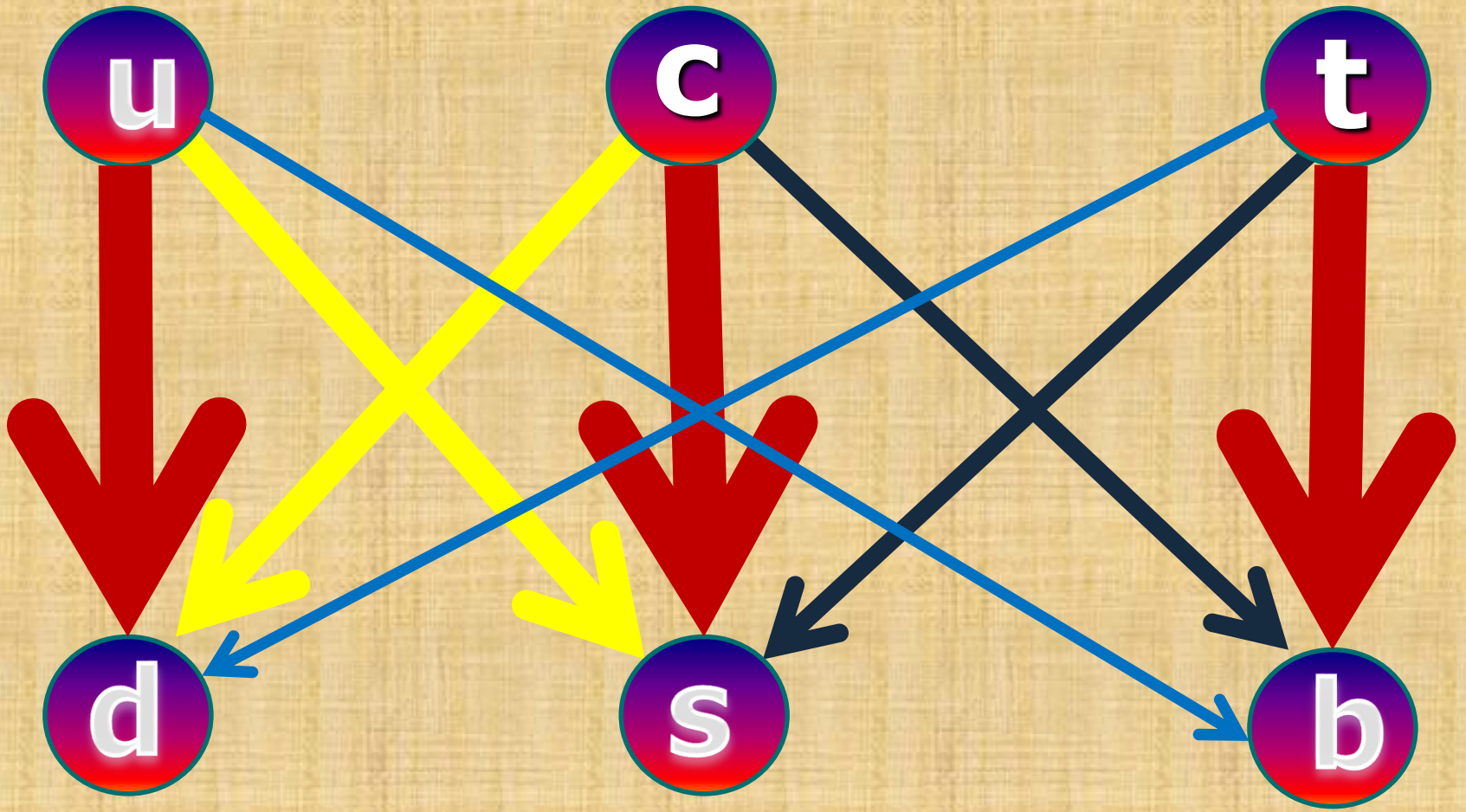
FLAVOR MIXING and NEUTRINO MASSES

H. FRITZSCH



FLAVOR MIXING

CKM - matrix

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

EXPERIMENTS

$$\left(|V_{CKM}|\right) \approx \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}$$

:H. Fritzsch – Z. Xing

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

θ_u θ θ_d

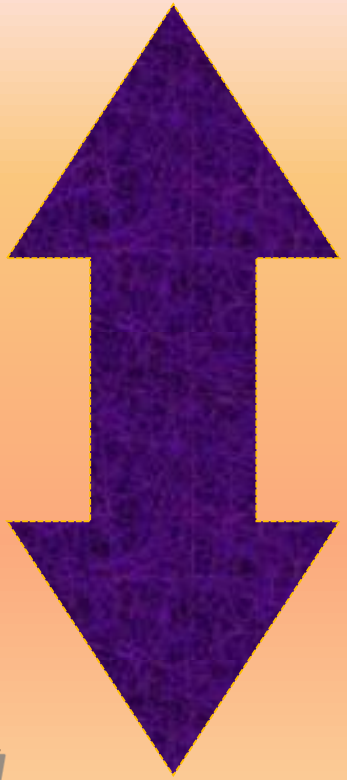
experiments

$$\theta_d \cong 11.7^o$$

$$\theta_u \cong 5.4^0$$

$$\theta \cong 2.4^0$$

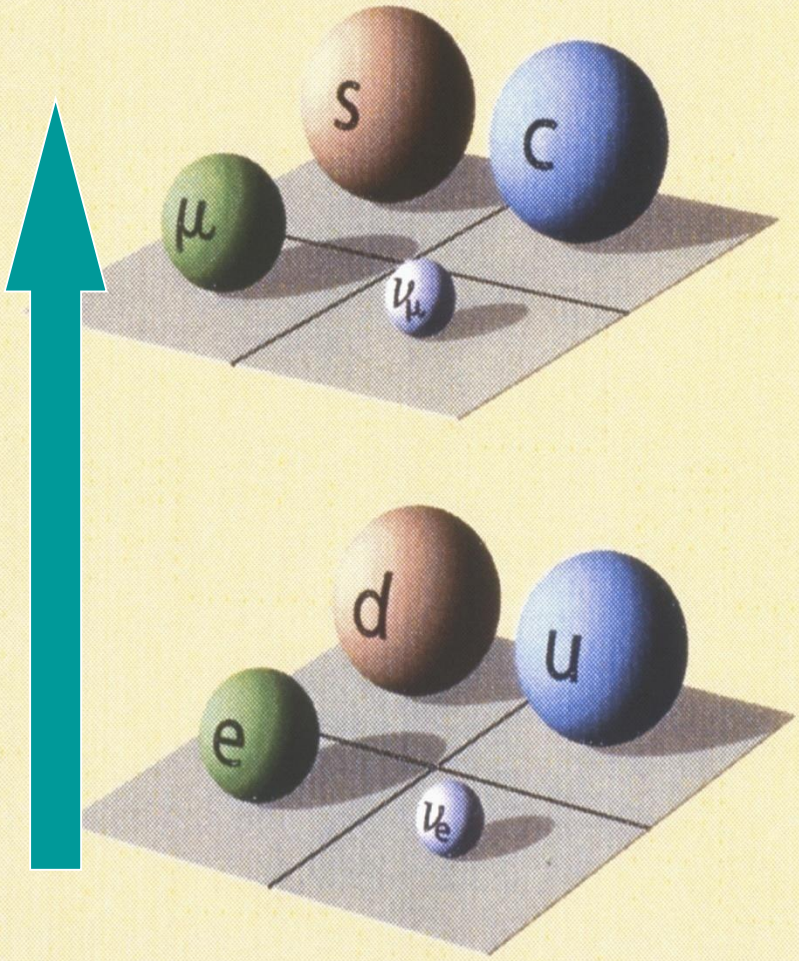
flavor mixing angles



fermion masses

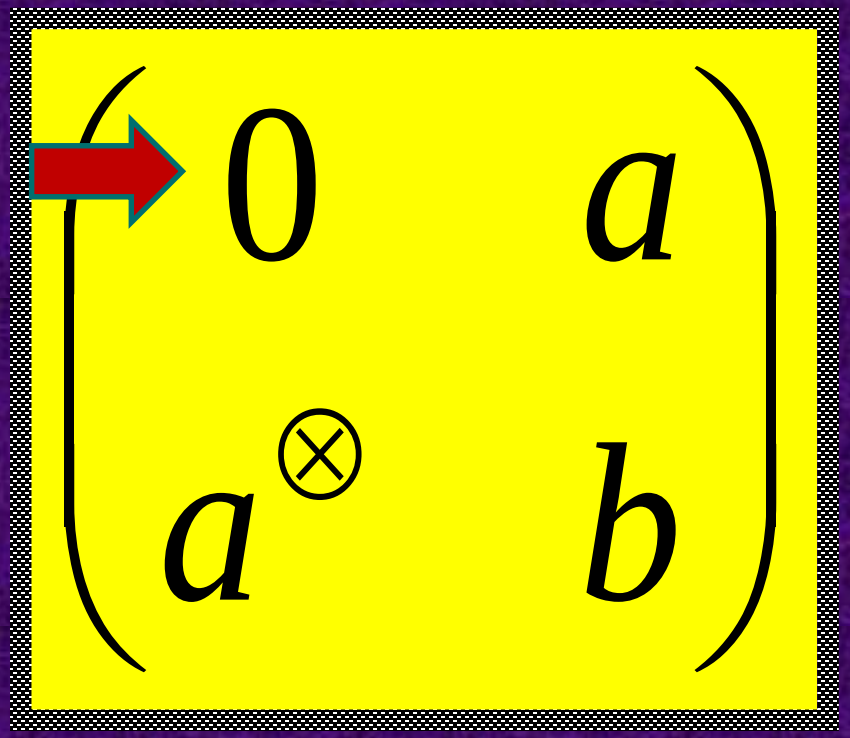
flavor mixing

2 families

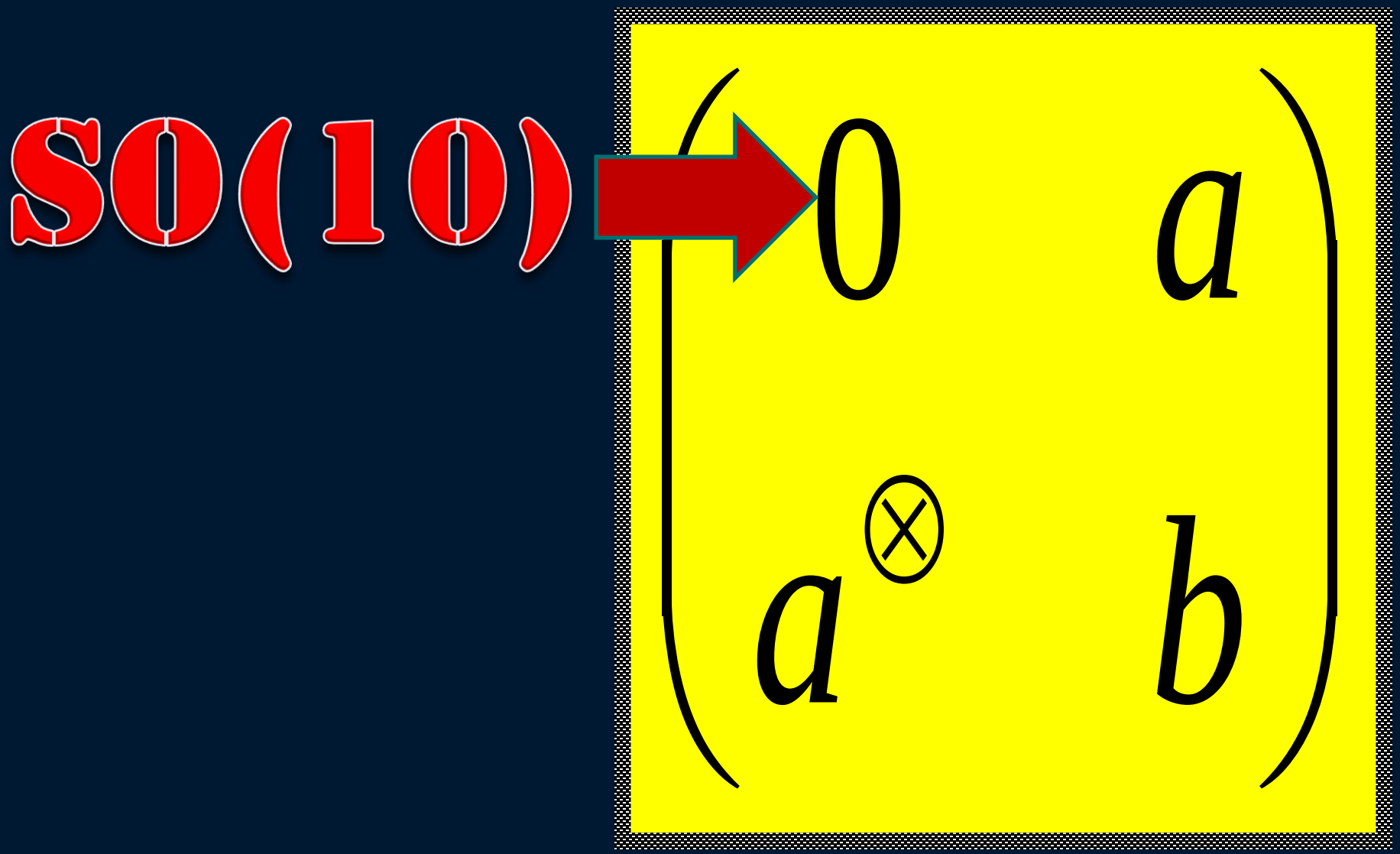


mass matrices

texture 0



H. Fritzsch - S. Weinberg / 1978


SO(10)
$\begin{pmatrix} 0 & a \\ a^{\otimes} & b \end{pmatrix}$

mixing angles <=> masses

$$\begin{pmatrix} 0 & a \\ a^{\otimes} & b \end{pmatrix} \succ \begin{pmatrix} -m_u & 0 \\ 0 & m_c \end{pmatrix}$$

$$\tan\theta_u = \sqrt{\frac{m_u}{m_c}} \qquad \theta_u \approx \sqrt{\frac{m_u}{m_c}}$$

OBSERVED QUARK MASSES

$$\sqrt{\frac{m_d}{m_s}} \approx 0.23 \qquad \sqrt{\frac{m_u}{m_c}} \approx 0.09$$

$$\theta_d \cong 13.0^o \qquad \theta_u \cong 5.4^0$$

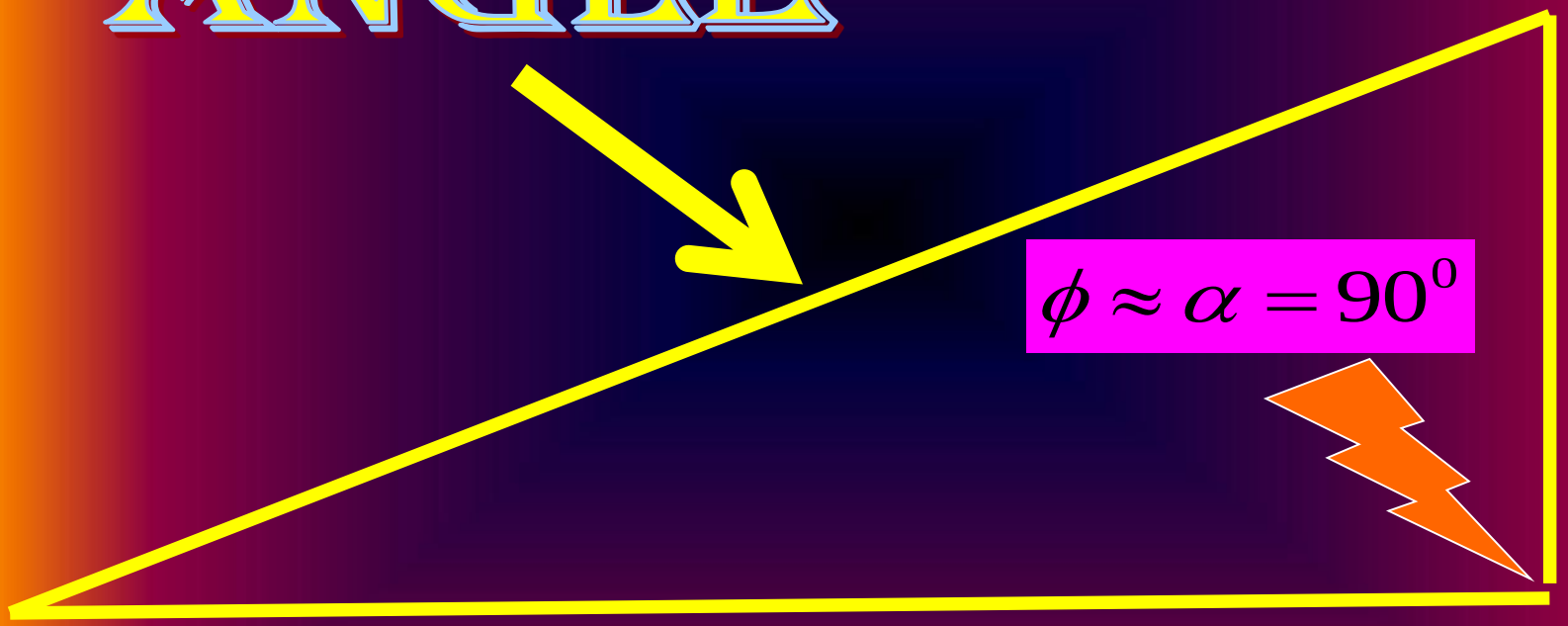
$$\sqrt{\frac{m_d}{m_s}} \approx 0.23$$

$$\sqrt{\frac{m_u}{m_c}} \approx 0.09$$

Cabibbo angle

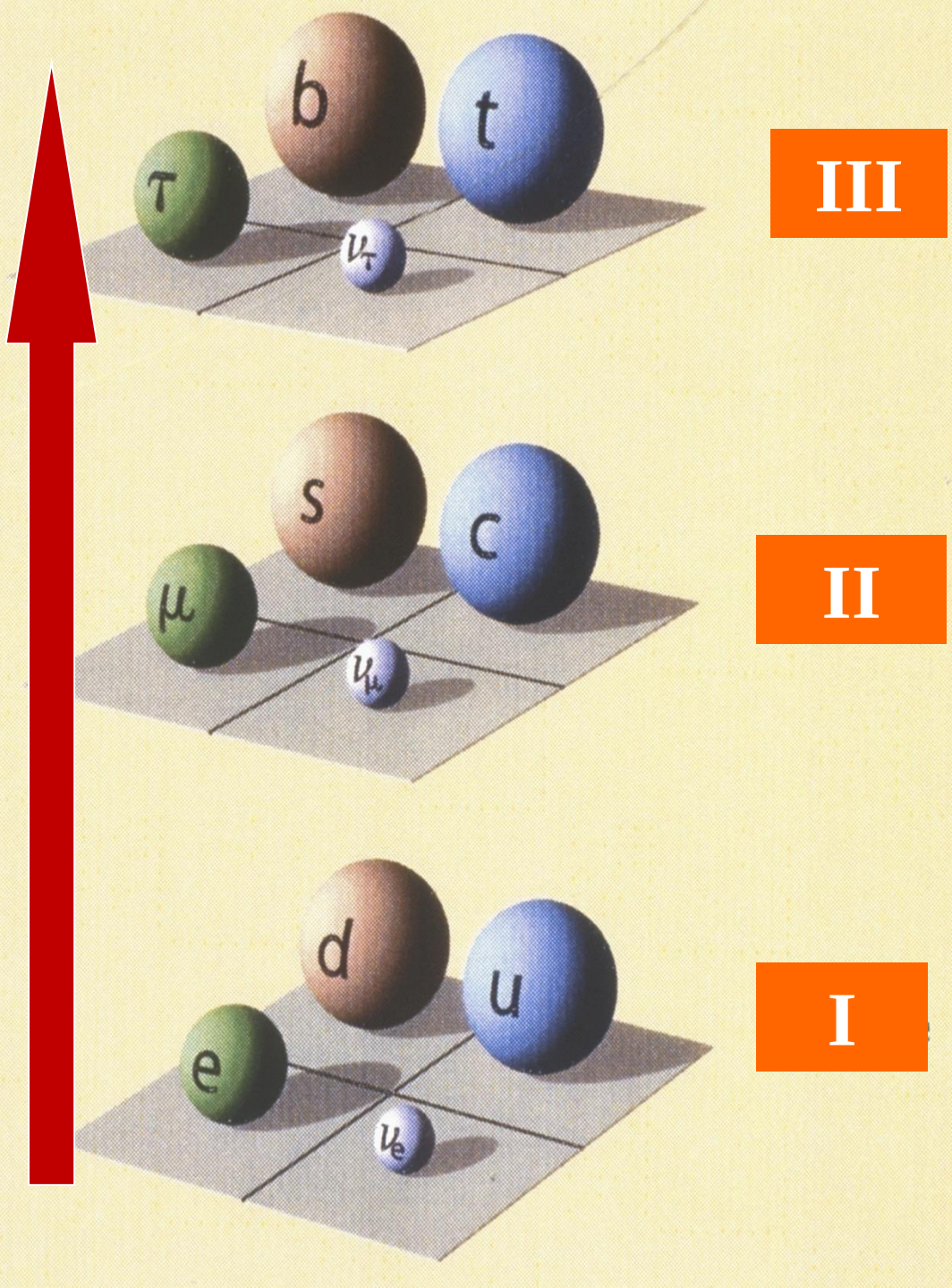
$$\theta_c \cong \left| \sqrt{\frac{m_d}{m_s}} - e^{i\phi} \sqrt{\frac{m_u}{m_c}} \right| \cong 13^0$$

CABIBBO ANGLE



3 families

flavor mixing

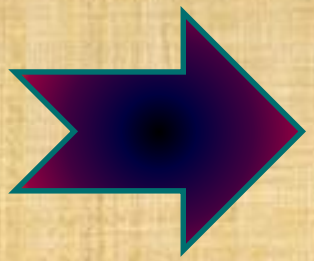


texture zeros

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

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

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



$$\tan\theta_u = \sqrt{\frac{m_u}{m_c}}$$

$$\tan\theta_d = \sqrt{\frac{m_d}{m_s}}$$

$$\tan\theta_d = \sqrt{\frac{m_d}{m_s}}$$

$$\theta_d \approx 13.0 \pm 0.4^o$$

$$Exp: 11.7^o \pm 2.6^o$$

$$\tan\theta_u = \sqrt{\frac{m_u}{m_c}}$$

$$\theta_u \approx 5.0^o \pm 0.7^o$$

$$Exp: 5.4^o \pm 1.1^o$$

Experiment :

$$V_{cb} = 0.0398 \ldots 0.0424$$

$$V_{cb} \cong \sqrt{\frac{m_s}{m_b}} - \sqrt{\frac{m_c}{m_t}}$$

$$V_{cb} \cong \sqrt{\frac{m_s}{m_b}} - \sqrt{\frac{m_c}{m_t}} \approx 0.04$$

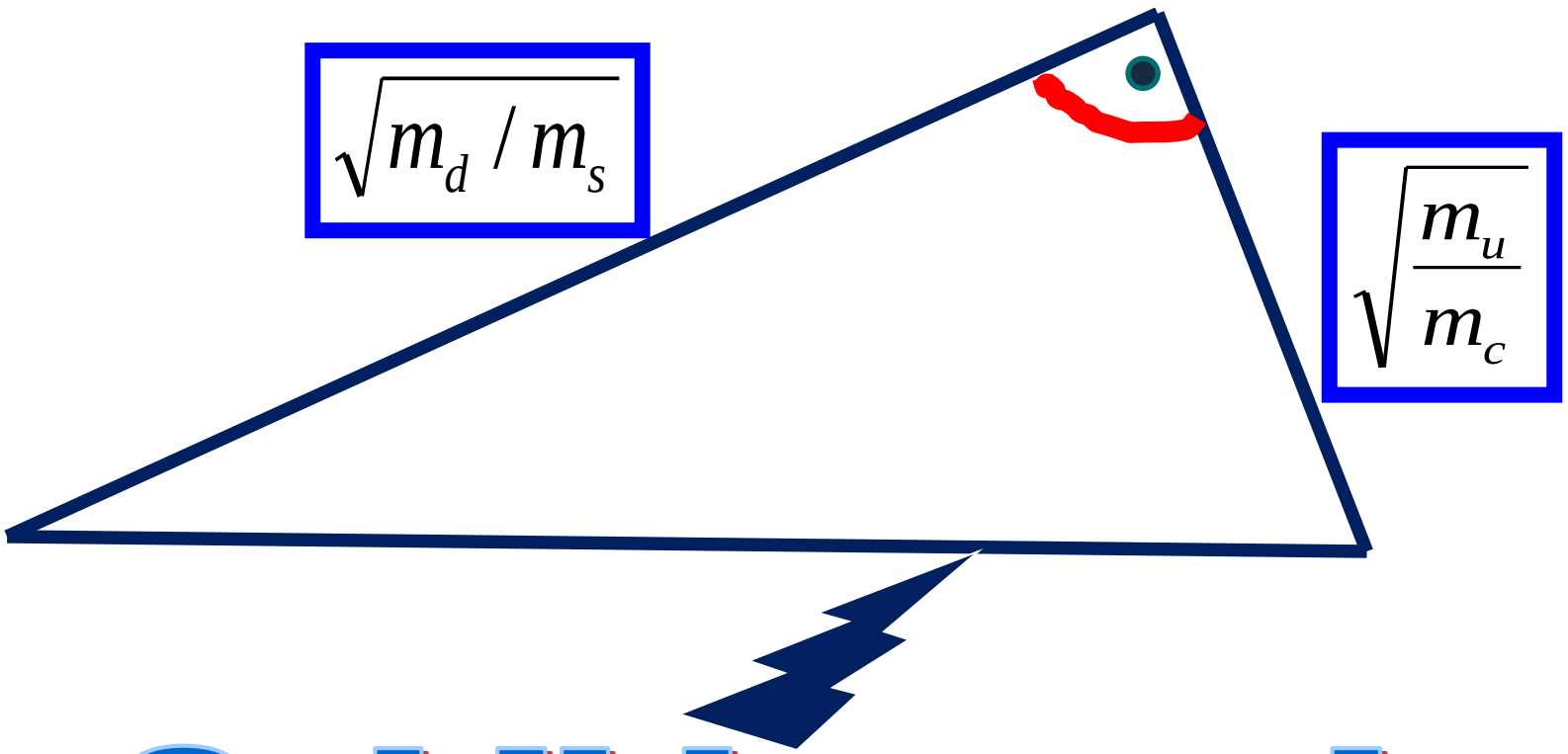
$$m_s \approx 0.075 \quad m_b \approx 4.2$$

$$m_c \approx 1.3 \quad m_t \approx 172$$

m: GeV

unitarity triangle

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cu} & V_{cs} & V_{cb} \\ V_{tu} & V_{ts} & V_{tb} \end{pmatrix}$$

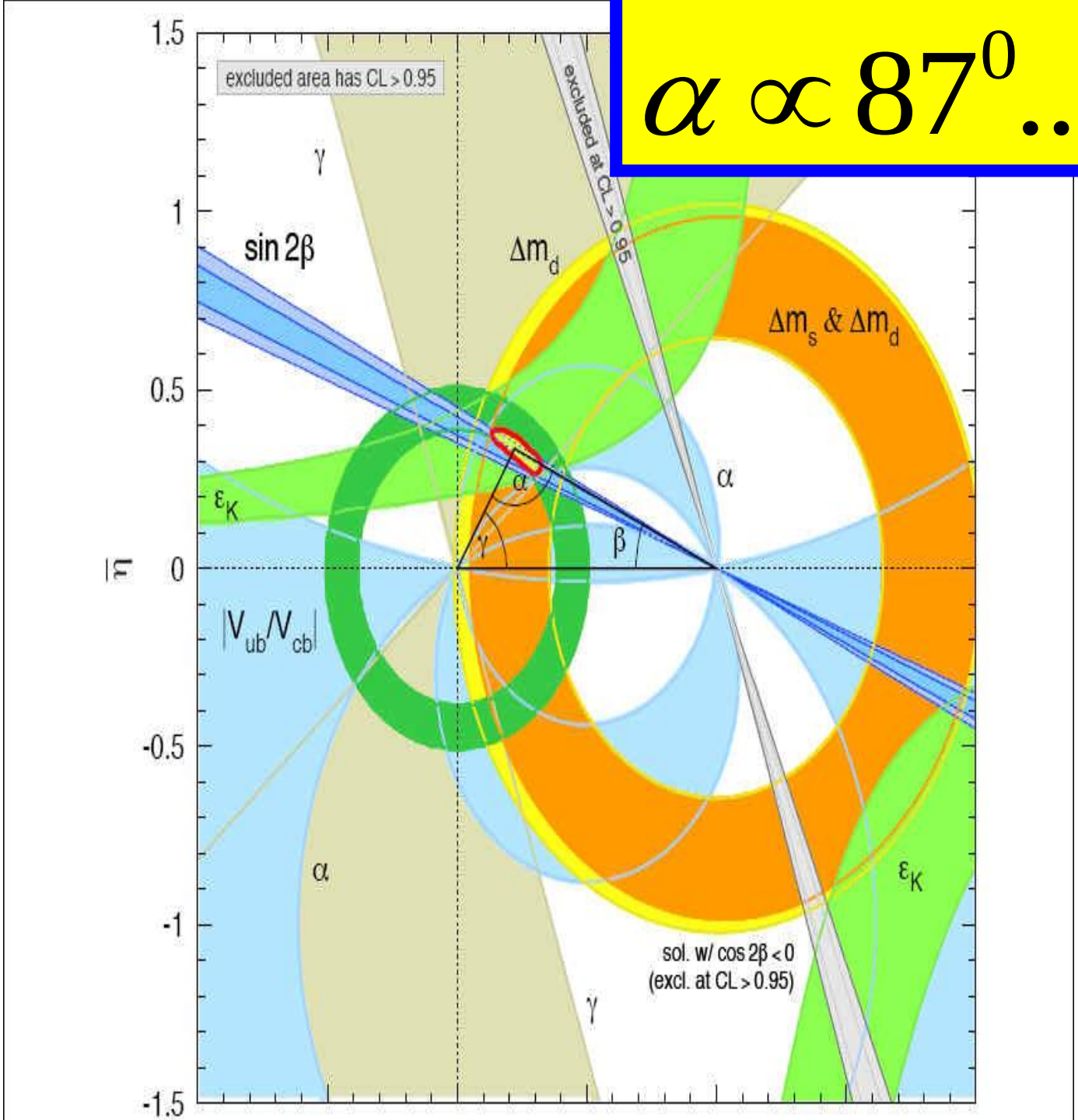


Cabibbo angle

unitarity triangle

(rectangular)

$\alpha \propto 87^0 ... 95^0$

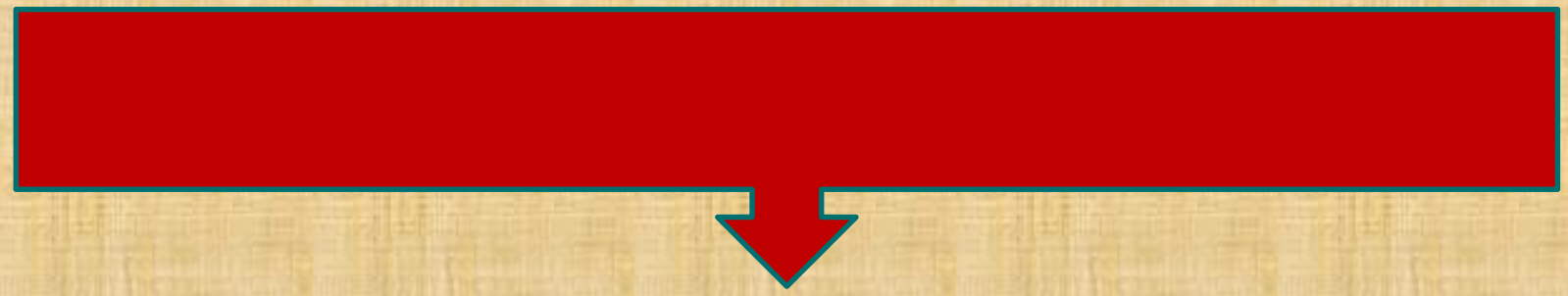


mixing of leptons

Bruno Pontecorvo

1913 - 1993

$$\nu_e = \cos\theta \cdot \nu_1 + \sin\theta \cdot \nu_2$$



neutrino mixing

B. PONTECORVO

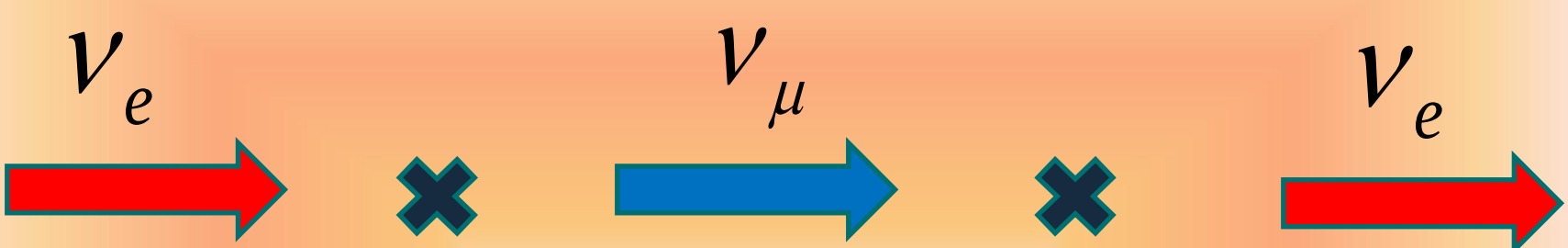
PHYS. JETP 6, 429

(1957)

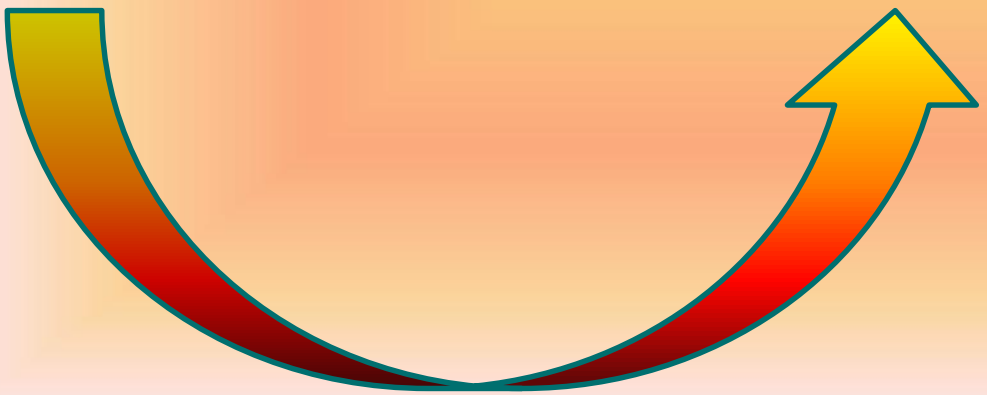
H. FRITZSCH - P. MINKOWSKI

PHYSICS LETTERS 62B, 76

(1975)



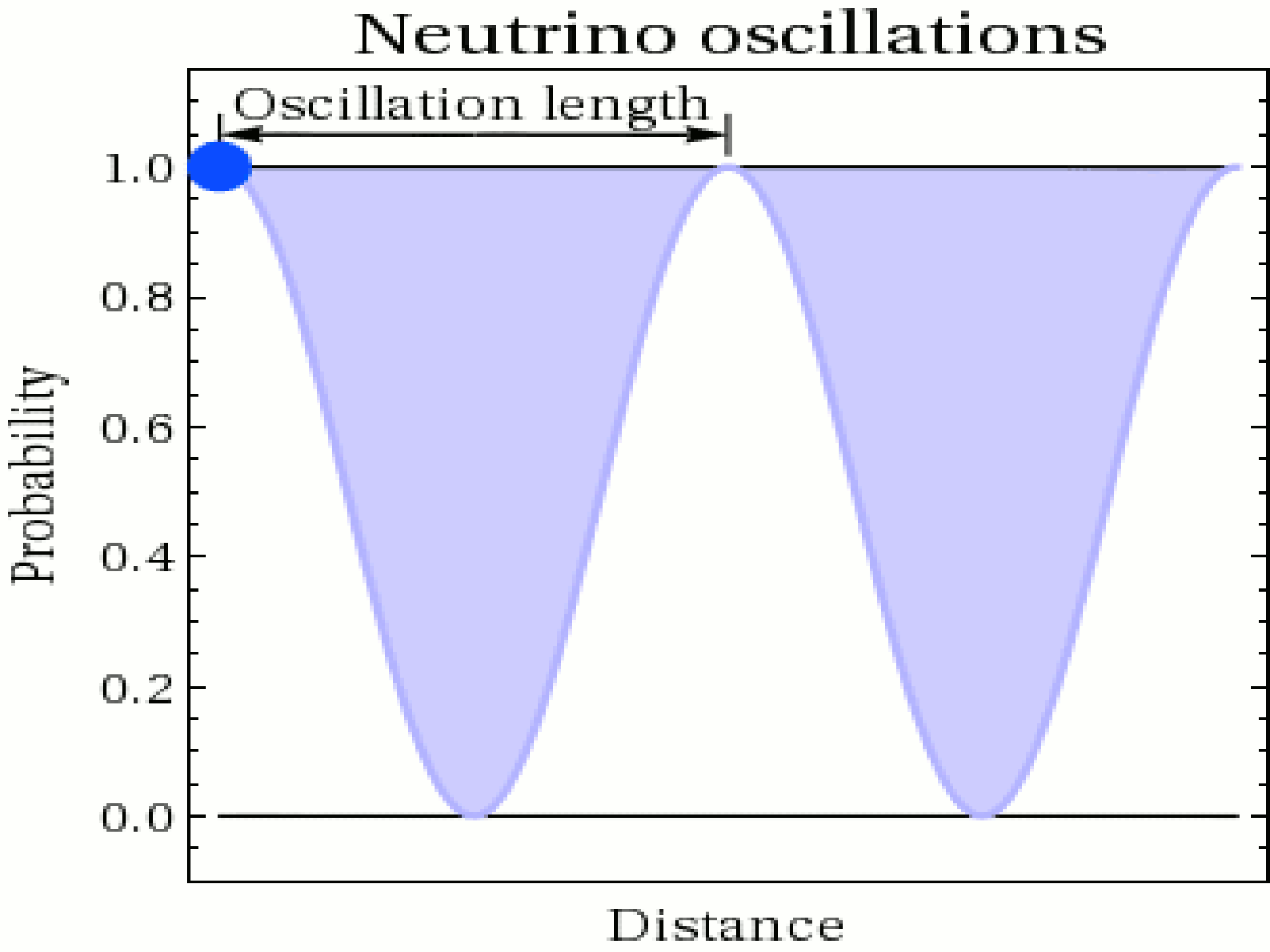
NEUTRINO OSCILLATIONS



$$\nu_e = \frac{1}{\sqrt{2}}\nu_1 + \frac{1}{\sqrt{2}}\nu_2$$

$$\nu_\mu = -\frac{1}{\sqrt{2}}\nu_1 + \frac{1}{\sqrt{2}}\nu_2$$

$$\Theta = \pi/2$$


Neutrino oscillations
Oscillation length
1.0
0.8
0.6
0.4
0.2
0.0
Probability
Distance

Fritzsch – Minkowski (1975)

2 - neutrino case

(ν_e, ν_μ)

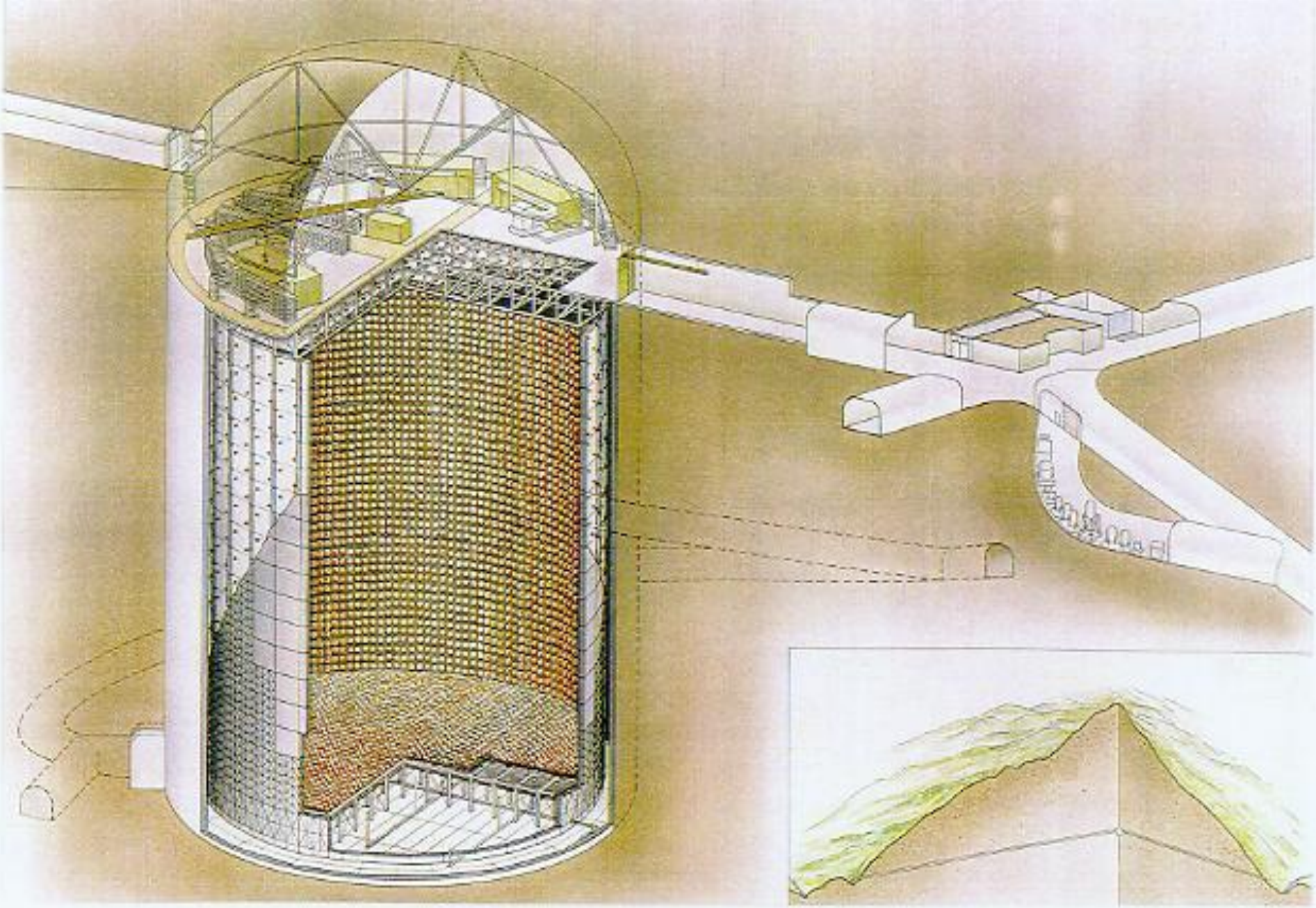
$$U \longrightarrow \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P_{\alpha \to \beta} \; (\alpha \neq \beta) \; =$$

$$\sin^2(2\theta) \cdot \sin^2 \frac{\Delta m^2 \cdot L}{4E}$$

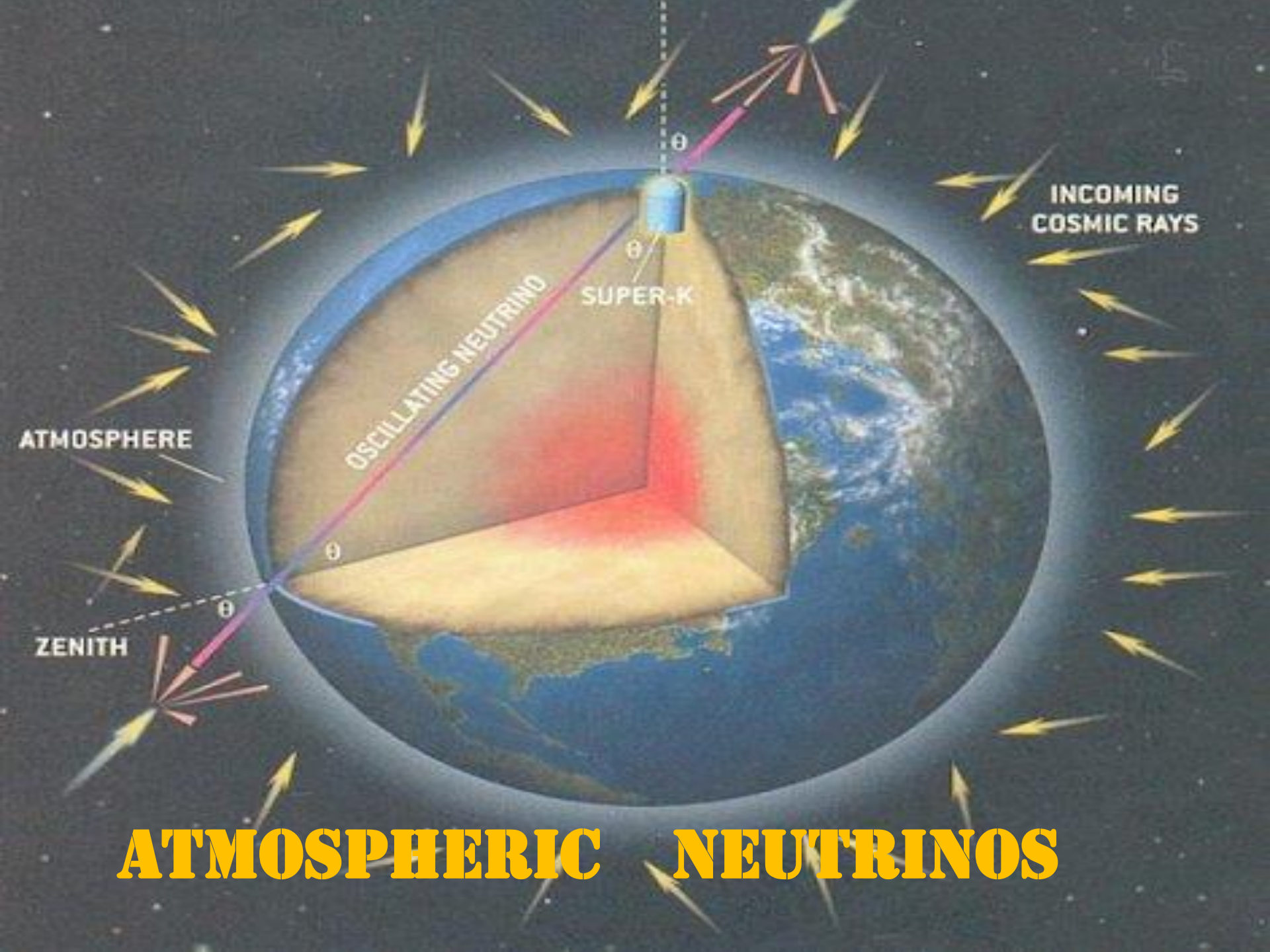
$$= \sin^2(2\theta) \cdot \sin^2\left(1.267 \cdot \frac{\Delta m^2 L}{E} \; \frac{GeV}{eV^2 km}\right)$$


Kamioka
Nemuro
Kushiro
Hiraizumi
Sado I.
YAMAGATA
NIIGATA
Mt. Zao
Sea of Japan
Wajima
Mt. Bandai
Notto pen.
L. Inawashiro
Itoigawa
TOYAMA
Nikko
KANAZAWA
L. Chuzenji
Shirakawa-go
UTSUNOMIYA
Tojimbo
Matsumoto
MITO
FUKUI
Takayama
MAEBASHI
Tango pen
Wakasa Bay
Kamikochi
HONSHU
URAWA
KOFU
Hikawa
TOKYO
Izushi
GIFU
Magome
L. Biwa
Fuji Five Lakes
CHIBA
Maibara
Mt. Fuji
KYOTO
NAGOYA
YOKOHAMA
Himeji
KOBE
OTSU
SHIZUOKA
Hakone
Atami
Awaji isl.
OSAKA
NARA
Ito
Asuka
Ise
Hamamatsu
Izu pen.
WAKAYAMA
Toba
Hongu
Shirahama
Shingu
Pacific Ocean
Naze

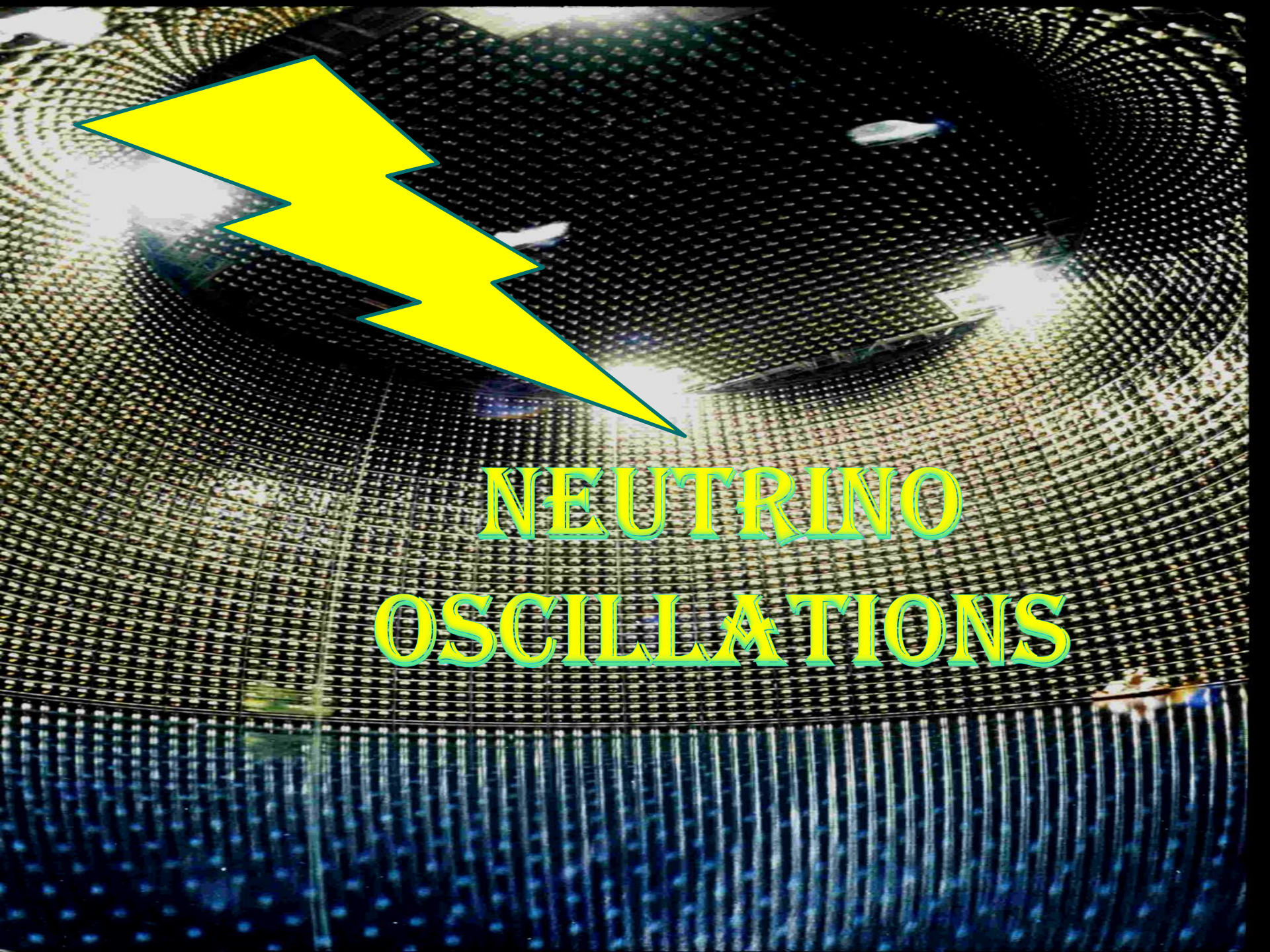


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NISSEN SEKKEI



ATMOSPHERIC NEUTRINOS


NEUTRINO
OSCILLATIONS

YOJI TOTSUKA

NOBEL PRIZE 2015

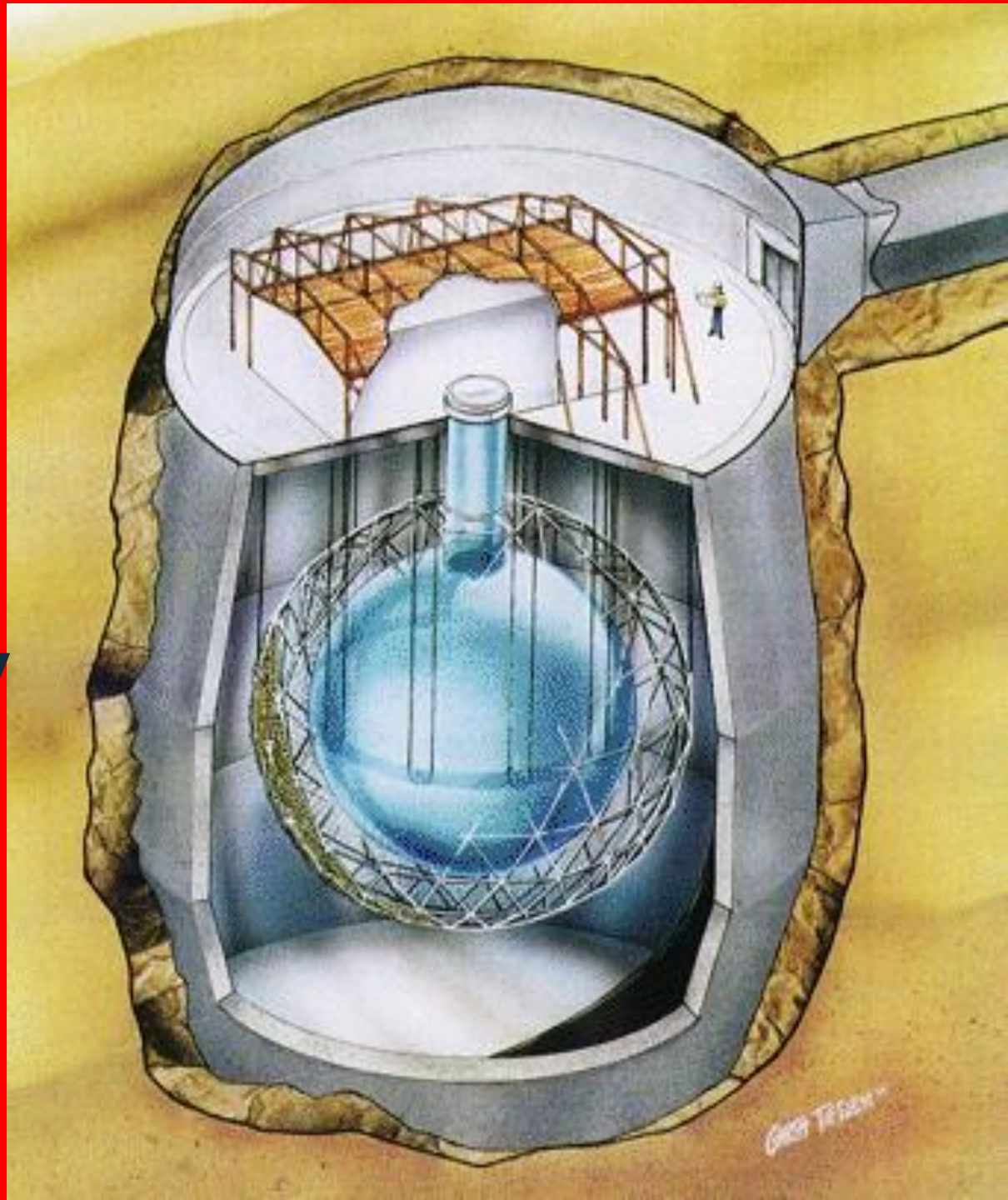
TAKAAKI KAJITA

2001 =>

Canada

Sudbury
Neutrino
Obervatory

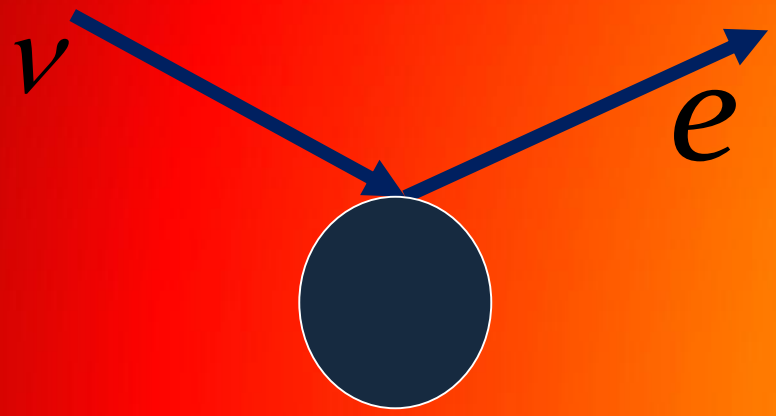
SNO



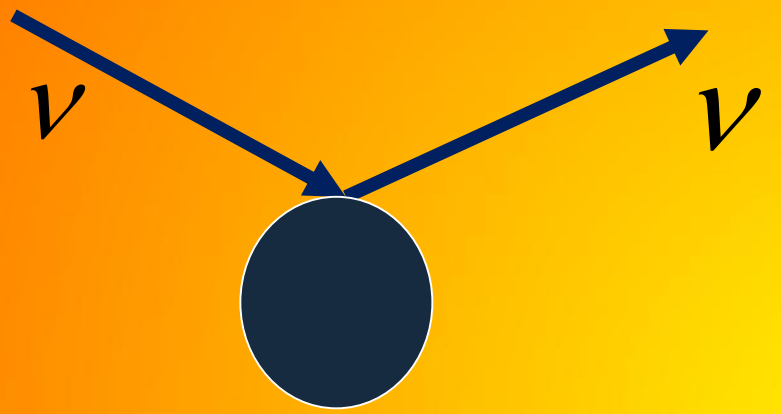
SNO

SOLAR NEUTRINOS

charged current

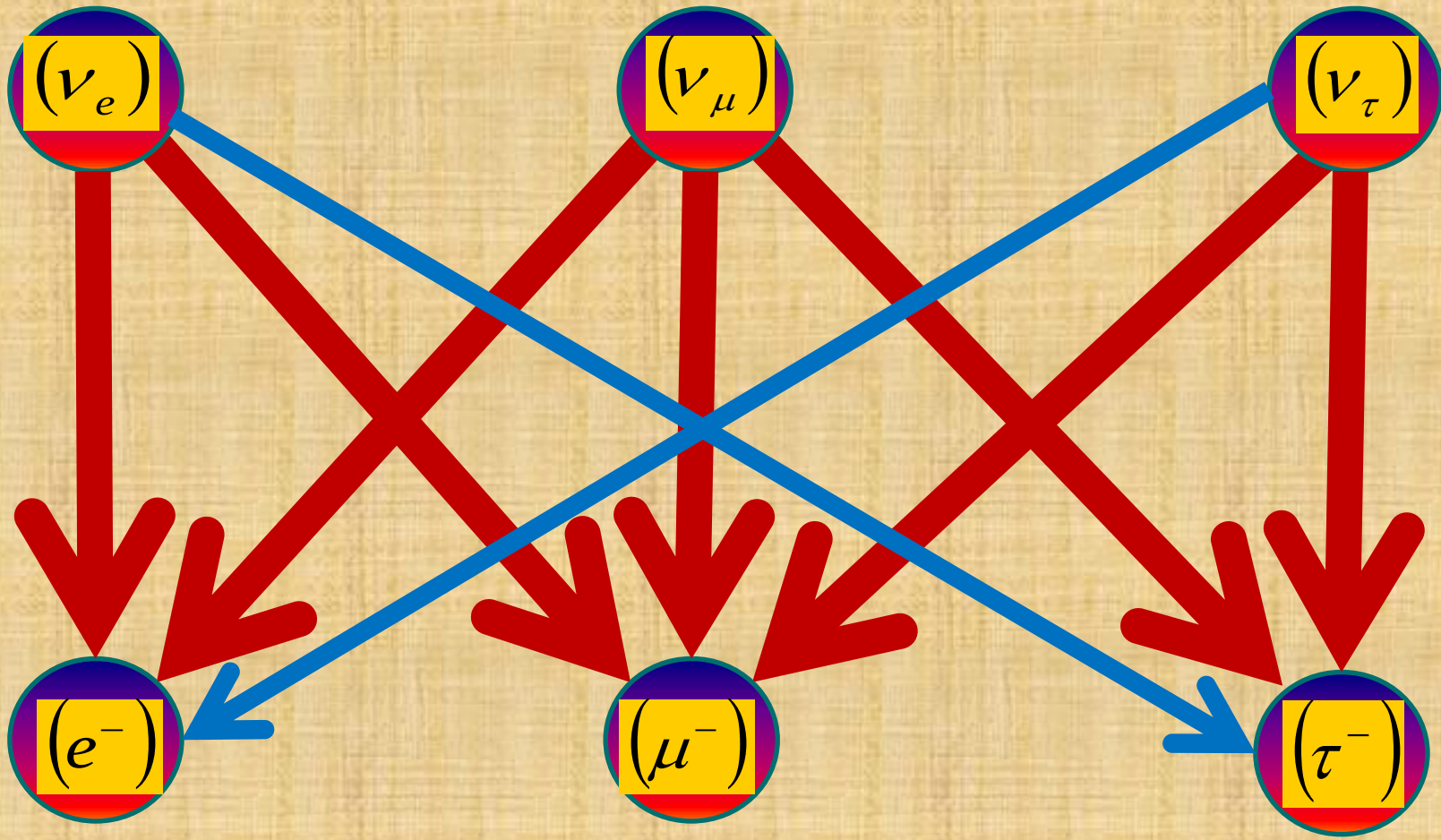


neutral current



Arthur McDonald

Nobel Prize 2015



FLAVOR MIXING

LEPTONS

neutrino mixing matrix

(==> CKM Matrix)

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

V = U P

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

$$U = \begin{bmatrix} \cos\theta_l & \sin\theta_l & 0 \\ -\sin\theta_l & \cos\theta_l & 0 \\ 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} e^{-i\varphi} & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \bullet \begin{bmatrix} \cos\theta_\nu & -\sin\theta_\nu & 0 \\ \sin\theta_\nu & \cos\theta_\nu & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

Fritzsch - Xing

Kamiokande - SNO

$$32^o \leq \theta_{sun} \leq 35^o$$

$$37^o \leq \theta_{at} \leq 40^o$$

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \cdot 10^{-5} eV^2$$

$$\Delta m^2_{32} = 2.43^{+0.06}_{-0.10} \cdot 10^{-3} eV^2$$

texture zeros

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

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

$$\tan\theta_{l} = \sqrt{\frac{m_e}{m_\mu}}$$

OBSERVATION

$$32^{o} \leq \theta_{sun} \leq 35^{o}$$

$$\Longrightarrow m_1 / m_2 = 0.39 \ldots 0.49$$

$$\Delta m^2_{21} \approx 7.5 \cdot 10^{-5} eV^2$$

$$\Delta m^2_{32} \approx 2.4 \cdot 10^{-3} eV^2$$

$$m_1 / m_2 \approx 0.44$$

==> neutrino masses

NEUTRINO MASSES

(eV)

$$m_1 \approx 0.004$$

$$m_2 \approx 0.010$$

$$m_3 \approx 0.050$$

$$\theta_{at} \approx \arctan\sqrt{\frac{m_2}{m_3}} + \arctan\sqrt{\frac{m_\mu}{m_\tau}}$$

$$\theta_{at} \approx 24^0 + 14^0$$

$$\theta_{at} \approx 38^0$$

???????? ????????

neutrino masses

very small

???????? ????????

1906 => 1938

Dirac mass ?

Majorana mass ?

seesaw mechanism

$$M_\nu = \begin{bmatrix} 0 & D \\ D & M \end{bmatrix}$$

$$m_\nu \cong \frac{D^2}{M}$$

HISTORY SEESAW

Footnote:

H. Fritzsch

M. Gell-Mann

P. Minkowski

PLB 59 (1975) 256

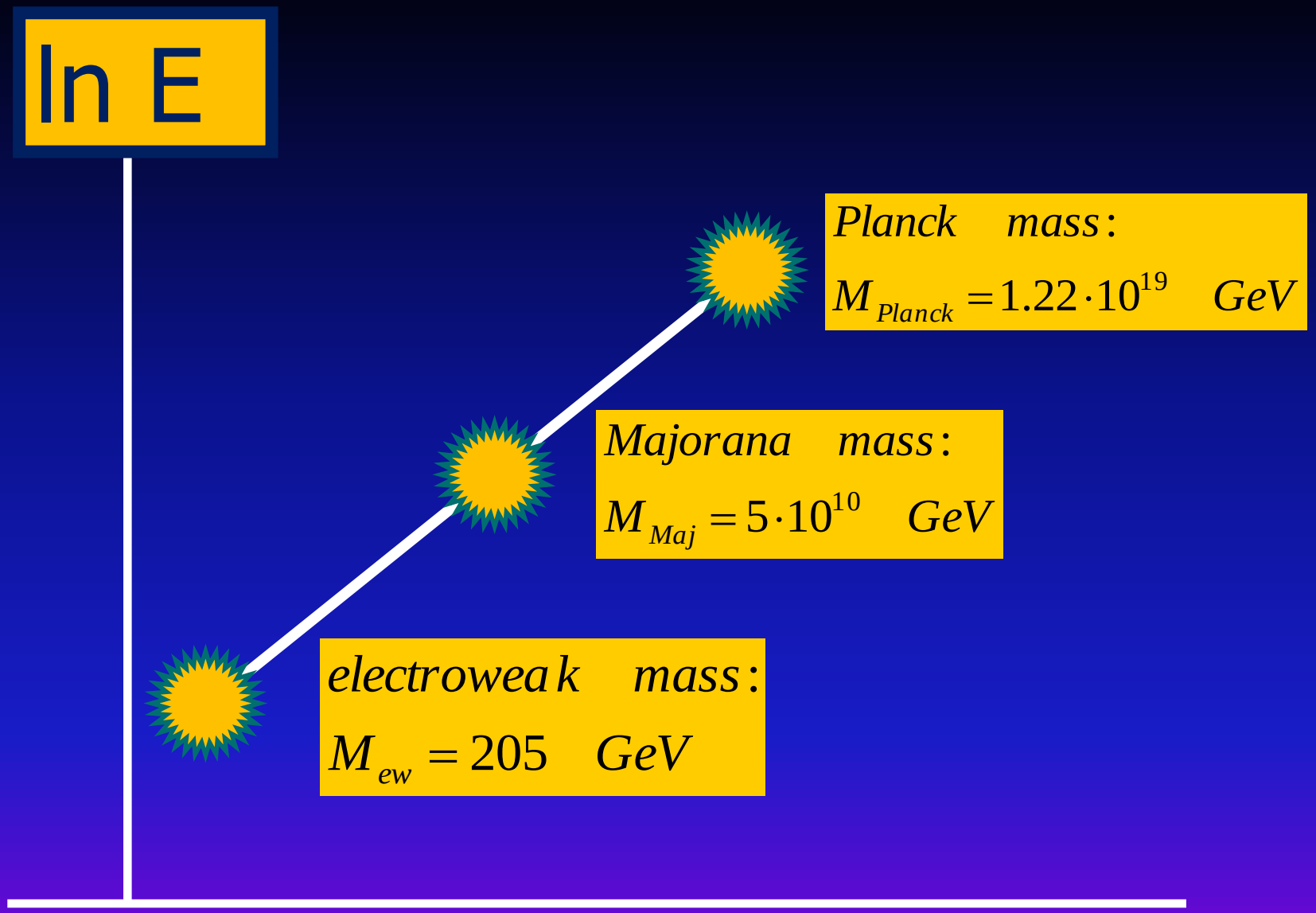
P. MINKOWSKI,
PLB 1976

T. Yanagida 1979

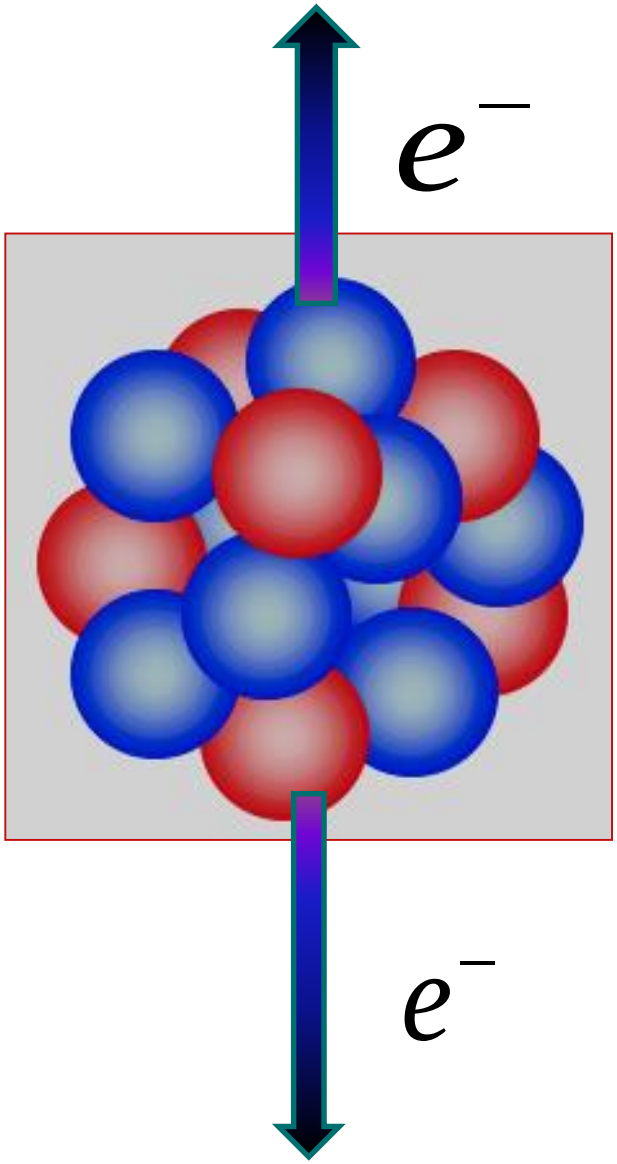
M. Gell-Mann, P. Ramond, R. Slansky 1979

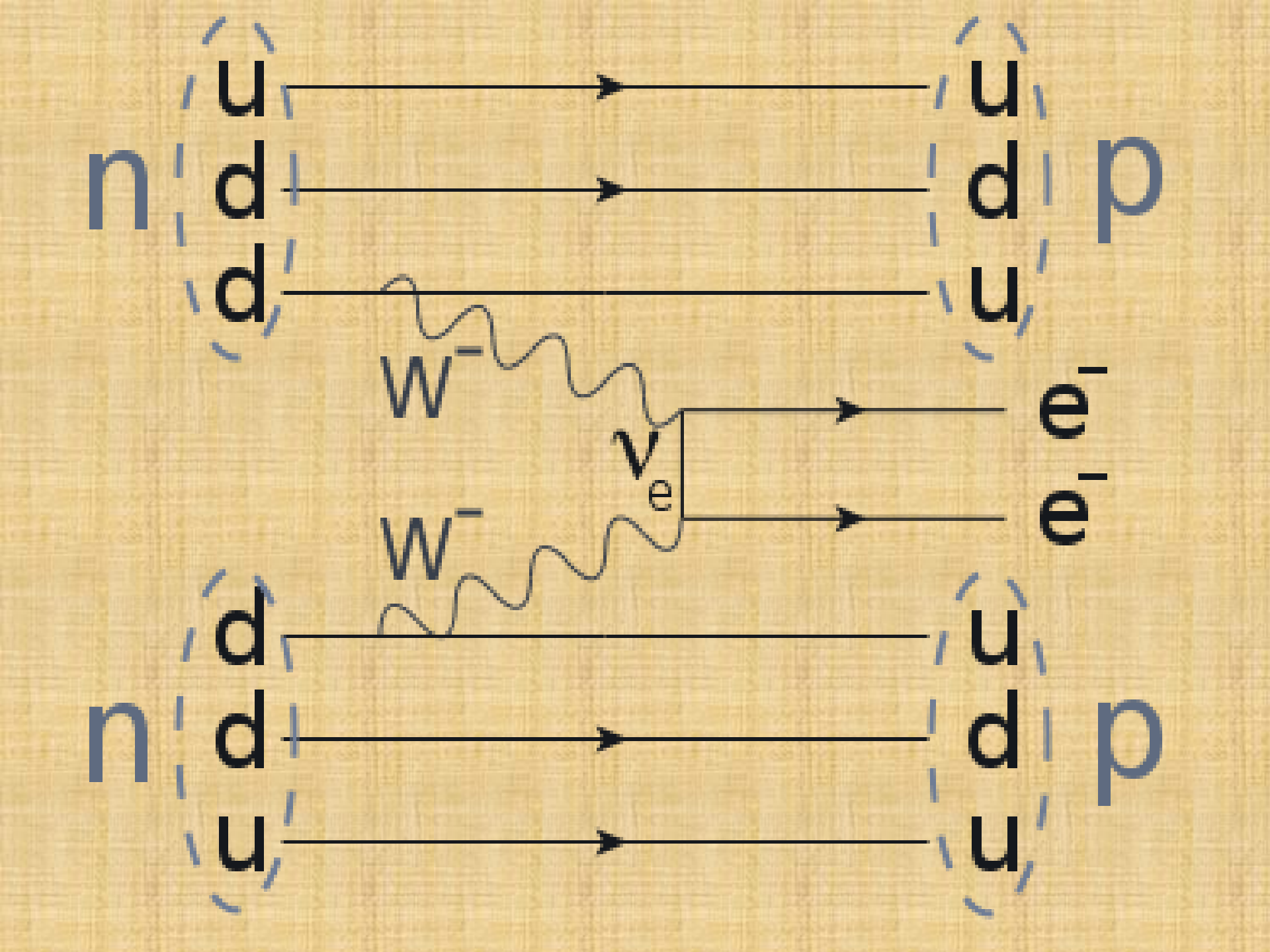
$$m_{\nu_\tau} = 0.050 \quad eV = \frac{m_\tau^2}{M_{Maj}}$$

$$M_{Maj} = 5 \cdot 10^{10}\, GeV$$


ln E
Planck mass:
$M_{Planck} = 1.22 \cdot 10^{19}$ GeV
Majorana mass:
$M_{Maj} = 5 \cdot 10^{10}$ GeV
electroweak mass:
$M_{ew} = 205$ GeV

NEUTRINOLESS DOUBLE BETA DECAY

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W⁻
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Gran Sasso Laboratory

CUORE EXPERIMENT

$$T_{1/2}^{0\nu}(^{130}Te) \geq 1.8 \cdot 10^{24}\ years$$

Effective Majorana neutrino mass:

< 0.243 eV

KAMLAND EXPERIMENT

Effective Majorana neutrino mass:

$$< 0.115 \text{ eV}$$

relevant mass term:

$$m_{eff.} = | V_{1e}^2 \cdot m_1 + V_{2e}^2 \cdot m_2 + V_{3e}^2 \cdot m_3 |$$

EXPECTED:

$$m_{eff.} \approx 0.005 eV$$

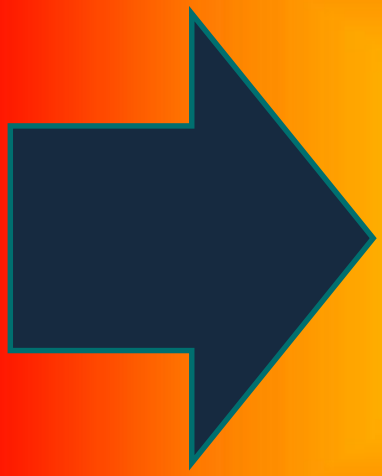
OBSERVED:

$$m_{eff.} < 0.115 eV$$

CONCLUSIONS

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

texture zeros



$$\tan\theta_u = \sqrt{\frac{m_u}{m_c}}$$

$$\tan\theta_d = \sqrt{\frac{m_d}{m_s}}$$

$$\theta_u \approx 5.0^o \pm 0.7^o$$

$$Exp: 5.4^o \pm 1.1^o$$

$$\theta_d \approx 13.0 \pm 0.4^o$$

$$Exp: 11.7^o \pm 2.6^o$$

NEUTRINO MASSES

(eV)

$$m_1 \approx 0.004$$

$$m_2 \approx 0.010$$

$$m_3 \approx 0.050$$

$$\theta_{at} \approx 38^{o}$$