Neutrini da reattori nucleari

I reattori nucleari sono una sorgente intensa di $\overline{\nu}_e$ dai decadimenti β dei frammenti di fissione.

Ogni reazione di fissione libera circa 200 MeV di energia e 6 $\overline{\nu}_e$.

$$\Downarrow$$

Il flusso é di circa $2 \cdot 10^{20}\, \overline{\nu}_e \;\; s^{-1}$ GWatt^{-1}, isotropo, $\langle E(\overline{\nu}_e\,)\rangle \simeq 0.5\, MeV$.

Storicamente i neutrini sono stati scoperti ad un reattore nucleare e i primi esperimenti di oscillazione sono stati condotti ai reattori.

La presente generazione di esperimenti di oscillazione ai reattori ricerca oscillazioni $\overline{\nu}_e \rightarrow \nu_x$ nella zona caratteristica delle oscillazioni di neutrini atmosferici: $\Delta m^2 = 3.5 \cdot 10^{-3}$ $\rightarrow L/E\ (km/GeV) \sim 5 \cdot 10^{-4} \rightarrow L \sim 1.5$ km.

Due esperimenti ad una distanza di circa 1 km da reattori nucleari: CHOOZ in Europa e PALO VERDE negli Stati Uniti.

Determinazione del flusso di neutrini

La misura sperimentale é la determinazione del numero assoluto di interazioni di neutrini sul rivelatore,

prompt positron signal, energy range.

$$\overline{\nu_e}\, p \rightarrow e^+ n$$

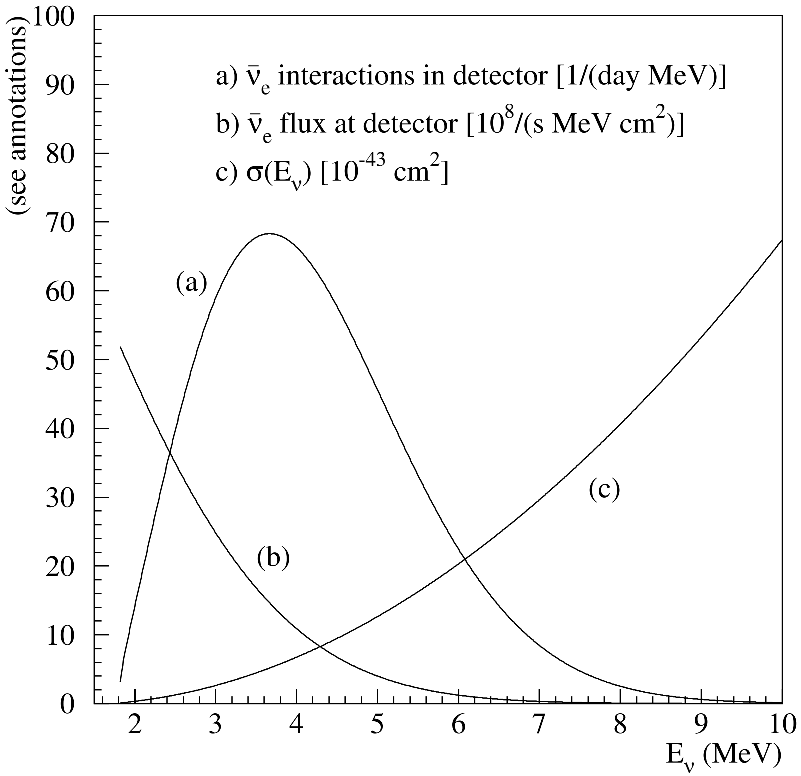
$$n + p \underset{\tau \simeq 186\,\mu s}{\longrightarrow} d + \gamma(2.2\,MeV)$$

delayed correlated photon.

in funzione dell'energia, confrontato con le stime di frequenza di interazioni di neutrini.

Per determinare quest'ultimo:

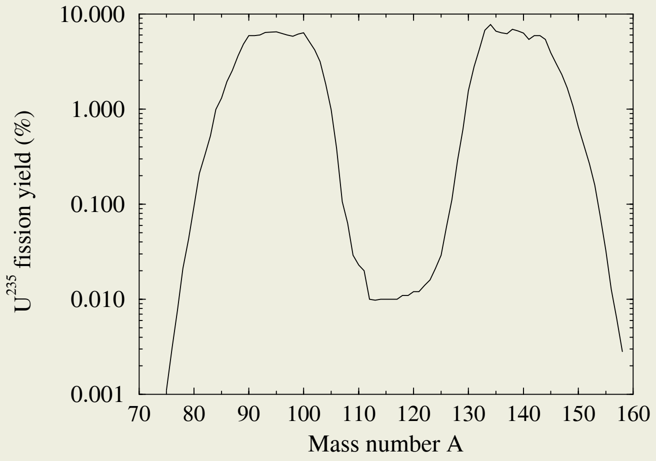
1. **Misura del potere termico del reattore**
2. **Determinazione dello spettro dei neutrini**
3. **Stima dell'osservabile sperimentale: lo spettro dei positroni nel rivelatore.**



La reazione piú comune e' la fissione di ^{235}U

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

I frammenti piú leggeri hanno in media $A \simeq 94$, i piú pesanti $A \simeq 140$. I nuclei stabili con $A = 94,\ 140$ sono ${}_{40}Zr^{94}$ e ${}_{58}Ce^{140}$. ^{235}U ha 98 protoni e 142 neutroni $\Rightarrow$ per raggiungere la stabilitá in media 6 neutroni devono decadere $\beta \Rightarrow 6\ \overline{\nu}_e$.

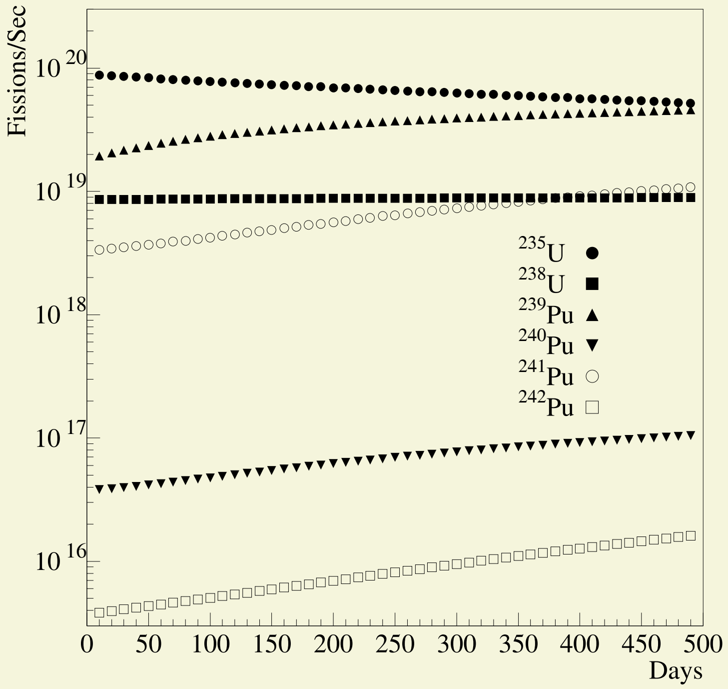


La soglia di produzione del processo di rivelazione $\overline{\nu}_e + p \rightarrow n + e^+$ é di $\sim 1.8\ MeV \Rightarrow$ solo il 25% dei neutrini da fissione é rivelabile.

Misura del potere termico del reattore

Tutti i neutrini da processi a basso Q-value, quali le scorte di combustibile stoccate nei reattori e la radioattivitá indotta nelle strutture del reattore, non producono neutrini rivelabili.

La composizione del combustibile del reattore varia nel tempo, ed é continuamente sotto monitoraggio (la potenza del reattore dipende dalla sua composizione).



Dalla frequenza di fissioni allo spettro degli $\overline{\nu}_e$

Lo spettro dei $\overline{\nu}_e$ per tre dei quattro principali isotopi (^{235}U, ^{239}Pu, ^{241}Pu), é derivato indirettamente da misure dello spettro di elettroni misurato direttamente. Il quarto componente principale, ^{238}U, é stimato a MonteCarlo, cosícome tutti i processi sulla catena di decadimento dei secondari. Errore sistematico: $\sim 1\%$.

Dai $\overline{\nu}_e$ ai positroni

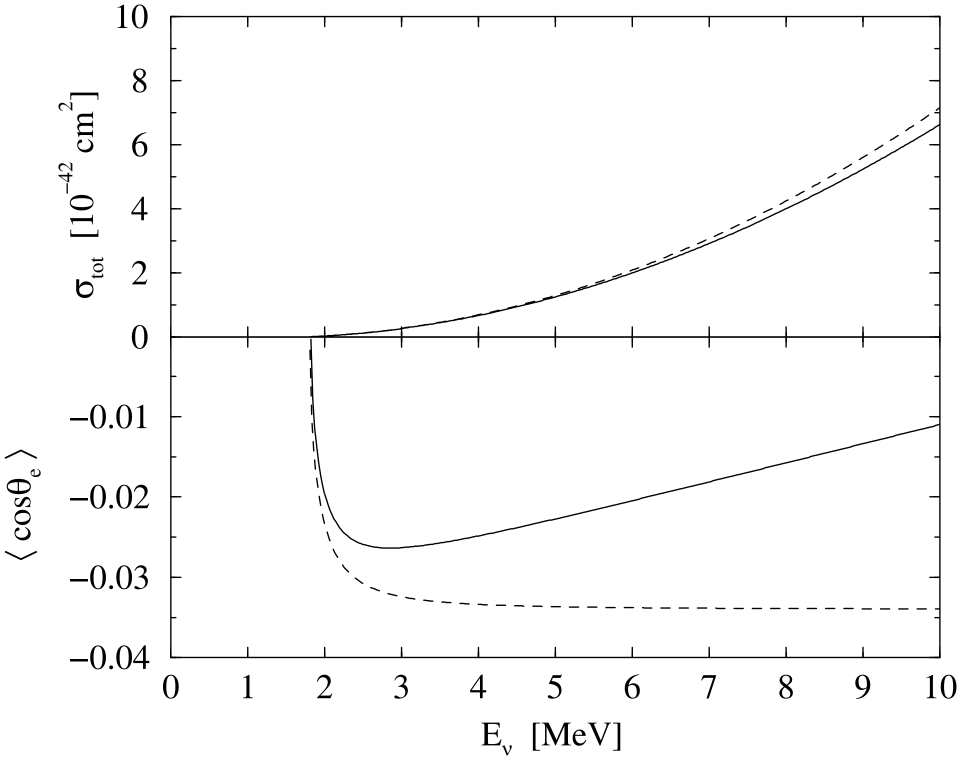
La sezione d'urto del processo $\overline{\nu}_e + p \rightarrow n + e^+$ é, al primo ordine:

$$\begin{aligned} \sigma^{(0)}_{tot} &= \sigma_0 \, (f^2 + 3g^2) \, E^{(0)}_e p^{(0)}_e \\ &= 0.0952 \left(\frac{E^{(0)}_e p^{(0)}_e}{1\,\mathrm{MeV}^2} \right) \times 10^{-42}\,\mathrm{cm}^2 \, , \end{aligned} \quad (1)$$

dove $E^{(0)}_e = E_\nu - (M_n - M_p)$ é l'energia del positronio (trascurando il rinculo del neutrone, marginale) $p^{(0)}_e$ il momento, $f = 1, g = 1.26$ sono le costandi di accoppiamento vettoriale e assiale. Infine

$$\sigma_0 = \frac{G_F^2 \cos^2\theta_C}{\pi} (1 + \Delta^R_{inner}) \, , \quad (2)$$

dove le correzioni radiative Δ^R_{inner} sono $\Delta^R_{inner} \simeq 0.024$.

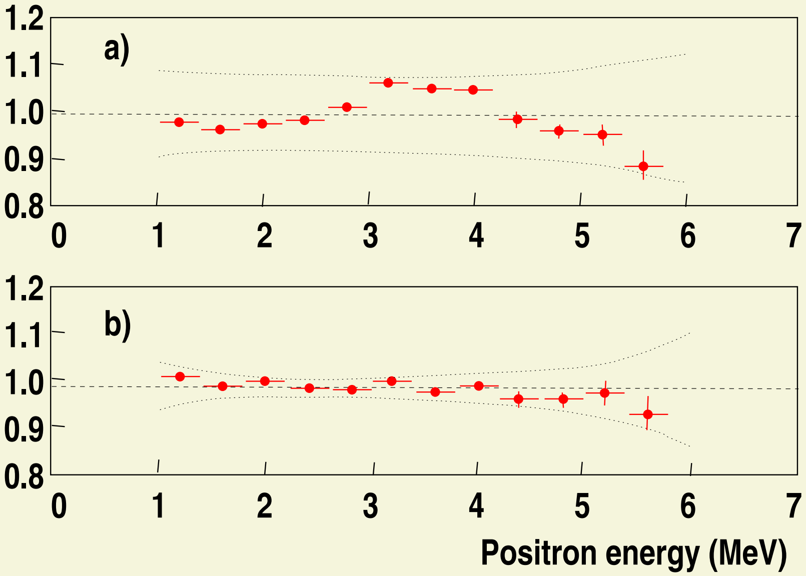


Linea solida: predizioni a $\mathcal{O}(1/M_n)$, tratteggiata $\mathcal{O}(1)$.

Accordo Predizioni Dati

Rapporto fra le misure dell'esperimento Bugey 3 (anni '80, ora si presume che non potesse vedere oscillazioni) e le predizioni dello spettro degli $\overline{\nu}_e$.

La curva b) é la predizione piú aggiornata.

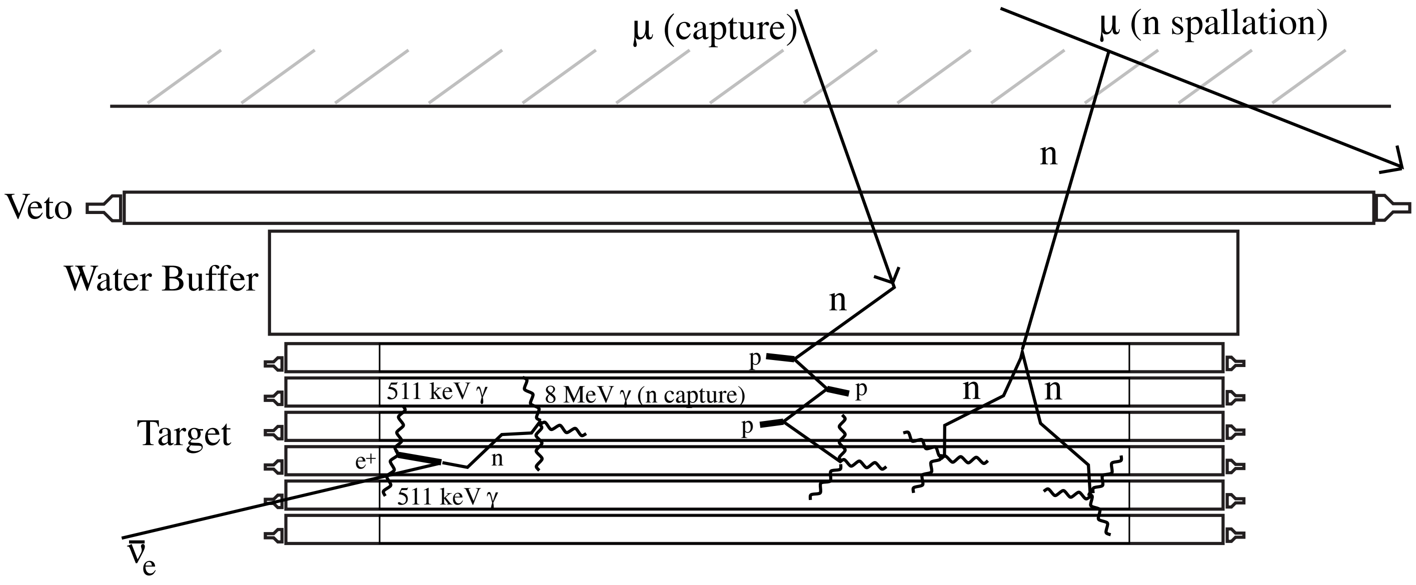


Summary degli errori sistematici (da `hep-ph/0107277`)

Origin and magnitude of systematic errors in PALO VERDE and CHOOZ. Note that the two experiments offer different breakdowns of their systematics. For simplicity we do not show the systematics for the PALO VERDE ON-OFF analysis. The PALO VERDE results are from the analysis of the full data set (Boehm *et al.* 2001).

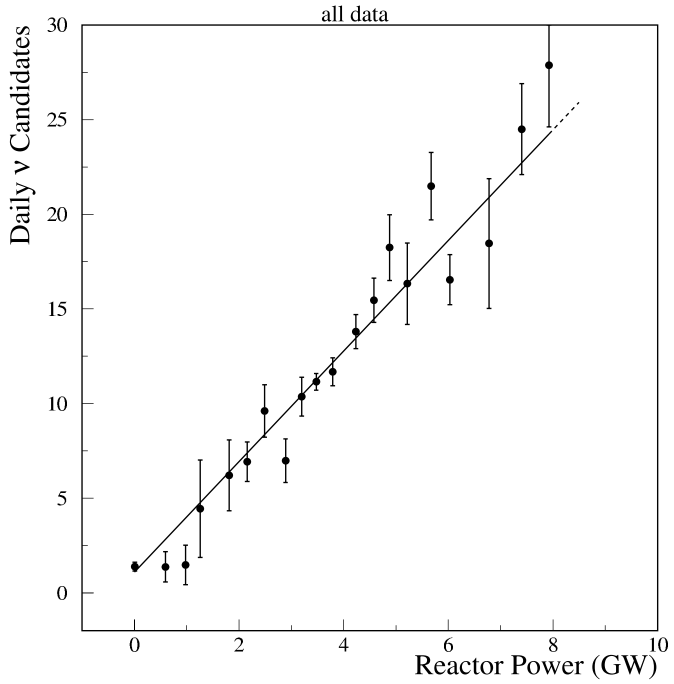
Systematic	CHOOZ (%)		PALO VERDE (%)	
$\sigma(\bar{\nu}_{\rm e} + {\rm p} \rightarrow {\rm n} + {\rm e}^+)$	1.9		-	
Number of p in target	0.8		-	
W_{th}	0.7		-	
Energy absorbed per fission	0.6		-	
Total rate prediction		2.3		2.1
$\rm e^+$ trigger eff.	-		2.0	
n trigger eff.	-		2.1	
$\overline{\nu}_e$ selection cuts	-		2.1	
$(1-\epsilon_1)B_{\rm pn}$ estimate	-		3.3	
Total $\overline{\nu}_e$ efficiency		1.5		4.9
Total		2.7		5.3

Fondi Sperimentali



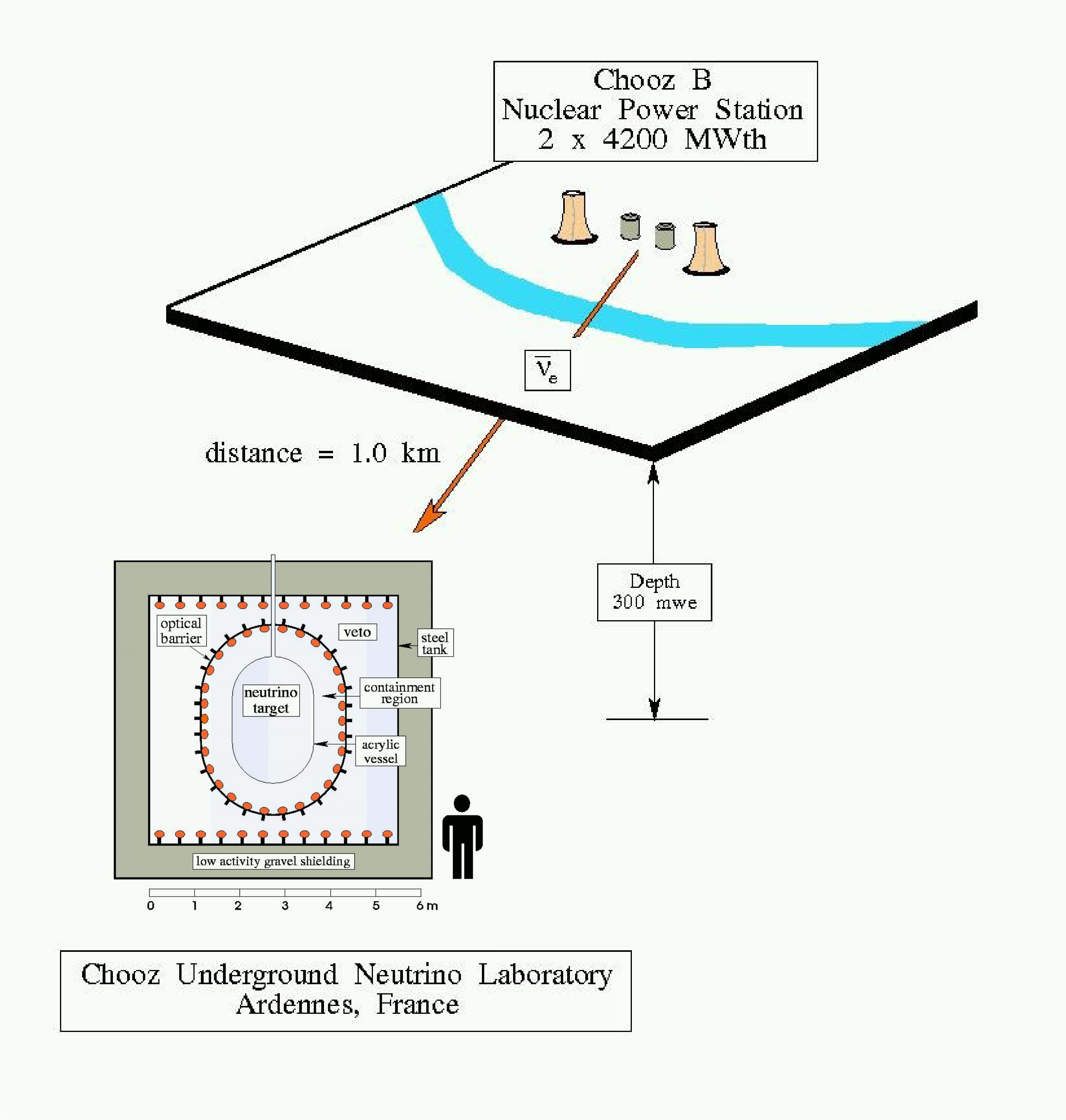
Principalmente due categorie:

- Fondi accidentali dati dalla coincidenza casuale di un segnale “positron-like” e uno “neutron-like”. Deducibile sperimentalmente misurando le probabilitá di singola dei due segnali.
- Fondi da neutroni indotti da raggi cosmici. Misurabili con precisione a reattore spento (se possibile! Nessuno pensa di spegnere un reattore di potenza per permettere ad un esperimento di oscillazione di misurare i propri fondi).

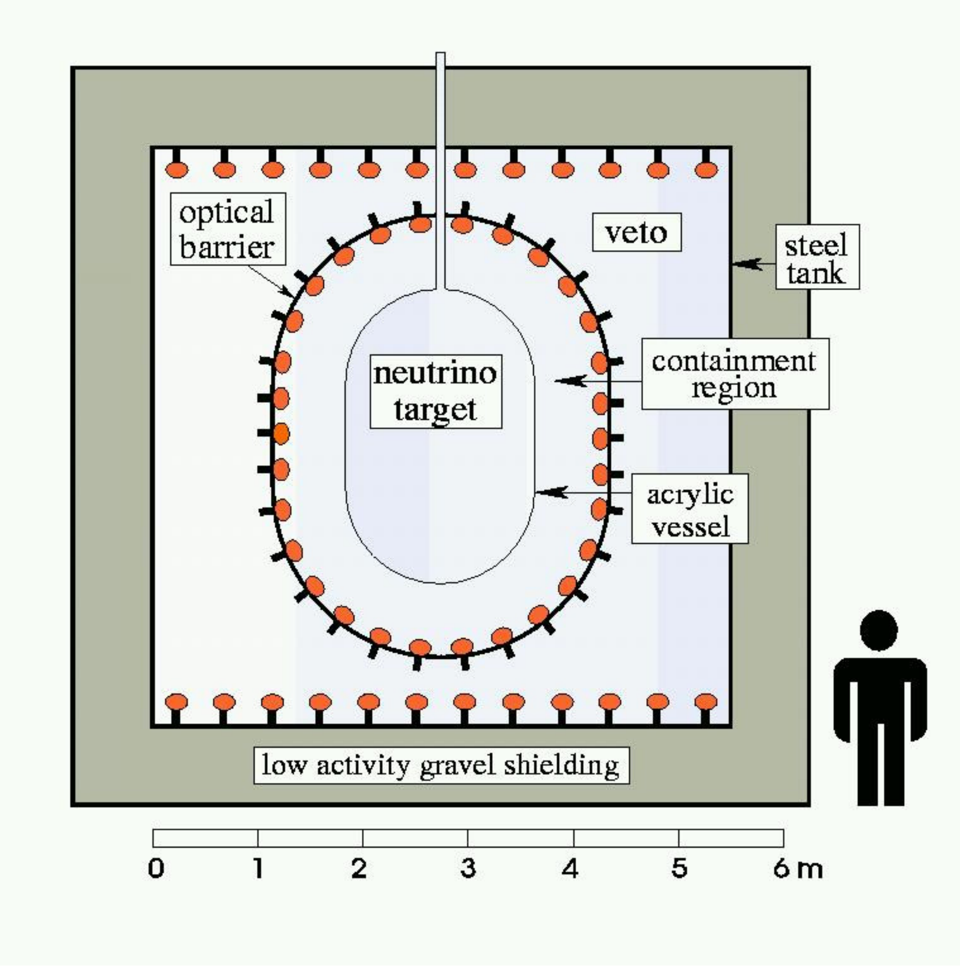


Conteggi nell’esperimento Chooz in funzione della potenza del reattore.

Esperimento CHOOZ (Francia-Italia-Russia-USA)



Il rivelatore CHOOZ



Rivelatore di 5 ton di scintillatore liquido drogato con gadolinio. Veto con scintillatore liquido.

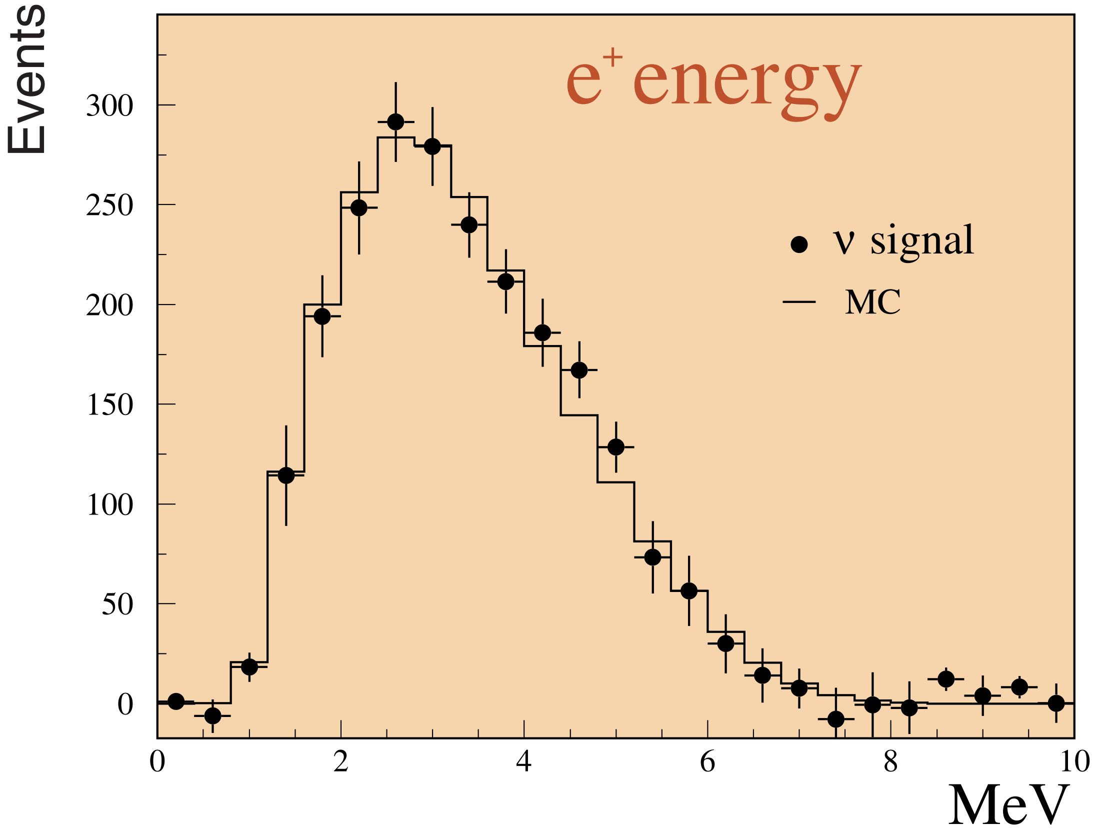
Rivelazione di $\overline{\nu}_e$:

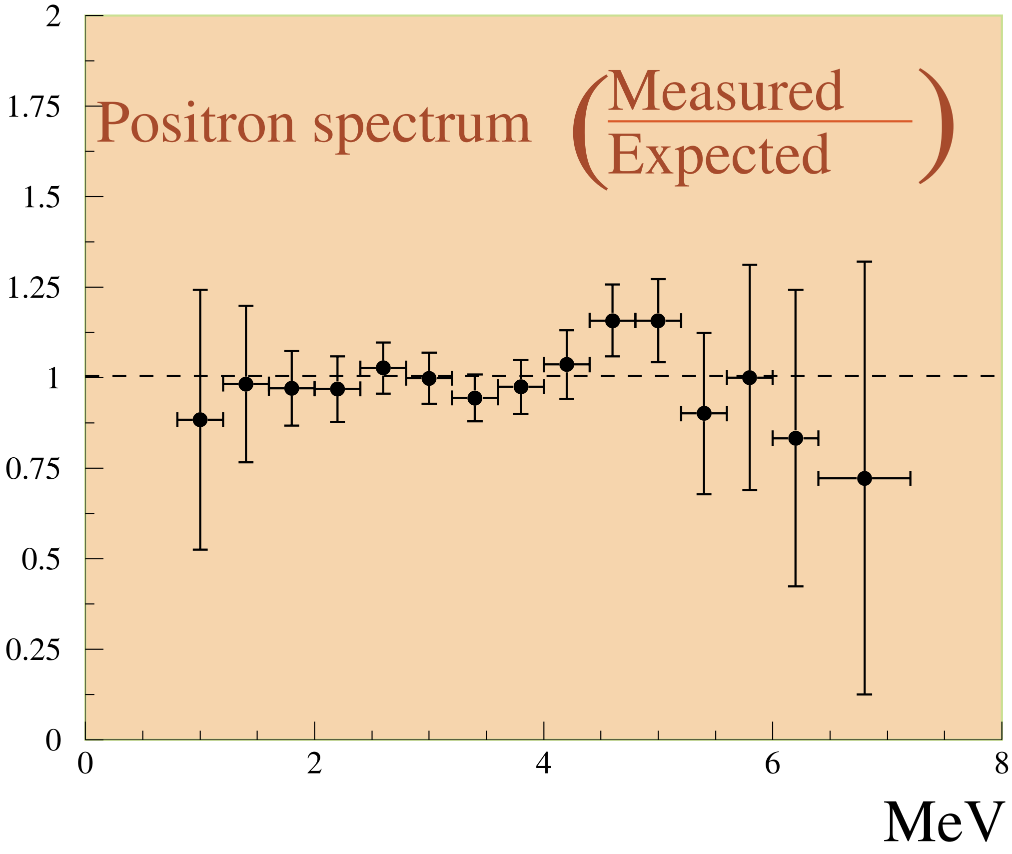
$$\overline{\nu}_e + p \rightarrow e^+ + n \quad E(\overline{\nu}_e) = E(e^+) + 1.804\,MeV$$

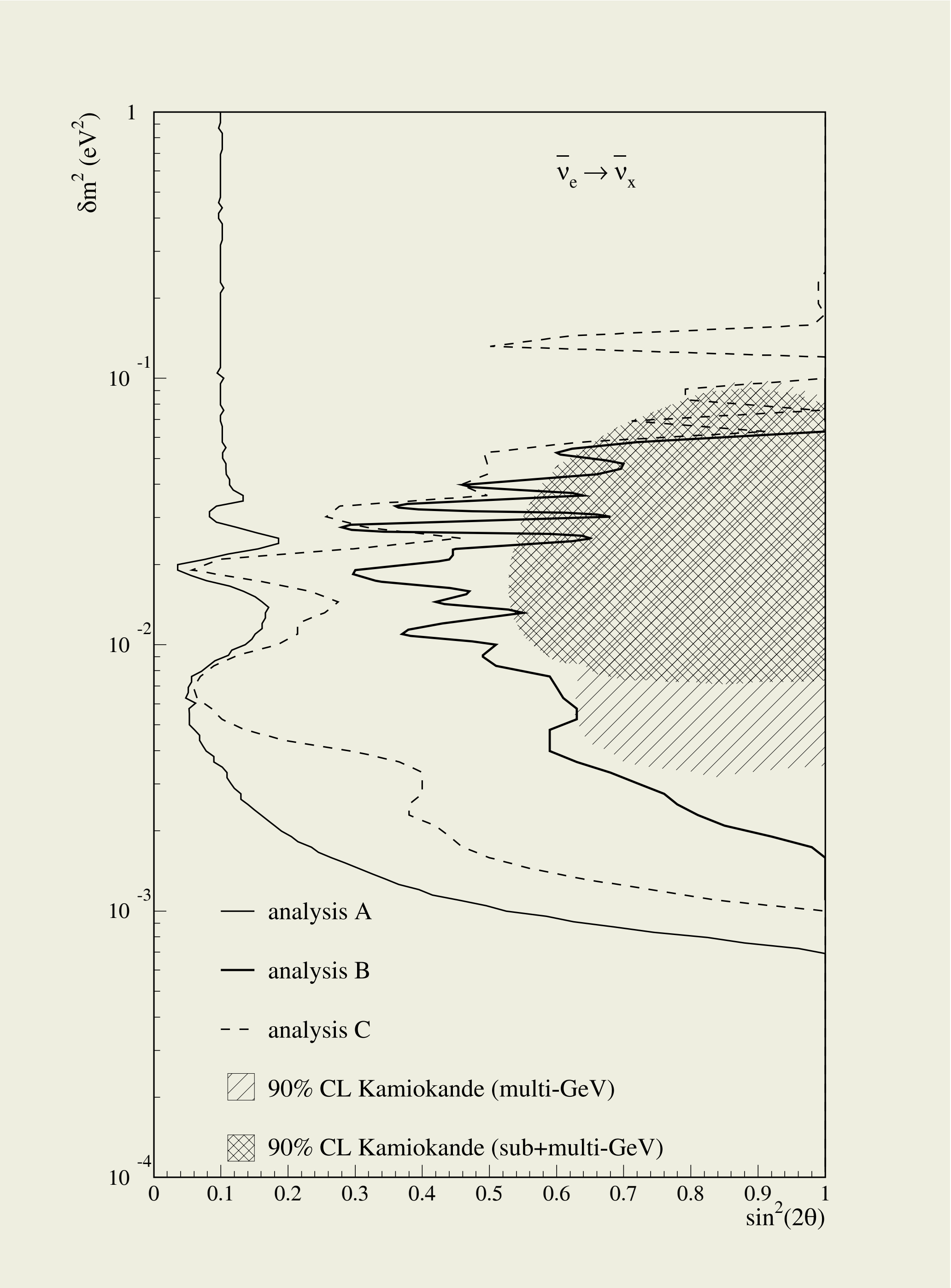
Due segnali in sequenza:

1. Prompt: e^+ seguito da $e^+e^- \rightarrow \gamma\gamma$
2. Ritardato: cattura del neutrone in gadolinio, dopo la termalizzazione, con rilascio di circa 8 MeV.

CHOOZ all data







Risultati finali di CHOOZ

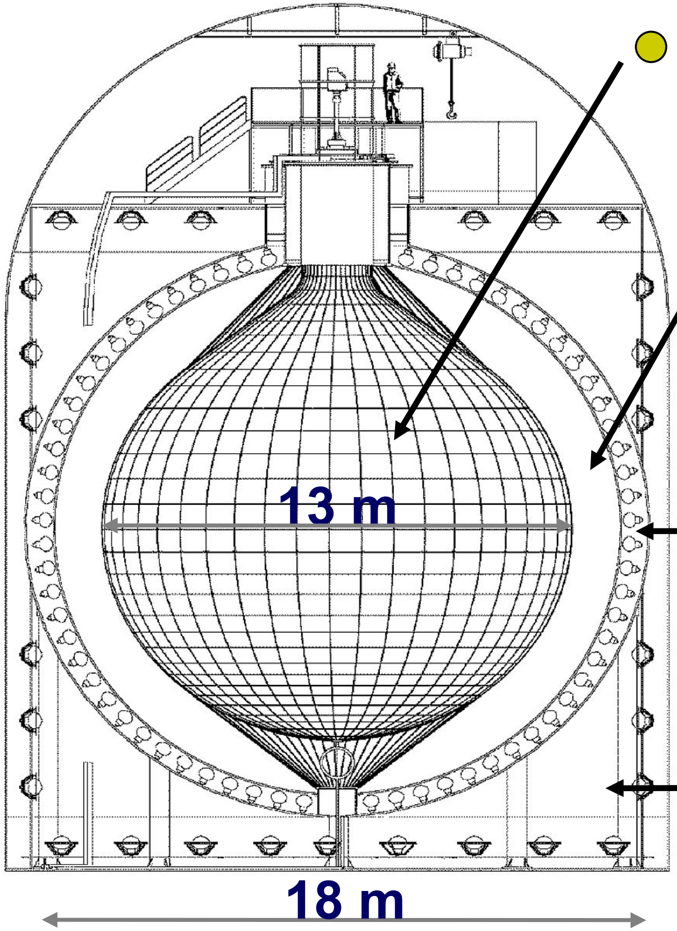
- **Analisi A** Spettro di $\overline{\nu}_e$ dopo aver sottratto i fondi. Sono utilizzati sia la rate assoluta che lo spettro.
- **Analisi B** Usa la differenza delle baseline ($\Delta L = 117.7\, m$) fra i due reattori.

  Molte delle sistematiche si cancellano, ma gli errori statistici sono maggiori e la sensibilitá in Δm^2 é ridotta data la baseline piú corta.
- **Analisi C** Solo la forma dello spettro é utilizzata.

Top Cited 1000+ Sperimentali in QSPIRES (al 6/11/05)

2850	WMAP	First Year Wilkinson Microwave observations: determination of cosmological parameters.	2003
2493	S. Perlmutter et al.,	Measurements of Omega and Lambda from 42 high redshift supernovae.	1999
2462	SuperKamiokande	Evidence for oscillation of atmospheric neutrinos.	1999
2441	Adam G. Riess et al.,	Observational evidence from supernovae for an accelerating universe and a cosmological constant.	1998
2261	David J. Schlegel, Douglas P. Finkbeiner, Marc Davis,	Maps of dust IR emission for use in estimation of reddening and CMBR foregrounds	1998
1523	WMAP	First year Wilkinson Microwave observations: preliminary maps and basic results.	2003
1395	S. Ting et al.,	Experimental observation of a heavy particle J.	1974
1307	B. Richter et al.,	Discovery of a narrow resonance in e+ e- annihilation.	1974
1275	J. Ashman et al.,	A measurement of the spin asymmetry in deep inelastic muon - proton scattering.	1998
1211	COBE	Structure in the COBE dmr first year maps.	1992
1186	CDF	Observation of TOP quark production in anti-p p collisions.	1995
1138	D0	Observation of the TOP quark.	1995
1109	SNO	Measurement of the rate of $\nu_e + D - p + p + e$ interactions produced by B-8 solar neutrinos at the Sudbury Neutrino Observatory.	2001
1078	V.L. Fitch, J.W. Cronin et al.	Evidence for the 2 Pi decay of the K(2)0 meson	1964
1053	SNO	Direct evidence for neutrino a ν flavor transform. from neutral current interactions in the Sudbury Neutrino Observatory.	2002
1052	CHOOZ	Limits on neutrino oscillations from the Chooz experiment.	1999
1026	S.W. Herb et al.,	Observation of a dimuon resonance at 9.5-GEV in 400-GEV proton - nucleus collisions.	1977
1024	ARGUS	Observation of B0 - anti-B0 mixing.	1987
1018	Homestake (R. Davis et al.)	Measurement of the solar ν_e flux with the Homestake chlorine detector .	1998

KamLAND detector



- 1000 tons of liquid scintillator
  80% dodecane + 20% pseudocumene + PPO
- Mineral oil
  $\Delta\rho$ = 0.3 % to guarantee balloon stabilisation
  Buffer against external radiation
- 1879 PMTs (1325 17" + 554 20")
  Photocathode coverage 34%
- Outer water Cerenkov detector
  → μ veto

Calibration performed with radioactive sources and spallation products

$\sigma_E \sim 6.2\% / \mathrm{sqrt}(E)$

A brief history of KamLAND

	Dates	Live time (days)
Start data taking	Jan 2002	-
Run A (data-set of 1st paper)	Mar 9 - Oct 6 2002	145.4*
Electronics upgrade & 20" PMT commissioning	Jan/Feb 2003	-
Run B	Oct - Jan 11 2004	369.7
Data-set presented here†	Mar 9, 2002 - Jan 11, 2004	515.1

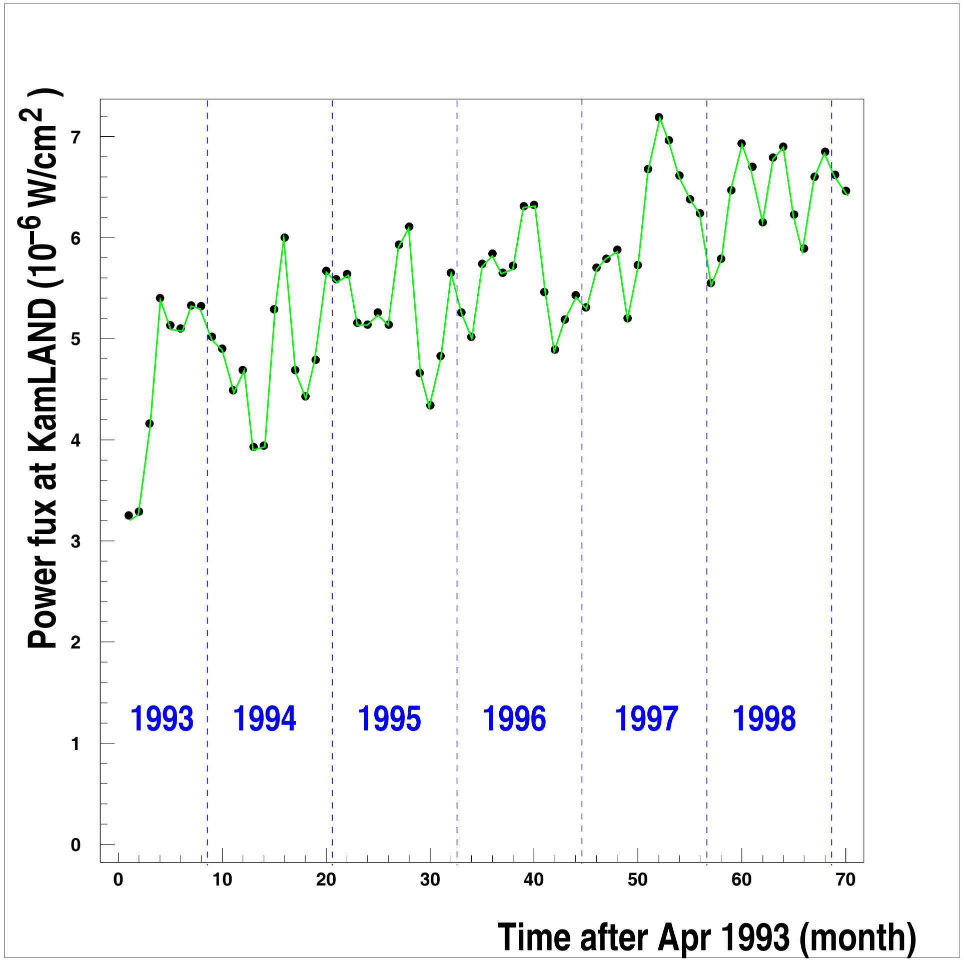
*Was 145.1 with old analysis

† T.Araki et al, arXiv:hep-ex/0406035 Jun 13, 04 submitted to Phys Rev Lett

Kamland e i reattori nucleari del Far-East

Site	Distance (km)	# of cores	P(ther.) (GW)	flux $(\bar{\nu}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$	Signal $(\bar{\nu}/\mathrm{yr})$
Japan					
Kashiwazaki	160.0	7	24.6	4.25x10^5	348.1
Ohi	179.5	4	13.7	1.88X10^5	154.0
Takahama	190.6	4	10.2	1.24x10^5	101.8
Hamaoka	214.0	4	10.6	1.03x10^5	84.1
Tsuruga	138.6	2	4.5	1.03x10^5	84.7
Shiga	80.6	1	1.6	1.08x10^5	88.8
Mihama	145.4	3	4.9	1.03x10^5	84.5
Fukushima–1	344.0	6	14.2	5.3x10^4	43.5
Fukushima–2	344.0	4	13.2	4.9x10^4	40.3
Tokai–II	294.6	1	3.3	1.7x10^4	13.7
Shimane	414.0	2	3.8	9.9x10^3	8.1
Onagawa	430.2	2	4.8	9.8x10^3	8.1
Ikata	561.2	3	6.0	8.4x10^3	6.9
Genkai	755.4	4	6.7	5.3x10^3	4.3
Sendai	824.1	2	3.3	3.5x10^3	2.8
Tomari	783.5	2	5.3	2.4x10^3	2.0
Korea					
Ulchin	~750	4	11.2	8.8x10^3	7.2
Wolsong	~690	4	8.1	7.5x10^3	5.2
Yonggwang	~940	6	16.8	8.4x10^3	6.9
Kori	~700	4	8.9	8.0x10^3	6.6
Total		69	175.7	1.34x10^6	1102

La richiesta di corrente elettrica in Giappone ha due picchi in estate/inverno, mentre in primavera/autunno la richiesta é minore. Il livello di potenza medio dei reattori rispecchia tale andamento e permette una stima dei fondi.



Reactor antineutrino selection

- Fiducial volume :

  $R_{prompt,\ delayed} < 5.5$ m (543.7 tons)

- Time correlation :

  $0.5\ \mu s < \Delta T_{d-p} < 1$ ms

- Space correlation :

  $\Delta R_{d-p} < 2$ m

- Delayed E :

  $1.8\ MeV < E_{delayed} < 2.6\ MeV$

- Prompt E :

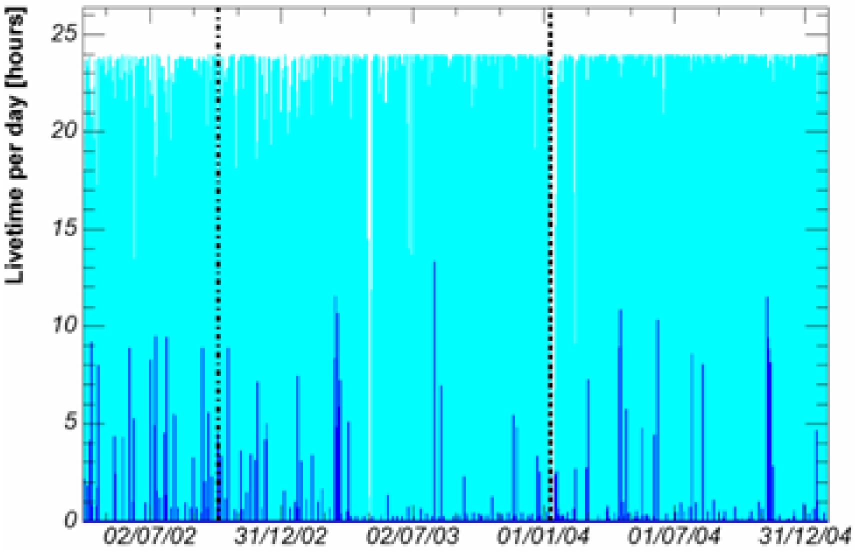
  $2.6\ MeV < E_{prompt} < 8.5\ MeV$

  Geo-ν end-point

Tagging efficiency : 89.8 %

Mar. 9, 2002 – Jan. 11, 2004

515.1 days lifetime

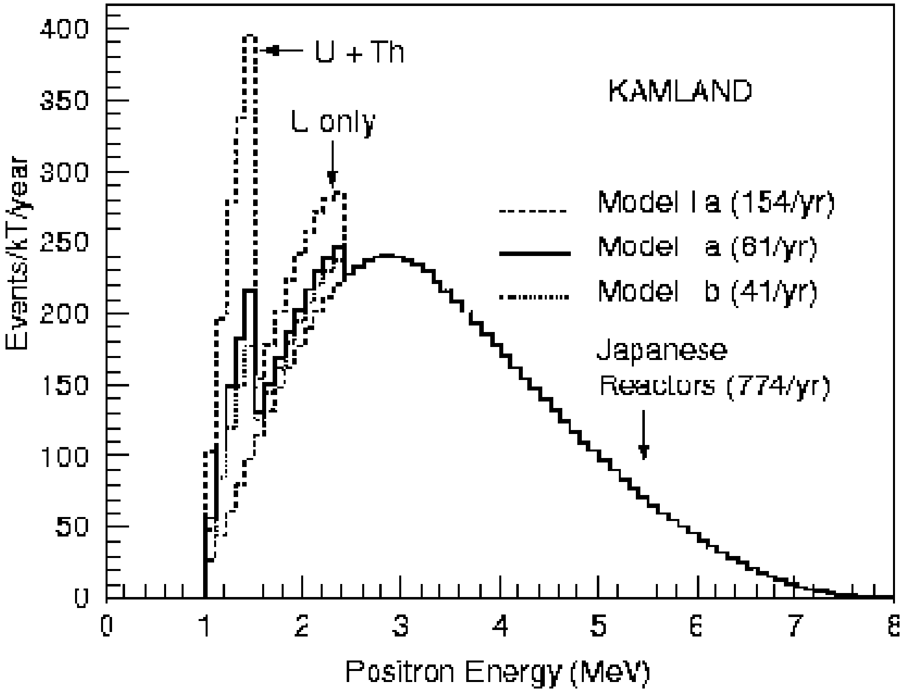


Kamland e i fondi

La terra irradia circa 40 TW di calore. Si stima che circa 16 TW siano di origine radiogenica, 90% di questi derivano da ^{238}U e ^{232}Th. I loro neutrini sono piú soffici di quelli irradiati dai reattori e in parte sopra la soglia di rivelazione degli $\overline{\nu}_e$.

Segnale/rumore atteso: 10:1

Background source	Rate (day^{-1})
Cosmic muons induces neutrons	0.1
Natural radioactivity (random coincidence)	0.15
Natural radioactivity (correlated)	0.005
Total predicted background	0.25
Reactor $\overline{\nu}_e$ signal (no oscillation)	2



Background

- Accidentals : 2.69 ± 0.02
- μ-induced β-neutron emitters
  ^{8}He,^{9}Li : 4.8 ± 0.9
- fast n < 0.89
- $^{13}C(\alpha,n)^{16}O$: 10.3 ± 7.1

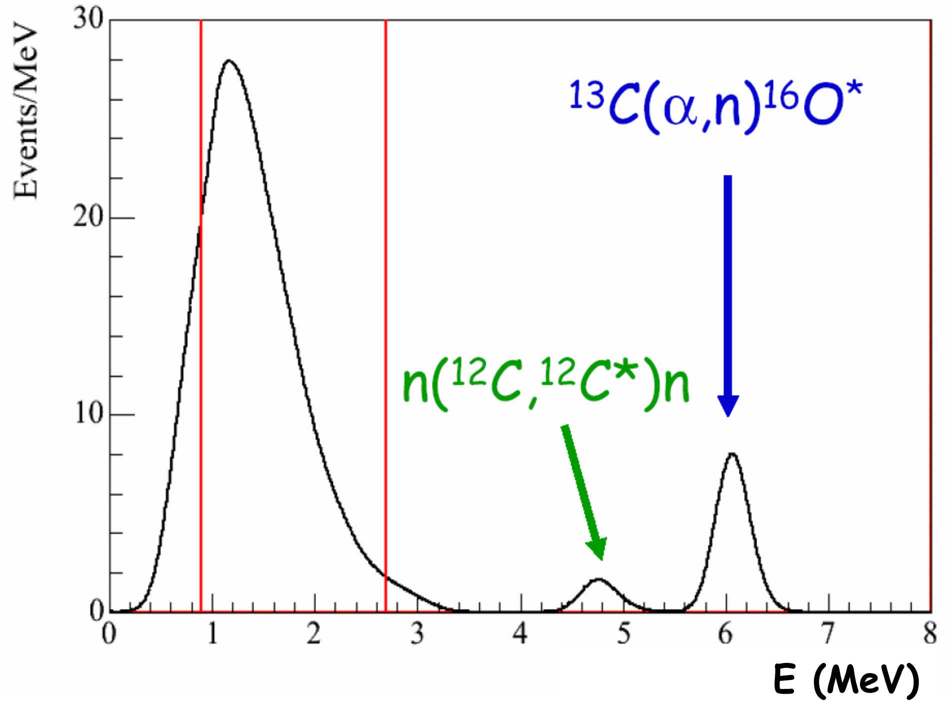
99% of α due to ^{210}Po

$$^{210}\mathrm{Pb} \rightarrow {}^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} \xrightarrow{\alpha\ (5.3\ \mathrm{MeV})} {}^{206}\mathrm{Pb}$$

➢ Total BG : 17.8 ± 7.3

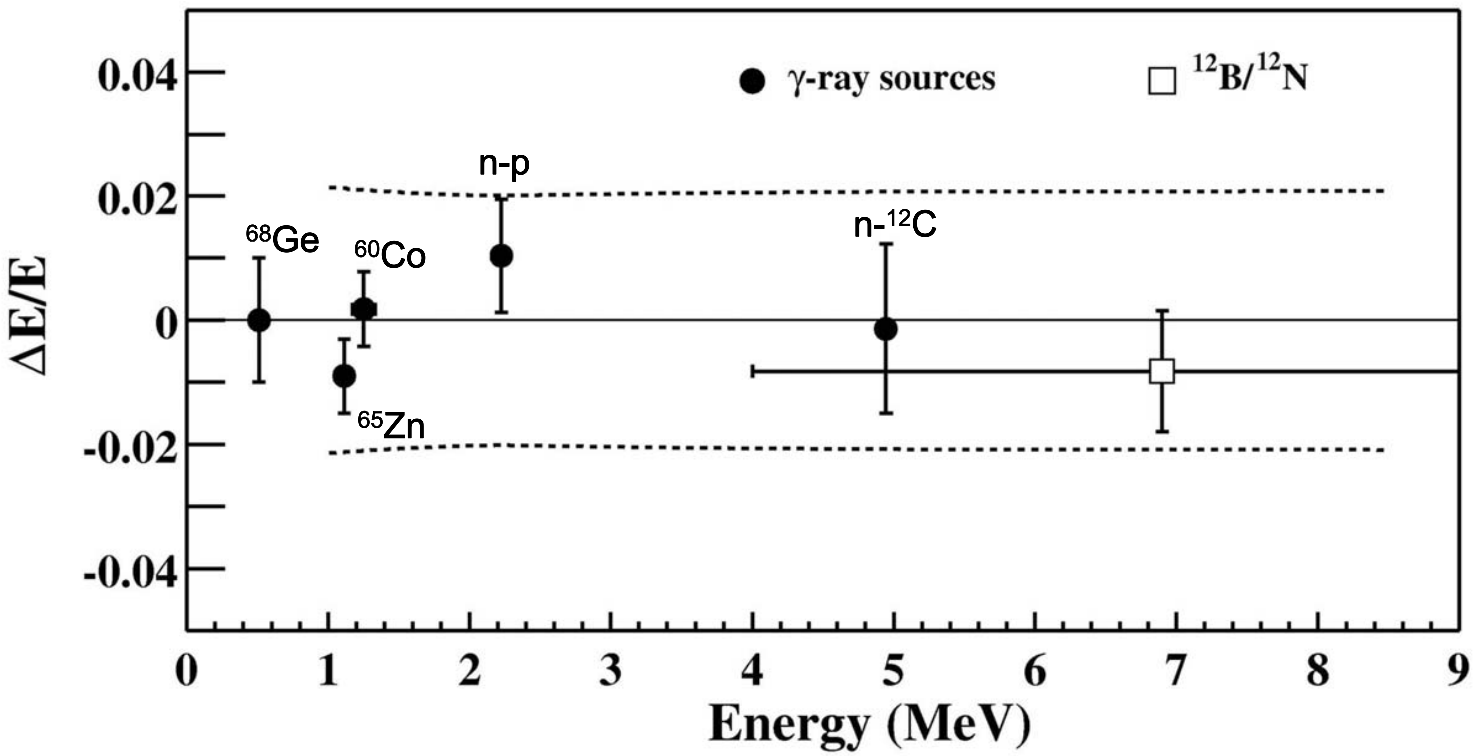
99% of (α,n) occur on ^{13}C

$^{13}C(\alpha,n)^{16}O$ spectrum



Reactor antineutrinos

Energy calibration uses discrete and ^{12}B/^{12}N



Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for and e-type depositions

/E ~ 6.2% at 1MeV

Kamland e gli errori sistematici

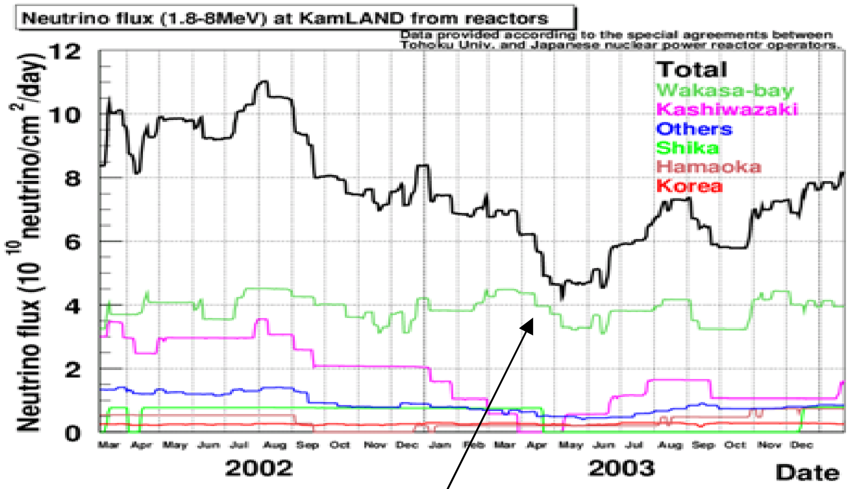
Fiducial Volume	4.7	Reactor power	2.1
Energy threshold	2.3	Fuel composition	1.0
Efficiency of cuts	1.6	$\overline{\nu}_e$ spectra	2.5
Livetime	0.06	Cross section	0.2
Total systematic uncertainty			6.5

Results

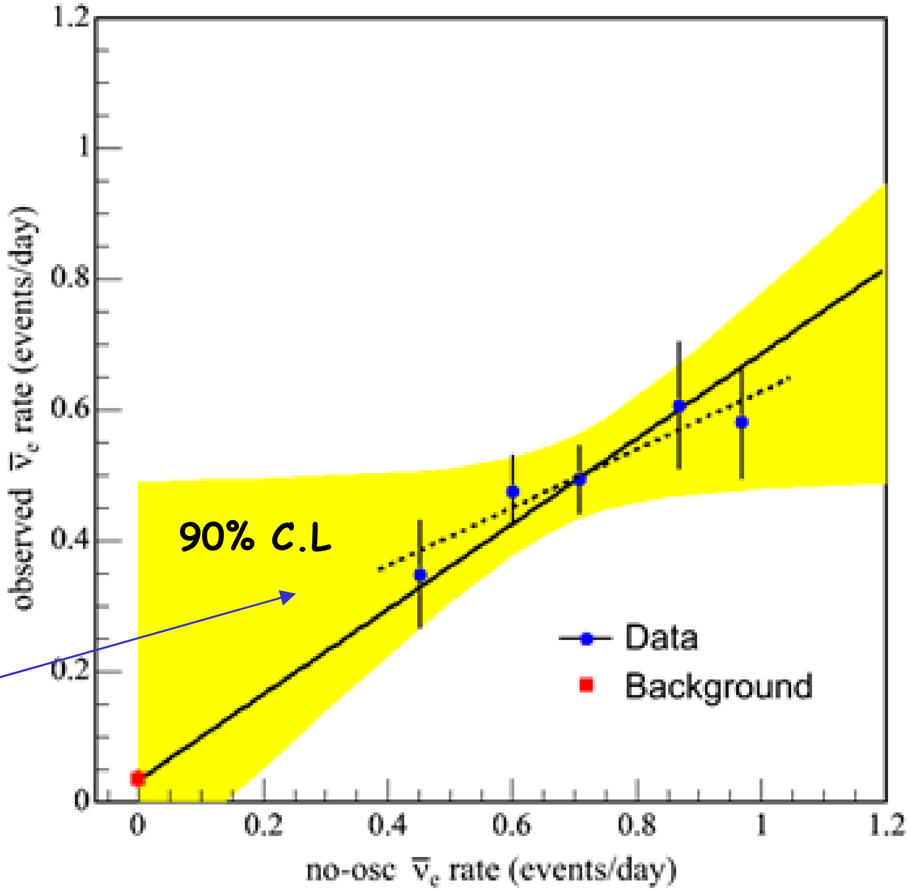
PRL 94, 081801 (2005)

$$\frac{N_{obs} - N_{BG}}{N_{exp}} = \frac{258 - 17.8 \pm 7.3}{365 \pm 24} = 0.658 \pm 0.044 \text{ (stat)} \pm 0.047 \text{ (syst)}$$

Disappearance confirmed at 99.998% CL



Signifiant variation of flux



Signal consistant with reactor antineutrino

Results

(766.3 ton·yr,
~4.7   the statistics of the first paper)

Observed events	258
No osc. expected	365±24(syst)
Background	7.5±1.3

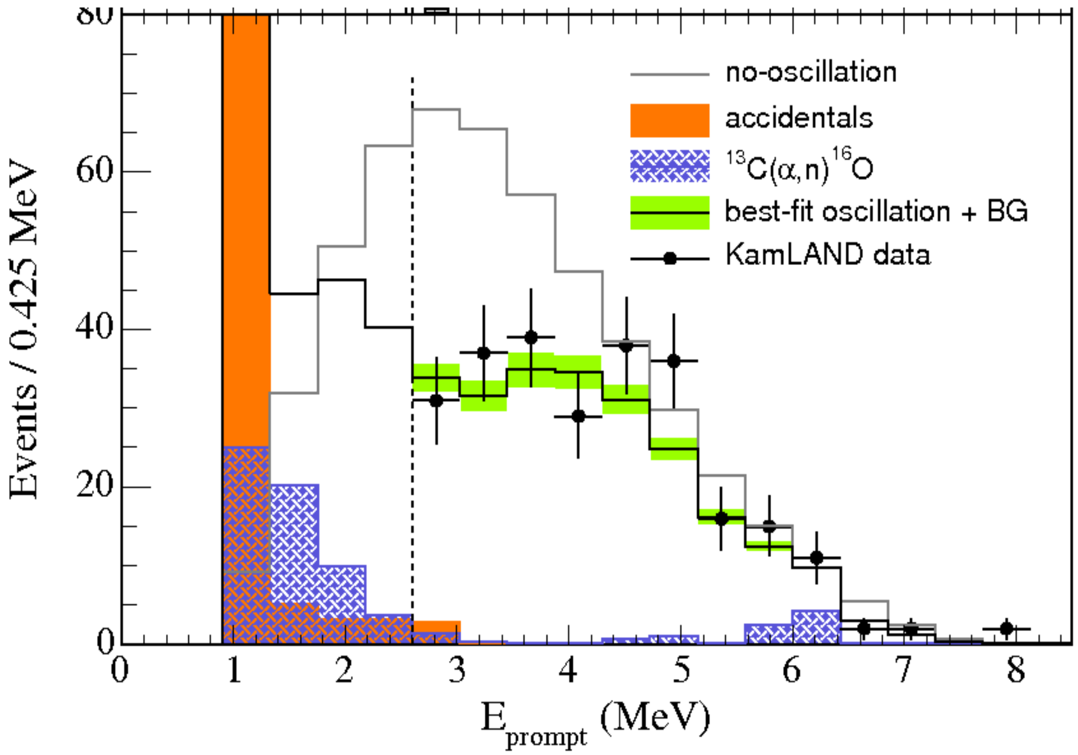
Background	Events
Accidentals	2.69±0.02
$^{8}He/^{9}Li$	4.8±0.9
μ-induced n	<0.89
Total	7.5±1.3

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

(Observed-Background)/Expected = 0.686±0.044(stat)±0.045(syst)

Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

Spectrum analysis

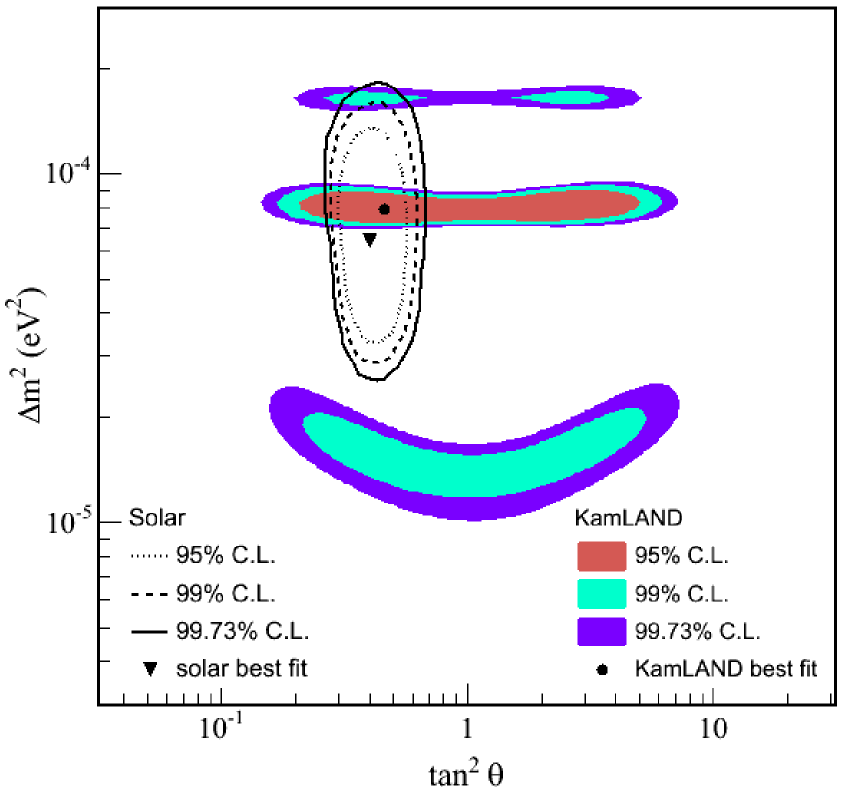


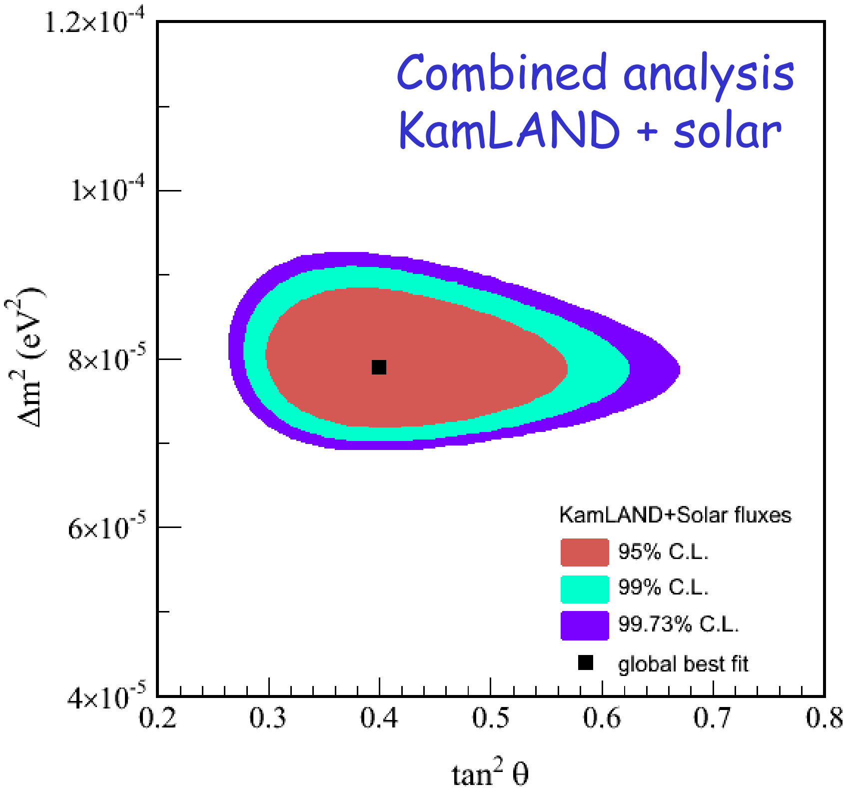
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ eV^2$$

$$\tan^2\theta = 0.46$$

Spectral distorsion at 99.6 % CL

KamLAND + solar data





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

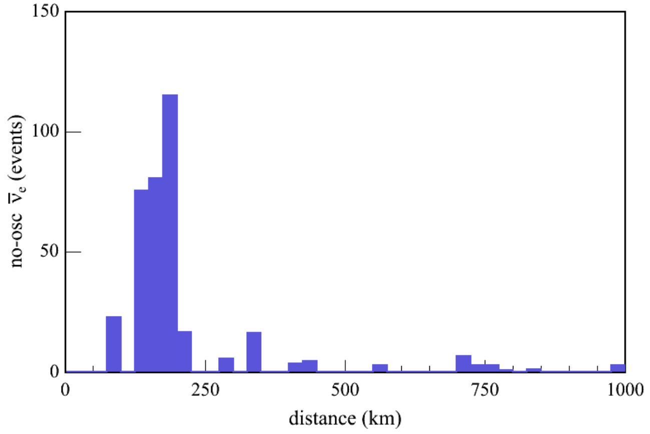
$\tan^2\theta = 0.40^{+0.10}_{-0.07}$

L_0/E Plot

- Oscillation depends on L/E

  KamLAND doesn't measure L, but the flux distribution has a strong peak

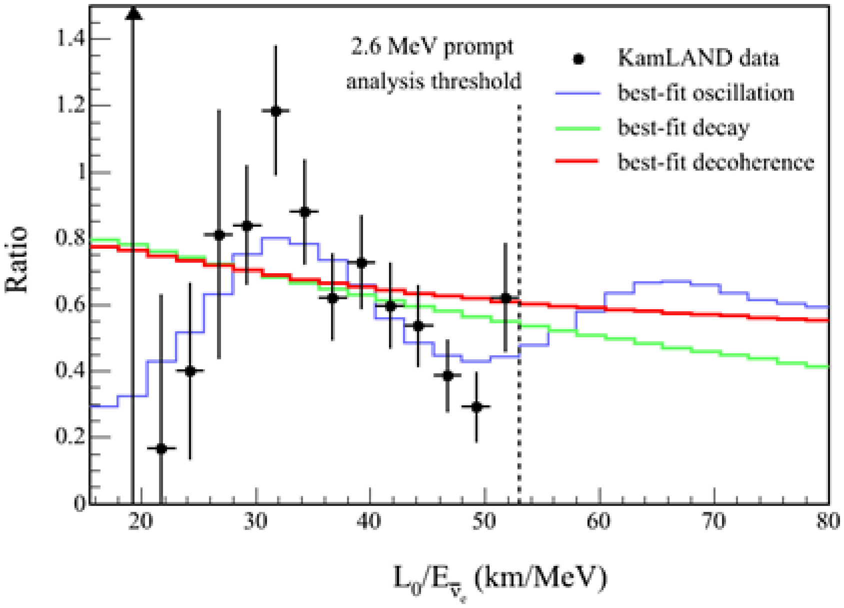
  A typical value L_0=180 km is used



- Disappearance hypotheses

  Goodness of fit:

0.7%	- decay
1.8%	- decoh
11.1%	- oscilla
(0.4%	- consta



- Data prefer oscillation to other hypotheses

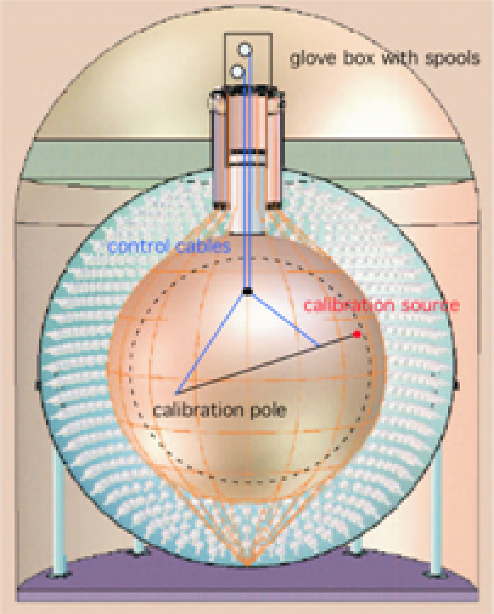
Future for reactor analysis

- More statistics

- 6.5% systematic errors are dominated by
  4.7% fiducial volume systematic
  "4π" calibration system → full fiducial volume calibration
  operational soon : 6.5 % → 4.5 %

- New reactor Shika 2 starting 2006, at 88 km, near first oscillation minimum : larger suppression rate

4π system

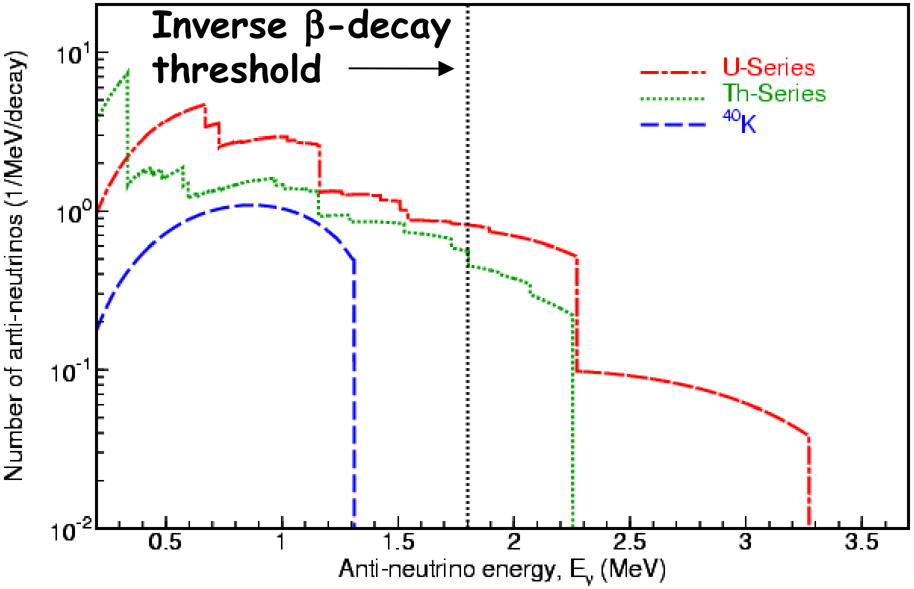


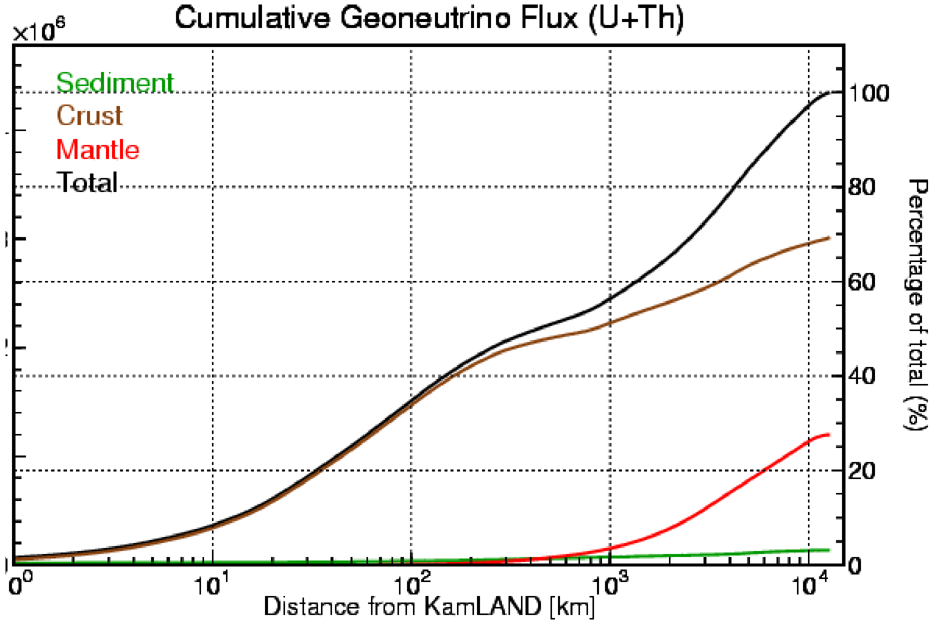
Geo-neutrinos

- Antineutrinos from ^{238}U, ^{232}Th and ^{40}K are an unique opportunity to bring insights in the Earth internal composition and energy generation mechanism

- KamLAND is the first detector sensitive enough to measure geo-ν from ^{238}U and ^{232}Th

- A reference model has been constructed based on BSE model (predicts 16 TW radiogenic power), crustal composition of Earth and intensive study of local geology


Inverse β-decay threshold

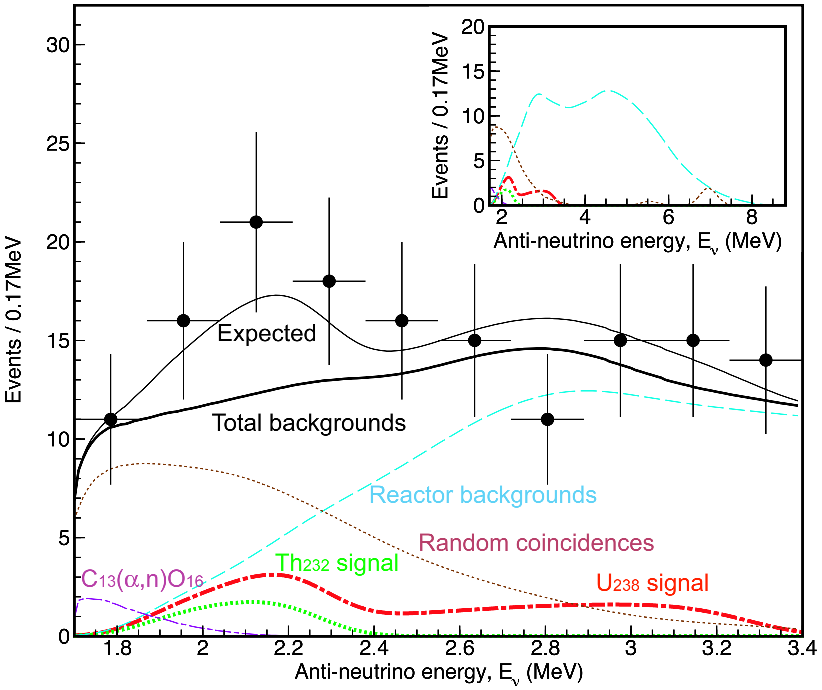

Cumulative Geoneutrino Flux (U+Th)

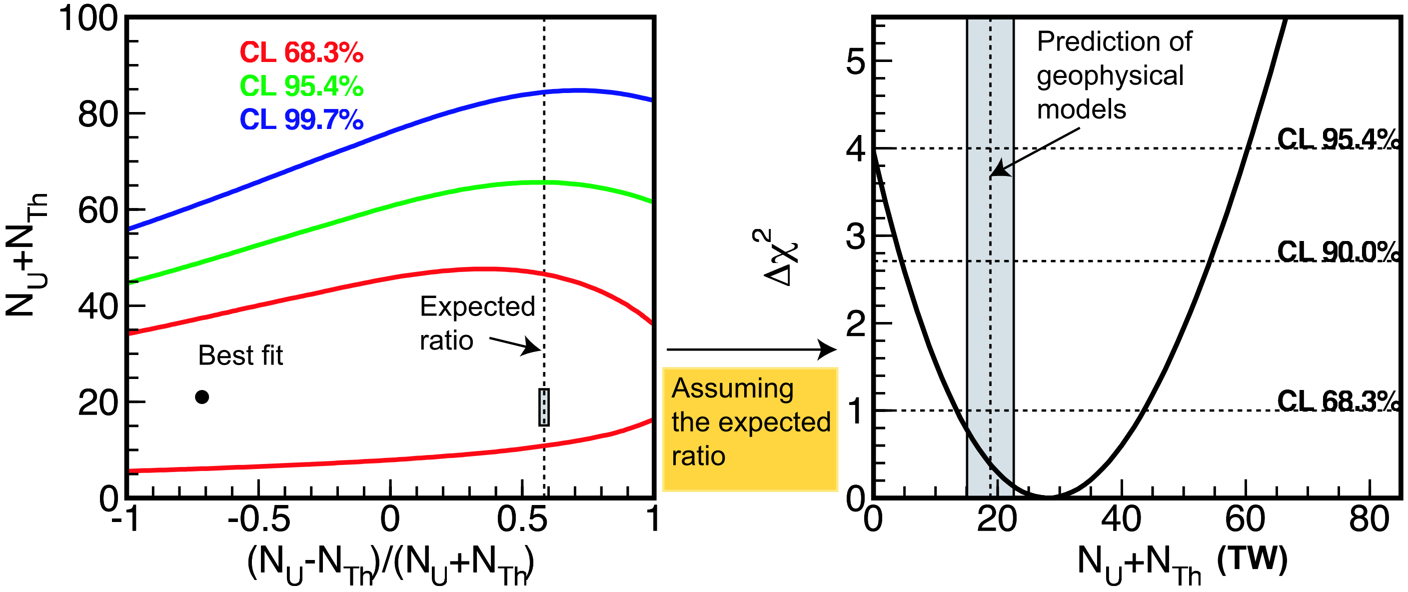
Fit to geoneutrinos

Backgrounds: 127 ± 13 events

Detected: 152 events

25^{+19}_{-18} geoneutrino candidates





Assuming the expected ratio