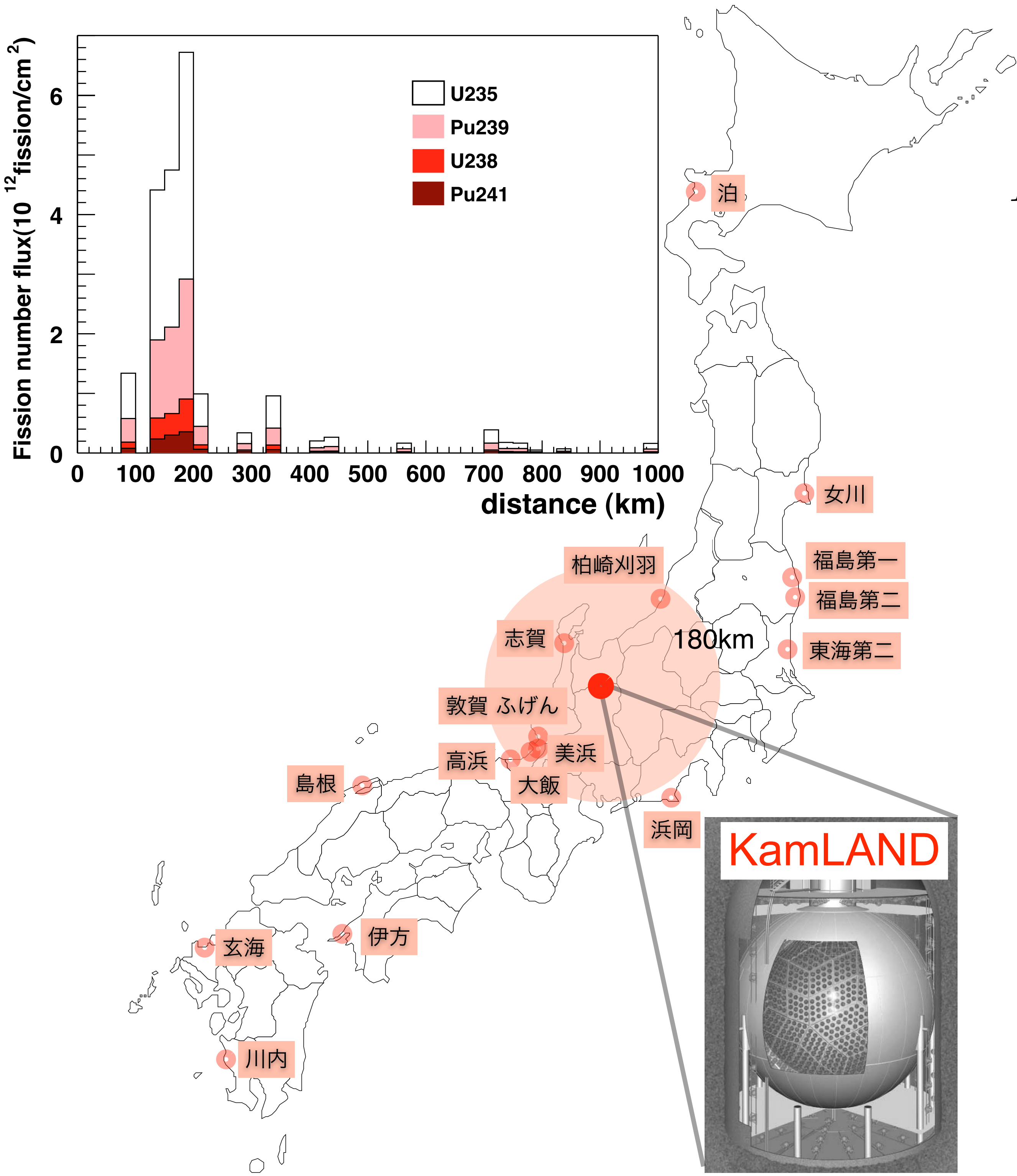
Reactor Neutrino Experiments





> 100 km baseline is necessary to explore the LMA solution

KamLAND Experiment



2 flavor neutrino oscillation

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]l[m]}{E[\mathrm{MeV}]}\right)$$

most sensitive region

$$\Delta m^2 = (1/1.27) \cdot (E[\mathrm{MeV}]/L[m]) \cdot (\pi/2)$$
$$\sim 3 \times 10^{-5}\mathrm{eV}^2$$

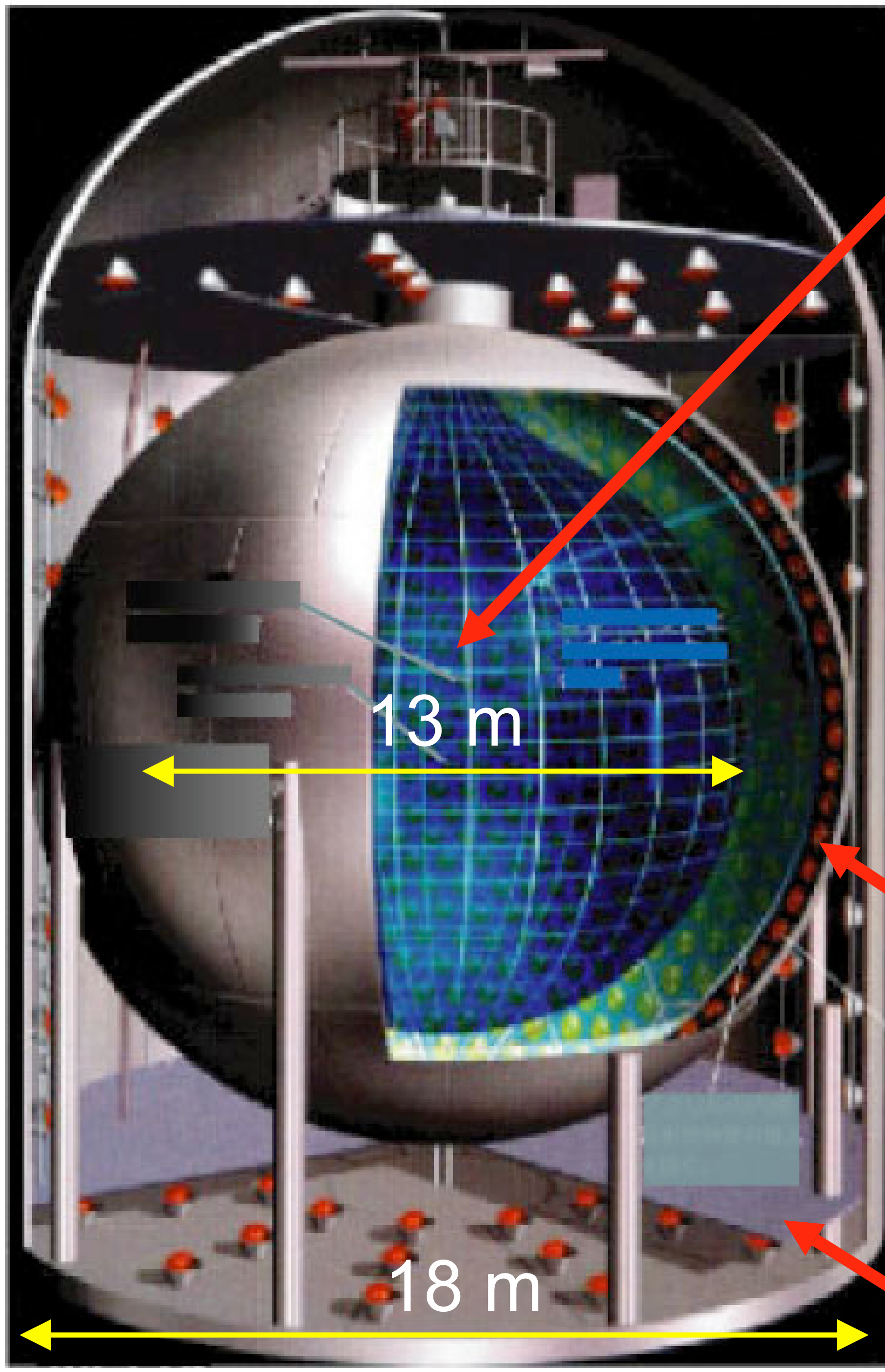
⟶ LMA solution

ΔL (distance spread from reactors)	
175 ± 35 km	~ 20%
ΔE (energy resolution)	
17 inch PMTs	$7.3\% / \sqrt{E(\mathrm{MeV})}$
17 inch + 20 inch	$6.2\% / \sqrt{E(\mathrm{MeV})}$

Good condition to confirm solar neutrino oscillation

KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

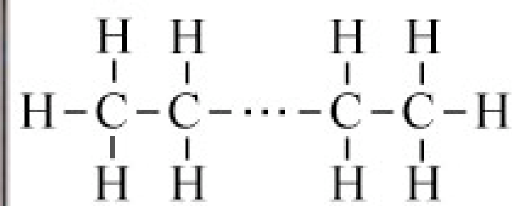


1,000 ton Liquid Scintillator

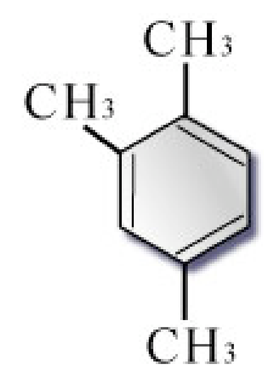
Pseudocumene (20%)

Dodecane (80%)

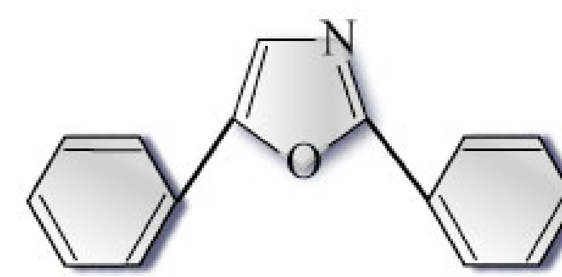
PPO (1.5 g/l)



Dodecane ($C_{12}H_{26}$) : 80%



Pseudocumene : 20%
(1,2,4-Trimethyl Benzene)



PPO : 1.5 g / l
(2,5-Diphenyloxazole)

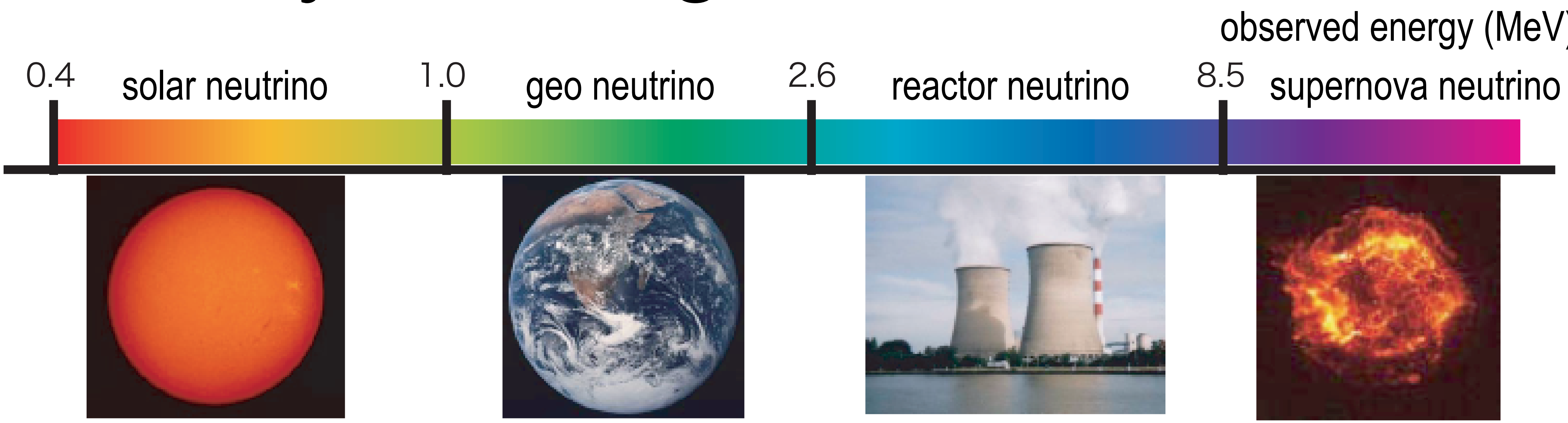
1,325 17 inch + 554 20 inch PMTs

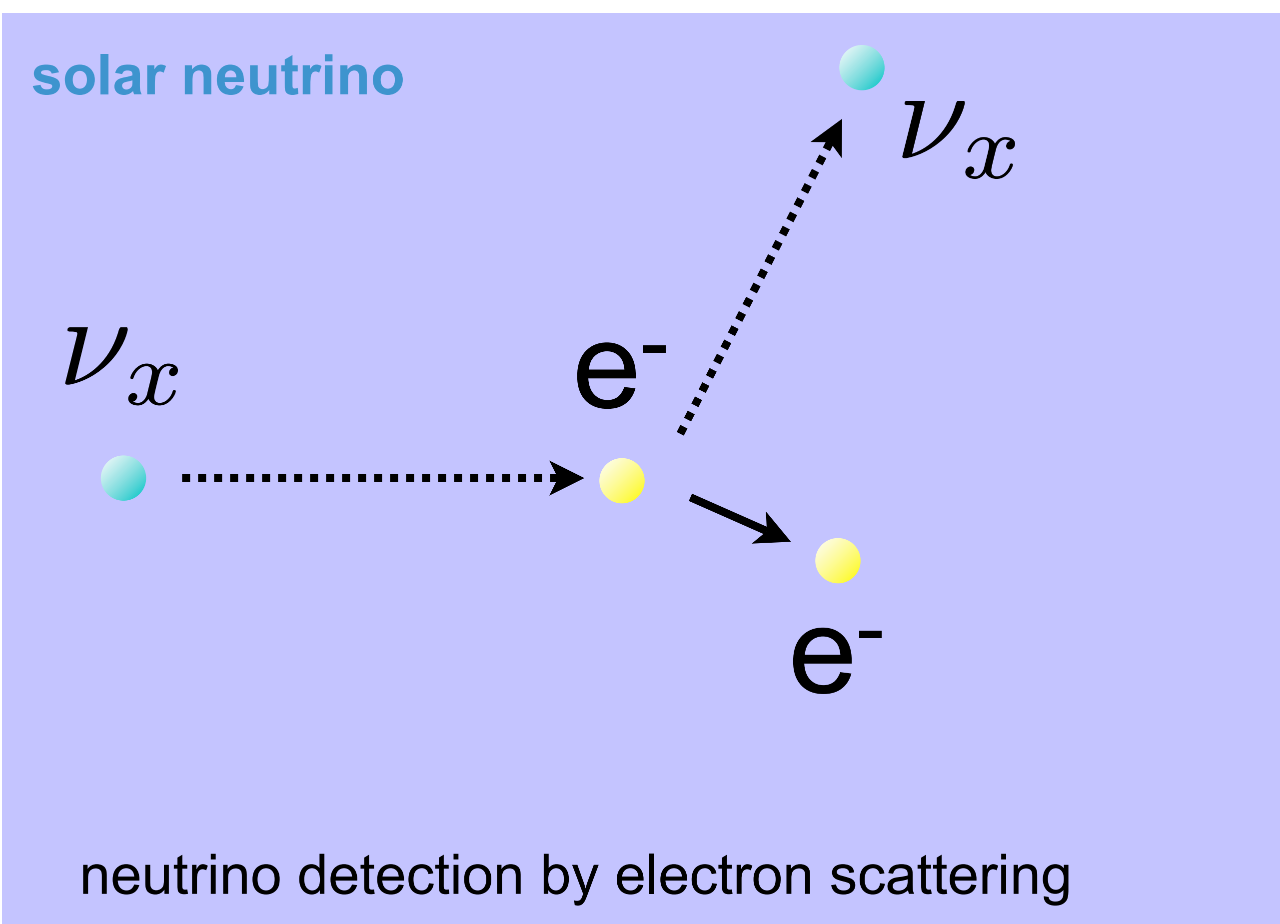
commissioned in February, 2003

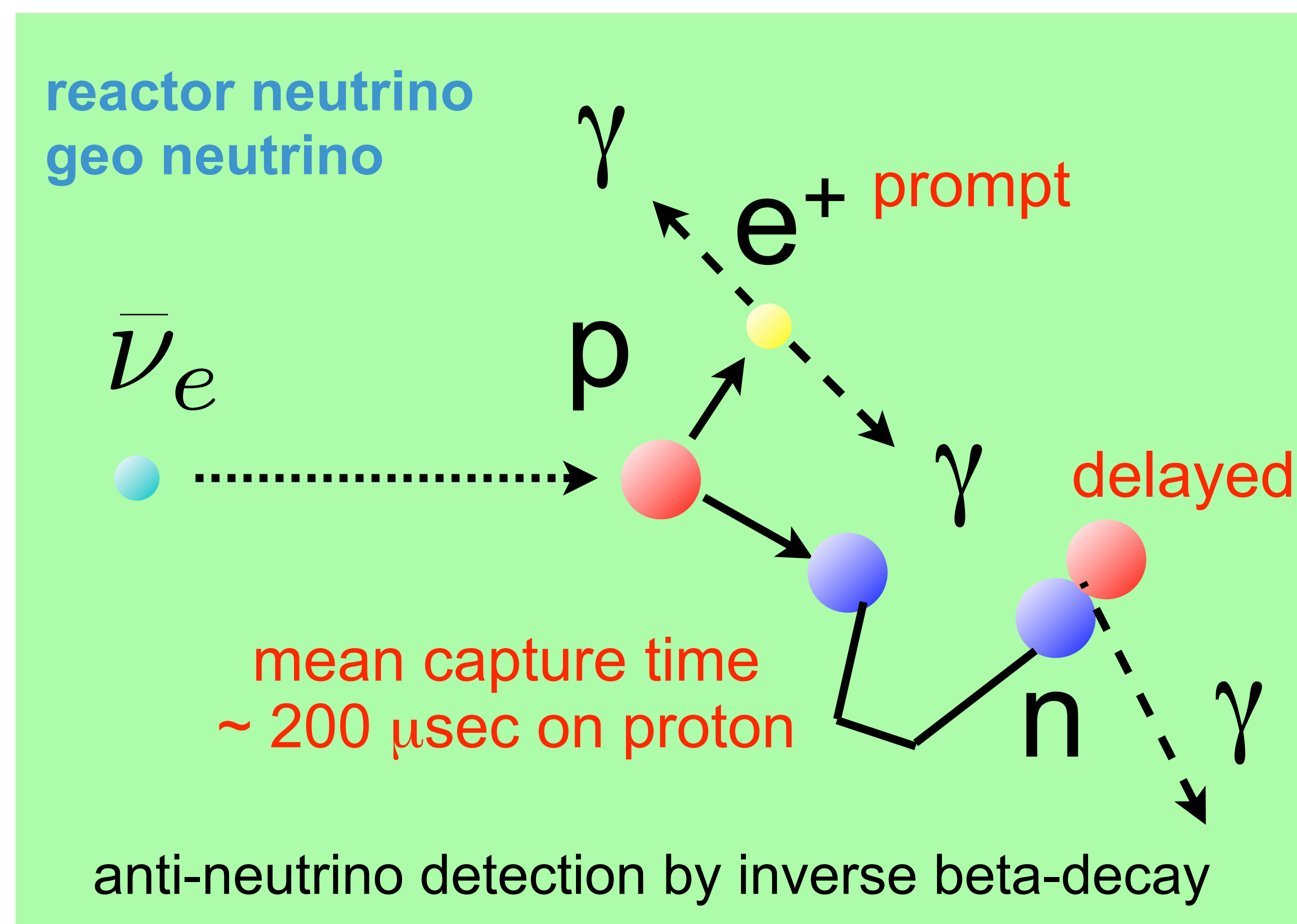
photocathode coverage : 22% → 34%

Water Cherenkov Outer Detector

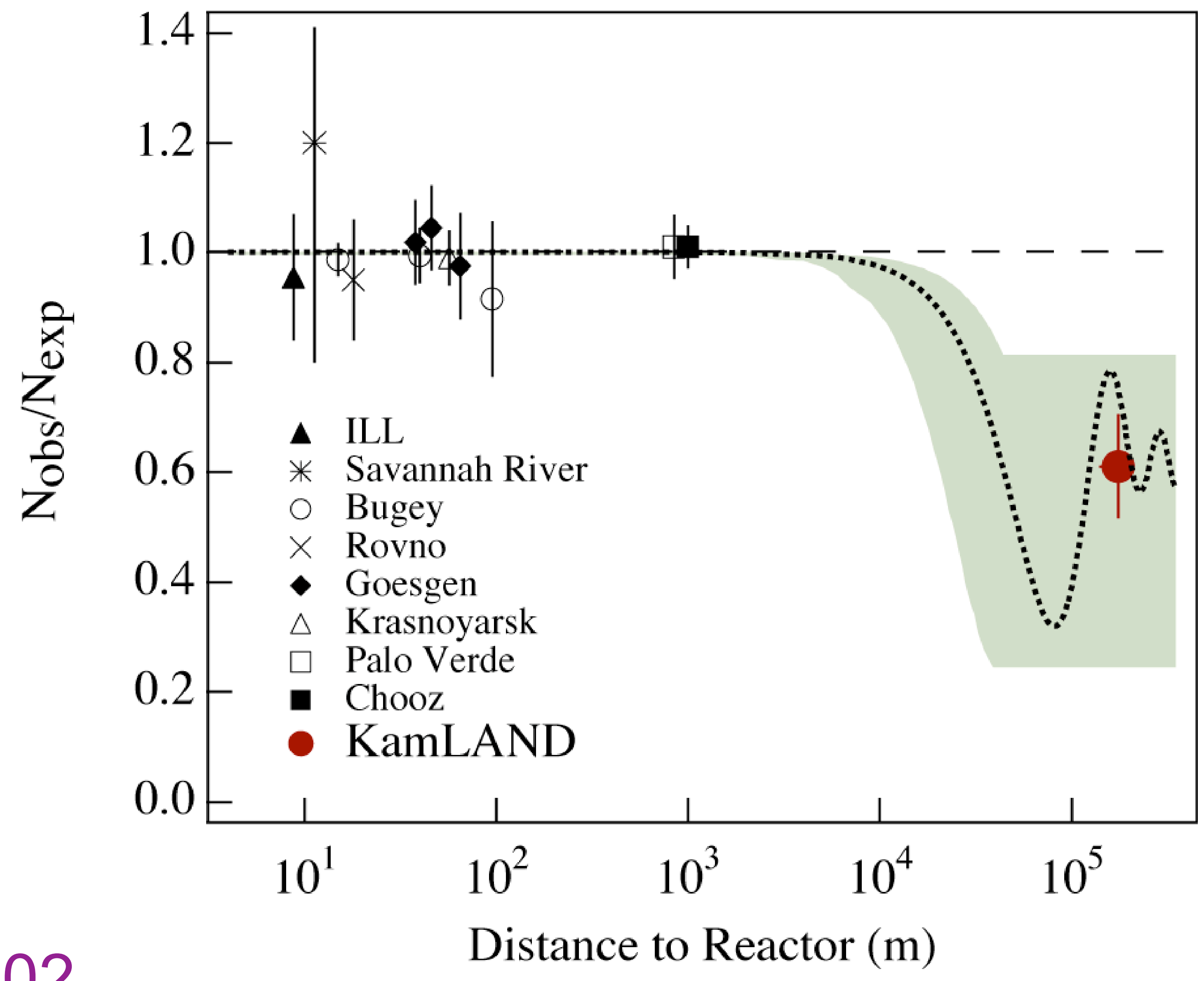
Physics Target in KamLAND







First Result :
Evidence for Reactor Antineutrino Disappearance

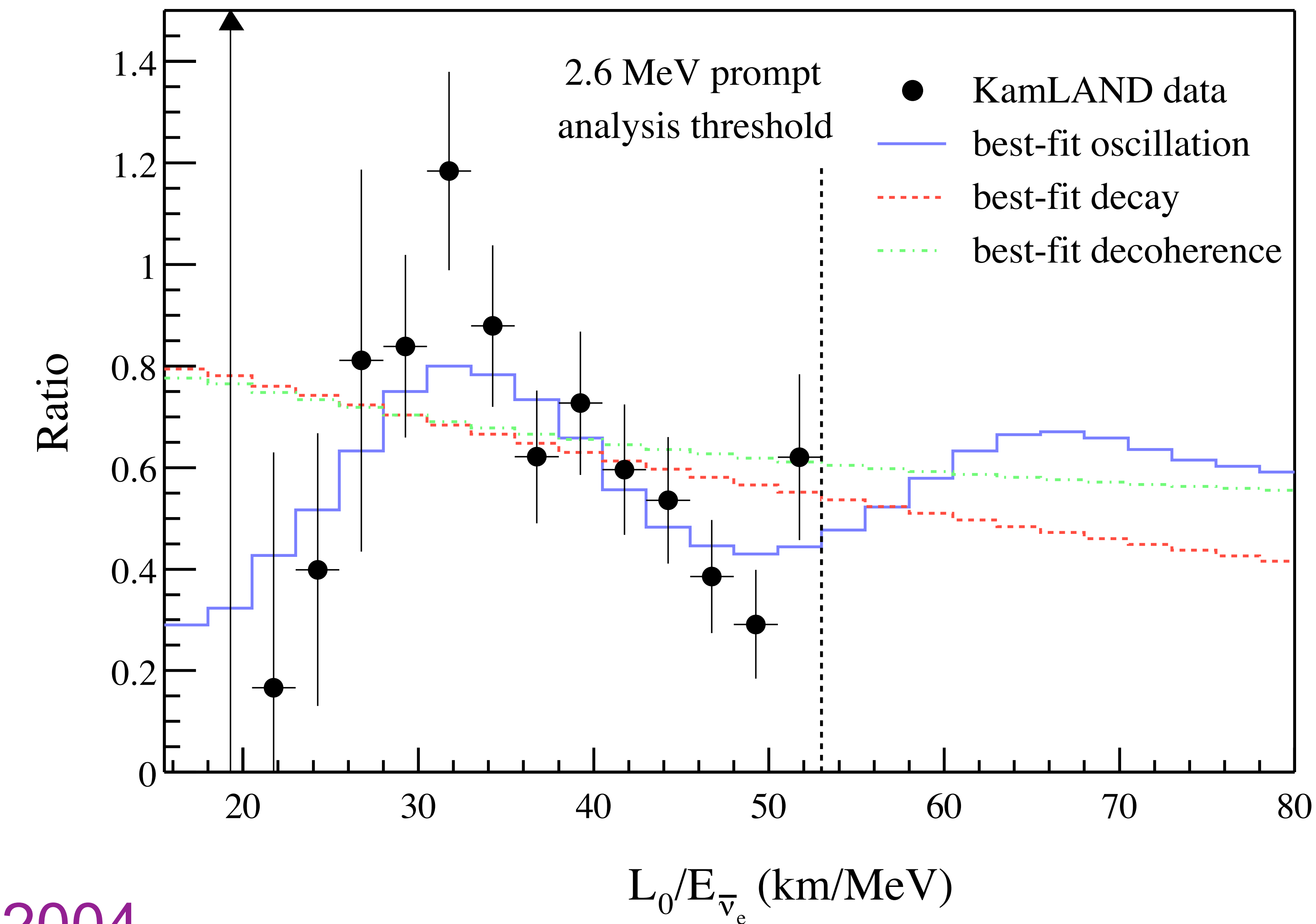


Dec. 2002

162 ton-year data-set

Disappearance Significance : 99.95% C.L.

Second Result :
Evidence of Spectral Distortion

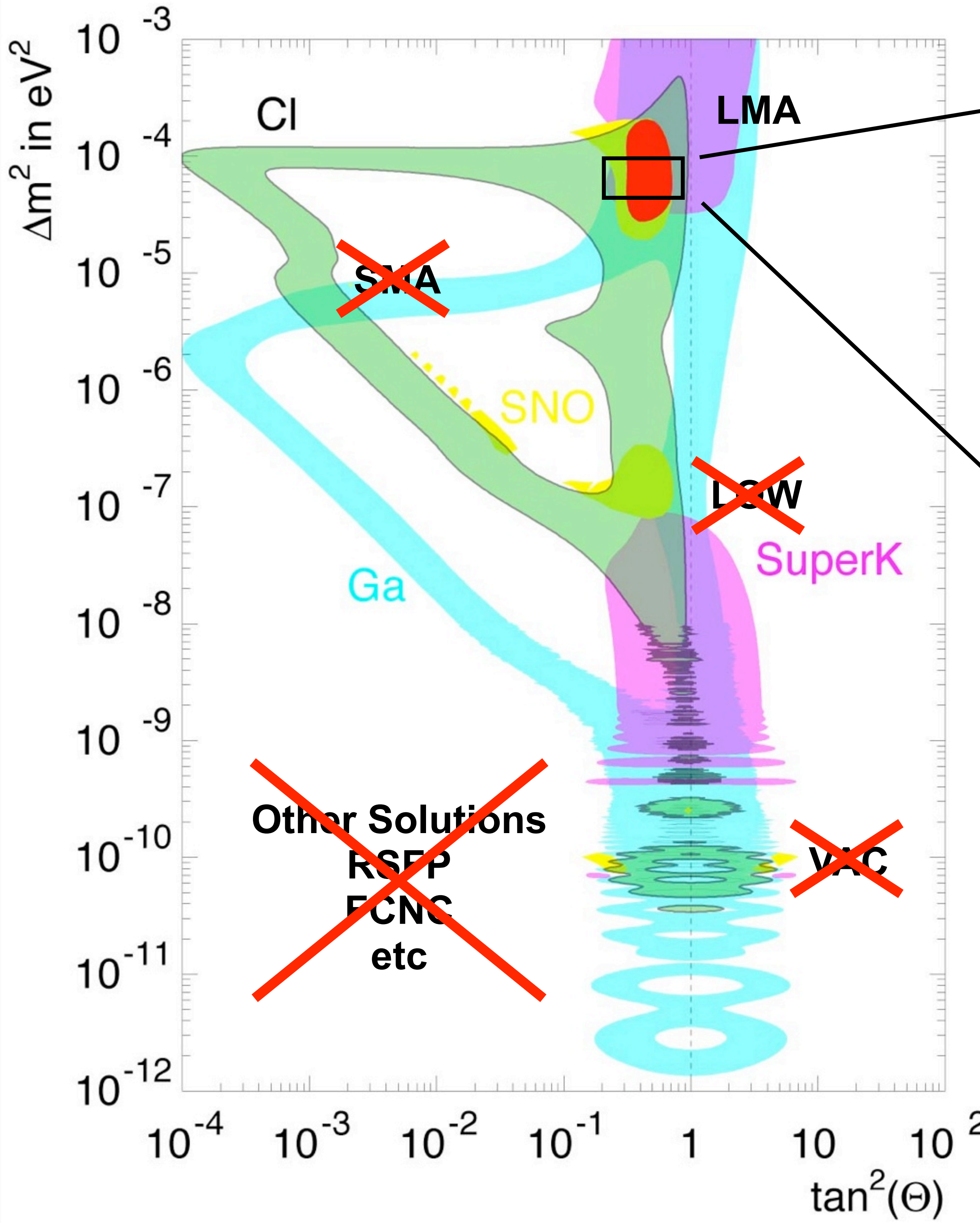


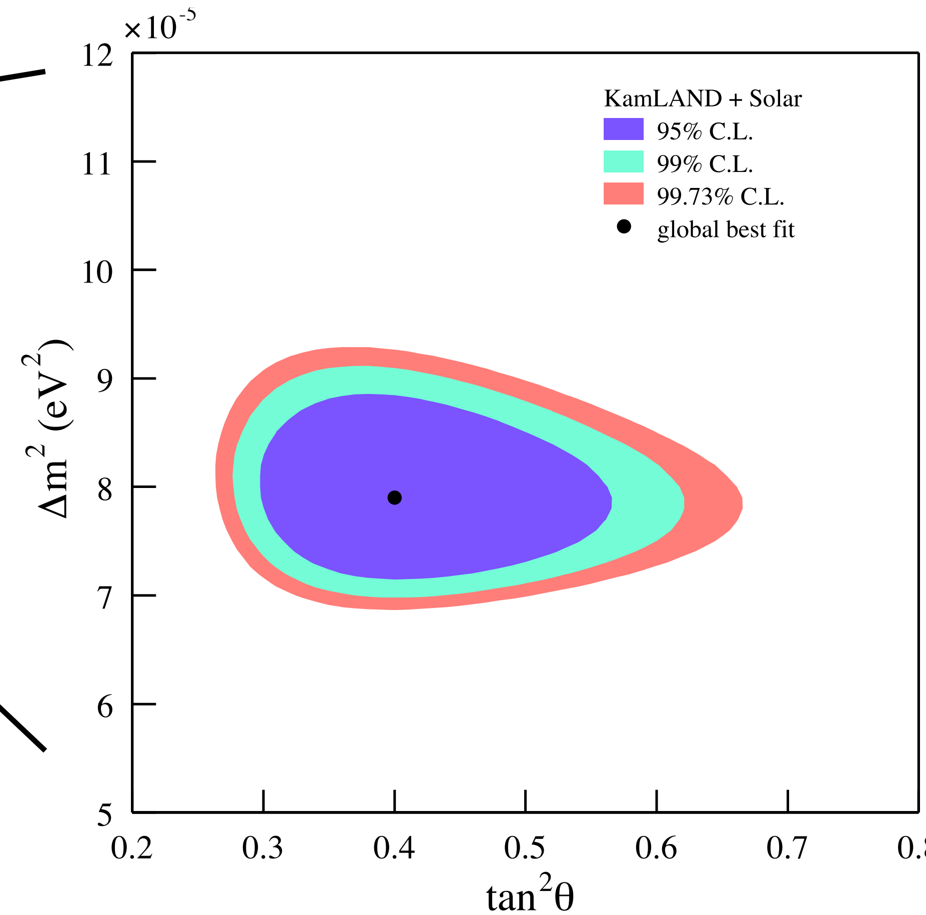
Jun. 2004

766 ton-year data-set

Distortion Significance : 99.6% C.L.

Precise Measurement of Oscillation Paramter





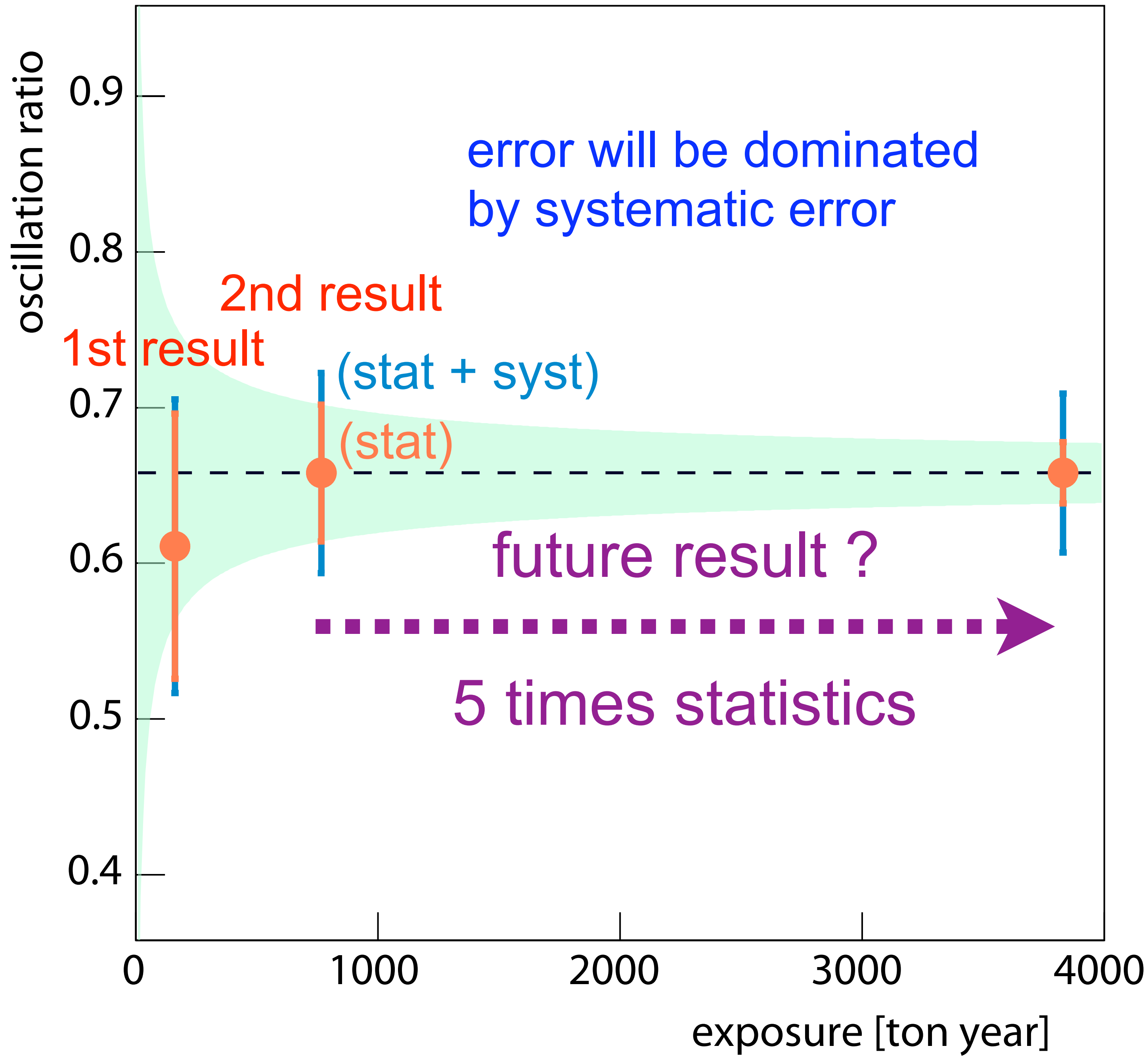
solar + KamLAND result

$$\tan^2\theta = 0.40^{+0.10}_{-0.07}$$

$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ \mathrm{eV}^2$$

Reactor Future Prospect

oscillation ratio = (N_{obs} - B.G.) / N_{exp}



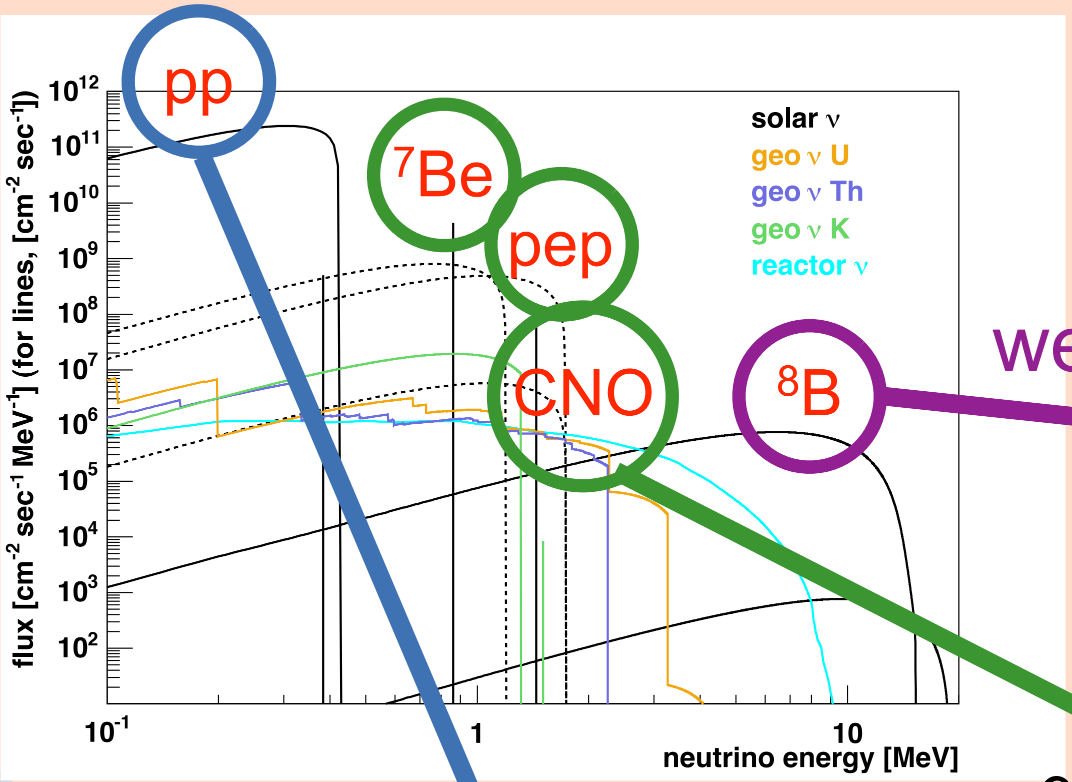
Systematic	%
Fiducial volume	4.7 (dominant)
Energy threshold	2.3
Efficiency of cuts	1.6
Livetime	0.06
Reactor power	2.1
Fuel composition	1.0
$\overline{\nu}_e$ spectra	2.5
Cross section	0.2
Total	6.5

Fiducial volume uncertainty will be reduced by full volume calibration (now planing)

full volume calibration ⟶ systematic uncertainty ~ 4%

Future Solar Neutrino Measurement

low energy solar neutrino observation



well understood

~ 0.01%

high energy

Super-Kamiokande
SNO

~ 9%

development stage ...

~ 91%

low energy

LENS (^{115}In)
MOON (^{100}Mo)
SIREN (^{160}Gd)

XMass
GENIUS
CLEAN
HERON

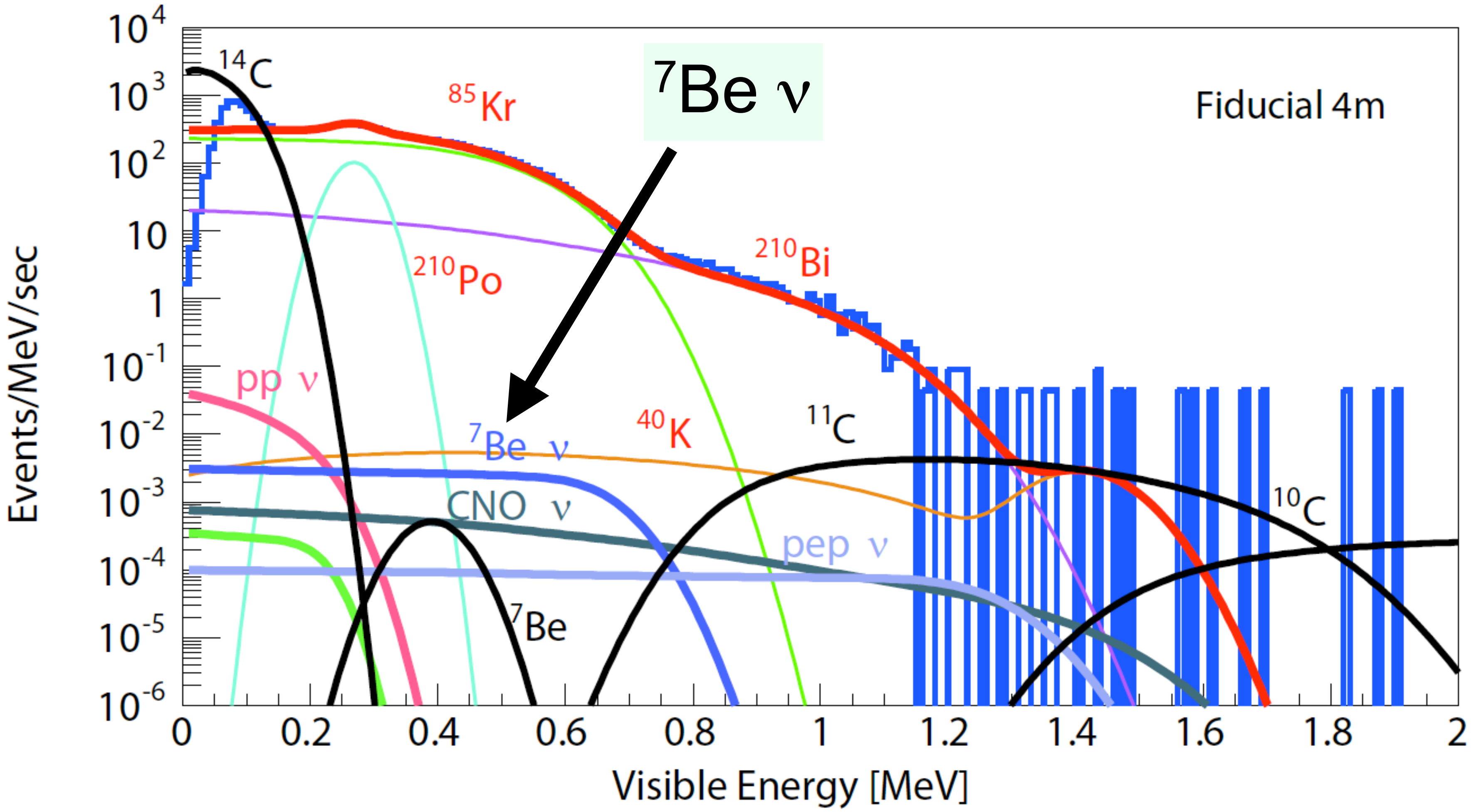
Borexino
KamLAND II
SNO+
LENA

$\nu_e n \rightarrow e^- p$

$\nu_e e^- \rightarrow \nu_e e^-$

KamLAND II (Solar Neutrino Phase)

KamLAND singles spectra



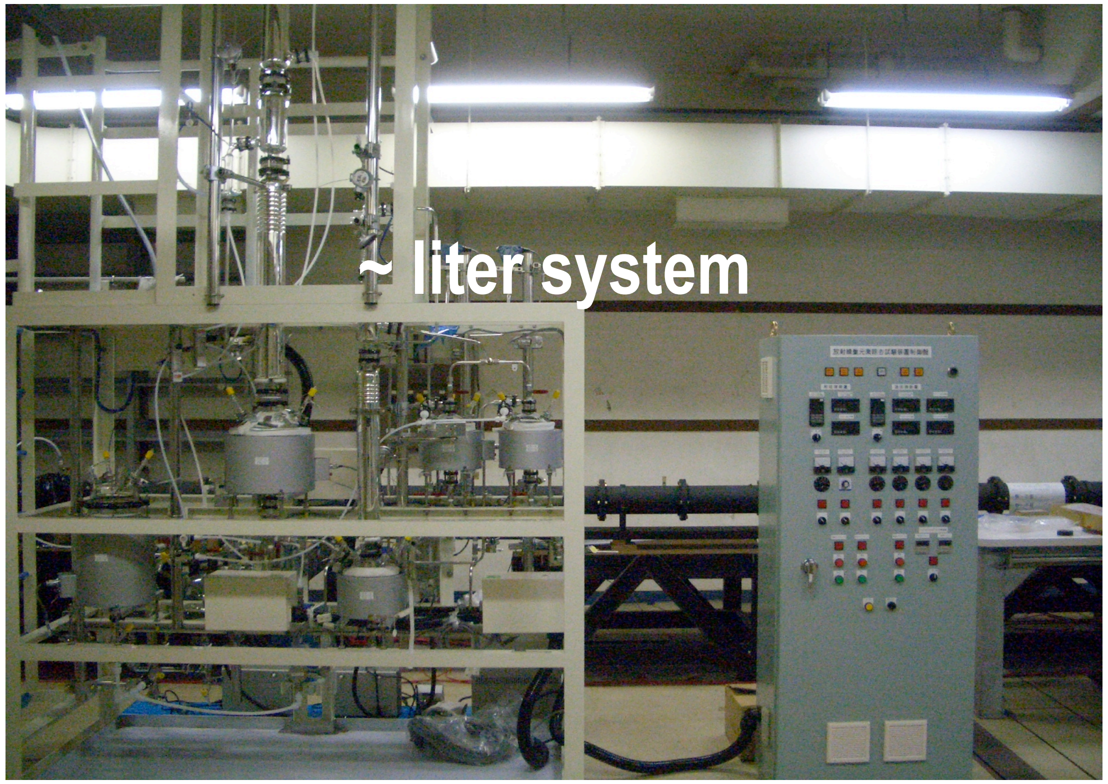
^{7}Be ν observation

B.G. reduction requirement ~ 1 μBq / m^3

Purification of Liquid Scintillator

distillation method

separation of substances based on boiling point differences



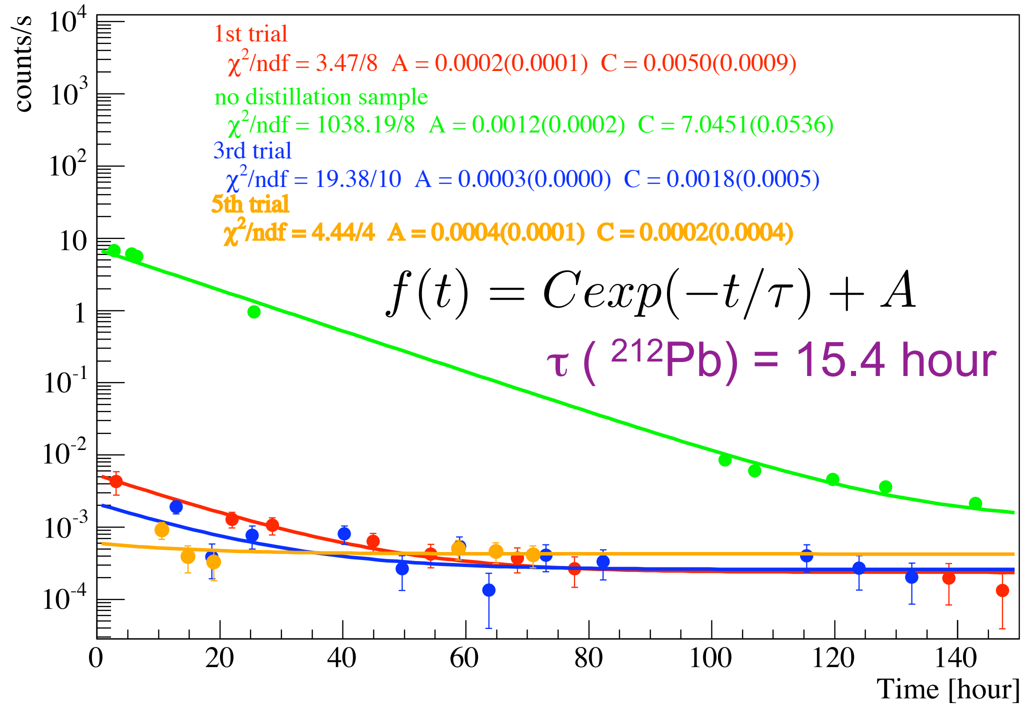
Real system

~ 1.5 kilo-liter / hour

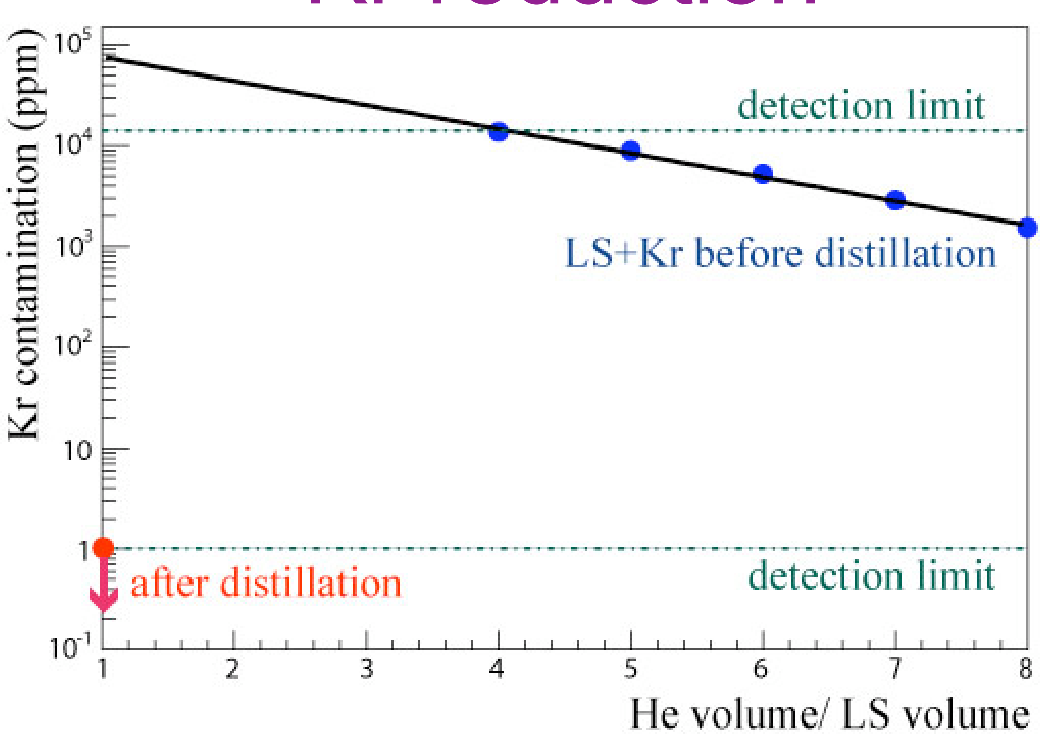
Construction from August, 2006

Reduction Efficiency by Distillation

Pb reduction



Kr reduction



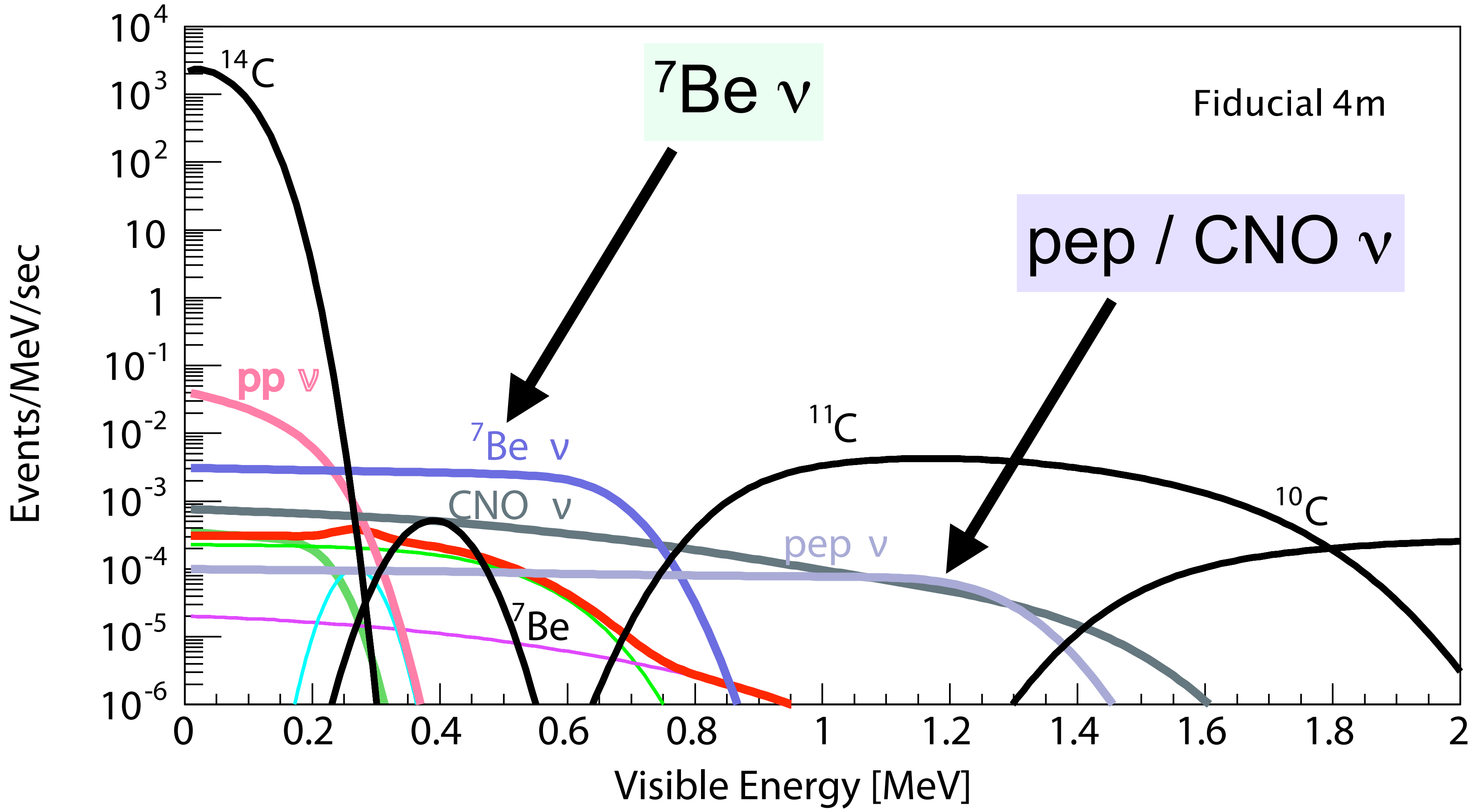
distillation in ~ liter-system

radioactive nuclei	reduction	goal
^{40}K	3.8×10^{-2} (PPO, ^{40}K)	**$10^{-1} \sim 10^{-2}$**
^{85}Kr	$< 1.3 \times 10^{-5}$ (Dodecane, Kr)	**$10^{-5} \sim 10^{-6}$**
^{210}Pb	$< 7.6 \times 10^{-5}$ (Dodecane, ^{212}Pb)	**$10^{-4} \sim 10^{-5}$**
^{222}Rn	6.0×10^{-4} (Dodecane, ^{222}Rn)	**$\sim 10^{-3}$**

almost succeeded in the reduction goal

Energy Spectra after Purification

assuming 10^{-6} reduction of ^{210}Pb, ^{85}Kr and ^{40}K



expected event rate (no oscillation)

0.3 < E < 0.8 MeV

^7Be ν	79.9 event / day
pep ν	3.8 event / day
CNO ν	16.3 event / day

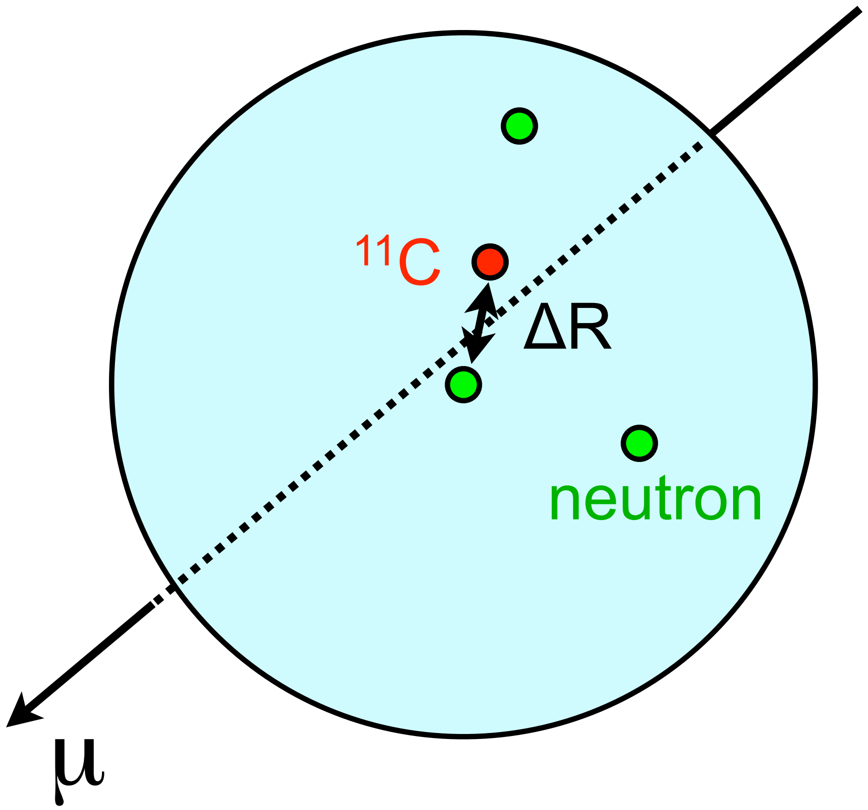
0.8 < E < 1.4 MeV

^{11}C is serious background

~ 1,000 events / day / kton

^{11}C rejection by neutron events

nuclear spallation reaction by cosmic-ray muons



^{11}C rejection by triple coincidence

(1) cosmic-ray muon

(2) neutron (mean capture time ~ 210 μsec)

(3) ^{11}C (lifetime = 29.4 min)

↓

point-like rejection (not track-like)
using neutron vertex information

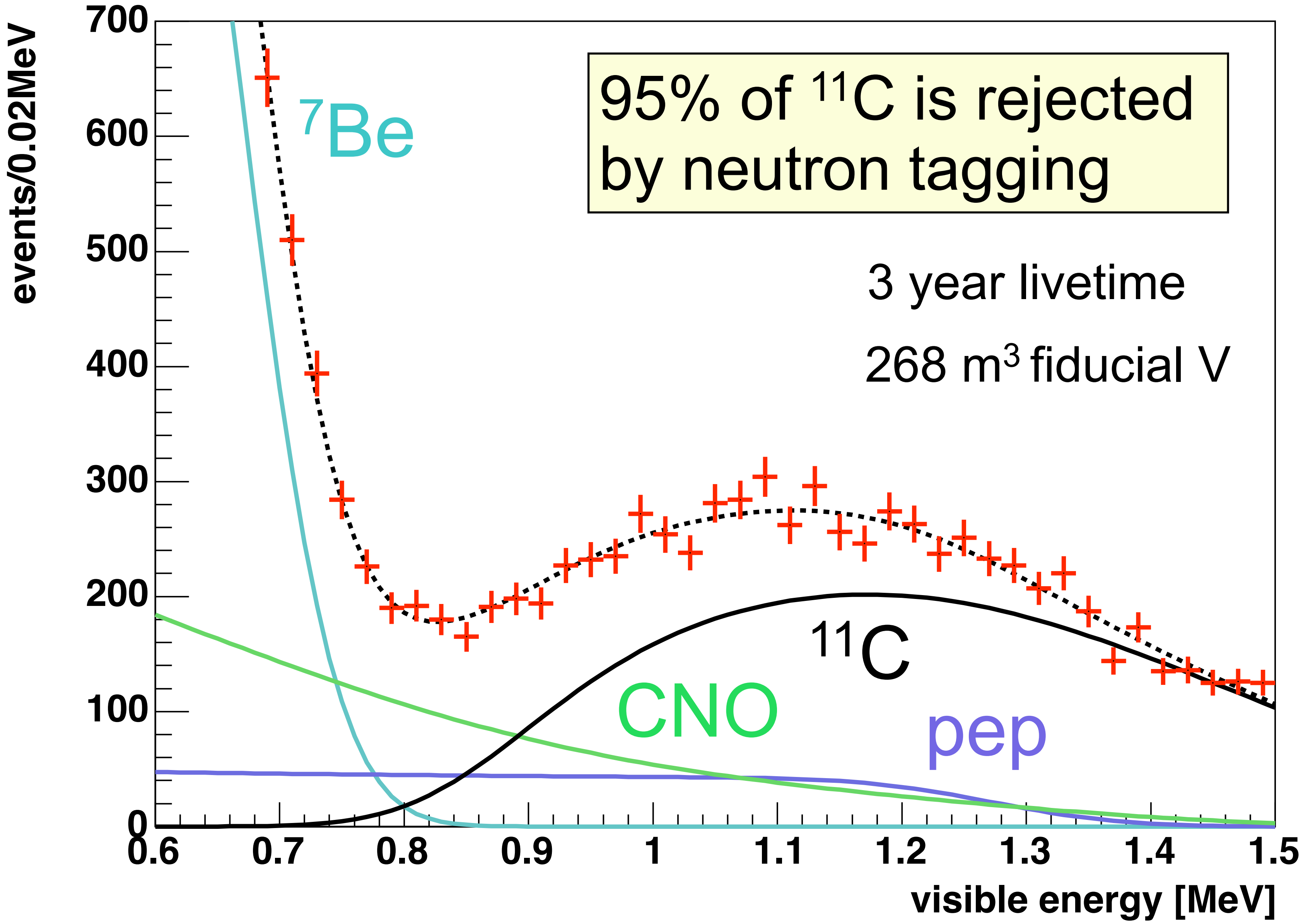
$$^{12}\mathrm{C} + \mathrm{X} \rightarrow {}^{11}\mathrm{C} + n + \mathrm{Y} + \cdots$$

$$\mathrm{X} = \gamma, n, p, \pi^-, \pi^+, e, \mu$$

n production rate ~ 95%   (Galbiati et al., hep-ph/0411002)

Energy Spectra after ^{11}C rejection

pep and CNO ν (0.8 < E < 1.4 MeV)



^{11}C rejection simulation

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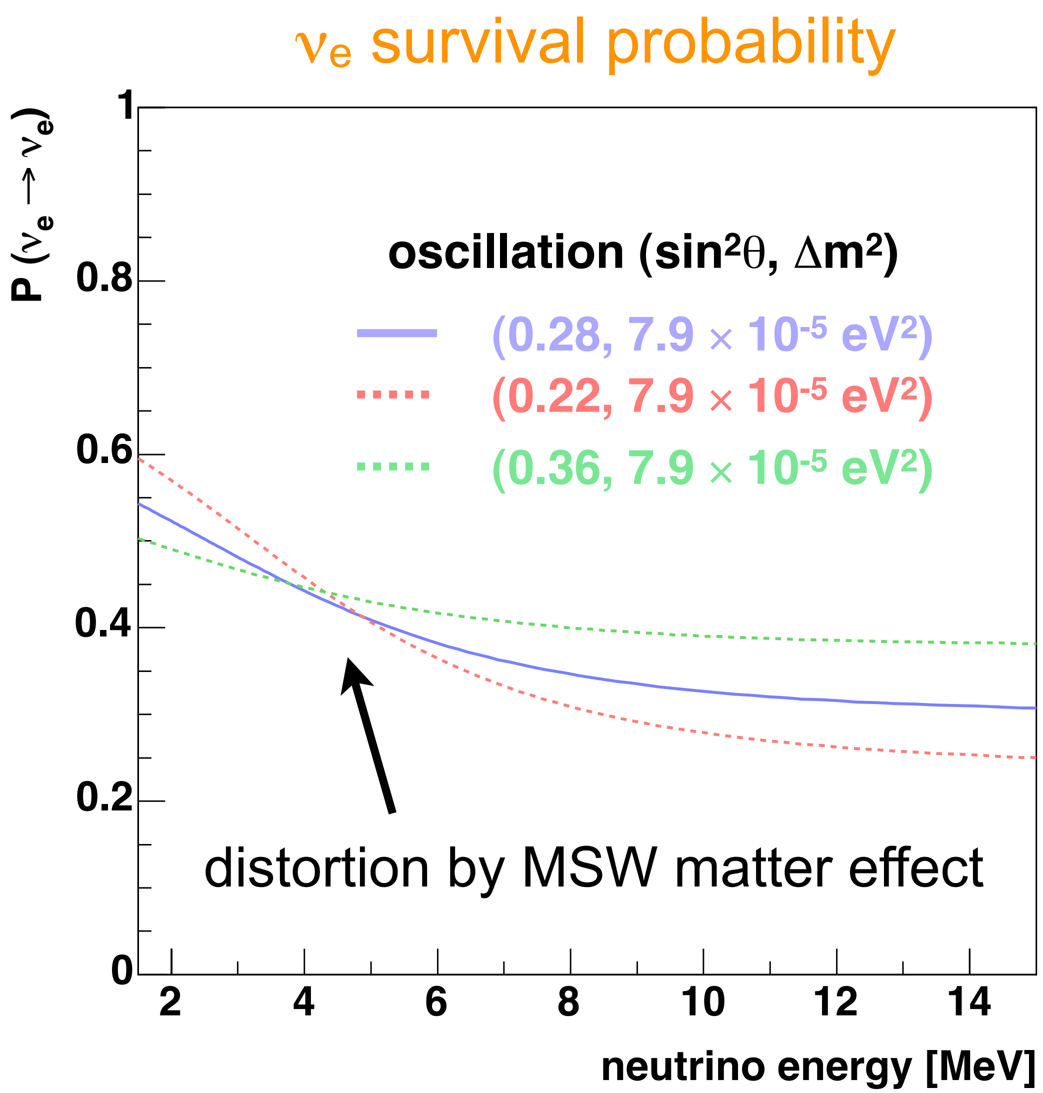
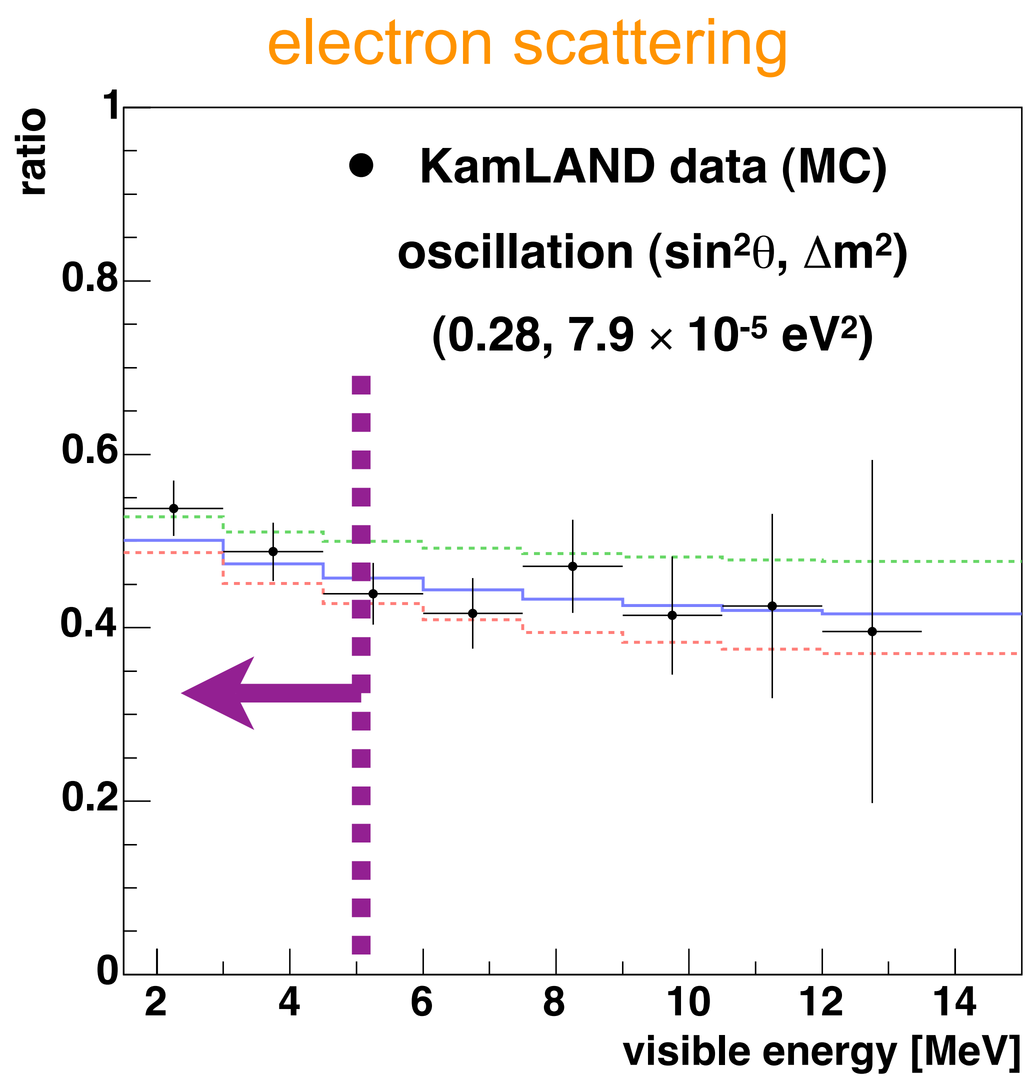
pep + CNO flux error ~ 6% (statistical error)

Low Energy ^{8}B Neutrino MSW Distortion





MC condition

3 year livetime, 268 m^3 fiducial V (assuming no background)
oscillation parameter : $(\sin^2\theta, \Delta m^2) = (0.28, 7.9 \times 10^{-5}\ eV^2)$

MSW distortion will be studied by ^{8}B neutrino

Summary

- Solar neutrino observation revealed ν_e deficit from the sun. **"solar neutrino problem"**
- Reactor neutrino experiment contributed to solutions in solar neutrino problem.

KamLAND experiment

↓

- oscillatory shape of reactor anti-neutrinos
- precise measurement of oscillation parameter

- In the future, observation of low energy solar neutrino will provide a greater understanding of the sun.