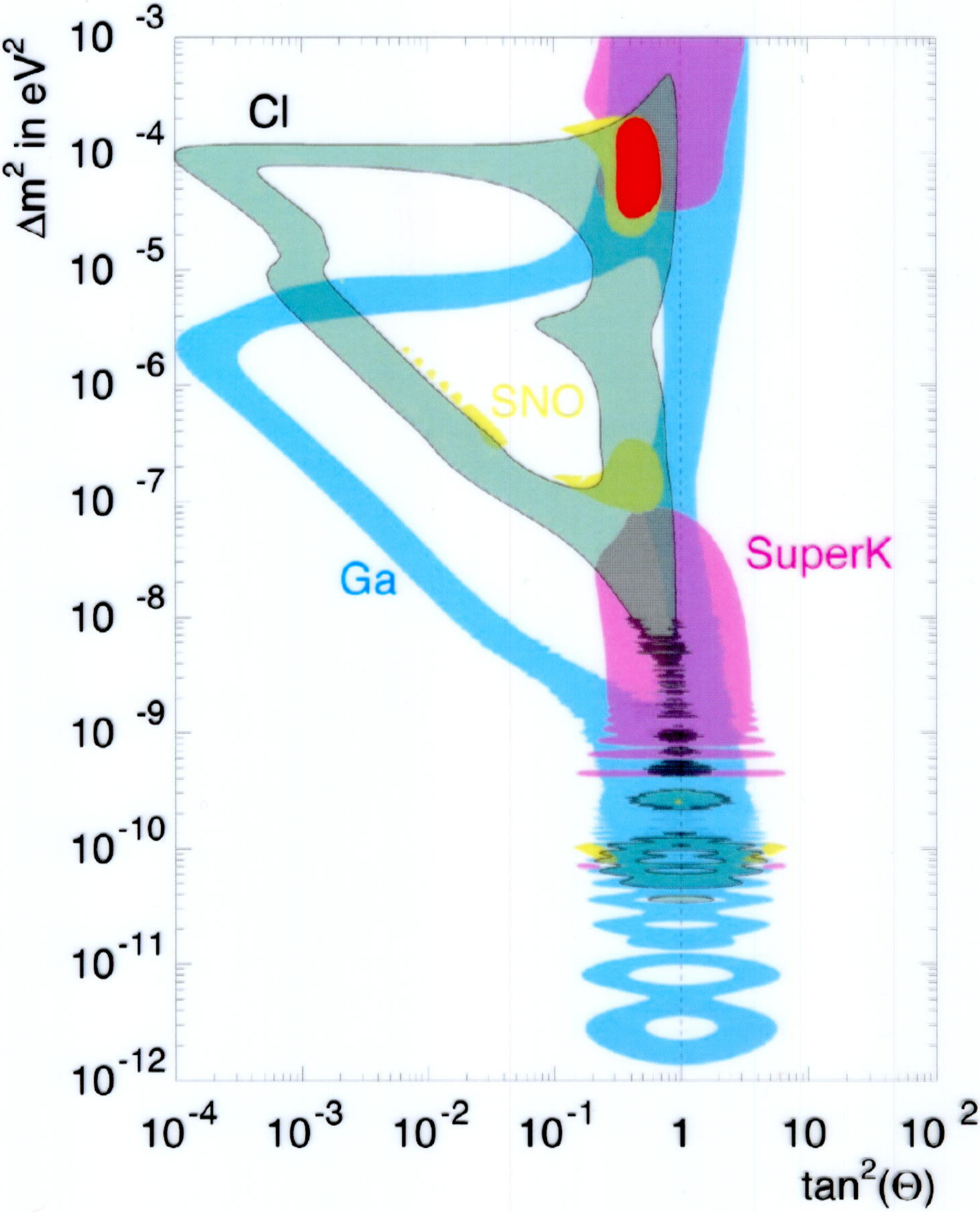


Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Cl
SNO
SuperK
Ga
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

The LMA solution looks likely.

KamLAND examines the solar neutrino problem with an artificial neutrino source.

$$P = 1 - \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 L / E\nu)$$

$$1.27 \, \Delta m^2 L / E\nu = \pi/2$$

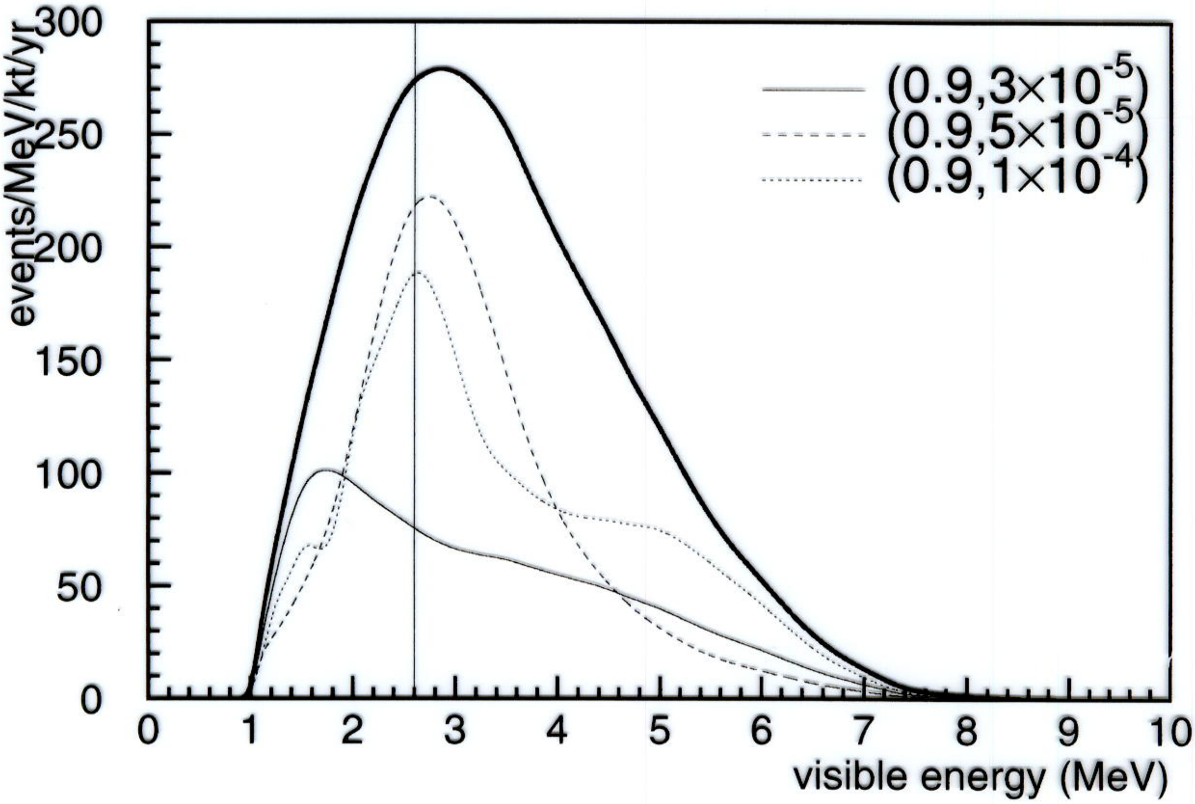
$E\nu \sim 5$ MeV for reactors

	mass (ton)	distance (km)	rate (ev/d)	Sensitive@ (eV^2)	
CHOOZ	5	1	24	6×10^{-3}	
Palo Verde	12	0.8	220	8×10^{-3}	
KamLAND	1000	~175	3	4×10^{-5}	Just on the LMA
BOREXINO	300	~800	0.1	8×10^{-6}	SK D/N excluded

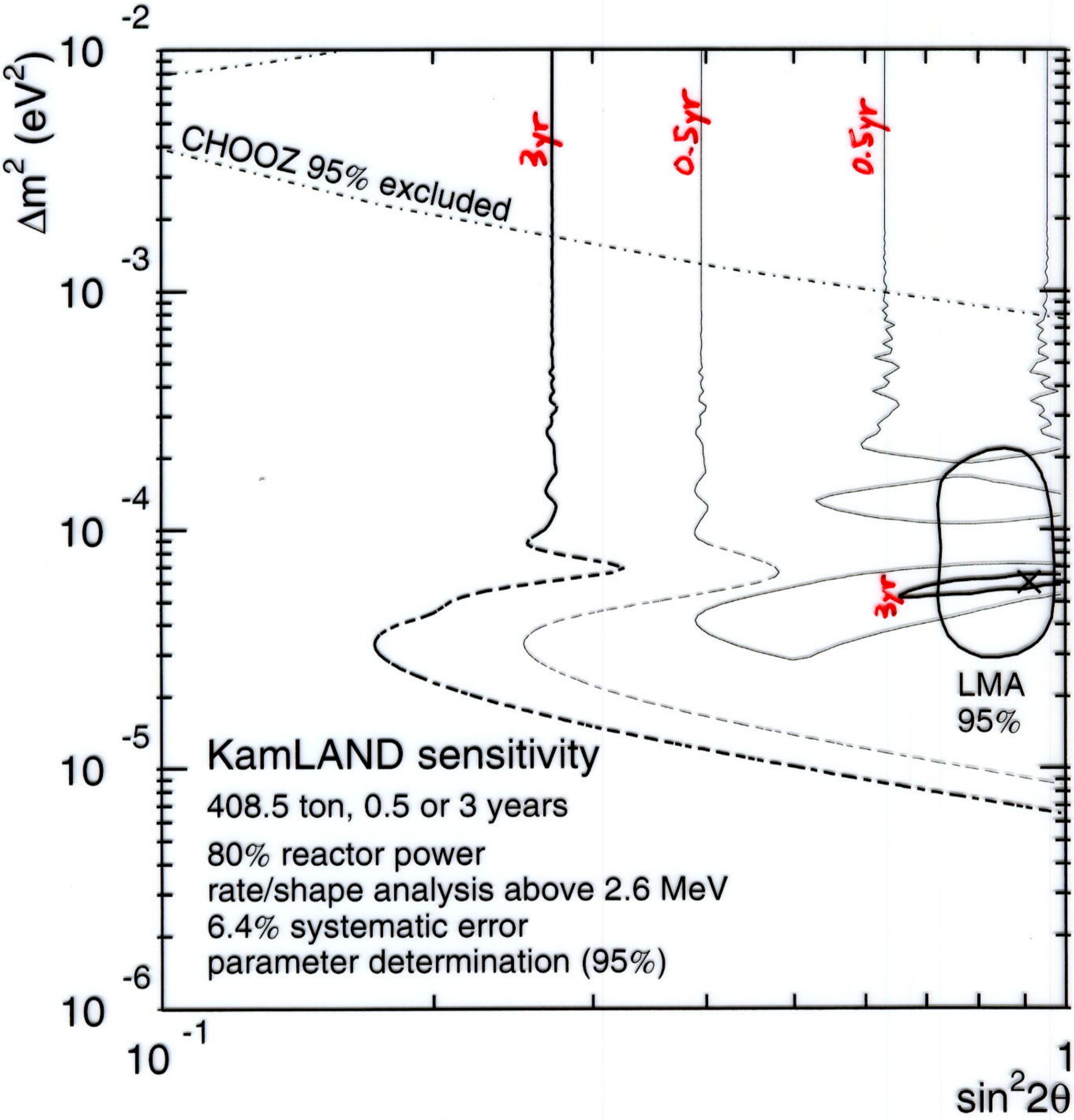
Only KamLAND has the best sensitivity just on the LMA.

If the LMA is not the case.

KamLAND is also aiming at observing ^7Be solar neutrinos.

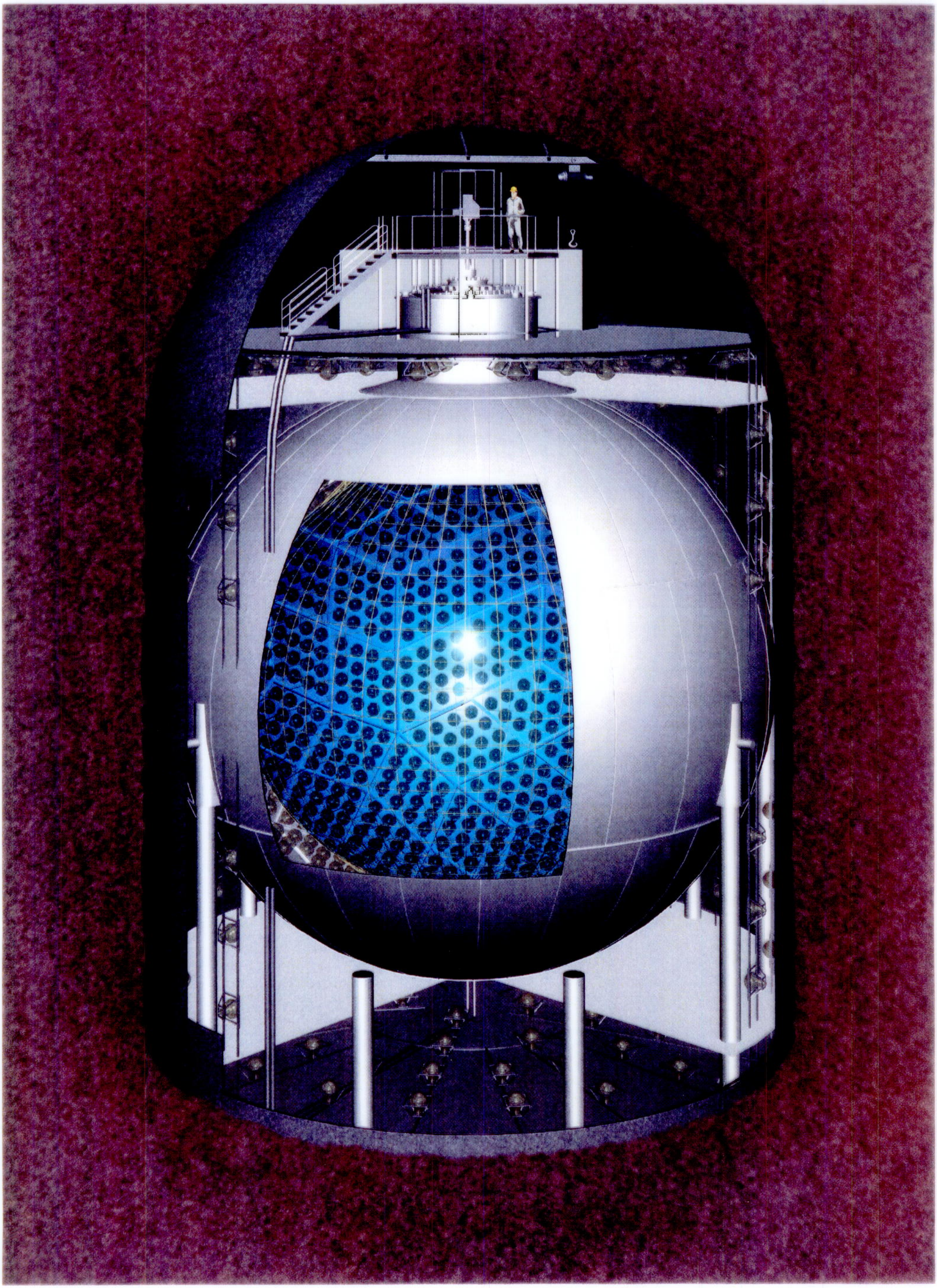


events/MeV/kt/yr
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
visible energy (MeV)
(0.9,3×10^-5)
(0.9,5×10^-5)
(0.9,1×10^-4)

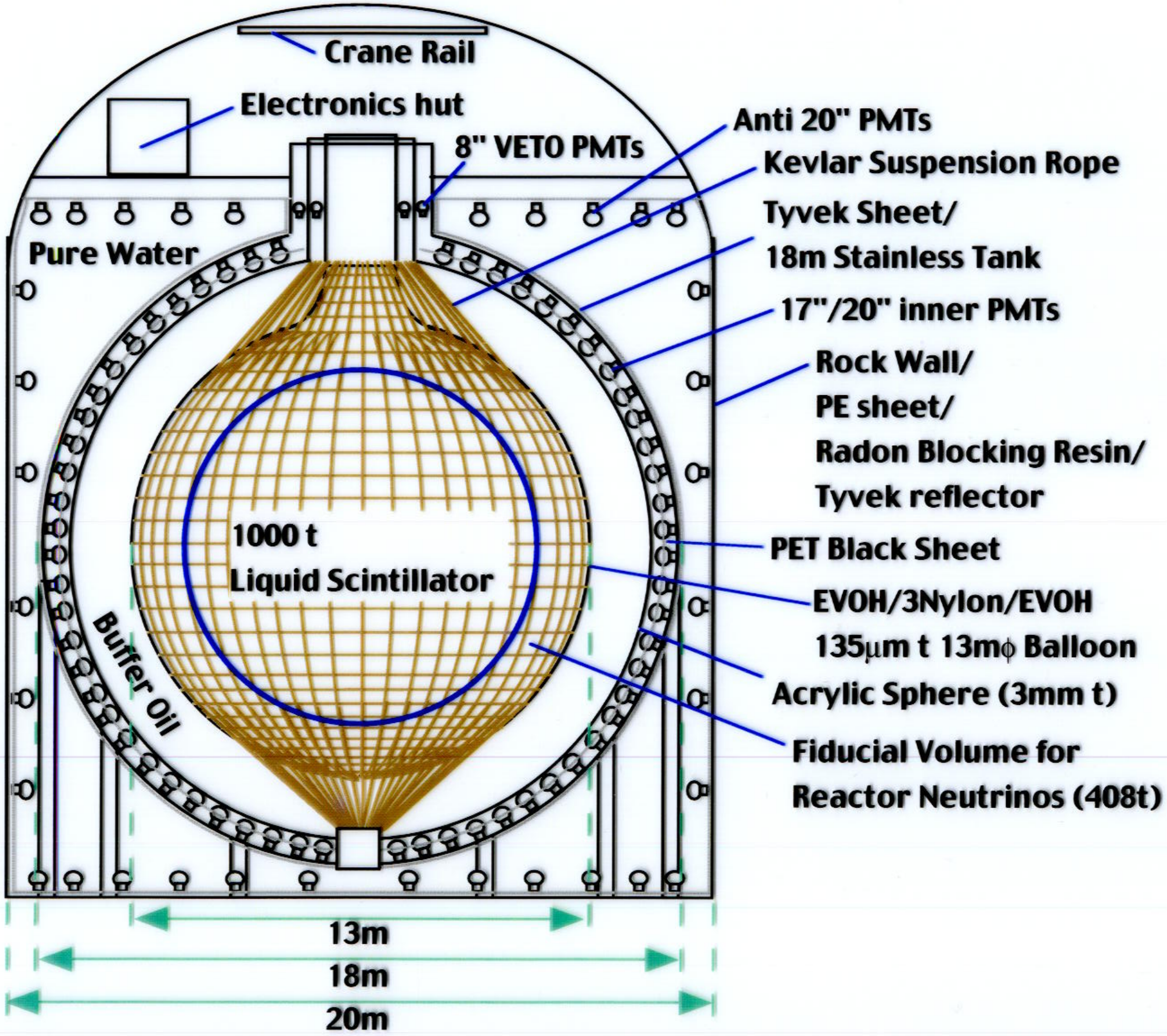


結果発表はもうすぐです。

お楽しみに……。



KamLAND Schematics



Liquid Scintillator

20% PseudoCumene

80% dodecane

1.5g/l PPO

8,000 photons/MeV

L = 10 m @400 nm

ρ_{LS}=0.780 g/cm^3

Buffer Oil

50% dodecane

50% isoparaffin

ρ_{LS}/ρ_{BO}=1.0004

PMTs

1325 17"PMTs σ ~1 nsec

22% coverage

(554 20"PMTs σ ~5 nsec)

(34% coverage)

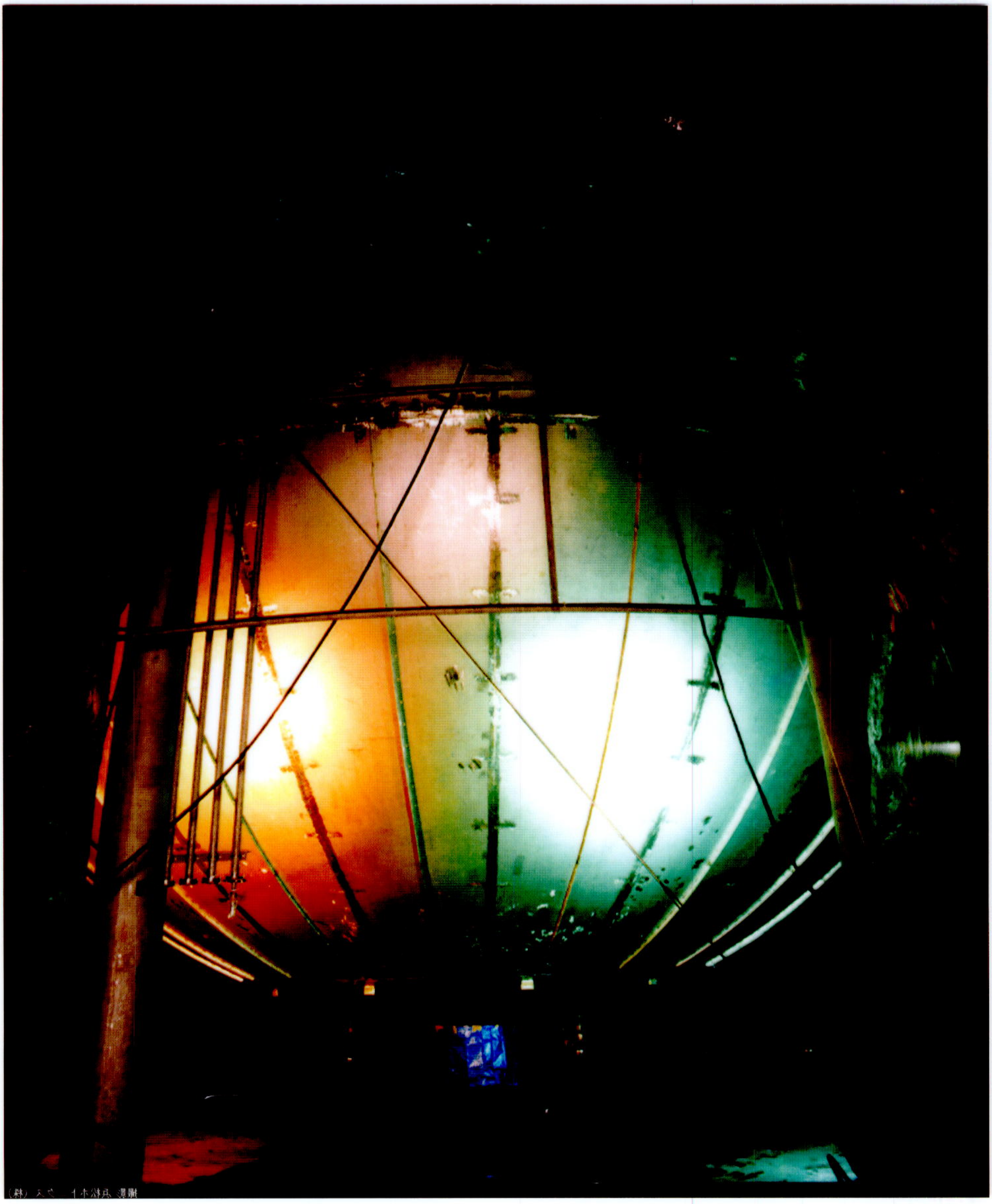
Energy Resolution

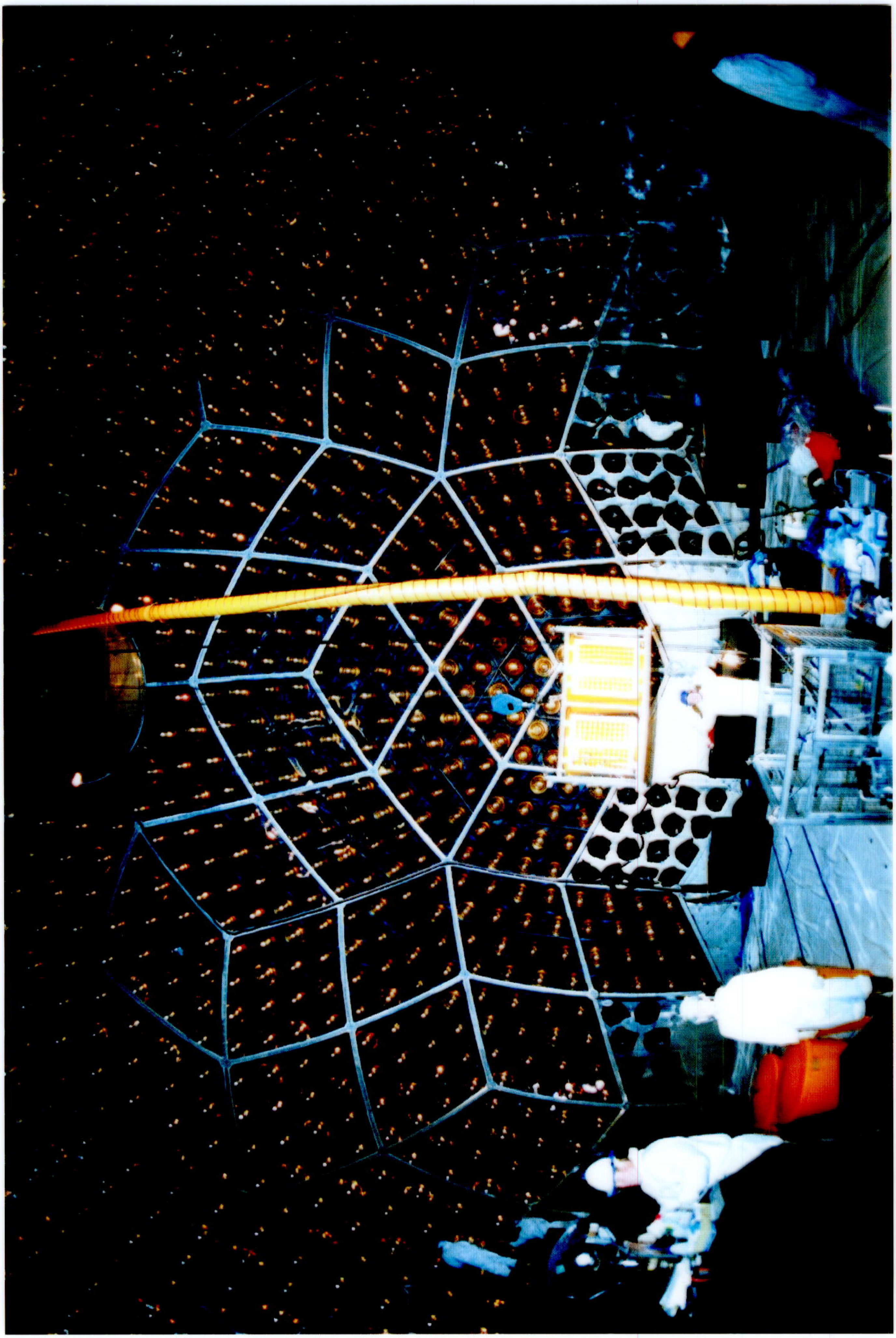
$\sigma/E \sim 7.5\%/\sqrt{E}$ (MeV) ~320p.e./MeV

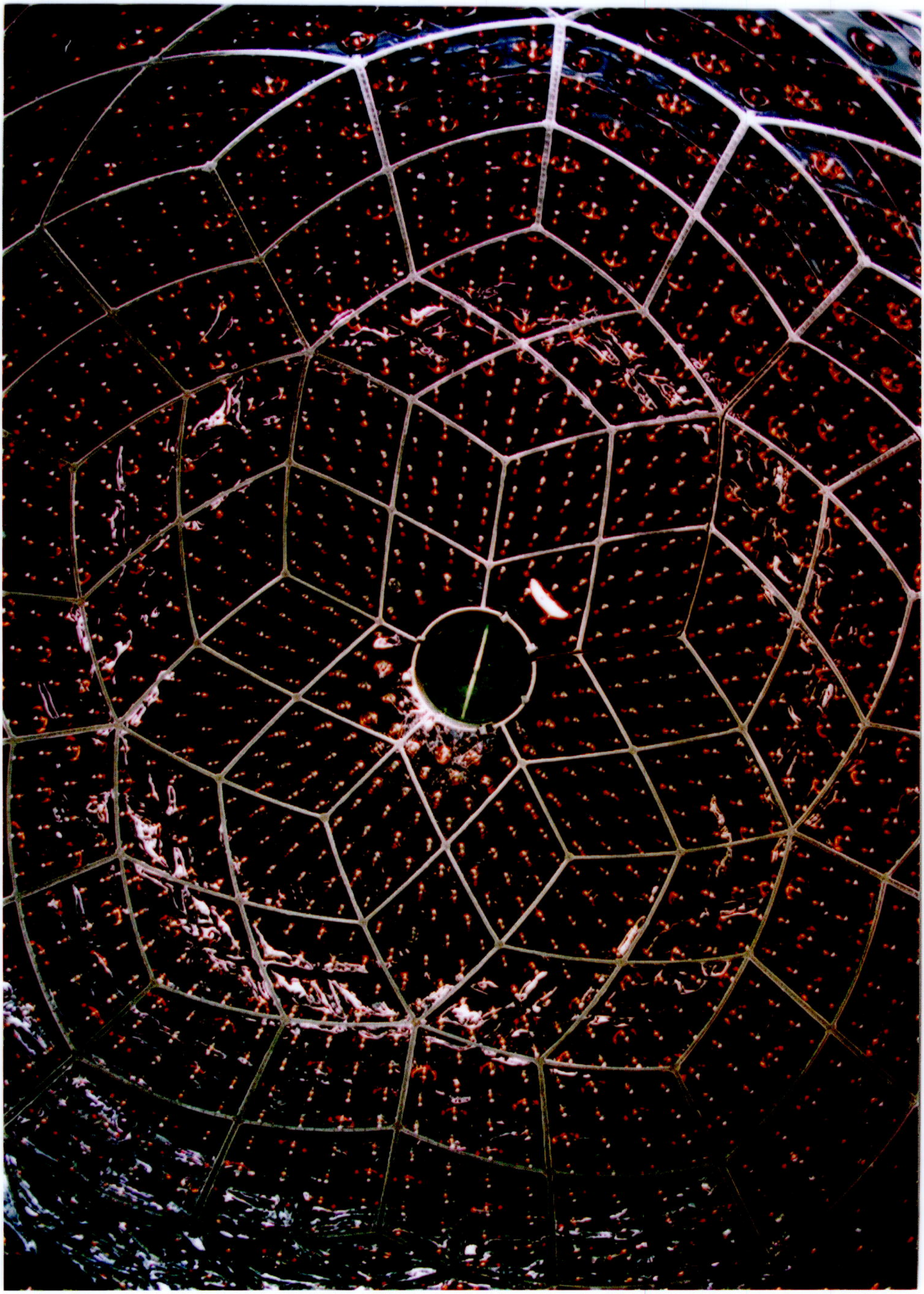
($\sigma/E \sim 6\%/\sqrt{E}$ (MeV)) (~500p.e./MeV)

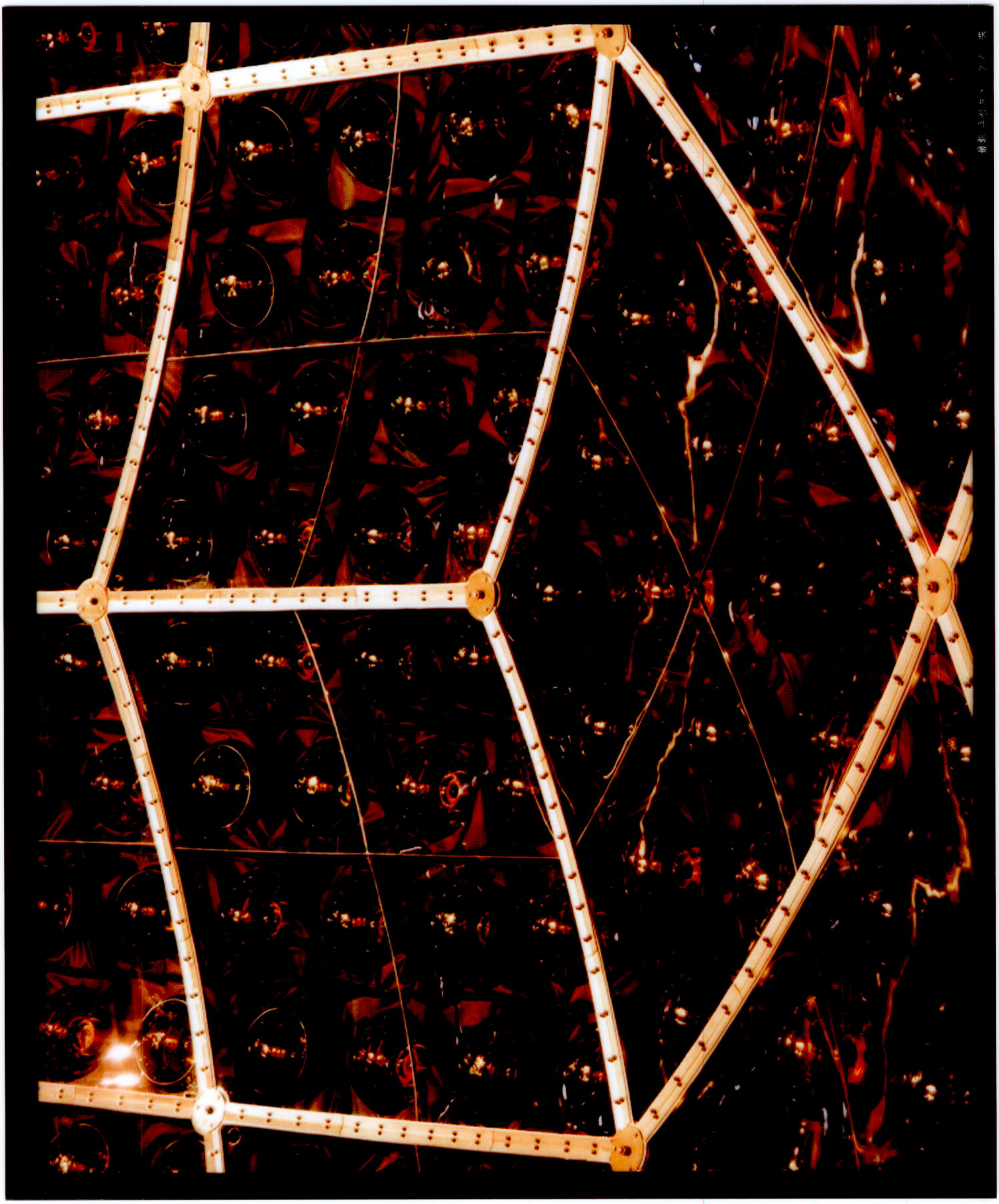
Vertex Resolution

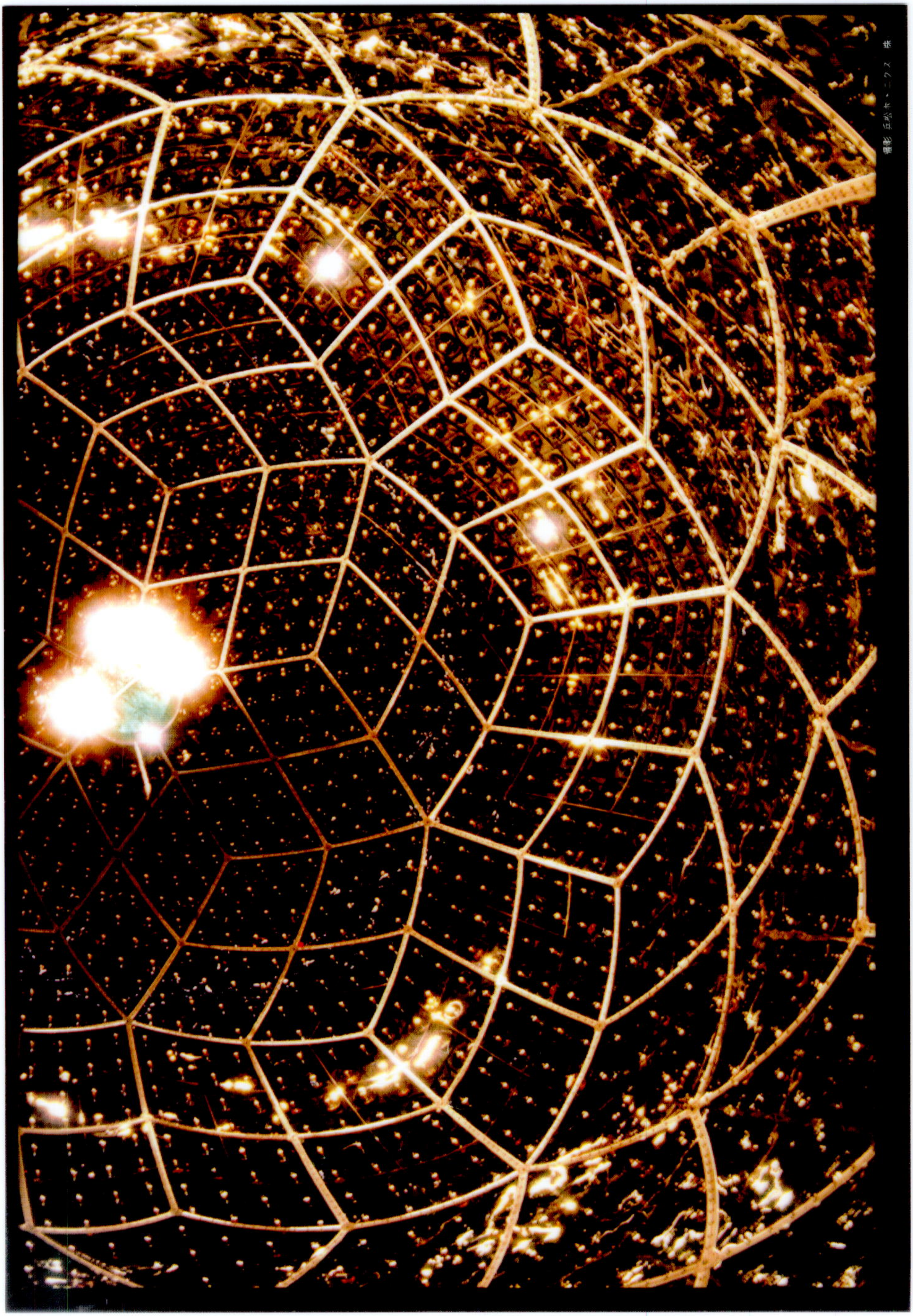
σ ~ 25 cm @ 1 MeV







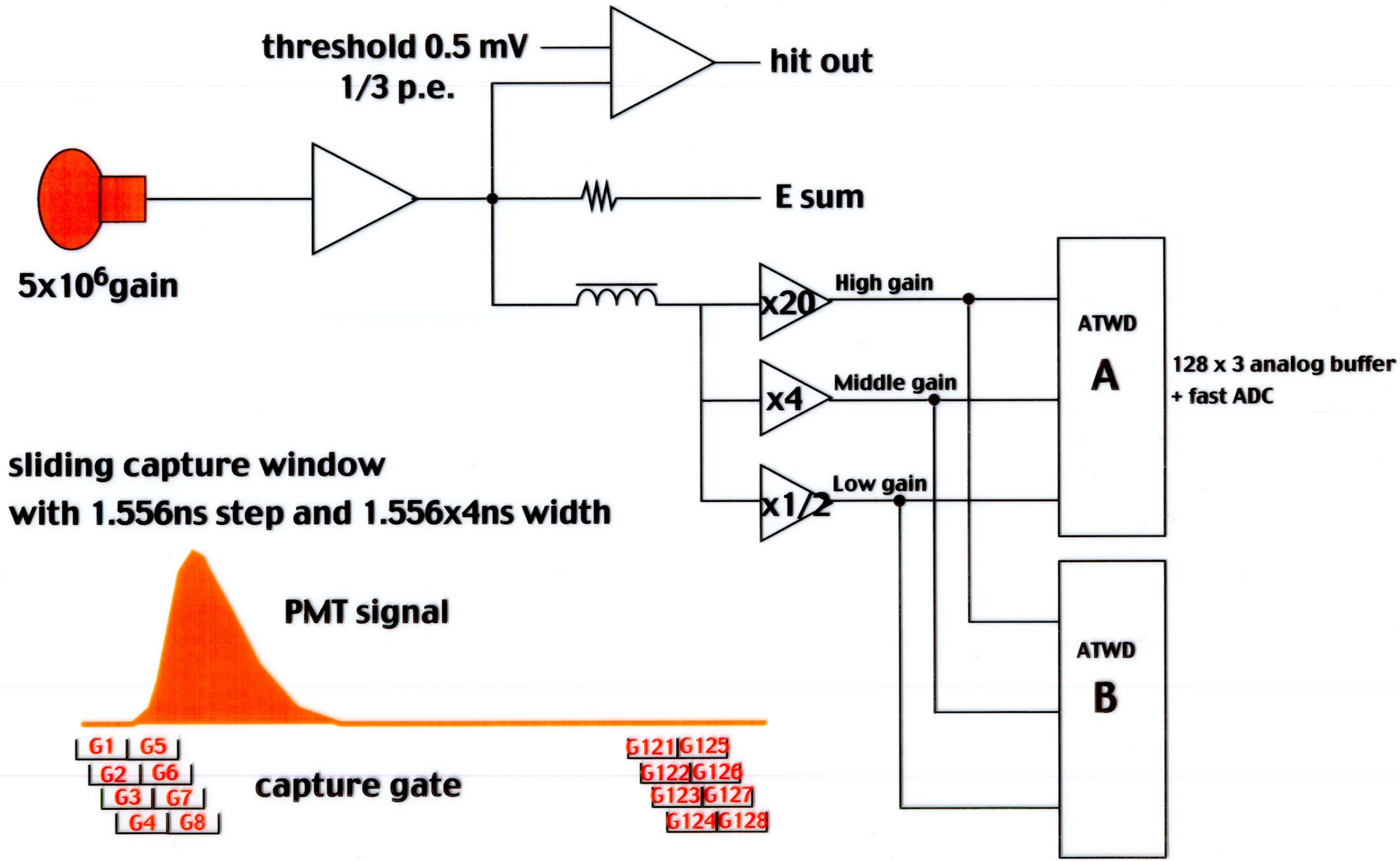


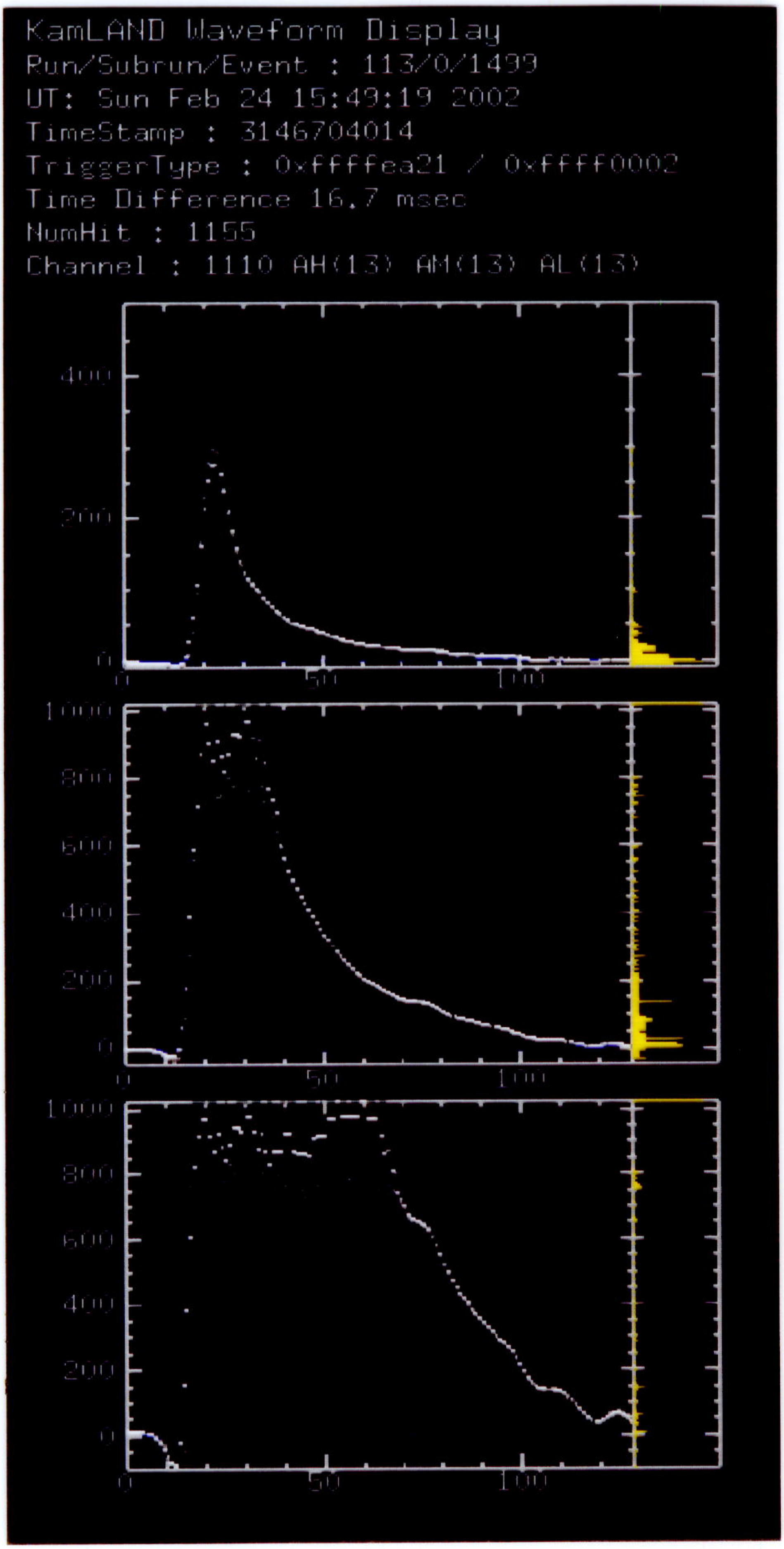


撮影 浜松ホトニクス 様

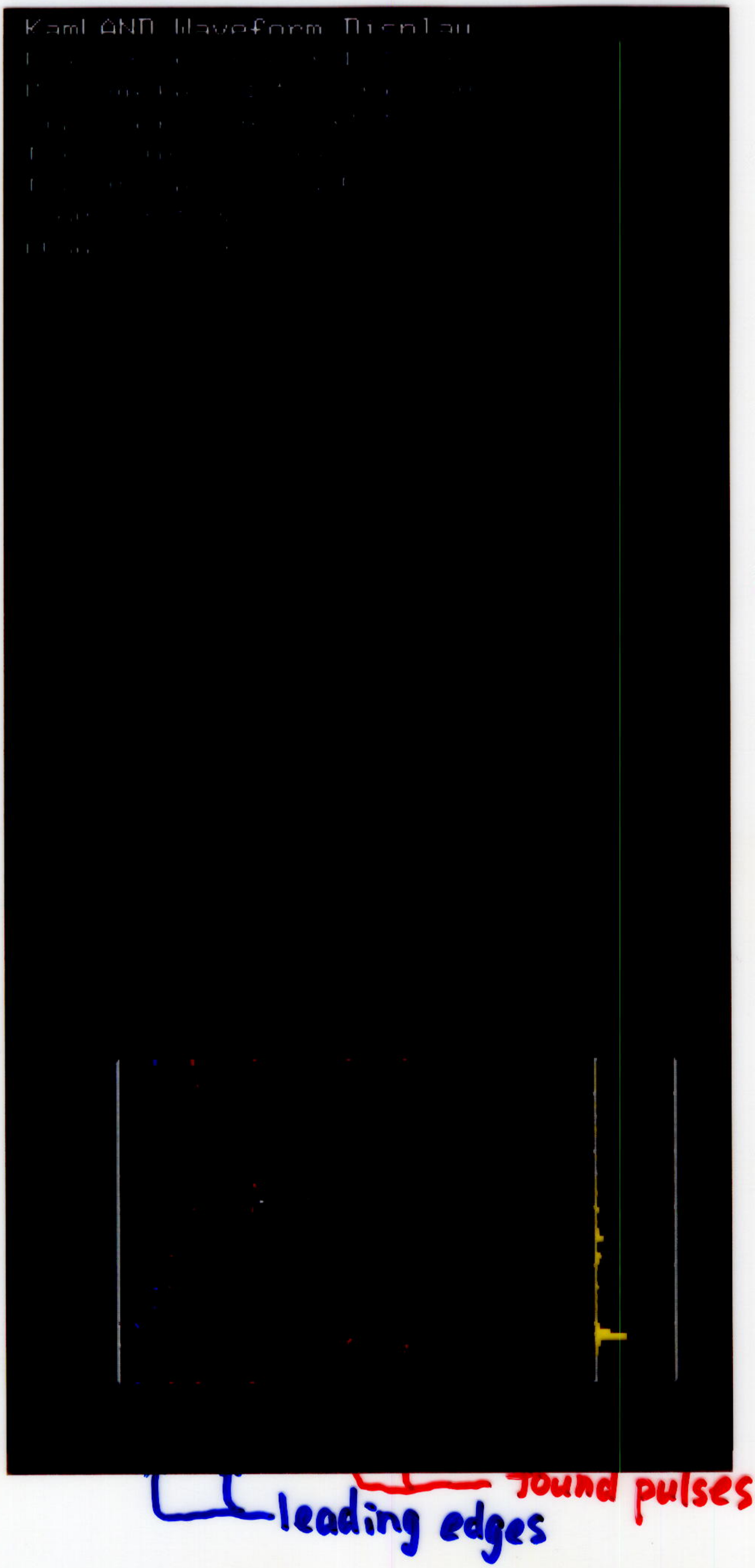
Front End Electronics

dual x 3gain x 10bits x 128depth
Analog Transient Waveform Digitizer




KamLAND Waveform Display
Run/Subrun/Event : 113/0/1499
UT: Sun Feb 24 15:49:19 2002
TimeStamp : 3146704014
TriggerType : 0xffffea21 / 0xffff0002
Time Difference 16.7 msec
NumHit : 1155
Channel : 1110 AH(13) AM(13) AL(13)
400
200
0
50
100
1000
800
600
400
200
0
50
100
1000
800
600
400
200
0
50
100

Multi Photon Analysis



Trigger scheme

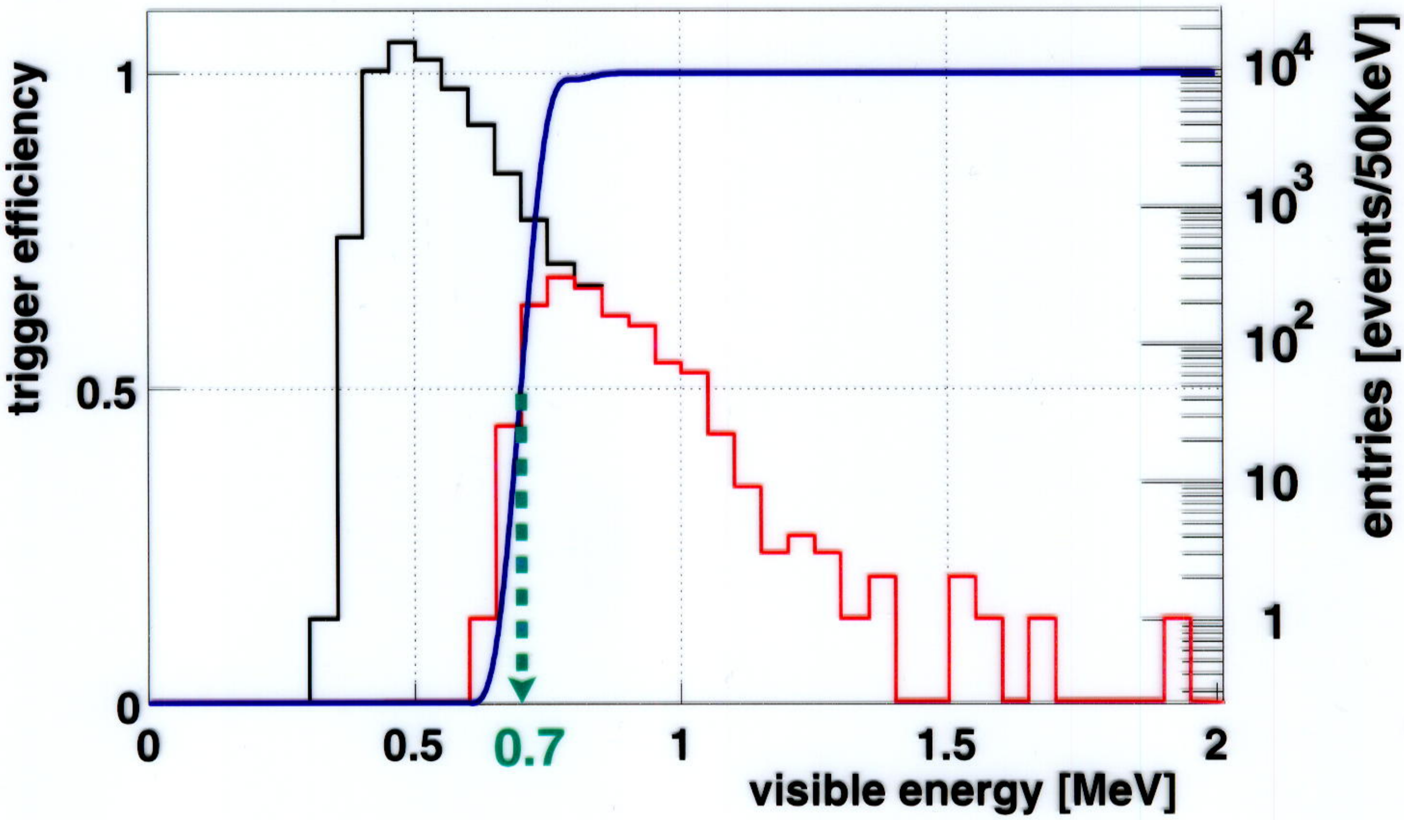
Digital # of hits information are acquired from all individual boards.
FPGA issues a trigger based on # of hits.
Very complex trigger criteria can be set in principle.

Current trigger condition

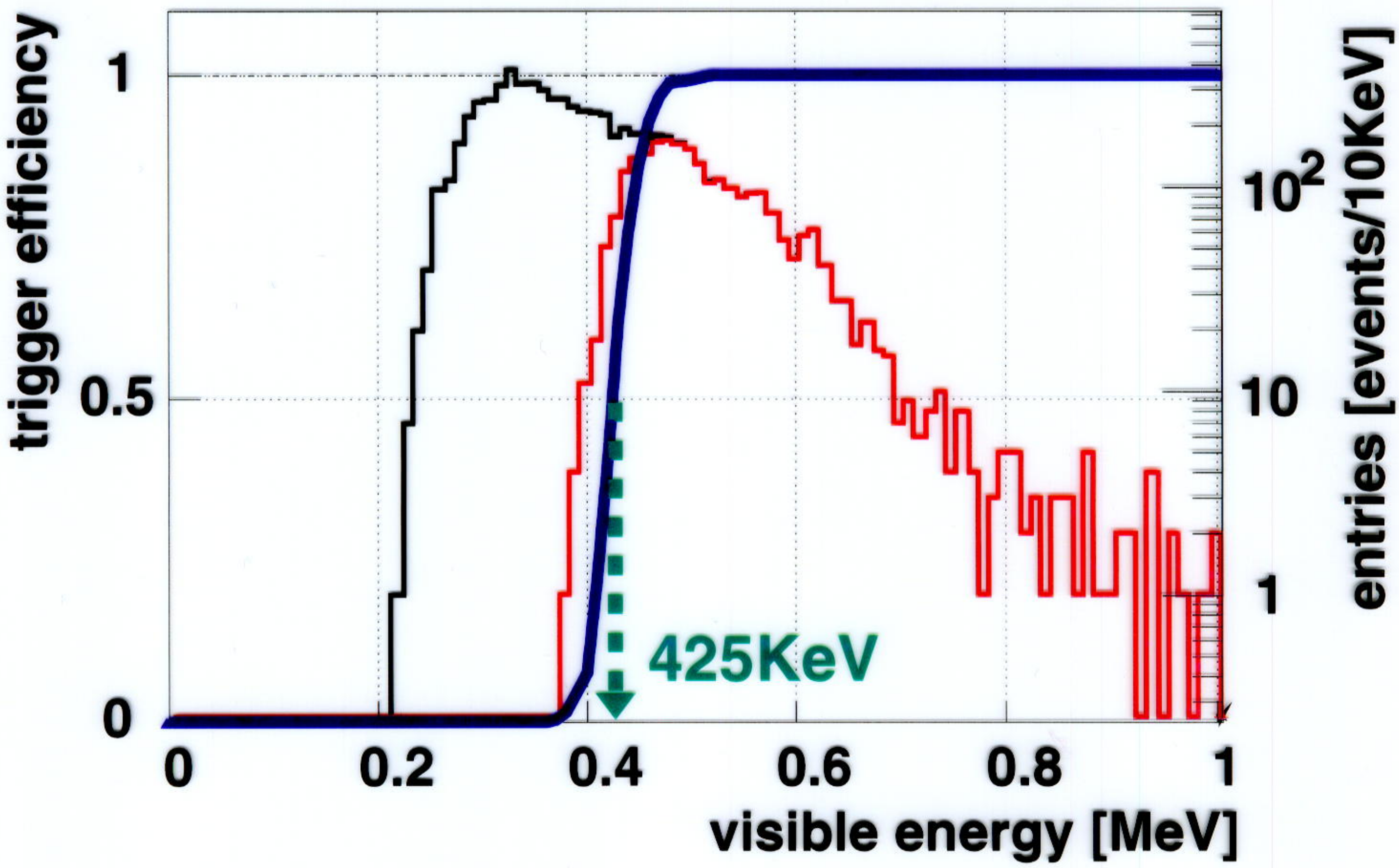
Prompt : Nhit >200 (~0.8MeV)
Delayed: Nhit >120 (~0.5MeV) for 1 msec after prompt

Trigger rate	~25 Hz
Data size	~150GB/day (online format)
	~100GB/day (off line format)
	~10GB/day (waveform analysis)

Trigger threshold is limited by the data size, but it is sufficiently low for the reactor neutrino observation.

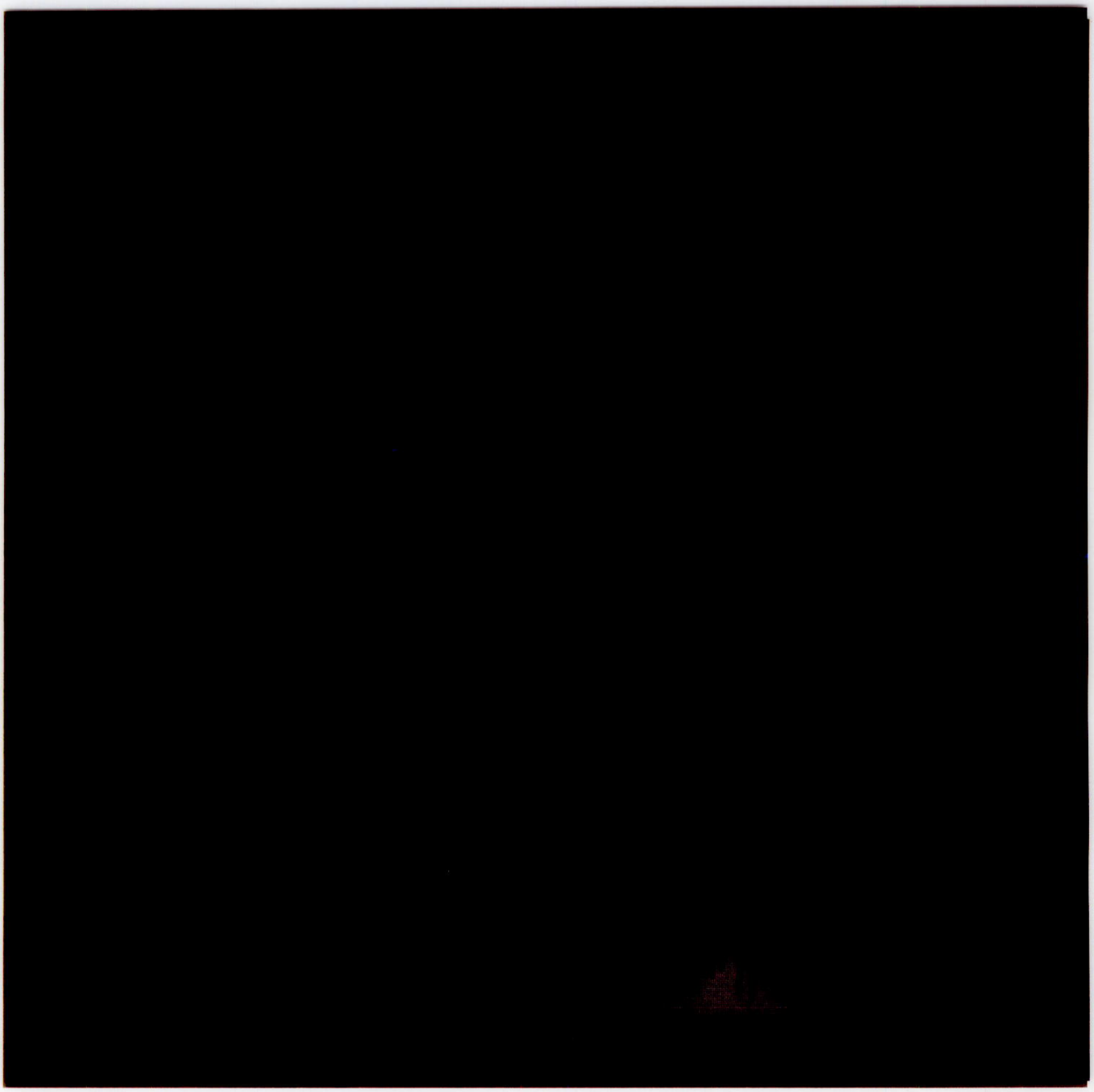


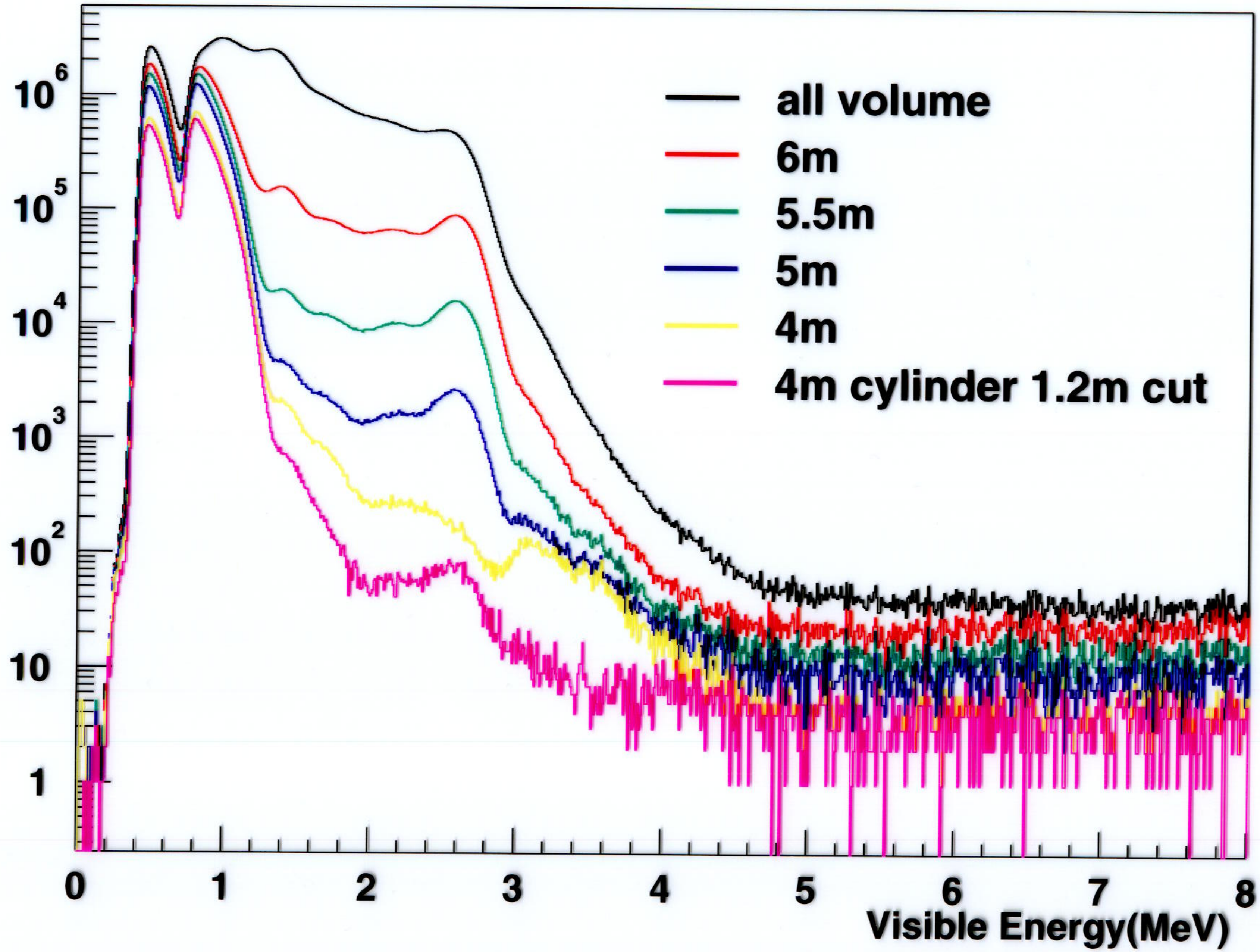
trigger efficiency
1
0.5
0
0
0.5
0.7
1
1.5
2
visible energy [MeV]
10^4
10^3
10^2
10
1
entries [events/50KeV]



trigger efficiency
1
0.5
0
0
0.2
0.4
0.6
0.8
1
visible energy [MeV]
entries [events/10KeV]
10^2
10
1
425KeV

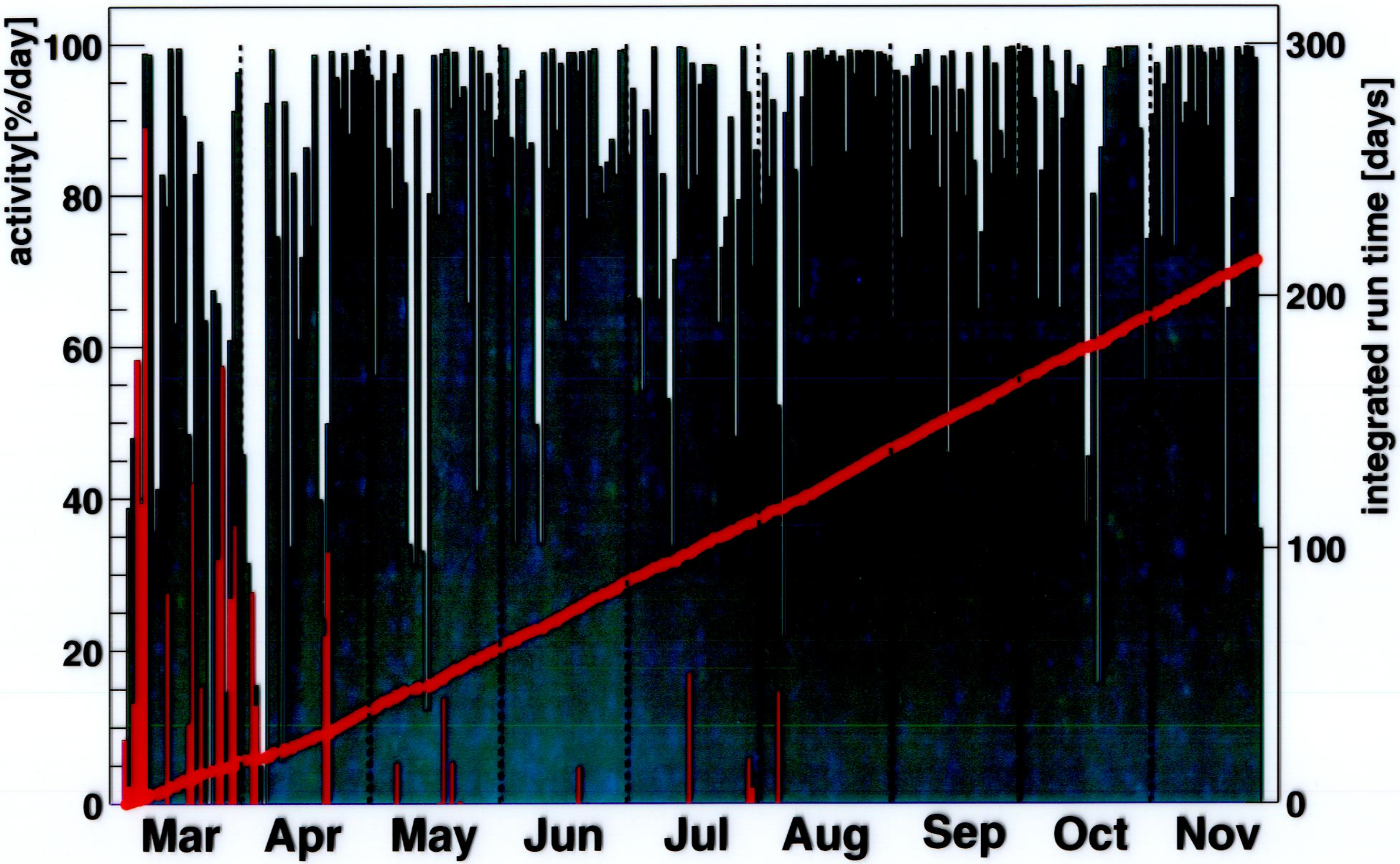
Typical Penetrating Muon
Cherenkov Ring from Clipping Muon



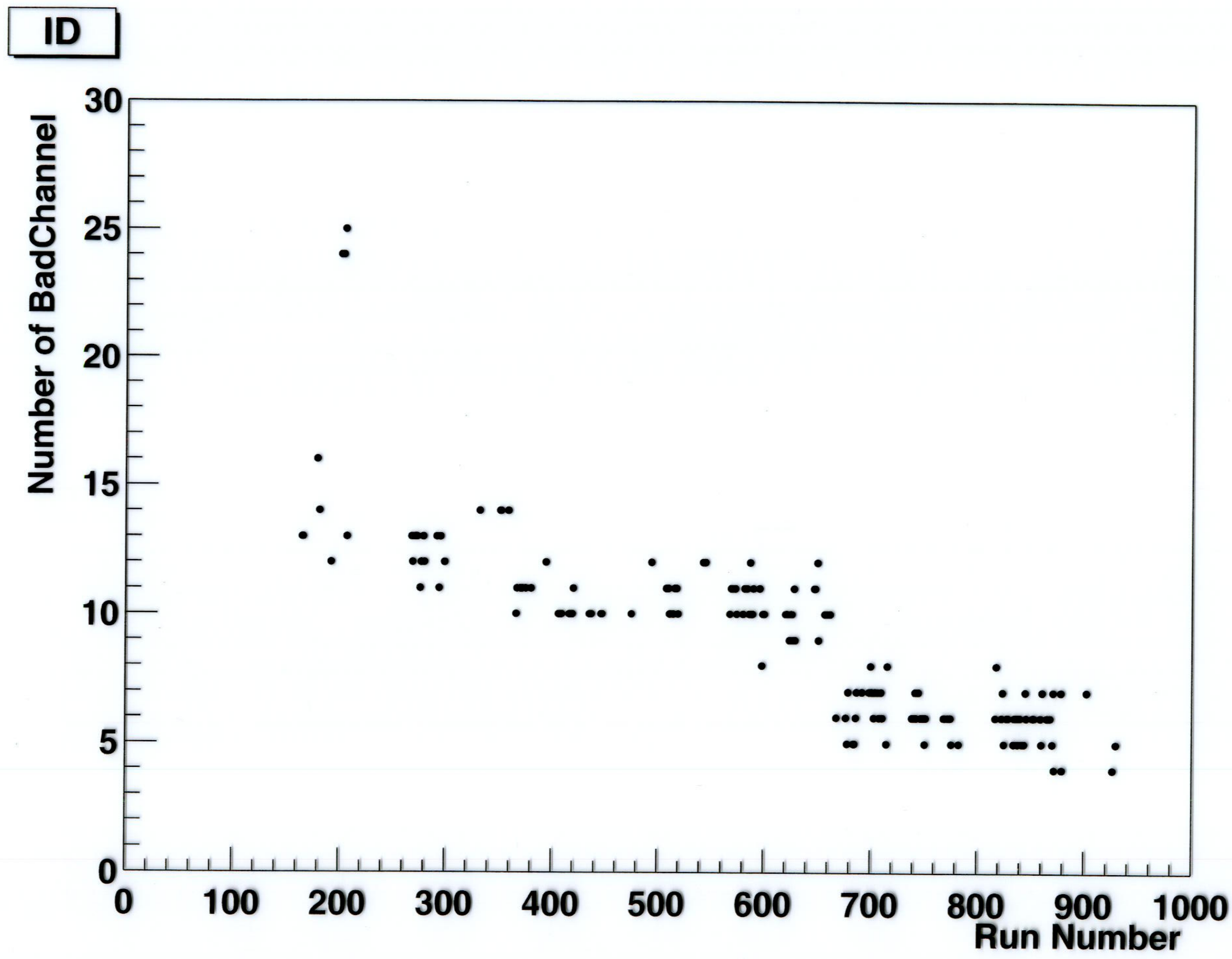

all volume
6m
5.5m
5m
4m
4m cylinder 1.2m cut
Visible Energy(MeV)

カムランドのこれまで

１９９７年　４月	カムランドプロジェクト始動
１９９８年　４月	カミオカンデ解体
２０００年　４月	球形タンク完成
２０００年　９月	PMT設置完了
２００１年　２月	バルーン設置完了
２００１年　９月	液体シンチレータ注入完了
２００１年１０月	電子回路到着
２００１年１１月２６日	最初のミューオン観測
２００２年　１月２２日	データ取得開始 ?



activity[%/day]
100
80
60
40
20
0
integrated run time [days]
300
200
100
0
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov



ID
Number of BadChannel
0
5
10
15
20
25
30
0
100
200
300
400
500
600
700
800
900
1000
Run Number

Power Reactors as a Neutrino Source

Rich and Cheap Neutrino Source

Total man-made thermal output with nuclear power reactors in the world amounts to ~1.1 TW.

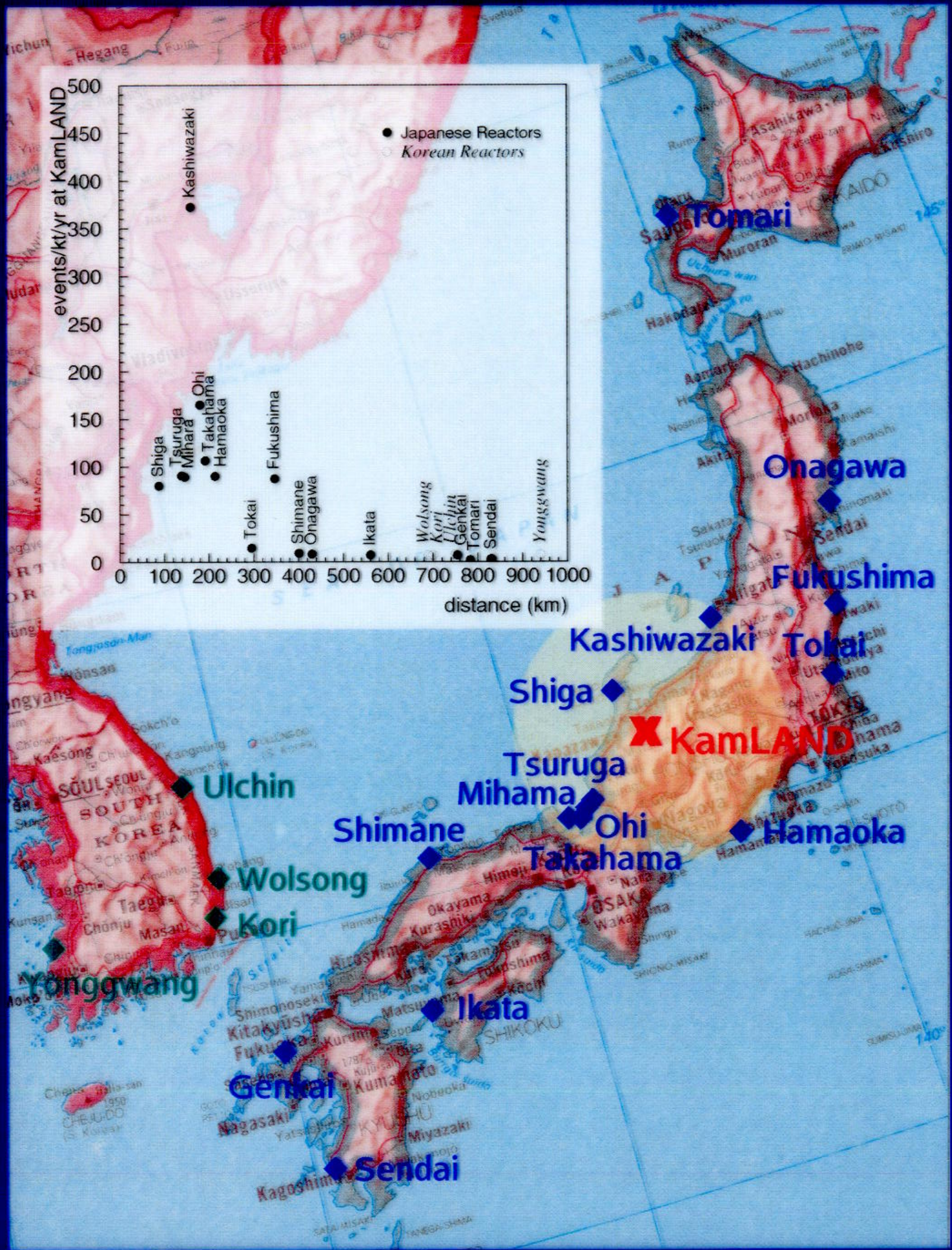
Japan	152 GW
Asia w/o Japan	60 GW
Europe	521 GW
North America	333 GW
Others	11 GW

It corresponds to 2×10^{23} anti electron neutrino creation / sec.

High Population

70 GW (7% of world total) is generated at 175 ± 30 km distance from Kamioka site.

This high population provides $5 \times 10^6/cm^2/sec$ of neutrino flux at Kamioka and it is measurable amount with an O(kiloton) underground detector.



80% of contribution comes from reactors located at ~200km from Kamioka.

If adopted for oscillation search

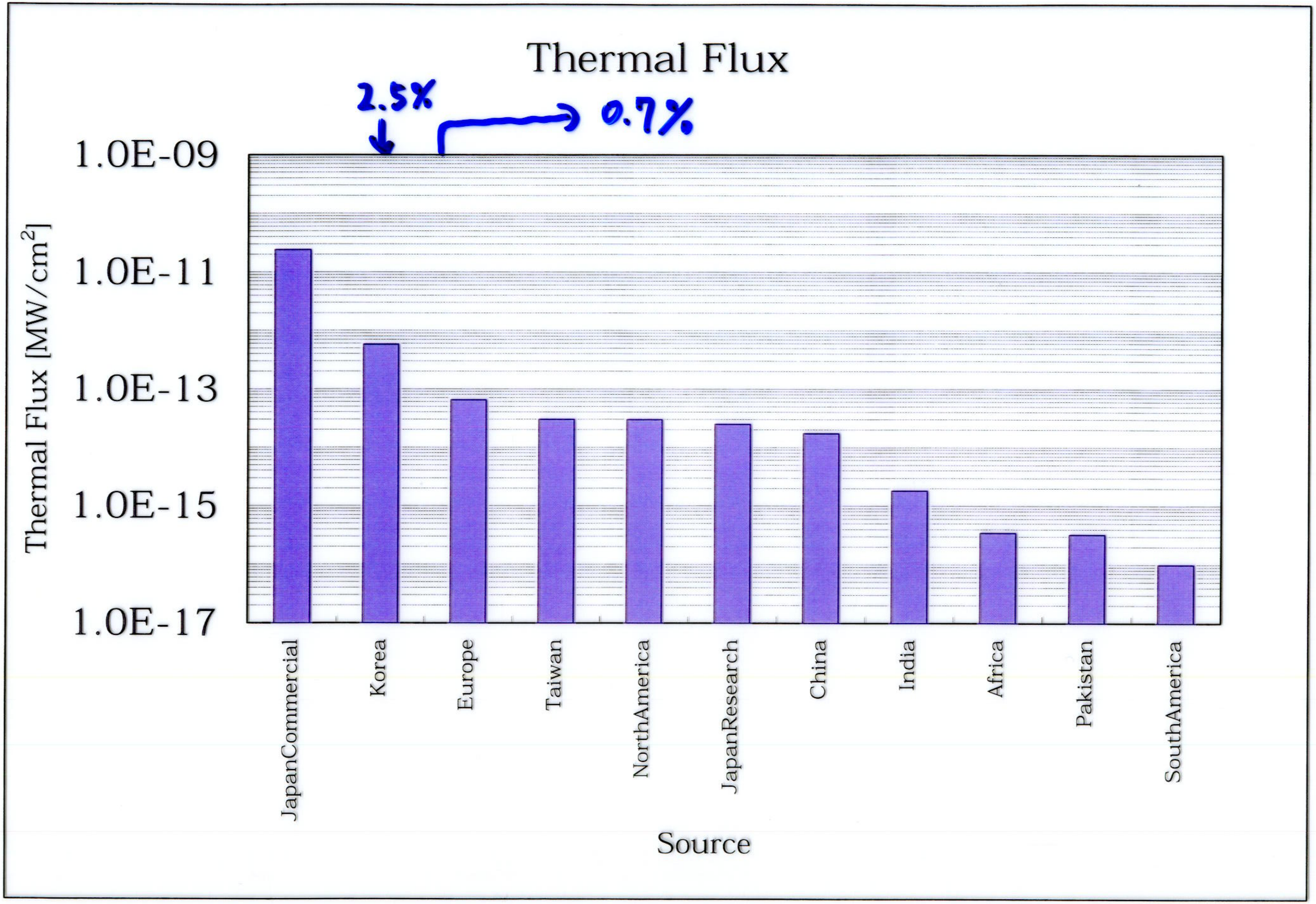
$$P=1-\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$$
$$||$$
$$\pi/2$$

Typical distance 175km
Typical energy 5MeV

↓

Sensitive @ $\Delta m^2 \sim 4\times10^{-5} eV^2$

Just on the LMA solution!

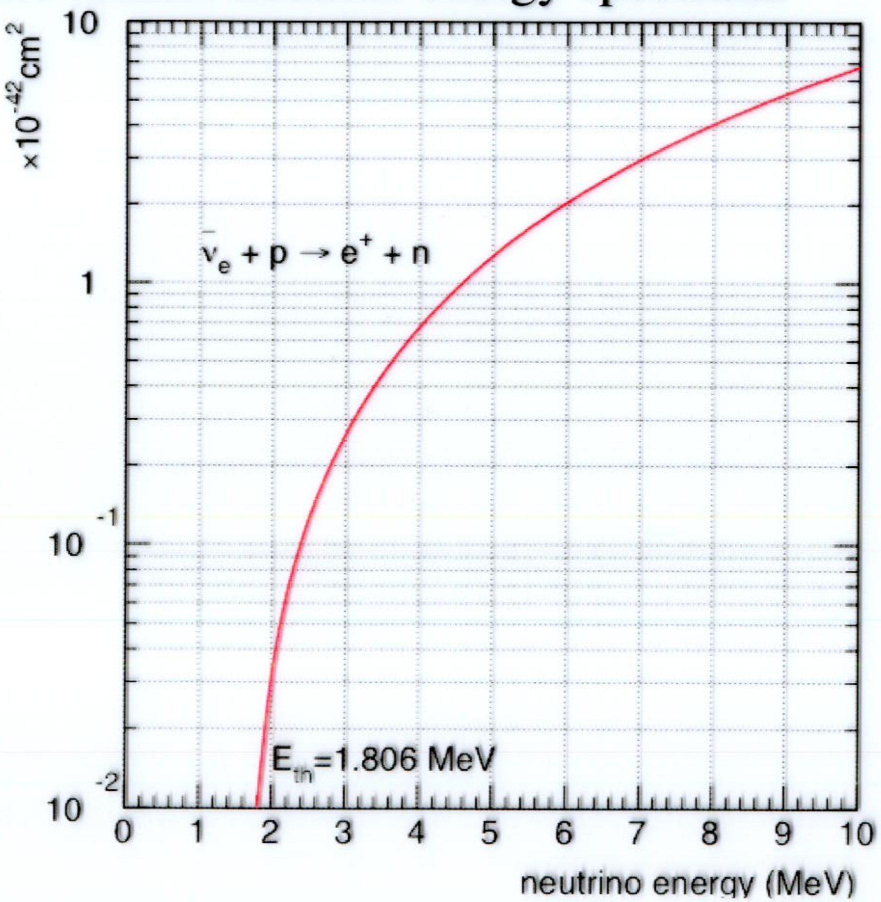

Thermal Flux
2.5%
0.7%
1.0E-09
1.0E-11
1.0E-13
1.0E-15
1.0E-17
Thermal Flux [MW/cm²]
JapanCommercial
Korea
Europe
Taiwan
NorthAmerica
JapanResearch
China
India
Africa
Pakistan
SouthAmerica
Source

Clear 2 fold delayed coincidence Signature

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \Rightarrow \quad n + p \rightarrow D + \gamma (2.22437\,MeV)$$

Capture time 210 μsec (KamLAND)

Theoretical uncertainty of neutrino cross section calculation is only 0.2% for the entire reactor neutrino energy spectrum.



Order(1/M) calculation

P.Vogel and J.F.Beacom hep-ph/9903553

Outer Radiative Correction

A.Kurylov, M.J.Ramsey-Musolf and P.Vogel

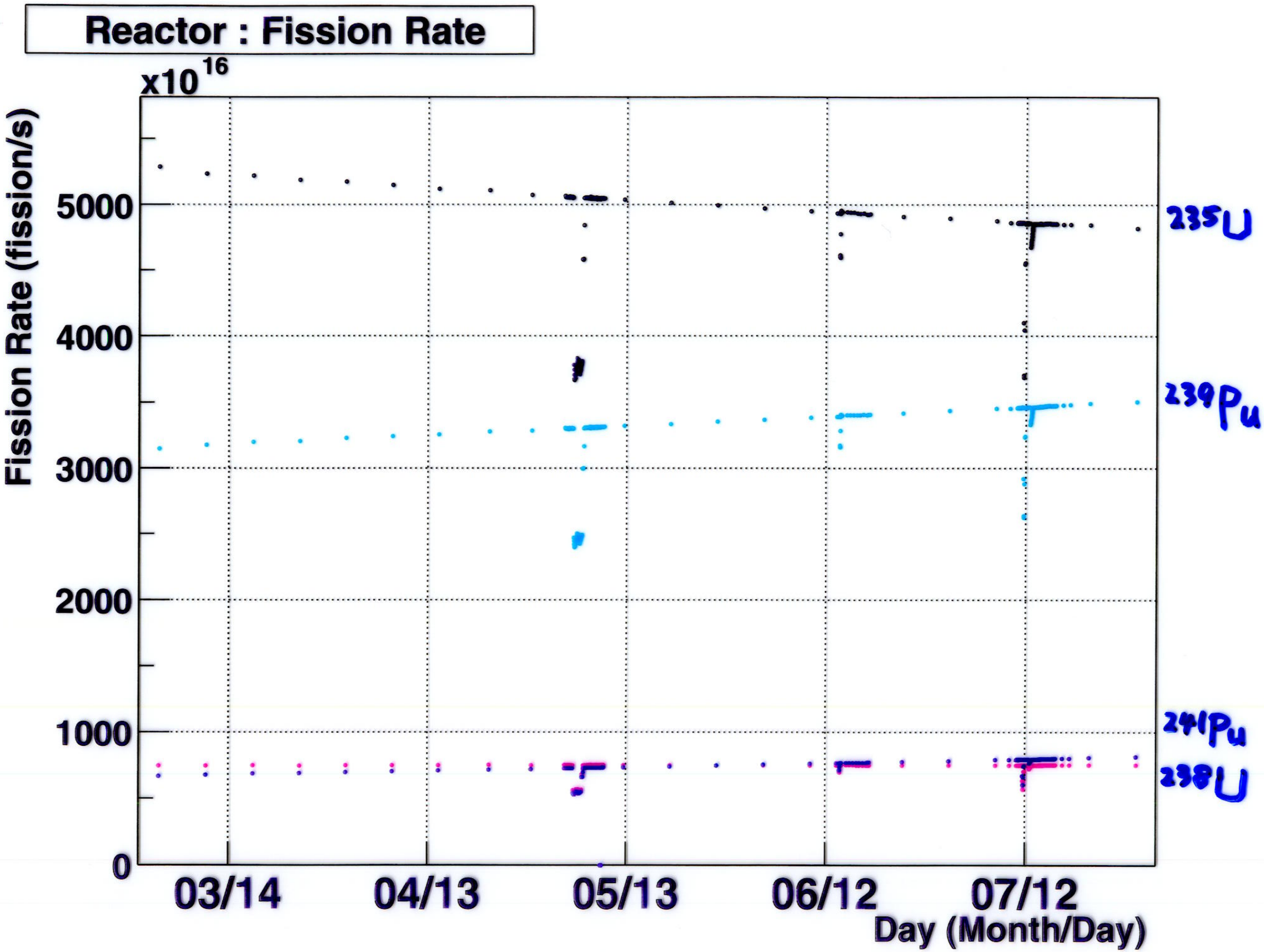
Fission Rate

Only 4 fissile nuclei contribute to reactor power outputs.

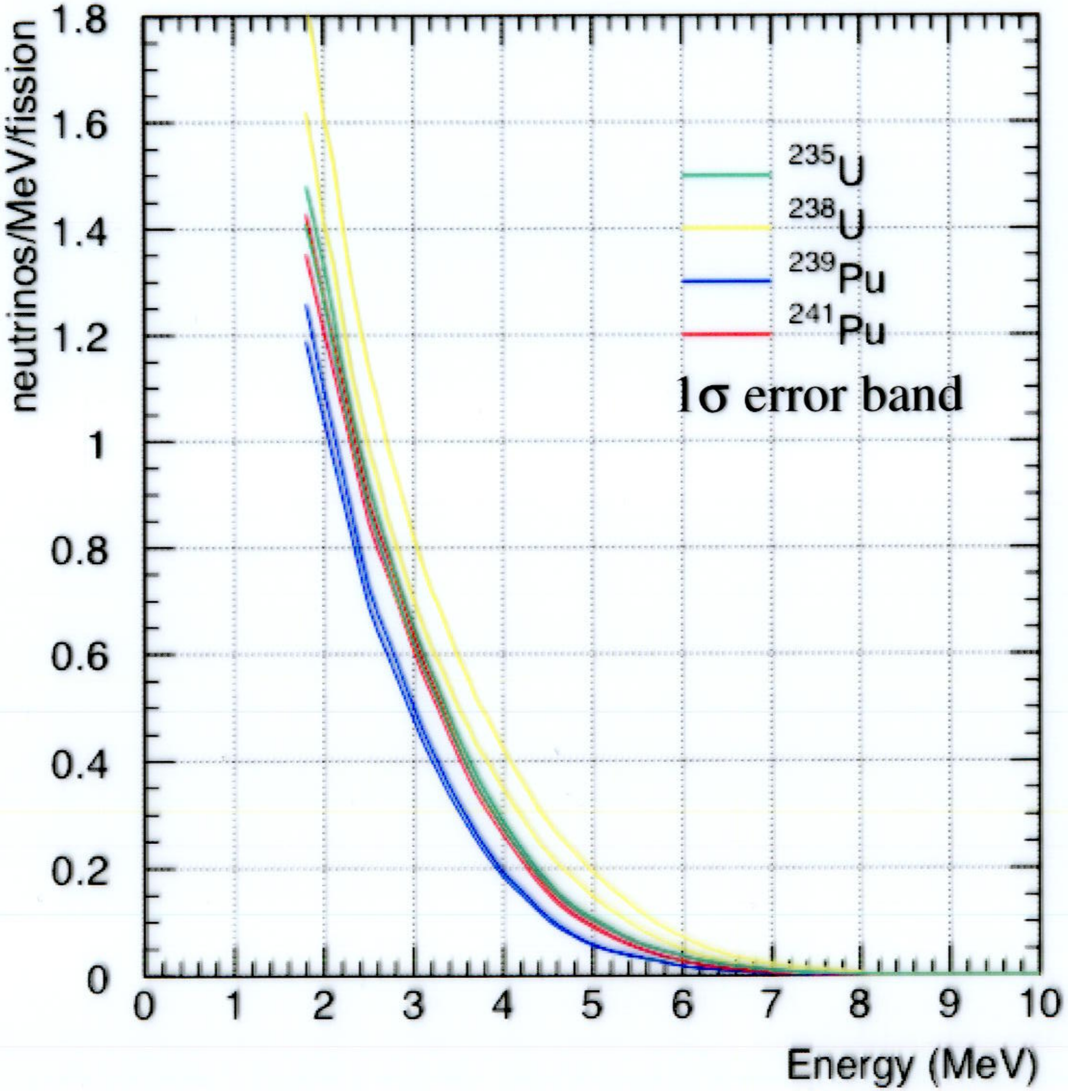
^{235}U	201.8 MeV
^{238}U	205.0 MeV
^{239}Pu	210.3 MeV
^{241}Pu	212.6 MeV

Normalization to the total fission rate is well defined by the measured thermal power output at much better than 2% level.

Contribution of each nuclei evolves as fuel burns (burn up effect).
Burn up effect can be accurately calculated knowing history of thermal power, fraction of new fuel and ^{235}U enrichment.
Systematic error to the neutrino event rate is much smaller than 1%.


Reactor : Fission Rate
x10^16
Fission Rate (fission/s)
5000
4000
3000
2000
1000
0
03/14
04/13
05/13
06/12
07/12
Day (Month/Day)
235U
239Pu
241Pu
238U

Fission Neutrino Spectra



Neutrino spectra are obtained by conversion of experimentally measured beta decay spectra except ^{238}U which doesn't break up with thermal neutrons.

Error in neutrino event rate is dominated by error of major fission nucleus, ^{235}U, and total error from spectrum is 2.25%.

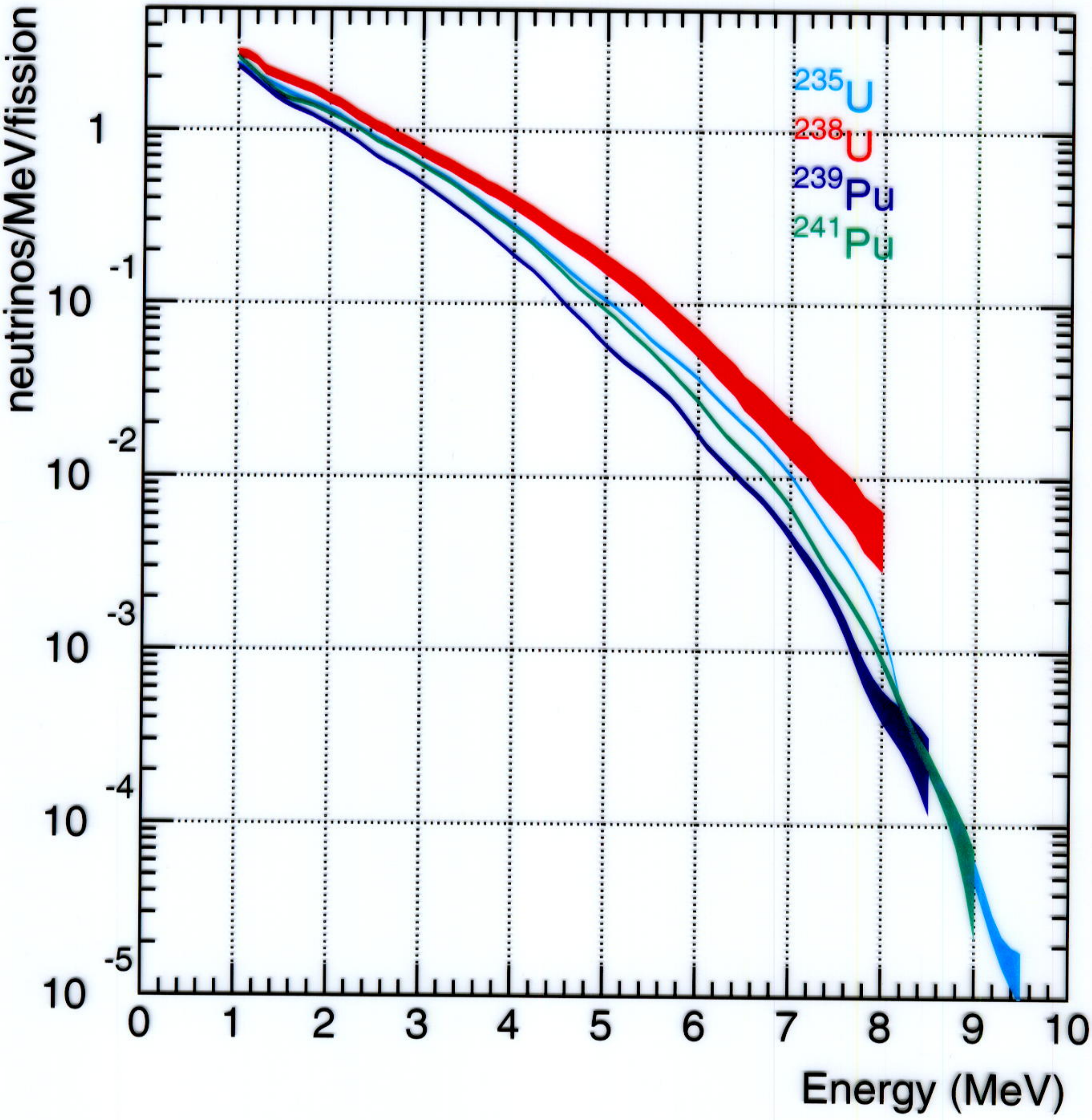
Experimental measurement

^{235}U Phys.Lett.B160(1985)325

$^{239,241}Pu$ Phys.Lett.B218(1989)365

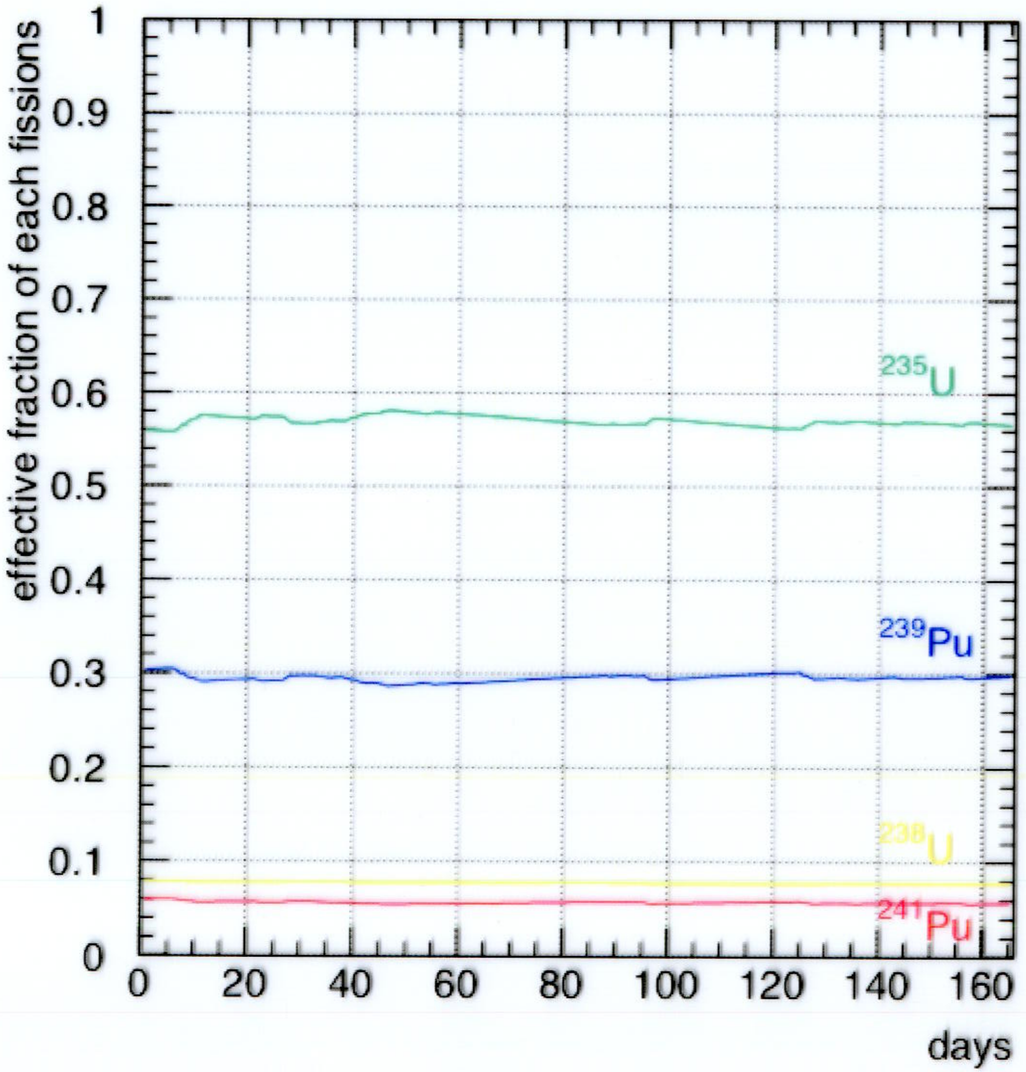
Theoretical calculation

^{238}U Phys.Rev.C24(1981)1543



neutrinos/MeV/fission
1
10^-1
10^-2
10^-3
10^-4
10^-5
0
1
2
3
4
5
6
7
8
9
10
Energy (MeV)
235U
238U
239Pu
241Pu

Burn up Effect at Kamioka



As fuel burns contribution of Pu increases in a single reactor core.

However, considering real situation (Bland new fuel is only one third or a quarter and many cores are contributing), composition change is very tiny.

Even Pu contribution changes by 10%, neutrino event rate changes by only 5%.

Non Equilibrium Effect

Actual neutrino emission comes from beta decays of fission nuclei.
Majority of those nuclei contributing neutrino experiment become equilibrium in a day.
This time lag introduces 0.28% uncertainty in the case of KamLAND which has down time for calibration, maintenance etc.

There are only a few long life contribution:

$$^{106}Ru \xrightarrow{T_{1/2}=372days} Rh \xrightarrow[E_{max}=3.541MeV]{} Pd$$

$$^{144}Ce \xrightarrow{T_{1/2}=285days} Pr \xrightarrow[E_{max}=2.996MeV]{} Nd$$

These long life nuclei are not included in experimentally determined fission neutrino spectra and introduces 0.65% systematic error in neutrino rate.

Ambiguity of Neutrino Event Rate

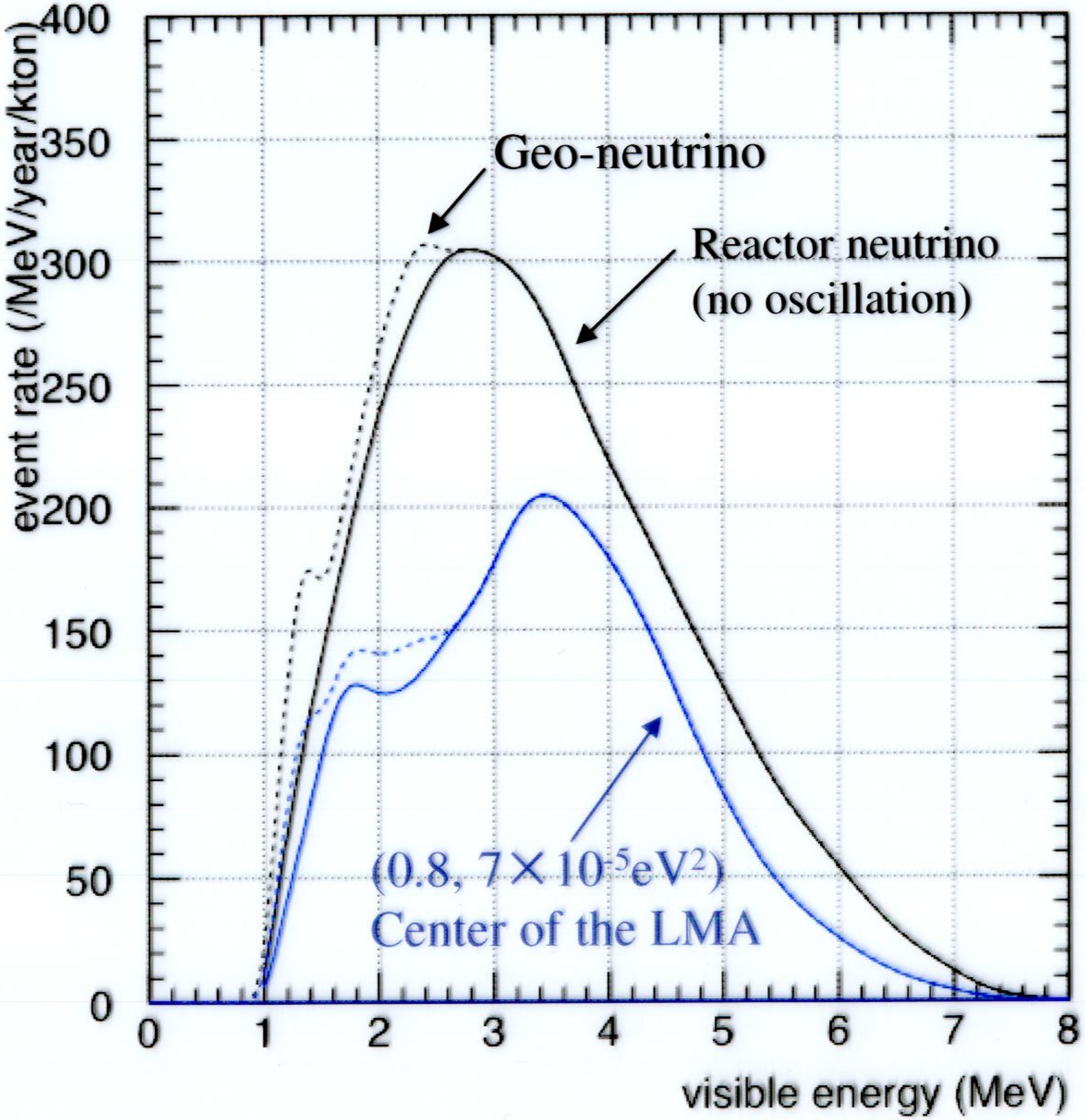
Conservative Accumulation of Various Uncertainties

Thermal Power Output	2%
Burn up Effect	1%
Long Life Beta Nuclei	0.65%
Time Lag of Beta Decay	0.28%
Korean Rectors	0.3%
Other Reactors	0.35%
Neutrino Spectra	2.25%
Cross Section	0.2%
Total Systematic Error	**3.3%**

Overall Calibration has been done with Bugey-3 (15m) experiment

$\sigma_f/\sigma_{V\text{-}A} = 98.7\% \pm 1.4\% \pm 2.7\%$ (Phys.Lett.B338(1994)383)

Expected anti-electron neutrino event at Kamioka

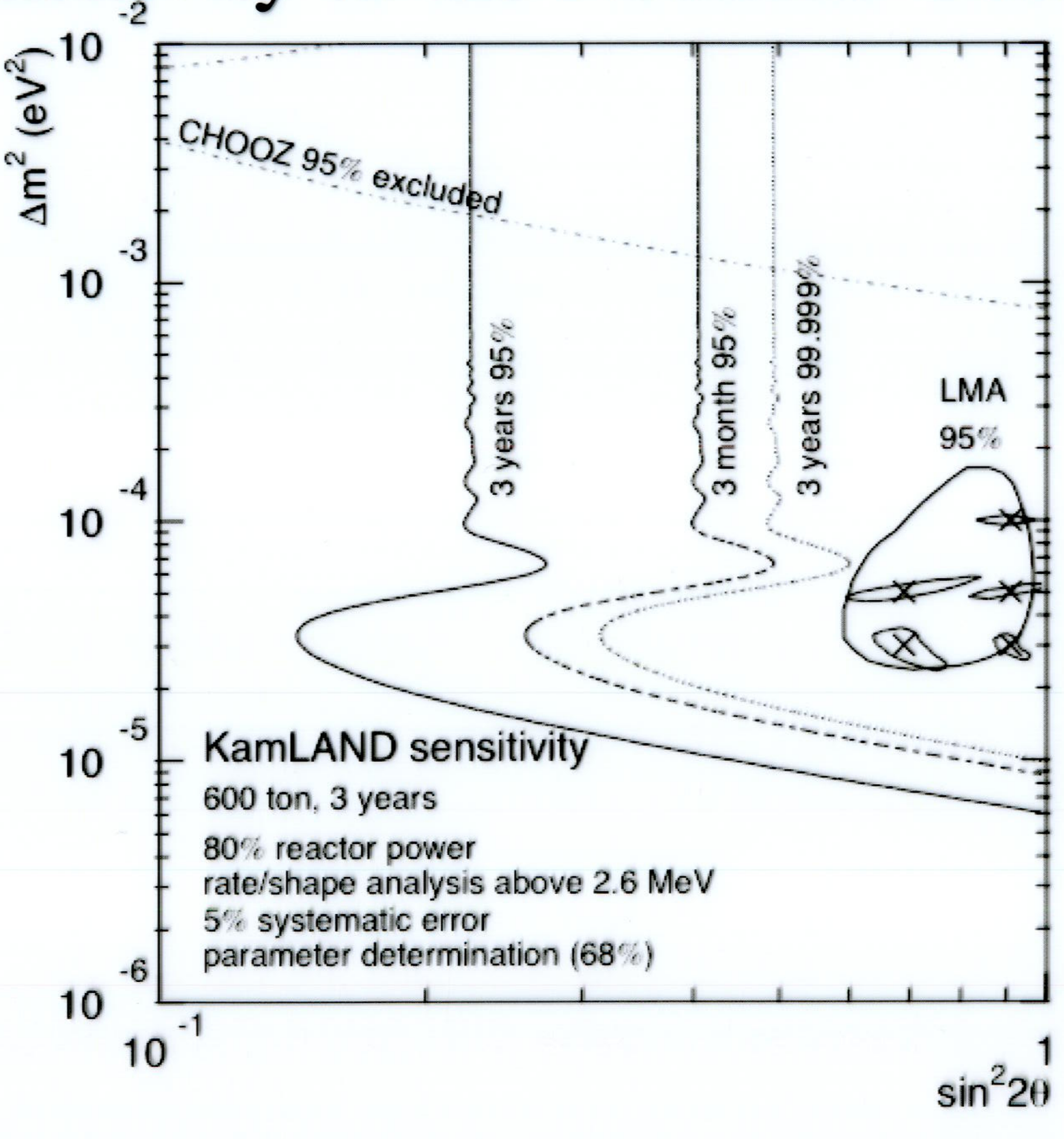


Reactor event rate
980 ev/yr/kton

Geo-neutrino rate
50 ev/yr/kton

Strong spectrum distortion at the LMA solution enables a precise parameter determination.

Sensitivity to the Neutrino Oscillation



^{232}Th chain

^{232}Th (1.4×10^{10} y)	E_α	E_γ	per ^{232} Th decays
	4013	-	0.779
↓	3954	64	0.221
^{228}Ra (5.8 y)	E_{β^-} Endpoint	E_γ	per ^{232} Th decays
↓	46	-	1.000
^{228}Ac (6.1 h)	E_{β^-} Endpoint	E_γ	per ^{232} Th decays
	2069	58	0.100
	403	755, 911, 58	0.007
	438	1631, 58	0.020
	438	1502, 129, 58	0.006
	444	1496, 129, 58	0.009
	481	1588,58	0.031
	481	1459, 129, 58	0.008
	596	99, 463,911,58	0.015
	596	99,463,969	0.011
	596	99,409,965,58	0.008
	596	563,911,58	0.016
	596	563,969	0.009
	596	509,965,58	0.010
	959	772,338,58	0.012
	959	840,270,58	0.005
	973	322,774,58	0.005
	973	322,503,328	0.005
	973	322,503,270,58	0.006
	973	1096,58	0.009
	973	1154	0.010
	1004	795,328	0.020
	1004	795, 270,58	0.023
	1104	965, 58	0.023
	1104	836,128,58	0.007
	1158	969	0.116
	1216	911	0.191
	1731	209,129,58	0.030
	1731	338,58	0.086
↓	1063	1064	0.202 *

^{228}Th (1.9 y)	E_α	E_γ	per ^{232} Th decays
	5423	-	0.715
↓	5340	84	0.285
^{224}Ra (3.7 d)	E_α	E_γ	per ^{232} Th decays
	5685	-	0.949
↓	5449	241	0.051
^{220}Rn (56 s)	E_α	E_γ	per ^{232} Th decays
↓	6288	-	1.000
^{216}Po (0.145 s)	E_α	E_γ	per ^{232} Th decays
↓	6778	-	1.000
^{212}Pb (11 h)	E_{β^-} Endpoint	E_γ	per ^{232} Th decays
	574	-	0.123
	274	300	0.052
↓	335	239	0.825
^{212}Bi (61 m)	E_{β^-} Endpoint	E_γ	per ^{232} Th decays
	2254	-	0.555
64%	634	1620	0.015
	742	785,727	0.011
	1527	727	0.044
↓	1127	1127	0.015*
^{212}Po (299 ns)	E_α	E_γ	per ^{232} Th decays
↓	8784	-	0.640
^{208}Pb (∞)			
^{212}Bi (61 m)	E_α	E_γ	per ^{232} Th decays
36%	6090	-	0.098
↓	6050	40	0.262
^{208}Tl (3.1 m)	E_{β^-} Endpoint	E_γ	per ^{232} Th decays
	1040	763,583,2615	0.008
	1292	511,583,2615	0.085
	1525	861,2615	0.052
	1525	277, 583, 2615	0.026
	1803	583,2615	0.175
↓	2500	2501	0.014 *
^{208}Pb (∞)			