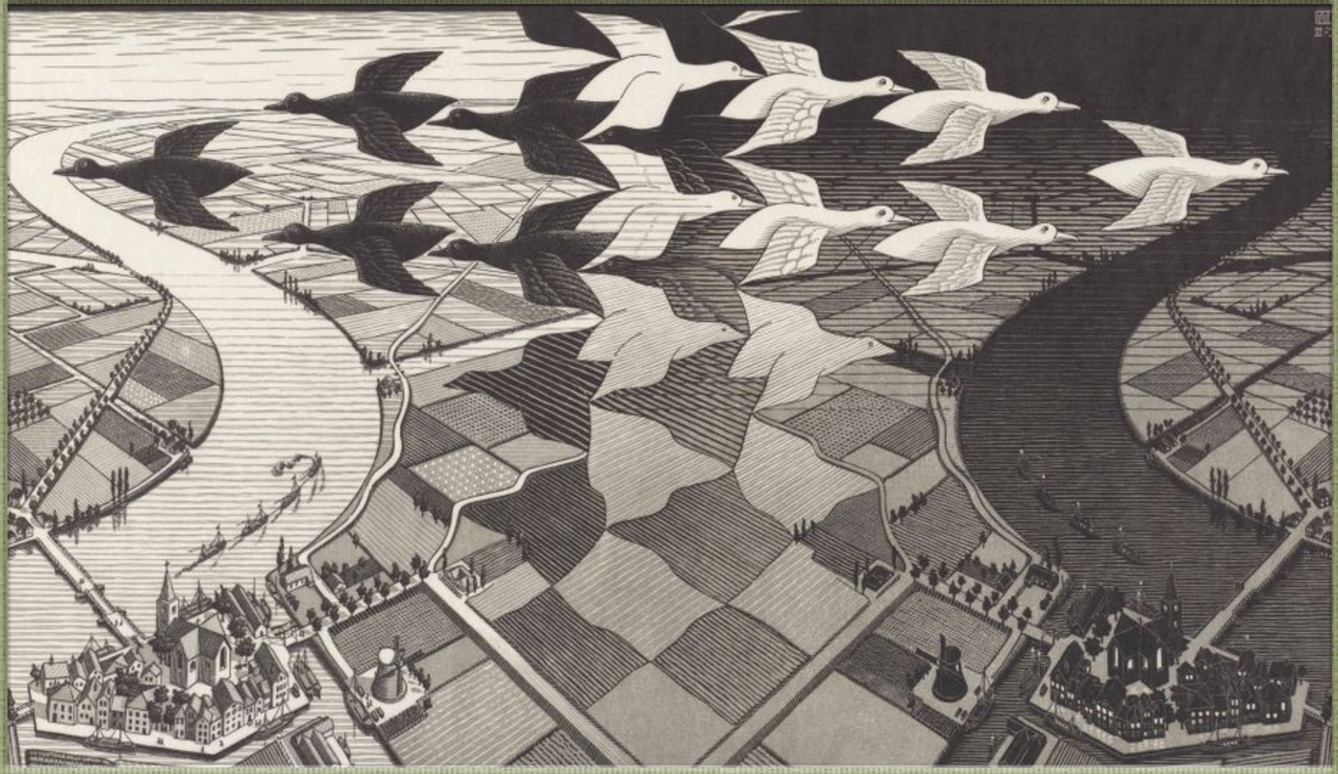
Neutrino:

chronicles of an aloof witness



Goran Senjanović
ICTP, Trieste

Fermilab, August 7, 2019

Neutrino: why so special?

elusive particle

mean free path = distance travelled before interacting

$$\simeq 10^{19} \text{ cm}$$

million times distance earth-sun ~ 1000 light years

travel to the edge of the universe

&

have been present from its birth → window into new physics

Neutrino: why so special?

elusive particle

mean free path = distance travelled before interacting
$\simeq 10^{19}$ cm

million times distance earth-sun ~ 1000 light years

travel to the edge of the universe

&

have been present from its birth → window into new physics

John Updike 1960

Cosmic

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

Cosmic

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

John Updike 1960

wrong

nature and origin of
neutrino mass - Holy Grail

The neutrino story

story of great scientific breakthroughs

but also

story of human drama,
disappearances and escapes

moreover,
an account of a lifelong personal struggle for
a self-contained, predictive theory of neutrino mass
- and a sense of finally having achieved it

The neutrino story

story of great scientific breakthroughs

but also

story of human drama,
disappearances and escapes

moreover,
an account of a lifelong personal struggle for
a self-contained, predictive theory of neutrino mass
- and a sense of finally having achieved it

The neutrino story

story of great scientific breakthroughs

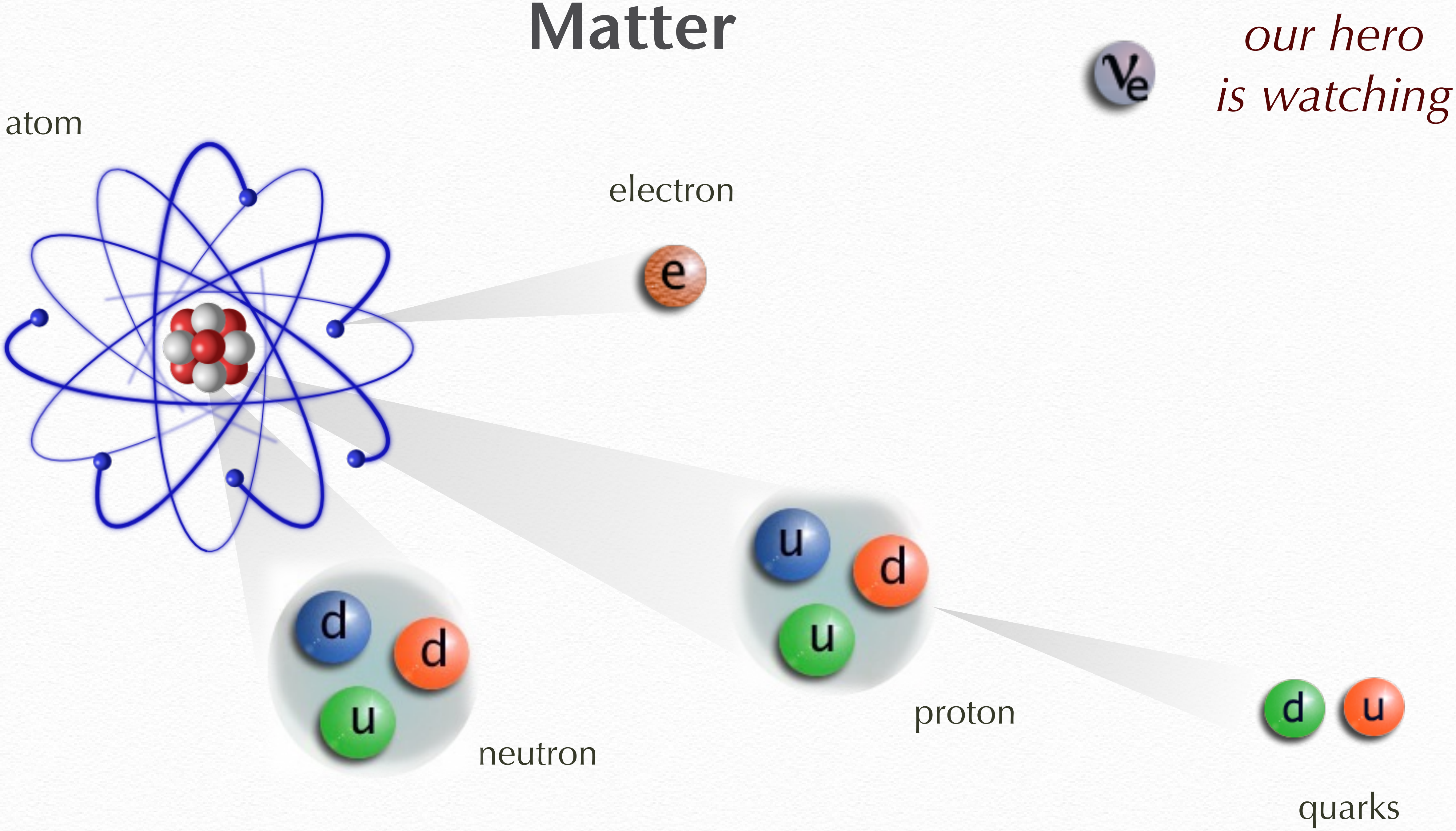
but also

story of human drama,
disappearances and escapes

moreover,
an account of a lifelong personal struggle for
a self-contained, predictive theory of neutrino mass
- and a sense of finally having achieved it

first things first

Matter



$$m_n \simeq m_p \simeq 1000\, m_e \qquad m_q \simeq 10\, m_e$$

Elementary particles

hadrons ⟵ quarks

leptons

hadros= stout, thick d u

e ν_e leptos =thin, fine

spin=1/2

charge:

ν_e	e	u	d
0	-1	2/3	-1/3

(neutron = 0 proton = +1)

spin ⟶ angular momentum at rest

particles keep spinning

Elementary particles

hadrons ← quarks

leptons

hadros= stout, thick d u

e ν_e leptos =thin, fine

spin=1/2	ν_e	e	u	d
charge:	0	-1	2/3	-1/3

(neutron = 0 proton = +1)

spin → angular momentum at rest

particles keep spinning

Standard Model of particle interactions

Forces have messengers

Electromagnetic	charged particles - quarks and electron
Strong	quarks
Weak	all - but neutrino only weak

Standard Model of particle interactions

Forces have messengers

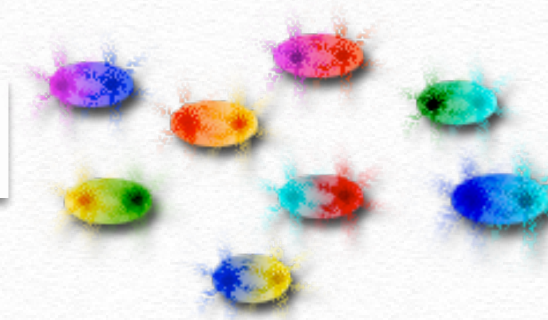
Electromagnetic

charged particles - quarks and electron

photon

Strong

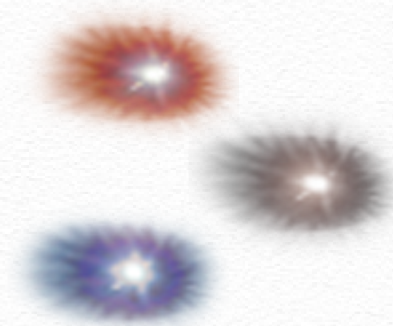
quarks



gluons

Weak

all - but neutrino only weak



$W^{\pm}$, Z bosons

Electro-magnetism - photon

messenger = photon

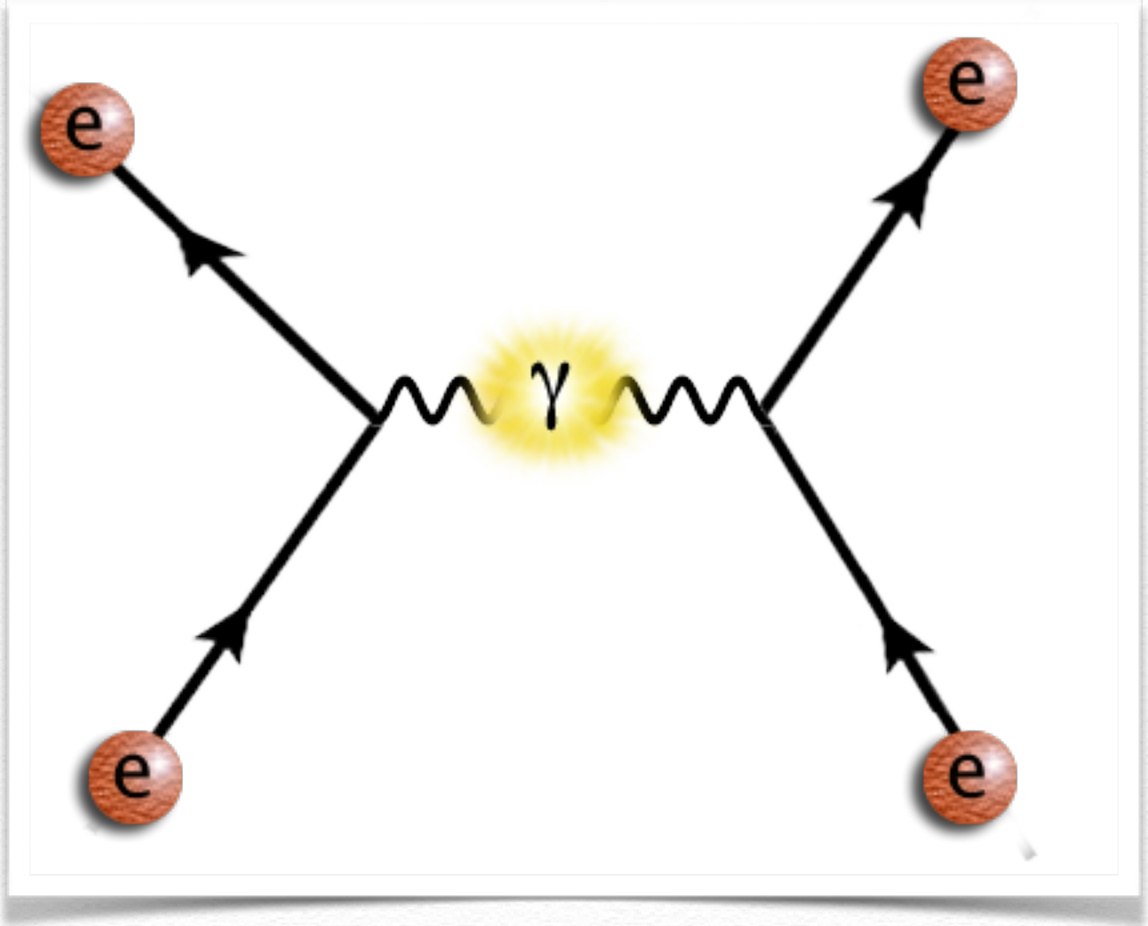
mass=0 spin=1

Electro-magnetism - photon

messenger = photon

mass=0 spin=1

Feynman 1948



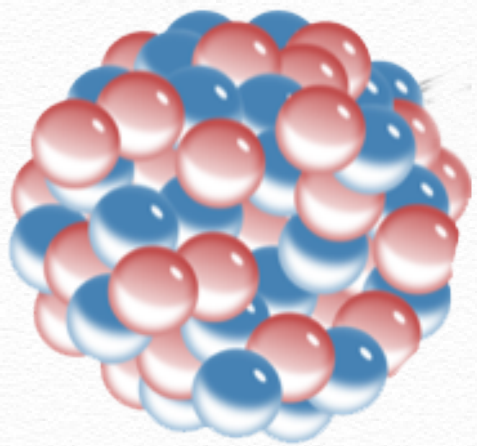
Weak interactions

&

birth of neutrino

Beta decay - missing energy

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^- \cdot$$



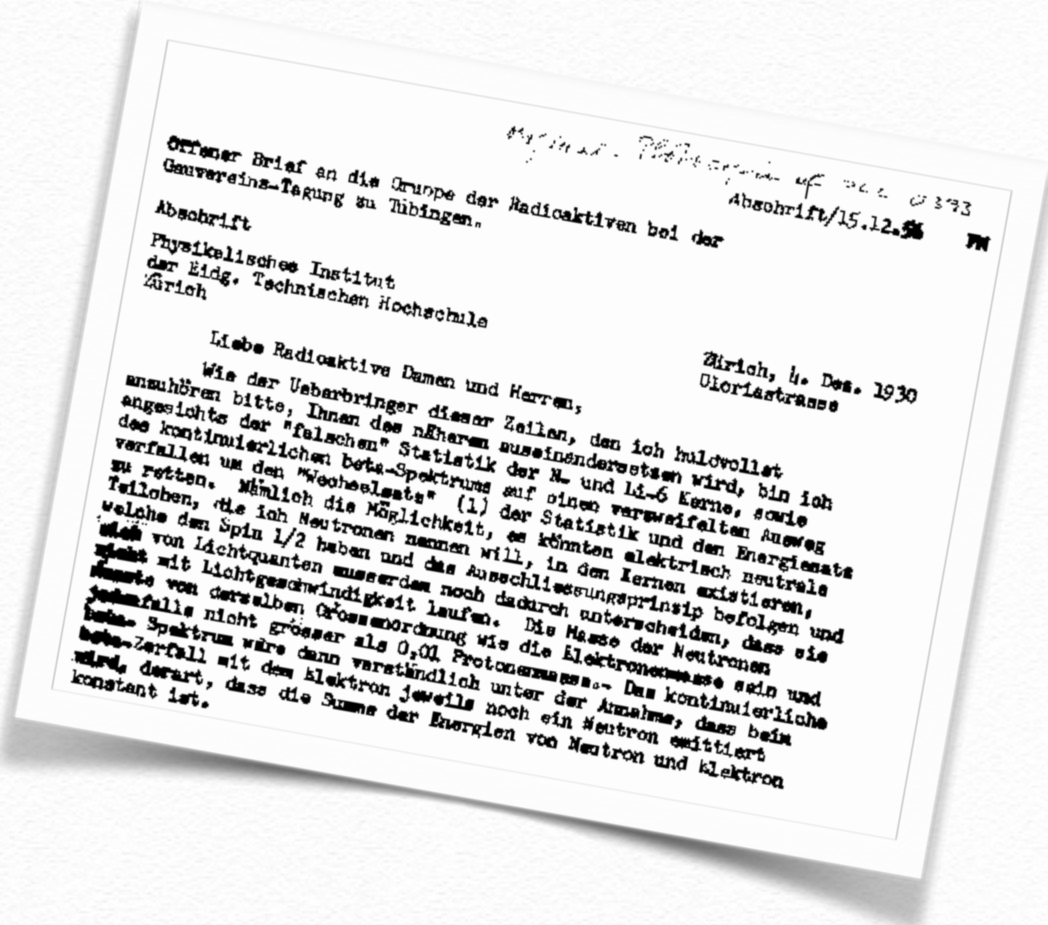
n -> p + e

electron energy continuous

Pauli 1930

suggests neutrino

- to conserve energy



Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift/15.12.56 PM

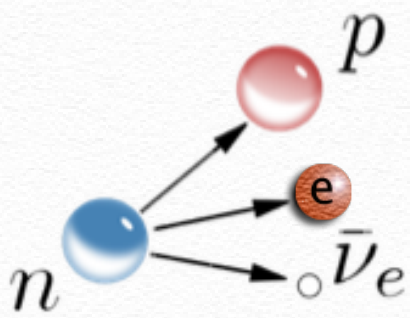
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

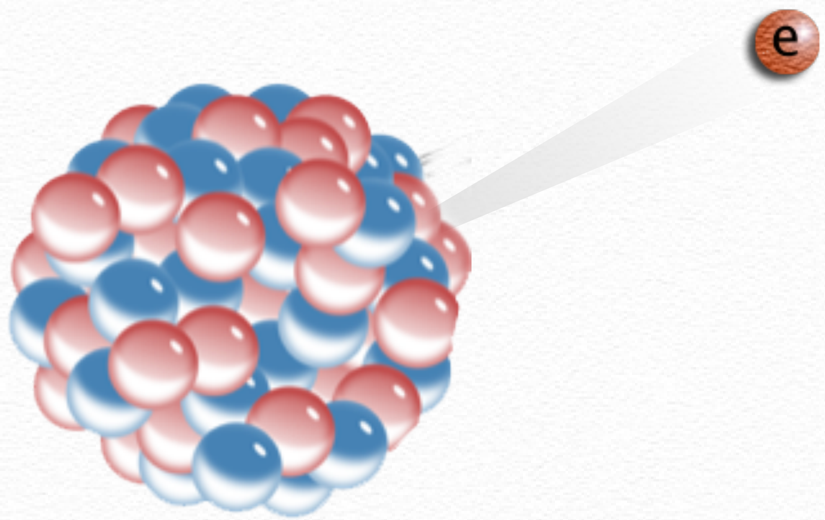
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



Wolfgang Pauli

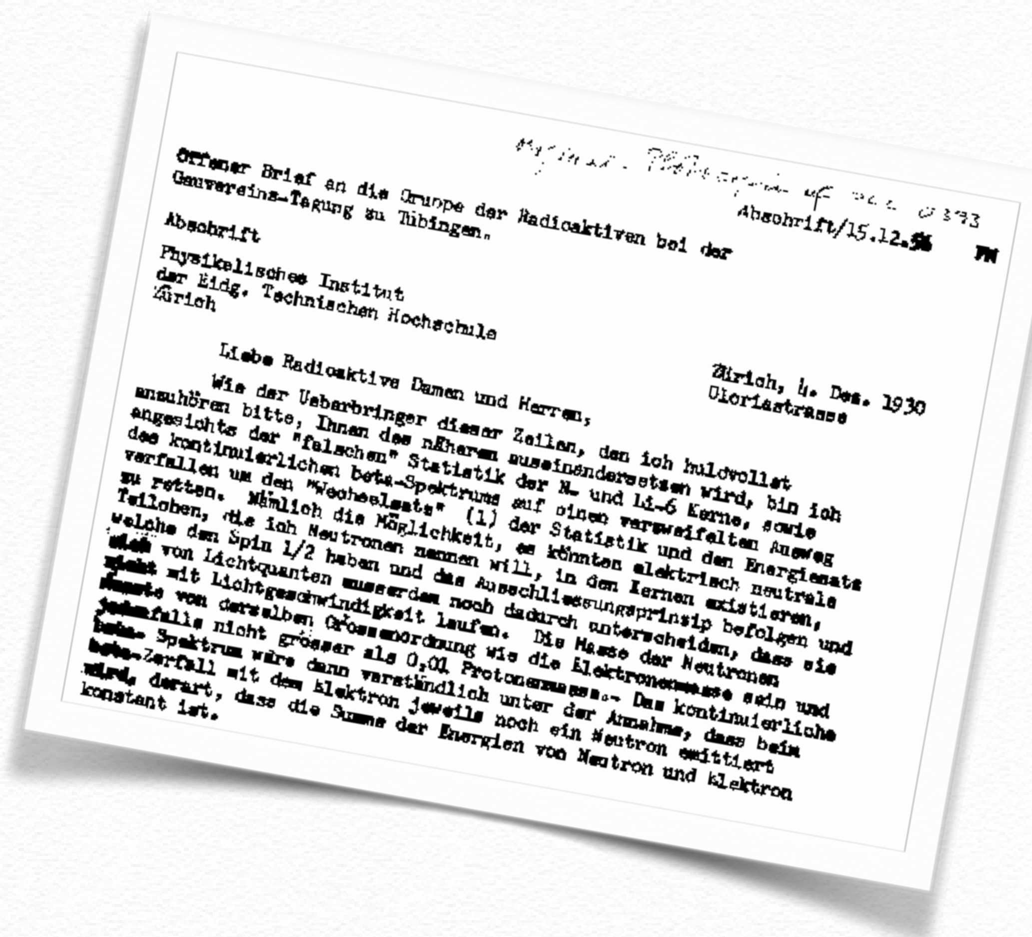
Beta decay - missing energy



$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni} + e^{-}$

n -> p + e

electron energy continuous



Pauli 1930

suggests neutrino

- to conserve energy

Abschrift/15.12.56 PN

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

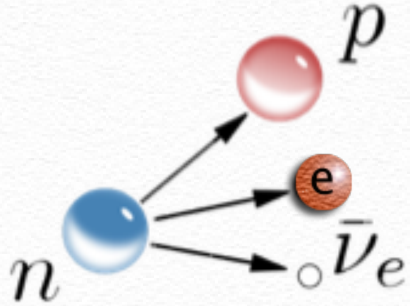
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Wolfgang Pauli



Fundamental theory - messenger W boson

modern view: $d \rightarrow u + e + \bar{\nu}$

$$\mathcal{H}_{fund} = \frac{g}{\sqrt{2}} J^{\mu}_{W} W^{+}_{\mu}$$

n = u d d   p = u u d

$$J^{W}_{\mu} = \bar{u}\gamma_{\mu} d + \bar{\nu}\gamma_{\mu} e$$

weak interaction
messenger: W

Fundamental theory - messenger W boson

modern view: $d \rightarrow u + e + \bar{\nu}$

$$\mathcal{H}_{fund} = \frac{g}{\sqrt{2}} J^{\mu}_{W} W^{+}_{\mu}$$

n = u d d   p = u u d

$$J^{W}_{\mu} = \bar{u}\gamma_{\mu}d + \bar{\nu}\gamma_{\mu}e$$

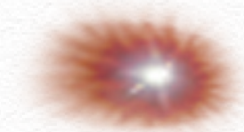
weak interaction
messenger: W

Discovering W

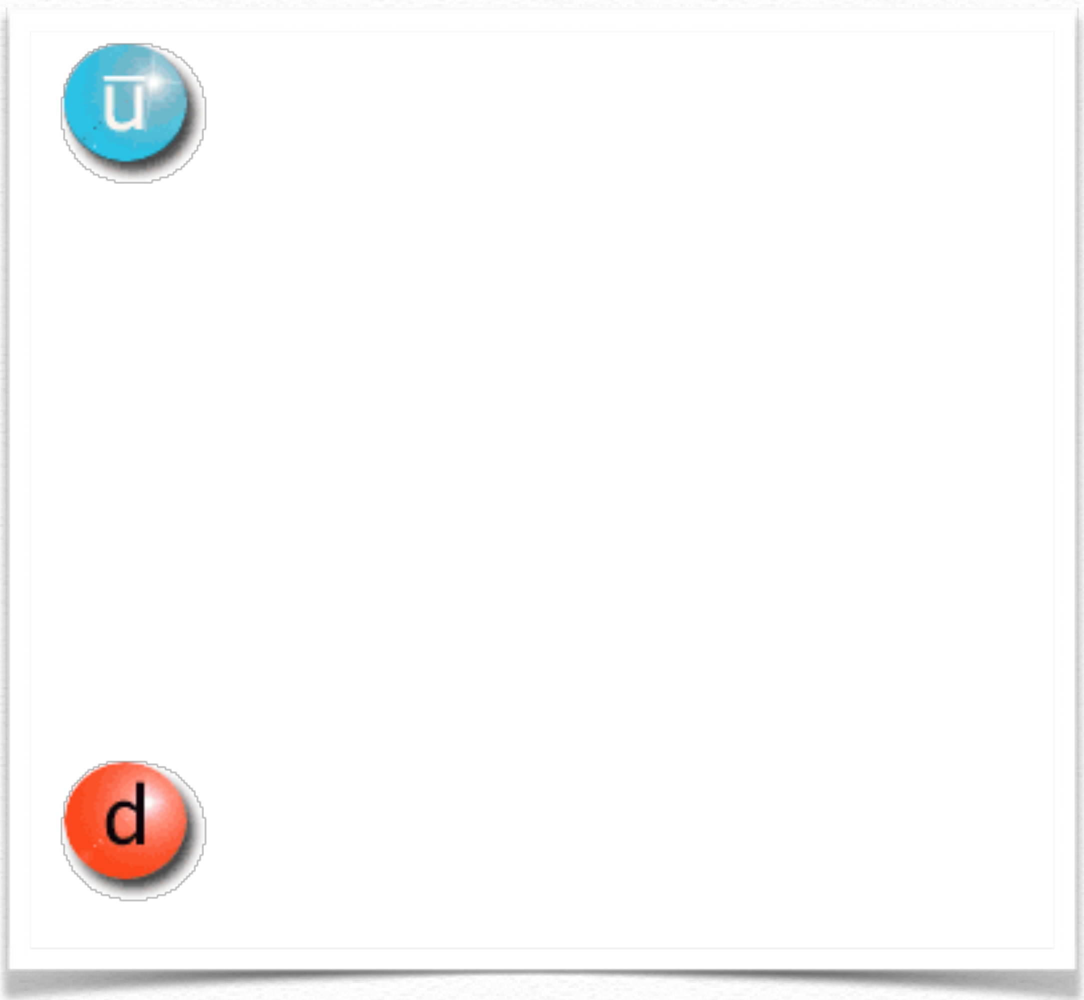
$$\mathcal{H}_{fund} = \frac{g}{\sqrt{2}} J^{\mu}_{W} W^{+}_{\mu}$$

Messenger = W boson

anti-proton



spin=1



heavy $M_W = 80\, m_p$

W discovery@CERN 1983

SPS - 7 km circumference

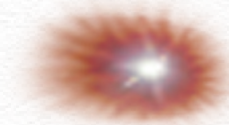
proton

Discovering W

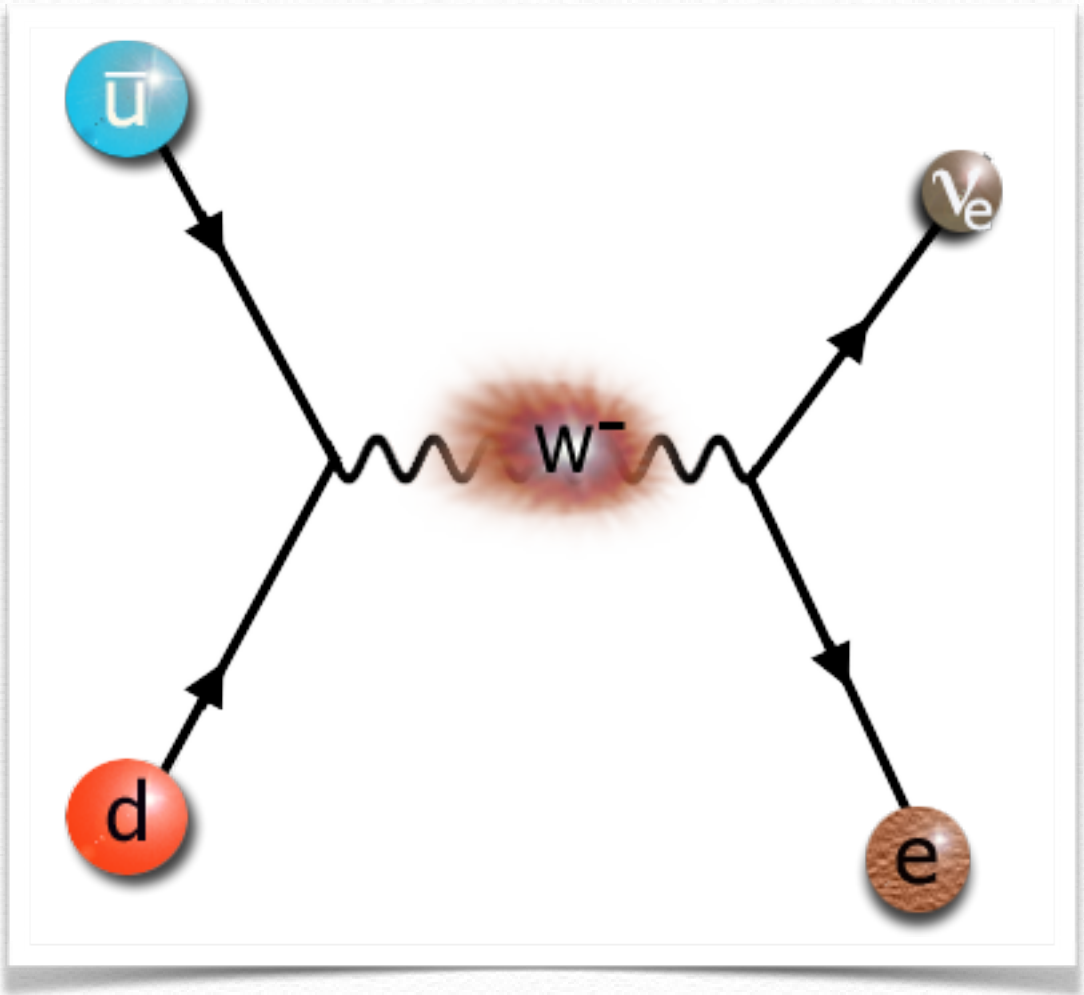
$$\mathcal{H}_{fund} = \frac{g}{\sqrt{2}} J_W^\mu W_\mu^+$$

Messenger = W boson

anti-proton



spin=1



heavy $M_W = 80\, m_p$

W discovery@CERN 1983

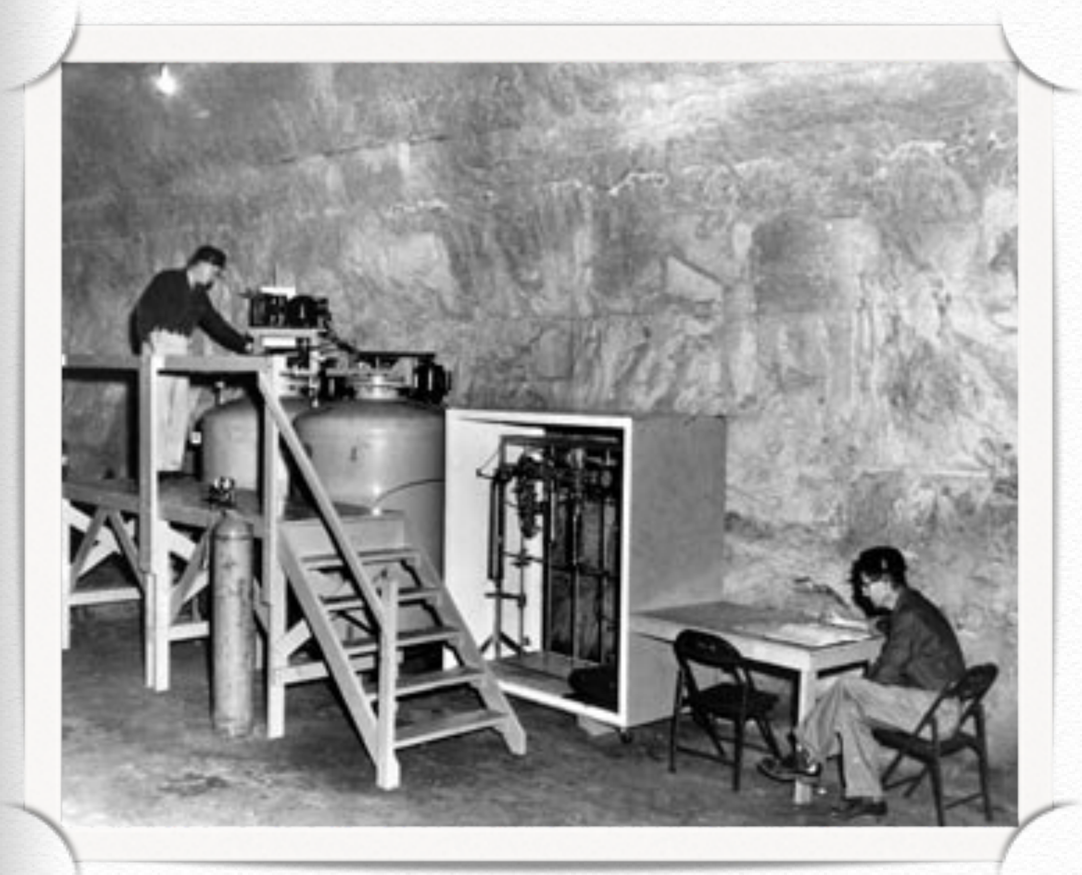
SPS - 7 km circumference

proton

Neutrino discovery

Pauli regrets introducing a ghost particle
that cannot ever be seen

Cowan, Reines 1956



use reactors = huge flux

Pontecorvo '40s

tens of trillions per square cm per second

water $p + \bar{\nu} = n + \bar{e}$

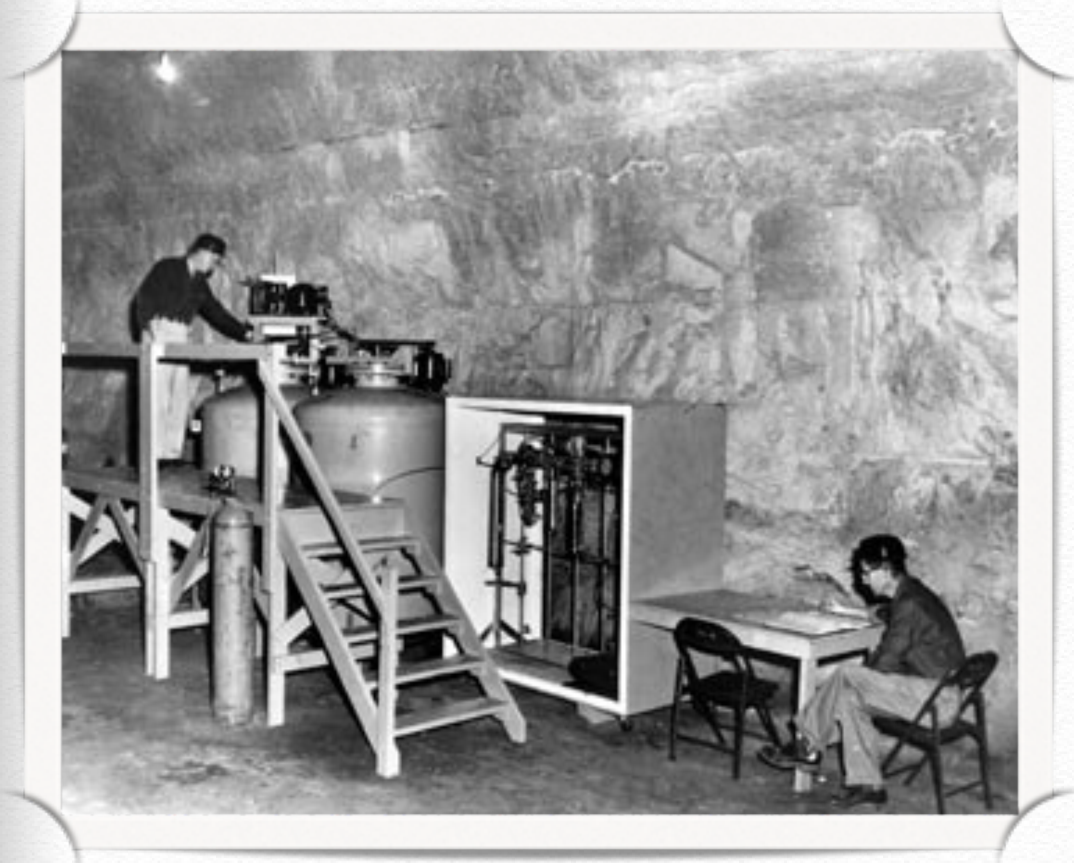
good old days

`Everything comes to him who knows how to wait.' *Pauli*

Neutrino discovery

Pauli regrets introducing a ghost particle
that cannot ever be seen

Cowan, Reines 1956 (Nobel prize 1995)



use reactors = huge flux

Pontecorvo '40s

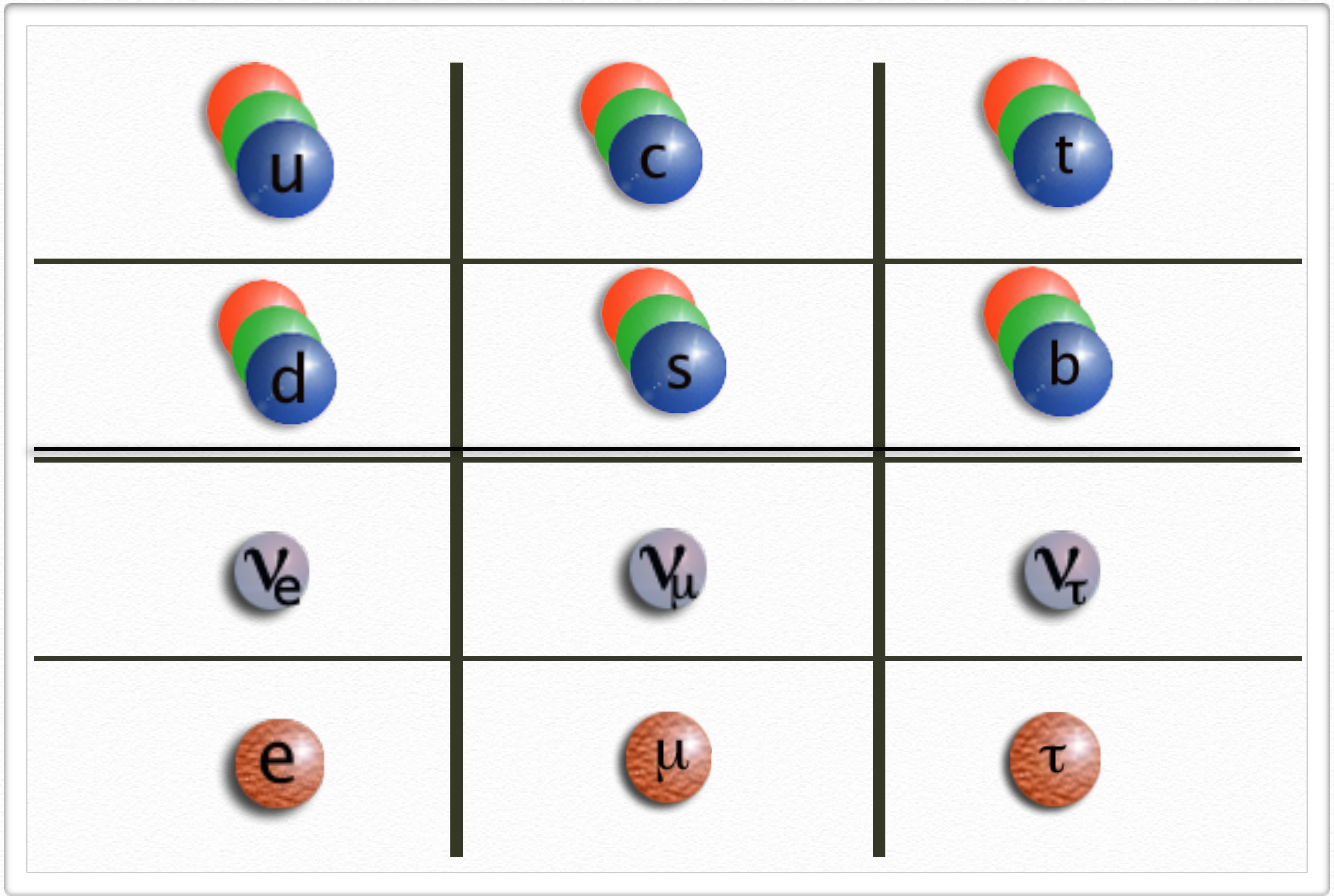
tens of trillions per square cm per second

water $p + \bar{\nu} = n + \bar{e}$

good old days

`Everything comes to him who knows how to wait.' *Pauli*

Digression - fermion families



Neutrino mass

Pontecorvo   1956-'60s

Neutrinos have mass:
he `feels' it

Bruno Pontecorvo

neutrino oscillations

metamorphosis: electron neutrino from the sun changes into muon neutrino (not observable)

Neutrino mass

Pontecorvo   1956-‘60s

Neutrinos have mass:
he `feels' it

neutrino oscillations

Bruno Pontecorvo

metamorphosis: electron neutrino from the sun changes
into muon neutrino (not observable)

imagine a **bird** detector
- cannot see **fish**

deficit of neutrinos from the sun

also, expect similar deficit in atmospheric neutrinos

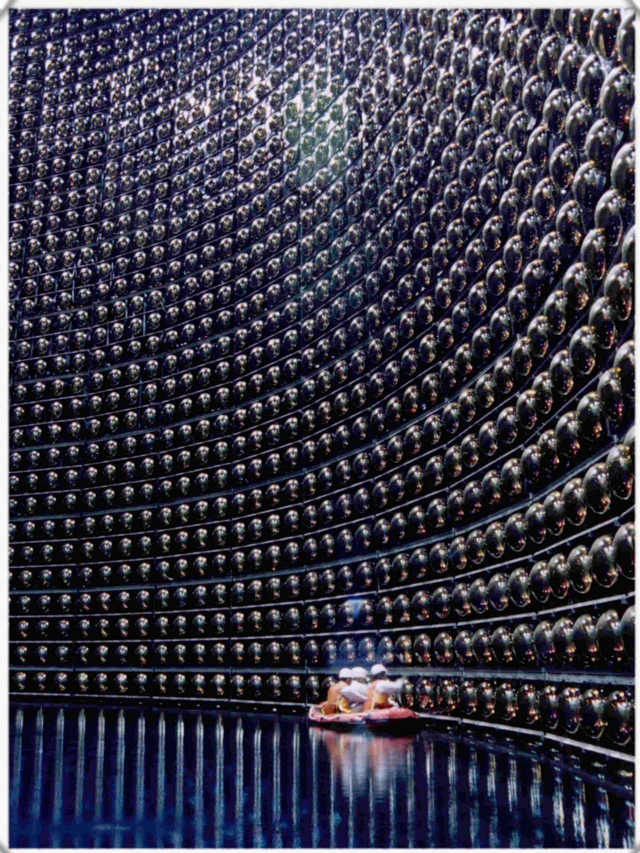
Pontecorvo's work ignored by and large

In 1950 he escapes with a family - wife and three kids
- in a dramatic fashion to Soviet Union. Cold war years

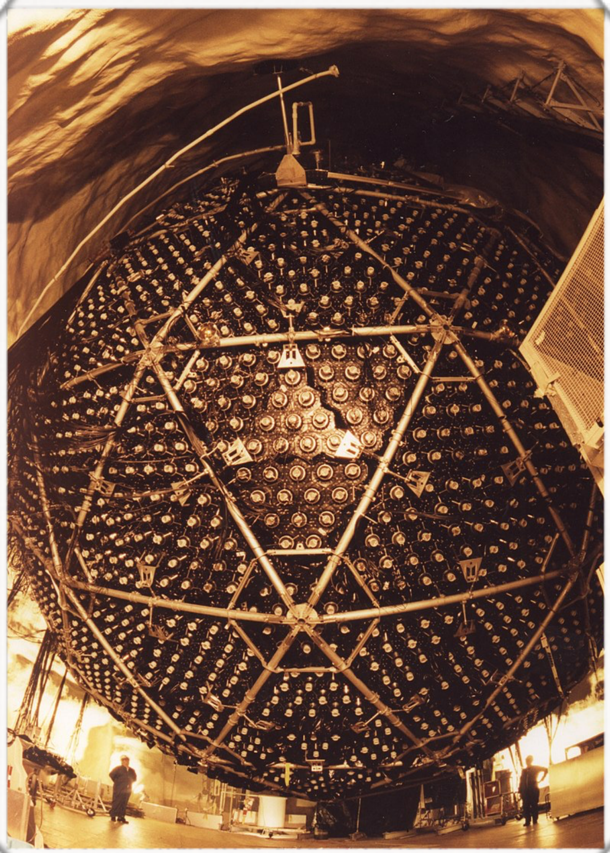
Neutrino oscillations discovery

*Super-Kamiokande ‘1998

solar neutrinos



$$m_\nu \simeq 10^{-7} m_e$$



atmospheric neutrinos

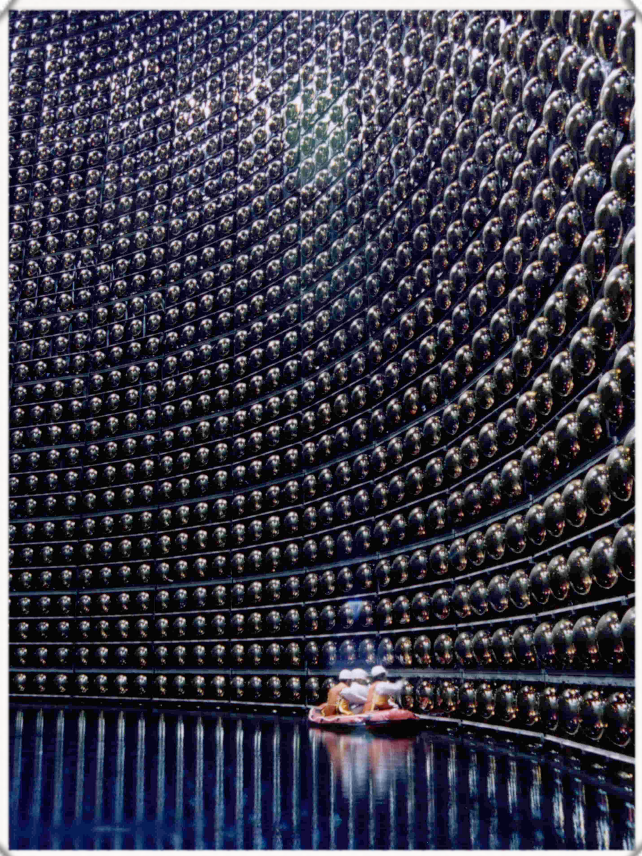
** Sudbury Neutrino Observatory ‘2001

Pontecorvo died five years before experimental proof

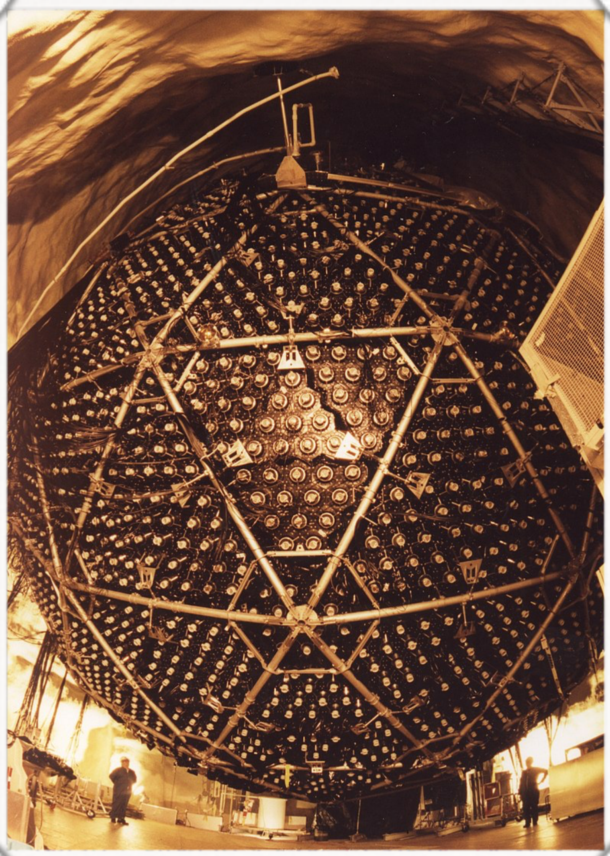
Neutrino oscillations discovery

*Super-Kamiokande ‘1998

solar neutrinos



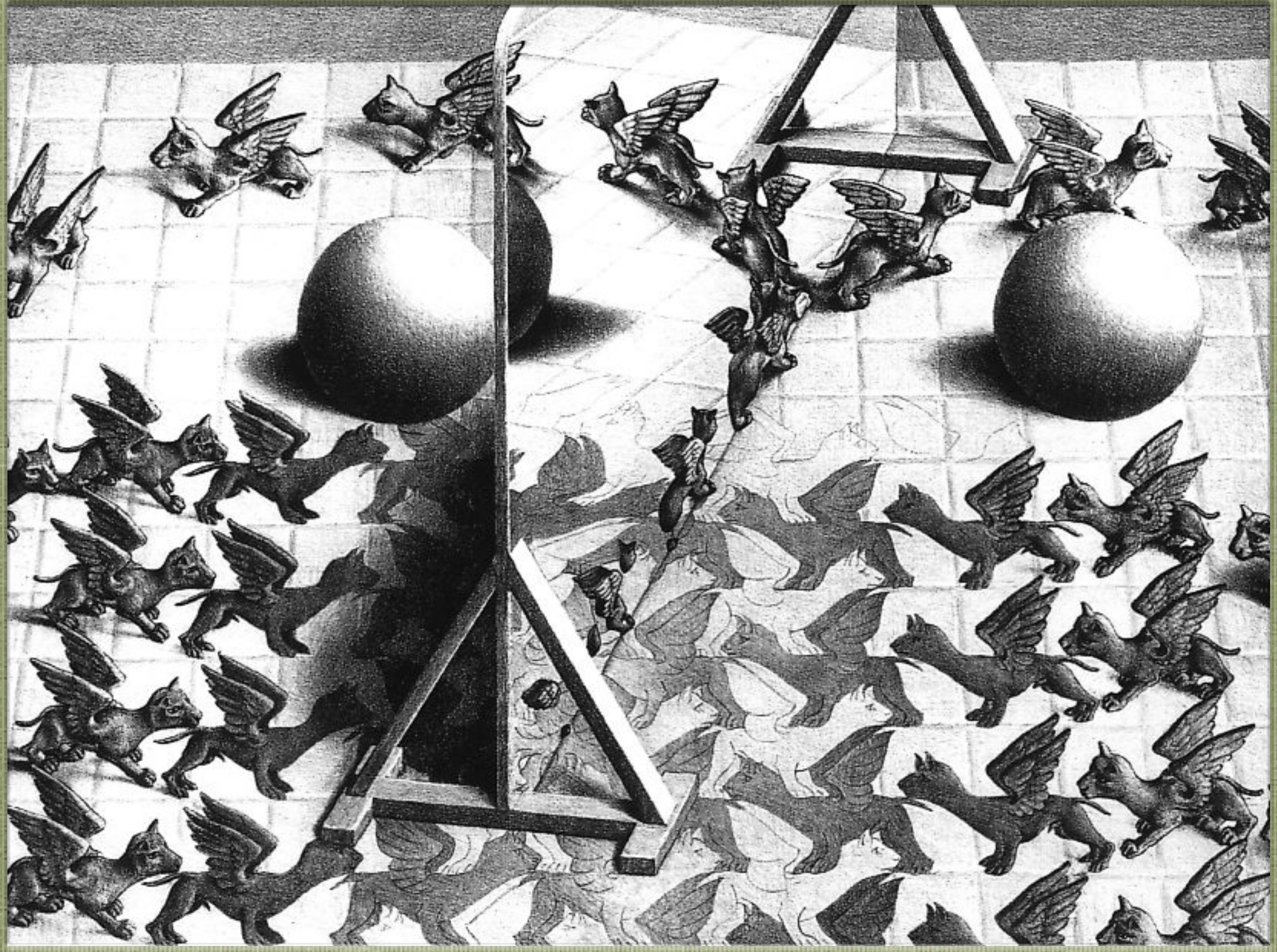
$$m_\nu \simeq 10^{-7} m_e$$



atmospheric neutrinos

** Sudbury Neutrino Observatory ‘2001

Pontecorvo died five years before experimental proof

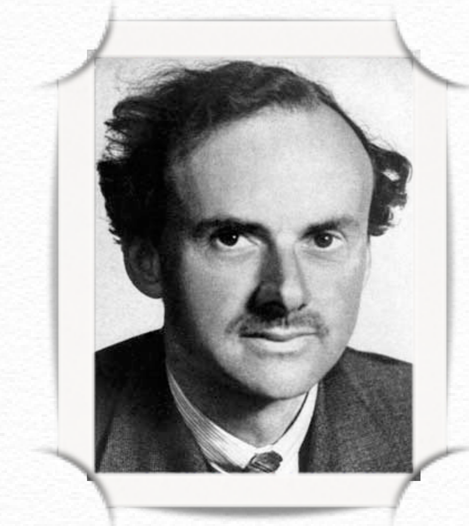


Particles and anti-particles

or

chirality and helicity

bombshell: anti-particles



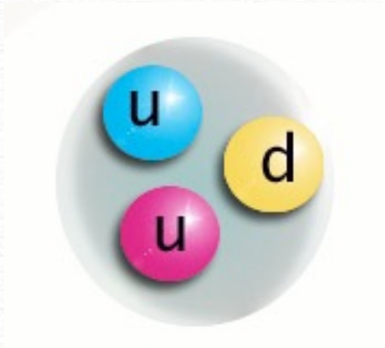
Dirac

Dirac 1928 $(i\gamma^\mu D_\mu - m)\psi = 0$ → spin

↓ *Chao 1929**

$\bar{e}$ positron (anti electron) 

*Anderson 1932**

$\bar{p}$ anti proton 

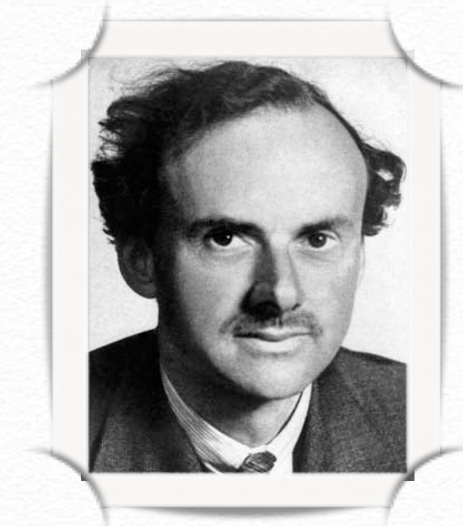
Segre', Chamberlain 1955

...

↓

different anti-particle for every particle

1931 bombshell: anti-particles



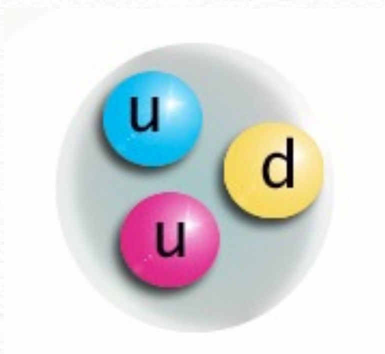
Dirac

Dirac 1928 $(i\gamma^\mu D_\mu - m)\psi = 0$ → spin

*Chao 1929**

$\bar{e}$ positron (anti electron) 

*Anderson 1932**

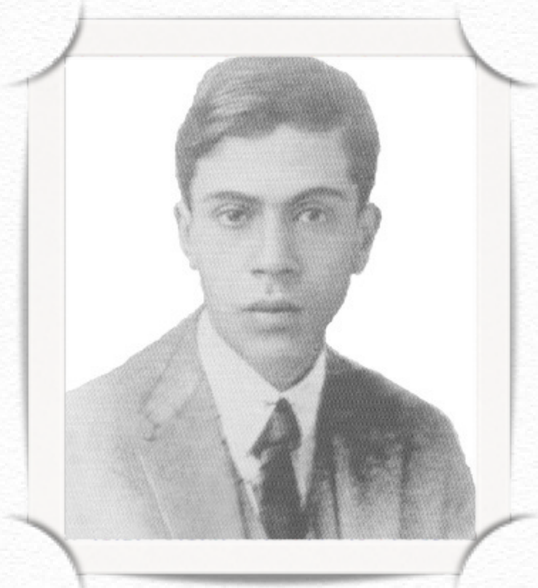
$\bar{p}$ anti proton 

Segre', Chamberlain 1955

...

different anti-particle for every particle

Enter Majorana

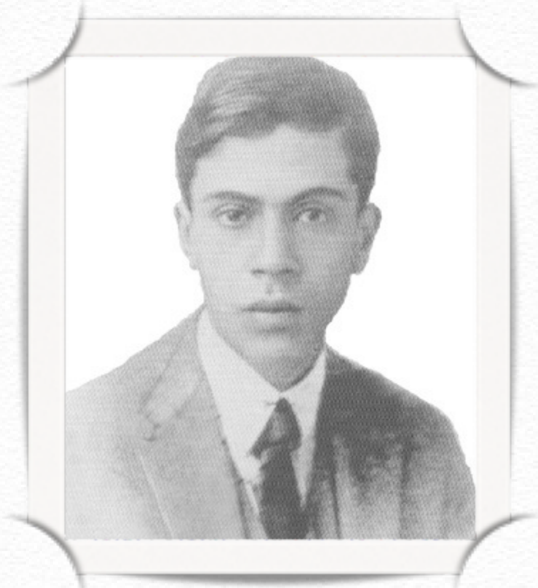


Ettore Majorana

32 years old

March 25, 1938:
boat ride from Palermo to Napoli

Enter Majorana



Ettore Majorana

32 years old

March 25, 1938:
boat ride from Palermo to Napoli

disappears

Enter Majorana

32 years old

March 25, 1938:
boat ride from Palermo to Napoli

disappears

Enter Majorana

32 years old

March 25, 1938:
boat ride from Palermo to Napoli

disappears

Suicide?

Monastery in Toscana?

Lived happily in Valencia, Venezuela?*

* Procura di Roma in 2015: yes

Enter Majorana

32 years old

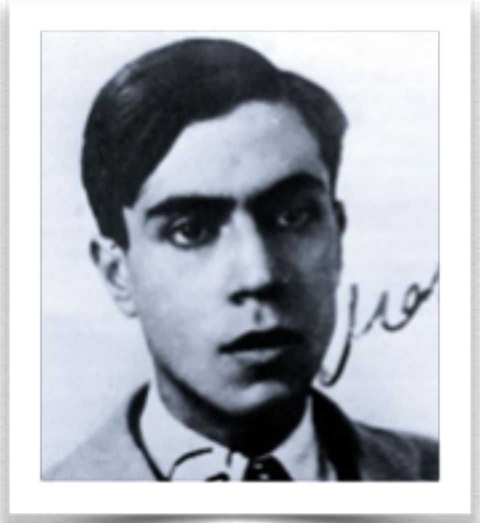
March 25, 1938:
boat ride from Palermo to Napoli

disappears

Suicide?

Monastery in Toscana?

Lived happily in Valencia, Venezuela?*



* Procura di Roma in 2015: yes

left a legacy:

in 1937 given a job in Napoli by special merit, on a condition to write a paper

Enter Majorana

32 years old

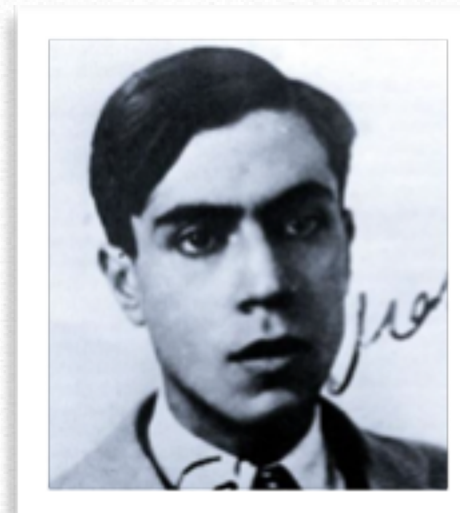
March 25, 1938:
boat ride from Palermo to Napoli

disappears

Suicide?

Monastery in Toscana?

Lived happily in Valencia, Venezuela?*



* Procura di Roma in 2015: yes

left a legacy:

in 1937 given a job in Napoli by special merit, on a condition to write a paper

Neutrino = anti neutrino?

possible only if massive

half particle  half anti-particle

How to test it?

$$\psi_M = \psi_\nu + \psi_\nu^*$$

$$\nu_M = \nu_L + \nu_L^*$$

creation of electrons from `nothing'

- nuclear beta decay *Furry 1938*
- Large Hadron Collider *Keung, Senjanovic 1983*

Neutrino = anti neutrino?

possible only if massive

half particle  half anti-particle

How to test it?

$$\psi_M = \psi_\nu + \psi_\nu^*$$

$$\nu_M = \nu_L + \nu_L^*$$

creation of electrons from `nothing'

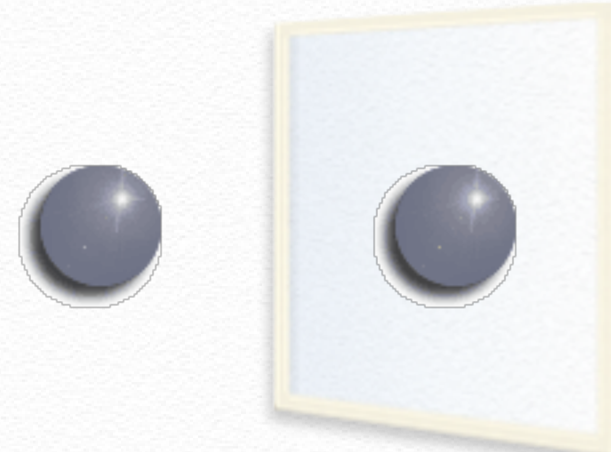
- nuclear beta decay *Furry 1938*
- Large Hadron Collider *Keung, Senjanovic 1983*

Left and right particles

chirality
(handedness):

intrinsic particle
property just like
mass, spin….

Left-handed (L) and right-handed (R) electrons, quarks



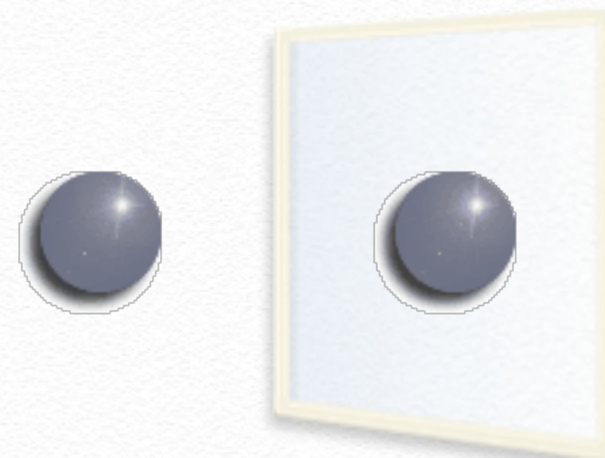
electron and positron: mirror images

Left and right particles

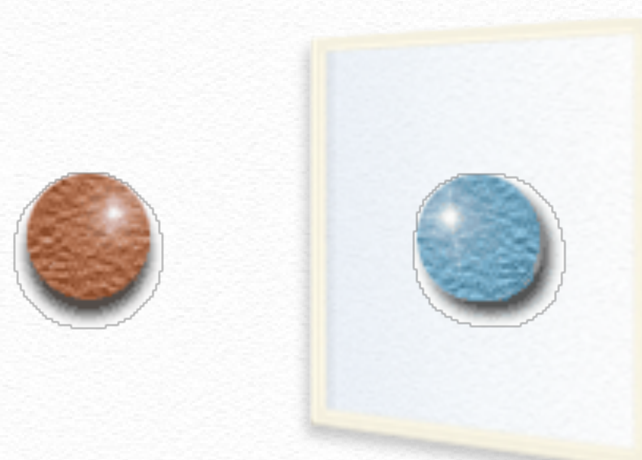
chirality (handedness):

intrinsic particle property just like mass, spin….

Left-handed (L) and right-handed (R) electrons, quarks



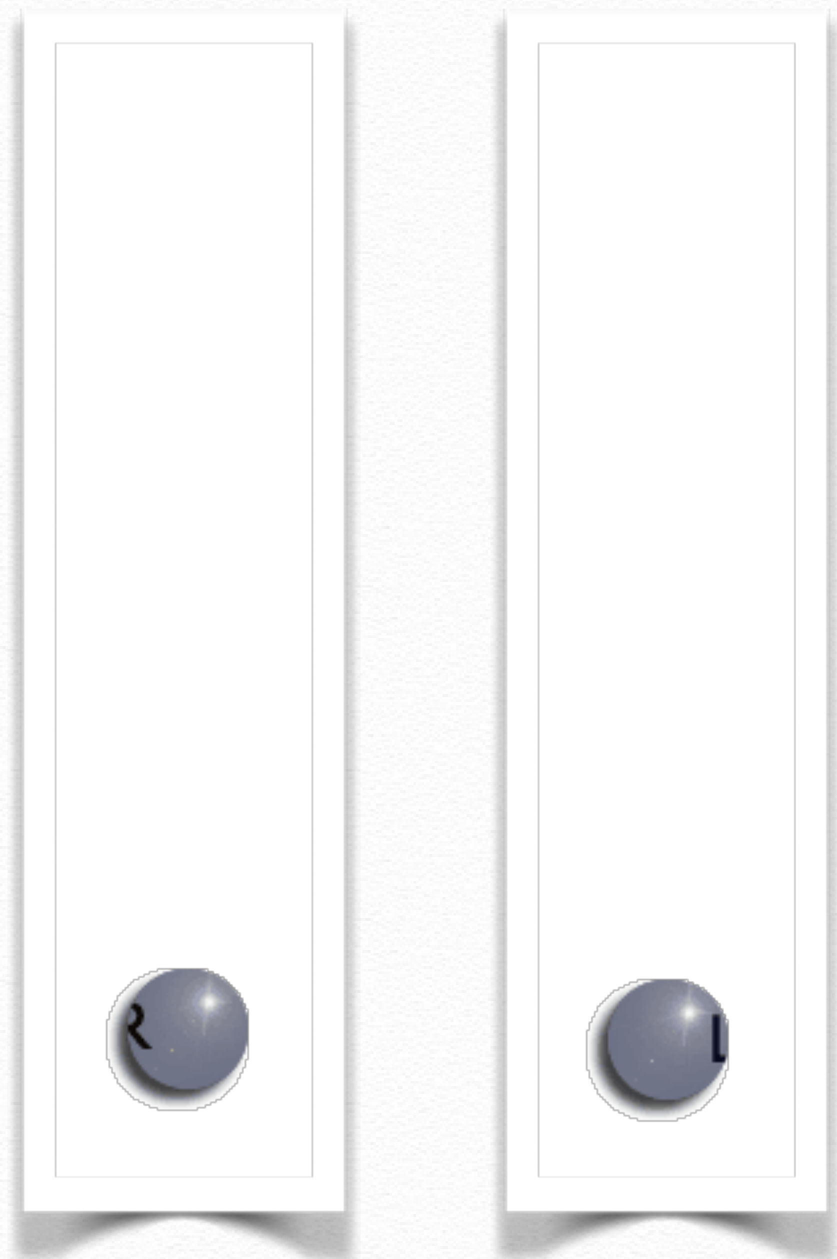
electron and positron: mirror images



Massless particles: chirality = just helicity

high energies:
particles effectively massless

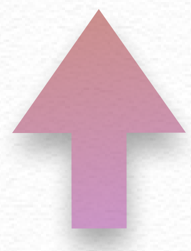
helicity:
projection of spin on the direction of motion



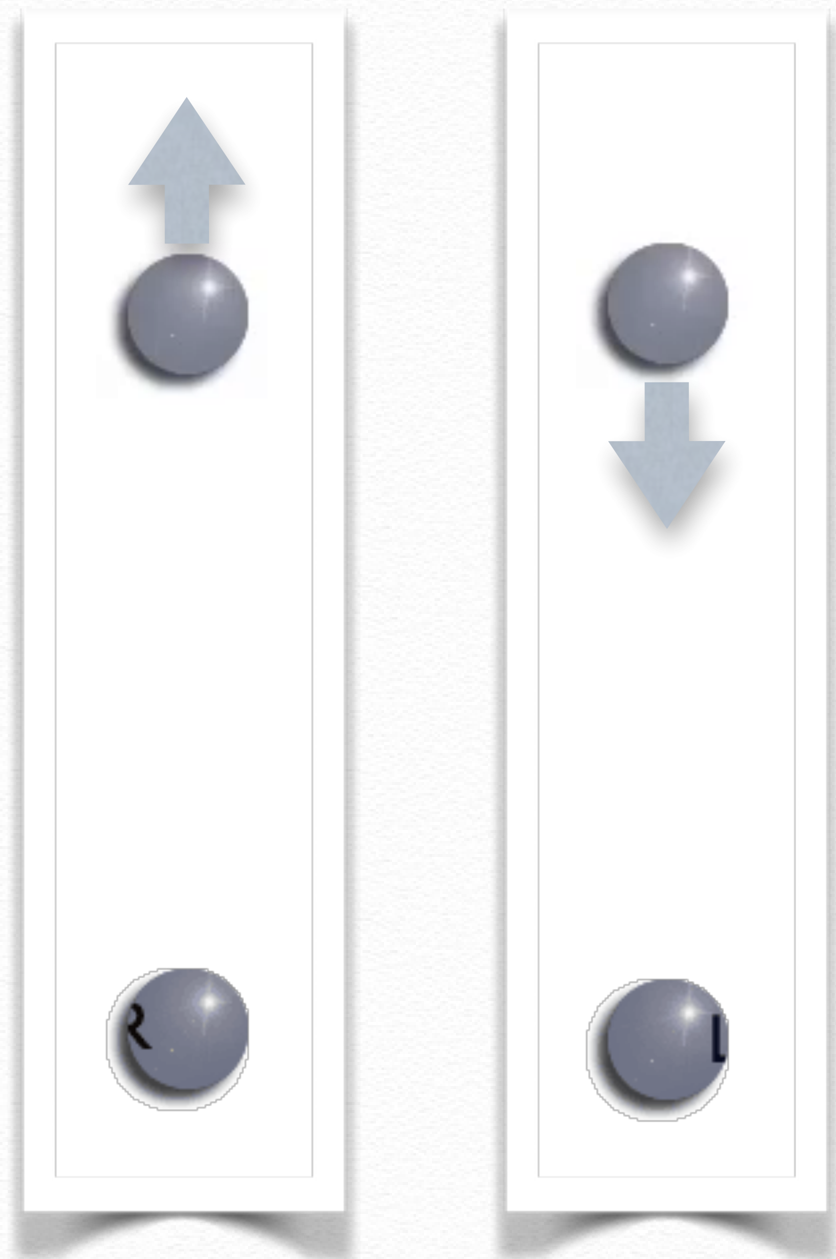
helicity: right left

Massless particles:
chirality = just helicity

high energies:
particles effectively massless

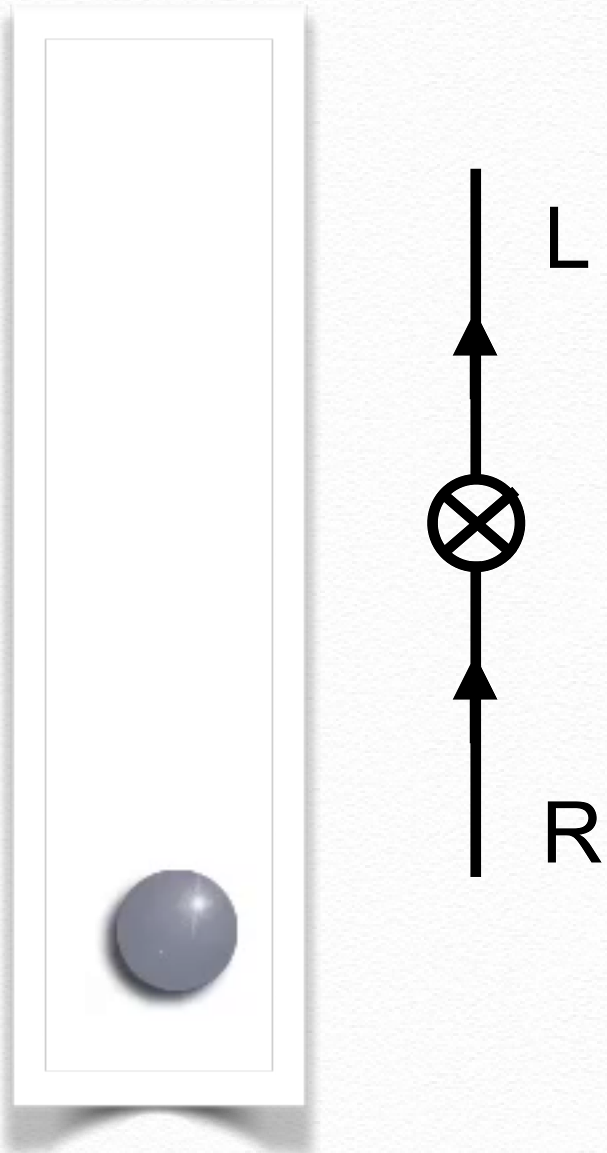


helicity:
projection of spin on the
direction of motion

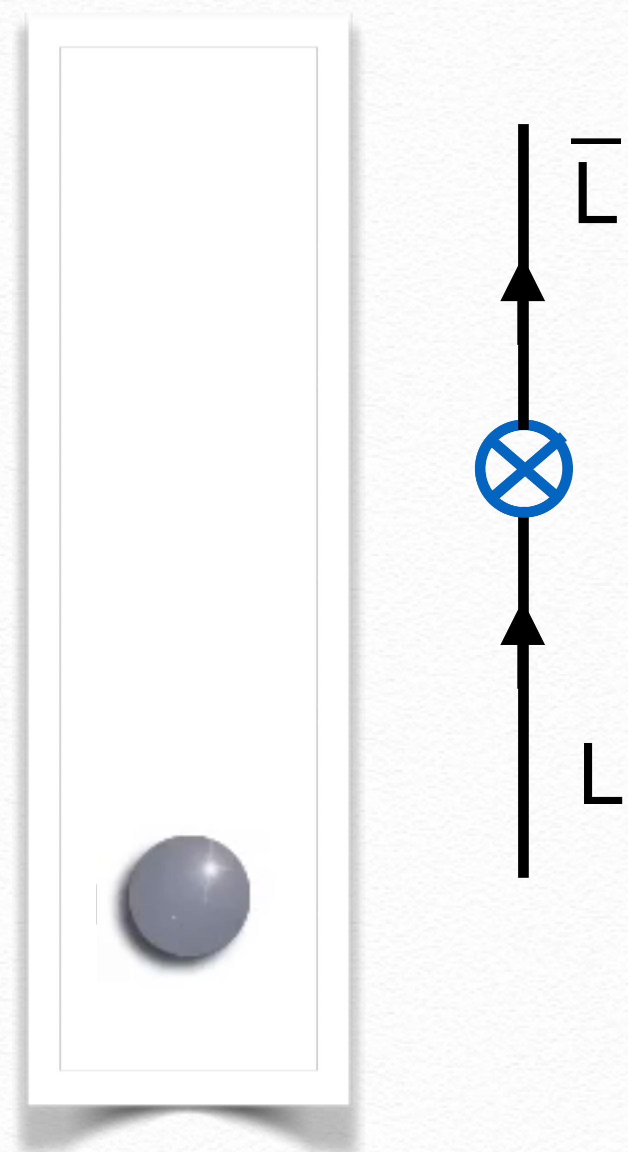


helicity: right left

Dirac mass



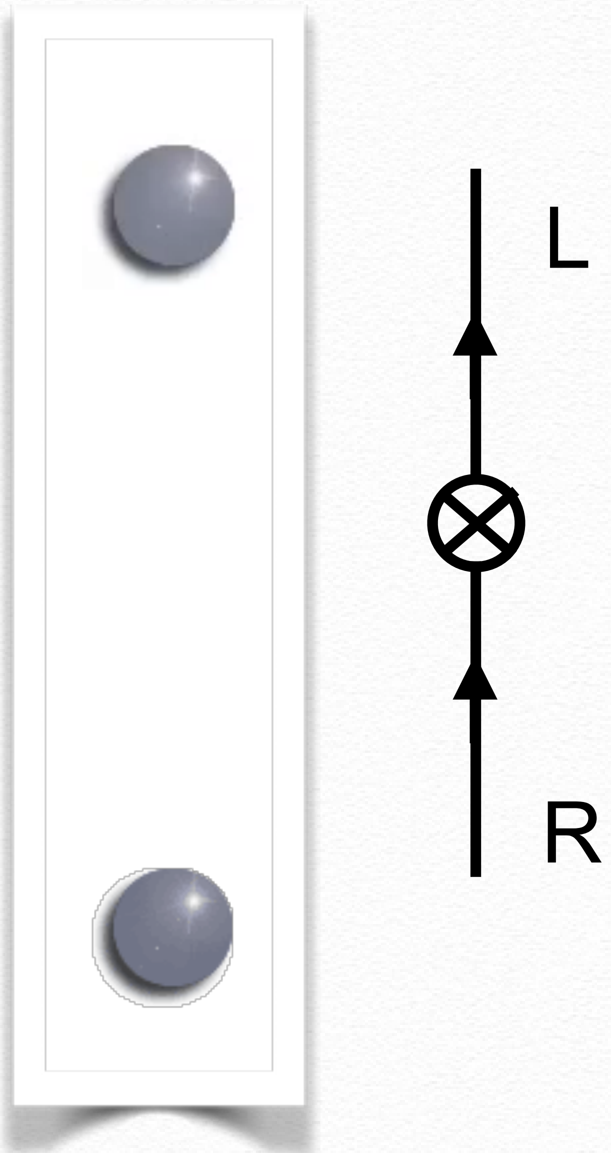
Majorana mass



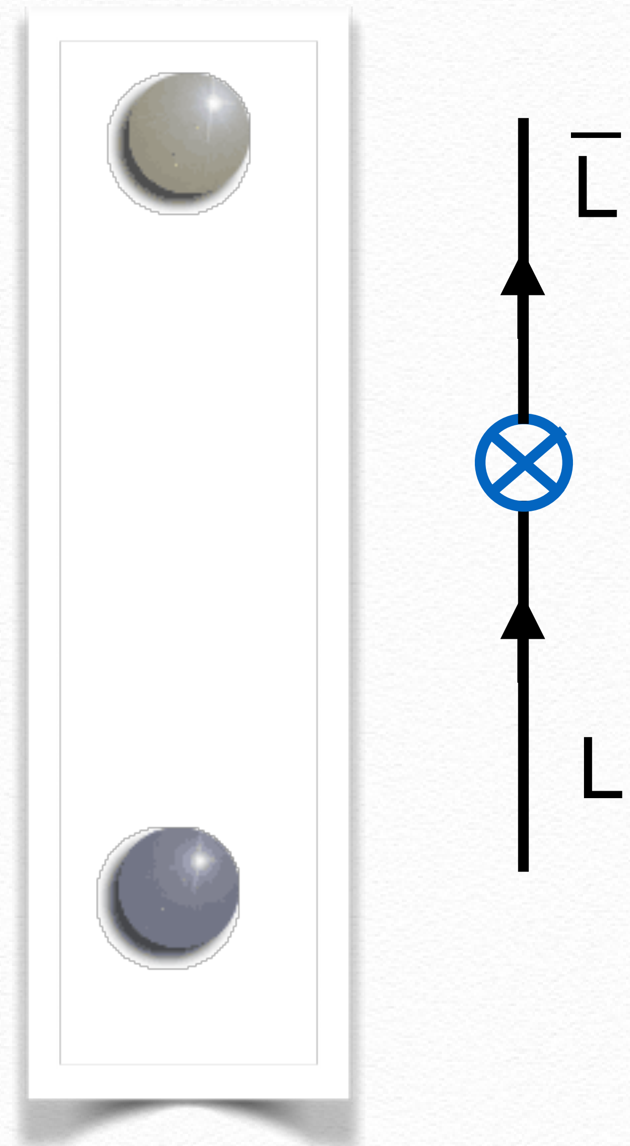
charge conserved in nature

only neutral particle

Dirac mass



Majorana mass



charge conserved in nature

↓

only neutral particle

Feynman diagrams

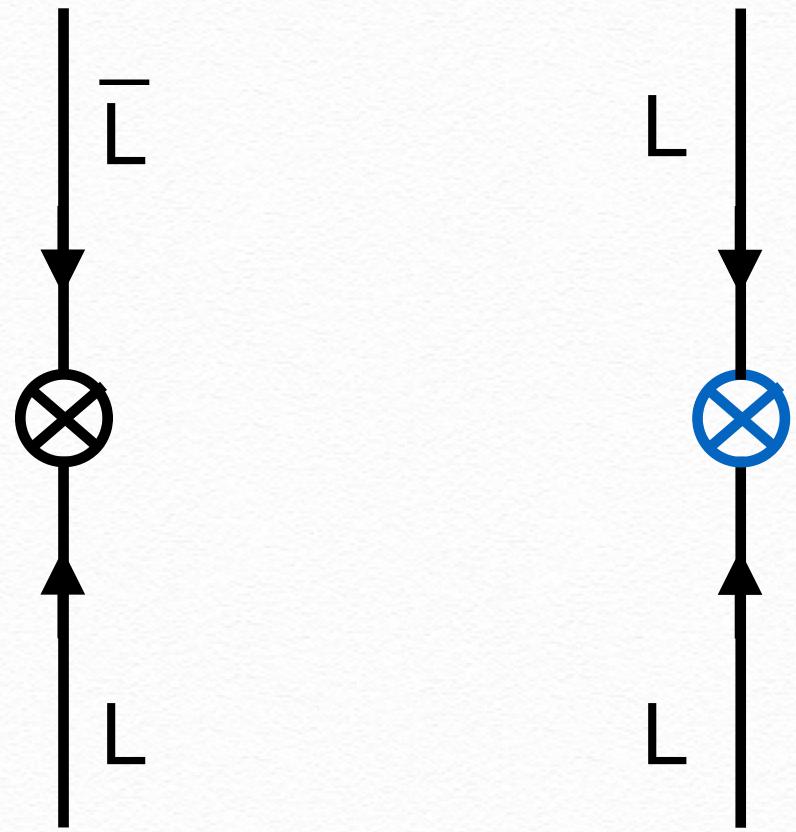
particle moving forwards in time = antiparticle moving backwards in time

Feynman diagrams

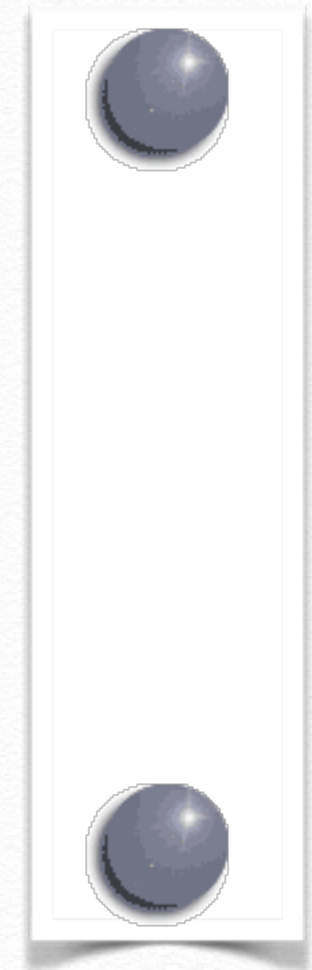
particle moving forwards in time = antiparticle moving backwards in time

Annihilation

Dirac



Majorana



particle-antiparticle

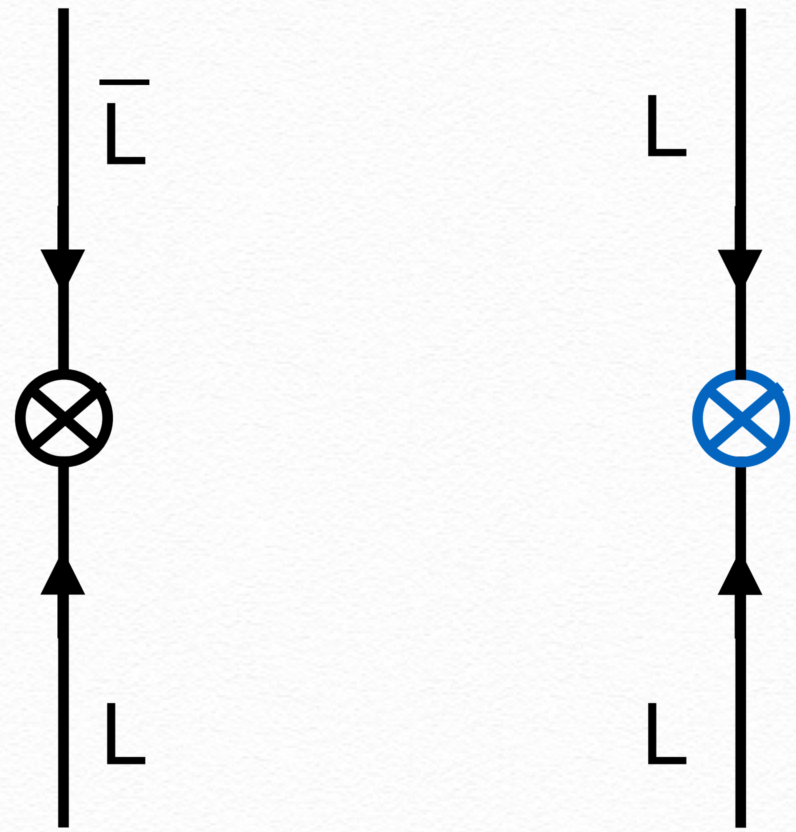
particle-particle

only neutral particle

Annihilation

Dirac

Majorana



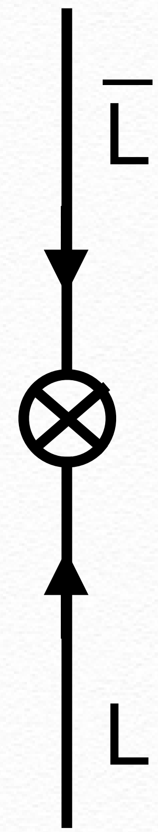
particle-antiparticle

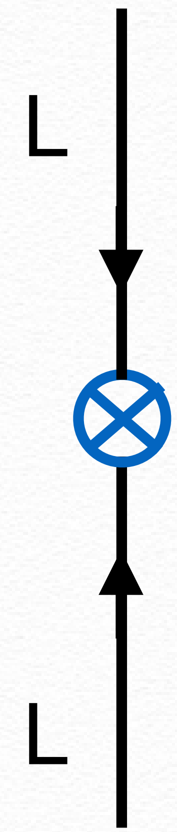
particle-particle

only neutral particle

Annihilation

Dirac





Majorana

particle-antiparticle

particle-particle

only neutral particle

Ready to test Majorana theory

neutrino = anti-neutrino

First: low energy
nuclear beta decay

Ready to test Majorana theory

neutrino = anti-neutrino

First: low energy
nuclear beta decay

Double-beta decay

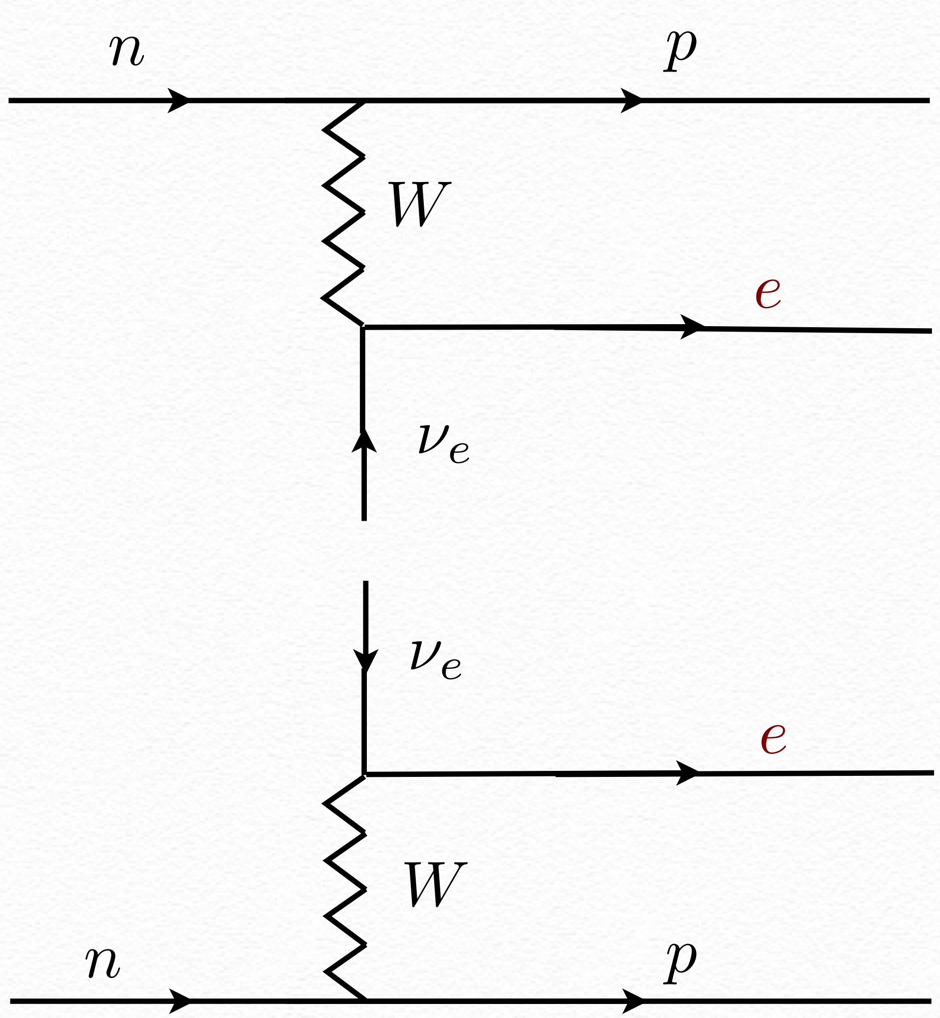
Maria Goeppert-Mayer 1935

$^{76}Ge \not\to {}^{76}As + e + \bar{\nu_e}$ daughter nucleus heavier

$^{76}Ge \to {}^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$

$\tau_{2\beta} \simeq 10^{21}\, yr$

$\tau_{\beta} \simeq 5\, yr$ Co -> Ni



Double-beta decay

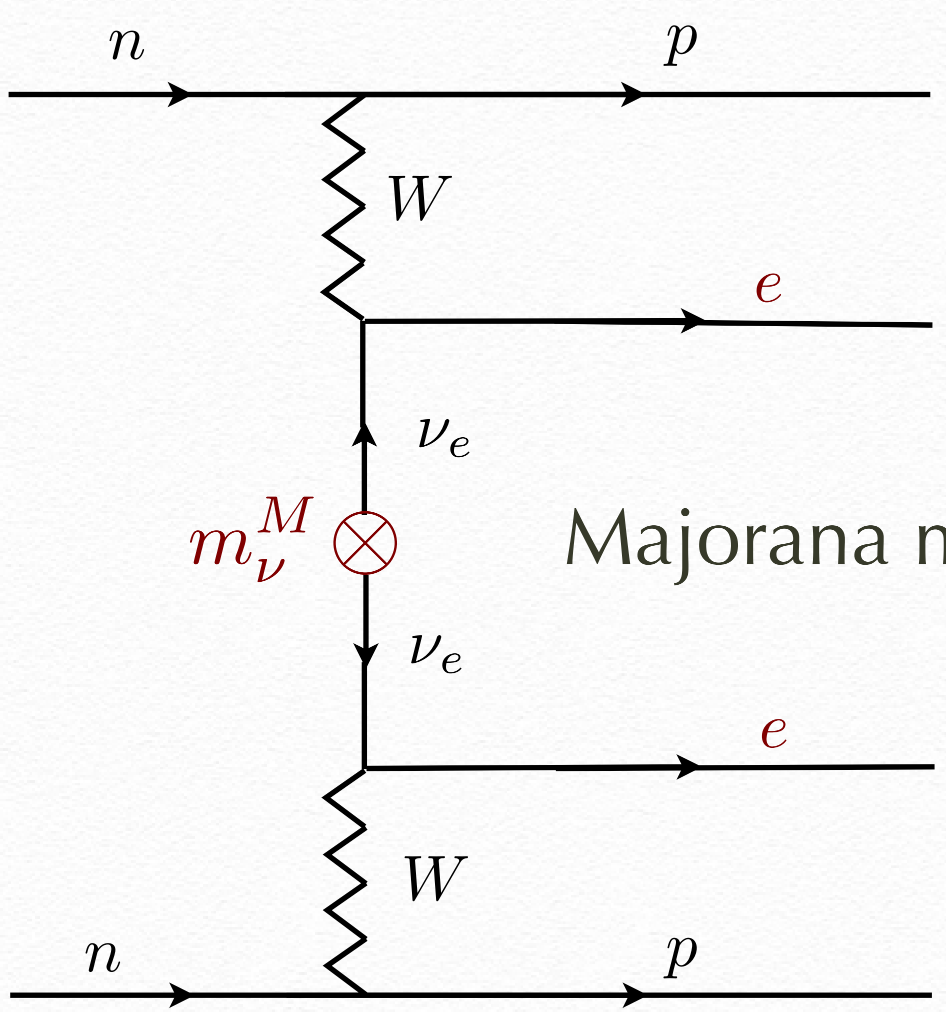
Maria Goeppert-Mayer 1935

$^{76}Ge \not\to {}^{76}As + e + \bar{\nu}_e$ daughter nucleus heavier

$^{76}Ge \to {}^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$

$\tau_{2\beta} \simeq 10^{21}\, yr$

$\tau_\beta \simeq 5\, yr$ Co -> Ni



Majorana mass

Neutrino-less Double-beta decay

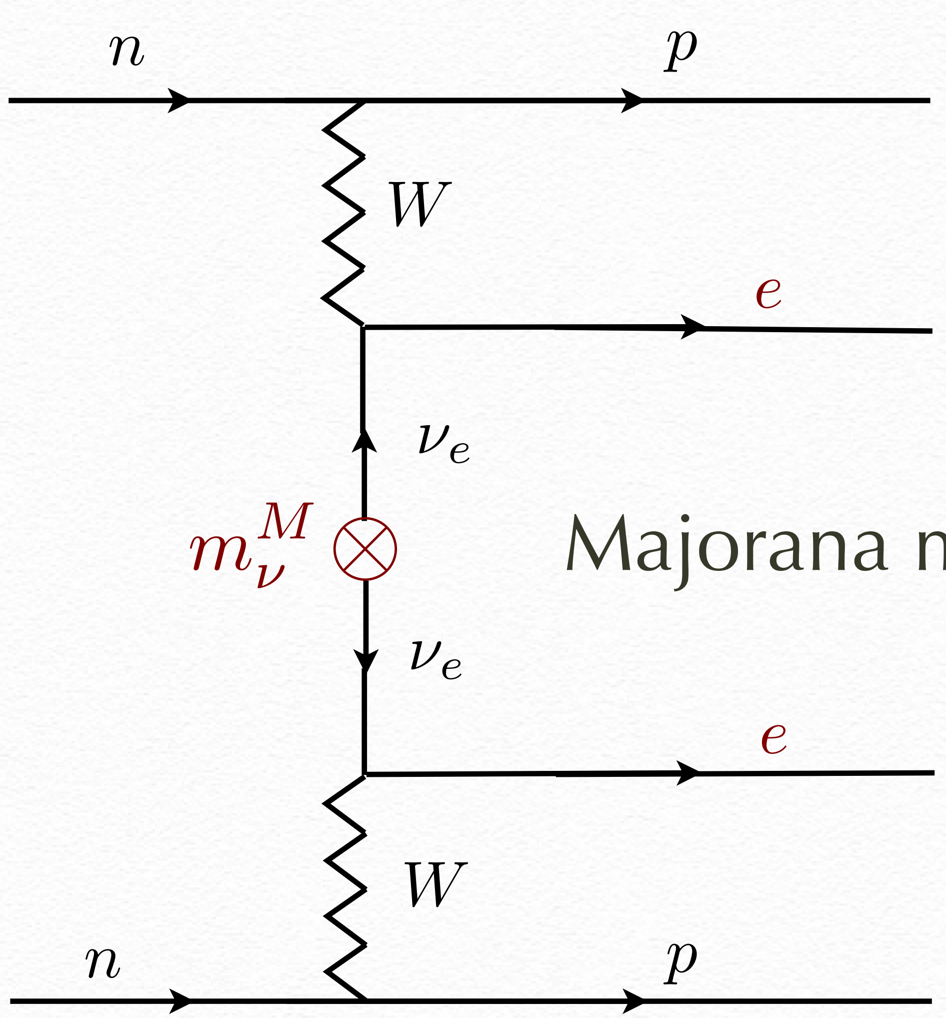
Maria Goeppert-Mayer 1935

$$^{76}Ge \not\to {}^{76}As + e + \bar{\nu}_e$$ daughter nucleus heavier

$$^{76}Ge \to {}^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$$

$\tau_{2\beta} \simeq 10^{21}\, yr$

$\tau_{\beta} \simeq 5\, yr$ Co -> Ni



Majorana mass

Neutrino-less Double-beta decay

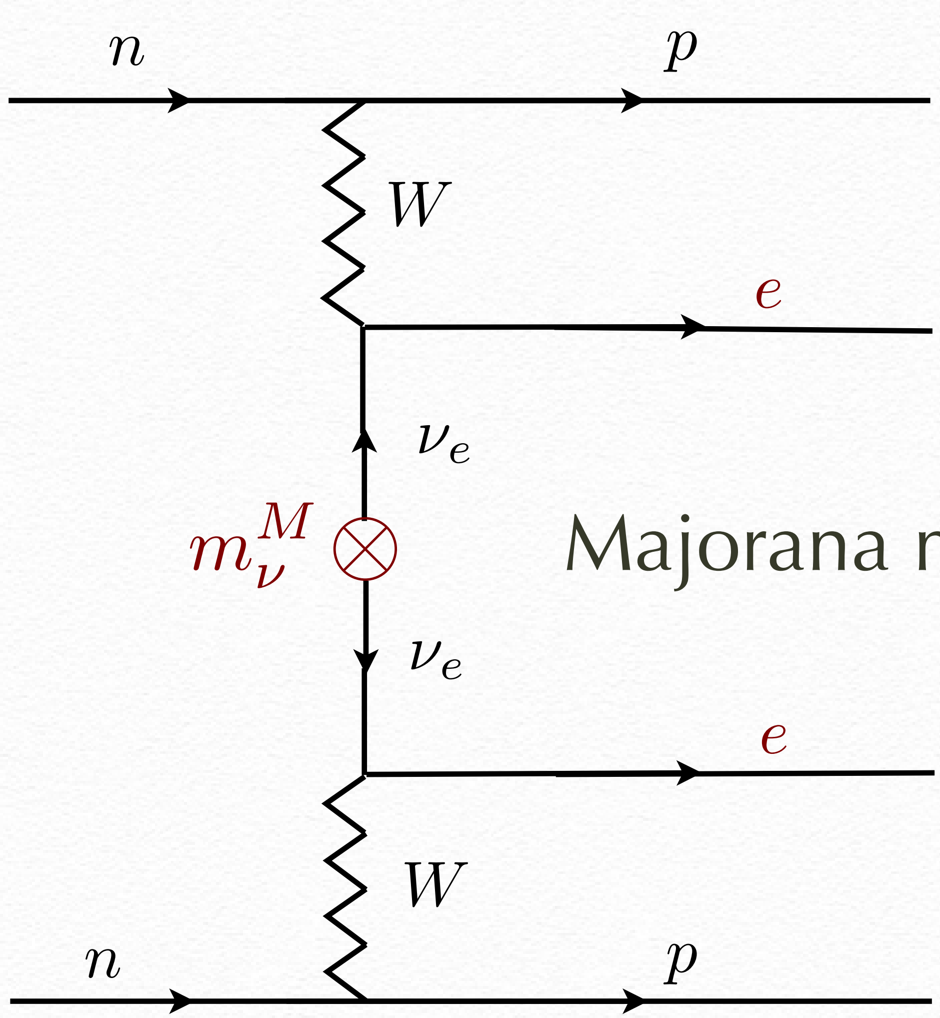
Maria Goeppert-Mayer 1935

$$^{76}Ge \not\to {}^{76}As + e + \bar{\nu}_e$$ daughter nucleus heavier

$$^{76}Ge \to {}^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$$

$$\tau_{2\beta} \simeq 10^{21}\, yr$$

$$\tau_{\beta} \simeq 5\, yr$$ Co -> Ni



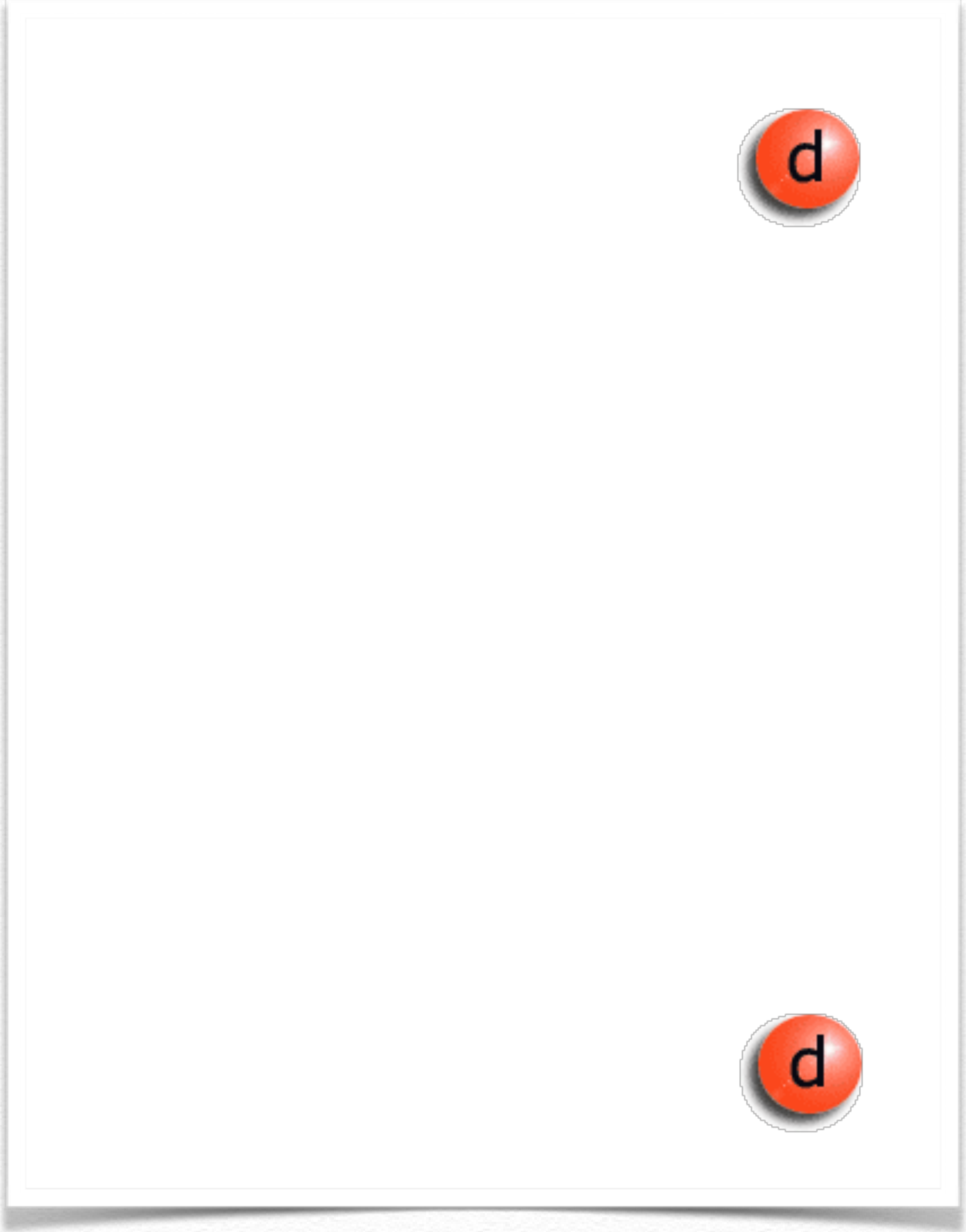
Majorana mass

$$^{76}Ge \to {}^{76}Se + e + e$$

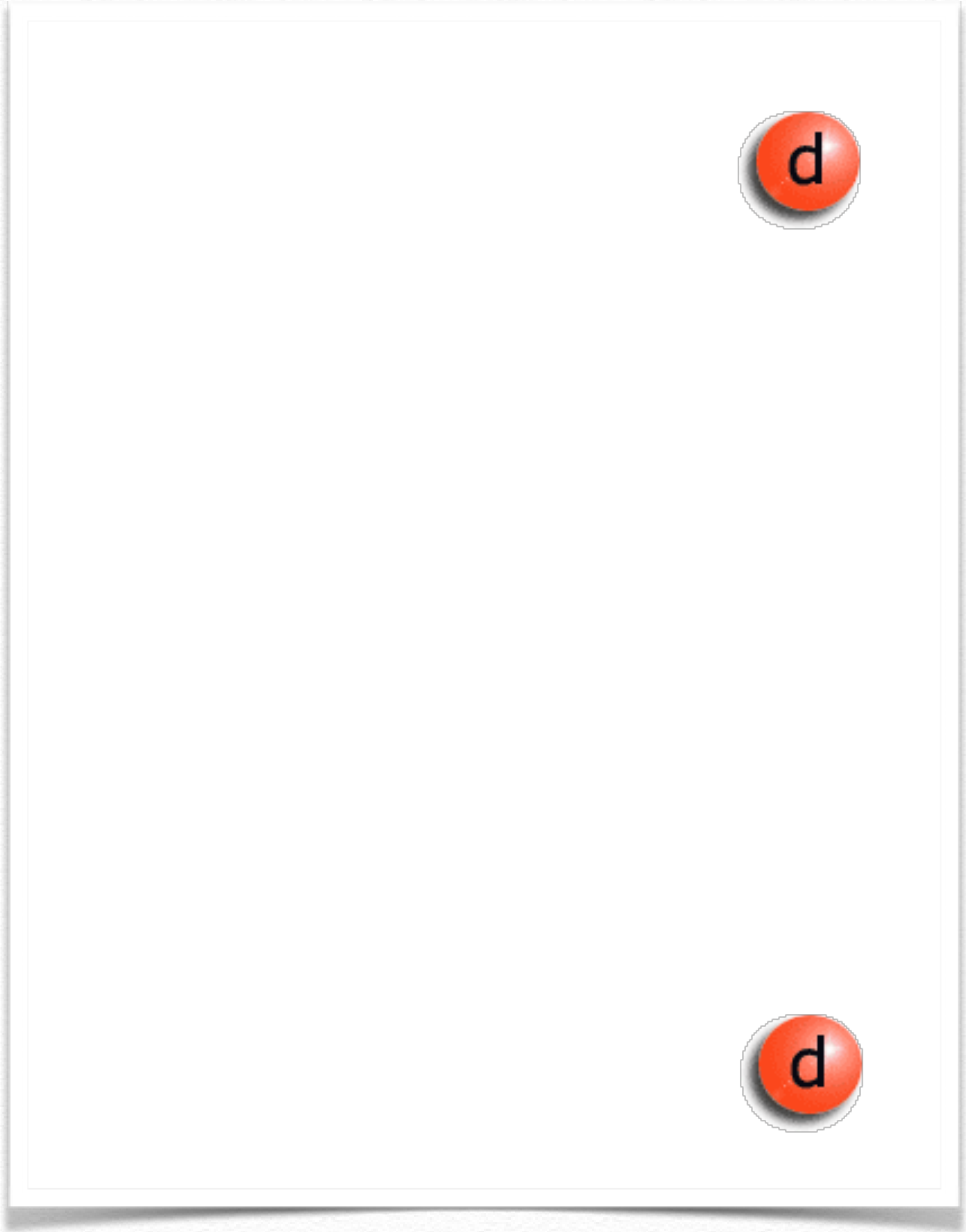
$$\tau_{0\nu 2\beta} \gtrsim 10^{25} yr$$

$$m_\nu^M \lesssim 1 eV \simeq 10^{-6}\, m_e$$

Neutrino-less double beta decay

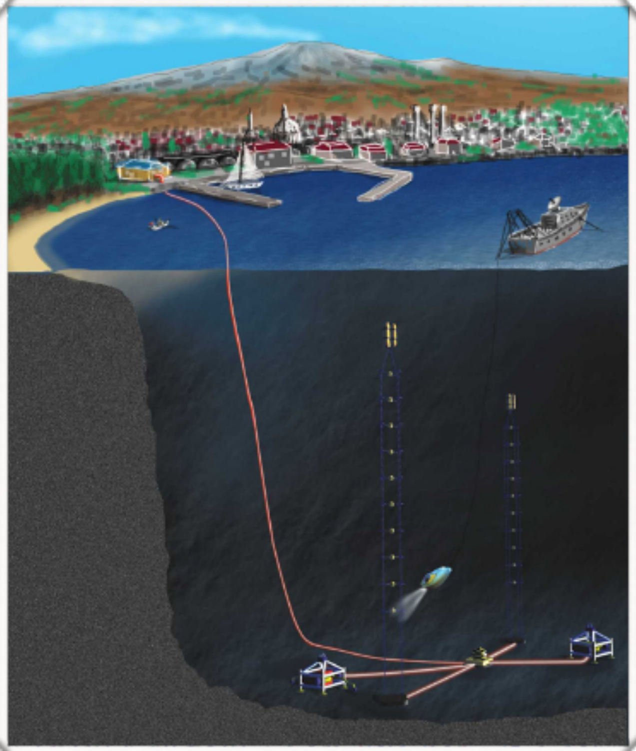


Neutrino-less double beta decay



Experiments

NEMO



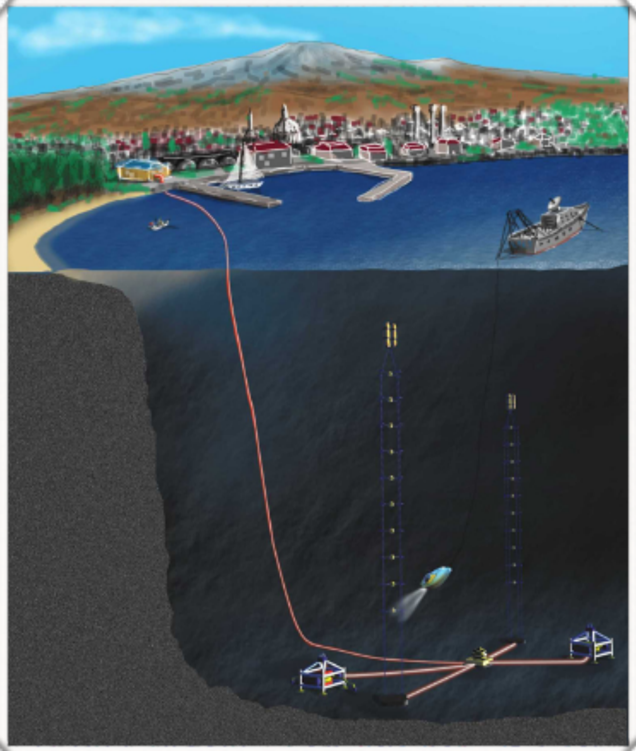
Neutrino Ettore Majorana Observatory

modern times

~ 100 people

exp.	mass [kg]	f_A	bkg. $[\frac{10^{-3}\text{cnt}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}]$	ΔE [keV]	eff.	enrich.	FOM	$T^{0\nu}_{1/2}$ 10^{25} yr	$m_{\beta\beta}$ meV
			past experiments						
Hd-Moscow	11	0.35	120	7	1	0.86	1	1.9	170-530
Cuoricino	41	1	170	16	0.9	0.28	1	0.4	210-500
NEMO-3	6.9	2.1	1.2	400	0.06	0.9	0.3	0.1	310-900
			running experiments						
EXO-200	100	0.55	1.5	100	0.55	0.81	6	4.2	75-170
Kaml.-Zen	12800	0.55	0.05	250	0.31	0.023	4	2.6	90-220
Kaml.-Zen2	12800	0.55	0.01	250	0.31	0.06	22	15	40-90
GERDA-I	15	0.35	20	8	0.8	0.86	2	3.9	120-370
GERDA-II	35	0.35	1	6	0.85	0.88	20	18	60-170
			experiments under construction						
Major.-Dem.	30	0.35	1	6	0.9	0.9	20	17	60-170
CUORE	750	1	10	12	0.9	0.27	19	7.5	50-110
SNO+	780000	1.5	0.0002	230	0.33	5.6E-5	3	0.8	100-240
NEXT	100	0.55	0.8	25	0.25	0.9	9	5.2	70-160
			proposed experiments						
S.NEMO	100	1.1	0.1	200	0.2	0.9	14	6.9	55-140
Lucifer	100	1.1	1	10	0.9	0.5	50	19	33-85

Experiments



NEMO

Holy Grail of neutrino physics

Neutrino Ettore Majorana Observatory

modern times

~ 100 people

exp.	mass [kg]	f_A	bkg. $[\frac{10^{-3}\text{cnt}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}]$	ΔE [keV]	eff.	enrich.	FOM	$T^{0\nu}_{1/2}$ 10^{25} yr	$m_{\beta\beta}$ meV
			past experiments						
Hd-Moscow	11	0.35	120	7	1	0.86	1	1.9	170-530
Cuoricino	41	1	170	16	0.9	0.28	1	0.4	210-500
NEMO-3	6.9	2.1	1.2	400	0.06	0.9	0.3	0.1	310-900
			running experiments						
EXO-200	100	0.55	1.5	100	0.55	0.81	6	4.2	75-170
Kaml.-Zen	12800	0.55	0.05	250	0.31	0.023	4	2.6	90-220
Kaml.-Zen2	12800	0.55	0.01	250	0.31	0.06	22	15	40-90
GERDA-I	15	0.35	20	8	0.8	0.86	2	3.9	120-370
GERDA-II	35	0.35	1	6	0.85	0.88	20	18	60-170
			experiments under construction						
Major.-Dem.	30	0.35	1	6	0.9	0.9	20	17	60-170
CUORE	750	1	10	12	0.9	0.27	19	7.5	50-110
SNO+	780000	1.5	0.0002	230	0.33	5.6E-5	3	0.8	100-240
NEXT	100	0.55	0.8	25	0.25	0.9	9	5.2	70-160
			proposed experiments						
S.NEMO	100	1.1	0.1	200	0.2	0.9	14	6.9	55-140
Lucifer	100	1.1	1	10	0.9	0.5	50	19	33-85

The nature and origin of neutrino mass

The nature and origin of neutrino mass

The question of mass: why so special?

Parity violation

What if L-R symmetry were broken?

solves a number of puzzles

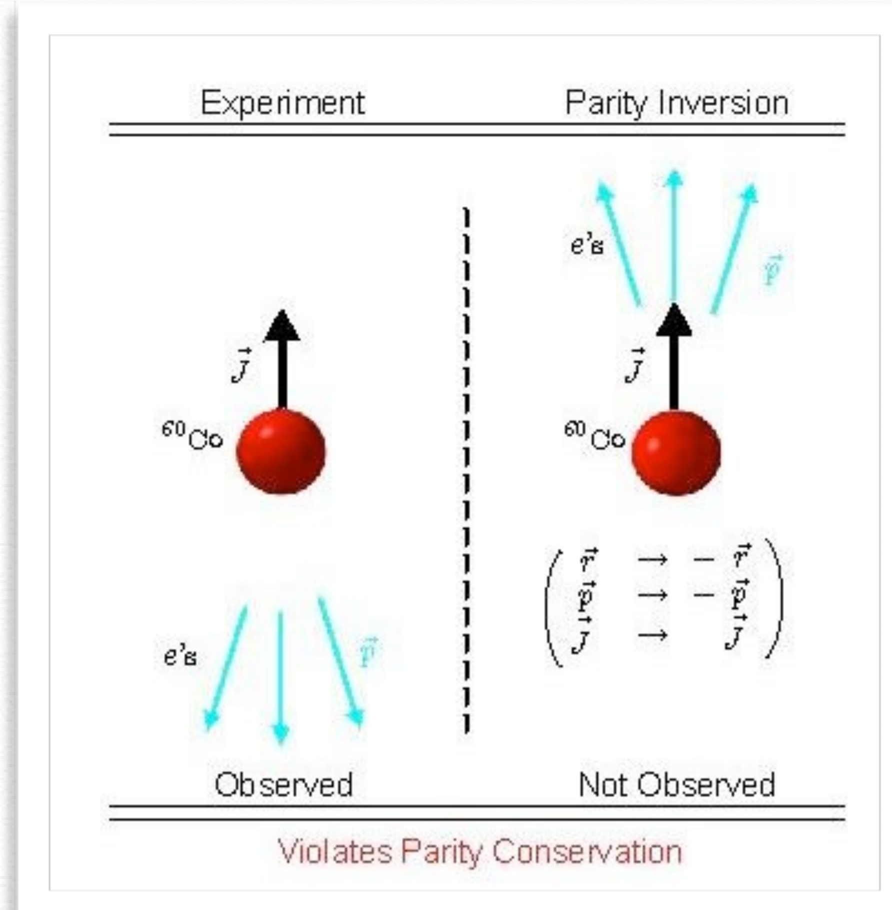
Chen Ning Yang & Tsung-Dao Lee

experiment

Wu et al 1956

Lederman et al 1956

Chien-Shiung Wu

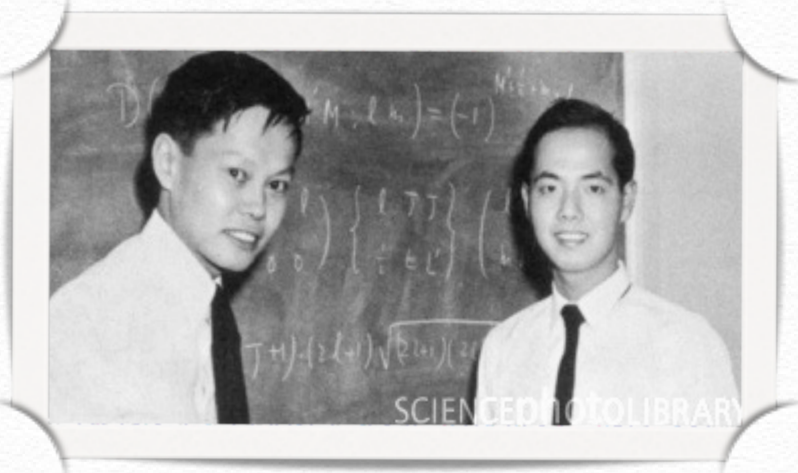


L-R symmetry completely broken

Parity violation

What if L-R symmetry were broken?

solves a number of puzzles



1956

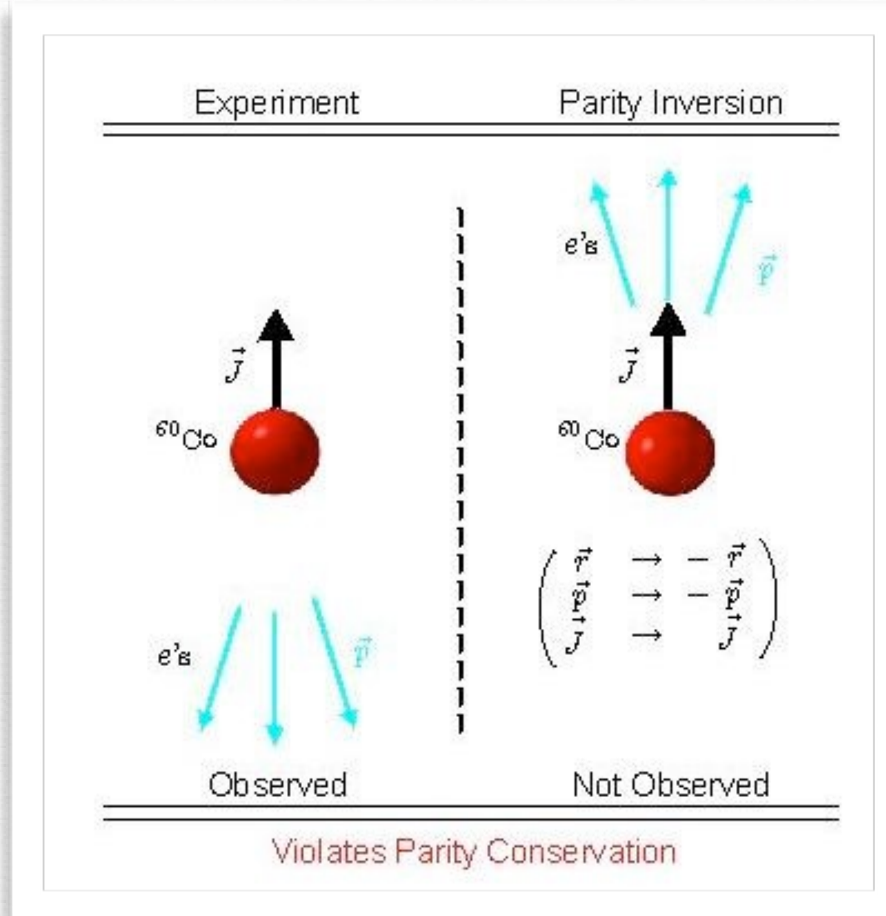
Chen Ning Yang & Tsung-Dao Lee

experiment

Wu et al 1956

Lederman et al 1956

Chien-Shiung Wu



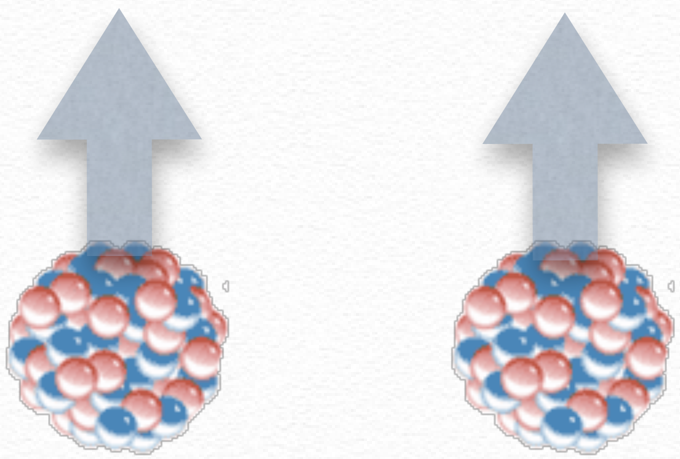
L-R symmetry completely broken

P VIOLATION

$$^{60}_{27}Co \rightarrow ^{60}_{26} Ni + e + \bar{\nu}_e$$

spin: $5 \;\rightarrow\; 4 \;+\; 1/2 \;+\; 1/2$

Wu et al 1956

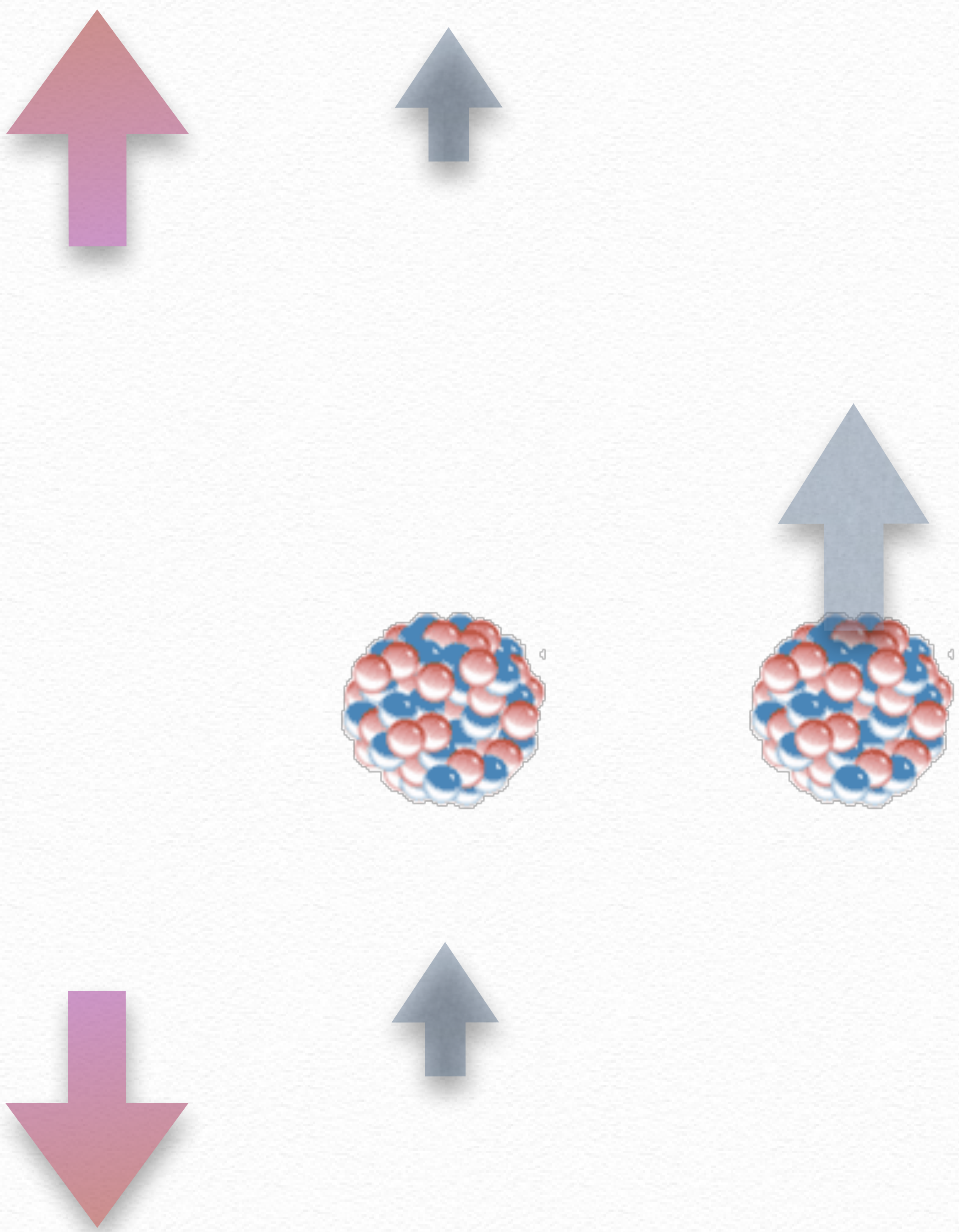


P VIOLATION

$$ {}^{60}_{27}Co \rightarrow {}^{60}_{26}Ni + e + \bar{\nu}_e $$

spin: $5 \rightarrow 4 + 1/2 + 1/2$

Wu et al 1956

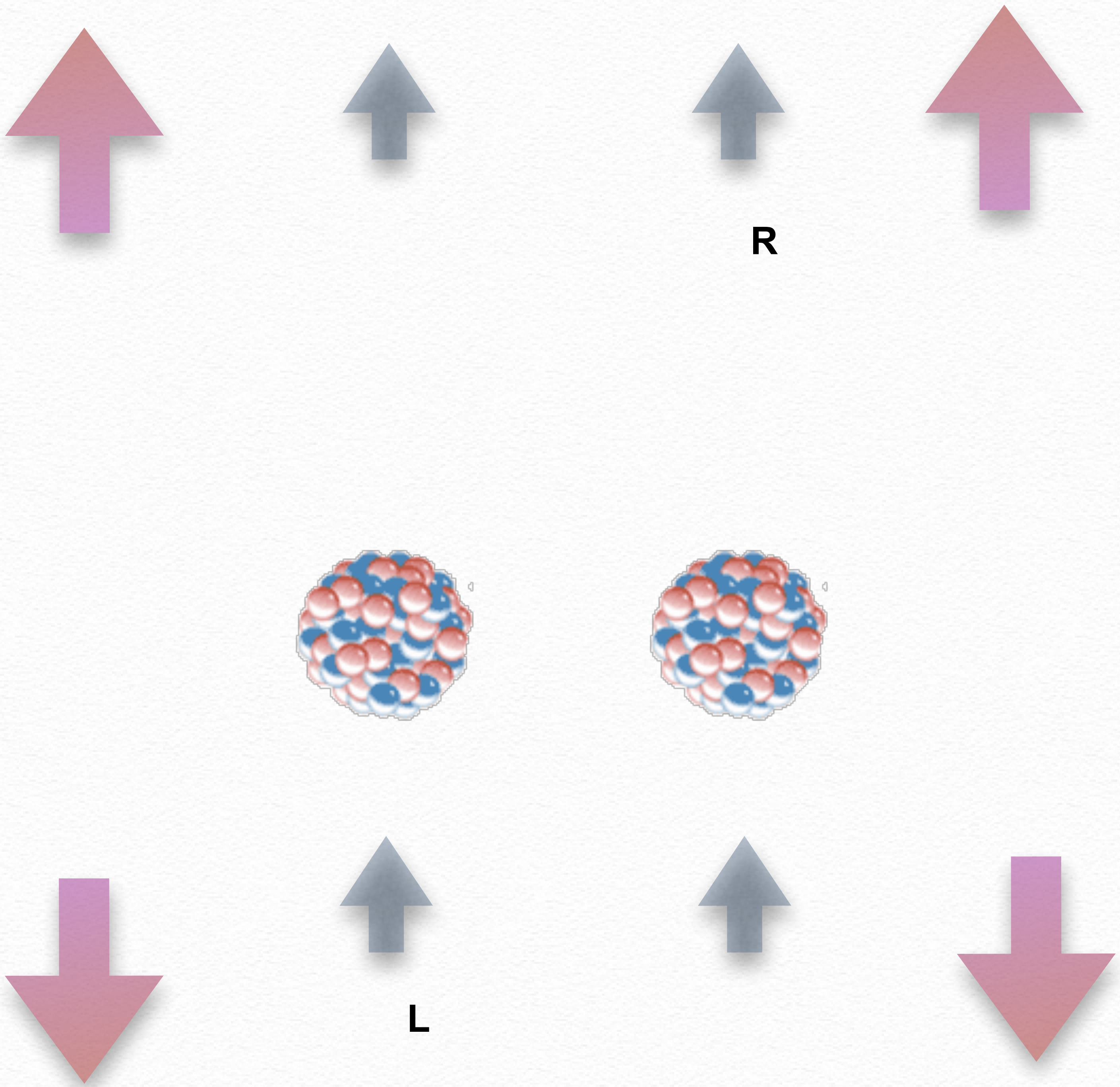


P VIOLATION

$$^{60}_{27}Co \rightarrow ^{60}_{26}Ni + e + \bar{\nu}_e$$

spin: $5 \rightarrow 4 + 1/2 + 1/2$

Wu et al 1956



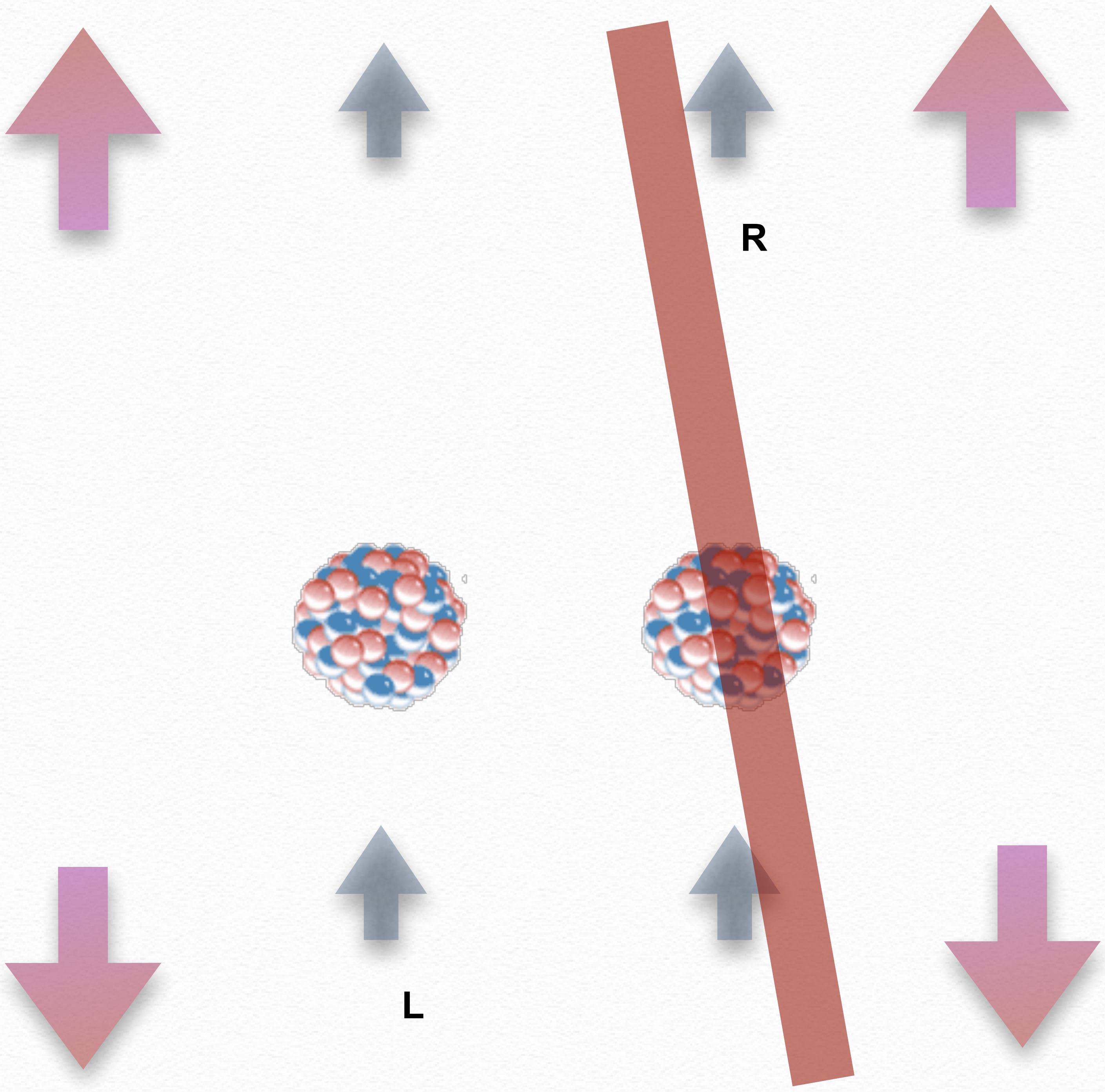
P VIOLATION

$$^{60}_{27}Co \rightarrow ^{60}_{26} Ni + e + \bar{\nu}_e$$

spin: $5 \rightarrow 4 + 1/2 + 1/2$

parity broken maximally

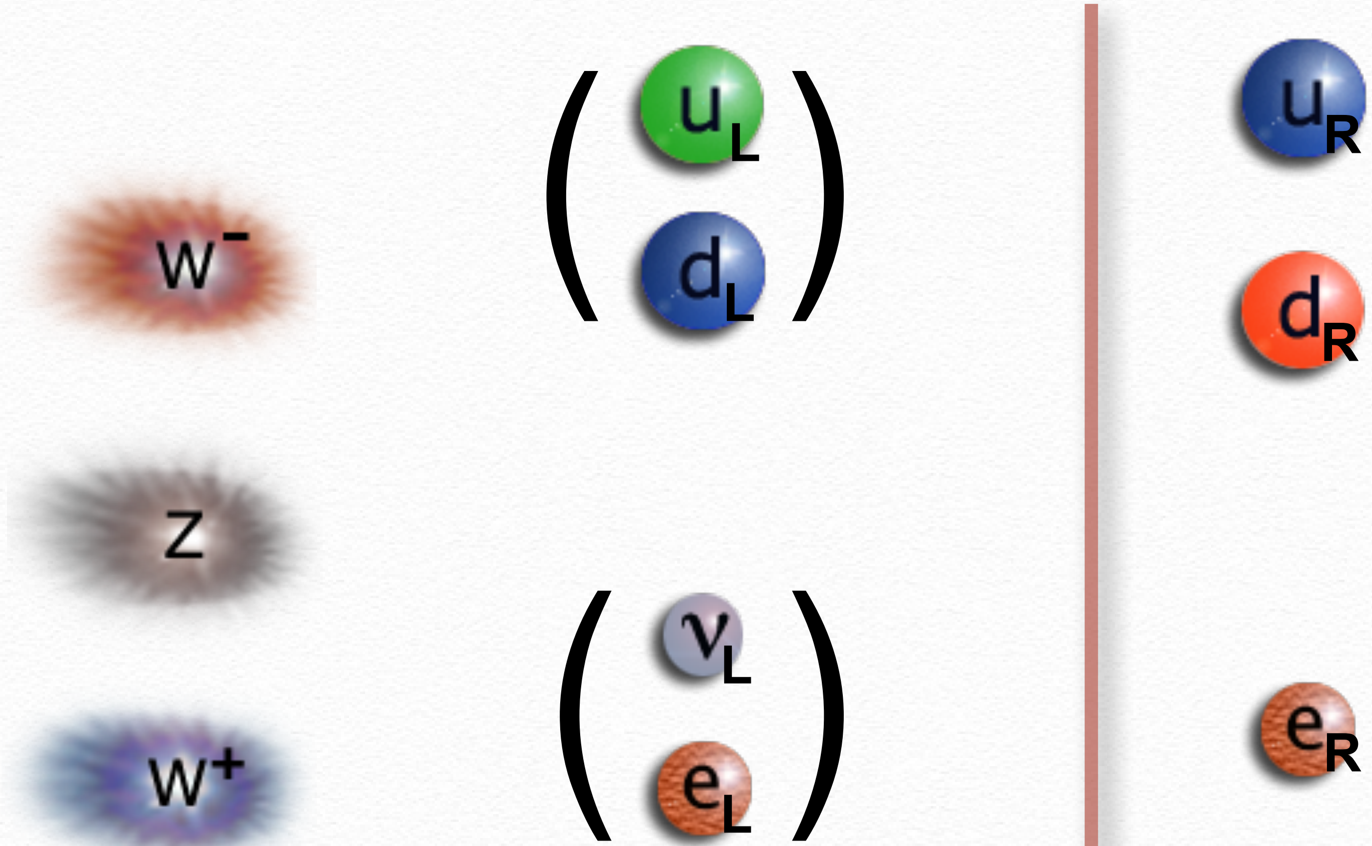
Wu et al 1956



Standard Model

L-R symmetry
broken completely

Glashow *Weinberg* *Salam* *1961-68*



quarks and electron
are
massless

LH particles - weak force

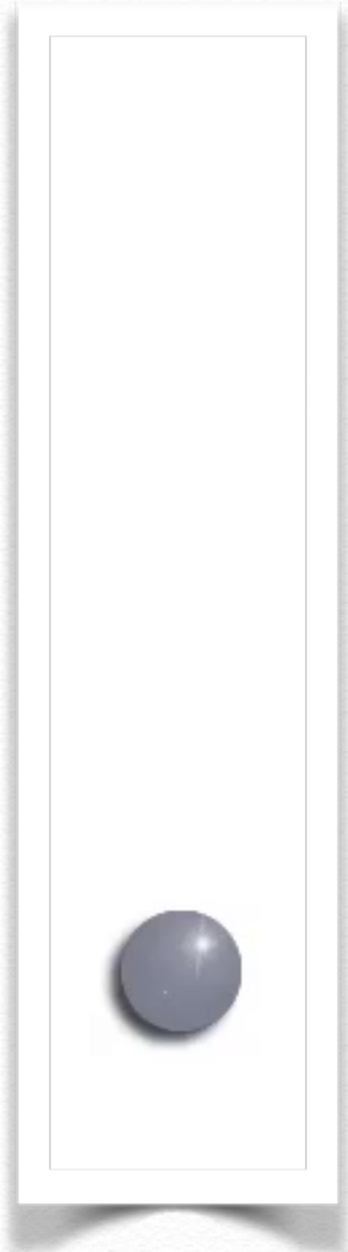
RH particles - no weak force

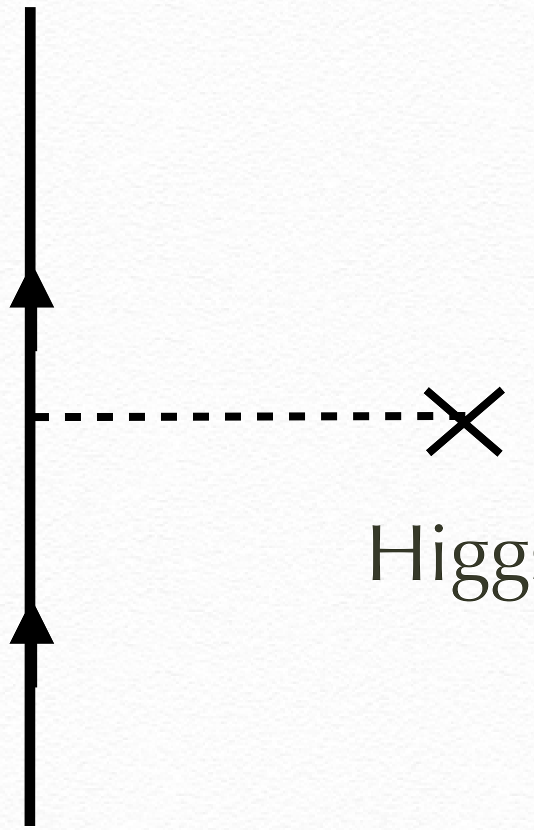
$$J_\mu^W = \bar{u}_L \gamma_\mu d_L + \bar{\nu}_L \gamma_\mu e_L$$

Quark and lepton masses: Higgs mechanism

Higgs 1964

Brout, Engler 1964





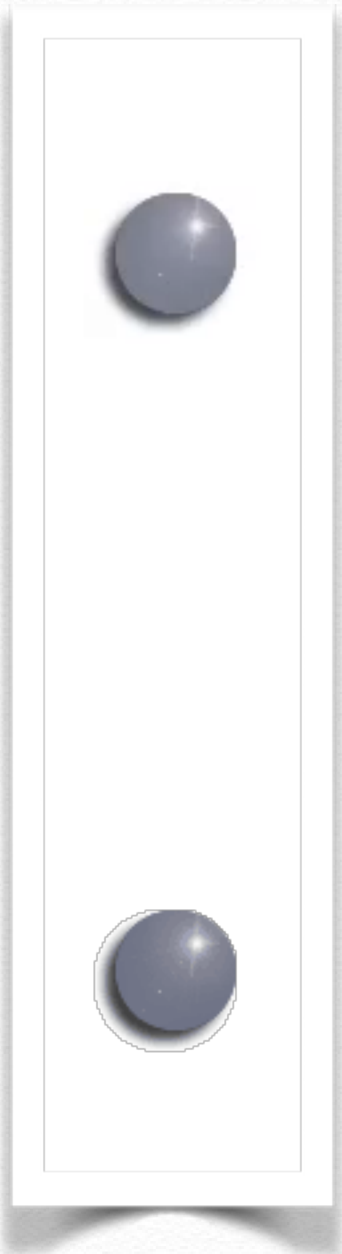
- Higgs boson - connects left with right
- LR asymmetry essential

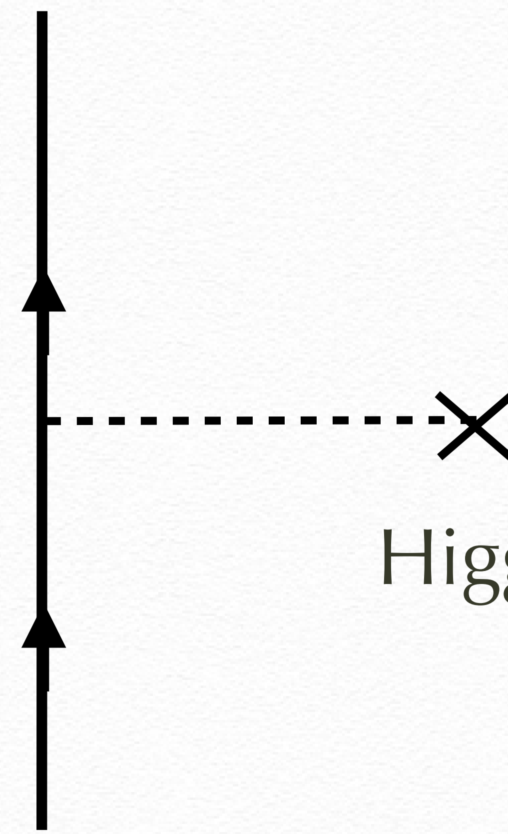
Weinberg 1967

Quark and lepton masses: Higgs mechanism

Higgs 1964

Brout, Engler 1964





- Higgs boson - connects left with right
- LR asymmetry essential

Weinberg 1967

Higgs boson `god's particle' *Higgs 1964*

`goddamn particle'

Lederman

- vacuum filled with Higgs field

- gives mass to W, Z, quarks and leptons

- new force proportional to mass

- s=0, charge =0 - hard to produce

talk about waiting

Higgs boson

`god's particle' *Higgs 1964*

`goddamn particle' *Lederman*

- vacuum filled with Higgs field

- gives mass to W, Z, quarks and leptons

- new force proportional to mass

- s=0, charge =0 - hard to produce

discovered in 2012@LHC - Tevatron not sufficient :(

talk about waiting

Origin of mass = Higgs mechanism

decays of Higgs boson predicted *Weinberg 1967*

$$\Gamma(h \to p\bar{p}) \propto m_p^2$$

any particle p (say quarks and leptons) that gets mass through Higgs mechanism

Question: neutrino mass the same?

Question - equally if not more important: nature of neutrino mass? Majorana?

Origin of mass = Higgs mechanism

decays of Higgs boson predicted *Weinberg 1967*

$$\Gamma(h \to p\bar{p}) \propto m_p^2$$

any particle p (say quarks and leptons) that gets mass through Higgs mechanism

Question: neutrino mass the same?

Question - equally if not more important: nature of neutrino mass? Majorana?

Origin of mass = Higgs mechanism

decays of Higgs boson predicted *Weinberg 1967*

$$\Gamma(h \to p\bar{p}) \propto m_p^2$$

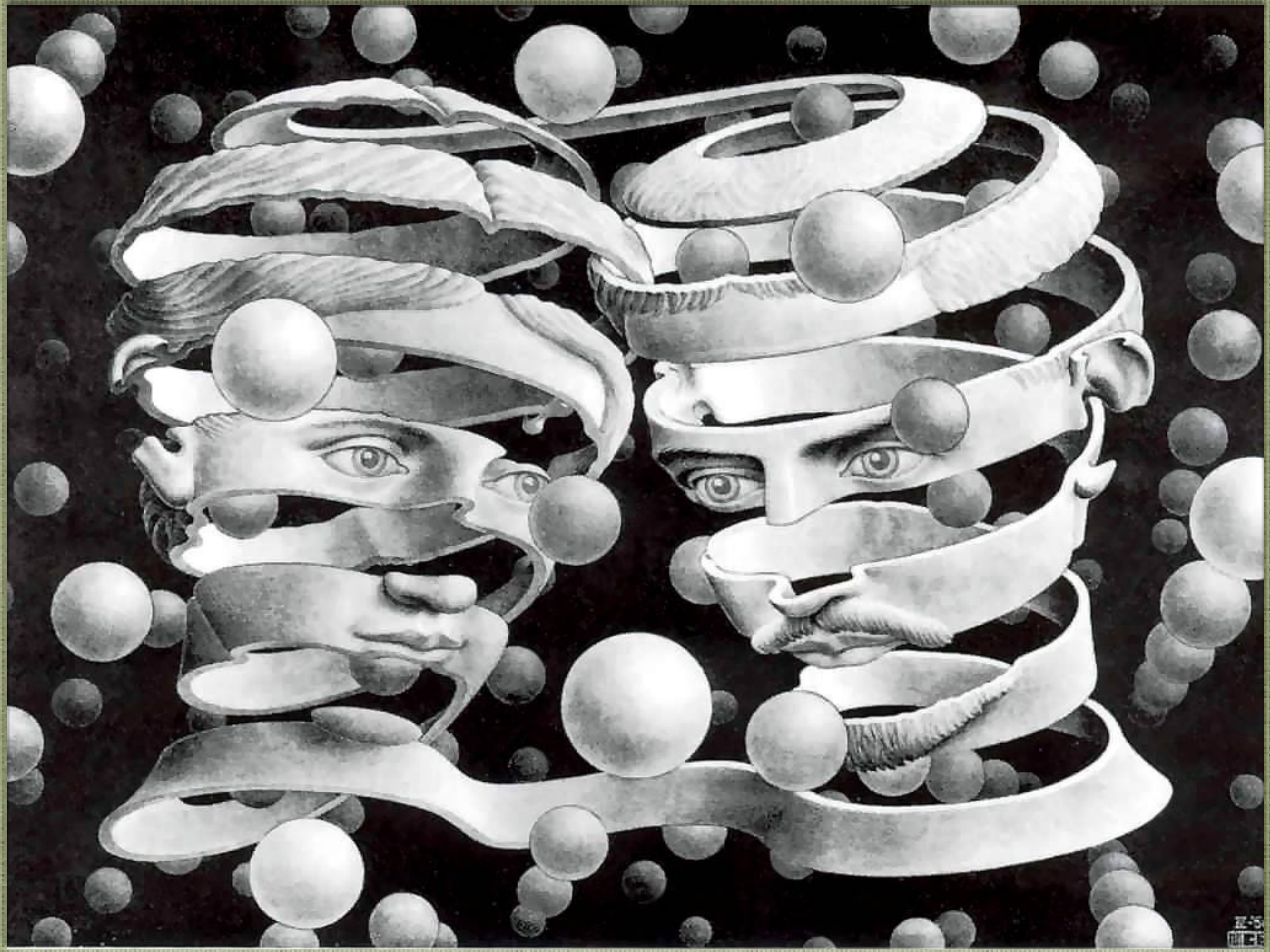
any particle p (say quarks and leptons) that
gets mass through Higgs mechanism

Question: neutrino mass the same?

Question - equally if not more important:
nature of neutrino mass? Majorana?

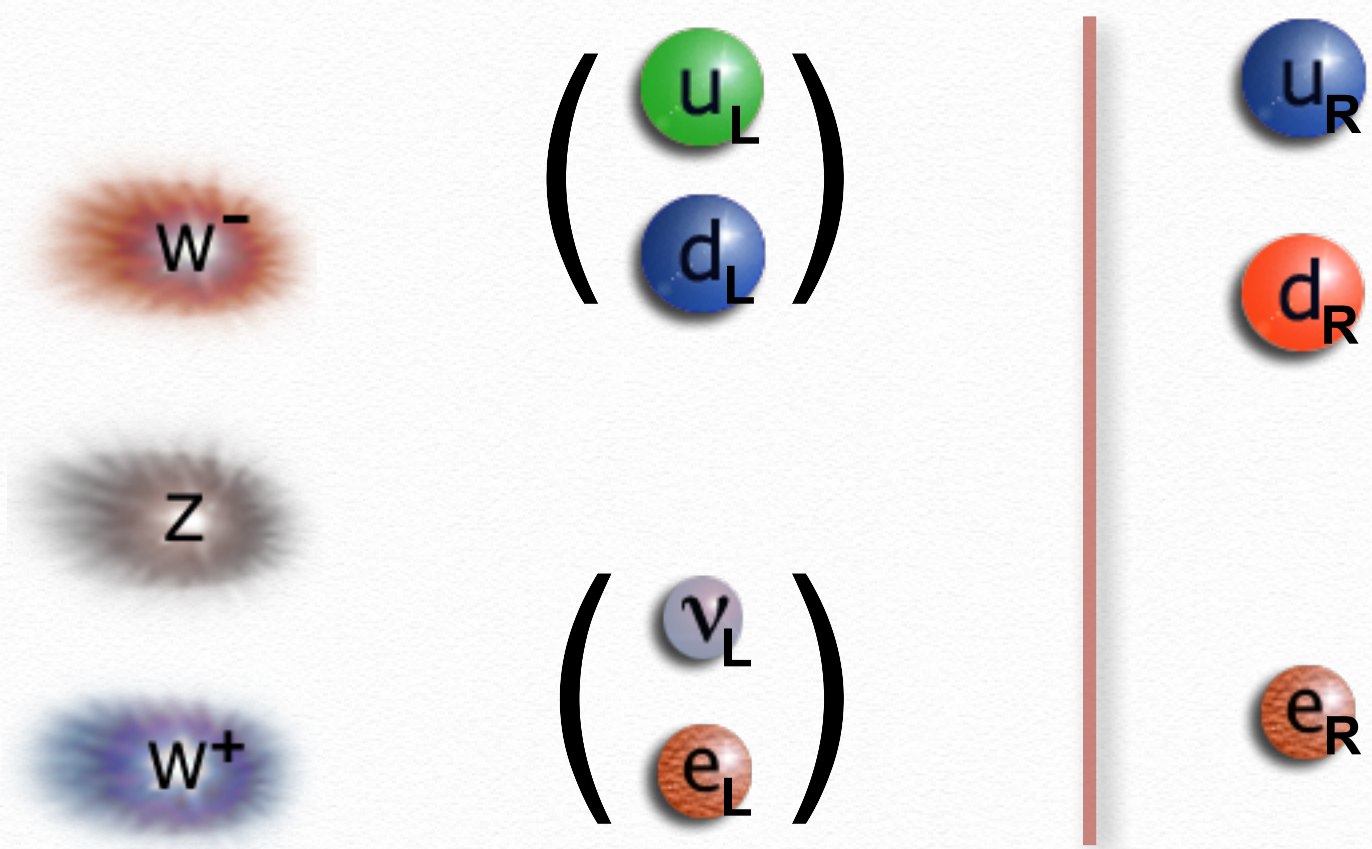
A personal touch

The theory



Standard Model = neutrino massless

L-R symmetry
broken completely

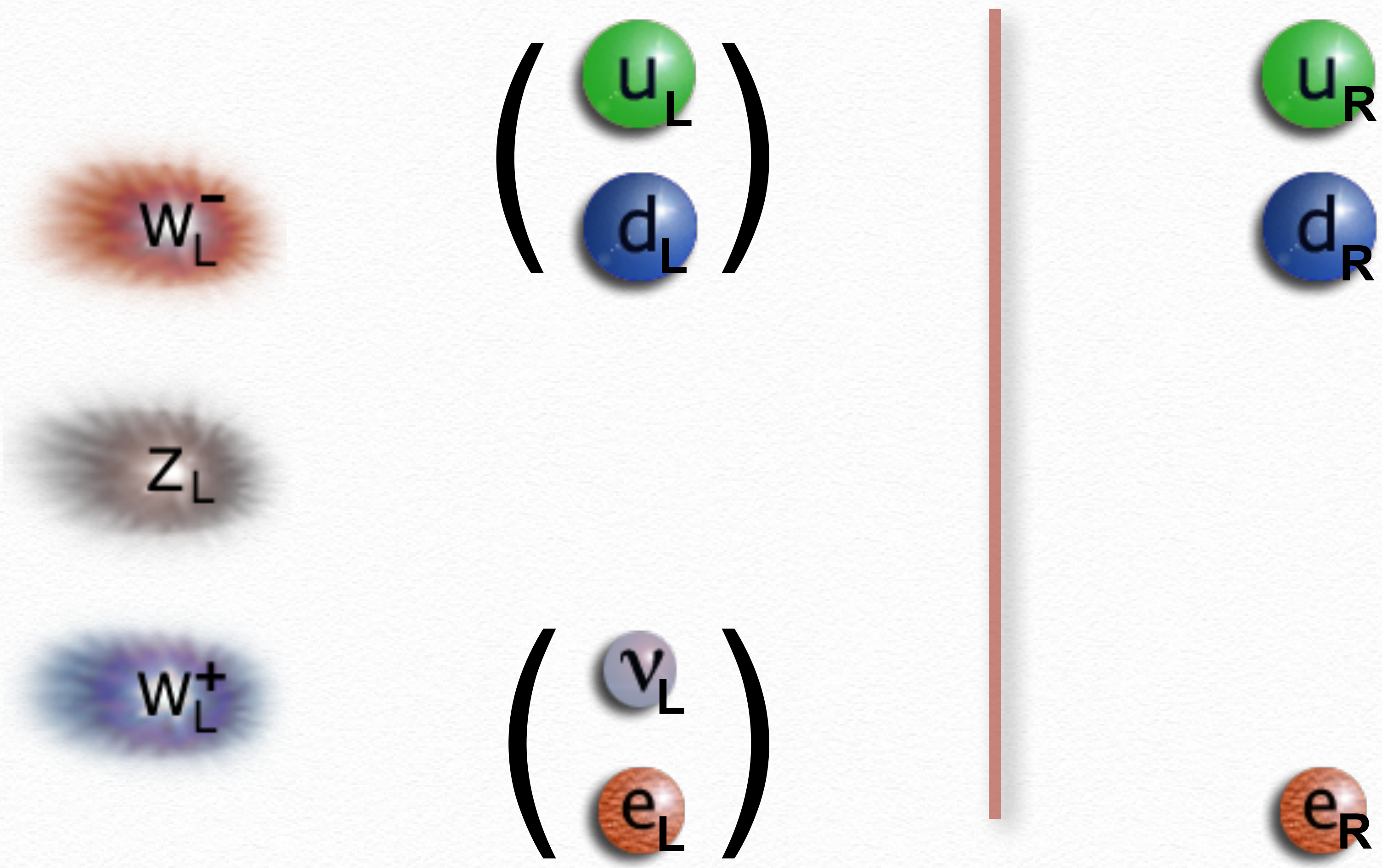


no ν_R

no neutrino mass

neutrino mass forbidden by SM structure/symmetry

Left-Right Symmetric Model

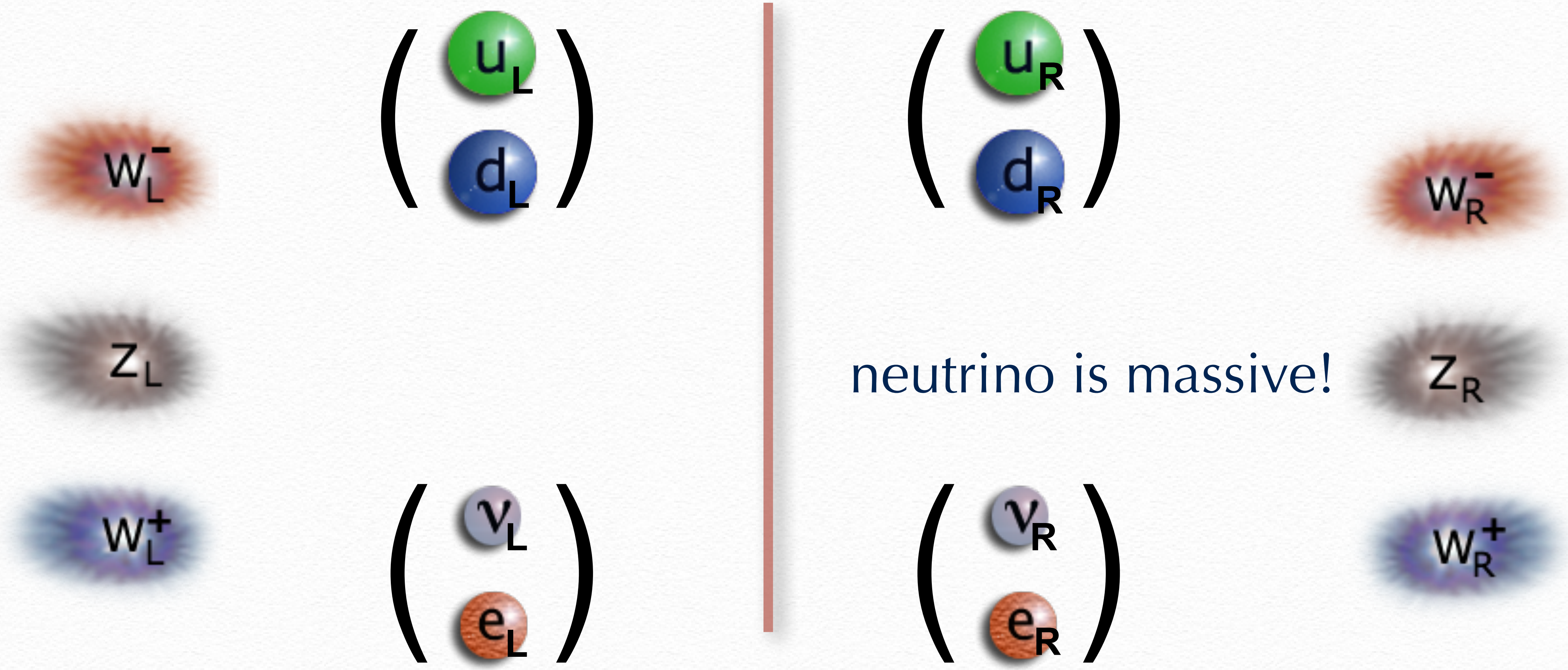


Neutrino mass long
before experiment

Left-Right Symmetric Model

Pati, Mohapatra, Salam 1974

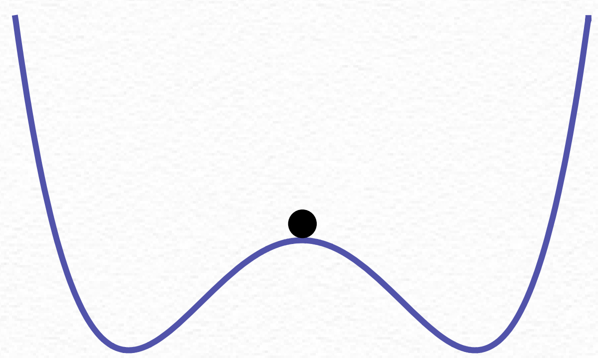
Mohapatra, GS 1975



Neutrino mass long
before experiment

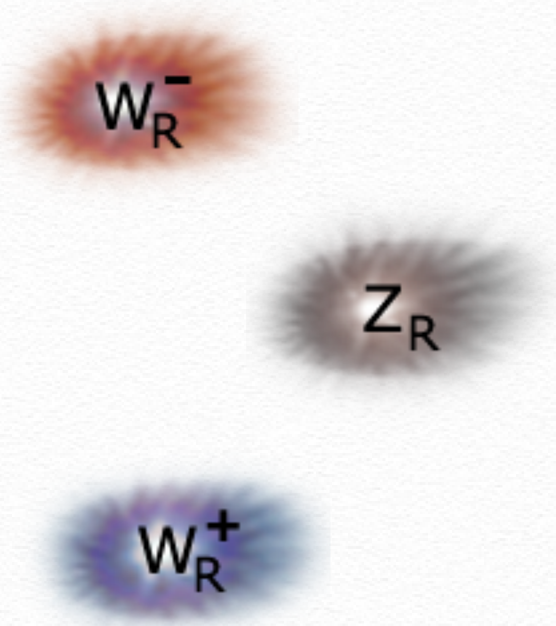
L-R symmetry breaking

Mohapatra, Senjanovic '75



Spontaneous

Senjanovic '79



New mediators very heavy

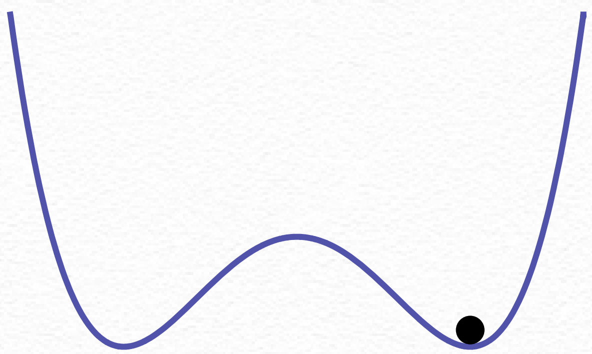
New "weak" force felt by right-handed particles - at high energy

$$m_{W_R} \gg m_{W_L}$$

Neutrino mass predicted long before experiment

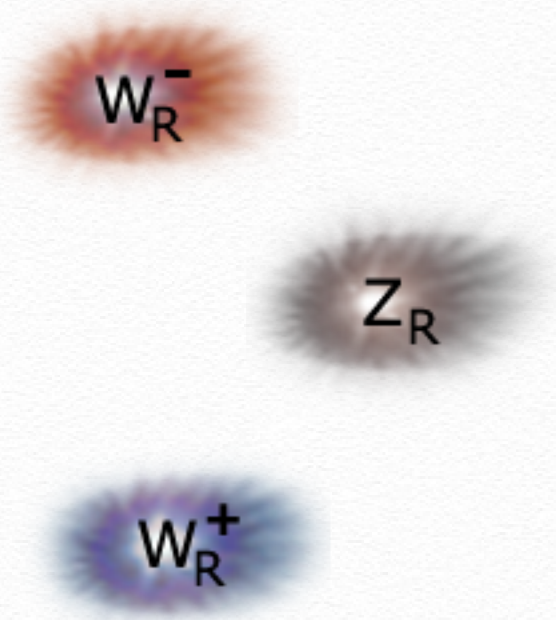
L-R symmetry breaking

Mohapatra, Senjanovic '75



Spontaneous

Senjanovic '79



New mediators
very heavy

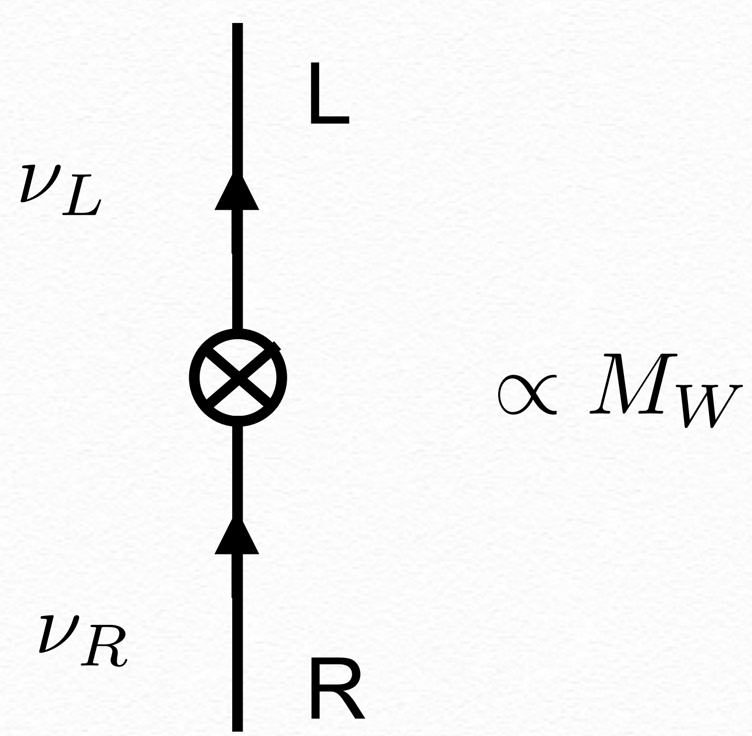
New "weak" force felt by
right-handed particles
- at high energy

$$m_{W_R} \gg m_{W_L}$$

Neutrino mass predicted
long before experiment

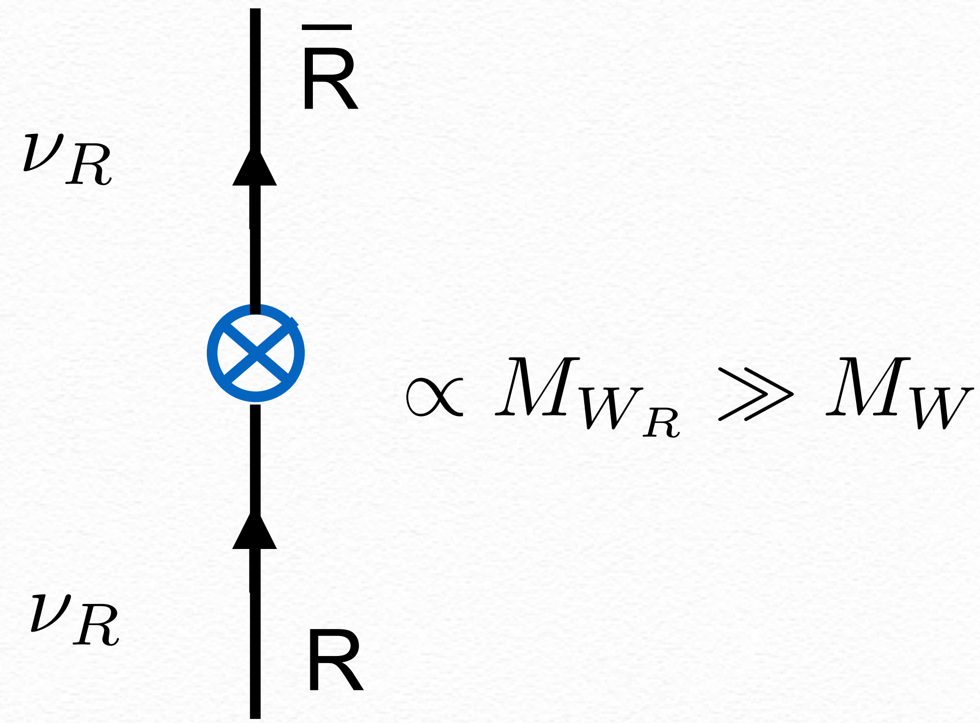
LR: Neutrino is a Majorana particle

Dirac mass, small:
combines L and R



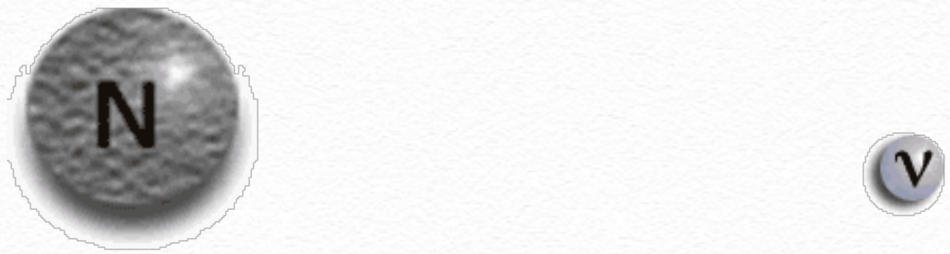
ν_L 

Majorana mass, large:
R has mass by itself



ν_R 

Seesaw mechanism for neutrino mass



neutrino is light,
since N is heavy

Minkowski *Mohapatra, Senjanovic*

Glashow *1977-1979*

Gell-Mann, Ramond, Slansky

Seesaw mechanism for neutrino mass

neutrino is light,
since N is heavy

seesaw mechanism -
main scenario for understanding
the lightness of neutrino

Minkowski *Mohapatra, Senjanovic*

Glashow *1977-1979*

Gell-Mann, Ramond, Slansky

Seesaw - art at the wall

Seesaw - art at the wall

US - Mexico border

Seesaw - art at the wall

US - Mexico border

1980's: Scale disaster

minimal model

Beall, Bander, Soni '81

$$M_{W_R} \gtrsim 3000 GeV \qquad (M_W = 80 GeV)$$

wait for LHC

Large Hadron Collider

truly modern times

proton on proton

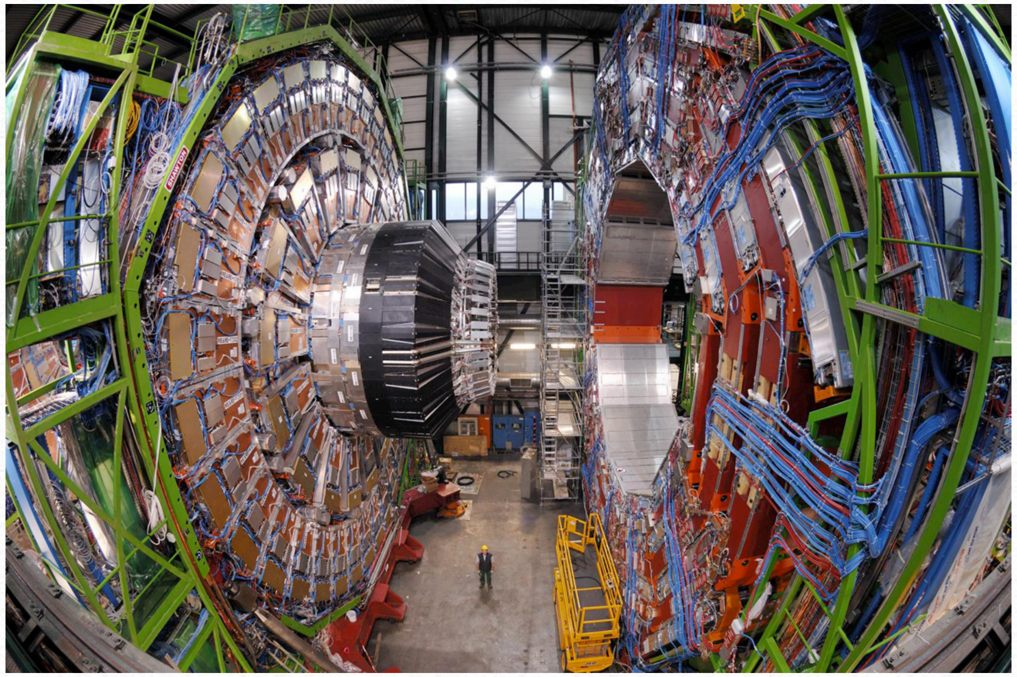
CMS detector

~ 3500 people

ATLAS detector

ring 27 km

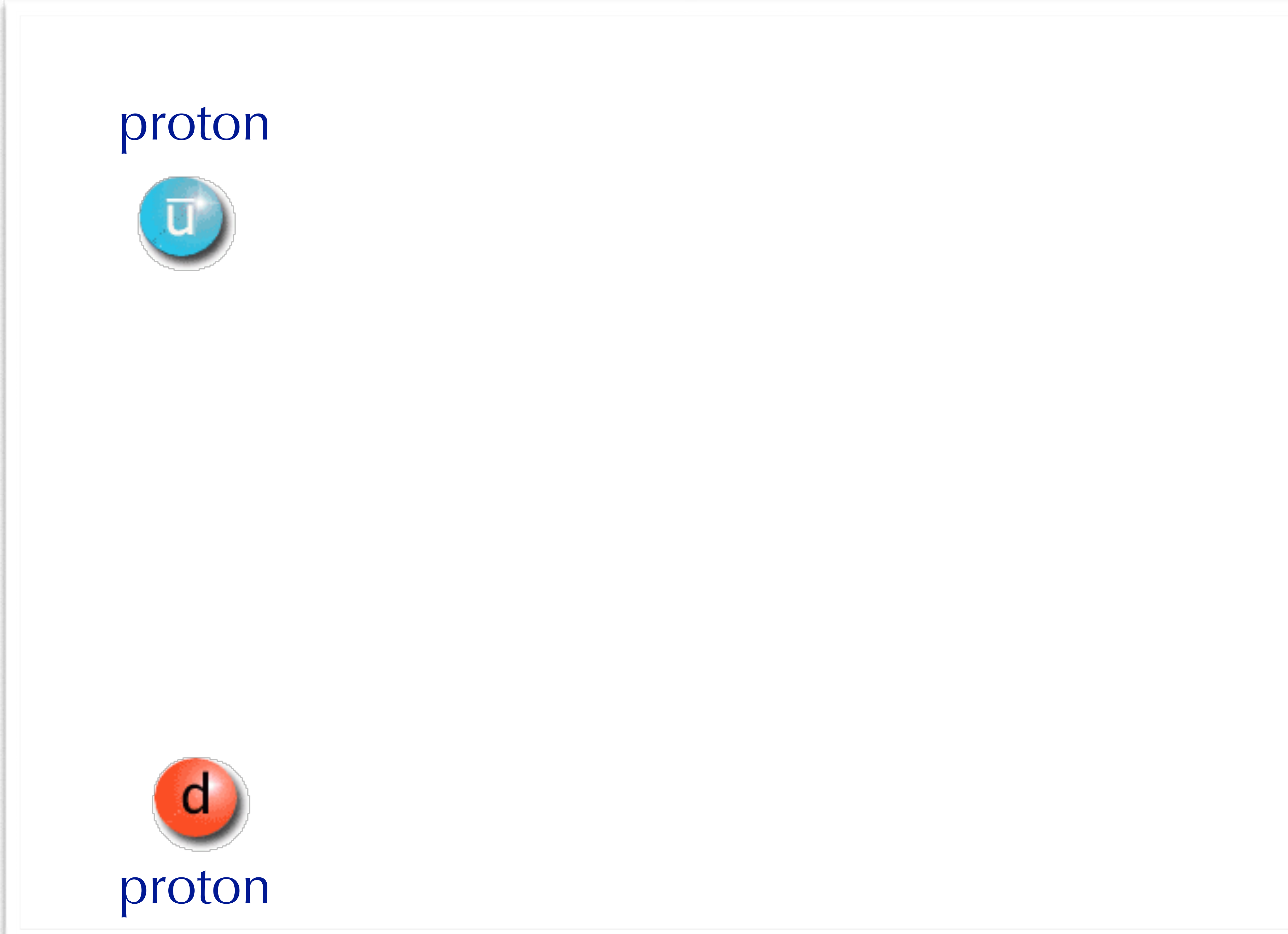
Compare with Tevatron
ring ~ 10 km



CMS detector

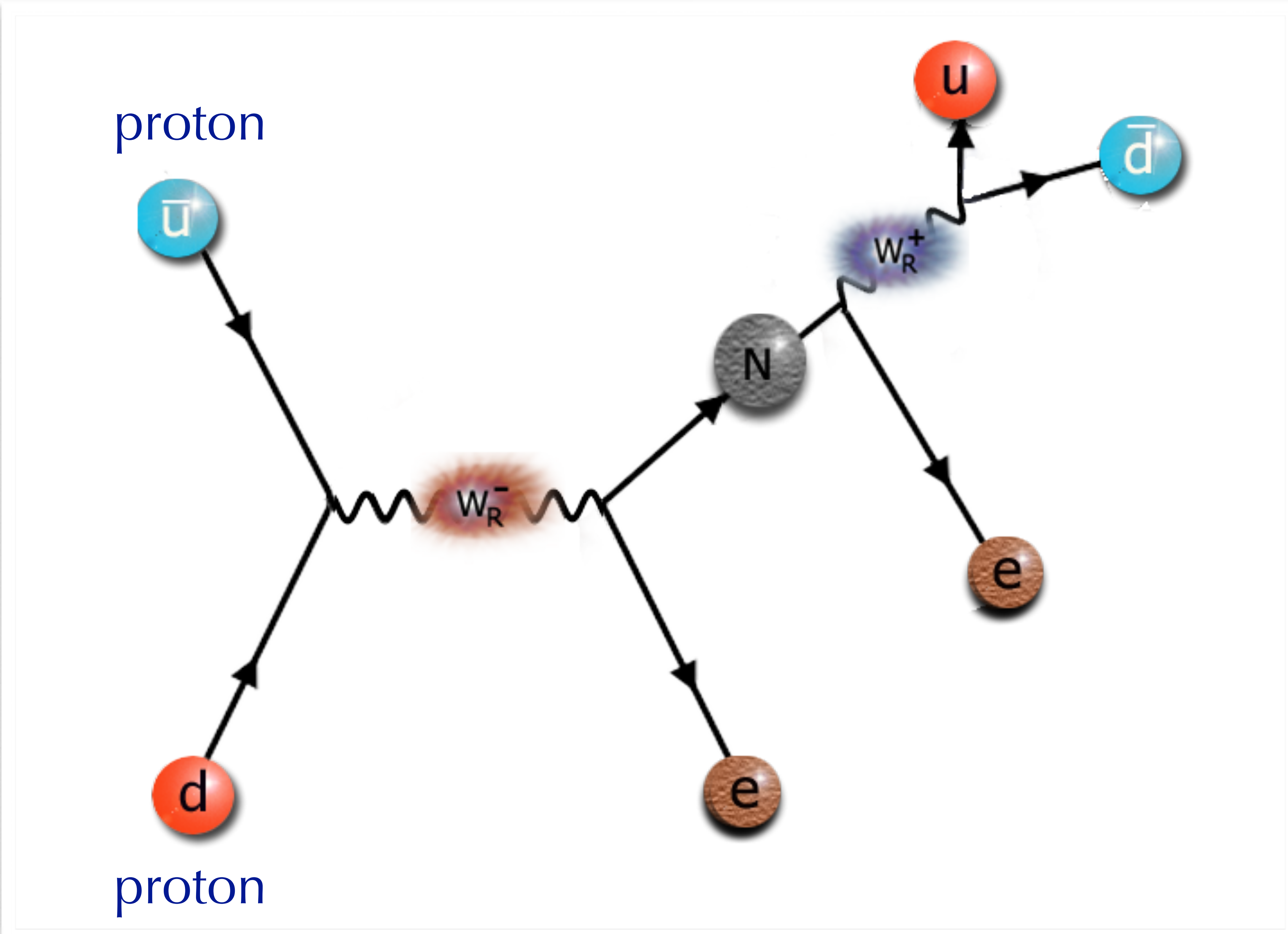
From Majorana to LHC

Keung, GS 1983



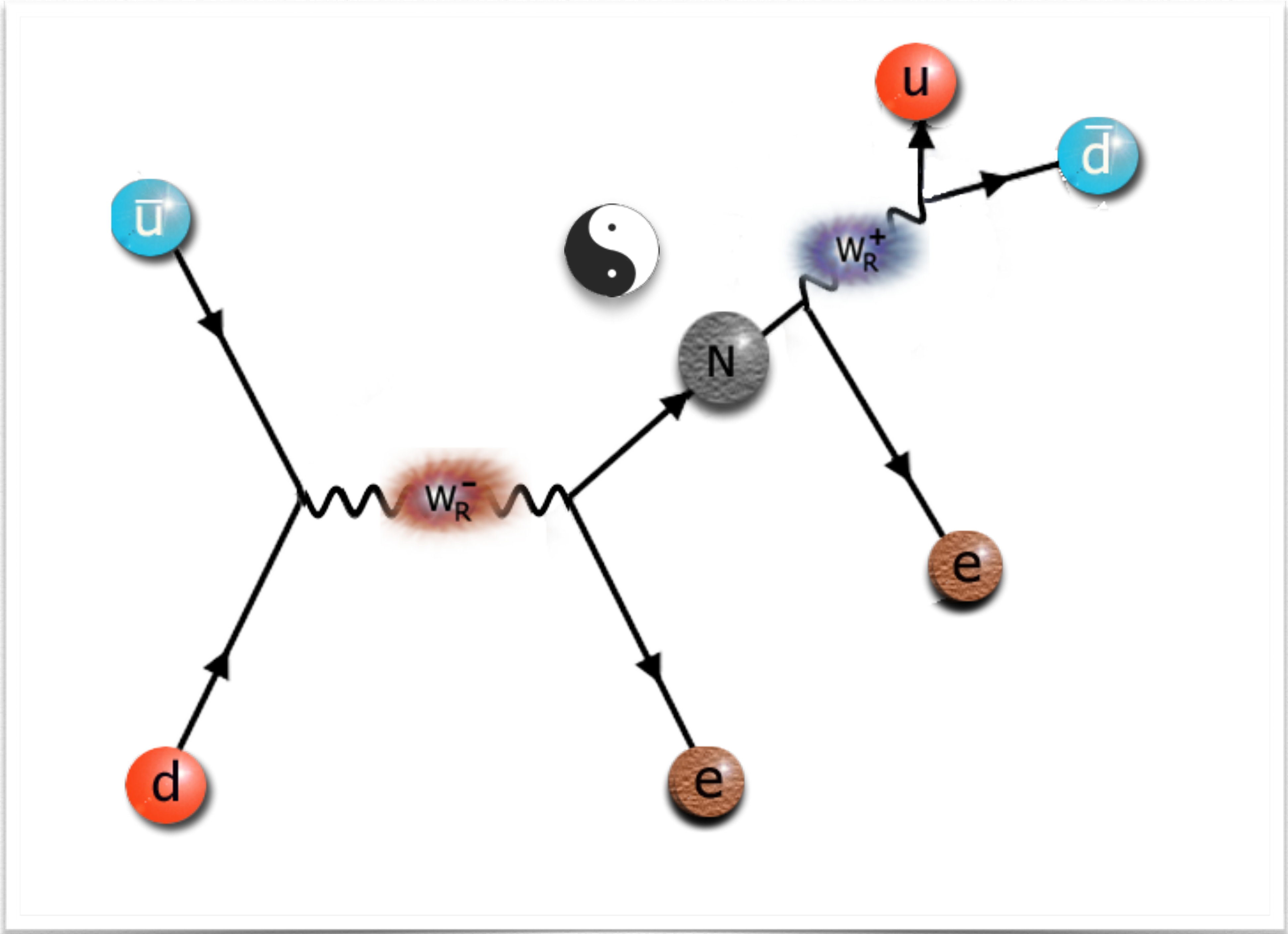
From Majorana to LHC

Keung, GS 1983



... and back

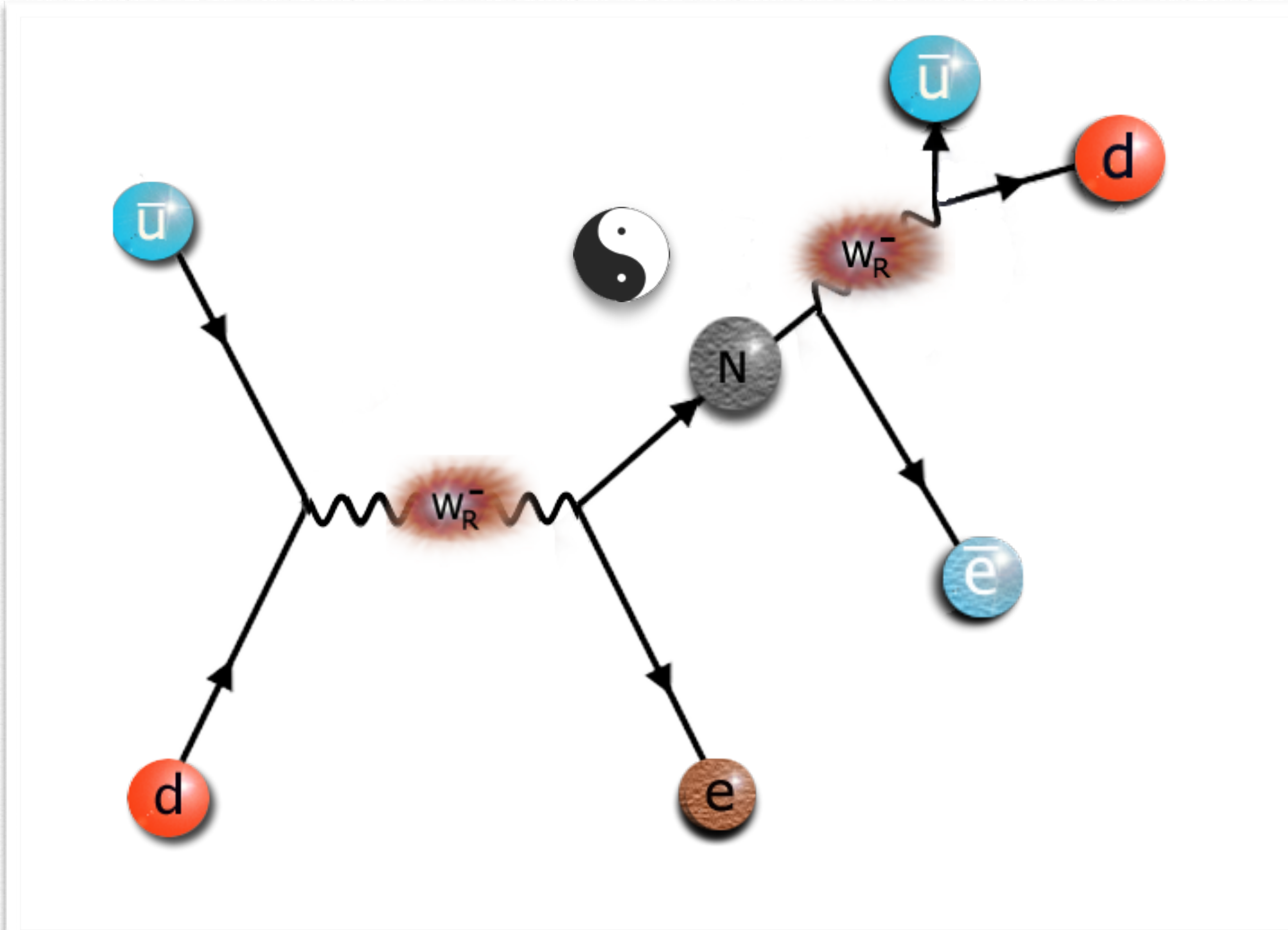
Keung, GS 1983



N = Majorana particle

… and back

Keung, GS 1983



N = Majorana particle ➜ decays equally into positron

Neutrino and Higgs

program of verifying Higgs mechanism for neutrino:
analog of Higgs-Weinberg for quarks and electron

Nemevsek, Senjanovic, Tello 2012

Senjanovic, Tello 2016, 2018

$$\Gamma(N \to We) \propto m_\nu m_N^2 / m_W^2$$

and a number of similar decays

testable at LHC

Keung, GS

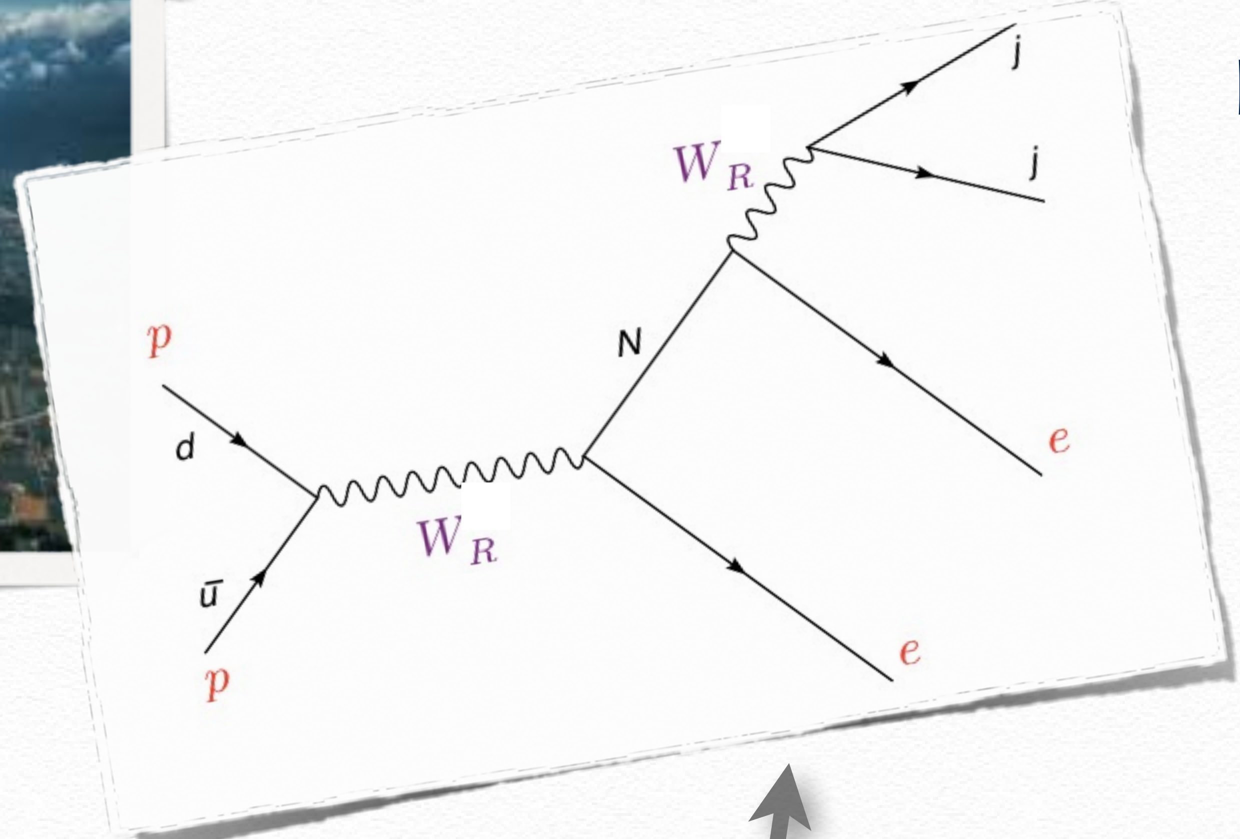


Figure 1

CMS, ATLAS:
dedicated search

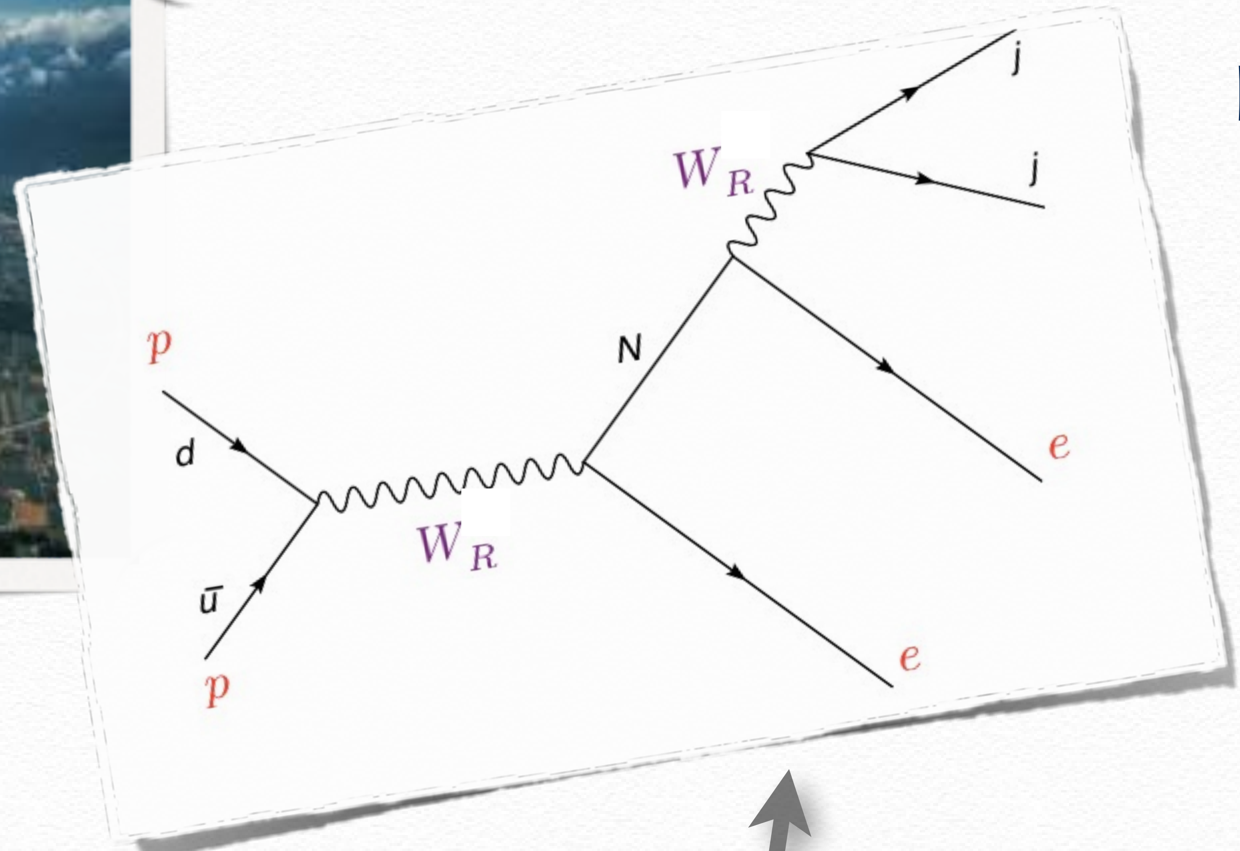
ATLAS 2019

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than

$$M_R > 5000 \text{ GeV} \qquad M_W = 80 \text{ GeV}$$

Keung, GS

Figure 1



CMS, ATLAS:
dedicated search

ATLAS 2019

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than

$M_R > 5000$ GeV $\qquad M_W = 80$ GeV

Need to know how to wait :)

Large Hadron Collider

- could probe the origin of neutrino mass
- could probe the Majorana nature of neutrino
- could resolve the mystery of L-R symmetry in Nature

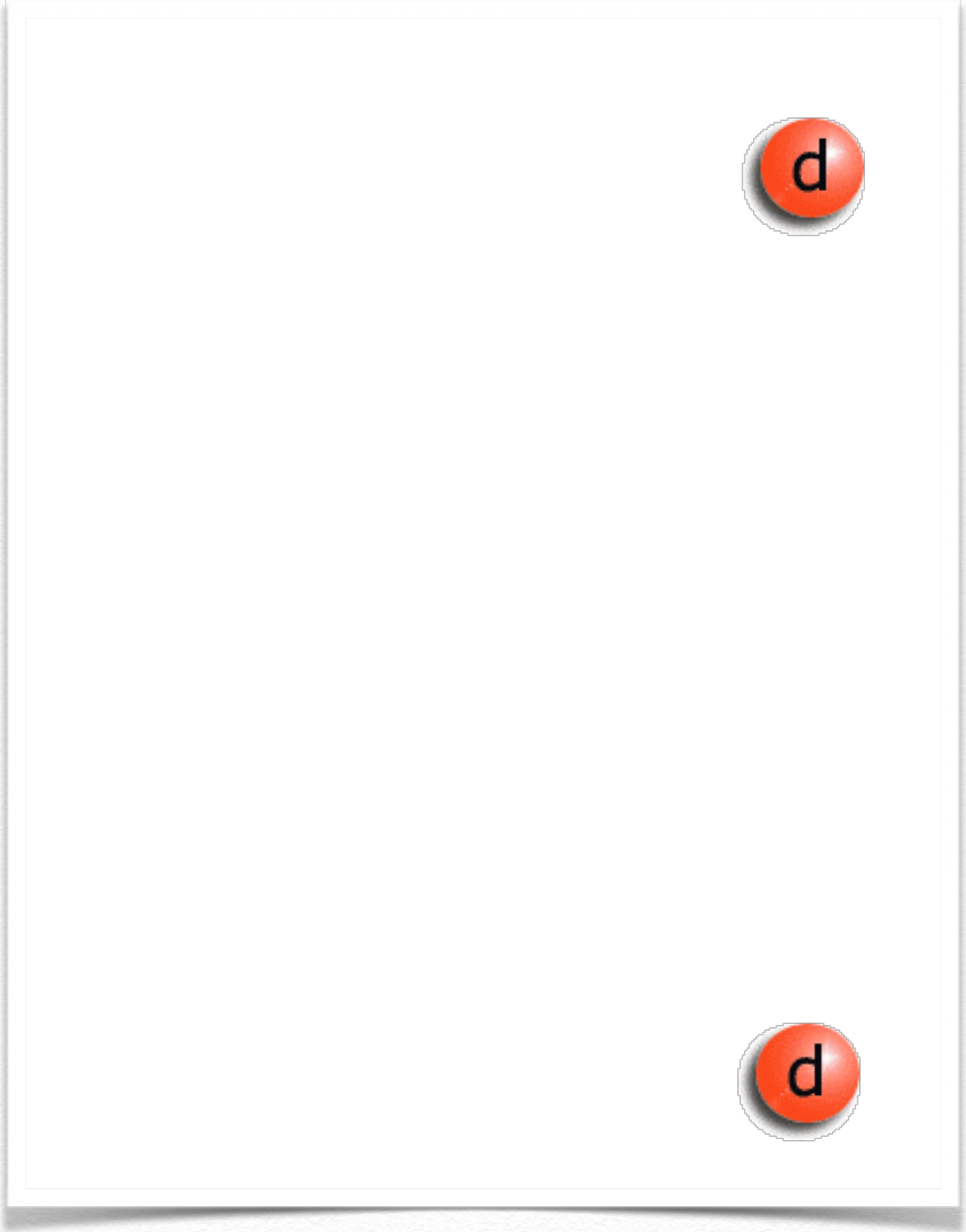
Large Hadron Collider

- could probe the origin of neutrino mass
- could probe the Majorana nature of neutrino
- could resolve the mystery of L-R symmetry in Nature

Thank you

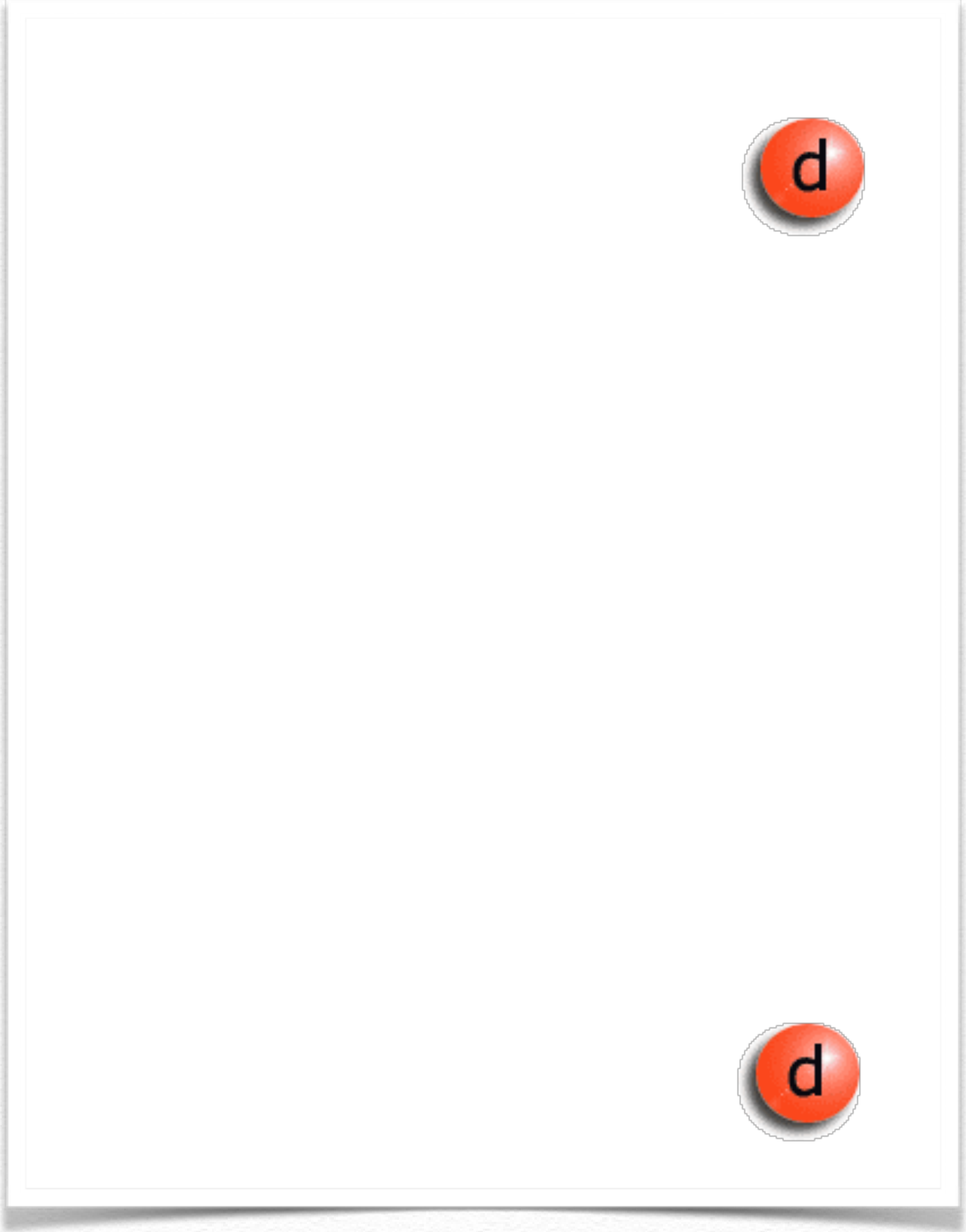
New source for double beta

Mohapatra, GS '79



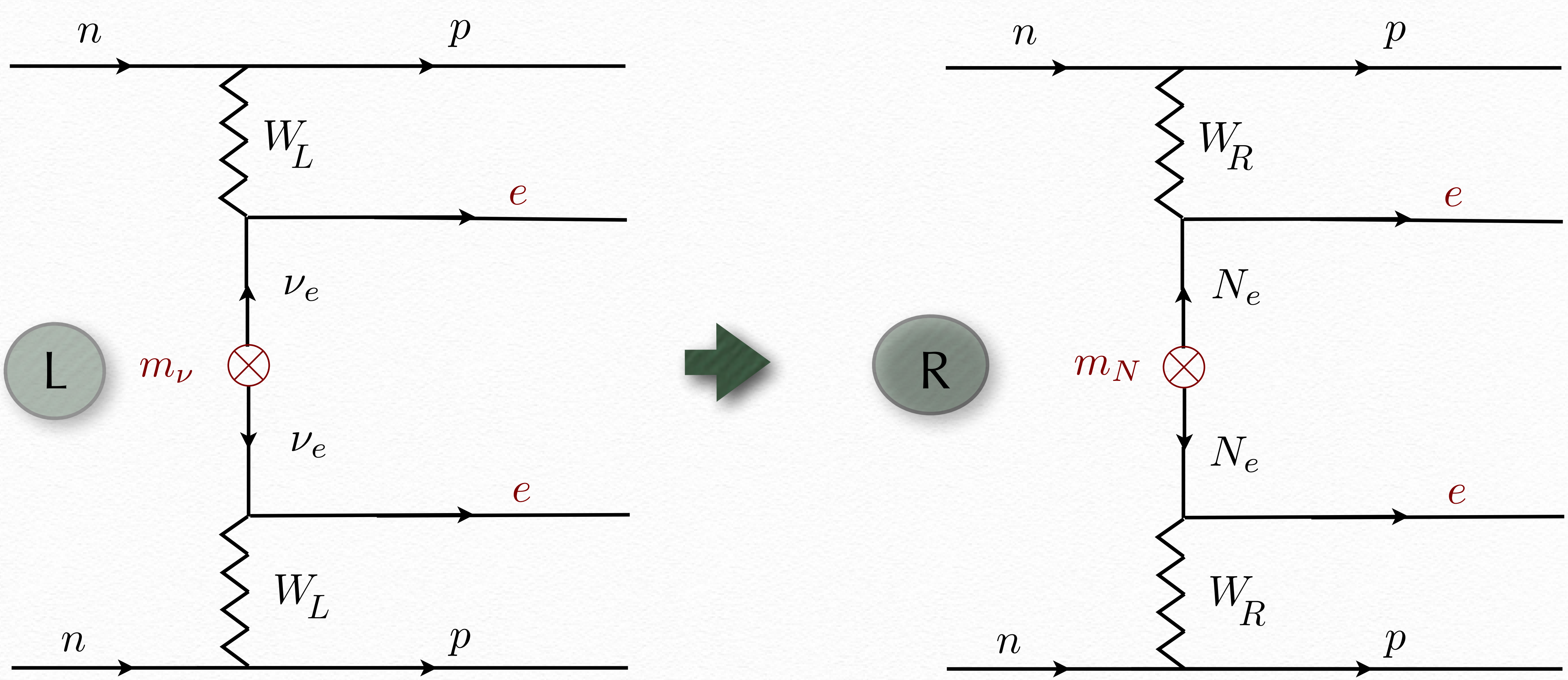
New source for double beta

Mohapatra, GS '79



New source for double beta

Mohapatra, GS '79



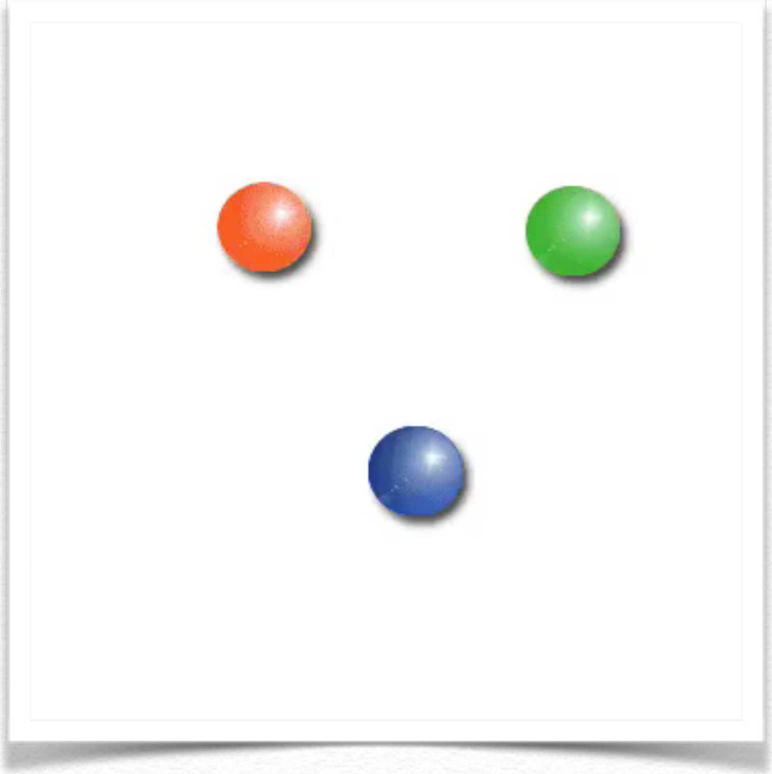
N= RH neutrino

Strong Interaction: QCD (Quantum chromodynamics):

strong force (-> nuclear) =
messengers gluons

"color" charge

proton



spin=1

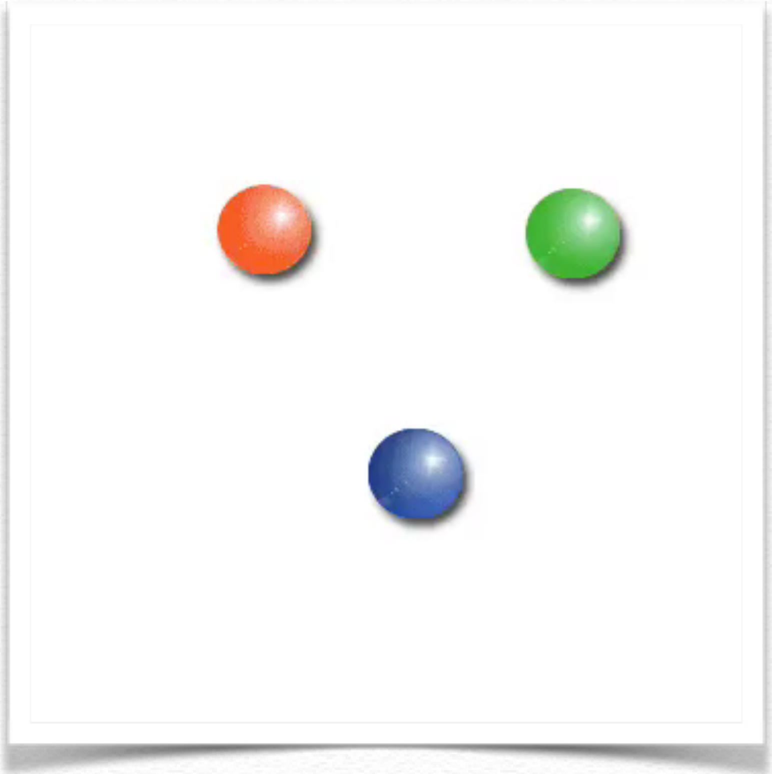
gluons have "color" too...

Strong Interaction: QCD (Quantum chromodynamics):

strong force (-> nuclear) =
messengers gluons

"color" charge

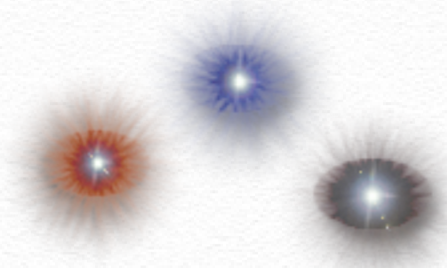
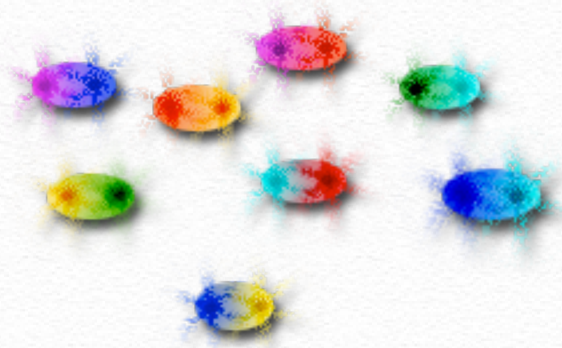
proton



spin=1

gluons have "color" too...

Standard Model of all Interactions *

- electromagnetic  photon
- weak  W, Z bosons
- strong  gluons

* but gravity: negligible

38 orders of magnitude weaker than electromagnetic

why does gravity matter?

why does matter gravitate?

⊙ sun - 10^{50} particles
zero charge