The road to detecting large CP violation in B decays

Global COE
Kyoto University

From Diversity to Universality

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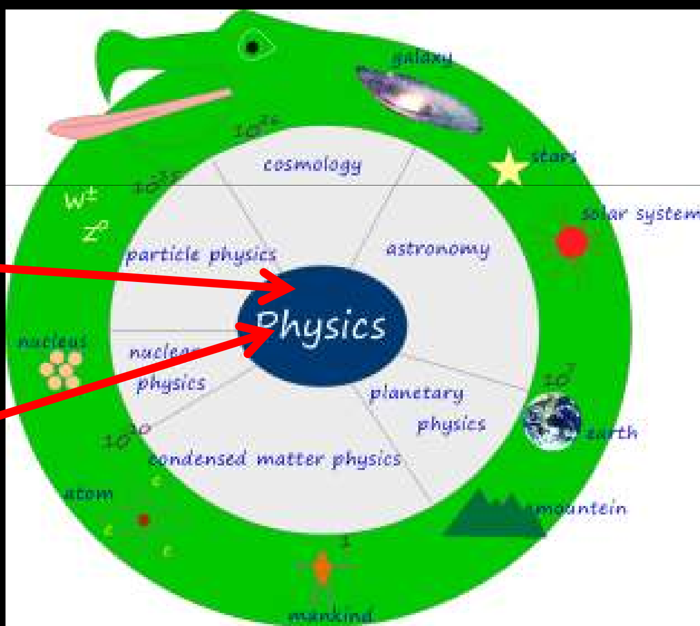
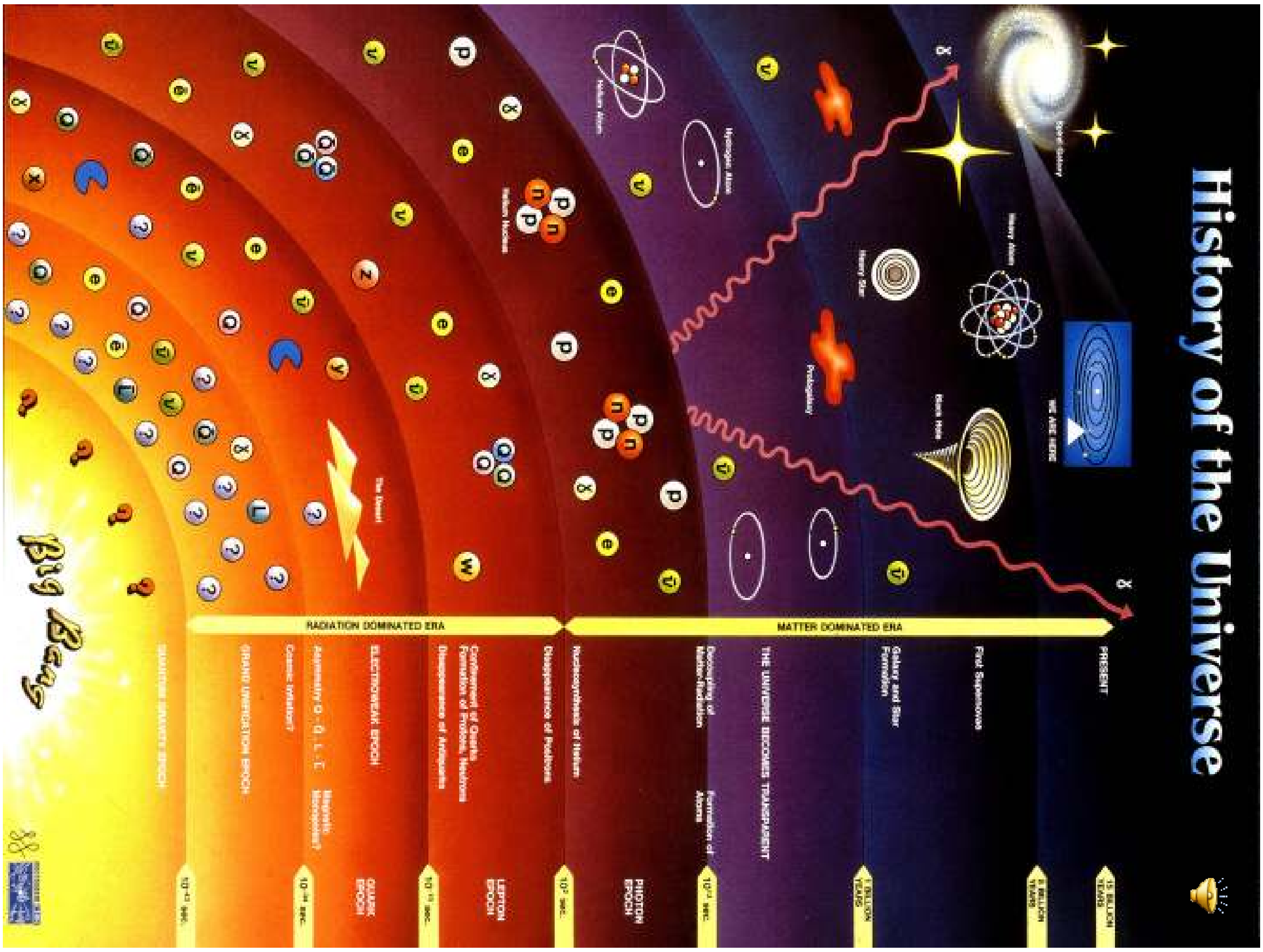
Nature consists of myriad scales of structure, from the tiny scales of elementary particles and atomic nuclei to the vast scale of the universe.

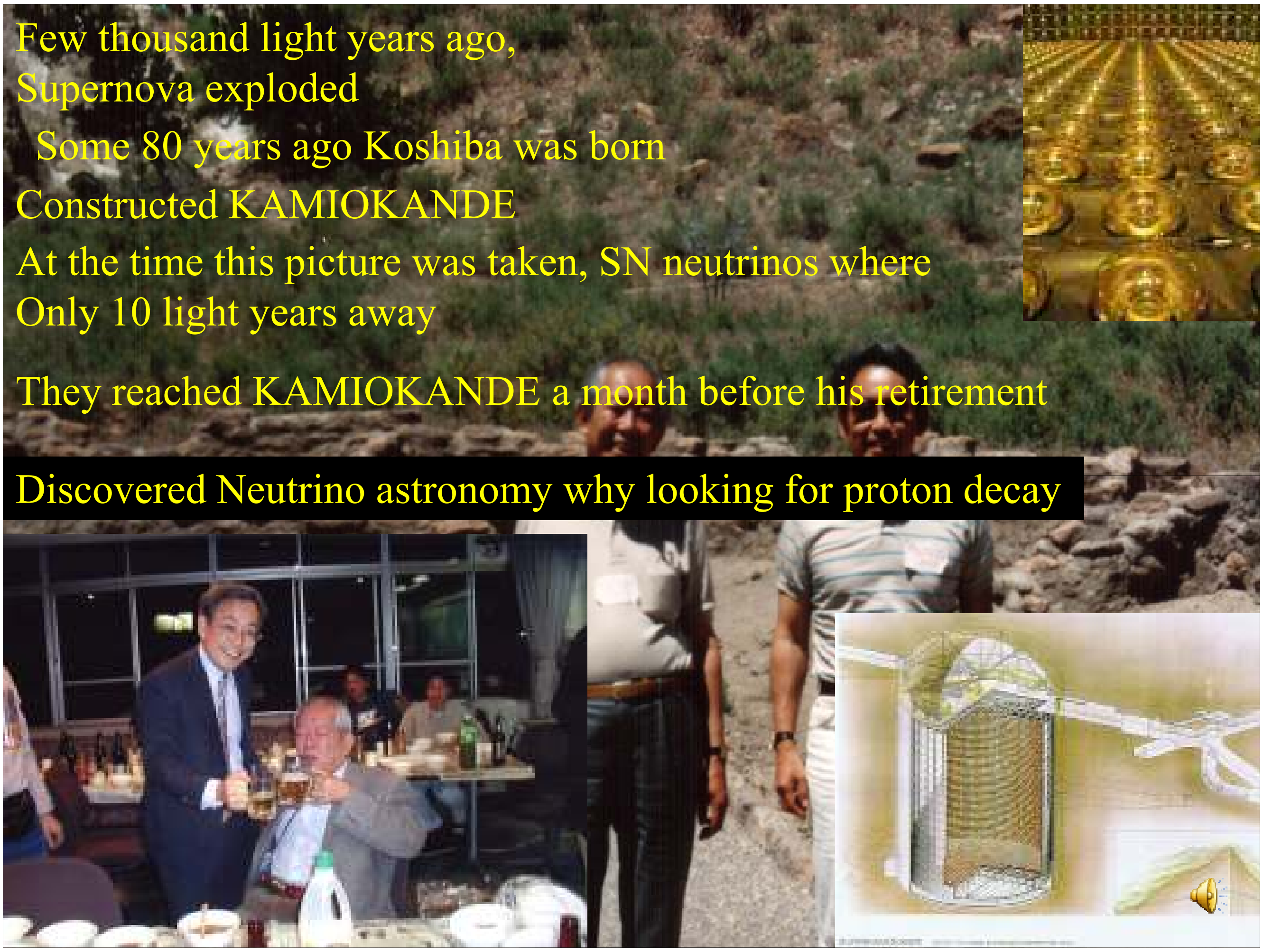
Our attempt to elucidate the great variety of phenomena exhibited over this complete range of scales is a pursuit of diversity.

By diversifying, we reach the fundamental understanding - the universal law which makes the universe tick.



http://www.cc.kyoto-su.ac.jp/department/physics/top_deptphys.html





Few thousand light years ago,
Supernova exploded
Some 80 years ago Koshiba was born
Constructed KAMIOKANDE
At the time this picture was taken, SN neutrinos where
Only 10 light years away

They reached KAMIOKANDE a month before his retirement

Discovered Neutrino astronomy why looking for proton decay

With neutrinos, we can
see the past
that is, beginning of the universe
when it was very very small .
Diversity--Univresality

Anti-Universe

While real number
is sufficient for Mech. and E&M

Complex number is needed for Quantum Mechanics

Most important equation:

$$[p, q] = i\hbar$$

Under time reversal symmetry

$$U^{\dagger} p U \rightarrow -p$$

$$U^{\dagger} q U \rightarrow q$$

If there is no "i" in quantum mechanics. It violates time reversal invariance

$$U^{\dagger}[p, q]U \rightarrow -[p, q]$$

$$U^{\dagger} i\hbar U \rightarrow -i\hbar$$

The time reversal symmetry is anti-unitary WIGNER

Quantum Field Theory

A particle state is represented by Φ

Then what is Φ^*

$$[\partial_\mu - ieA_\mu - m][\partial^\mu - ieA^\mu - m]\Phi = 0$$

$$[\partial_\mu + ieA_\mu - m][\partial^\mu + ieA^\mu - m]\Phi^* = 0$$

If Φ corresponds to a particle,
Φ^* corresponds to an antiparticle with same mass and opposite charge

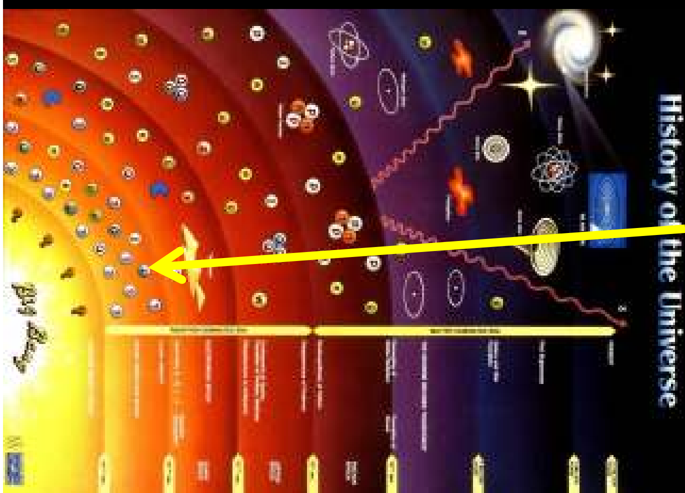
Complex field implies antiparticle

CP symmetry

$$CP^{-1}\Phi CP = \Phi^\dagger$$

Particle $\longrightarrow$ Antiparticle

$$CP^{-1}HCP = H$$



Energy particles and antiparticles

$\gamma\gamma$ □ e^+e^-

The world of particles is exactly the same as the world of antiparticles

But, matter and antimatter will annihilate each other

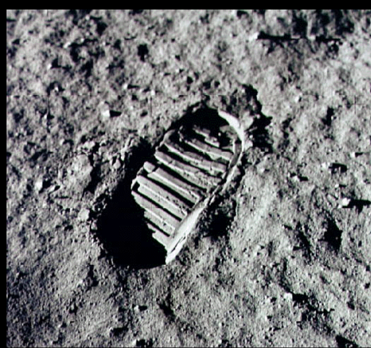
Or, there is anti-universe

Collision of two galaxies

Spitzer/Hubble View of NGC 2207 & IC 2163
NASA, ESA / JPL-Caltech / STScI / D. Elmegreen (Vassar)

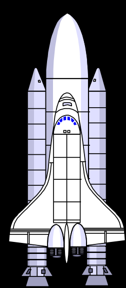
Spitzer Space Telescope • IRAC
ssc2006-11b

How do you know that moon is not made out of anti-particles?



- First giant footstep for the mankind
- The moon is not made out of antiparticles

Is the anti-universe really lost?



Alpha Matter Spectrometer
Space Shuttle NASA program

The biggest puzzle in the universe

t = 154 billion years

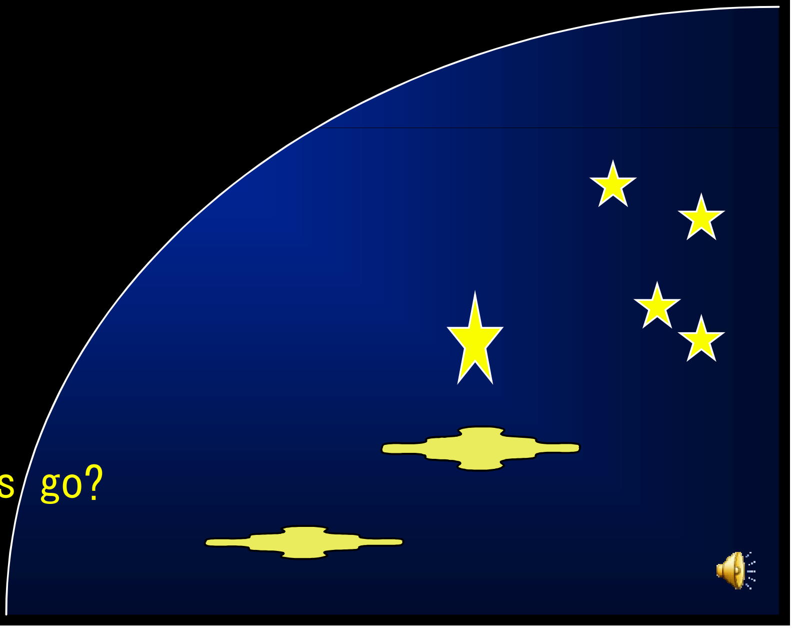
$r = 10^{29} cm$

$T = -270°C$

$200\gamma / cm^3$

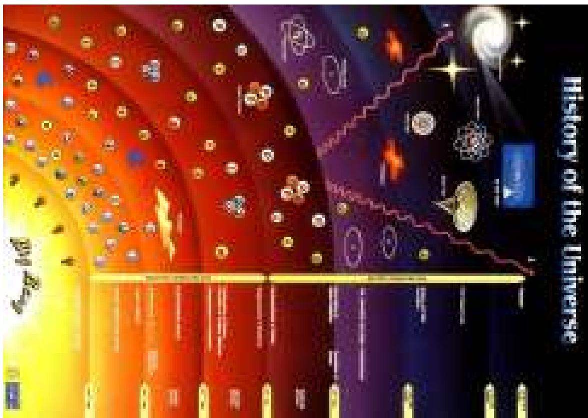
10^{80} p, n

0 $\bar{p}, \bar{n}$



Where did antiparticles go?

Sakharov's idea



$r = 10^{-34} - 10^{-10}$ sec

$X \rightarrow qe$

$\bar{X} \rightarrow \bar{q}\bar{e}$

There is a bit of mismatch

$\gamma\ \gamma\ \gamma\ \gamma\ \gamma\ \gamma$

$\gamma\ \gamma\ \gamma\ \gamma\ \gamma\ \gamma$

CPV

About the mismatch

$X \rightarrow qe$ $N = 10^{88} + 10^{80}$

$\bar{X} \rightarrow \bar{q}\bar{e}$ $\bar{N} = 10^{88}$

No partner to annihilate

Present universe is created
From these particles

Big Puzzle

CP violation
and our existence

The entire universe is
created by CP violation
at very tiny scale

**First we needed to
be certain about the KM theory**

CP symmetry and complex phase

$$H = ch + c^* h^\dagger$$

h particle dynamics

$h^\dagger$ antiparticle dynamics

$$CPhCP^\dagger = h^\dagger$$

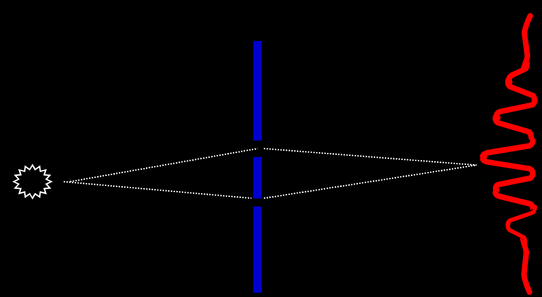
$$CPHCP^\dagger = ch^\dagger + c^* h$$

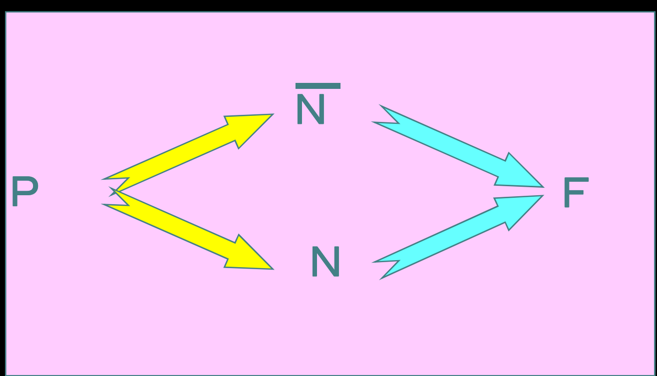
If c is complex, worlds is not invariant under CP

How do we detect phase?

Experimentalists can only count the number of particles
They can't use protractor to measure the phase angle!

Measuring an angle by counting particles in optics





Measuring a phase angle between two Paths

$$|A(P \to F)|^2 \neq |A(\overline{P} \to F_{CP})|^2$$

CPV The phase between two amplitudes

Quiz

Why is electric charge real?

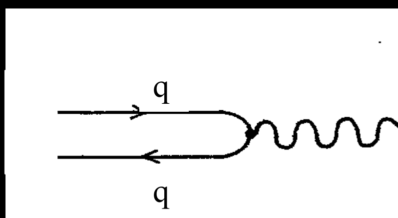
$$\vec{F} = e\vec{E}$$

$$\vec{F} = e(\vec{v} \times \vec{B})$$

Even if e is complex,
it can be absorbed in E and B

QFT

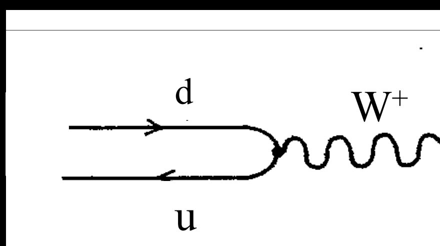
QED



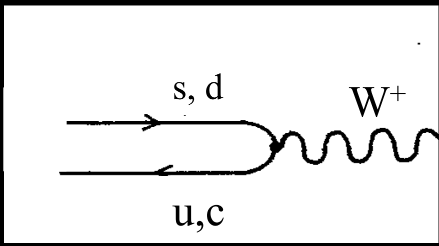
$$ie\ \bar{q}\gamma_\mu q\ A^\mu$$

Even if e is complex it can be absorbed in A

Weak Intinteraction



$$ig_{ud}\quad \bar{u}\gamma_\mu(1-\gamma_5)d\quad W^\mu$$



$$ig_{ud} \quad \bar{u}\gamma_\mu(1-\gamma_5)d \quad W^\mu$$

$$ig_{cd} \quad \bar{c}\gamma_\mu(1-\gamma_5)d \quad W^\mu$$

$$ig_{us} \quad \bar{u}\gamma_\mu(1-\gamma_5)s \quad W^\mu$$

$$ig_{cs} \quad \bar{c}\gamma_\mu(1-\gamma_5)s \quad W^\mu$$

Remember, you only count external particles!
You can't see their phases!

all 4 phases in g_{ij} can be absorbed by adjusting s, c, d, u and W phases

Kobayashi-Maskawa Theory

Not so if we have 3 generations.

$g_{ud}, \ g_{us}, \ g_{ub}$

$g_{cd}, \ g_{cs}, \ g_{cb}$

$g_{td}, \ g_{ts}, \ g_{tb}$

u, c, t
d, s, b
W

9 coupling constants
7 fields

One phase becomes an observable

Kobayashi-Maskawa Theory

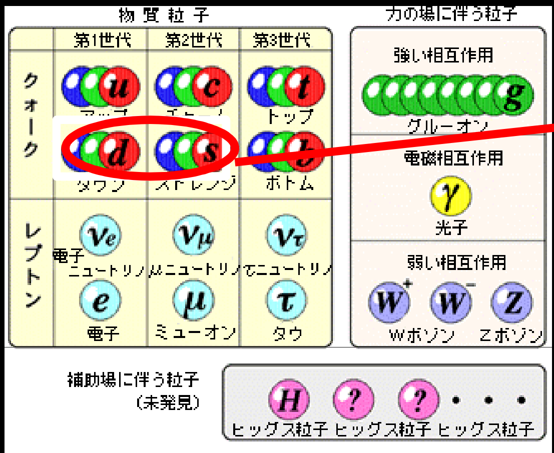


図1 現在の素粒子像「標準模型」の世界

$\bar{s}d = K^0 \quad s\bar{d} = \bar{K}^0$

K Meson

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\bar{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)} = 2\times10^{-3}$$

It requires three generations of quarks

The reason K meson CP violation is small is that it involves only 1st and 2nd generations

Tiny CP violation

$\bar{s}d = K^0 \quad s\bar{d} = \bar{K}^0$

$$\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\bar{K}^0 \to \pi^+\pi^-)$$

1980

Cronin Fitch

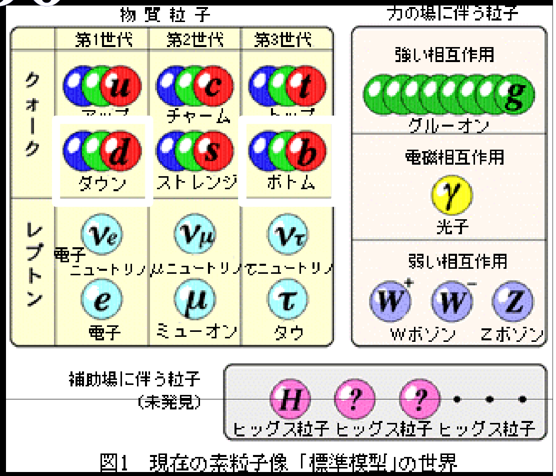
$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\bar{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)} = 2\times10^{-3}$$

My prediction 1980

K Meson

$$\bar{s}d = K^0 \quad s\bar{d} = \bar{K}^0$$

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\bar{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)} = 2\times 10^{-3}$$

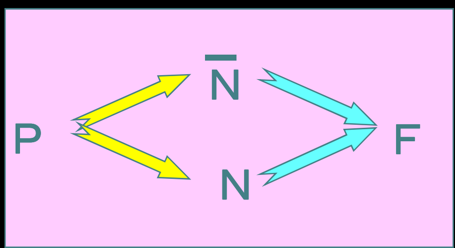


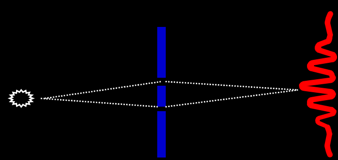
B Meson

$$\bar{b}d = B^0 \quad b\bar{d} = \bar{B}^0$$

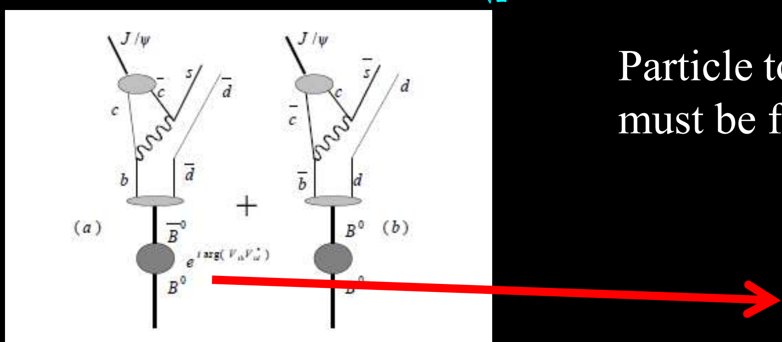
$$\frac{\Gamma(B^0 \to \psi K_S) - \Gamma(\bar{B}^0 \to \psi K_S)}{\Gamma(B^0 \to \psi K_S) + \Gamma(\bar{B}^0 \to \psi K_S)} = 0.7$$

METHOD TO OBSERVE PHASE

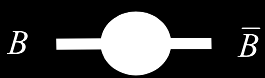




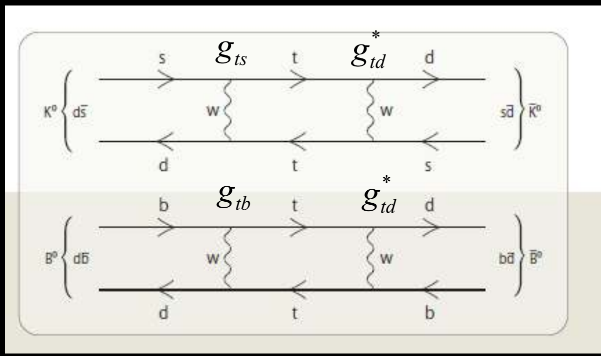
$$|\bar{K}_0\rangle = \frac{1}{\sqrt{2}}(|K_s\rangle - |K_L\rangle) \qquad |K_0\rangle = \frac{1}{\sqrt{2}}(|K_s\rangle + |K_L\rangle)$$

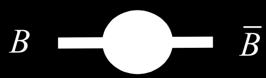


Particle to antiparticle transition must be found



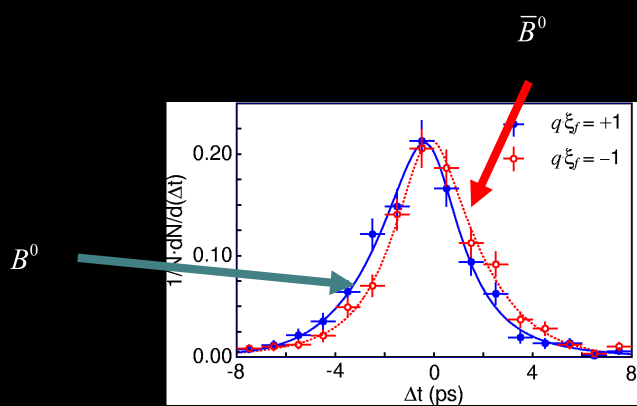
$$e^{i\arg(g_{tb}g_{td}^*)}$$

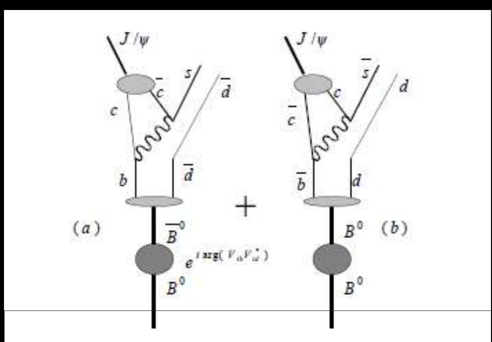


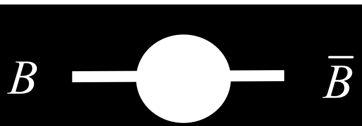


$$e^{i\arg(g_{tb}g_{td}^*)}$$

Theory



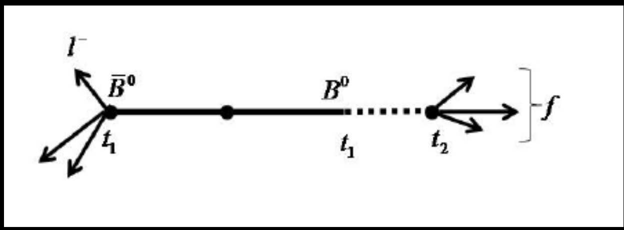


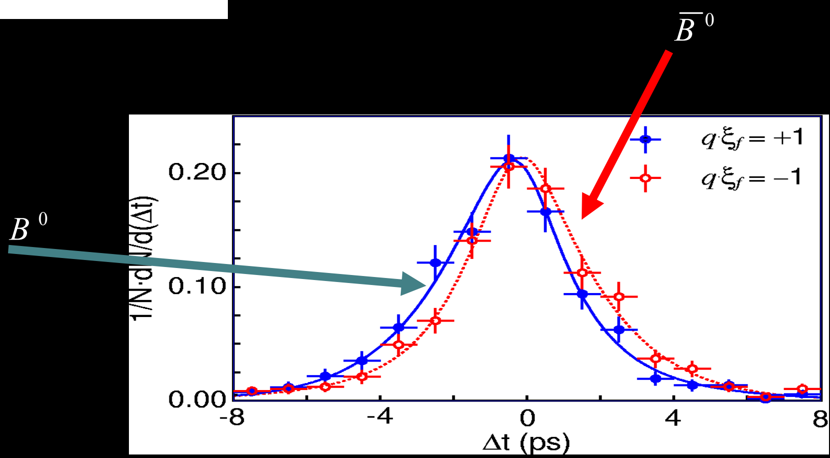


$$e^{i\arg(g_{tb}g_{td}^*)}$$

$$\frac{\Gamma(B^0 \to \psi K_S) - \Gamma(\overline{B}^0 \to \psi K_S)}{\Gamma(B^0 \to \psi K_S) + \Gamma(\overline{B}^0 \to \psi K_S)} = 0.7$$

All you have to do:





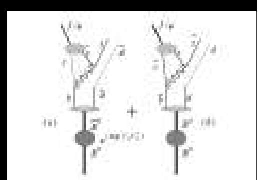
What is so difficult?

B meson has not been discovered

$e^+ + e^- \to B^0 + \bar{B}^0$

Simple computation impied B meson lifetime to be 0.001ps

10% asymmetry, if B meson lifetime is at least 1ps



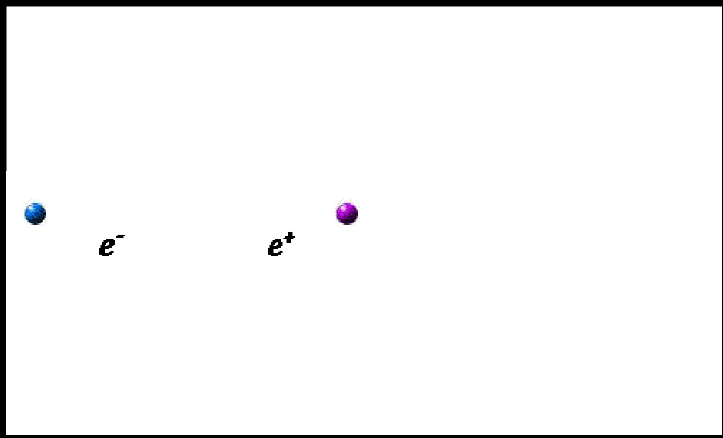
$B^0 \to \psi K_S$ is very rare. Once every 10^4 B^0decays

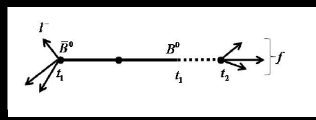
To detect 10% asymmetry, we need 1000 times more luminosity than any accerlerator that existed at that time

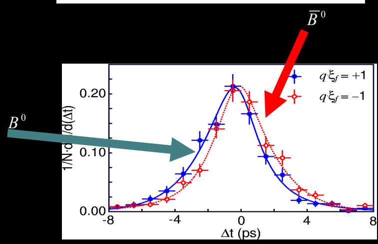
Experimentalists got suddenly interested after the discovery of B-anti B mixing

$e^{i\arg(g_{tb}g_{td}^{*})}$

But, there was a problem!







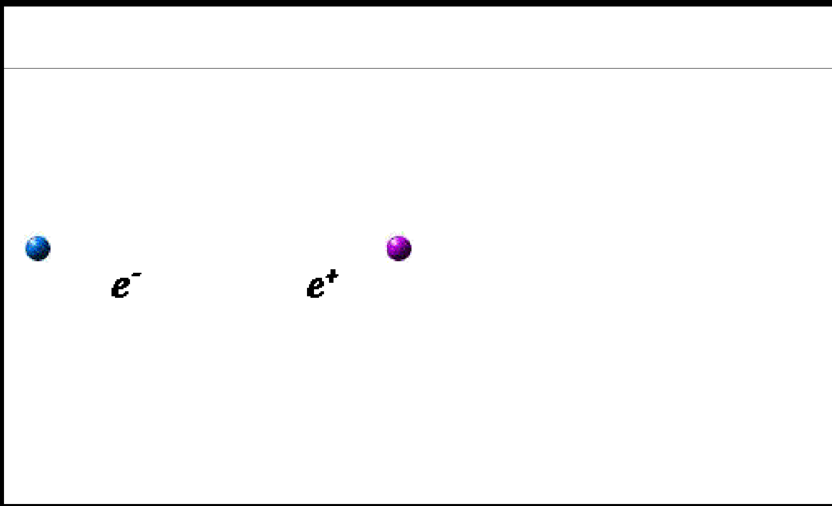
Impossible at symmetric collider

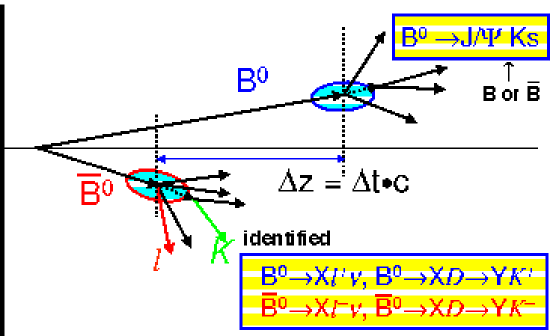
B decays in 10^{-12} sec.
Light travels only 3mm during that time.
B travels only 0.02mm before it decays.

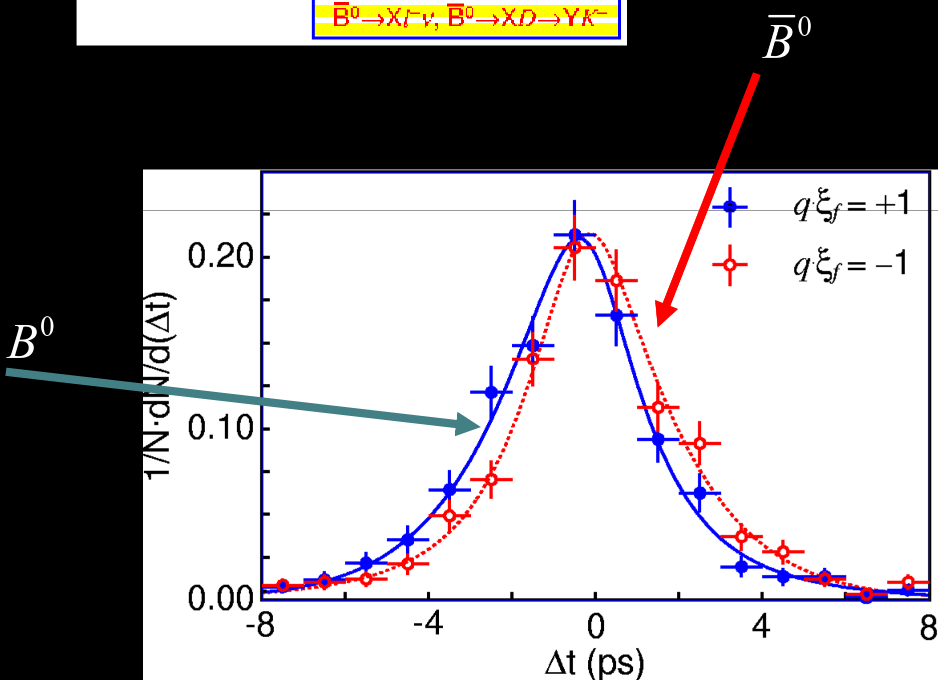
Oddone’s idea
Build an asymmetric collider

9GeV+3GeV asymmetric collider

200μm spaceial resolution







Now it is possibe to measure the decay length

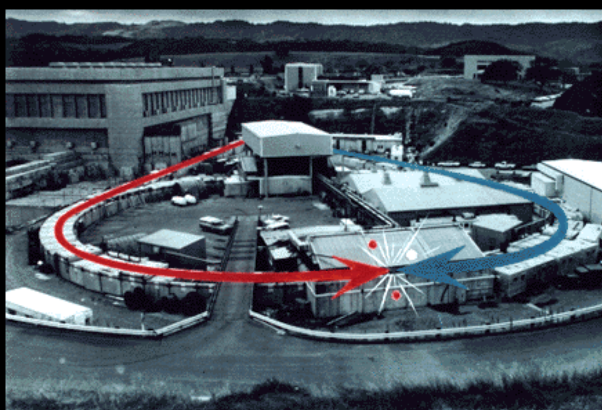
KEK machine experts
said asymmetric collider
is impossible
the beams will blow up

1994
SLAC started building it in January
KEK in April
beginning of 7 years marathon

I was a KEK LCPAC member

Style of building machines at SLAC and at KEK is different

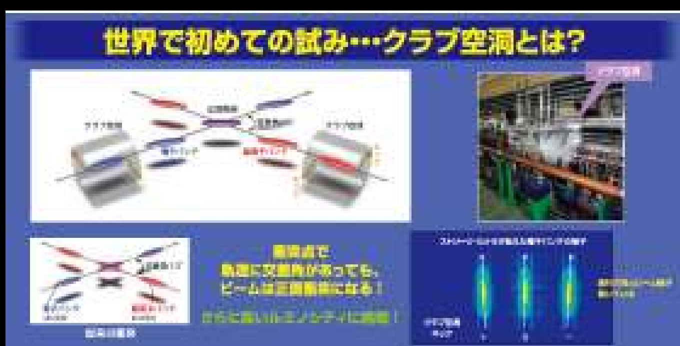
SLAC built an acelerator on a parking lot and won 2 Nobel Prizes



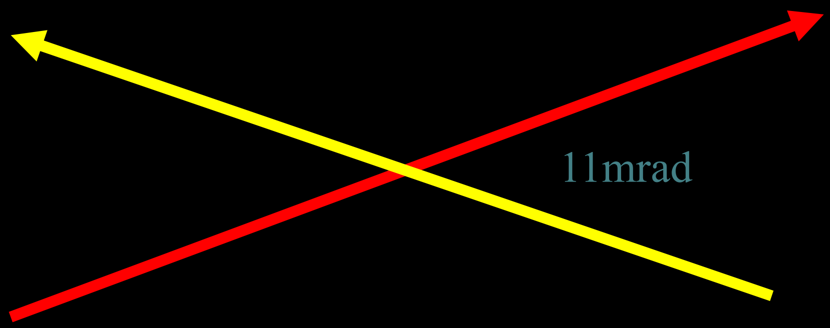
www2.slac.stanford.edu/vvc/experiments/spear.html

The only goal at SLAC
was to discover large CPV first!

KEK's goal
not only to discover CPV
but to build a beautiful machine



Doris gave up finite angle crossing



1 year loss

come out last!

“How do you know that
Finite angle crossing will work?”

"OK according to our simulation!”

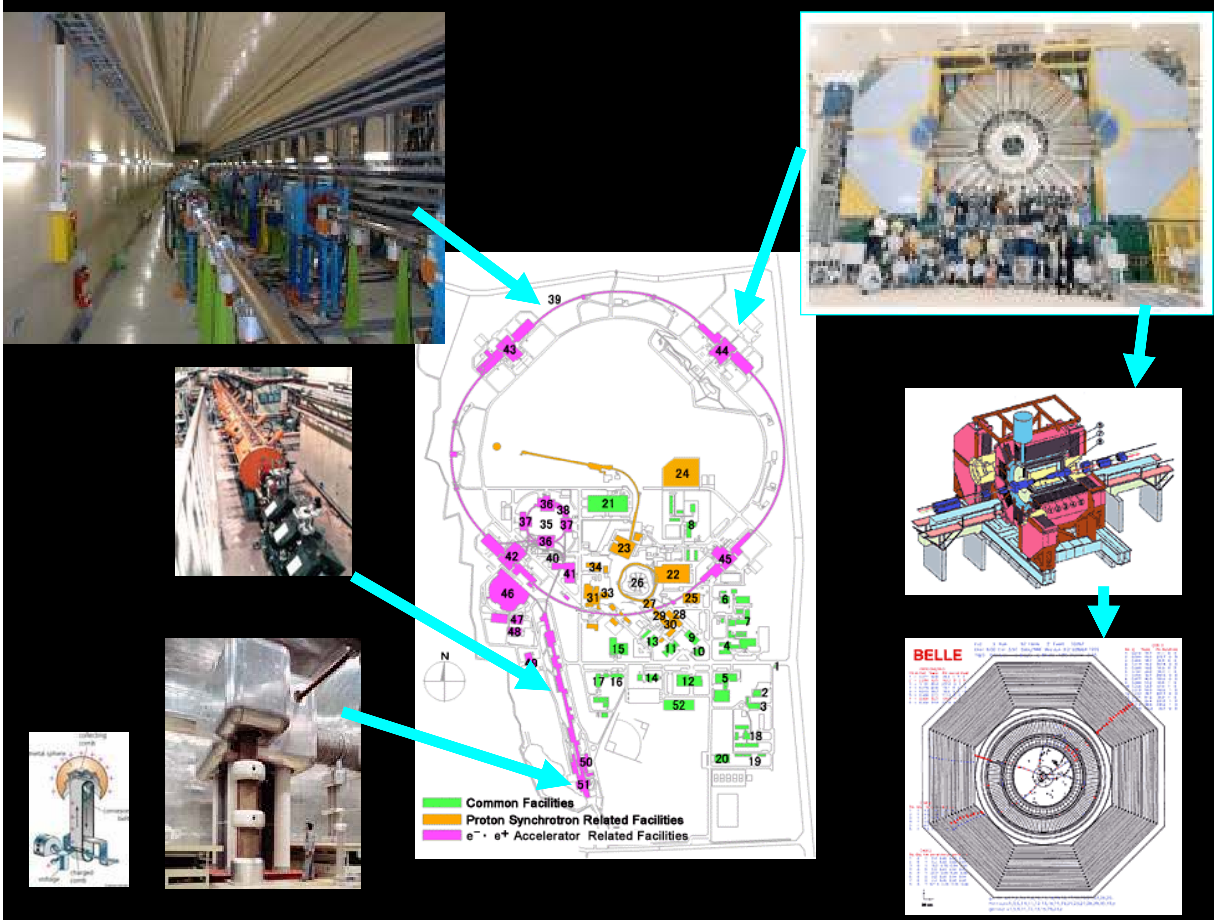
“Can you simulate the failure at Doris?"

“I don’t know, I don’t know their parameters!”

Why don’ you hop on a plane and find out!

PEPII started January, 1994 and KEKB in April,1994

7/23/98	First collision	PEPII
1/29/99	First collision	KEKB
2/8/99	$5.2x10^{32}$	PEPII
3/26/99	$1.2x10^{31}$	KEKB
5/26/99	Babar commissioned	PEPII
6/1/99	Belle commissioned	KEKB
11/11/99	8 $B \rightarrow \psi K_S$ events	PEPII
11/11/99	2 $B \rightarrow \psi K_S$ events	KEKB



The discovery of the large CPV in $B \to \psi K_S$

July, 2000 ICHEP Osaka

$\sin 2\phi_1 = 0.45 \pm 0.44(stat) \pm 0.09(syst)$ *Belle*

$\sin 2\phi_1 = 0.12 \pm 0.37(stat) \pm 0.09(syst)$ *BaBar*

July, 2001 Lepton Photon

$\sin 2\phi_1 = 0.99 \pm 0.14(stat) \pm 0.06(syst)$ *Belle*

$\sin 2\phi_1 = 0.59 \pm 0.14(stat) \pm 0.05(syst)$ *Babar*

KEKB team knew what they were doing!

What would have happened If God did not like KEKB

If SLAC's value was 0.99

2000

$\sin 2\phi_1 = 0.99 \pm 0.37(stat) \pm 0.09(syst)$

$\sin 2\phi_1 = 0.99 \pm 0.25(stat) \pm 0.09(syst)$ with double statistics in 6 months

They would have announced the discovery before Lepton Photon

God did not give SLAC a favorable dice

This proves
the validity of KM theory

Does not explain the
baryon asymmetry

New CPV is needed

The challenge
of the next generation

My guarantee

Emergence
of the new CP violation

Why we exist?