Why do we exist?

The story of
Three mixed-up generations &
Half a Nobel Prize

2008 Nobel Prize (1/2)

Nambu: "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

2008 Nobel Prize (1/2)

Kobayashi & Maskawa: "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

"(KM provided) a framework for understanding why matter dominates over anti-matter in our universe

"and also how neutrinos change their character as they propagate to the Earth from the Sun"

APS News

Nov 2008

Main ideas

- We exist because of *CP* violation
- *CP* violation possible only for 3 (not 2) generations that mix
- Quark mixing
  - Kobayashi-Maskawa
- Lepton mixing
  - To be measured at Daya Bay (CUHK)

Matter is made of

- protons
  neutrons
- electrons

- quarks
- leptons

Quarks

			Charge	Strong	Weak
u	*c*	*t*	2/3	Y	Y
d	*s*	*b*	-1/3	Y	Y

3 generations

- proton = *uud*
- neutron = *udd*

- Only *u*, *d*, *s* known in 1960s
- Discovered *c* in 1974 (Richter & Ting)
- Discovered *b* , *t* in 1977 , 1994

Leptons

			Charge	Strong	Weak
ν_e	ν_μ	ν_τ	0	N	Y
e	μ	τ	-1	N	Y

3 generations

- Discovered τ in 1977 (Perl)
- Why 3 generations?
- “Who ordered the muon?”
  — Rabi

Why do we exist?

- Matter >> Anti-matter

$$\frac{n(\mathrm{B})}{n(\overline{\mathrm{B}})} \approx \infty \ (\text{solar system})$$

$$10^4 \ (\text{cosmic rays})$$

- Huge asymmetry?

Huge asymmetry?

Imagine

PAST $$n(\mathrm{B}) = 101, \quad n(\overline{\mathrm{B}}) = 100$$

$$\mathrm{B} + \overline{\mathrm{B}} \to 2\gamma$$

Let there be light

NOW $$n(\mathrm{B}) = 1, \quad n(\overline{\mathrm{B}}) = 0, \quad n(\gamma) = 200$$

Revealed as

$$\frac{n(\mathrm{B})}{n(\overline{\mathrm{B}})} \approx \infty$$

$$\frac{n(\mathrm{B})}{n(\gamma)} \equiv \eta \quad \approx \quad 0.5\times 10^{-9}$$

Experimental value

So we need

- Only a small asymmetry
- From symmetric initial condition?

Sakharov conditions

- Baryon number non-conservation
- Out of thermal equilibrium
- *CP* violation

Avoids detailed mechanism

Baryon number non-conservation

Proton should decay!

$$p \to e^+ + \pi^0$$

Experimental search

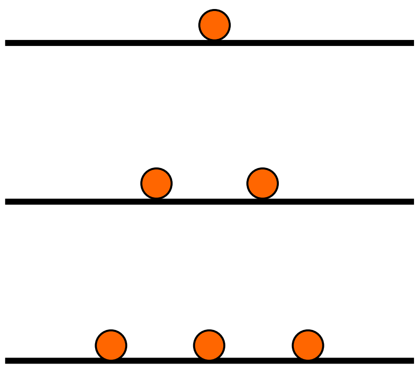
$$T > 10^{32} \text{ years}$$

We won't exist forever

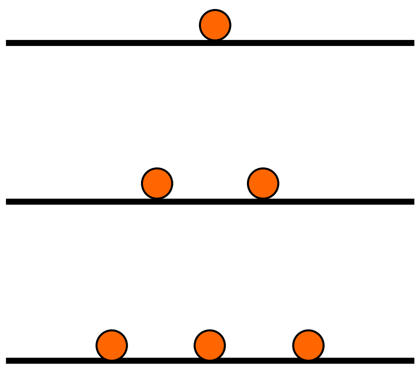
$$\text{Age of universe} = 1.4 \times 10^{10} \text{ years}$$

$$1\,\text{kton} = 5 \times 10^{32} \text{ protons}$$

Equilibrium



B



$\overline{B}$

$$n \propto e^{-E/kT}$$

CP violation

- Need a difference between matter and anti-matter processes, eg

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

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

Relating matter / anti-matter

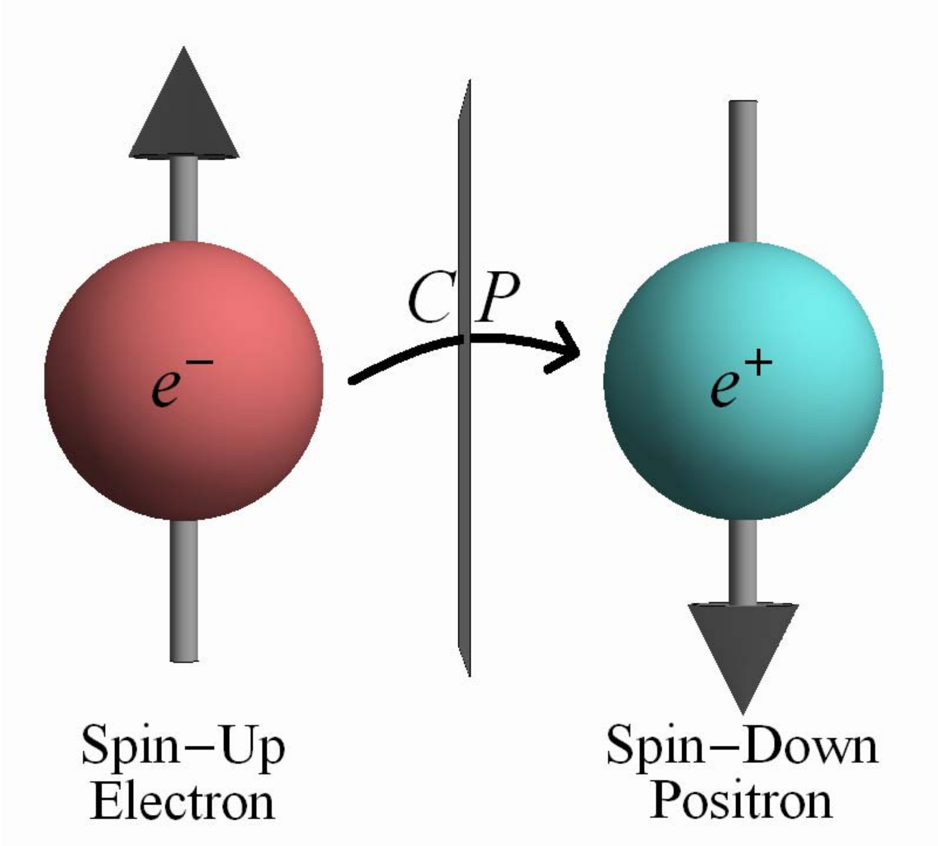
- *C* alone does not work
- In weak interactions,

$$q_{\mathrm{L}} \text{ behaves same as } \bar{q}_{\mathrm{R}}$$

$$l_{\mathrm{L}} \text{ behaves same as } \bar{l}_{\mathrm{R}}$$

- *C*, *P* individually violated (Lee & Yang)
- *CP* ok ??

CP



- But if *CP* ok
- then will still maintain balance between matter and anti-matter

- Sakharov predicted (1966) *CP* violation
- in order to explain net matter

CP : observation and theory

1964 CP violation observed

Cronin and Fitch

1967+ Standard Model (SM)

Glashow, Salam, Weinberg (electroweak)

Politzer, Gross, Wilczek (strong)

- But difficult to accommodate CP violation in SM

Observation of *CP* violation

Background

Pseudoscalars have *CP* = -1

$$K^0 \qquad K^+$$

$$\pi^- \qquad \pi^0 \qquad \pi^+$$

$$K^- \qquad \overline{K}^0$$

$$CP\left|K^0\right\rangle = -\left|\overline{K}^0\right\rangle \quad , \quad CP\left|\overline{K}^0\right\rangle = -\left|K^0\right\rangle$$

$$\left|K_1\right\rangle \equiv 2^{-1/2}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right)$$

$$\left|K_2\right\rangle \equiv 2^{-1/2}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right)$$

$$CP\left|K_1\right\rangle = \boxed{+}\left|K_1\right\rangle \quad , \quad CP\left|K_2\right\rangle = \boxed{-}\left|K_2\right\rangle$$

Expected

$$K_1 \to 2\pi \quad \text{fast} \quad \tau = 0.9\times10^{-10}\ \text{s}$$

$$K_2 \to 3\pi \quad \text{slow} \quad \tau = 6\times10^{-8}\ \text{s}$$

600 times

$$m(K) = 497\ ,\ m(\pi) = 135$$

$$m(K) - 2m(\pi) = 227\ ,\ m(K) - 3m(\pi) = 92$$

(units of MeV)

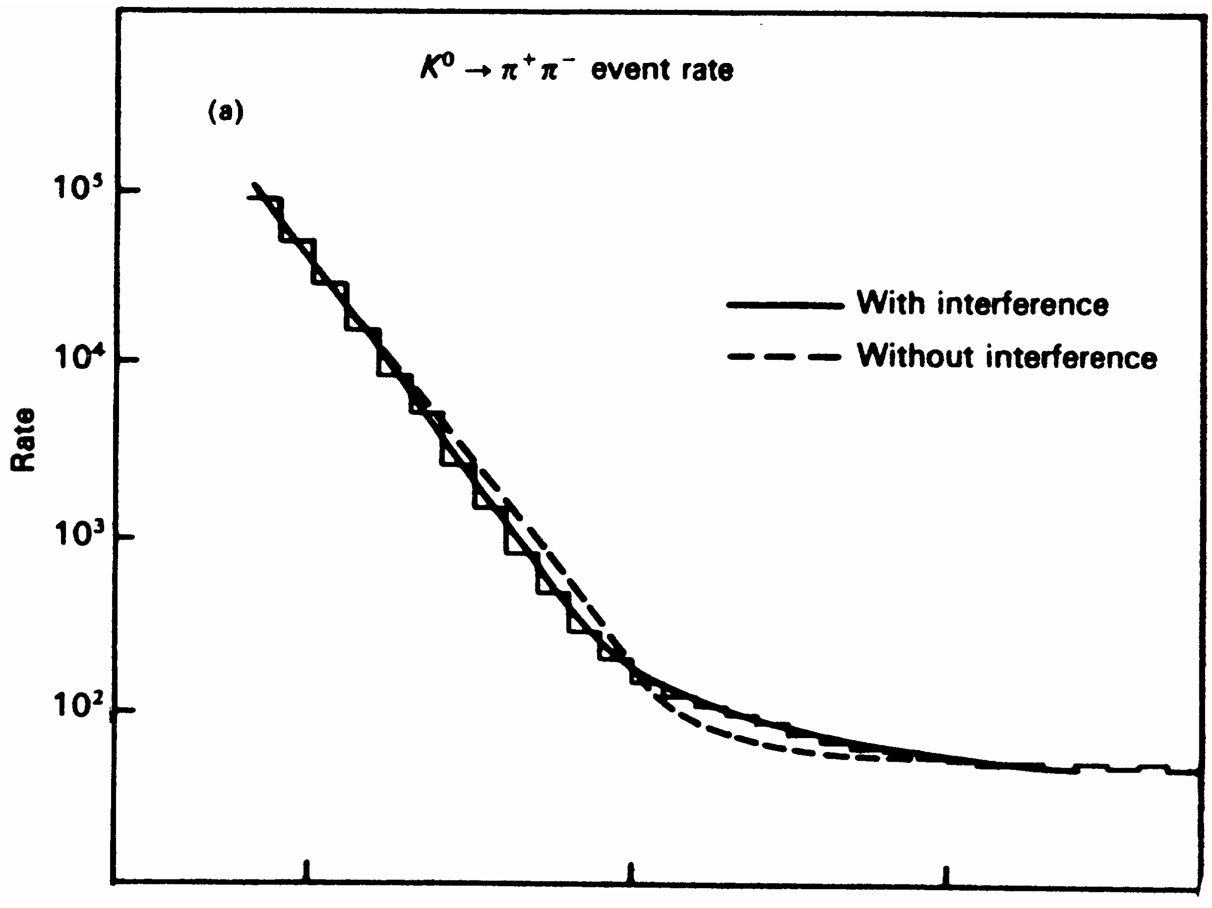
Observed

Cronin & Fitch (1964)

$$K_{\mathrm{L}} \to 2\pi$$

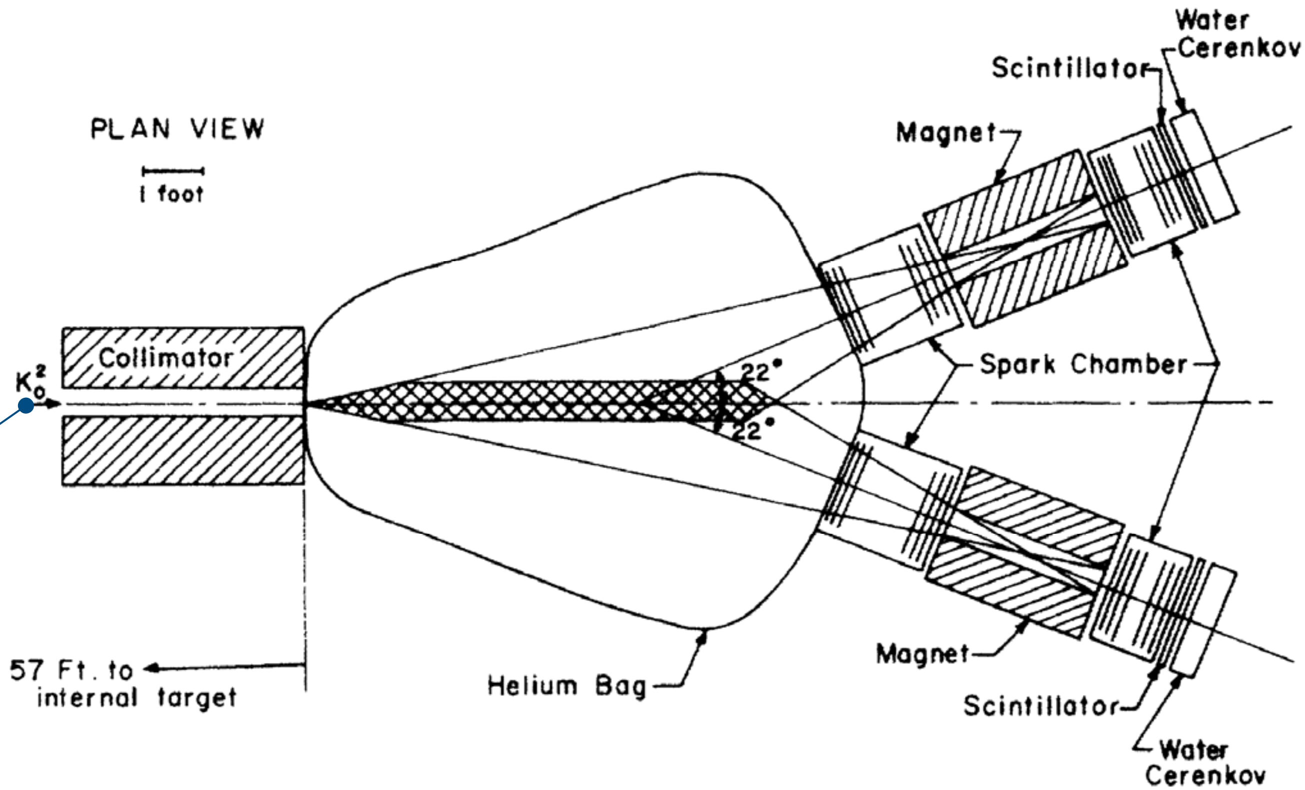
$$\mathrm{BR} \equiv \varepsilon = 2\times10^{-3}$$

$$K_{\mathrm{L}} \neq K_{2}$$



$K^0 \to \pi^+\pi^-$ event rate
(a)
10^5
10^4
10^3
10^2
Rate
With interference
Without interference

K_1 decayed away by this point

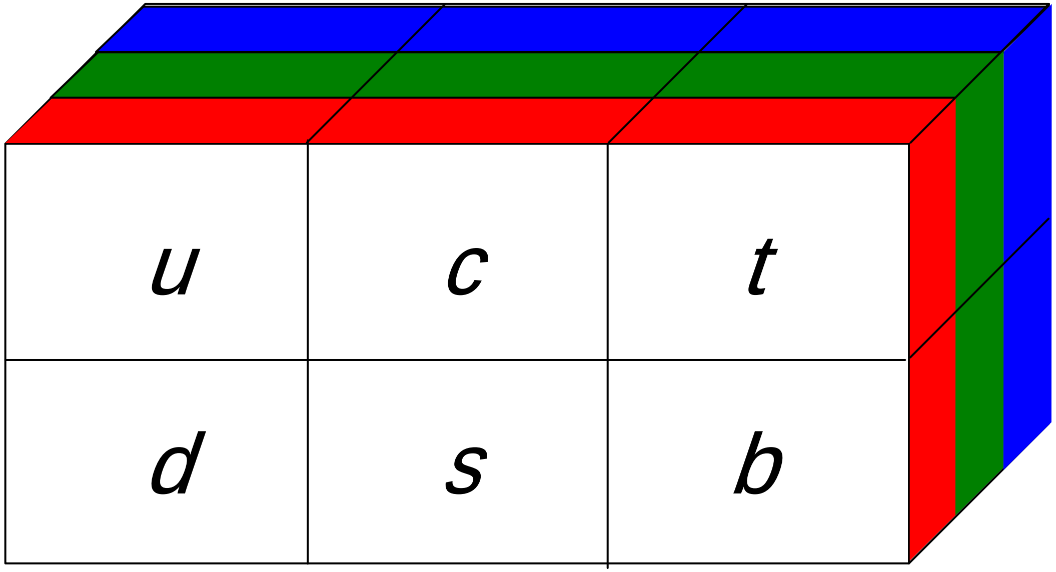


- Heuristic estimate

$$\eta \approx G_{\mathrm{wk}}\,\varepsilon$$

- But need detailed theory of process

Standard Model

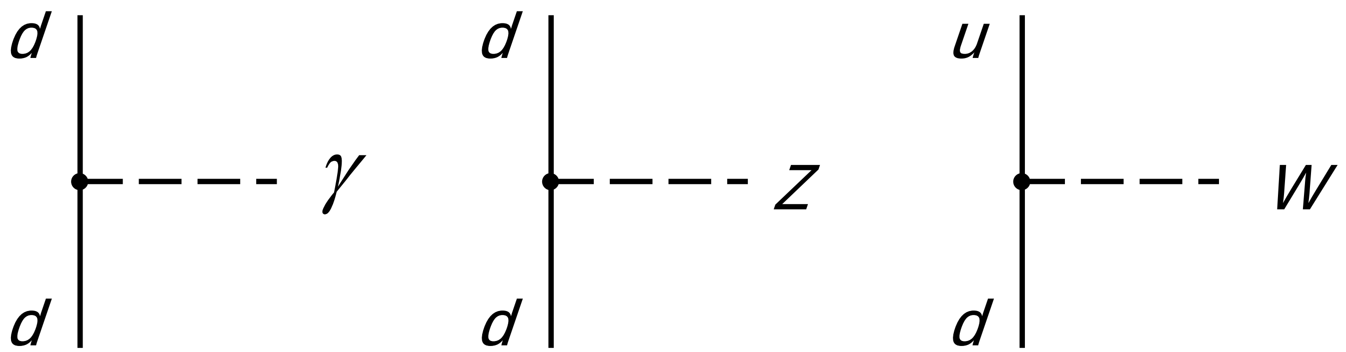


SU(3) x SU(2) x U(1)

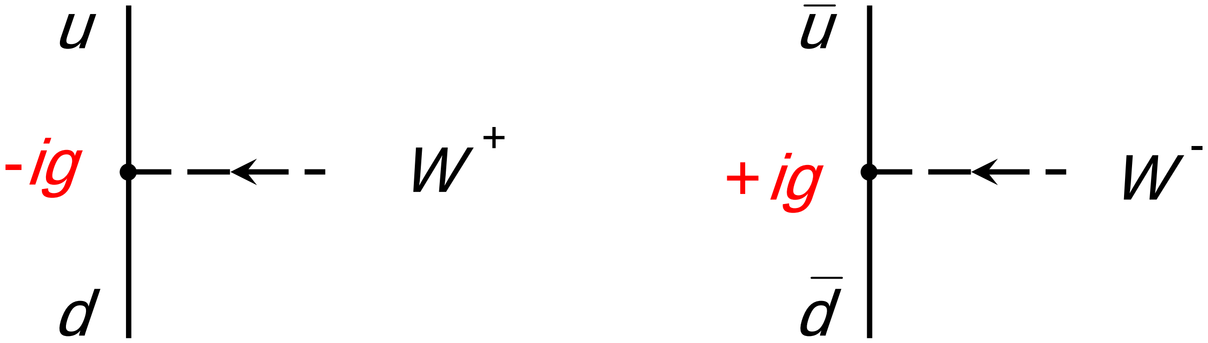
Features of SM

- Gauge theory (Yang, Mills)
  - Renormalizable (Fadeev, Popov, ‘t Hooft, Veltman)
  - All forces long-ranged?
- Spontaneously broken (Nambu, Goldstone, Higgs)
  - W and Z acquire mass
  - Weak interaction short-ranged

Electroweak SU(2) X U(1)

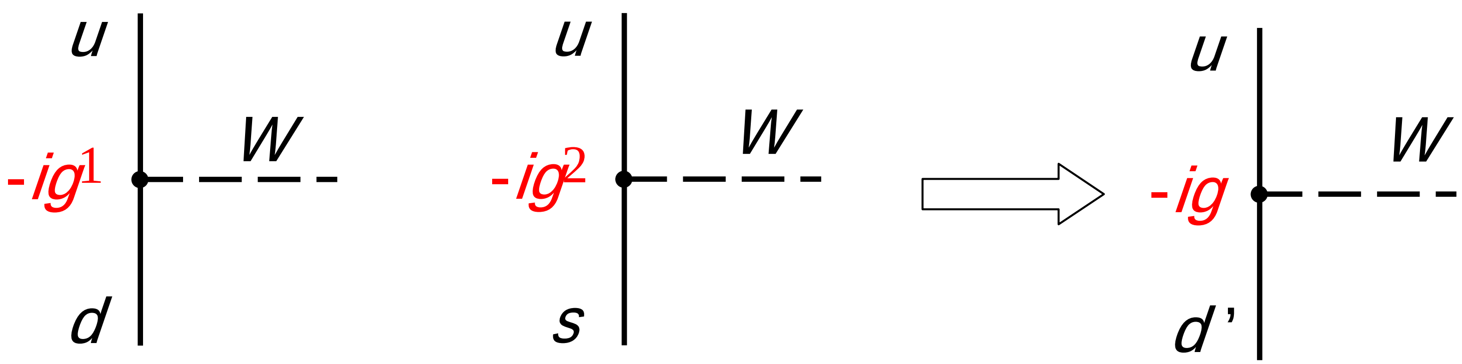


- Such diagrams (or Lagrangian) do not give rise to *CP* violation



Mixing: Cabibbo

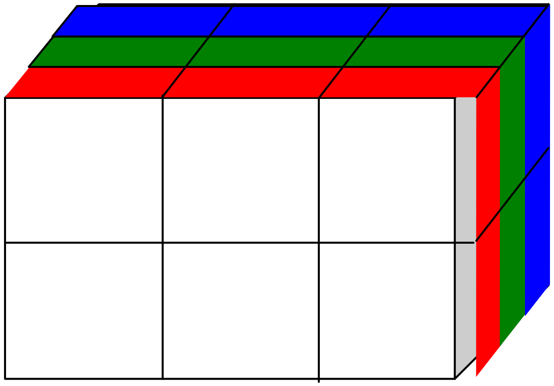
- Back in 1960s, only *u*, *d*, *s*



$$d' = d\cos\theta + s\sin\theta$$

$$U = (u, c, t, \ldots) \quad \text{charge} \quad 2/3$$

$$D = (d, s, b, \ldots) \quad \text{charge} \quad -1/3$$



- Mass (propagation) eigenstates are diagonal

$$H = U^{+} M_u U + D^{+} M_d D$$

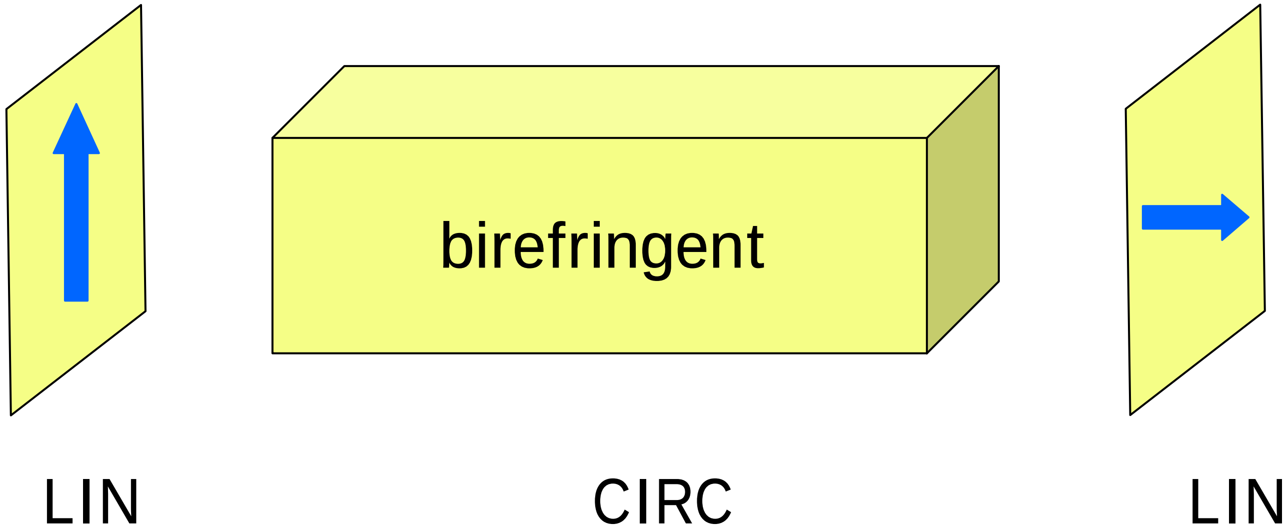
- Interaction eigenstates are linear combinations

$$U' = T_u U \quad , \quad D' = T_d D$$

- Interaction (charged) takes the form

$$U'^{+} D' = U^{+} T_u^{+} T_d D = U^{+} \boxed{V} D$$

Optical analogy



$$U'^{+}D' = U^{+}T_u^{+}T_d D = U^{+}VD$$

- V is N x N unitary matrix (KM)
- Same for antiquarks
- If there is phase, then CP violated

KM observation

- An $N \times N$ unitary matrix
- Remove phase convention
- Will have remaining complex phase only if $N \geqq 3$

Count parameters

$$\begin{pmatrix} x & o & o & o \\ & x & o & o \\ & & x & o \\ & & & x \end{pmatrix}$$

$N \times N$ matrix $V \Rightarrow 2N^2$ parameters

$V^+V = I \Rightarrow N + 2\times[N(N-1)/2] = N^2$ conditions

Phase convention $= 2N - 1$

Remaining parameters $= N^2 - (2N-1) = (N-1)^2$

$= 0, 1, 4, 9, \ldots$ for $N = 1, 2, 3, 4, \ldots$

Parameters in orthogonal matrix

$= 0, 1, 3, 6, \ldots$ for $N = 1, 2, 3, 4, \ldots$

KM result

- For 2 generations, cannot have nontrivial phase
- For 3 or more generations, there would in general be a phase
- Therefore *CP* violation

- KM predicted 3rd generation in 1972
- Found in 1977, 1994

The KM matrix

$$V = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Two steps

- Measure the parameters
  - Mostly done
- Understanding the parameters
  - Still mystery

KM matrix

This is why we exist??

$$s_{12} = \lambda \ , \ s_{23} = A\lambda^2 \ , \ s_{13}e^{i\delta} = A\lambda^3(\rho + i\eta)$$

$$\lambda = 0.226 \ , \ A = 0.81$$

$$\rho = 0.135 \ , \ \eta = 0.35$$

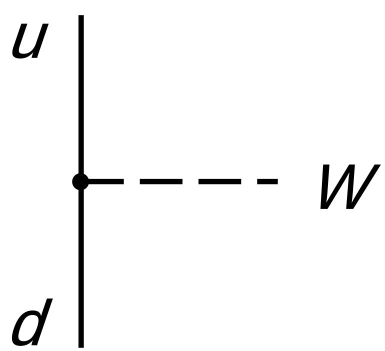
implies $\delta \approx 70^{o}$

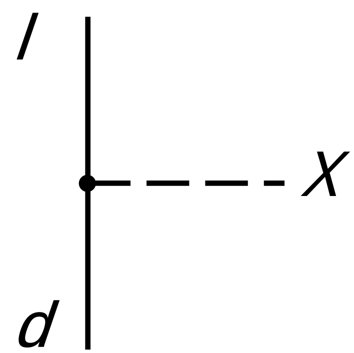
(Ignored some difference between $\rho \,/\, \bar{\rho}$ and $\eta \,/\, \bar{\eta}$ which is order λ^2)

Not quite

- SM does not have baryon number non-conservation
- Needs GUT

GUT





- Many uncertainties
- Nothing firmly known
- But need lepton sector

The lepton sector

- Neutrinos also mix
- Same parameterization
- Two differences
  - Possibility of Majorana: 2 more phases
  - Neutrinos can be free: masses unambiguous

Neutrino mixing

$$s_{12}^2 \approx 0.33 \quad , \quad \theta_{12} \approx 35^{\circ}$$

$$s_{23}^2 \approx 0.5 \quad , \quad \theta_{23} \approx 45^{\circ}$$

$$s_{13}^2 \leq 0.03 \quad , \quad \text{to be measured at Daya Bay}$$

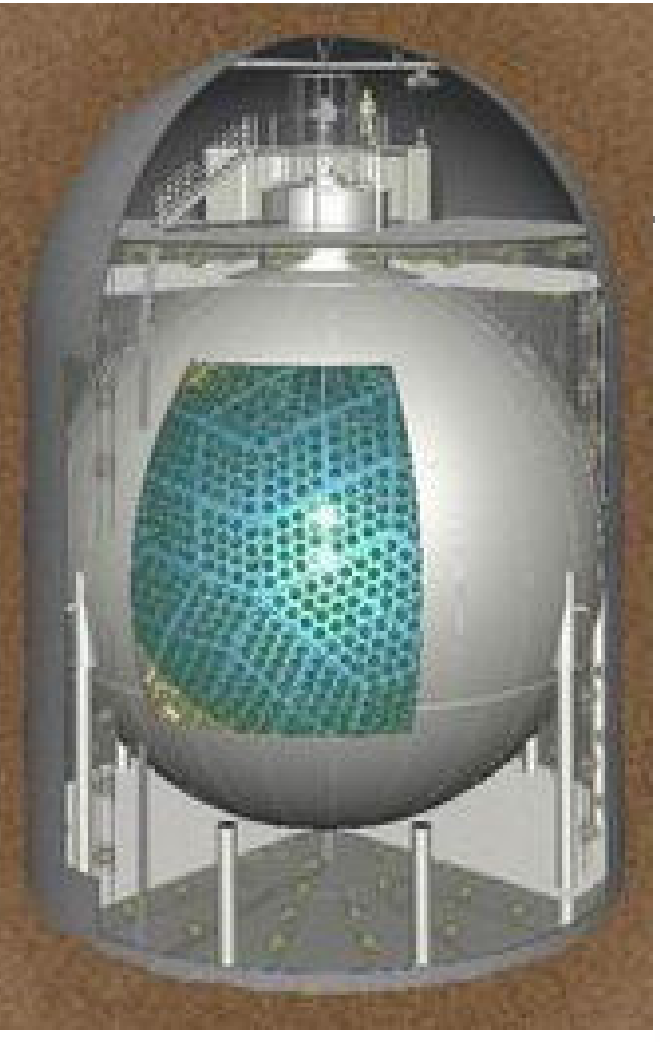
$$\delta = ???$$

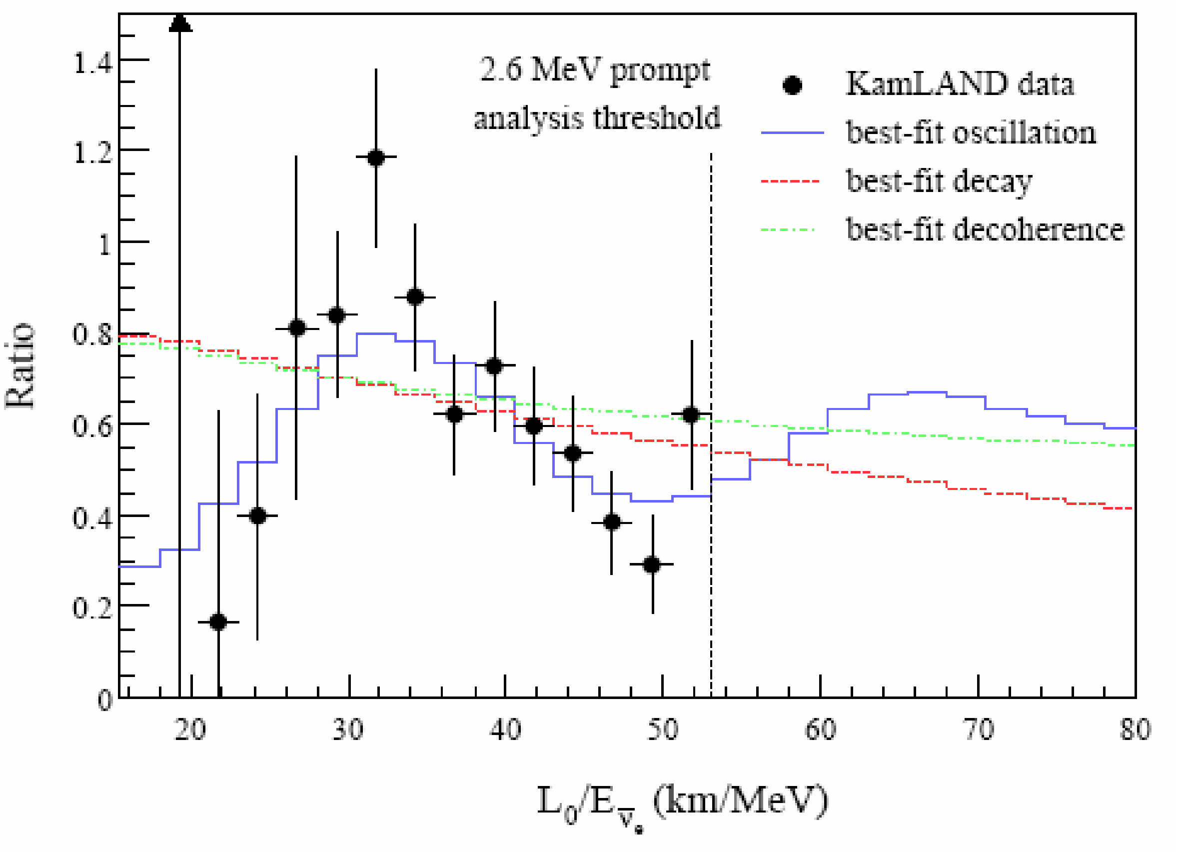
1-2 mixing

- Electron neutrinos produced in sun
- Oscillate between 2 states
- Detect at earth
- Reduced flux of ~1/3
- Solar neutrino problem
  - Bahcall, Davis, …

1-2 mixing

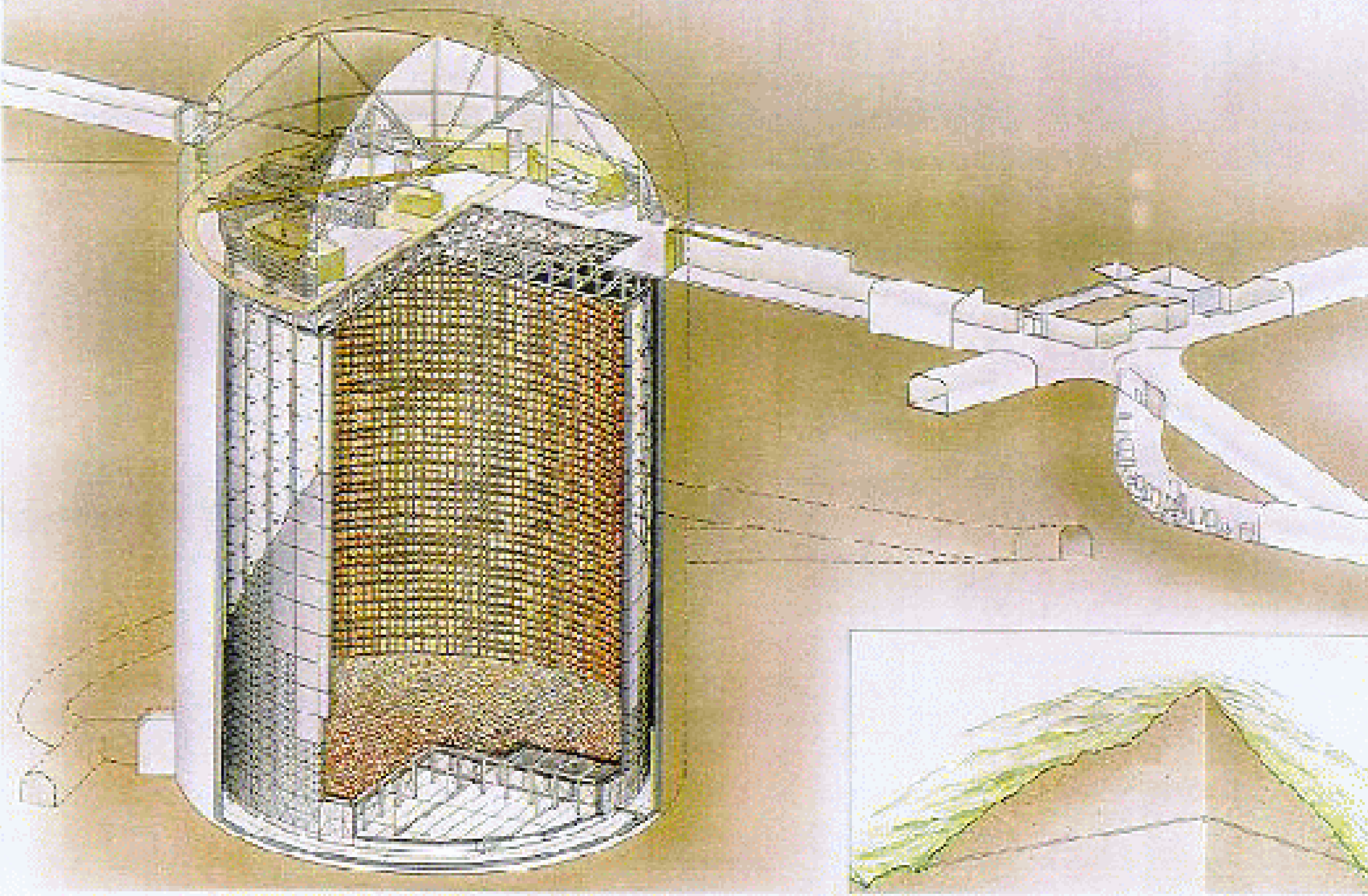
- Wavelength of oscillation depends on mass diff between 1, 2
- Measured by KAMLand
- Order of 100 km (2nd minimum)




2.6 MeV prompt
analysis threshold
KamLAND data
best-fit oscillation
best-fit decay
best-fit decoherence
Ratio
$L_0/E_{\bar{\nu}_e}$ (km/MeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
20
30
40
50
60
70
80

2-3 mixing

- Muon neutrinos produced in atm
- Oscillate between 2 states
- Detect at ground level
- Deduced flux
  - depends on energy
  - depends on zenith angle



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

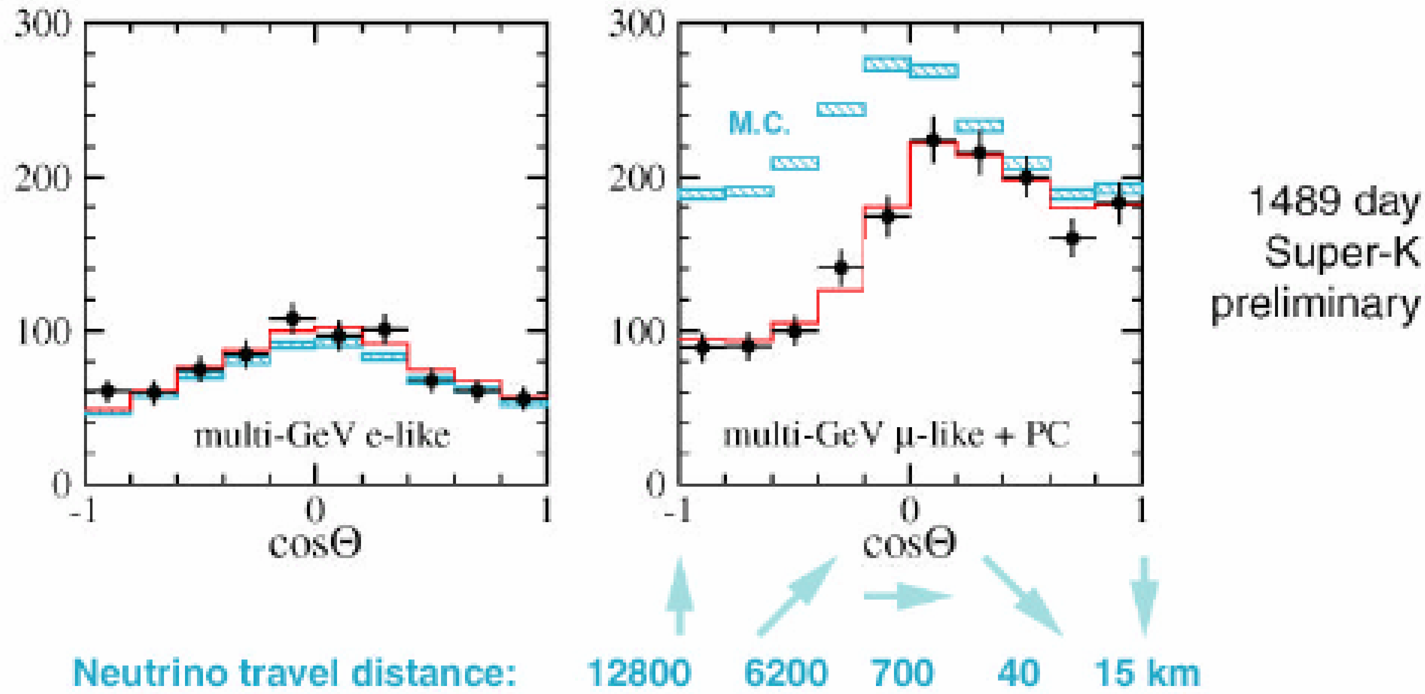
Super-K – zenith angle for multi-GeV events

Contained events, multi-GeV only (E_{vis}>1.33 GeV) :

multi-GeV: $$\left(\frac{N_{UP} - N_{DOWN}}{N_{UP} + N_{DOWN}}\right)_{\mu\text{-like}} = -0.303 \pm 0.030_{\text{stat.}} \pm 0.004_{\text{sys.}}$$

M.C. simulations (without oscillations)

› 10σ deviation!



1-3 mixing

- Electron (anti)-neutrinos produced in reactor
- Measure flux at ~ 1 km
- 1-2 mixing has too long wavelength (~100 km)

Experimental conditions

- Reactors to produce flux
- Hill to shield cosmic rays
- Distance of 1-2 km to do expt

- Daya Bay (~18 GW_{th})
- Chooz, France

55 km
SHENZHEN
HONG KONG
DAYA WAN
MIRS BAY
DEEP BAY
YANTIAN
Yantian Port
WUTONG SHAN
FUTIAN
LUOHU
BAO'AN
NANSHAN
Shekou
Chiwan Port
Mawan Port
LO WU
FANLING
TAI PO
TOLO HARBOUR
TIN SHUI WAI
YUEN LONG
TUEN MUN
TAI MO SHAN
TSUEN WAN
SHA TIN
MA ON SHAN
SAI KUNG
KOWLOON PEAK
KOWLOON
TSEUNG KWAN O
Hong Kong Island
VICTORIA PEAK
Aberdeen
Lantau Island
TUNG CHUNG
LANTAU PEAK
Chek Lap Kok
Peng Chau
Hei Ling Chau
Cheung Chau
Lamma Island
Soko Islands
Po Toi Islands
Ninepin Group
Tung Lung Chau
Waglan Island
Basalt Island
Town Island
Crooked Island
Crescent Island
Double Island
Ping Chau
QINIANG SHAN
Nan'ao
Dapeng
Gangkou Liedao
Xi Zhou
Mabian
Dalajia
Xiaosanmen Dao
Nelingding Dao
Lung Kwu Chau
The Brothers
Ma Wan
Tsing Yi
Stanley
Guishan
Dazhi Zhou
Boundary of Special Administrative Region
LEGEND
Railway
Main road
Secondary road
Built-up area / Cultivation
Airport / Major port
Power station
Peak (in metres)
Contours
Sea depth in metres
Series AR/18/IRS
Edition 7 2002
Survey and Mapping Office, Lands Department
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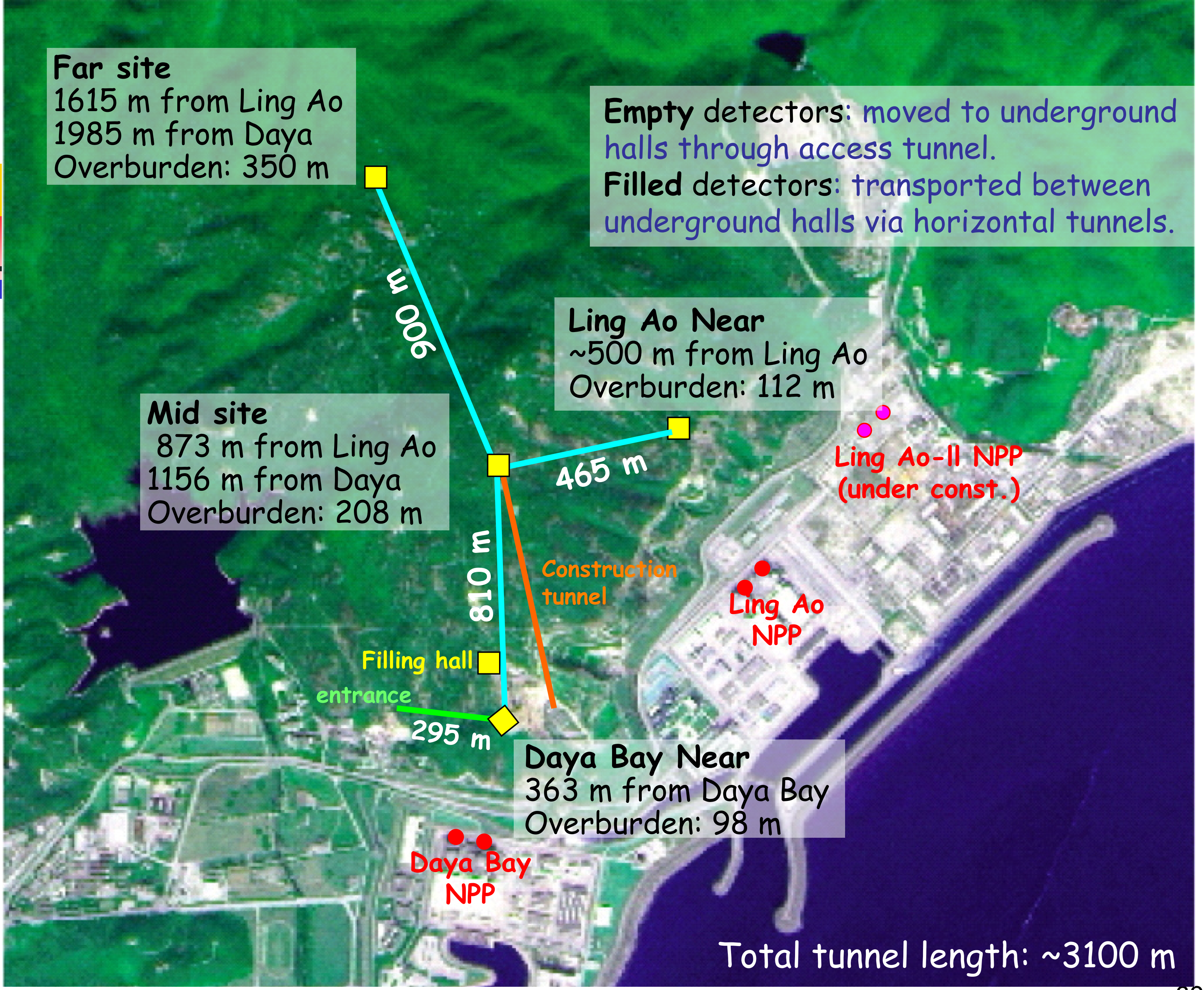
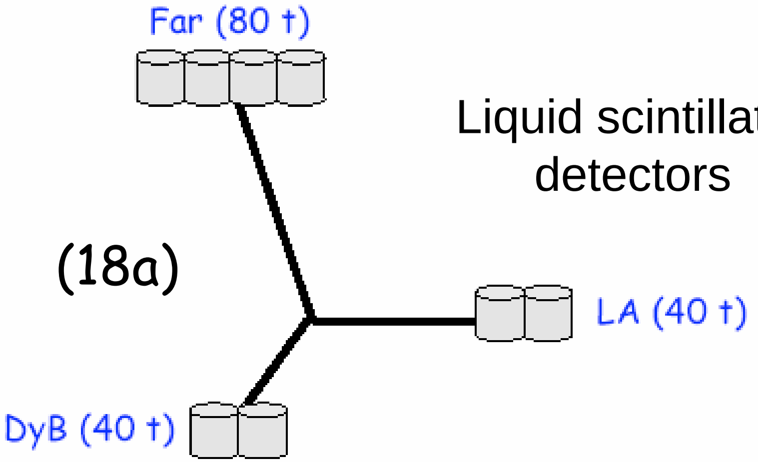
Daya Bay


Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: transported between underground halls via horizontal tunnels.
900 m
Ling Ao Near
~500 m from Ling Ao
Overburden: 112 m
Mid site
873 m from Ling Ao
1156 m from Daya
Overburden: 208 m
465 m
Ling Ao-II NPP
(under const.)
810 m
Construction
tunnel
Ling Ao
NPP
Filling hall
entrance
295 m
Daya Bay Near
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP
Total tunnel length: ~3100 m

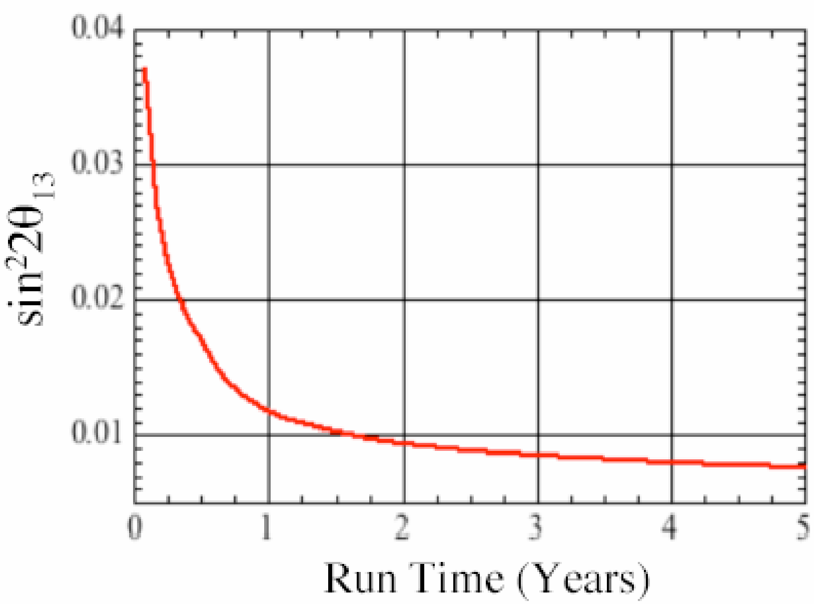
Sensitivity of $Sin^2 2\theta_{13}$

(18a)

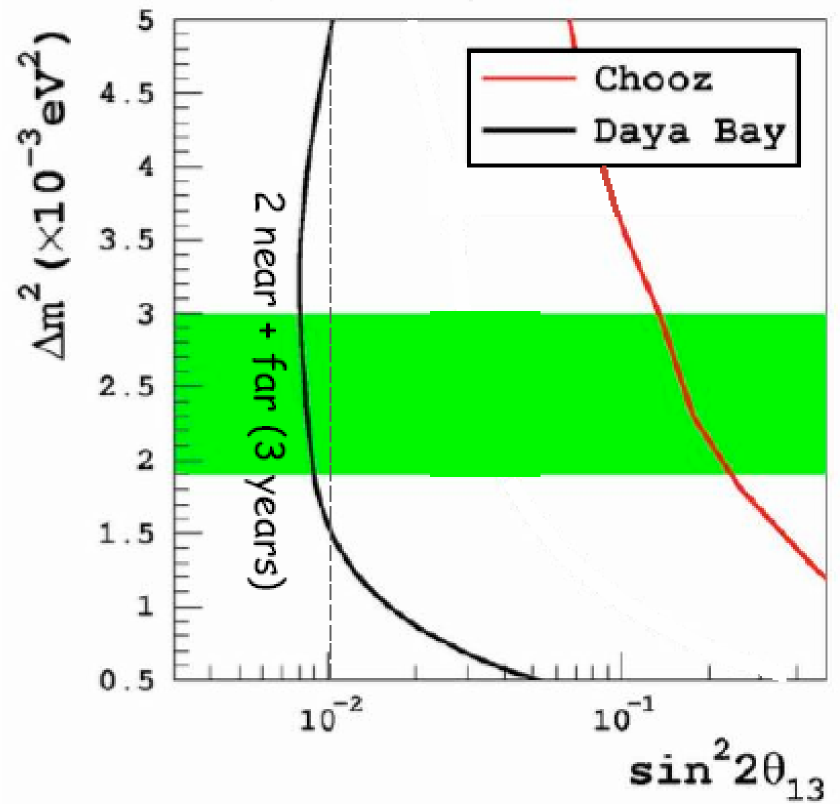


Liquid scintillator detectors

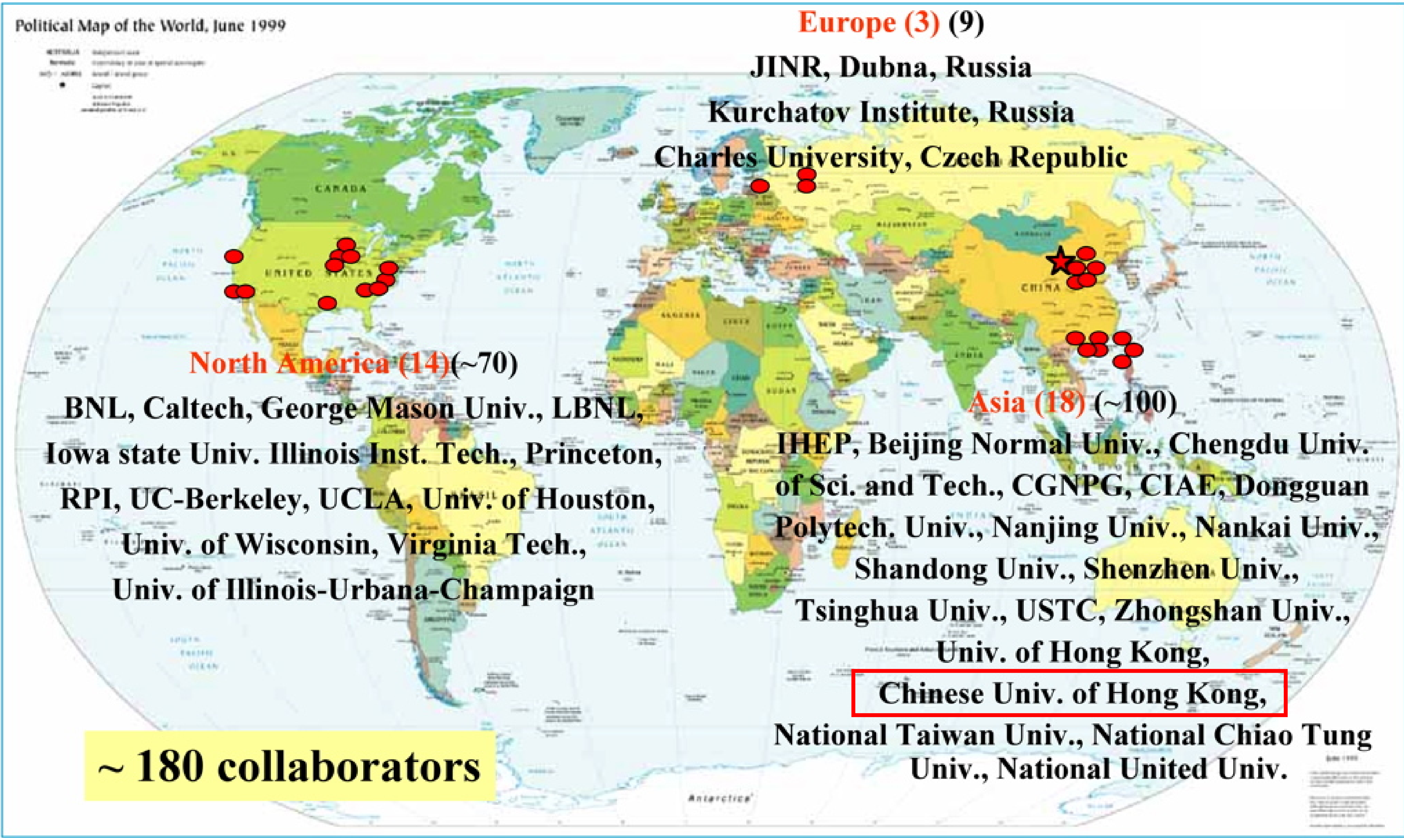
- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector



90% confidence level



The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(~70)

BNL, Caltech, George Mason Univ., LBNL,
Iowa state Univ. Illinois Inst. Tech., Princeton,
RPI, UC-Berkeley, UCLA, Univ. of Houston,
Univ. of Wisconsin, Virginia Tech.,
Univ. of Illinois-Urbana-Champaign

Asia (18) (~100)

IHEP, Beijing Normal Univ., Chengdu Univ.
of Sci. and Tech., CGNPG, CIAE, Dongguan
Polytech. Univ., Nanjing Univ., Nankai Univ.,
Shandong 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.

~ 180 collaborators

The Hong Kong Team

http://theta13.phy.cuhk.edu.hk/

The Hong Kong team

- More than 30 undergraduates have helped!






HK team

- LED calibration system
- Data Acquisition System (part)
- Prototype detector (Aberdeen Tunnel)
- Simulation and analysis (part of a large team)
- Offline monitoring
- CUHK as a data center (??)

One step at a time

- Measure the parameters
- Understand the quark sector
- Understand the lepton sector
- Grand unification
  - 3 Sakharov conditions
- Why do we exist?