Neutrino Physics

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Lecture A:
Neutrino's history and lepton family

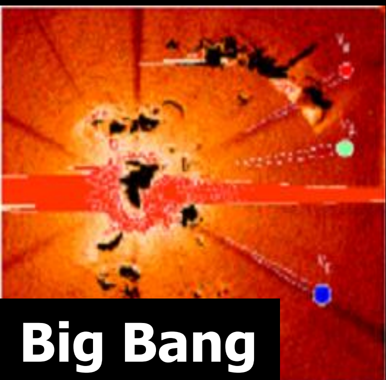
Lecture B:
Neutrino masses and flavor mixing

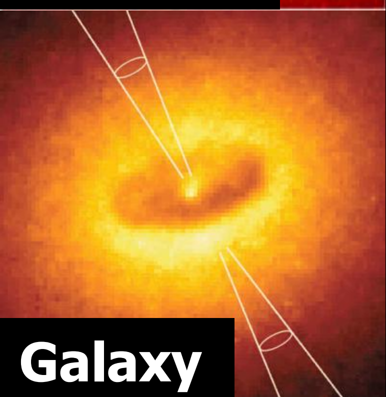
Lecture C:
Neutrino oscillation phenomenology

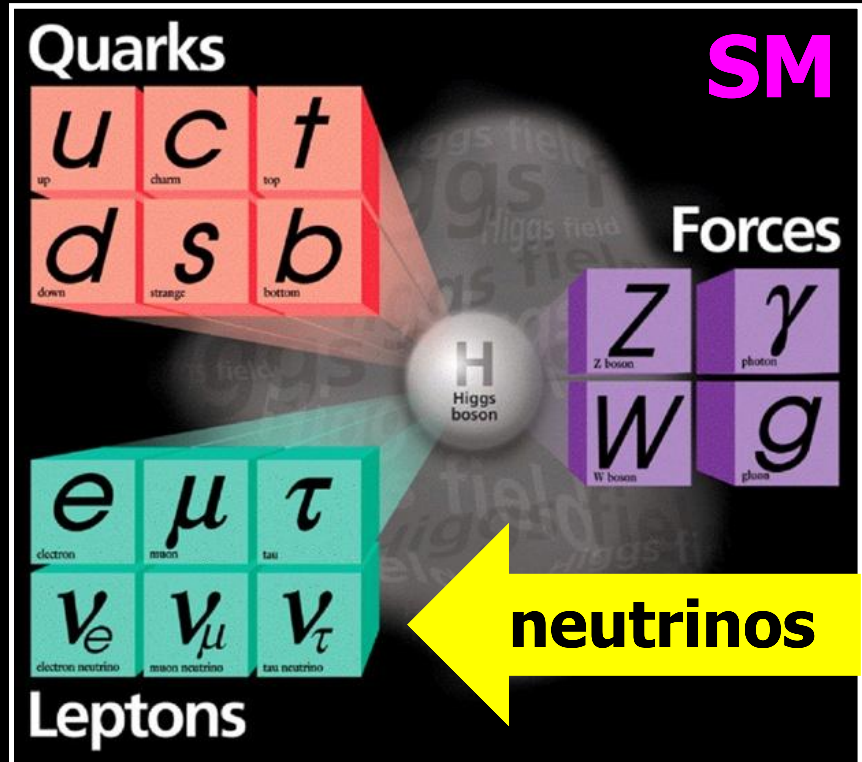
Lecture D:
Selected topics on cosmic neutrinos

@ Weihai High Energy Physics School, 2—10/8/2015

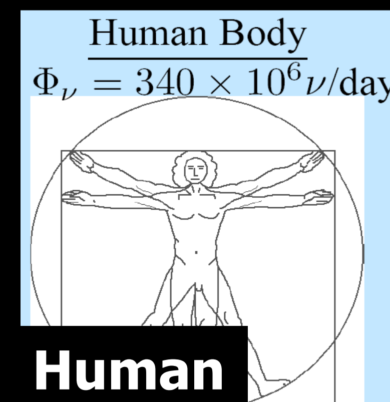
Neutrinos: how elusive they are?

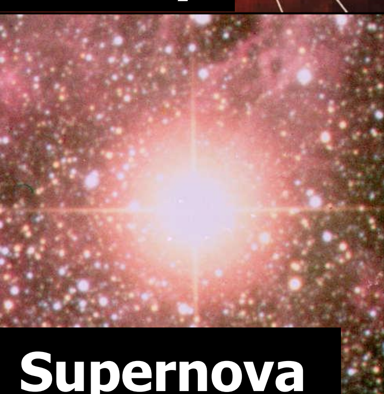


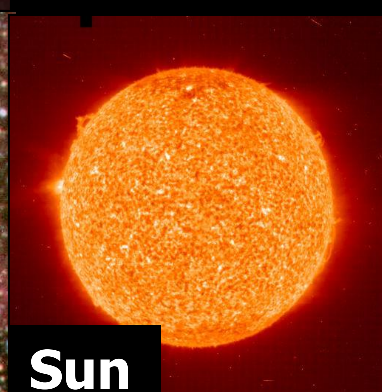


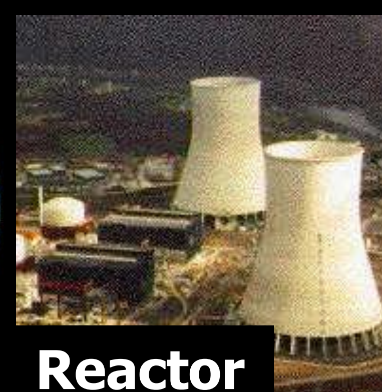


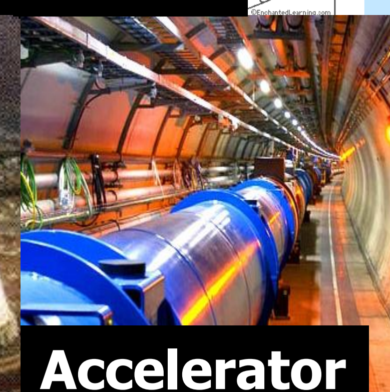
charge = 0
spin = ½
mass = 0
speed = c



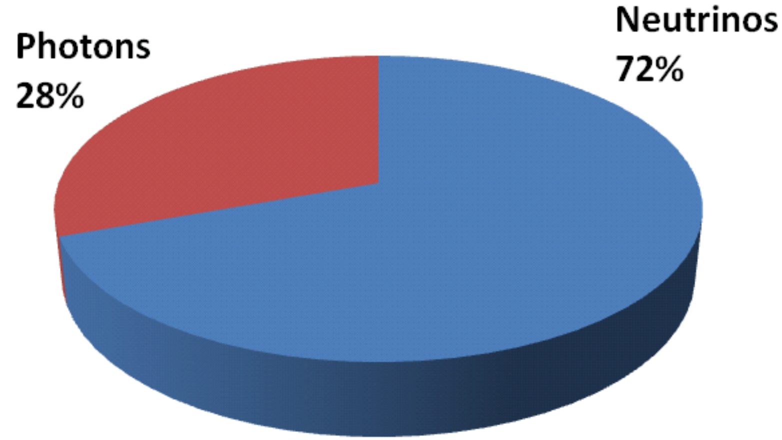




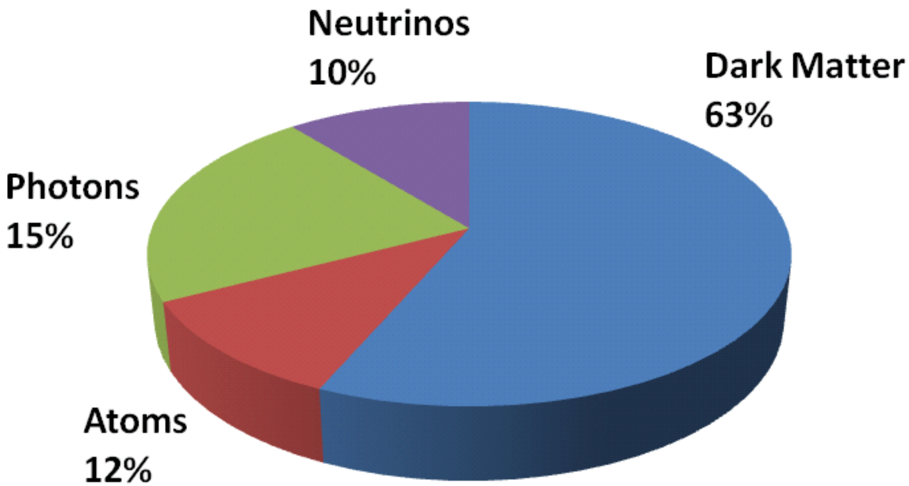




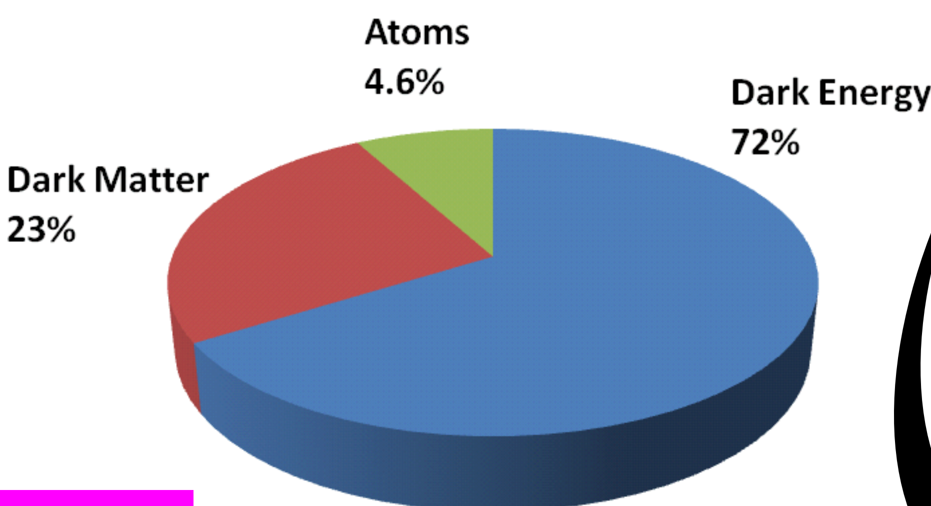
NEUTRINOS in the UNIVERSE



neutrino decoupling
t = 1 second



photon decoupling
t = 380 000 years



< 1%

Today
t = 13.7 billion years

A very important role in the evolution of the Universe

ν ν ν

Open Questions

the absolute ν mass scale?

how small is θ_{13}? (Daya Bay!)

ν mass hierarchy? (JUNO?)

CP violation? (MOMENT?)

the Dirac/Majorana nature?

the Majorana phases?

how many species? ...

cosmic ν background?

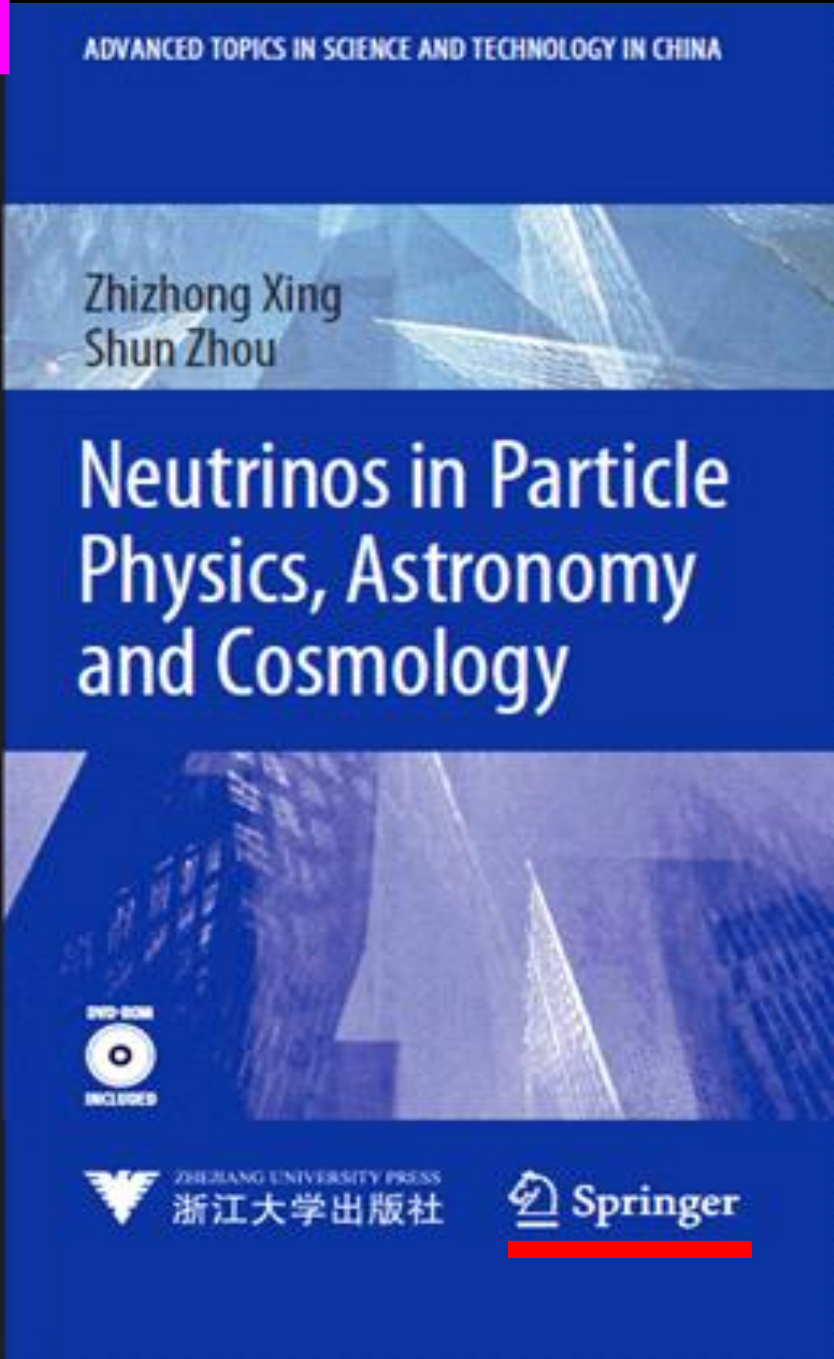
supernova & stellar ν's?

Ultrahigh-energy cosmic ν's?

warm dark matter?

matter-antimatter asymmetry...

Monograph 2011 (426 pages)



Lecture A

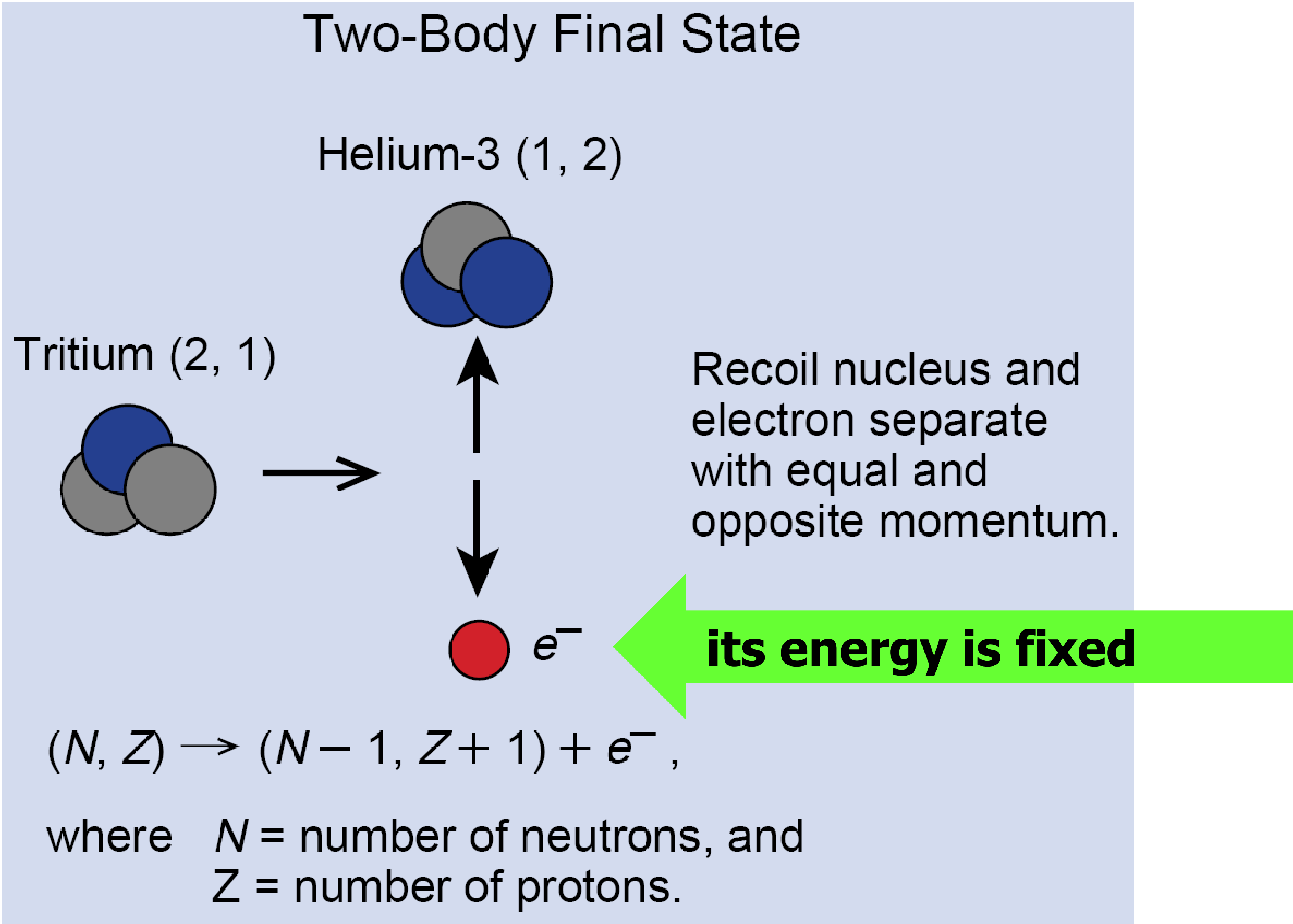
- ★ **Neutrinos from new physics**
- ★ **Interactions and discoveries**
- ★ **Flavors / families of leptons**

Steven Weinberg (2003): **Learn something about the history of science, or at a minimum the history of your own branch of science.**

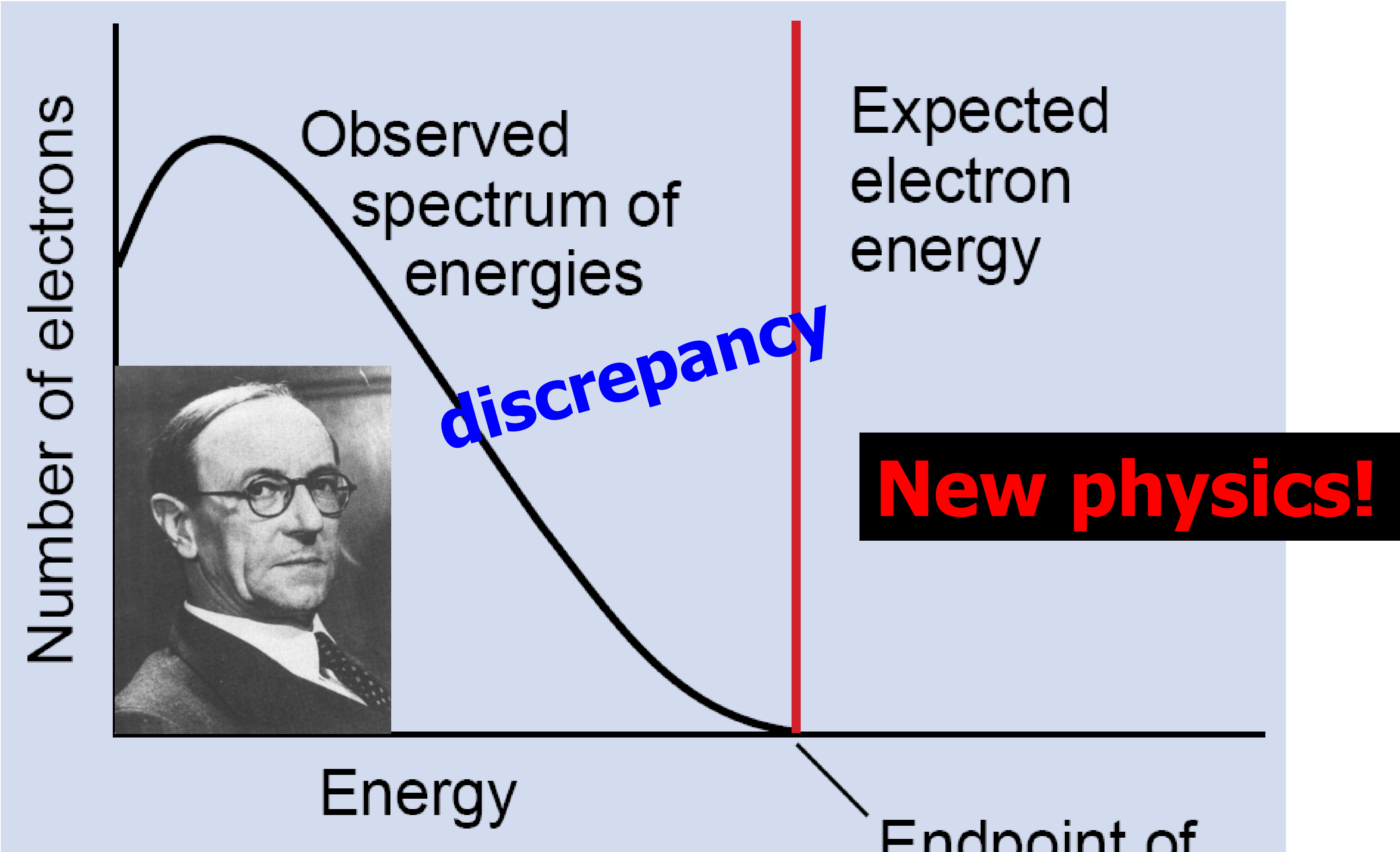
The history of science can make your work seem more worthwhile to you.

You can get great satisfaction by recognizing that your work in science is a part of history.

Beta decay in 1930

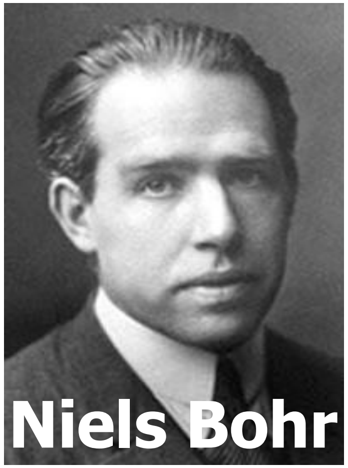


Energy crisis?



J. Chadwick 1914/C. Ellis 1920-1927

Desperate remedy



two viewpoints on new physics

- ♣ giving up sth
- ♣ adding in sth

Wolfgang Pauli (1930)

The Desperate Remedy

4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

Pauli’s letter

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the ‘false’ statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the “exchange theorem”* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

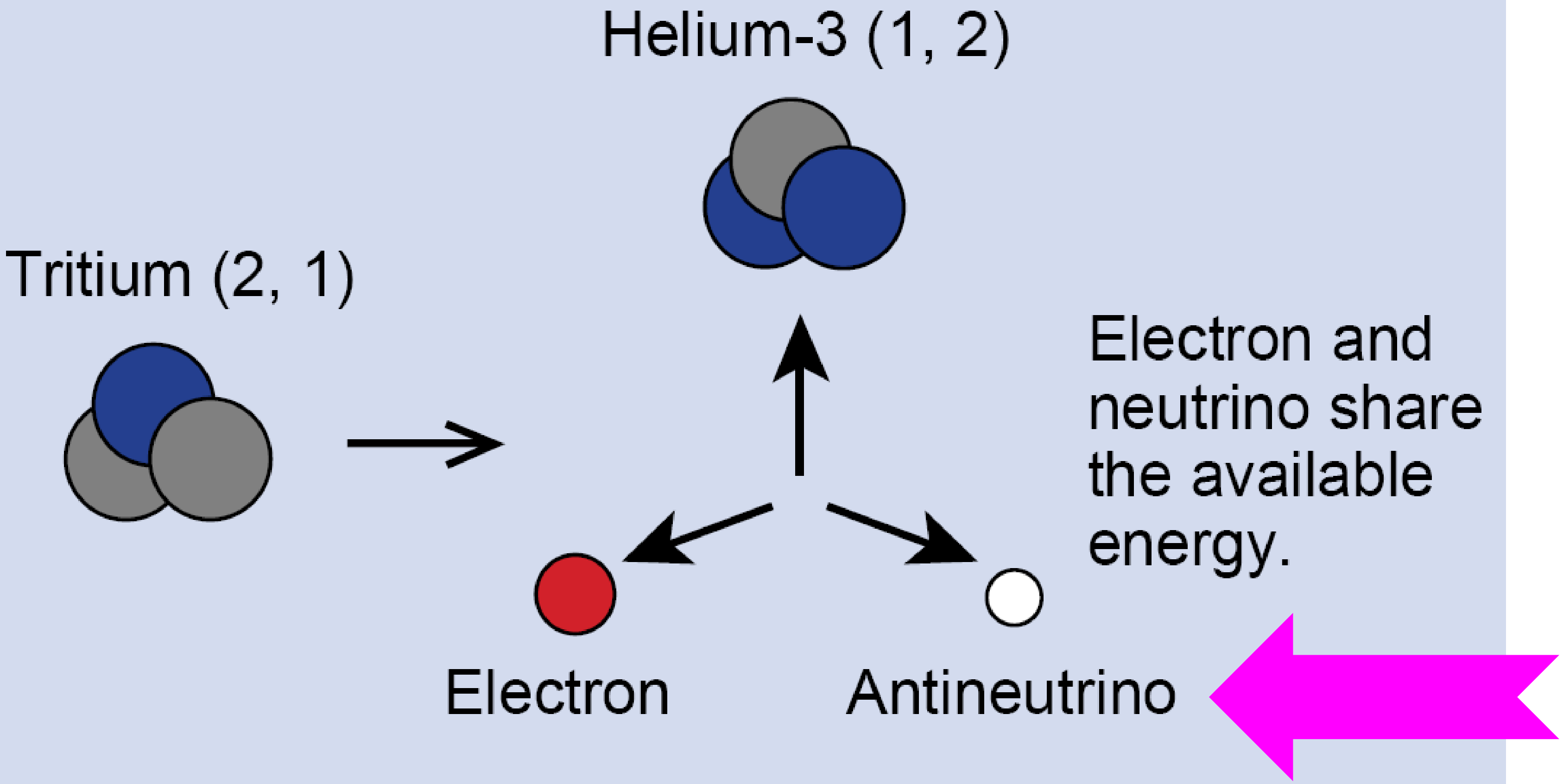
But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right.—Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

Pauli's picture of β decay

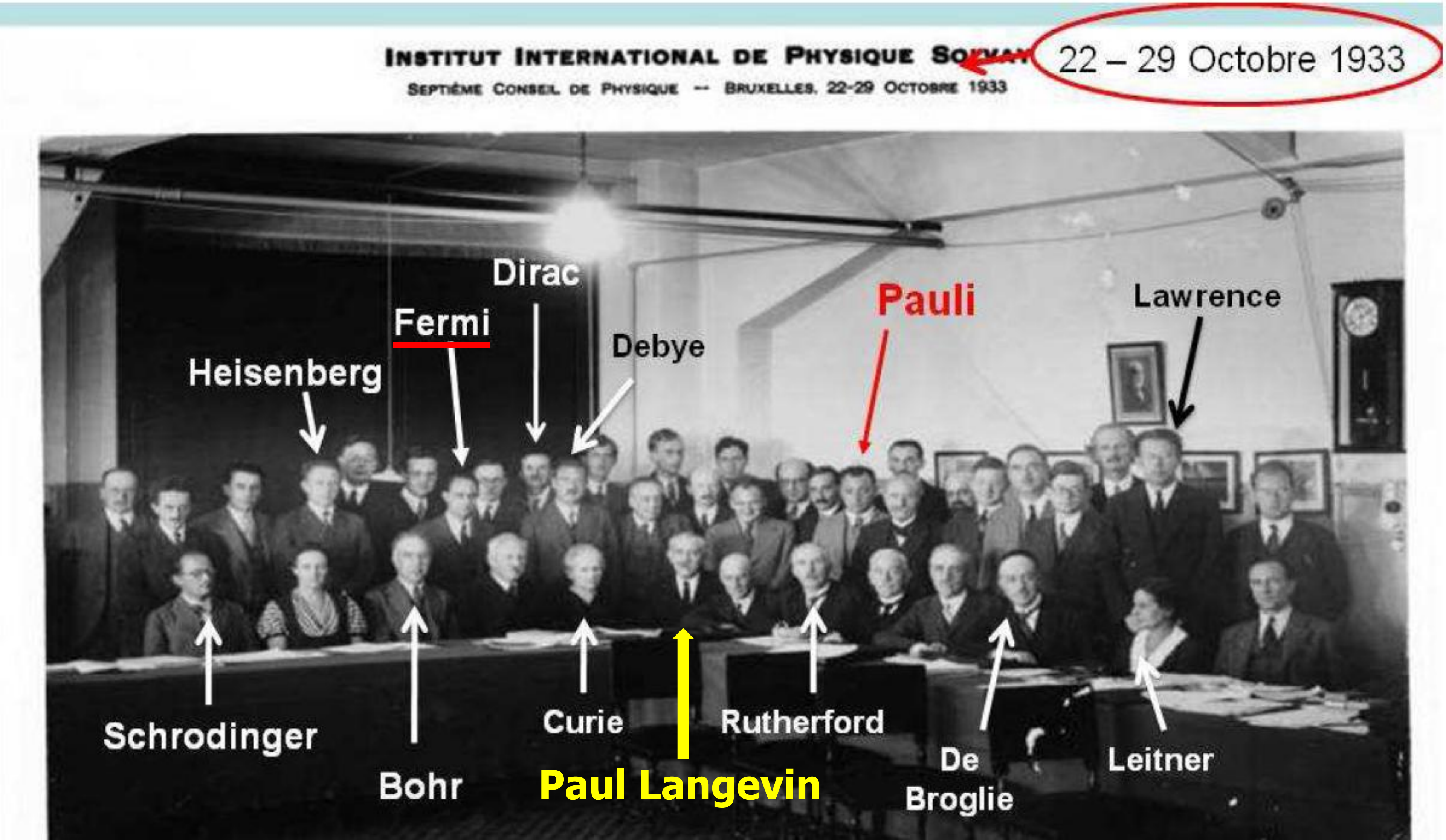
Three-Body Final State



$$(N, Z) \longrightarrow (N-1, Z+1) + e^- + \bar{\nu} \quad .$$

Solvay 1933

Pauli gave a talk on his neutrino proposal in this congress.



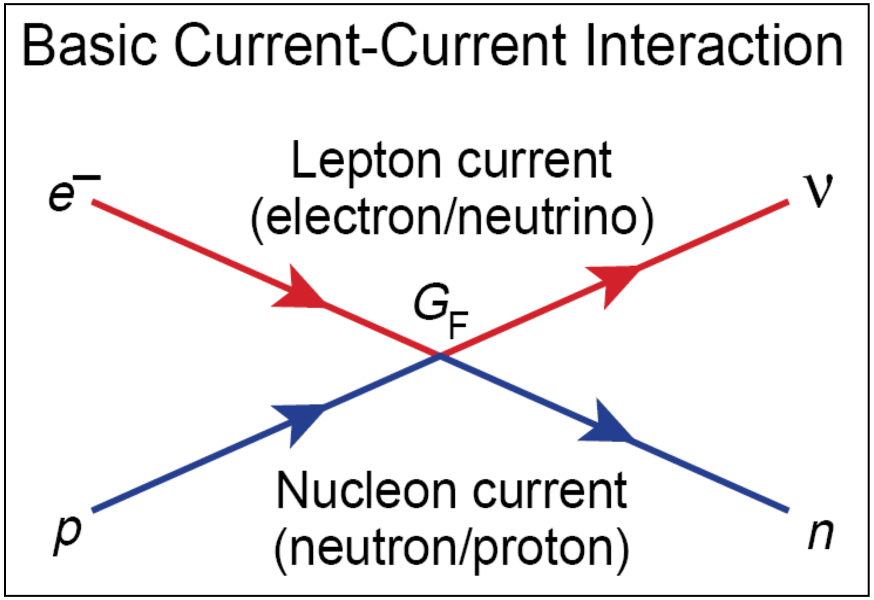
Fermi's theory

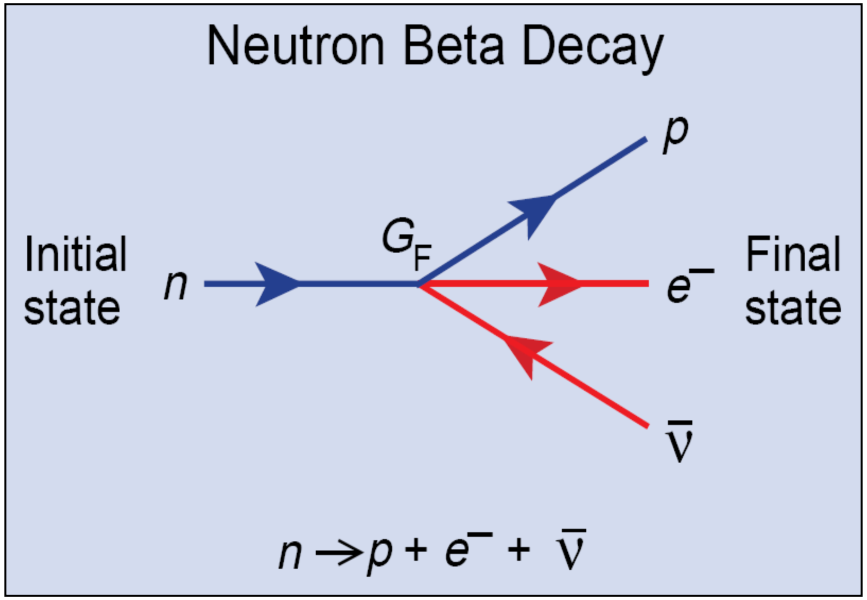
Enrico Fermi assumed a new force for β decay by combining 3 brand-new concepts:

★ **Pauli's hypothesis: neutrinos**

★ **Dirac's thought: creation of particles**

★ **Heisenberg's idea: neutron is related to proton**





Fermi’s paper

E. Fermi's publications on the Weak Interaction

REJECTED

E. Fermi, “Tentative Theory of Beta Rays”
Letter Submitted to Nature (1933)

31 Dec, 1933


ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL' ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi “beta”

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

This is Fermi’s best theoretical work
---- C.N. Yang

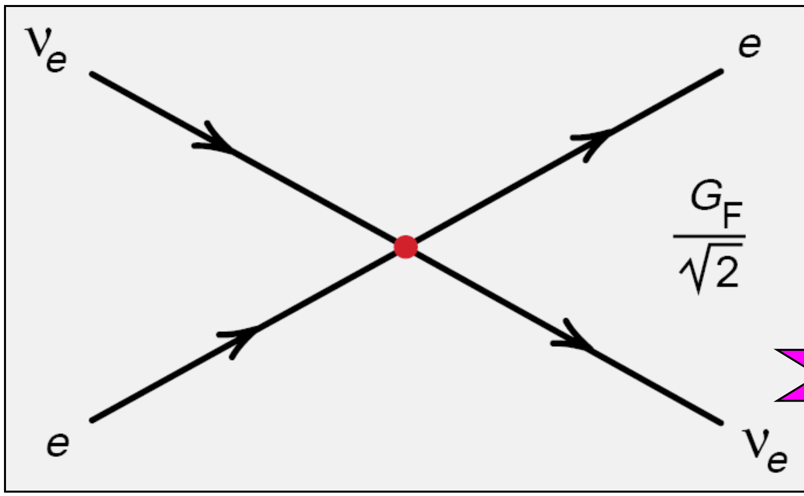
“I will be remembered for this paper!”

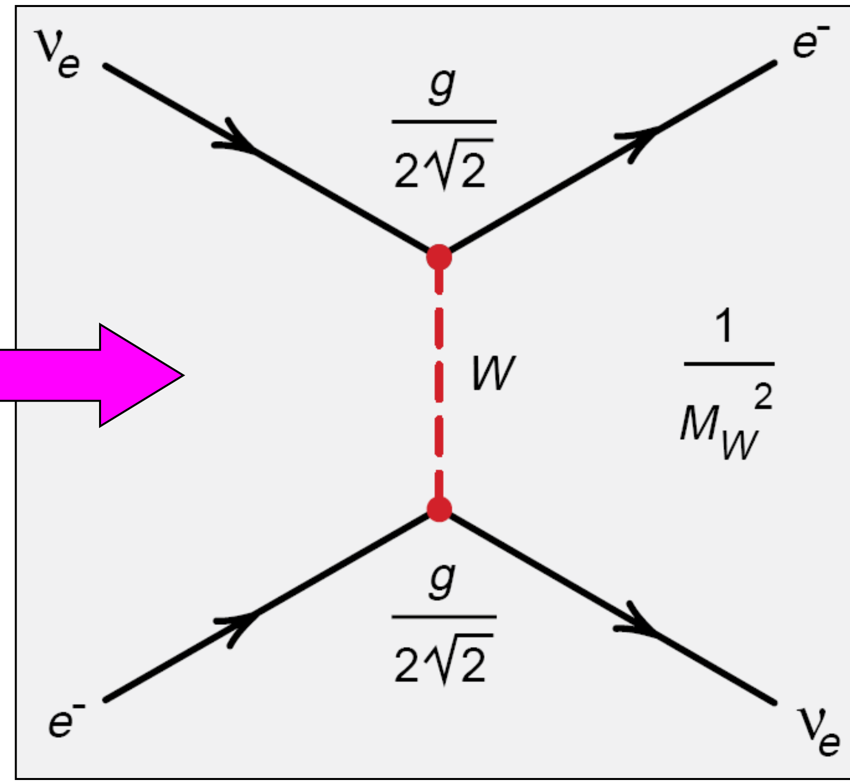
------ Fermi in Italian Alps, Christmas 1933

Published first in this journal and later in Z. Phys. in 1934.

Weak interactions

From Fermi's current-current interaction to weak charged-current gauge interactions.





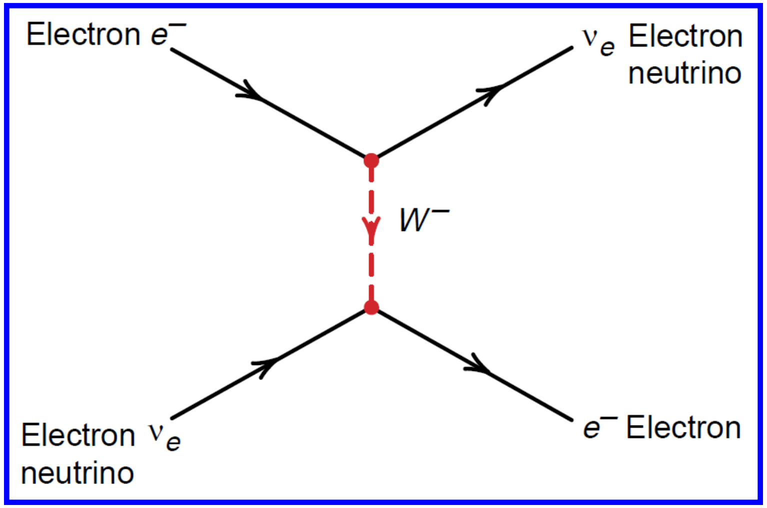
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

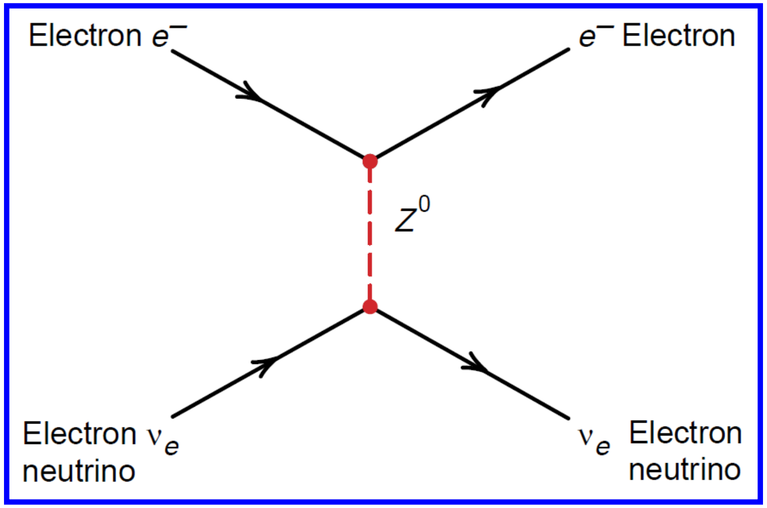
$$\boxed{M_W = 80.4\,\mathrm{GeV}}$$

$$\boxed{G_F = 1.66 \times 10^{-5}\ \mathrm{GeV}^{-2}}$$

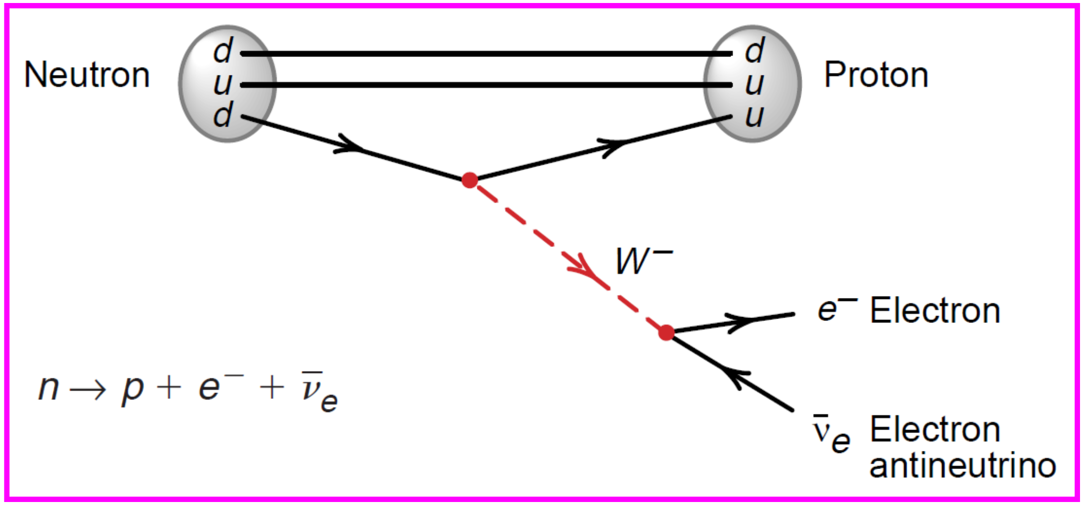
Typical processes

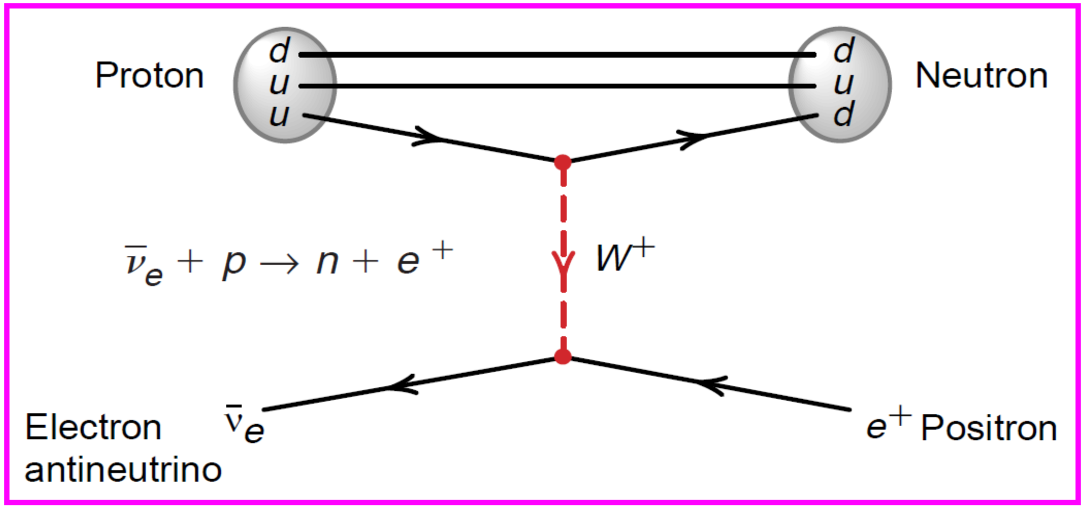
Electron-neutrino scattering





Neutron β decay / inverse β decay

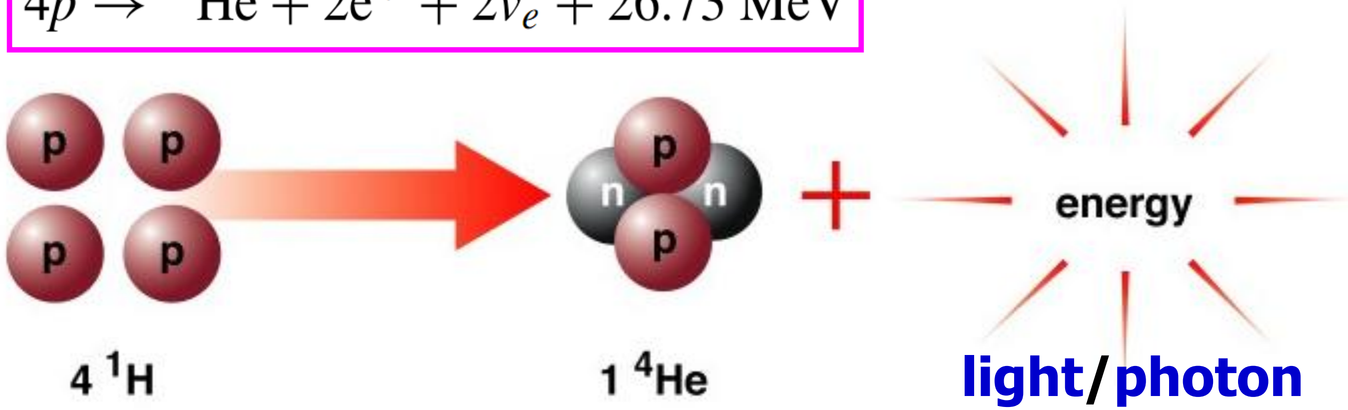




Exercise: **draw an electron-antineutrino scattering Feynman diagram.**

Why the sun shines?

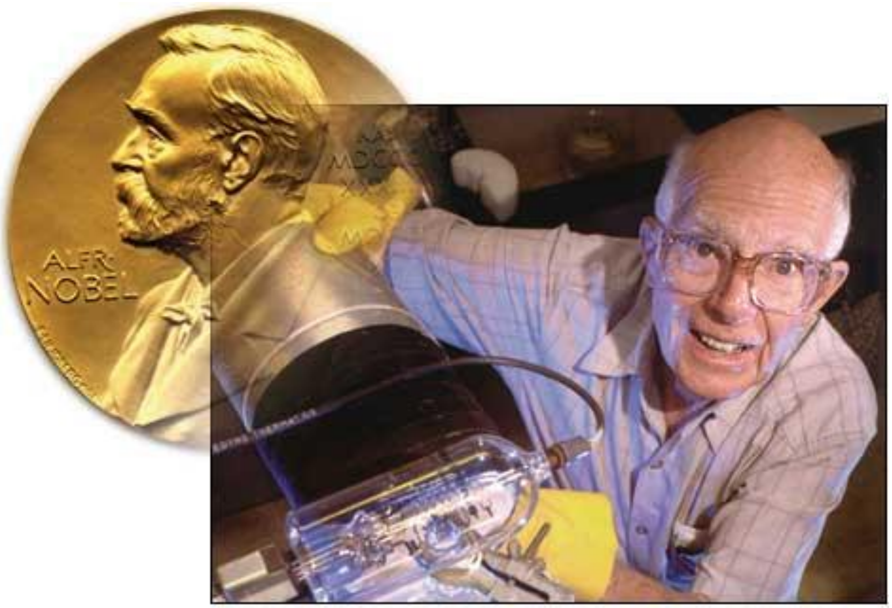
$$4p \rightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_e + 26.73\ \mathrm{MeV}$$



$+ 2e^{+} + 2\nu_e$

neutrino

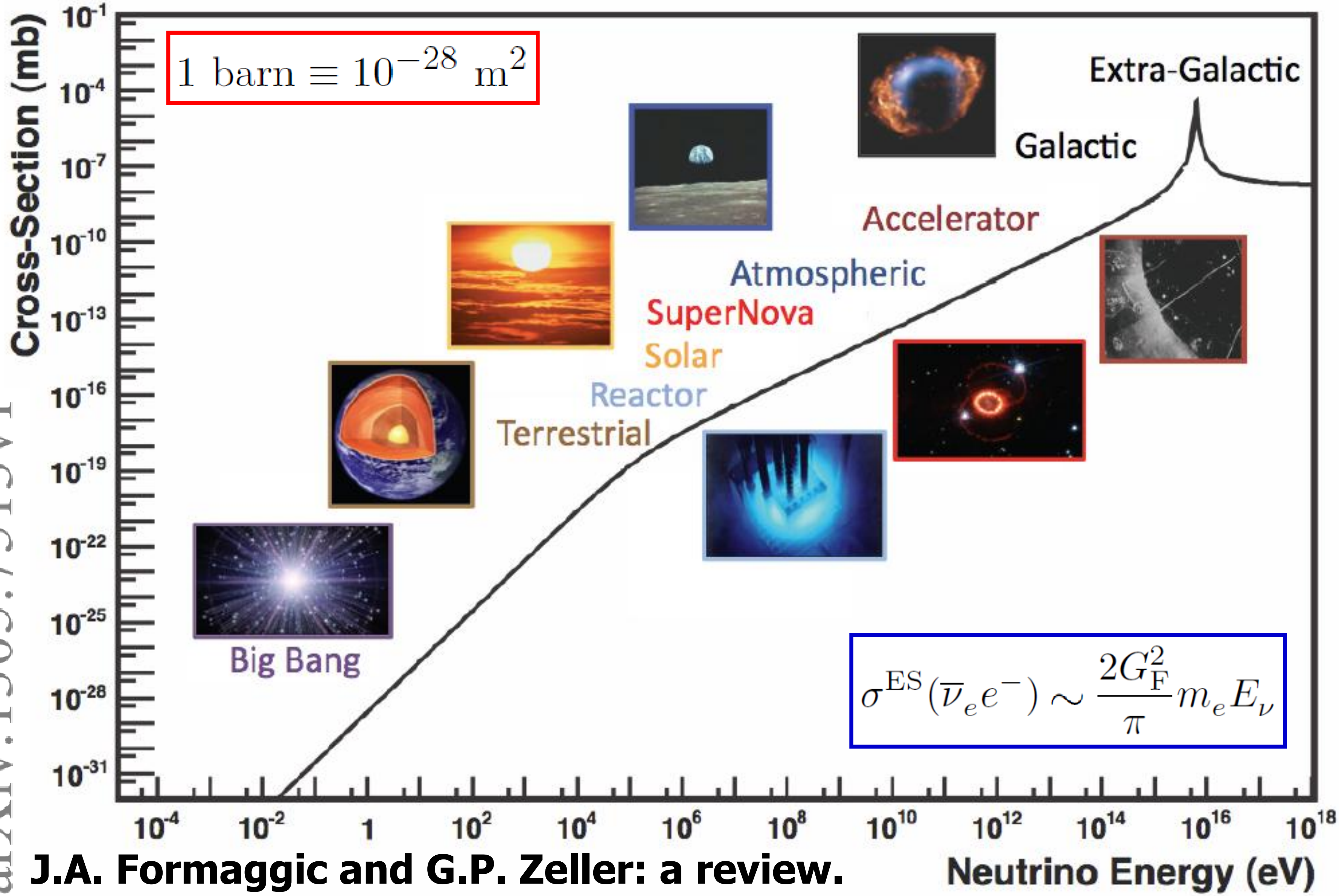
Hans Bethe (1939), George Gamow & Mario Schoenberg (1940, 1941)



Raymond Davis: born in 1914, discovery in 1968 and Nobel Prize in 2002

Observed the solar neutrino and its anomaly in 1968

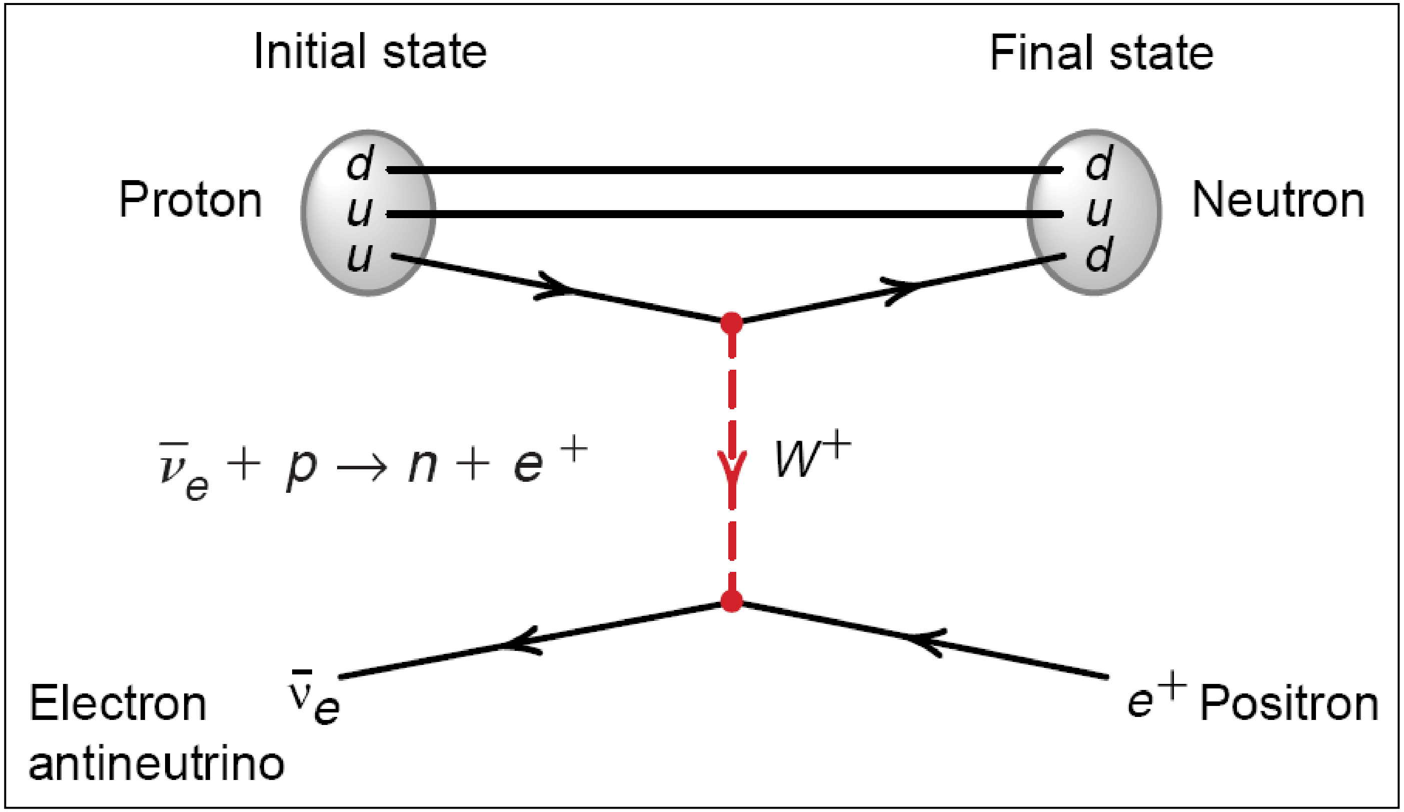
Too shy to be seen?

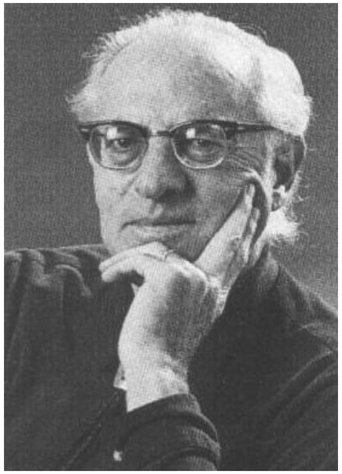


J.A. Formaggic and G.P. Zeller: a review.

Impossible challenge

An inverse β decay to detect neutrinos (Hans Bethe 1936)



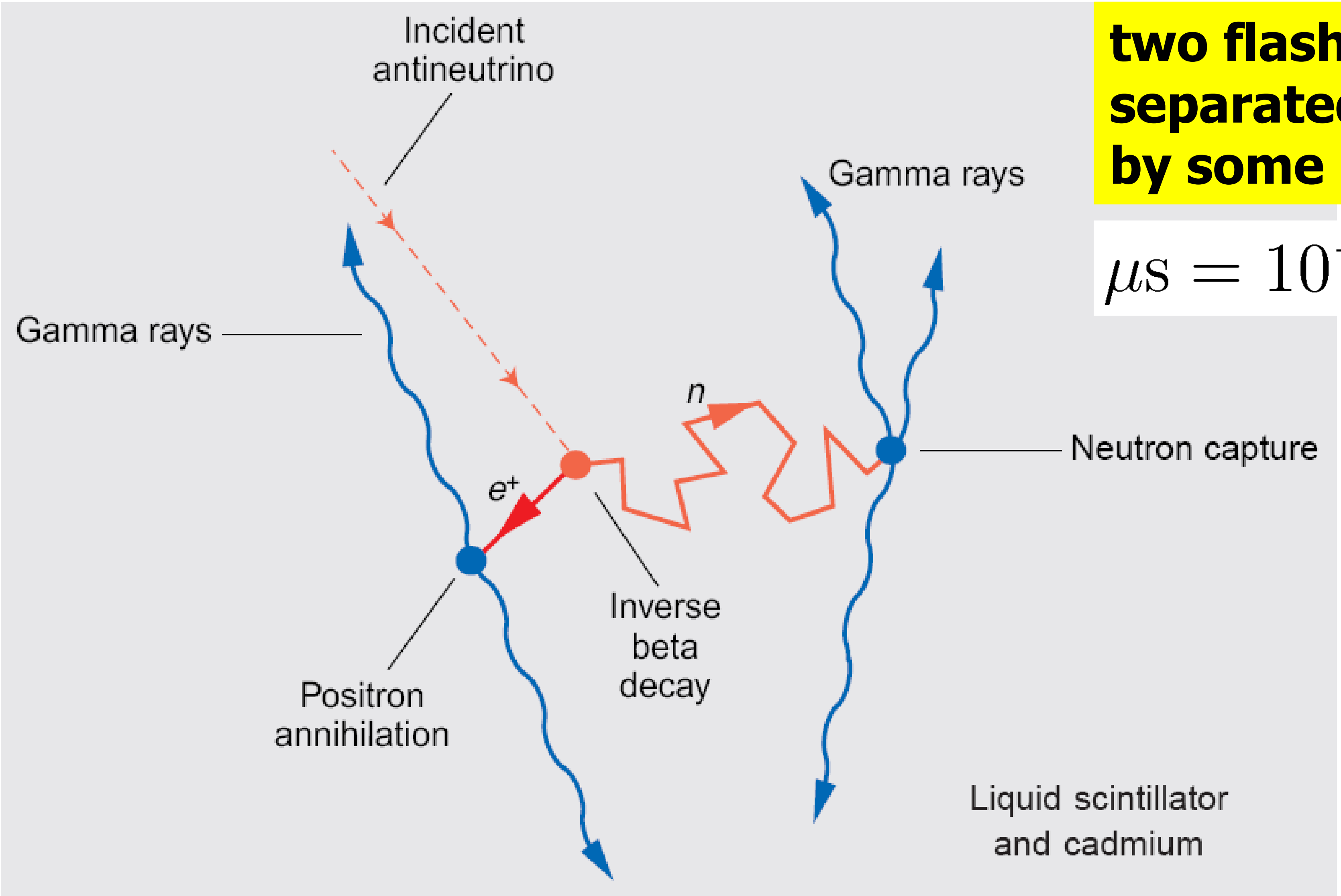


Very intense sources of neutrinos (1950's): fission bombs and fission reactors.

Frederick Reines & Clyde Cowan's Project (1951).

Reactor antineutrinos

Decision in 1952: neutrinos from a fission reactor.



two flashes separated by some μs

$$\mu s = 10^{-6}s$$

Positive result?

Reines and Cowan's telegram to Pauli on 14/06/1956:

We're happy to inform you that we've definitely detected neutrinos from fission fragments by observing inverse β decay of protons. Observed cross section agrees well with expected $\underline{6\times 10^{-44}\,\mathrm{cm}^2}$. **(Pauli didn't reply, a case of champagne)**

Such a theoretical value was based on a parity-conserving formulation of the β decay with 4 independent degrees of freedom for ν's.

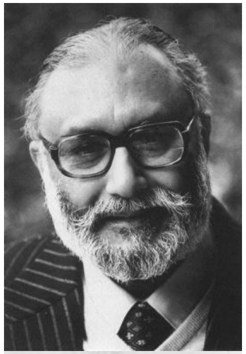
$$\boxed{\sigma(\overline{\nu}_e p) = \sigma(\nu_e n) \approx 9.1\times 10^{-44}\left(\frac{E_\nu}{\mathrm{MeV}}\right)^2\ \mathrm{cm}^2}$$

This value is at least doubled after the discovery of parity violation in 1957, leading to the two-component neutrino theory in 1957 and the V–A weak theory in 1958.

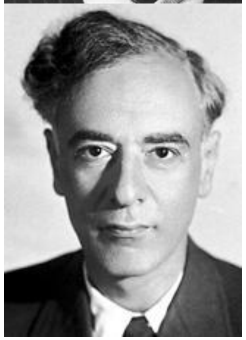
Neutrinos in 1957

The neutrino should have no mass: 2-component ν theory

★ **Abdus Salam**
received 15/11/1956,
Nuovo Cim. 5 (1957) 299



★ **Lev Landau**
received 9/1/1957,
Nucl. Phys. 3 (1957) 127



★ **T.D. Lee, C.N. Yang**
received 10/1/1957,
Phys. Rev. 105 (1957) 1671

John Ward wrote to **Salam**:
So many congratulations and fond hopes for at least one-third of a Nobel Prize.

——— **Norman Bombey** in "Abdus Salam: How to Win the Nobel Prize", Preprint arXiv:1109.1972 (9/2011).

Bruno Pontecorvo challenged the massless ν theory in 1957

Nobel Prize

A new paper on this experiment published in Phys. Rev. in 1960 reported a cross section twice as large as that given in 1956.

Reines (1979): our initial analysis grossly overestimated the detection efficiency with the result that the measured cross section was at first thought to be in good agreement with [the pre-parity violation] prediction.

Skepticism

{over 39 years}

The Nobel Prize finally came to Frederick Reines in 1995!

Pontecorvo's idea

★ Theory of the Symmetry of Electrons and Positrons

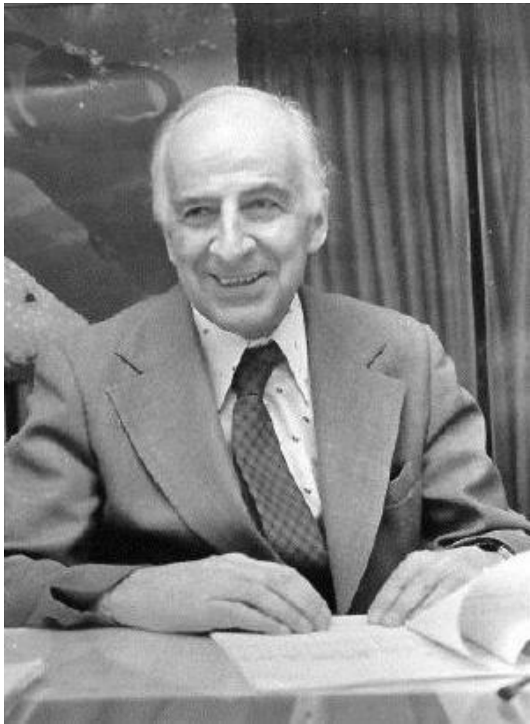
Ettore Majorana

Nuovo Cim. 14 (1937) 171

Are massive neutrinos and antineutrinos identical or different —— a fundamental puzzling question in particle physics.

★ Mesonium and Anti-mesonium

Bruno Pontecorvo

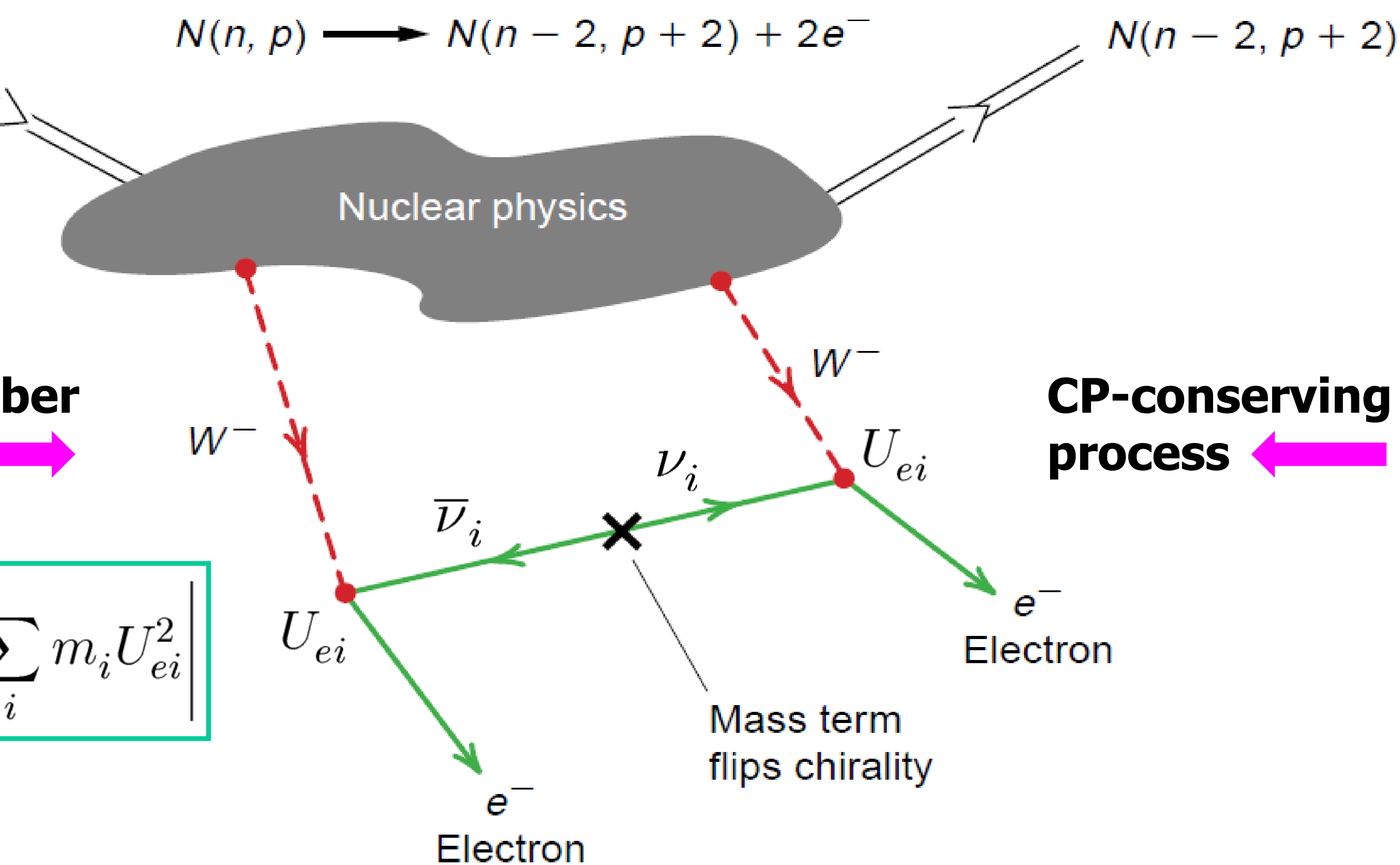


Zh. Eksp. Teor. Fiz. 33 (1957) 549
Sov. Phys. JETP 6 (1957) 429

If the two-component neutrino theory turned out to be incorrect and if the conservation law of neutrino charge didn't apply, then neutrino-antineutrino transitions would in principle be possible to take place in vacuum.

0νββ

The neutrinoless double beta decay can happen if massive neutrinos are the Majorana particles:



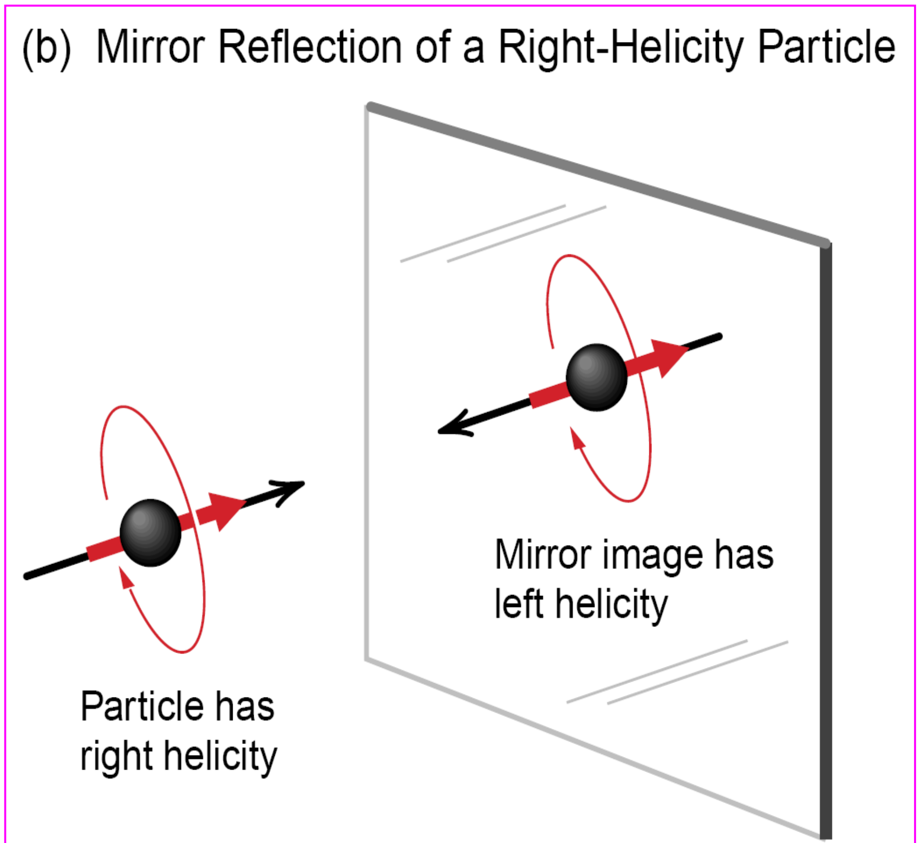
Lepton number violation ➡

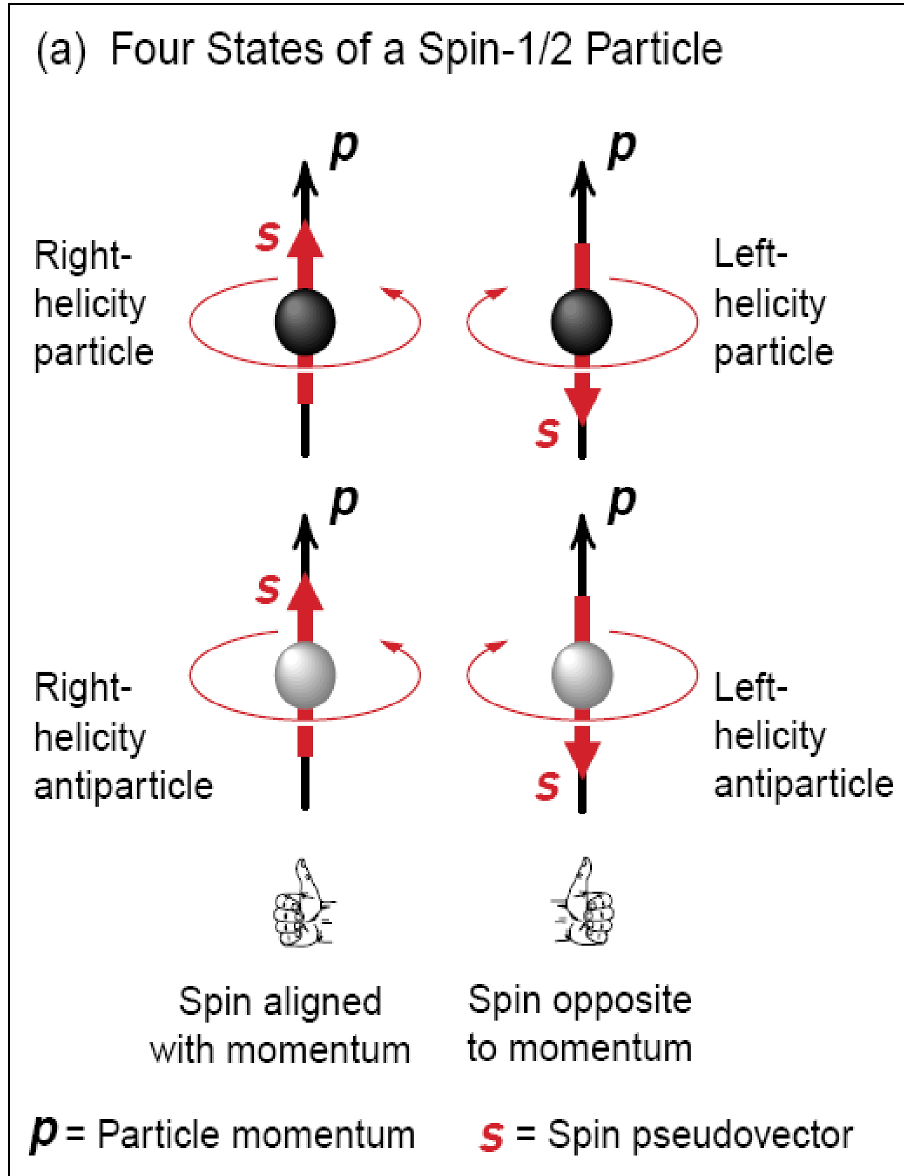
CP-conserving process ⬅

$$|\langle m \rangle_{ee}| = \left| \sum_i m_i U_{ei}^2 \right|$$

Parity and Helicity

Parity and Helicity: if parity were conserved, a spin-1/2 particle would exist in both left- & right-helicity states.



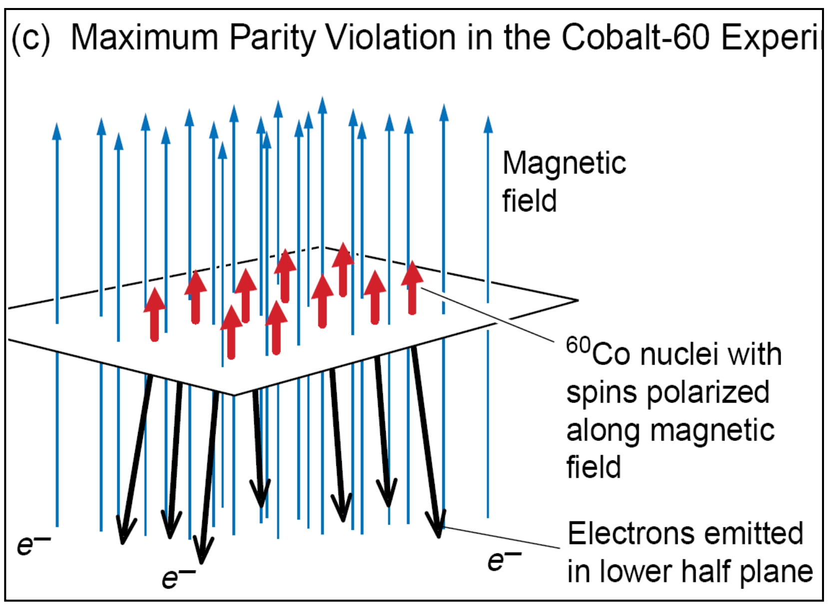


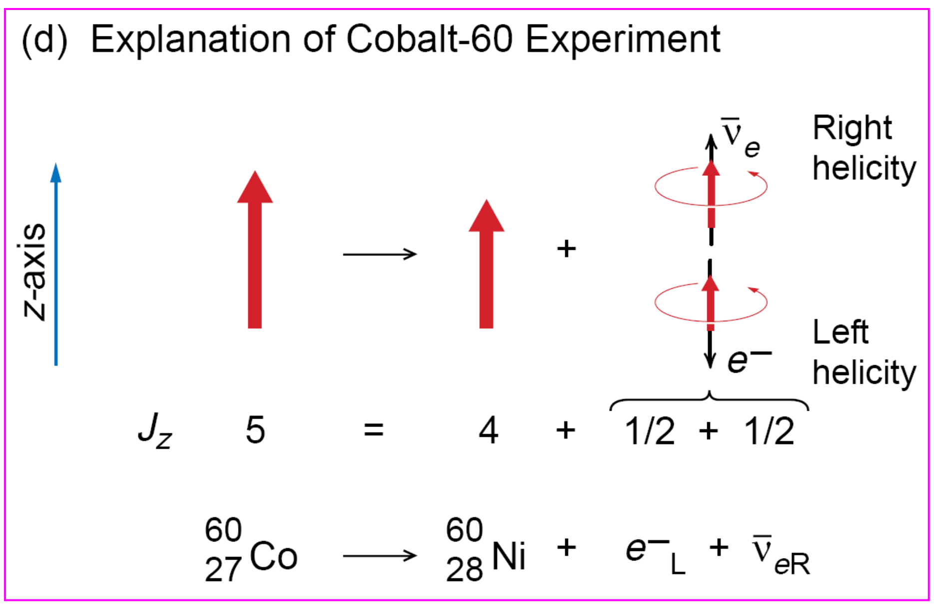
Wu's Experiment

C.S. Wu aligned the spins of Cobalt-60 nuclei along an external magnetic field and then measured the directions of the electrons emitted by those nuclei. She observed maximal parity violation!

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

Lee & Yang's two-component neutrino theory explained the data but implied: neutrinos are left-handed & massless!





在1957年1月4日的星期五午餐会上，李政道向他的同事们透露了这一令人振奋的实验结果。莱德曼（Leon Lederman）意识到问题的重要性，当晚就打电话给他的合作者加尔文（Richard Garwin），建议利用哥伦比亚大学的回旋加速器所产生的极化μ子做实验，从另一种途径检验弱相互作用中的宇称不守恒。他们连夜行动起来，四天之内就得到了可靠的实验数据，并写出了论文的初稿。李政道得知这一消息后，劝阻莱德曼等人不要马上投稿，否则对吴健雄的团队来说是不公平的，因为后者已经辛苦地工作了好几个月，而且率先得到了实验证据。1月15日，哥伦比亚大学举行了记者招待会，吴健雄和莱德曼两个团队分别报告了他们的重大科学发现：宇称在弱相互作用中的确是不守恒的！他们在记者招待会的当天将各自的论文投到了《物理评论》（Physical Review）。半个月之后，两篇论文并列发表出来；同一年的年底，李政道和杨振宁荣获了诺贝尔物理学奖。

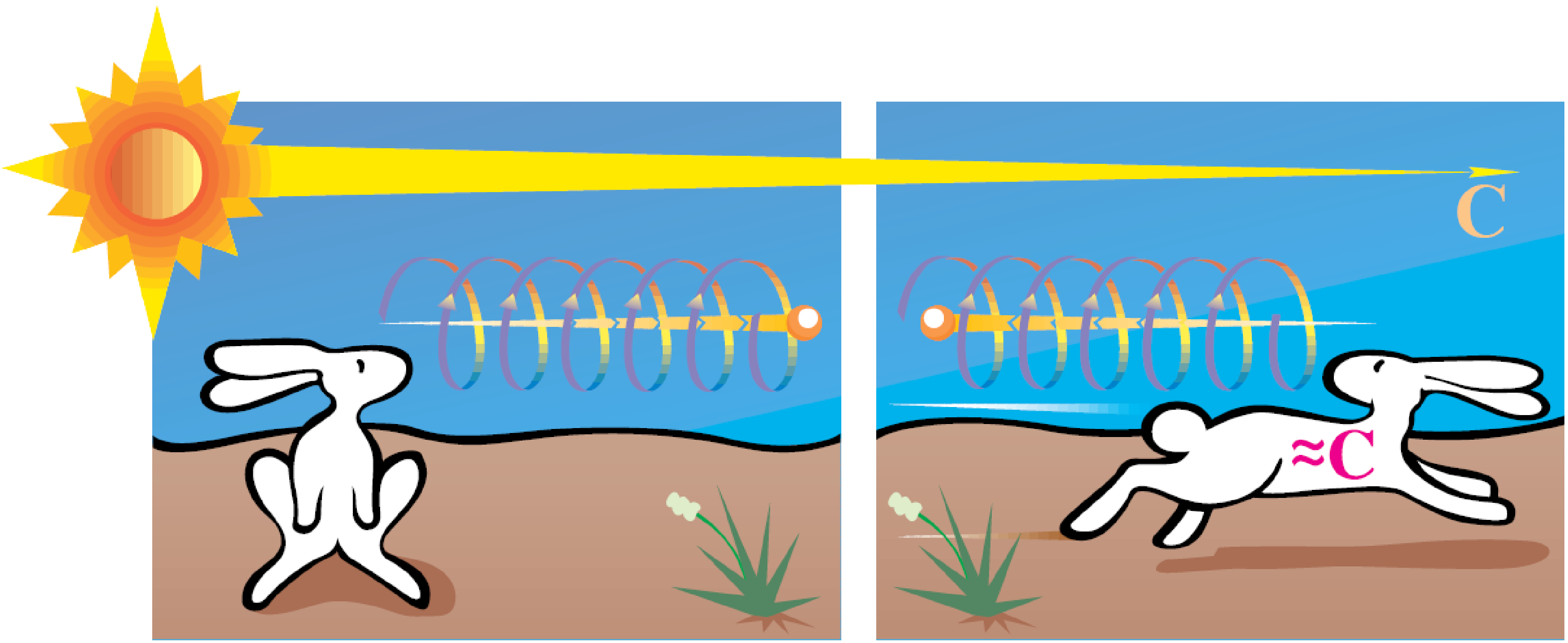
论文比肩的背后？

Helicity

The Helicity of a fermion relates its spin to its direction of motion

$$\lambda = \boldsymbol{s} \cdot \boldsymbol{p}/|\boldsymbol{p}| = \pm 1/2$$

A massive particle's helicity isn't relativistically invariant.



Looks like a left-handed corkscrew. No—like a right-handed corkscrew!

Left-handed

A proof of the **negative helicity** **of a neutrino was done in 1958.**

$$\boxed{{}^{152}_{63}Eu(0^-) + e^- \rightarrow {}^{152}_{62}Sm^*(1^-) + \nu}$$

$$\lambda = \boldsymbol{s} \cdot \boldsymbol{p} / |\boldsymbol{p}| = \pm 1/2$$

In this reaction, the *Sm nucleus recoils from the neutrino. It decays into the ground state simply by emitting a γ particle. Then the polarization of this γ particle measures the neutrino's helicity in a rather non-trivial way.**

$$\boxed{\lambda = -1/2}$$

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$ (negative helicity).

Handedness

The Handedness of a spin-1/2 particle is a relativistically invariant quantity to describe this particle's spin states.

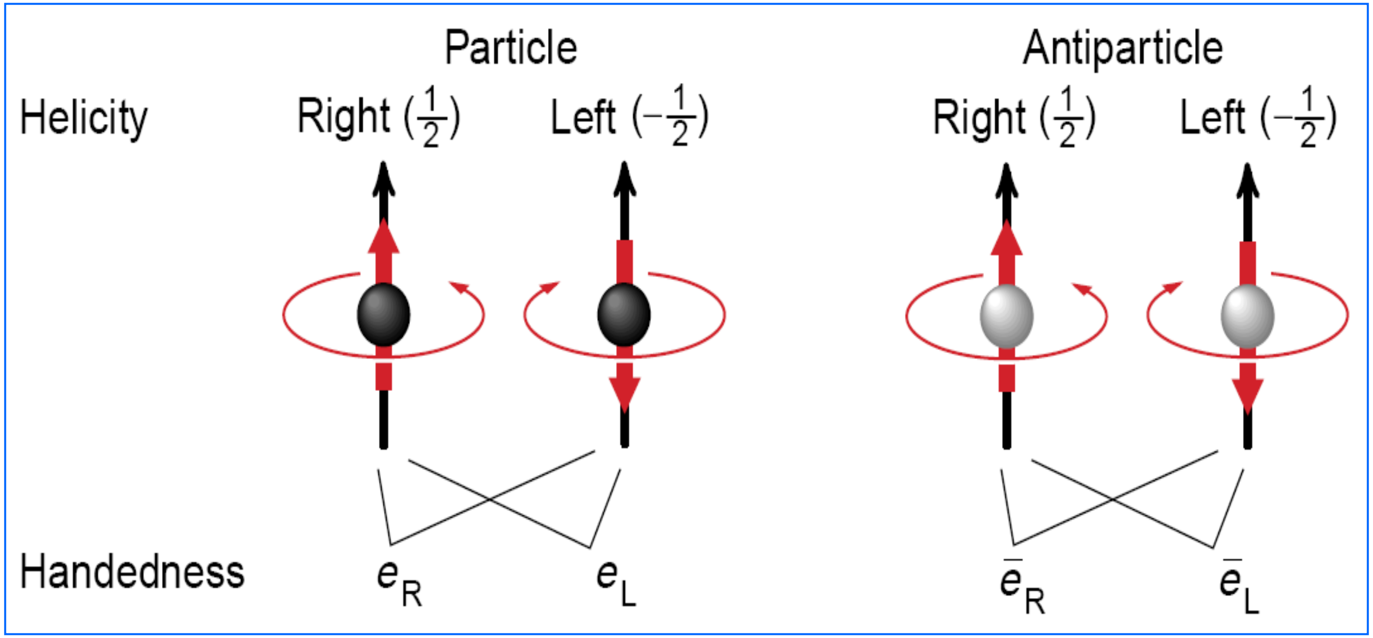
2 independent handedness or chirality states: left & right.

A massless or massive particle can always be decomposed into two independent components: left- and right-handed.

$$\psi = \psi_{\mathrm{L}} + \psi_{\mathrm{R}}$$

$$\psi_{\mathrm{L}} = \frac{1+\gamma_5}{2}\psi$$

$$\psi_{\mathrm{R}} = \frac{1-\gamma_5}{2}\psi$$

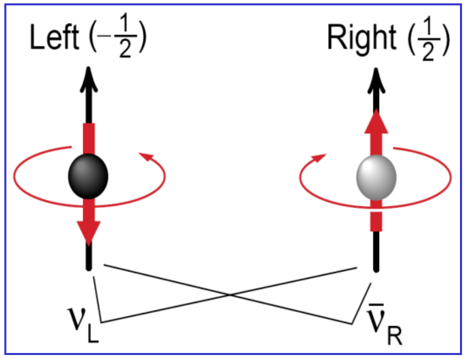


Weak states

The Handedness is an essential quantity for describing the weak force (see the table for the 1st-family in the SM).

For example:

The right-handed electron is a weak isospin singlet: it does not interact with the W boson, but it does couple to the photon and to the Z boson.

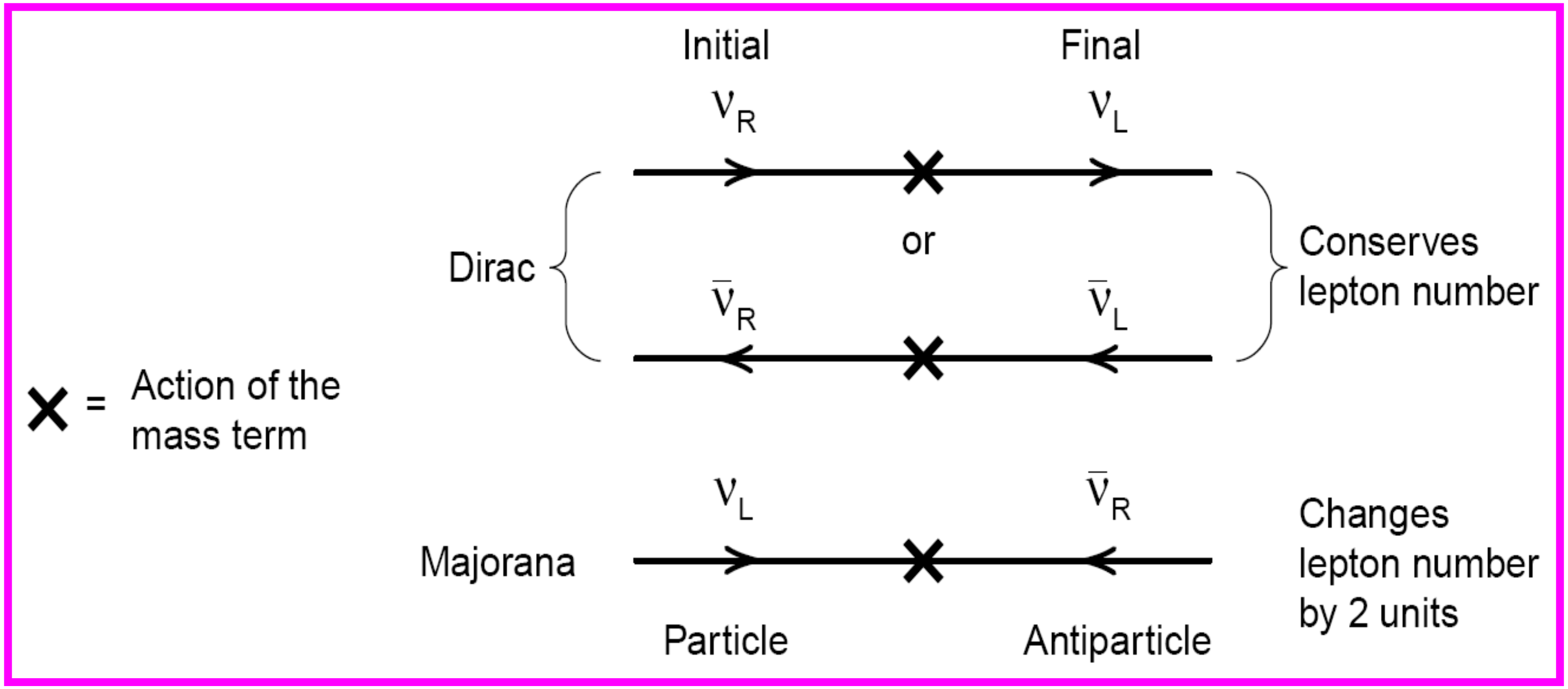


Particle Number N	Handedness N_x	Particle States	Weak Isotopic Charge I_3^W	Weak Hypercharge Y^W	Electric Charge Q
+1	L	e_L	−1/2	−1	−1
+1	L	ν_L	+1/2	−1	0
−1	R	$\bar{e}_R$	+1/2	+1	+1
−1	R	$\bar{\nu}_R$	−1/2	+1	0
+1	R	e_R	0	−2	−1
−1	L	$\bar{e}_L$	0	+2	+1
+1	R	ν_R			
−1	L	$\bar{\nu}_L$			

absent in SM

Mass terms

The Handedness is also a crucial concept for the origin of particle masses. Any interaction giving a spin-1/2 particle a nonzero mass must flip its left- and right-handed states.



$$\left|e_{\mathrm{L}}\right\rangle \propto \left|e_{-1/2}\right\rangle + m/E\left|e_{+1/2}\right\rangle$$
$$\left|e_{\mathrm{R}}\right\rangle \propto \left|e_{+1/2}\right\rangle - m/E\left|e_{-1/2}\right\rangle$$

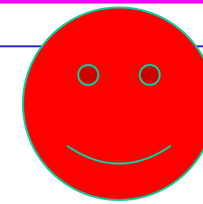
2 handed states in terms of 2 helicity states: if m = 0, handedness = helicity; if m << E, it holds approximately (in a relativistic limit).

Helicity + Handedness

Exercise: which decay mode is more likely?

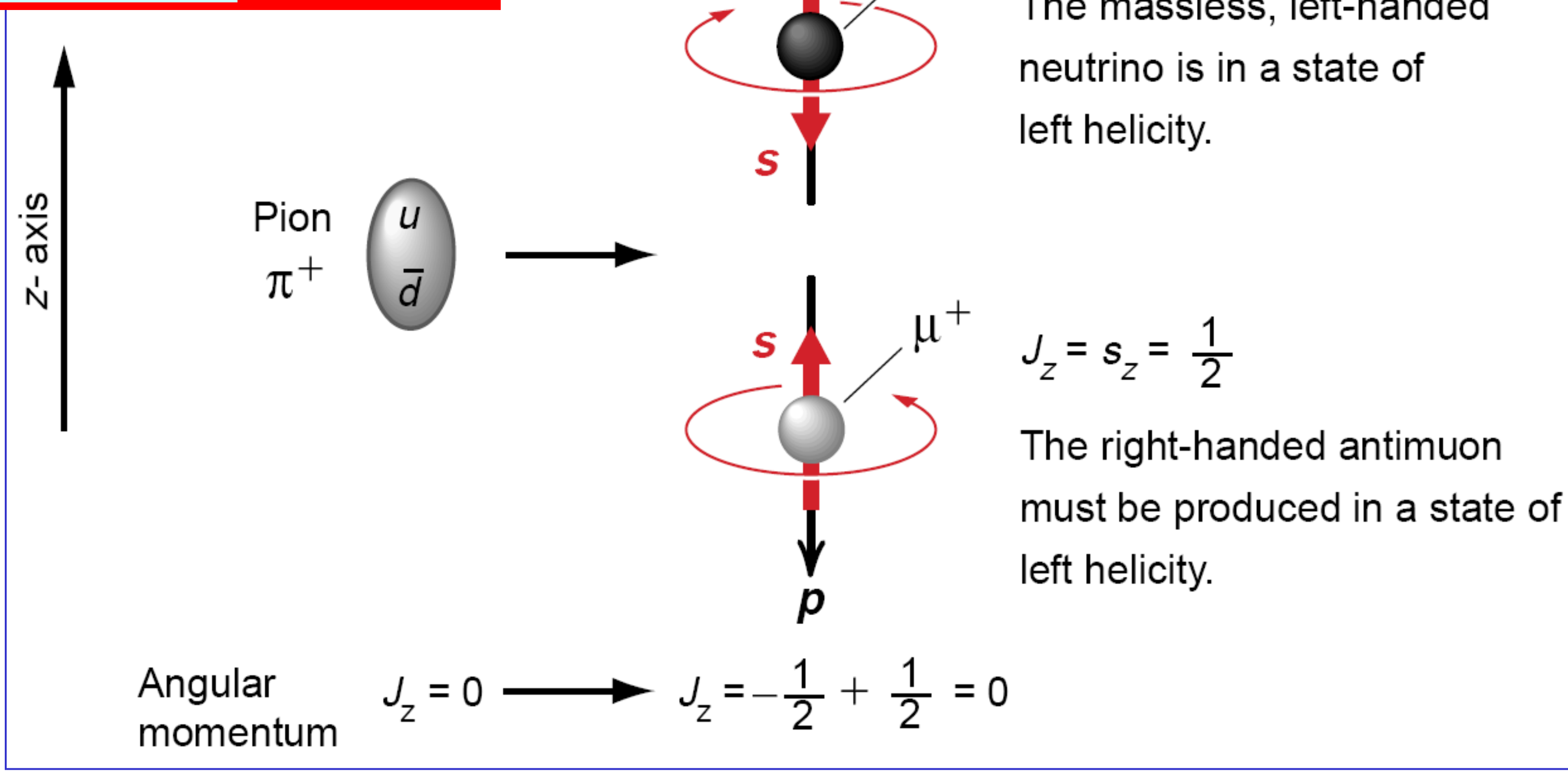
$$\pi^+ \to e^+ + \nu_e$$

$$\pi^+ \to \mu^+ + \nu_\mu$$



$$\left|\mu_{\mathrm{L}}^+\right\rangle \propto \left|\mu_{-1/2}^+\right\rangle + m/E\left|\mu_{+1/2}^+\right\rangle$$

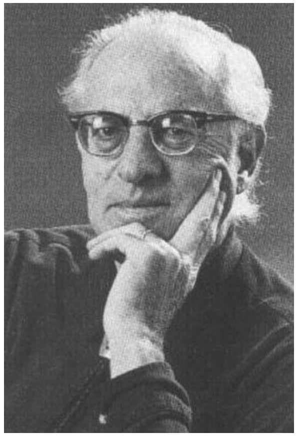
$$\left|\mu_{\mathrm{R}}^+\right\rangle \propto \left|\mu_{+1/2}^+\right\rangle - m/E\left|\mu_{-1/2}^+\right\rangle$$



Electron and its neutrino

The electron was discovered in 1897 by Joseph Thomson.

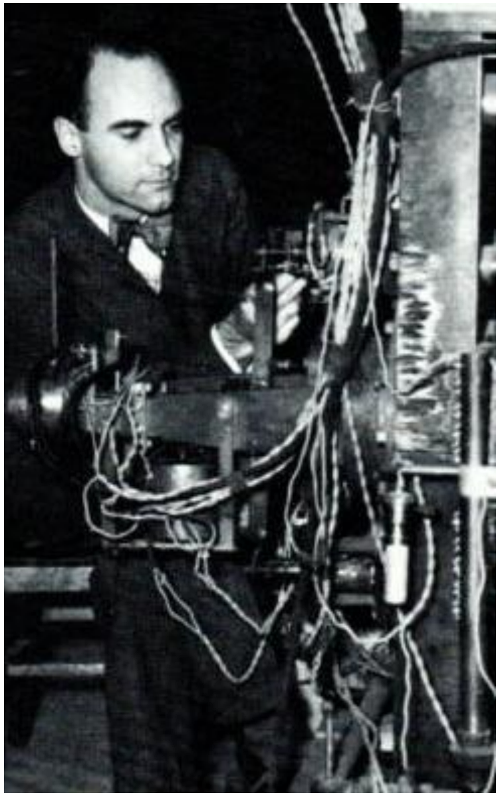
The electron's anti-particle, positron, was predicted by Paul Dirac in 1928, and discovered by Carl Anderson in 1932.



In 1956 Clyde Cowan and Frederick Reines discovered the positron's partner, electron antineutrino.

Muon

The muon particle, a sister of the electron, was discovered in 1936 by Carl Anderson and his first student S. Neddermeyer; and independently by J. Street *et al*.



It was not Hideki Yukawa's "pion". And it was the first flavor puzzle.

Isidor Rabi famously asked:

Who ordered that?

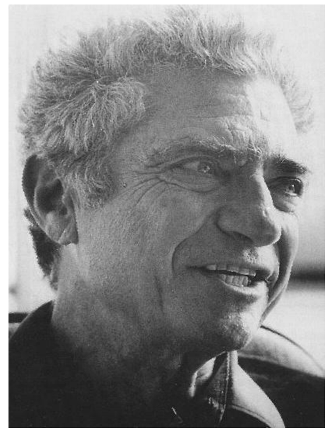
Isidor Isaac Rabi

FAMILY

Muon neutrino

The muon neutrino was discovered by Leon Lederman, Melvin Schwartz and Jack Steinberger in 1962.

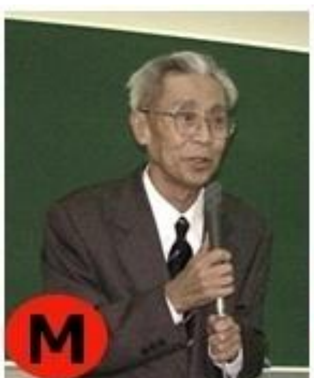


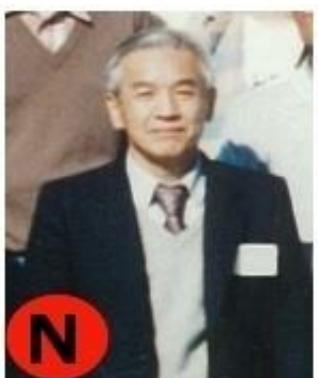



Lee and Yang

Neutrino conversion proposed by Z. Maki, M. Nakagawa and S. Sakata in 1962.

Bruno Pontecorvo

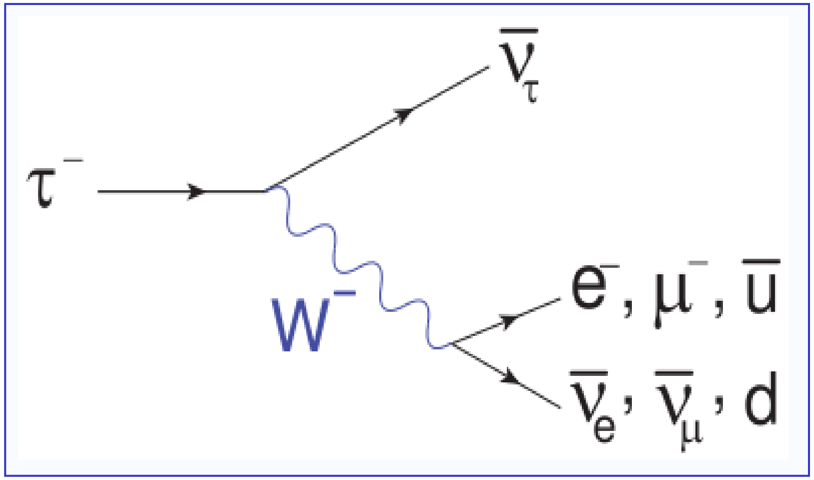


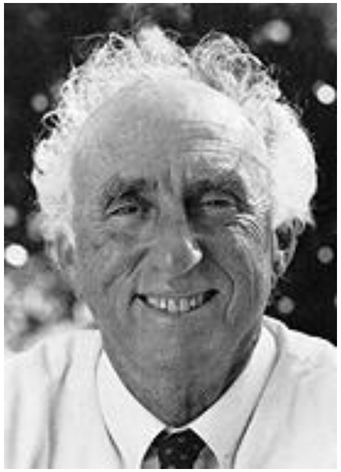


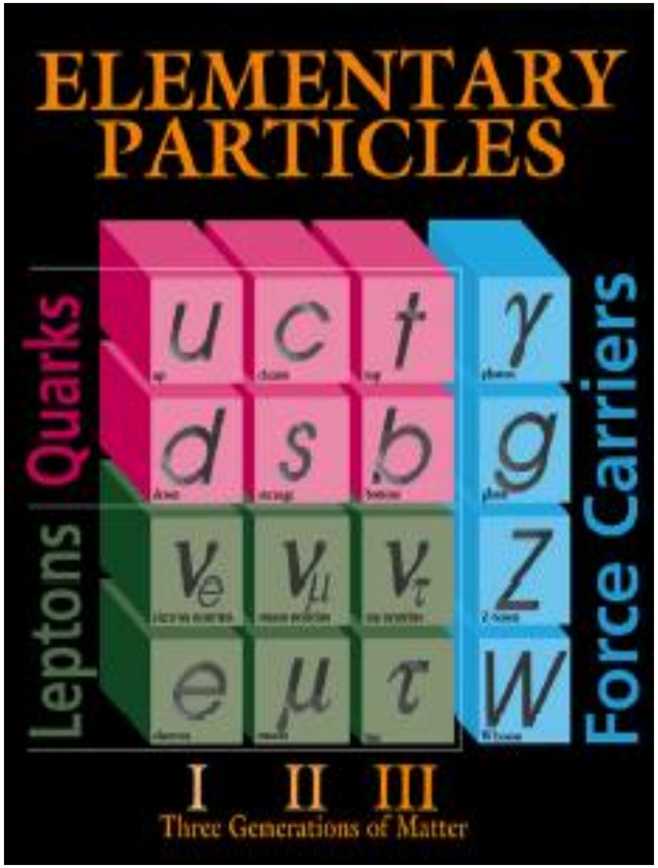

Tau and its neutrino

The tau particle was discovered by Martin Perl in 1975 via:

$$e^{+} + e^{-} \rightarrow e^{\pm} + \mu^{\mp} + \text{undetected particles}$$







In 2000, the tau neutrino was finally discovered at the Fermilab.

The lepton family is complete!

Leptonic Nobel Prizes

e	J.J. Thomson 1897	J.J. Thomson 1906 (NP)
ν_e	C.L. Cowan et al. 1956	F.J. Reines 1995 (NP)
μ	J.C. Street et al. C.D. Anderson 1936	1975 – 1936 = 1936 – 1897 = 39
ν_μ	G. Danby et al. 1962	M. Schwartz, L.M. Lederman, J. Steinberger 1988 (NP)
τ	M.L. Perl et al. 1975	M.L. Perl 1995 (NP)
ν_τ	K. Kodama et al. 2000	

Antimatter: Positron.
Predicted by P.A.M. Dirac in 1928.
Discovered by C.D. Anderson in 1932; Nobel Prize in 1936.

Sarma-Xing Theorem

In 1995 it was an Indian theorist who first discovered the 39-year gap of charged leptons.

2) **NOBEL LEPTONS.**
By K.V.L. Sarma (Tata Inst.),. TIFR-TH-95-56, Dec 1995. 13pp.
Submitted to Curr. Sci.
e-Print Archive: **hep-ph/9512420**

1975 + 39 = 2014

A summary of the discoveries made in the world of leptons is given in Table 1. We see that the third generation has started getting Nobel prizes. It is amusing that the charged-leptons crop up with a 39-year gap and may be the 4th one would show up in the year 2114. For the present, the available experimental information implies that there are no charged leptons which are heavier than tau and lighter than 45 GeV.

My contribution: corrected 2114 to 2014, so the discovery would be possible 100 years earlier (last year)!

Lepton (flavor) number

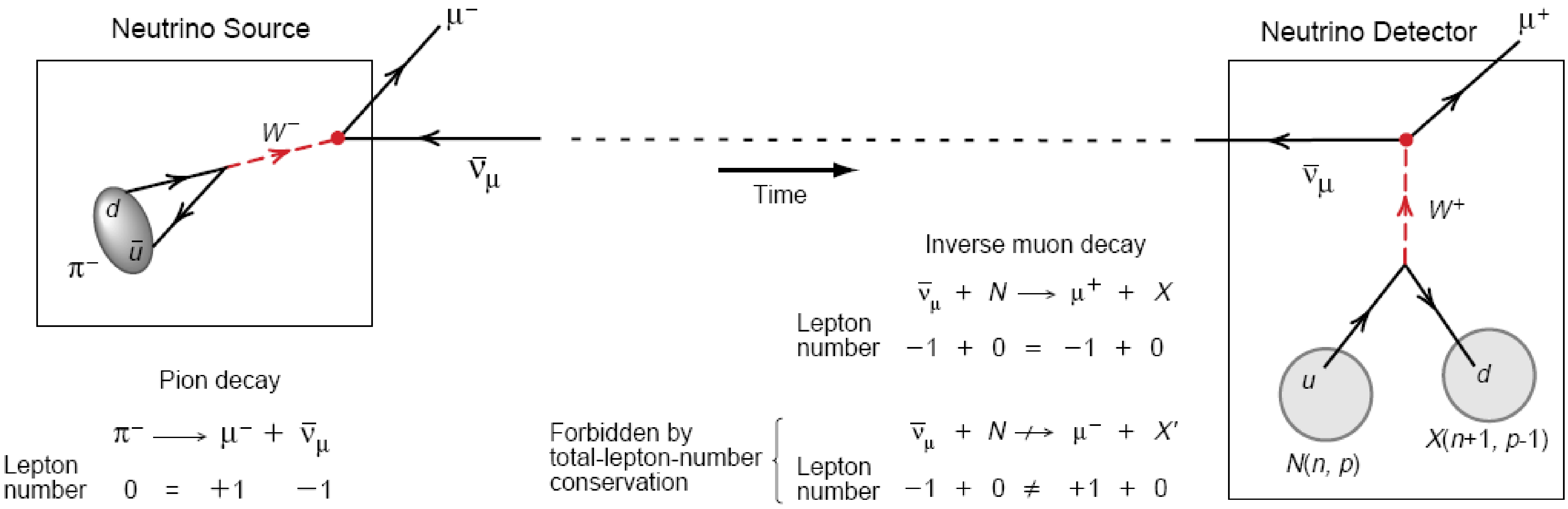
	e^-	ν_e	e^+	$\overline{\nu}_e$	μ^-	ν_μ	μ^+	$\overline{\nu}_\mu$	τ^-	ν_τ	τ^+	$\overline{\nu}_\tau$
L	$+1$	$+1$	-1	-1	$+1$	$+1$	-1	-1	$+1$	$+1$	-1	-1
L_e	$+1$	$+1$	-1	-1	0	0	0	0	0	0	0	0
L_μ	0	0	0	0	$+1$	$+1$	-1	-1	0	0	0	0
L_τ	0	0	0	0	0	0	0	0	$+1$	$+1$	-1	-1

In the SM: (a) all neutrinos are massless; (b) the left-handed neutrino and the right-handed anti-neutrino are distinct particles which cannot transmute into each other.

Law One: the total lepton number is conserved. But it will be violated if neutrinos have finite masses and are the Majorana particles.

Law Two: the individual lepton flavor number is also conserved. But it has been proved to be violated in the neutrino sector.

Examples



ALLOWED

$$\mu^+ \to e^+ + \gamma$$

$$\mu^+ \to e^+ + e^- + e^+$$

$$\mu^- + N(n, p) \to e^- + N(n, p)$$

$$\mu^- + N(n, p) \to e^+ + N(n + 2, p - 2)$$

$$\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$$

FORBIDDEN

Exercise: why they are forbidden?

Appendix: B and L

Question: **Why ordinary particle interactions, restricted by local gauge invariance + renormalizability in the SM, conserve the baryon number *B*, the total lepton number *L* and lepton flavor numbers Le, $L\mu$, $L\tau$ (i.e., global symmetries of the SM)?**

E. Witten (Neutrino 2000): "Using the fields of the SM, it is impossible at the classical level to violate the baryon and lepton number symmetries by renormalizable interactions."

G. 't Hooft (1976): Non-perturbative quantum effects can break most of the SM global symmetries, preserving only $B - L$.

Renormalizable interactions have dimensionless couplings, but unrenormalizable interactions may be suppressed by an inverse power of *M* with *M* being the scale where the SM breaks down.

$$\boxed{L_{\text{effective}} = L_{\text{SM}} + \sum_n \frac{1}{M^n} O^{4+n}}$$