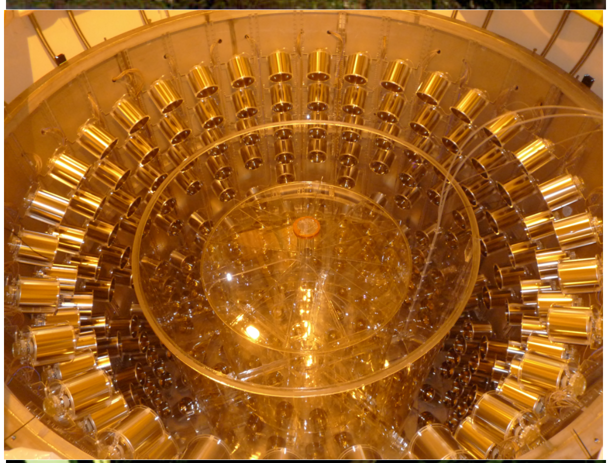
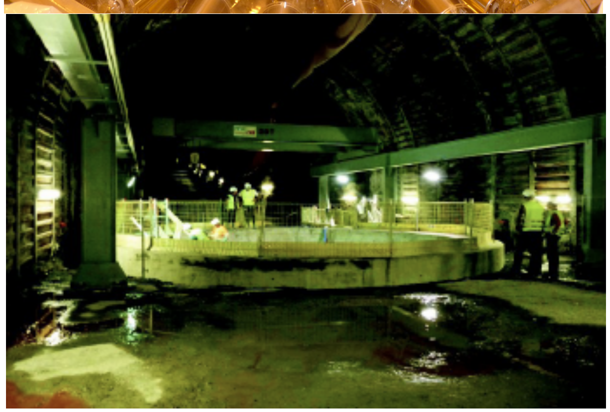




Double Chooz: The Show Goes On!

Lindley Winslow
University of California Los Angeles
On behalf of the Double Chooz Collaboration

The Double Chooz Collaboration:

Brazil
- CBPF
- UNICAMP
- UFABC

France
- APC
- CEA/DSM/IRFU:
  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC

Germany
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München
- U. Hamburg

Japan
- Tohoku U.
- Tokyo Inst. Tech.
- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima Inst. Tech.

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

Theory favored small $\sin^2 2\theta_{13}$!

Theory	Order of Magnitude Prediction
L_e-L_μ-L_τ	0.00001
SO(3)	0.00001
S3 and S4	0.001
A4 Tetrahedral	0.001
Texture Zero	0.001
RH Dominance	0.01
SO(10) with Sym/Antisym Contributions	0.01
SO(10) with lopsided masses	0.1

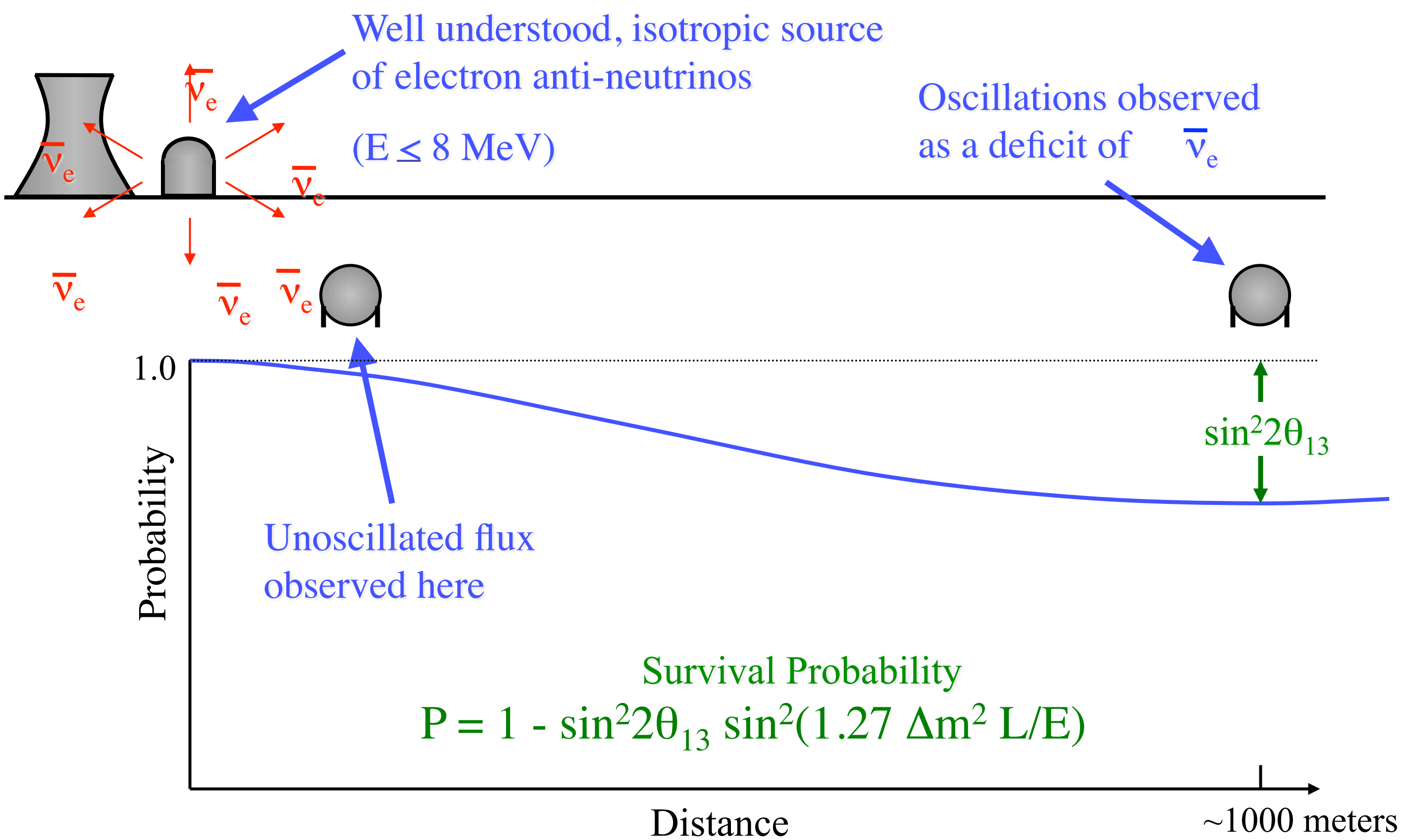
Model Review by Albright et. al. ArXiv:0803.4176

Neutrino Factory Designs

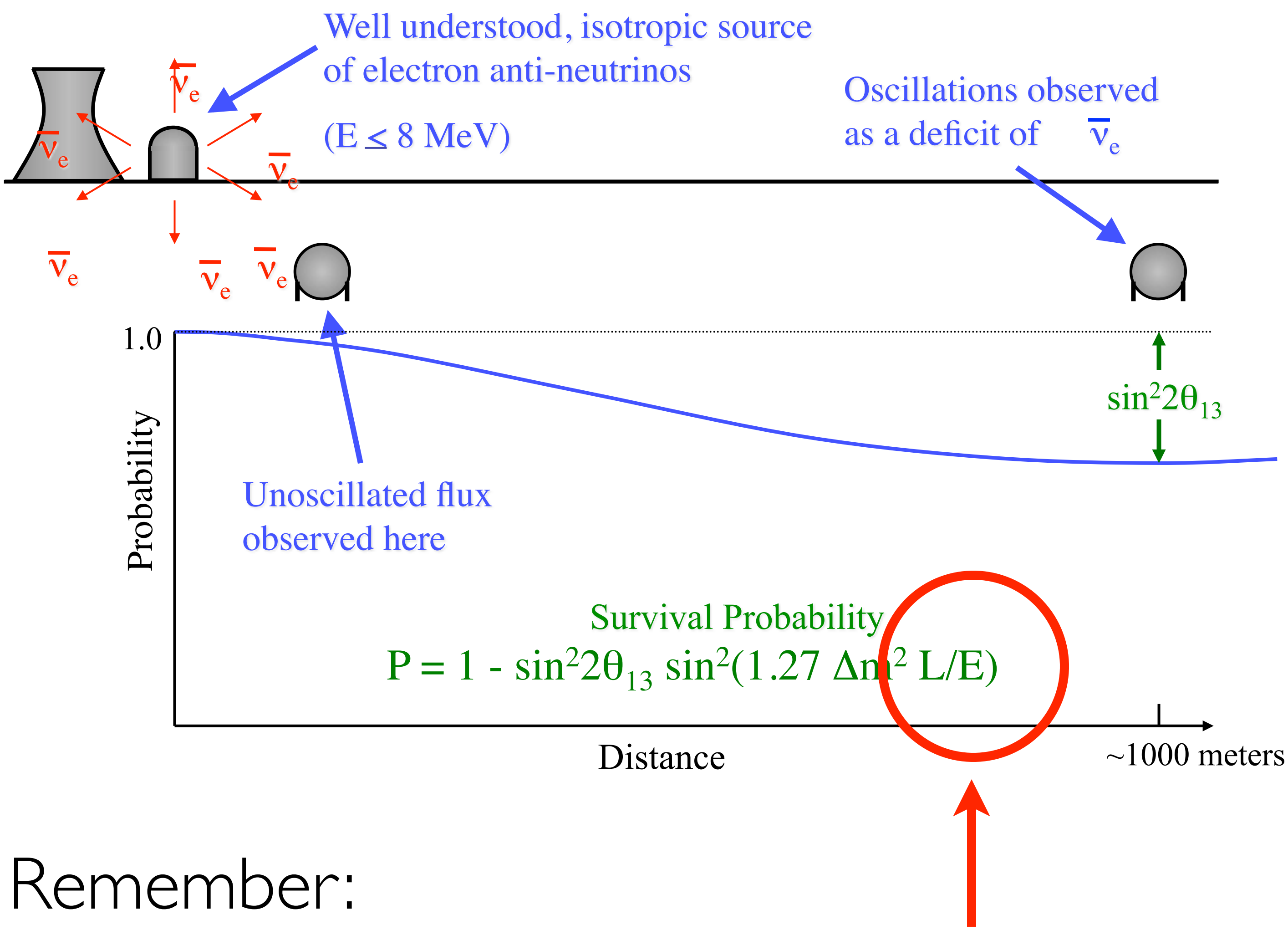
Reactor Experiment Design

Limit as of 2011

Measuring the last mixing angle:



Measuring the last mixing angle:



Remember:

We are looking for an effect as a function of L/E.

Construction Underway!

Double Chooz Analysis is Unique:

- Analysis uses BOTH Rate and Energy information

➙*Detailed Energy Response Model*

- Simple Reactor Configuration

➙ *Multiple analysis periods.*

- Multiple Detector Phases - Now Far Detector Only

➙*Detailed Reactor Model*

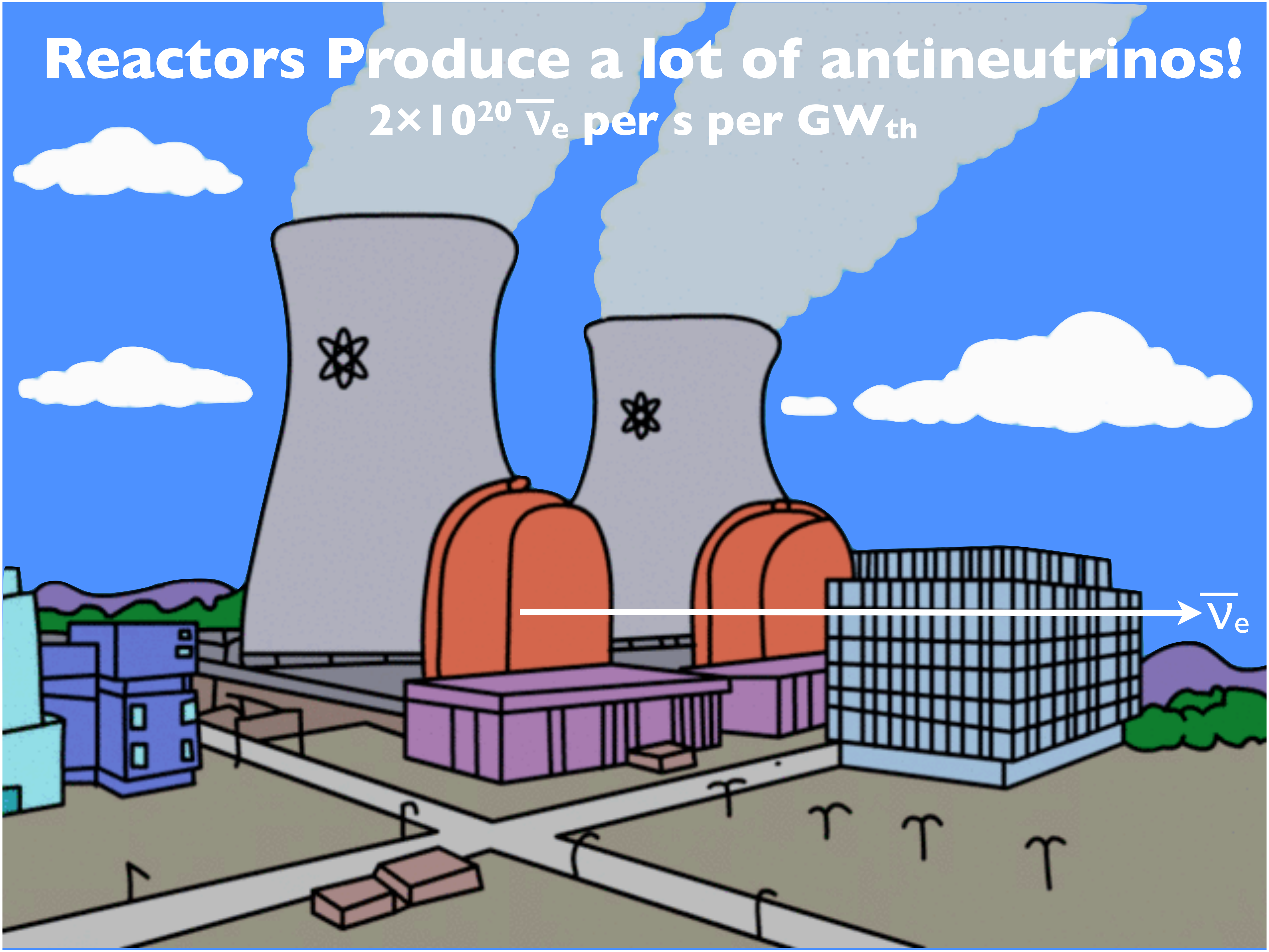
Reactor Basics

θ_{13} is Large!

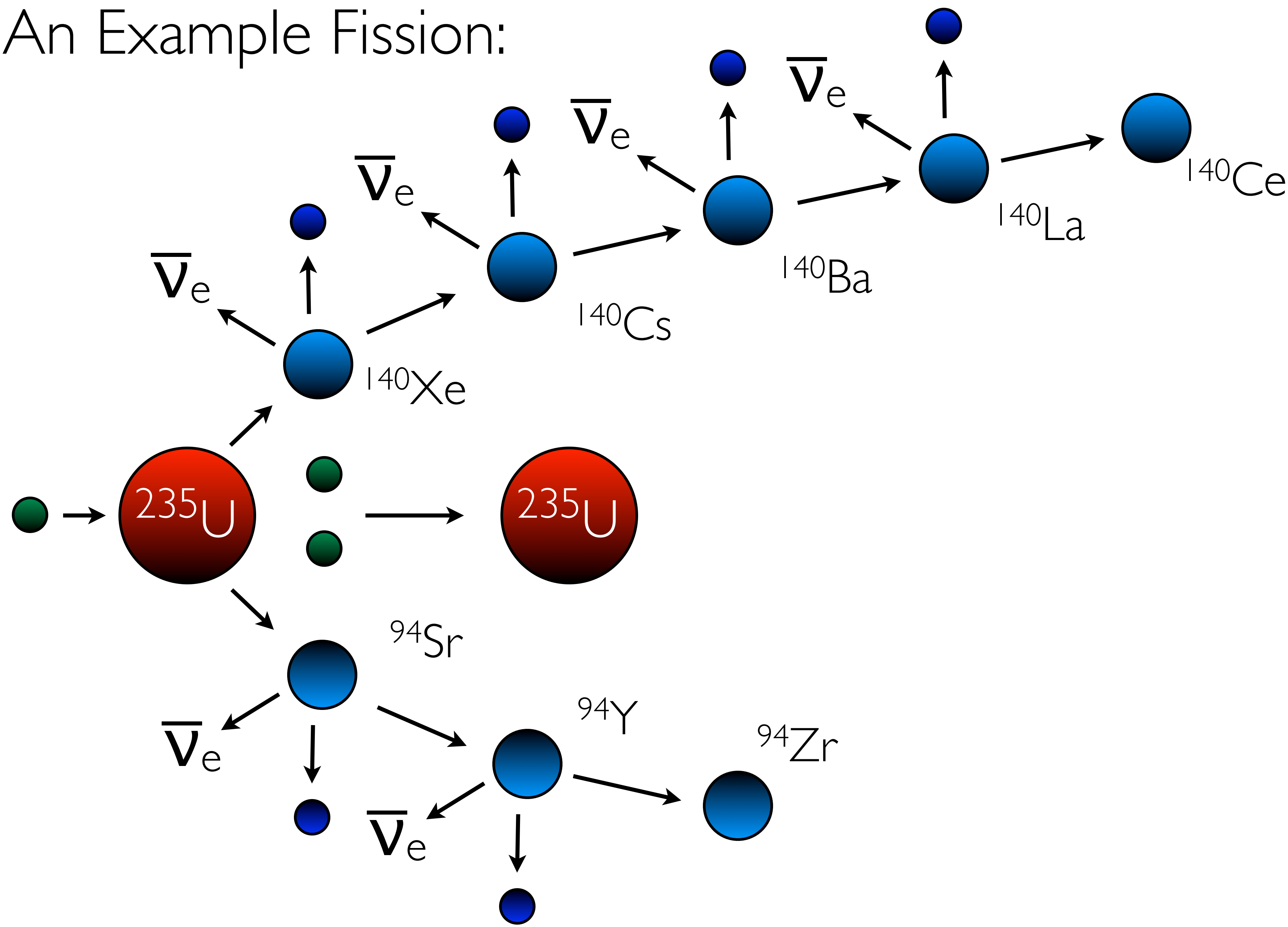
The Future

Reactors Produce a lot of antineutrinos!

$2 \times 10^{20}\ \overline{\nu}_e$ per s per GW_{th}

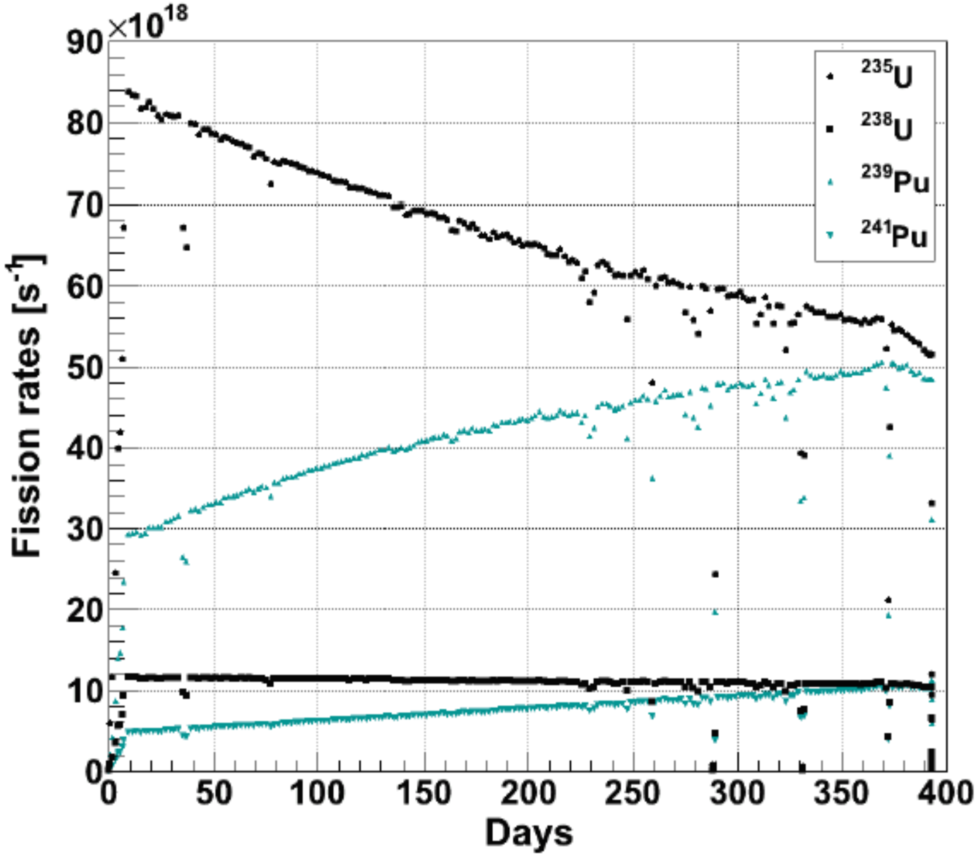


An Example Fission:



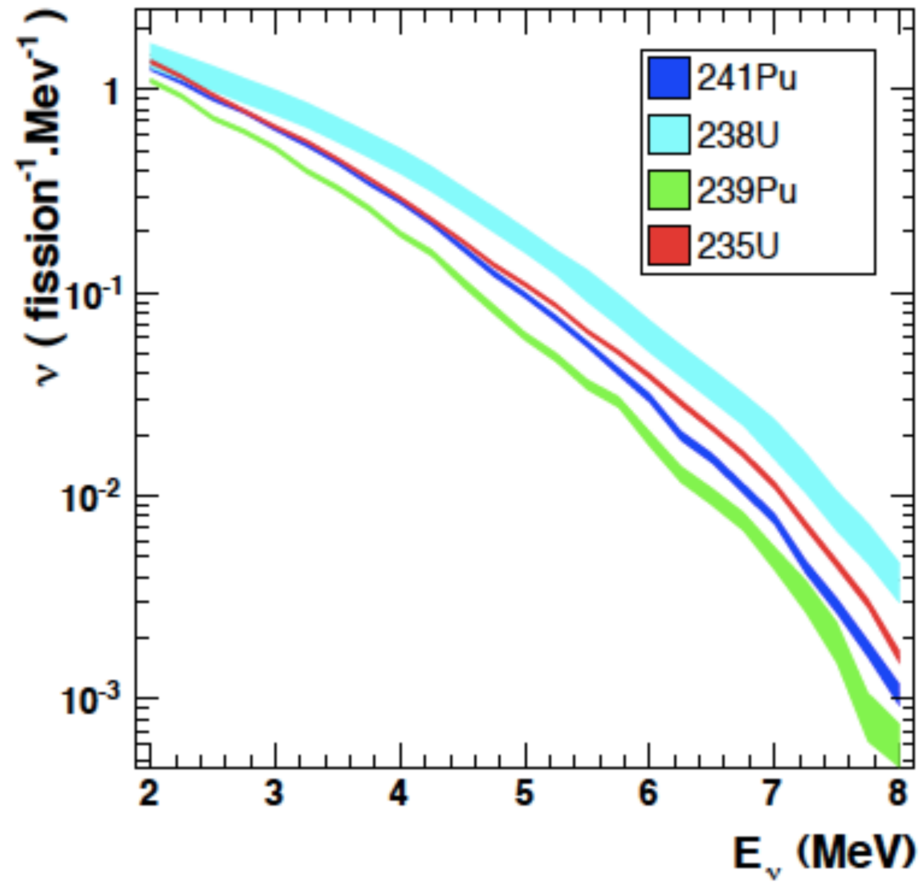
Obtaining the Neutrino Prediction:

Fission Rates



×

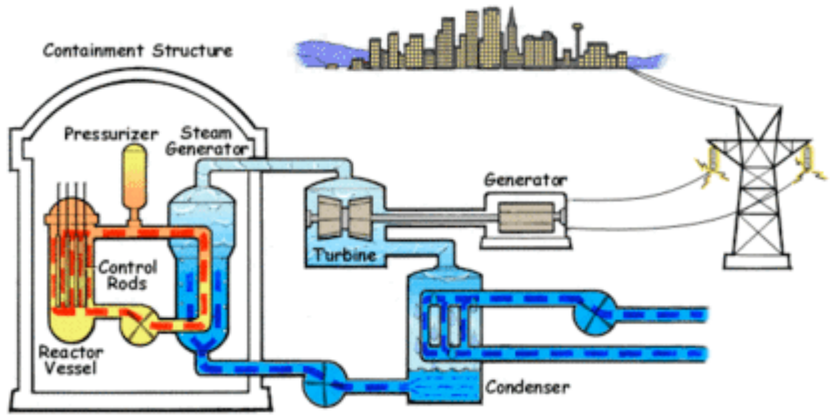
Spectra per Fission



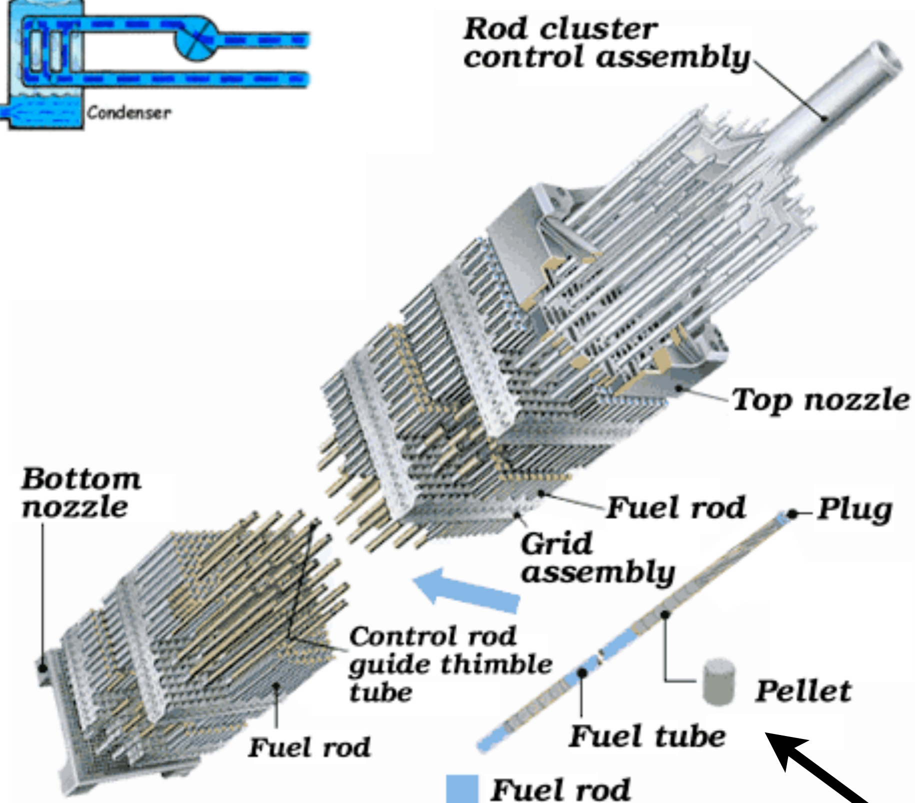
Reactor core simulated with detailed inputs from the power company.

Measured at devoted experiment at the ILL research reactor.

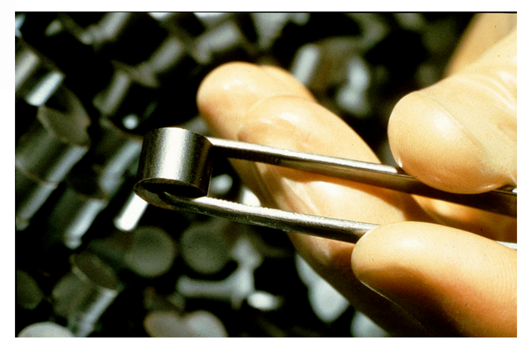
Nuclear Reactor Basics



Fuel Assembly



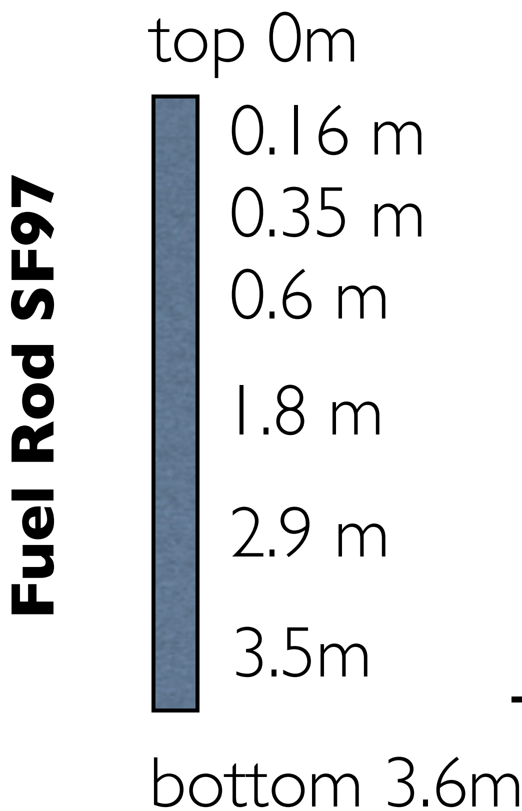
UO_2 Fuel



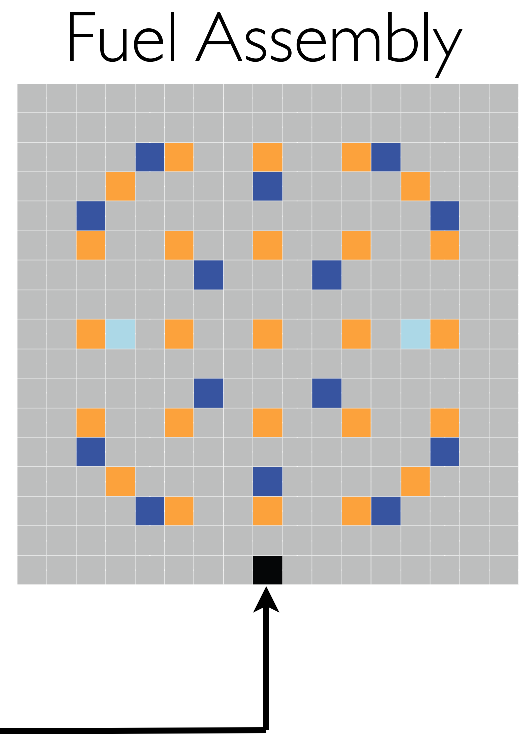
Fuel is arranged in assemblies.

Takahama Benchmark

Published information of the irradiation history of fuel rods installed in a PWR reactor. A chemical assay is performed at the end of three fuel cycles.

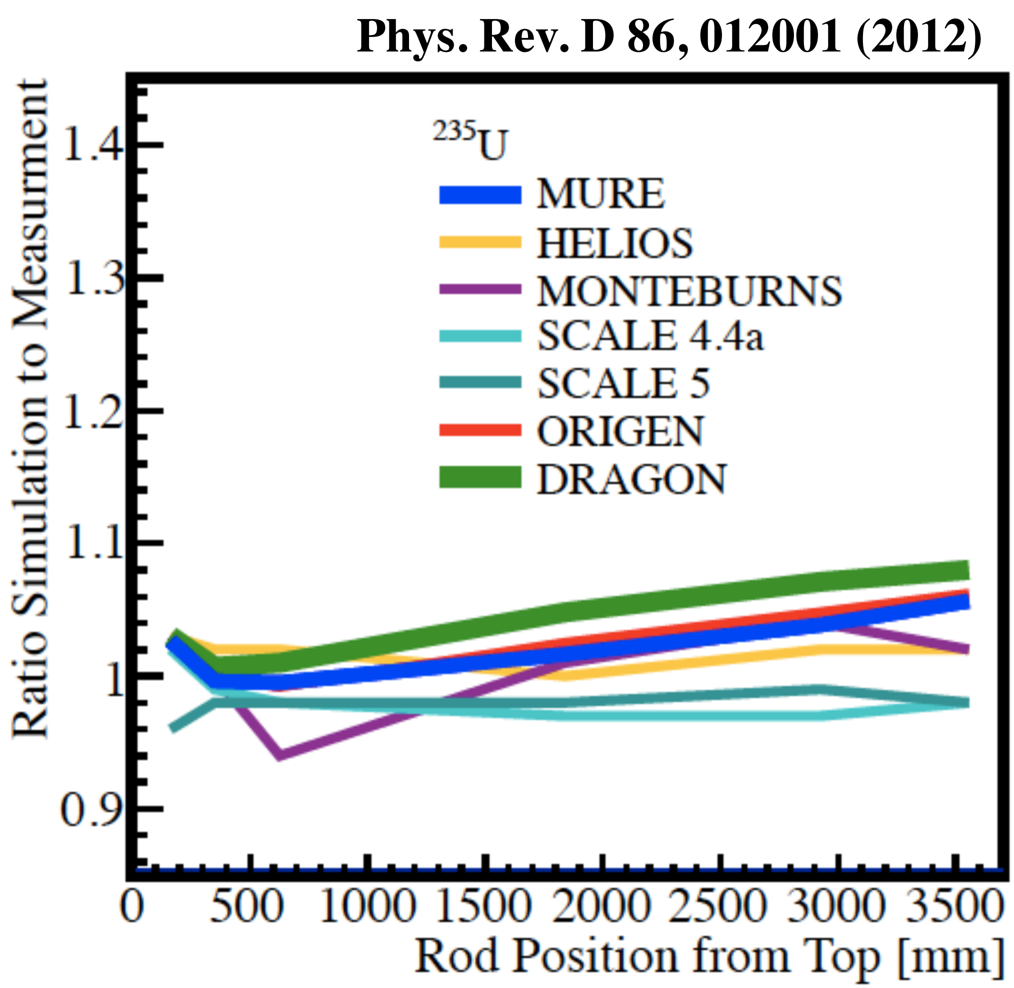


Six samples were taken along the rod.



We concentrate on SF97.

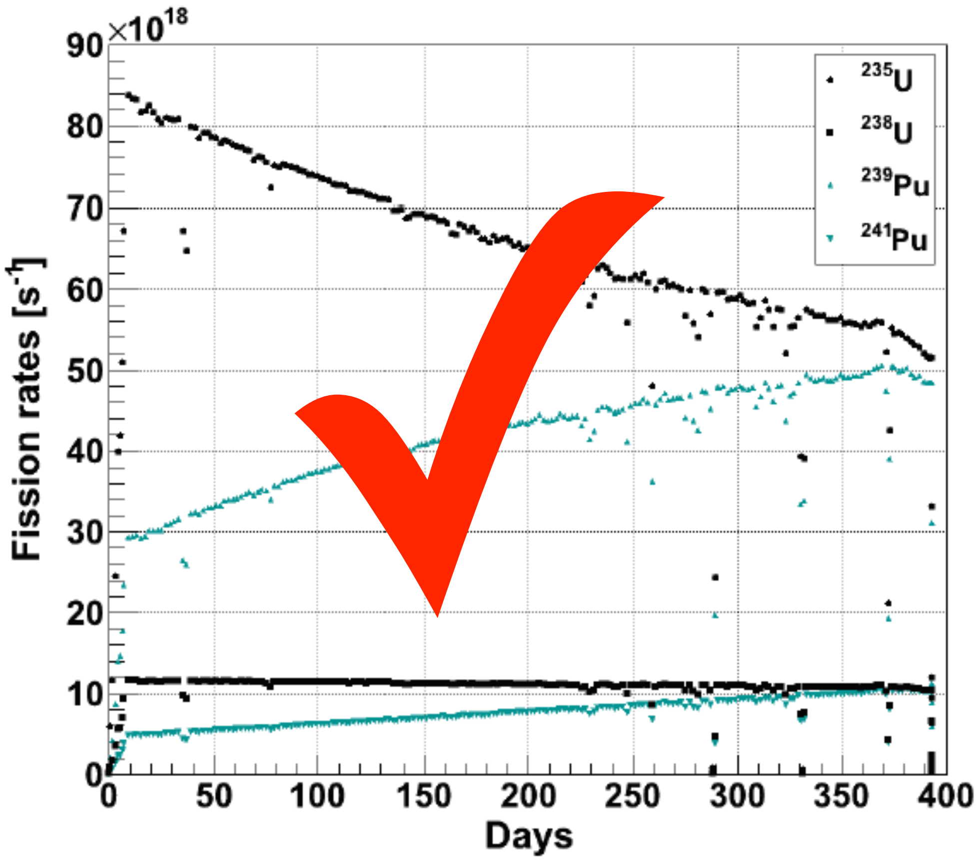
Result of Takahama Benchmark for ^{235}U:



Simulations agree with measurements and other codes within the uncertainties of the simulations' inputs.

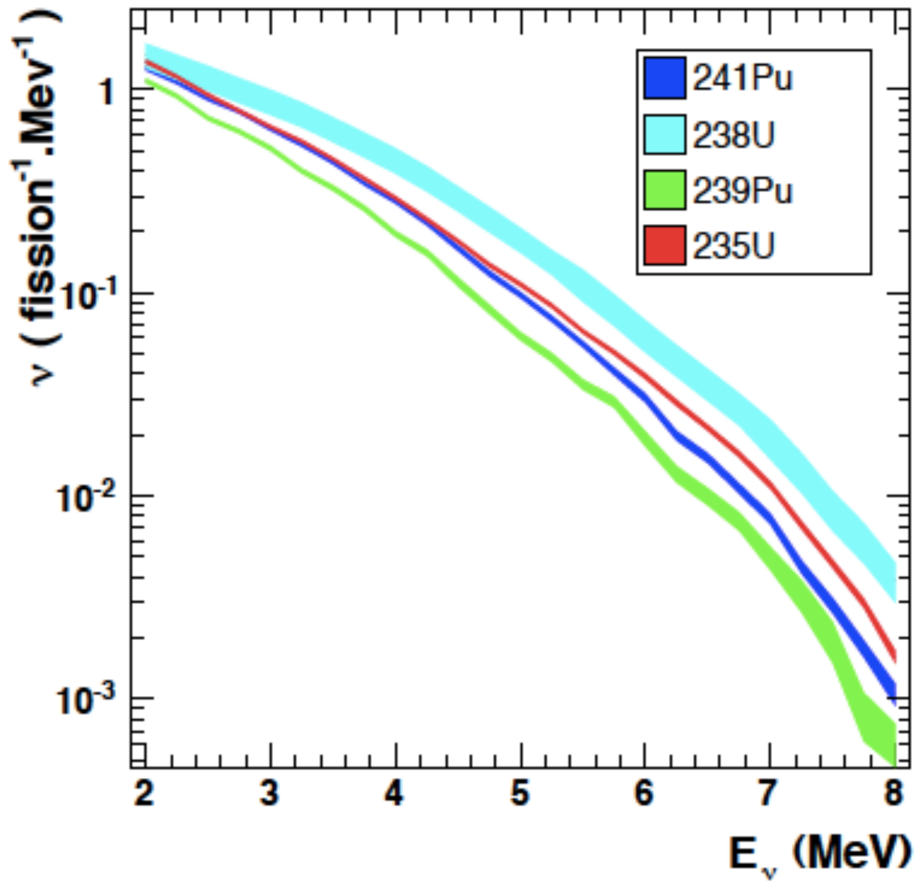
Obtaining the Neutrino Prediction:

Fission Rates



×

Spectra per Fission



Reactor core simulated with detailed inputs from the power company.

Measured at devoted experiment at the ILL research reactor.

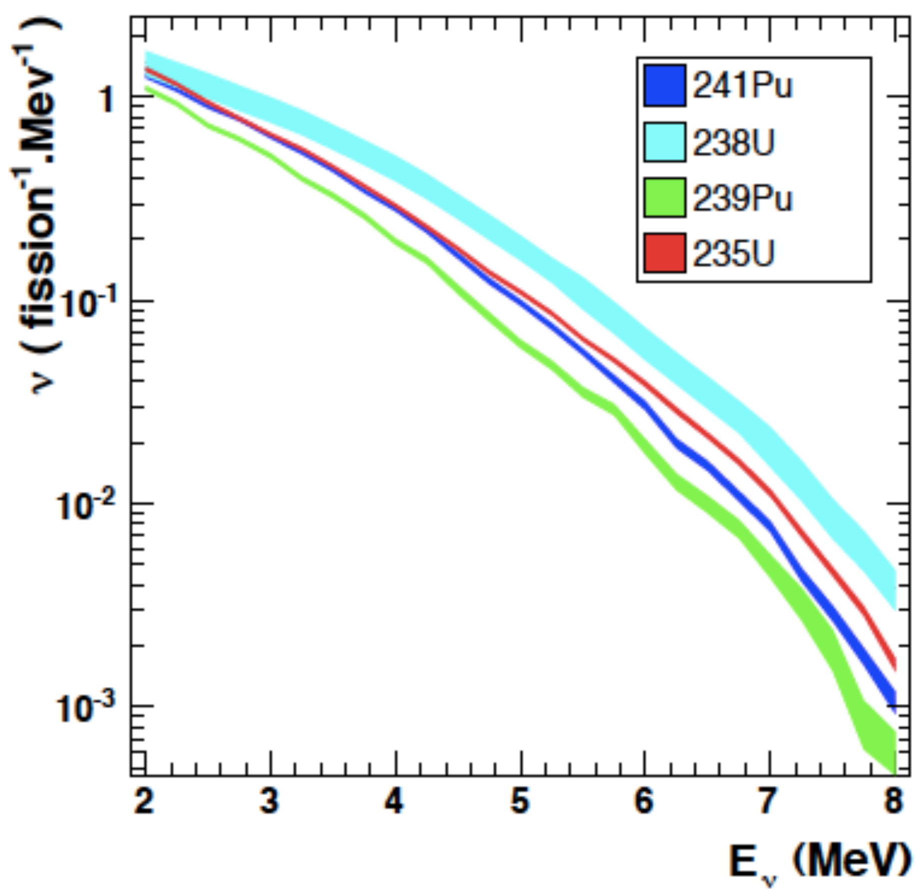
Average Cross Section per Fission:

$$\langle \sigma_f \rangle = \sum_k \alpha_k \langle \sigma_f \rangle_k = \sum_k \alpha_k \int_0^\infty dE S_k(E) \sigma_{IBD}(E)$$

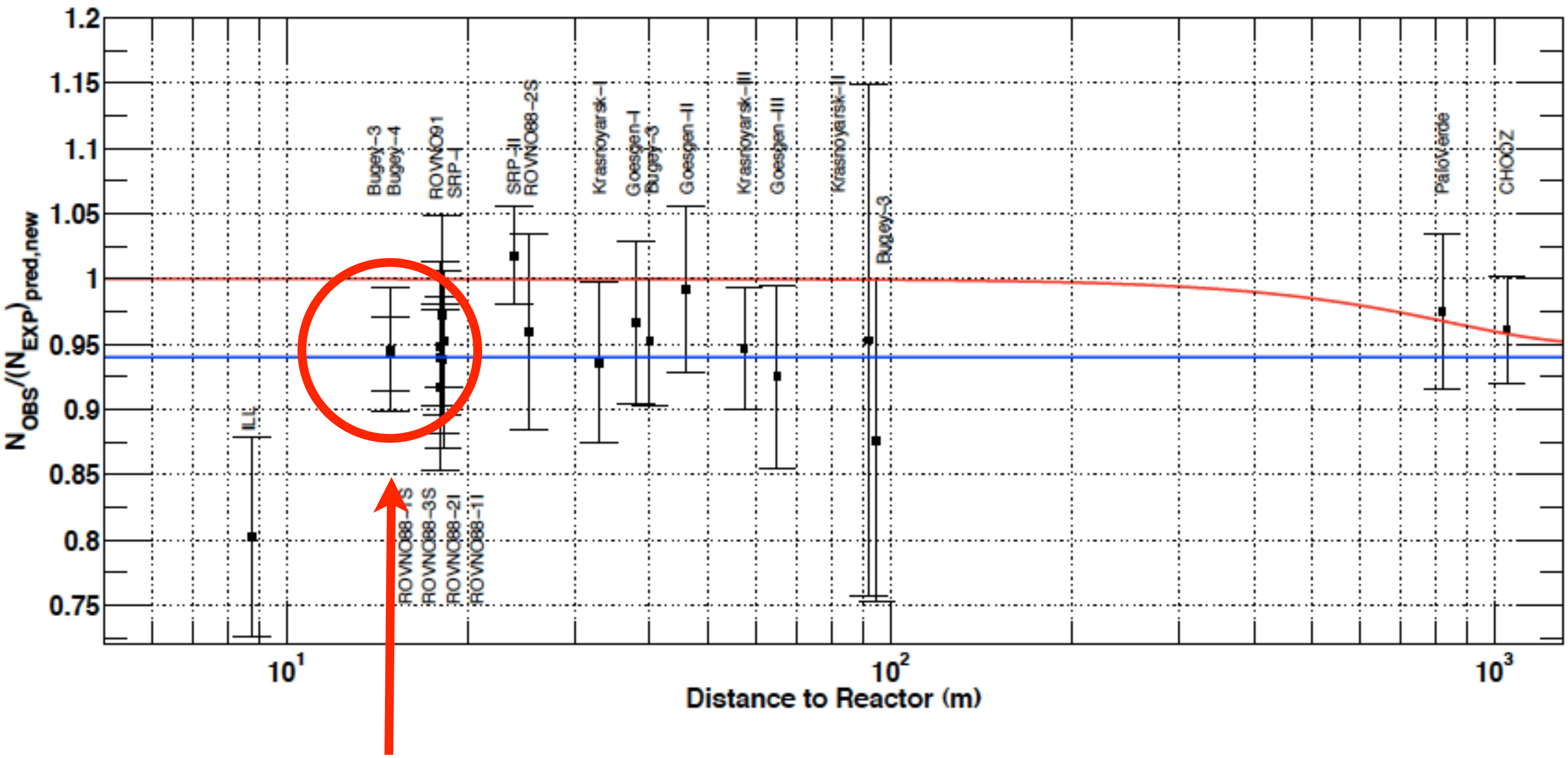
MURE

Fractional Fission Rates

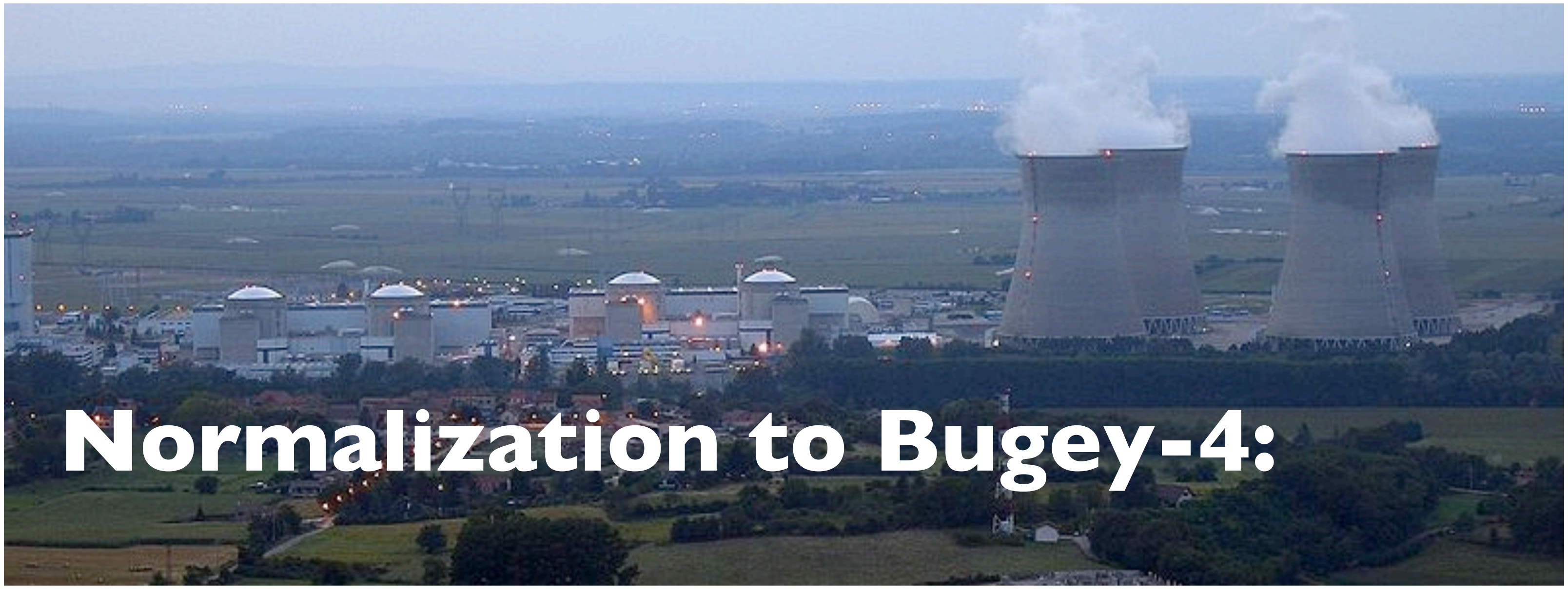
^{235}U	0.496±0.016
^{239}Pu	0.351±0.013
^{238}U	0.087±0.006
^{241}Pu	0.066±0.007



Normalization to Bugey-4:



The experiment with the smallest uncertainty, 1.4%.

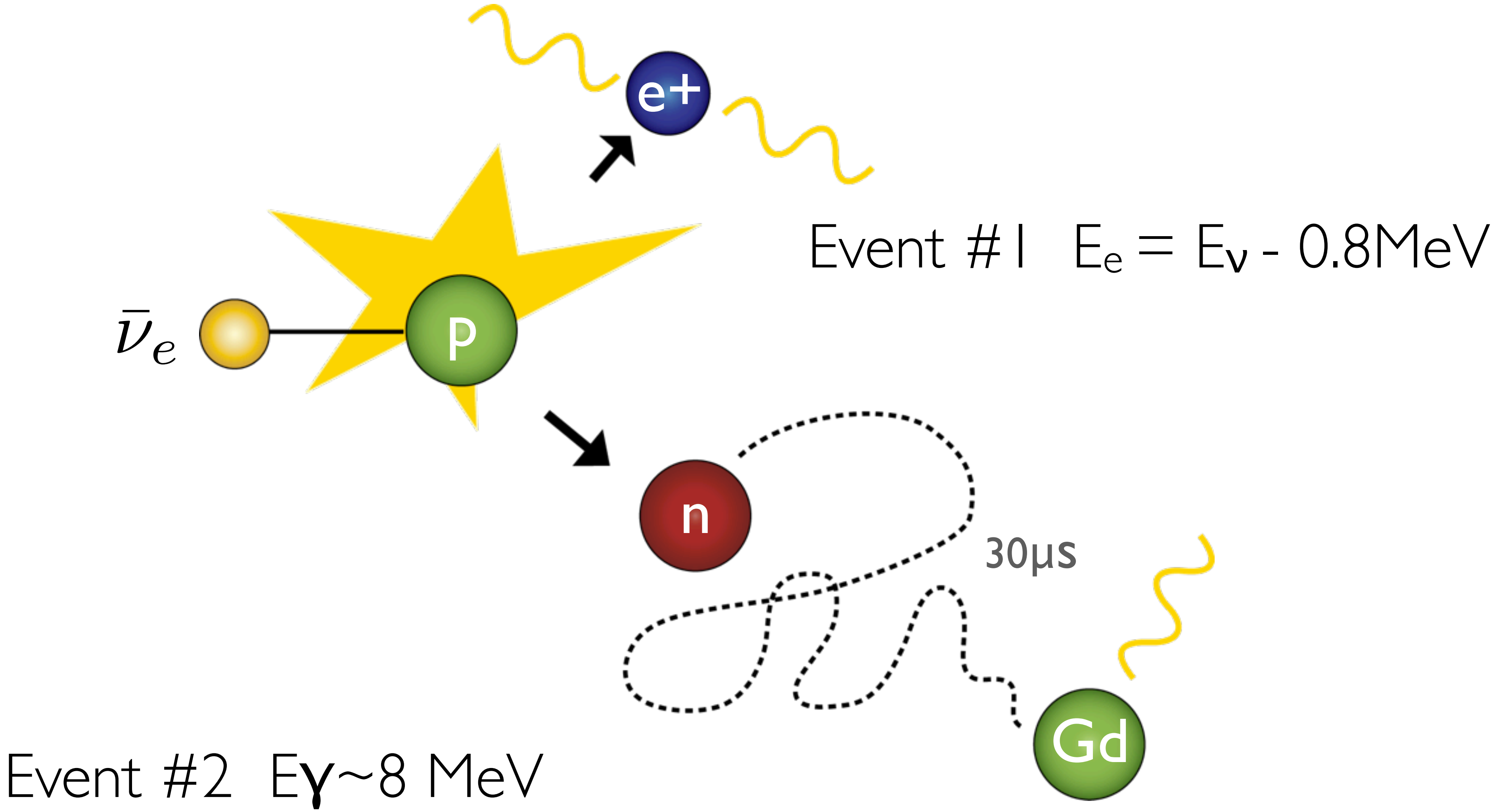


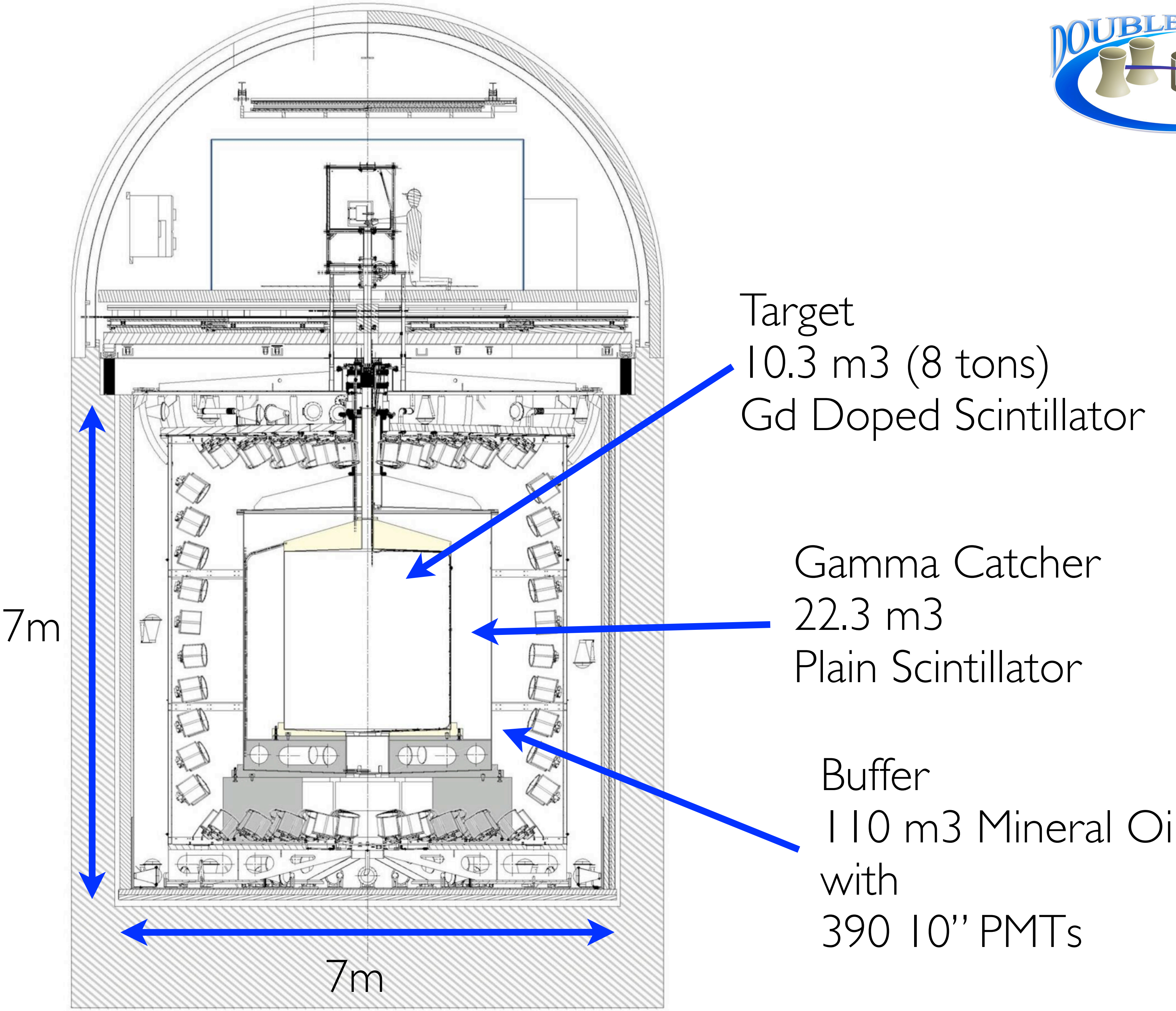
Normalization to Bugey-4:

$$\langle \sigma_f \rangle_R = \langle \sigma_f \rangle^{Bugey} + \sum_k (\alpha_k^R - \alpha_k^{Bugey}) \langle \sigma_f \rangle_k$$

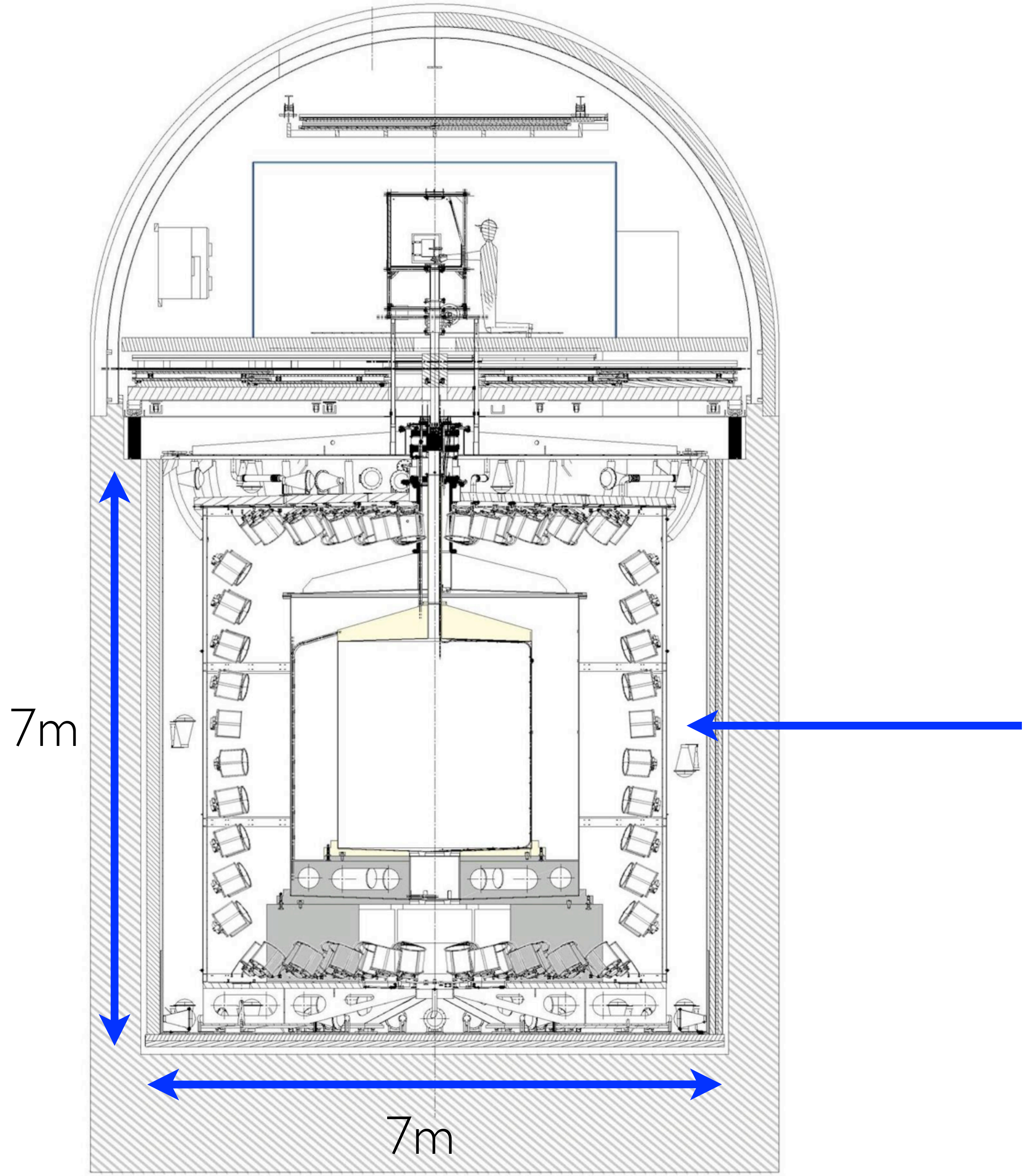
$$N_i^{exp} = \frac{\epsilon N_p}{4\pi} \sum_{R=B1,B2} \frac{1}{L_R{}^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \times \left(\frac{\langle \sigma_f \rangle_R}{(\sum_k \alpha_k^R \langle \sigma_f \rangle_k)} \sum_k \alpha_k^R \langle \sigma_f \rangle_k^i \right)$$

The Signal: Inverse Beta Decay

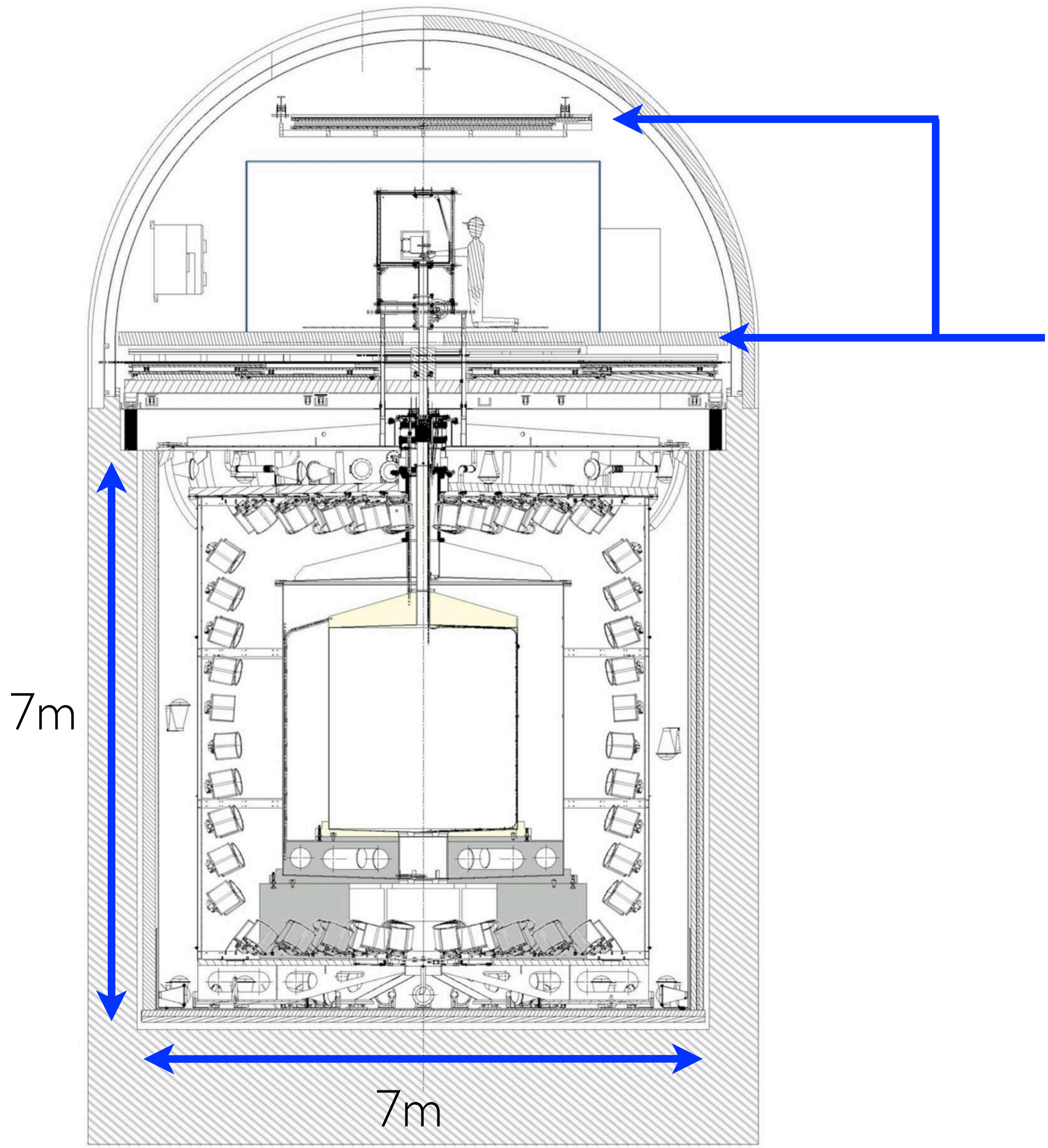




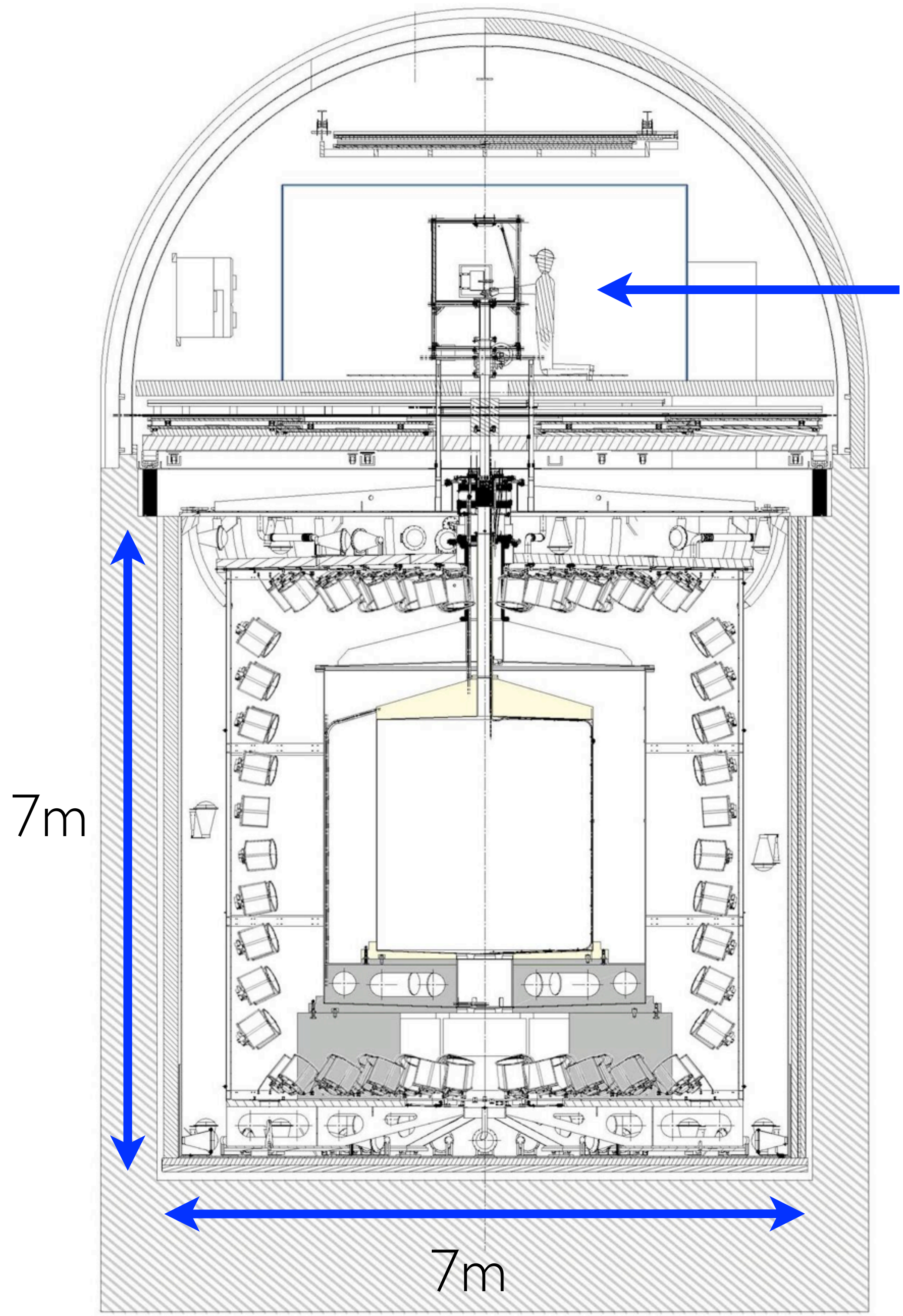
Target
10.3 m3 (8 tons)
Gd Doped Scintillator
Gamma Catcher
22.3 m3
Plain Scintillator
Buffer
110 m3 Mineral Oil
with
390 10'' PMTs
7m
7m



Inner Veto
90 m3 LAB Scintillator
with
78 8'' PMTs



Outer Veto
Precision muon tracking with plastic scintillator readout with fibers and multi-anode PMTs.



Calibration Systems

- Z-Axis
- Guide Tube in Gamma Catcher
- Light Injection (all volumes)
- Buffer Tube
- Articulated Arm

Last November's Result: (DC1stPub)

Phys. Rev. Lett. *108 131801 (2012)*

New Result:
Double the Statistics!
Improved Systematics!

Keep your eye on the ArXiv!

Selecting Antineutrino Coincidence:

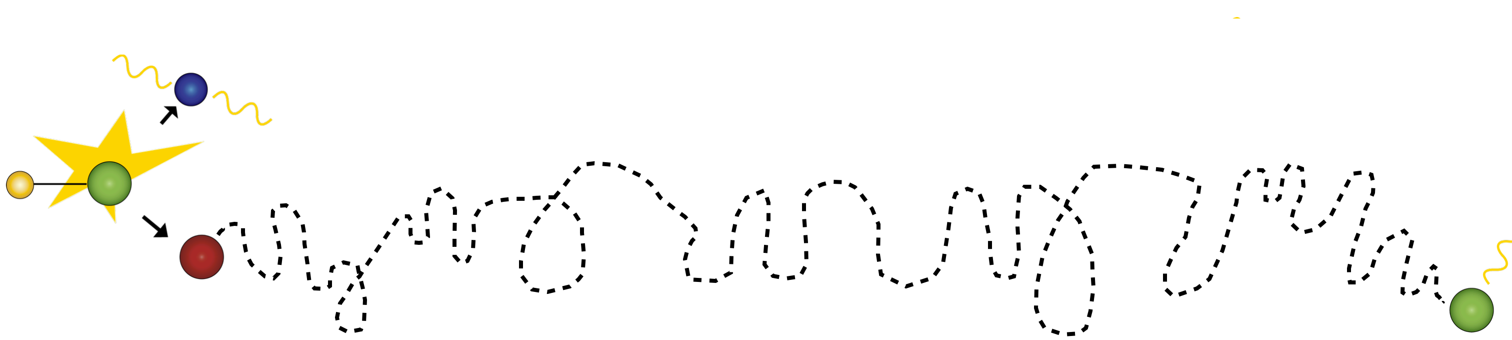
$2\ \mu s < \Delta t < 100\ \mu s$

Event #1

- 0.7 MeV < E < 12.2 MeV

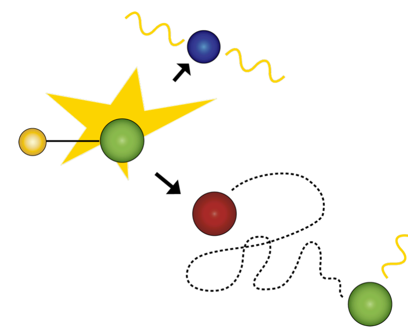
Event #2

- 6.0 MeV < E < 12 MeV



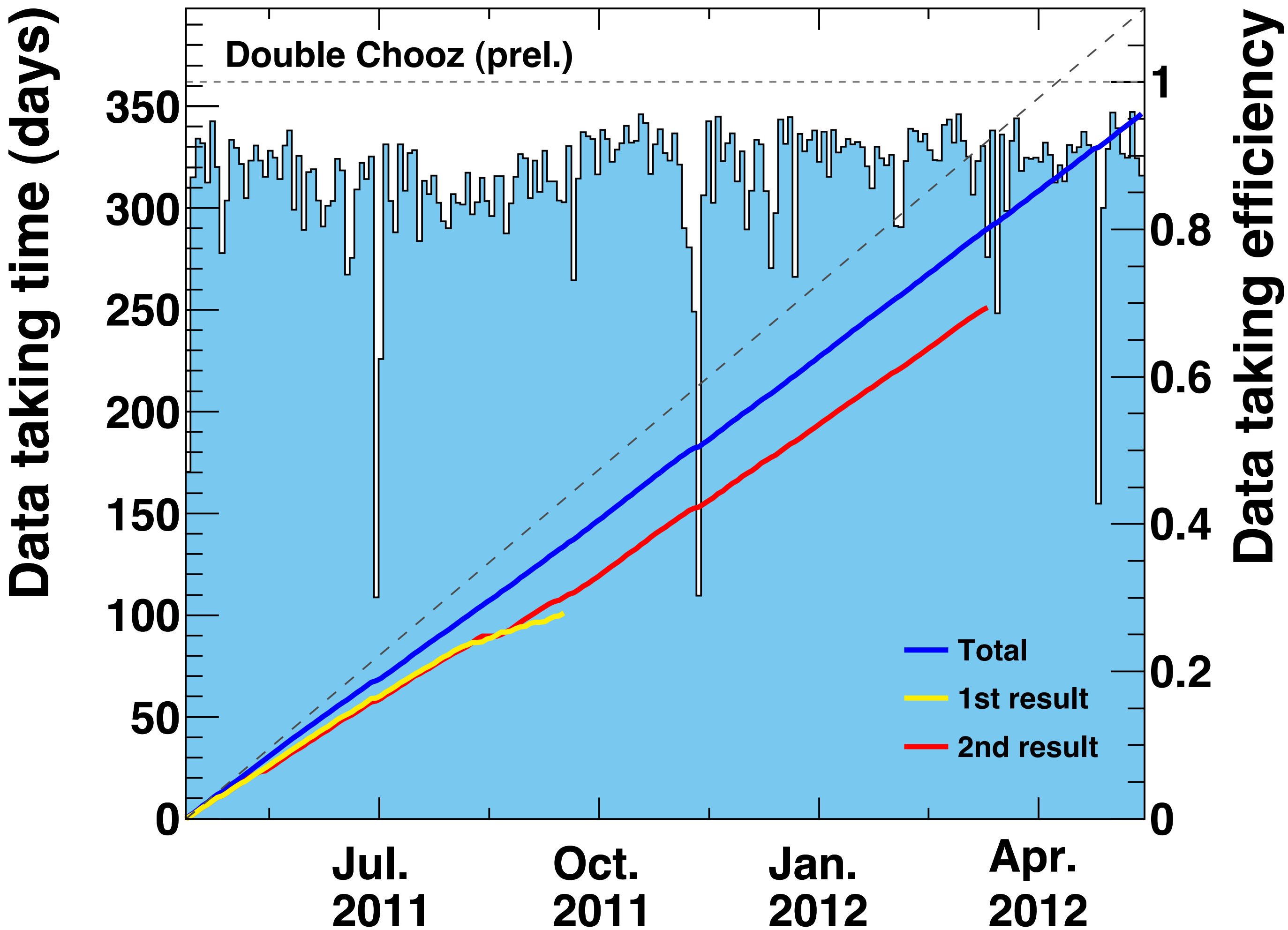
Selecting Antineutrinos General:

- Event Quality Cuts (PMT Light Noise Cuts)
- "Isolation in Time" Cut
- Muon Veto, No coincident IV signal.
- Muon Veto, 1ms following muon event.
- Muon Veto, 500 ms following high energy muon event (> 600 MeV deposited).
- Muon Veto, No coincident OV signal.



These are new and reduce muon related backgrounds!

Collecting Data Since April 13, 2011...

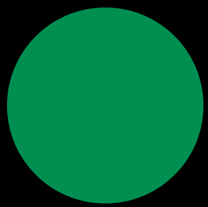


*We see **8249** neutrino candidates in **227.9** live days.*

Remember:
Reactor Experiments are antineutrino disappearance experiments.

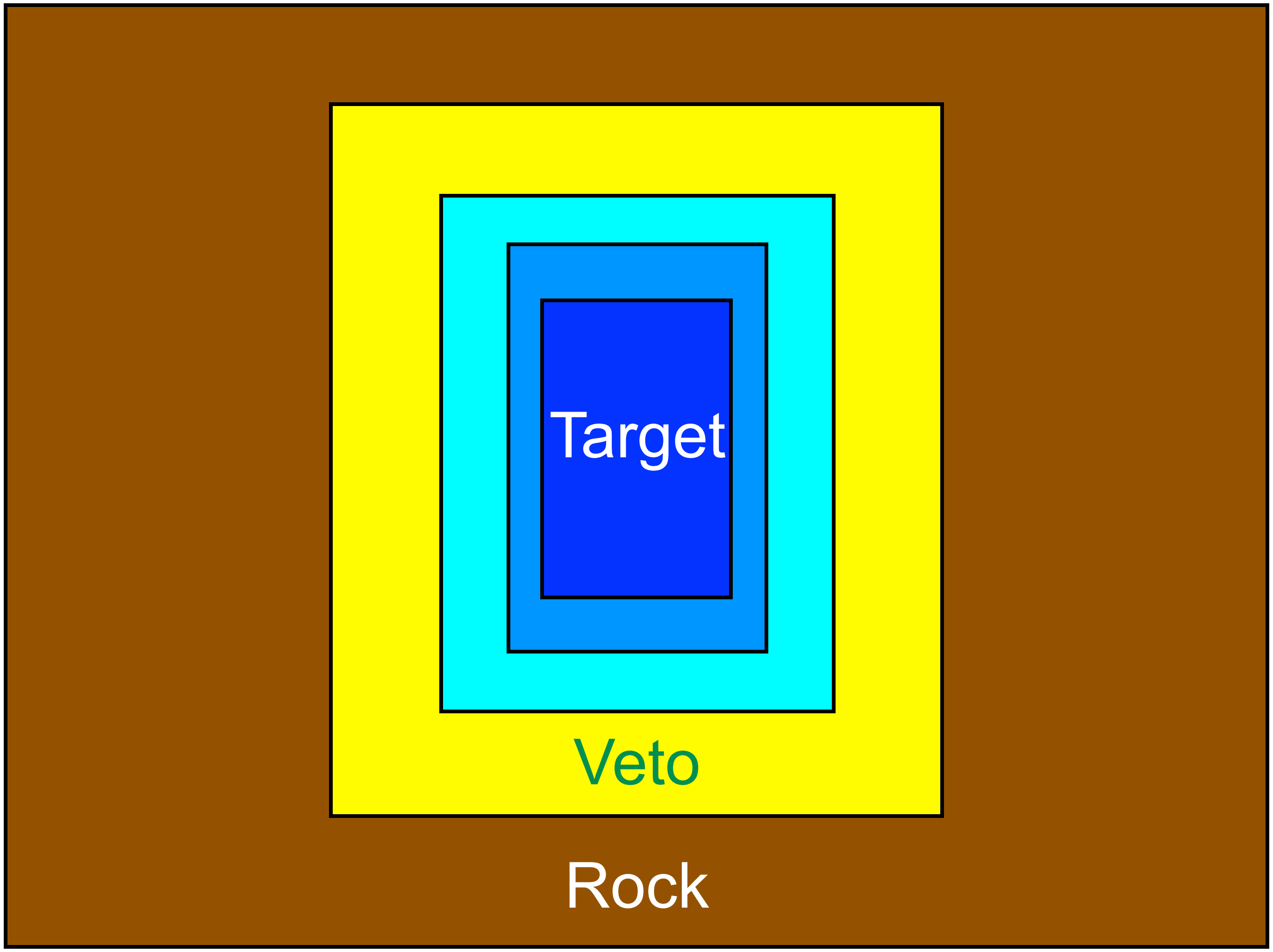
→Background subtraction is key.

Neutrons Neutrons Neutrons

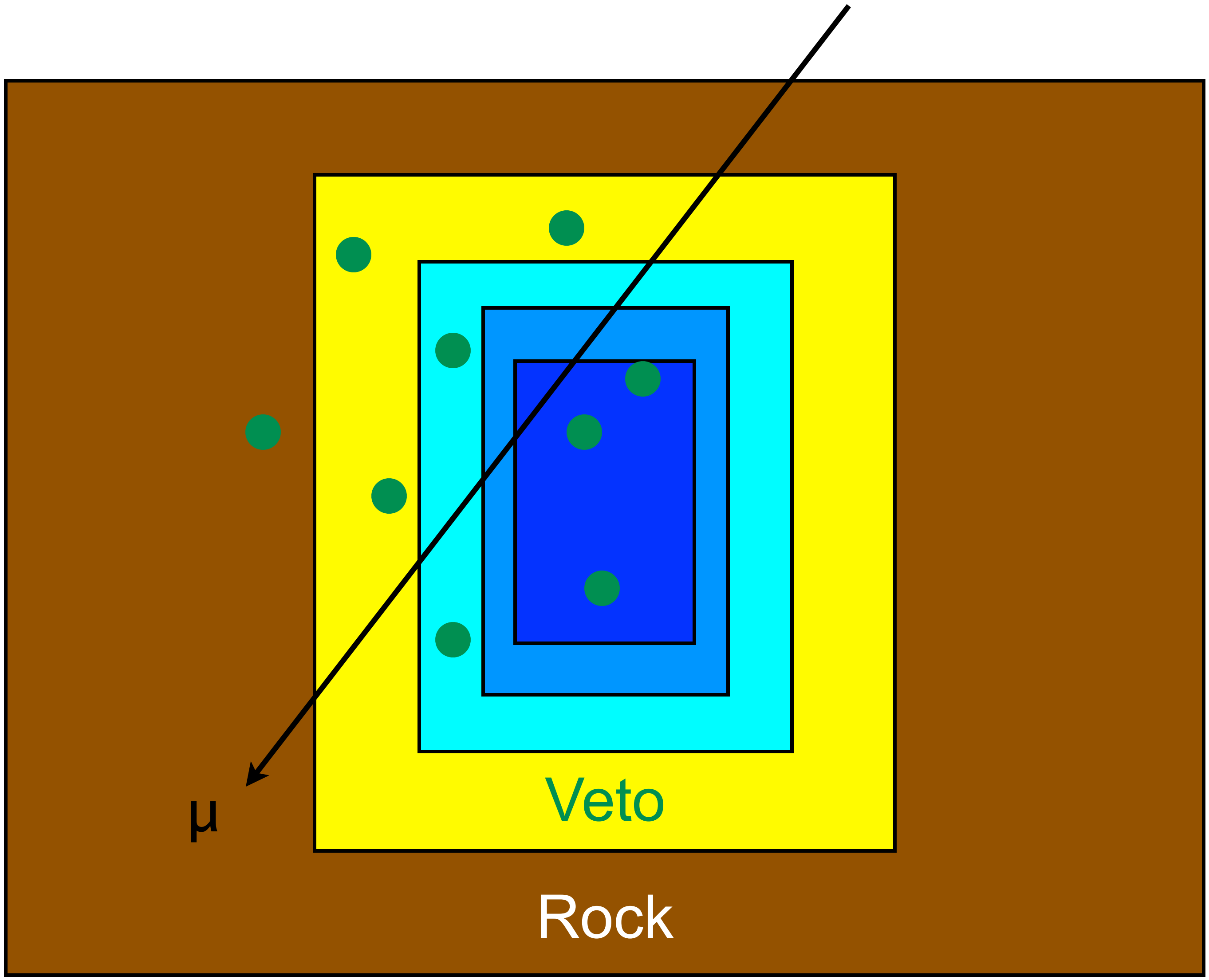


Neutrons Neutrons Neutrons

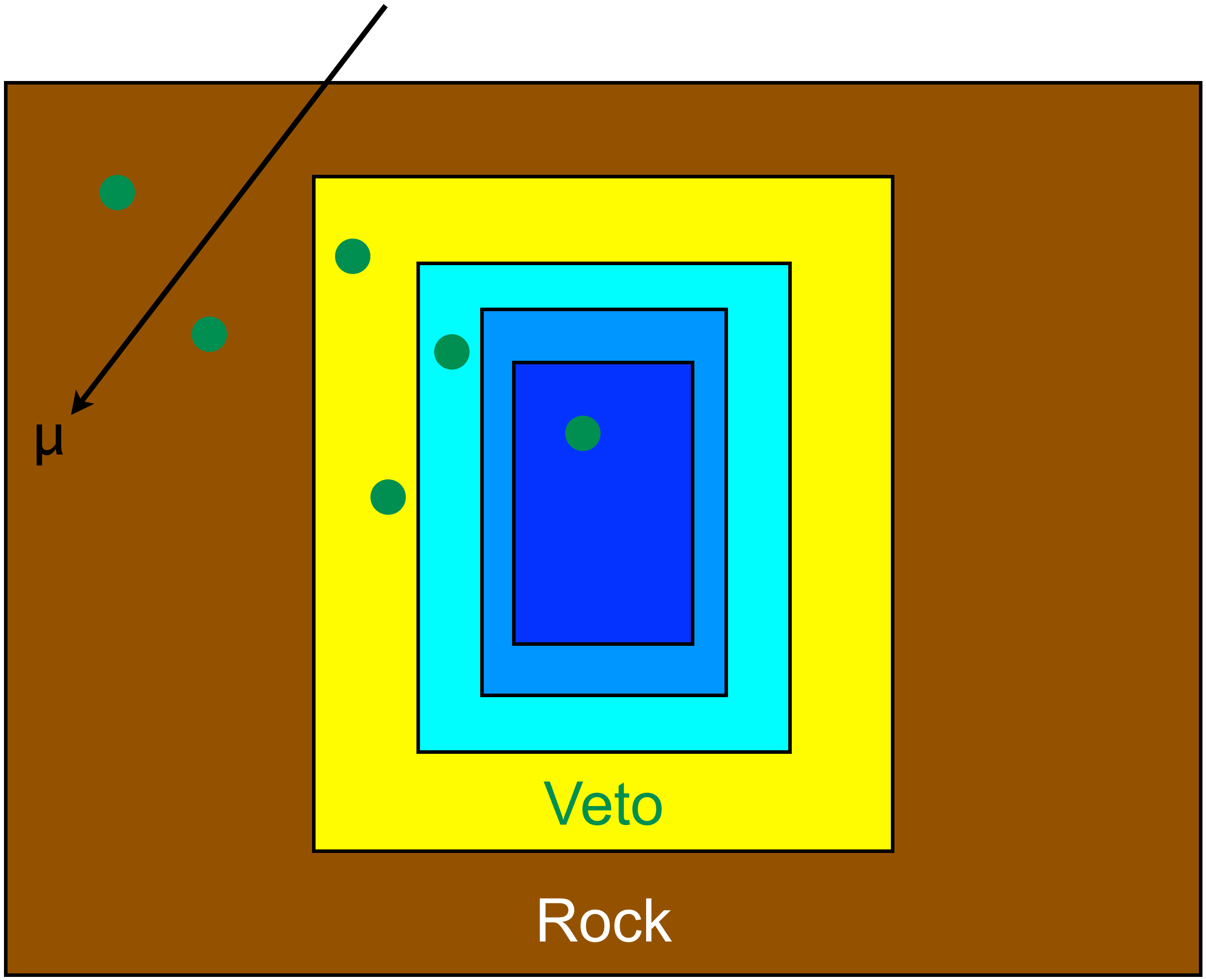
Some Basic Diagrams:



These neutrons we can veto...



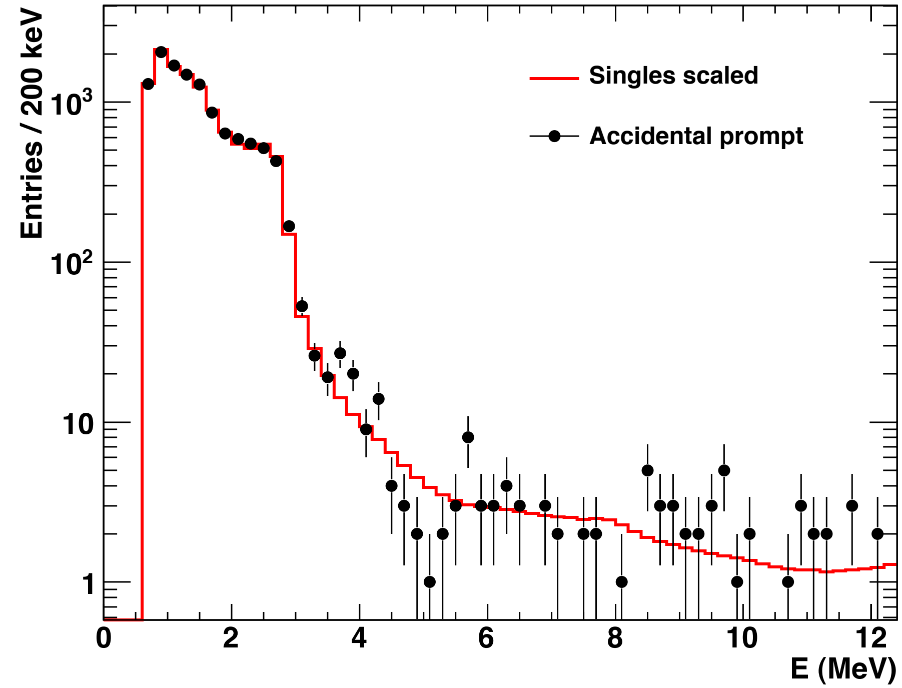
Muons Passing through the Rock:

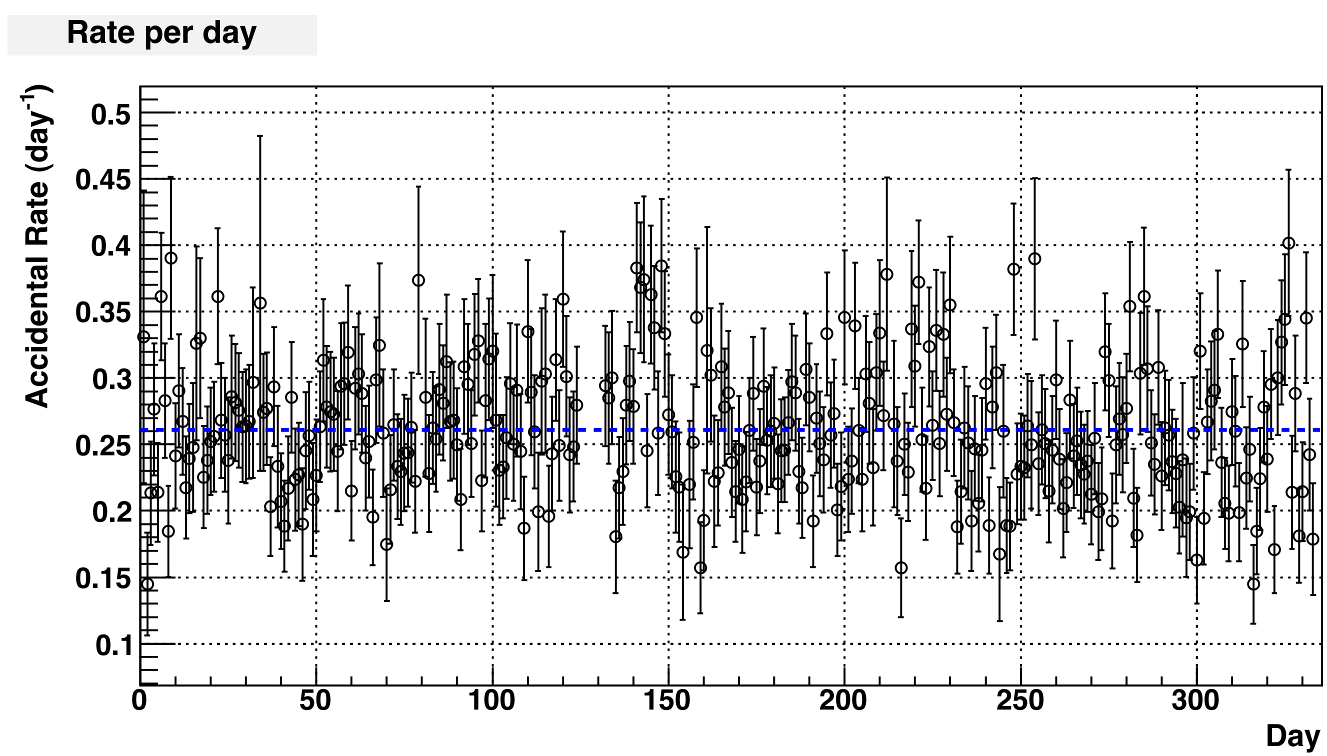


These create two kinds of backgrounds: accidental and fast neutron.

Accidental Coincidences:

R = 0.261±0.002 events per day

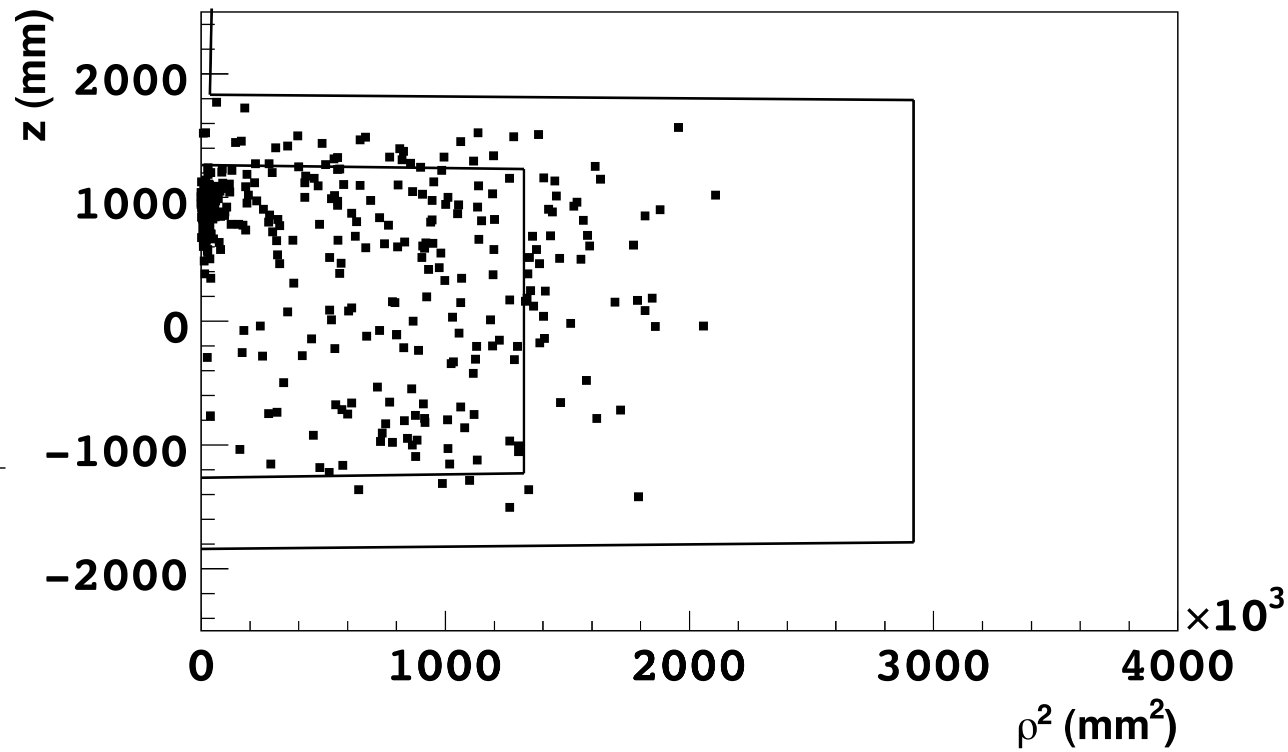


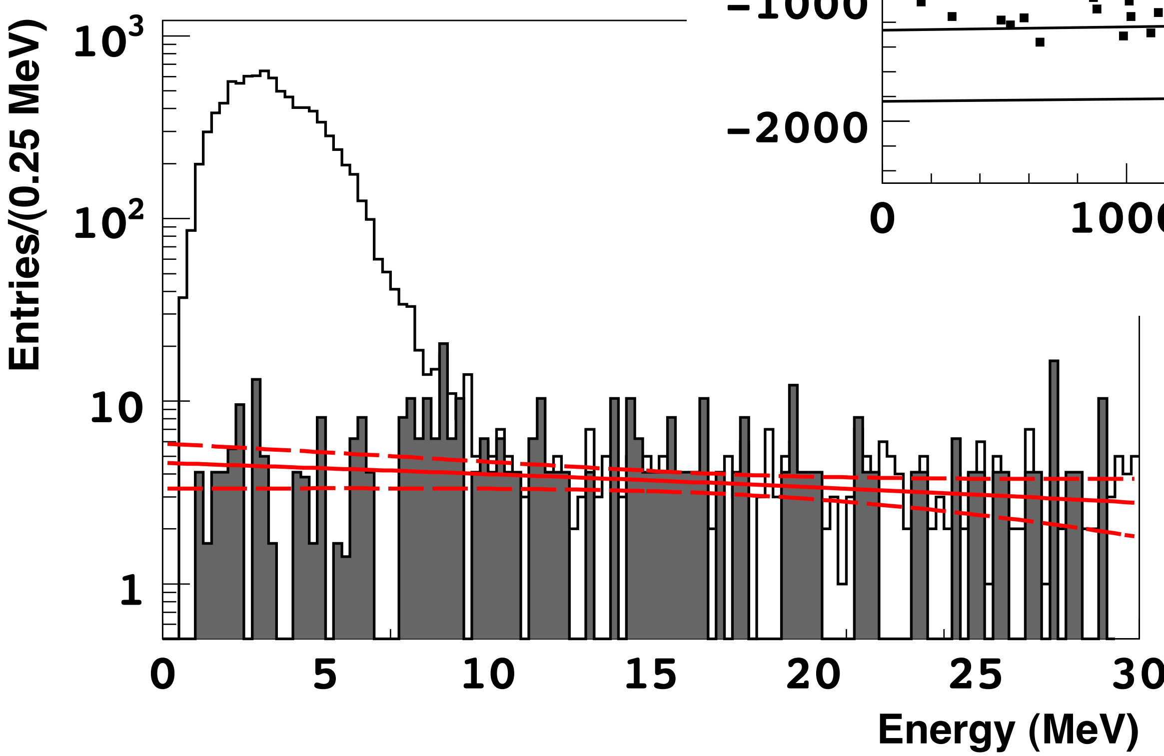


Fast Neutron and Stopped Muons:

R = 0.67±0.20 events per day

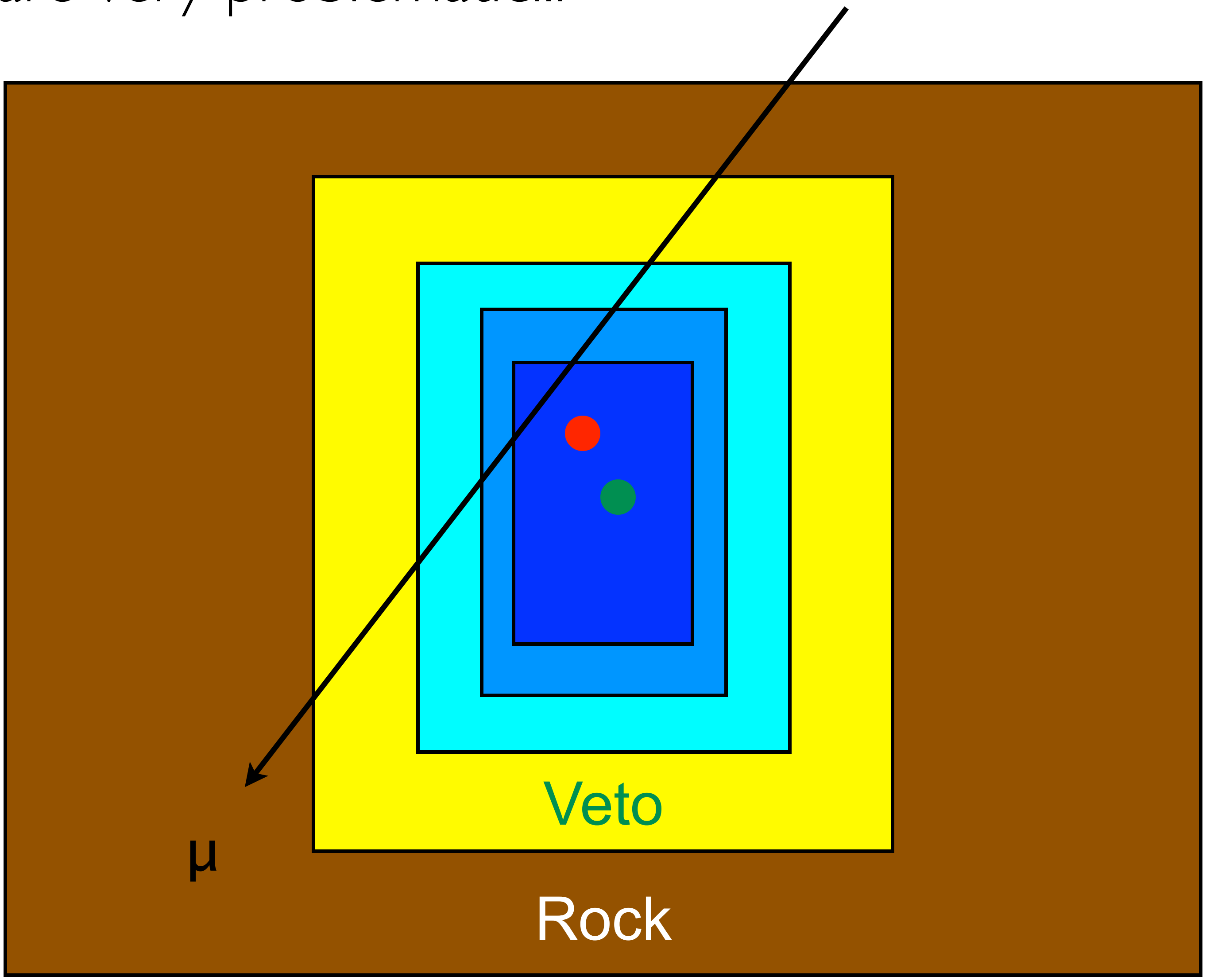
Fast neutrons are attenuated the center of the detector while stopped muons come down the chimney.





Prompt Event energy extends beyond reactor antineutrino spectrum.

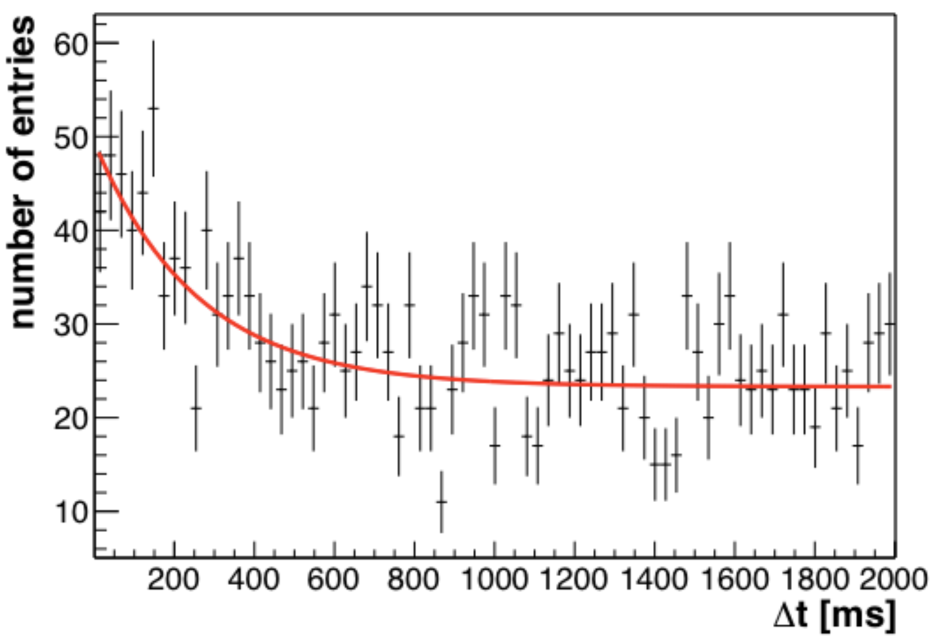
These are very problematic...



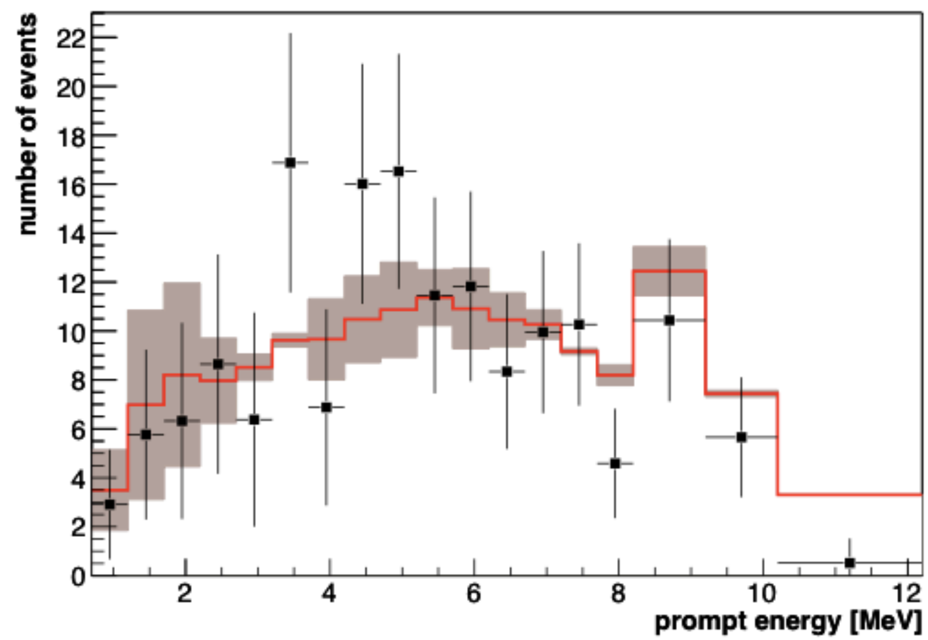
In addition to neutrons, muons can produce light isotopes. ^{9}Li and ^{8}He decay through β-delayed neutron emission.

^{9}Li Decay:
$R = 1.25 \pm 0.54$ events per day after muon vetoes.

Time to >600 MeV deposited Muon



Background Subtracted Energy Spectrum

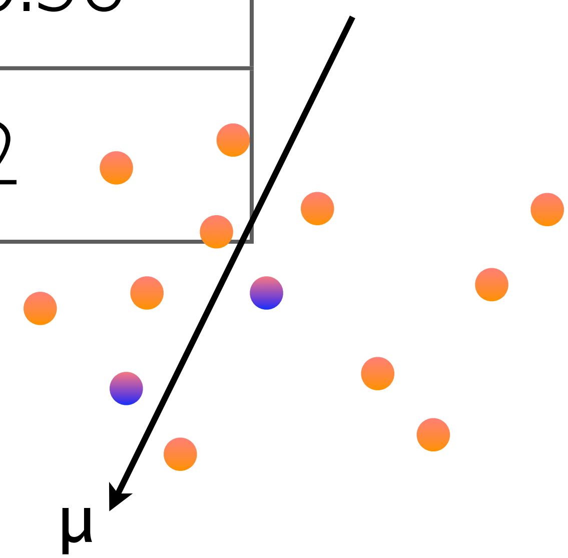


Without the high energy muon veto would have been $R = 2.05 {+0.62} {-0.52}$ events per day.

Background Summary:

	Events per Day
^{9}Li	1.25±0.54
Fast-N + Stopped Muons	0.67±0.20
Accidental	0.261±0.002
Total	2.13±0.58
Candidates	36.2

We have 1.6% uncertainty due to the backgrounds, but they can be constrained in a Rate + Shape analysis.

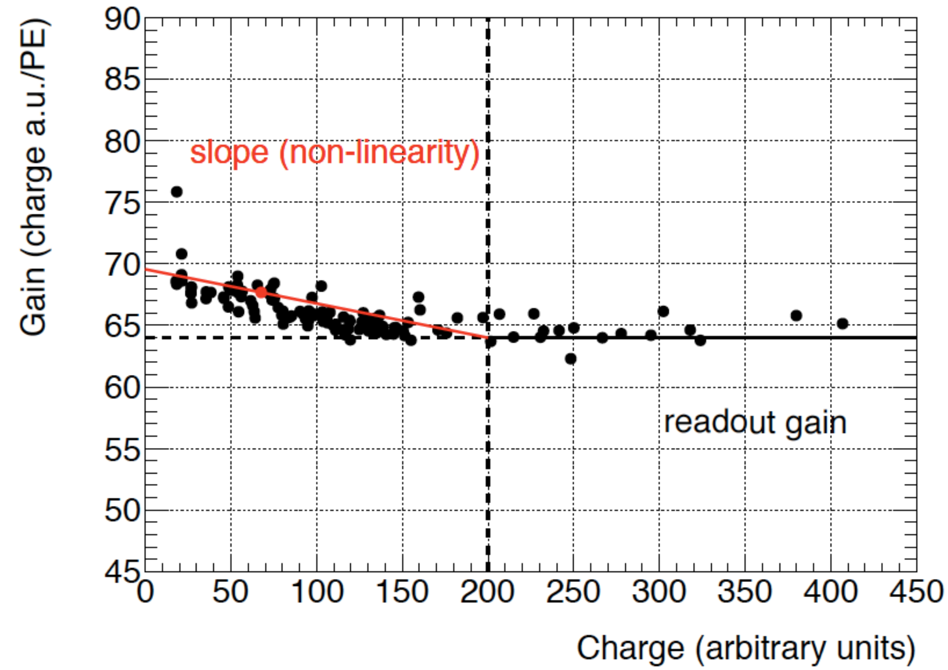


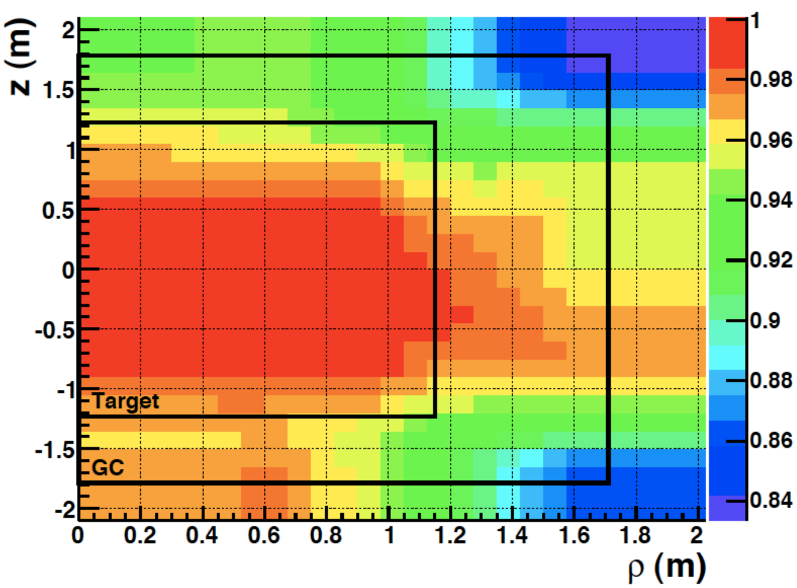
Statistics 1.1% (1.6%)
Reactor 1.7%
Backgrounds 1.6% (3.0%)
Detector 1.0% (2.1%)

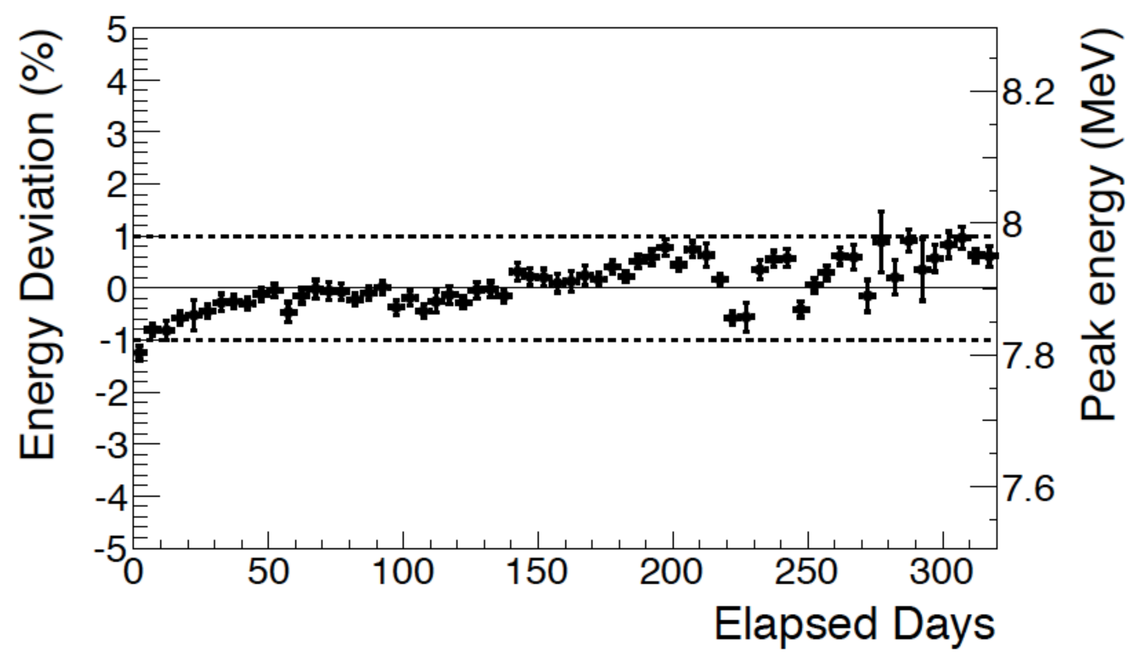
(compare to DC1stPub)

Energy Scale Improvements:

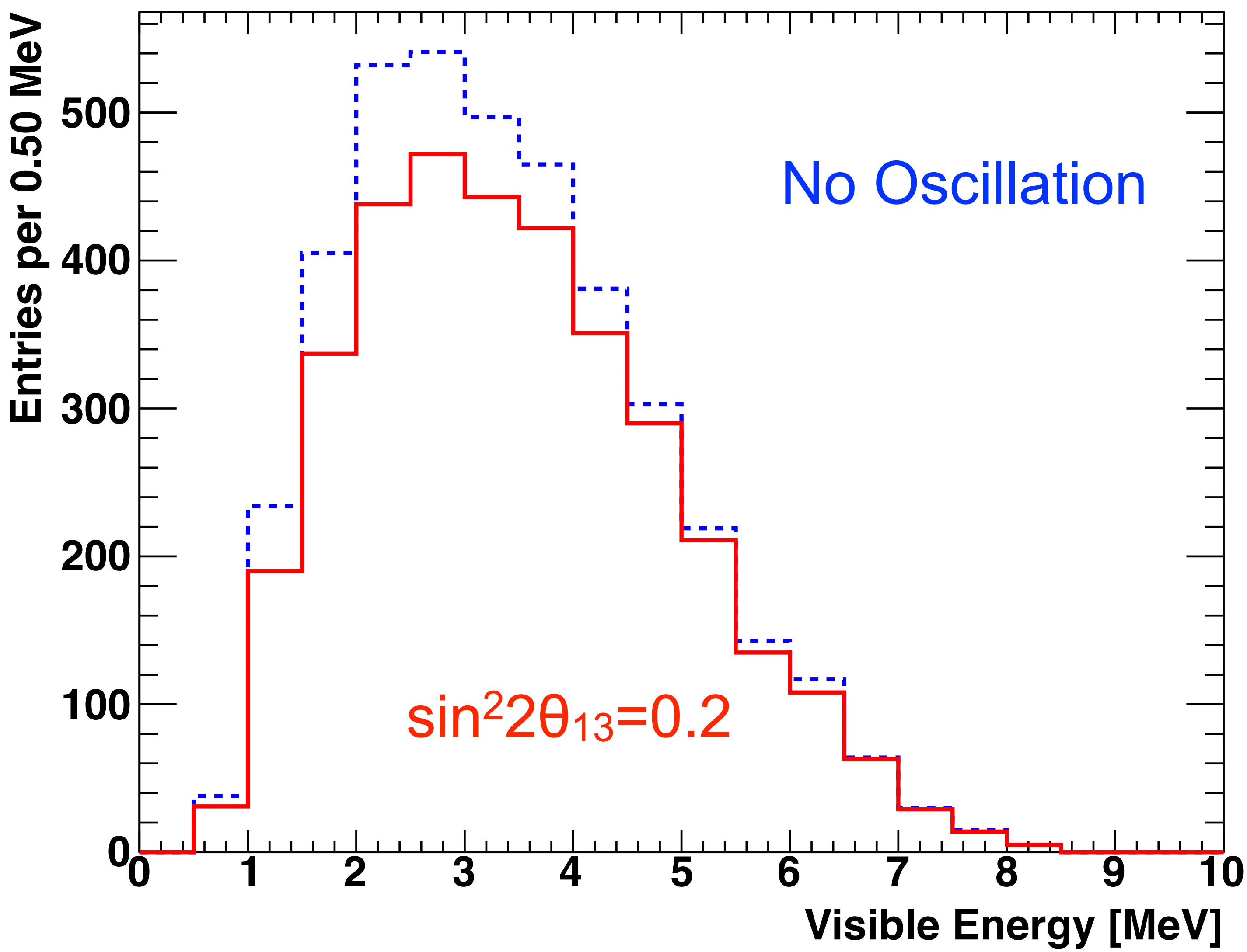
LED calibration system used to correct electronics non-linearity, and neutron capture maps to correct position dependence.







Example Prediction:



This analysis uses rates, energy information and two periods (1 reactor and 2 reactor).

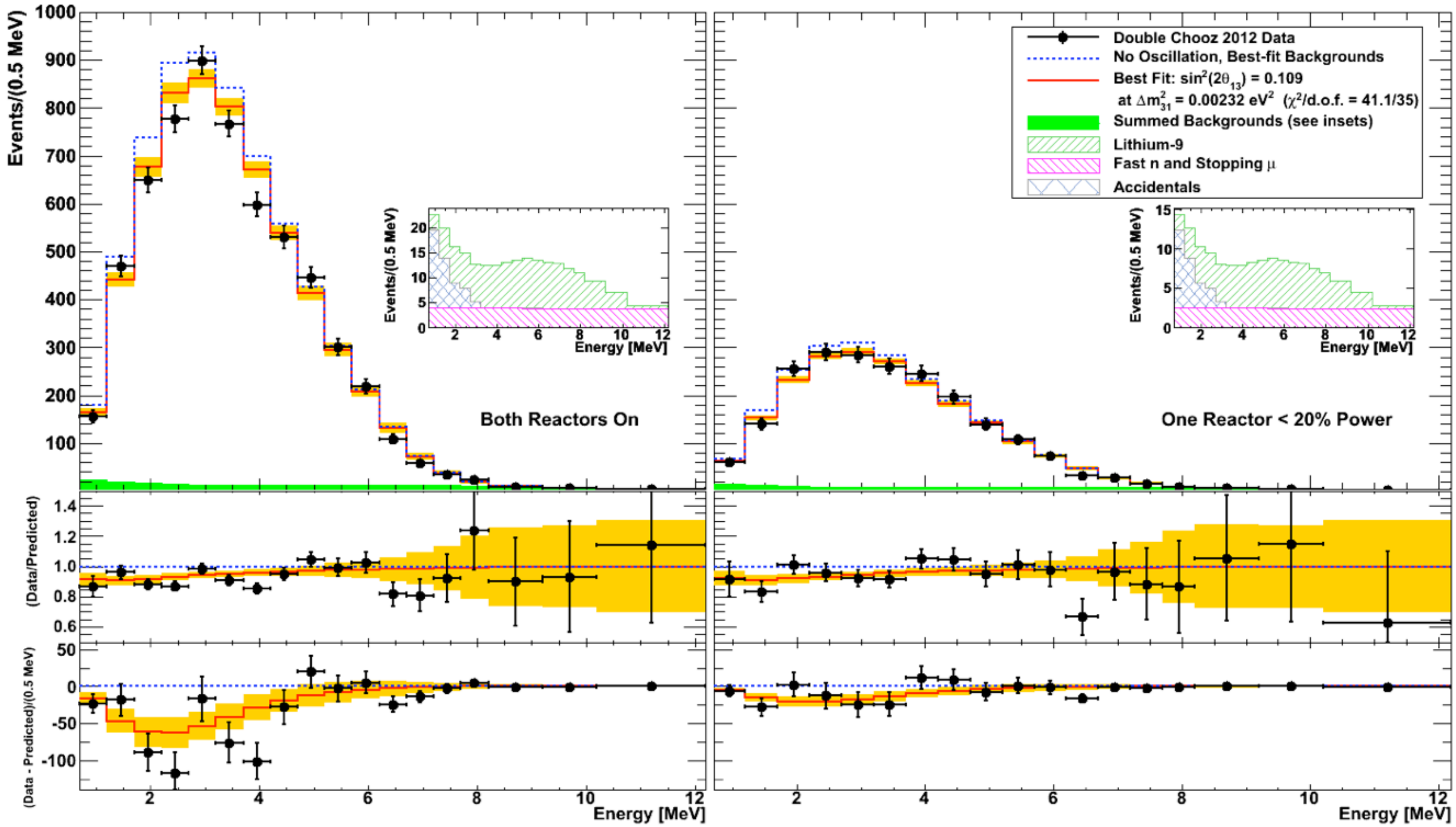
Rate Only:

$\sin^2 2\theta_{13} = 0.170 \pm 0.035(\text{stat}) \pm 0.040(\text{sys})$

Rate + Shape

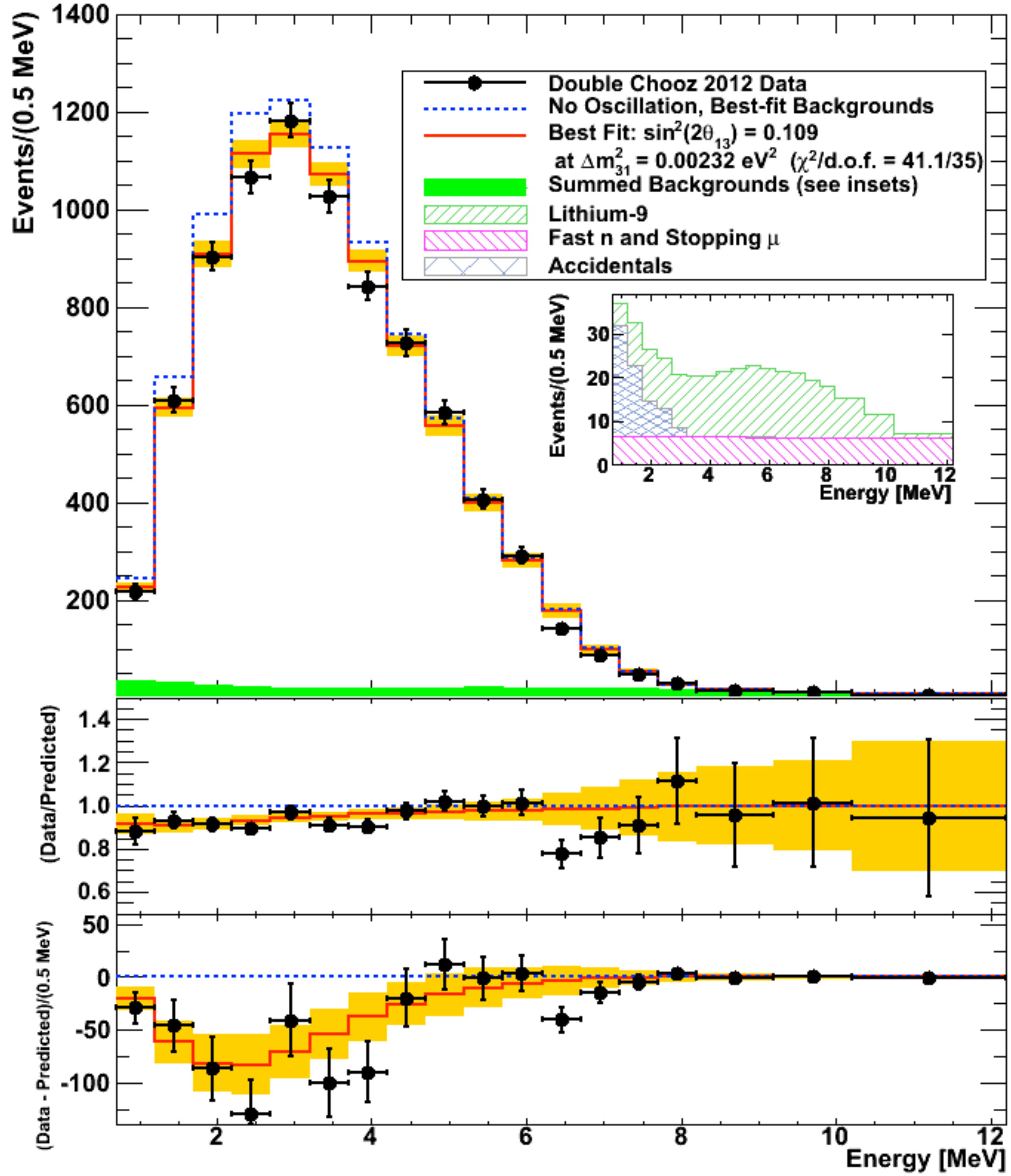
$\sin^2 2\theta_{13}$ = 0.109±0.030(stat)±0.025(sys)

χ^2/NDF = 42.1/35



$\sin^2 2\theta_{13} > 0$ at 3.1σ !

Examining all of the data together.

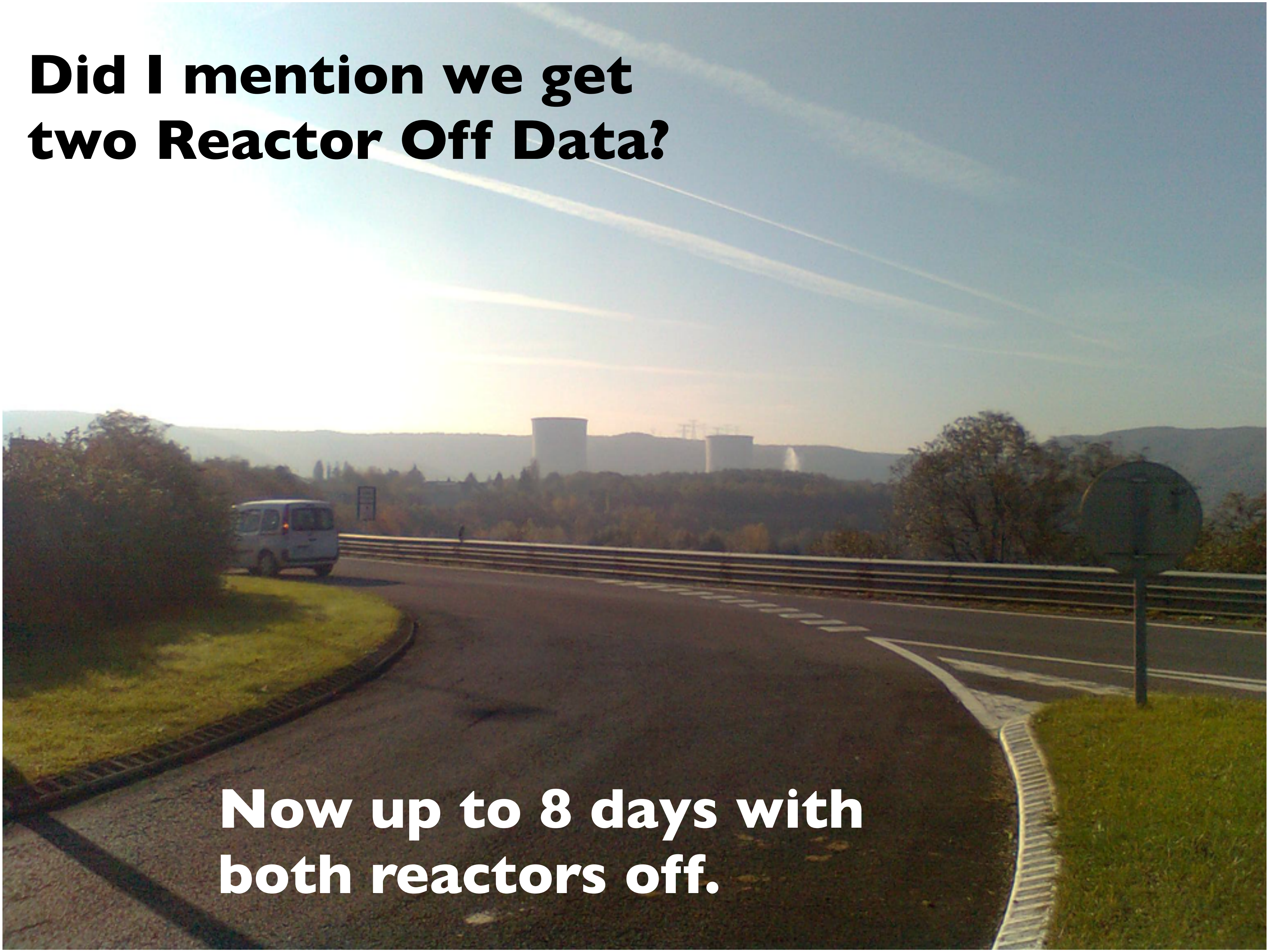


Moving Forward!

Continued Analysis Work:

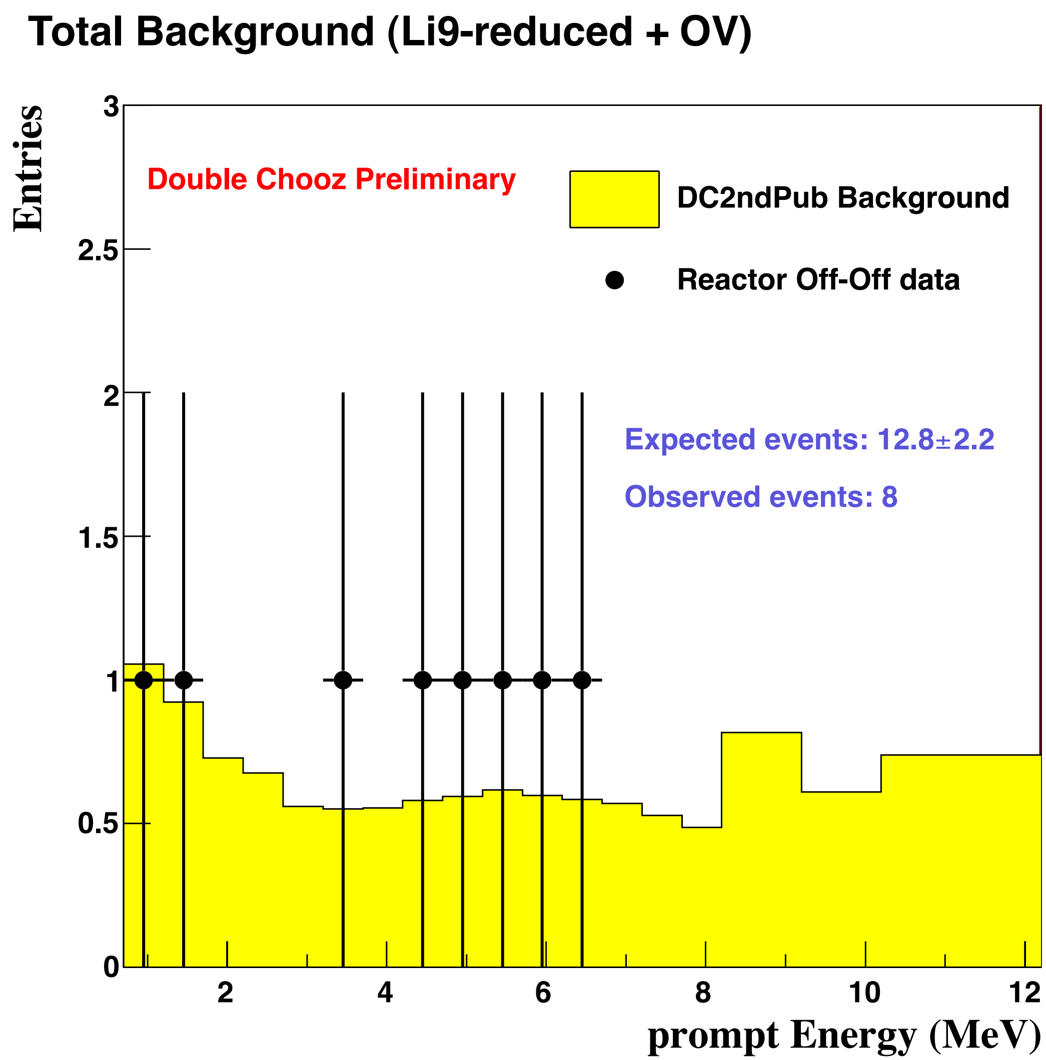
- More Data
- Continue to work on energy response model
- Reactor model improvements
- Add hydrogen captures to analysis
- Improve background estimates

Did I mention we get two Reactor Off Data?



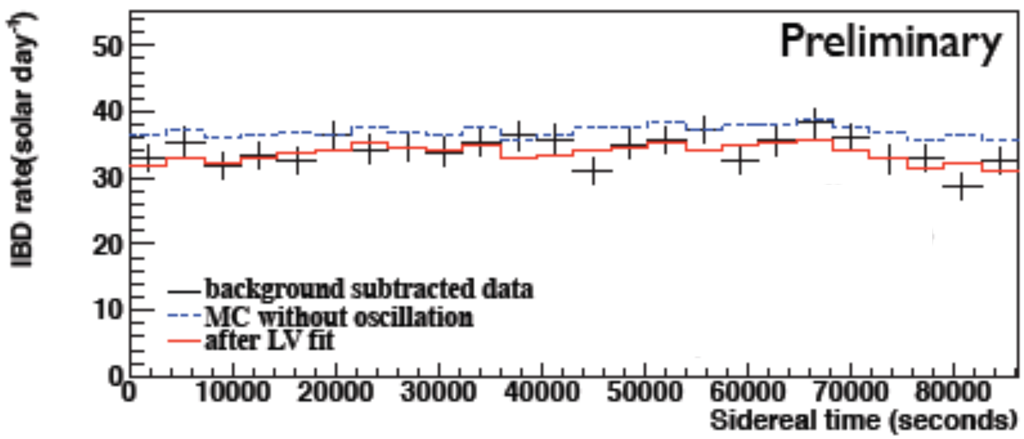
Now up to 8 days with both reactors off.

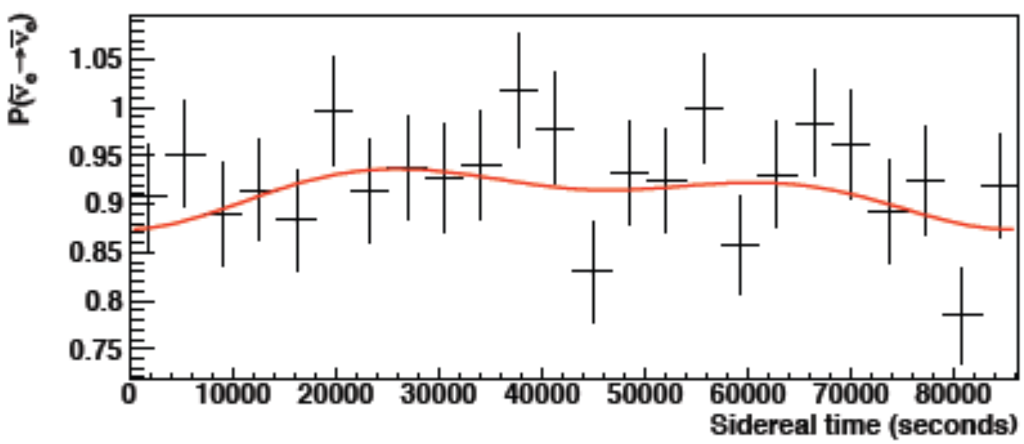
After analyis cuts in 6.84 days of live time observed 8 events. → Nice agreement with 12.8±2.2 predicted for this period.



Test Result Stability in Time....

And look for Lorentz Violation.



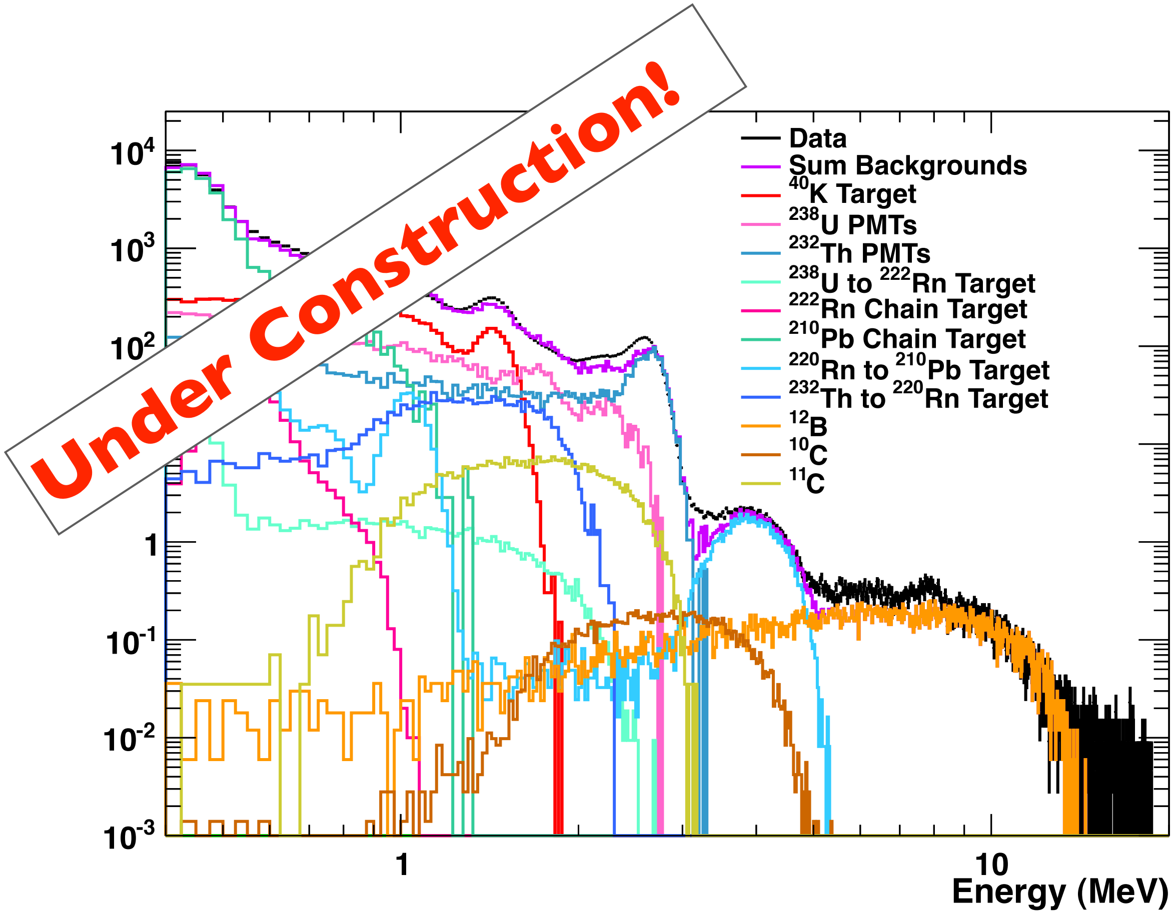


Lorentz violation in the neutrino sector implies the universe has a preferred direction. You can look for its effect by examining the oscillation probability as a function of sidereal time.

See Kostelecký and Mewes PRD70(2004)076002

Strong limits for $\nu_e \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$; however, there is an opportunity to observe $\nu_e \to \nu_\tau$ in reactor experiments.

Test Energy Response and Background Levels....



...and look for Double Beta Decay.

^{160}Gd is a double beta decay candidate with an endpoint of 1.72 MeV. Double Chooz has the potential to improve the current limit if background levels, especially those from U/Th are not too high.

Near Detector Under Construction:

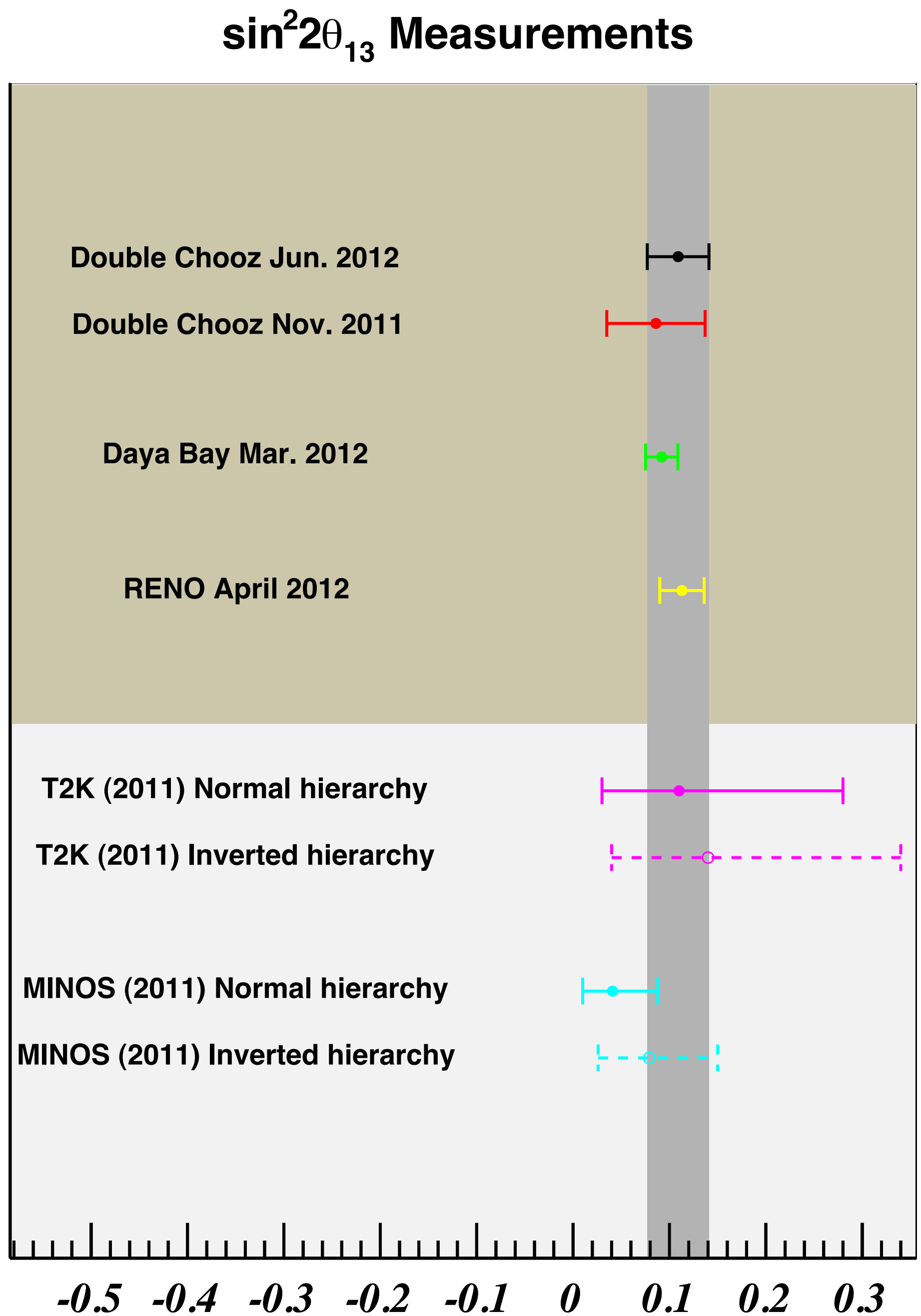
Completed by the end of 2013.

Conclusions:

- Double Chooz updates its ***rate*** and ***shape*** analysis with improved statistics and systematics.

- Double Chooz excludes null oscillation hypothesis at 99.9% (3.1σ).

- Double Chooz's simple reactor configuration allows for unique analyses.

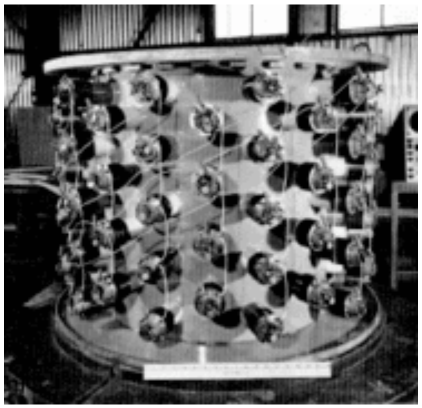


The Chooz Goes On!

More Slides

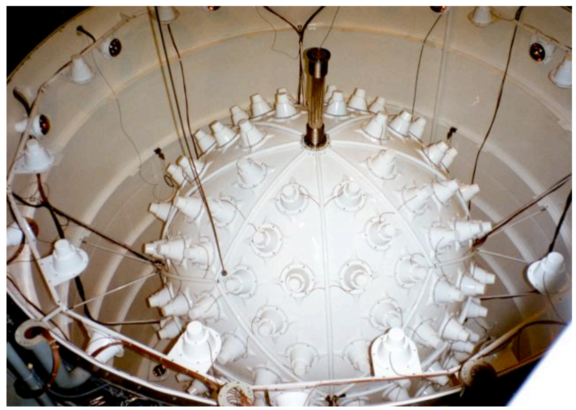
A long history of reactor experiments...

Poltergeist



1956

Chooz

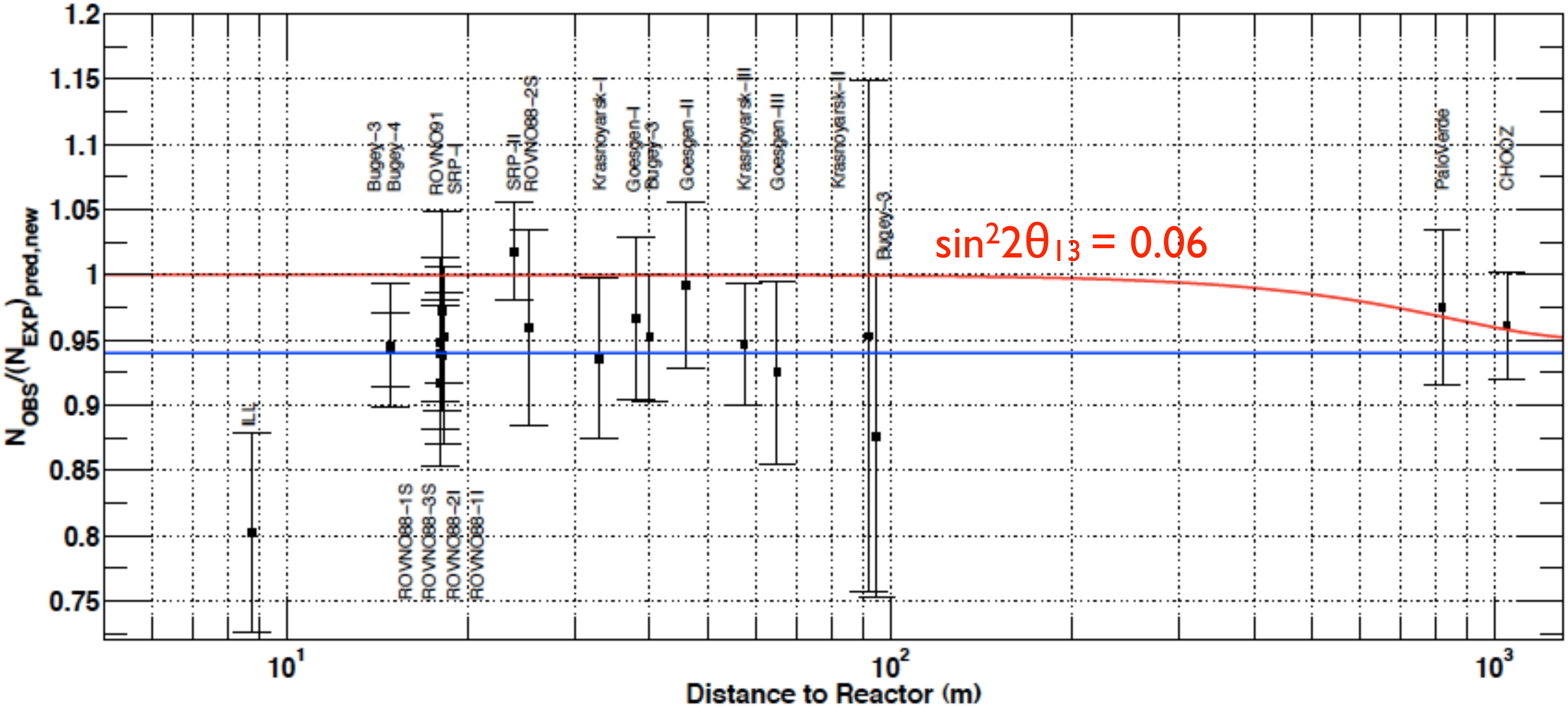


1999

KamLAND

2002

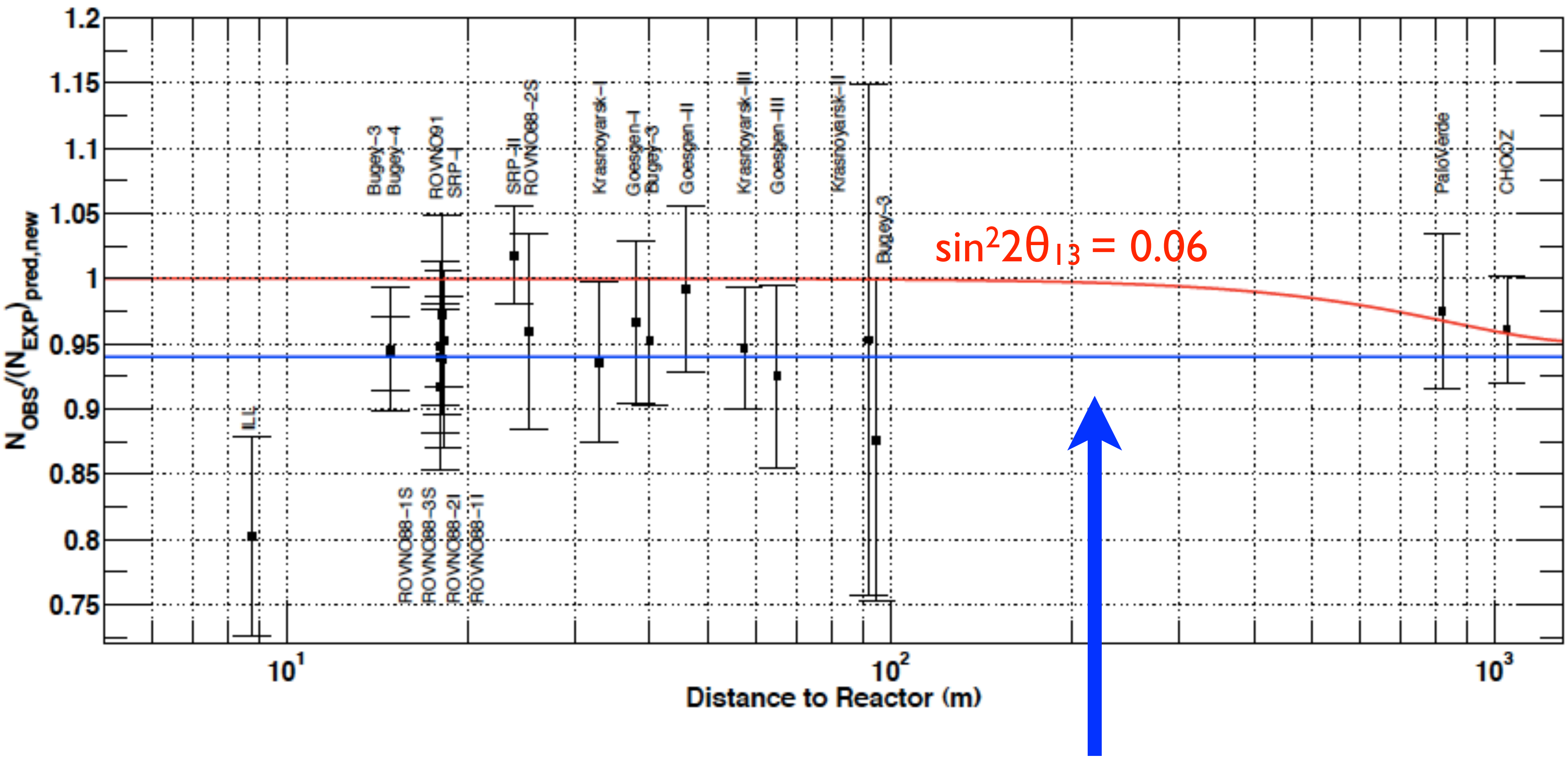
The Re-Analysis of the Spectra:



All the experiments are now low.

See Phys.Rev. D83 (2011) 073006

The Re-Analysis of the Spectra:



Sterile Neutrino at ~1eV^2?

See Phys.Rev. D83 (2011) 073006