Reactor neutrinos: toward oscillations

Petr Vogel, Caltech

History of neutrinos, Paris, Sept. 7, 2018

Plan:Sketch of history of reactor neutrino physics over five decades since the Reines-Cowan proof of neutrino existence in the late 50s till the advent of the present era of precision reactor neutrino oscillation experiments.

There are three chapters of this story:

i) Exploration of possibilities in the 60s and 70s;
F. Reines and collaborators observe reactor neutrino reactions involving protons, deuterons and electrons as targets.

ii) Looking for oscillations under the streetlamp in the 80s and 90s;
experiments with detectors at the most convenient positions, less than 100 m from the reactor core. Exploring the reactor neutrino spectrum.

iii) Exploring oscillations with known (almost) Δm^2_{atm} and Δm^2_{sol} :
Once atmospheric and solar neutrinos were discovered, and the corresponding Δm^2_{atm} and Δm^2_{sol} roughly determined, it became clear that the distance L should be at least ~50 km to explore oscillations corresponding to Δm^2_{sol}, realized with KamLAND, and L = 1-2 km for Δm^2_{atm} leading to Chooz, Palo Verde and the present generation Daya-Bay, RENO and DoubleChooz.

Reminder: Electron antineutrino induced reactions observable at reactors:

$\bar{\nu} + p \rightarrow e^+ + n$	ccp	$\sigma \simeq 63\times10^{-44}$ cm^2/fission	$E_{th} = 1.8$ MeV
$\bar{\nu} + d \rightarrow e^+ + n + n$	ccd	$\sigma \simeq 1.1\times10^{-44}$ cm^2/fission	$E_{th} = 4.0$ MeV
$\bar{\nu} + d \rightarrow \bar{\nu} + n + p$	ncd	$\sigma \simeq 3.1\times10^{-44}$ cm^2/fission	$E_{th} = 2.2$ MeV
$\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$	el. sc.	$\sigma \simeq 0.4\times10^{-44}$ cm^2/fission	E_{range} 1-6 MeV

All these reactions were actually studied with reactor neutrinos. (see E. Pasierb et al. , Phys. Rev. Lett. **43**, 96 (1979) for the reactions on deuterium, and F. Reines et al., Phys. Rev. Lett. **37**, 315 (1976) for the neutrino electron scattering)
For oscillations, obviously, the most suitable, and hence almost exclusively used is the inverse neutron beta decay (IBD) or ccp reaction.

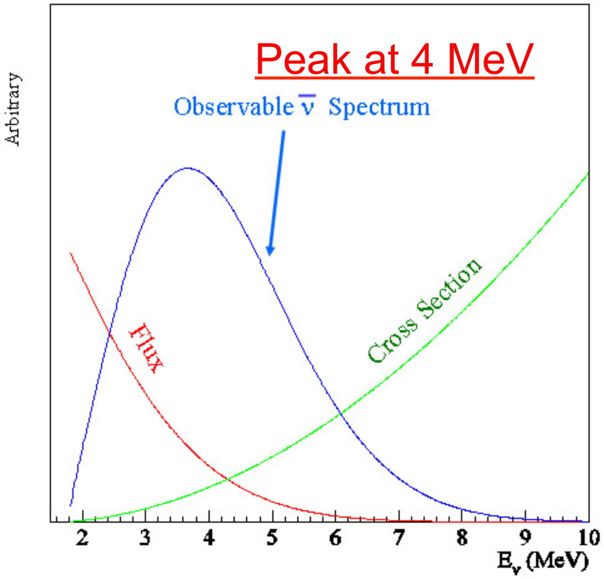
Reactor electron antineutrinos are usually detected through the inverse neutron beta decay (IBD)

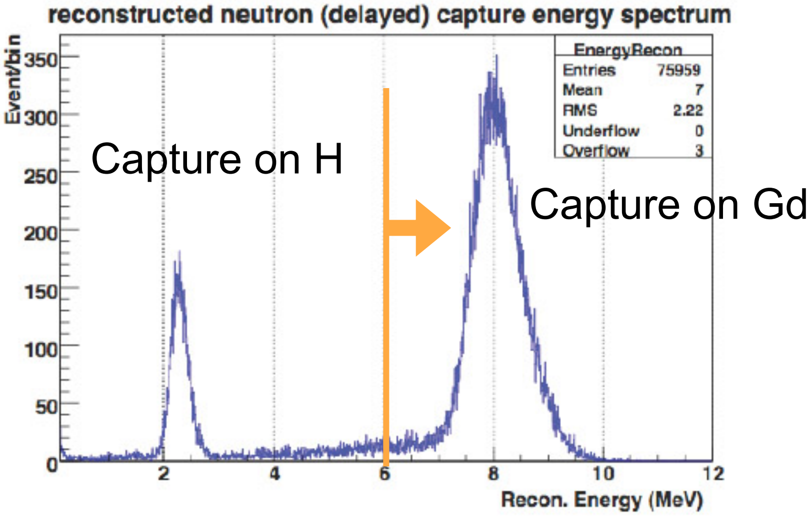
Prompt signal

$$e^{+} + e^{-} \rightarrow 2\gamma$$

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

Capture on H or Gd,
Delayed signal, 2.2, 8 MeV





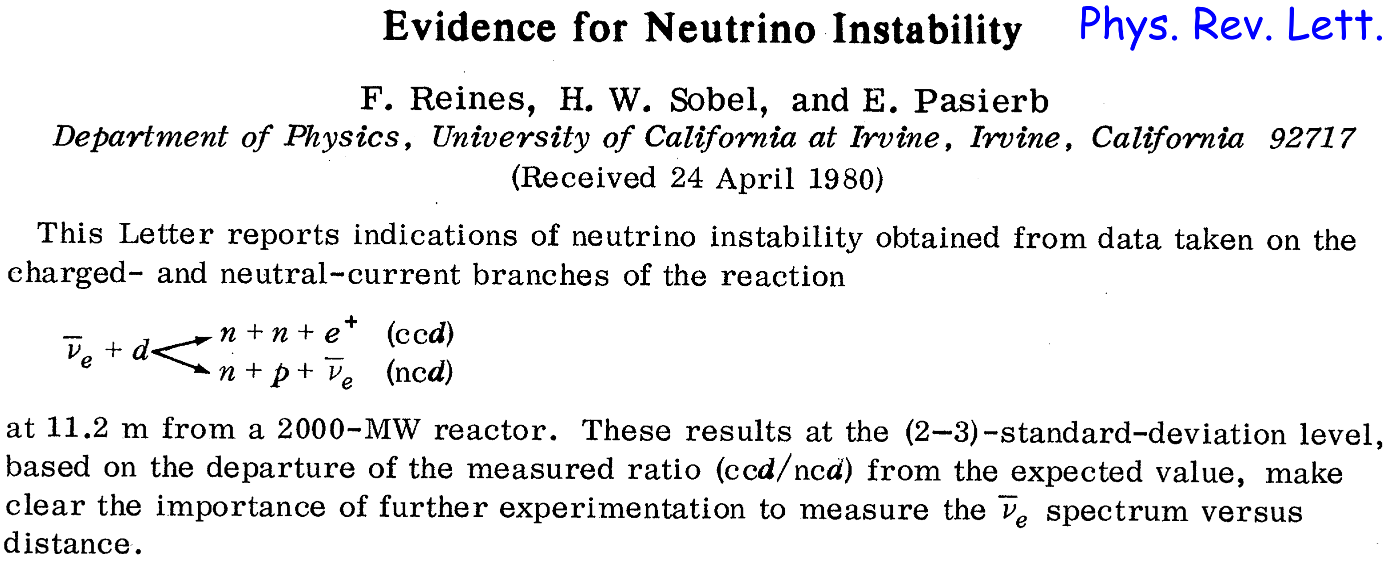
Neutron capture after thermalization

- **Inverse beta decay reaction,** proposed by Pontecorvo, called Cowan-Reines reaction
- **Coincidence of**
  - Prompt: positron, energy correlated to neutrino energy
  - Delayed: neutron capture
- **10,000 times bkg reduction**

In late 70s the idea of neutrino oscillations became a hot subject (note that the famous Phys. Rept. by Bilenky and Pontecorvo appeared in 1978.)

Reactor experiments with ~MeV neutrinos were reasonably realistic at that time, with detectors at $L < 100$ m from the reactor core and were sensitive to the oscillations with Δm^2 near 1 eV^2.

Large number (more that 20) of such experiments were performed, constraining a range of Δm^2 and mixing angles.



Evidence for Neutrino Instability

Phys. Rev. Lett. **45**, 1307 (1980)

F. Reines, H. W. Sobel, and E. Pasierb
Department of Physics, University of California at Irvine, Irvine, California 92717

(Received 24 April 1980)

This Letter reports indications of neutrino instability obtained from data taken on the charged- and neutral-current branches of the reaction

$$\bar{\nu}_e + d \begin{cases} \nearrow n + n + e^+ & (\mathrm{cc}d) \\ \searrow n + p + \bar{\nu}_e & (\mathrm{nc}d) \end{cases}$$

at 11.2 m from a 2000-MW reactor. These results at the (2–3)-standard-deviation level, based on the departure of the measured ratio (cc$d$/nc$d$) from the expected value, make clear the importance of further experimentation to measure the $\bar{\nu}_e$ spectrum versus distance.

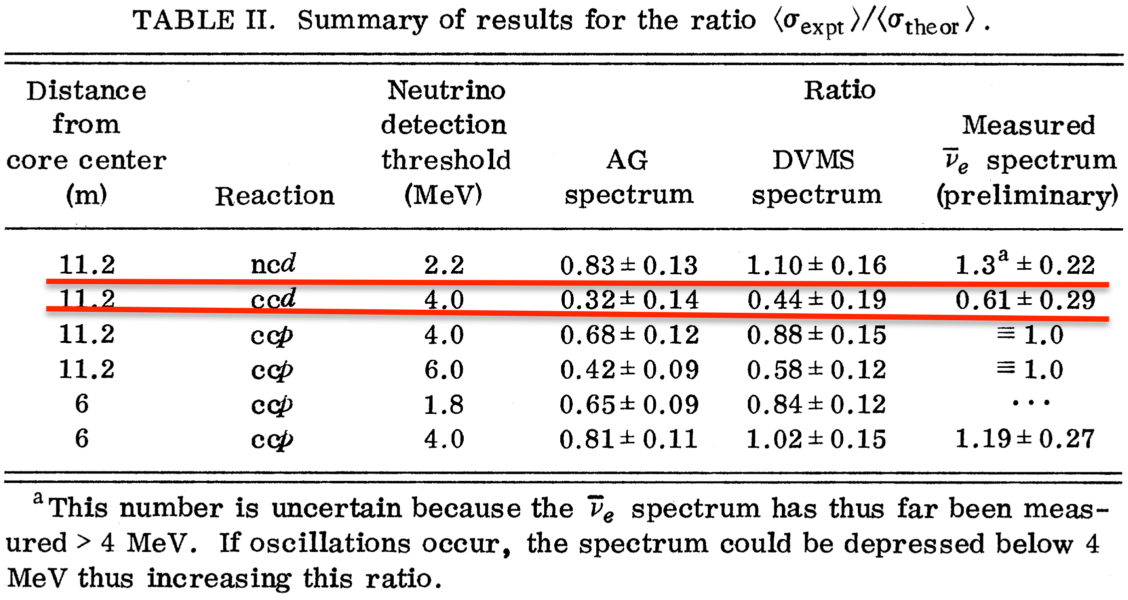


TABLE II. Summary of results for the ratio $\langle\sigma_{\mathrm{expt}}\rangle/\langle\sigma_{\mathrm{theor}}\rangle$.

Distance from core center (m)	Reaction	Neutrino detection threshold (MeV)	Ratio AG spectrum	Ratio DVMS spectrum	Ratio Measured $\bar{\nu}_e$ spectrum (preliminary)
11.2	nc$d$	2.2	0.83 ± 0.13	1.10 ± 0.16	1.3^{a} ± 0.22
11.2	cc$d$	4.0	0.32 ± 0.14	0.44 ± 0.19	0.61 ± 0.29
11.2	cc$p$	4.0	0.68 ± 0.12	0.88 ± 0.15	≡ 1.0
11.2	cc$p$	6.0	0.42 ± 0.09	0.58 ± 0.12	≡ 1.0
6	cc$p$	1.8	0.65 ± 0.09	0.84 ± 0.12	...
6	cc$p$	4.0	0.81 ± 0.11	1.02 ± 0.15	1.19 ± 0.27

[a] This number is uncertain because the $\bar{\nu}_e$ spectrum has thus far been measured > 4 MeV. If oscillations occur, the spectrum could be depressed below 4 MeV thus increasing this ratio.

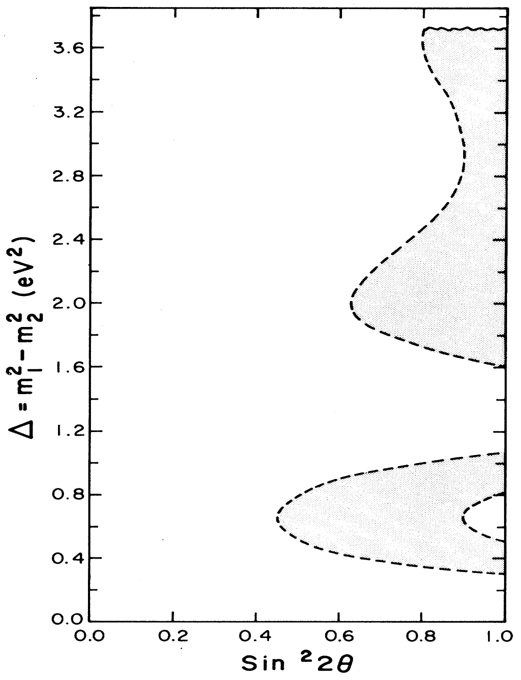
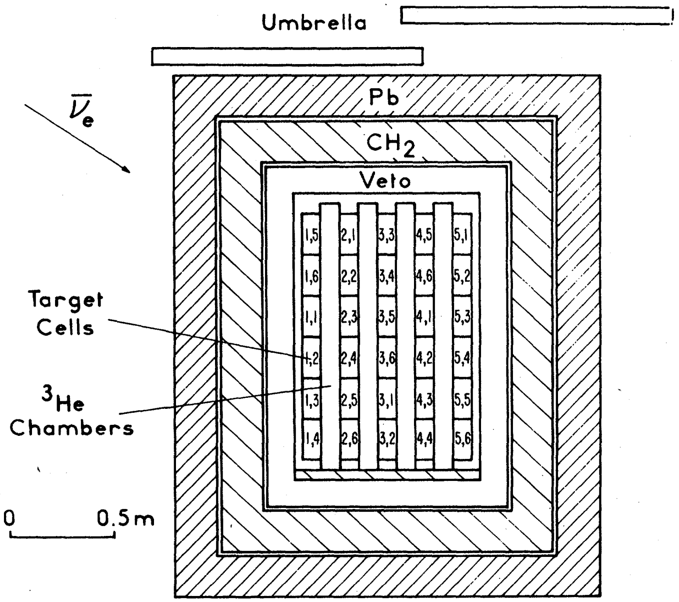


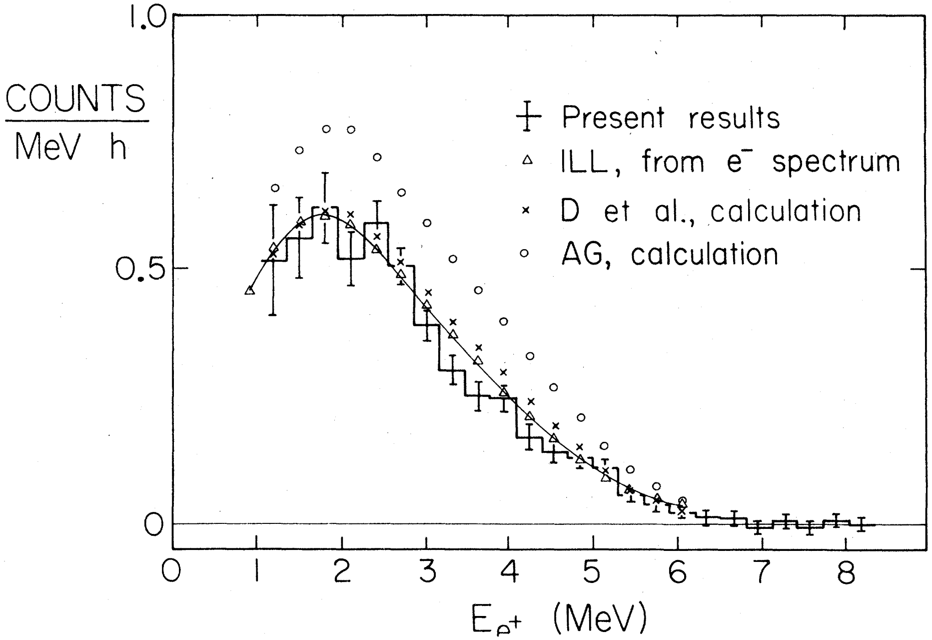
FIG. 1. Allowed regions of Δ and $\sin^2 2\theta$ for $\mathcal{R} = 0.38 \pm 0.21$.

The claim for evidence of oscillations officially withdrawn in F. Reines, Nucl. Phys. **A396**, 469c (1983).

The ILL experiment: H. Kwon *et al.* Phys. Rev. D **24**, 1097 (1981):

57 MW reactor with ^{235}U enriched to 93%, detector at 8.76 m, 377 l





Conclusion: No evidence for oscillations and

The ratio of the experimental to expected integral positron yield for $E_{e^+} > 1$ MeV was found to be

$$\frac{\int Y_{\mathrm{exp}}(E_{e^+})dE_{e^+}}{\int Y_{\mathrm{no\ osc}}(E_{e^+})dE_{e^+}} = 0.955 \pm 0.035(\text{statistical})$$

$$\pm 0.11\ (\text{systematic}) .$$

However this happened 15 years later:

A. Houmadda et al. Appl. Radiat. Isot. Vol. **46**, 449 (1995). Quotes:

In the spring of 1990, it was announced that the operating power of the high-flux reactor of Institute Laue Langevin (ILL), Grenoble, had been incorrectly reported since its earliest days of operation. One impact of this is that the ILL reactor was operated at **1.095 times** it's rated full power (57 MW thermal). It also affects the results of experiment conducted by a collaboration from Caltech, Munich, and ISN-GRENOBLE which searched for neutrino oscillations at ILL reactor.

In conclusion, the reanalysis of ILL experiment shows a depletion of 18% in the neutrino flux. (Neutron lifetime and the reactor flux were also changed.) Thus the ratio of experimental to expected integral positron yield is only 0.832 ± 3.5 %(stat) ± 8.87 %(syst).

Note that in the recent Osiris experiment (G. Boireau et al., 1509.05610) at 7.21m distance, fuel enriched to 19.75% of ^{235}U, $R_{obs}/R_{pred} = 1.014 \pm 0.108$.
The conditions are quite similar to the ILL experiment, yet the result agrees with the expectations. Hence the disagreement at ILL remains unexplained.

Clearly, the knowledge of the reactor neutrino spectrum is crucial. So, how it could be determined?

There are two ways, each with its strengths and weaknesses:

1) Add the beta decay spectra of **all** fission fragments. That obviously requires the knowledge of the fission yields (how often is a given isotope produced in fission), halflifes, branching ratios, and endpoints of all beta branches, and spectrum shape of each of them. And error bars of all of that.
2) Measure the **electron** spectrum associated with fission and convert it into the neutrino spectrum using the fact that the electron and neutrino share the available energy of each decay. Requires a realistic estimate of the error involved in the conversion. The electron spectra of ^{235}U,^{239}Pu, and ^{241}Pu fission were determined in 1980-1990 at ILL, Grenoble. They were republished with finer binning in arXiv 1405.3501. Less accurate ^{238}U spectrum for fast neutron fission is in Haag et al., PRL 112,122501 (2014).

Electron and antineutrino spectrum associated with fission is composed of ~6000 beta decay branches from the decay of the neutron rich fission fragments

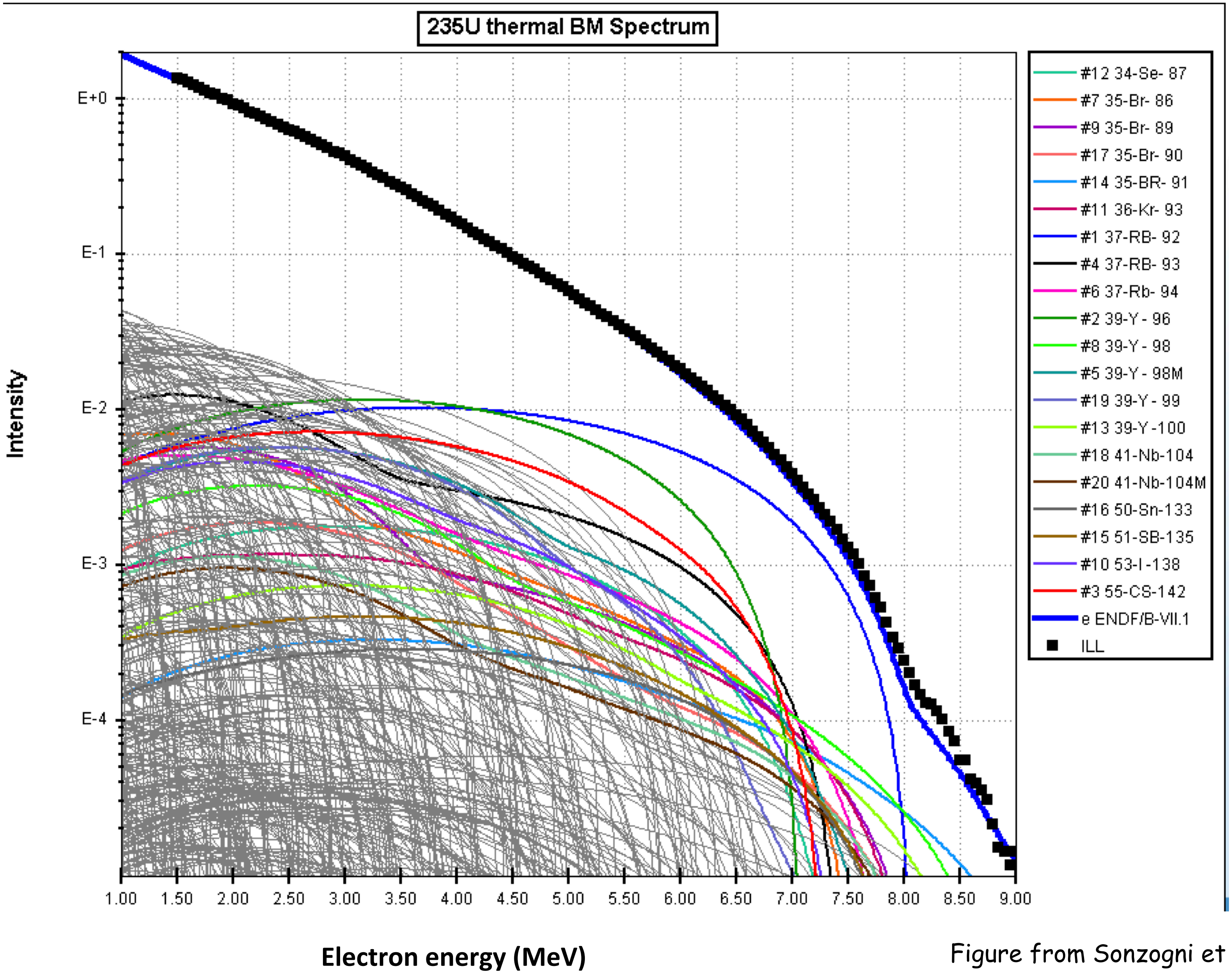
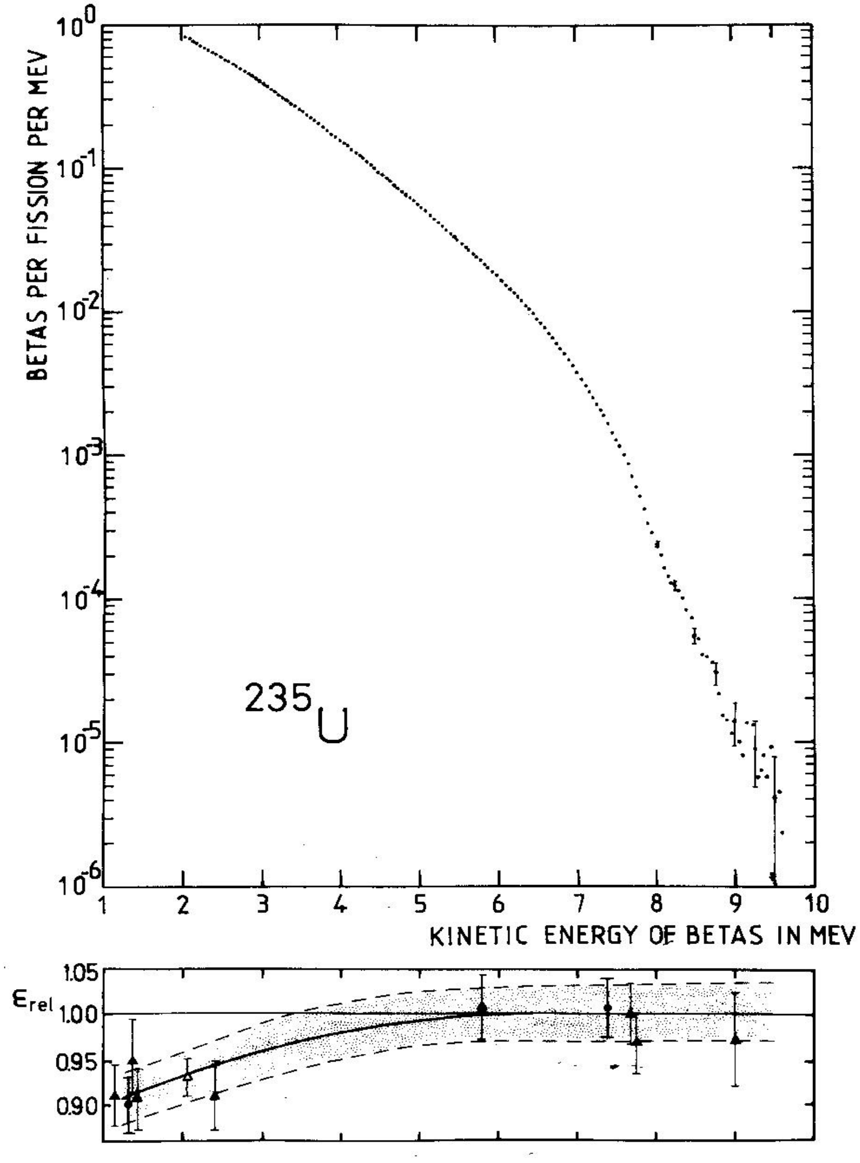
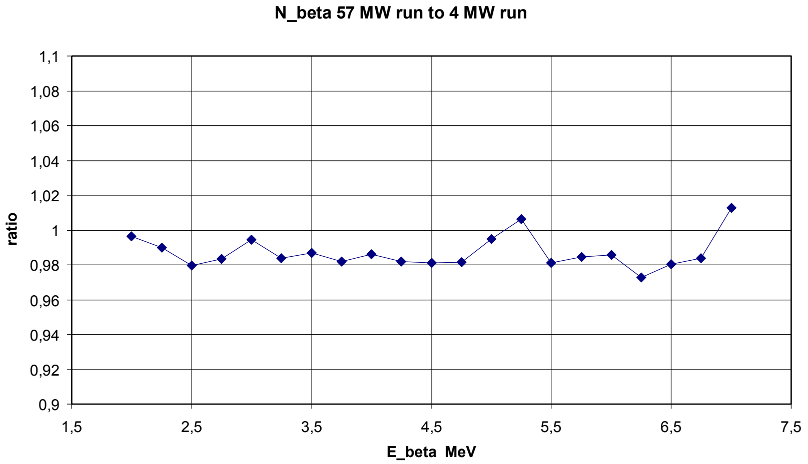


Figure from Sonzogni et al, PRC 91,011301



Measured electron spectrum of ^{235}U, and the statistical errors



Ratio of the ^{235}U beta spectra measured at two different reactor powers, 57 and 4 MW. statistical uncertainly below 1%; very different backgrounds

Slide from K. Schreckenbach, SNAC, 2011

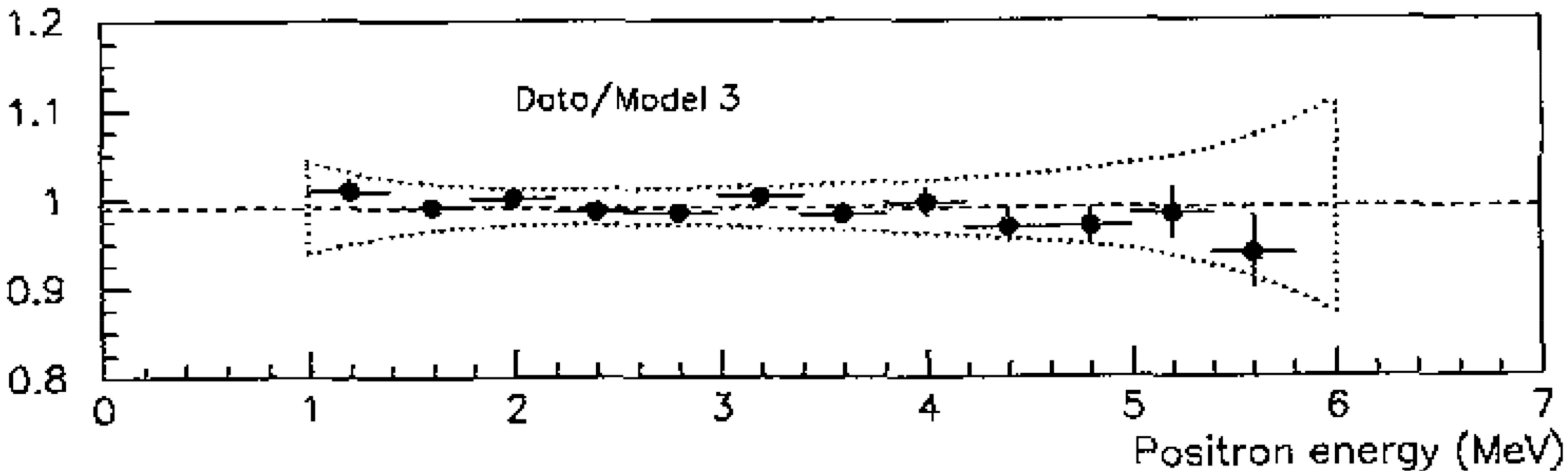
Physics Letters B 374 (1996) 243–248

Comparison of anti-neutrino reactor spectrum models with the Bugey 3 measurements

B. Achkar[b], R. Aleksan[e], M. Avenier[b], G. Bagieu[b], J. Bouchez[e], R. Brissot[b], et al.

Abstract

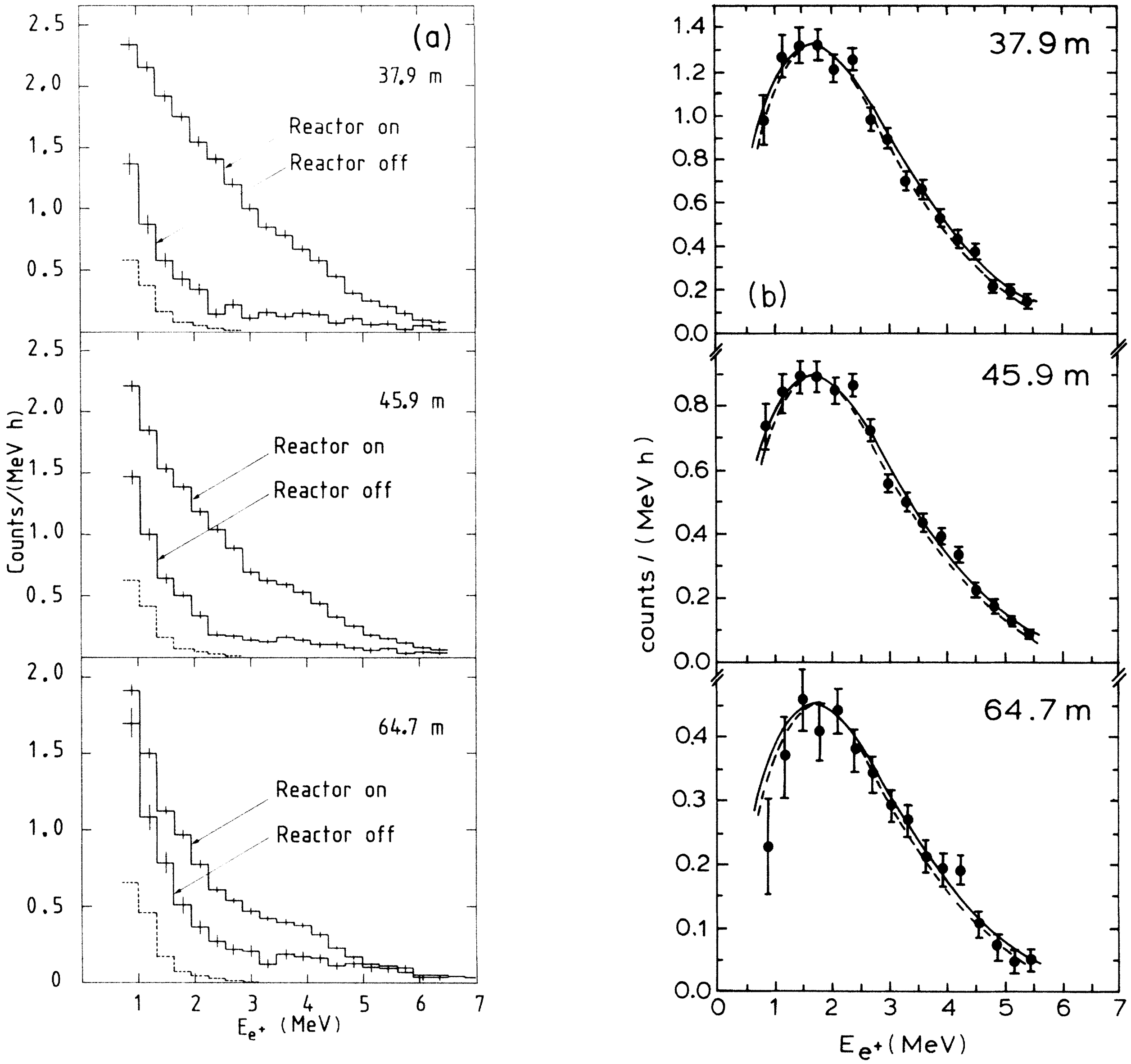
The Bugey 3 neutrino oscillation experiment has provided high statistics neutrino energy spectra recorded at 15 and 40 meters from a nuclear reactor core. Assuming no oscillations, the measured spectra favor a model of reactor spectrum based on the beta spectra measured at ILL.



Model 3: Based on the conversion of the ILL electron spectra by Schreckebach et al.
Note the perfect agreement. No hint of the ``bump”.

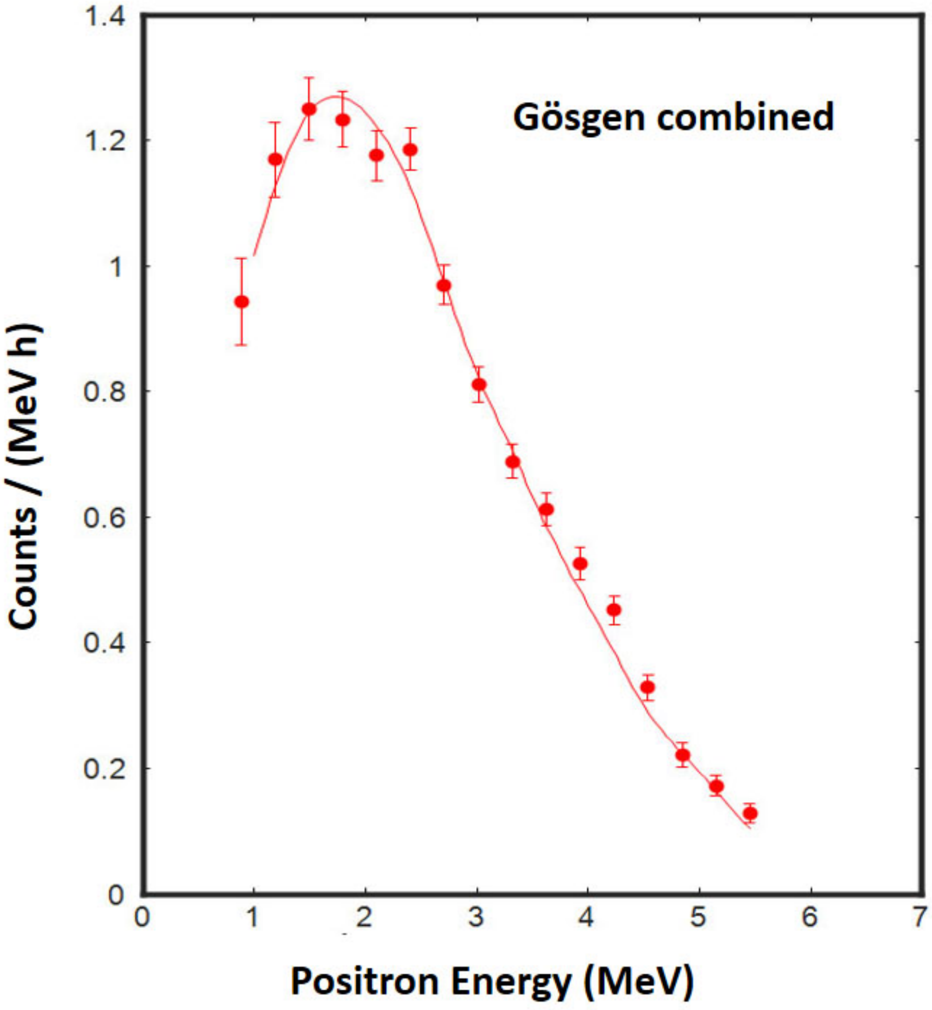
The `positron energy’ is just the kinetic energy, no annihilation. The ``bump” should be centered at about 4 MeV.

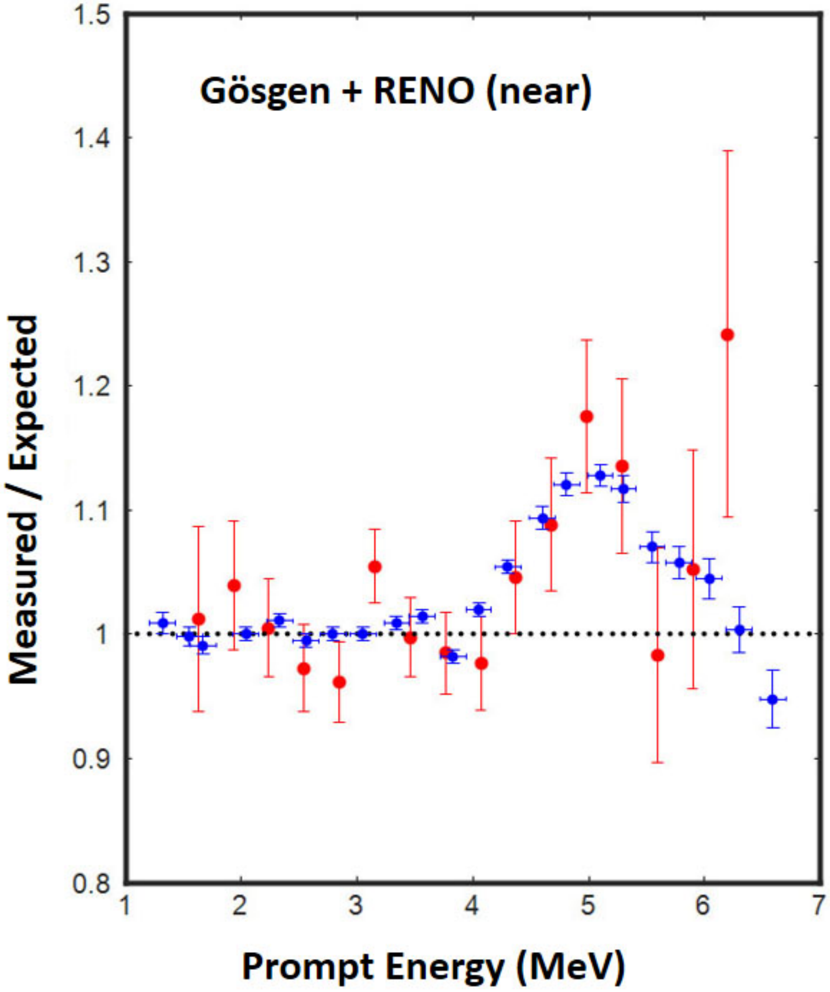
Goesgen experiments (1981-1985): Analogous detector to that of ILL was used in Goesgen (Switzerland) with a single power reactor. About 10^4 events observed at each distance. No evidence for oscillations but, perhaps, a hint for the``bump”. Not recognized at the time, though.



G. Zacek et al. Phys. Rev. D **34**, 2621 (1986)

When the data at three distances are combined together, excess at ~ 5 MeV becomes visible. Plotted as a ratio the ``bump" clearly emerges, very similar to the one observed by RENO or Chooz. The significance is ~3σ.The likelihood test (statistical errors only) excludes no-bump hypothesis at 3.8σ level.





Plots by Viktor and Gabriele Zacek, see 1807.01810

This is the end of the era of essentially blind exploration. In the late 1990 the phenomenon of neutrino oscillations was, at least tentatively, established.

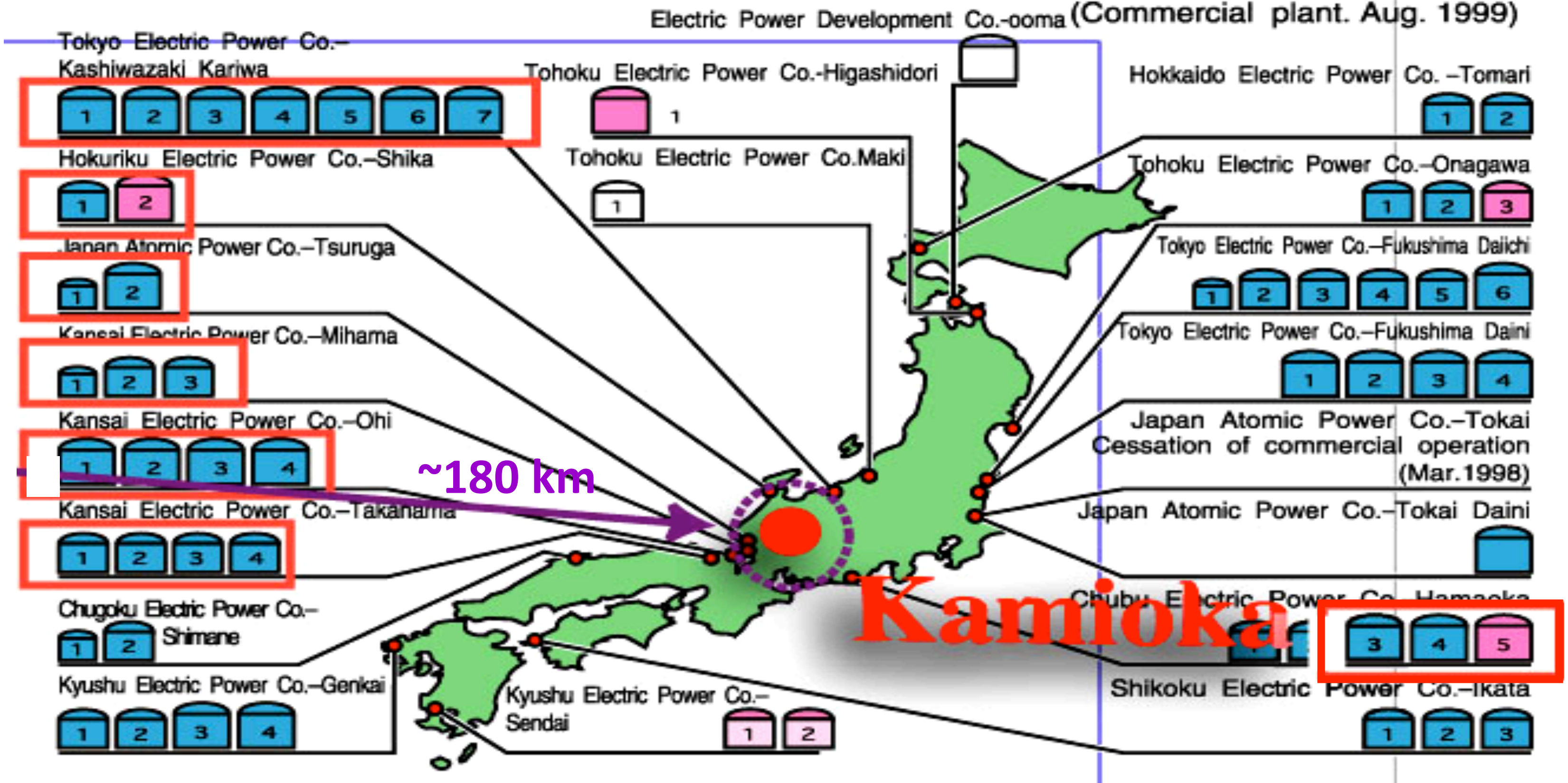
Study of atmospheric neutrinos led to the assignment of $\Delta m^2_{atm} \sim 2\text{-}4 \times 10^{-3}$ eV^2. Study of solar neutrinos had, still, several possible solutions, but increasingly the LMA with $\Delta m^2_{sol} \sim 10^{-4}$ eV^2 became the preferred one.

For the reactor neutrino physics it suggested two areas:

1) Perform experiments at ~ 1 km corresponding to the Δm^2_{atm} and try to determine or constrain the angle θ_{13}. Note that atmospheric neutrinos, with nearly maximal $\nu_\mu \rightarrow \nu_\tau$ oscillation probability are insensitive to θ_{13}. This program was realized by the Chooz and Palo Verde experiments.
2) Perform an experiment at ~ 100 km corresponding to the Δm^2_{sol} and try to demonstrate the validity of the oscillation interpretation of the solar neutrino observations. This program was realized by the KamLAND experiment.

Nuclear Power Stations in Japan

(Commercial plant. Aug. 1999)



Output scale

Under 0.5Million kW

Under 1Million kW

Over 1Million kW

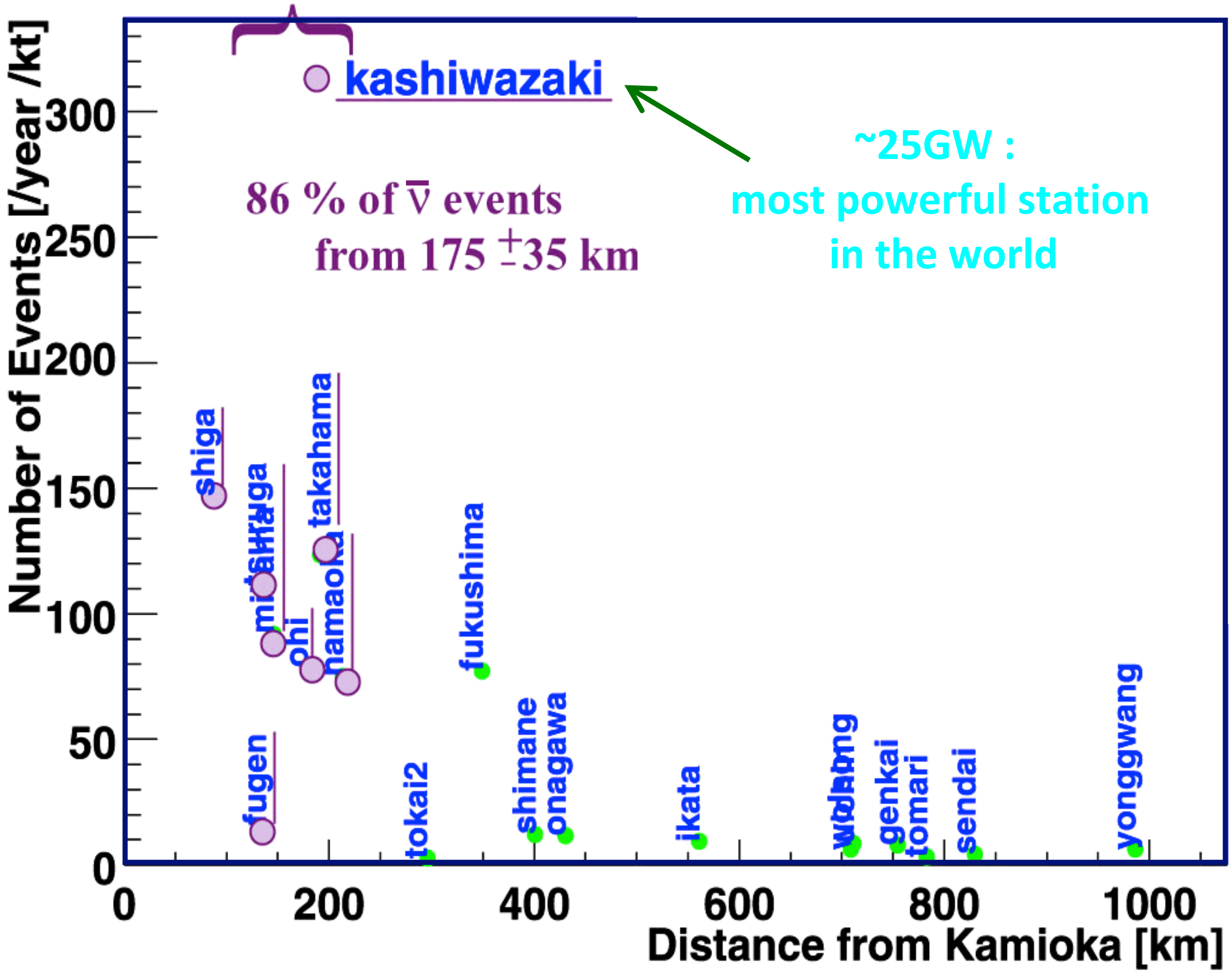
Operating station

Under construction

In planning stage

	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788

~80 GW : 6% of world nuclear power



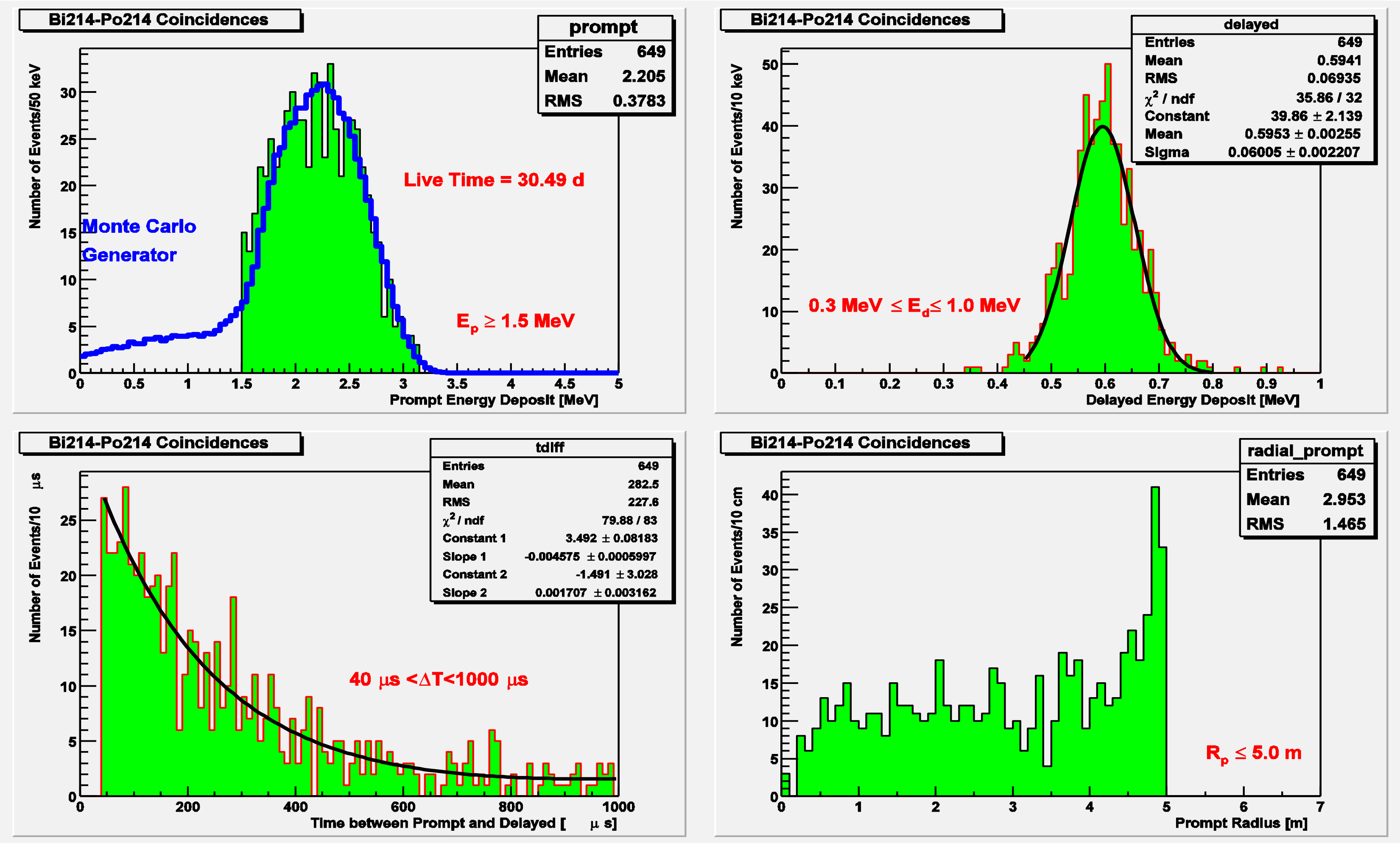
86 % of $\bar{\nu}$ events from 175 $^{+}_{-}$35 km

~25GW :
most powerful station
in the world

^{238}U: $(3.5\pm0.5)\cdot10^{-18}$ g/g

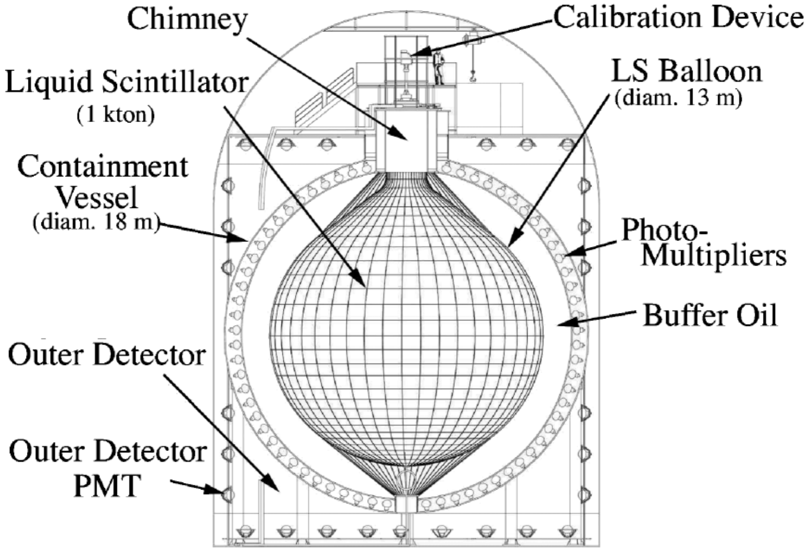
needed 10^{-14} g/g

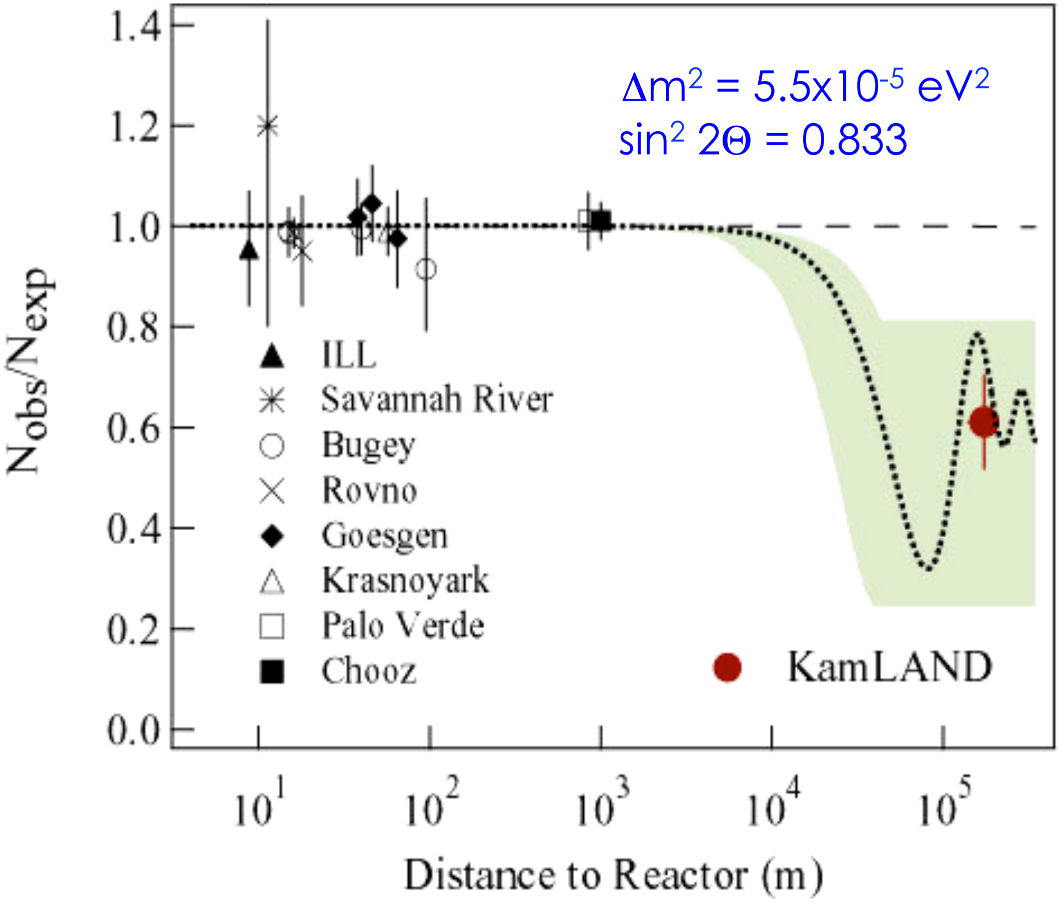
^{232}Th: $(5.2\pm0.8)\cdot10^{-17}$ g/g



τ=(219±29) µs Expected: 237 µs

KamLAND experiment: ~1 kt detector exposed to the combined flux of all reactors in Japan. Average L ~ 180 km. Observed rate ~0.3 events/(ton x year), which is $0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$ of the no oscillation expactation.





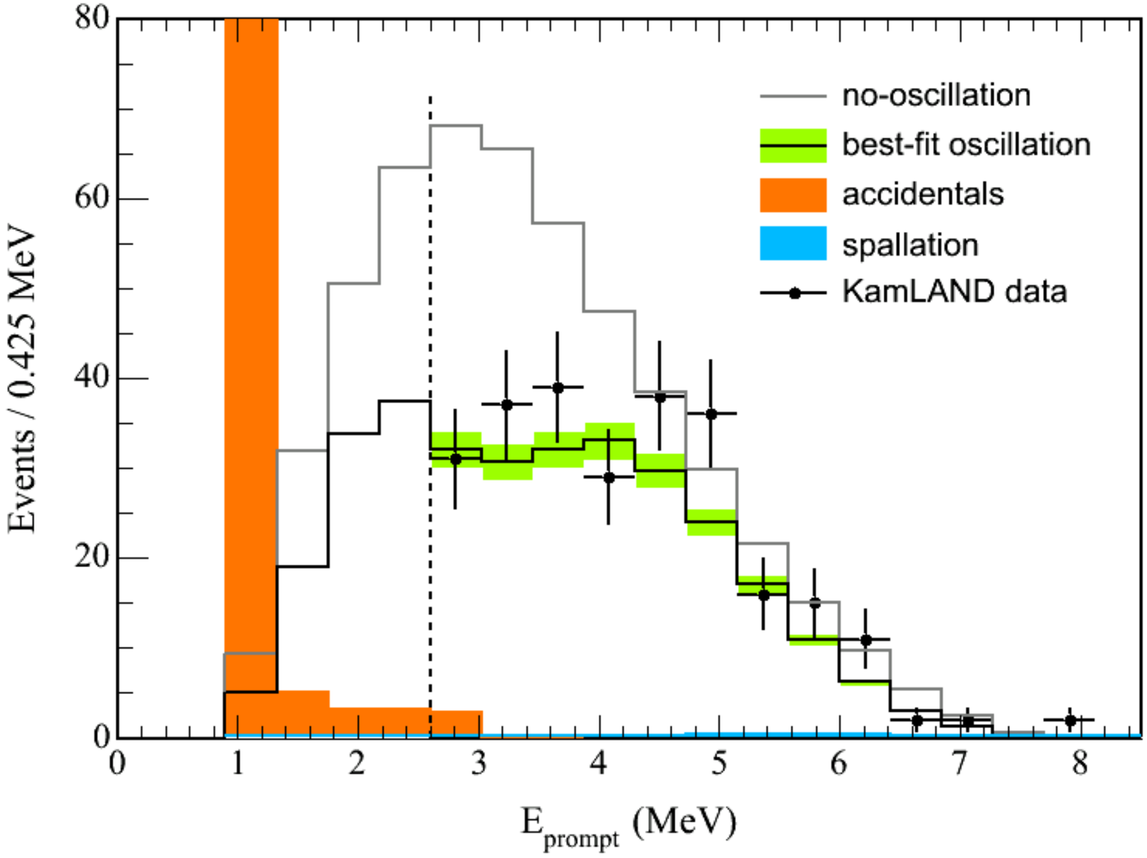
$\Delta m^2 = 5.5\text{x}10^{-5}\ \text{eV}^2$

$\sin^2 2\Theta = 0.833$

Mixing parameters of G.Fogli et al., PRD66, 010001-406, (2002)

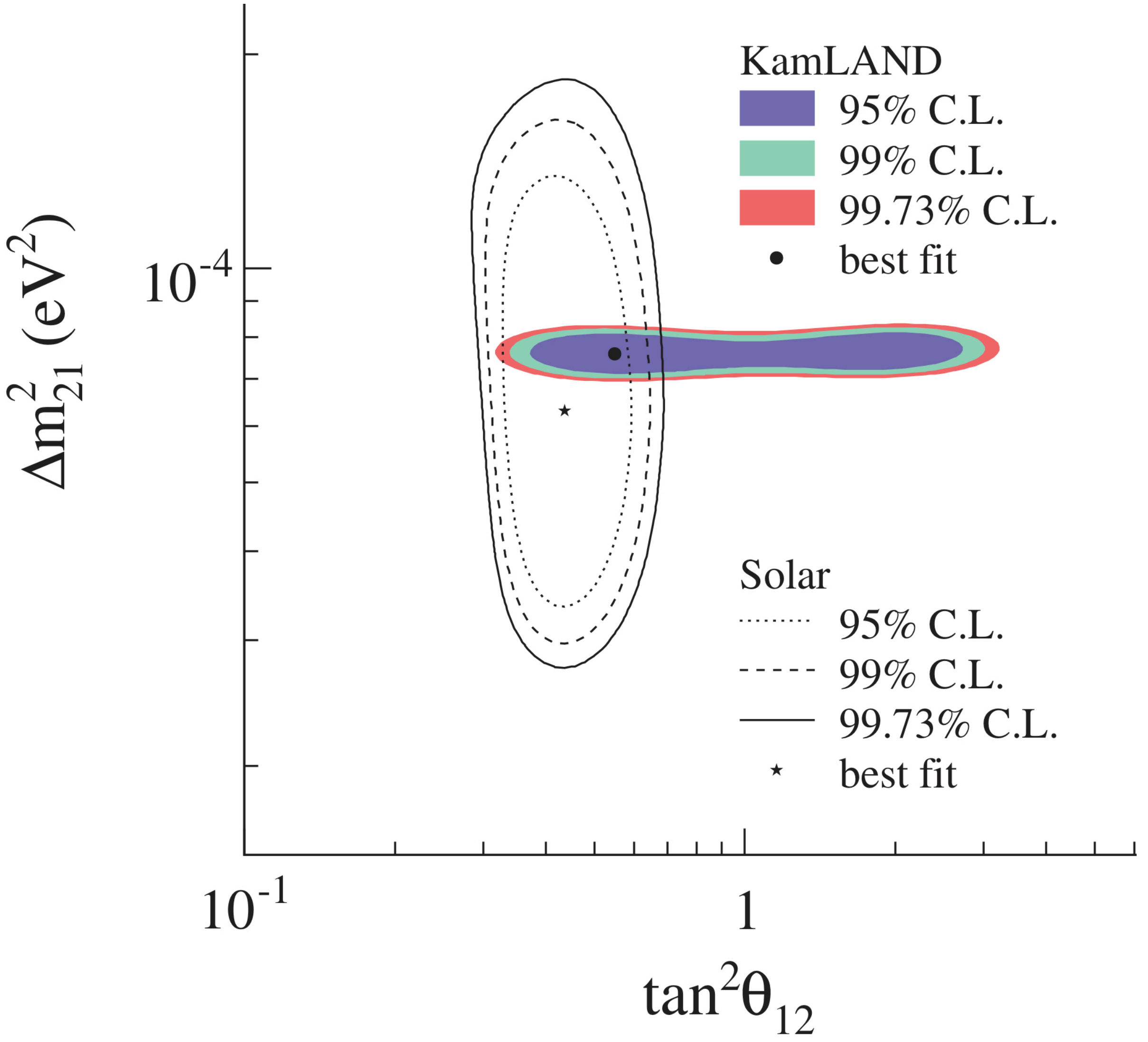
From Eguchi et al., PRL 90, 021802 (2003)

Energy spectrum adds substantial information



Fit to rate and shape analysis gives $\Delta m^2 = (7.9^{+0.6}_{-0.5}) \times 10^{-5} eV^2$ with a large uncertainty on $\tan^2\theta = 0.46$

T. Araki et al. Phys. Rev. Lett. **94**, 081801 (2005)

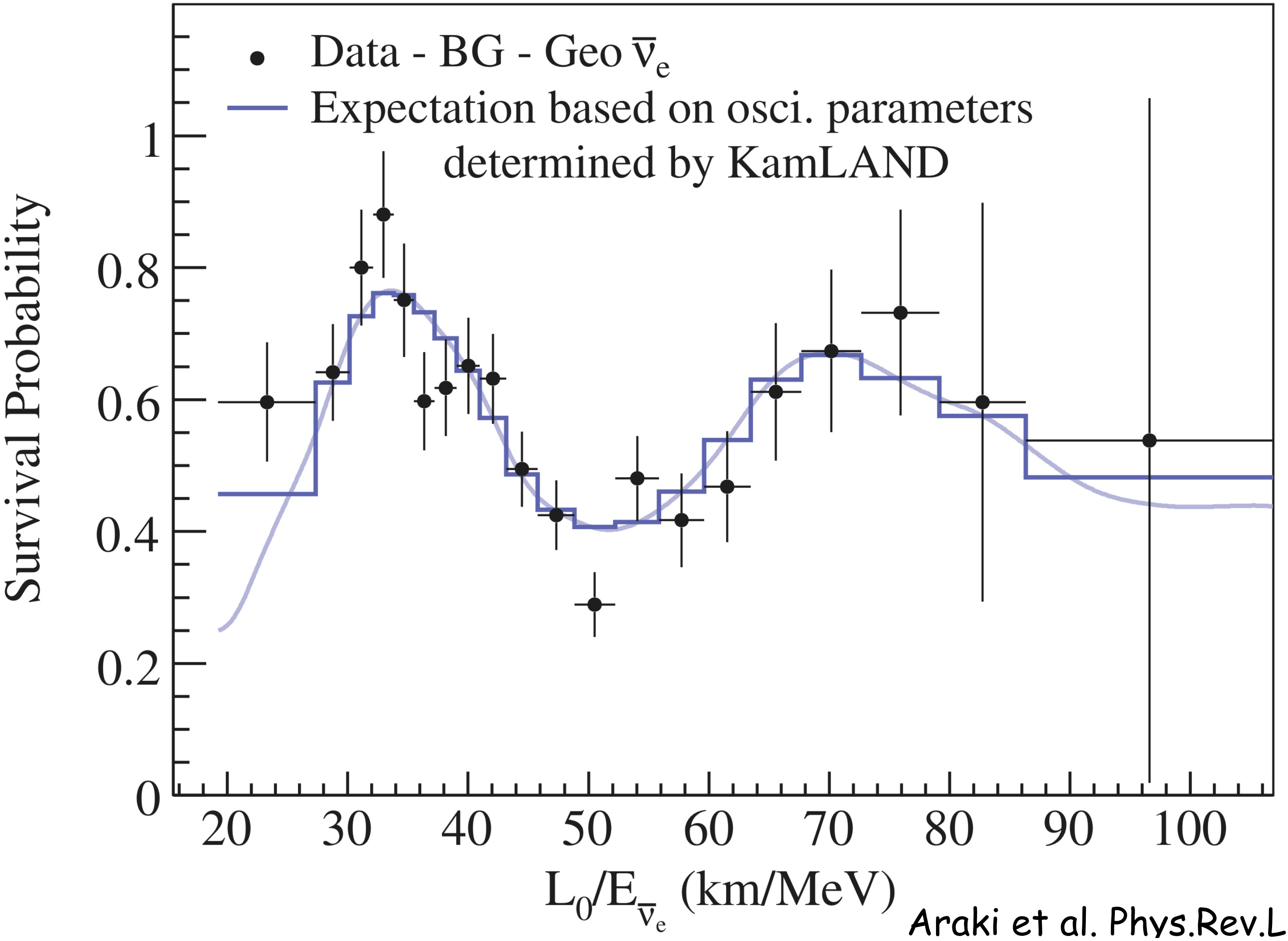


Allowed regions from KamLAND and solar neutrino experiments, two flavor anbalysis. $\Delta m^2=(7.58^{+0.14}_{-0.13}(\text{stat})^{0.15}_{-0.15}(\text{syst}))\times 10^{-5}\text{eV}^2$

Present global analysis, three flavors Δm^2_{21} = 7.53+-0.18, $\tan^2\theta_{12}$ = 0.443+-0.019

Araki et al. Phys.Rev.Lett.**100**,221803(2008)

KamLAND uses a range of L and it cannot assign a specific L to each event. Nevertheless the ratio of detected/expected for L_0/E (or 1/E) is an interesting quantity, as it decouples **oscillation pattern** from the reactor energy spectrum



Araki et al. Phys.Rev.Lett.**100**,221803

spares

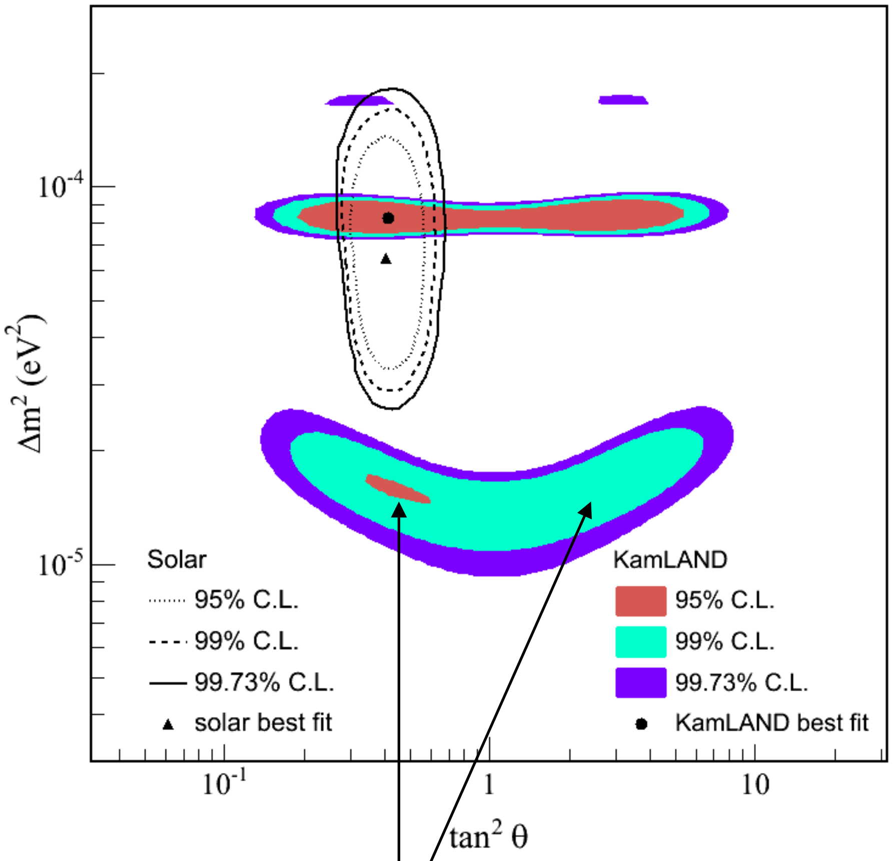
Simple estimate of the cross section:
At low (~MeV)energies it can depend only on E (the energy of the neutrino or positron). Hence $\sigma \sim G_F^2 E^2 (\hbar c)^2$.
$G_F = 1.17 \times 10^{-11}$ MeV^{-2}, $\hbar c = 2\times10^{-11}$MeV cm.
Thus $\sigma \sim 10^{-44}$ cm^2 (as in Bethe and Peierls 1934)

Better, lowest order in E_e/M_n estimate:
The IBD cross section: $\overline{\nu} + p \rightarrow n + e^+$ is simply related to the neutron beta decay $n \rightarrow p + e^- + \overline{\nu}$
Namely $\sigma \cong 2\pi^2/m_e^5 \times E_e\, p_e / f\, \tau_n$ where τ_n is the neutron lifetime. Corrections are easy to evaluate accurately and thus the uncertainty in σ is the same as in τ_n ~1%.

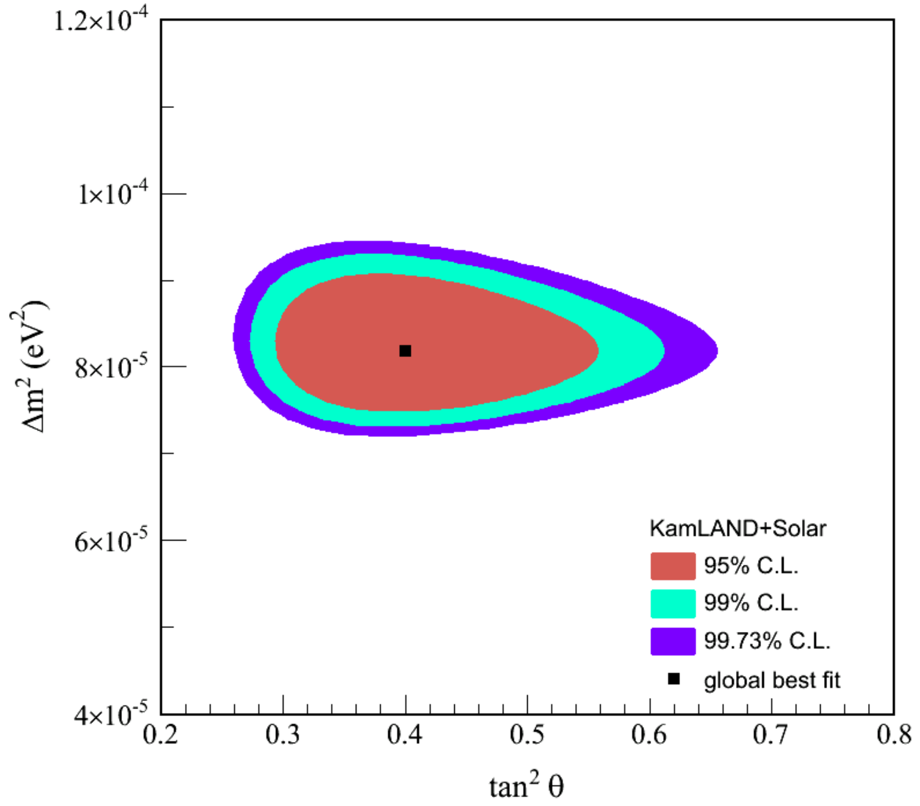
Combined solar ν - KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

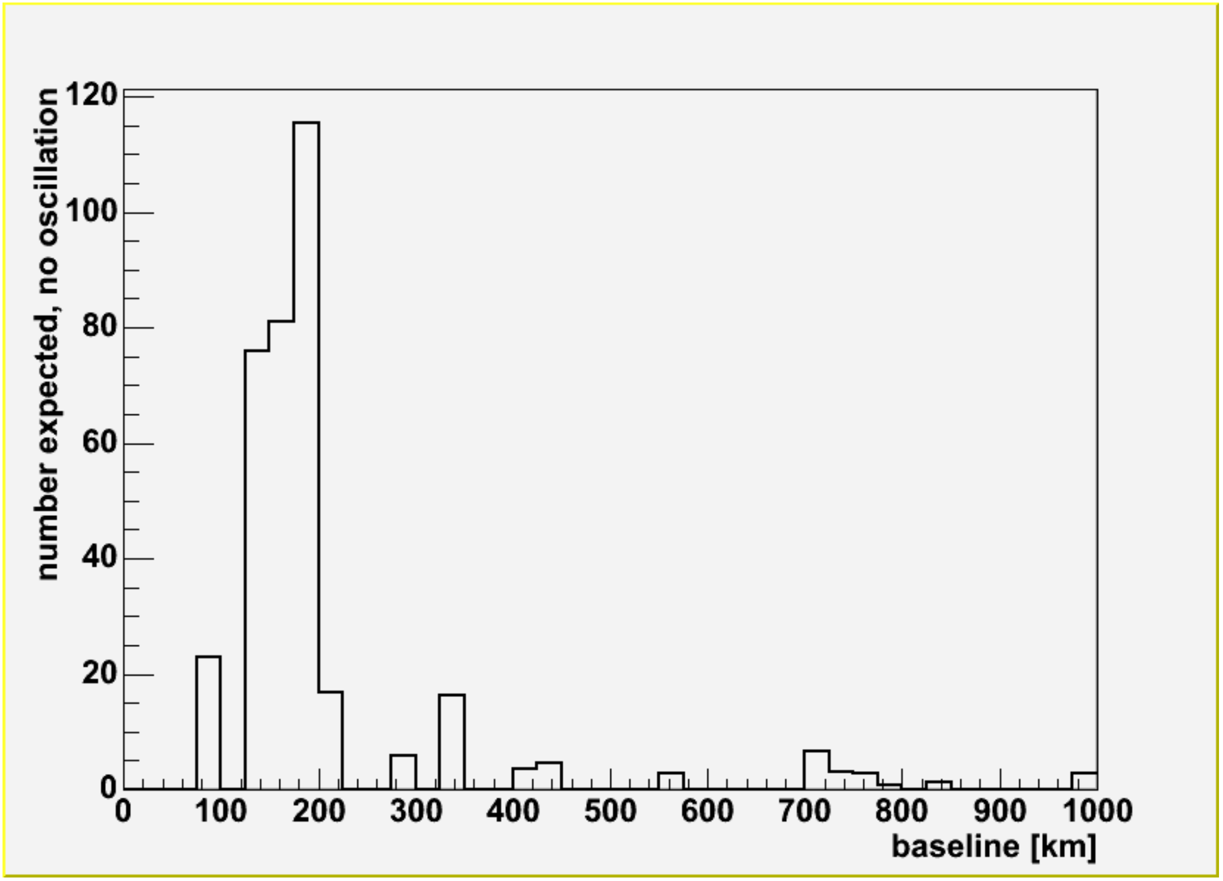
$$\tan^2 \theta_{12} = 0.40^{+0.09}_{-0.07}$$



Includes (small) matter effects



A limited range of baselines contribute to the flux of reactor antineutrinos at Kamioka



Over the data period
Reported here

Korean reactors
3.4±0.3%

Rest of the world
+JP research reactors
1.1±0.5%

Japanese spent fuel
0.04±0.02%