Discovery of CP violation in Leptons: Challenges and Possibilities

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Plan

- Introduction
- C, P and CP
- Matter Antimatter Asymmetry
- CP violation in the Quark sector
- CP violation of leptons
- Current status and prospects

Aim of Particle Physics

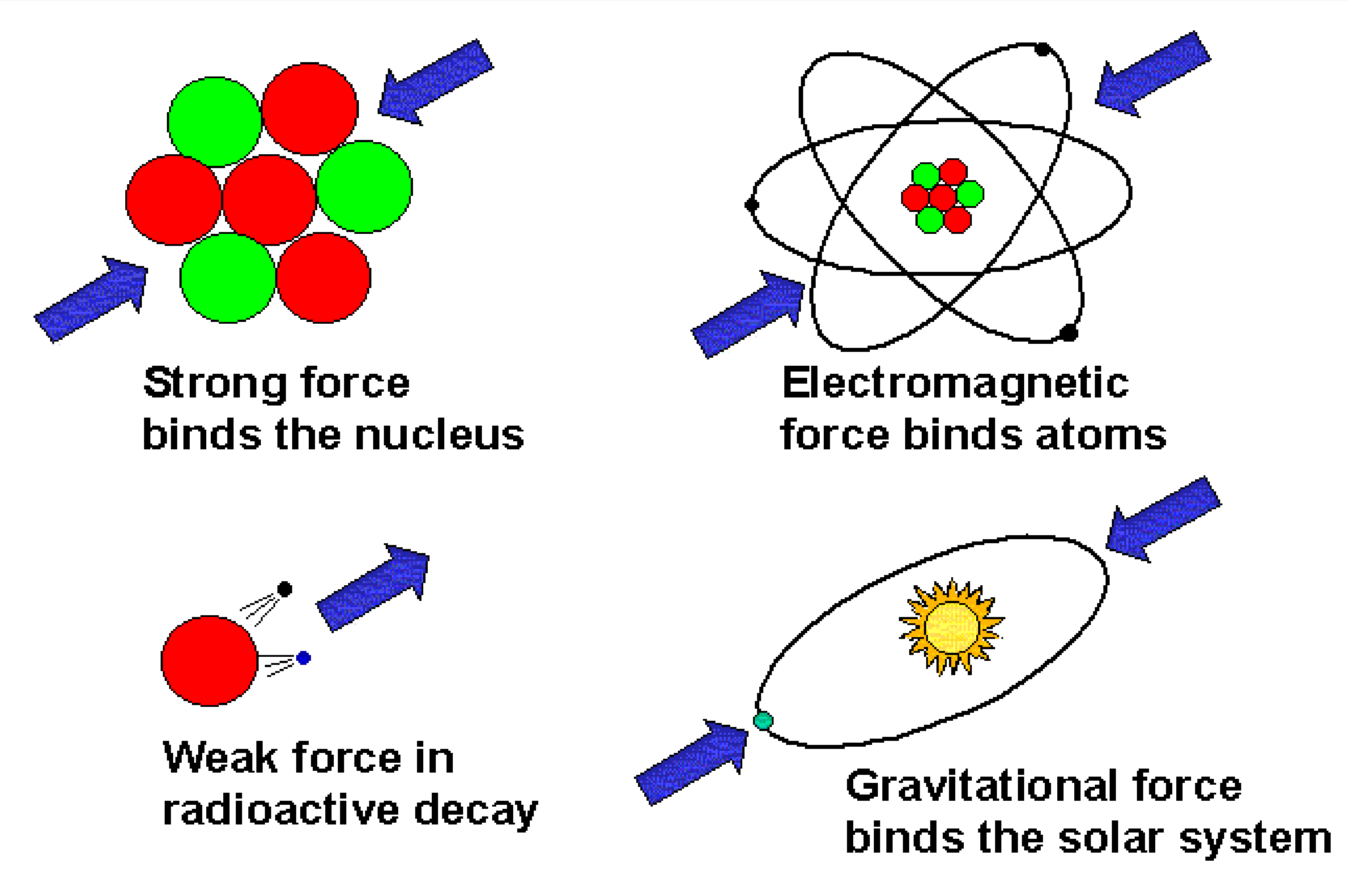
- What are the Elementary Constituents of Matter?

What are the forces that control their behaviour at the most basic level? (guided by symmetry principles)

Symmetries

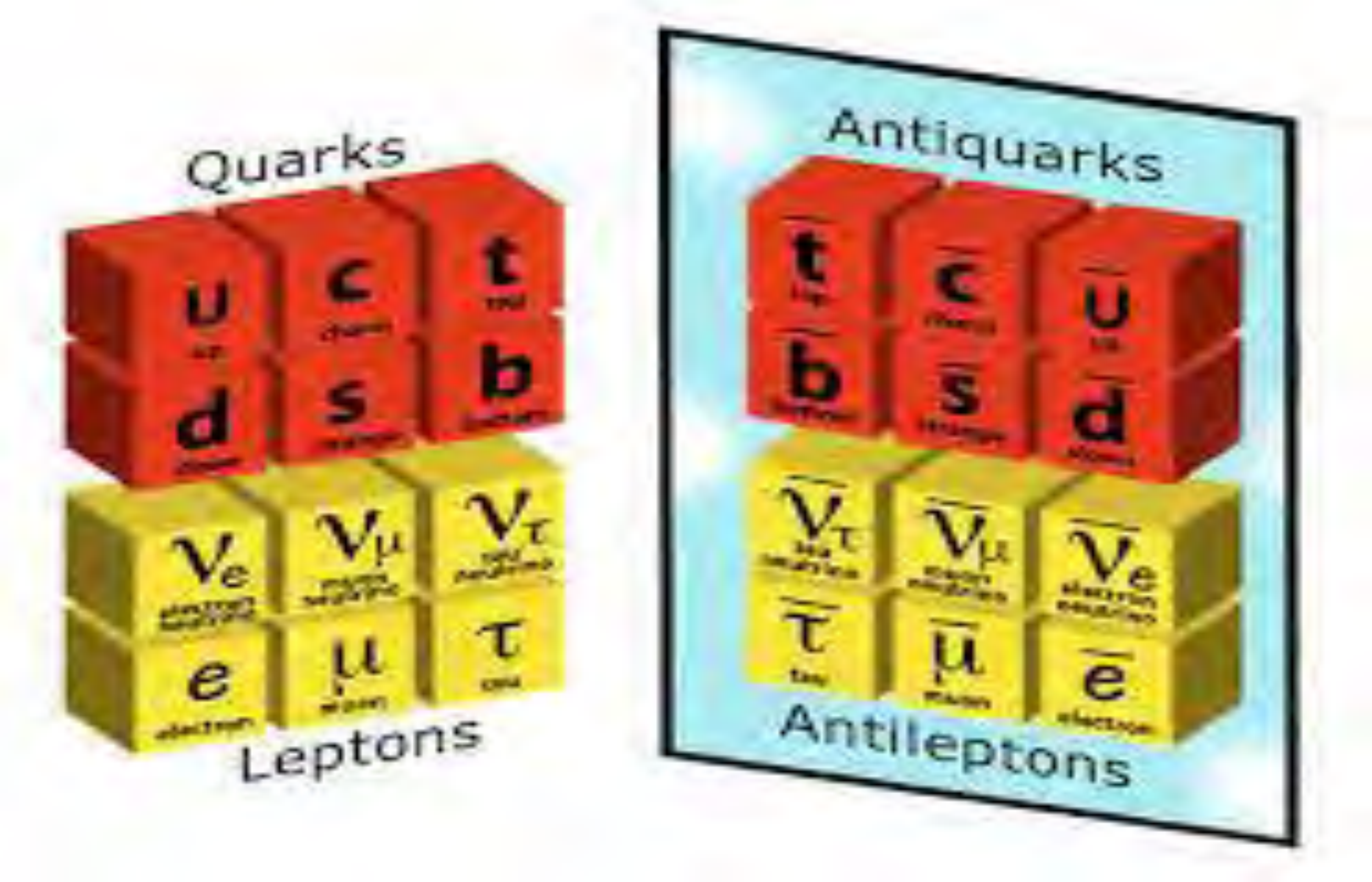
- Symmetries play an important role in physics
- Interactions of fundamental constituents of matter are governed by symmetry principles (internal symmetries)
- What are these symmetries ? Are these exact ?
- Symmetries implies conservation laws
- In nature we see many symmetries all around us

The four fundamental forces



The Standard Model of Particle Physics

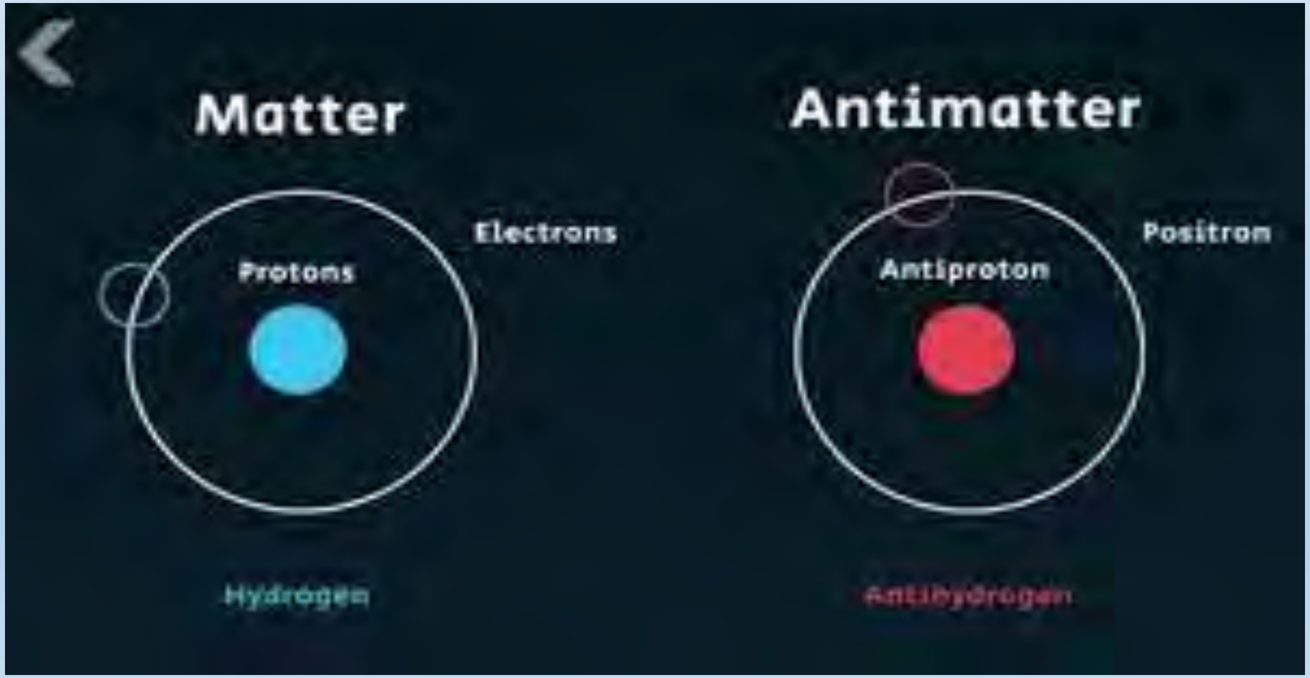
- Governed by the symmetry principles of strong, weak and electromagnetic interactions
- Contains the fundamental particles, the force careers and the Higgs

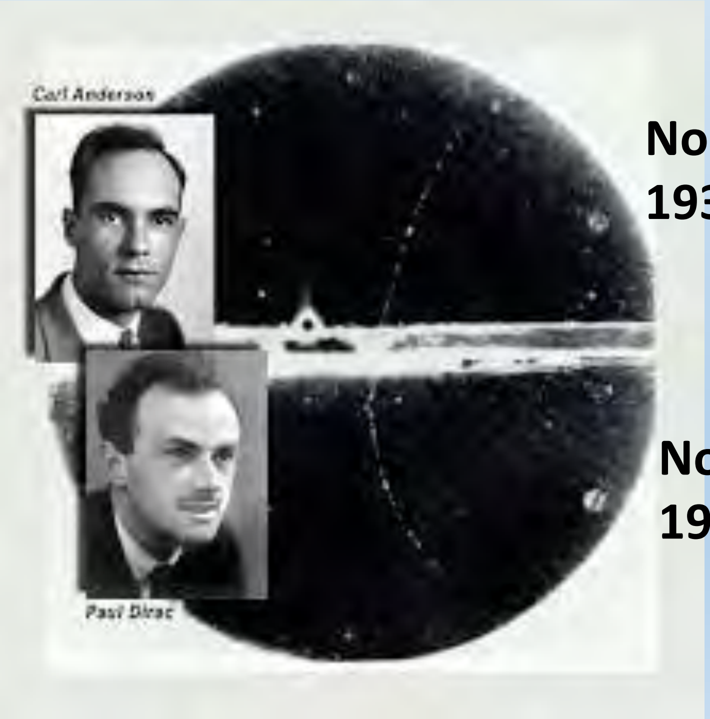


- All visible matter in the Universe made up of the first generation of particles u,d,e

Antiparticles

- P.A.M. Dirac in 1928 while studying relativistic electrons predicted **existence of antiparticles**
- In 1932 Anderson while studying cosmic rays in cloud chamber found a track left by "something positively charged and same mass as electrons". He termed them as **positrons – the antiparticle of electron**





Nobel Prize in 1936

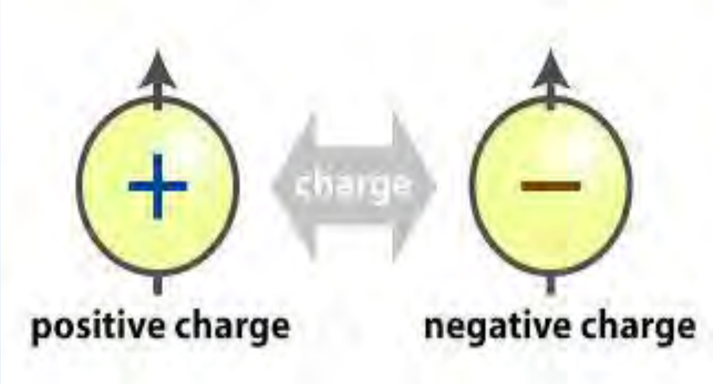
Nobel Prize in 1933

C , P and CP Symmetry

C $\longrightarrow$ **Charge Conjugation**

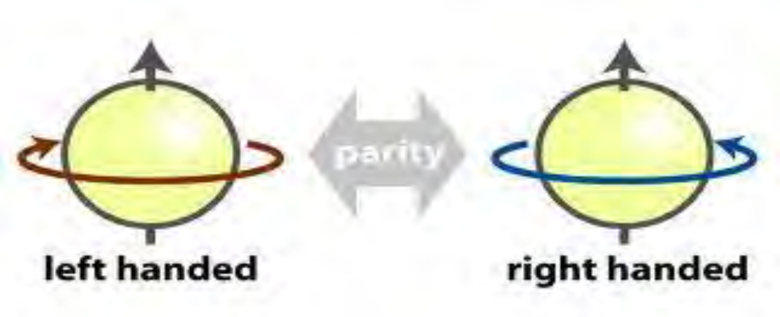
inverts all internal quantum numbers

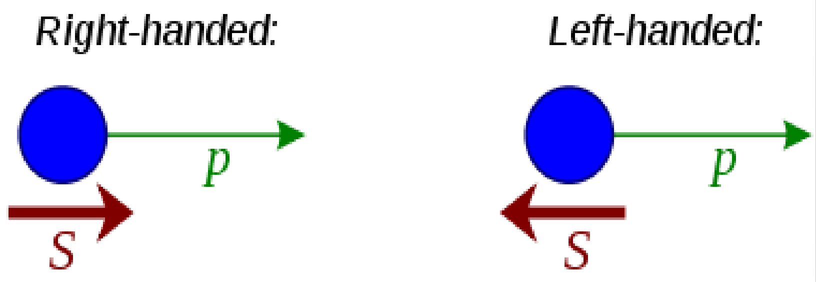
Takes particles to antiparticles



P $\longrightarrow$ **Parity**

(Inverts all spatial co-ordinates)



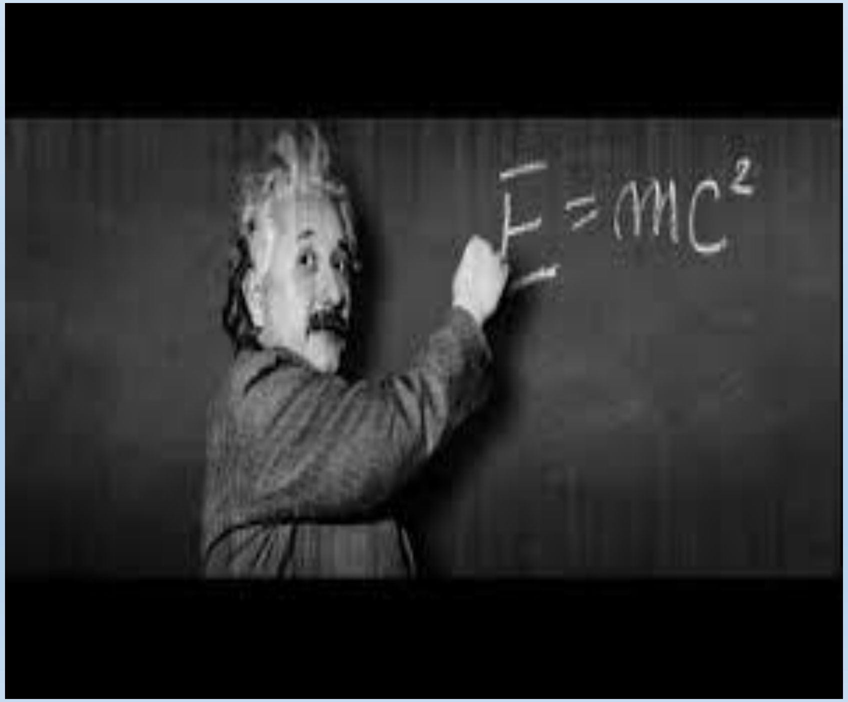


CP $\longrightarrow$ **Charge Conjugation X Parity**

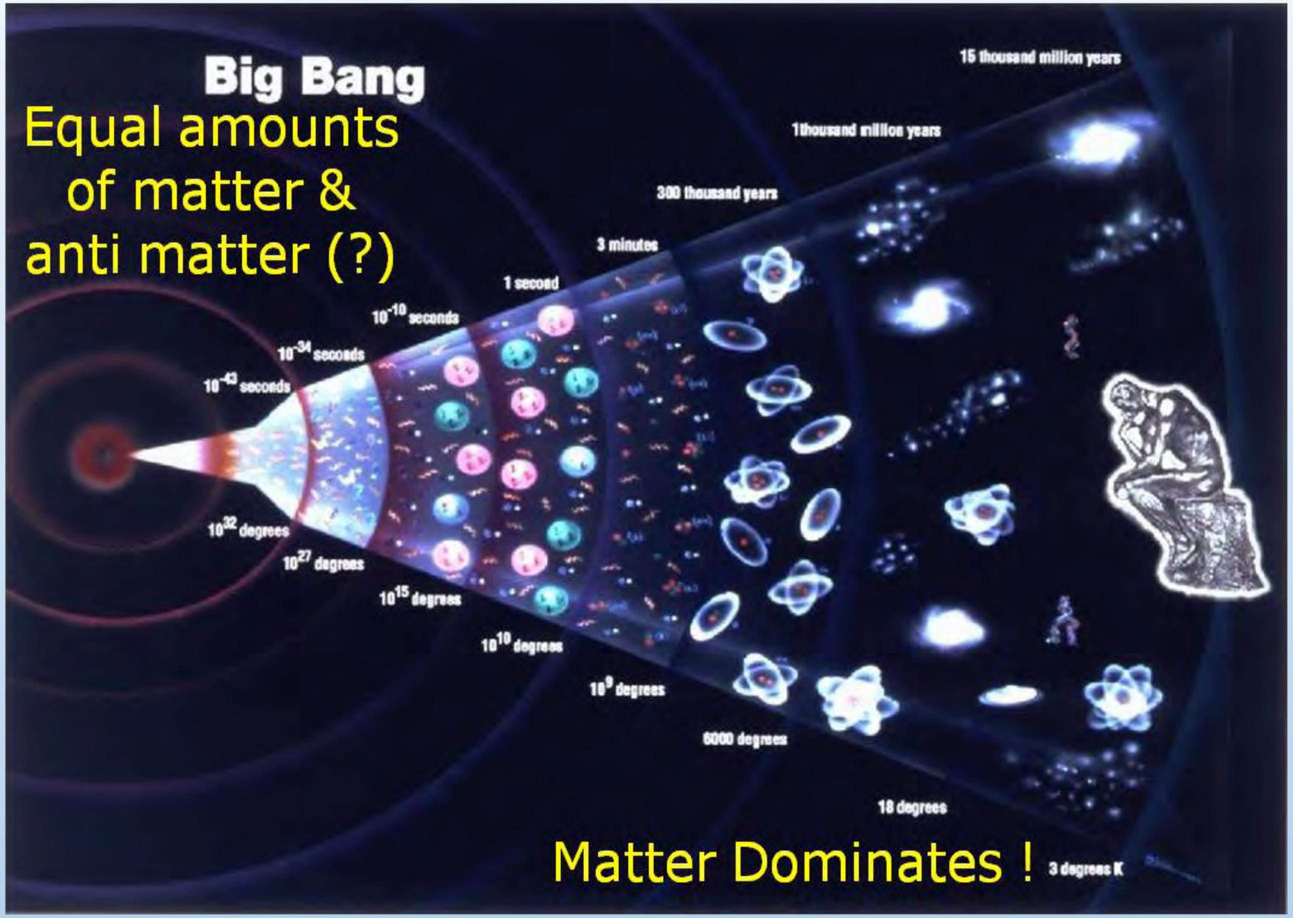
- **a symmetry of the elementary particles relating matter and antimatter**

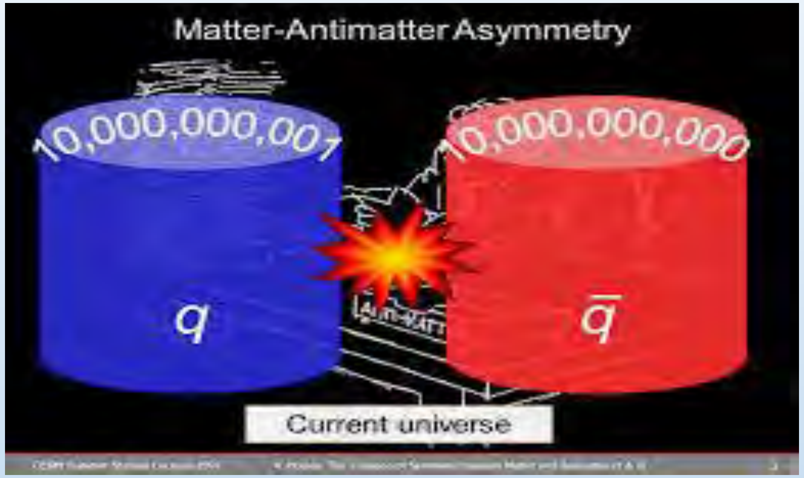
Matter and Antimatter

- Particles and antiparticles have same mass but opposite charge and other quantum numbers
- Matter and antimatter are created in pairs
- They annihilate each other into energy



Where is the antimatter ?



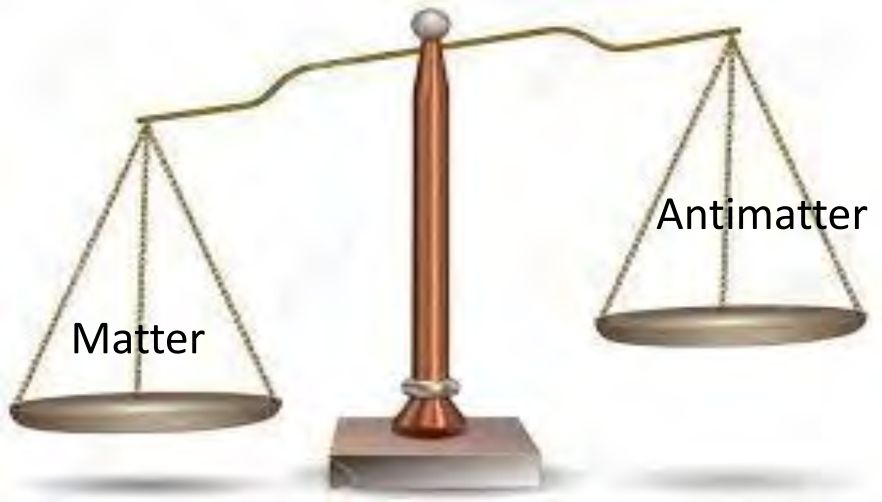


- ➢ There is an asymmetry in the primordial matter and antimatter

- ➢ Antimatter can be produced in accelerators, by cosmic rays

Matter Antimatter asymmetry

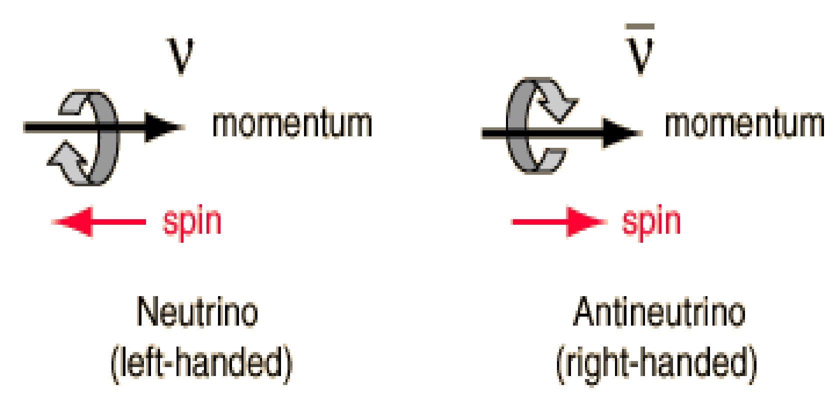
- **Present universe is matter dominated**
- **Is CP violation responsible for matter antimatter asymmetry ?**



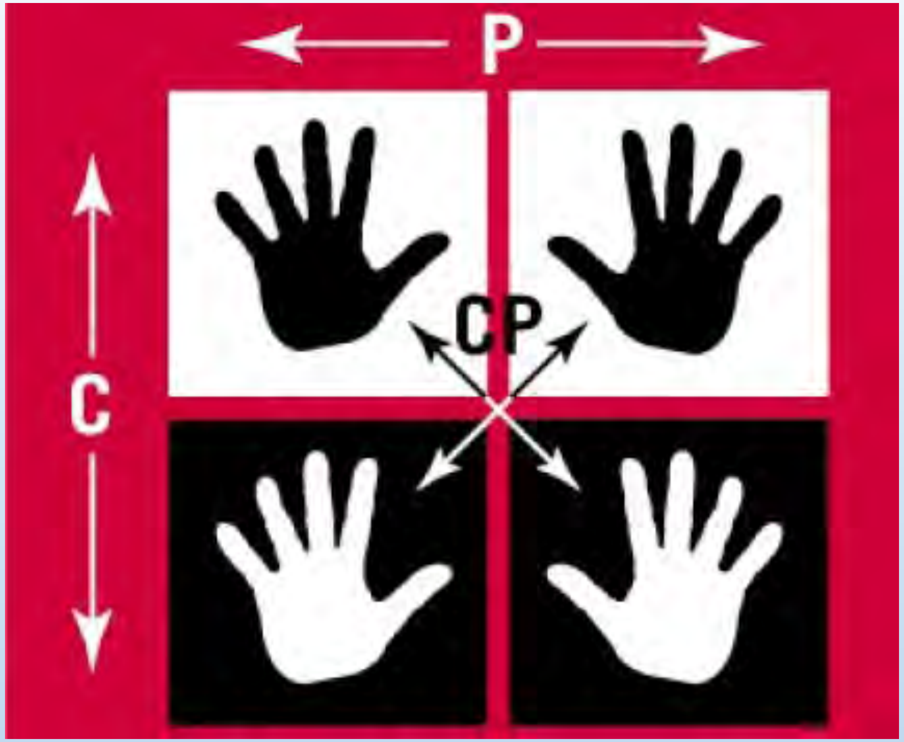
Parity Violation

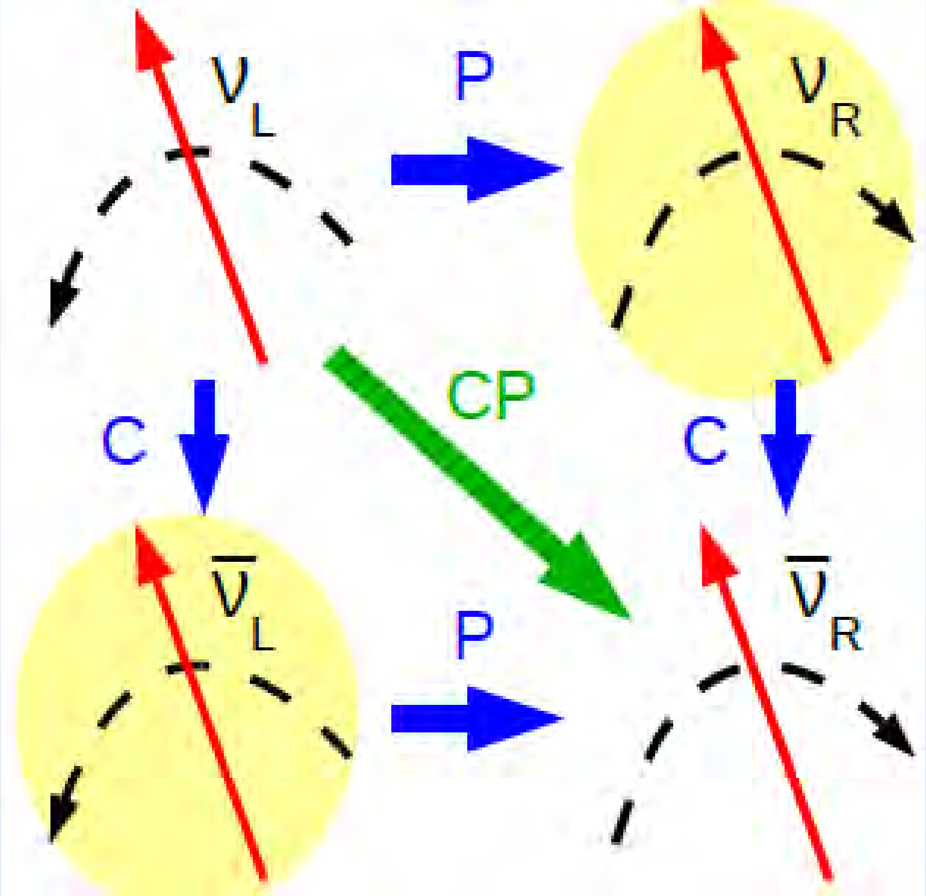
In 1956 Lee and Yang pointed out that some particles taking part in weak interaction may violate the parity symmetry (Nobel Prize in 1957)

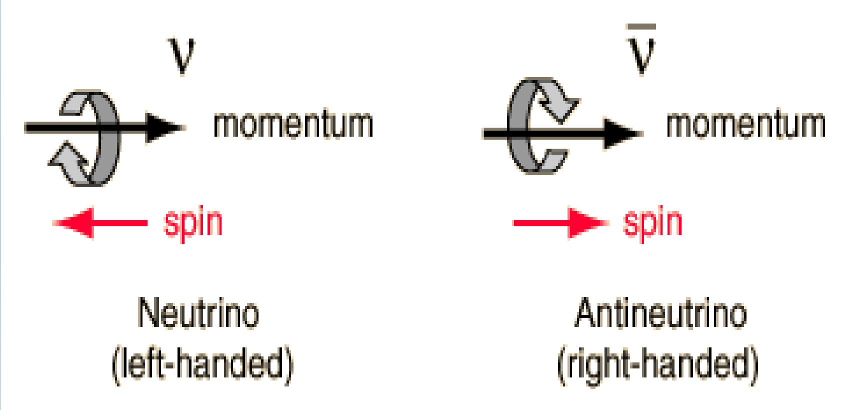
Experimental verification by C.S. Wu using β-decays of $^{60}\mathrm{Co}$



P,C violation but CP conservation

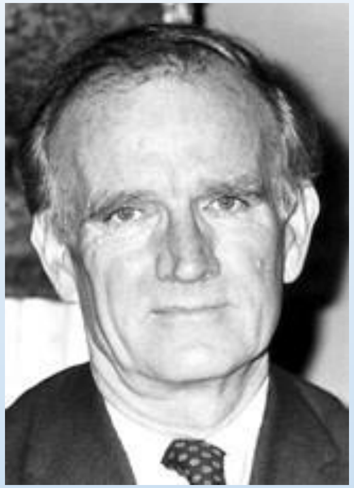




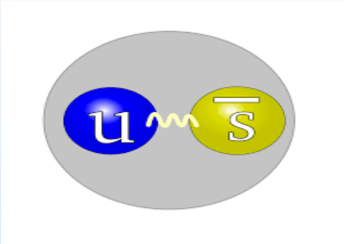


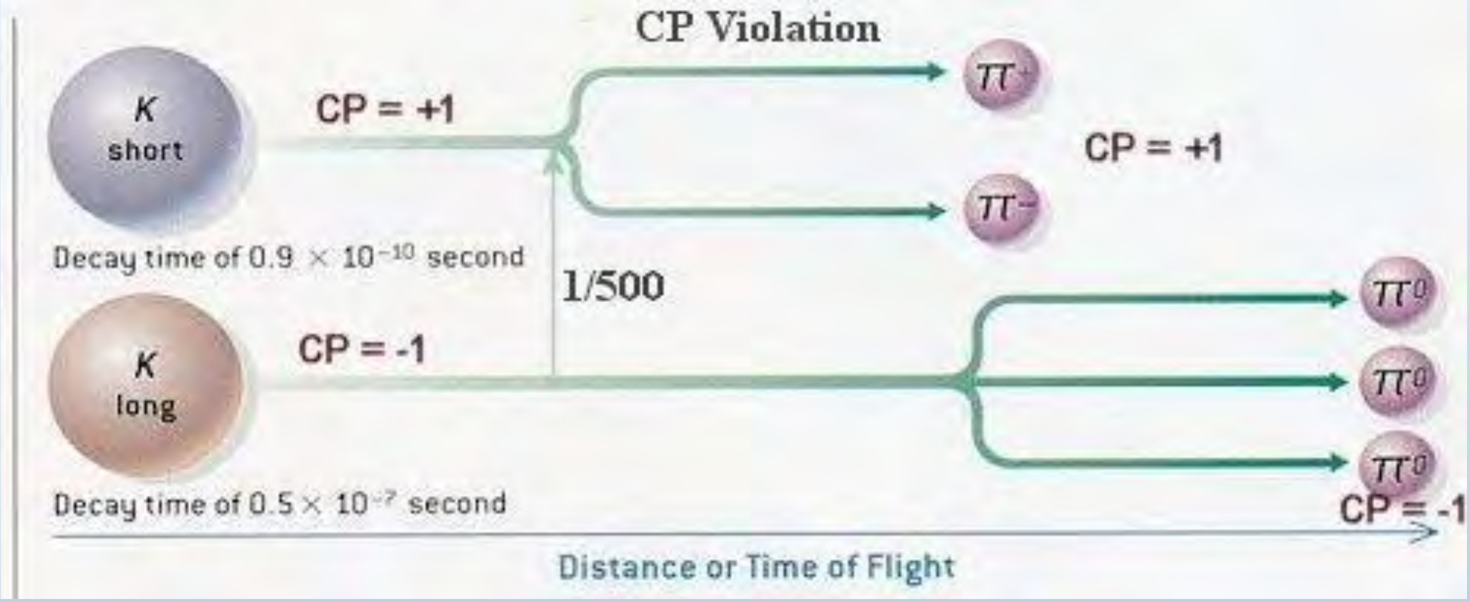
- No right handed neutrinos → P violation
- No left handed antineutrino → C violation
- CP is conserved (Landau)

CP violation



However CP violation was observed in 1964 by Cronin and Fitch in decays of K-mesons





Nobel Prize in 1980

- ➢ K-mesons made up of quarks and antiquarks
- ➢ Thus CP violation in quark sector was established

CP violation in Standard Model : The CKM way

Weak Interaction couples to the rotated quark states (Cabbibo)

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

3X3 complex unitary matrix

-Described by 3 angles and 1 phase

--CP violation

- requires at least 3 quarks

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

Not sufficient to generate the observed Baryon asymmetry

Is there CP violation in the lepton sector ?

The Nobel prize in Physics in 2008
To Kobayashi and Maskawa

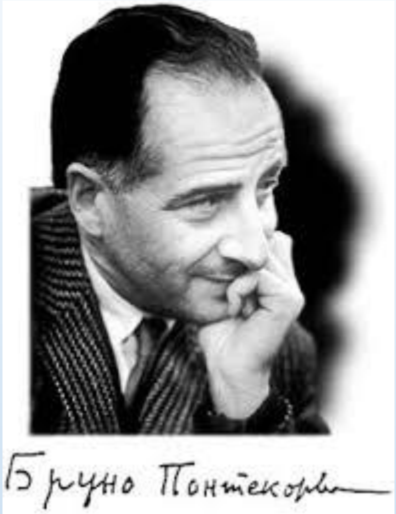
The PMNS matrix for Neutrinos

- Massive neutrinos can be in two types of states
- These states are related as

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

The states in Which neutrinos Are produced ⟵

⟶ The states in which Neutrinos travel

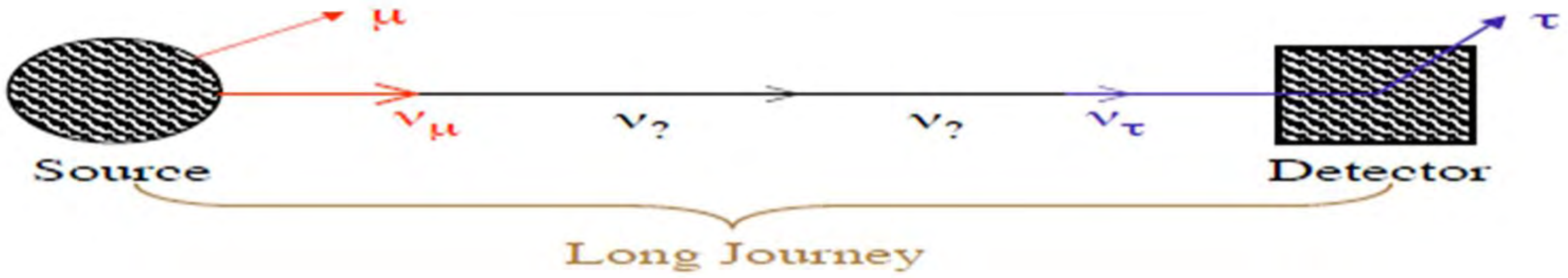


This U again has 3 mixing angles and 1 phase

This mixing gives rise to neutrino oscillations which have been observed

Neutrino Oscillation

- It has been found that neutrinos can change flavour after passing through a distance



- This is possible if neutrinos have Mass and Mixing
- The conversion probability can be oscillatory $\longrightarrow$ Neutrino Oscillation $\rightarrow$ quantum mechanical interference phenomena

Neutrinos change themselves

Neutrino Oscillation : Three Flavours

If neutrinos have mass then $\nu_\alpha = \Sigma_i U_{\alpha i} \nu_i$

Flavour states

Mass states

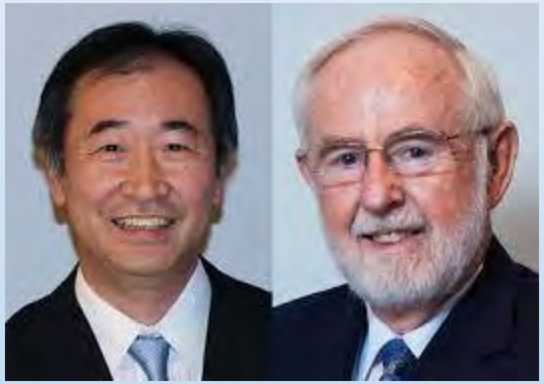
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin^2 \Delta_{ij} - 2 \sum_{i>j} \mathrm{Im}[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin 2\Delta_{ij}$$

$\Delta_{ij} = \Delta m^2_{ij} L / 4E$ $\quad$ $\Delta m^2_{ij} = m^2_j - m^2_i$ $\quad$ $\bar{\nu} : U \to U^*$

- Oscillations measure neutrino mass squared differences and mixing angles
- CP violation is through the complex phase in U
- Opposite sign for neutrinos and antineutrinos

Current Status

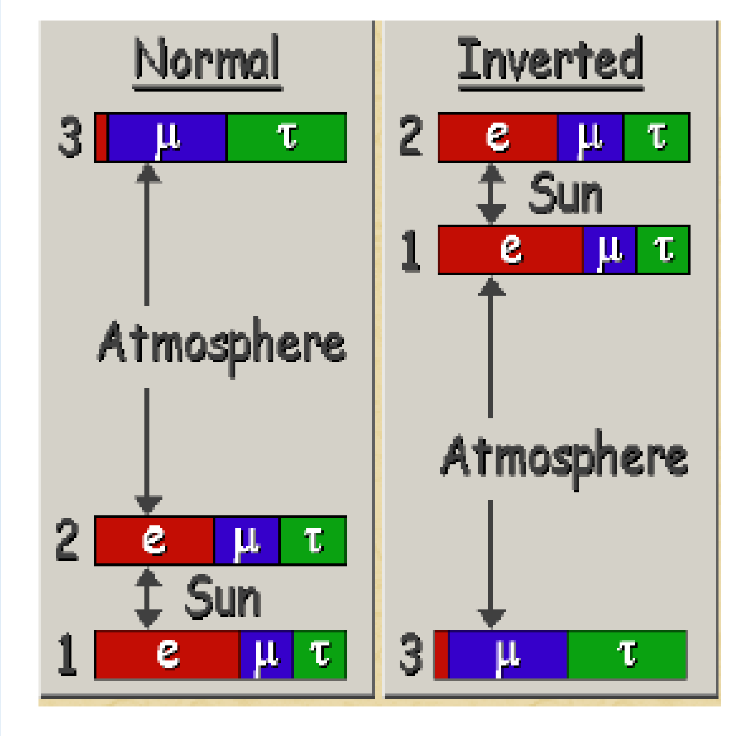
➢ The oscillation experiments involving solar, atmospheric, reactor and accelerator experiments have determined most of the parameters with considerable precision



Nobel Prize in 2015 to A. McDonald and T.Kajita

➢ The main unknown parameters are :

❖ The ordering of the mass states or mass hierarchy
❖ The CP phase



CP violation in lepton sector

- **Discovery of Leptonic CP violation requires**

$$A_{CP} = \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \neq 0$$

- This difference is at the level of few percent
- Measuring such small effects need large data samples, big detectors, very good knowledge of the systematics
- **Problem of degeneracies ⟹ different parameters giving same probability and hence equally good fit to the data**

- The most challenging neutrino oscillation parameter measurement so far

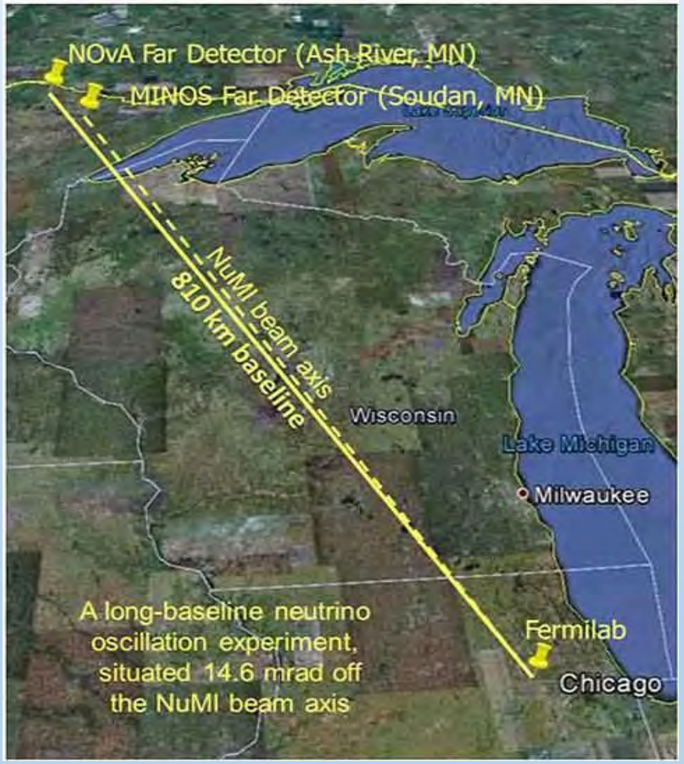
Experiments for δ_{CP} (running)

- Accelerator based experiments which can generate beams of muon and anti-muon neutrinos

T2K in Japan

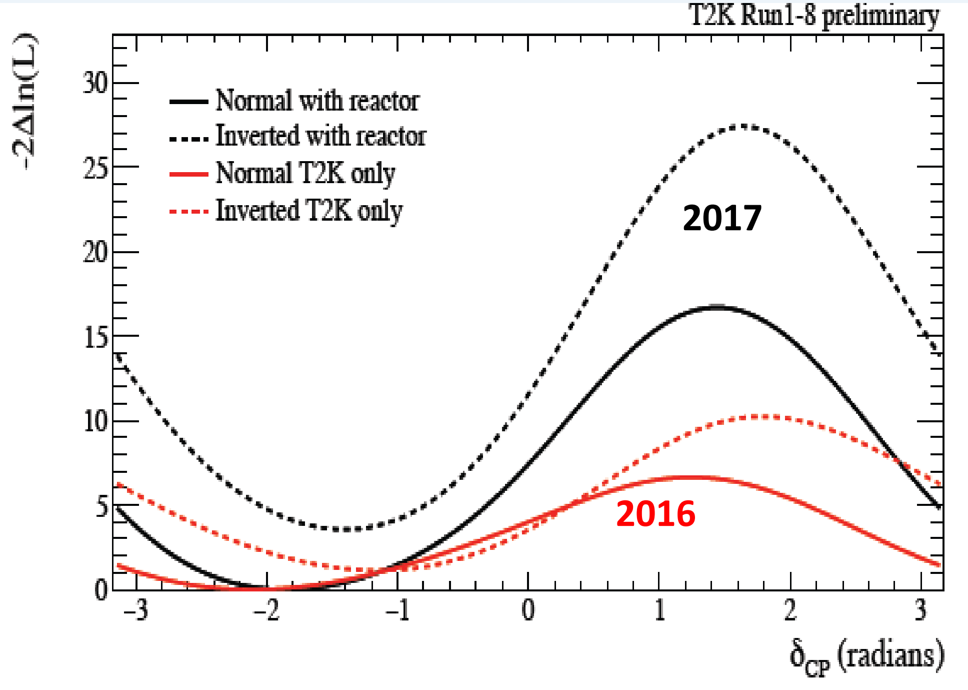
Baseline of 295 km from Tokai to Kamioka

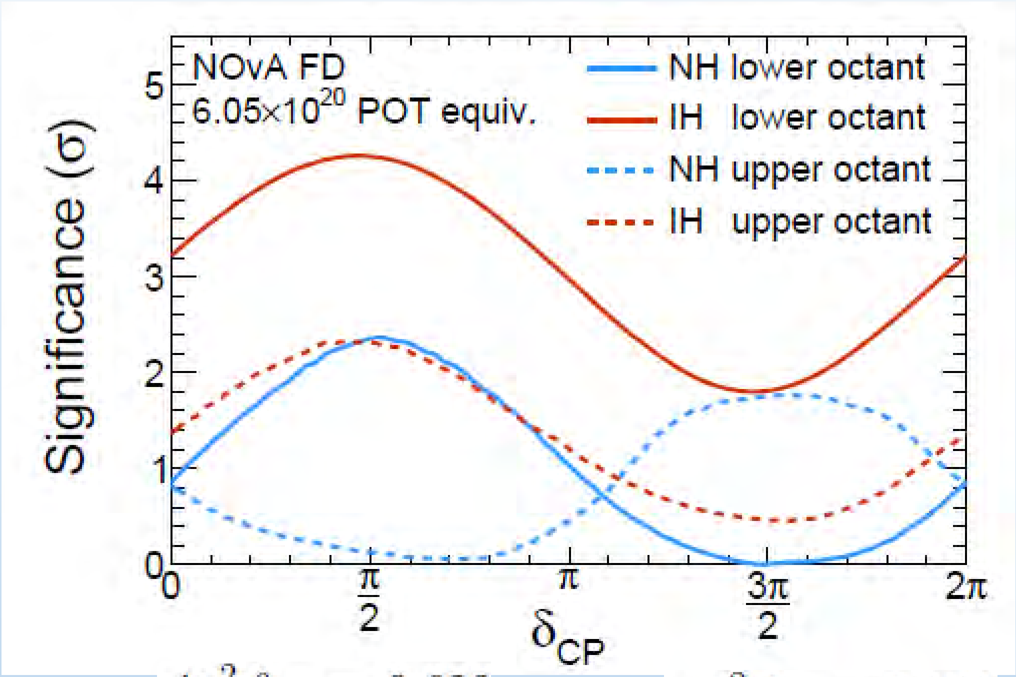
NOVA in USA



Baseline of 810 km from Fermilab to Minnesota

δ_{CP} from T2K and NOVA (current status)





$\sin^2\theta_{23} = 0.623$
$\delta_{CP} = 0.74\pi$

$\sin^2\theta_{23} = 0.404,$
$\delta_{CP} = 1.48\pi$

- **Best-fit value close to** 270°

- **Two degenerate solutions**

M. Hartz, KEK Colloquium, August 2017

Phys.Rev.Lett. 118 (2017) no.23, 231801

Parameter Degeneracies

Problem:

Degeneracy: Two different sets of neutrino oscillation parameters giving rise to same oscillation probability i.e.,

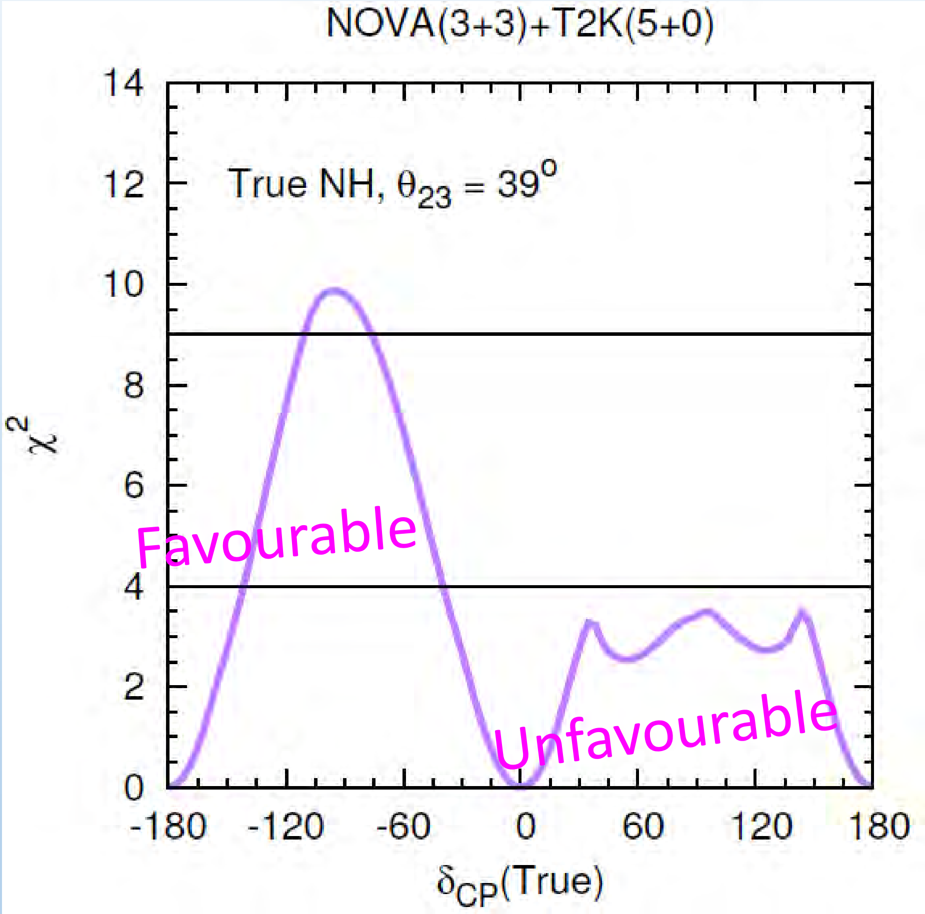
$$P_{\alpha\beta}(x) = P_{\alpha\beta}(y)$$

x, y: different sets of oscillation parameters i.e.,
$x = x(\theta_{ij}, \delta_{CP}, \Delta_{ij})$, $y = y(\theta'_{ij}, \delta'_{CP}, \Delta'_{ij})$

Conclusion:

Measurement of x will be confused with measurement of y

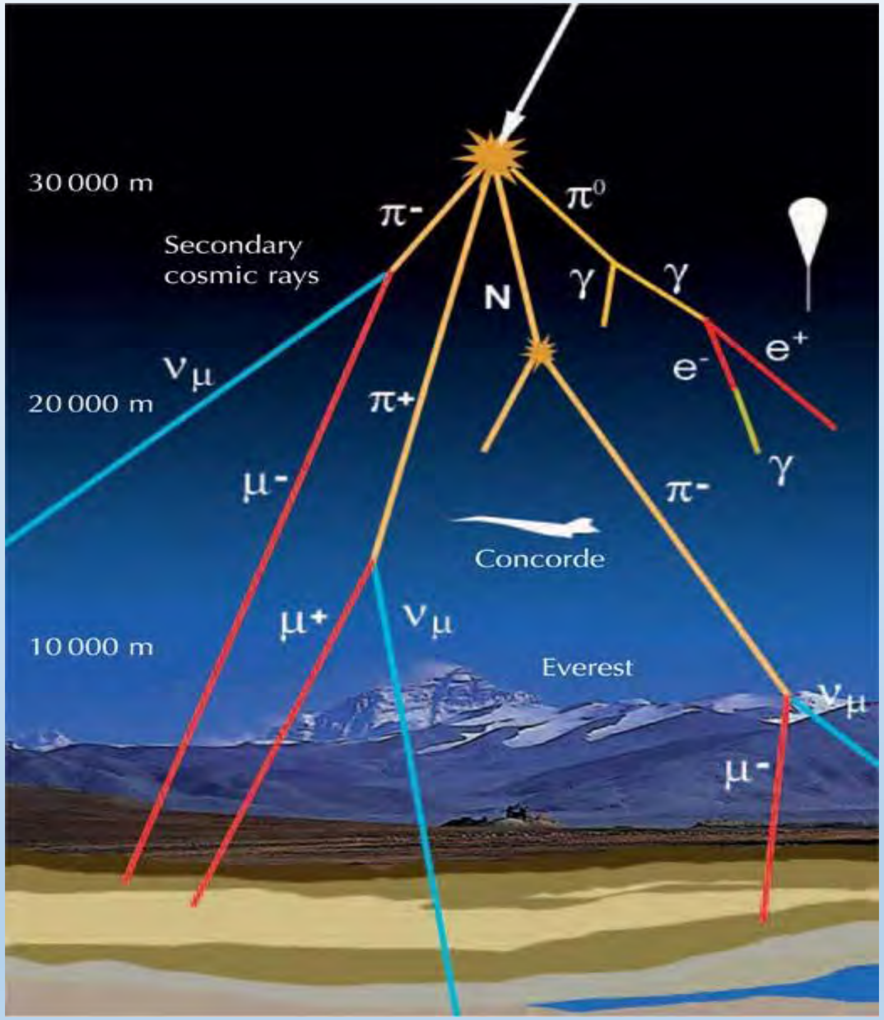
CP discovery : T2K and NOVA (future)



- To determine whether the value of the CP phase is different from 0 or 180

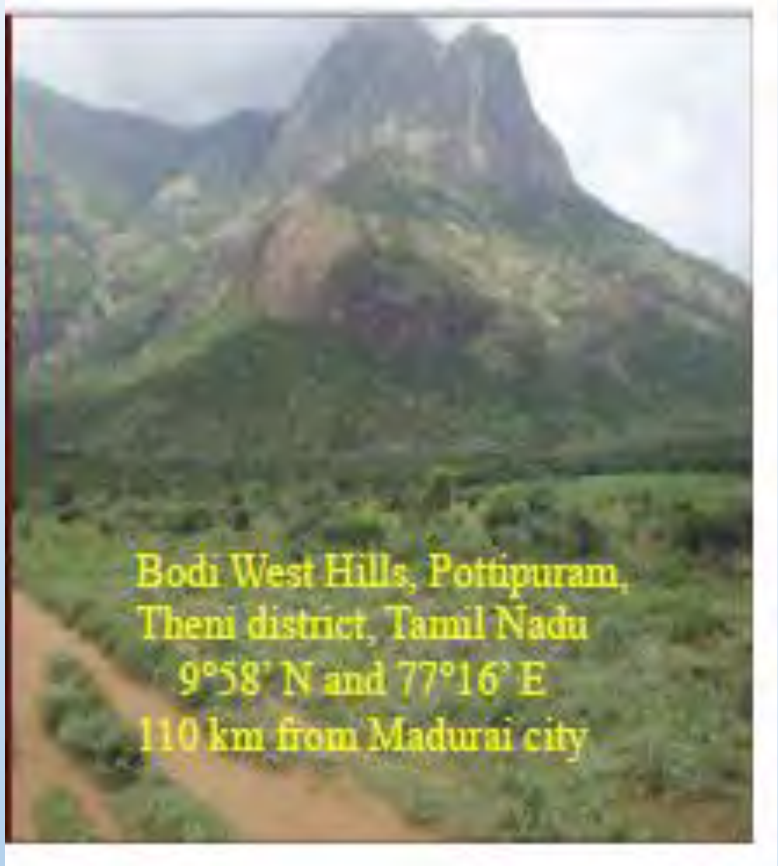
- **Beam Neutrino experiments like T2K /NoVA have good sensitivity in one half region of parameter space because of degeneracies**

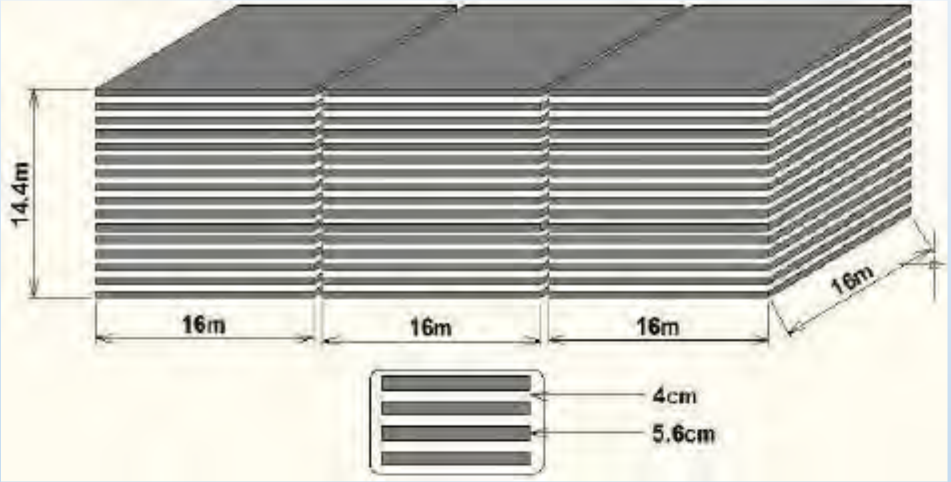
Atmospheric neutrinos



- Neutrinos and antineutrinos are produced when cosmic rays hit the air molecule
- First detection of atmospheric neutrinos in Kolar Gold Mine in India
- Super-Kamiokande experiment in Japan has observed neutrino oscillation using atmospheric neutrinos

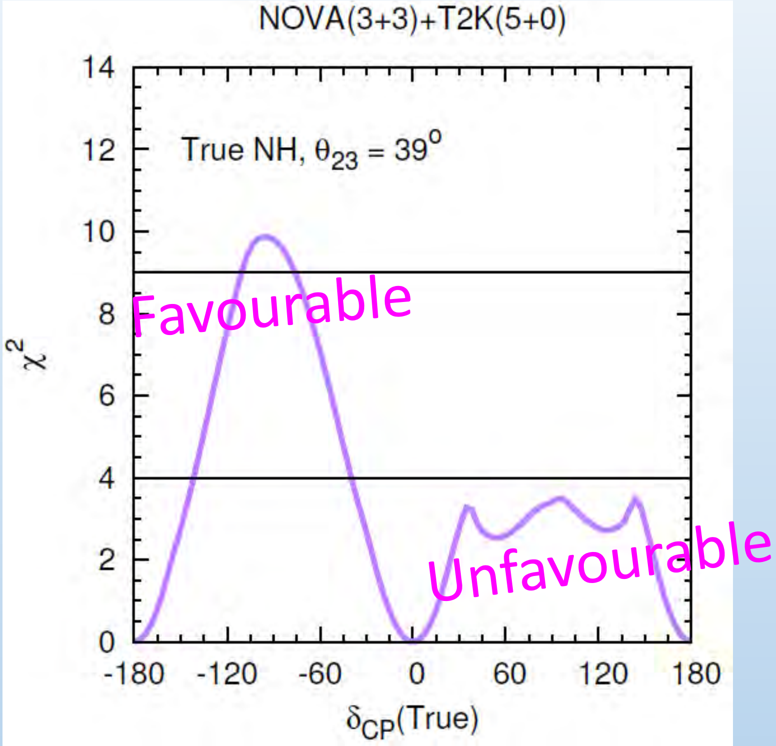
India-Based Neutrino Observatory (INO)

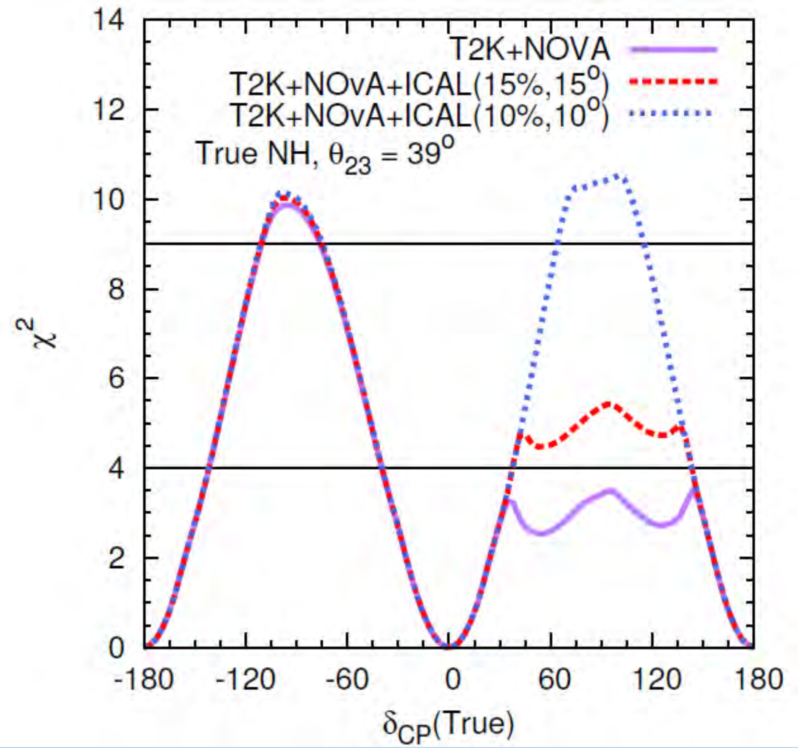




- 50 kton magnetized iron detector
- Can observe atmospheric neutrinos
- Determine unknown neutrino properties like mass ordering

INO + T2K + NOvA





Combining INO withT2K+NOvA can resolve degeneracies enhancing the CP sensitivity in the unfavourable part of the parameter space of T2K and NOvA

M. Ghosh, P. Ghoshal,Goswami, S. Raut , Phys. RevD 20 14, Nucl. Phys. B, 2014

Concluding remarks

- CP is a symmetry connecting matter and antimatter
- CP violation could be a reason for the observed matter and antimatter asymmetry of the universe
- CP violation has been observed in the quark sector
- Searches on for observation of CP violation in the lepton sector
- This is expected to come from accelerator based experiments
- We pointed out the importance of atmospheric neutrinos in particular INO in this endevour


Thank You