The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1951-28

Workshop on the original of P, CP and T Violation

2 - 5 July 2008

Flavor Symmetries, Neutrino Masses and Mixing

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Flavor Symmetries, Neutrino Masses and Mixing

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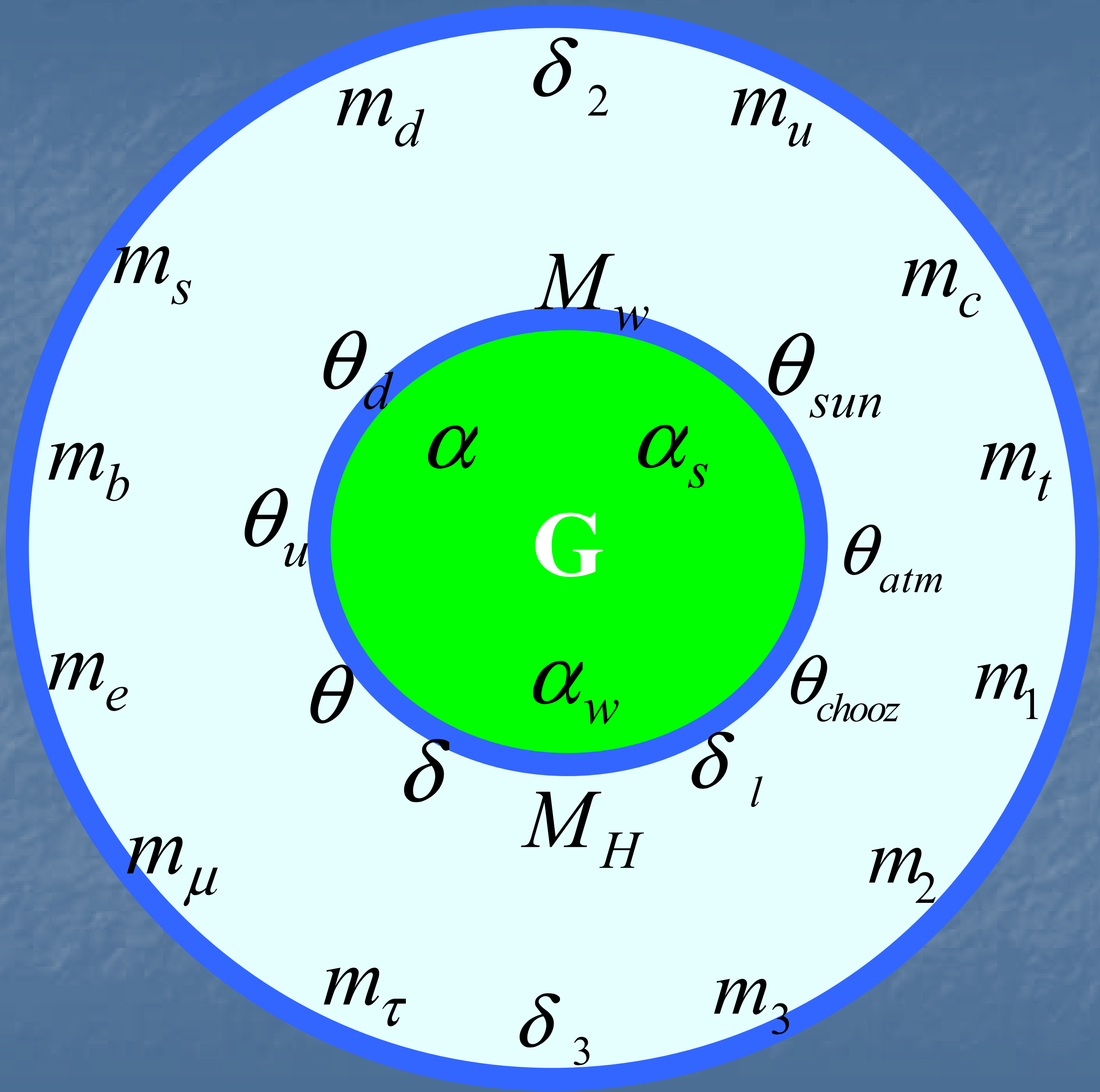
Standard Model:

28 fundamental constants

22=>fermion masses


δ_2
m_d
m_u
m_s
M_w
m_c
θ_d
θ_{sun}
α
α_s
m_b
m_t
θ_u
G
θ_{atm}
m_e
θ
α_w
θ_{chooz}
m_1
δ
δ_l
M_H
m_μ
m_2
m_τ
δ_3
m_3

6 quark masses

6 lepton masses

4 mixing parameters for quarks

6 mixing parameters for neutrinos

2 phases for Majorana mass

22

Mixing for three families

CKM

Quarks

$$V=\begin{bmatrix} c_u & s_u & 0 \\ -s_u & c_u & 0 \\ 0 & 0 & 1 \end{bmatrix}\bullet\begin{bmatrix} e^{-i\phi} & 0 & 0 \\ 0 & c & s \\ 0 & -s & c \end{bmatrix}\bullet\begin{bmatrix} c_d & -s_d & 0 \\ s_d & c_d & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

phase 90 degrees?

(==> Xing)

Theory: *Reflection Symmetries* *-SO(10)-*

$$\begin{pmatrix} 0 & A & 0 \\ A^* & C & B \\ 0 & B^* & D \end{pmatrix}$$

3 texture zeros

$$\tan\theta_d = \sqrt{m_d} / \sqrt{m_s} \qquad \tan\theta_u = \sqrt{m_u} / \sqrt{m_c}$$

agrees well with experiment

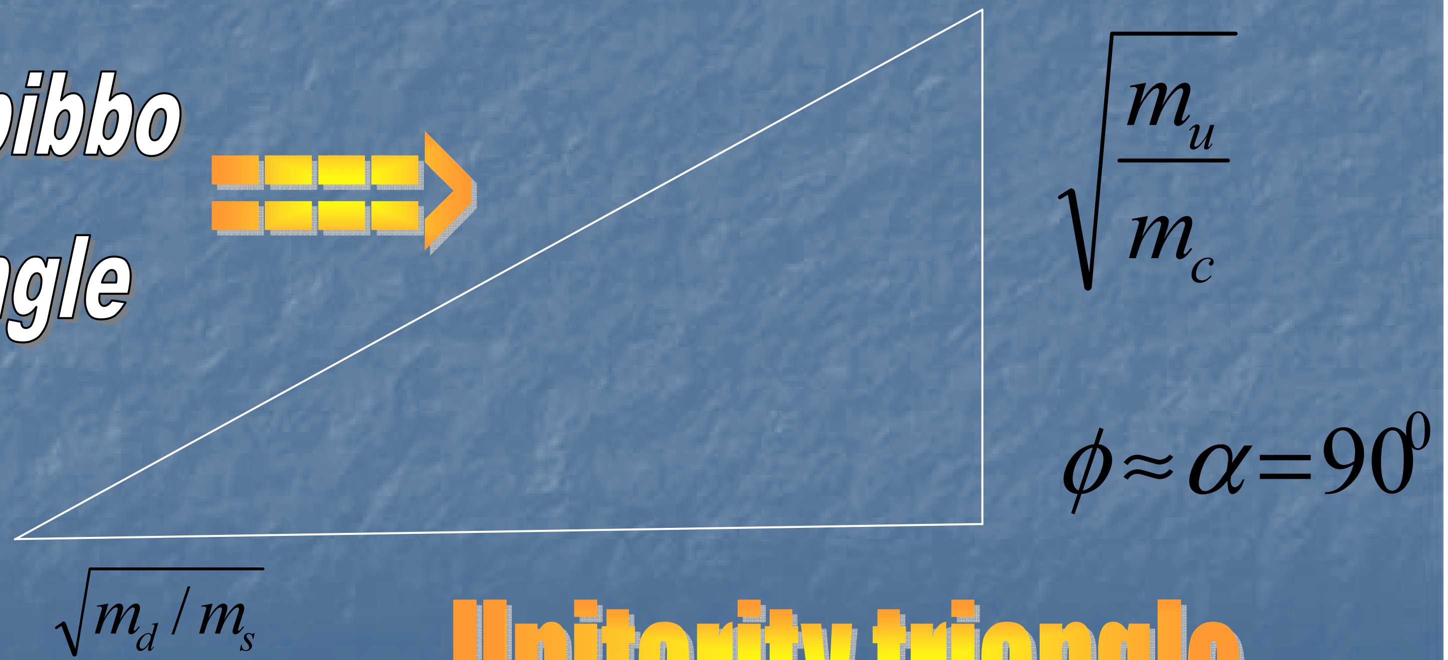
$$\theta_u \cong 5.4^o$$

$$\theta_d \cong 11.1^o$$

$$\theta \cong 2.4^o$$

$$\varphi \approx 90^0$$

Cabibbo angle



Unitarity triangle

CKM:

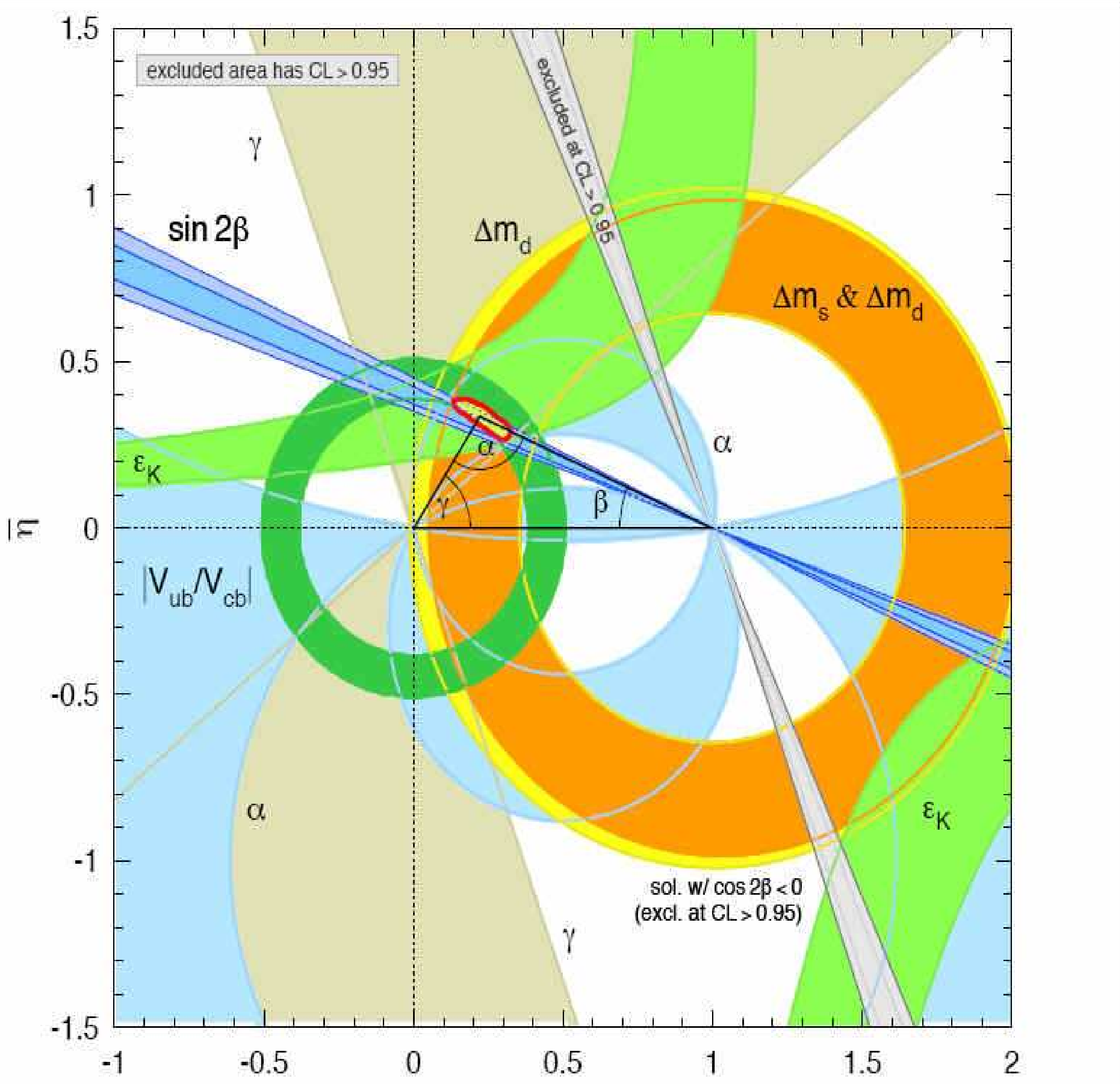
$$\begin{pmatrix} 0.9738 & 0.227 & 0.004 \\ 0.227 & 0.973 & 0.042 \\ 0.008 & 0.042 & 1 \end{pmatrix}$$

m(u)=5.3 m(c)=1100
m(d)=8.2 m(s)= 170 MeV

$Phi = 90^{o}$

==>

$$\begin{pmatrix} 0.974i+0.015 & 0.214i+0.07 & 0.003 \\ 0.07i+0.214 & -0.015i+0.97 & 0.042 \\ -0.009 & -0.041 & 1 \end{pmatrix}$$



excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δm_d
Δm_s & Δm_d
α
β
ε_K
|V_ub/V_cb|
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2

alpha: 86° ... 95°

$$M = \begin{pmatrix} 0 & A & 0 \\ A^* & \mathbf{0} & B \\ 0 & B^* & D \end{pmatrix} \ ?$$

$$\tan\theta \cong \left| \sqrt{\frac{m_c}{m_t}} - e^{i\phi}\sqrt{\frac{m_s}{m_b}} \right| \approx 0.042$$

m(t) < 70 GeV

=> C ≠ 0

Neutrino Mixing

Neutrino Mixing Matrix:

==> Pontecorvo

$$V = \begin{pmatrix} V_{1e} & V_{2e} & V_{3e} \\ V_{1\mu} & V_{2\mu} & V_{3\mu} \\ V_{1\tau} & V_{2\tau} & V_{3\tau} \end{pmatrix}$$

Neutrino mixing

V=UxP

$$P = \begin{bmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$U = \begin{bmatrix} c_l & s_l & 0 \\ -s_l & c_l & 0 \\ 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} e^{-i\varphi} & 0 & 0 \\ 0 & c & s \\ 0 & -s & c \end{bmatrix} \bullet \begin{bmatrix} c_\nu & -s_\nu & 0 \\ s_\nu & c_\nu & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta_l \approx reactor - angle$ $\qquad \theta \approx \theta_{at}$ $\qquad \theta_\nu \approx \theta_{sun}$

Kamiokande, SNO

$$30^o \leq \theta_{sun} \leq 39.2^o$$

$$36.8^o \leq \theta_{at} \leq 53.2^o$$

$$\Delta m_{21}^2 \approx 8 \cdot 10^{-5} eV^2$$

$$\Delta m^2{}_{32} \approx 2.5 \cdot 10^{-3} eV^2$$

Mean values of angles

$$\theta_{sun} = 34.6^o$$

$$\theta_{atm} = 45^o$$

$$\theta_{chooz} = 4.6^o$$

$$V = \begin{pmatrix} 0.821 & 0.568 & 0.08 \\ -0.047 - 0.40 \bullet e^{-i\delta} & -0.03 + 0.58 \bullet e^{-i\delta} & 0.70 \\ -0.047 + 0.40 \bullet e^{-i\delta} & -0.03 - 0.58 \bullet e^{-i\delta} & 0.70 \end{pmatrix}$$

$$U = \begin{bmatrix} c_l & s_l & 0 \\ -s_l & c_l & 0 \\ 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} e^{-i\varphi} & 0 & 0 \\ 0 & c & s \\ 0 & -s & c \end{bmatrix} \bullet \begin{bmatrix} c_\nu & -s_\nu & 0 \\ s_\nu & c_\nu & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

same pattern as for quarks:

$$\tan\theta_\nu = \sqrt{\frac{m_1}{m_2}} \qquad \tan\theta_l = \sqrt{\frac{m_e}{m_\mu}} \cong 0.07$$

Observation:

$$\theta_\nu \approx 33^o \quad \_\_ \quad \theta \approx 45^o$$

$$\tan\theta_\nu = \sqrt{\frac{m_1}{m_2}}$$

$$==> m_1 / m_2 \approx 0.42$$

weak mass hierarchy for neutrinos

Neutrino masses fixed, since the mass differences are given by the experiment, and the angles are fixed by the mass matrix

$$m_1^{\ 2} = \frac{\sin^4\theta_\nu}{\cos 2\theta_\nu}\Delta m_{21}^{\ 2}$$

$$m_2^{\ 2} = \frac{\cos^4\theta_\nu}{\cos 2\theta_\nu}\Delta m_{21}^{\ 2}$$

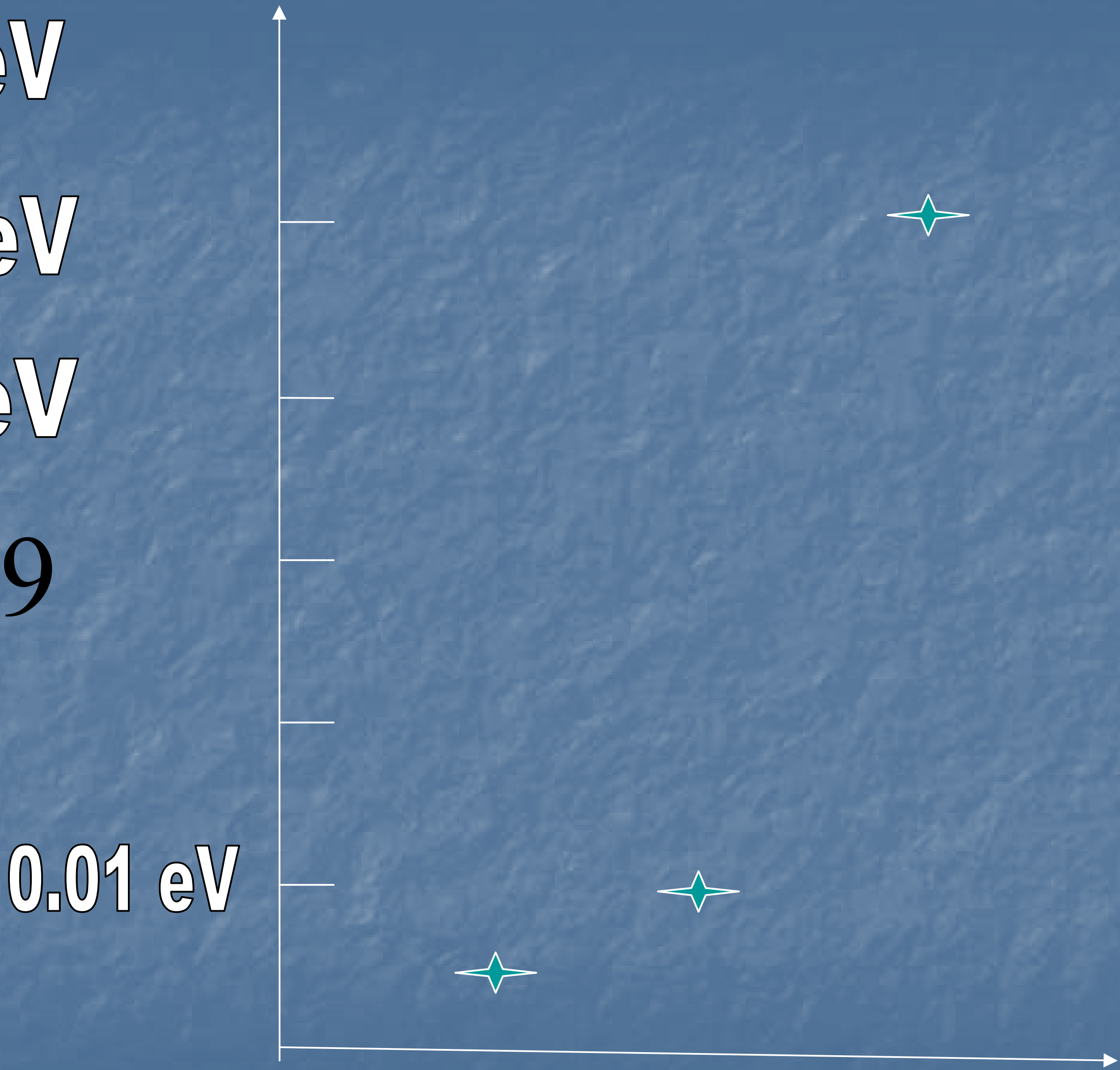
$$m_3^{\ 2} = \frac{\cos^4\theta_\nu}{\cos 2\theta_\nu}\Delta m_{21}^{\ 2} + \Delta m_{32}^{\ 2}$$

$m_1 \approx 0.0041$ eV

$m_2 \approx 0.0097$ eV

$m_3 \approx 0.051$ eV

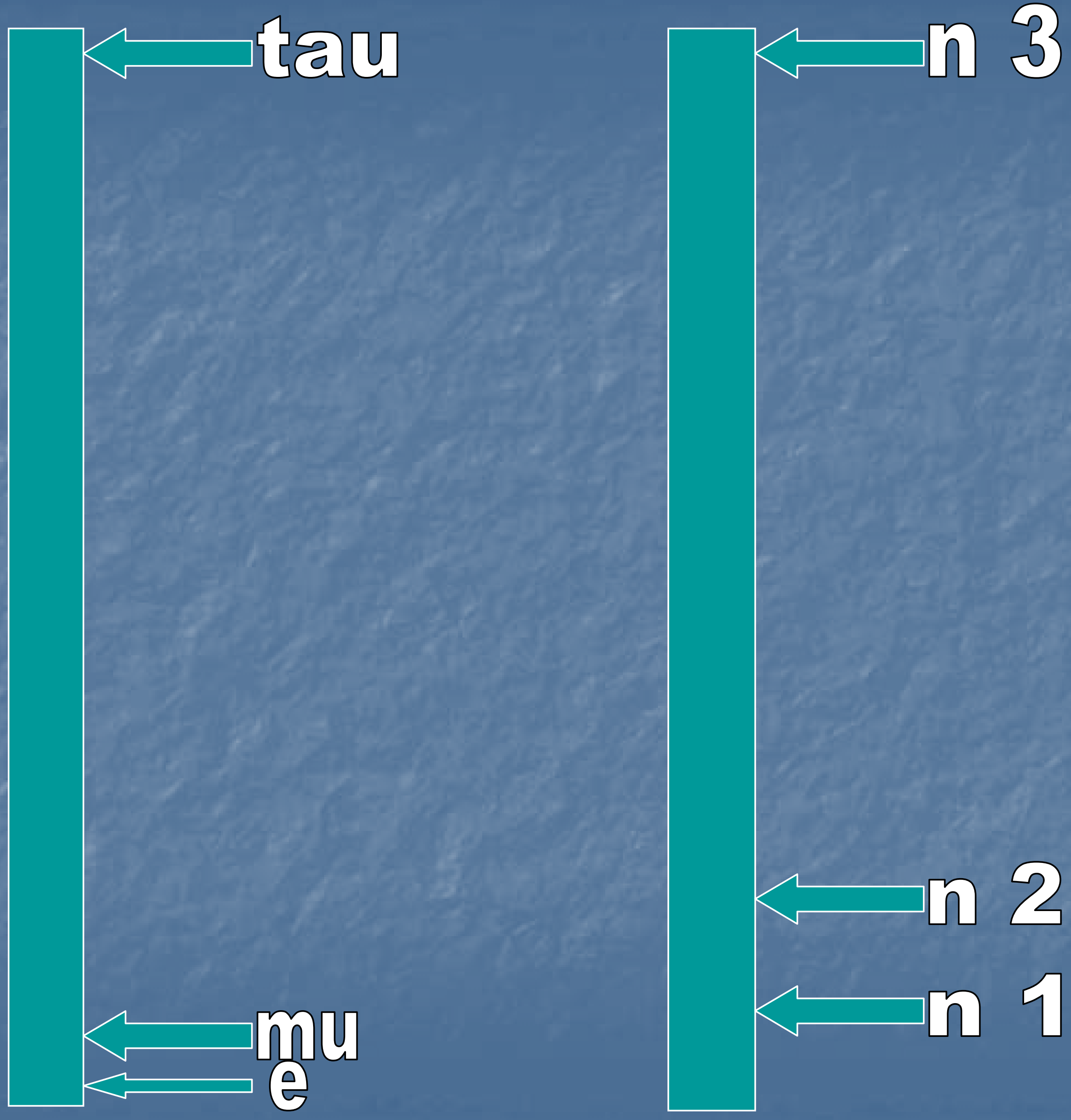
$m_2 / m_3 \approx 0.19$



neutrino masses <<1 eV

Masses

(relative)



Neutrino masses less hierarchical than the masses of the charged leptons

Large mixing angles for neutrinos due to weak hierarchy

Solar angle: 33°

==> m(1)/m(2) = 0.42

$$m^2{}_\tau / M = m_\nu$$

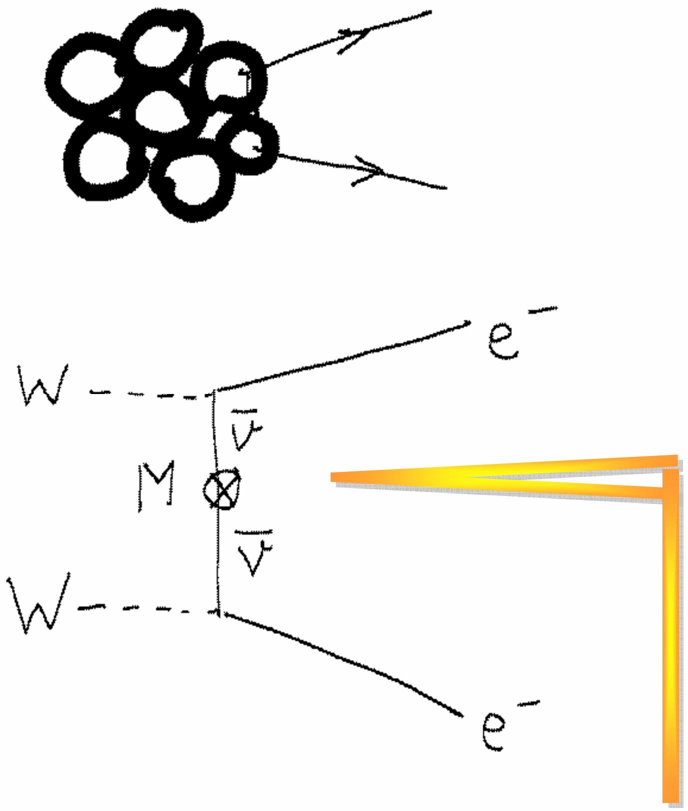
= 0.051 eV

See-saw:

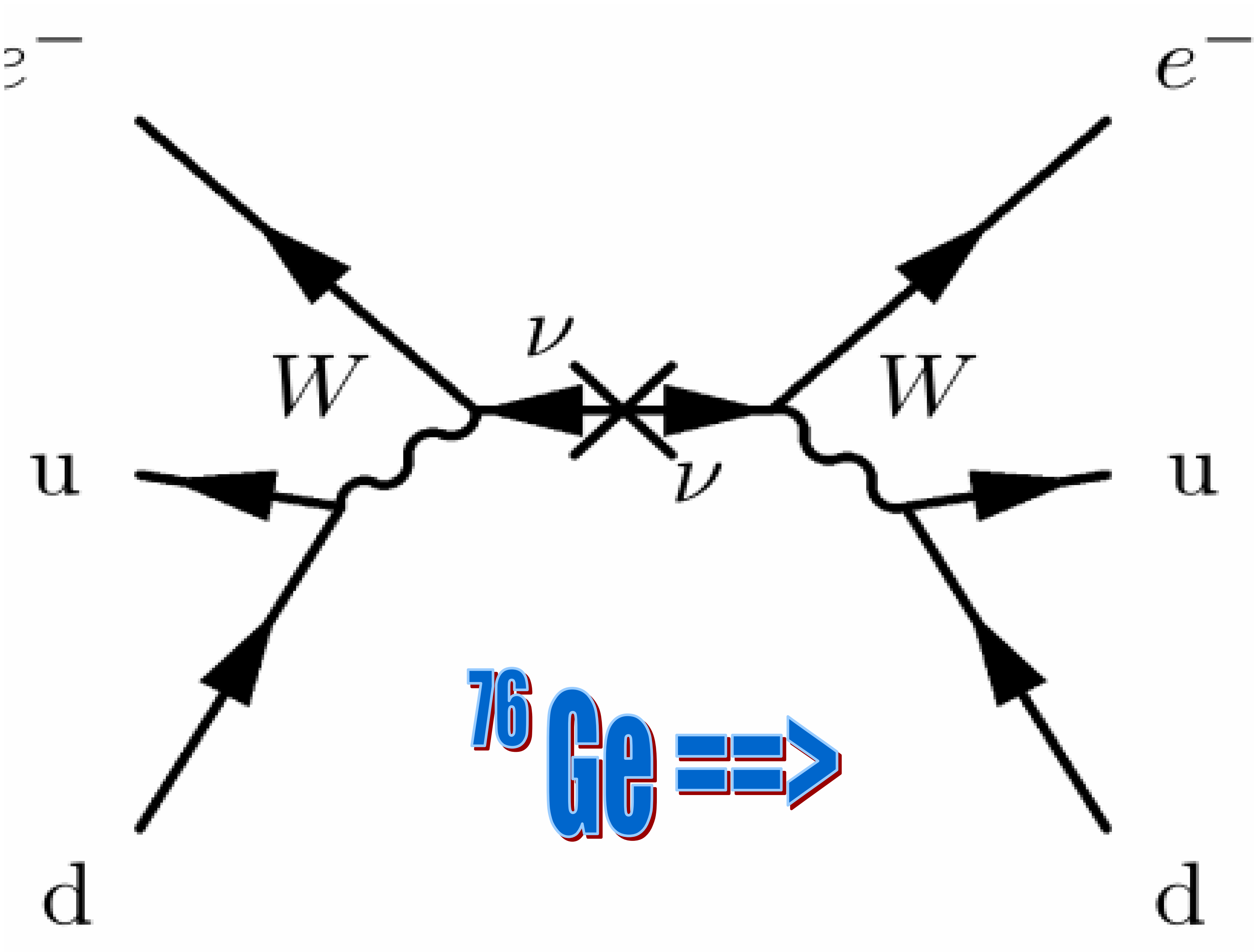
M about 6.2 x 10 ^{10} GeV

Possible in case of a Majorana mass term

Neutrinoless double β-decay



Majorana: particle = antiparticle



e⁻
e⁻
ν
W
W
ν
u
u
d
d
76Ge ==>

Double Beta Decay

Present limit about 0.23 ev

Cuoricino Exp.: Te (130)
Gran Sasso Lab.

Relevant mass term 0.05 eV.

Improvement by about 50 necessary!

Leptons: mass matrices

$$M = \begin{bmatrix} 0 & A & 0 \\ A^* & 0 & B \\ 0 & B^* & D \end{bmatrix}$$

Reflection symmetry in SO(10) theory

leptons:

$$M = \begin{bmatrix} 0 & A & 0 \\ A^* & 0 & B \\ 0 & B^* & D \end{bmatrix}$$

quarks:

$$M = \begin{bmatrix} 0 & A & 0 \\ A^* & C & B \\ 0 & B^* & D \end{bmatrix}$$

What is atm. angle?

$$\theta = \theta_1 + \theta_2$$

$$\theta_1 \approx \sqrt{m_\mu} / \sqrt{m_\tau} \approx 14^o$$

$$\theta_2 \approx \sqrt{m_2} / \sqrt{m_3} \approx 26^o$$

$$=========> \theta \cong 40^o$$

$$\sin^2 \theta \cong 0.97$$

(ok with exp.)

Neutrino Mixing Matrix:

$$V = \begin{pmatrix} V_{1e} & V_{2e} & V_{3e} \\ V_{1\mu} & V_{2\mu} & V_{3\mu} \\ V_{1\tau} & V_{2\tau} & V_{3\tau} \end{pmatrix}$$

<====== not 0

Prediction for mixing of reactor neutrinos:

$$V_{3e} \approx \frac{1}{\sqrt{2}} \bullet \sqrt{\frac{m_e}{m_\mu}} = 0.049$$

Present limit:

V(e3) < 0.1

New experiments:

Daya Bay (China) =>0.03

Conclude:

Neutrino masses might be Dirac masses or Majorana masses.

Mixing angles for quarks are fixed by ratios of quark masses. Very good agreement with experiment.

This works also well for leptons. One finds, using the observed mass differences:

m(1)/m(2)=0.42, m(2)/m(3)=0.19.

m(1): 0.0041 eV
m(2): 0.0097 eV
m(3): 0.051 eV

Atmospheric angle about 40 degrees

Neutrinoless double beta decay: difficult

Reactor neutrinos: V (3e) ~ 0.052

(Daya Bay exp.)