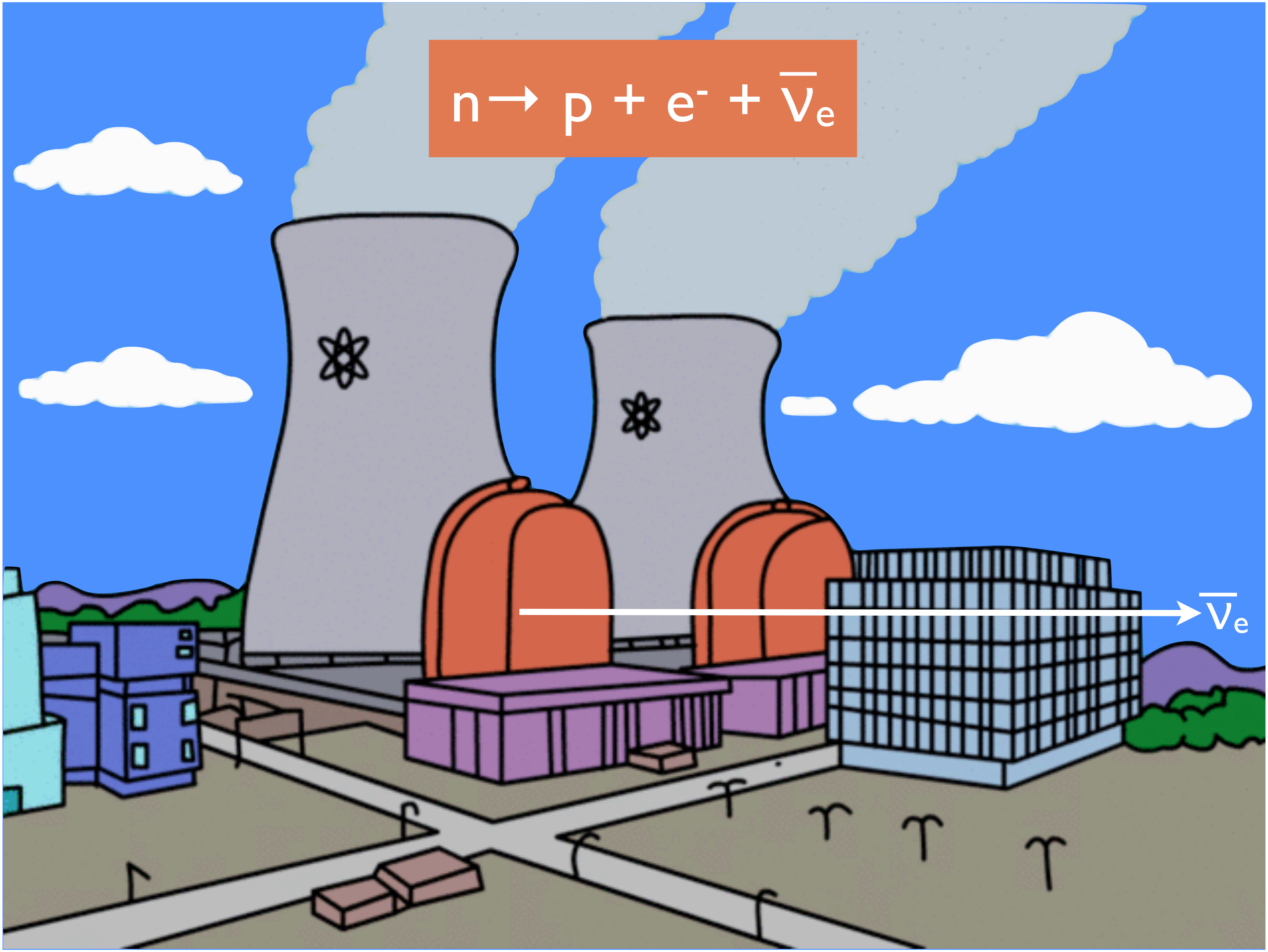
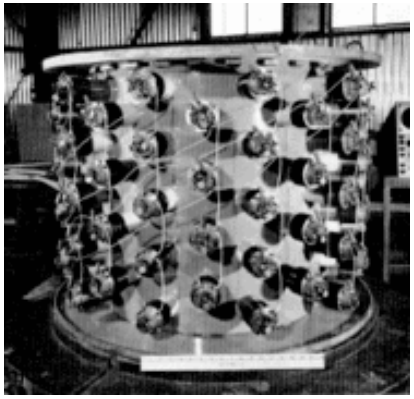
Simulation of Reactors for Antineutrino Experiments Using DRAGON.

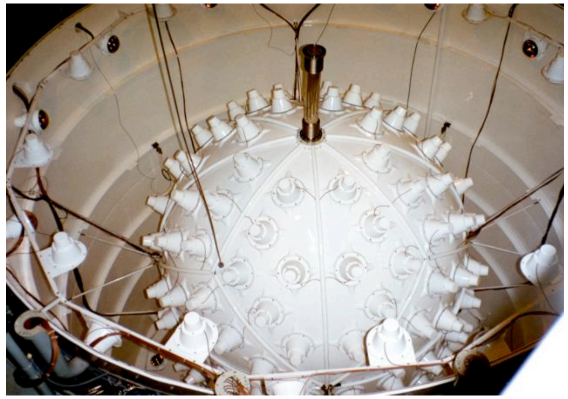
DPF 2011

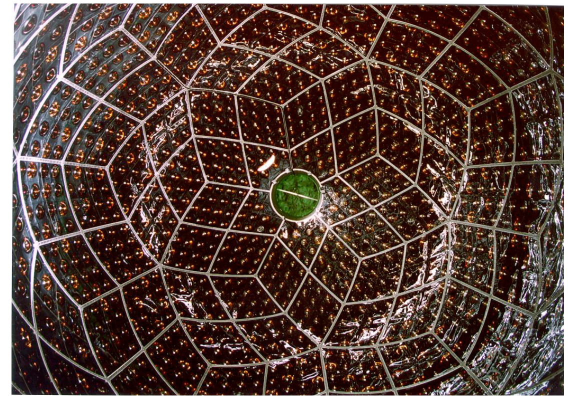
Lindley Winslow

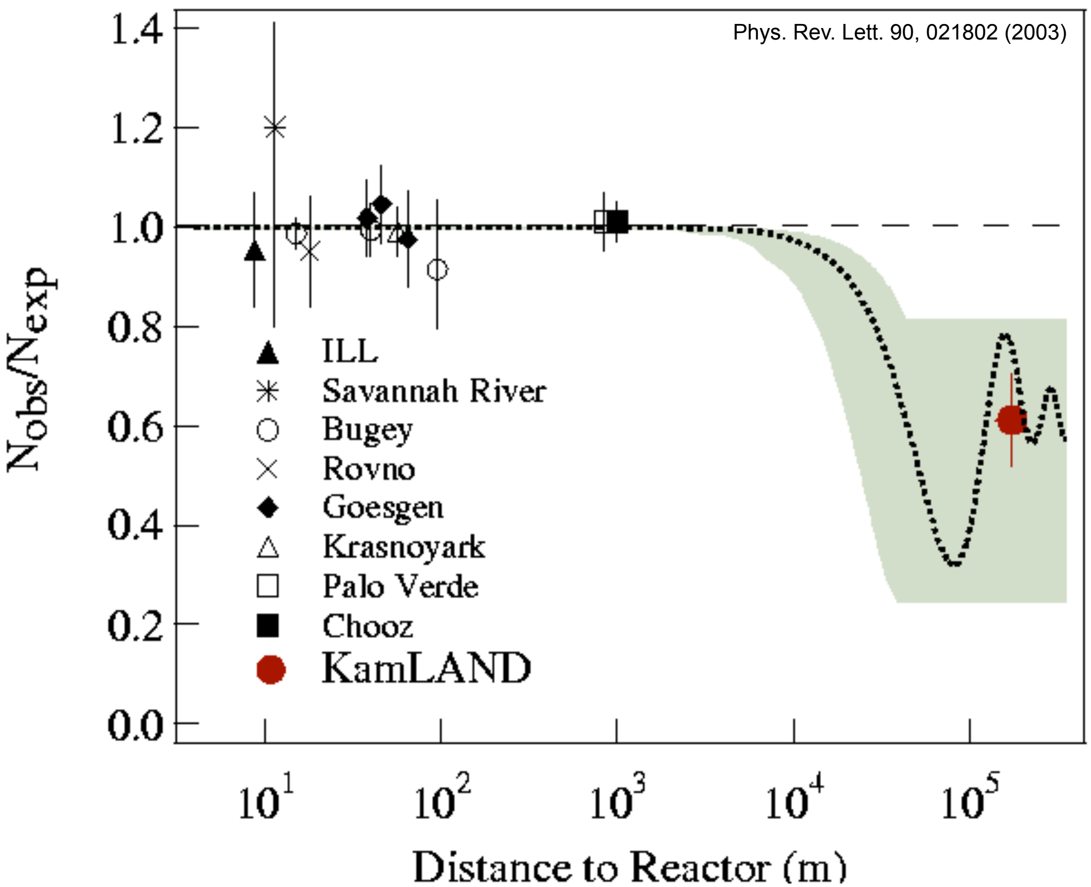

$n \rightarrow p + e^- + \bar{\nu}_e$
$\bar{\nu}_e$

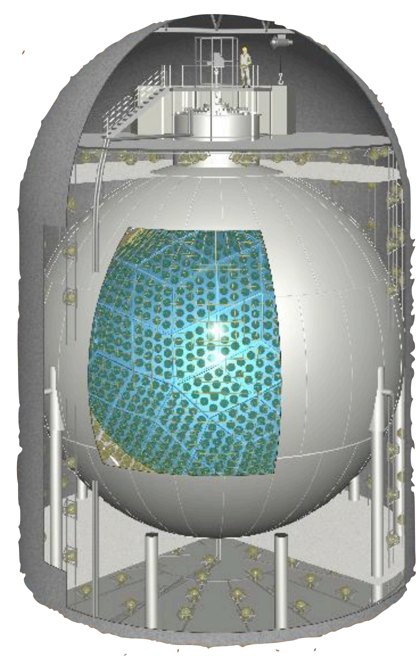
A Long History of Reactor Neutrinos











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A Particular Experiment:

The Double Chooz Collaboration:

APC Paris CNRS/IN2P3, CEA/DSM/IRFU, SPP, SPhN, SEDU, SIS, SENAC, IPHC Strasbourg, Subatech Nantes, ULB

Aachen U., Hamburg U., MPIK Heidelberg, TU München, EKU Tübingen

CIEMAT Madrid

Sussex U.

INR RAS, IPC RAS, RRC Kurchatov

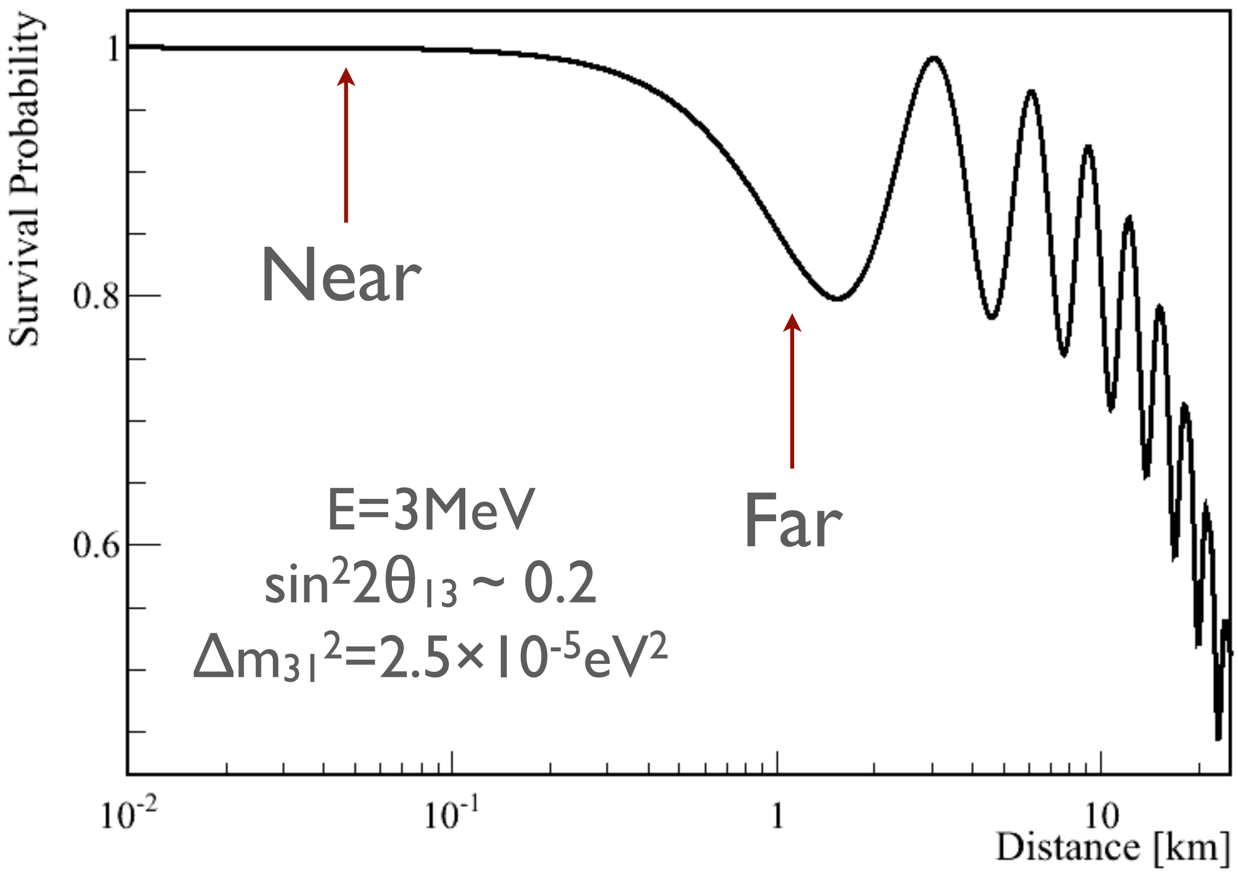
HIT, Kobe U., Niigata U., Tohoku U., TGU, TIT, TMU

Alabama U., ANL, Chicago U., Columbia U., UC Davis, Drexel U., IIT, Kansas State U., LLNL, MIT, Notre Dame U., Sandia NL, Tennesse U.

CBPF, UNICAMP

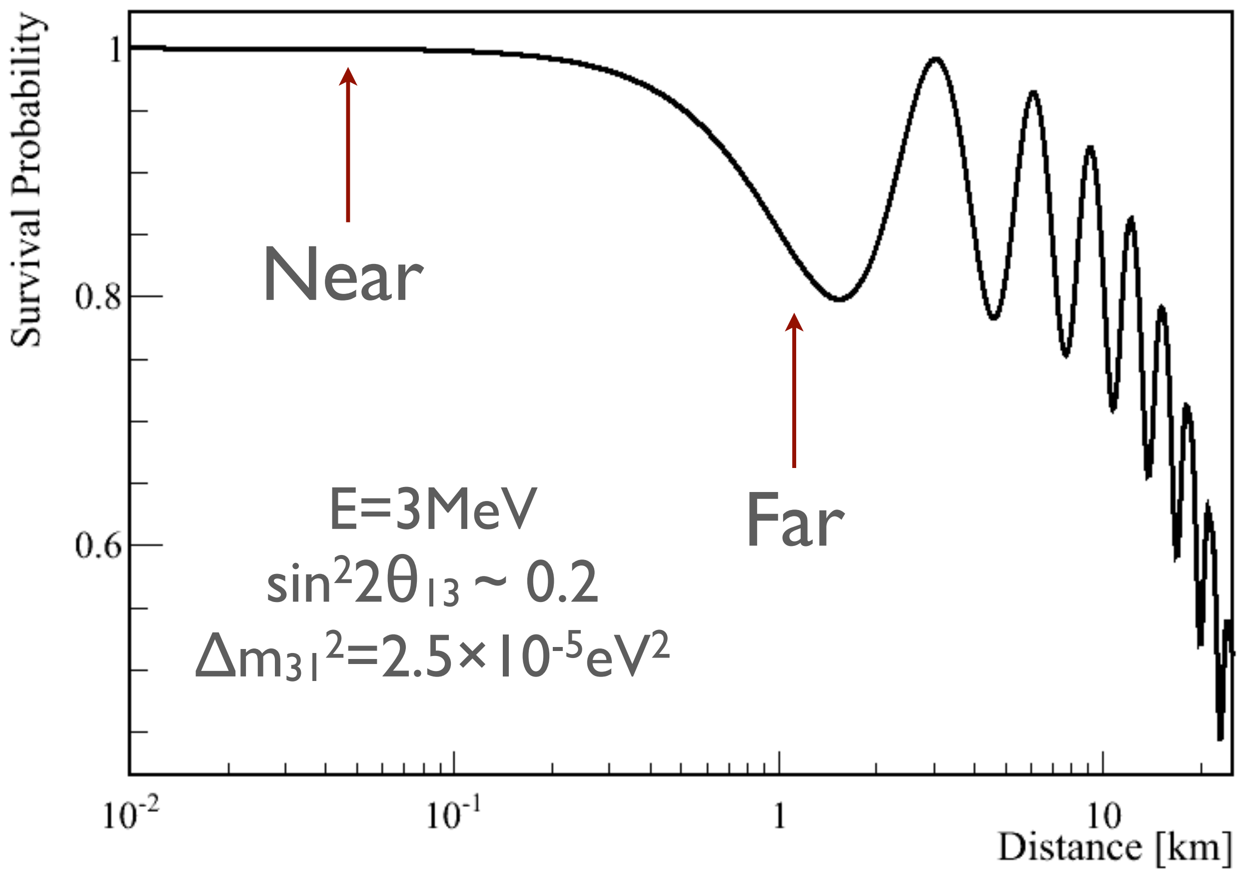
Measuring θ13: The Most Complicated Formula:

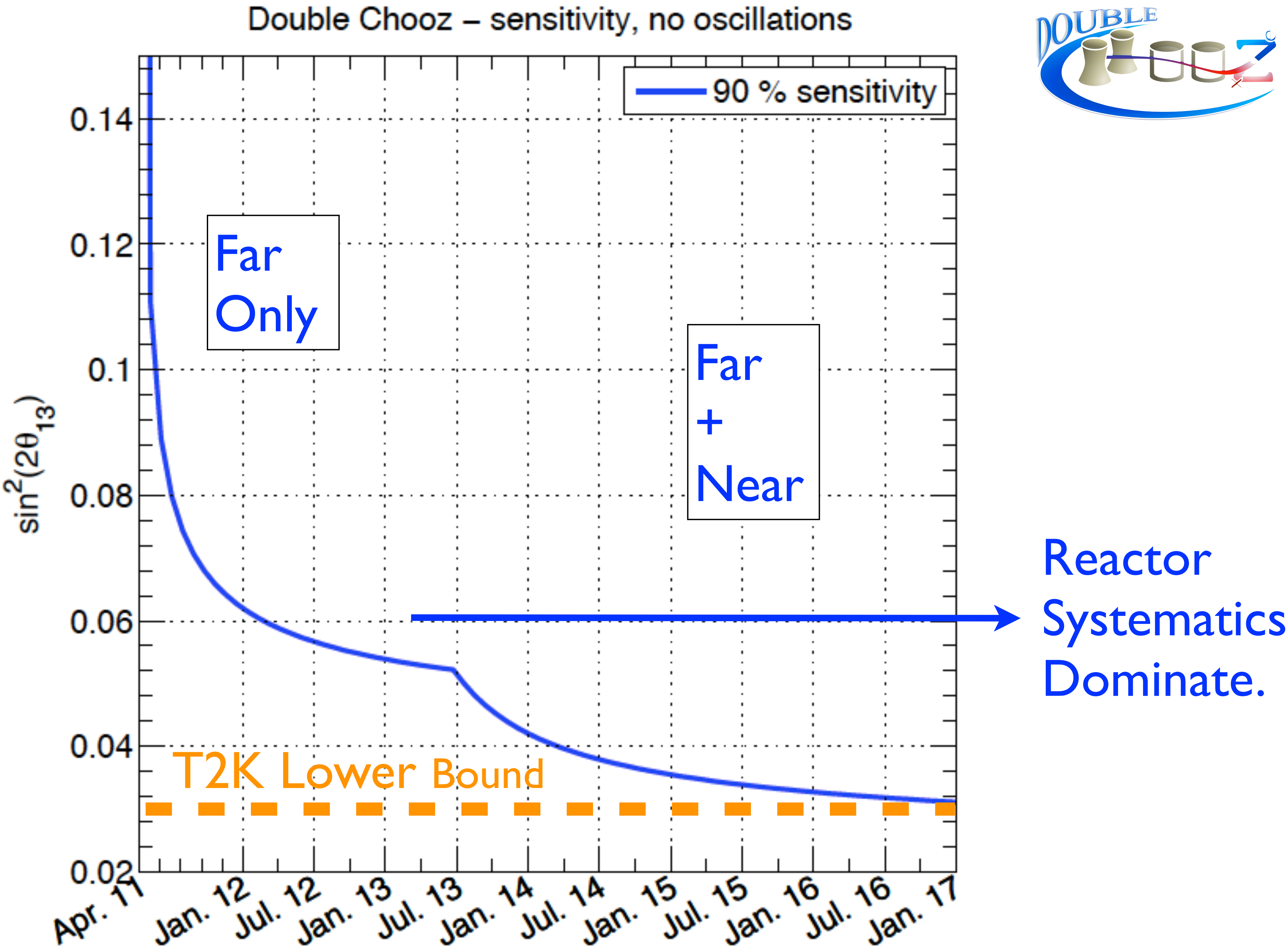
$$P(\bar{\nu_e} \rightarrow \bar{\nu_e}) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \frac{1}{2} \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{2E} \sin^2 \frac{\Delta m^2_{21} L}{2E} - \left(\cos^4 \theta_{13} \sin^2 2\theta_{12} + \sin^2 \theta_{12} \sin^2 2\theta_{13} \cos \frac{\Delta m^2_{31} L}{2E} \right) \sin^2 \frac{\Delta m^2_{21} L}{4E}.$$



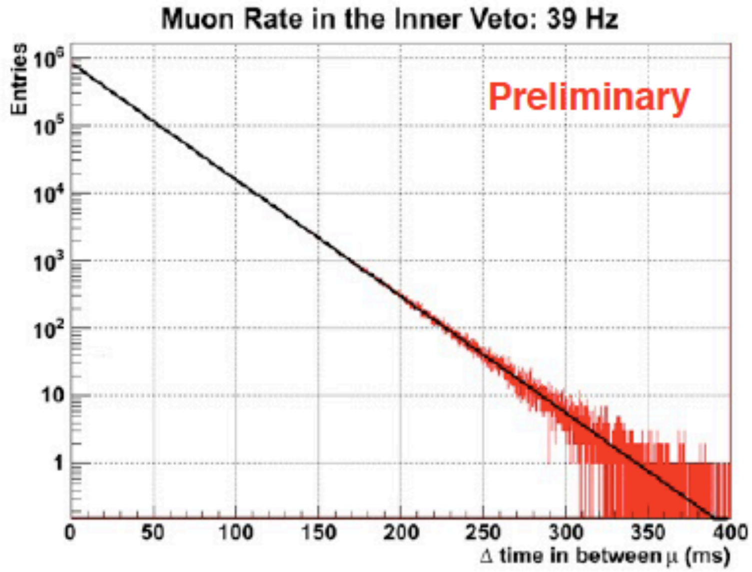
And Really....

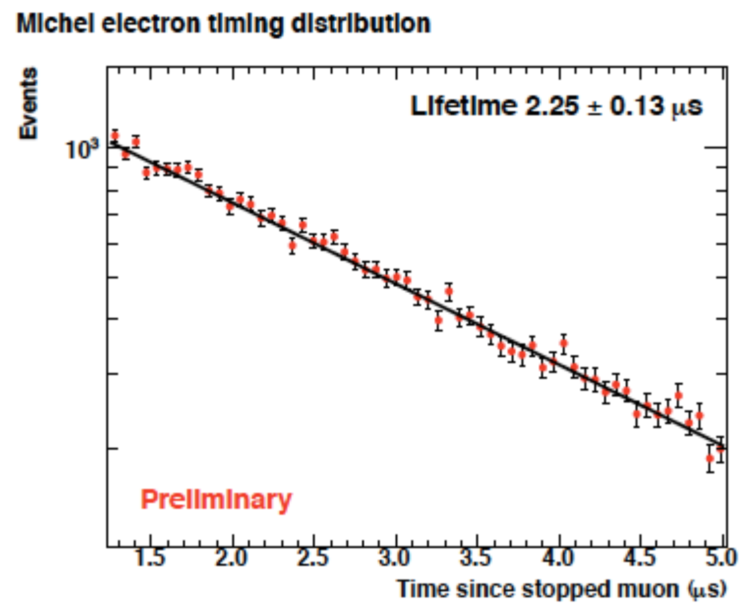
$$P(\bar{\nu_e} \rightarrow \bar{\nu_e}) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

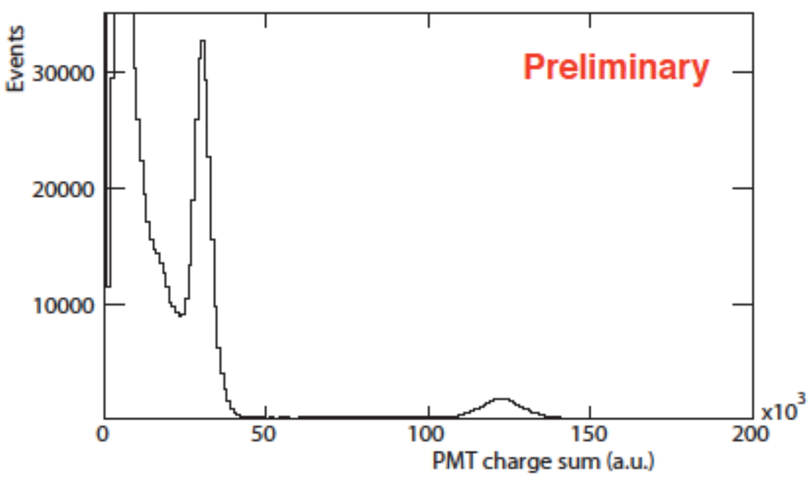


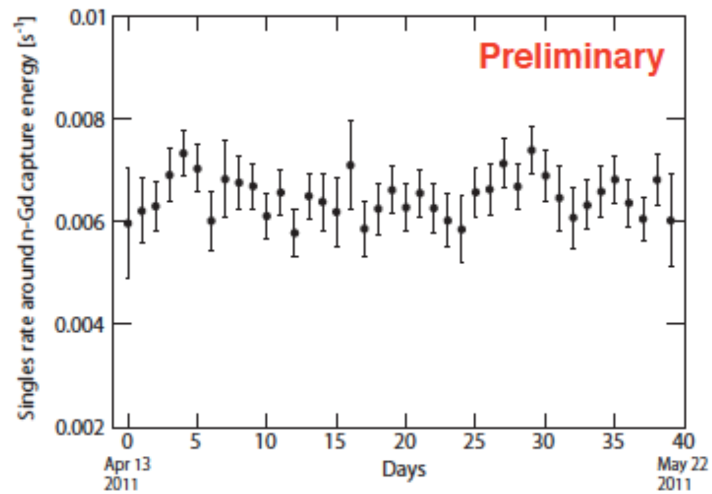

Double Chooz – sensitivity, no oscillations
90 % sensitivity
$\sin^2(2\theta_{13})$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
Apr. 11
Jan. 12
Jul. 12
Jan. 13
Jul. 13
Jan. 14
Jul. 14
Jan. 15
Jul. 15
Jan. 16
Jul. 16
Jan. 17
Far Only
Far + Near
T2K Lower Bound
Reactor Systematics Dominate.

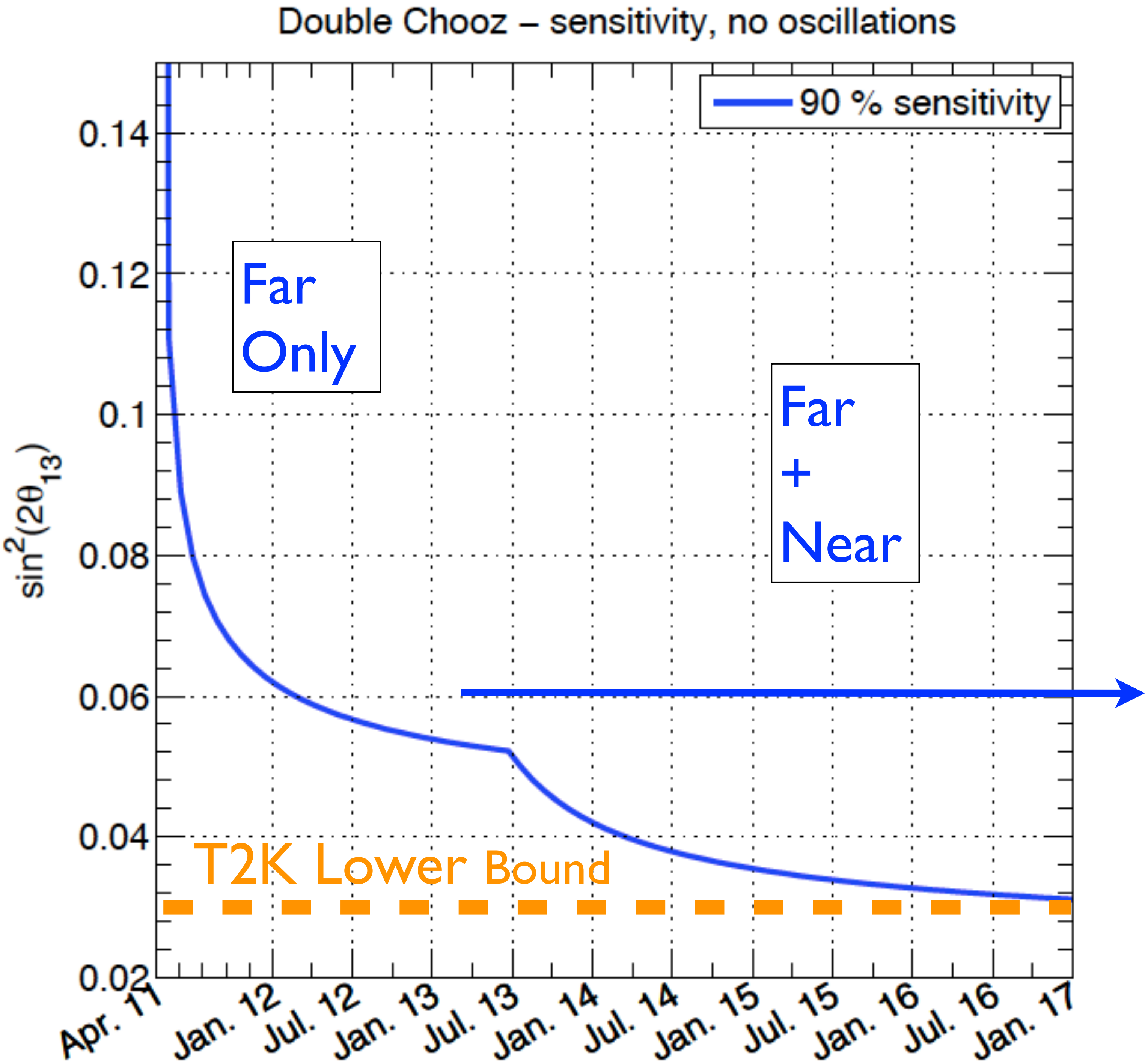
And It's taking data....









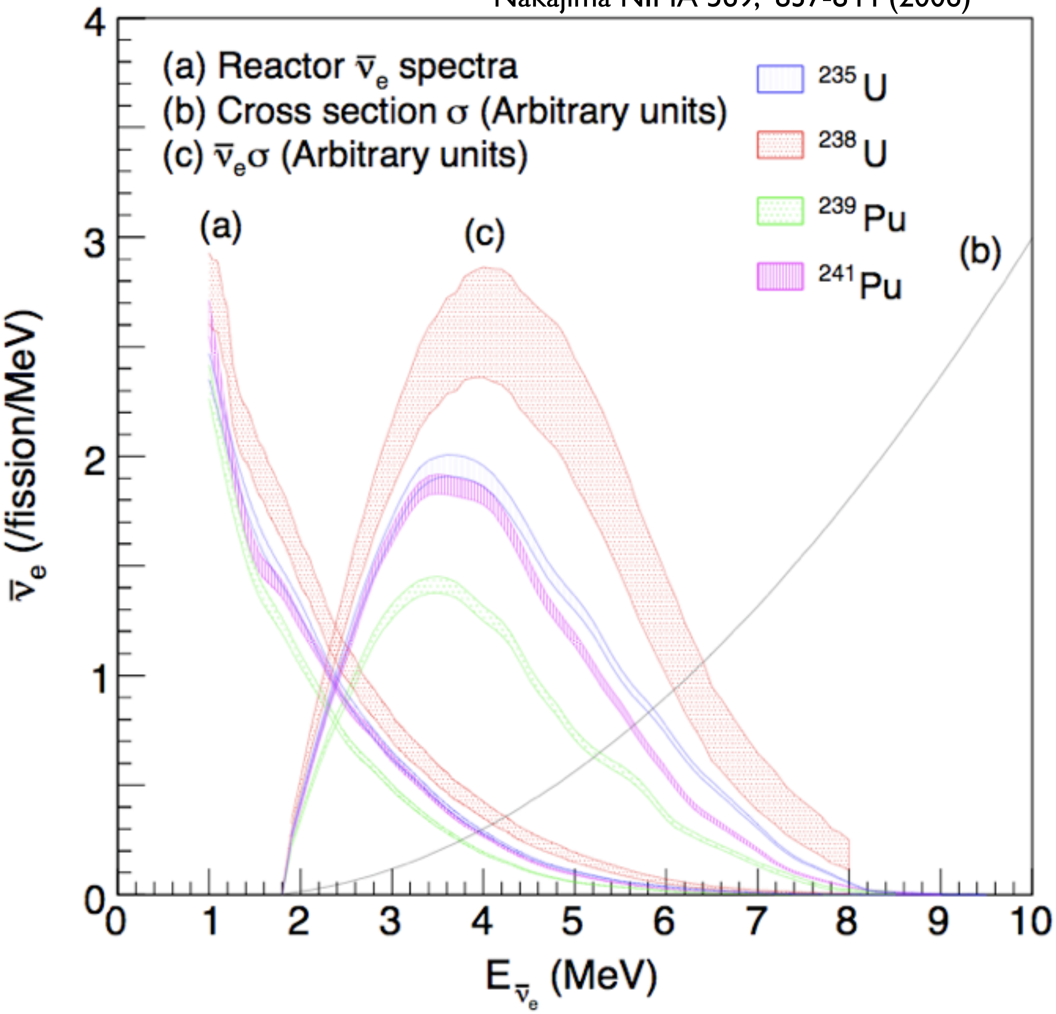


Reactor Systematics Dominate.

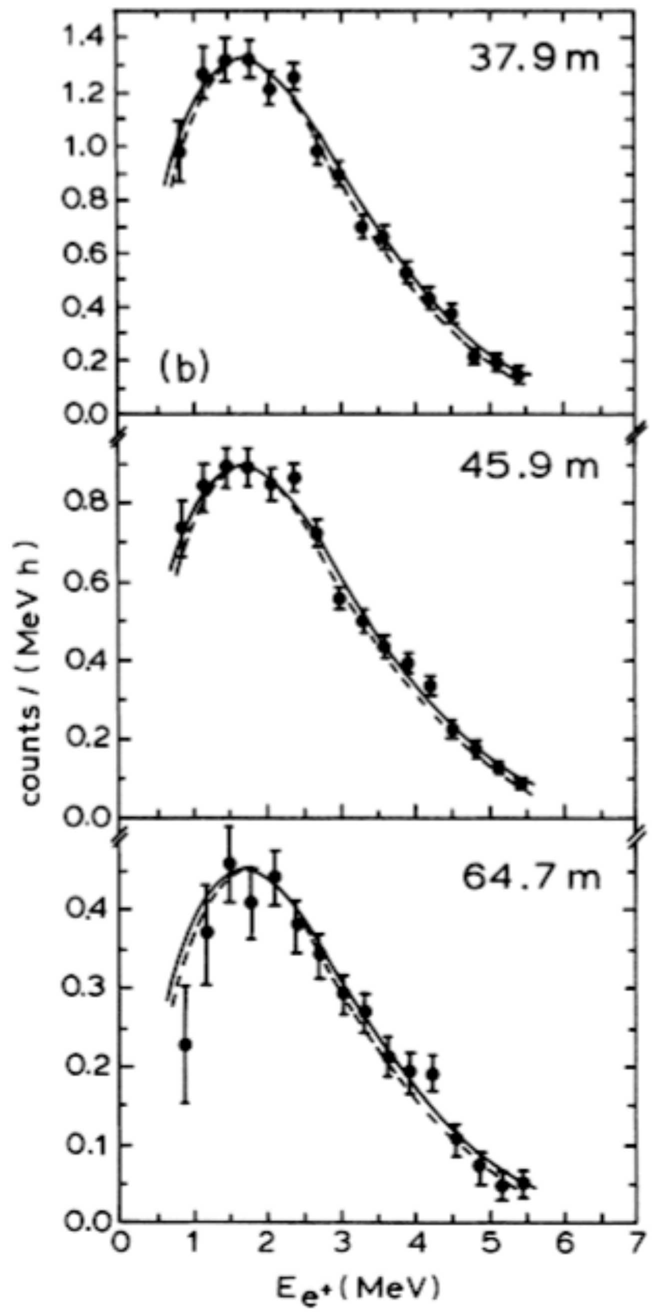
A Few More Details on Reactor Anti-Neutrinos:

- 2×10^{20} anti-neutrinos per s per GW_{th}

Nakajima NIMA 569, 837-844 (2006)

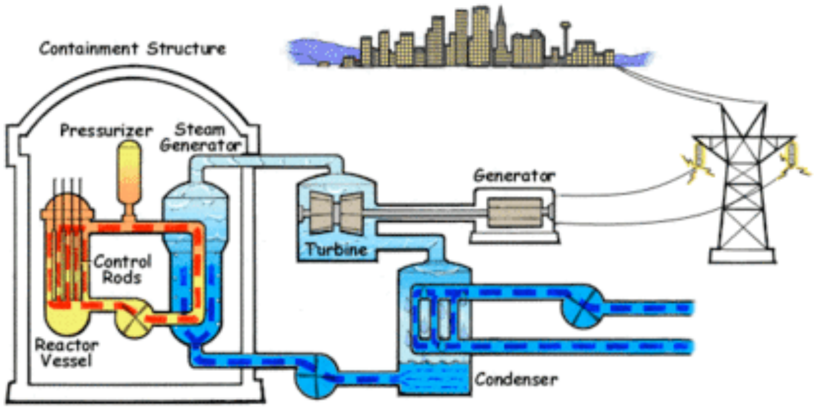


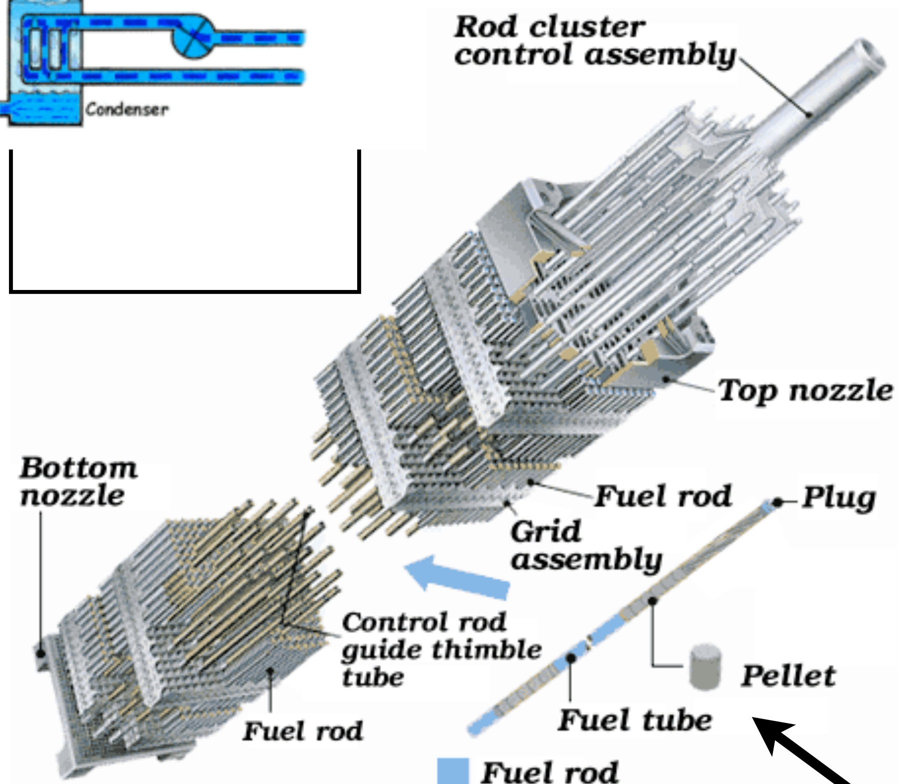
Gösgen Measured Reactor Spectrum

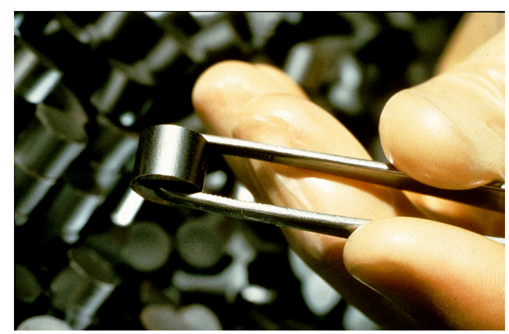


Phys. Rev. D 34, 2621-2636 (1986)

Simulating fission rates...
How do reactors work?

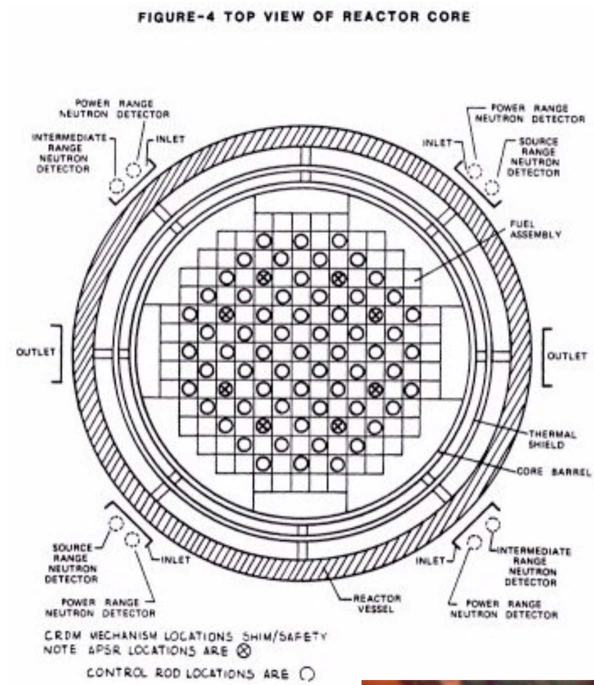


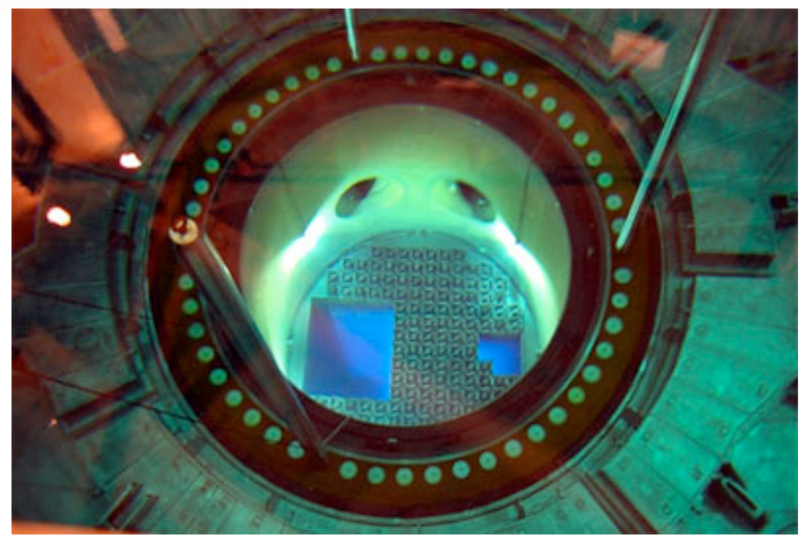




Fuel is arranged in assemblies.

The assemblies are inserted into the reactor vessel.





Enter the Dragon....

- Dragon is a 2D assembly code that directly solves the neutron transport equations (*Meaning it's really fast*).

- We input detailed geometry and fuel compositions and then evolve the reactor in time.

- We then sum up the results of each assembly to get the total number of fissions in the core.

- Double Chooz is also doing these calculations with MURE (a MCNP based full core simulation).

G.Marleau @ Polytechnique Montreal
http://www.polymtl.ca/nucleaire/DRAGON/en/index.php

The Takahama Benchmark

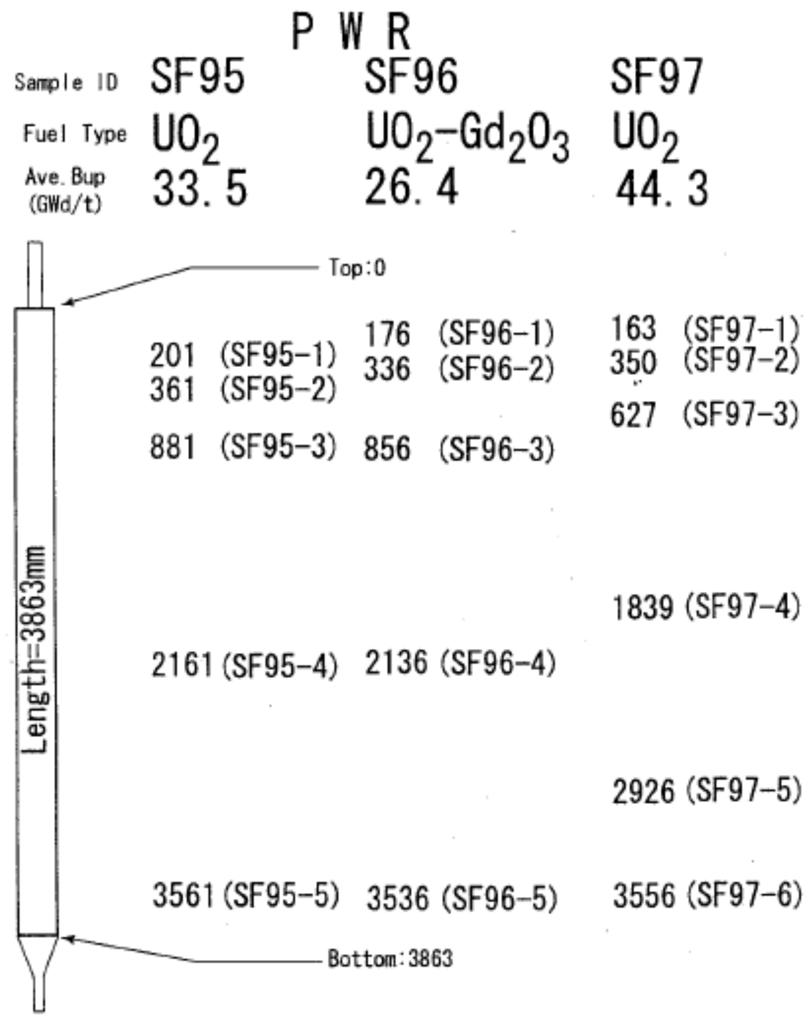
JAERI-Tech 2000-071
(ORNL/TR-2001/01)

It is an amazing amount of work...

Sample group	Reactor type	Reactor name	Assembly type	Assembly average burnup (GWd/t)	Assembly name	ROD POS.	Enrichment
SF95	PWR	Takahama 3	17×17	33.1	NT3G23	A-Q	4.1% UO_2
SF96	PWR	Takahama 3	17×17	33.1	NT3G23	C-M	2.6% UO_2 – 6% Gd_2O_3
SF97	PWR	Takahama 3	17×17	43.2	NT3G24	I-Q	4.1% UO_2
SF98	BWR	Fukushima-Daini-2	8×8-2	33.4	2F2DN23	B-2	3.9% UO_2
SF99	BWR	Fukushima-Daini-2	8×8-2	33.4	2F2DN23	C-2	3.4% UO_2 – 3.0 (4.5)% Gd_2O_3

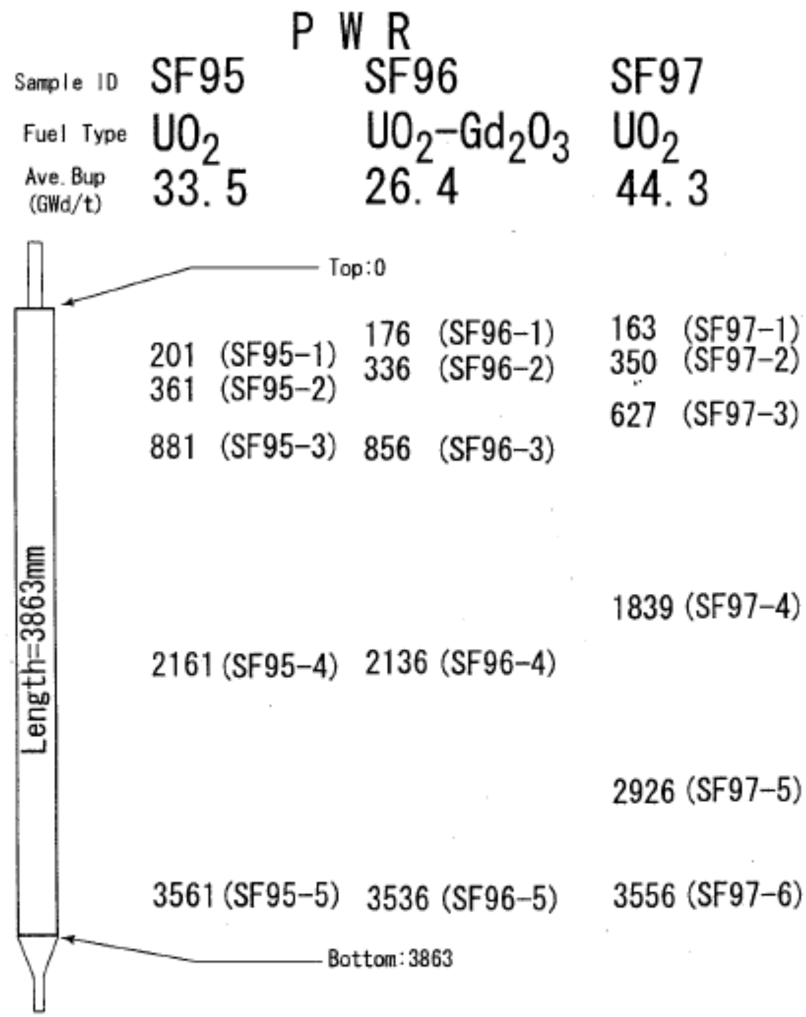
But Takahama is the most like Chooz.

There are three rods that were studied.



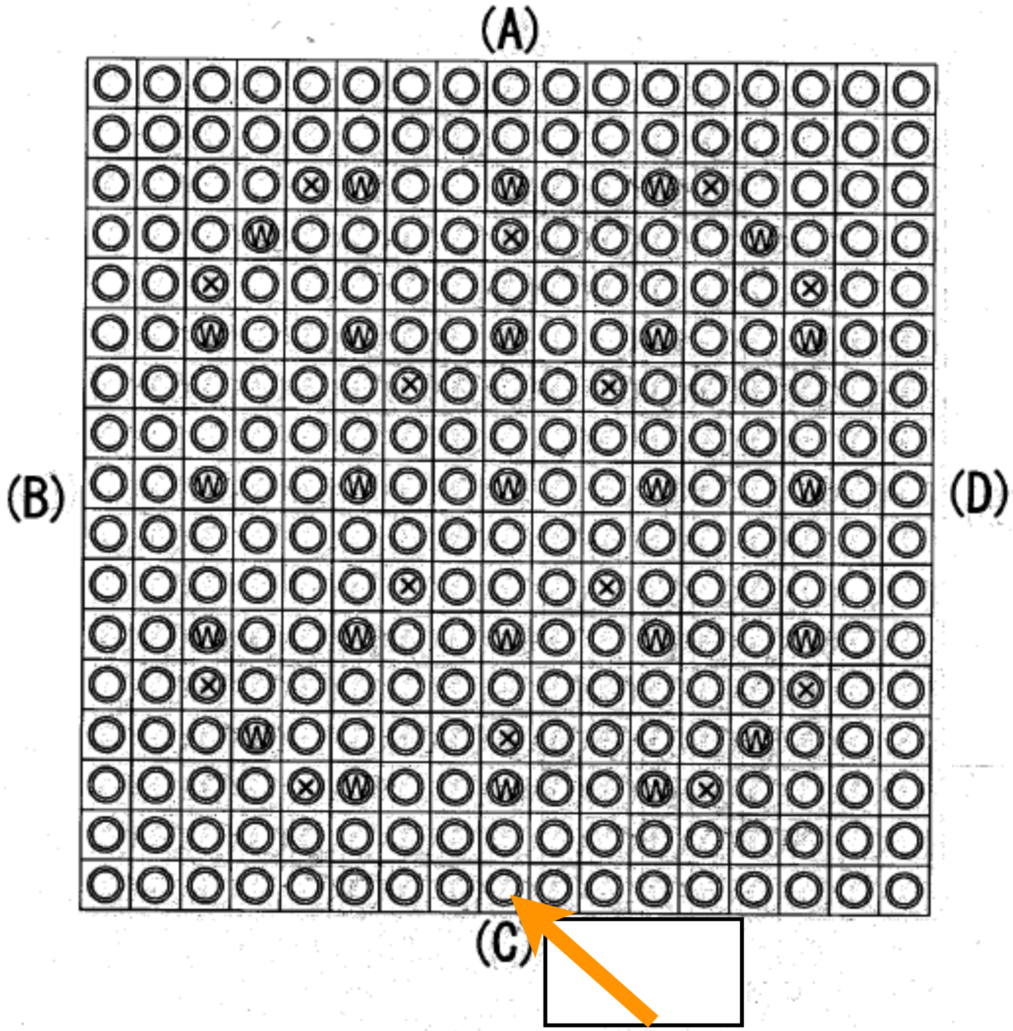
I am going to concentrate on SF97.

There are three rods that were studied.



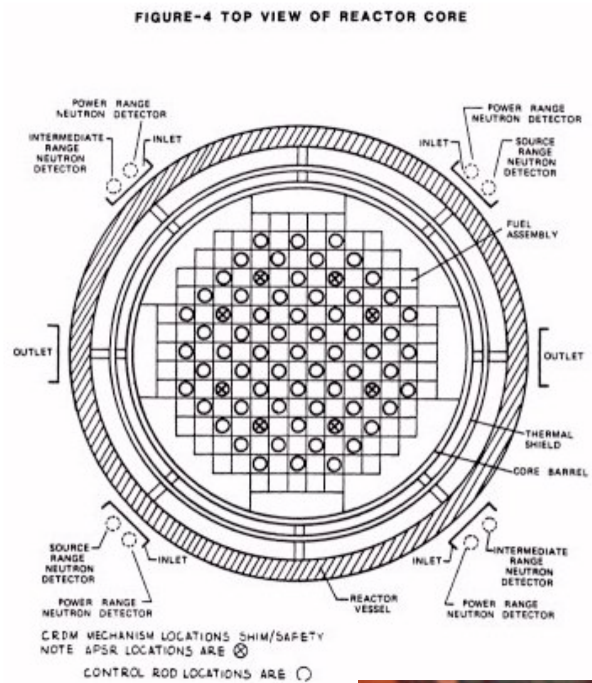
They used both scanning techniques and destructive assays.

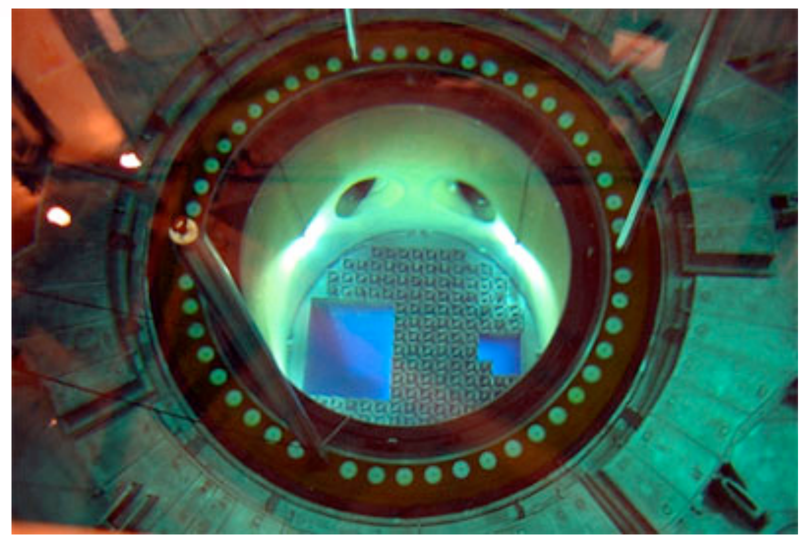
Where in the assembly is SF97?



It is located here near the edge.

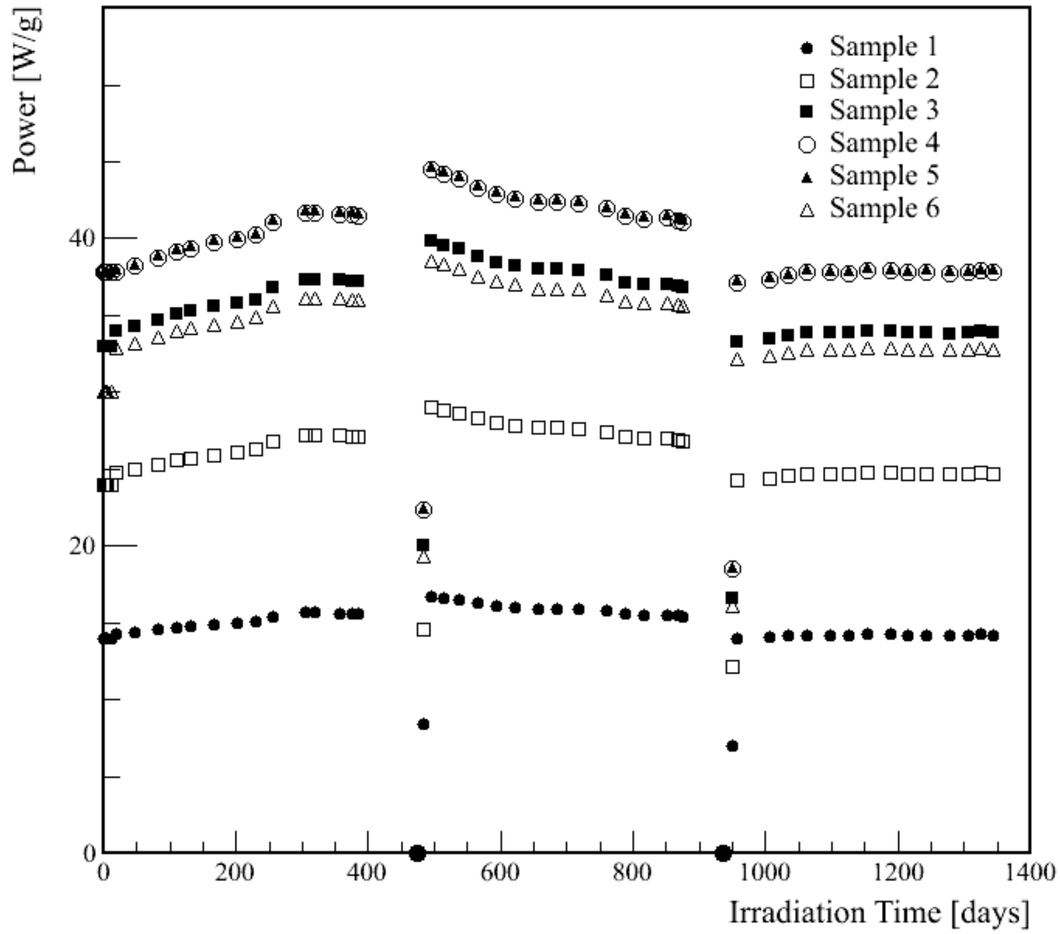
This assembly was inserted into the Takahama reactor vessel.





Unique to Takahama is the detailed power history along the rod.

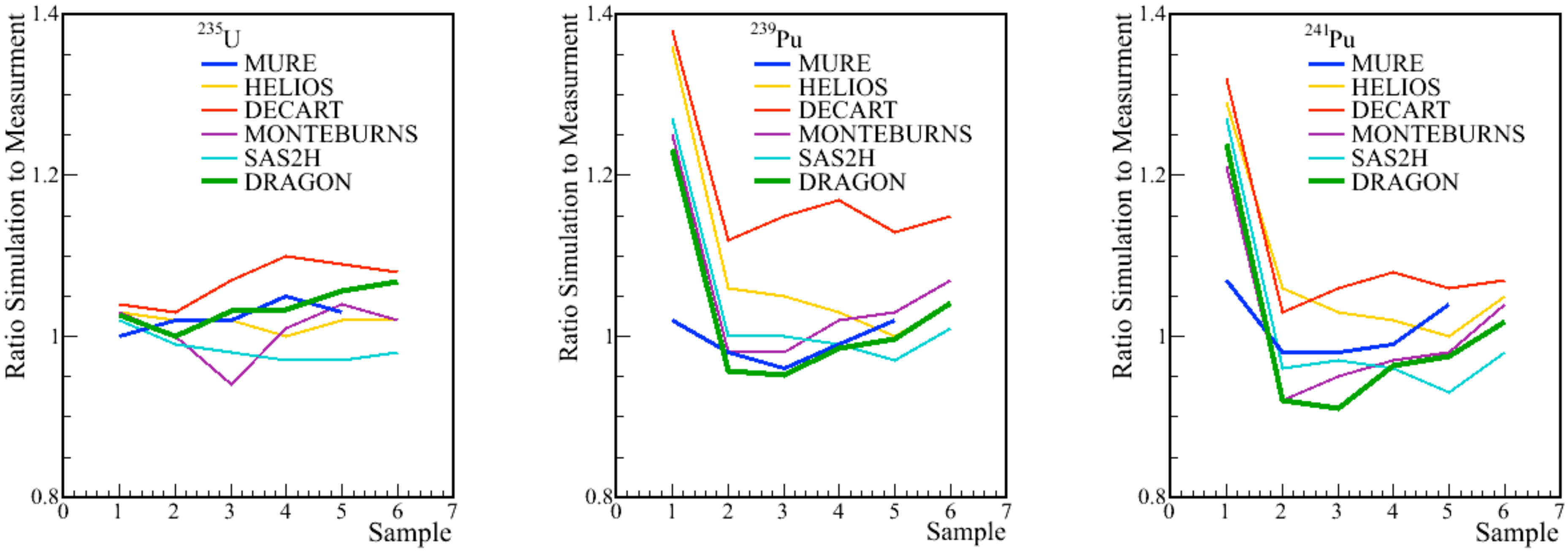
This is obtained by using the ^{148}Nd buildup coupled with simulations of the reactor (3% uncertainty).



With the detailed geometry and power history we are ready to simulate Takahama.

Understanding the performance....

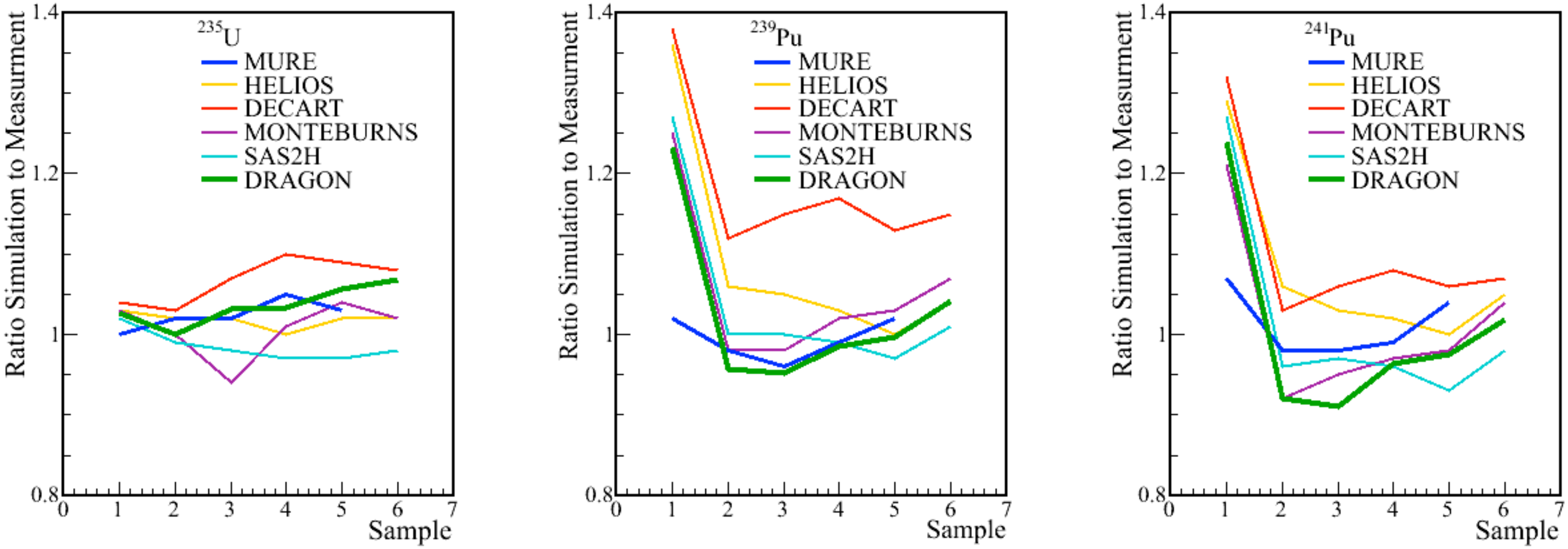
After the three cycles a destructive chemical assay was performed. The uncertainties on the mass inventories is ~0.3%.



DRAGON is performing well!

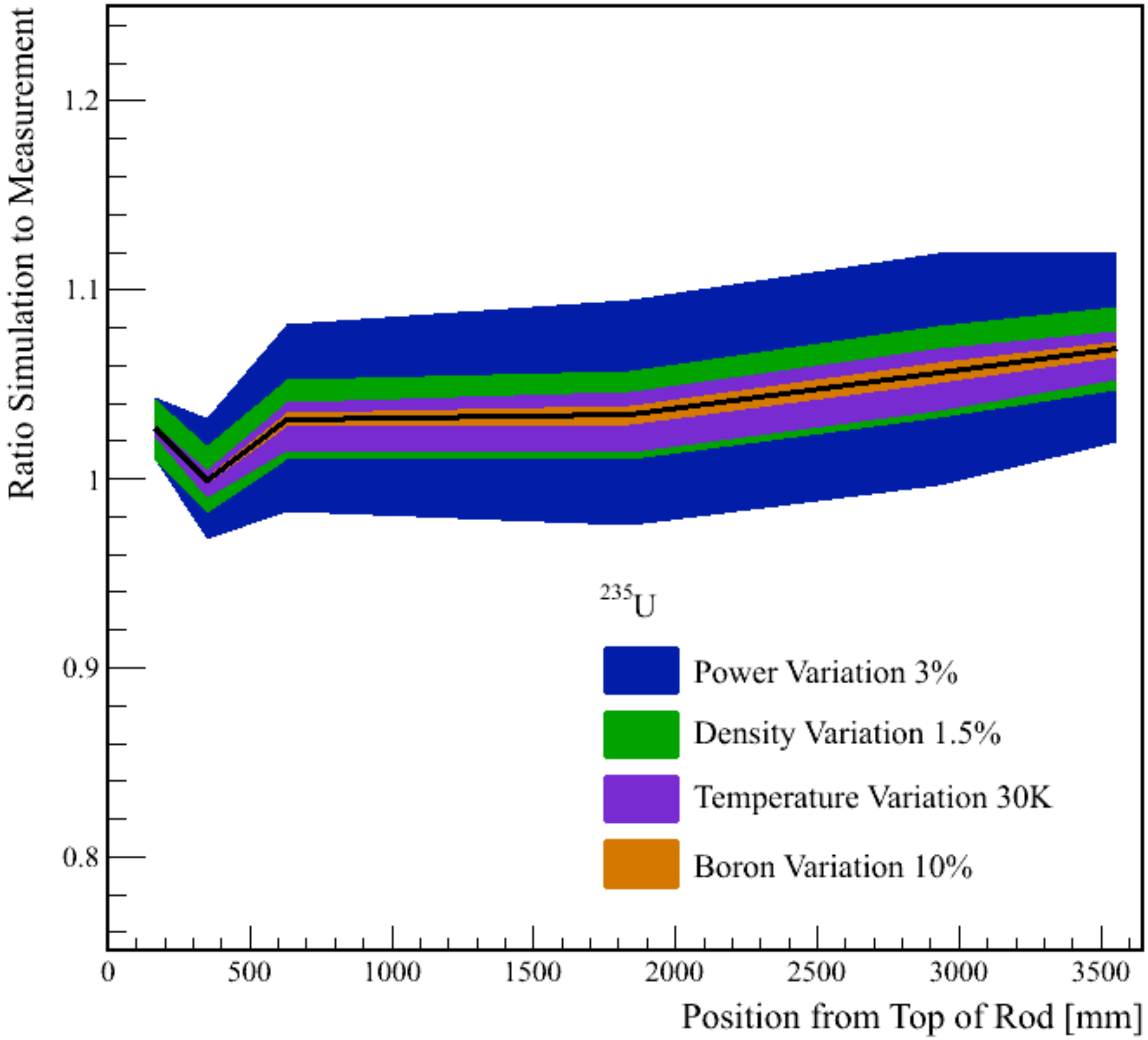
Understanding the performance....

$$^{238}\mathrm{U} \rightarrow {}^{239}\mathrm{Pu} \rightarrow {}^{240}\mathrm{Pu} \rightarrow {}^{241}\mathrm{Pu} \rightarrow \ldots \rightarrow {}^{244}\mathrm{Cm}$$

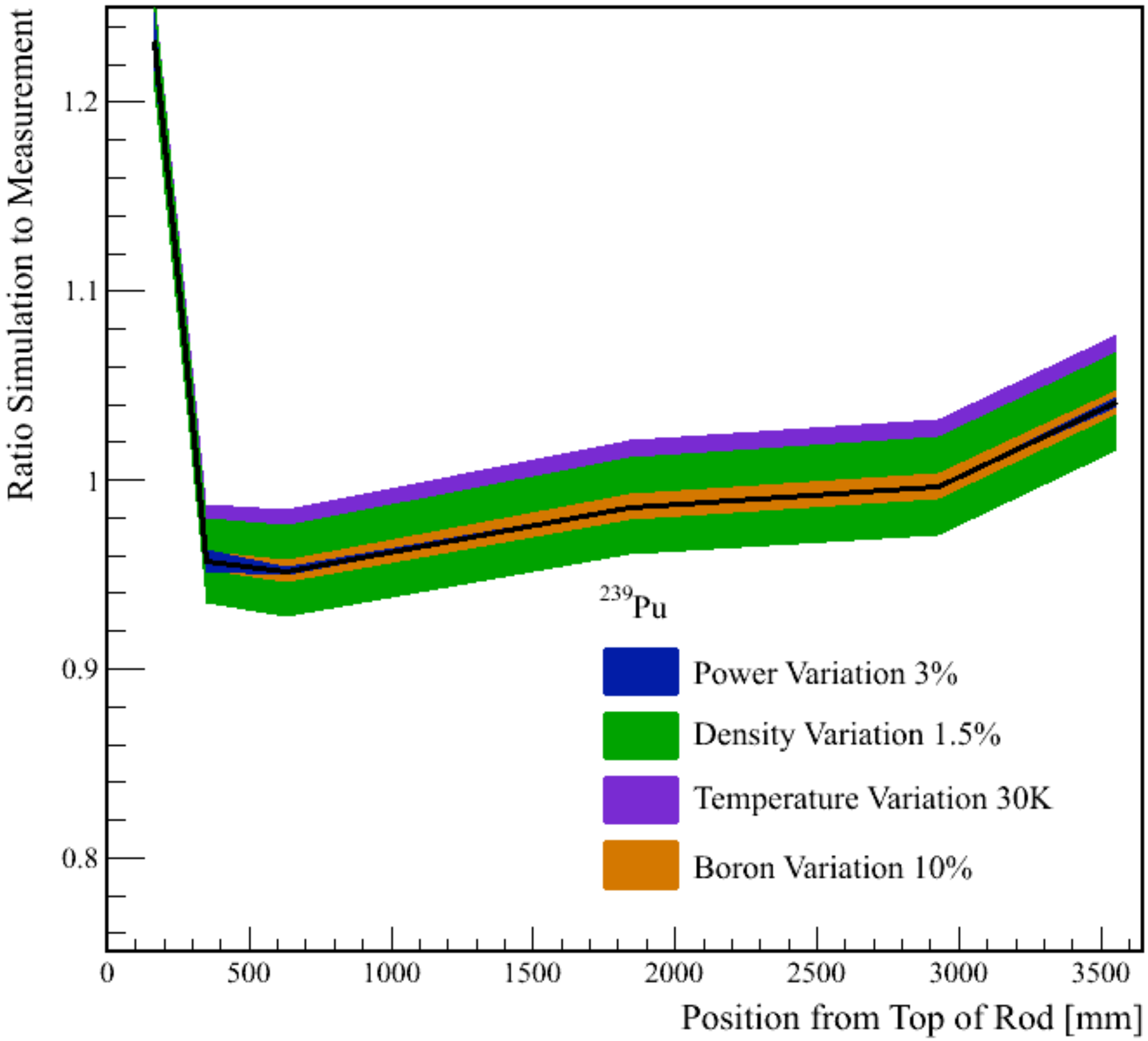


This is discussed nicely in
Djurcic, Detwiler et al.
J. Phys. G: Nucl. Part. Phys. 36 045002

^{235}U highly correlate to the power variation.

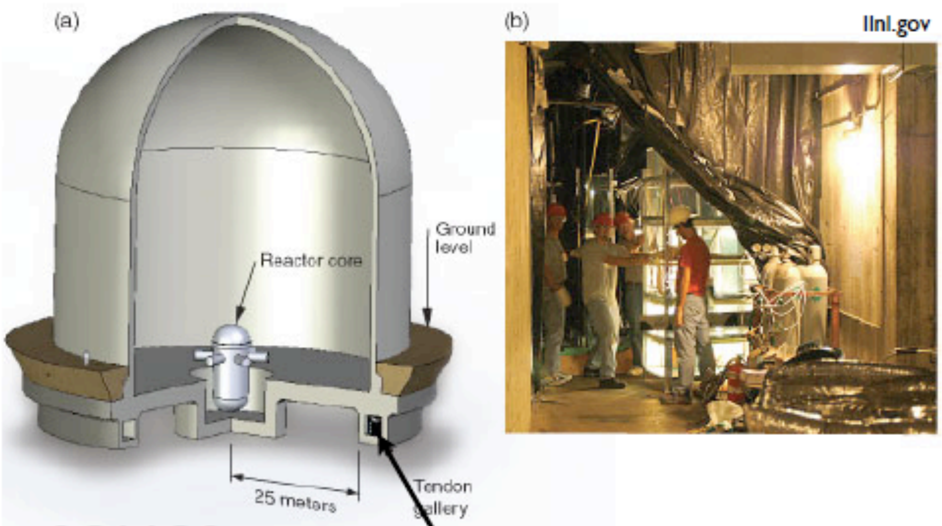


^{239}Pu is dominated by other things.

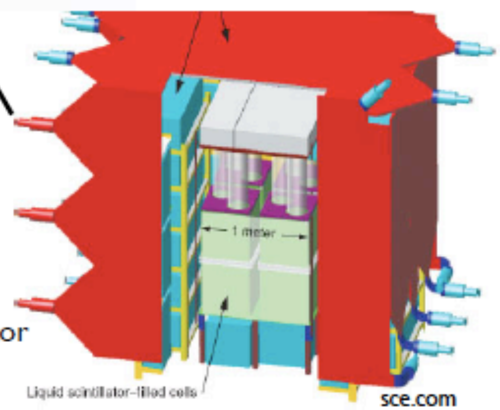


Using SONGs Data to Verify Reactor Models:

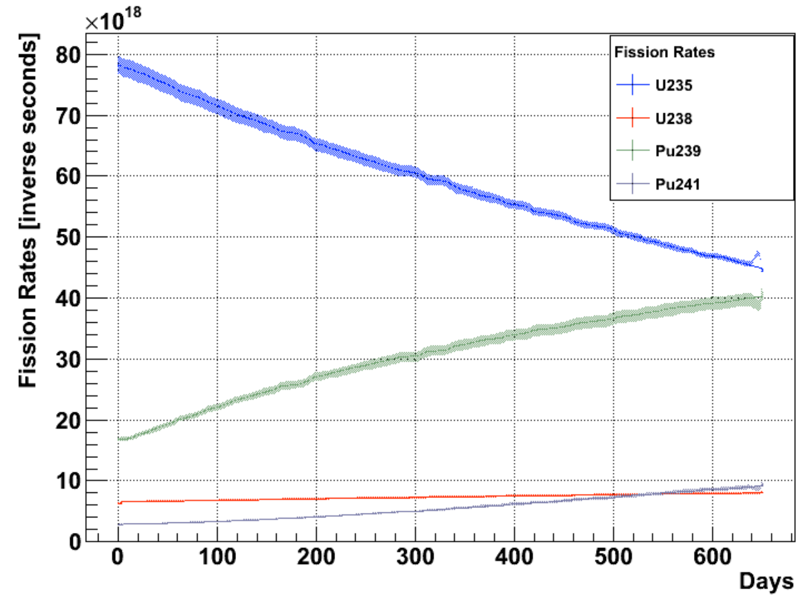
San Onofre Nuclear Generating Station

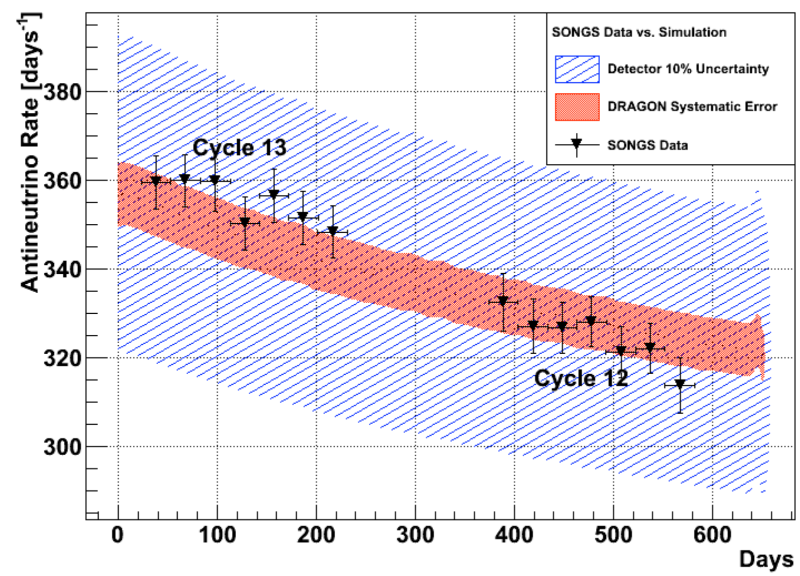


SONGS reactor: 3.438 GWth output



SONGS detector: 0.64 ton liquid scintillator doped with Gd





Data from LLNL and Sandia NL

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In the End.

- Dragon is a 2D assembly code that directly solves the neutron transport equations (*Meaning it's really fast*).

- We performed the Takahama benchmark and it is performing as well as the standard reactor modeling codes.

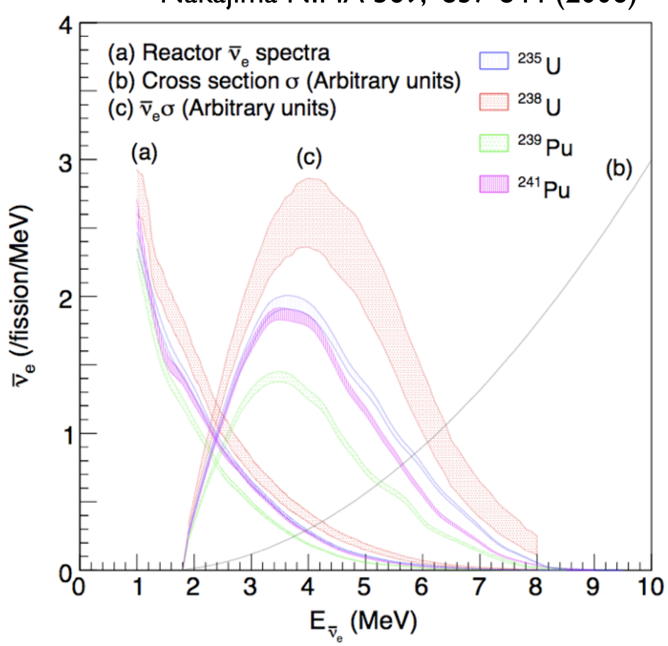
- You can get it yourself: http://www.polymtl.ca/nucleaire/DRAGON/en/index.php

And Just In Case....

The Other half of your prediction...the Spectra

$$S_{\rm tot}(E) = \sum_{k={}^{235}{\rm U},{}^{238}{\rm U},{}^{239}{\rm Pu},{}^{241}{\rm Pu}} \alpha_k \times S_k(E)$$

Nakajima NIMA 569, 837-844 (2006)

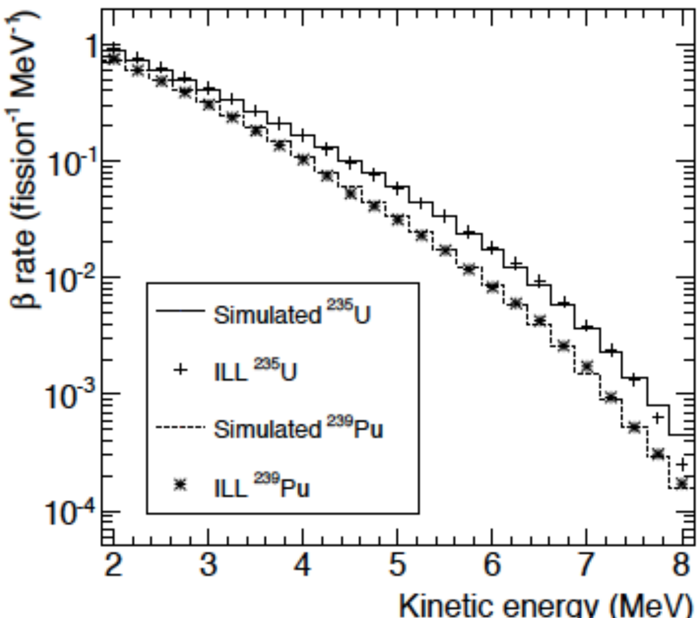


Number of Fissions per Isotope

Anti-neutrino spectra from the Isotopes

Where did the spectra come from?

The beta spectrum of ^{235}U, ^{239}Pu and ^{241}Pu were measured using a spectrometer.

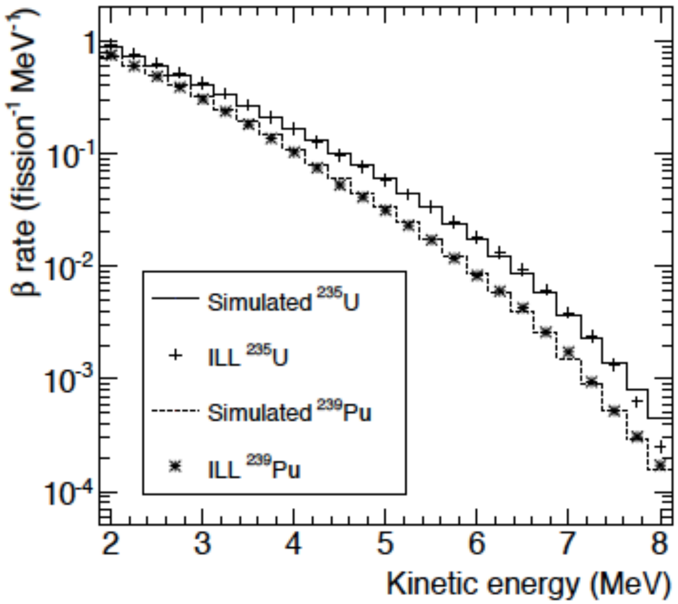


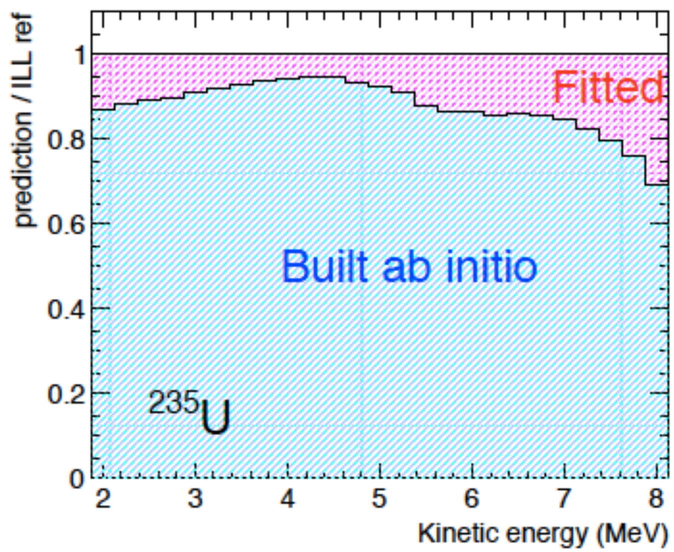
arXiv:1101.2663v3

$$S^b_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$
$$\times \underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

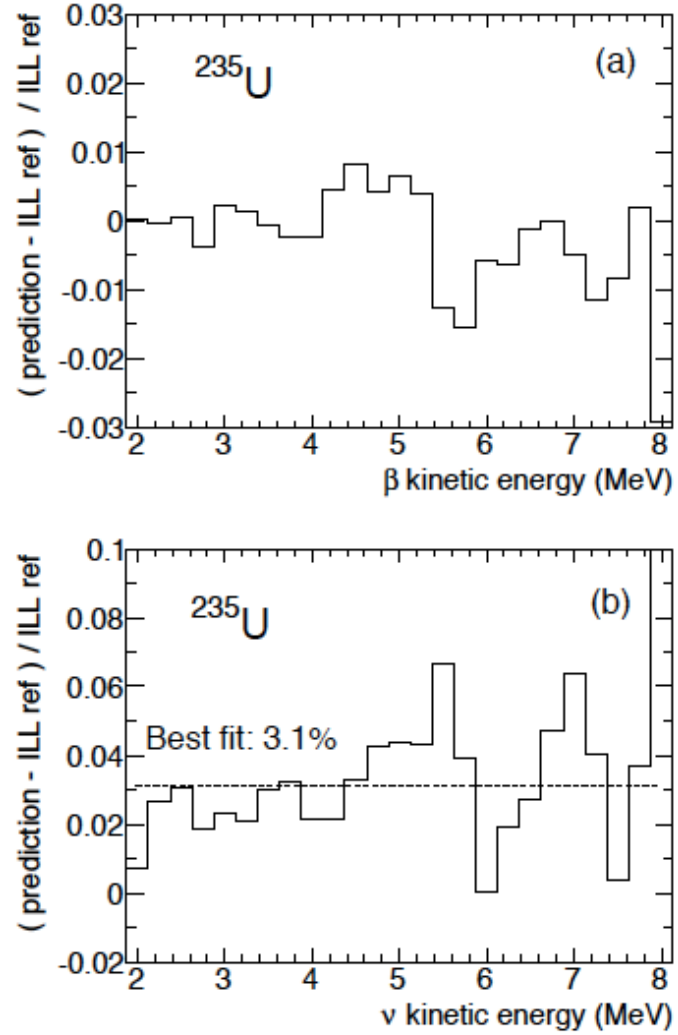
Now you use energy conservation to extract the neutrino spectrum.

Updating the Extraction....





arXiv:1101.2663v3



➡Shift of 3.1%, Oh My!

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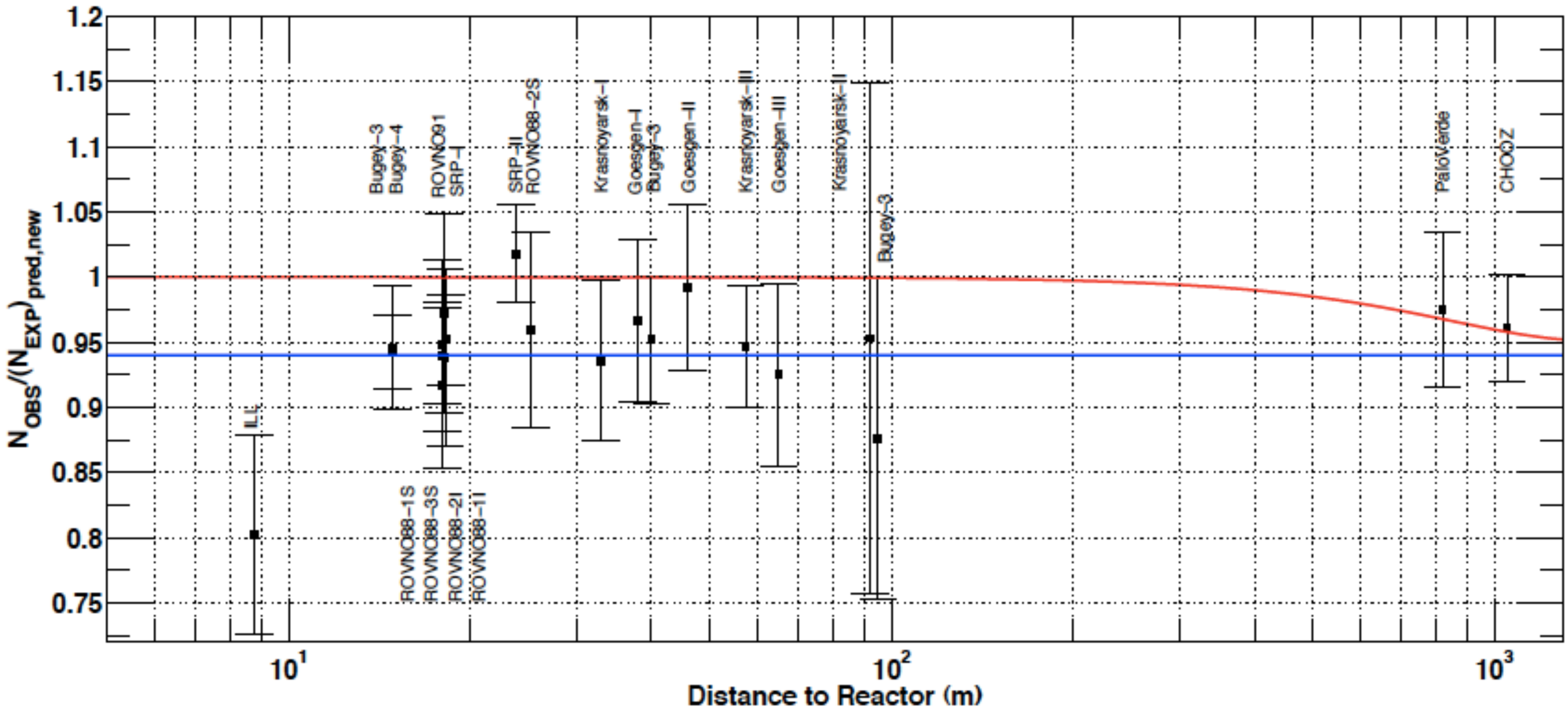
Is this evidence for sterile neutrinos?

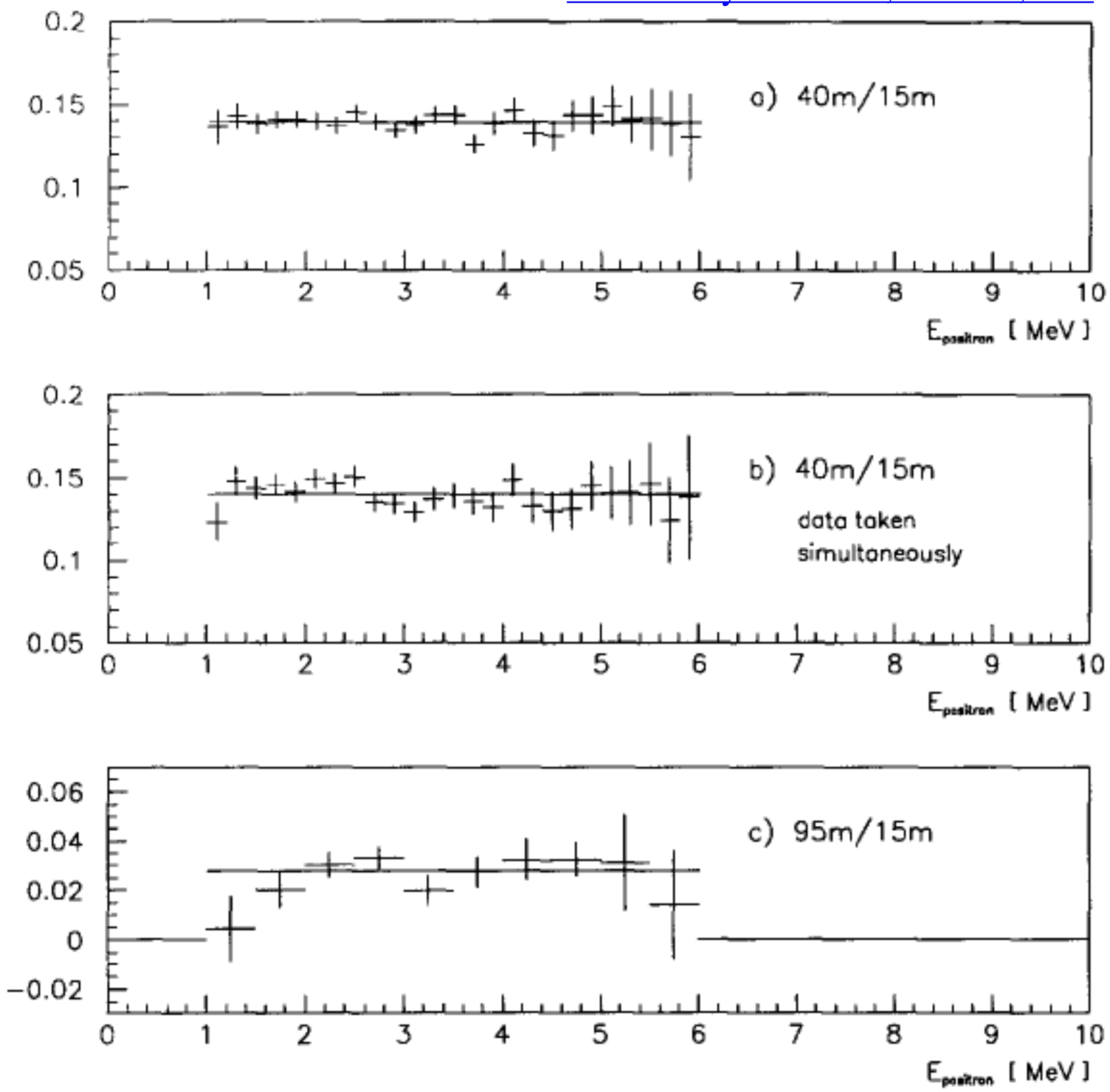
arXiv:1101.2755v4



The blue line is a fit to a 4th neutrino state with a mass splitting of >1eV^2.

Not to be confused with Bugey-3 in 1995

Nuclear Physics B 434, 503-532,1995



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and these measurements are tricky...

Bugey in 1984

Physics Letters 148B 387-394, 1984

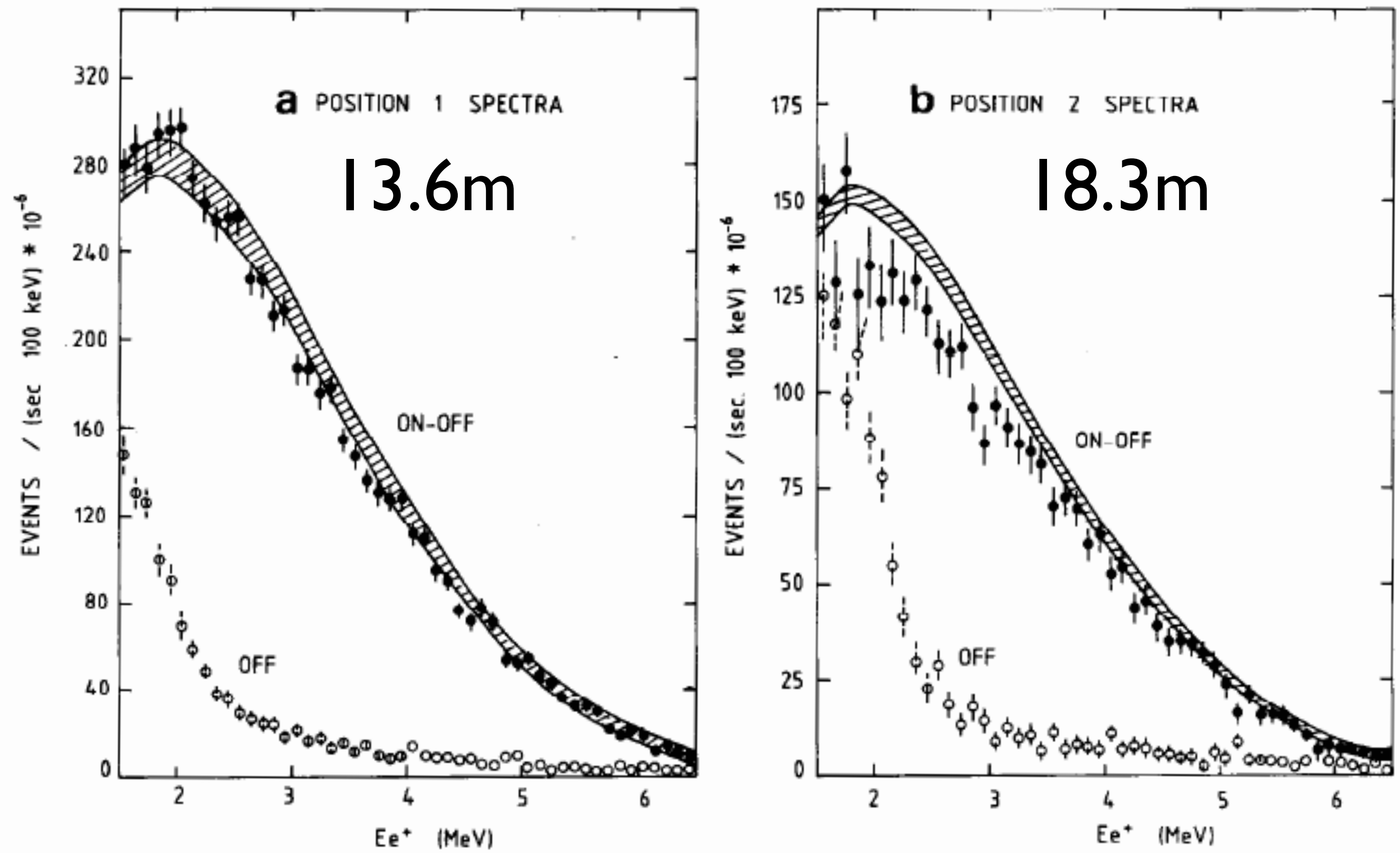

Fig. 2. (a) Positron energy spectrum measured at position 1 (reactor OFF subtracted). The data points with dashed error bars show the reactor OFF spectrum. The error bars are statistical. The expected positron energy spectrum is shown as a shaded band delimited by the point-to-point errors. (b) Ditto at position 2.

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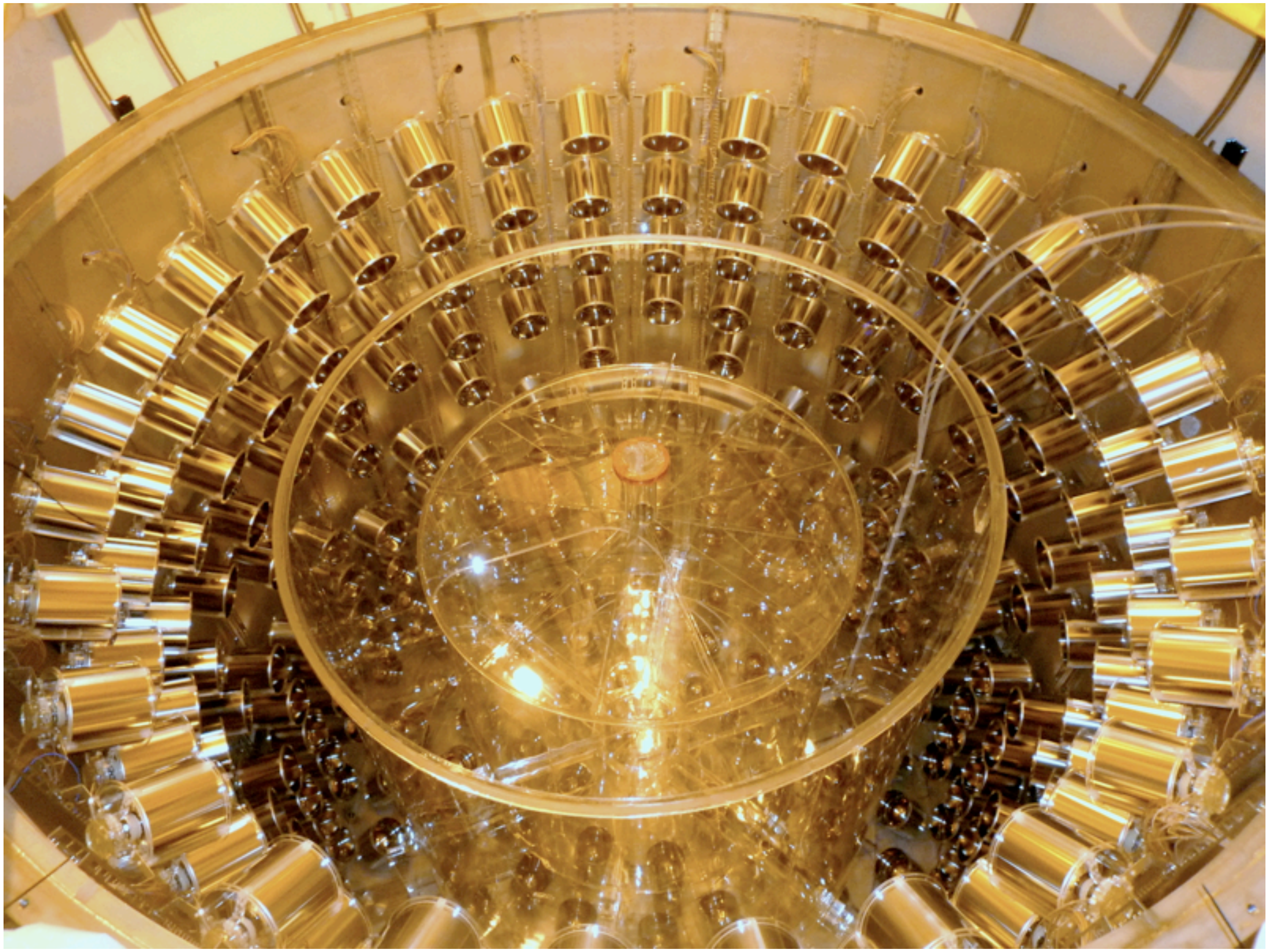
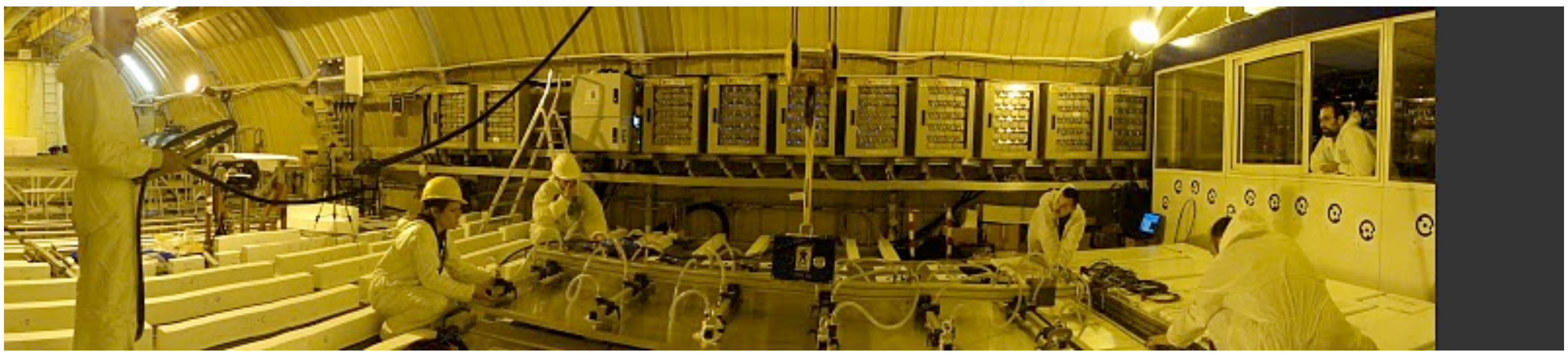
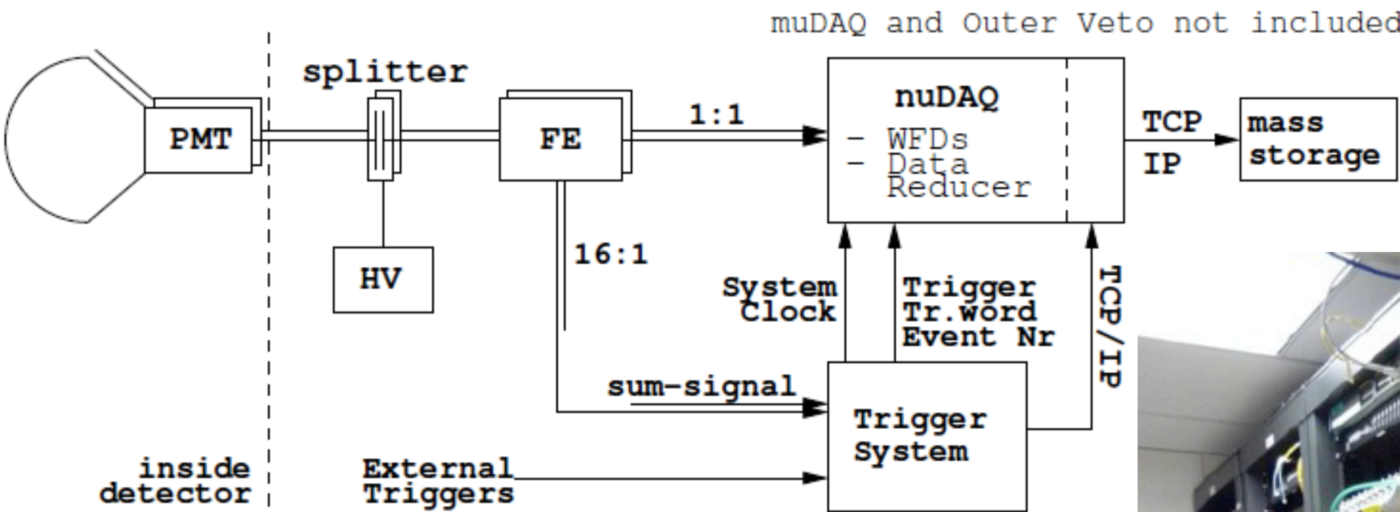


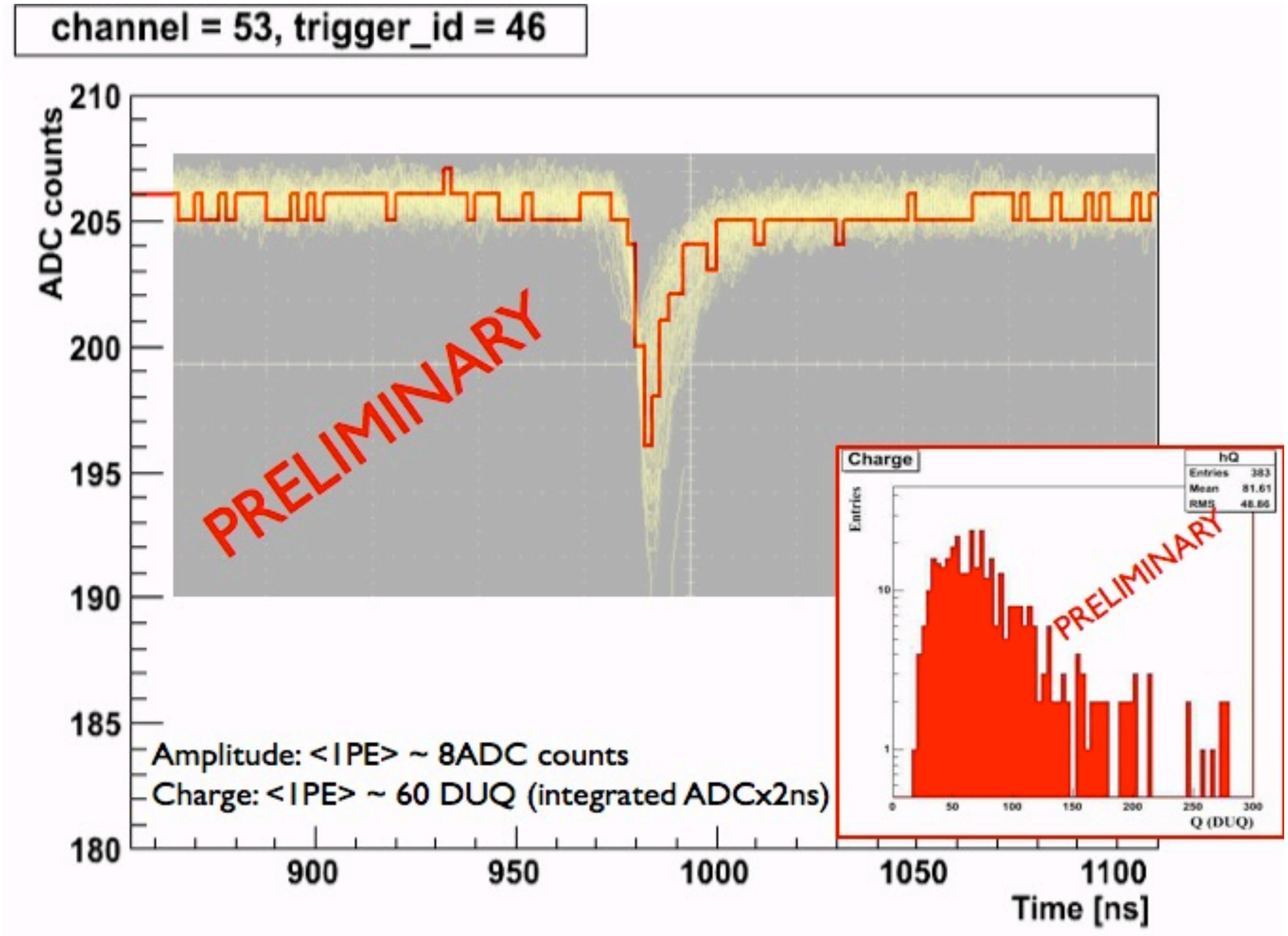




The Electronics:

- Signal + HV on one cable.
- Frontend cards shape pulses, corrects baseline and integrates charge.
- Analog Trigger triggers on photoelectron equivalent.
- 500MHz Caen digitizers record pulses.
- Subset of PMTs sent to second system to record muon events.

Single Photo-Electron Data:



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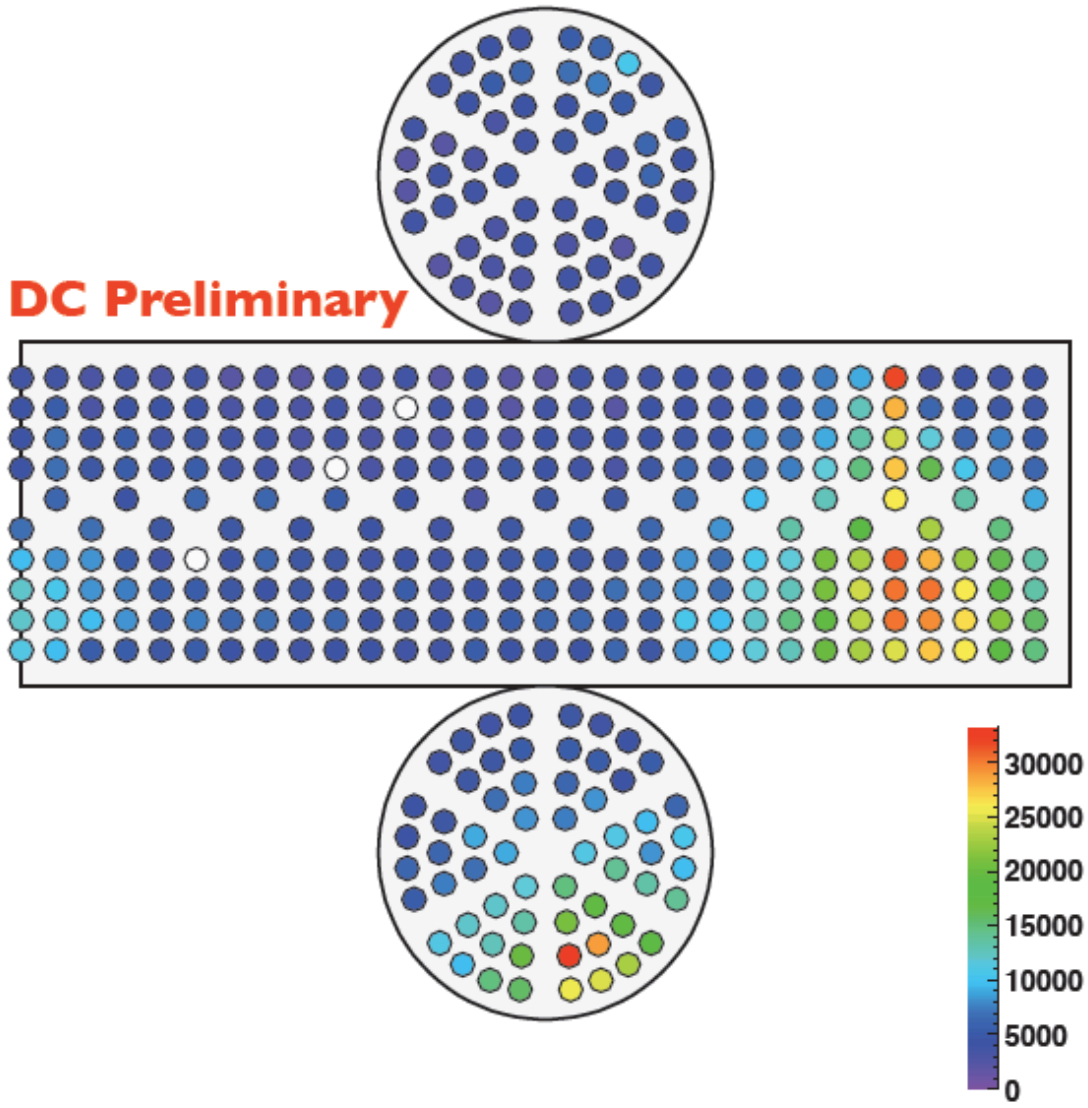
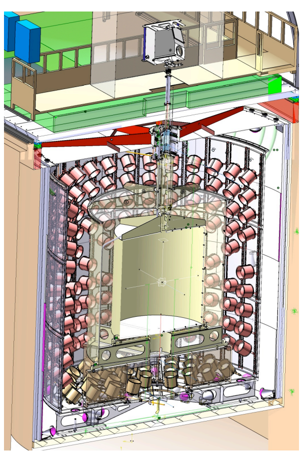
Inner Detector Muon Event





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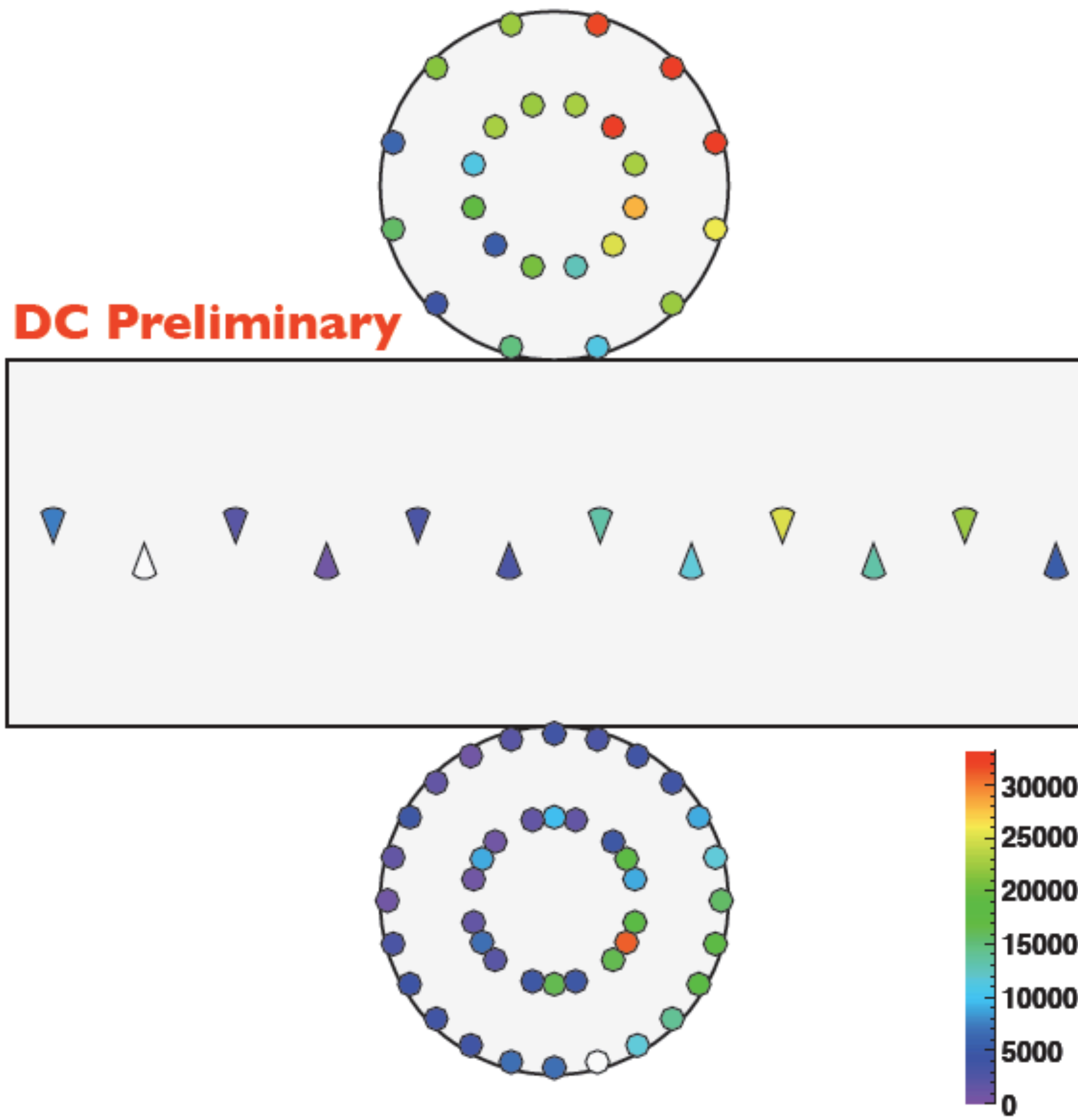
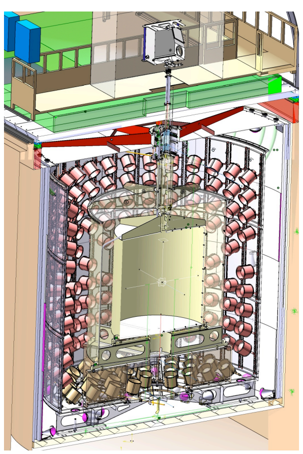
Inner Veto Muon Event





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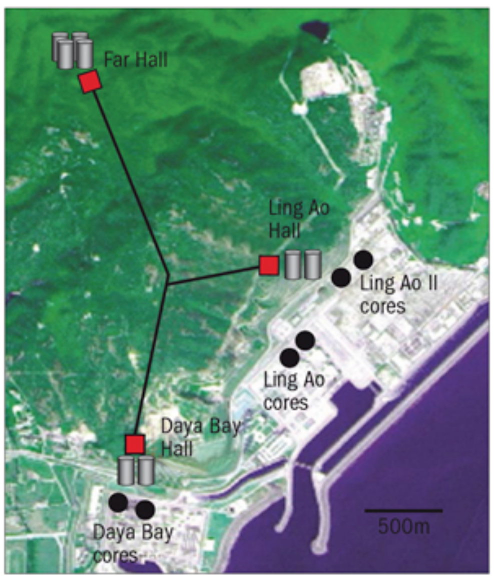
And then there were three:



arXiv:hep-ex/0701029v1

arXiv:1003.1391v1

arXiv:hep-ex/0606025v4

The Three Experiments:

	Double Chooz	Daya Bay	RENO
Reactor Cores	2 Cores	6 Cores	6 Cores
Total Power	8.54 GW	11.6 GW†	16.4 GW
Target Mass	8.24 tons	20 tons	15 tons
Near Distance	400m	300-500m†	290m
Near Overburden	115 m.w.e	~100 m.w.e†	130 m.w.e
Far Distance	1.05km	1.6-1.9km	1.4km
Far Overburden	300 m.w.e.	350 m.w.e	460 m.w.e.
Events per Day	425/43	1600/400†	5000/100

† Daya Bay will increase to 17.4GW in 2011, has two near sites, and uses multiple detectors per site.

Why the two detectors?

		Chooz	Double Chooz
Reactor	ν flux and spectrum	1.9%	<0.1%
	Reactor Power	0.7-2%	<0.1%
Detector	Solid Angle	0.3%	<0.1%
	Target Mass	0.3%	0.2%
	Density	0.3%	<0.1%
	H/C and Gd ratio	1.2%	<0.2%
	Spatial Effects	1.0%	<0.1%
	Live time	-	<0.2%
Analysis	From 3-7 cuts.	1.5%	0.2-0.3%
	Total	2.7%	<0.6%

The Estimated Background Rates:

Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
CHOOZ		Rate (d^{-1})	—	—	—	—	0.6 ± 0.4
(24 ν/d)		Rate (d^{-1})	0.42 ± 0.05		$1.01 \pm 0.04(stat) \pm 0.1(sys)$		
	Far	bkg/ν	1.6%		4%		
		Systematics	0.2%		0.4%		
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.5 ± 0.8	0.2 ± 0.2	< 0.1	1.4 ± 0.5
(69 ν/d)	Far	bkg/ν	0.7%	2.2%	0.2%	<0.1%	1.4%
		Systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz		Rate (d^{-1})	5 ± 3	17 ± 9	1.3 ± 1.3	0.4	9 ± 5
(1012 ν/d)	Near	bkg/ν	0.5%	1.7%	0.13%	<0.1%	1%
		Systematics	<0.1%	<0.1%	0.2%	<0.1%	0.2%

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