The Unfinished Standard Model

Pierre Ramond
Institute for Fundamental Theory
University of Florida

"pandemically inspired"

Historical Perspective

The Standard Model

Completions

Neutrino Strategy

Physics in the shadow of genius

“history does not repeat itself, but it sure rhymes” (Mark Twain)

Newton century

apply Newton’s laws to phenomena

electromagnetism → new physics

Einstein century

quantum mechanics

general relativity

standard model

dark matter → ?

Vacuum physics

Descartes: full of vortices

Newton: full of nothing

Einstein: full of quanta

Standard model vacuum

Brownian motion calculation → Avogadro's number

cosmological constant calculation → space-time?

"history does not repeat itself, but it sure rhymes" (Mark Twain)

(Unfinished) Standard Model

theory of strong, weak and electromagnetic forces

between chiral leptons and quarks

a beautiful edifice built on a suspect foundation:

flat space-time

"renormalizable" quantum field theory"

relativistic effective quantum field theory
with logarithmic uv cut-off

with a neutral scalar particle (Higgs)

much lighter than the cut-off energy

Explanation of such small mass awaits...

(supersymmetry?)

Local Symmetries: $SU_3 \times SU_2 \times U_1$

Global Symmetries: $U_{1(B-L)}$ $U_{1(PQ)}$?

Three chiral families

survived fifty years of experimental tests

accommodates but not explain
the origin of neutrino masses

does not challenge established principles

Standard Model & General Relativity

offers a natural uv cut-off where space-time breaks down

absence of gravitational chiral anomaly

requires BOTH chiral leptons and quarks

Standard Model & Dark Matter

does not require dark matter for its consistency

interacts with dark matter

Dark Matter $\longrightarrow$ new particle(s) or ... game changer?

Dirac's Principle of Mathematical Beauty

bimodal exploration of Nature

experiment and observation & mathematical reasoning

"where simplicity (Newton's equation)

and

beauty (Einstein's special relativity) clash

opt for beauty"

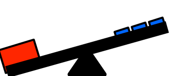
Could simplicity and beauty meet at the Standard Model cut-off?

Standard Model is weakly coupled at CERN scales

enables theoretical exploration of physics
at shorter distances
via
the perturbative renormalization group

intersections of gauge and Yukawa couplings

in the ultraviolet?



bridge to shorter distances

Grand Unification of local symmetries

convergence of gauge couplings in the uv

patterns of fermion quantum numbers

$$SU_3 \times SU_2 \times U_1 \longrightarrow SU_5,\ SO_{10},\ E_6,\ \ldots$$

baryon number violation

proton decay $\longrightarrow$ cut-off deep in uv

$$\approx 10^{15-16}\ GeV$$

two scales: Higgs mass << uv cut-off

intersection of b-quark and tau-lepton masses

scale-dependent mass ratio

at the Υ-mass $\quad m_b \approx 3 m_\tau$

SU(5) says $\quad m_b = m_\tau$

factor of three from the renormalization group

sets another uv scale $\approx 10^8\ GeV$

new particles required below this scale

to avoid fast proton decay

(slows down QCD running)

bridge to the mystery of neutrino masses

Neutrinos

born in the mind of a theorist

detected south of the Mason-Dixon line

the original chiral particles

harbingers of new physics

rewarding research area

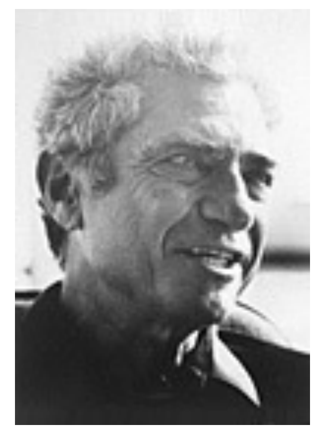
Nobels

E. Fermi
1938

W. Pauli
1945

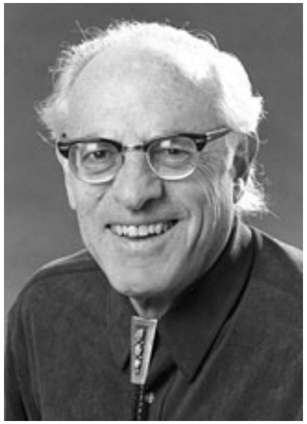
L. Lederman
1988

M. Schwartz
1988



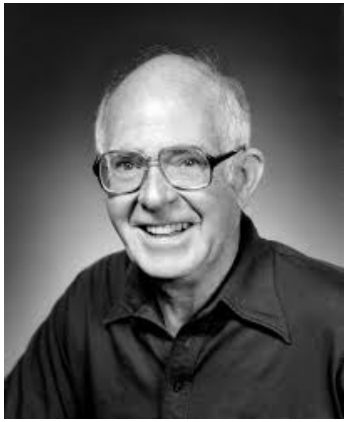
J. Steinberger
1988

Nobels



F. Reines

1995



R. Davis

2002

M. Koshiba

2002

T. Kajita

2015

A. McDonald

2015

ν hall of fame

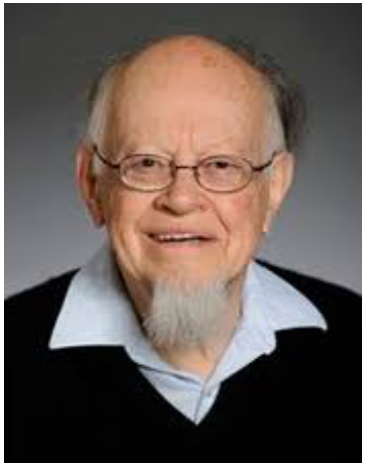
E. Majorana

B. Pontecorvo

M. Goldhaber

S. Sakata

J. Bahcall



L. Wolfenstein

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 ... but only those who wager can win ... Unfortunately, I cannot personally appear in Tubingen, since I am indispensable here on account of a ball…"*

Wolgang Pauli

(within a year Pauli was under analysis with C. Jung)

Pauli's two problems

Pauli exclusion principle

1930 Nitrogen nucleus: fermion with 14 protons and 7 electrons

surrounded by 7"chemistry" electrons

Raman line intensities: N nucleus is a Boson

Energy conservation

continuous energy spectrum of the beta-decay electron

Pauli's fermion X solves both problems

Nitrogen nucleus: 14 protons +7 electrons + X

$$N \to N' + e^- + \quad X$$

1931 Chadwick's neutron solves the Nitrogen problem

Nitrogen nucleus: 7 protons+ 7 neutrons

"little neutron" remains: 1933 Fermi asserts

"the neutrino (Pauli's particle) is not in the nucleus

it is created and emitted during beta emission

DISCOVERY

(twenty-six years laters)

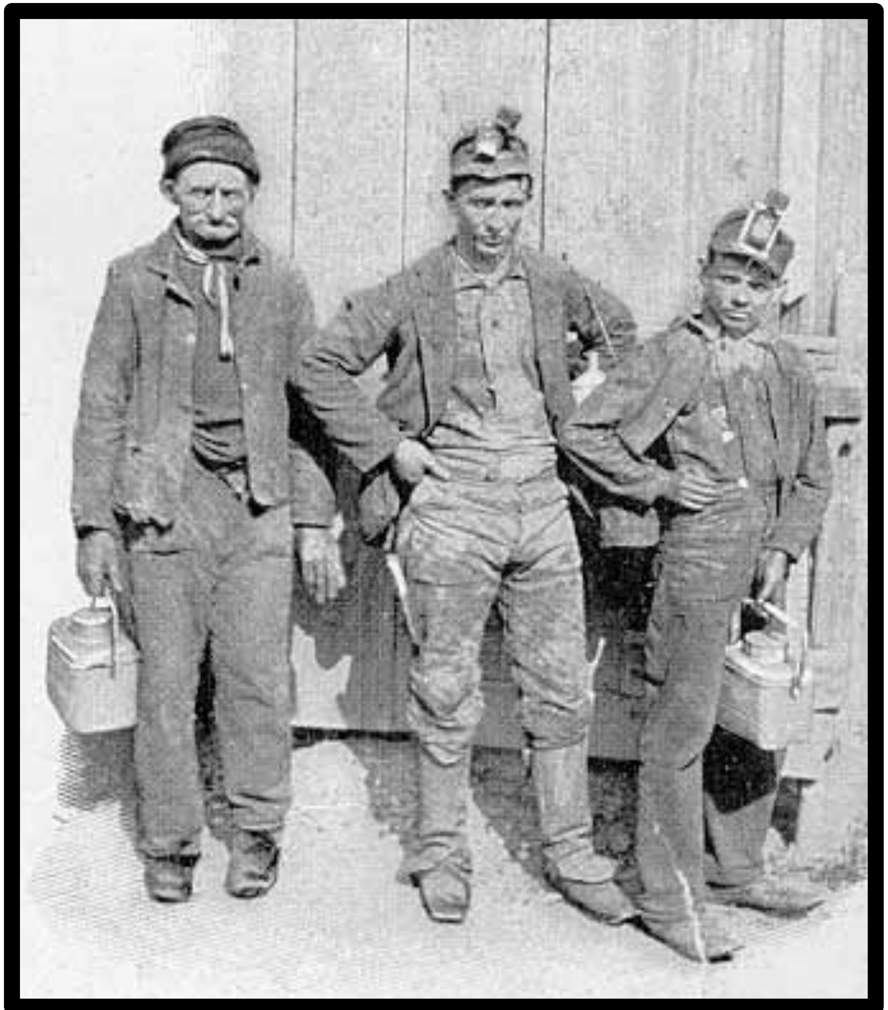
Project Poltergeist

Clyde Cowan

Fred Reines

longevity required

prospecting for neutrinos should be a family affair



the Pontecorvo brothers

Guido

Bruno

Gillo

1945 Bruno proposes a clever way to detect neutrinos

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

Fermi thought it was not practical,
Pontecorvo never published

Ray Davis uses

it to count neutrinos

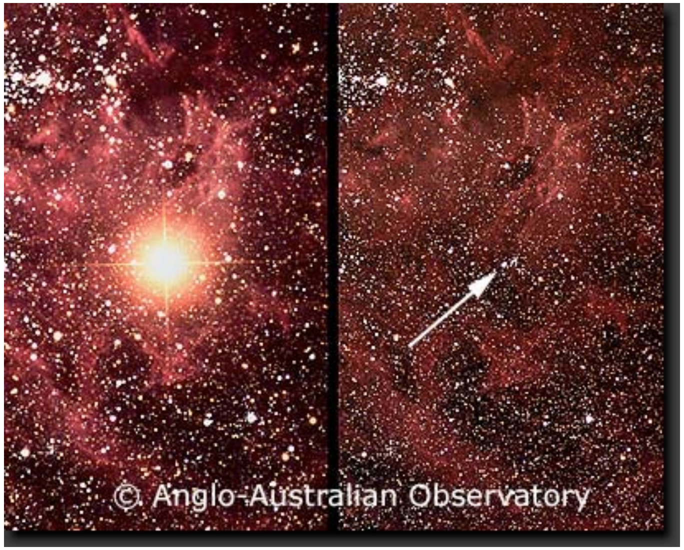
from the Sun

at the Homestake gold mine in Lead, SD

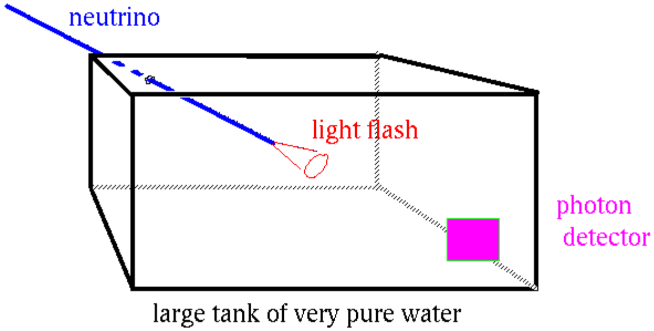
Davis and his graduate students, taking out the Argon

Davis finds one third the expected rate!

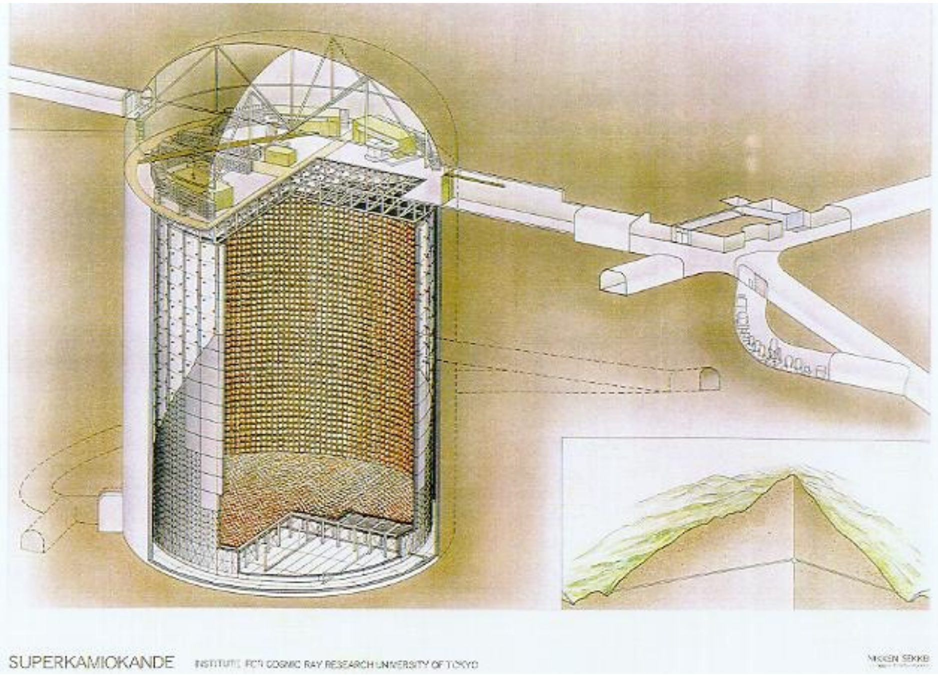
1987A Supernova



underground proton decay detectors



become neutrino detectors



neutrinos from

cosmic rays

the Sun

$N_{\nu_\mu} \approx N_{\nu_e}$ expect 2:1

$N_{\nu_\mu}^{up} \neq N_{\nu_\mu}^{down}$ expect equal number

$N_{\nu_\mu}^{up}$ zenith angle dependence

two-flavor oscillations $\nu_\mu \longleftrightarrow \nu_\tau$ $\theta_{23} \approx 45^\circ$

Davis solar ν_e deficit confirmed

neutrinos have mass

Deuterium dissociation by neutrinos

$$\nu_e + D \rightarrow p + p + e^-$$

neutrino-electron elastic scattering

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

electron neutrinos oscillate

solar ν_e deficit confirmed

solar ν_e flux confirmed

large solar angle $\approx 36^o$

counts number of neutrino flavors

reactor mixing angle

$$\frac{L}{E}$$

near detector

far detector

small reactor angle $\approx 8.5^\circ$

THEORY

why are neutrinos so light?

three Standard Model neutrinos

$$\begin{pmatrix}\nu_e \\ e\end{pmatrix} \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$$

members of weak doublets $I_{3\mathrm{w}} = +\frac{1}{2}$

Majorana mass $m\,\nu\nu$ $\Delta I_W = 1$ $\Delta L = 2$

violates lepton number

add "right-handed neutrino" $\overline{N}$ with $I_\mathrm{w} = 0$

Dirac mass $m\,\nu\overline{N}$ $\Delta I_\mathrm{w} = \frac{1}{2}$ $\Delta L = 0$

Dirac and Majorana unite

Dirac

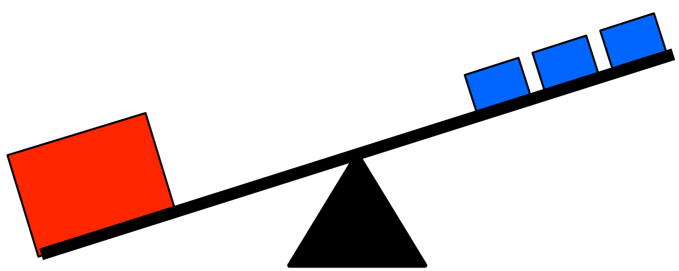
$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

Majorana

M >> m

large

M



$$m\left(\frac{m}{M}\right)$$

small

Standard Model scale

$$\frac{m}{M} = \frac{\Delta I_{\mathrm{w}} = \frac{1}{2}}{\Delta I_{\mathrm{w}} = 0}$$

new physics scale

meV "Di-Maj" neutrino mass

$$\sum m_\nu \leq 115\, meV \longrightarrow M \geq 10^{16}\, GeV$$

convergence region of gauge couplings

coincidence?

neutrino mixing

$$\mathcal{U}_{PMNS} = \mathcal{U}_{-1}^{\dagger}\,\mathcal{U}_{Seesaw}$$

SM physics

new physics

$$\theta_{\rm expt} \sim \theta_{\rm small} + \theta_{\rm new}$$

$\theta_{\rm small} \leq$ Cabibbo angle $\longrightarrow$ "Cabibbo Haze" in the data

data: two large & one small mixing angles

$\theta_{12} \approx 33.6^\circ \pm 2^\circ$ $\quad\theta_{23} \approx 47.6^\circ \pm 3.6^\circ$ $\quad\theta_{13} \approx 8.5^\circ \pm .4^\circ$

Quark Mixing Matrix

bridge between up-quarks and down-quarks

largest angle is the Cabibbo angle

lepton mixing matrix

Pontecorvo-Maki-Nakagawa-Sakata

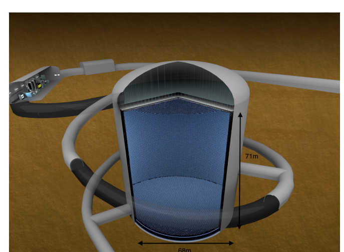
a bridge to the unknown

Lepton mixing (Pontecorvo-Maki-Nakagawa-Sakata)

large angles offer hope to explain baryon asymmetry

$\Delta L = 0$ Dirac CP-violating phase $\delta_{\rm CP} \; = \; 1.37 \pm .17\pi$

$\Delta L = 2$ two Majorana CP-violating phases



theoretical challenge

devise model where this split-up is natural

e.g. TBM

$$\begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Seesaw side $\theta_{12} = 35.3^\circ \quad \theta_{23} = 45^\circ \quad \theta_{13} = 0$

Standard Model side $\theta_{12} = \theta_{23} = 0 \quad \theta_{13} \neq 0$

"Majorana crystal" at the cut-off?

Dirac's simple and beautiful?

no need to build temples to the Sun

we know where it is all the time

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?

the

end

neutrino mass hierarchy