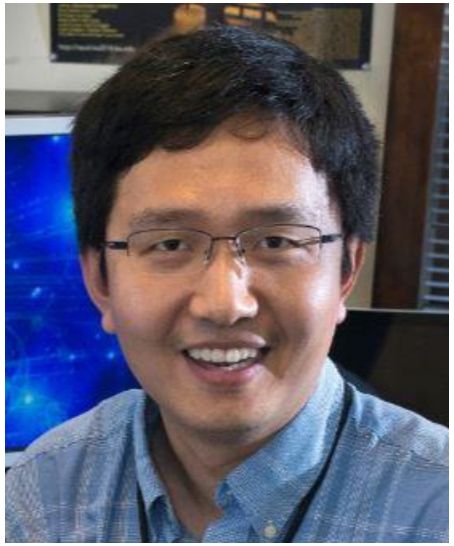
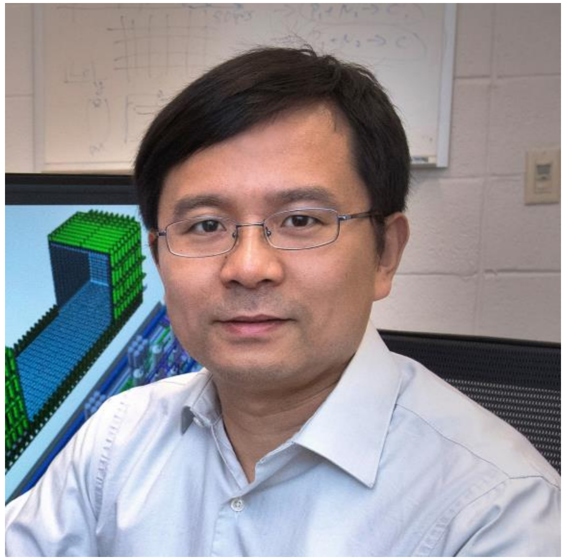
Reactor Neutrinos



Xin Qian
xqian@bnl.gov

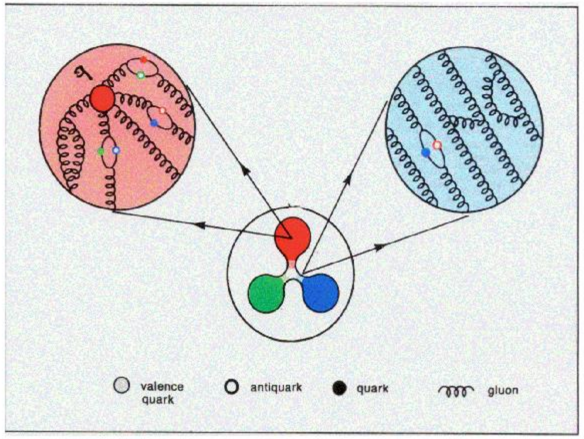


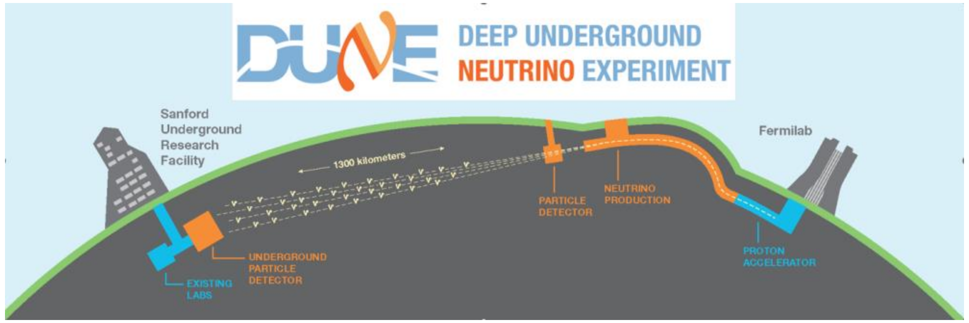
Brookhaven™ National Laboratory

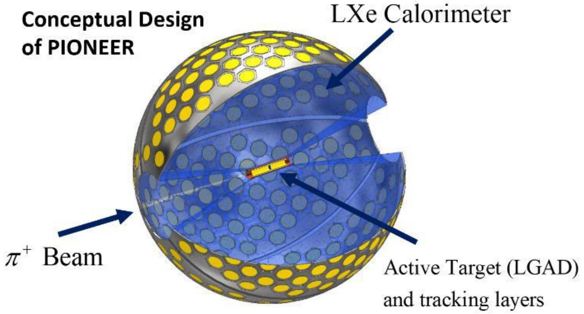
Borrowed many materials from my colleague Dr. Chao Zhang (czhang@bnl.gov), who is traveling right now

Me and Reactor Neutrinos

- Physicist in the Electronic Detector Group (EDG), Physics Department, BNL
  - PhD @ Duke University (2010)
    - Nucleon spin structure with electron scattering
  - Post-doc @ Caltech (2010-2013)
    - Daya Bay experiment (China)
    - LBNE → DUNE experiment
  - Staff Scientist @ BNL (2013-Now): [BNL | Staff | Xin Qian, Physics Department]
    - PROSPECT experiment (US)
    - LArTPC technology development for DUNE
    - PIONEER: rare decay experiment







Worlds’ First Nuclear Reactor

Chicago Pile-1 (CP-1) **~ 0.5 W power**

- Part of the Manhattan Project
  - Did you watch “Oppenheimer” last weekend?
- Design
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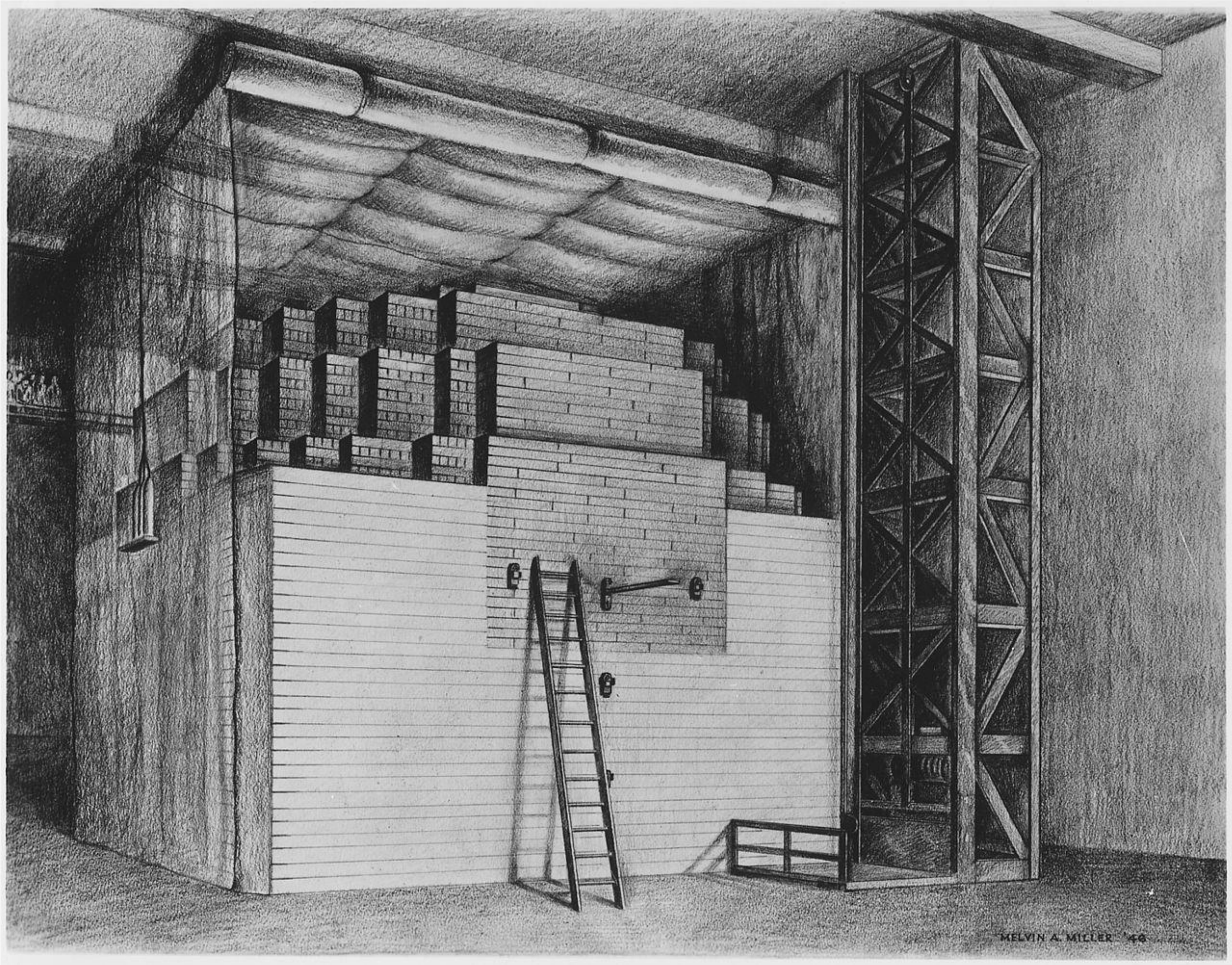
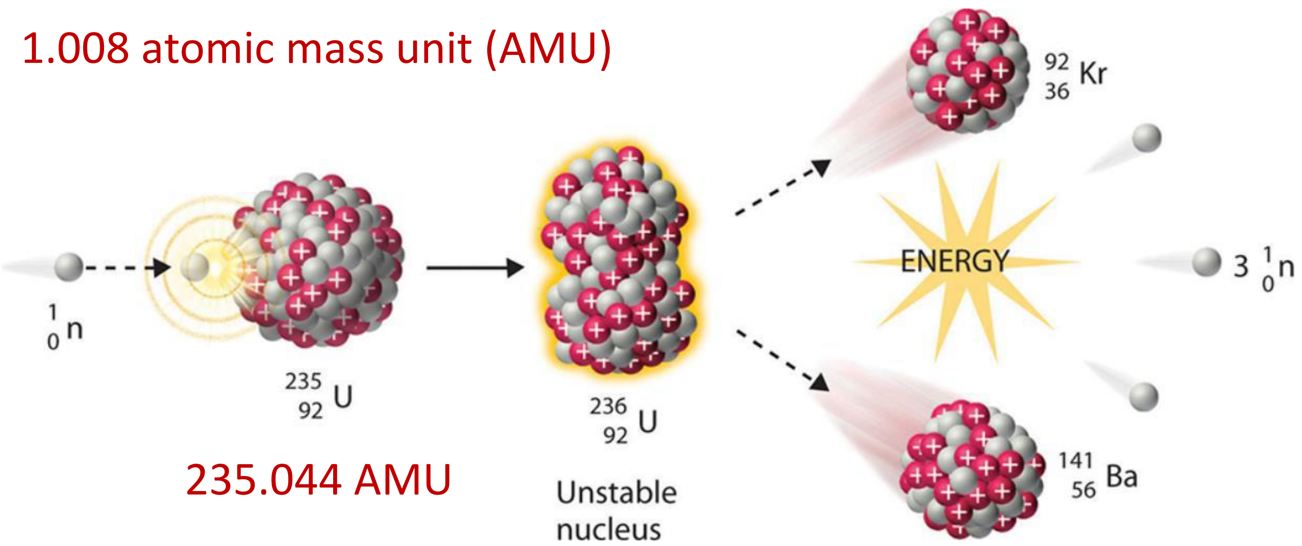

CP-1 in a squash court under the stands of Staff Field @ U. Chicago

Fission and Energy Release $E = mc^2$



91.926 AMU

1.008 atomic mass unit (AMU)

235.044 AMU

140.883 AMU

1 fission ≈ 0.219 AMU ≈ 200 MeV

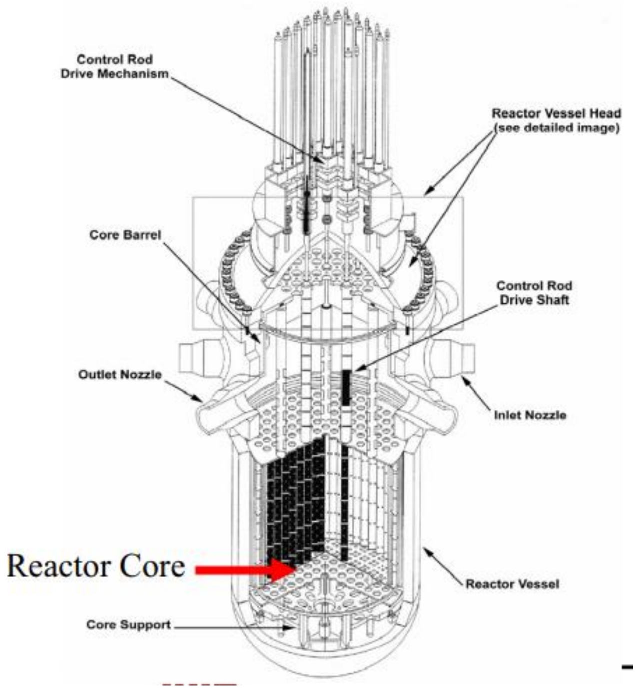
- 1 g of U-235 fission = 24,000 kwh
  - 3.2 tons of coal
  - 12.6 barrel of oil
  - Lightening of a small city overnight
- Energy density (energy/mass) of U-235 = 28,000 times of that of coal

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

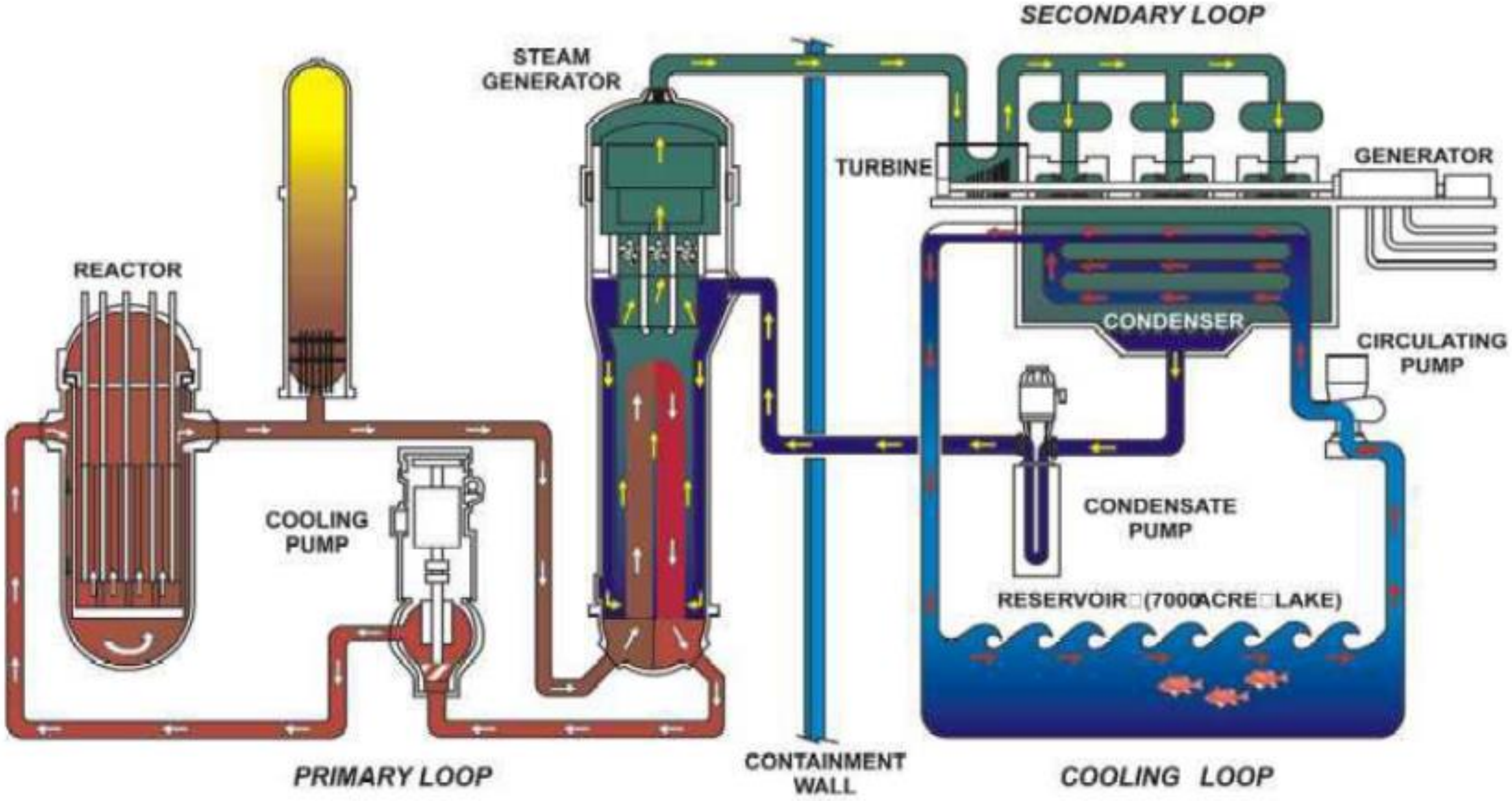
- Thermal neutrons: needs “moderator” to slow down neutrinos (water, graphite etc.)
- Controllable fission: engineering to make output neutron = 1



Core Heat Removal
- Coolant: Heat Transfer
- Safety Systems

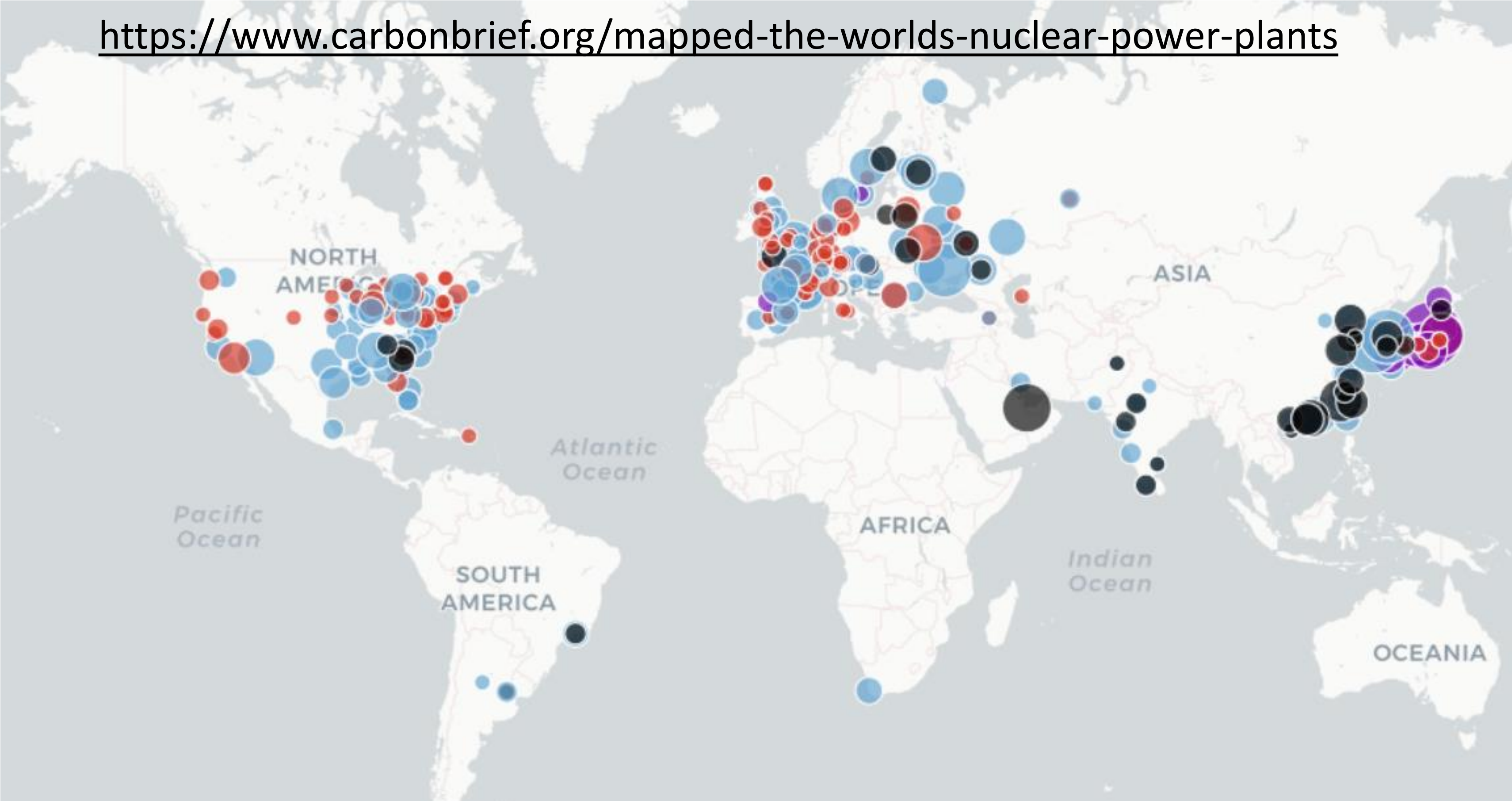
- Confinement of Radioactivity
- Electricity Production
- Spent fuel processing

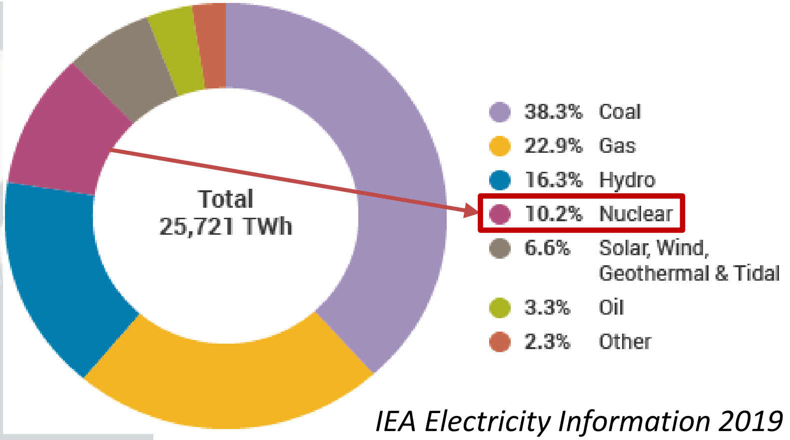
Schematic of a Pressurized Water Reactor (PWR)



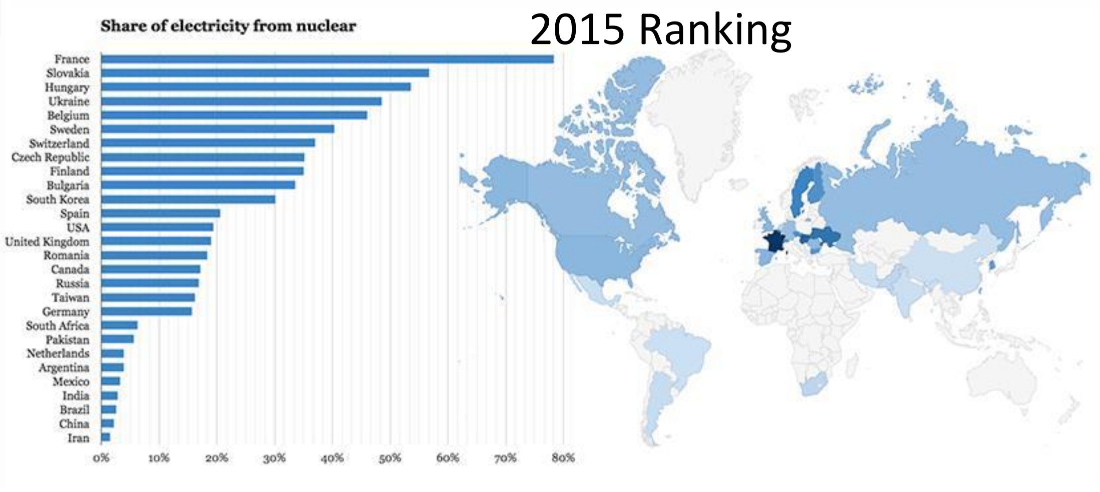
Reactor Core Design:
- Core Power Distribution
- Ability to shutdown plant
- No fuel failure or melting

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


https://www.carbonbrief.org/mapped-the-worlds-nuclear-power-plants



IEA Electricity Information 2019



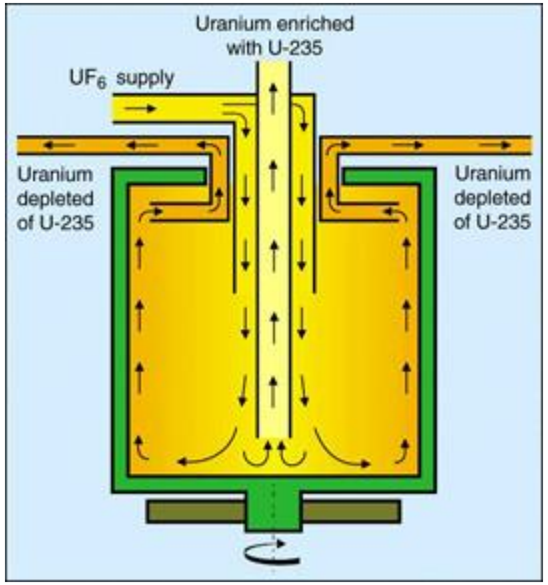
2015 Ranking

- **>450** operating nuclear reactors with **>50** under construction in **>30** countries, contributing to **~10%** of global electricity

Production of Weapon-graded Plutonium

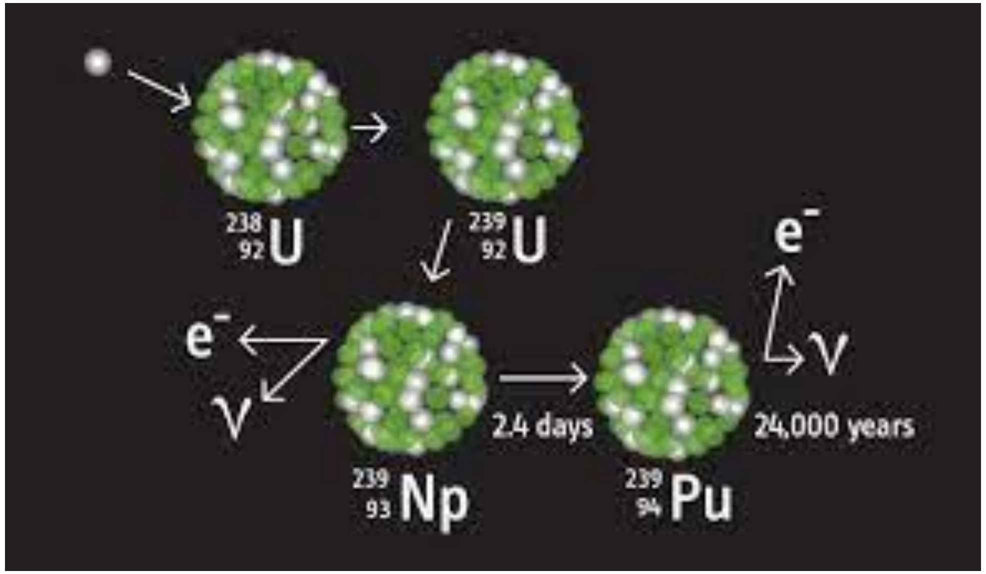
U-235: 52 kg critical mass

- Natural abundance of 0.72% (mostly U-238)
- 90% and above is needed for weapon graded → electromagnetic separation, diffusions, centrifuges, highly technically challenging



Pu-239: 10 kg critical mass

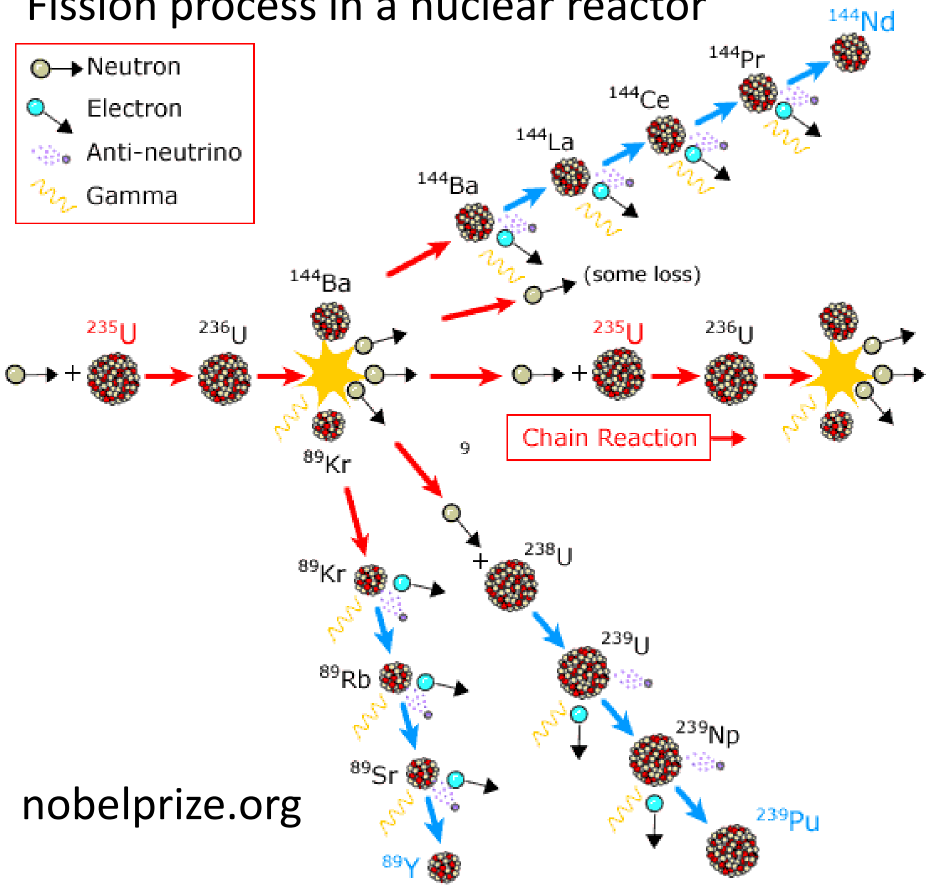
- 93% and above for weapon graded
- Produced in nuclear reactors → given enough time, all U-238 → Pu



- Safeguards efforts (e.g. WATCHMAN: arXiv:1502.01132)

Nuclear Reactor as Antineutrino Source

Fission process in a nuclear reactor

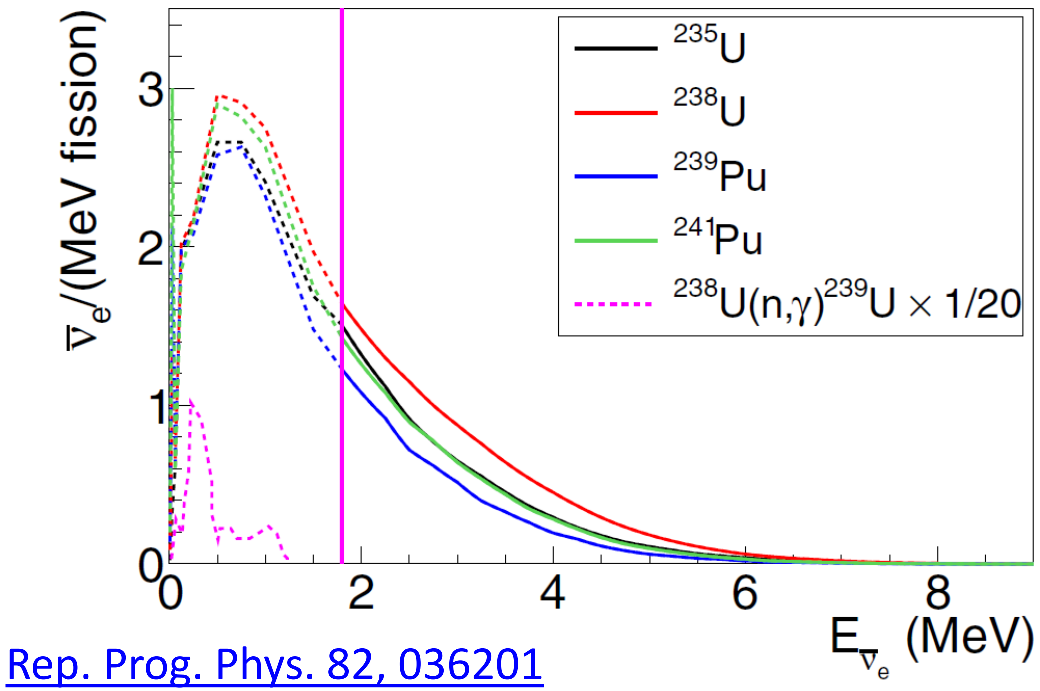


nobelprize.org

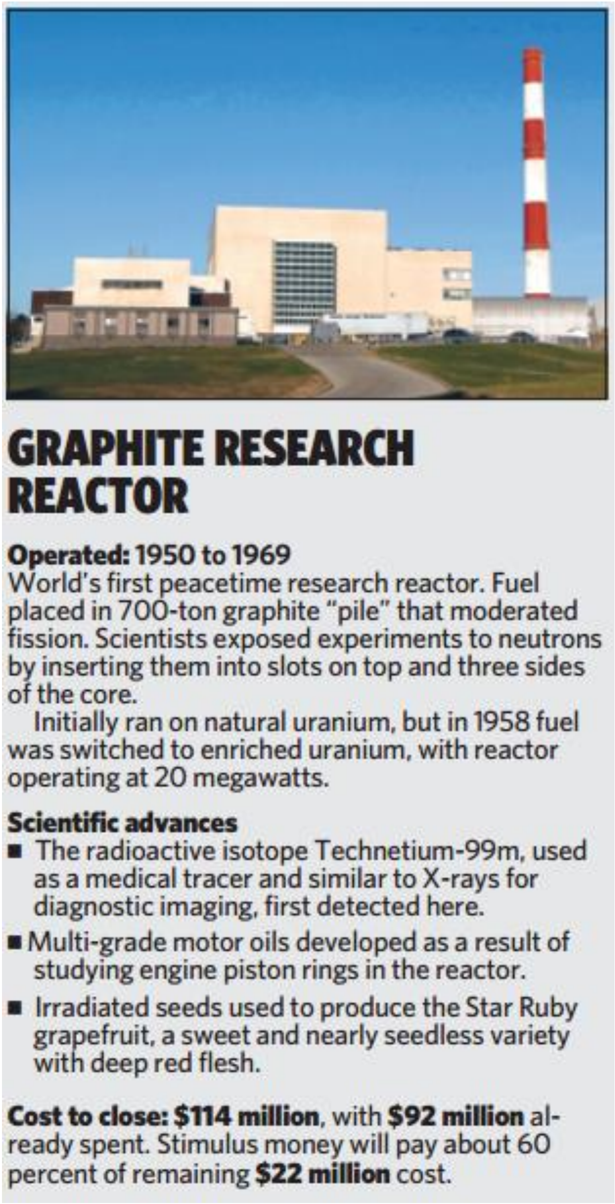
- Pure anti-ν_e source with ~6 anti-ν_e per fission
- ~2 x 10^{20} anti-ν_e/sec per GigaWatt thermal power (GW_{th})

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

Reactor Antineutrino Spectrum



Rep. Prog. Phys. 82, 036201



GRAPHITE RESEARCH REACTOR

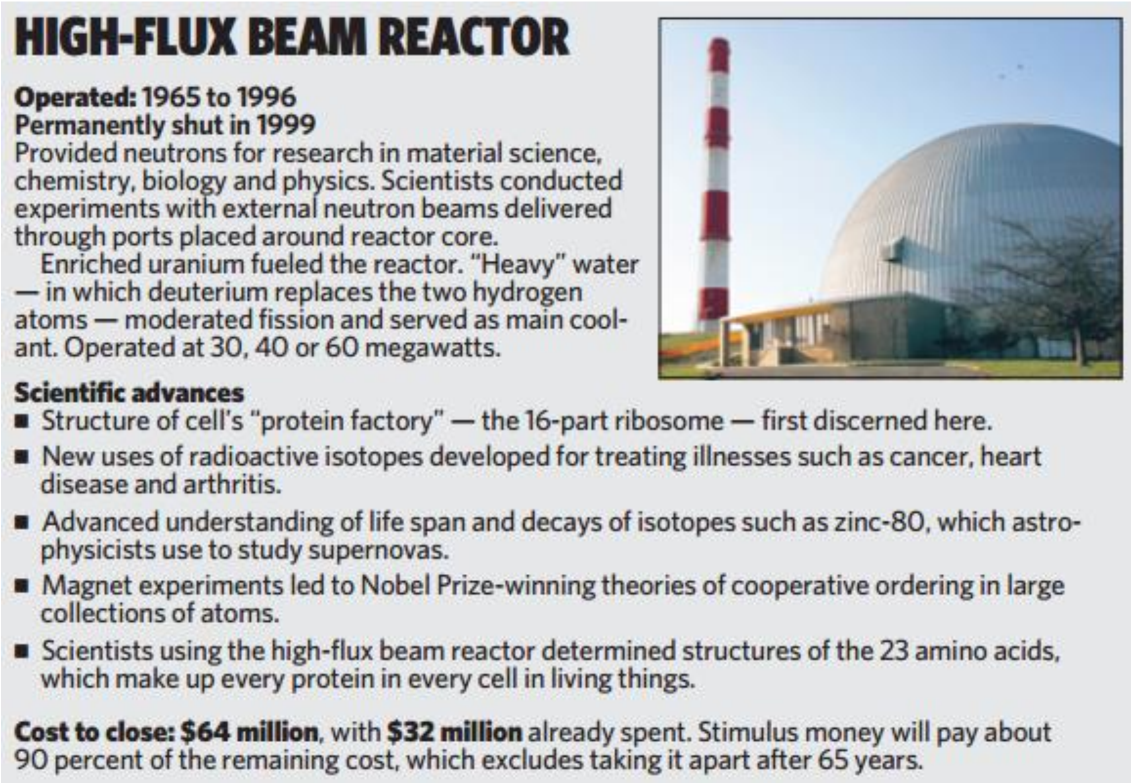
Operated: 1950 to 1969
World's first peacetime research reactor. Fuel placed in 700-ton graphite "pile" that moderated fission. Scientists exposed experiments to neutrons by inserting them into slots on top and three sides of the core.

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 physics. Scientists conducted experiments with external neutron beams delivered through ports placed around reactor core.

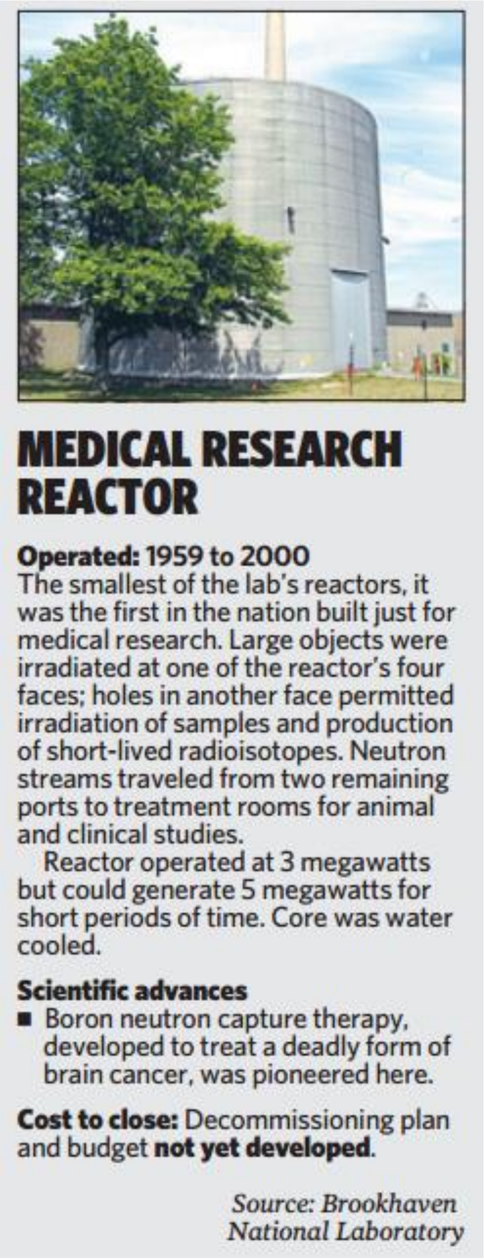
Enriched uranium fueled the reactor. "Heavy" water — in which deuterium replaces the two hydrogen atoms — moderated fission and served as main coolant. Operated at 30, 40 or 60 megawatts.

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.

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



MEDICAL RESEARCH REACTOR

Operated: 1959 to 2000
The smallest of the lab's reactors, it was the first in the nation 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

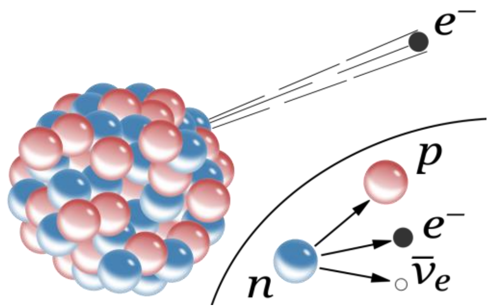
https://www.bnl.gov/about/history/reactors.php

Homework Problem 1

- How many antineutrinos are produced per second for a typical 3-gigawatt (thermal) commercial reactor?
    1. Each fission releases ~200 MeV energy. How many fissions are produced per second?

    2. Each fission produce ~6 antineutrinos on average from the beta-decay chains. How many antineutrinos are produced per second?

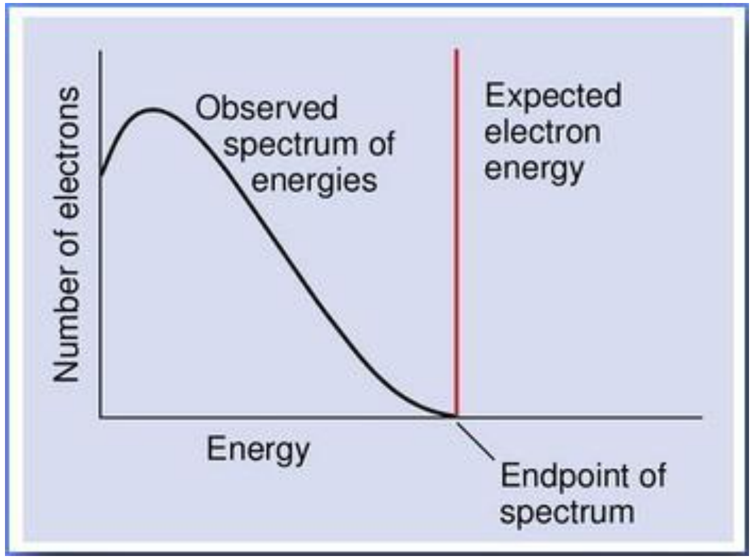
Neutrino and Beta Decay

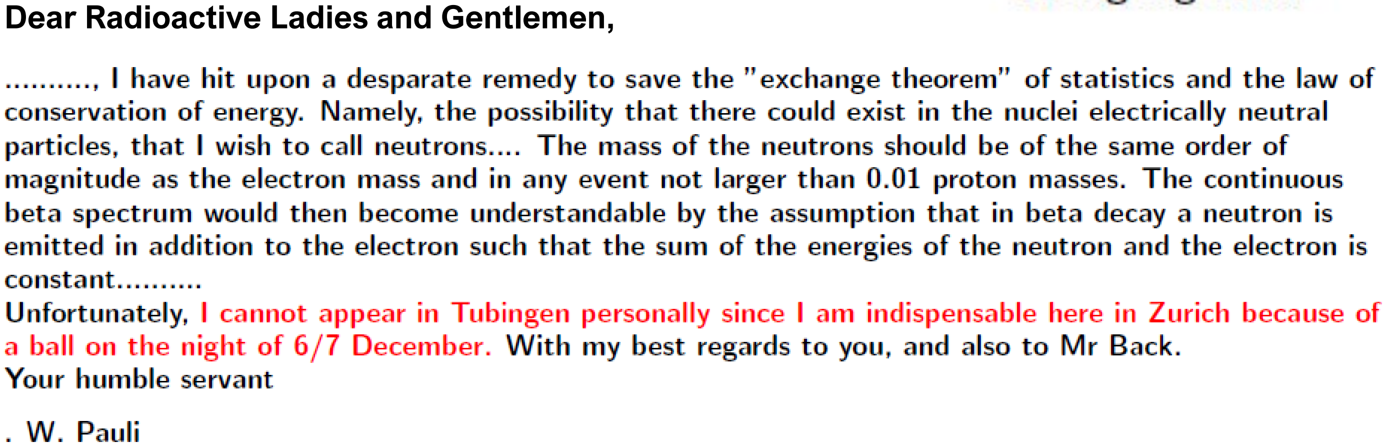


$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + e^- + \bar{\nu}_e$$

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

Wolfgang Pauli





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..........

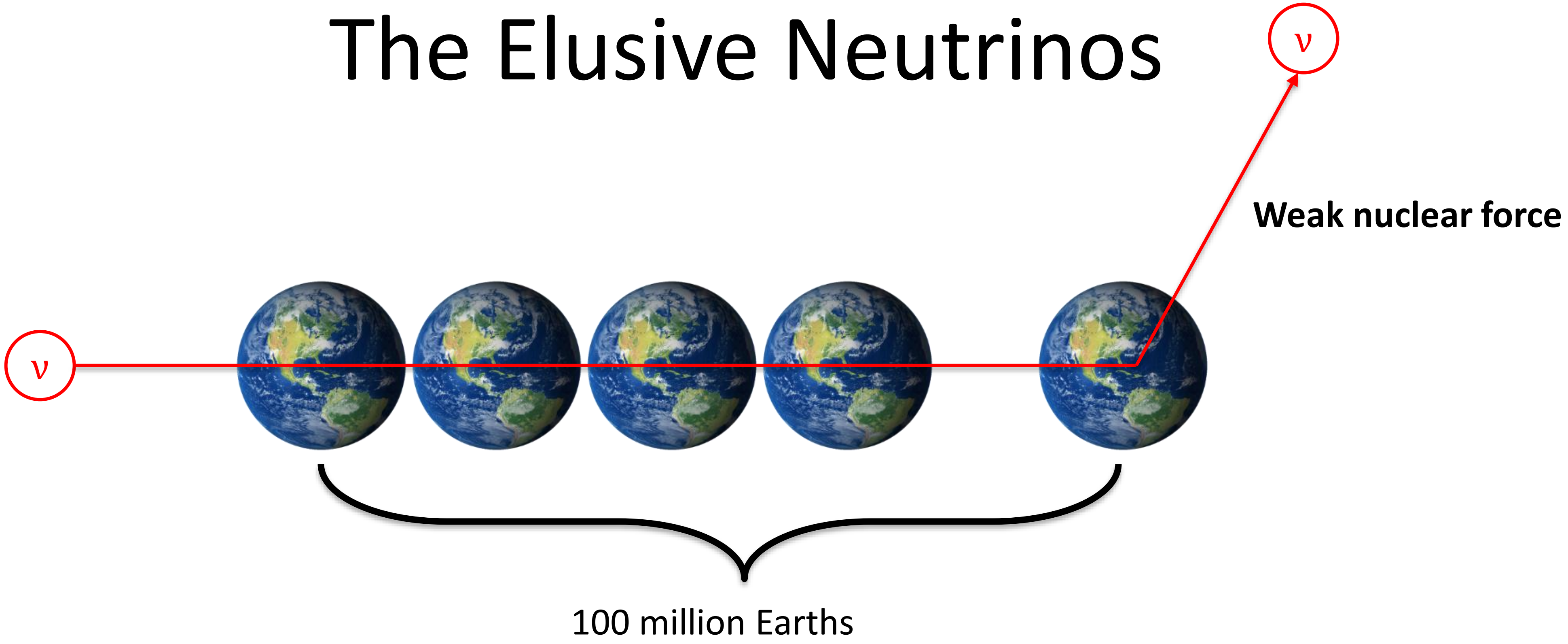
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

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

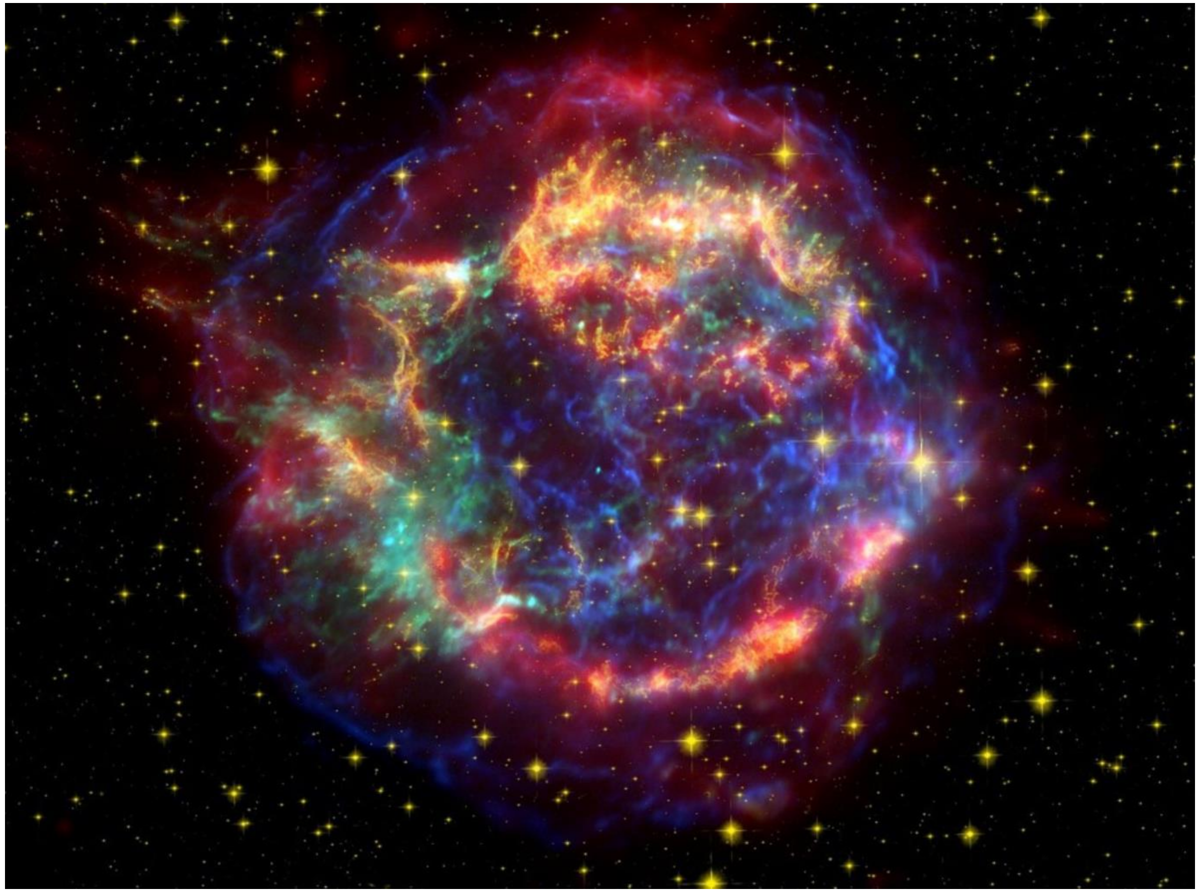
The Elusive Neutrinos

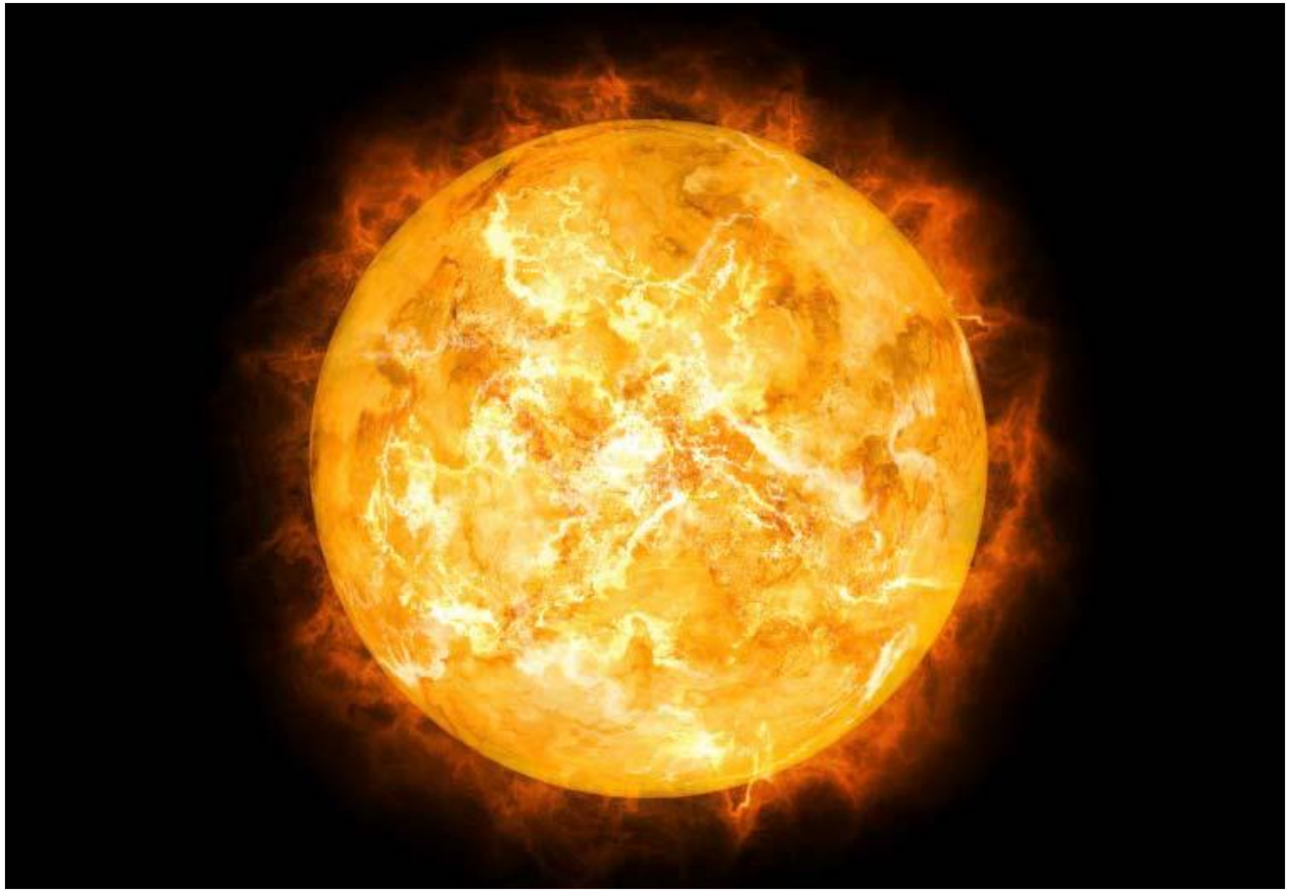


Neutrino detection requires:

- 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

Neutrinos from the Universe

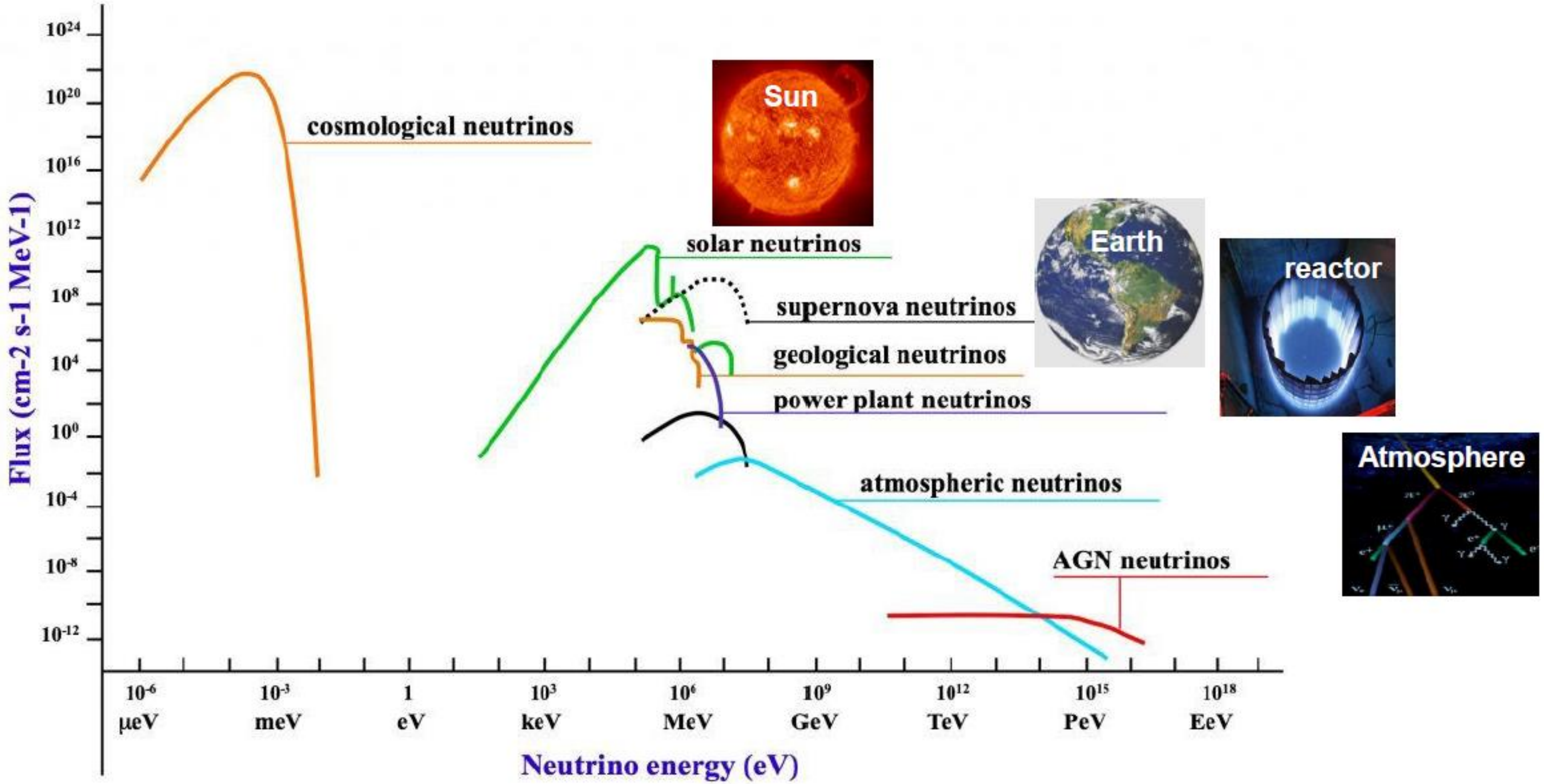




99% of the energy in a core collapse supernova explosion is carried away by neutrinos

10^{38} ν_e/s are produced by the sun

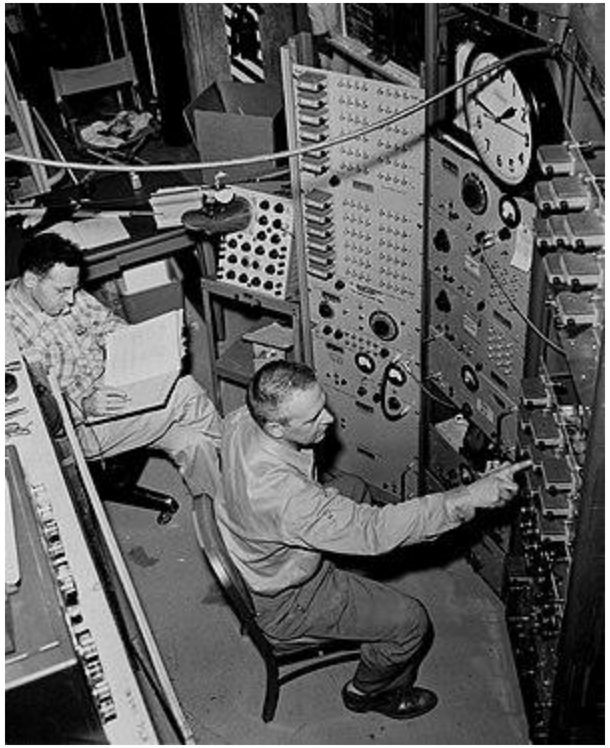
Neutrino Sources

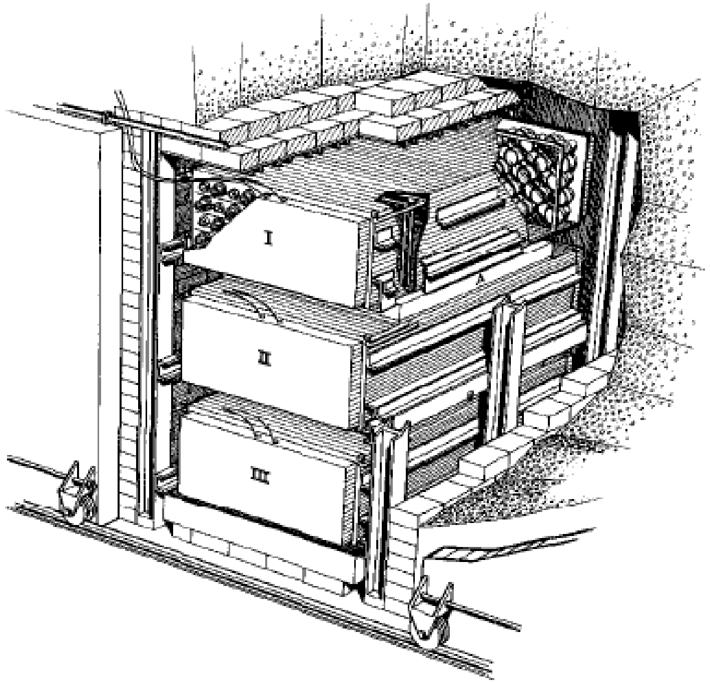


Neutrinos: First Detection

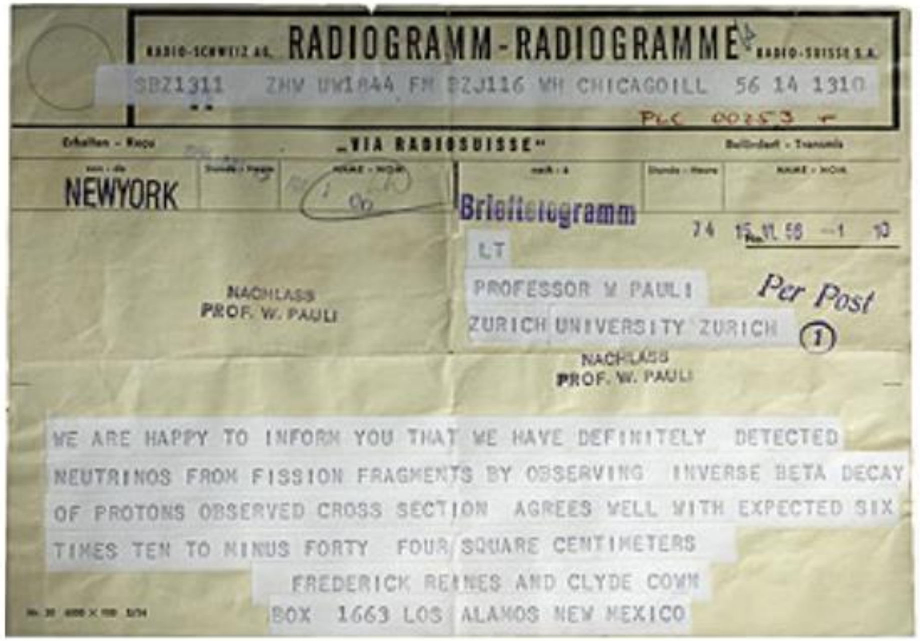
Reines and Cowan's telegram to W. Pauli (1956)

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



RADIO-SCHWEIZ AG. RADIOGRAMM - RADIOGRAMME RADIO-SUISSE S.A.

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PLC 00253

"VIA RADIOSUISSE"

NEWYORK

Briefteiegramm

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LT

PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

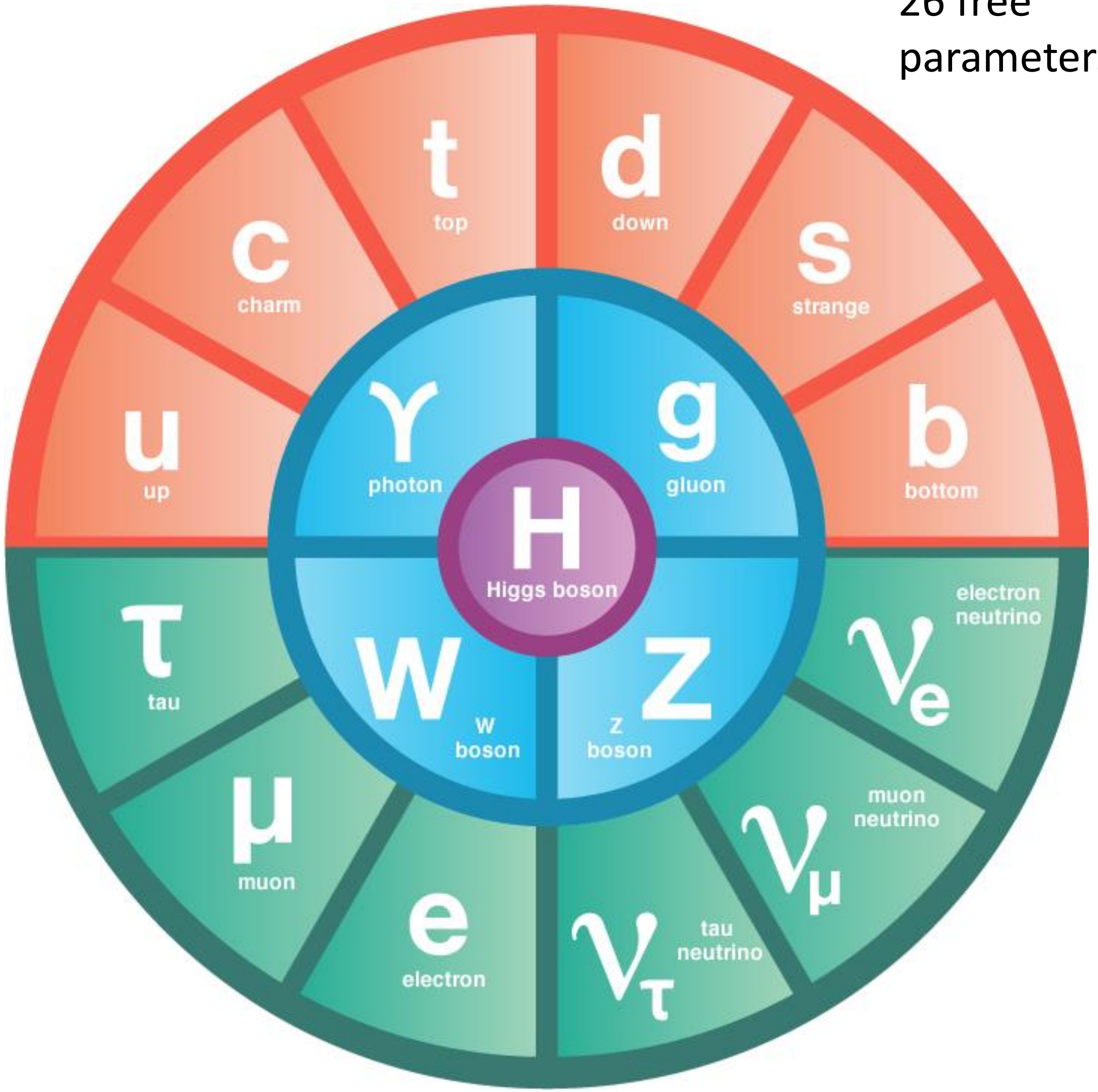
Per Post ①

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

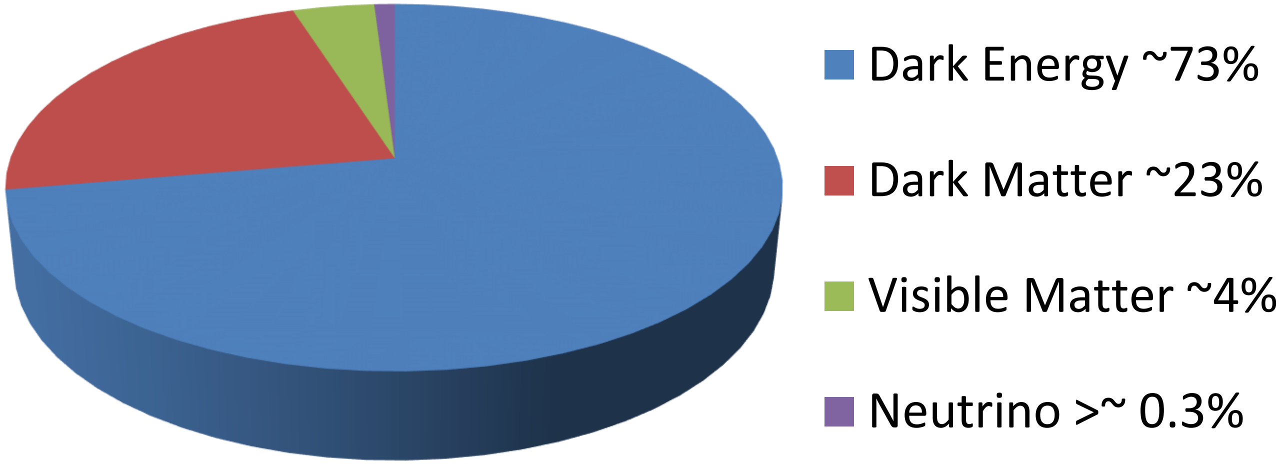
FREDERICK REINES AND CLYDE COWM
BOX 1663 LOS ALAMOS NEW MEXICO

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



26 free parameters

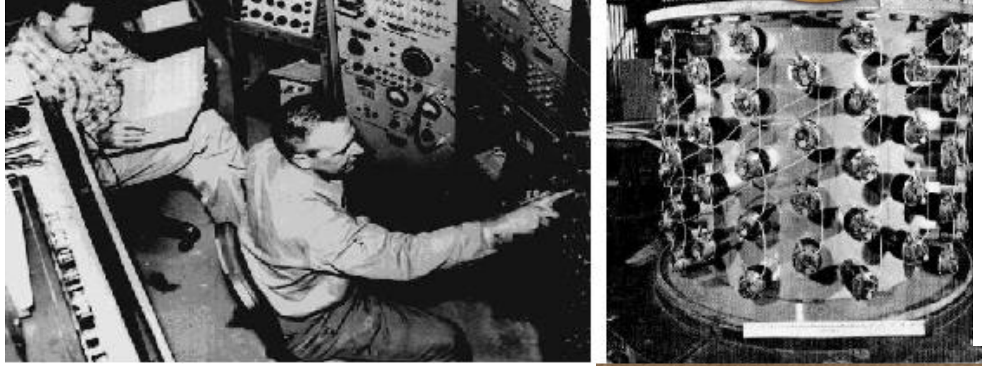
Energy Budget of the Universe

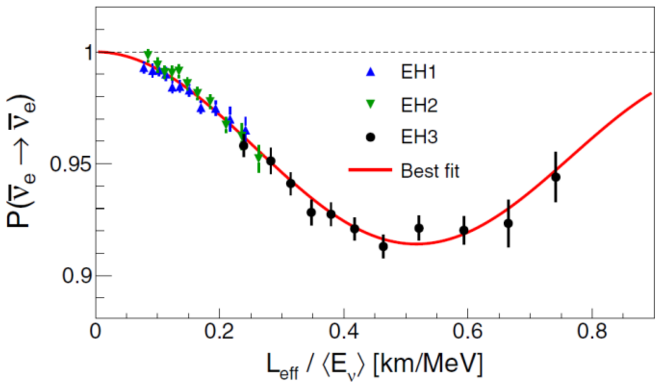


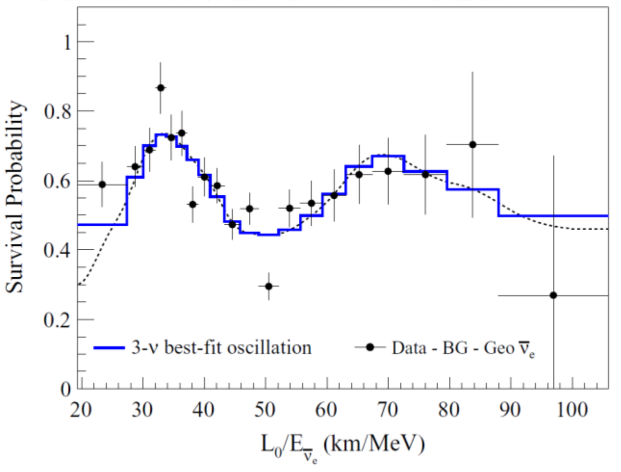
As fundamental particles in the standard model of particle physics, neutrinos are the second most abundant (known) particles in our universe

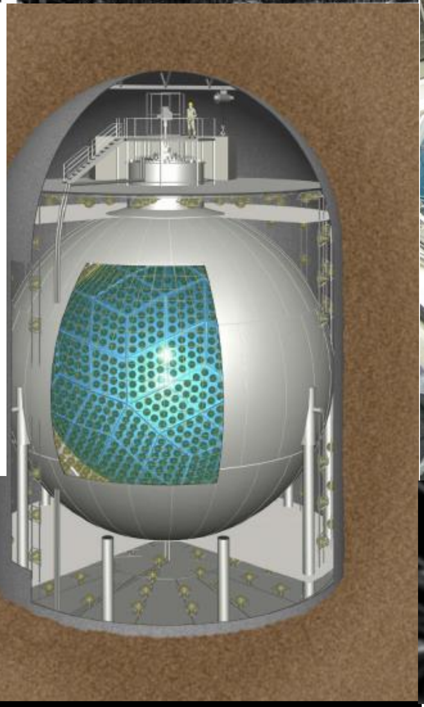
Discoveries with Reactor Anti-ν

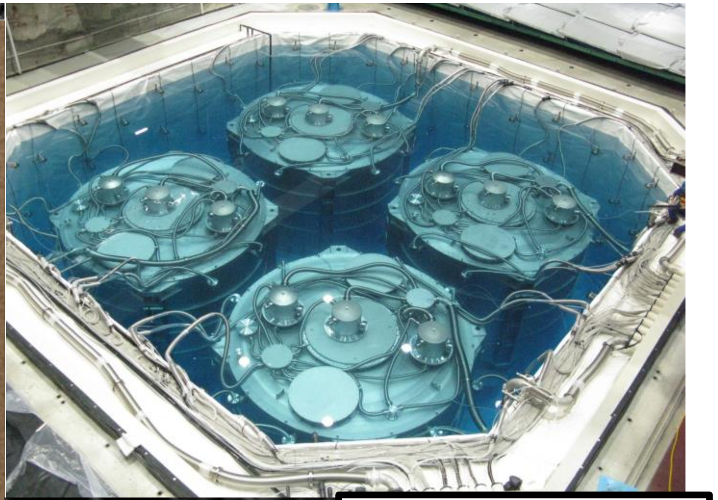
1950s: Reines and Cowan











2010s: Daya Bay

2000s: KamLAND

Courtesy of Karsten Heeger

- Detection of anti-ν
- Solving solar ν problem on Earth
- Measurement of non-zero 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)

Reactor Models

$$\mathbf{S}(E_\nu) = \mathbf{c} \cdot \sum_i f_i \cdot s_i\,(E_\nu) \cdot \sigma(E_\nu)$$

reactor thermal power, energy released per fission, baseline, target protons, detection efficiency, oscillation, etc.

isotope fission fraction

isotope neutrino spectra

IBD cross section

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

Sonzogni et al
PRC 91, 011301

~6000 decay branches

Latest update @ PRL 123, 022502

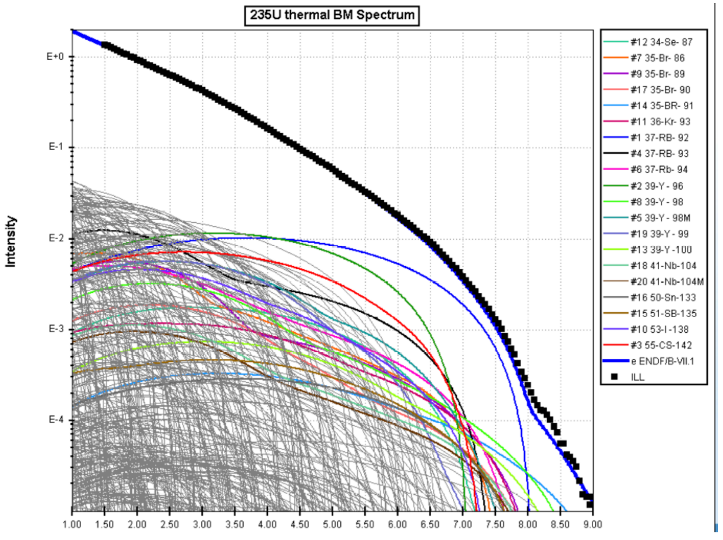
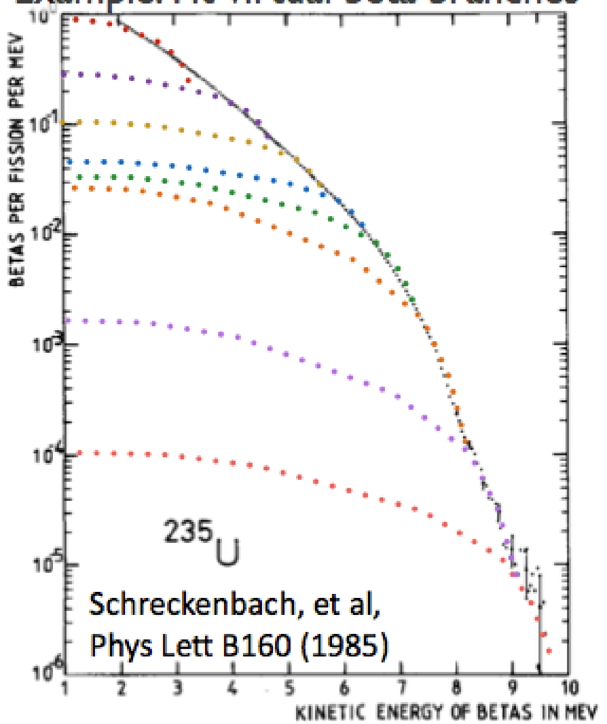


Figure from Sonzogni et

- Conversion Method
  - Measure total outgoing beta-decay electron energy spectra
  - Predict corresponding anti-neutrino spectra with >30 virtual branches
  - Considered to be more precise: ~2.5% uncertainty

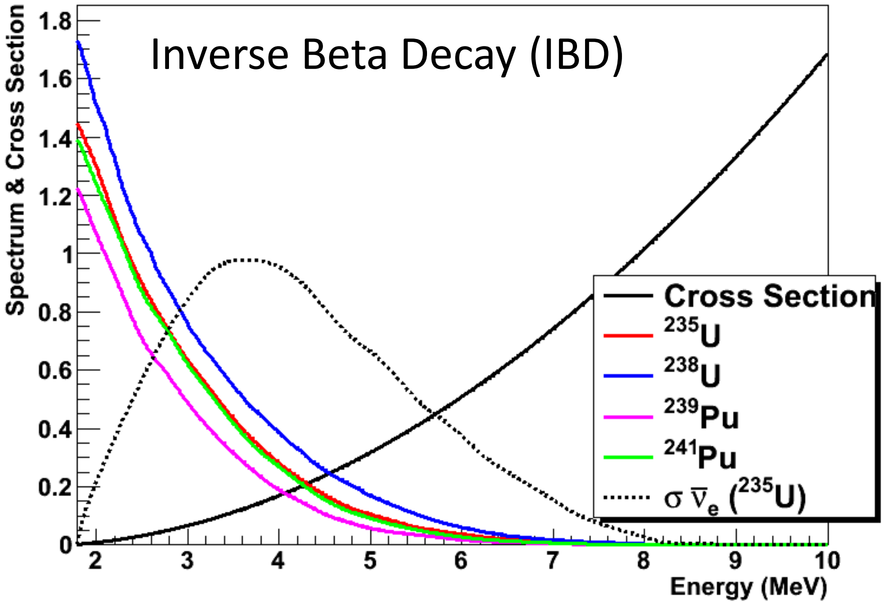
Example: Fit virtual beta branches



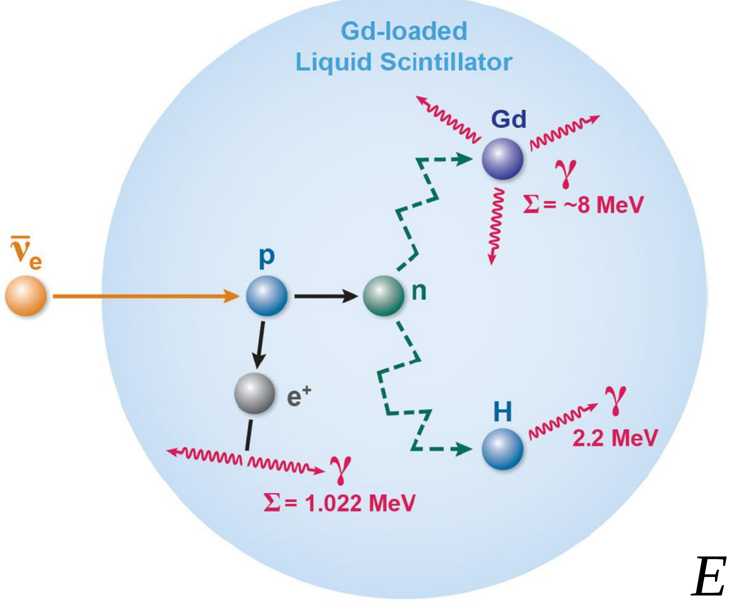
Schreckenbach, et al, Phys Lett B160 (1985)

Reactor Anti-ν_e Detection

Channel	Interaction Type	Cross section (10^{-44} cm^2/fission)	Threshold (MeV)
$\bar{\nu}_e + p \to e^+ + n$	CC	$\sim$63	1.8
$\bar{\nu}_e + d \to n + n + e^+$	CC	$\sim$1.1	4.0
$\bar{\nu}_e + d \to n + p + \bar{\nu}_e$	NC	$\sim$3.1	2.2
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	CC/NC	$\sim$0.4	0
$\bar{\nu}_e + A \to \bar{\nu}_e + A$	NC	$\sim 9.2 \times N^2$	0



Coincidence signal of IBD:



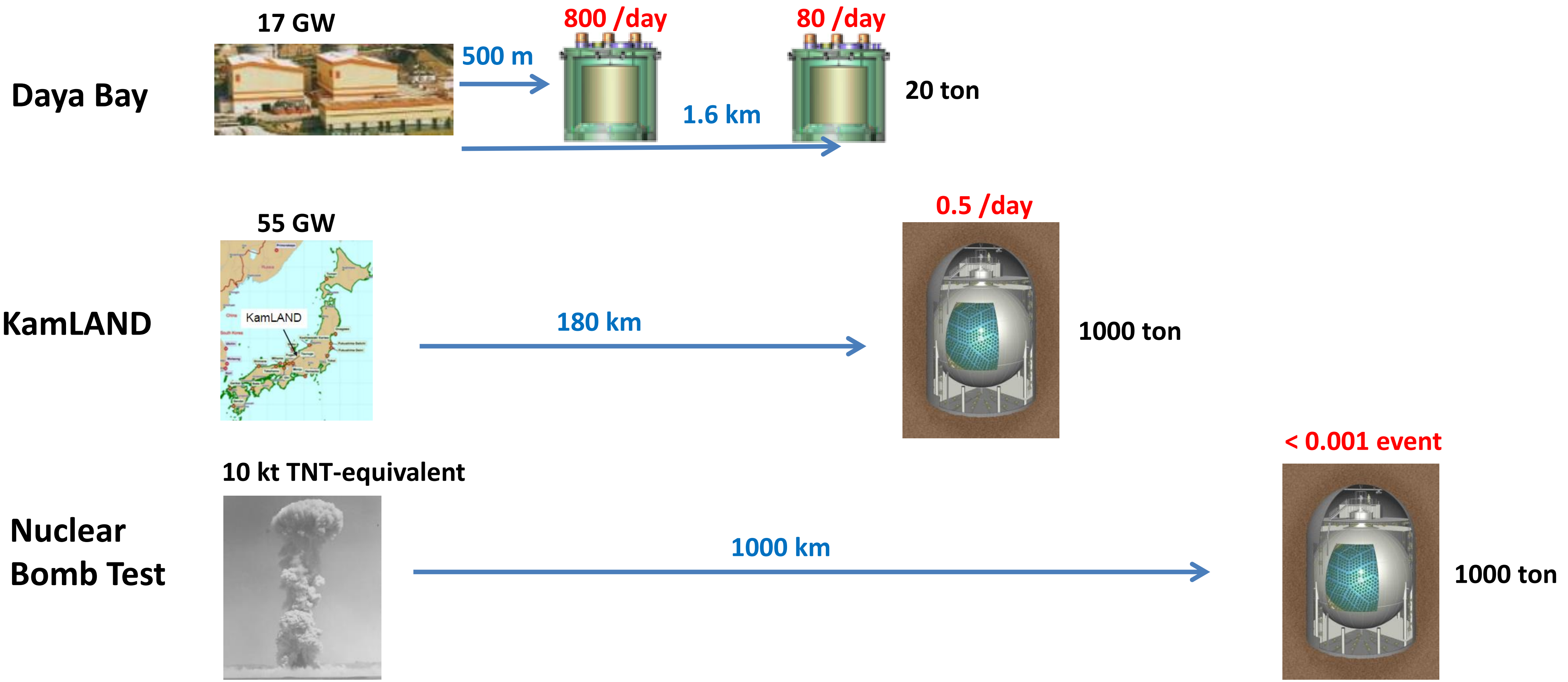
Target nucleus	Process	Thermal neutron Cross section (barn)
H	$n + p \to d + \gamma$ (2.2 MeV)	$\sim$0.33
^{3}He	$n + {}^3\mathrm{He} \to p + {}^3\mathrm{H} + 0.764$ MeV	$\sim$5300
^{6}Li	$n + {}^6\mathrm{Li} \to \alpha + {}^3\mathrm{H} + 4.6$ MeV	$\sim$950
^{10}B	$n + {}^{10}\mathrm{B} \to \alpha + {}^7\mathrm{Li} + 6.2$ MeV	$\sim$3860
^{108}Cd	$n + {}^{108}\mathrm{Cd} \to {}^{109m}\mathrm{Cd} \to {}^{109}\mathrm{Cd} + \gamma$ (0.059 MeV)	$\sim$1000[a]
Gd	$n + {}^{155}\mathrm{Gd} \to {}^{156}\mathrm{Gd} + \gamma s$ (8.5 MeV)	$\sim$61 000
	$n + {}^{157}\mathrm{Gd} \to {}^{158}\mathrm{Gd} + \gamma s$ (7.9 MeV)	$\sim$256 000

$$E_{prompt} \approx E_\nu - E_n - 0.78 MeV$$

Rep. Prog. Phys. 82, 036201

Event Rate

- Depending on the power of the reactors, size of the detectors, and the distance between them



Daya Bay

17 GW

500 m

800 /day

1.6 km

80 /day

20 ton

KamLAND

55 GW

180 km

0.5 /day

1000 ton

Nuclear Bomb Test

10 kt TNT-equivalent

1000 km

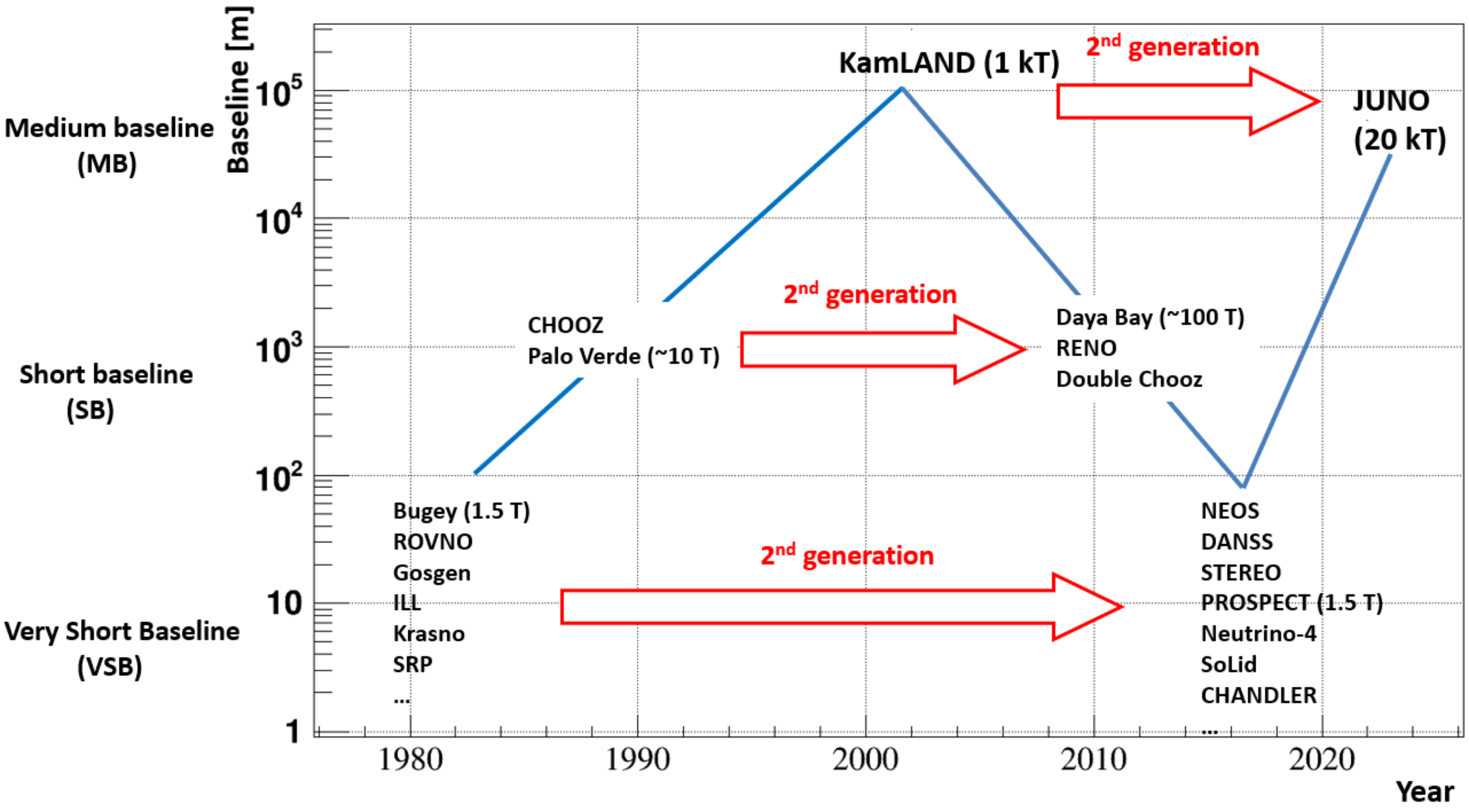
< 0.001 event

1000 ton

Homework Problem 2

- Daya Bay's antineutrino detector (AD) is a 20-ton liquid scintillator detector. The far ADs are placed at ~1.6 km away from reactors with a total power of ~17 GW. How many inverse beta decay(IBD) reactions are expected per day in each far AD?
  1. The hydrogen mass fraction in the AD is ~12%. How many free protons (from hydrogen) are there in each AD?
  2. How many reactor antineutrinos per cm^2 per second is expected at the AD? (this is referred as the "flux")
  3. The average IBD cross section is ~$3x10^{-43}$ cm^2 , calculate event rate = flux * cross section * number of protons, assuming 100% detection efficiency. (remember that IBD can only detect 1/3 of all reactor antineutrinos)

Reactor Neutrino Experiments

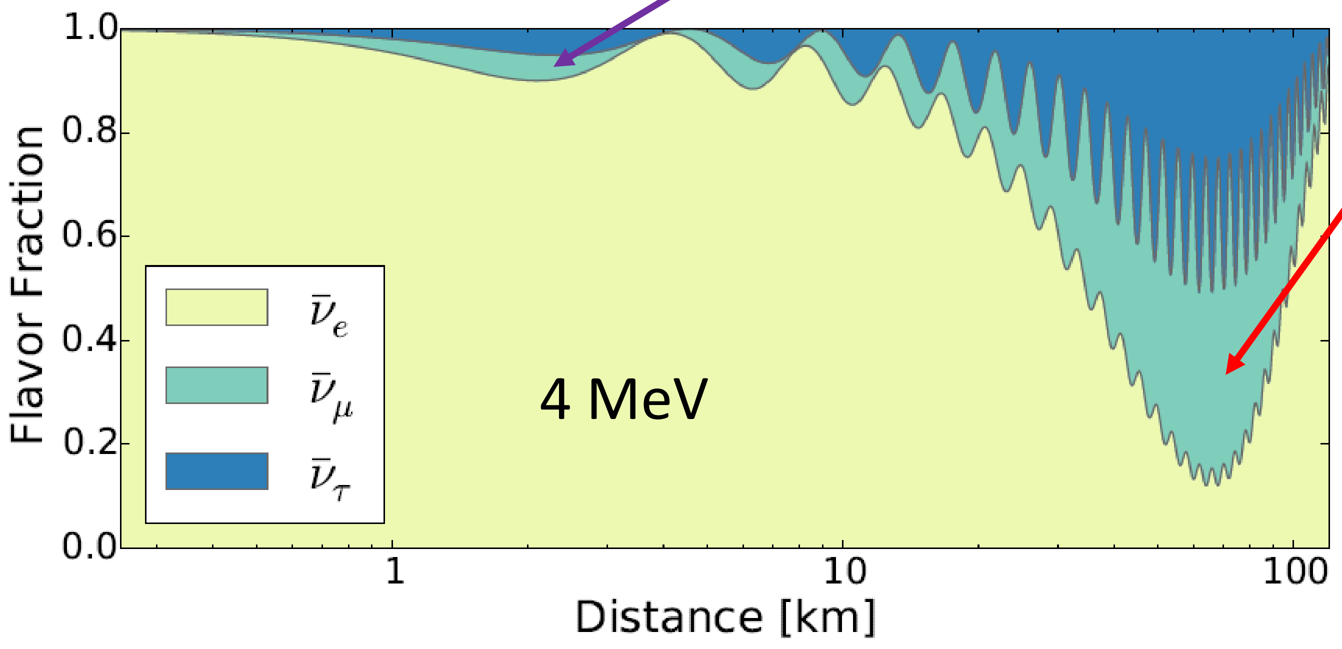


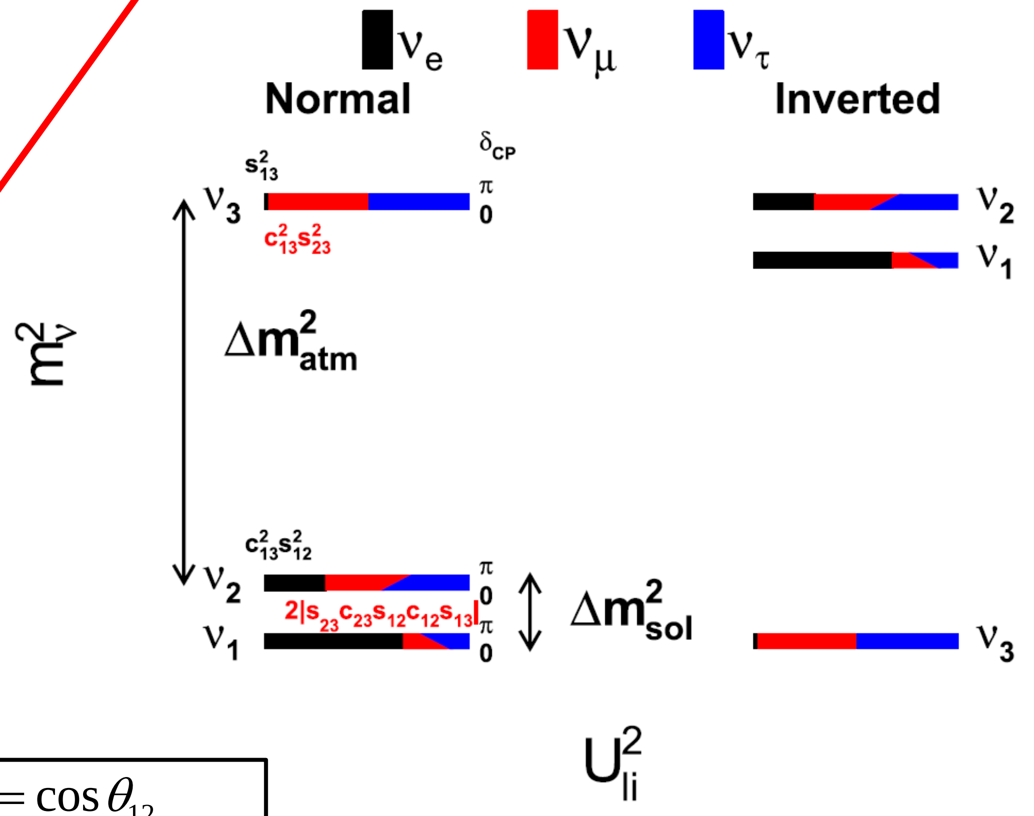
Courtesy of Chao Zhang

- Four major motivations:
  - Measurement of fundamental parameters (MB, SB)
  - Search for new physics (VSB, SB, MB)
  - Measurement of neutrino flux, spectrum, evolution (SB, VSB)
  - Technology development (MB, VSB, SB)

Measurement of Fundamental Parameters

$$\boxed{P(\overline{\nu_e} \rightarrow \overline{\nu_e}) \approx 1 - 4s_{13}^2 \cdot c_{13}^2 \cdot \sin^2\left(\Delta m_{atm}^2 \cdot \frac{L}{E}\right) - 4c_{13}^4 \cdot s_{12}^2 \cdot c_{12}^2 \cdot \sin^2\left(\Delta m_{sol}^2 \cdot \frac{L}{E}\right)}$$

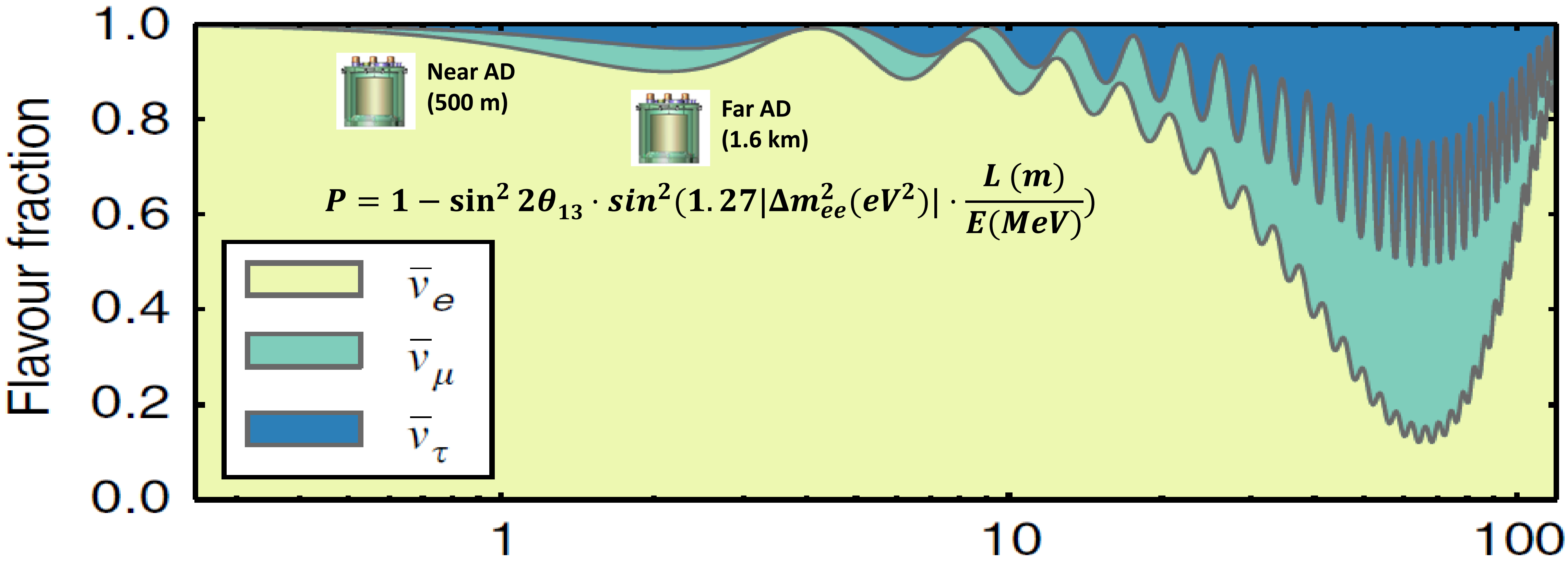




Nat. commun. 6, 6935

$$s_{13} = \sin\theta_{13} \qquad c_{12} = \cos\theta_{12}$$
$$\Delta m_{atm}^2 \approx | m_3^2 - m_1^2 | \qquad \Delta m_{sol}^2 = m_2^2 - m_1^2$$

Prog. Part. Nucl. Phys. 83, 1



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

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

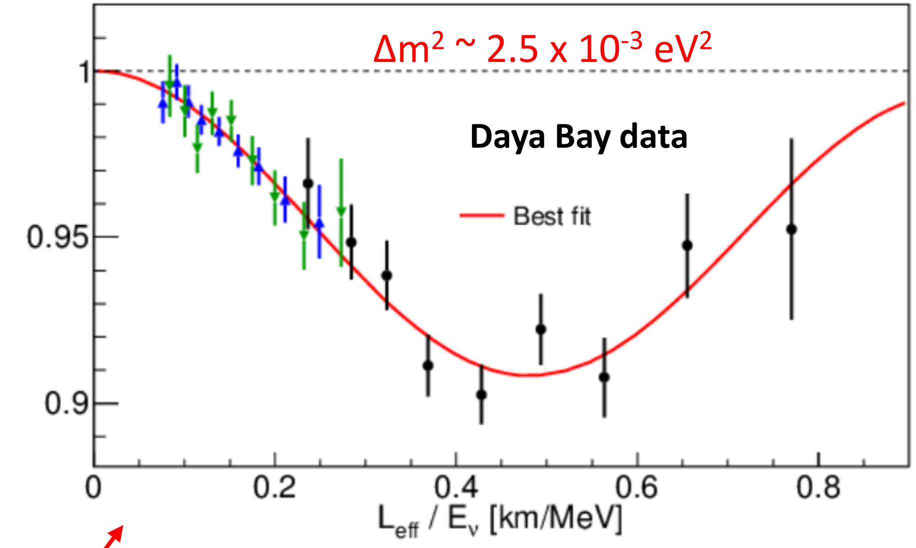
Far/Near Neutrino Ratio

Detector Target Mass

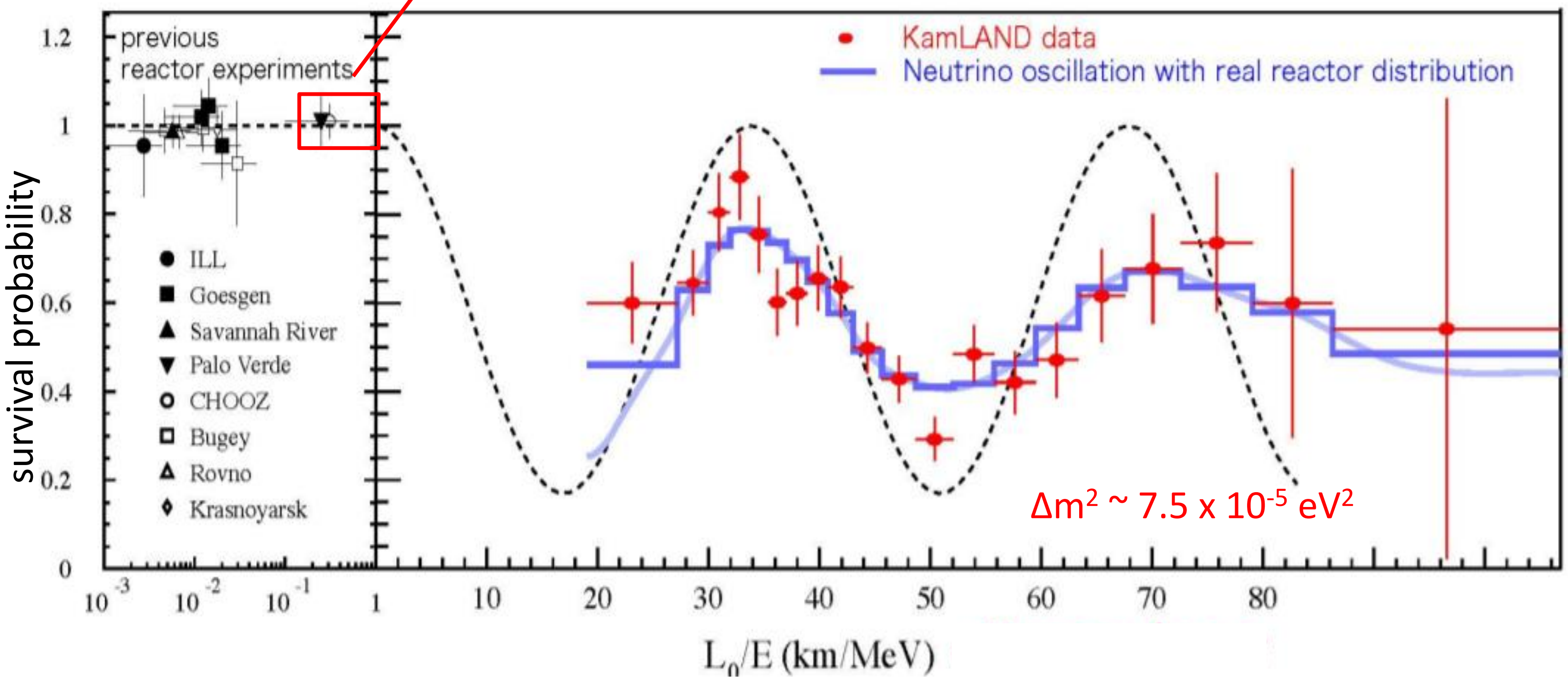
Distance from Reactor

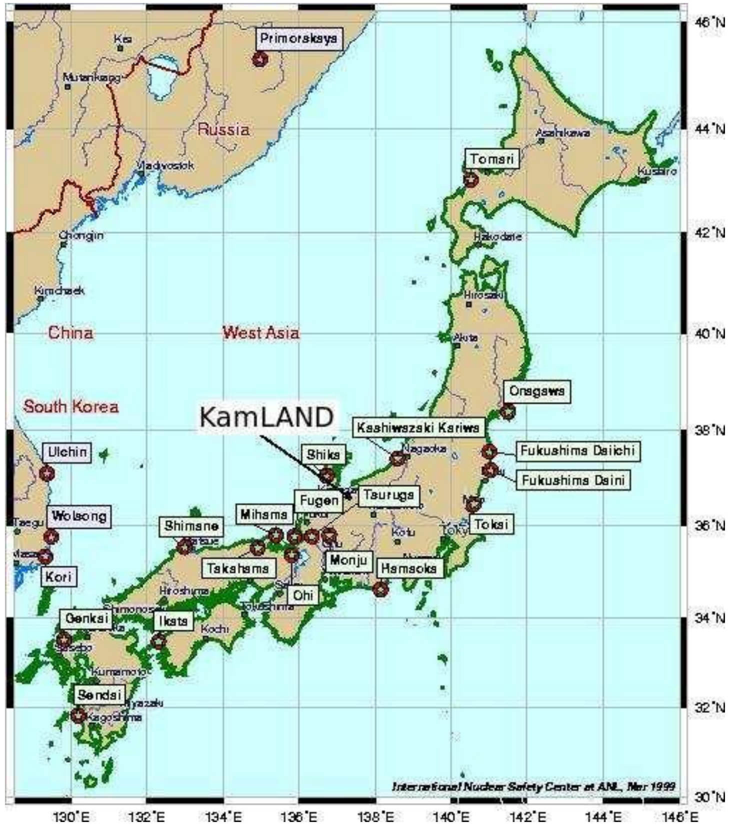
Detector Efficiency

Survival Probability (θ_{13})



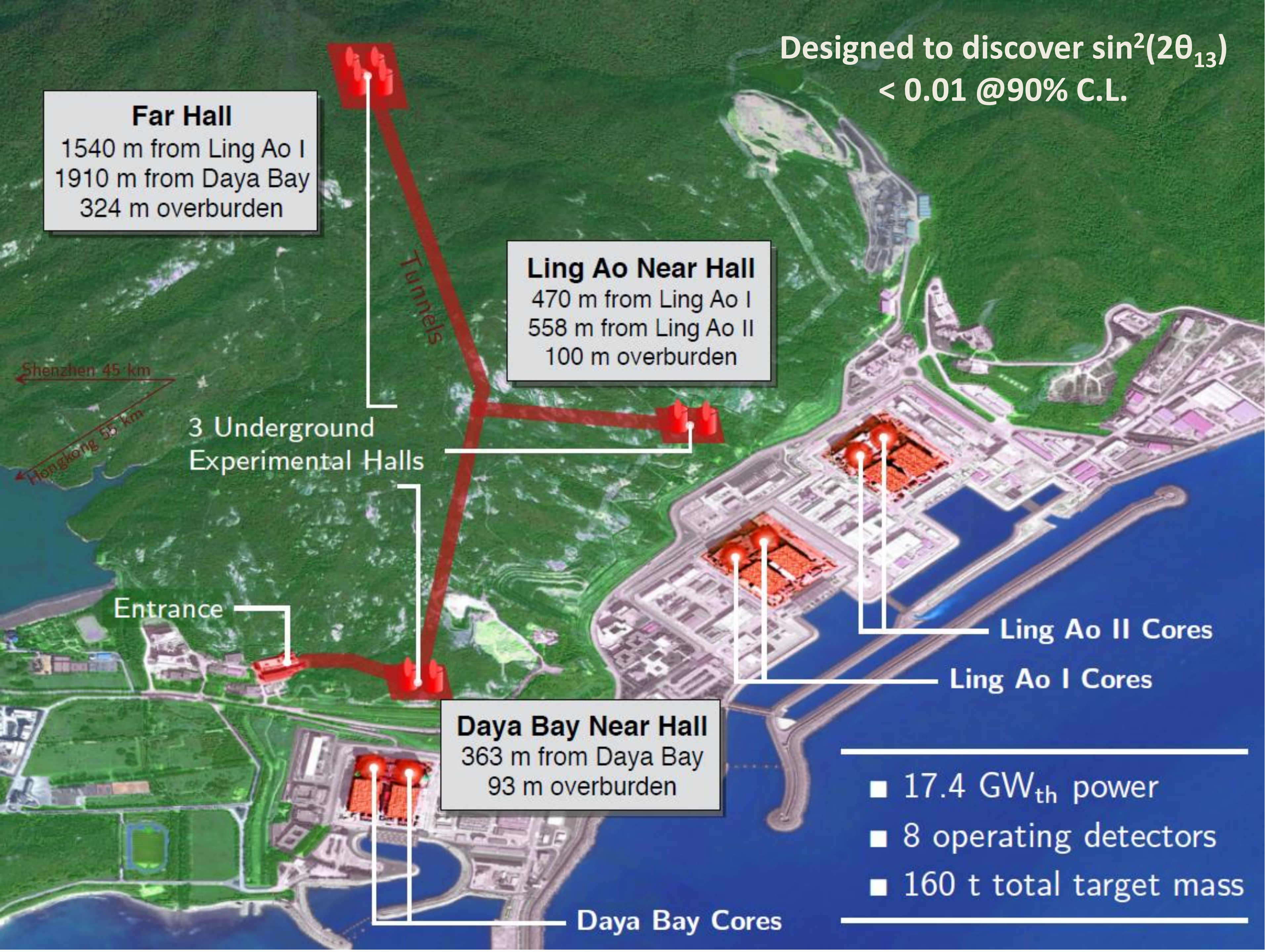
My post-doc work @ Caltech





Chao Zhang’s Ph. D thesis

Image credit: H. Murayama



Designed to discover $\sin^2(2\theta_{13})$ < 0.01 @90% C.L.

Statistics

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

Systematics

❑Reactor

- Far/Near relative measurement

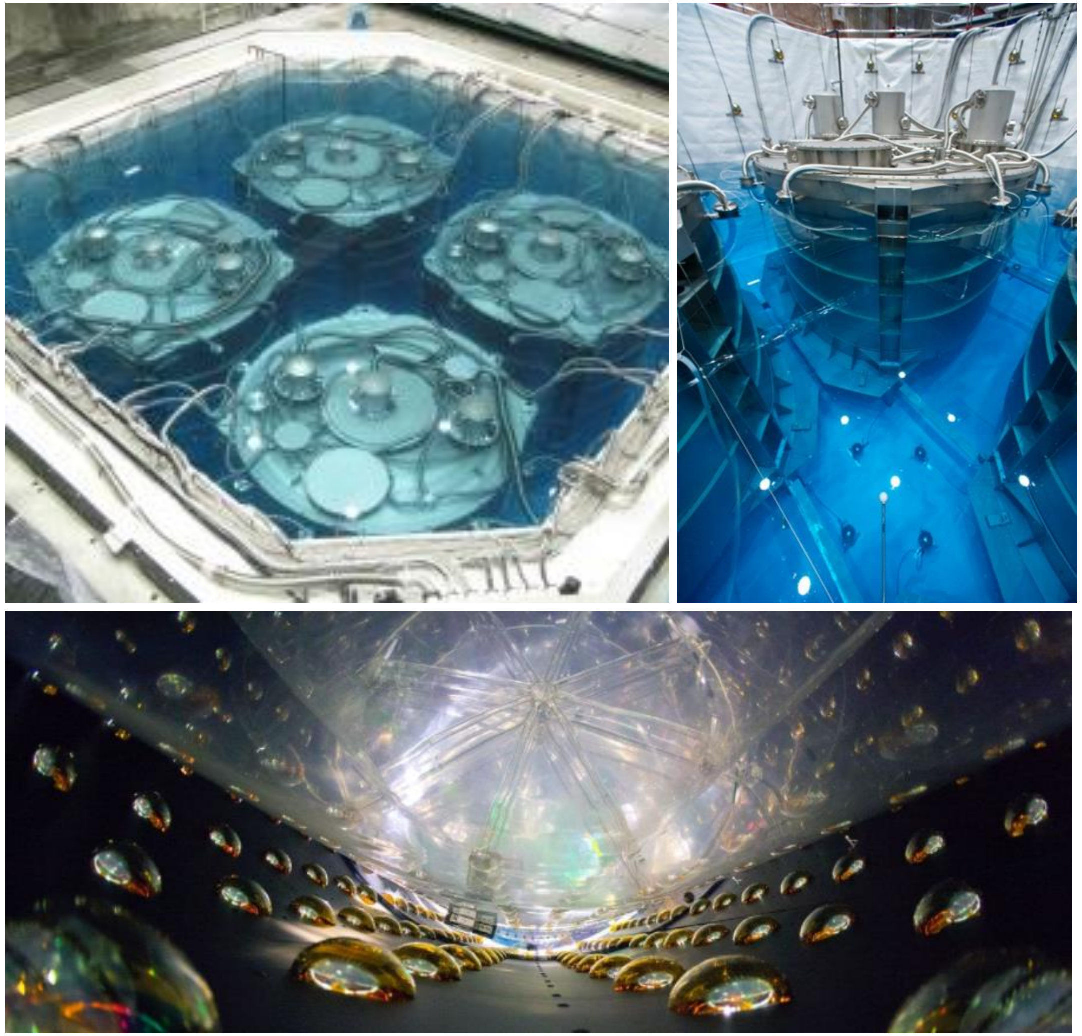
❑Detector

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

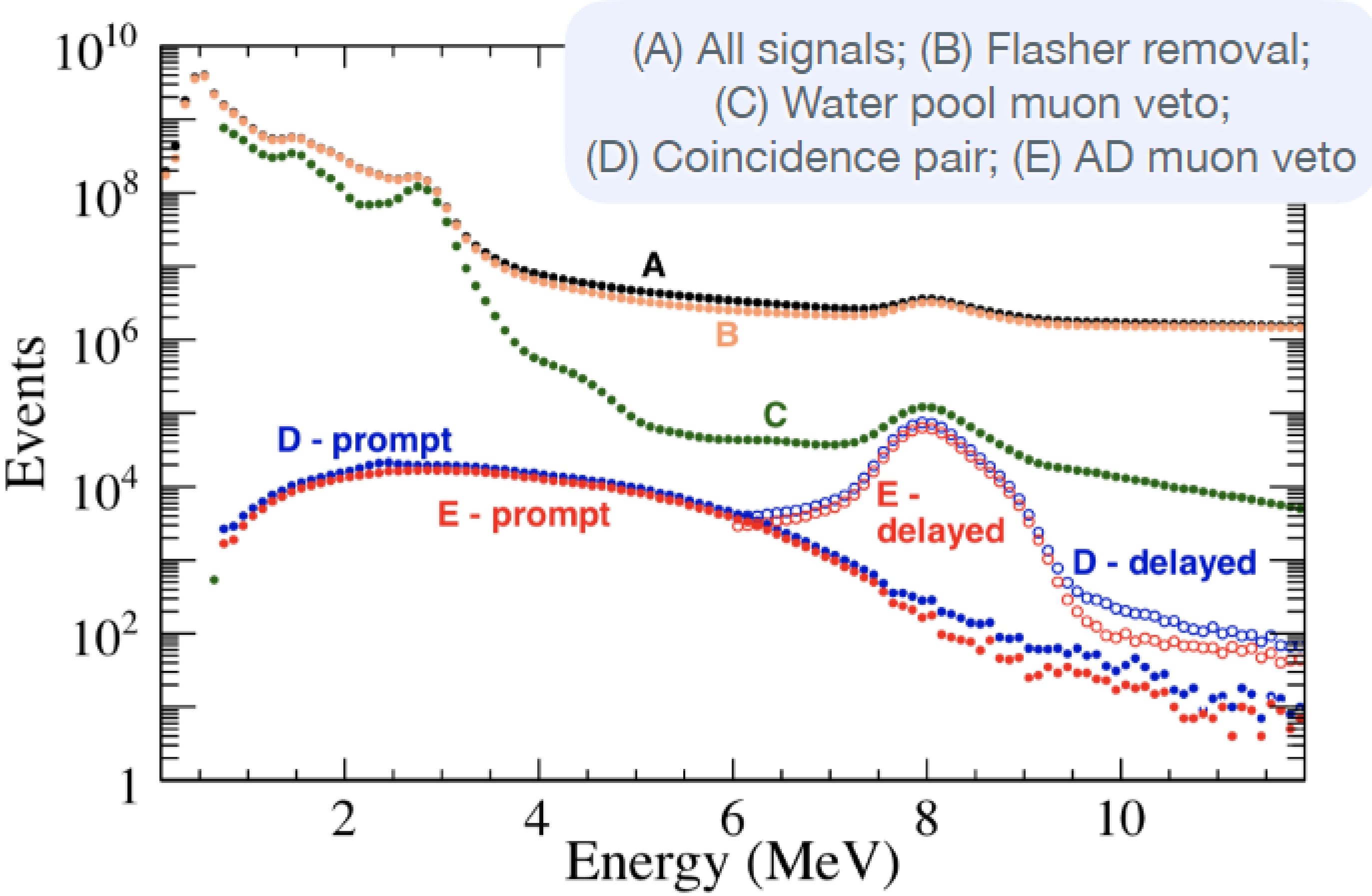
❑Background

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

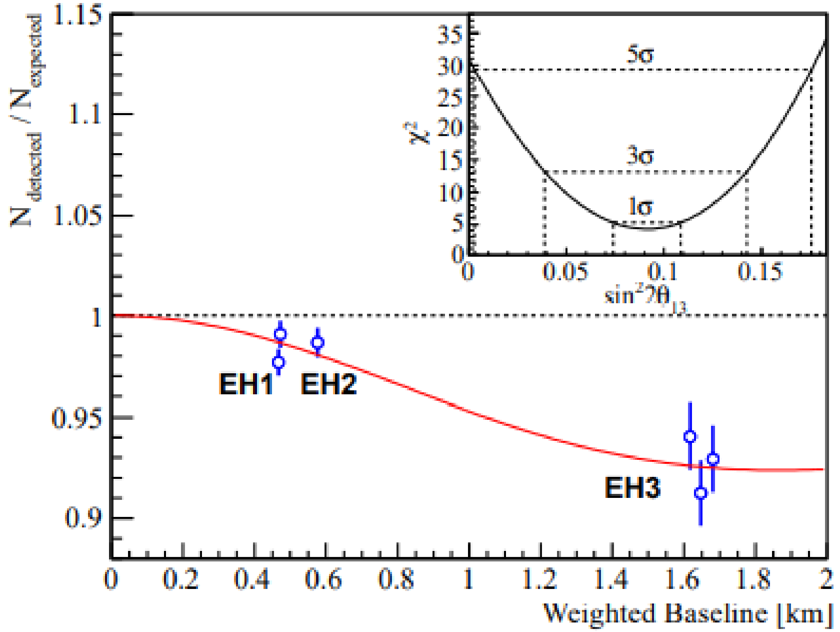
Detection of Reactor Neutrino in Daya Bay



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



- 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)

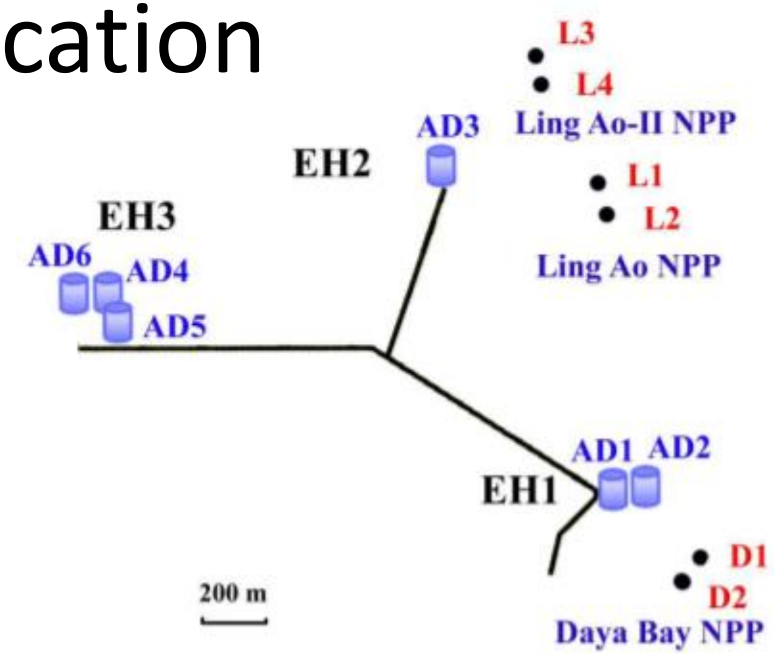
BNL virtual mini-symposium: The Daya Bay Reactor Neutrino Experiment and the Discovery of Non-zero Theta13

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

Homework Problem 3

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

Reactor and Detector Location

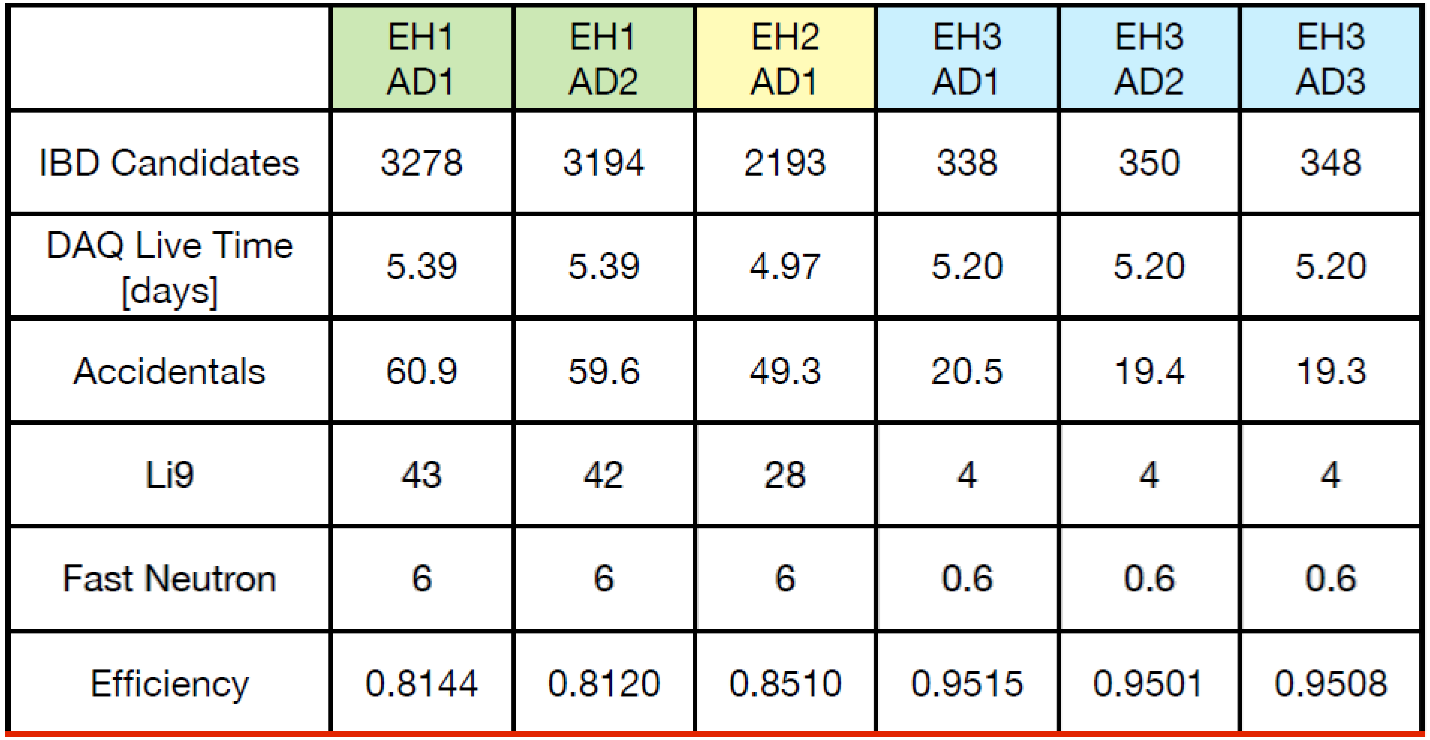


Reactor	D1	D2	L1	L2	L3	L4
x (m)	43.0	-44.6	856.0	792.3	1143.6	1076.5
y (m)	-7.0	6.9	830.9	767.9	1206.1	1138.5
z (m)	-12.0	-12.0	-12.0	-12.0	-12.0	-12.0

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

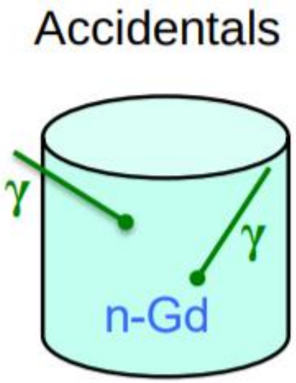
Backgrounds

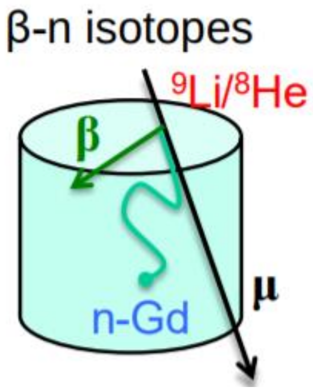
- ☐ Calculate the signal rate per day after efficiency correction
  - EH1-AD1: (3278 - 60.9 – 43 - 6) / 0.8144 / 5.39 = 721.7 events/day
- ☐ Calculate the statistical error on the signal rate
  - EH1-AD1: sqrt(3278)/0.8144/5.39 = 13.0 events/day

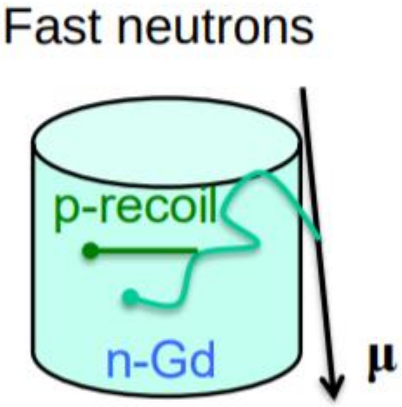
Background t

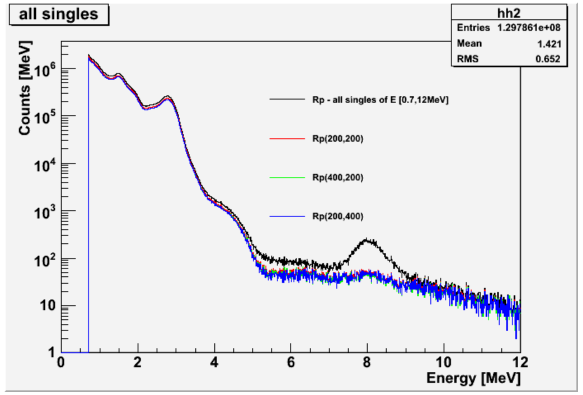
- Accidentals: statistically calculate from uncorrelated singles
- Li9 / He8: measure time distribution of after-muon events
- Fast neutron: measure energy spectrum from AD/water/RPC tagged muon events

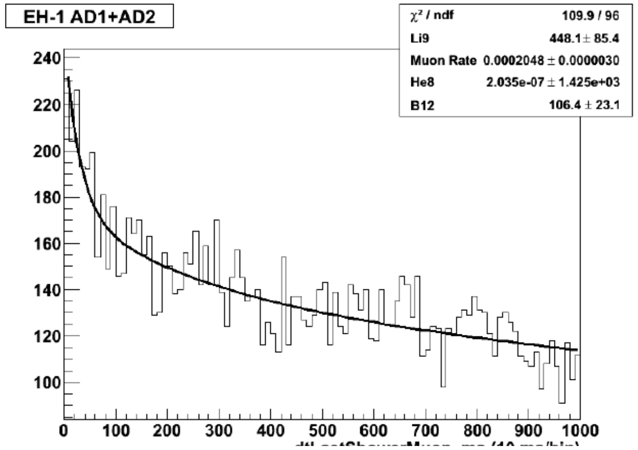
Background	Near	Far	Uncertainty
Accidentals	1.4%	2.3%	negligible
Li-9 / He-8	0.4%	0.4%	~30%
Fast neutron	0.1%	0.1%	~30%

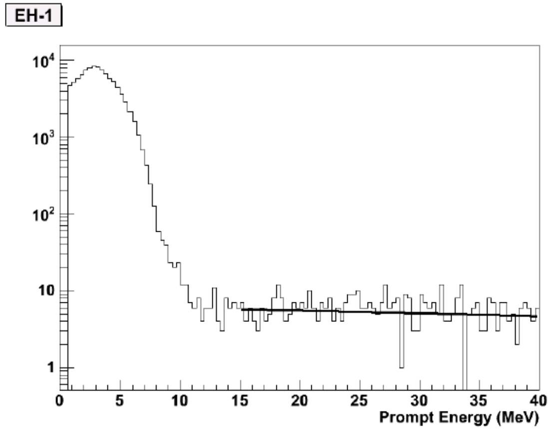












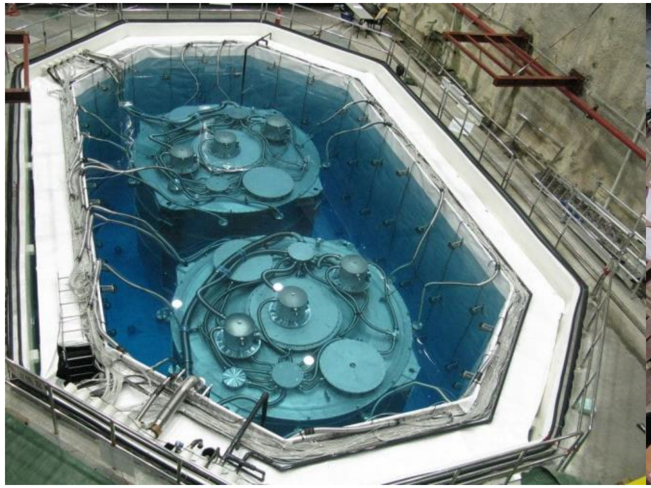
- How to discover the smallest neutrino oscillation with 5 days of Daya Bay reactor neutrino data?
  1. Plot the measured antineutrino signal rate of each AD vs. the expected flux, assuming each AD has the same size, and each reactor has the same power.
  2. Fit the data (what function to use?) with 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?

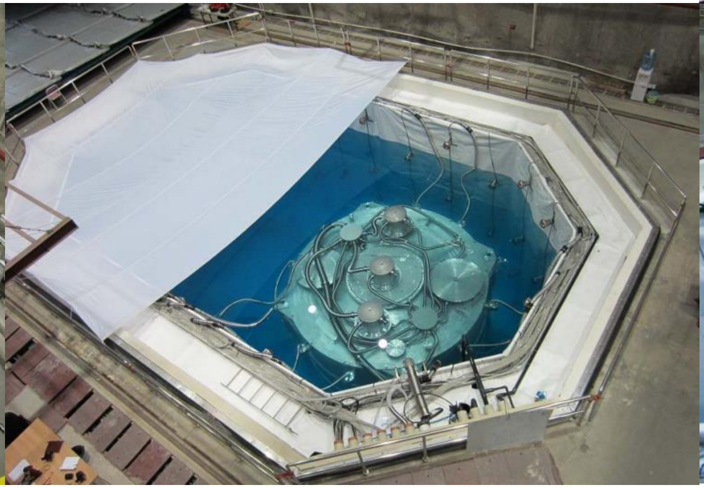
$$P = 1 - \sin^2 2\theta_{13} \cdot sin^2(1.27|\Delta m^2_{ee}(eV^2)| \cdot \frac{L\ (m)}{E(MeV)})$$

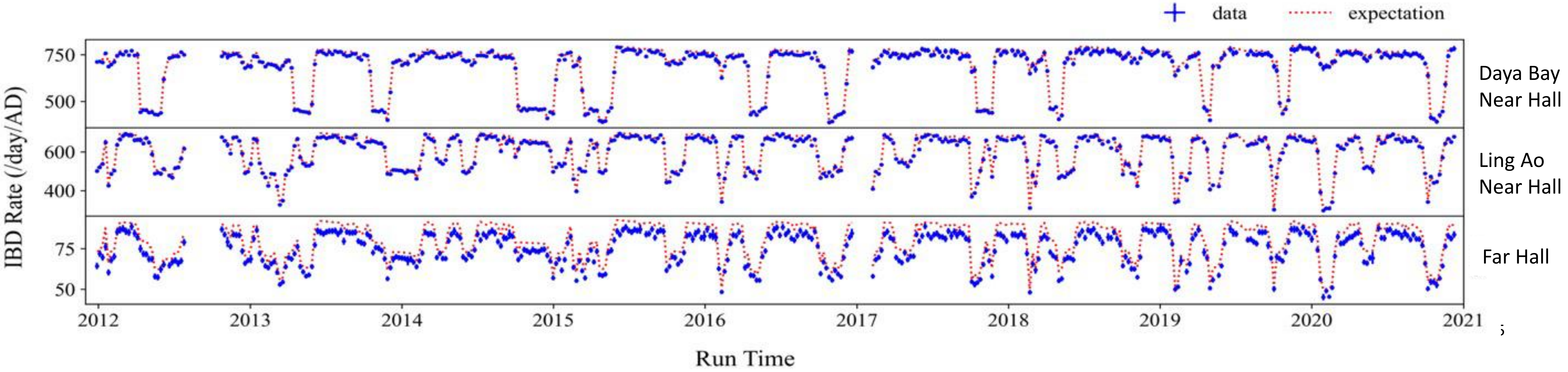
Δm^2	2.4×10^{-3} (eV^2)
L	1.66×10^3 (m)
E	3.5 (MeV)

❑ Data taking (12/24/2011 – 12/12/2020)

- 3275 days, 5.5M $\bar{\nu}_e$ events
  largest reactor neutrino data sample in the world







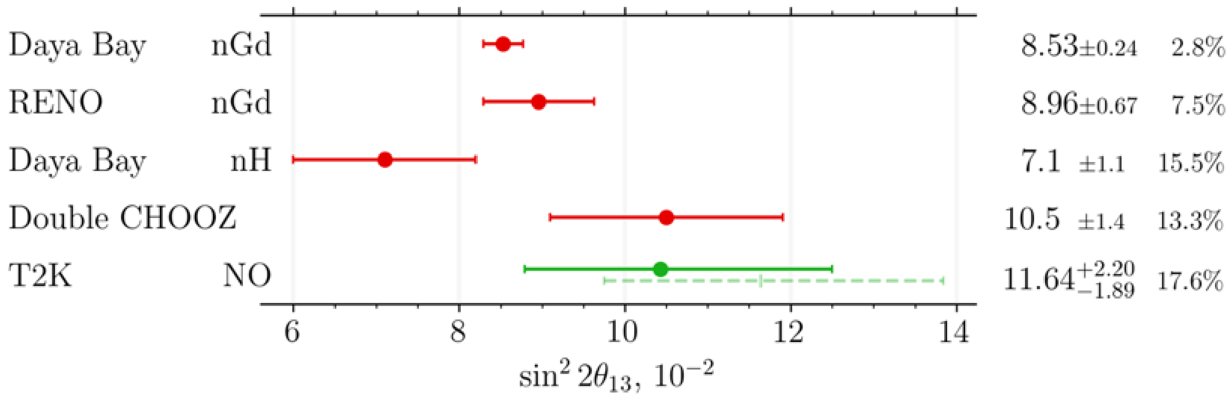
Precision Oscillation (1/26 free parameters in the SM)

Final results with the full data set

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

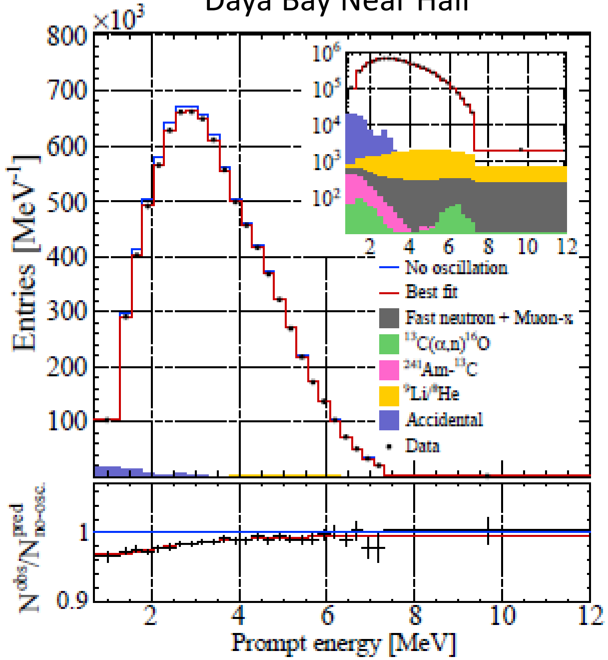
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

(2.8% precision)

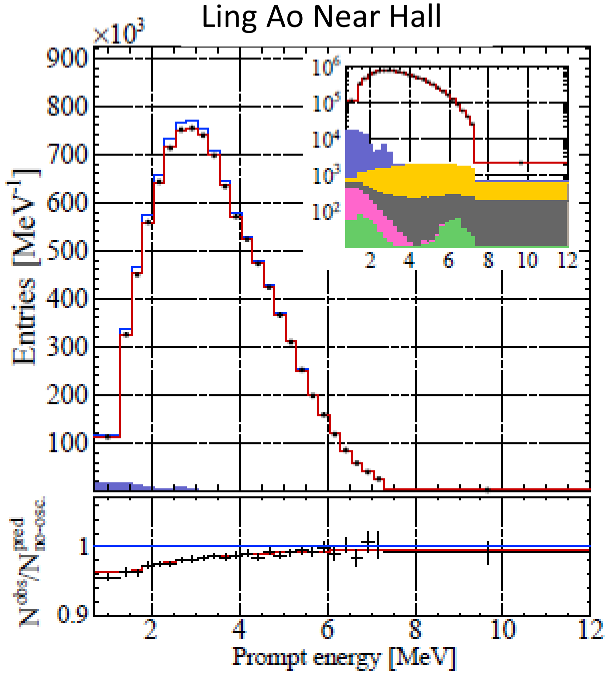


- Likely to be the best measurement in the foreseeable future
- Critical input to the current and future long-baseline experiments (DUNE)

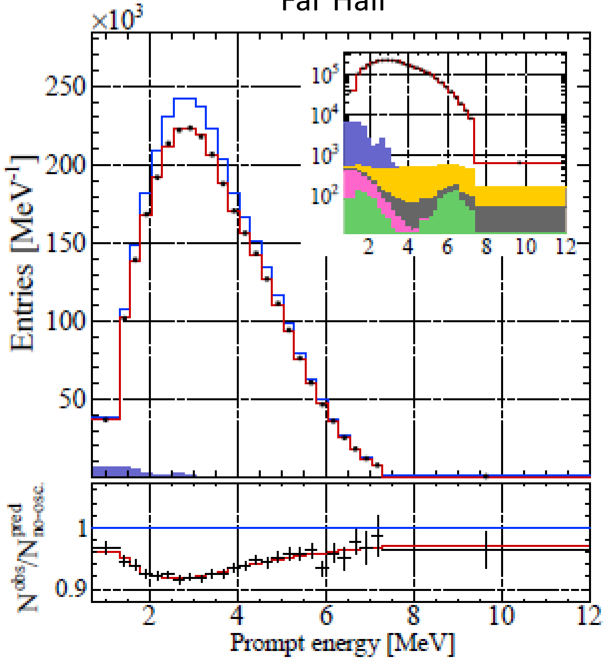
Daya Bay Near Hall



Ling Ao Near Hall



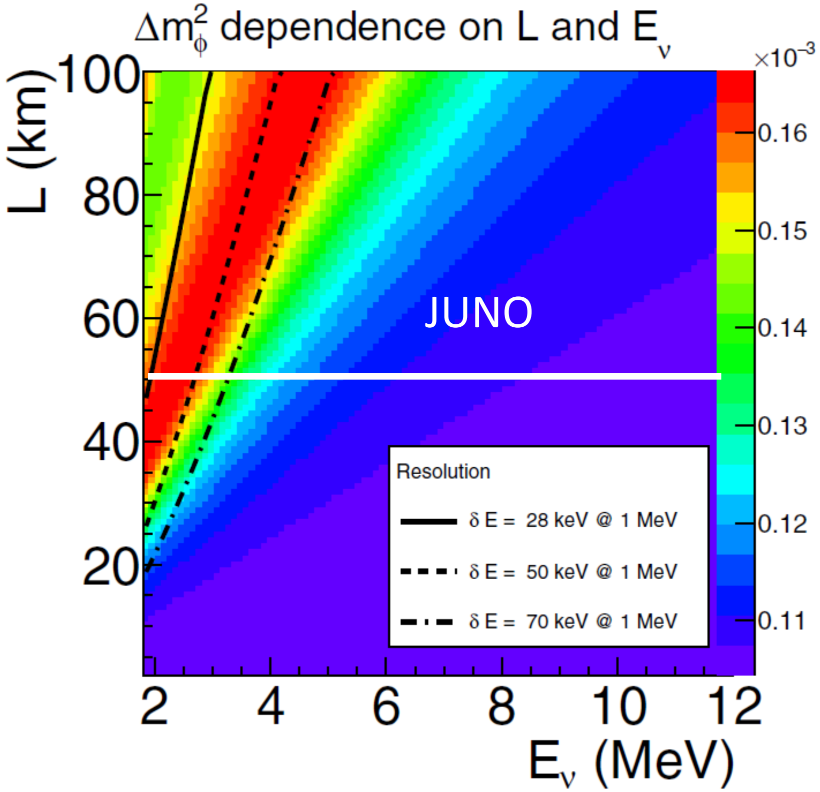
Far Hall



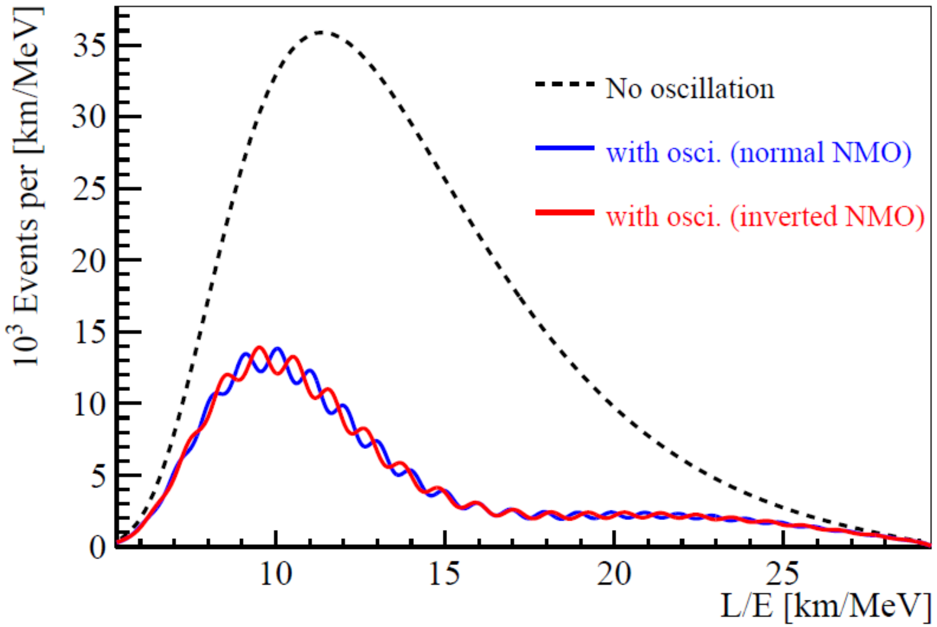
Resolution of the Neutrino Mass Hierarchy (MH or NMO) with Reactors

- 20 kt JUNO detector with better than 3% energy resolution @ 1 MeV and better than 1% energy scale determination
- ~100k neutrino events with ~27 GW_{th} → 3σ MH sensitivity*

* See PRD 86, 113011 for the statistical interpretation of MH sensitivity



PRD 87, 033005

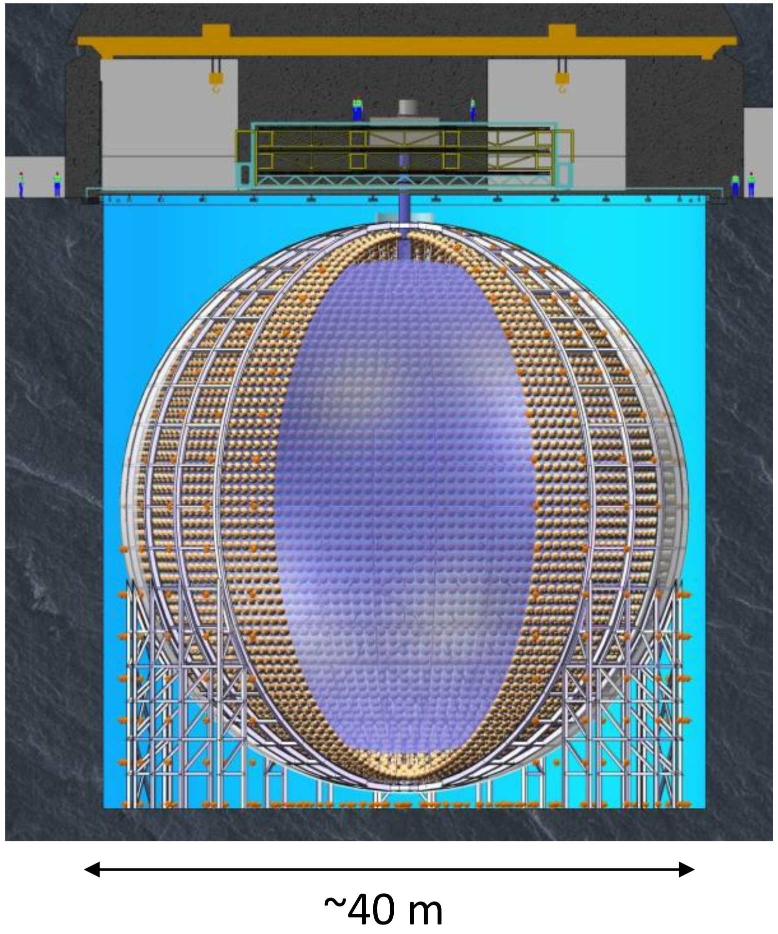


Ann. Rev. Nucl. Part. Sci. 67, 183

$$\Delta m^2_{eff} = \begin{cases} \text{normal} \;: 2\Delta m^2_{32} + m^2_\phi(E_\nu) \\ \text{inverted} : 2\Delta m^2_{32} - m^2_\phi(E_\nu) \end{cases}$$

Micro-Channel Plate PMT and High-Light-Yield Liquid Scintillator (LS)

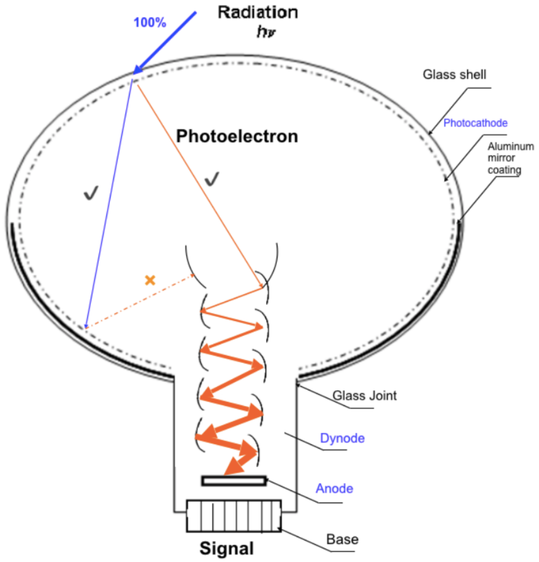
20 kT liquid scintillator



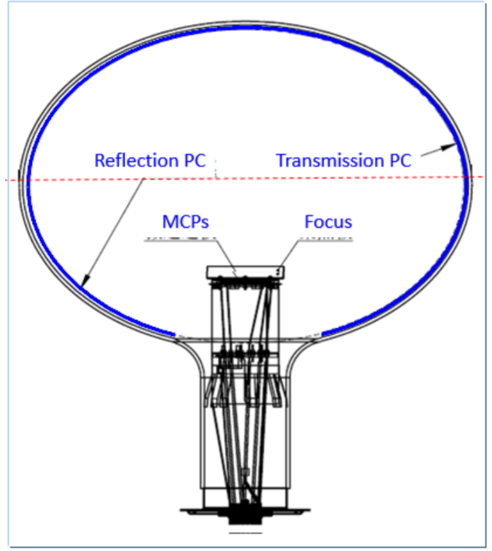
3% energy resolution
@ 1 MeV

PMTs:
17,600 20’’ PMT
25,000 3’’ PMT
Coverage 77.5%

LS:
10^4 PE/MeV
L_{att} > 20 m @ 430 nm
Low background



Dynode:(**PDE**)= QE_{Trans} * CE
= 20% * 70% = 14% (2009)
= 30% * 90% = 27% (2015)



MCP :(**PDE**)= QE_{Trans} * CE
= 27% * 100% = 27% (2016)

http://juno.ihep.cas.cn/

PDE: Photon Detection Efficiency

Construction Process of JUNO

Questions?