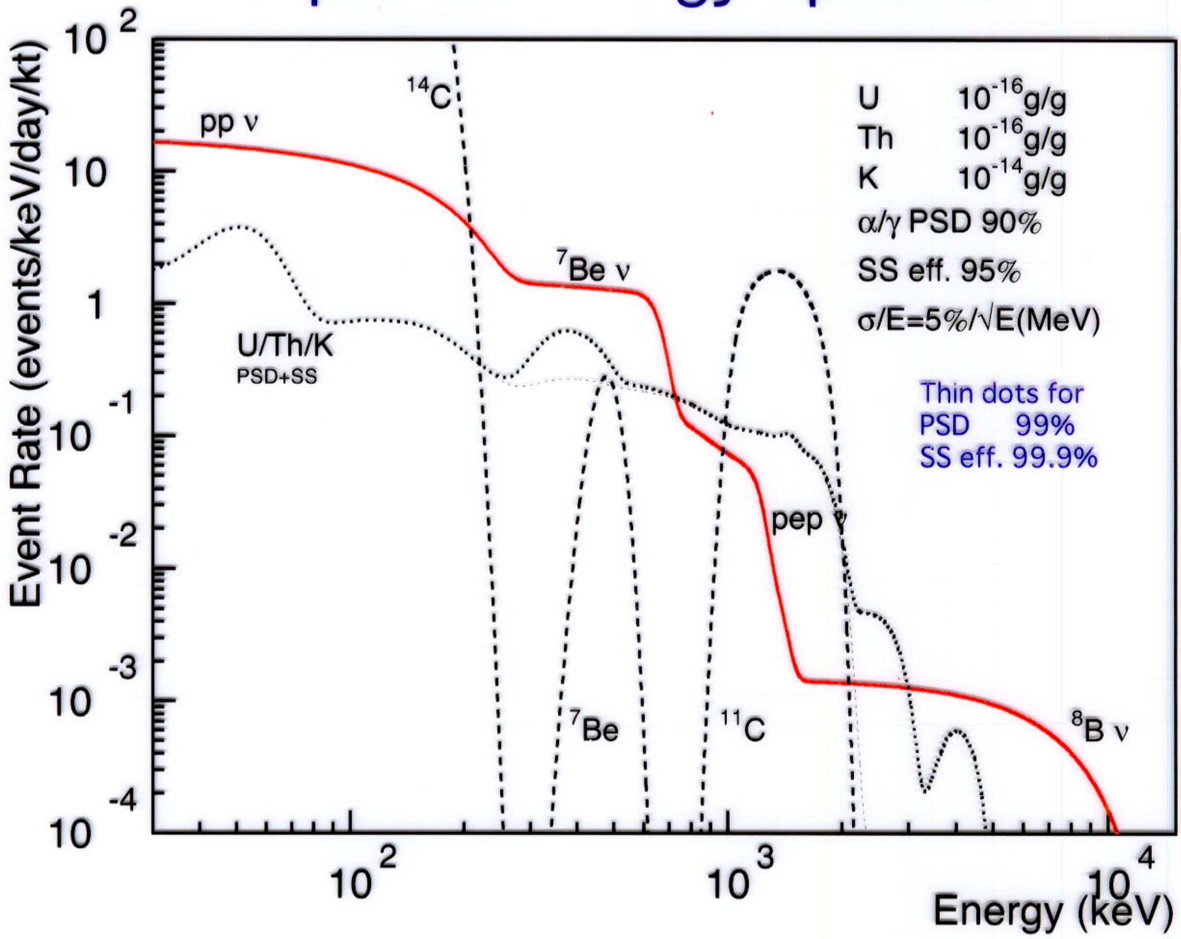
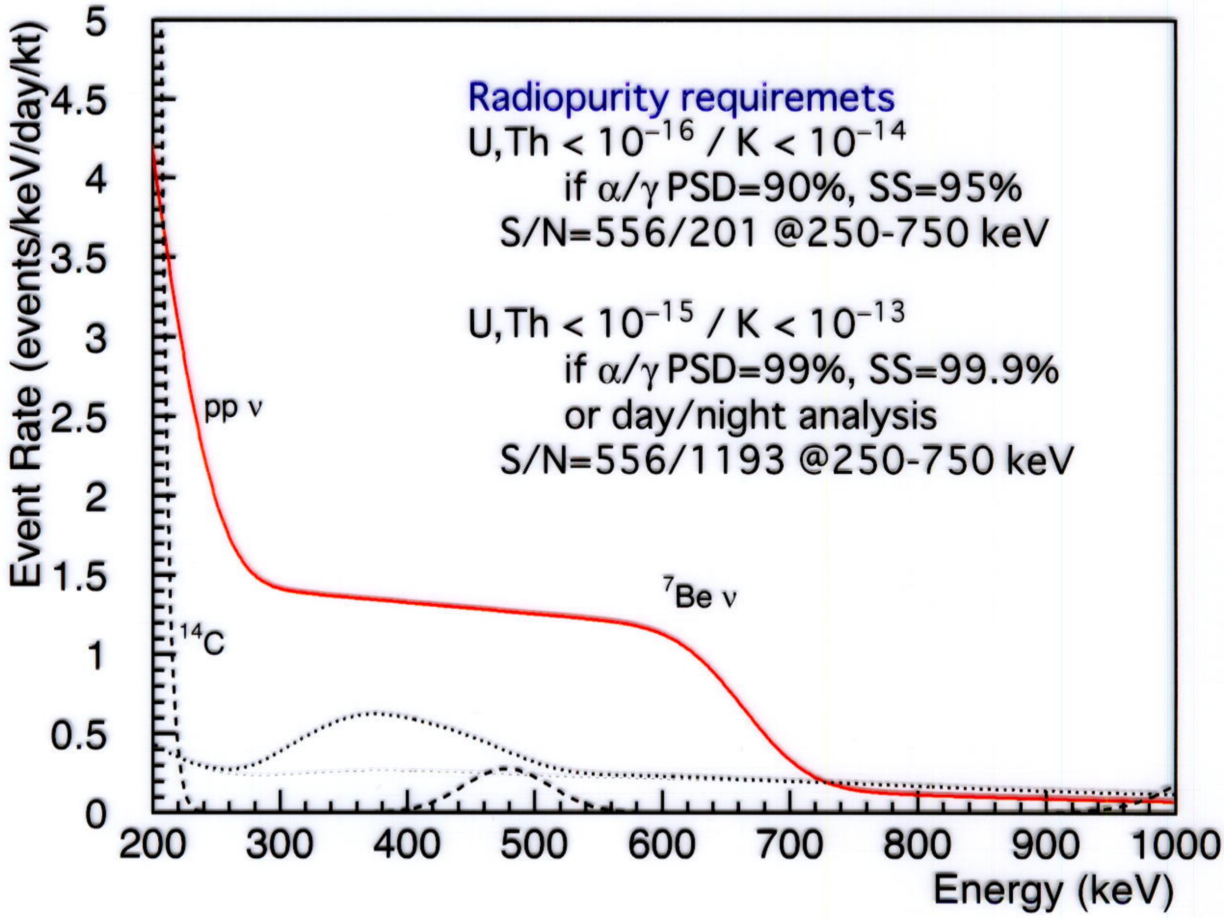
^{238}U chain

^{238}U (4.5 × 10^9 y)	E_α	E_γ	per ^{238}U decays
↓	4198	-	0.790
	4151	50	0.210
^{234}Th (24.1 d)	E_{β^-} Endpoint	E_γ	per ^{238}U decays
↓	273	-	0.703
	160	113	0.022
	181	92	0.192
	136	137	0.083 *
^{234}Pa (1.2 m)	E_{β^-} Endpoint	E_γ	per ^{238}U decays
↓	2197	-	0.982
	1153	1001,43	0.009
	1099	1098	0.009 *
^{234}U (2.5 × 10^5 y)	E_α	E_γ	per ^{238}U decays
↓	4775	-	0.714
	4722	53	0.286
^{230}Th (7.5 × 10^4 y)	E_α	E_γ	per ^{238}U decays
↓	4688	-	0.763
	4621	68	0.237
^{226}Ra (1600 y)	E_α	E_γ	per ^{238}U decays
↓	4784	-	0.944
	4602	186	0.056
^{222}Rn (3.8 d)	E_α	E_γ	per ^{238}U decays
↓	5490	-	1.000
^{218}Po (3.1 m)	E_α	E_γ	per ^{238}U decays
↓	6002	-	1.000
^{214}Pb (26.8 m)	E_{β^-} Endpoint	E_γ	per ^{238}U decays
↓	1023	-	0.093
	184	839	0.006
	234	786,53	0.009
	671	352	0.460
	728	295	0.288
	728	242,53	0.117
	511	512	0.027 *

^{214}Bi (19.9 m)	E_{β^-} Endpoint	E_γ	per ^{238}U decays
↓	3272	-	0.199
	790	1208,665,609	0.005
	824	2448	0.015
	824	1838,609	0.004
	1068	2204	0.048
	1153	1509,609	0.022
	1153	2119	0.012
	1255	1408,609	0.029
	1261	1402,609	0.015
	1278	1385,609	0.009
	1382	1281,609	0.015
	1425	1847	0.021
	1425	1238,609	0.059
	1508	1764	0.149
	1508	1155,609	0.016
	1542	1120,609	0.144
	1542	1730	0.028
	1729	934,609	0.027
	1857	806,609	0.009
	1894	1378	0.032
	1894	768,609	0.040
	1636	1636	0.102*
^{214}Po (164 μs)	E_α	E_γ	per ^{238}U decays
↓	6902	800	0.0001
	7687	-	0.9999
^{210}Pb (22 y)	E_{β^-} Endpoint	E_γ	per ^{238}U decays
↓	64	-	0.160
	17	47	0.840
^{210}Bi (5.0 d)	E_{β^-} Endpoint	E_γ	per ^{238}U decays
↓	1163	-	1.000
^{210}Po (138 d)	E_α	E_γ	per ^{238}U decays
↓	5304	-	1.000
^{206}Pb (∞)			

Expected Energy Spectra





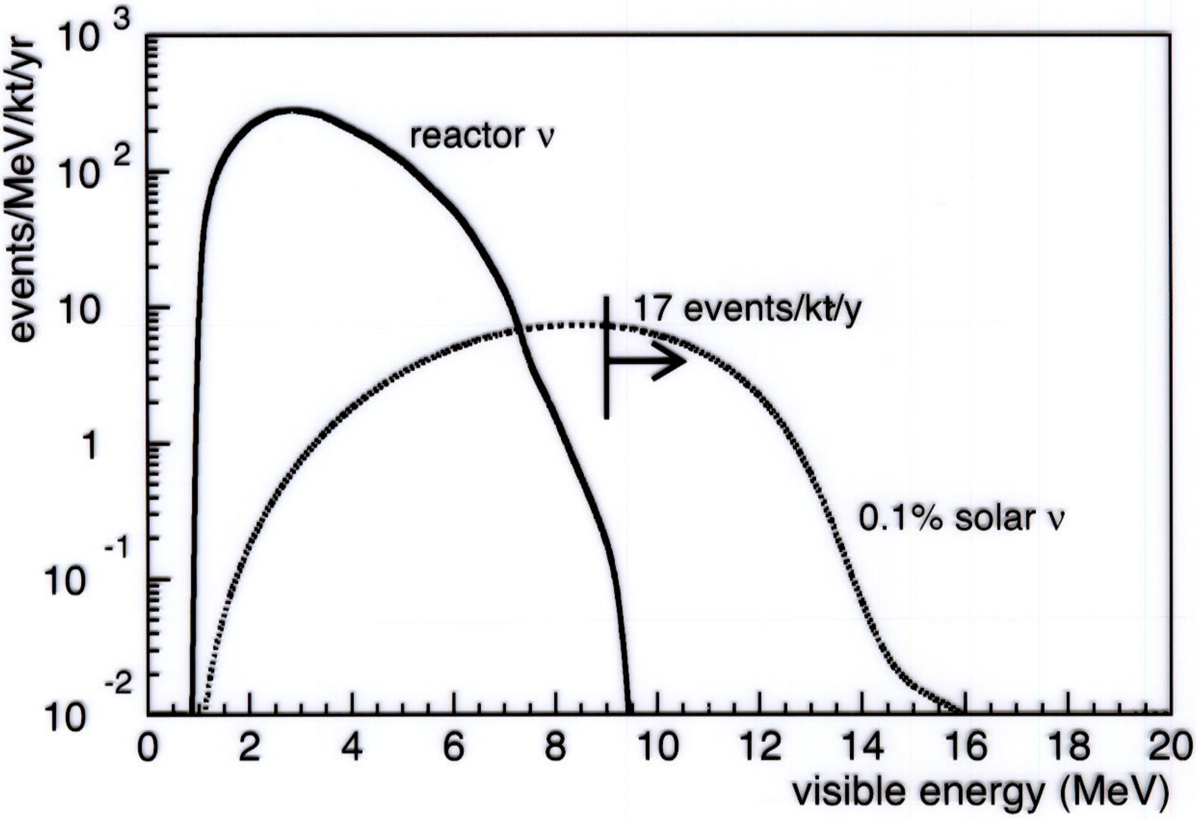
Search for $\overline{\nu}_e$ from the Sun

$$\nu_e \xrightarrow{\text{RSFP}} \overline{\nu}_\mu \xrightarrow{\text{VAC}} \overline{\nu}_e$$

Current Best Limit

$\phi(\overline{\nu}_e) < 0.95\% \, \phi(^8B)$ 90%C.L. with SK data

(preliminary result in Y.Gando's master thesis)



KamLAND will improve the limit by factor 10.

核子崩壊 $n \rightarrow \nu\nu\bar{\nu}$

^{12}Cの$S_{1/2}$状態の中性子が崩壊すると、、、

$^{12}C \rightarrow {}^{11}C^{*} + \nu\nu\bar{\nu}$

└→ $^{10}C^{*} + n$　（数%）

└→ $^{10}C + \gamma$　$T_{1/2}=19.255sec$

└→ $^{10}B + e^{+}(\gamma) + \bar{\nu}$

(1.91MeV β^{+} + 0.72MeV γ)

$\gamma + e^{+} + n$ の３重同時計測ができる。

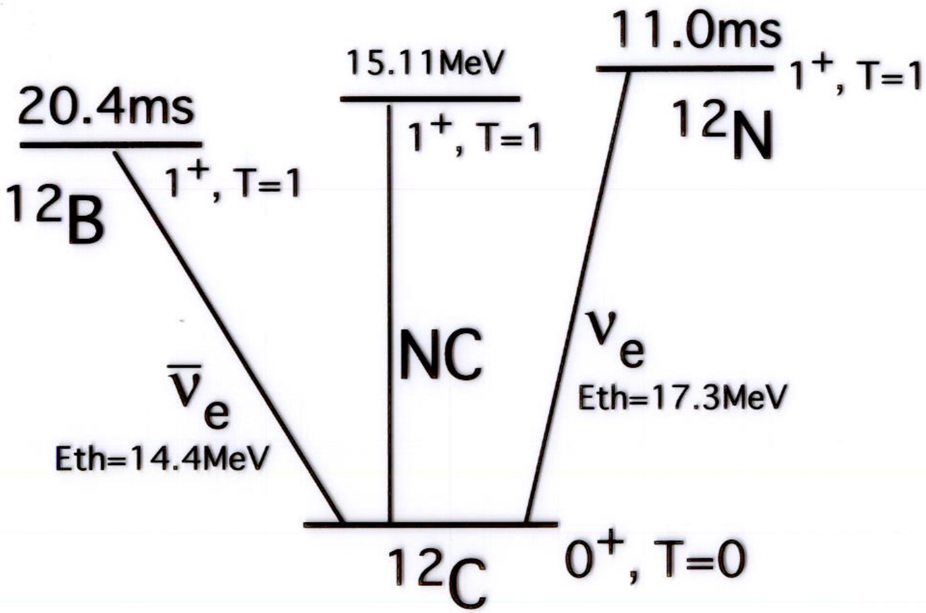
これまでのリミット　1.6×10^{25} years に対し

感度　$\sim3\times10^{30}$ years が達成できる。

超新星ニュートリノ観測

* $T(\nu_x)(\sim 8\,\mathrm{MeV}) > T(\bar{\nu}_e)(\sim 5\,\mathrm{MeV}) > T(\nu_e)(\sim 3.5\,\mathrm{MeV})$

$\bar{\nu}_e + p \rightarrow e^+ + n$ 330 events/kt @GC

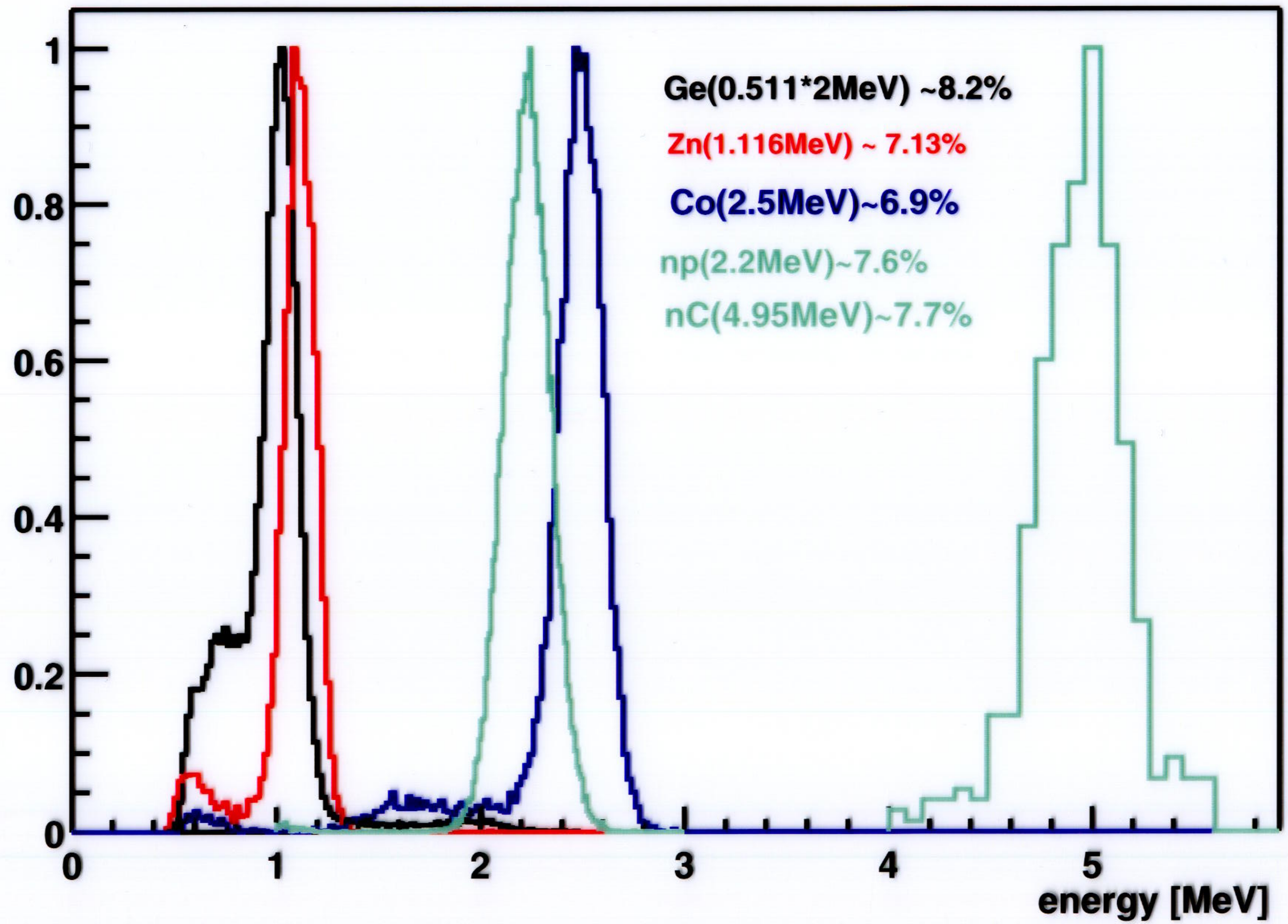


~10 CC events/kt @GC

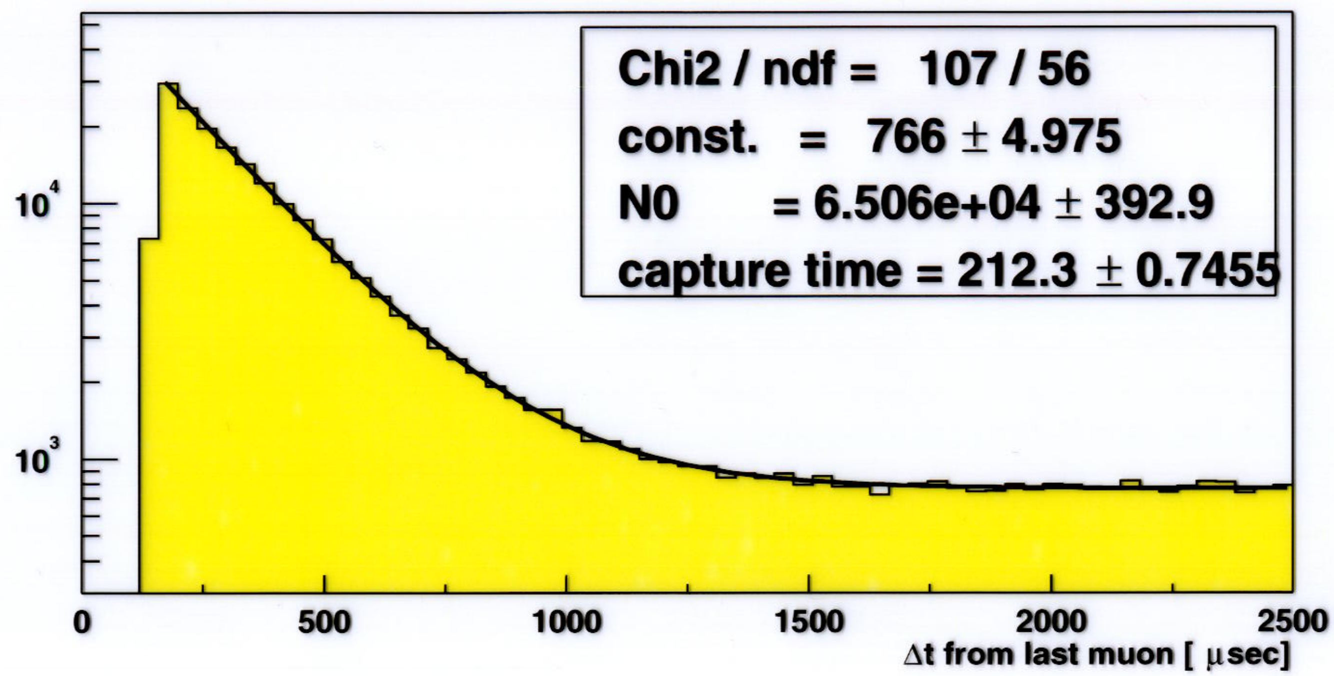
~60 NC events/kt

(w/ oscillation 20~40 CC events)

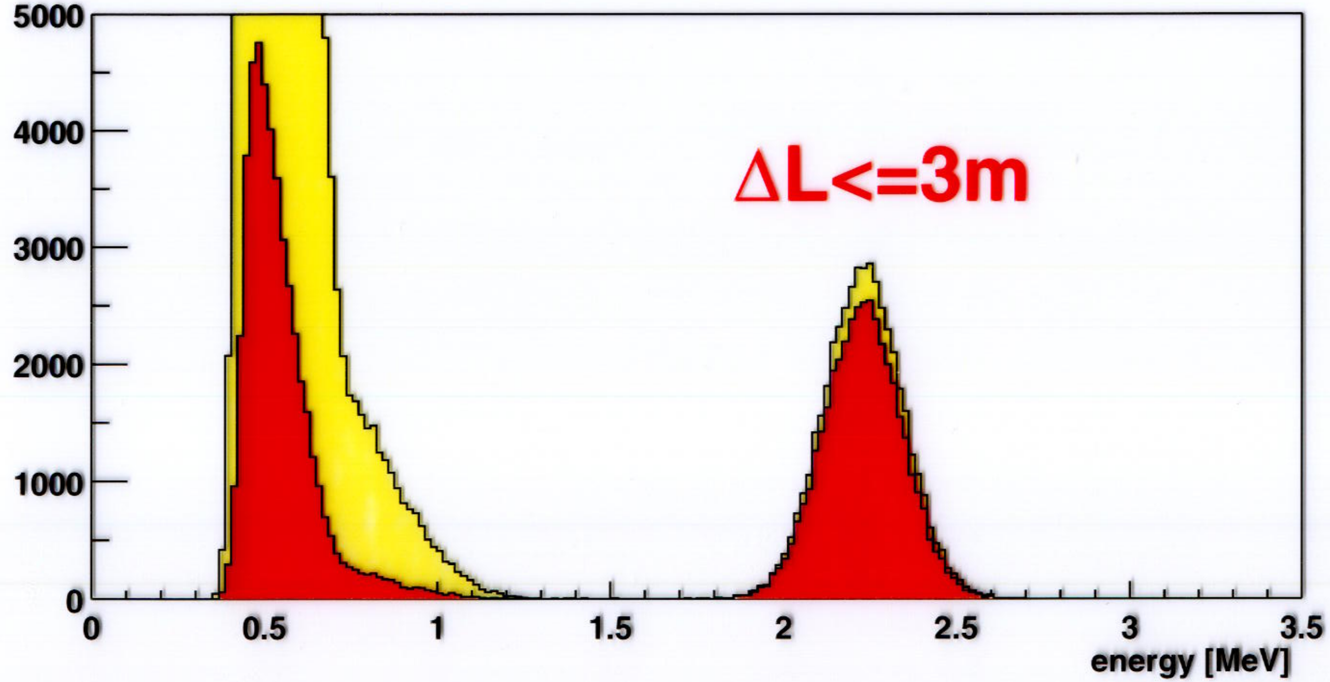
$\nu_x(\bar{\nu}_x) + p \rightarrow \nu_x(\bar{\nu}_x) + p$ ~300 events/kt (>150 keV)



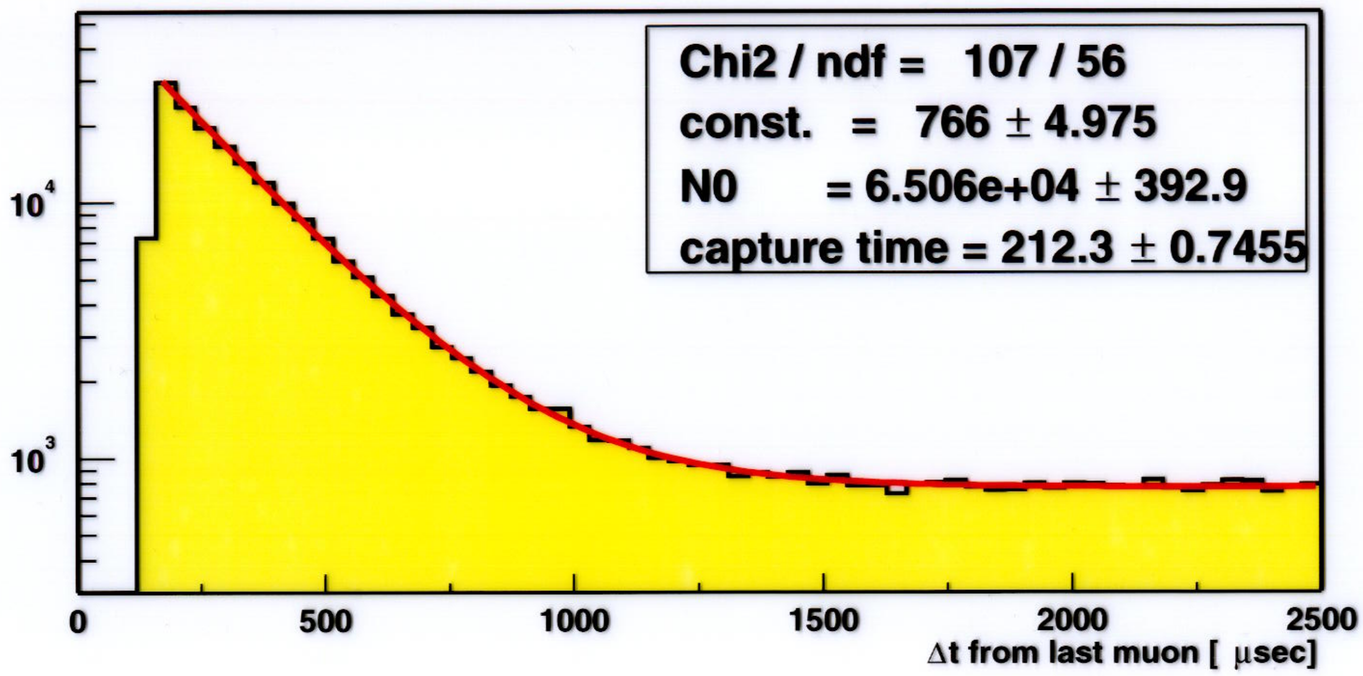
Ge(0.511*2MeV) ~8.2%
Zn(1.116MeV) ~ 7.13%
Co(2.5MeV)~6.9%
np(2.2MeV)~7.6%
nC(4.95MeV)~7.7%
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
energy [MeV]



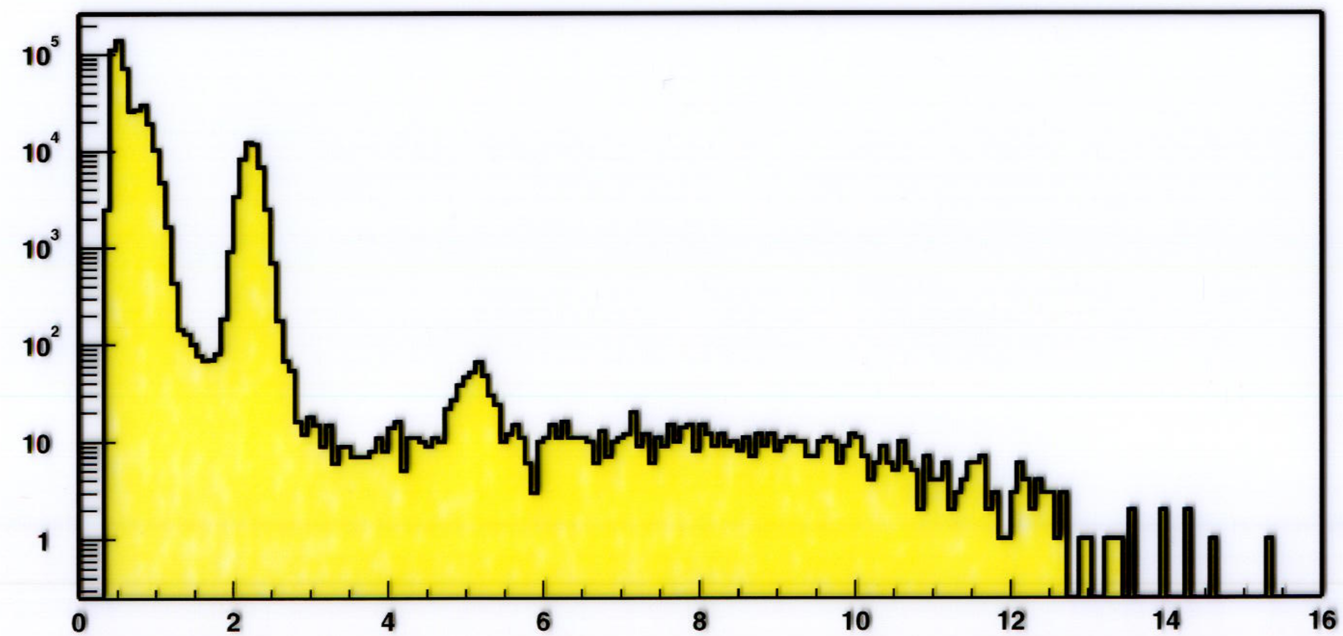
Chi2 / ndf = 107 / 56
const. = 766 ± 4.975
N0 = 6.506e+04 ± 392.9
capture time = 212.3 ± 0.7455
10^4
10^3
0
500
1000
1500
2000
2500
Δt from last muon [μsec]

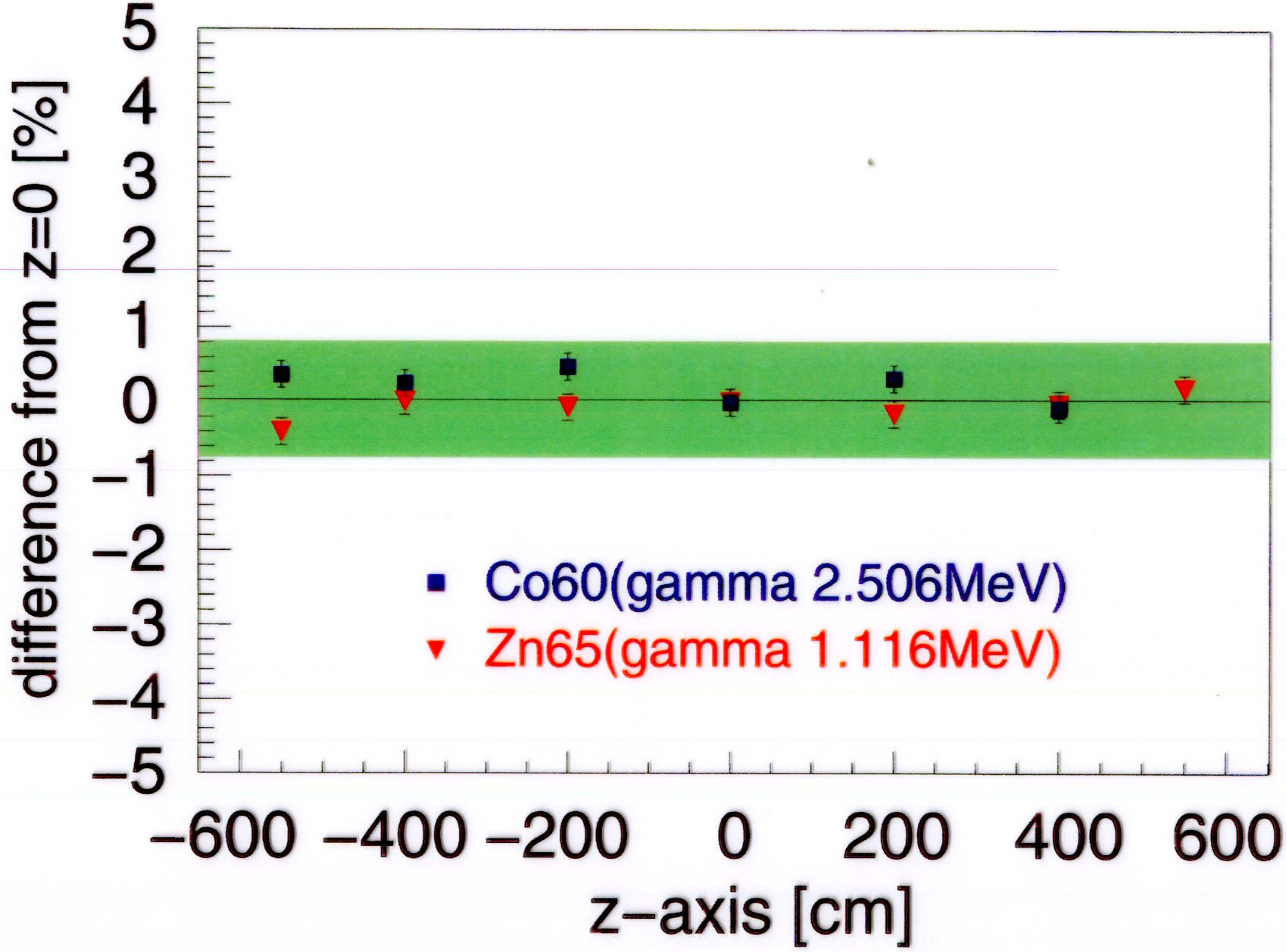


ΔL<=3m
5000
4000
3000
2000
1000
0
0.5
1
1.5
2
2.5
3
3.5
energy [MeV]

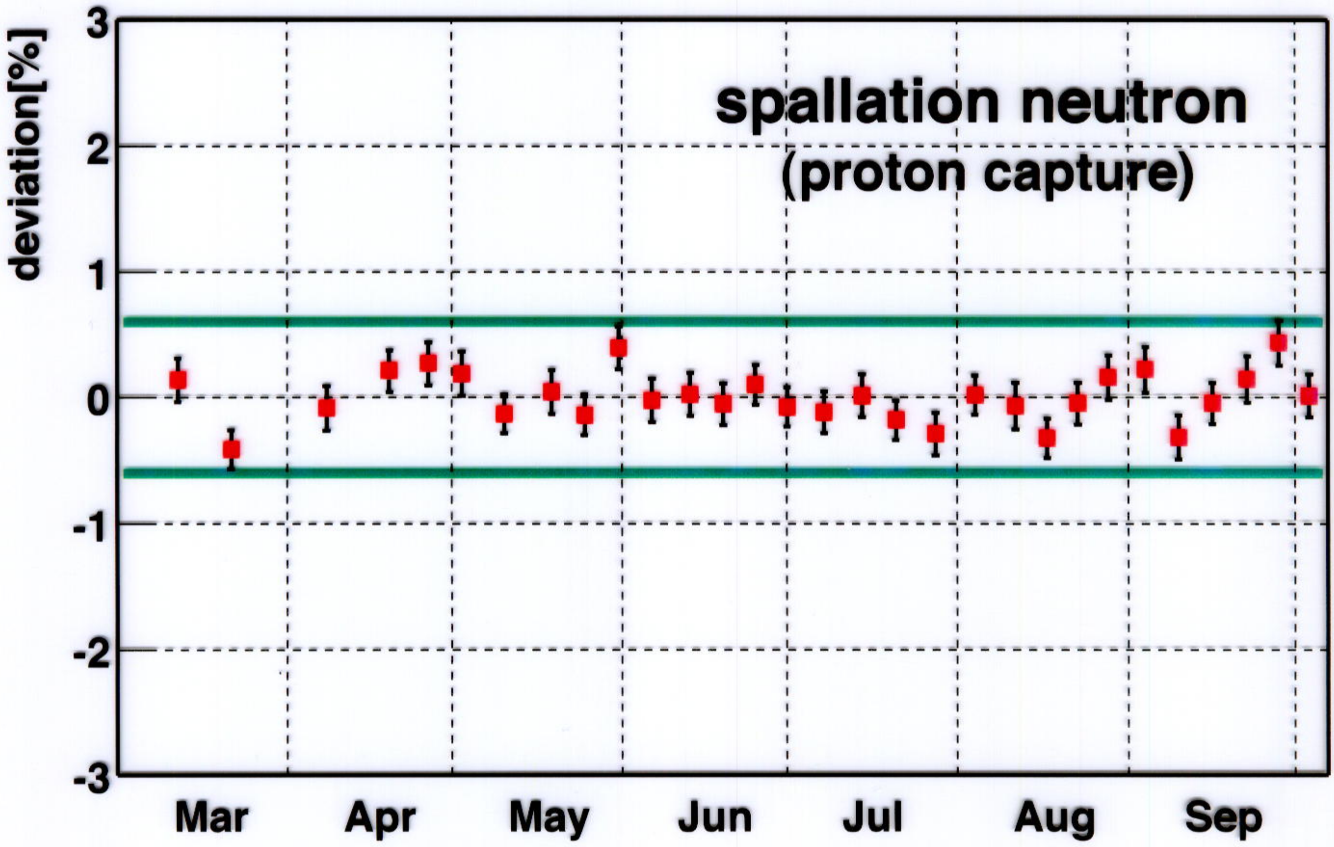


Chi2 / ndf = 107 / 56
const. = 766 ± 4.975
N0 = 6.506e+04 ± 392.9
capture time = 212.3 ± 0.7455
Δt from last muon [μsec]

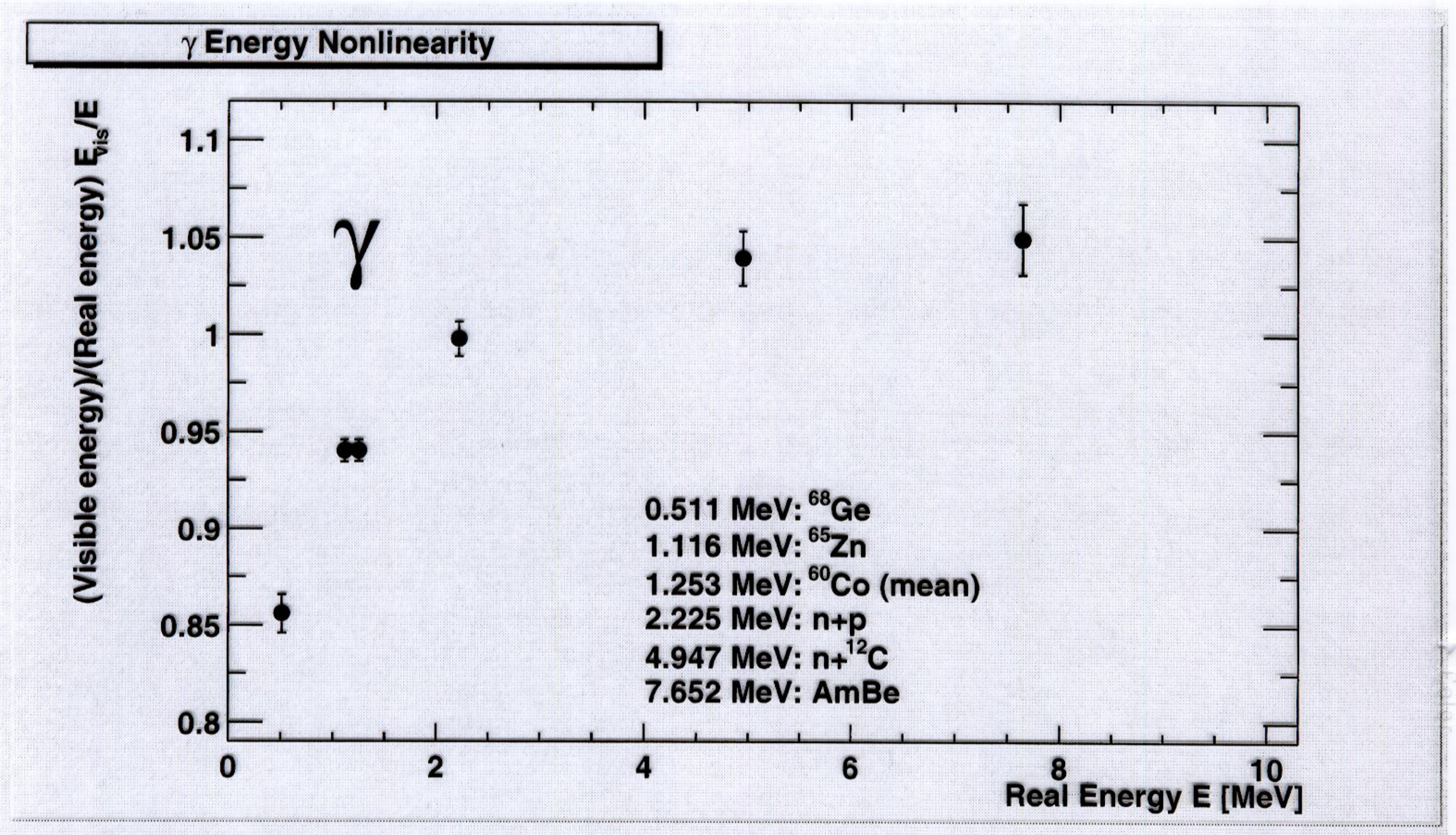




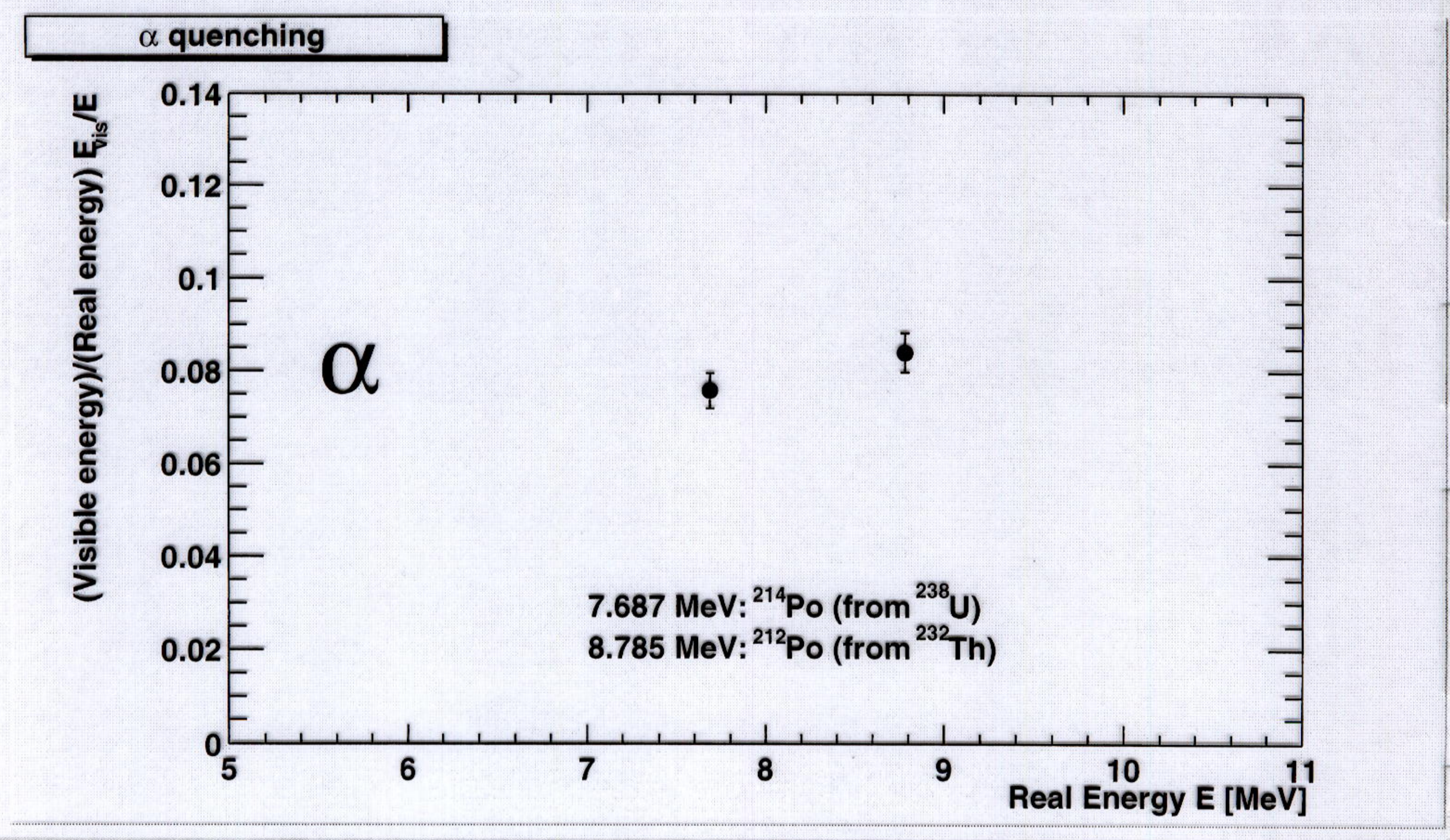
difference from z=0 [%]
5
4
3
2
1
0
−1
−2
−3
−4
−5
Co60(gamma 2.506MeV)
Zn65(gamma 1.116MeV)
−600
−400
−200
0
200
400
600
z−axis [cm]



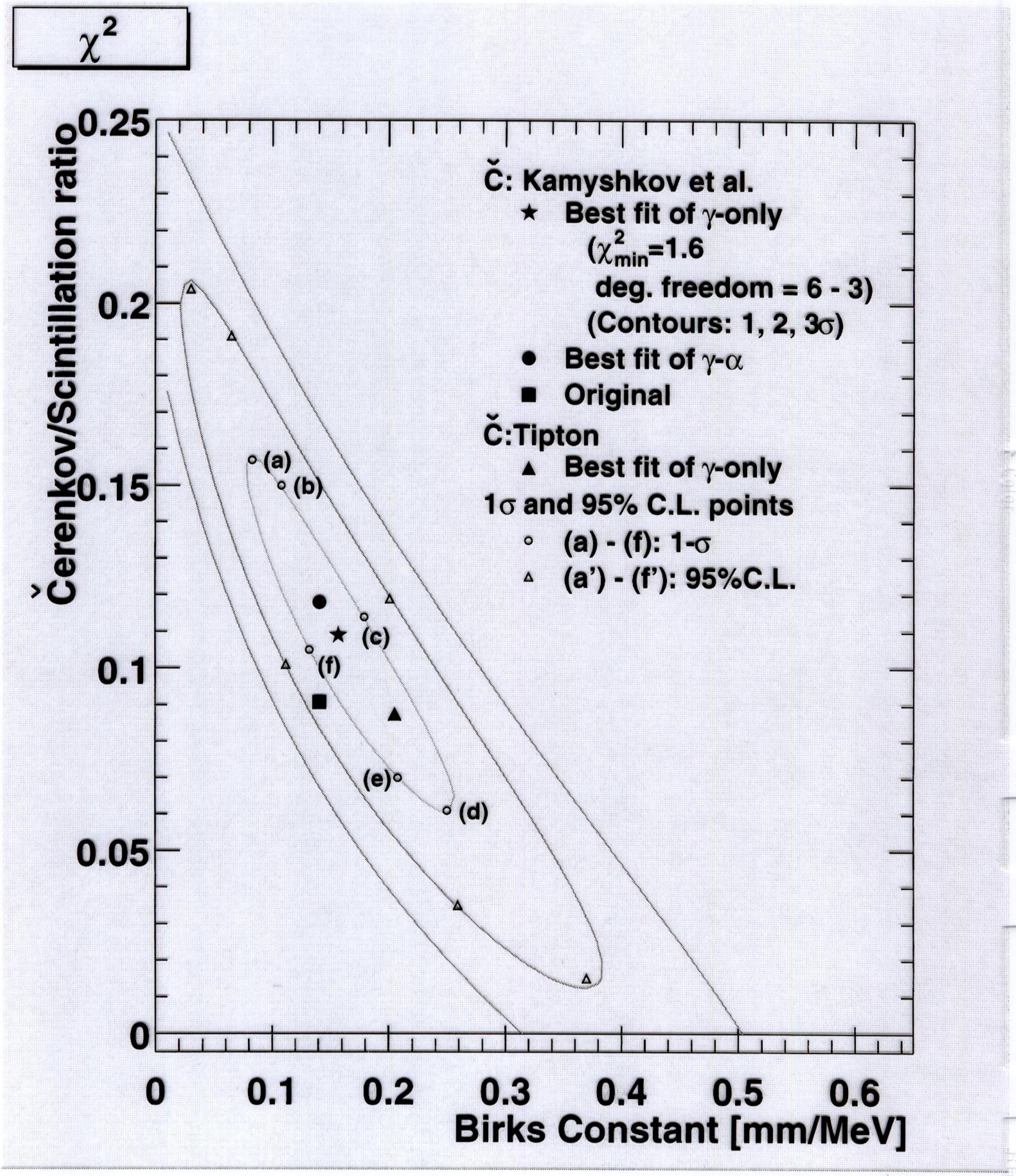
spallation neutron
(proton capture)
deviation[%]
3
2
1
0
-1
-2
-3
Mar
Apr
May
Jun
Jul
Aug
Sep



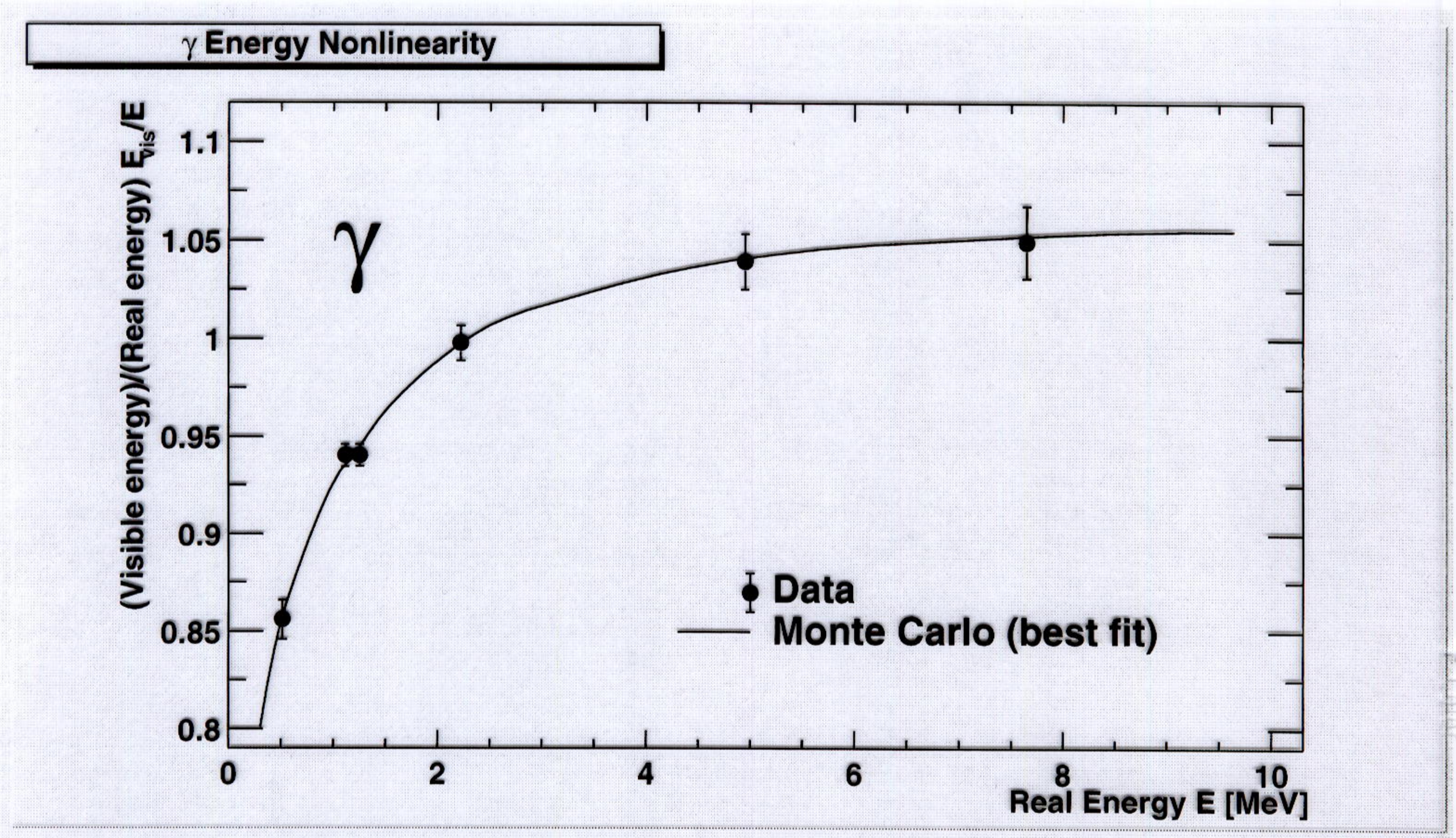
γ Energy Nonlinearity
(Visible energy)/(Real energy) E_vis/E
γ
0.511 MeV: 68Ge
1.116 MeV: 65Zn
1.253 MeV: 60Co (mean)
2.225 MeV: n+p
4.947 MeV: n+12C
7.652 MeV: AmBe
Real Energy E [MeV]

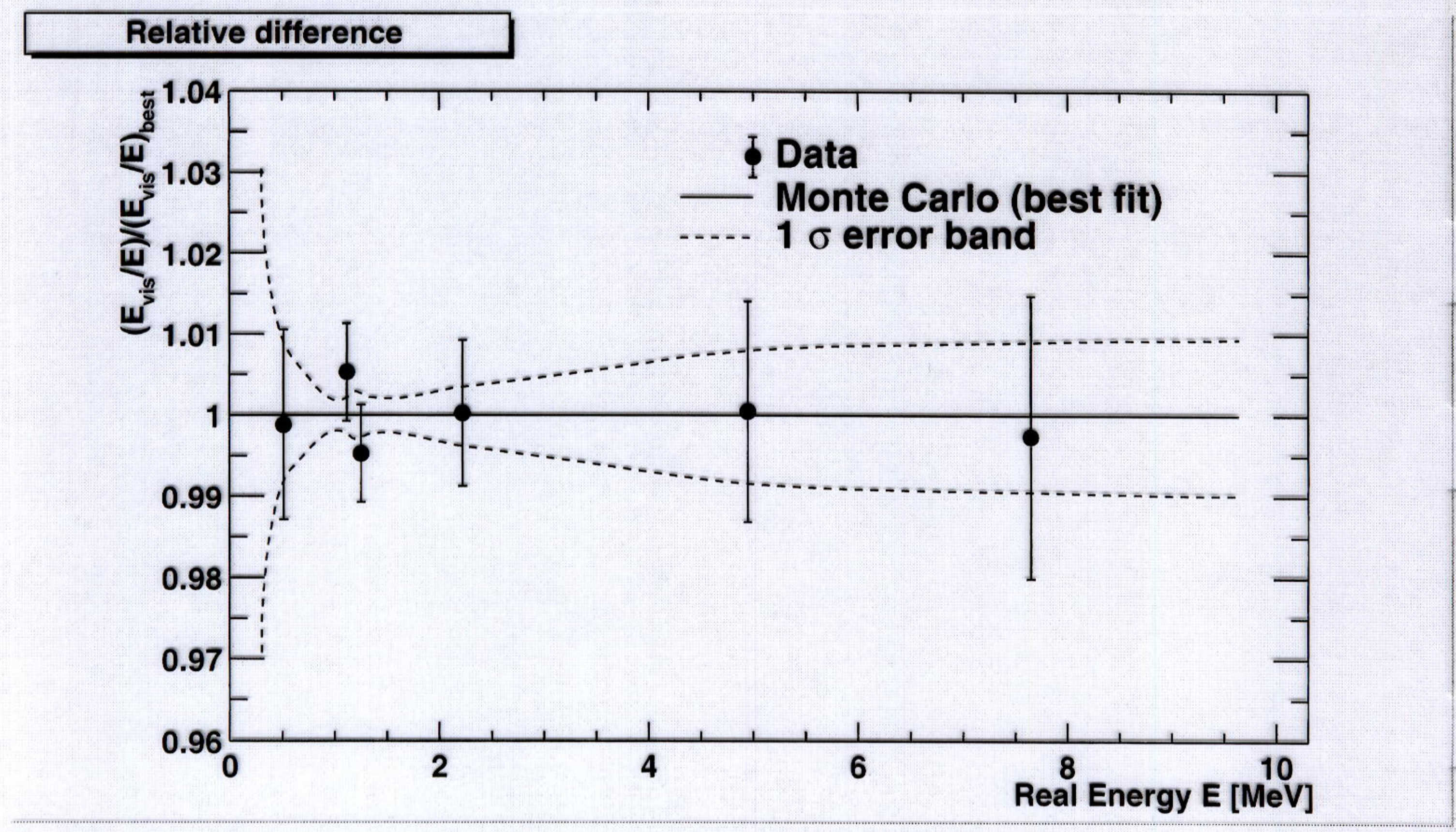


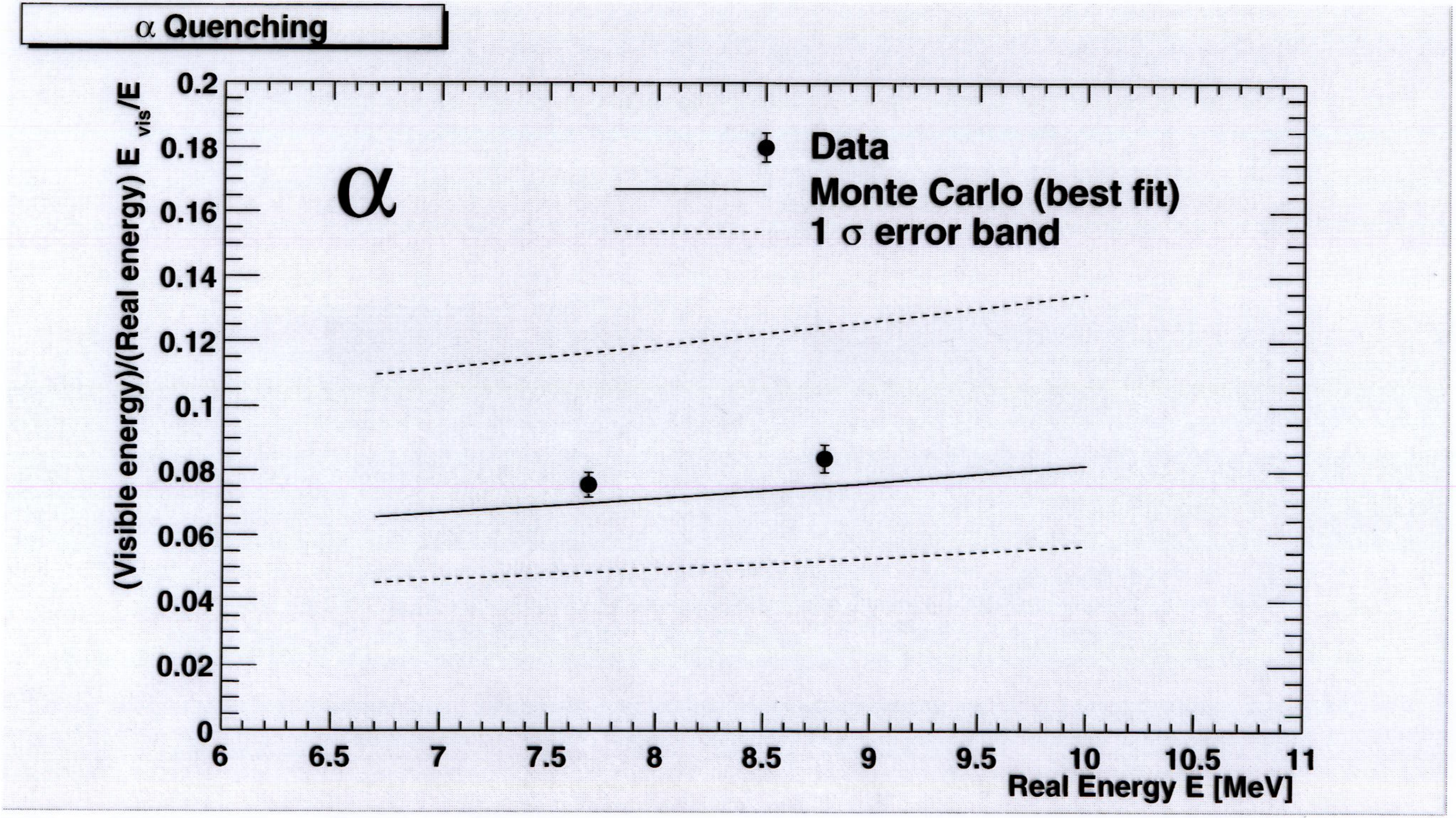
α quenching
(Visible energy)/(Real energy) E_vis/E
α
7.687 MeV: 214Po (from 238U)
8.785 MeV: 212Po (from 232Th)
Real Energy E [MeV]

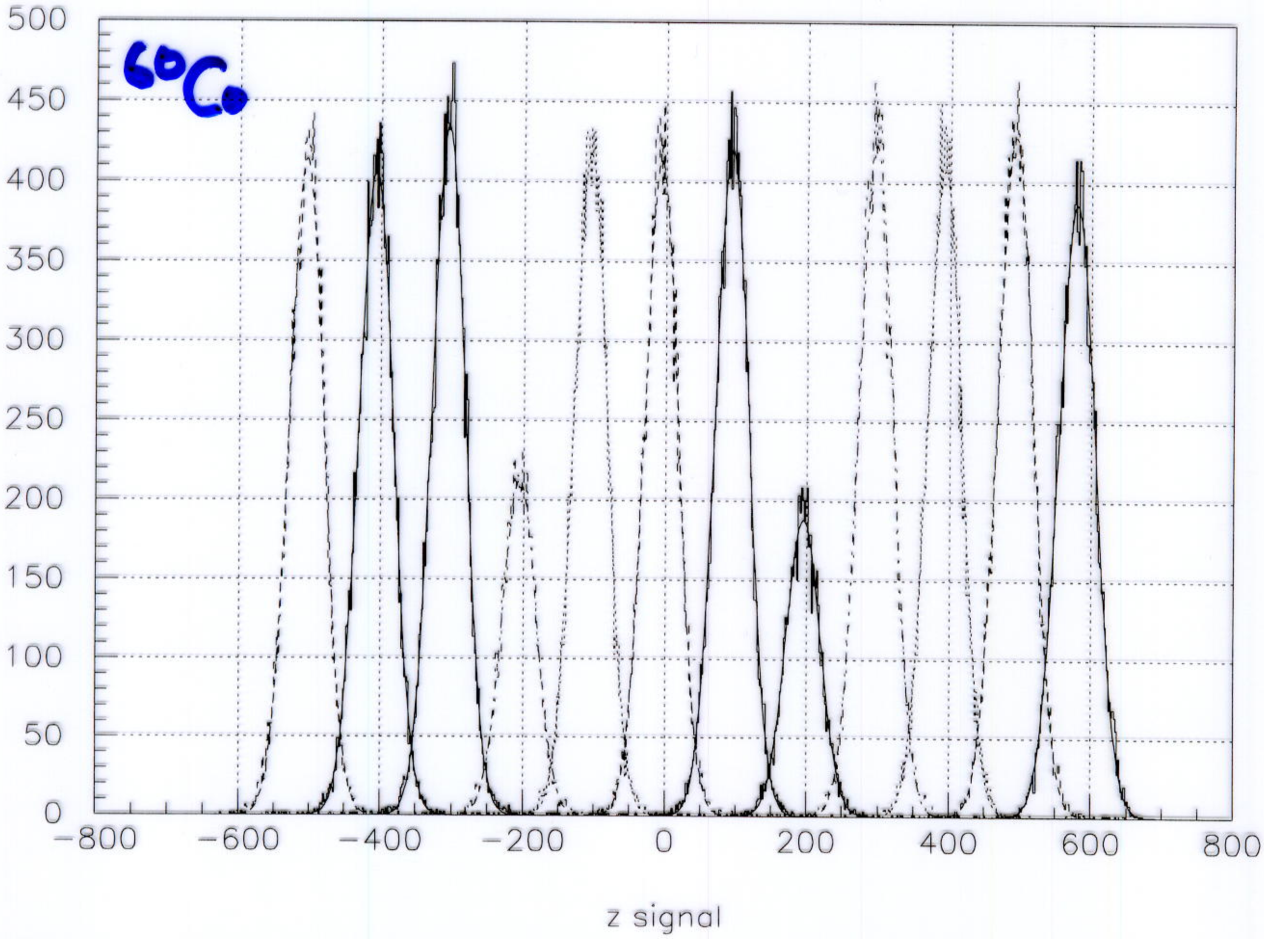


χ²
Čerenkov/Scintillation ratio
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
Birks Constant [mm/MeV]
Č: Kamyshkov et al.
★ Best fit of γ-only
(χ²min=1.6
deg. freedom = 6 - 3)
(Contours: 1, 2, 3σ)
● Best fit of γ-α
■ Original
Č:Tipton
▲ Best fit of γ-only
1σ and 95% C.L. points
○ (a) - (f): 1-σ
△ (a') - (f'): 95%C.L.
(a)
(b)
(c)
(d)
(e)
(f)

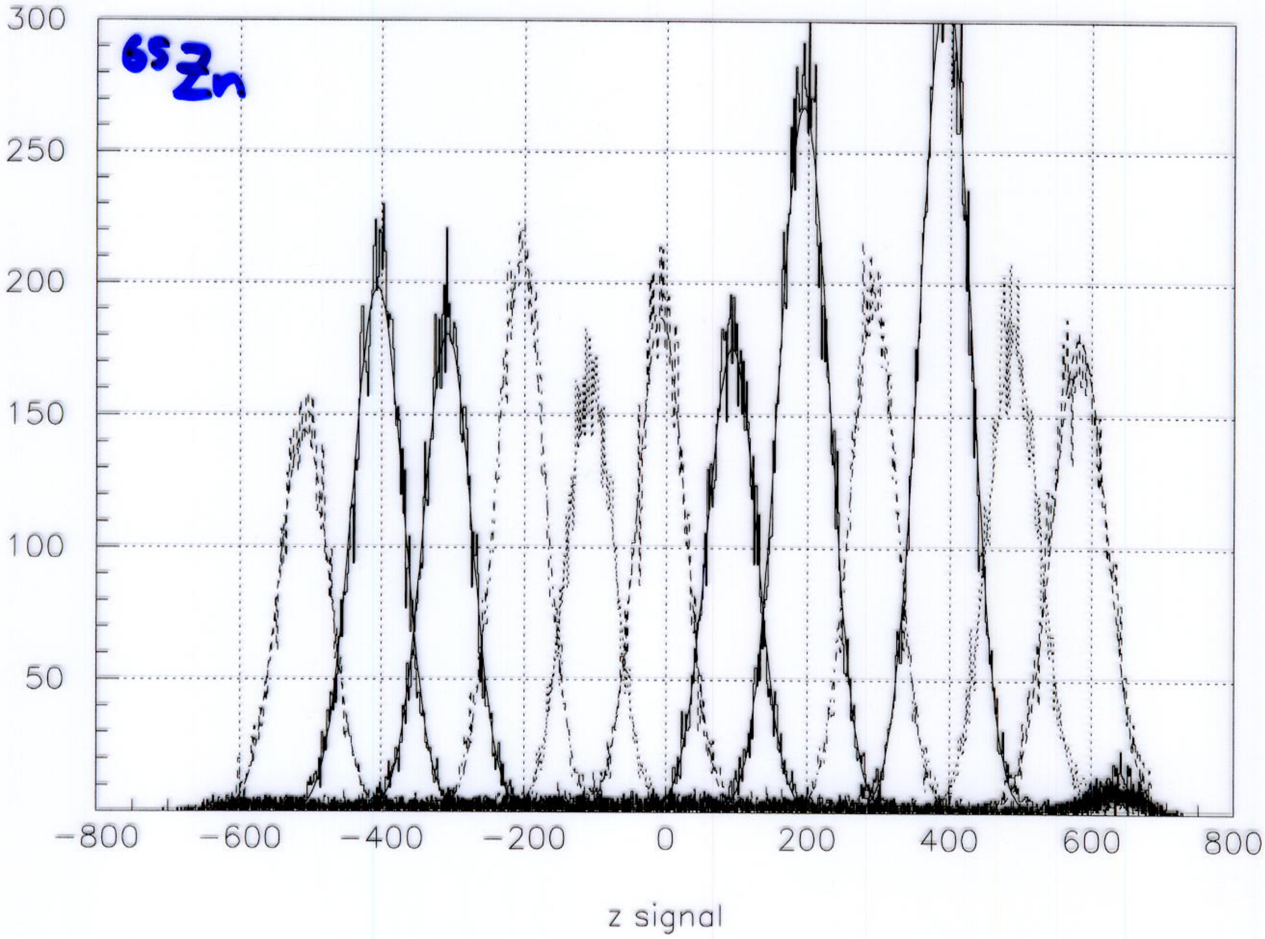

γ Energy Nonlinearity
(Visible energy)/(Real energy) E_vis/E
γ
Data
Monte Carlo (best fit)
Real Energy E [MeV]


Relative difference
(E_vis/E)/(E_vis/E)_best
Data
Monte Carlo (best fit)
1 σ error band
Real Energy E [MeV]

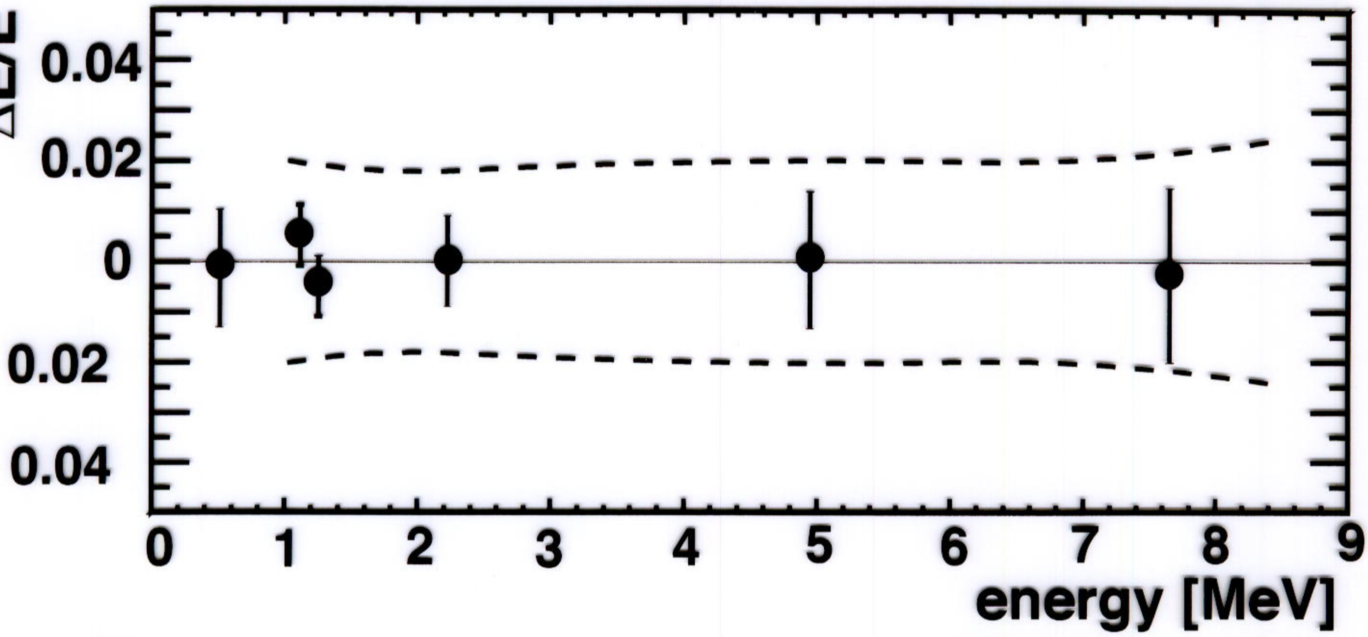

α Quenching
α
Data
Monte Carlo (best fit)
1 σ error band
(Visible energy)/(Real energy) E vis/E
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
Real Energy E [MeV]

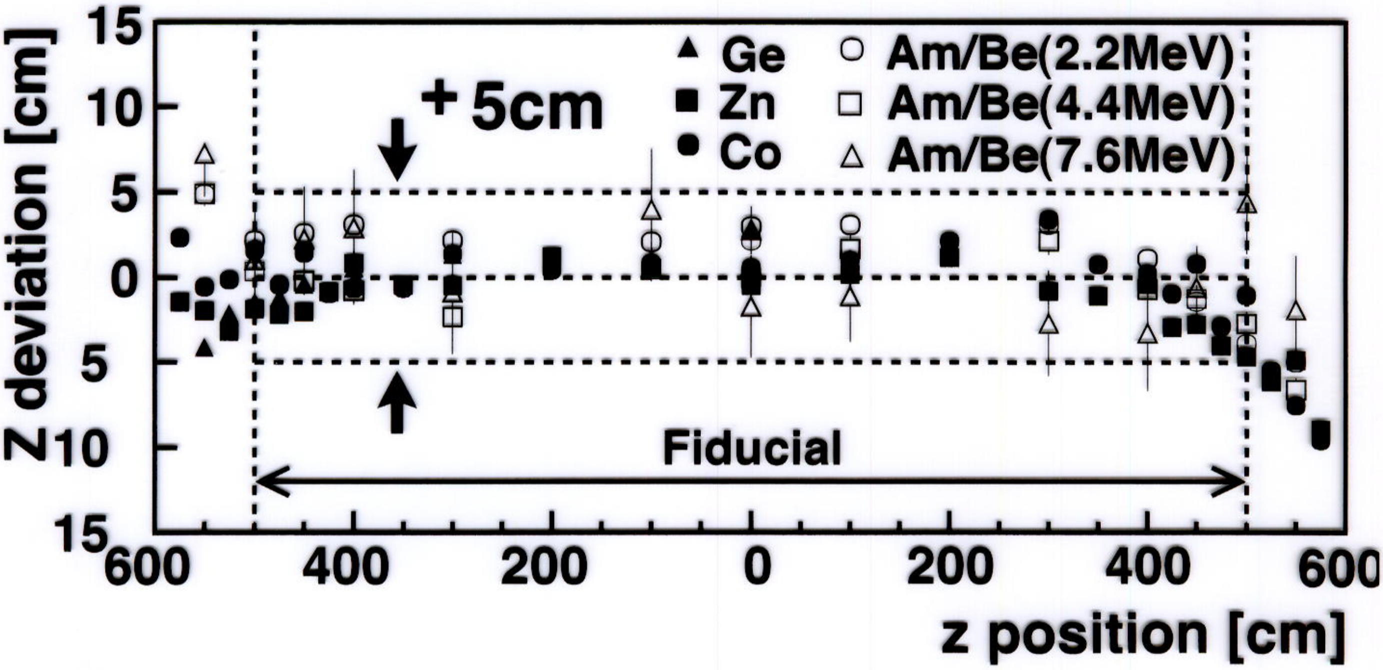


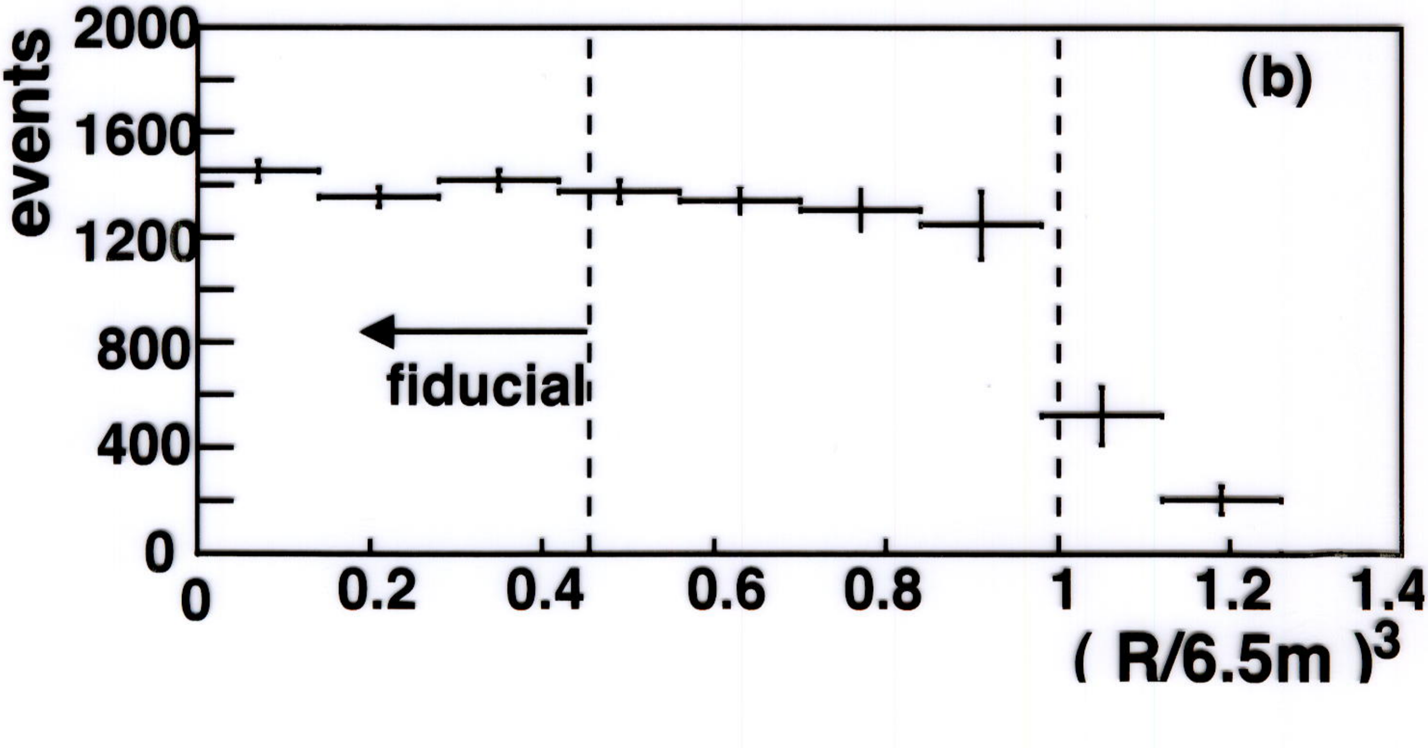
60Co
500
450
400
350
300
250
200
150
100
50
0
−800
−600
−400
−200
0
200
400
600
800
z signal

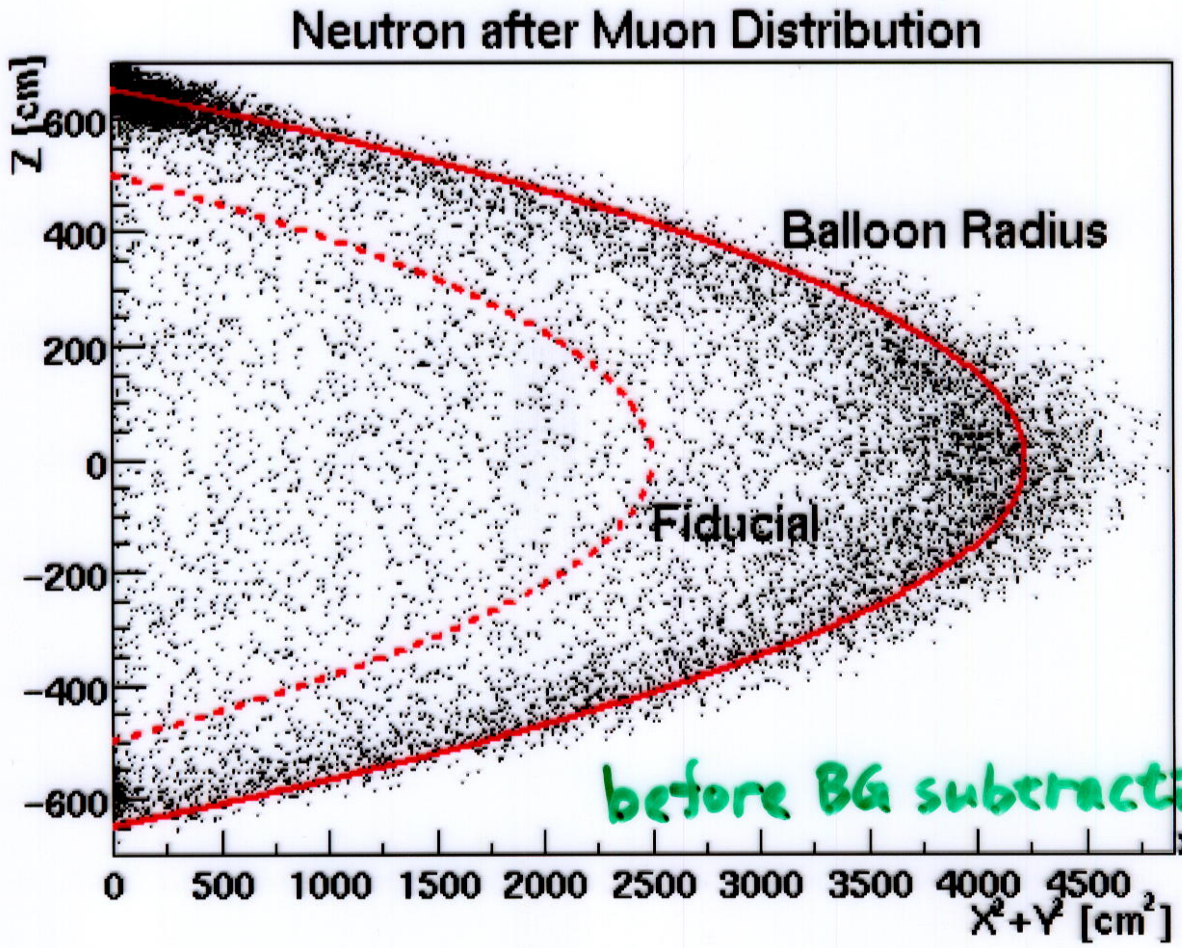


65Zn
300
250
200
150
100
50
−800
−600
−400
−200
0
200
400
600
800
z signal

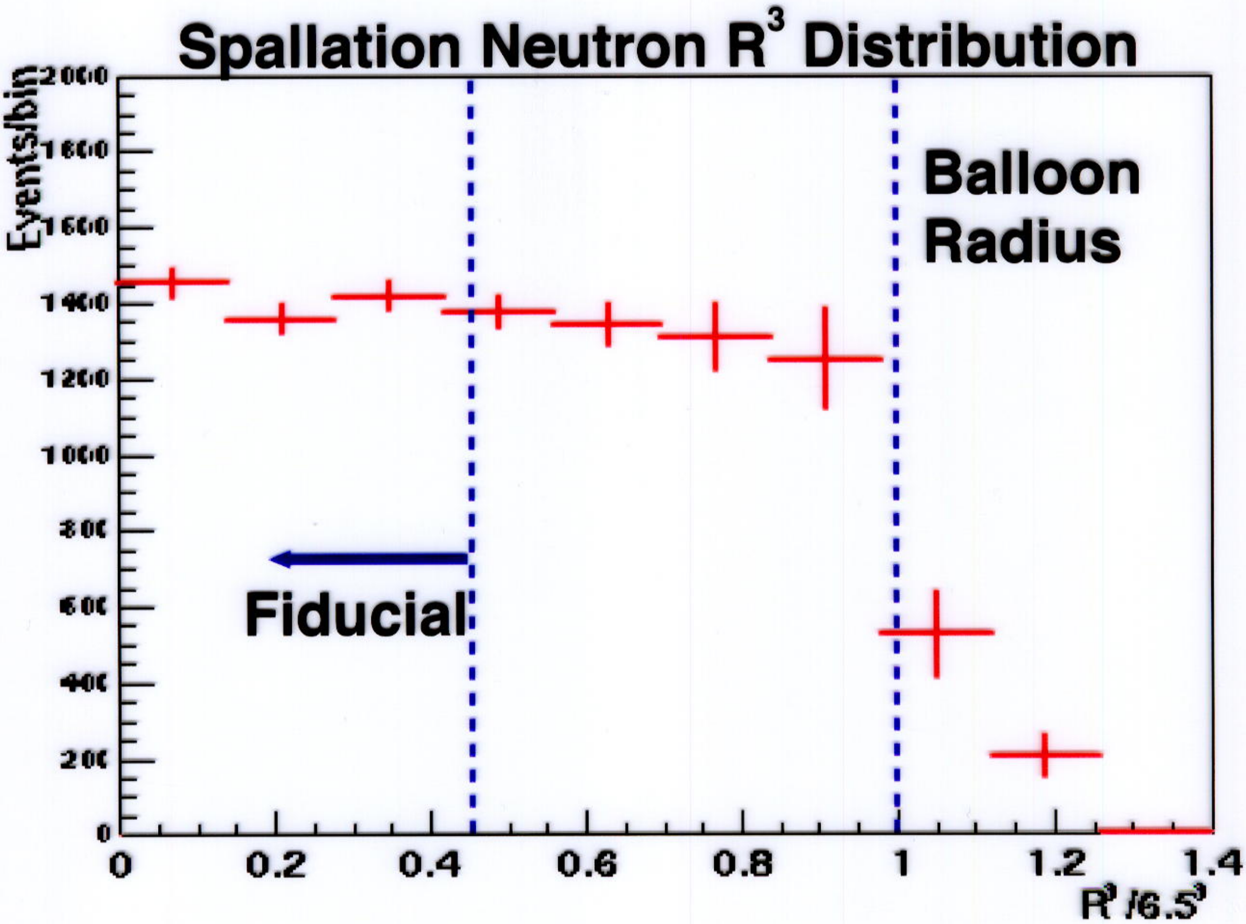

ΔE/E
0.04
0.02
0
0.02
0.04
0 1 2 3 4 5 6 7 8 9
energy [MeV]


Z deviation [cm]
15
10
5
0
5
10
15
Ge
Zn
Co
Am/Be(2.2MeV)
Am/Be(4.4MeV)
Am/Be(7.6MeV)
+ 5cm
Fiducial
600 400 200 0 200 400 600
z position [cm]

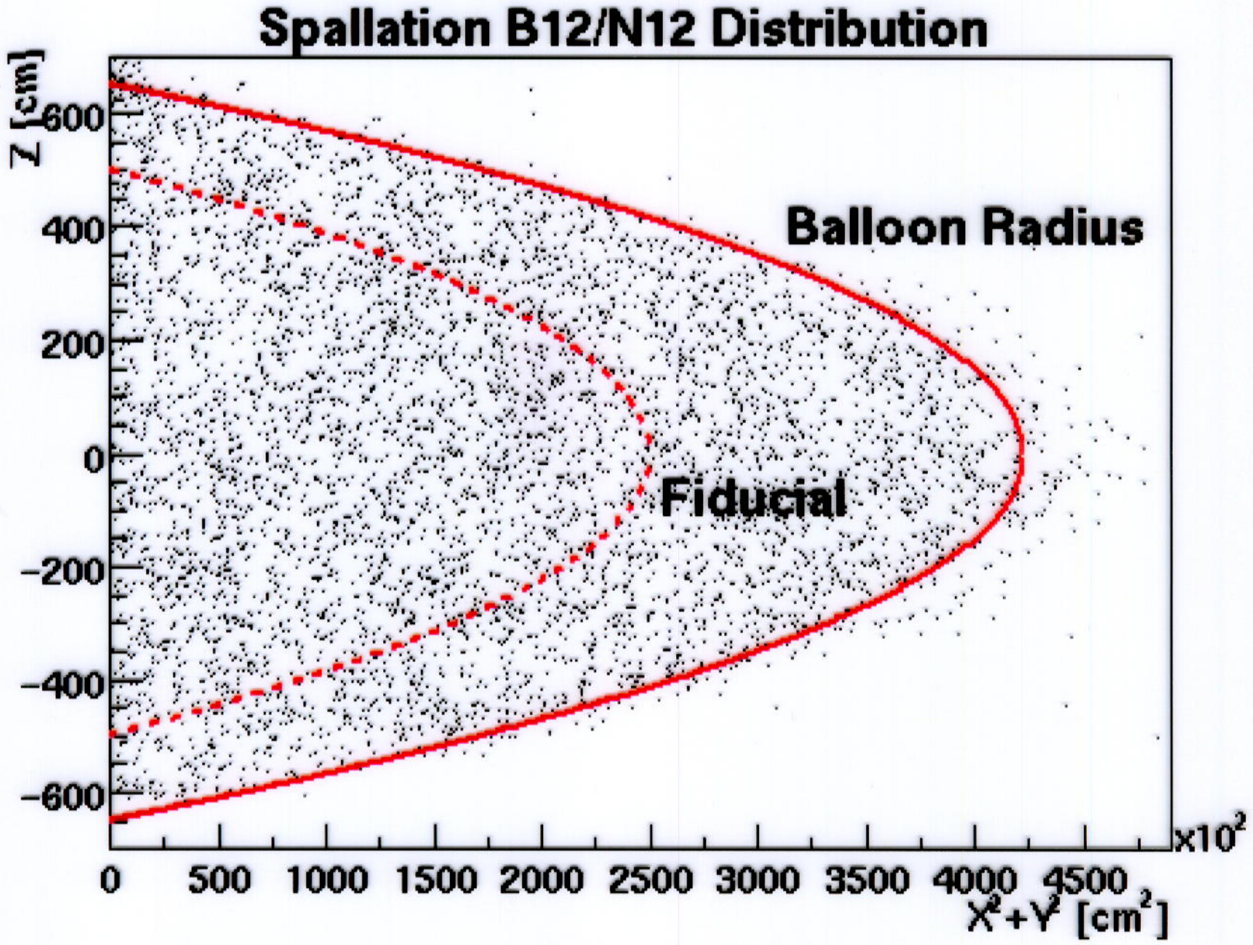

events
2000
1600
1200
800
400
0
(b)
fiducial
0 0.2 0.4 0.6 0.8 1 1.2 1.4
(R/6.5m)³

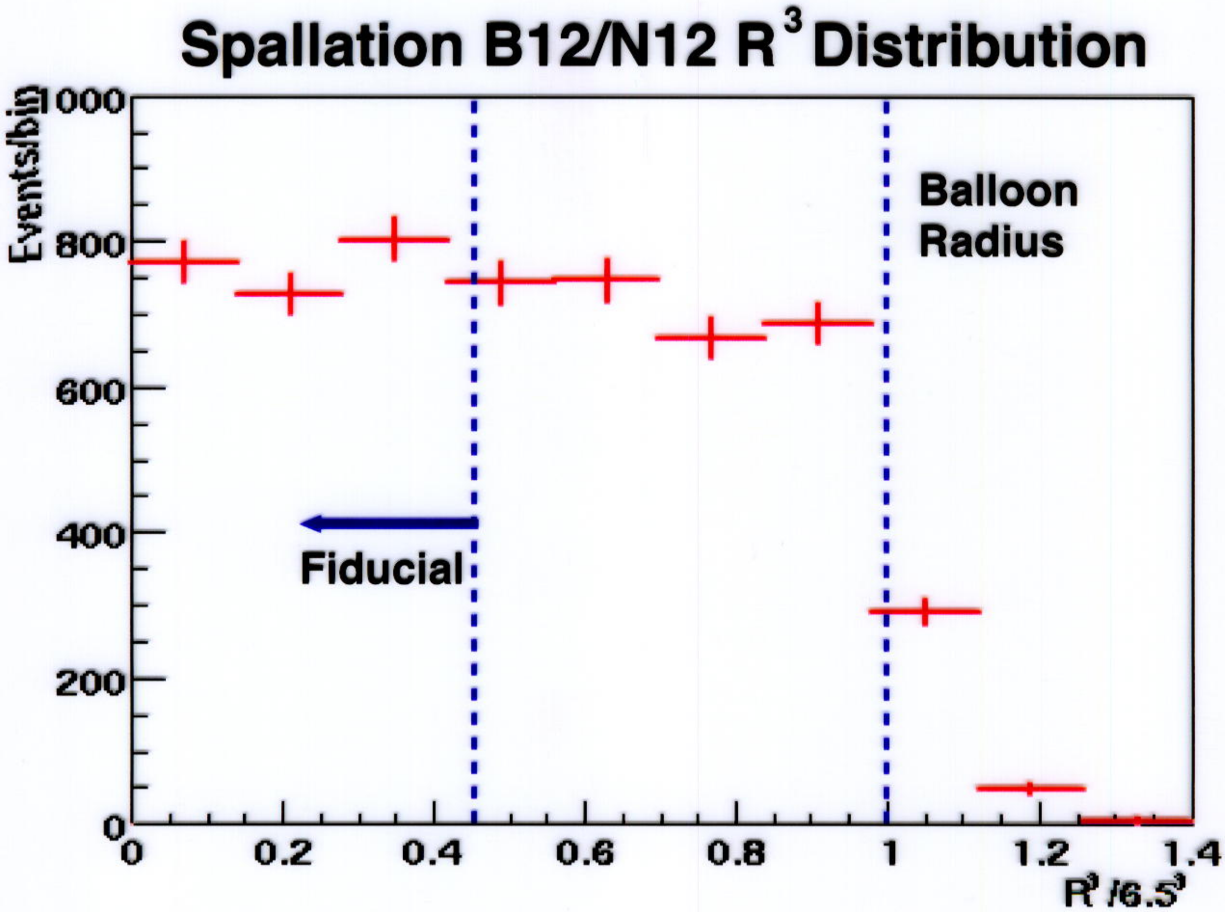


before BG subtraction



−1.48 ± 2.58% → ± 4.06%





$+0.16 \pm 3.34\% \rightarrow \pm 3.5\%$

Achieved Systematic Errors

LS total mass	2.13%	$1171 \pm 25\ m^3$
Fiducial/Total	4.06%	
Energy Threshold	2.13%	
Reactor Power	2.05%	
Fuel Composition	1.0%	
Time Lag	0.28%	
Neutrino Spectra	2.48%	
Cross Section	0.2%	
Live Time	0.07%	
Delayed Tag	2.06%	
Total Error	6.42%	

Systematic errors achieved by middle baseline experiments

Palo Verde

systematic	Method1(%)	Method2(%)
e+ efficiency	4	4
n efficiency	3	3
$\bar{\nu}_e$ flux prediction	3	3
$\bar{\nu}_e$ selection cuts	8	4
B_{pn} estimate	–	4
Total	10	8

CHOOZ

parameter	relative error (%)
reaction cross section	1.9
number of protons	0.8
detection efficiency	1.5
reactor power	0.7
energy absorbed per fission	0.6
combined	2.7%

KamLAND goal 5% ?

放射性不純物に対する要請

＊原子炉ニュートリノ

LS: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-13}, 10^{-13}, 10^{-14}$ g/g, 1mBq/m^3

BO: ^{232}Th 10^{-12}g/g

＊地球ニュートリノ

LS: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-14}, 10^{-14}, 10^{-15}$ g/g, 100μBq/m^3

BO: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-13}, 10^{-13}, 10^{-14}$ g/g, 1mBq/m^3

＊太陽ニュートリノ

日夜変動

LS: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-15}, 10^{-15}, 10^{-17}$ g/g, 100μBq/m^3

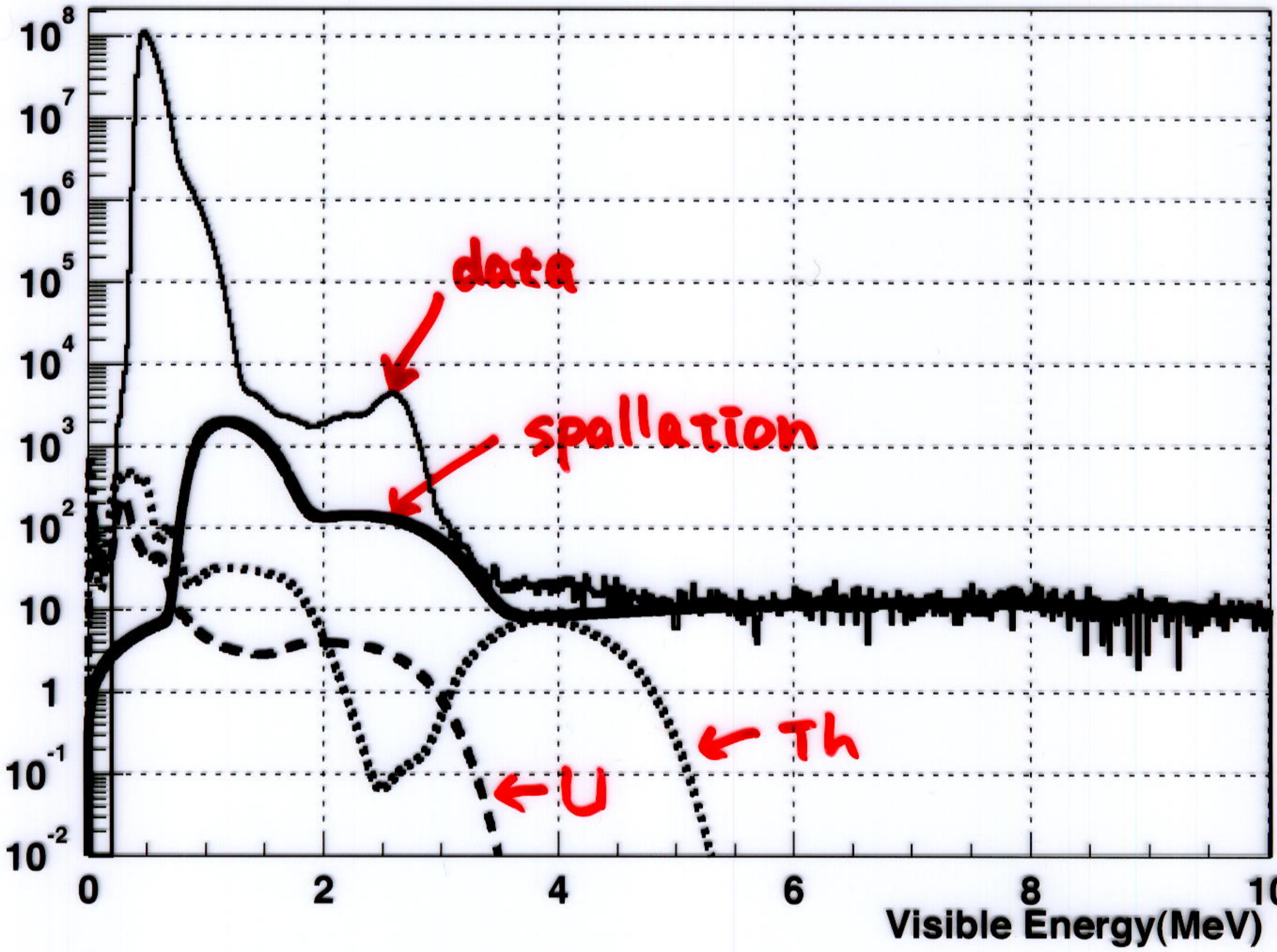
BO: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-13}, 10^{-13}, 10^{-15}$ g/g, 1mBq/m^3

その他

LS: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-16}, 10^{-16}, 10^{-18}$ g/g, 10μBq/m^3

BO: $^{238}U/^{232}Th/^{40}K/^{222}Rn$ $10^{-14}, 10^{-14}, 10^{-16}$ g/g, 100μBq/m^3

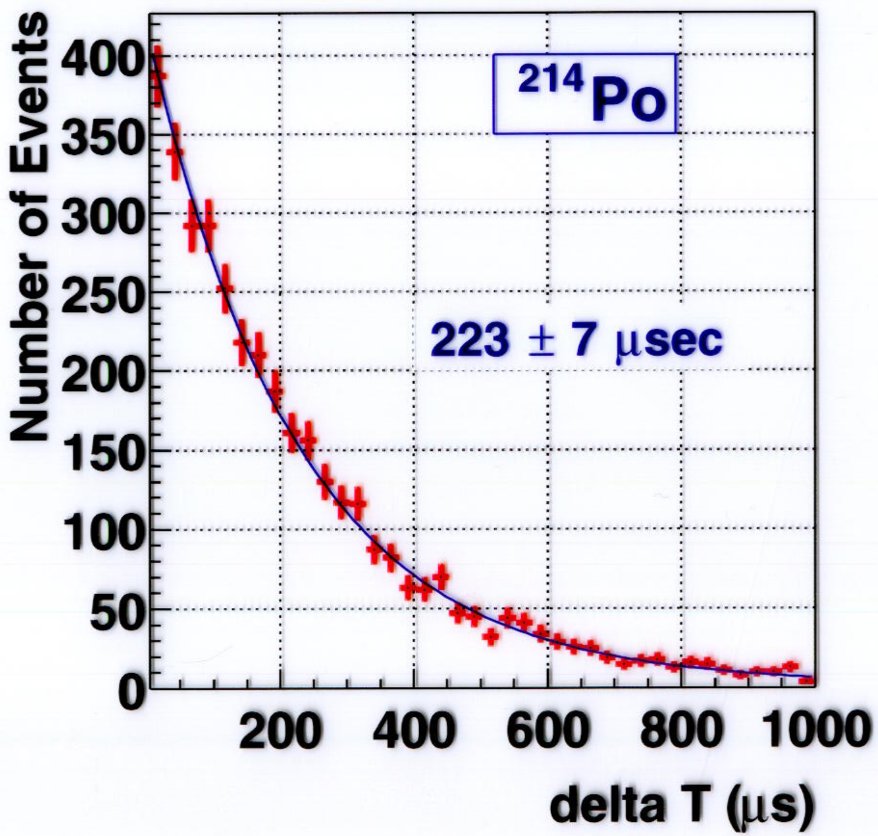
許容できる鉱山のほこり　100mg (LS), 10g (BO)

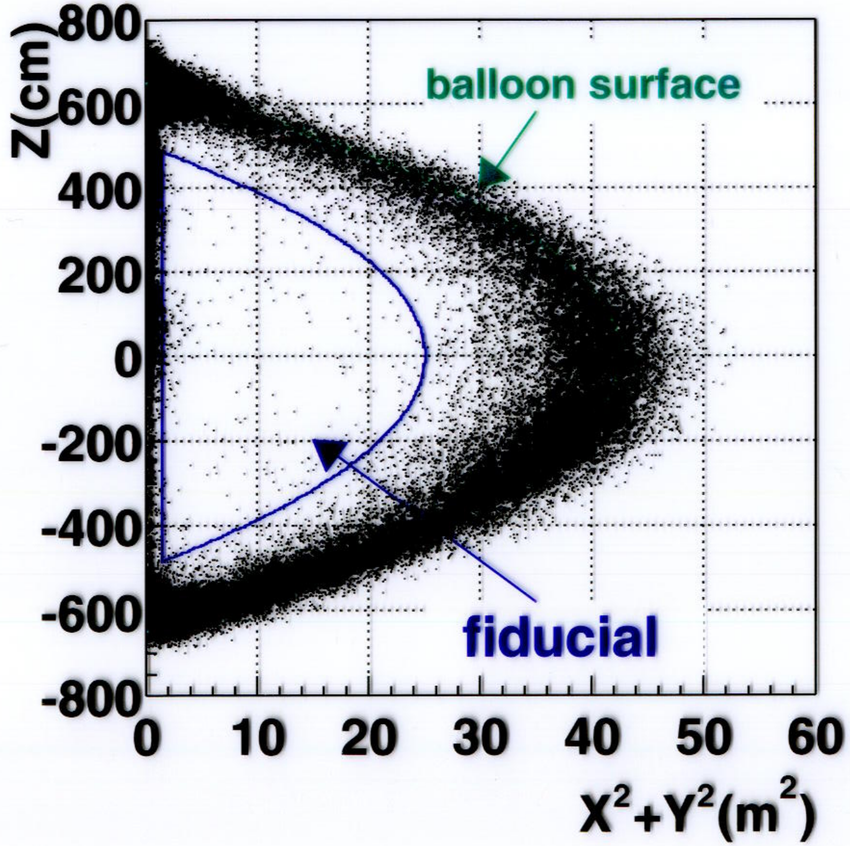


data
spallation
← Th
← U
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
0
2
4
6
8
10
Visible Energy(MeV)

$$^{214}Bi \xrightarrow{\beta,\gamma} {}^{214}Po \xrightarrow[7.687\,MeV]{\alpha}$$

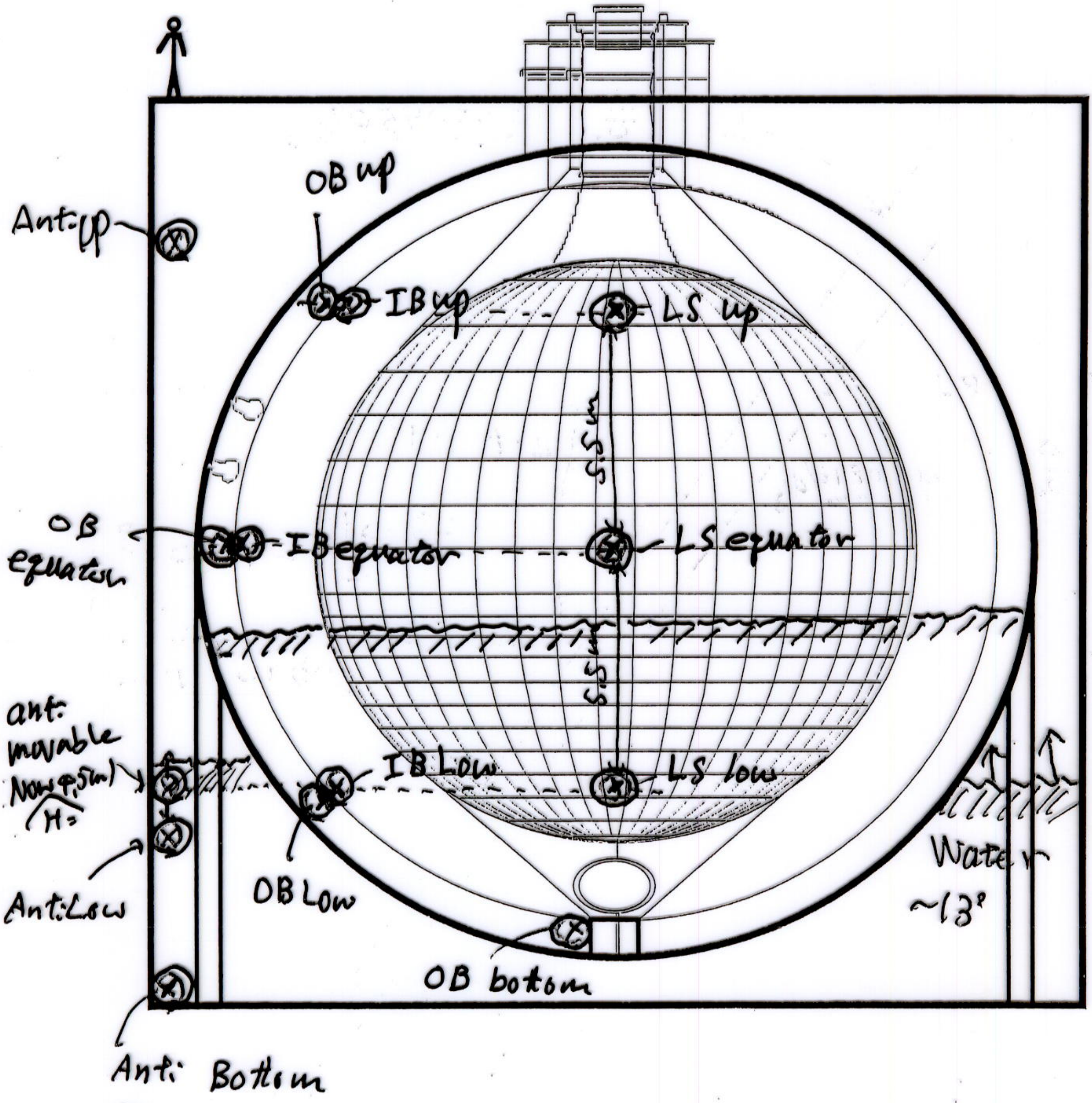
$\tau = 237\,\mu s$





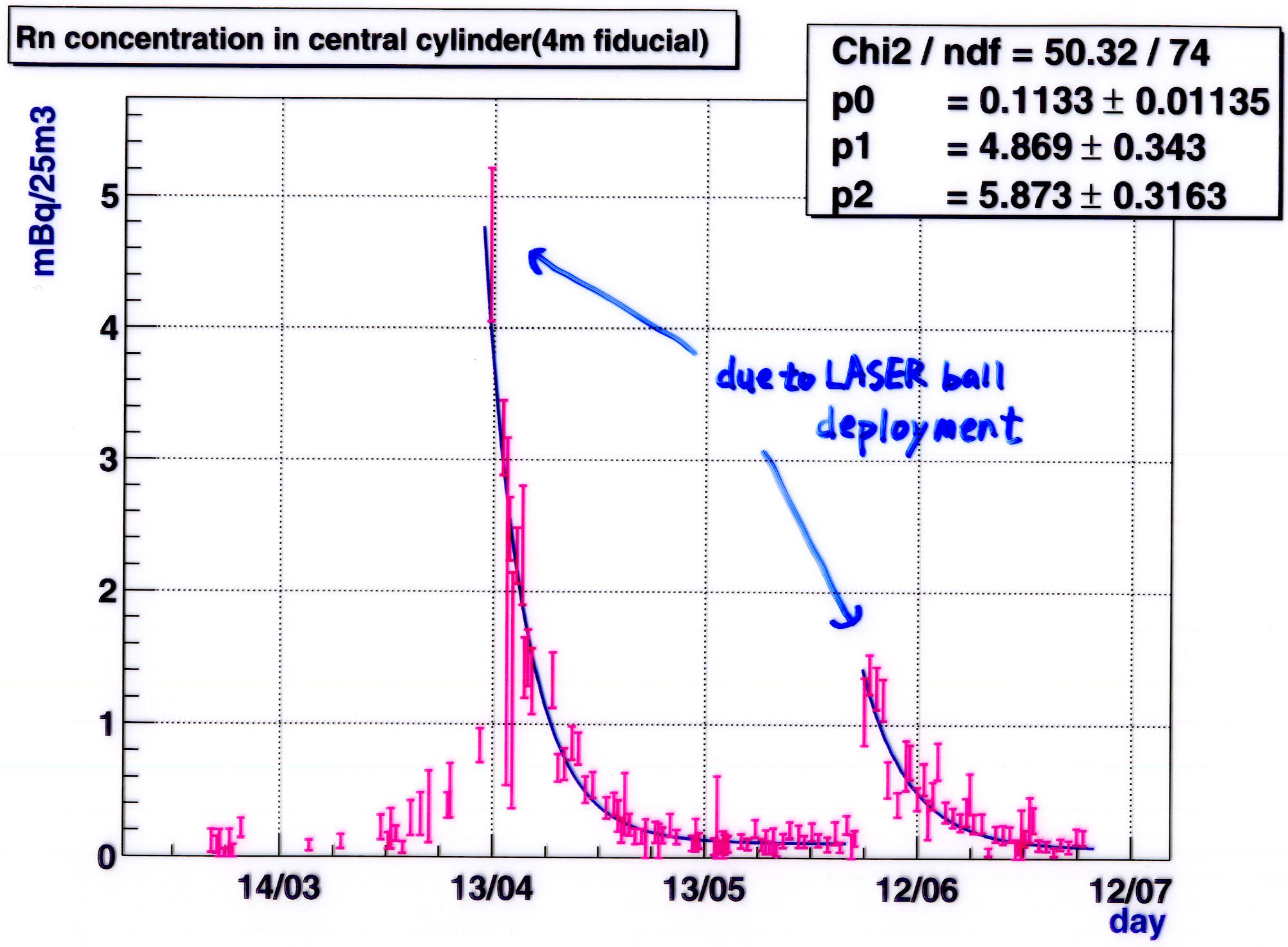
positions of Pt thermo tips.

(14 thermo Pt tips)

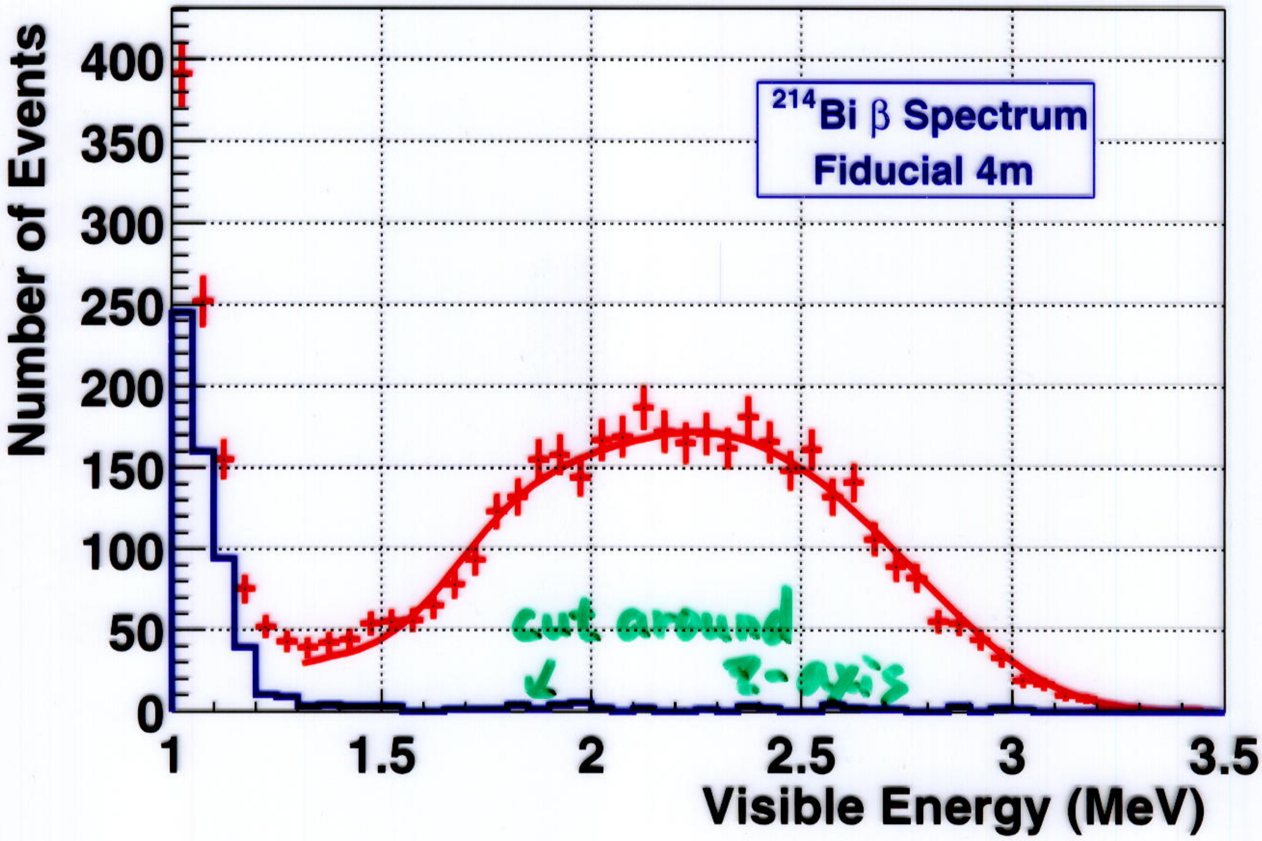


Pt thermometers are suspended at z=5.5, 0, -5.5 m

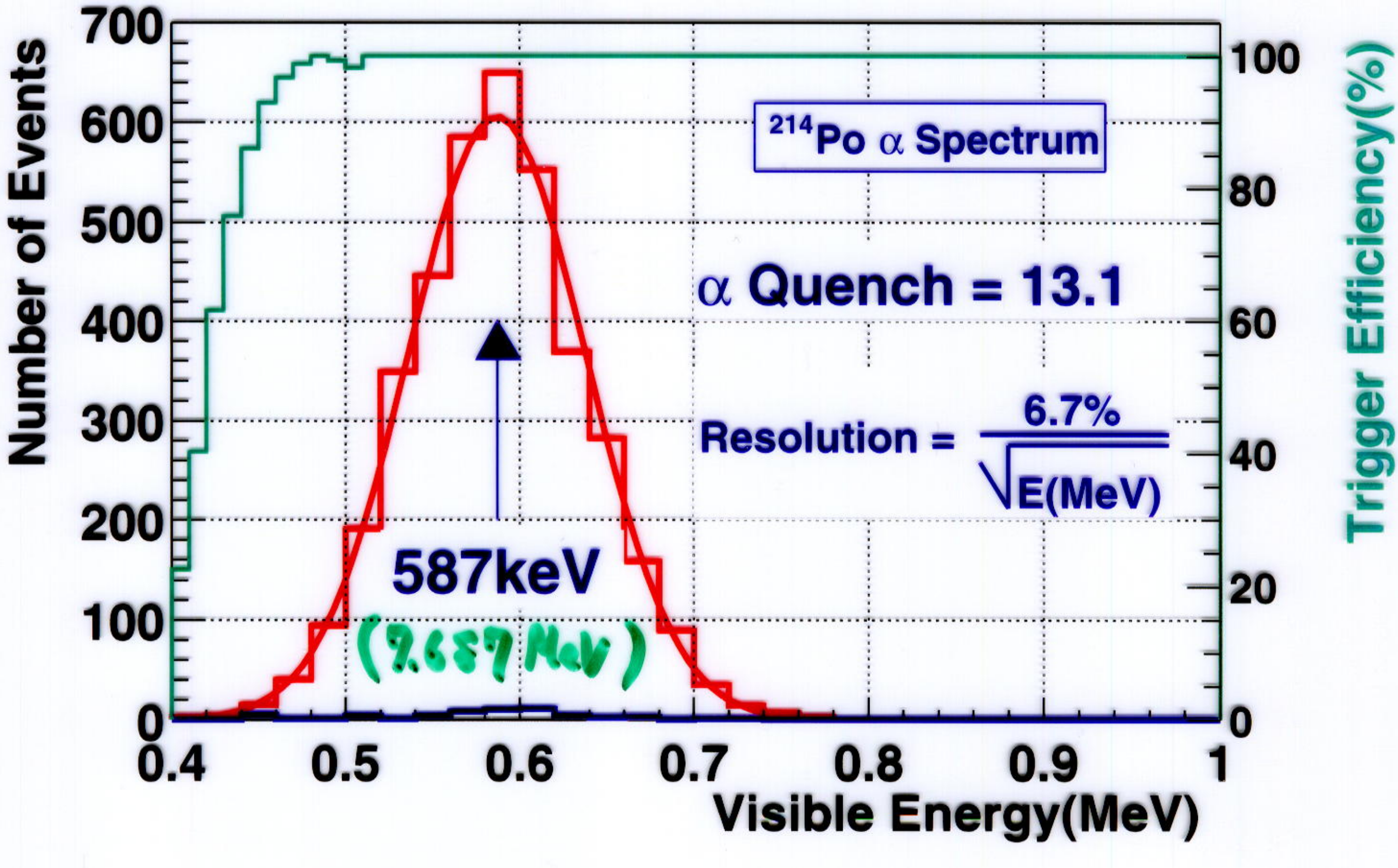
(Pt w/ stainless capsule)



Rn concentration in central cylinder(4m fiducial)
Chi2 / ndf = 50.32 / 74
p0 = 0.1133 ± 0.01135
p1 = 4.869 ± 0.343
p2 = 5.873 ± 0.3163
mBq/25m3
0
1
2
3
4
5
14/03
13/04
13/05
12/06
12/07
day
due to LASER ball deployment



Number of Events
400
350
300
250
200
150
100
50
0
1
1.5
2
2.5
3
3.5
Visible Energy (MeV)
^{214}Bi β Spectrum
Fiducial 4m
cut around
z-axis

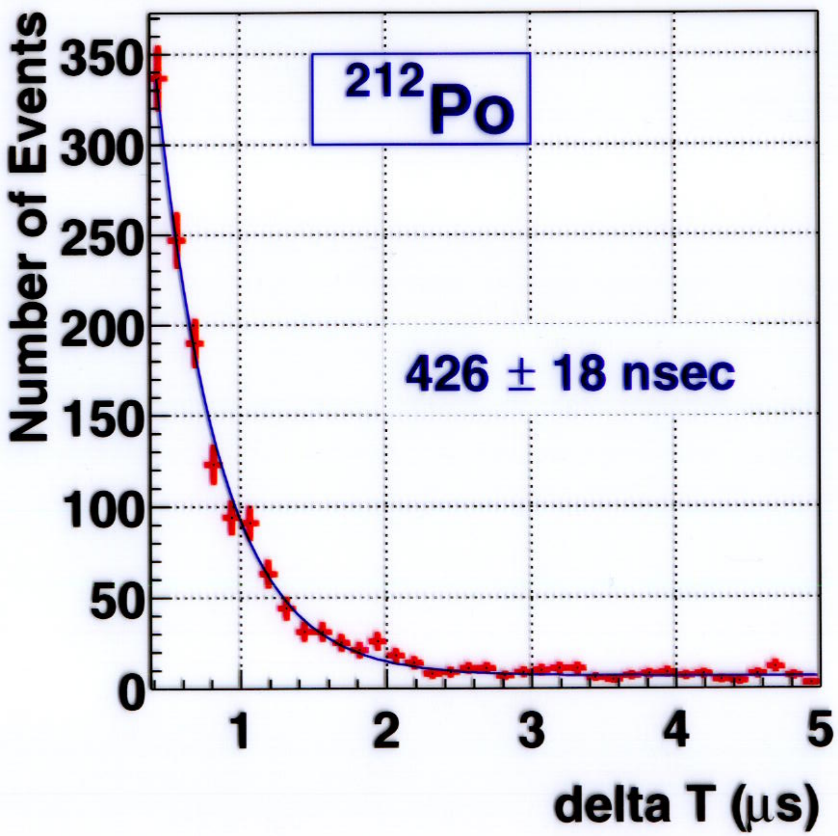


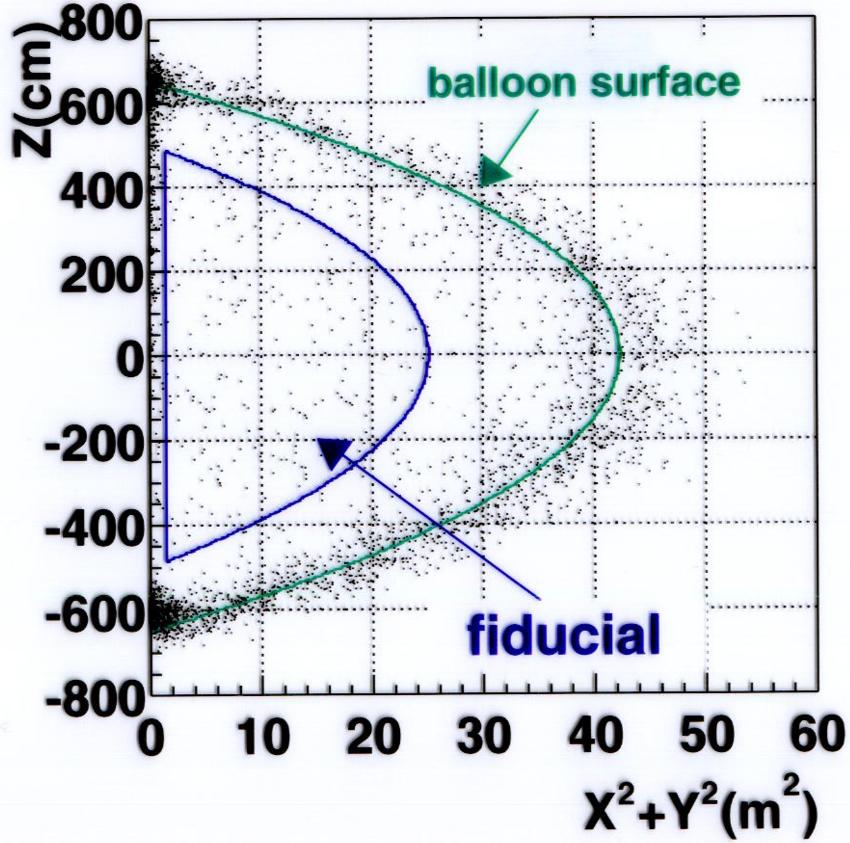
Number of Events
700
600
500
400
300
200
100
0
0.4
0.5
0.6
0.7
0.8
0.9
1
Visible Energy(MeV)
Trigger Efficiency(%)
100
80
60
40
20
0
^{214}Po α Spectrum
α Quench = 13.1
Resolution = 6.7% / √E(MeV)
587keV
(7.687 MeV)

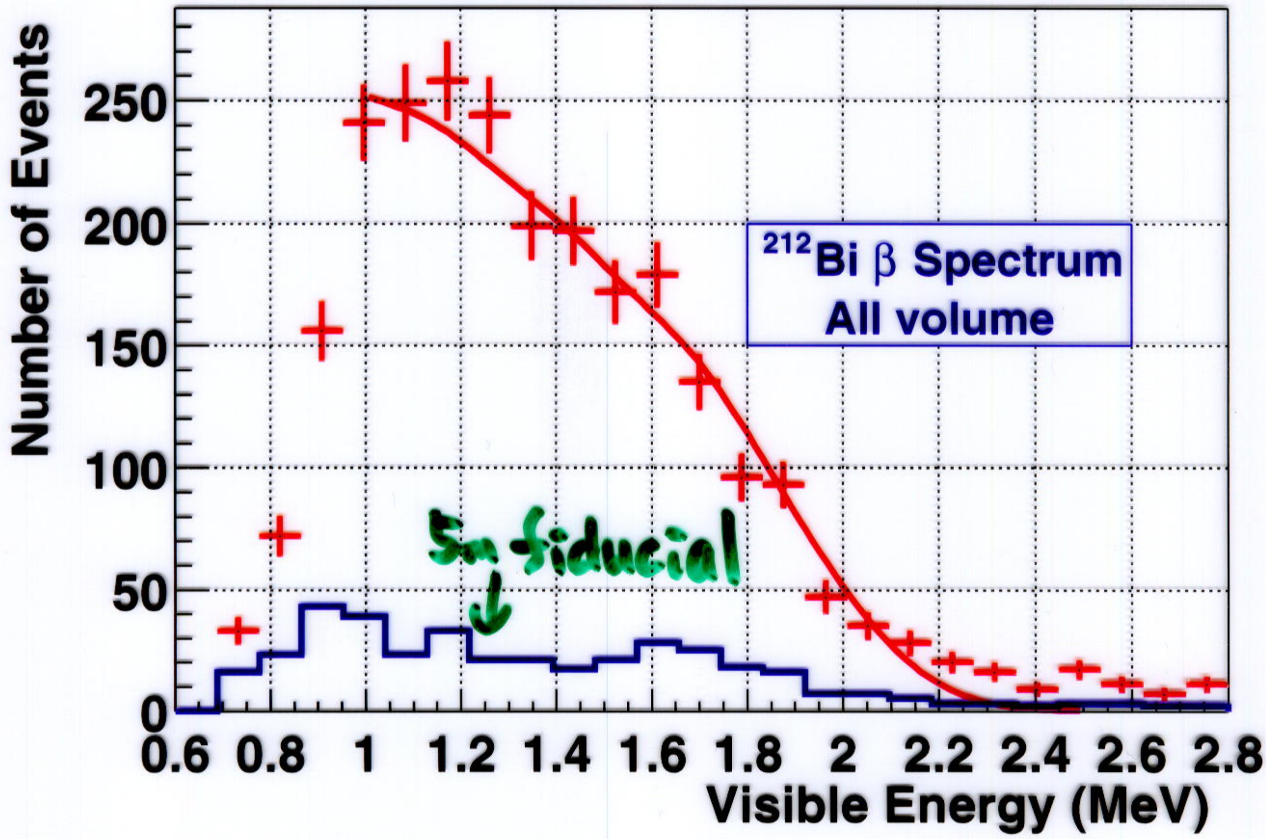
$^{212}Bi \xrightarrow{\beta,\gamma} {}^{212}Po \xrightarrow{\alpha}$

8.784 MeV

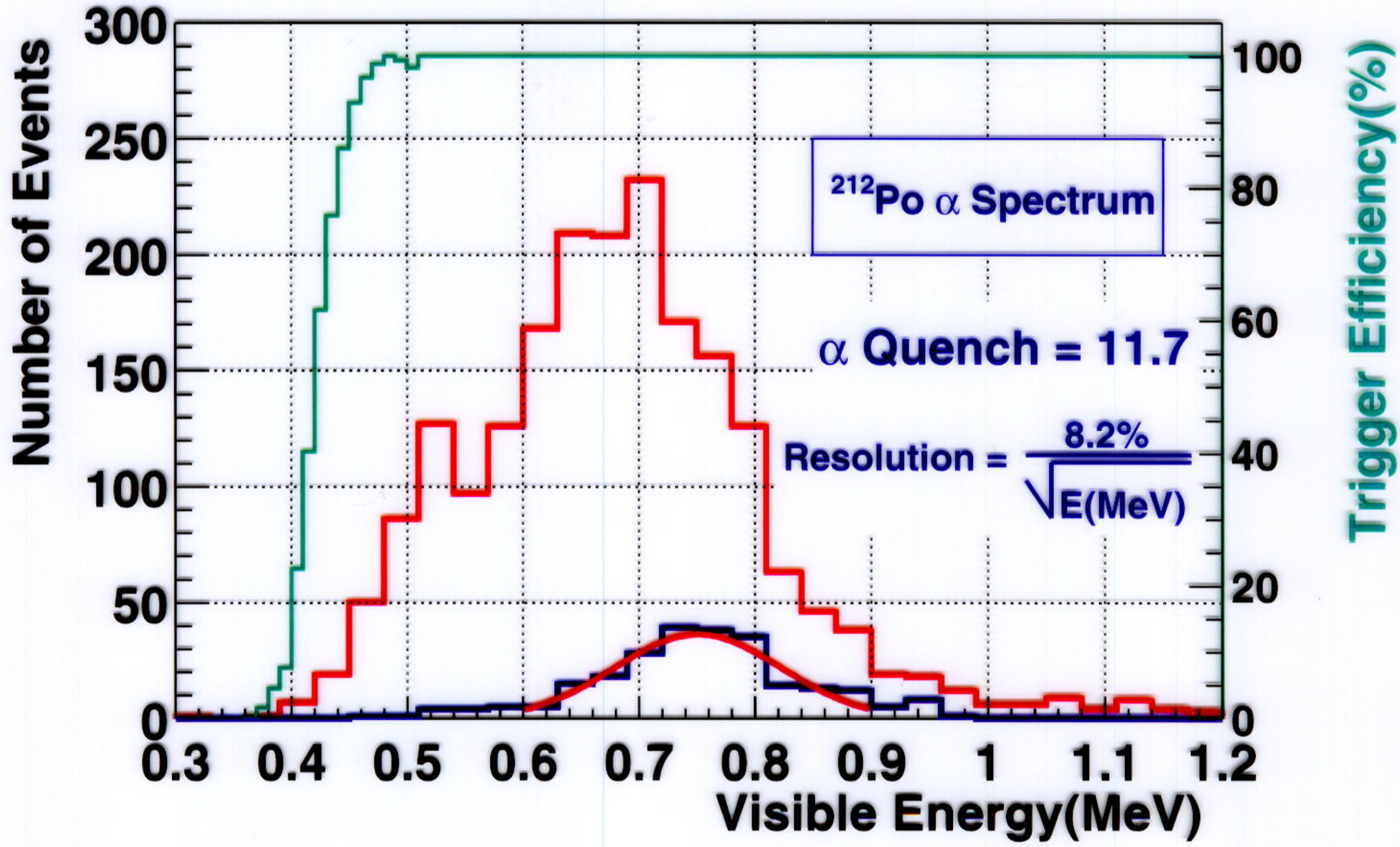
$\tau \simeq 0.431 \mu s$







Number of Events
250
200
150
100
50
0
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
Visible Energy (MeV)
212Bi β Spectrum
All volume
5m fiducial



Number of Events
300
250
200
150
100
50
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
Visible Energy(MeV)
Trigger Efficiency(%)
100
80
60
40
20
0
212Po α Spectrum
α Quench = 11.7
Resolution = 8.2% / √E(MeV)

Measured Impurity Level

^{238}U	$3.5 \pm 0.5 \times 10^{-18}$ g/g
^{232}Th	$5.2 \pm 0.8 \times 10^{-17}$ g/g
^{40}K	$< 2.7 \times 10^{-16}$ g/g
^{85}Kr	1 Bq/m^3
^{210}Pb	0.1 Bq/m^3

Achieved Background Level

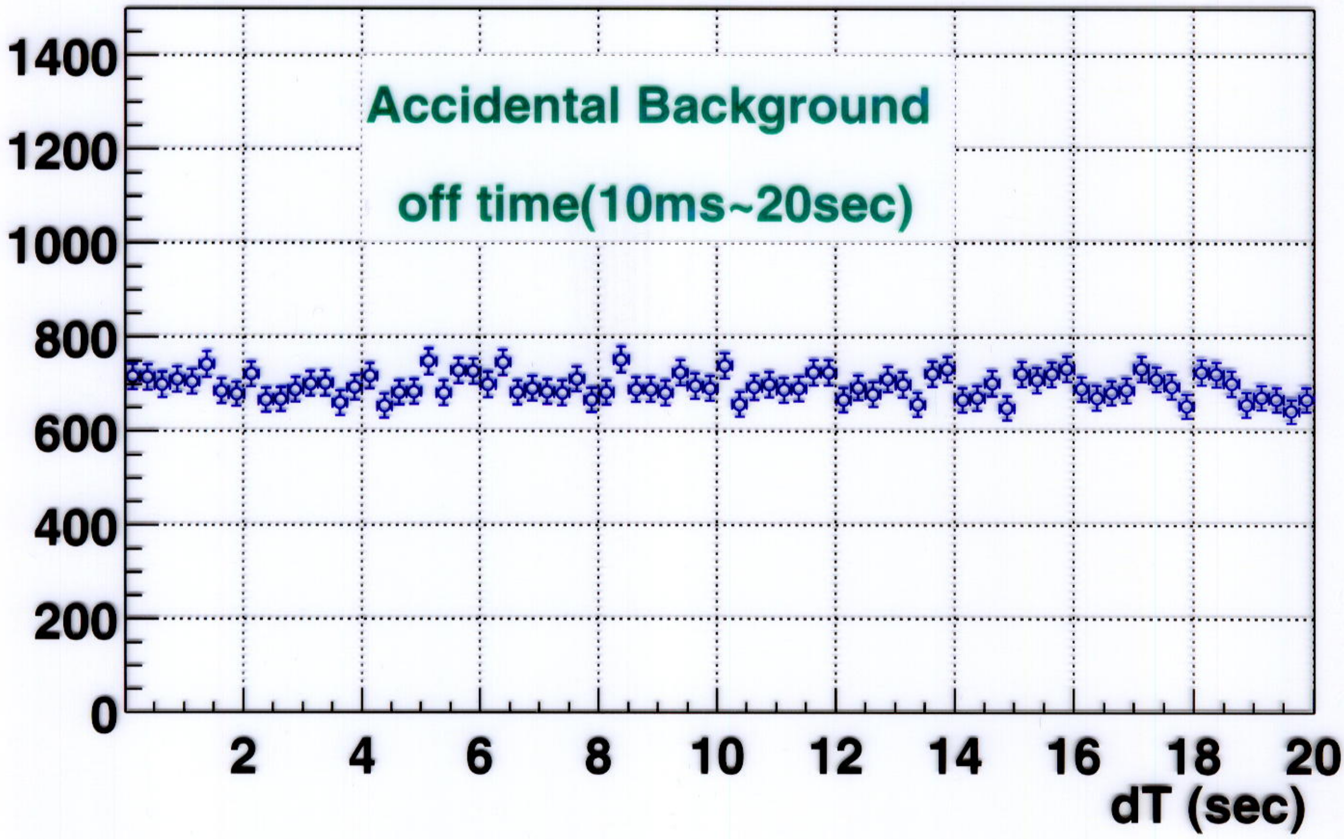
	0.9 MeV threshold	2.6 MeV threshold
Accidental	1.2×10^{-2} ev/day	6×10^{-5} ev/day
9Li/8He	$8 \pm 8 \times 10^{-3}$ ev/day	$7 \pm 7 \times 10^{-3}$ ev/day
fast neutron	$< 3 \times 10^{-3}$ ev/day	$< 3 \times 10^{-3}$ ev/day
16TWgeo-ν	6×10^{-2} ev/day	3×10^{-4} ev/day
$\text{Total}_{\text{w/o geo}}$	0.02 ± 0.01 ev/day	$7 \pm 7 \times 10^{-3}$ ev/day
S/N	~50	~100

Impurities in the LS

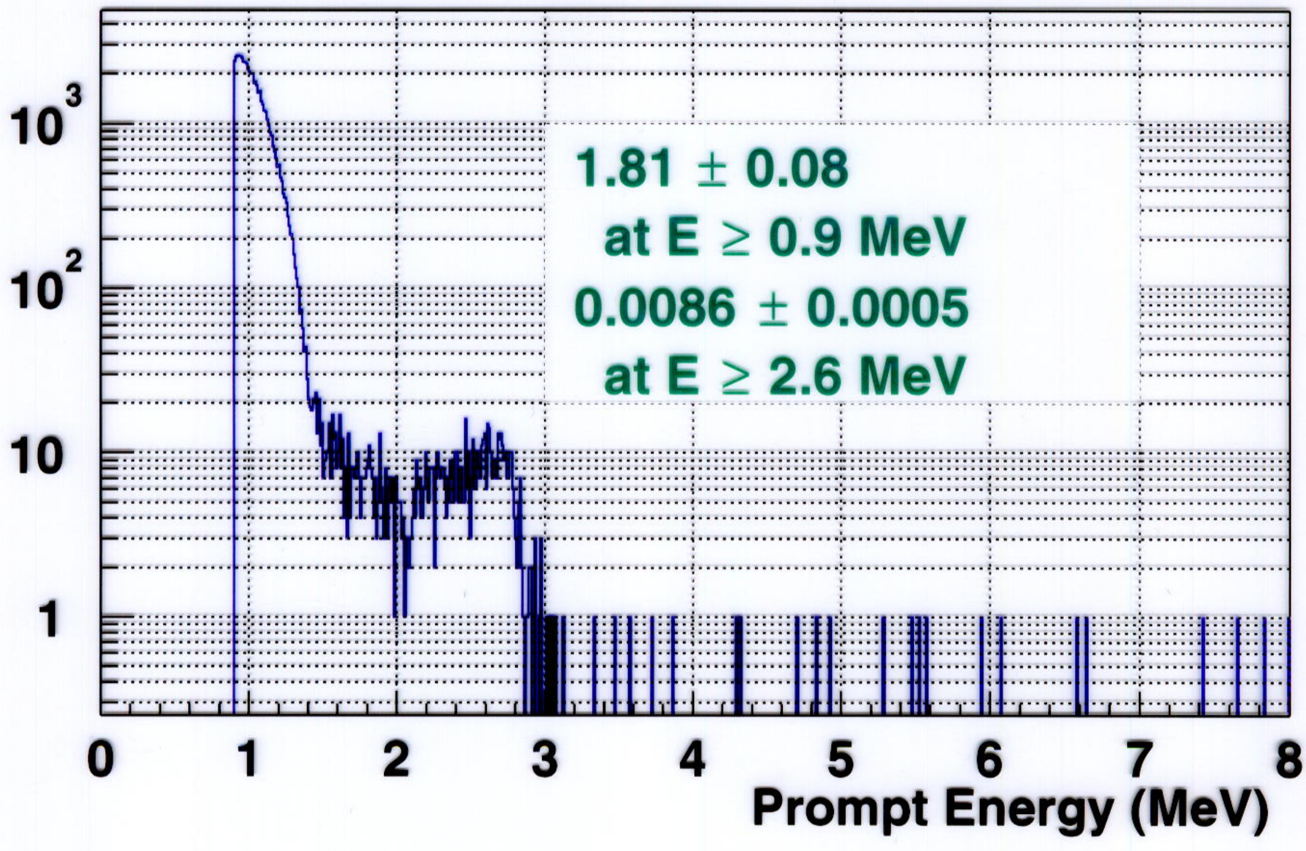
			Requirements reactor	solar
^{222}Rn	$0.03\mu Bq/m^3$	^{214}Bi->^{214}Po(τ=237μsec)		
^{238}U	$(3.5 \pm 0.5)\times 10^{-18}$ g/g	(assuming equilibrium)	10^{-13}g/g	10^{-16}g/g
^{232}Th	$(5.2 \pm 0.8)\times 10^{-17}$g/g	^{212}Bi->^{212}Po(τ=0.431μsec)	10^{-13}g/g	10^{-16}g/g
^{40}K	$<2.7\times 10^{-16}$g/g	single rate	10^{-14}g/g	10^{-18}g/g
^{85}Kr	~$1Bq/m^3$	single rate/delayed coincidence		$1\mu Bq/m^3$
^{210}Pb	~$100mBq/m^3$	single rate		$1\mu Bq/m^3$

Impurities on the balloon

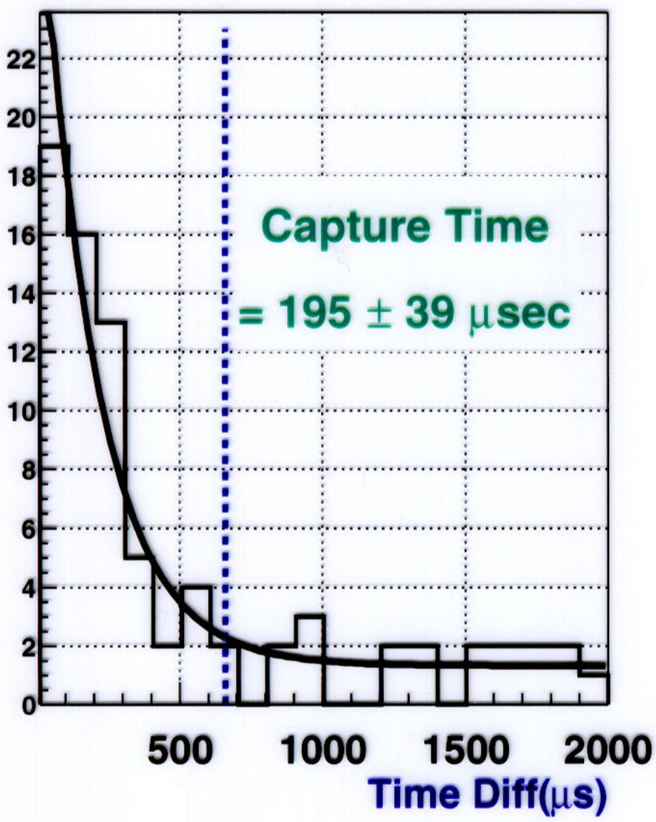
^{222}Rn	4.0×10^{-4}Bq	^{214}Bi->^{214}Po(τ=237μsec)
^{238}U	3.1×10^{-8}g	(assuming equilibrium)
	corresponds to 0.9g of mine dust	
^{232}Th	9.7×10^{-4}Bq	^{212}Bi->^{212}Po(τ=0.431μsec)
	corresponds to 0.1g of mine dust	

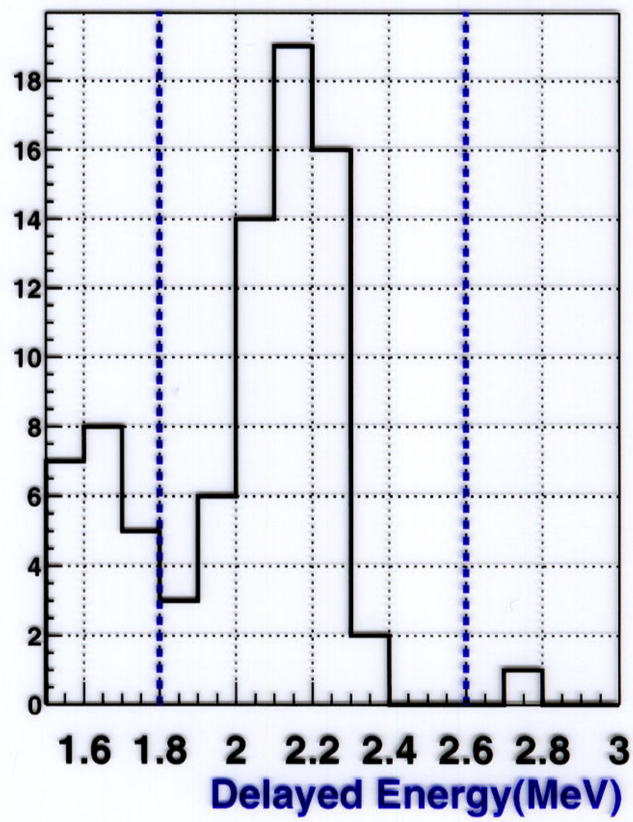


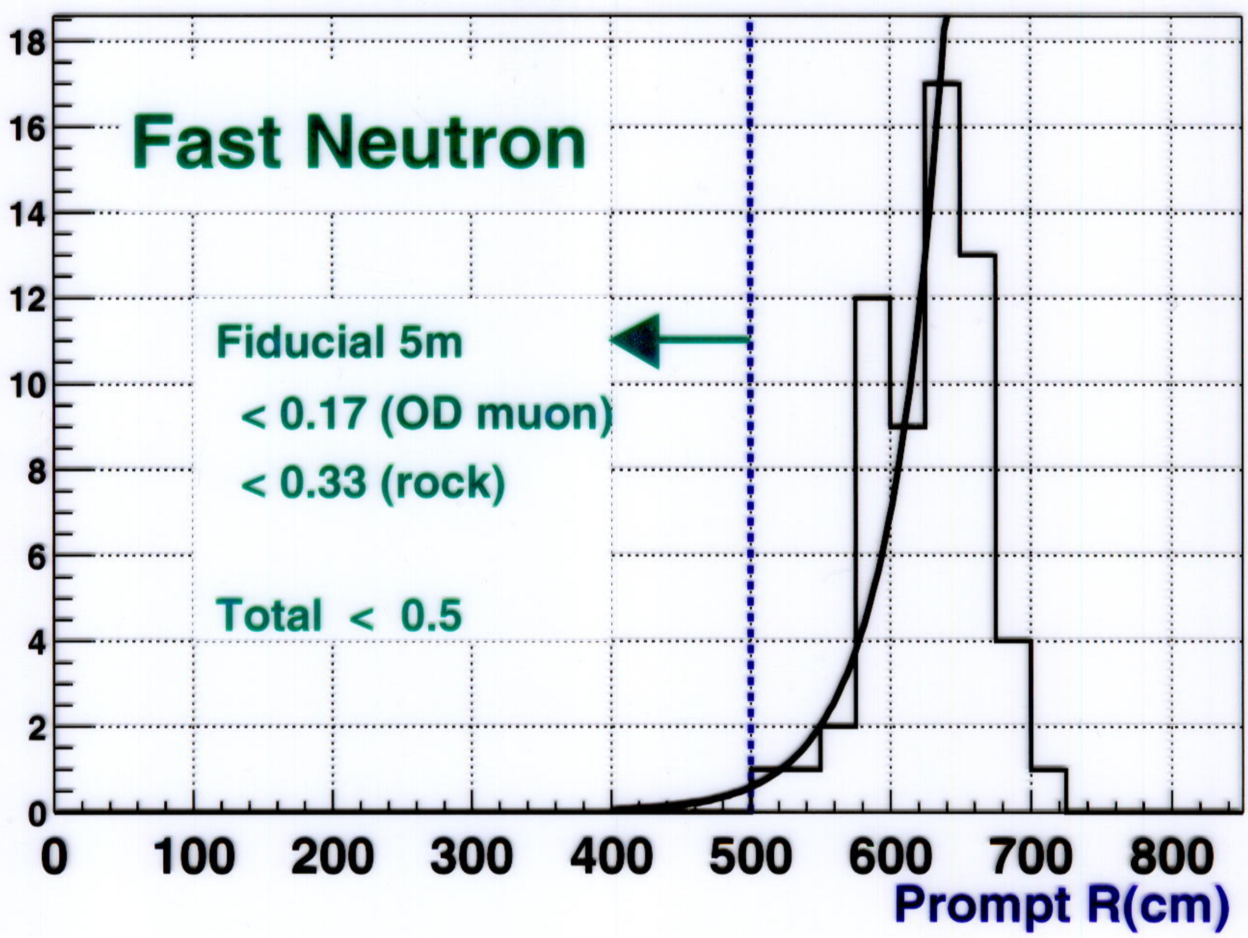
Accidental Background
off time(10ms~20sec)
1400
1200
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
18
20
dT (sec)



10^3
10^2
10
1
1.81 ± 0.08
at E ≥ 0.9 MeV
0.0086 ± 0.0005
at E ≥ 2.6 MeV
0
1
2
3
4
5
6
7
8
Prompt Energy (MeV)


Capture Time
= 195 ± 39 μsec
500
1000
1500
2000
Time Diff(μs)


1.6
1.8
2
2.2
2.4
2.6
2.8
3
Delayed Energy(MeV)


Fast Neutron
Fiducial 5m
< 0.17 (OD muon)
< 0.33 (rock)
Total < 0.5
0
100
200
300
400
500
600
700
800
Prompt R(cm)

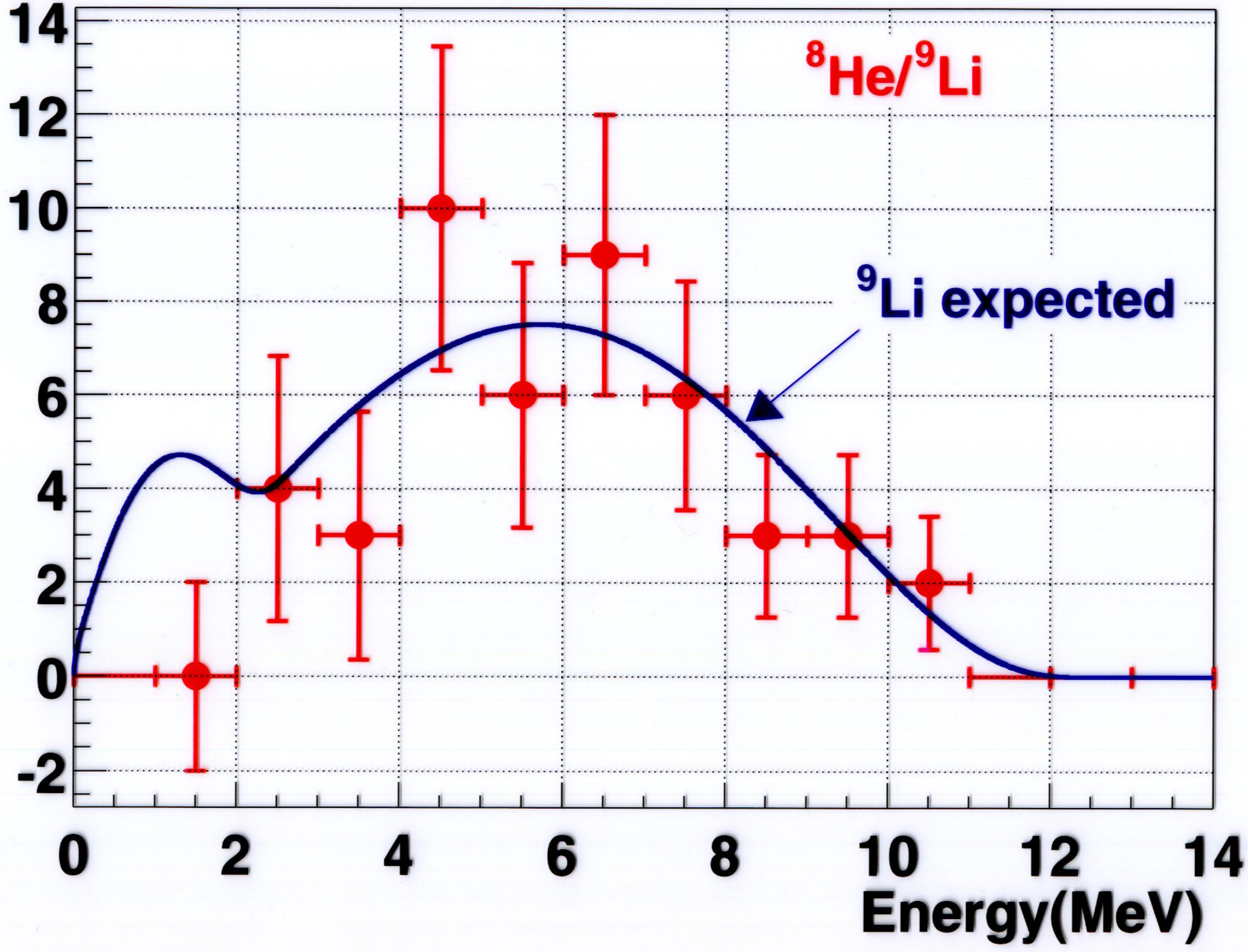
Spallation

	$T_{1/2}$	decay MeV	Hagner et al. expected rate /day/kton	measured at KamLAND /day/kton
11C	20.38min	0.96 β+	1039±106	
10C	19.26s	1.9 β+,0.72 γ	139±15	
total neutron			1317±195.6	1157.6±7(stat)
8He/9Li	0.12/0.18s	10.6/13.6 β-	2.4±0.5	4.7±1.3
7Be	53.3d	0.478 γ (10%)	21.4±2.9	
11Be	13.80s	11.5 β-	<2.4	
8Li	0.84s	16.0 β-	5.0±2.9	
6He	0.81s	3.5 β-	18.9±2.1	
8B	0.77s	13.7 β+	7.9±1.4	
9C	0.13s	16.0 β+	5.5±1.8	

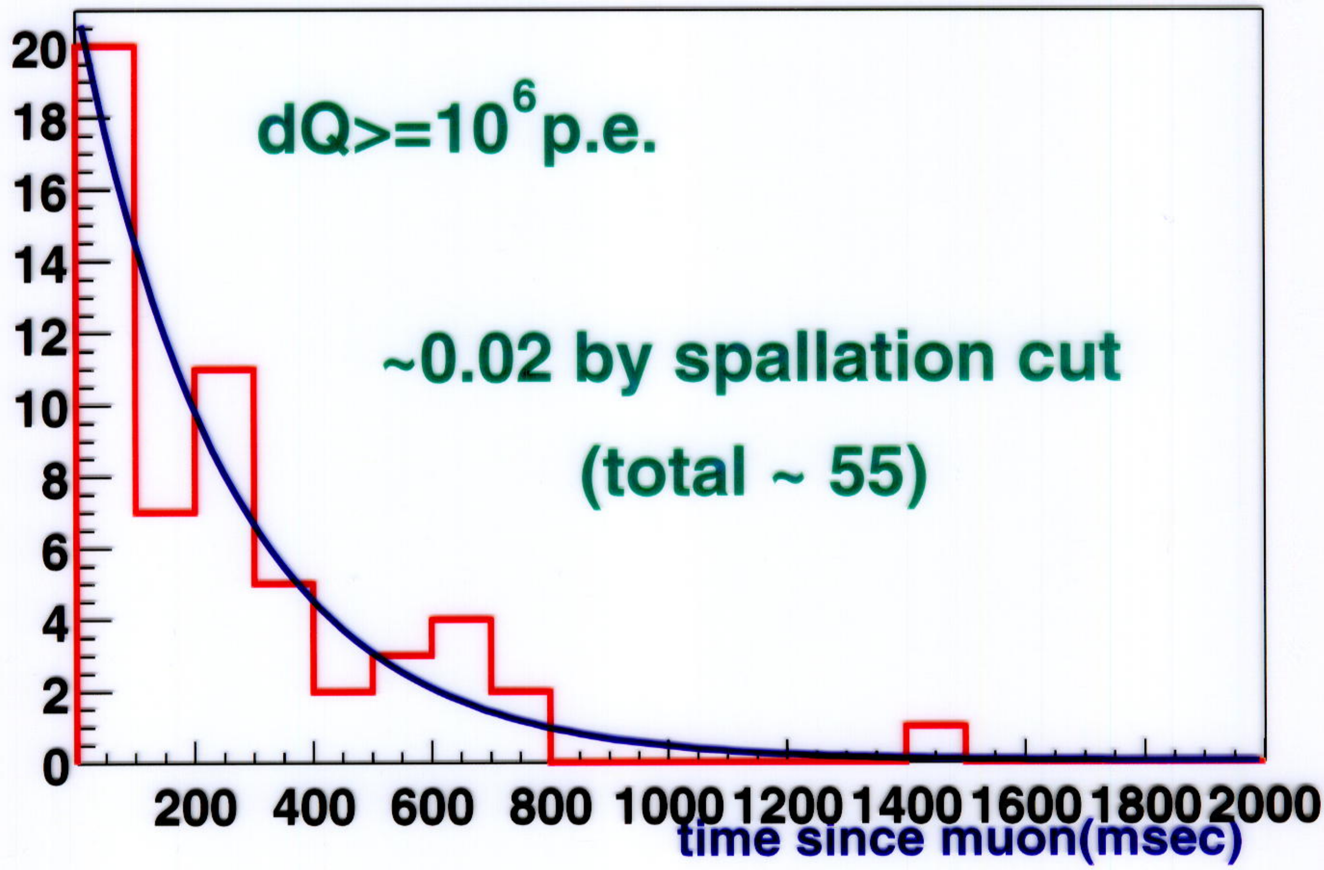
Backgrounds to be carefully rejected

$^{8}He \rightarrow {}^{8}Li + \beta^-$ (84%)
$\phantom{^{8}He \rightarrow} {}^{7}Li + \beta^- + n$ (16%)

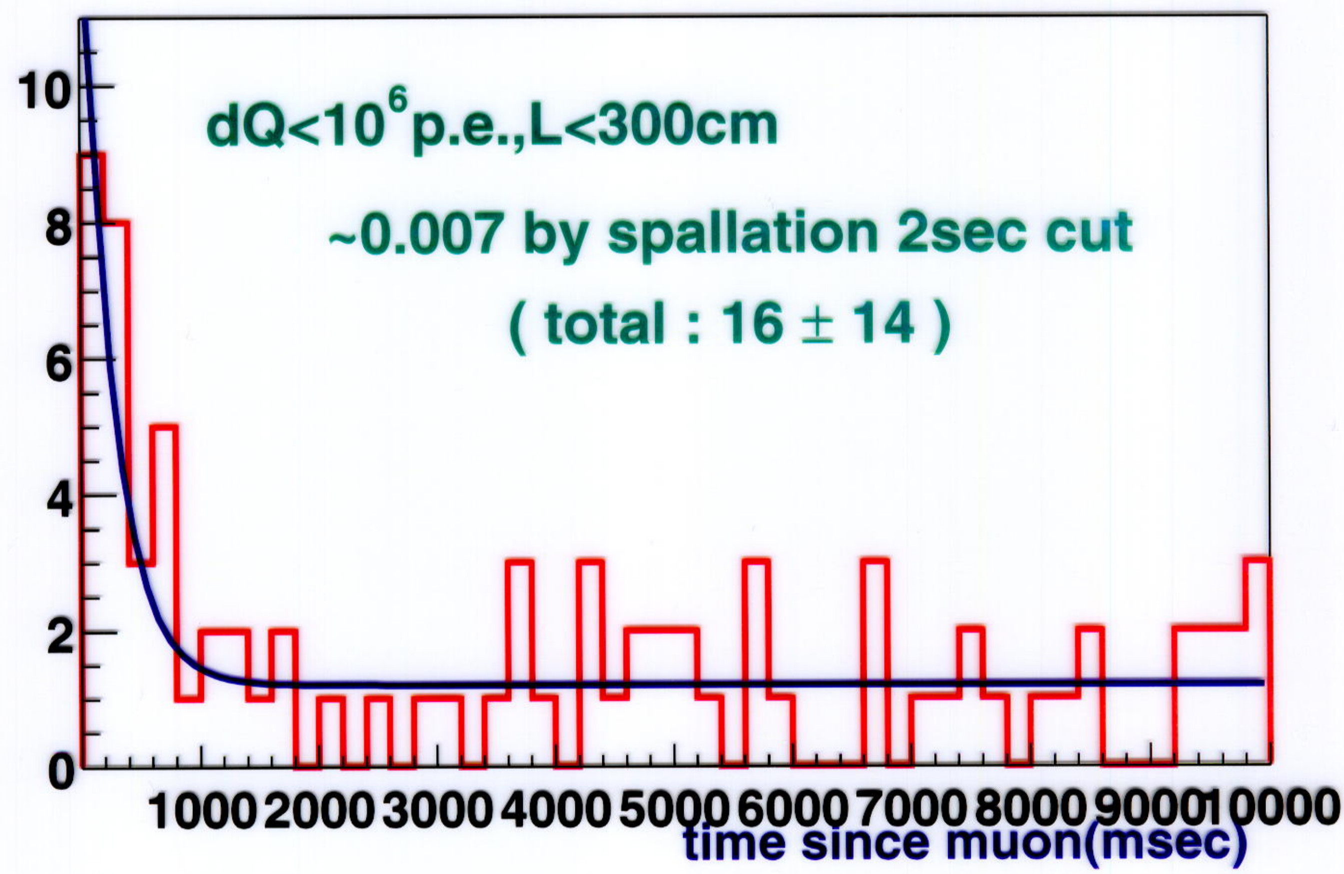
$^{9}Li \rightarrow {}^{9}Be + \beta^-$ (50%)
$\phantom{^{9}Li \rightarrow} {}^{8}Be + \beta^- + n$ (50%)



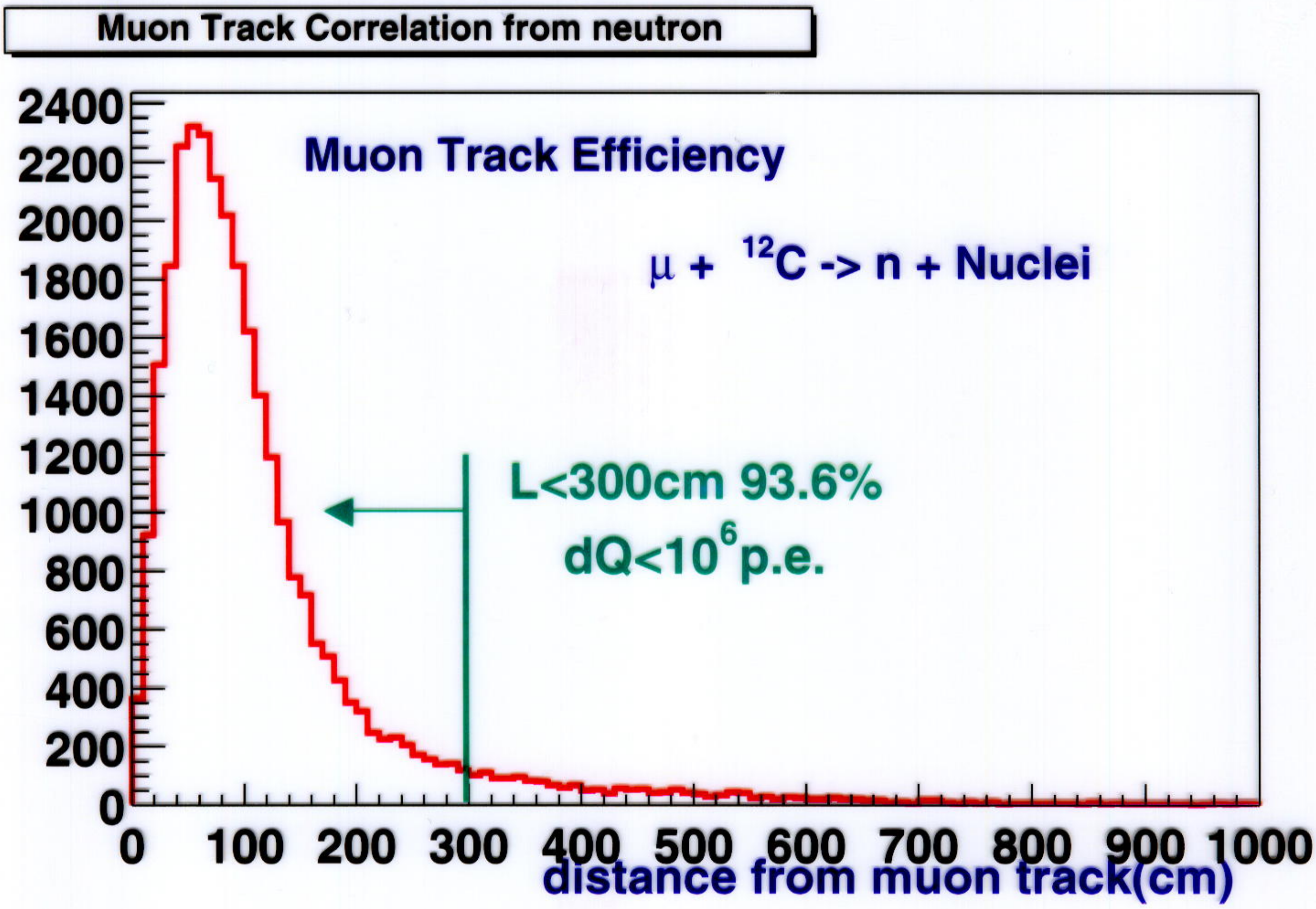
^{8}He/^{9}Li
^{9}Li expected
Energy(MeV)



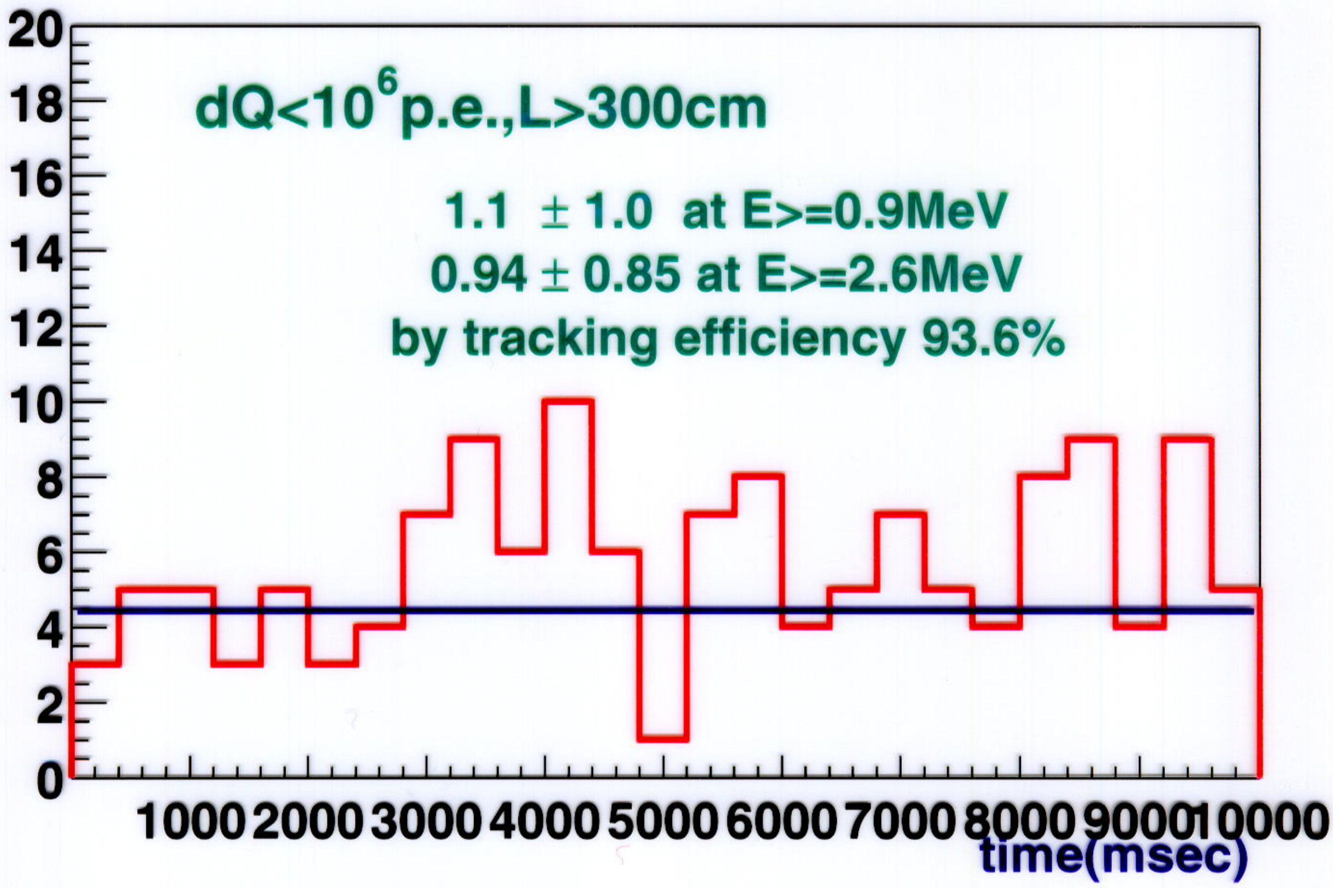
dQ>=10^6 p.e.
~0.02 by spallation cut
(total ~ 55)
time since muon(msec)



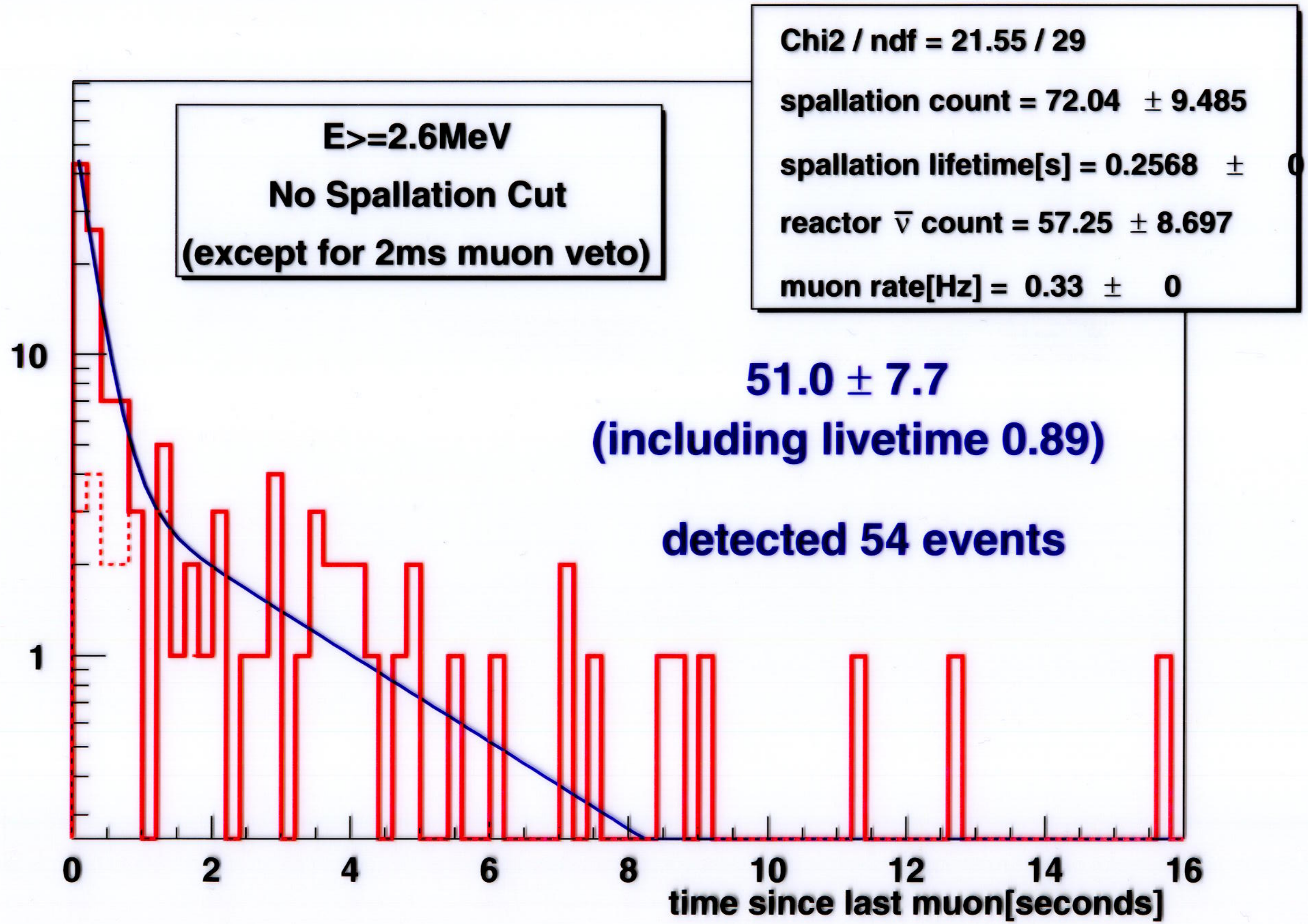
dQ<10^6 p.e.,L<300cm
~0.007 by spallation 2sec cut
(total : 16 ± 14)
time since muon(msec)



Muon Track Correlation from neutron
Muon Track Efficiency
μ + 12C -> n + Nuclei
L<300cm 93.6%
dQ<10^6 p.e.
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0 100 200 300 400 500 600 700 800 900 1000
distance from muon track(cm)

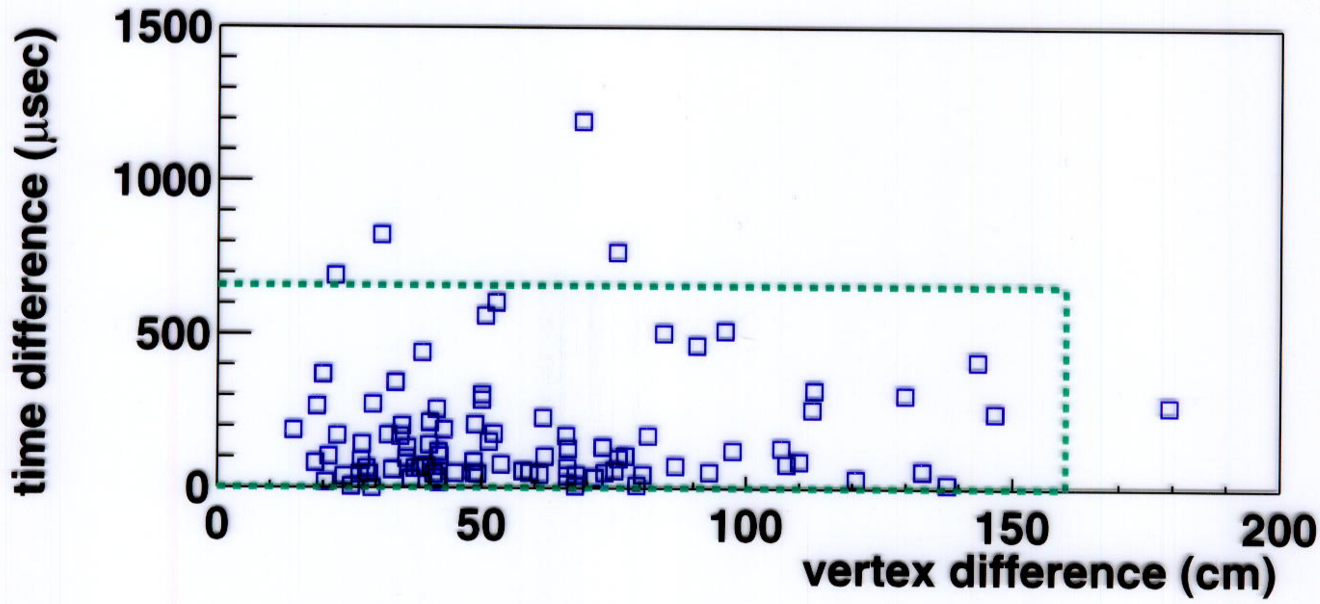


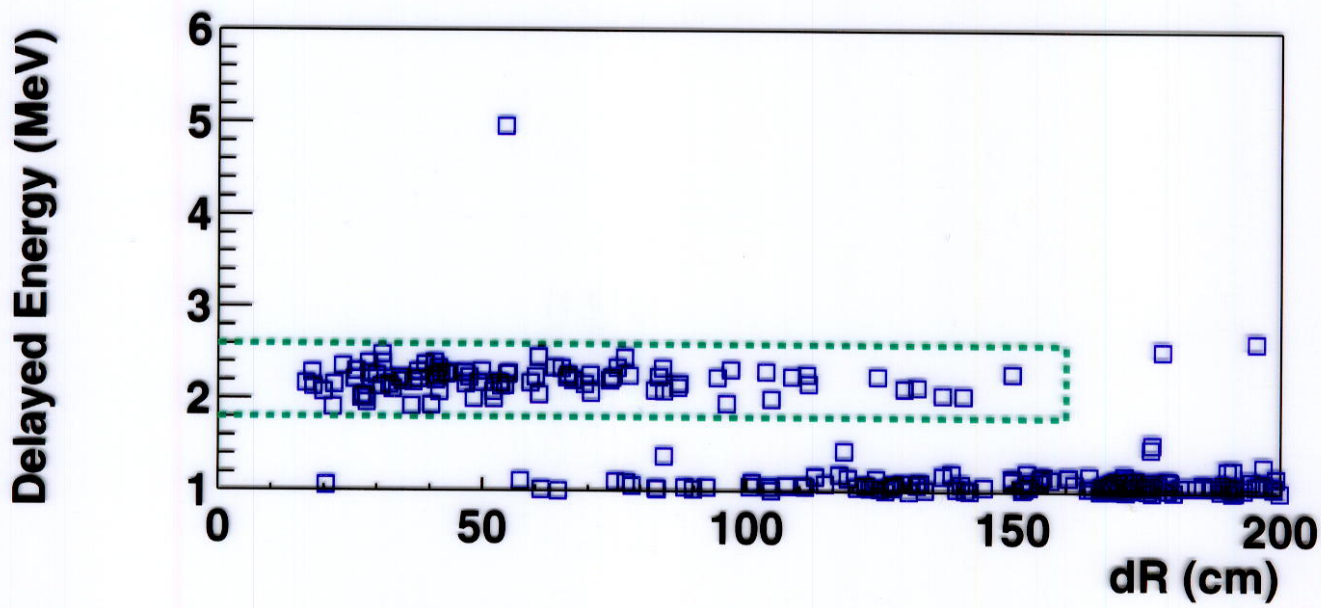
dQ<10^6 p.e.,L>300cm
1.1 ± 1.0 at E>=0.9MeV
0.94 ± 0.85 at E>=2.6MeV
by tracking efficiency 93.6%
20
18
16
14
12
10
8
6
4
2
0
1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
time(msec)

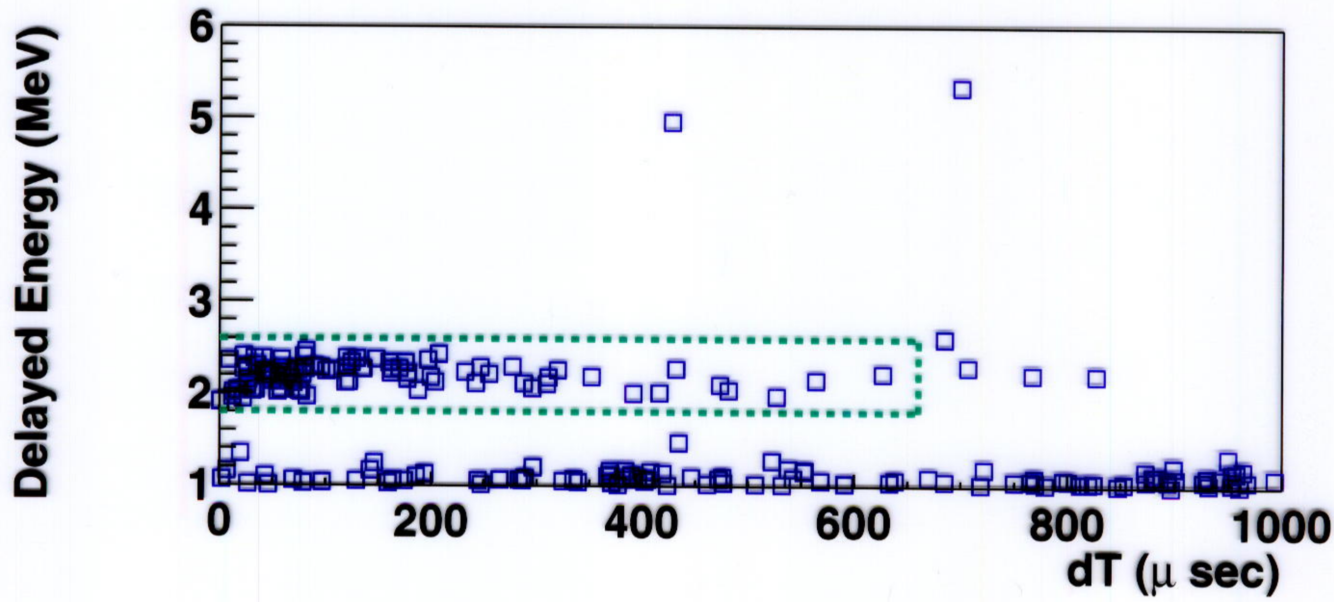

E>=2.6MeV
No Spallation Cut
(except for 2ms muon veto)
Chi2 / ndf = 21.55 / 29
spallation count = 72.04 ± 9.485
spallation lifetime[s] = 0.2568 ± 0
reactor $\overline{\nu}$ count = 57.25 ± 8.697
muon rate[Hz] = 0.33 ± 0
51.0 ± 7.7
(including livetime 0.89)
detected 54 events
10
1
0
2
4
6
8
10
12
14
16
time since last muon[seconds]

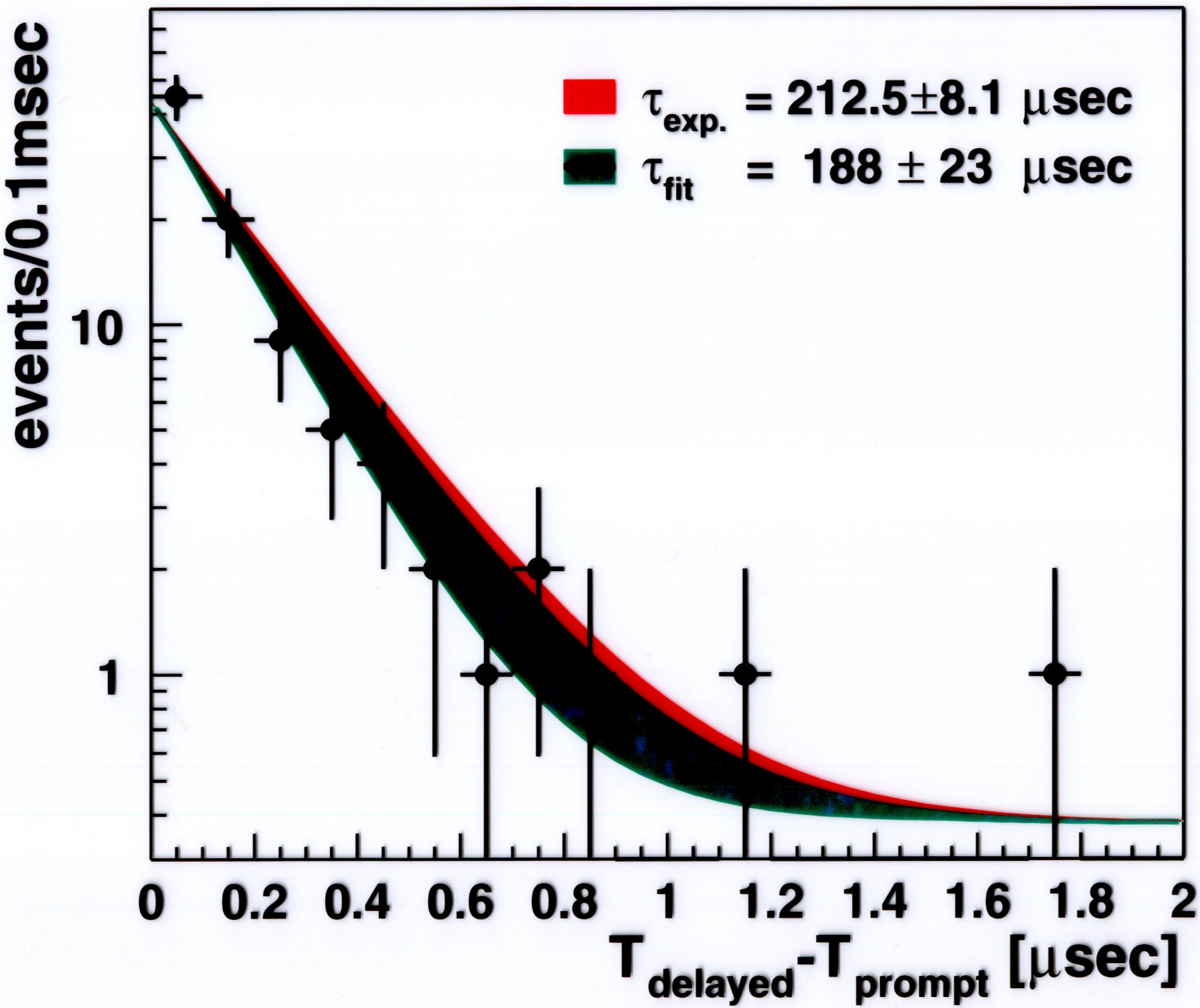
Event Selection

(1) Fiducial Cut	radius < 5m, 3.46e31 free protons
(2) timing correlation	$0.5<dt<660\mu sec$, $\tau=212\mu sec$
(3) vertex correlation	$dr<1.6m$
(4) delayed energy	$1.8<E<2.6MeV$
(5) thermometer cut	$r>1.2m$
	detection efficiency 78.3%
(6) spallation cut	$t<2sec$, $dQ>10^6$p.e.
	$t<2sec$, $dr<3m$, $dQ<10^6$p.e.
	dead time = 11.4%
(7) energy threshold	Evis > 2.6MeV
Expected Signal Rate	0.60 ev/day

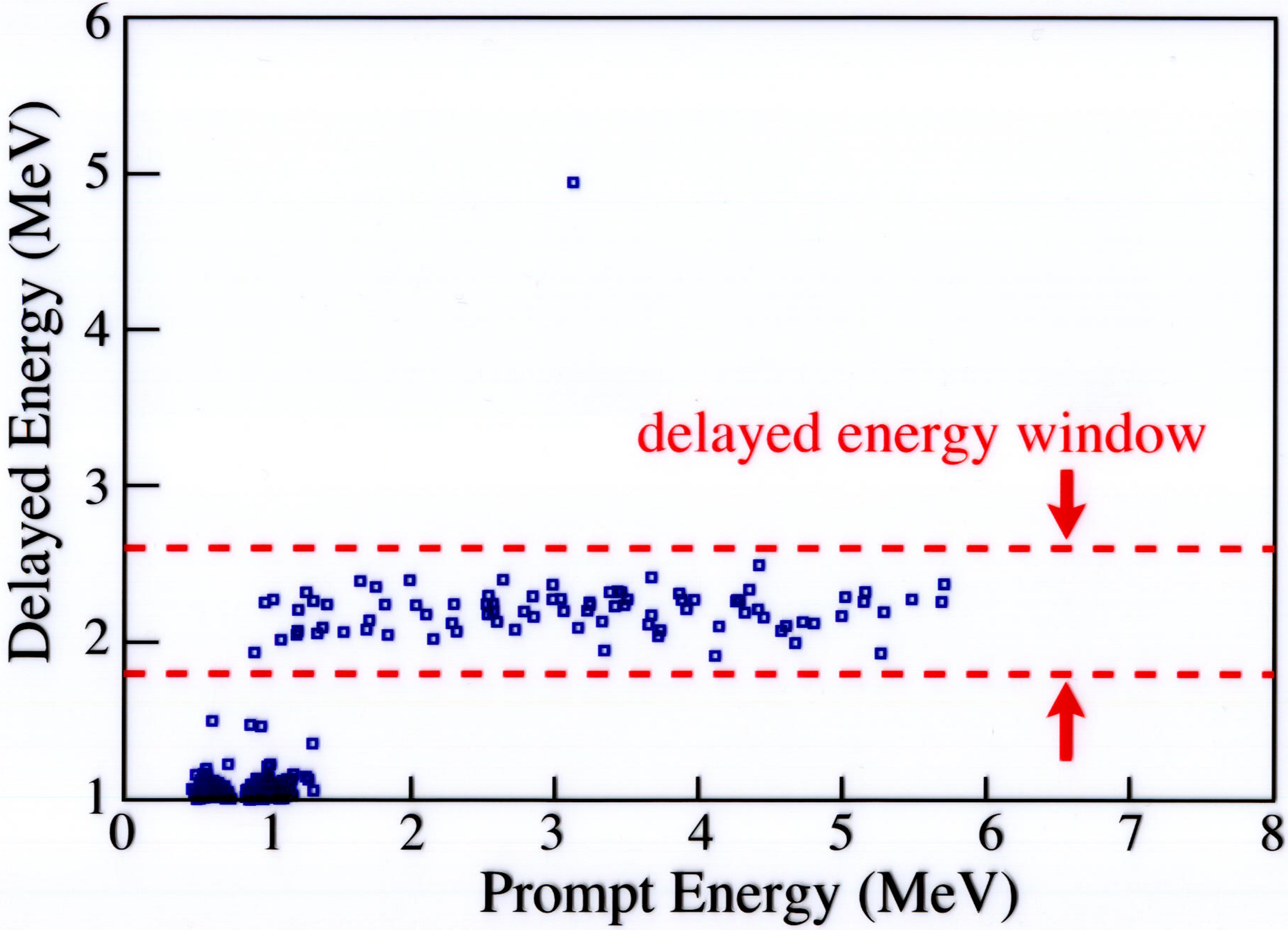

1500
1000
500
0
time difference (μsec)
0
50
100
150
200
vertex difference (cm)


6
5
4
3
2
1
Delayed Energy (MeV)
0
50
100
150
200
dR (cm)

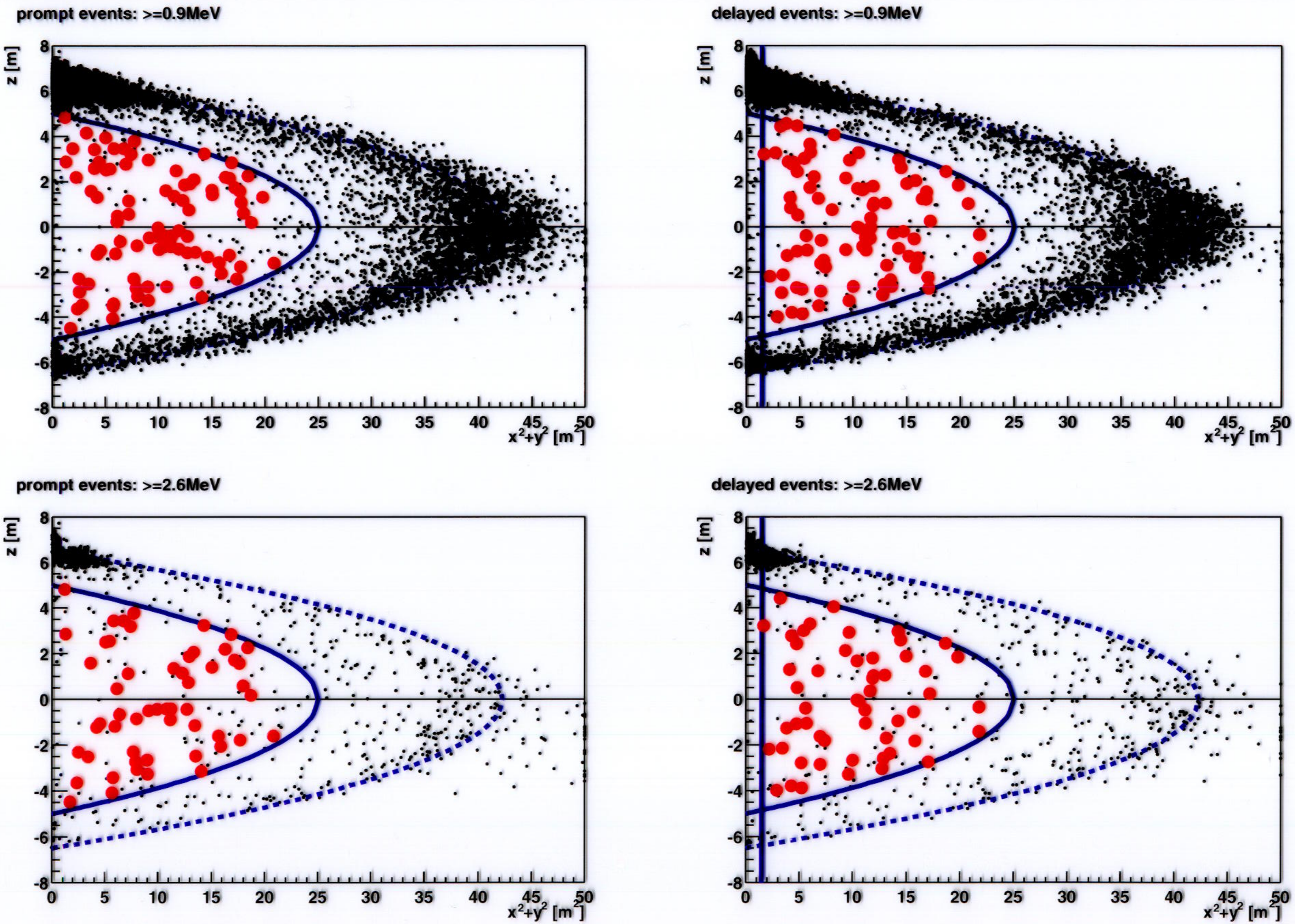

6
5
4
3
2
1
Delayed Energy (MeV)
0
200
400
600
800
1000
dT (μ sec)

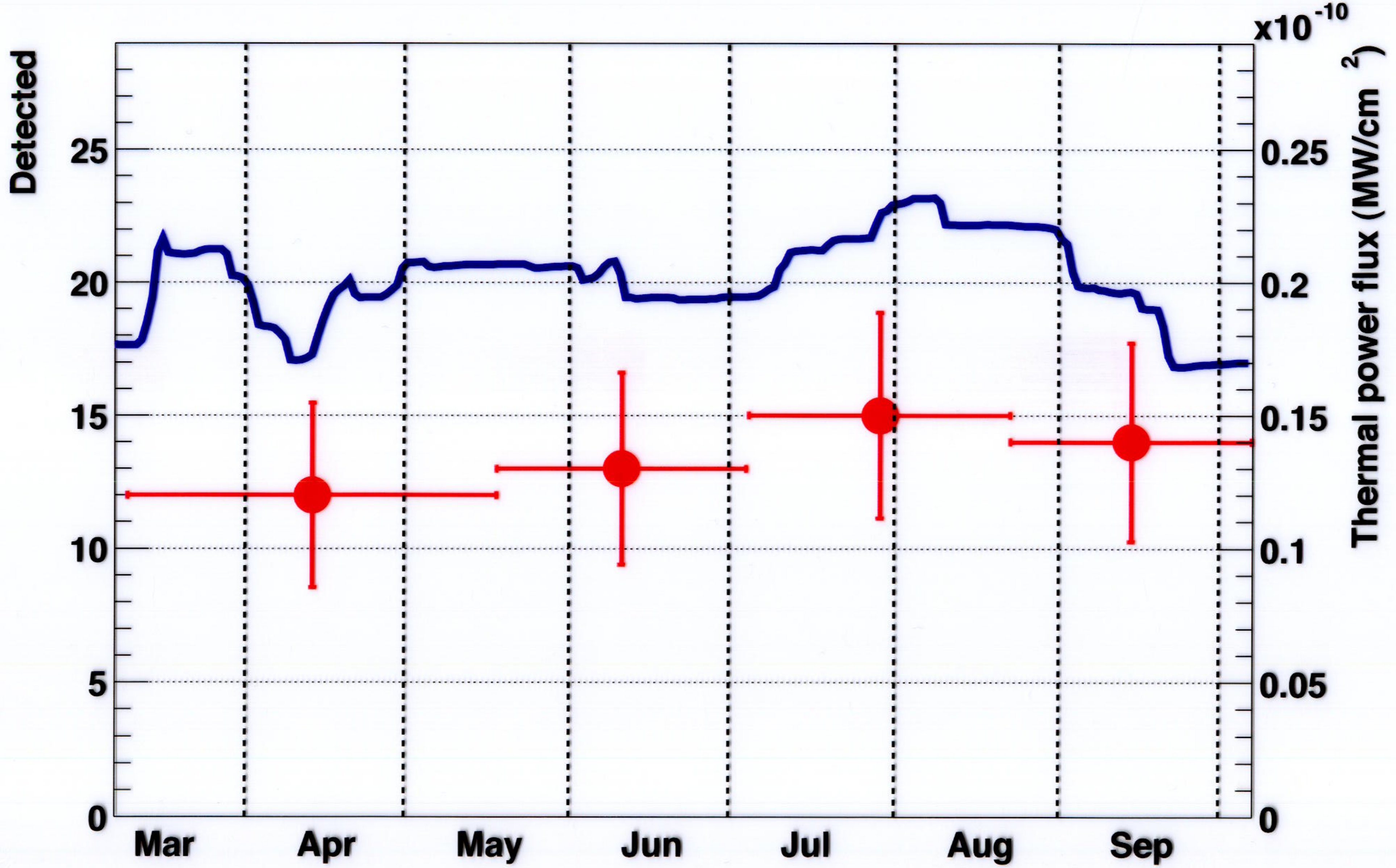


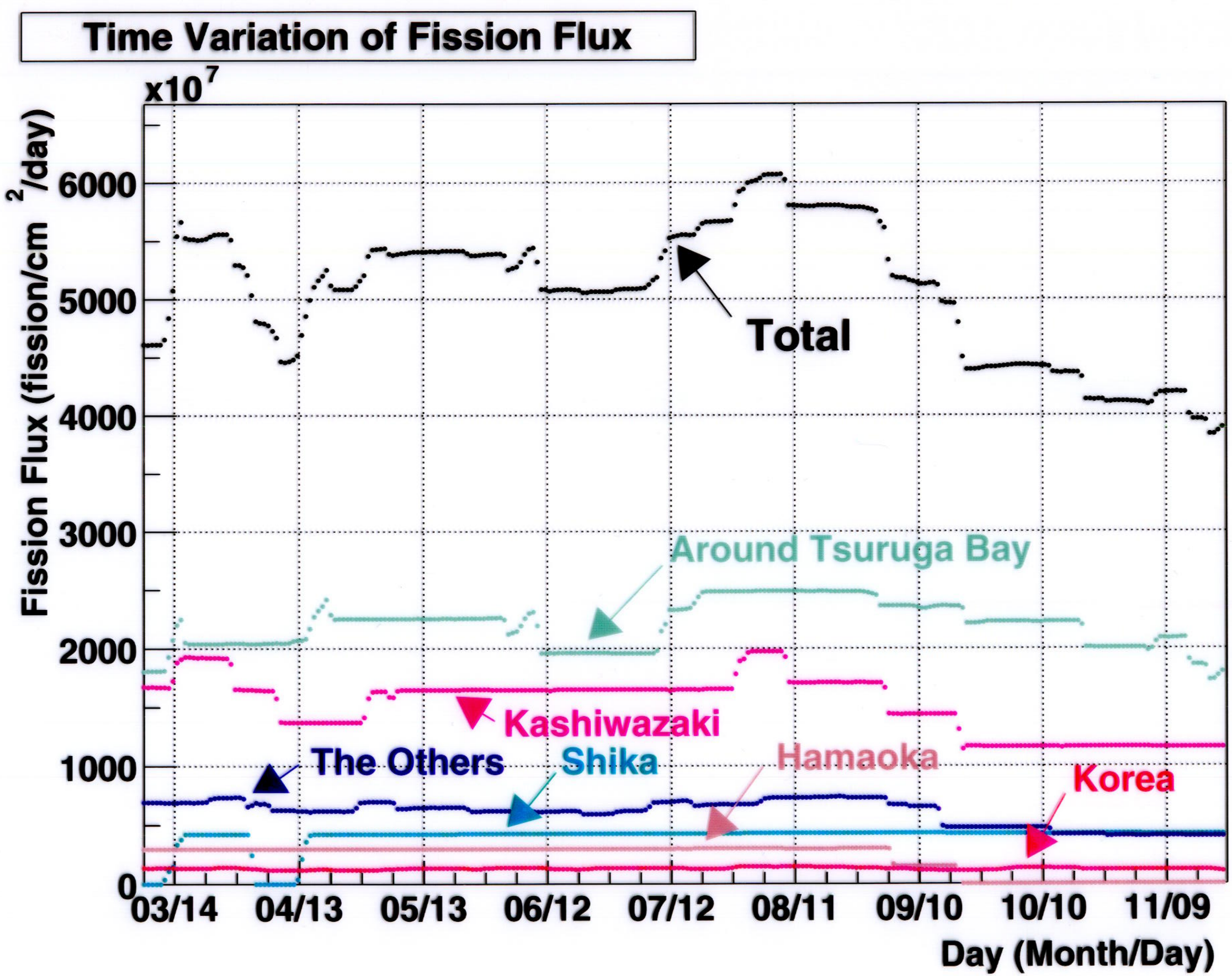
events/0.1msec
10
1
τexp. = 212.5±8.1 μsec
τfit = 188 ± 23 μsec
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Tdelayed-Tprompt [μsec]



delayed energy window
Delayed Energy (MeV)
Prompt Energy (MeV)
0
1
2
3
4
5
6
7
8


prompt events: >=0.9MeV
delayed events: >=0.9MeV
prompt events: >=2.6MeV
delayed events: >=2.6MeV
z [m]
x^2+y^2 [m^2]


Detected
Thermal power flux (MW/cm 2)
x10-10
25
20
15
10
5
0
0.25
0.2
0.15
0.1
0.05
0
Mar
Apr
May
Jun
Jul
Aug
Sep



Time Variation of Fission Flux
x10^7
Fission Flux (fission/cm^2/day)
6000
5000
4000
3000
2000
1000
0
03/14
04/13
05/13
06/12
07/12
08/11
09/10
10/10
11/09
Day (Month/Day)
Total
Around Tsuruga Bay
Kashiwazaki
The Others
Shika
Hamaoka
Korea

Data Summary

from March 4 through October 6, 2002

(145.1 live days)

E_{prompt} > 2.6 MeV

Expected neutrino:	86.8±5.6
Expected BG:	0.95±0.99
Observed:	54

R=0.611±0.085(stat)±0.041(syst)

99.95% CL. disappearance

E_{prompt} > 0.9 MeV

Expected neutrino:	124.8±7.5
Expected BG:	2.91±1.12 (+ ~9 geo-nu)
Observed:	85

R=0.586

$$\chi^2 = \frac{(0.611 - R(\sin^2 2\theta, \Delta m^2))^2}{0.085^2 + 0.041^2}$$

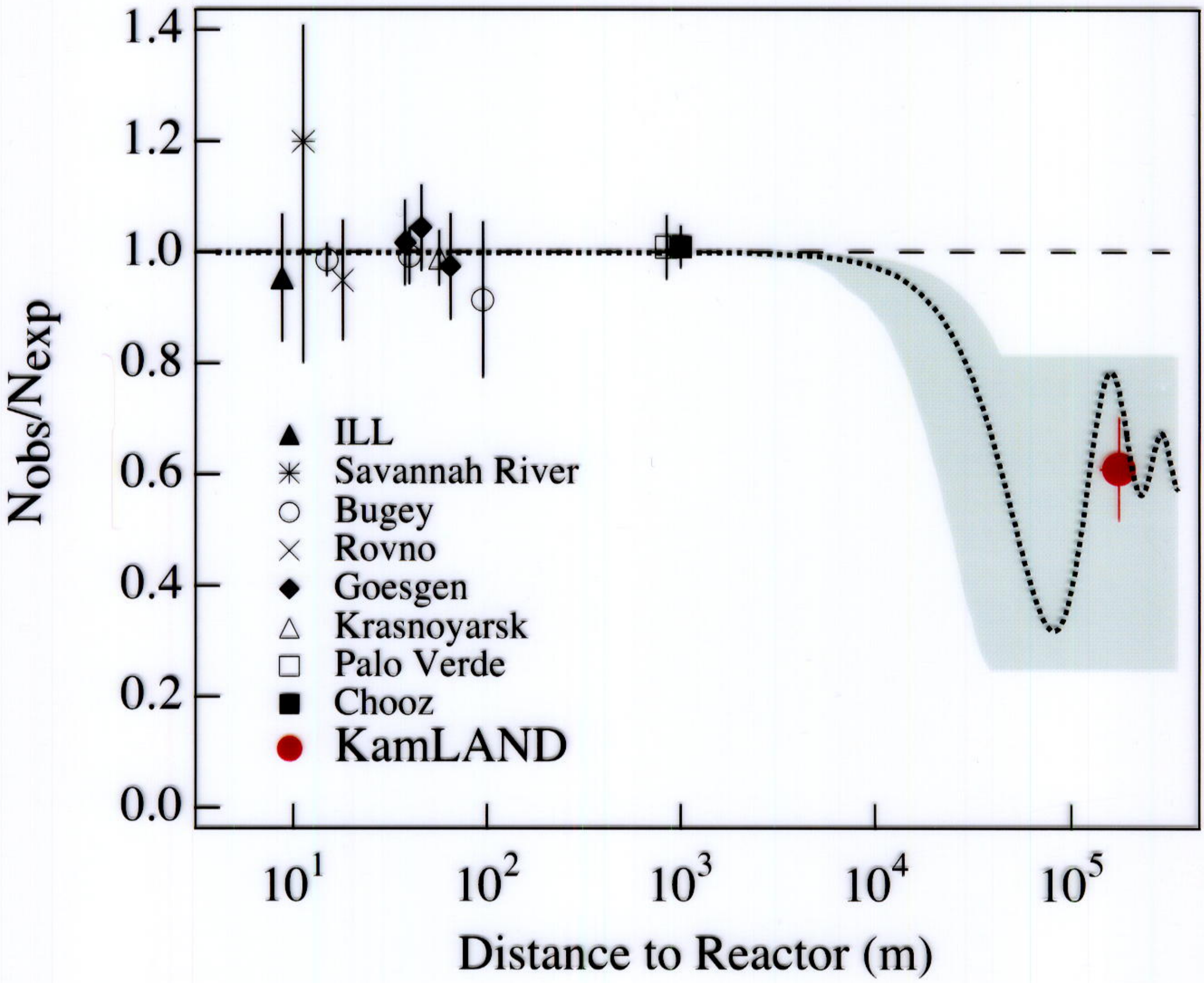
$$\chi^2 = \frac{(N_{obs} - N_{BG} - N_{osc}(\sin^2 2\theta, \Delta m^2))^2}{N_{osc} + (N_{osc} \times \sigma_{sys})^2 + \sigma_{BG}^2} = \frac{(54 - 0.95 - N_{osc})^2}{N_{osc} + (N_{osc} \times 0.064)^2 + 0.99^2}$$

$$P = \frac{1}{\sqrt{2\pi\{(N_{osc} \times \sigma_{sys})^2 + \sigma_{BG}^2\}}} \int_{-\infty}^{+\infty} \left[\exp\left\{ -\frac{(N_{osc} + N_{BG} - x)^2}{(N_{osc} \times \sigma_{sys})^2 + \sigma_{BG}^2} \right\} \times \sum_{n=0}^{N_{obs}} P_n(x) \right] dx$$

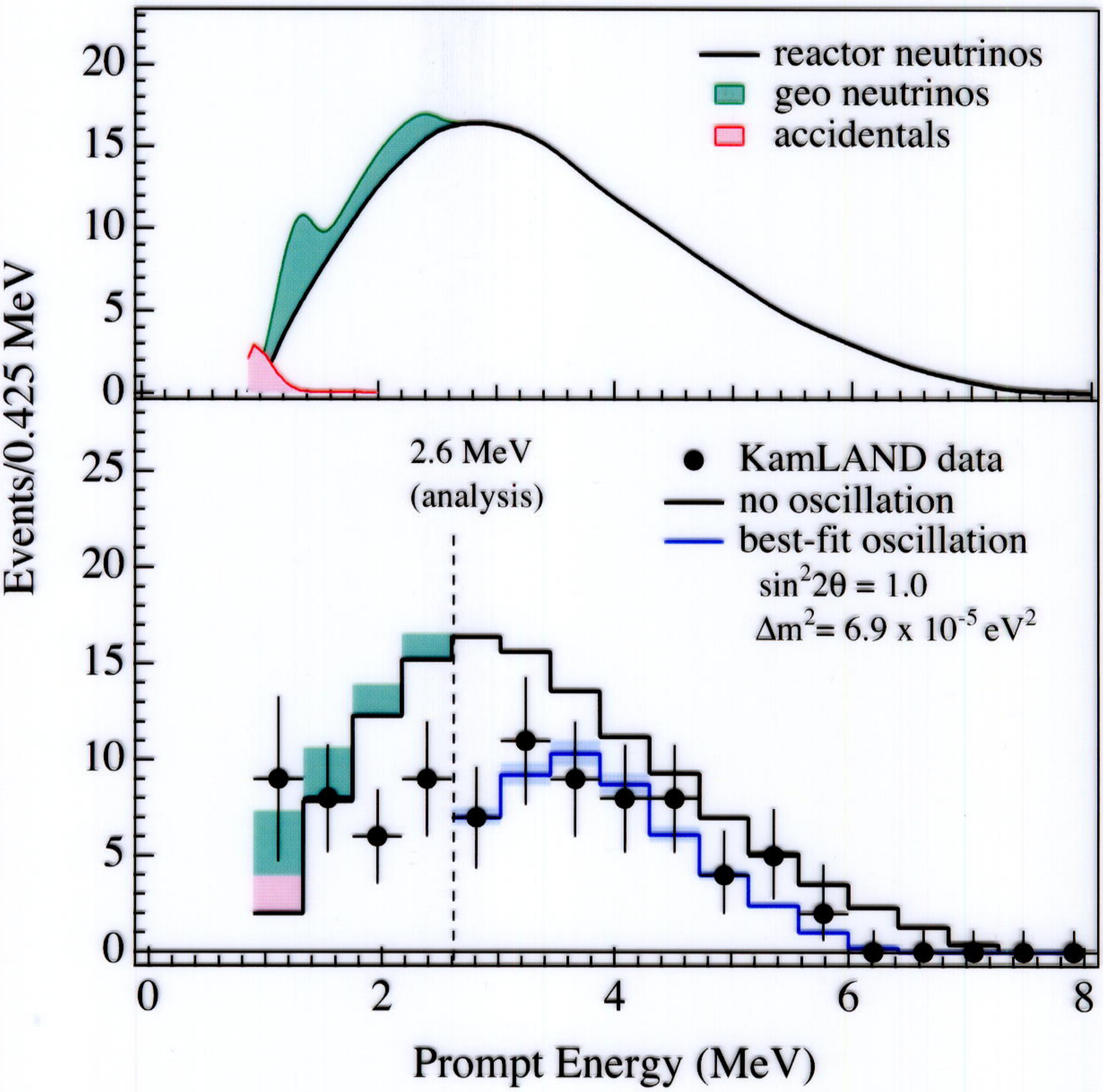
$$\chi^2 = \chi^2_{rate}(\sin^2 2\theta, \Delta m^2, N_{BG1\sim2}, \alpha_{1\sim4}) - 2\log L_{shape}(\sin^2 2\theta, \Delta m^2, N_{BG1\sim2}, \alpha_{1\sim4})$$
$$+ \chi^2_{BG}(N_{BG1\sim2}) + \chi^2_{distortion}(\alpha_{1\sim4})$$

$N_{BG1\sim2}$: number of spallation backgrounds

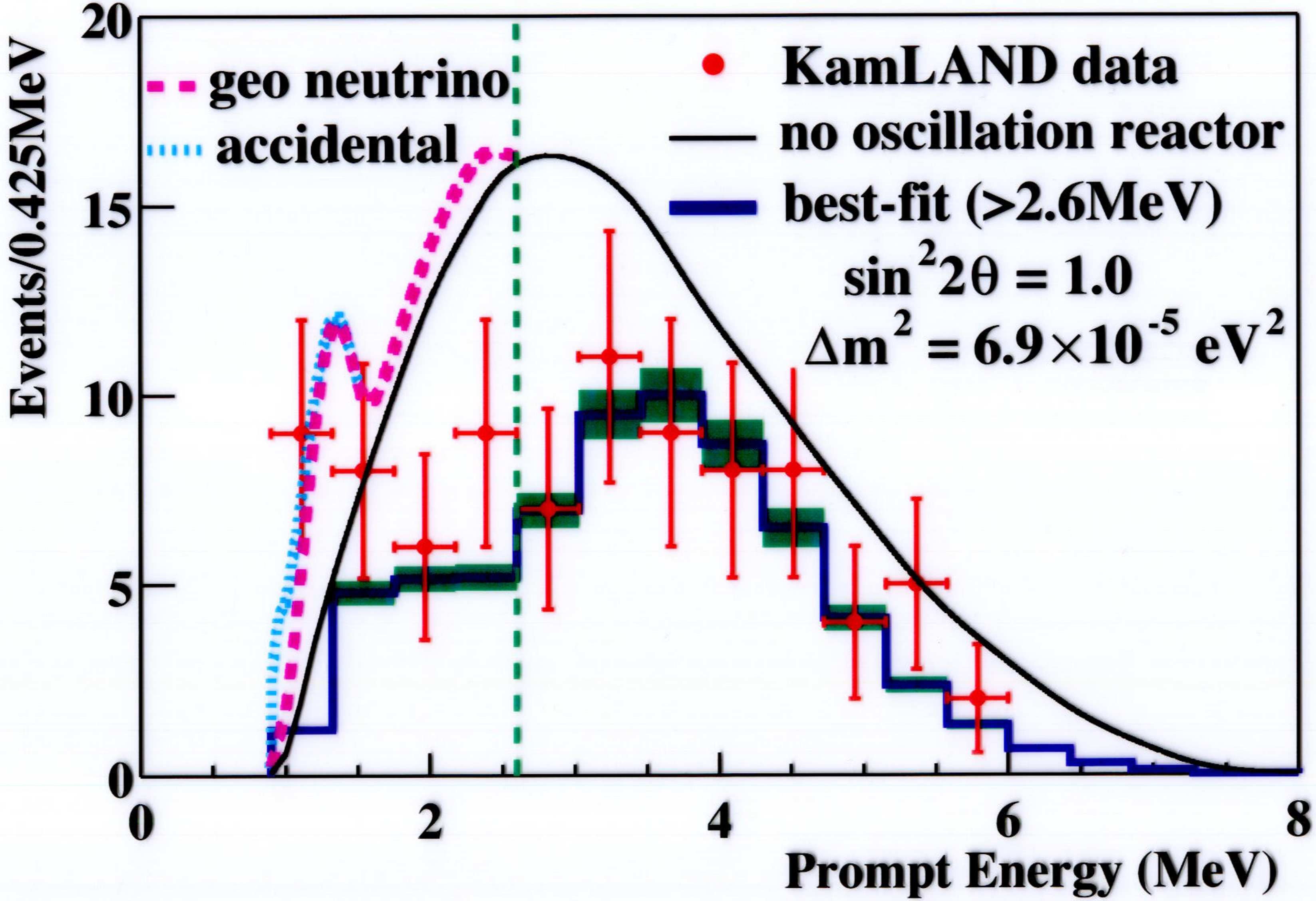
$\alpha_{1\sim4}$: parameters for shape distortion from energy scale, resolution, neutrino spectra and fiducial volume



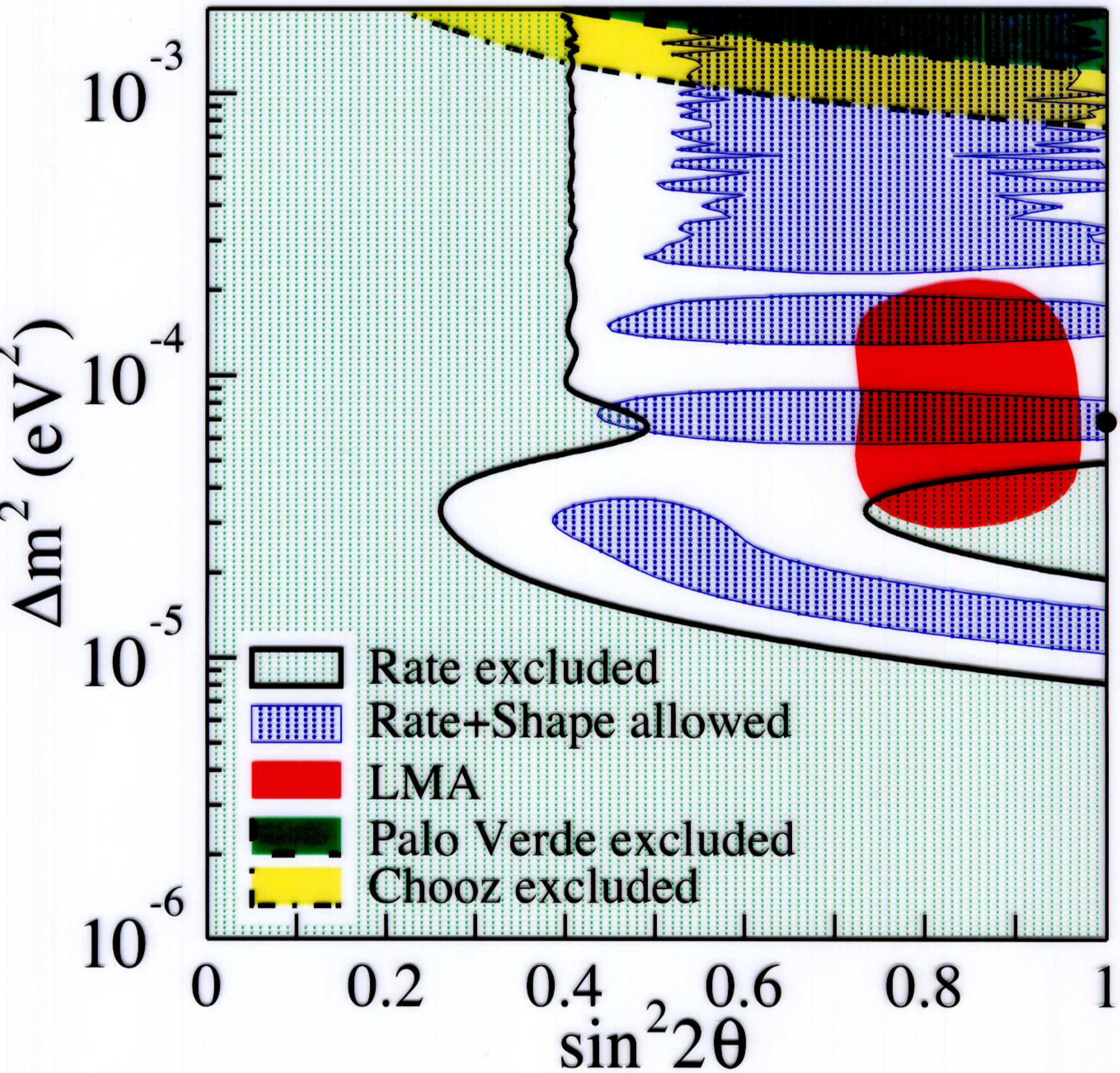
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)



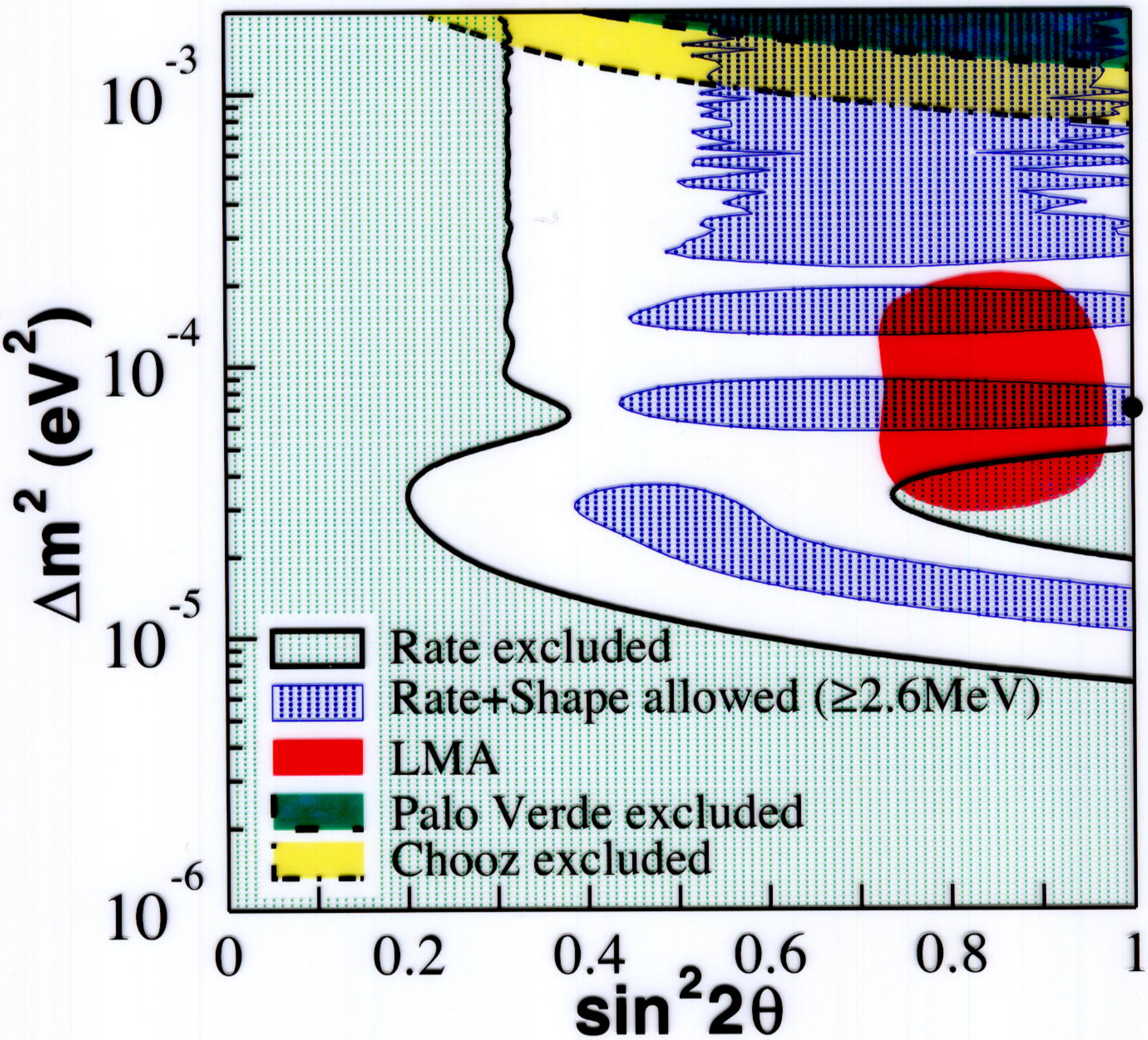
reactor neutrinos
geo neutrinos
accidentals
Events/0.425 MeV
2.6 MeV
(analysis)
KamLAND data
no oscillation
best-fit oscillation
sin²2θ = 1.0
Δm²= 6.9 x 10⁻⁵ eV²
Prompt Energy (MeV)



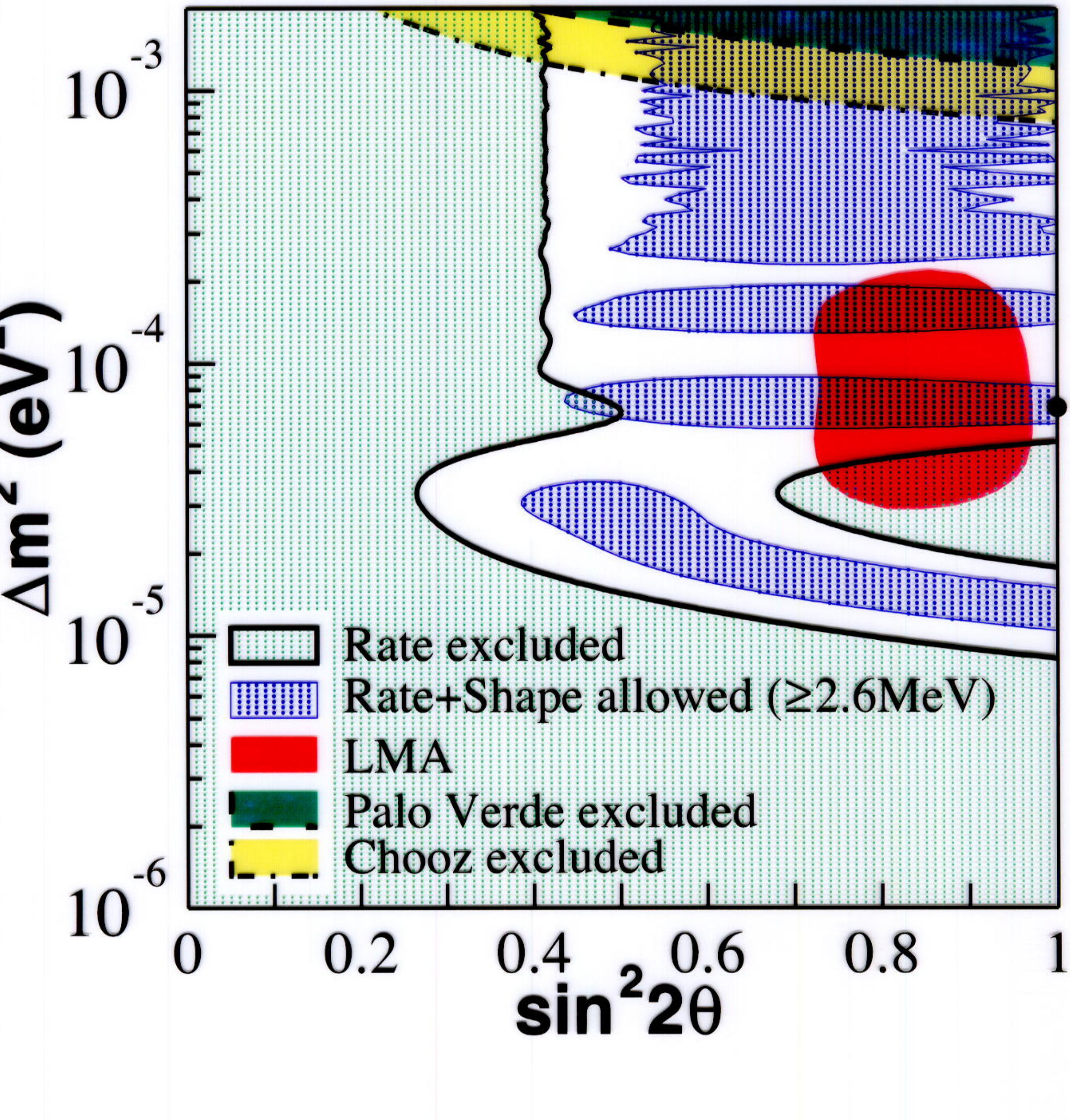
geo neutrino
accidental
KamLAND data
no oscillation reactor
best-fit (>2.6MeV)
$\sin^2 2\theta = 1.0$
$\Delta m^2 = 6.9\times10^{-5}$ eV^2
Events/0.425MeV
Prompt Energy (MeV)
0
2
4
6
8
5
10
15
20



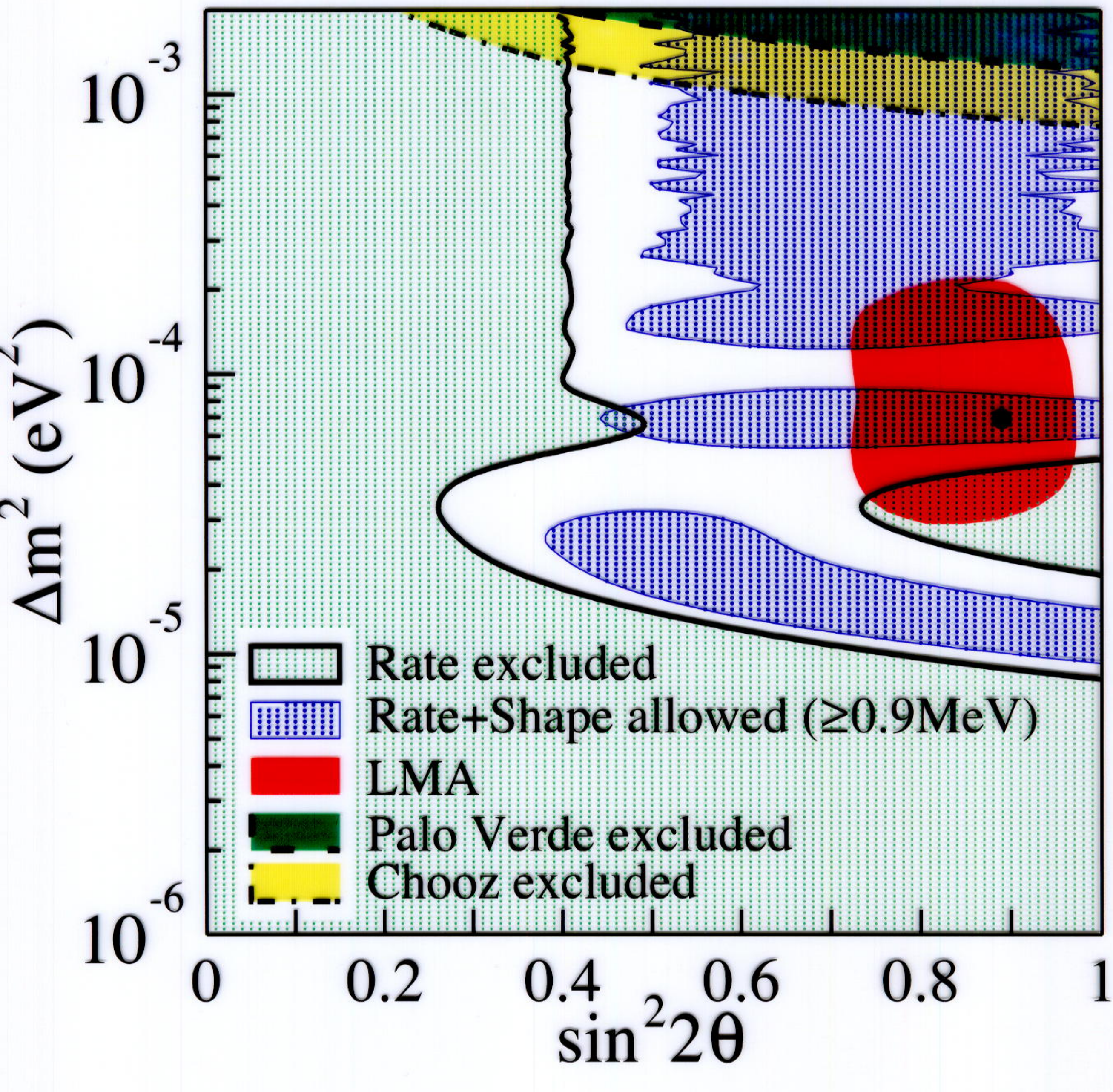
10^-3
10^-4
10^-5
10^-6
Δm^2 (eV^2)
0
0.2
0.4
0.6
0.8
1
sin^2 2θ
Rate excluded
Rate+Shape allowed
LMA
Palo Verde excluded
Chooz excluded



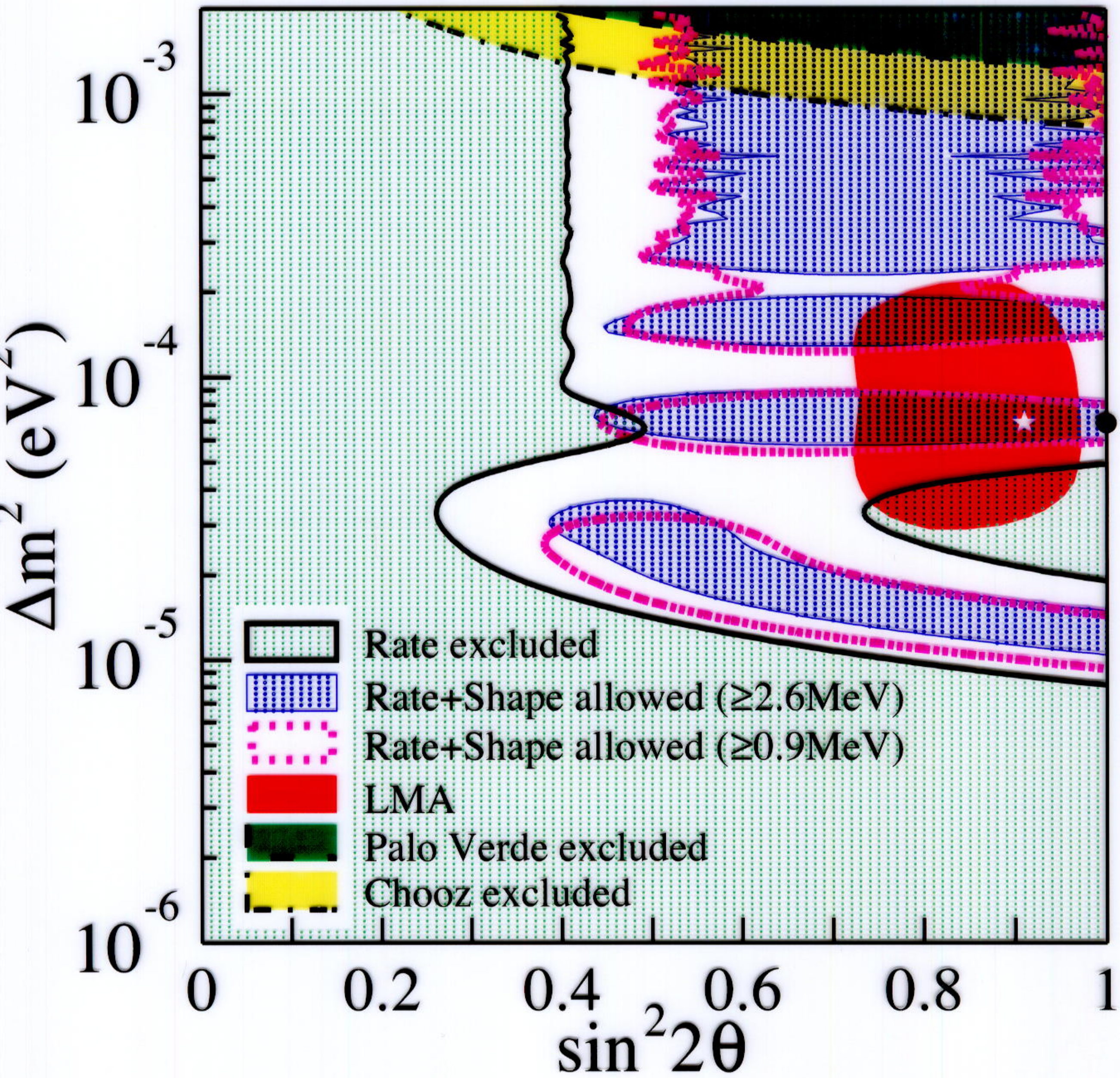
errors on expected



Poisson statistics for rate analysis



Rate excluded
Rate+Shape allowed (≥0.9MeV)
LMA
Palo Verde excluded
Chooz excluded
10^-3
10^-4
10^-5
10^-6
Δm^2 (eV^2)
0
0.2
0.4
0.6
0.8
1
sin^2 2θ



10^{-3}
10^{-4}
10^{-5}
10^{-6}
Δm^2 (eV^2)
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$
Rate excluded
Rate+Shape allowed (≥2.6MeV)
Rate+Shape allowed (≥0.9MeV)
LMA
Palo Verde excluded
Chooz excluded

Rate + Shape Analysis

$E_{prompt} > 2.6$ MeV

Best fit @ $(\sin^2 2\theta, \Delta m^2) = (1.0, 6.9e{-5} eV^2)$

Two bands overlap with the LMA solution.

Preference to the maximal mixing is not strong.

$E_{prompt} > 0.9$ MeV

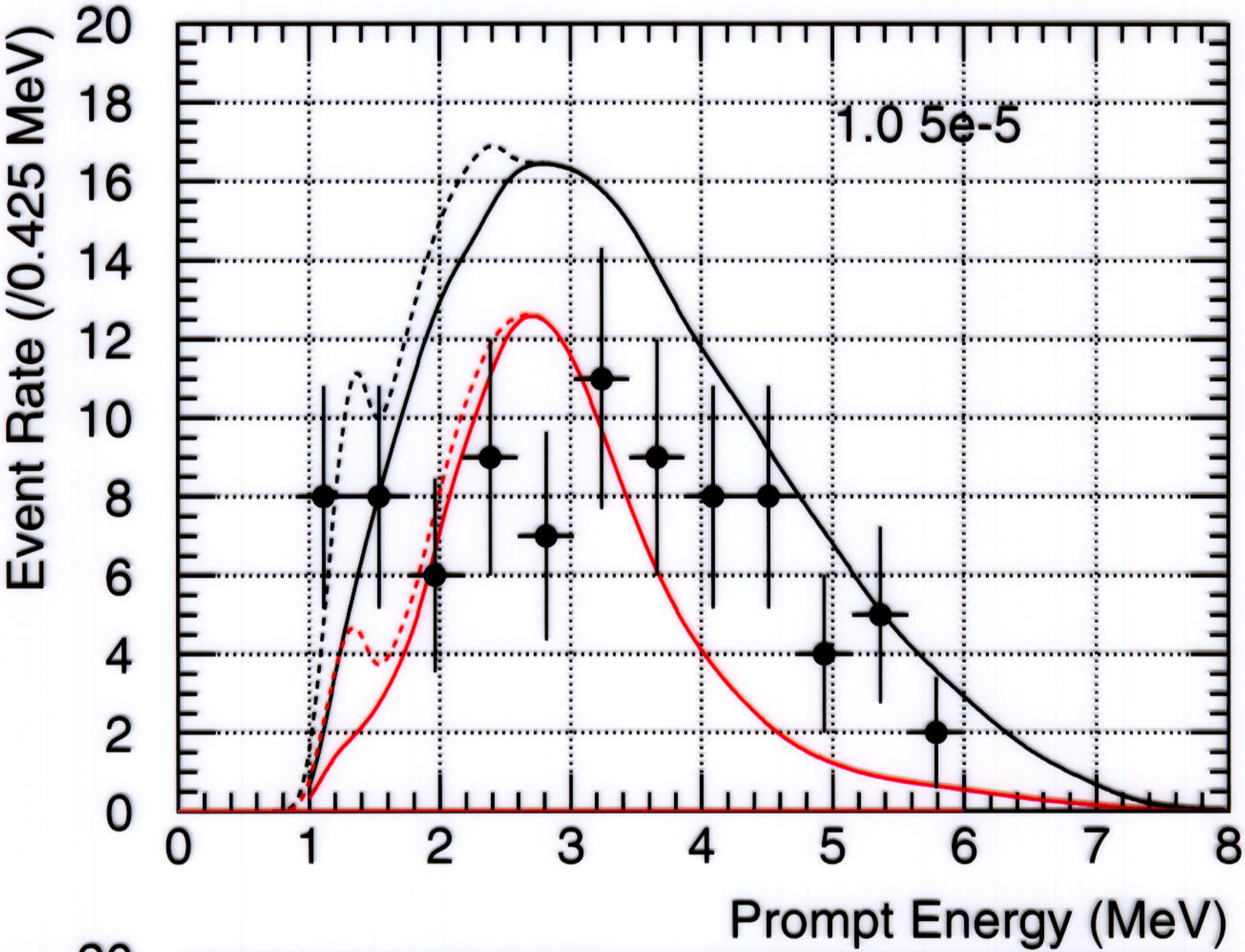
Best fit @ $(\sin^2 2\theta, \Delta m^2) = (0.91, 6.9e{-5} eV^2)$

Geo-nu's are treated as free parameters.

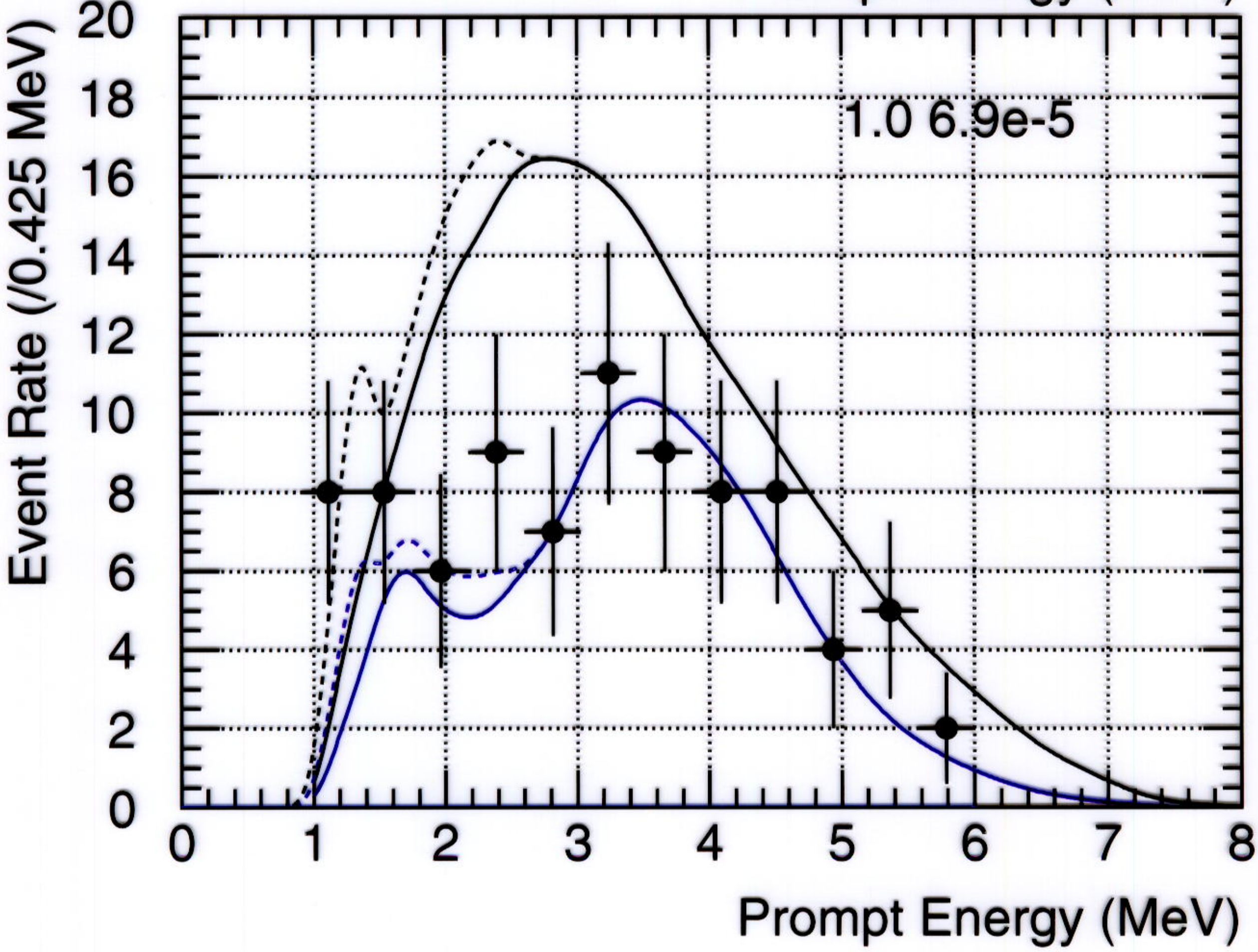
No significant statistical contribution from low energy.

Contours are quite consistent with 2.6 MeV analysis.

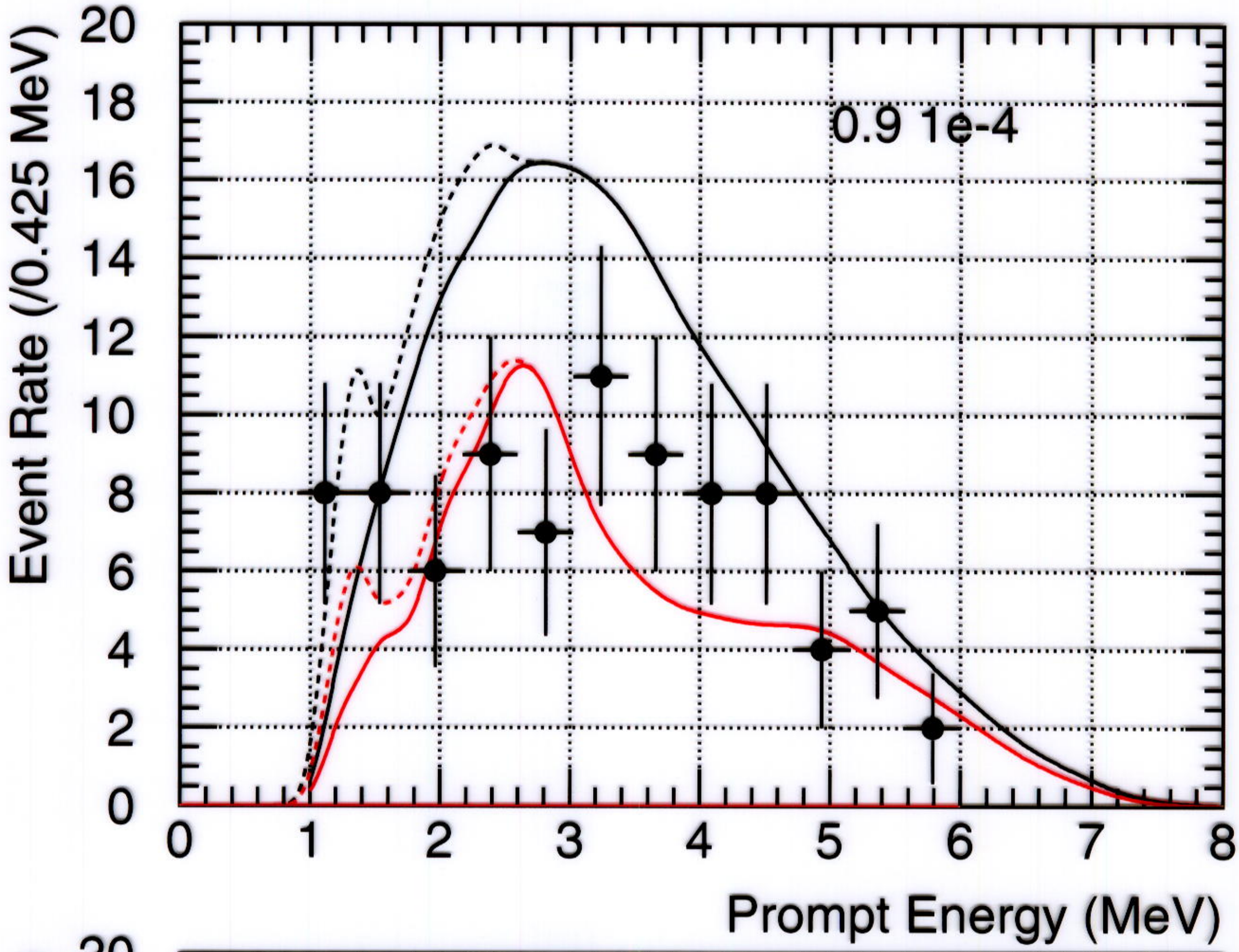
Nothing funny in the low energy region.



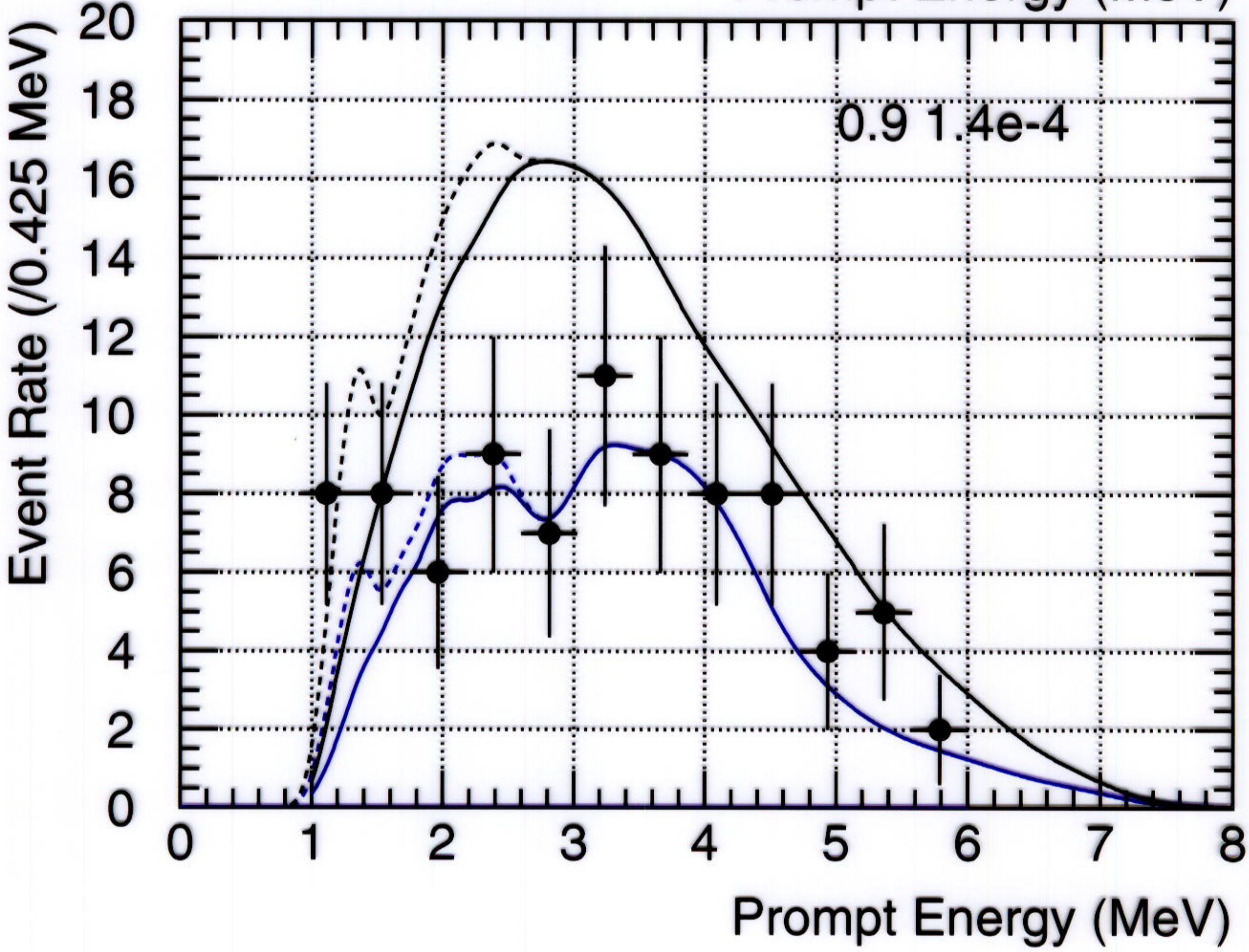
Event Rate (/0.425 MeV)
1.0 5e-5
Prompt Energy (MeV)



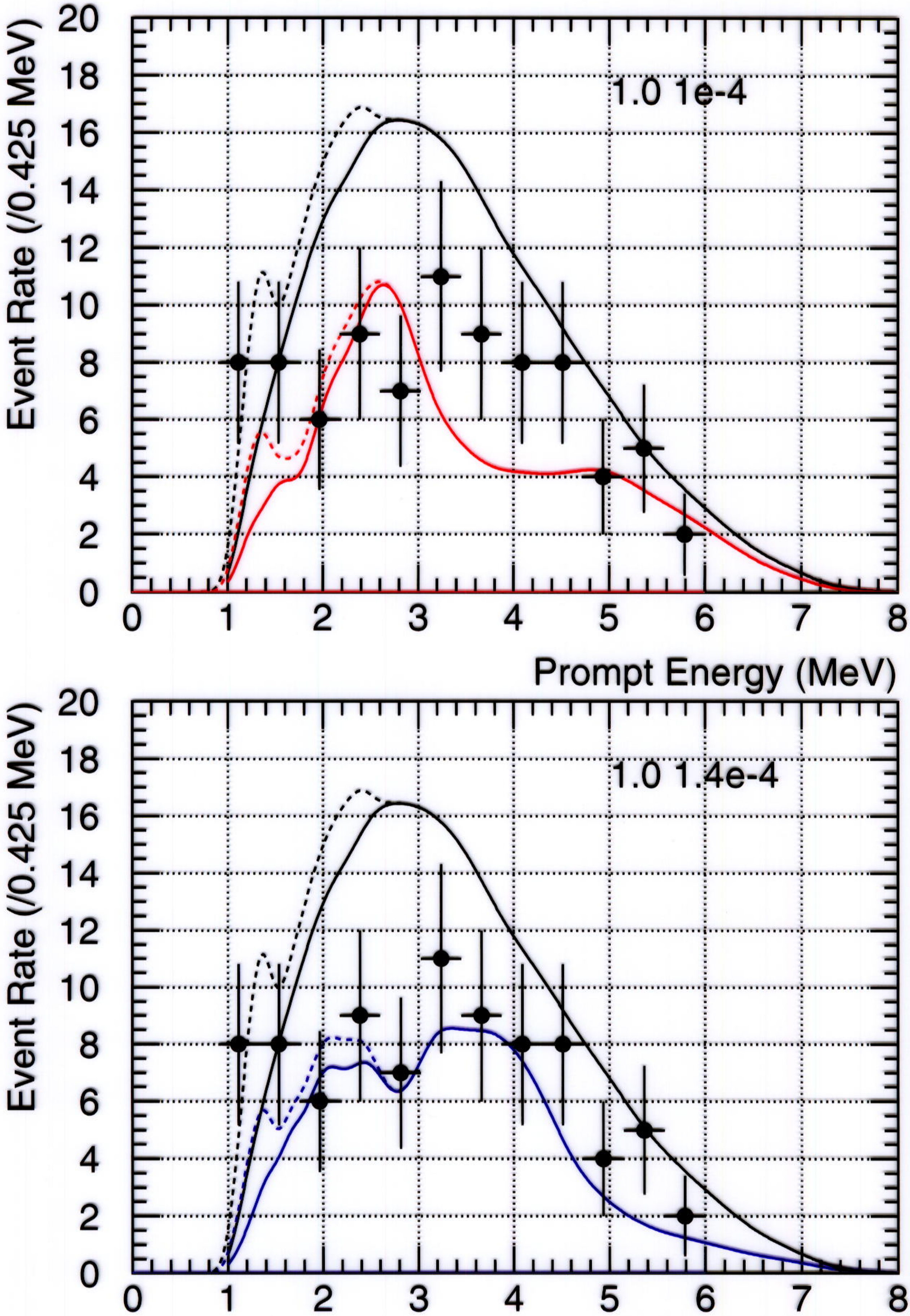
Event Rate (/0.425 MeV)
1.0 6.9e-5
Prompt Energy (MeV)

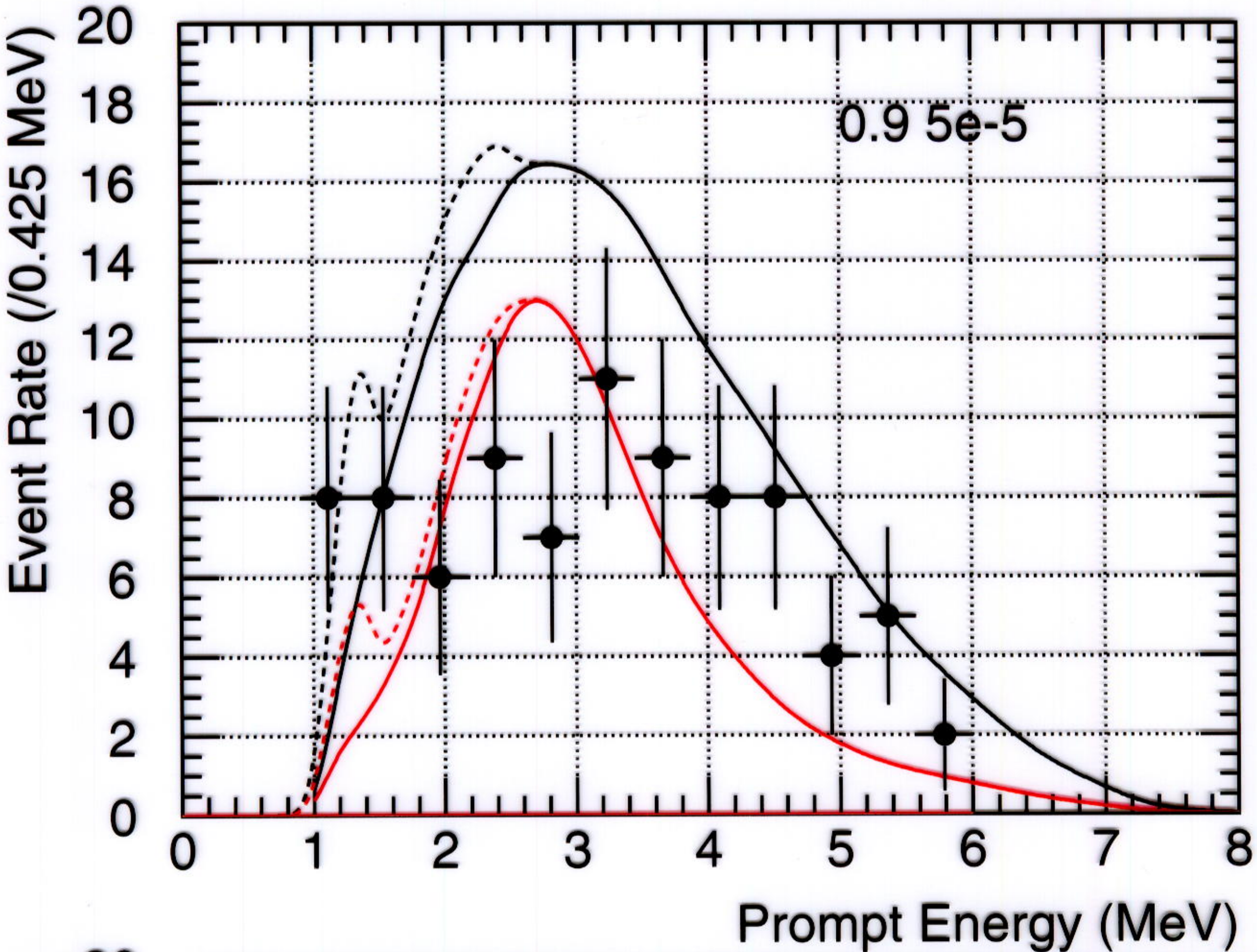


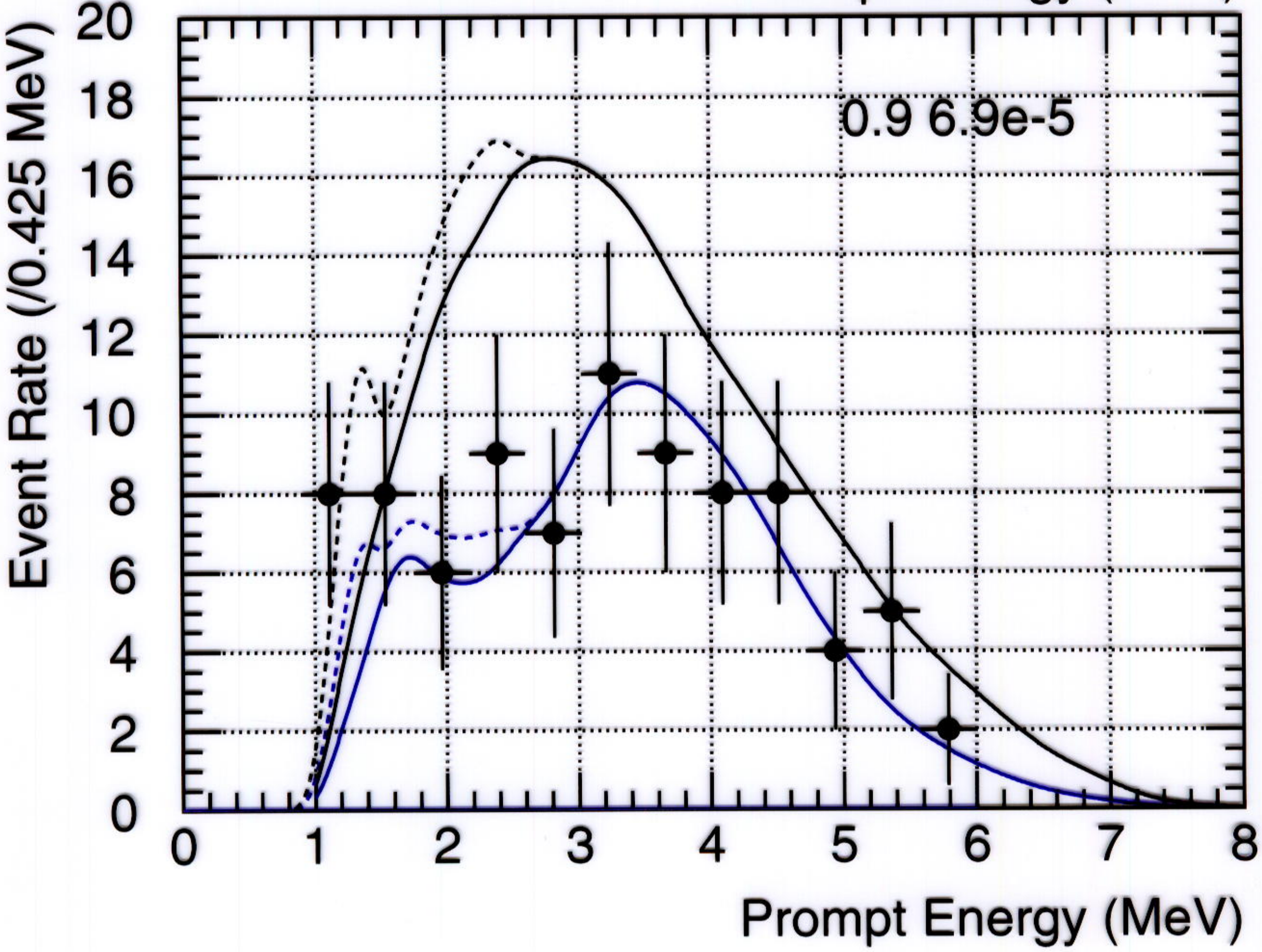
0.9 1e-4
Event Rate (/0.425 MeV)
Prompt Energy (MeV)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
20



0.9 1.4e-4
Event Rate (/0.425 MeV)
Prompt Energy (MeV)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
20


1.0 1e-4
Event Rate (/0.425 MeV)
Prompt Energy (MeV)
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
6
7
8
1.0 1.4e-4
Event Rate (/0.425 MeV)
Prompt Energy (MeV)


0.9 5e-5
Event Rate (/0.425 MeV)
Prompt Energy (MeV)


0.9 6.9e-5
Event Rate (/0.425 MeV)
Prompt Energy (MeV)

Geo-neutrinos ??

A model

crust	U	1.8 ppm
mantle	U	0.01 ppm
Th/U	3.6	

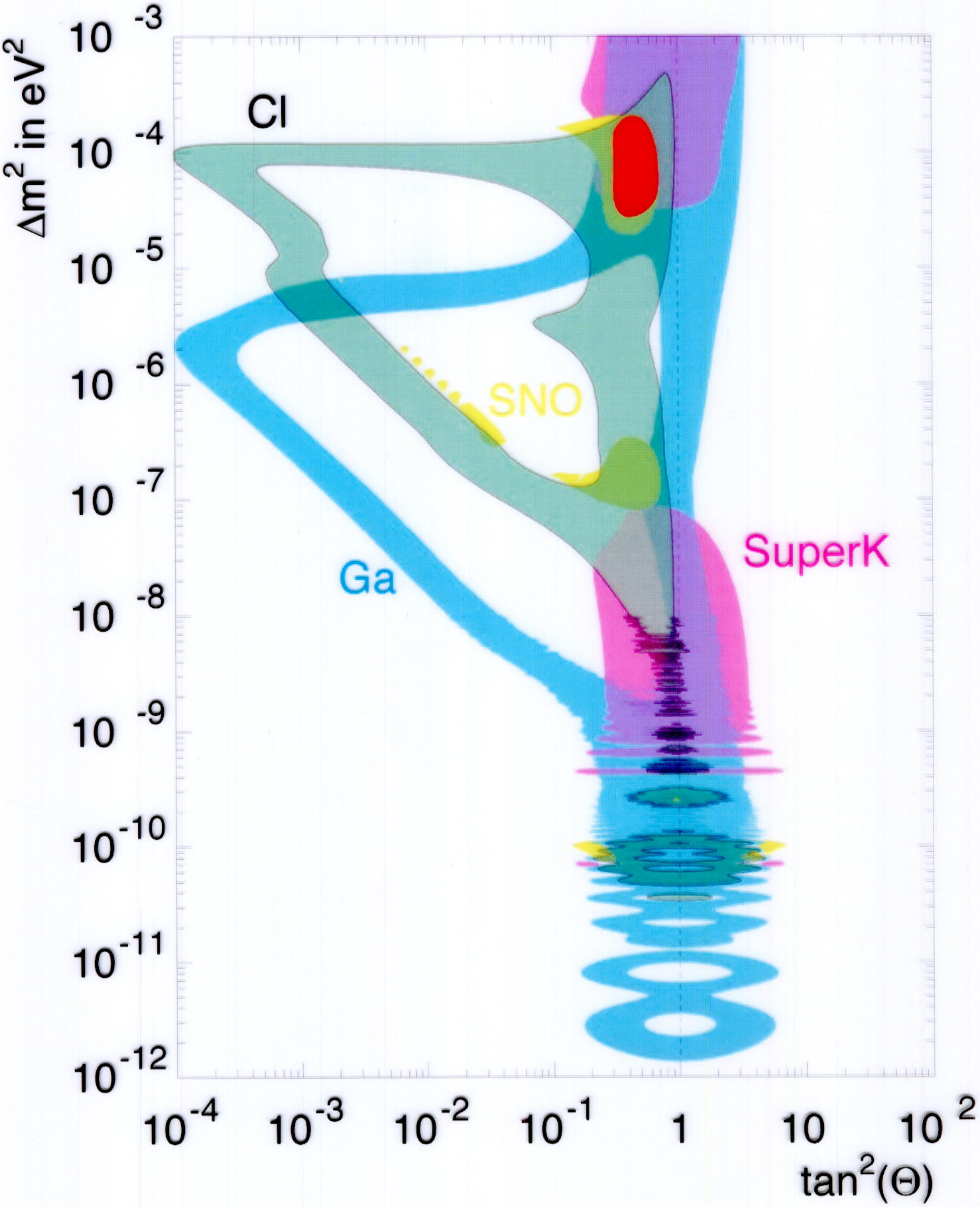
→ 16 TW heat flow
~9 events in our data

Best fit with 0.9 MeV rate + shape analysis (0.91, 6.9e−5)

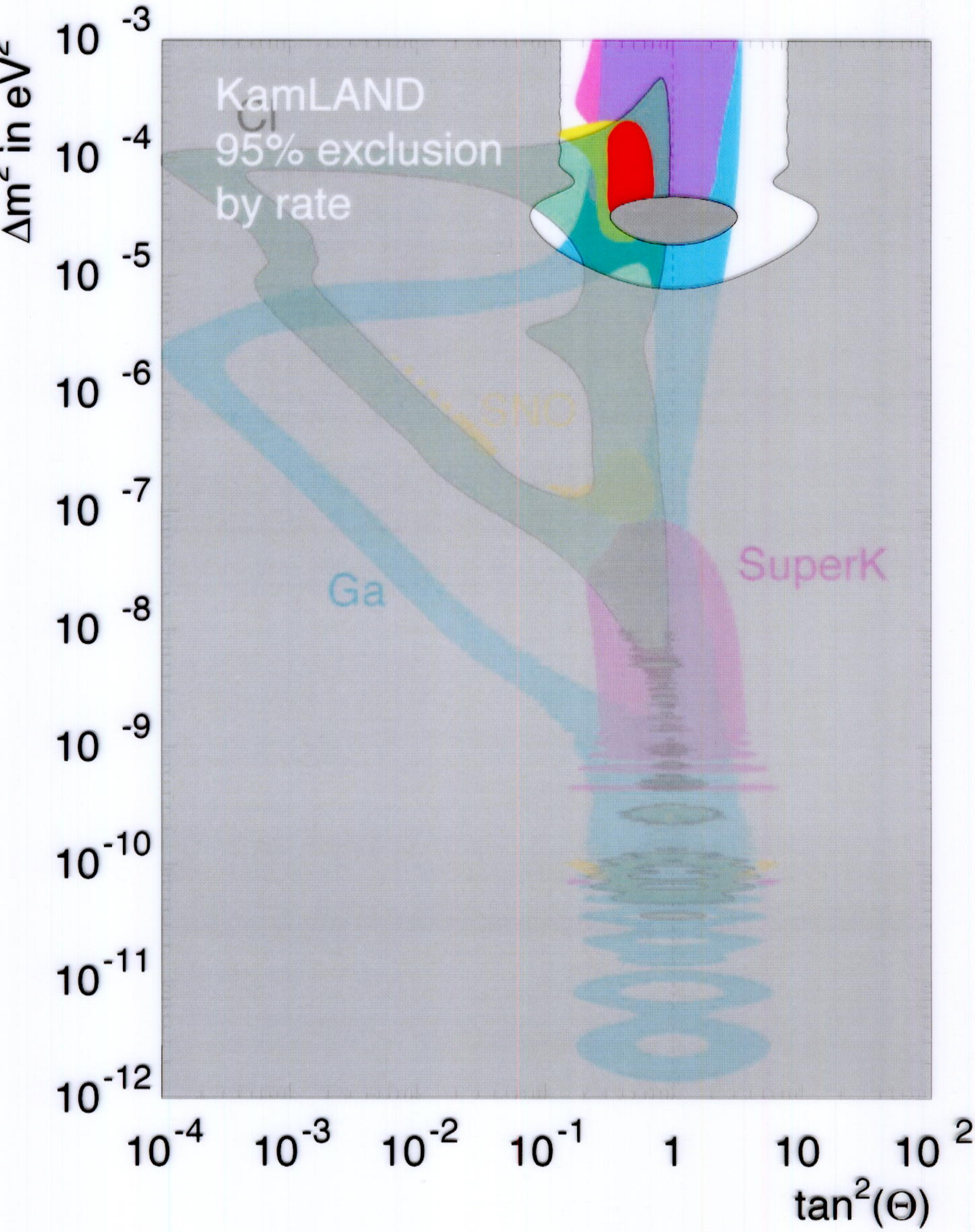
U 4 events
Th 5 events

→ ~40 TW
consistent with 16 TW at 1 sigma
0~110 TW at 95% C.L.

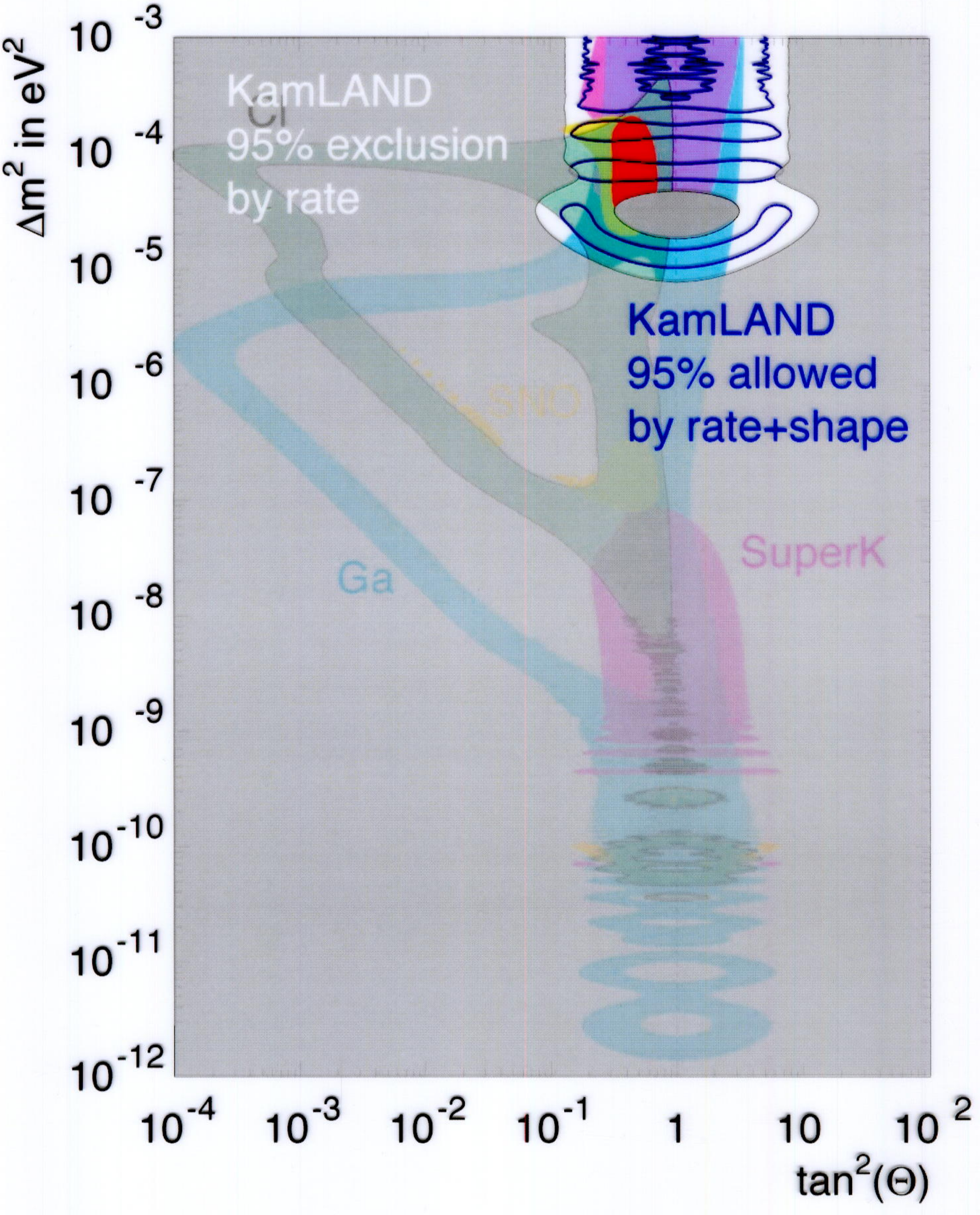
No meaningful sensitivity yet but hinted?



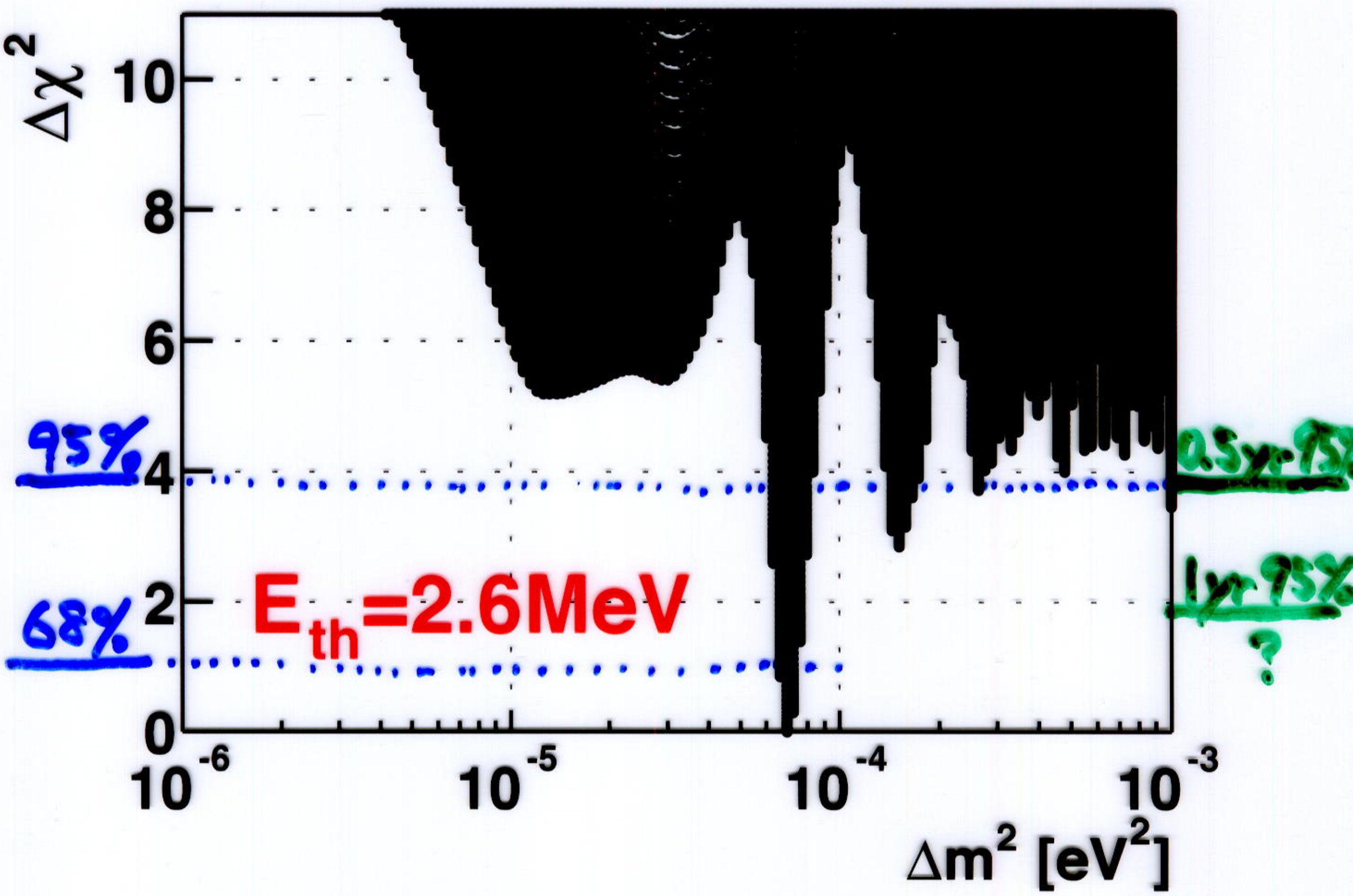
Δm² in eV²
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
10-10
10-11
10-12
Cl
SNO
SuperK
Ga
10-4
10-3
10-2
10-1
1
10
10 2
tan²(Θ)

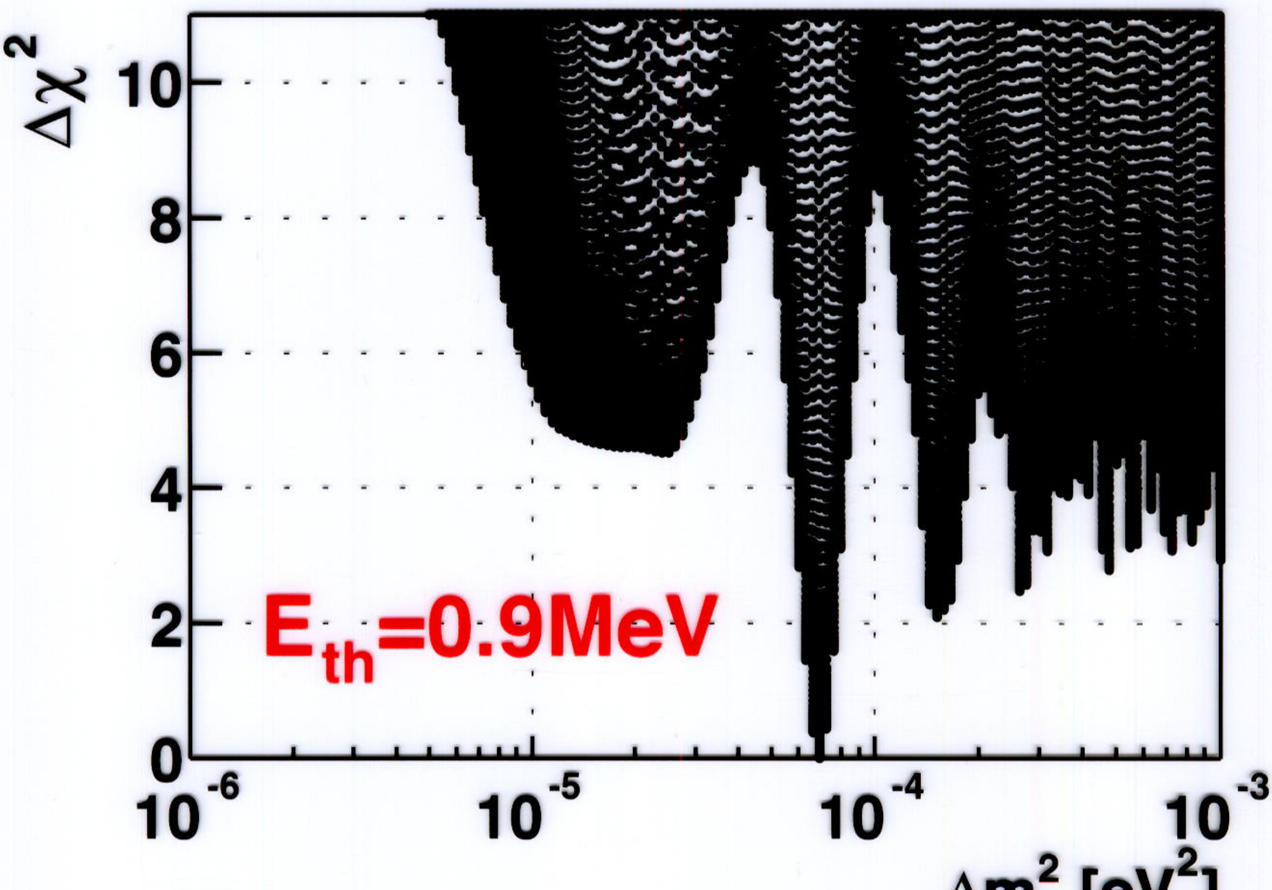


KamLAND
95% exclusion
by rate
Cl
SNO
Ga
SuperK
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$



Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
KamLAND
95% exclusion
by rate
Cl
KamLAND
95% allowed
by rate+shape
SNO
SuperK
Ga
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$


95%
68%
$\Delta\chi^2$
10
8
6
4
2
0
E_{th}=2.6MeV
0.5yr 95
1yr 95%
?
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Δm^2 [eV^2]


$\Delta\chi^2$
10
8
6
4
2
0
E_{th}=0.9MeV
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Δm^2 [eV^2]

Summary

KamLAND observed evidence of neutrino disappearance at 99.95% CL.
(54 observed, 86.8±5.6 expected, 0.95±0.99 BG.)

R=0.611±0.085(stat)±0.041(syst)

This completes ~50 yr quest for this type of measurement.

Highlight of reactor neutrino experiments

All oscilation solutions but the LMA solution for the solar neutrino problem are excluded. This answers the ~30 yr solar neutrino problem.

The LMA is the answer!

Geo-neutrino indication is seen. More statistics will give total earth radioheating.

Opening of neutrino geophysics

KamLAND gets into a precision measurement of oscillation parameters.
One more year data may improve the precision drastically.
Bi-products (limits on solar nuebar, relic nuebar, proton decay etc.) will appear soon.

Stay in tune!