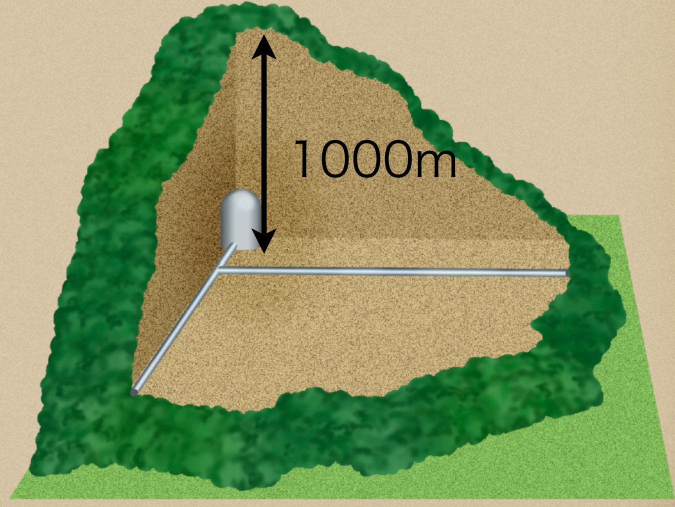
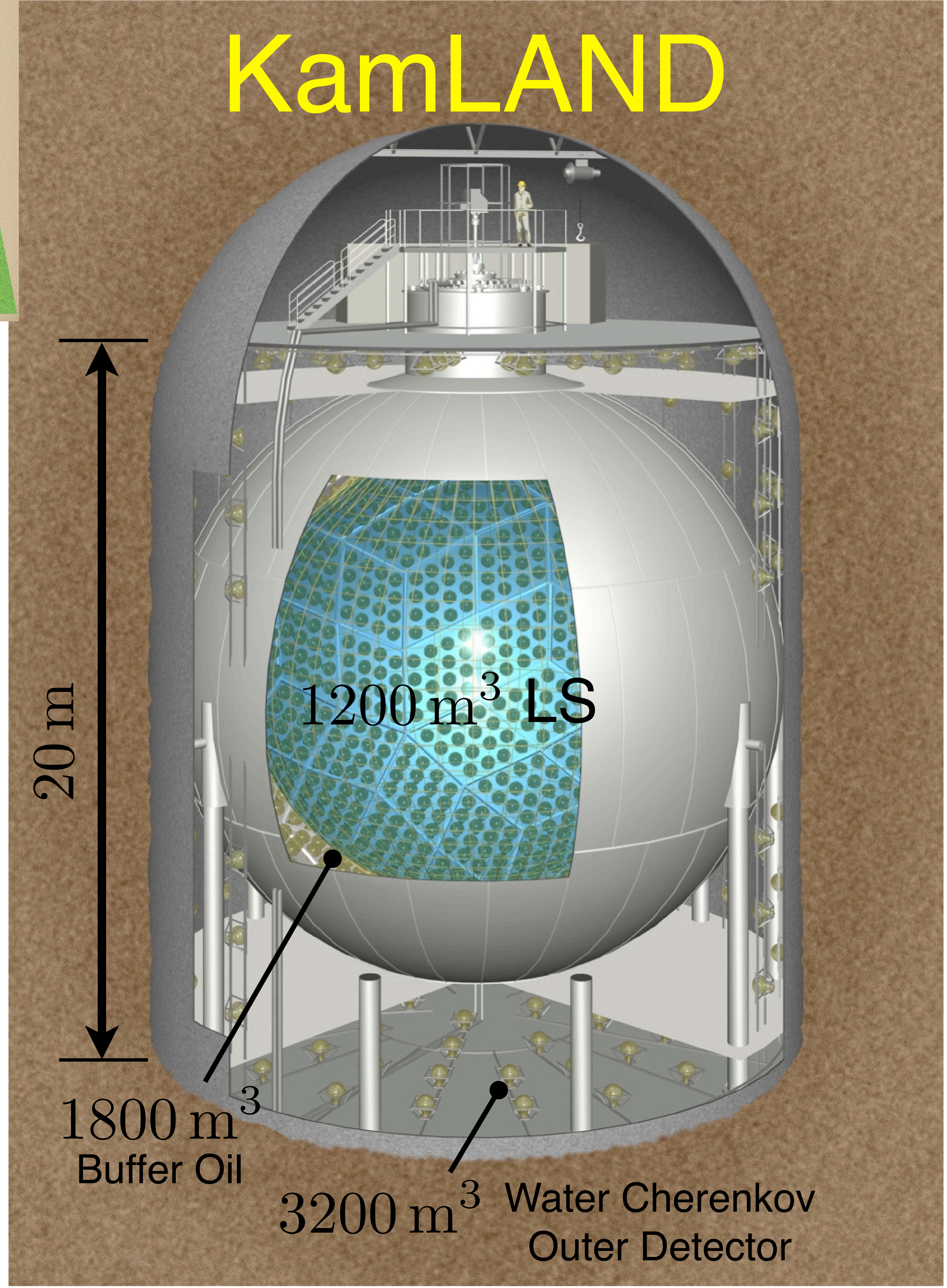
# Status and Prospects of KamLAND

Kunio Inoue
Research Center for Neutrino Science, Tohoku University

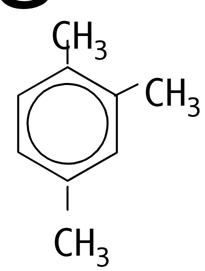
Windows to new paradigm in particle physics, 14-16 February 2005, Sendai, Japan



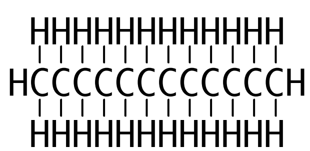

long. $137^\circ 18' 43.495''$
lat. $36^\circ 25' 35.562''$
alt. $358\,\mathrm{m}$



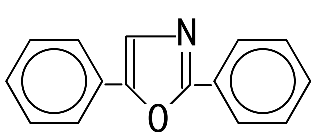

# LS




20%




80%




1.5g/l

$\rho = 0.78\,\mathrm{g/cm^3}$

$8000\,\mathrm{photons/MeV}$

$\lambda \sim 10\,\mathrm{m}$

# BO

50% dodecane
50% isoparaffin

$$\frac{\rho_{\mathrm{LS}}}{\rho_{\mathrm{BO}}} = 1.0004$$

1325 17”-PMTs
+
554 20”-PMTs
(since Feb 2003)

photo-coverage
22% --> 34%

$\sim 500\,\mathrm{p.e./MeV}$

# Various Physics Targets with wide energy range

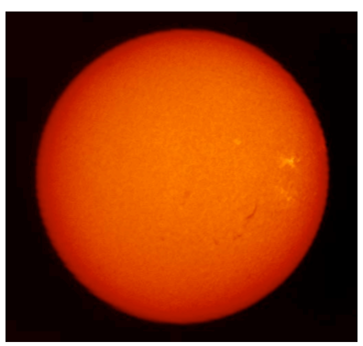
0.4 1.0 2.6 8.5 Visible energy [MeV]

neutrino electron elastic scattering

$\nu + e^- \rightarrow \nu + e^-$

inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

[7]Be solar neutrino



Neutrino Astrophysics

verification of SSM

future
2nd phase

geo-neutrino

Neutrino Geophysics

verification of earth evolution model

forthcoming

reactor neutrino

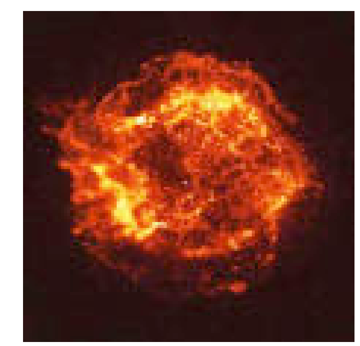
Neutrino Physics

Precision measurement of oscillation parameters

1st results
PRL 90, 021802 (2003)

2nd results
hep-ex/0406035

supernova relic neutrino etc.



Neutrino Cosmology

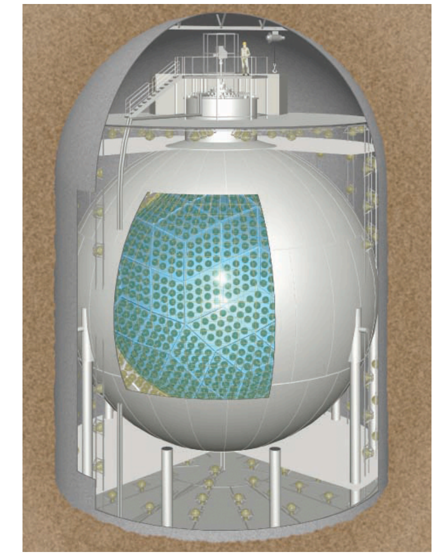
verification of universe evolution

Solar $\bar{\nu}_e$
PRL 92, 071301 (2004)

# Reactor neutrino detection

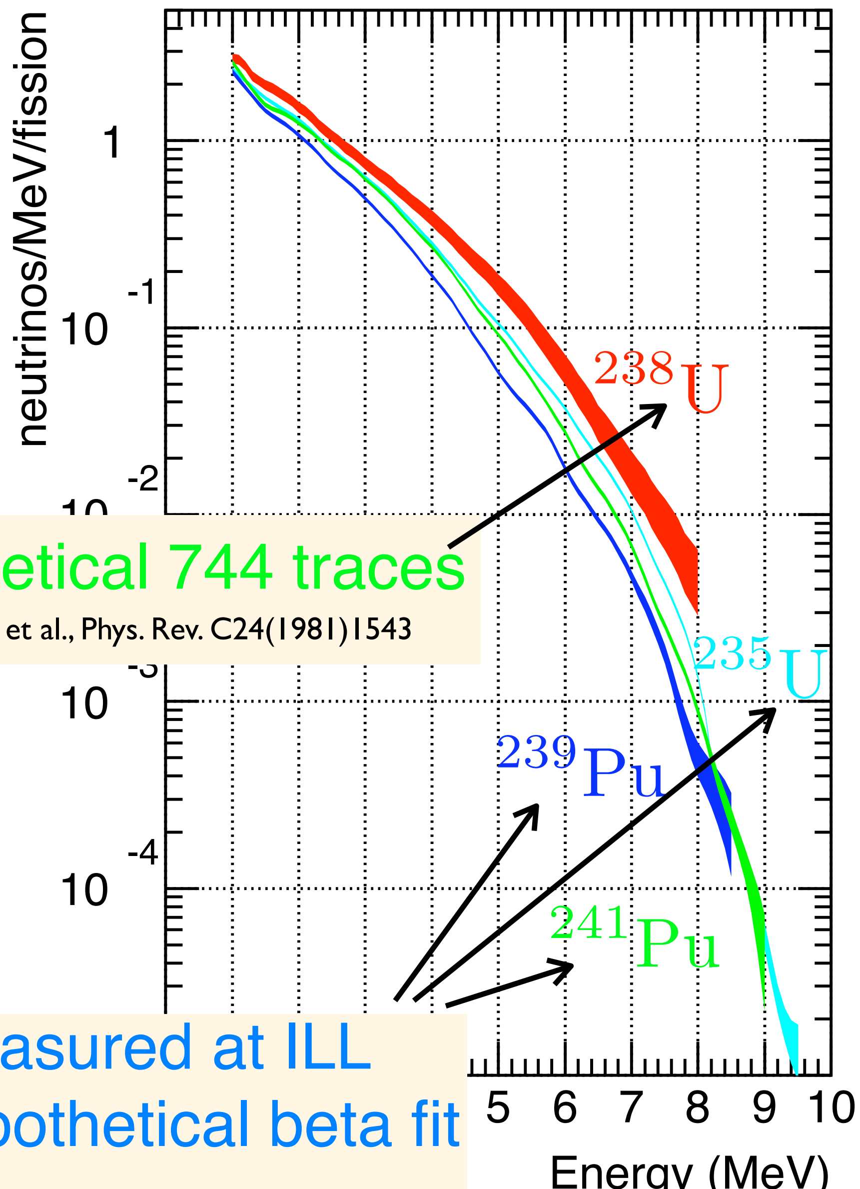
$\sim 2 \times 10^{20}\ \bar{\nu}_e/\mathrm{GW_{th}}/\mathrm{sec}$

$\bar{\nu}_e$ ~99.999% $(E > 1.8\,\mathrm{MeV})$



$^{235}\mathrm{U} : 201.7,\ ^{238}\mathrm{U} : 205.0,\ ^{239}\mathrm{Pu} : 210.0,\ ^{241}\mathrm{Pu} : 212.4\,\mathrm{MeV}$

M.F.James, J.Nucl.Energy 23(1969)517




theoretical 744 traces

P.Vogel et al., Phys. Rev. C24(1981)1543

measured at ILL

30 hypothetical beta fit

K.Schreckenbach et al., Phys.Lett.B160(1985)325

A.A.Hahn et al., Phys.Lett.B218(1989)365

$$E_{\mathrm{th}} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\,\mathrm{MeV}$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

prompt signal

$$e^+ + e^- \rightarrow 2\gamma \qquad E_{\mathrm{vis}} \sim E_\nu - 0.78\,\mathrm{MeV} > 1.022\,\mathrm{MeV}$$

$\tau \sim 210\ \mu\mathrm{sec}$

$$n + p \rightarrow d + \gamma(2.2\,\mathrm{MeV})$$

delayed signal

$\sigma(\bar{\nu}_e p)$ is calculable at 0.2% accuracy.

P.Vogel and J.F.Beacom, Phys.Rev.D60(1999)053003

A.Kurylov et al., Phys.Rev.C67(2003)035502

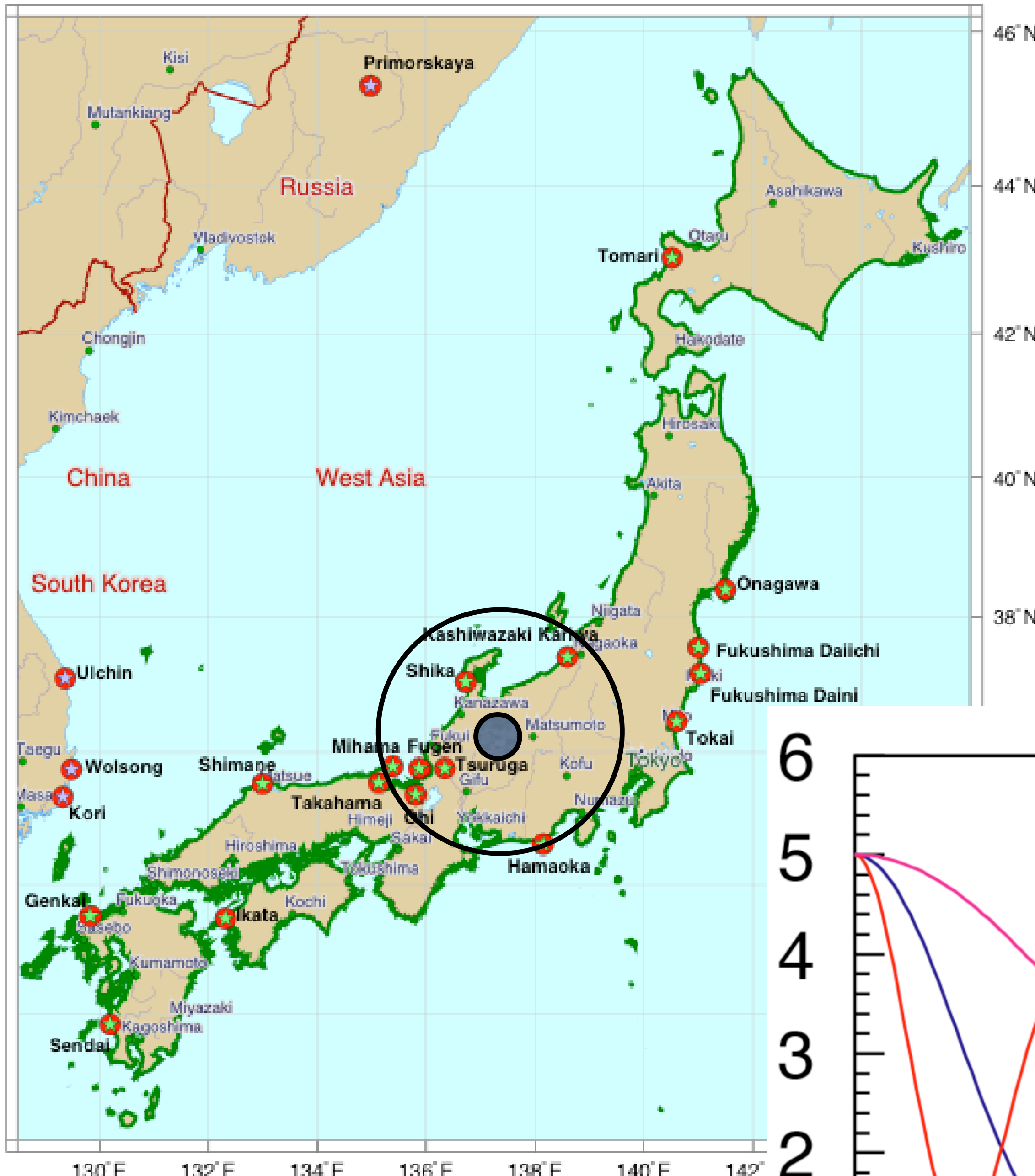
with a help of inverse reaction

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\sigma_{\mathrm{tot}}^{(0)} = \frac{2\pi^2/m_e^5}{f^{R}_{\mathrm{p.s.}}\tau_n} E_e^{(0)} p_e^{(0)}$$

$$\tau_n = 885.7 \pm 0.8\,\mathrm{sec}$$

# Neutrino oscillation study with spread reactors




70 GW (7% of world total) is generated at 130-220 km distance from Kamioka.

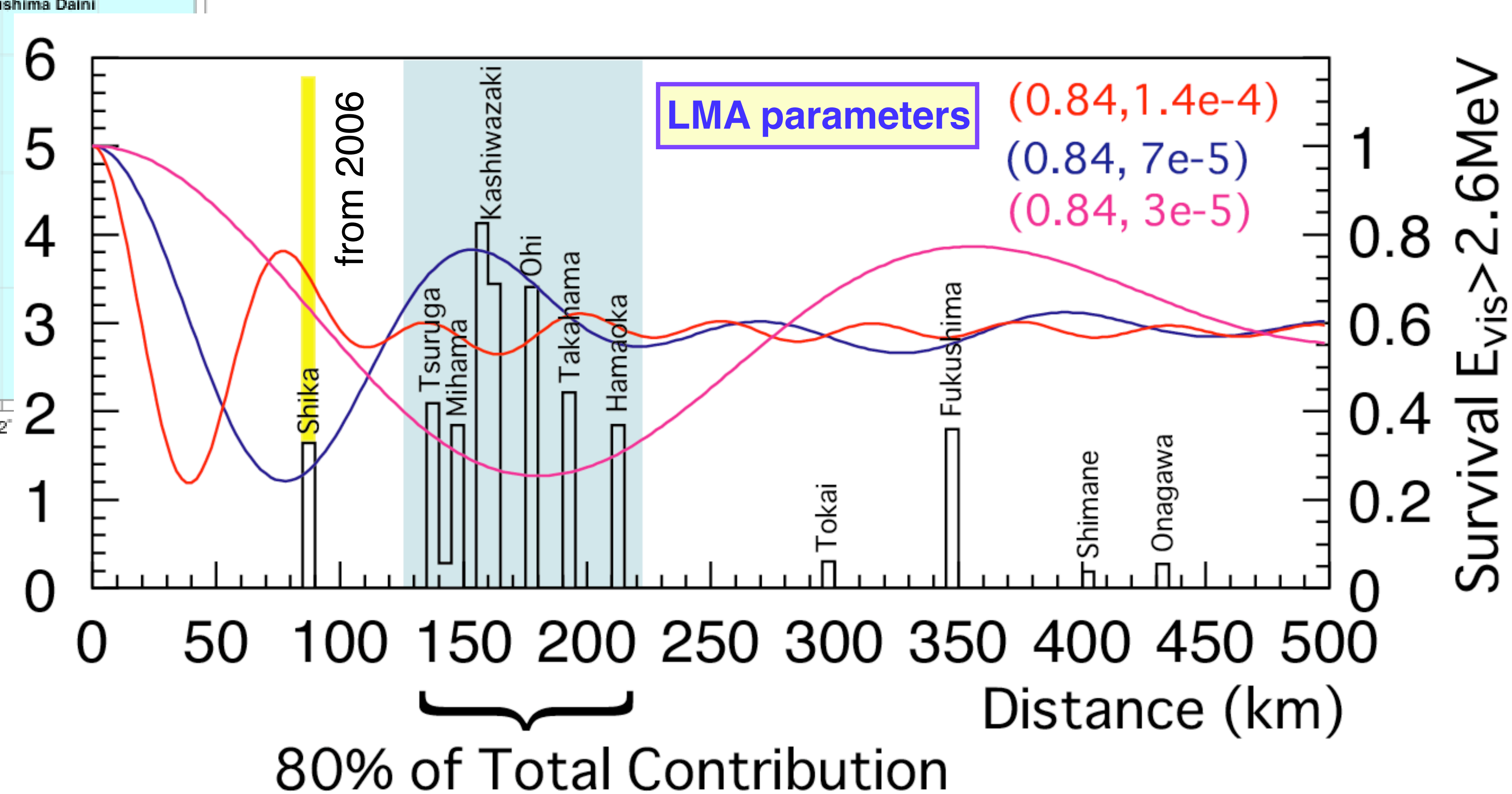
Reactor neutrino flux, $\sim 6 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$

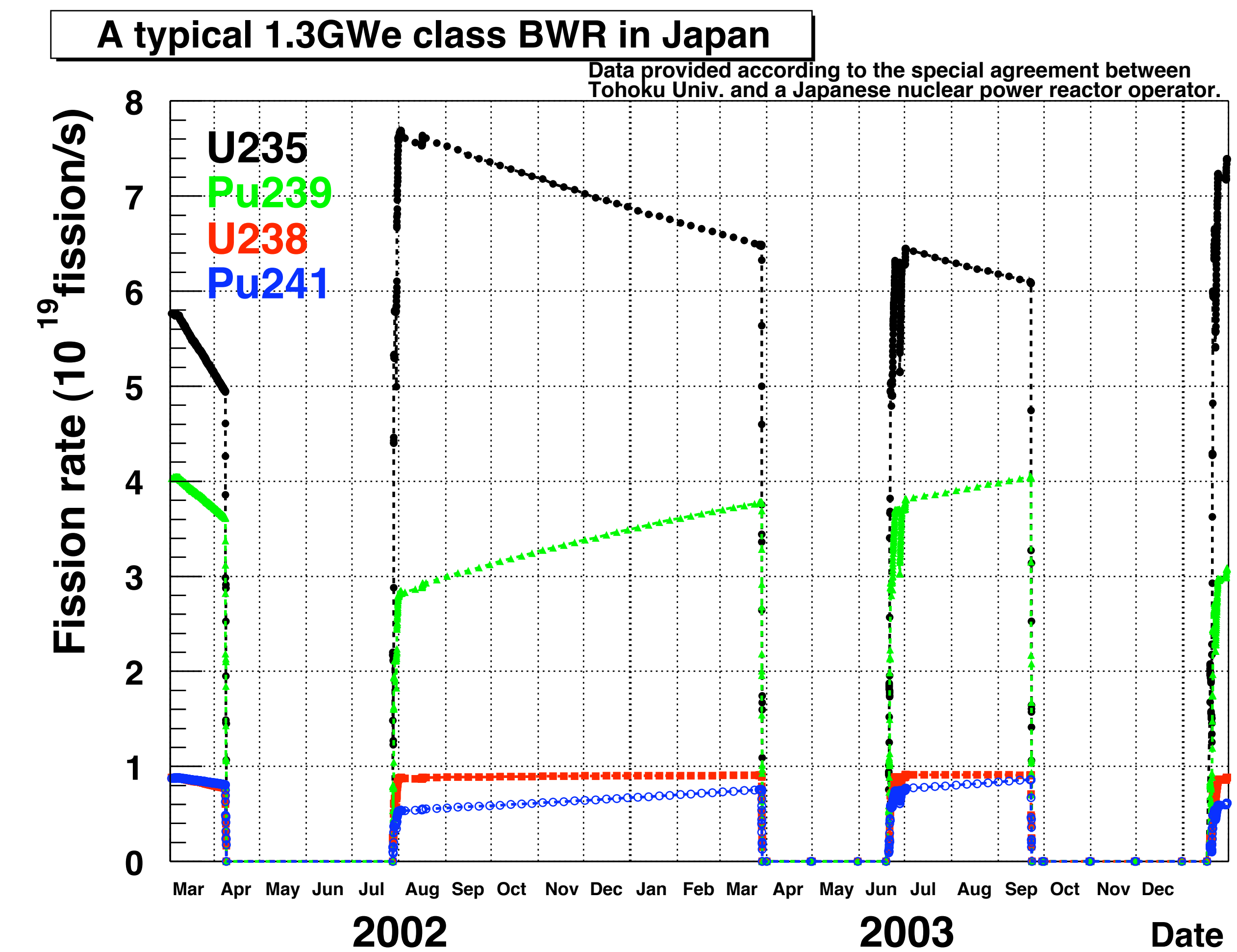
~95.5% from Japan
~3.5% from Korea

(2nd result period)

effective distance ~180km

(weighted average by event rate up to 400 km)

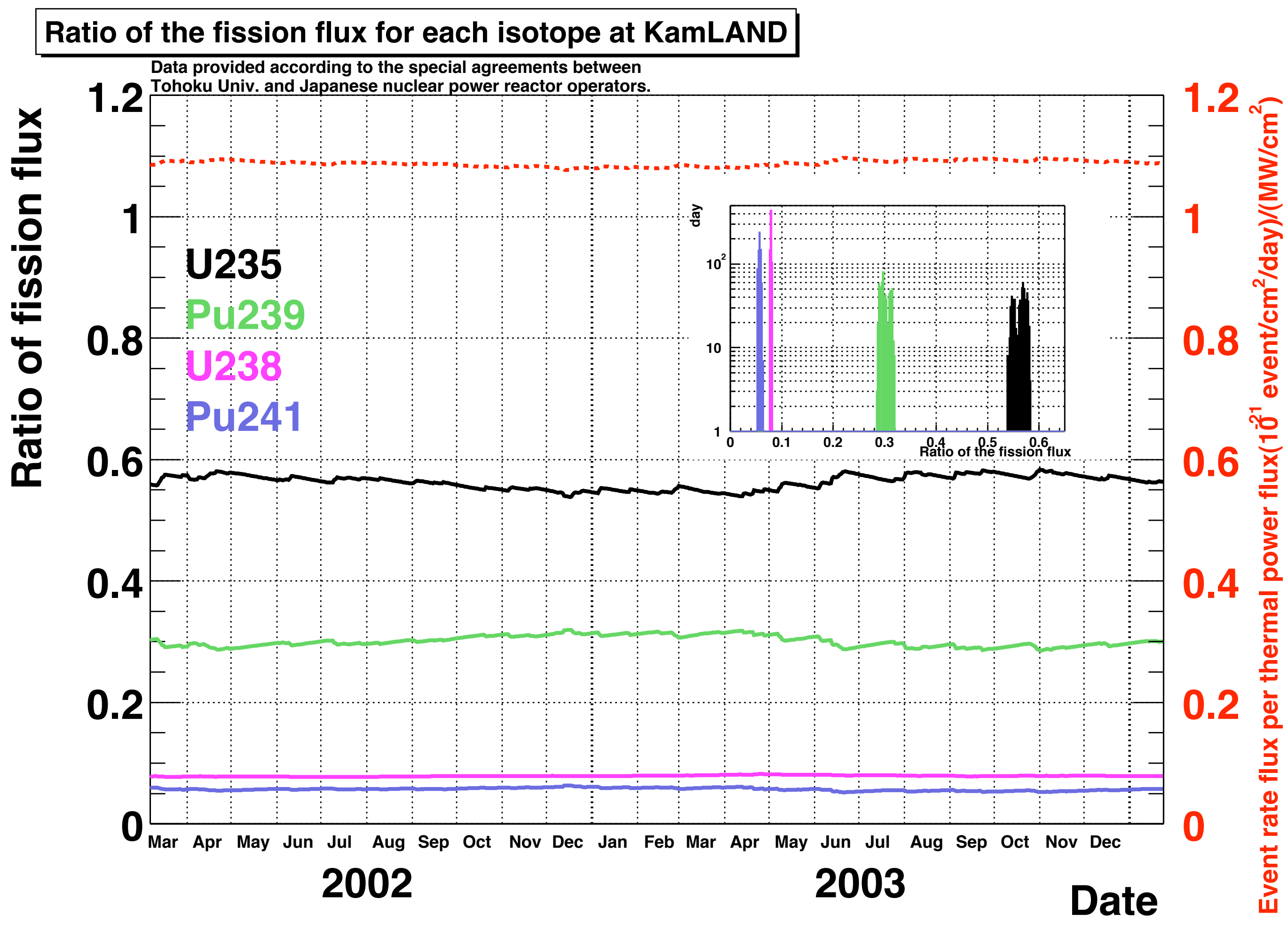


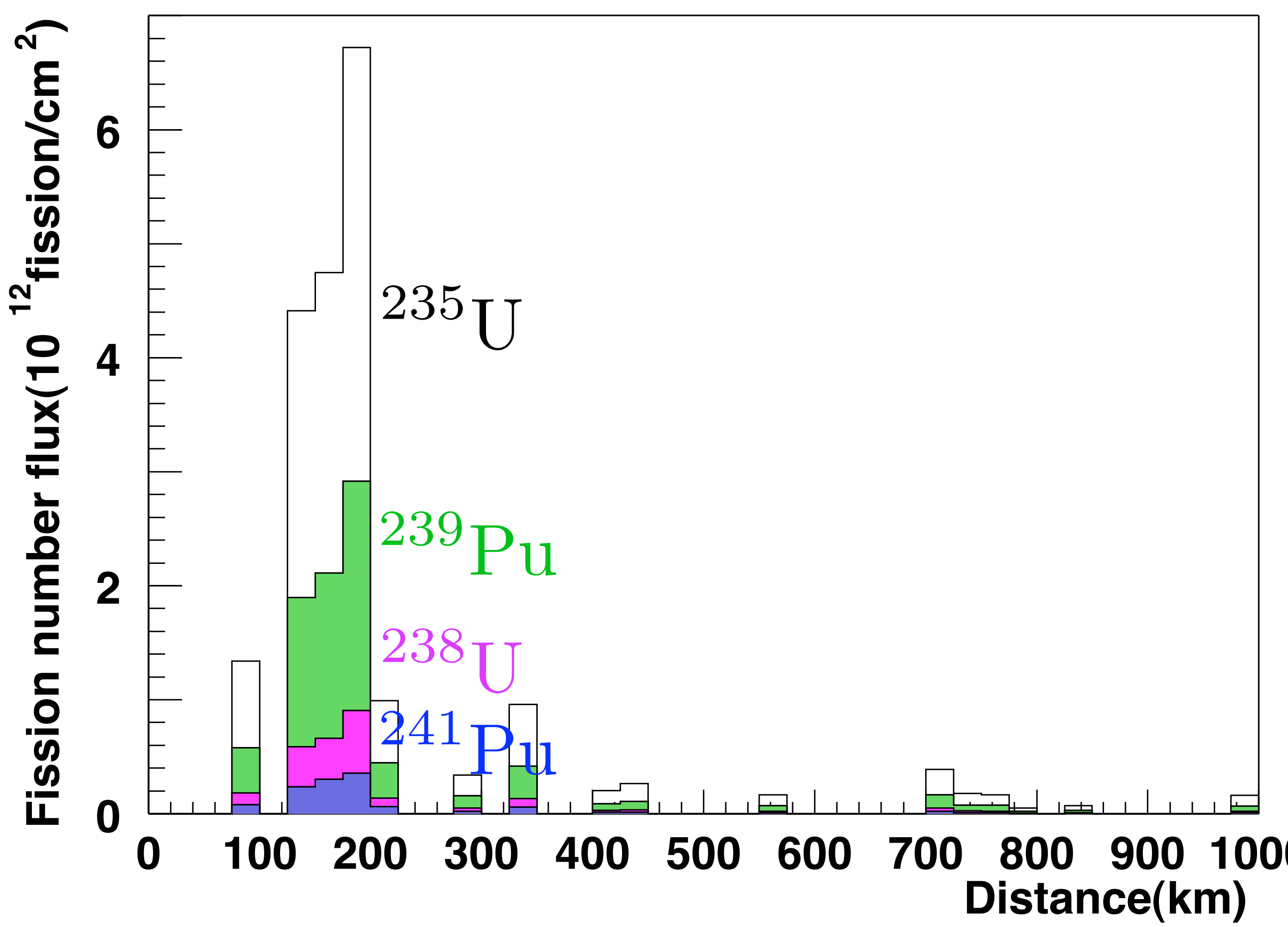


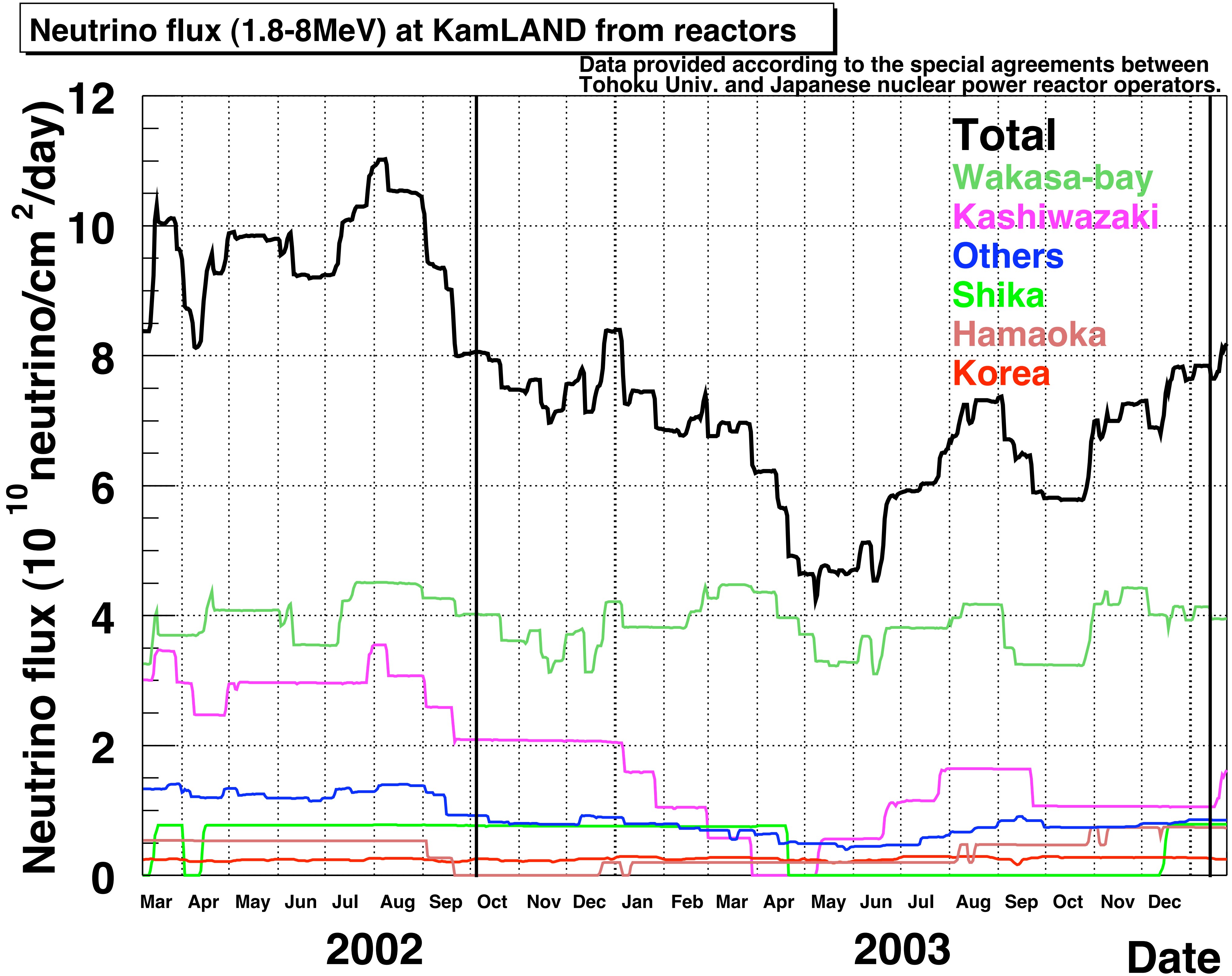

Burn-up is calculable from history of thermal power, fraction of new fuel and $^{235}$U enrichment.

$$^{235}\mathrm{U} : ^{239}\mathrm{Pu} : ^{238}\mathrm{U} : ^{241}\mathrm{Pu} = 0.563 : 0.301 : 0.079 : 0.057$$

(average over second result period)






| | |
|---|---|
| Detailed information from Japanese reactors | 95.5% |
| History of electric power output from Korean reactors | 3.4% |
| Nominal power from the other reactors | 1.1% |

# 1st result

## Data Summary

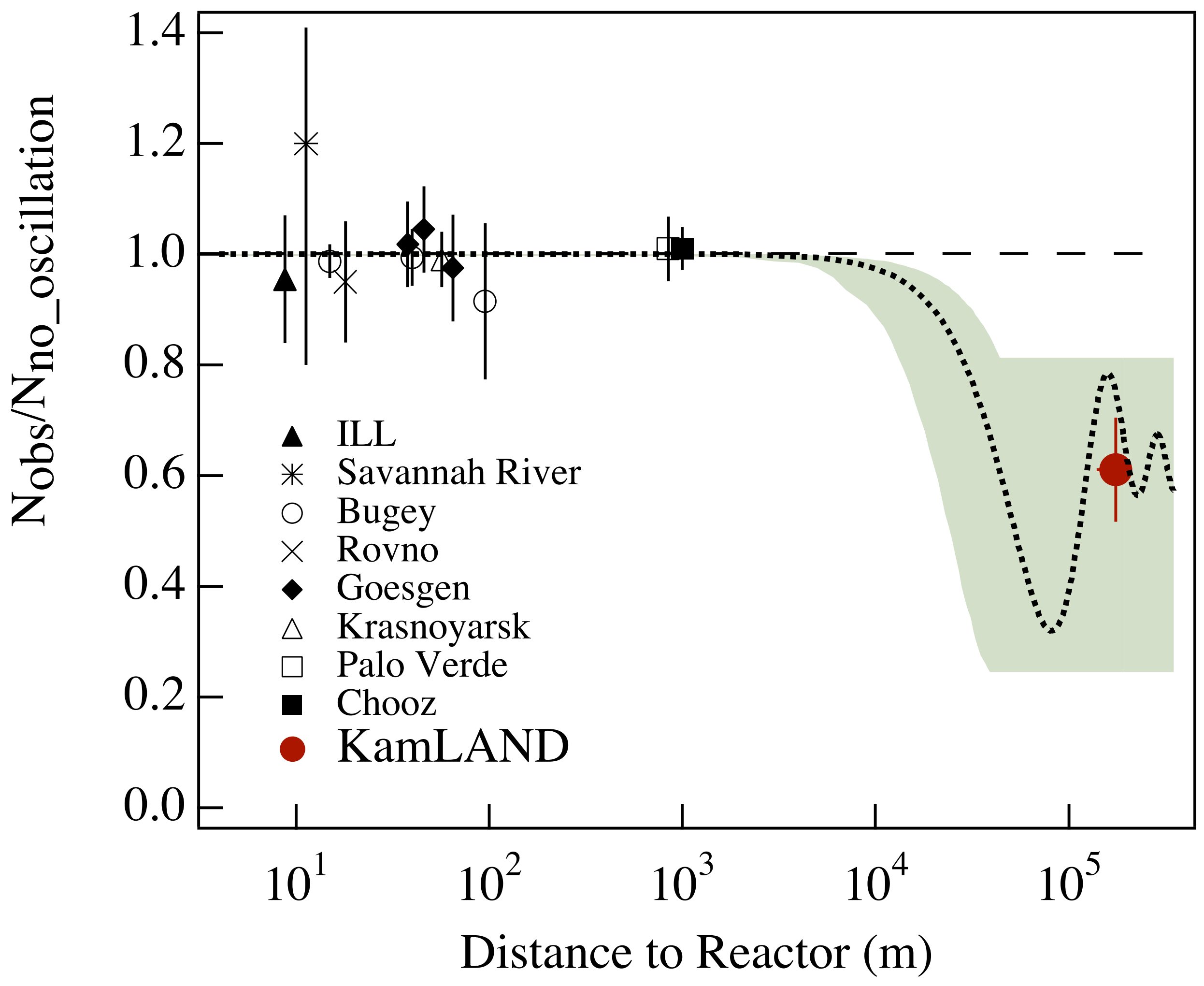
from March 4 to October 6, 2002
145.1 live days, 162 ton-year exposure

### Analysis threshold 2.6 MeV

| | |
|---|---|
| expected signal | $86.8 \pm 5.6$ |
| BG | $1 \pm 1$ |
| observed | $54$ |

Neutrino disappearance at 99.95% CL.

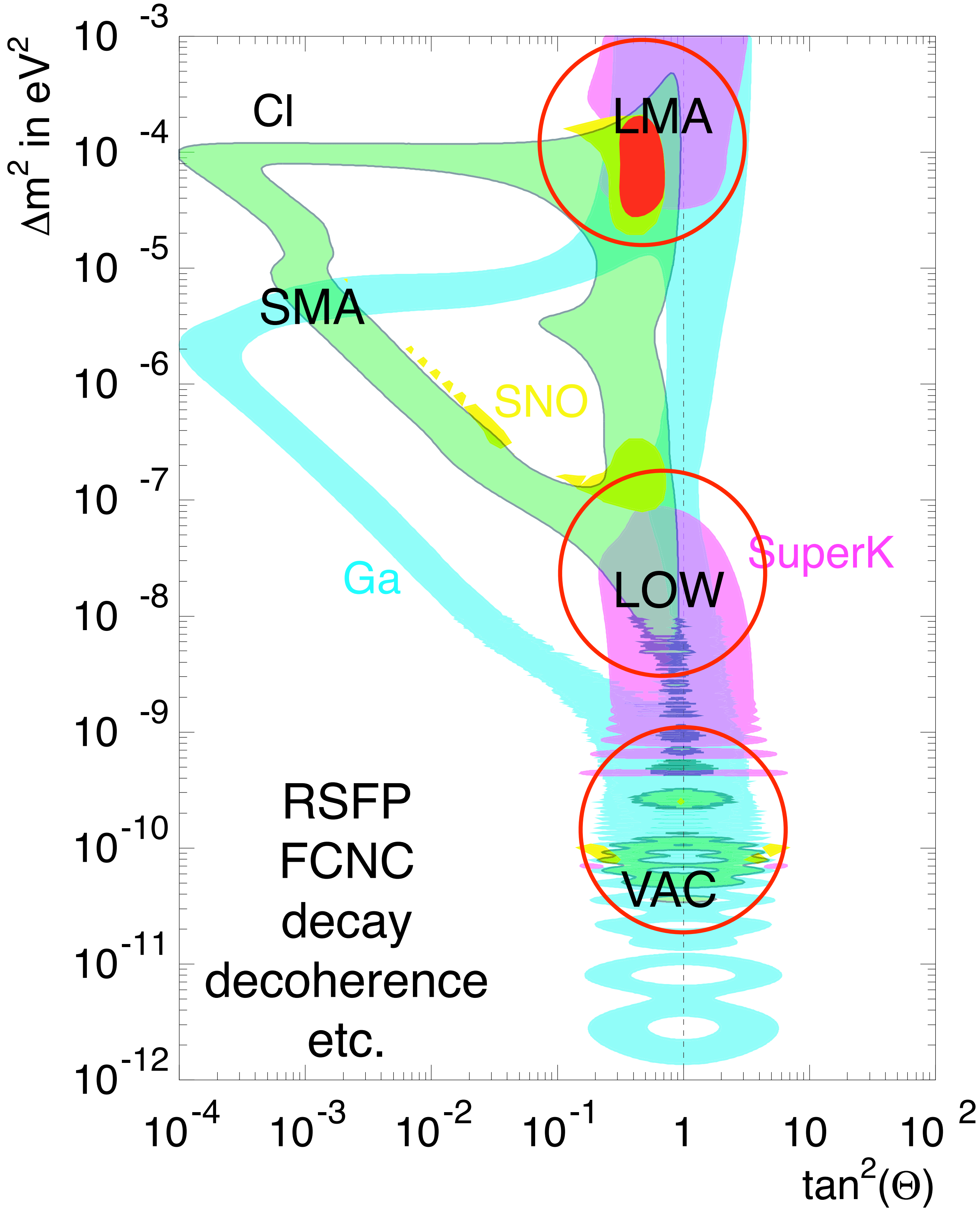
$$R = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$$



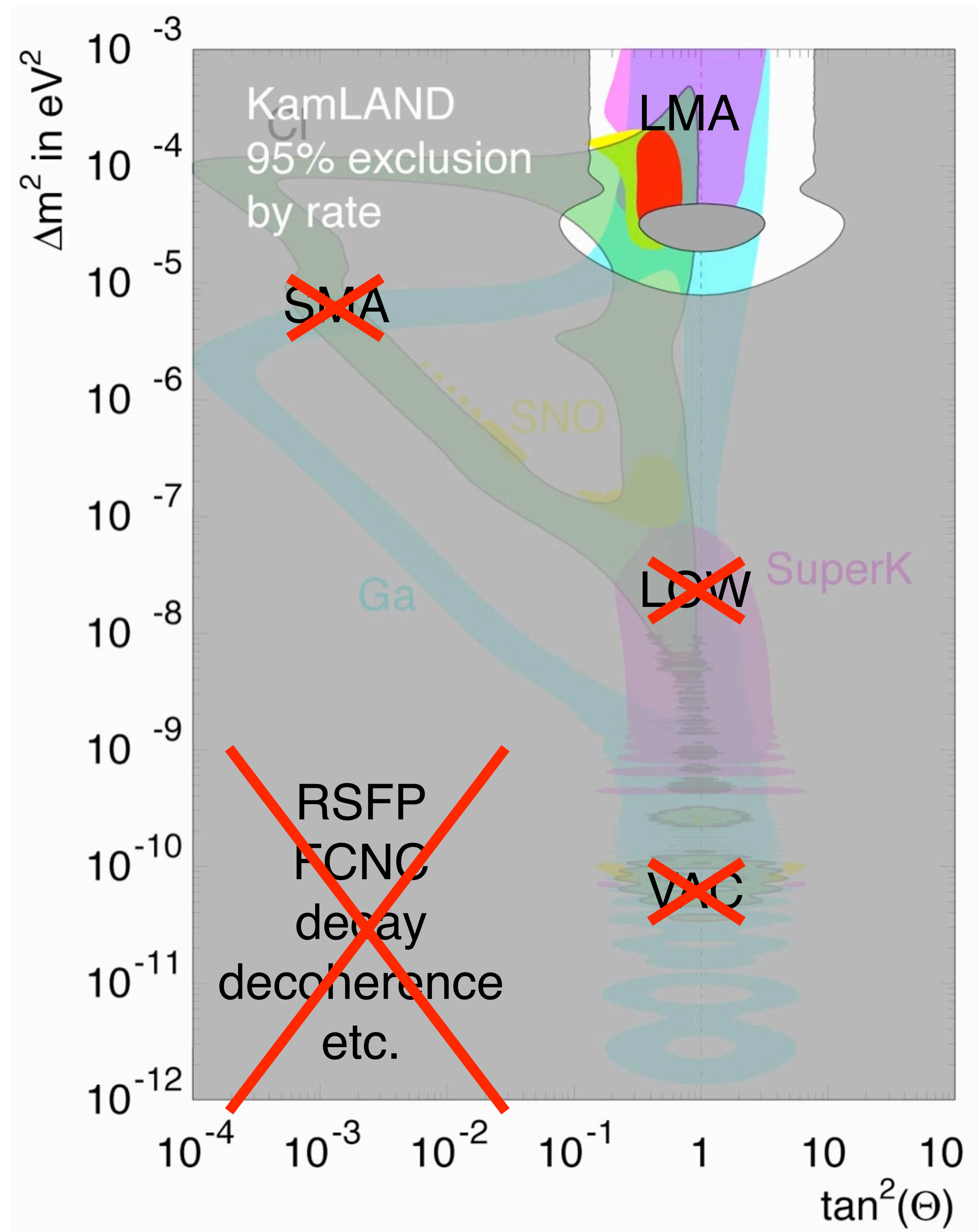

KamLAND collaboration, Phys.Rev.Lett.90(2003)021802

## Evidence for reactor neutrino disappearance

## 2 gen. Neutrino oscillation parameters consistent with each solar results




## with KamLAND rate




Reactor neutrino disappearance excluded all but LMA from leading phenomena.

# Analysis Improvements

Fiducial volume was enlarged thanks to more uniform energy scale and less vertex bias.

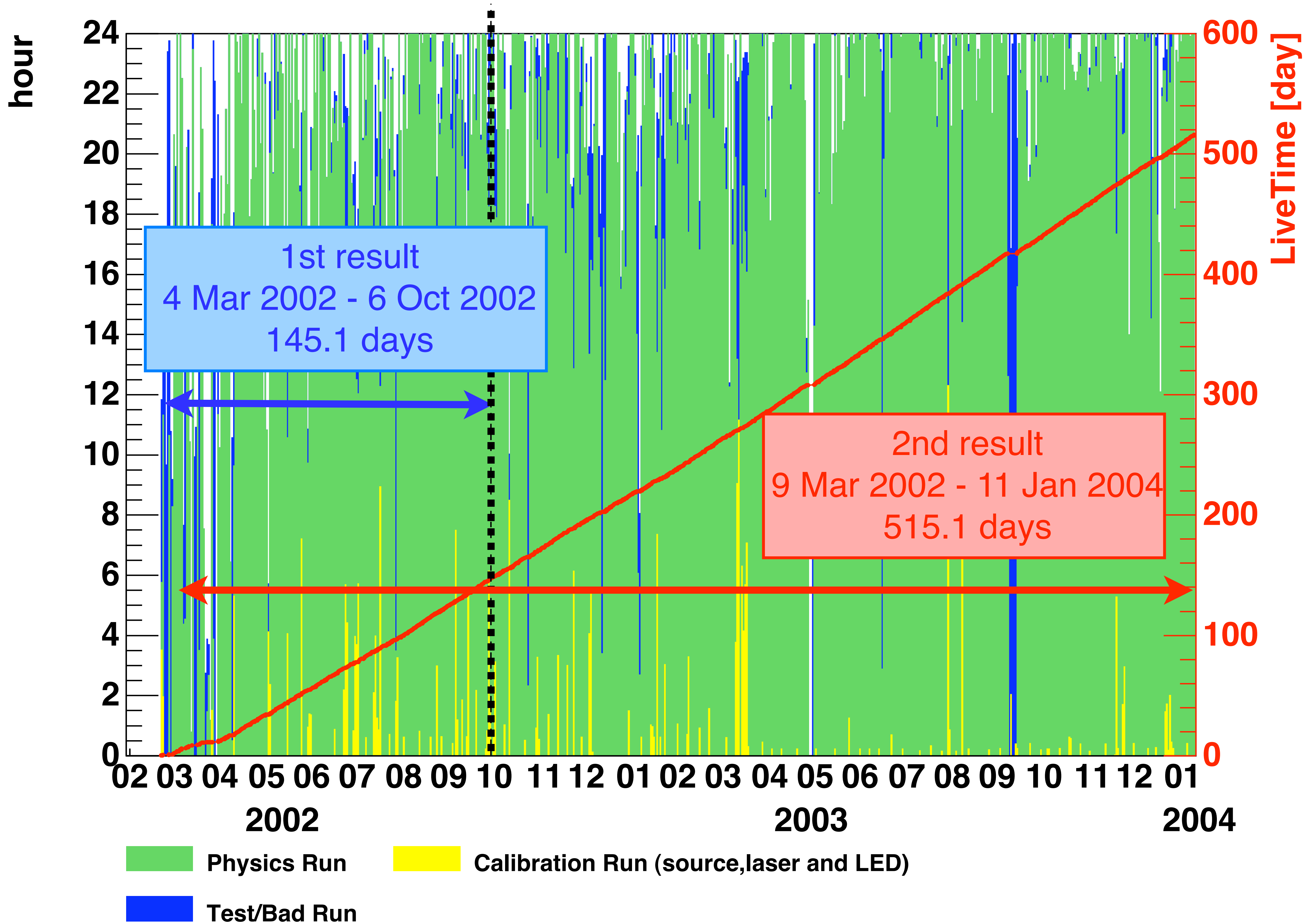
5m --> 5.5m factor 1.33

Coincidence criteria were loosened to increase detection efficiency focusing on reactor neutrinos.

78.3% --> 89.8% factor 1.15

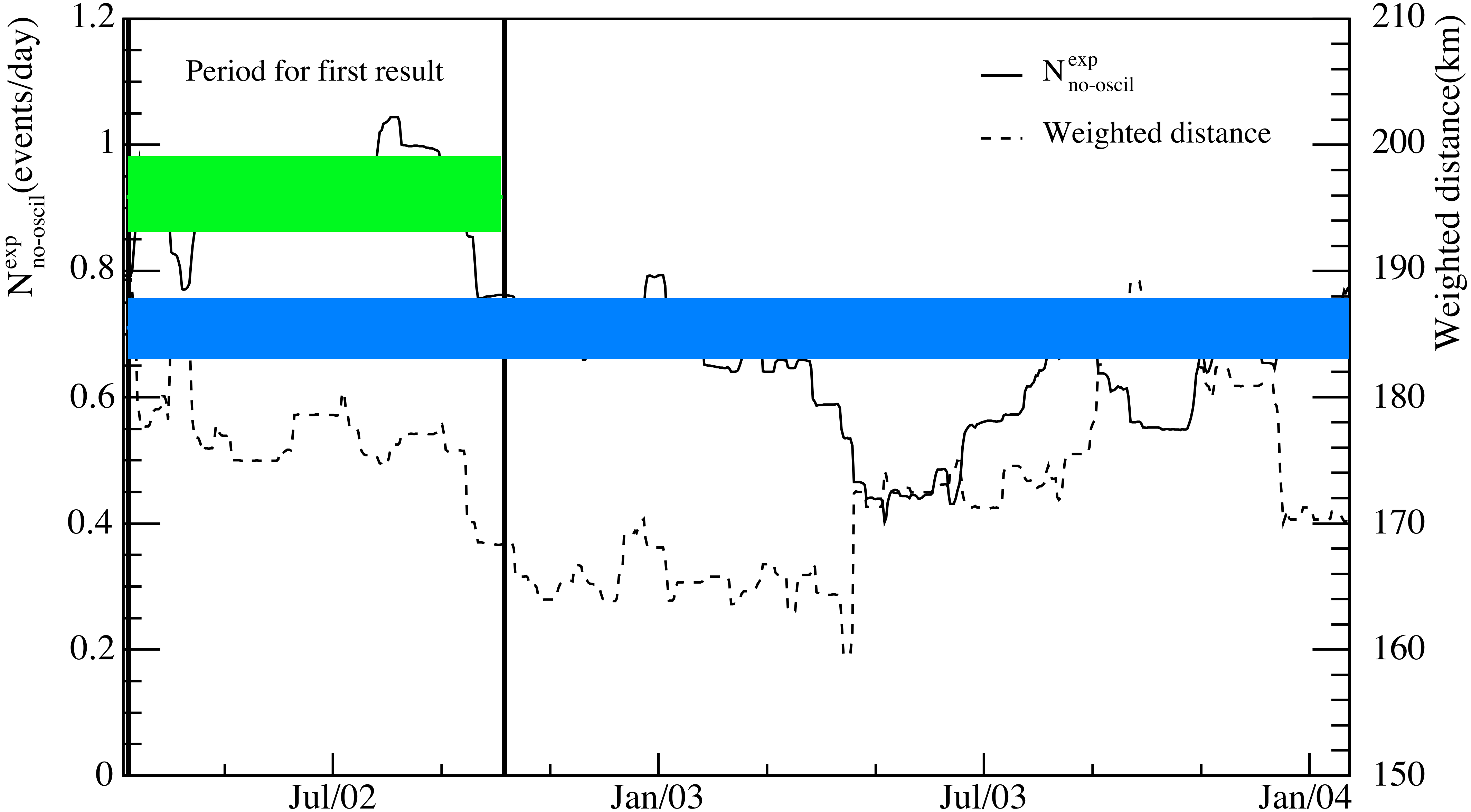
And more run time.

# X 3.55 live time



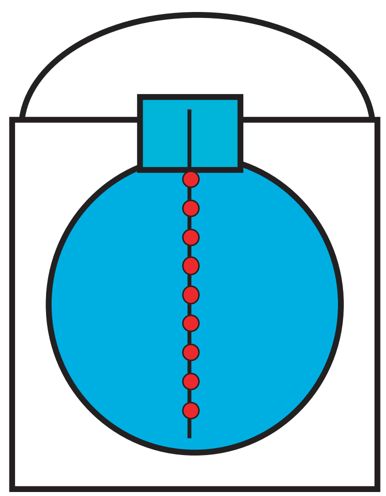
# Finally, lower reactor operation

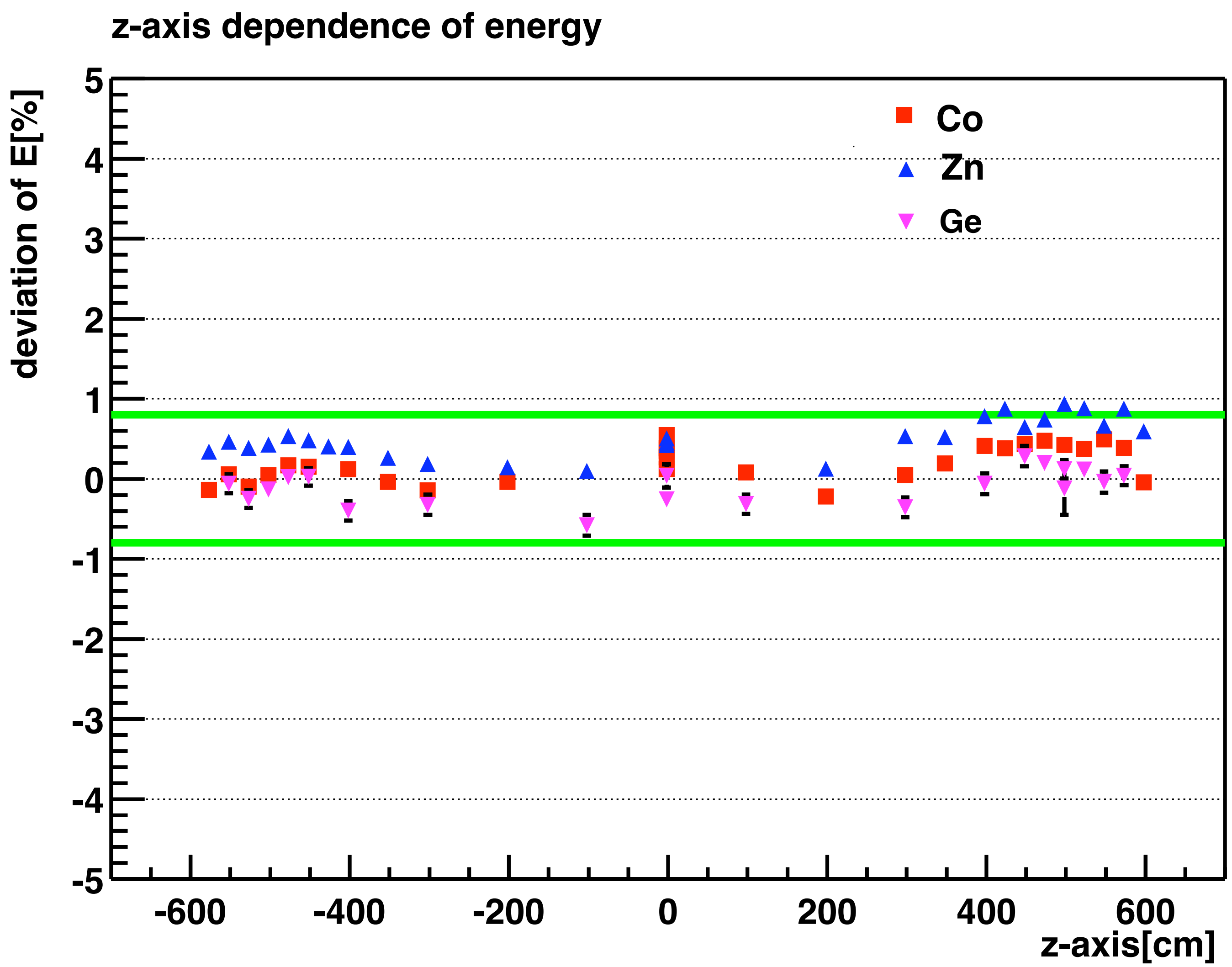
## X 0.77



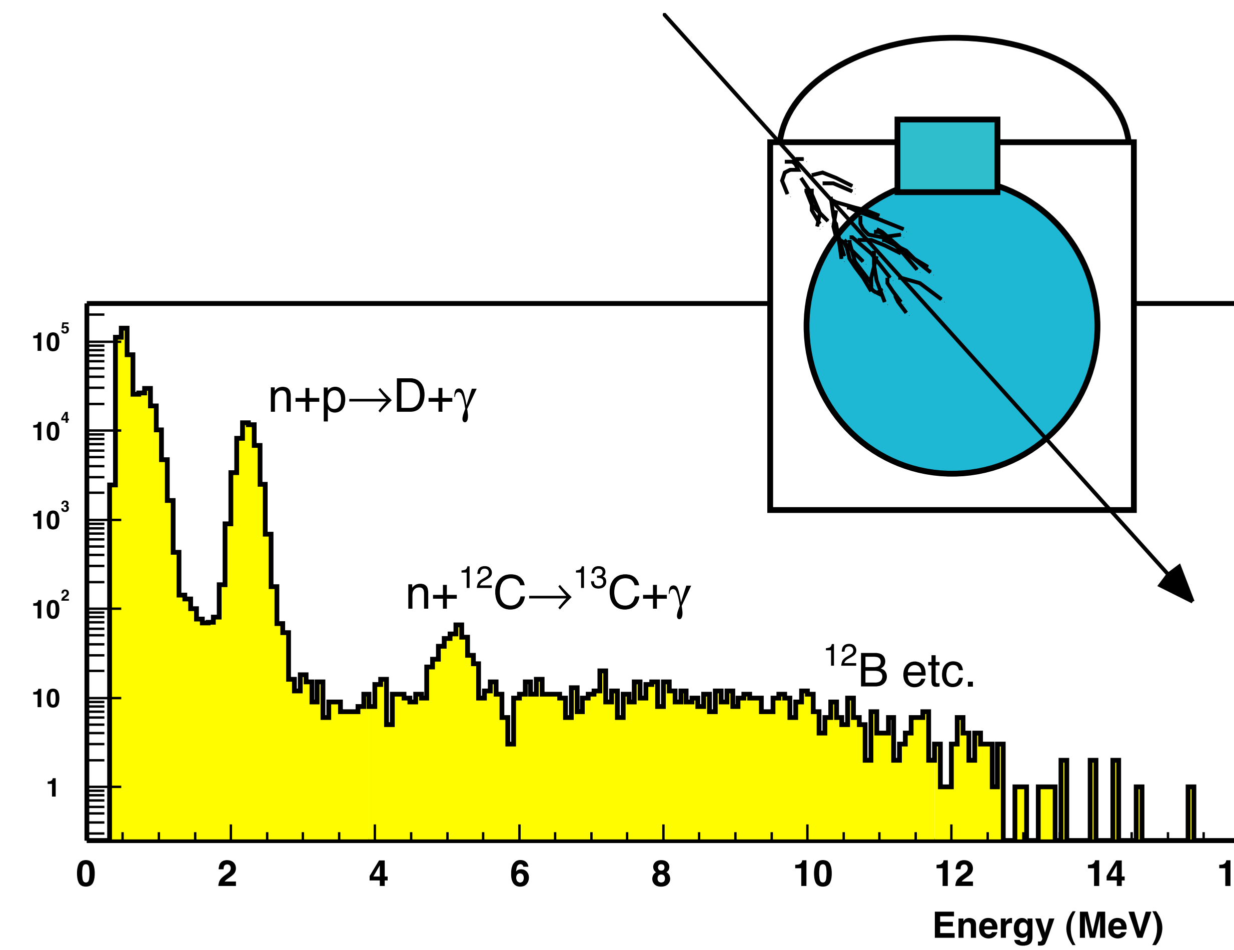

## Statistical improvement --> X 4.2

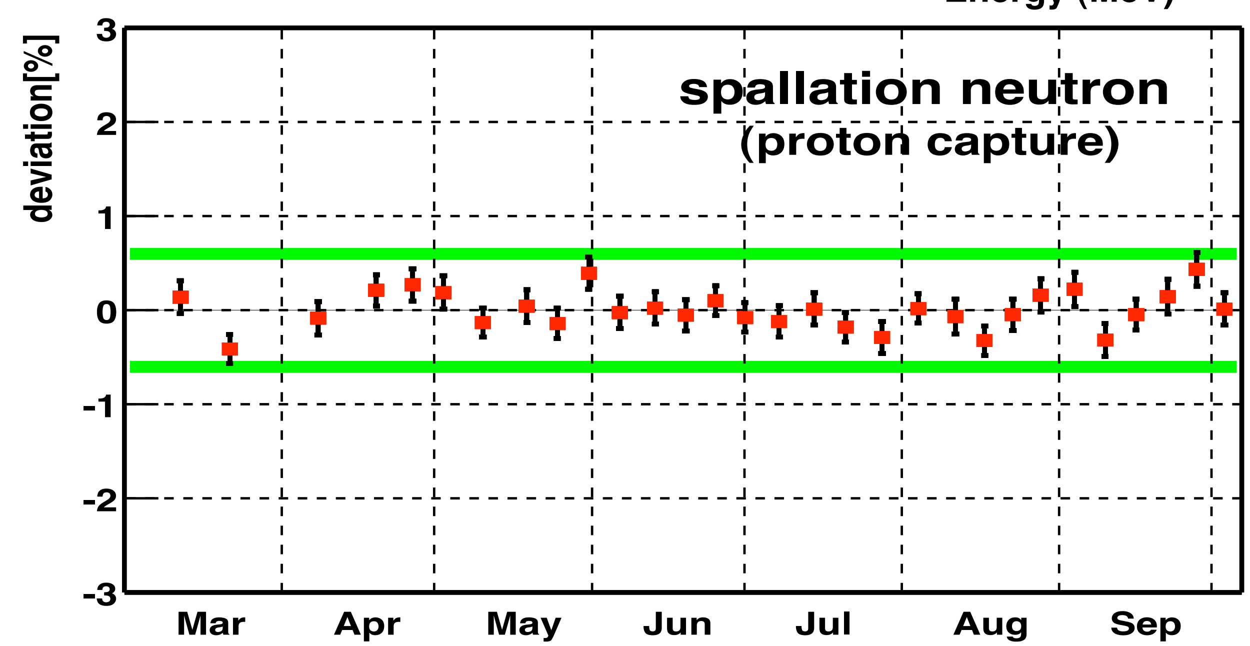
# Energy Calibration with Radioactive Sources

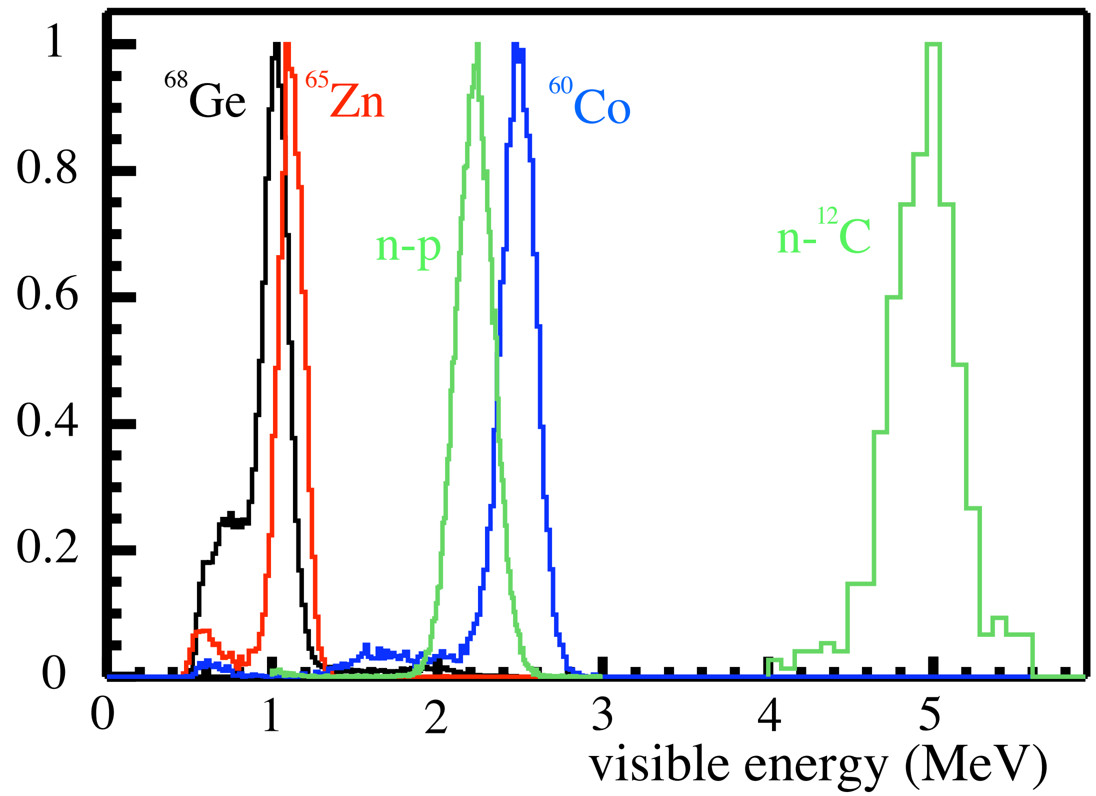


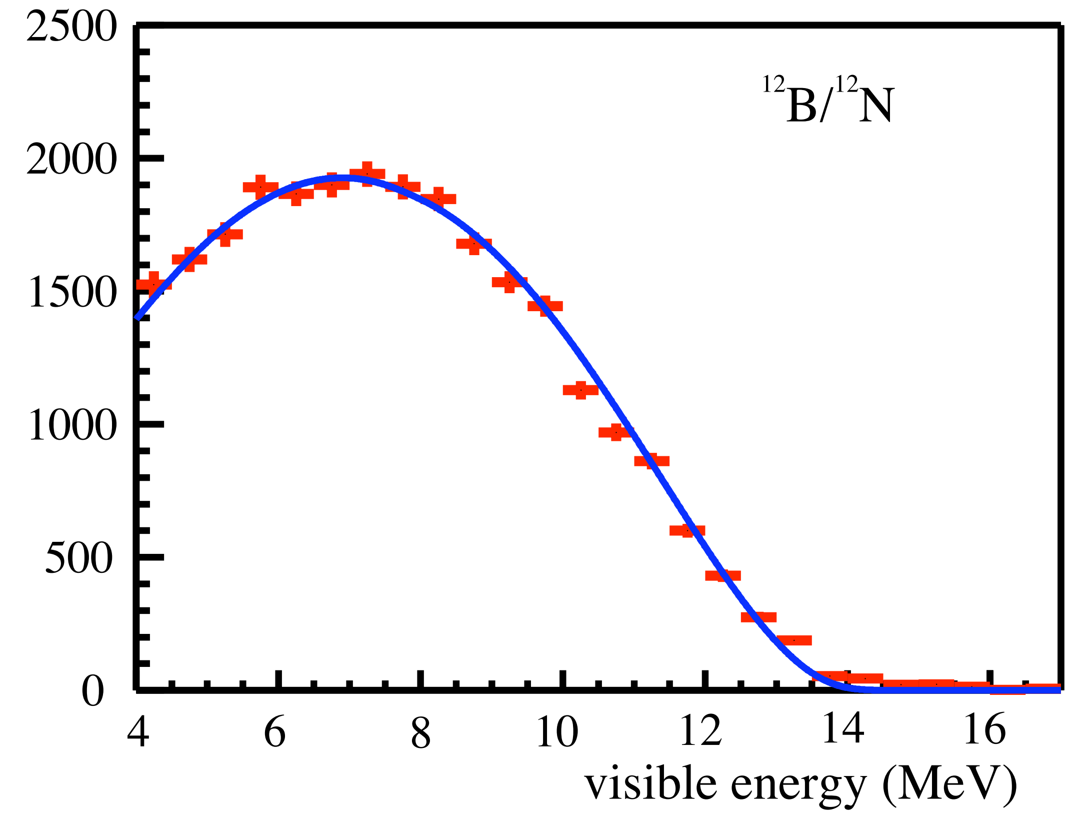



# with Muon Spallation



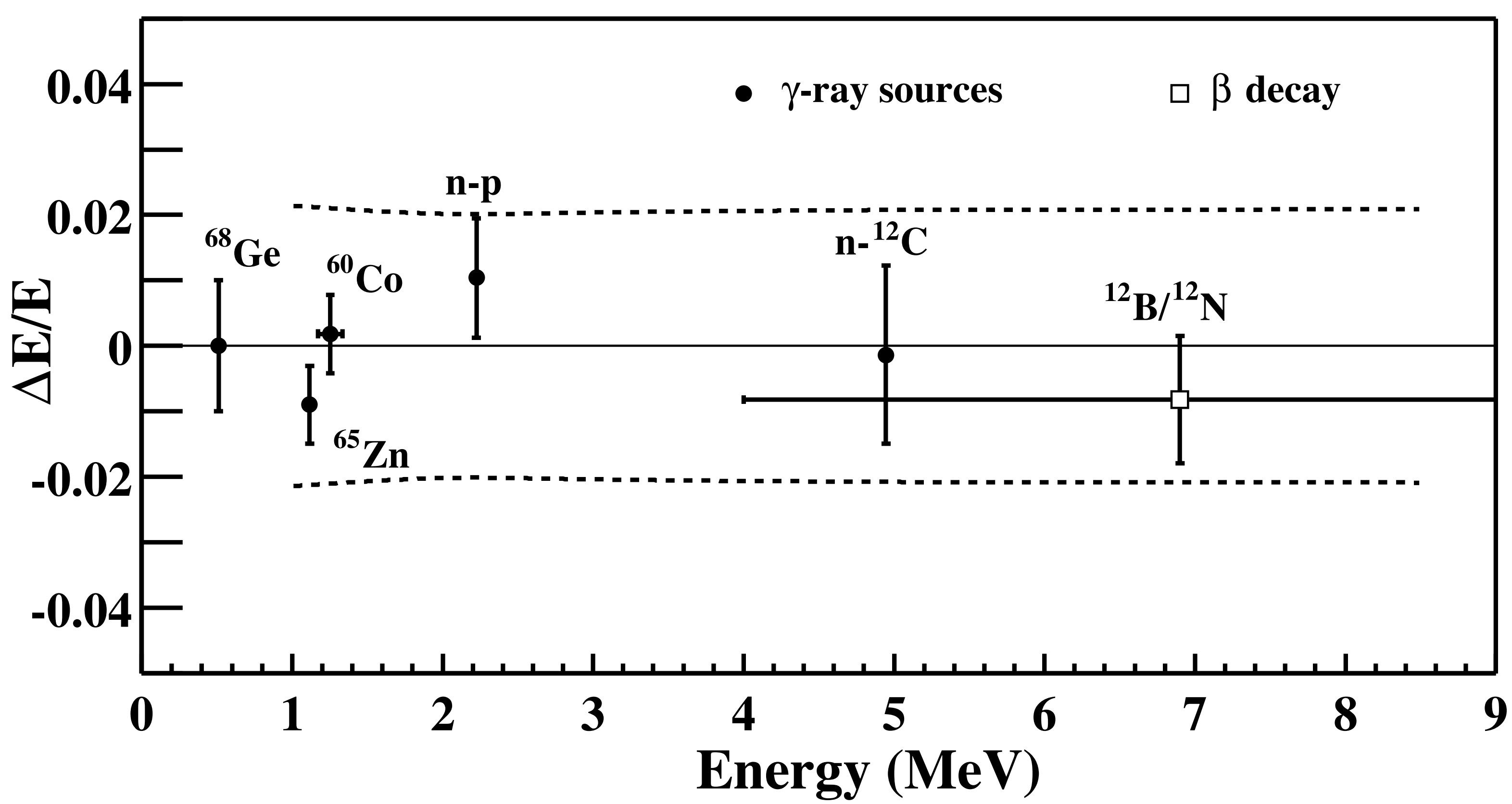





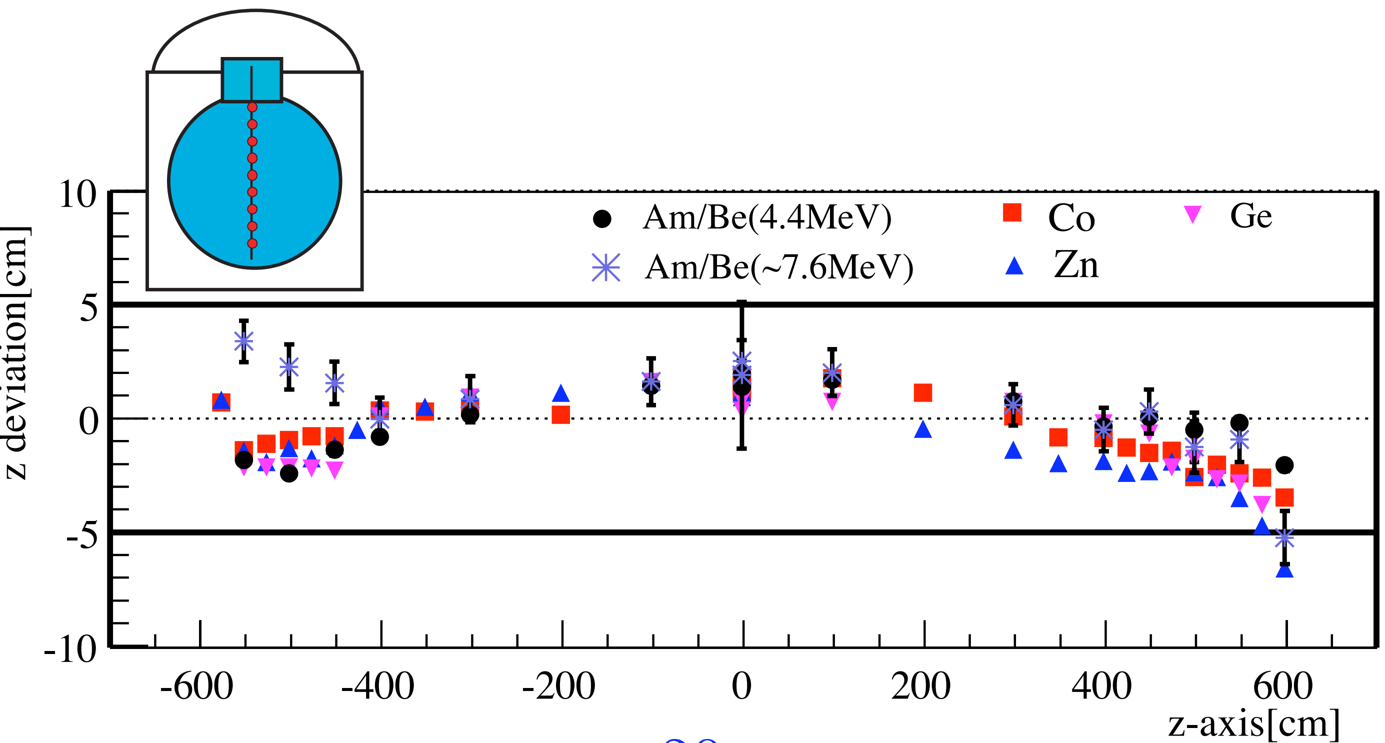

$$\frac{\sigma}{E} \sim \frac{6.2\%}{\sqrt{E}}$$ with 20” PMTs

$\sim 7.5\% \rightarrow \sim 7.3\%$ without 20” PMTs



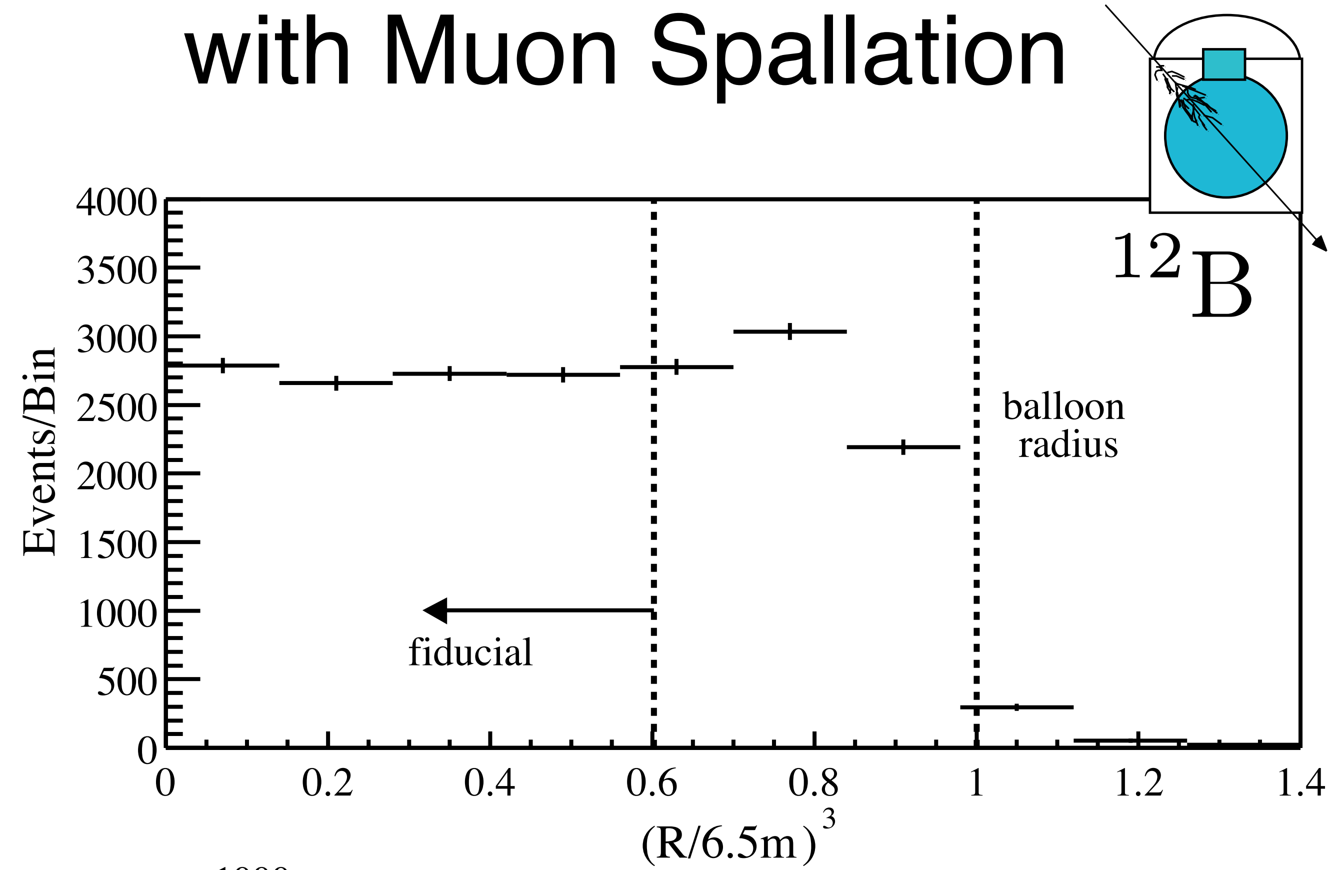

| Energy scale error at 2.6 MeV | |
|---|---|
| Cherenkov/Birks | 1.0% |
| Time dependence | 1.3% |
| Position dependence | 1.0% |
| 20” PMT non-linearity | 0.8% |
| Total | 2.0% |

# Fiducial Volume Calibration with Radioactive Sources

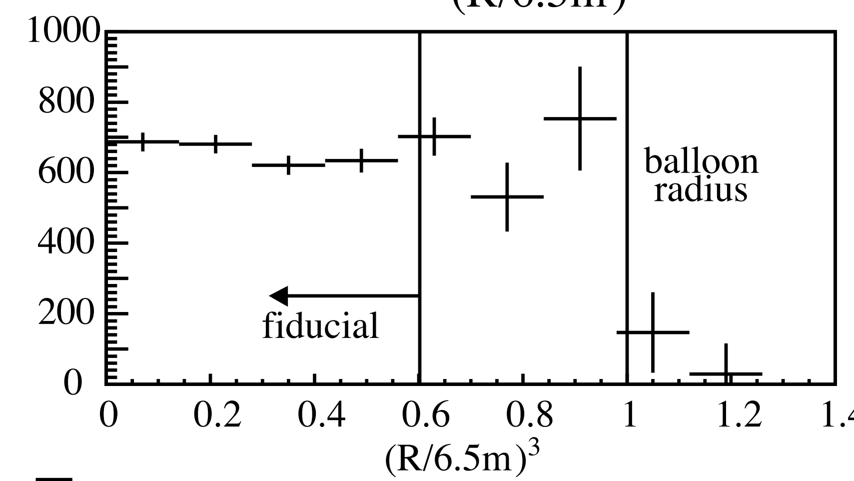



$\sigma_{x,y,z} \sim \frac{20\text{cm}}{\sqrt{E}}$ with 20" PMTs

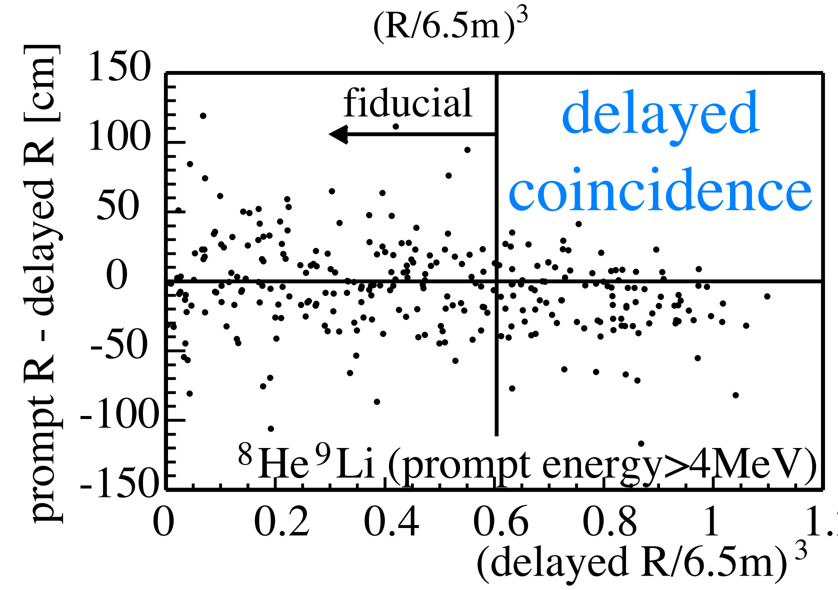
# with Muon Spallation




$^{12}$B




p(n, $\gamma$)d




$^9$Li

$\beta + n$

# Fiducial/Total Volume Ratios

| | |
|---|---|
| geometrical | $0.595 \pm 0.013 \quad \left(= \frac{696.9\,\text{m}^3}{1171 \pm 25\,\text{m}^3}\right)$ |
| $^{12}$B | $0.607 \pm 0.006 \pm 0.006$ |
| p(n, $\gamma$)d | $0.587 \pm 0.013$ |
| $^9$Li relative | $< 2.7\%$ |

**conservative volume error 4.7%**

# So far Achieved Systematic Errors

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

# Event Selection

## delayed coincidence

$$0.5 < \Delta T < 1000\,\mu\text{sec} \quad (660\,\mu\text{sec})$$

$$\Delta R < 2\text{m} \quad (1.6\,\text{m})$$

$$1.8 < E_{\text{delayed}} < 2.6\,\text{MeV}$$ (neutron capture)

## fiducial volume

$$R_{\text{prompt, delayed}} < 5.5\text{m} \quad (5.0\,\text{m})$$

$$543.7\,\text{ton} \quad (408.5\,\text{ton})$$

$$N_{\text{p}} = 4.61 \times 10^{31} \; (3.46 \times 10^{31})$$

## spallation cuts

$$\Delta T_{\mu} < 2\text{msec}$$

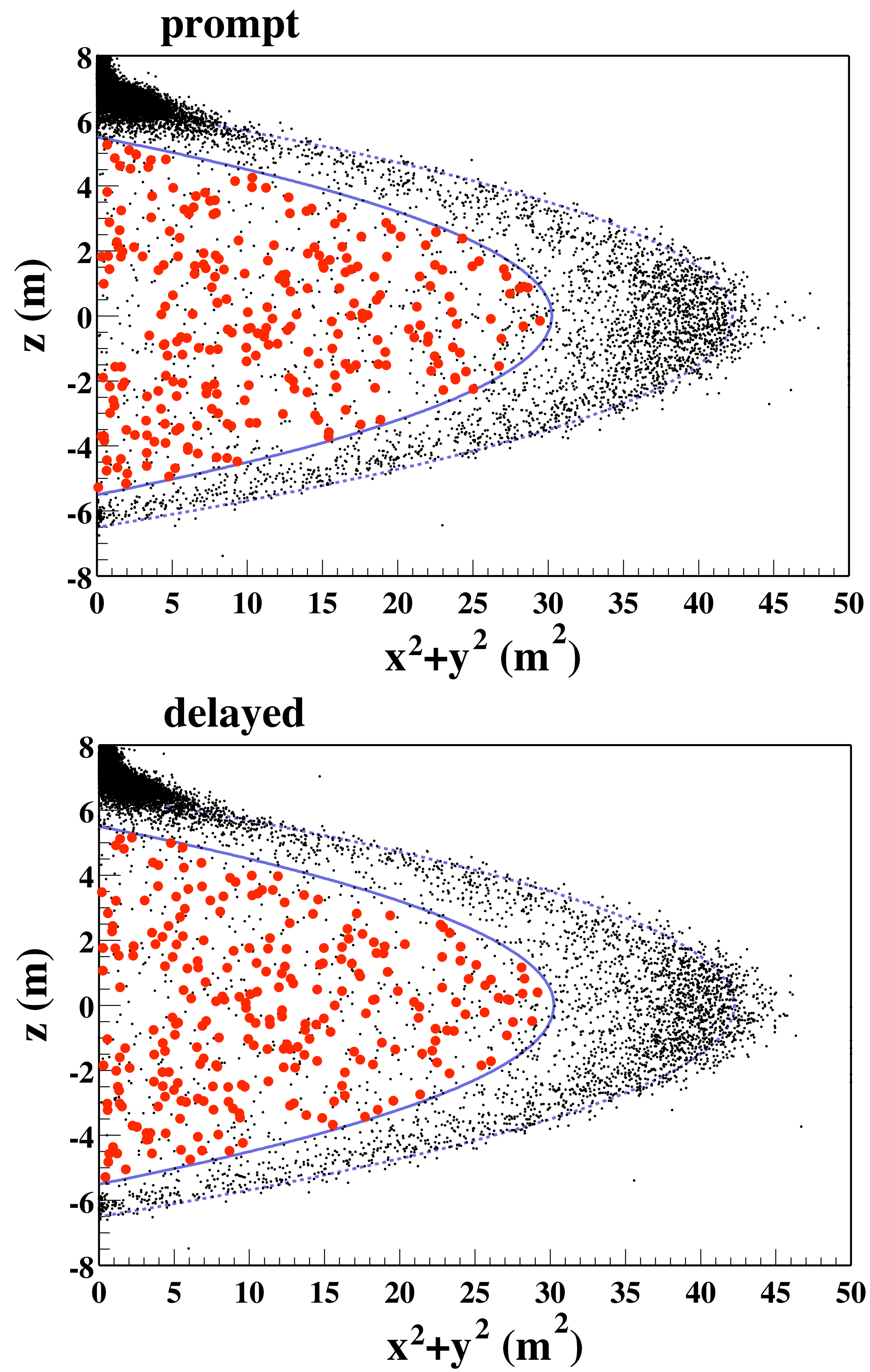
$$\Delta T_{\mu} < 2\text{sec} \quad E_{\text{extra}} > 3\text{GeV} \text{ or } \Delta L < 3\text{m}$$ (showering)

dead time 9.7% (11.4%)

## reactor energy window

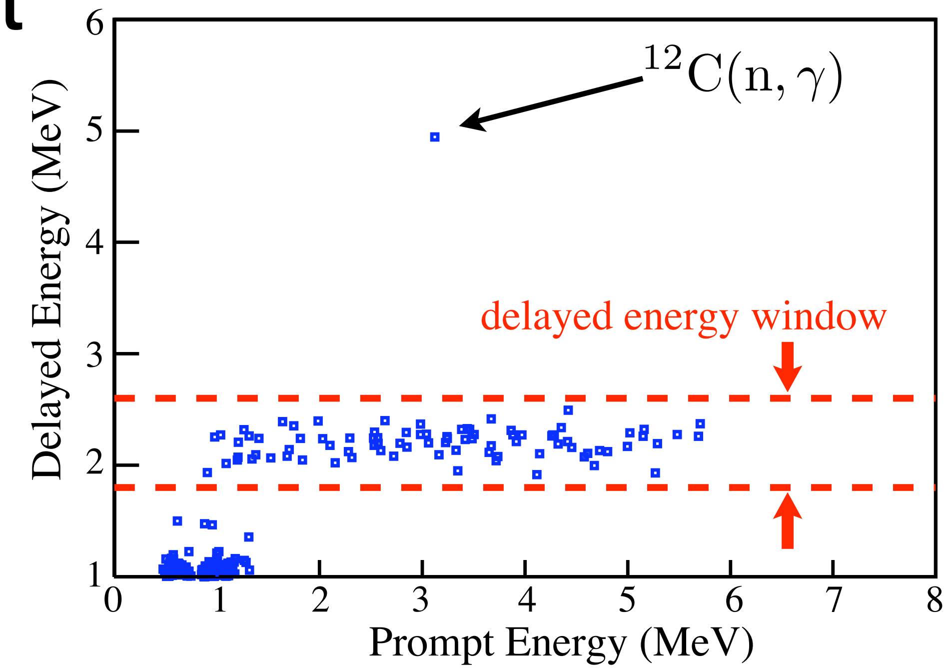
$$2.6 < E_{\text{prompt}} < 8.5\,\text{MeV}$$

Total detection efficiency 89.8% (78.3%)

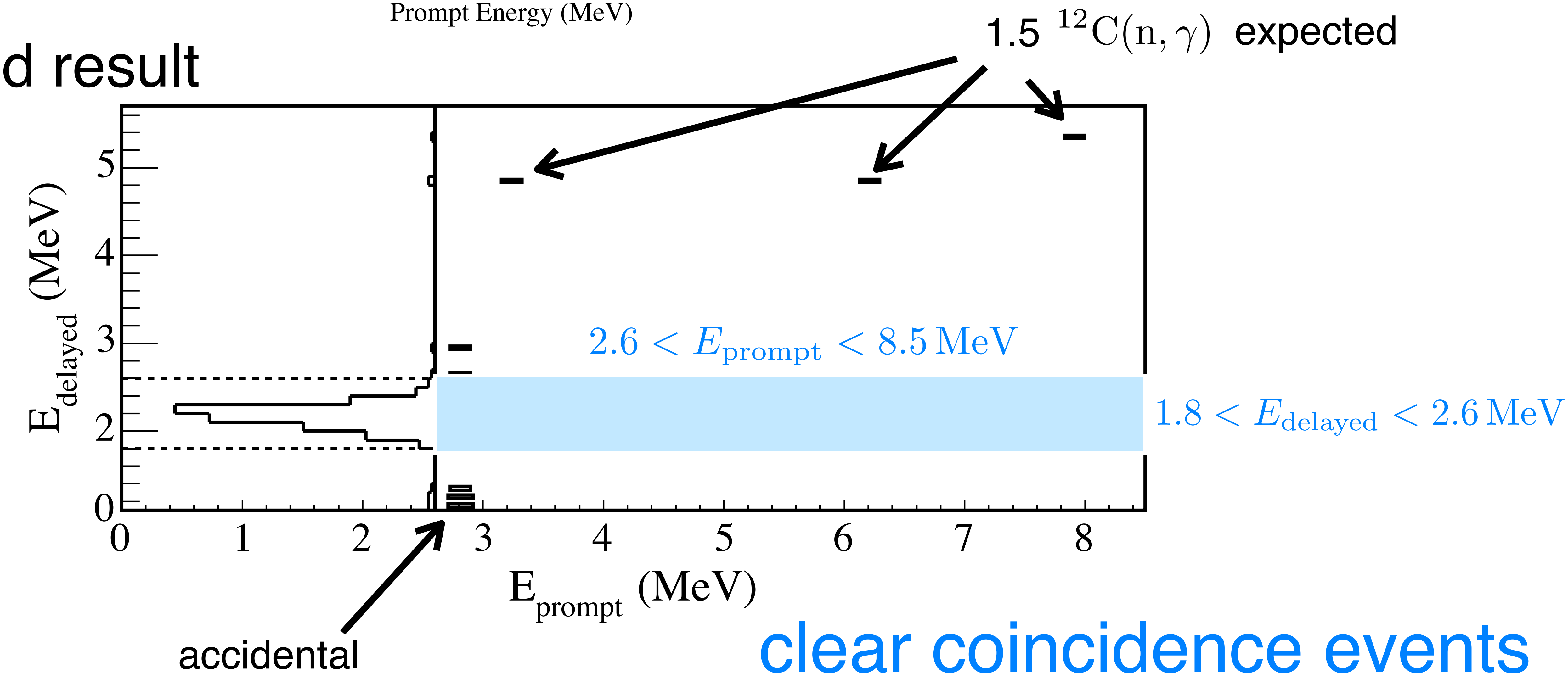


# Delayed vs. Prompt Energy

1st result



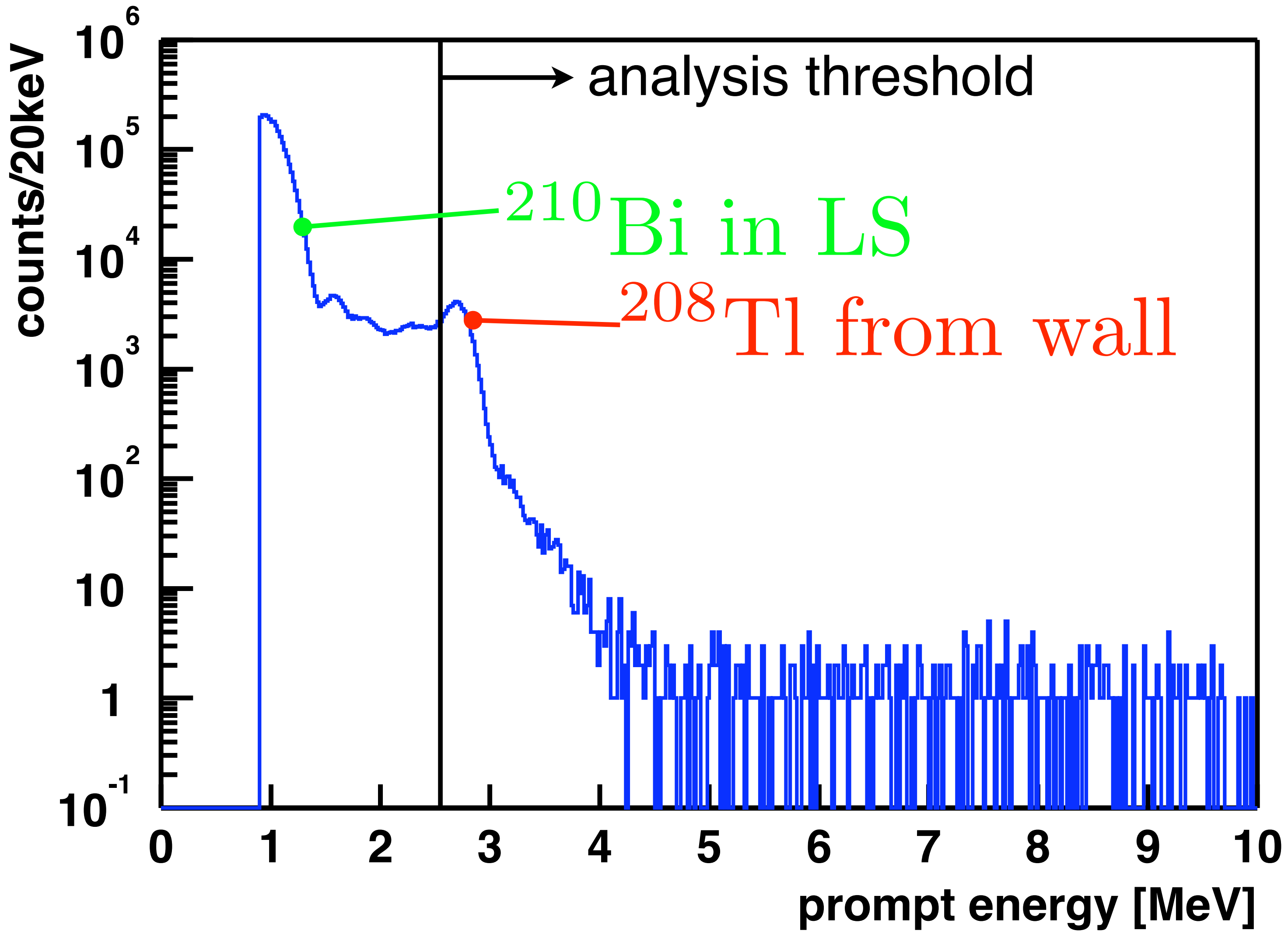

2nd result




clear coincidence events

# Backgrounds

## Accidental Coincidence




1st result (5m fiducial 162 ton-yr)

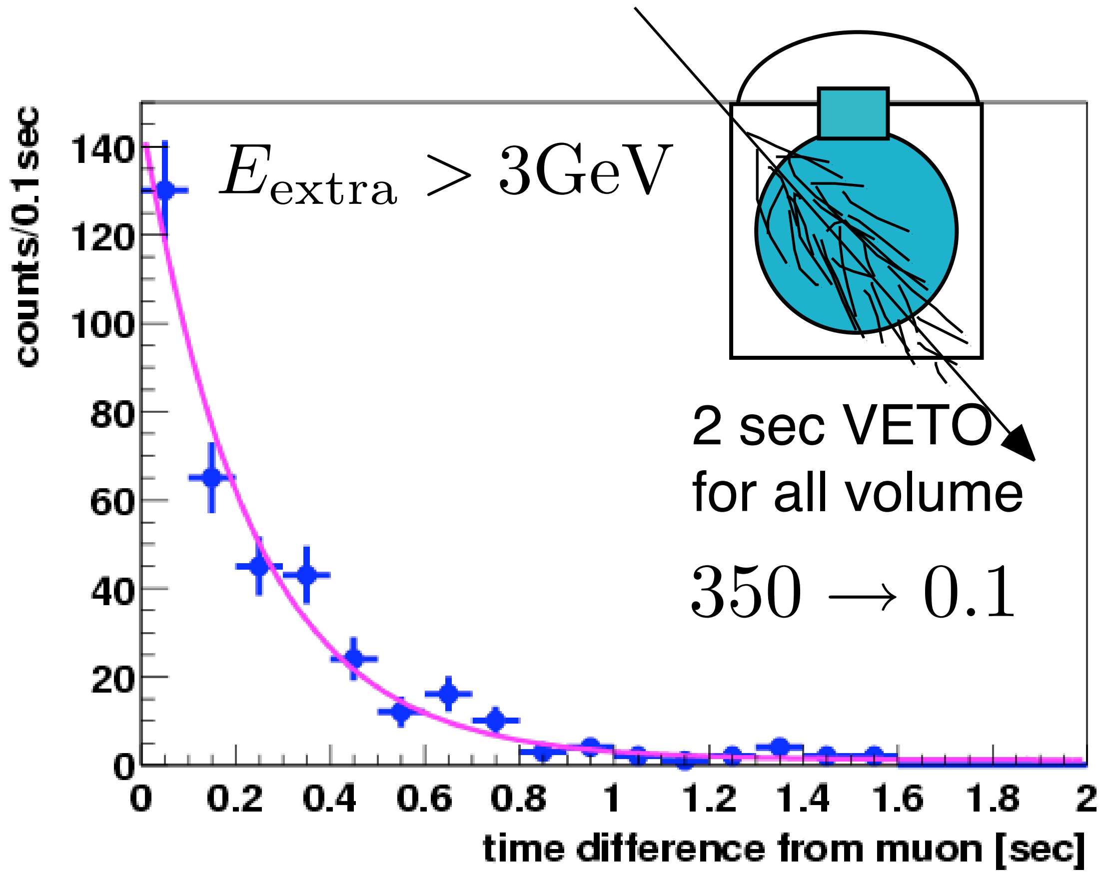
$$0.0086 \pm 0.00005$$

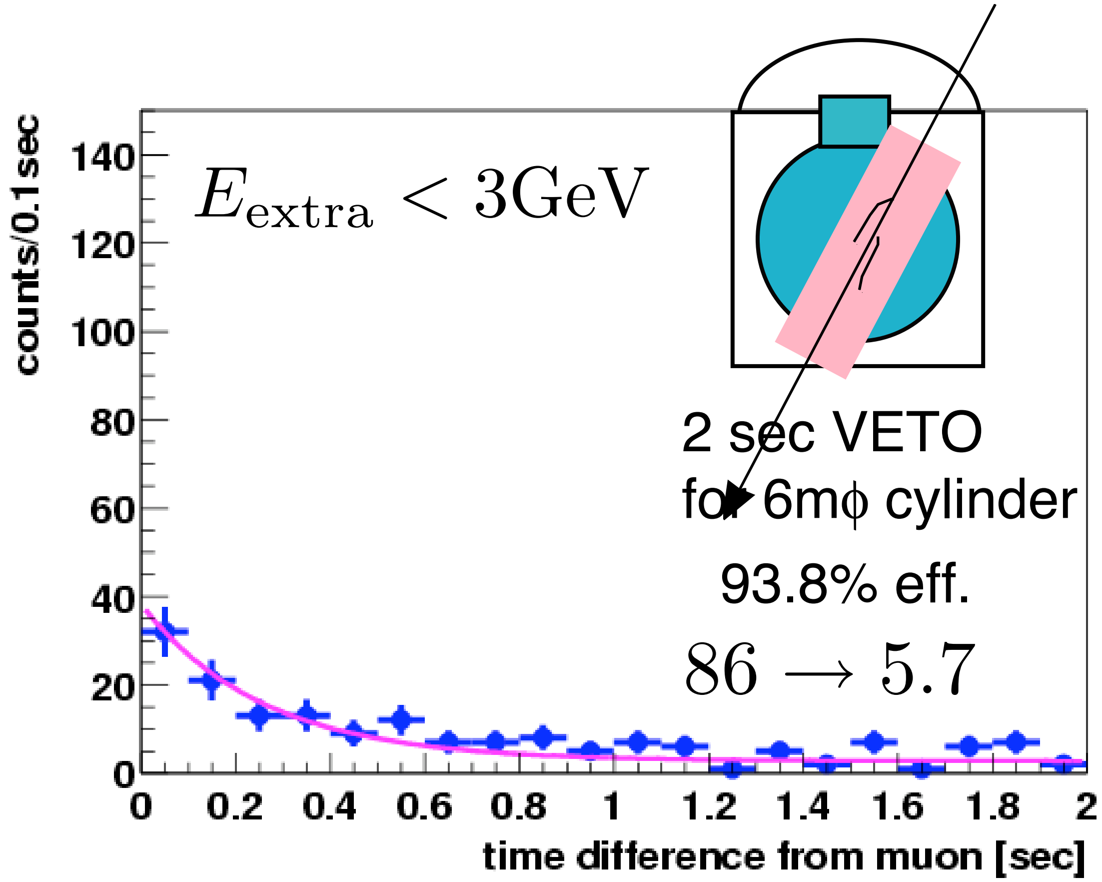
2nd results (5.5m fiducial 766.3 ton-yr)

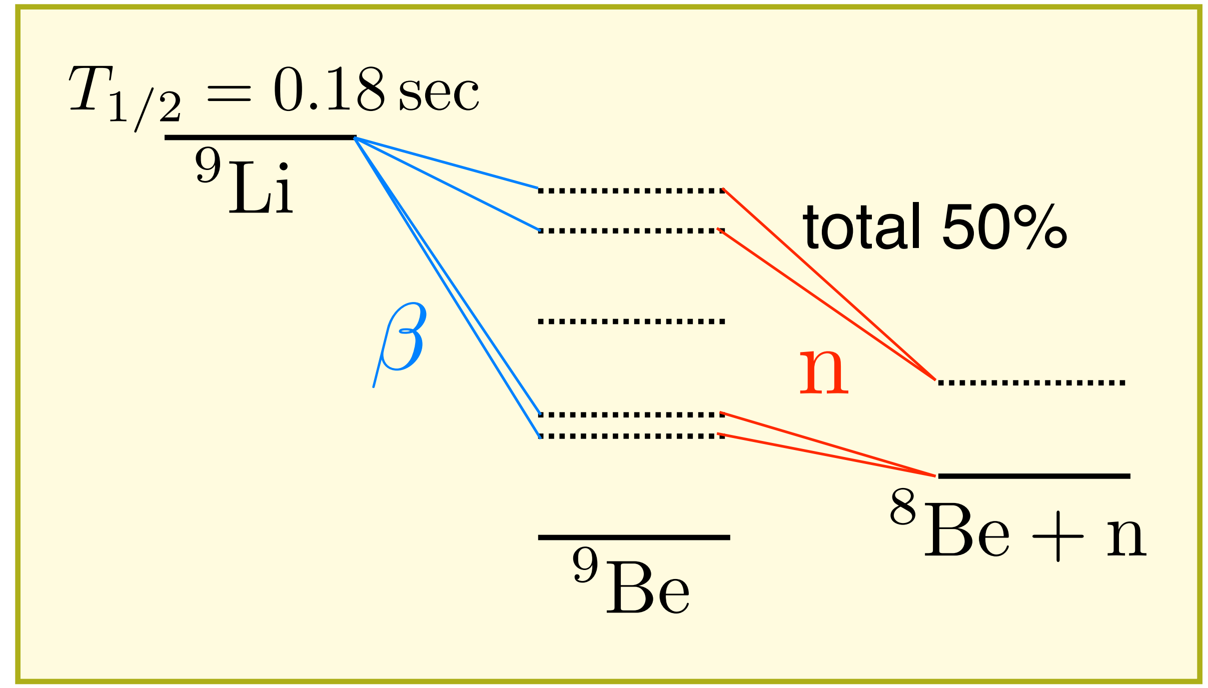
$$2.69 \pm 0.02$$

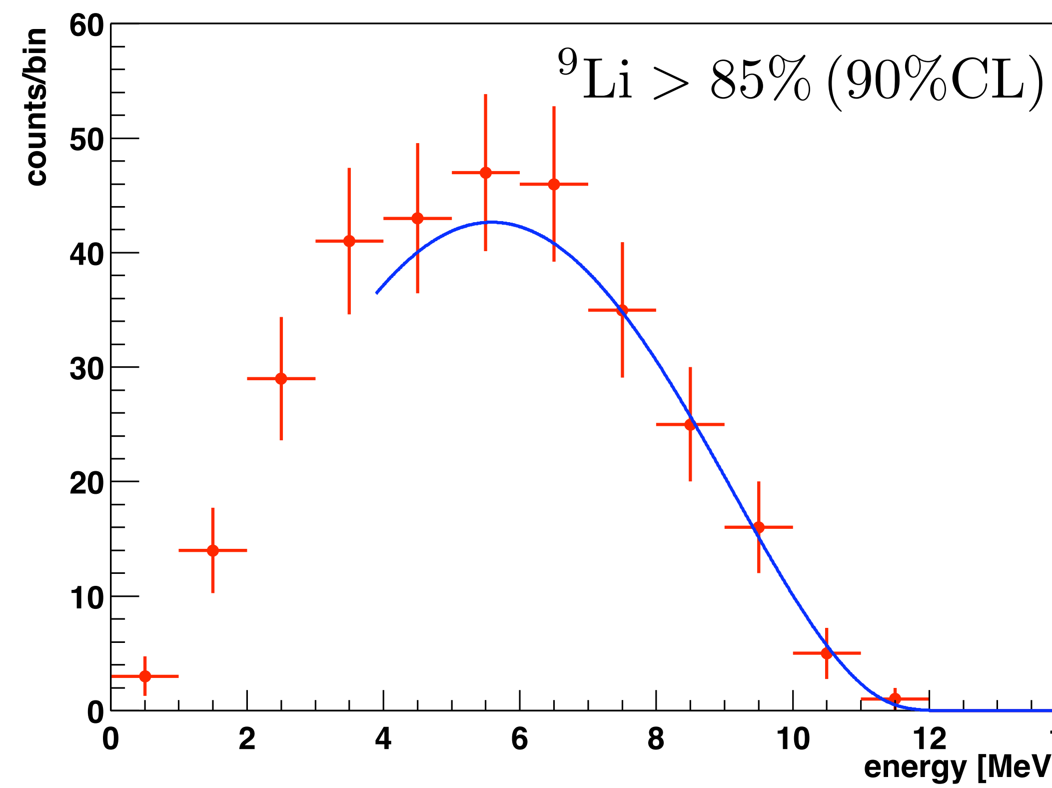
Fiducial volume is limited by accidental backgrounds.

# Spallation events



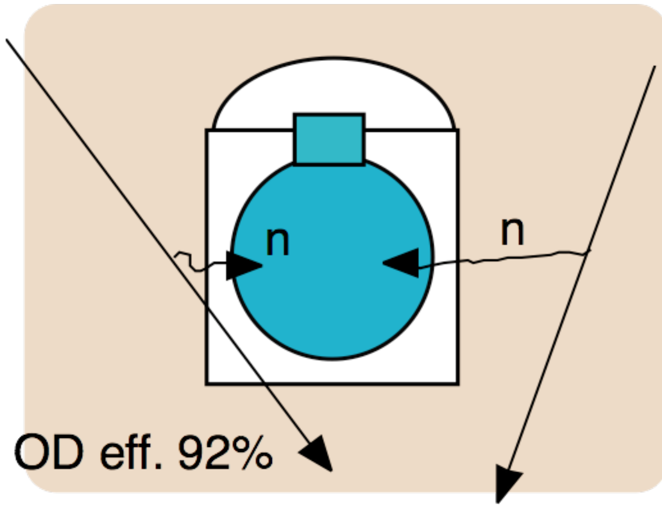




detection eff. 98.7%

$4.8 \pm 0.9$ events ($E > 2.6\,\mathrm{MeV}$)

(2nd result)

# Fast neutron

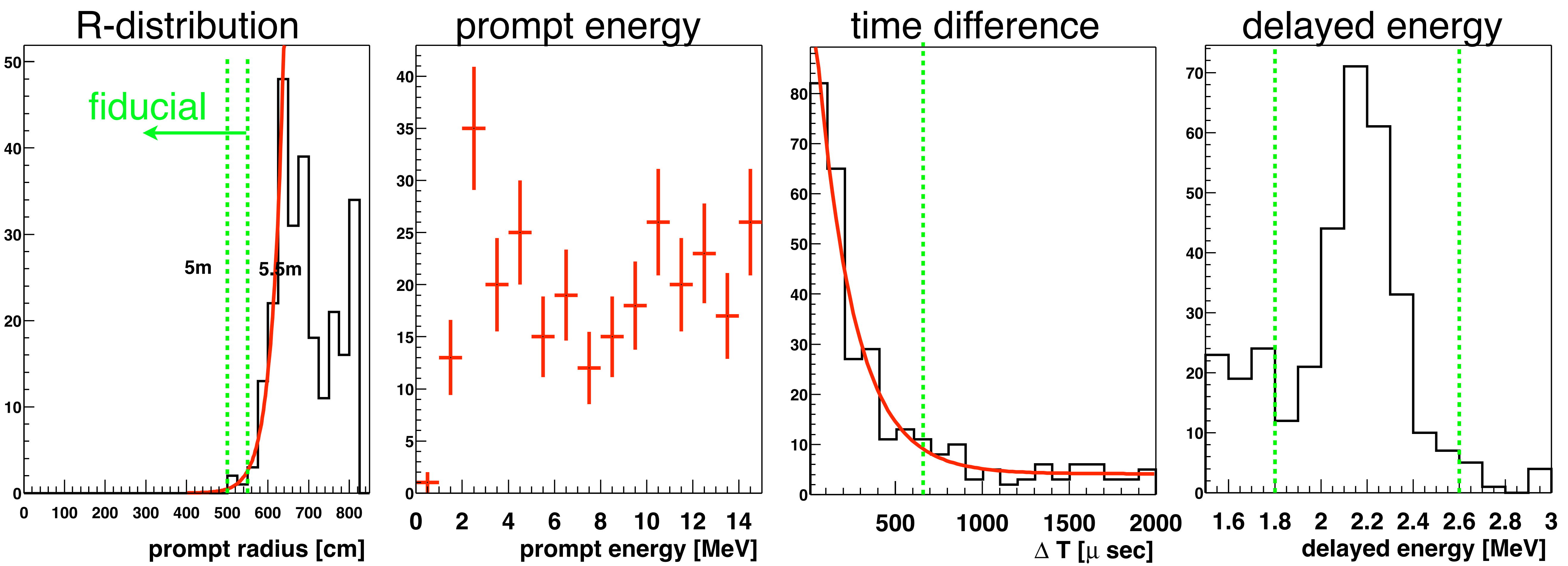



recoiled proton
+
neutron capture

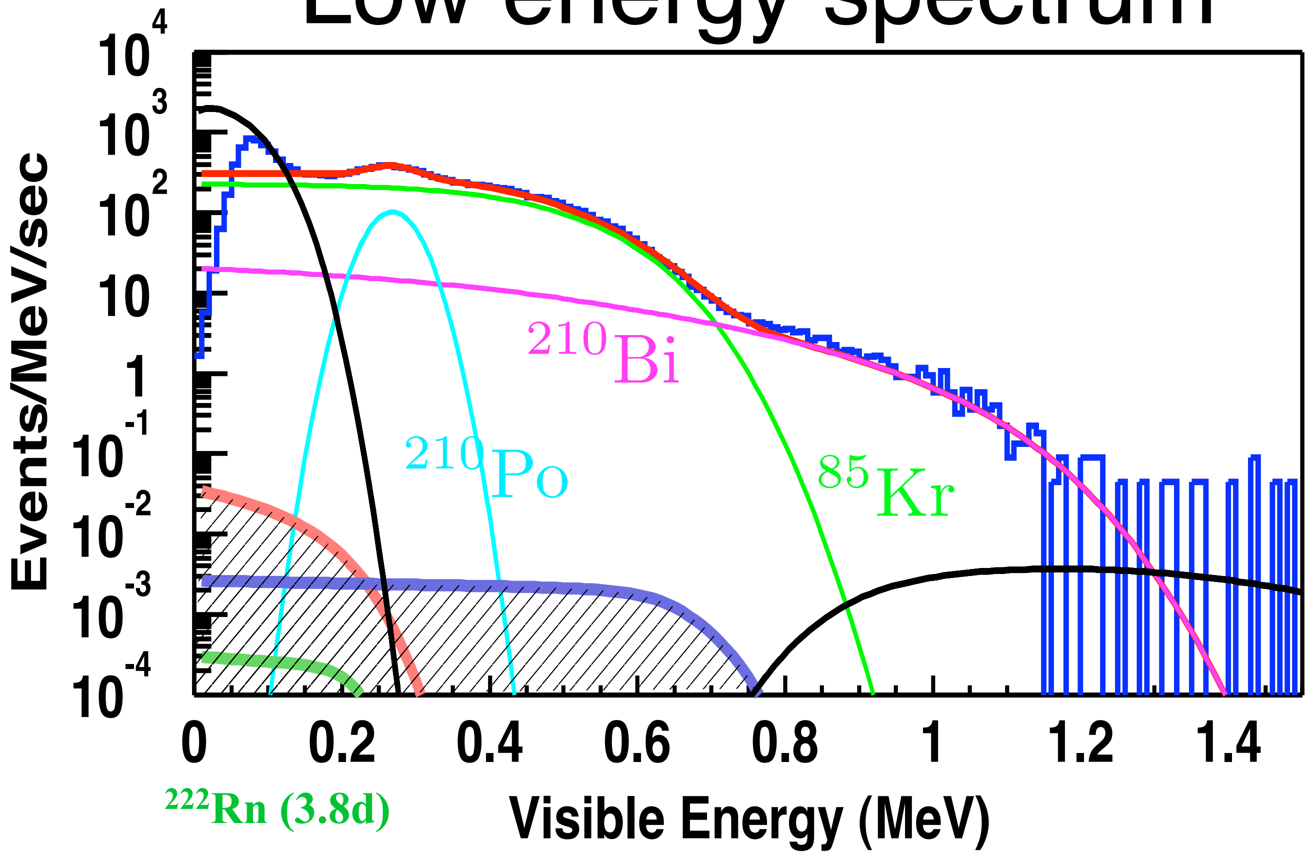
| | |
|---|---|
| OD miss-tagging | <0.4 |
| rock penetrating | <0.5 |
| Total | <0.9 |

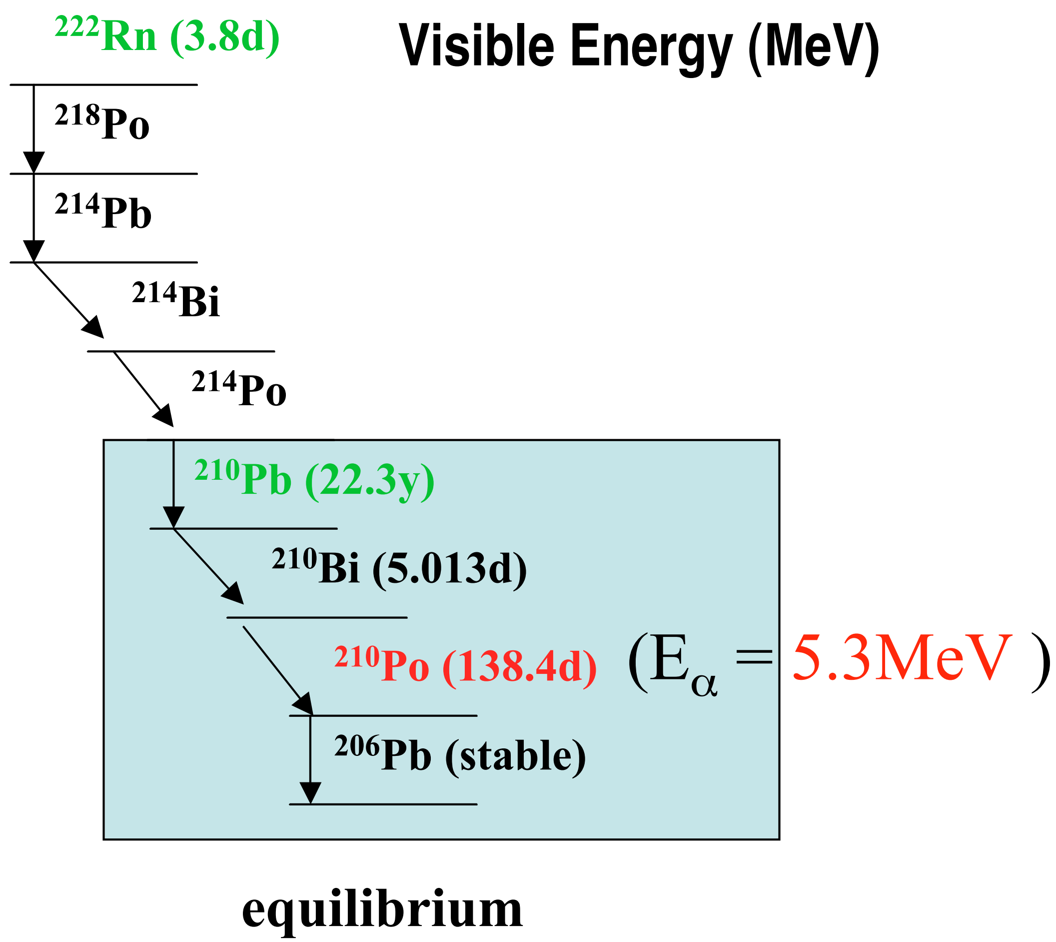
(2nd result)

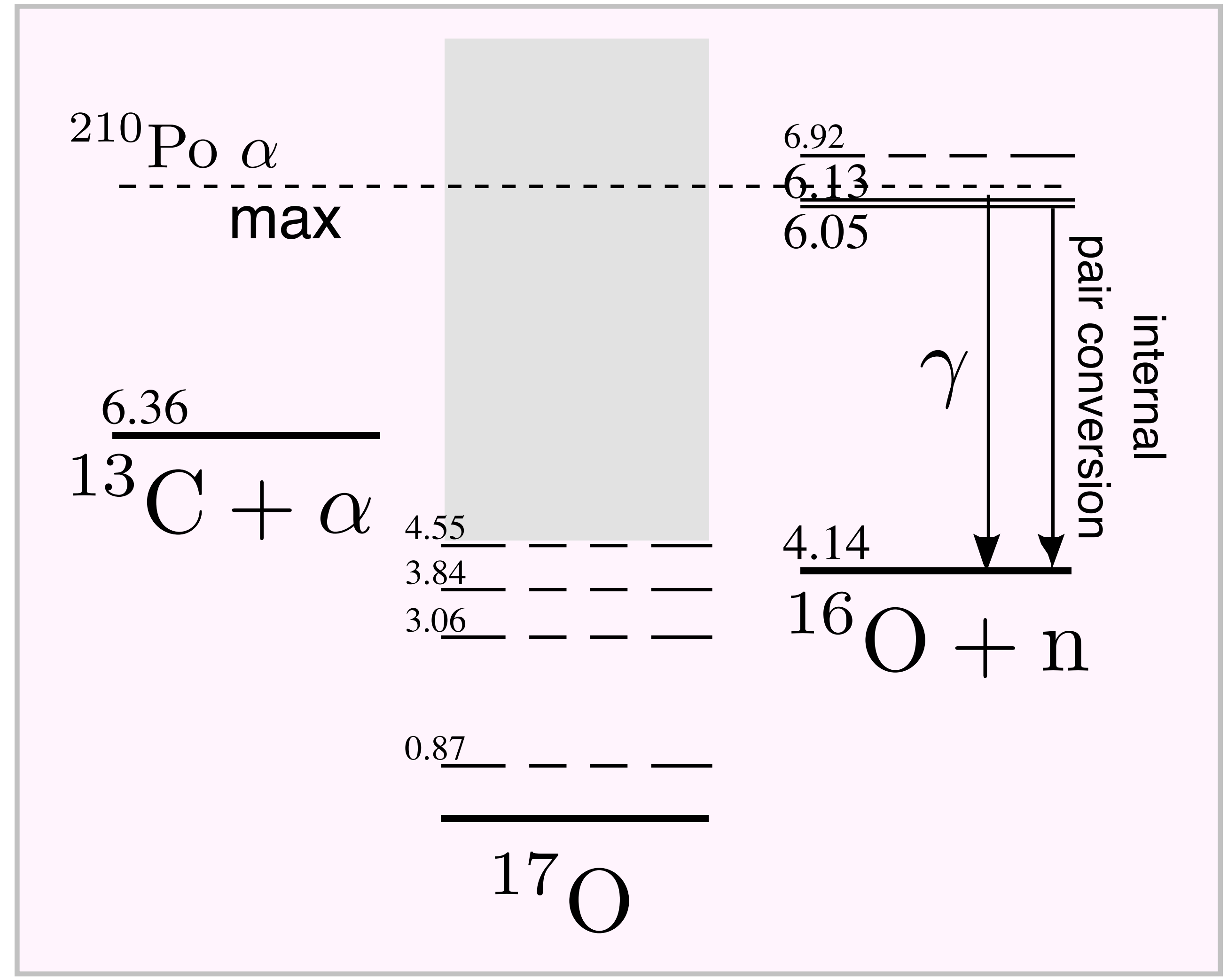
## Tagged events



# Low energy spectrum




| | |
|---|---|
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O(g.s.)}$ | low energy |
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O(g.s.)}$ $\rightarrow ^{12}\mathrm{C}(\mathrm{n},\mathrm{n}\gamma)^{12}\mathrm{C}$ | ~4.4 MeV |
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}^*(6.13)$ $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}^*(6.05)$ | ~6 MeV |

$$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O} \quad \sim 10^{-7}$$

1.1% abundance (measured)

10.3±7.1 events (E>2.6MeV)

# Background summary

515.1 days, >2.6MeV, 5.5m fiducial

| | |
|---|---|
| Accidental Coincidence | $2.69 \pm 0.02$ |
| Spallation events | $4.8 \pm 0.9$ |
| Fast neutron | $< 0.9$ |
| $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$ | $10.3 \pm 7.1$ |
| Total | $17.8 \pm 7.3$ |

# 2nd result

## Data Summary

from 9 Mar 2002 to 11 Jan 2004
515.1 live days, 766.3 ton-year exposure
×4.7 exposure (×3.55 live time, ×1.33 fiducial)

| | |
|---|---|
| expected signal | $365.2 \pm 23.7$ |
| BG | $17.8 \pm 7.3$ |
| observed | $258$ |

Neutrino disappearance at 99.998% CL.

$$R = 0.658 \pm 0.044(\text{stat}) \pm 0.047(\text{syst})$$

$$R = 0.601 \pm 0.069 \pm 0.042$$

for Mar to Oct 2002

is consistent with first results

KamLAND collaboration, hep-ex/0406035

# 1st result

## Data Summary

from March 4 to October 6, 2002
145.1 live days, 162 ton-year exposure

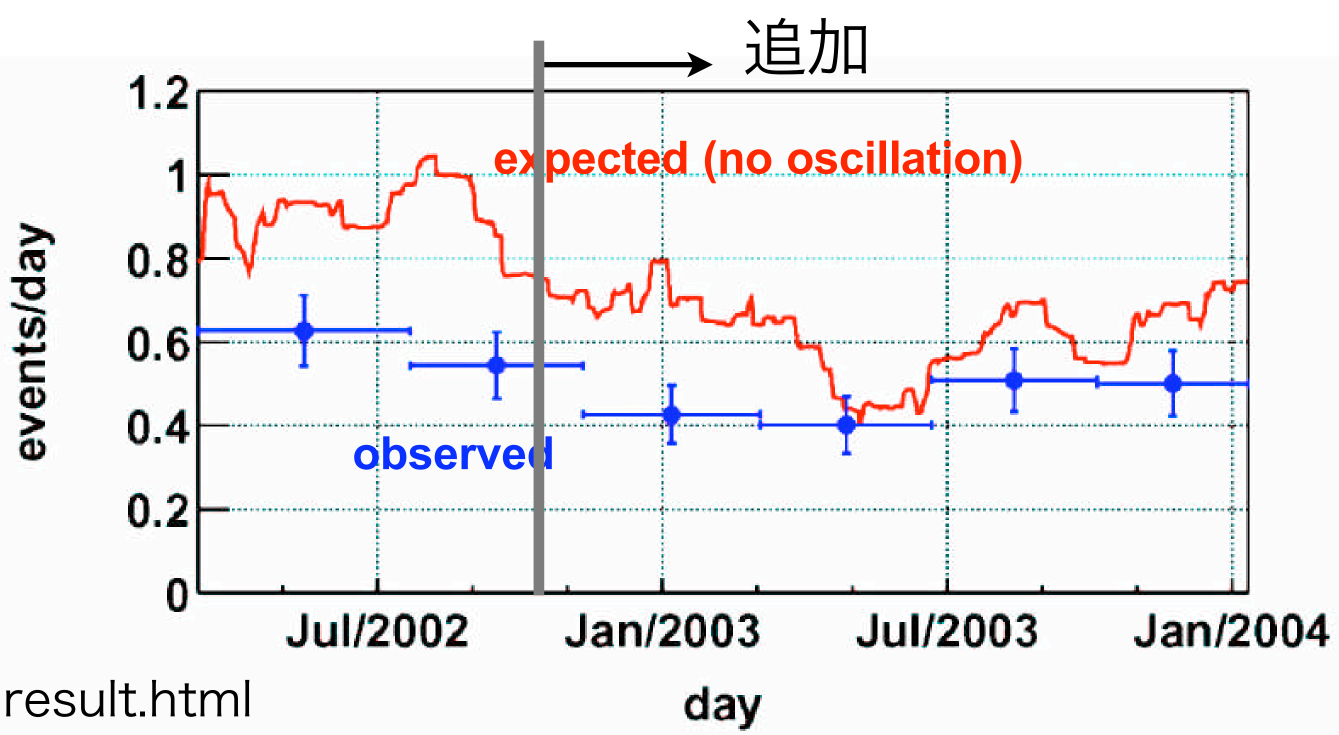
| | |
|---|---|
| expected signal | $86.8 \pm 5.6$ |
| BG | $2.8 \pm 1.7$ |
| observed | $54$ |

Neutrino disappearance at 99.95% CL.

$$R = 0.589 \pm 0.085(\text{stat}) \pm 0.042(\text{syst})$$

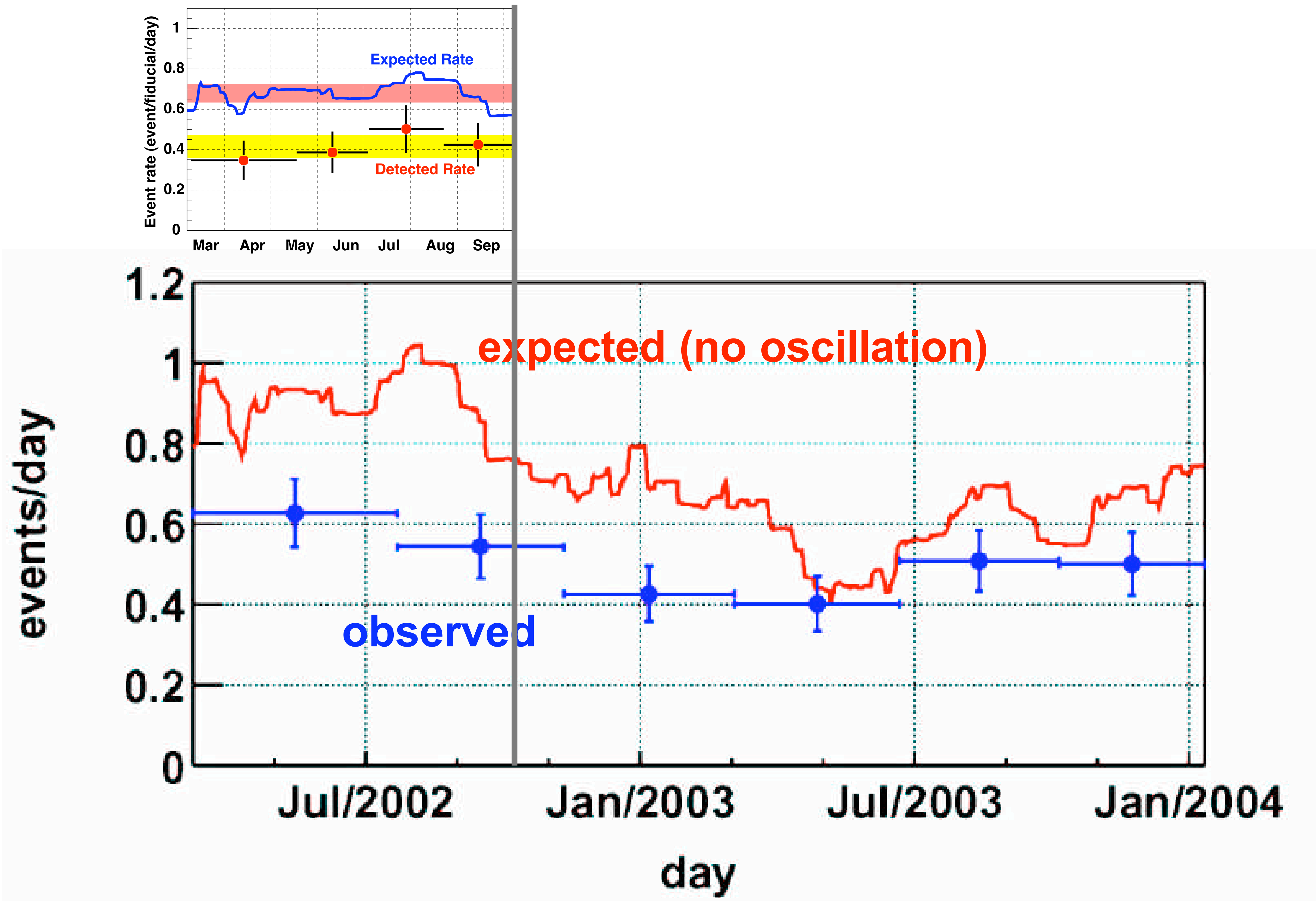
with new background correction

KamLAND collaboration, Phys.Rev.Lett.90(2003)021802

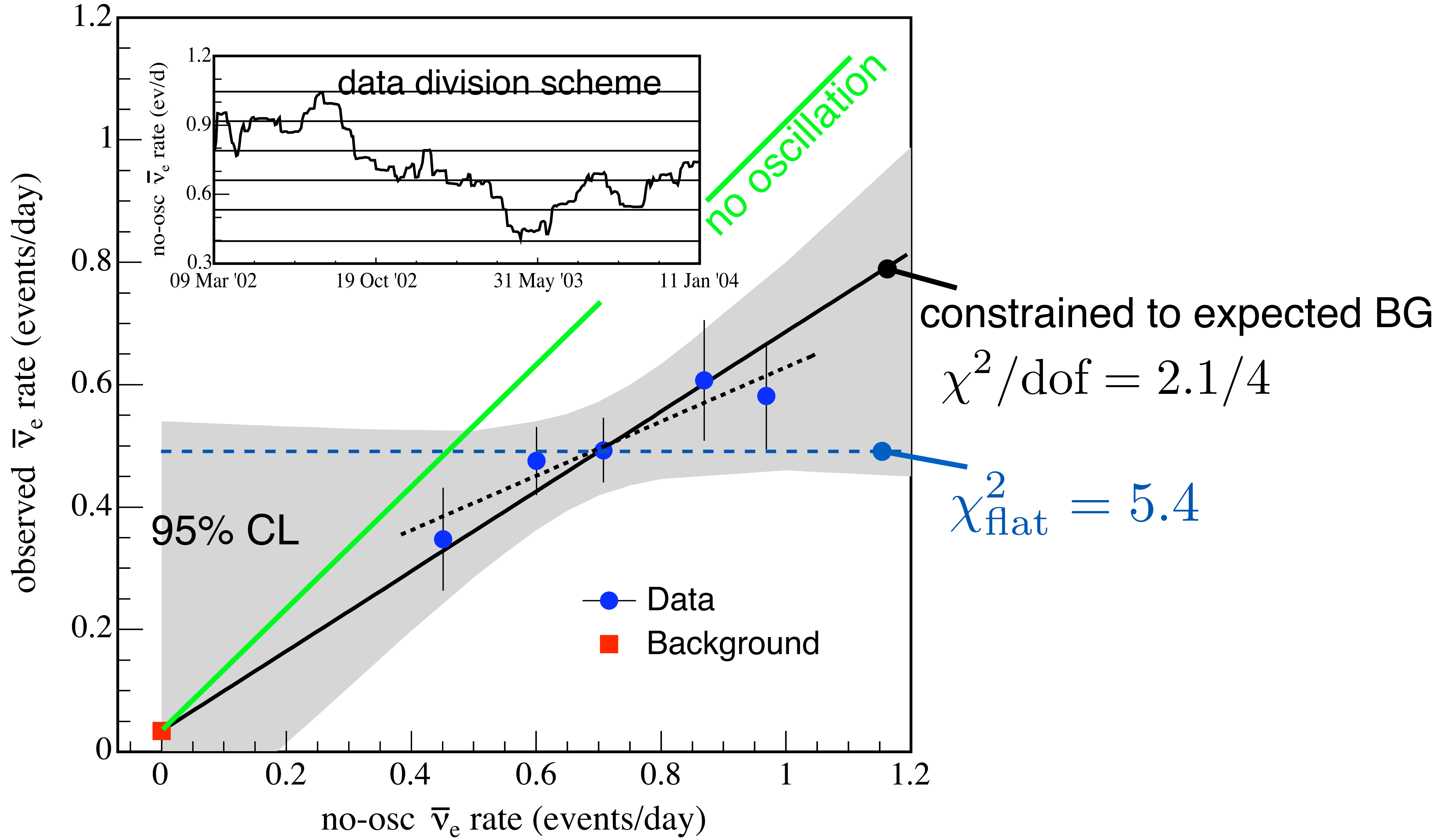



Event list and relevant numbers are available at
http://www.awa.tohoku.ac.jp/KamLAND/datarelease/2ndresult.html

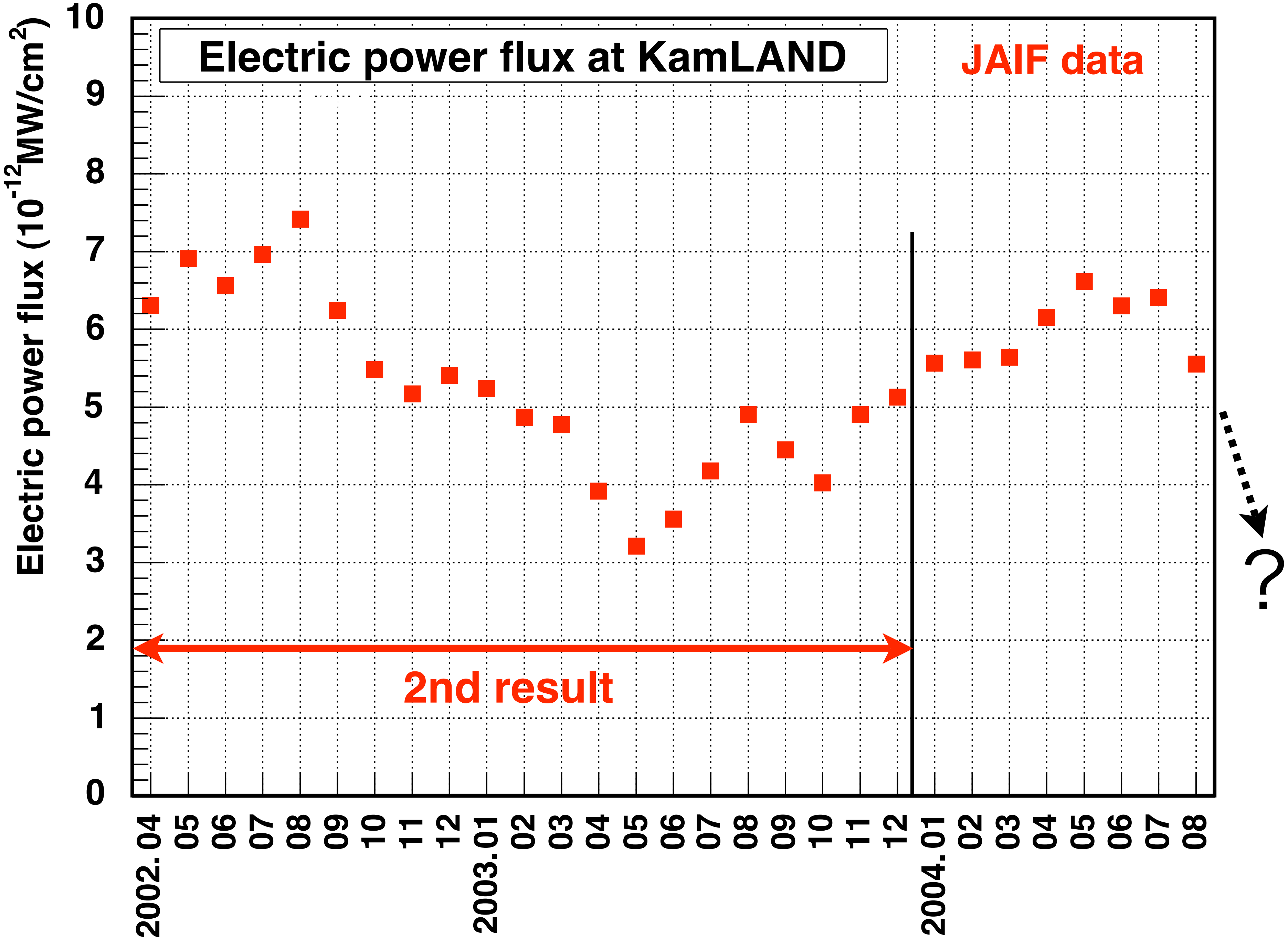
# Expected and observed time variation



# Correlation with reactor power

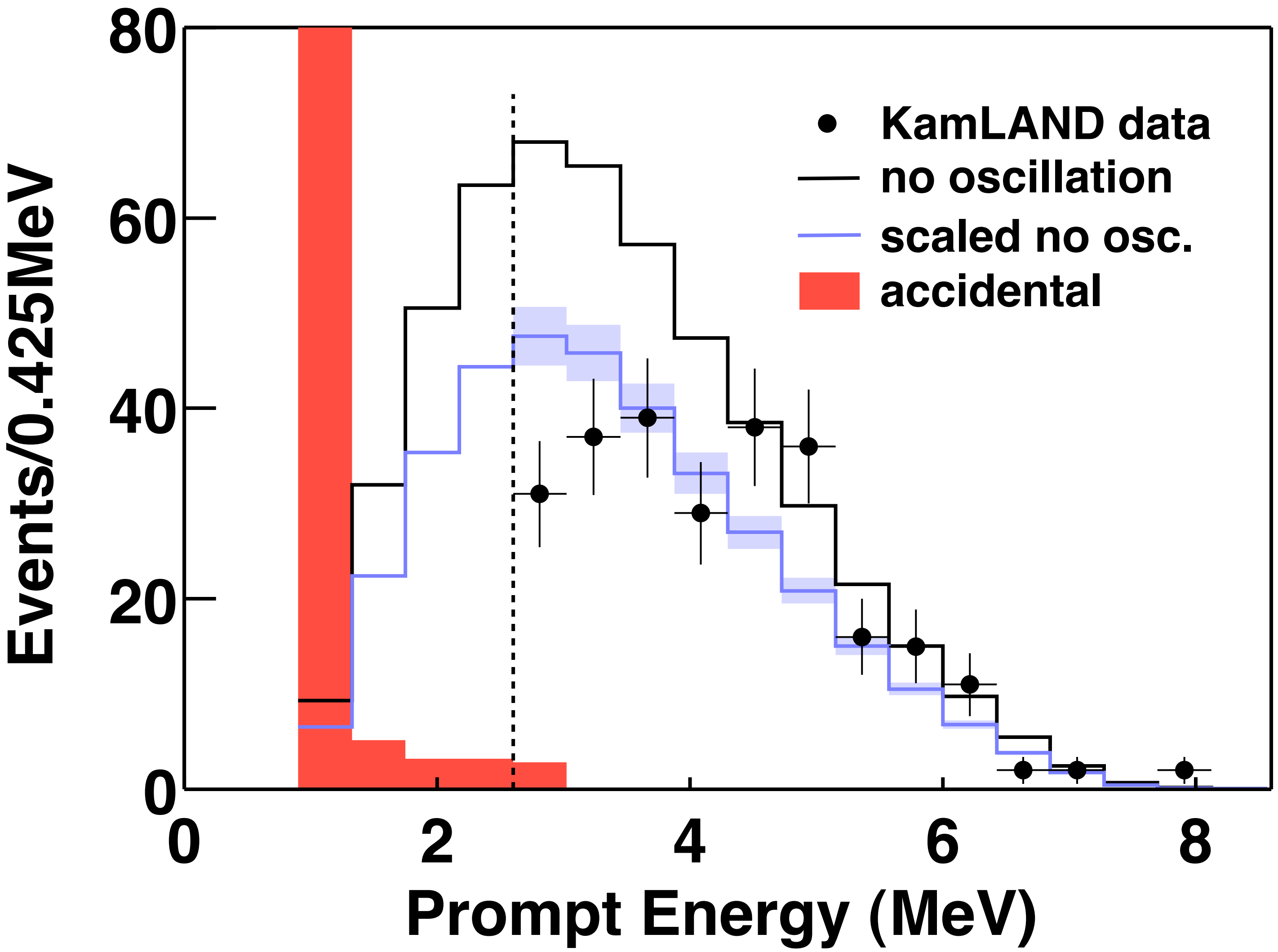


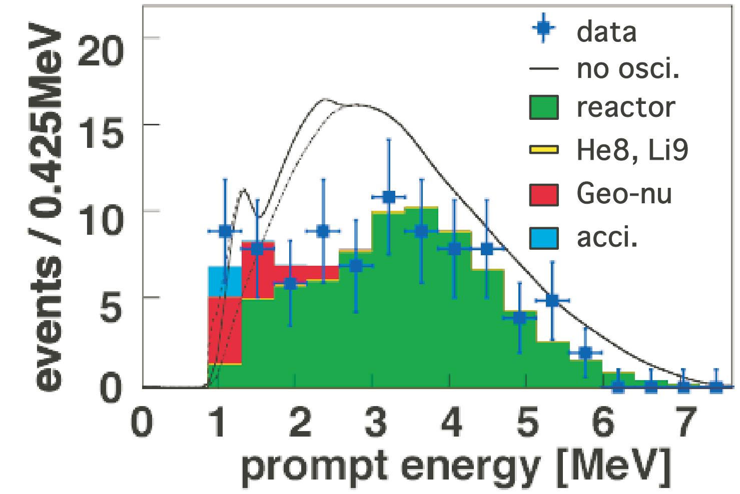

Current statistics is not enough to say definite thing.




Recent extensive inspection may provide another chance to investigate the correlation.

# Energy Spectrum

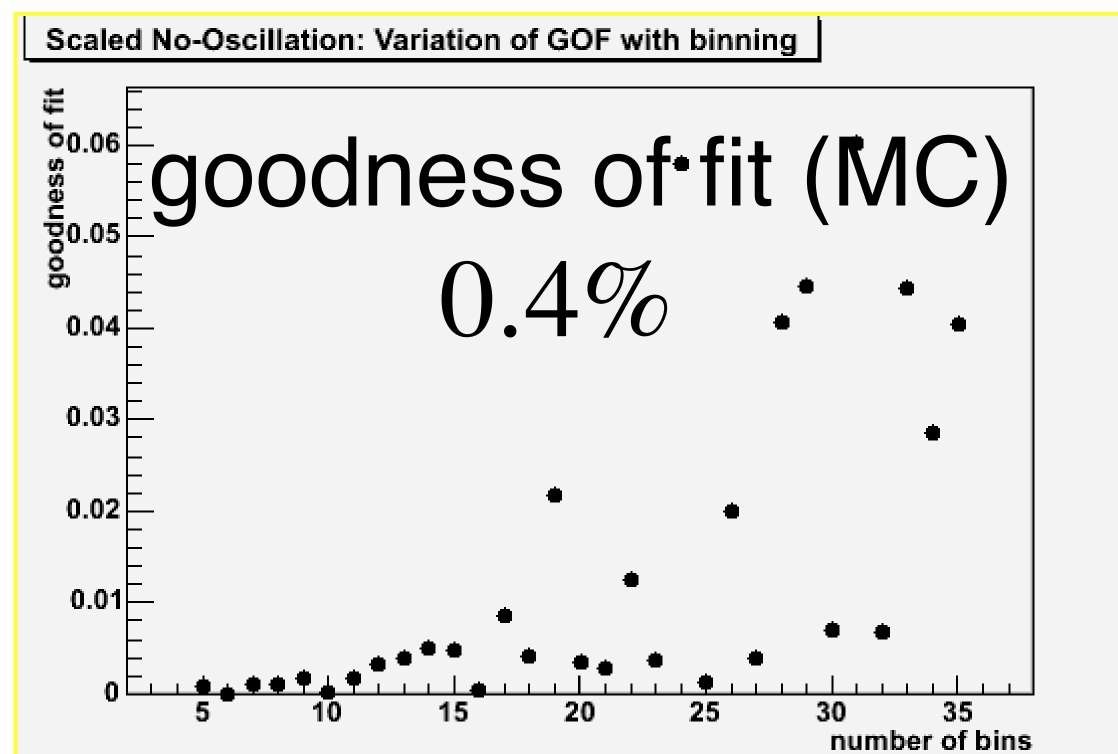



hypothesis test of scaled no oscillation

$$\chi^2/\mathrm{dof} = 37.3/19$$

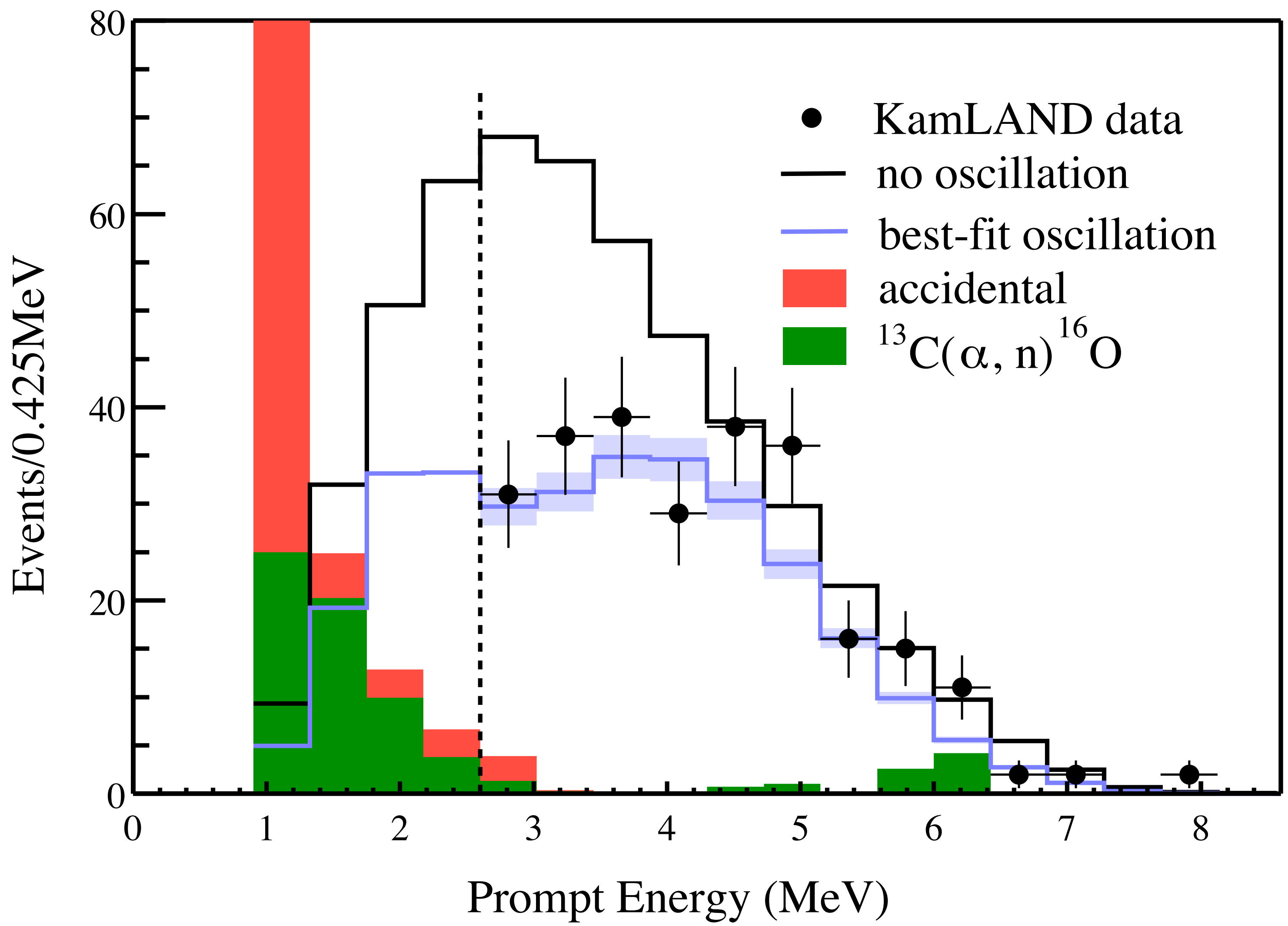
for 20 equal probability bins




spectral distortion at >99.6% CL

rate + shape 99.999995% CL

| Model | Best fit parameters (by unbin-likelihood method) | $\chi^2/\mathrm{dof}$ (equal probability 20 bins) | GOF (MC based) |
|---|---|---|---|
| oscillation | $(\sin^2 2\theta, \Delta m^2) = (0.86, 7.9\times10^{-5}\,\mathrm{eV}^2)$ | $24.2/17$ | $11.1\%$ |
| decay | $(\sin^2\theta, m_2/c\tau) = (1.0,\ 0.011\,\mathrm{MeV/km})$ | $35.8/17$ | $0.7\%$ |
| decoherence | $(\sin^2 2\theta, \gamma) = (1.0,\ 0.030\,\mathrm{MeV/km})$ | $32.2/17$ | $1.8\%$ |



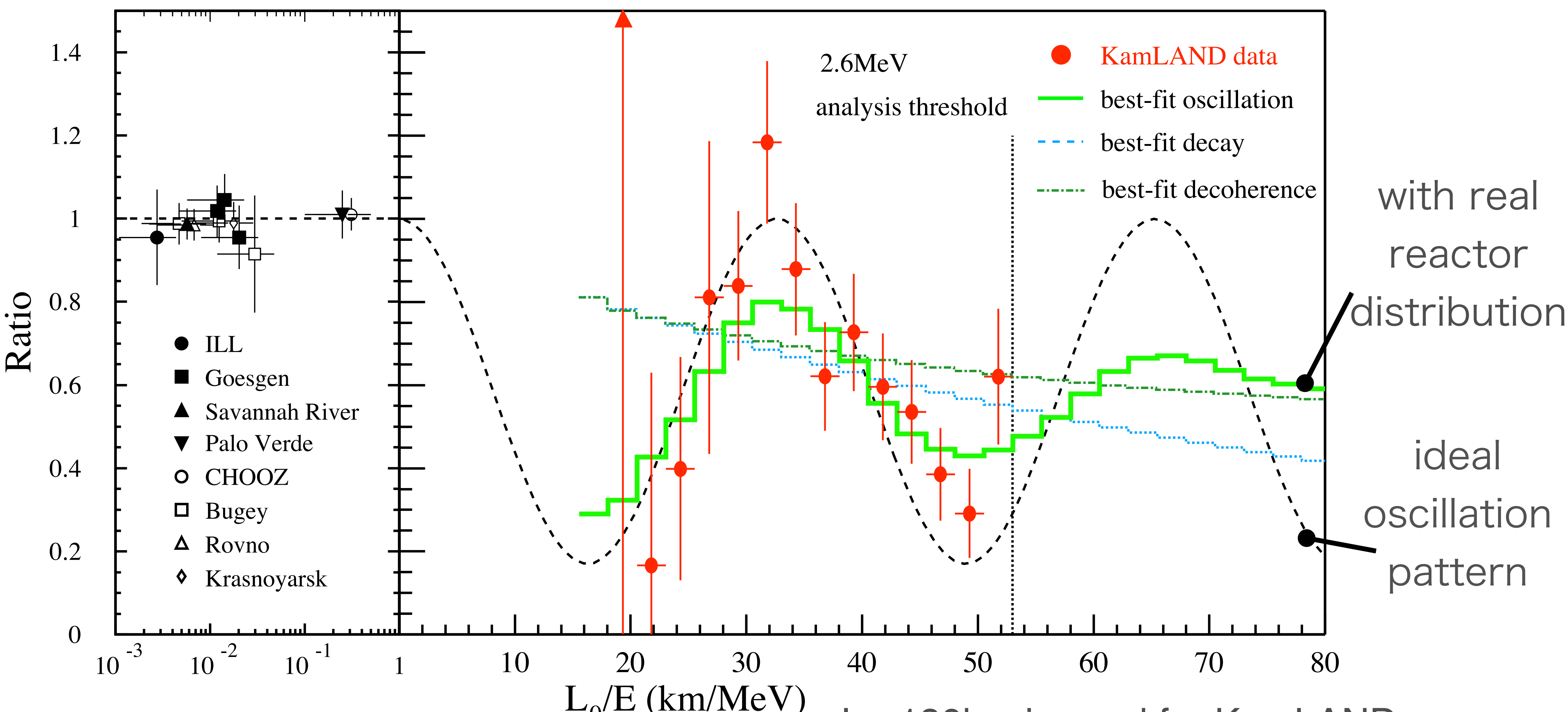

Significant spectral distortion supports neutrino oscillation.

# Clear oscillation pattern has been seen.

oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$

decay $P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$

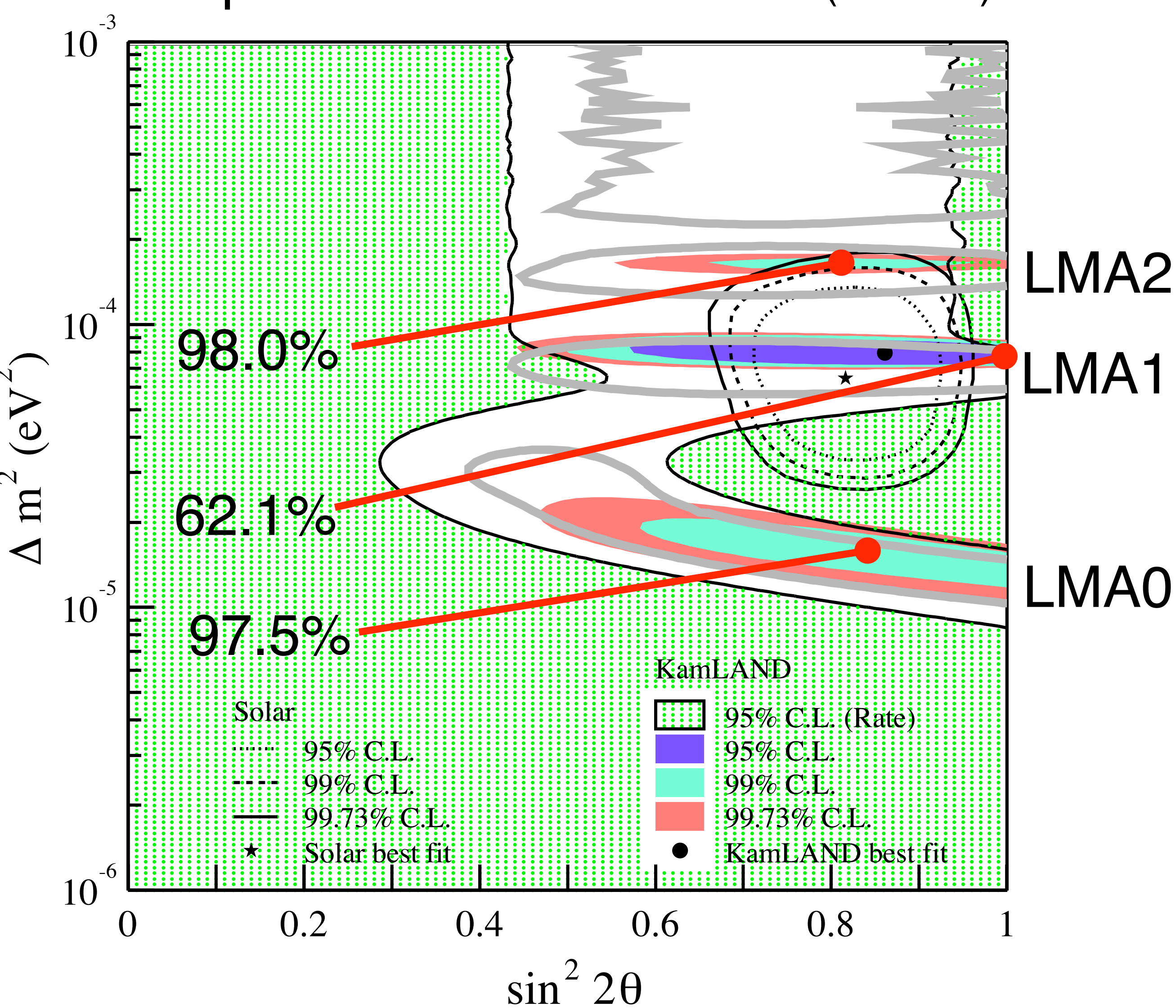
decoherence $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$



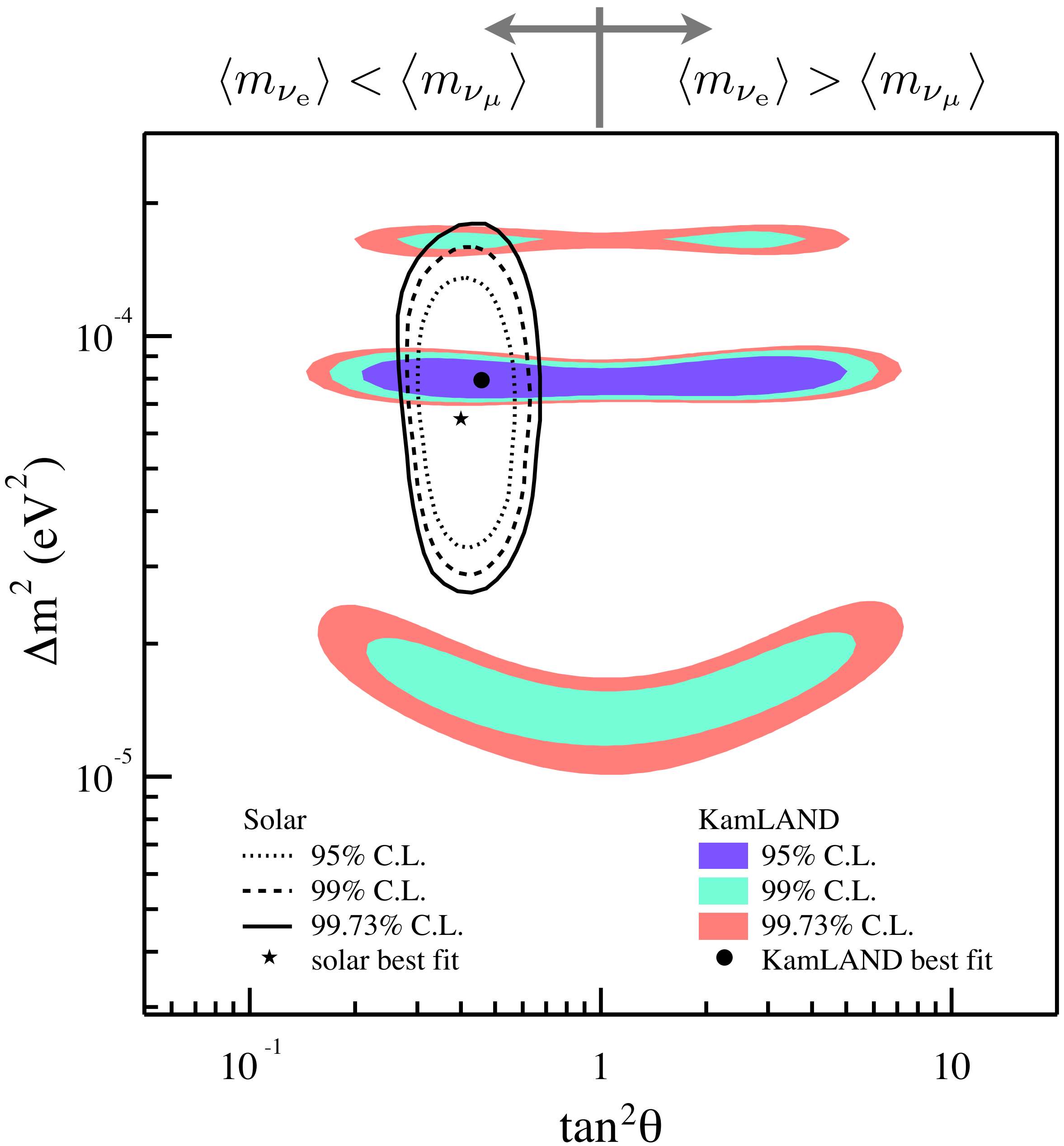

$L_0$=180km is used for KamLAND

# Measurement of neutrino oscillation parameters

comparison with 1st results (95%CL)



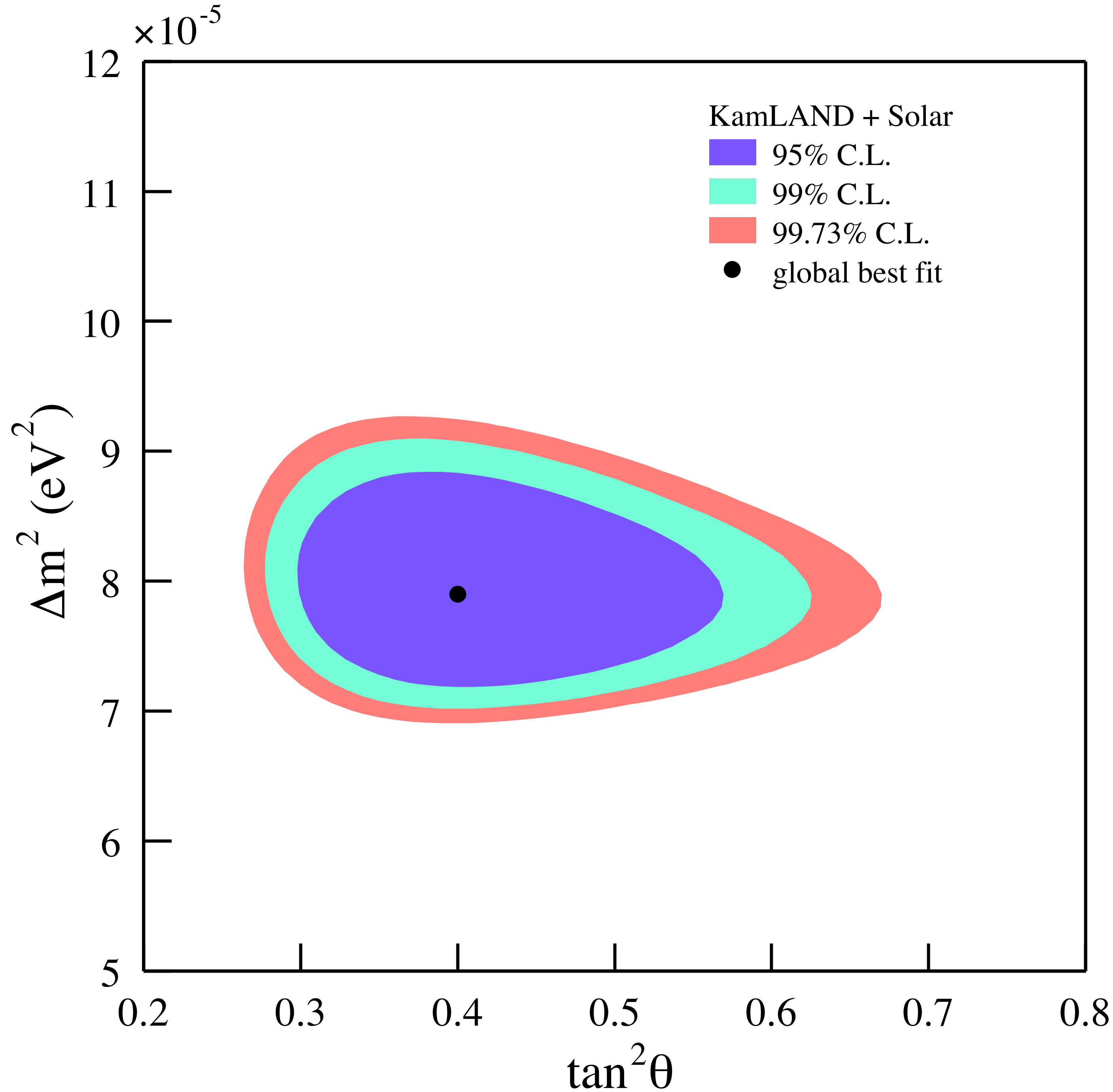

matter effect makes small difference




best fit rate+shape $(\tan^2\theta, \Delta m^2) = (0.46,\ 7.9 \times 10^{-5}\,\mathrm{eV}^2)$

best fit shape-only $(\tan^2\theta, \Delta m^2) = (0.76,\ 8.0 \times 10^{-5}\,\mathrm{eV}^2)$

Assuming CPT invariance




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

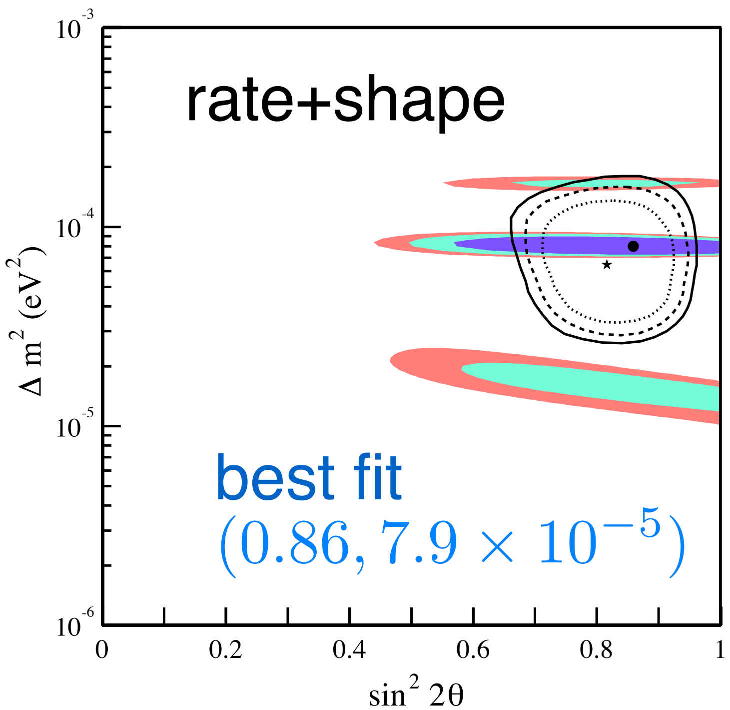
several orders ->

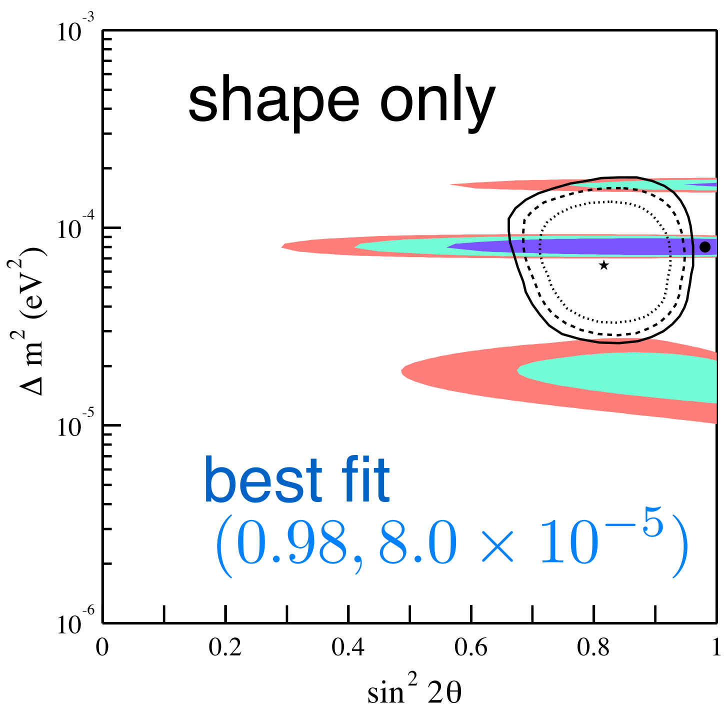
less than 10%

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

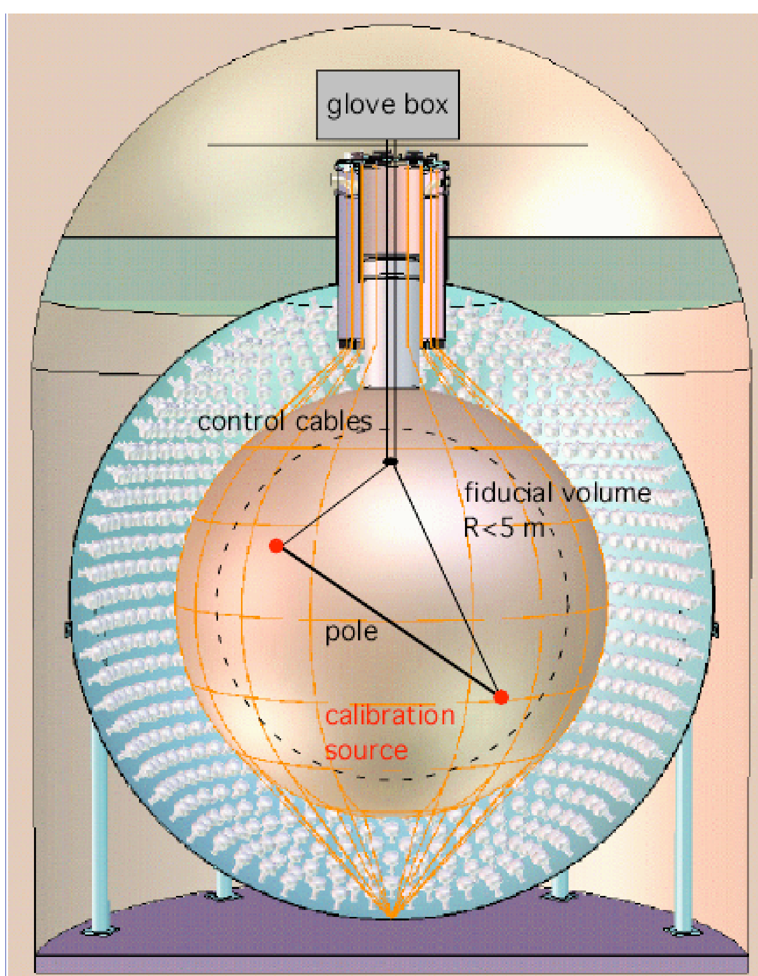
Precise determination of oscillation parameters made possible to use neutrinos as a new probe.

# Further improvement of systematic errors

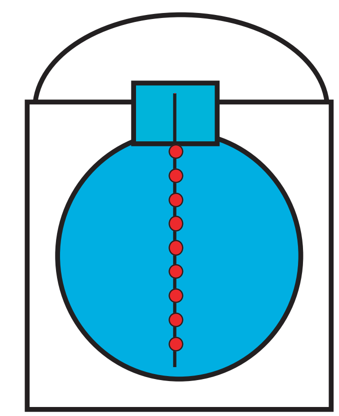



Rate information doesn't have a strong impact on the precision due to large systematic errors.

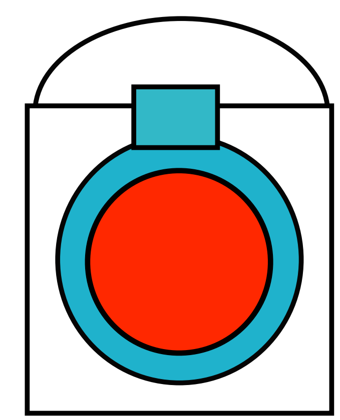



z-axis calibration



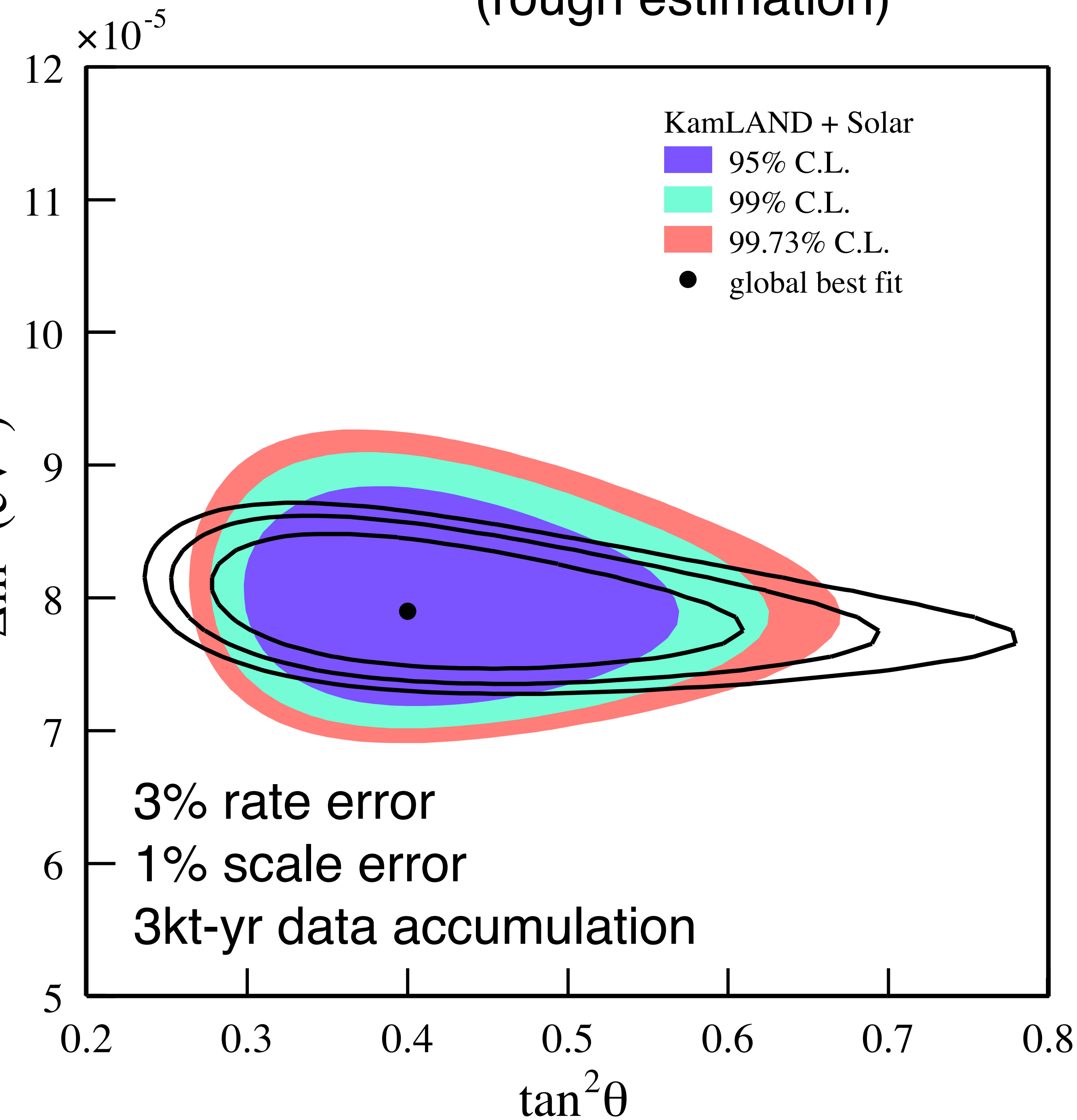
↓

full volume calibration



# KamLAND only rate+shape sensitivity

(rough estimation)




factor ~2 improvement?

capability to reject full mixing

mixing angle determination comparable with current solar data

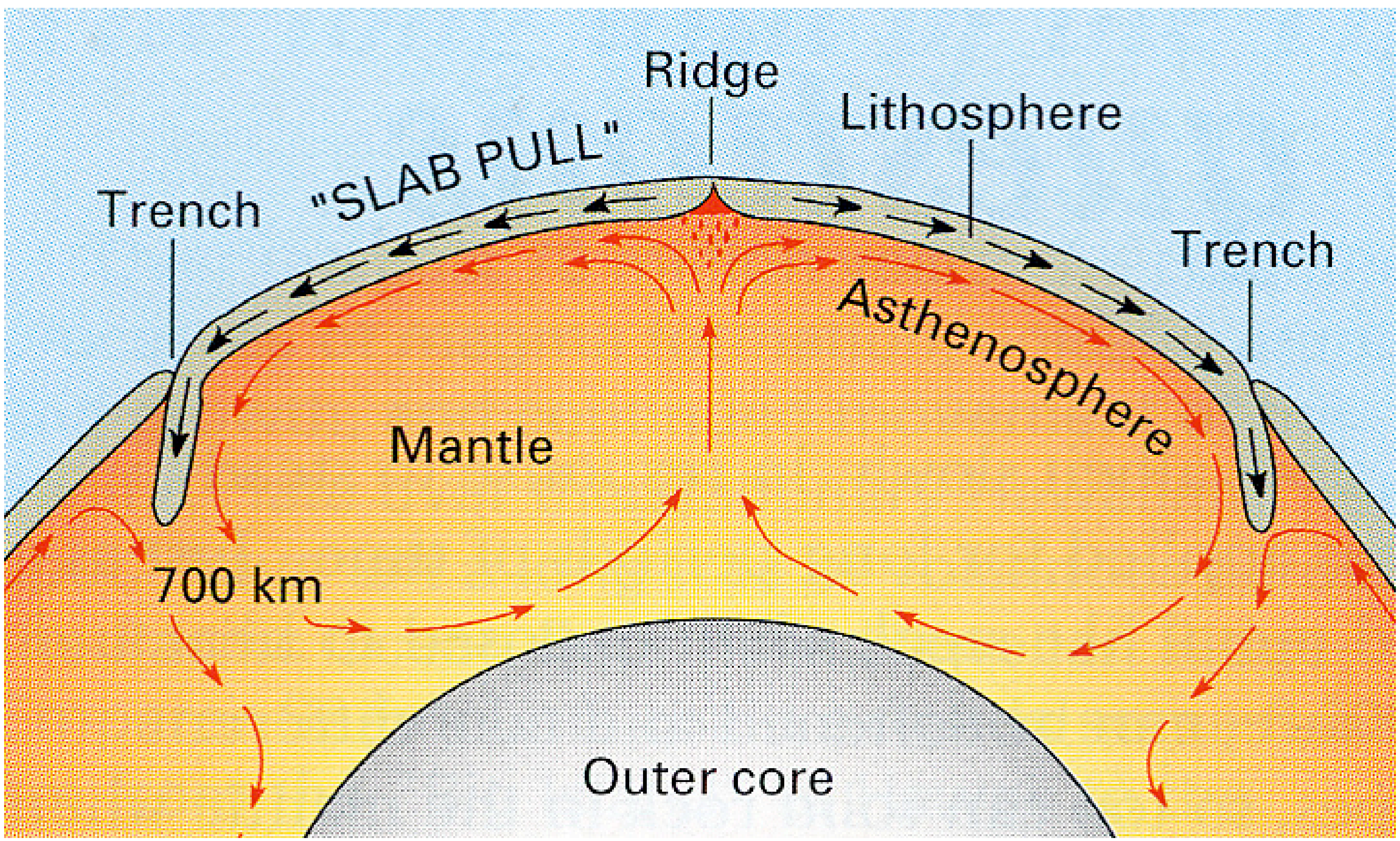
# Geo-neutrino Observation

(No public data yet, sorry)

## Important motivations

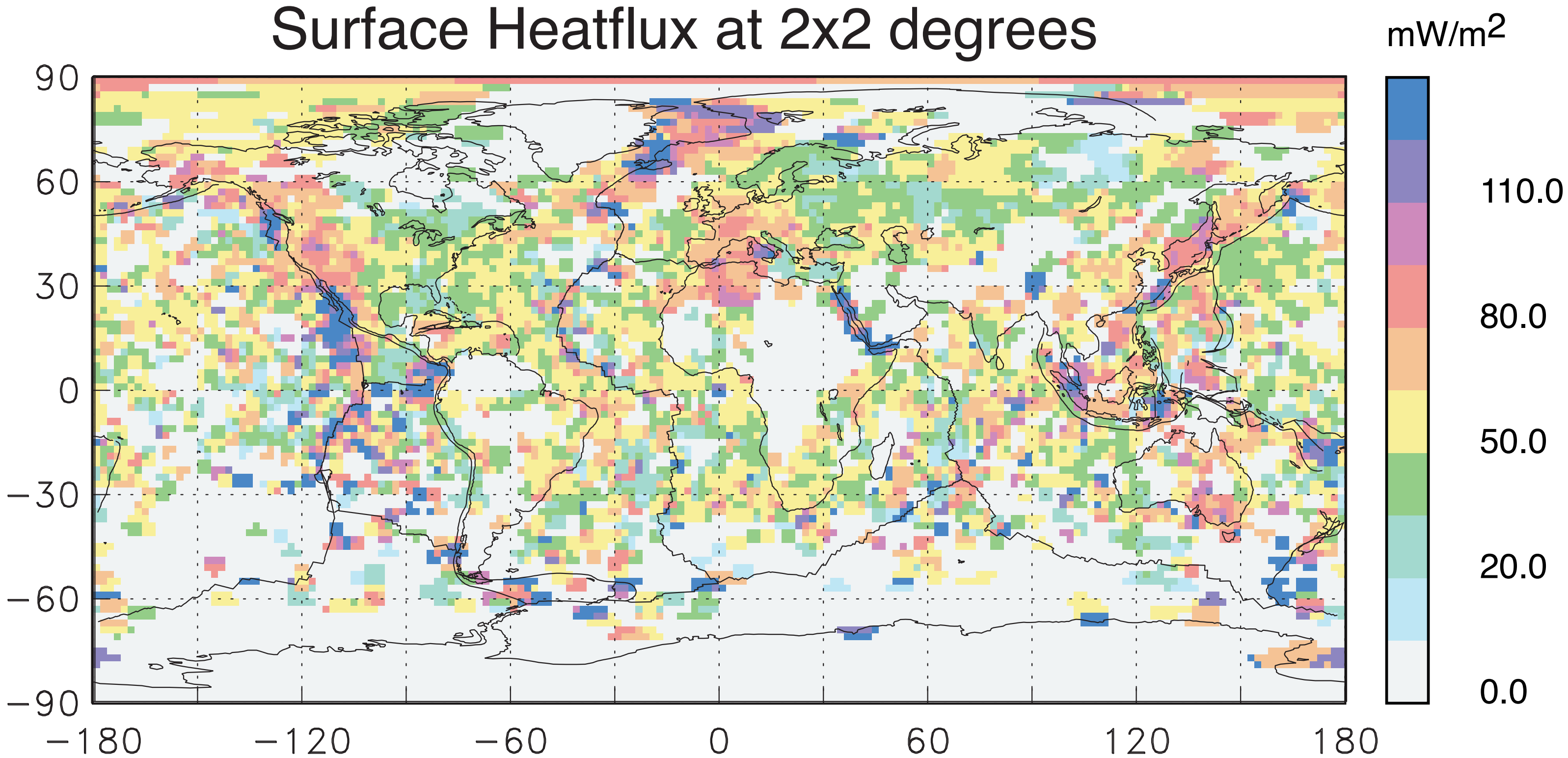
(1) What is the heat source that drives earth dynamics?

(2) Is there another way to observe the interior directly?



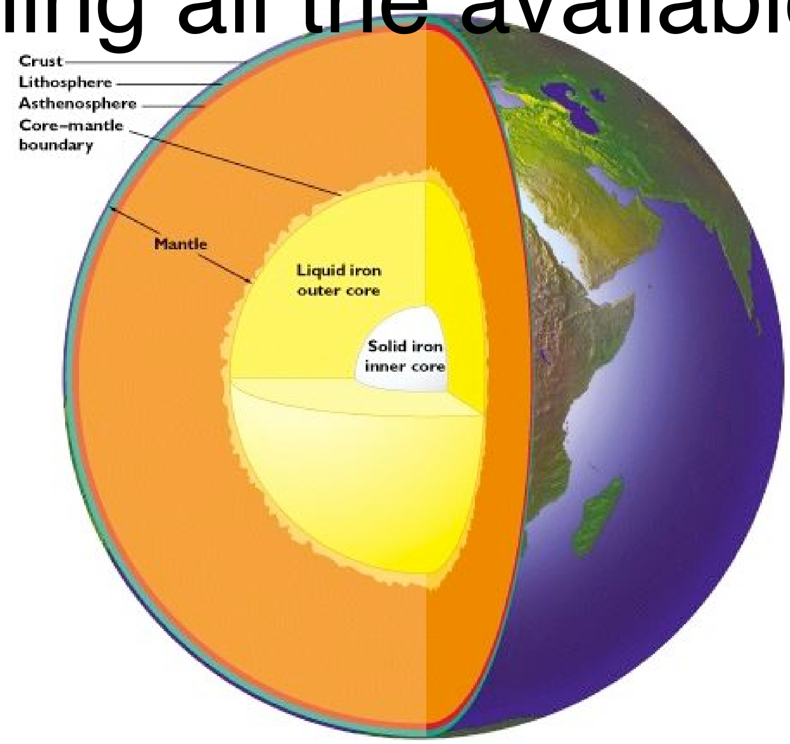
# (1) What is the heat source?

## Surface heat flow measurement




Total flow 44 TW is 40 times of world total reactor power.

## Combining all the available geo-chemical knowledge,




## Radioactivity 20 TW

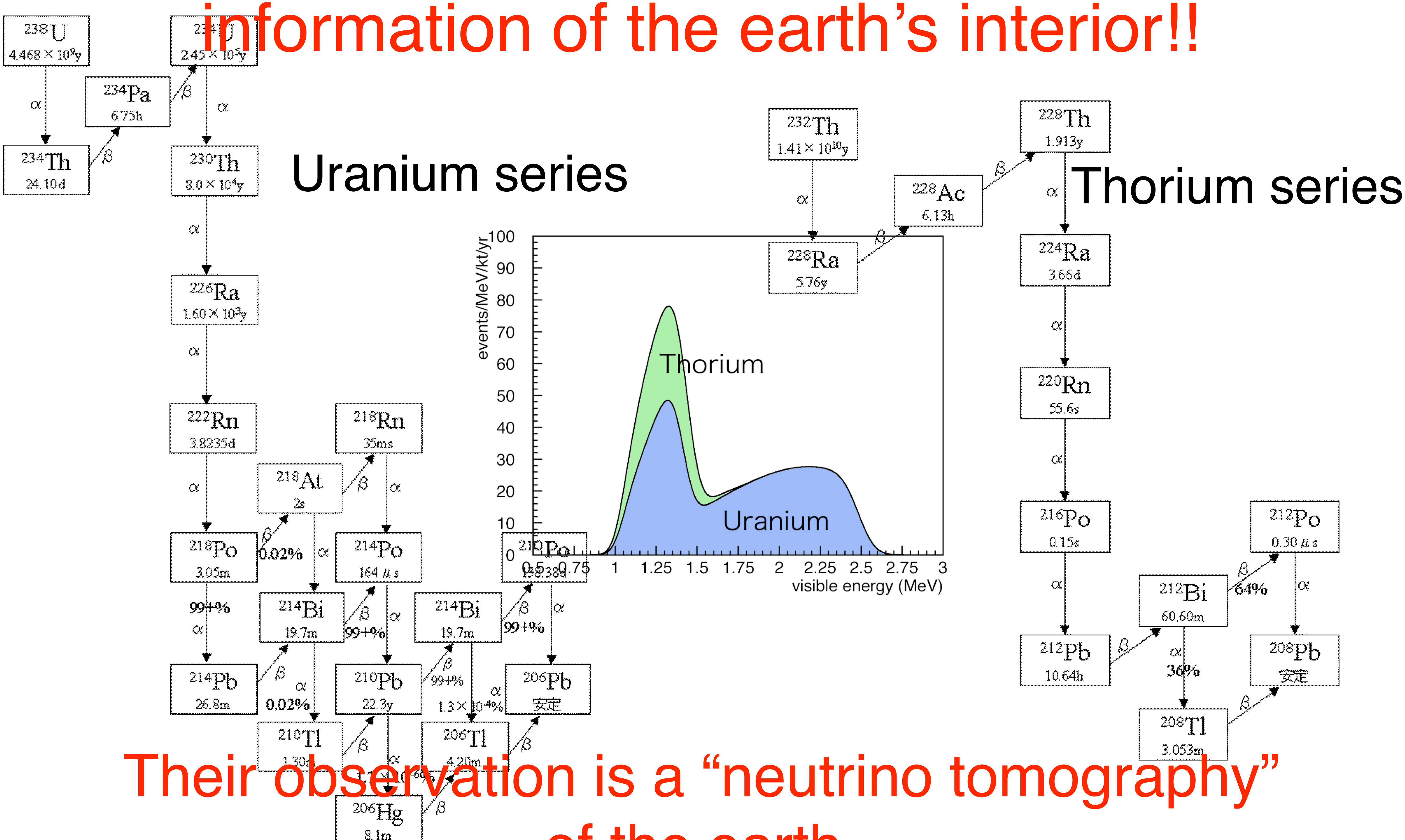
Uranium 8TW, Thorium 8TW, Potassium 4TW

## The rests are

residual heat, latent heat, gravitational energy etc.

U,Th are condensed in the crust and the earth is something like wrapped in a heat blanket.

# Neutrinos from radioactivity provide direct information of the earth’s interior!!




# Their observation is a “neutrino tomography” of the earth.

# Toward $^7$Be Solar Neutrino Observation

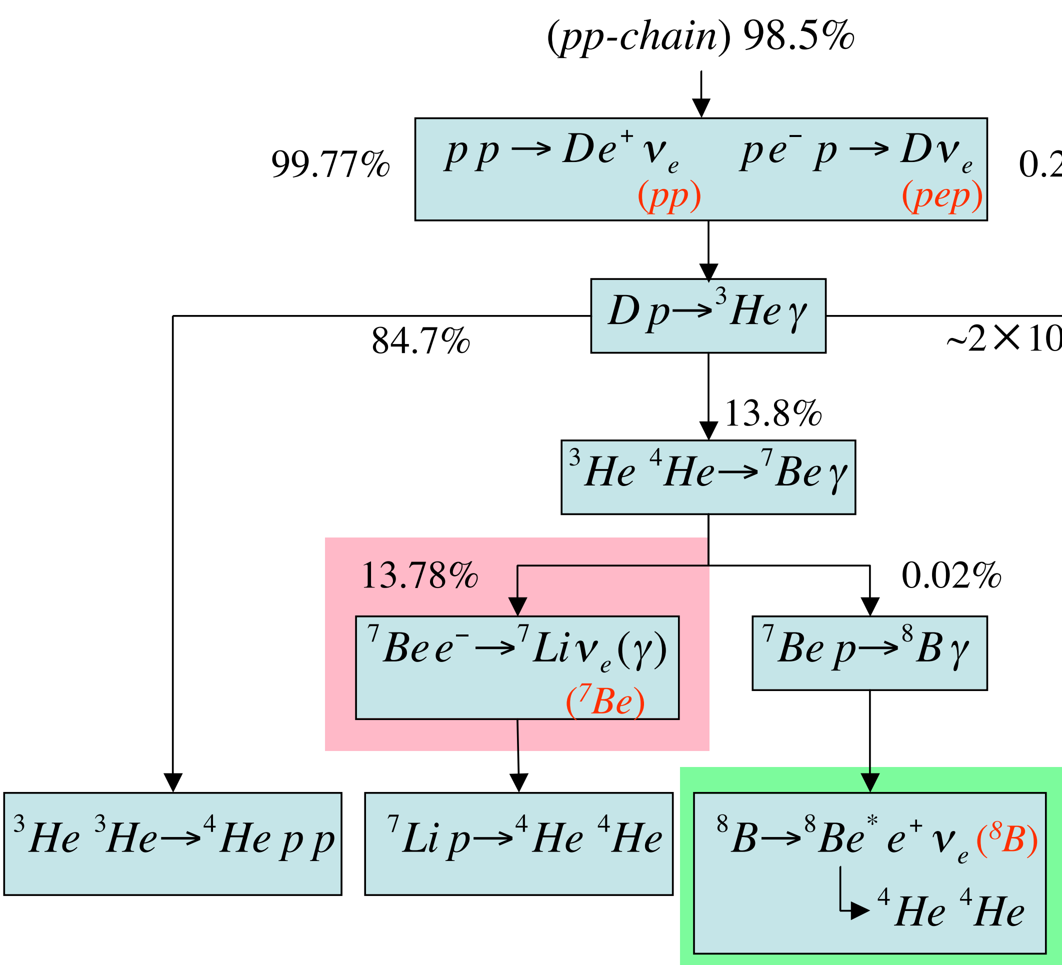
Verification of the SSM with more abundant neutrinos is important.

Real time measurement of low energy solar neutrinos has never been done

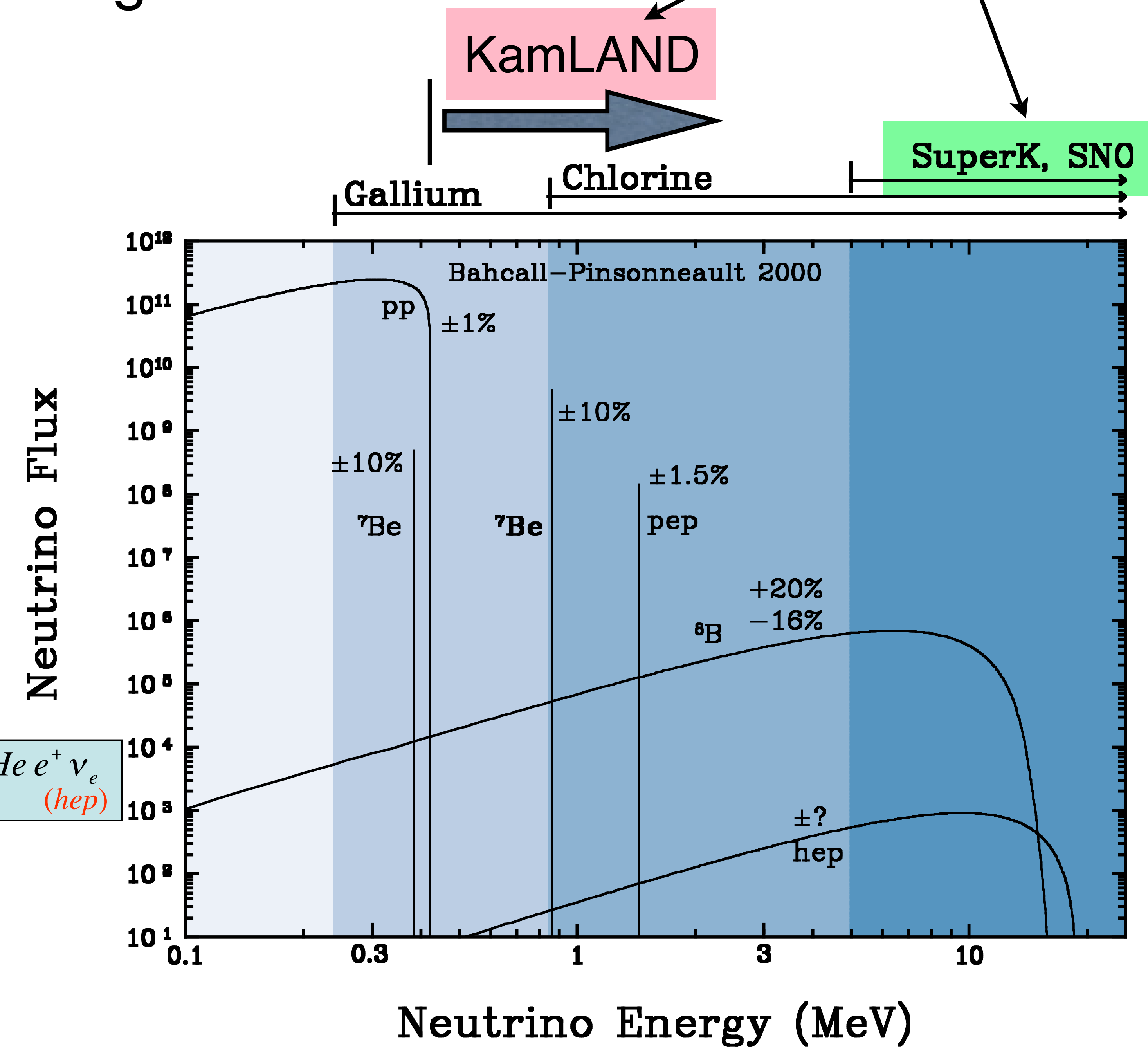
It may help improving oscillation parameter measurement.

It has good sensitivity on neutrino magnetic moment.

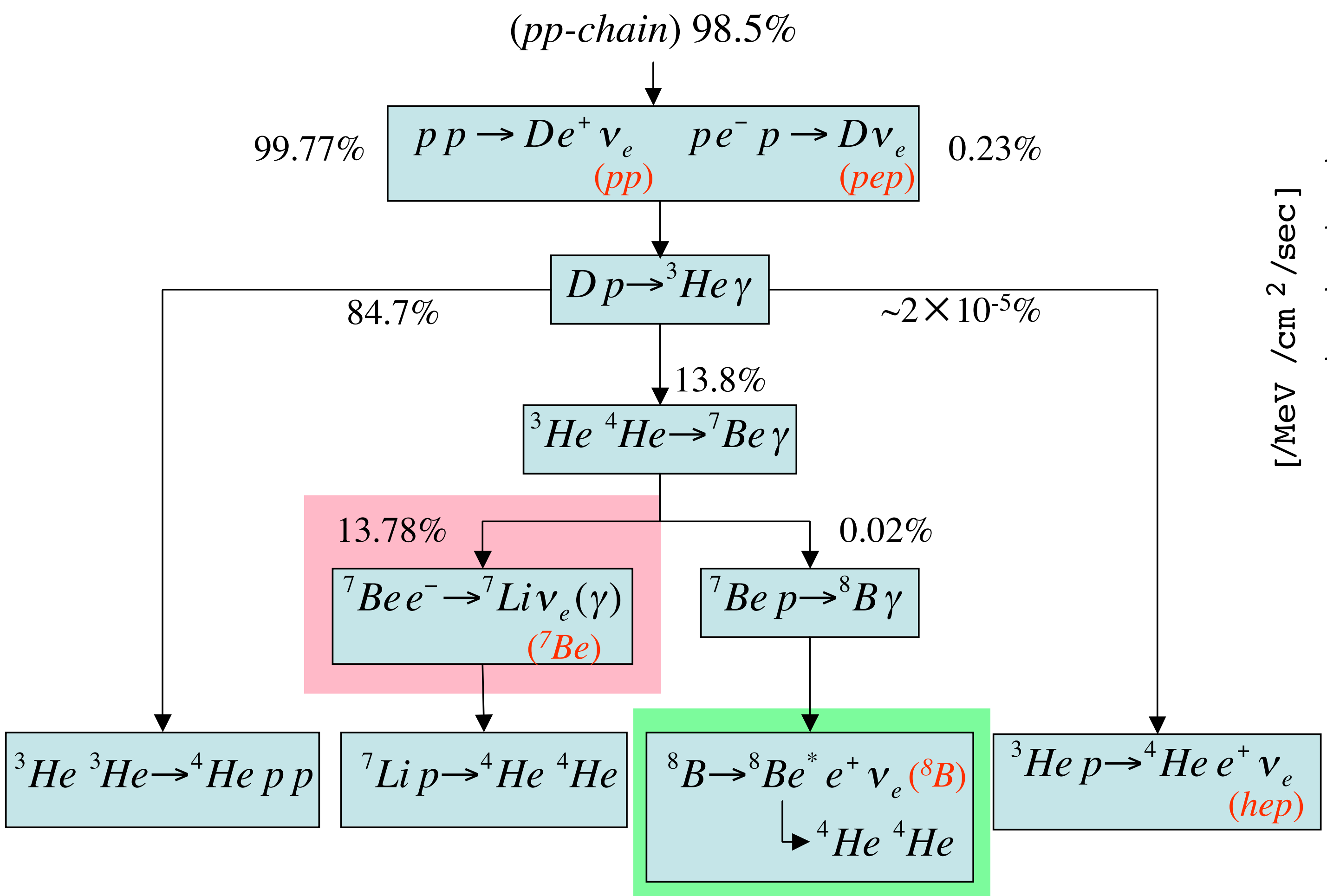
Fusion reaction in the Sun



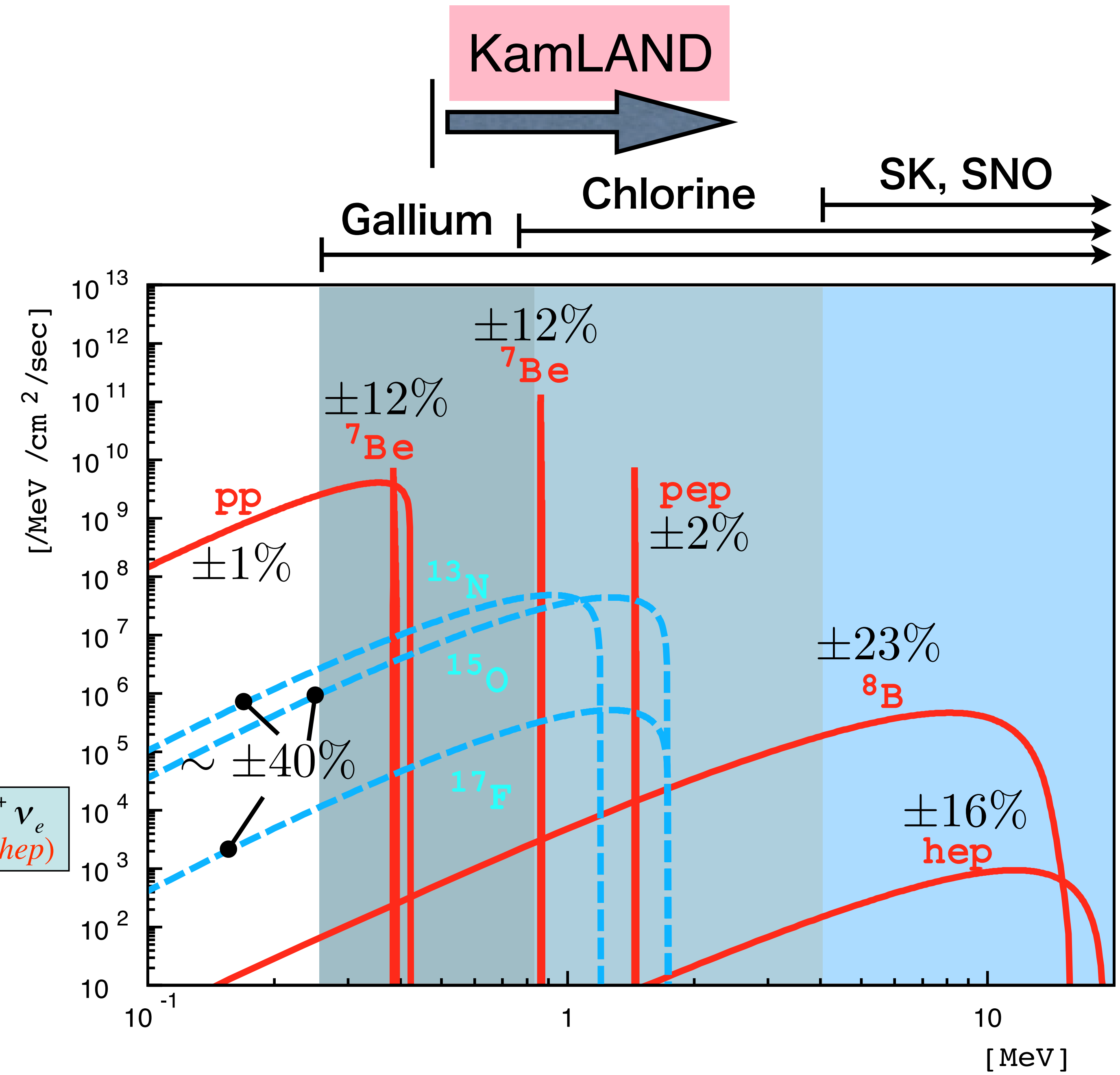

$^7$Be ~14% $^8$B ~0.02%



# Solar neutrino observation

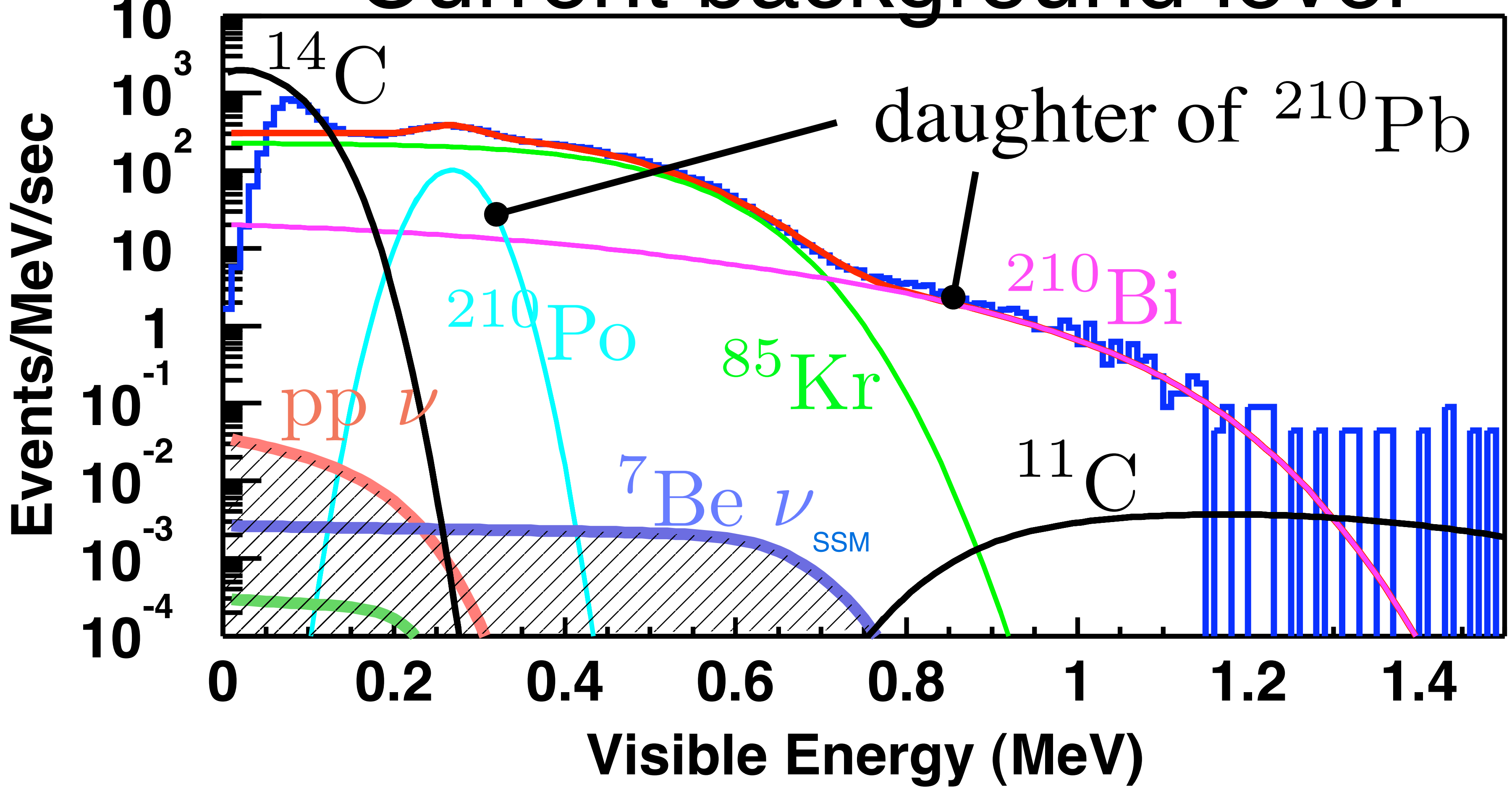



$^7$Be ~14%   $^8$B ~0.02%




Branching ratio to $^7$Be neutrino is larger and theoretical uncertainty is smaller. Its flux is so far measured at only 40% level.

# Current background level




| Background | now | goal |
|---|---|---|
| $^{238}$U(by Bi-Po) | $3.5 \times 10^{-18}$g/g | **OK!!** |
| $^{238}$U(by $^{234}$Pa) | $\mathbf{O}(10^{-15}$g/g)(Max.) | $10^{-18}$g/g |
| $^{232}$Th (by Bi-Po) | $5.2 \times 10^{-17}$g/g | **OK!!** |
| $^{40}$K | $2.7 \times 10^{-16}$g/g(max.) | $< 10^{-18}$g/g |
| $^{210}$Pb | $\sim 10^{-20}$g/g | $5 \times 10^{-25}$g/g $\sim 1\mu$Bq/m$^3$ |
| $^{85}$Kr, $^{39}$Ar | $^{85}$Kr =0.7Bq/m$^3$ | $1\mu$Bq/m$^3$ |
| $^{222}$Rn (after purification) | $^{238}$U $= 3.5 \times 10^{-18}$g/g $= 3.3 \times 10^{-8}$Bq/m$^3$ | **OK!!** ($1\mu$Bq/m$^3$) |
| $^{222}$Rn (during purification) | | 1mBq/m$^3$ $^{210}$Pb $= 0.5\mu$Bq/m$^3$ after decay |

**required further improvement**

$$\frac{1}{10^{4\sim5}}$$

$$\frac{1}{10^{\sim6}}$$

# Purification achievement

- $N_2$ gas purge

  $N_2$/LS=25 ---> ~1/10 Rn, ~1/100 Kr

- Fractional Distillation (164°C, 300 hPa)

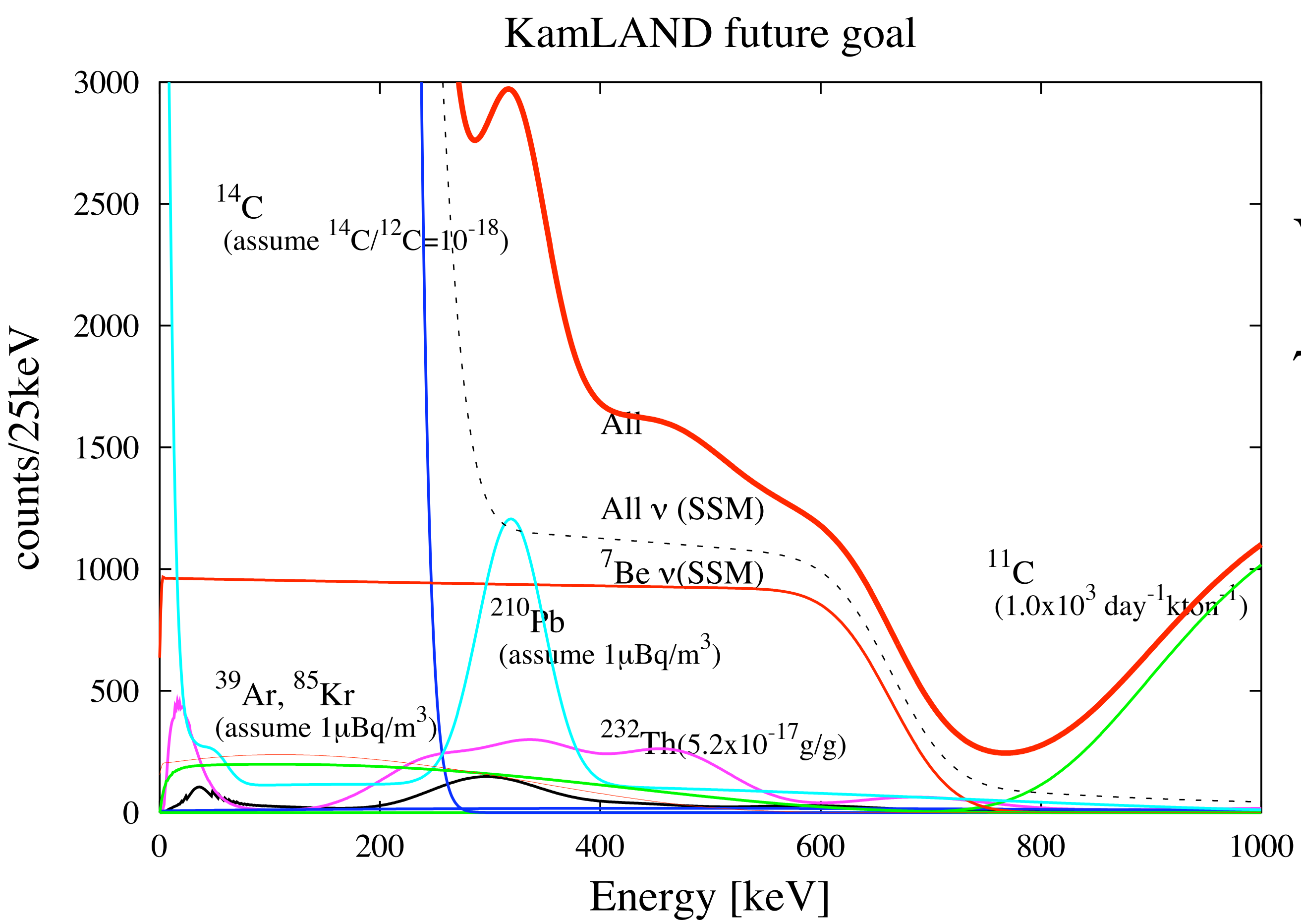
  $3\times10^{-5}$ Pb

  $1\times10^{-5}$ Rn

  $<2\times10^{-6}$ Kr

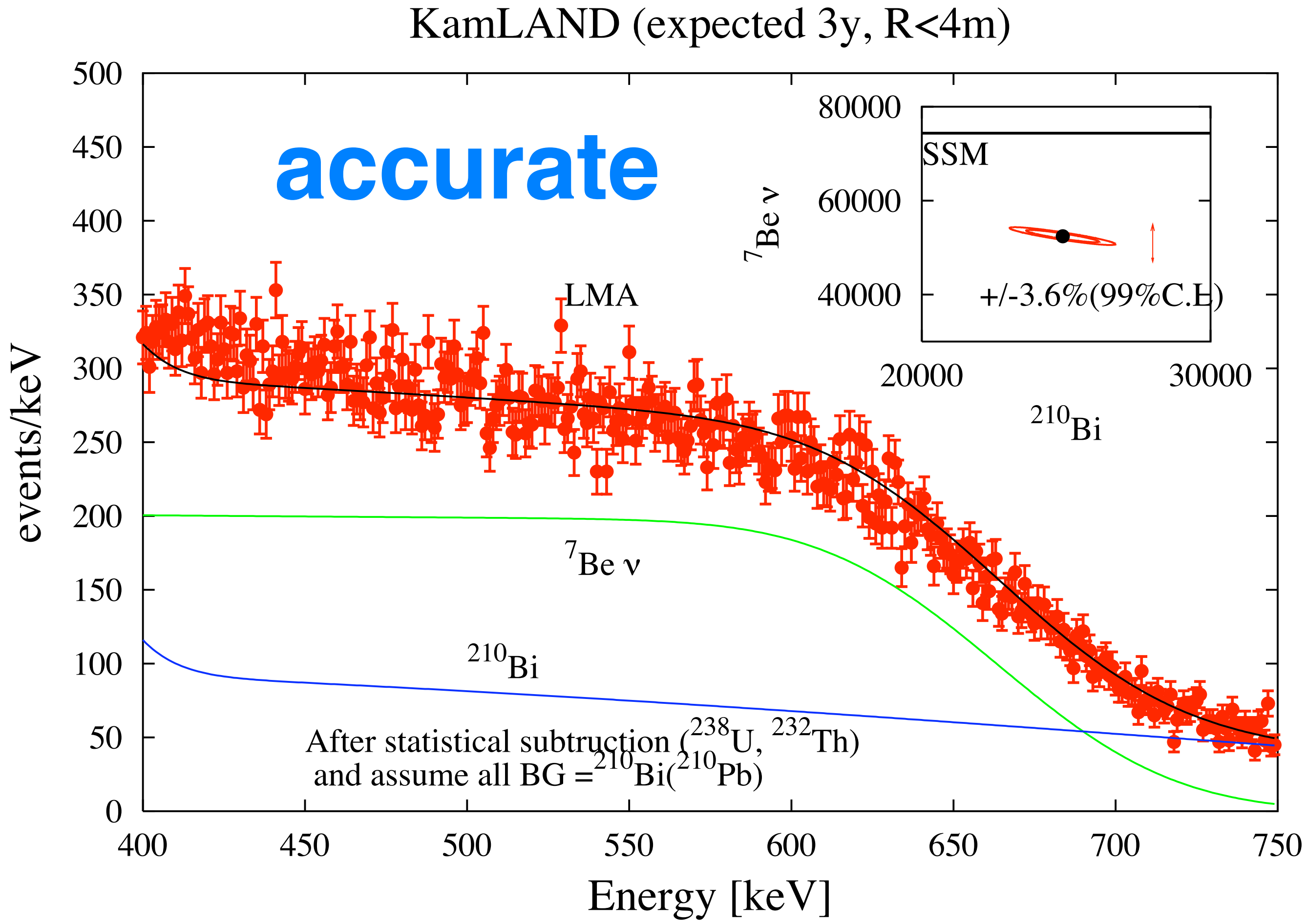
  Residual impurities will be some organic lead (e.g. tetra-ethyl-lead) and they disintegrate at ~200 °C.

Required performance is almost achieved.

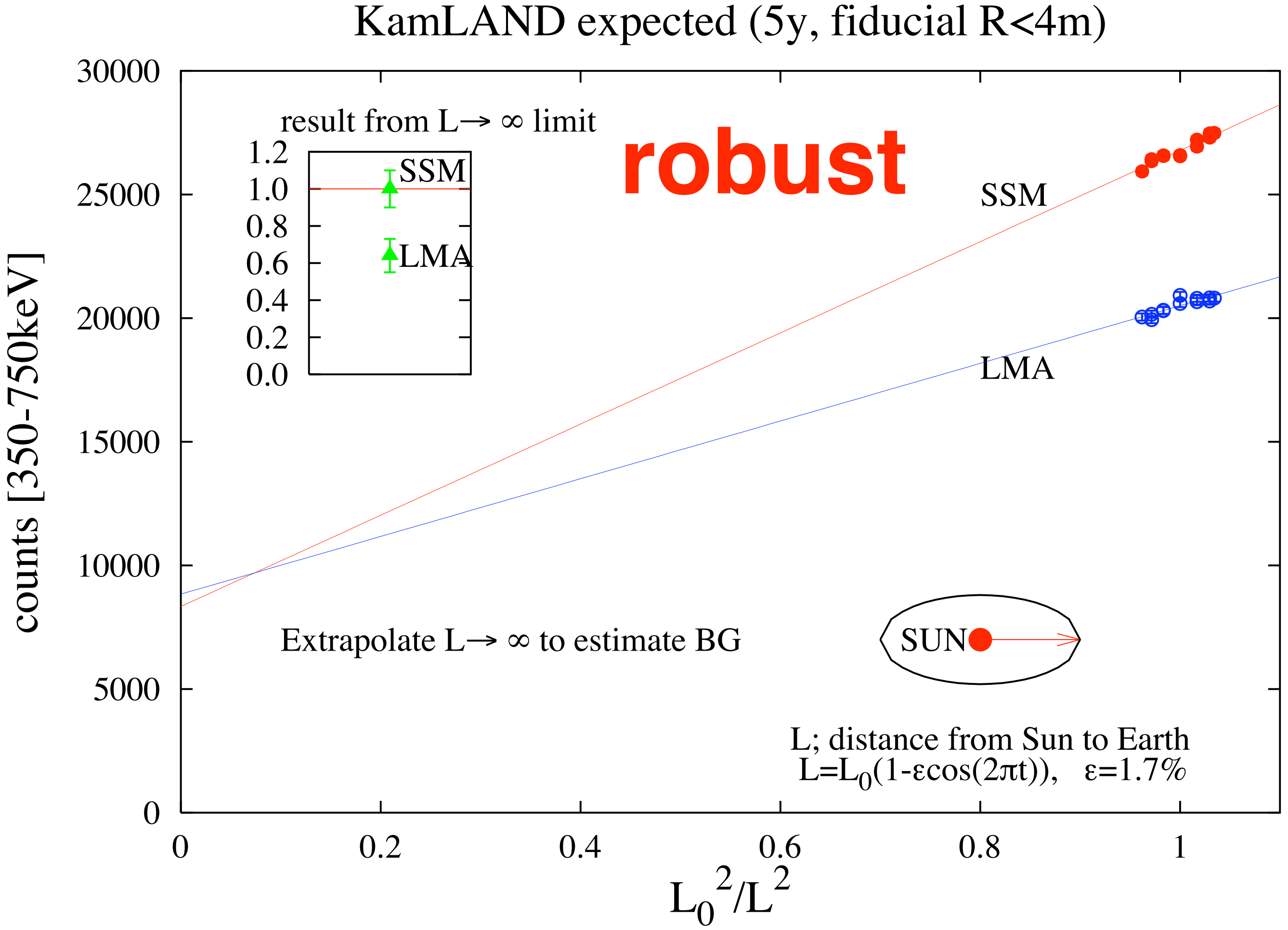



When the required reduction is achieved, $^7$Be neutrinos will be seen in the window between $^{14}$C and $^{11}$C background.

## BG subtraction with shape fit




## BG subtraction with seasonal variation



# Summary

(1) Updated results strengthened evidence of neutrino disappearance.

(2) Spectral distortion is observed at >99.6% CL.

(3) Rate+shape data excluded no oscillation at 99.999995% CL.

(4) L/E plot shows clear oscillatory behavior.

(5) Oscillation parameters are measured precisely. $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2$

(6) Forthcoming geo-nu observation will pioneer “Neutrino geo-physics”.

(7) KamLAND will push forward “Neutrino Astrophysics” with $^{7}$Be solar neutrino observation.


KamLAND
Thank you!