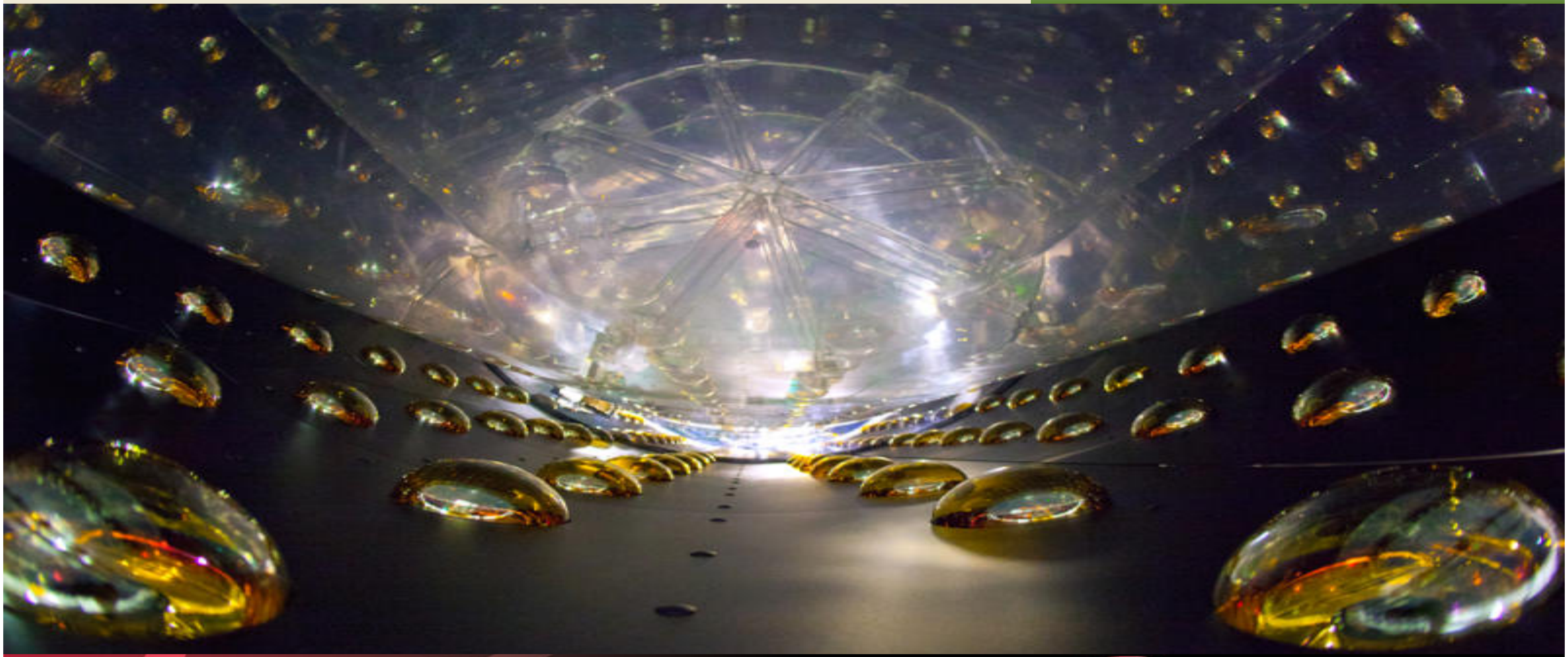
Neutrinos
And the Origin of Matter

R. D. McKeown



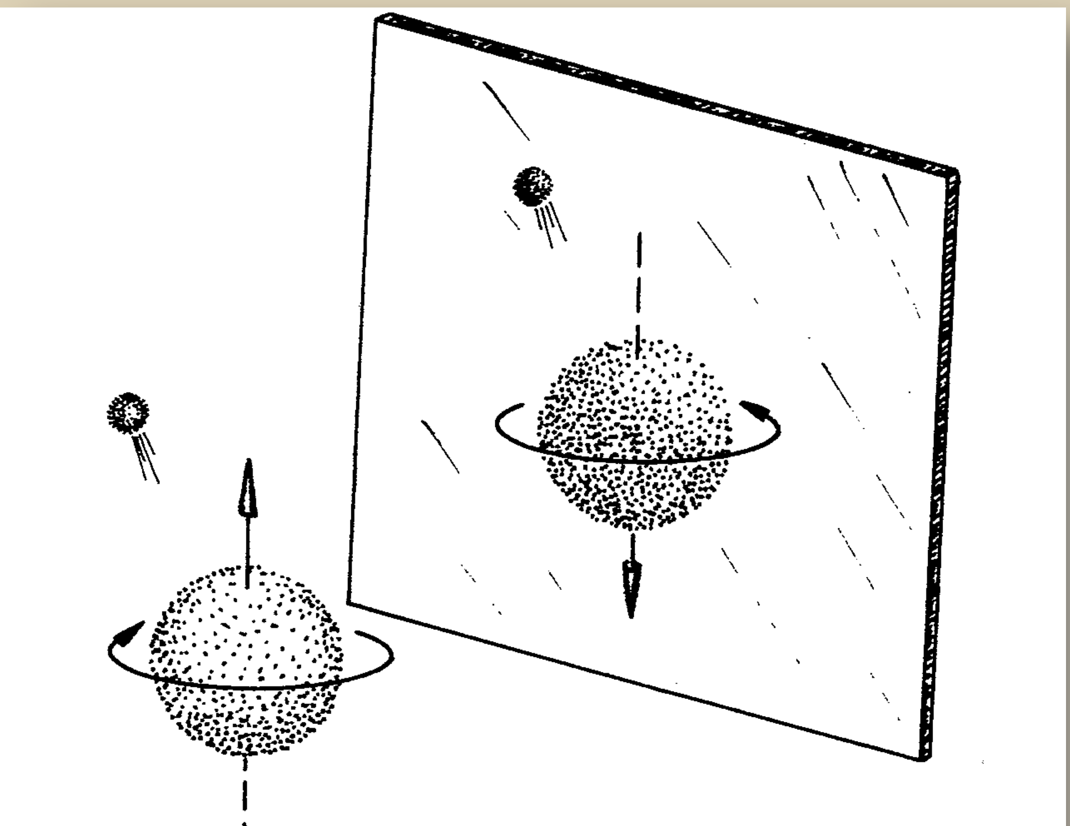
SPECC-2012
Dec.17, 2012

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- The Lack of Symmetry
- Why are we here…
- Recent experimental results
- Outlook

1956 – A Year of Revolution

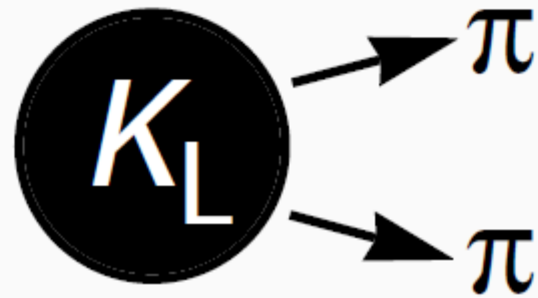


(A. Zee)

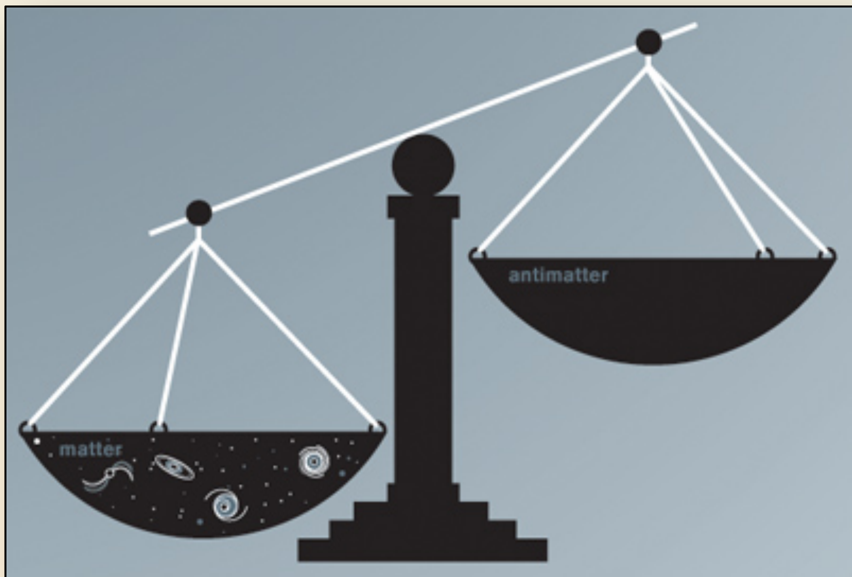
FOR THE FIRST TIME –

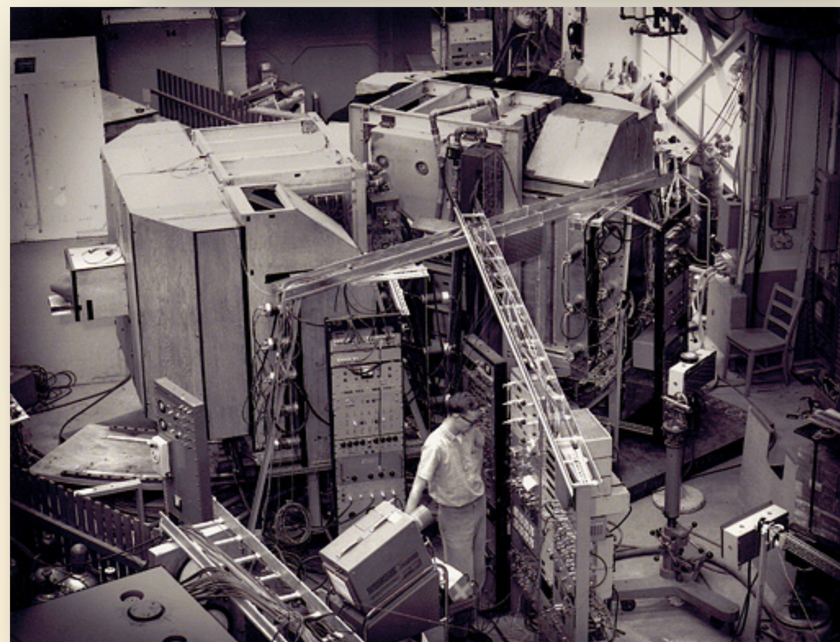
A FORCE OF NATURE WAS <u>ASYMMETRIC</u>

1964 - More Violation of Symmetry



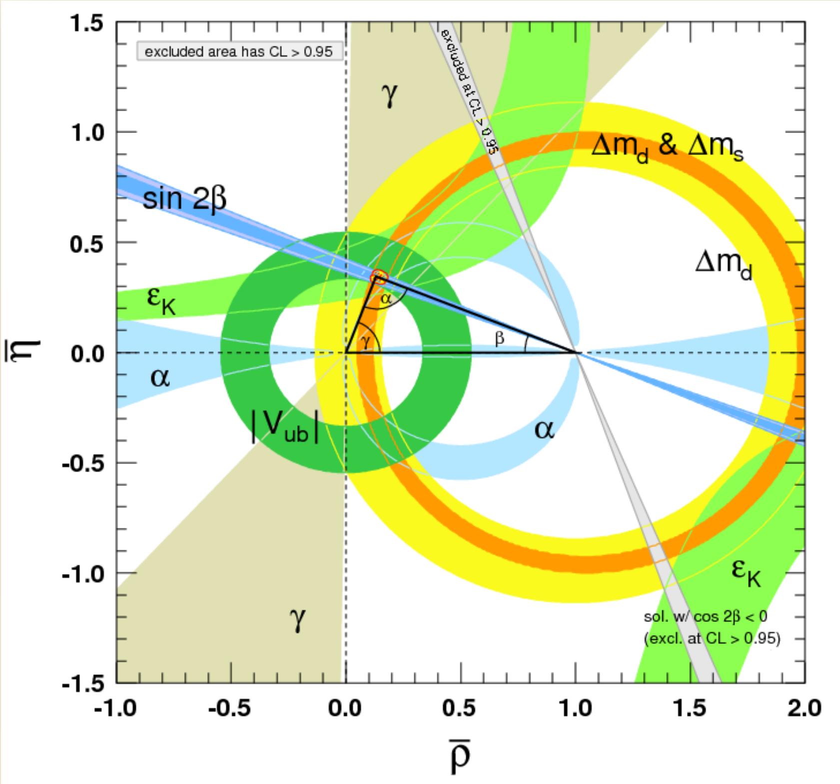
1:500





Cabibbo – Kobayashi - Maskawa

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Matter – Antimatter Asymmetry

(The universe contains matter, not antimatter)

Sakharov Criteria (1967):

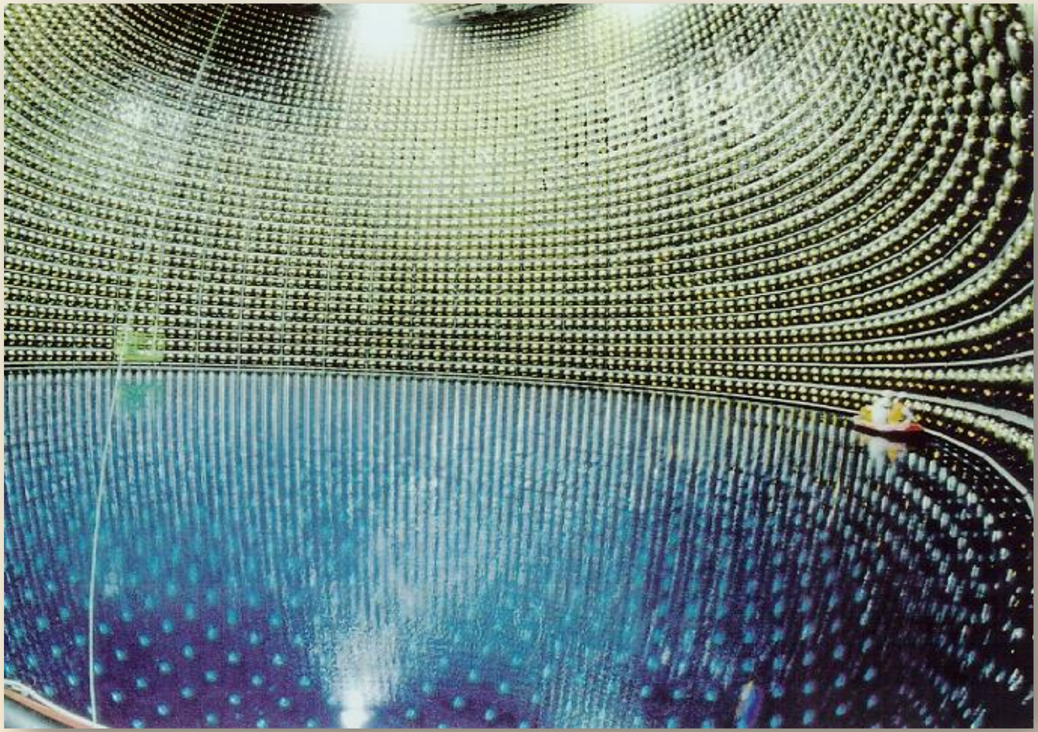
- Baryon number violation (or L→B) (no evidence yet!)
- CP violation (Quark (CKM) matrix? Not enough!)
- Non-equilibrium
  (universe expands, OK, need phase transition?)

e.g., N-decay, EDM's, ν mixing

Baryon Number Violation?

Search for proton decay

$$p \rightarrow e^{+} + \pi^{0}$$



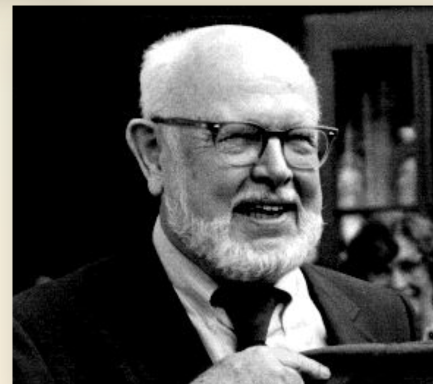
Super-Kamiokande

Meanwhile….

Why Does the Sun Shine?

- Sun ≡ Ball of H gas compressed by gravity
  $\rightarrow$ HEAT (not enough)
- HEAT $\rightarrow$ Nuclear fusion
  $p + p \rightarrow d + e^{+} + \nu + \text{energy}$

THE ASTROPHYSICAL JOURNAL
Vol. 137, No. 1, January 1963



SOLAR NEUTRINO FLUX*

The discovery by Holmgren and Johnston (1958, 1959) of an unexpectedly large cross-section for the $He^3(\alpha, \gamma)Be^7$ reaction led to studies by Fowler (1958) and Cameron (1958) which showed that the proton-proton chain in the present sun is frequently completed by a series of reactions involving Be^7. Fowler and Cameron also discussed the possibility that the decay of B^8, formed by $Be^7(p, \gamma)B^8$ reactions in the interior of the sun, produces a terrestrially measurable flux of high-energy neutrinos ($0 < E_\nu < 14$ Mev). The detection of solar neutrinos is the only experiment that we can think of which could provide *direct* evidence of specific nuclear reactions occurring in the interior of a star.

We have made use of recently obtained accurate values for the Be^7 electron-capture cross-section (Bahcall 1962) and the Be^7 formation cross-section (Parker and Kavanagh 1962) to make a detailed calculation of the expected B^8 solar neutrino flux. Other relevant nuclear cross-sections have been taken from the report of Fowler (1960). The cross-section constants, corrected for shielding factors, which we have used are, in units of kev-barns, as follows: $S_{11} = 3.5 \times 10^{-22}$, $S_{33} = 1300$, $S_{34} = 0.5$, $S_{17} = 0.03$. The Be^7 decay rate is

$$\lambda_e(Be^7) = 2.12 \times 10^{-9} \rho (1 + x_H) T_6^{-1/2} \text{ sec}^{-1} .$$

The rate of neutrino emission per gram has been integrated over a new model for the interior of the present sun (Iben and Sears 1962); this model has a central temperature of 16.2×10^6 ° K, a central density of 142 gm/cm^3, and a central composition $x_H = 0.333$, $x_{He} = 0.633$, compared with a surface composition of $x_H = 0.630$, $x_{He} = 0.336$. The opacity and energy-generation rates with B^8 reactions included were taken from the work of Iben and Ehrman (1962); we find that 1.0×10^{35} high-energy neutrinos are generated in the sun per second and that the expected neutrino flux at the earth from B^8 decays in the sun is

$$\phi_\nu(B^8) = 3.6 \times 10^7 \text{ neutrinos cm}^{-2} \text{ sec}^{-1} .$$

The neutrino generation corresponds approximately to 1 neutrino for every 1500 proton-proton reactions, and the flux should be compared with the value of 6.4×10^{10} low-energy neutrinos cm^{-2} sec^{-1} from the *pp*-reaction and the Be^7-decays. The flux is a factor of 10 less than could be detected with current experimental techniques using the $Cl^{37}(\nu, e)A^{37}$ reaction and a detector consisting of 10^5 gallons of perchlorethylene (Davis 1962).

However, Davis (1962) has pointed out to us that the more energetic Be^7 neutrinos ($E_\nu = 0.861$ MeV, 88 per cent; 0.383 MeV, 12 per cent) are just above threshold for detection by Cl^{37} absorption ($Q = -0.814$ MeV). The Be^7 solar neutrino flux above the Cl^{37} threshold is

$$\phi_\nu(Be^7; 0.861 \text{ MeV}) = 1.0 \times 10^{+10} \text{ cm}^{-2} \text{ sec}^{-1} .$$

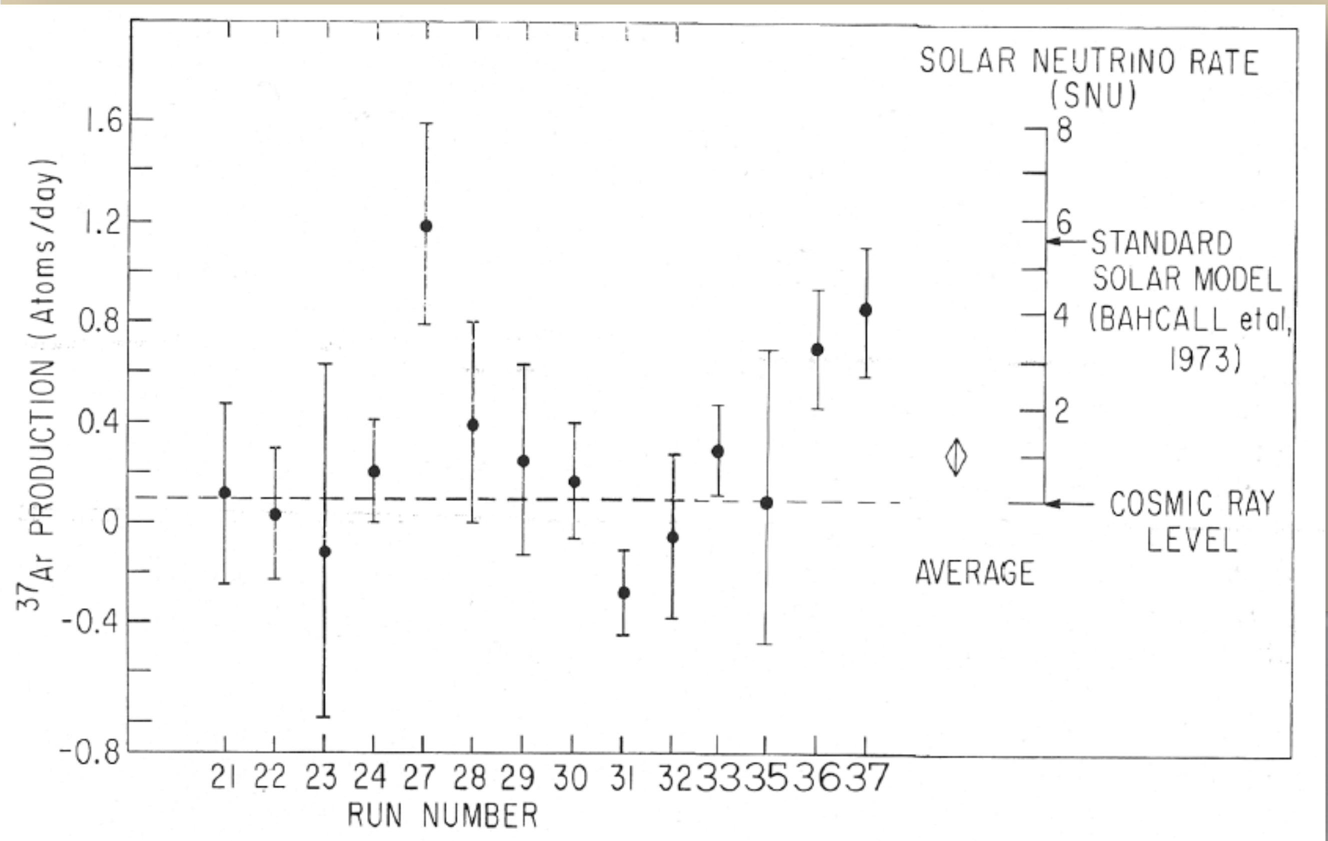
Since the Cl^{37} neutrino-absorption cross-section for the 0.861-MeV Be^7 neutrinos is about a factor of 200 less than the average absorption cross-section for B^8 neutrinos, about one-half of the detectable solar neutrino flux are from B^8 decays, according to the model of Iben and Sears (1962).

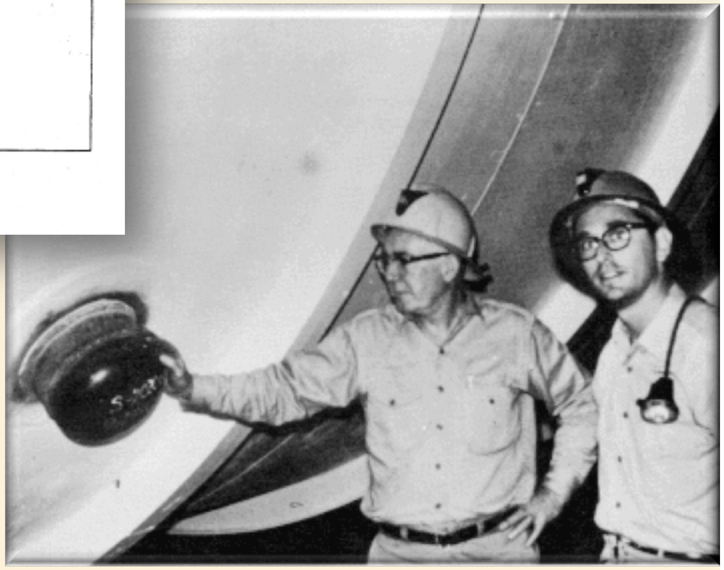
J. N. BAHCALL
WILLIAM A. FOWLER
I. IBEN, JR.
R. L. SEARS

December 1, 1962

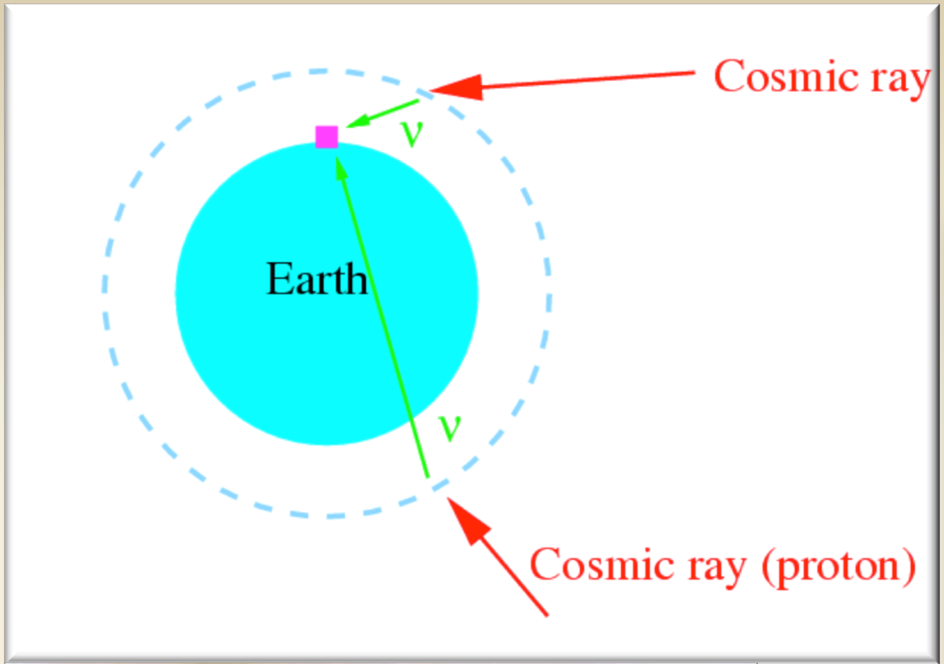
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

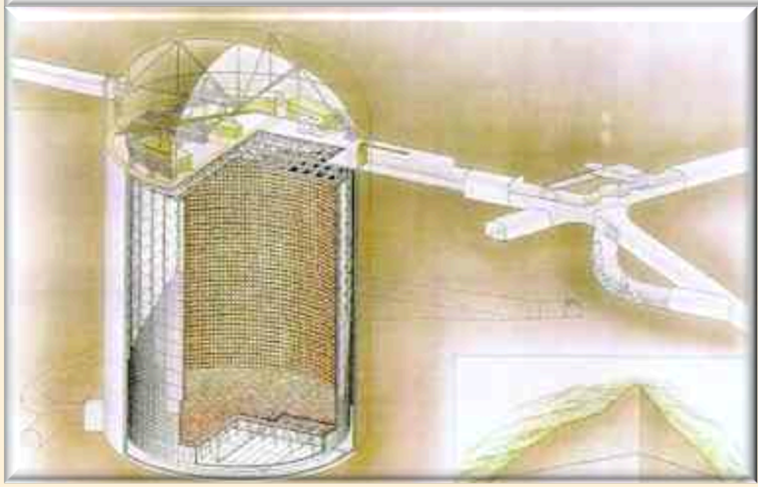
Not Enough Neutrinos!



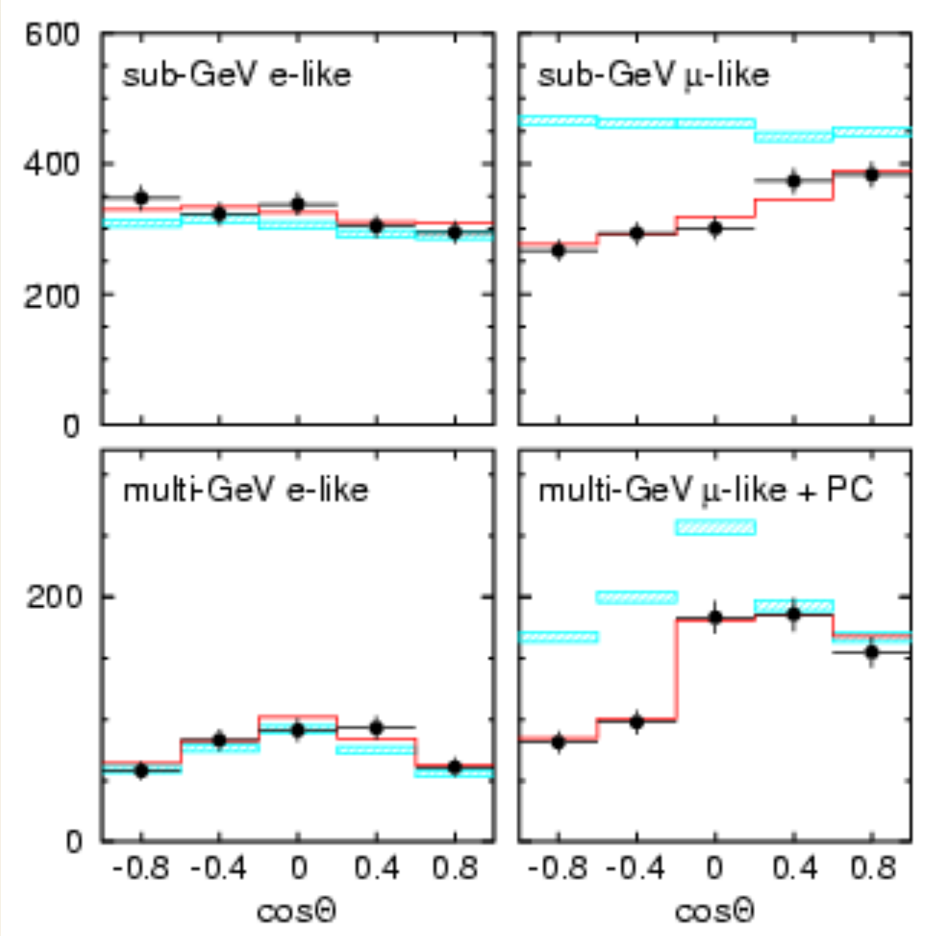


Super-Kamiokande (1998)

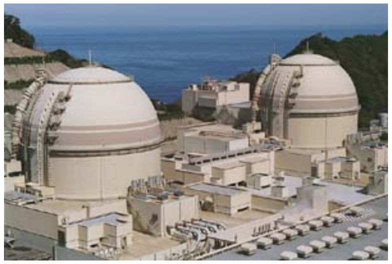


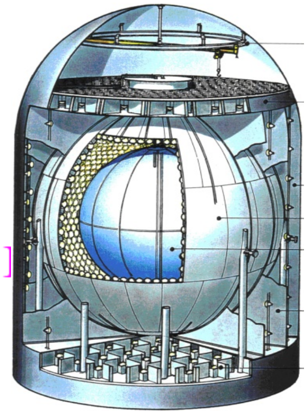


First evidence for neutrino oscillations!



Neutrino Mass and Mixing





Two Generation Model

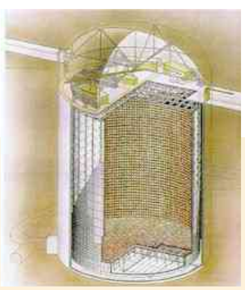
$$|\nu_e\rangle \xrightarrow{\;L\;} A_e\,|\nu_e\rangle + A_\mu\,|\nu_\mu\rangle$$

ν_1, ν_2 mass eigenstates m_1, m_2

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$\Delta m^2 = m_1^2 - m_2^2$$

$$P_\mu = |A_\mu|^2 = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



$$P_e = |A_e|^2 = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$E_\nu = 1$ GeV, $\Delta m^2 = 10^{-3}$ eV^2 , $L = 1240$ km

- **Neutrinos have mass!**
- **Substantial flavor mixing!**

Three Generations of Neutrinos

Pontecorvo Maki – Nakagawa – Sakata Matrix

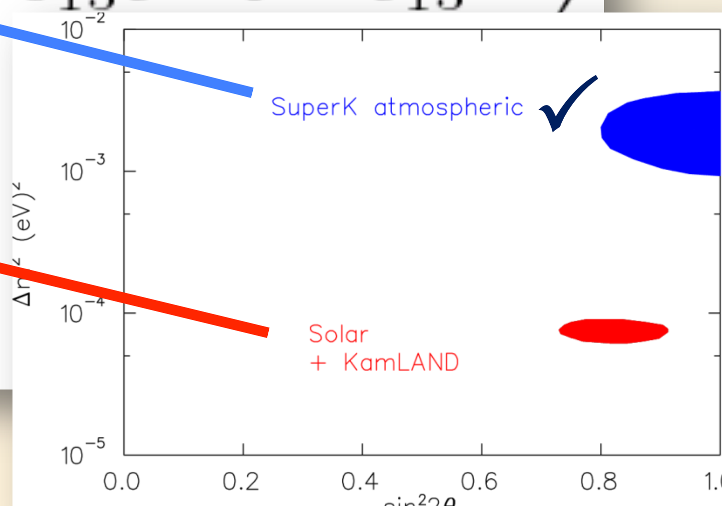
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

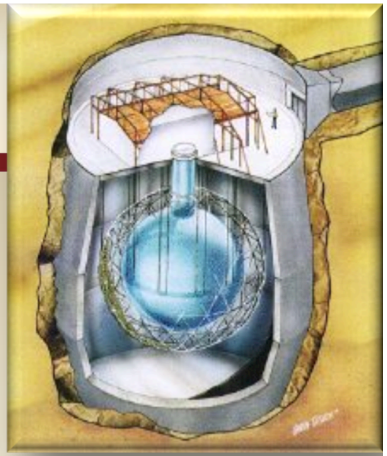
3rd mixing angle,
Gateway to CP violation

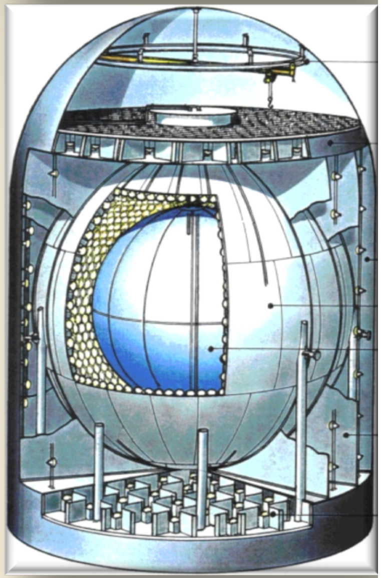
CP violation

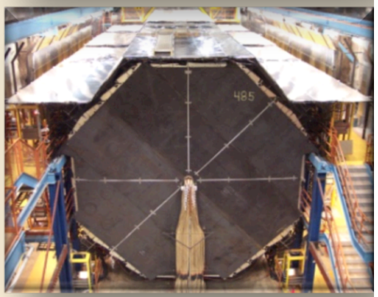


Progress Since 2000

- Sudbury Neutrino Observatory (SNO)
  → flavor change responsible for solar ν_e deficit
- KamLAND
  → observes oscillation pattern, δm_{12}^2
- K2K & MINOS
  → precise determination of δm_{23}^2, θ_{23}
- Daya Bay (2012)
  → discovery of θ_{13}

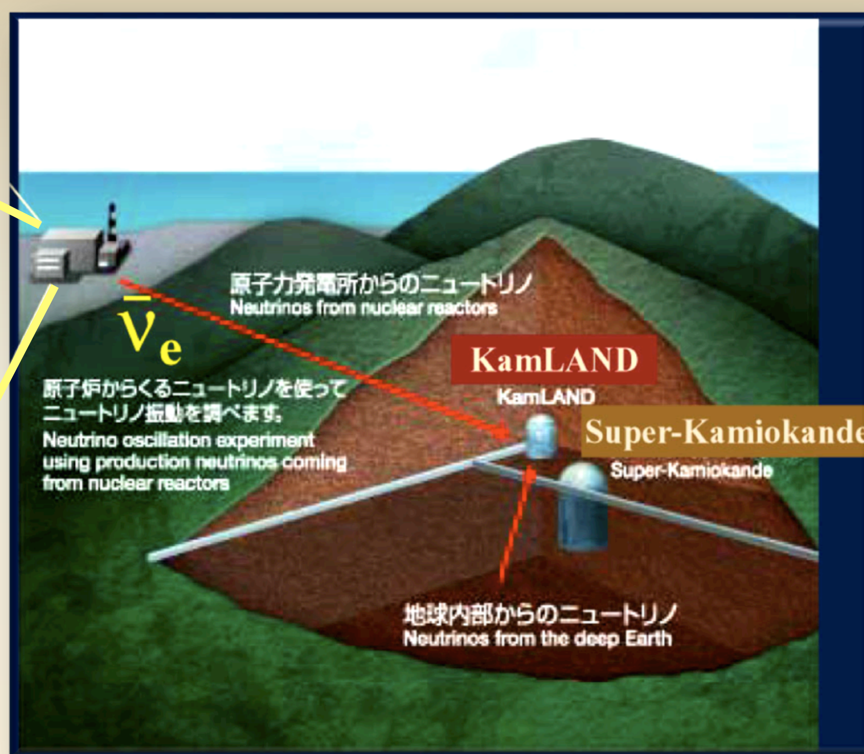






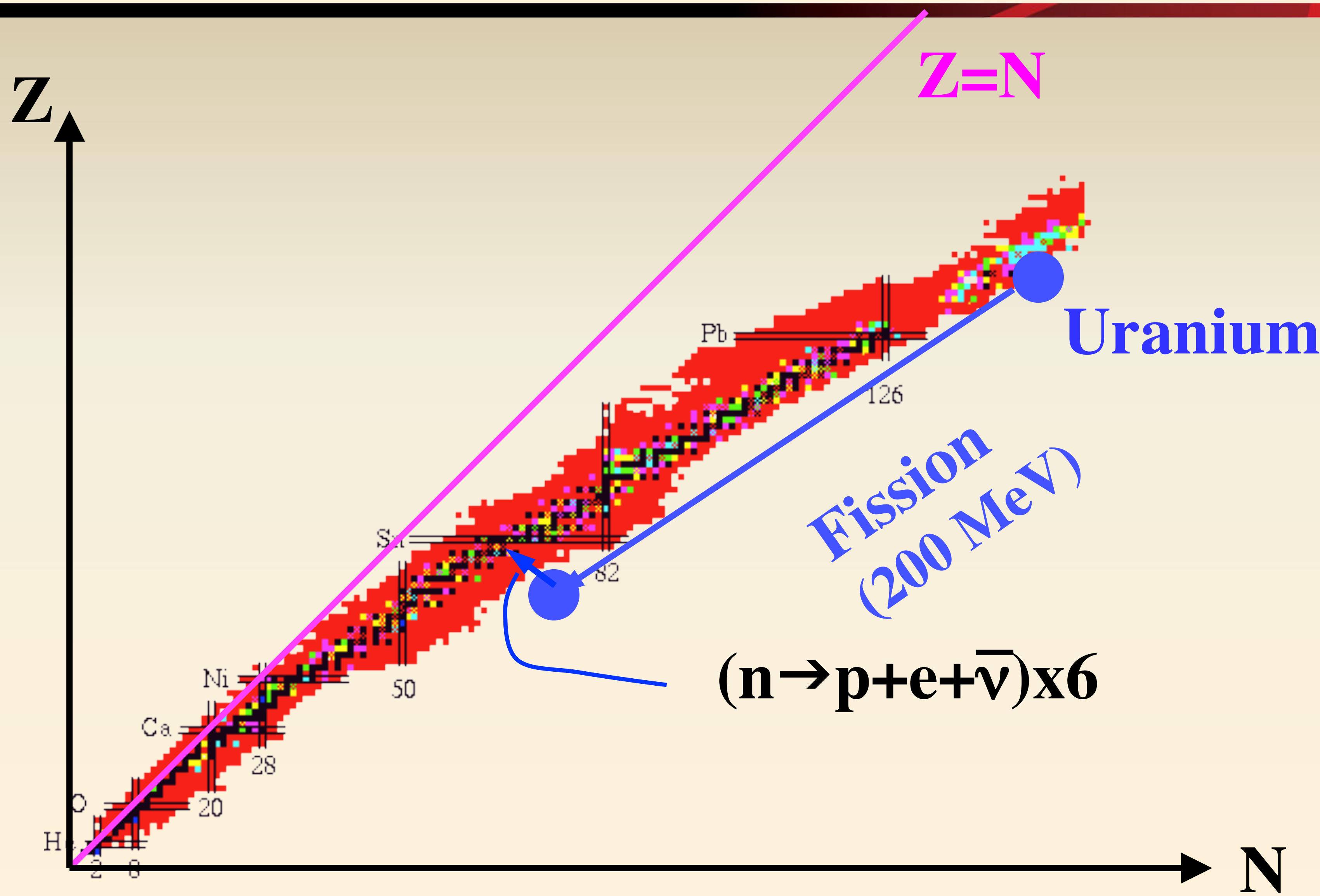
KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector



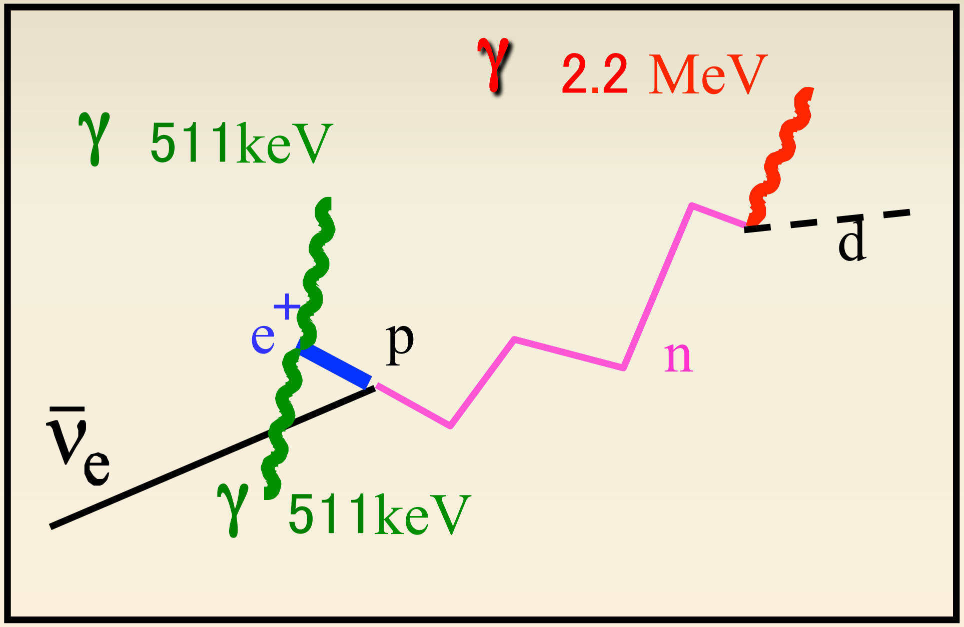
- $\bar{\nu}_e$ from n-rich fission products
- detection via inverse beta decay ($\nu_e+\bar{p}\rightarrow e^+ + n$)
- Measure flux and <u>energy spectrum</u>

Nuclear Reactors make Antineutrinos



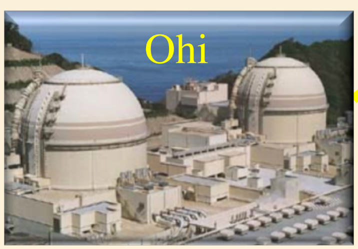
Detection Signal

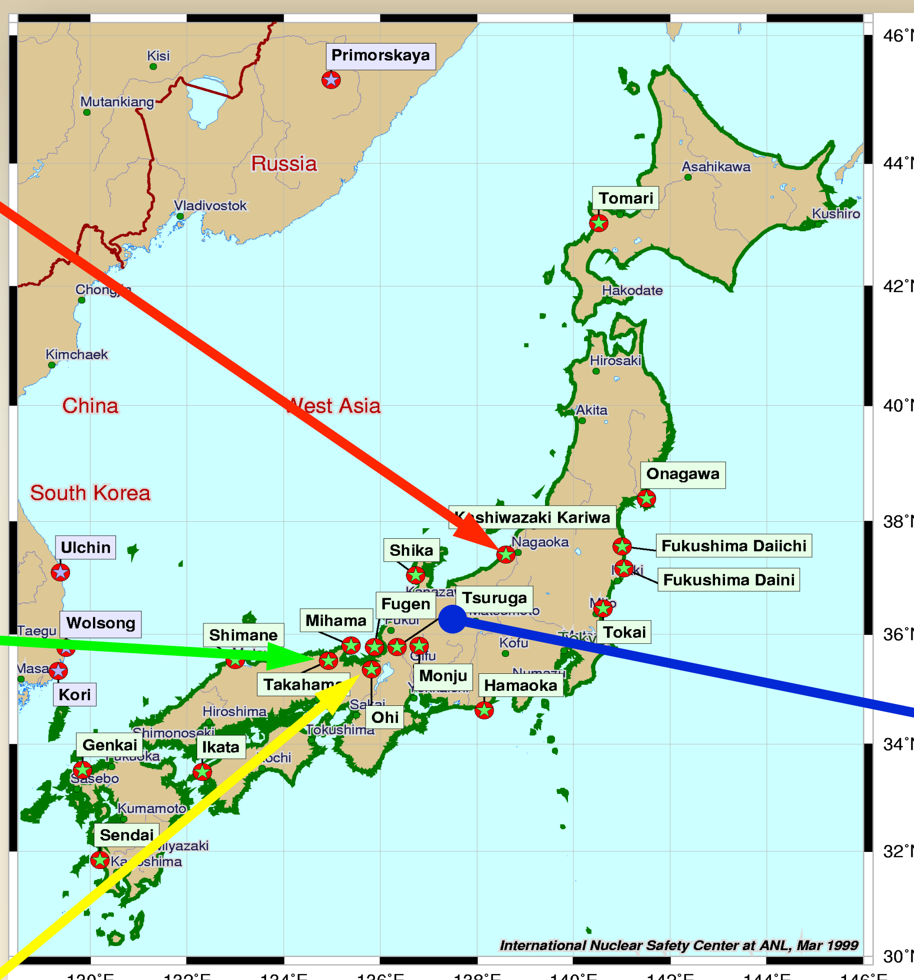
$\overline{\nu} + p \rightarrow n + e^+$



Coincidence signal:

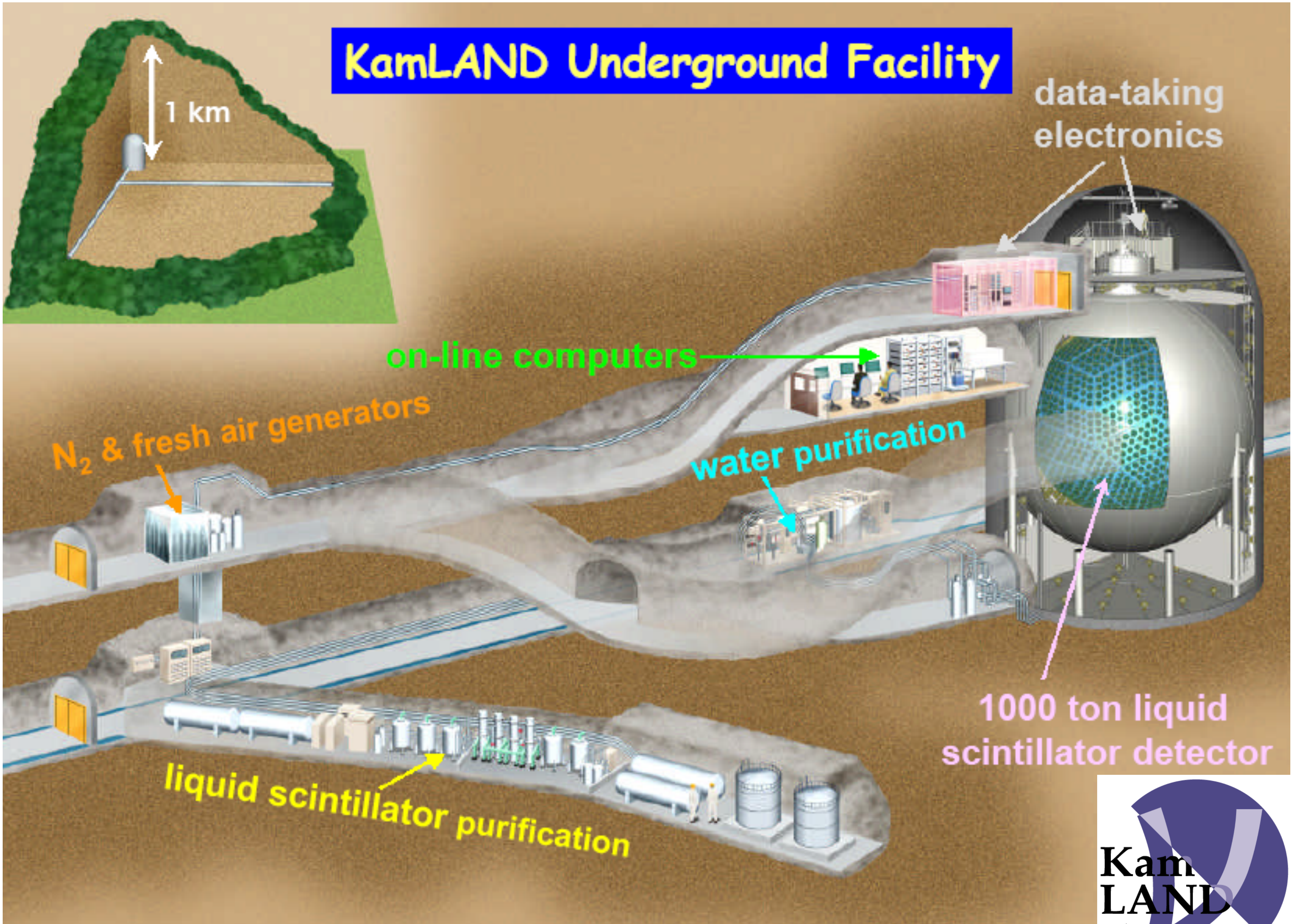
- Prompt: e^+ annihilation → $E_\nu = E_{prompt} + \overline{E}_n + 0.8$ MeV
- Delayed: **n+p** 180 μs capture time, 2.2 MeV
  n+Gd 30 μs capture time, 8 MeV



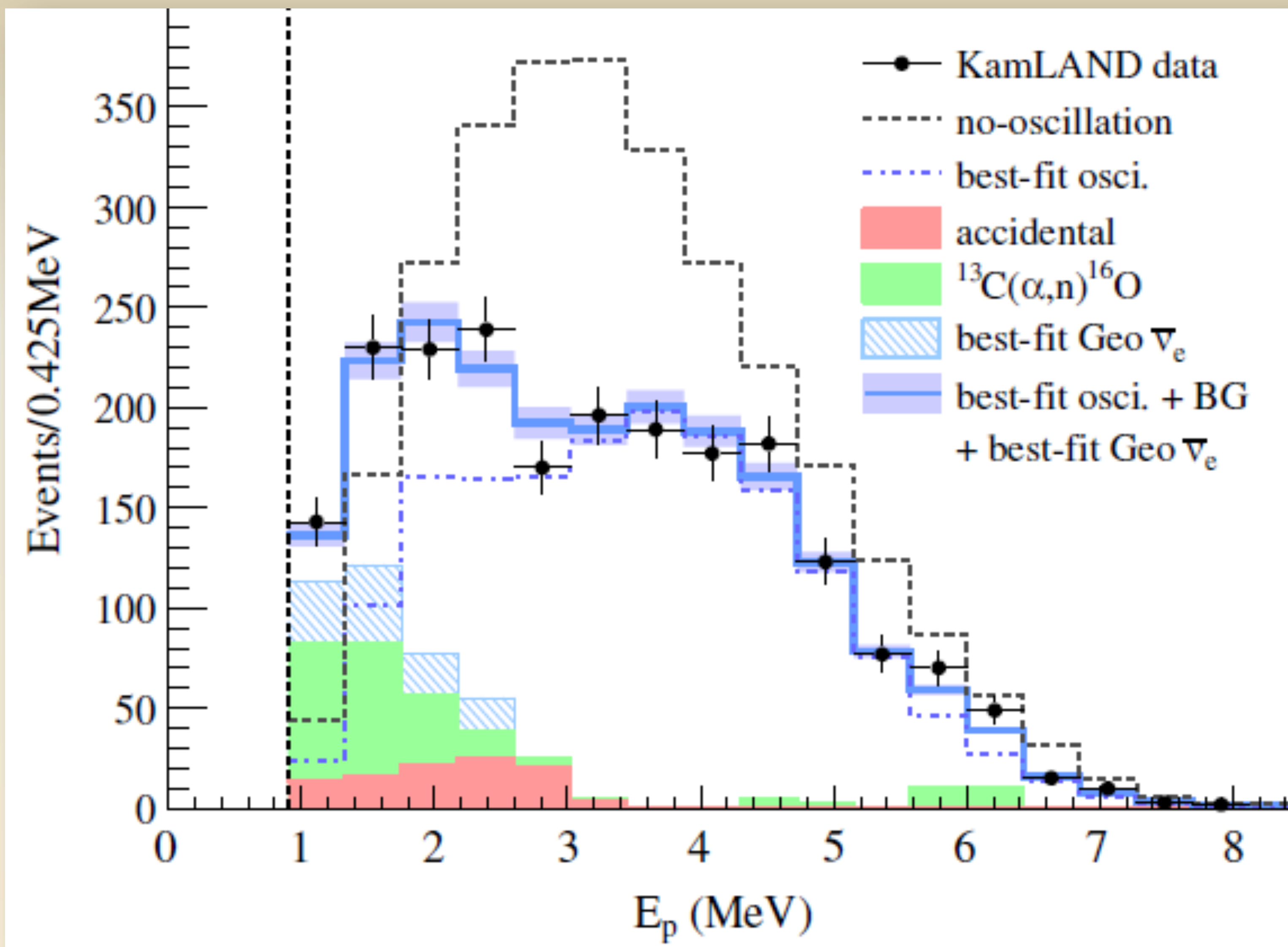


KamLAND used the entire Japanese nuclear power industry as a long-baseline neutrino source

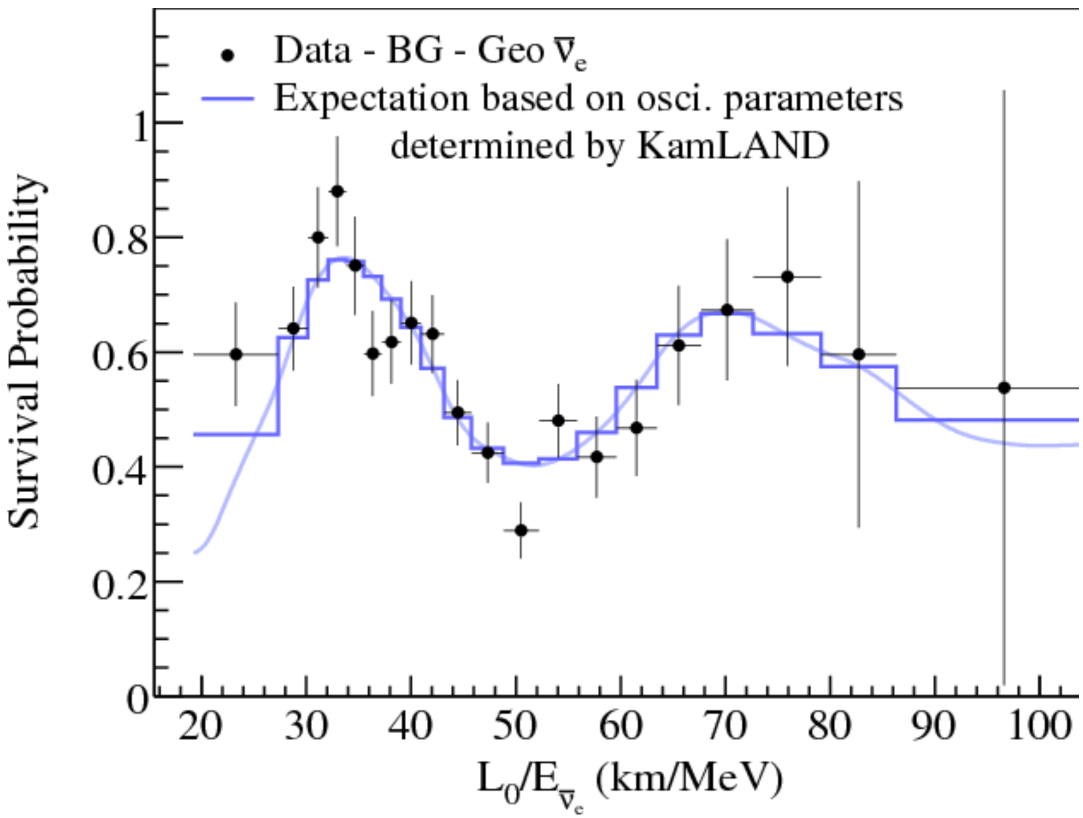
KamLAND Underground Facility

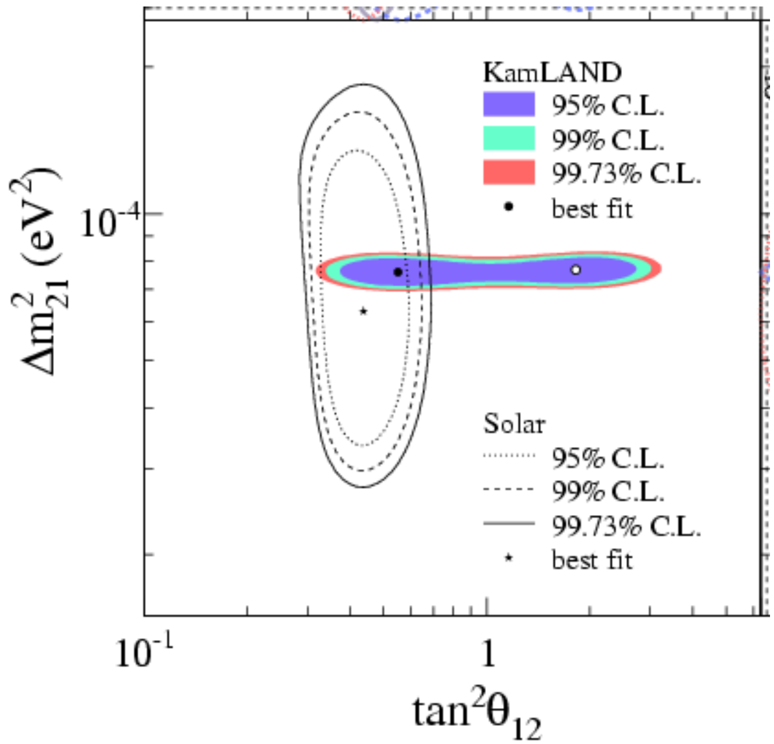


Energy Spectrum



KamLAND Result (2008)





PRL 100, 221803 (2008)

Best combined fit values:

$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}$ eV^2

$\tan^2\theta = 0.47^{+0.06}_{-0.05}$

Jefferson Lab

Pontecorvo Maki – Nakagawa – Sakata Matrix

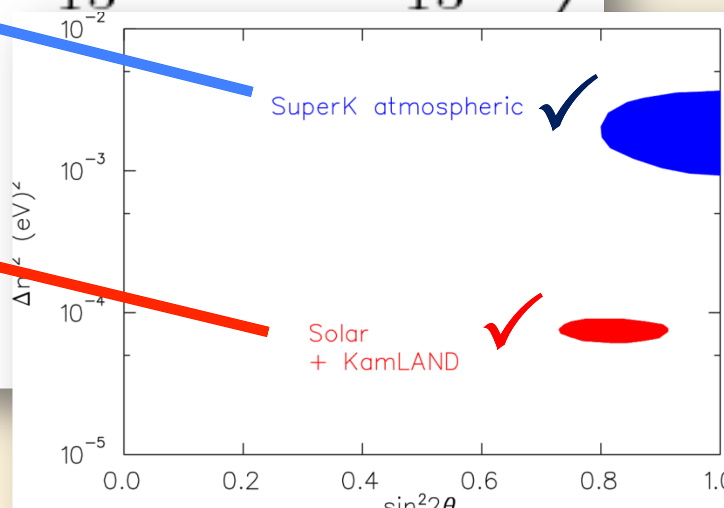
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

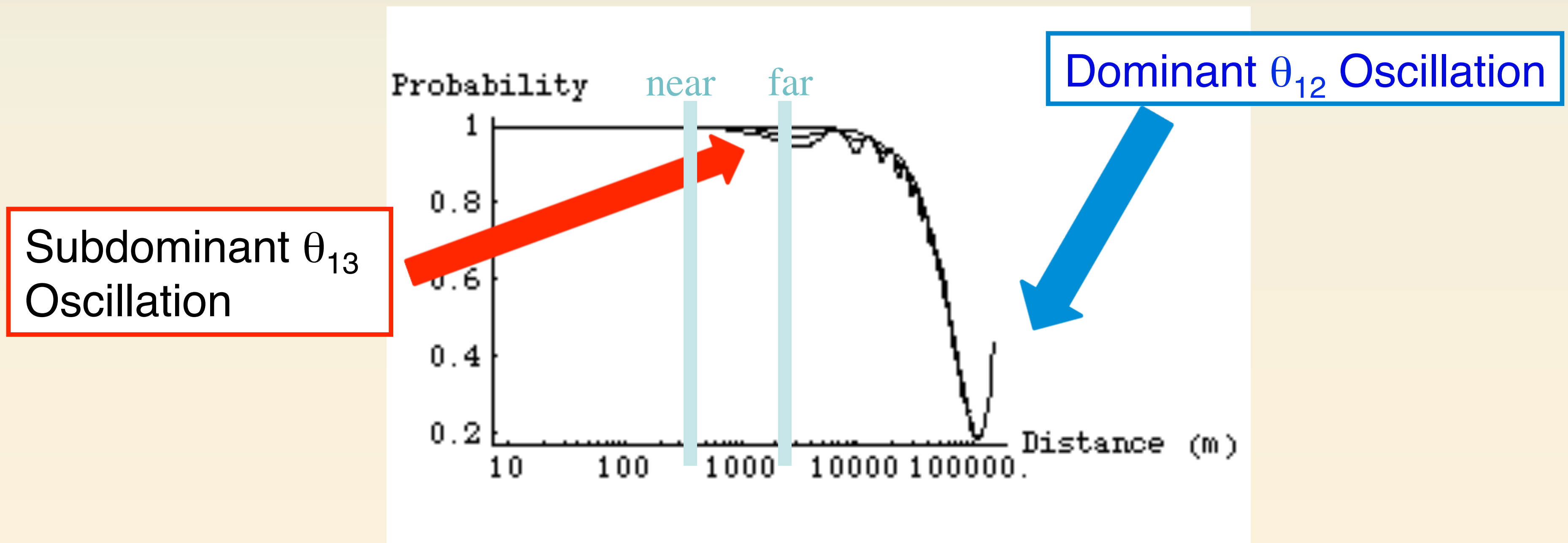
Gateway to CP Violation!

CP violation



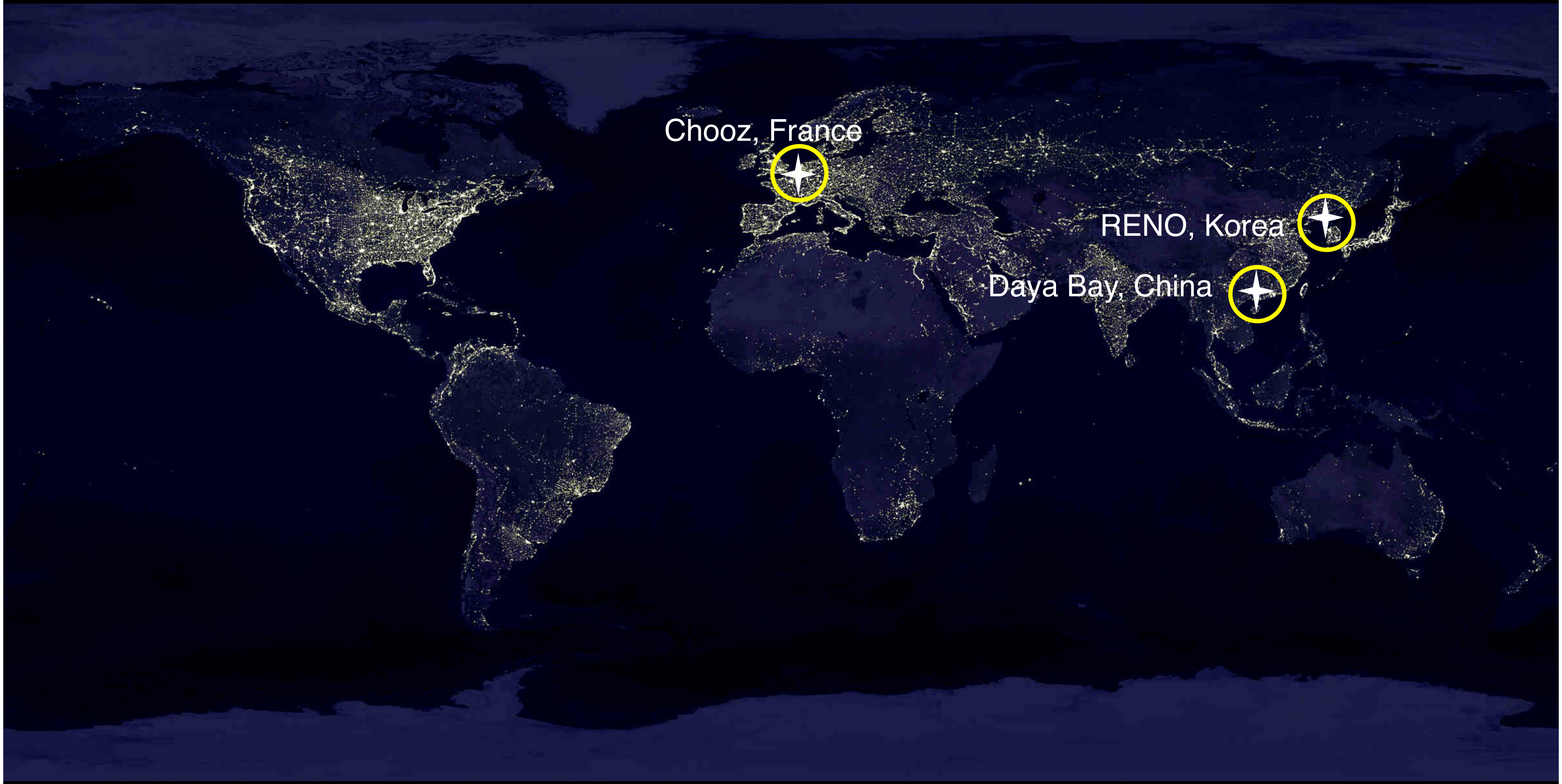
$\bar{\nu}_e$ Survival Probability (3 generations)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

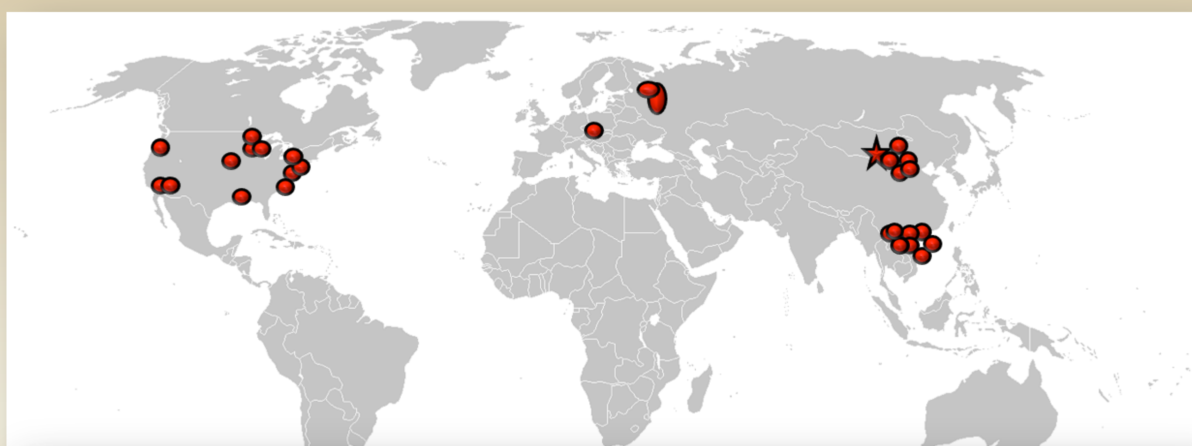


- "Clean" measurements of θ, Δm^2
- Use 2 detector sites

New Reactor θ_{13} Neutrino Experiments



Daya Bay Collaboration
An International Effort



Asia (20)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)
Brookhaven Natl' Lab, Cal Tech, Cincinnati, Houston, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl' Lab, Princeton, Rensselaer Polytech, UC Berkeley, UCLA, Wisconsin, William & Mary, Virginia Tech, Illinois, Siena College

Europe (3)
Charles Univ,. Dubna, Kurchatov Inst.

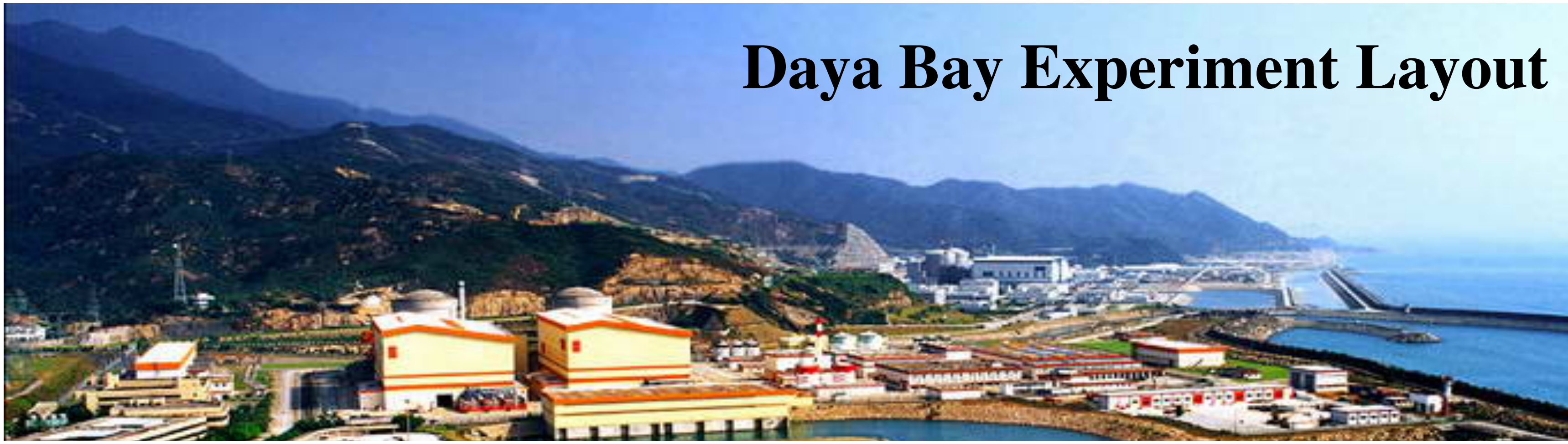
~240 collaborators

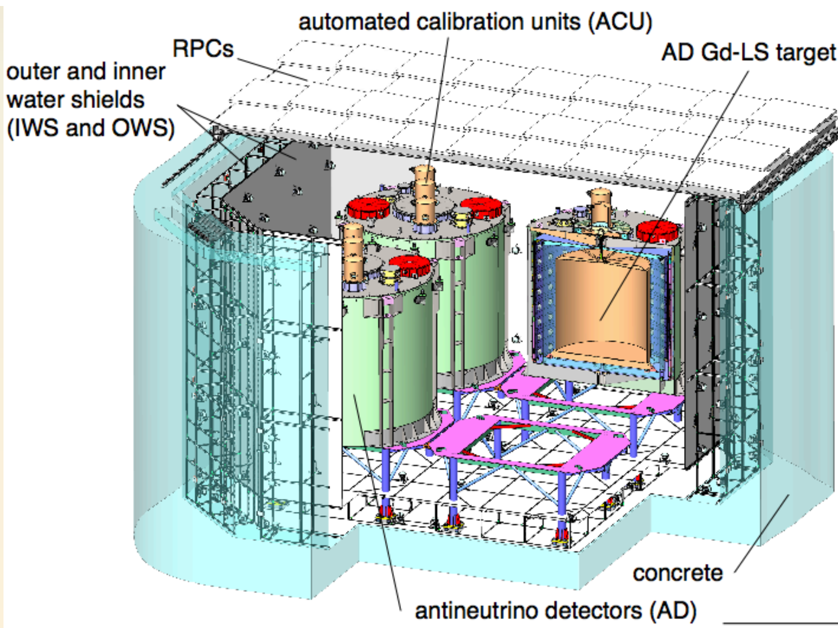
Daya Bay - A Powerful Neutrino Source

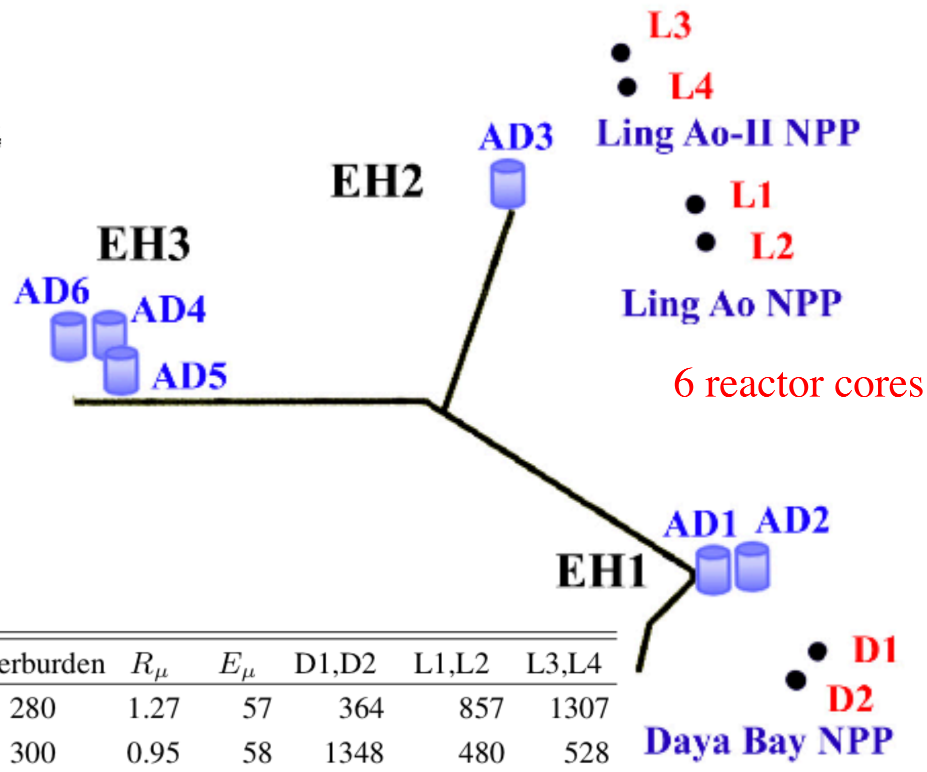
- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW$_{th}$ (6 x 2.95 GW$_{th}$)
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce ~2×10^{20} antineutrinos/sec/GW

Daya Bay Experiment Layout



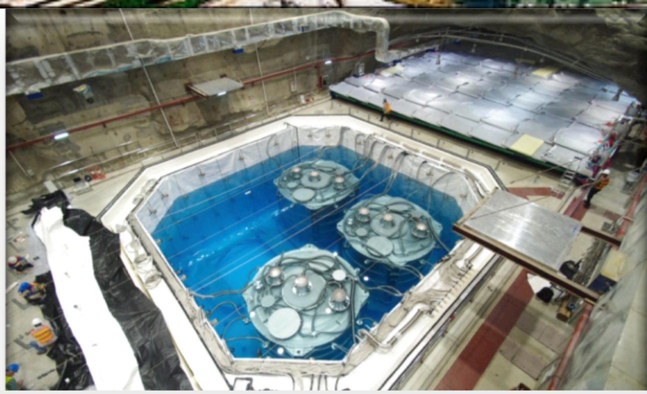




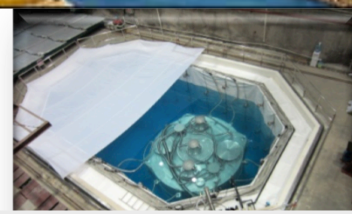
	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

6 antineutrino detectors in 3 underground experimental halls

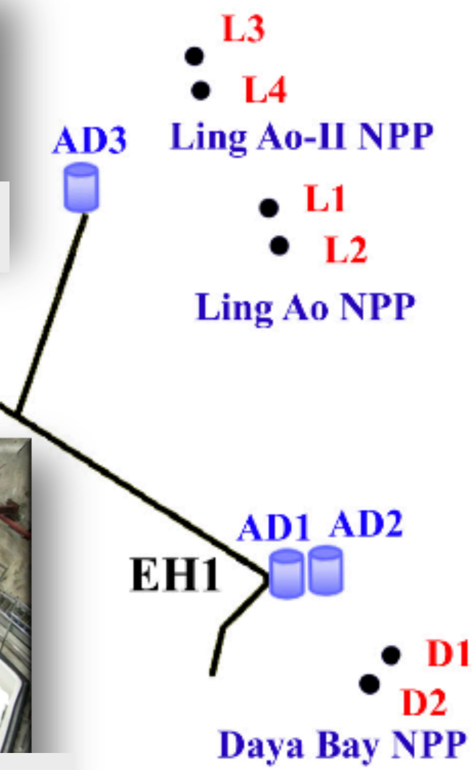
Daya Bay Experiment Layout

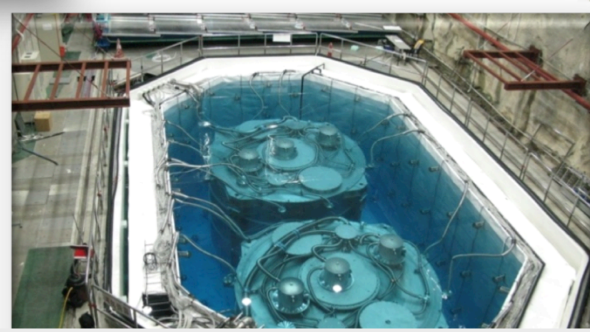


Hall 3: began 3AD operation on Dec. 24, 2011



Hall 2: began 1 AD operation on Nov. 5, 2011

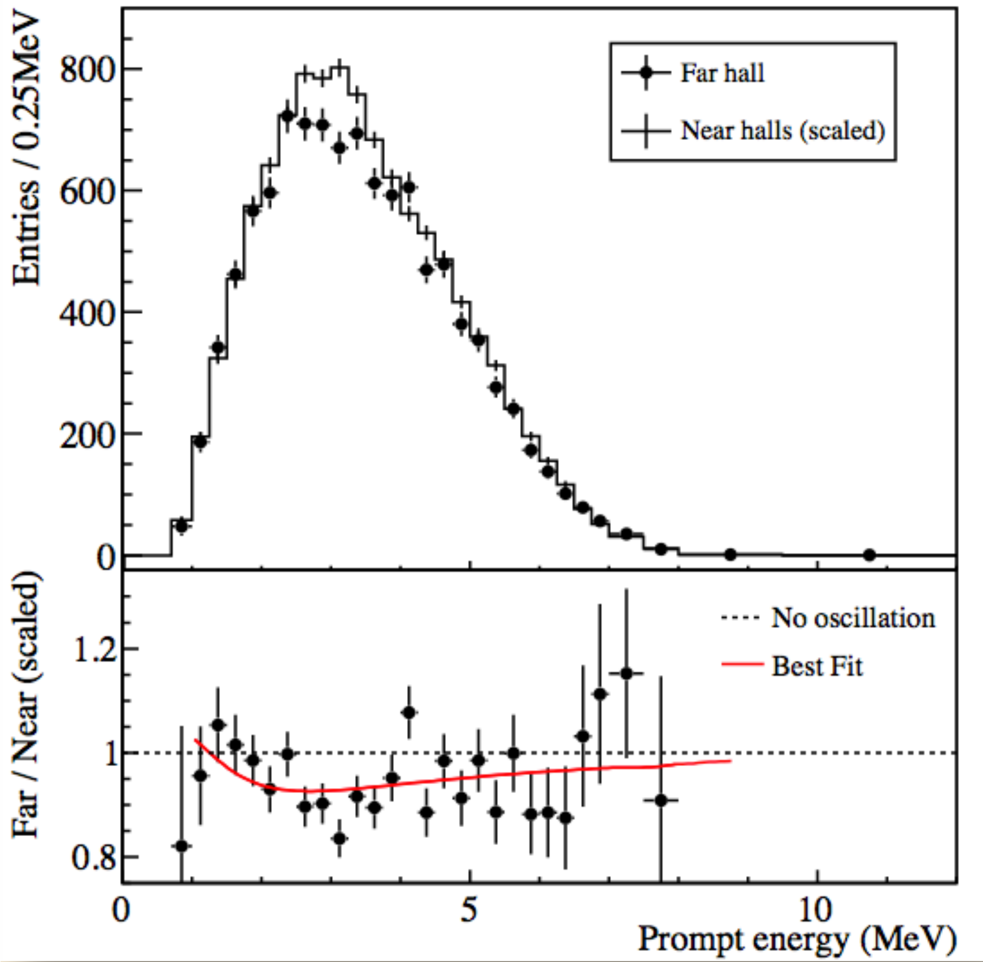




Hall 1: began 2AD operation on Sep. 23, 2011

Far vs. Near Comparison

Compare measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

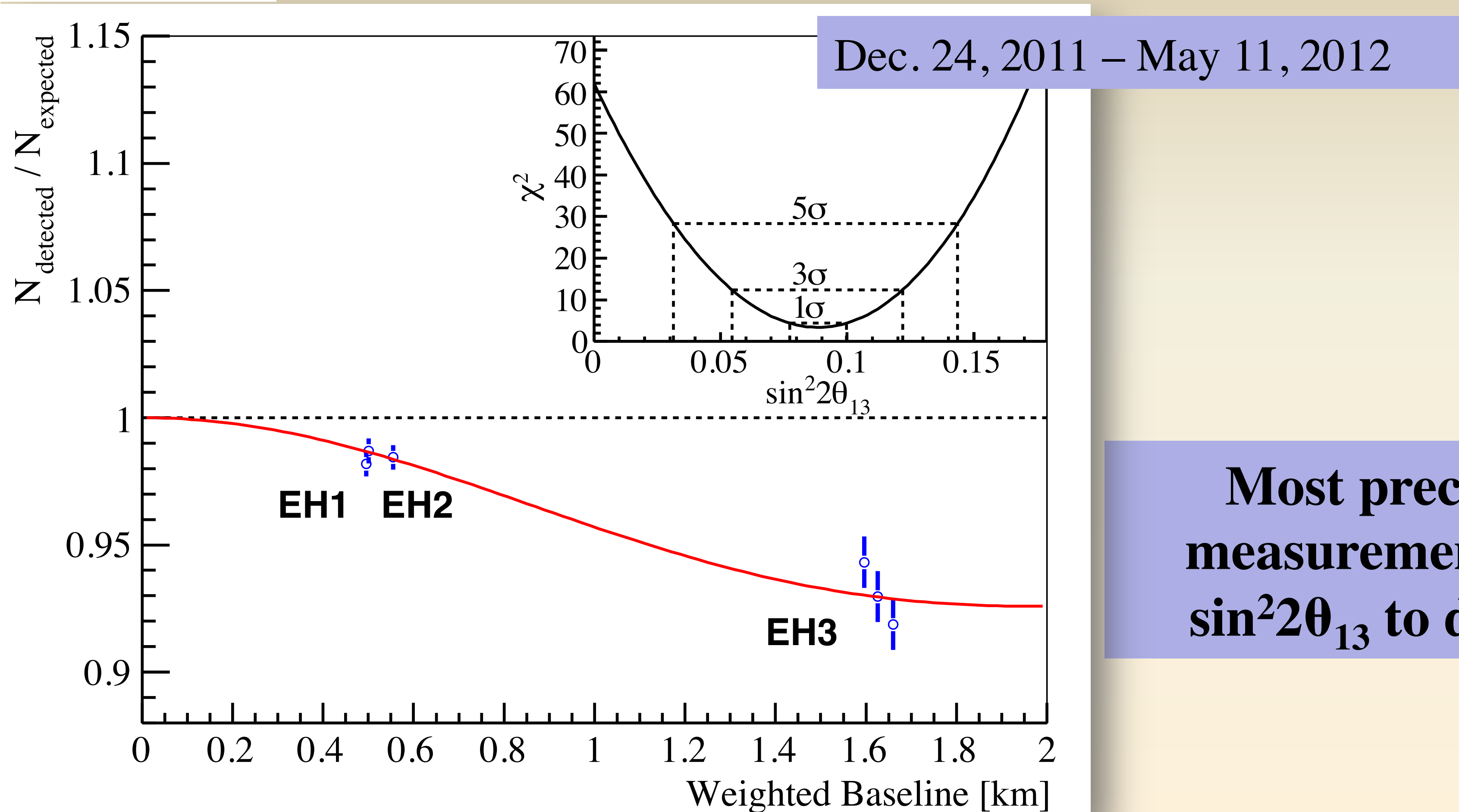
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied;
θ_{13} value from shape analysis is not recommended.

Jefferson Lab

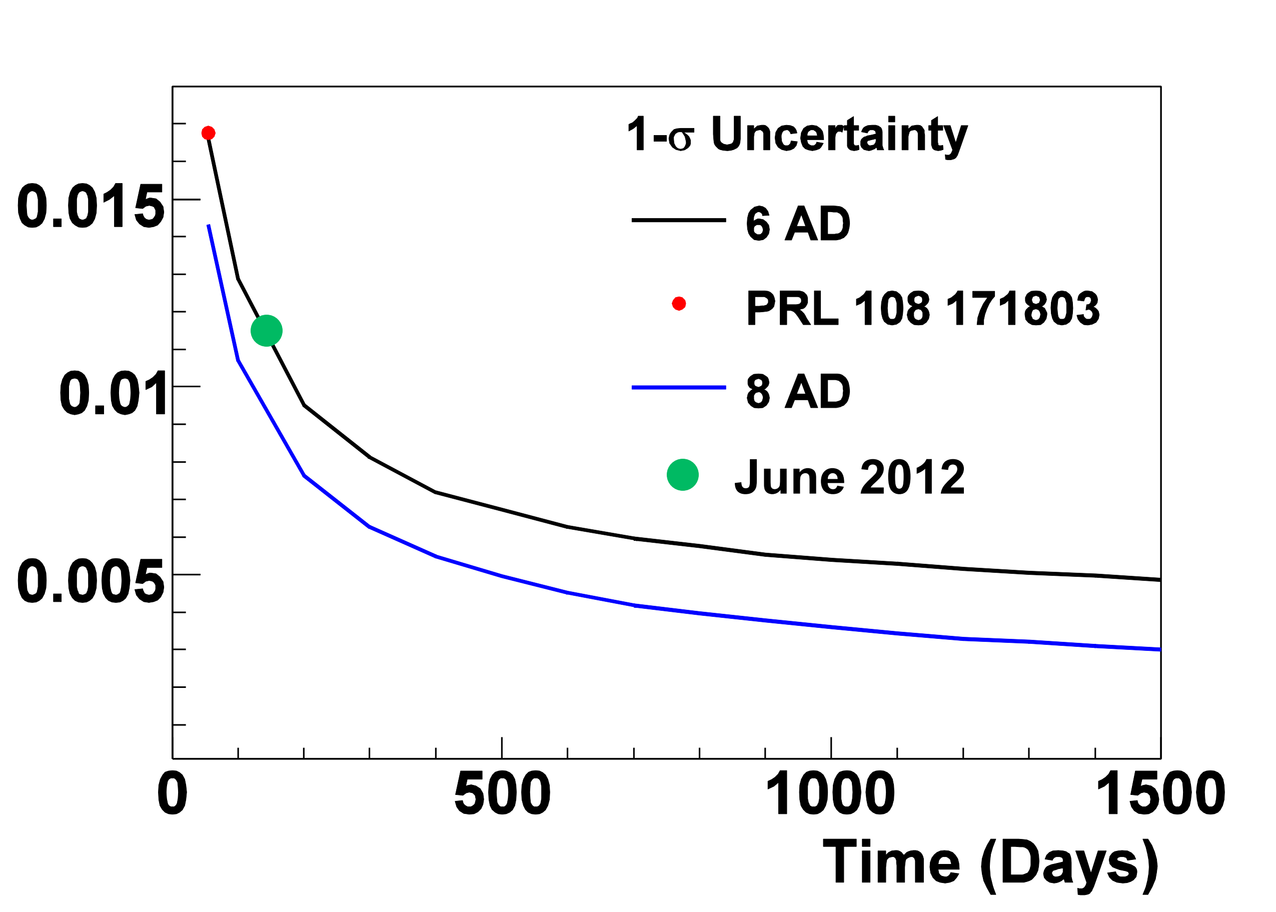
Rate Analysis
(Updated June 2012)



Most precise measurement of $\sin^2 2\theta_{13}$ to date.

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

Future Sensitivity to $\sin^2 2\theta_{13}$



Neutrino Mixing versus Quark Mixing

Leptons

$$U_\ell = \begin{pmatrix} 0.85 & 0.52 & 0.15 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & 0.59 & 0.70 \end{pmatrix}$$

Why so different???

Quarks

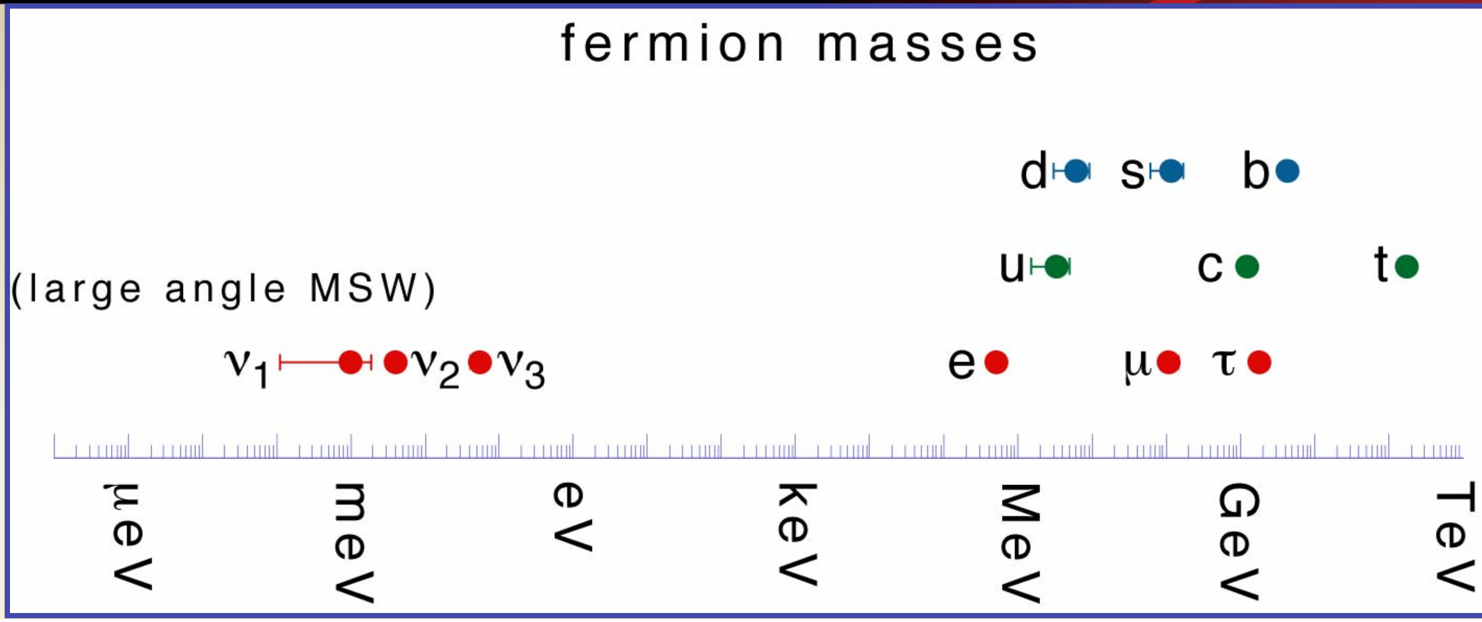
$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.003 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

Tri-bimaximal neutrino mixing:

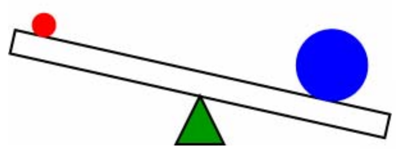
$$U_{\mathrm{TBM}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

(Harrison, Perkins, Scott 1999)

The Mass Puzzle

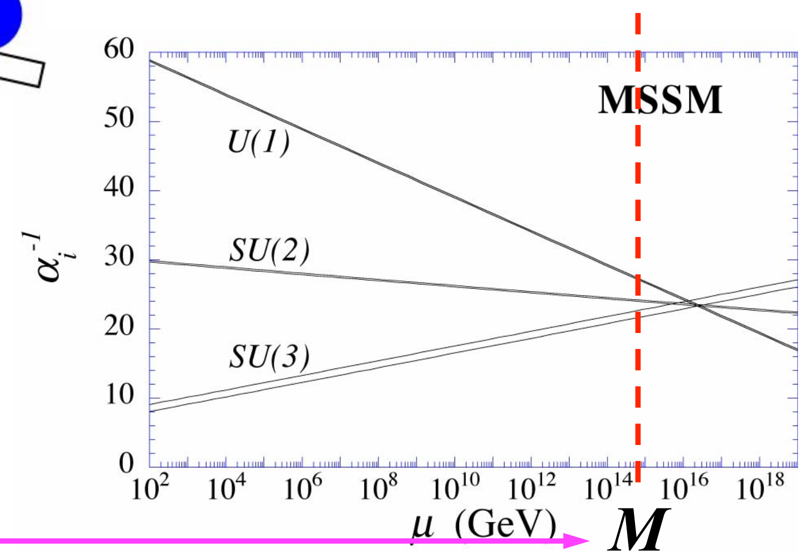


"Seesaw mechanism"



$$\begin{pmatrix}\nu_L & \nu_R\end{pmatrix}\begin{pmatrix} & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix}$$

$$m_\nu = \frac{m_D^2}{M} << m_D$$



Leptogenesis

- CP Violation implies different rates for matter, antimatter production via heavy Neutrino decay:

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \bar{\nu} + \overline{H^0}\right)$$

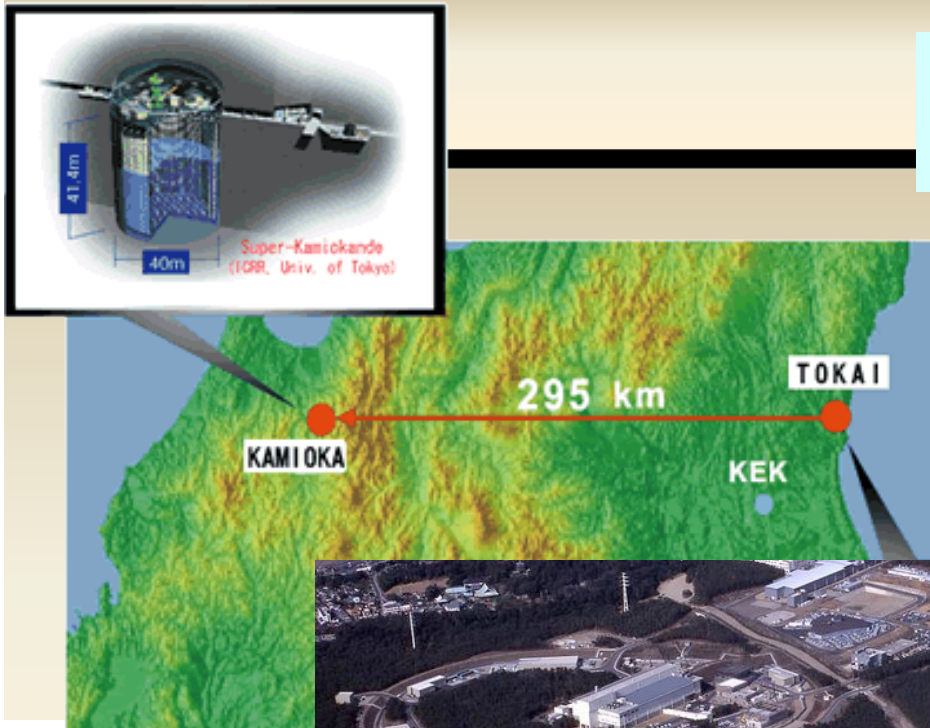
- Lepton asymmetry converted to baryon asymmetry:

Leptogenesis

We have all the ingredients except demonstration of CP violation in lepton sector!

→ New Experiments…

ν_e Appearance



T2K- From Tokai To Kamioka

Mass hierarchy (+/-)

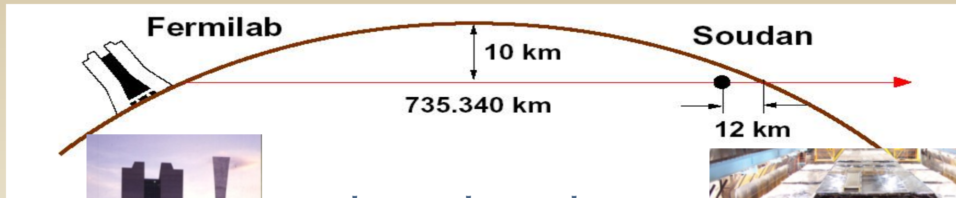
CP violation

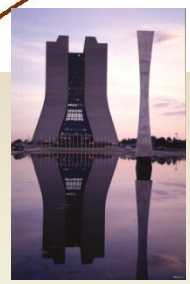
matter

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
& + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right] .
\end{aligned}
$$

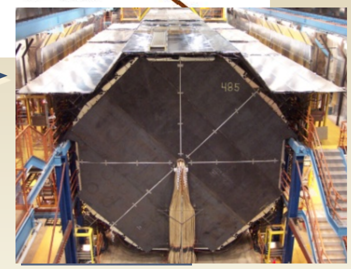
Current US (Fermilab) Program

MINOS



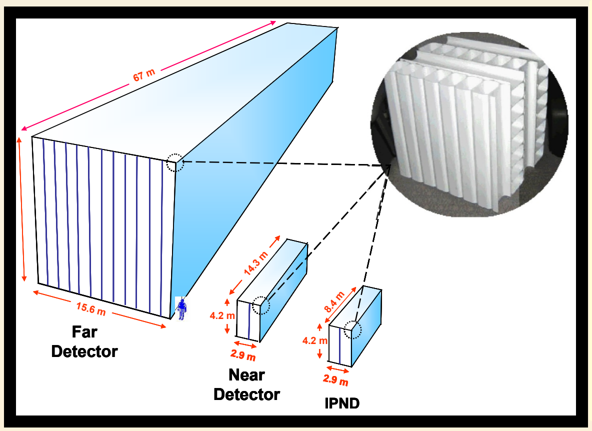


←long baseline→

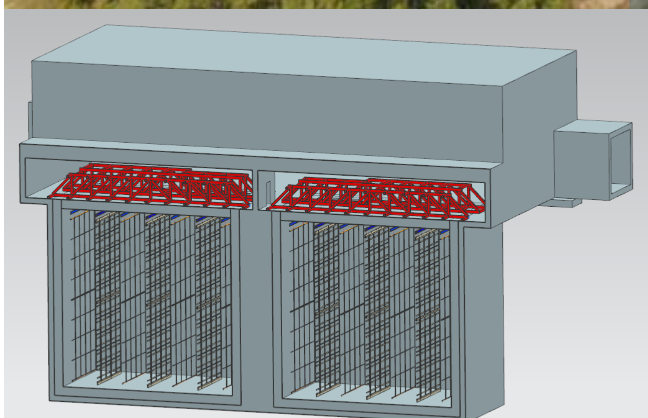


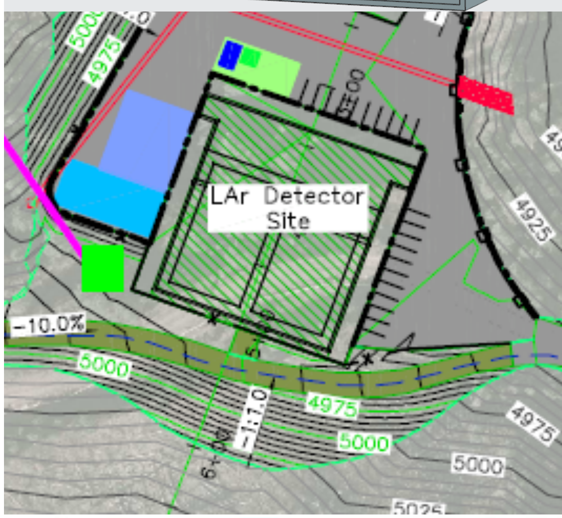
ν_μ **disappearance:**
$\Delta m_{23}^2 = 2.43 \pm 0.13 \times 10^{-3}\ eV^2$

$\nu_\mu \rightarrow \nu_e$



Fermilab to Homestake (LBNE)





Summary

- Many exciting discoveries in neutrino physics
- Some extraordinary serendipity
- Many bold and creative ideas
- Clever, demanding and increasingly expensive experiments
- Future experiments are planned to study mass hierarchy, CP violation, supernova neutrinos …

Perhaps we will soon know why and how the matter we are made of came into existence!


Stay Tuned !!

Why are we really "here"?

- [61] is the 18th prime number. The previous is 59, with which it comprises a twin prime. Sixty-one is a cuban prime of the form

.
$$p = (x^3 - y^3)/(x - y), x = y + 1$$

- Sixty-one might be the largest prime that divides the product of the next two primes plus 1. If there is a larger such prime, it would have to be greater than 179,424,673.[citation needed]
- 61 is 9th Mersenne prime exponent. ($2^{61} - 1$ = 2,305,843,009,213,693,951)
- Sixty-one is the sum of two squares, $5^2 + 6^2$, and it is also a centered square number, a centered hexagonal number and a centered decagonal number.
- Since 8! + 1 is divisible by 61 but 61 is not one more than a multiple of 8, 61 is a Pillai prime. In the list of Fortunate numbers, 61 occurs thrice, since adding 61 to either the tenth, twelfth or seventeenth primorial gives a prime number (namely 6,469,693,291; 7,420,738,134,871; and 1,922,760,350,154,212,639,131).
- It is also a Keith number, because it recurs in a Fibonacci-like sequence started from its base 10 digits: 6, 1, 7, 8, 15, 23, 38, 61...

Happy Birthday Steve!!