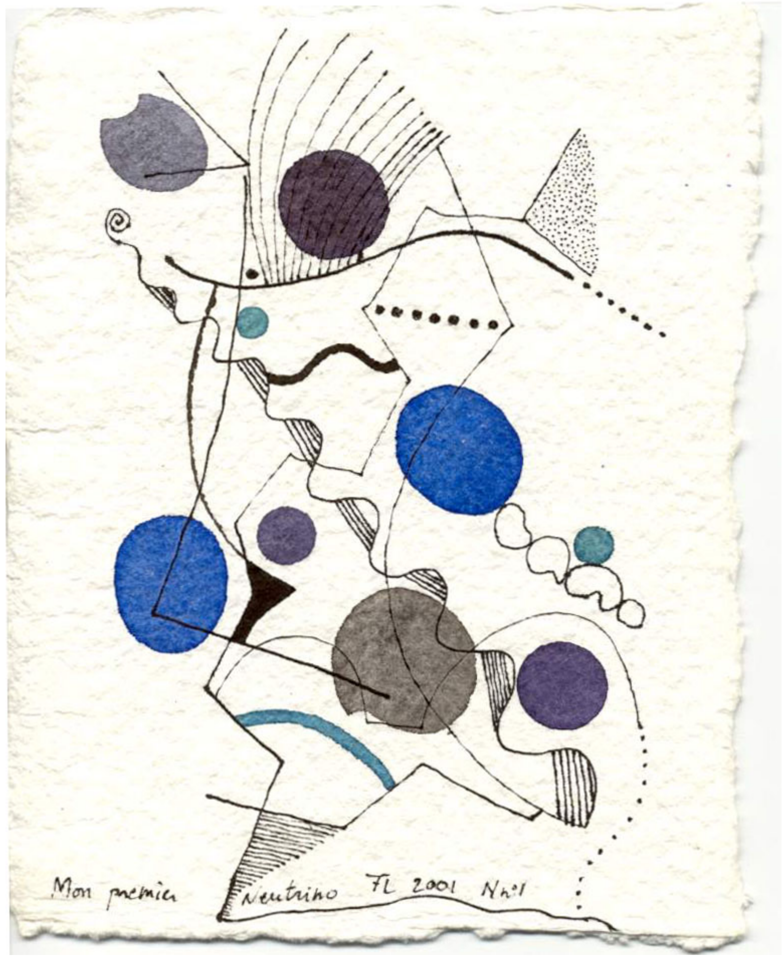
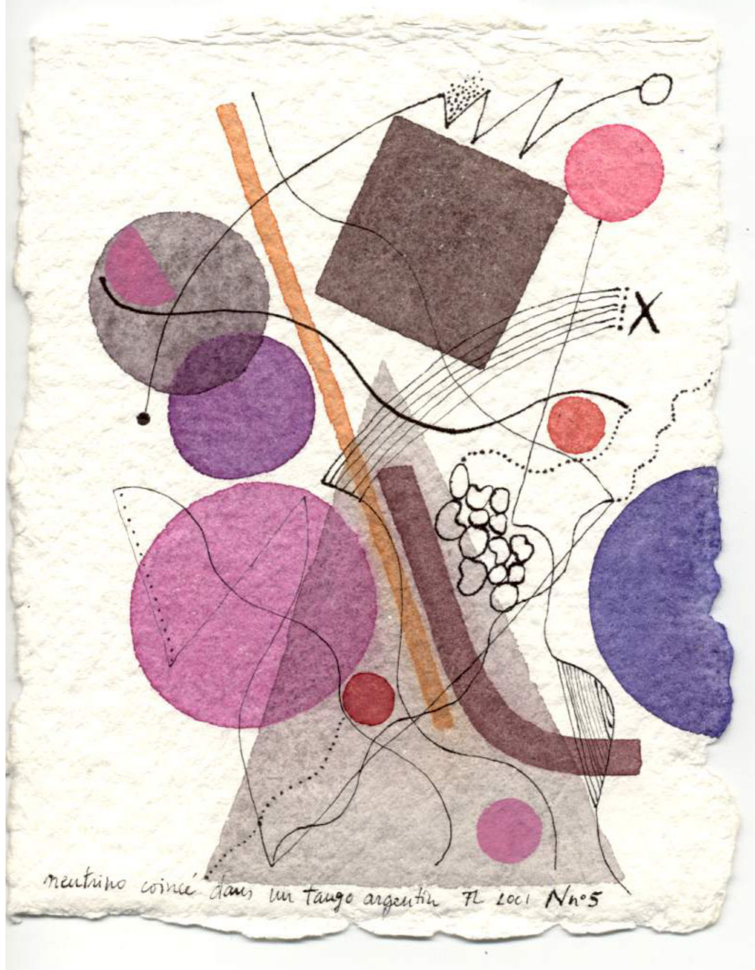
Neutrinos and Particle Physics Models





Pierre Ramond
Institute for Fundamental Theory
University of Florida

Editorial

Early History

Neutrino masses

Neutrinos & Yukawa Unification

Neutrino

revealed by pure thought

to save a fundamental principle

NOT by direct measurement

and treated with suspicion by most physicists

YET ...

Neutrinos never quite fit current dogma

Left-handed in an ambidextrous world parity violation

Massless because of new symmetries? (Volkov-Akulov, Fayet)

Absurdly light: sign of a new scale?

Large neutrino mixings

CP violation

Matter Asymmetry

Leptogenesis

Keys to Yukawa Unification?

Sun

Messengers from the Universe

Supernovas

Blazers

Neutrino Masses & Mixings:

Only Physics Beyond the Standard Model

a small portion of physicists works on neutrinos

but not all ignored neutrinos

νobels

E. Fermi
1938

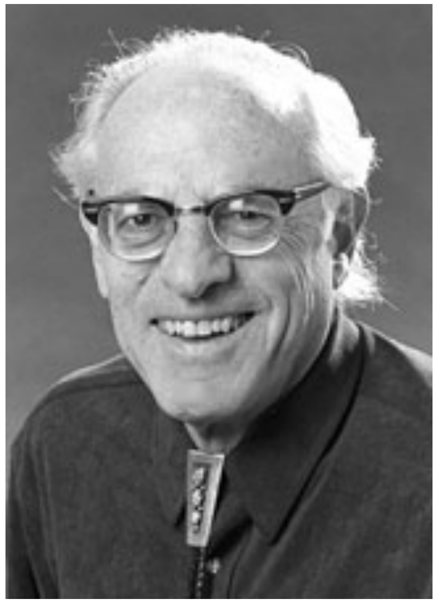
W. Pauli
1945

L. Lederman
1988

M. Schwartz
1988

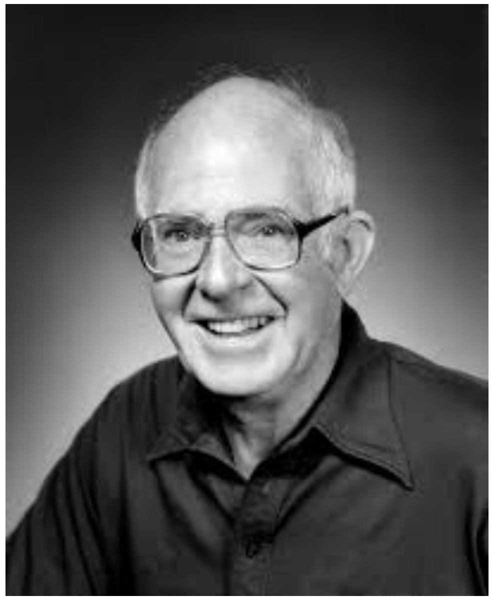
J. Steinberger
1988

νobels



F. Reines

1995



R. Davis

2002

M. Koshiba

2002

T. Kajita

2015

A. McDonald

2015

ν hall of fame

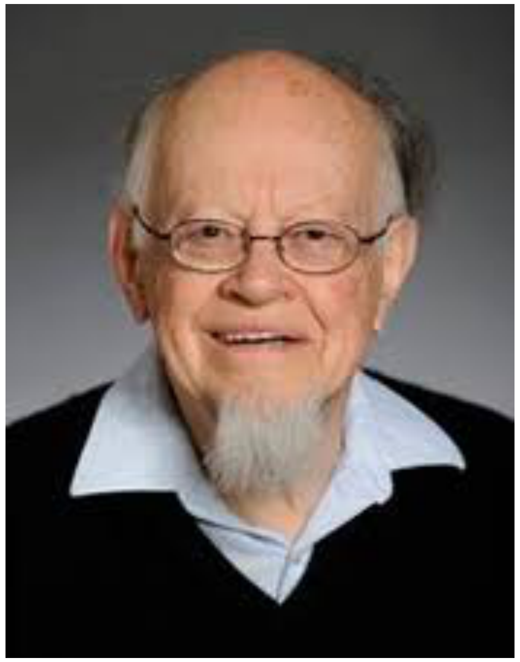
E. Majorana

B. Pontecorvo

M. Goldhaber

S. Sakata

J. Bahcall



L. Wolfenstein

Early History

Zurich, December 4, 1930

“ Dear Radioactive Ladies and Gentlemen:

I have hit upon a desperate remedy to save the “exchange theorem” of statistics and the energy theorem. … there could exist in the nuclei electrically neutral particles… which have spin ½, and … do not travel with the velocity of light. The continuous beta spectrum would then become understandable.
I do not feel secure enough to publish anything about this idea …
only those who wager can win.

Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball…

Pauli

Pauli at Pasadena meeting June 1931:

my little neutron is bound in the nucleus

Pauli divorces actress Kate Depner

Pauli under analysis with C. Jung

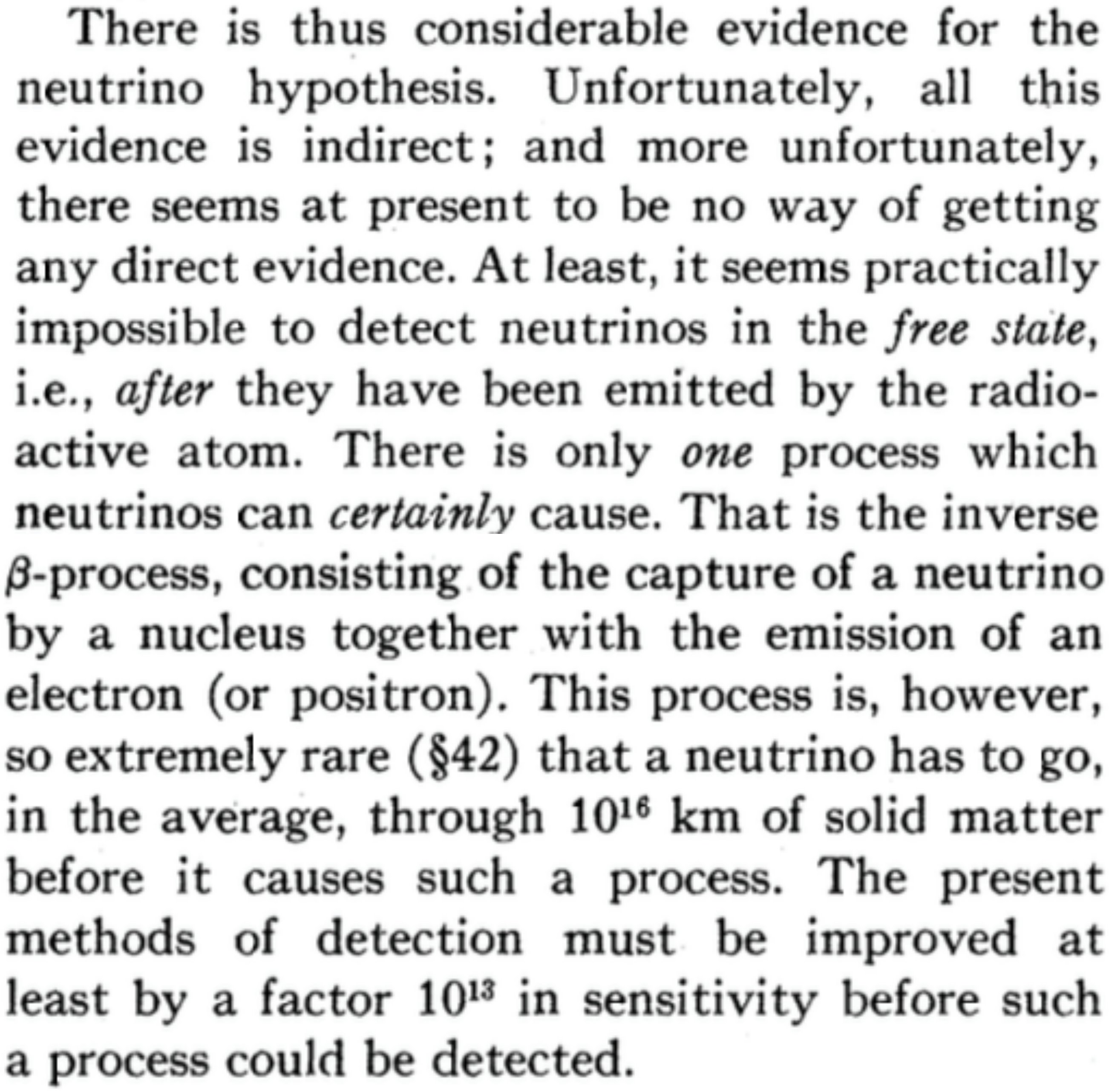
Two years later

Chadwick discovers the Neutron   Nitrogen problem solved

1933-1934 Fermi:

Pauli's little neutron is a free particle, the "neutrino"

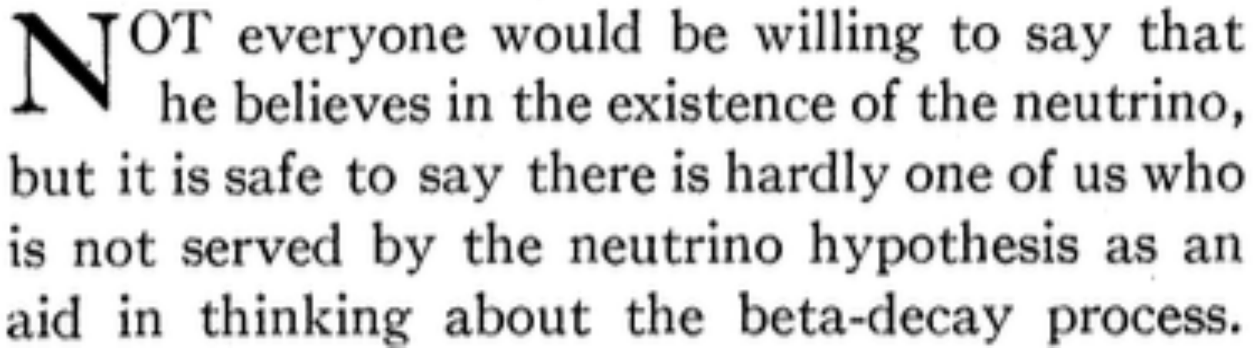
1936: Bethe-Bacher (Rev Mod Phys)



There is thus considerable evidence for the neutrino hypothesis. Unfortunately, all this evidence is indirect; and more unfortunately, there seems at present to be no way of getting any direct evidence. At least, it seems practically impossible to detect neutrinos in the *free state*, i.e., *after* they have been emitted by the radioactive atom. There is only *one* process which neutrinos can *certainly* cause. That is the inverse β-process, consisting of the capture of a neutrino by a nucleus together with the emission of an electron (or positron). This process is, however, so extremely rare (§42) that a neutrino has to go, in the average, through 10^{16} km of solid matter before it causes such a process. The present methods of detection must be improved at least by a factor 10^{13} in sensitivity before such a process could be detected.

1938: neutrino “n” renamed ν by E.M. Lyman

1948: H. R. Crane (Rev Mod Phys)



NOT everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say there is hardly one of us who is not served by the neutrino hypothesis as an aid in thinking about the beta-decay process.

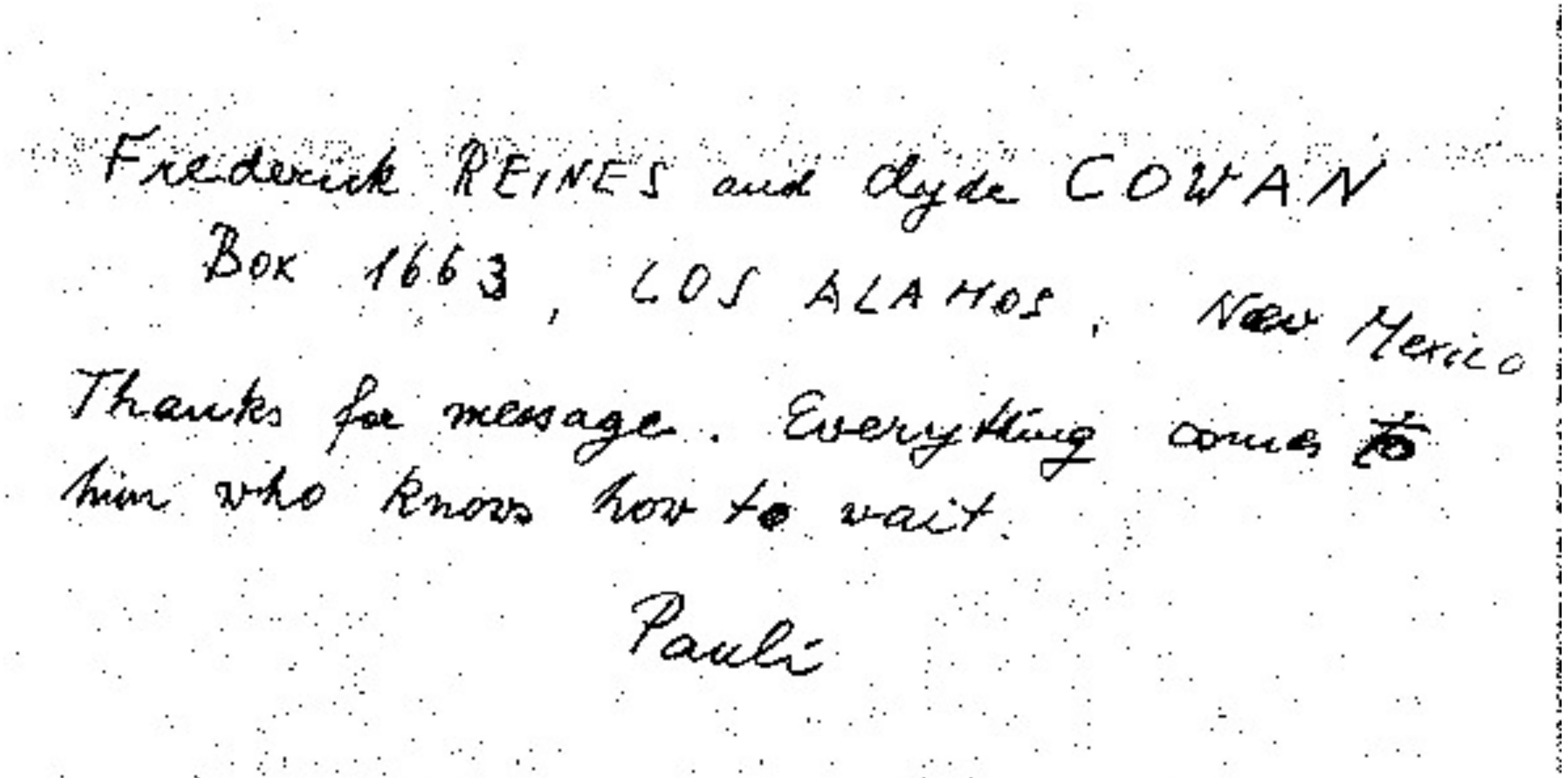
1953-1956: Cowan and Reines

Project Poltergeist

"Detection of the free neutrino" Phys Rev 92,830 (1953)

"Status of an experiment to detect the free neutrino"
invited talk at January 1954 APS meeting

"Detection of the free neutrino: a confirmation"
Nature, 124,3212 (1956)



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

1937 E. Majorana (Il Nuovo Cimento 14, 171)

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

1939 W. Furry (Phys Rev 56, 1184)

applies Majorana neutrino to $\beta\beta_{0\nu}$ decay

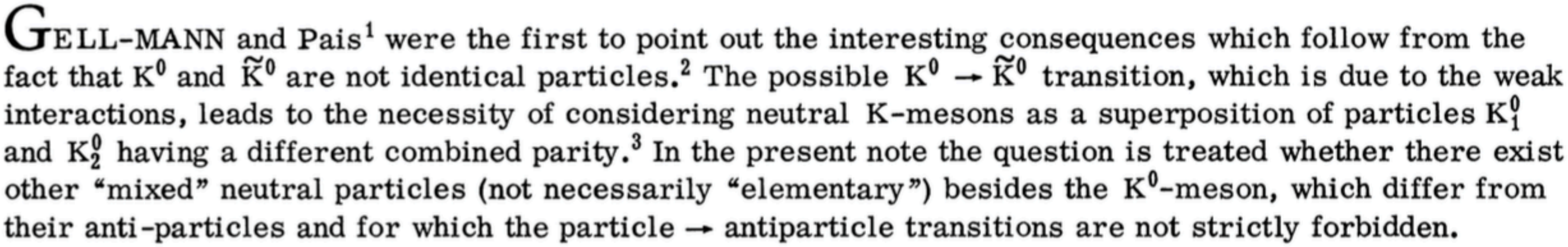
1945: Pontecorvo (Chalk River preprint)

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

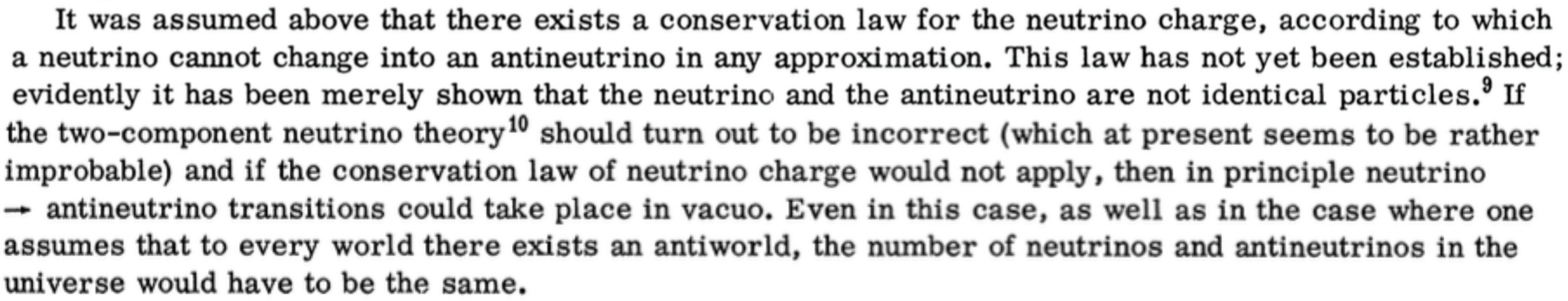
“nice but not practical” (Fermi)

1957: R Davis designs pilot experiment at the Savanah River reactor to detect neutrinos!

B. Pontecorvo (J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 549 (1957)



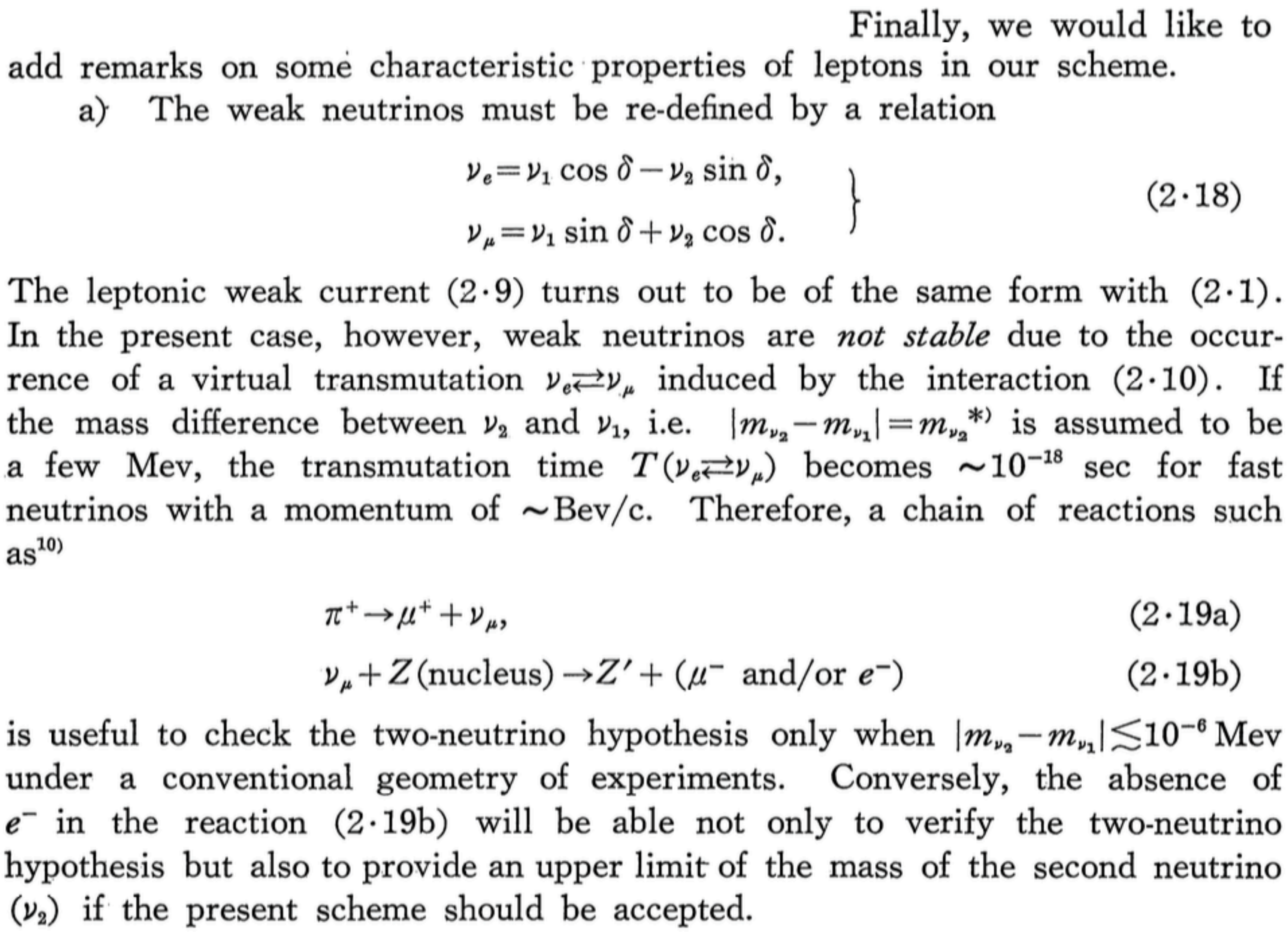
GELL-MANN and Pais[1] were the first to point out the interesting consequences which follow from the fact that K^0 and $\widetilde{K}^0$ are not identical particles.[2] The possible $K^0 \rightarrow \widetilde{K}^0$ transition, which is due to the weak interactions, leads to the necessity of considering neutral K-mesons as a superposition of particles K_1^0 and K_2^0 having a different combined parity.[3] In the present note the question is treated whether there exist other "mixed" neutral particles (not necessarily "elementary") besides the K^0-meson, which differ from their anti-particles and for which the particle → antiparticle transitions are not strictly forbidden.



It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and the antineutrino are not identical particles.[9] If the two-component neutrino theory[10] should turn out to be incorrect (which at present seems to be rather improbable) and if the conservation law of neutrino charge would not apply, then in principle neutrino → antineutrino transitions could take place in vacuo. Even in this case, as well as in the case where one assumes that to every world there exists an antiworld, the number of neutrinos and antineutrinos in the universe would have to be the same.

neutrino-antineutrino transitions (oscillations)

1962: Maki Nakagawa Sakata (Prog Theo Phys 28, 870)



Finally, we would like to add remarks on some characteristic properties of leptons in our scheme.

a) The weak neutrinos must be re-defined by a relation

$$\left.\begin{aligned}\nu_e&=\nu_1\cos\delta-\nu_2\sin\delta,\\ \nu_\mu&=\nu_1\sin\delta+\nu_2\cos\delta.\end{aligned}\right\}\qquad(2\cdot18)$$

The leptonic weak current (2·9) turns out to be of the same form with (2·1). In the present case, however, weak neutrinos are *not stable* due to the occurrence of a virtual transmutation $\nu_e\rightleftarrows\nu_\mu$ induced by the interaction (2·10). If the mass difference between ν_2 and ν_1, i.e. $|m_{\nu_2}-m_{\nu_1}|=m_{\nu_2}$*) is assumed to be a few Mev, the transmutation time $T(\nu_e\rightleftarrows\nu_\mu)$ becomes $\sim10^{-18}$ sec for fast neutrinos with a momentum of ~Bev/c. Therefore, a chain of reactions such as[10)]

$$\pi^+\rightarrow\mu^++\nu_\mu,\qquad(2\cdot19\text{a})$$

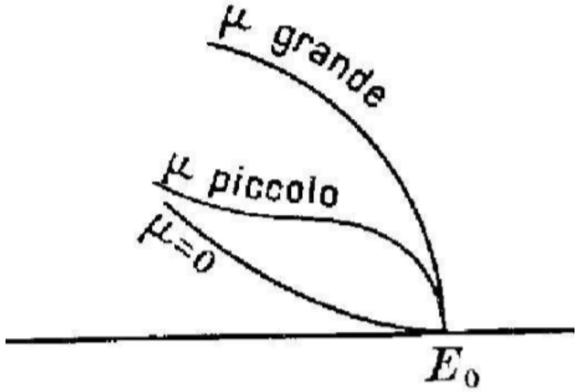
$$\nu_\mu+Z(\text{nucleus})\rightarrow Z'+(\mu^-\text{ and/or }e^-)\qquad(2\cdot19\text{b})$$

is useful to check the two-neutrino hypothesis only when $|m_{\nu_2}-m_{\nu_1}|\lesssim10^{-6}$ Mev under a conventional geometry of experiments. Conversely, the absence of e^- in the reaction (2·19b) will be able not only to verify the two-neutrino hypothesis but also to provide an upper limit of the mass of the second neutrino (ν_2) if the present scheme should be accepted.

flavor mixing and flavor transitions (oscillations)

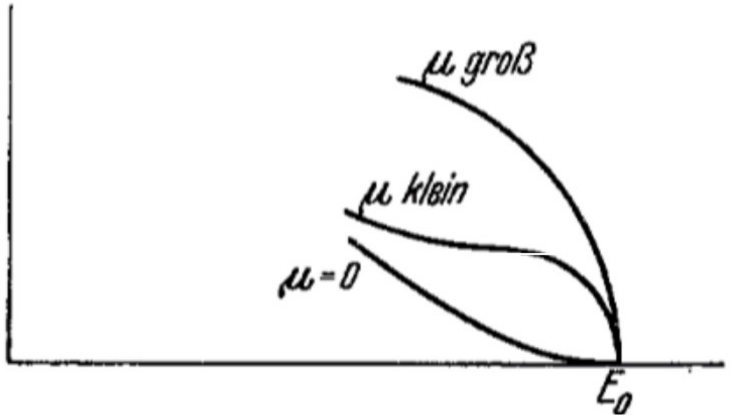
Neutrino masses

theorists weigh in



extreme kinematics

(Fermi 1933-34)



absurdly light neutrinos

"beyond the Standard Model" light

Standard Model Neutrinos

$$L_i = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_i \qquad \bar{e}_j \qquad H$$ (BEH boson)

New Leptonic BEHs

	$L_{[i}L_{j]}$	isosinglet	S^-	$\ell = 2$
fermion bilinears	$L_{(i}L_{j)}$	isotriplet	T	$\ell = 2$ (type II)
	$\bar{e}_i\bar{e}_j$	isosinglet	S^{++}	$\ell = -2$

New Fermions

$(L_i\bar{H})_0$ isosinglet neutrinos N_j (type I)

$(L_i\bar{H})_1$ isotriplet leptons Σ_j (type III) physics of scalar extensions determined by potential

$\mu (H\,H)_1 T$ (type II)

$\mu' \, S^{++} S^- S^-$

cubic terms $|\Delta\ell = 2|$

$\mu'' S^{++} (T\,T)_0$

$\mu''' S^+ S^+ (T\,T)_0$

total lepton number broken at μ-scales

quartic terms $|\Delta\ell = 0|$

loop level mass models

simplest add extra BEH boson H' $\mu (H'H)_0 S^+$

flavor-antisymmetric coupling $L_{[i}L_{j]}\ S^+$

(Zee; Babu; Ma; Gustafsson, No, Rivera;...)

(Type I: Minkowski;Yanagida; Gell-Mann, Ramond, Slansky; Glashow)

(Type II: Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich; Schecter, Valle; Mohapatra et al,; Ma;...)

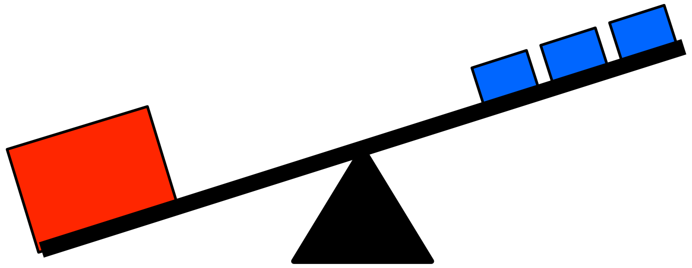
(Type III: Foot, He, Joshi; Ma;...)

A Winning Combination: Dirac and Majorana

Dirac mass $m\,(L\bar{H})_0 \cdot N$ $|\Delta\ell = 0|$

Majorana mass $M\,N \cdot N$ $|\Delta\ell = 2|$

Suppression $$\frac{m}{M} \sim \frac{\Delta I_{\rm w} = \frac{1}{2}}{\Delta I_{\rm w} = 0} \sim \frac{\rm EW}{\rm GUT} \ll 1$$



$$m_\nu = m\frac{m}{M}$$

Natural GUT Scale $SU_5,\ SO_{10},\ E_6, \cdots$

Neutrino Phases and Mixings

link Electroweak to GUT physics $\mathcal{U}_{PMNS} = \mathcal{U}^{\dagger}_{-1}\mathcal{U}_{Seesaw}$

$\mathcal{U}_{-1}$ diagonalizes charged lepton Yukawas: $\Delta I_{\rm w} = \frac{1}{2}$ physics

$\mathcal{U}_{Seesaw}$ diagonalizes the seesaw: $\Delta I_{\rm w} = 0$ physics

symbolically $\theta_{expt} \approx \theta_{Seesaw}\ \text{“}+\text{”}\ \theta_{EW}$

θ_{EW} “Cabibbo Haze” angles less than CKM’s

θ_{Seesaw} from $\Delta I_{\rm w} = 0$ physics

Masses

oscillations

$$\Delta_{12}^2 \equiv |m_{\nu_1}^2 - m_{\nu_2}^2| = (8.68\ meV)^2$$

$$\Delta_{13}^2 \equiv |m_{\nu_1}^2 - m_{\nu_3}^2| = (49.40\ meV)^2$$

cosmology

$$m_{\nu_1} + m_{\nu_2} + m_{\nu_3} \ \leq \ 0.22\ eV$$

Angles

reactor angle $\theta_{13} = 8.37^\circ \pm .16^\circ$ $< \theta_{Cabibbo}$

neutrino surprise: two large angles

atmospheric $\theta_{23} = 40.2^\circ{}^{+1.4^\circ}_{-1.6^\circ}$

$\Delta I_{\mathrm{w}} = 0$ physics

solar $\theta_{12} = 33.6^\circ \pm 0.8^\circ$

$\Delta\ell = 0$ one Dirac phase

$\Delta\ell = 2$ two Majorana phases

solar and atmospheric angles mostly from θ_{Seesaw}

reactor angle from either θ_{EW} and/or θ_{Seesaw}

Neutrinos & Yukawa Unification

Dirac's Path

Seek Simplicity and Beauty

in gauge couplings

in Yukawa couplings

Tension in the Yukawa Sector

At GUT scale, quark and neutrino

gauge couplings unify

disparate Yukawa couplings

small quark mixing angles < 13^0

neutrino surprise!

two large neutrino mixing angles

Majorana Crystal at GUT scale

Discrete Family Symmetry at GUT scale

(Pakvasa, Sugawara; Ma; 10^3 more authors ...)

three chiral families

discrete SU_3, SU_2 subgroups

SU_2 : A4 double cover, ...

SU_3 : Δ_{27}, ... , T_7, PSL(2,7)

Grand Unification Primer

Yukawa Couplings

u

d

e

Grand Unification Primer

Yukawa Couplings

u

d

e

ν_D

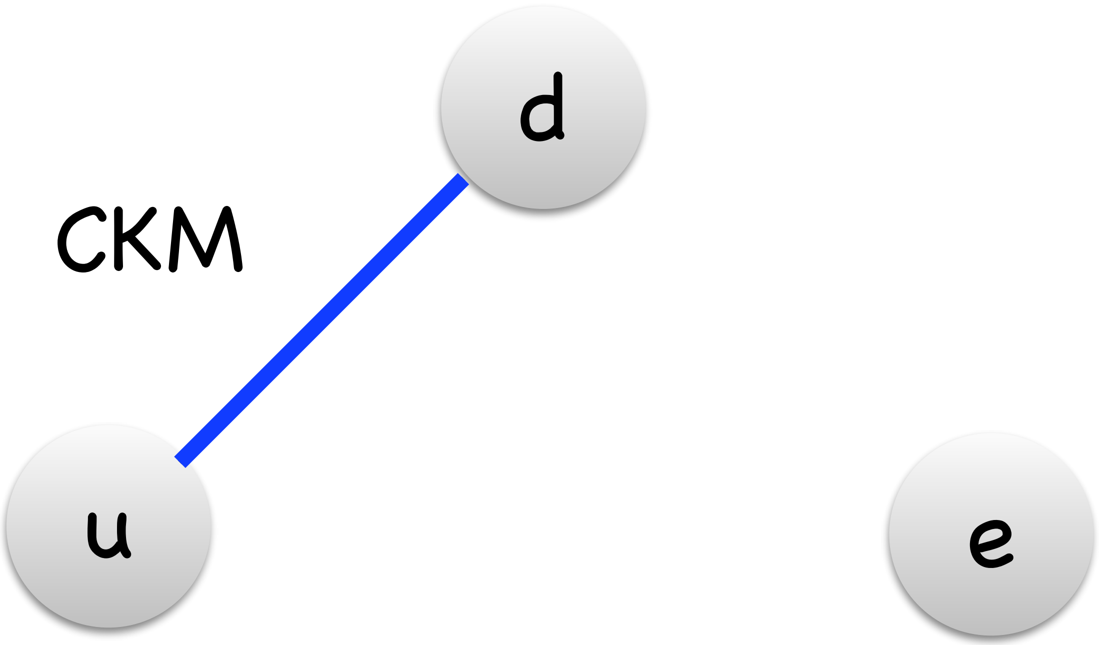
Grand Unification Primer

Yukawa Couplings

u d e ν_D

Majorana mass

M


d
CKM
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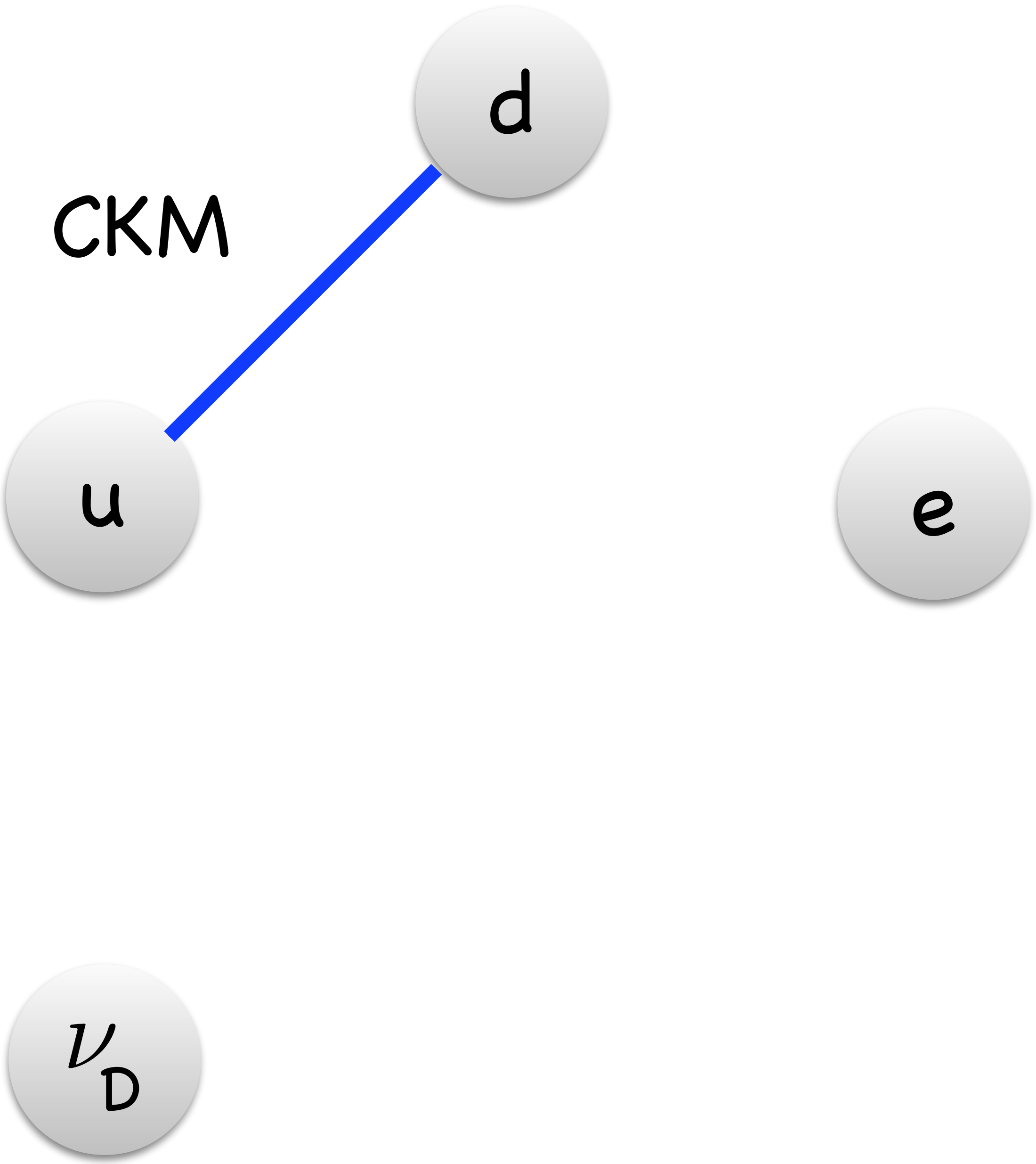


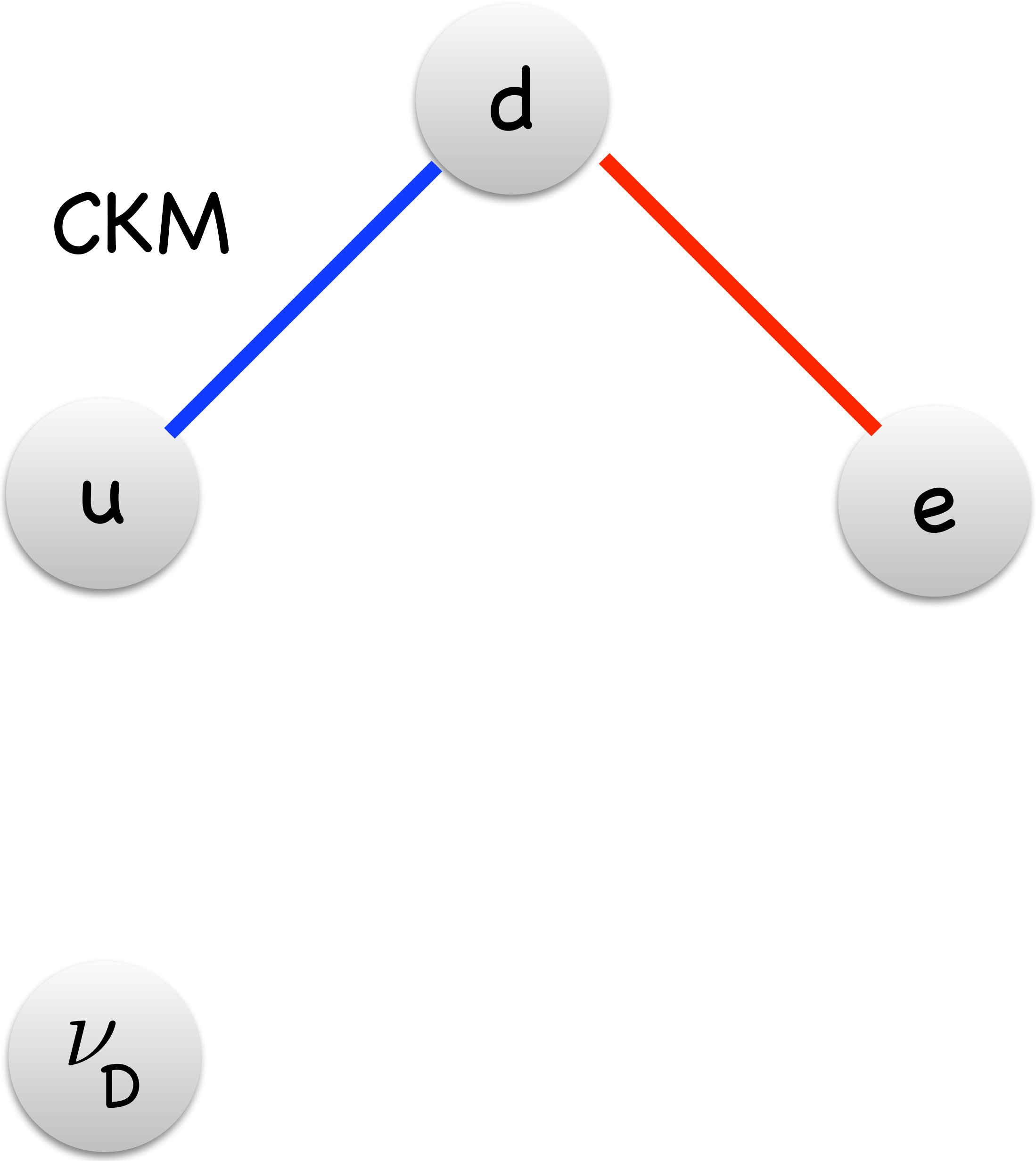
d

CKM

u

e

ν_D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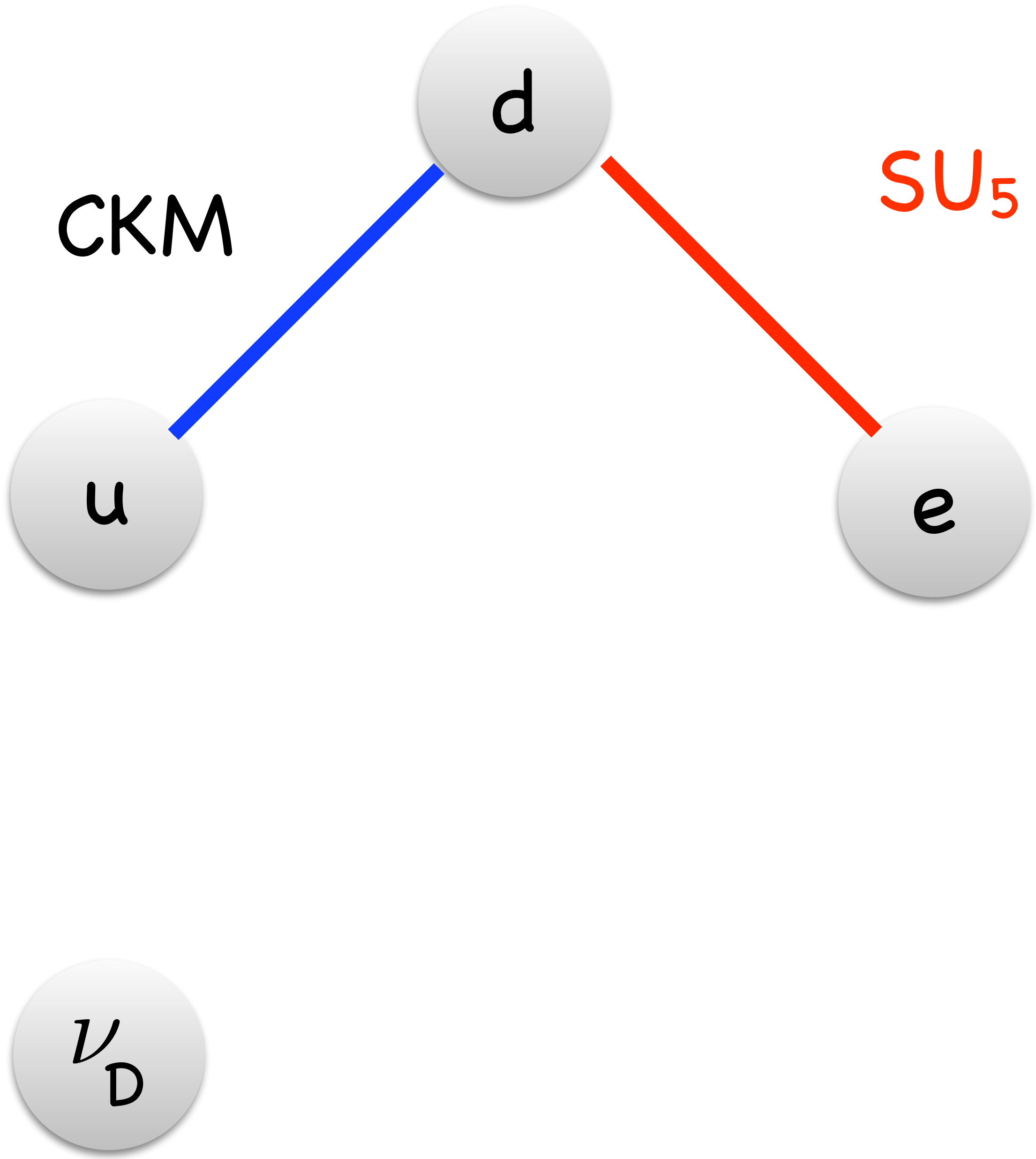
d
CKM
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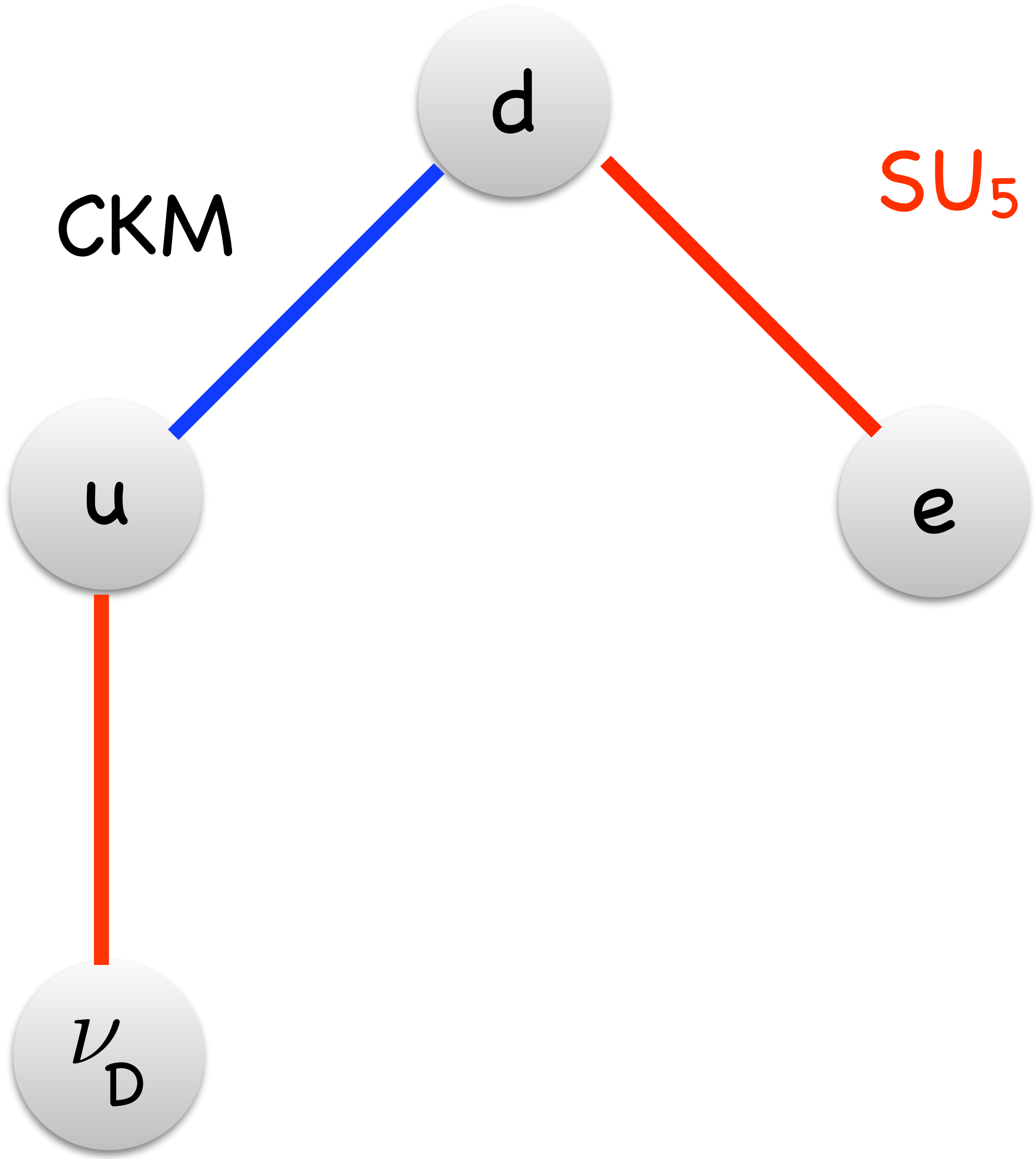d
CKM
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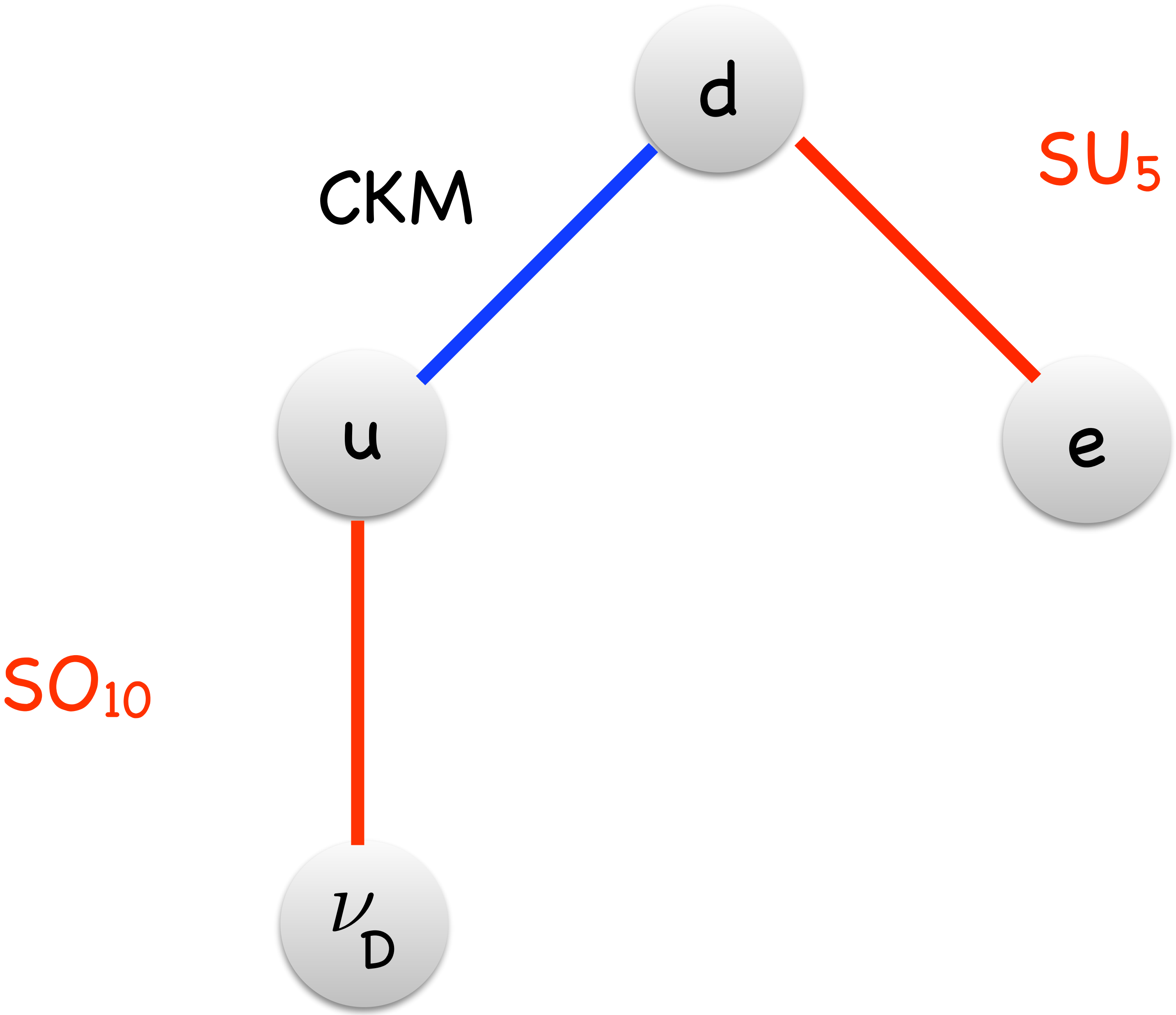
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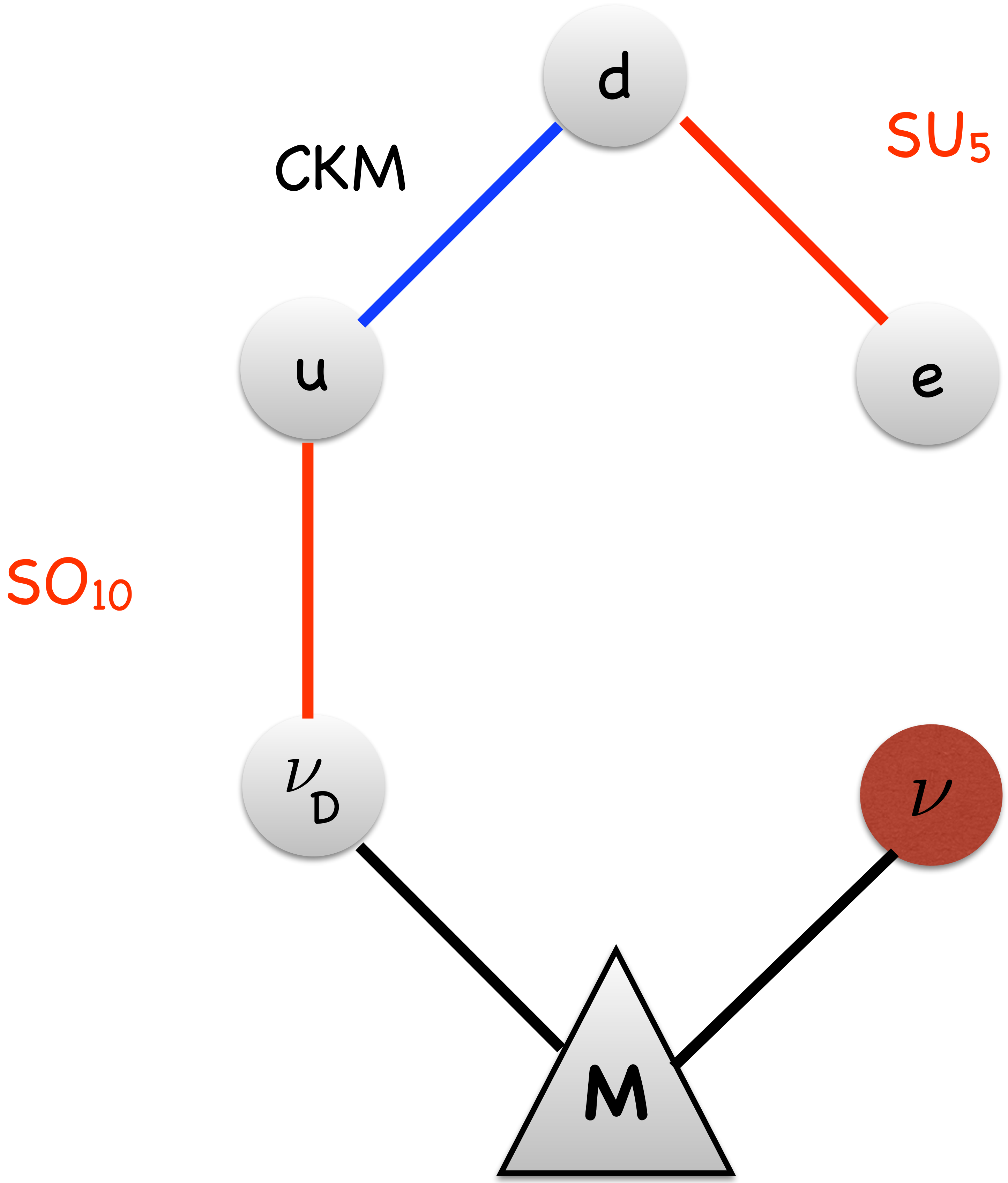
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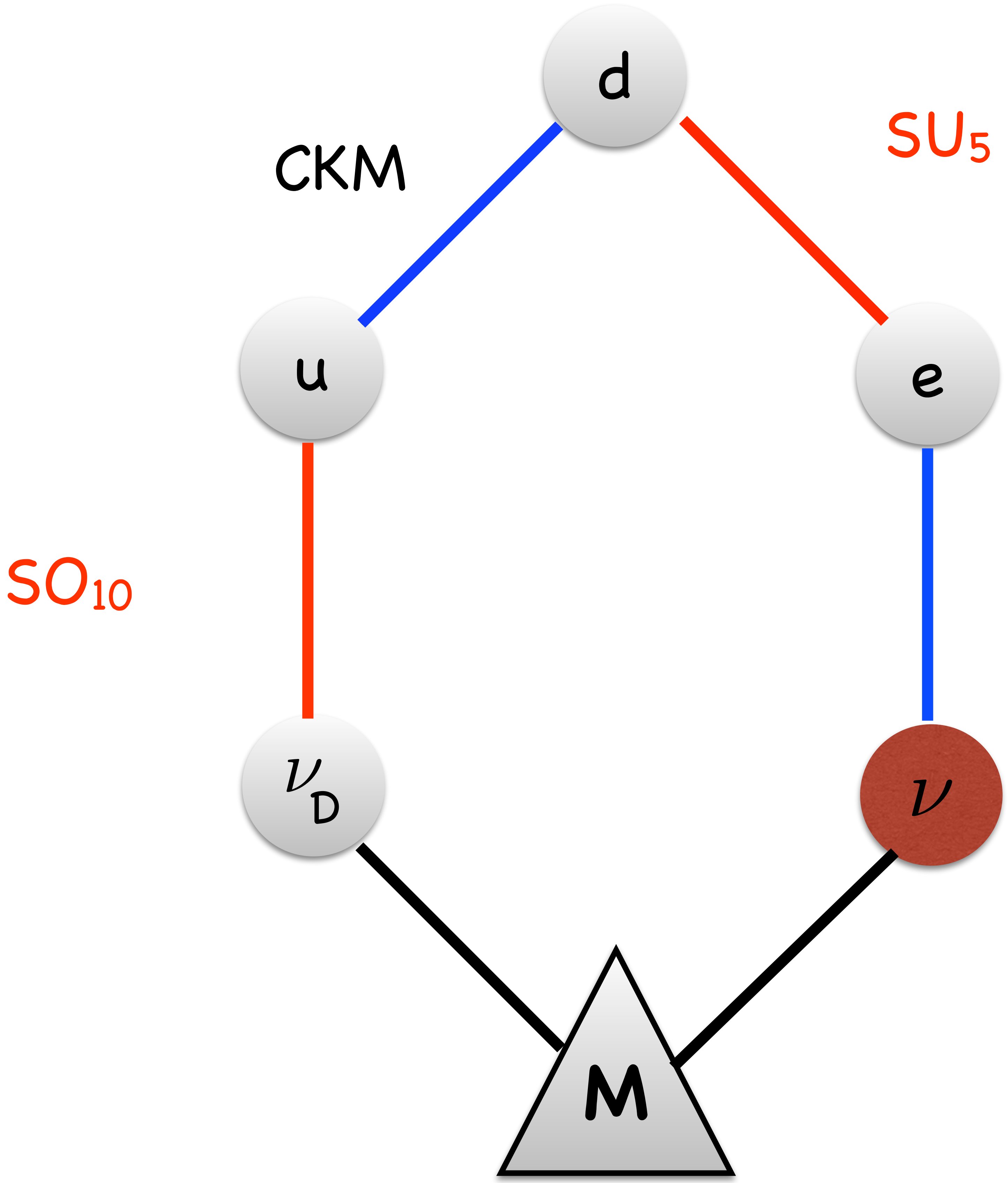d
CKM
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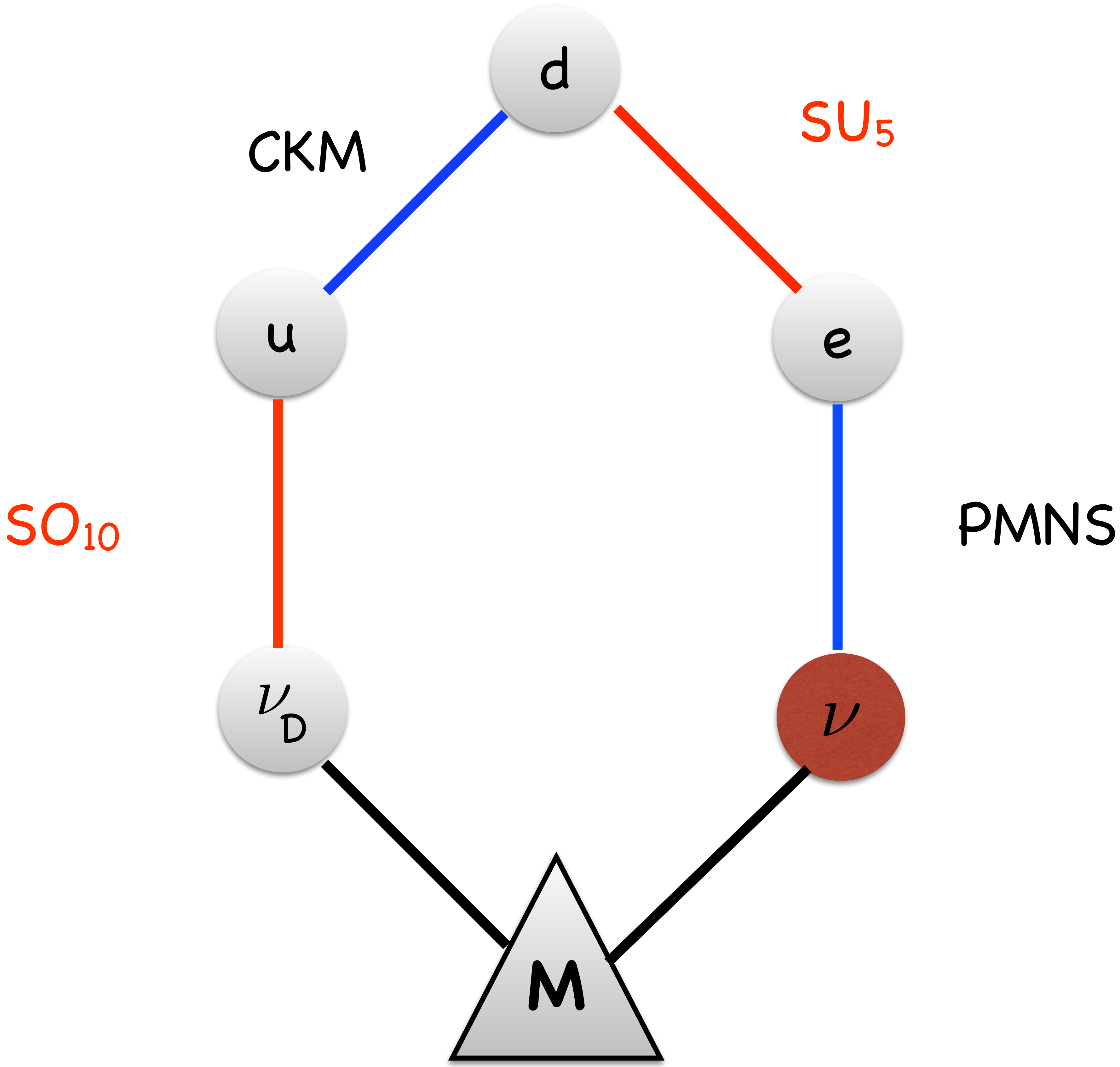
d
CKM
SU5
u
e
SO10
PMNS
ν_D
ν
M

Seesaw Simplicity

small angle	**all** from "Cabibbo Haze"
two large angles	**only** from Seesaw

Tri-Bi-Maximal Matrix

"pretty matrix with an ugly name" (L. Everett)

$$\mathcal{U}_{Seesaw} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

simplest SO_{10}

$$Y^{2/3} = Y^{\nu_D} = \begin{pmatrix} \epsilon^4 & 0 & \\ 0 & \epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

correlated hierarchy

Majorana mass $$\mathcal{M} = \begin{pmatrix} \epsilon^4 & 0 & \\ 0 & \epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathcal{M}' \begin{pmatrix} \epsilon^4 & 0 & \\ 0 & \epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\mathcal{M}'$ inverse eigenvalues = neutrino masses

$\mathcal{M}'$ TBM diagonalization: relations among its elements

(12)=(13); (22)=(33); (23) – (22) = – (11) – (12)

PSL(2,7) coupling (22) = (23); $|\frac{m_{\nu_1}}{m_{\nu_2}}| = \frac{1}{2}$

$$m_{\nu_3} \sim 50\ meV, \quad m_{\nu_2} \sim 11\ meV, \quad m_{\nu_1} \sim 5.5\ meV$$

BUT

TBM Mixing requires asymmetric Yukawa Matrices

(J. Kile, J. M. Pérez, PR, J. Zhang, 2014)

SU$_5$ Yukawas

(M. H. Rahat, PR, B. Xu, 2018)

$$Y^{\bar{\mathbf{5}}} \quad : \quad \frac{1}{3}\begin{pmatrix} 2\sqrt{\rho^2+\eta^2}\lambda^4 & \lambda^3 & 3A\sqrt{\rho^2+\eta^2}\lambda^3 \\ \lambda^3 & 0 & 3A\lambda^2 \\ 3A\sqrt{\rho^2+\eta^2}\lambda^3 & 3A\lambda^2 & 3 \end{pmatrix} + \frac{2}{3A}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$Y^{\overline{\mathbf{45}}} \quad : \quad \frac{1}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

A, ρ, η, λ Wolfenstein parameters

satisfies CKM, Gatto & Gut-scale Georgi-Jarlskog relations

$$\lambda \approx \sqrt{\frac{m_d}{m_s}} \qquad m_b = m_\tau; \quad m_\mu = 3m_s; \quad m_d = 3m_e$$

PMNS angles

θ_{13} 2.26° above pdg

θ_{23} 2.9° below pdg

θ_{12} 6.16° above pdg

Phase ϕ in TBM matrix reduces θ_{13}

$\cos\phi = 0.2$ brings θ_{13} to its pdf value

PMNS angles

θ_{13} at pdg

θ_{23} 0.66° below pdg

θ_{12} 0.51° above pdg

Jarlskog-Greenberg invariant $J = |0.027|$

$$\delta_{CP} = \begin{cases} 1.32\pi & \text{- sign} \\ 0.67\pi & \text{+ sign} \end{cases}$$

neutrino detectors

Super K

SNO

SUPER K

KamLAND
Kamioka Liquid scintillator Anti-Neutrino Detector

Gallex

SNO

T2K

Soudan
Fermilab
Main
Injector
Neutrino
Oscillation
Search

DOUBLE CHOOZ

Daya Bay
θ_{13}

RENO
ν θ_{13}

KATRIN
Karlsruhe
Tritium
Neutrino
Experiment

NOvA

DUNE

The Sun Never Sets

on neutrino detectors

A Prediction

Neutrino Chronology

	Revelation	1930
2(13) yrs later	Detection	1956
2^2(17) yrs later	Oscillations	1998

Neutrino Chronology

	Revelation	1930
2(13) yrs later	Detection	1956
$2^2(17)$ yrs later	Oscillations	1998
$2^3(19)$ yrs later		

Neutrino Chronology

	Revelation	1930
2(13) yrs later	Detection	1956
2^2(17) yrs later	Oscillations	1998
2^3(19) yrs later	$\beta\beta_{0\nu}$ decay	2052!

Neutrino Chronology

	Revelation	1930
2(13) yrs later	Detection	1956
2^2(17) yrs later	Oscillations	1998
2^3(19) yrs later	$\beta\beta_{0\nu}$ decay	2052!

longevity required

neutrinos prospecting should

be a family affair