Recent Results from KamLAND

21th Neutrino Meeting

Nov. 2, 2007

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KamLAND Collaboration

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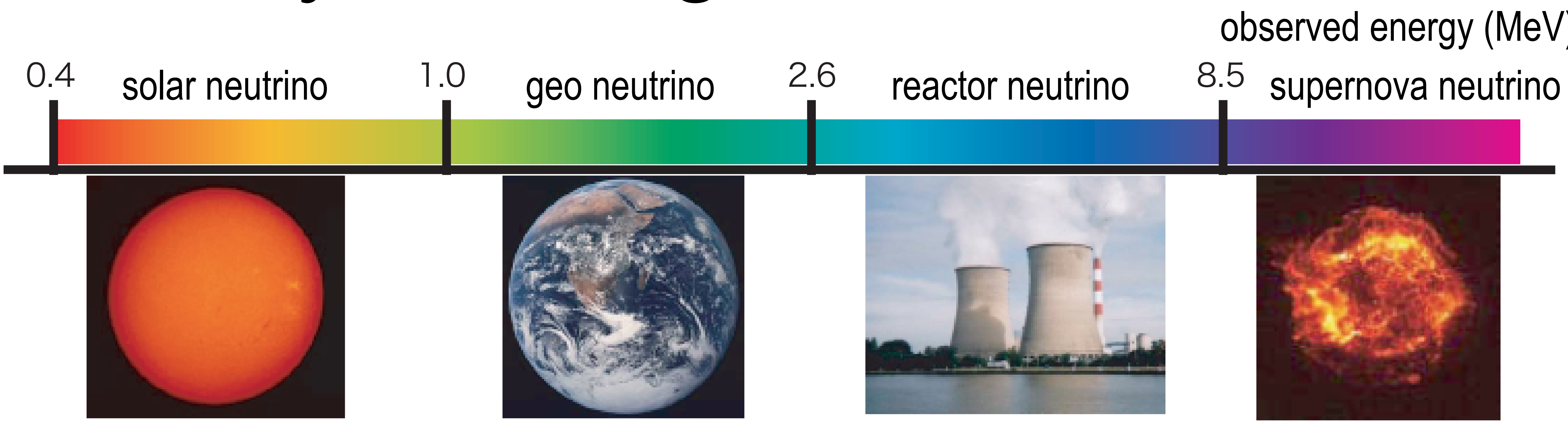
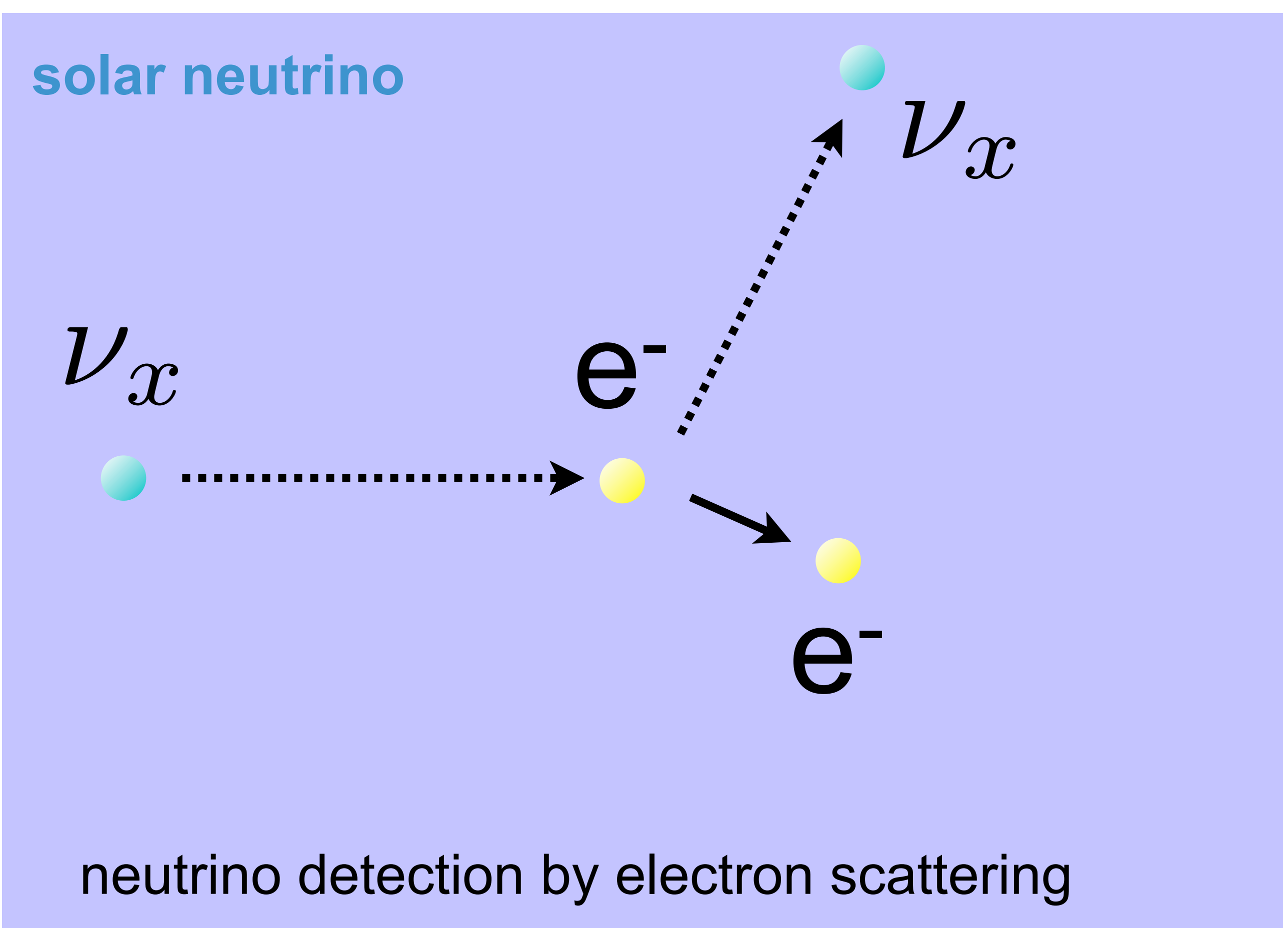
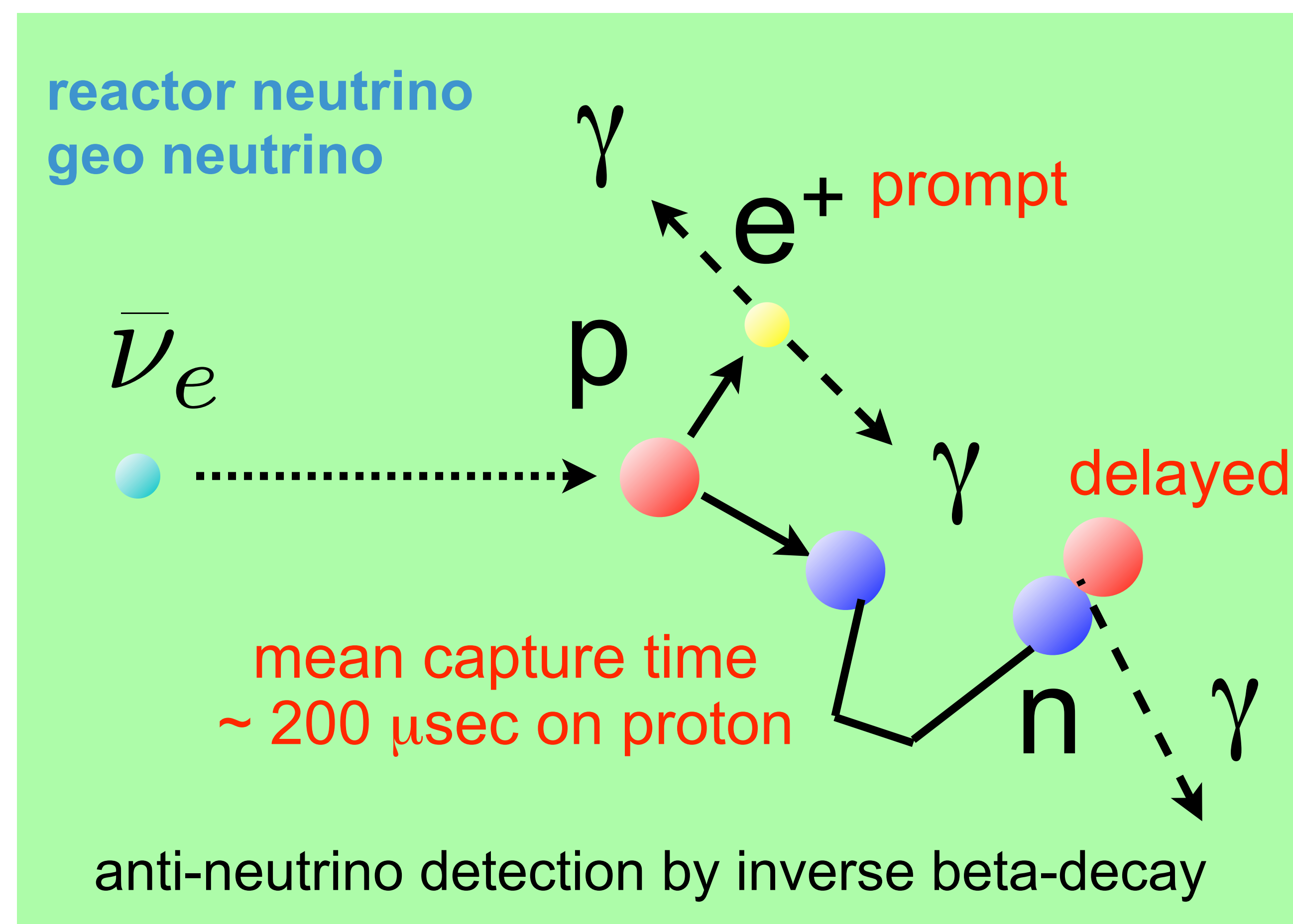
Physics Target in KamLAND

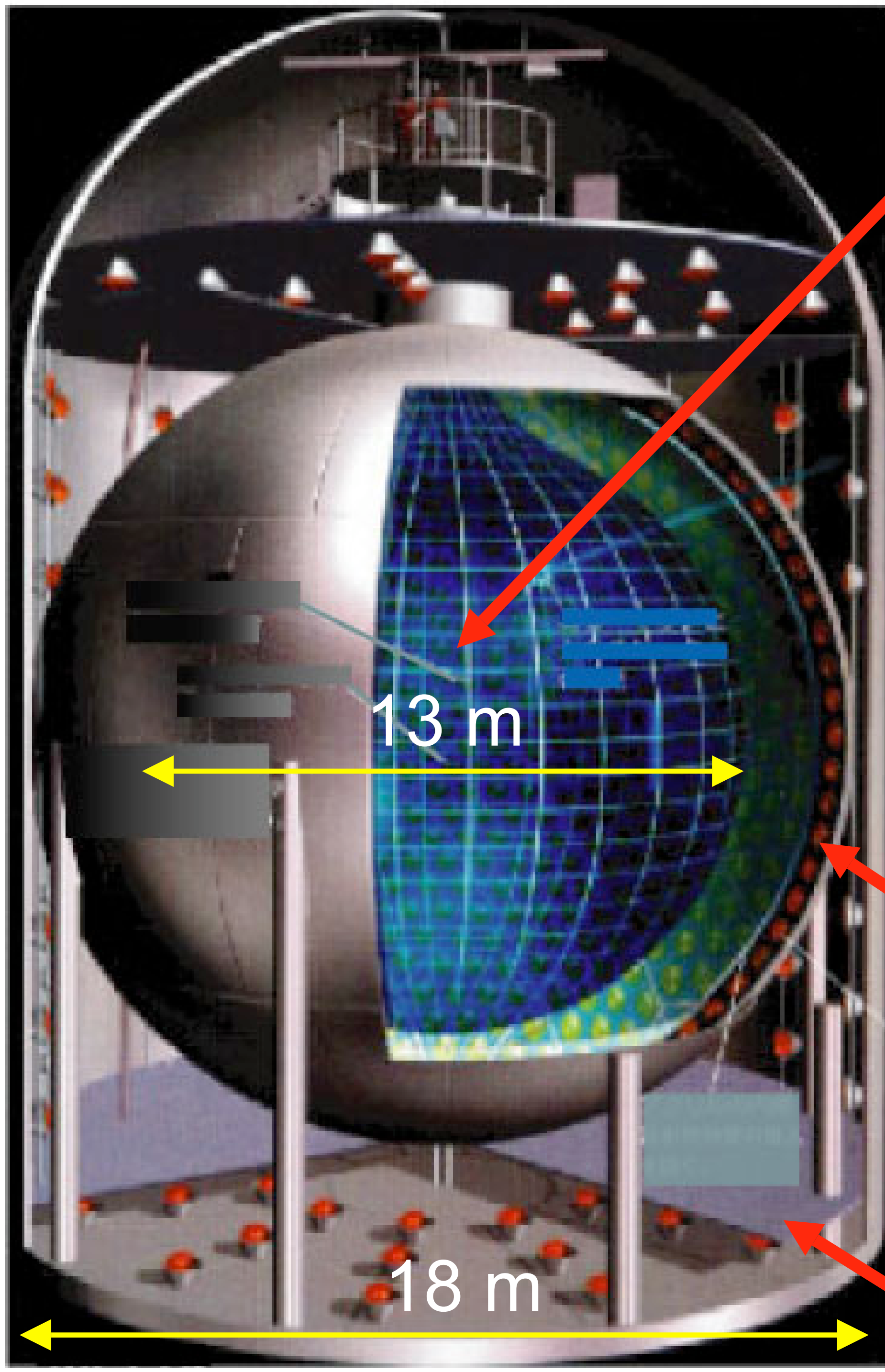






KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

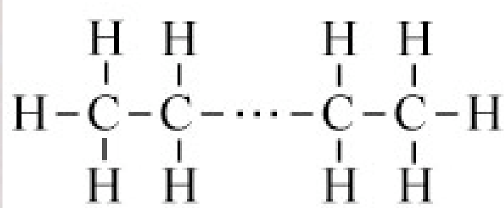


1,000 ton Liquid Scintillator

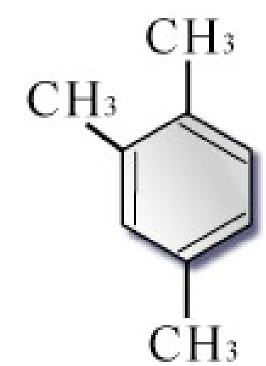
Pseudocumene (20%)

Dodecane (80%)

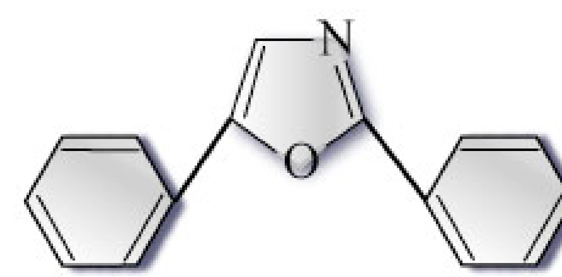
PPO (1.5 g/l)



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%

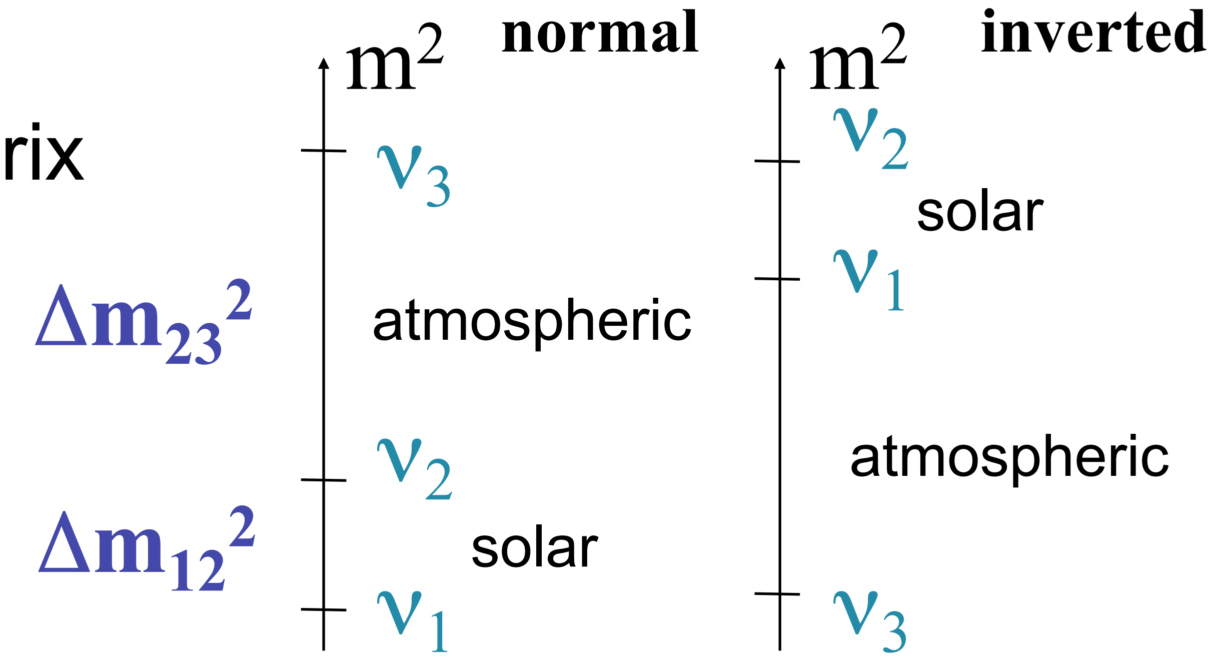
Water Cherenkov Outer Detector

Reactor Neutrino

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

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

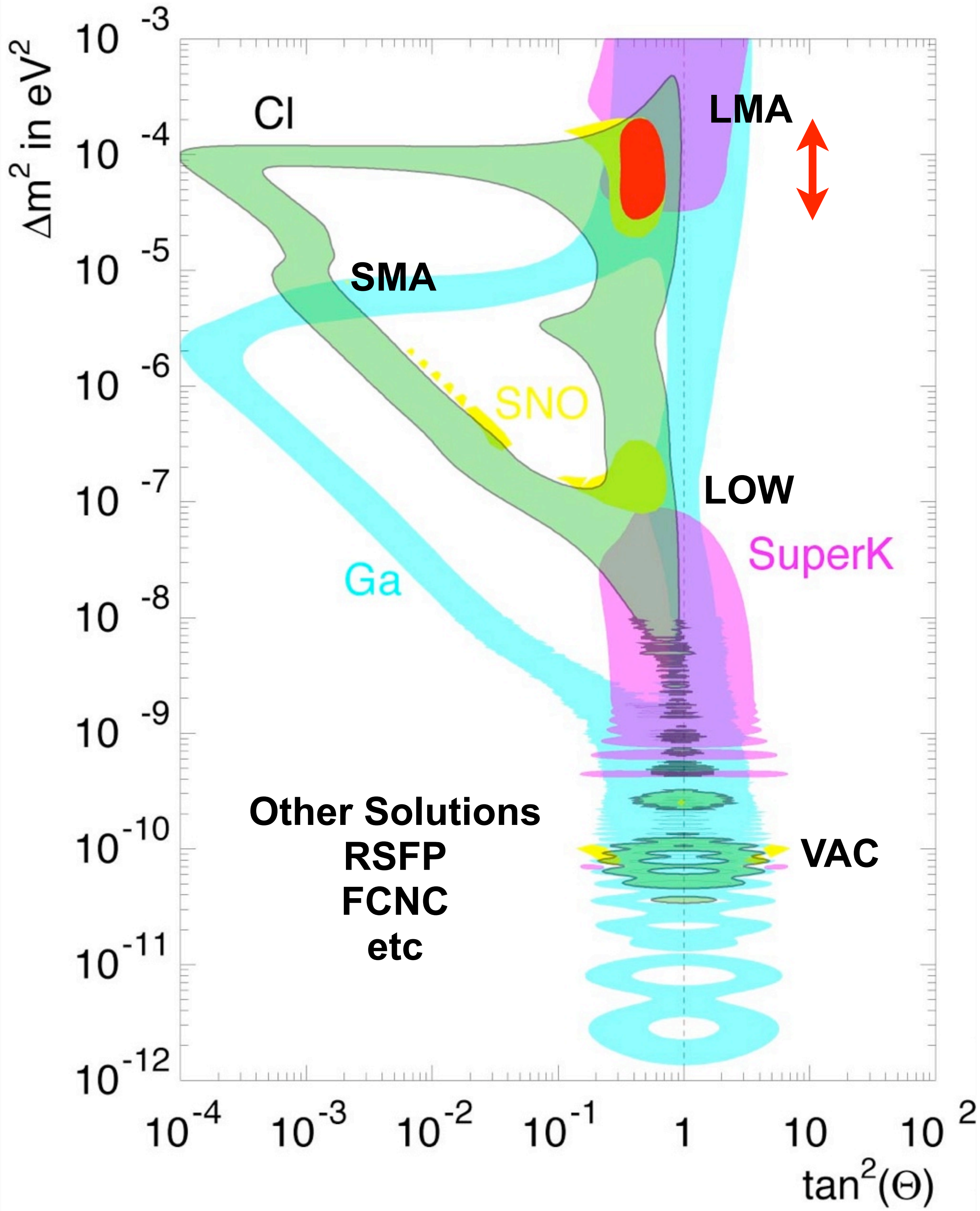
atmospheric solar

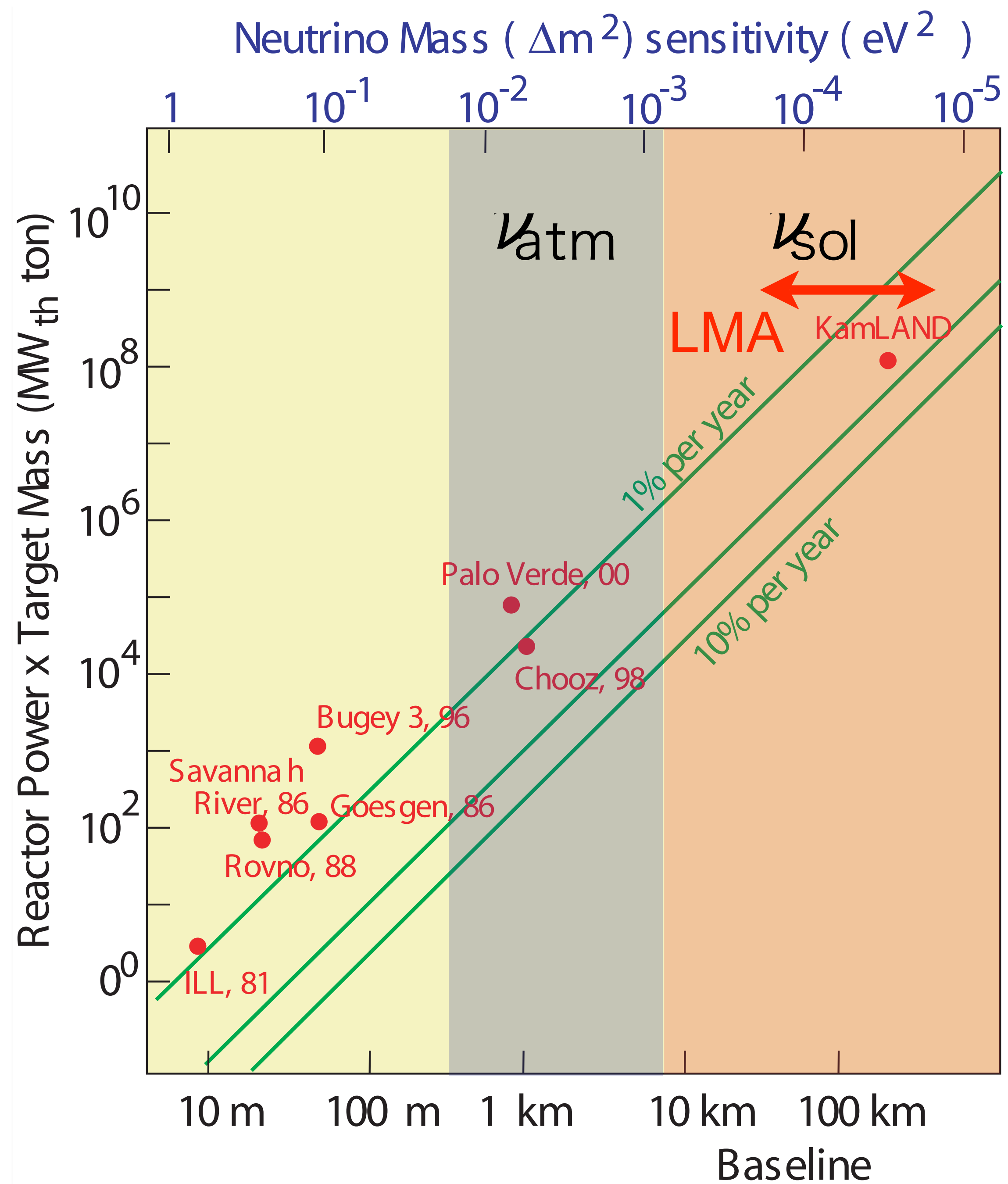
6 parameters : 3 mixing angle, 2 mass difference, 1 CP phase

+ 2 Majorana phase

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

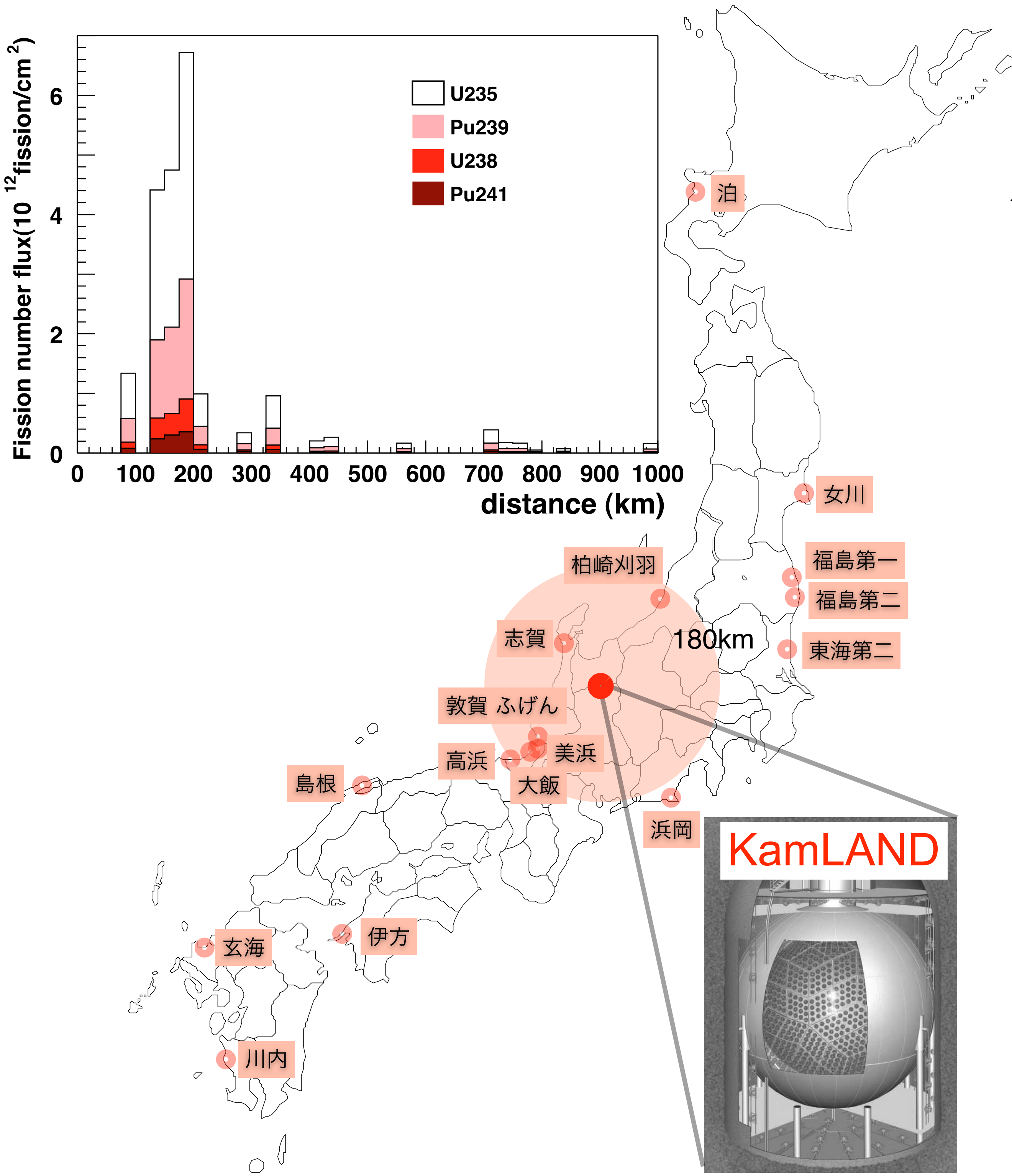
Solar Neutrino Problem





> 100 km baseline is necessary to explore the LMA solution

KamLAND Experiment



2 flavor neutrino oscillation

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

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	$7.4\% / \sqrt{E(\mathrm{MeV})}$
17 inch + 20 inch	$6.5\% / \sqrt{E(\mathrm{MeV})}$

Good condition to confirm solar neutrino oscillation

Reactor and Geo Neutrino Analysis

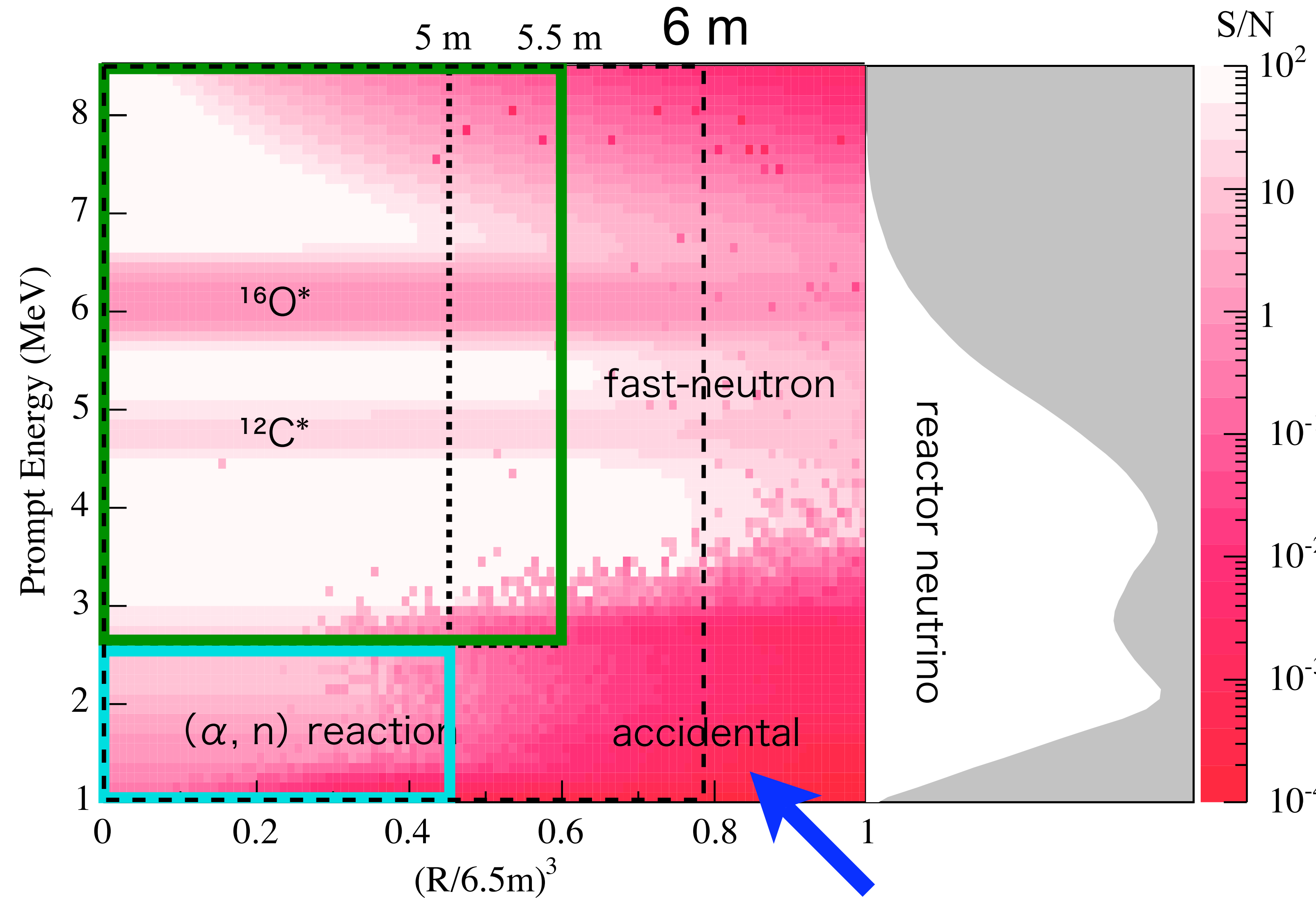
previous result

separated analysis window for reactor and geo neutrinos

reactor neutrino
(2.6 - 8.5 MeV, R 5.5 m)

geo neutrino
(0.9 - 2.6 MeV, R 5.0 m)

S / B ratio map (energy v.s. radius)



large accidental B.G. caused by external γ-rays

Analysis improvement

(1) efficient accidental background rejection

(2) combined analysis of reactor and geo neutrinos

Anti-Neutrino Event Selection

(a) Accidental B.G. discrimination

discriminator based on 5 parameters (E_d, ΔR, ΔT, R_p, R_d)

$$L_{ratio} = f_{\bar{\nu}} / (f_{\bar{\nu}} + f_{accidental})$$

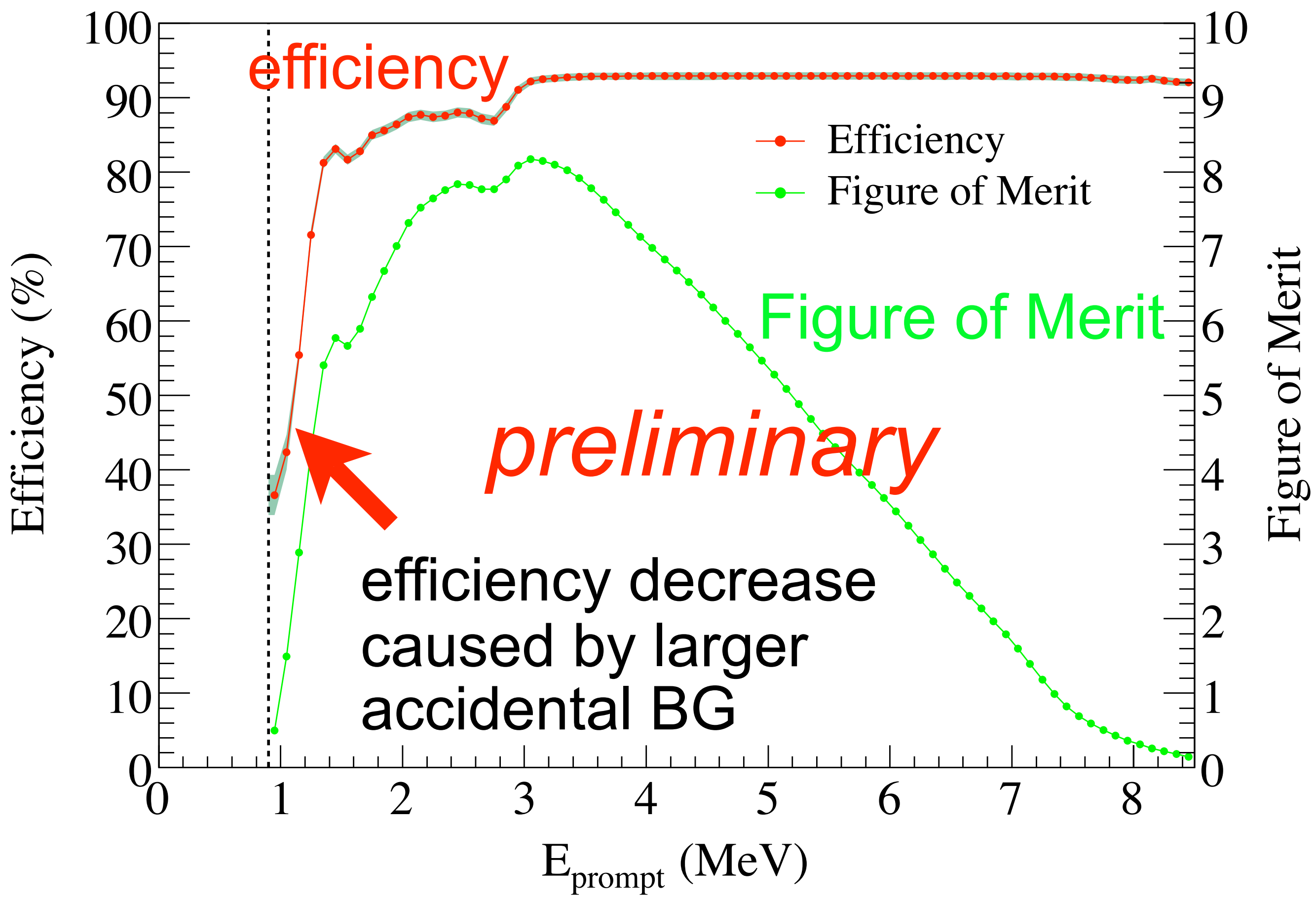
f : PDF

Selection : Maximize "Figure of Merit" $\frac{S}{\sqrt{S + B_{accidental}}}$

(b) μ spallation cut

- $\Delta T_\mu > 2$ s after showing μ ($\Delta Q > 10^6$ p.e.)
- $\Delta T_\mu > 2$ s or $\Delta L > 3$ m after non-showering μ

Detection efficiency



2.2 < E_{prompt} < 2.3 MeV

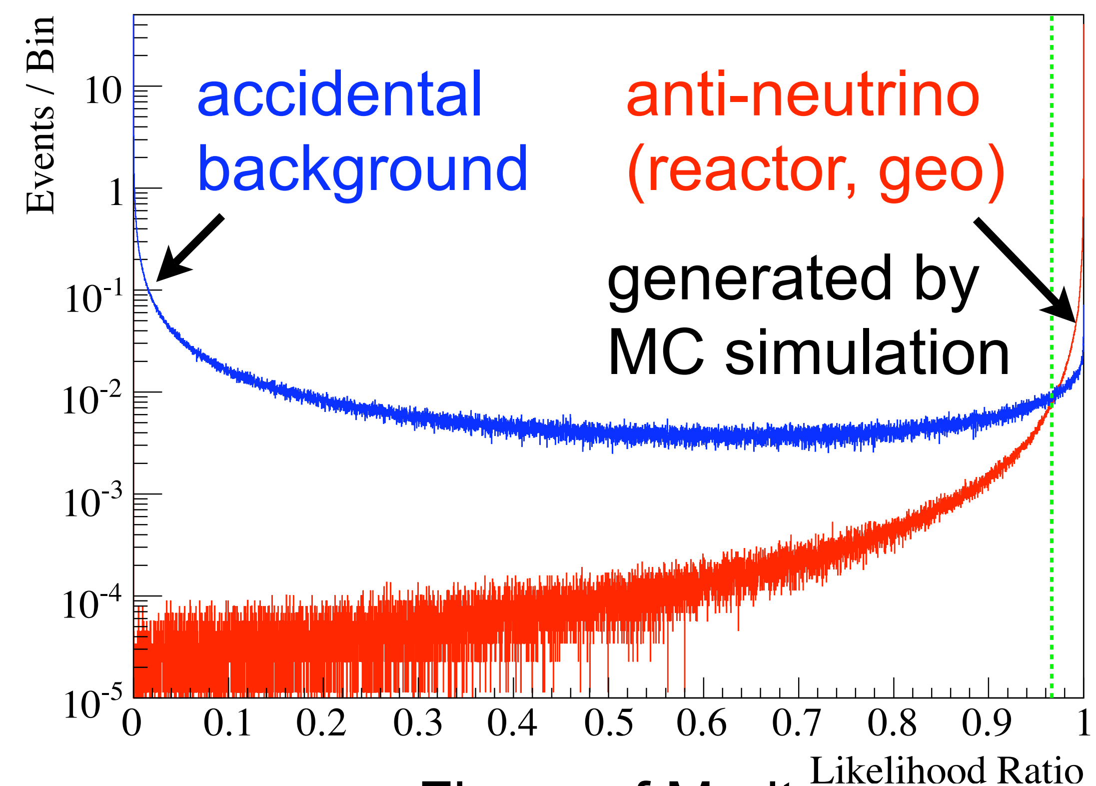
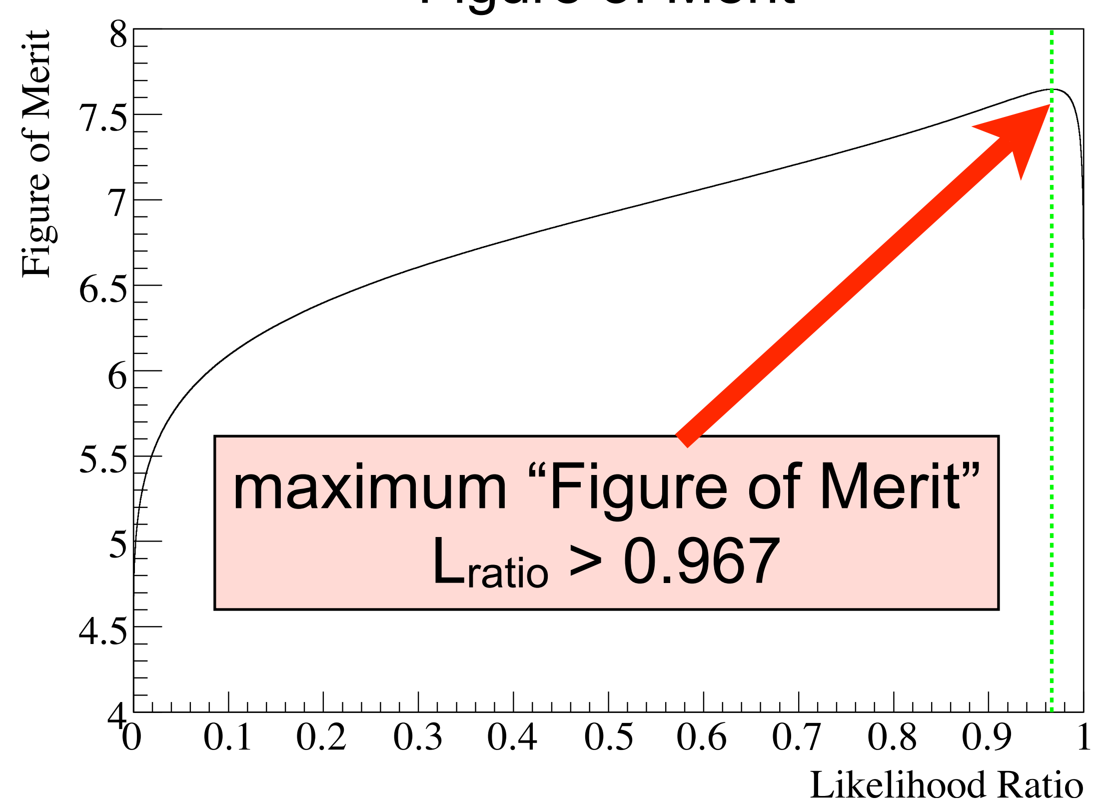
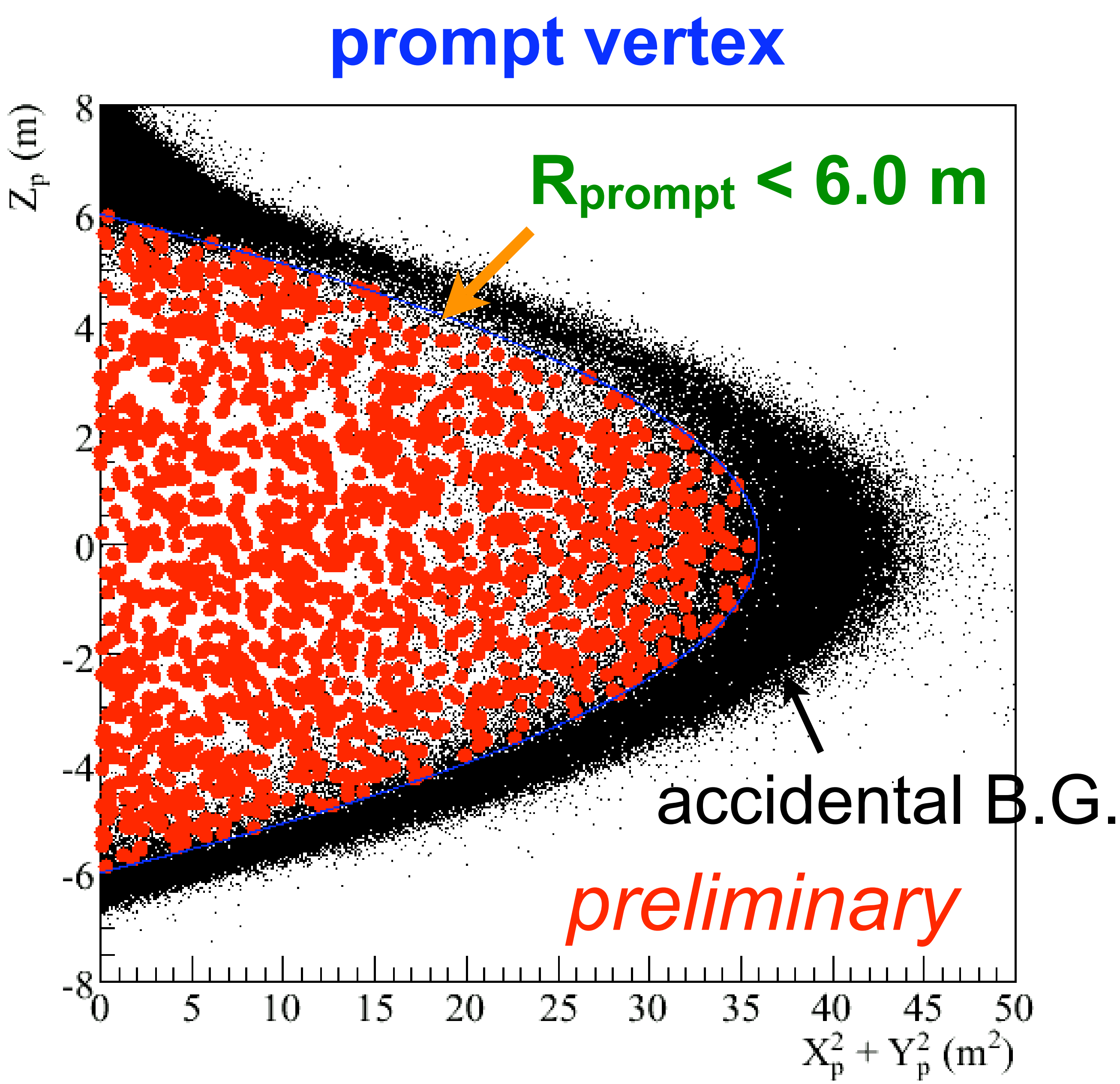
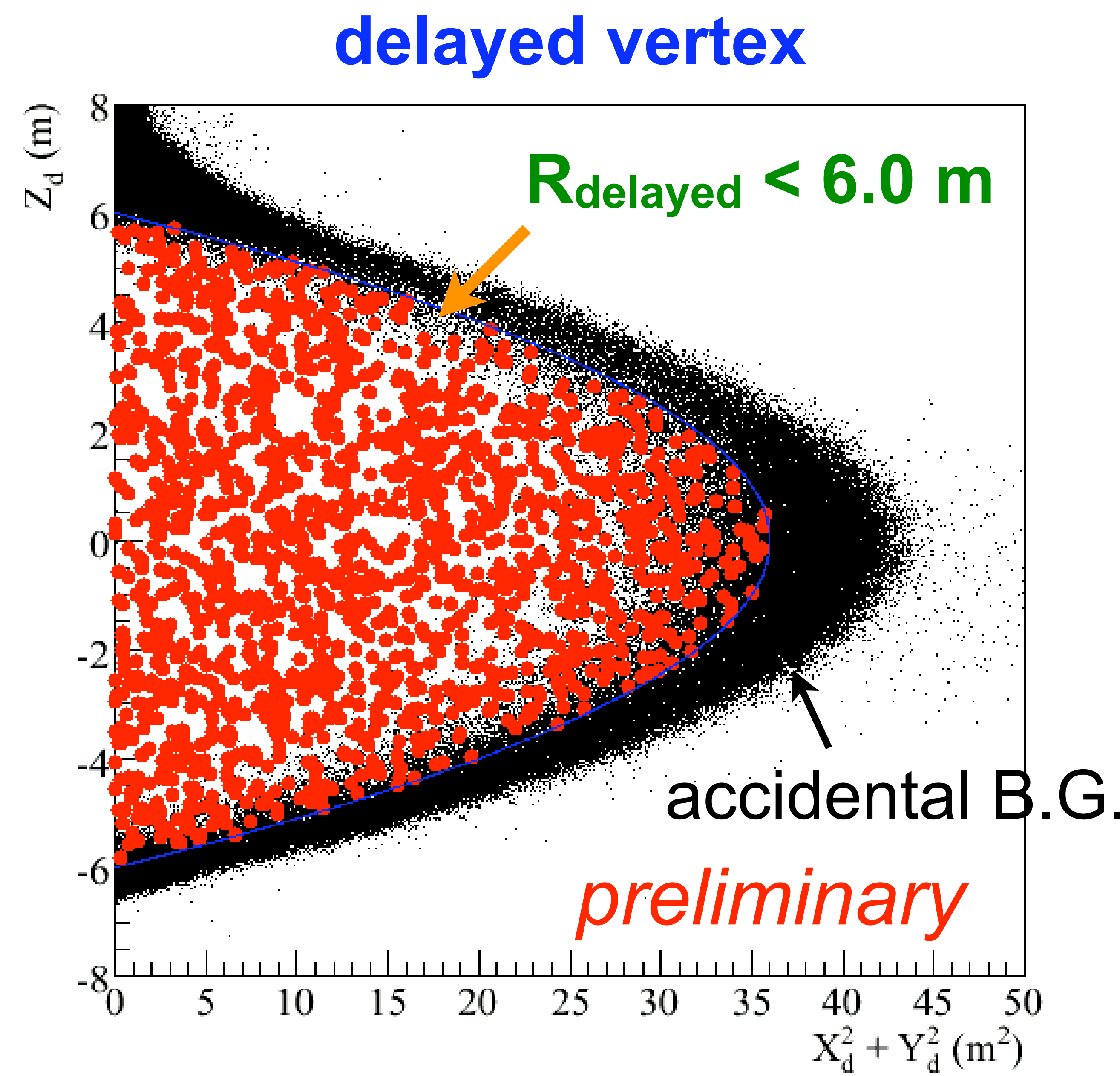


Figure of Merit



Anti-Neutrino Candidates





black : before L_{ratio} selection

red : candidate

Accidental backgrounds are suppressed by L_{ratio} selection

Systematic Uncertainty

<u>"full volume" calibration lowered the fiducial volume error</u>

(4.7% in previous analysis)

preliminary

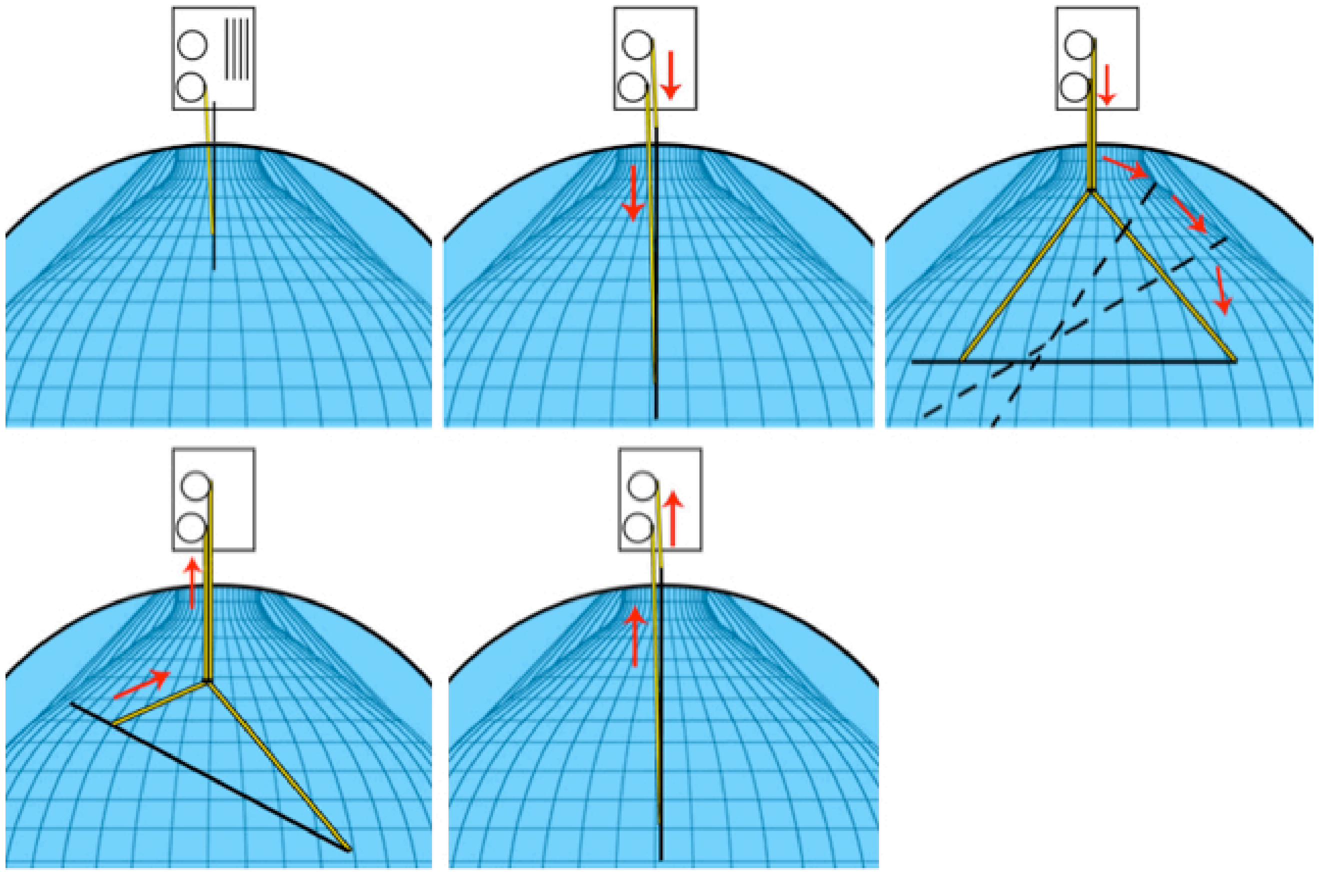
Detector related	
Fiducial volume	1.8%
Energy scale	1.5%
L-selection eff.	0.6%
OD veto	0.2%
Cross section	0.2%
	2.4%

Reactor related	
$\overline{\nu}_e$ spectra	2.4%
Reactor power	2.1%
Fuel composition	1.0%
Long-lived nuclei	0.3%
Time lag	0.01%
	3.4%

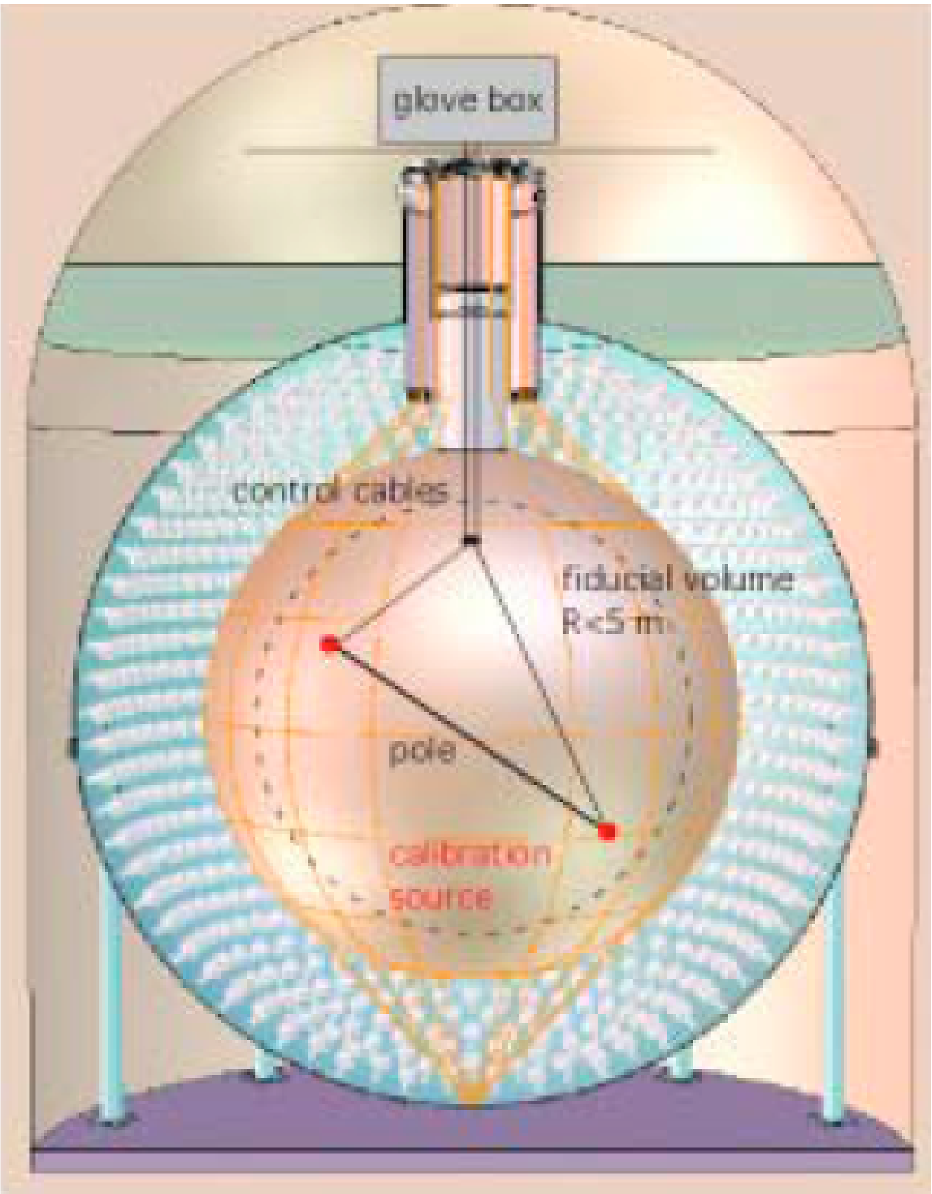
Total systematic uncertainty : 4.1%

New Calibration System

4pi calibration system



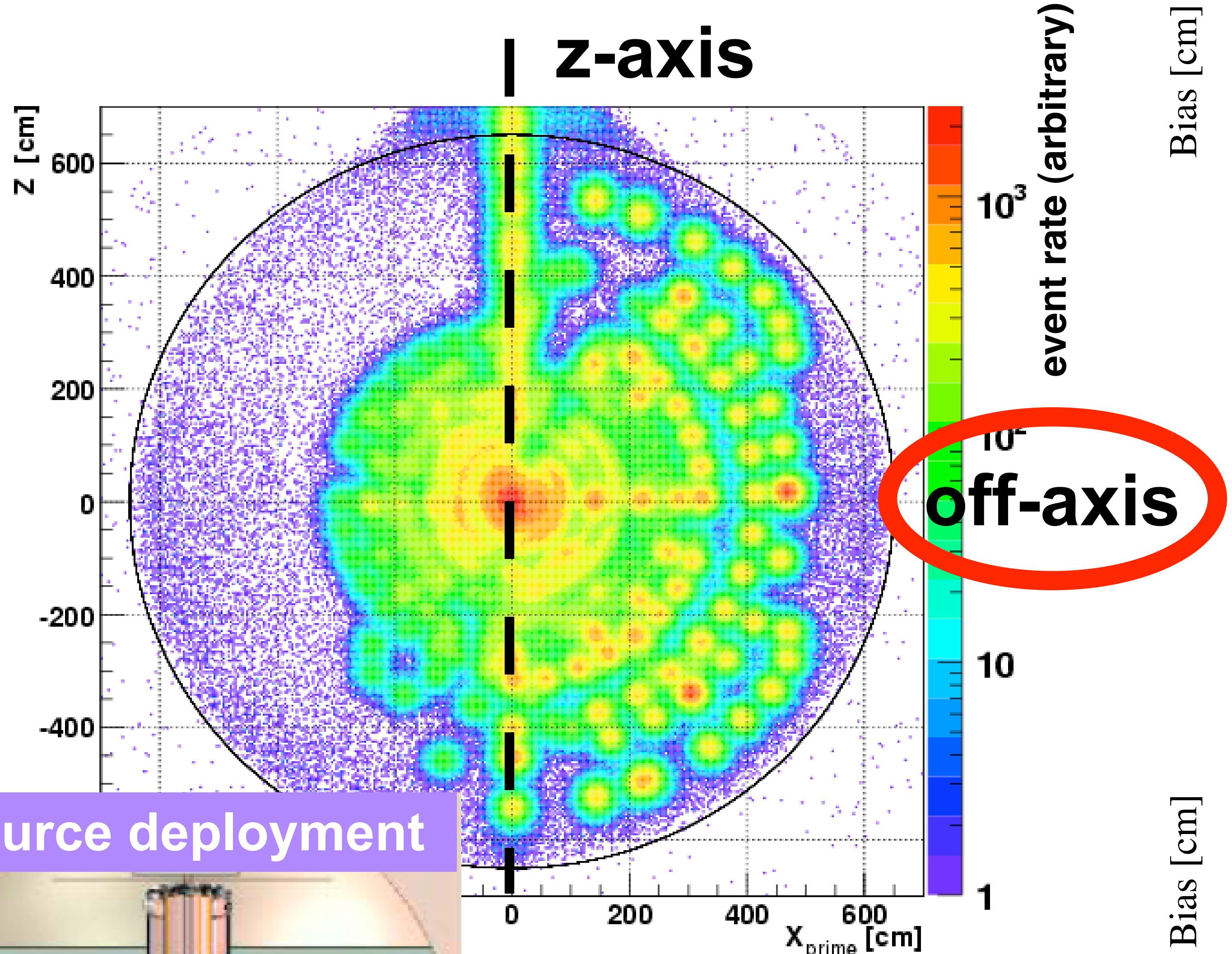
position dependence of
reconstructed energy and vertex

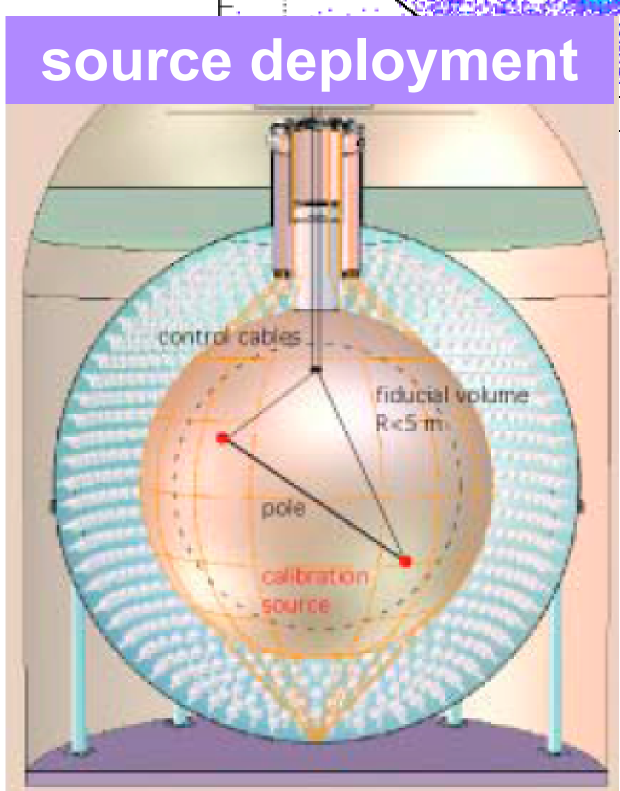


z-dependence → (r, θ, φ)-dependence

z-axis calibration → full volume calibration

Full Volume Calibration



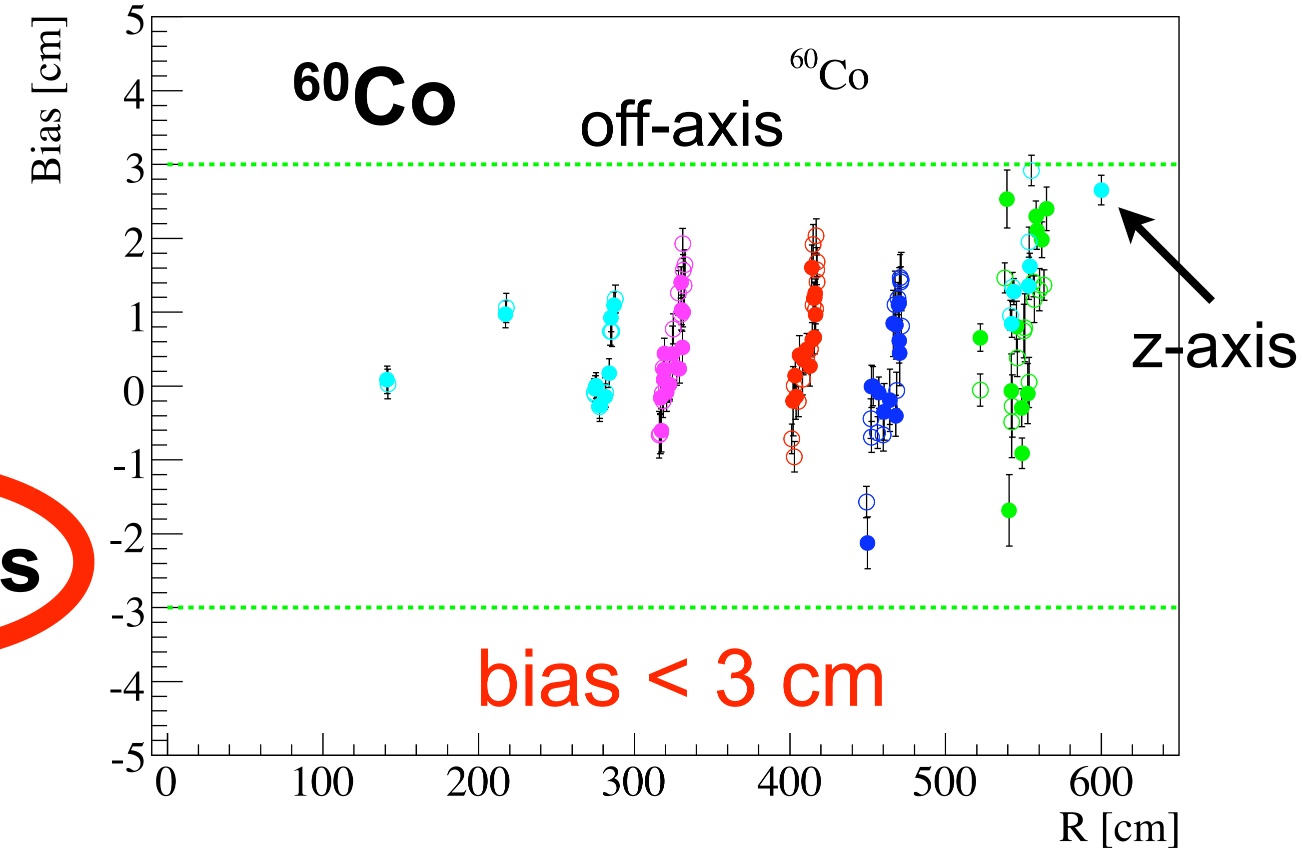


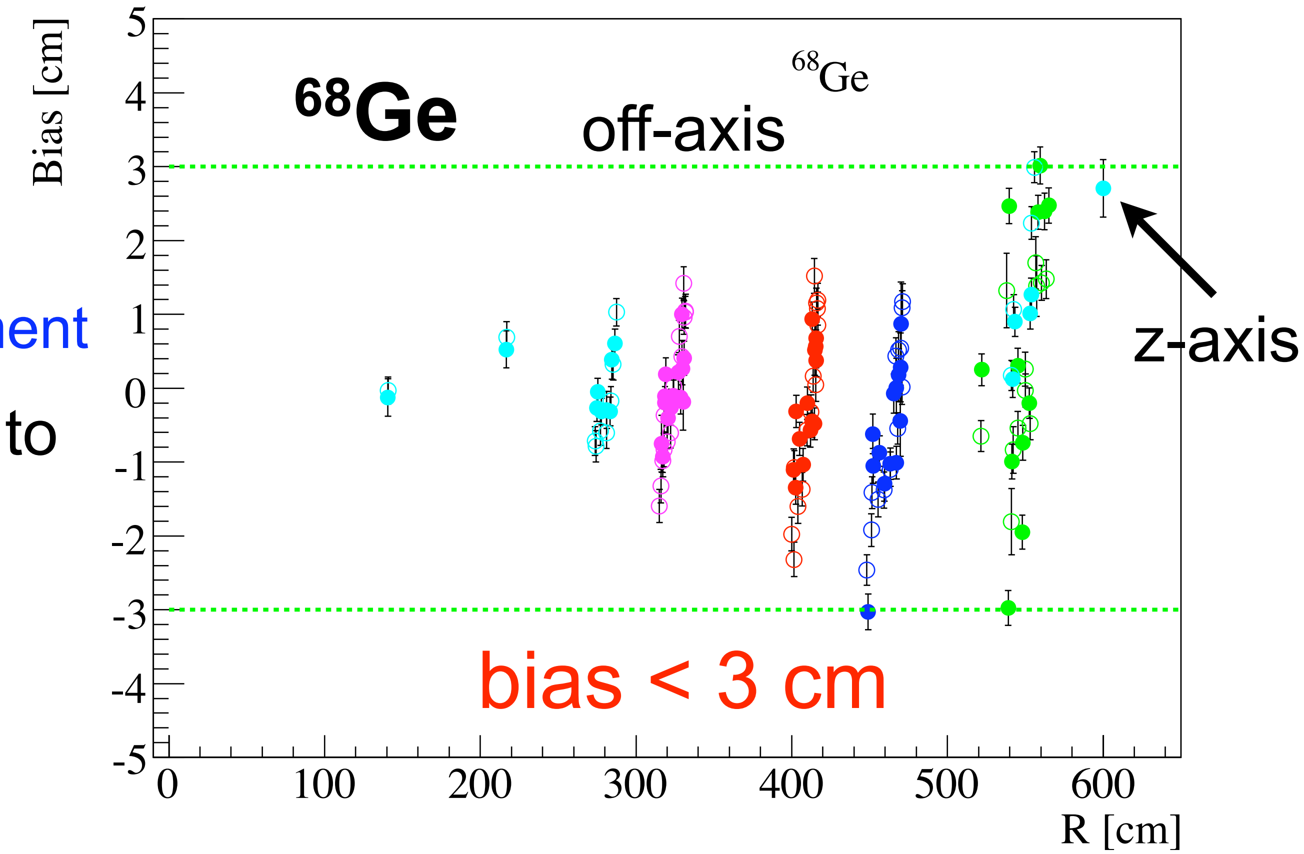
“4pi calibration” system for the off-axis source deployment

bias < 3 cm corresponds to 1.8% volume uncertainty

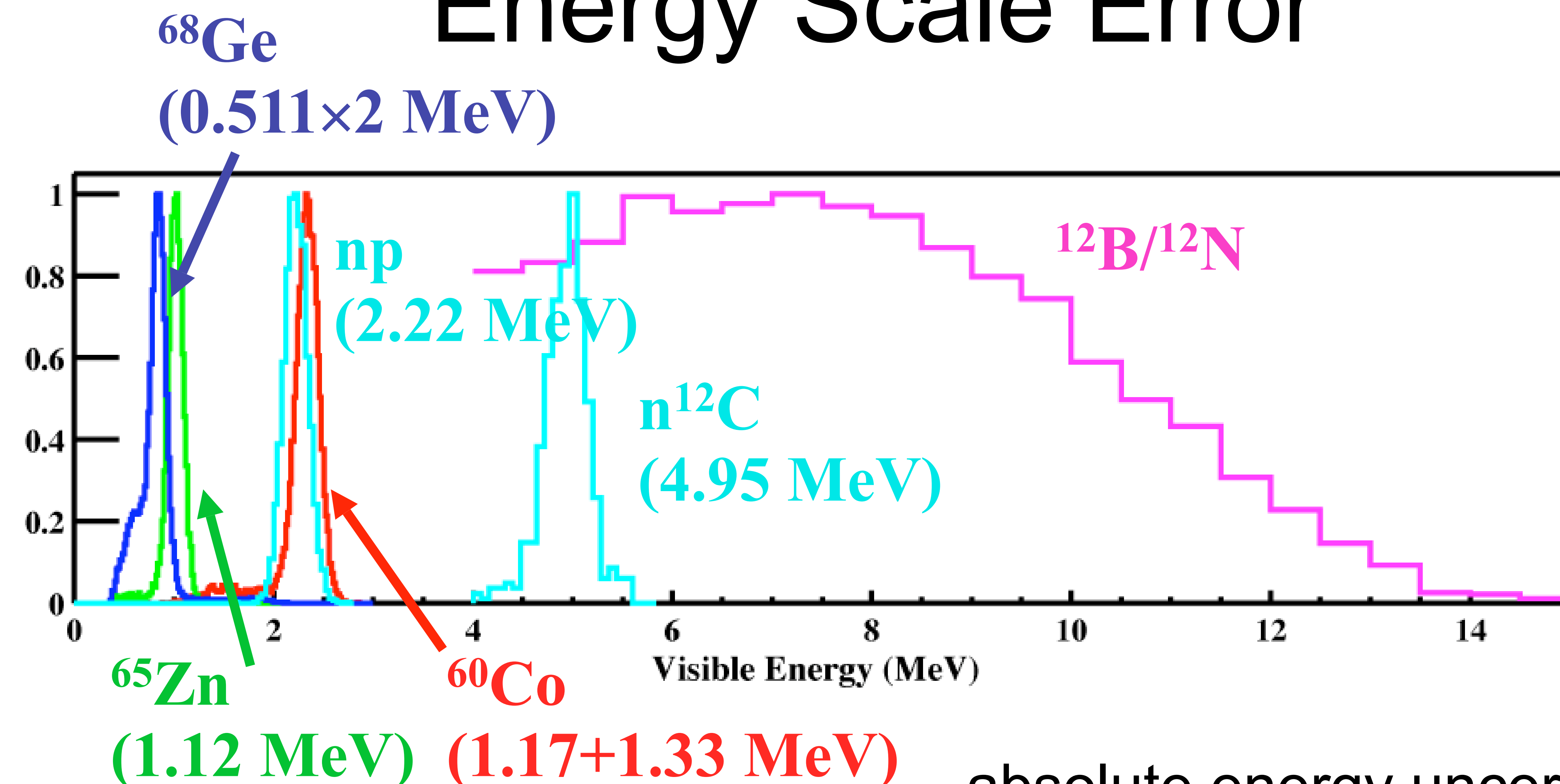
↓

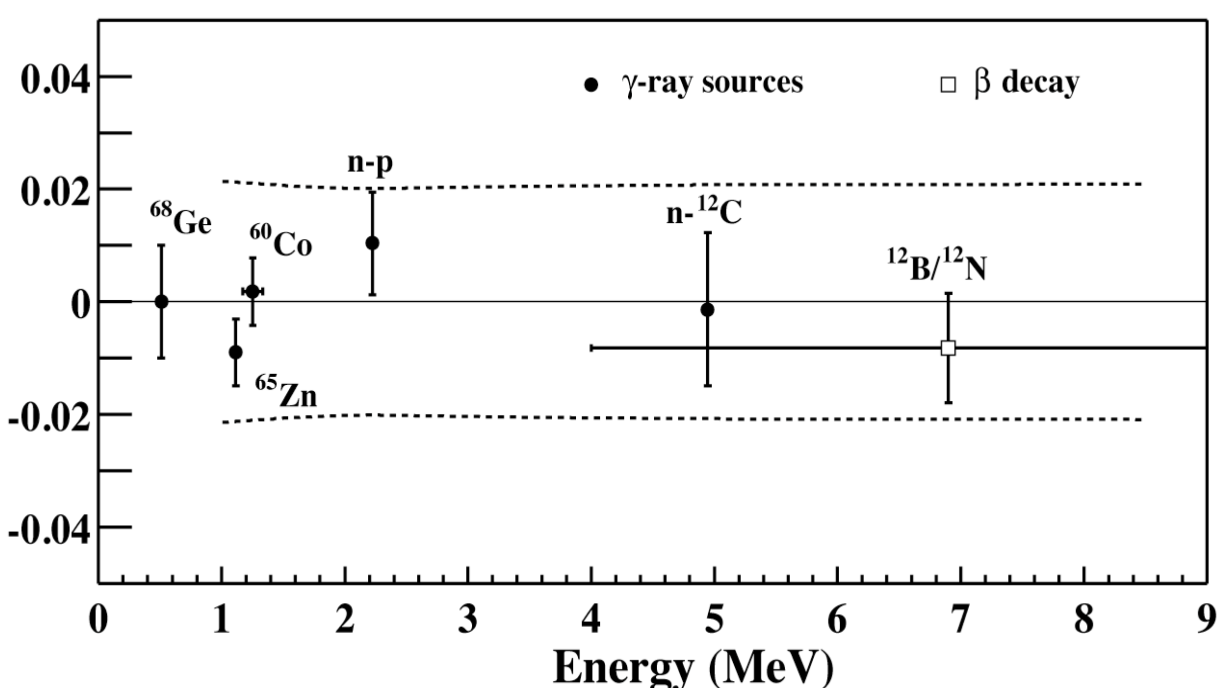
cross-checked by $^{12}B/^{12}N$ uniformity





Energy Scale Error



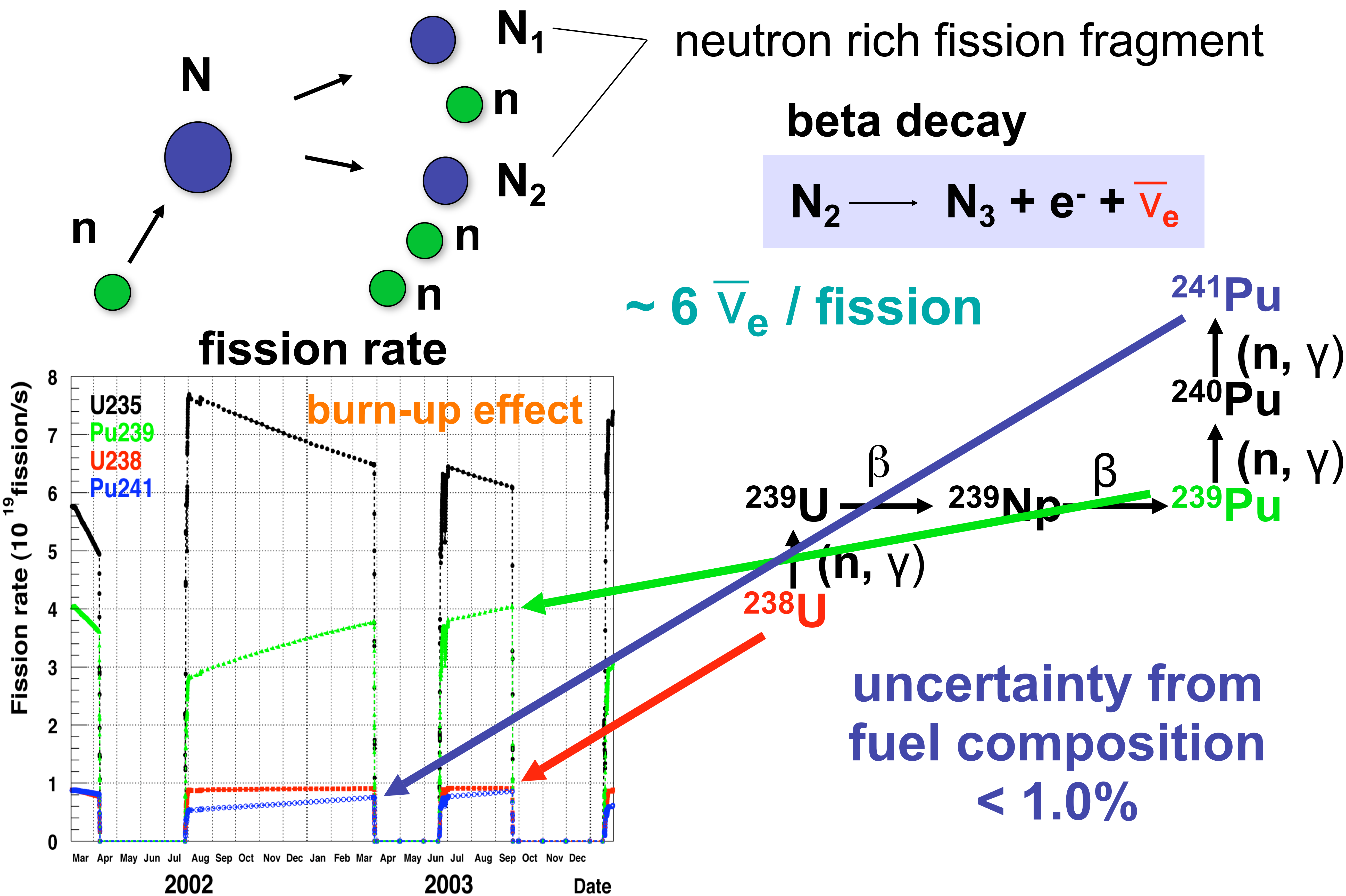


absolute energy uncertainty from time and space over the full data-set is 1.4%

↓

dominant systematic error for Δm^2 measurement

Nuclear Fission



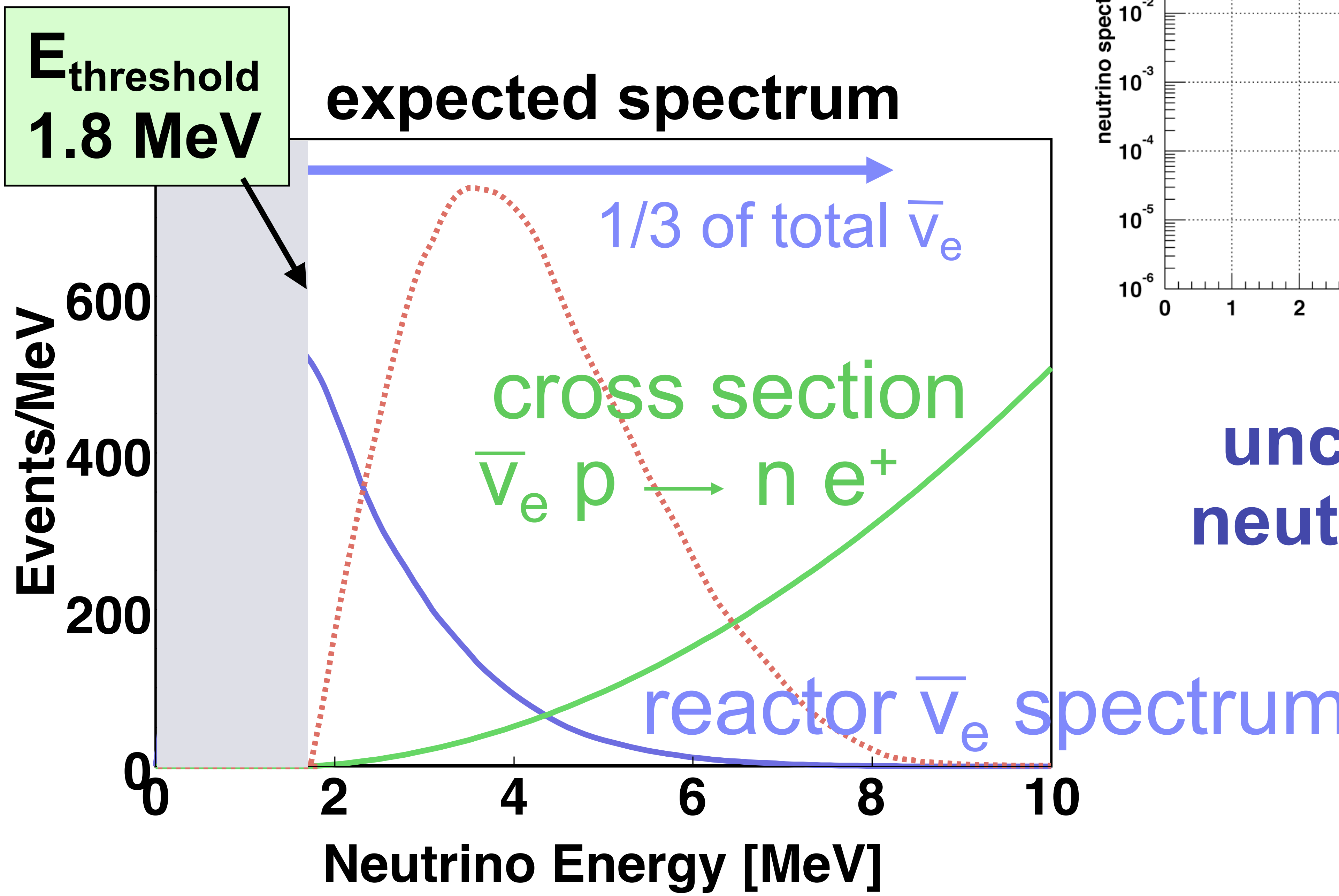
uncertainty from fuel composition < 1.0%

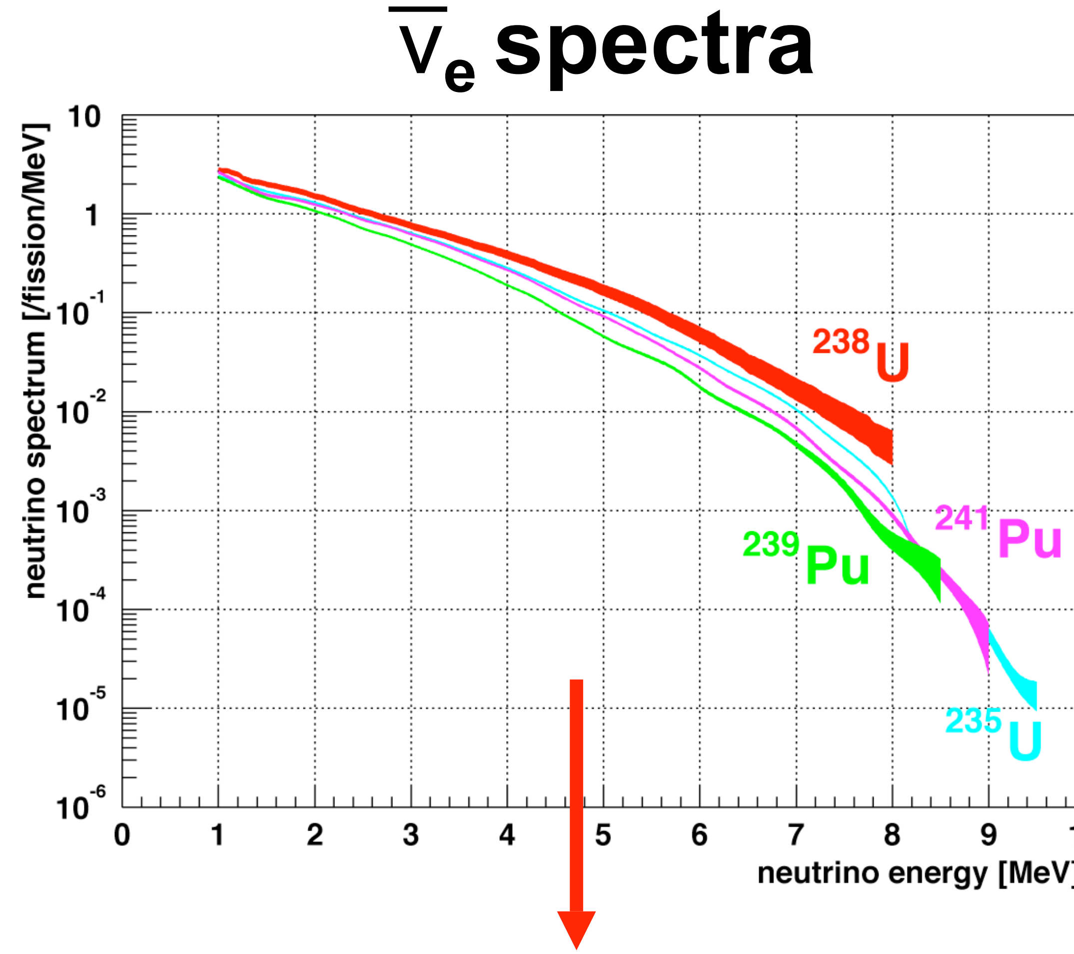
Reactor Anti-Neutrino Spectrum

overall fission ratio

$^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu =$

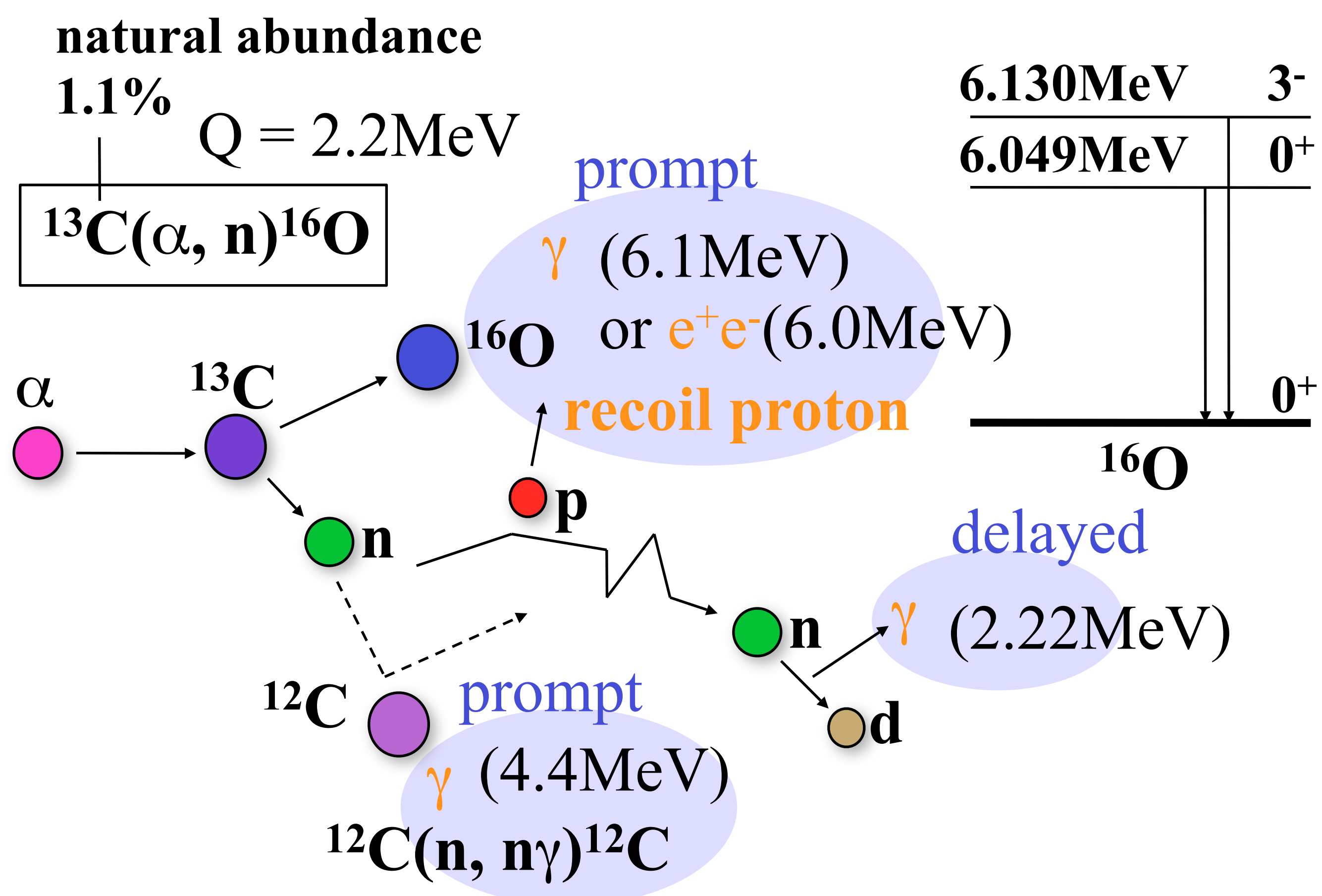
<u>0.570 : 0.078 : 0.295 : 0.057</u>



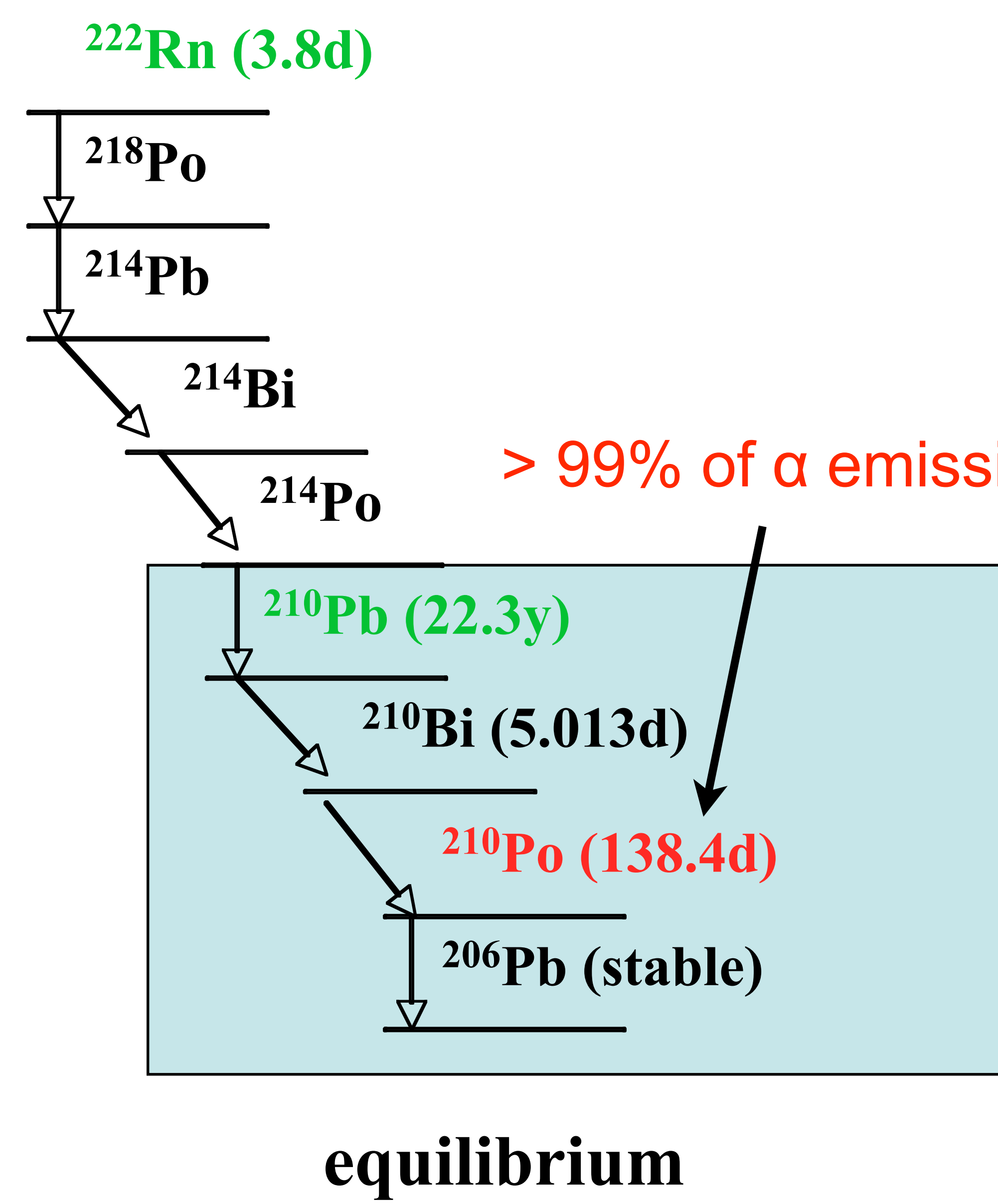


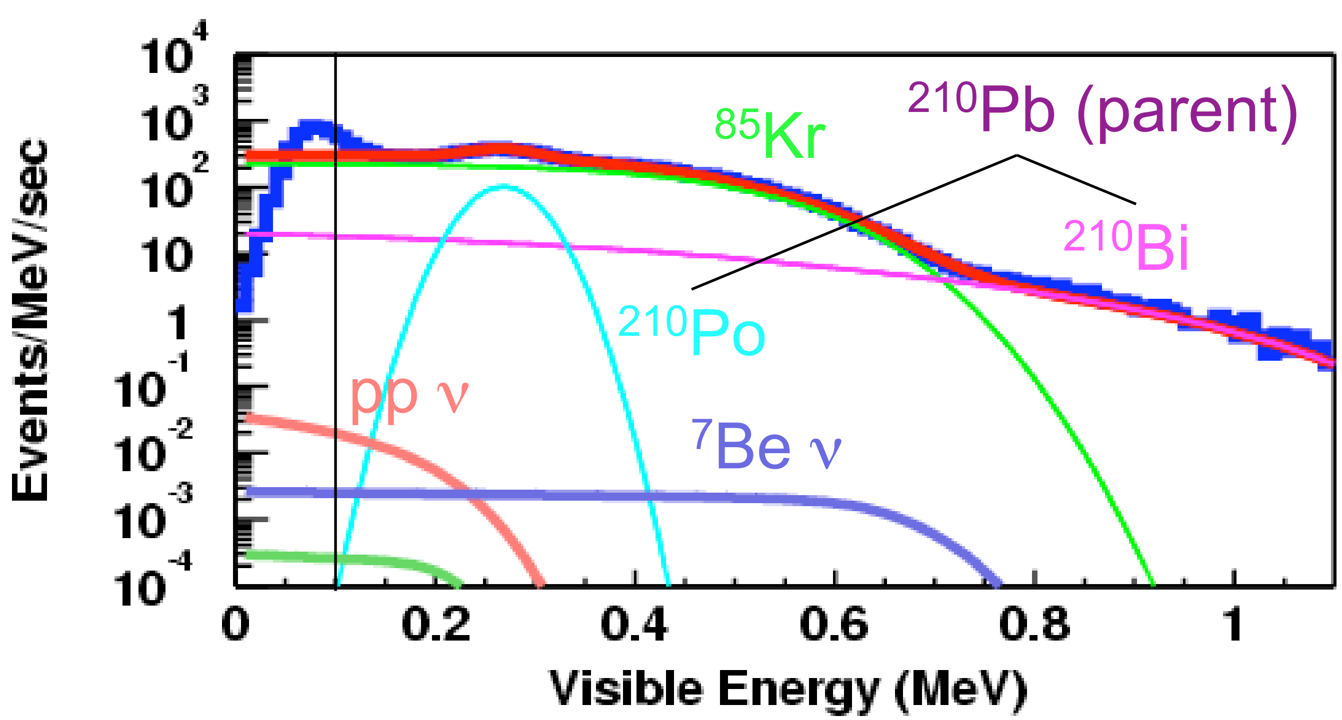
uncertainty from neutrino spectrum 2.4%

(α, n) Background Estimation



α source (^{238}U series)



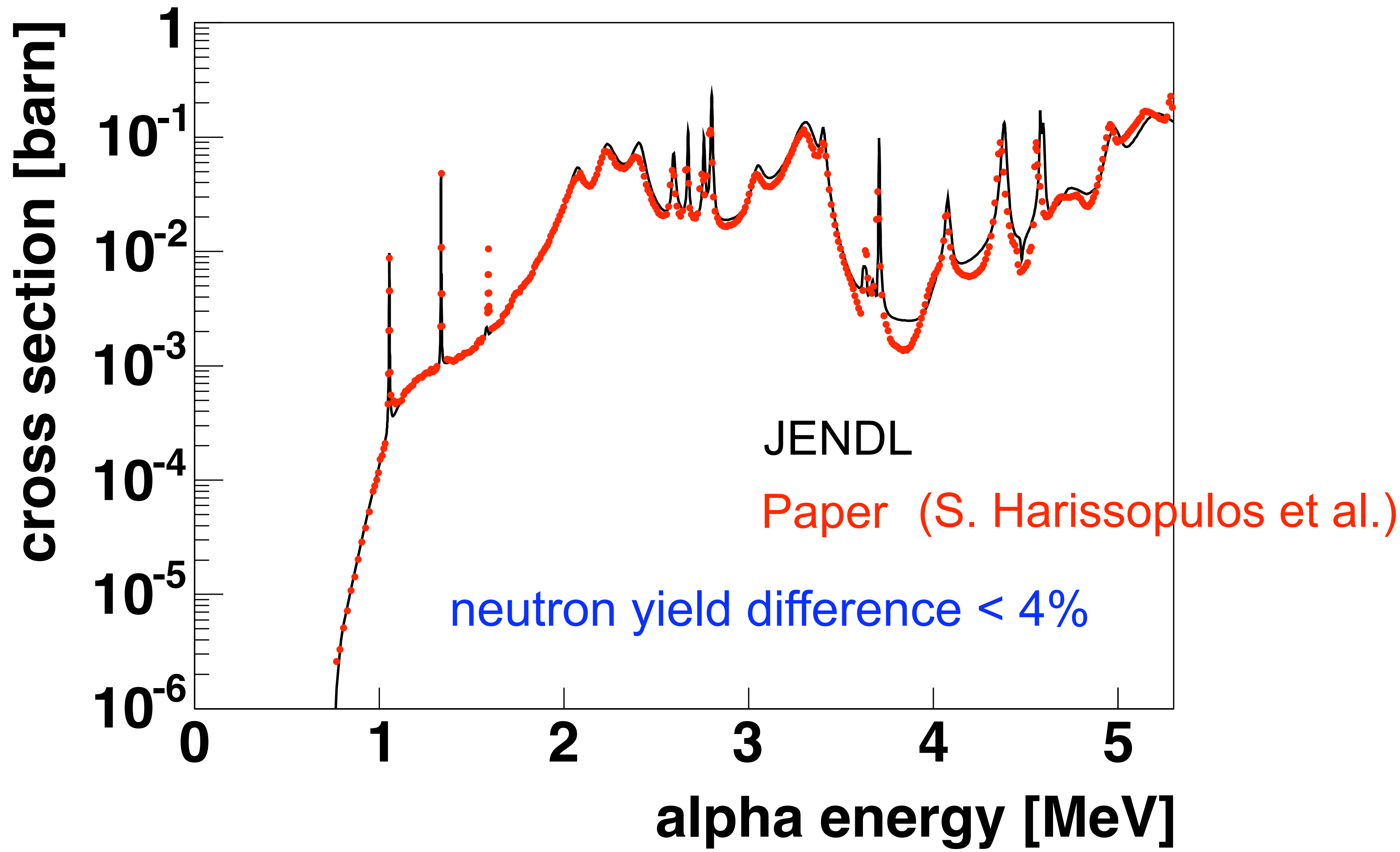


fiducial R 6.0 m

<u>5.56×10^9 decays / livetime</u>

(E_α = 5.3 MeV)

$^{13}C(\alpha, n)^{16}O$ Cross Section



JENDL

fitted by theoretical function using old data ⟶ 20% error

Paper : 4% precision for total cross section

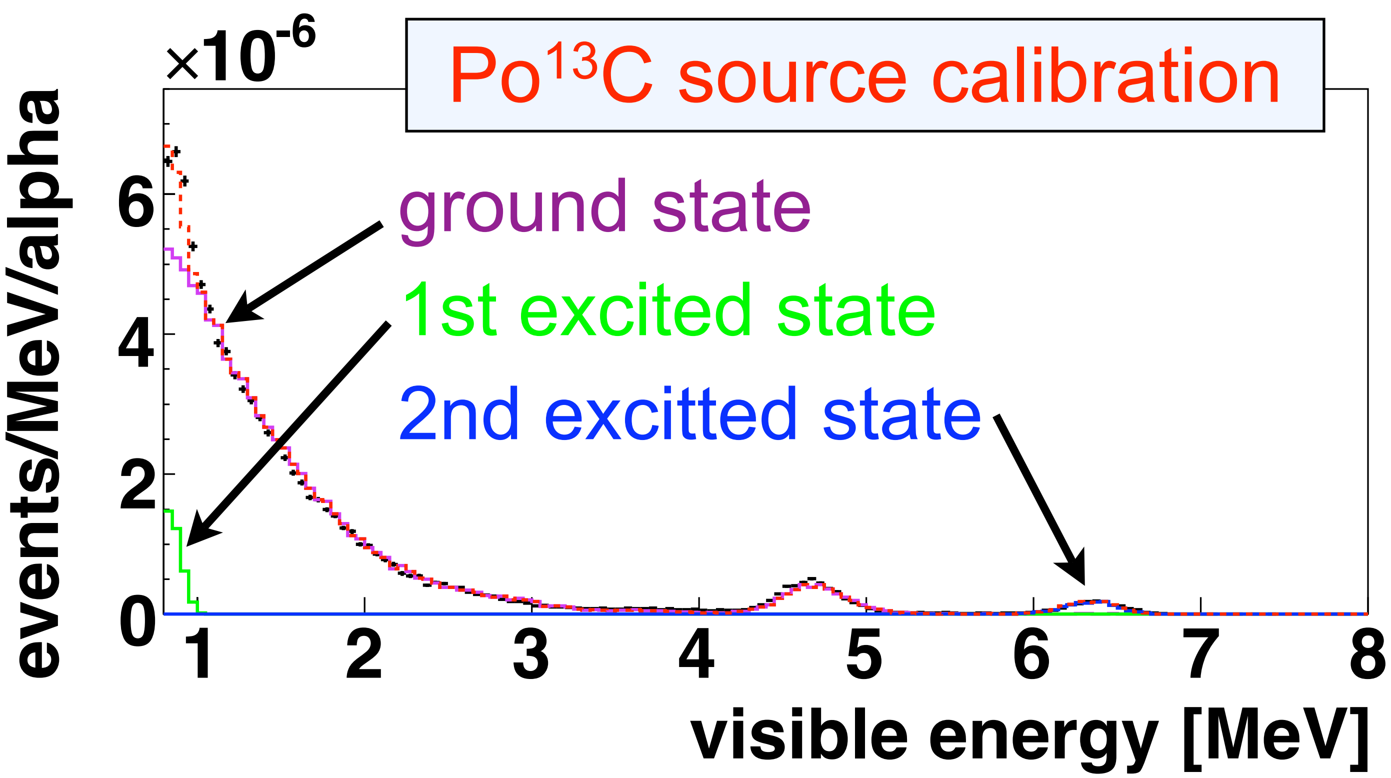
(α, n) Background Estimation

Improvement

(1) cross section measurement at 4% precision

(2) proton quenching measurement at a neutron facility

(3) $Po^{13}C$ source calibration



(α, n) background estimation

163.3 ± 18.0 events for ground state

18.7 ± 3.7 events for excited state

Estimation uncertainty

11% for ground state

20% for excited state

Rate Analysis above 2.6 MeV

“Reactor” rate analysis
(2.6 MeV threshold)

No osci. expected 1549

Background 63

Observed events 985

Ratio = (obs. - B.G.) / No osci.

0.594 ± 0.020(stat) ± 0.026(syst)

8.5σ disappearance significance

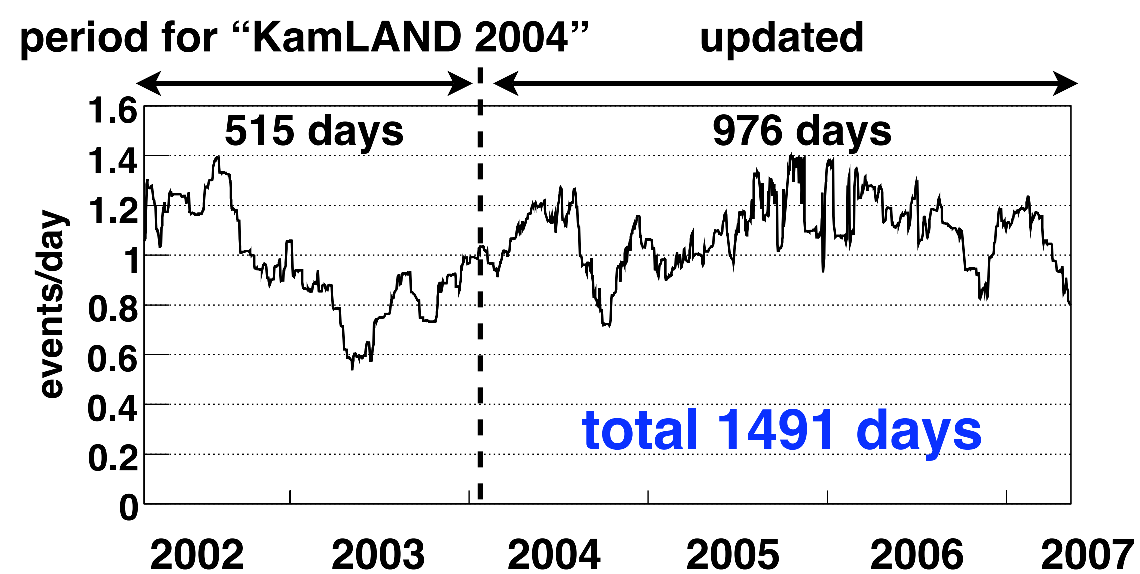
Fit constrained through B.G. expected

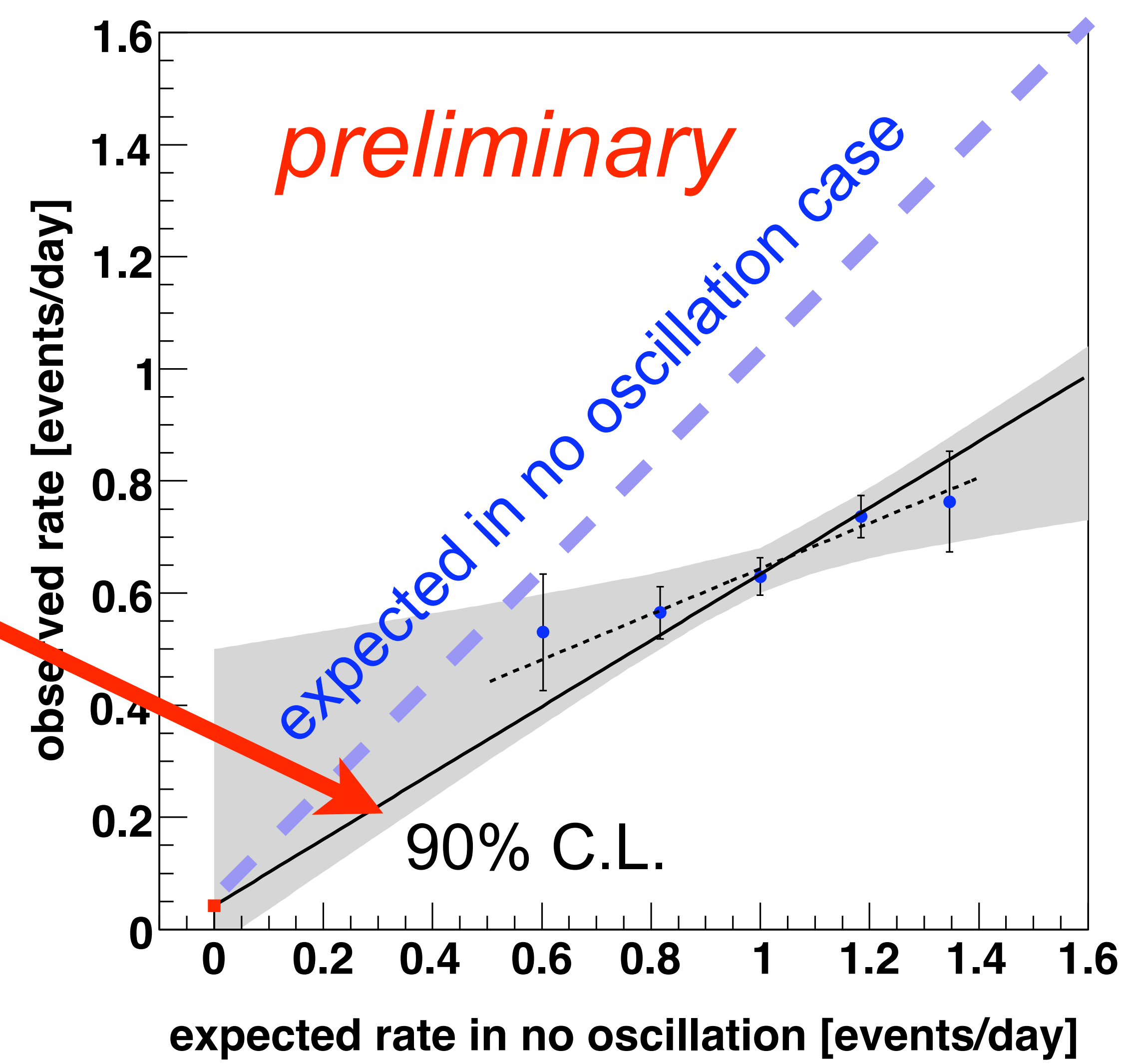
χ^2 / ndf = 3.1 / 4

Fit with a horizontal line

χ^2 / ndf = 11.8 / 4

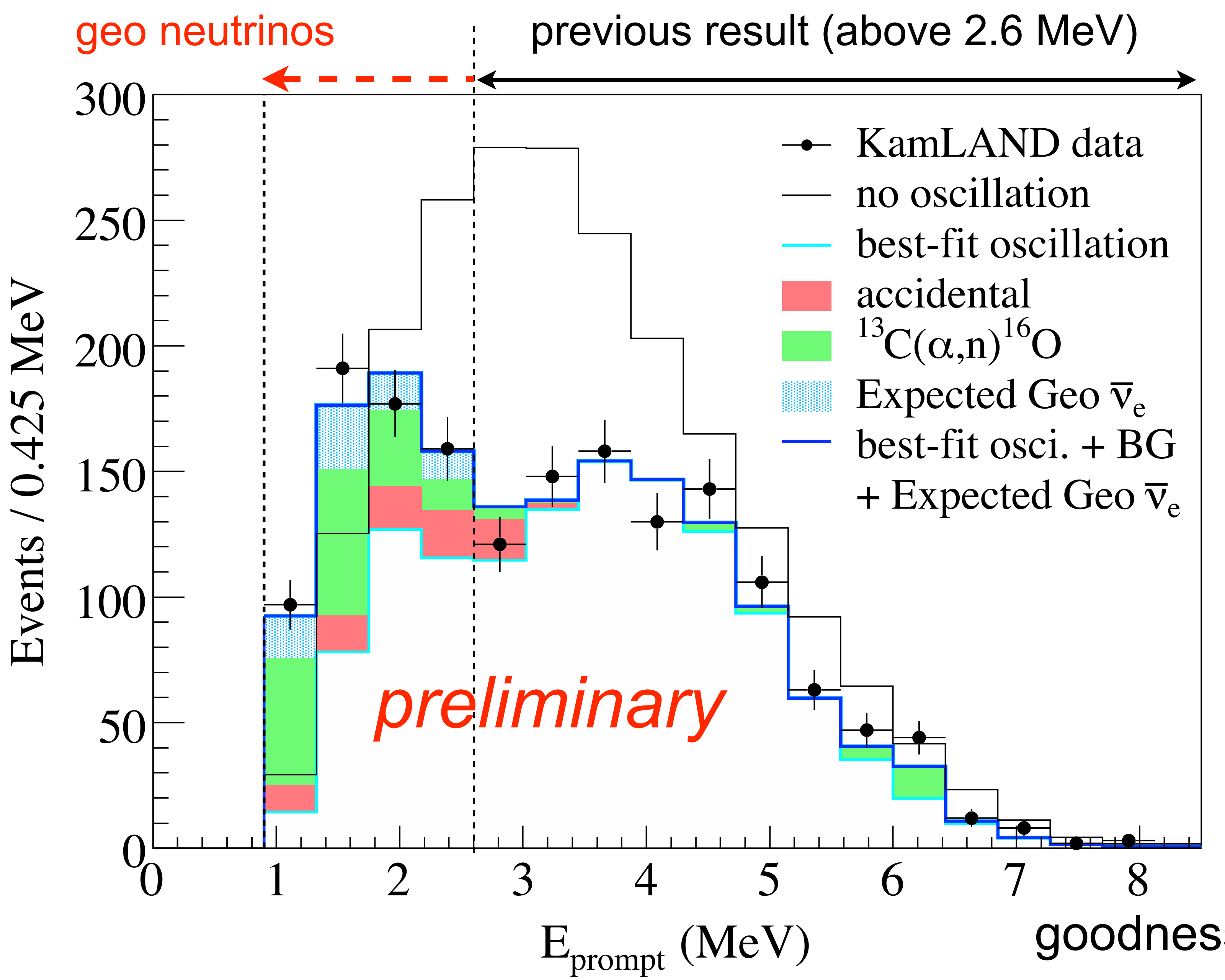
(1.9% C.L.)





Energy Spectrum above 0.9 MeV

exposure : 2881 ton-year (3.8 × 766 ton-year for "KamLAND 2004")



"Geo + Reactor" combined analysis

No osci. expected	2178
Background (w/o geo neutrino)	276
Observed events	1609

best-fit

$(\tan^2\theta, \Delta m^2) = (0.56, 7.58 \times 10^{-5}\ eV^2)$

free parameter : geo neutrinos
(U, Th) = (39.3, 29.4) events

goodness of fit using equal probability bins

best-fit χ^2 / ndf = 21.0 / 16 (18.0% C.L.)

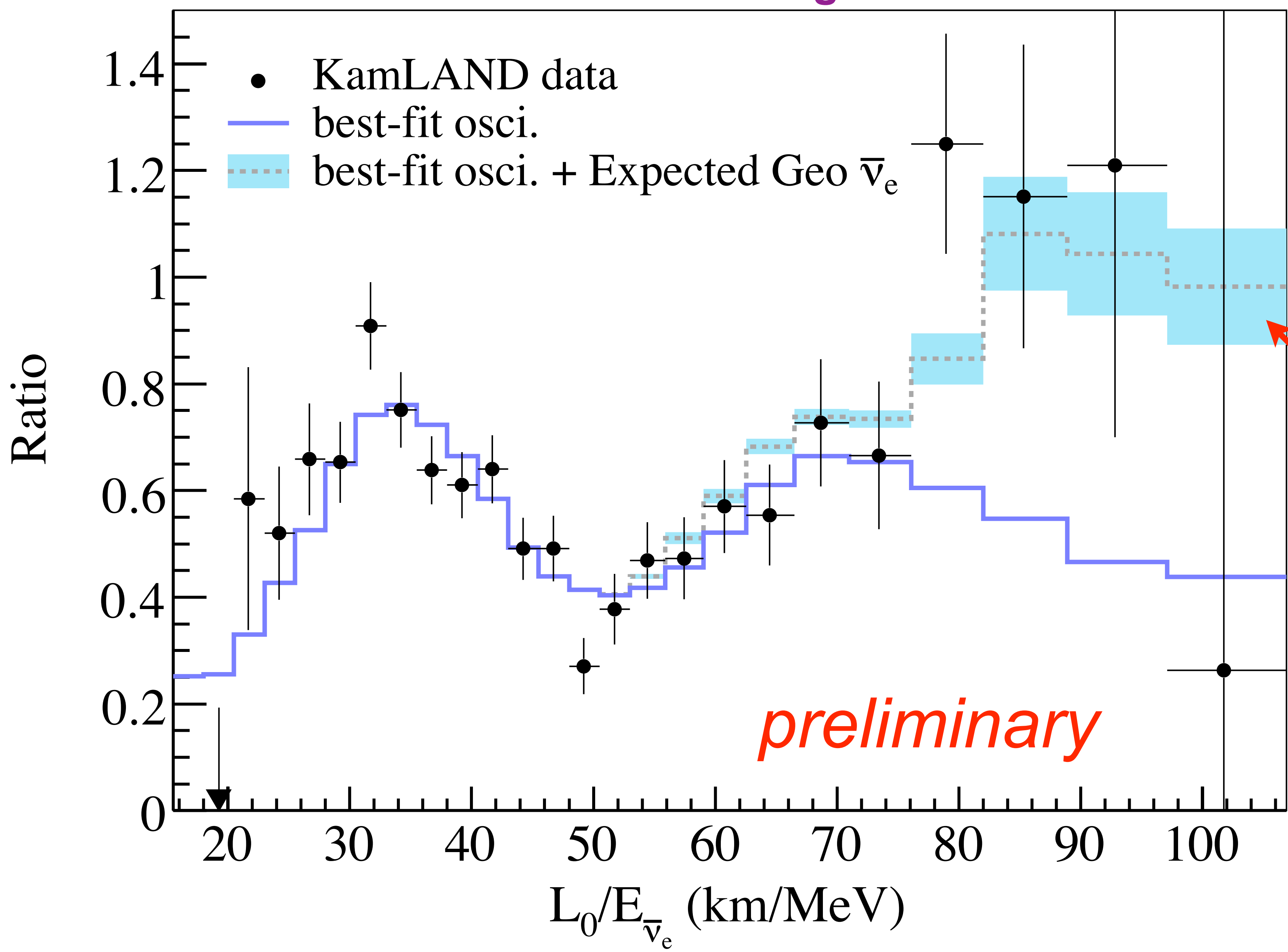
no osci. χ^2 / ndf = 63.9 / 17

Scaled no oscillation spectrum is excluded at 5.2σ

L/E plot

Ratio = (observed - B.G.) / (no osci. expected)

w/o geo neutrino



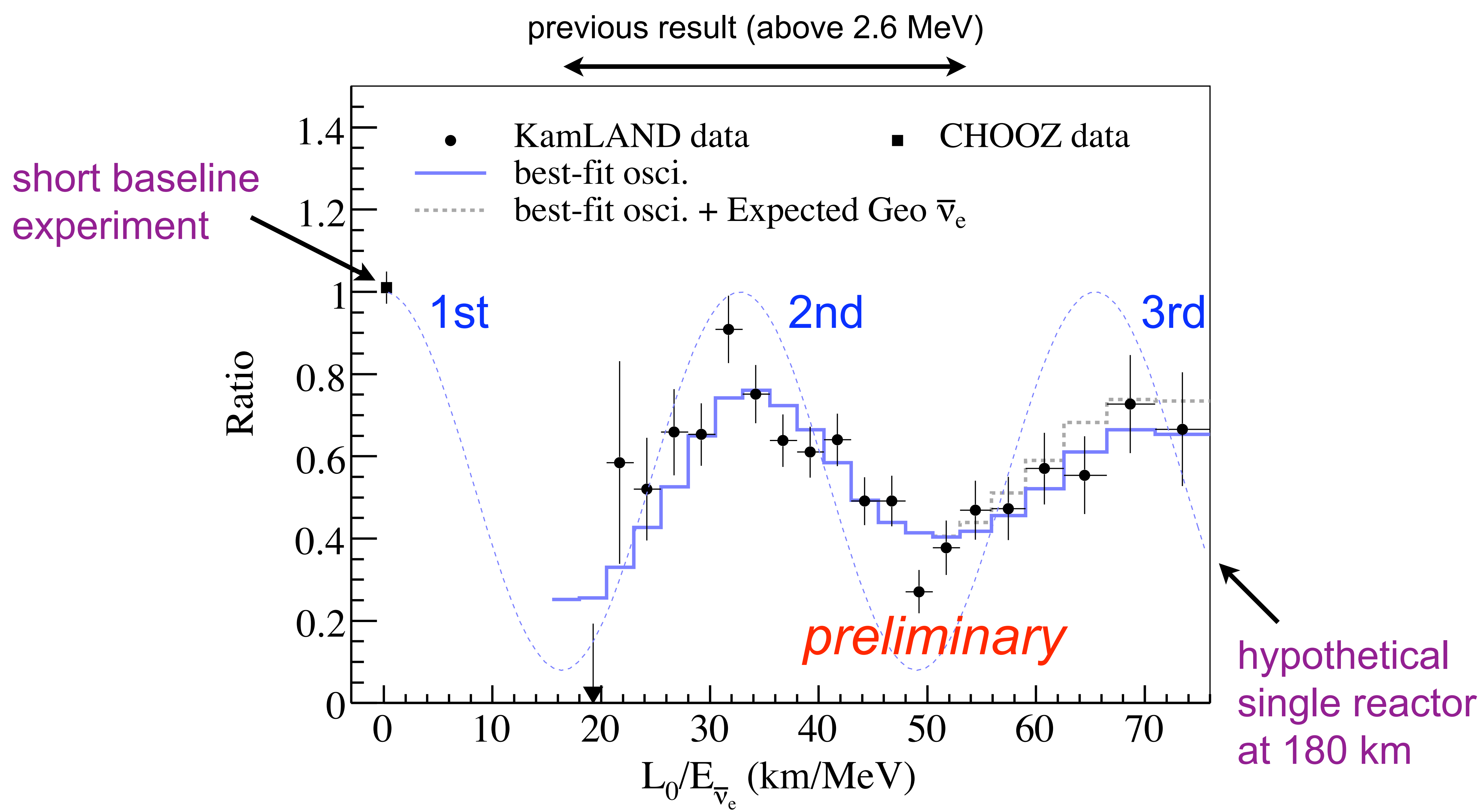
consistent with geo neutrino expectation from an earth model

20% geo neutrino flux uncertainty (a claim based on the geology)

L_0 : a fixed baseline (180 km)

Distortion effect is clearly illustrated by L/E plot

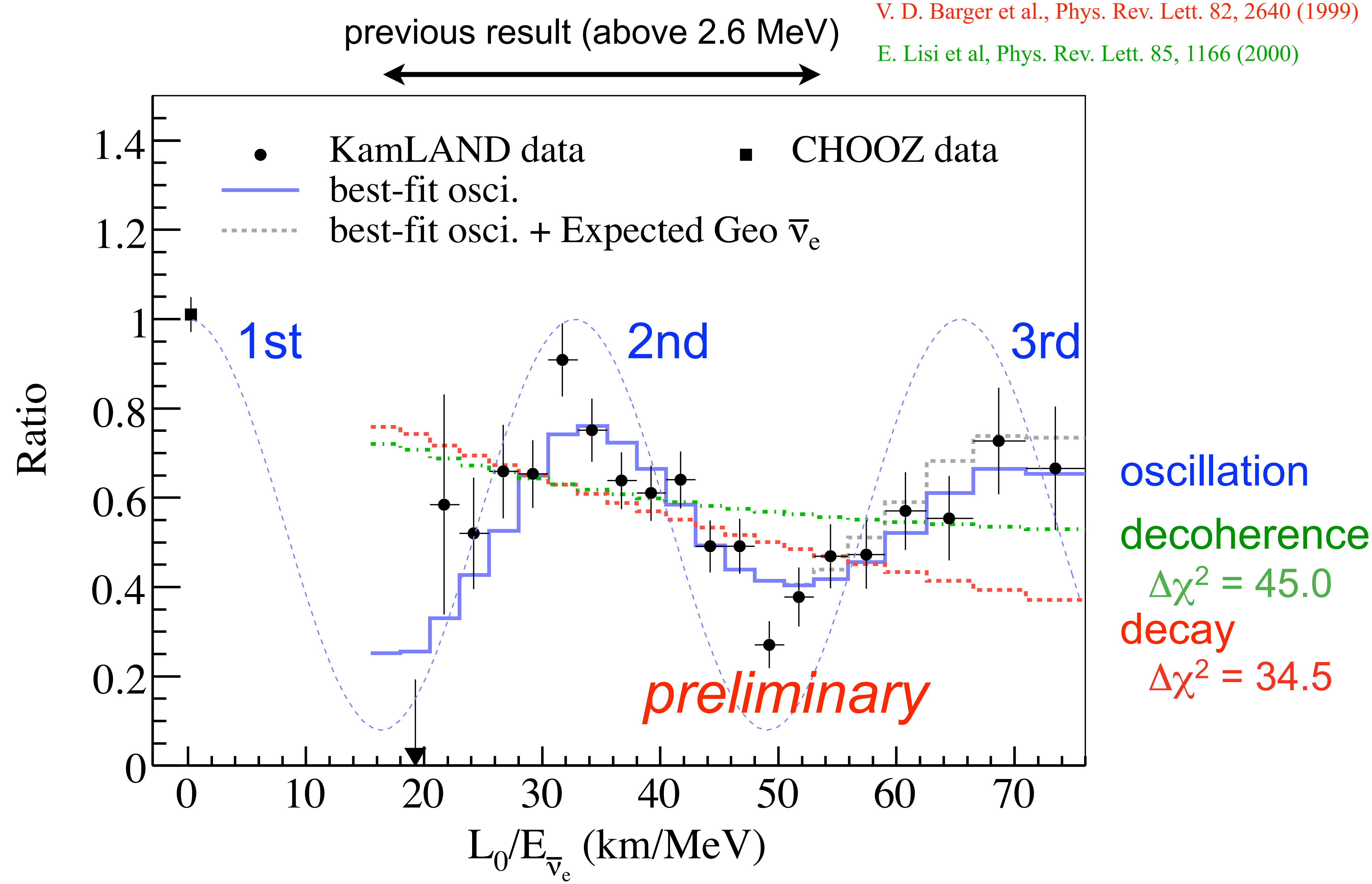
Neutrino Oscillation



KamLAND covers the 2nd and 3rd maximum

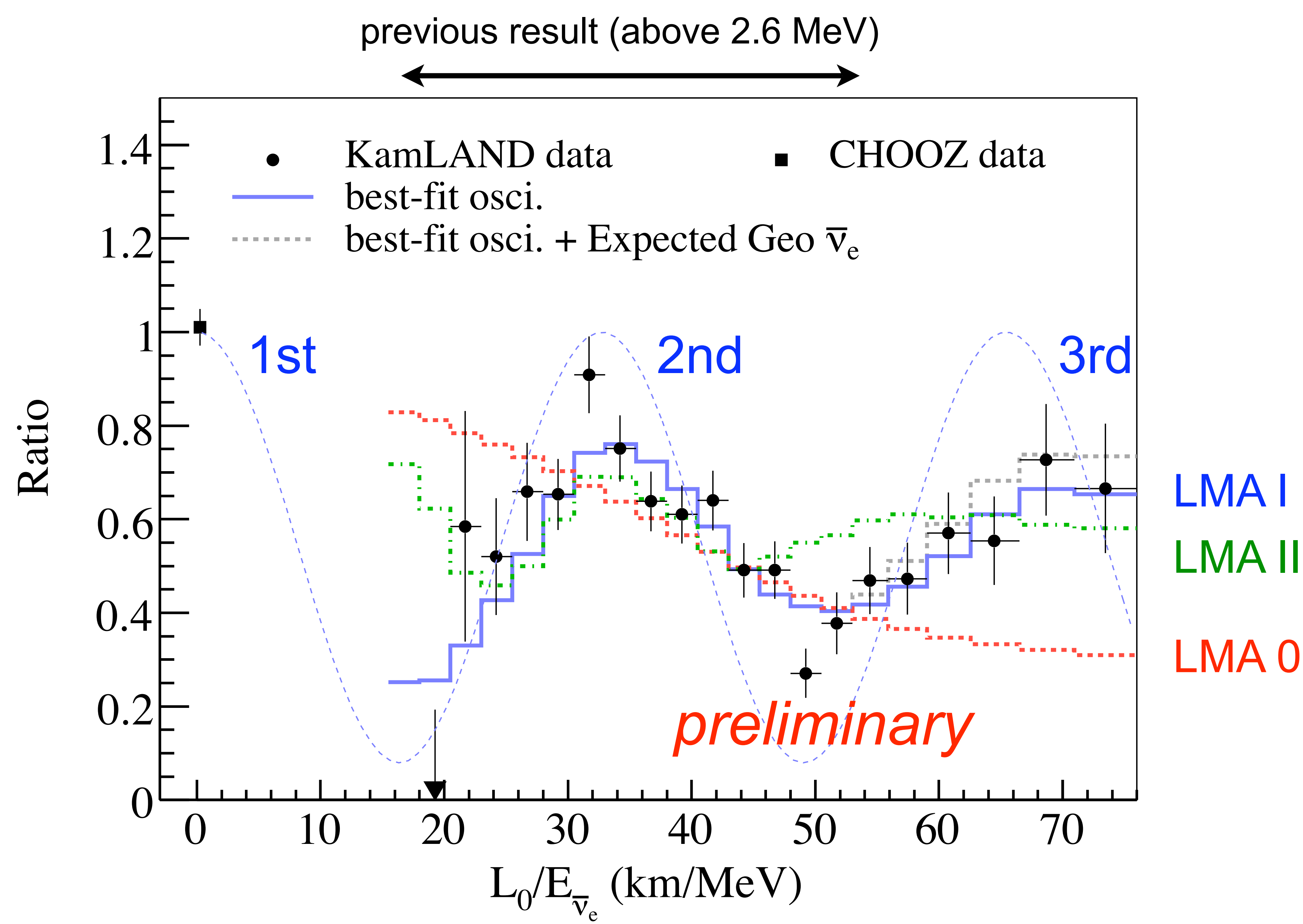
→ **characteristic of neutrino oscillation**

Alternate Hypothesis



best model is neutrino oscillation

Alternate Wavelength

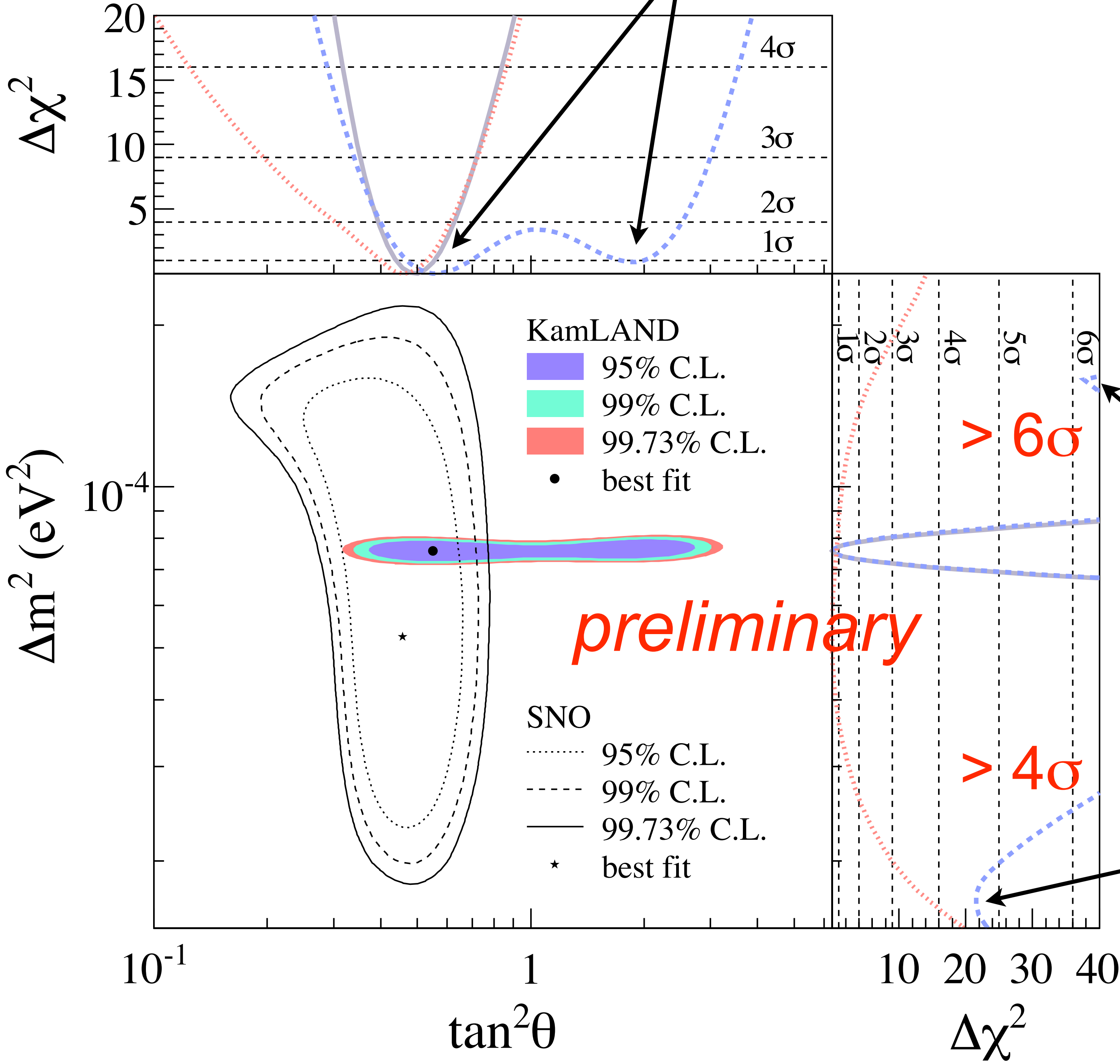


LMA 0 and LMA II are disfavored at more than 4σ

Oscillation Parameters

small matter effect

SNO KamLAND



LMA II

LMA 0

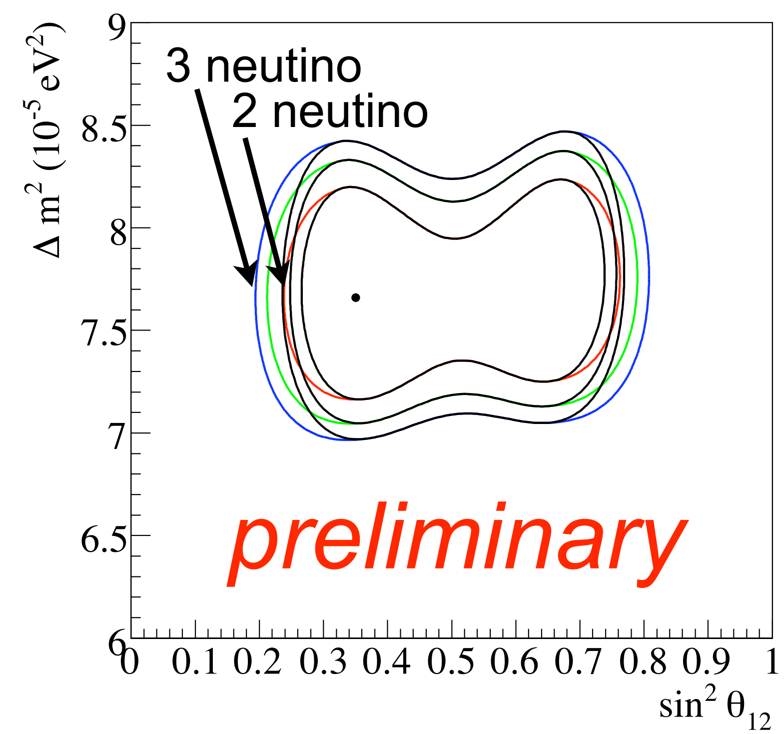
KamLAND only

$\tan^2\theta = 0.56^{+0.14}_{-0.09}$

$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$

(marginalized error)

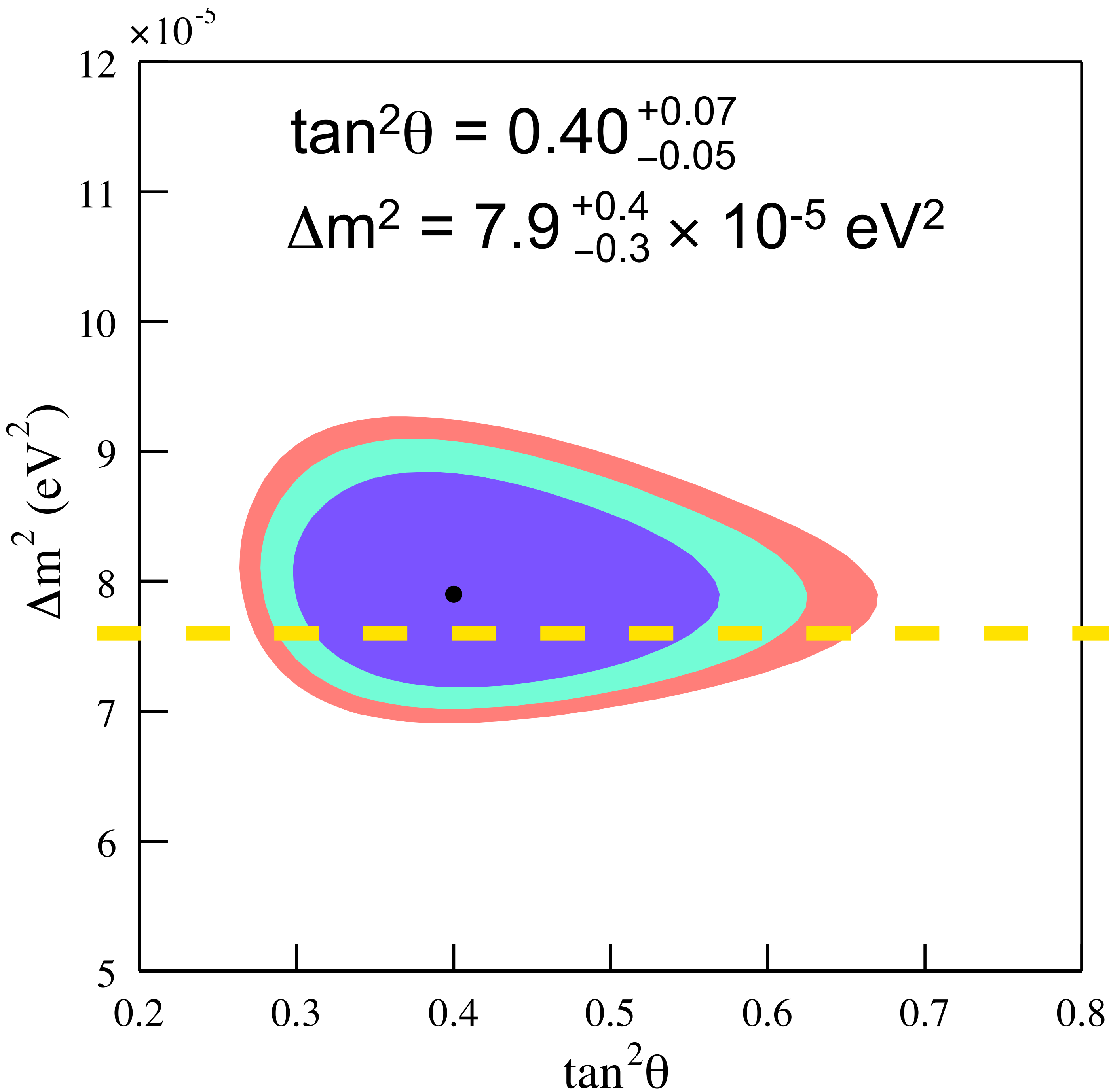
3 neutrino effect



same result for Δm^2

Precise measurement of Δm^2

KamLAND 2004



This result

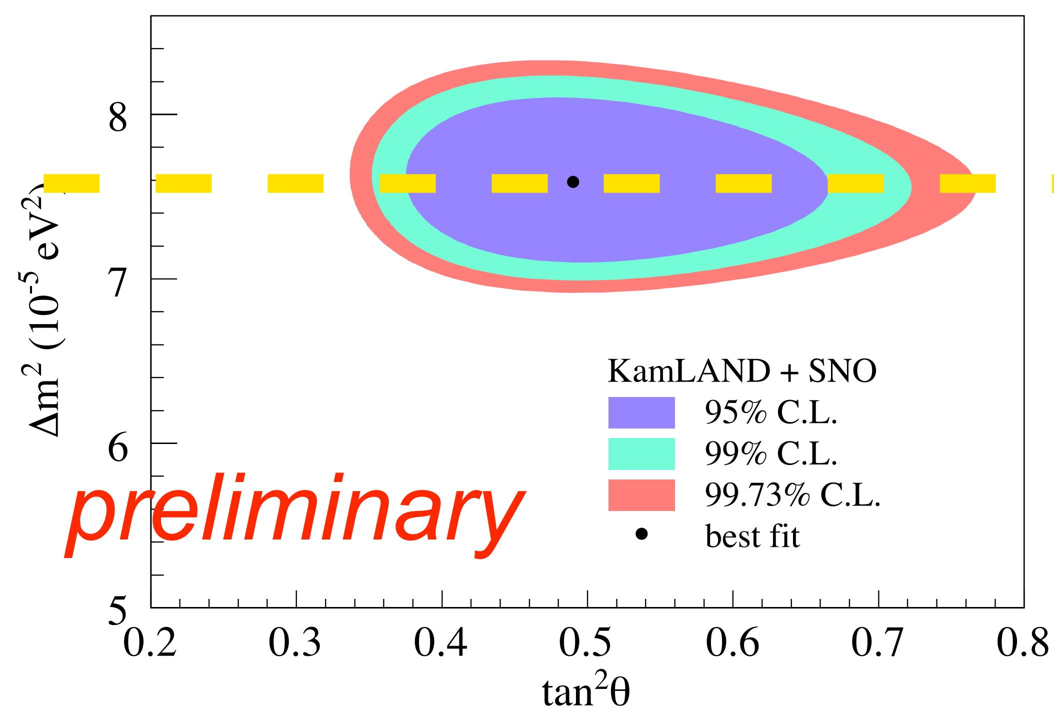
KamLAND + SNO

$\tan^2\theta = 0.49^{+0.07}_{-0.05}$

$\Delta m^2 = 7.59^{+0.20}_{-0.21} \times 10^{-5}$ eV^2

Δm^2 : systematic uncertainty 2.0%

dominated by linear energy scale uncertainty

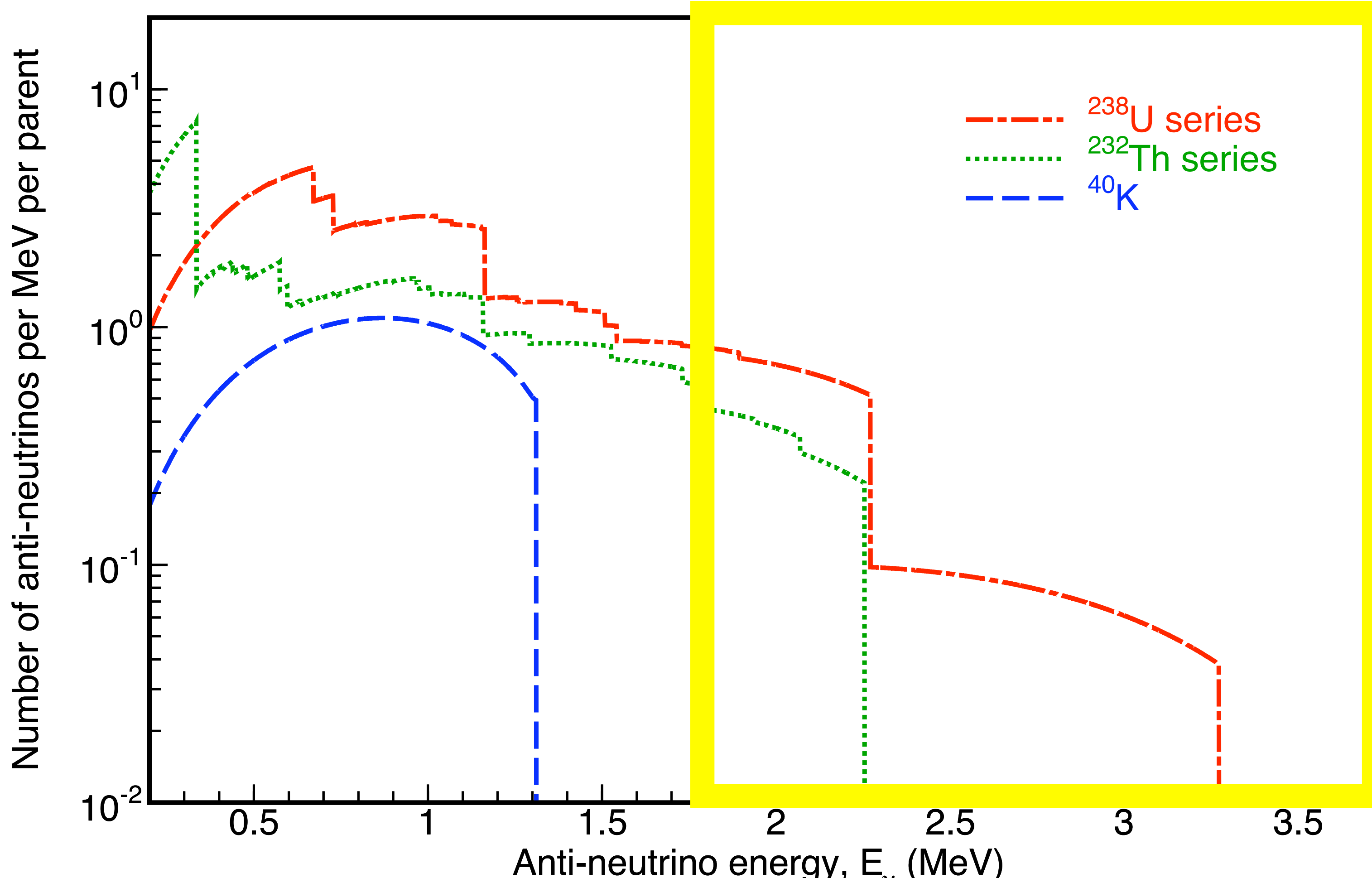


Δm^2 is measured at 2.8% precision by KamLAND

Geo Neutrino

Geo Neutrino Detection in KamLAND

anti-neutrino flux



window for KamLAND

beta-decay

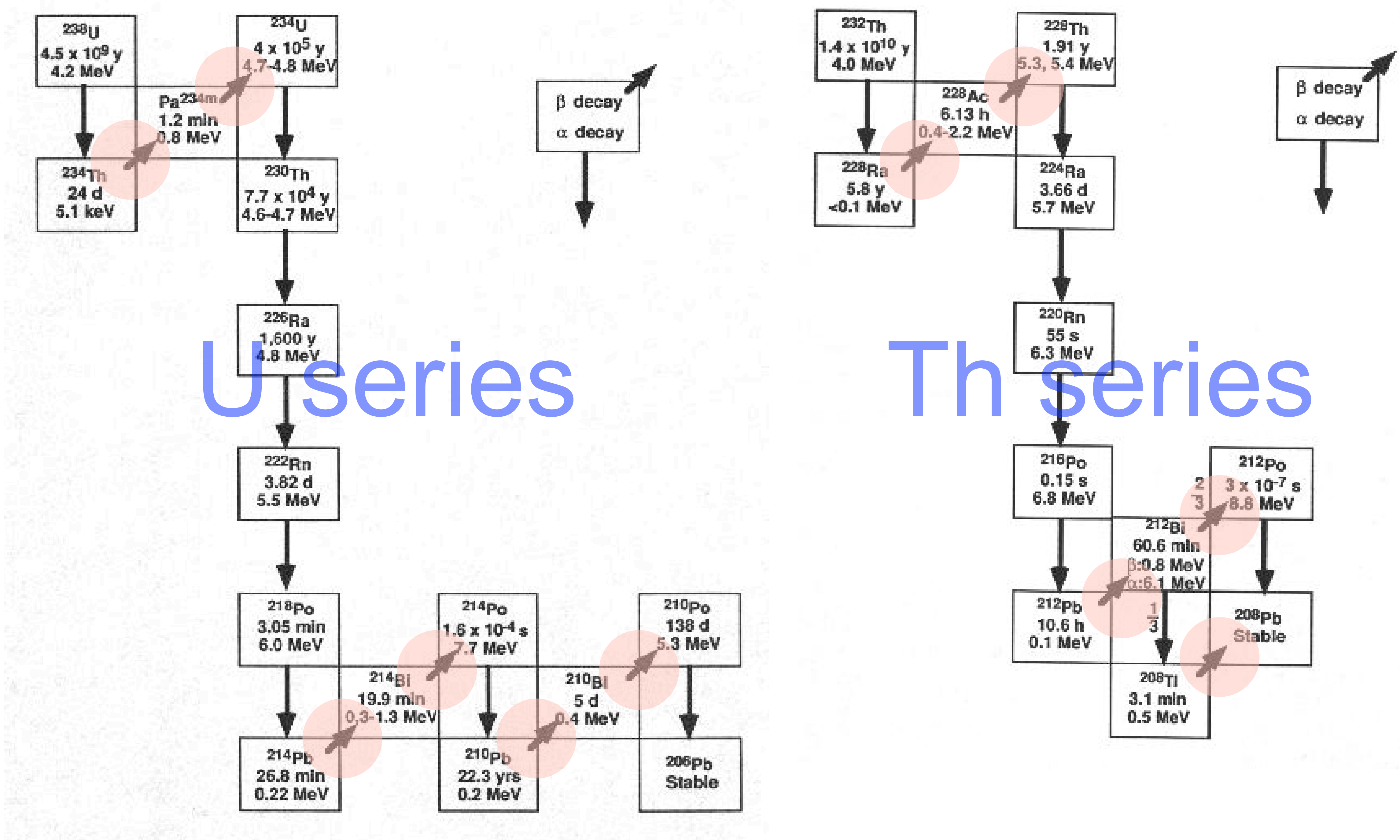
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}\ \ (100\%)$$

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

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ \ (89.28\%)$$

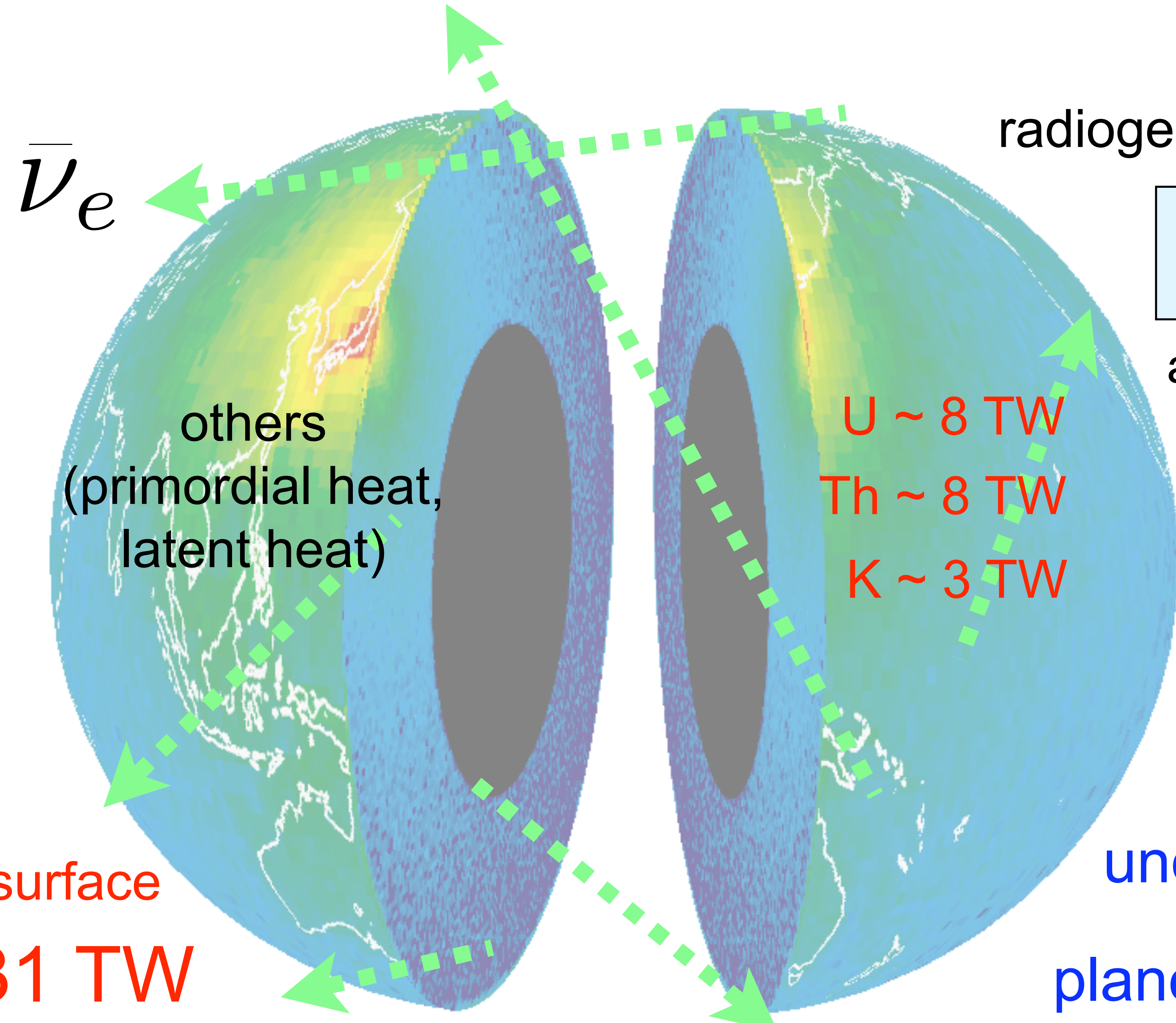
$$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\mathrm{MeV}(10.72\%)$$

Geo Neutrino Production



Anti-neutrinos are produced by beta-decays,
and radiogenic heat are generated by all decays

Earth Energetics



radiogenic heat generation

BSE (bulk silicate Earth) model

analyses of meteorite

total ~ 19 TW

heat flow from surface

44TW or 31 TW

understanding heat
↓
planet dynamics and formation mechanisms

Geo neutrino detection directly tests the radiogenic heat generation

Reference Earth Model

UCC U : 2.8 ppm / Th : 10.7 ppm

MCC U : 1.6 ppm / Th : 6.1 ppm

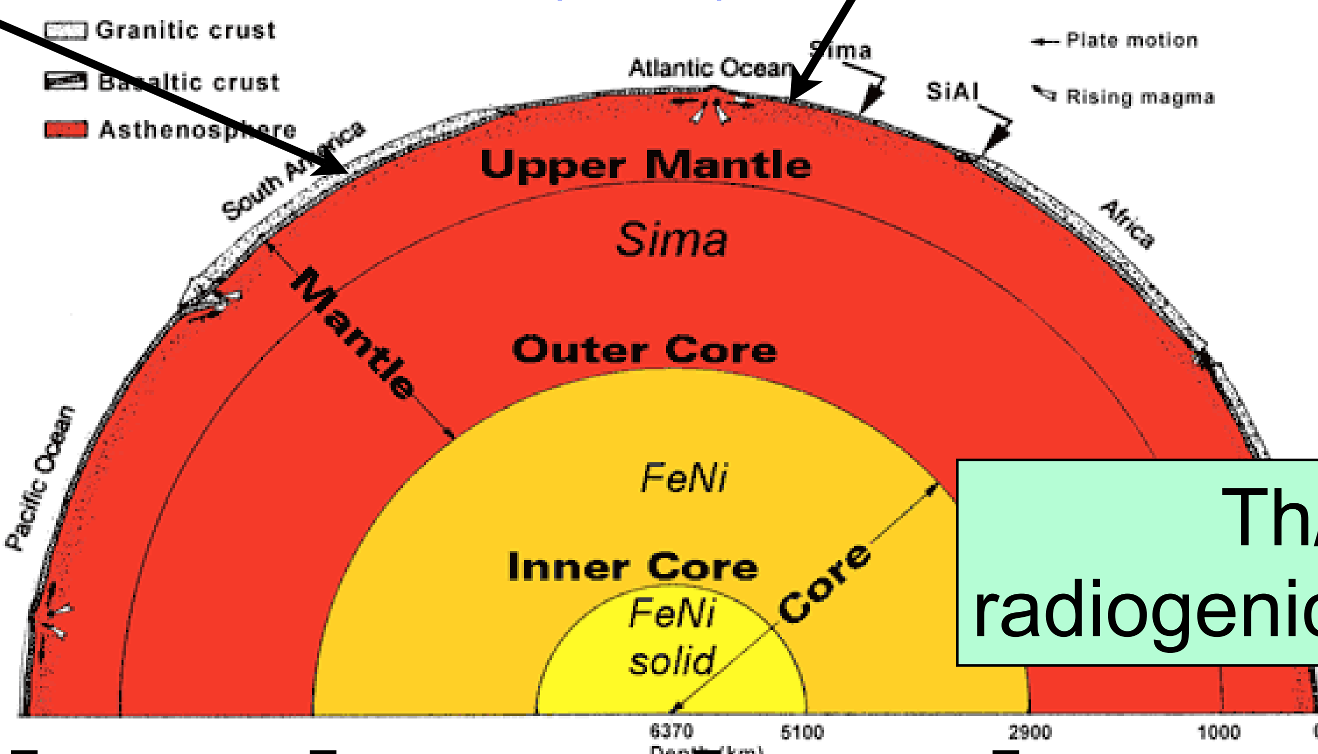
LCC U : 0.2 ppm / Th : 1.2 ppm

oceanic crust

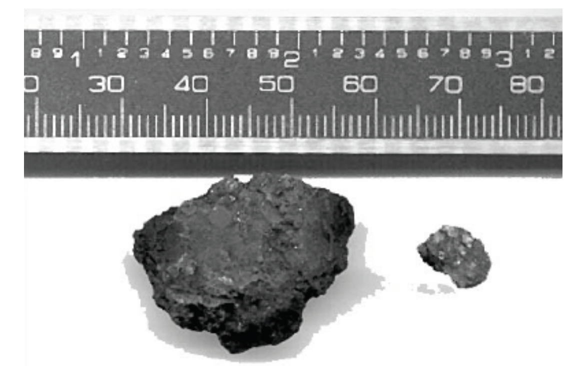
U : 0.10 ppm / Th : 0.22 ppm

continental crust

Rudnick et al. (1995)



chondrite meteorite



Th/U ~ 3.9
radiogenic heat ~ 16 TW

mantle

U : 0.012 ppm / Th : 0.048 ppm

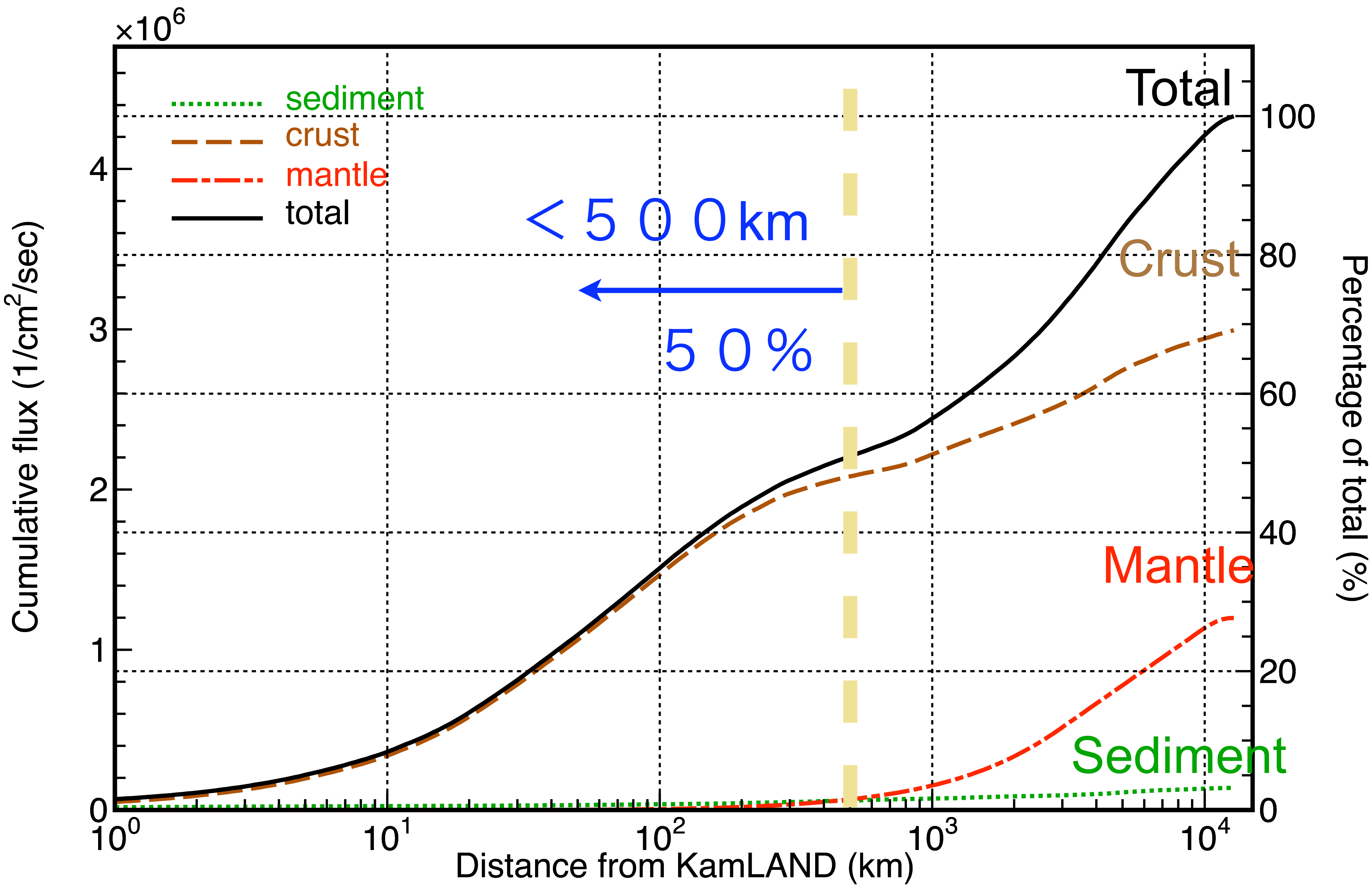
core

U : 0 ppm / Th : 0 ppm

no U/Th in core

Mantle = Meteorite (BSE model) − Crust

Distance and Cumulative Flux



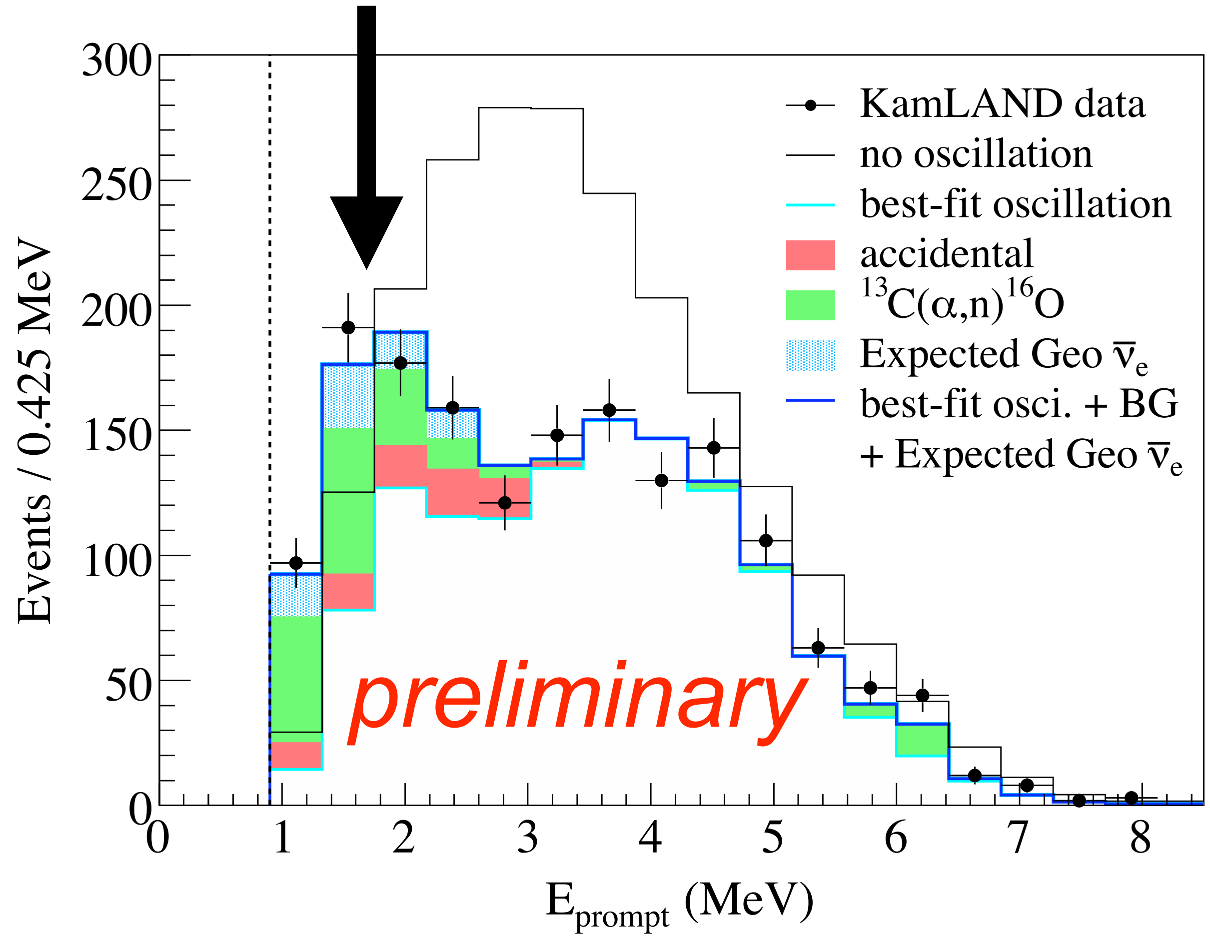
neutrino oscillation $P(E, L) \sim 1 - \frac{1}{2} \sin^2 2\theta_{12}$

50% of the total flux originates within 500 km

Geo Neutrino Estimation

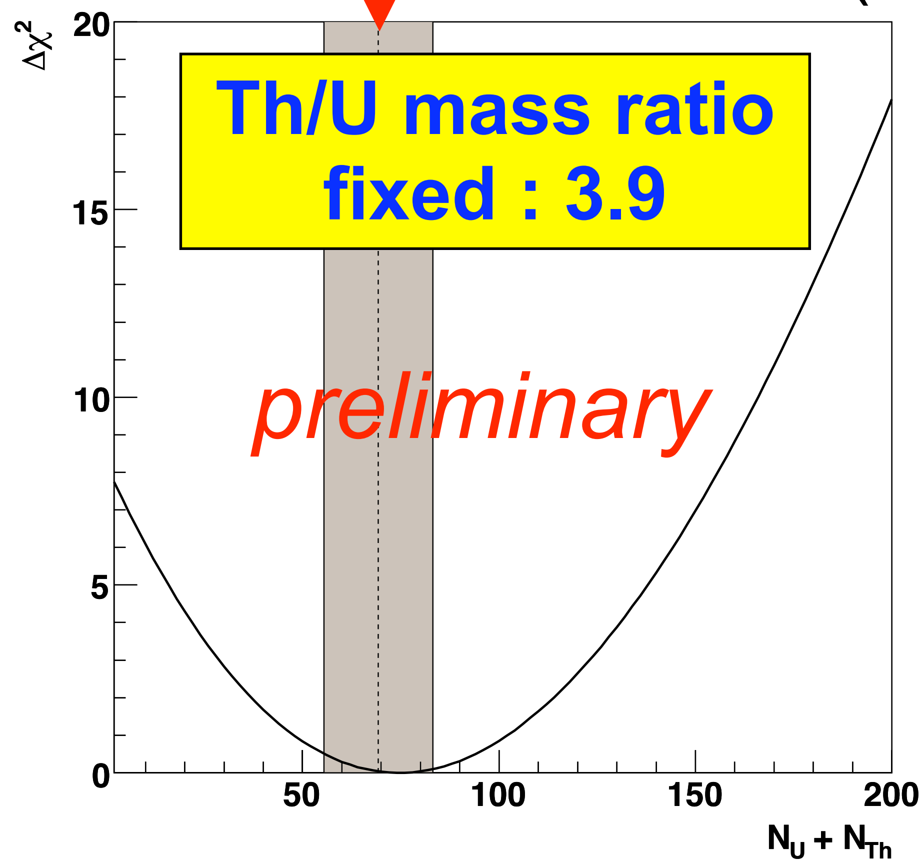
Analysis : KamLAND (rate + shape + time) + SNO

geo neutrinos (U, Th)



model expected

69.3 events (36.5 TNU)



Reference model (16 TW)

U : 56.2 event (28.9 TNU)

Th : 13.1 event (7.6 TNU)

U+Th = $74.9^{+27.3}_{-27.2}$ event

$39.4^{+14.4}_{-14.3}$ TNU

(previous result : $57.4^{+32.0}_{-30.0}$ TNU)

TNU (Terrestrial Neutrino Unit) = events/10^{32} target-proton/year

Summary

- KamLAND improved sensitivity to $\overline{\nu}_e$ observation.

data-set : 766 ton-yr → 2881 ton-yr
E threshold : 2.6 MeV → 0.9 MeV
syst. uncertainty : 6.5% → 4.1%

(α, n) B.G. uncertainty :
32% → 10% (ground state)
100% → 20% (excited state)

- In the reactor neutrino analyses, we showed

- Oscillatory shape including 2nd and 3rd maximum
- Exclusion of LMA II and 0 at more than 4σ C.L.
- Precise measurement of oscillation parameters.

KamLAND only $\tan^2\theta = 0.56^{+0.14}_{-0.09}$ $\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$

KamLAND + SNO $\tan^2\theta = 0.49^{+0.07}_{-0.05}$ $\Delta m^2 = 7.59^{+0.20}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$

- Geo neutrino flux is measured with better precision.