Reactor Neutrinos

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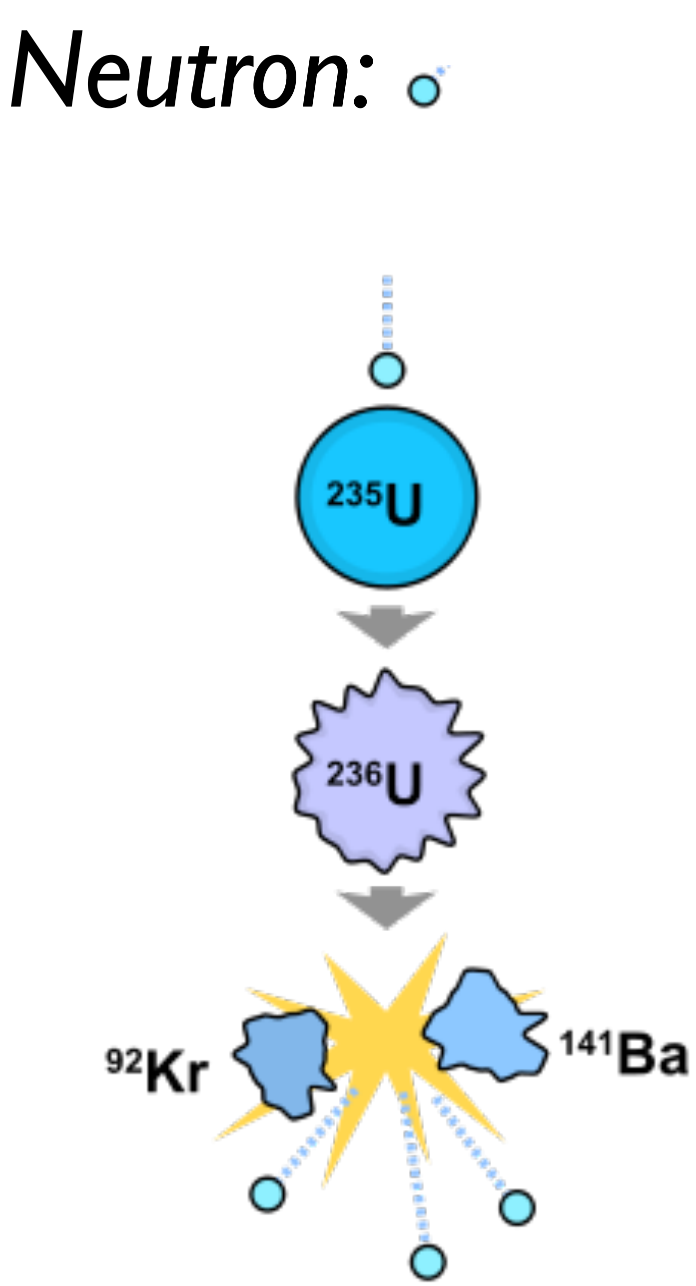
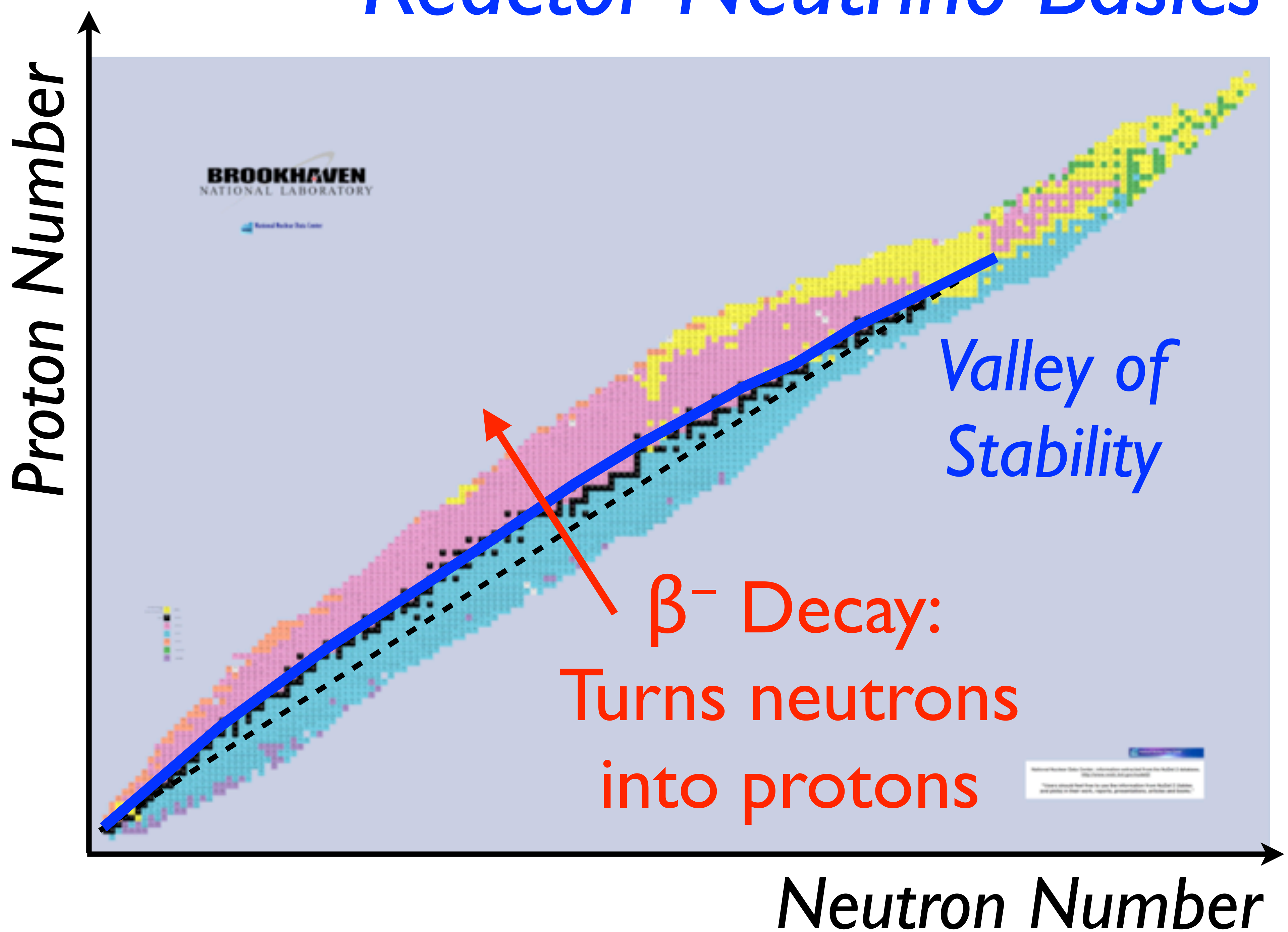
Plan for this Lecture

- How do nuclear reactors produce neutrinos? What kind of neutrinos? How many?
- Neutrinos are difficult to detect. What are the special problems? How do we deal with them?
- What is the physics behind detection of reactor neutrinos? What are the techniques?
- Many of us are interested in reactor neutrinos because they can be used to answer fundamental questions. What is some of this current research?

Reactor Neutrino Basics



Schematic of the fission process



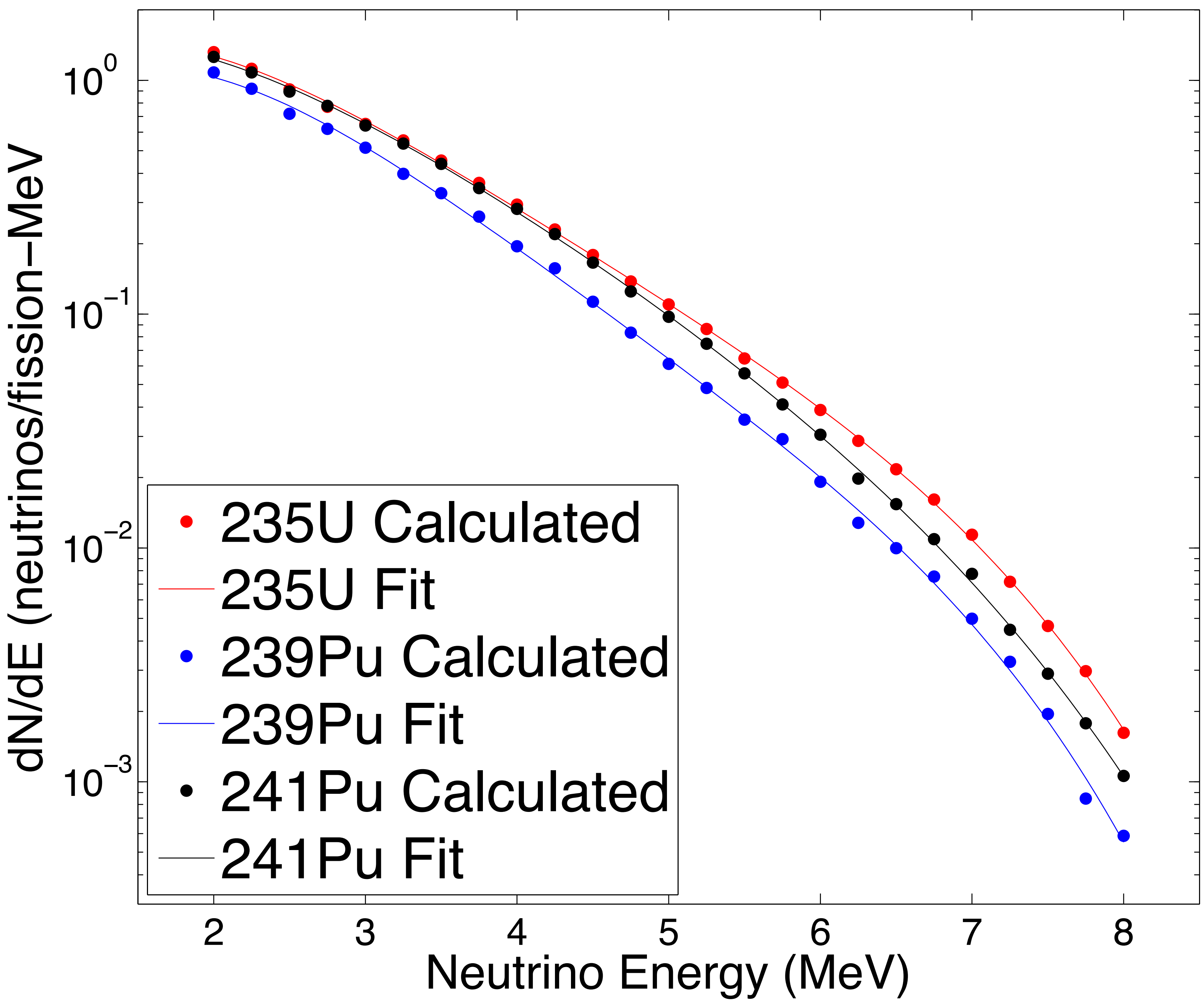
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

...so we learn the following:

- We see, therefore, that nuclear reactors are a source of "electron anti-neutrinos", i.e. $\overline{\nu}_e$
- Several beta decays needed to return the fission fragment isotope to the "valley of stability"
- Nuclear power reactors are <u>intense</u> sources of electron antineutrinos
- Precise calculations of the antineutrino intensity and spectral shape are <u>challenging</u>.
  - Additional difficulty: Fuel evolution in the core

Calculating Reactor Spectra

Recent Example: P. Huber, Phys. Rev. C84(2011)024617



Remember: A real experiment must take into account how the fission isotopes evolve over time in the reactor core!

Exercise

Estimate the neutrino flux from a 4GW power reactor.

Assume that ^{235}U (Z=92, A=235) splits into two equal parts, and the Coulomb energy when the fragments are just touching is the source of all power in the reactor. To a good approximation, the radius of a nucleus with atomic mass A is $R=1.25A^{1/3}$ fm. Also assume that the fragments undergo four beta decays before reaching the valley of stability.

Find the antineutrino flux at a distance of 300m.

Answer: 1.3×10^{10}/cm^2-sec

Detecting Reactor $\overline{\nu}_e$

Remember: All Neutrino Cross Sections are "Small"

- Need intense sources and large detectors
- Fake signals, i.e. "backgrounds", are a problem

Number of detected events per second

= Flux (neutrinos per second per cm^2)

× Interaction cross section (cm^2)

× Number of "targets"

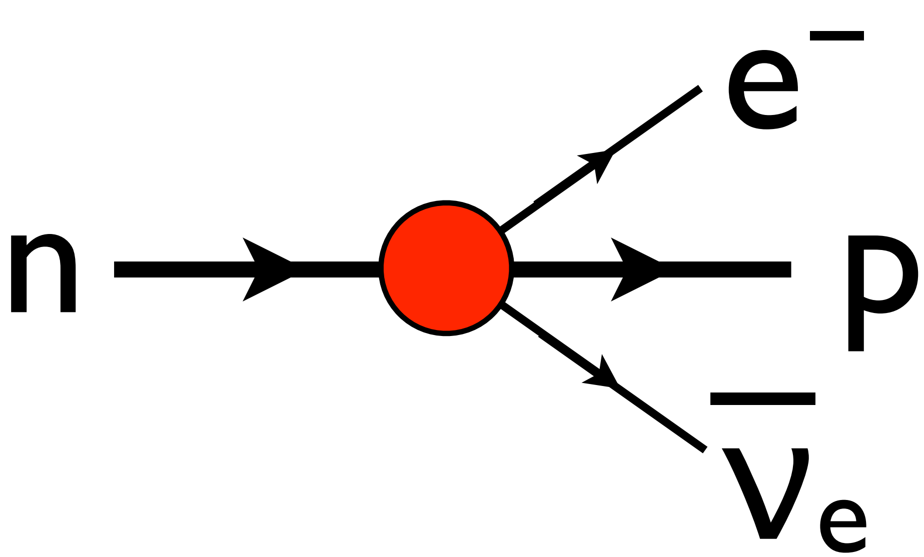
× Detection efficiency

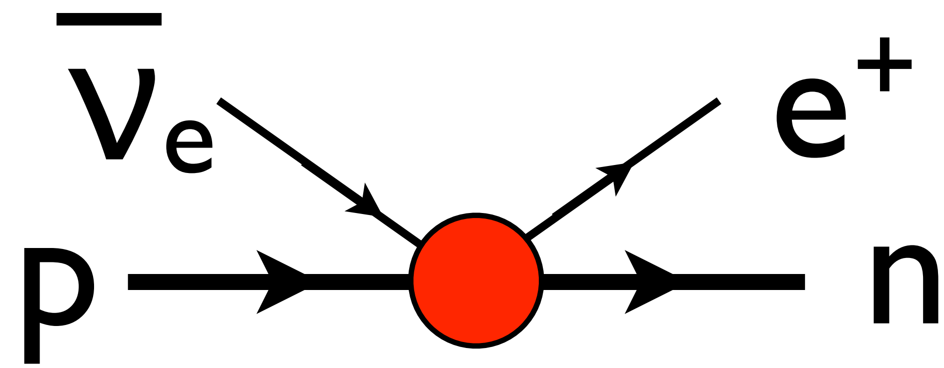
For Reactor Neutrinos: $\overline{\nu}_e + p \rightarrow e^+ + n$

Inverse Beta Decay Cross Section

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

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





Measure neutron lifetime to predict cross section!

$$\sigma^{(0)}_{tot} = \frac{2\pi^2/m_e^5}{f^R \tau_n} E_e^{(0)} p_e^{(0)} = 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1 \ \mathrm{MeV}^2} \right) \times 10^{-42} \ \mathrm{cm}^2$$

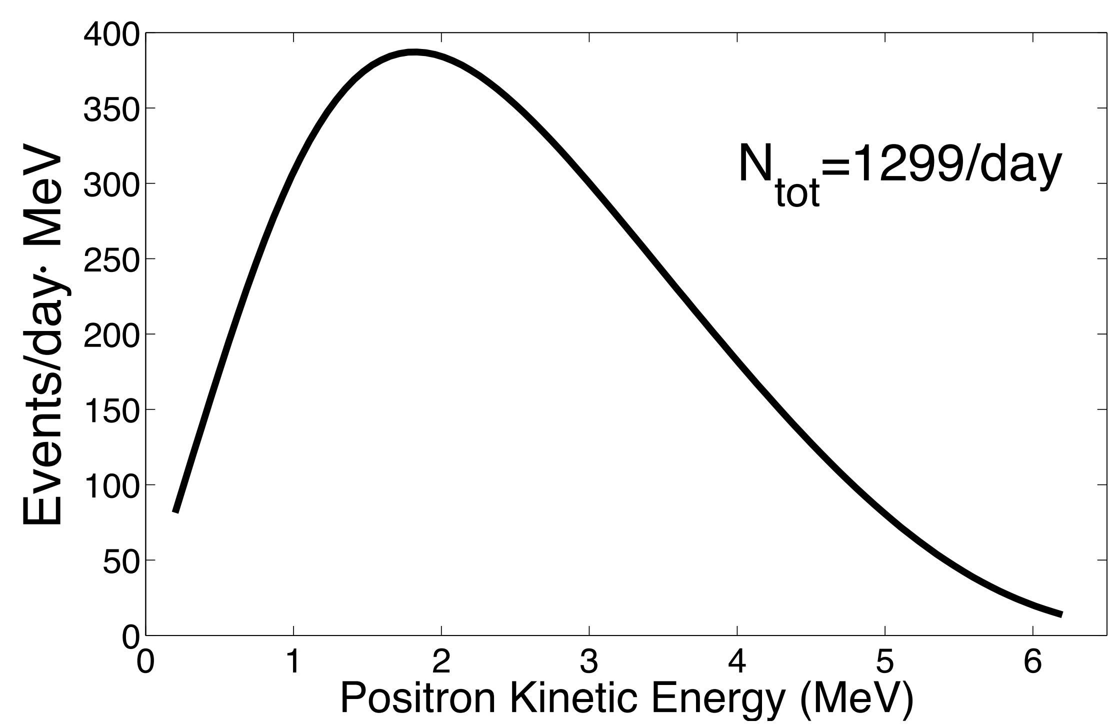
P. VOGEL AND J. F. BEACOM PHYSICAL REVIEW D **60** 053003

Exercise

Calculate the detected positron spectrum.

Using the ^{235}U neutrino spectrum calculated by Huber, find the number of events per MeV per day in a 20ton detector. Assume the detector material has a chemical composition equivalent to CH_2. Plot the spectrum as a function of positron kinetic energy. Take the detector efficiency to be unity. Integrate over positron energy for the total number of events.

Answer:



Use the antineutrino flux you calculated for a 4GW reactor at a distance of 300m.

"Prompt" and "Delayed" Signals

- Detectors are big and neutrino events are rare.
- It will be difficult to find ~1000 events per day in a 20 ton detector (about 5m in size).
- We need an additional handle with which we can identify inverse beta decay events!

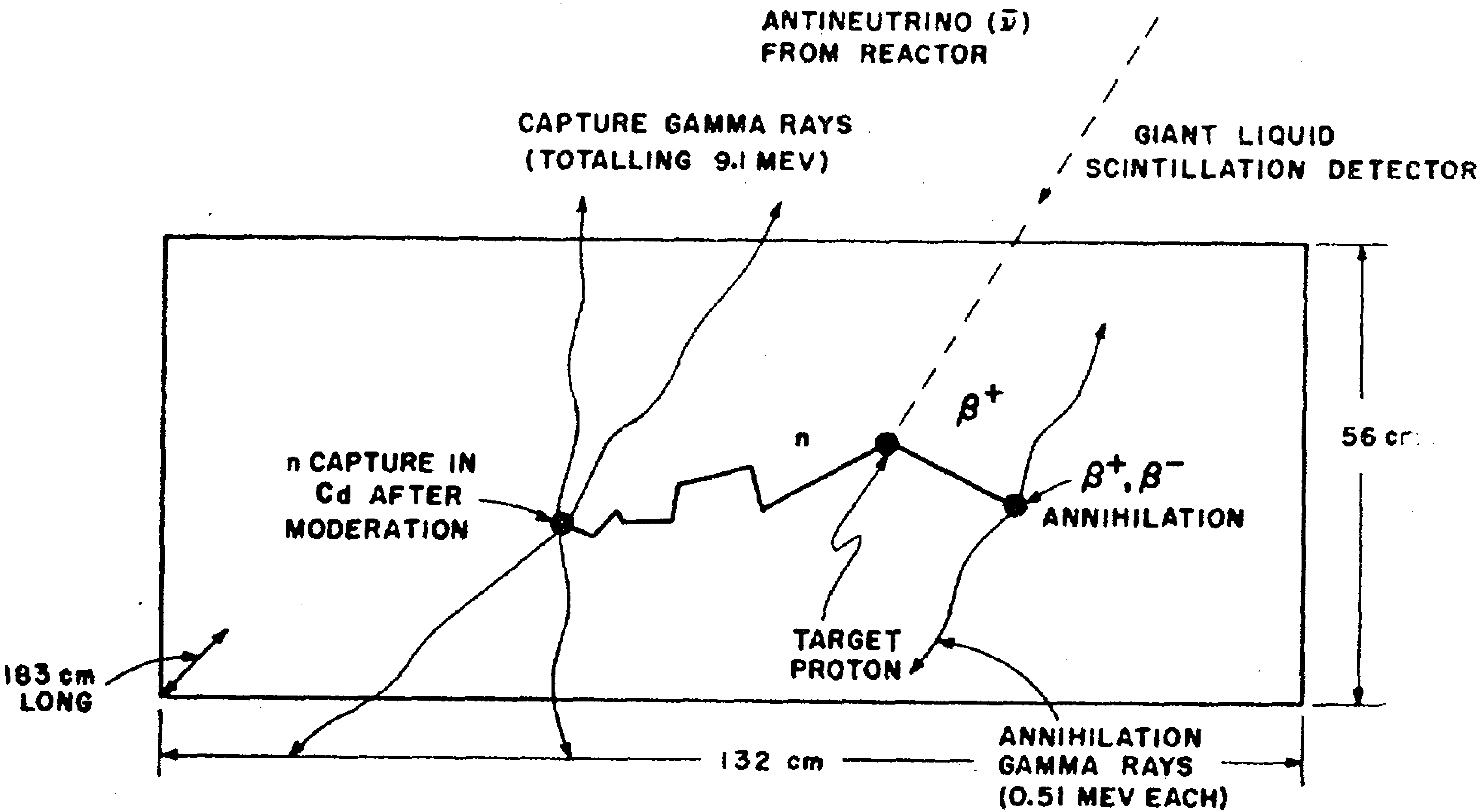
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

The electron is "prompt". It is the primary signal.

The neutron walks around in the detector before it captures on something. Its signal is "delayed".

Ancient Example ("Discovery")

Reines and Cowan, Phys.Rev. 113(1959)273



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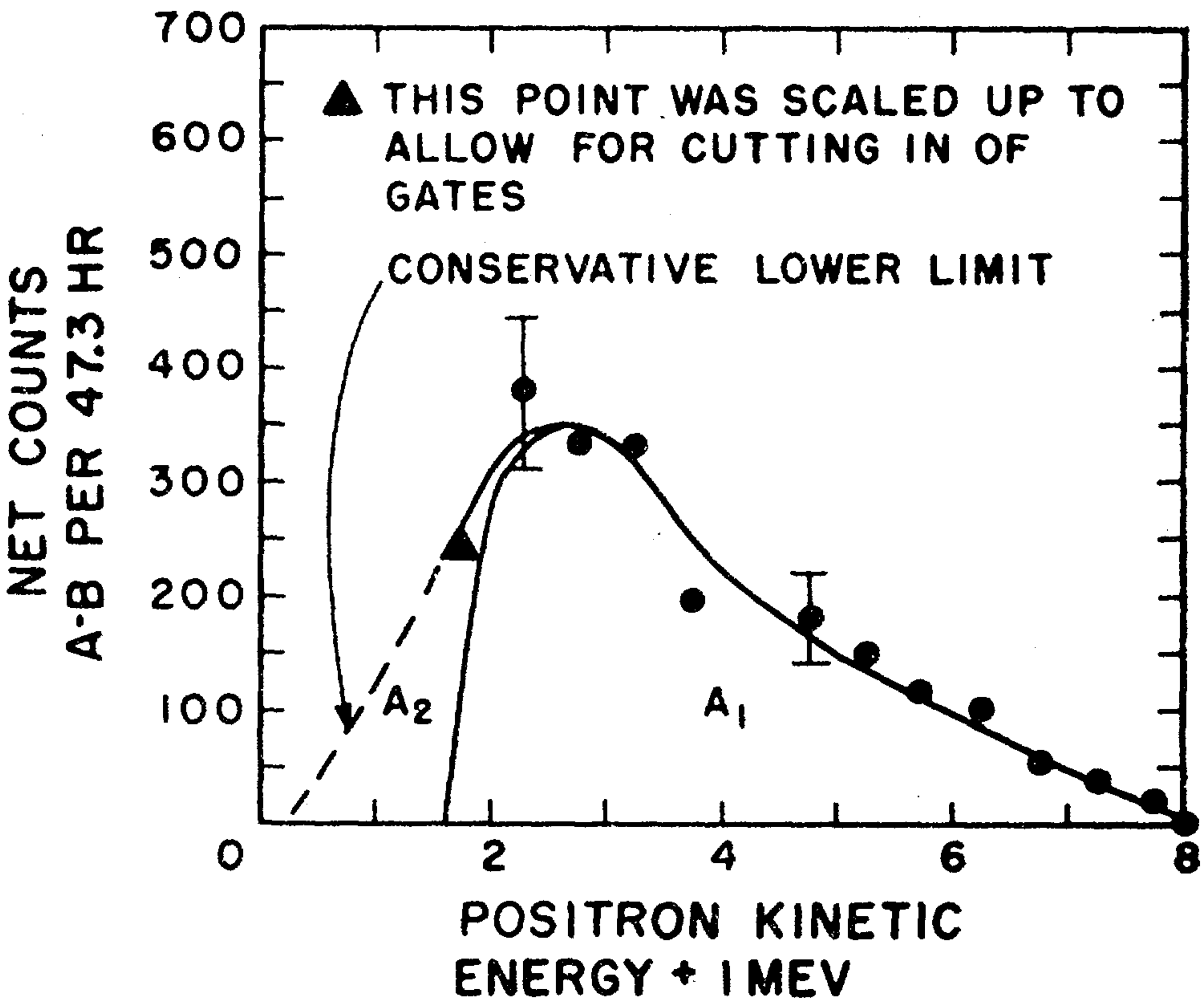
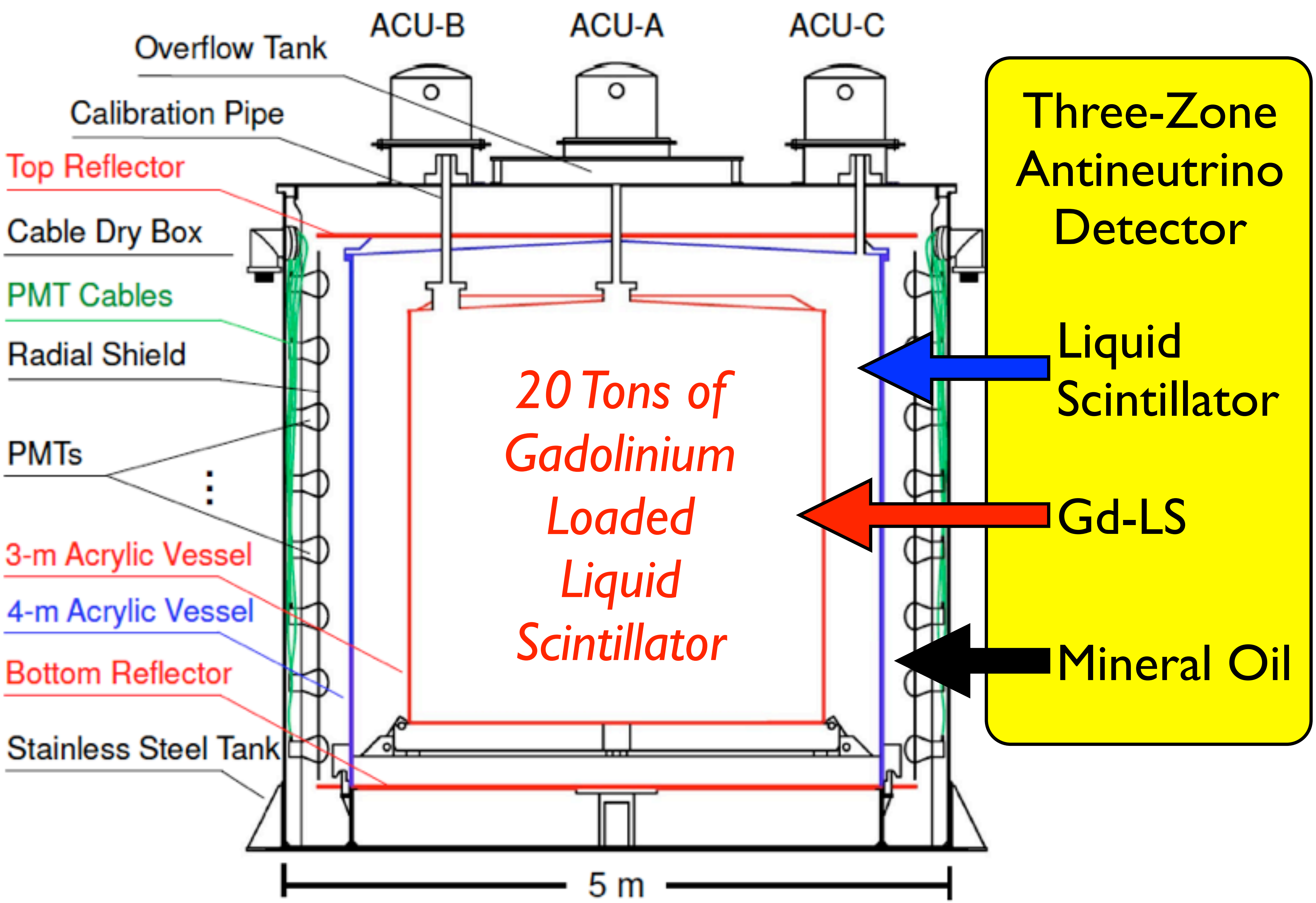


Recall your calculation of the spectrum shape from the previous exercise!

Modern Example ("Precision")

Daya Bay: NIM A685(2012)78 & PRL108 (2012) 171803



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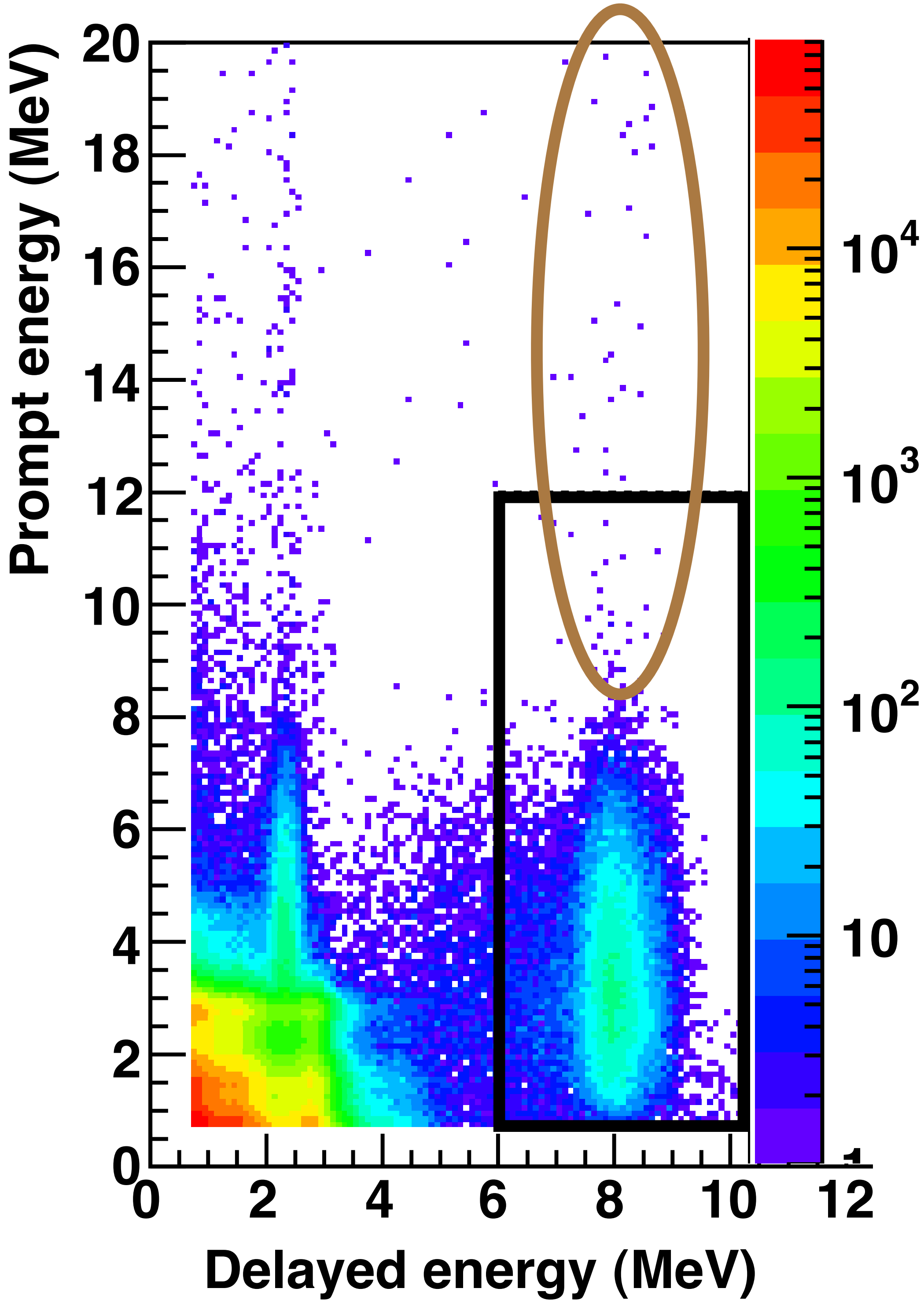
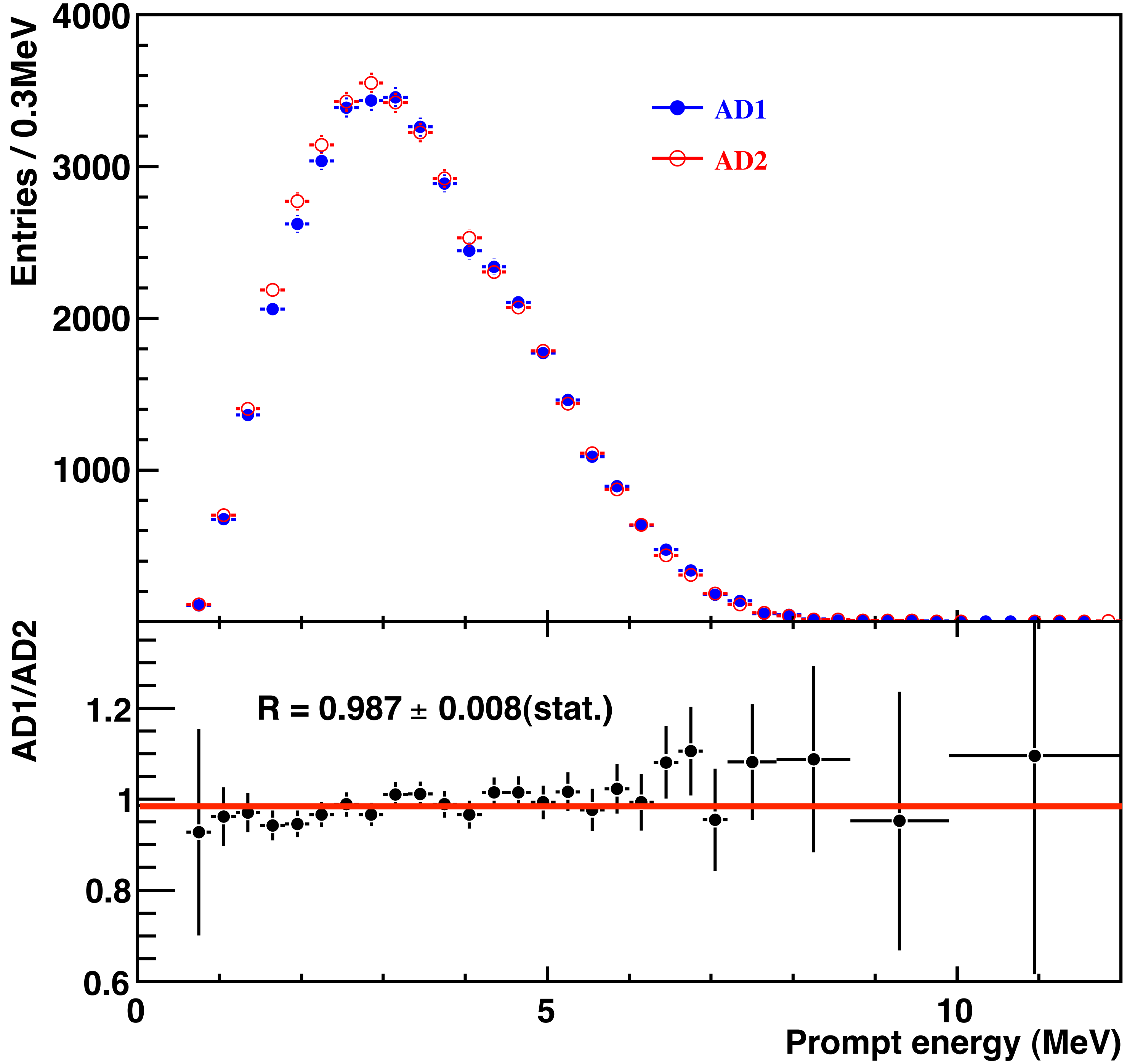


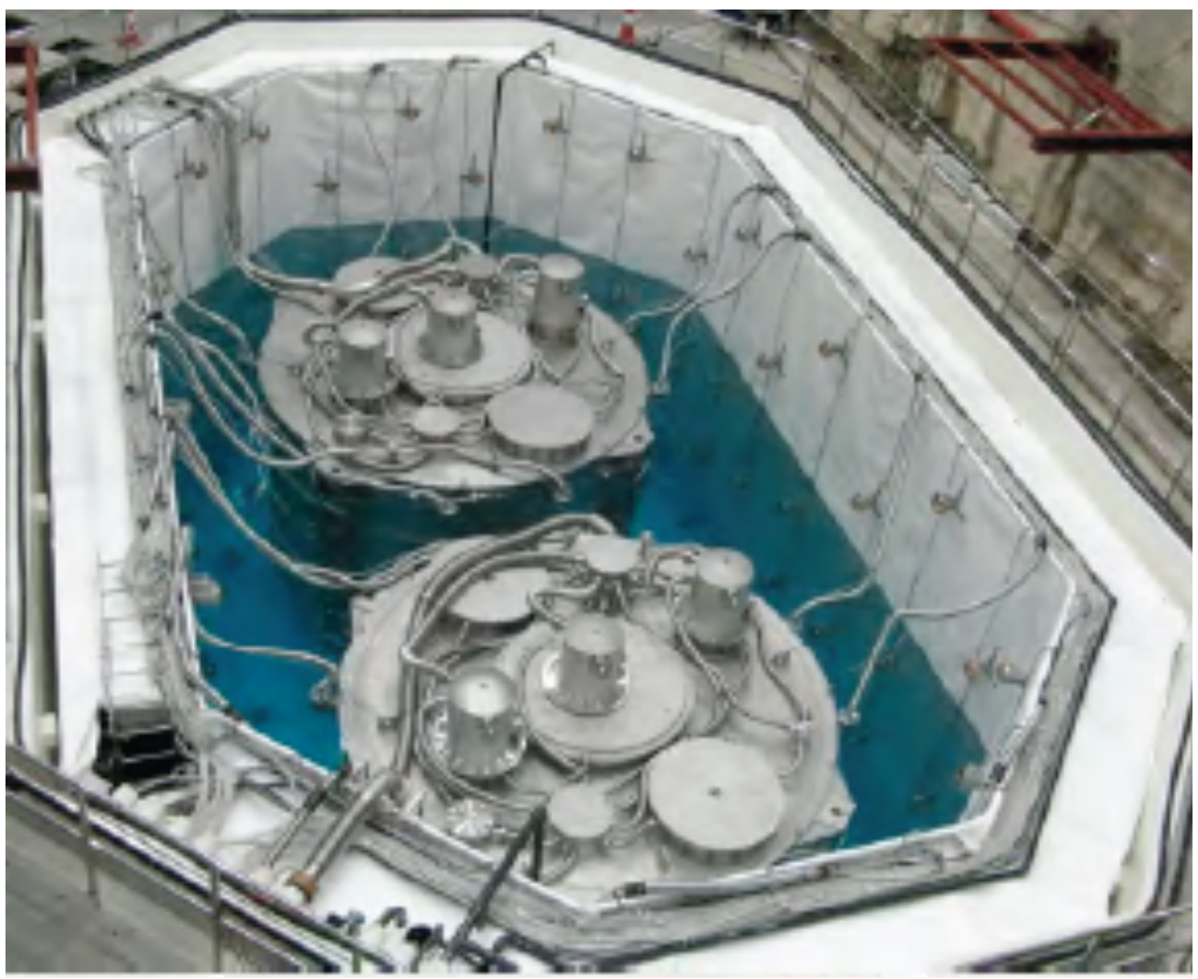


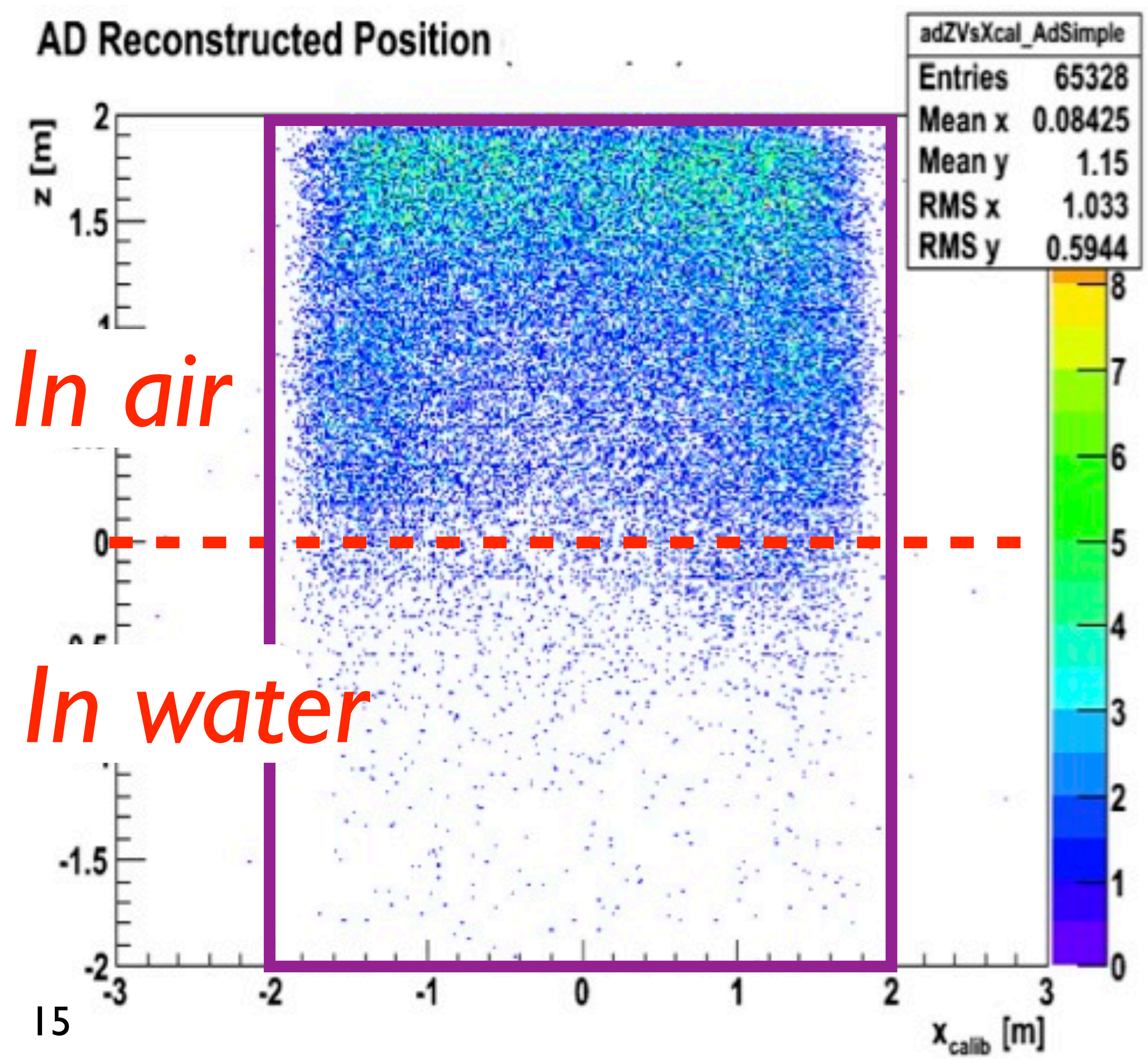
Note: Cosmic Ray Neutrons

Shielding: Cosmic Rays and Radioactivity

arXiv:1003.1391

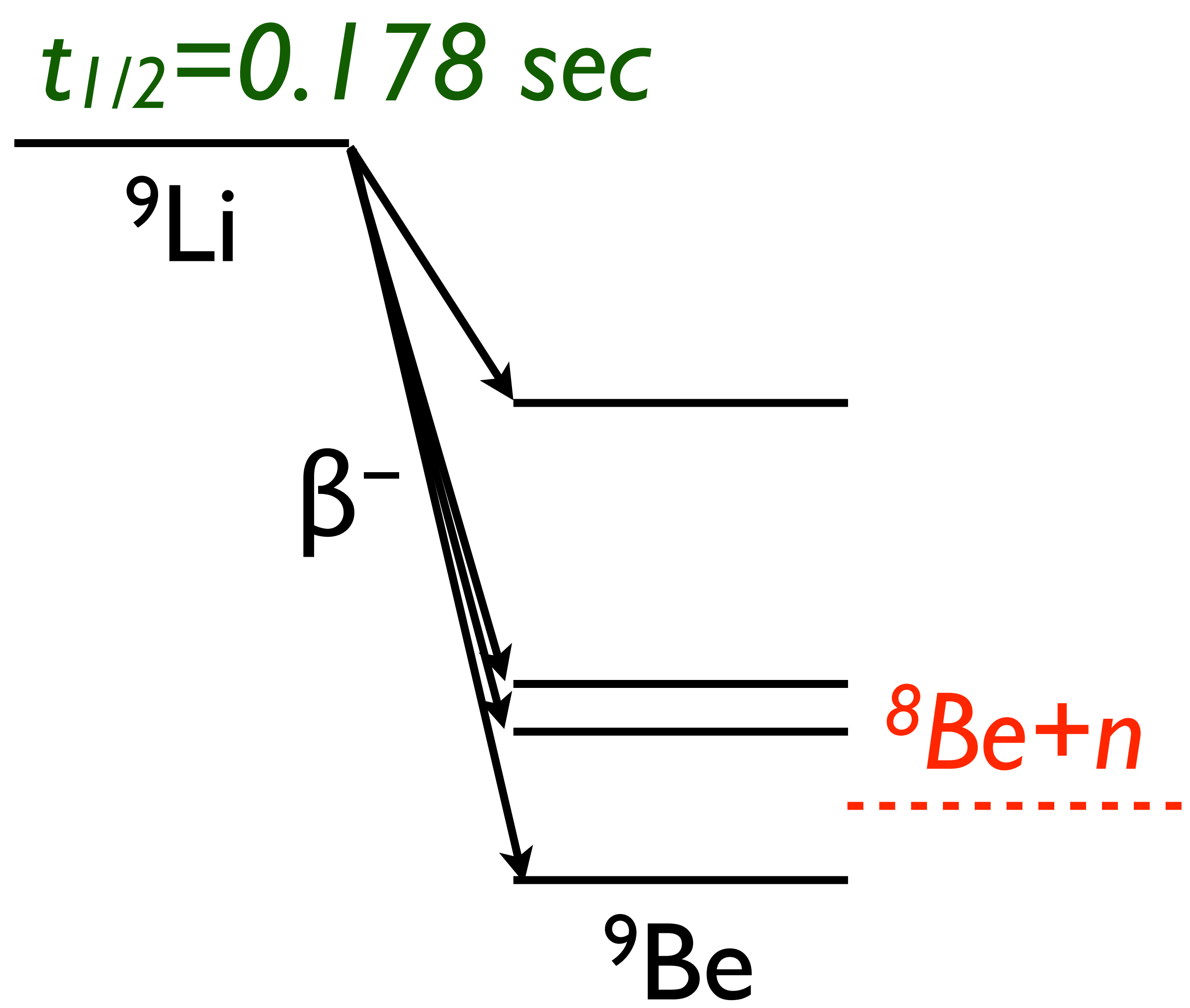
Experiment	Location	Total Reactor Thermal Output (GW_{th})	Detector Distance Near/Far (m)	Overburden Near/Far (mwe)	Target Mass (Near/Far) (tons)
Double Chooz	France	8.7	410/1067	115/300	10/10
Daya Bay	China	11.6(17.4)	360(500)/1985(1613)	260/910	$40 \times 2/10$
RENO	Korea	16.4	292/1380	110/450	16.1/16.1





The Insidious Background

$n_{Cosmic} + {}^{12}C_{Detector} \rightarrow {}^{9}Li$ + *other stuff*, then...



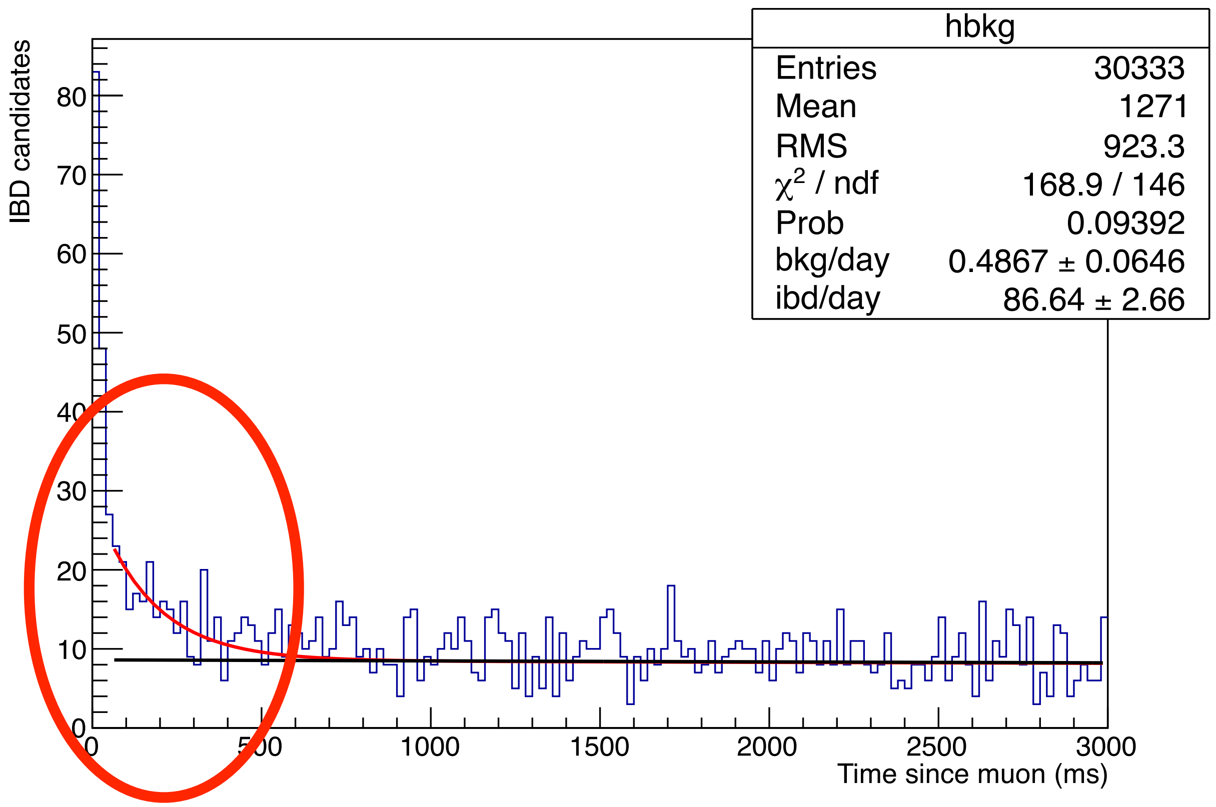
Approximately 50% of the beta decays of ^{9}Li lead to a free neutron in the end.

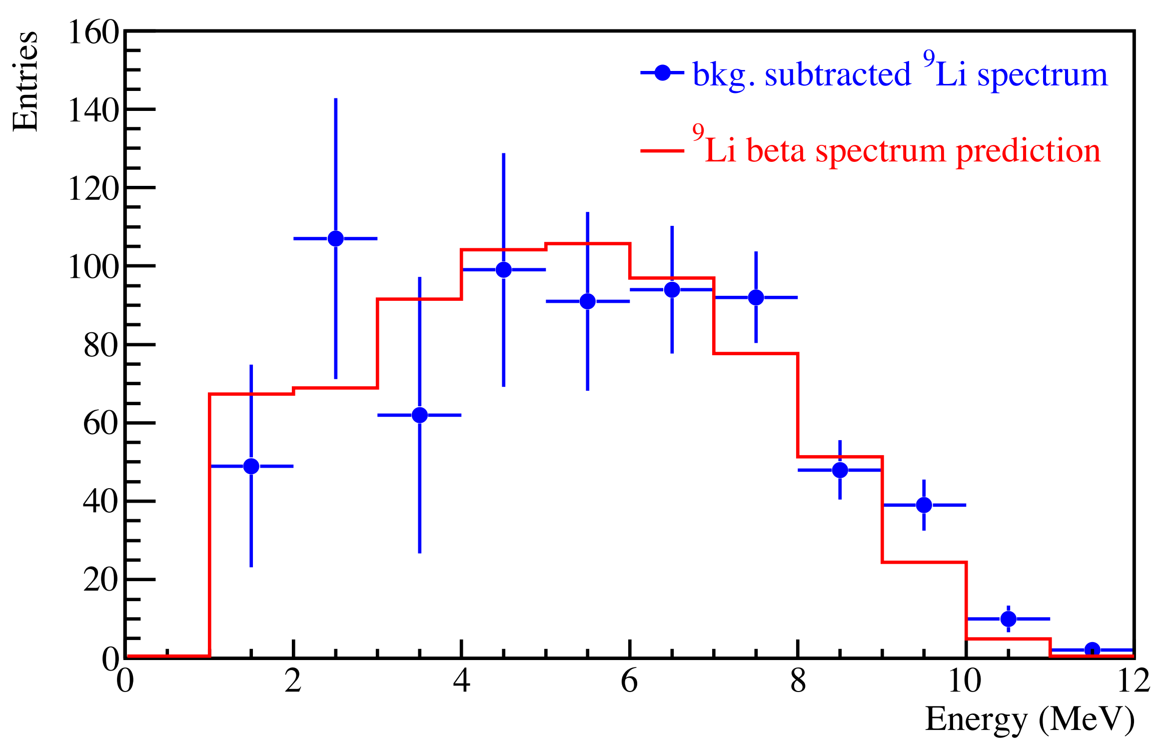
The combination of β^- and neutron looks just like a "prompt" and "delayed" neutrino signature!

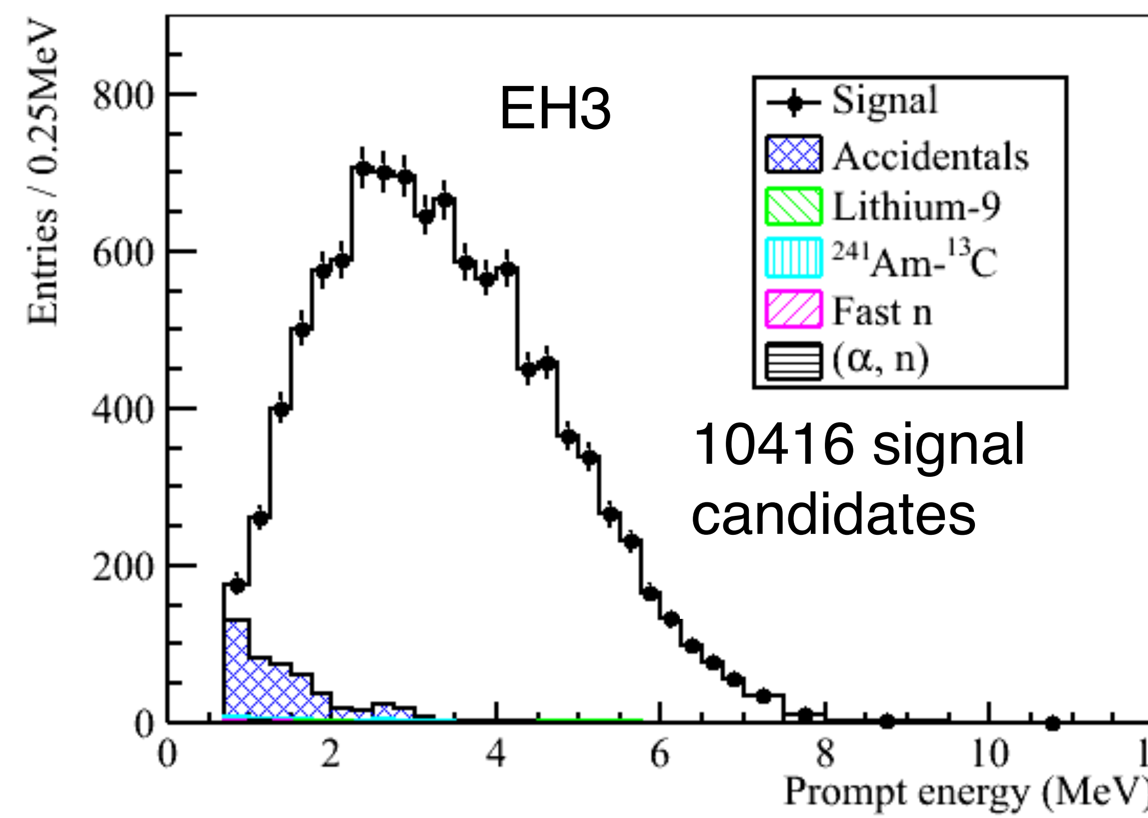
Use the half life to measure the (hopefully small) contribution and subtract it from your signal.

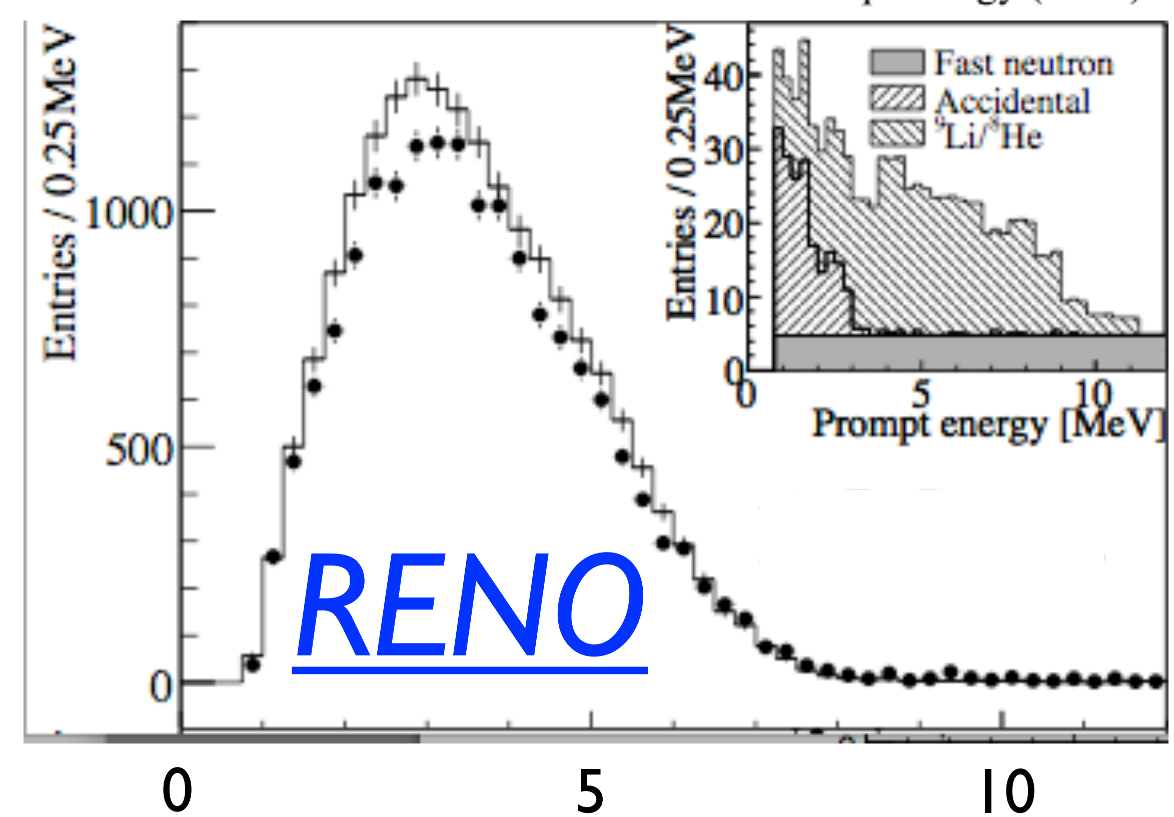
Examples

Daya Bay

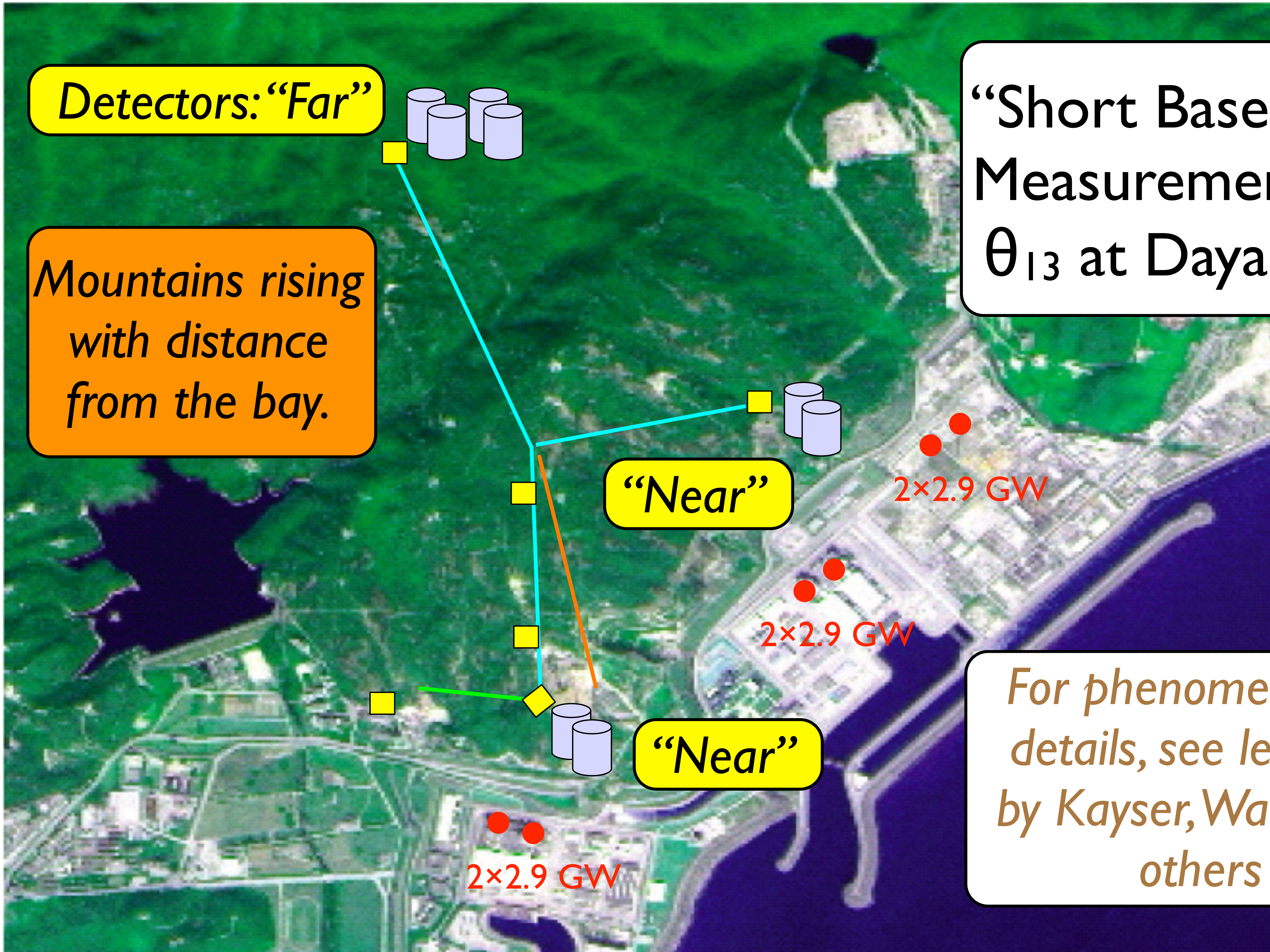








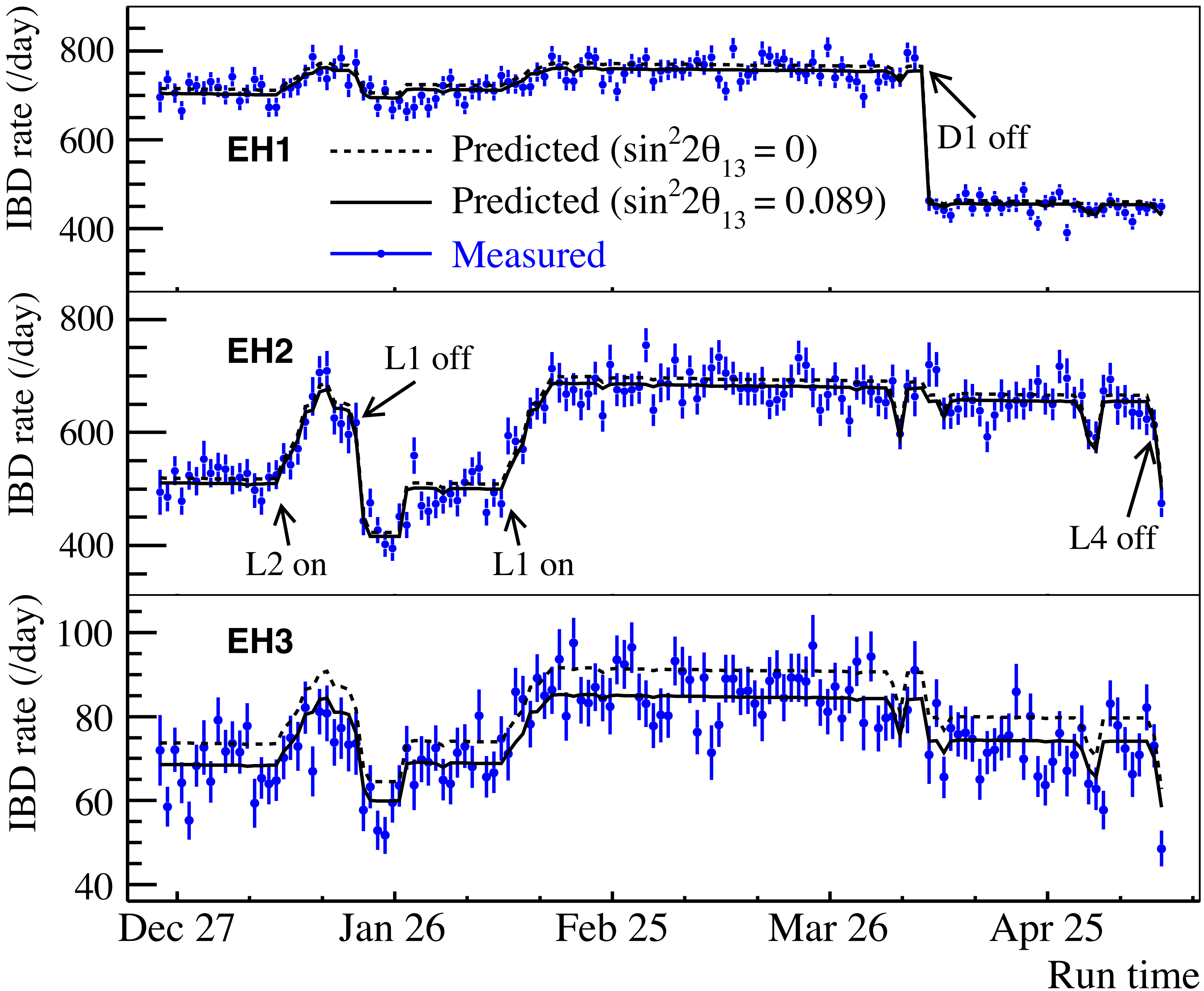
Application: Neutrino Oscillations



"Short Baseline" Measurement of θ_{13} at Daya Bay

For phenomenology details, see lectures by Kayser, Wark, and others

Daya Bay: Rate and Reactor Power



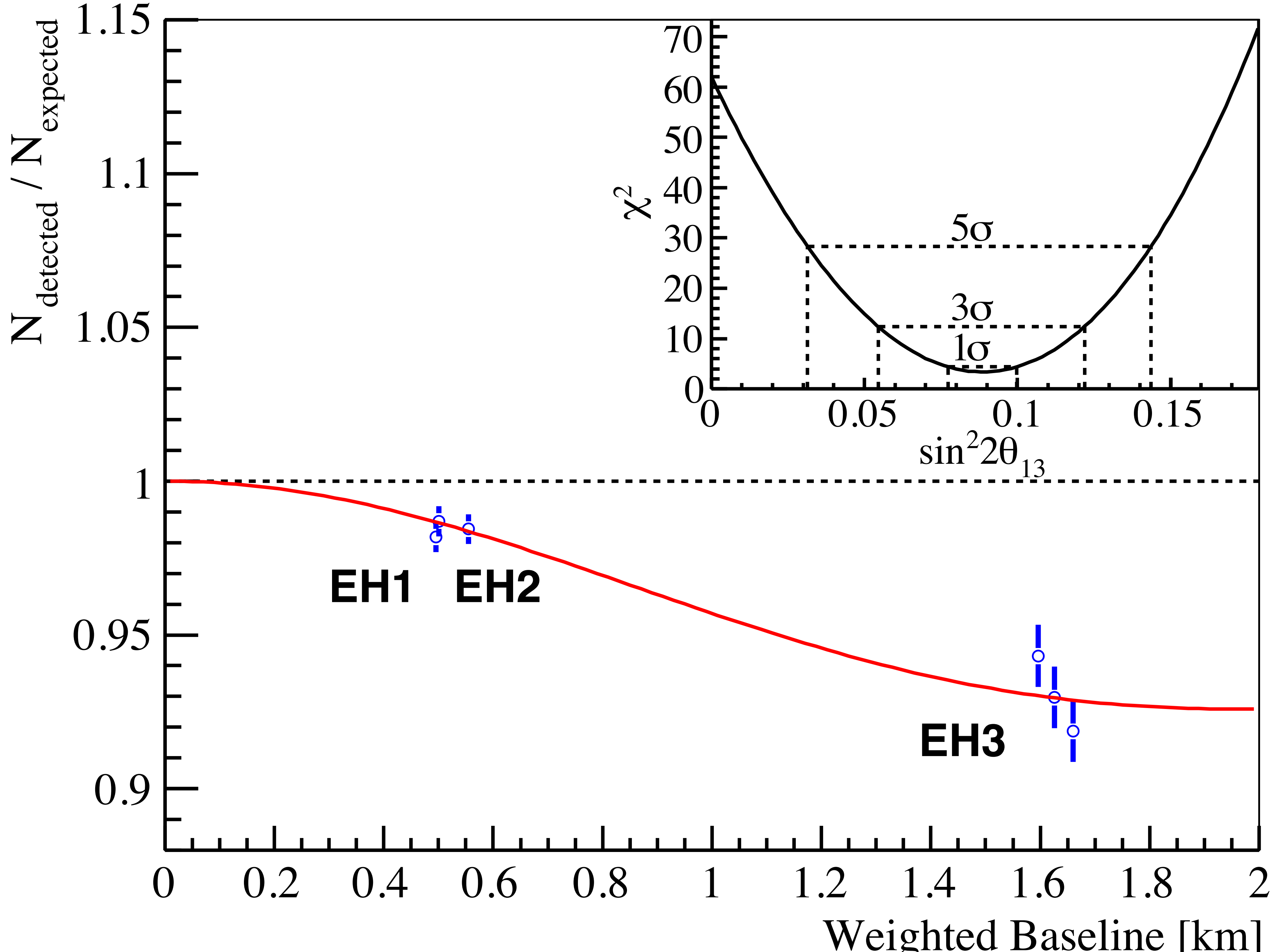
"Near"

"Near"

"Far"

Daya Bay: "Antineutrino Disappearence"

$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$

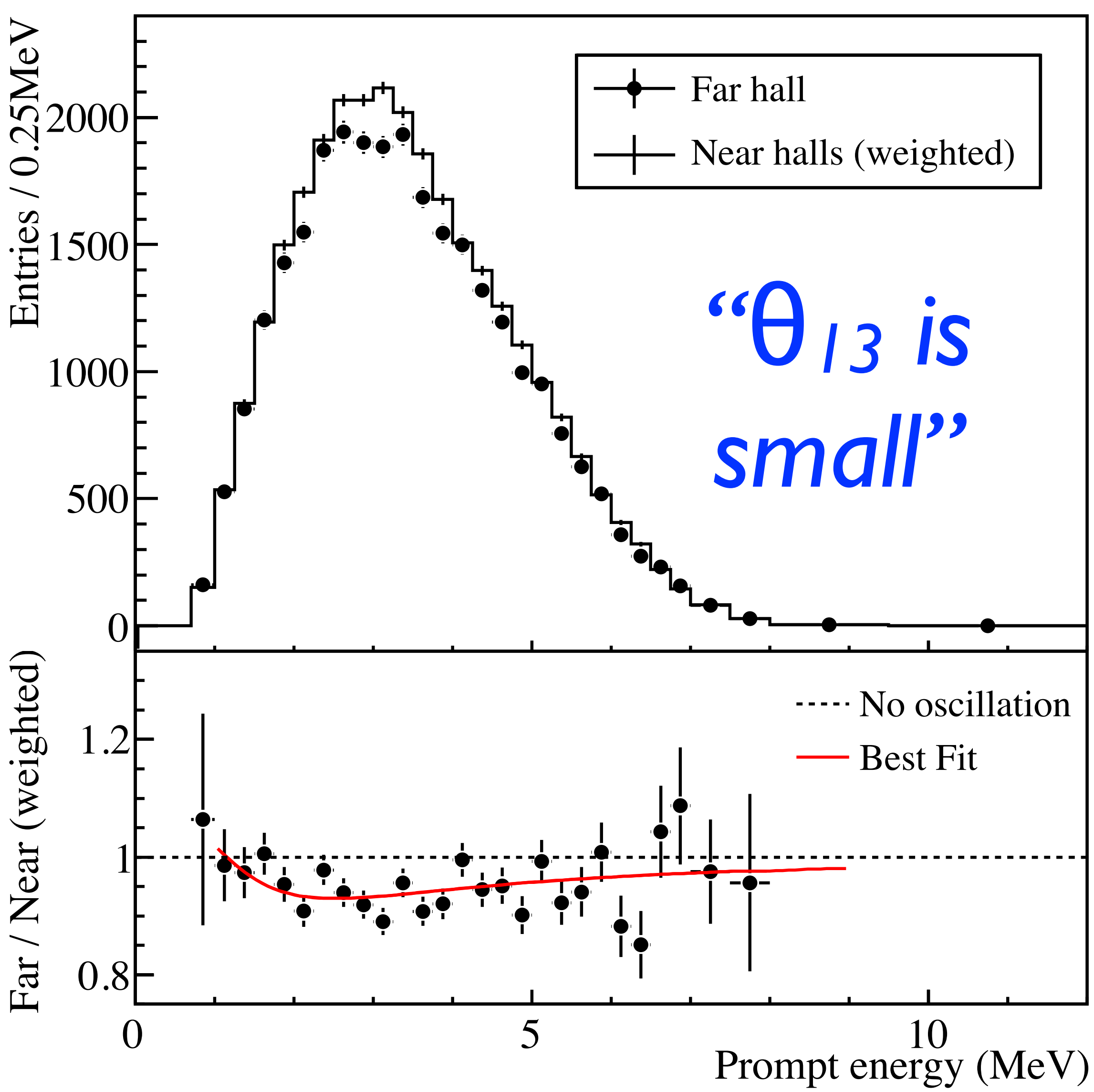


Calculate the expected distortion in the shape of the positron spectrum, using our current knowledge of the neutrino mixing angles, at 1.6km and at 100km.

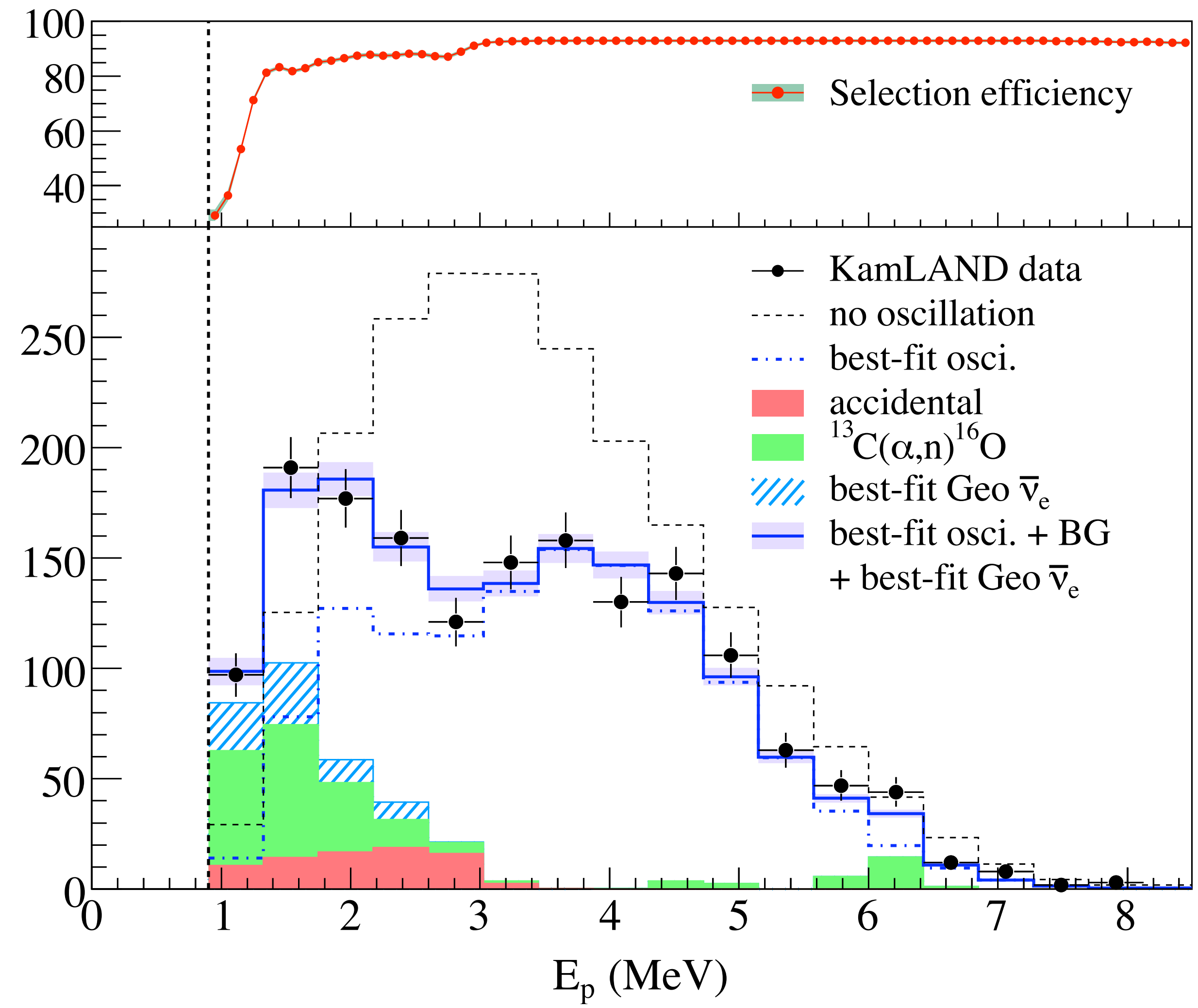
Exercise

Answer: Daya Bay (1.6km)

Answer: KamLAND (100km)



"θ_{13} is small"



"θ_{12} is big"

Conclusion

Nuclear power reactors are intense and useful sources of electron antineutrinos.

Having led to the discovery of the neutrino more than 60 years ago, reactors have become a workhorse for neutrino physics in the past decade.

Precision experiments can now be done with reactor neutrinos. More good stuff to come!

Thank You!