CP-violation

The matter with the Antimatter

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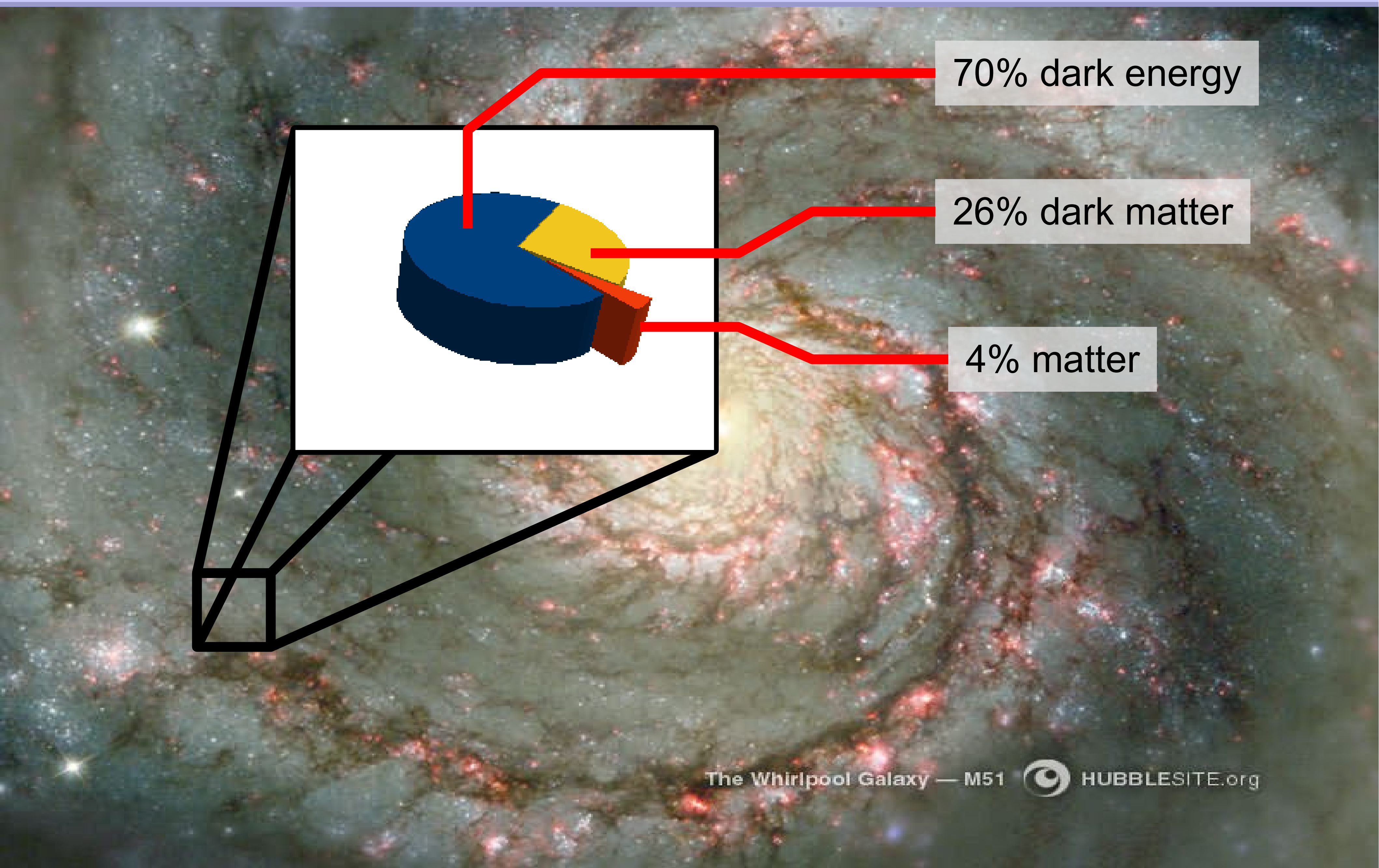
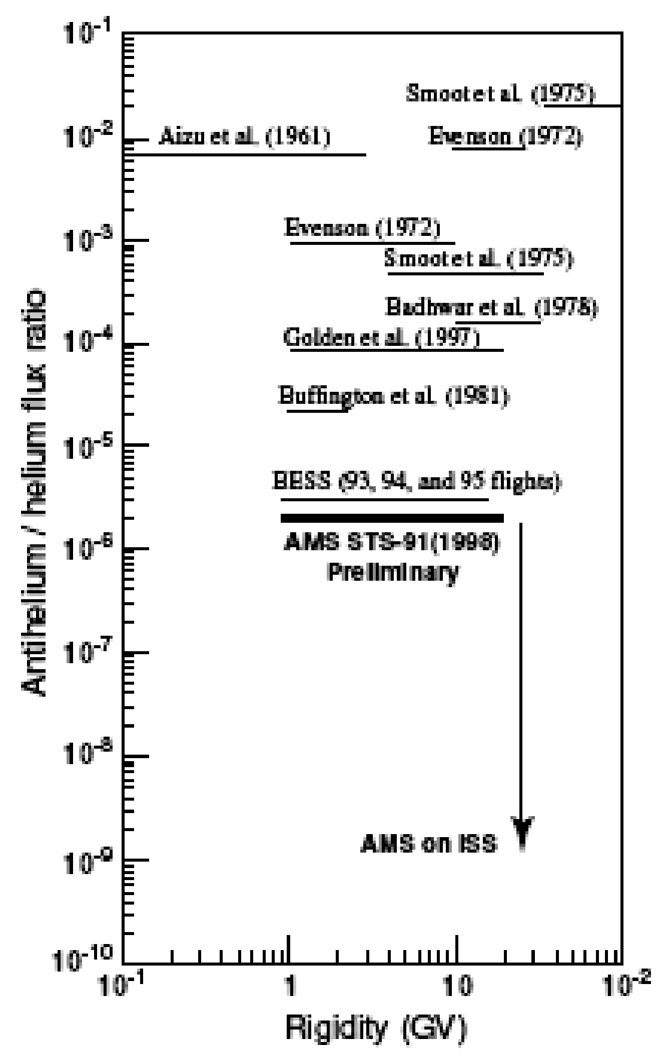
The universe



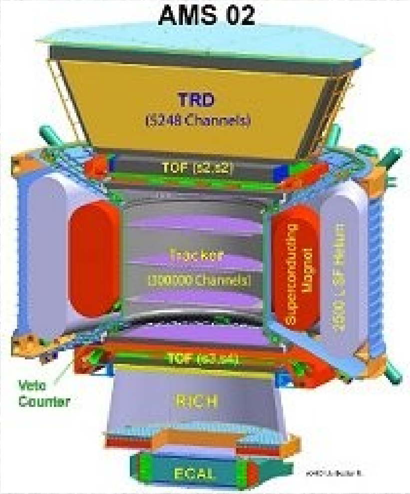
Search for antimatter



"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons."

"It is quite possible that for some of the stars it is the other way about ... ***In fact, there may be half the stars of each kind."***

Paul A.M. Dirac, Nobel Laureate Speech, 1933



So far, **no** antimatter dominated region in the universe has been found.

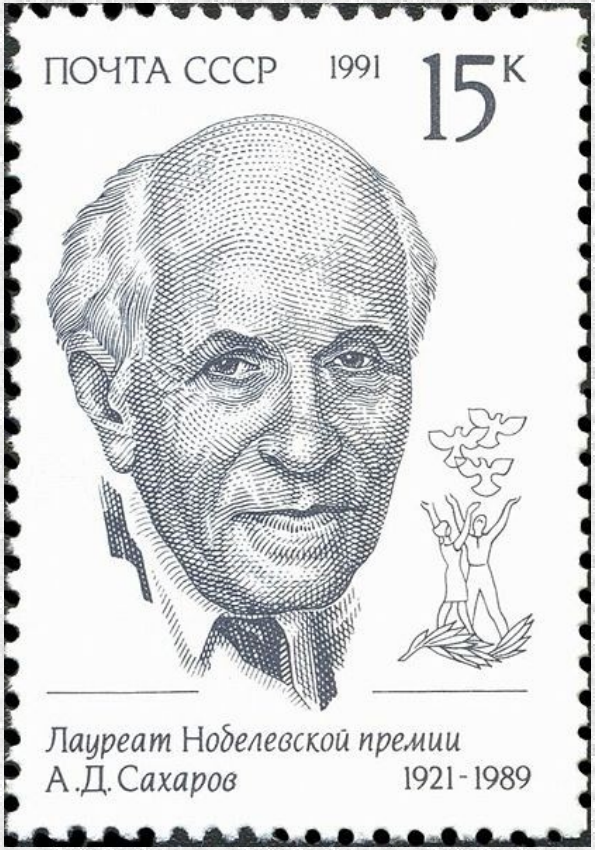
Sakharov's conditions

In 1967, A.D. Sakharov* named three necessary conditions to explain the different production rates of matter and antimatter:

(1) Baryon number violation

(2) C- and CP-violation

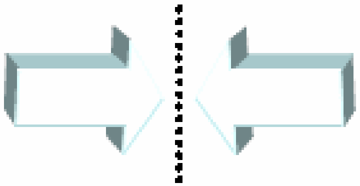
(3) Interactions out of thermal equilibrium



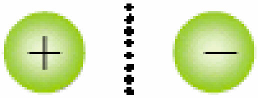
* 1921 - 1989, Nobel peace prize in 1975

Symmetries P, C and T

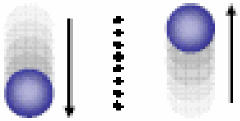
- Parity, *P*
  - Parity reflects a system through the origin. Converts right-handed coordinate systems to left-handed ones.
  - Vectors change sign but axial vectors remain unchanged
    - $\vec{x} \to -\vec{x}$, $\vec{p} \to -\vec{p}$, but $\vec{L} = \vec{x} \times \vec{p} \to \vec{L}$



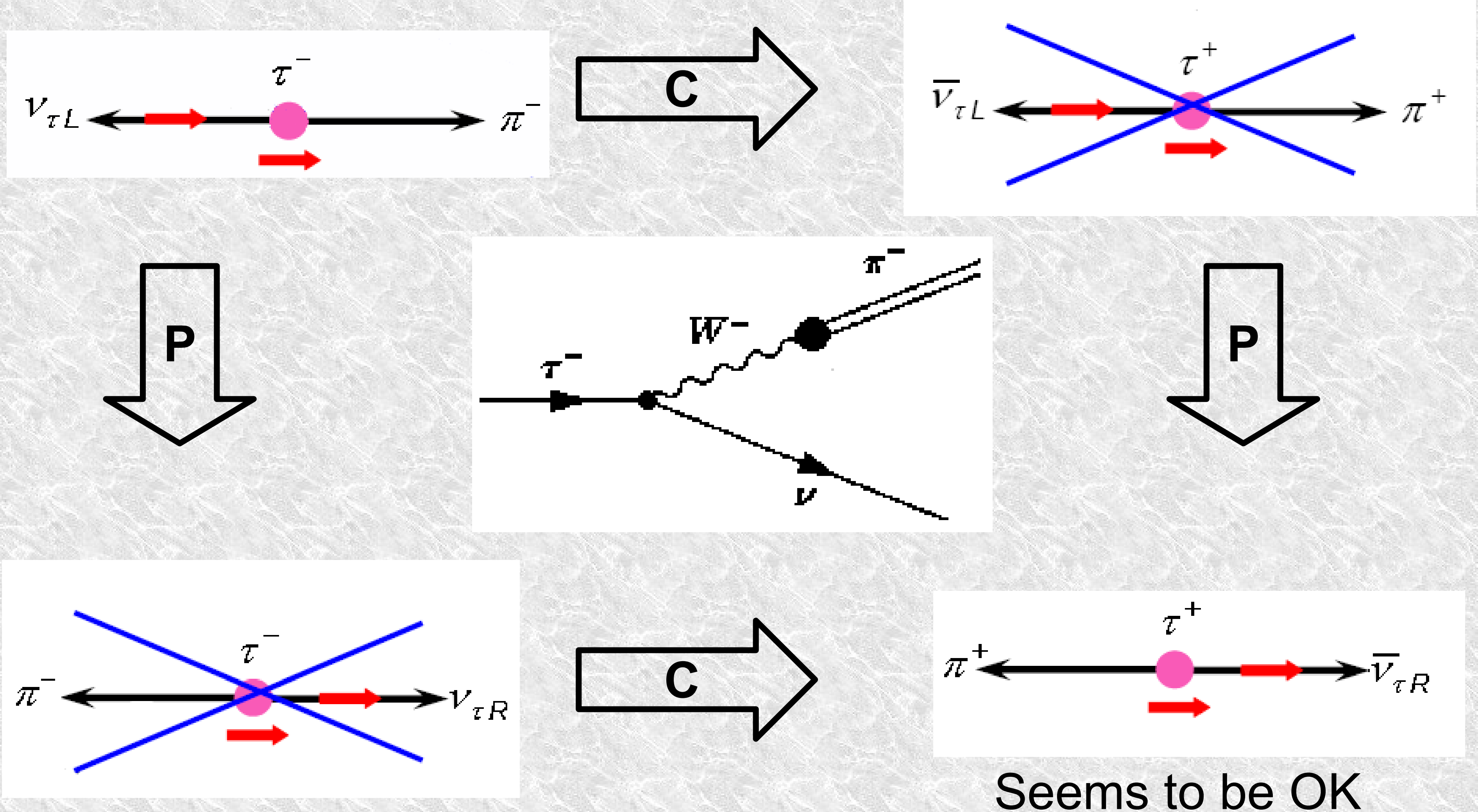
- Charge Conjugation, *C*
  - Charge conjugation turns a particle into its anti-particle
    - $e^+ \to e^-$, $K^- \to K^+$



- Time Reversal, *T*
  - Changes, for example, the direction of motion of particles
    - $t \to -t$



C- and P-violation in weak interactions



Seems to be OK

A little bit of theory

The charged current interactions for quarks are given by

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u_{Li}} \gamma^\mu (V_{\mathrm{CKM}})_{ij} d_{Lj} W_\mu^+ + \mathrm{h.c.}$$

The CKM describes the mixing of the weak eigenstates and the mass eigenstates

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

Parameter

NxN matrix	N=2	N=3
complex matrix = 2N² parameter	8	18
Unitary => N² conditions	4	9
Every quark field absorbs an phase	0	3
Can not measure global phase	1	4

=====================================

Quark mixing angles	1	3
complex phase => CP-violating	0	1

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation

Lincon Wolfenstein 1983:

λ, A, ρ, η

$s_{12} = \lambda \quad s_{23} = A\lambda^2$

$s_{13} \sin\delta_{13} = A\lambda^3\eta$

$s_{13} \cos\delta_{13} = A\lambda^3\rho$

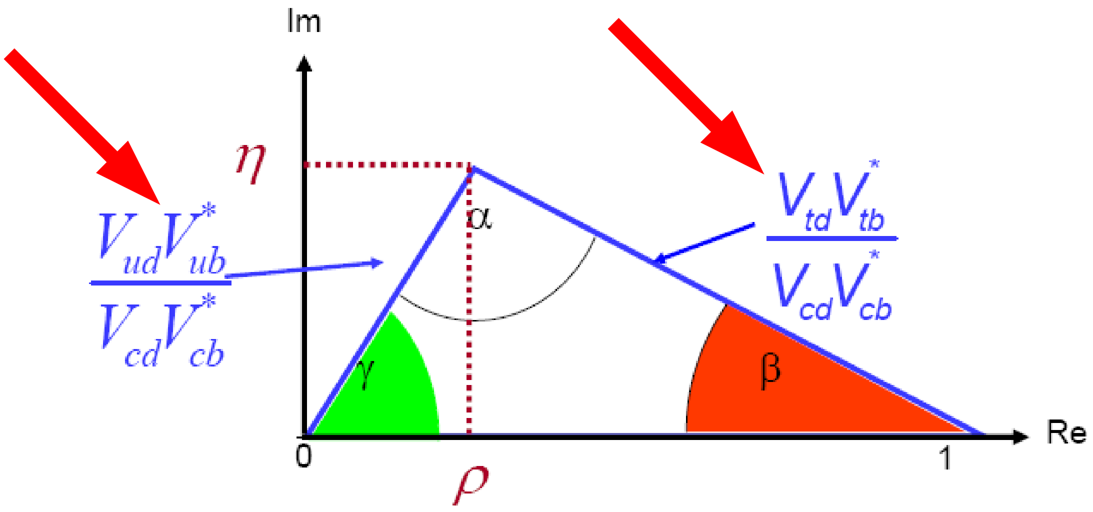
→ hierarchy expressed by orders of λ **= sin$\theta_c \approx$ 0.22**

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitarity

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \qquad \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\begin{pmatrix} 1 & 1 & \overset{\substack{b\to u \\ \downarrow}}{e^{-i\gamma}} \\ 1 & 1 & 1 \\ \underset{\substack{\uparrow \\ t\to d}}{e^{-i\beta}} & 1 & 1 \end{pmatrix}$$

Classification

- CP-violation can occur in three forms
  - CP-violation in a decay
    - Example: $B^0 \rightarrow K^+\pi^-$
  - CP-violation in oscillation
    - Mass eigenstates ≠ weak eigenstates
    - Example: neutral Kaon system
  - CP-violation in the interference of decay and oscillation
    - The same final state can be reached by particle/antiparticle + oscillation between these two
    - Example: $B_d \rightarrow J/\psi K_s$-System

CP-violation: decay (I)

Compare the decays of:

Particle decays to final state

Antiparticle to “anti” final state

$$A_f = < f|\mathcal{H}|B^0 >$$
$$\bar{A}_{\bar{f}} = < \bar{f}|\mathcal{H}|\bar{B}^0 >$$

If CP is violated:

$$|\frac{\bar{A}_{\bar{f}}}{A_f}| \neq 1$$

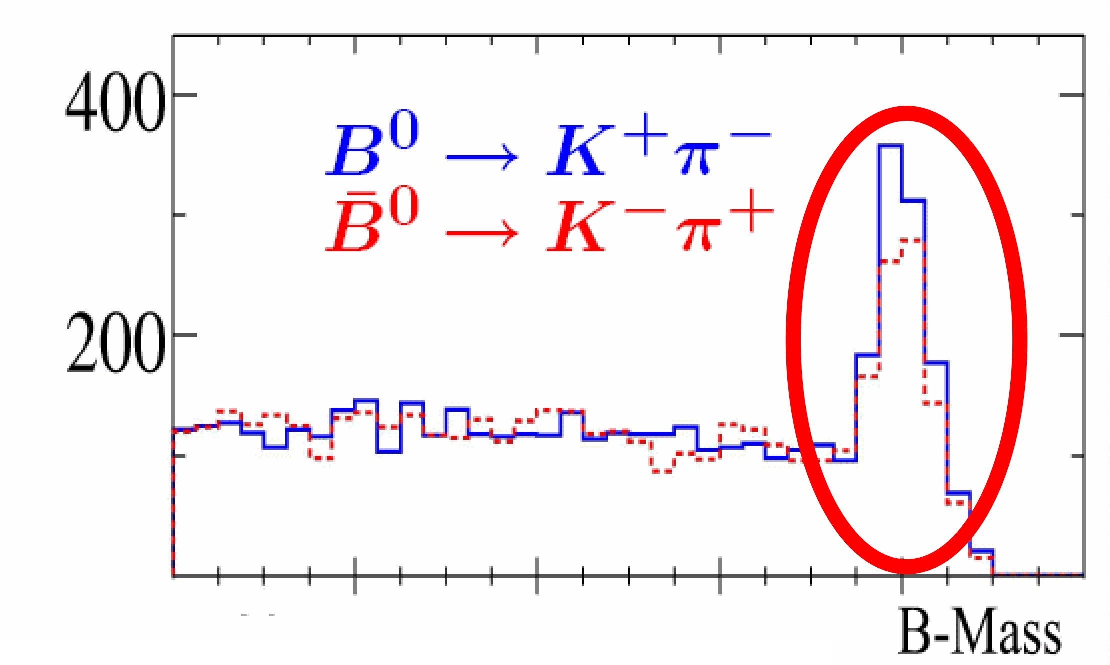
For charged mesons, this is the only possible source of CP-violation, as there is no mixing.

CP-violation: decay (II)

$B^0 \rightarrow K^+\pi^-$

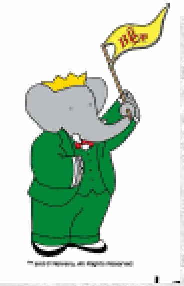
CP

$\bar{B}^0 \rightarrow K^-\pi^+$



$$\mathcal{A}_{f\pm} \equiv \frac{\Gamma(M^- \rightarrow f^-) - \Gamma(M^+ \rightarrow f^+)}{\Gamma(M^- \rightarrow f^-) + \Gamma(M^+ \rightarrow f^+)} = \frac{|\overline{A}_{f-}/A_{f+}|^2 - 1}{|\overline{A}_{f-}/A_{f+}|^2 + 1}$$

$$\mathcal{A}_{K^\mp\pi^\pm} = -0.115 \pm 0.018.$$



CP-violation: mixing (I)

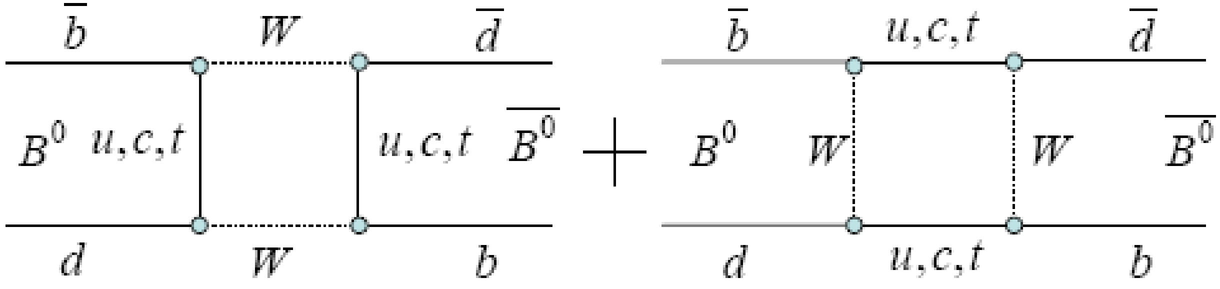
Neutral mesons:

$$|P^0\rangle: \quad K^0 = |d\bar{s}\rangle \quad D^0 = |\bar{u}c\rangle \quad B_d^0 = |d\bar{b}\rangle \quad B_s^0 = |s\bar{b}\rangle$$

$$|\overline{P^0}\rangle: \quad \overline{K^0} = |\bar{d}s\rangle \quad \overline{D^0} = |\bar{u}c\rangle \quad \overline{B_d^0} = |d\bar{b}\rangle \quad \overline{B_s^0} = |s\bar{b}\rangle$$

Standard Model predicts oscillations of neutral Mesons:

$$B_d^0 \Leftrightarrow \overline{B_d^0}$$



Transition can be described by matrix element: $\langle \overline{B_d^0} | H_W | B_d^0 \rangle$

CP-violation: mixing (II)

mass eigenstates ≠
weak eigenstates:

$$|P_L\rangle = p|P^0\rangle + q|\overline{P^0}\rangle \quad \text{with } m_L, \Gamma_L$$

$$|P_H\rangle = p|P^0\rangle - q|\overline{P^0}\rangle \quad \text{with } m_H, \Gamma_H$$

$|p|^2 + |q|^2 = 1$ complex coefficients

Now, let time evolve:

Rate particle→ antiparticle

$$P(B^0 \to \overline{B^0}) = \frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

and vis versa

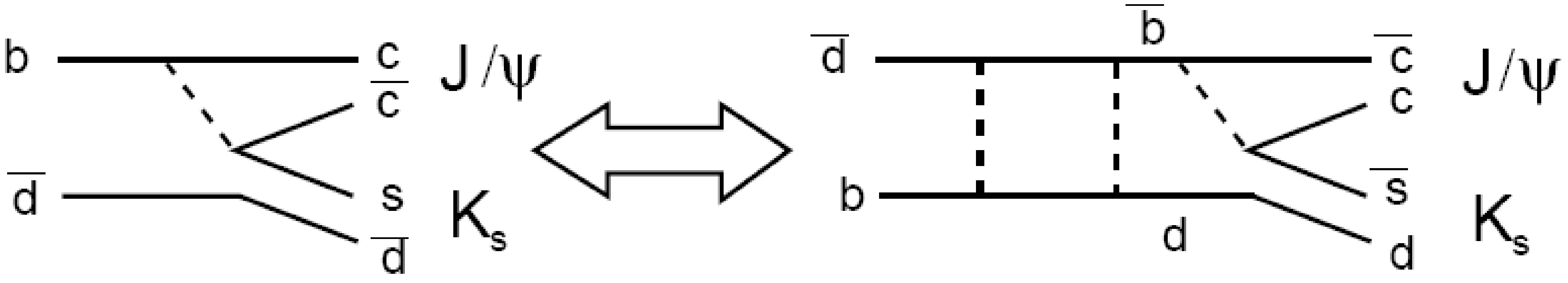
$$P(\overline{B^0} \to B^0) = \frac{1}{4}\left|\frac{p}{q}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

If CP is violated:

$$P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0) \Rightarrow \left|\frac{q}{p}\right| \neq 1$$

CP-violation: interference of mixing and decay (I)

A combination of oscillation and decay



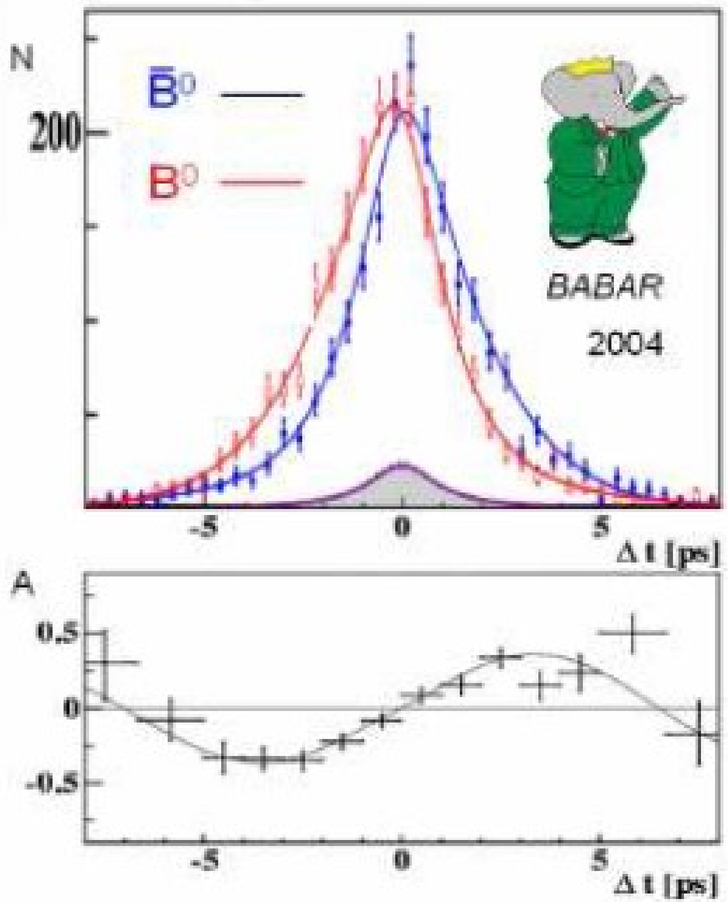
$$\mathcal{A}(t) = \frac{\Gamma(\bar{B} \rightarrow J/\psi K_s)(t) - \Gamma(B \rightarrow J/\psi K_s)(t)}{\Gamma(\bar{B} \rightarrow J/\psi K_s)(t) + \Gamma(B \rightarrow J/\psi K_s)(t)}$$

$$= \sin 2(\phi_{mix} + \phi_{J/\psi K_s}) * \sin(\Delta m_d t)$$

$$\phi_{mix} = arg(V_{td} V_{tb}^*)$$

$$\phi_{J/\Psi K_s} = arg((V_{cb} V_{cd}^*)(V_{us} V_{ud}^*))$$

CP-violation: interference of mixing and decay (II)



$$\mathcal{A}(t) = \sin(2\beta)\sin(\Delta m_d t)$$

Babar:

$$\sin(2\beta) = 0.722 \pm 0.040 \pm 0.023$$

Belle:

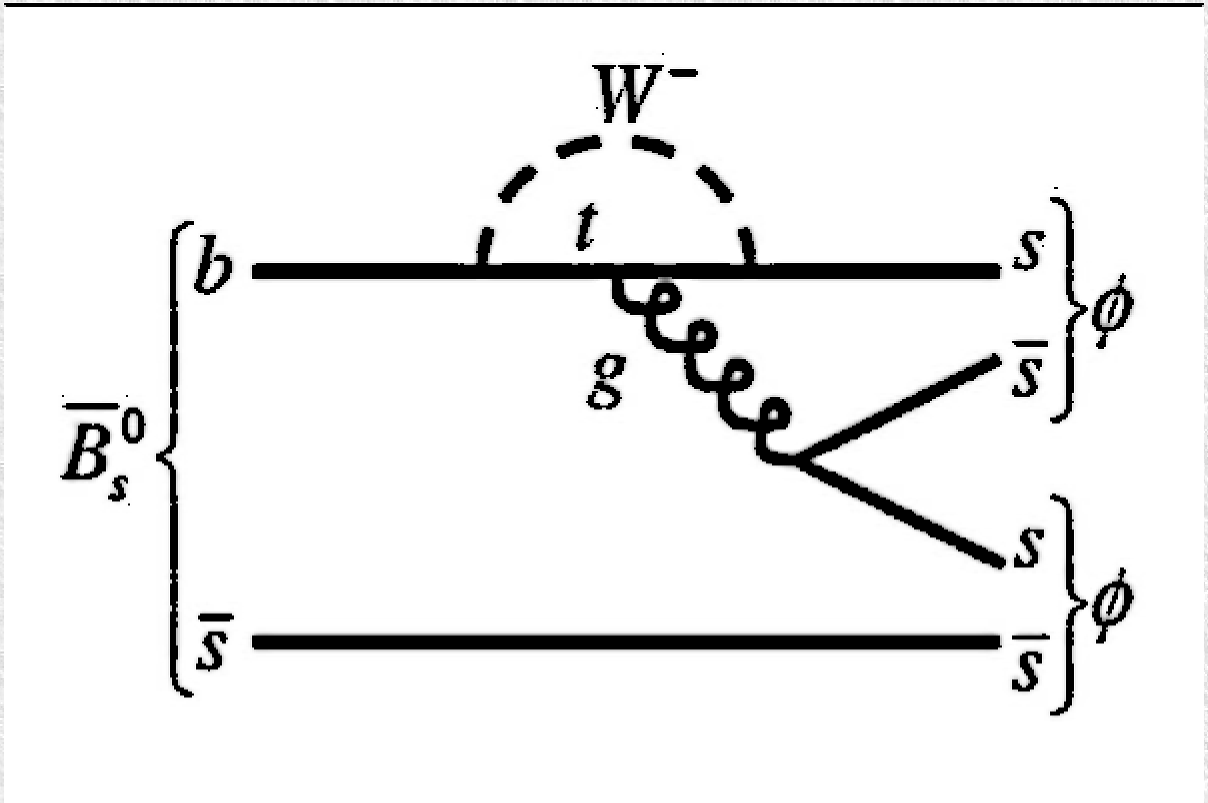
$$\sin(2\beta) = 0.652 \pm 0.039 \pm 0.020$$

History

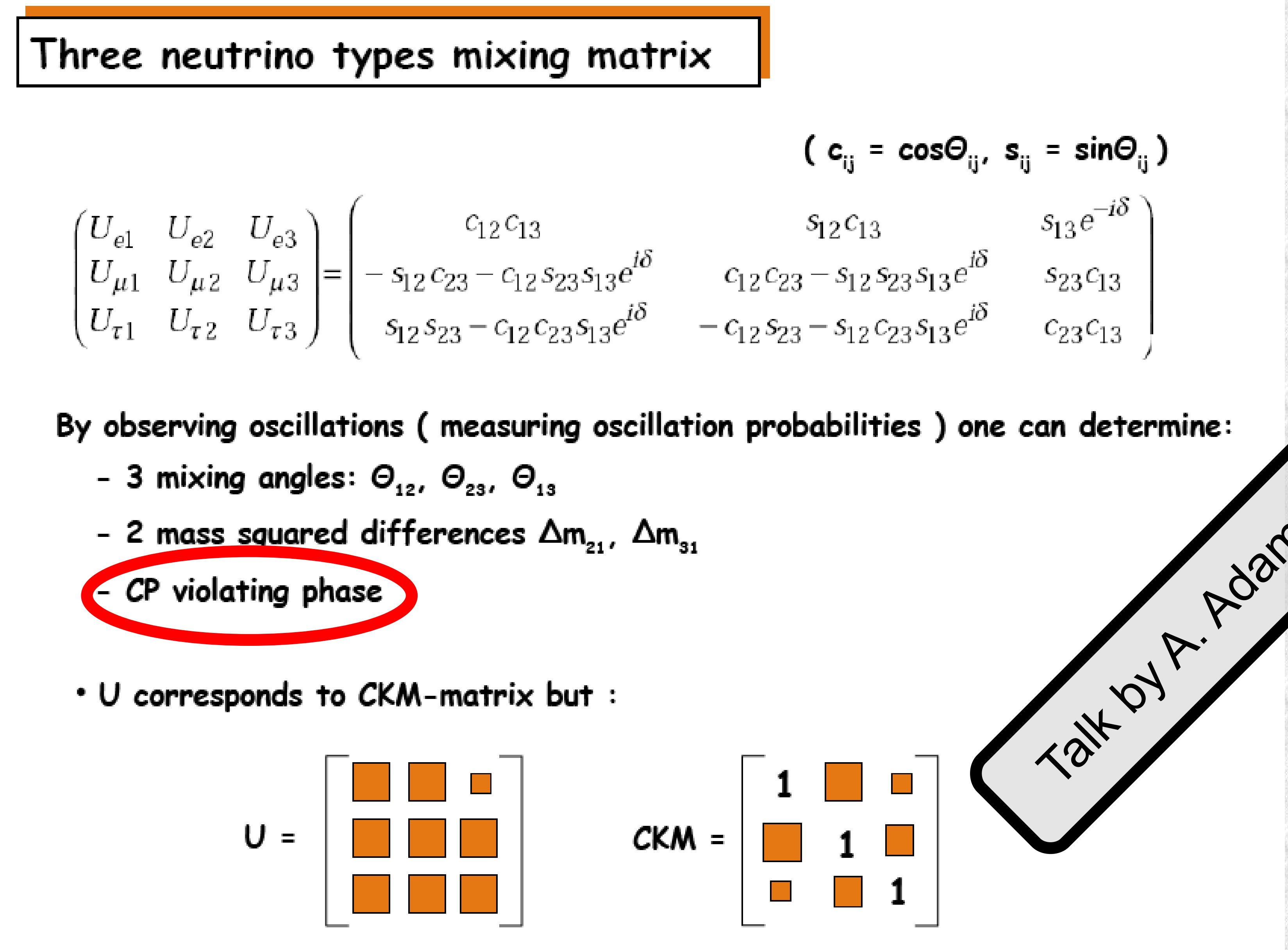
- 1957: weak interaction violates C & P
- 1964: CP-violation in $K^0\overline{K^0}$ mixing
- 1967: Sakharov's conditions
- 1973: CP-violation formulated within the SM
- 1987: ARGUS finds $B^0\overline{B^0}$ mixing
- 1999: direct CP-violation in K decay confirmed
- 2000: Measurement of CP-violation in the B-system
- 2004: direct CP-violation in the B-system

So, where is the antimatter?

The SM does not generate enough CP-violation to explain the observed matter-antimatter asymmetry, but e.g. Supersymmetry introduces a lot of CP-violating phases.



Neutrinos



Three neutrino types mixing matrix

($c_{ij} = \cos\Theta_{ij}$, $s_{ij} = \sin\Theta_{ij}$)

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

By observing oscillations (measuring oscillation probabilities) one can determine:

- 3 mixing angles: Θ_{12}, Θ_{23}, Θ_{13}
- 2 mass squared differences Δm_{21}, Δm_{31}
- CP violating phase

- U corresponds to CKM-matrix but :

$$U = \begin{bmatrix} \blacksquare & \blacksquare & \scriptstyle\blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{bmatrix} \qquad CKM = \begin{bmatrix} 1 & \blacksquare & \scriptstyle\blacksquare \\ \blacksquare & 1 & \blacksquare \\ \scriptstyle\blacksquare & \blacksquare & 1 \end{bmatrix}$$

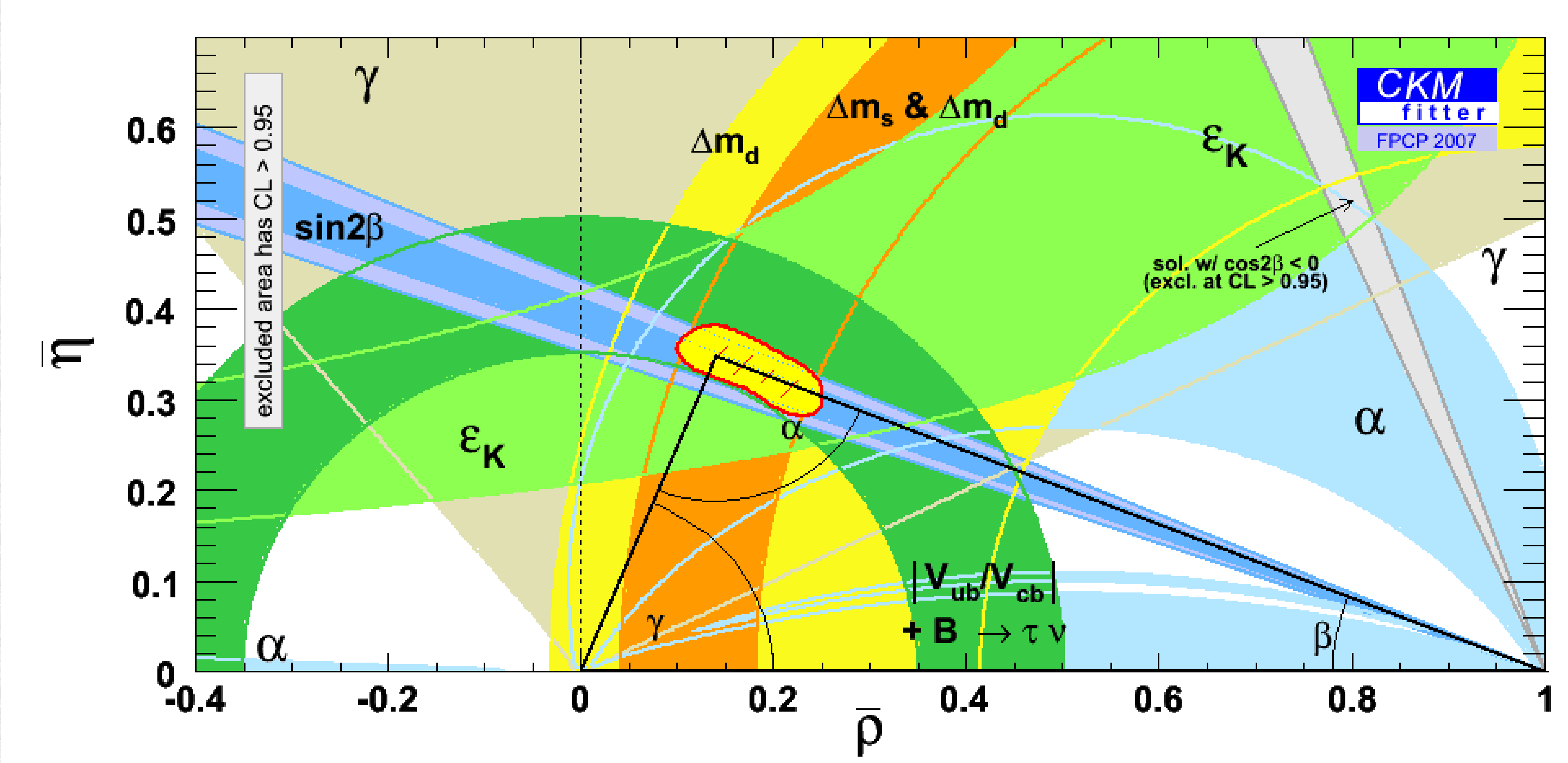
Talk by A. Adametz

Summary

- CP-violation is of fundamental importance for our understanding of the universe
- CP-violation in rare decays is a complementary approach for the search of new physics
- All three types of CP-violation have been observed

Next stop:

The triangle so far



CKM values

$\|V_{ud}\|$	=	0.97400	[+0.00017	-0.00018]
$\|V_{us}\|$	=	0.22653	[+0.00075	-0.00077]
$\|V_{ub}\|$	=	0.00357	[+0.00017	-0.00017]
$\|V_{cd}\|$	=	0.22638	[+0.00076	-0.00076]
$\|V_{cs}\|$	=	0.97316	[+0.00018	-0.00018]
$\|V_{cb}\|$	=	0.0405	[+0.0032	-0.0029]
$\|V_{td}\|$	=	0.00868	[+0.00025	-0.00033]
$\|V_{ts}\|$	=	0.0407	[+0.0009	-0.0008]
$\|V_{tb}\|$	=	0.999135	[+0.000036	-0.000037]