

# Neutrinos from nuclear reactors

Nuclear reactors are a very intense source of  $\bar{\nu}_e$  from  $\beta$  decays of the fission fragments.

Every  
fission reaction emits about 200 MeV of energy and 6  $\bar{\nu}_e$ .  
 $\downarrow$   
Flux  $\sim 2 \cdot 10^{20} \bar{\nu}_e s^{-1} \text{GWatt}^{-1}$ , isotropic,  $\langle E(\bar{\nu}_e) \rangle \simeq 0.5 \text{ MeV}$ .

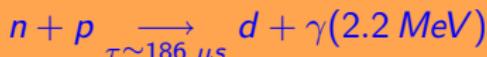
Latest  
oscillation experiments look for  $\bar{\nu}_e$  disappearance at  
different baselines:

- $L = \mathcal{O}(2\text{km}) \Rightarrow$  atmospheric regime: Chooz,  
Palo Verde
- $L = \mathcal{O}(150\text{km}) \Rightarrow$  solar regime: Kamland

# Neutrino flux

Detect absolute number of neutrino interaction and distortions of their spectrum

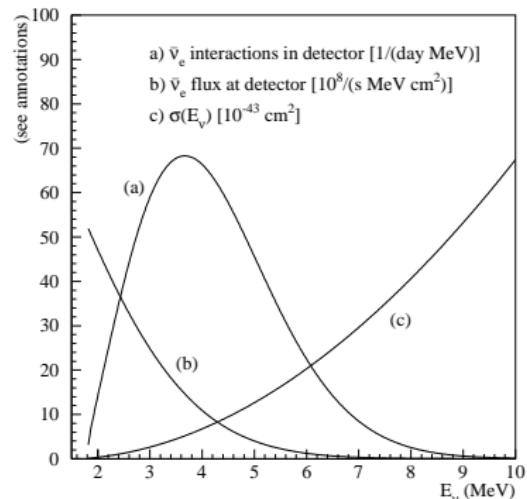
prompt positron signal, energy range.



delayed correlated photon.

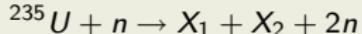
To determine neutrino flux:

- ① Measure of the reactor thermal power**
- ② Determination of the neutrino spectrum**
- ③ Definition of the experimental observable: positron momentum spectrum.**

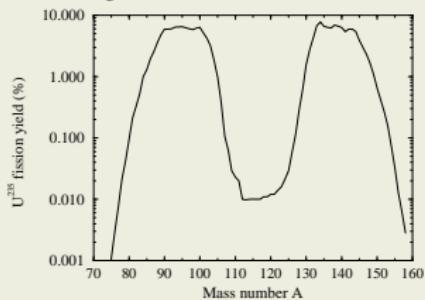


# Thermal power of the reactor

The leading reaction is  $^{235}U$  fission:



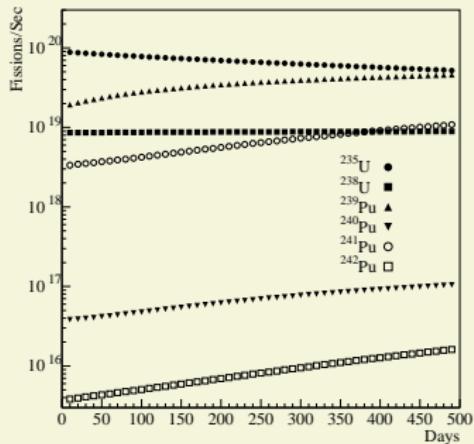
The lightest fragment have on average  $A \simeq 94$ , the heavier:  $A \simeq 140$ . Stable nuclei with  $A = 94, 140$  are  $_{40}Zr^{94}$  e  $_{58}Ce^{140}$ .  $^{235}U$  has 98 protons and 142 neutrons  $\Rightarrow$  to reach the stability, on average it needs 6 neutron  $\beta$  decays  $\Rightarrow 6 \bar{\nu}_e$ .



The interaction process  $\bar{\nu}_e + p \rightarrow n + e^+$  has a threshold of  $\sim 1.8$  MeV  $\Rightarrow$  only  $\sim 25\%$  of neutrinos can be detected.

All the neutrinos from low Q-value processes, as nuclear fuel stored in the reactors and radioactivity induced in the nuclear plant structures, don't produce detectable neutrinos.

The fuel composition of the reactor core changes with the time, it's under monitor (reactor power depends from its composition).



## From fission rate to the $\bar{\nu}_e$ spectrum

The  $\bar{\nu}_e$  spectrum of three of the four principal fission nuclei: ( $^{235}U$ ,  $^{239}Pu$ ,  $^{241}Pu$ ), has been derived by measuring the electron spectrum. The fourth:  $^{238}U$ , has been computed from nuclear models, as well all the processes in the decay chain. Systematic error:  $\sim 1\%$ .

## From $\bar{\nu}_e$ to positrons

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

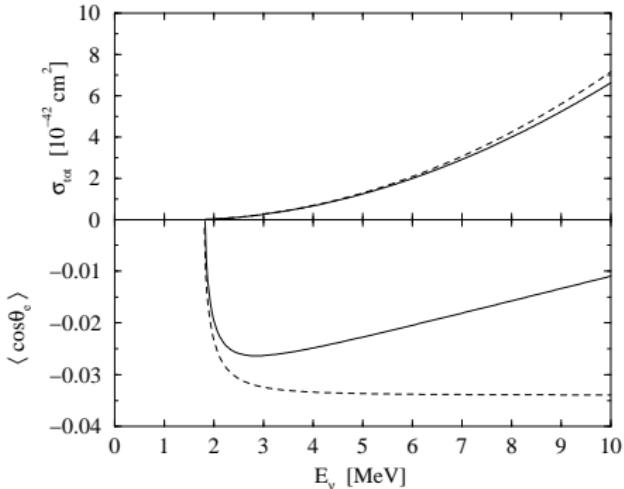
$$\begin{aligned}\sigma_{tot}^{(0)} &= \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)} \\ &= 0.0952 \left( \frac{E_e^{(0)} p_e^{(0)}}{1 \text{ MeV}^2} \right) \times 10^{-42} \text{ cm}^2 (1)\end{aligned}$$

$E_e^{(0)} = E_\nu - (M_n - M_p)$ : positron energy (neglecting neutron recoil, marginal effect)  $p_e^{(0)}$  momentum,

$f = 1, g = 1.26$  vector and axial coupling constants

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

radiative corrections:  $\Delta_{inner}^R \simeq 0.024$ .



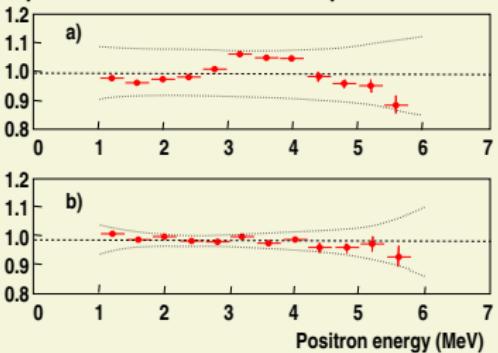
Solid lines: predictions at  $\mathcal{O}(1/M_n)$ , dashed  $\mathcal{O}(1)$ .

## Data/prediction agreement

Experiment Bugey 3 (years 80', now)

considered a non oscillation experiment): expected and measured  $\bar{\nu}_e$  spectrum.

Curve b) is the most updated prediction.

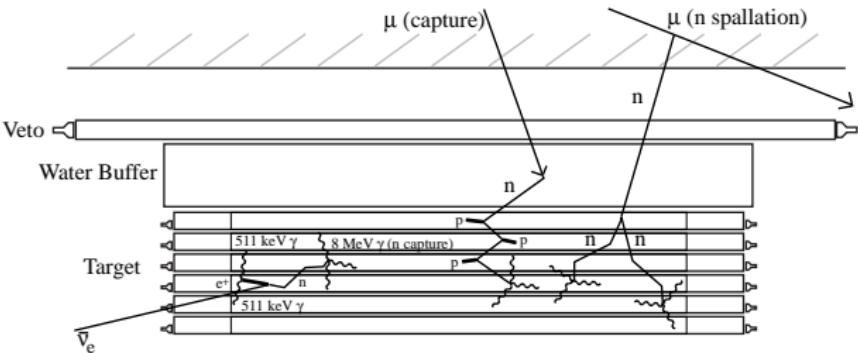


## Systematic errors summary

(from 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).

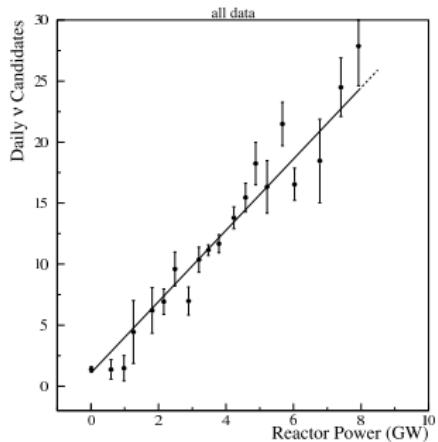
Systematic	CHOOZ (%)	P.V. (%)
$\sigma(\bar{\nu}_e + p \rightarrow n + e^+)$	1.9	-
Number of p in target	0.8	-
$W_{th}$	0.7	-
Energy abs. per fission	0.6	-
Total rate prediction	2.3	2.1
$e^+$ trigger eff.	-	2.0
n trigger eff.	-	2.1
$\bar{\nu}_e$ selection cuts	-	2.1
$(1 - \epsilon_1)B_{pn}$ estimate	-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

# Experimental backgrounds



## Two main categories:

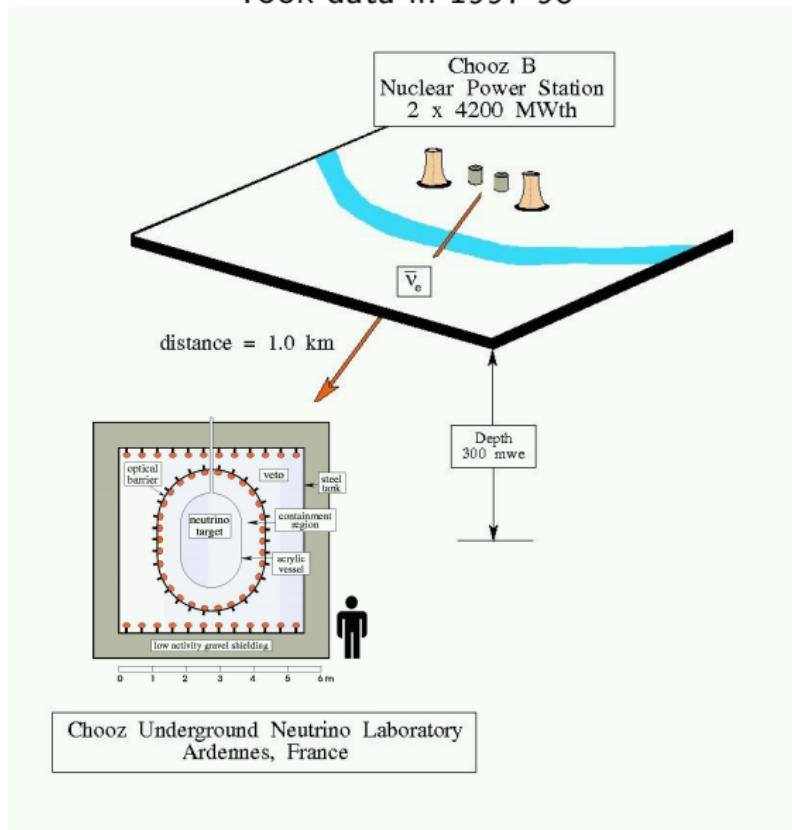
- Accidental backgrounds from the random superposition of a "positron-like" and "neutron-like" signals. Directly estimated from the measured rates of the two processes.
- Backgrounds from neutrons induced by cosmic rays. They can be measured only if the reactor is off (impossible to pay to have a reactor shutdown).



Chooz counting rate as function of the reactors power.

# CHOOZ experiment (France-Italy-Russia-USA)

Took data in 1997-98



# CHOOZ detector

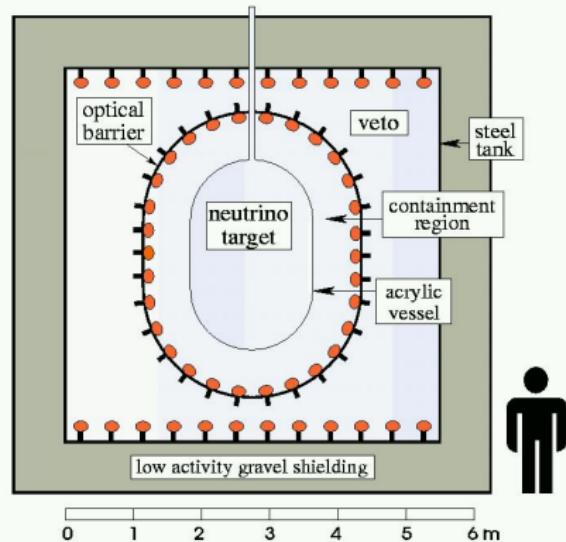
5 ton liquid scintillator detector doped with gadolinium. Active liquid scintillator veto.

$\bar{\nu}_e$  detection:

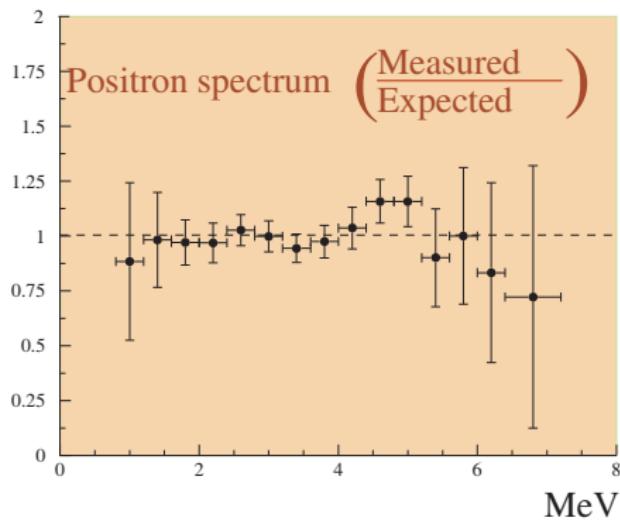
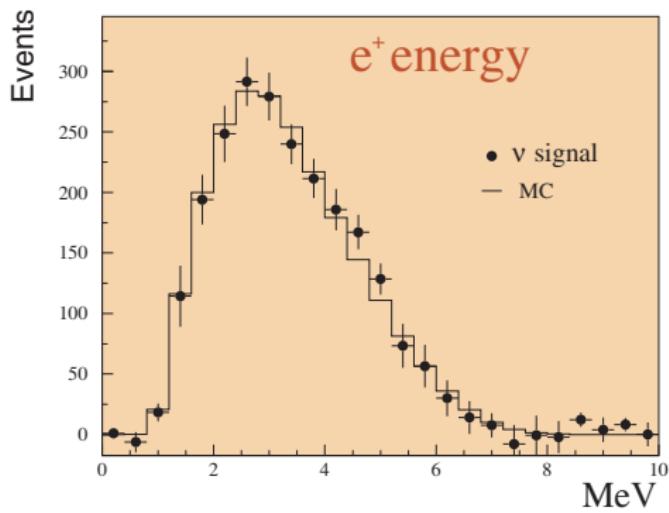
$$\bar{\nu}_e + p \rightarrow e^+ + n \quad E(\bar{\nu}_e) = E(e^+) + 1.804$$

Two signals in delayed coincidence:

- ① Prompt:  $e^+$  followed by  $e^+e^- \rightarrow \gamma\gamma$
- ② Delayed: neutron capture in gadolinium, after thermalization, releasing  $\sim 8$  MeV.

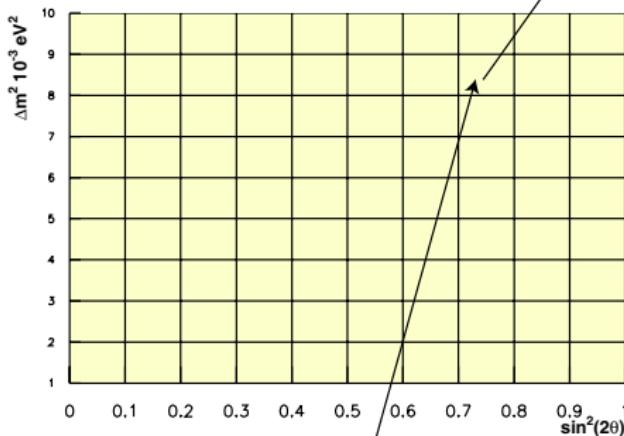


## CHOOZ data

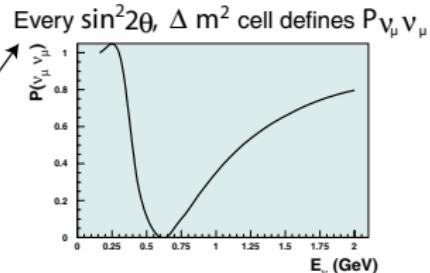


## How to build the signal/exclusion plot

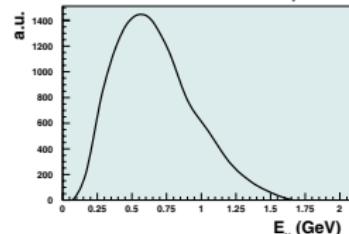
Grid in the  $\sin^2 2\theta, \Delta m^2$  plane



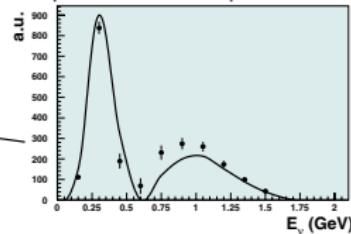
Fill the grid with the  $\chi^2$



That modulates the non-oscillated predicted spectrum



The prediction is compared to the data



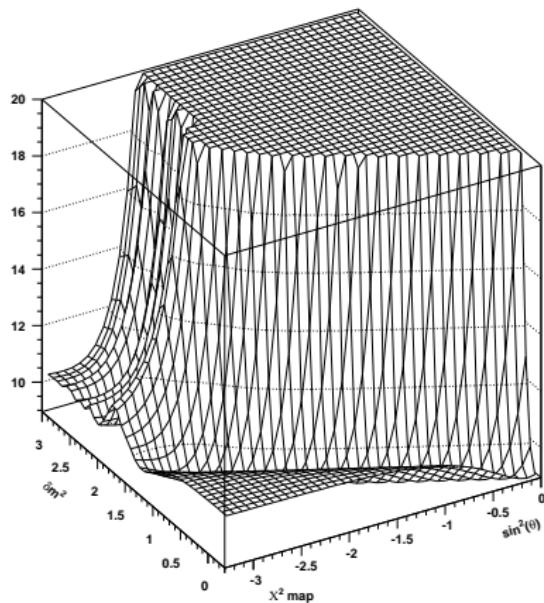
# How to build the signal/exclusion plot (II)

- The minimum of the  $\chi^2$  distribution is the best fit
- The region at a given confidence level (CL) is defined by the contour at a given  $\Delta\chi^2$  from the minimum.
- The CL is computed from the probability distribution of a  $\chi^2$  at two degrees of freedom ( $(\sin^2 2\theta, \Delta m^2)$ )

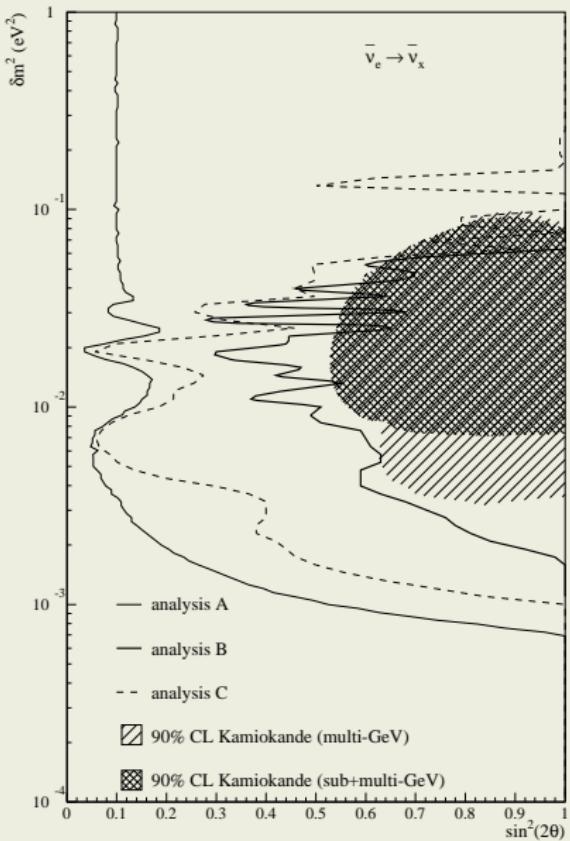
**Question:** Why  $\Delta\chi^2$  and not  $\chi^2$ ?

**Hint:** Why two degrees of freedom?

A more formal approach in G.Feldman and R.Cousins, Phys.Rev.D57:3873-3889,1998



# CHOOZ final results

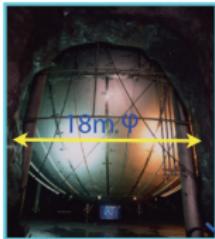


- **Analysis A**  $\bar{\nu}_e$  spectrum after background subtraction. Both the absolute rate and the spectrum are used.
- **Analysis B** Uses the different baseline ( $\Delta L = 117.7 \text{ m}$ ) of the two reactors.  
Many systematic errors cancel, but statistical errors are bigger and the  $\Delta m^2$  sensitivity is reduced by the shorter baseline.
- **Analysis C** Only spectrum information is used.

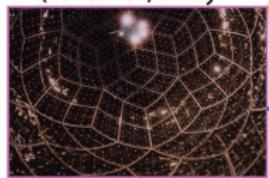
## Top Cited 1000+ Sperimentalli in QSPIRES (al 6/11/05)

2850	WMA P	First Year Wilkinson Microwave observations: determination of cosmologicalparameters.	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 evidencefrom supernovae for an accelerating universe and a cosmologicalconstant.	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	WMA P	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 deepinelastic 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 $\nu_e + D \rightarrow p + p + e^-$ 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 evidencefor neutrino a $\nu$ 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 resonanceat 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 $\nu_e$ flux with the Homestake chlorine detector	1998

Stainless steel tank



1879 PMT  
(17" & 20") array



Balloon (Nylon/EVOH)



# KamLAND Detector

## Kamioka Liquid Scintillator Antineutrino Detector

Calibration  
system in  
Rn-free air

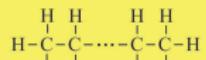
Electronics  
hut

13m

20m

Outer detector : 3.2kton water shield  
and 225 20"PMT's to detect cosmic  
μ's

Liquid Scintillator  
~1kton



Normal

dodecane ( $\text{C}_{12}\text{H}_{26}$ )  
(80%)



Pseudocumene  
(20%)



PPO (1.36  
 $\pm 0.03\text{g/l}$ )

Buffer Oil (dodecane)

Vertex resolution

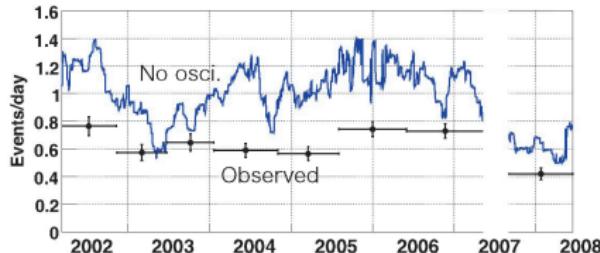
$$\sim 12\text{cm}/\sqrt{\text{E}_{[\text{MeV}]}}$$

Energy resolution

$$6.5\%/\sqrt{\text{E}_{[\text{MeV}]}}$$

# Kamland and the far east reactors

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



# Kamland and systematic errors

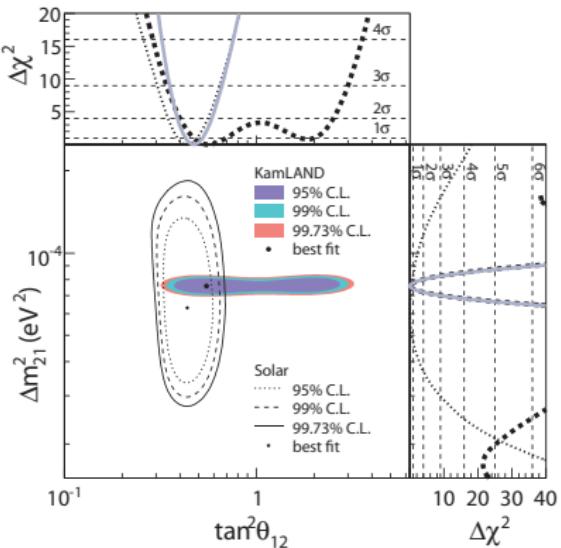
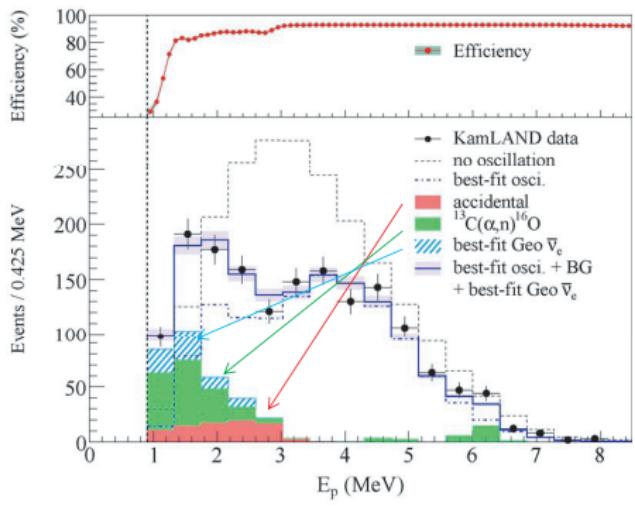
	Detector-related (%)		Reactor-related (%)	
$\Delta m_{21}^2$	Energy scale	1.9	$\bar{\nu}_e$ -spectra	0.6
	Fiducial volume	1.8	$\bar{\nu}_e$ -spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

# Kamland Results (I)

## # of Observed and Expected Events

	<b><i>KL1</i></b>	<b><i>KL2</i></b>	<b><i>KL3</i></b>
<b>Exposure (ton•yr)</b>	<b>162</b>	<b>766</b>	<b>2881</b>
<b>Observed ev.</b>	<b>54</b>	<b>258</b>	<b>1609</b>
( $E_{\text{prompt}}$ : MeV)	(>2.6)	(>2.6)	(>0.9)
<b>Expected ev.</b>	<b><math>86.8 \pm 5.6</math></b>	<b><math>365.2 \pm 23.7</math></b>	<b><math>2179 \pm 89</math></b>
 <b>Background ev.</b>	 	 	 
accidental	$0.95 \pm 0.99$	$17.5 \pm 7.3$	$276.1 \pm 23.5$
	0.0086	2.69	80.5
	$\pm 0.0005$	$\pm 0.02$	$\pm 0.1$
$^9\text{Li}/^8\text{He} (\beta, n)$	$0.94 \pm 0.85$	$4.8 \pm 0.9$	$13.6 \pm 1.0$
fast neutron	$0 \pm 0.5$	< 0.89	< 9.0
$^{13}\text{C}(\alpha, n)^{16}\text{O}_{\text{gs, 1st, 2nd}}$		$10.3 \pm 7.1$	$182.0 \pm 17.7$
 <b><math>(N_{\text{obs}} - N_{\text{back}})/N_{\text{expect}}</math></b>	 <b>0.611</b>	 <b>0.658</b>	 <b>0.593</b>
<b>(<math>\pm \text{stat} \pm \text{syst}</math>)</b>	<b><math>\pm 0.085 \pm 0.041</math></b>	<b><math>\pm 0.044 \pm 0.047</math></b>	<b><math>\pm 0.020 \pm 0.026</math></b>
	<b>99.95 % CL</b>	<b>99.995 % CL</b>	<b>8.5 <math>\sigma</math></b>

# Kamland Results (II)

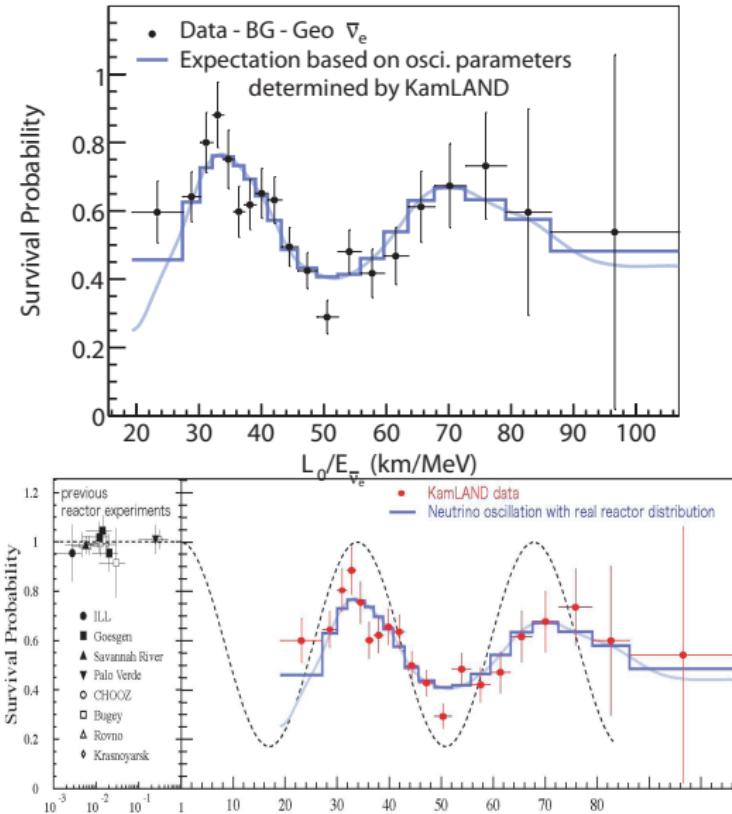


**Fit to scaled no-oscillation spectrum  
: exclude at 5.1  $\sigma$**

$$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta = 0.56^{+0.14}_{-0.09}$$

# KamLAND Results (III)



# Kamland Geoneutrinos

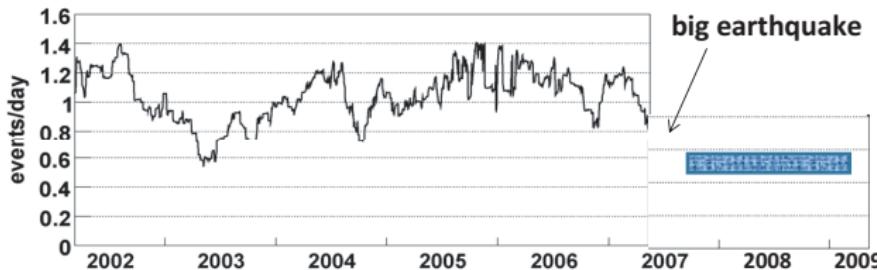
## Geo-Reactor

- Natural nuclear reactor in the center of the Earth was proposed in 2001 as the energy source of geo-magnetic field.
- Not a mainstream theory, but not ruled out by any evidence.
- Explains mechanism for flips of the geo-magnetic field.



# Kamland Geoneutrinos: results

## Signature from Geo-Reactor



Kashiwazaki power station : 24.3 GW

Detailed operational records from all 55 reactors in Japan

$\gamma$ -intercept :  
Geo-Reactor + BG

Upper limit on hypothetical georeactor at Earth's center of 6.2TW at 90% C.L.

theoretical prediction : 3 TW

