The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2047-16

Workshop Towards Neutrino Technologies

13 - 17 July 2009

Experimental investigation of geoneutrinos with KamLAND

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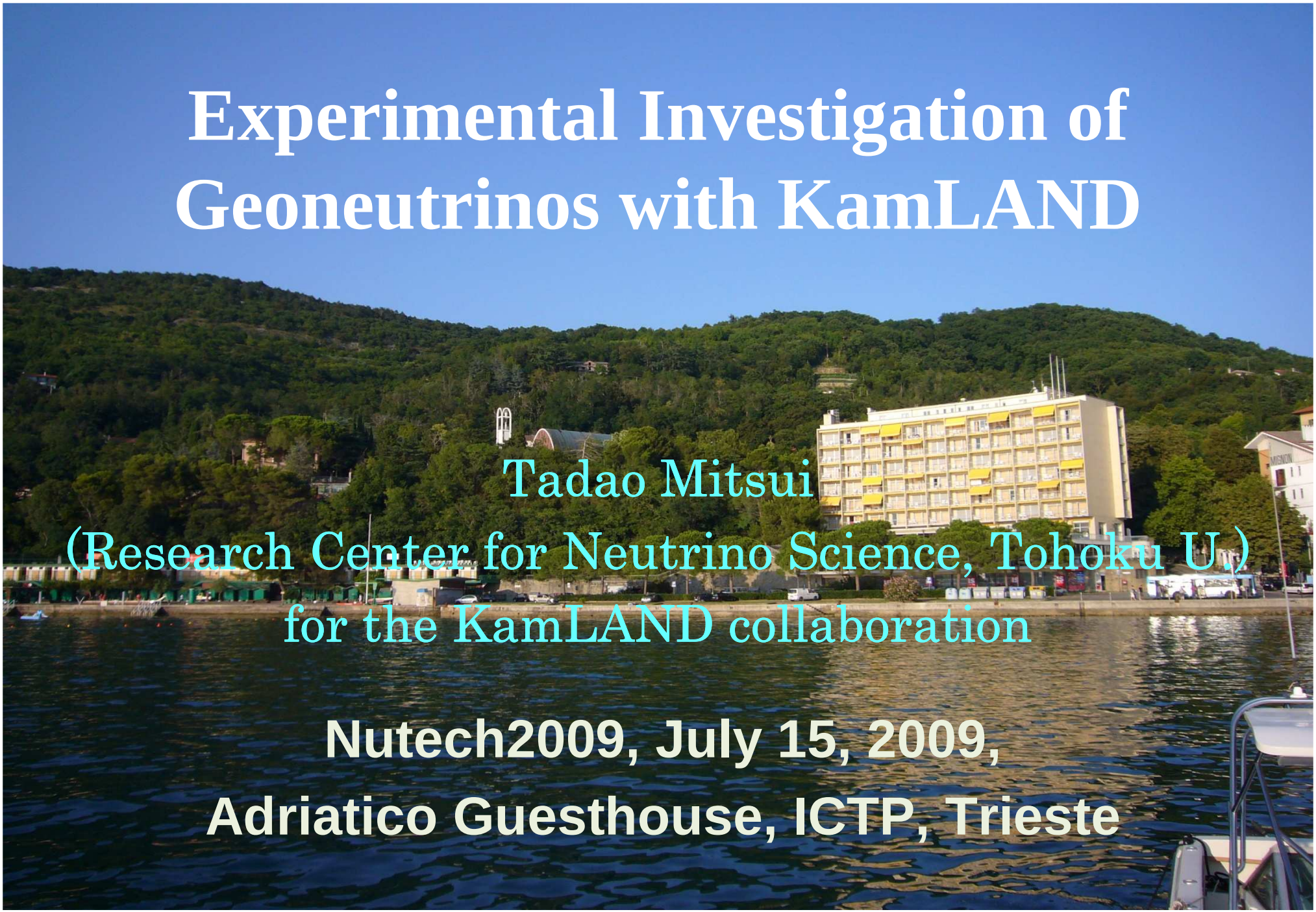
Experimental Investigation of Geoneutrinos with KamLAND



Tadao Mitsui
(Research Center for Neutrino Science, Tohoku U.)
for the KamLAND collaboration

Nutech2009, July 15, 2009,
Adriatico Guesthouse, ICTP, Trieste

Outline

- Geoneutrinos
- KamLAND detector
- KamLAND is just an experiment Towards Neutrino Technologies
- Geoneutrino: data-2005 vs. data-2008
- Future

Geoneutrinos

Geoneutrinos

- Electron antineutrinos produced in the Earth's interior (crust and mantle) by decays of ^{238}U, ^{232}Th, and ^{40}K
- Decays of ^{238}U, ^{232}Th, and ^{40}K :

  ~40% of Earth's power
- Earth's power: $\rightarrow$ plate tectonics, earthquakes, volcanoes, geomagnetism, …
- Origin and history of the Earth
- Pointed out since ν discovered

  (1950's, G. Gamow, …)

Geoneutrinos: neutrino technology for geology

- Direct measurement of chemical composition of the Earth
  - Seismic wave: distribution of sound velocity (chemical composition is deduced from it)
  - Sampling: limited to shallow crust (~10 km depth)
  - geo-ν: deeper and chemical information (U, Th are marked by radio isotopes)
- Heat balance and history of the Earth

Chemical composition of the Earth

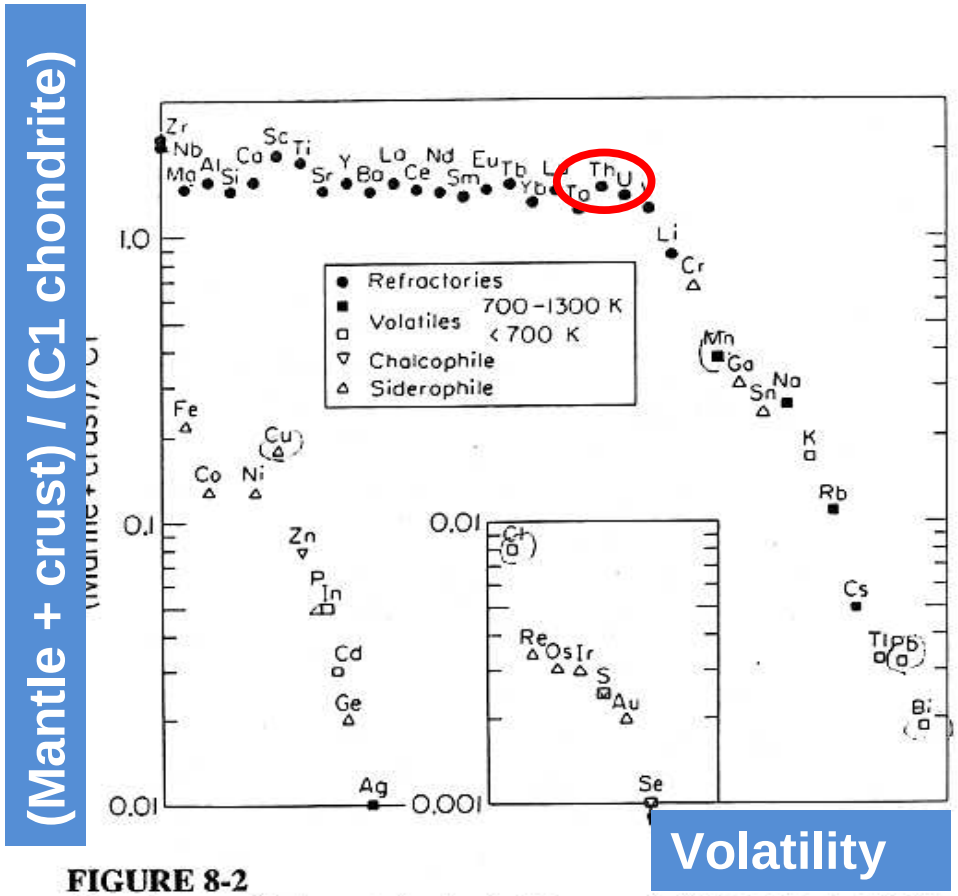
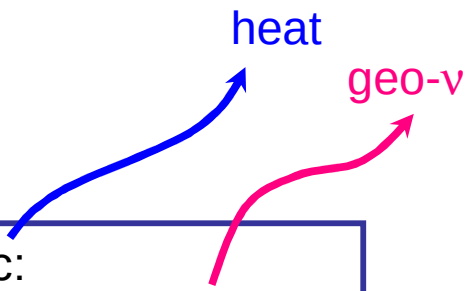


FIGURE 8-2
Abundances of elements in "primitive mantle" (mantle + crust) relative to C1, derived by mixing mantle components to obtain chondritic ratios of the refractory lithophile elements.

- See prof. McDonough's talk for better (the best) understanding
- U and Th: "lithophile" (favors the silicate phase), and not very volatile: good calibration point of the model

Heat balance of the Earth



Heat flow measurement:

44 TW? (Pollack H.N. et al, Rev. Geophys 31, 267)

31 TW? (Hofmeister, A.M et al. Tectonophysics 395)

=

(?)

Radiogenic:

19 TW(McDonough et a. Chem. Geol. 120, 223)

+

Cooling of core, solidification of outer core, … (originates from initial gravitational energy)

Calculation of geo-ν energy spectrum

$^{238}\mathrm{U} \xrightarrow[100\%]{} {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ [\mathrm{MeV}]$

T1/2= 4.47 billion y

$^{232}\mathrm{Th} \xrightarrow[100\%]{} {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ [\mathrm{MeV}]$

T1/2= 14.05 billion y

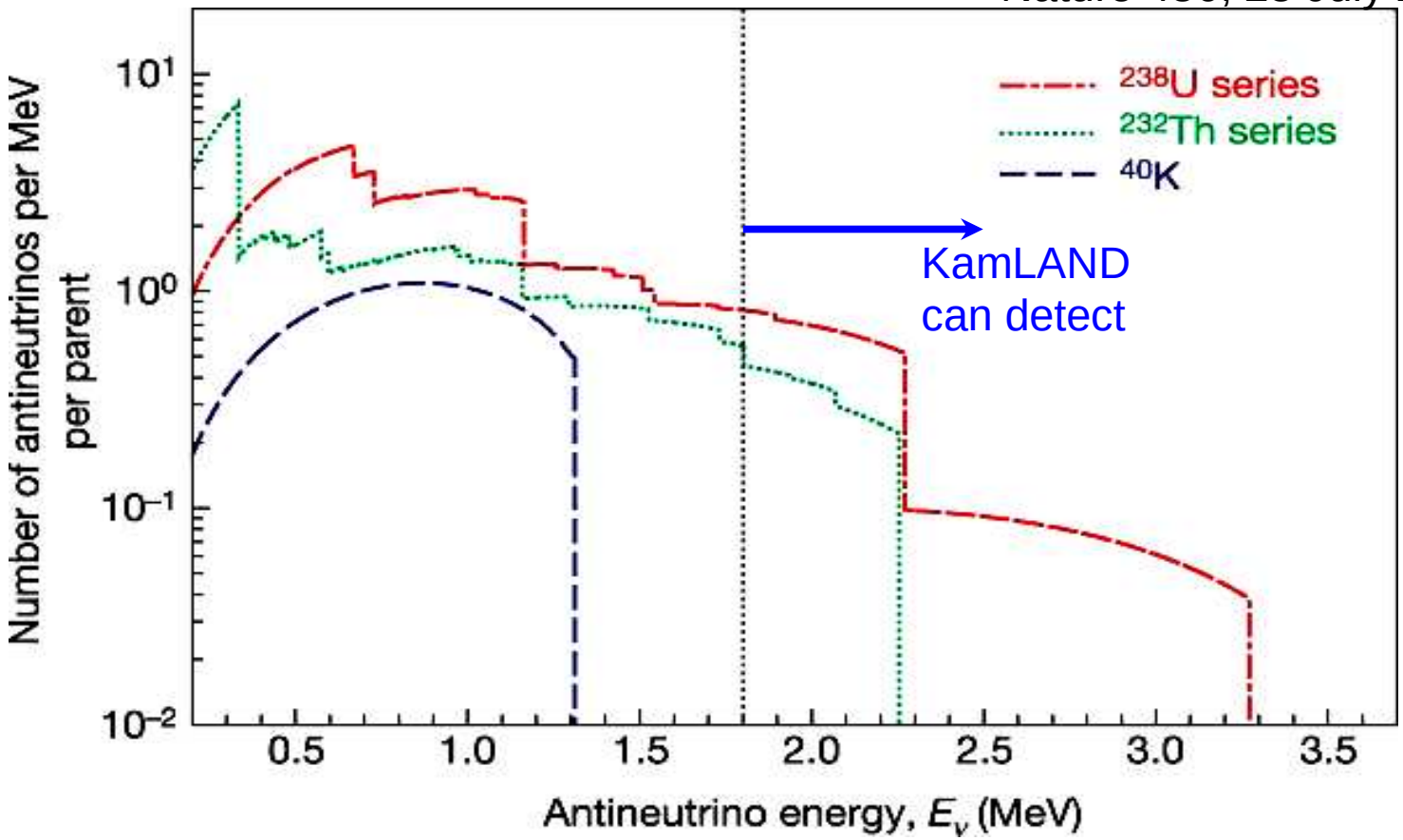
$^{40}\mathrm{K} \xrightarrow[89.28\%]{} {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.311\ [\mathrm{MeV}]$

$^{40}\mathrm{K} + e^{-} \xrightarrow[10.72\%]{} {}^{40}\mathrm{Ar} + \nu_e + 1.505\ [\mathrm{MeV}]$

T1/2= 1.28 billion y

Calculation of geo-ν energy spectrum

Nature 436, 28 July 2005



The expected ^{238}U, ^{232}Th, and ^{40}K decay chain electron anti-neutino energy distribution. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to ^{40}K electron antineutrinos.

Calculation of geo-ν absolute rate

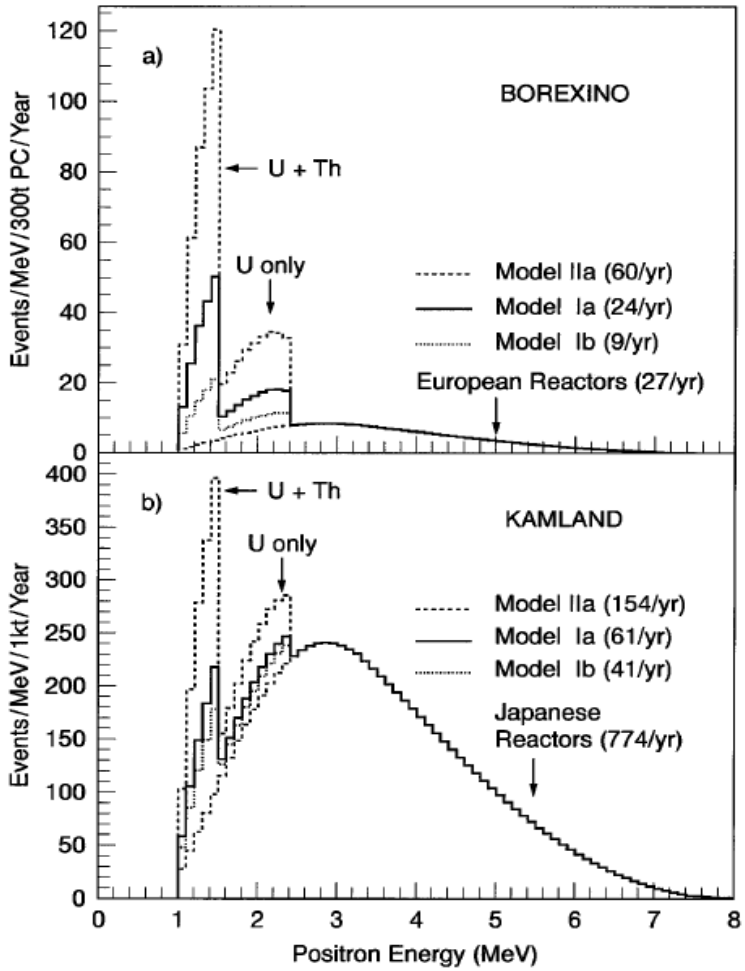


FIG. 2. $\bar{\nu}_e$ (positron) signal spectra from the Earth and from nuclear reactors at Borexino (a) and at Kamland (b). The signal rates point to several years of measurement for data of statistical significance to different aspects of geophysical interpretation.

- Reference-1: R.S. Raghavan et al, PRL 80, 635(1998)
- For Borexino and KamLAND
- Extraction mantle and crust contributions by 2-point observation

Calculation of geo-ν absolute rate

- Reference-2: F. Mantovani et al., PRD 69, 013001(2004)
- Geochemical map, uncertainties are discussed

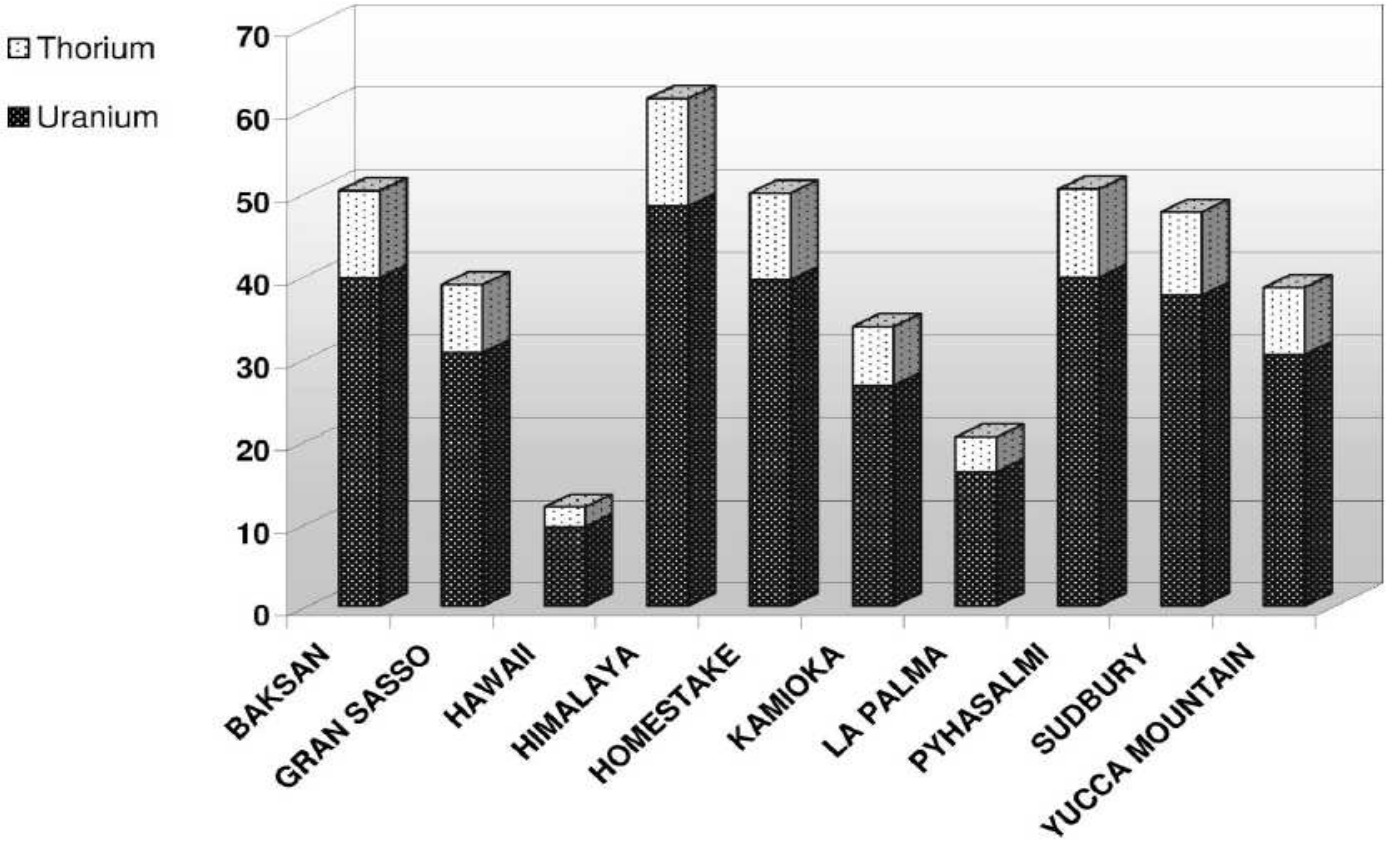
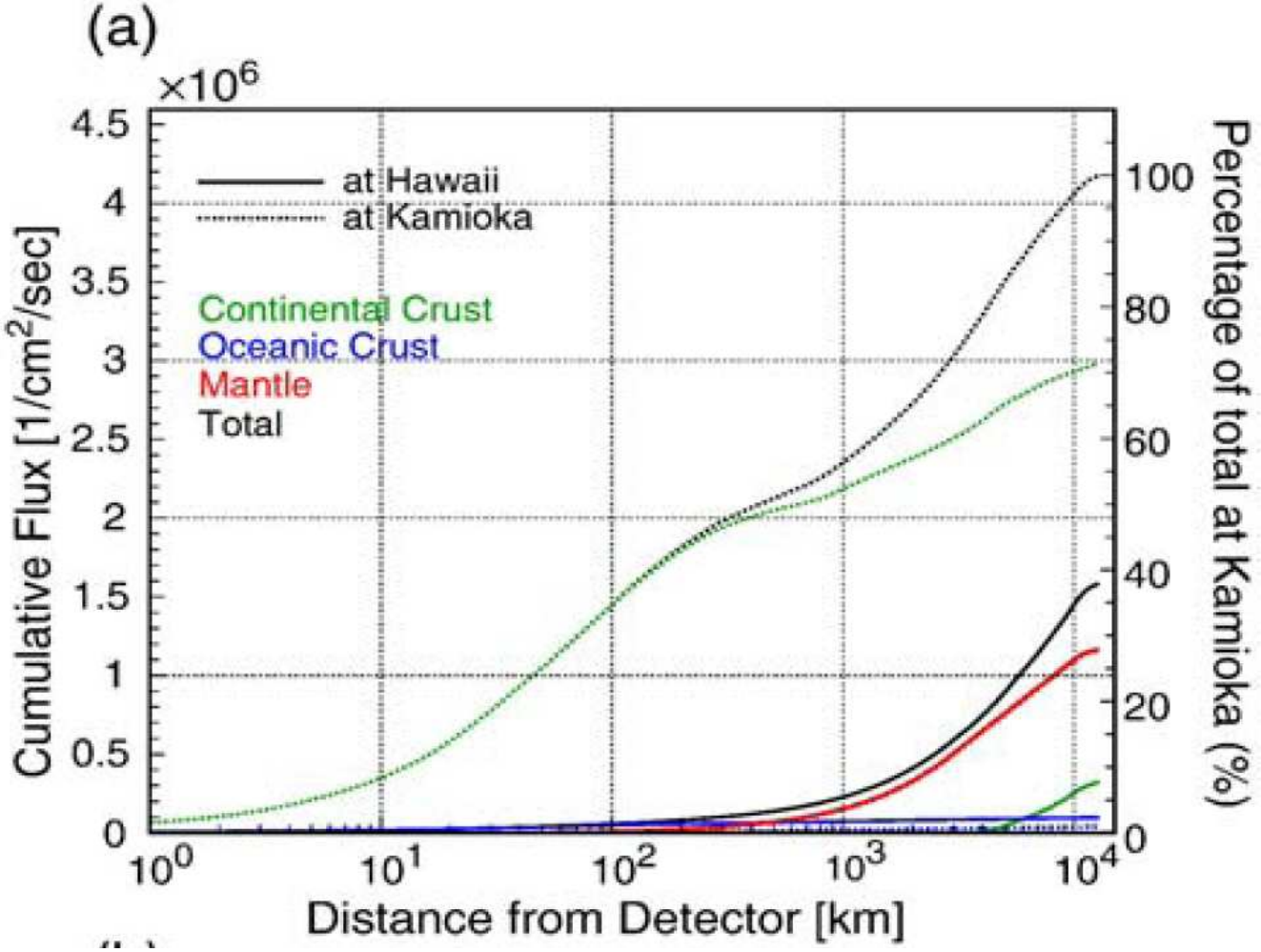


FIG. 5. Yields predicted in the reference model for 10^{32} proton yr, 100% efficiency, assuming the best fit oscillation parameters, $\delta m^2 = 7.3 \times 10^{-5}$ eV^2 and $\sin^2(2\theta) = 0.863$.

Calculation of geo-ν absolute rate

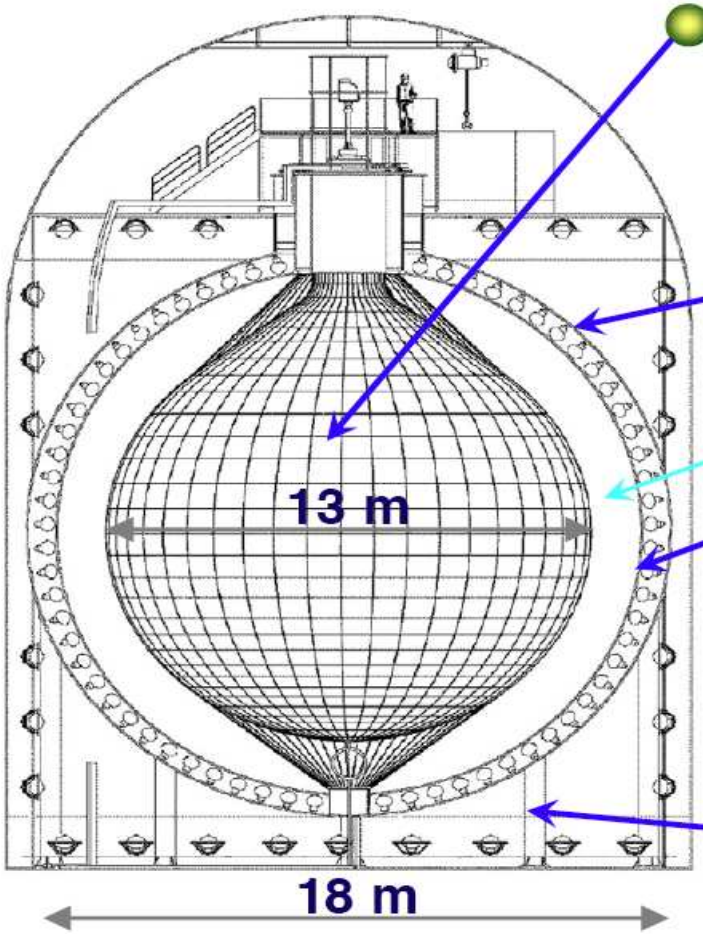


- Reference-3: S. Enomoto et al., Earth, Planet Sci. Lett. 258, 147 (2007)
- Sorry for missing references here…

KamLAND detector

KamLAND detector

- detector location: old Kamiokande site
  : 2700 m.w.e.



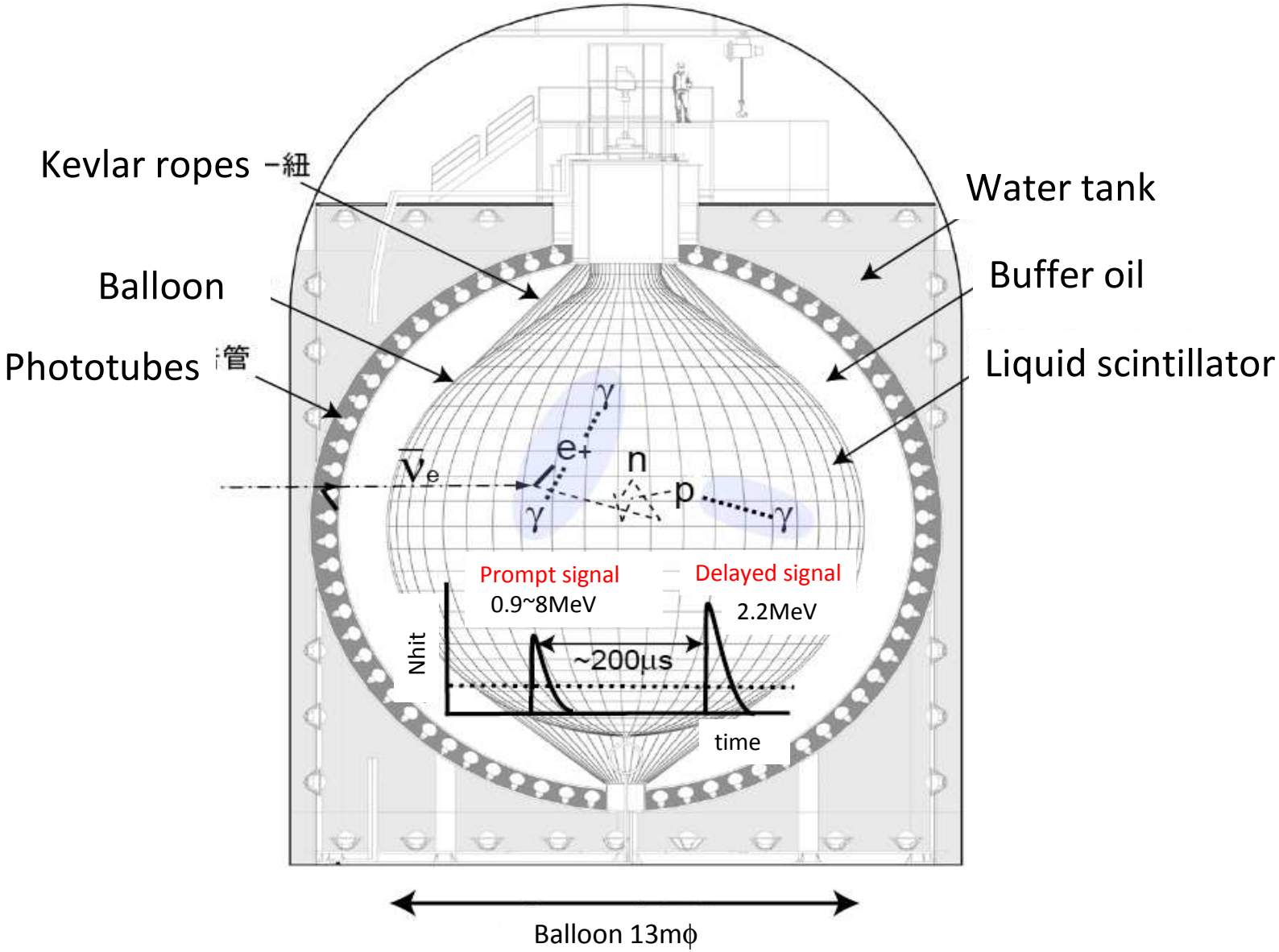
- 1000 ton liquid scintillator
  : 80% (dodecane) + 20% (pseudocumene)
  + 1.36 g/l PPO
  : housed in spherical plastic balloon
- 3000 m^3 stainless steel vessel
  : filled with a mixture of paraffin oil and dodecane ($\Delta\rho$ = 0.04%)
- 1325 17-inch + 554 20-inch PMT's

commissioned in February, 2003

photocathode coverage : 22% → 34%
energy resolution at 1 MeV : 7.3% → 6.3%

- water Cerenkov outer detector

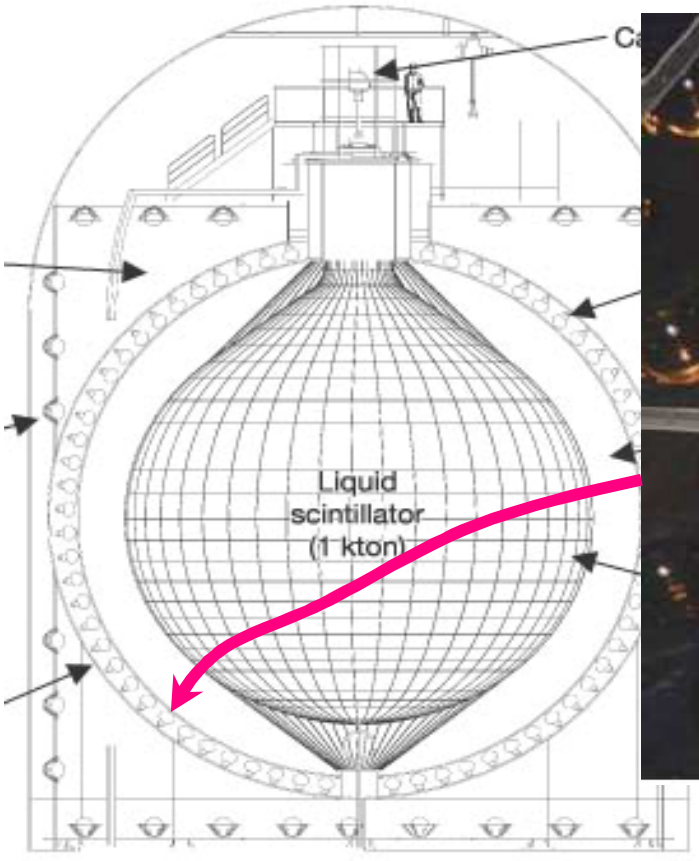
Kamioka Liquid *Antineutrino* Detector



Phototube installation by physicists

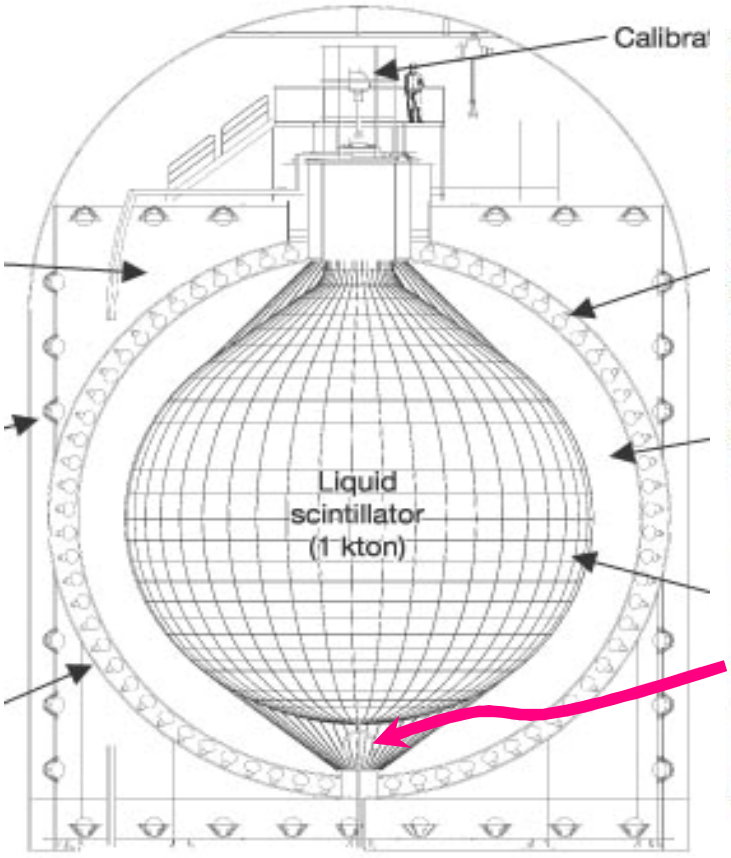
Not stuntmen

Fall, 2000



Neutrino technology is rather low technology

Bottom pipe of the balloon (the most weak part of the detector)



April 2001

Just an experiment Towards Neutrino Technology

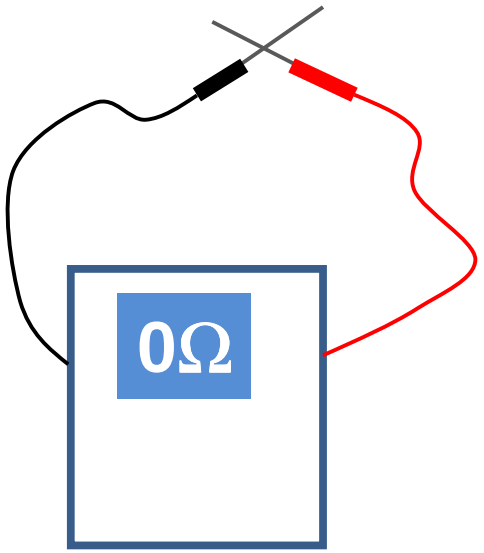
Calibration (correction) of new probe

- Neutrino is a new probe
- Probe calibration is needed

For θ_{12} and Δm^2_{12},

- Calibration in matter: solar ν
- Calibration in vacuum: KamLAND

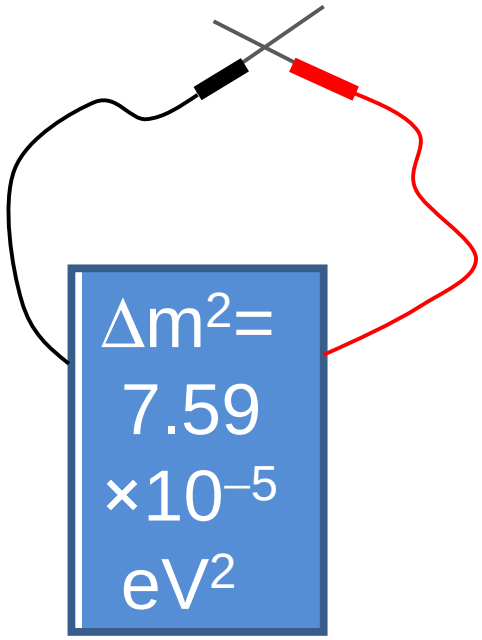
(CPT invariance is assumed)



Calibration (correction) of new probe

For θ_{12} and Δm^2_{12},

- Calibration in matter: solar ν
- Calibration in vacuum: KamLAND
  (CPT invariance is assumed)



- Calibration in vacuum: real baseline
  - meaningful in demonstrating
    Mikheyev-Smirnov-Wolfenstein effect
    (A.Yu.Smirnov arXive:hep-ph0305106(2003))
  - Precise Δm^2
    (due to fixed mass igenvalues in vacuum)

Solar+KamLAND: until 2004

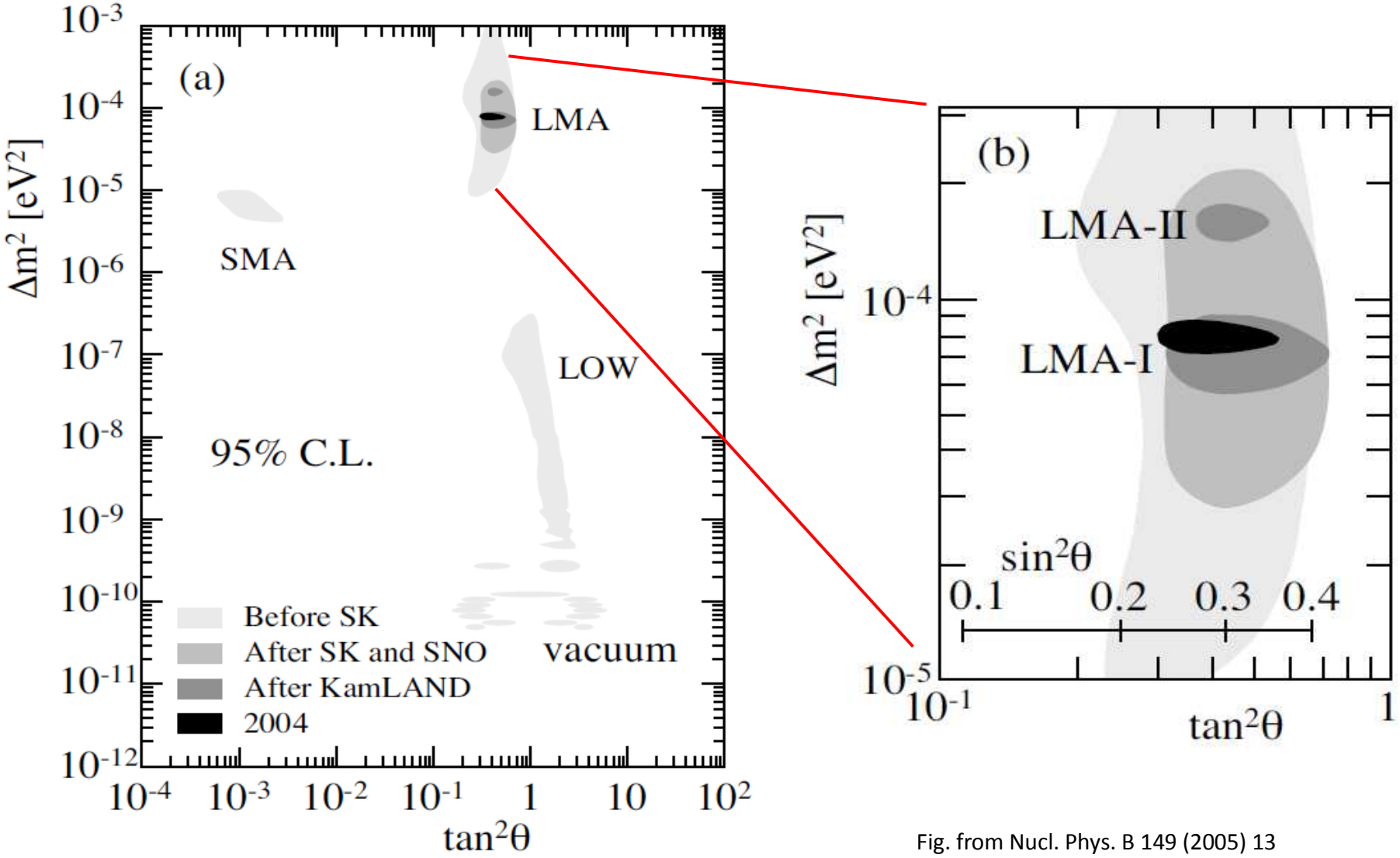
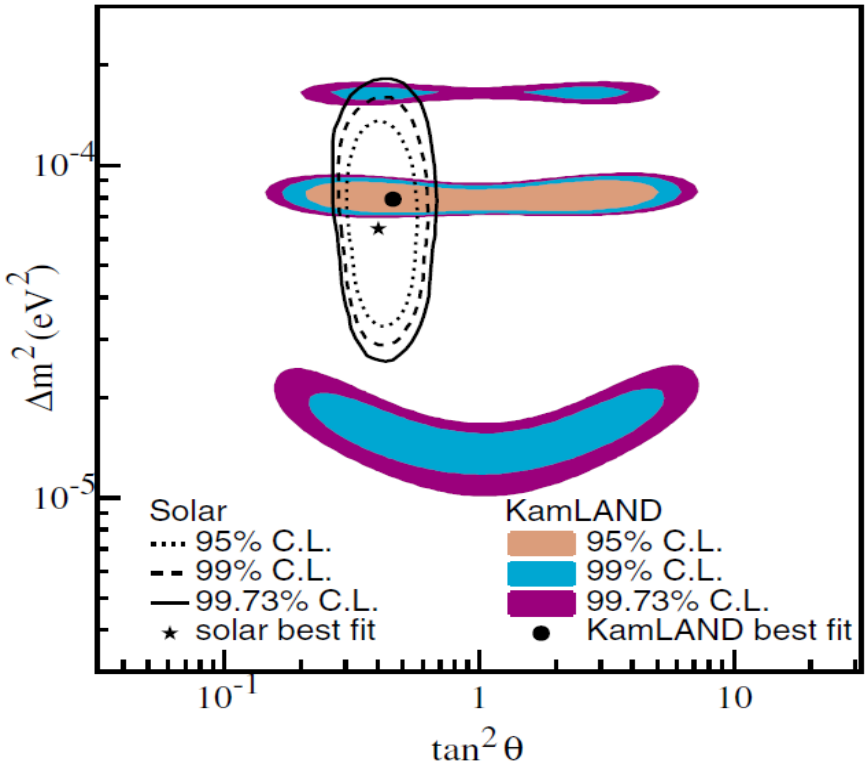
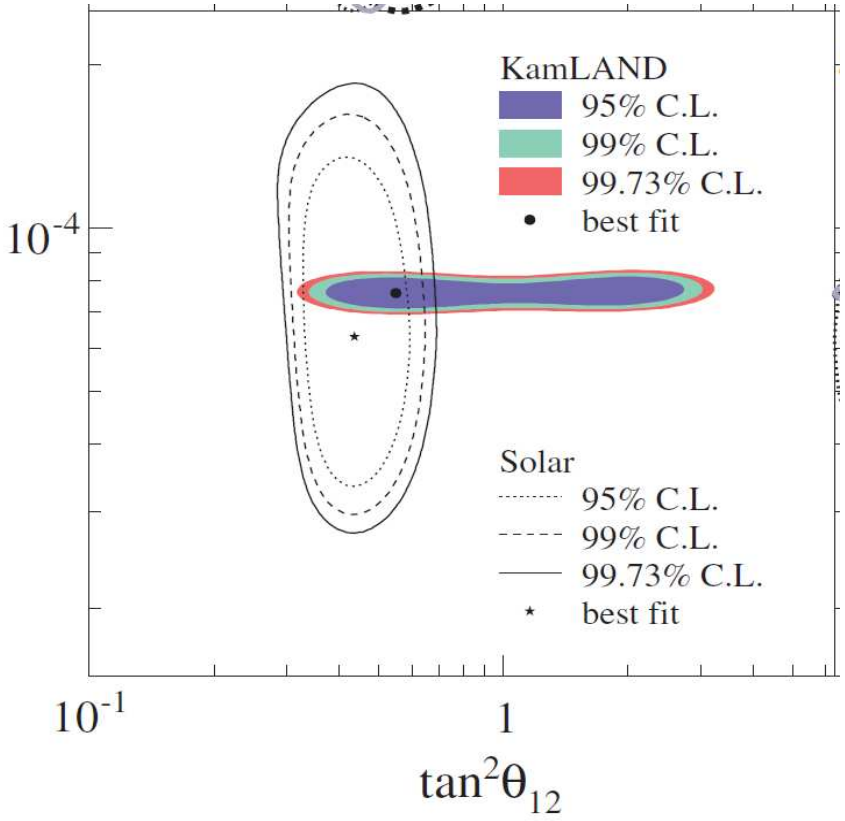


Fig. from Nucl. Phys. B 149 (2005) 13

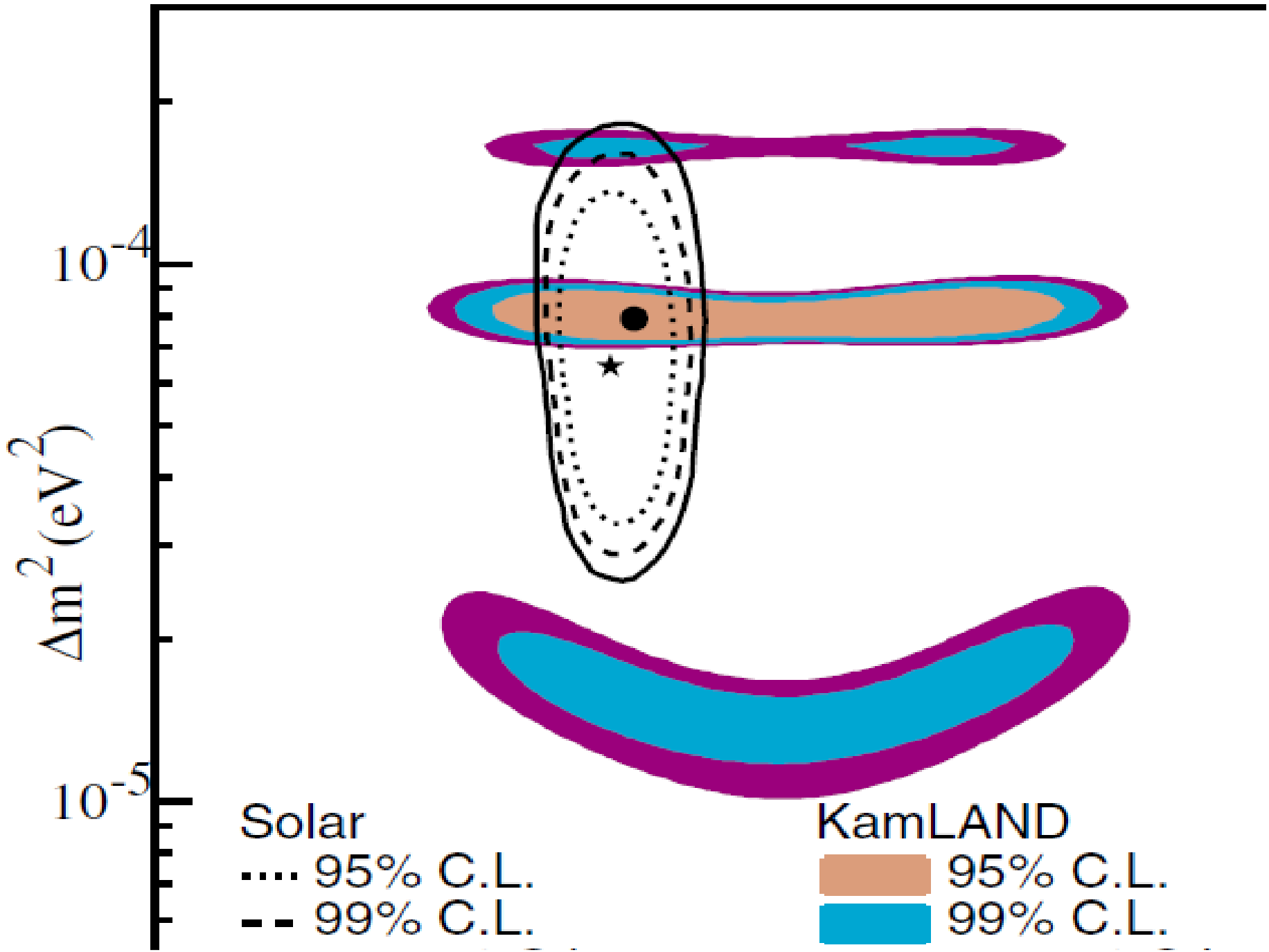
KamLAND: 2004 vs. 2008

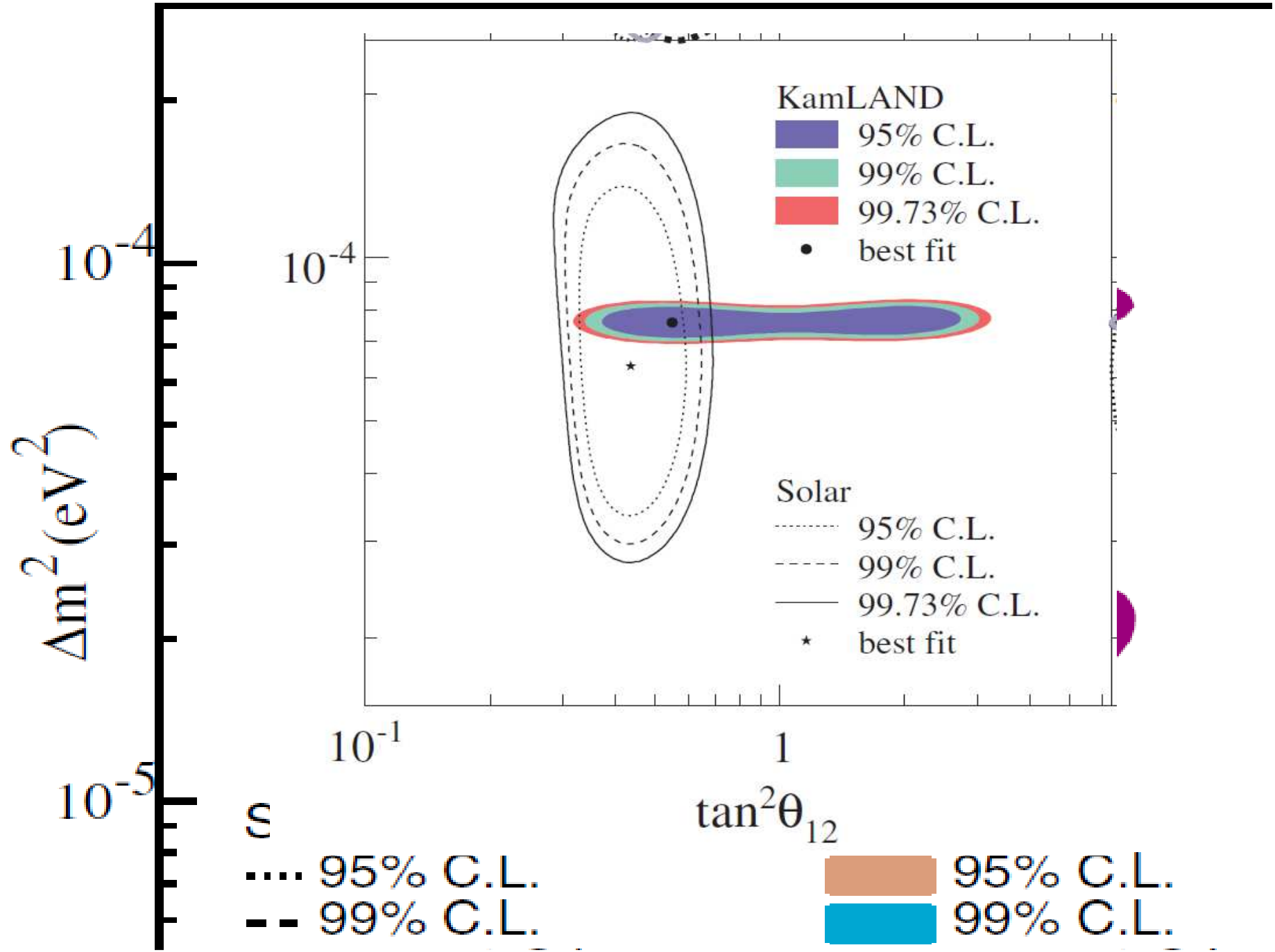




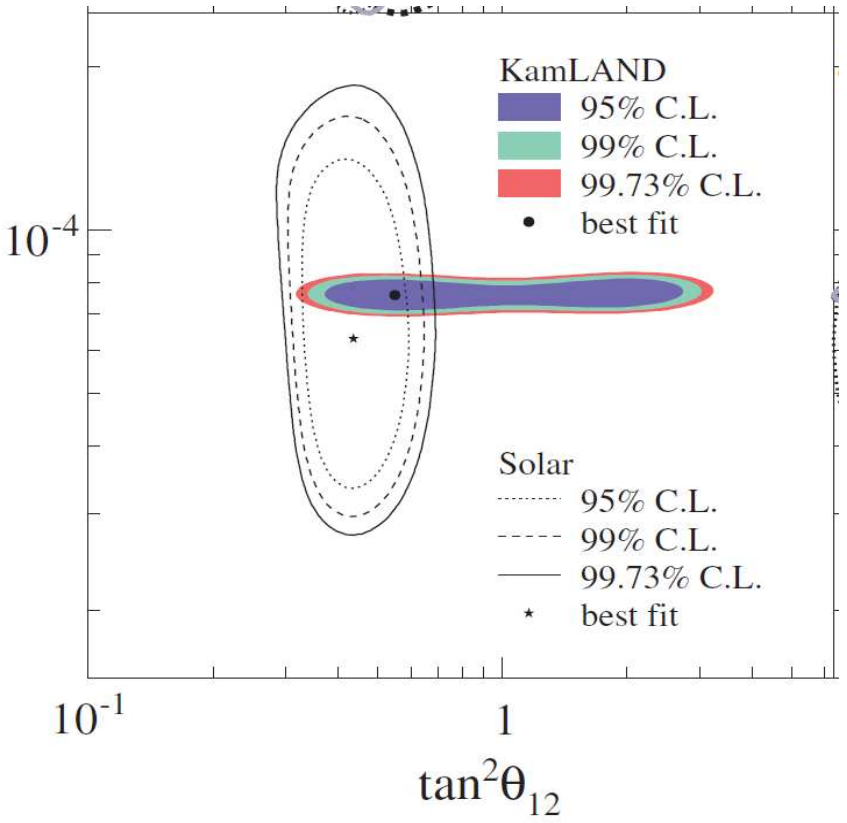
Data-2004
PRL94,081801

Data-2008
PRL100,221803


10^{-4}
10^{-5}
$\Delta m^2 (eV^2)$
Solar
95% C.L.
99% C.L.
KamLAND
95% C.L.
99% C.L.


KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best fit
Solar
95% C.L.
99% C.L.
99.73% C.L.
best fit
10^{-4}
10^{-5}
$\Delta m^2(eV^2)$
10^{-1}
1
$\tan^2\theta_{12}$
95% C.L.
99% C.L.

KamLAND: Data-2008



Data-2008 PRL100,221803

$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}$ eV^2

- Δm^2 uncertainty: about 2/3 of data-2004 ("$^{+0.6}_{-0.5}$" in data-2004 was not marginalized)
- LIA-0, and II disappeared by more than 3σ
- Of course θ is also important. For state-of-the-art "calibration" see E. Lisi (July 13)

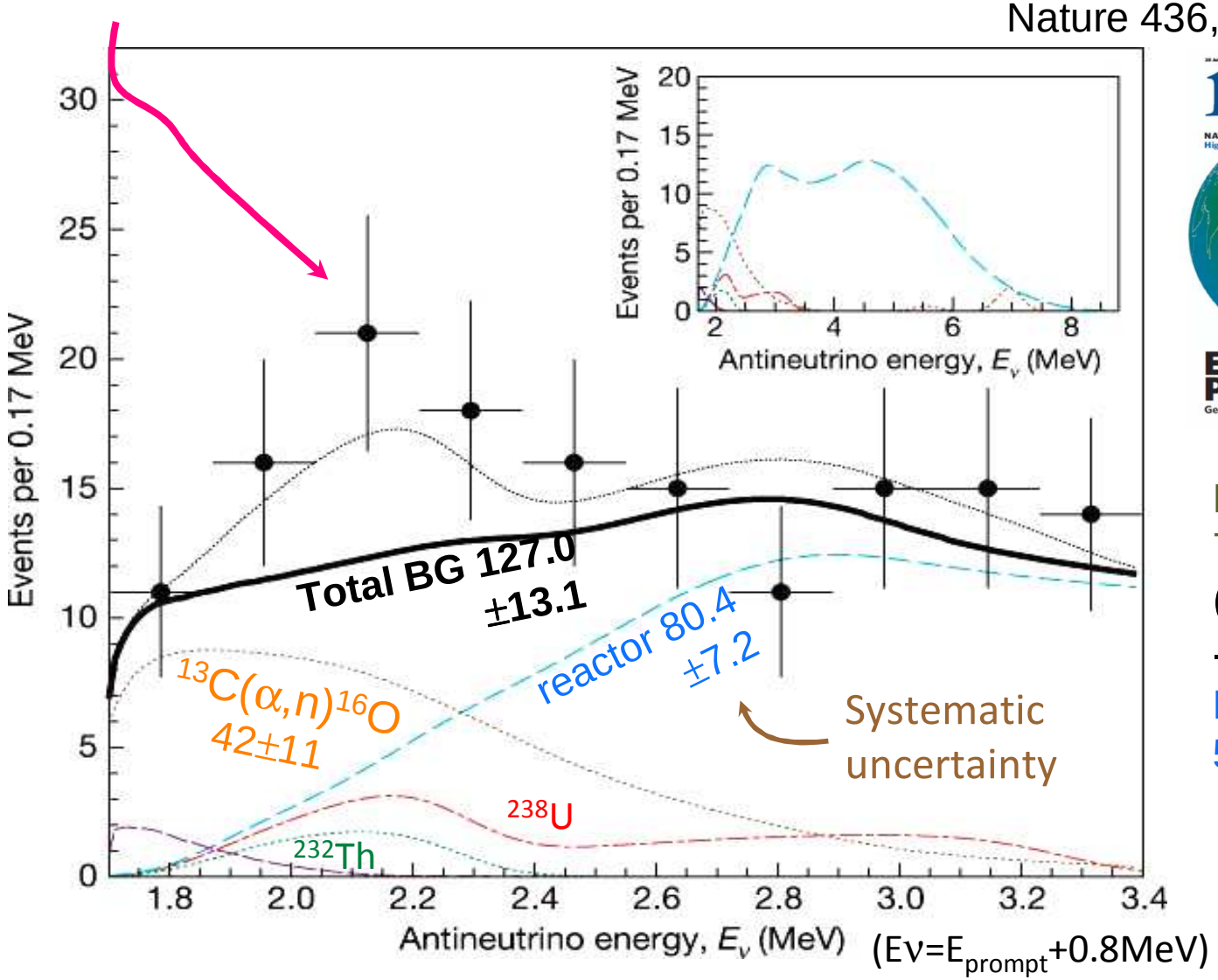
Geoneutrino: data-2005 vs. data-2008

Data-2004:	**PRL94, 081801**	**(Reactor)**
Data-2005:	**Nature436, 28**	**(Geo)**
Data-2008:	**PRL100,221803**	**(Combined)**

Data-2005

152 events observed
"signal" 25 $^{+19}_{-18}$

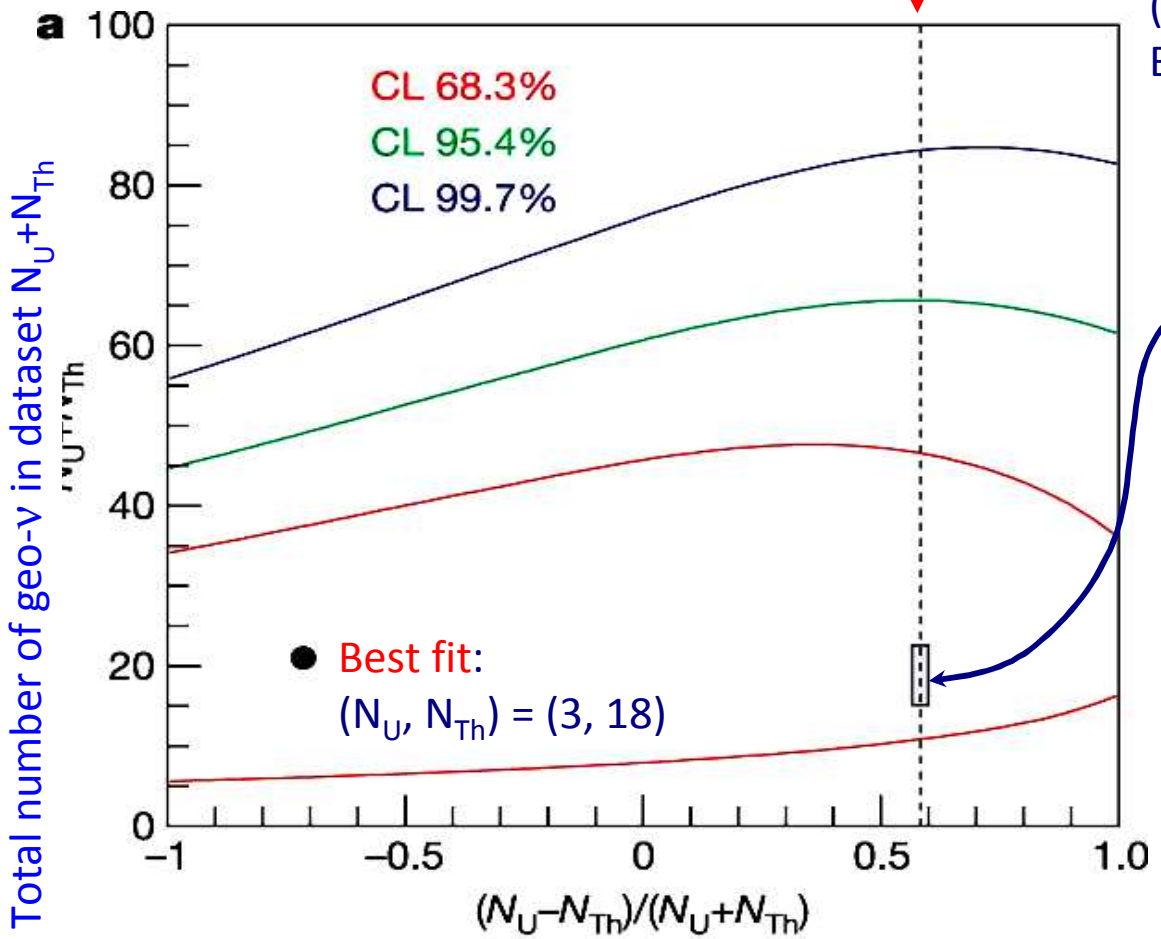
Nature 436, 28 July 2005



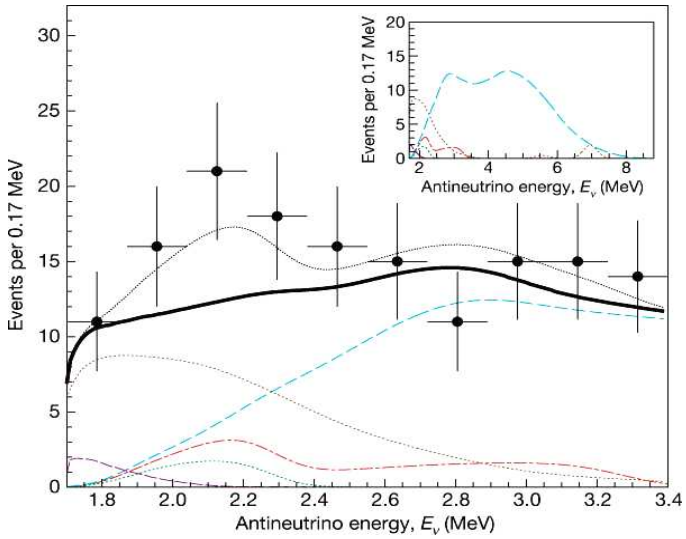
Data-set:
749.1 days
(Mar. 9, 2002
-Oct. 30, 2004)
Fiducial:
5 m radius

Rate + Shape analysis

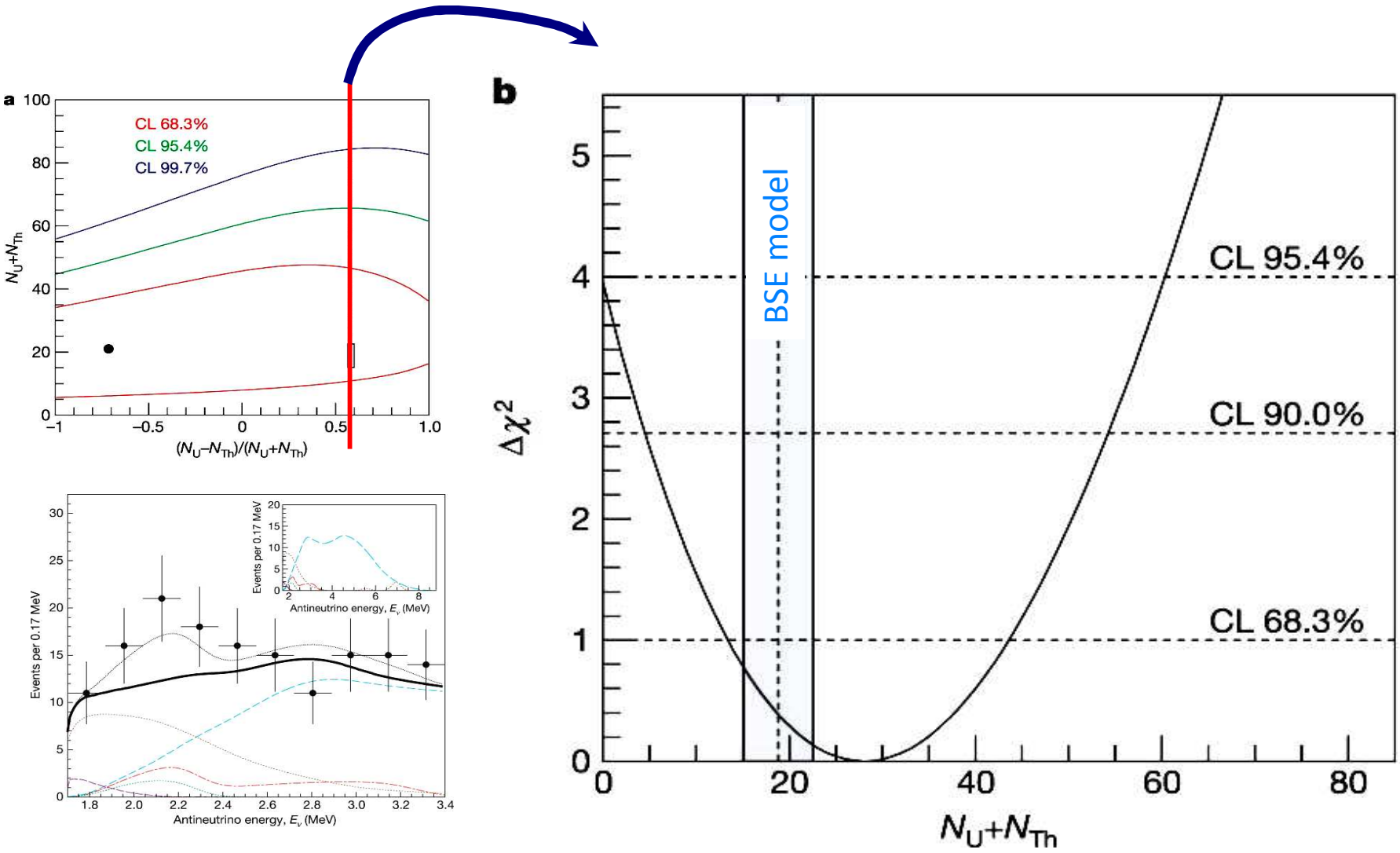
Th/U=3.9 (in mass ratio)
("definitely" expected in
BSE model ("chondritic"))



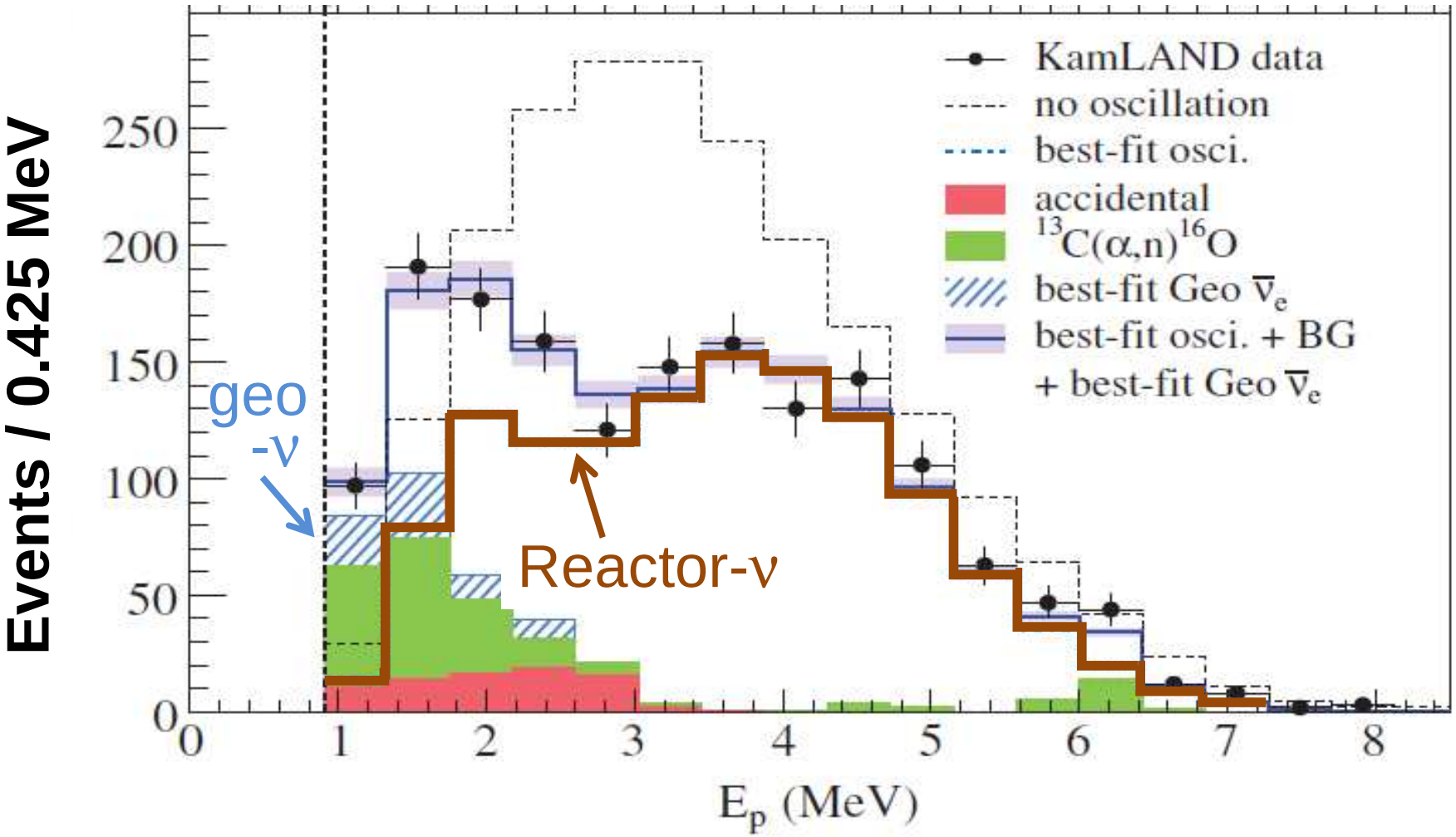
BSE model



Th/U=3.9: fixed

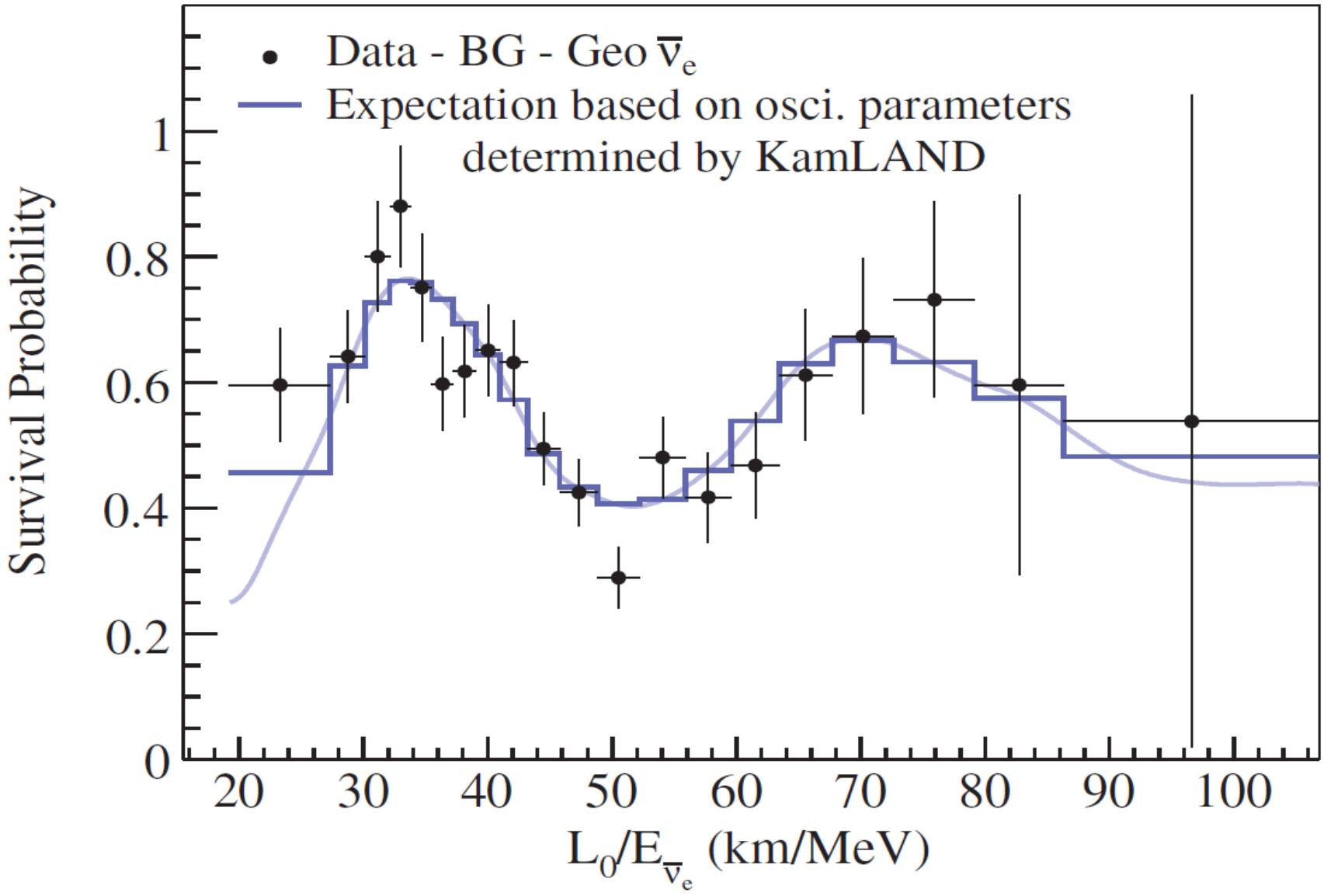

a
CL 68.3%
CL 95.4%
CL 99.7%
N_U+N_{Th}
$(N_U-N_{Th})/(N_U+N_{Th})$
Events per 0.17 MeV
Antineutrino energy, E_ν (MeV)
b
BSE model
CL 95.4%
CL 90.0%
CL 68.3%
$\Delta\chi^2$
N_U+N_{Th}

Data-2008



Data-2005: 7.09×10^{31} proton yr
Data-2008: 2.44×10^{32} proton yr (×3.4)

Data-2008


Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters
determined by KamLAND
Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

Data-2008

- geo-ν (U+Th, ratio fixed):

  $4.4 \pm 1.6 \times 10^{6}$ cm^{-2} s^{-1} (73±27 events)
- Finite signal: 2.7σ (~2σ for Data-2005)
- U+Th: 69.7 events expected

  in Reference-3 (Enomoto)
- Georeactor at the center of the Earth

  < 6.2 TW (solar + KamLAND data)

“Probe calibration” and geo-ν

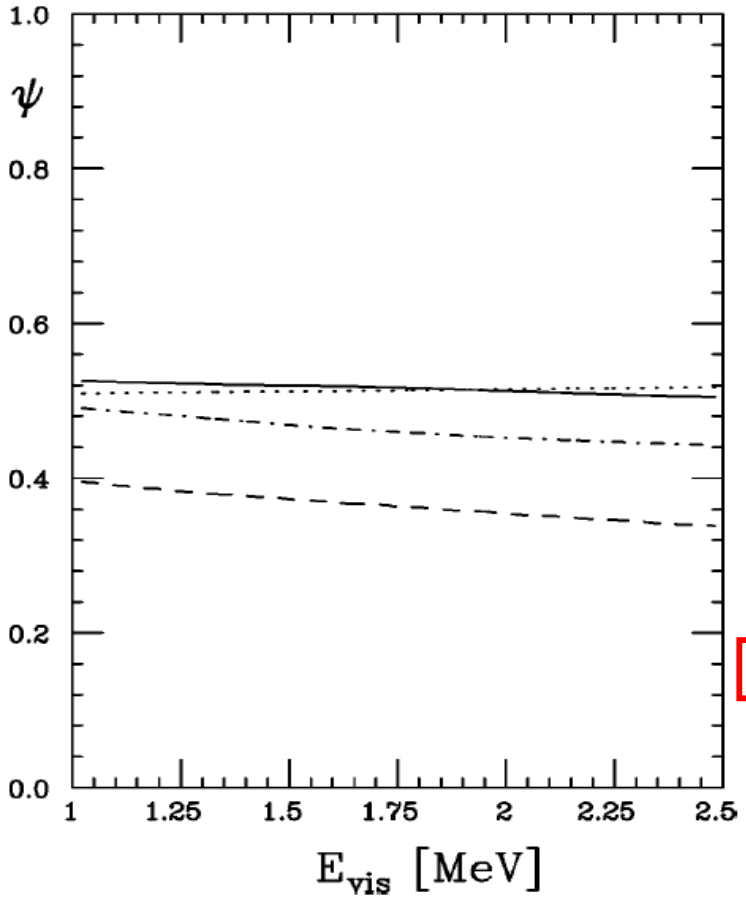
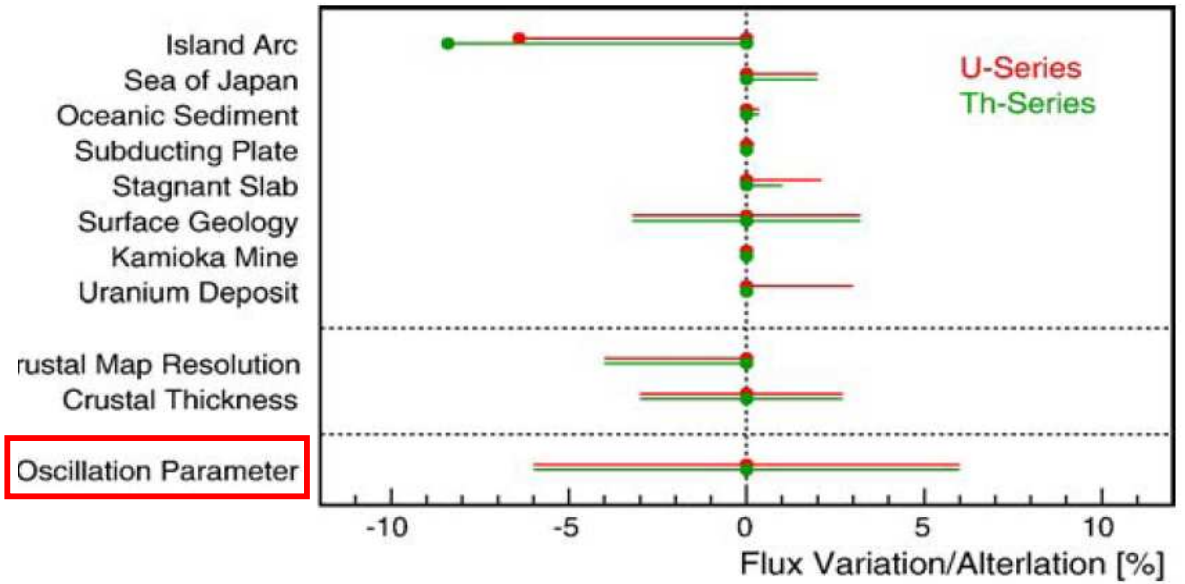


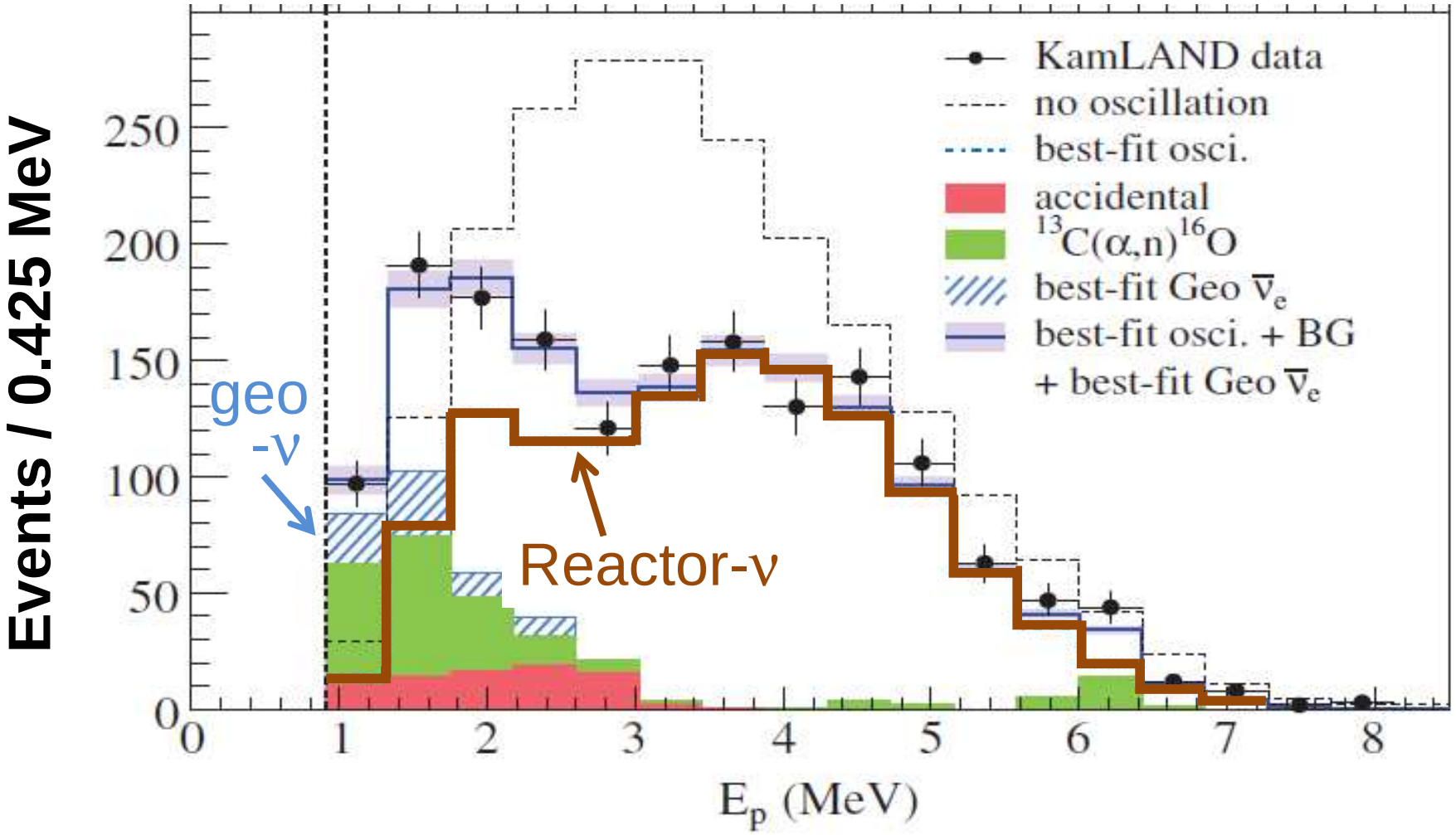
FIG. 7. Spectrum deformation. The function ψ, defined in Eq. (14), as function of the visible energy $E_{vis}=T+2m_e$ in MeV for four values of δm^2: 1×10^{-5} eV^2 (dash line), 3×10^{-5} eV^2 (dot dash line), 7.3×10^{-5} eV^2 (solid line), and 20×10^{-5} eV^2 (dot line).

Reference-2

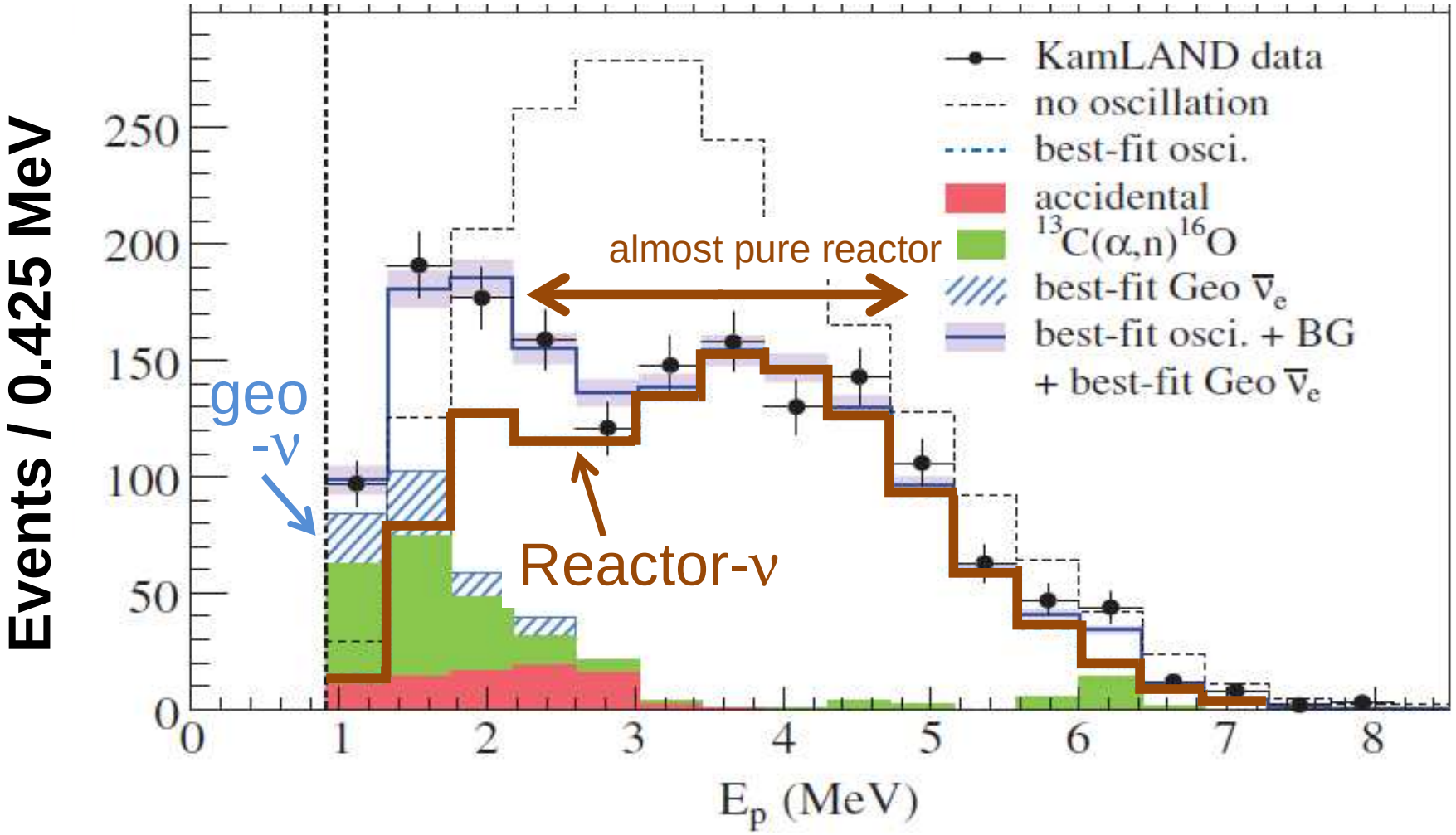


Reference-3

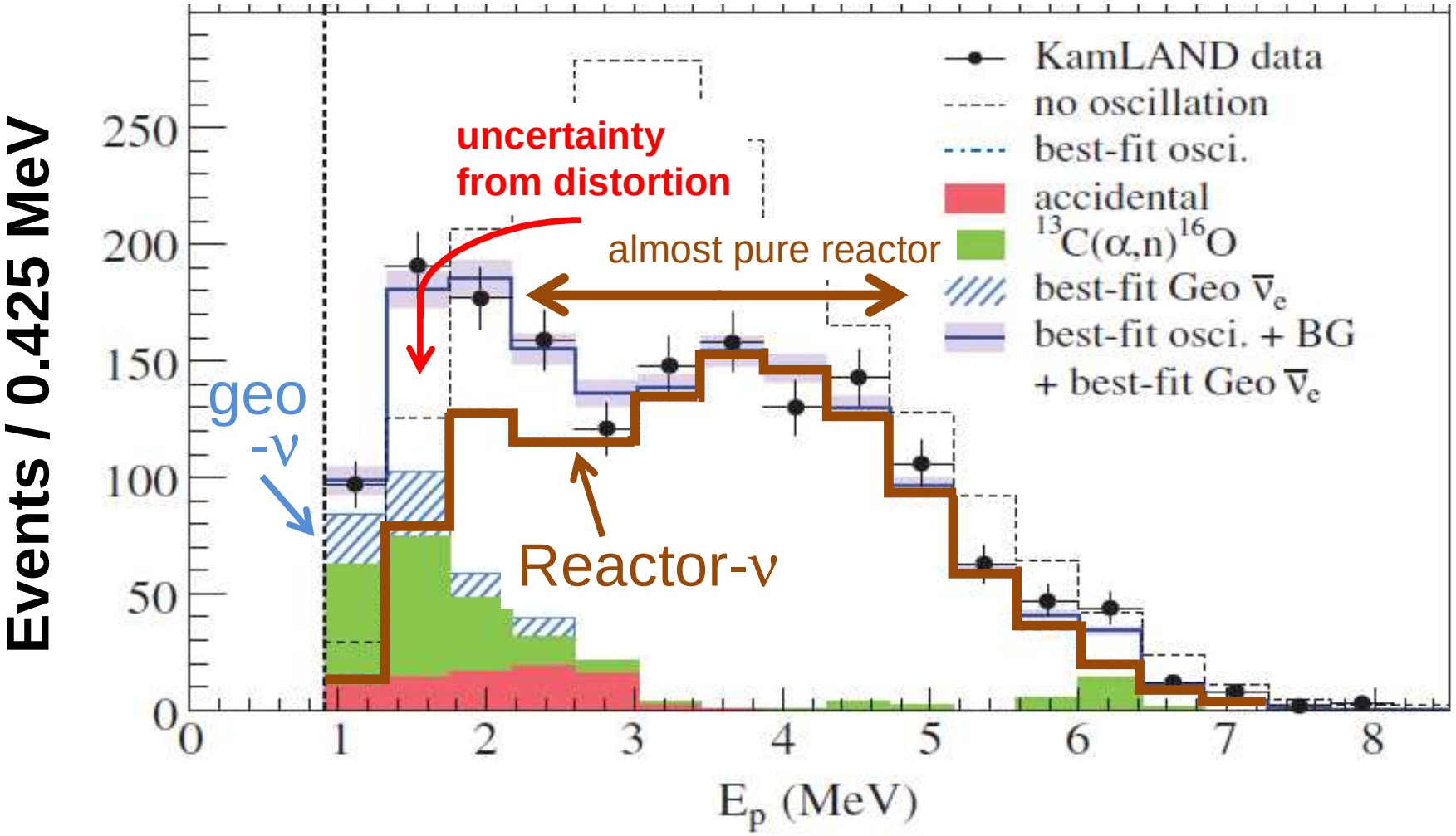
Also for reactor bg uncertainty, θ and Δm^2 are important



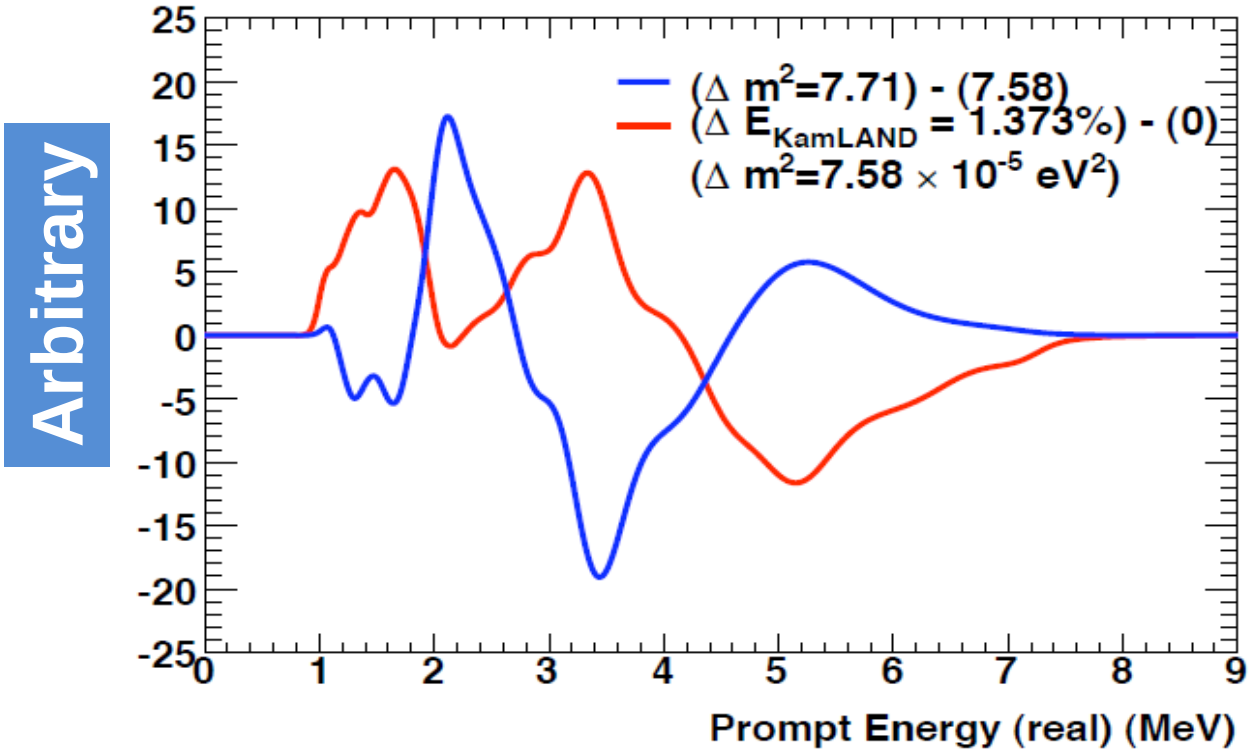
Reactor event rate is constrained from high statistics above $E_p > 2.6$ MeV



Only problem is the spectral distortion



Careful analysis of distortion



- "Right distortion" by Δm^2 vs. "wrong distortion" by energy scale error
- Other "wrong distortion" (reactor spectral uncertainty etc) are carefully examined

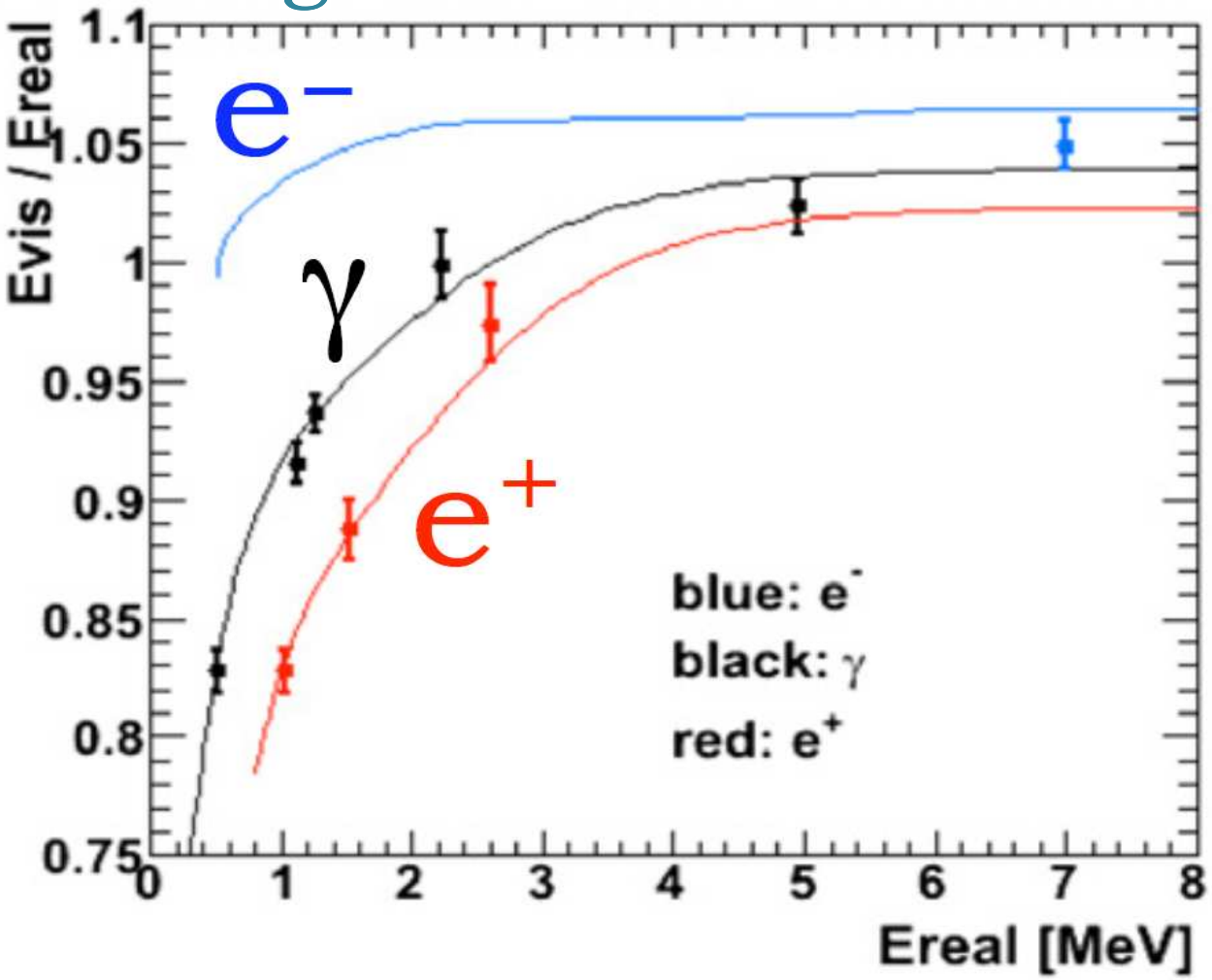
Systematic uncertainty is now becoming dominant

TABLE I. Estimated systematic uncertainties relevant for the neutrino oscillation parameters Δm^2_{21} and θ_{12}.

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\bar{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\bar{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

Total Δm^2 uncertainty (KamLAND+solar): **2.77 %**

Energy scale determination in the organic scintillator



Cherenkov-Birks model

Future

Future

- Data are being taken with ^{210}Po-reduced scintillator (distillation was done 2006~2009)
- Directional sensitivity
  - Vertex resolution:
  - KamLAND : ~300 p.e., 10cm, 1 kton
  - Imaging: ~1 p.e., 1cm, 100 cc
    (see H. Watanabe)
  - “new technology” but 10^7 enlargement of the target volume is needed: continue the development
- Continue to provide the “prove calibration” for future multi-point measurement (Borexino, SNO+, Hanohano, LENA, EARTH, …)


Grazie mille!
for your attention