

CP Violation and Flavor Mixing

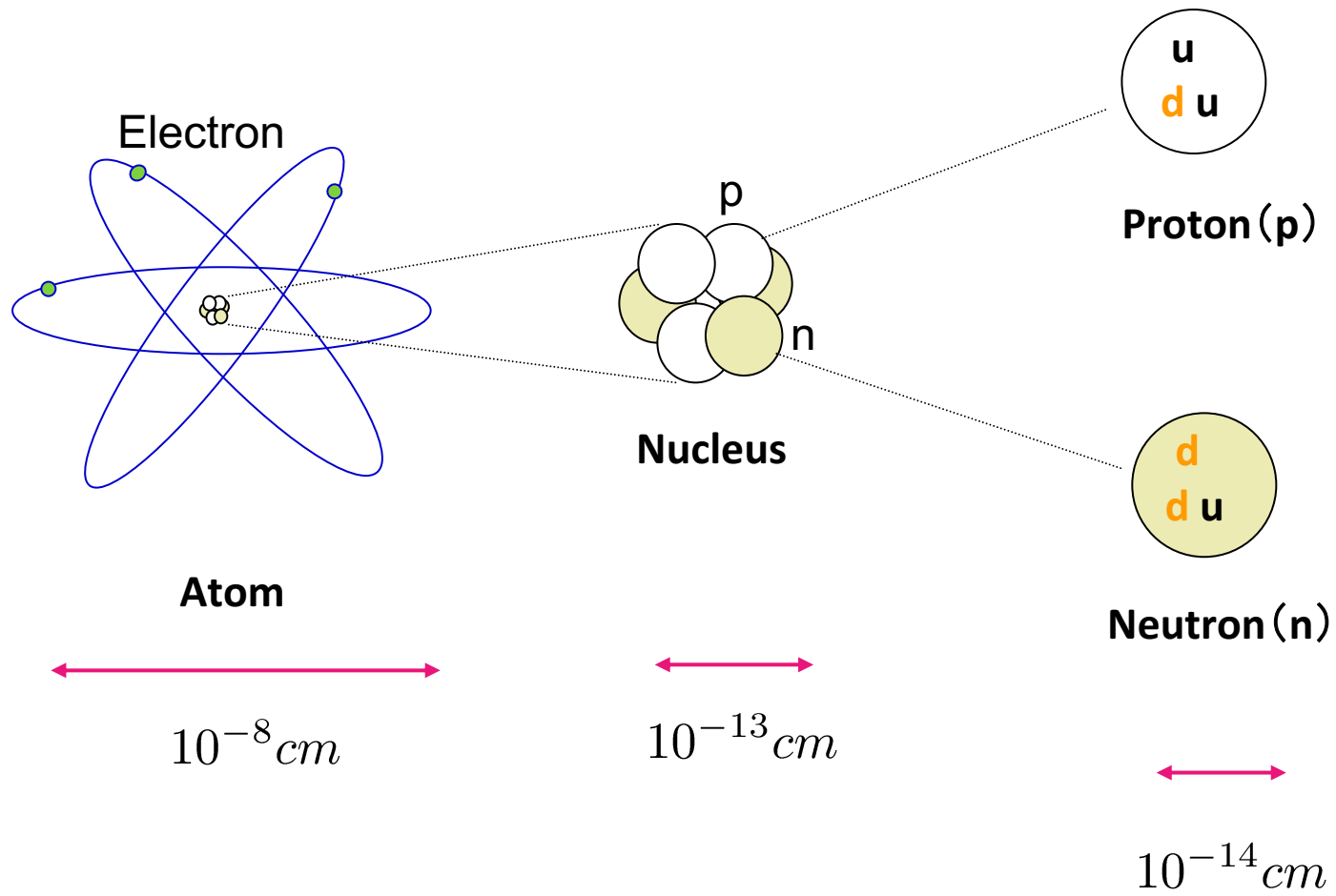
Makoto Kobayashi

KEK and JSPS

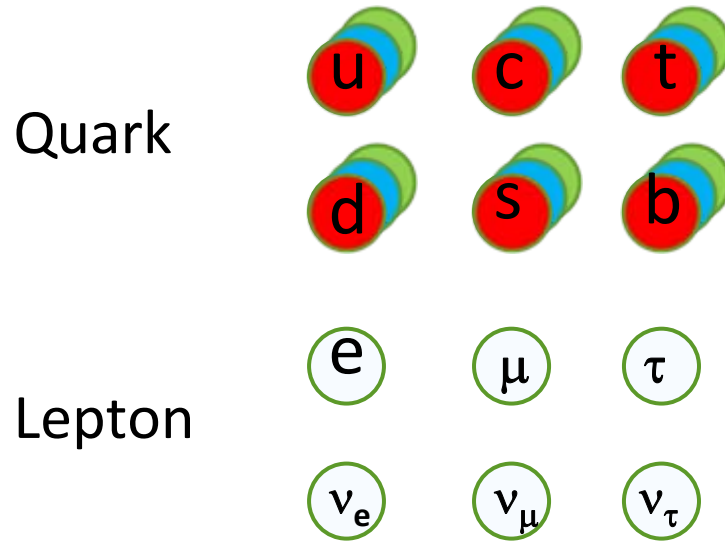
Plan

1. Introduction to the Standard Model
2. Sakata and His Group
3. The CP Paper with Maskawa
4. Experimental Verification at B-factories
5. Lepton Flavor Mixing

Introduction to the Standard Model



Fundamental Particles



Fundamental Interactions

- Strong Interaction
- Electro-Magnetic Interaction
- Weak Interaction

QCD

Weinberg-Salam-Glashow Theory

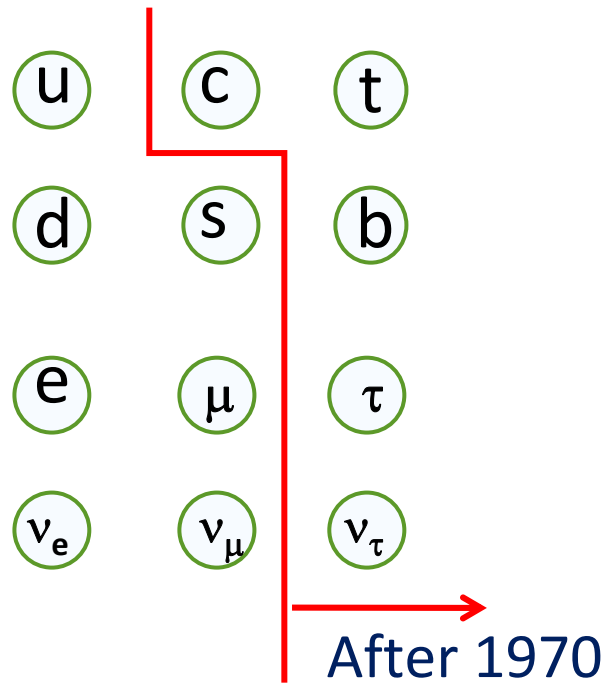
Established in 1970's

- Development of gauge theory 1971 't Hooft

Electro-Magnetic Interaction
Strong Interaction
Weak Interaction

- Discoveries of new flavors

1964 Gell-Mann
quark model
u, d, s



1973
Kobayashi Maskawa
Six-Quark Model

1947~ Discovery of Strange Particles

Hadron : strongly interacting particle

p n $\pi^{\pm 0}$ Λ

Λ $\Sigma^{\pm 0}$ Ξ K^{\pm} K^0 Λ

Strange Particles



Courtesy of Sakata Memorial Archival Library

Shoichi Sakata

1911-1970

1956 Sakata Sakata Model

All the hadrons are composite states of

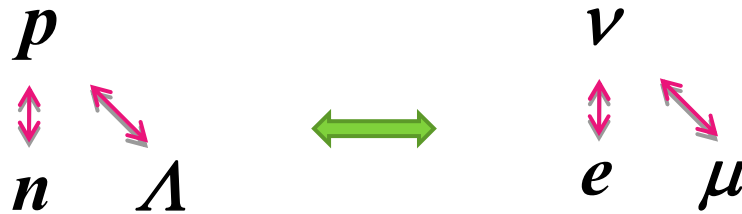
p, n, Λ

: Fundamental Triplet

Weak Interaction in the Sakata Model

$$\beta\text{-decay} \quad n \rightarrow p + e^{-} + \bar{\nu}$$

$$\text{strange particle} \quad \Lambda \rightarrow p + e^{-} + \bar{\nu}$$



1959 Gamba, Marshak, Okubo
B-L Symmetry

1960 Maki, Nakagawa, Ohnuki, Sakata

Nagoya Model :

$$p = \langle B^+ \nu \rangle, n = \langle B^+ e \rangle, \Lambda = \langle B^+ \mu \rangle$$

1962 Discovery of Two Neutrinos

$$\begin{array}{cc}
 \nu_e & \nu_\mu \\
 \updownarrow & \updownarrow \\
 e & \mu
 \end{array}$$

Lepton Flavor Mixing
MNS Matrix

1962 Maki, Nakagawa, Sakata

$$p = \langle B^+ \nu_1 \rangle, \quad n = \langle B^+ e \rangle, \quad \Lambda = \langle B^+ \mu \rangle, \quad p' = \langle B^+ \nu_2 \rangle$$

$$\nu_1 = \cos\theta \nu_e + \sin\theta \nu_\mu$$

$$\nu_2 = -\sin\theta \nu_e + \cos\theta \nu_\mu$$

→ Neutrino Oscillation

→ 4th Fundamental Particle (GIM scheme)

1962 Katayama, Matumoto, Tanaka, Yamada

Cosmic Ray Events

1971 Niu et al.

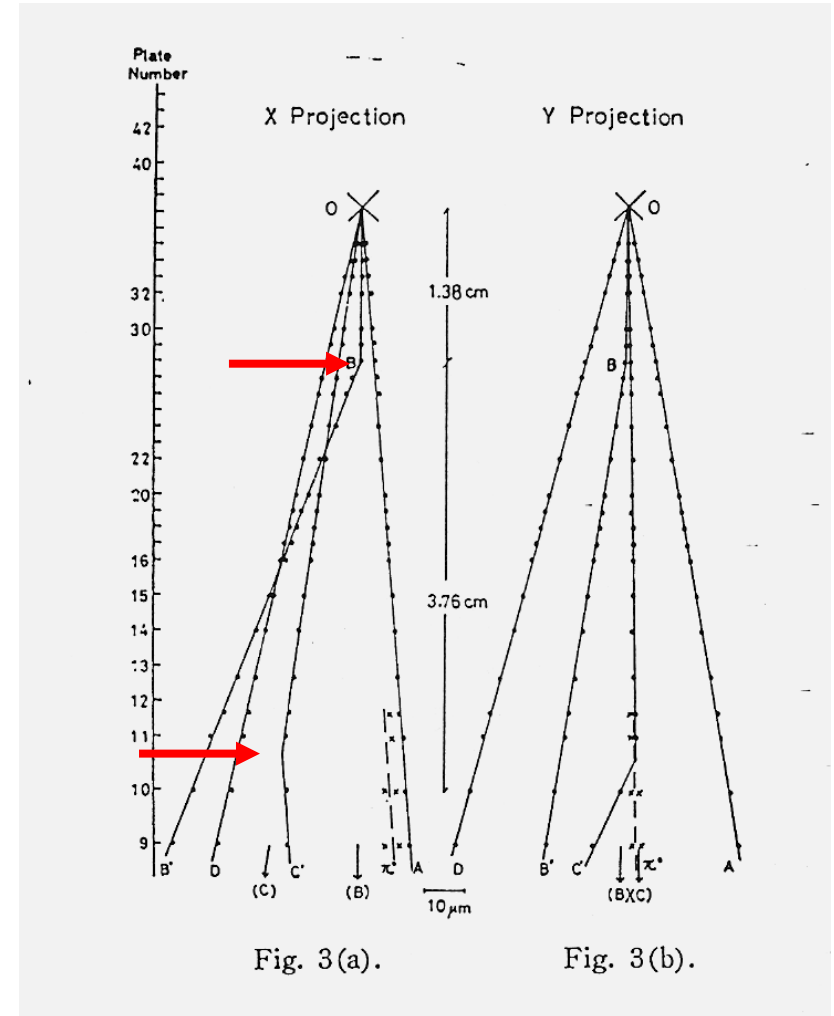
Evidence for the 4th element?



Some Japanese groups began to investigate the four-quark model

Emulsion Technique

- Applied to accelerator exp.
- Life time measurement of the new flavors



1971 't Hooft : Renormalization of Non-Abelian gauge theory

→ Renormalizable Electro-Weak Theory

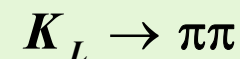
(Weinberg-Salam-Glashow)

1973 Kobayashi, Maskawa

How to accommodate CP violation

CP Violation

1964 Cronin et al.



Essential difference
between particles
and anti-particles

What we found

- Not possible in four-quark models
- Existence of unknown particles
- A possible candidate is six-quark model

Flavor Mixing

Mismatch between gauge symmetry and particle spectra

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

CP Violation

Complex elements not removable by the phase convention

$$\begin{pmatrix} e^{-i\delta_u} & 0 \\ 0 & e^{-i\delta_c} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} e^{i\delta_d} & 0 \\ 0 & e^{i\delta_s} \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$$

6-Quark Model

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- An imaginary number parameter violates CP

- 1974 Discovery of J/ψ \longrightarrow c-quark
- 1975 Discovery of τ -lepton

1975 S. Pakvasa, H. Sugawara

1976 J.R Ellis, M-K Gaillard, D. Nanopoulos

- 1977 Discovery of Y \longrightarrow b-quark
- 1995 Discovery of t-quark

Large CP violation in the B-meson system

1980 Carter, Sanda

1981 Bigi, Sanda

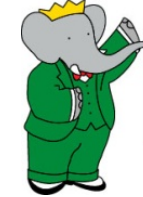


B-Factory

$B_d^-: \bar{b}d$ $\bar{B}_d^+: \bar{d}b$

$B_u^-: \bar{b}u$ $\bar{B}_u^+: \bar{u}b$

B-Mesons



KEKB/Belle (Japan)

PEP-II/BaBar (US)

$E(e^-)=8\text{GeV}$,
 $E(e^+)=3.5\text{GeV}$
Finite angle beam crossing

Feature

$E(e^-)=9\text{GeV}$,
 $E(e^+)=3.1\text{GeV}$
Zero angle beam crossing

1994

Governmental Approval

1993

May 1999 –
still running

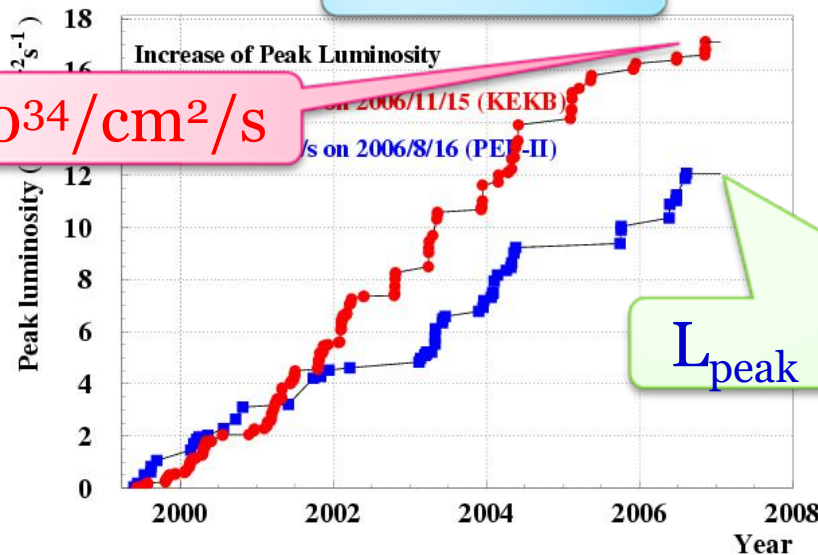
Experiment

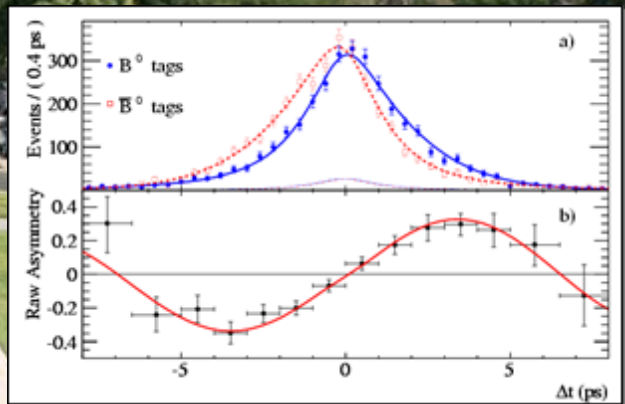
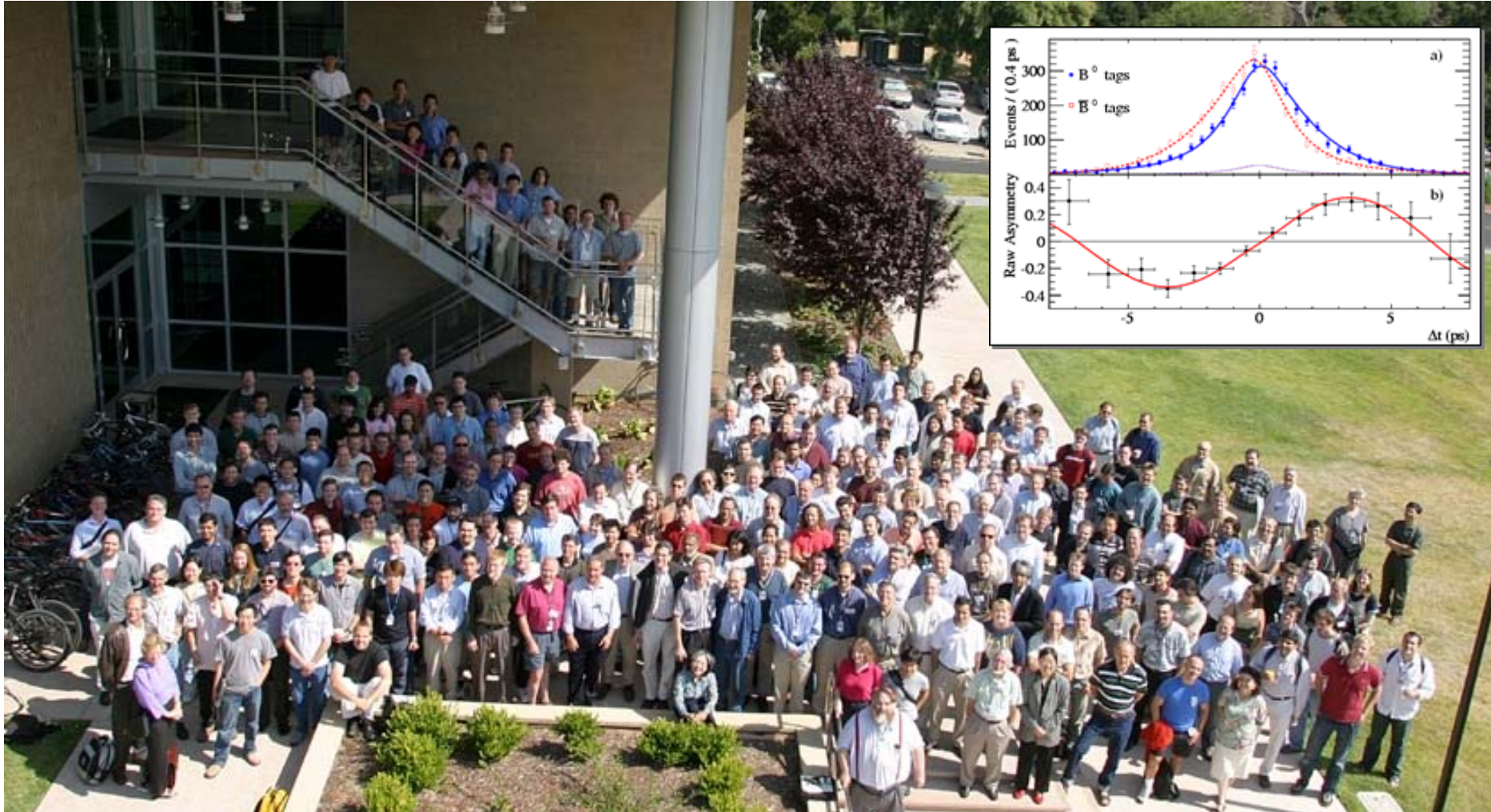
May 1999 –
Apr. 2008

$L_{\text{peak}} = 1.7 \times 10^{34} / \text{cm}^2 / \text{s}$

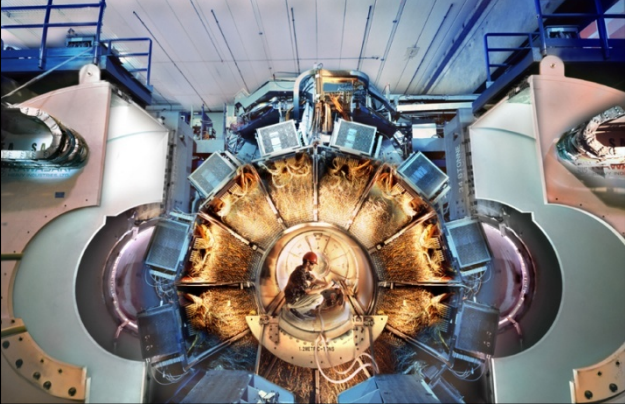
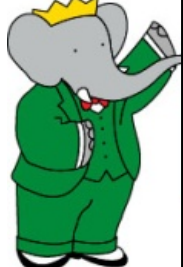
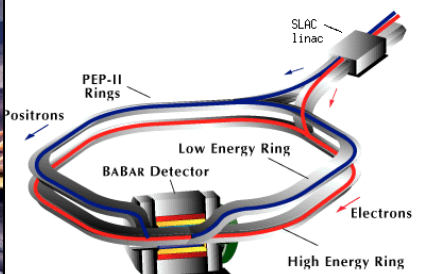
Friendly competition of two experiments over a decade

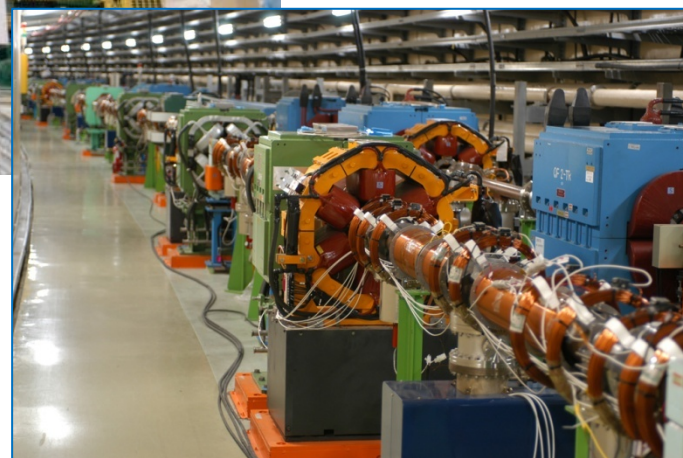
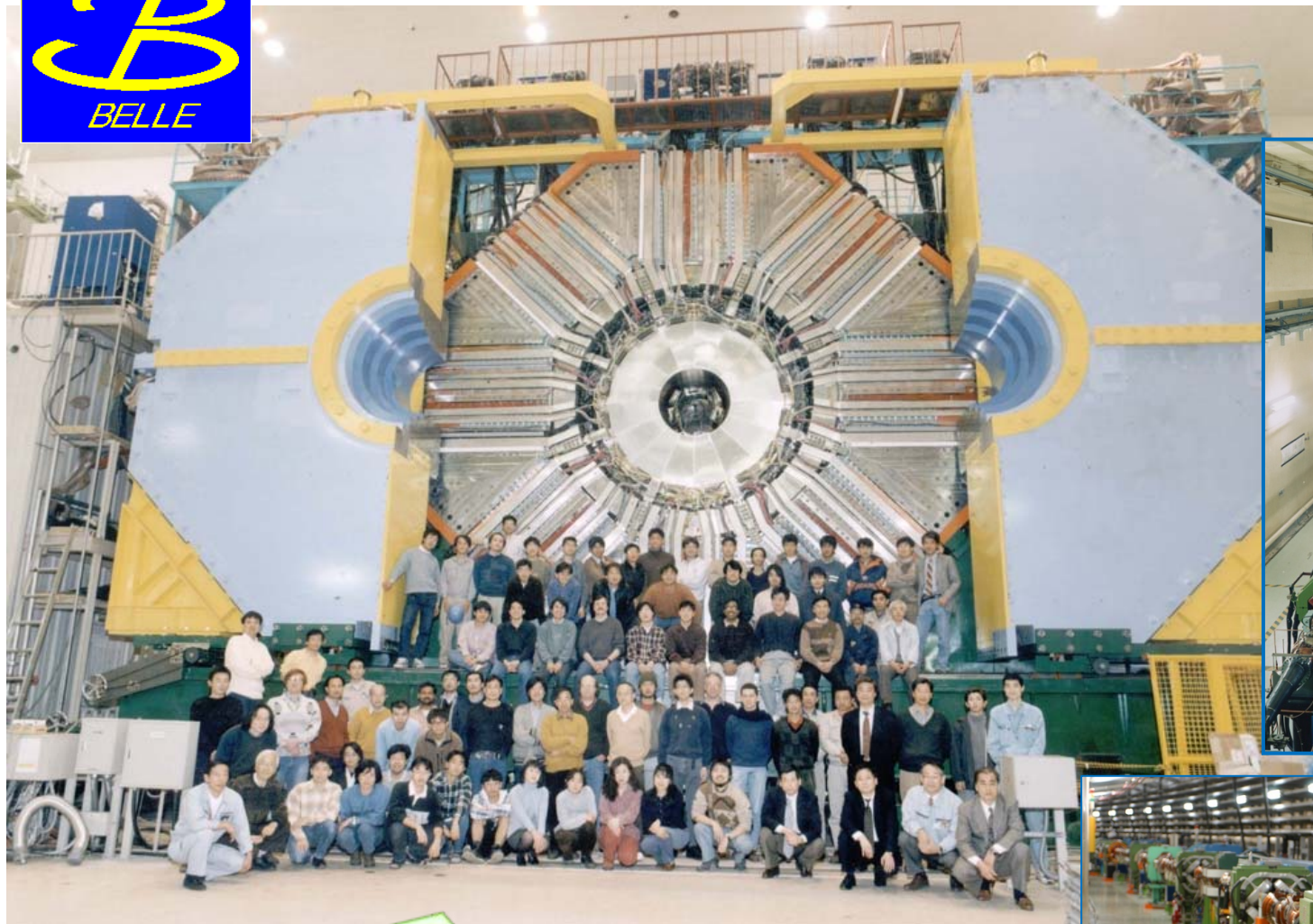
$L_{\text{peak}} = 1.2 \times 10^{34} / \text{cm}^2 / \text{s}$





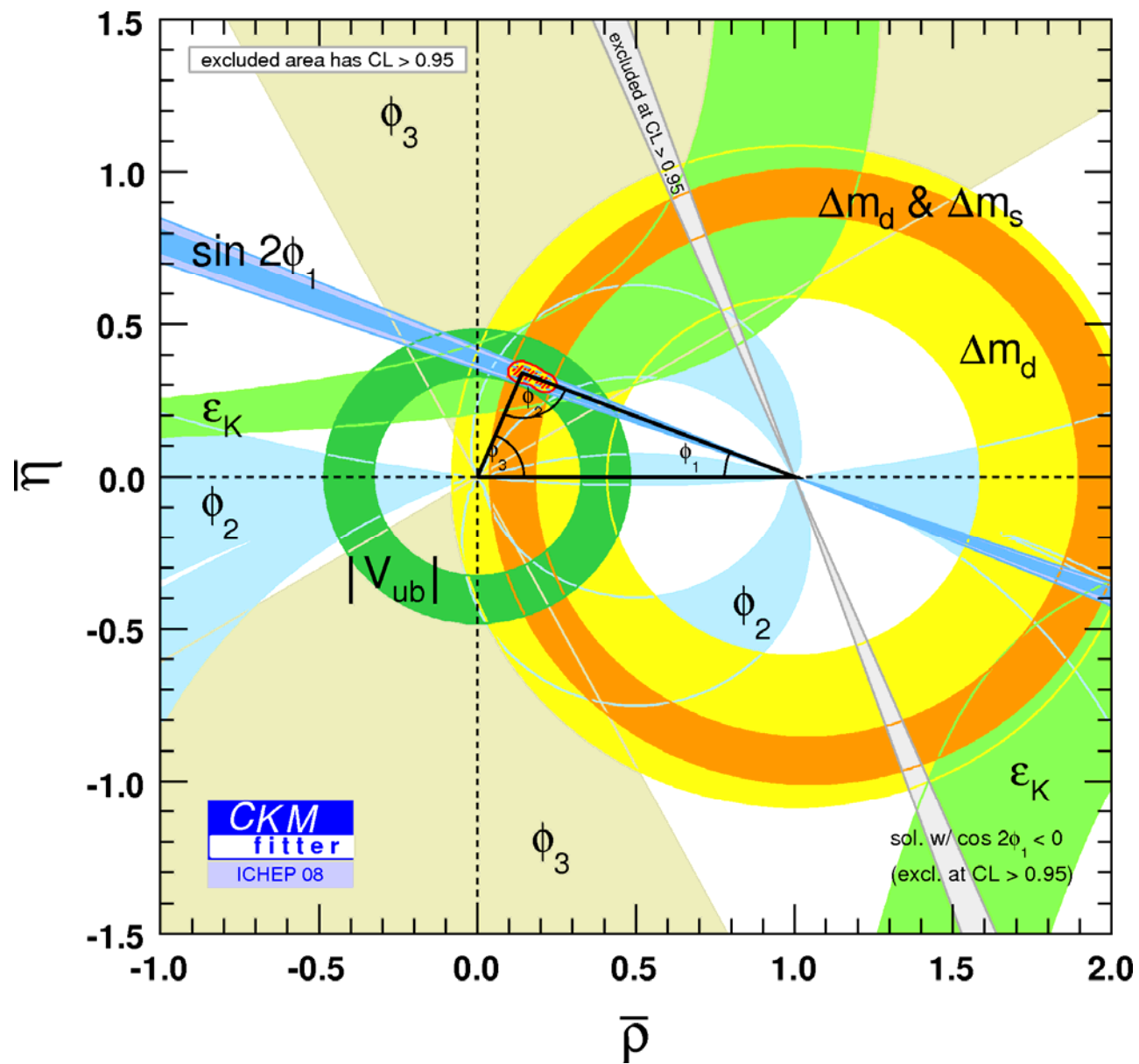
PeP-II





Belle:
14 countries, 59 institutes,
about 400 researchers

Experimental Verification at B-Factories



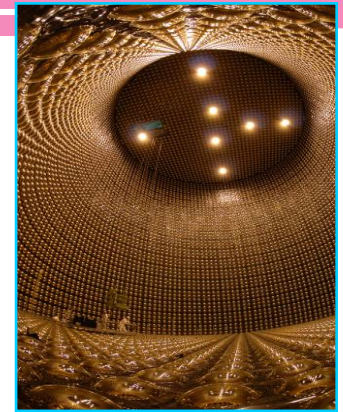
Present Status of CP Violation

B-factory results show that quark mixing is the dominant source of CP violation

B-factory results allow room for additional source from new physics

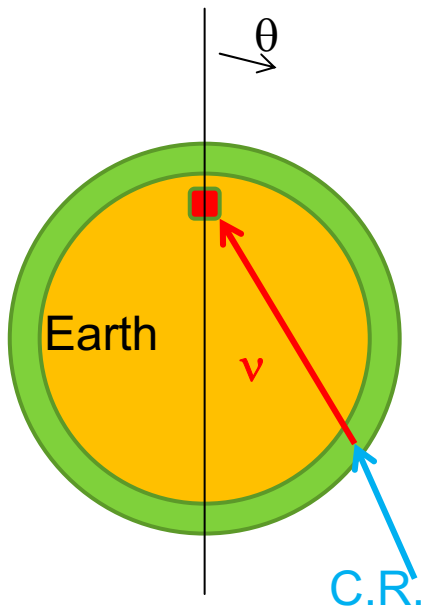
Matter dominance of the Universe seems requiring new source of CP violation

Discovery of neutrino oscillation at Super-Kamiokande using atmospheric neutrinos



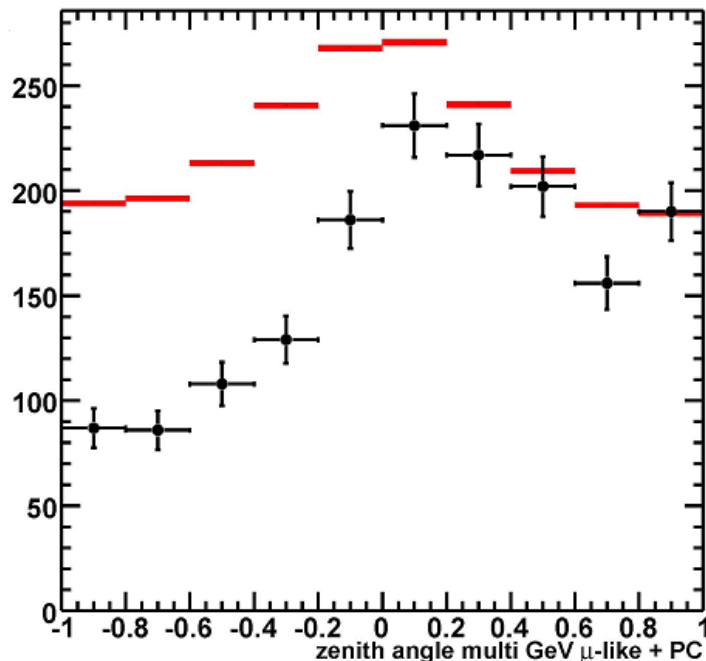
Super-K 1996~

Atmospheric Neutrino



Multi-GeV μ -like + PC

Super Kamiokande I Preliminary 1489.2 days



J.Raaf, Talk at Neutrino 2008



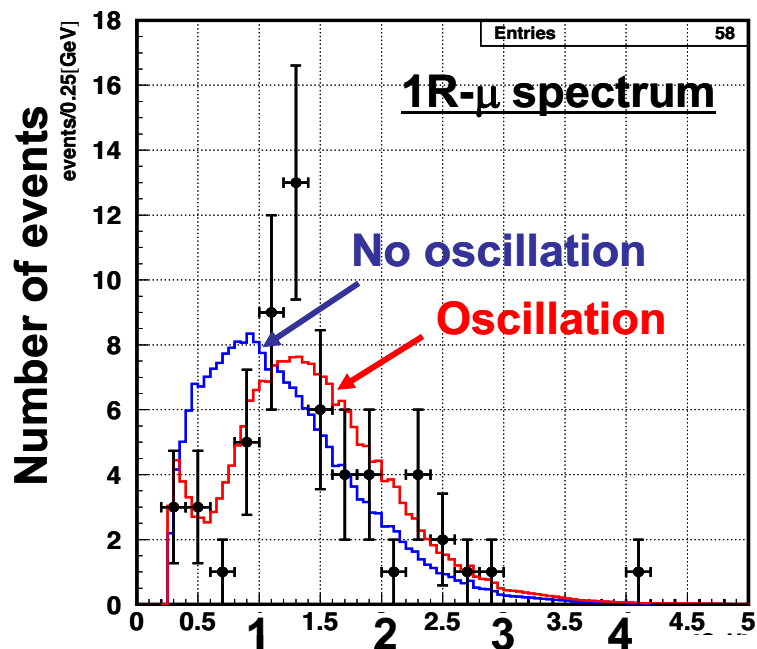
Courtesy of KEK

Yoichi Totsuka
1942-2008

K2K experiment

ν_μ : KEK-PS

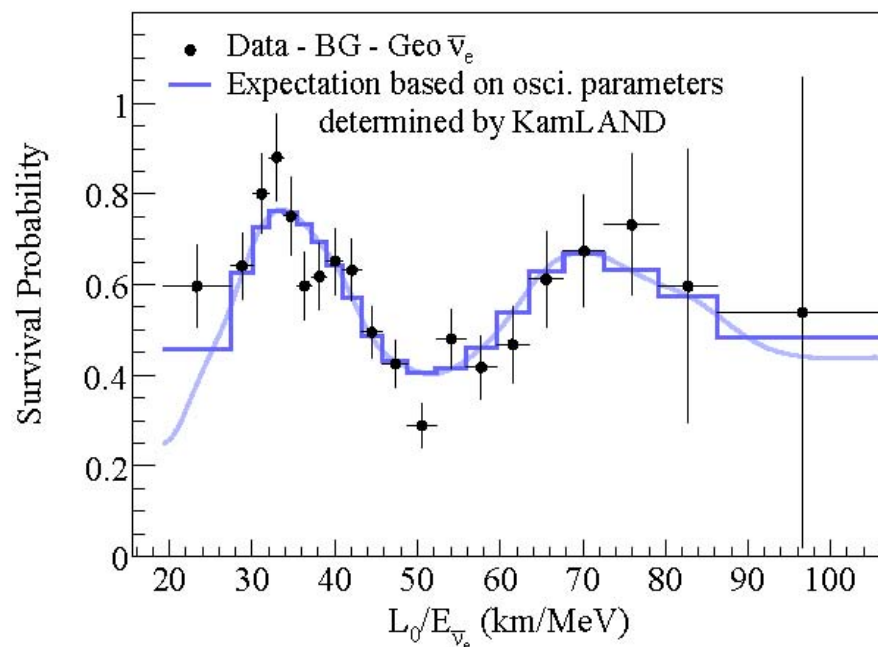
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ν_μ disappearance

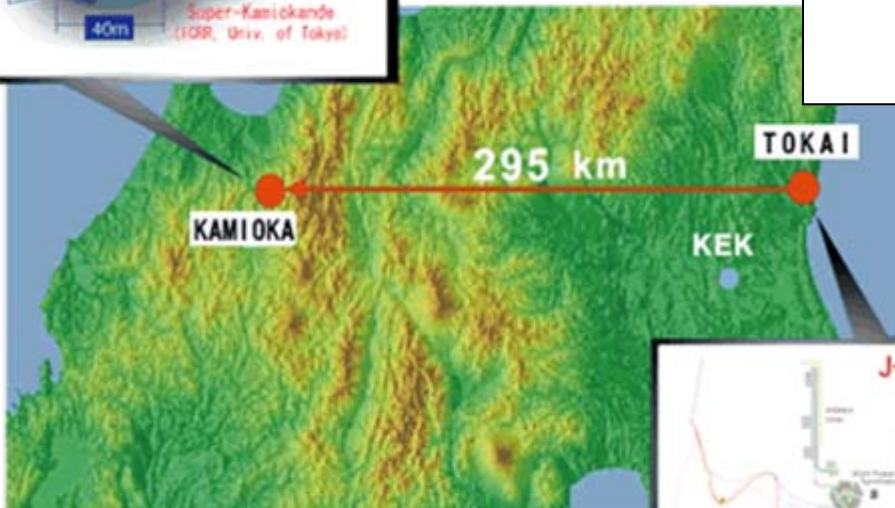
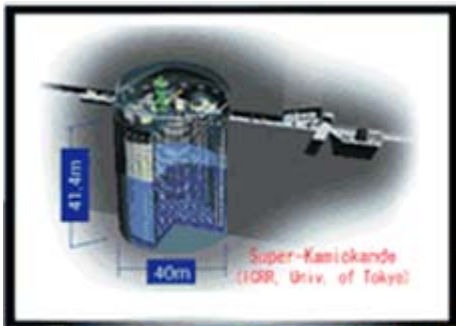
KamLAND experiment

$\bar{\nu}_e$: reactor



$\bar{\nu}_e$ disappearance

T2K experiment



ν_{μ} created at JPARC
→ Super-K

Aiming to discover
 ν_e appearance