First Results from KamLAND

Evidence for Reactor Anti-neutrino Disappearance

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The KamLAND Collaboration

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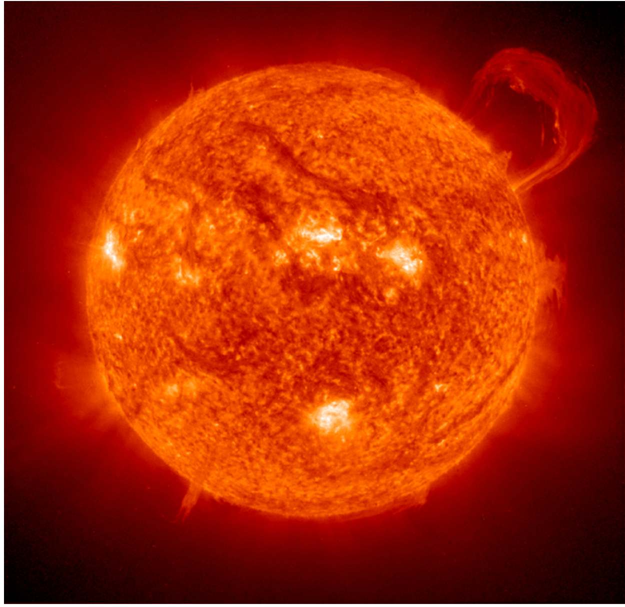
ν_e are abundant by-products of nuclear fusion in the sun



$$p + p \rightarrow {}^2H + e^+ + \nu_e + 0.42 MeV$$

"pp" 99.75%

$$p + e^- + p \rightarrow {}^2H + \nu_e + 1.44 MeV$$

"pep" 0.25%

$$^2H + p \rightarrow {}^3He + \gamma + 5.49\ MeV$$

86%

$$^3He + {}^3He \rightarrow \alpha + 2p + 12.86 MeV$$

14%

$$^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59 MeV$$

"hep" 2.4*10-5

$$^3He + p \rightarrow \alpha + e^+ + \nu_e$$

"7Be" 99.89%

$$^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e + 0.8617 MeV$$

$$^7Li + p \rightarrow \alpha + \alpha + 17.35 MeV$$

0.11%

$$^7Be + p \rightarrow {}^8B + \gamma + 0.14 MeV$$

"8B" 0.11%

$$^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6 MeV$$

$$^8Be \rightarrow \alpha + \alpha + 3 MeV$$

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What is the mass of the neutrino?

- Two electron volts.
- Nobody knows.
- Zero.

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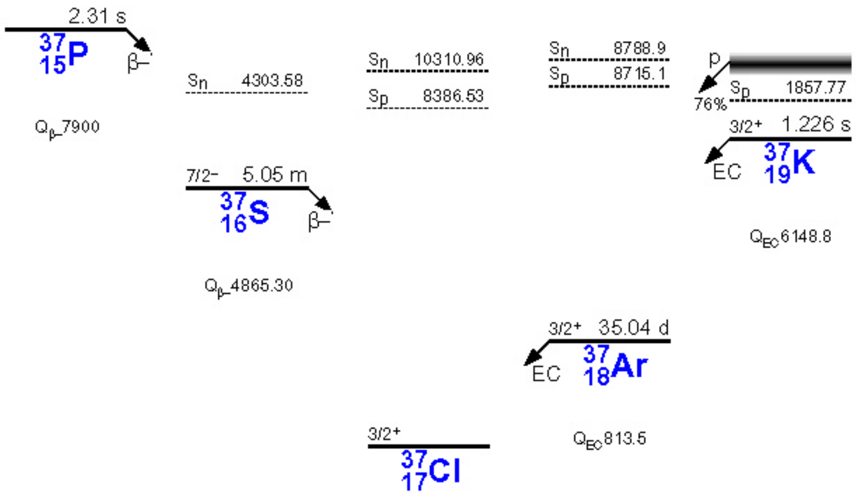


Homestake Mine, Lead SD
1400 m underground

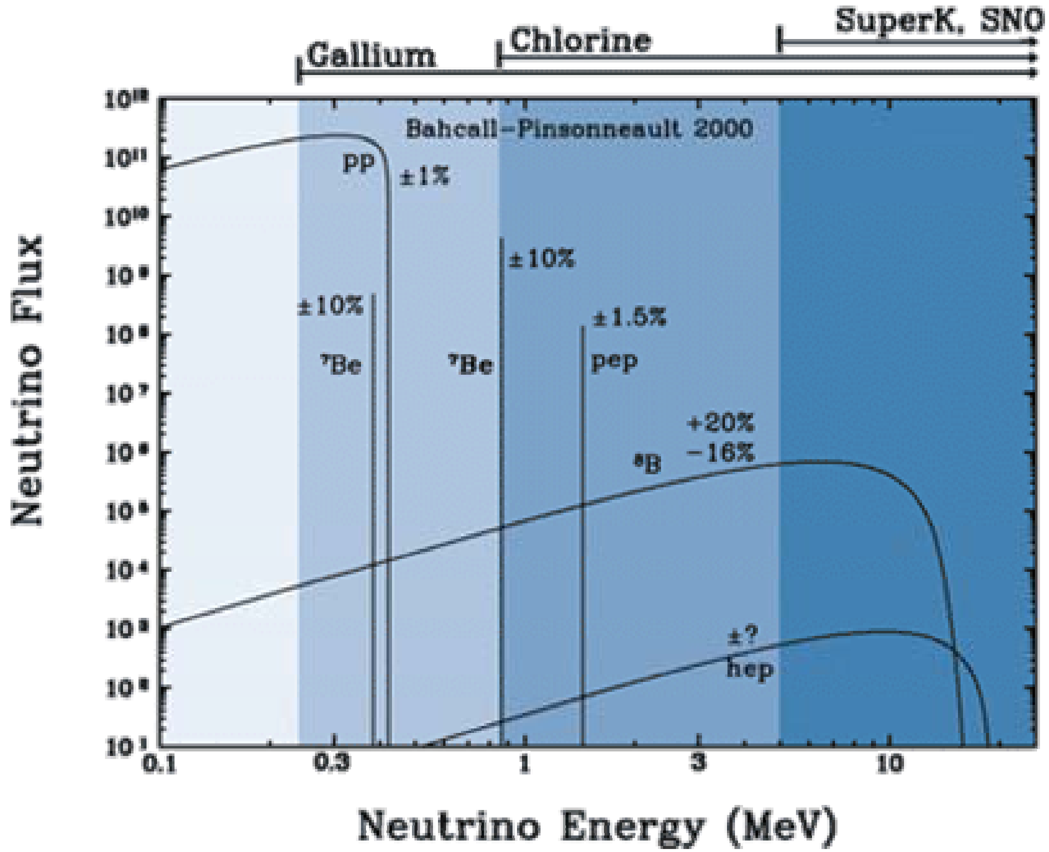
615 tons of perchloroethilene (C_2Cl_4)

$2.2*10^{30}$ atoms of ^{37}Cl
^{36}Ar or ^{38}Ar added to the fluid as carrier gas

Data taken continuously since 1967 (!)

3 types of experiments detecting solar neutrinos

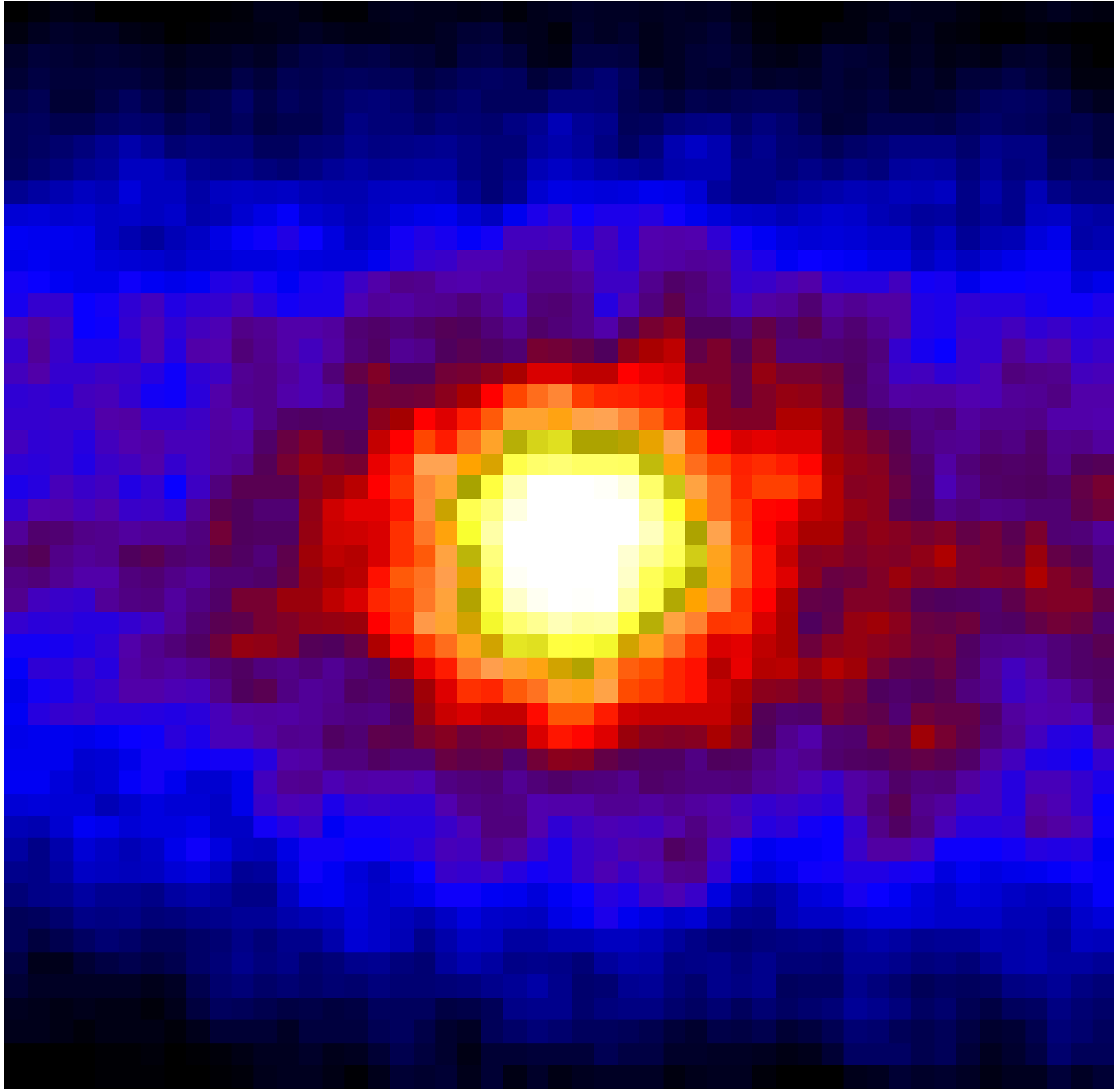
- Chlorine: $^{37}Cl+\nu_e={}^{37}Ar+e^-$
  1 exp running >30 yrs (US)
- Gallium: $^{71}Ga+\nu_e={}^{71}Ge+e^-$
  3 exp (Russia, Italy)
- Cerenkov: $e^-+\nu_e=e^-+\nu_e$
  3 exp (Japan, Canada)



Conclusion:

- We detect ns ! : nuclear
fusion powers the sun

- The sun is still shining (this is not trivial: it takes ~ 1Myr for a photon to emerge from the sun)

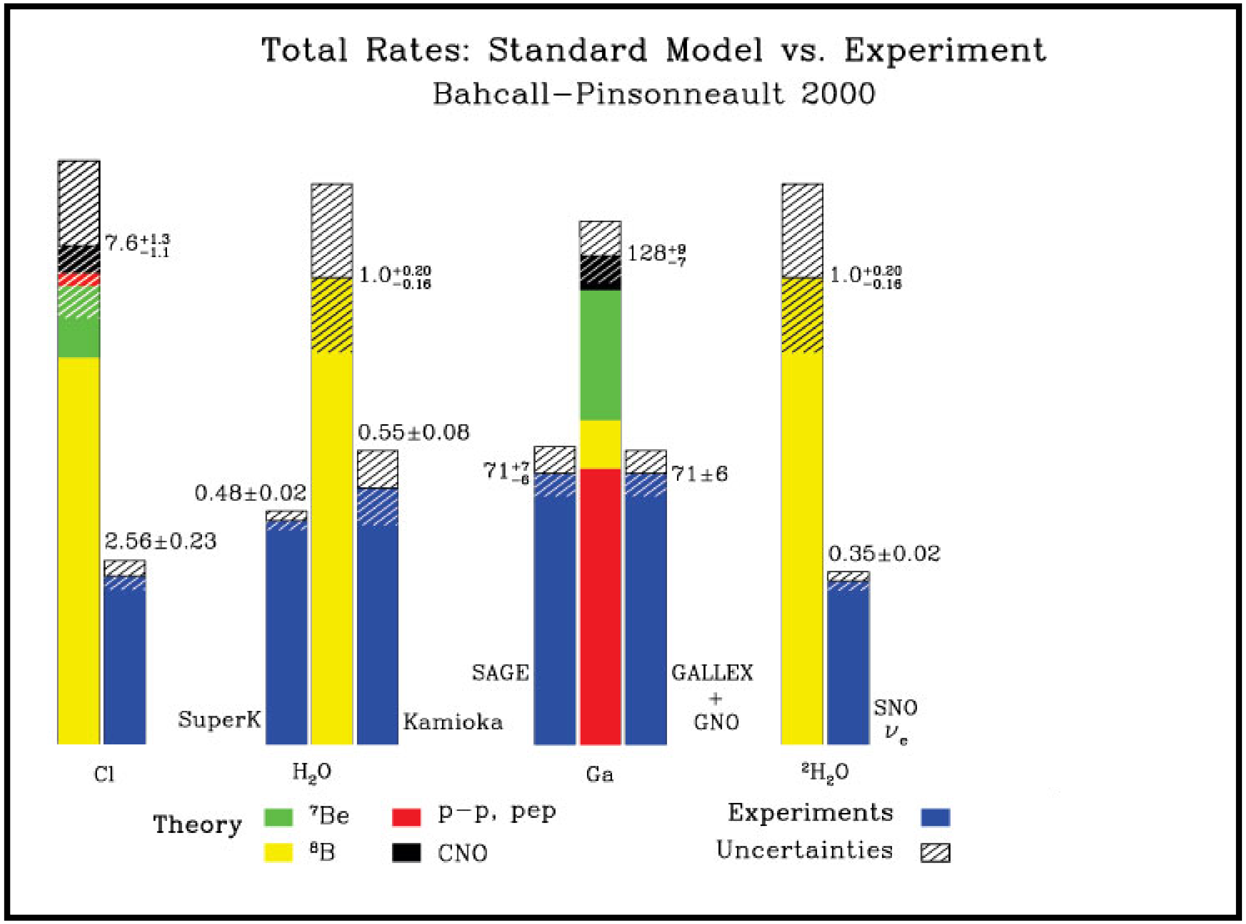


The sun imaged with neutrinos
(courtesy R.Svoboda and the SK collab.)

Conclusion':

We do not see enough νs !

- *do we understand the sun well enough ?*
- ***are νs playing tricks ?***



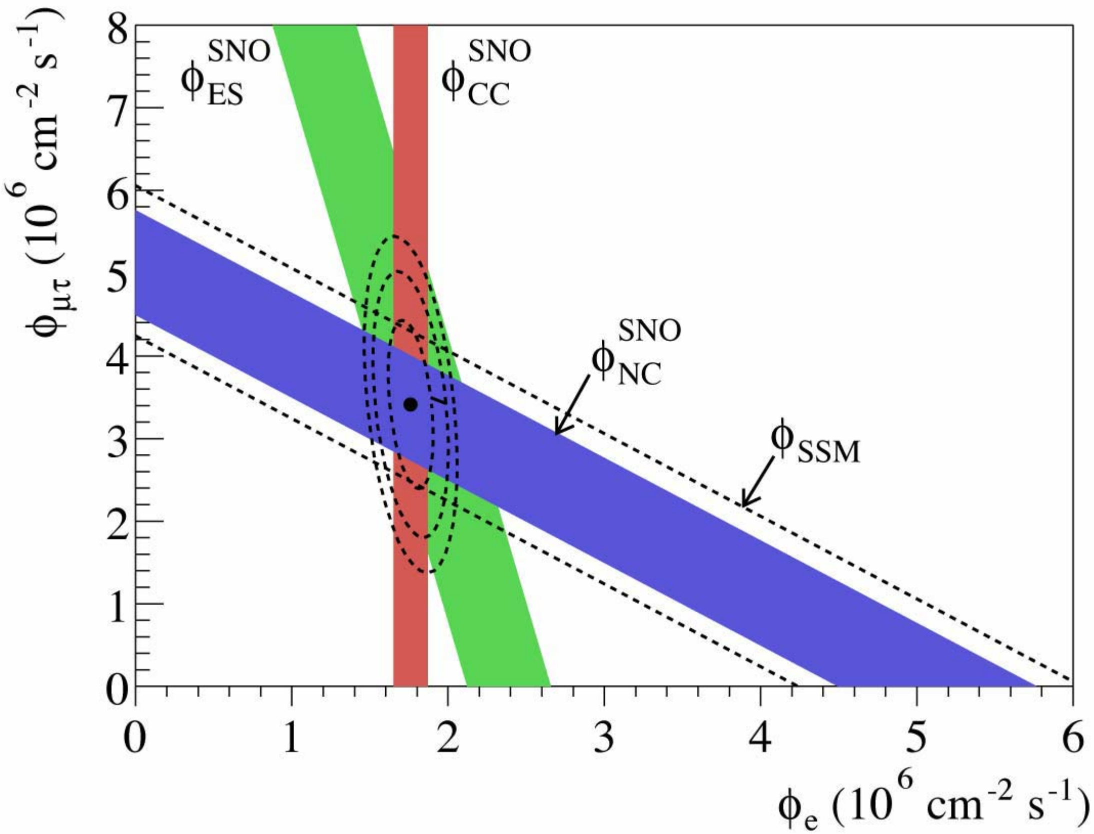
"It starts to be really interesting ! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately it will not be easy to demonstrate this, even if nature works this way…" B.Pontecorvo, 1972

SNO: 1 kton of D_2O

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

sensitive to a ν_e, ν_x mix



$$\nu_e + {}^2H \rightarrow \nu_x + p + n$$

equally sensitive to all neutrinos

$$\nu_e + {}^2H \rightarrow p + p + e^-$$

sensitive to ν_e only

If m_ν is non-zero then leptons could behave like quarks

➡ the weak interaction eigenstate $\left|\nu_j\right\rangle$ is a superposition of mass eigenstates $\left|\nu_j\right\rangle = \sum_j U_{jl}\left|\nu_l\right\rangle$

U_{jl} is a 3×3 unitary matrix (like the CKM matrix for quarks)

What propagates is the mass eigenstate $\left|\nu_l\right\rangle$

Flight path

$$\left|\nu_l(t)\right\rangle = e^{-i(E_i t - p_i L)}\left|\nu_l(0)\right\rangle \cong e^{-i(m_j^2/2E)L}\left|\nu_l(0)\right\rangle$$

What is produced and detected is $\left|\nu_j\right\rangle$

Assuming

$E_i = E >> m_i \qquad p_i >> m_i$

$$\left|\nu_j\right\rangle \cong \sum_l U_{lj} e^{-i(m_l^2/2E)L} \left|\nu_l\right\rangle \cong \sum_{j'} \sum_l U_{lj} e^{-i(m_l^2/2E)L} U_{j'l}^* \left|\nu_{j'}\right\rangle$$

…that is neutrinos "acquire" components from other flavors as they propagate

We can define a "transition probability"

$$P(\nu_{j'} \to \nu_j, L) = \left| \sum_l U_{lj} U_{j'l}^* e^{-i(m_l^2/2E)L} \right|^2$$

…a periodic function of the baseline L

For 2 flavors this simplifies:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Only one mixing parameter θ

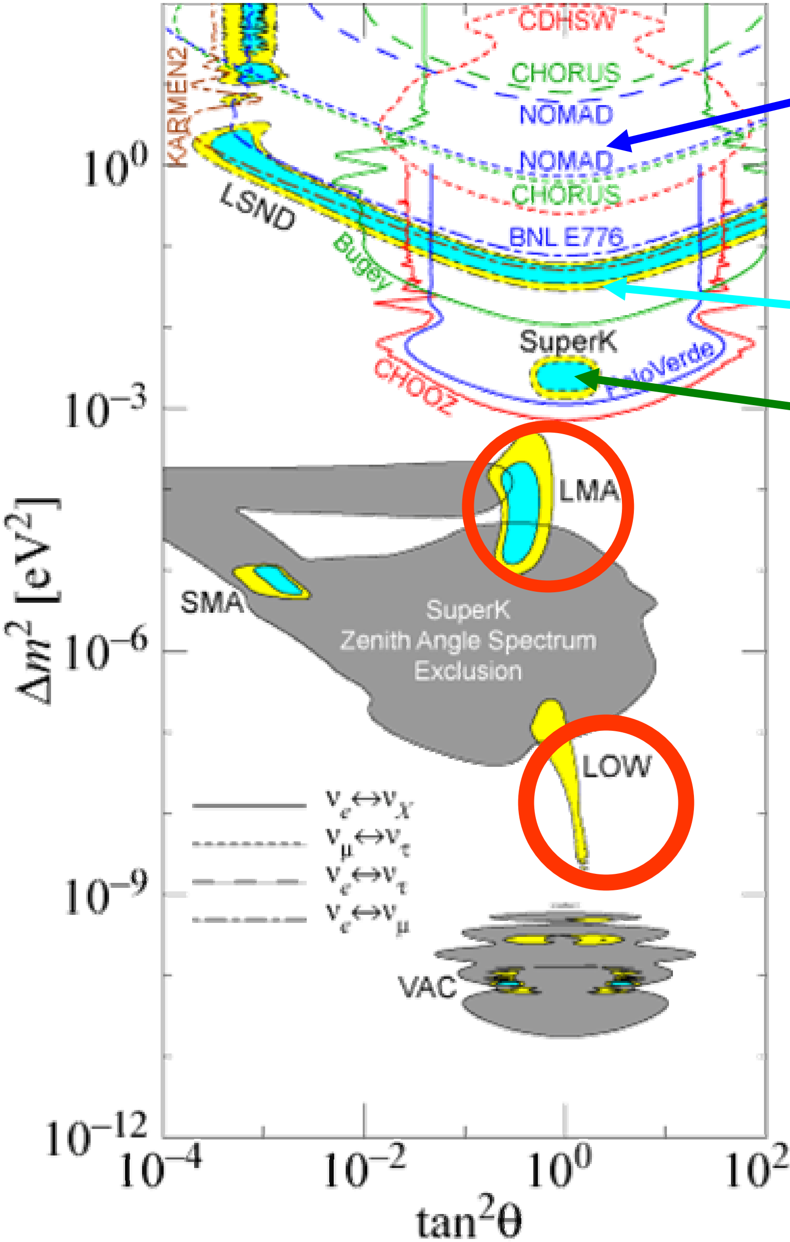
$m_1^2 - m_2^2$
[eV²]

[km]

$$P(\nu_e \to \nu_\mu, L) = \sin^2 2\theta \;\; \sin^2 \frac{1.3\Delta m^2 L}{E}$$

[MeV]

Neutrino oscillations ➡ $m_\nu \neq 0$



Excluded regions from other experiments

Possible oscillations from LSND

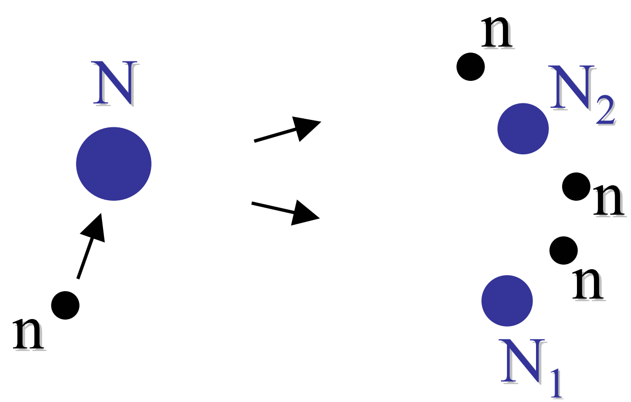
Oscillations from "atmospheric neutrinos"

If the correct interpretation is that neutrinos oscillate only two solutions are compatible with all solar data

All of this is very interesting…

…but wouldn't it be great if we could reproduce it with with artificial means ?

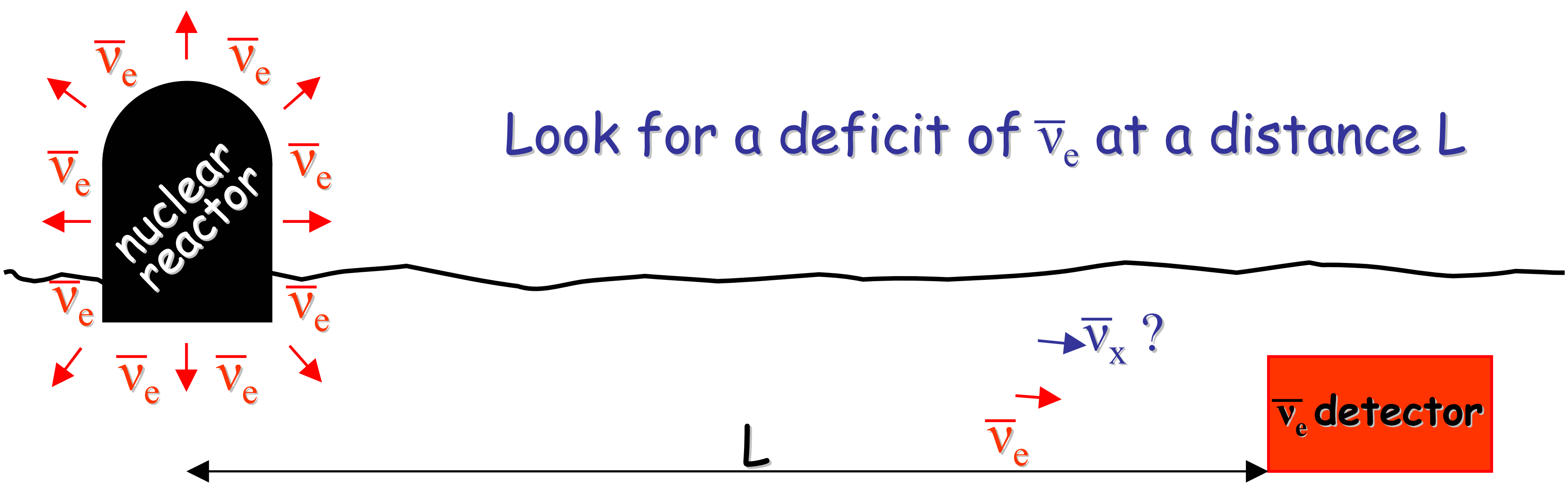
Nuclear reactors are very intense sources of ν_e deriving from beta-decay of the neutron-rich fission fragments



N_1 and N_2 still have too many neutrons and decay

$$N_2 \rightarrow N_3 + e^- + \nu_e$$

Look for a deficit of $\overline{\nu}_e$ at a distance L

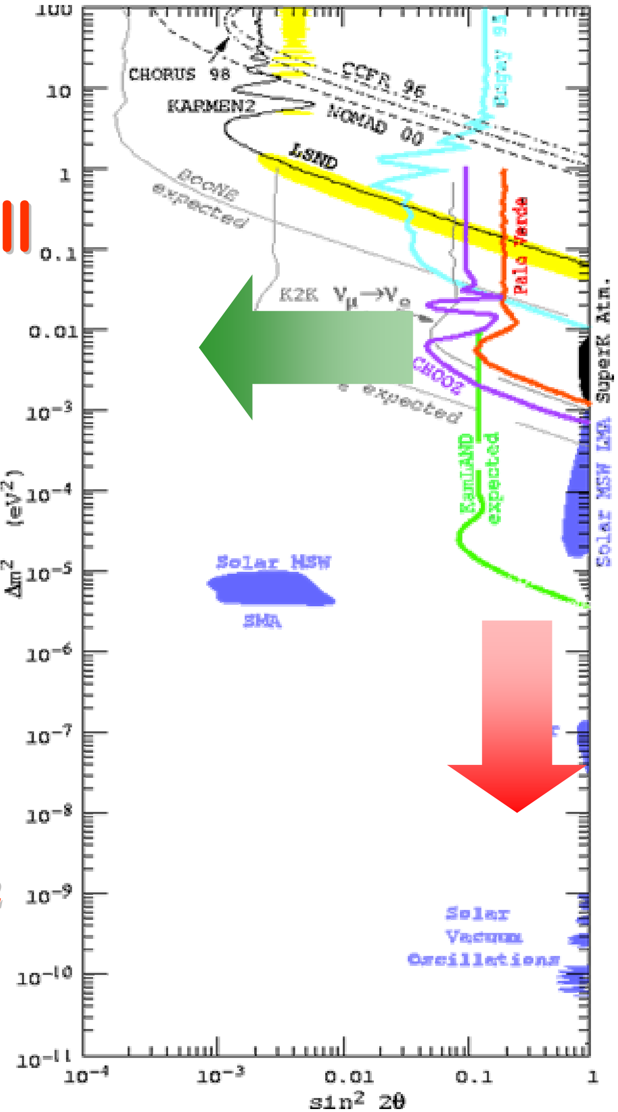


Fred Reines preparing a reactor anti-neutrino detector (circa 1953)

Complementary properties of
Reactors and Accelerators

E_ν~few MeV

- Can probe very small Δm^2
- Disappearance only $\rightarrow$ fair $\sin^2 2\theta$ sensitivity
- 4π source $\rightarrow$ detector mass grows with L^2



E_ν~few GeV

- Good mass sensitivity requires very large L
- Appearance possible (produce μ and τ)
- "Collimated" beam

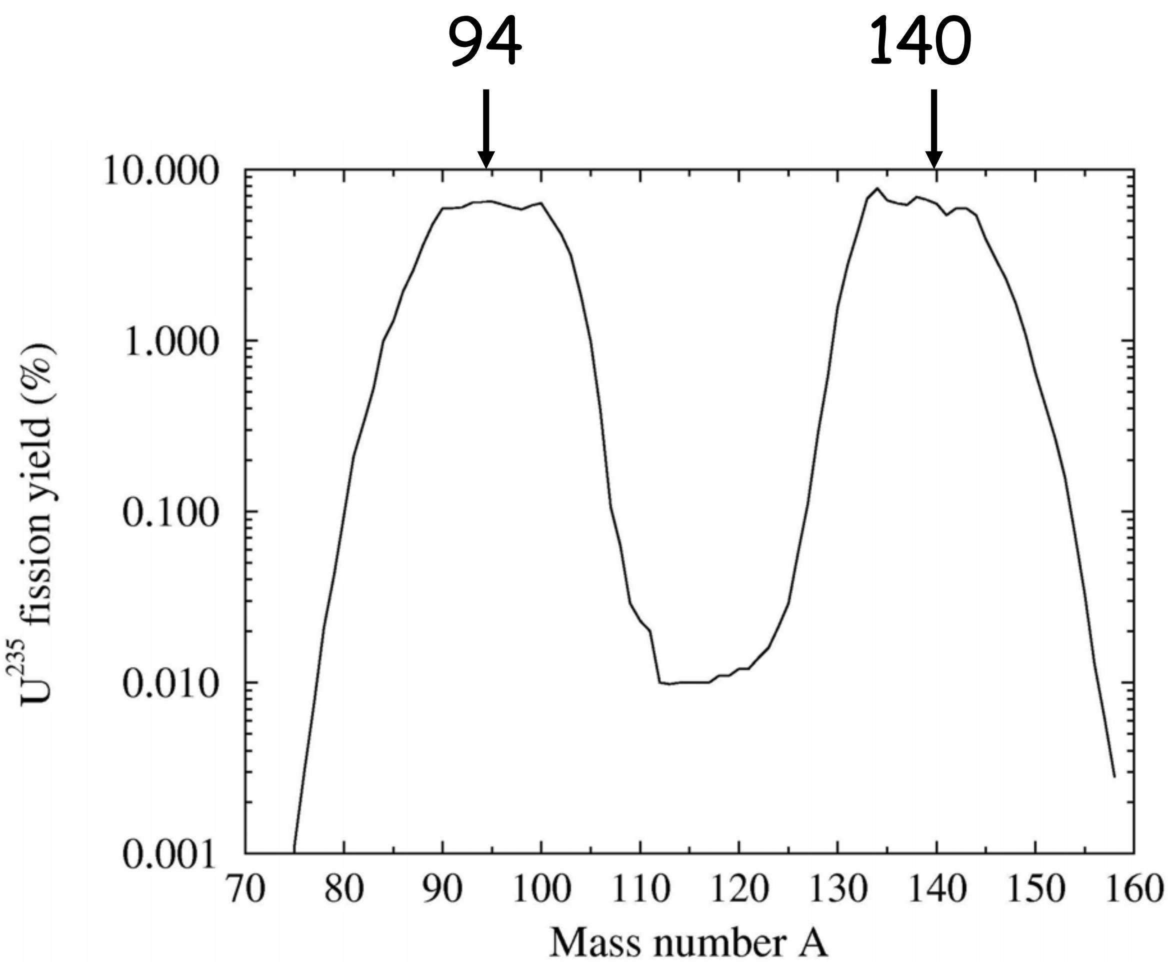
Example: ^{235}U fission

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

stable nuclei with A
most likely from fission

$^{94}_{40}Zr$ $^{140}_{58}Ce$

together these have
98 protons and
136 neutrons



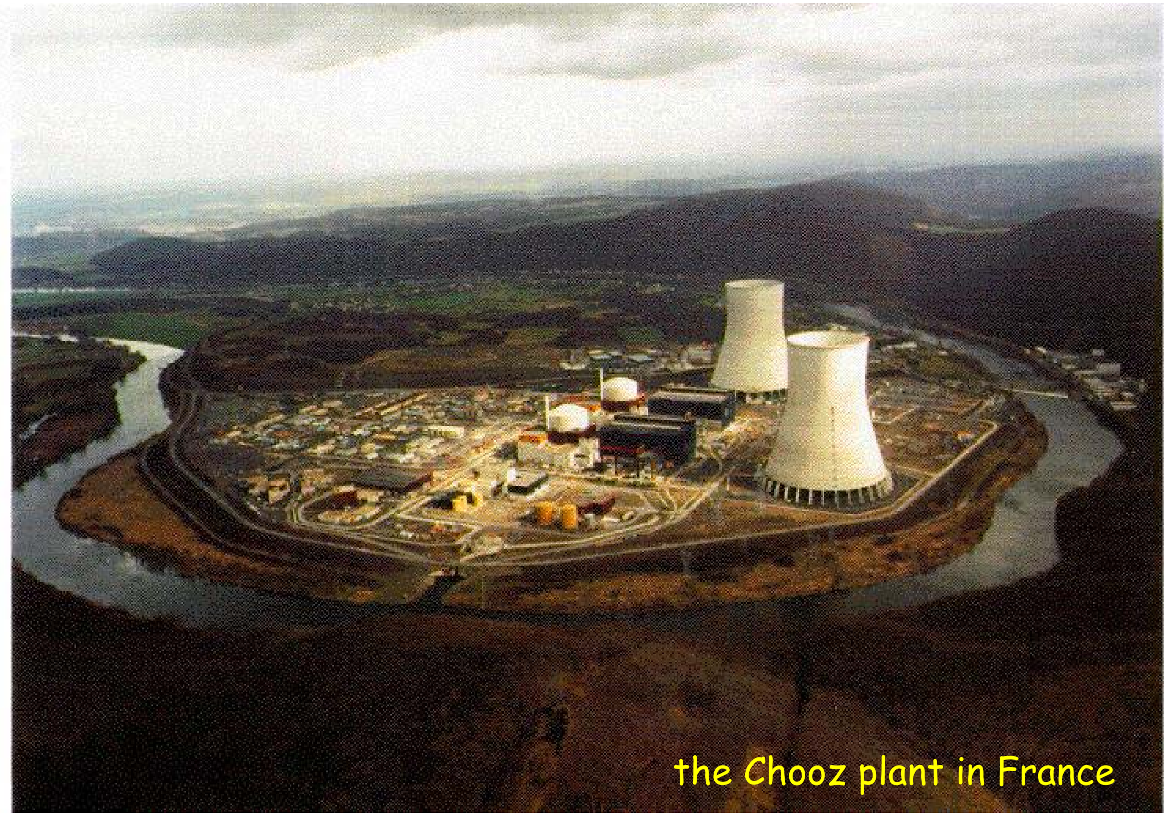
so, on average 6 n have to
decay to 6 p to reach stable matter

Power/commercial reactors are generally used since only requirement is to have large power

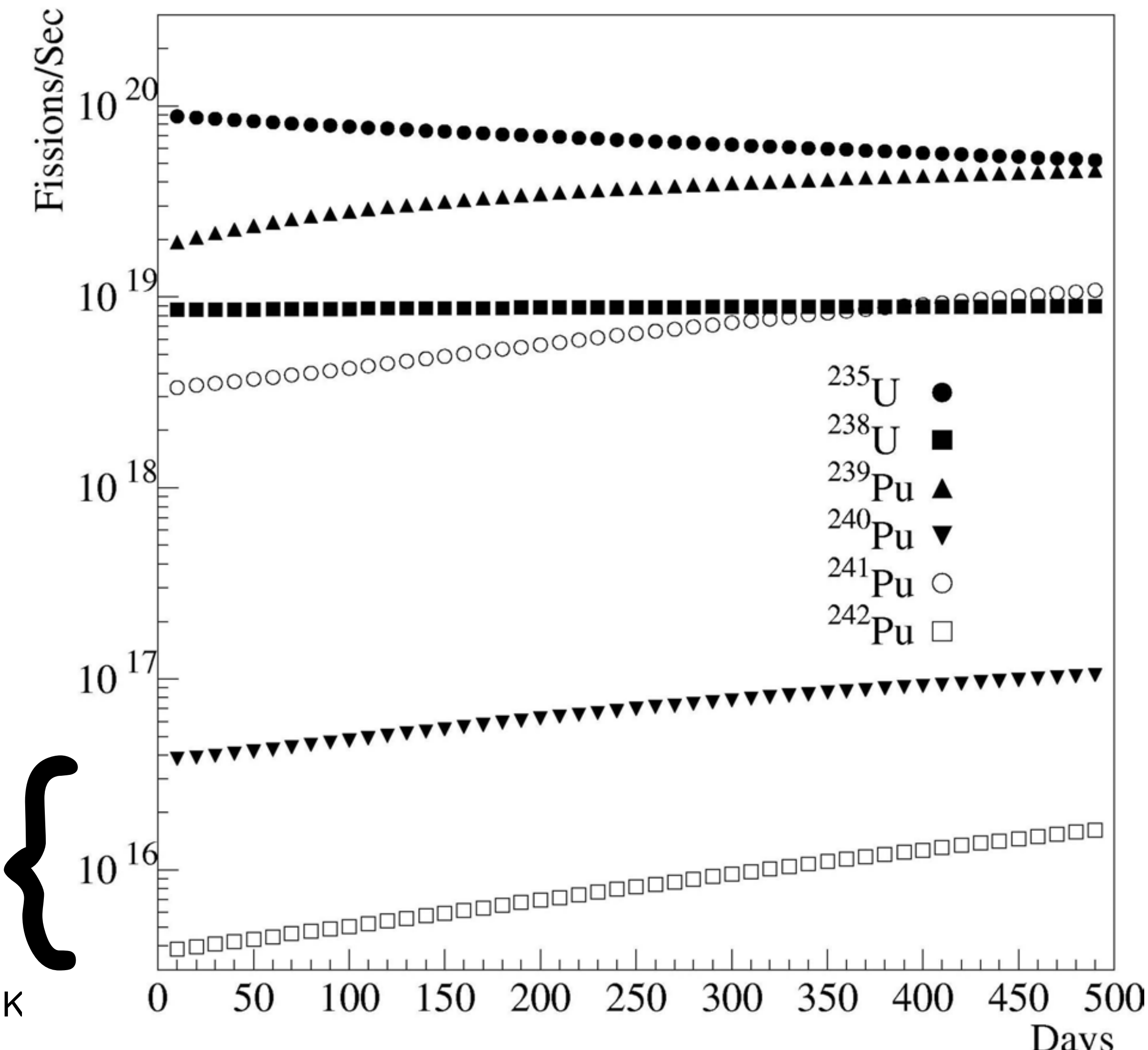
$$200 MeV / fission$$

$$6\overline{\nu}_e / fission$$

A typical large power reactor produces 3 $GW_{thermal}$ and $6 \cdot 10^{20}$ antineutrinos/s



>99.9% of $\bar{\nu}$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



contribution <10^{-3} not taken into account for neutrino flux calculations

ν det. at low energy is tricky: beware of backgrounds !

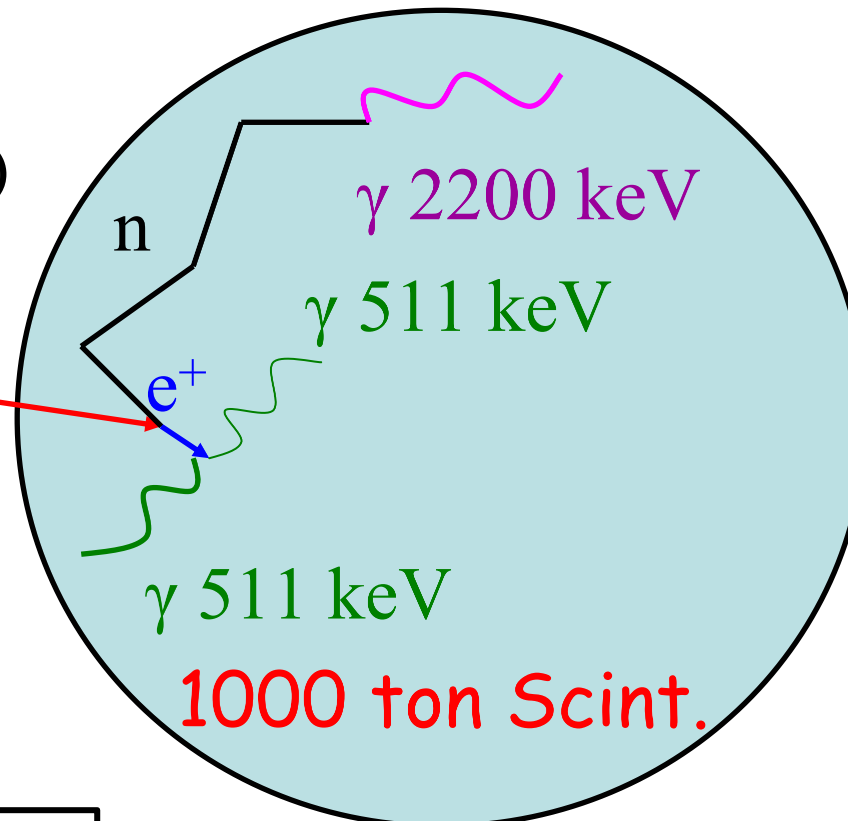
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\downarrow \; \tau \approx 200\ \mu s$$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$

Event tagging by delayed coincidence in energy, time and space

$\bar{\nu}_e$



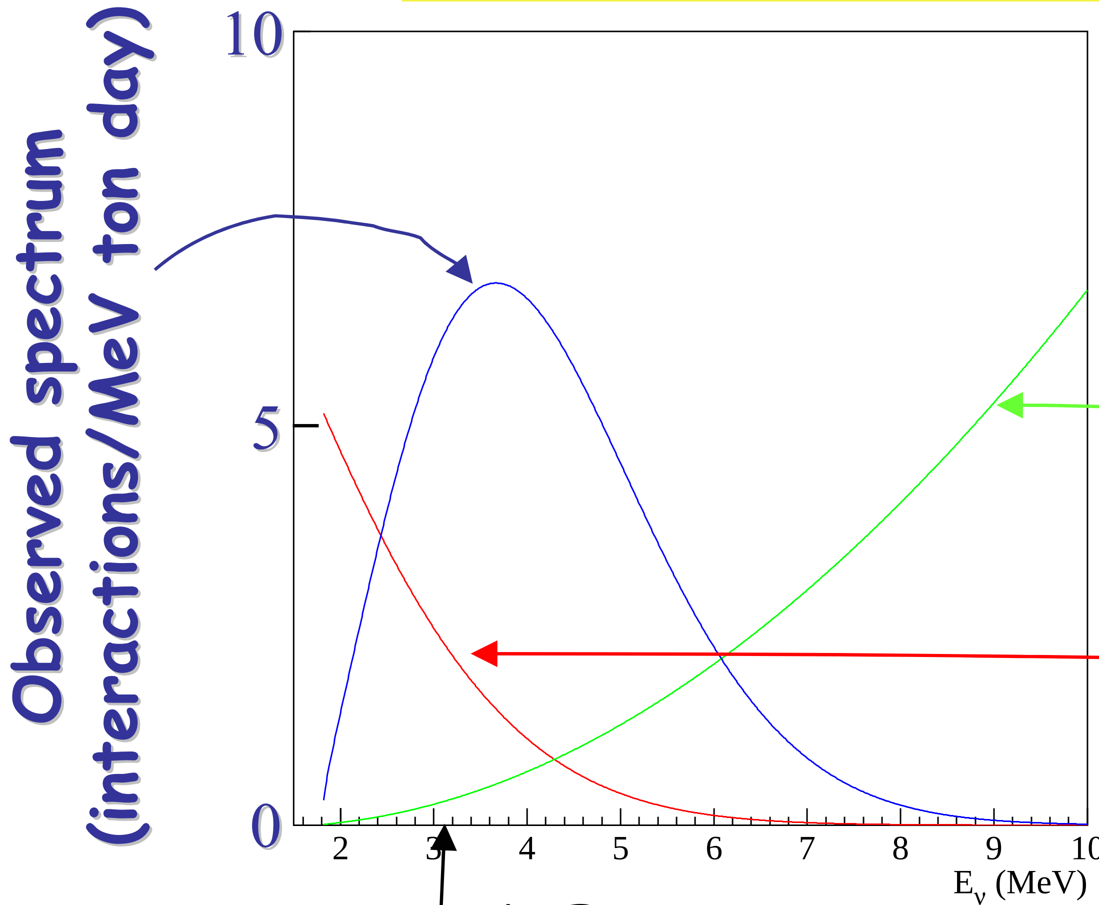
10-40 keV

800 MeV

$$E_{\bar{\nu}} \cong E_{e^+} + E_n + \overbrace{(M_n - M_p) + m_{e^+}}$$

→ E_ν measurement

The $\bar{\nu}_e$ energy spectrum



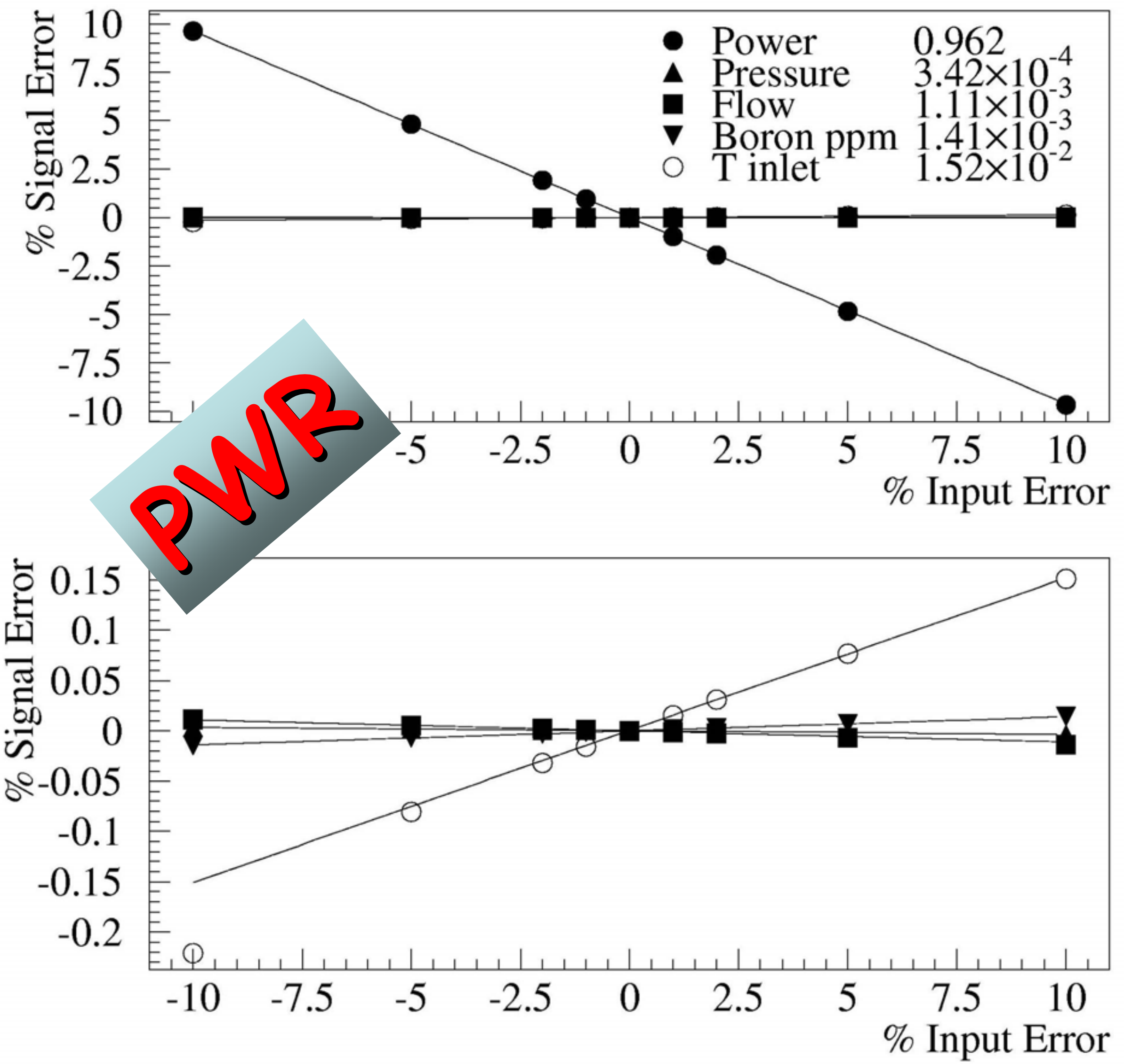
$\nu_e + p \rightarrow n + e^+$ cross section ($\sim 10^{-42}$ cm^2)

Calculated reactor $\bar{\nu}_e$ spectrum (10^{-8} /s MeV GW_{th})

Neutrinos with E<1.8 MeV are not detected

So in practice only ~1.5 neutrinos/fission can be detected above threshold

…disappearance experiments…
how well do we know the flux and spectrum ?
The 200 MeV/fission part:



Thermal power is routinely measured by the reactor operator in order to adjust the reactor to the highest licensed power

Economics push the error on this to 0.6-0.7%

how well do we know the flux and spectrum ?

The 6 $\bar{\nu}$/fission part:

Anti-neutrino spectra from ^{235}U, ^{239}Pu and ^{241}Pu fission can be derived from β^- spectroscopy

This is not entirely trivial as there are very many fission branches and then many possible β decays for each branch

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

The $\bar{\nu}$ yield from ^{238}U derives from fast-neutron fission and could not be measured in the papers above

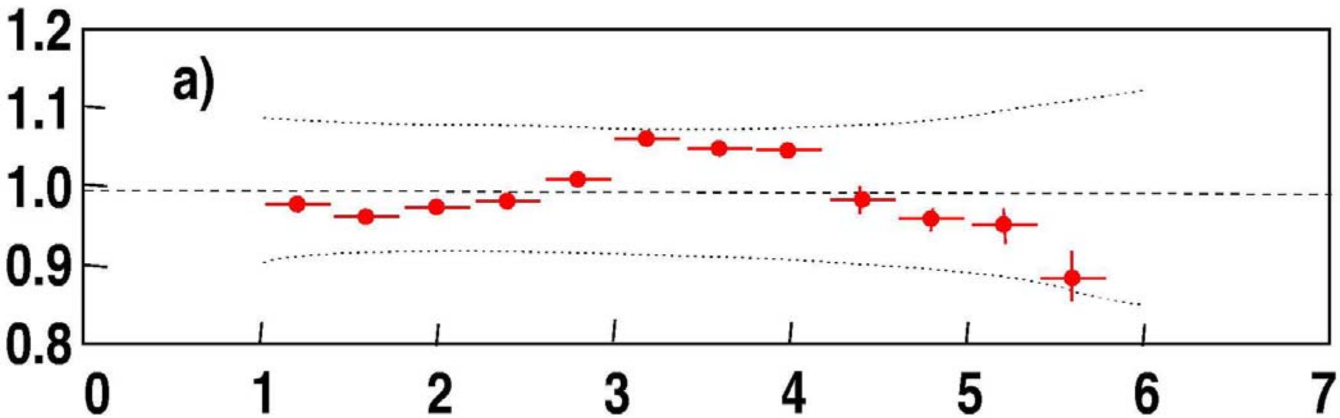
…but one can also calculate the $\bar{\nu}$ yield from first principles

Errors of about 10% are typical in these calculations that have to include ~1000 channels

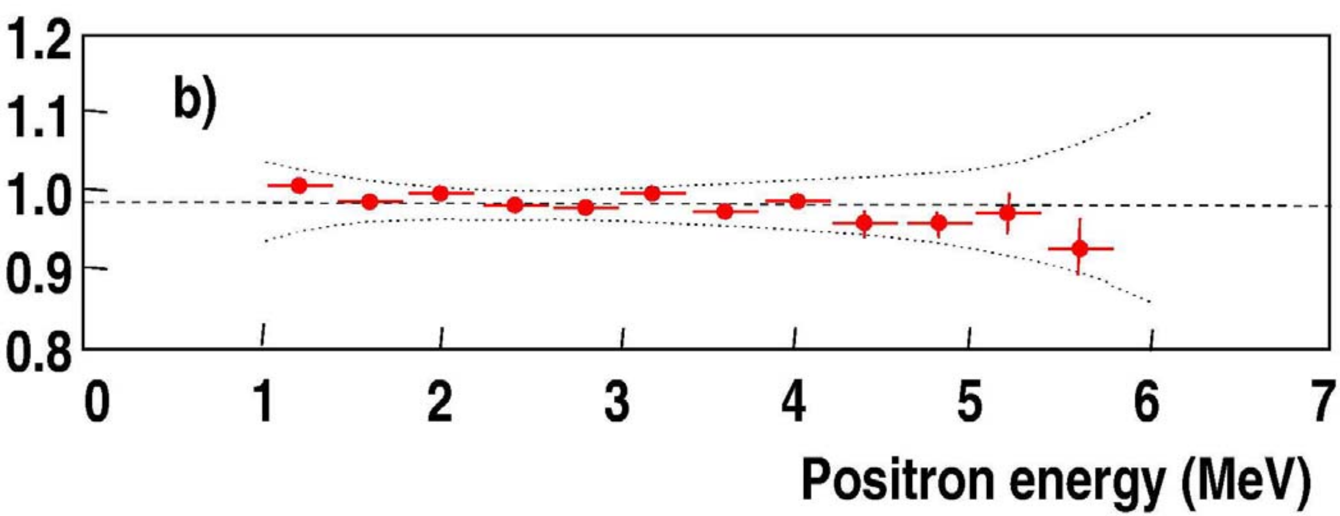
So, ^{238}U that contributes about 11% to the total yield, introduces a total error of about 1%

All these techniques can be cross-checked using precise $\bar{\nu}$ spectra measured at short baseline reactor experiments

From Bugey3 exp (short baseline, 1.5*10^5 events)

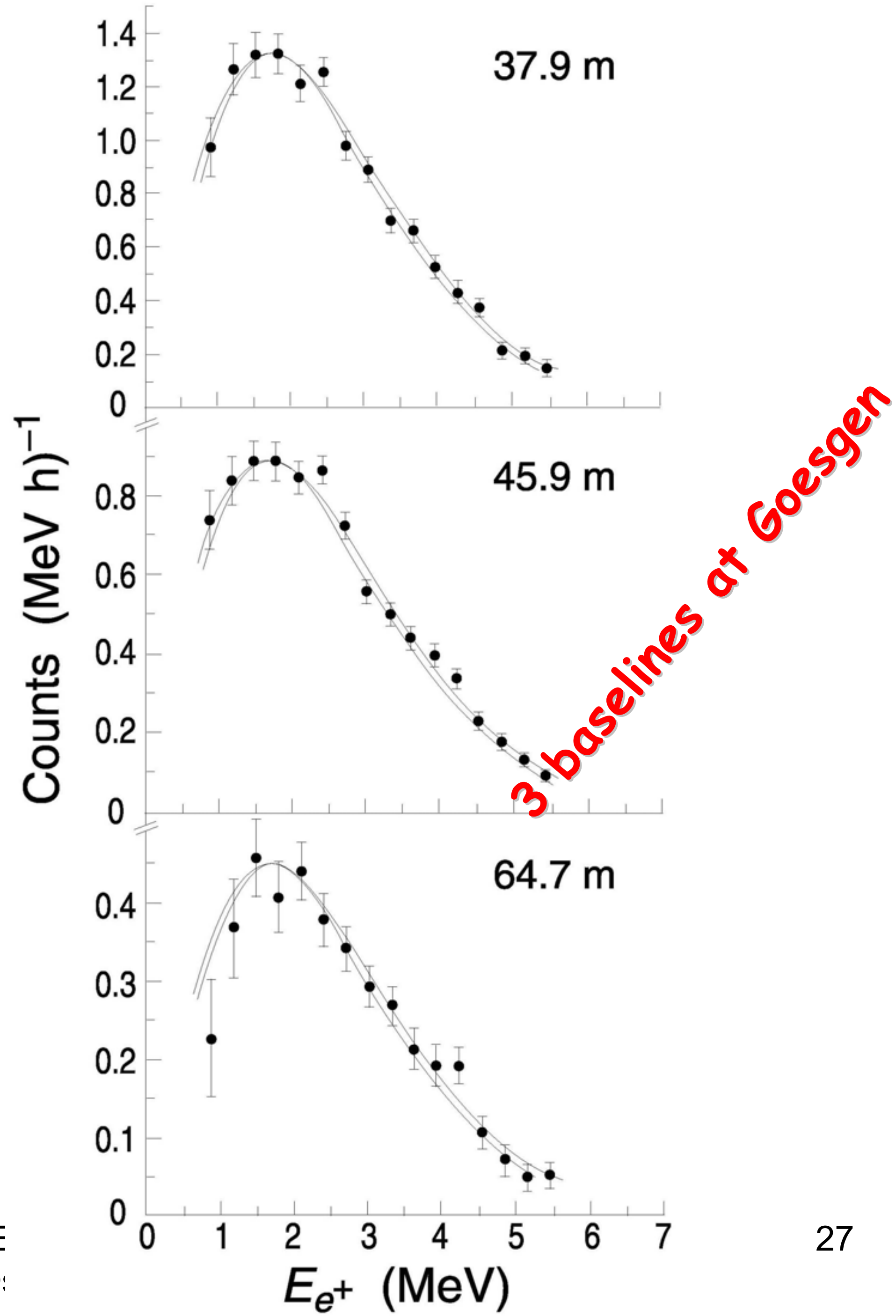


Bugey3/"first principle calculation"

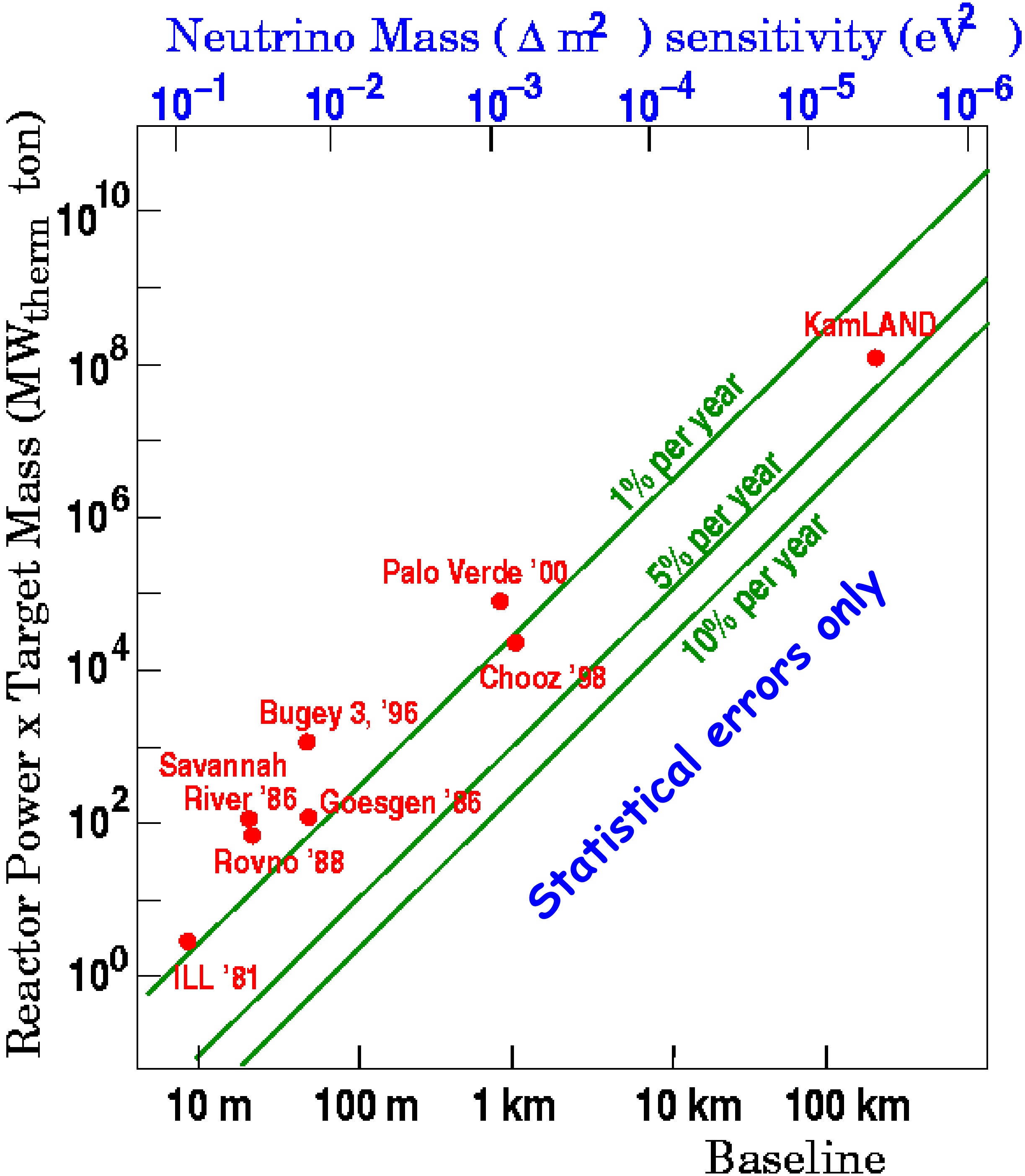


Bugey3/"best prediction" ***(uses β-spectra where possible and calculation for ^{238}U)***

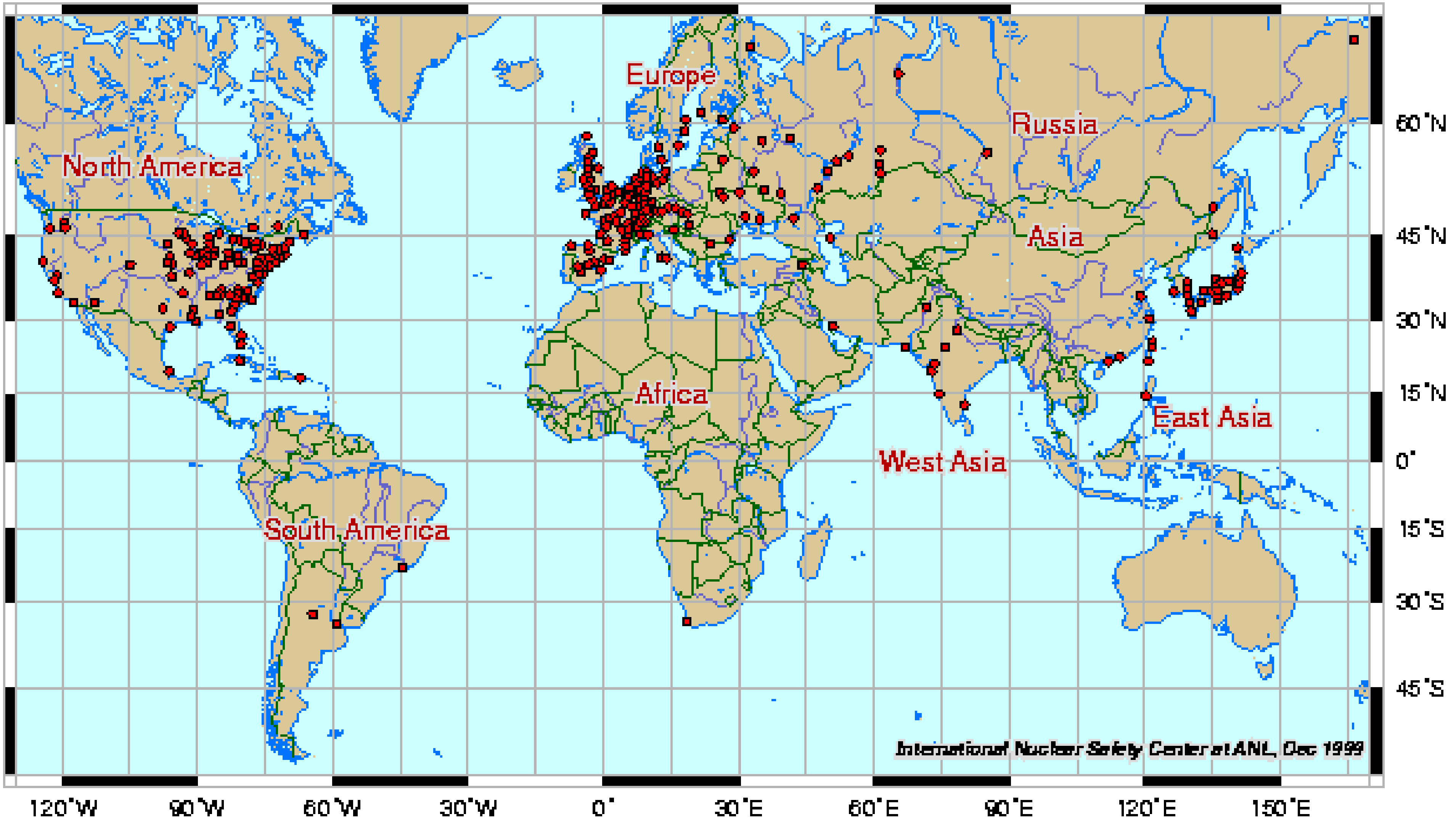
Of course the use of short baseline experiments to check normalization implies no oscillations, as it can be directly checked in cases where the baseline was varied



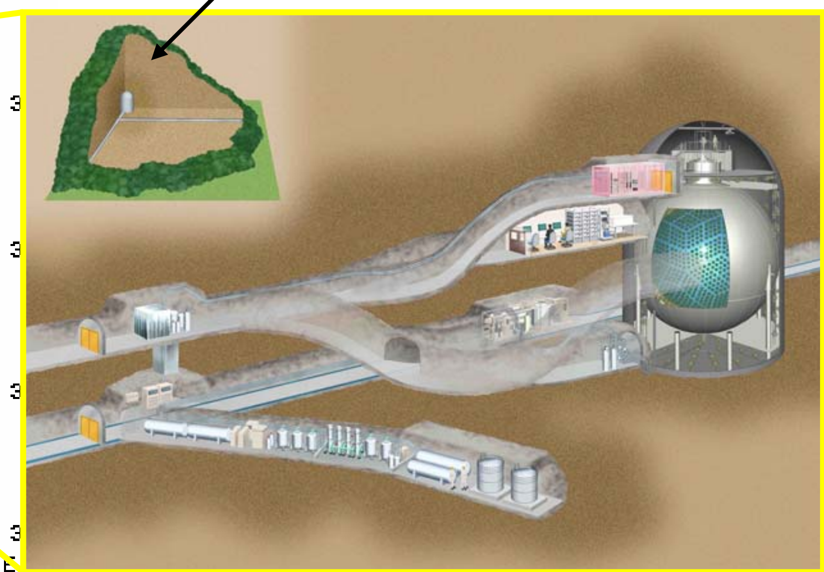
An experiment relevant for solar ν will have ~100 km baseline and hence will need a huge detector and a "huge source"



Need to think regionally: large concentration of nuclear power plants exist in Europe, eastern US and Japan

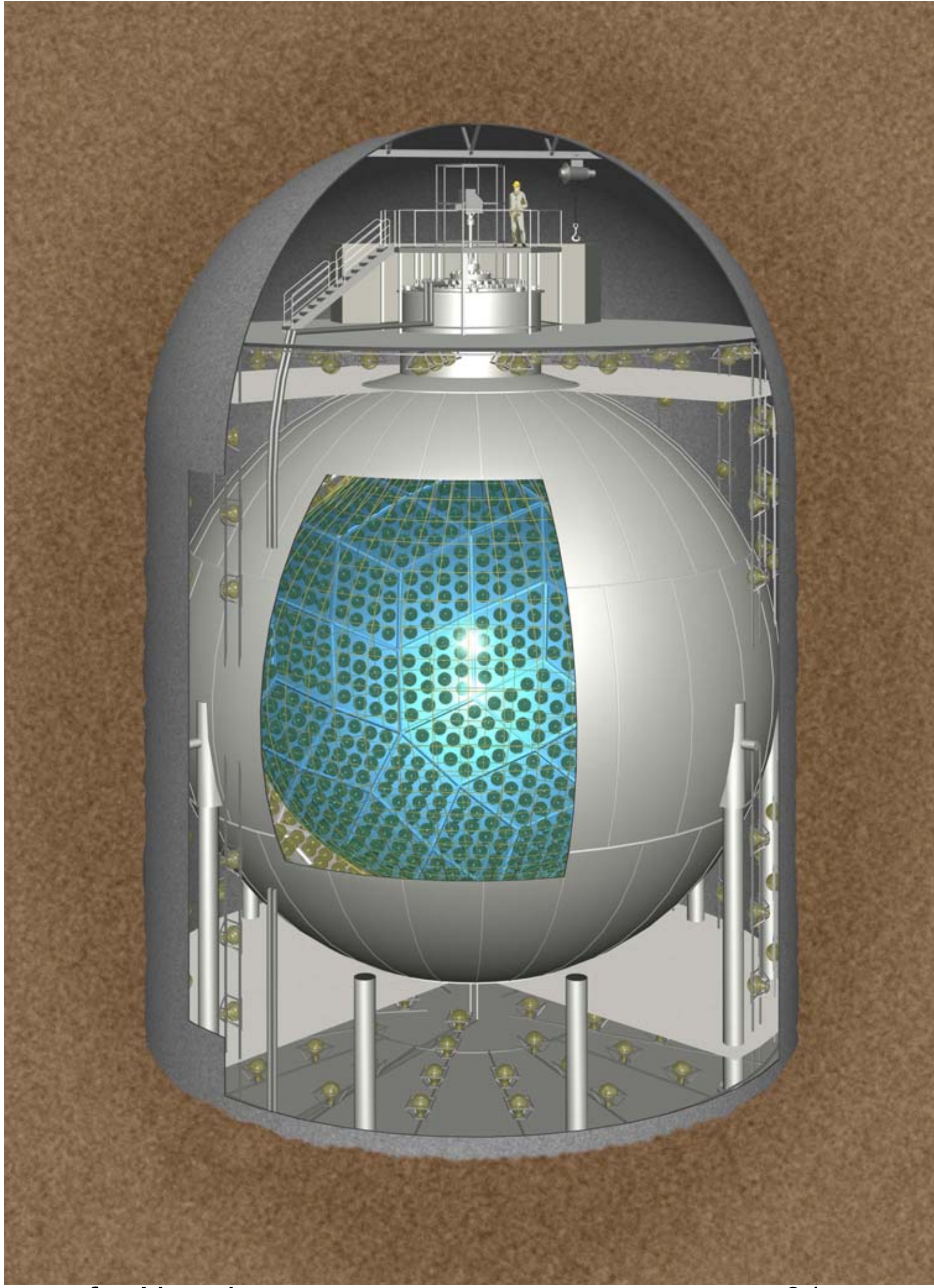


~1 km high
Mt Ikenoyama



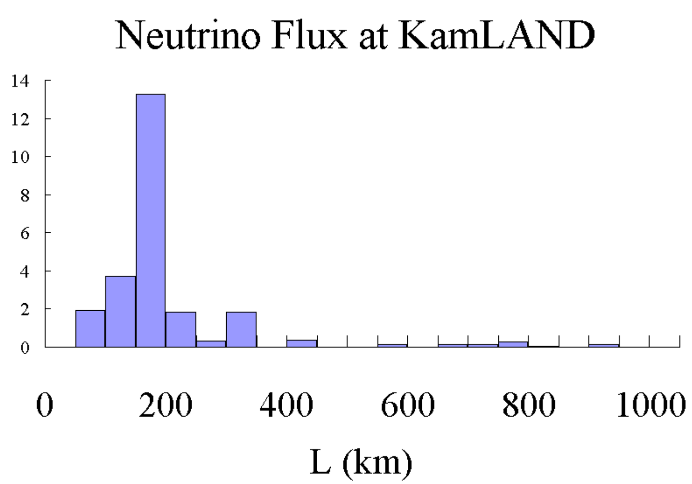
KamLAND: the ultimate reactor neutrino oscillation experiment

- 1 kton liq. Scint. Detector
  in the Kamioka cavern
- ~1300 17" fast PMTs
- ~700 20" large area PMTs
- 30% photocathode coverage
- H_2O Cerenkov veto counter
- Multi-hit deadtime-less
  electronics
- Δm^2 sensitivity $7*10^{-6}$ eV^2
  LMA-MSW solution
  within reach on the earth !



Site	Distance (km)	# of cores	P(ther.) (GW)	flux ($\bar{\nu}$ cm^{-2}s^{-1})	Signal ($\bar{\nu}$/yr)
Japan					
Kashiwazaki	160.0	7	24.6	4.25×10^5	348.1
Ohi	179.5	4	13.7	$1.88\mathrm{X}10^5$	154.0
Takahama	190.6	4	10.2	1.24×10^5	101.8
Hamaoka	214.0	4	10.6	1.03×10^5	84.1
Tsuruga	138.6	2	4.5	1.03×10^5	84.7
Shiga	80.6	1	1.6	1.08×10^5	88.8
Mihama	145.4	3	4.9	1.03×10^5	84.5
Fukushima-1	344.0	6	14.2	5.3×10^4	43.5
Fukushima-2	344.0	4	13.2	4.9×10^4	40.3
Tokai-II	294.6	1	3.3	1.7×10^4	13.7
Shimane	414.0	2	3.8	9.9×10^3	8.1
Onagawa	430.2	2	4.8	9.8×10^3	8.1
Ikata	561.2	3	6.0	8.4×10^3	6.9
Genkai	755.4	4	6.7	5.3×10^3	4.3
Sendai	824.1	2	3.3	3.5×10^3	2.8
Tomari	783.5	2	5.3	2.4×10^3	2.0
Korea					
Ulchin	~750	4	11.2	8.8×10^3	7.2
Wolsong	~690	4	8.1	7.5×10^3	5.2
Yonggwang	~940	6	16.8	8.4×10^3	6.9
Kori	~700	4	8.9	8.0×10^3	6.6
Total		69	175.7	1.34×10^6	1102

Baseline is limited: 85.3% of signal has 140 km < L < 344 km



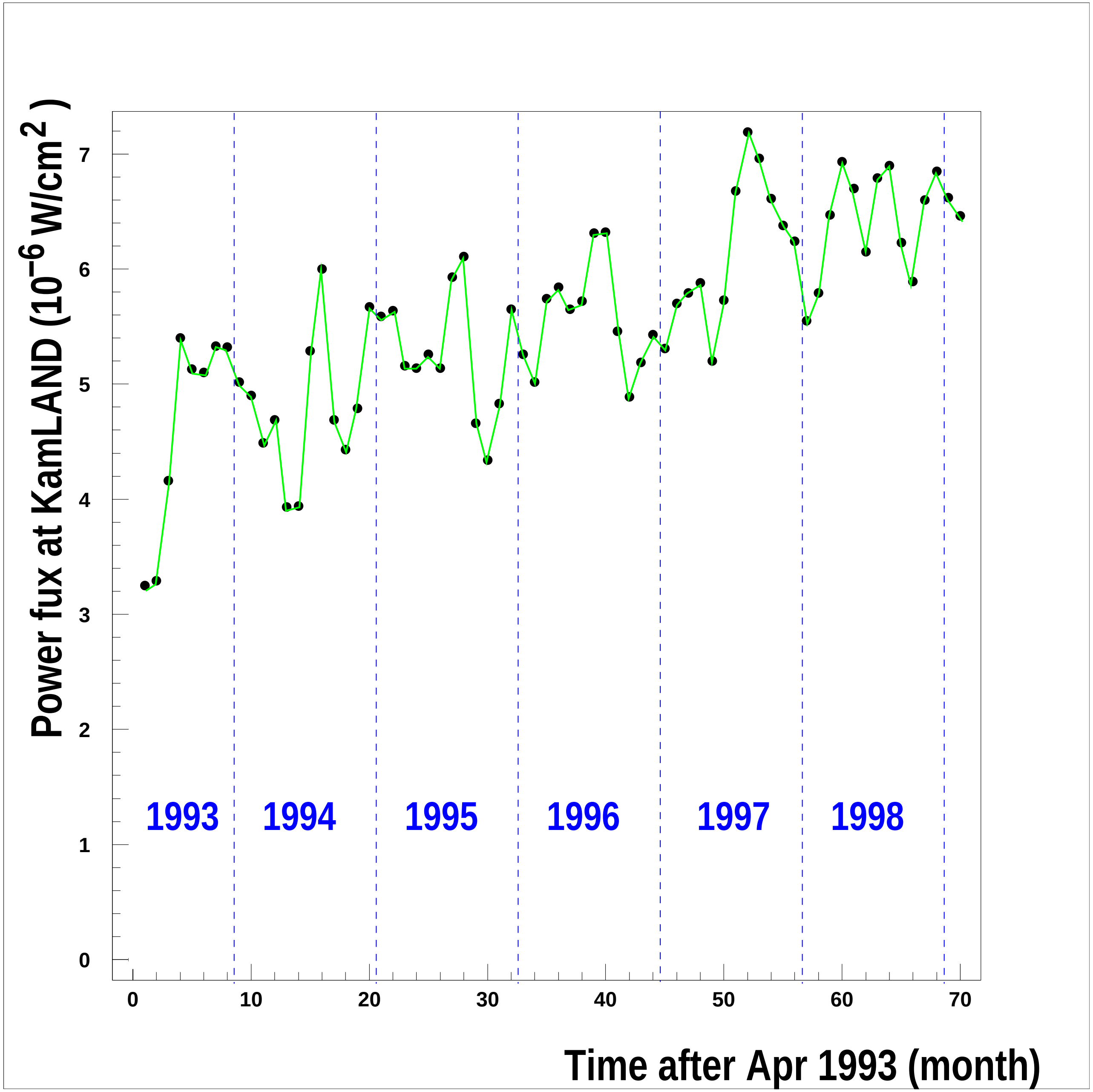
The total electric power produced "as a by-product" of the νs is:

- ~60 GW or...
- ~4% of the world's manmade power or…
- ~20% of the world's nuclear power

Total expected signal from reactors in 1 kton: ≈2 ev/day

Expected S/N ratio ≈ 20

@ 10^{-14} U, Th, ^{40}K contamination in the scintillator


Power fux at KamLAND (10^{-6} W/cm^2)
Time after Apr 1993 (month)
1993
1994
1995
1996
1997
1998

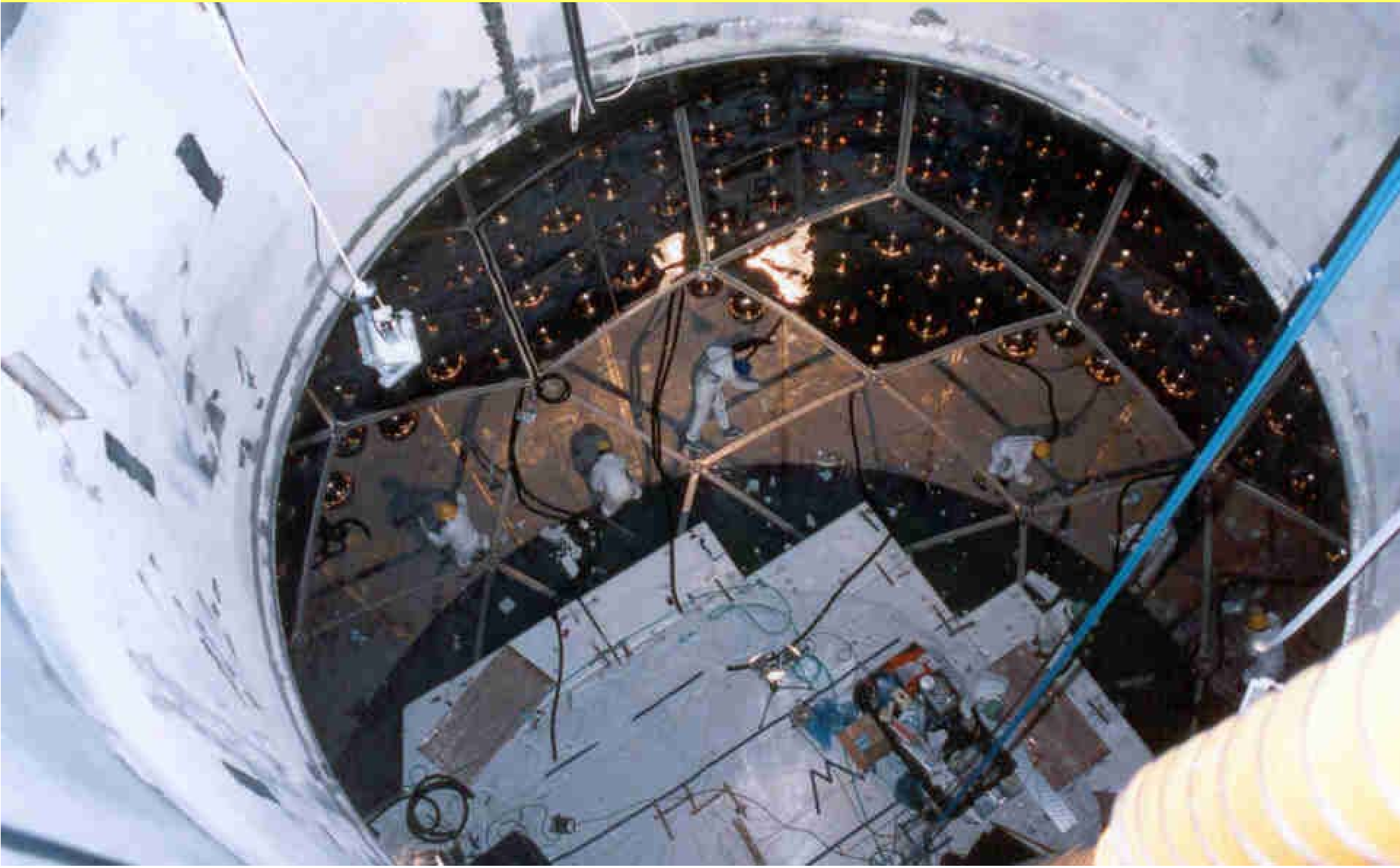
Since reactors produce $\bar{\nu}_e$ while the sun produces ν_e the equivalence of solar neutrino oscillations with what can be observed with the KamLAND reactor experiment rests on the validity of CPT

An unexpected oscillation pattern in KamLAND could be an indication of CPT violation

KamLAND: neutrino physics on a shinkansen

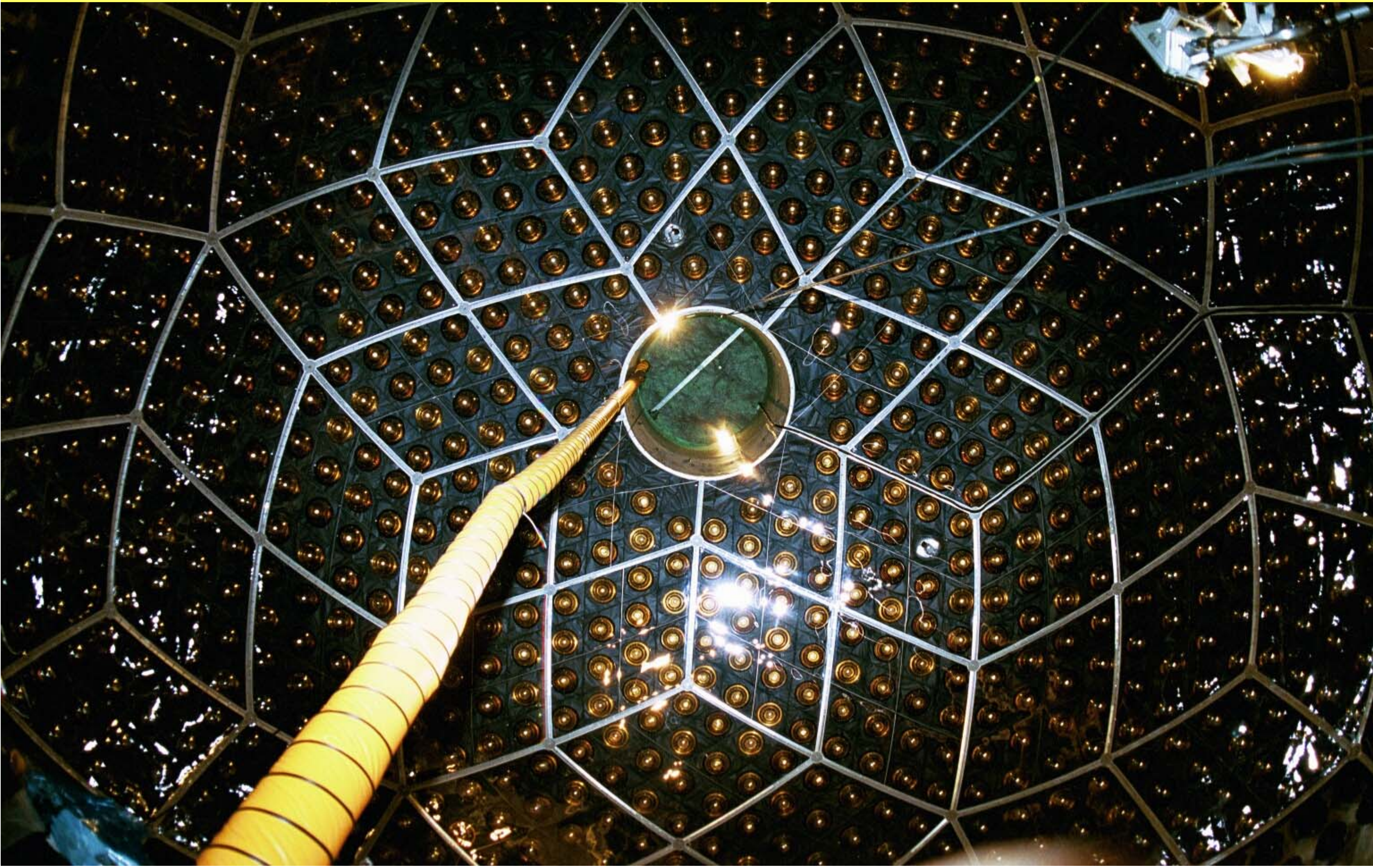
•Summer 2000	PMT installation
•Winter 2000-01	Veto counter installation
•Feb 2001	Balloon insertion
•Mar-Apr 2001	Balloon inflation and test
•Apr-May 2001	Plumbing for fill
•Jun-Sept 2001	Fill MO and LS
•Aug-Sept 2001	Eng. runs with Macro Elec.
•Sept 2001	FEE/DAQ/Trigger int. (LBL)
•end Sept 2001	First data taking with FEE
•Jan 22, 2002	Begin Data Taking
•Dec 6, 2002	First Physics Paper (hep-ex/0212021)

Cleaning the KamLAND sphere (Summer 2000)



Installing 17” and 20” PMTs in KamLAND (Summer 2000)

The completed detector, looking up

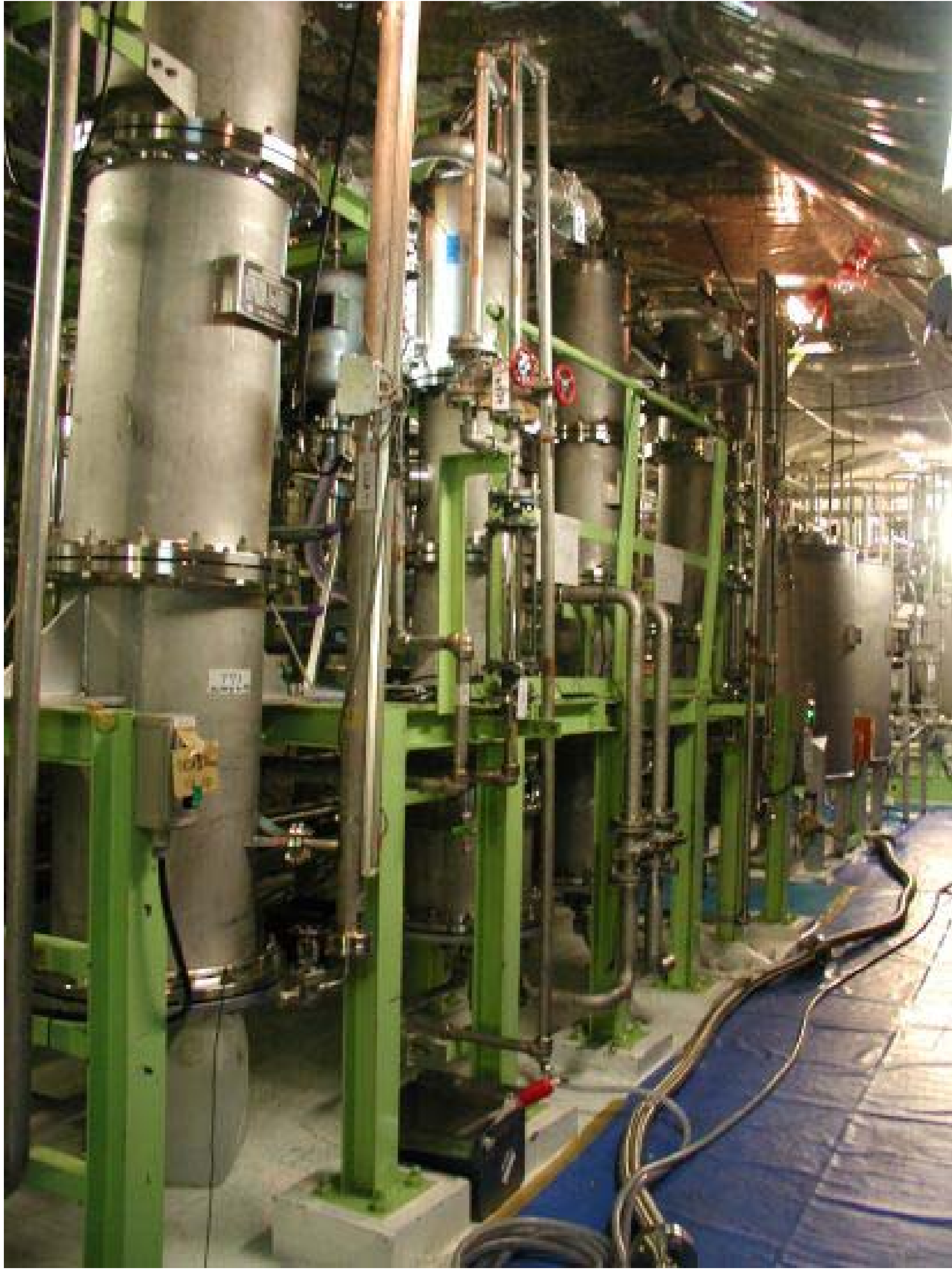


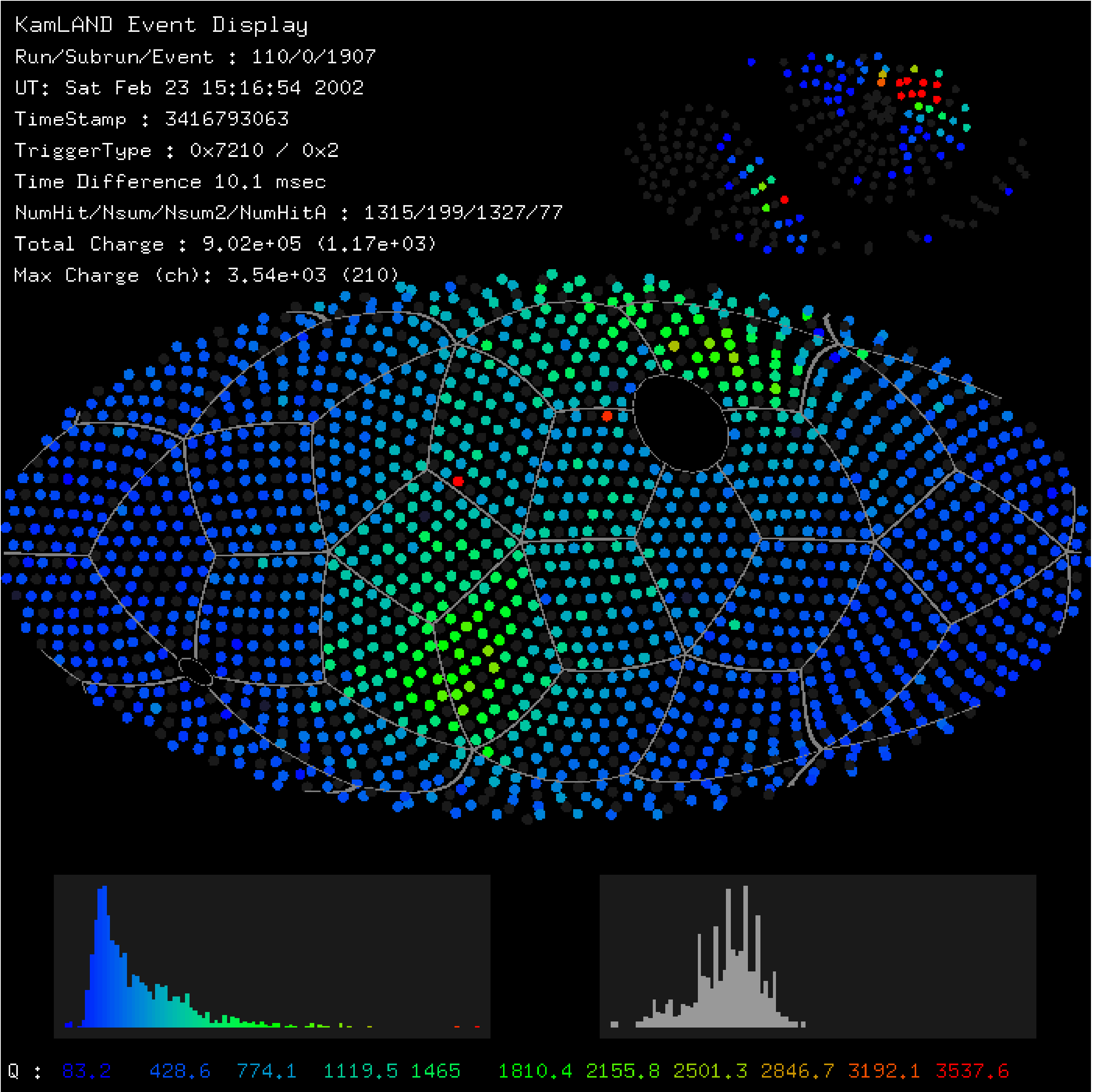
Scintillator is a blend of 20% pseudocumene and 80% dodecane

Different density paraffines are used to tune the density of buffer to 0.995 of that of the scintillator

PPO concentration is 1.5 g/l of the final scint.

During blending the liquids are pre-purified.

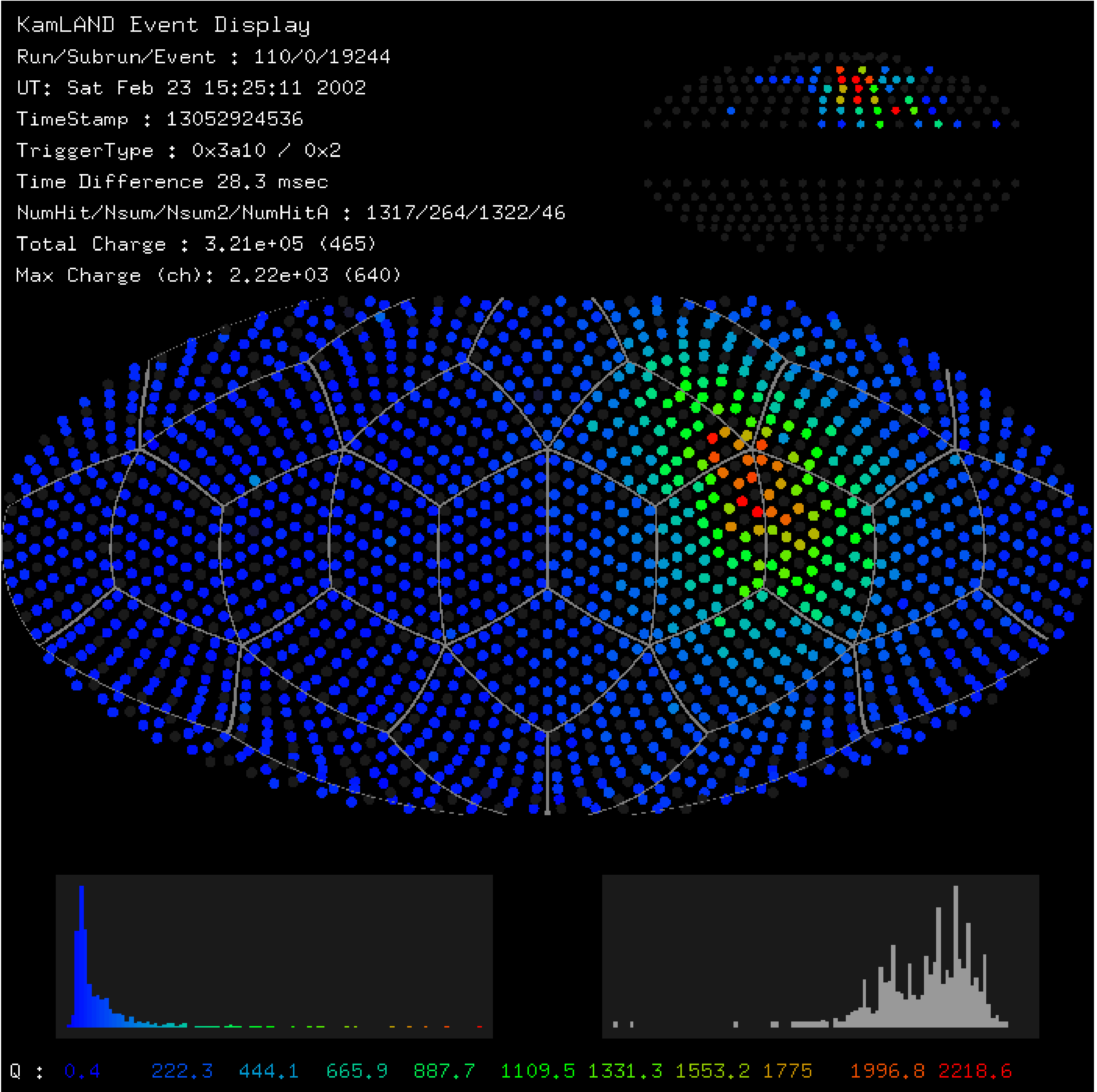




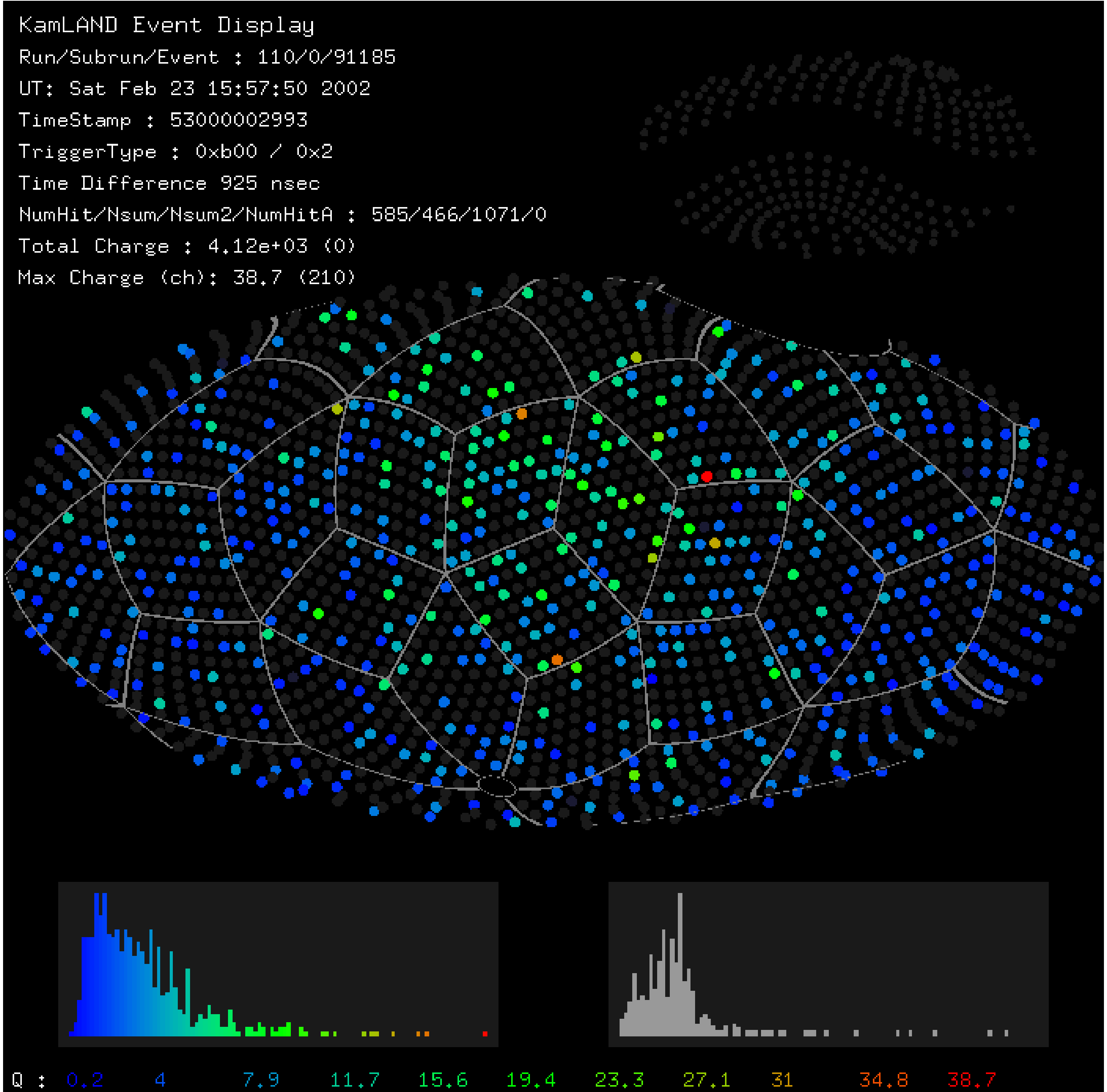
through-going muon

color is pulseheight

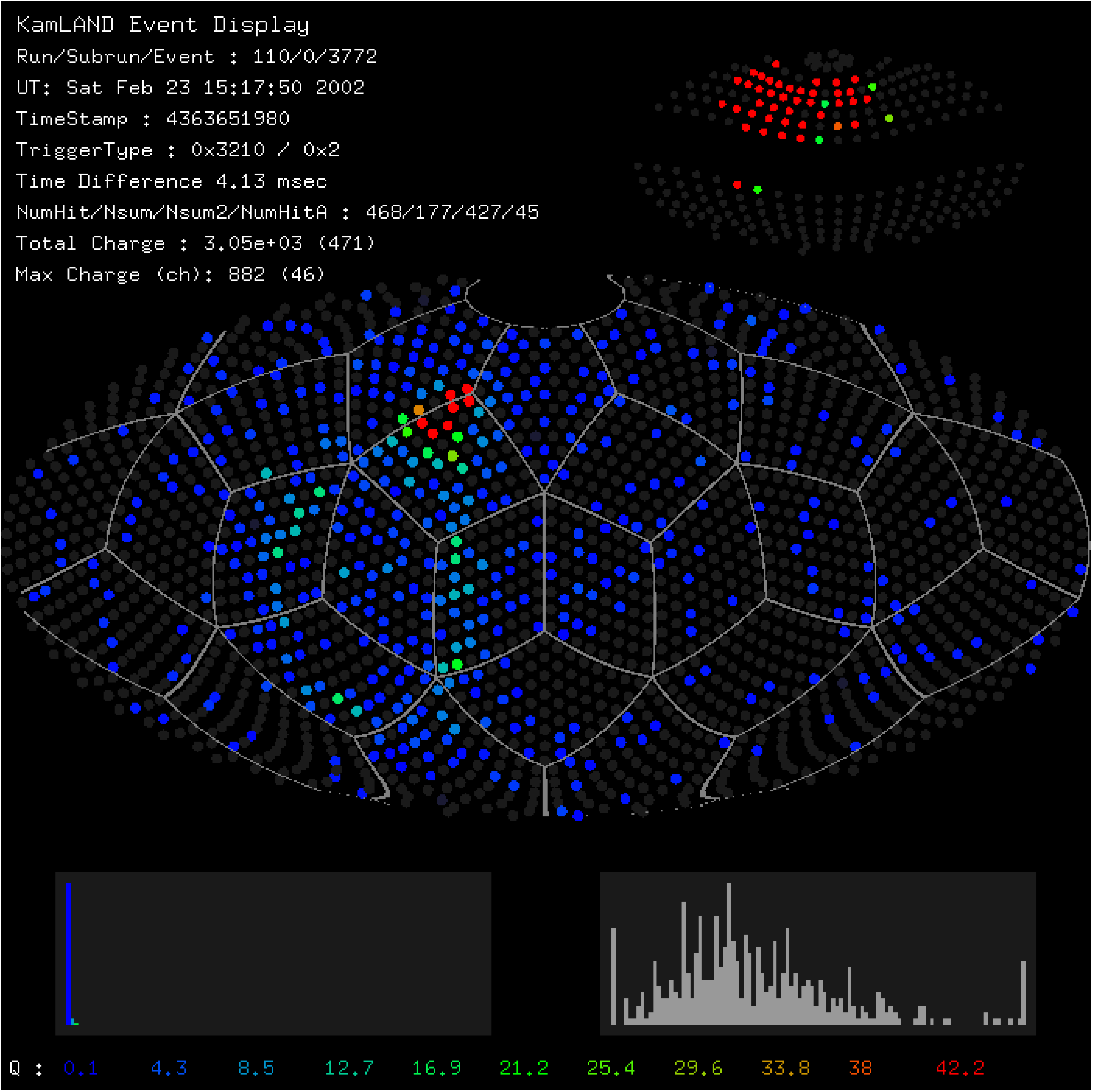
all tubes illuminated



Stopped muon



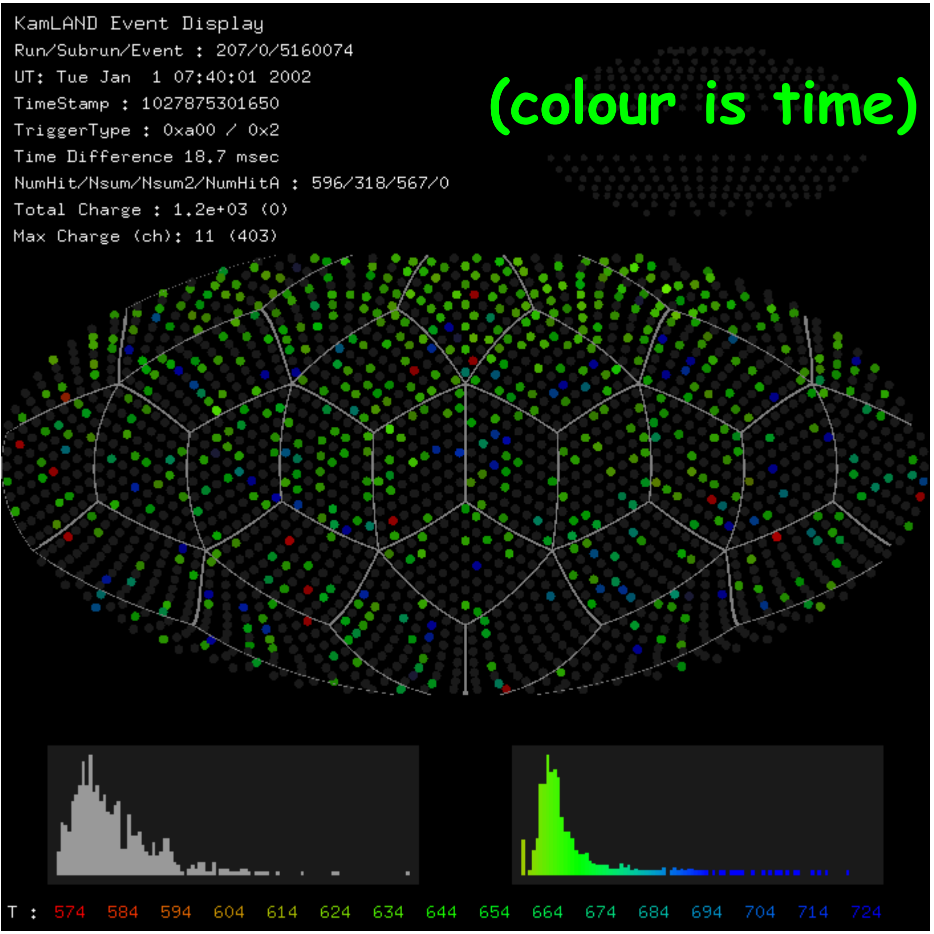
…decaying into a Michel electron

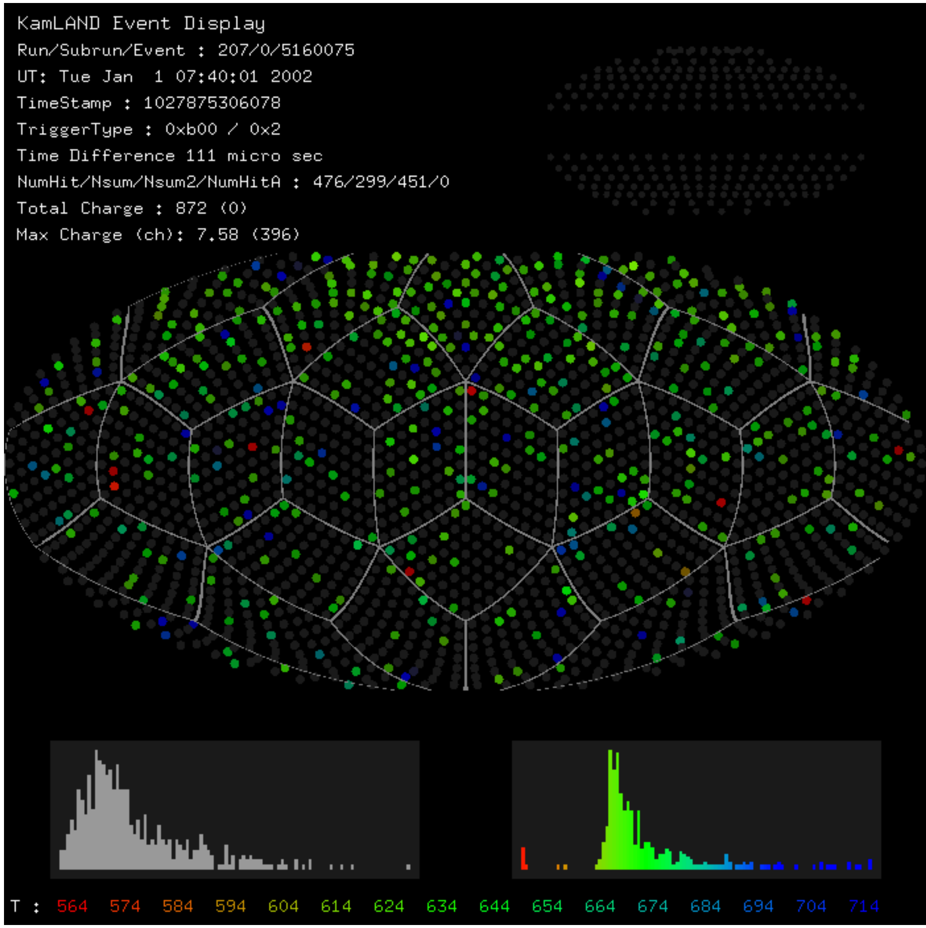


Corner-clipper muon:

Cherenkov ring in the buffer but no scintillation activity

Anti-Neutrino Candidate





Prompt Signal
E = 3.20 MeV

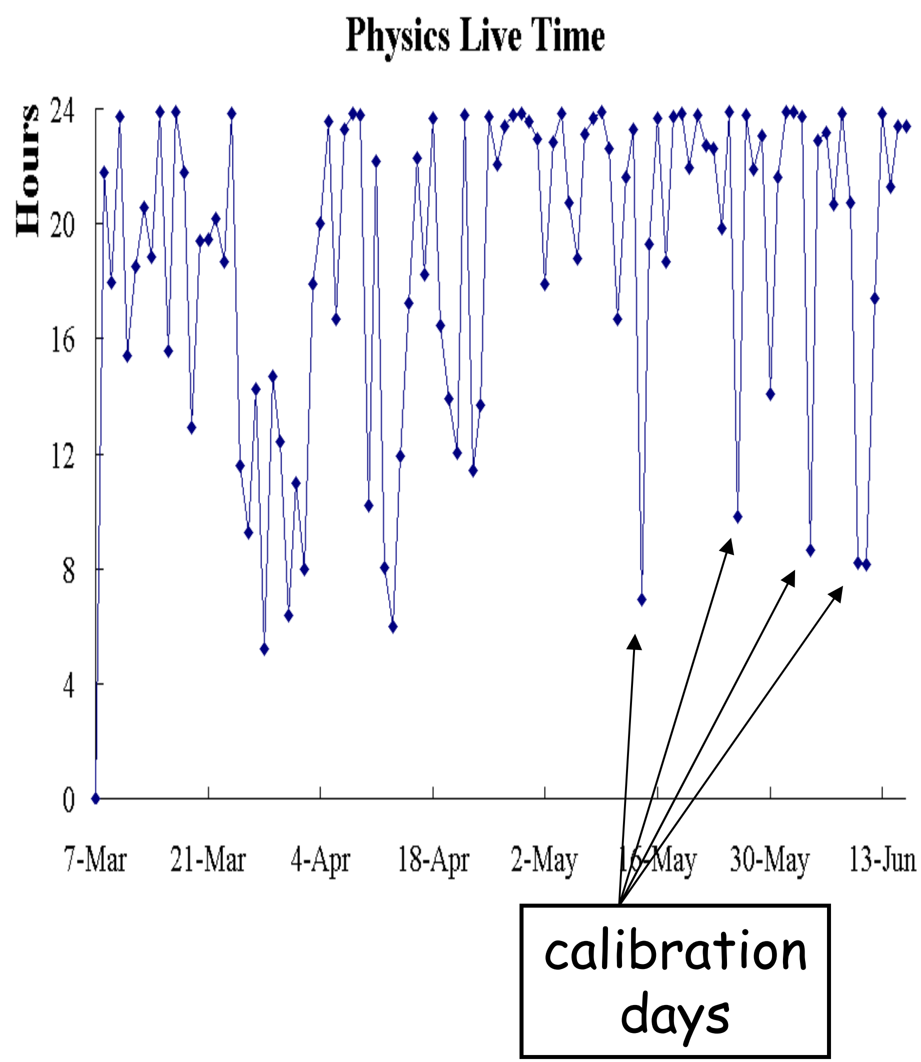
Δt = 111 μs
ΔR = 34 cm

Delayed Signal
E = 2.22 MeV

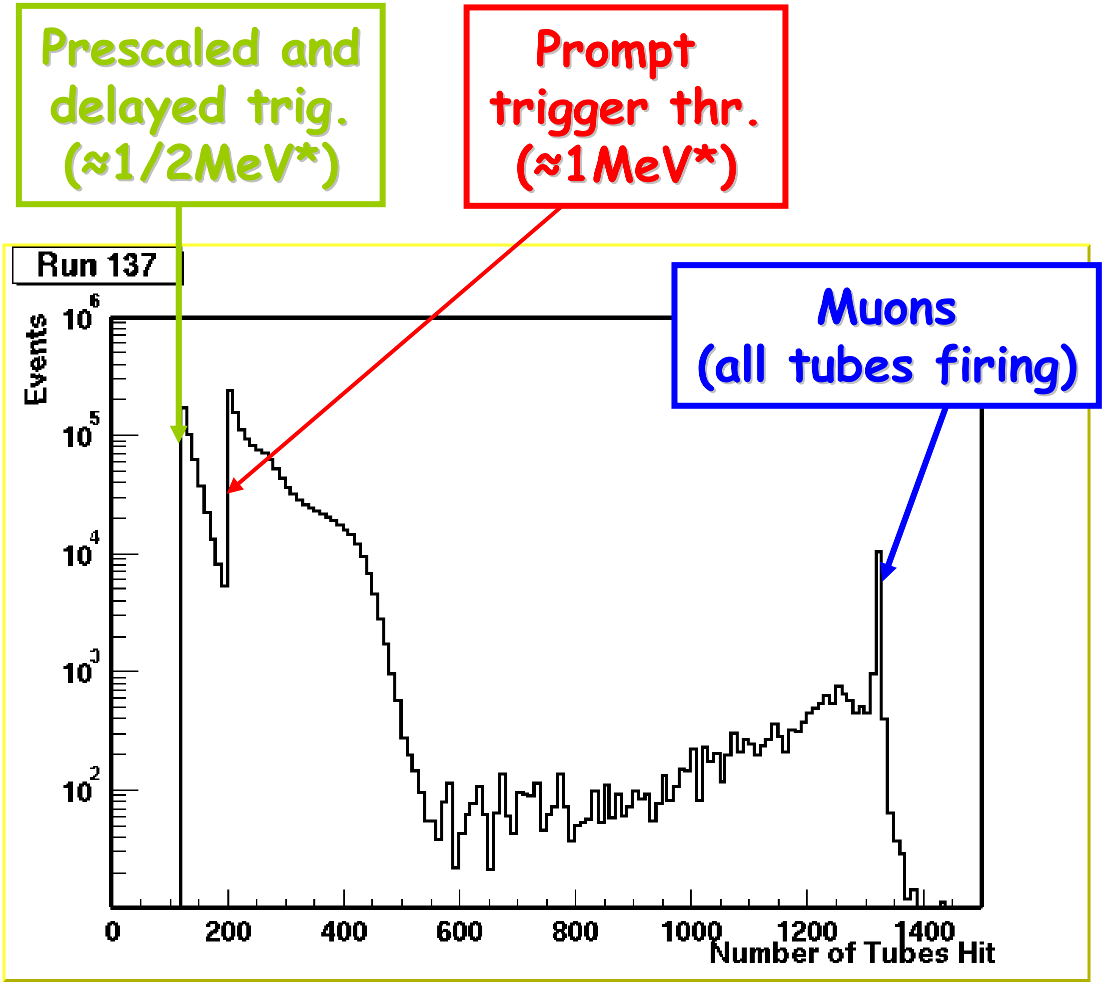
The data set

Used for this analysis:
Mar 4 – Oct 6, 2002
Total 145.1 days

370 M triggers



Triggering KamLAND

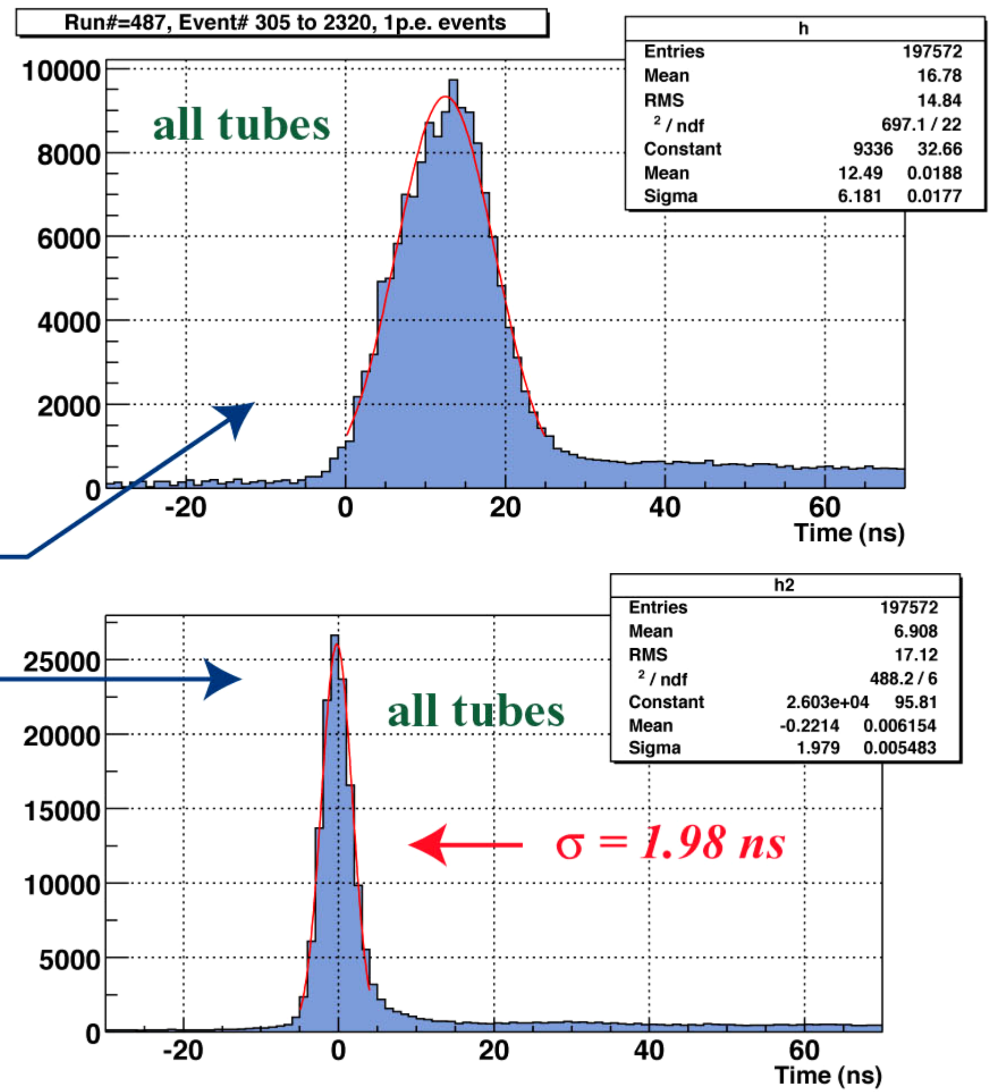


- Single ch. ATWD threshold 1/3 p.e. (0.5 mV)
- Correlated (antineutrino):
  - promt >~ 0.7MeV
  - del'd (1 ms) >~0.4 MeV
- Prescaled singles >~0.4 MeV
- Trigger data readout for all singles >~0.4 MeV
- (Supernova "burst trigger")

*Approximate energy, exact energy value depends on location in the detector

The position of an energy deposit is found by time of arrival of light to the different PMTs

Timing calibration was done using a dye laser (λ= 500 nm)

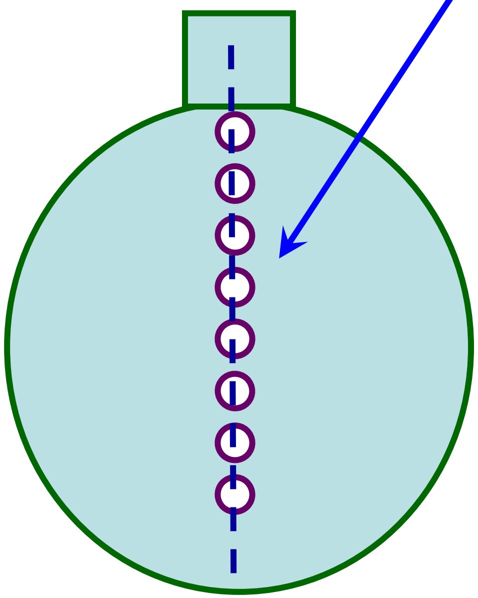


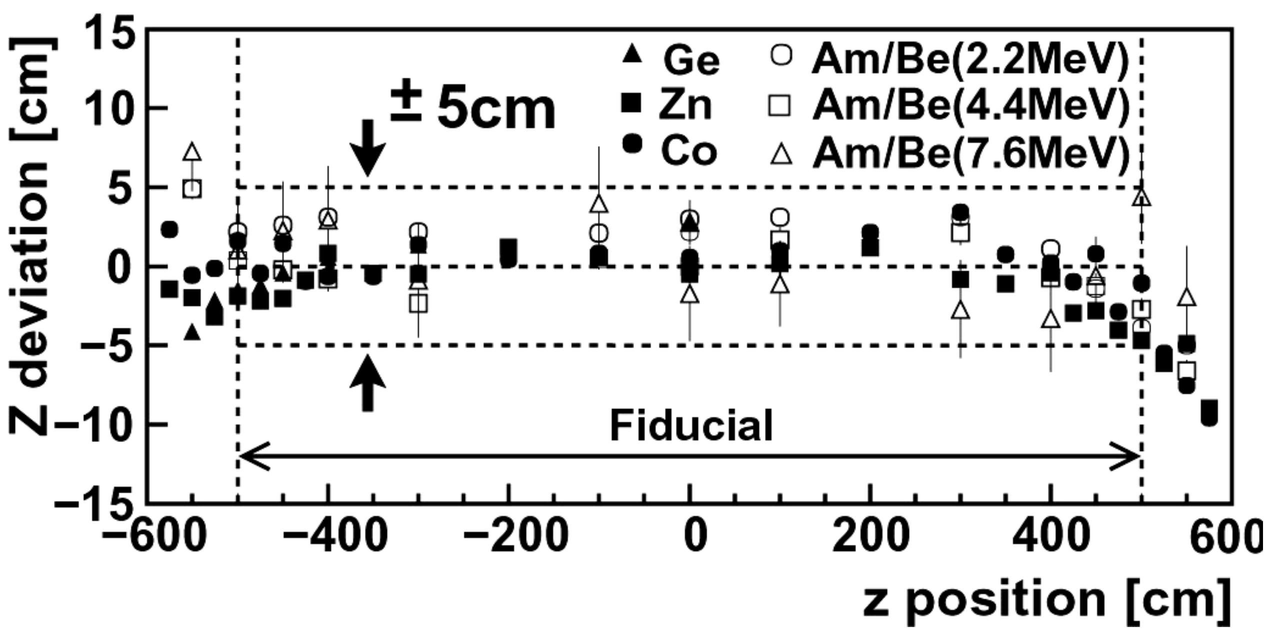
single p.e. events
before
and
after
correction

Position Reconstruction Uncertainty Along the Vertical Axis

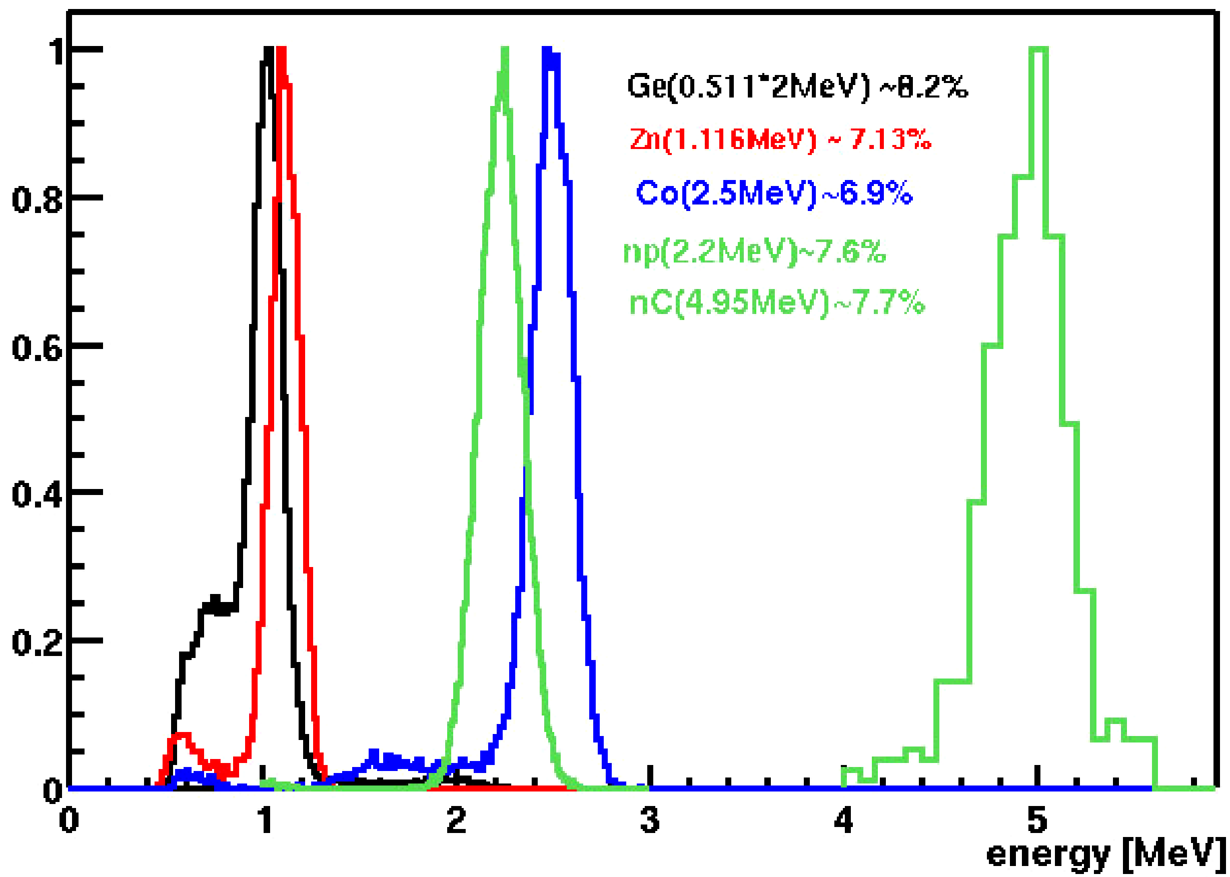
^{68}Ge : 1.012 MeV ($\gamma + \gamma$) ^{65}Zn : 1.116 MeV (γ)

^{60}Co : 2.506 MeV ($\gamma + \gamma$) AmBe : 2.20 , 4.40, 7.6 MeV (γ)





Energy calibration and resolution



$\Delta E/E \sim 7.5\% / \sqrt{E}$, Light Yield: 260 p.e./MeV

Autoradiography of KamLAND

$$^{238}U : \; ^{214}Bi \xrightarrow[\beta+\gamma]{} \; ^{214}Po \xrightarrow[\alpha]{} \; ^{210}Pb$$

$E = 3.27\ MeV$ $\quad$ $E = 7.69\ MeV$

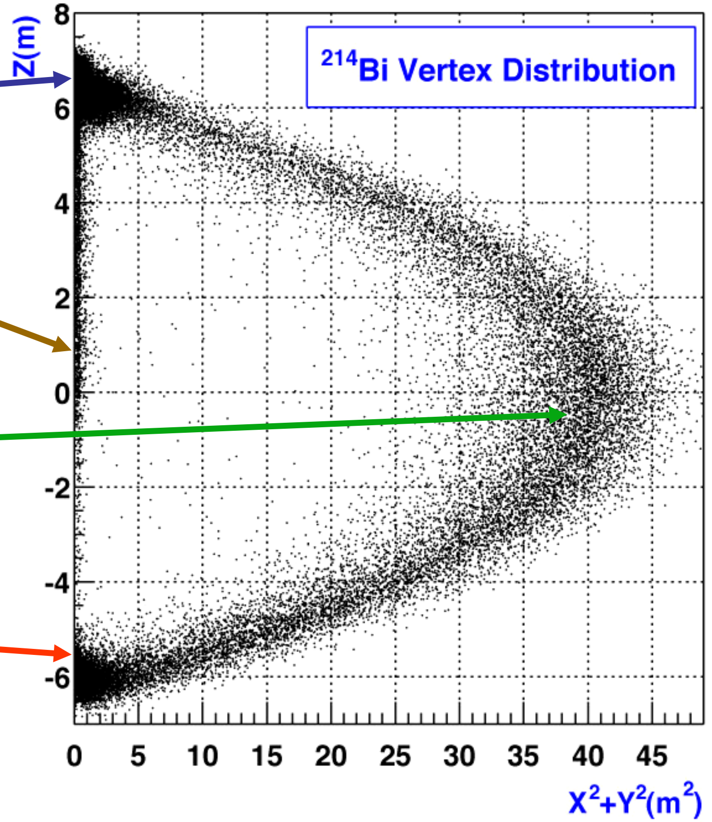
$\tau = 28.7\ min.$ $\quad$ $\tau = 237\ \mu s$

Top flange and chimney region

Central thermometer

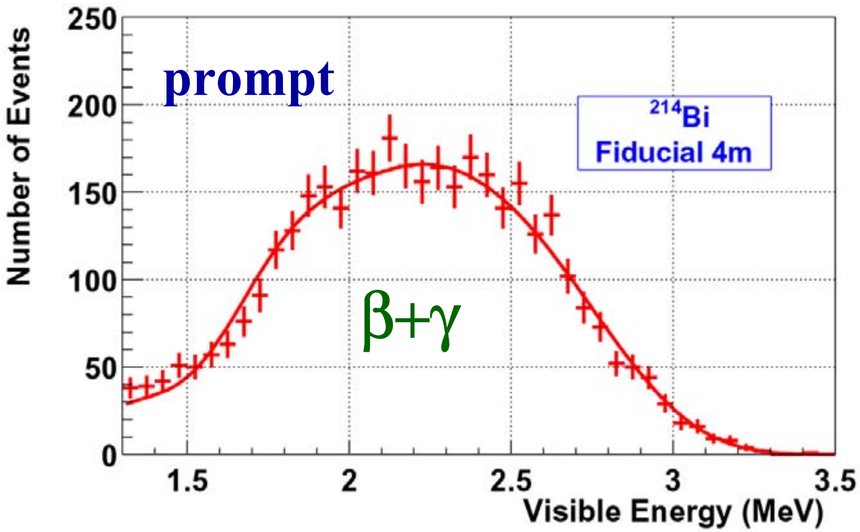
Balloon

Bottom flange and plumbing

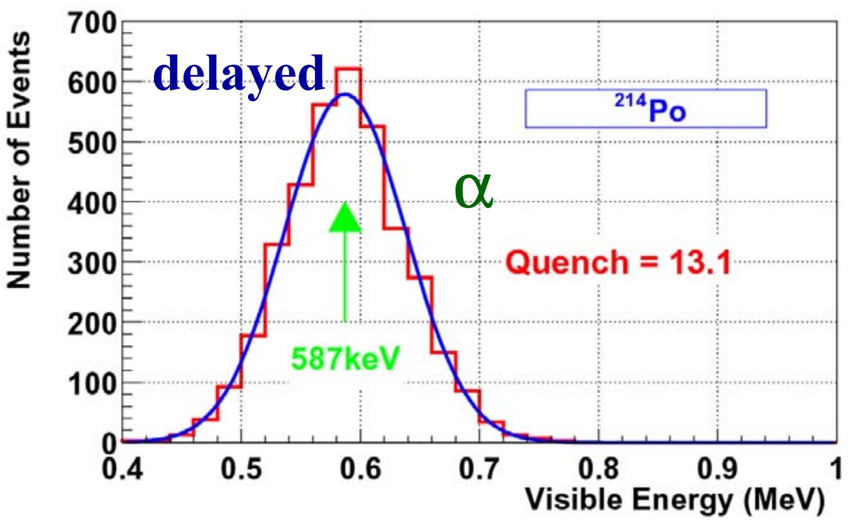


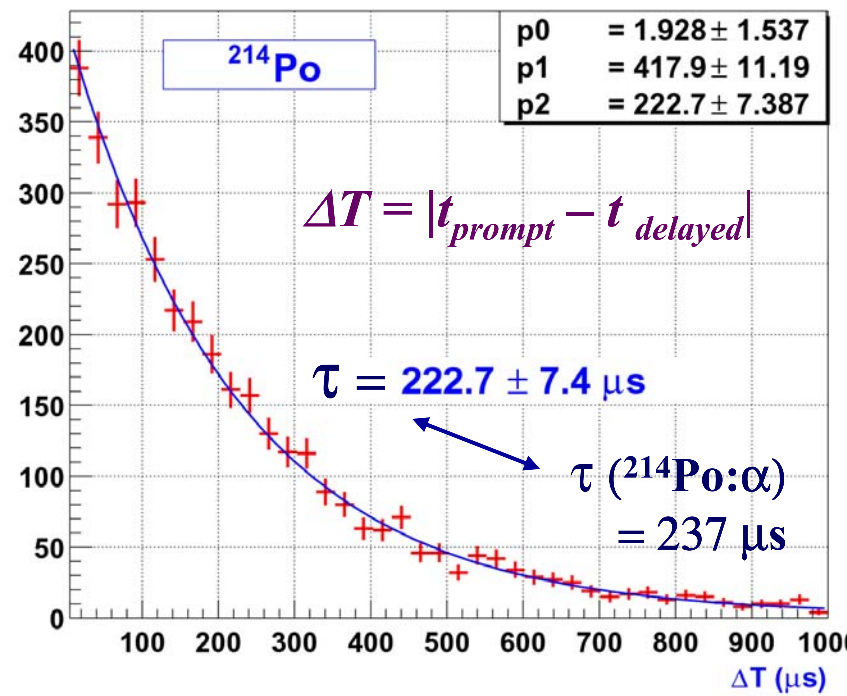
Correlations can be used to quantitatively measure scintillator contamination:

^{214}Bi – ^{214}Po – ^{210}Pb Signal

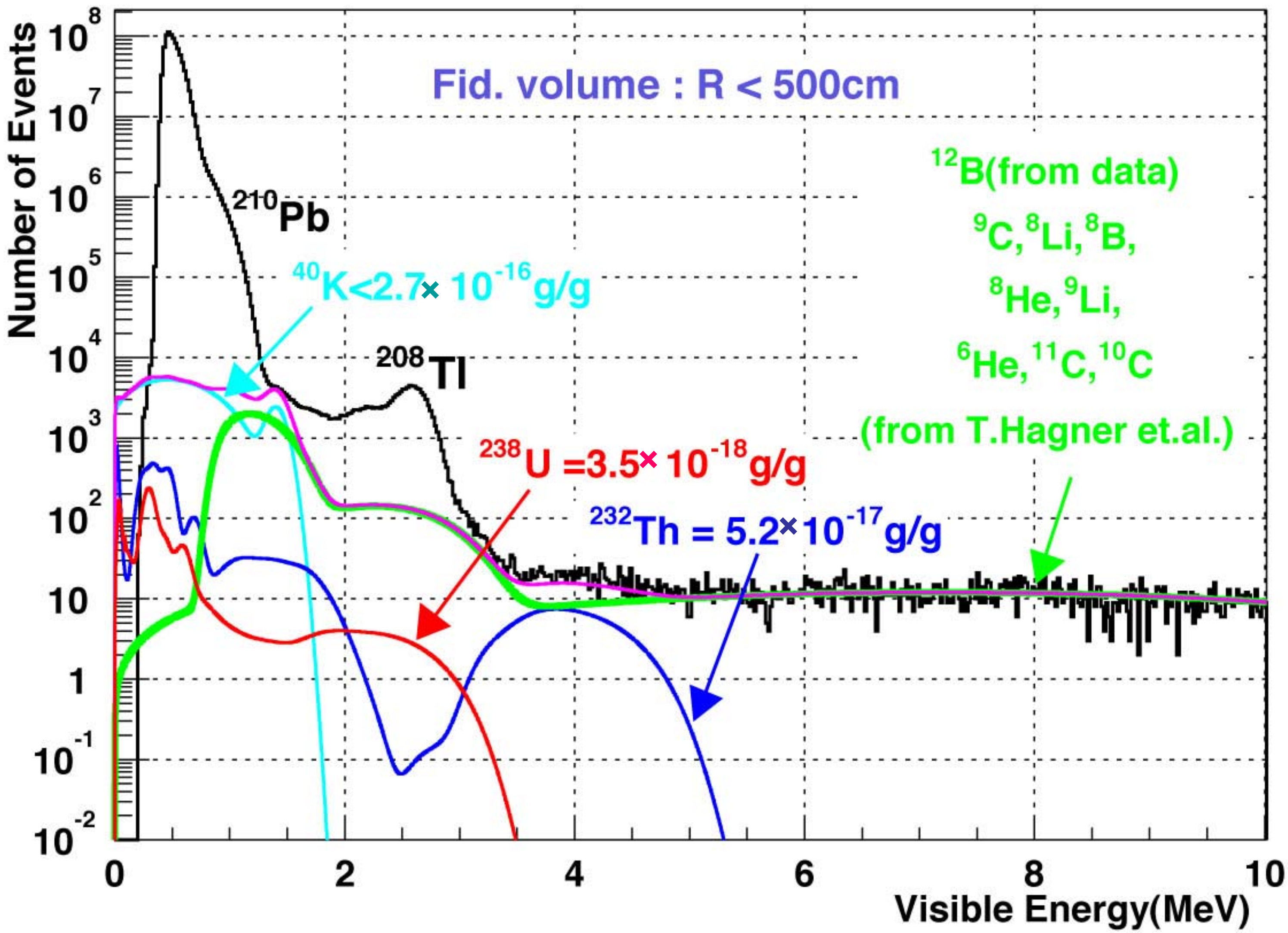


$^{238}U = (3.5 \pm 0.5) \times 10^{-18}$ g/g

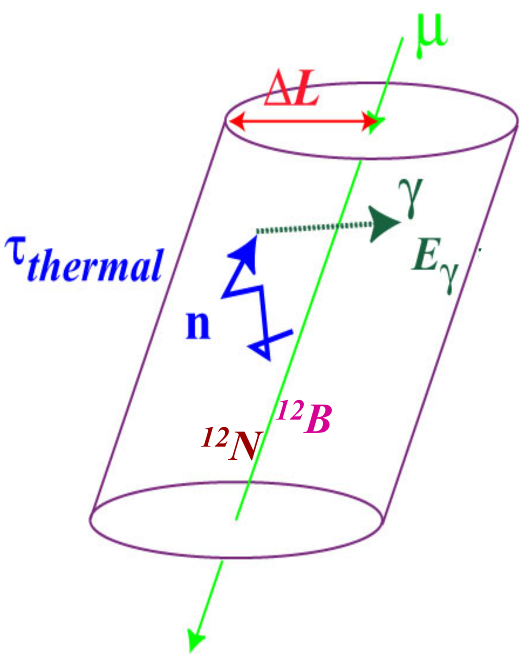


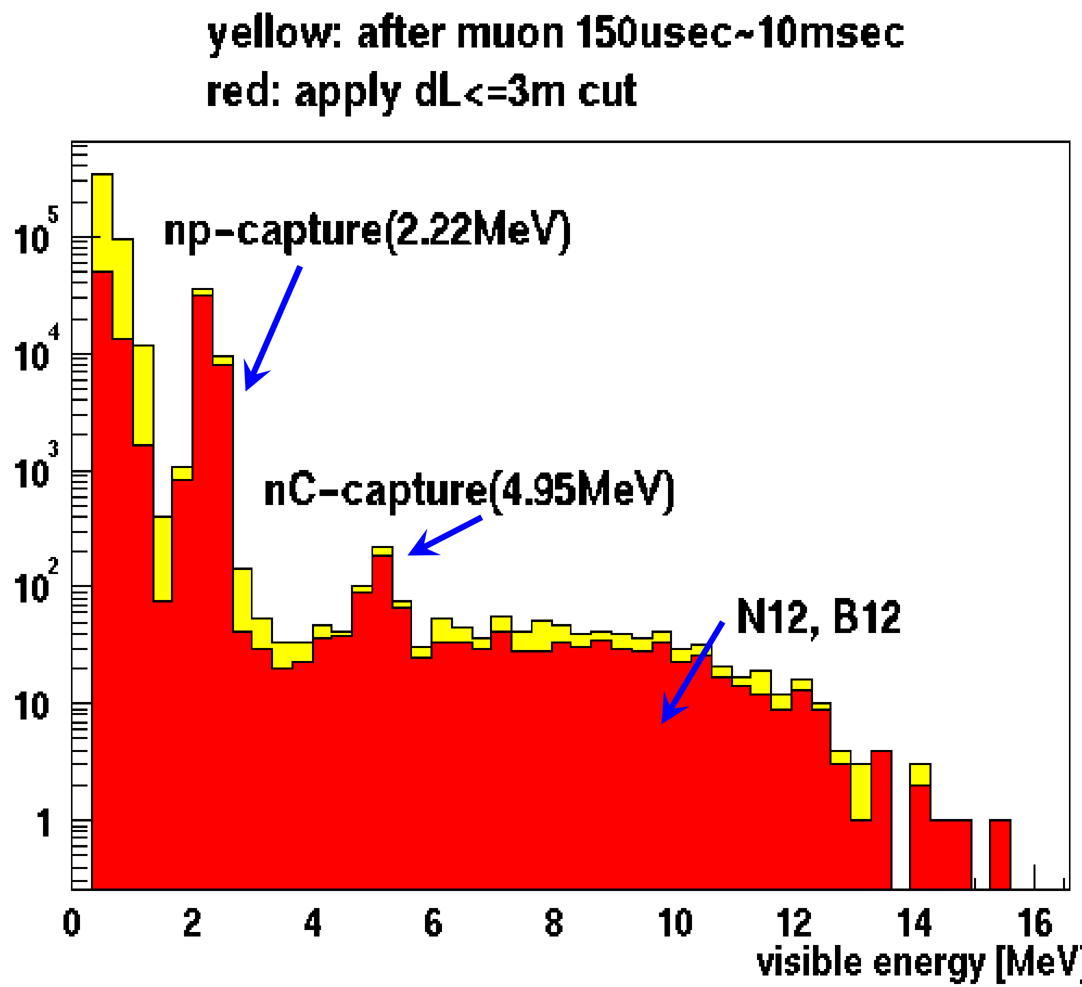


KamLAND is probably the lowest radioactivity environment on Earth !



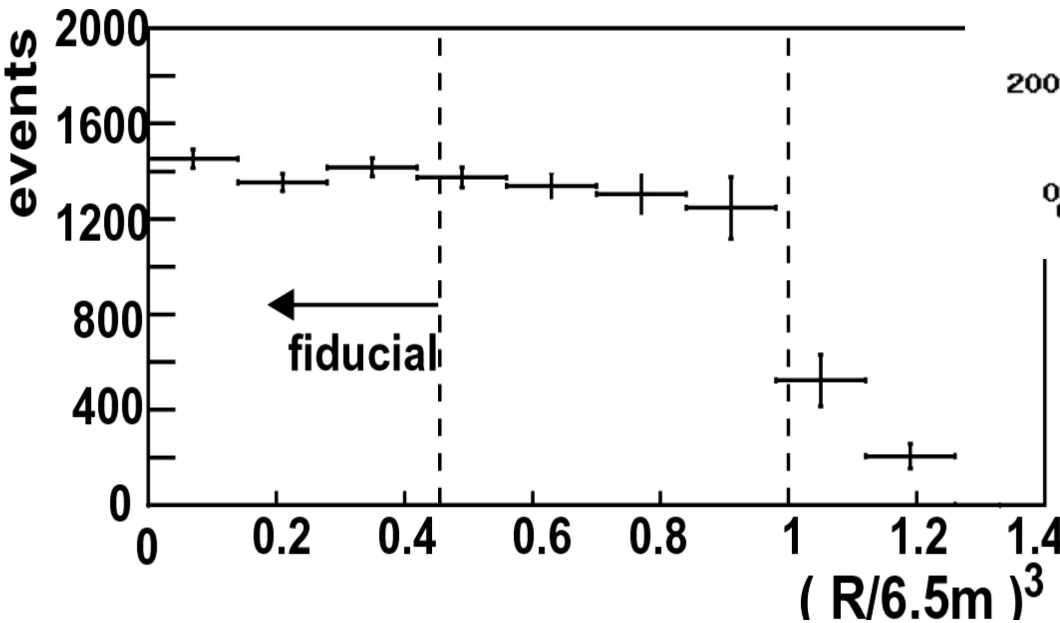
μ-Induced Neutrons & Spallation-$^{12}B/^{12}N$ are both a background and a calibration source

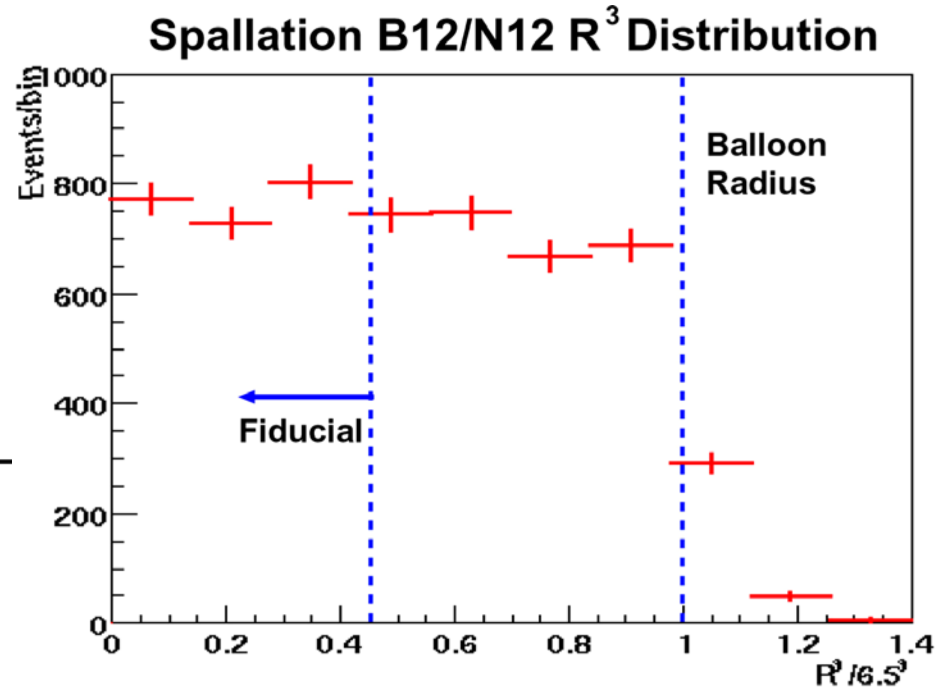




In particular neutrons & $^{12}B/^{12}N$ are the best tool to establish the fiducial volume

$R_{fid} = 6.5$ m
$R_{fid} = 5$ m
$\Delta V_{fid}/V_{fid} = 4.6$ %





Fiducial mass 408 ton (out of 1000)

Selecting anti-neutrinos

- $0.5\ \mu s < \Delta T_{e-n} < 660\ \mu s$
- $\Delta R_{e-n} < 1.6$ m
- 1.8 MeV $< E_n < 2.6$ MeV

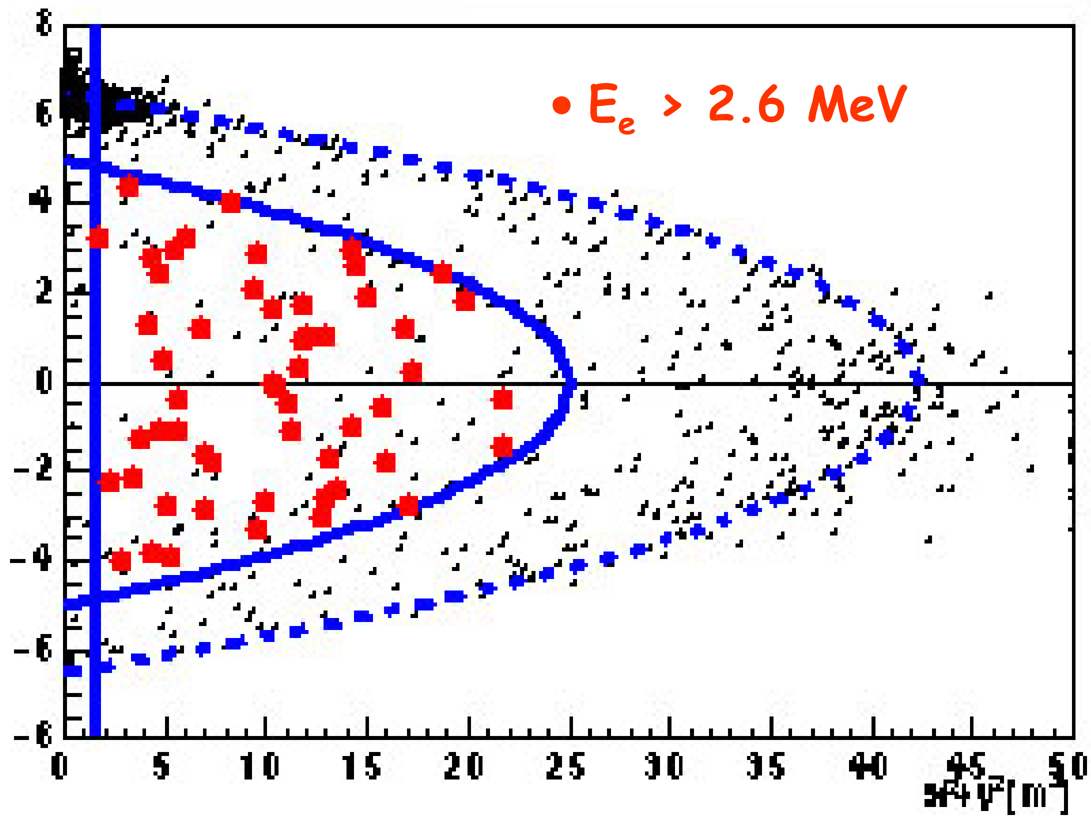
Tagging efficiency 78.3%

- 2 s veto for showering μ (E>3GeV)
- 2 s veto in a R = 3 m tube along all μ

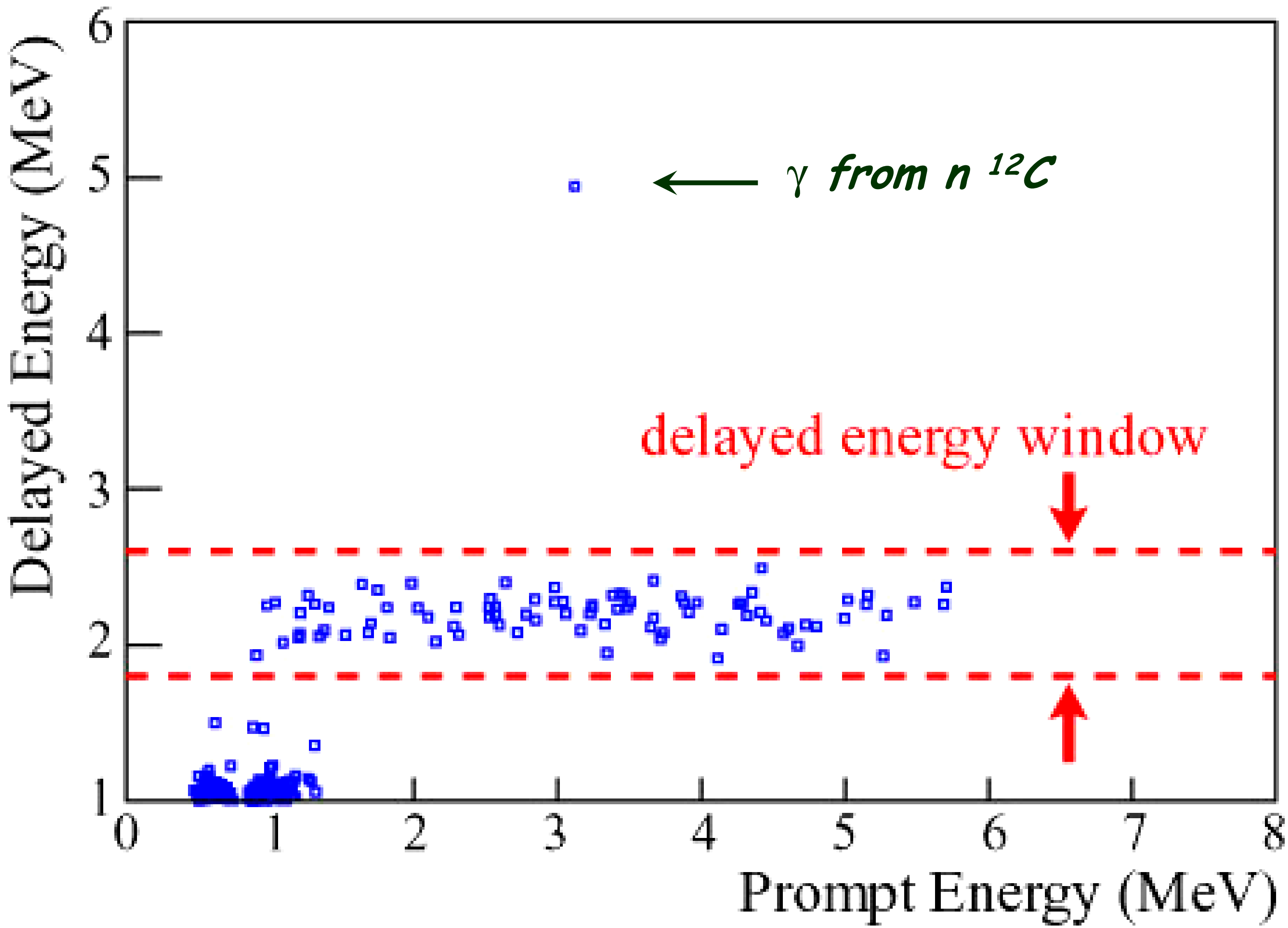
Dead-time 11.4%

- R < 5 m
- thermometer cut $[x^2+y^2>(1.2m)^2]$

3.46×10^{31} free protons



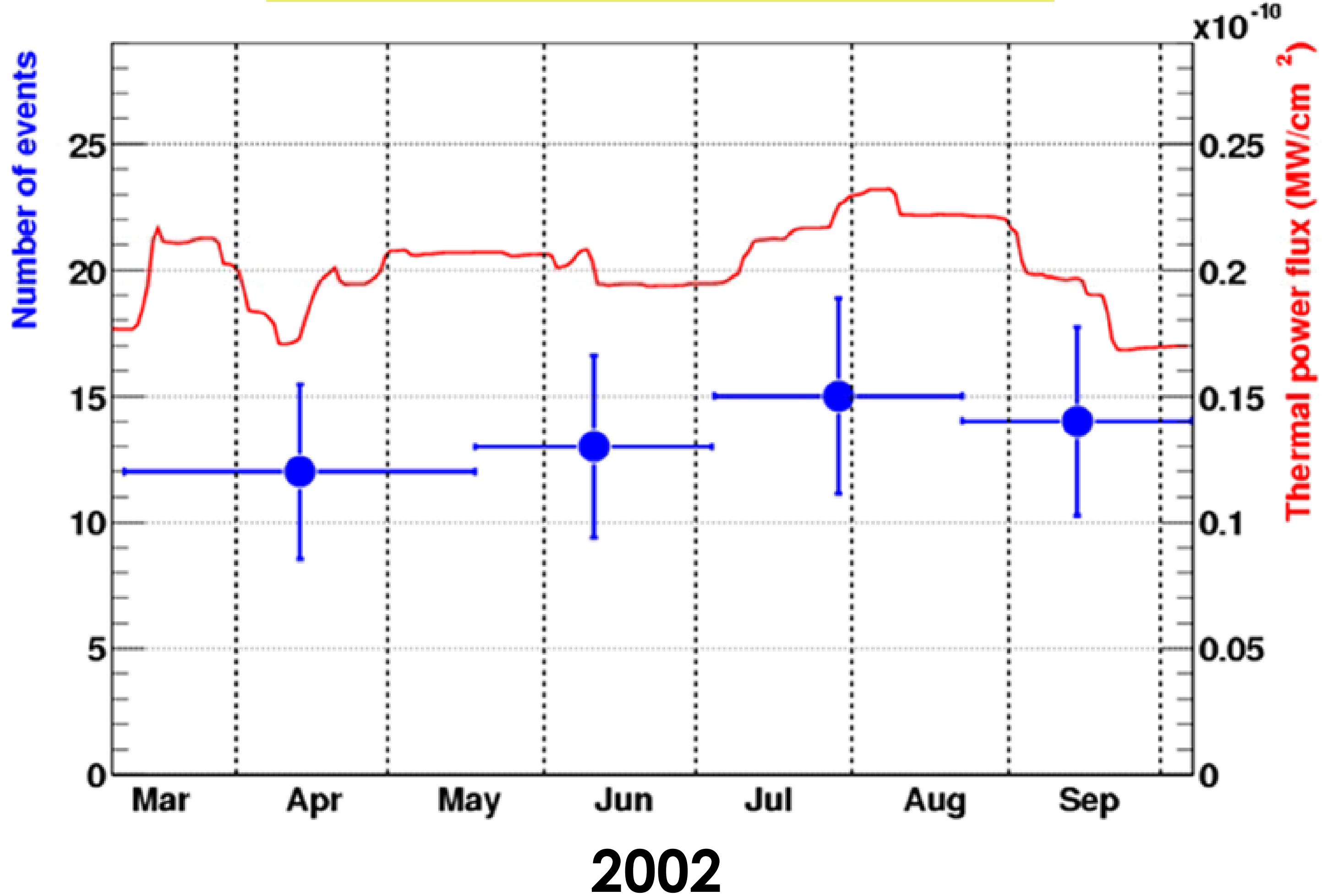
All cuts applied BUT the one on delayed energy



Estimated Systematic Uncertainties

	%
Total LS mass	2.1
Fiducial mass ratio	4.1
Energy threshold	2.1
Selection cuts	2.1
Live time	0.07
Reactor power	2.0
Fuel composition	1.0
Time lag	0.28
ν_e spectra	2.5
Cross section	0.2
Total systematic error	**6.4 %**

Time Dependence of Reactor Power and Signals



Observed Event Rates with $E_{prompt} > 2.6$ MeV

Data	**54 events**
Expected	**86.8 ± 5.6 events**
Total Background	**0.95 ± 0.99 events**
accidental	*0.0086 ± 0.0005*
$^{9}Li/^{8}He$	*0.94 ± 0.85*
fast neutron	*< 0.5*

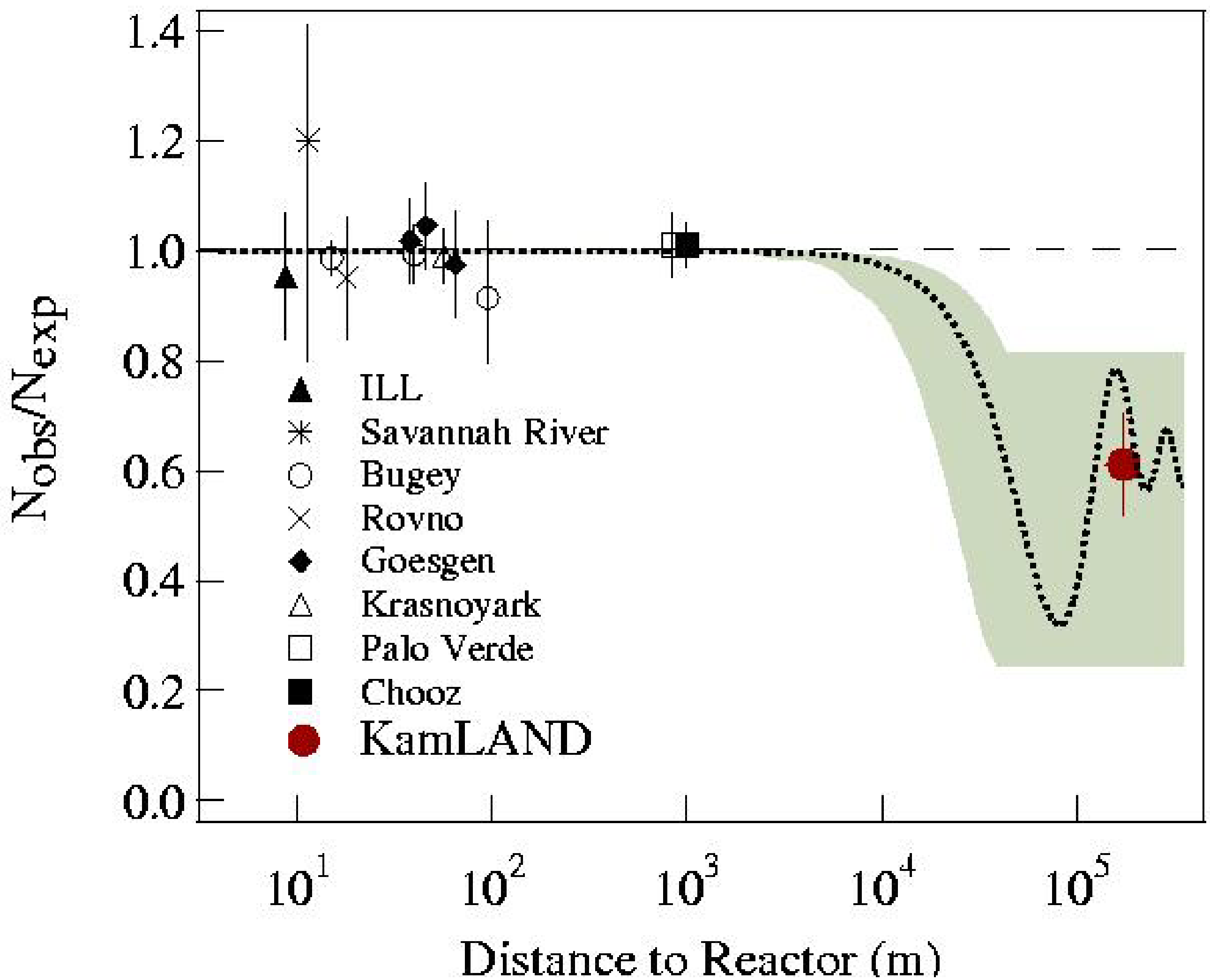
Evidence for Reactor $\bar{\nu}_e$ Disappearance

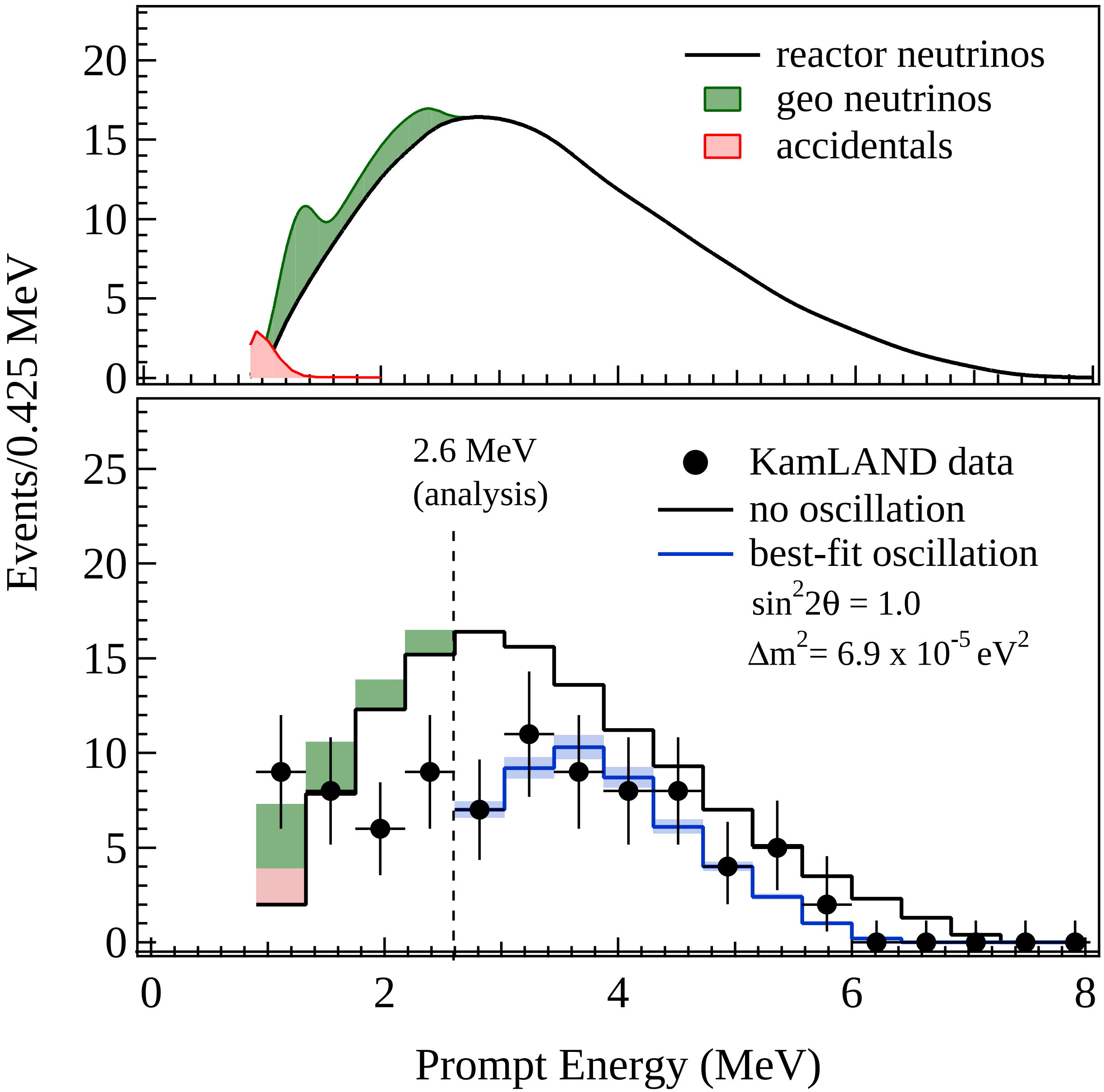
for $E_\nu > 3.4$ MeV

$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085\ (\text{stat}) \pm 0.041\ (\text{syst})$$

Inconsistent with $1/R^2$ flux dependence at 99.95 % C.L.

After 30 years of work reactor neutrinos finally are unmasked !





Almost back-ground free measurement !

Shape prefers deformation

…but…

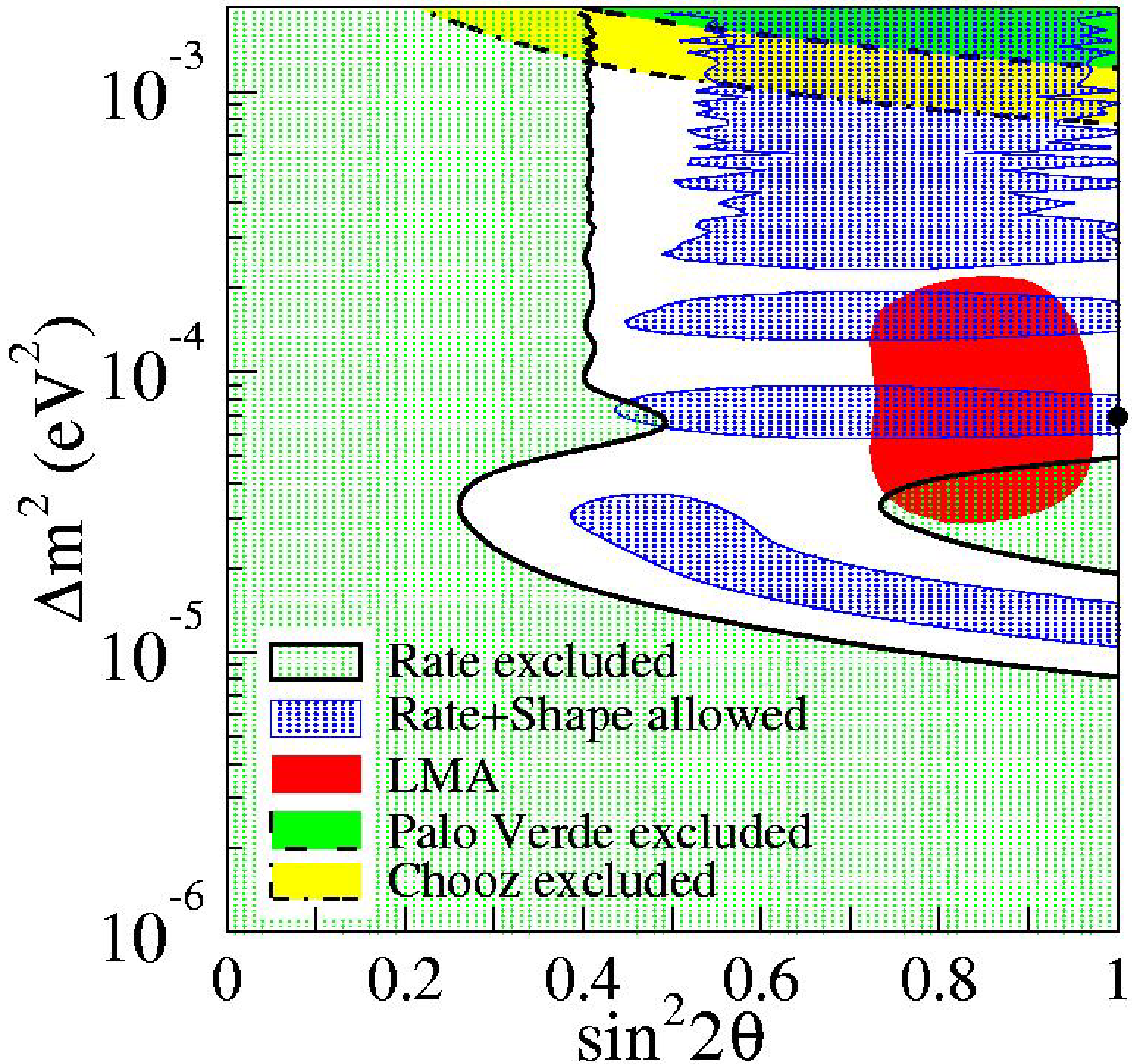
Scaled no-osc. shape compat. at 53% CL → need more data for this

Fit to Oscillations for E_{prompt} > 2.6 MeV

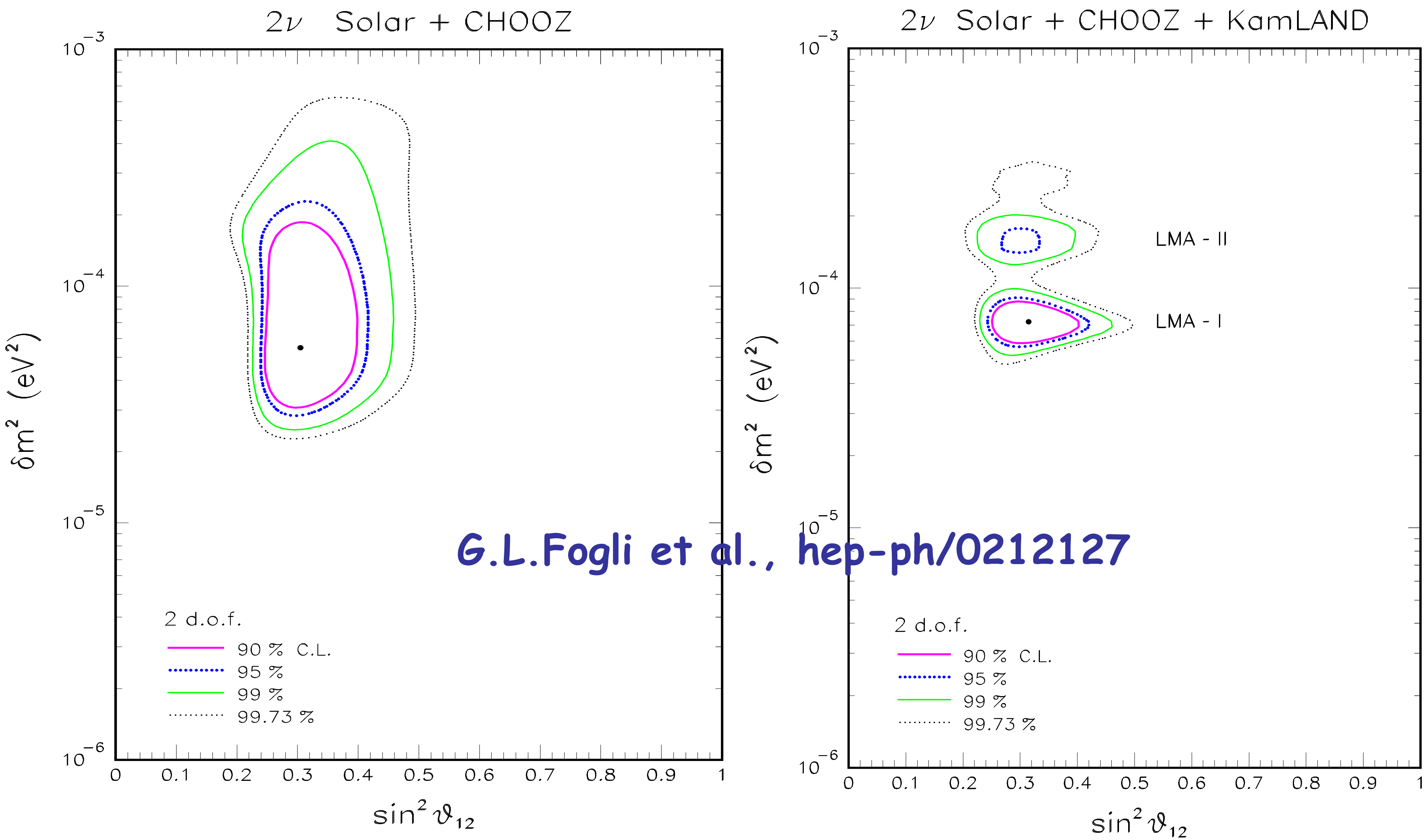
Best fit :

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

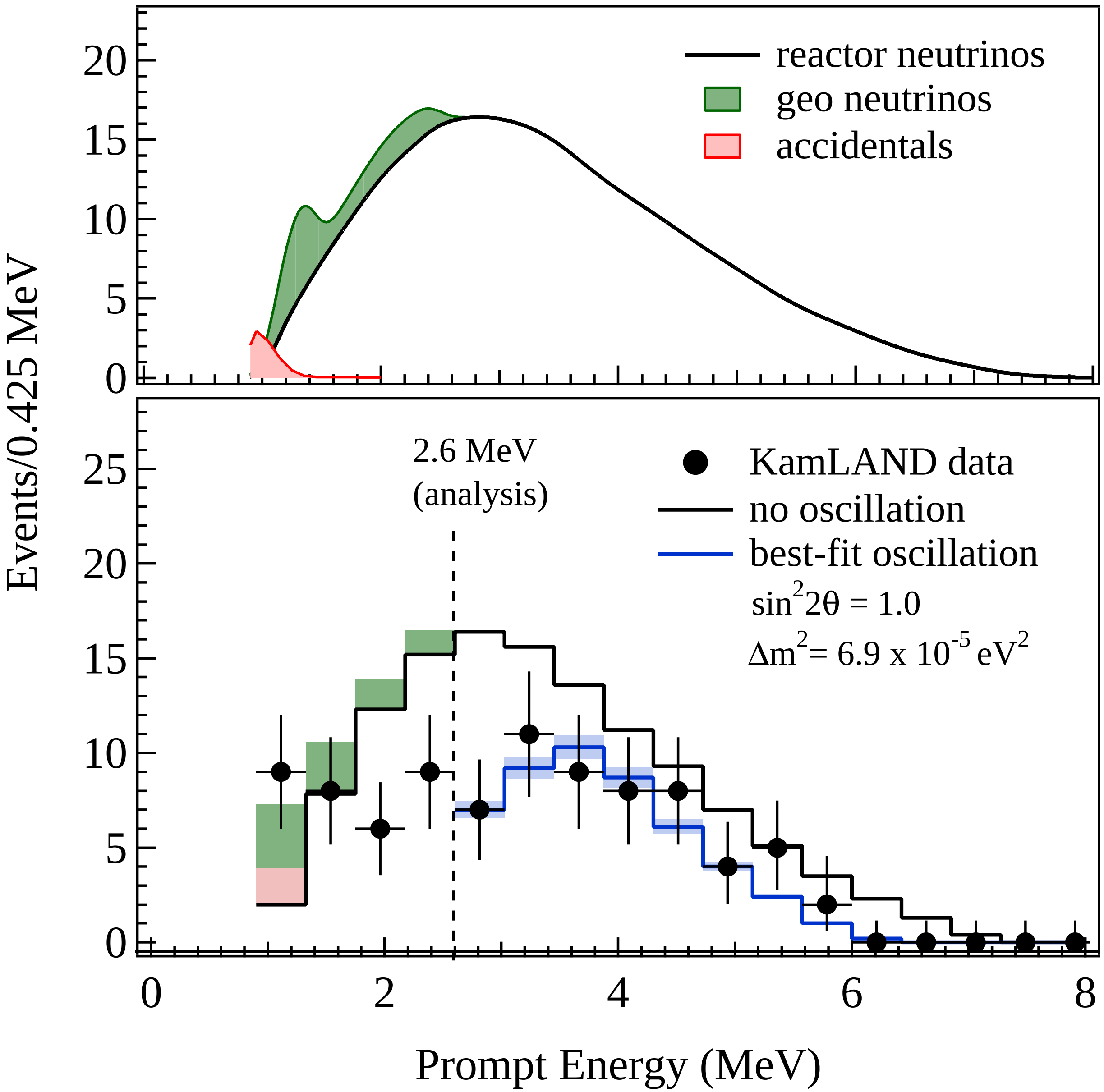
$\sin^2 2\theta = 1.0$



A number (5 as of this morning) of phenomenological papers have appeared on the LANL server even before our preprint



G.L.Fogli et al., hep-ph/0212127



Almost back-ground free measurement !

Shape prefers deformation

…but…

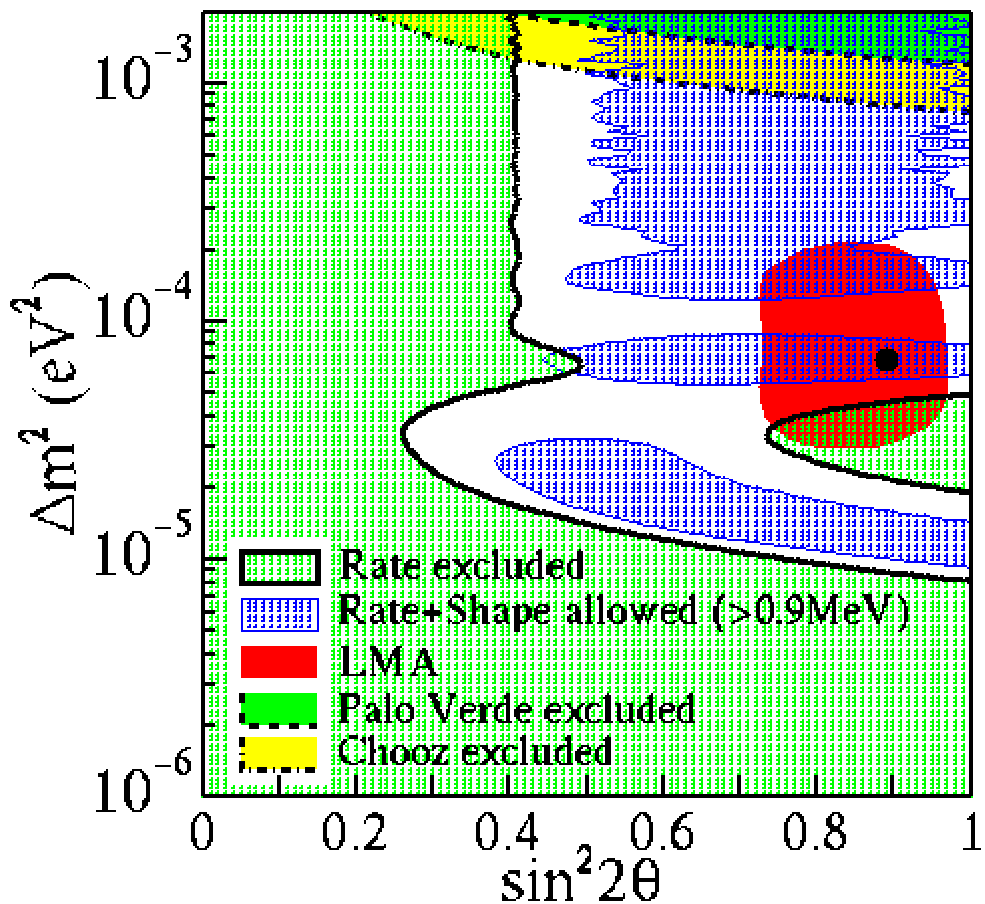
Scaled no-osc. shape compat. at 53% CL → need more data for this

Fit to Oscillations for E_{prompt} > 0.9 MeV (inverse β decay threshold)

Fix background but float geo-neutrinos in the fit

Best fit:
$\Delta m^2 = 6.9\times10^{-5}\ eV^2$
$\sin^2 2\theta = 0.91$

Resulting geo-neutrinos
4 events for ^{238}U
5 events for ^{232}Th
…still compatible with all sensible geophysical models at 95% CL



Conclusions:

KamLAND observes a >4 sigma deficit of reactor anti-neutrinos

Assuming that CPT is conserved the interpretation of this result in terms of oscillations is smack in the middle of the LMA-MSW solution:
The solar neutrino puzzle is now completely understood: we can reproduce it on Earth !

We can move on and use neutrinos to do solar physics !

More precision data on oscillation and many other phenomena is on the way… stay tuned !