Noi siamo pervasi da un flusso di neutrini

- $\sim 10^7 \nu$ relici dal Big Bang
- $\sim 10^{14} \nu/s$ dal sole
- $\sim 5 \cdot 10^{10} \nu/s$ dalla radioattività naturale
- $\sim 10^{10} \nu/s$ dai reattori nucleari
- $\sim 10^3 \nu/s$ dai interazioni di raggi cosmici nell'atmosfera
- $\sim 4 \cdot 10^3 \nu/s$ dai decadimenti del Potassio 40 presente nel nostro corpo ($\sim 20\ mg$).

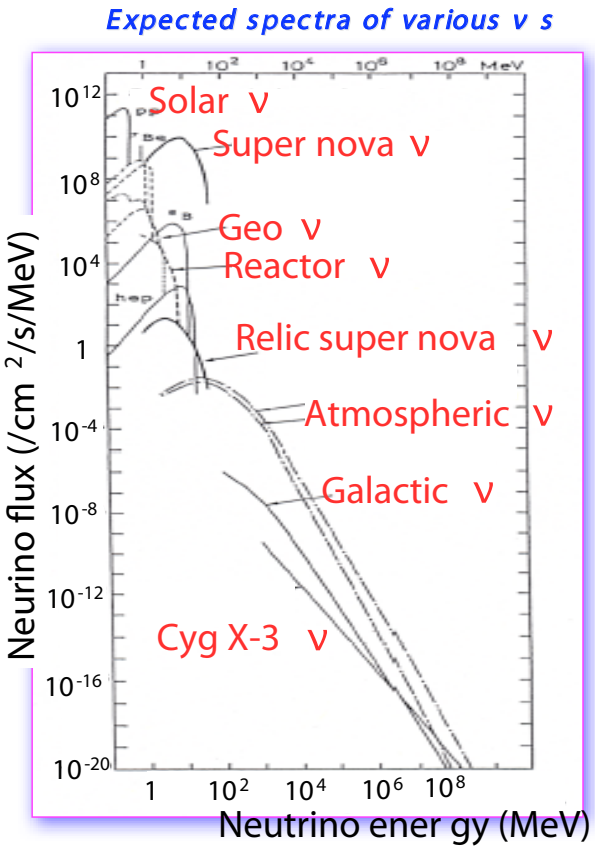
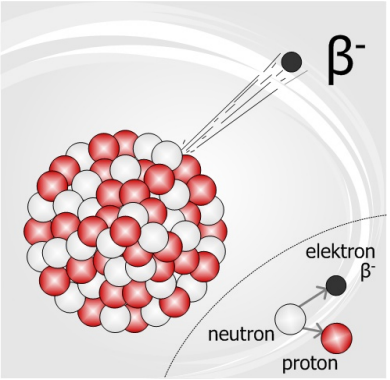


Figura 7.15.
[Per concessione di John Hart. Field Enterprises].

La prima evidenza dei neutrini

Decadimenti beta (Becquerel (44), 1896):
nucleo (A,Z) $\rightarrow$ (A,Z+1) + elettrone
Decadimento a due corpi, conservazione di energia e impulso $\rightarrow$ l'elettrone deve uscire ad energia fissa



Evidenze sperimentali: Hahn (32) e Meitner (43), 1911, Chadwick (29) 1920-1927 e molti altri: l'elettrone ha uno spettro di energia continuo.
Lettera di Hahn a Rutherford: *"... radium E (ora ^{210}Bi) is the worst of all. We can only obtain a fairly broad band. We formerly thought that it was as narrow as the other bands [as found in other emitters], but that is not true. It looks as if secondary effects had a maximum influence on rays of a medium velocity like radium E."*
Risposta di Rutherford: *"... The continuous β-ray spectrum observed for uranium X and radium E may be ultimately resolved for a number of lines."*

Problemi sperimentali: effetti secondari nella propagazione degli elettroni dalla sorgente al rivelatore (spesso lastra fotografica in campo magnetico) Produzione di raggi γ dalla sorgente. Insufficente risoluzione sperimentale.

Alla fine degli anni '20 comunque l'evidenza sperimentale dello spettro continuo degli elettroni era ormai inconfutabile.

N. Bohr: " Nei decadimenti beta non si conserva l'energia-impulso"

L'ipotesi (disperata) di Pauli

Il decadimento è a tre corpi $\rightarrow$ lo spettro dell'elettrone deve essere continuo.
Lettera del 1930 ad un meeting di fisici a Tubingen Wolfgang Pauli (30) scrive

" Dear radioactive ladies and gentlemen,

I have come upon a desperate way out regarding . . . [some fairly obscure data], as well as to the continuous β-spectrum, in order to save . . . The energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin 1/2 and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity. . . . The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant."

Pauli lascia scritto nei suo diari: *"Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally."*

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La proposta di Pauli è assolutamente innovativa, in quanto il suo "neutrone" è la prima proposta di una particella che non faccia parte della materia ordinaria.

1933: Enrico Fermi battezza e quantizza il neutrino

Nel 1933 Enrico Fermi (32) propone una teoria generale per spiegare i decadimenti beta: la teoria delle interazioni deboli.

È la prima forma di interazione proposta senza analogo classico

Inoltre, siccome la terza particella emessa nel decadimento beta è molto leggera, propone di chiamarla **neutrino**.

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Fermi sottomette l'articolo a Nature, che lo rigetta con questa motivazione:
"Abstract speculations too far from physical reality to be of any interest to the readers"

...one obviously would never be able to see a neutrino

1934, Bethe (28) e Peierls (27) calcolano la sezione d'urto per i processi $\nu + n \rightarrow e^- + p$ e $\overline{\nu} + p \rightarrow e^+ + n$.
L'articolo conclude: "... This meant that one obviously would never be able to see a neutrino."
La sezione d'urto (σ) risultava essere

$$\sigma \simeq 2.3 \cdot 10^{-44} cm^2 \left(\frac{p_e E_e}{m_e^2}\right) ,$$

$\Rightarrow$ in acqua il cammino libero medio (λ) di un neutrino da 2.5 MeV risulta $2.5 \cdot 10^{20}\, cm \simeq$ lo spessore del disco della galassia; in piombo circa un anno luce.

Flusso (ν/cm^2/s) $\times$ σ (cm^2) $\times$ Particelle bersaglio = Interazioni di ν/s
λ = Peso Atomico (g) / (Avogadro $\times$ densità (g/cm^3) $\times$ σ (cm^2))

1937: Neutrini di Majorana

Nel 1937 E. Majorana (31) pubblica la sua teoria delle forze nucleari.

In questa prevede che il neutrino corrisponda alla sua antiparticella.

A tutt'oggi questa ipotesi è ancora al centro di indagini sperimentali.

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 $\overline{\nu}_e$.

$$\Downarrow$$

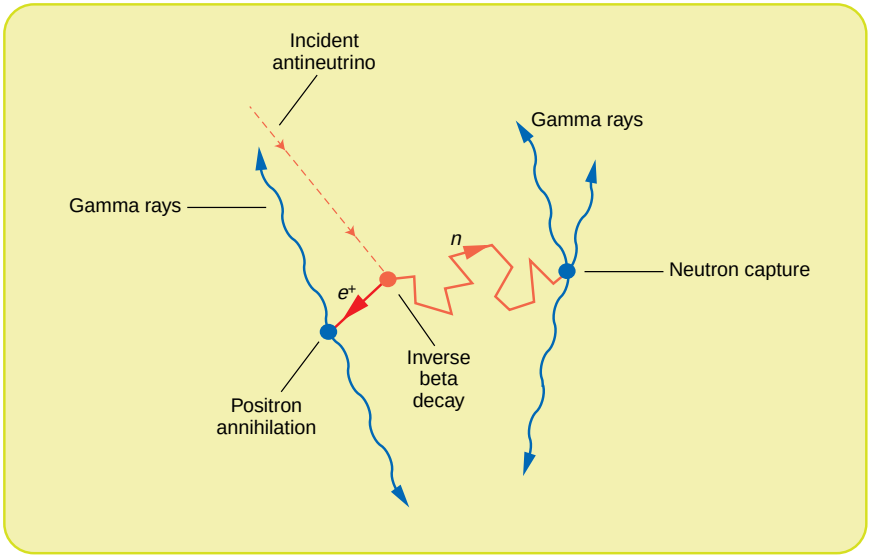
Il flusso è di circa $2 \cdot 10^{20}\ \overline{\nu}_e\ s^{-1}\ \mathrm{GWatt}^{-1}$, isotropo, $\langle E(\overline{\nu}_e)\rangle \simeq 0.5\,MeV$.

Segnale del positrone

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

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

Segnale ritardato γ.



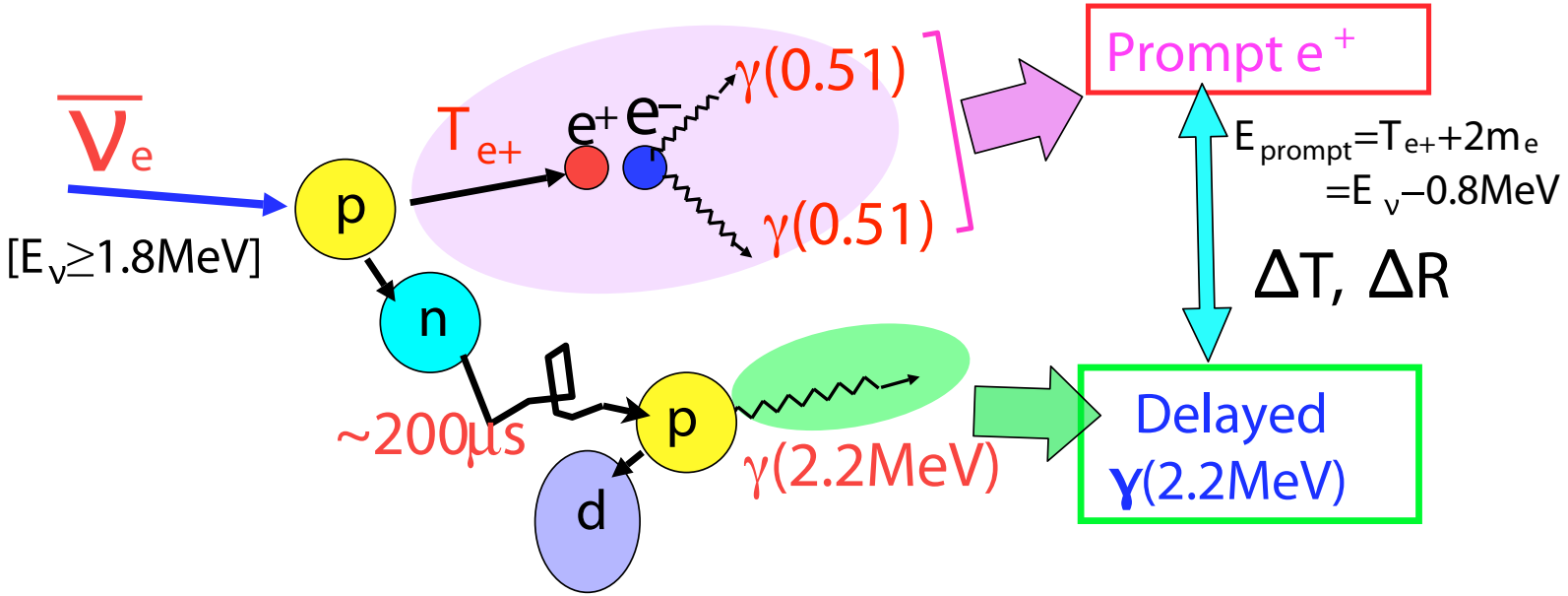
$\overline{\nu}_e$ in scintillatore liquido

prompt positron signal, energy range.

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

$$n + p \xrightarrow[\tau \simeq 186\ \mu s]{} d + \gamma(2.2\ MeV)$$

delayed correlated photon.



Rivelazione diretta dei neutrini, Reines, Cowan et al 1956

- Un primo disegno concettuale per rivelare neutrini da una esplosione nucleare nel 1952.
- Un primo esperimento per la rivelazione di neutrini al reattore di Hanford nel 1953. Il rivelatore era una tank di 300 l di scintillatore liquido (in precedenza il piu' grande rivelatore di scintillatore liquido non superava i 10 l). I fondi dal reattore erano fermati da schermi in boro-paraffina intervallati con lastre di piombo. I fondi da raggi cosmici risultarono essere piu' di un ordine di grandezza maggiori dal segnale atteso:

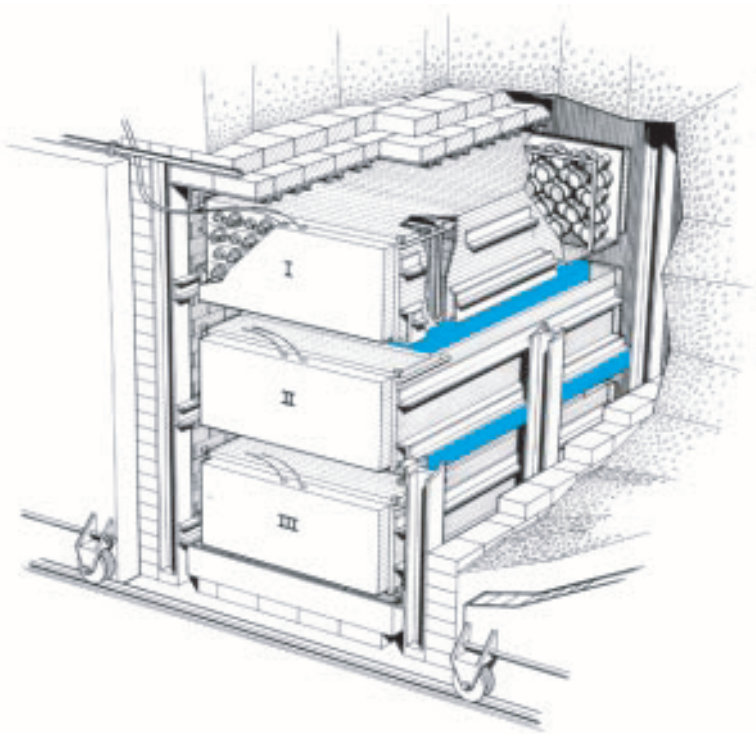
> *" The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the cottails, but our evidence would not stand up in count."*

Rivelazione diretta dei neutrini, Reines, Cowan et al 1956 (II)

Per upgradare il rivelatore il gruppo dovette impegnarsi ad affrontare per la prima volta enormi problemi sperimentali:

- Sviluppo di rivelatori liquidi: resa in luce, stabilita', dipendenza dalla temperatura, produzione in larga scala etc.
- Componenti a bassa radioattivita'
- Schermi anti-radiazioni.
- Disegno di un rivelatore in grado di vetare i raggi cosmici
- Sviluppo dell'elettronica per le coincidenza ritardate
- Analisi dei dati in grado di dedurre le frequenze delle coincidenze accidentali.

L'esperimento di Savannah River



- Due grandi vasche di plastica (A e B) riempite d'acqua ⇒ bersaglio per le interazioni degli antineutrini.
- Cloruro di Cadmio sciolto nell'acqua ⇒ nuclei con grande sezione d'urto per la cattura dei neutroni.
- Le vasche d'acqua erano interposte fra 3 grandi vasche di scintillatore liquido (I, II e III), con una capacita' totale di 4200 litri, ognuna con 110 fotomoltiplicatori per rivelare i gamma dell'annichilazione del positrone e la cattura del neutrone

Un evento di neutrino nella tank avrebbe prodotto:

- Un positrone la cui annichilazione avrebbe prodotto due gamma back to back ⇒ coincidenza veloce dei segnali nelle tank I e II.
- Cattura del neutrone ⇒ segnali di gamma nella tank I o II separati in tempo fra i 3 e 10 μs.
- Nessun segnale dalla tank III perche' la tank II era abbastanza grande da fermare tutti i raggi gamma prodotti dalla interazione.

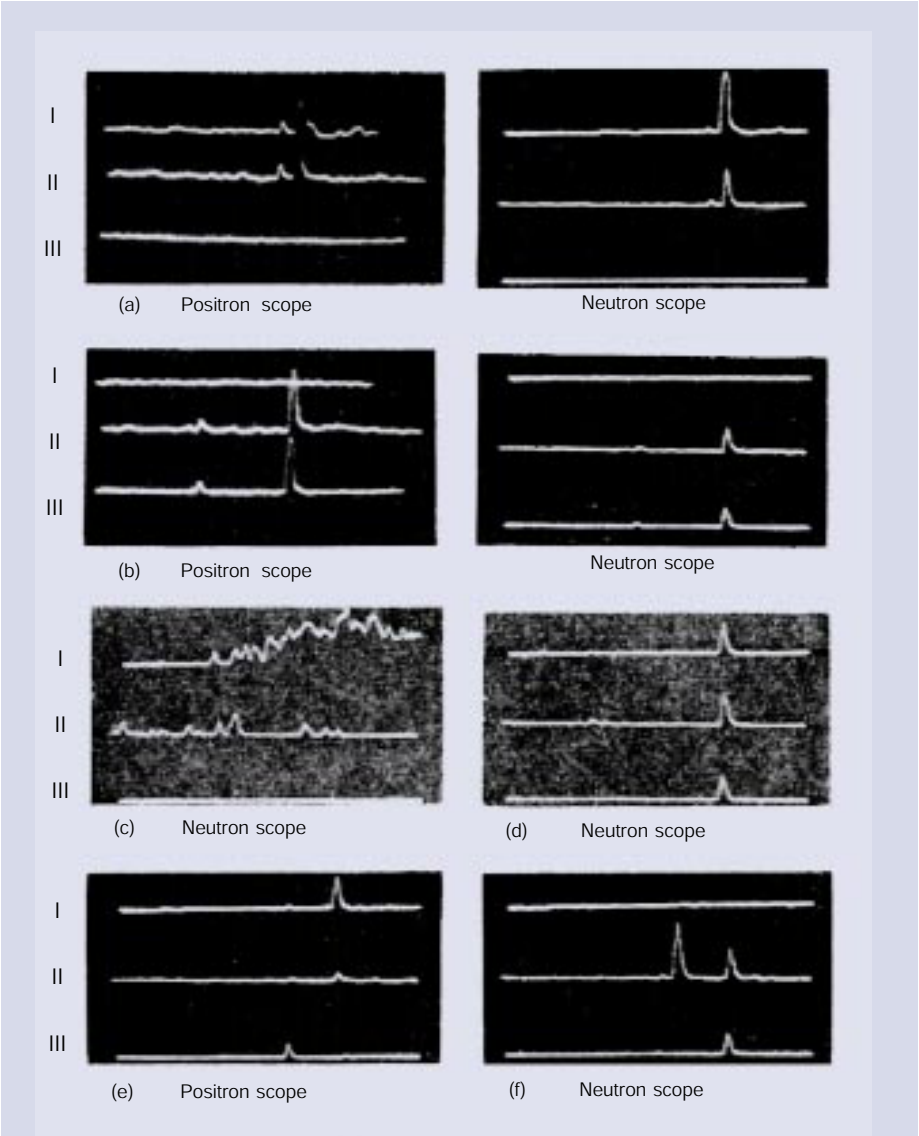


Figure 5. Oscilloscope Traces from the Savannah River Experiments
In these oscilloscope pictures, traces from detectors I, II, and III are labeled I, II, and III, respectively. The label under each frame indicates whether the signals were recorded by the scope for positron annihilation or the scope for neutron capture. Acceptable delayed-coincidence signals are shown in (a) and (b), while rejected signals are pictured in (c) through (f).

(a) The delayed-coincidence signal in these two frames has occurred in the top triad of the detector because the pulses appeared in detectors I and II. *Positron scope*: The pulse energies in detectors I and II were 0.30 MeV and 0.35 MeV, respectively. The pulses reached the positron circuit in prompt coincidence (less than 0.2 microsecond apart) and were accepted as a signal of positron annihilation. *Neutron scope*: The pulse energies in detectors I and II were 5.8 MeV and 3.3 MeV, respectively. These pulses arrived in prompt coincidence and were accepted as a signal of neutron capture. The delay between the positron and neutron signals was 2.5 microseconds. (b) The delayed-coincidence signal in these two frames has occurred in the bottom triad because the pulses appeared in detectors II and III. *Positron scope*: The pulse energies in detectors II and III were 0.25 MeV and 0.30 MeV, respectively. *eutron scope*: The pulse energies in detectors II and III were 2.0 MeV and 1.7 MeV, respectively. The delay between the positron and eutron signals was 13.5 microseconds. (c) The pulses from the neutron circuit were the result of electrical noise. (d) These three ulses from the neutron circuit were caused by a cosmic-ray event. (e) These three pulses from the positron circuit were caused by cosmic-ray event. (f) These pulses may have been caused by a cosmic-ray event. They were rejected as a signal of neutron capture ecause of the extra pulse from detector II. Frames like this one occurred more often than would be expected from chance oincidences. They were, however, not often enough to affect the results considerably. These data appeared in Reines, Cowan, Harrison, et al. 1960.

14/6/1956, telegramma a Pauli:

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters"

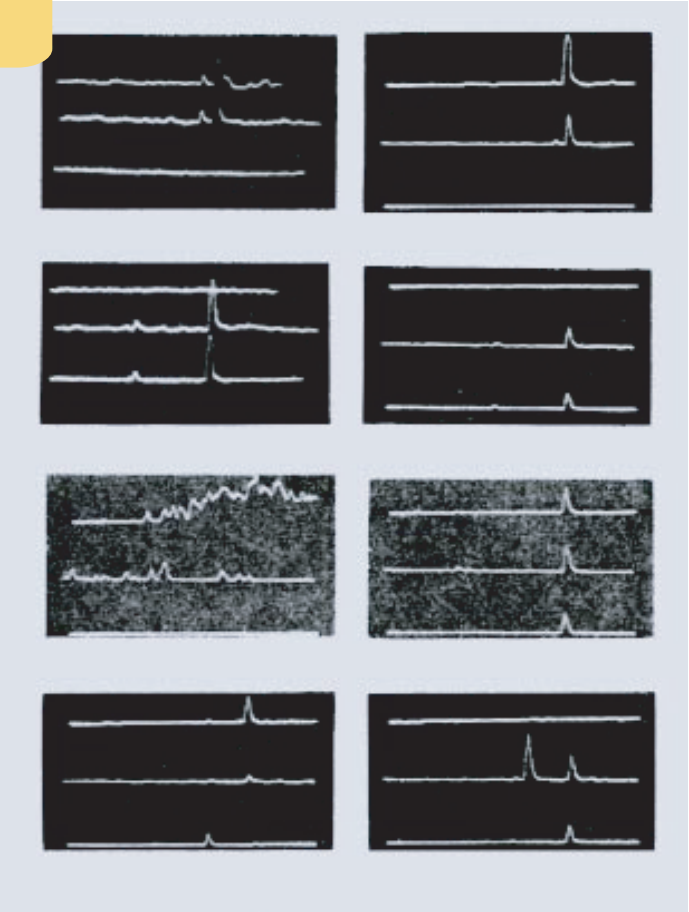
Numero di eventi con reattore acceso - numero di eventi con reattore spento: 3 ± 0.2/ora.

- Verifica che il segnale prompt e' dovuto a raggi gamma da 0.5 MeV: inserzione di fogli di Piombo di spessore variabile fra bersaglio e rivelatore $\Rightarrow$ il segnale diminuisce come previsto.
- Verifica che il segnale ritardato e' dovuto a cattura del neutrone da cadmio: sostituendo il bersaglio con acqua pura il segnale diminuiva di un fattore circa 100.

Primo articolo del 1956: sezione d'urto misurata in accordo entro il 5% rispetto alle stime teoriche. Gli errori sistematici sul flusso di neutrini dal reattore e l'efficienza di rivelazione erano almeno al 50%.

Articolo finale del 1960: la sezione d'urto misurata aumentava di un fattore 2 grazie alla miglior conoscenza delle efficienze di rivelazione. Nel frattempo anche la sezione d'urto teorica era aumentata di un fattore 2 includendo la violazione di parita'.

Premio Nobel
1995



Oscillazioni di neutrini

Accoppiamenti di massa

$$\begin{pmatrix} \overline{\nu}_R^e & \overline{\nu}_R^\mu & \overline{\nu}_R^\tau \end{pmatrix} M_{3\times 3} \begin{pmatrix} \nu_L^e \\ \nu_L^\mu \\ \nu_L^\tau \end{pmatrix}$$

$$M_{3\times 3} = \lambda v^2 \begin{pmatrix} \nu_L^e \\ \nu_L^\mu \\ \nu_L^\tau \end{pmatrix}$$

Accoppiamenti deboli

$$\begin{pmatrix} \overline{e}_L & \overline{\mu}_L & \overline{\tau}_L \end{pmatrix} W_\mu^+ \gamma^\mu \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_L^e \\ \nu_L^\mu \\ \nu_L^\tau \end{pmatrix}$$

Diagonalizzando la matrice di massa

$$\begin{pmatrix} \nu_R^1 & \nu_R^2 & \nu_R^3 \end{pmatrix} \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} \begin{pmatrix} \nu_L^1 \\ \nu_L^2 \\ \nu_L^3 \end{pmatrix}$$

Accoppiamenti deboli

$$(\overline{e}_L\ \overline{\mu}_L\ \overline{\tau}_L) W_\mu^+ \gamma^\mu V_{\mathrm{PNMS}} \begin{pmatrix} \nu_L^1 \\ \nu_L^2 \\ \nu_L^3 \end{pmatrix}$$

Matrice di Mixing

La matrice V_{PMNS} (Pontecorvo, Maki, Nakagawa, Sakata) connette autostati di massa e autostati di sapore

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{\mathrm{PNMS}} \begin{pmatrix} \nu^1 \\ \nu^2 \\ \nu^3 \end{pmatrix}$$

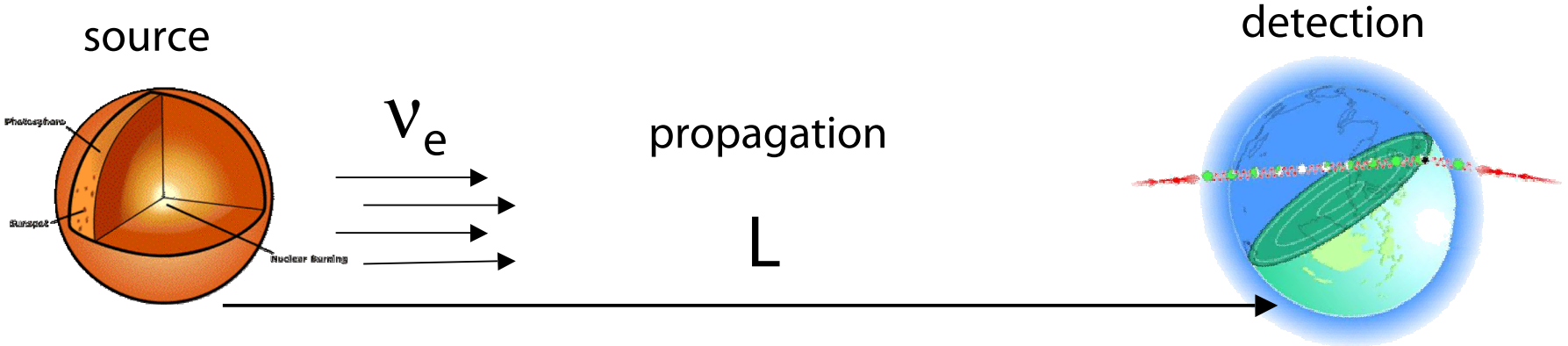
B. Pontecorvo, 1958 Postula per primo la possibilità di oscillazioni di neutrini nella forma $\nu \rightleftharpoons \overline{\nu}$

Maki, Nakagawa e Sakata, 1962 propongono per primi l'ipotesi di oscillazione di sapori di neutrino. L'articolo passa pressochè inosservato. Questo molto prima dell'angolo di Cabibbo e della matrice di Kobayashi Maskawa

Oscillazioni a due neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Oscillazioni di neutrini



Una interazione debole produce un neutrino di un dato sapore
$|\,\nu(x_0)\rangle = |\,\nu_e\rangle = c\,|\,\nu_1\rangle + s\,|\,\nu_2\rangle$

L'autostato di massa si propaga a velocità diverse
$|\,\nu(x_0)\rangle = (c\,|\,\nu_1\rangle e^{i(Et-\vec{k_1}\vec{x})} + s\,|\,\nu_2\rangle e^{i(Et-\vec{k_2}\vec{x})})$

Il neutrino è rivelato attraverso una interazione debole ma a questo punto è in uno stato diverso
$|\,\nu(L)\rangle$

$$\nu_\mu N \to \mu^- X$$

Probabilità di oscillazioni a due neutrini

Da cui la probabilità di oscillazione

$$P(\nu_e \rightarrow \nu_\mu) = \mid \langle \nu_\mu \mid \nu(L) \rangle \mid^2$$

Essendo

$$\mid \vec{k} \mid \simeq E - \frac{m^2}{2E} \Rightarrow \mid \nu(L) \rangle \simeq e^{-iEt} \left(c \cdot e^{-i \frac{m_1^2}{2E} L} \mid \nu_1 \rangle + s \cdot e^{-i \frac{m_2^2}{2E} L} \mid \nu_2 \rangle \right)$$

Si ottiene

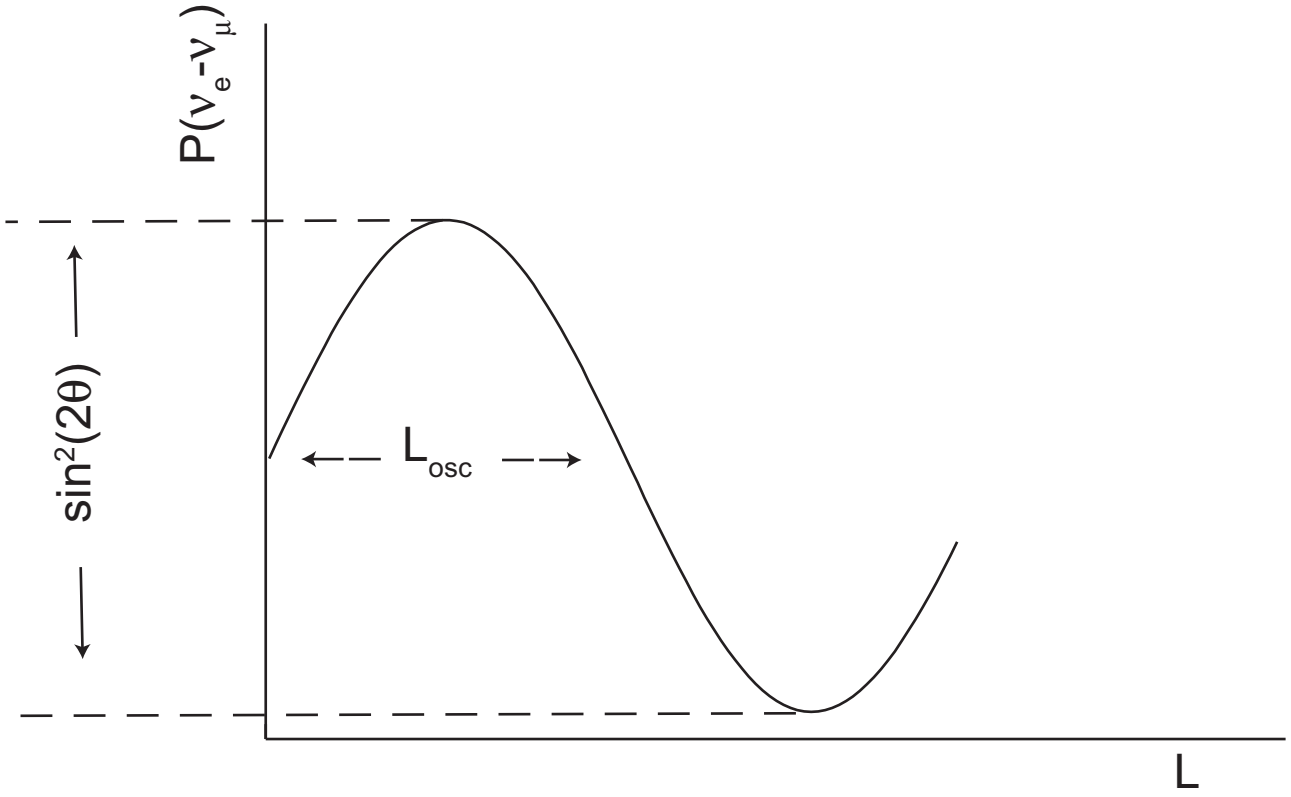
$$P(\nu_e \rightarrow \nu_\mu) = \mid \langle \nu_\mu \mid \nu(L) \rangle \mid^2 = \left| -sc \cdot e^{-i \frac{m_1^2}{2E} L} + cs \cdot e^{-i \frac{m_2^2}{2E} L} \right|^2 = 4s^2c^2 \left(1 - \cos \frac{(m_1^2 - m_2^2)}{2E} L \right)$$

$$\boldsymbol{P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2}{4E} L}$$

Oscillazioni a due neutrini (fine)

$$P_{\nu_e \to \nu_\mu}(L) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2[eV^2]}{E[GeV]} L[km]$$

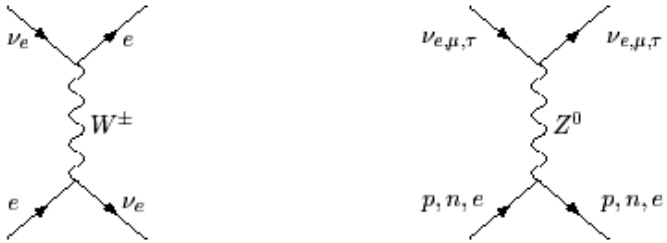
$$P_{\nu_e \to \nu_e}(L) = 1 - P_{\nu_e \to \nu_\mu}(L)$$



$$L_{\rm osc} = 2\pi \frac{E[GeV]}{1.27 \Delta m^2[eV^2]}$$

Oscillazioni di neutrini nella materia

Le hamiltoniane di interazione di ν_e, ν_μ, ν_τ nella materia sono diverse: i ν_e sono gli unici che possono interagire con gli elettroni attraverso lo scambio di un $W\pm$, mentre tutti i sapore di neutrini possono interagire con protoni, neutroni e elettroni scambiando una Z^0.



Ne consegue che la probabilità di oscillazione di neutrini cambia nella materia, con un carattere risonante della probabilità di oscillazione: effetto Mikheyev-Smirnov-Wolfenstein (MSW)

$$\tilde{m}_\nu^2 = 1/2(m_1^2 + m_2^2 + A) = \pm 1/2\sqrt{\left[(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2)^2 \sin^2 2\theta\right]}$$

$$\sin^2 2\tilde{\theta} = \frac{(\Delta m^2)^2 \sin^2 2\theta}{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2)^2 \sin^2 2\theta}$$

con $A = \pm\sqrt{2} E G_F N_e$; G_F costante di Fermi; N_e densità di neutrini nella materia.

Oscillazioni di neutrini nella materia (II)

$$P_{\nu_e \to \nu_\mu}(L) = \sin^2 2\tilde{\theta} sin^2(2\pi \frac{L}{\tilde{L}_{osc}})$$

$$\tilde{L}_{\mathrm{osc}} = 2\pi \frac{E[GeV]}{1.27 \Delta \tilde{m}^2 [eV^2]}$$

Condizione di risonanza

$$\Delta m^2 \cos 2\theta = \pm \sqrt{2} E G_F N_e$$

In questo modo la probabilità di transizione può essere grande anche in presenza di piccoli angoli di mixing.

Il caso di tre neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu^1 \\ \nu^2 \\ \nu^3 \end{pmatrix}$$

$$U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP}) =$$

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{\rm CP}} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta_{\rm CP}} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta_{\rm CP}} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta_{\rm CP}} & c_{13}c_{13} \end{pmatrix} \quad (1)$$

$$P(\nu_\alpha \to \nu_\beta) = -4\sum_{k>j} Re[W^{jk}_{\alpha\beta}] \sin^2 \frac{\Delta m^2_{jk} L}{4E_\nu} \pm 2\sum_{k>j} Im[W^{jk}_{\alpha\beta}] \sin^2 \frac{\Delta m^2_{jk} L}{2E_\nu}, \quad (2)$$

$\alpha = e, \mu, \tau$, $j = 1, 2, 3$, $W^{jk}_{\alpha\beta} = U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}$.

Formule di oscillazioni a tre neutrini

$$P_{\nu_\mu \to \nu_e} = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{C}$$

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

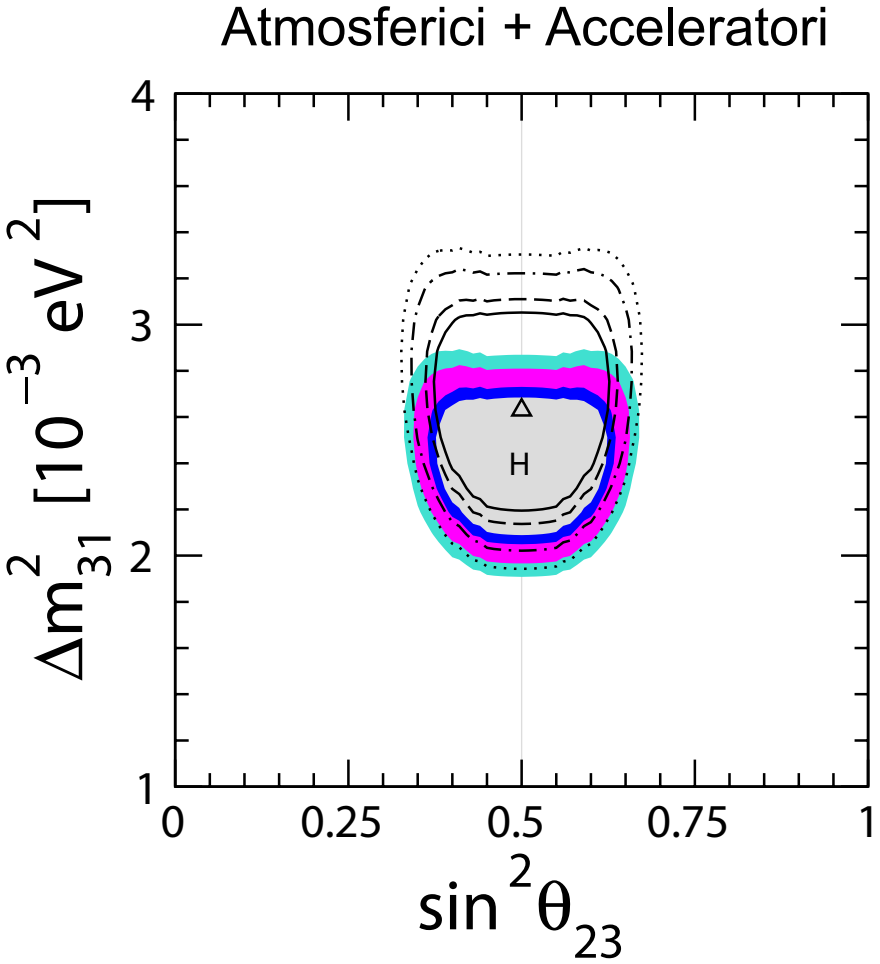
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar dri}$$

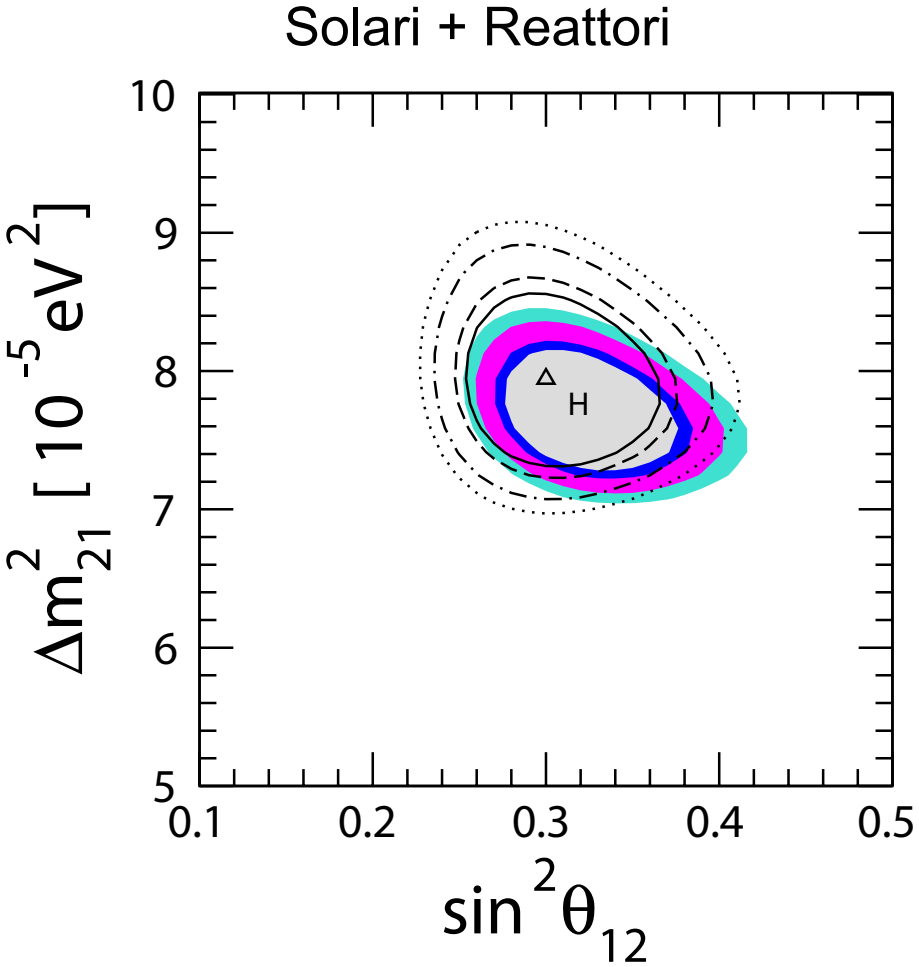
$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

$$1 - P_{\overline{\nu}_e - \overline{\nu}_e} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m_{31}^2 L/4E) + (\Delta m_{21}^2/\Delta m_{31}^2)^2)(\Delta m_{31}^2 L/4E)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

Per le oscillazioni finora sono stati utilizzati

- Neutrini Solari
- Neutrini Atmosferici
- Neutrini da Reattori
- Neutrini da Acceleratori





I neutrini sono MOLTO diversi dei quarks. (I)

Neutrinos
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks
$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

La matrice di mixing dei neutrini U_{MNSP} è molto diversa dalla matrice di mixing dei quark U_{CKM}

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

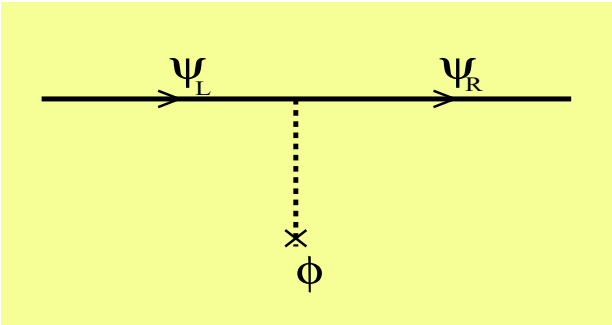
Neutrini Atmosferici — Unknown — Neutrini Solari

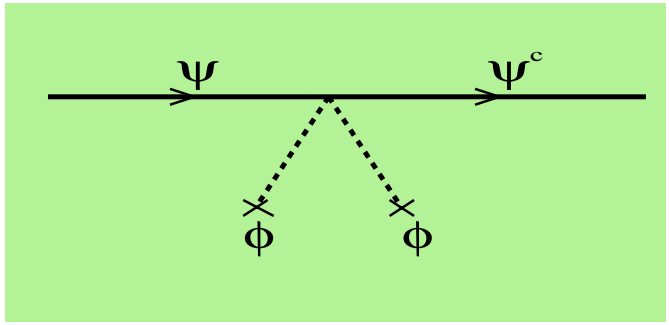
$\theta_{13} \to 0 \quad \Rightarrow$ La matrice 3x3 di mixing diventa il prodotto di due matrici 2x2.

I neutrini sono MOLTO diversi dei quarks. (II)

$u \sim 5$ MeV	$c \sim 1$ GeV	$t \sim 175$GeV	$e \sim 0.5$ MeV	$\mu \sim 0.1$ GeV	$\tau \sim 2$G
$d \sim 8$ MeV	$s \sim 0.1$ GeV	$b \sim 5$GeV	$\nu_e \leq \mathcal{O}(1\,eV)$	$\nu_\mu \leq \mathcal{O}(1\,eV)$	$\nu_\tau \leq \mathcal{O}(1$

Come può lo stesso modello generare rapporti di masse così diversi?





$$\lambda_\nu \overline{\Psi}_R \Phi \Psi_L + h.c.$$
$$m_f = \lambda_f v$$
$$L$$

$$\frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c.$$
$$m_f = \alpha_\nu \frac{v^2}{M}$$
$$\not{L}$$

Il meccanismo di massa dei neutrini ha al denominatore una massa M, se questa è associata ad una scala di energie molto alta (quelle della Grande Unificazione per esempio) la piccolezza della massa dei neutrini viene spiegata in maniera naturale. Questo meccanismo di massa (see-saw) prevede anche venga violata la conservazione del numero leptonico L.

Neutrinos from nuclear reactors

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

Every fission reaction emits about 200 MeV of energy and 6 $\overline{\nu}_e$.

$$\Downarrow$$

Flux $\sim 2 \cdot 10^{20}\ \overline{\nu}_e\ s^{-1}\ \mathrm{GWatt}^{-1}$, isotropic, $\langle E(\overline{\nu}_e)\rangle \simeq 0.5\ MeV$.

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

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

Neutrino flux

Detect absolute number of neutrino interaction and distortions of their spectrum

prompt positron signal, energy range.

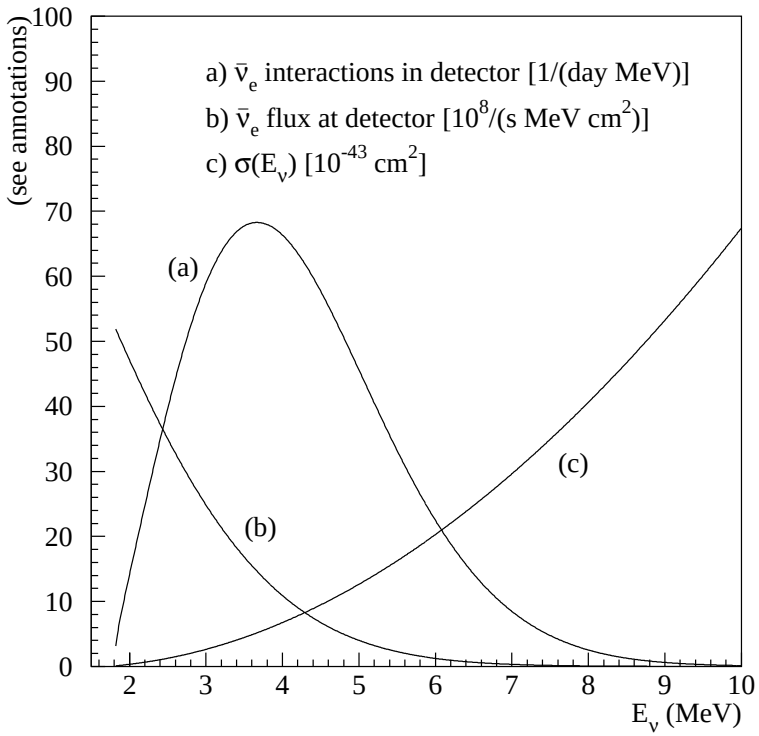
$$\overline{\nu_e} p \rightarrow e^+ n$$

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

delayed correlated photon.

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.**

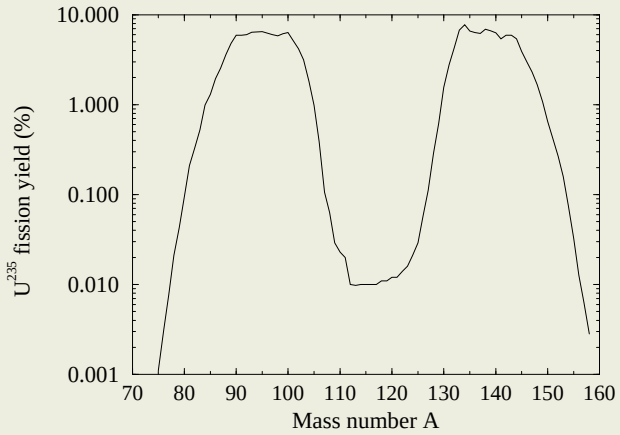


Thermal power of the reactor

The leading reaction is ^{235}U fission:

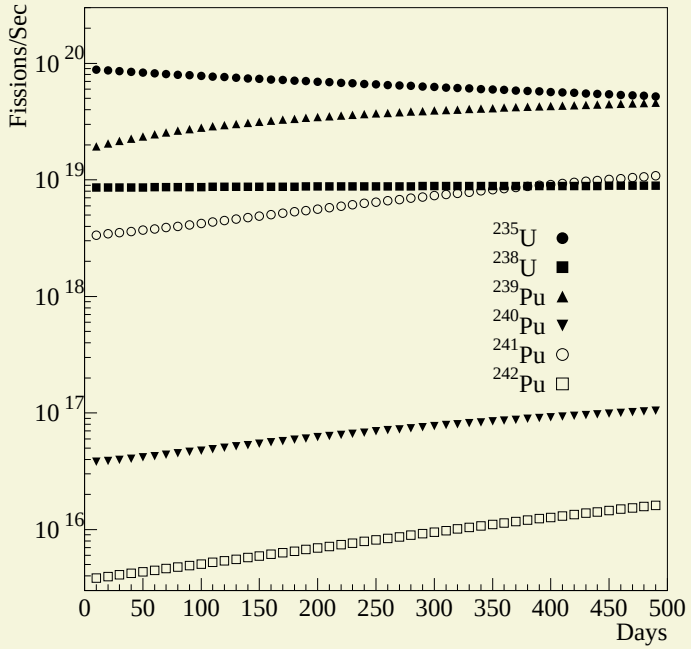
$$^{235}U + n \rightarrow X_1 + X_2 + 2n$$

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 β decays $\Rightarrow$ 6 $\overline{\nu}_e$.



The interaction process $\overline{\nu}_e + p \rightarrow n + e^+$ 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).



ν spectrum emitted by a reactor

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector reactor neutrino experiments

Reactor data

Thermal power, $\delta P_{th} \leq 1\%$

Reactor evolution codes

Fraction of fissions from isotope k, δa_k=few % but large anti-correl @ fixed P_{th}

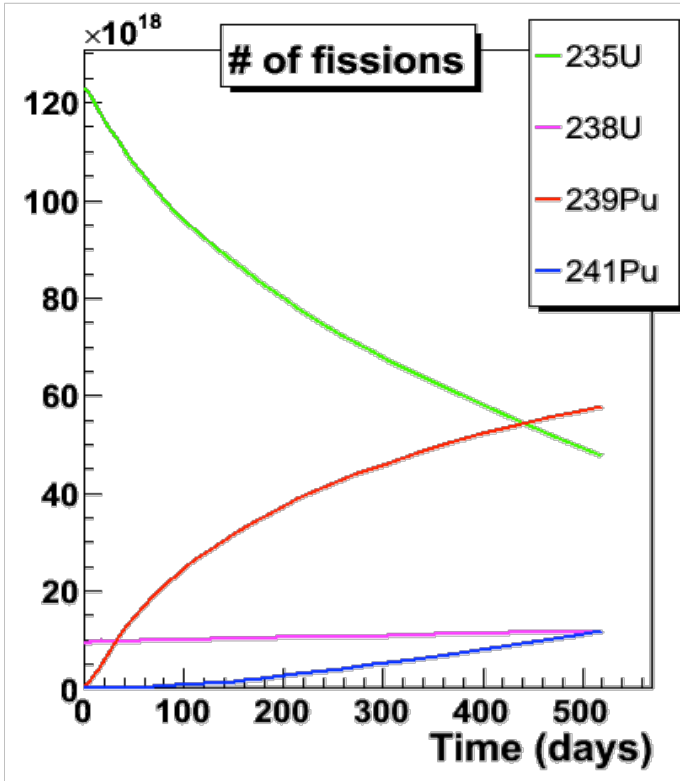
$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

Nuclear databases

E released per fissions of isotope k, $\delta E_k \approx 0.3\%$

ν spectrum per fission
This work !

$k = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$



The guts of $S_k(E)$

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branch of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

Theory of β-decay

$$S^b_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

$$\times \quad \underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

$$\delta^b_{fp}(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

Complementary approaches to compute the ν flux

Ab initio

Integral measurements

Sum of all fission products' activities

fission product inventory (t)

fission rates (t)

- Fission Yields (JEFF, ENDF, JENDL)
- Life time

Sum of all β-branches of each fission product

Build total spectrum from sum of β-branches

Reference spectrum per isotope

Theory of β-decay

- Complete β-decays schemes (ENSDF)
- β-strength (Greenwood et al.)
- Total β spectrum per nucleus (Rudstam et al.)
- Masses (Q_b)
- Nuclear models …

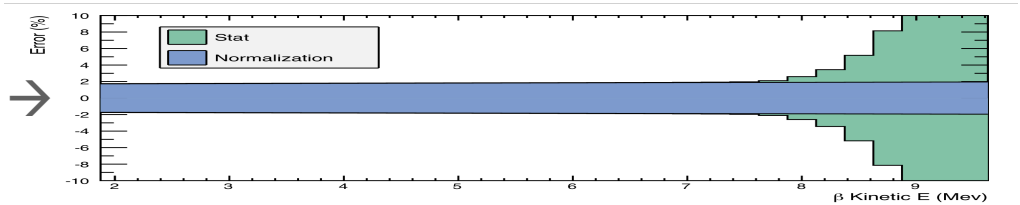
- ILL electron data

Full ab-inito | **Our mixed approach** | **Effective**

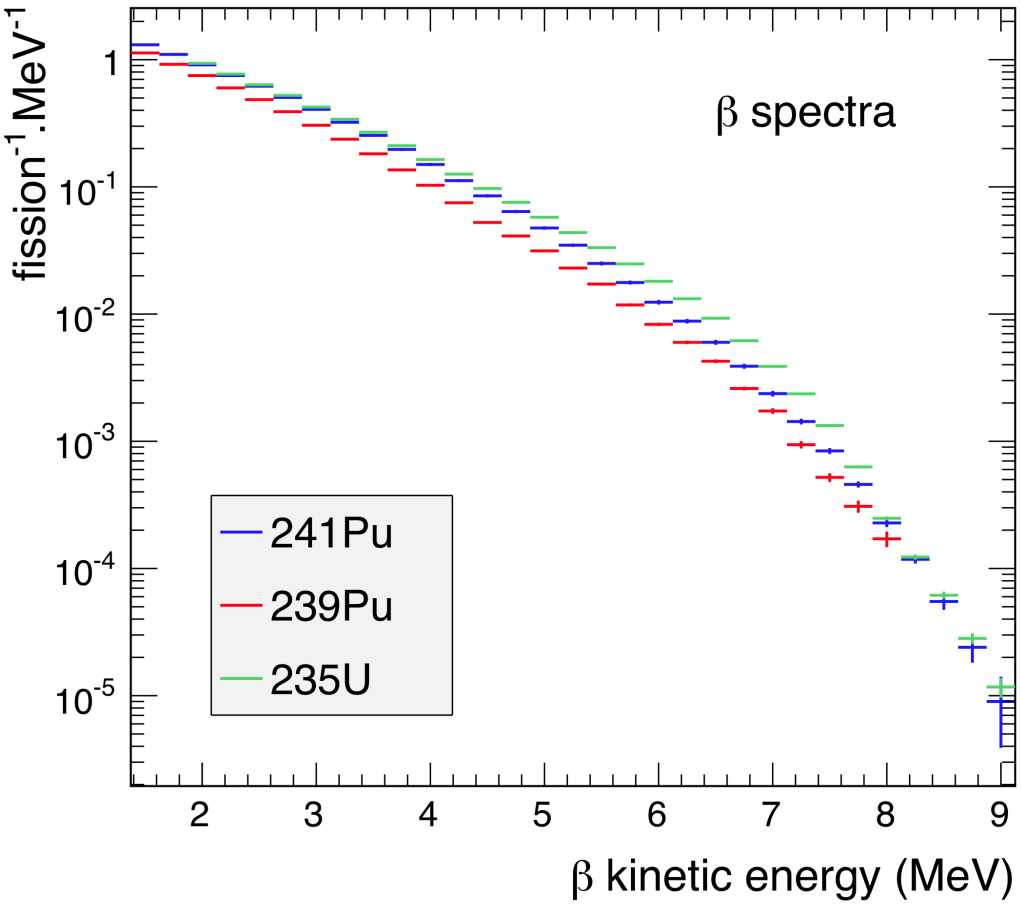
The ILL electron Data Anchorage

Unique reference to be met by any other measurement or calculation

uncertainty →

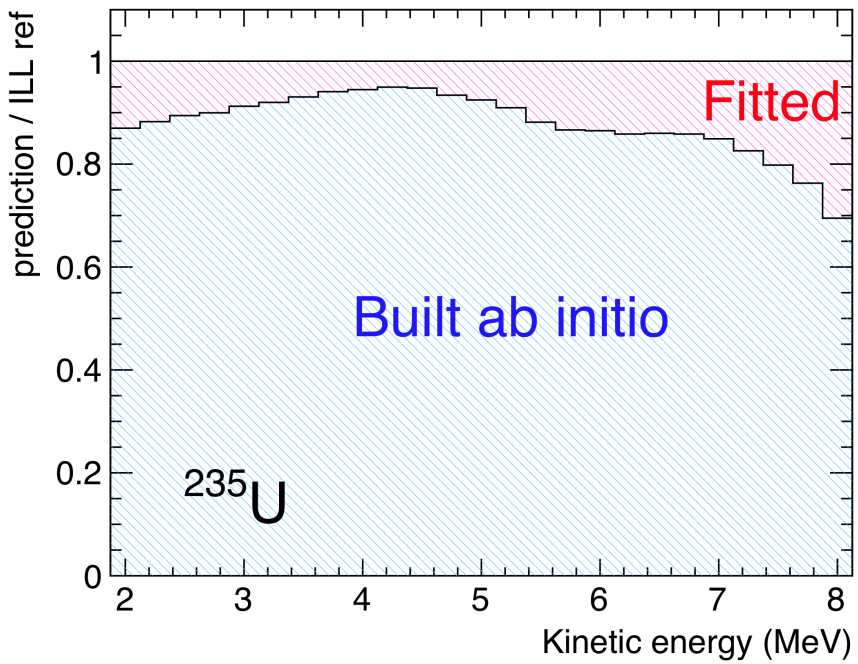


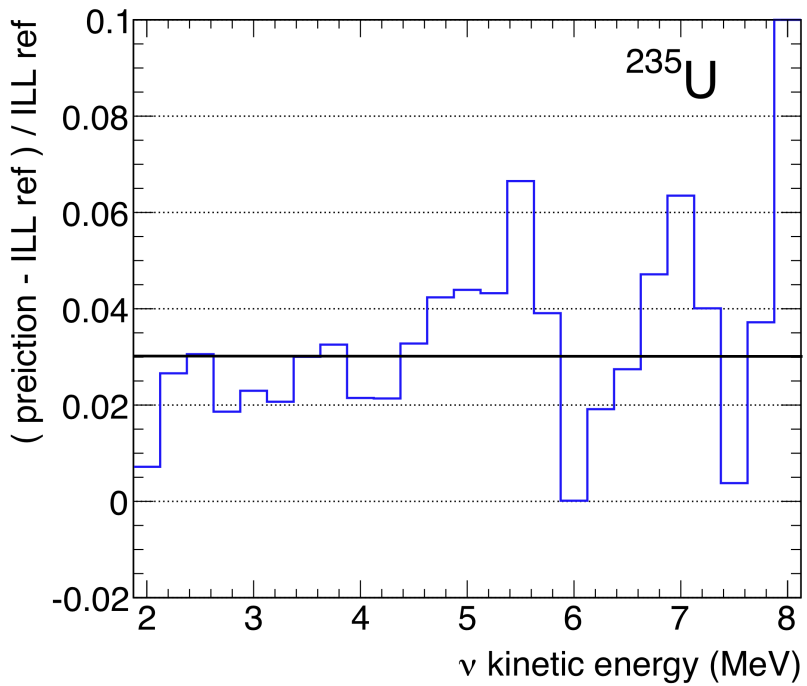
- Accurate e⁻ measurements @ ILL' (1980-89):
  - High resolution magn. spectrometer
  - Intense and pure thermal n spectrum from the core
  - Extensive use of reference internal conversion electron lines → Normalization (1.8%)



The New Mixed Conversion Approach

1. **SAME** ILL e- data Anchorage
2. Ab-Initio: “true” distribution of β-branches reproduces >90% of ILL e^- data.
3. Old-procedure: five effective anchorage-branches to the remaining 10%.





- **+3% normalization shift with respect to old ν spectrum**
- **Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)**
- **Stringent Test Performed – Origin of the bias identified**

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

The $\overline{\nu}_e$ 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 $\overline{\nu}_e$ to positrons

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

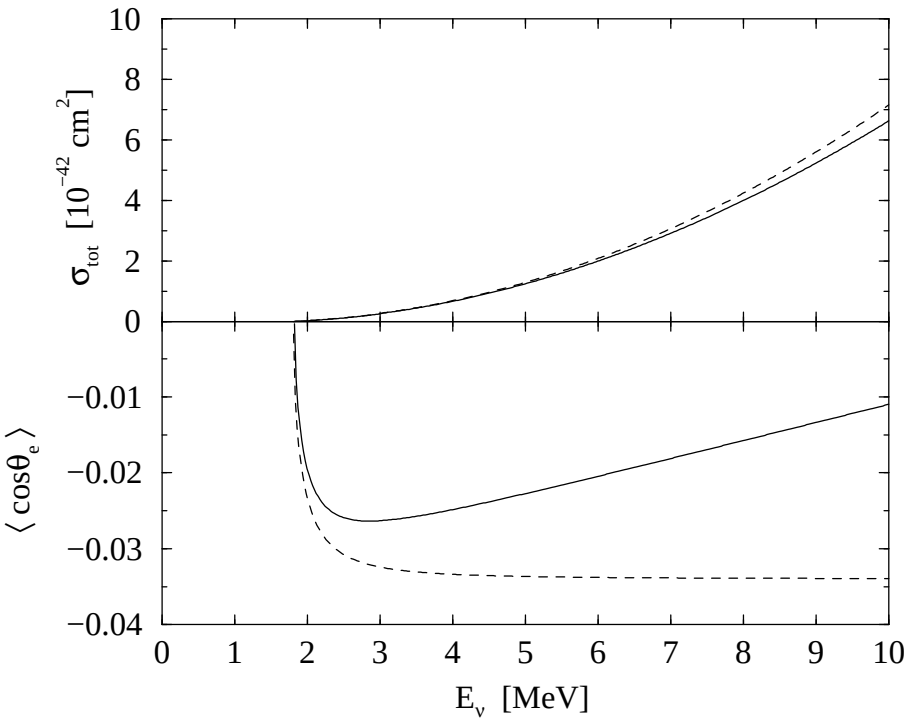
$$\begin{aligned} \sigma_{tot}^{(0)} &= \sigma_0 \left(f^2 + 3g^2\right) E_e^{(0)} p_e^{(0)} \\ &= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1\ \mathrm{MeV}^2}\right) \times 10^{-42}\ \mathrm{cm}^2 \end{aligned} \quad (3)$$

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

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

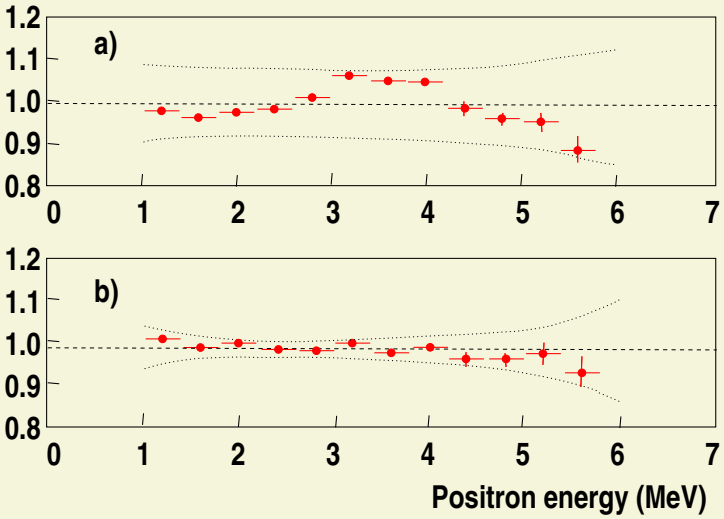
$$\sigma_0 = \frac{G_F^2 \cos^2\theta_C}{\pi}(1 + \Delta_{inner}^R)\ , \quad (4)$$

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



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

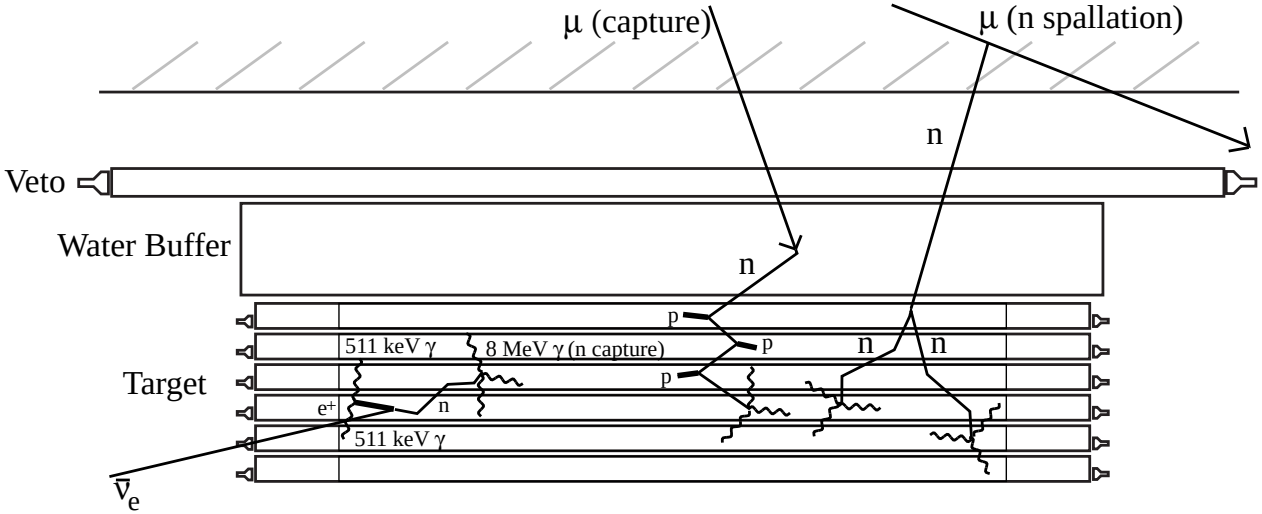
Experiment Bugey 3 (years 80', the very recent reanalysis of reactor antineutrino flux yields interprets its result as a $\sim$ 3% deficit): expected and measured $\overline{\nu}_e$ spectrum.
Curve b) is the most updated prediction.



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).

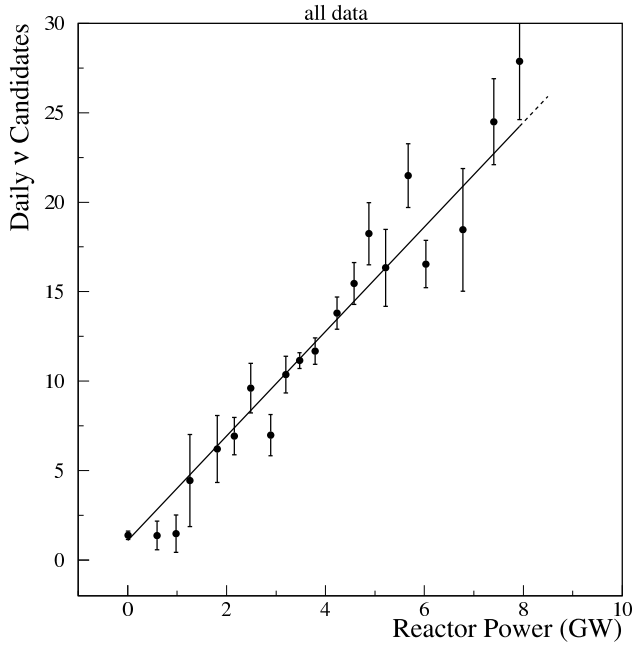
Systematic	CHOOZ (%)		P.V. (%)	
$\sigma(\overline{\nu}_e + p \rightarrow n + e^+)$	1.9		-	
Number of p in target	0.8		-	
W_{th}	0.7		-	
Energy abs. per fission	0.6		-	
Total rate prediction		2.3		2.1
e^+ trigger eff.	-		2.0	
n trigger eff.	-		2.1	
$\overline{\nu}_e$ selection cuts	-		2.1	
$(1-\epsilon_1)B_{pn}$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

Experimental backgrounds



Two main categories:

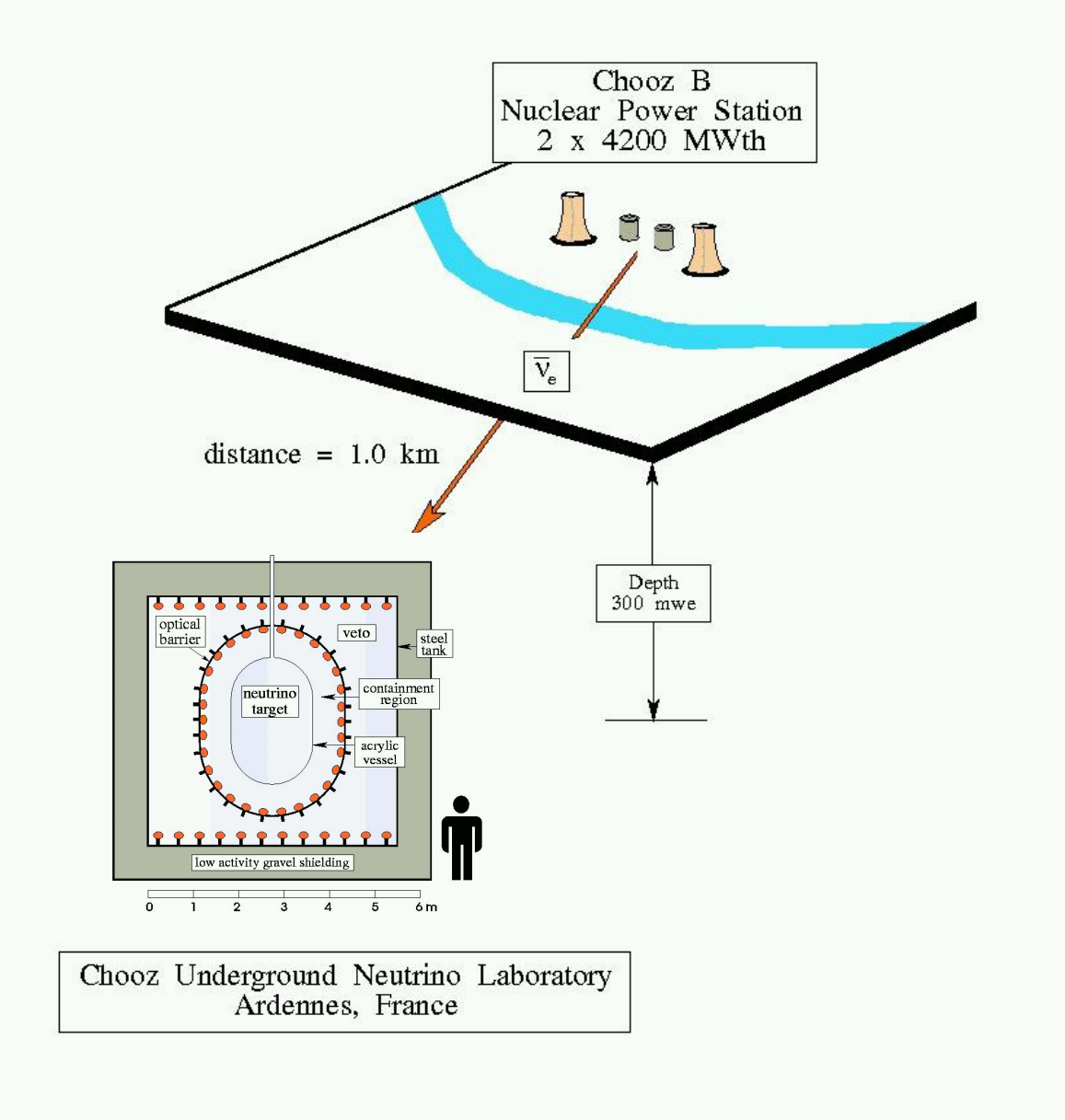
- Accidental backgrounds from the random superposition of a "positron-like" and "neutron-like" signals. Directly estimated from the measured rates of the two processes.
- Backgrounds from neutrons induced by cosmic rays. They can be measured only if the reactor is off (impossible to pay to have a reactor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



Chooz counting rate as function of the reactors power.

CHOOZ experiment (France-Italy-Russia-USA)

Took data in 1997-98



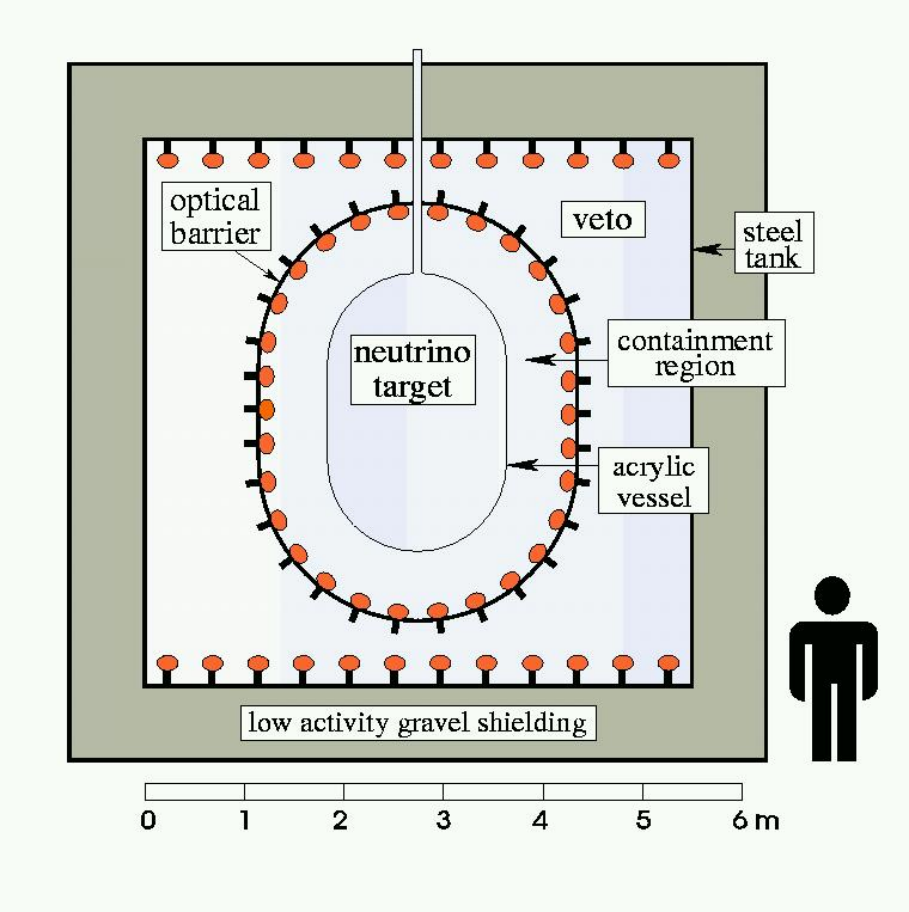
CHOOZ detector

5 ton liquid scintillator detector doped with gadolinium. Active liquid scintillator veto.
$\overline{\nu}_e$ detection:

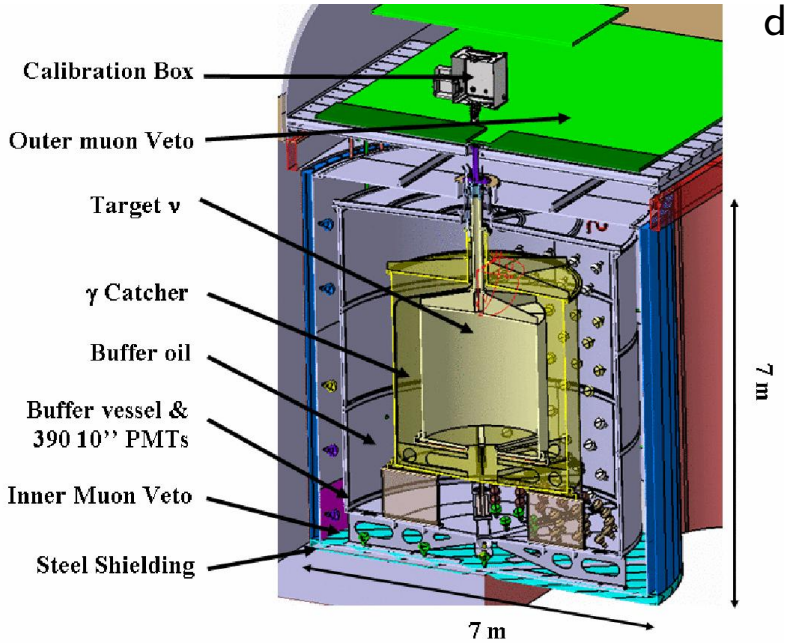
$$\overline{\nu}_e + p \rightarrow e^+ + n \quad E(\overline{\nu}_e) = E(e^+) + 1.804\ M$$

Two signals in delayed coincidence:

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



Disegno di un rivelatore ai reattori



Inner detector Scintillatore liquido drogato con Gadolinio (0.1%) in un recipiente acrilico. Il Gadolinio aumenta la sezione d'urto dei neutroni, diminuendo il tempo di cattura da $\sim$ 170 μs a $\sim$ 27 μs $\Rightarrow$ riduzione del rumore non correlato. Inoltre aumenta l'energia dei gamma prodotti dalla cattura da $\sim$ 2 MeV a $\sim$ 8 MeV.

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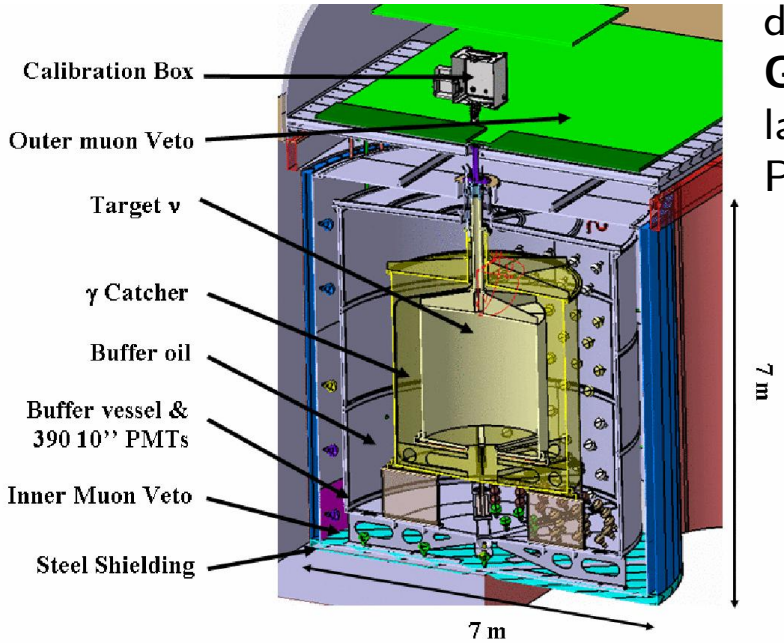

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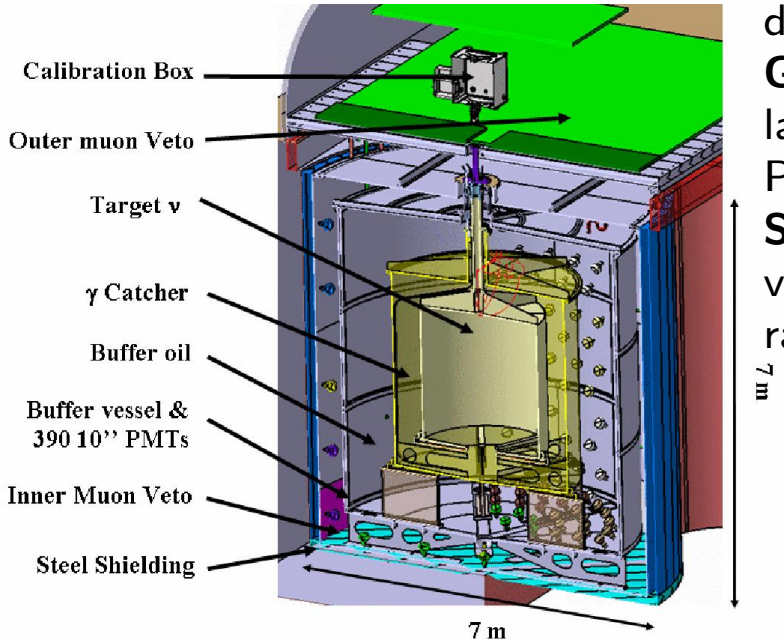
Gamma catcher: Scintillatore liquido non drogato per la cattura dei gamma emessi dalla cattura dei neutroni. Permette una migliore definizione del volume fiduciale.

Disegno di un rivelatore ai reattori



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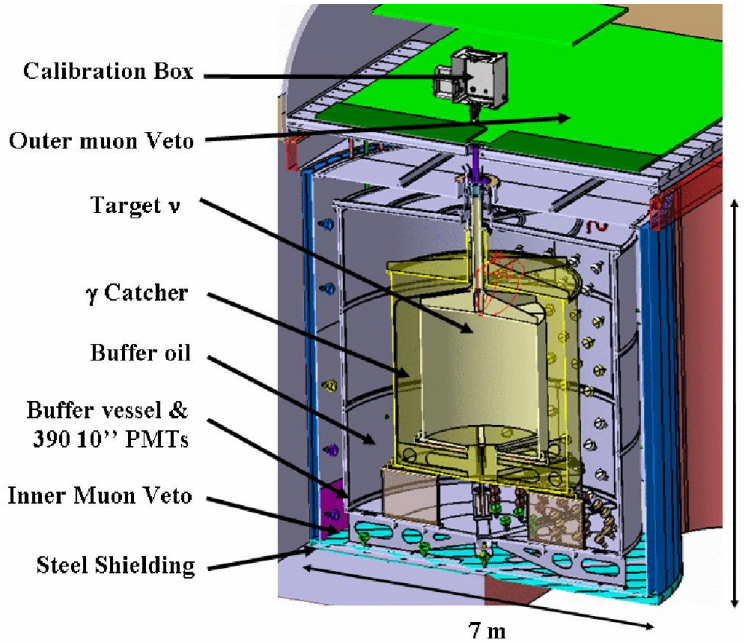
Schermo per i fototubi: Olio non scintillatore, separa il volume attivo dai fototubi, che sono la maggior sorgente di radioattività all'interno del rivelatore.

Disegno di un rivelatore ai reattori



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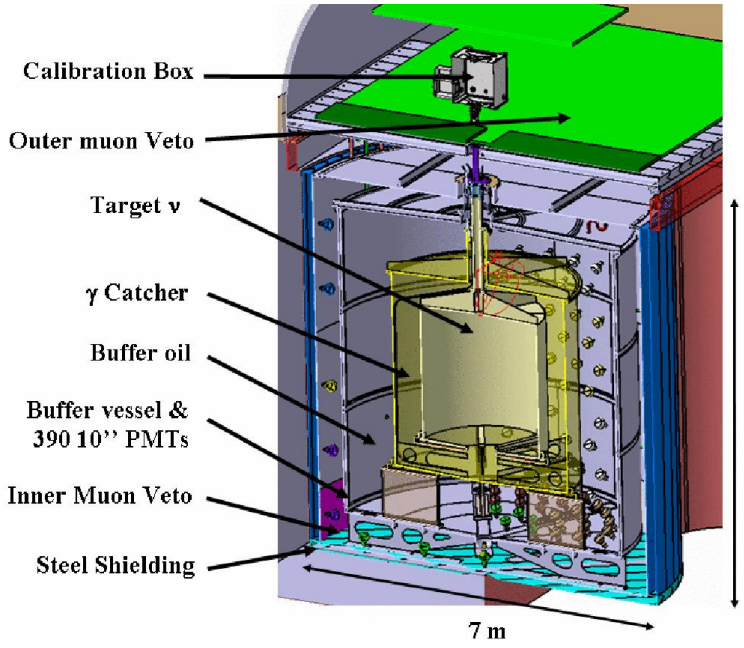
Inner veto: Per schermare i Compton indotti da radioattività esterna e da muoni passanti. È equipaggiato da fototubi.

Disegno di un rivelatore ai reattori



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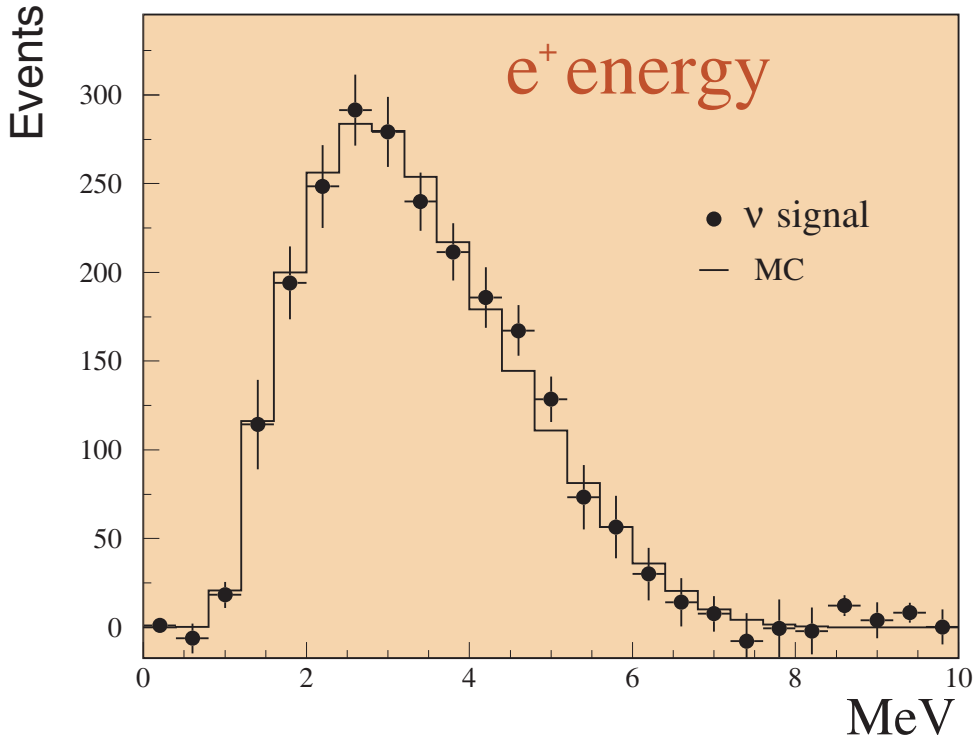
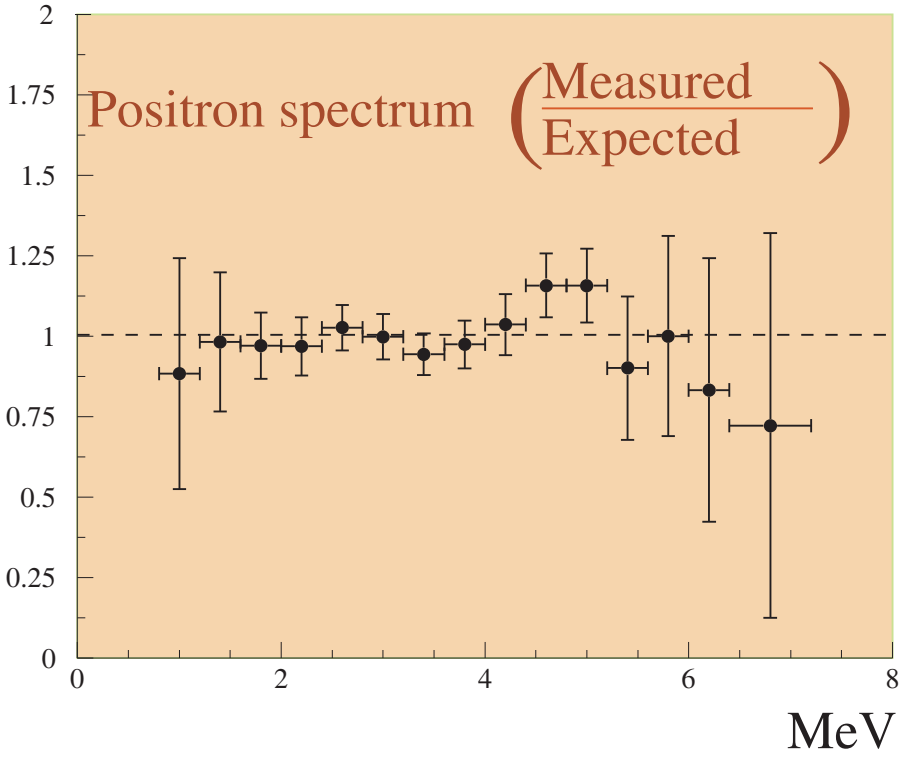
Inner veto: Per schermare i Compton indotti da radioattività esterna e da muoni passanti. È equipaggiato da fototubi.

Outer veto: Scintillatore solido (Double Chooz) o water Cherenkov (RENO e Daya Bay). Per vetare i μ passanti. Necessaria una profondità di almeno 100 m.w.e (dove i tempi morti indotti sono del 25%). Alcuni elementi prodotti dai iμ, come ^{8}He and ^{9}Li, con tempi di decadimento di 119 ms and 174 ms non possono comunque essere vetati.

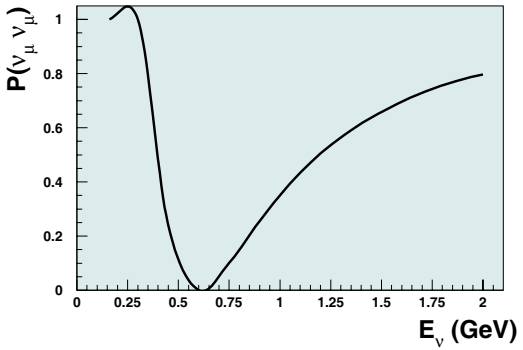
CHOOZ data


Events
e+ energy
ν signal
MC
300
250
200
150
100
50
0
0
2
4
6
8
10
MeV

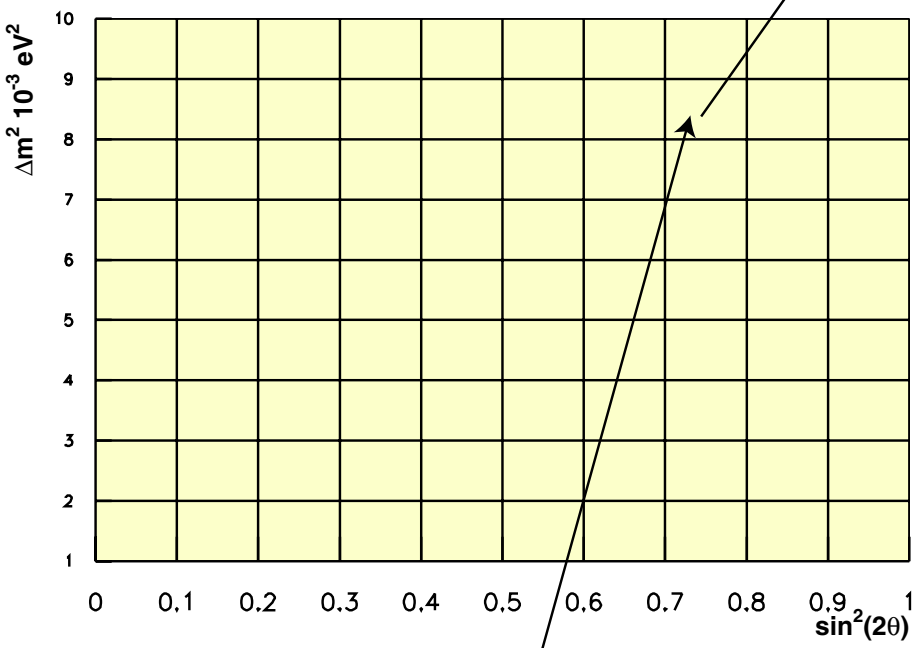

Positron spectrum
Measured
Expected
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
2
4
6
8
MeV

How to build the signal/exclusion plot

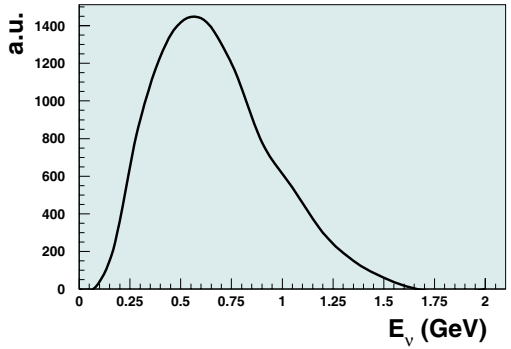
Every $\sin^2 2\theta$, Δm^2 cell defines $P_{\nu_\mu \nu_\mu}$



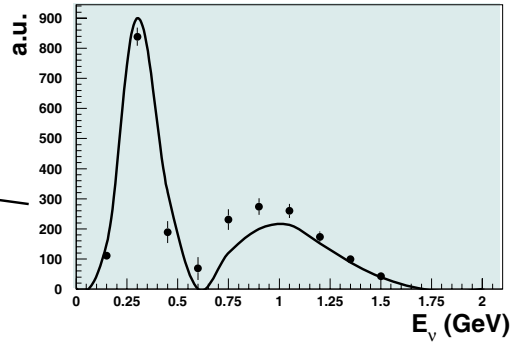
Grid in the $\sin^2 2\theta, \Delta m^2$ plane



That modulates the non-oscillated predicted spectrum



The prediction is compared to the data



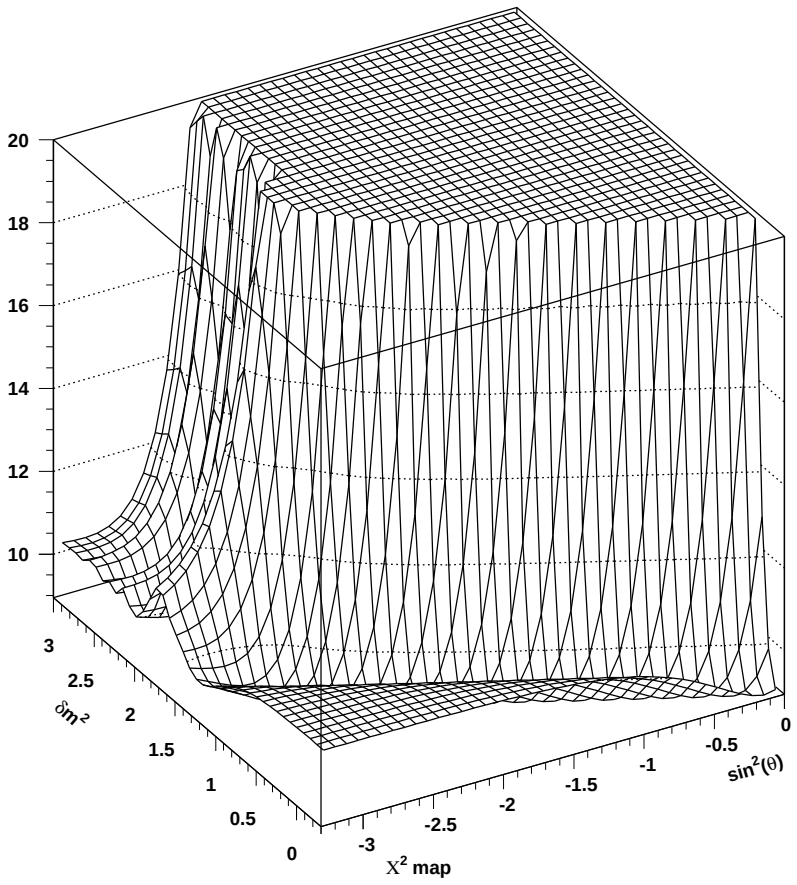
Fill the grid with the χ^2

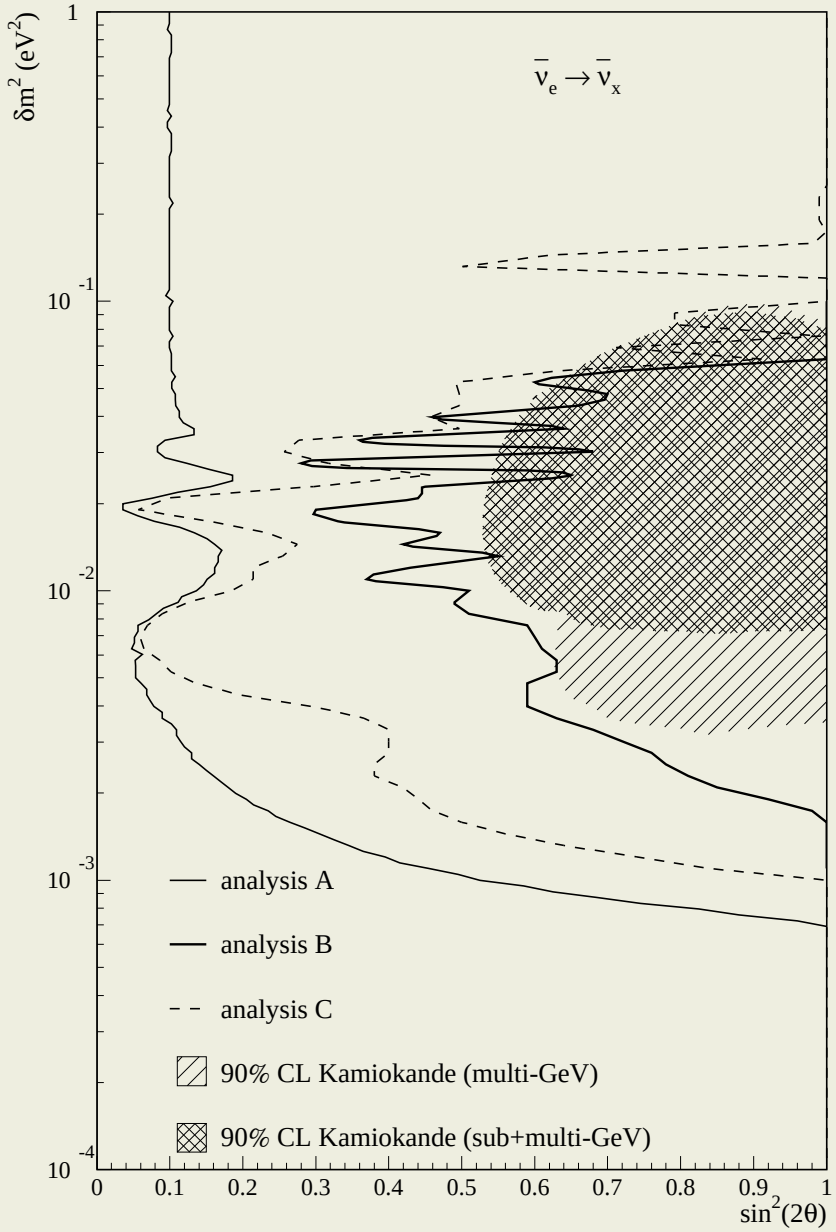
How to build the signal/exclusion plot (II)

- The minimum of the χ^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 χ^2 at two degrees of freedom $(\sin^2 2\theta, \Delta m^2)$

Question: Why $\Delta\chi^2$ and not χ^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** $\overline{\nu}_e$ spectrum after background subtraction. Both the absolute rate and the spectrum are used.
- **Analysis B** Uses the different baseline ($\Delta L = 117.7\,m$) of the two reactors.
  Many systematic errors cancel, but statistical errors are bigger and the Δm^2 sensitivity is reduced by the shorter baseline.
- **Analysis C** Only spectrum information is used.

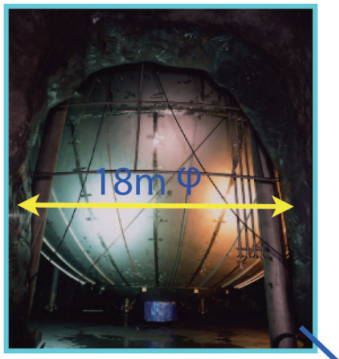
Top Cited 1000+ Sperimentali in QSPIRES (al 6/11/05)

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 ν_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

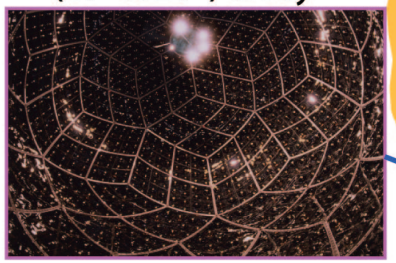
KamLAND Detector

Kamioka Liquid Scintillator Antineutrino Detector

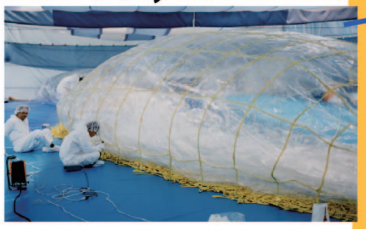
Stainless steel tank

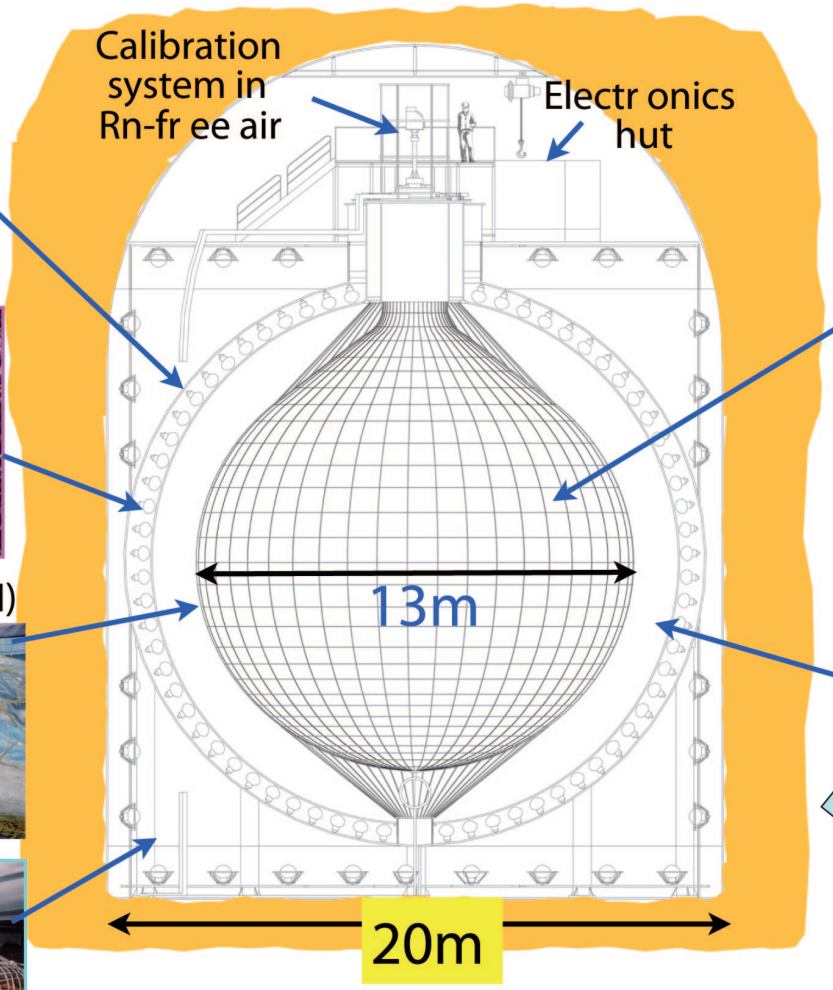


1879 PMT (17"& 20") array

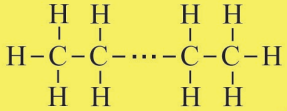


Balloon (Nylon/EVOH)

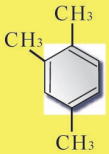




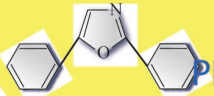
Liquid Scintillator ~1kton



Normal dodecane ($C_{12}H_{26}$) (80%)



Pseudocumene (20%)



PPO (1.36 ±0.03g/l)

Buffer Oil (dodecane)

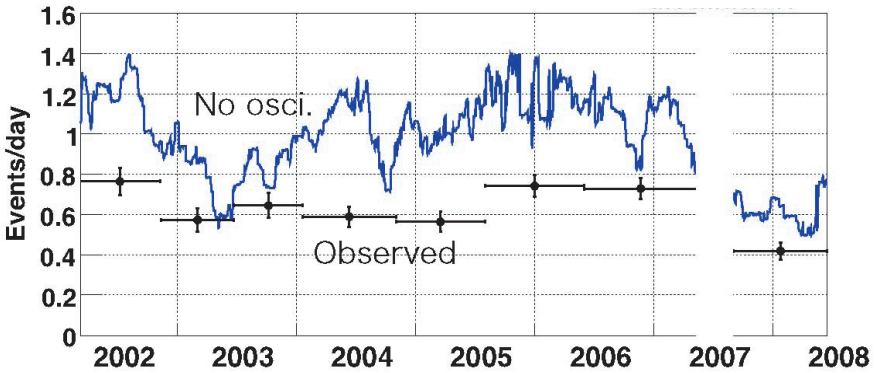
Vertex resolution ~12cm/ $\sqrt{E_{[MeV]}}$

Energy resolution 6.5%/ $\sqrt{E_{[MeV]}}$

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

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)
Japan					
Kashiwazaki	160.0	7	24.6	4.25×10^5	348.1
Ohi	179.5	4	13.7	1.88×10^5	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



Kamland and systematic errors

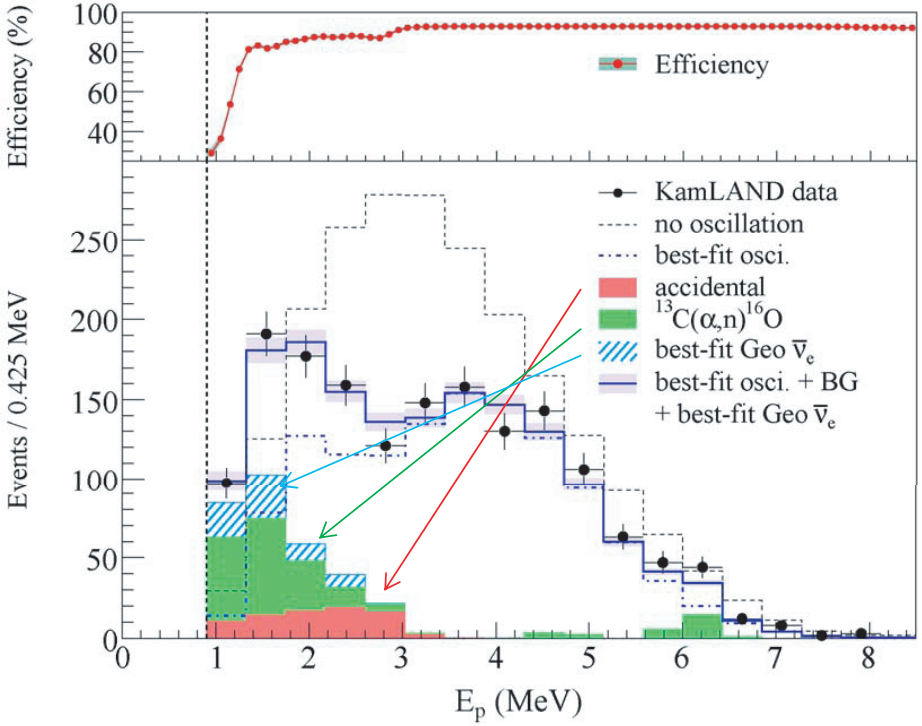
	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\overline{\nu}_e$-spectra	0.6
Event rate	Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

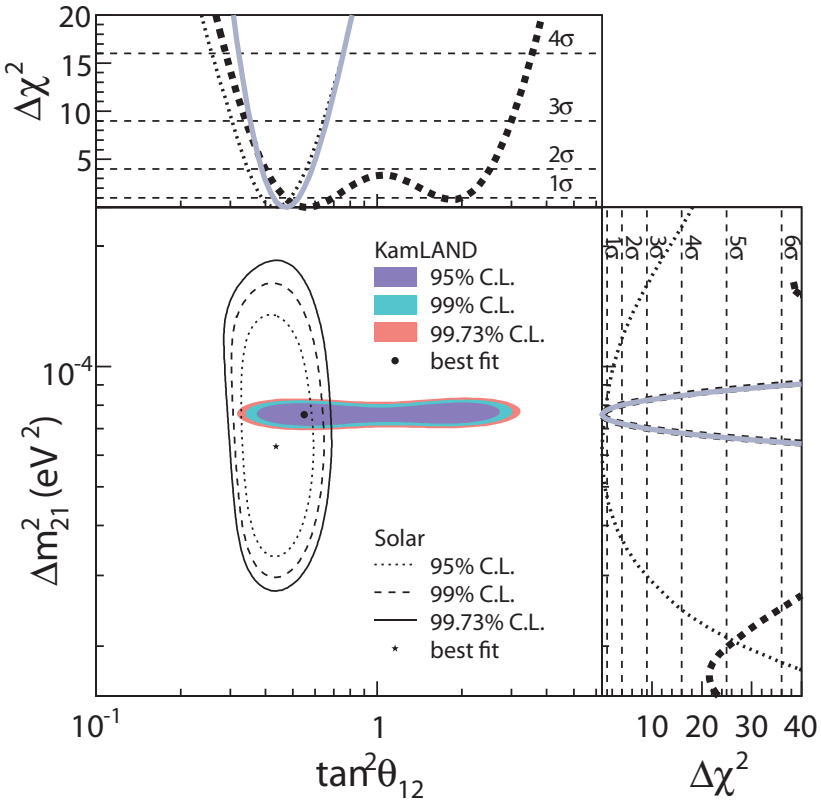
Kamland Results (I)

of Observed and Expected Events

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

Kamland Results (II)



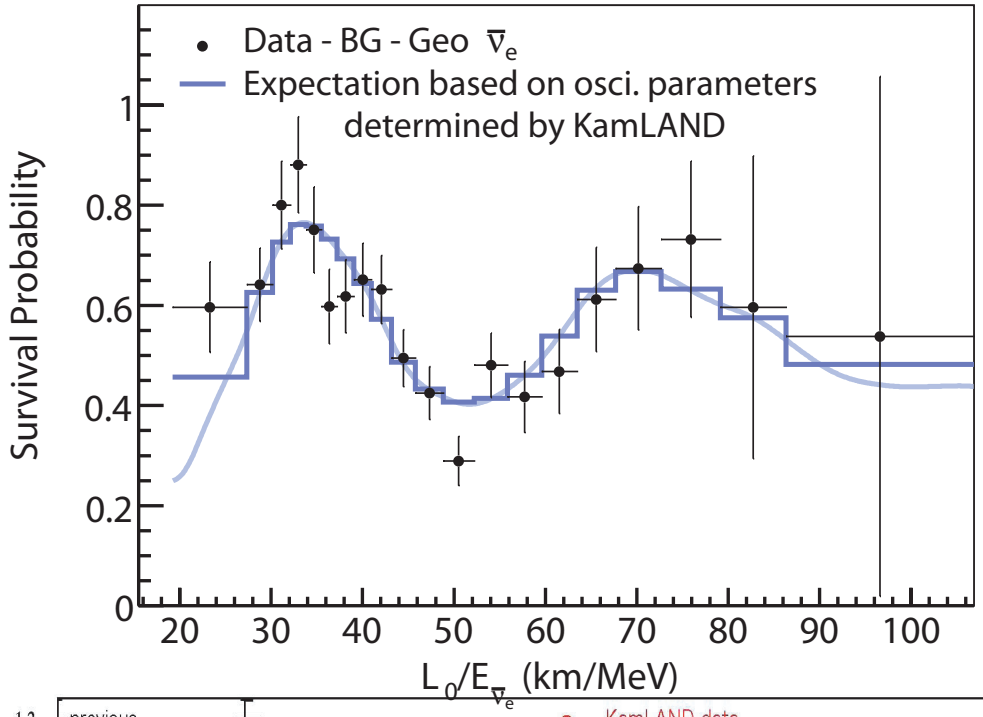


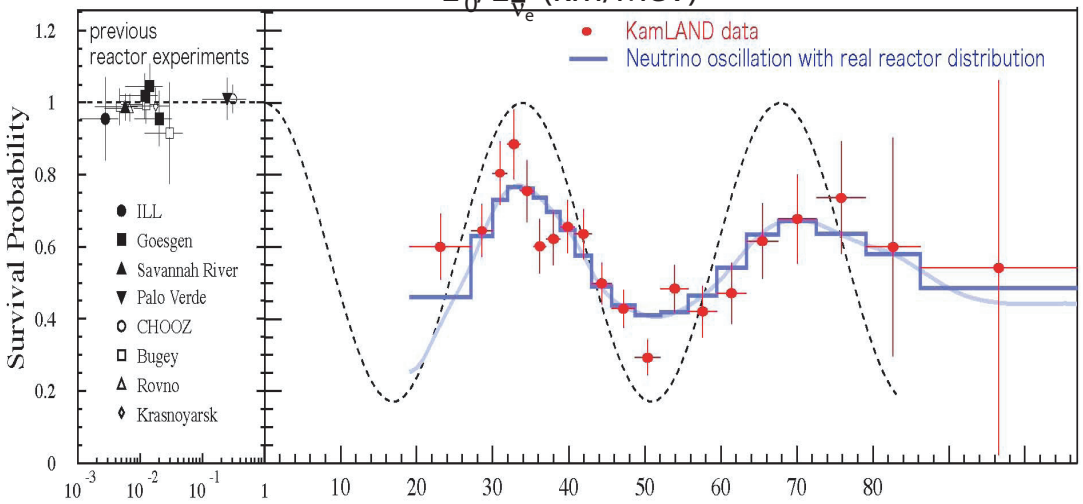
Fit to scaled no-oscillation spectrum : exclude at 5.1 σ

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

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

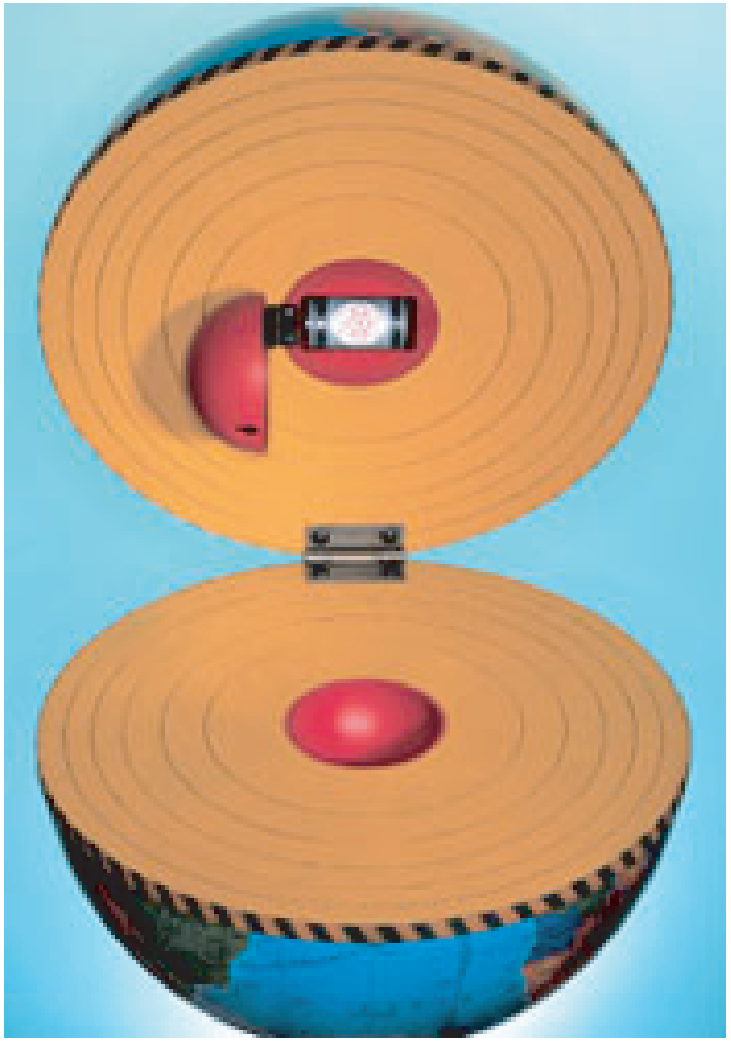
Kamland Results (III)





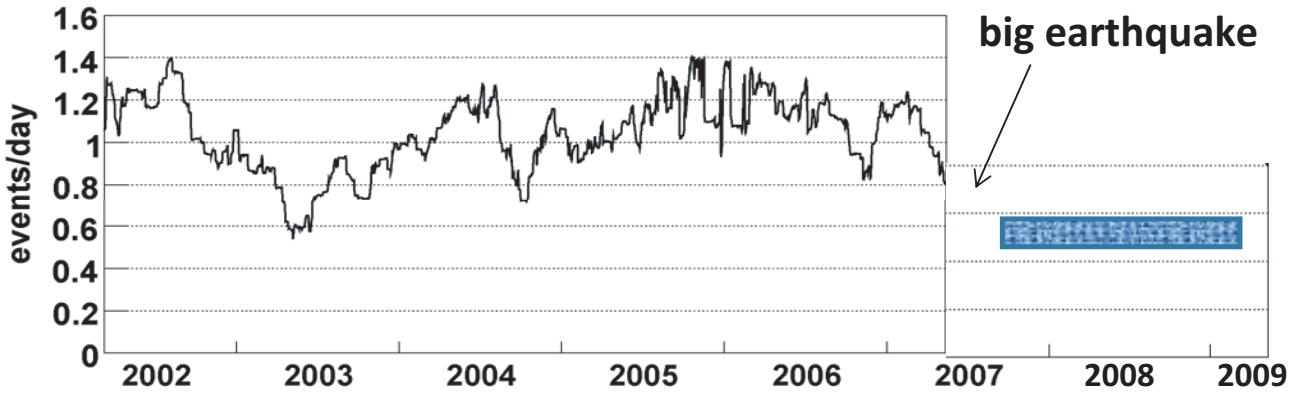
Geo-Reactor

- 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

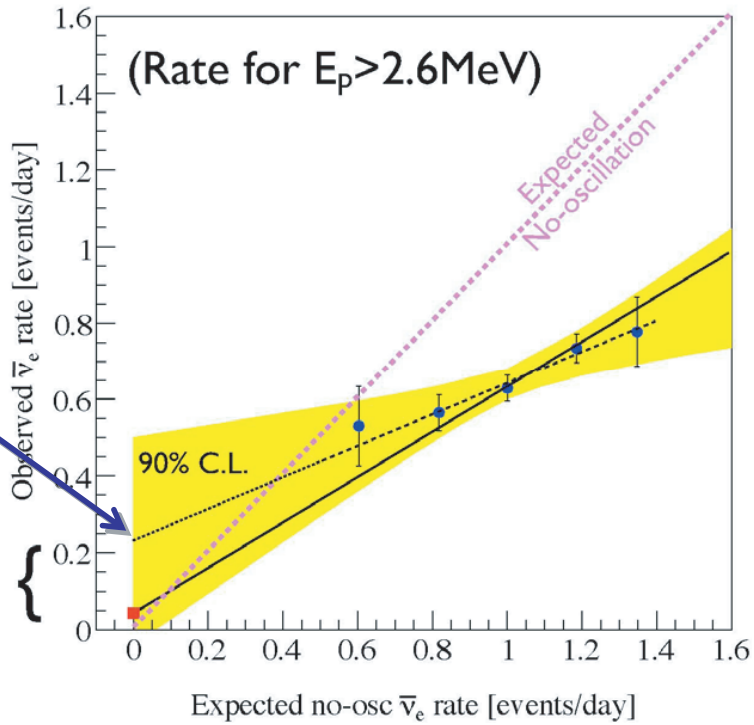
Signature from Geo-Reactor



Kashiwazaki power station : 24.3 GW

Detailed operational records from all 55 reactors in Japan

Y-intercept : Geo-Reactor + BG



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

theoretical prediction : 3 TW