Present Status and Future Prospects of KamLAND

The International Workshop on
Double Beta Decay and Neutrinos

Jun. 12, 2007

Itaru Shimizu (Tohoku Univ.)

Solar Neutrinos :
Prediction and Measurement

Prediction

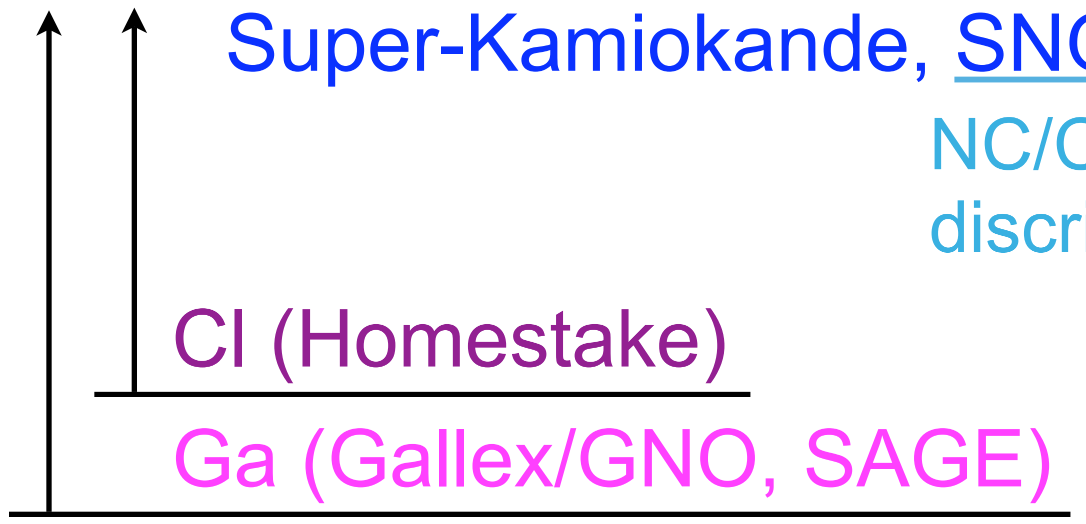
SSM (Standard Solar Model)

high energy ↑

^8B ν	0.01%
CNO ν	1.6%
pep ν	0.2%
^7Be ν	7%
pp ν	91%

low energy ↓

Measurement



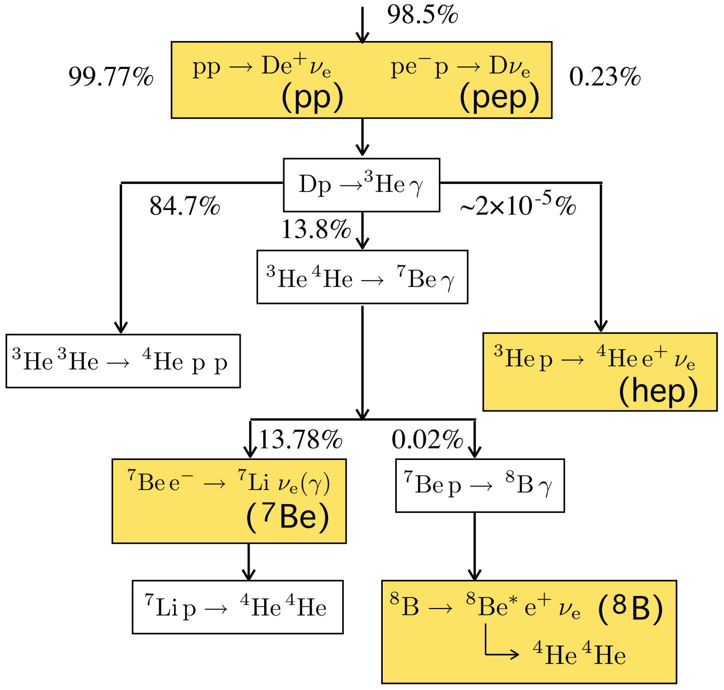
Super-Kamiokande, SNO

NC/CC discrimination

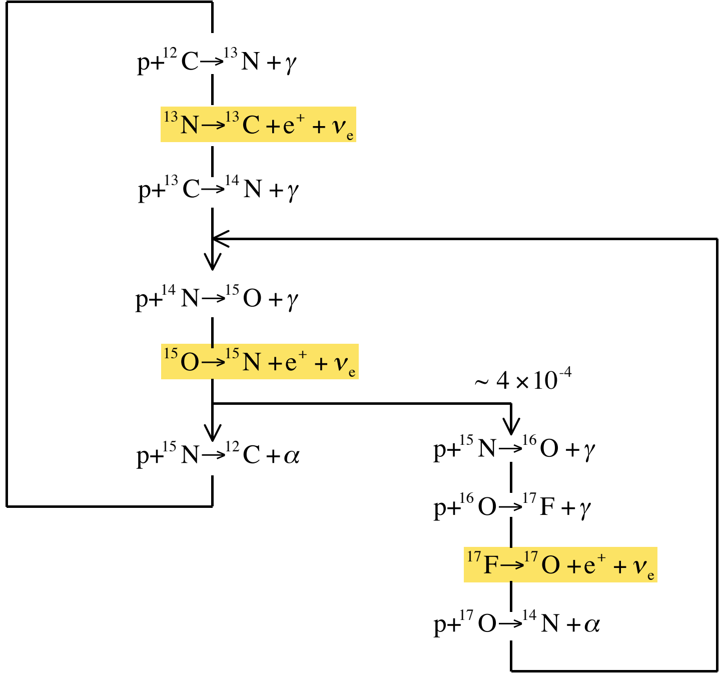
Cl (Homestake)

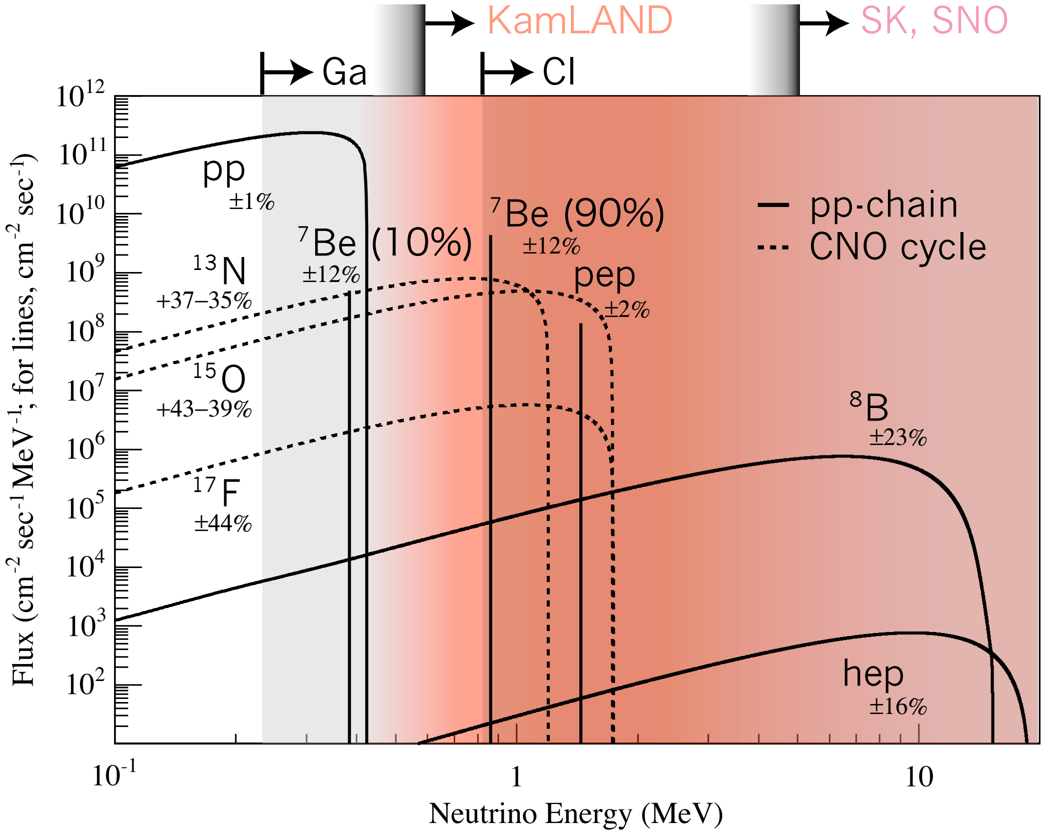
Ga (Gallex/GNO, SAGE)

pp chain



CNO cycle

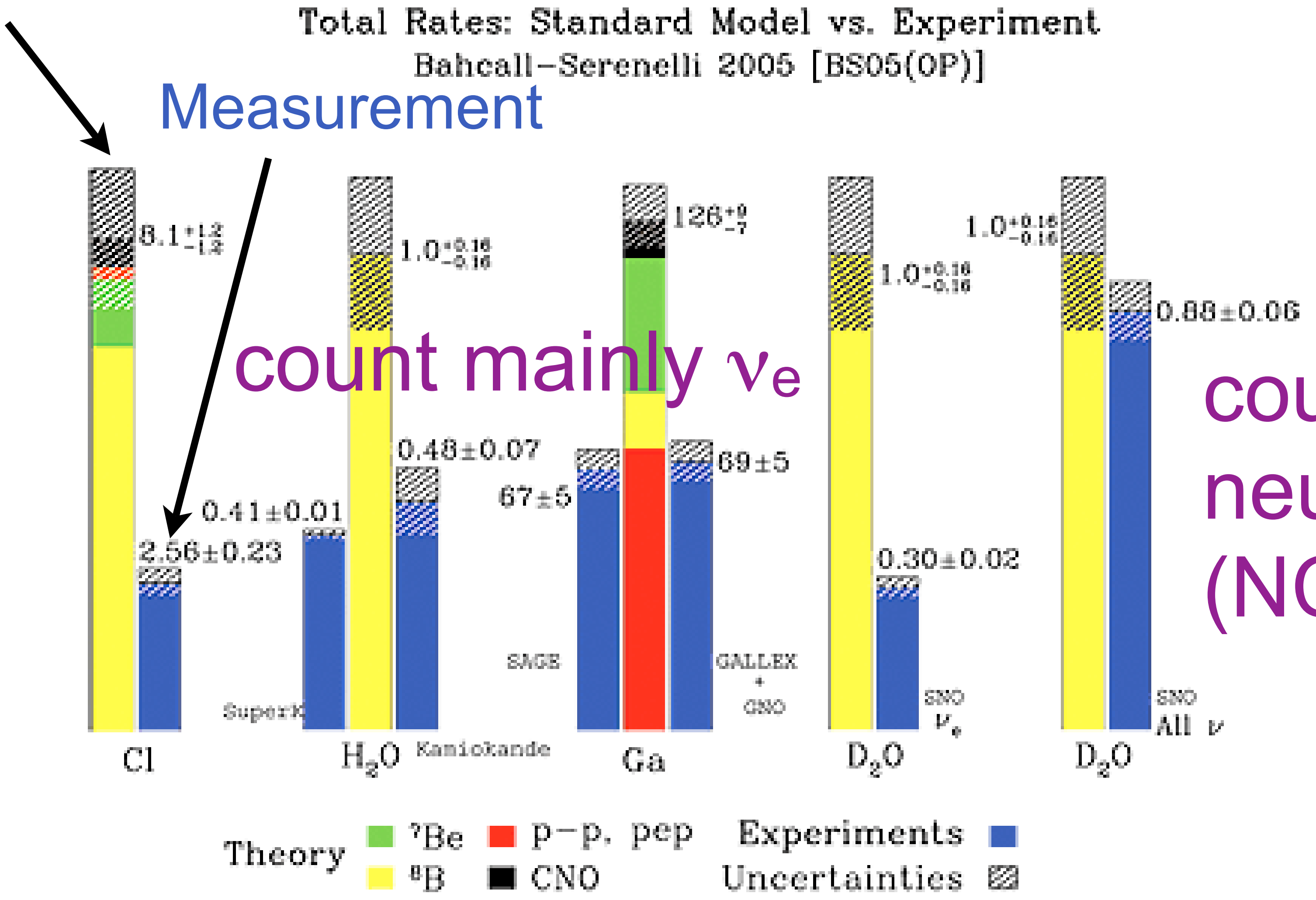




Solar Neutrino Problem

Prediction

Measurement



count mainly ν_e

count all neutrino types (NC)

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

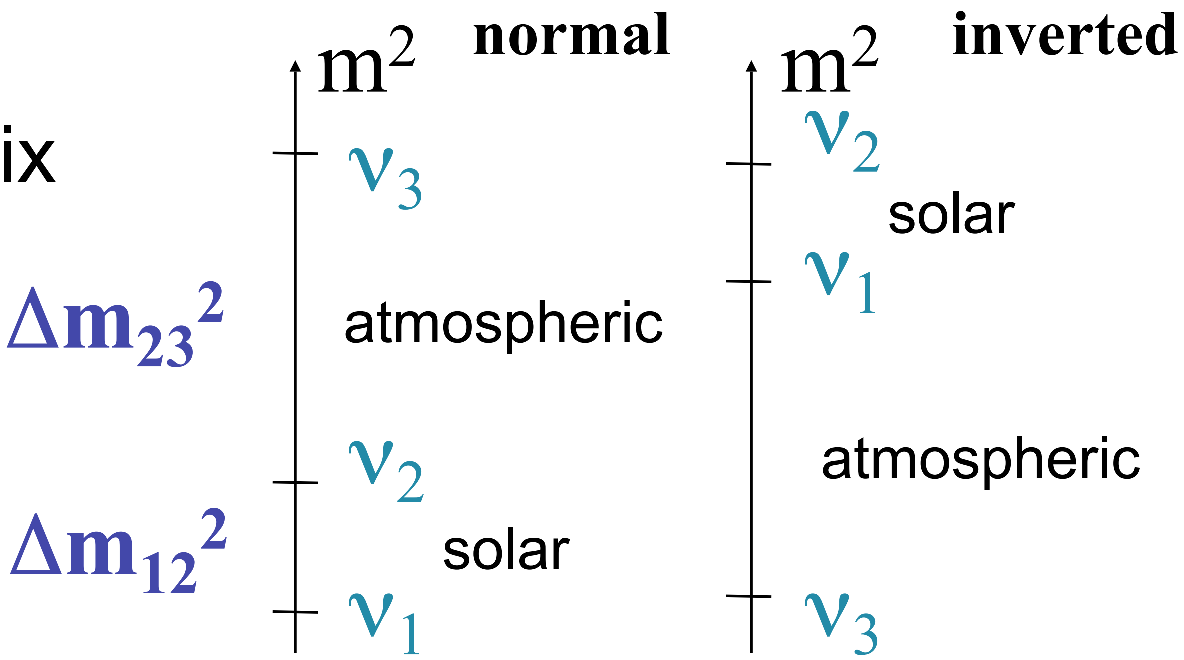
all neutrino type   ~ 1

Measurements show significant ν_e deficit from the sun

Neutrino Oscillations

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 angles, 2 mass differences, 1 CP phase

\+ 2 Majorana phase

↓

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

KamLAND Experiment

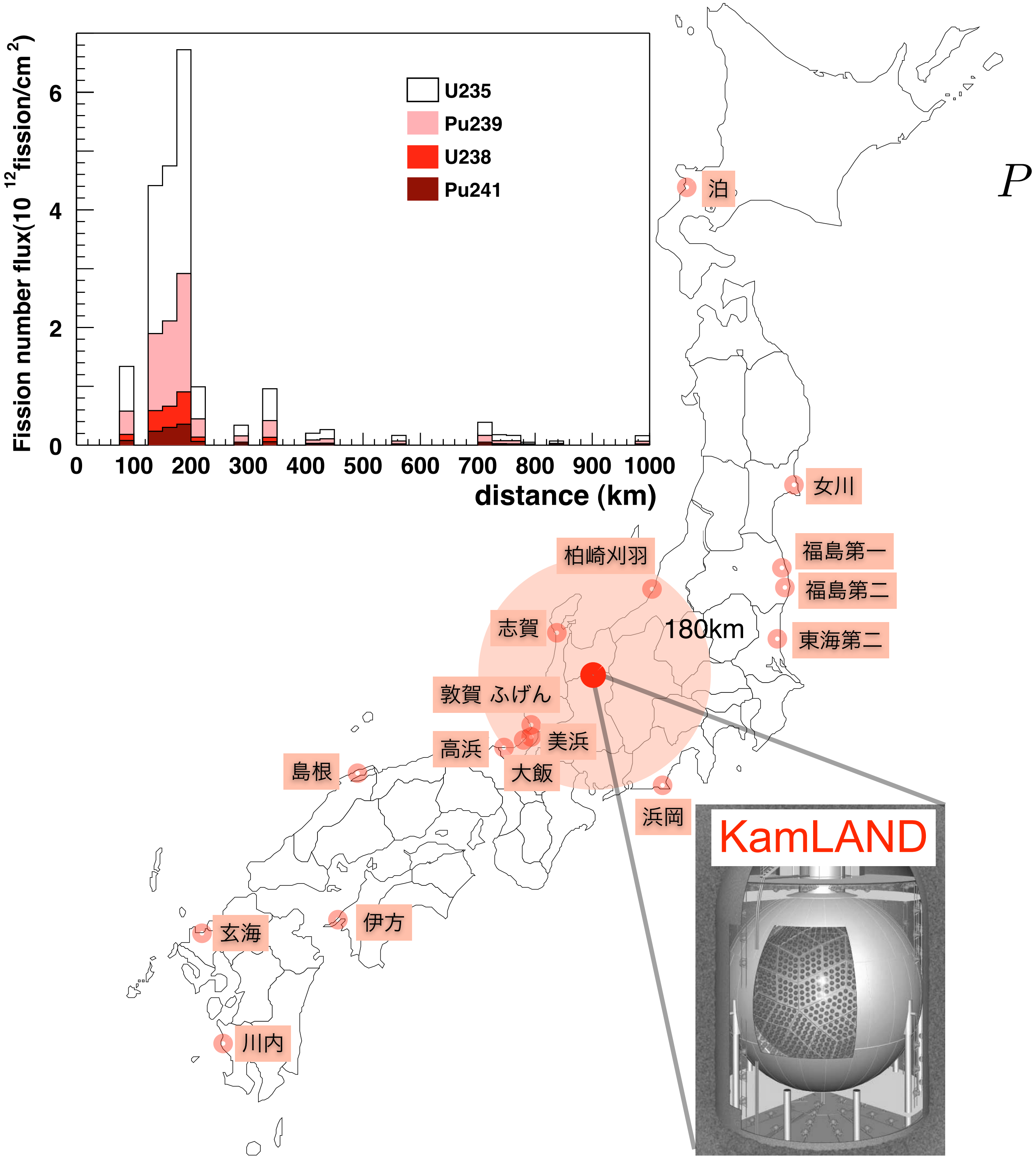
KamLAND Collaboration

T. Araki,1 K. Eguchi,1 S. Enomoto,1 K. Furuno,1 K. Ichimura,1 H. Ikeda,1 K. Inoue,1 K. Ishihara,1,* T. Iwamoto,1,†
T. Kawashima,1 Y. Kishimoto,1 M. Koga,1 Y. Koseki,1 T. Maeda,1 T. Mitsui,1 M. Motoki,1 K. Nakajima,1 H. Ogawa,1
K. Owada,1 J.-S. Ricol,1 I. Shimizu,1 J. Shirai,1 F. Suekane,1 A. Suzuki,1 K. Tada,1 O. Tajima,1 K. Tamae,1 Y. Tsuda,1
H. Watanabe,1 J. Busenitz,2 T. Classen,2 Z. Djurcic,2 G. Keefer,2 K. McKinny,2 D.-M. Mei,2,‡ A. Piepke,2 E. Yakushev,2
B. E. Berger,3 Y. D. Chan,3 M. P. Decowski,3 D. A. Dwyer,3 S. J. Freedman,3 Y. Fu,3 B. K. Fujikawa,3 J. Goldman,3
F. Gray,3 K. M. Heeger,3 K. T. Lesko,3 K.-B. Luk,3 H. Murayama,3,x A.W. P. Poon,3 H. M. Steiner,3 L. A. Winslow,3
G. A. Horton-Smith,4,k C. Mauger,4 R. D. McKeown,4 P. Vogel,4 C. E. Lane,5 T. Miletic,5 P.W. Gorham,6 G. Guillian,6
J. G. Learned,6 J. Maricic,6 S. Matsuno,6 S. Pakvasa,6 S. Dazeley,7 S. Hatakeyama,7 A. Rojas,7 R. Svoboda,7
B. D. Dieterle,8 J. Detwiler,9 G. Gratta,9 K. Ishii,9 N. Tolich,9 Y. Uchida,9,{ M. Batygov,10 W. Bugg,10 Y. Efremenko,10
Y. Kamyshkov,10 A. Kozlov,10 Y. Nakamura,10 C. R. Gould,11 H. J. Karwowski,11 D. M. Markoff,11 J. A. Messimore,11
K. Nakamura,11 R. M. Rohm,11W. Tornow,11 R.Wendell,11 A. R. Young,11 M.-J. Chen,12 Y.-F.Wang,12 and F. Piquemal13

(KamLAND Collaboration)

1Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
2Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA
3Physics Department, University of California at Berkeley, Berkeley, California 94720, USA,
and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
4W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA
5Physics Department, Drexel University, Philadelphia, Pennsylvania 19104, USA
6Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA
7Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA
8Physics Department, University of New Mexico, Albuquerque, New Mexico 87131, USA
9Physics Department, Stanford University, Stanford, California 94305, USA
10Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
11Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA,
and Physics Departments at Duke University, North Carolina State University,
and the University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA
12Institute of High Energy Physics, Beijing 100039, People's Republic of China
13CEN Bordeaux-Gradignan, IN2P3-CNRS and University Bordeaux I, F-33175 Gradignan Cedex, France

KamLAND Experiment



2 flavor neutrino oscillation

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

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%

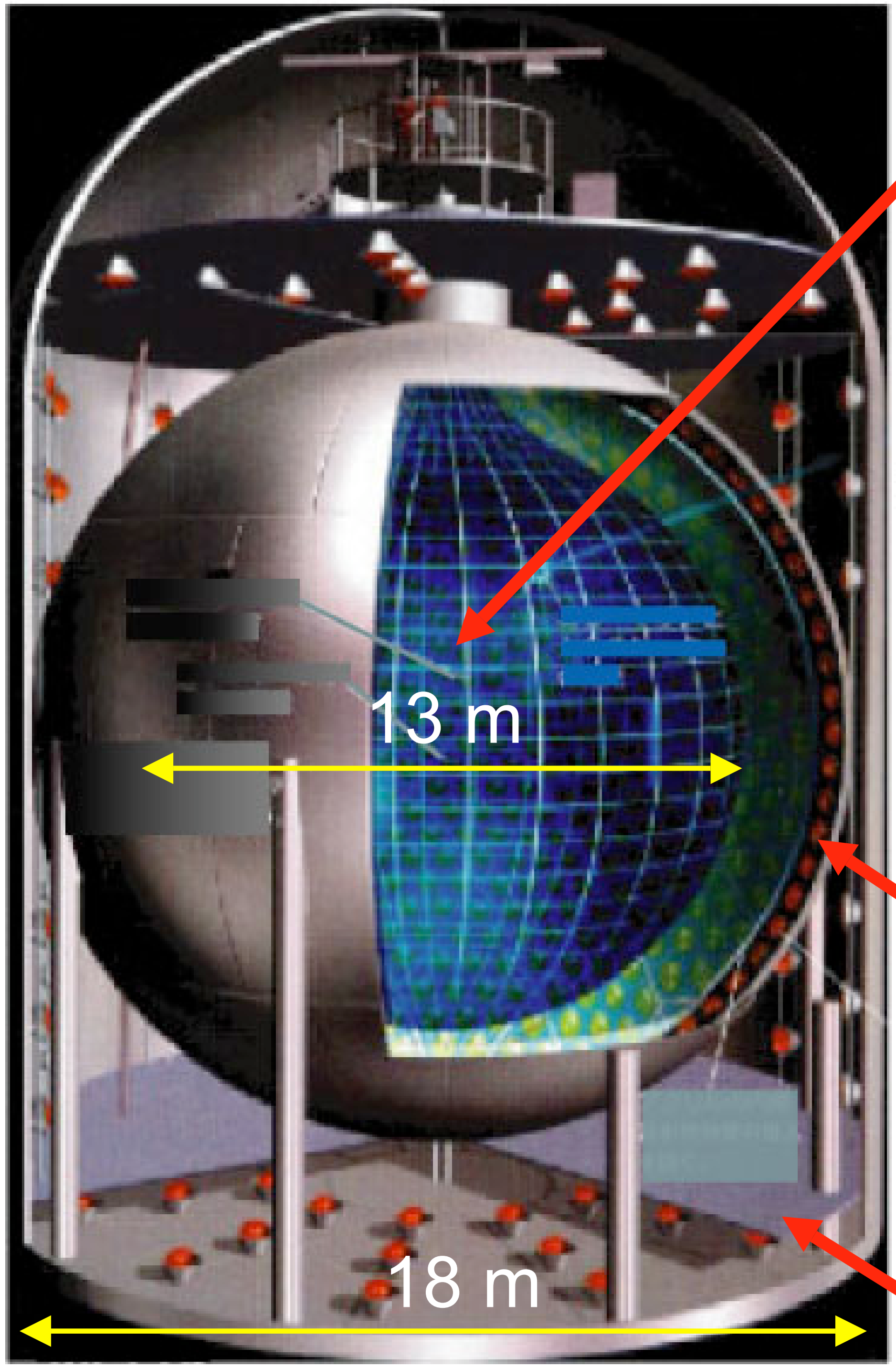
ΔE (energy resolution)

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

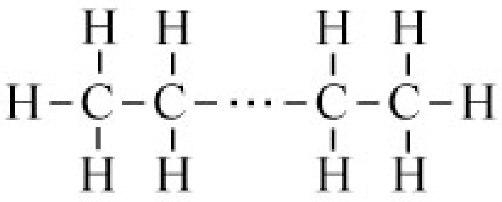


1,000 ton Liquid Scintillator

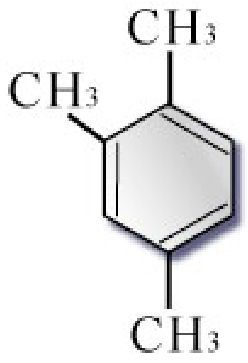
Pseudocumene (20%)

Dodecane (80%)

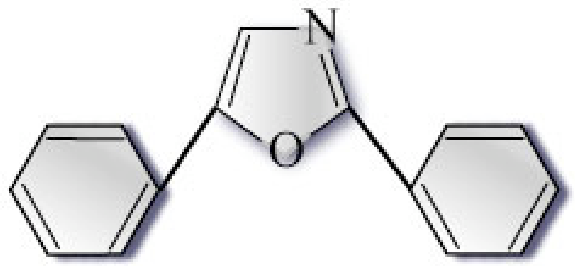
PPO (1.5 g/l)



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



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



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

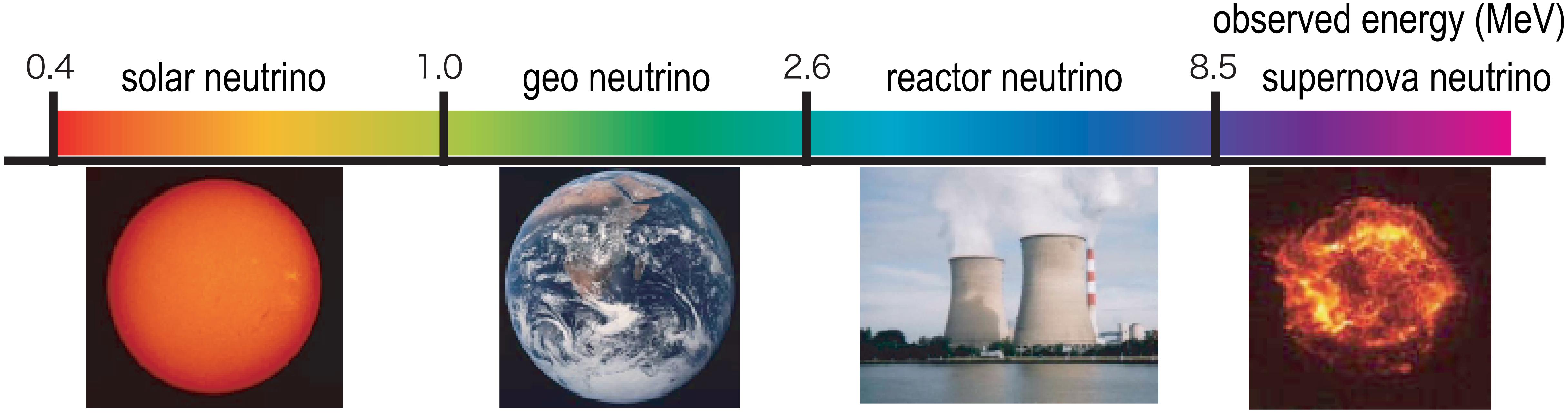
1,325 17 inch + 554 20 inch PMTs

commissioned in February, 2003

photocathode coverage : 22% → 34%

Water Cherenkov Outer Detector

Physics Target in KamLAND

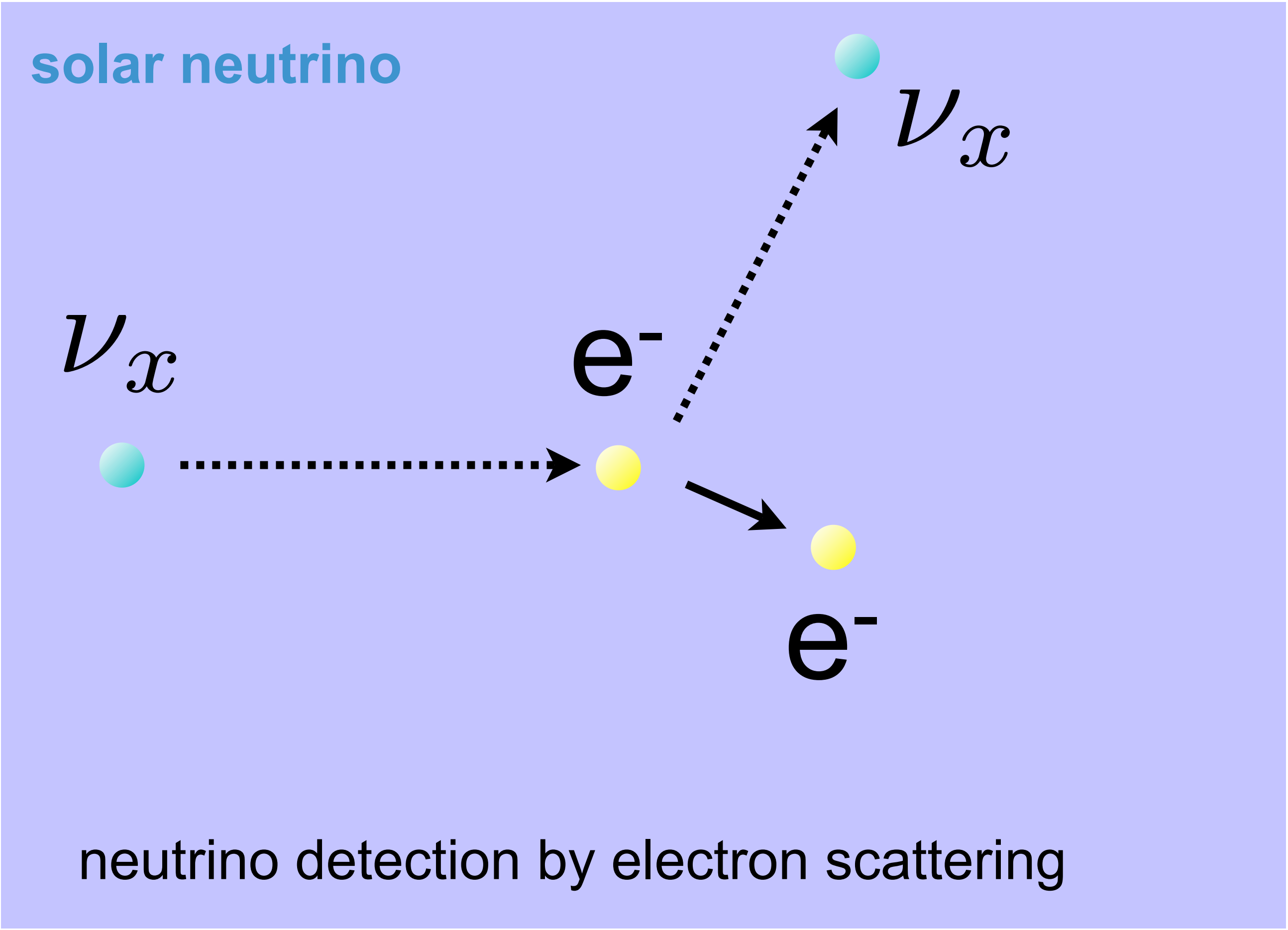

observed energy (MeV)

0.4 solar neutrino

1.0 geo neutrino

2.6 reactor neutrino

8.5 supernova neutrino


solar neutrino

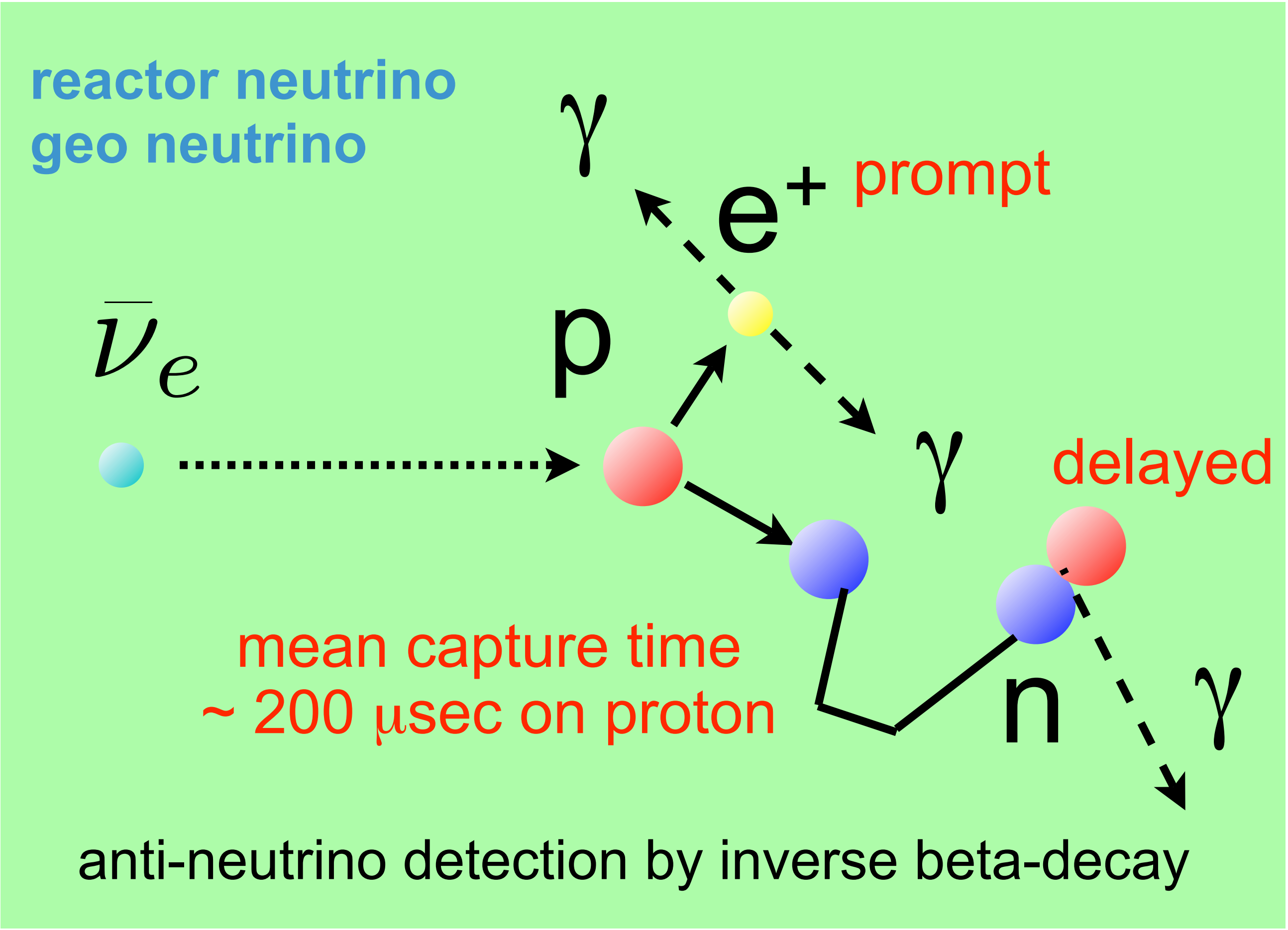
ν_x

e^-

ν_x

e^-

neutrino detection by electron scattering


reactor neutrino
geo neutrino

γ

e^+ prompt

$\bar{\nu}_e$

p

γ

delayed

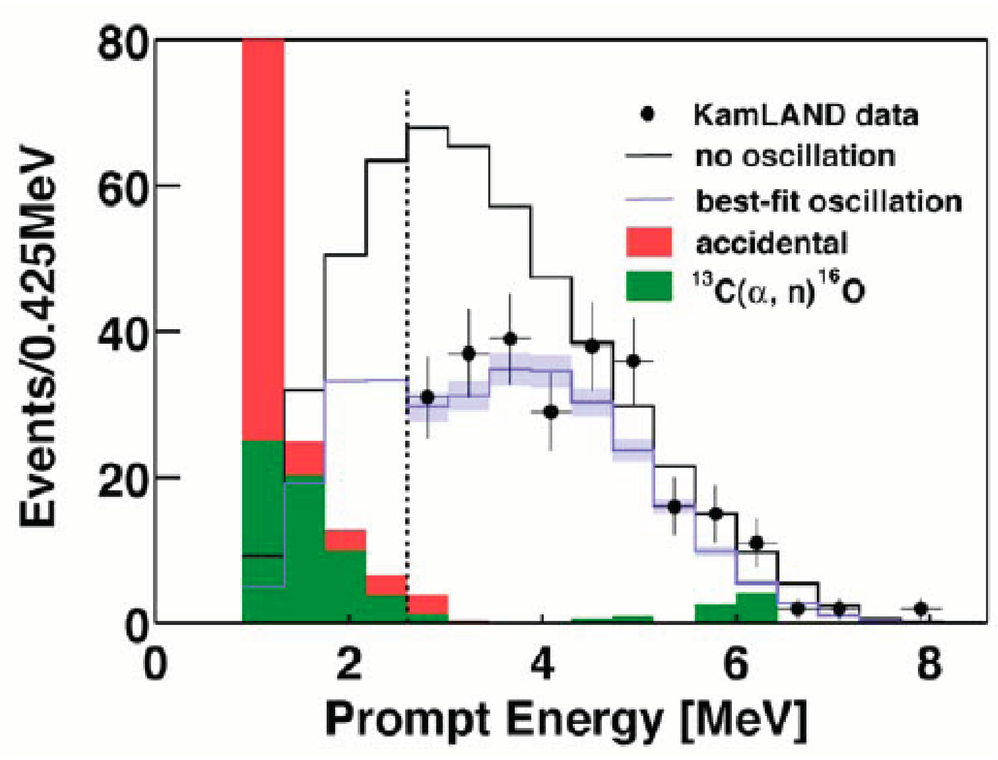
mean capture time
~ 200 μsec on proton

n

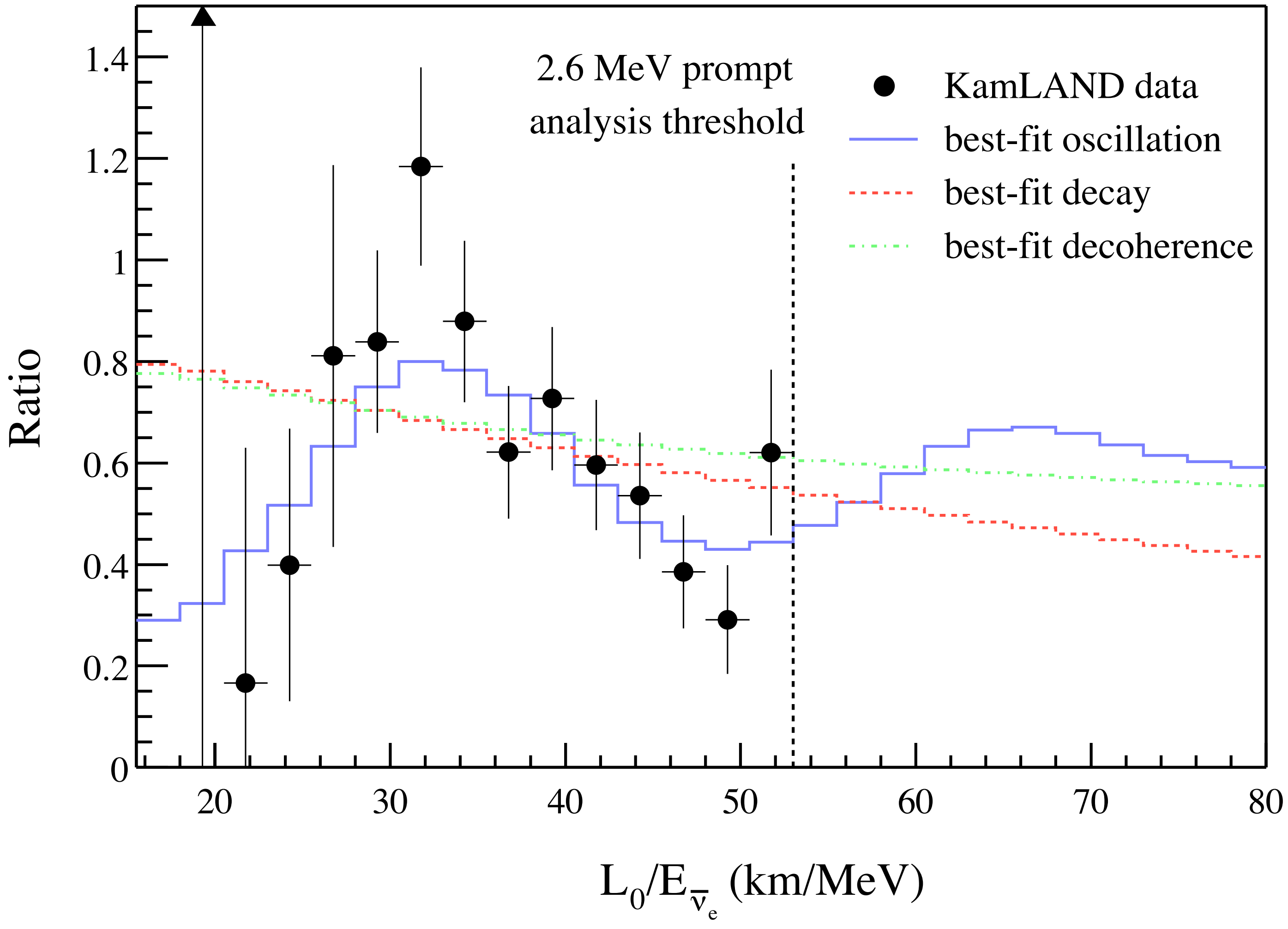
γ

anti-neutrino detection by inverse beta-decay

Evidence of Disappearance and Distortion



766 ton-year data-set



Rate

$N_{obs} / N_{expected\ (no\ oscillation)} = 0.658 \pm 0.044(stat) \pm 0.042(syst)$

Disappearance : 99.998% C.L.

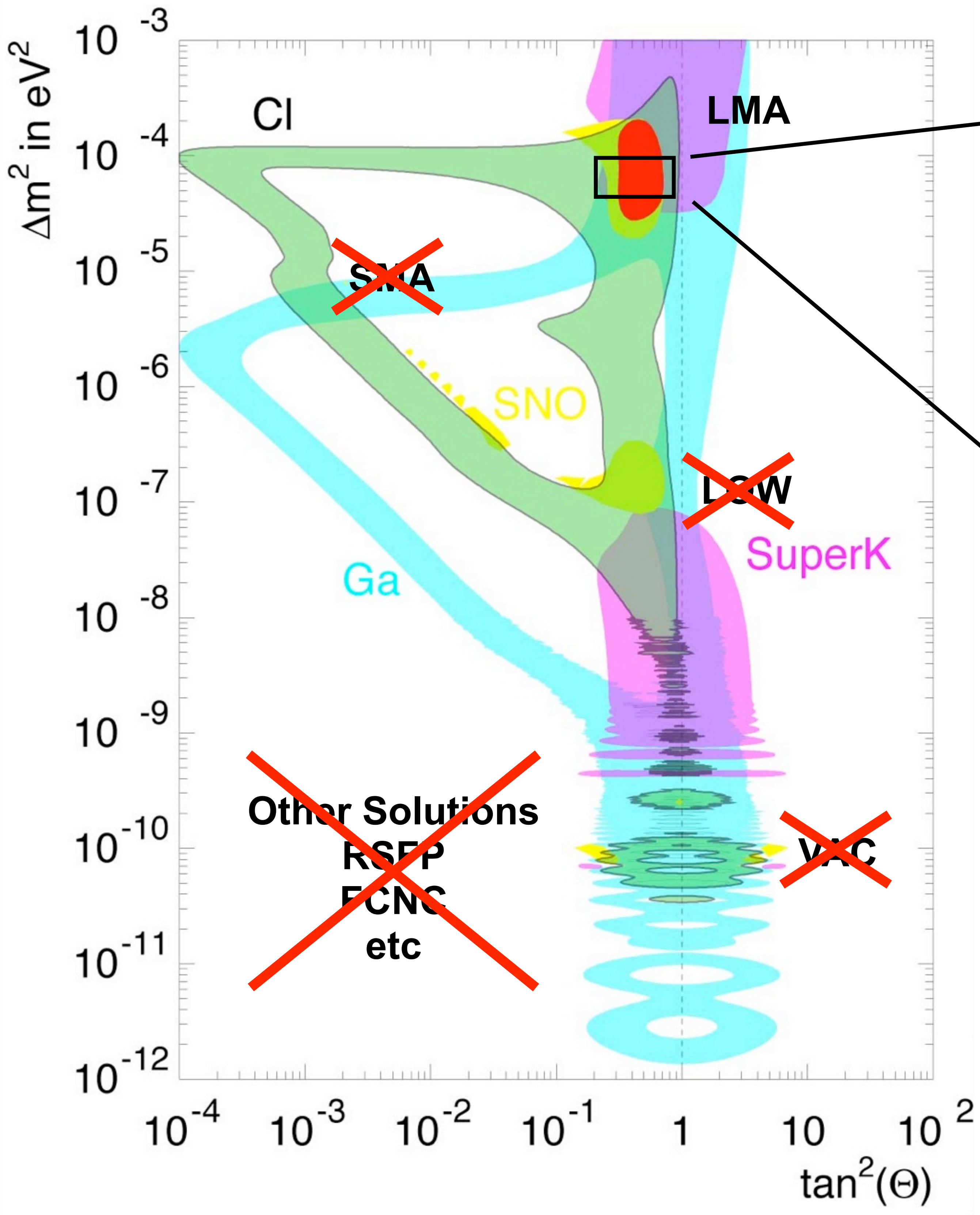
Shape

$\chi^2 / ndf = 37.3 / 19$ (scaled no oscillation)

Distortion : 99.6% C.L.

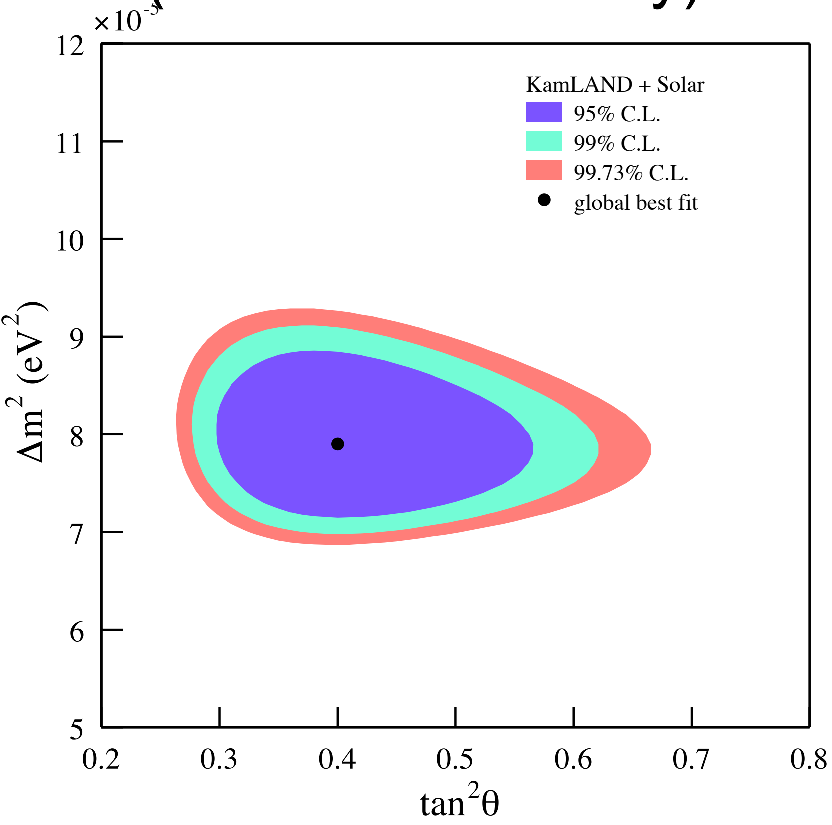
Rate + Shape (combined) 99.999995% C.L.

Precise Measurement of Oscillation Parameter



solar + KamLAND result

(livetime 515.1 day)



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

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

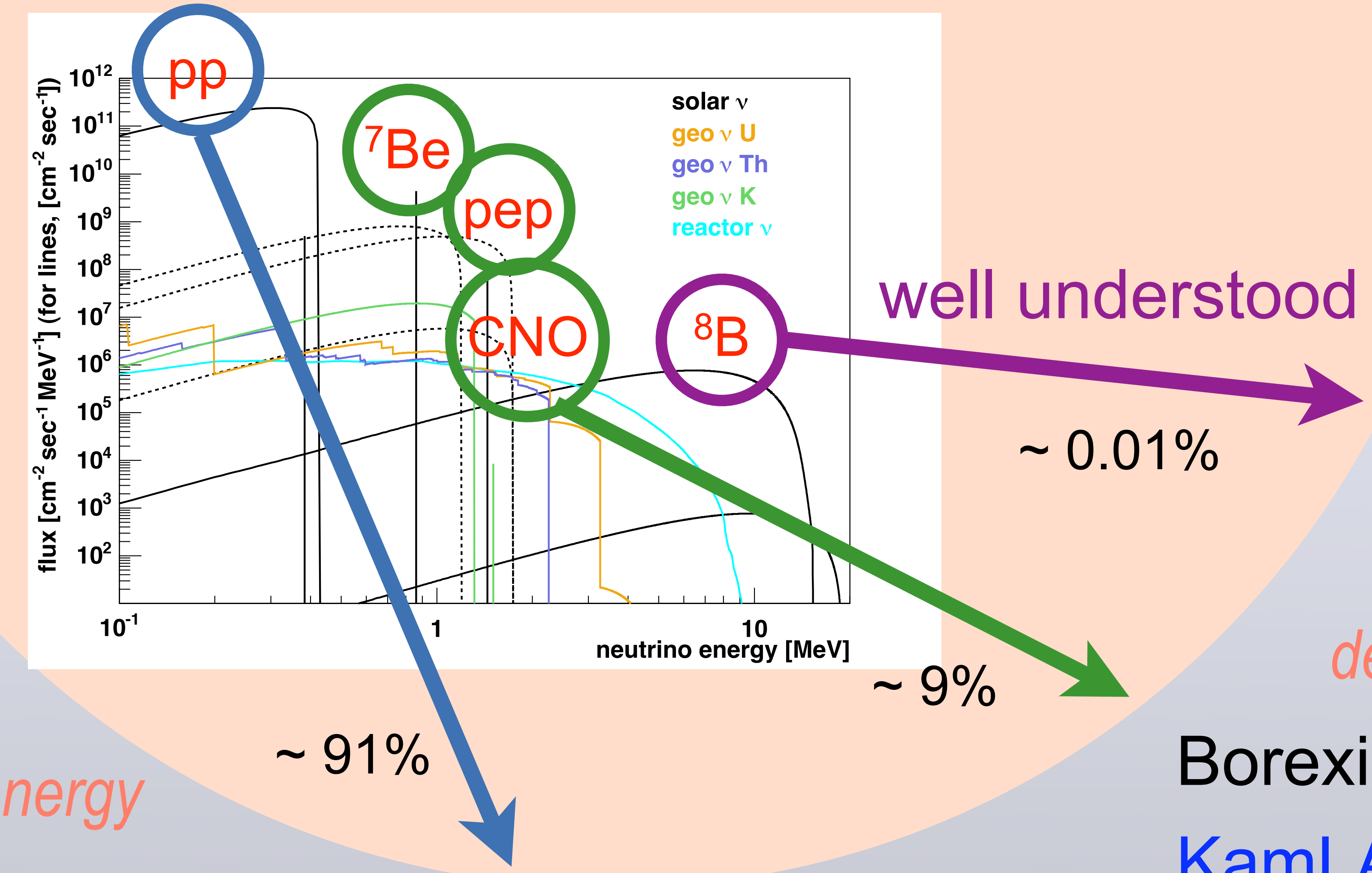
present status

- Statistics increase ~ 3 times
- Full volume calibration can reduce the systematic uncertainty

Future Prospects
KamLAND II
(Solar Neutrino Phase)

Future Solar Neutrino Measurement

low energy solar neutrino observation



well understood

~ 0.01%

~ 9%

~ 91%

high energy

Super-Kamiokande
SNO

development stage ...

Borexino
KamLAND II
} working

SNO+
LENA

low energy

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

XMass
CLEAN

$$\nu_e n \rightarrow e^- p$$

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

Status of the Solar Model

- heavy element abundance

new solar model

AGS05 abundance lower abundance of heavy elements

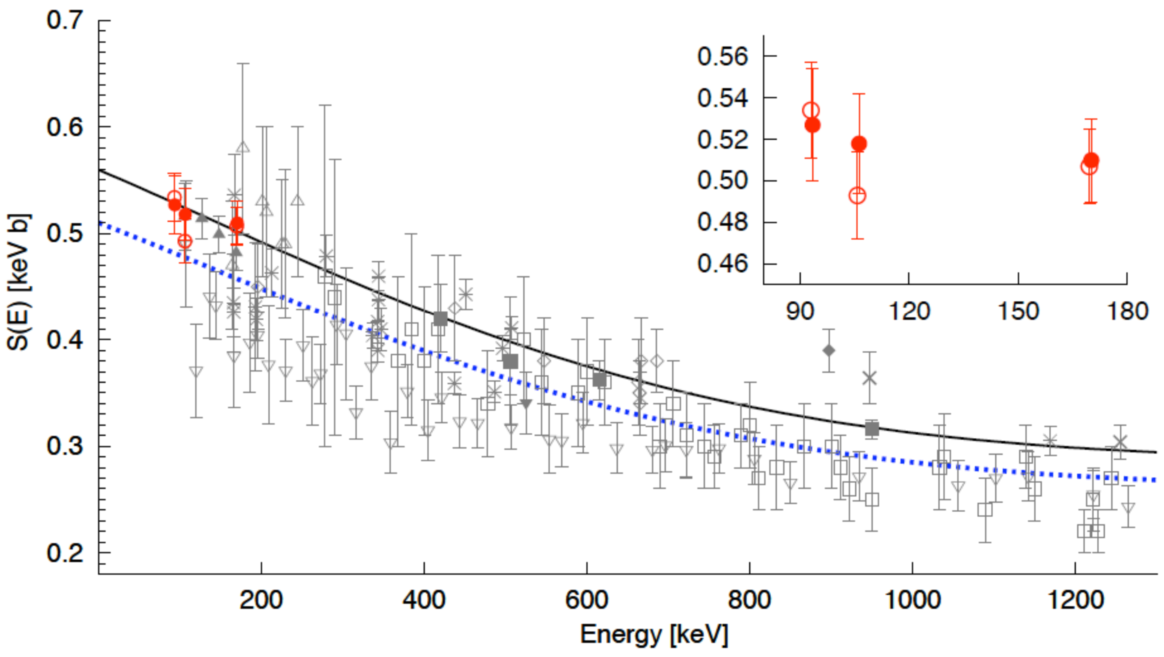
improved measurement ↕ strong disagreement

helioseismological measurement

- nuclear cross sections

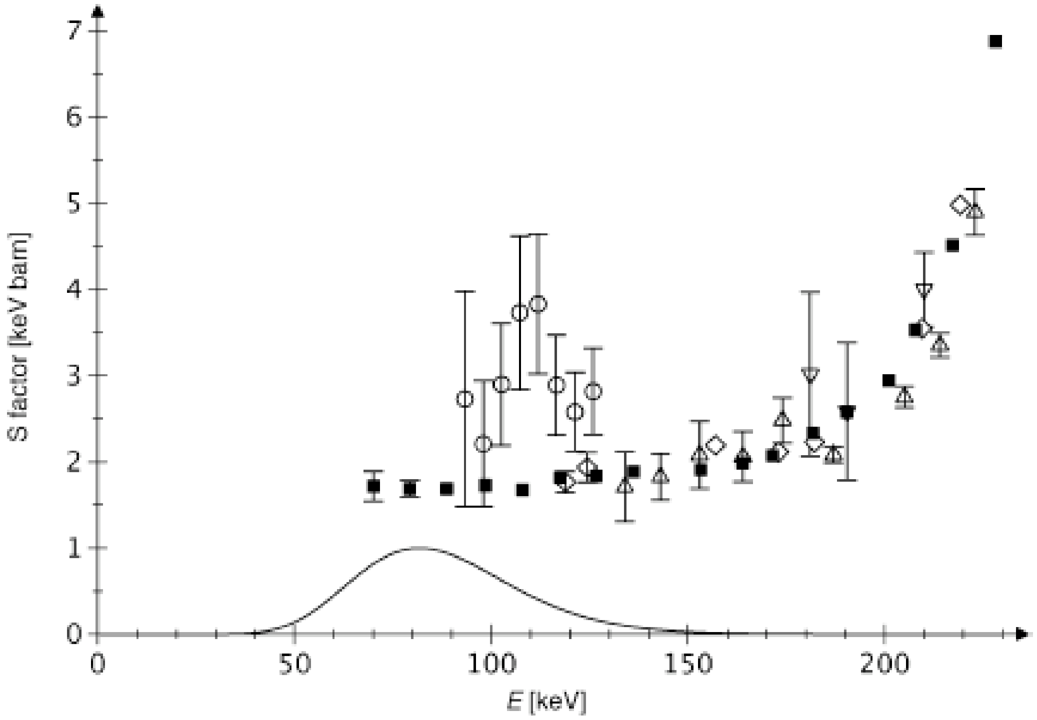
$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ LUNA results $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$

F. Confortola et al., nucl-ex/0705.2151 (2007)



S(0) = 0.560 ± 0.017 keV b

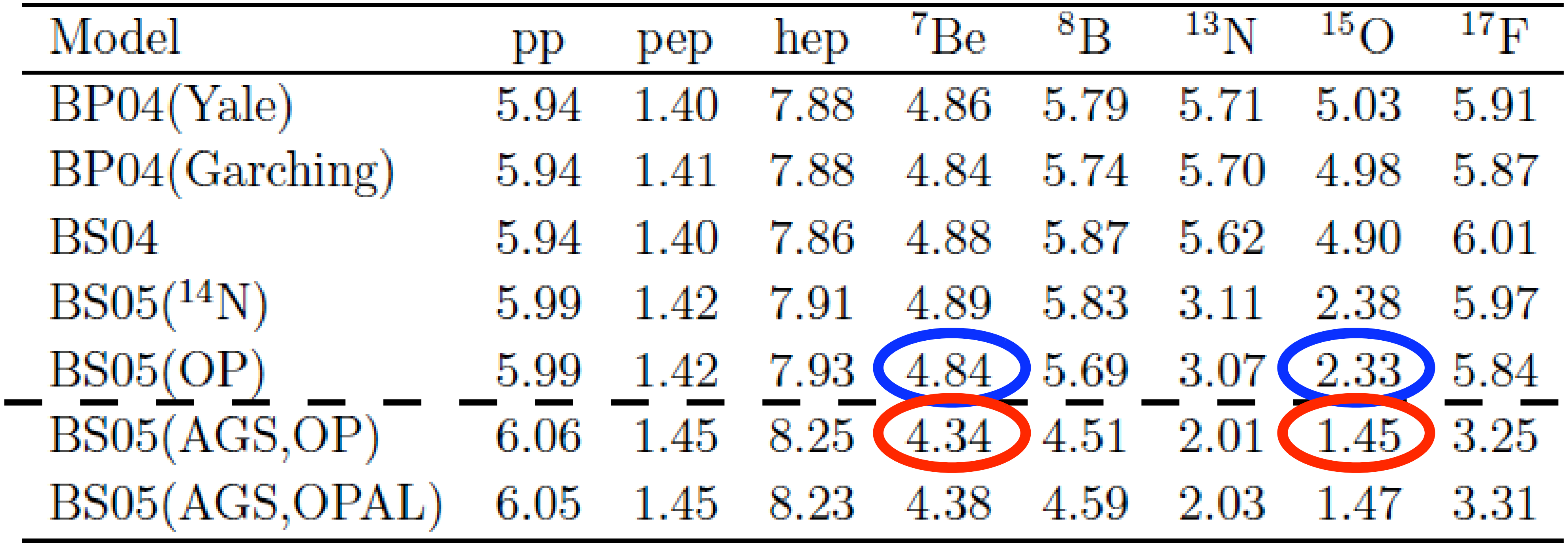
A. Lemut et al., Phys. Lett. B 634, 483 (2006)



S(0) = 1.7 ± 0.2 keV b

Predicted Solar Neutrino Flux

J.N. Bahcall and A.M. Serenelli, Astro. Phys. J. 621, 85 (2005)



Model	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
BP04(Yale)	5.94	1.40	7.88	4.86	5.79	5.71	5.03	5.91
BP04(Garching)	5.94	1.41	7.88	4.84	5.74	5.70	4.98	5.87
BS04	5.94	1.40	7.86	4.88	5.87	5.62	4.90	6.01
BS05(^{14}N)	5.99	1.42	7.91	4.89	5.83	3.11	2.38	5.97
BS05(OP)	5.99	1.42	7.93	4.84	5.69	3.07	2.33	5.84
BS05(AGS,OP)	6.06	1.45	8.25	4.34	4.51	2.01	1.45	3.25
BS05(AGS,OPAL)	6.05	1.45	8.23	4.38	4.59	2.03	1.47	3.31

GS98

AGS05

-10%

S_{34} : 2.5%

-38%

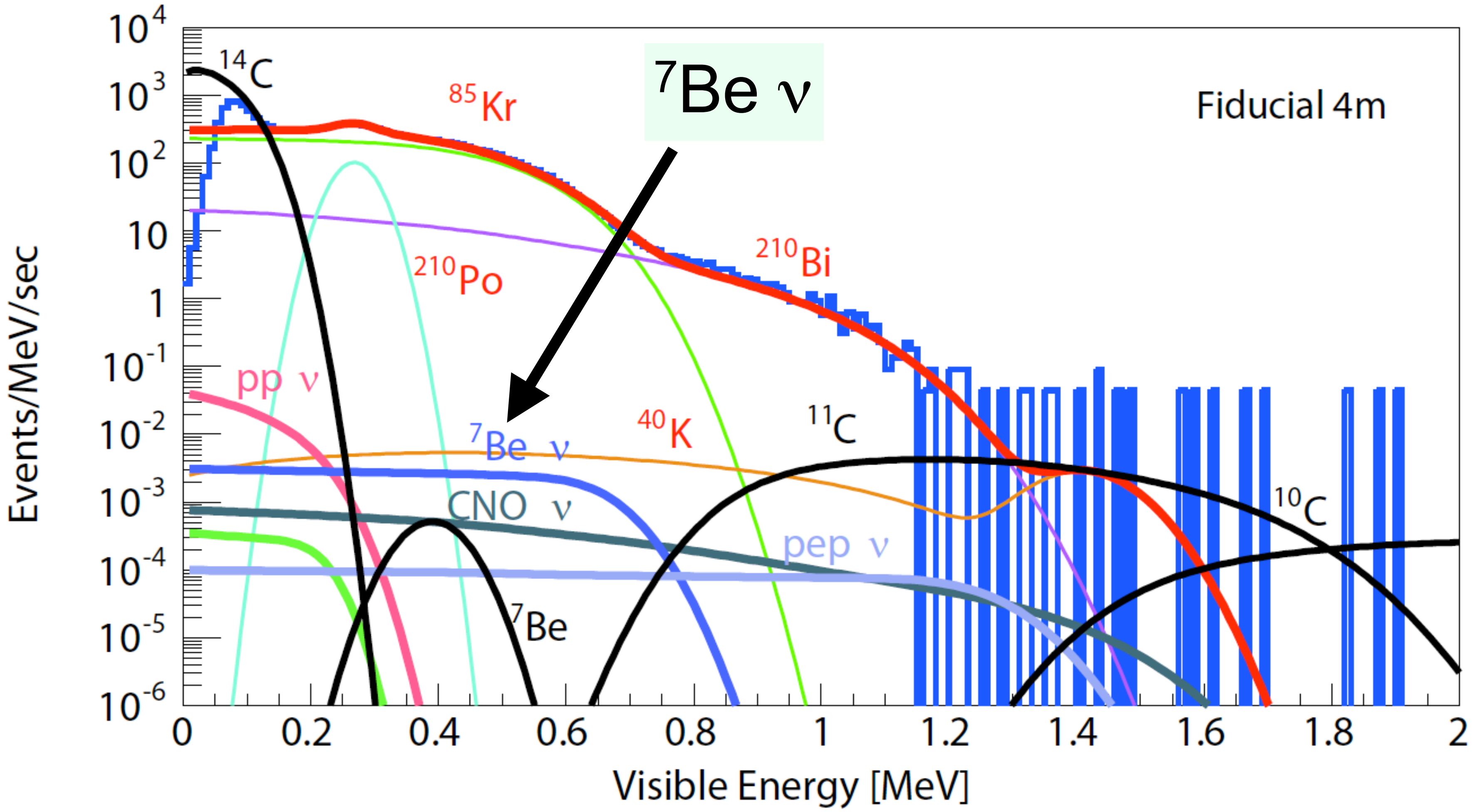
$S_{1,14}$: 8.4%

- LUNA experiment measured nuclear cross section precisely
- Dominant error comes from heavy element abundance

KamLAND will measure ^{7}Be and CNO solar neutrinos and test the lower abundance of heavy element (AGS05)

KamLAND II (Solar Neutrino Phase)

KamLAND singles spectra

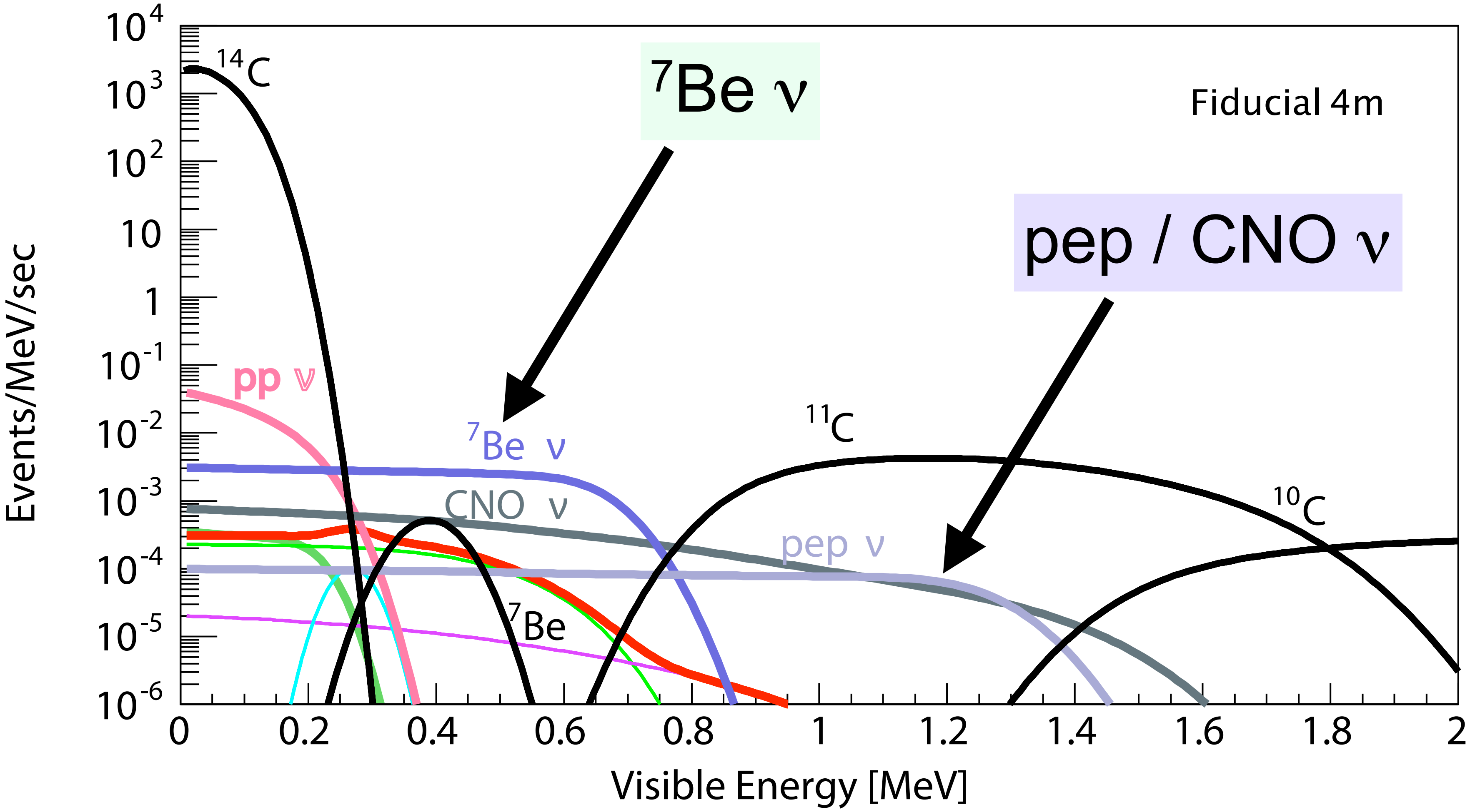


^{7}Be ν observation

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

Energy Spectra after Purification

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


^{7}Be ν

pep / CNO ν

expected event rate (no oscillation)   0.3 < E < 0.8 MeV

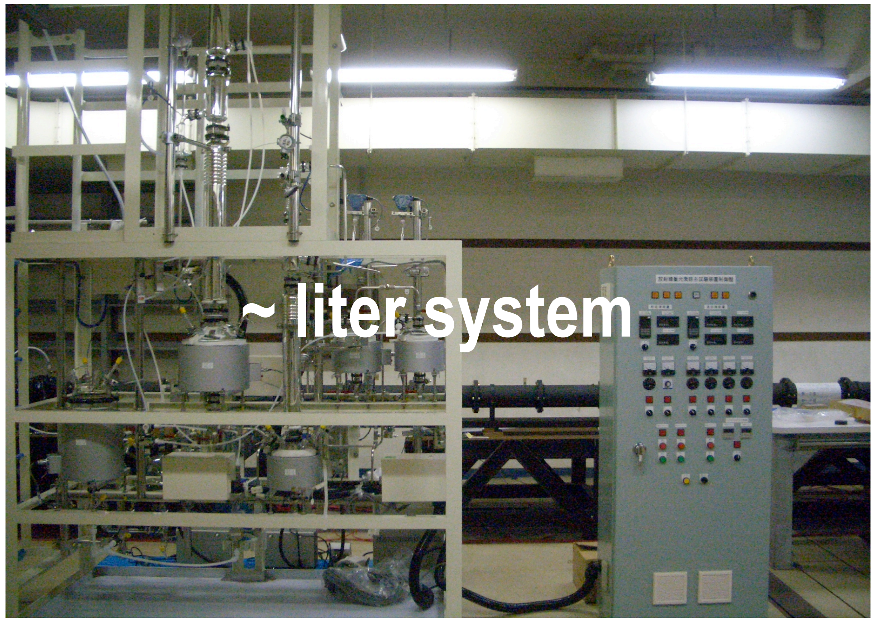
^{7}Be ν	79.9 events / day
pep ν	3.8 events / day
CNO ν	16.3 events / day

Purification of Liquid Scintillator

distillation method

separation of substances based on boiling point differences

~ milli-liter system



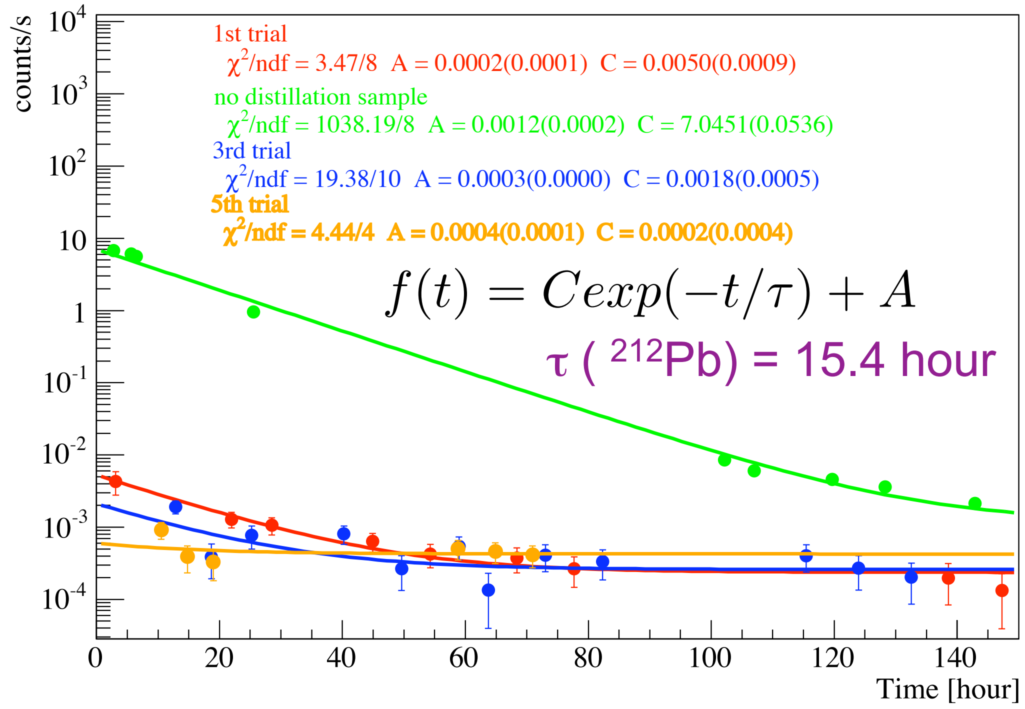
~ liter system

real system

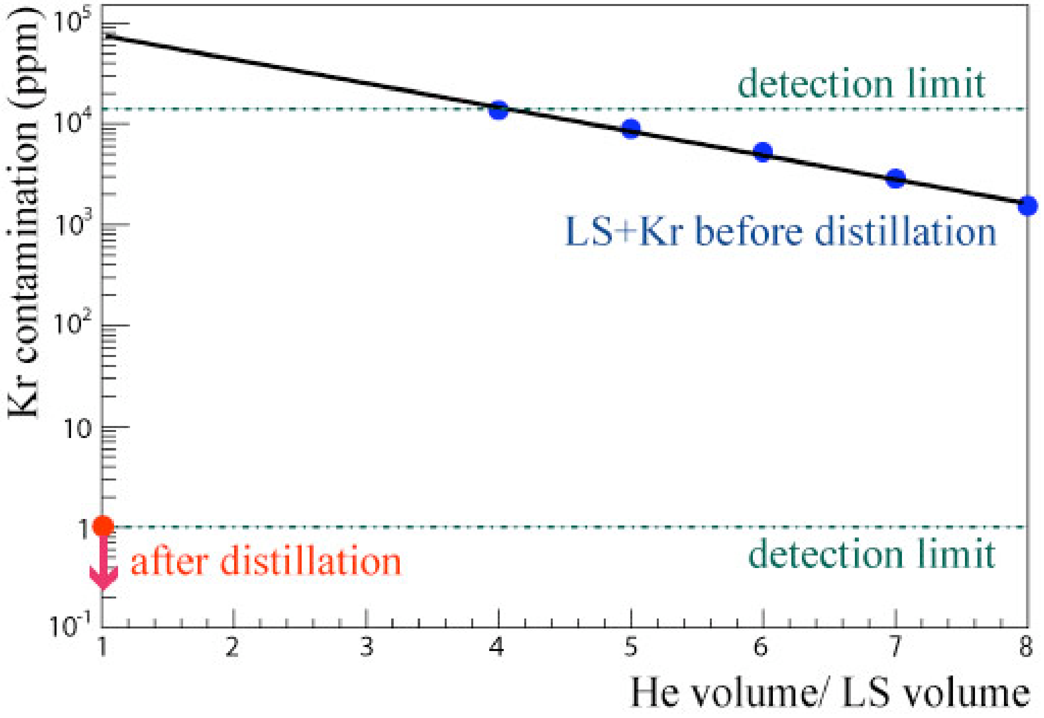
~ 1.5 kilo-liter / hour

Reduction Efficiency by Distillation

Pb reduction



Kr reduction



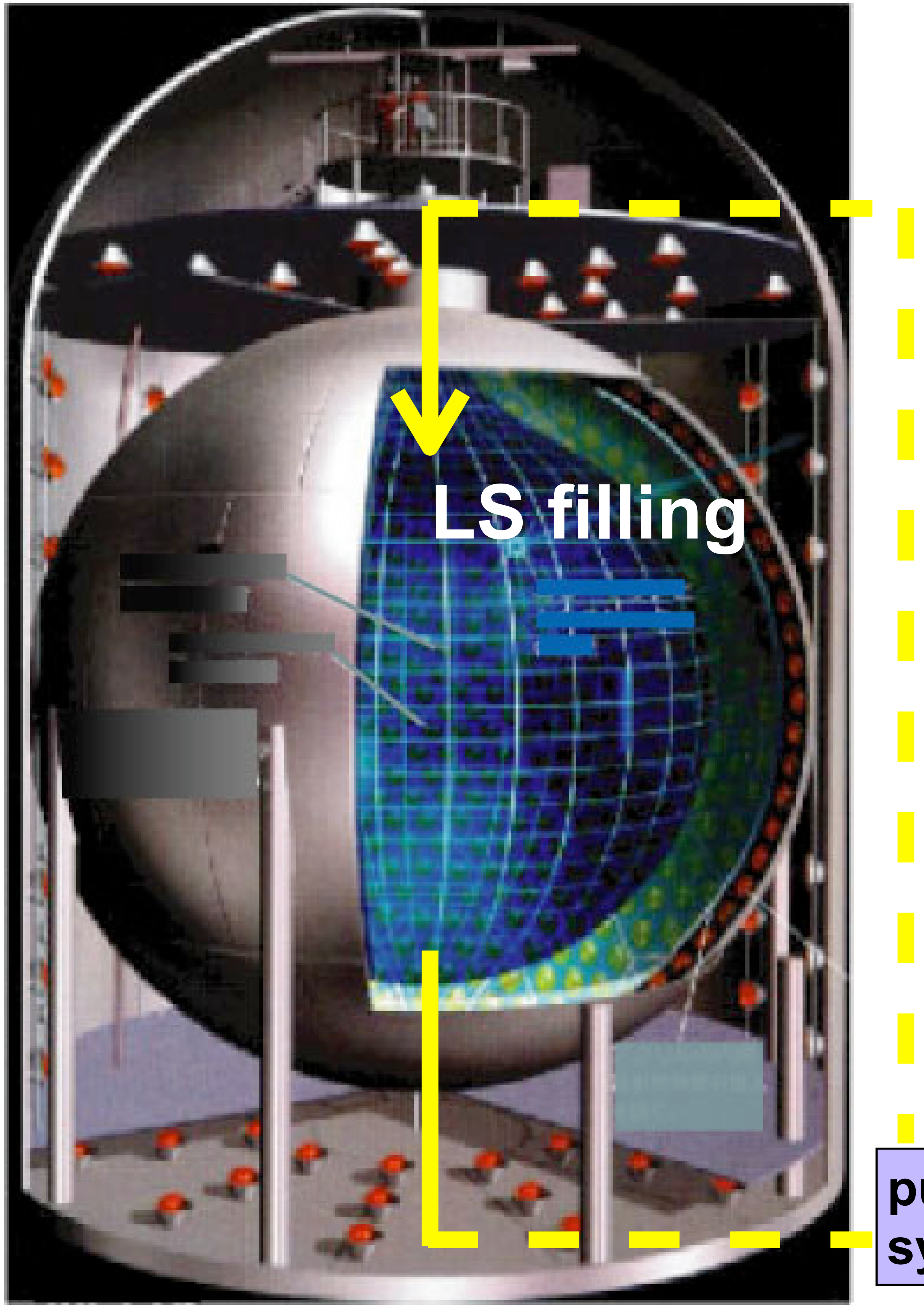
distillation in ~ liter-system

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

↓

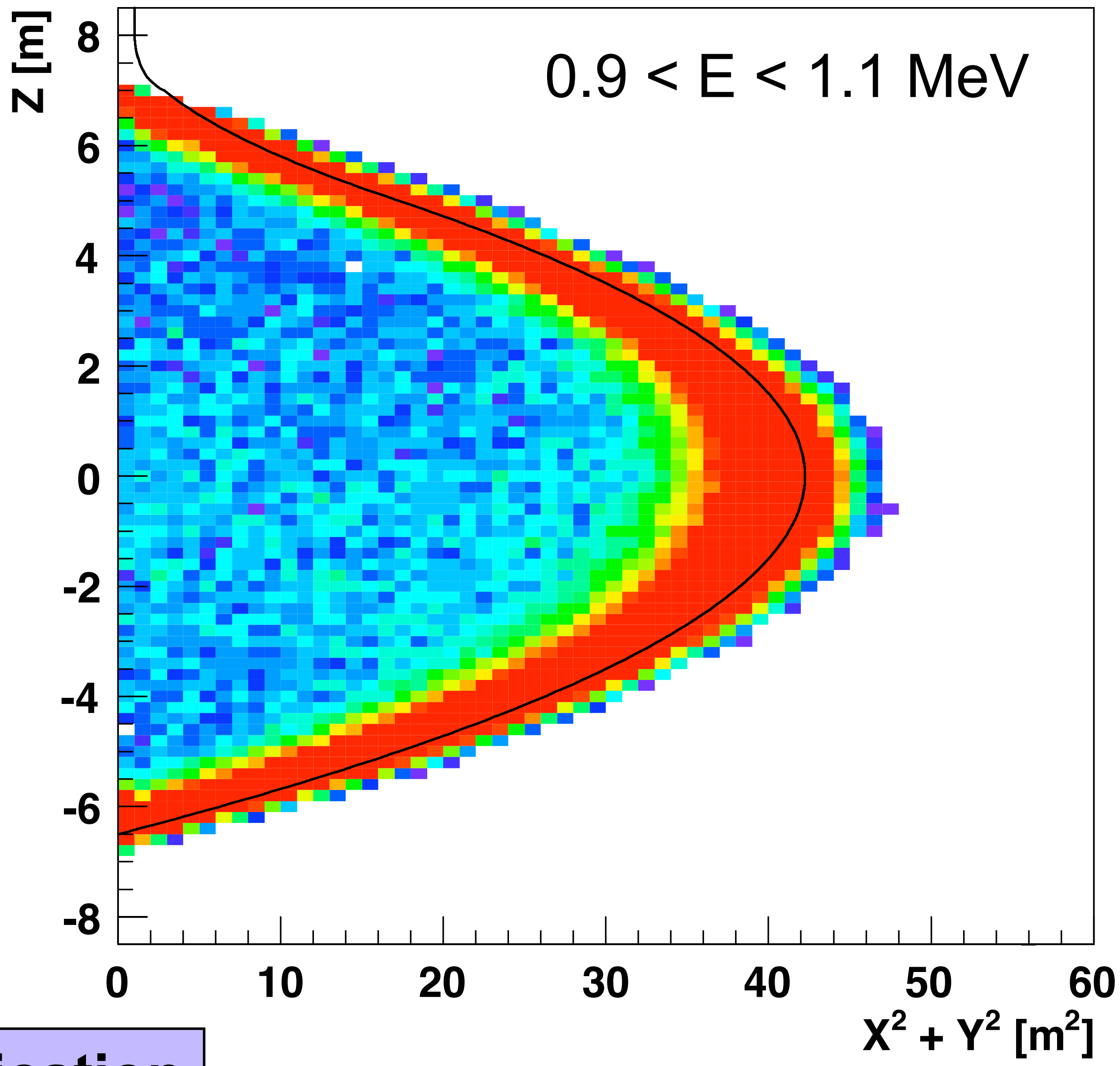
almost succeeded in the reduction goal

Purification Status in Real System

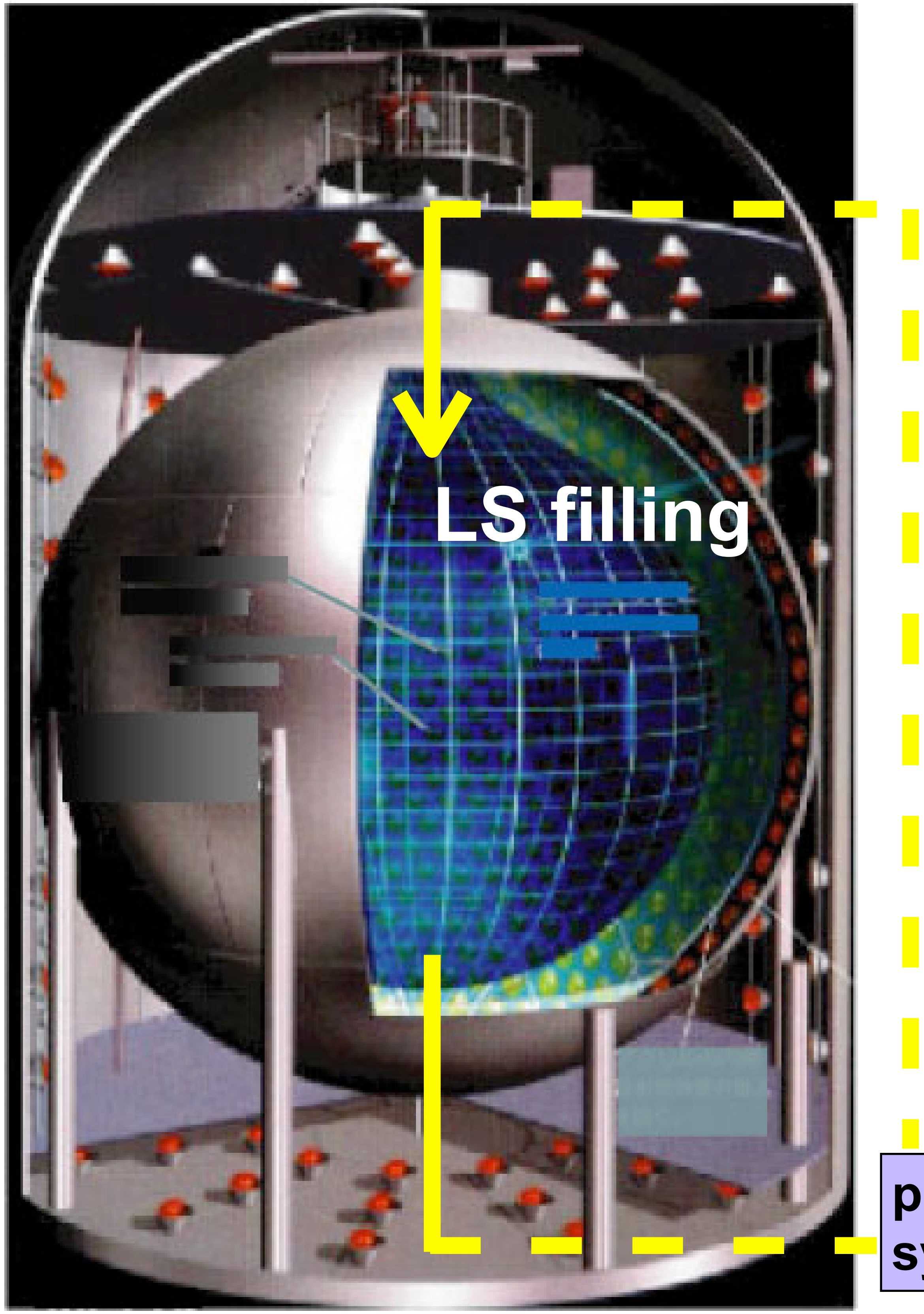


purification system

event rate map before purification (arbitrary units)

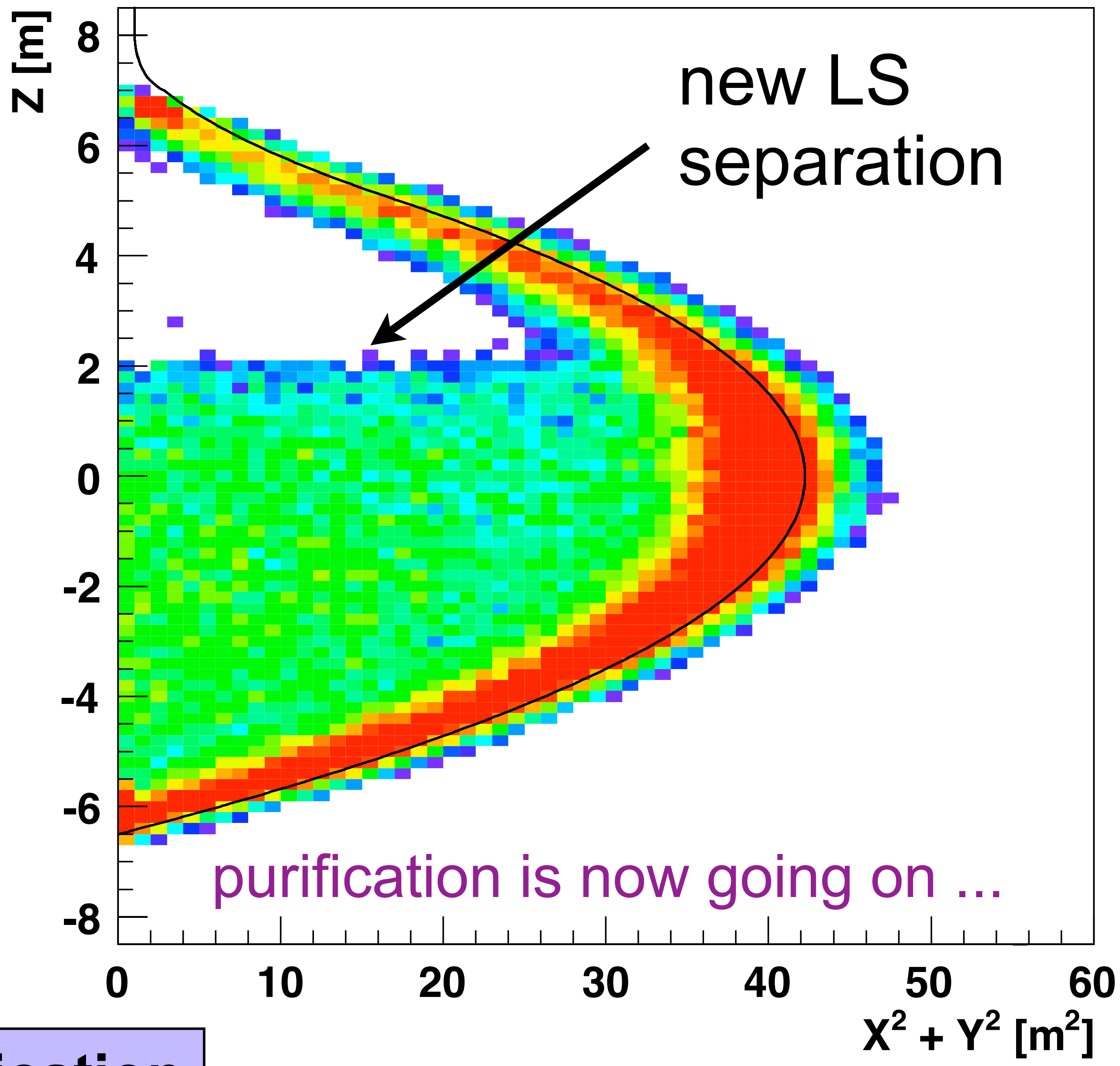


Purification Status in Real System



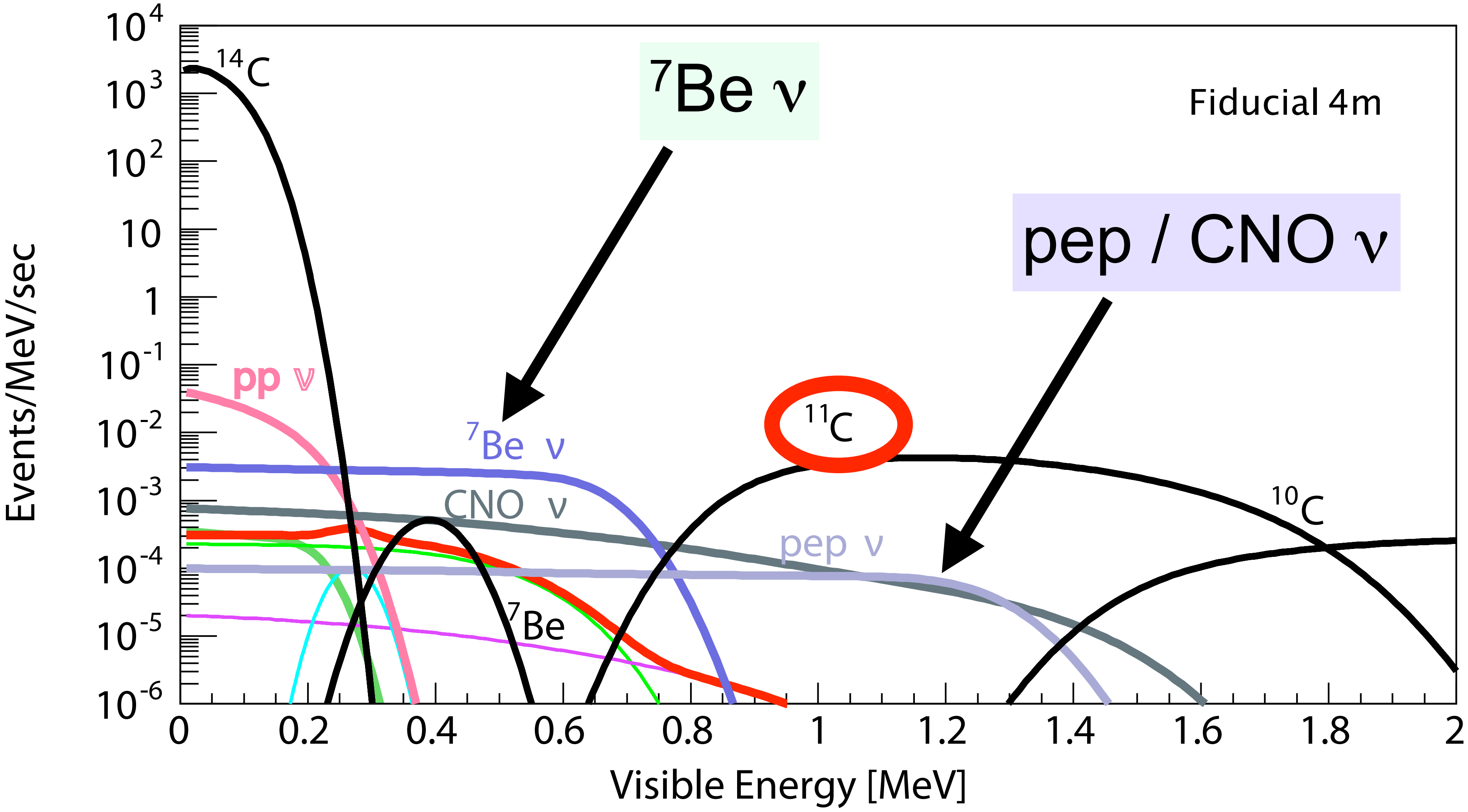
purification system

event rate map after purification (arbitrary units)



~ 300 m^3 after 10 day operation

Muon Spallation Background



^{7}Be ν

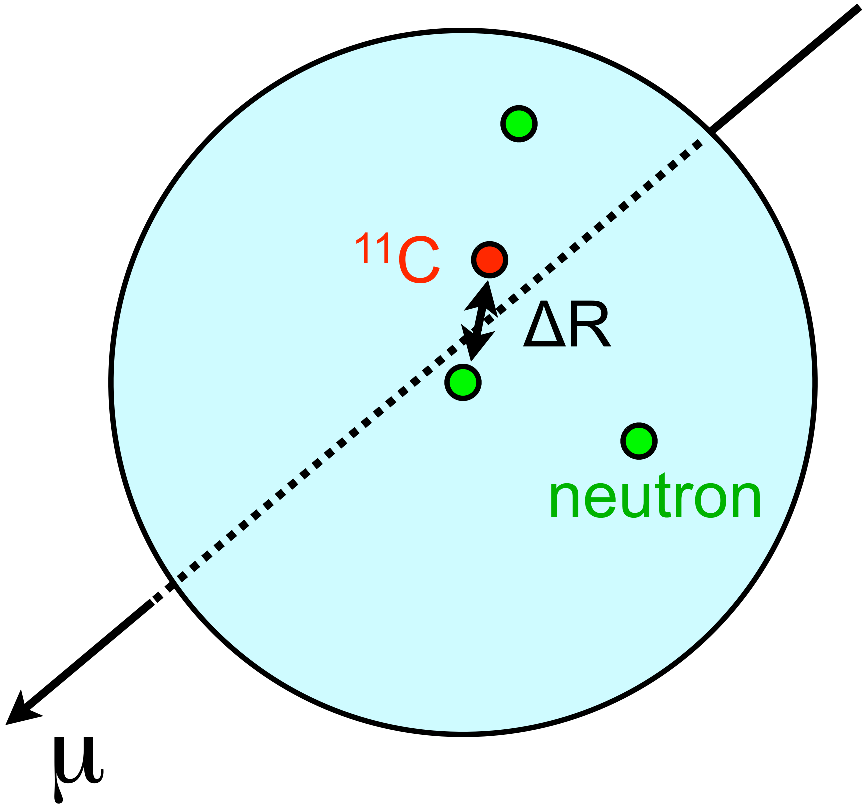
pep / CNO ν

	Life time	Q value	Hagner et al. (ev/d/kton)
^{10}C	27.8 sec	3.65 MeV (β^+)	139
^{11}C	29.4 min	1.98 MeV (β^+)	1039
^{7}Be	76.9 day	0.478 MeV (EC)	231

serious B.G.
for pep / CNO ν

^{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

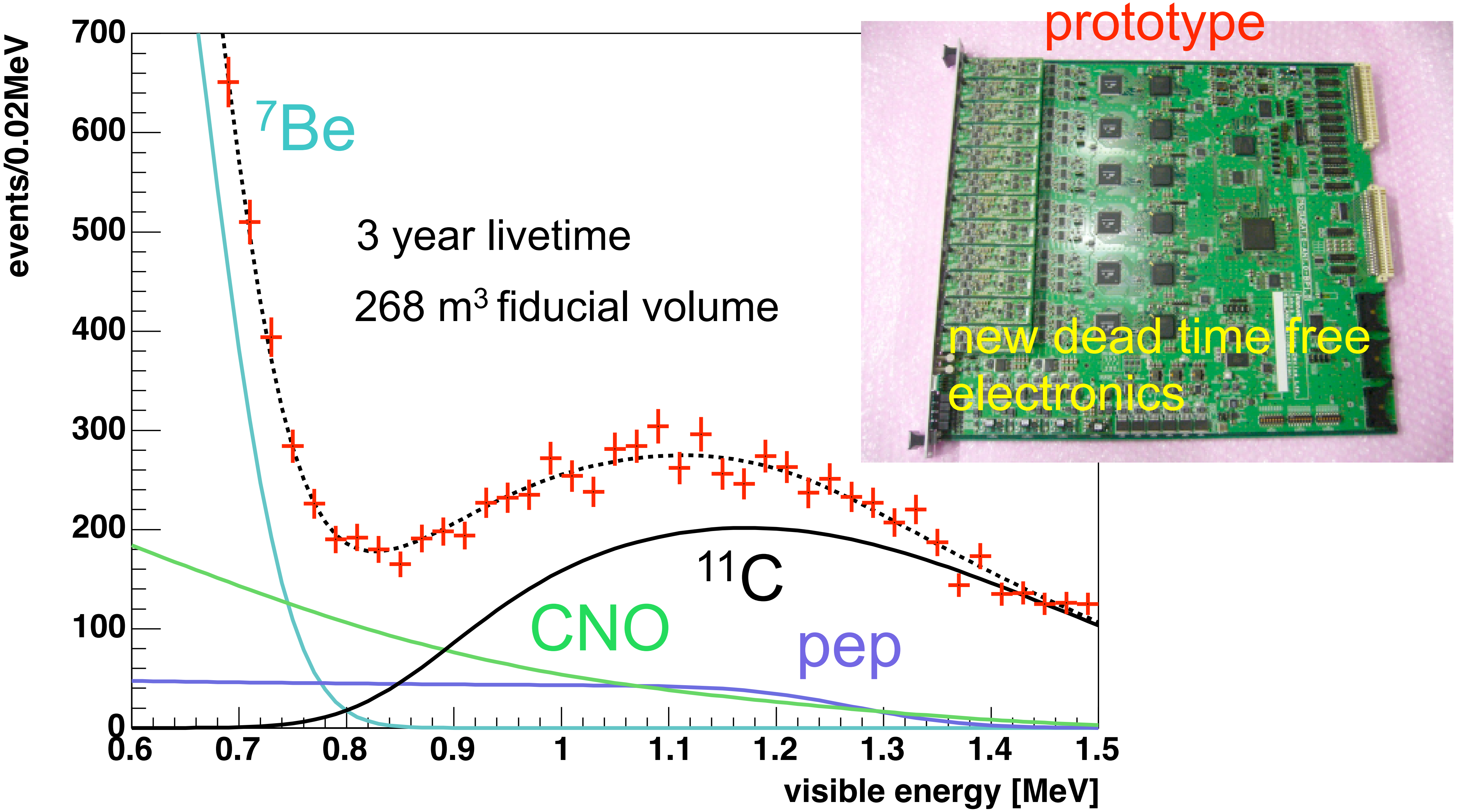
$$^{12}\mathrm{C} + \mathrm{X} \rightarrow {}^{11}\mathrm{C} + n + \mathrm{Y} + \cdots$$

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

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

Energy Spectra after ^{11}C Rejection

95% of ^{11}C is rejected by neutron tagging



^{11}C rejection simulation

↓

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

Double Beta Decay with KamLAND Detector : what could be done

Double Beta Decay in KamLAND

Characteristics

(1) Large amount of liquid scintillator (1,000 ton LS)

(2) Target isotope can be dissolved in the LS

advantages

- high statistics by large target isotope
- low external B.G. by self shielding

disadvantages

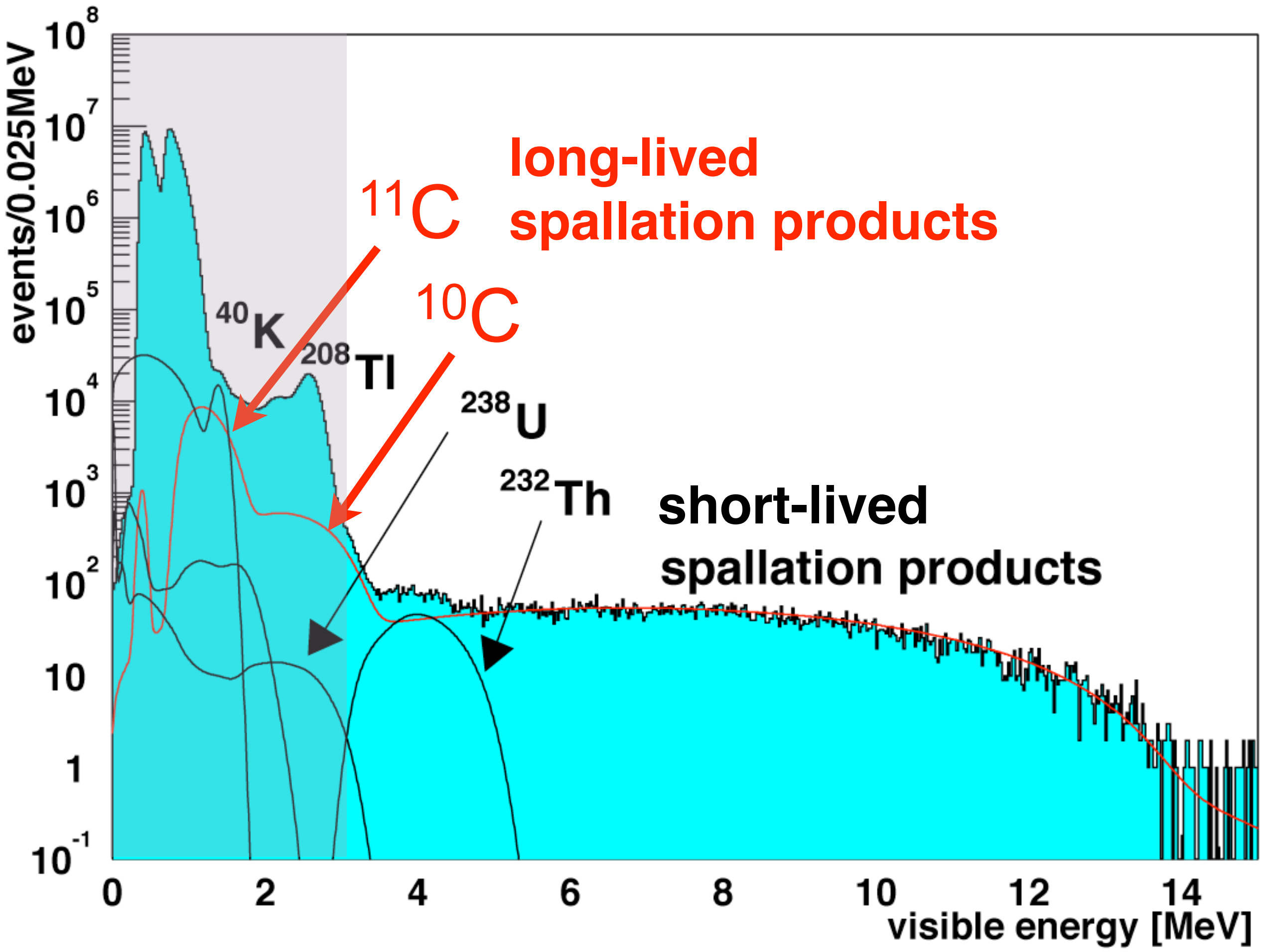
- poor energy resolution

  energy resolution ~ 6.2% / sqrt(MeV)

- muon spallation B.G. from ^{12}C target

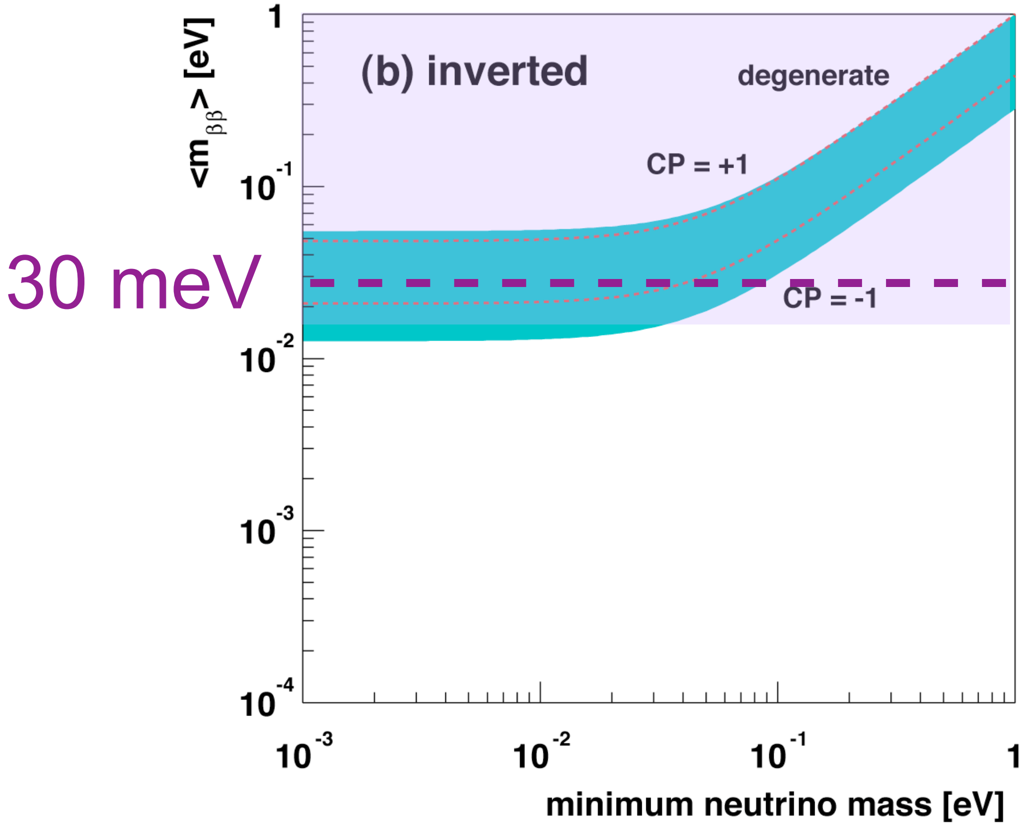
  low energy backgrounds (E < 3 MeV) are dominated by ^{11}C, ^{10}C

KamLAND singles spectra



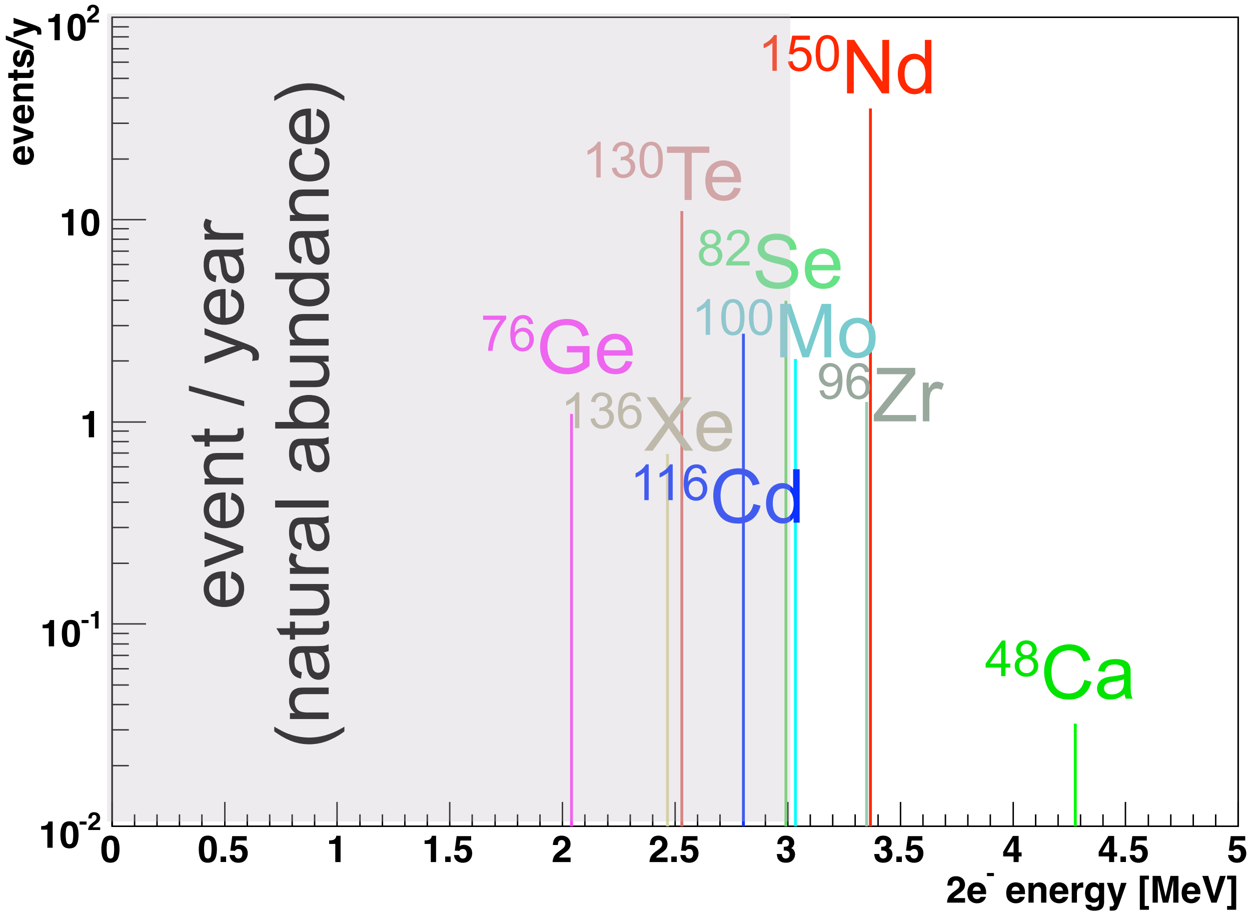
Target Isotope for 0νββ search

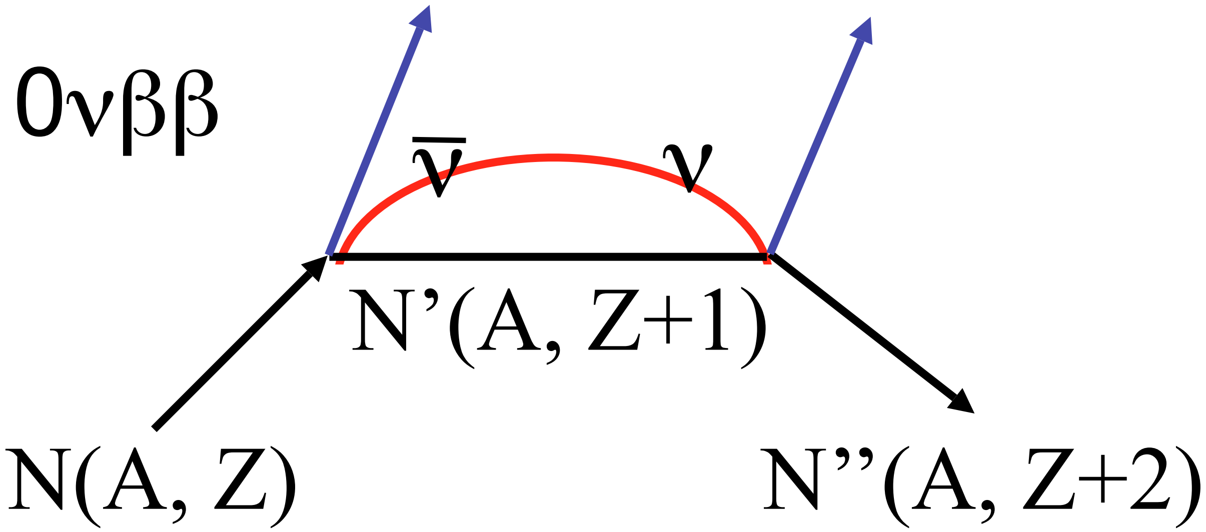
Majorana + inverted hierarchy



$<m_{\beta\beta}>$ = 30 meV

1.0 wt% loaded LS (544 ton)





^{150}Nd : 36 events / year
natural abundance : 5.9%

Nd-loaded scintillator in SNO++

(M. Chen, INT Underground Science Workshop)

Background Consideration

(1) 2νββ

- The NEMO-3 experiment gives a finite value for ^{150}Nd half-life :[9.7 ± 0.7(stat) ± 1.0(syst)] × 10^{18} y.

172 ± 22 events / 3y (3.45 < E < 3.65 MeV)

(2) muon spallation products

- long-lived products --- ^{11}Be (lifetime 19.9 sec, Q = 11.5 MeV)

8 ± 4 events / 3y (preliminary) (3.45 < E < 3.65 MeV)

(3) radioactive impurity in LS

- ^{208}Tl (Q = 5.0 MeV) beta decay

~ 700 events / 3 y (KamLAND LS) (3.45 < E < 3.65 MeV)

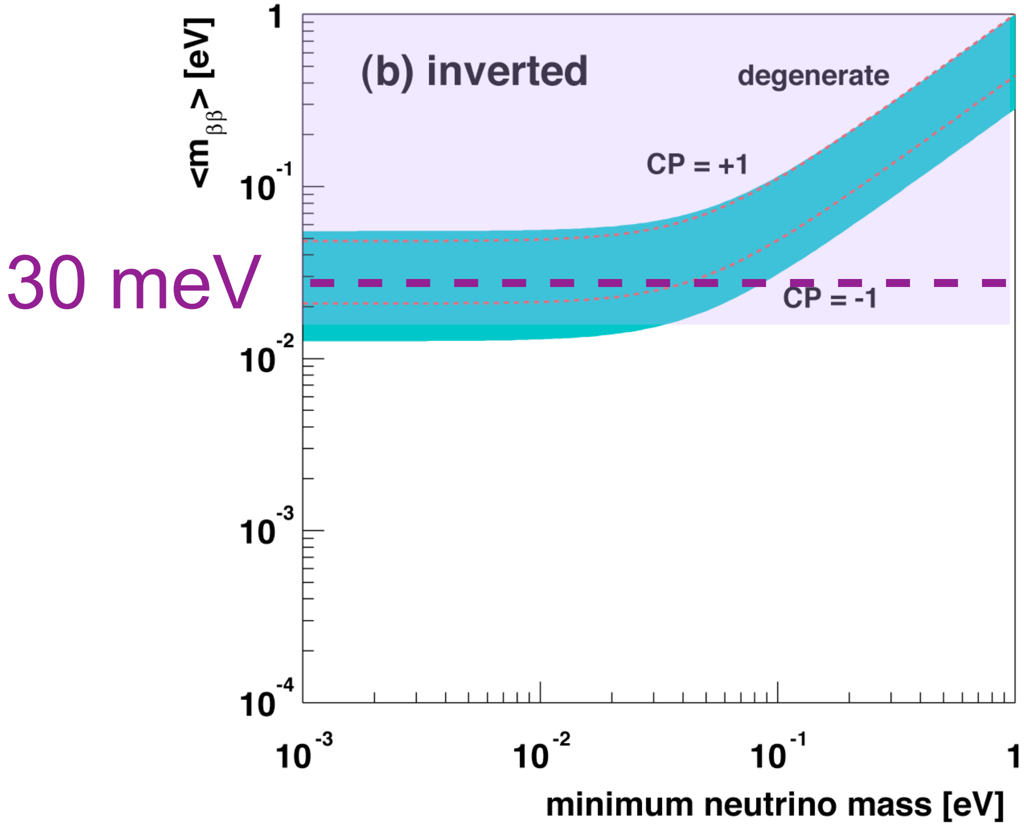
^{232}Th chain → **^{212}Bi 87.4 min** $\xrightarrow{\alpha\ (35.9\%)}$ 6.2 MeV **^{208}Tl 4.4 min** $\xrightarrow{\beta}$ 5.0 MeV **^{208}Pb stable**

visible energy ~ 0.4 MeV

delayed coincidence tagging → ~ 10^{-3} rejection of ^{208}Tl with 10% inefficiency (after purification of low energy B.G.)

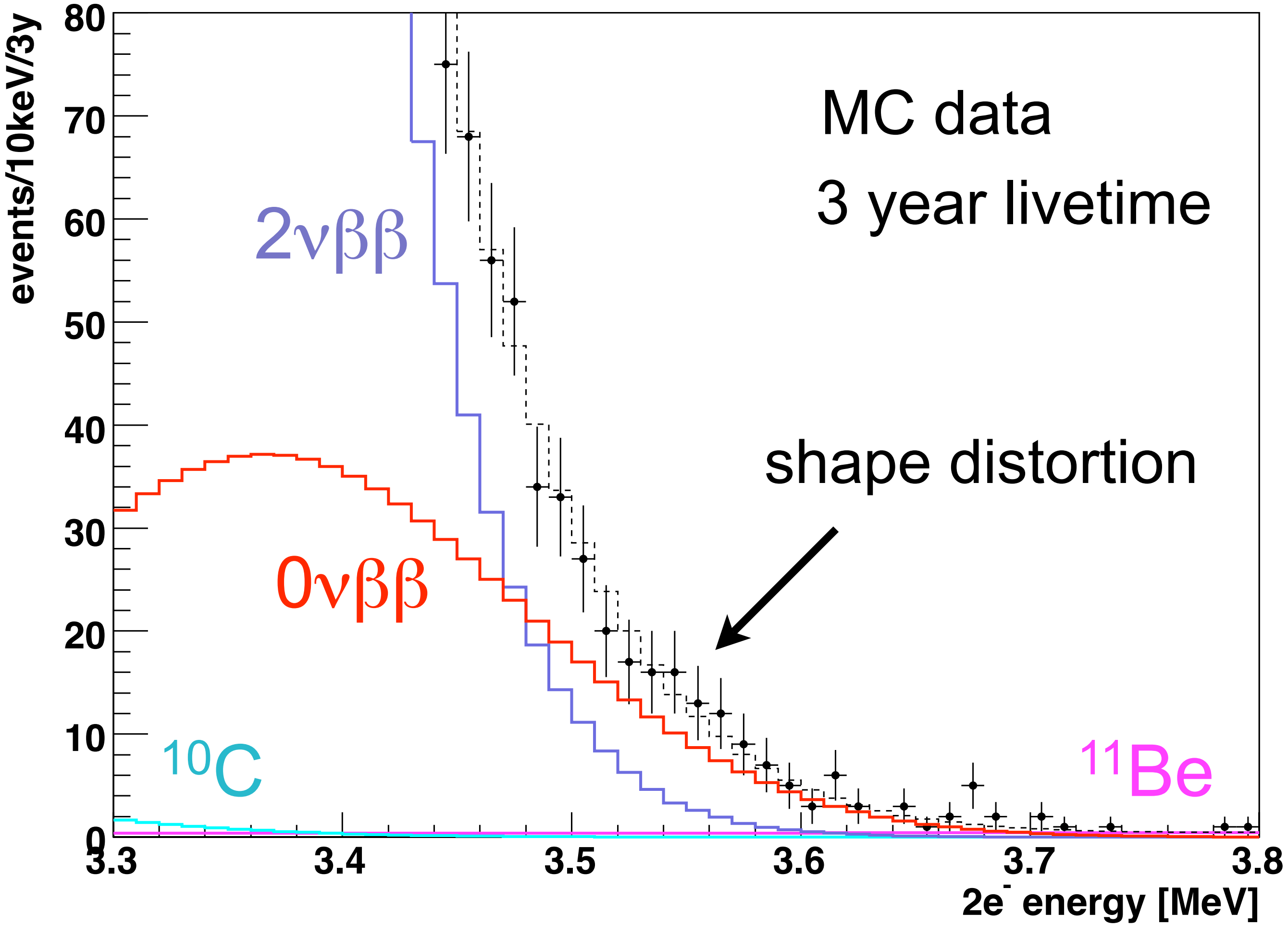
Energy Spectrum in KamLAND

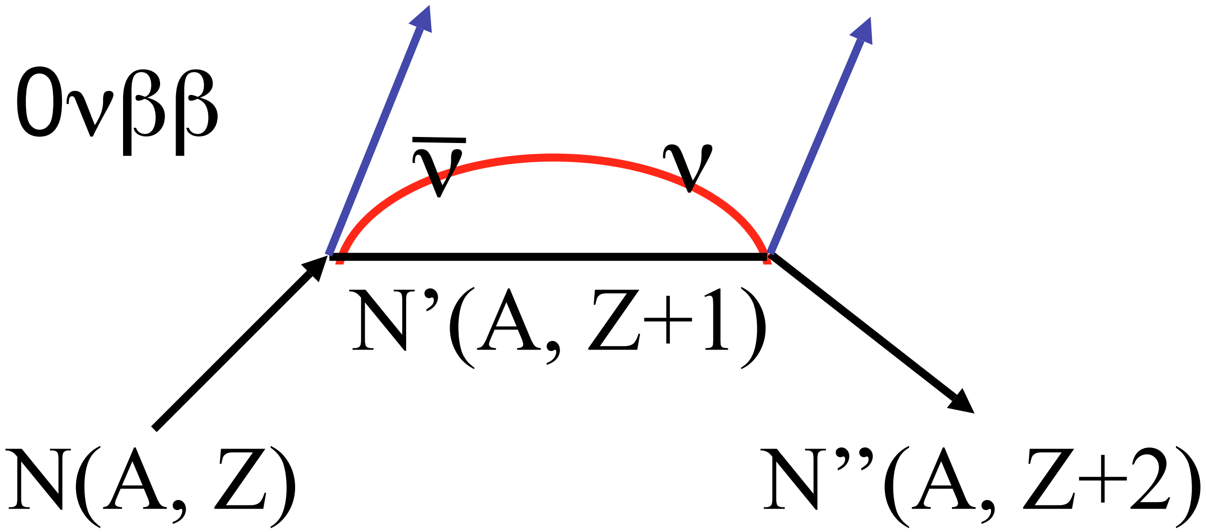
Majorana + inverted hierarchy



$<m_{\beta\beta}>$ = 30 meV

1.0 wt% loaded LS (544 ton)





^{150}Nd : 350 events / year

enrichment : 60% ~ 10 times target

energy resolution : 6.2% / sqrt(MeV)

(assuming current resolution in KamLAND)

Prospects for 0νββ search

- enrichment

AVLIS (Atomic Vapor Laser Isotope Separation) in France

possibility of high production rate ~ kg/h for ^{150}Nd

2000 ~ 2003 : MENPHIS facility ~ few kg/h for ^{235}U

- detector improvements

- energy resolution (light yield)

wavelength shifter to cancel the chemical quenching by Nd compounds

- energy scale

need to keep energy scale and resolution stability within 0.5%

- sensitivity

- energy spectrum statistical test

$\langle m_{\beta\beta} \rangle$ = 30 meV : 6 sigma significance for 3 year measurement

⟶ Majorana + inverted hierarchy test

Summary

Results and prospects for KamLAND

- Reactor neutrino experiment contributed to the solution of the solar neutrino problem.

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

- We will start ^{7}Be, pep and CNO solar neutrino observation after the purification of LS.

  purification of LS is now going on ...

Double beta decay

- Possibility of double beta decay experiment with the KamLAND detector was considered.