Reactor Neutrino Experiments

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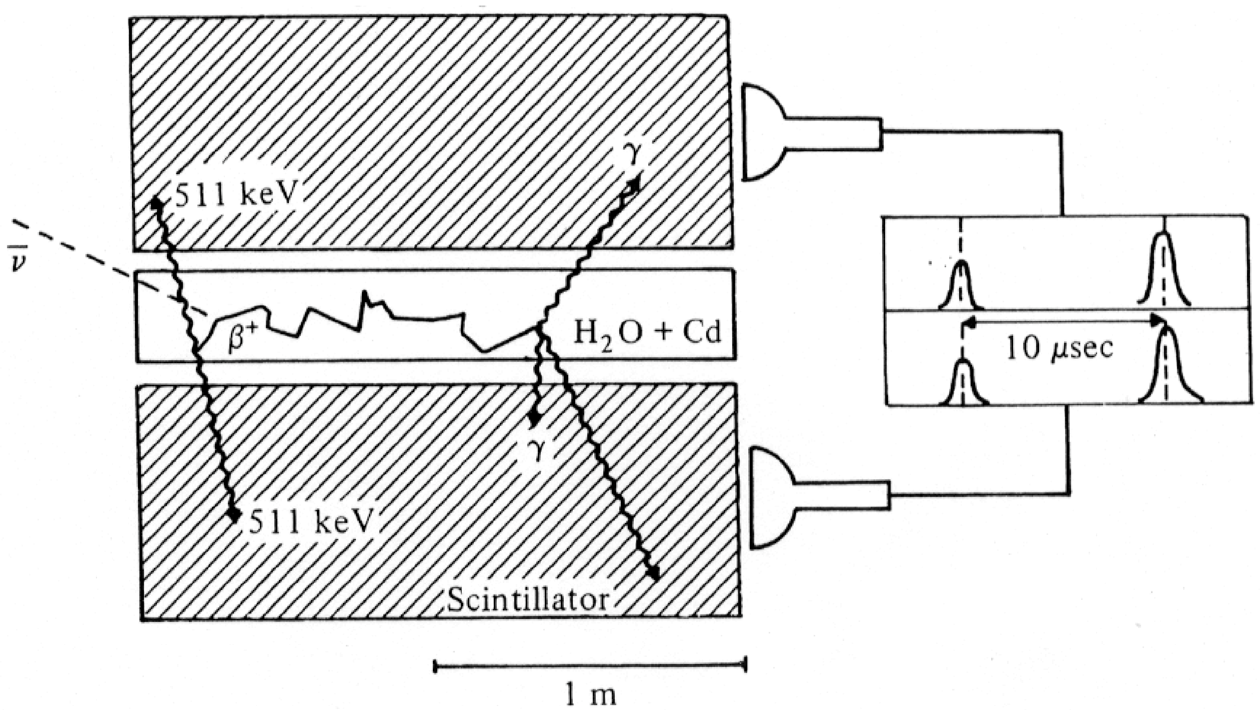
Outline

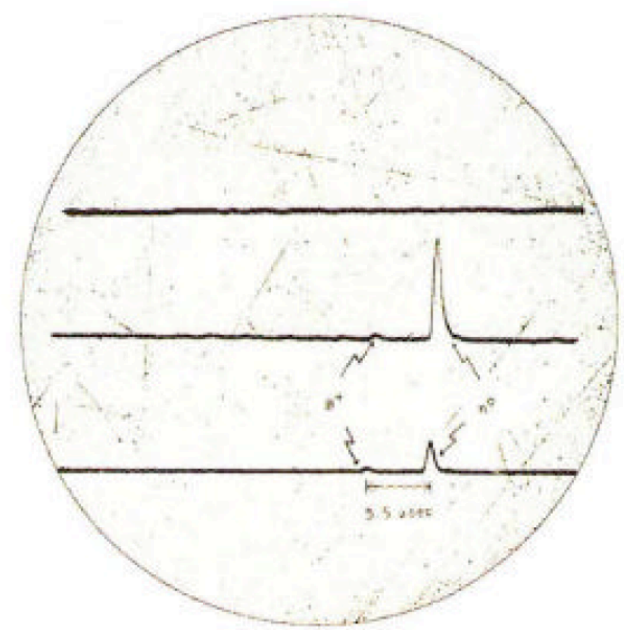
- KamLAND experiment
- θ_{13} experiments
- Search for μ_ν
- Summary

The first neutrino observation was done by Reines and Cowan in 1956 with reactor neutrinos.

Key points of the experiment (Poltergeist) were;

Powerful rector (700 MW) at Savannah river,
Large amount of proton target (200 liters water),
Signal detection with LS (1400 liters) and 55 PMTs,
12 m underground to reduce cosmic ray induced backgrounds,
11 m baseline.





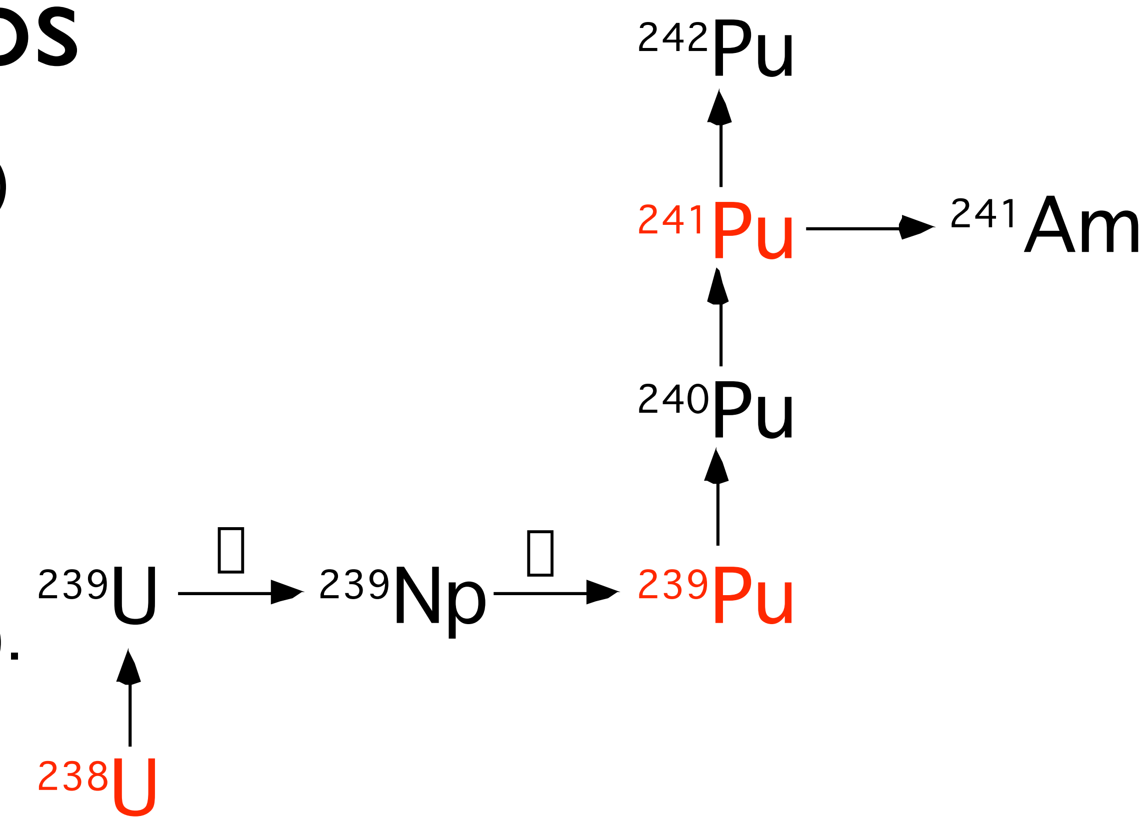
first neutrino

A modern experiment in 2003 is still a simple extension of the “Poltergeist.”

70 GW (effective), Proton target (1000 ton LS), 1879 PMTs,
1000 m underground, ~180 km baseline.

This extension becomes possible by many important improvements on knowledge of reactor neutrinos.

Reactor Neutrinos



- Only 4 fissile nuclei (U235,U238,Pu239,Pu241) are important. The others contribute only 0.1% level.
- Fission fragments repeat beta-decay and emit anti-electron-neutrinos (electron-neutrino contamination is ~10ppm level above 1.8 MeV).
- Fission rate is strongly correlated with thermal power output (measurable at much better than 2% accuracy).

$$^{235}U : 201.7\pm0.6,\ ^{238}U : 205.0\pm0.9,\ ^{239}Pu : 210.0\pm0.9,\ ^{241}Pu : 212.4\pm1.0 MeV$$

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

- One fission causes ~6 neutrino emission in average. Thus, neutrino intensity is $\sim 2\times10^{20}\ \bar{\nu}_e/GW_{th}/sec$.
- Fission spectra reach equilibrium within a day above ~2 MeV. Except only a few cases such as;

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

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

V.I.Kopeikin et al., Physics of Atomic Nuclei, 64-5(2001)849

Neutrino Spectra

U235, Pu239, Pu241

Beta spectra were measured with a spectrometer irradiating thermal neutrons at ILL.

Fitting with 30 hypothetical beta branches and convert each branches to neutrino spectrum.

K.Schreckenbach et al., Phys.Lett.B160(1985)325
A.A.Hahn et al., Phys.Lett.B218(1989)365

U238

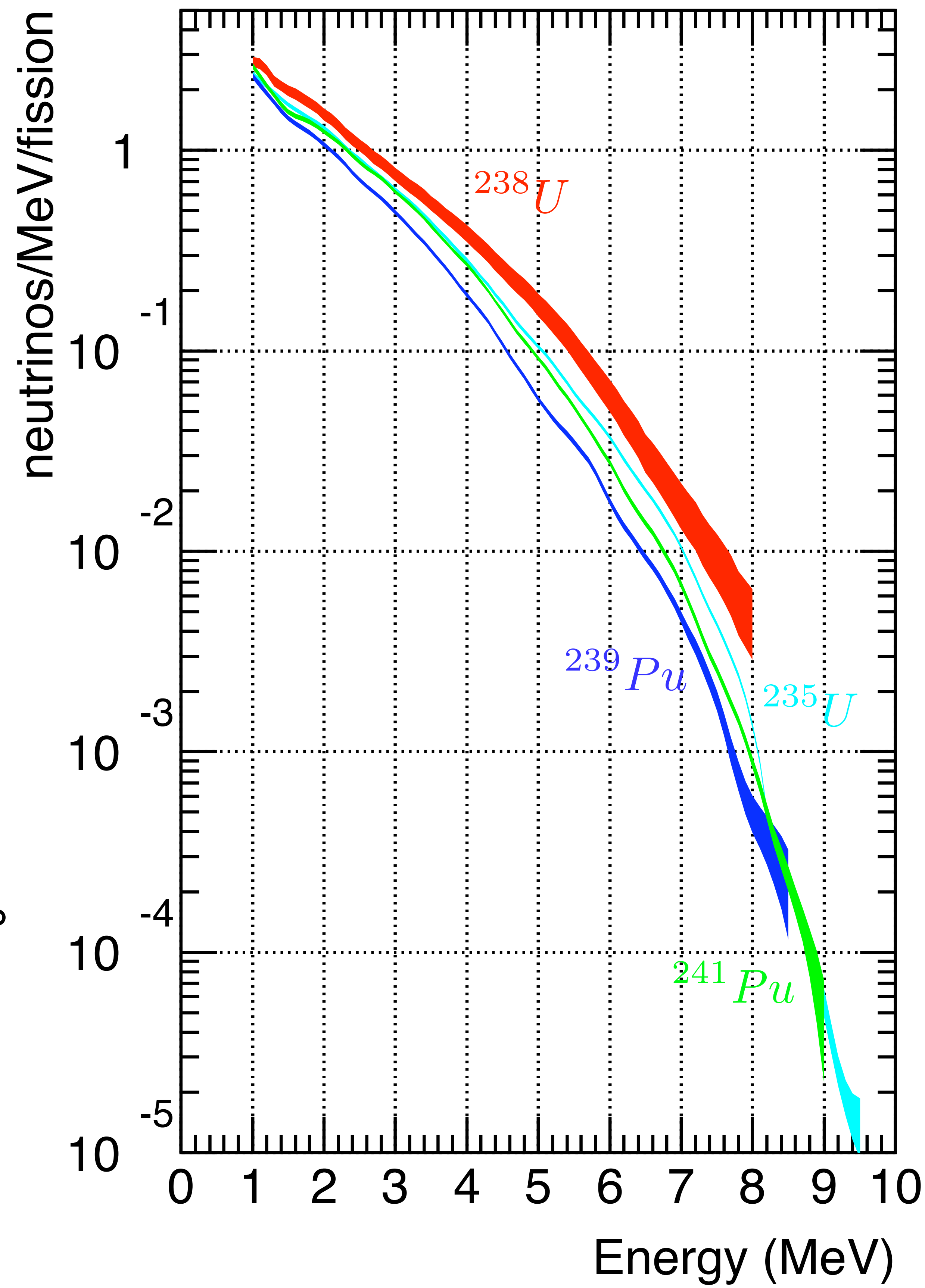
No fission with thermal neutrons

Theoretical calculation tracing 744 unstable fission products

Error is larger, but small contribution ~8%

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

Knowing time evolution of fuel composition, error from spectra calculation is ~2.3%.



Cross Section

Inverse beta decay

provides powerful delayed coincidence.

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

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad e^+ + e^- \rightarrow 2\gamma$$

prompt signals

thermalization

$$n + X \rightarrow X' + \gamma$$

delayed signal

$$X = H, Gd, Cd, {}^3He\ etc$$

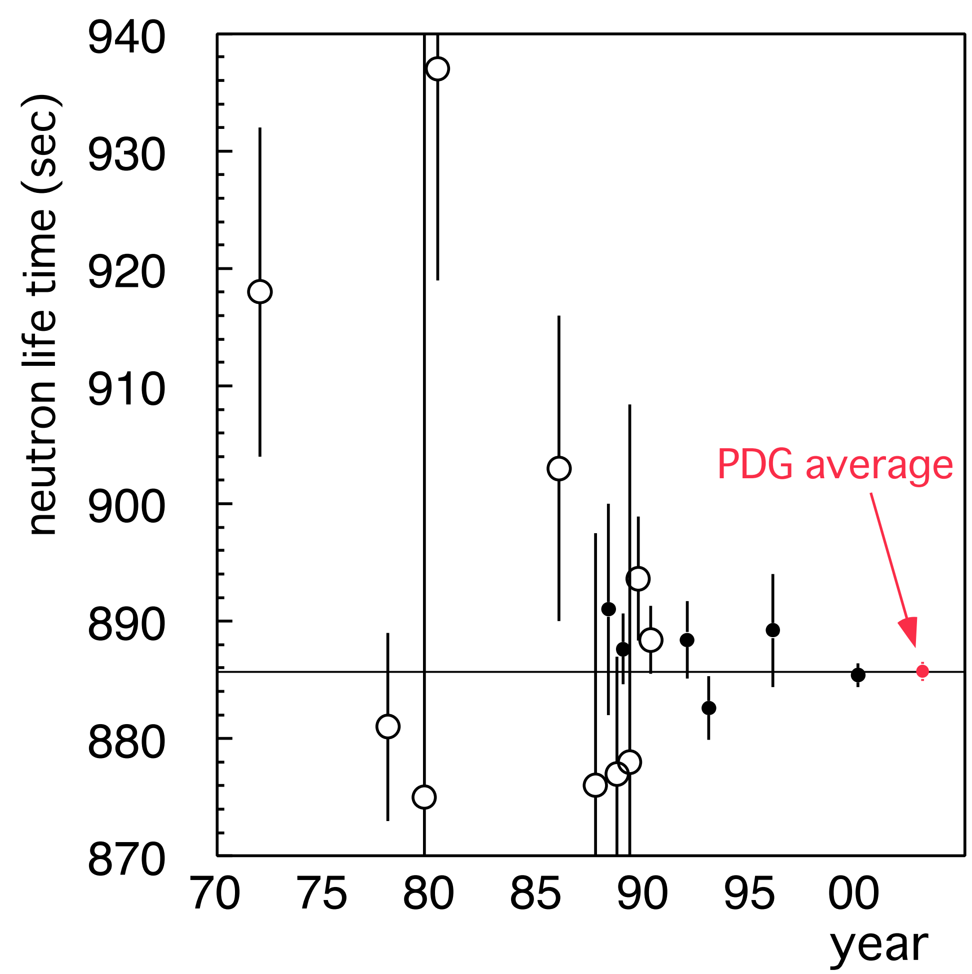
Cross section is well related to neutron life time.

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

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

$$\tau_n = 885.7 \pm 0.8 sec$$

With O(1/M) corrections, precision is 0.2 %. (Coulomb, weak magnetism, recoil, inner and outer radiative).



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

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

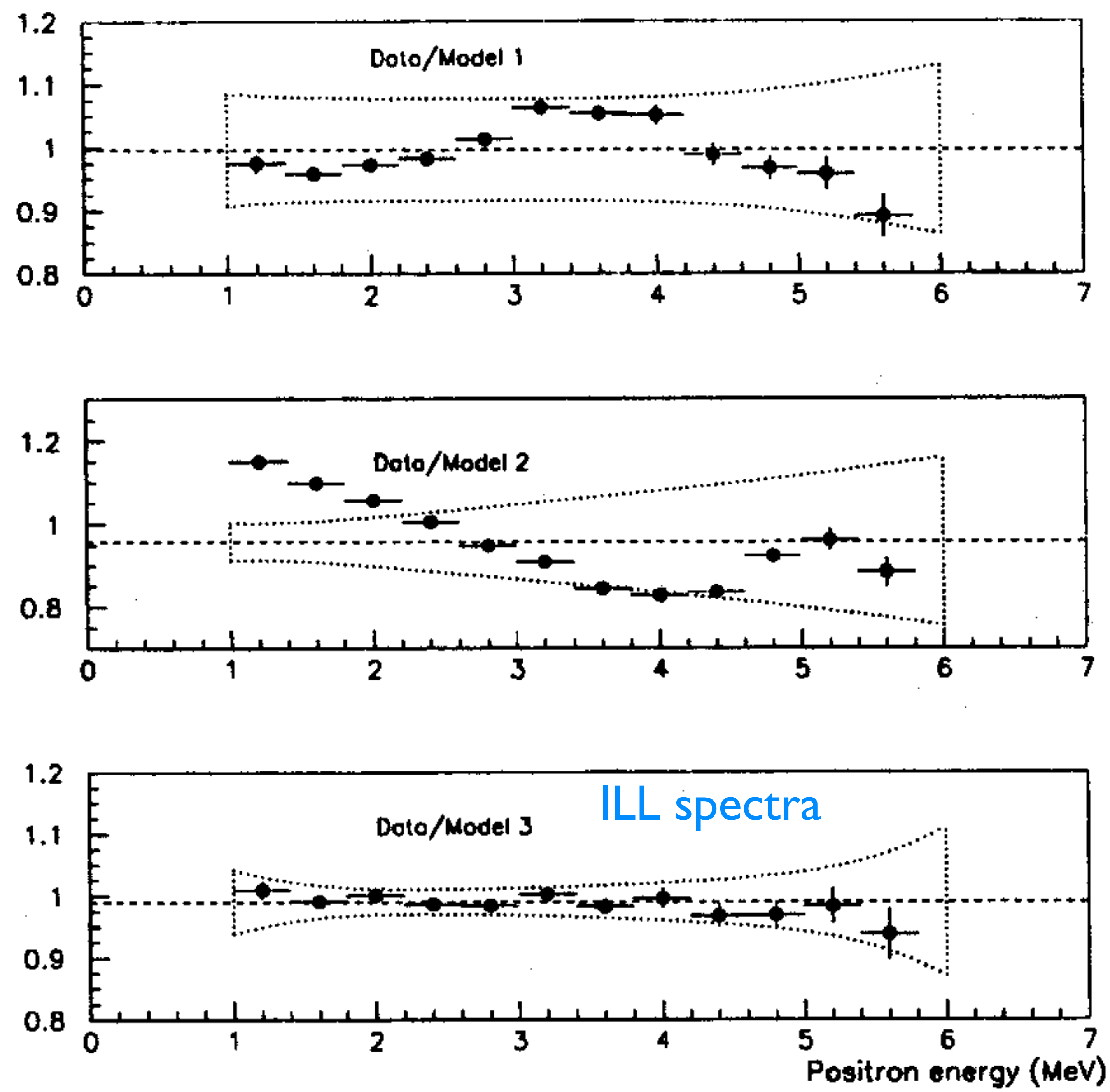
Validity of Spectra & Cross-section Calculation

Bugey measured an overall reaction rate with 1.4% accuracy and is in good agreement with the calculation.

Y.Declais et al., Phys.Lett.B338(1994)383

$$\sigma_f = 5.750 \times 10^{-43} cm^2/fission \pm 1.4\%$$
$$\sigma_{V-A} = 5.824 \times 10^{-43} cm^2/fission \pm 2.7\%$$

$$\sigma_f/\sigma_{V-A} = 0.987 \pm 1.4\% \pm 2.7\%$$

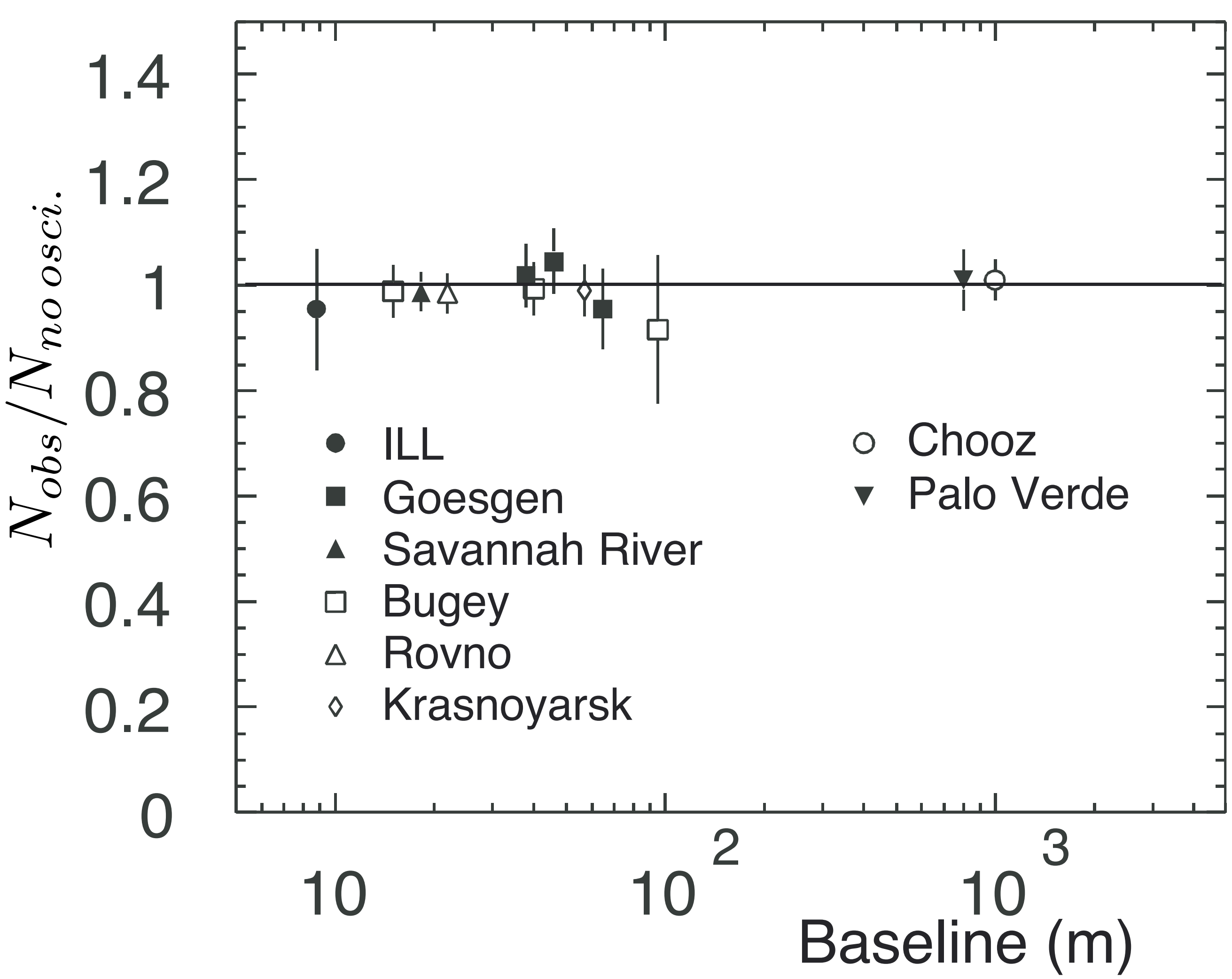


Bugey-3 tested models of neutrino spectra and the ILL spectra shows excellent agreement. B.Achkar et al., Phys.Lett.B374(1996)243

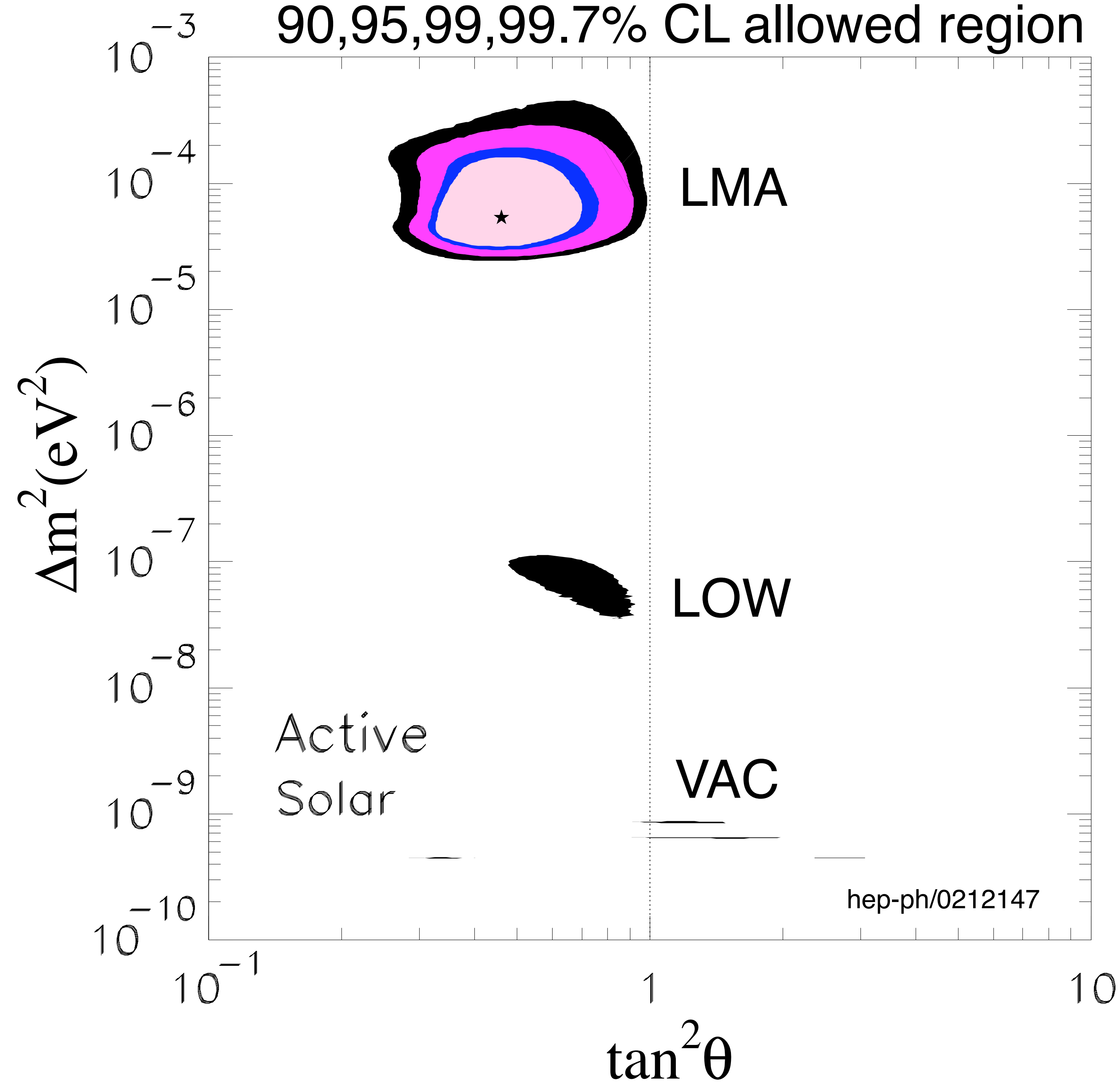
A few % precision is achievable without near detector for flux normalization.

Status before KamLAND

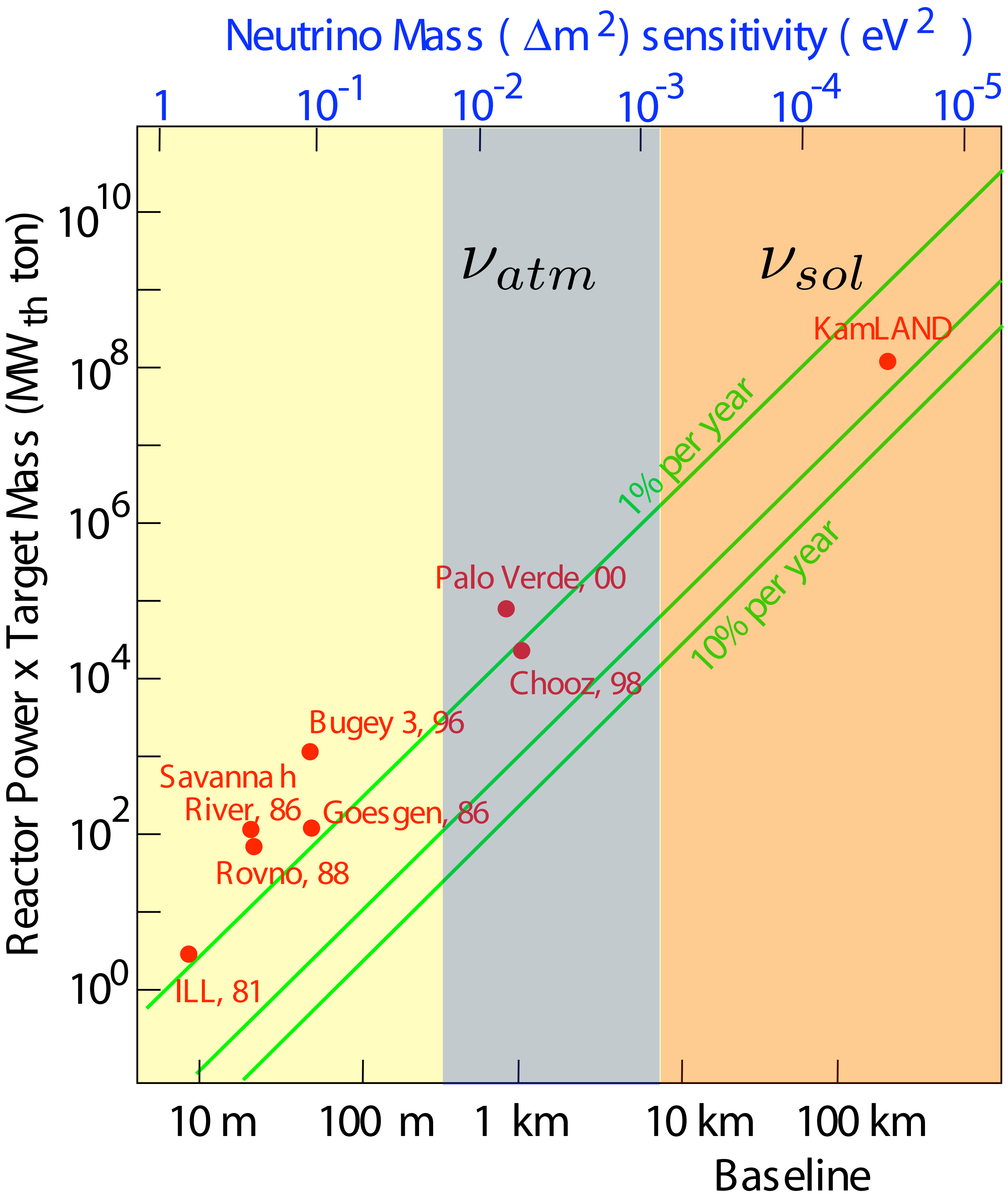
Oscillation Search up to 1 km baseline



Global Solar Neutrino Analysis
90,95,99,99.7% CL allowed region

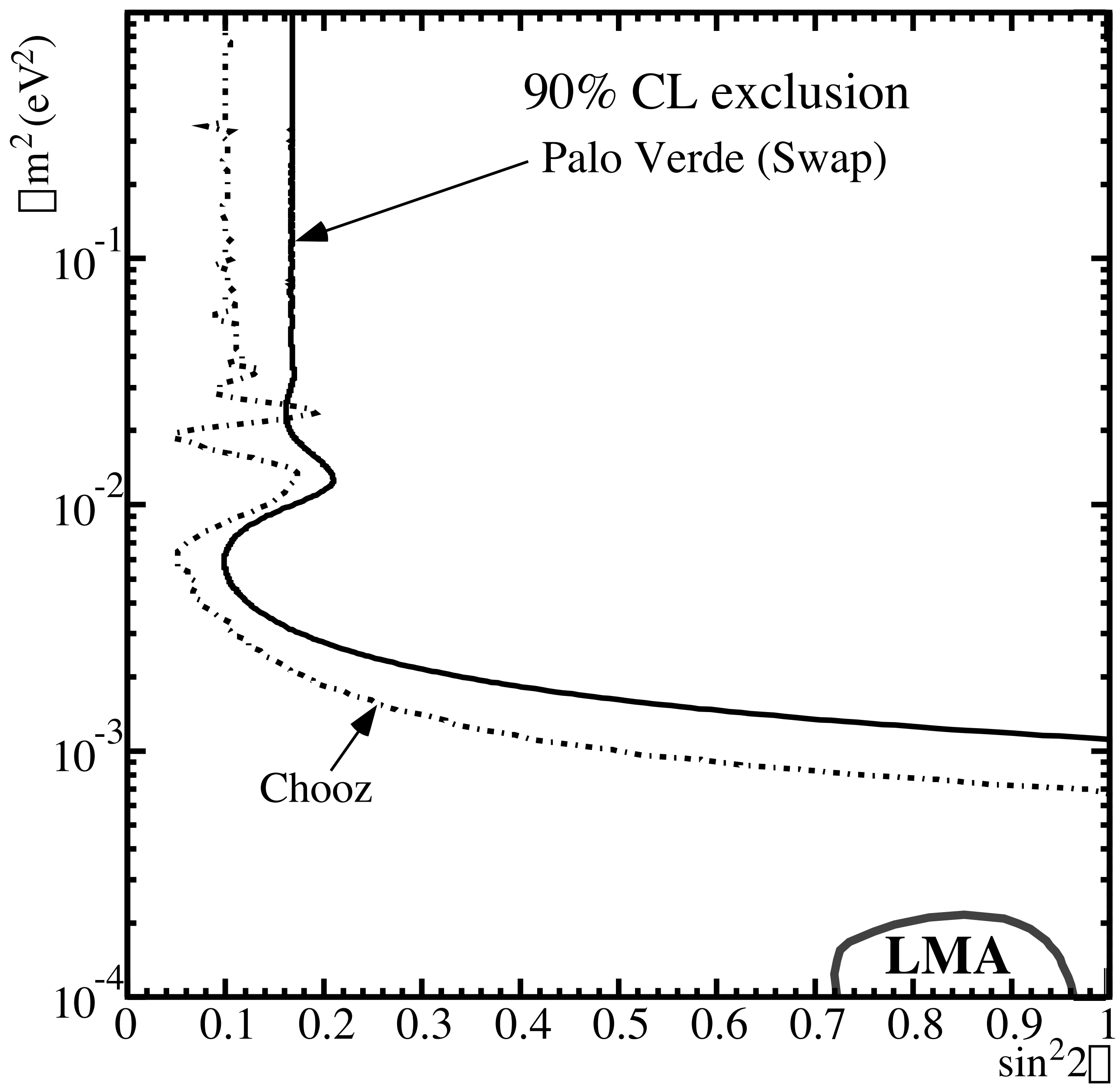


SFP, Decay, FCNSI, ~~CPT~~ ???



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2(1.27 \times \frac{\Delta m^2(eV^2)L(m)}{E(MeV)})$$

$$E_{reactor} \sim 5MeV$$



More than 100 km baseline is necessary to explore the LMA solution.

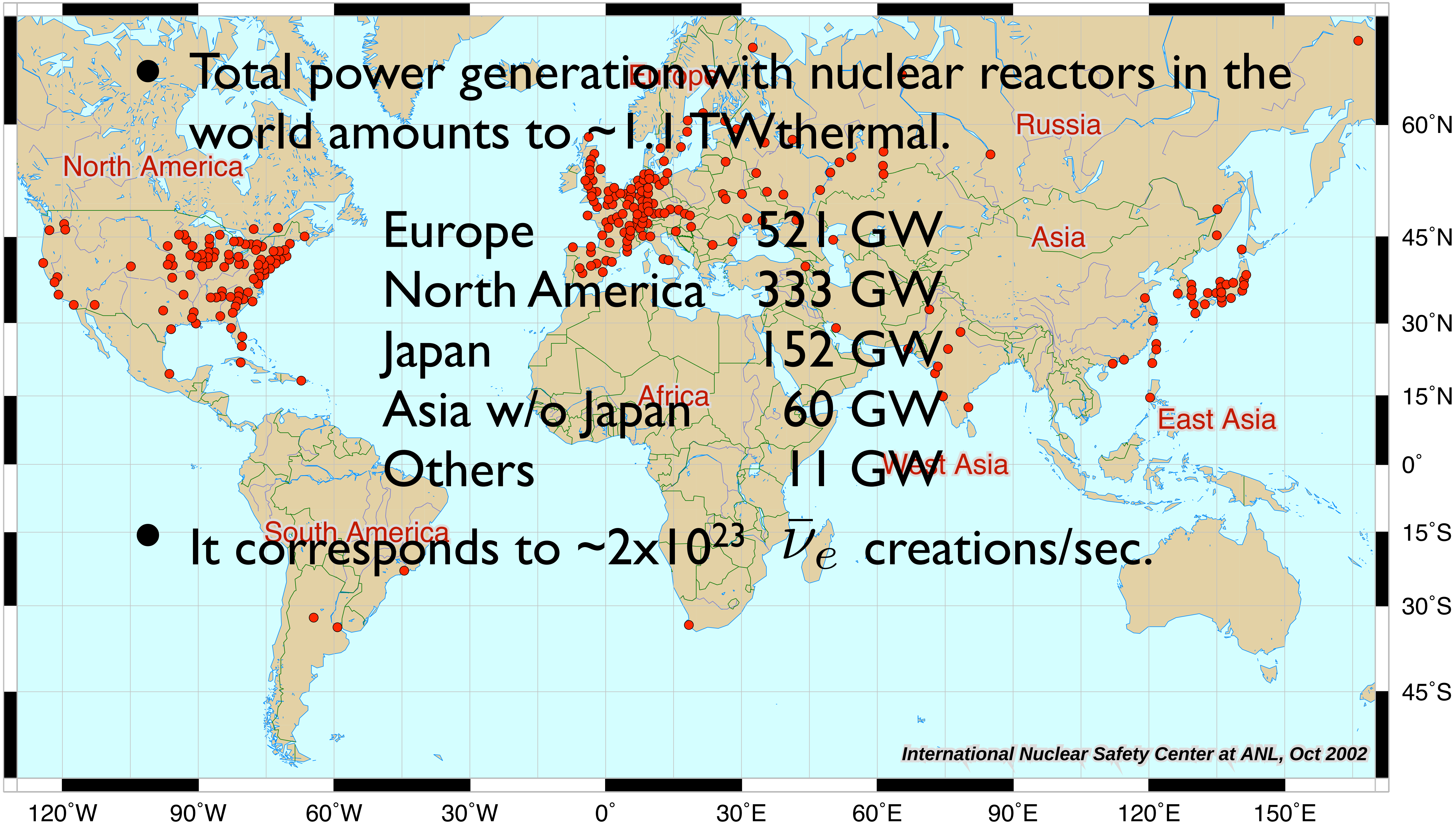
Powerful Reactor, Big Detector and Deep Underground

Where is a powerful reactor?

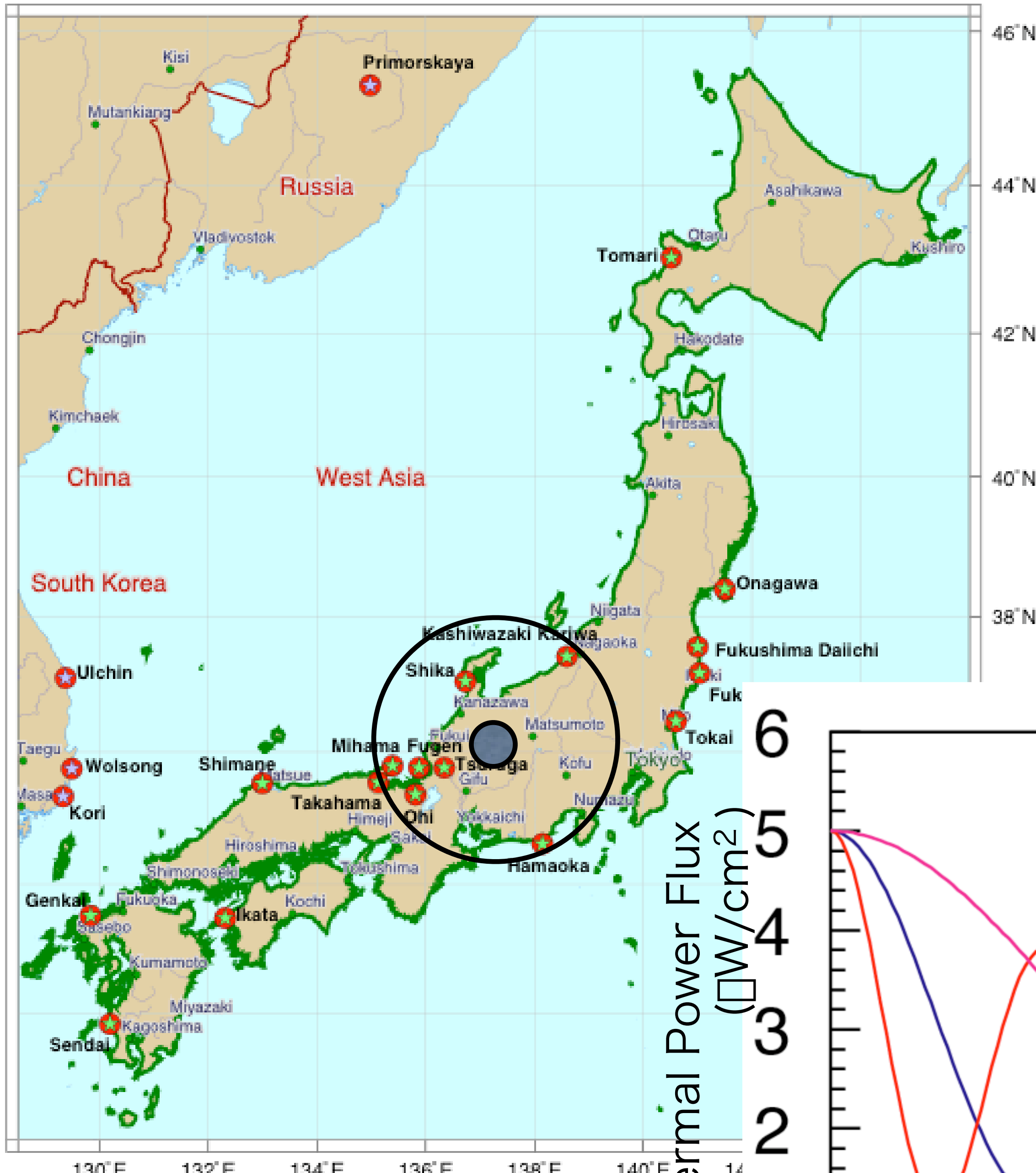
- Total power generation with nuclear reactors in the world amounts to ~1.1 TWthermal.

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

- It corresponds to ~2x10^{23} $\bar{\nu}_e$ creations/sec.



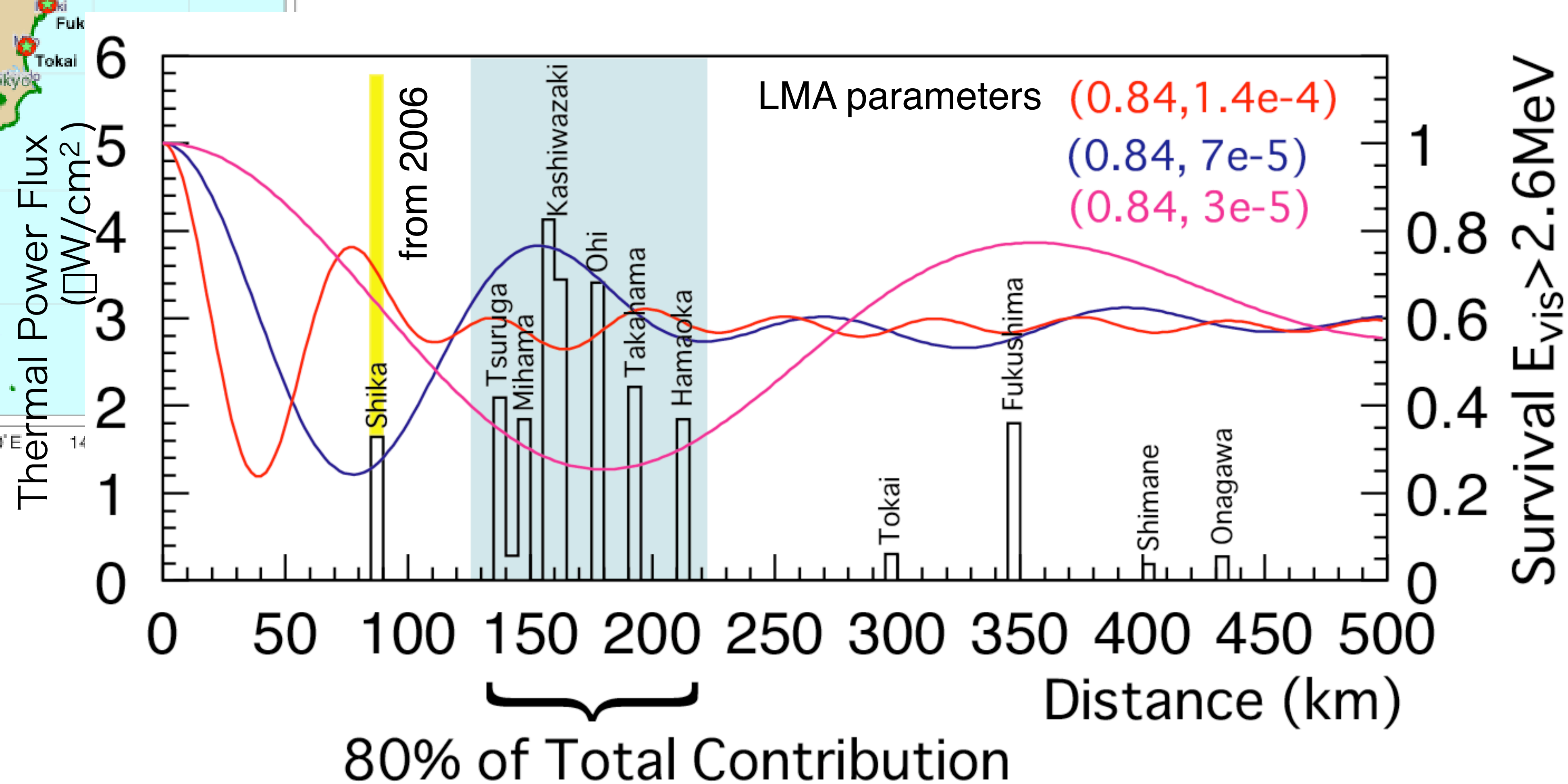
It is Kamioka!



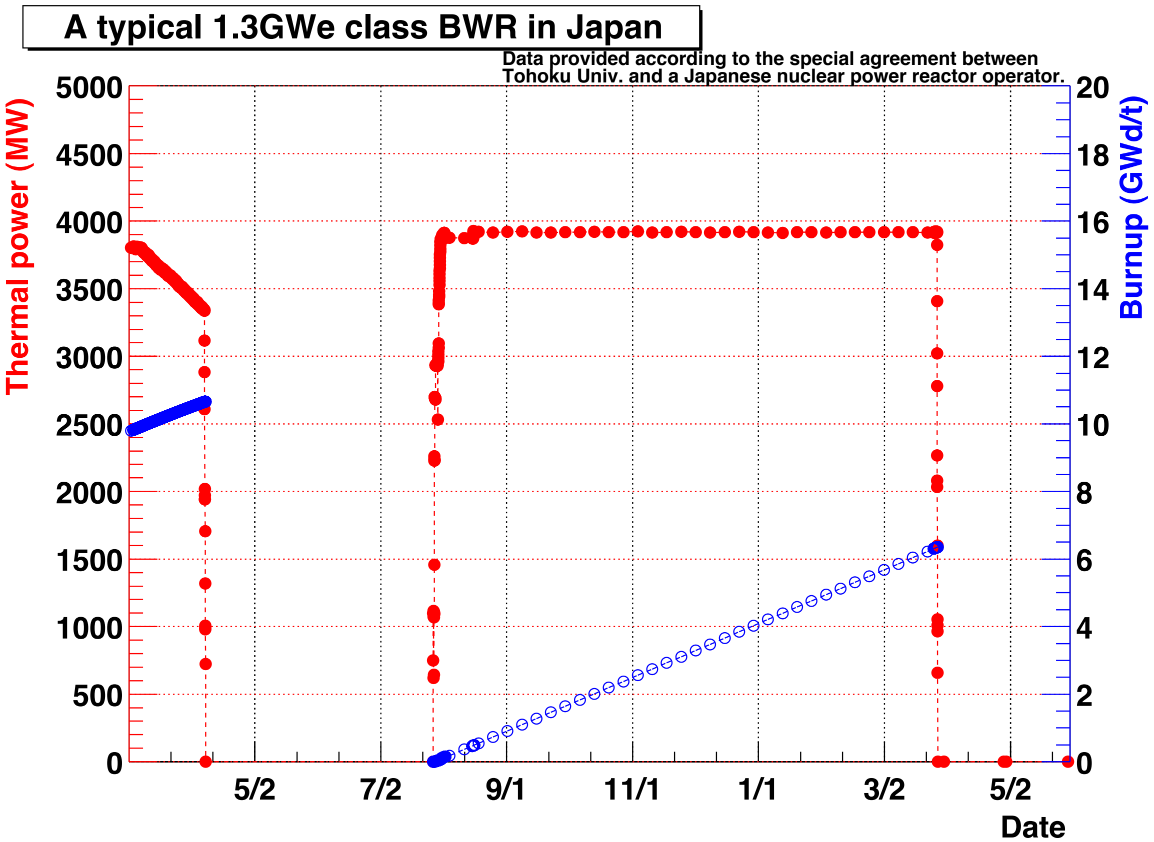
70 GW (7% of world total) is generated at 130-240 km distance from Kamioka.

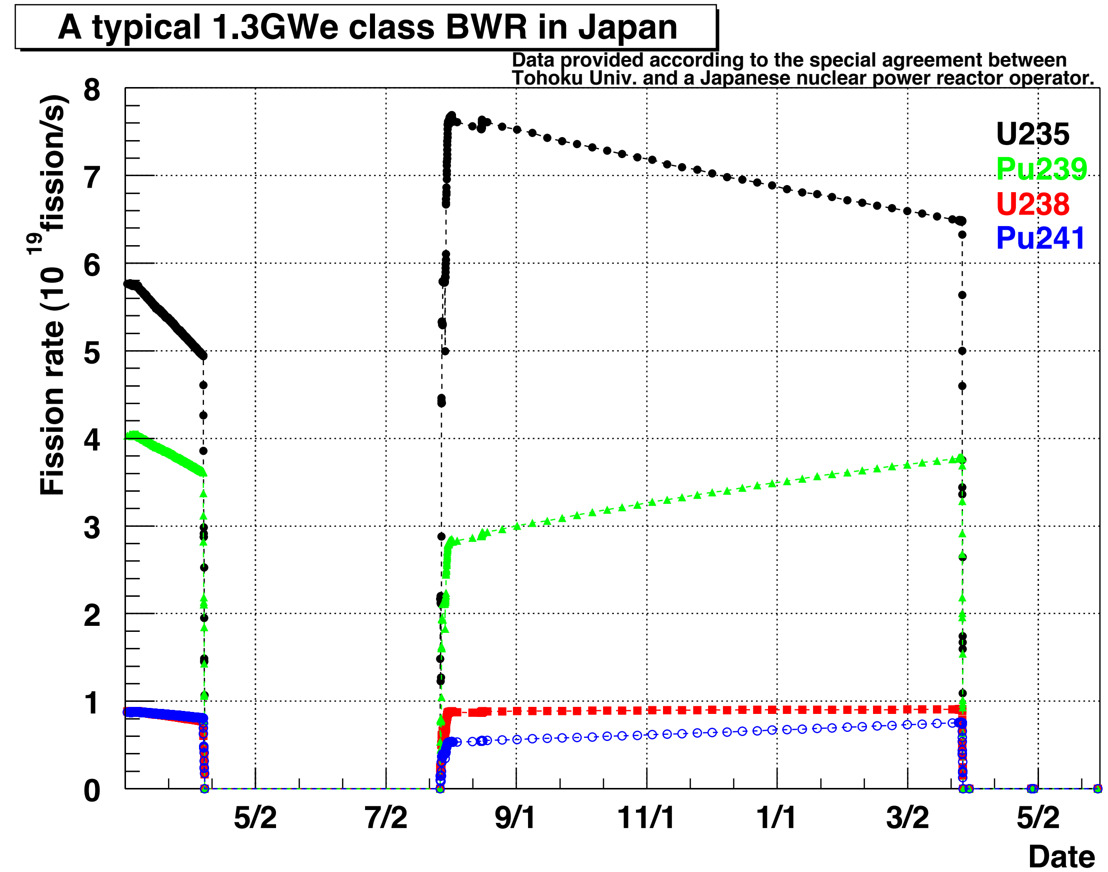
Reactor neutrino flux, $\sim 5 \times 10^6/cm^2/sec$ requires O(kiloton) underground detector.

There is a former Kamiokande cavity at 1000 m (2700 mwe) underground.



~97% from Japan
~2.5% from Korea

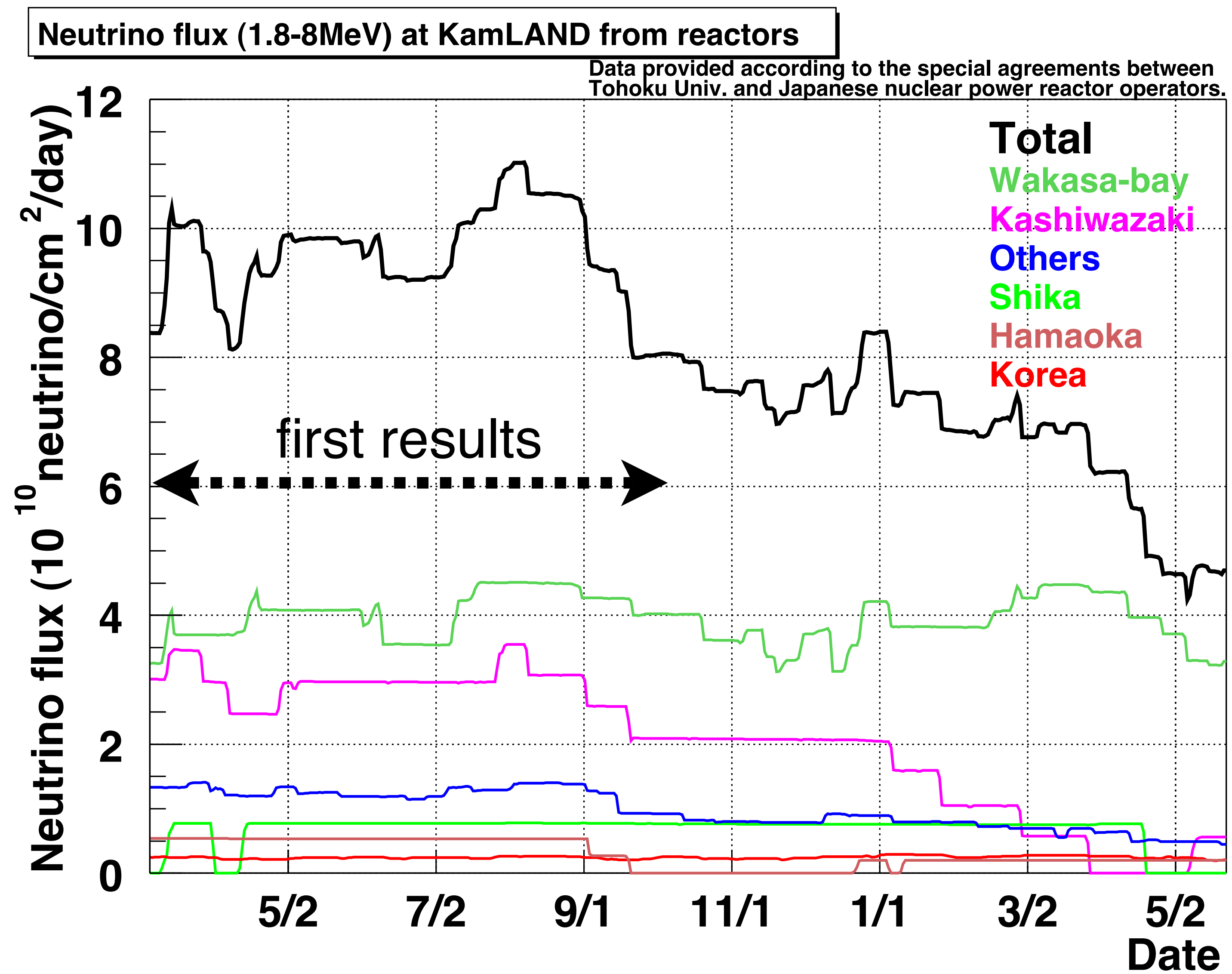




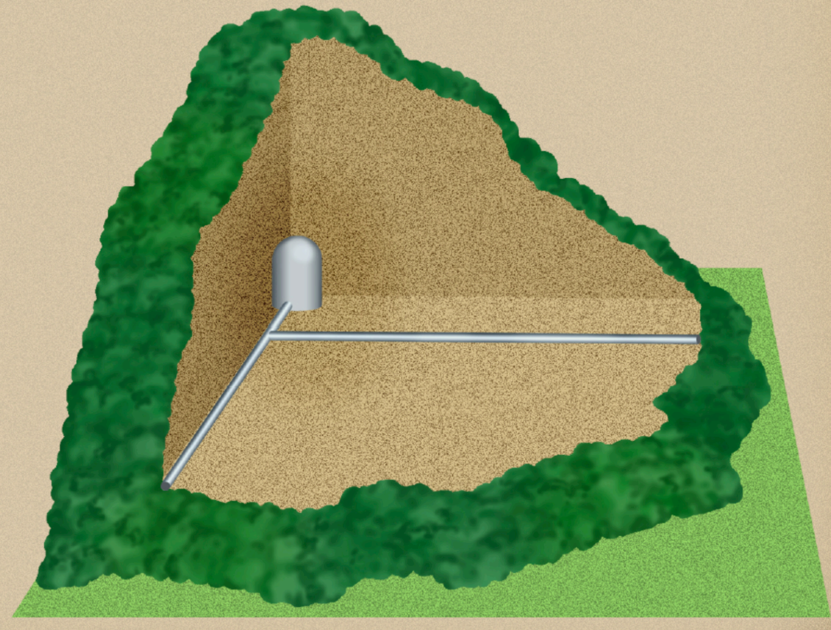
Available information

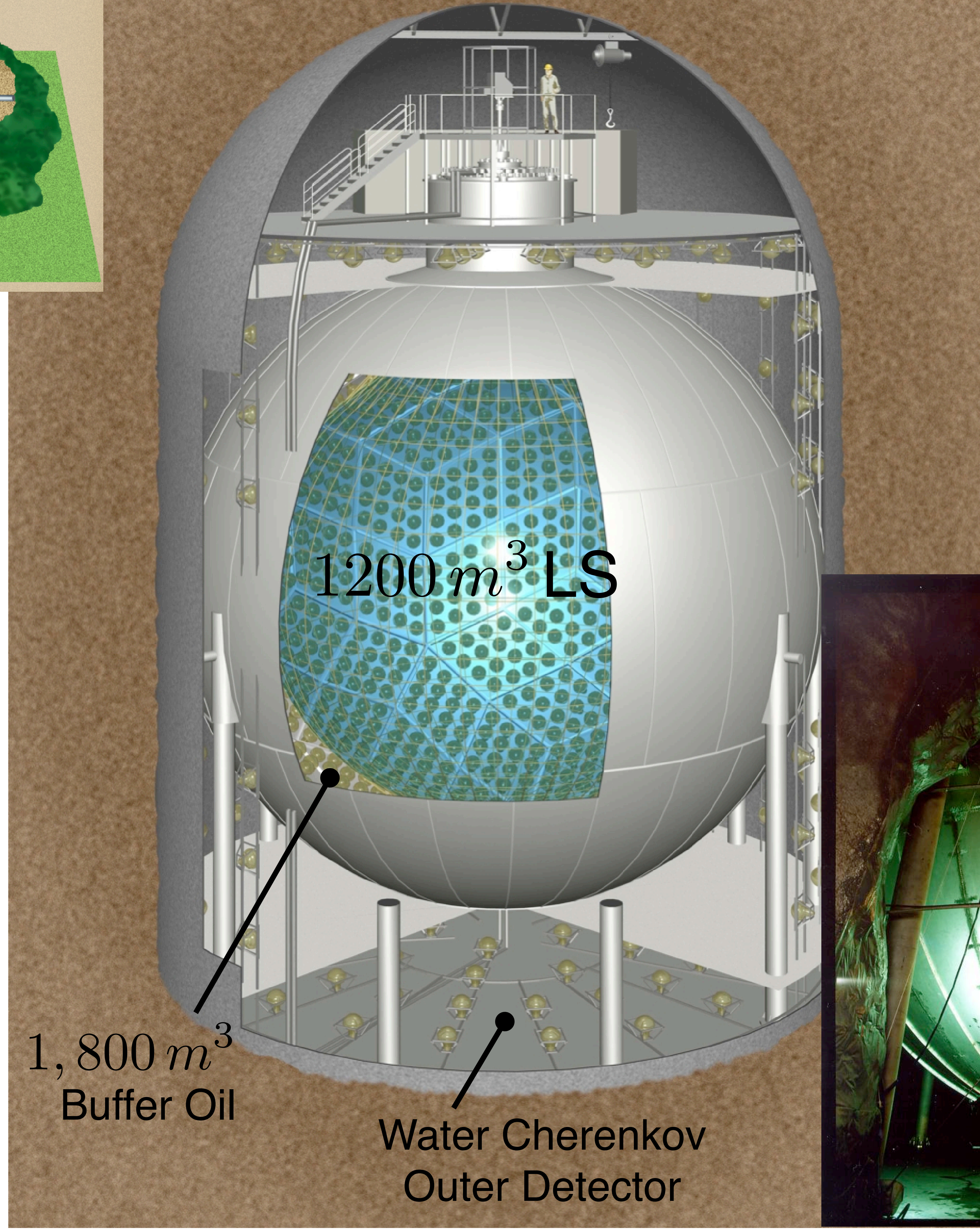
History of thermal power,
new fuel volume ratio,
fuel enrichment,
burn up
from 52 Japanese reactors

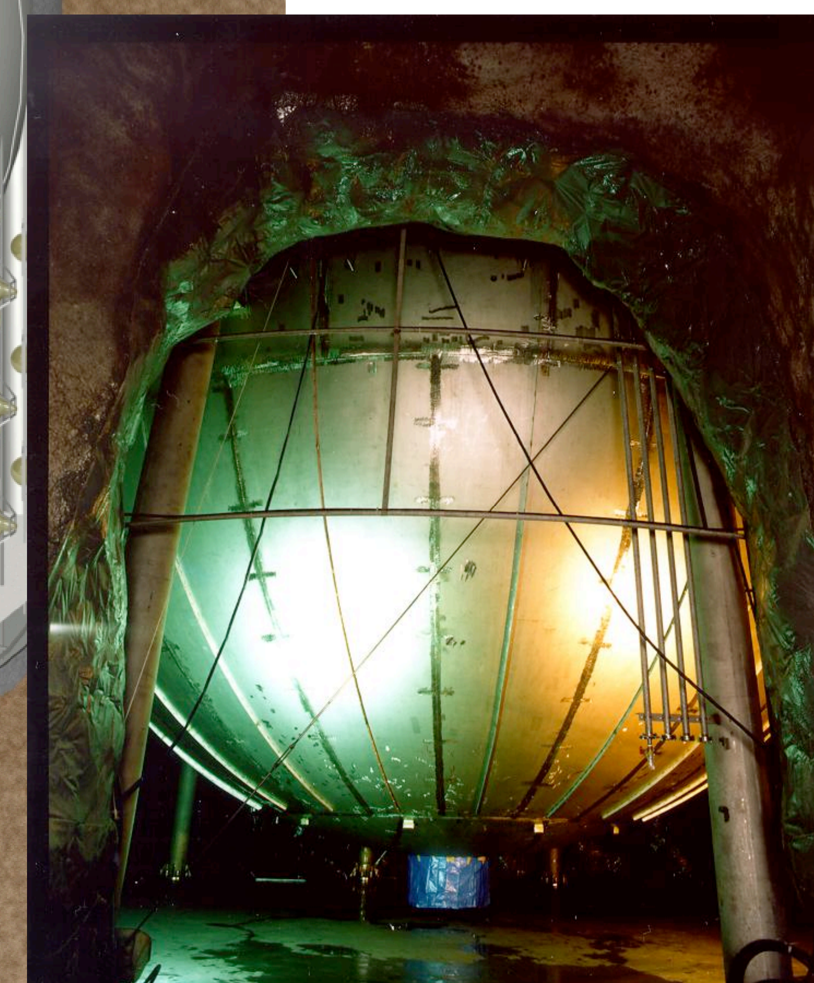
History of electric power
from 18 Korean reactors



KamLAND





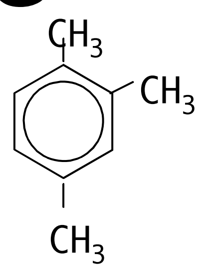


BO

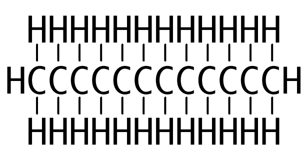
50% dodecane
50% isoparaffin

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

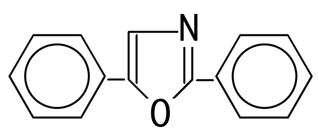
LS



20%



80%



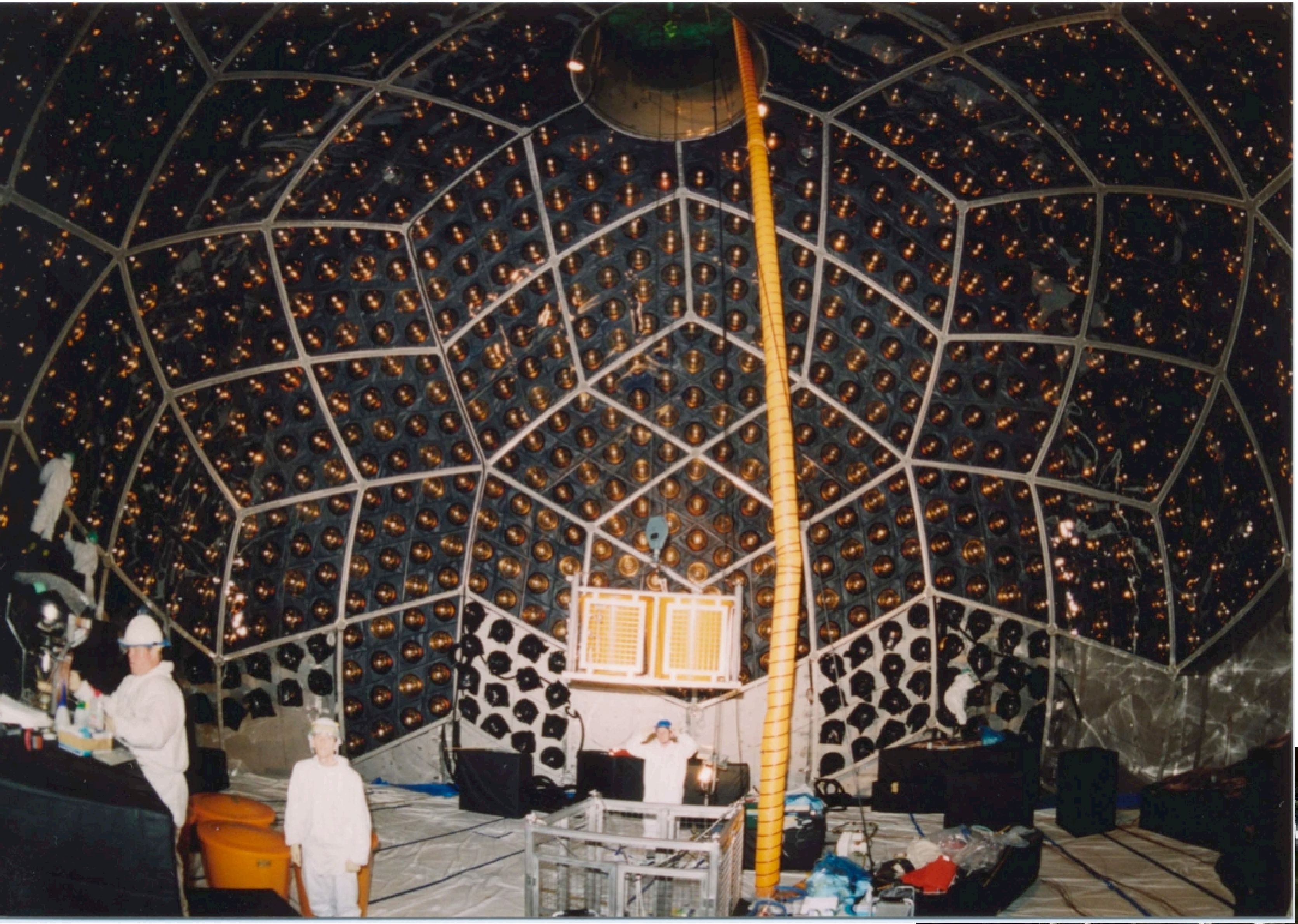
1.5g/l

$$\rho = 0.78g/cm^3$$

$$8,000 photons/MeV$$

$$\lambda \sim 10\,m$$

34% photo-coverage
with
1325 17” and 554 20”
photo-tubes



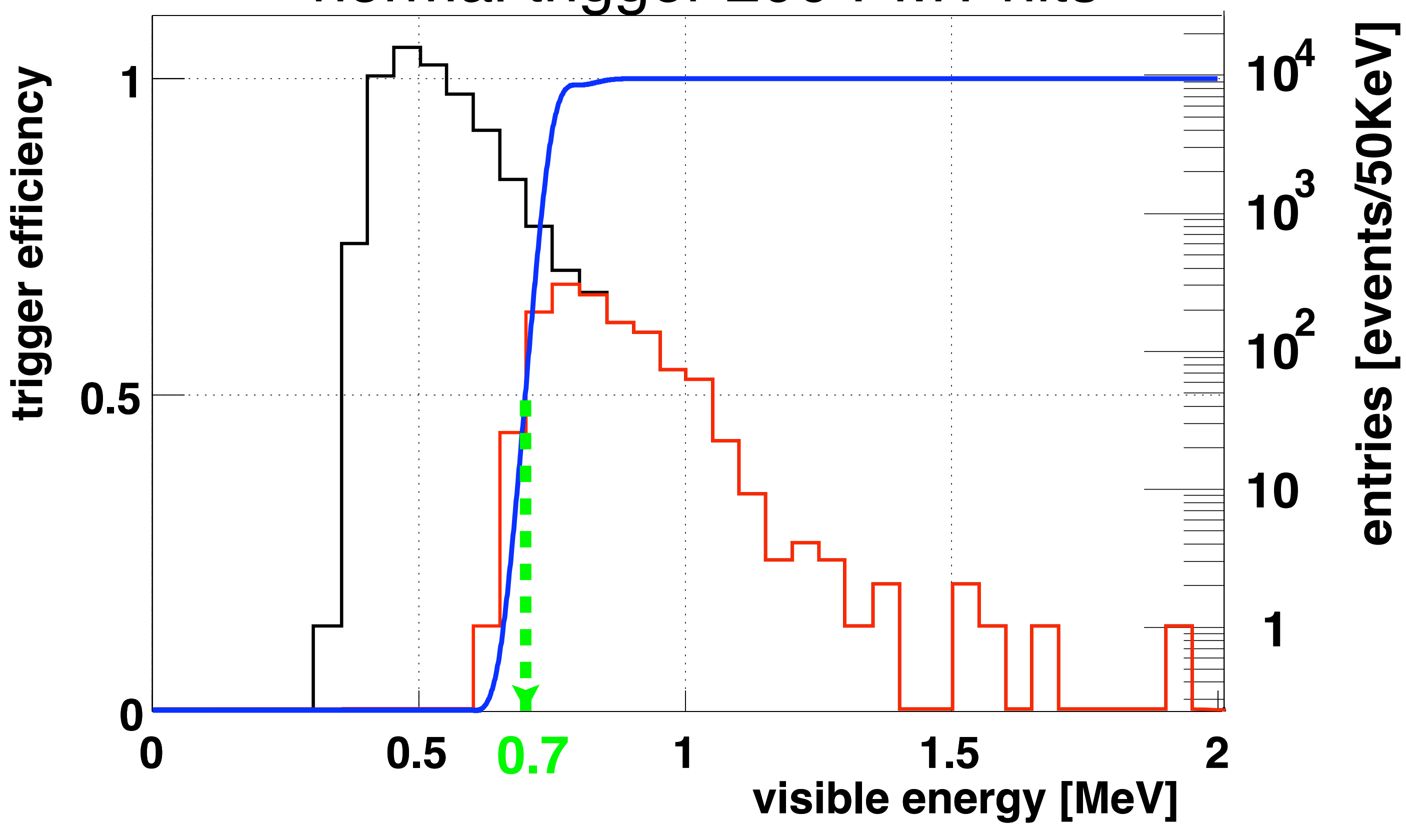
PMT installation in August 2000

$135\,\mu m$ thick 13m diameter
EVOH/Ny/Ny/Ny/EVOH multilayer film

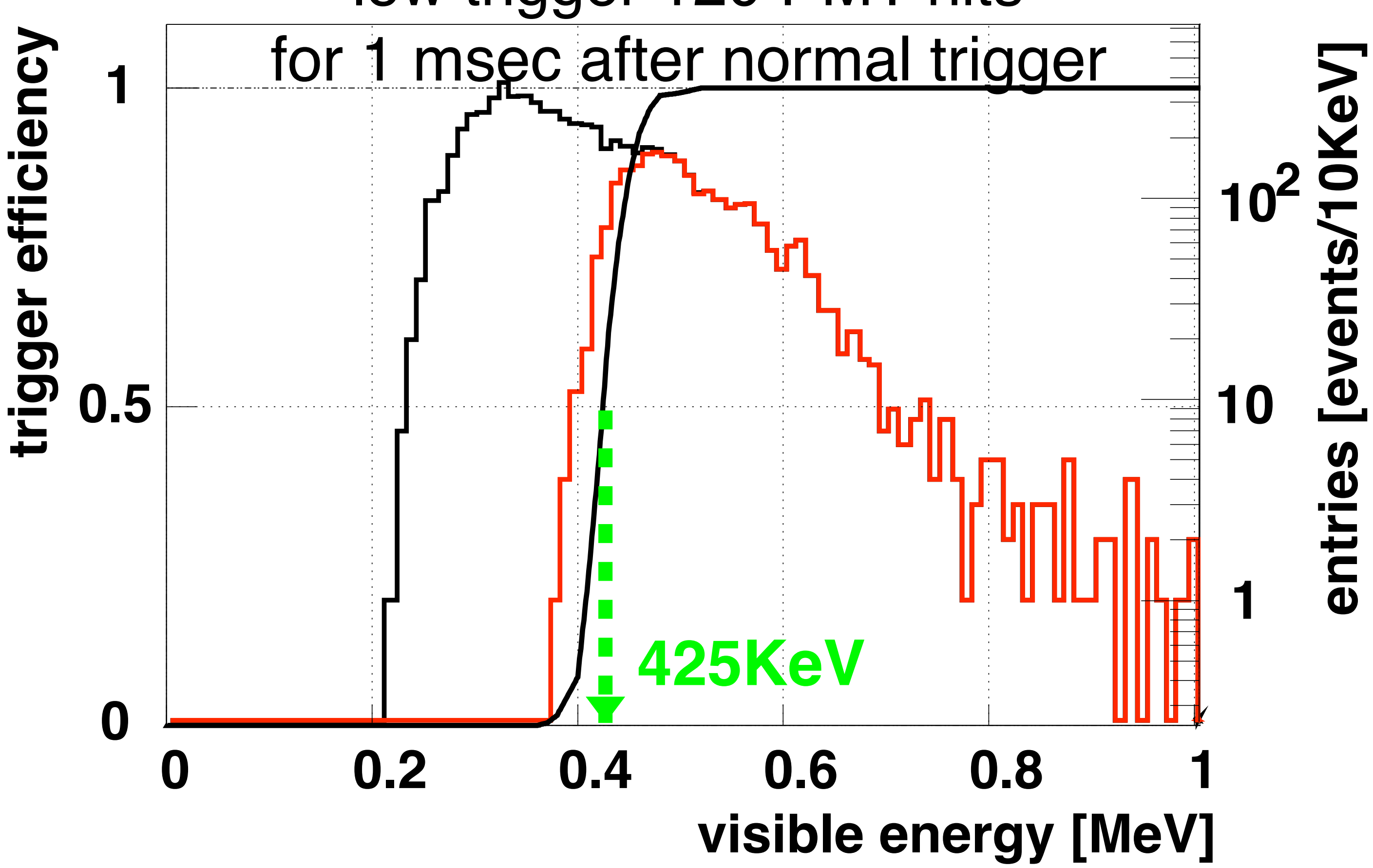
Balloon deployment in February 2001

Event Trigger

normal trigger 200 PMT hits



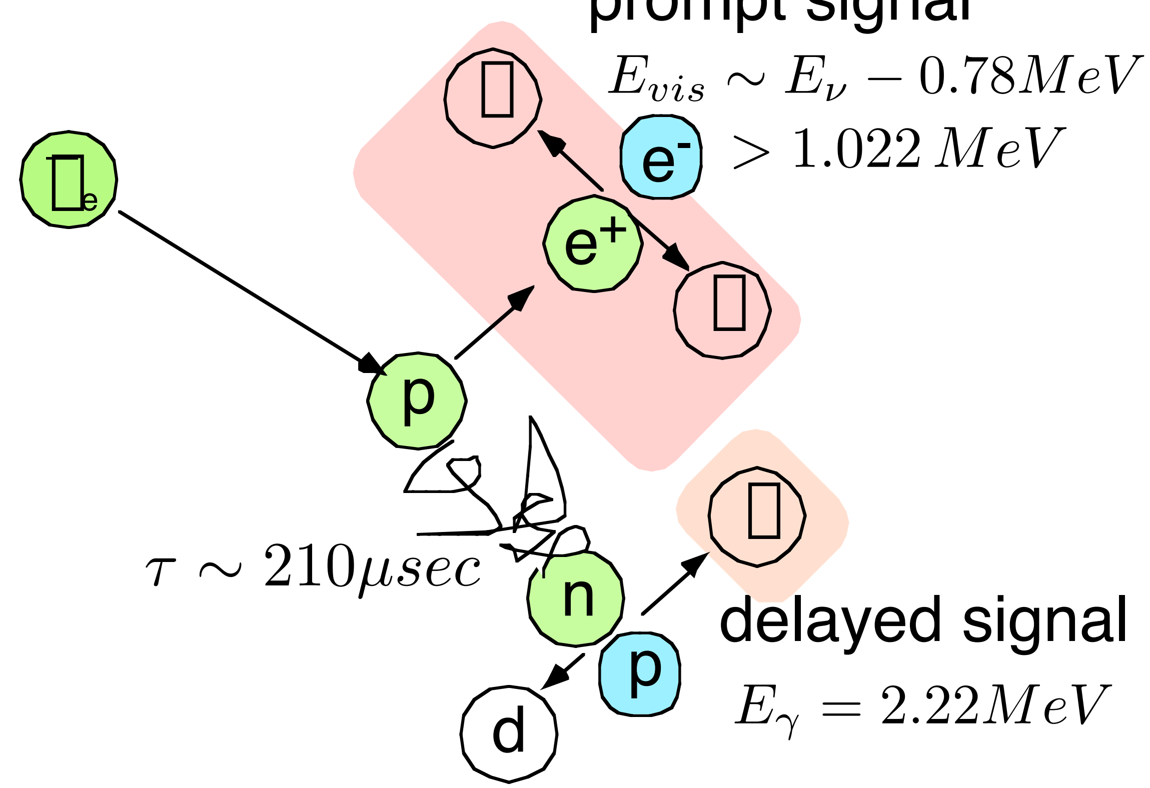
low trigger 120 PMT hits



Neutrino signal

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

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



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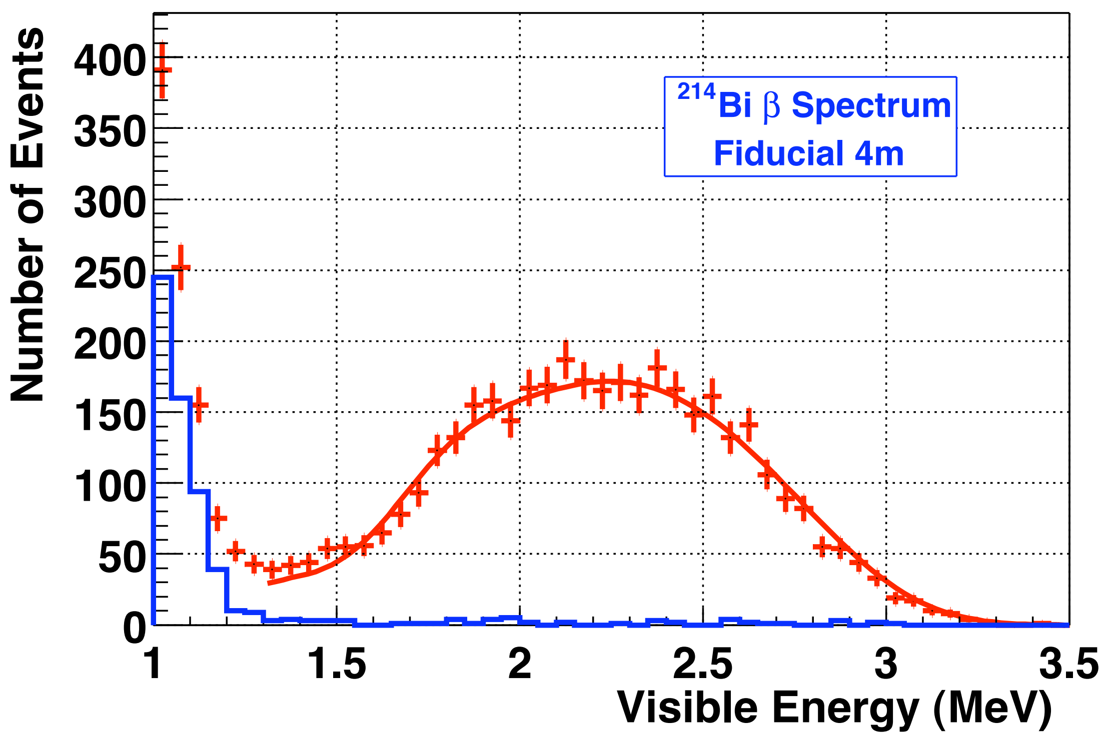
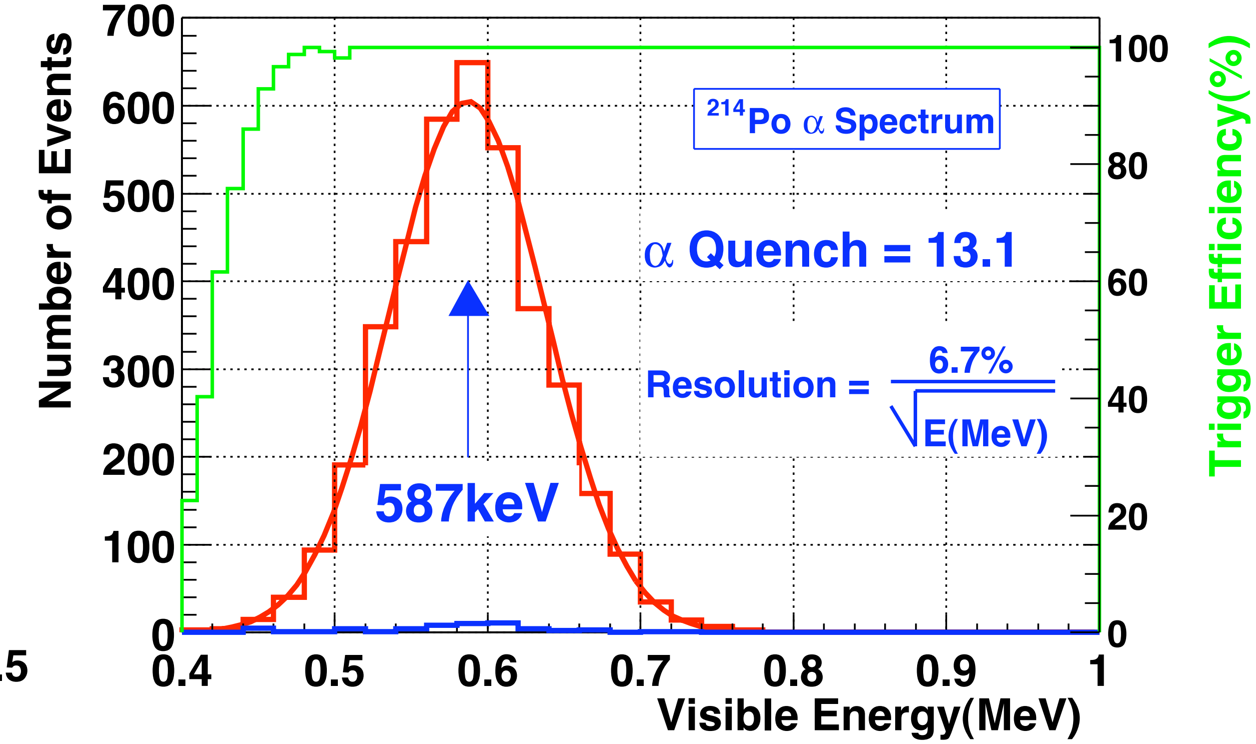
low trigger for impurity measurement

$$^{214}Bi \xrightarrow{\beta,\gamma} {}^{214}Po \xrightarrow[7.687MeV]{\alpha} {}^{210}Pb$$

τ=237μs

Impurity Measurement

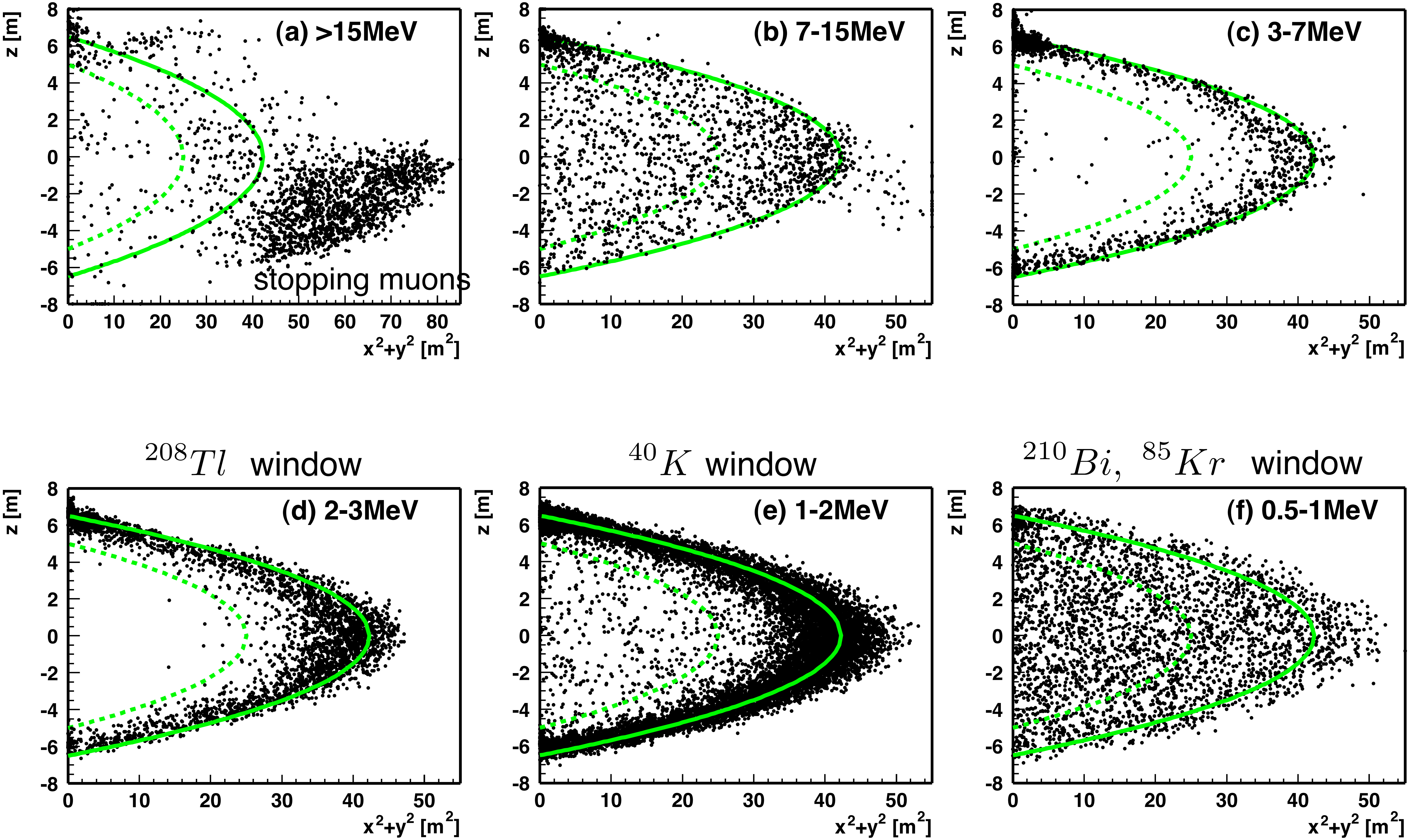




Impurities in the LS			Requirements Reactor	Requirements Solar
^{222}Rn	$0.03\mu Bq/m^3$	$^{214}Bi \rightarrow ^{214}Po(\tau = 237\mu sec)$		
^{238}U	$(3.5 \pm 0.5) \times 10^{-18} g/g$	assume equilibrium	$10^{-13} g/g$	$10^{-16} g/g$
^{232}Th	$(5.2 \pm 0.8) \times 10^{-17} g/g$	$^{212}Bi \rightarrow ^{212}Po(\tau = 0.431\mu sec)$	$10^{-13} g/g$	$10^{-16} g/g$
^{40}K	$< 2 \times 10^{-16} g/g$	single rate	$10^{-14} g/g$	$10^{-18} g/g$
^{85}Kr	$\sim 1\, Bq/m^3$	single rate/delayed coincidence		$1\, \mu Bq/m^3$
^{210}Pb	$\sim 100\, mBq/m^3$	single rate		$1\, \mu Bq/m^3$

Impurities on the Balloon		
^{222}Rn $4.0 \times 10^{-4}\, Bq$	^{238}U $3.1 \times 10^{-8}\, g$ ~0.9g mine dust	^{232}Th $9.7 \times 10^{-4}\, Bq$ ~0.1g mine dust

Vertex Distribution



Background

(in 162 ton-yr sample)

Accidental Coincidence

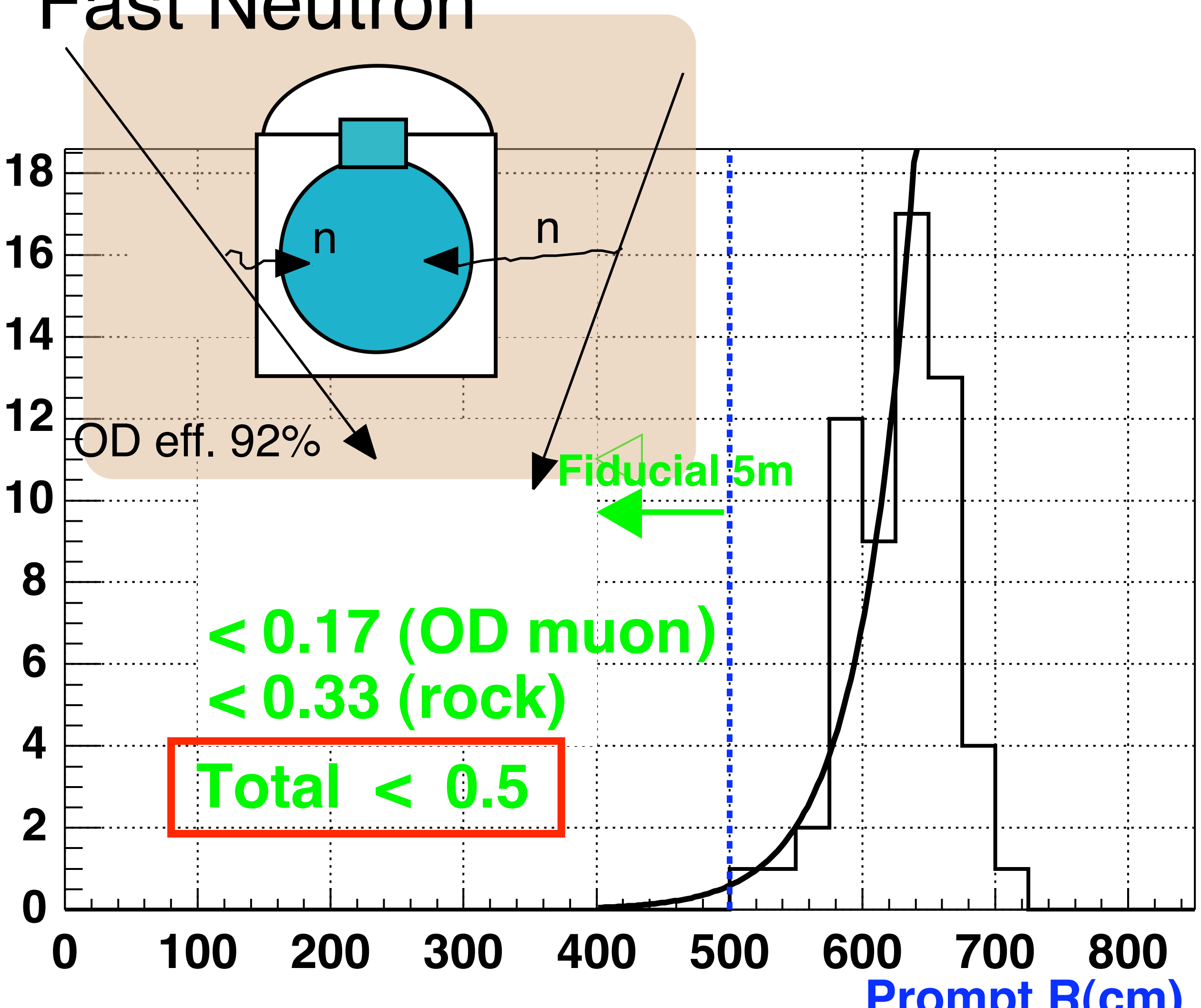
(2.6 MeV threshold)

$$0.0086 \pm 0.0005$$

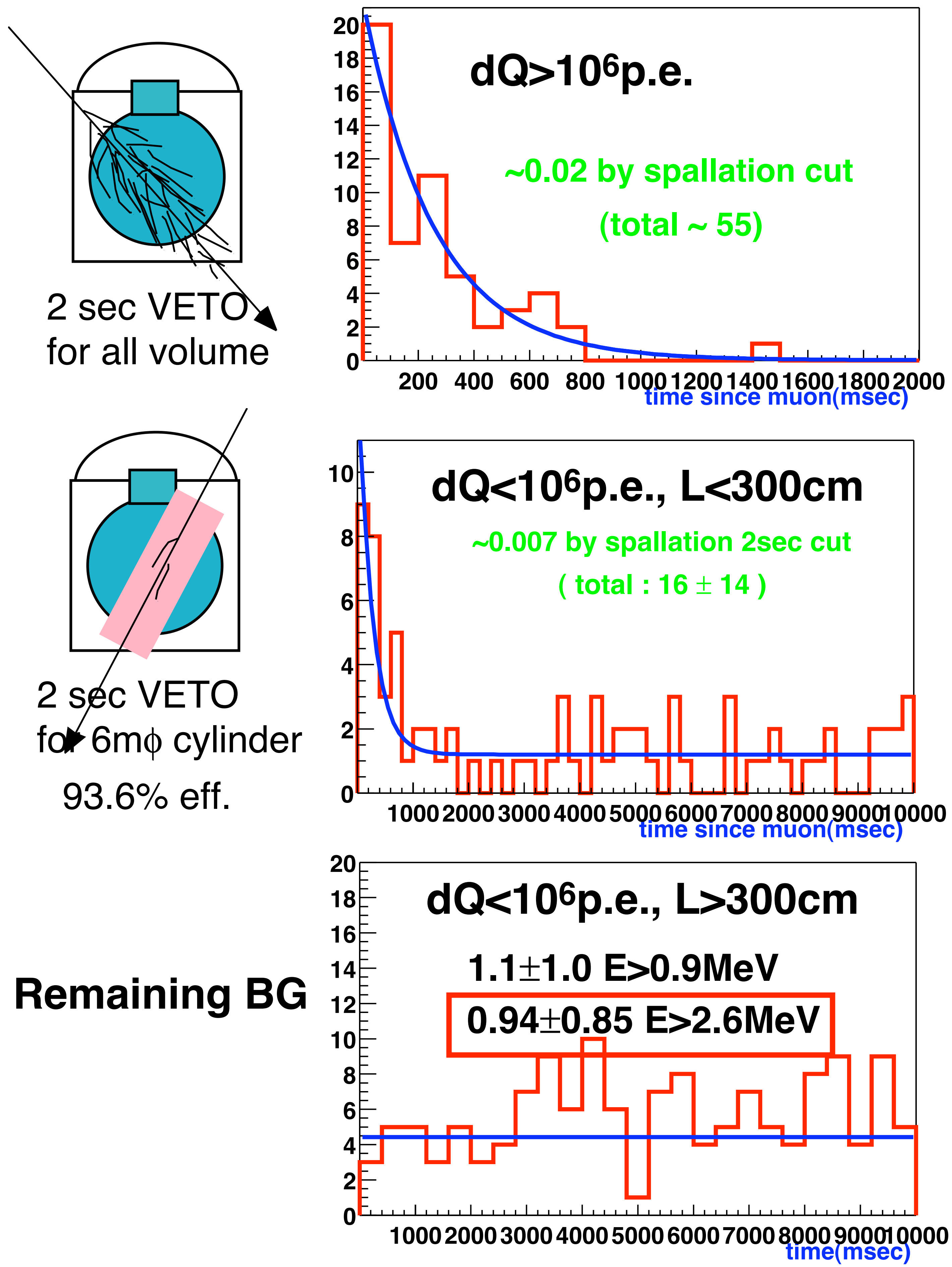
(0.9 MeV threshold)

$$1.81 \pm 0.08 \quad {}^{210}Bi + {}^{208}Tl$$

Fast Neutron



Spallation Products (^{9}Li β+n decay)

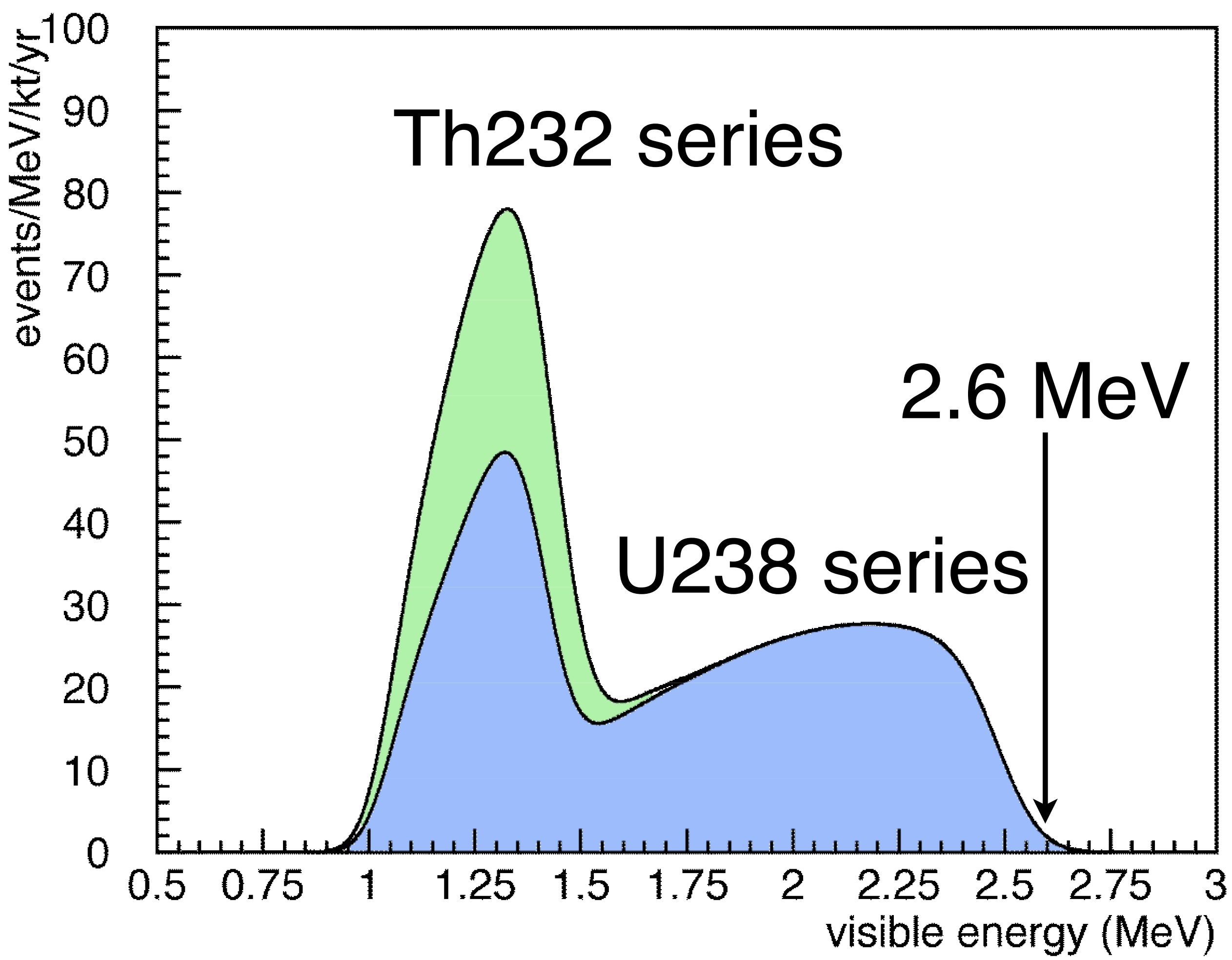


Background

(in 162 ton-yr sample)

	0.9 MeV	2.6 MeV
Total B.G.	2.9 ± 1.1	1 ± 1

Another important B.G.



A guess (16 TW)

~9 events (0.9 MeV)

~0.04 events (2.6 MeV)

$\bar{\nu}_e$ from the earth has never been observed, before.

If observed, it opens a new field of "Neutrino Geo-physics."

Event Selection

(1) fiducial cut $R < 5\,m$ 3.46×10^{31} free protons

(2) timing correlation $0.5 < dT < 660\,\mu sec,\ \tau = 212\,\mu sec$

(3) vertex correlation $|r_{prompt} - r_{delayed}| < 1.6\,m$

(4) delayed energy $1.8 < E < 2.6\,MeV$

(5) thermometer cut $\sqrt{x^2 + y^2} > 1.2\,m$

detection efficiency 78.3%

(6) spallation cut

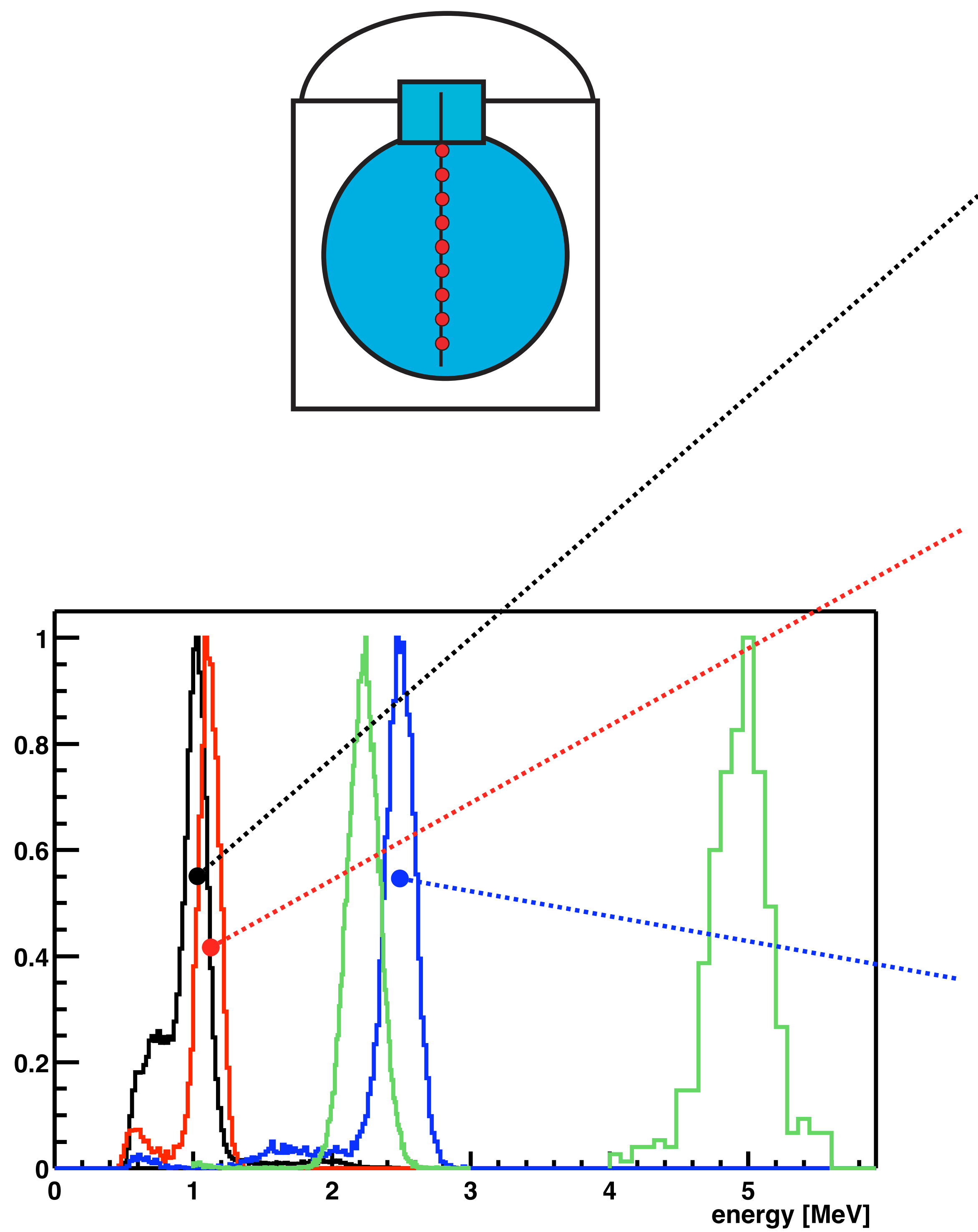
all vol. $(dQ > 10^6\,p.e.)$ or $L < 3\,m$ $(dQ < 10^6\,p.e.)$ VETO for $2\,sec$

dead time 11.4 %

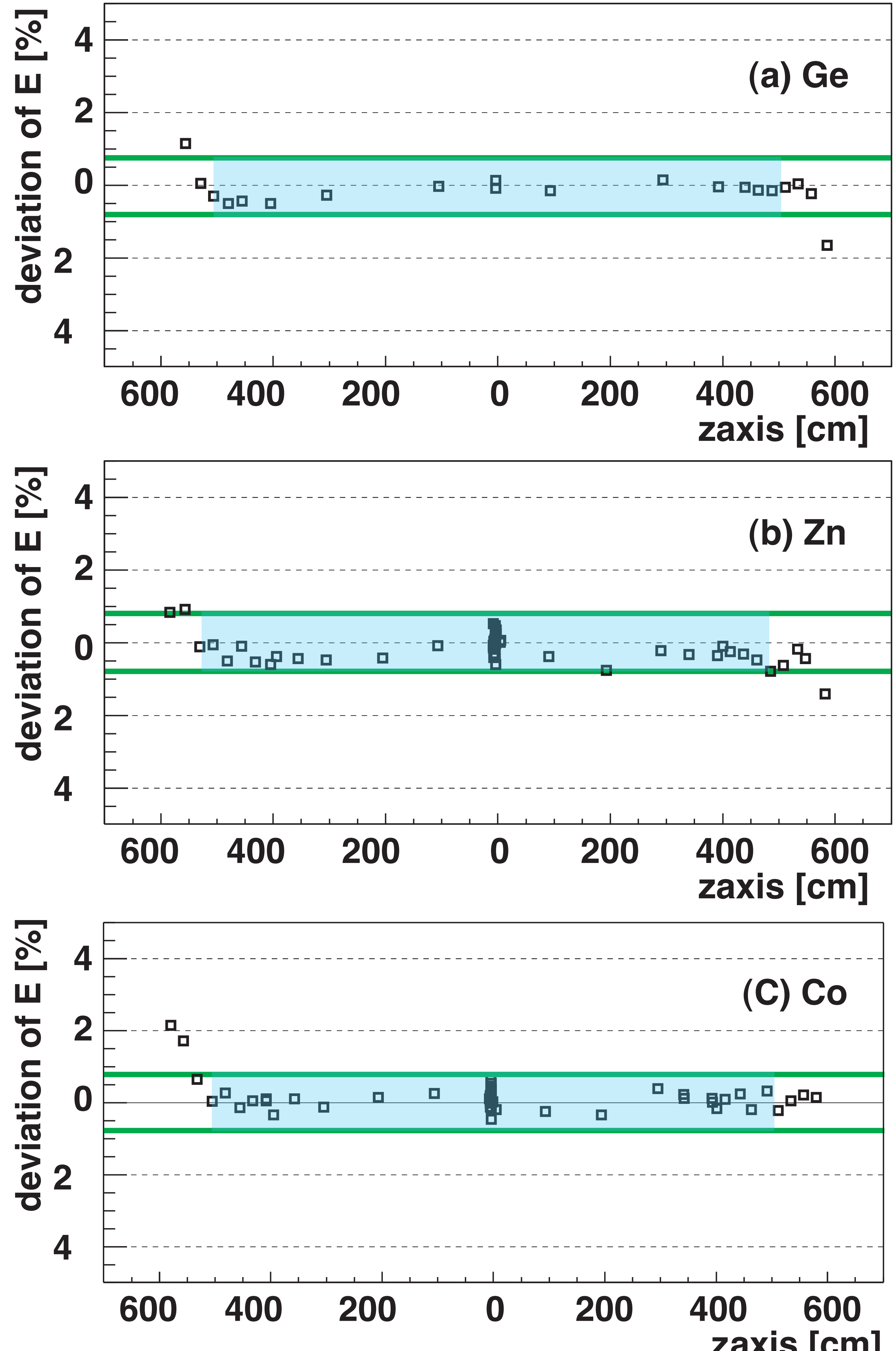
(7) energy threshold $E_{vis} > 2.6\,MeV$

Endpoint energy of geo-$\bar{\nu}_e$ event is 2.5 MeV.

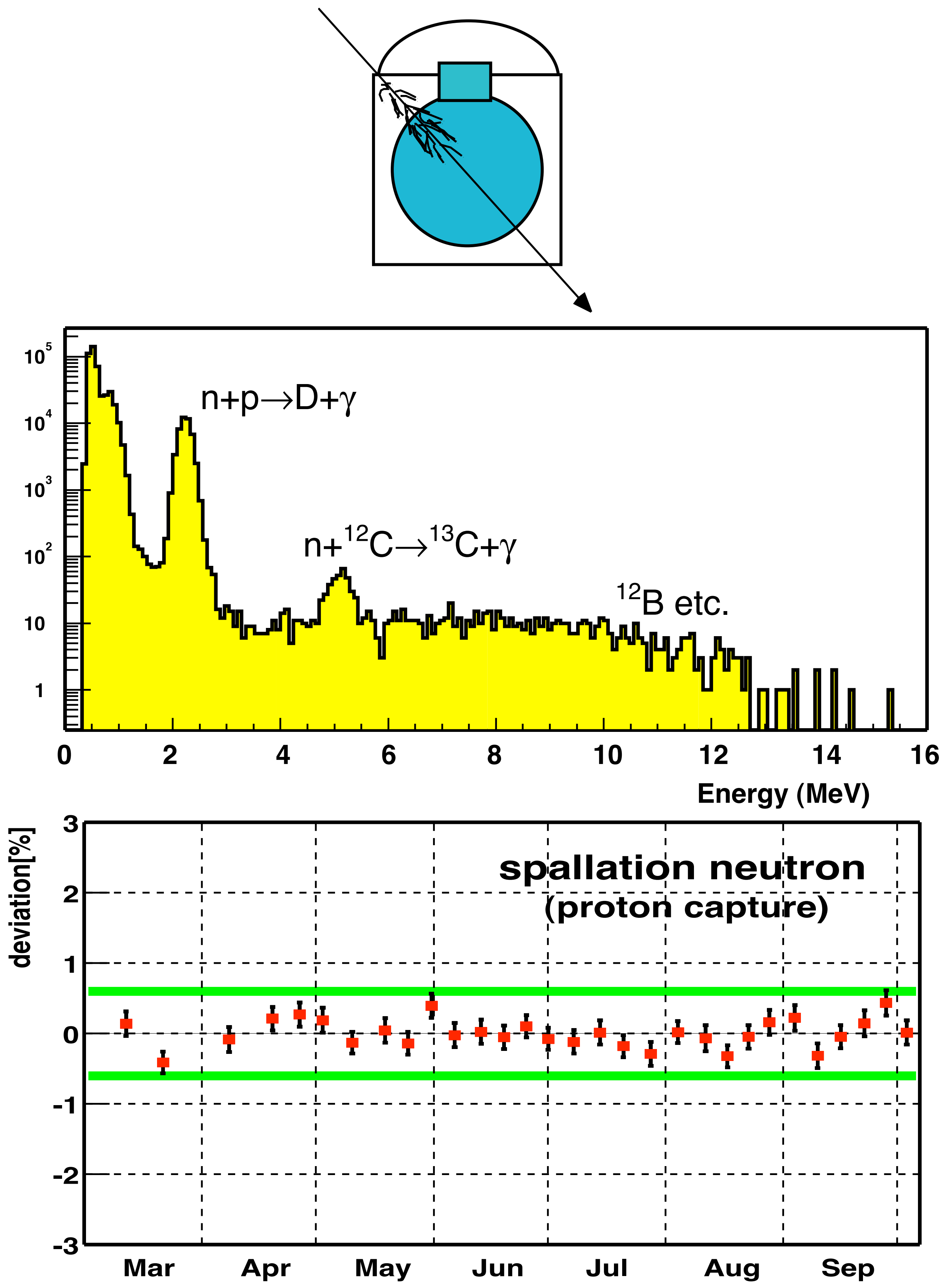
Energy Calibration with Radioactive Sources



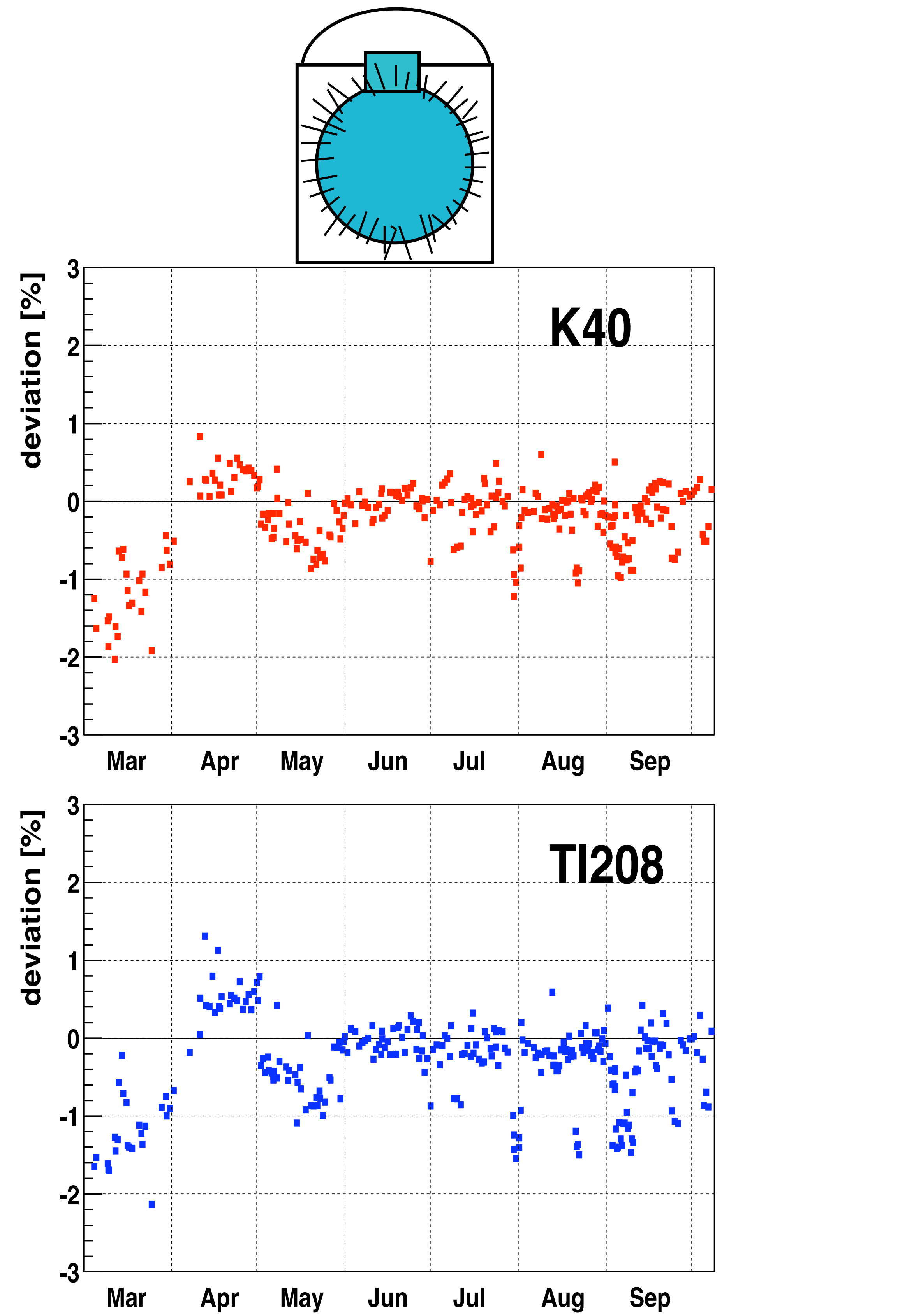
$$\frac{\sigma}{E} \sim \frac{7.5\%}{\sqrt{E}}$$



Energy Calibration with Muon Spallation

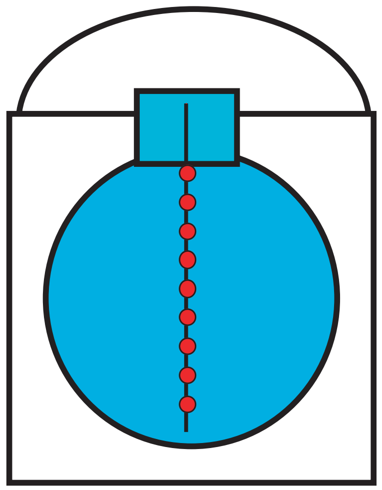


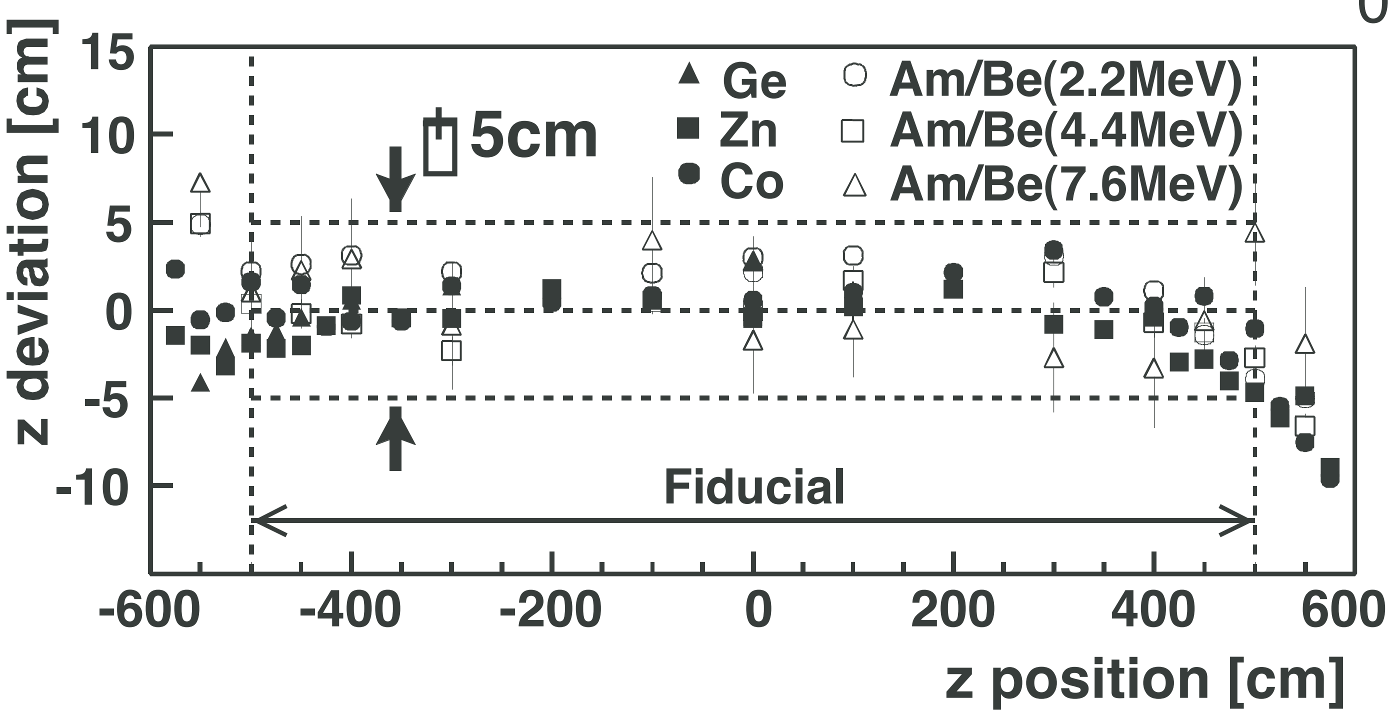
with gammas from material



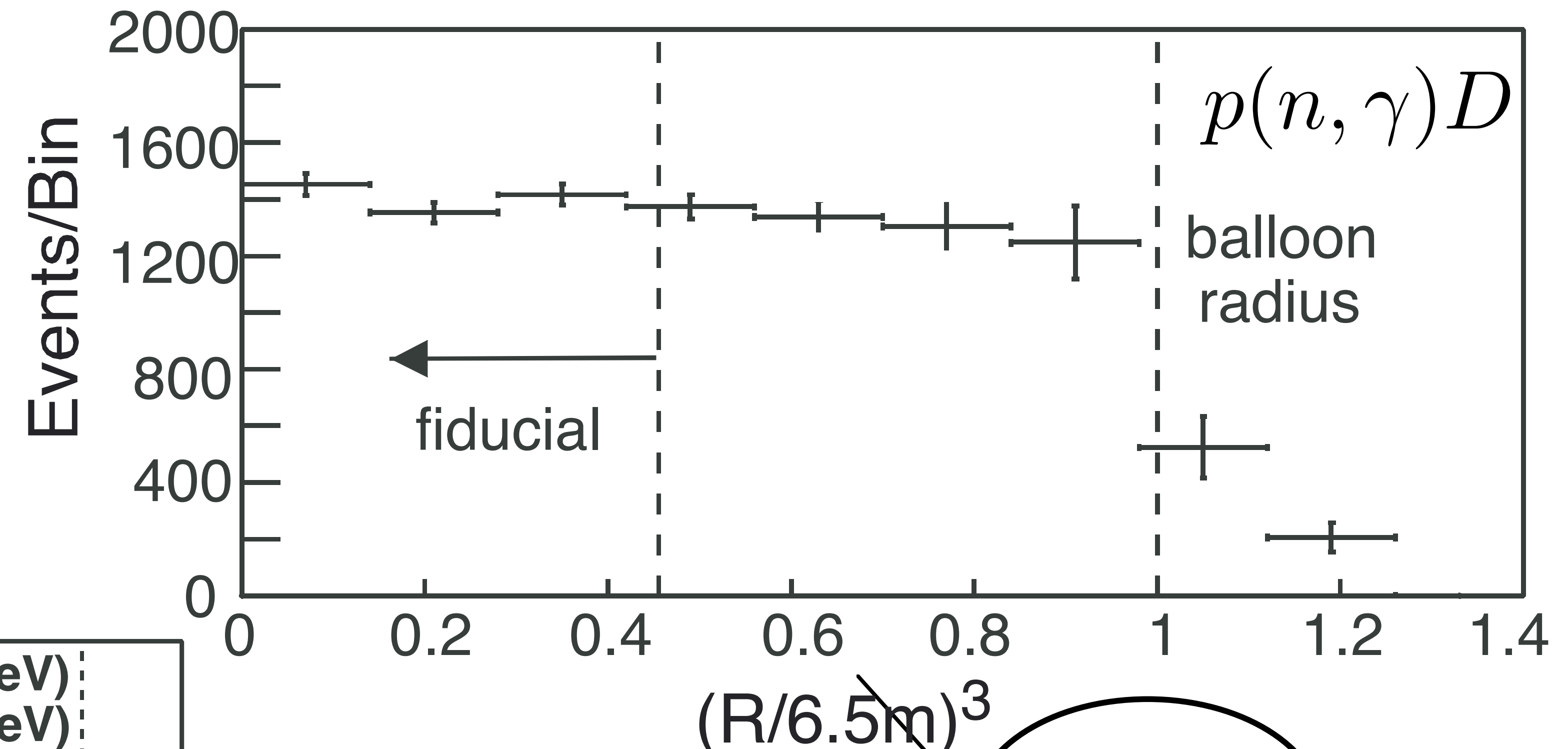
Fiducial Volume Calibration with Radioactive Sources

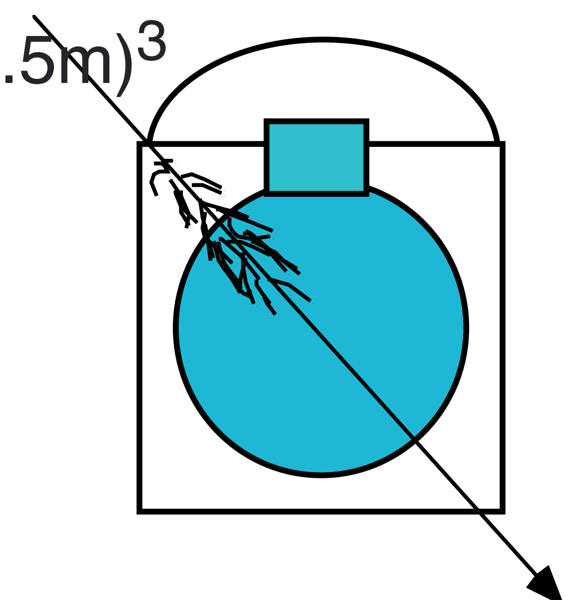
with Spallation Events





$$\sigma_{x,y,z} \sim \frac{30\,cm}{\sqrt{E}}$$





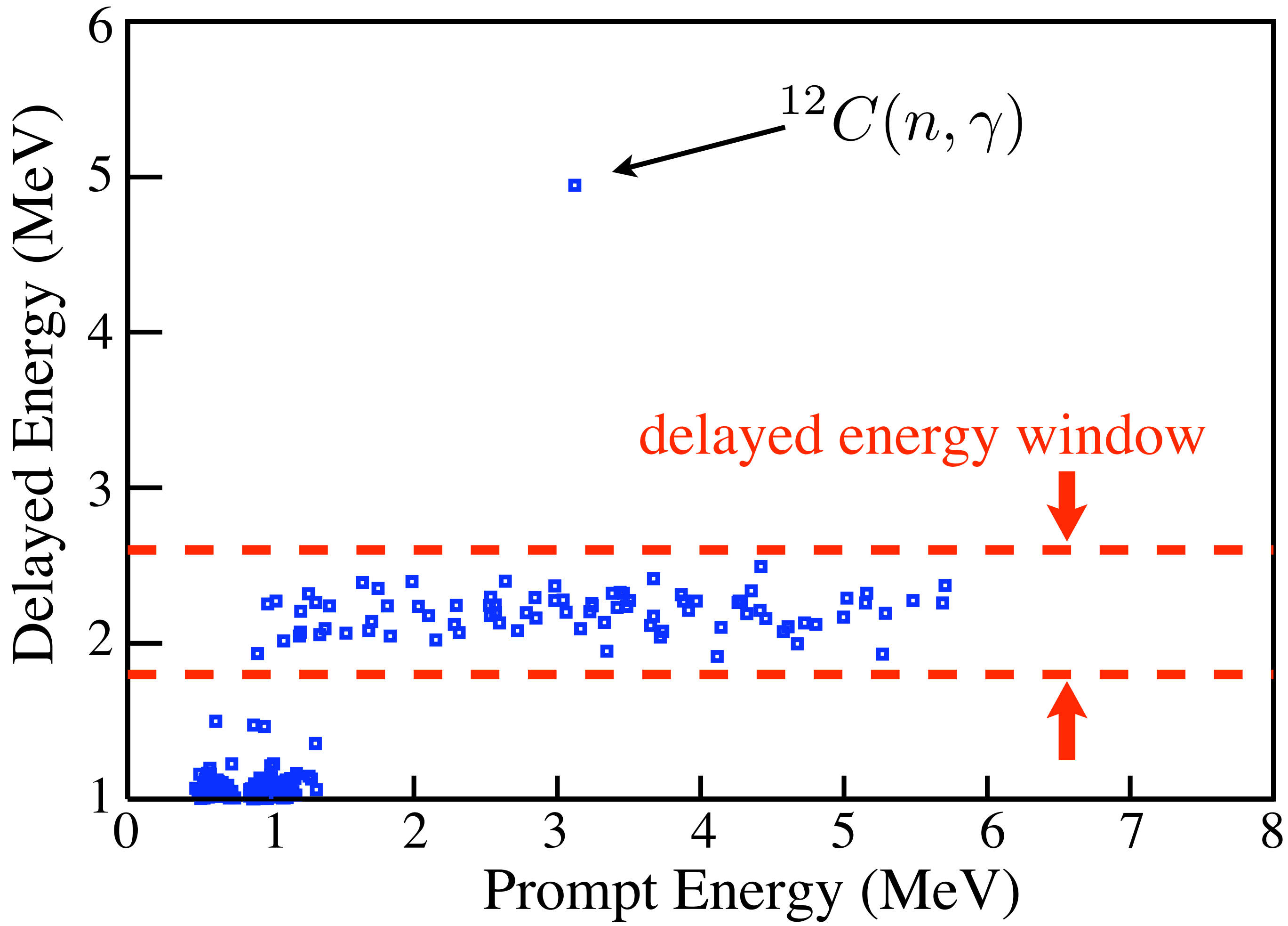
$$\frac{\Delta V}{V} = \pm 4.1\% \quad p(n,\gamma)D$$

$$\pm 3.5\% \quad {}^{12}B$$

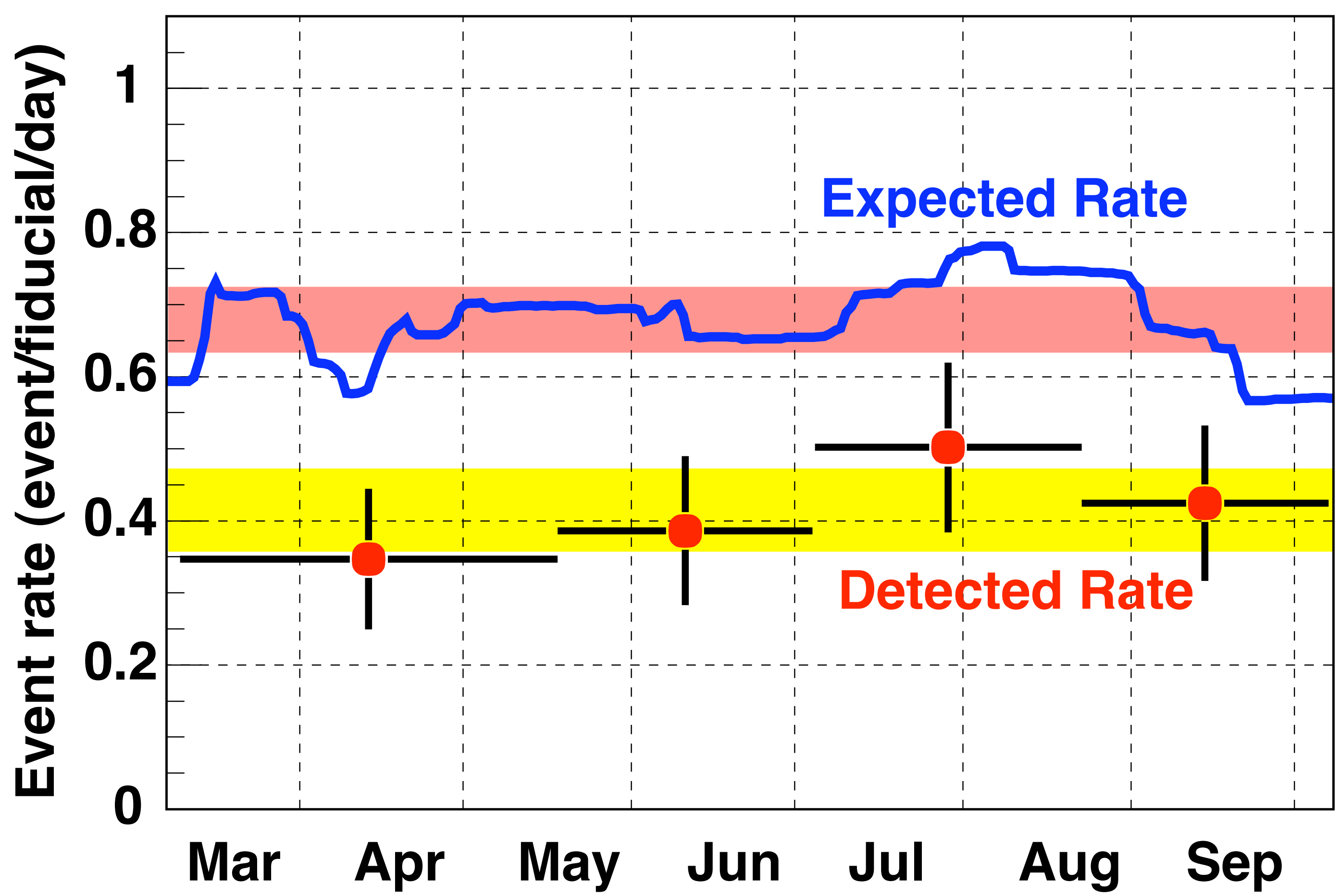
Statistical error dominates

So far Achieved Systematic Errors

	0.9MeV	2.6MeV		
Thermal Power	2.0	2.0	Reactor related 3.4%	Japanese reactors contribute ~97% of neutrino flux.
Korean Reactors	0.25	0.25	Reactor related 3.4%	Only electric power is known but contribution is ~2.5%.
Other Reactors	0.35	0.35	Reactor related 3.4%	Contribution is only 0.7%.
Burn-up effect	1.0	1.0	Reactor related 3.4%	fraction of U235/U238/Pu239/Pu241
Long-life Nuclei	0.5	0.002	Reactor related 3.4%	contribution of Ru106 and Ce144
Time-lag of beta decay	0.3	0.3	Reactor related 3.4%	<1 day time lag for an equilibrium
Neutrino Spectra	2.3	2.5	Reactor related 3.4%	PLB160(1985)325, PLB218(1989)365, PRC24(1981)1543
Cross section	0.2	0.2		PRD60(1999)053003, PRC67(2003)035502
Total LS mass	2.1	2.1	Detector 5.5%	$1171 \pm 25\, m^3$
Fiducial Volume Ratio	4.1	4.1	Detector 5.5%	vertex distribution of spallation neutron
Energy Threshold	-	2.1	Detector 5.5%	position 1.4%, time 0.6%, quench 1.02%, dark 0.4% ->1.91%
Efficiency of Cuts	2.1	2.1	Detector 5.5%	capture time, space correlation, energy window
Live Time	0.07	0.07	Detector 5.5%	
Total	6.0%	6.4%		



$^{12}C(n,\gamma)$
delayed energy window
Delayed Energy (MeV)
Prompt Energy (MeV)



Expected Rate
Detected Rate
Event rate (event/fiducial/day)
Mar
Apr
May
Jun
Jul
Aug
Sep

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 ± 5.6
BG	1 ± 1
observed	54

Neutrino disappearance at 99.95% CL.

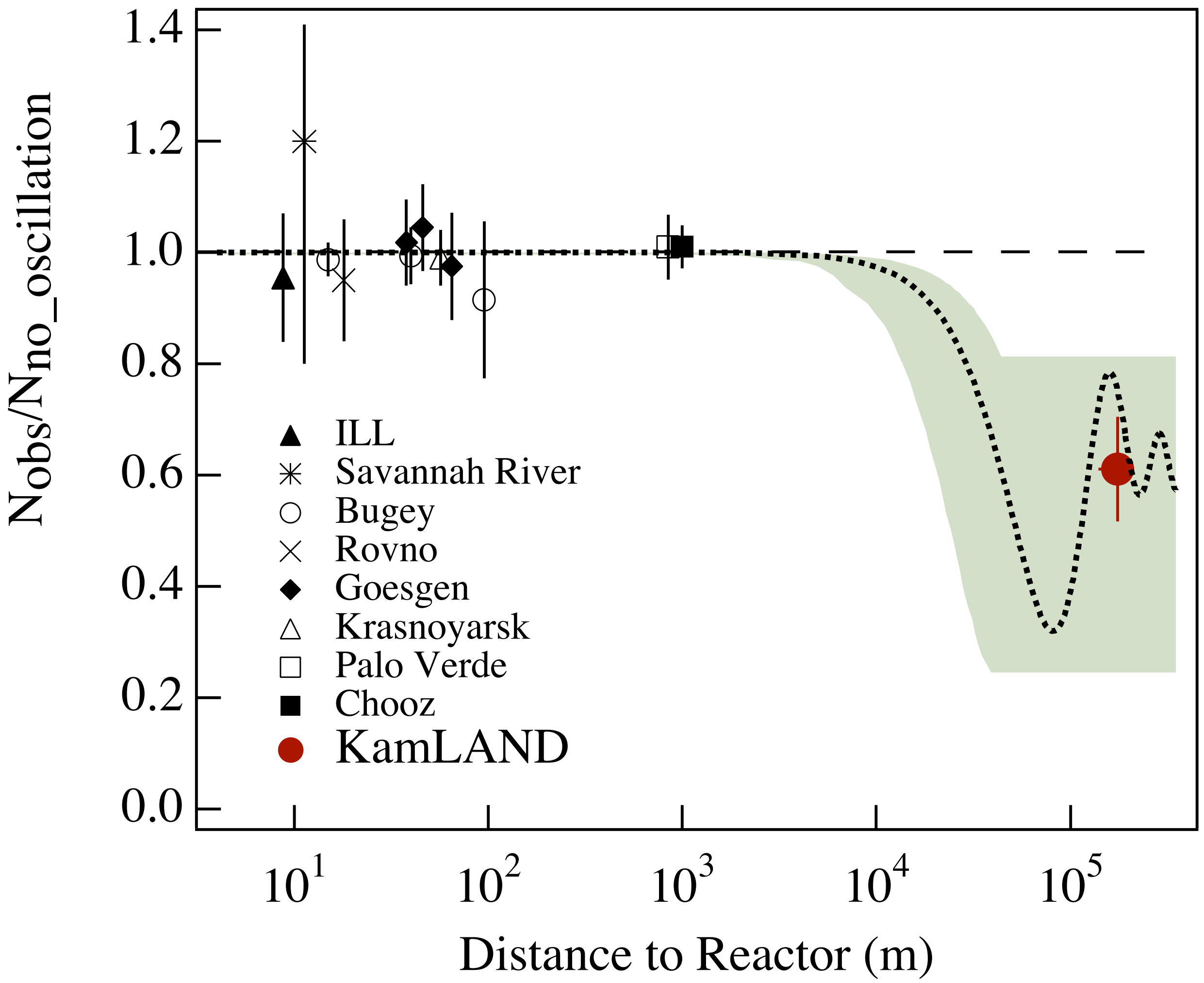
$$R = 0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst})$$

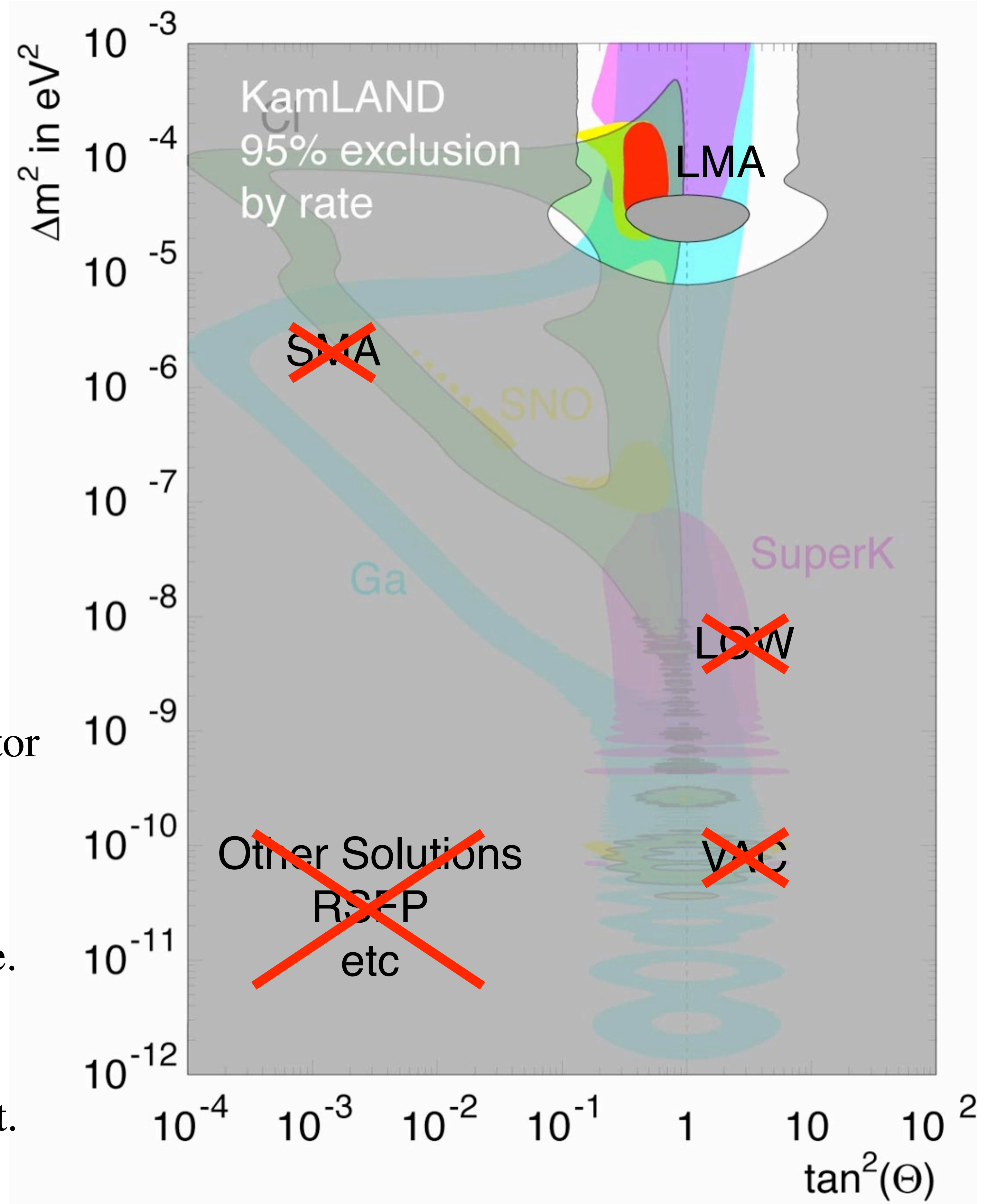
KamLAND collaboration, Phys.Rev.Lett.90(2003)021802

Analysis threshold 0.9 MeV

expected signal	124.8 ± 7.5
BG	$2.9 \pm 1.1 \ (+ \sim 9\nu_{geo})$
observed	86

Rate Analysis



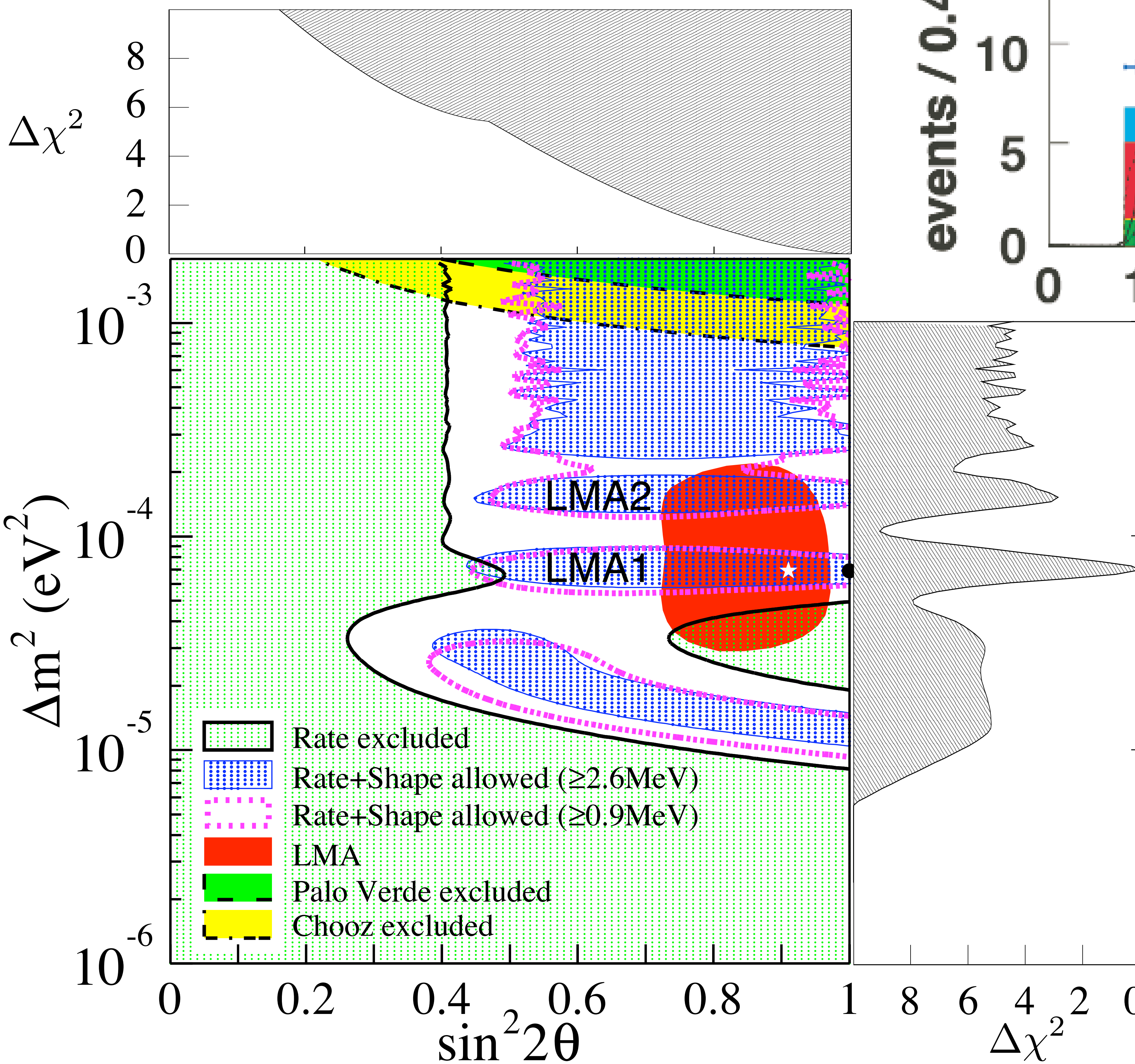


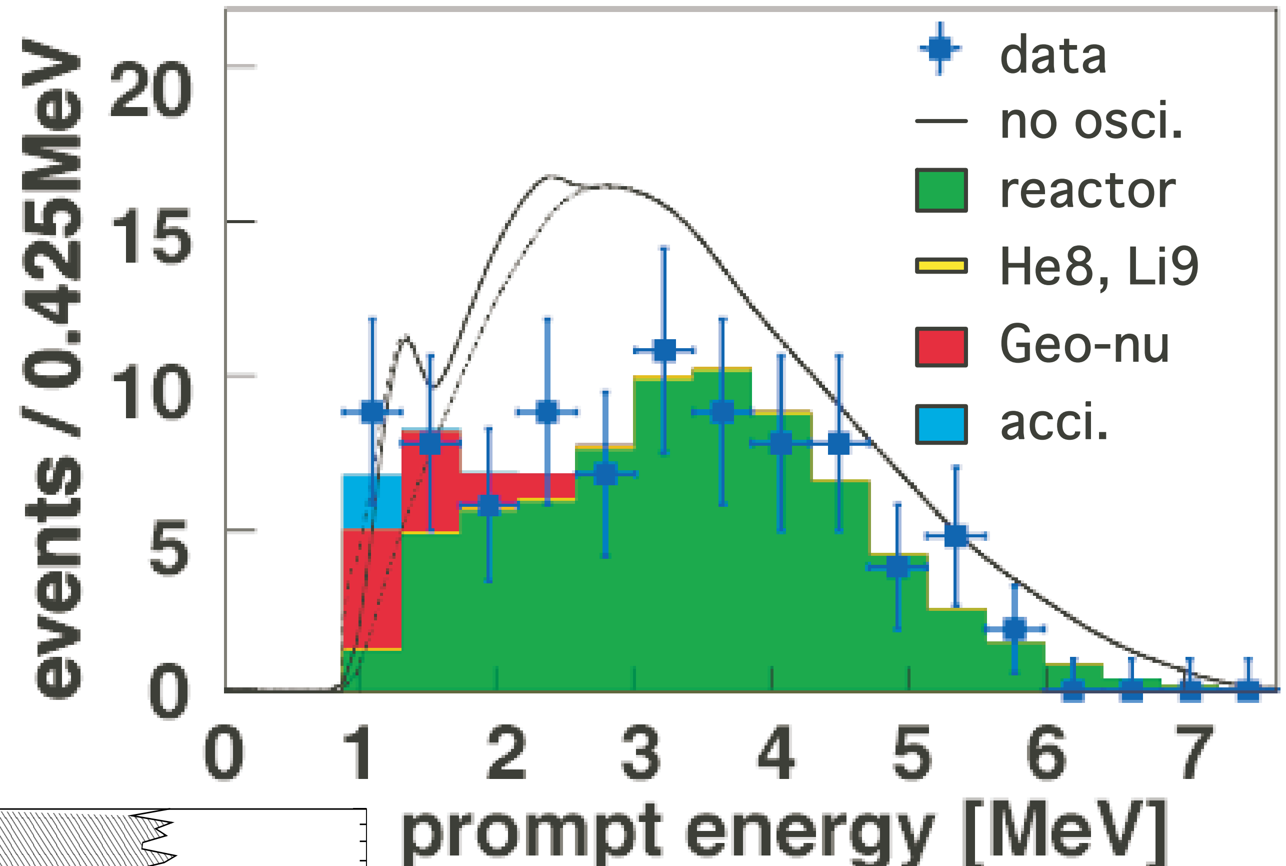
KamLAND has observed an evidence for reactor neutrino disappearance at ~180 km distance.

SMA, LOW, VAC solutions are excluded at 99.95% confidence level under CPT invariance.

Other solutions (such as RSFP) are no more leading phenomena of the solar neutrino deficit.

Rate + Shape Analysis





Best Fit E > 2.6 MeV

$$\sin^2 2\theta = 1.0$$

$$\Delta m^2 = 6.9 \times 10^{-5} eV^2$$

Best Fit E > 0.9 MeV

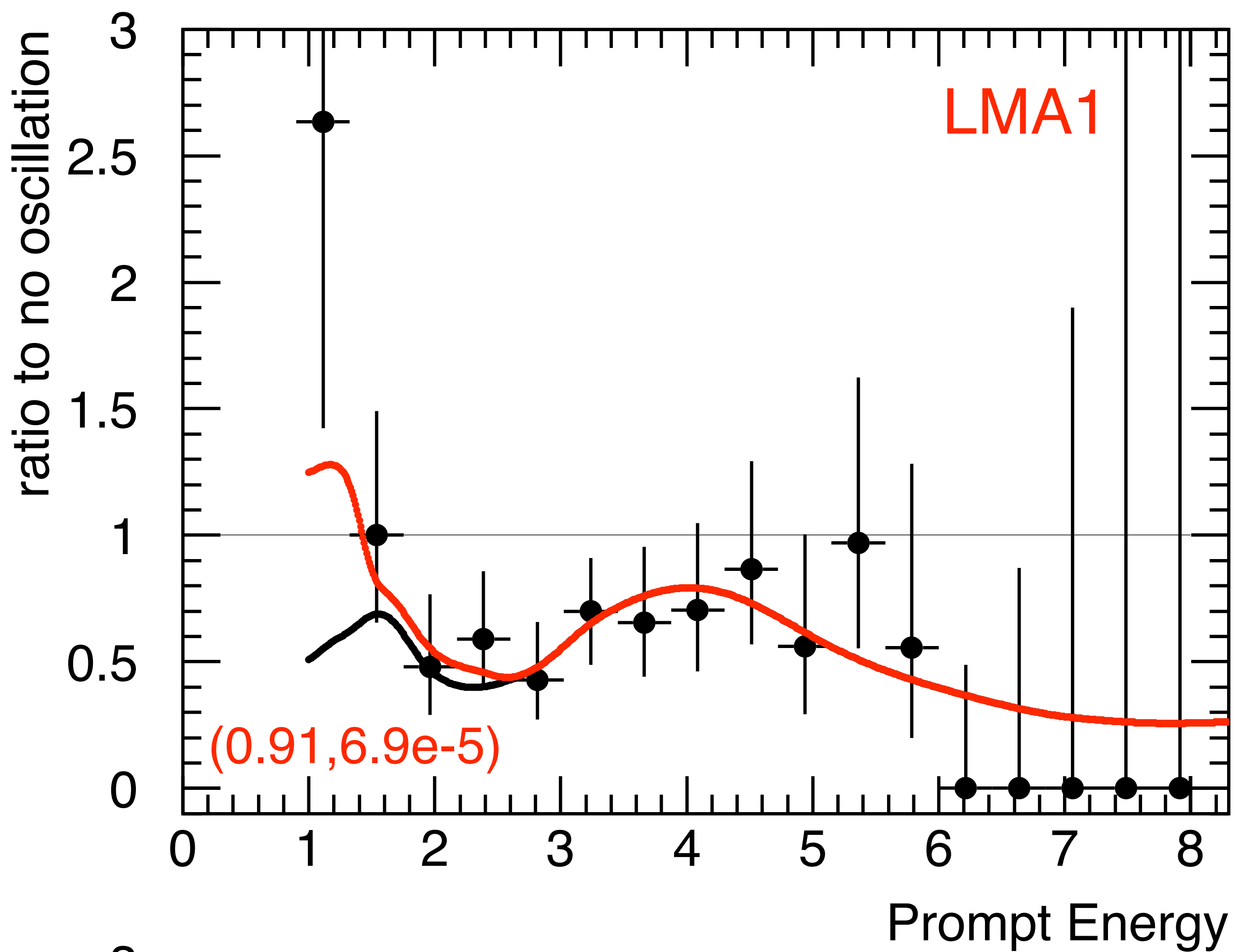
$$\sin^2 2\theta = 0.91$$

$$\Delta m^2 = 6.9 \times 10^{-5} eV^2$$

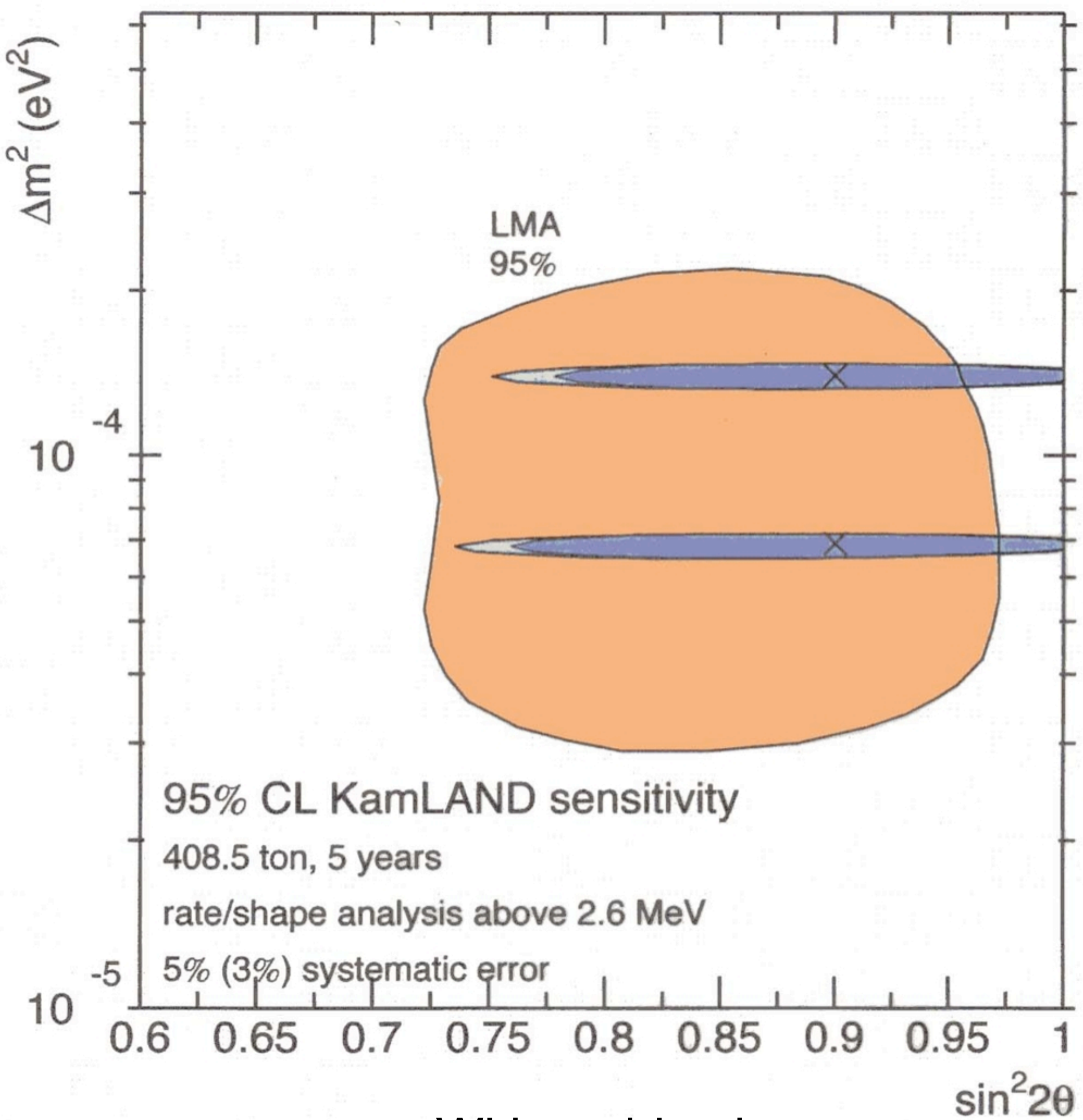
$$\bar{\nu}_{geo}(^{238}U) = 4$$

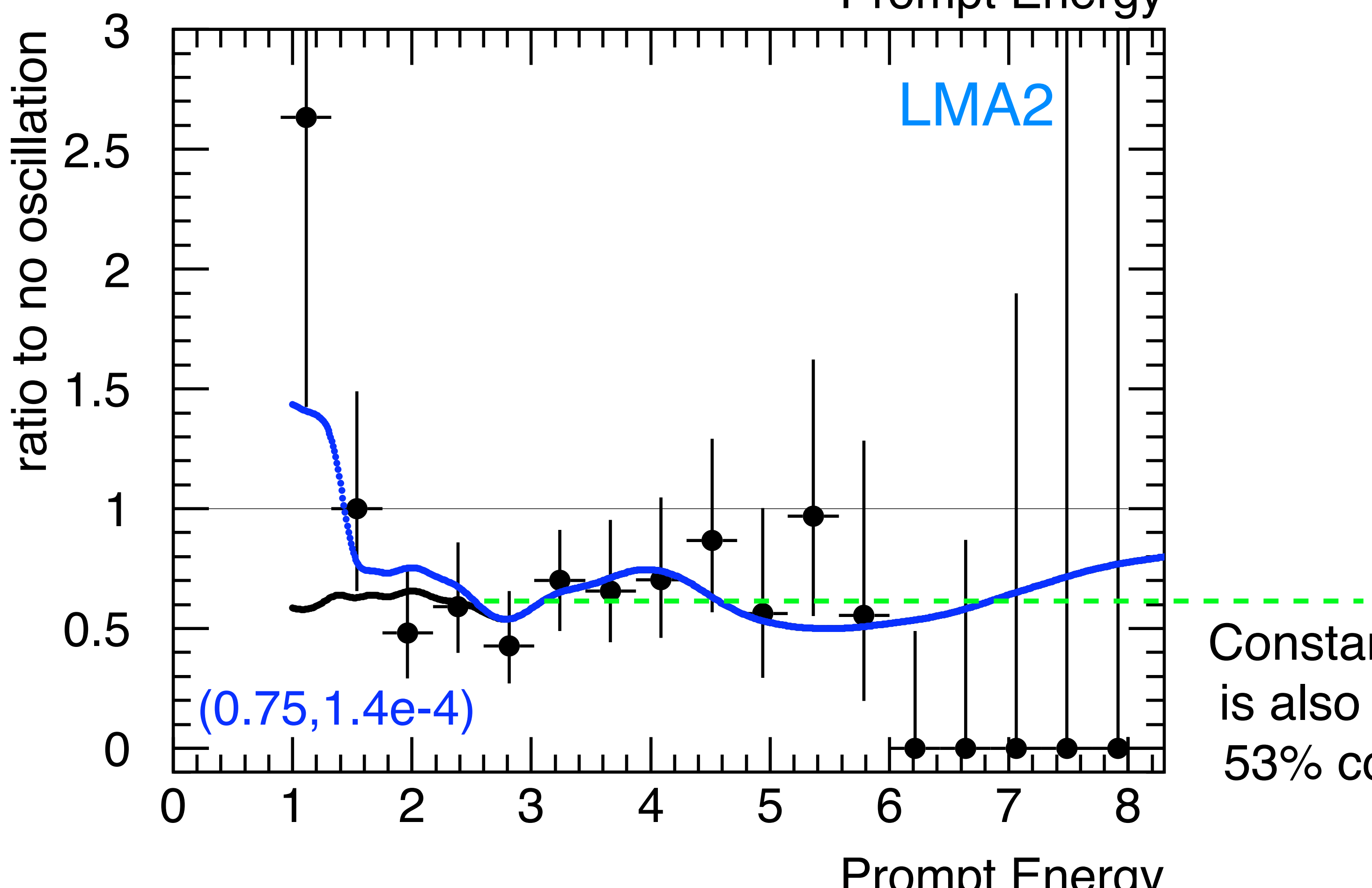
$$\bar{\nu}_{geo}(^{232}Th) = 5$$

hint of geo-nu,
but consistent with 0 at 95% CL



BG is subtracted and Geo-neutrinos with a model (16 TW) are included.

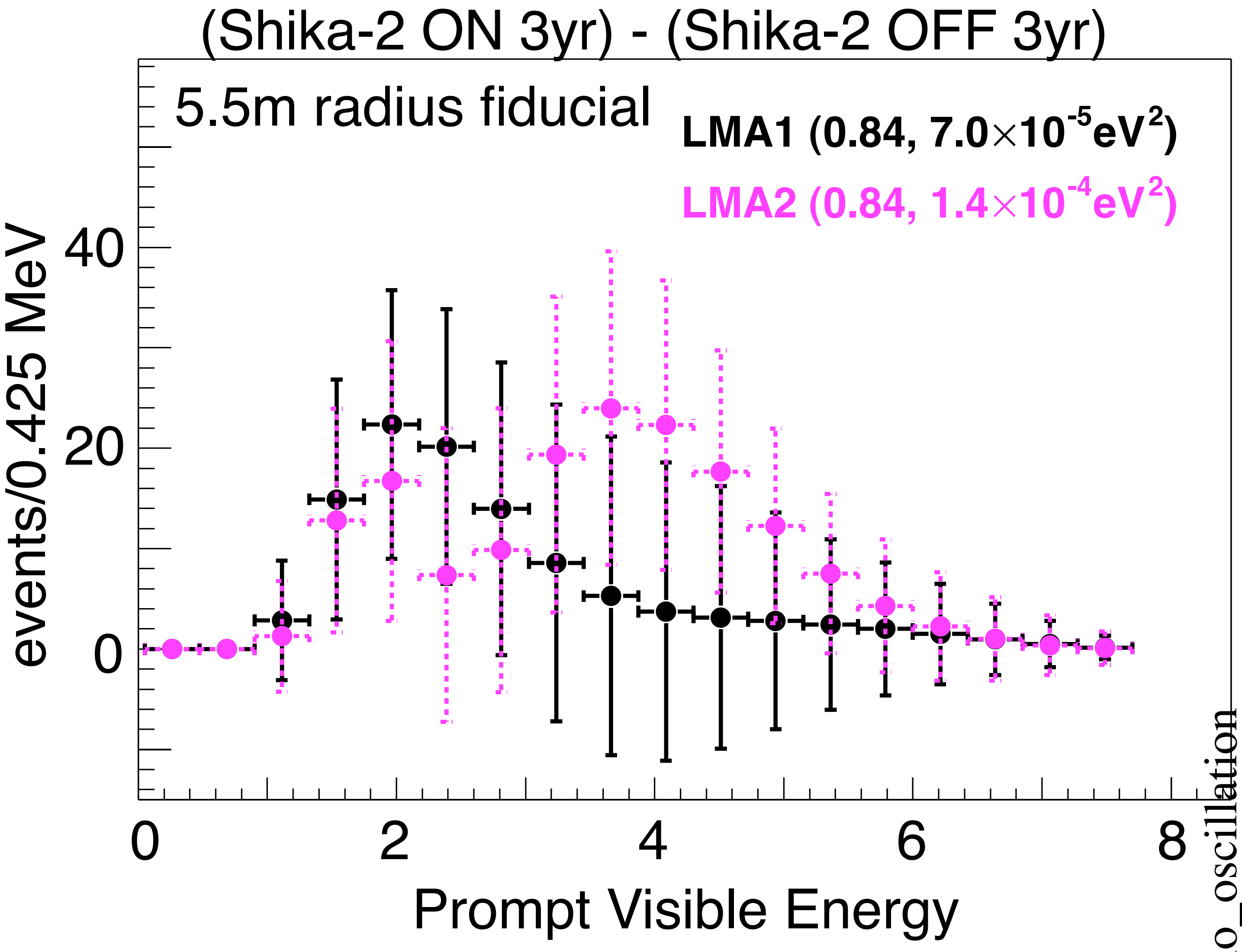




Constant suppresion is also consistent at 53% confidence for now.

Without big changes, KamLAND will pinpoint Δm^2_{21} .

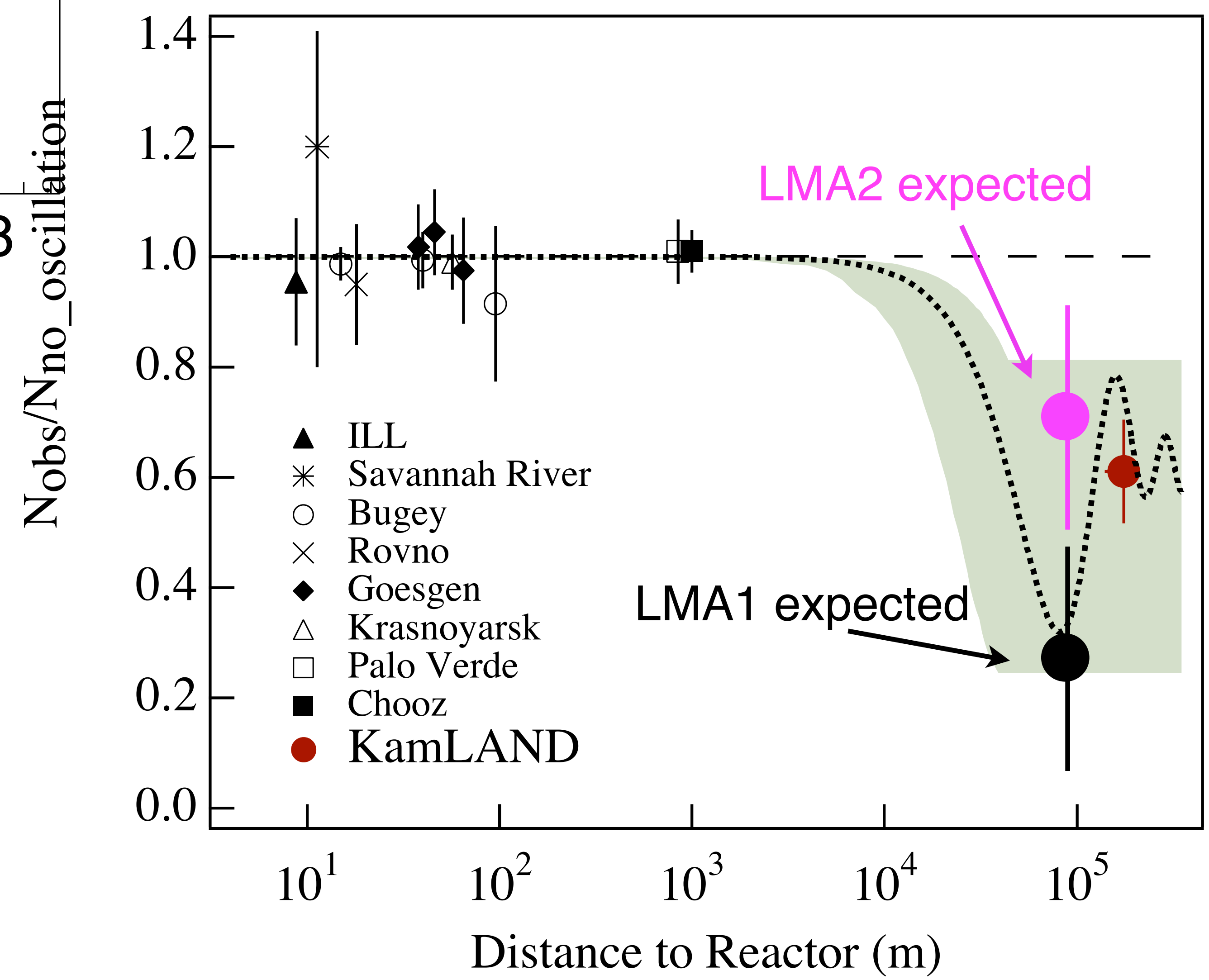
Shika-2 at 88km starts in 2006.



$$R_{LMA2} = \frac{121 \pm 36}{173}$$

$$R_{LMA1} = \frac{45 \pm 37}{173}$$

Oscillatory pattern may be seen as an evidence for oscillation.



θ_{13} experiments

MNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}\,e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}\,e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric, K2K	Accelerator, Reactor, ...	Solar, KamLAND
$\theta_{23} \sim 45^\circ$	Not measured yet	$\theta_{12} \sim 30^\circ$

θ_{13}

the last unmeasured mixing angle

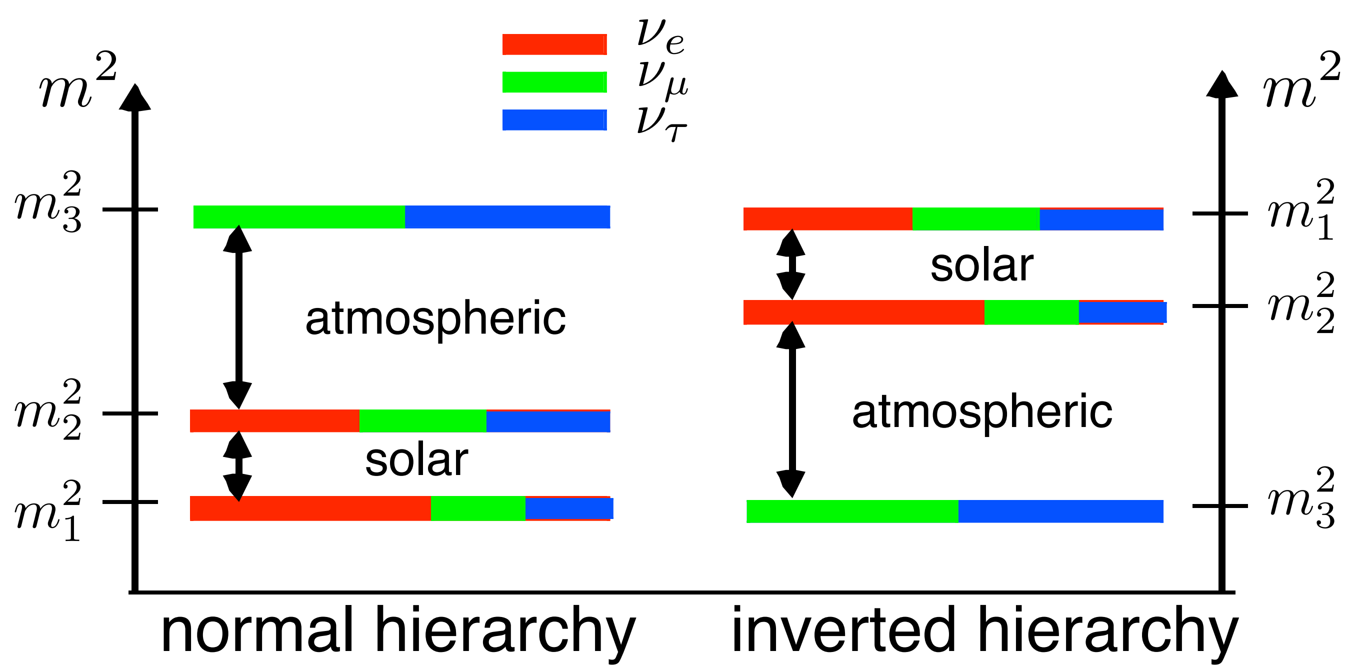
determine accessibility to the CP phase

Accelerator appearance experiment

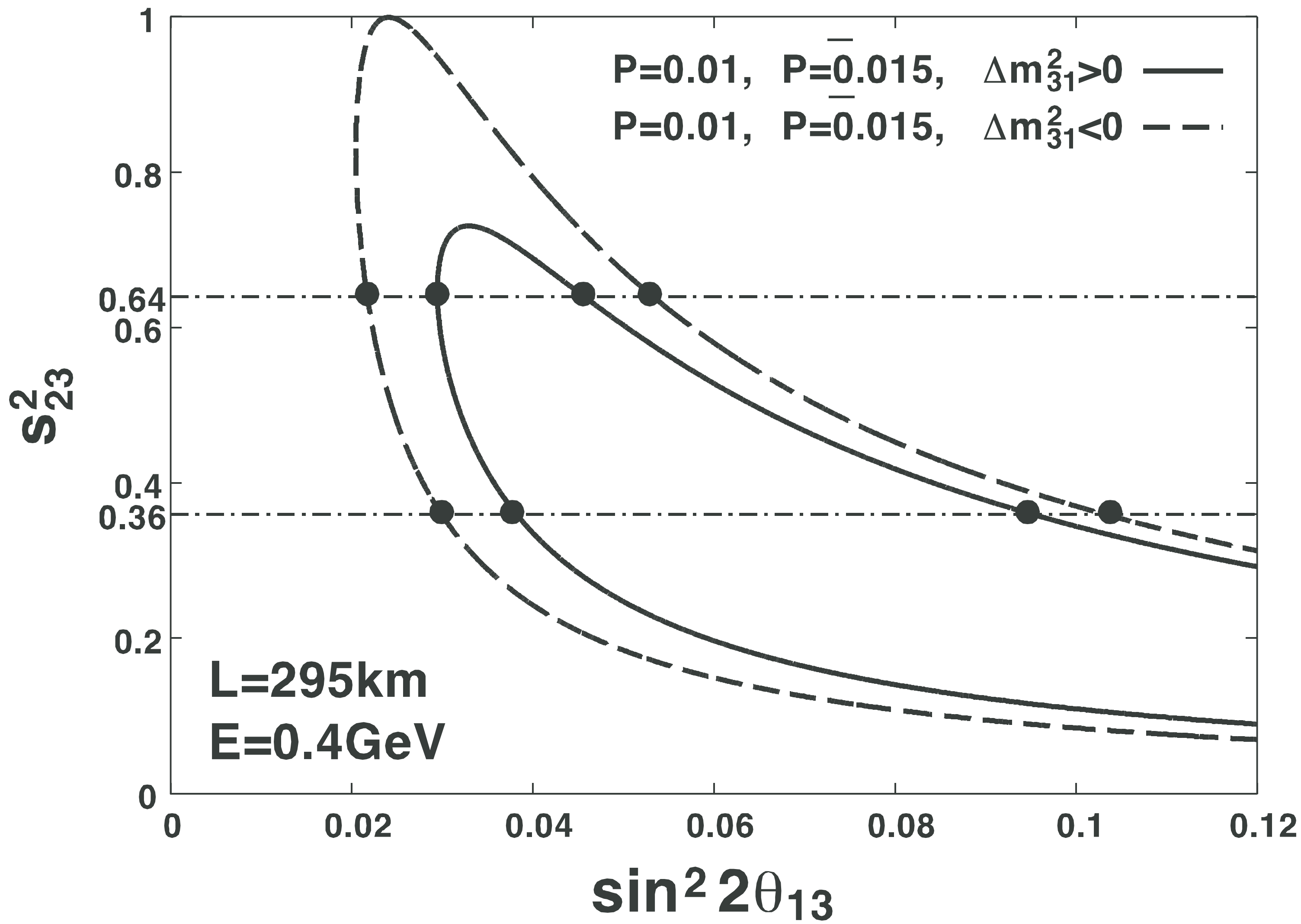
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
& + 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \quad \text{CP non-violating} \\
& - 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \quad \text{CP violating} \\
& + 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2 \Delta_{21} \quad \text{CP non-violating} \\
& - 8 c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2 s_{13}^2) \frac{aL}{4E} \cos\Delta_{32} \sin\Delta_{31} \quad \text{matter effect}
\end{aligned}
$$

$a = 2\sqrt{2} G_F N_e E$ $\quad$ $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ $\quad$ $a \to -a, \; \delta \to -\delta$

potential to measure:
- CP phase, δ
- $\mathrm{sign}(\theta_{23} - 45^\circ)$ $\quad$ $s_{23}^2 = \dfrac{1 \pm \sqrt{1 - \sin^2 2\theta_{23}}}{2}$
- $\mathrm{sign}(\Delta m_{31}^2)$ $\quad$ mass hierarchy



on the other hand, θ_{13} measurement is affected by them (”parameter degeneracy”)



hep-ph/0211111

Reactor disappearance experiment

$P_{NH}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4\, s_{13}^2 c_{13}^2 \sin^2 \Delta_{31}$ — CHOOZ-type experiments, O(1 km) oscillation

$- 4\, c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}$ — KamLAND experiment, O(100 km) oscillation

$+ 2\, s_{13}^2 c_{13}^2 s_{12}^2 \left[\cos(2\Delta_{31} - 2\Delta_{21}) - \cos 2\Delta_{31}\right]$ — HLMA experiment

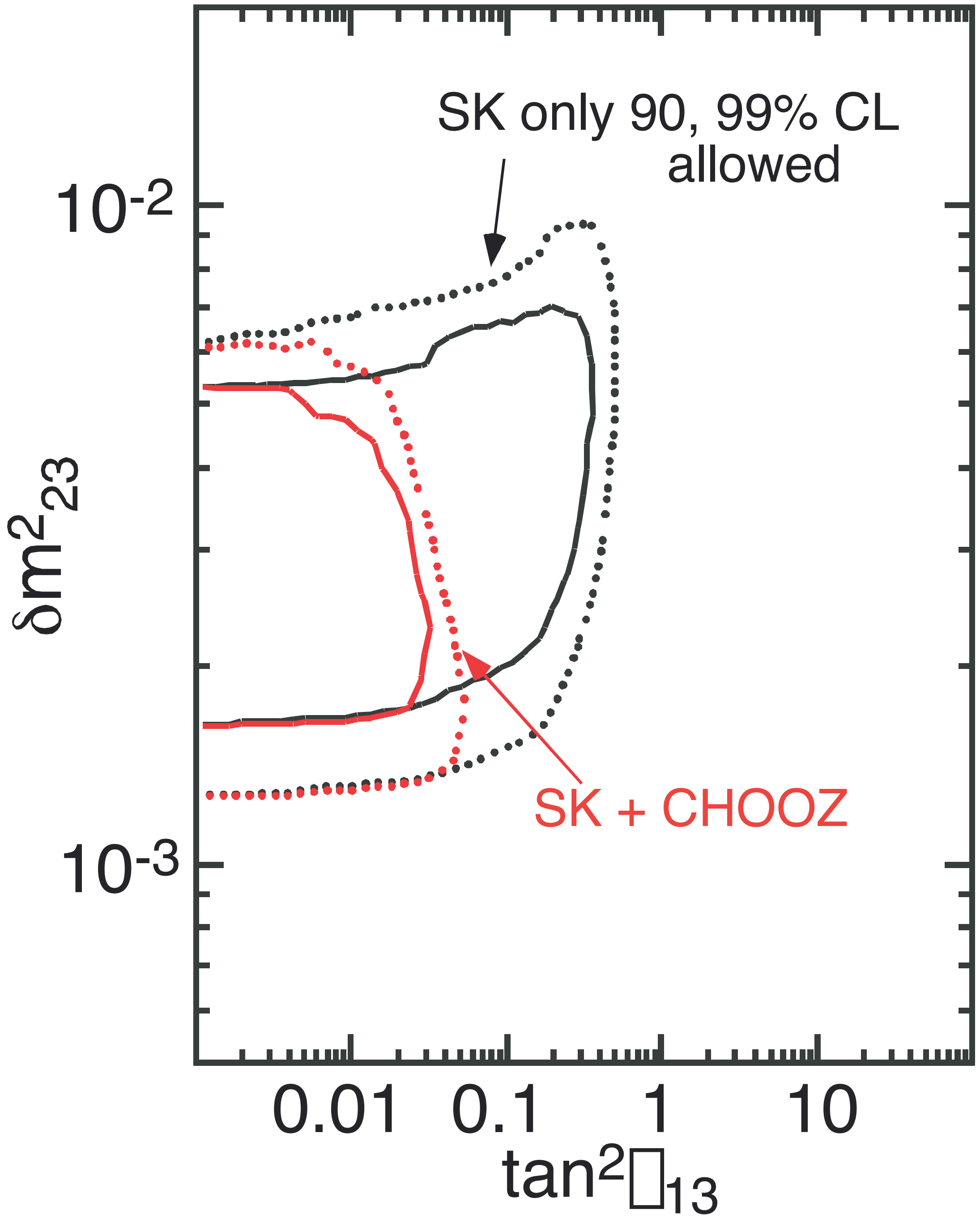
$P_{IH}(\bar{\nu}_e \to \bar{\nu}_e)$: c_{12}^2

Reactor measurement is free from them and is complementary.

Current best limit

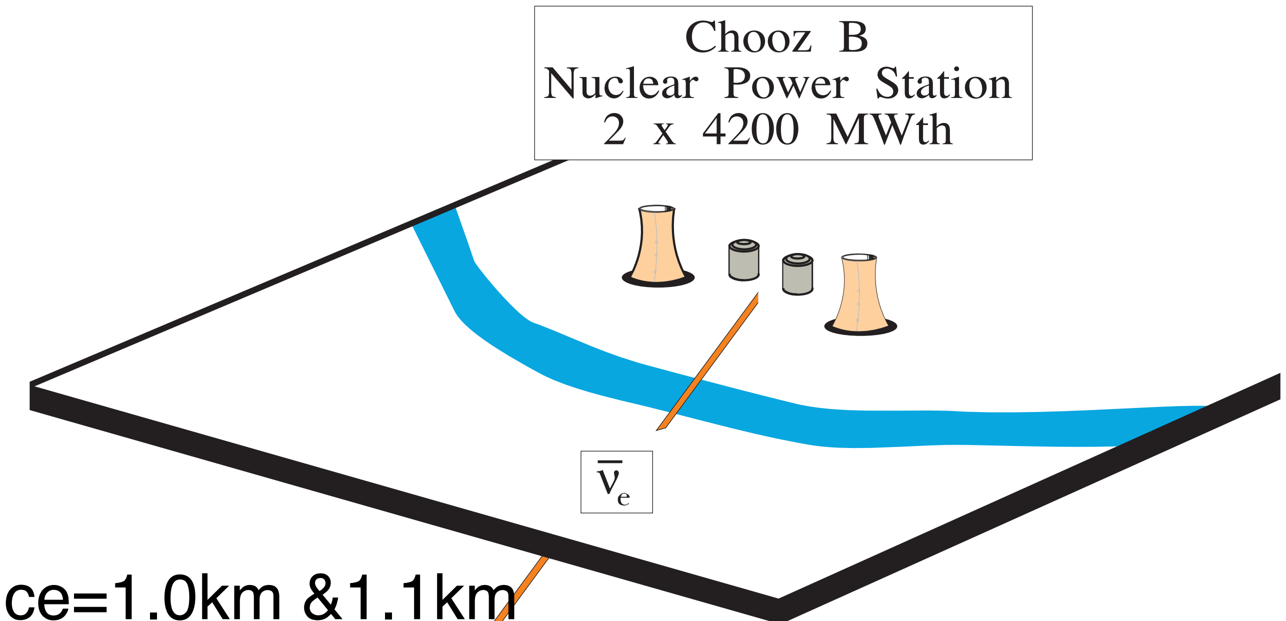
$$\theta_{13} < 10^\circ$$

M.Apollonio et al., Eur.Phys.J.C27(2003)331



In order to explore smaller mixing, what can we learn from CHOOZ and Palo Verde?

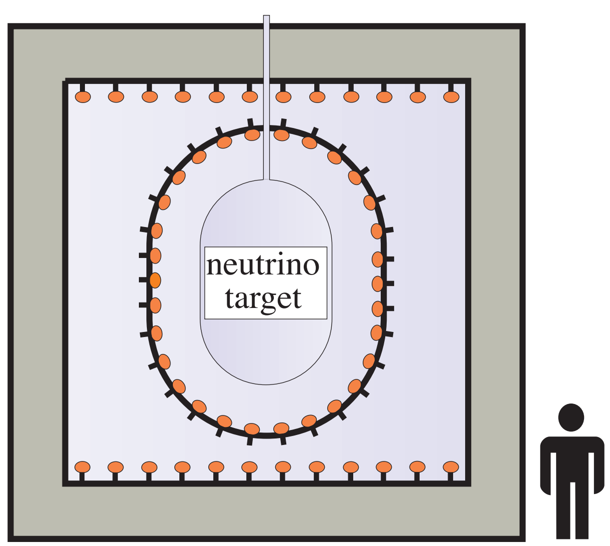
CHOOZ



distance=1.0km &1.1km

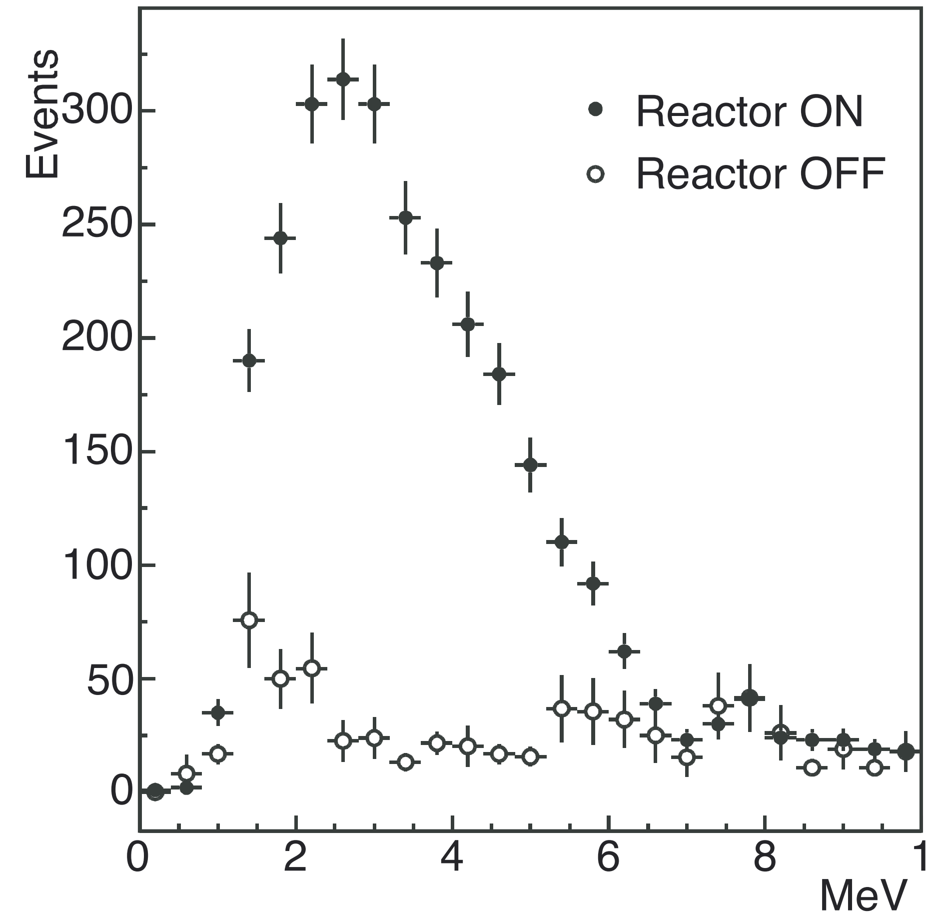
depth=300mwe

S/N ratio is 10~20.



Chooz Underground Neutrino Laboratory
Ardennes, France

5 ton LS with 0.09% Gd loading



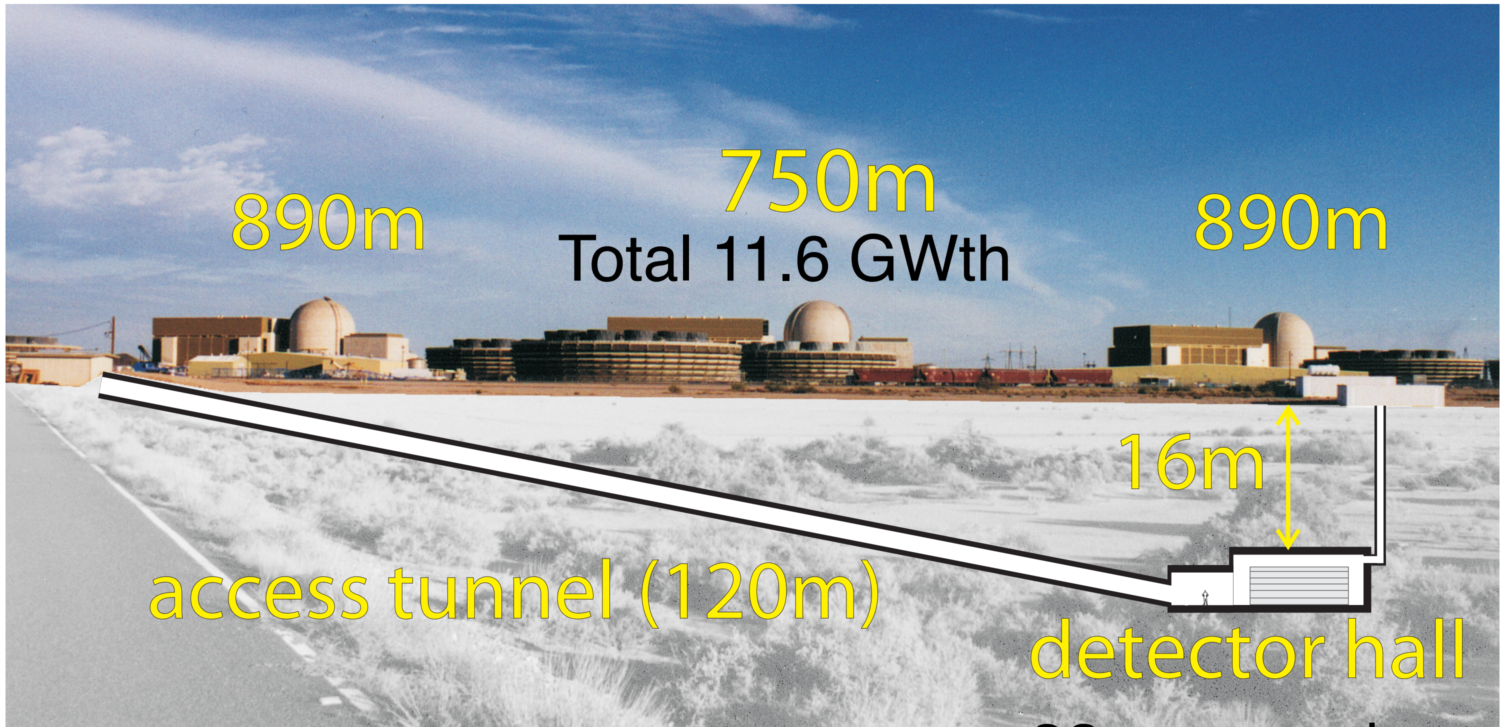
$$R = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$$

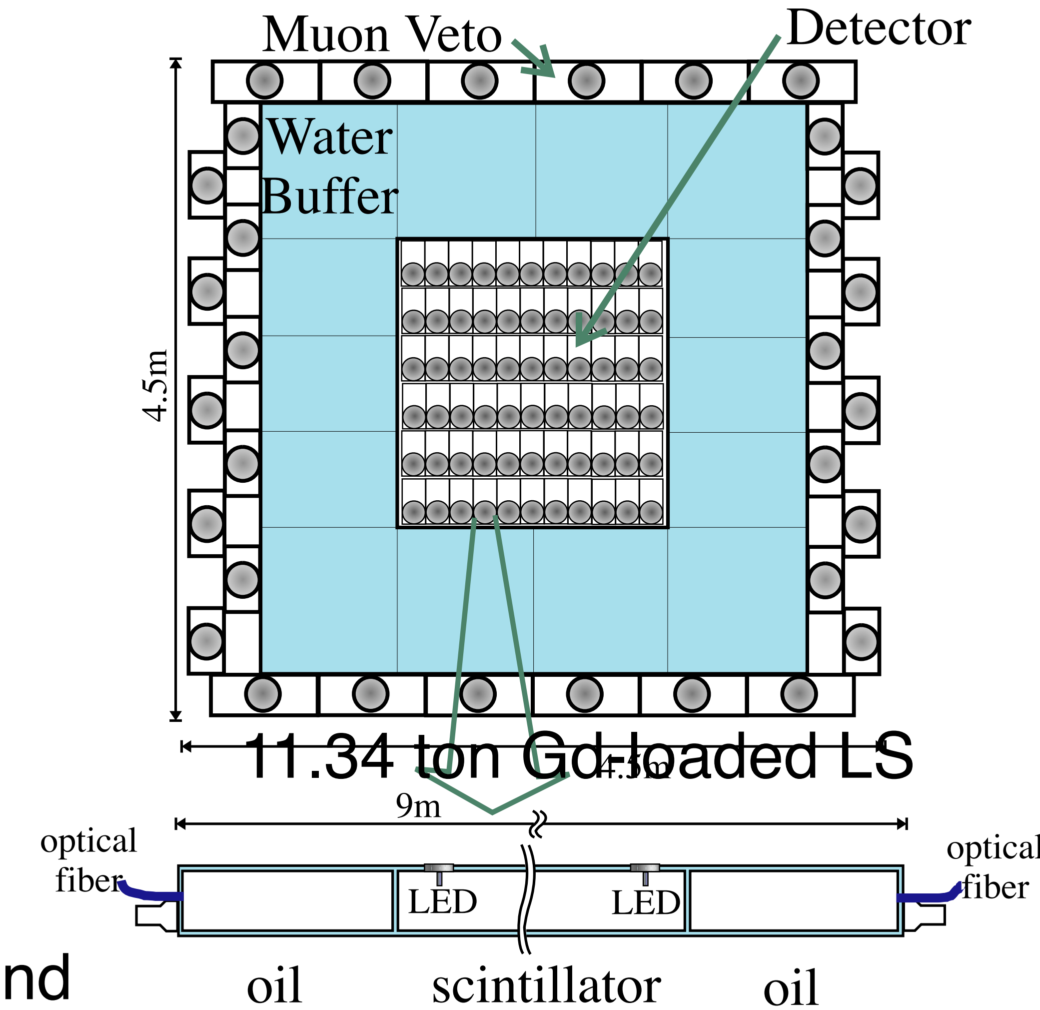
Systematic Errors

reactor cross section	1.9%
# of proton	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy release/fission	0.6%
Total	2.7%

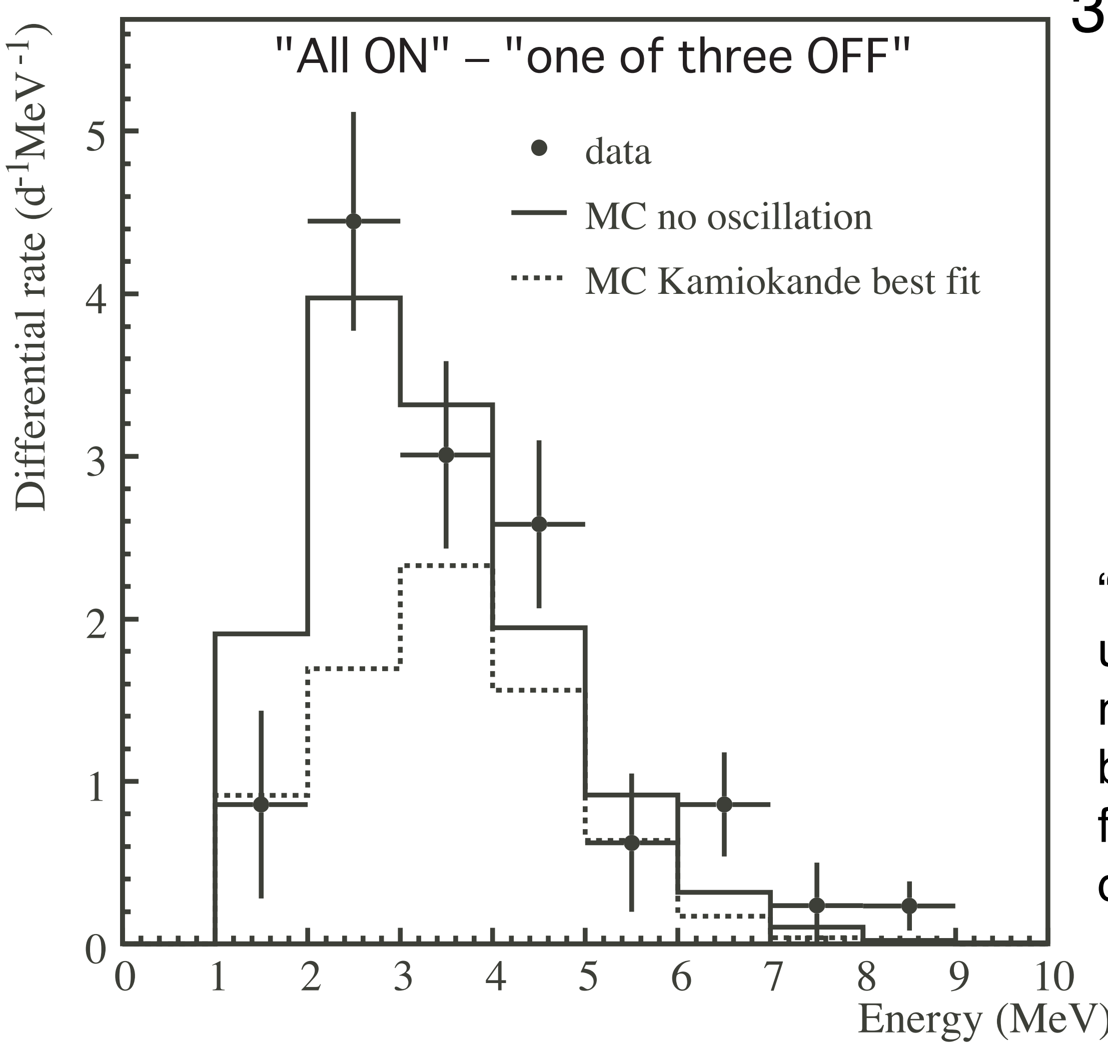
Near/Far detector system is necessary.

Palo Verde





32 mwe underground
S/N ratio is 0.5~1.



OR

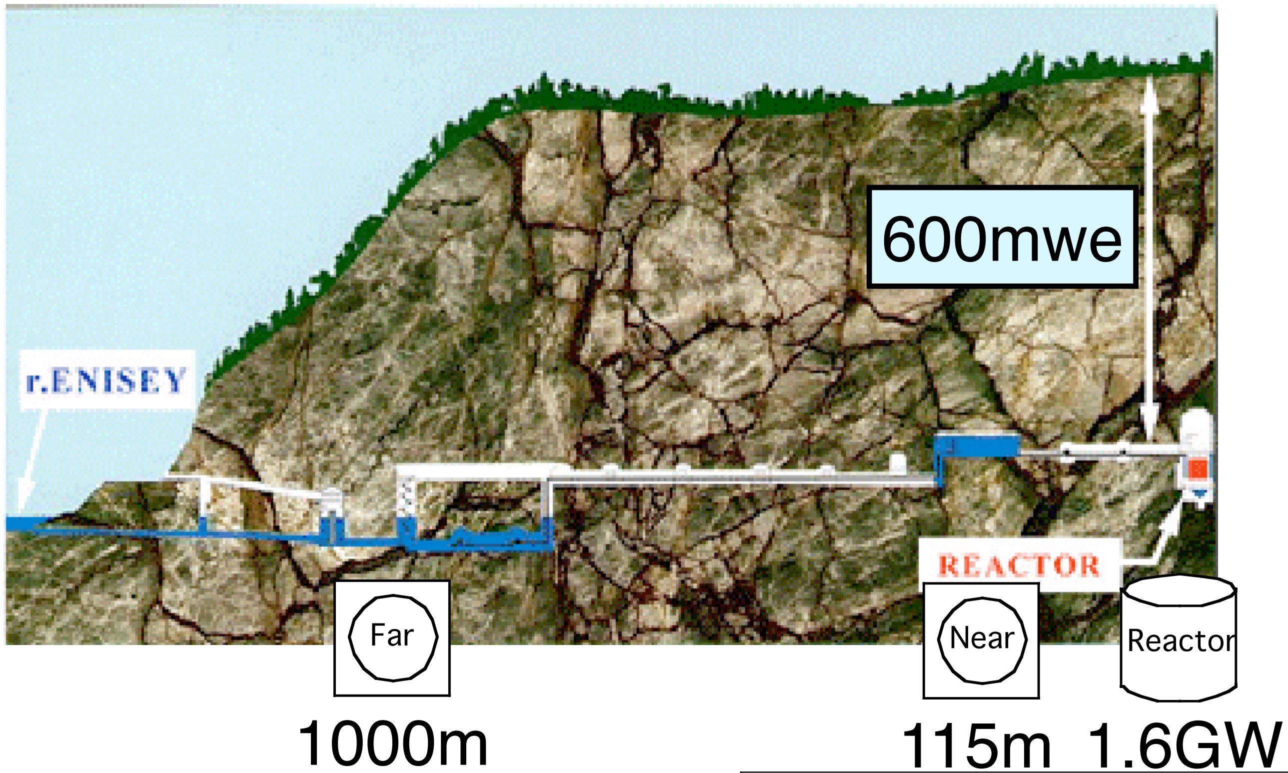
“swap” subtracts uncorrelated and two neutron backgrounds by swapping selection for prompt and delayed signals.

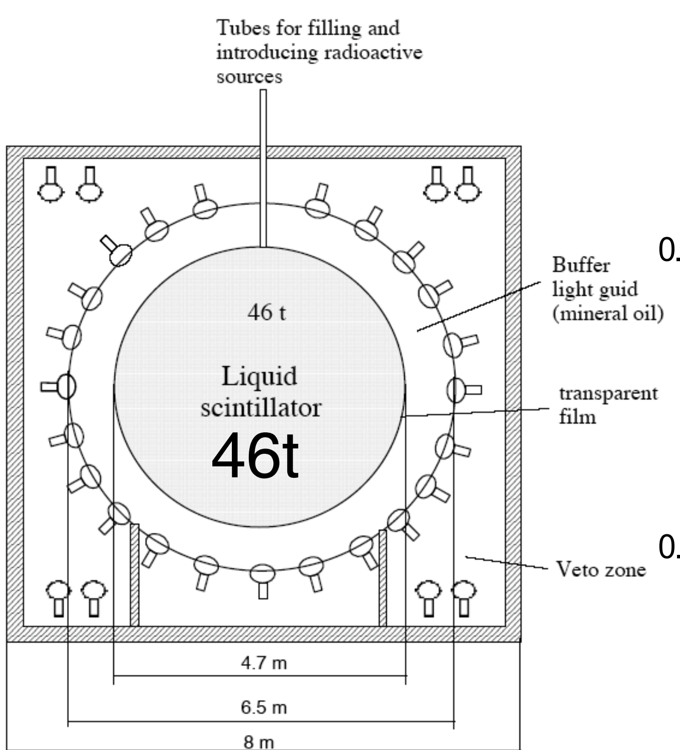
Systematic Errors

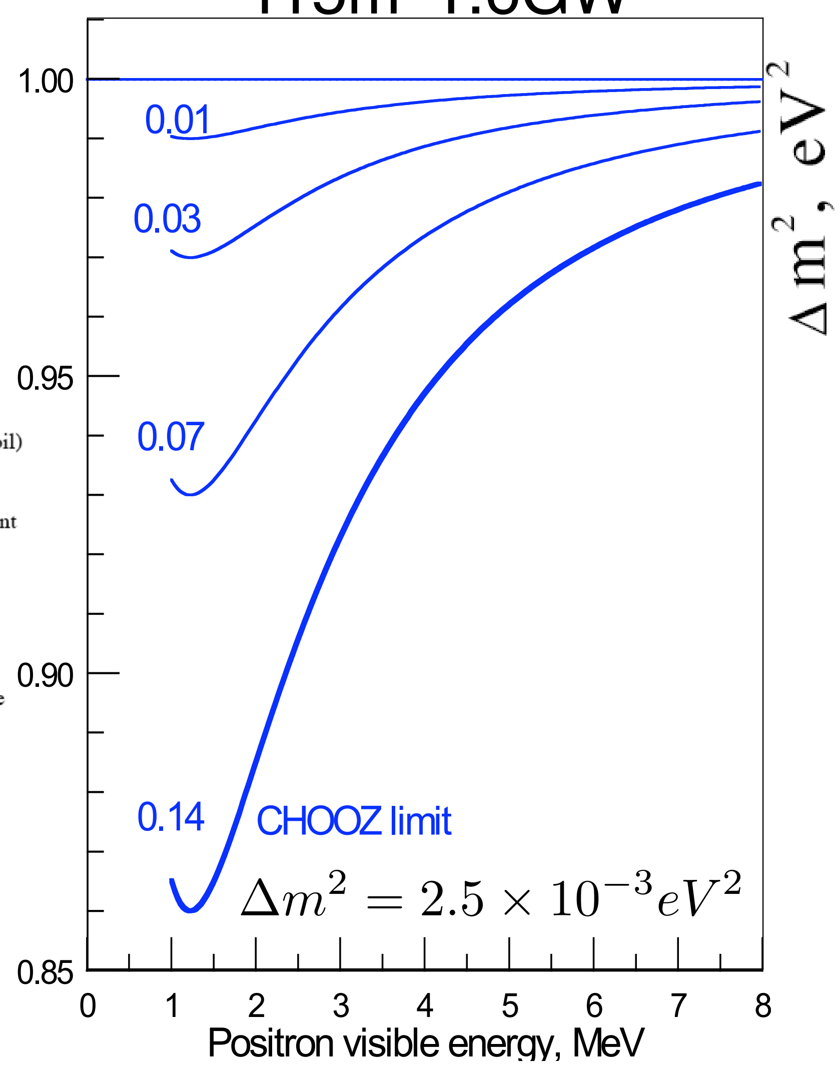
	Reac.Power	swap
e+ trig. eff.	2.0	2.0
n trig. eff.	2.1	2.1
flux prediction	2.1	2.1
selection cuts	4.5	2.1
b.g. variation	2.1	N/A
$(1-\epsilon_1)B_{pn}$	N/A	3.3
Total	6.1	5.3

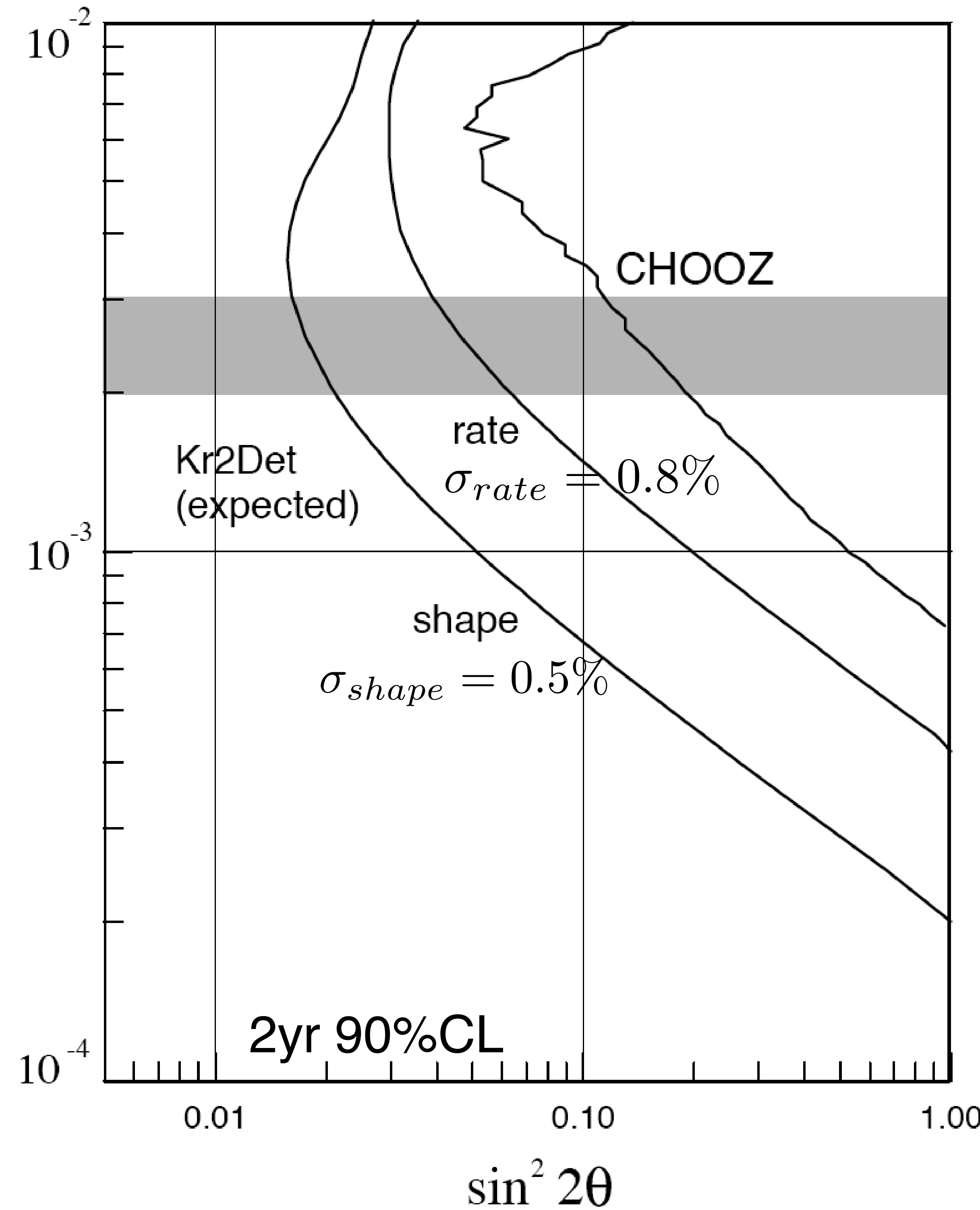
Be deep (>300 mwe)!

Krasnoyarsk (Kr2Det) hep-ex/0211070



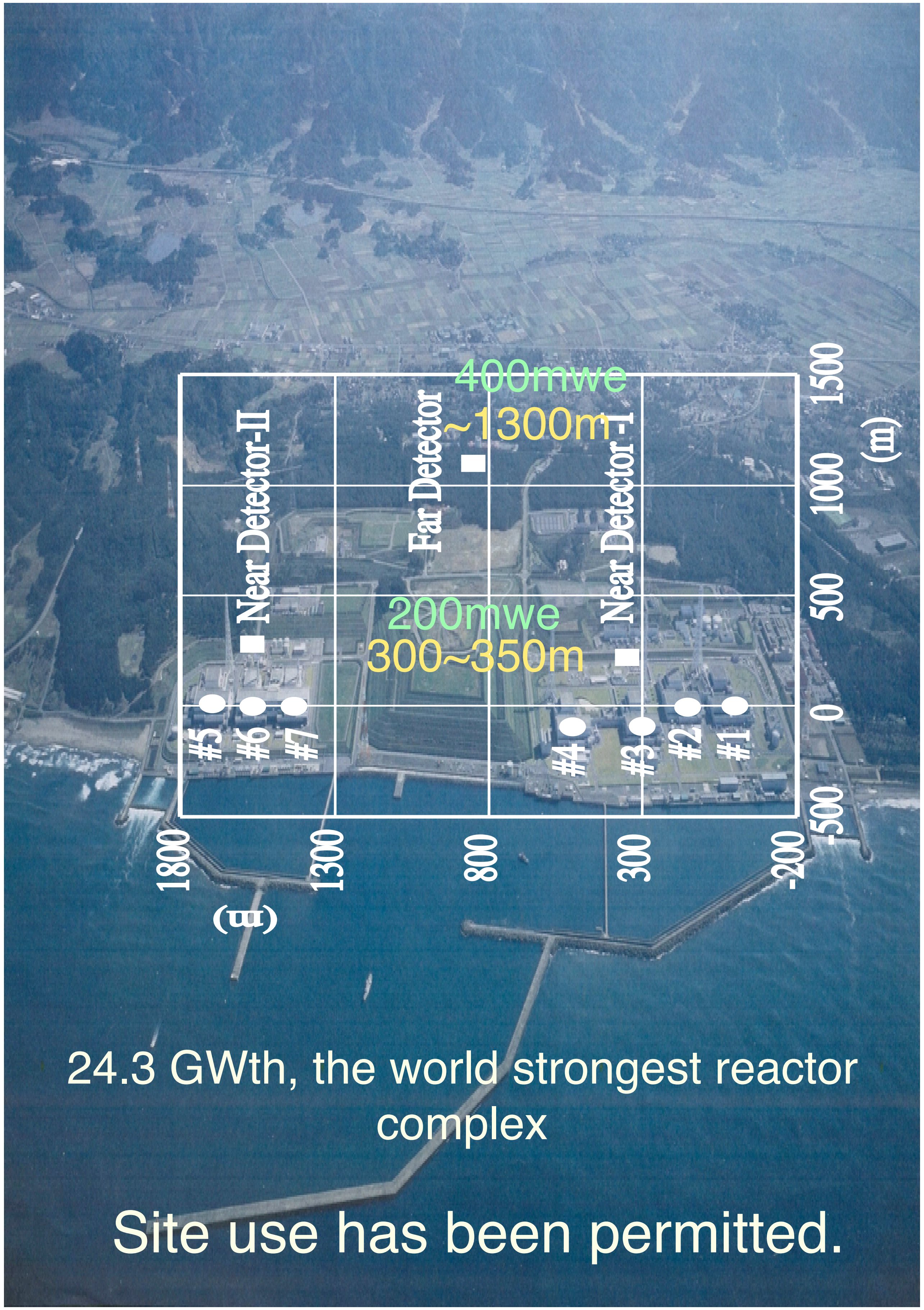


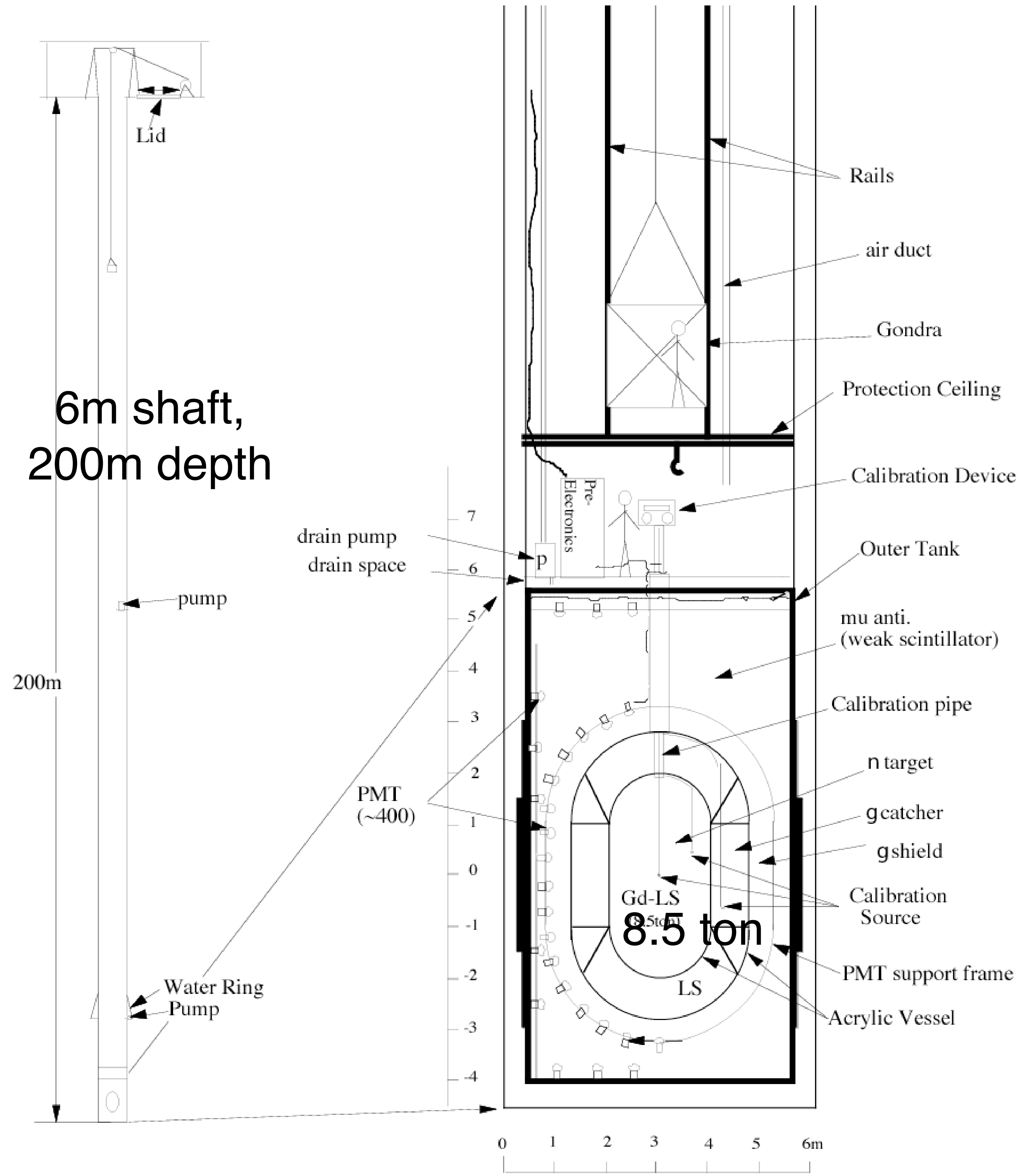




Kashiwazaki

hep-ex/0306029





Improvements from CHOOZ

Statistical error
2.8% ---> ~0.5% (2yr)
powerful reactor and longer run

Systematic error
2.7% ---> 0.5~1%
identical near/far detectors

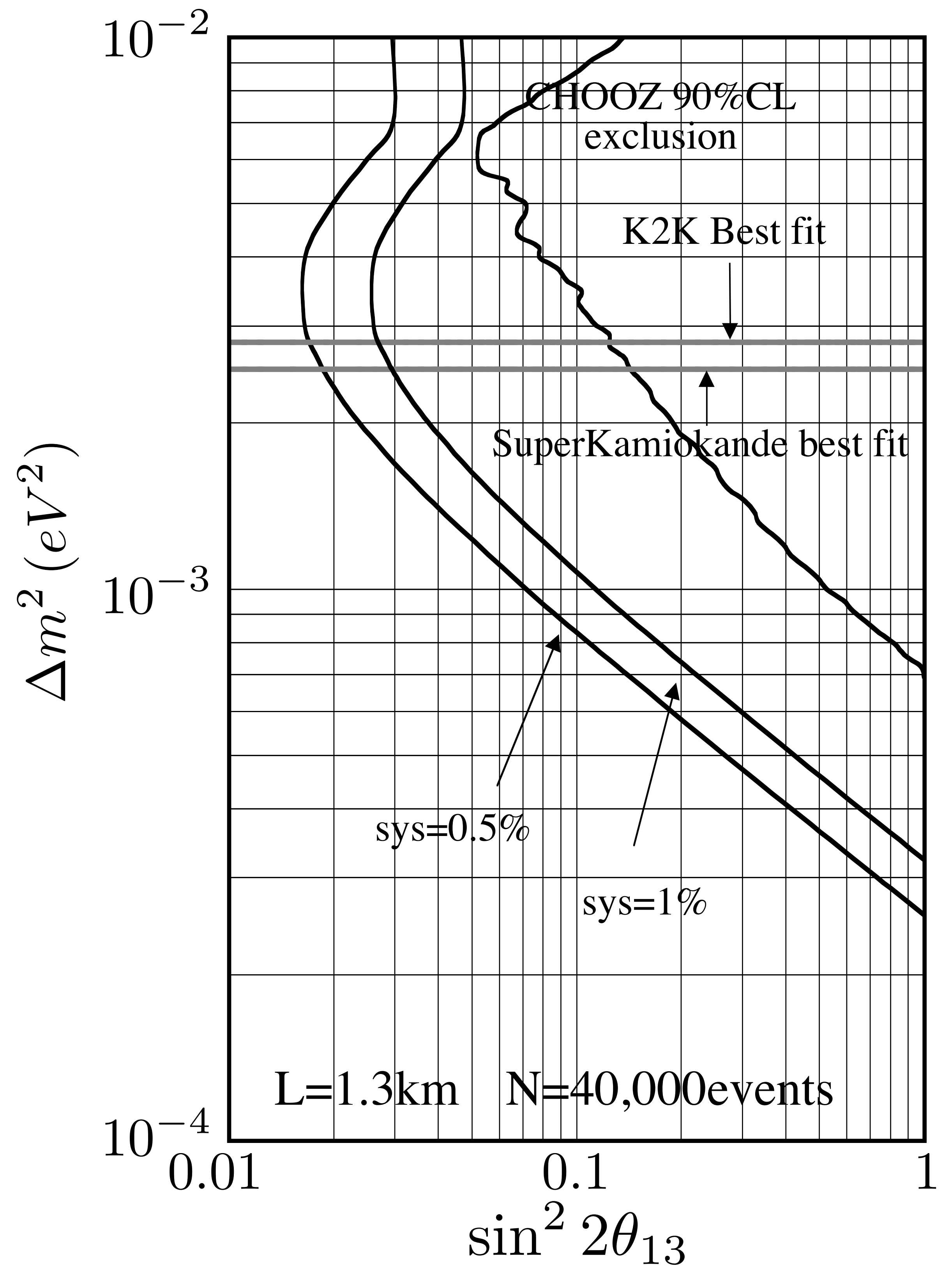
Background
N/S=6% ---> 1.6%
high signal/muon rate

Baseline
1 km ---> 1.3 km

$\sin^2 2\theta_{13}$ Sensitivity
0.15 ---> 0.016~0.025 (@2.6e-3)

Possible Schedule

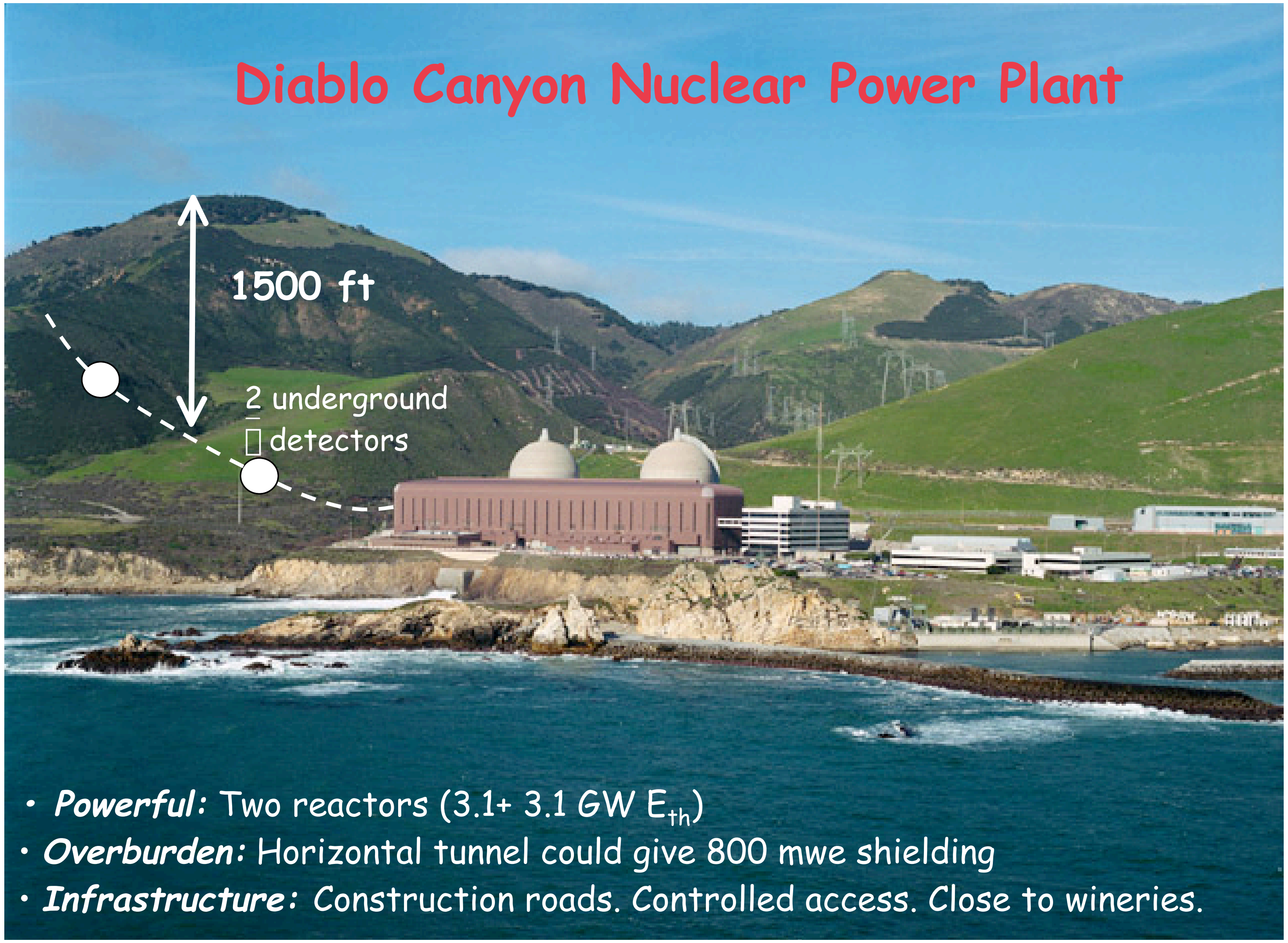
2003 R&D
2004 R&D
2005 Construction
2006 Construction
2007 Data taking start
2008 1st result (20k events)
2009 result (40k events)
2010
2011
2012 final result (100k events)
2013

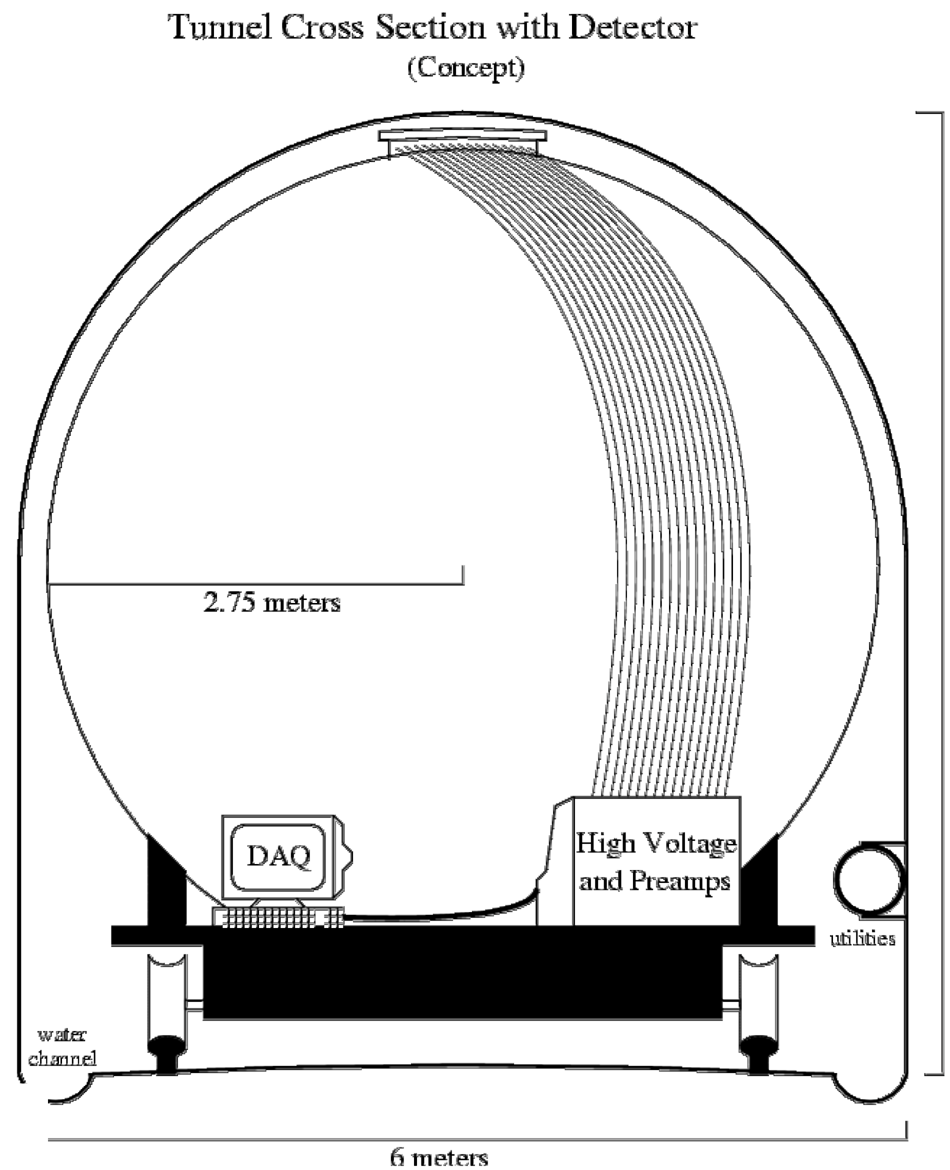


US activity

for example
http://home.fnal.gov/~link/theta_13/,
http://kmheeger.lbl.gov/theta13/

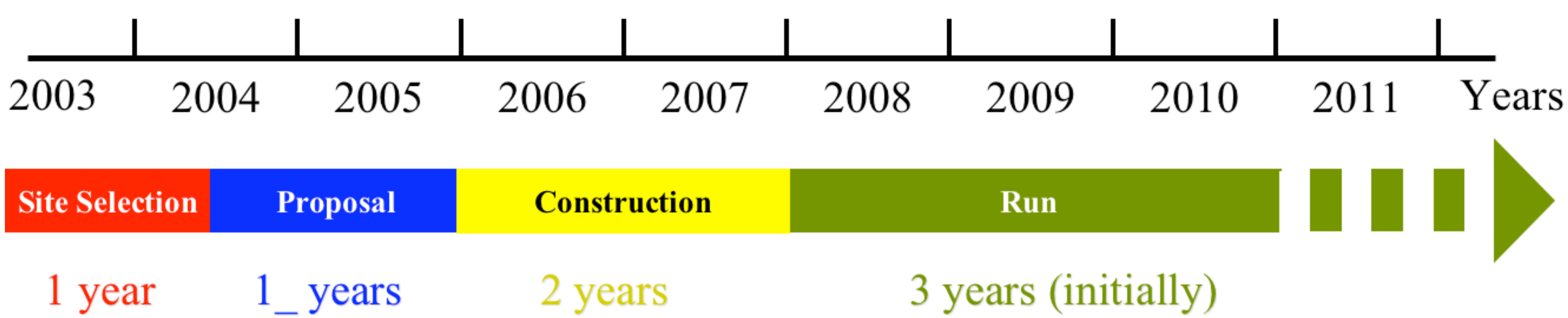
Site selection is under way. One candidate is





Movable far detector is investigated
to calibrate near/far detectors head to head.

Experiment Timeline



Activity in Europe

for example
http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre3.ppt

Site selection is under way.

	D_{far} (km)	P (GW_{th})	N_{events} per year	Target Volume Proposed	Target volume Kashiwasaki eq.	Free protons Kashiwasaki eq. (events per year)
CHOOZ	1.0	8.2	13925	5 tons	-	-
Kr2Det	1.1	1.6	2245	50 tons	54.3 tons	$4.13\ 10^{30}$ (24406)
Kashiwasaki	1.3	24.3	24418	5 tons	5.0 tons	$3.78\ 10^{29}$
Diabolo Canyon	1.2	6.2	73118	50 tons	16.7 tons	$1.27\ 10^{30}$ (24437)
Wolf Creek	1.2	3.1	36559	50 tons	33.4 tons	$2.54\ 10^{30}$ (24437)
Paluel	1.8	16.5	34698	20 tons	14.0 tons	$1.07\ 10^{30}$ (24207)
Cruas	1.8	11.7	24530	20 tons	20.0 tons	$1.50\ 10^{30}$ (24437)
Penly	1.8	8.3	17339	20 tons	28.1 tons	$2.14\ 10^{30}$ (24411)
Flamanville	1.8	8.3	17339	20 tons	28.1 tons	$2.14\ 10^{30}$ (24411)

HLMA 20-30 km 112 tons

hep-ex/0203013, hep-ph/0306017

if LMA2, $\Delta m^2_{31} < 2.5 \times 10^{-3}\, eV^2$ and $\sin^2\theta_{13} > 0.03$,
mass hierarchy can be determined with 125GWkTy data.

Search for Neutrino Magnetic Moment

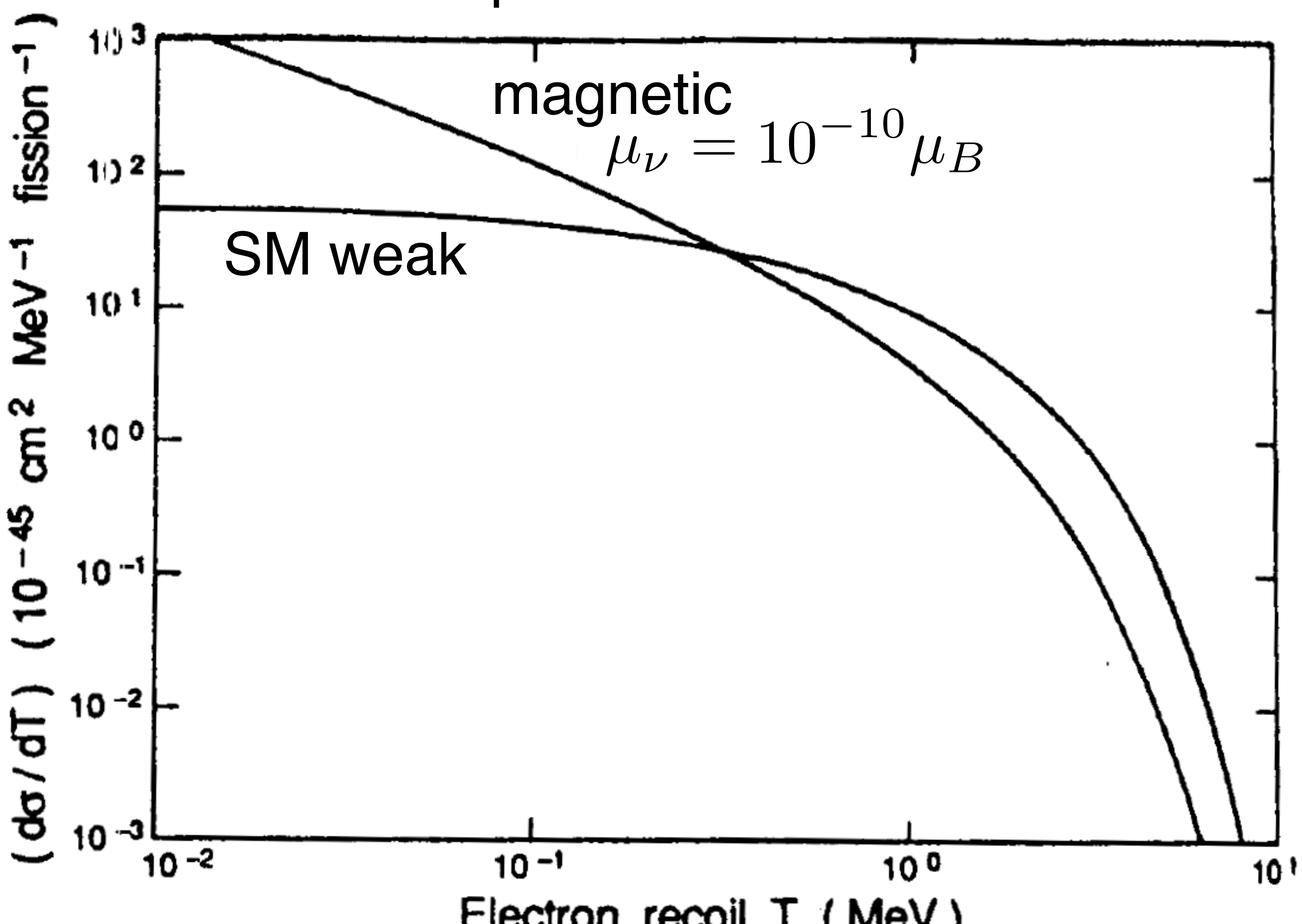
Detection Reaction

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right] + \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{1 - T/E_\nu}{T}$$

Standard Model Weak Interaction

Magnetic Moment Interaction

Calculated spectrum for a U235 reactor

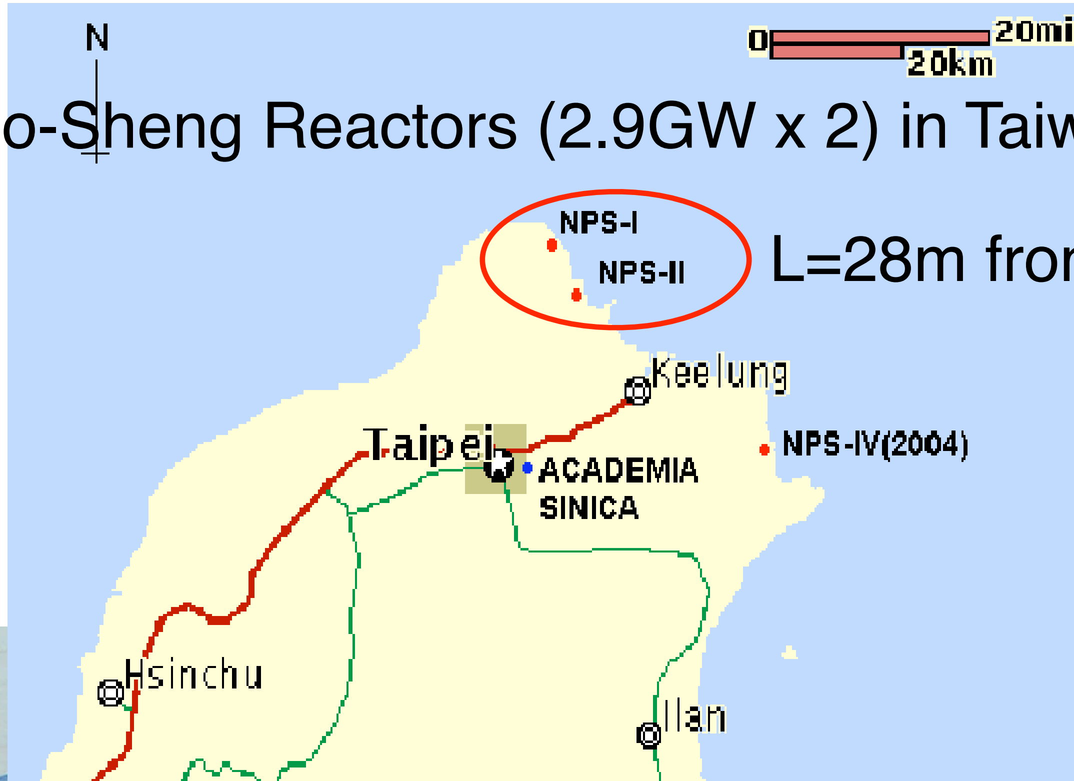


Look for excess in low recoil energy

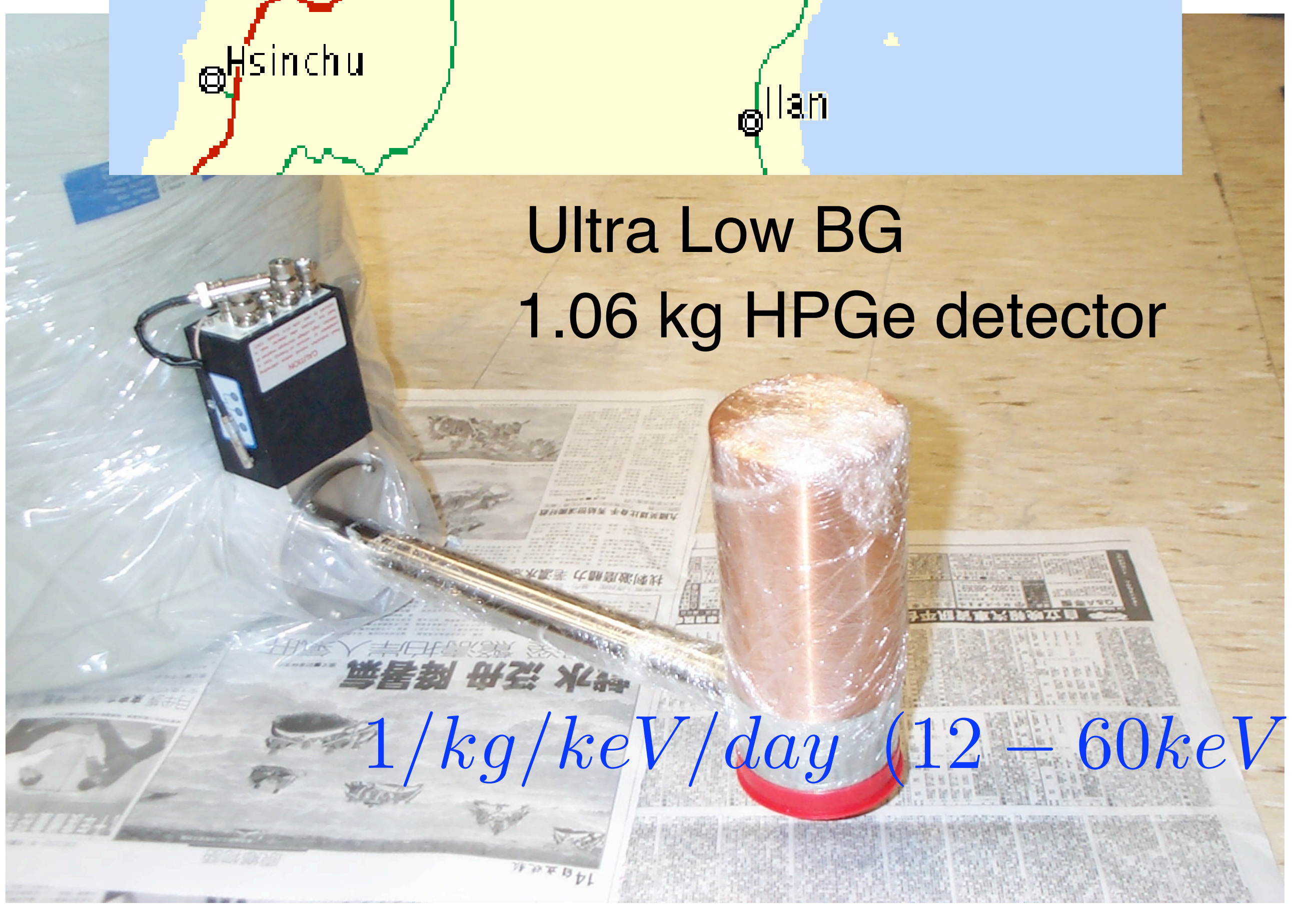
TEXONO experiment

Phys.Rev.Lett.90(2003)131802

Kuo-Sheng Reactors (2.9GW x 2) in Taiwan



L=28m from KPS-1

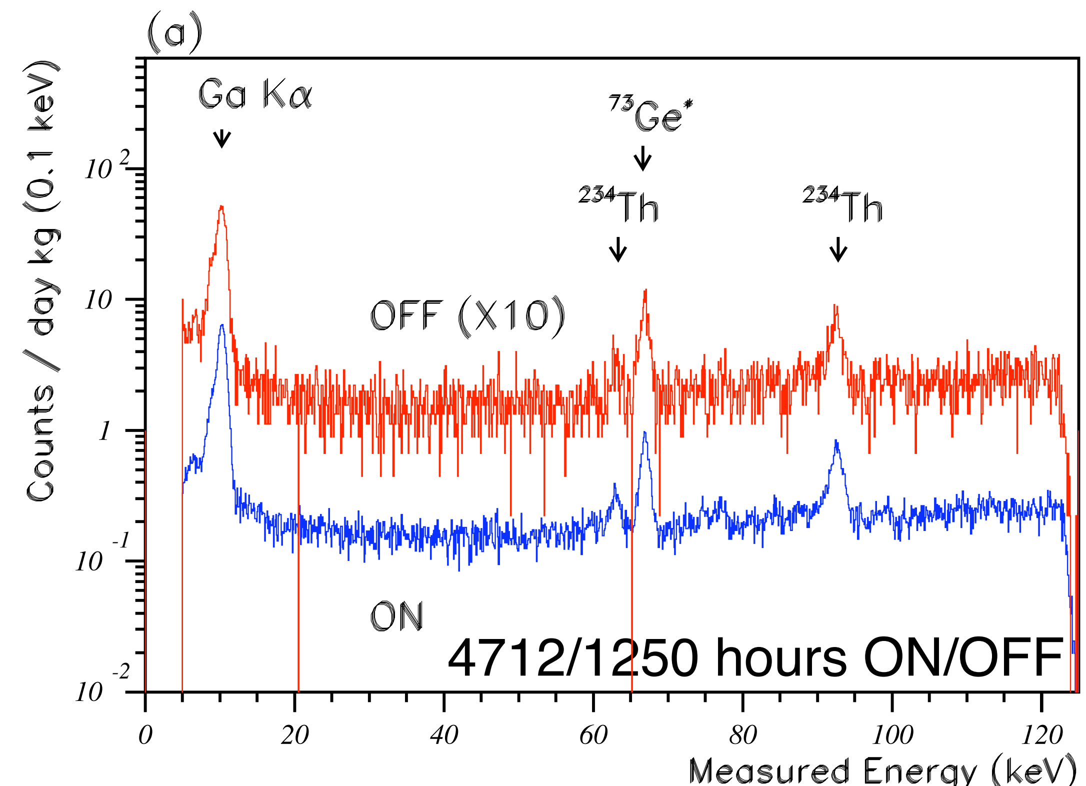


Ultra Low BG
1.06 kg HPGe detector

$1/kg/keV/day\ (12-60keV)$

with NaI(Tl), CsI(Tl) anti-compton detector

low threshold energy 5 keV

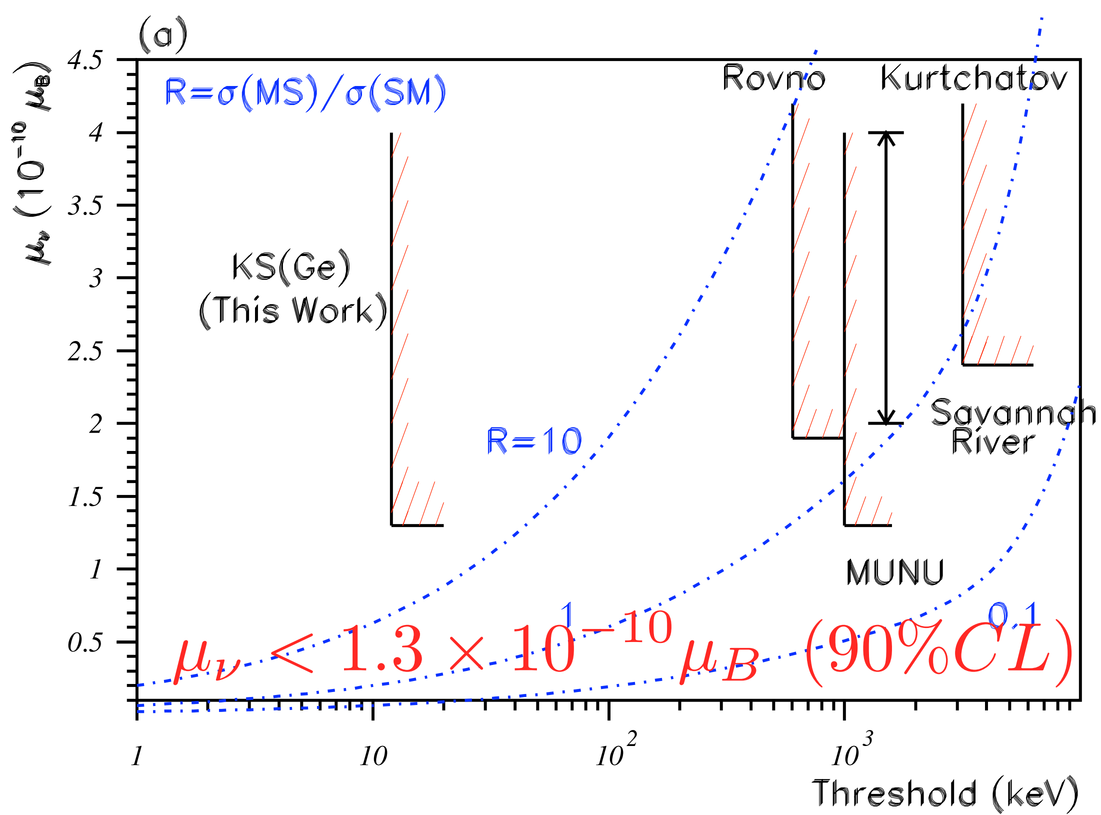


4712/1250 hours ON/OFF

fit ON spectra to

$$\phi_{OFF} + \phi_{SM} + \kappa^2 \phi_{MM}[10^{-10}\mu_B]$$

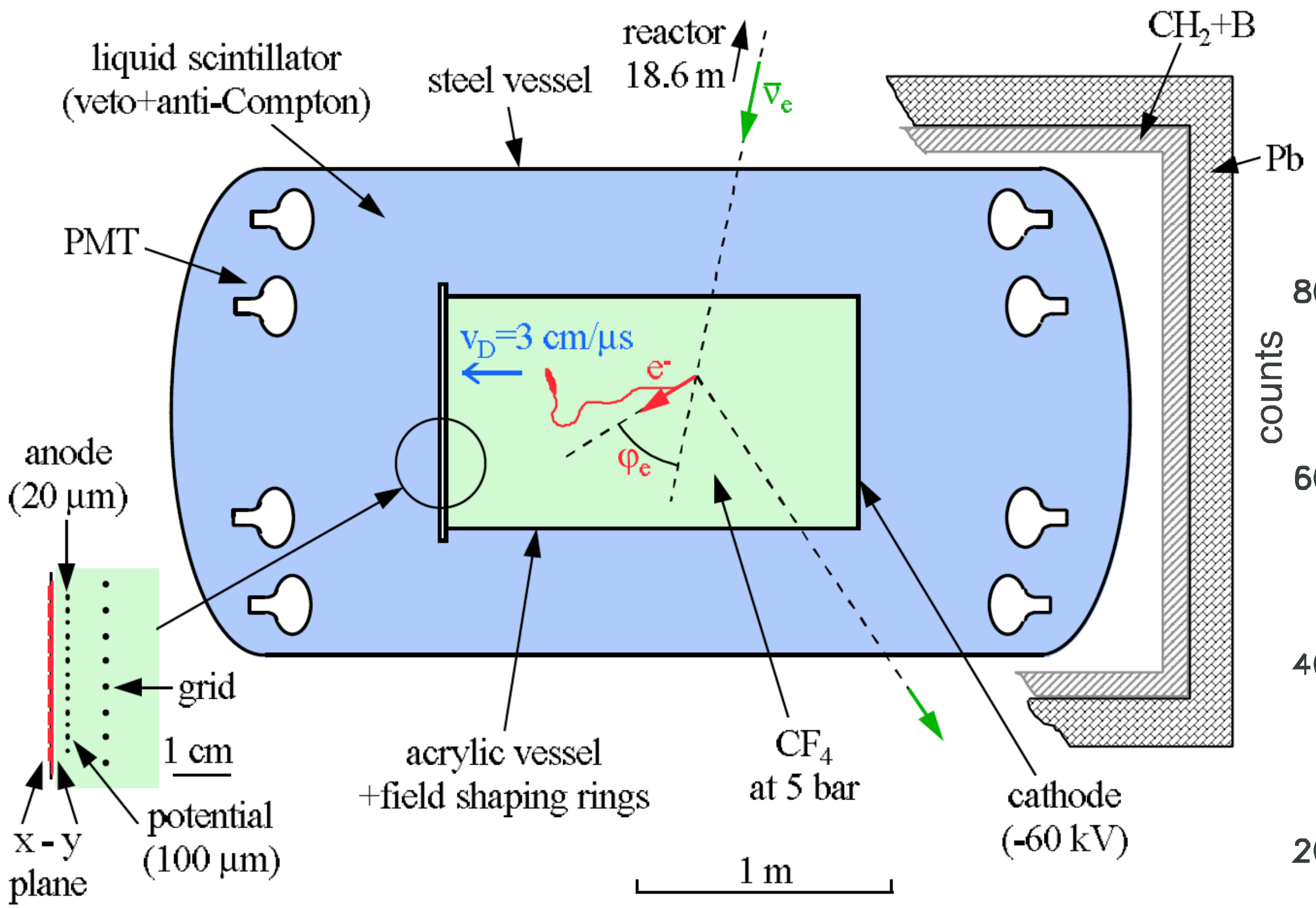
$$\kappa^2 = -0.4 \pm 1.3(\mathrm{stat}) \pm 0.4(\mathrm{sys})$$

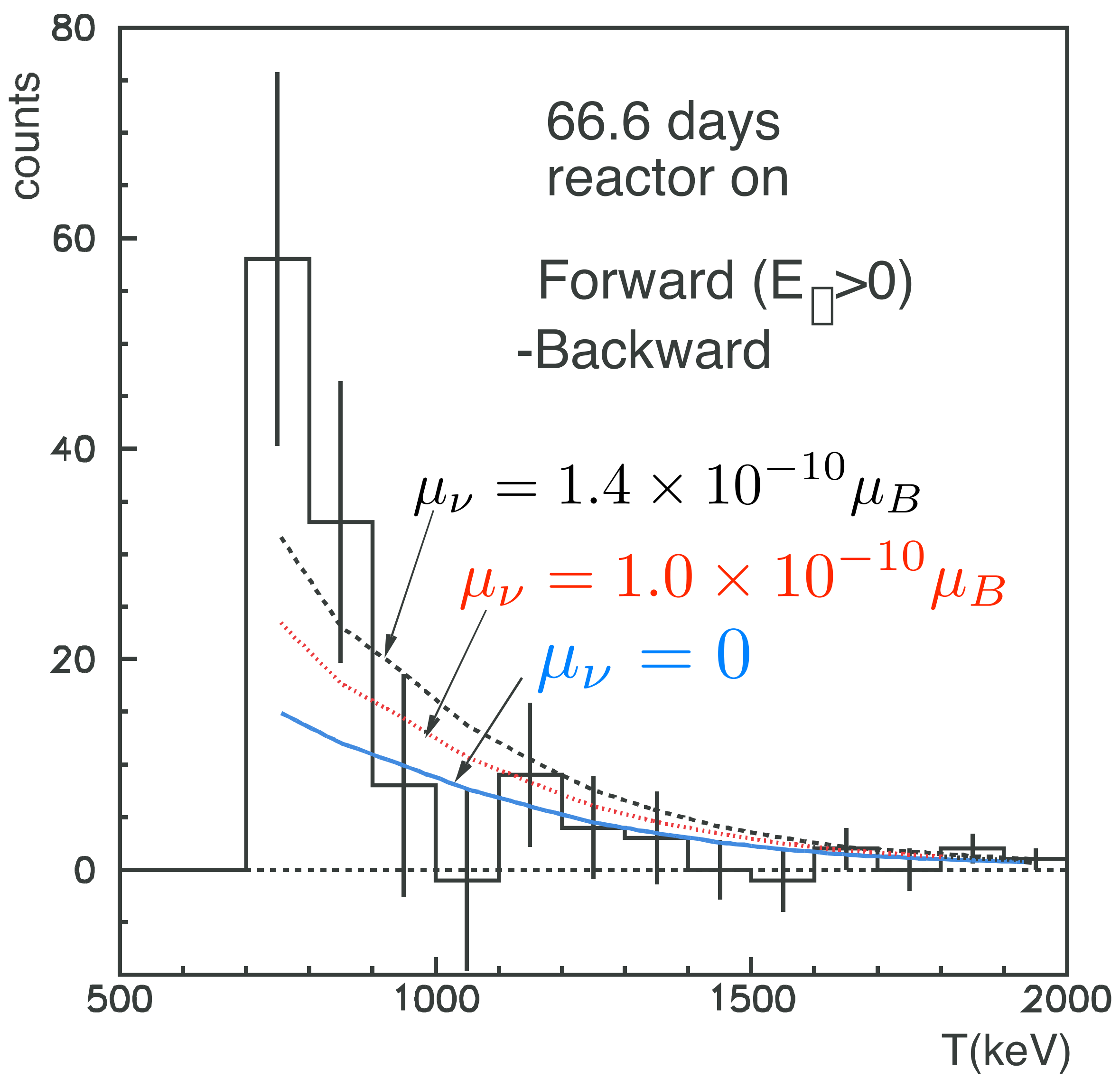


$\mu_\nu < 1.3 \times 10^{-10} \mu_B\ (90\%CL)$

MUNU experiment

Phys.Lett.B564(2003)190





2750 MWth Reactor in Bugey

CF4 TPC with target mass 11.4 kg

Analysis threshold 900 keV which corresponds to well understood neutrino energy, $E_\nu > 1.8\,MeV$.

$$\mu_\nu < 1.0 \times 10^{-10} \mu_B \ \ (90\% CL)$$

Summary

KamLAND has observed an evidence for reactor neutrino disappearance at ~ 180km distance with 99.95% confidence level.

$$R = 0.611 \pm 0.085 \pm 0.041$$

Assuming CPT invariance, only the LMA solution is compatible with the deficit.

Last unmeasured mixing angle can be explored with reactor experiments down to $\sin^2 2\theta_{13} \sim 0.02$ comparable to LBL sensitivity.
It is relatively cheaper and quicker, and is complementary to accelerator experiments.
Various possibilities are discussed and international collaboration are being formed.

Direct searches for neutrino magnetic moment are extensively performed.
The best limit, so far, is $\mu_\nu < 1.0 \times 10^{-10} \mu_B \ (90\% CL)$.

Thank you.