Reactor Neutrinos

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Outline

- ❑ Nuclear Reactors
- ❑ Reactor Neutrinos
- ❑ Experimental detection
- ❑ The Daya Bay experiment

About me

- ❑ A physicist in the Electronic Detector Group (EDG), Physics Department, BNL
  - ▪ PhD at CalTech (2011)
    - o KamLAND experiment (Japan)
  - ▪ Came to BNL as a postdoc then became a staff
    - o Daya Bay experiment (China)
    - o PROSPECT experiment (US)
  - ▪ Love cats

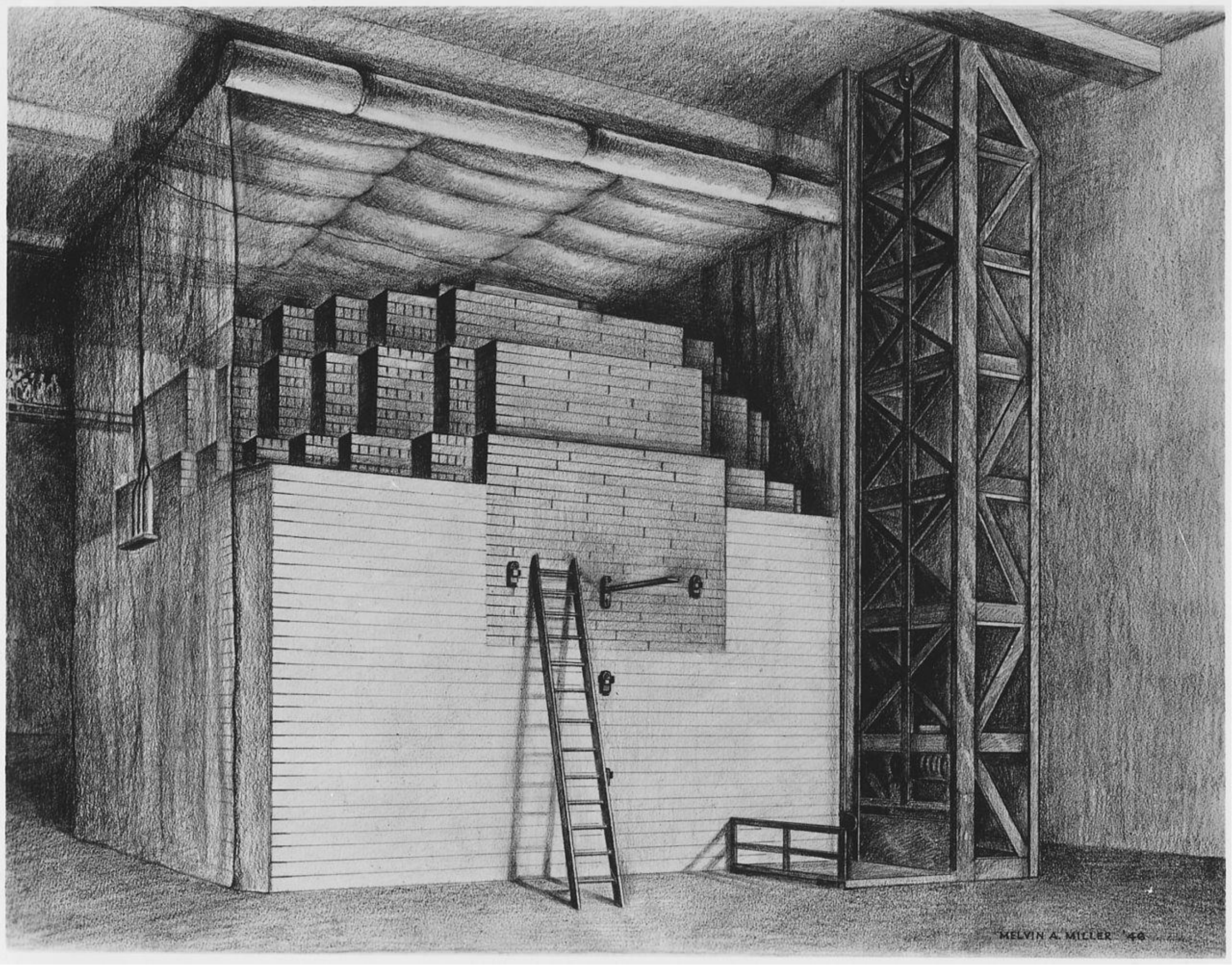



World's First Nuclear Reactor

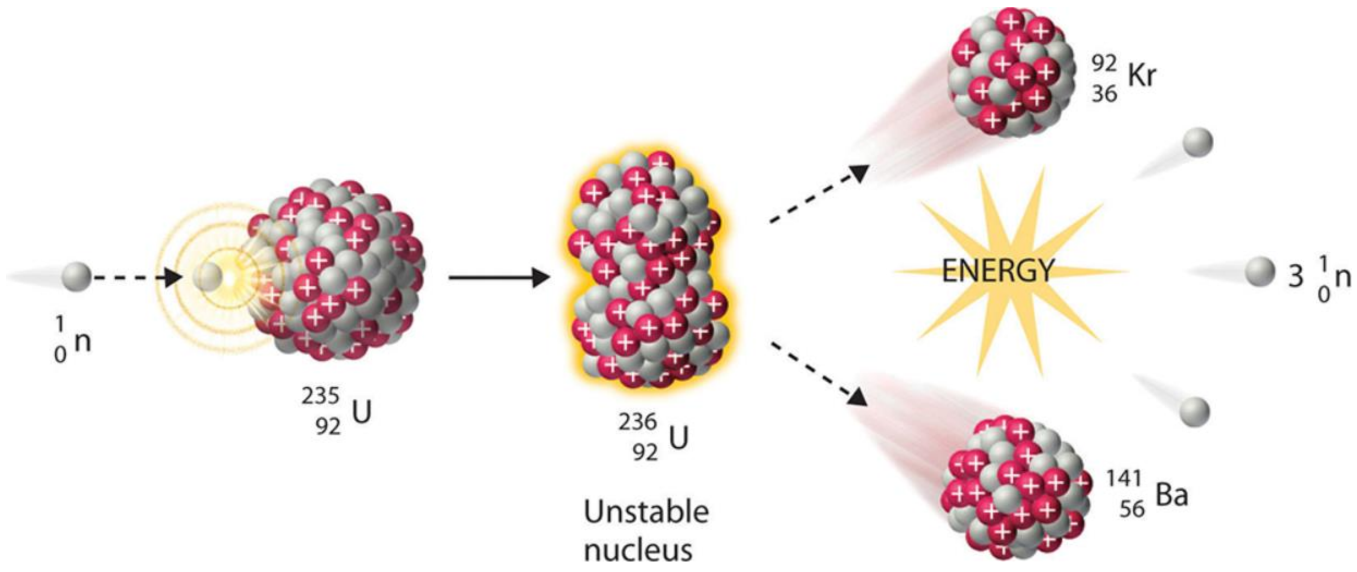
Chicago Pile-1 (CP-1)

- Part of the Manhattan Project
- Designed and tested by a team of 49 scientists led by Enrico Fermi at U. Chicago
- Dec 2, 1942: first human-made self-sustaining nuclear chain reaction
  - Fuel: 40-ton Uranium Oxide and 6-ton Uranium Metal
  - Neutron moderator: 380-ton Graphite blocks
  - Control rods: Cadmium sheets

CP-1 in a squash court under the stands of Stagg Field at U. Chicago



Fission and Energy Release



1 fission = 200 Mev

1 gram U-235 fissioned = $8.6x10^{10}$ joules = 24,000 kwh

(Equivalent to lighting a small city for overnight)

24,000 kwh requires 3.2 tons of coal

12.6 bbls oil

Energy Density (energy / mass)

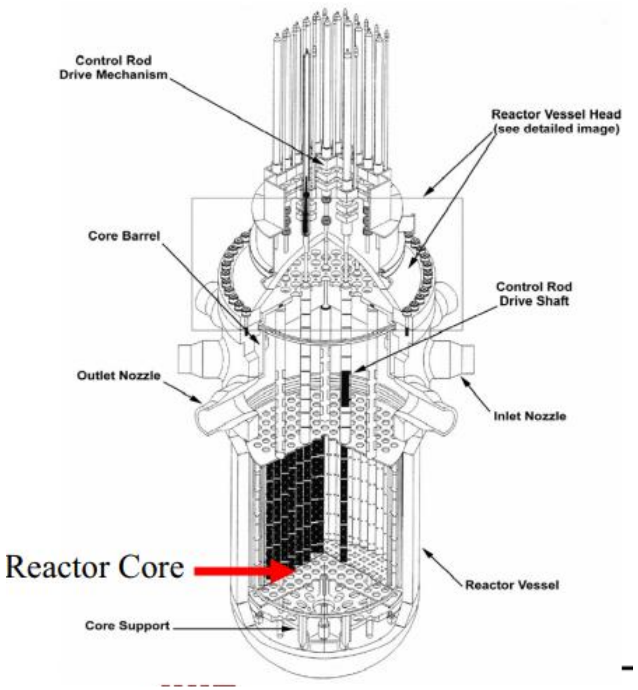
Energy Density of U-235 = 28,000 times energy density of coal

Key properties of fission

- ❑ Release substantial energy (mostly as kinetic energy of the fission fragments)
- ❑ Release excess neutrons: possibility of chain reaction.

Reactor design requirement

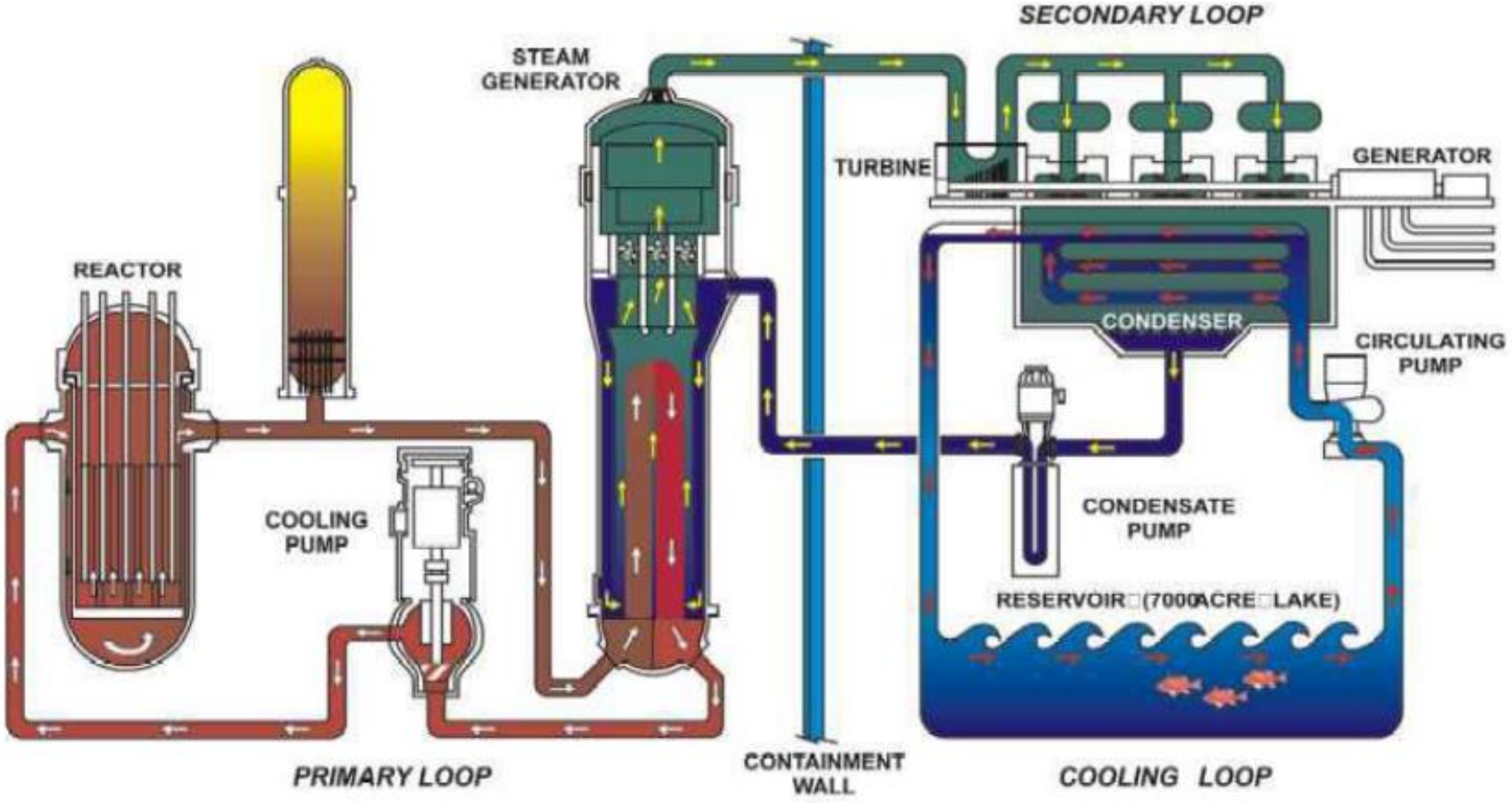
- ❑ Fission requires thermal neutron: needs "moderator" to slow down neutrons
  - Water, heavy water (D_2O), Graphite, etc.
- ❑ Controllable fission: reactor engineering to make output neutron = 1 (critical condition)



- ❑ Core Heat Removal
- Coolant: Heat Transfer
- Safety Systems (Emergency)

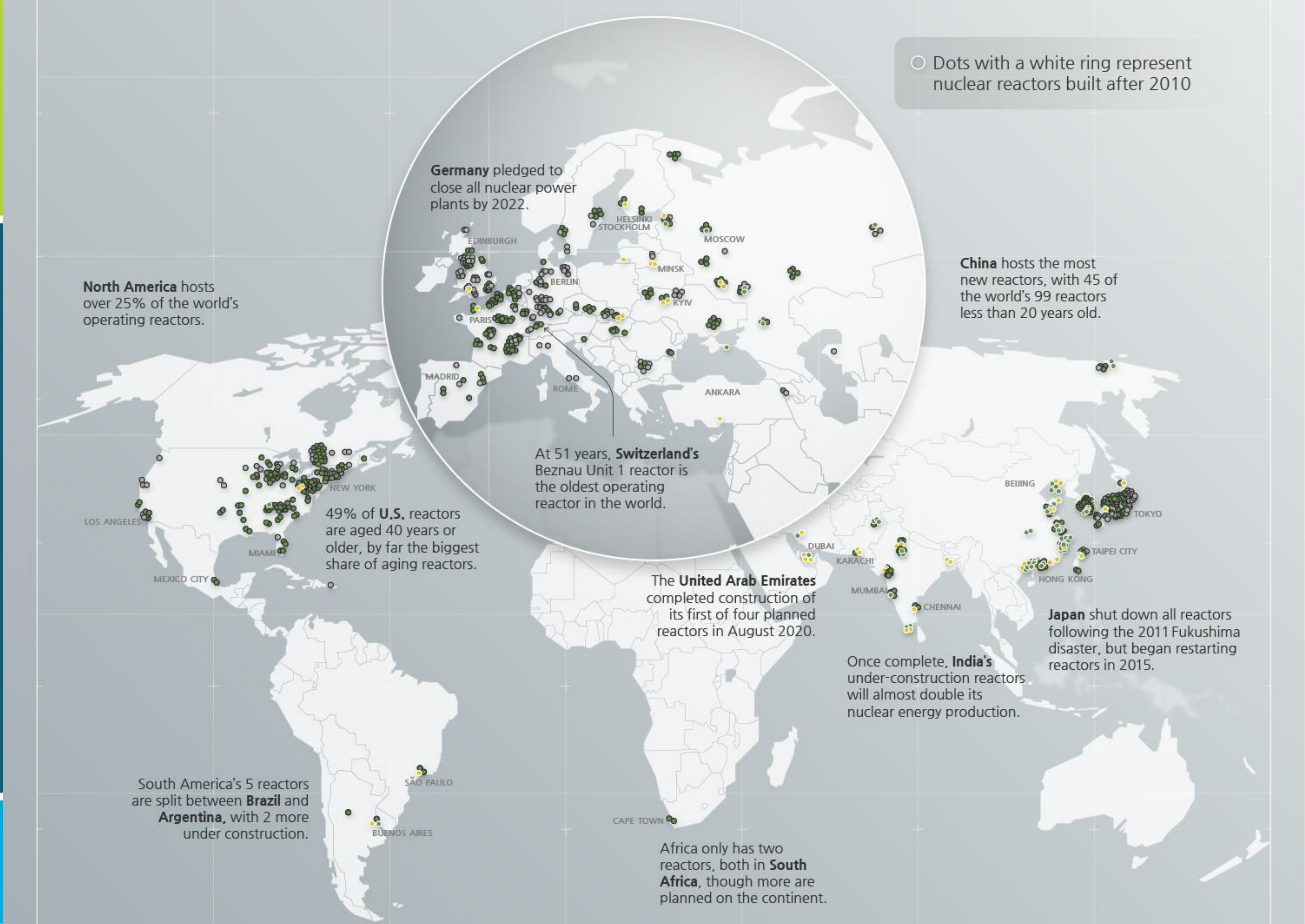
- ❑ Confinement of Radioactivity
- ❑ Electricity Production
- ❑ Spent fuel processing

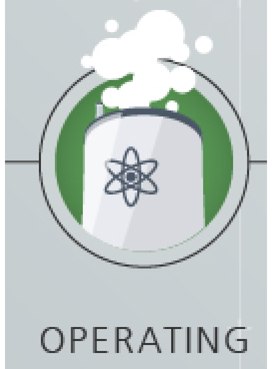
Schematic of a Pressurized Water Reactor (PWR)

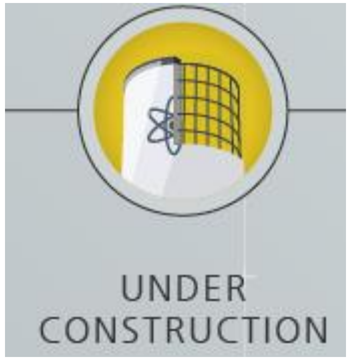


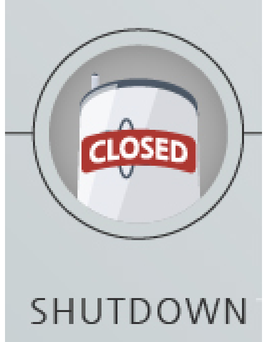
- ❑ Reactor Core Design
- Core Power Distribution
- Ability to shutdown plant
- no fuel failure or melting

Full video with annotations: [Breazeale Nuclear Reactor Start up, 500kW, 1MW, and Shut Down (ANNOTATED) - YouTube]


Dots with a white ring represent nuclear reactors built after 2010
Germany pledged to close all nuclear power plants by 2022.
North America hosts over 25% of the world's operating reactors.
China hosts the most new reactors, with 45 of the world's 99 reactors less than 20 years old.
At 51 years, **Switzerland's** Beznau Unit 1 reactor is the oldest operating reactor in the world.
49% of **U.S.** reactors are aged 40 years or older, by far the biggest share of aging reactors.
The **United Arab Emirates** completed construction of its first of four planned reactors in August 2020.
Japan shut down all reactors following the 2011 Fukushima disaster, but began restarting reactors in 2015.
Once complete, **India's** under-construction reactors will almost double its nuclear energy production.
South America's 5 reactors are split between **Brazil** and **Argentina**, with 2 more under construction.
Africa only has two reactors, both in **South Africa**, though more are planned on the continent.
EDINBURGH
HELSINKI
STOCKHOLM
MOSCOW
MINSK
BERLIN
KYIV
PARIS
MADRID
ROME
ANKARA
NEW YORK
LOS ANGELES
MIAMI
MEXICO CITY
BEIJING
TOKYO
TAIPEI CITY
HONG KONG
DUBAI
KARACHI
MUMBAI
CHENNAI
SÃO PAULO
BUENOS AIRES
CAPE TOWN


OPERATING

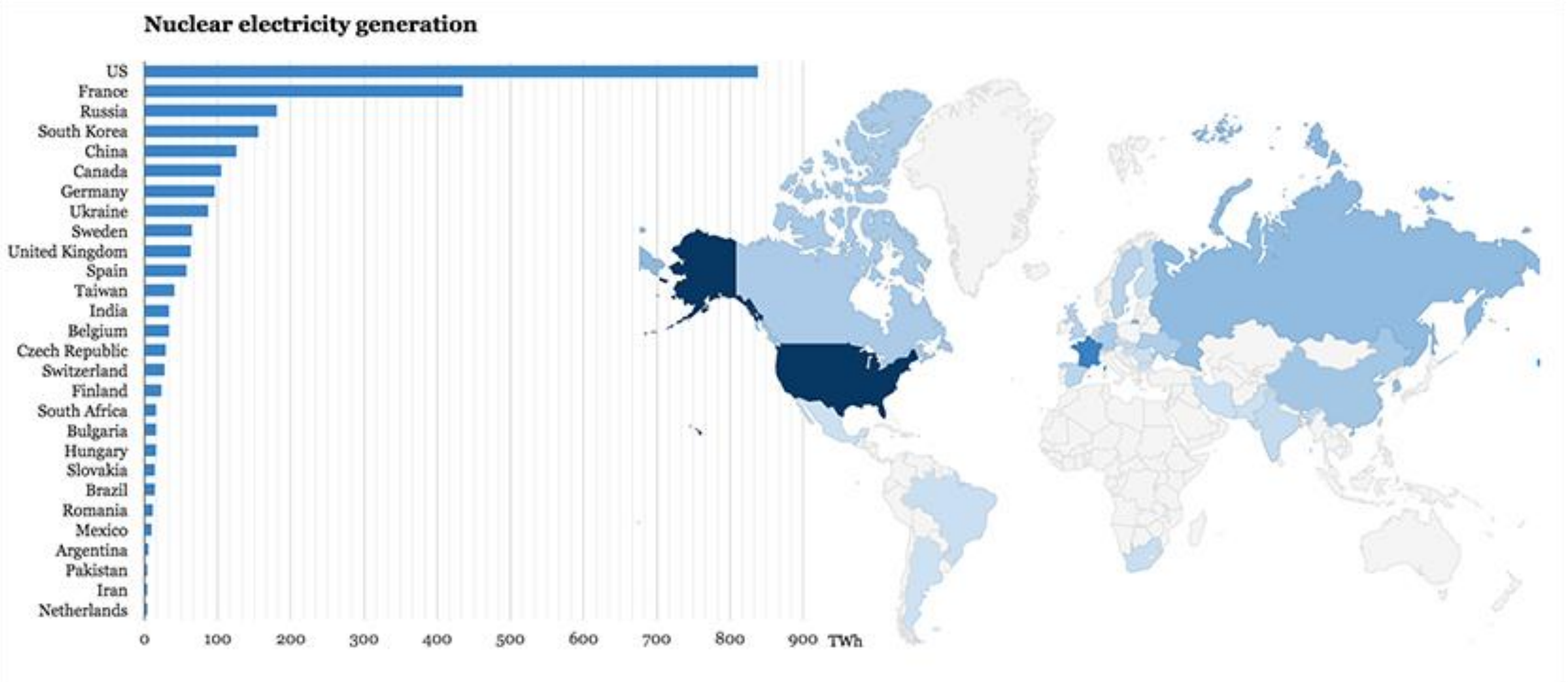

UNDER CONSTRUCTION


CLOSED
SHUTDOWN

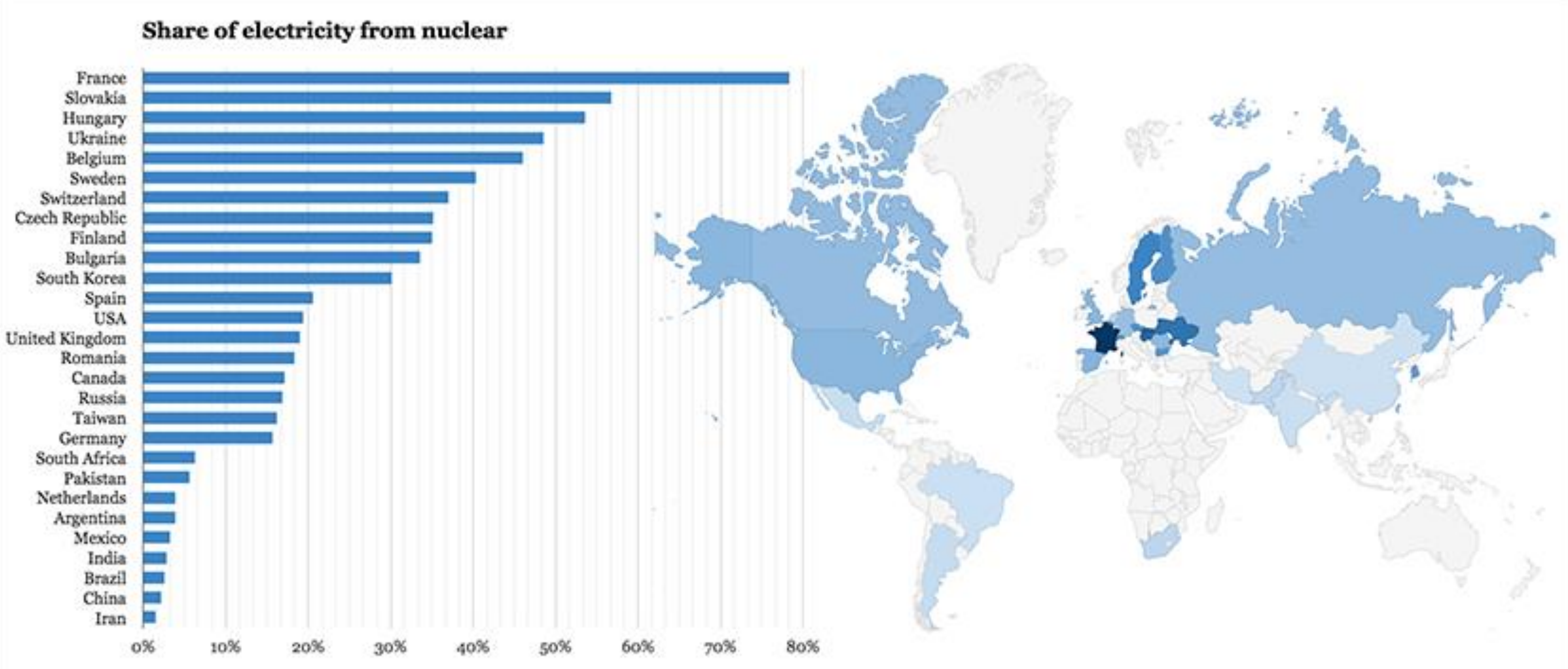
Map link

Country Ranking in 2015

Total Electricity from nuclear



Percentage from nuclear



Nuclear Reactor as a Research Tool: Neutron Source

GRAPHITE RESEARCH REACTOR

Operated: 1950 to 1969
World's first peacetime research reactor. Fuel plac~~ed in 700-ton graphite~~ "pile" that moderated fission. Scientists exposed experiments to neutrons by inserting them into slots on top and three sides of the core.

Initially ran on natural uranium, but in 1958 fuel was switched to enriched uranium, with reactor operating at 20 megawatts.

Scientific advances

- The radioactive isotope Technetium-99m, used as a medical tracer and similar to X-rays for diagnostic imaging, first detected here.
- Multi-grade motor oils developed as a result of studying engine piston rings in the reactor.
- Irradiated seeds used to produce the Star Ruby grapefruit, a sweet and nearly seedless variety with deep red flesh.

Cost to close: $114 million, with **$92 million** already spent. Stimulus money will pay about 60 percent of remaining **$22 million** cost.

HIGH-FLUX BEAM REACTOR

Operated: 1965 to 1996
Permanently shut in 1999
Provided neutrons for research in material science, ~~chemistry, biology and ph~~ysics. Scientists conducted experiments with external neutron beams delivered through ports placed around reactor core.

Enriched uranium fueled the reactor. "Heavy" water — in which deuterium replaces the two hydrogen atoms — moderated fission and served as main coolant. Operated at 30, 40 or 60 megawatts.

Scientific advances

- Structure of cell's "protein factory" — the 16-part ribosome — first discerned here.
- New uses of radioactive isotopes developed for treating illnesses such as cancer, heart disease and arthritis.
- Advanced understanding of life span and decays of isotopes such as zinc-80, which astrophysicists use to study supernovas.
- Magnet experiments led to Nobel Prize-winning theories of cooperative ordering in large collections of atoms.
- Scientists using the high-flux beam reactor determined structures of the 23 amino acids, which make up every protein in every cell in living things.

Cost to close: $64 million, with **$32 million** already spent. Stimulus money will pay about 90 percent of the remaining cost, which excludes taking it apart after 65 years.

MEDICAL RESEARCH REACTOR

Operated: 1959 to 2000
The smallest of the lab's reactors, it ~~was the first in the na~~tion built just for medical research. Large objects were irradiated at one of the reactor's four faces; holes in another face permitted irradiation of samples and production of short-lived radioisotopes. Neutron streams traveled from two remaining ports to treatment rooms for animal and clinical studies.

Reactor operated at 3 megawatts but could generate 5 megawatts for short periods of time. Core was water cooled.

Scientific advances

- Boron neutron capture therapy, developed to treat a deadly form of brain cancer, was pioneered here.

Cost to close: Decommissioning plan and budget **not yet developed**.

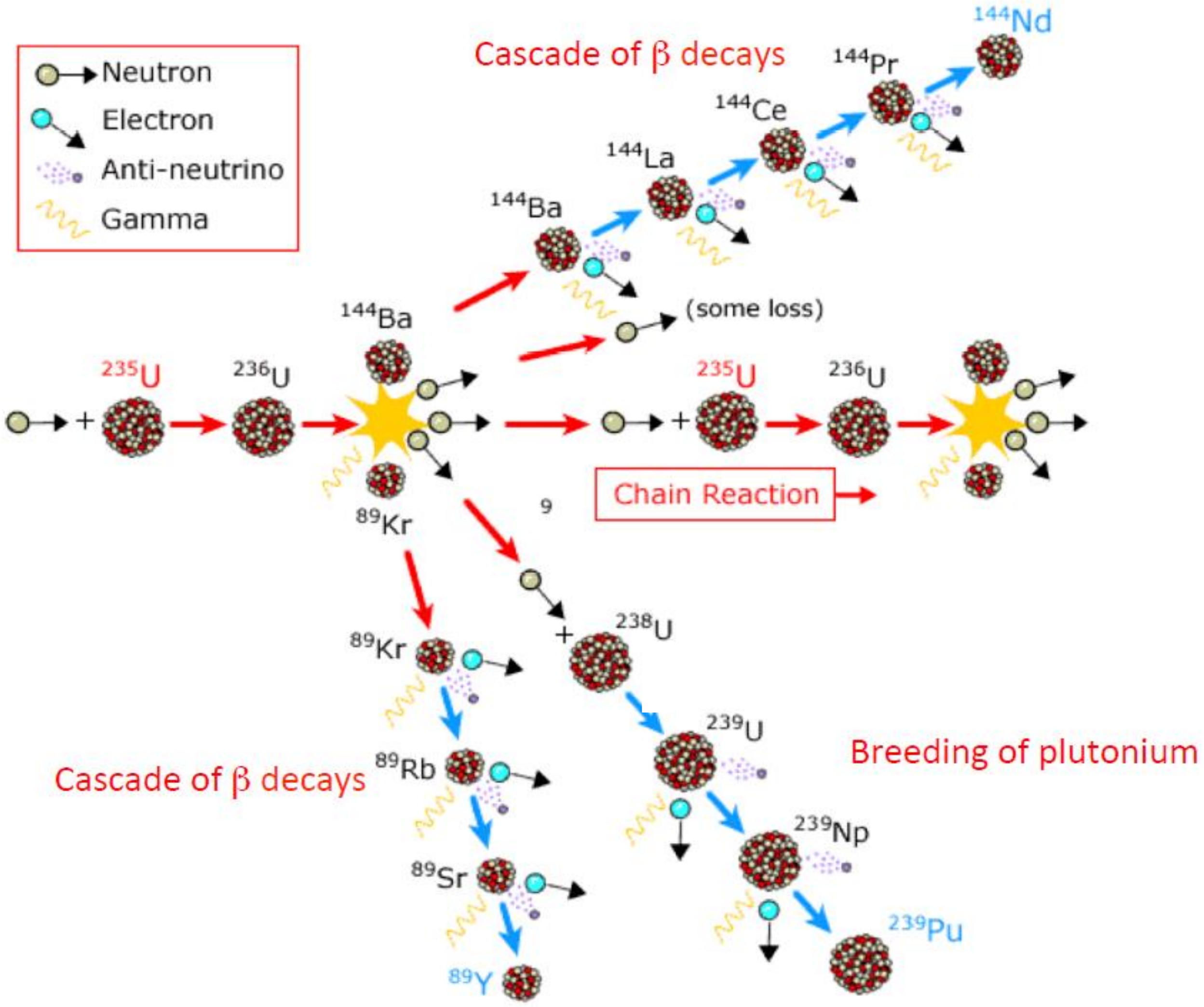
Source: Brookhaven National Laboratory

NEWSDAY, MONDAY, MAY 4, 2009 **www.newsday.com**

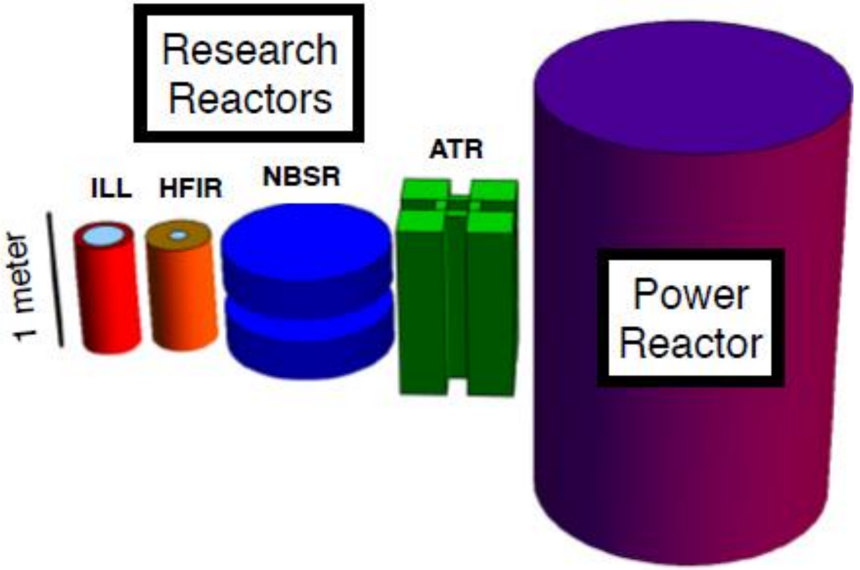
- research reactors typically ~10 MW
- BNL's past 3 reactors
  - BGRR, HFBR, BMRR

https://www.bnl.gov/about/history/reactors.php

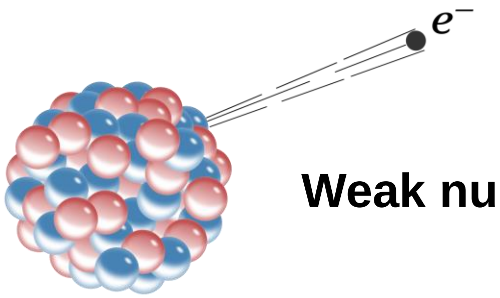
Nuclear Reactor as (anti)Neutrino Source



- Nuclear reactors produce pure $\bar{\nu}_e$ from beta decays of fission daughters
  - neutrino energy: < 10 MeV, peak ~ 4 MeV
- 6 $\bar{\nu}_e$ / fission
- 2 x 10^{20} $\bar{\nu}_e$ / sec per GW_{th} (free for physicists)



Beta Decay and Neutrino History



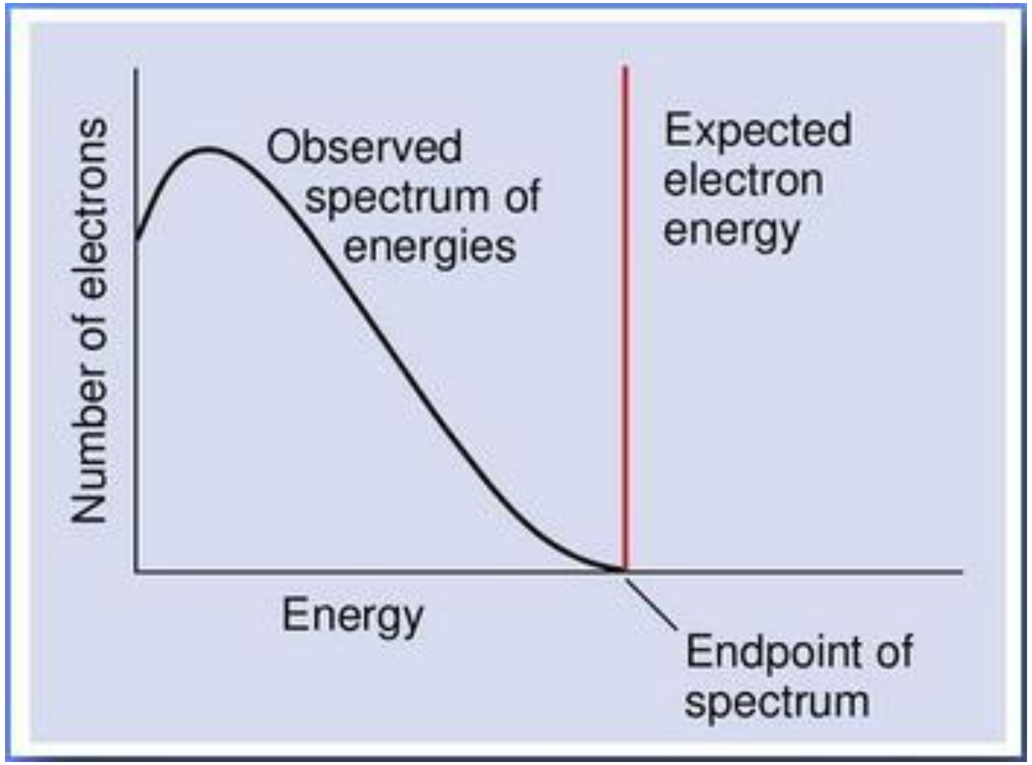
Weak nuclear force

number of protons and neutrons

$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + e^-$$

number of protons

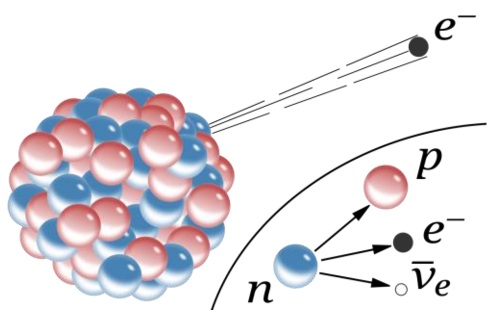
$$n \rightarrow p^+ + e^-$$



1899 – 1927

Rutherford, Meitner, Hahn, Chadwick, Ellis, Mott, *et. al*

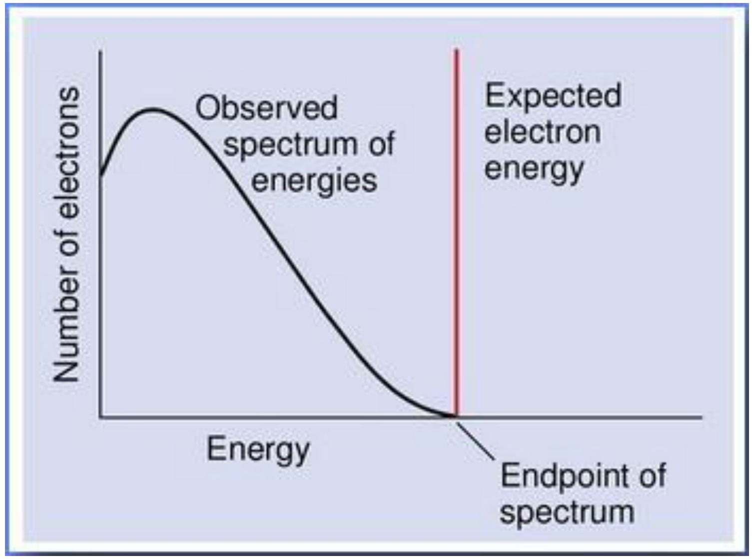
Neutrino: Proposed as a hypothetical particle



$$^{210}_{83}\mathrm{Bi} \rightarrow \, ^{210}_{84}\mathrm{Po} + e^- + \bar{\nu}_e$$

Wolfgang Pauli

1930: Pauli's letter to physicists at a workshop in Tubingen



Dear Radioactive Ladies and Gentlemen,

.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant..........

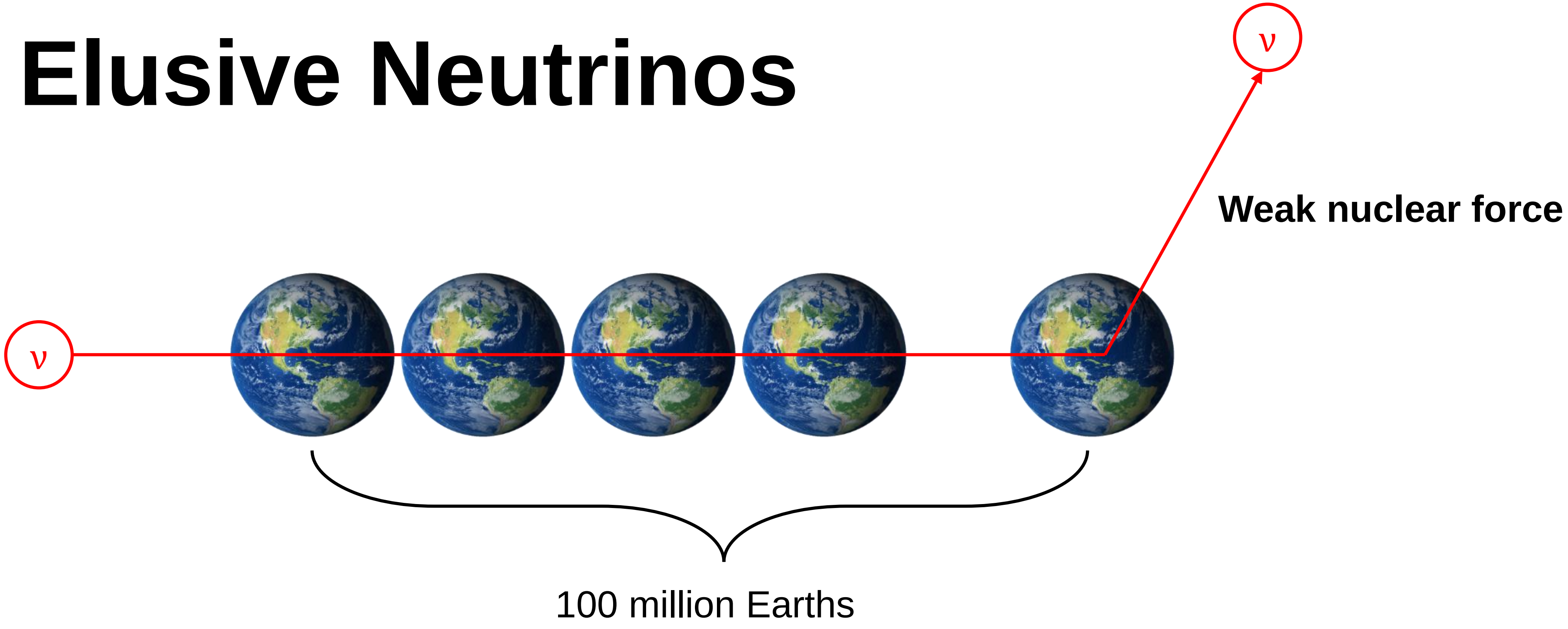
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

"I have done a terrible thing. I have postulated a particle that cannot be detected."

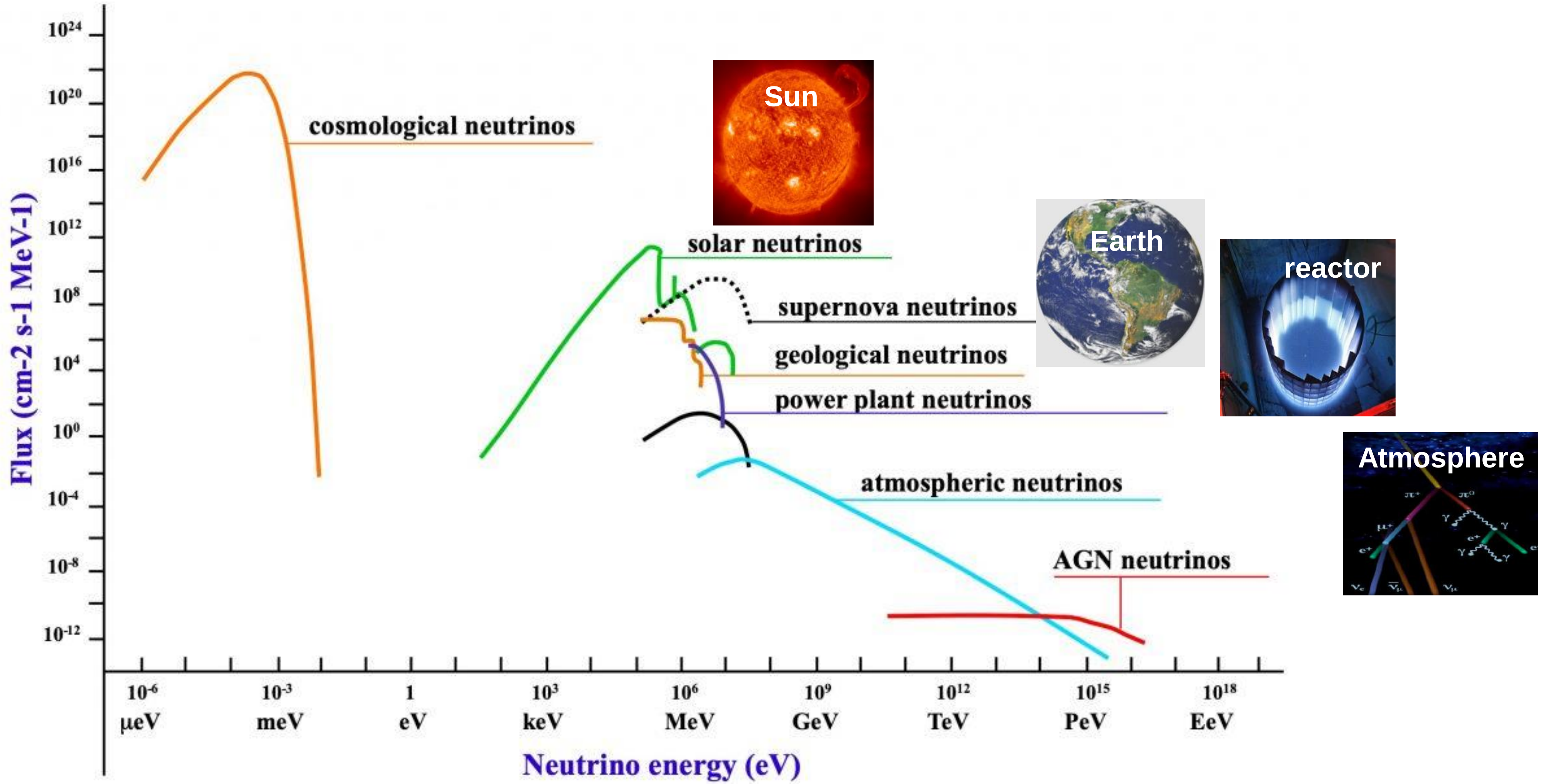
The Elusive Neutrinos



Neutrino detection requires:

- ❑ An intensive neutrino source: a billion trillion (~10^{21}) ν per second
- ❑ A huge neutrino detector: tons to kilotons of target material
- ❑ A distinctive method to tell "neutrino interactions" from other backgrounds

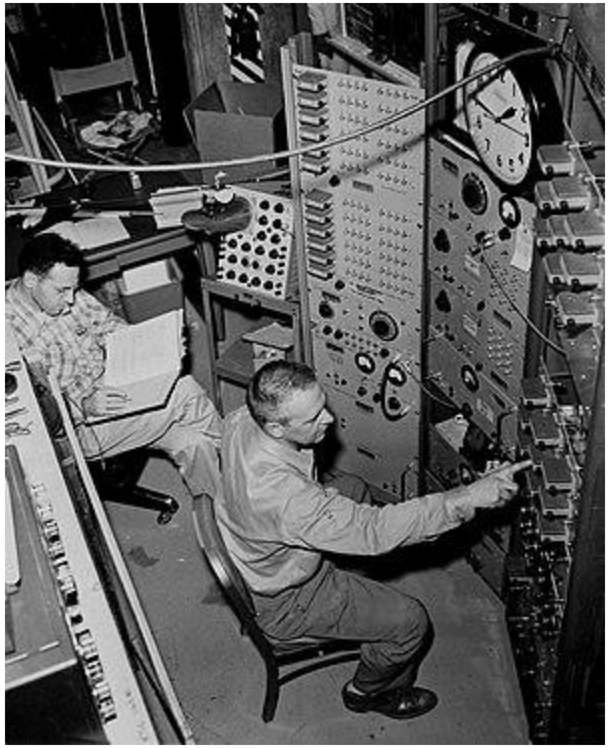
Neutrino Sources

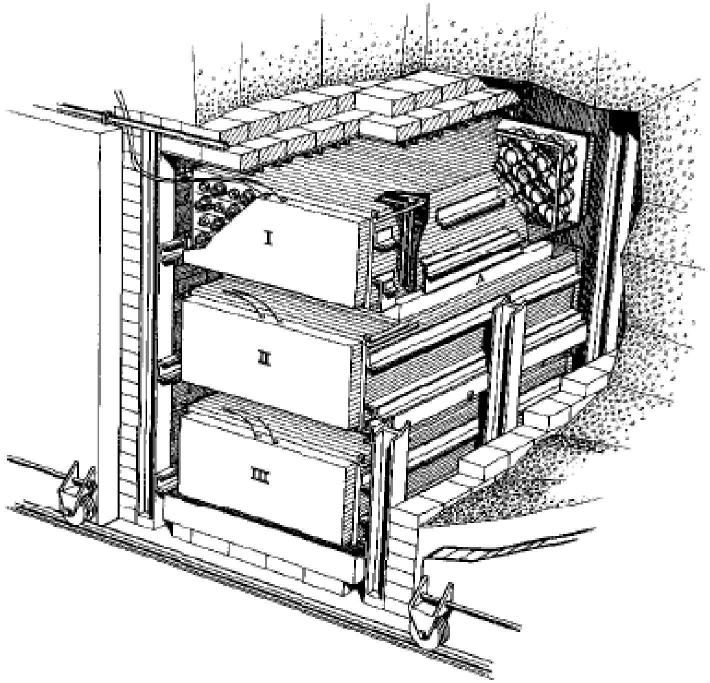


Neutrinos: First Detection

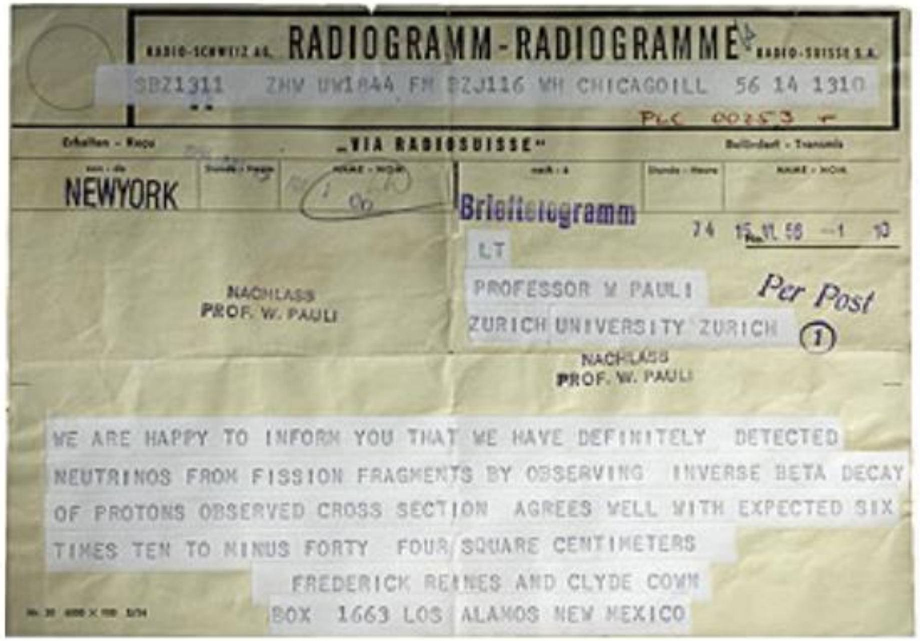
Reines and Cowan's telegram to W. Pauli (1956)

Frederick Reines and Clyde Cowan first detected (anti)neutrinos using the Savanah River nuclear reactor in South Carolina in 1956. (26 years after Pauli's proposal)





Target: Water + $CdCl_2$
Detector: Liquid Scintillator + PMTs



RADIOGRAMM-RADIOGRAMME

SBZ1311 ZHV UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

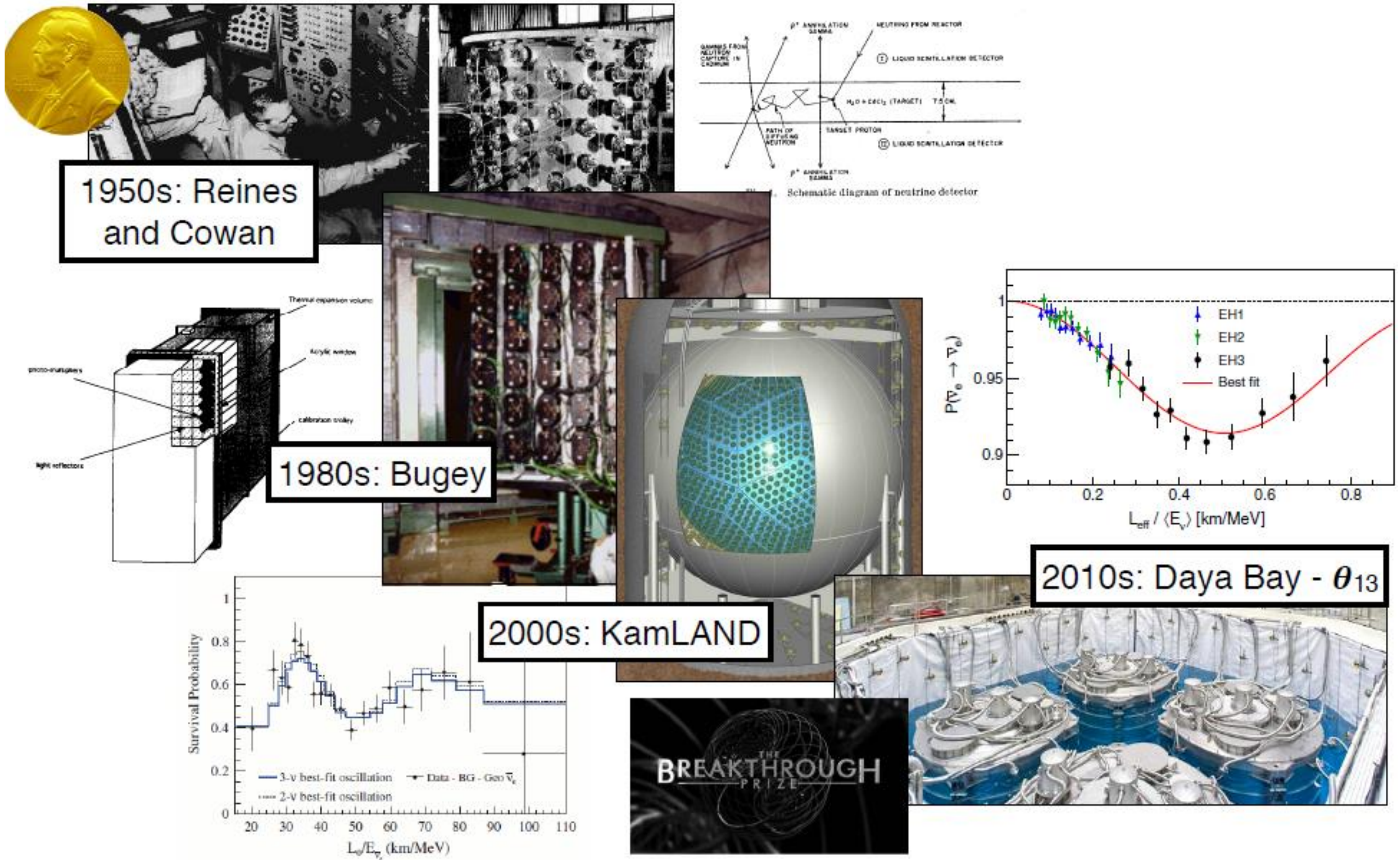
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons"

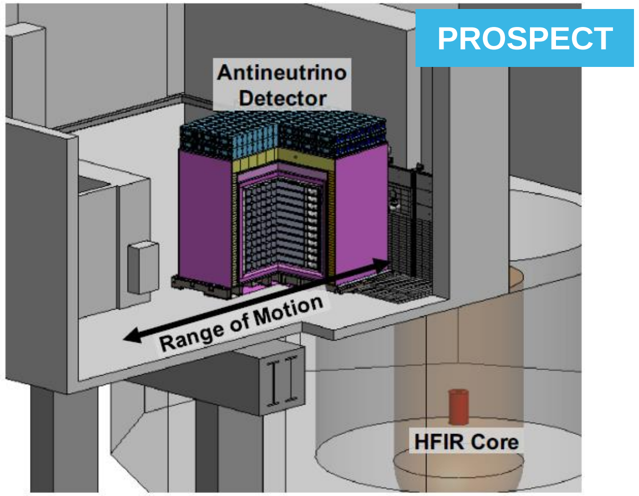
History of Reactor Neutrino Experiments

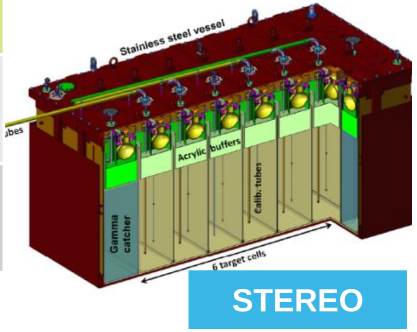


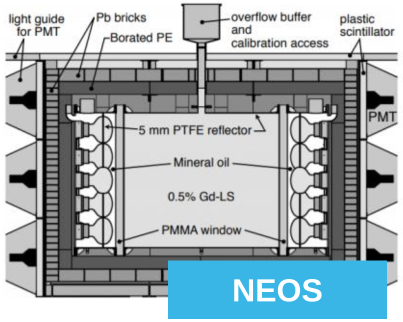
- Discovery of ν
- Solving solar ν problem on Earth
- Discovery of smallest oscillation angle θ_{13}
- Currently hold the best precision of
  - Δm^2_{21} (KamLAND)
  - θ_{13} (Daya Bay)
- Comparable precision to accelerator-based experiments
  - $|\Delta m^2_{32}|$ (Daya Bay)

A lot of recent short-baseline reactor experiments (2010 – now)

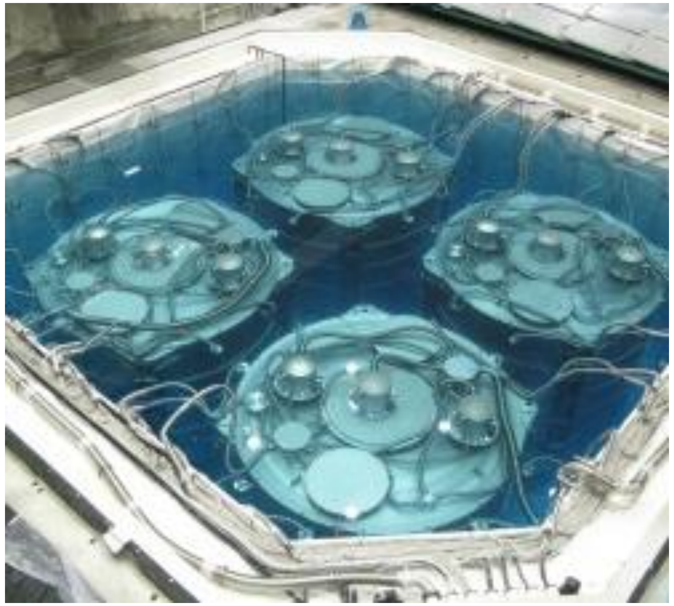
Experiment	Reactor	Baseline (m)	Overburden (m.w.e)	Mass (ton)	Segmentation	Energy res. (@ 1 MeV)
NEOS (South Korea)	LEU 2.8 GW	23.7	~20	1.0	none	5%
Nucifer (France)	HEU 70 MW	7.2	~12	0.6	none	10%
NEUTRINO4 (Russia)	HEU 100 MW	6 - 12	~10	0.3	2D	
DANSS (Russia)	LEU 3.1 GW	10.7 - 12.7	~50	1.1	2D	17%
STEREO (France)	HEU 58 MW	9 – 11	~15	1.6	1D 25 cm	8%
PROSPECT (USA)	HEU 85 MW	7 - 12	< 1	1.5	2D 15cm	4.5%
SoLid (UK Fr Bel US)	HEU 70 MW	6 - 9	~10	1.6	3D 5cm	14%
CHANDLER (USA)	HEU 75 MW	5.5 - 10	~10	1.0	3D 5cm	6%
NuLAT (USA)	HEU 20 MW	4	few	1	3D 5cm	4%

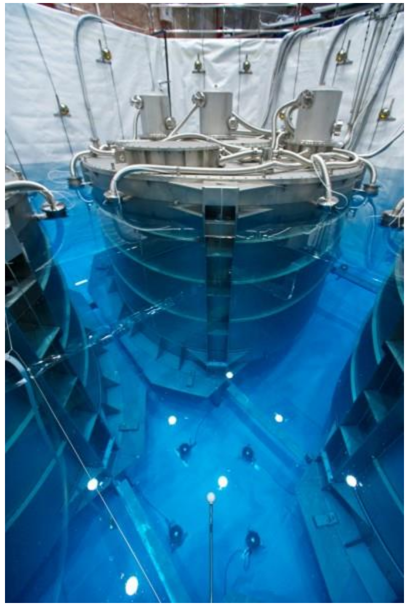


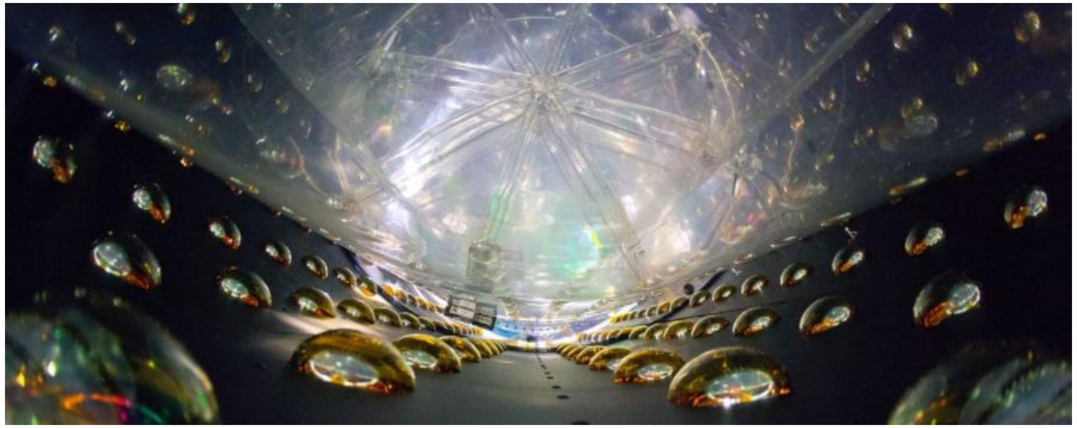




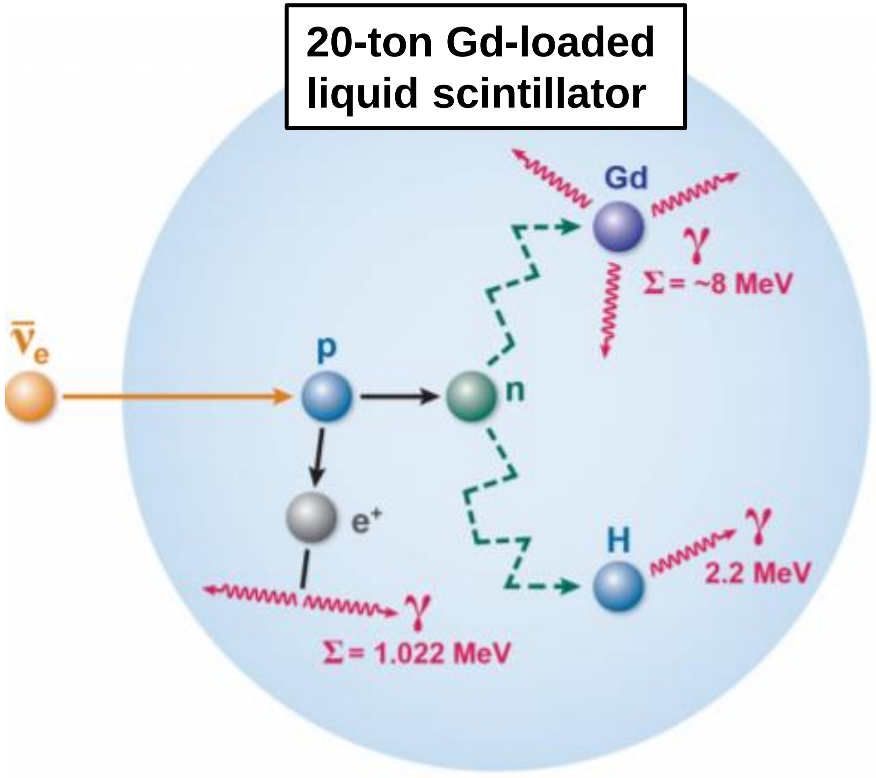
Detecting Reactor Neutrinos







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



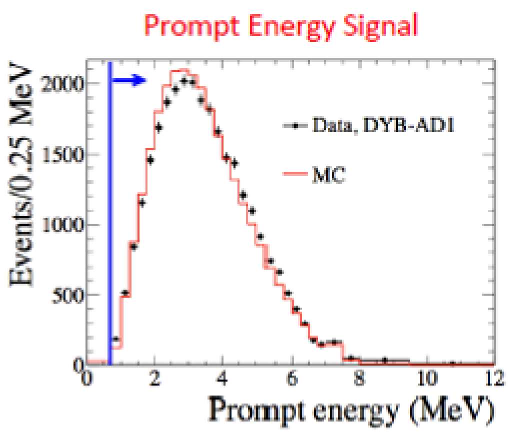
Daya Bay Reactor Neutrino Experiment

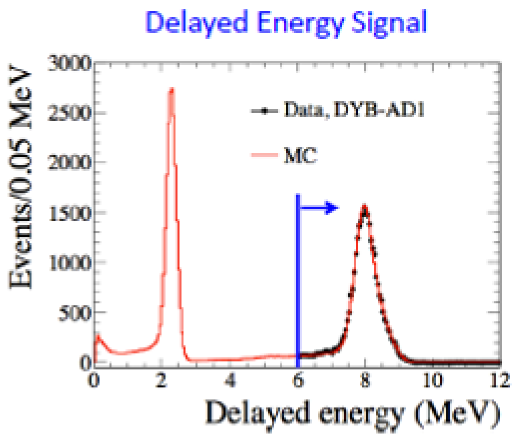
Detecting Reactor Neutrinos

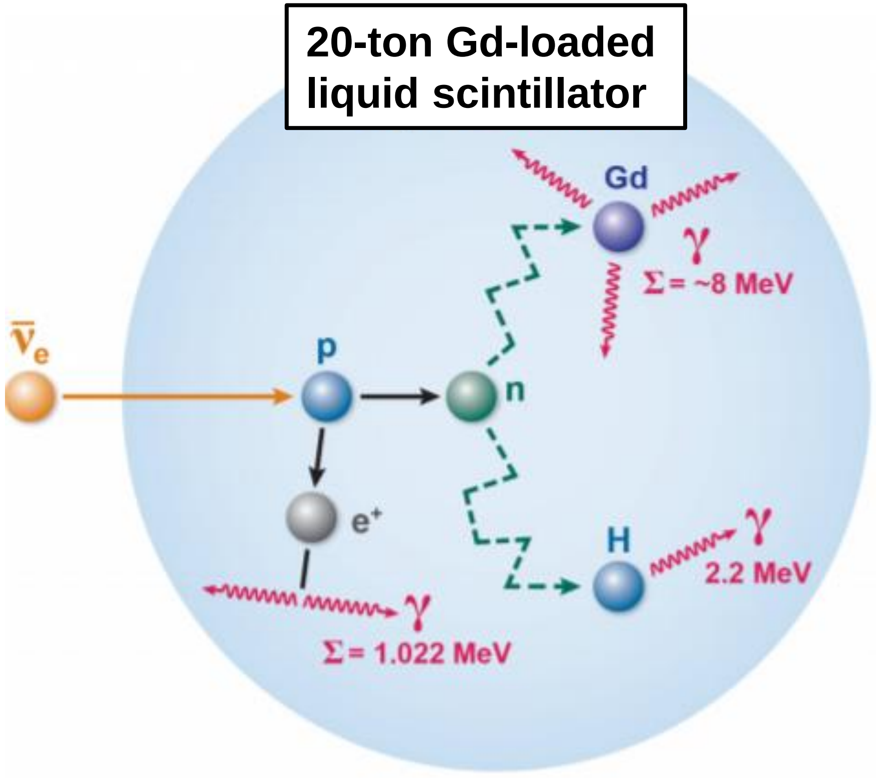
Inverse Beta Decay (IBD)

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

- $E_{threshold}$ = 1.8 MeV
- 'Large' cross section $\sigma \sim 10^{-42}$ cm^2
- Distinctive coincidence signature in a large liquid scintillator detector







Daya Bay Reactor Neutrino Experiment

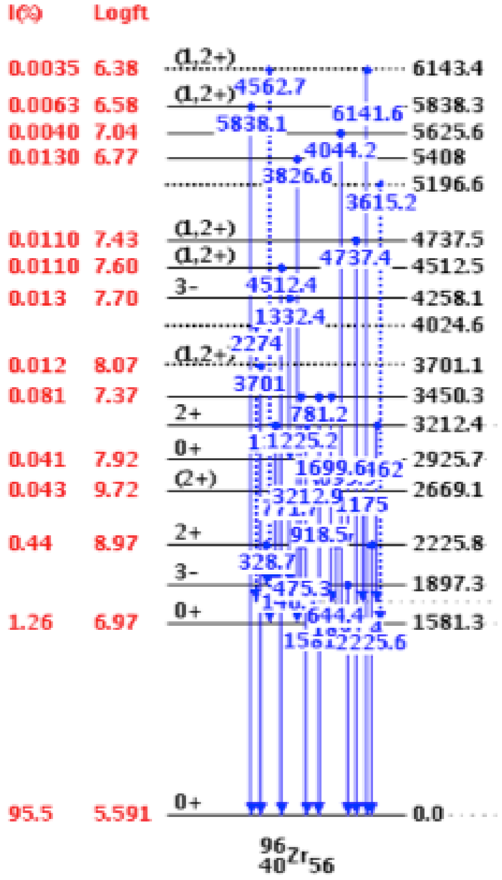
Predict Reactor Antineutrino Flux (I)

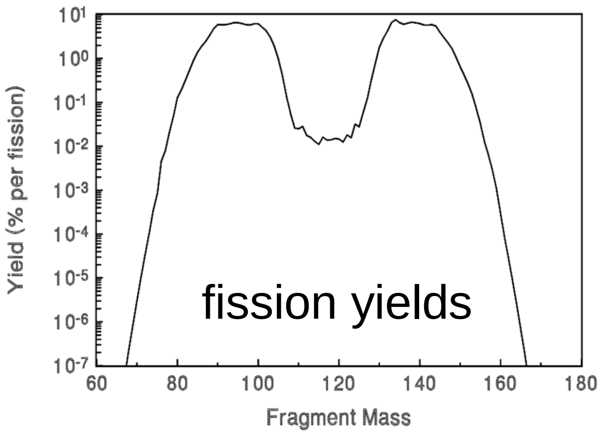
- Summation (ab initio) method
  - Calculate each beta-decay spectrum using nuclear databases: fission yields, decay schemes, etc.
  - ~10% uncertainty

National Nuclear Data Center — BROOKHAVEN NATIONAL LABORATORY

http://www.nndc.bnl.gov

Example: ^{96}Y decay





In total, >6000 tabulated decay branches.

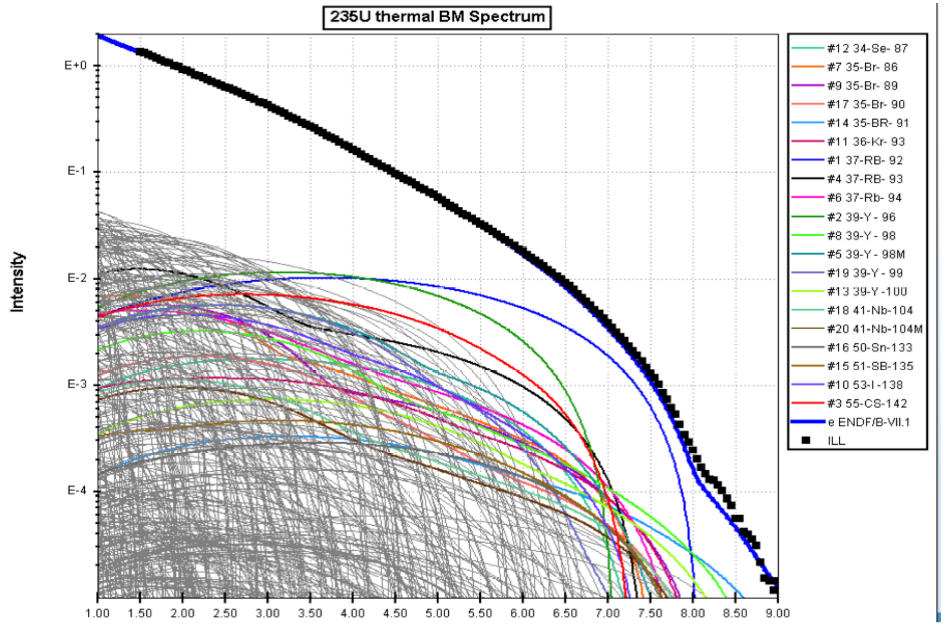
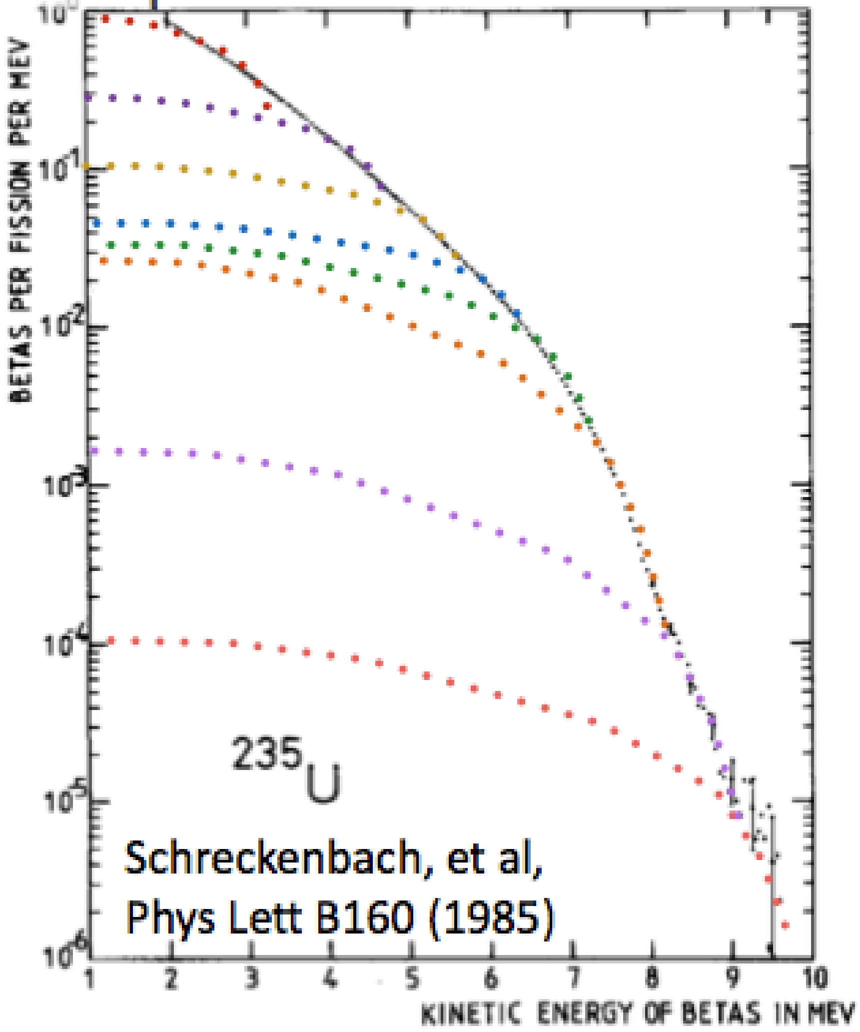


Figure from Sonzogni et

Predict Reactor Antineutrino Flux (II)

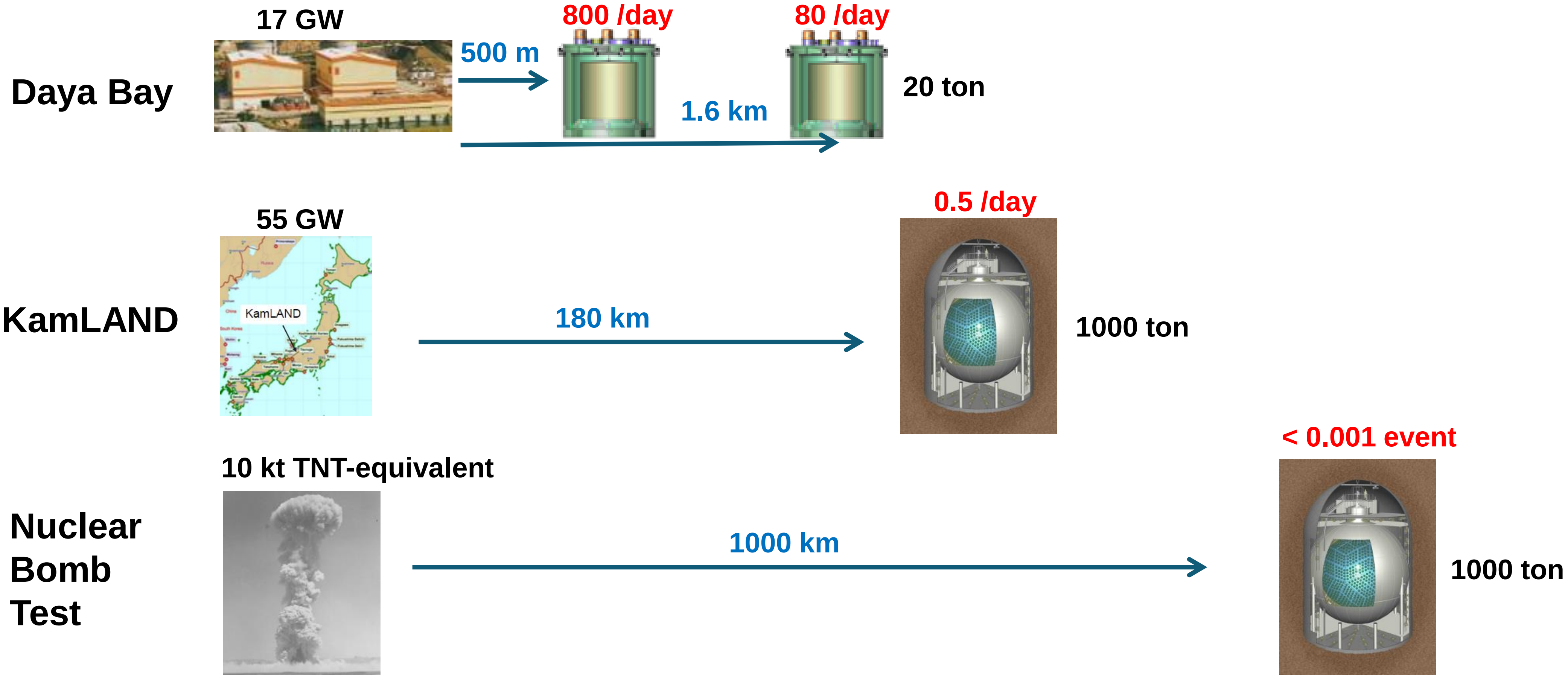
- **Conversion Method**
  - Expose fission parents to thermal neutrons and measure total outgoing beta-decay electron energy spectra. (*Experiments done at ILL in the 1980s*)
  - Predict corresponding anti-neutrino spectra with >30 virtual branches
  - Re-analyses in 2011 increased prediction by ~5%
  - More precise (~2.5%) but recent works indicate >5% uncertainty

Example: Fit virtual beta branches

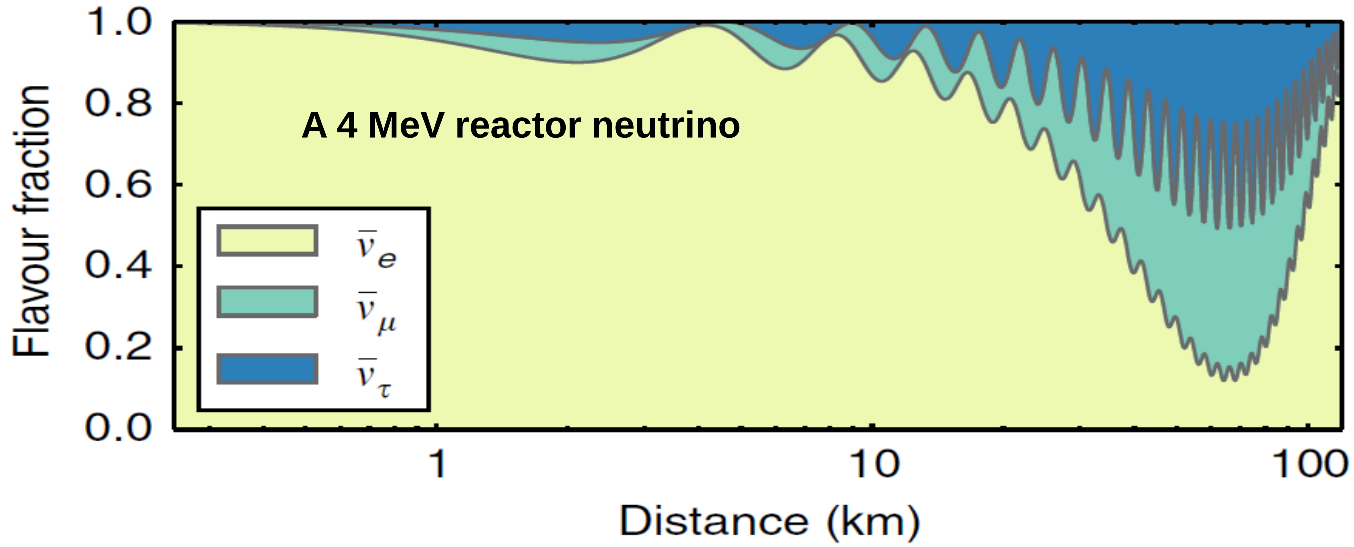


Event Rate

- Depending on the <u>power</u> of the reactors, <u>size</u> of the detectors, and the <u>distance</u> between them



Neutrino Oscillations with Reactors

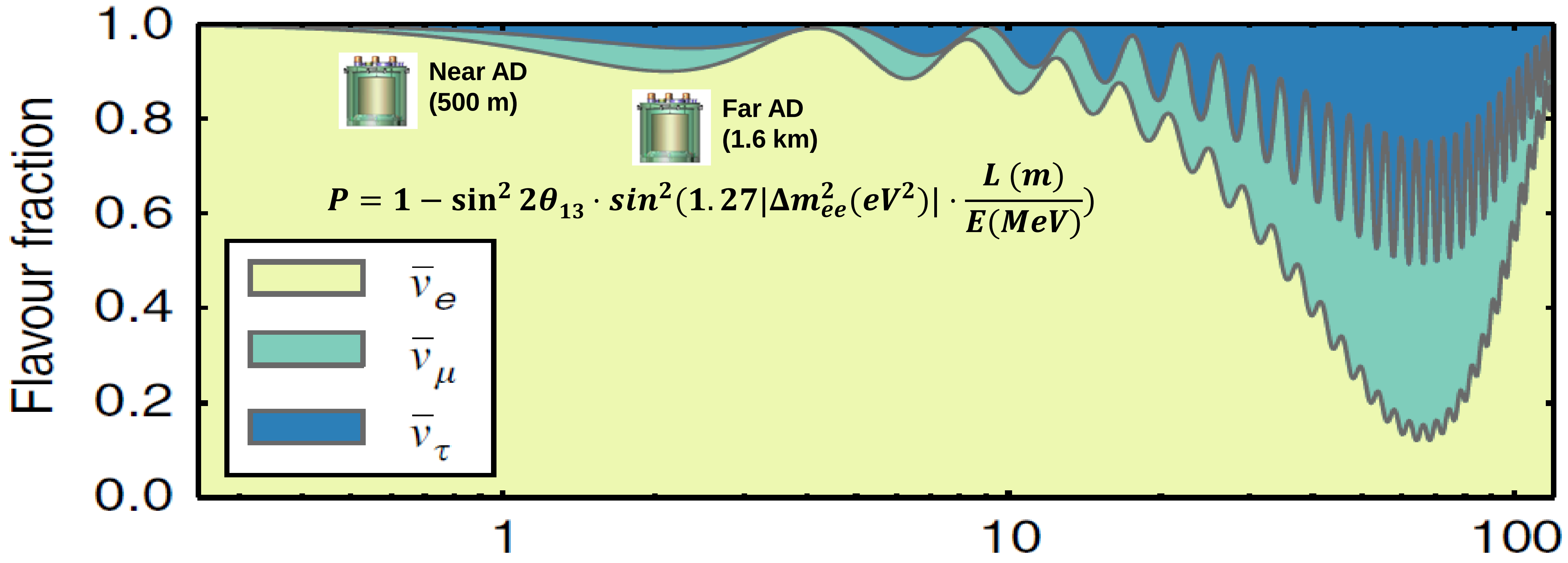


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

↓

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{pmatrix}$$

Solar / Long baseline reactor	Short baseline reactor / Long baseline accelerator	Atmospheric / Long baseline accelerator	Neutrinoless double beta decay



$$\frac{N_{far}}{N_{near}} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\cdot\left(\frac{L_n}{L_f}\right)^2\cdot\left(\frac{\varepsilon_f}{\varepsilon_n}\right)\cdot\left(\frac{P_{survival}(E,L_f)}{P_{survival}(E,L_n)}\right)$$

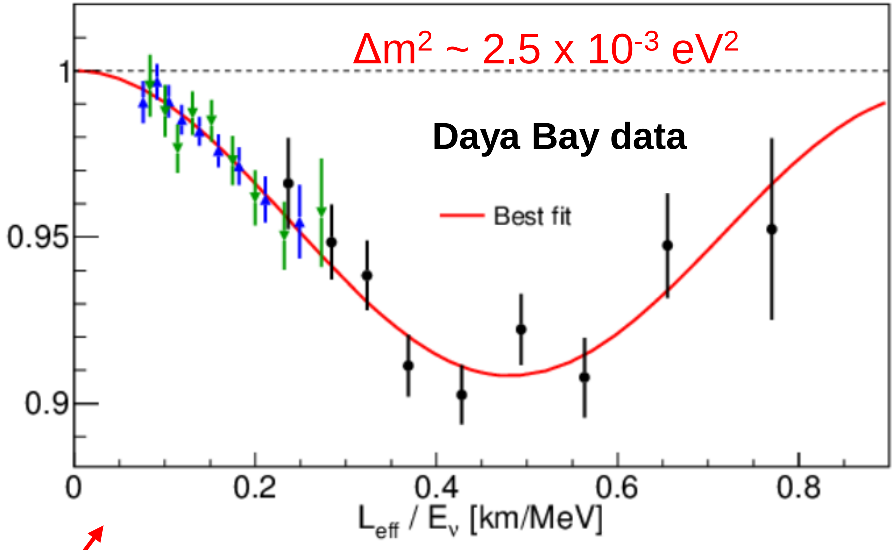
Far/Near Neutrino Ratio

Detector Target Mass

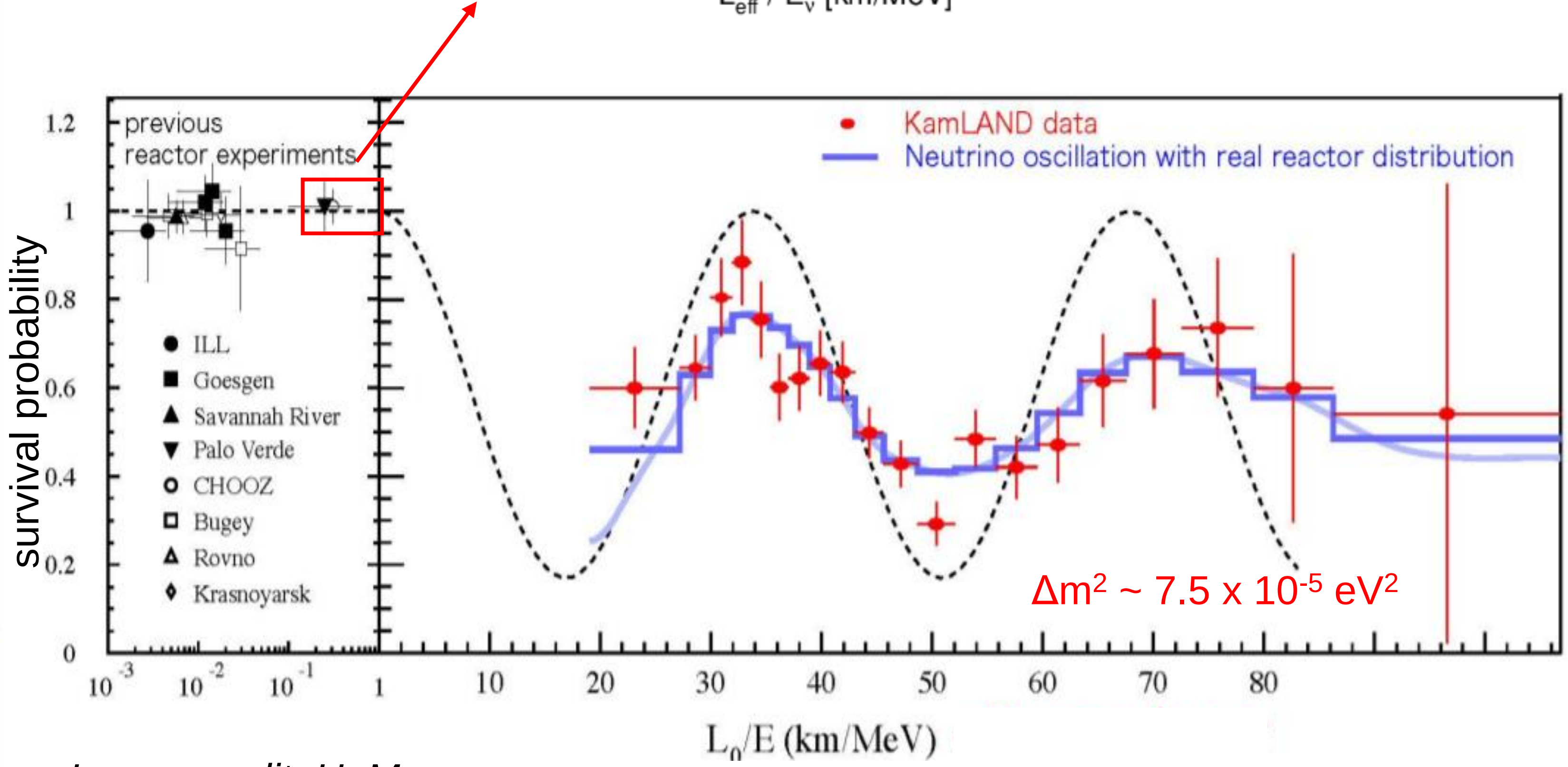
Distance from Reactor

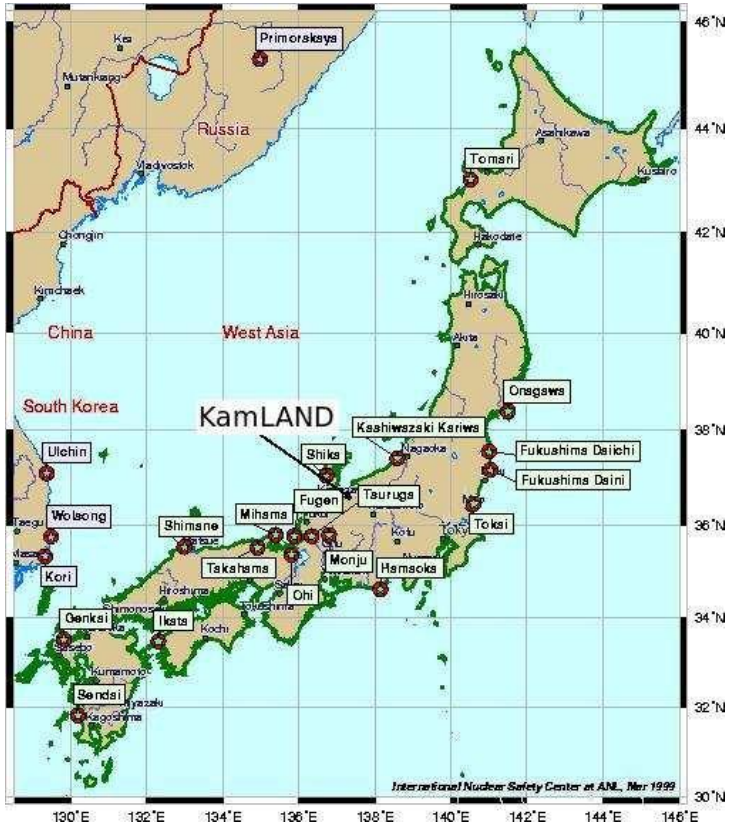
Detector Efficiency

Survival Probability (θ_{13})



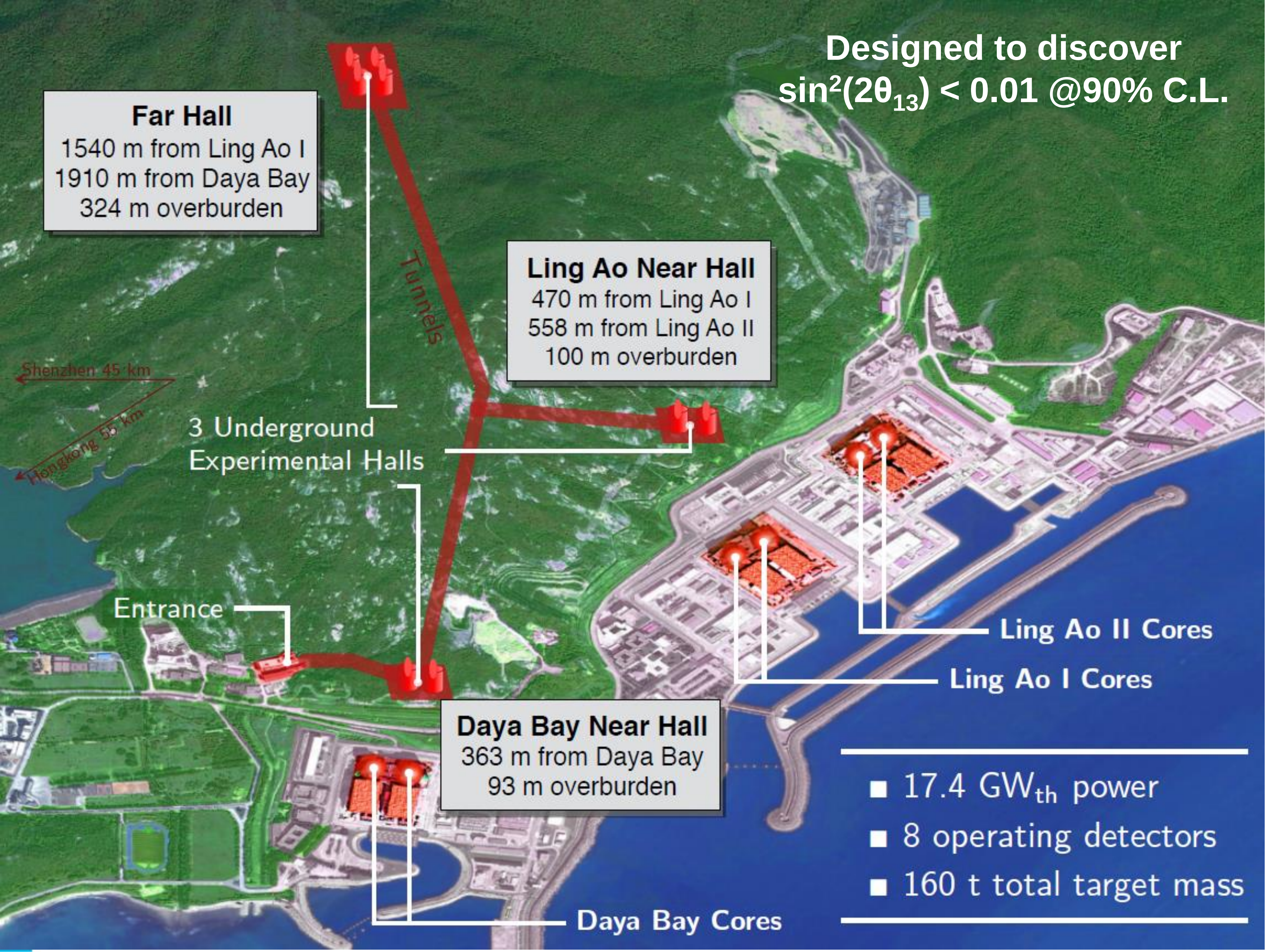
My postdoc work at BNL





My Ph.D. thesis

Image credit: H. Murayama



Statistics

- powerful reactors (17.4 GW_{th}) + large detectors (80 ton at Far site)

Systematics

❑Reactor

- Far/Near relative measurement

❑Detector

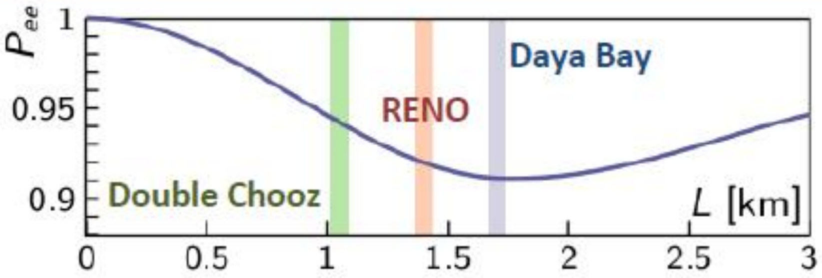
- multiple functionally identical detectors (4 Near + 4 Far)

❑Background

- deep underground (860 m.w.e at far site)

Baseline Optimization

- Detector locations optimized to known parameter space of $|\Delta m^2_{ee}|$
- Far site maximizes term dependent on $\sin^2 2\theta_{13}$



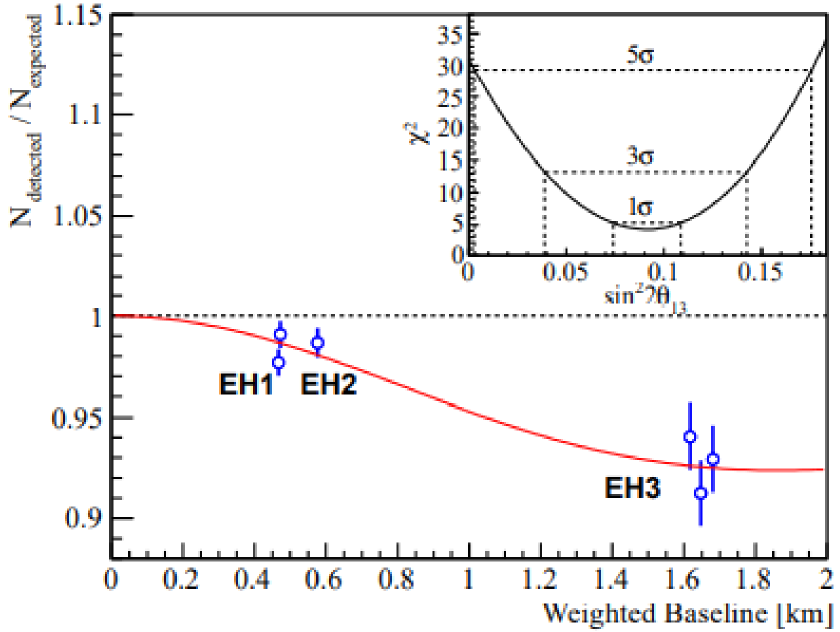
Go strong, big and deep!

	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

BNL Daya Bay Group, 2011

Discovery of non-zero θ_{13} at 5.2 σ

- 2011/12/24 – 2012/2/17 (55 days)
- 6 detectors in operation first



Phys. Rev. Lett. 108, 171803 (2012)

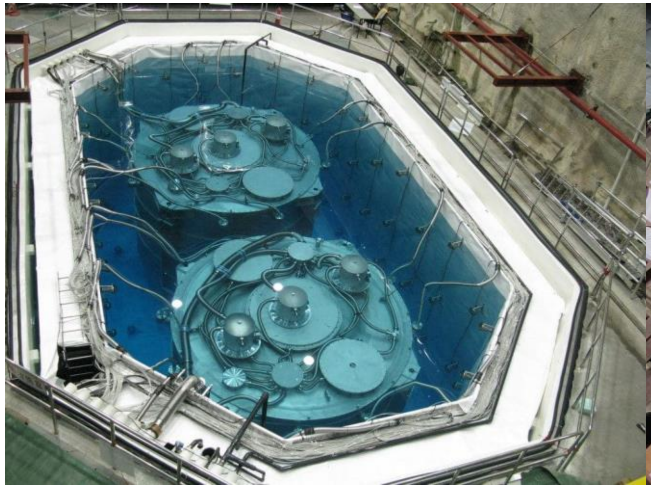
In fact, in the first 5 days we already knew that θ_{13} is large from the data. In the homework I'll give you all the inputs to do a simplified analysis.

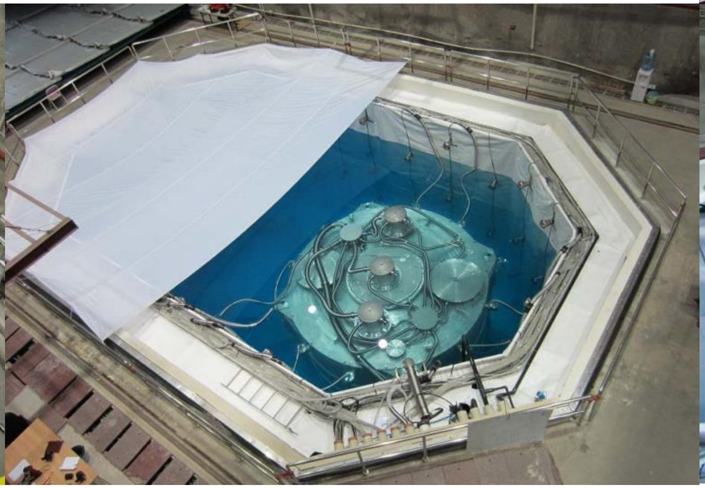
End of operation ceremony (Dec 24, 2011 - Dec 12, 2020)

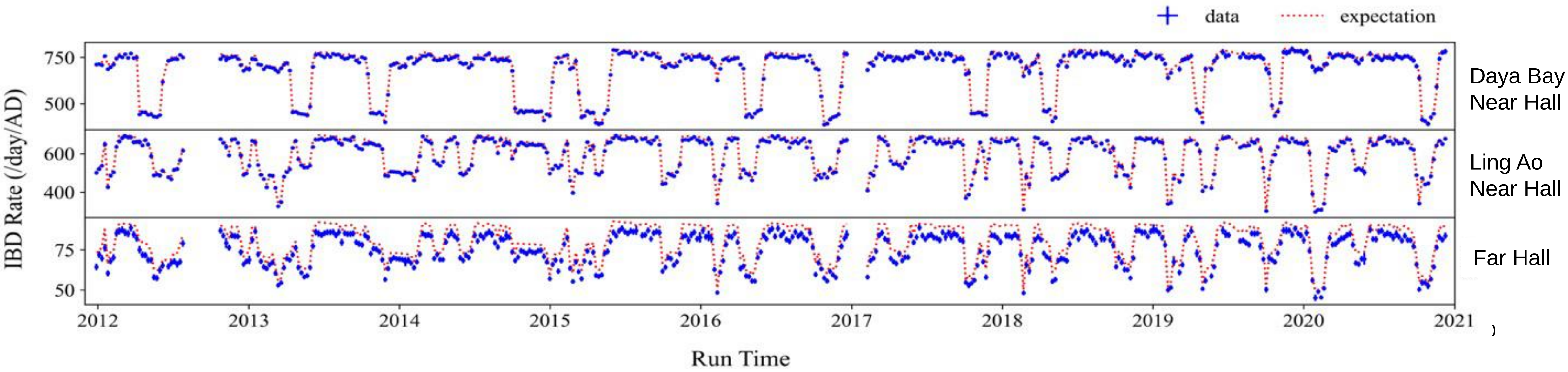
BNL virtual mini-symposium: The Daya Bay Reactor Neutrino Experiment and the Discovery of Non-zero Theta13

https://indico.bnl.gov/event/9947/

- Data taking (12/24/2011 – 12/12/2020)
  - 3275 days, 5.5M $\bar{\nu}_e$ events
    largest reactor neutrino data sample in the world







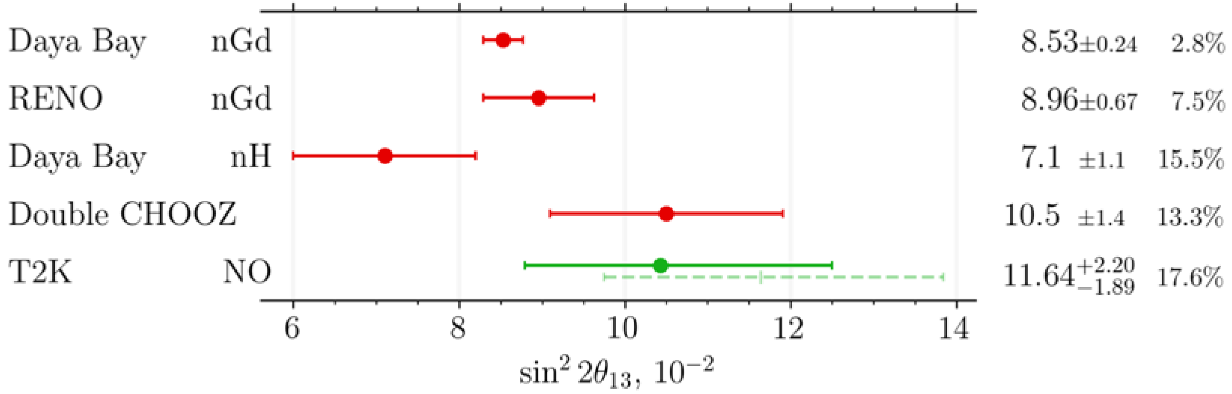
Precision Oscillation

- **Final results with the full data set**

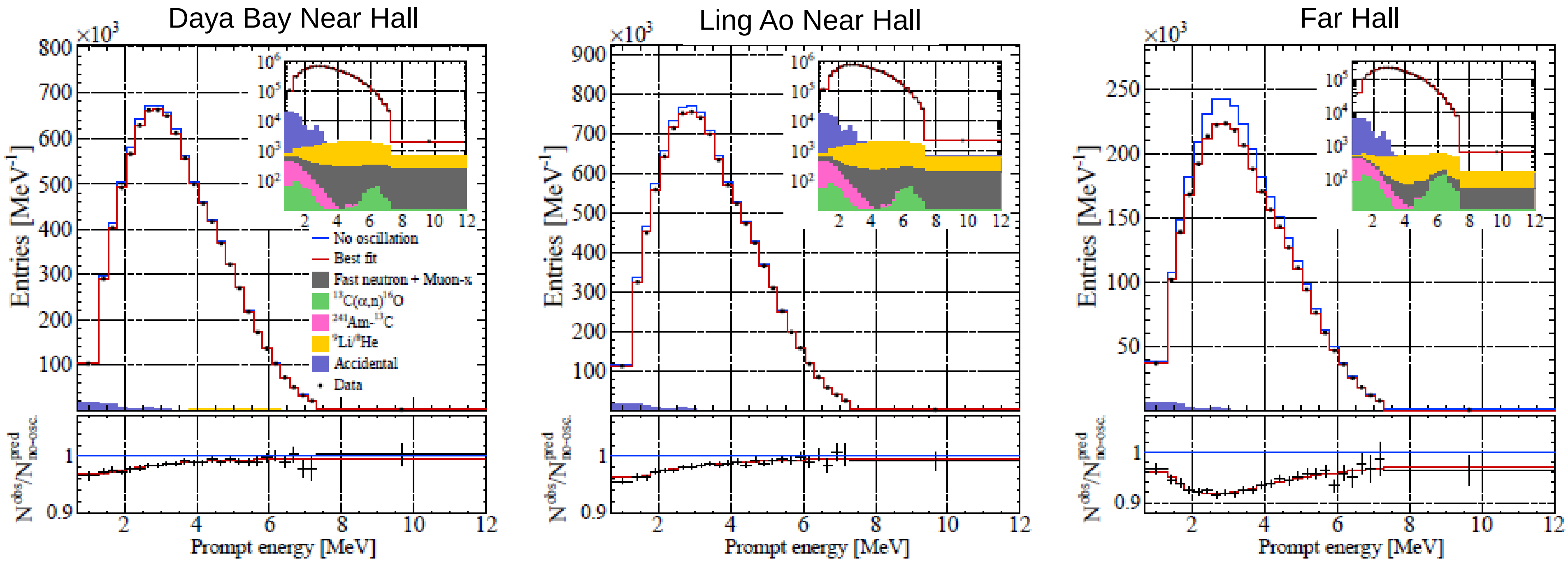
Phys. Rev. Lett. 130, 161802 (2023)

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

(2.8% precision)



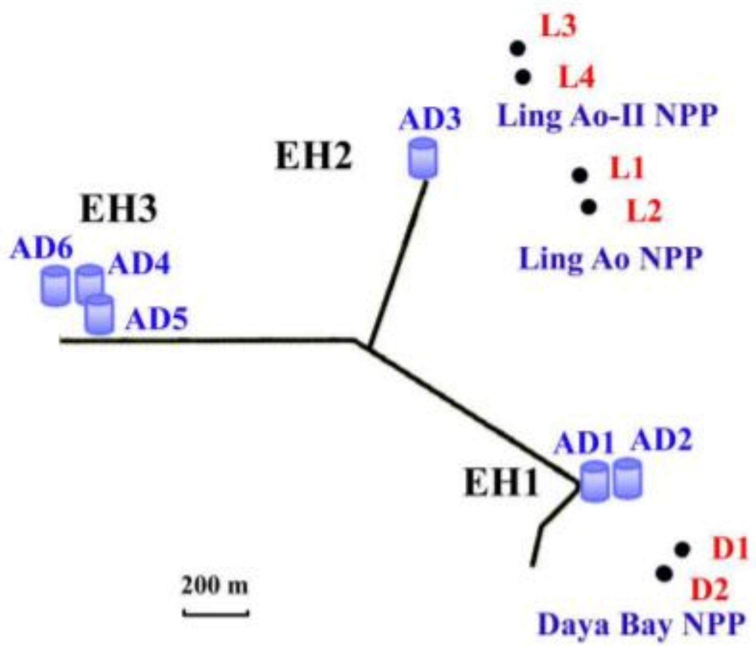
- Likely to be the best measurement in the foreseeable future
- Critical input to the current and future long-baseline experiments (DUNE)



Homework Problem

- How to discover the smallest neutrino oscillation with 5 days of Daya Bay reactor neutrino data?

Reactor and Detector Location



Reactor	D1	D2	L1	L2	L3	L4
x (m)	43.0	-44.6	856.0	792.3	1143.6	1076.5
y (m)	-7.0	6.9	830.9	767.9	1206.1	1138.5
z (m)	-12.0	-12.0	-12.0	-12.0	-12.0	-12.0

AD	1	2	3	4	5	6
x (m)	94.5	97.8	584.1	-254.3	-259.5	257.3
y (m)	350.2	345.2	1216.2	1892.6	1889.6	897.8
z (m)	-20.0	-20.0	-16.6	-15.4	-15.4	-15.4

- All reactor cores operated at approximately equal power for the 5 days
  - L2 was powered off during the 5 days

Summary of event selection for the first 5 days

	EH1 AD1	EH1 AD2	EH2 AD1	EH3 AD1	EH3 AD2	EH3 AD3
IBD Candidates	3278	3194	2193	338	350	348
DAQ Live Time [days]	5.39	5.39	4.97	5.20	5.20	5.20
Accidentals	60.9	59.6	49.3	20.5	19.4	19.3
Li9	43	42	28	4	4	4
Fast Neutron	6	6	6	0.6	0.6	0.6
Efficiency	0.8144	0.8120	0.8510	0.9515	0.9501	0.9508

Signal + Backgrounds

Backgrounds

- Calculate the signal rate per day after efficiency correction
  - EH1-AD1: (3278 - 60.9 – 43 - 6) / 0.8144 / 5.39 = 721.7 events/day
- Calculate the statistical error on the signal rate
  - EH1-AD1: sqrt(3278)/0.8144/5.39 = 13.0 events/day

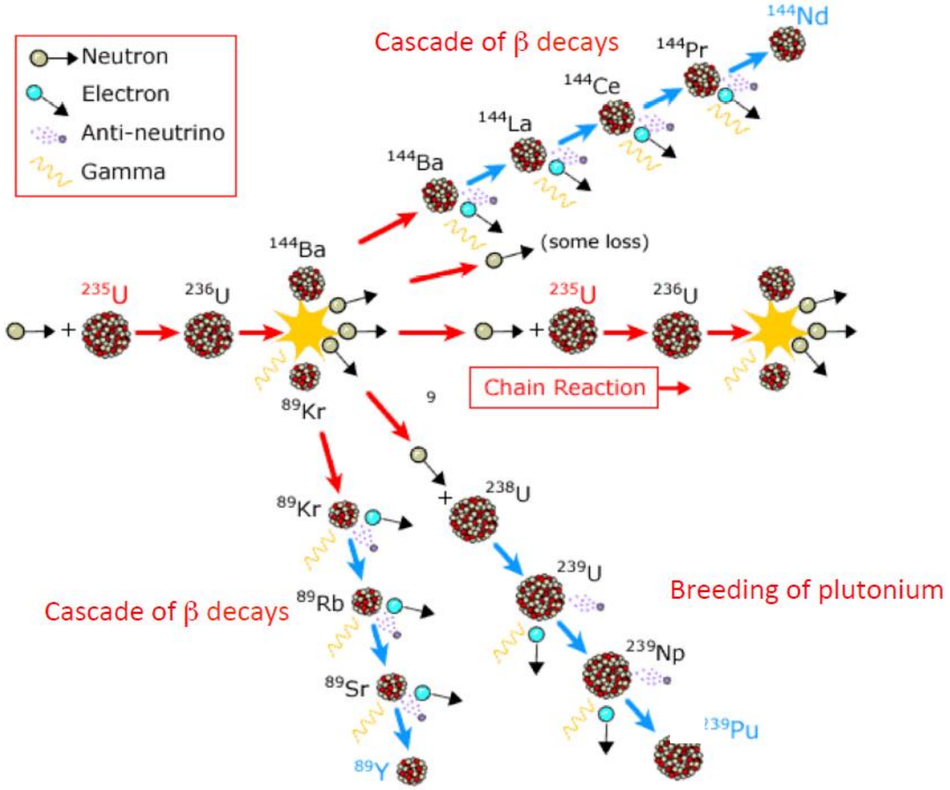
- How to discover the smallest neutrino oscillation with 5 days of Daya Bay reactor neutrino data?
  1. Plot the measured antineutrino signal rate of each AD vs. the expected flux, assuming each AD has the same size, and each reactor has the same power.
  2. Fit the data (what function to use?) with the near ADs and extrapolate to the far ADs. What do you see?
  3. What is the "survival probability" in the far ADs relative to the near ADs? What is the statistical significance of this observation?
  4. What is the size of θ_{13} using the oscillation formula?

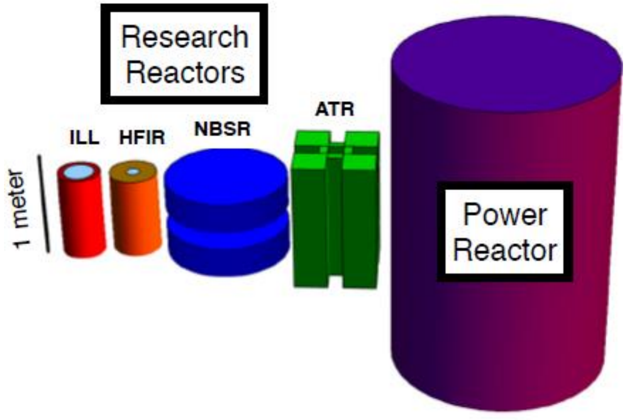
$$P = 1 - \sin^2 2\theta_{13} \cdot sin^2(1.27|\Delta m^2_{ee}(eV^2)| \cdot \frac{L\ (m)}{E(MeV)})$$

Δm^2	2.4×10^{-3} (eV^2)
L	1.66×10^3 (m)
E	3.5 (MeV)

Backup Slides

Nuclear Reactor as (anti)Neutrino Source





- Nuclear reactors produce pure $\overline{\nu}_e$ from beta decays of fission daughters
  - neutrino energy: < 10 MeV, peak ~ 4 MeV
- 6 $\overline{\nu}_e$ / fission
- 2 x 10^{20} $\overline{\nu}_e$ / sec per GW_{th} (free for physicists)

- Commercial reactors in Nuclear Power Plants have low-enriched uranium (LEU) cores
  - Mixture of fissions: ^{235}U (~55%), ^{239}Pu (~30%), ^{238}U (~10%), ^{241}Pu (~5%)
  - Large power: ~3 GW_{th}
- Research reactors have highly-enriched uranium (HEU) cores
  - ^{235}U fission fraction ~99%
  - Lower power, few tens of MW_{th}
  - compact size

Background Components

- Accidentals: statistically calculate from uncorrelated singles
- Li9 / He8: measure time distribution of after-muon events
- Fast neutron: measure energy spectrum from AD/water/RPC tagged muon events

Background	Near	Far	Uncertainty
Accidentals	1.4%	2.3%	negligible
Li-9 / He-8	0.4%	0.4%	~30%
Fast neutron	0.1%	0.1%	~30%