flavor mixing

Masses -
Charged leptons and quarks (MeV)

electron: 0.51 muon: 105.7 tau: 1 777

u: 5.3 c: 1 200 t: 173 000

d: 7.8 s: 130 b: 4 300

(u, d, c, s - quark masses at 1 GeV)

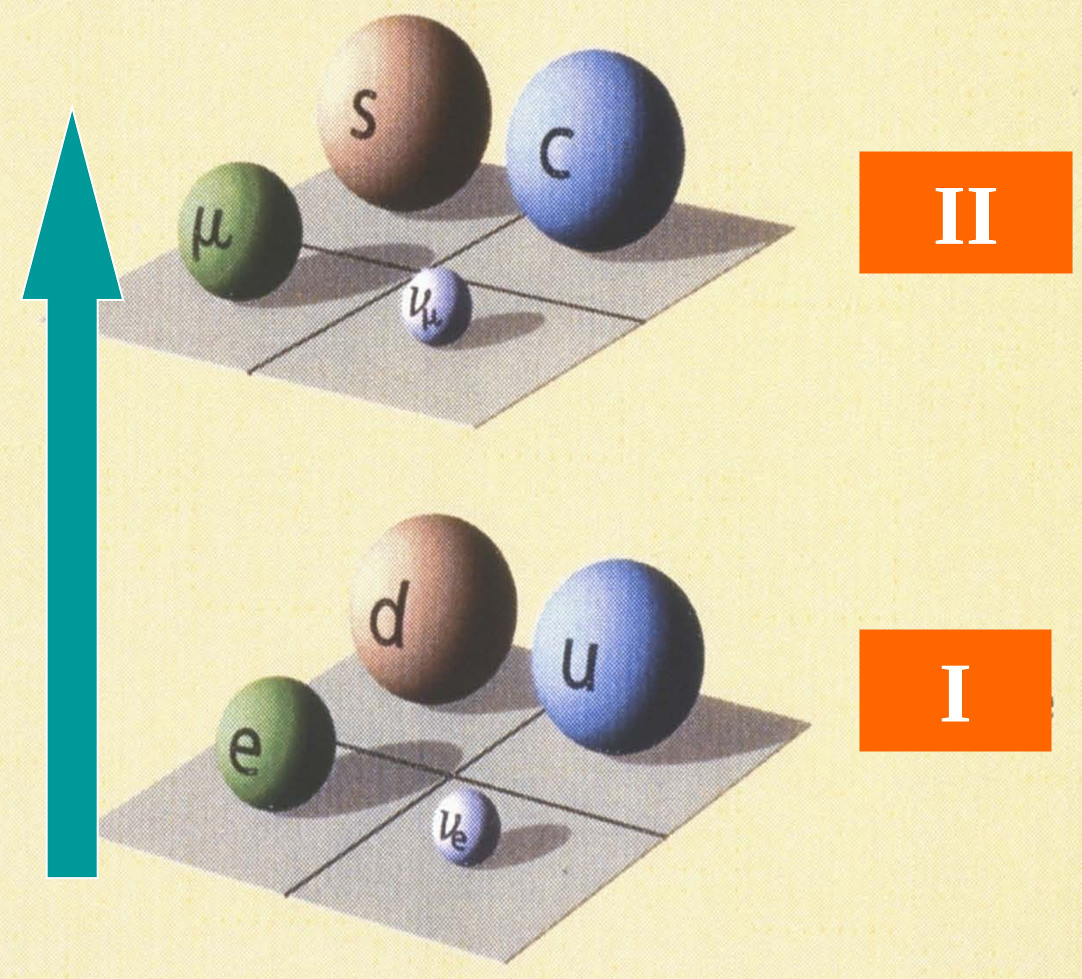
flavor mixing angles

↕

fermion masses

flavor mixing

2 families



$$\left\langle \frac{u}{d\cos\theta_c + s\sin\theta_c} \right\rangle ==== \left\langle \frac{c}{-d\sin\theta_c + s\cos\theta_c} \right\rangle$$

mixing of mass eigenstates by weak interaction

(Cabibbo angle)

$$\theta_c \approx 13^0$$

mass matrices:

texture 0

u,c - d,s

$$\begin{pmatrix} 0 & a \\ a^{\otimes} & b \end{pmatrix}$$

H. Fritzsch
S. Weinberg
1978

texture zero

SU(2) x SU(2)

SU(2) x SU(2)

==>

Grand Unification

Grand Unification

SU(3)xSU(2)xU(1)

==>SO(10)

Fritzsch - Minkowski; Georgi - 1975

SO(10)

SO(6) x SO(4)

SU(4) x SU(2,L) x SU(2,R)

SU(3) x SU(2,L) x U(1)

In SO(10):

lefthanded and righthanded neutrinos

Electroweak theory:

$SU(2)_L \times SU(2)_R \times U(1)$

↑

M(W,R) >> M(W,L)

Weak gauge group:

$$SU(2)_L \times SU(2)_R \times U(1)$$

2 scalars:

$$\left(\frac{1}{2}, \frac{1}{2}\right)$$

$$U = \begin{pmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{pmatrix} \quad V = \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix}$$

Interaction

$$g_1 \overline{(u_0, d_0)}_L \, U \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_R + g_2 \overline{(u_0, d_0)}_L \, U \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_R$$

$$+ g_3 \overline{(c_0, s_0)}_L \, U \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_R + g_4 \overline{(c_0, s_0)}_L \, U \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_R$$

$$+ \text{h.c.} + U \longrightarrow V, \quad g_1 \longrightarrow g_1', \text{etc.}$$

$$+ g_5 \overline{(u_0, d_0)}_L \, \tau_2 U^{+} \tau_2 \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_R + \ldots$$

$$+ U^{*} \longrightarrow V^{+}, \quad g_5 \longrightarrow g_5'.$$

U(1) x U(1) symmetry

$$\begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_L \to e^{i\alpha} \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_L \qquad \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_R \to e^{-i\alpha} \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_R$$

$$\begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_L \to e^{i\beta} \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_L \qquad \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_R \to e^{-i\beta} \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_R$$

$$U \to e^{2\beta i} U \qquad V \to e^{i(\alpha+\beta)} V$$

$$\rightarrow g\,\overline{(c_0, s_0)}_L \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_R + h\,\overline{(c_0, s_0)}_L V \begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_R$$

$$+ h'\,\overline{(u_0, d_0)}_L V \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_R + h.c.$$

==> mass matrix

$$\begin{pmatrix} 0 & a \\ a^* & b \end{pmatrix}$$

mixing angles <=> masses

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

$$\tan 2\theta_u = \frac{2\sqrt{m_u m_c}}{m_c - m_u} \qquad \theta_u \approx \sqrt{\frac{m_u}{m_c}}$$

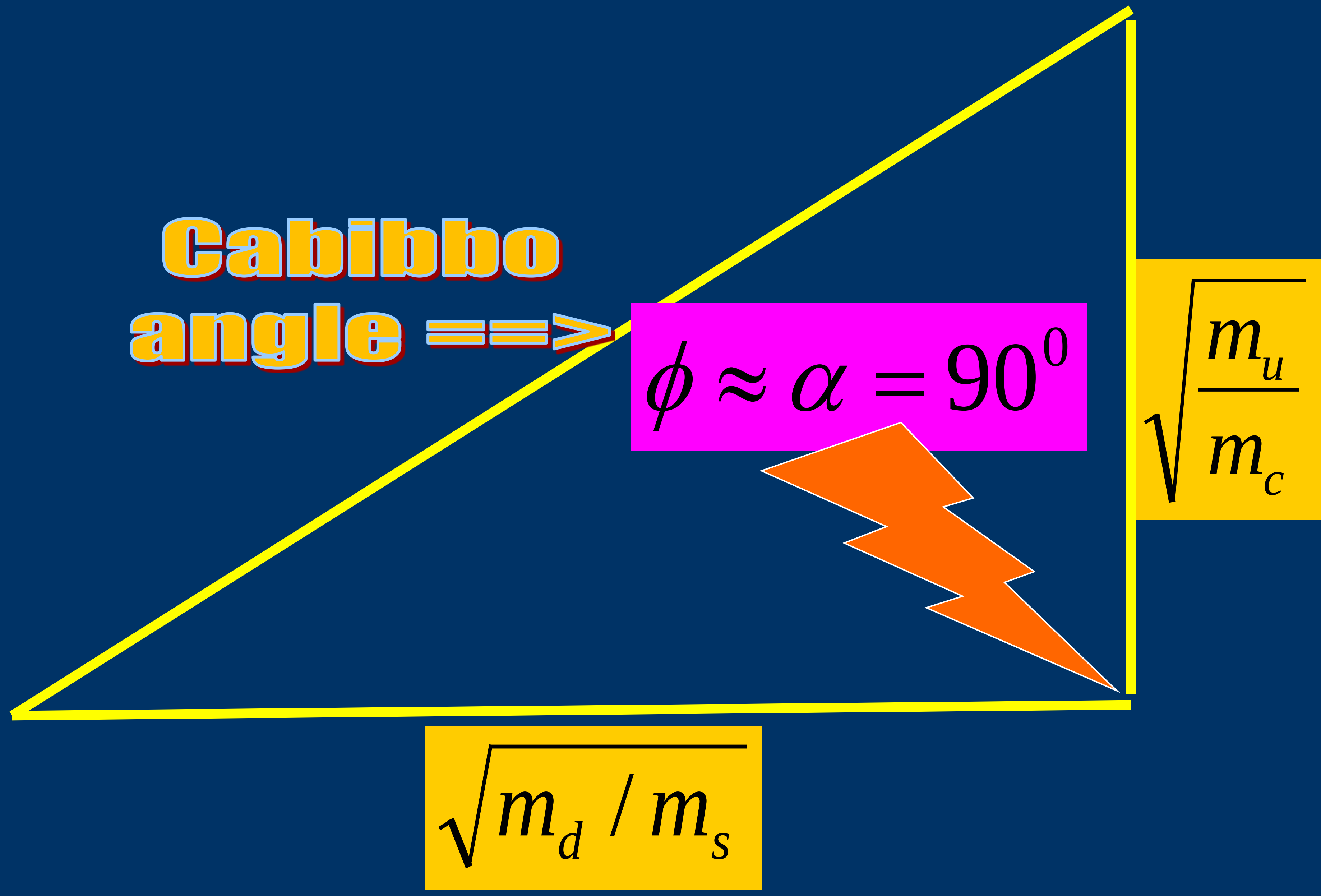
$$\sqrt{\frac{m_d}{m_s}} \approx 0.21$$

$$\sqrt{\frac{m_u}{m_c}} \approx 0.07$$

Cabibbo angle

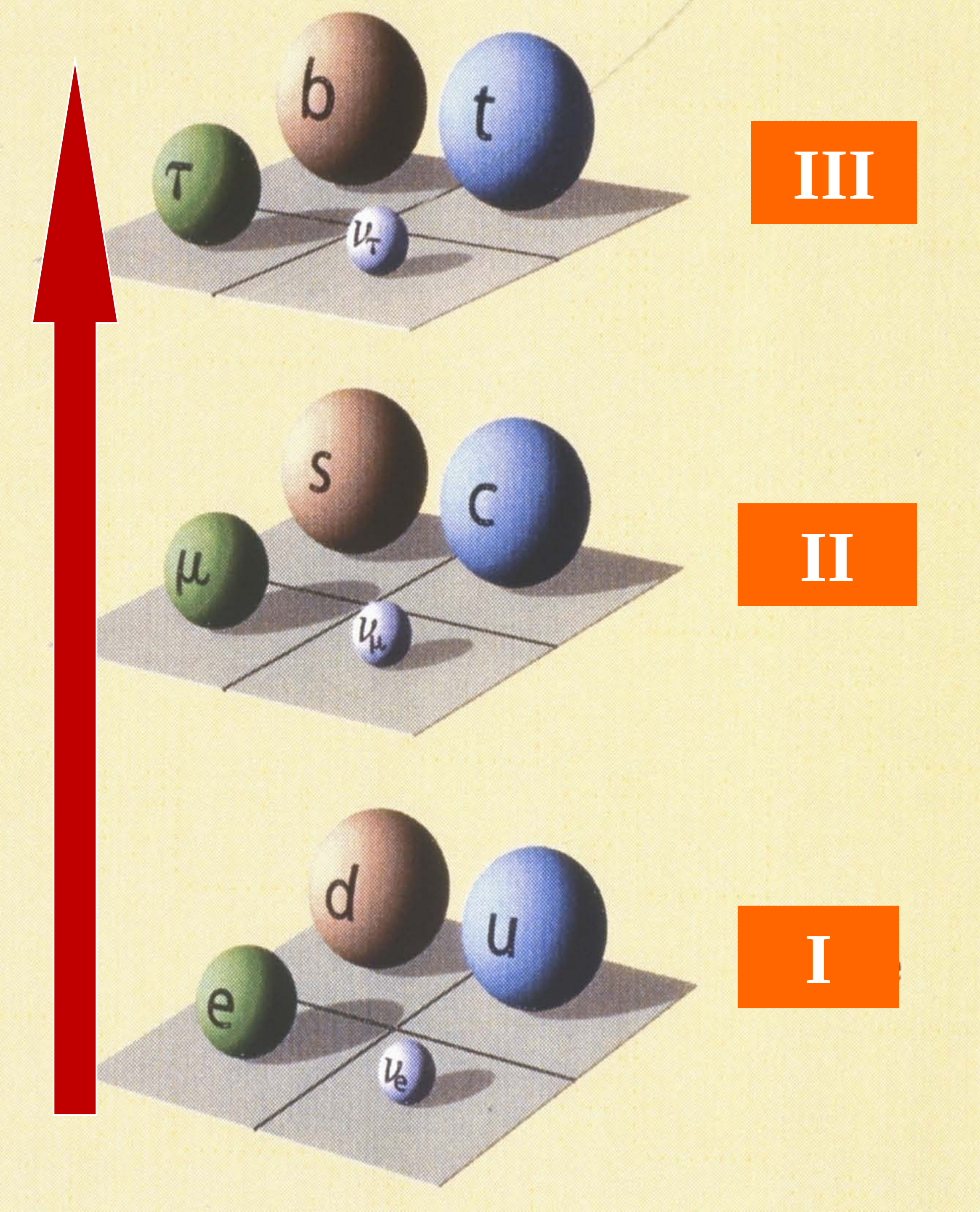
$$13^o$$

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


Cabibbo angle ==>
$\phi \approx \alpha = 90^0$
$\sqrt{\frac{m_u}{m_c}}$
$\sqrt{m_d / m_s}$

3 families

flavor mixing



6 leptons – 6 quarks

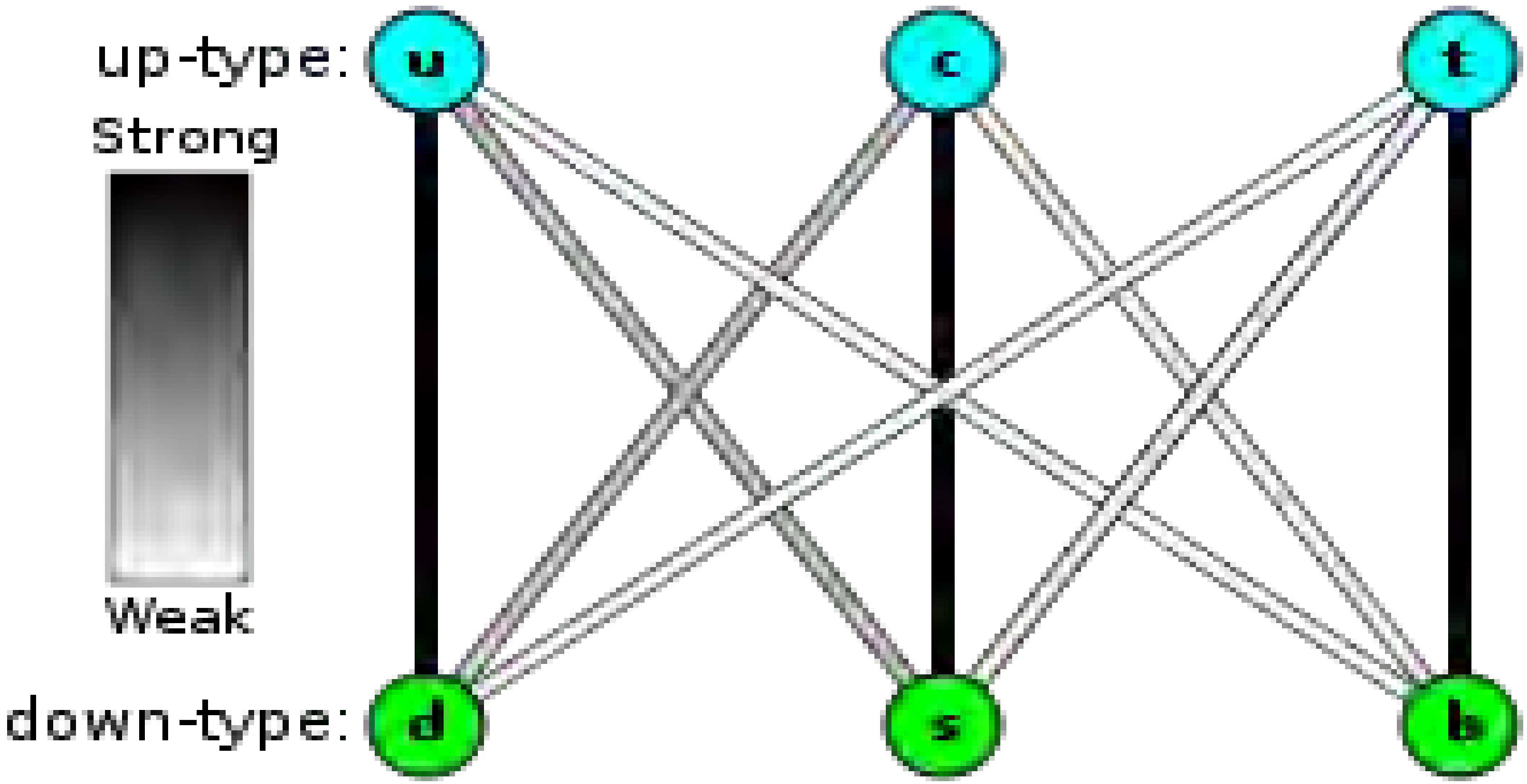
$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix} \qquad \begin{pmatrix} u & c & t \\ d' & s' & b' \end{pmatrix}$$

3 doublets

$$\begin{pmatrix} d' & s' & b' \end{pmatrix}$$

flavor mixing

$$\begin{pmatrix} d & s & b \end{pmatrix}$$



weak transitions and weak mixing

CKM-matrix

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

observed CKM – matrix

$$\begin{bmatrix} 0{,}97459 & 0{,}2257 & 0{,}00359 \\ 0{,}2256 & 0{,}97334 & 0{,}0415 \\ 0{,}00874 & 0{,}0407 & 0{,}999133 \end{bmatrix}$$

flavor mixing =>

CKM - matrix

three angles - one phase

CKM matrix

standard parametrization

$$angles: \theta_{12}, \theta_{23}, \theta_{13}$$

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \bullet \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \bullet \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

New parametrization:

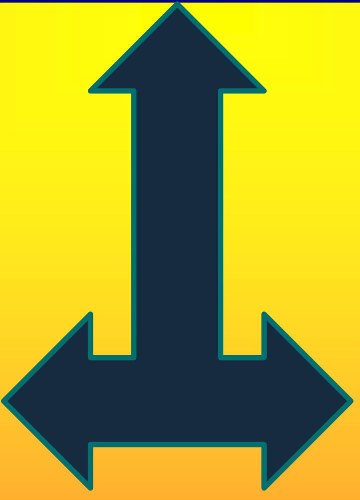
$$V = \begin{bmatrix} c_u & s_u & 0 \\ -s_u & c_u & 0 \\ 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} e^{-i\phi} & 0 & 0 \\ 0 & c & s \\ 0 & -s & c \end{bmatrix} \bullet \begin{bmatrix} c_d & -s_d & 0 \\ s_d & c_d & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

H. Fritzsch - Z. Xing

texture zeros:

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

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



$$\frac{V_{ub}}{V_{cb}} \cong \sqrt{\frac{m_u}{m_c}} \qquad \frac{V_{td}}{V_{ts}} \cong \sqrt{\frac{m_d}{m_s}}$$

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

$$\Updownarrow$$

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

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

The angles

$$\theta_u \quad - \quad \theta_d$$

have been measured separately.

SLAC
DESY
KEK
FNAL
CERN

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

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

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

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

$$\tan\theta_u = \sqrt{m_u} \,/\, \sqrt{m_c}$$

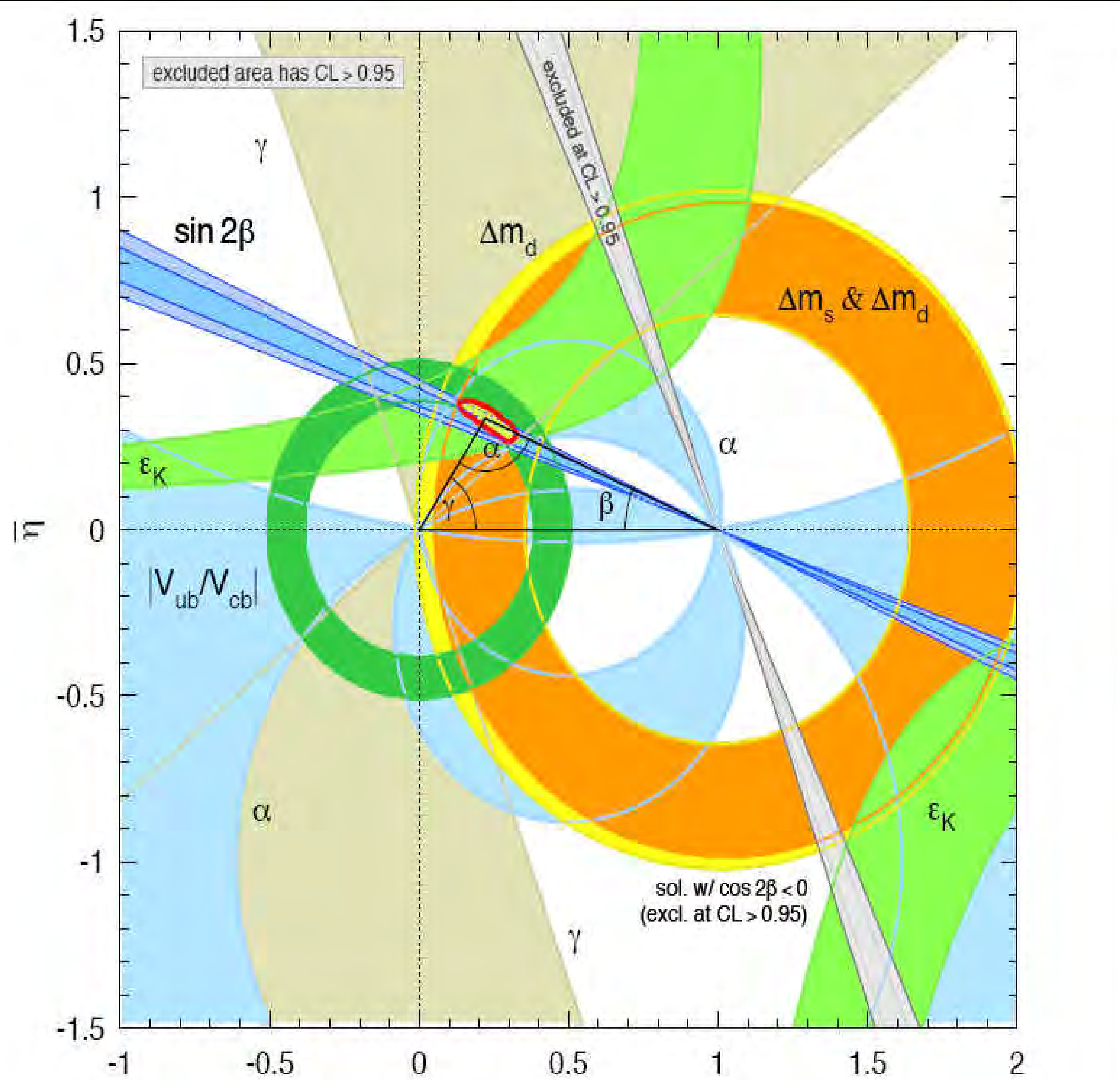
$$\theta_u \approx 5.0^o \pm 0.7^o$$

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

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

unitarity triangle

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



alpha: 86 ... 95 degrees

Cabibbo angle

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

$$\sqrt{m_d / m_s}$$

$$\phi \approx \alpha = 90^0$$

Unitarity triangle

(rectangular)

Unitarity triangle:

$$\tan\beta = \frac{\sin\theta_u \cos\theta_d}{\cos\theta_u \sin\theta_d}$$

==>

$$\sin 2\beta \cong 0.663$$

$$Exp: \sin 2\beta = 0.681 \pm 0.025$$

$$\phi \approx \alpha = 90^0$$

Maximal CP-violation

neutrinos

Standard Model

neutrinos => lefthanded

no mass

neutrino oscillations

Since 1998:

Observation of neutrino oscillations in Kamioka (Japan)

➔Neutrinos must have a mass

$$\left\langle \frac{u}{d\cos\theta_c + s\sin\theta_c} \right\rangle \left\langle \frac{c}{-d\sin\theta_c + s\cos\theta_c} \right\rangle$$

$$\left\langle \frac{\nu_e}{e} \right\rangle \left\langle \frac{\nu_\mu}{\mu} \right\rangle$$

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

$$\nu_\mu = -\sin\theta \cdot \nu_1 + \cos\theta \cdot \nu_2$$

Pontecorvo - 1957

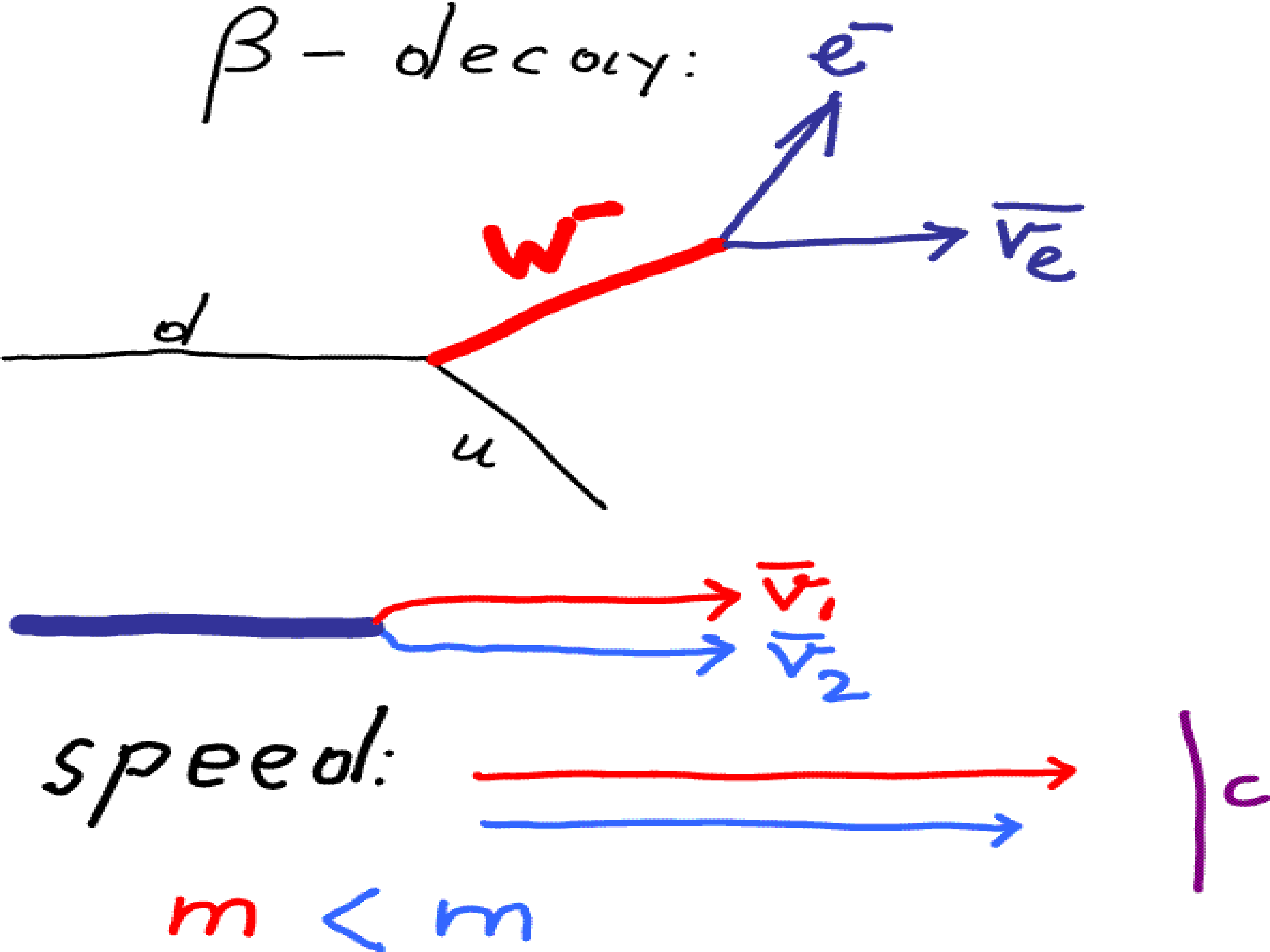
neutrino mixing

Bruno Pontecorvo

1913 - 1993

A neutrino is produced with a certain momentum.
The different mass eigenstates propagate with different velocities, less than the speed of light. The composition of the neutrino state is changing.

→ neutrino oscillation



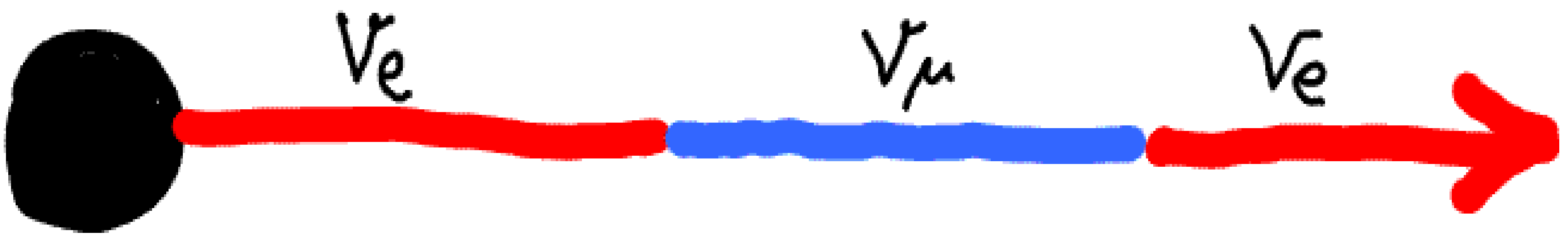
β - decay:
e⁻
W⁻
ν̄e
d
u
ν̄1
ν̄2
speed:
c
m < m

neutrino oscillation

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

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

$$\Theta = \pi/2$$



propagation of neutrino: mass eigenstate

$$\left|\nu_i(t)\right\rangle = e^{-i(E_i t - \vec{p}\vec{x})}\left|\nu_i(0)\right\rangle$$

$$\left|\vec{p}\right| >> m_i$$

$$===> E_i = \sqrt{\vec{p}^2 + m_i^{\ 2}} \approx E + \frac{m_i^{\ 2}}{2E}$$

$$\left|\nu_i(L)\right\rangle = e^{-im_i^{\ 2}L/2E}\left|\nu_i(0)\right\rangle$$

$$\hbar = c = 1$$

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}\vec{x})} |\nu_i(0)\rangle$$

$$|\vec{p}_i| \gg m_i$$

$$\longrightarrow$$

$$E_i = \sqrt{(\vec{p}_i)^2 + m_i^2}$$

$$\cong |\vec{p}_i| + \frac{m_i^2}{2p_i} \approx E + \frac{m_i^2}{2E}$$

$$t \approx L$$

$$|\nu_i(L)\rangle = e^{-i m_i^2 L/2E} |\nu_i(0)\rangle$$

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

ν_α: ν_e, ν_μ, ν_τ

ν_i: 3 mass eigenstates

---

probability to change flavor:

$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2$$

$$= \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-i\cdot m_i^2 L/(2E)}\right|^2$$

2 - neutrino case

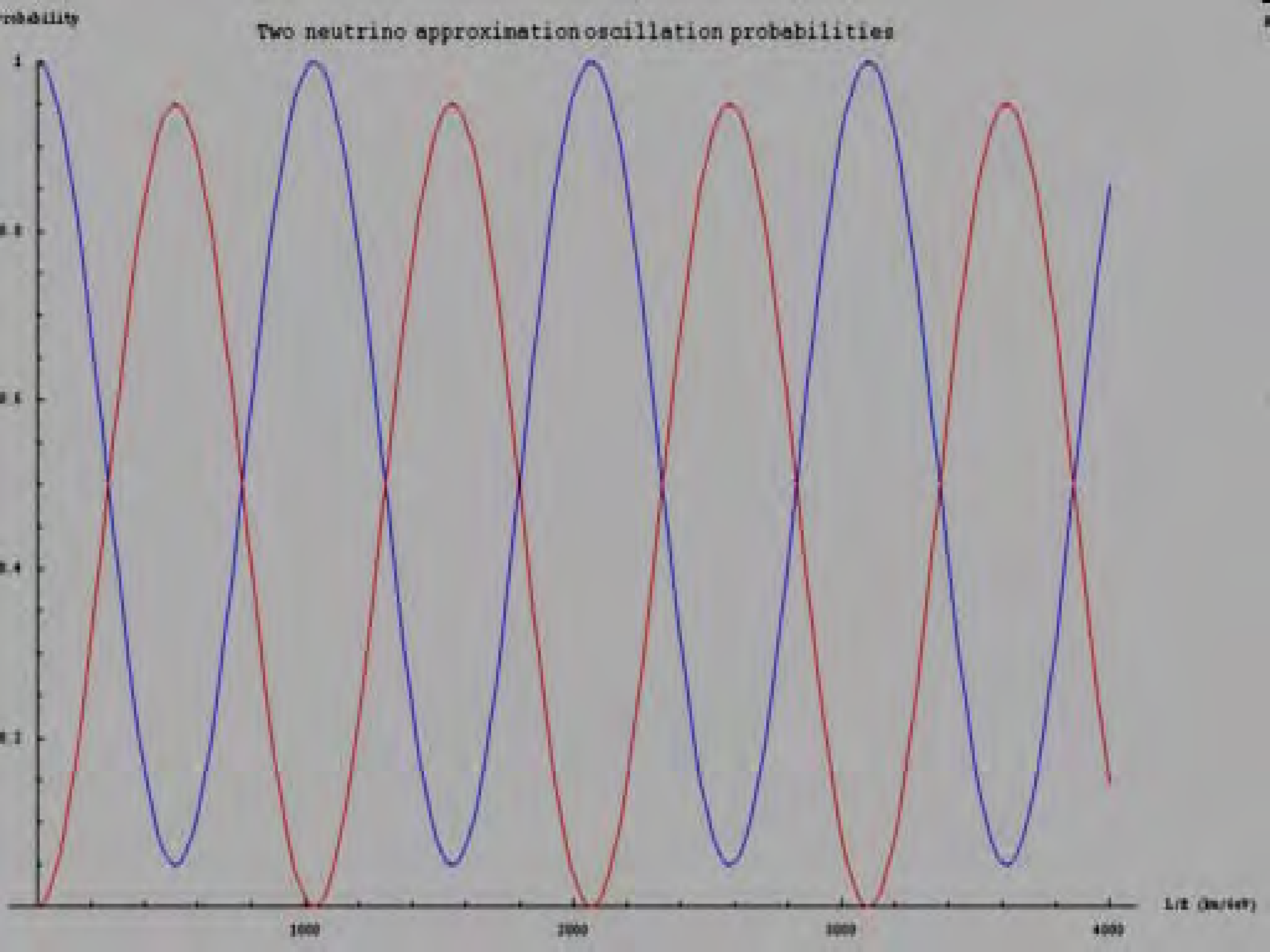
(ν_e, ν_μ)

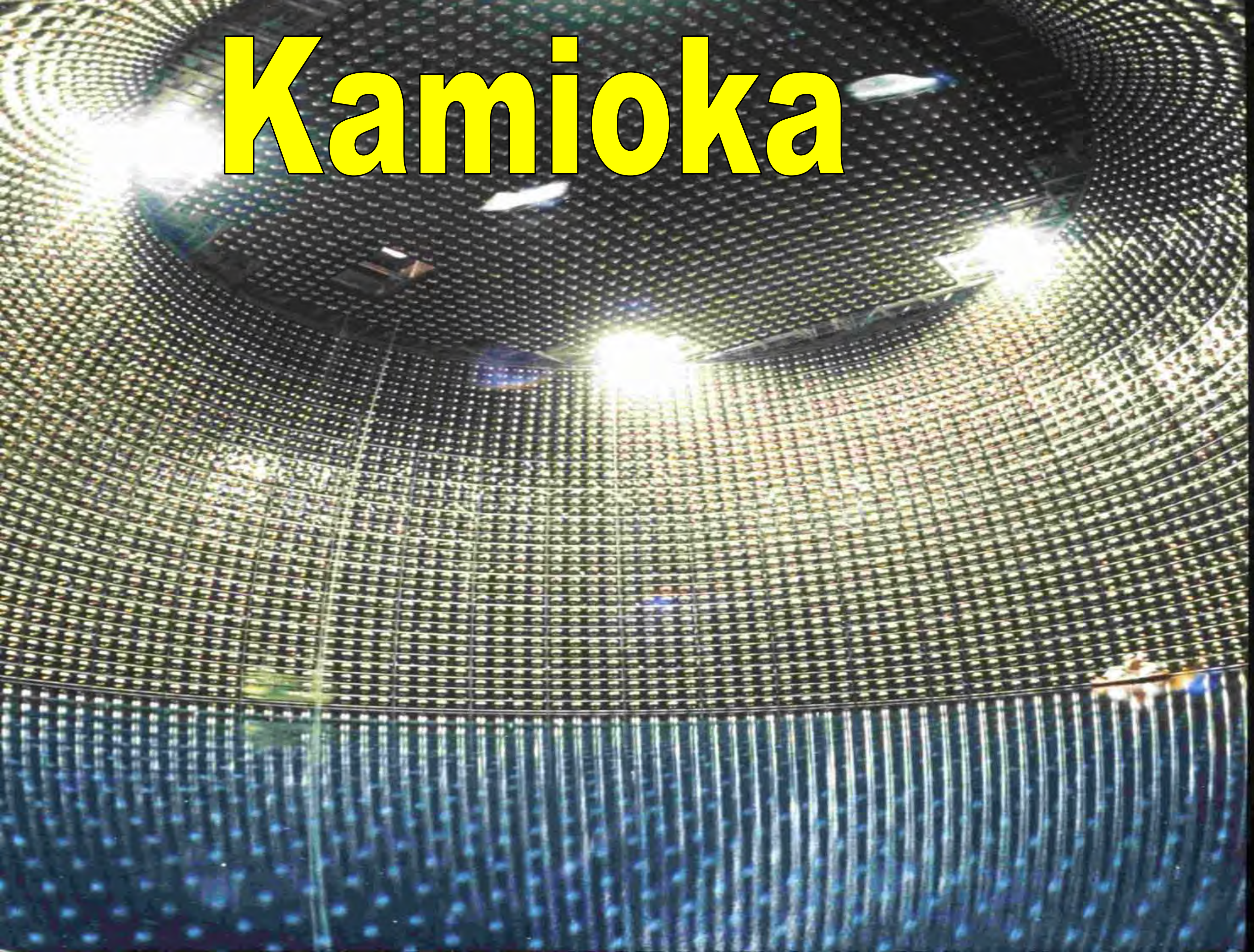
$$U \longrightarrow \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

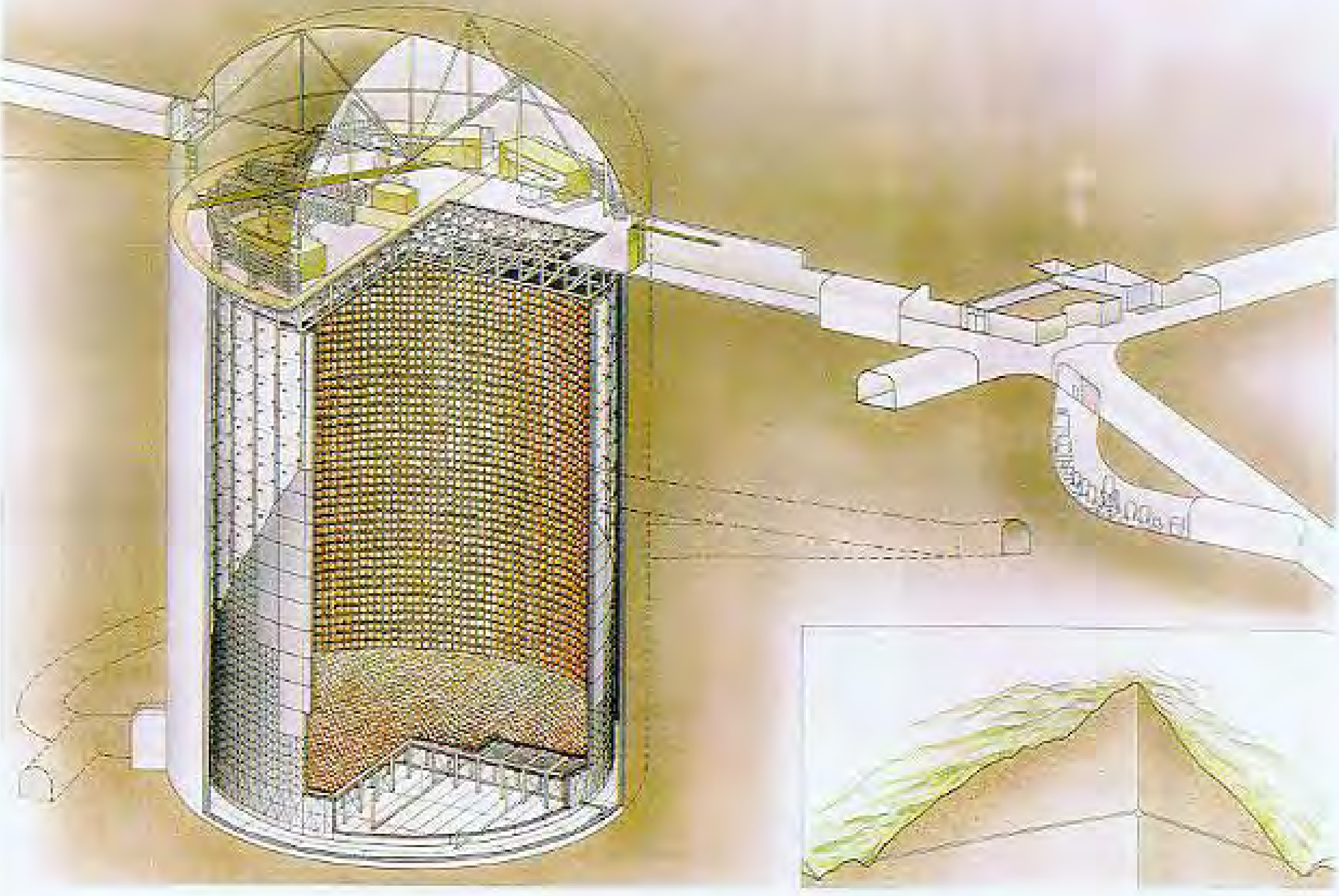
$$P_{\alpha\to\beta}(\alpha \neq \beta) =$$

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

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


Two neutrino approximation oscillation probabilities
Probability
1
0.8
0.6
0.4
0.2
1000
2000
3000
4000


Kamioka



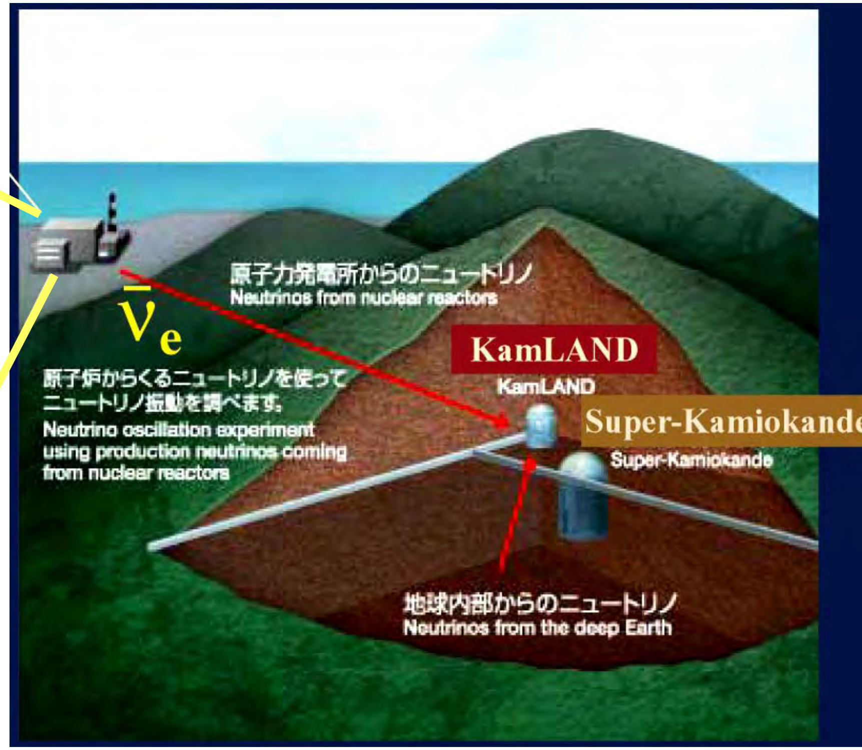
SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SEKKEI

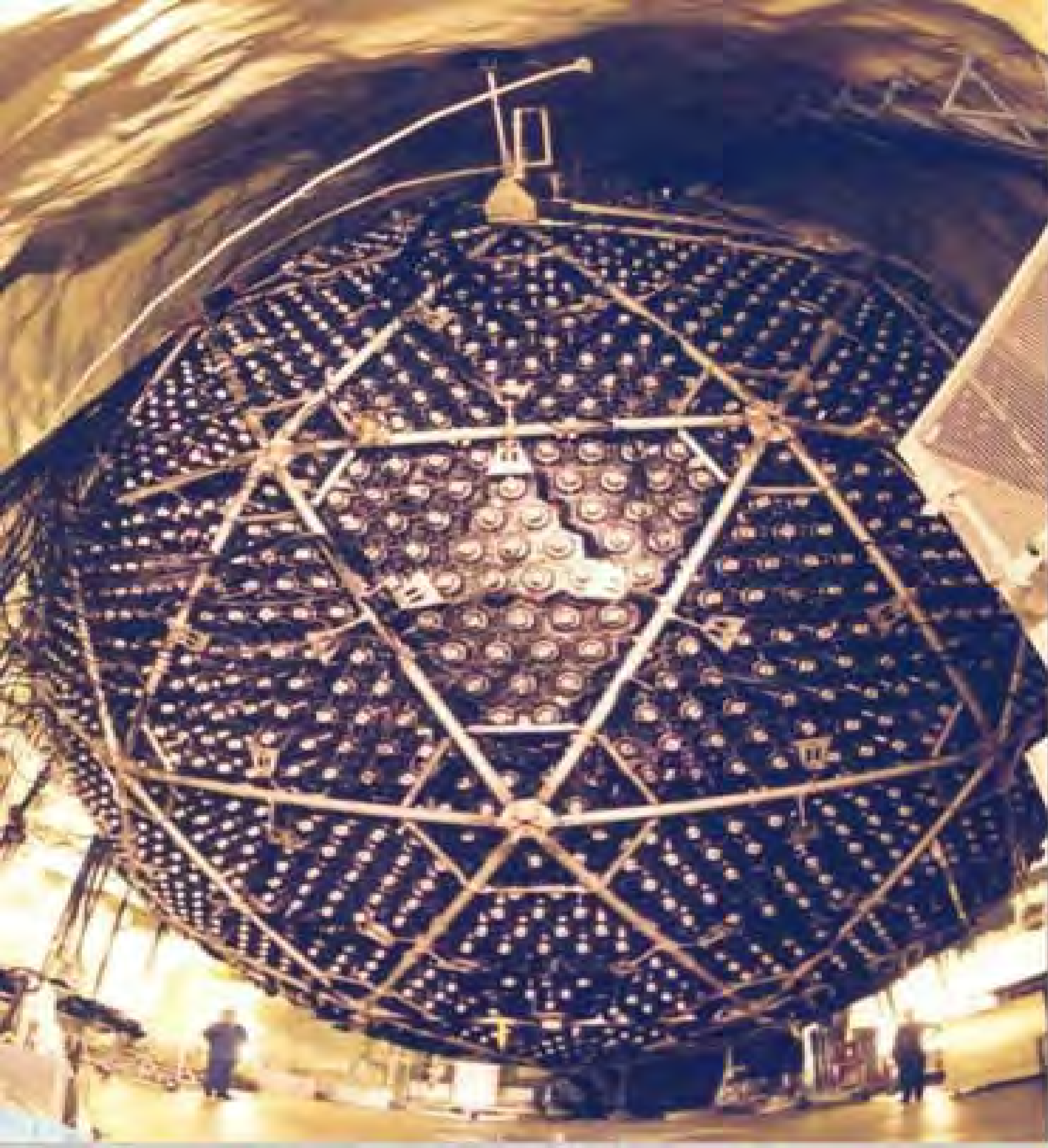

Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
250 km
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotron
Front
Detector

Kamland experiment (Kamioka)


Kashiwazaki Nuclear Power Station : 25 GW



- Long Baseline (180 km)
- Calibrated source(s)
- Large detector (1 kton)
- Deep underground (2700 mwe)



S N O

Sudbury Neutrino Observatory

Canada

Sudbury Neutrino Observatory (SNO)

- Schwer-Wasser-Čerenkov-Detektor
- Ontario, USA

Kessel, Ø 12m

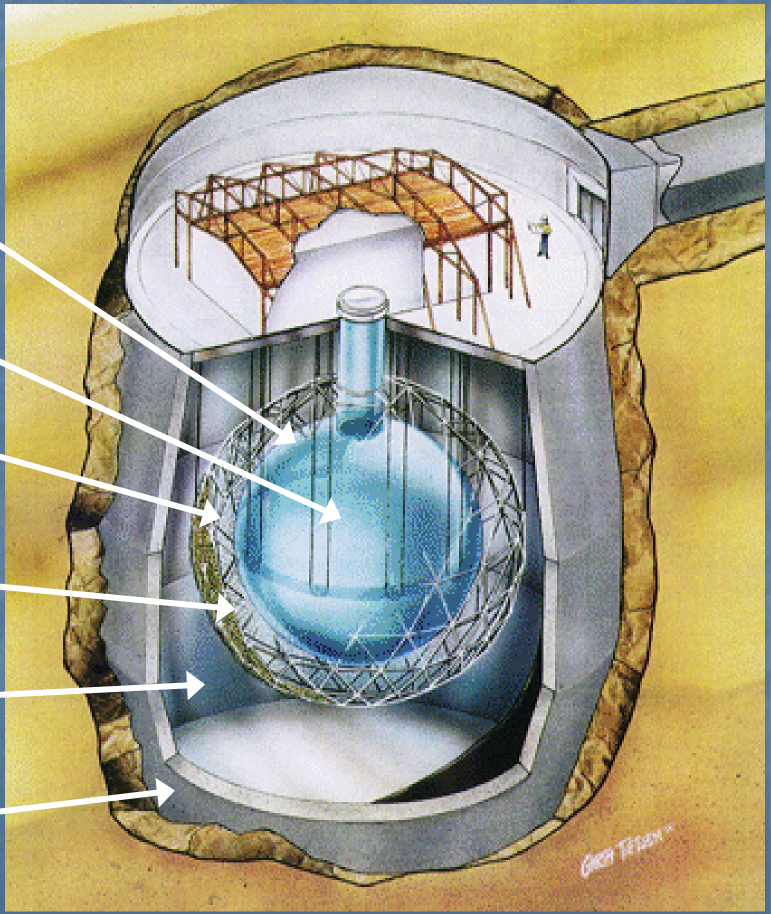
1000 t D_2O

Unterstützungsstruktur
9500 PMTs
(60% Abdeckung)

innere Wasserabschirmung
1700 t

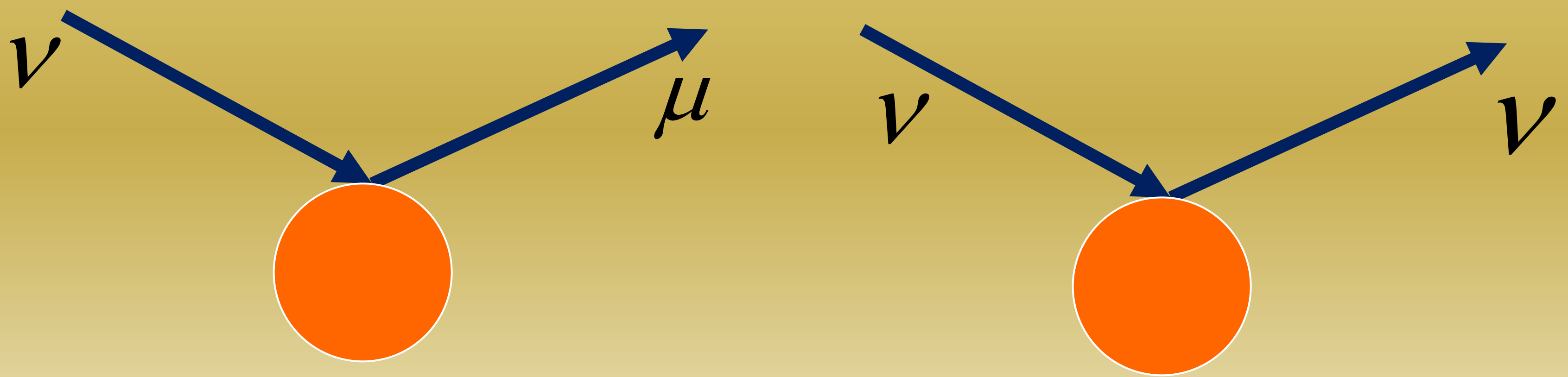
äußere Wasserabschirmung
5300 t

Abschirmung



S N O

charged current and neutral current



neutrino oscillations:

neutrinos

→

massive fermions

Kamiokande, SNO, Kamland

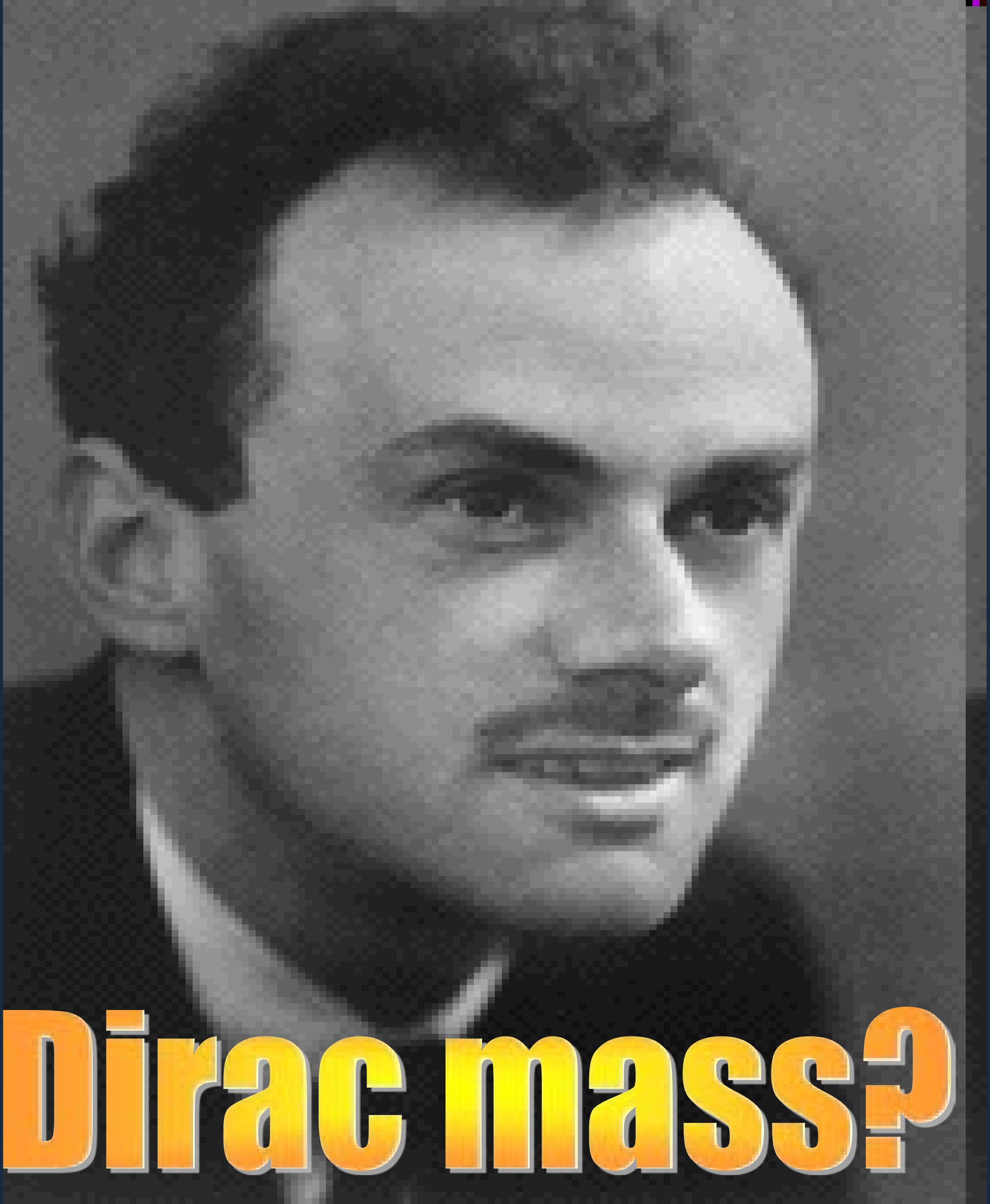
neutrino mass differences

$$\Delta m_{21}{}^{2} \approx 8^{+0.6}_{-0.4} \cdot 10^{-5} eV^{2}$$

$$\Delta m^{2}_{32} \approx 2.4^{+0.6}_{-0.5} \cdot 10^{-3} eV^{2}$$

neutrino masses

type of mass term?


Dirac mass?

Majorana mass?

Superposition of Dirac mass and Majorana mass:

See-Saw Mechanism

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

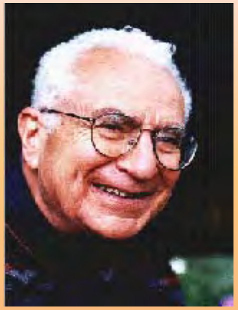
D: Dirac mass

M: Majorana mass

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

Minkowski 1976
Yanagida
Gell-Mann, Ramond, Slansky
1978

History of Seesaw



Footnote:
H. Fritzsch, M. Gell-Mann,
P. Minkowski, PLB 59 (1975) 256

This idea was very clearly elaborated by Minkowski in his paper PLB 67 (1977) 421 ---- but it was unjustly forgotten until 2004.

The idea was later on embedded into the GUT frameworks in 1979 and 1980:

— T. Yanagida 1979
— M. Gell-Mann, P. Ramond, R. Slansky 1979
— S. Glashow 1979
— R. Mohapatra, G. Senjanovic 1980

It was Yanagida who named this mechanism as “seesaw”.

Neutrino Masses

Mass terms for charged leptons and neutrinos are not parallel ➔

Neutrino Mixing

(Pontecorvo ,1957... ==>)

neutrino mixing matrix

(==> CKM Matrix)

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

$$\nu_e = V_{1e}\nu_1 + V_{2e}\nu_2 + V_{3e}\nu_3$$

$$\nu_\mu = V_{1\mu}\nu_1 + V_{2\mu}\nu_2 + V_{3\mu}\nu_3$$

$$\nu_\tau = V_{1\tau}\nu_1 + V_{2\tau}\nu_2 + V_{3\tau}\nu_3$$

V = U x P

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

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

$$\begin{bmatrix} \cos\theta_v & -\sin\theta_v & 0 \\ \sin\theta_v & \cos\theta_v & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\theta \approx \theta_{at}$$

$$\theta_v \approx \theta_{sun}$$

F., Xing

$$\theta_l \approx reactor - angle$$

$$(unknown)$$

Kamiokande, SNO

$$31.7^o \le \theta_{sun} \le 36.3^o$$

$$38^o \le \theta_{at} \le 52^o$$

$$\Delta m_{21}{}^2 \approx 7.6 \cdot 10^{-5} eV^2$$

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

3 texture zeros

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

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

$$\tan 2\theta_l=\frac{2\sqrt{m_e m_\mu}}{m_\mu-m_e}\cong 0.0695$$

$$\tan 2\theta_\nu=\frac{2\sqrt{m_1 m_2}}{m_2-m_1}$$

observation

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

$$==> m_1 / m_2 \approx 0.42_{-0.04}^{+0.12}$$

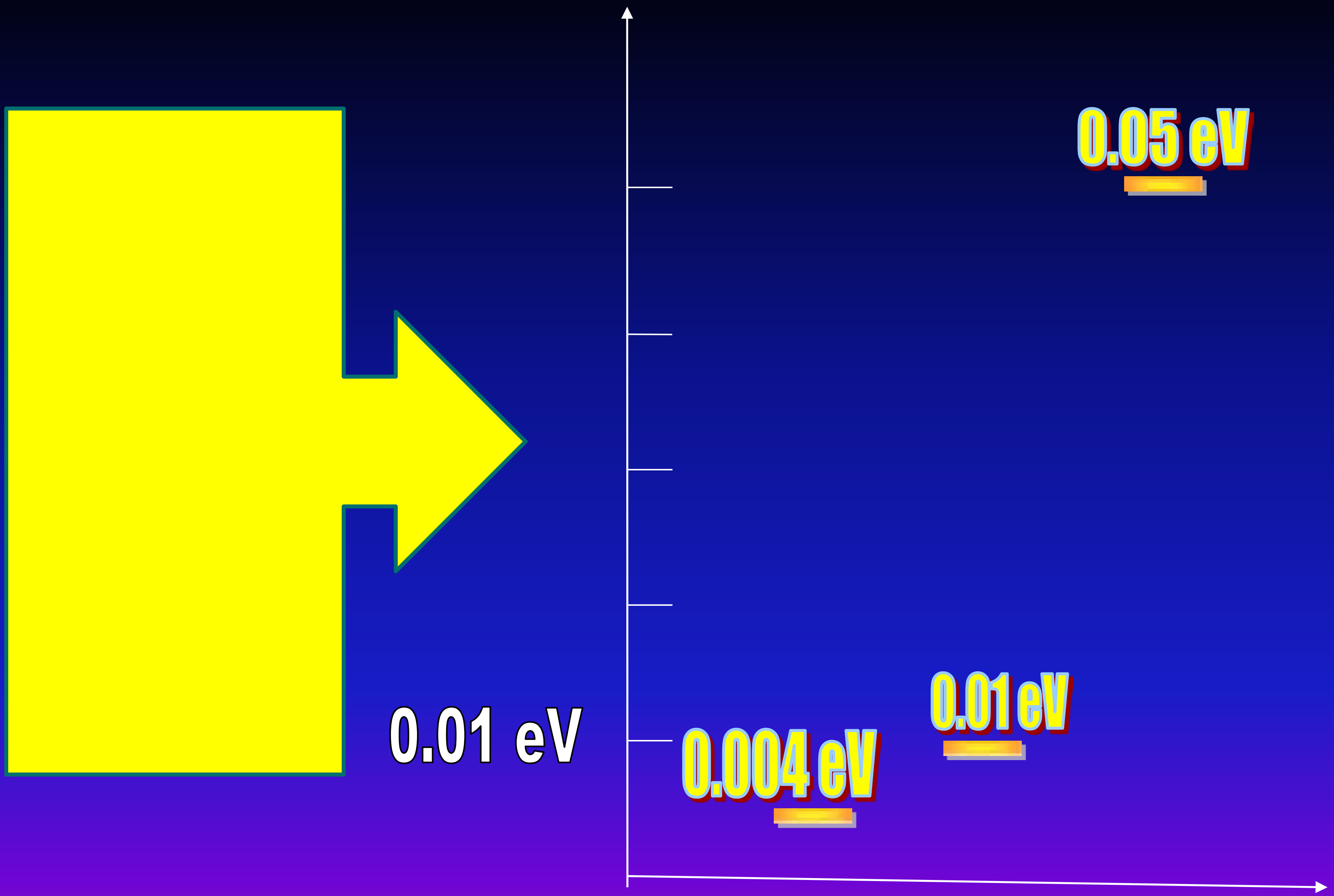
weak mass hierarchy

$$m_1 / m_2 \approx 0.42$$

$$\Delta m_{21}{}^2 \approx 7.6 \cdot 10^{-5} eV^2$$

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

==> neutrino masses


0.05 eV
0.01 eV
0.004 eV
0.01 eV

m(1) = (0.0040 +/- 0.001) eV

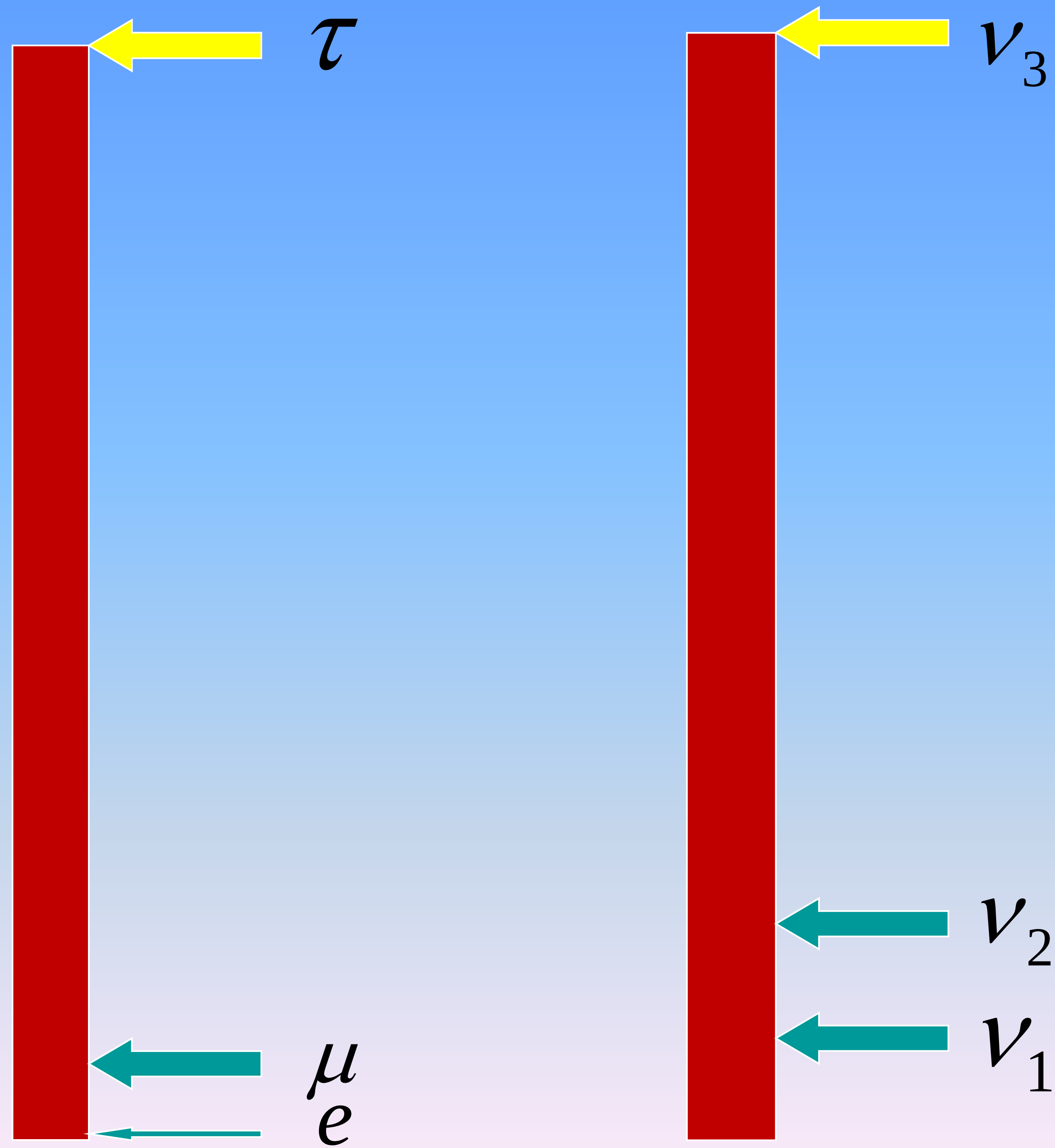
m(2) = (0.0096 +/- 0.002)eV

m(3) = (0.049 eV +/- 0-007) eV

normal mass hierarchy
(no inversion)

masses

(relative)



weak mass hierarchy for neutrinos

→

large mixing angles

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**

relations between quark masses ?

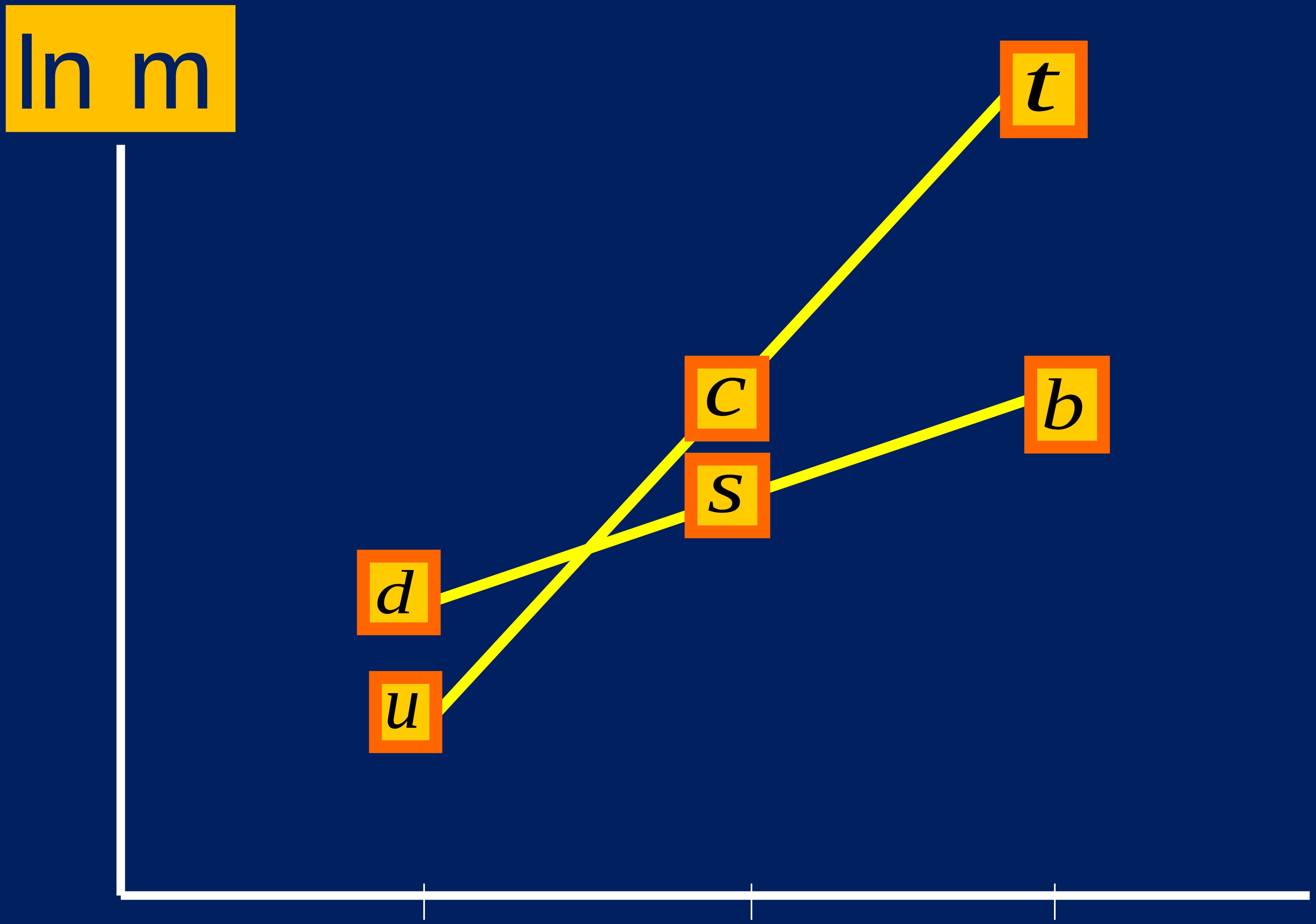
- Observed:

$$m(c) : m(t) = m(u):m(c)$$

1/207 1/207

$$m(s):m(b) = m(d):m(s)$$

1/23 1/23


ln m
t
c
b
s
d
u

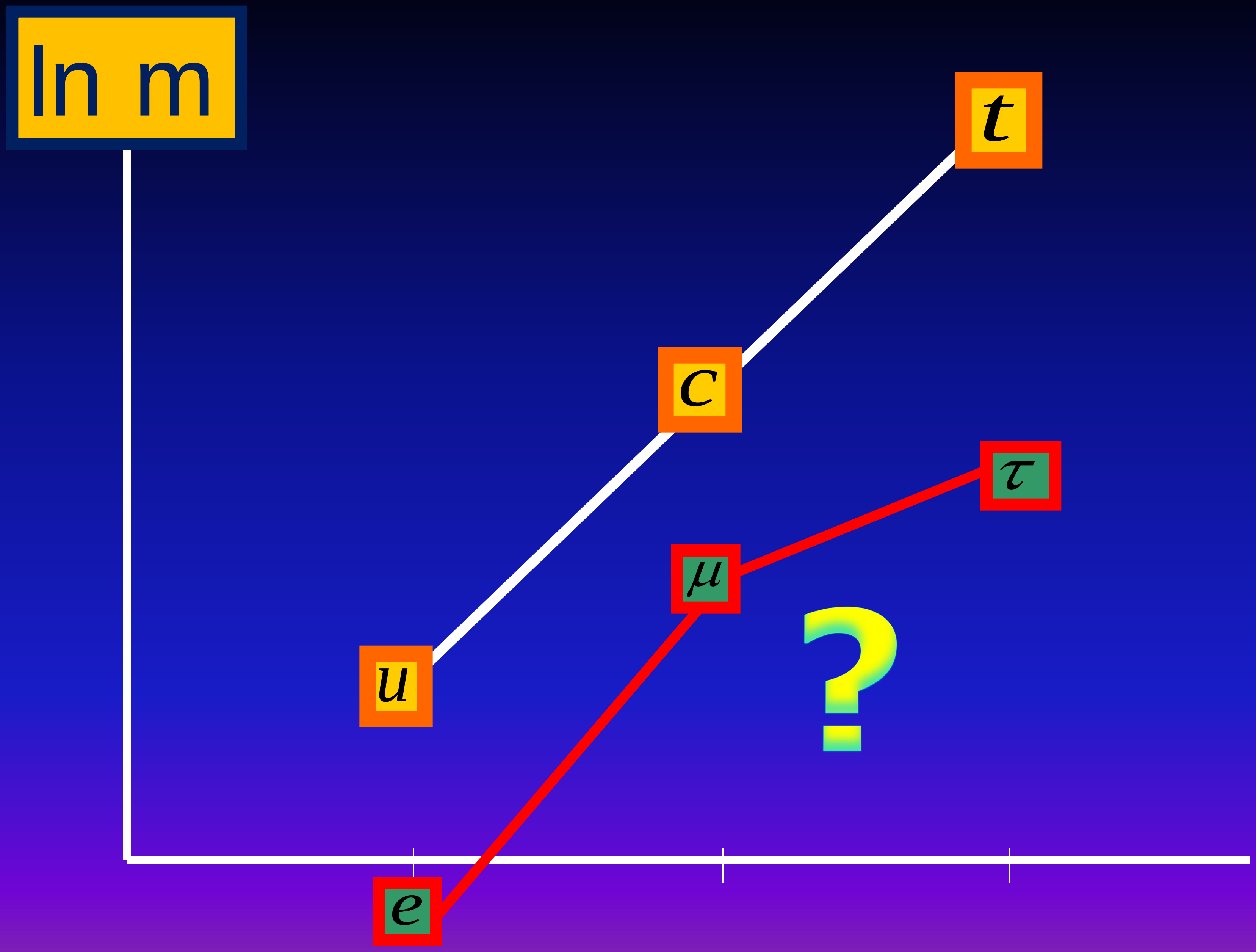
$$m_e \cong 0.511 \quad MeV$$

$$m_\mu \cong 105.66 \quad MeV$$

$$m_\tau \cong 1776.8 \quad MeV$$

$$\frac{m_\mu}{m_\tau} \cong 0.0595$$

$$\frac{m_e}{m_\mu} \cong 0.0048$$

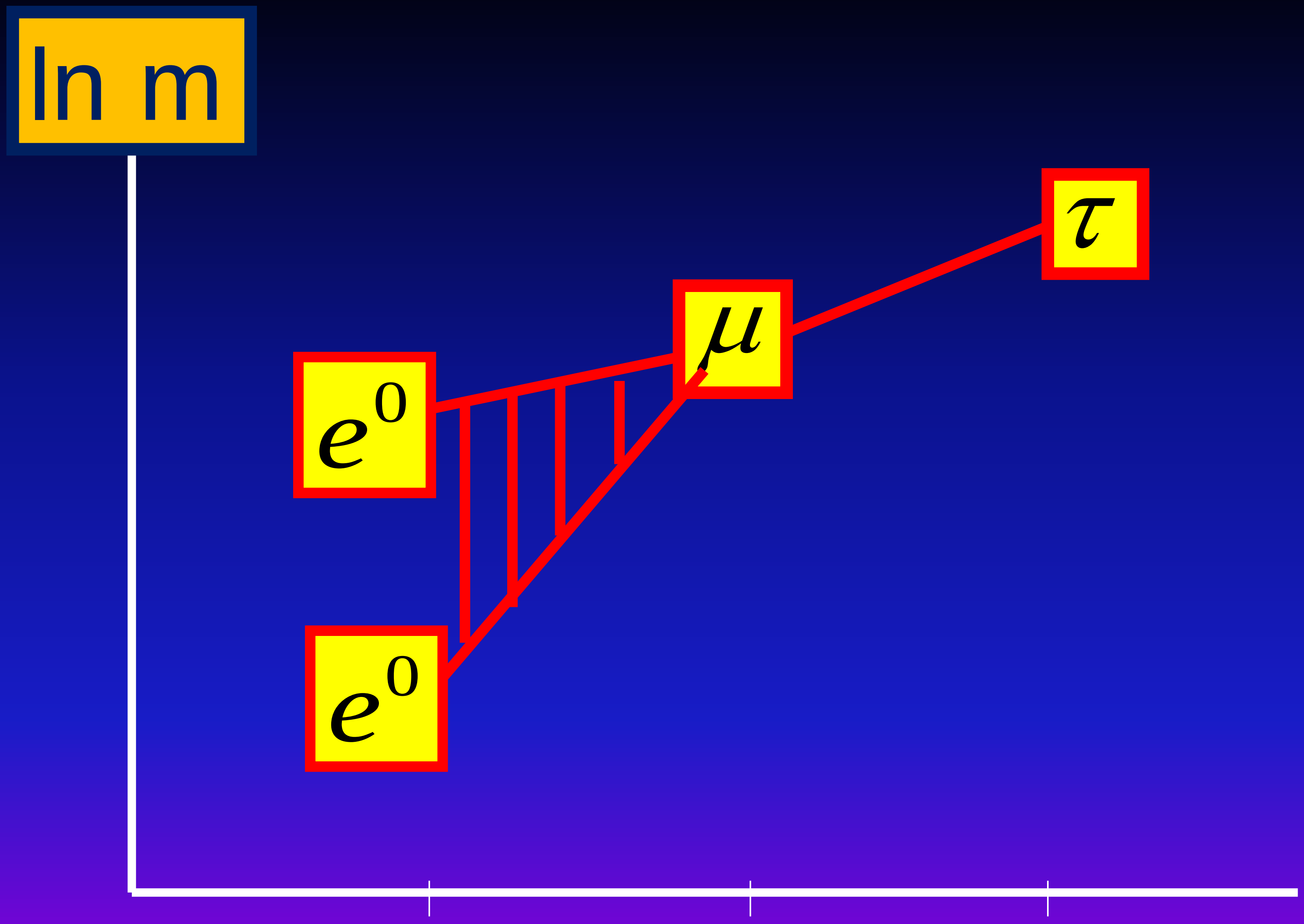


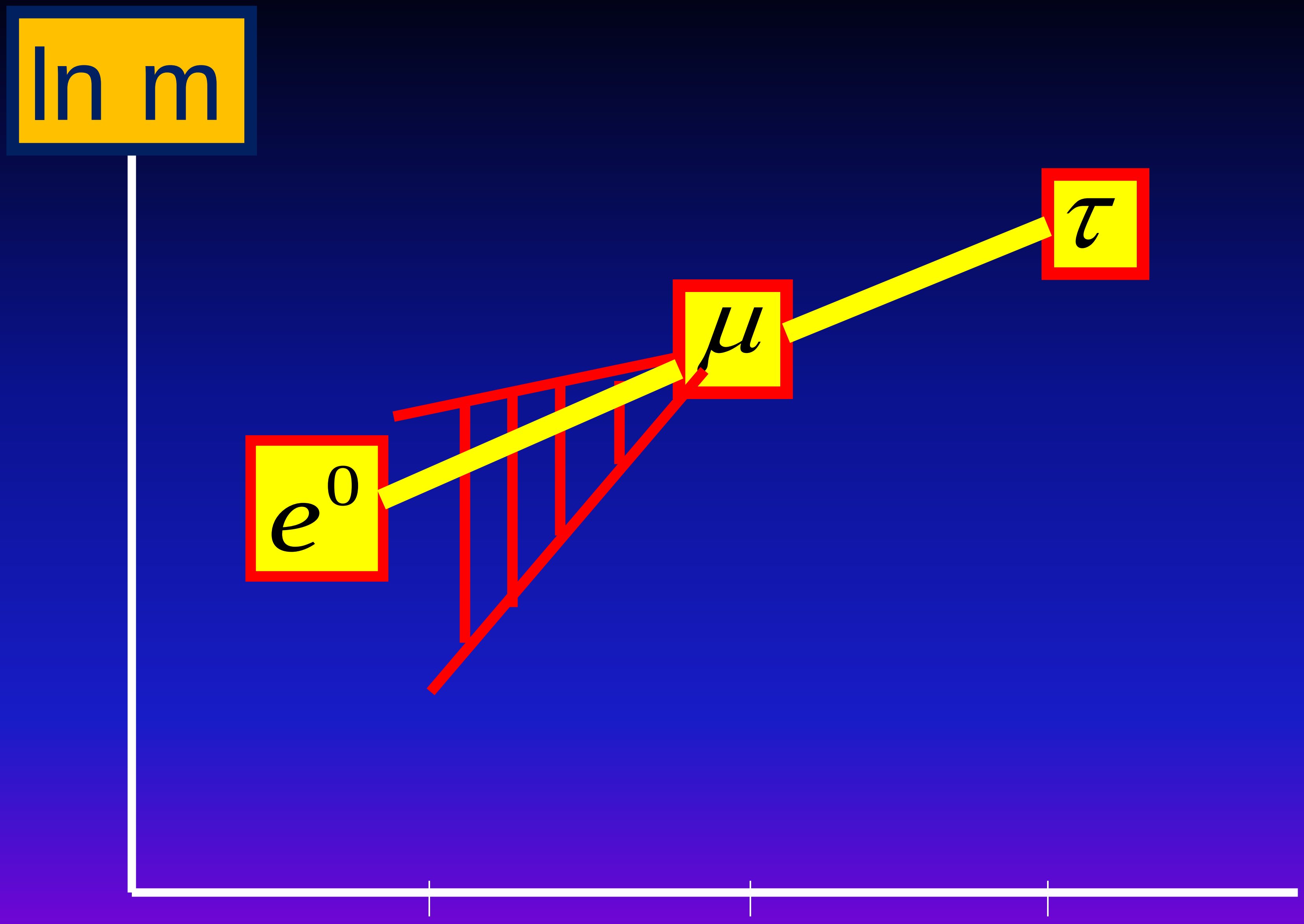
ln m
t
c
τ
μ
?
u
e

radiative corrections

$$m(e) = m(e^0) + const.\left(\frac{\alpha}{\pi}\right)m(\tau) + \ldots$$

$$\frac{\alpha}{\pi}m(\tau) \cong 3.95\,MeV$$


ln m
τ
μ
e^0
e^0



ln m
e^0
μ
τ

radiative corrections

$$m(e) = m(e^0) + const.\left(\frac{\alpha}{\pi}\right)m(\tau) + \ldots$$

$$\approx 6.3 \quad MeV - 5.8 \quad MeV \approx 0.511 \quad MeV$$

$$m\left(e^0\right) \approx 6.3 \quad MeV$$

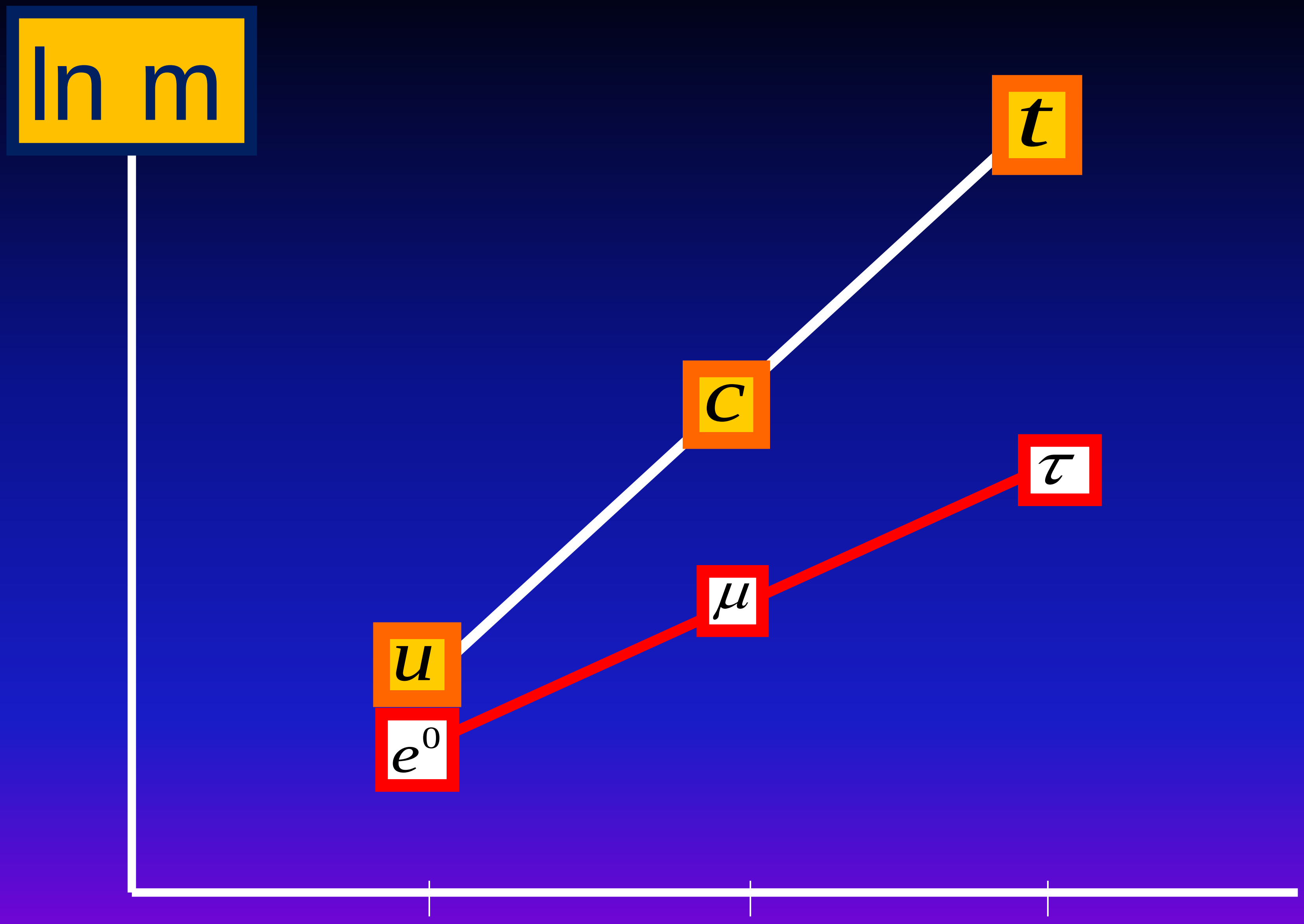
muon and tauon not much changed by radiative corrections

$$m(\mu) = m(\mu^{o}) + const.\left(\frac{\alpha}{\pi}\right) m(\tau) + \ldots$$

$$\approx 111.5 \quad MeV - 5.8 \quad MeV \approx 105.7 \quad MeV$$

$$\frac{m_\mu^0}{m_\tau^0} \cong 0.06$$

$$\frac{m_e^o}{m_\mu^0} \cong 0.06$$


ln m
t
c
τ
μ
u
e^0

$$V_{e3} = \sin\theta_l \sin\theta_{at}$$

$$\tan\theta_l = \sqrt{\frac{m_e^0}{m_\mu^0}} \cong 0.25$$

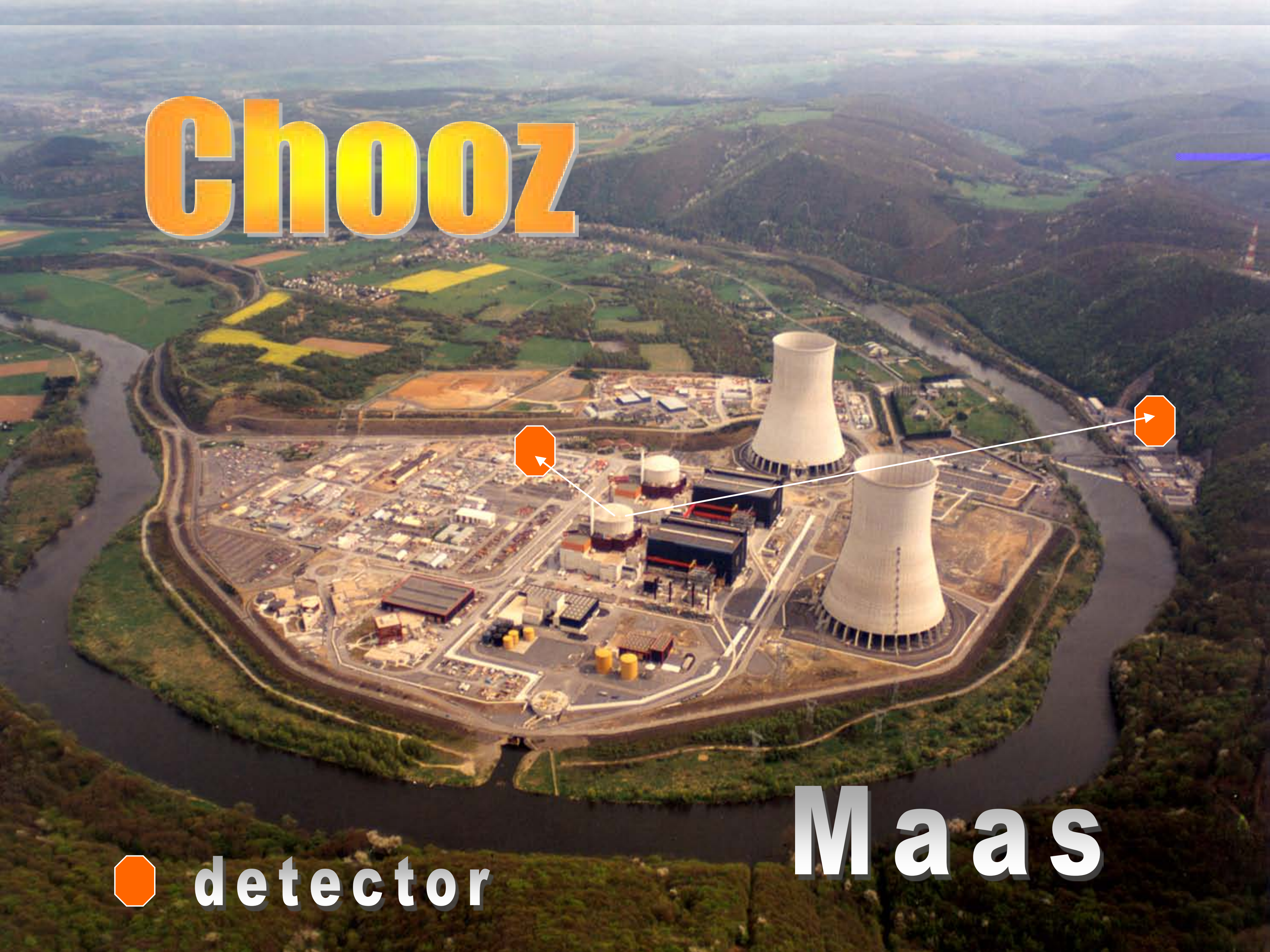
$$38^o \leq \theta_{at} \leq 52^o$$

$$\left|V_{e3}\right| = \sin\theta_{13} \Rightarrow 0.148 \ldots 0.190$$

$$\sin^2 2\theta_{13} \cong 0.1124 \pm 0.027$$

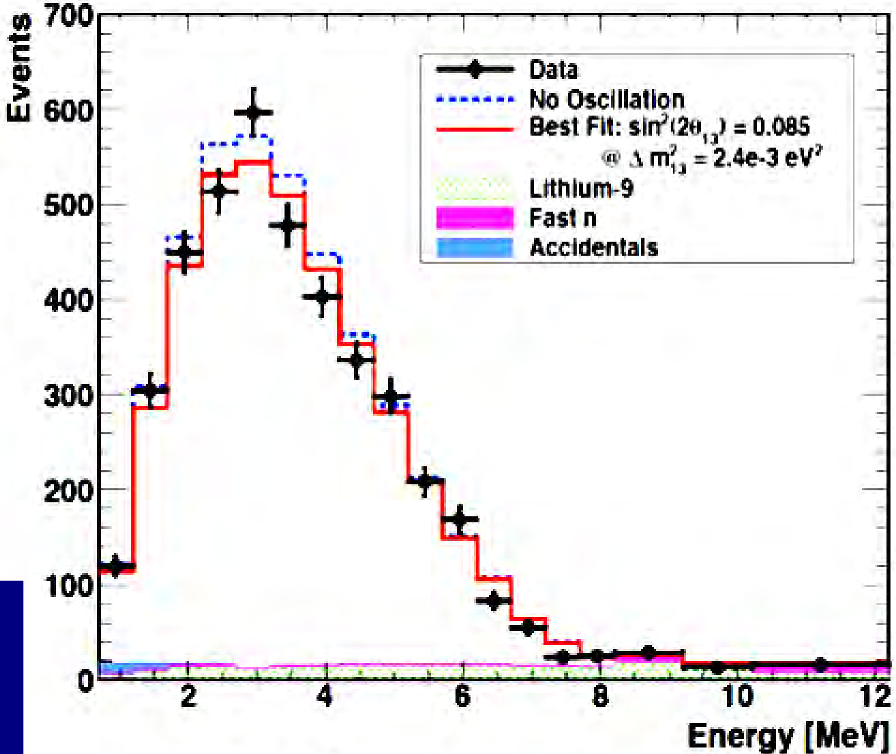
$$= 0.085 \Leftrightarrow 0.139$$


North Sea
NETHERLANDS
Maas
Rhine
Zeebrugge
Oostende
Brugge
Antwerp
F L A N D E R S
Gent
Mechelen
Kortrijk
Aalst
Schelde
Leuven
BRUSSELS
GER.
Liège
Meuse
Mons
Charleroi
Namur
Botrange
W A L L O N I A
Escaut
A R D E N N E S
Chooz
Bastogne
LUX.
FRANCE
Meuse
0 20 40 km
0 20 40 mi


Chooz
Maas
detector

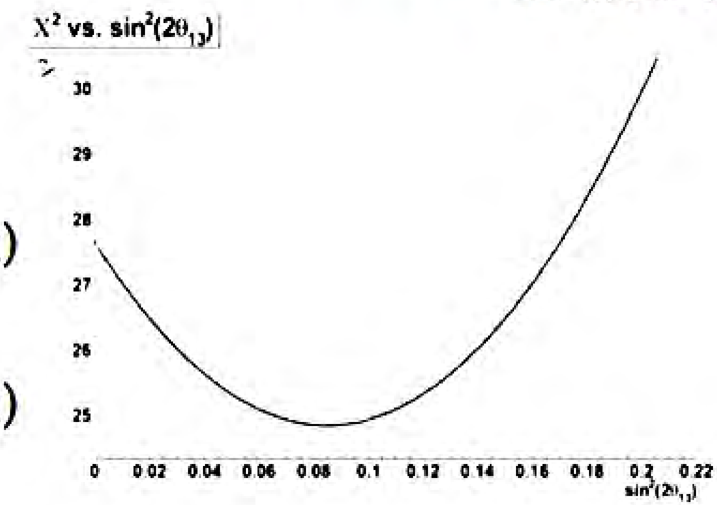
Double Chooz

First neutrino oscillation data release of DC at LowNu11 @ Seoul (Korea)



Expect:

$$\sin^2 2\theta_{13} \approx 0.11$$



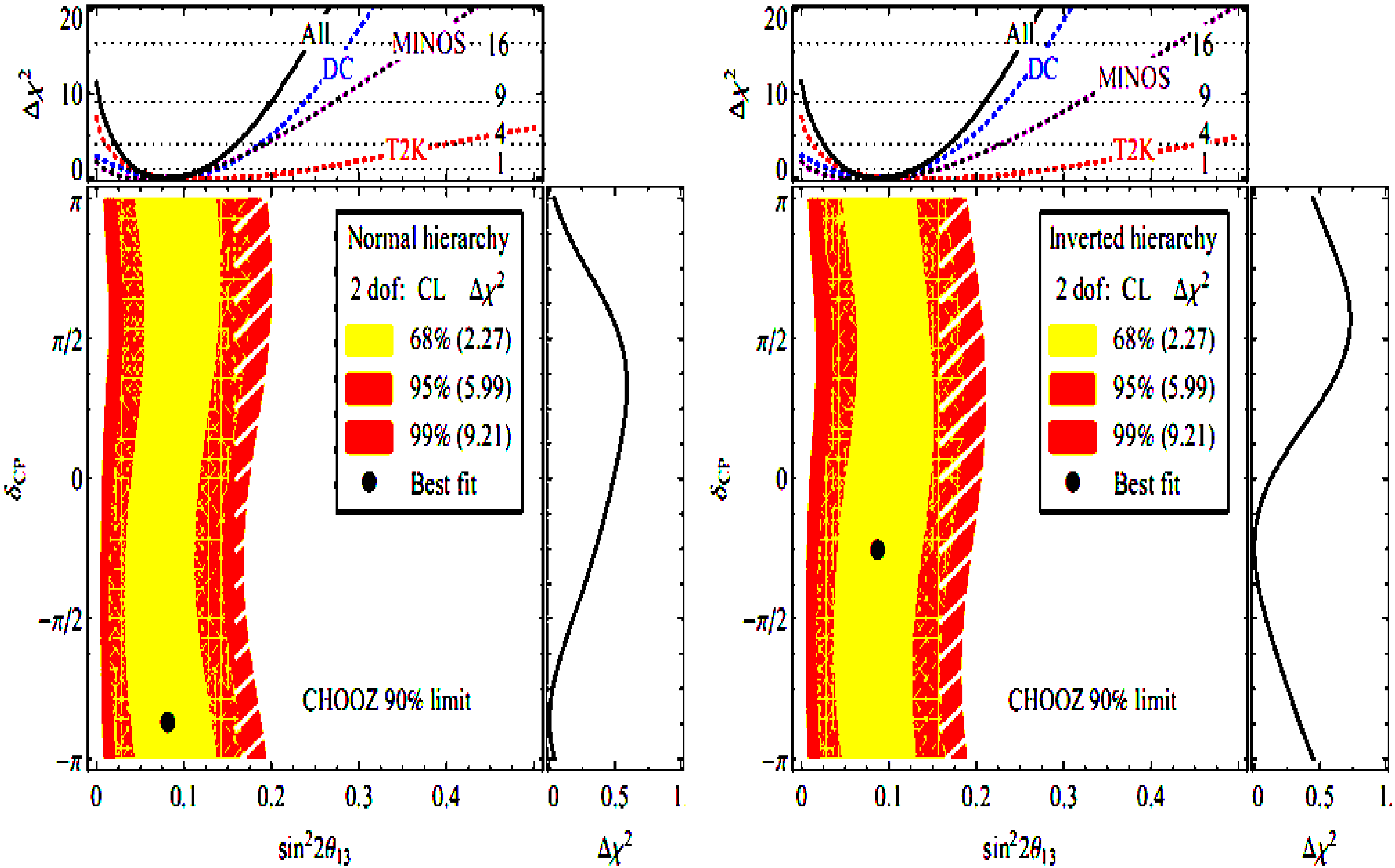
Rate + Shape Analysis:

$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

Rate Only:

$\sin^2(2\theta_{13}) = 0.093 \pm 0.029(\text{stat}) \pm 0.073(\text{syst})$

Combined? Best fit: $\sin^2 2\theta_{13} = 0.08$



Reno experiment (South Korea)

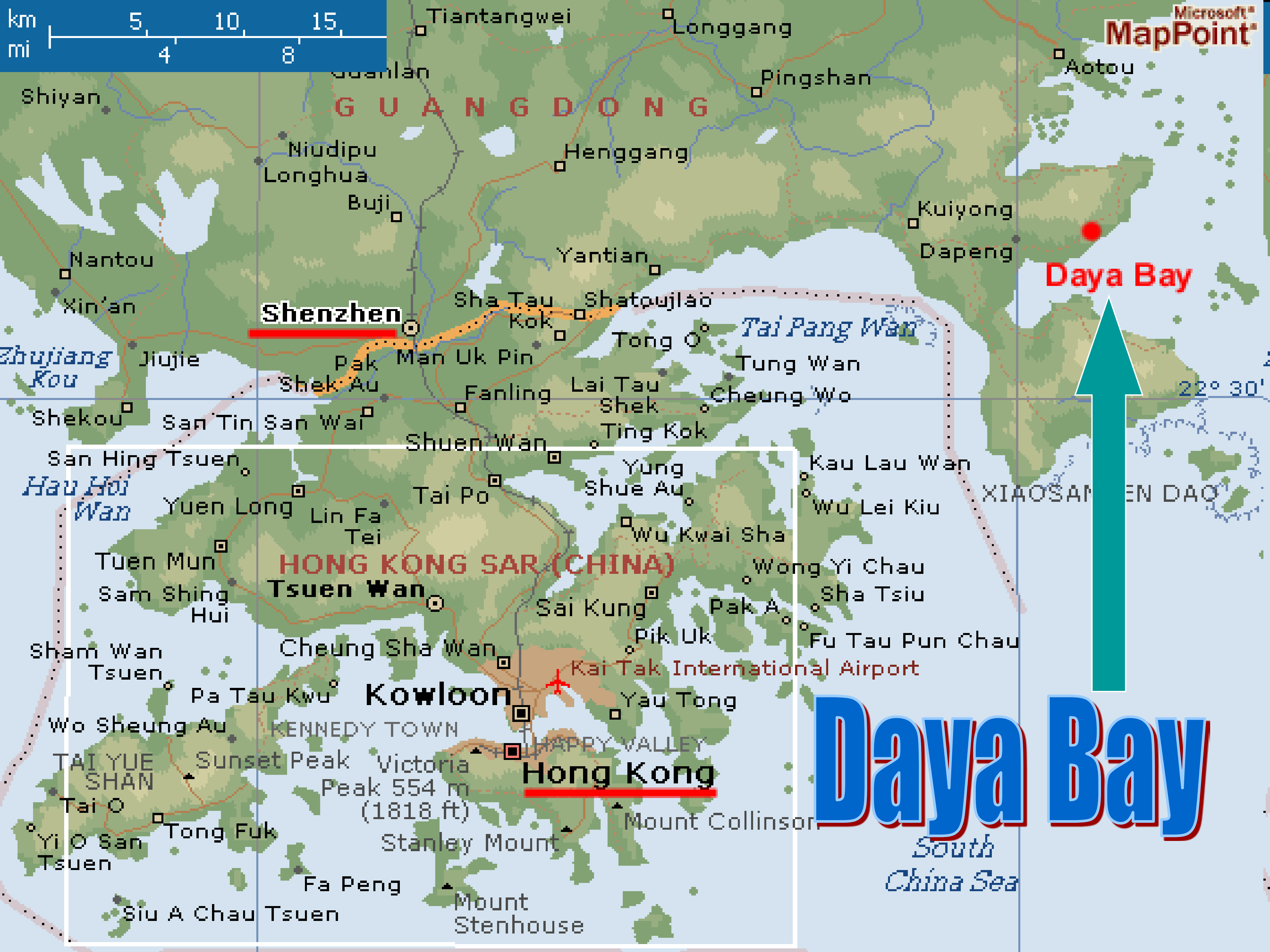
$$\sin^2 2\theta_{13} = 0.1124 \pm 0.027$$

$$\theta_{13} = 9.8^0 \pm 1.3^0$$

Reno

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.005$$

Daya Bay Experiment

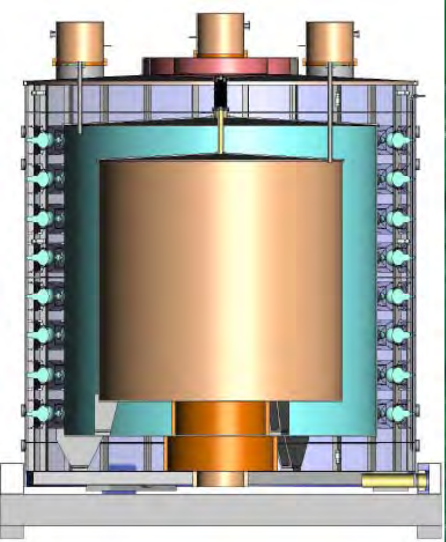


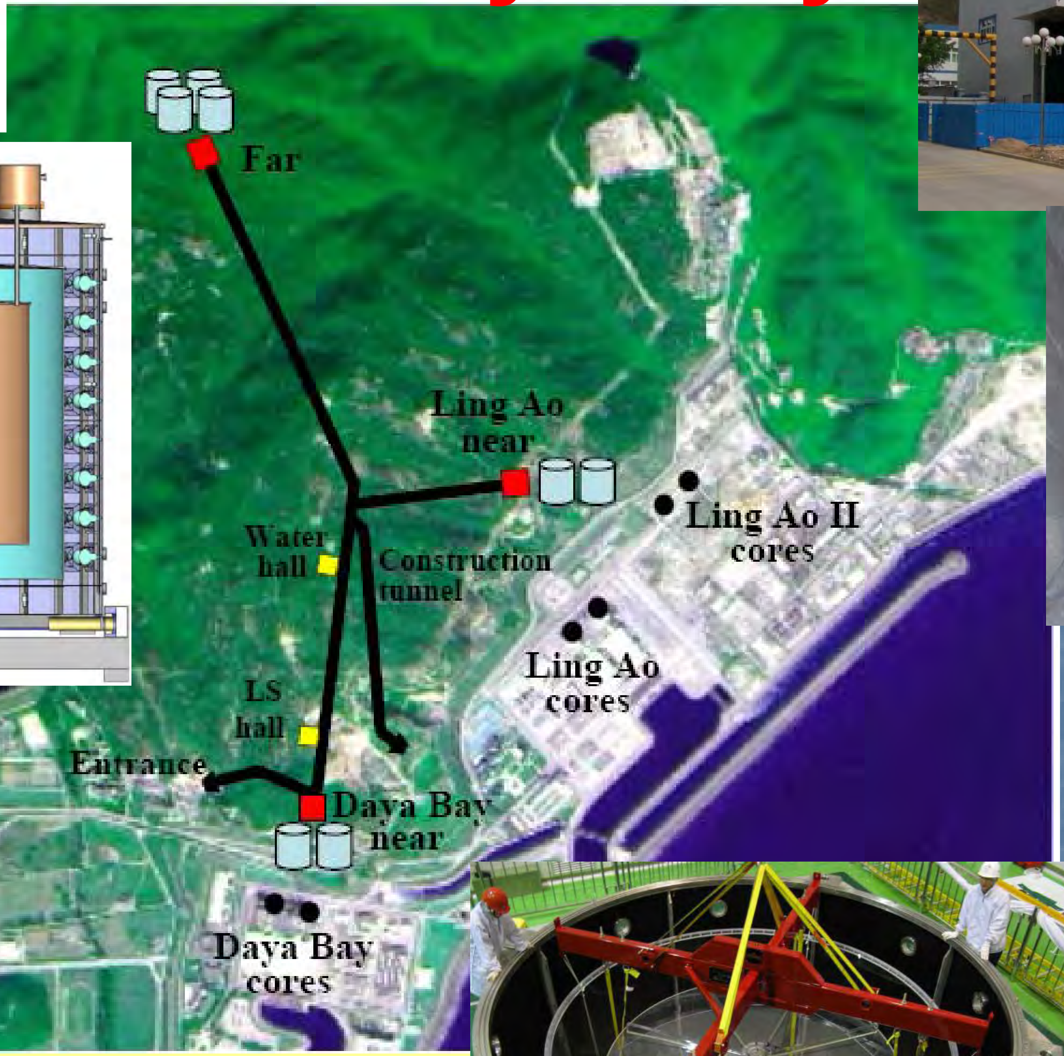
km 5 10 15
mi 4 8
Microsoft® MapPoint®
Tiantangwei
Longgang
Guanlan
Pingshan
Aotou
Shiyan
GUANGDONG
Niudipu
Longhua
Henggang
Buji
Kuiyong
Dapeng
Nantou
Yantian
Daya Bay
Xin'an
Shenzhen
Sha Tau Kok
Shatoujiao
Zhujiang Kou
Jiujie
Pak Shek Au
Man Uk Pin
Tong O
Tai Pang Wan
Tung Wan
Fanling
Lai Tau Shek
Cheung Wo
22° 30'
Shekou
San Tin San Wai
Ting Kok
Shuen Wan
San Hing Tsuen
Kau Lau Wan
Yung Shue Au
Hau Hoi Wan
Yuen Long
Lin Fa Tei
Tai Po
Wu Lei Kiu
XIAOSAN EN DAO
Wu Kwai Sha
Tuen Mun
HONG KONG SAR (CHINA)
Wong Yi Chau
Sam Shing Hui
Tsuen Wan
Sha Tsiu
Sai Kung
Pak A
Pik Uk
Sham Wan Tsuen
Cheung Sha Wan
Fu Tau Pun Chau
Kai Tak International Airport
Pa Tau Kwu
Kowloon
Yau Tong
Wo Sheung Au
KENNEDY TOWN
HAPPY VALLEY
TAI YUE SHAN
Sunset Peak
Victoria Peak 554 m (1818 ft)
Hong Kong
Tai O
Tong Fuk
Mount Collinson
Yi O San Tsuen
Stanley Mount
South China Sea
Fa Peng
Siu A Chau Tsuen
Mount Stenhouse
Daya Bay


Daya Bay
4 reactors


far detector
near detector
LingAo II
LingAo cores
near detector
Daya Bay cores
Daya Bay

Daya Bay





Total Tunnel length ~3000 m

- Multiple detectors per site cross-check detector efficiency
- Two near sites sample flux from reactor groups

$$\sin^2 2\theta_{13} = 0.1124 \pm 0.027$$

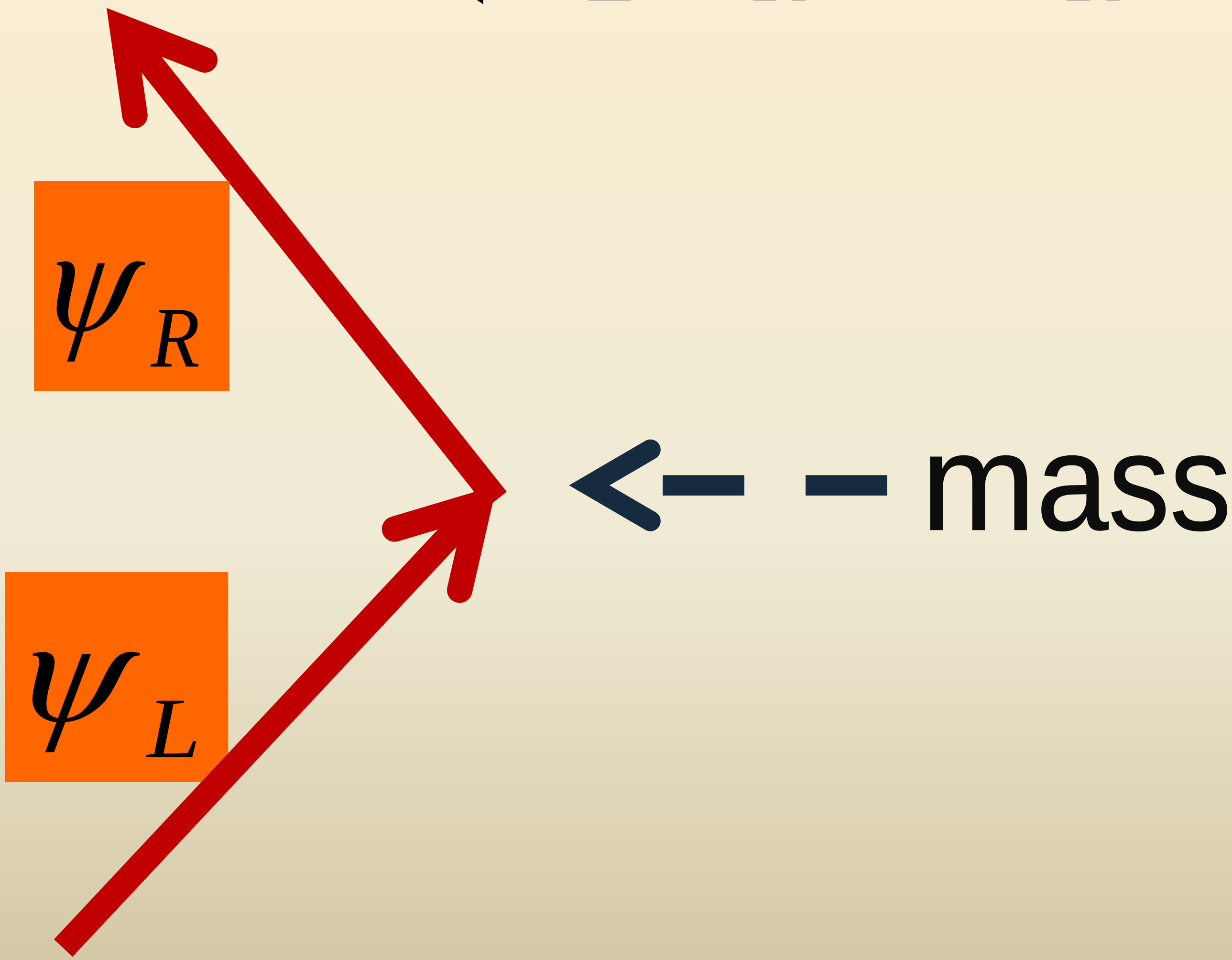
$$\theta_{13} = 9.8^0 \pm 1.3^0$$

Daya Bay

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$$

Dirac mass

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$



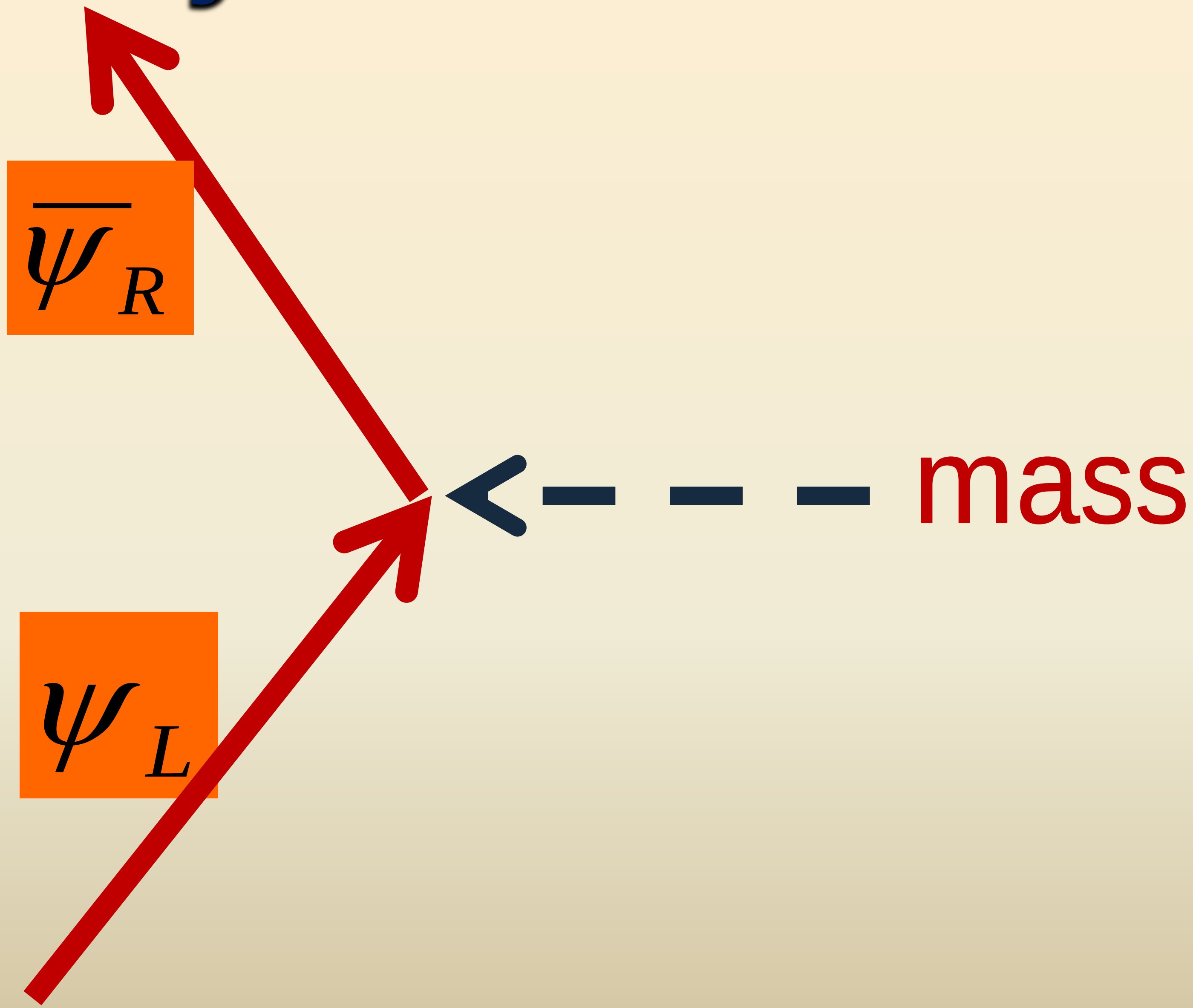
Majorana mass?

Majorana masses:

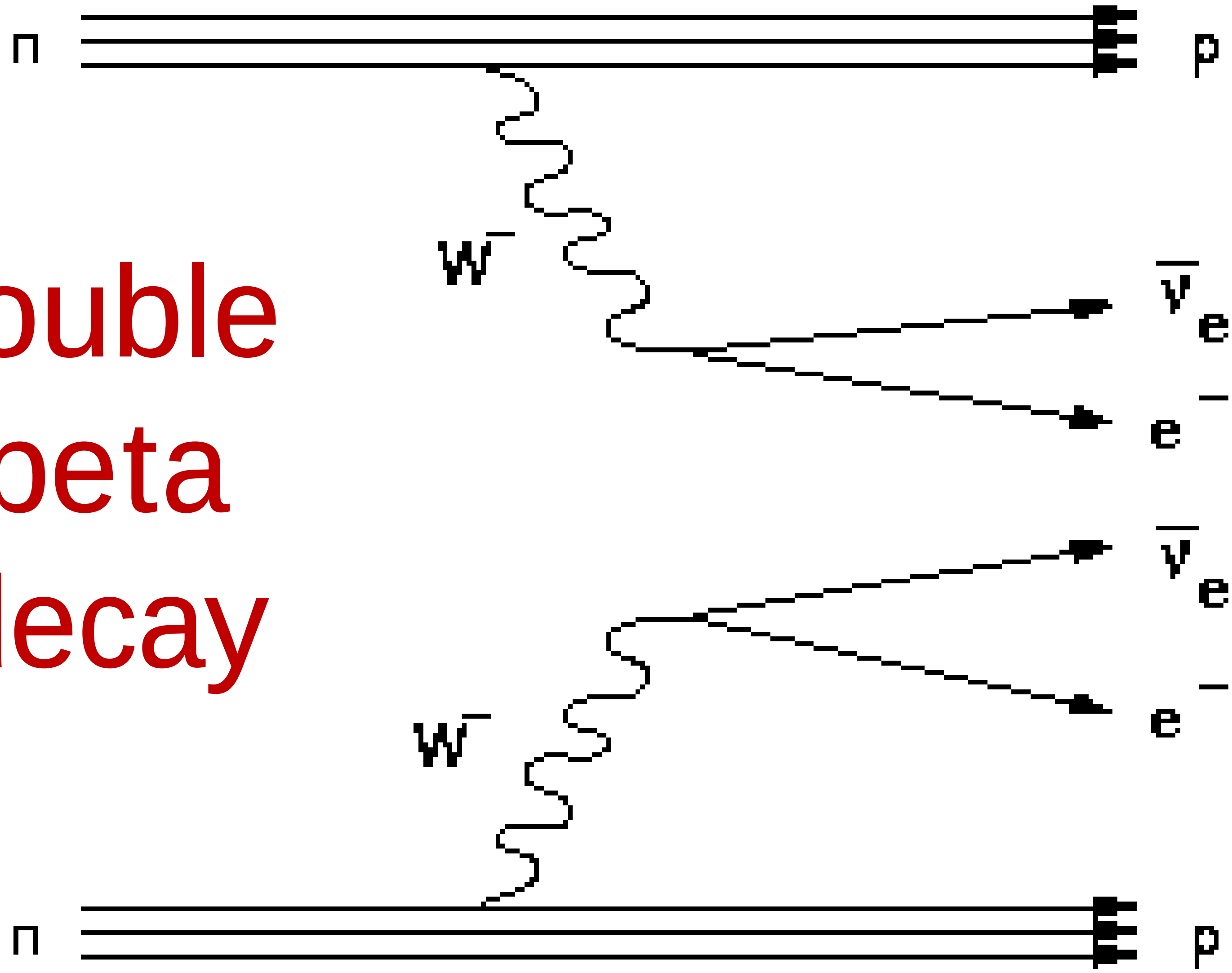
no fermion number

neutrino = antineutrino

Majorana mass



double beta decay

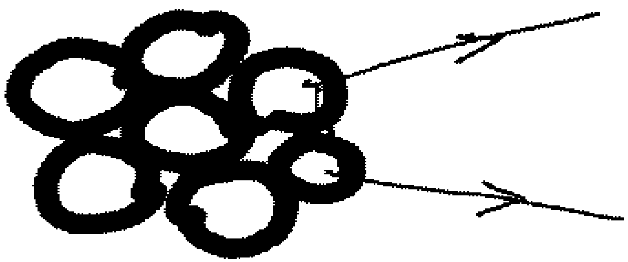


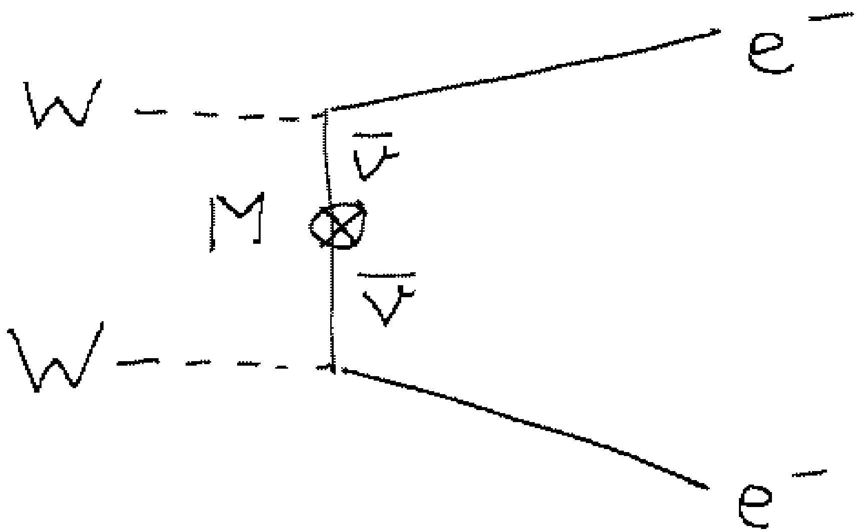
double beta decay
first observed in 1987 (82 Se)

Now seen in decay of

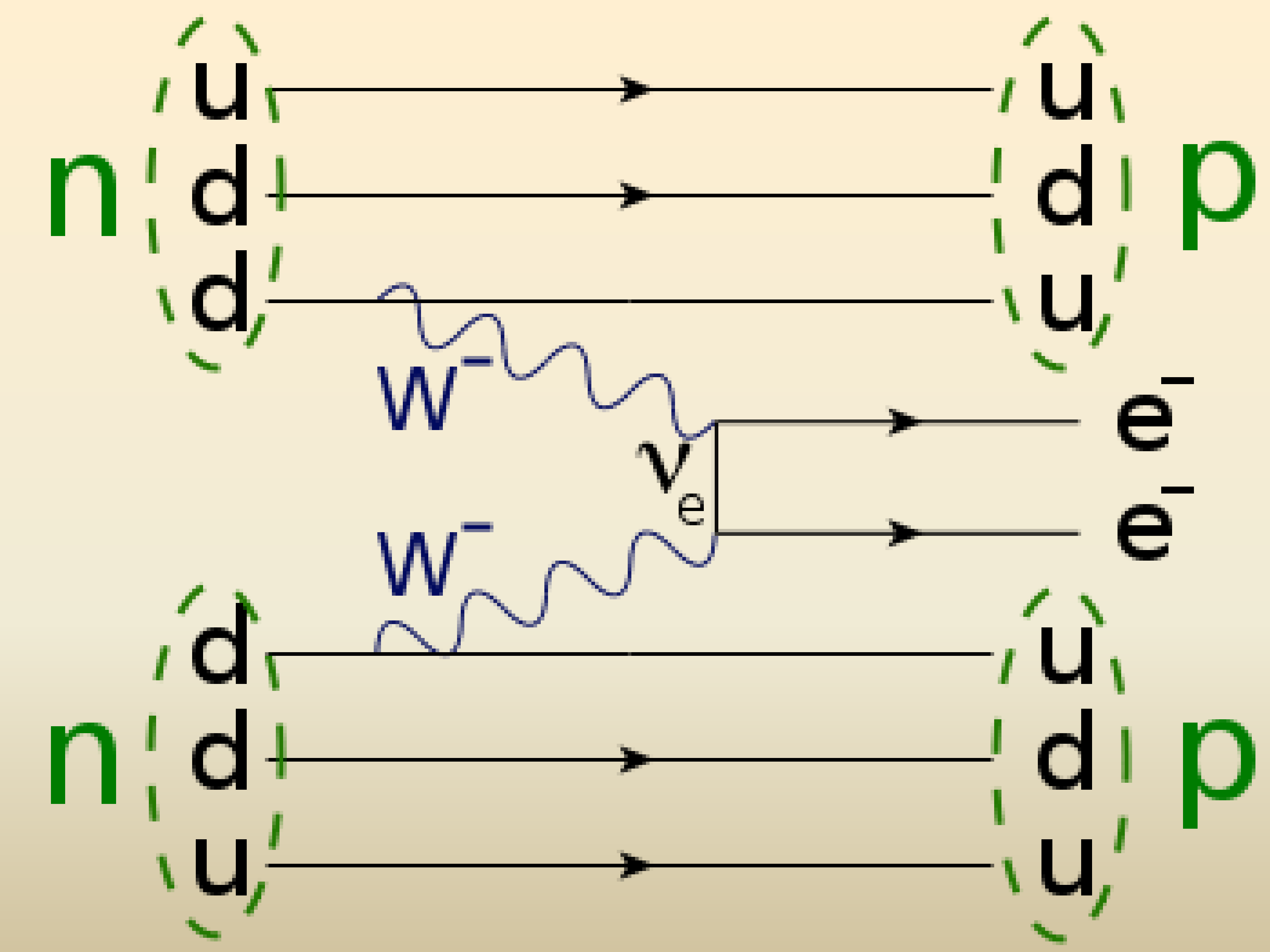
48 Ca	76 Ge	82 Se
96 Zr	100 Mo	116 Cd
128 Te	130 Te	130 Ba
136 Xe	150 Nd	238 U

Neutrinoless double β-decay





(decay via Majorana mass term)



n
u
d
d
p
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d
u
W⁻
νe
e⁻
e⁻
W⁻
n
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d
u
p
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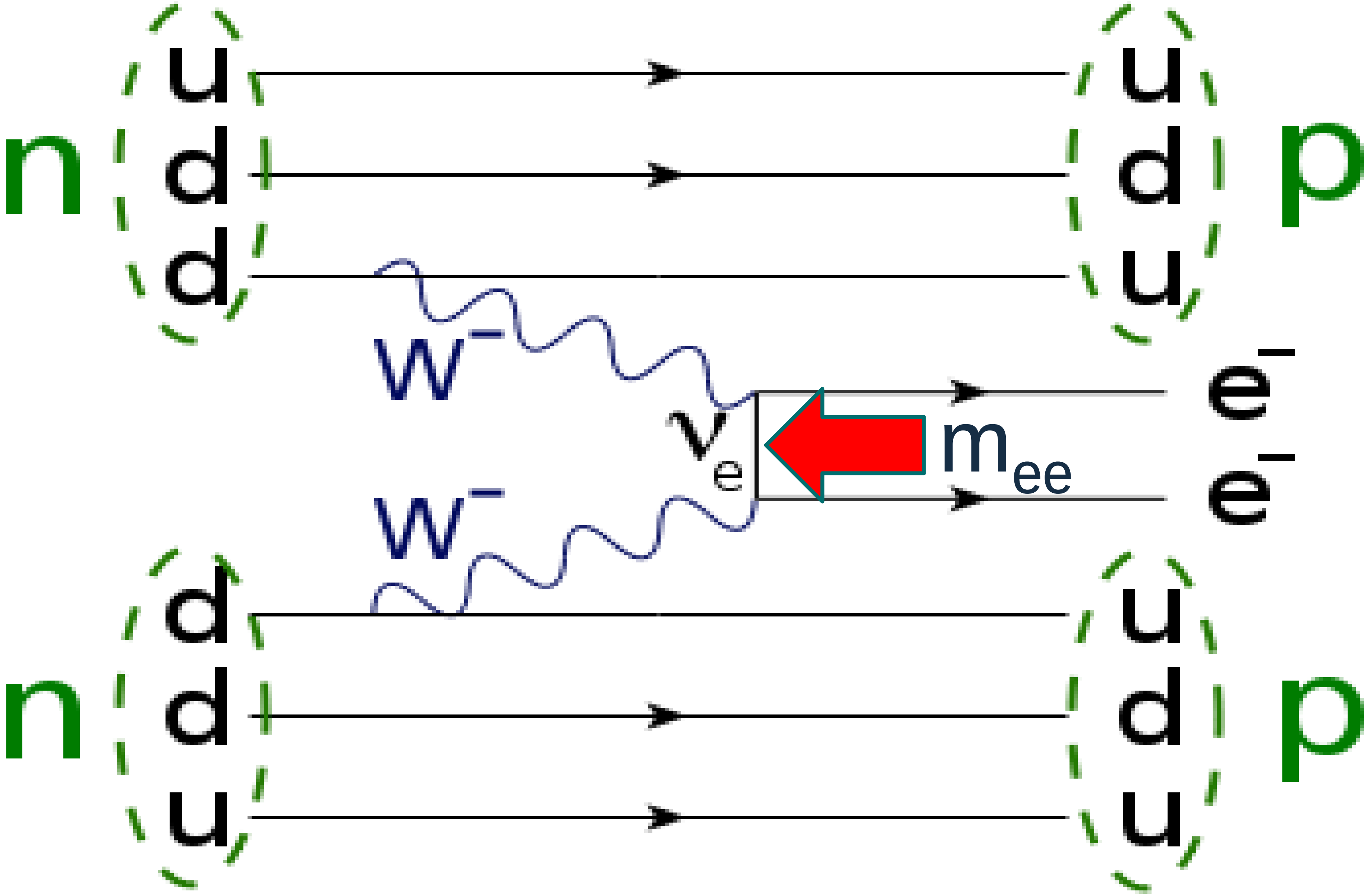
d
u



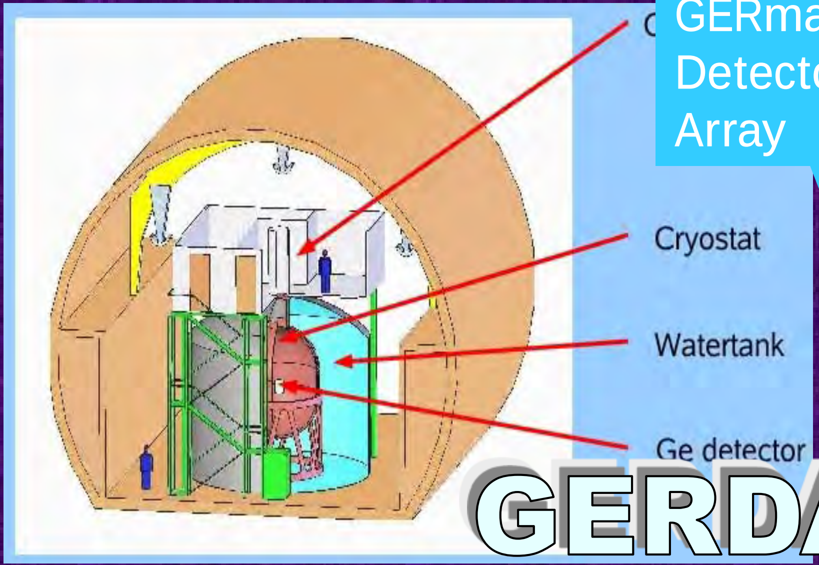
$$m_{ee} = U_{e1}^2\, m_1 + U_{e2}^2\, m_2\, e^{\iota\alpha} + U_{e3}^2\, m_3\, e^{\iota\beta}$$

Cuoricino Experiment
Te (130)
Gran Sasso Laboratory

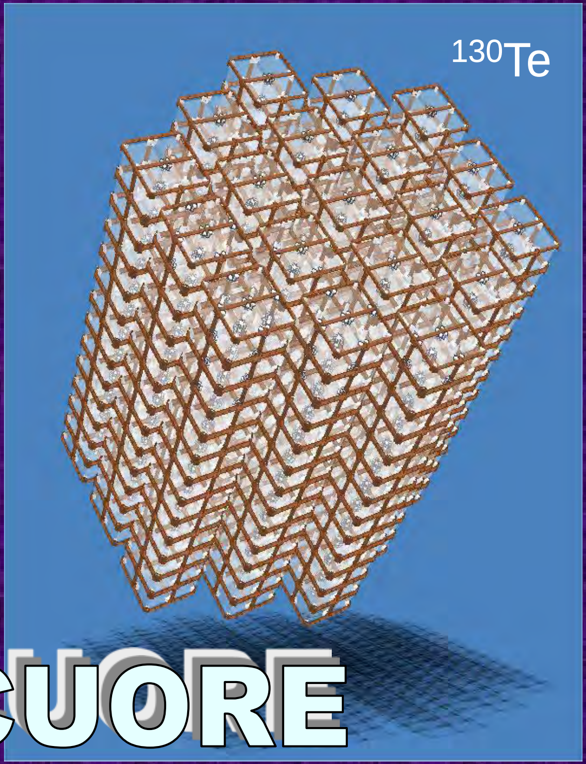
present limit Majorana neutrino mass ~ 0.23 ev

Gran Sasso

New experiments



GERDA



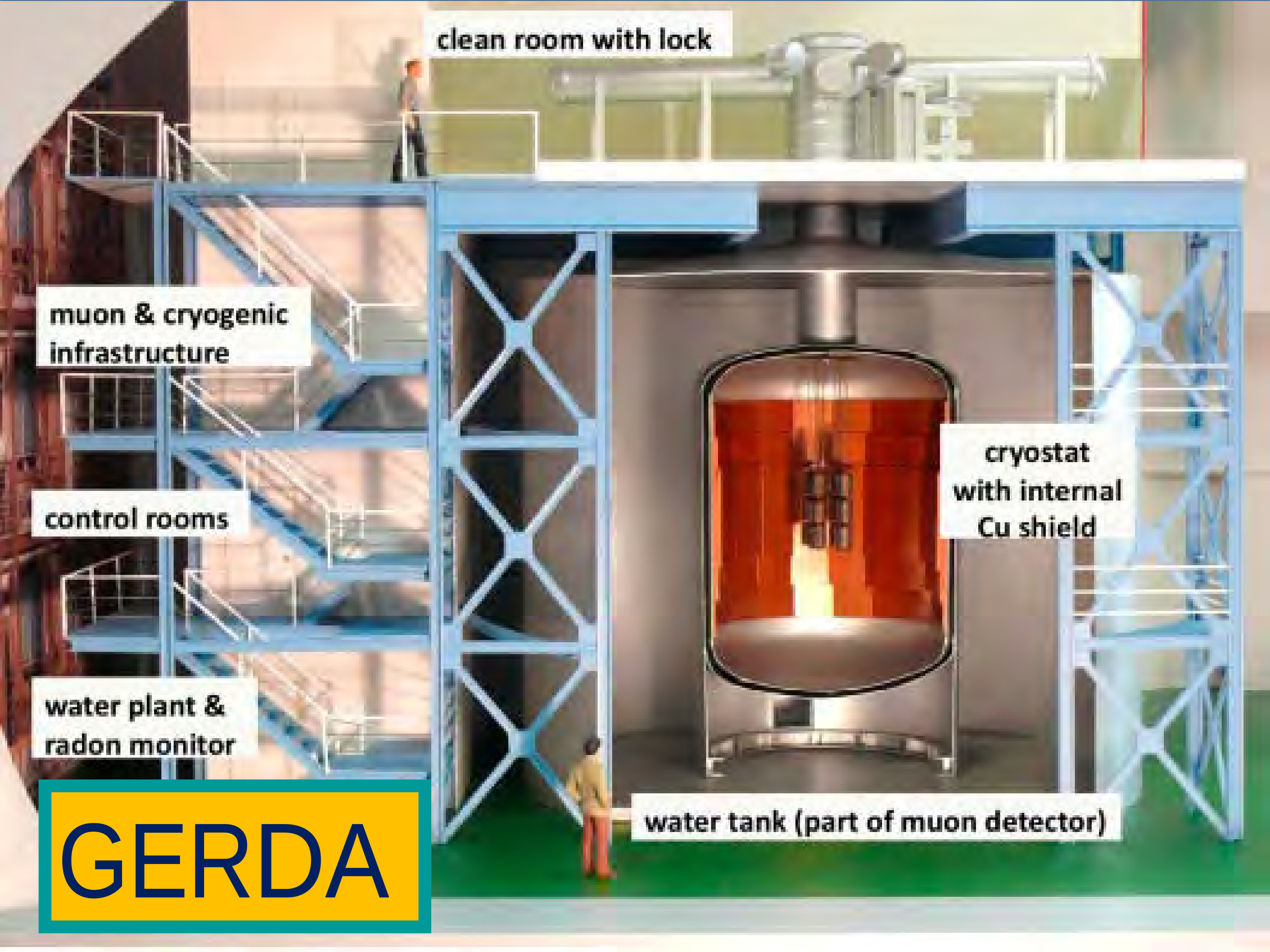
CUORE

Cryogenic Underground Observatory for Rare Events

Phase I: 15 kg y: 0.3 – 0.9 eV
Phase II: 37.5 kg y: 0.09 – 0.29 eV
Phase III: 1 ton 0.01 eV

EXO-200

Xe- Observatory


clean room with lock
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
cryostat with internal Cu shield
water tank (part of muon detector)
GERDA

$$m_{eff.} = V_{1e}^2 \cdot m_1 + V_{2e}^2 \cdot m_2 + V_{3e}^2 \cdot m_3 \leq 0.23 \quad eV$$

expected:

$$m_{eff.} = 0.0027 + 0.0043 + 0.0085 \approx 0.016$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\nu_1\ldots\ldots\ldots\ldots\nu_2\ldots\ldots\ldots\ldots\nu_3\ldots$$

factor 15 improvement !?

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

$$\varphi = \frac{\pi}{2} \Rightarrow$$

maximal
CP-violation

maximal CP – violation also for neutrinos

==> reactor neutrinos

Conclusions

fermion masses remain a mystery

flavor mixing angles for quarks
are given by the quark mass ratios

(theory <=> experiment)

mass matrices of quarks and leptons:

Structure:

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

3 texture zeros

flavor mixing angles

↕

mass ratios

of

quarks / leptons

neutrino masses

m(1): 0.0041 eV
m(2): 0.0097 eV
m(3): 0.0510 eV

… neutrinoless double beta decay

improvement:

factor 15 necessary

$$\left|V_{e3}\right| \approx 0.17$$

$$\sin^2 2\theta_{13} \approx 0.11$$

texture zero
mass matrices

masses of quarks - leptons

flavor mixing angles