Genesis of the *neutrino* concept

how the current theoretical frameworks were developed

Francesco Vissani
INFN, Laboratori Nazionali del Gran Sasso

C O N T E N T S

Why talk about it? The **original arguments** of great scientists are not always the definitive ones.

However, they have an **evocative power** that orients and prepares the subsequent discussions.

And when the original arguments are forgotten, they are replaced by **myths**, aimed at the desired end.

This creates an apparent sense of **stability**, but at the price of inhibiting critical thinking and renewal.

CHAPTER 1

Beginning of thirties: evolution of the models of the nucleus.
Meaning of Pauli's neutrino

premise: first model of the nucleus

the observation of α and β ray high energy emission suggests that these are ***nuclear fragments*** *(van den Broek 1911)*

1st stable model of the nucleus (reviewed by Rutherford 1920):

a conglomerate of electrons and protons

this ***e-p model*** *will last from the second decade of 1900 till the discovery of neutron (1932), and even a bit later*

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Many questions arise, in particular:

- the e-p model **cannot** reproduce the β ray continuous spectrum, first observed by Chadwick 1914, definitely confirmed end of 20s
- an additional **problem** emerges in 1928: the spin of ^{14}N nucleus is integer - but if it is (14*p*,7*e*) it should be semi-integer

the most popular way out from the first problem, supported by Bohr at the time, was that ***energy is violated in*** *β* ***ray emission***

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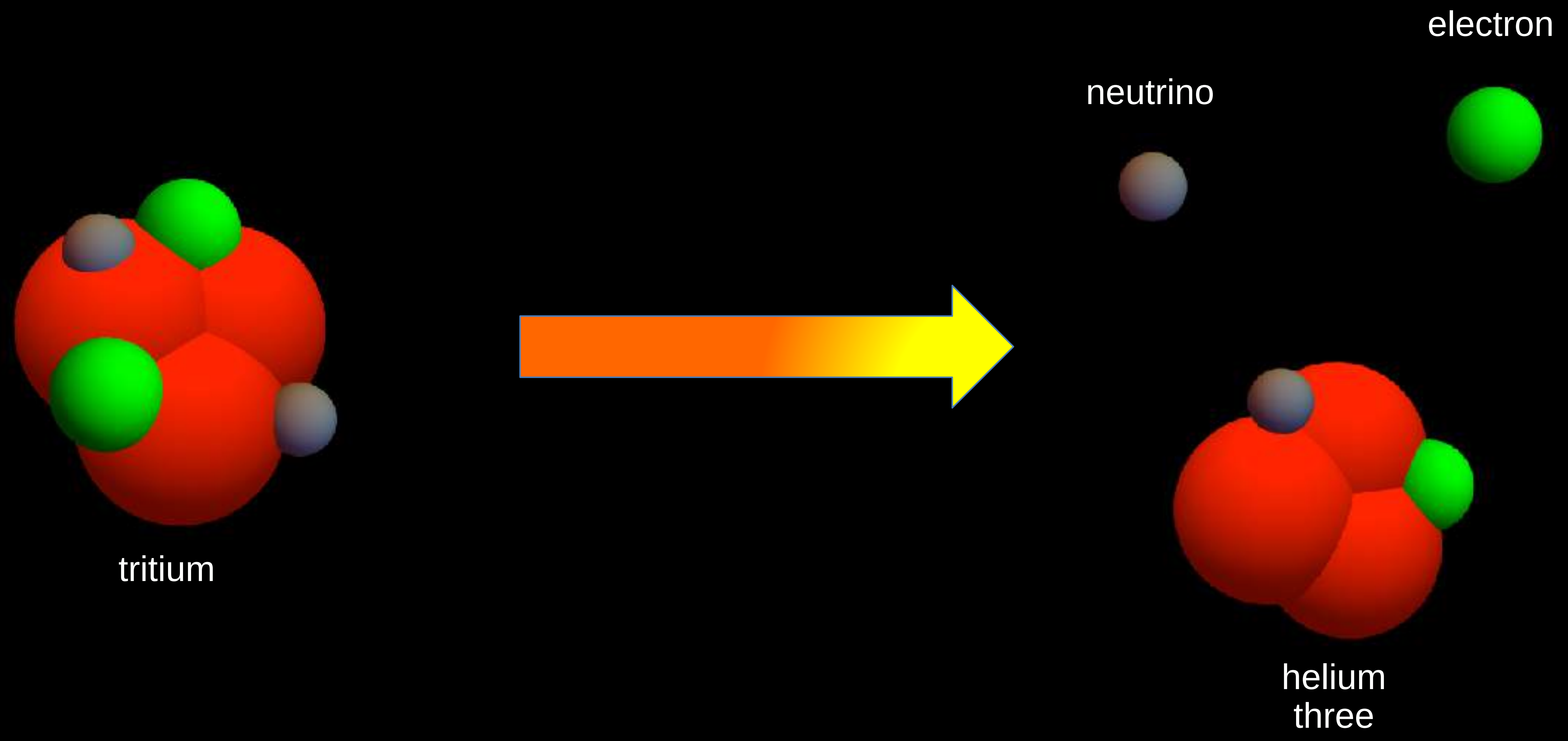
Also Pauli's model (1930) solves the problems, however saving energy conservation

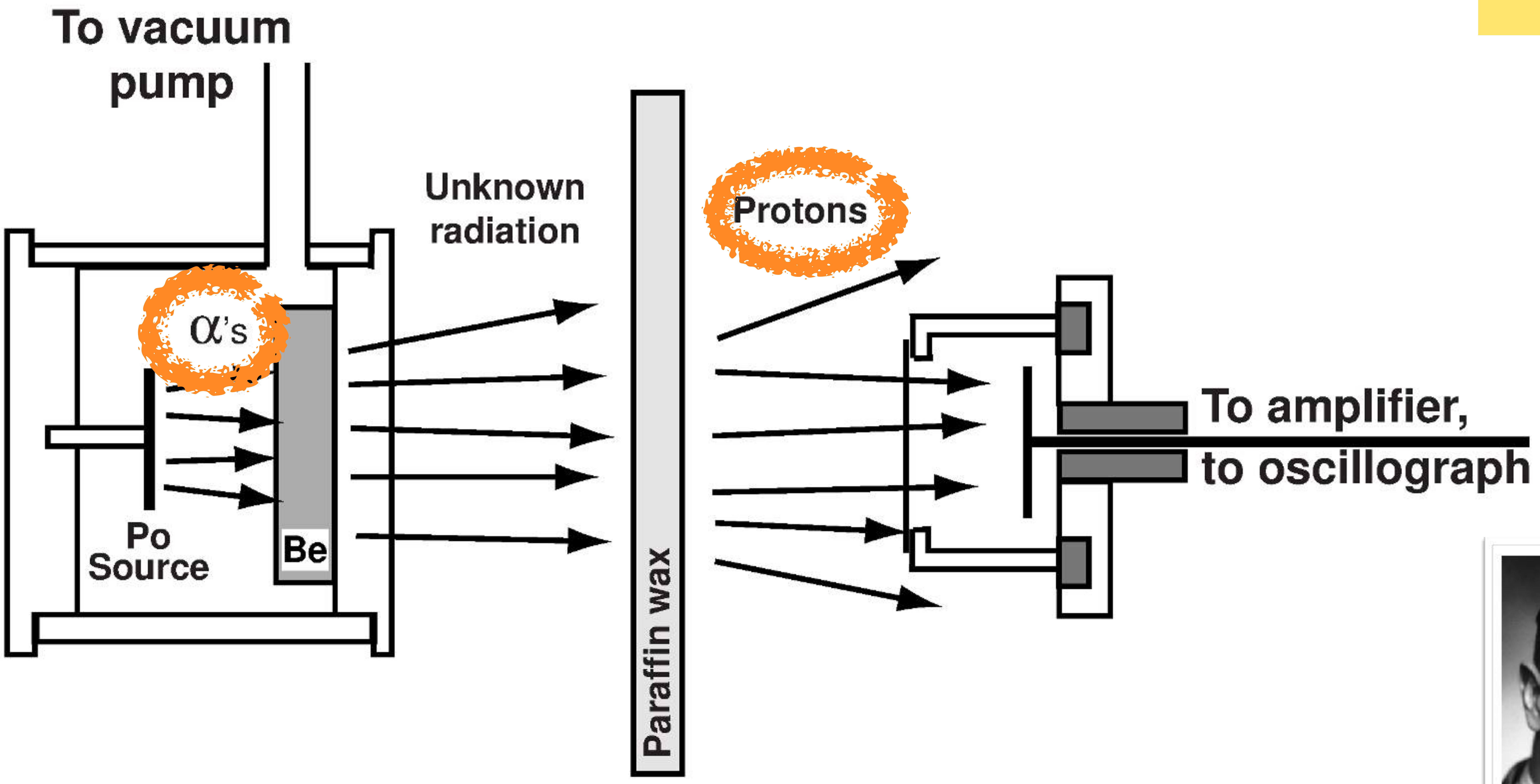


nucleus with electrons, protons and neutrinos.
the latter subtracts energy in the β decay

Chadwick's discovers the neutron

Nobel 1936

1932



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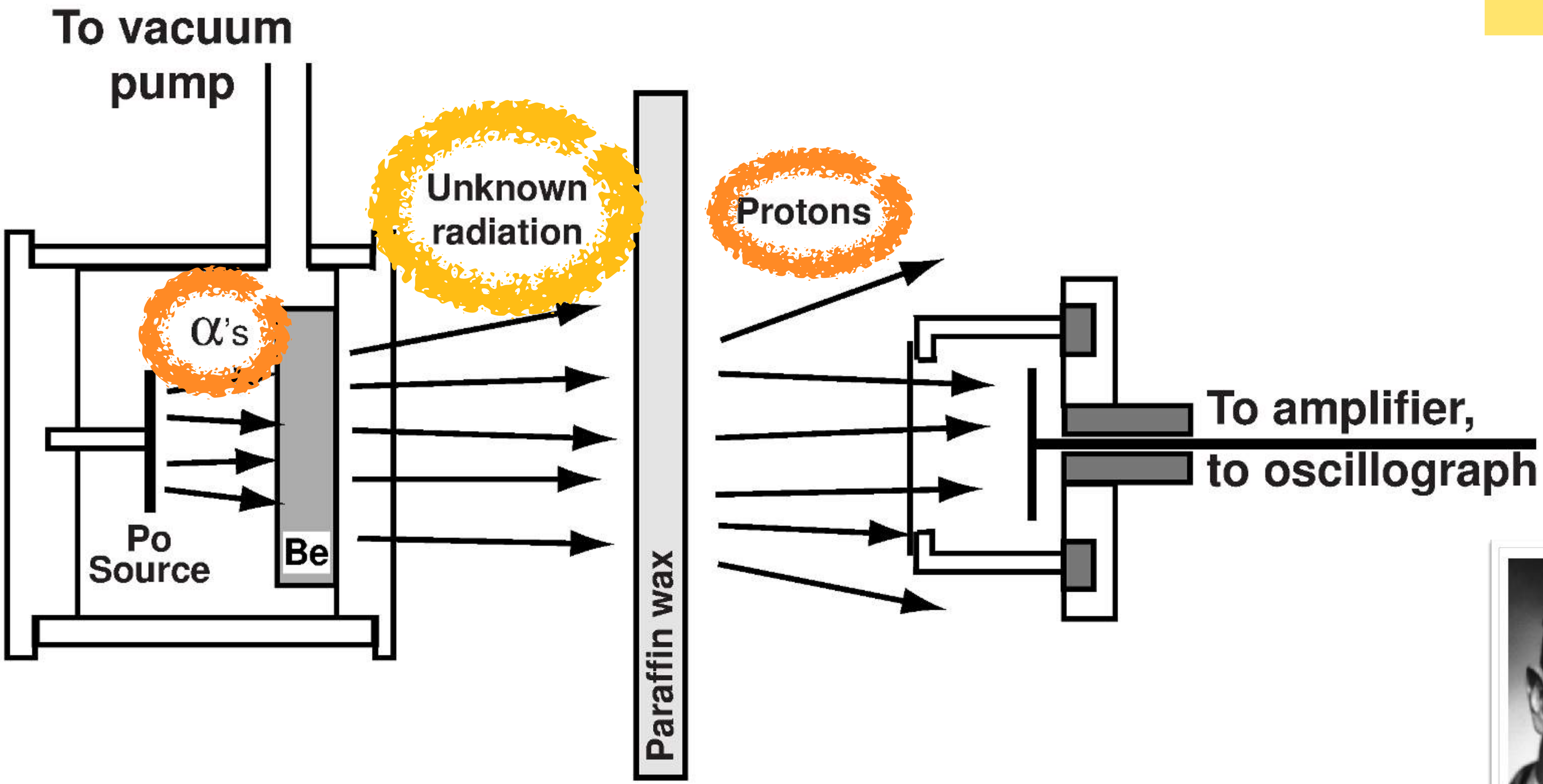
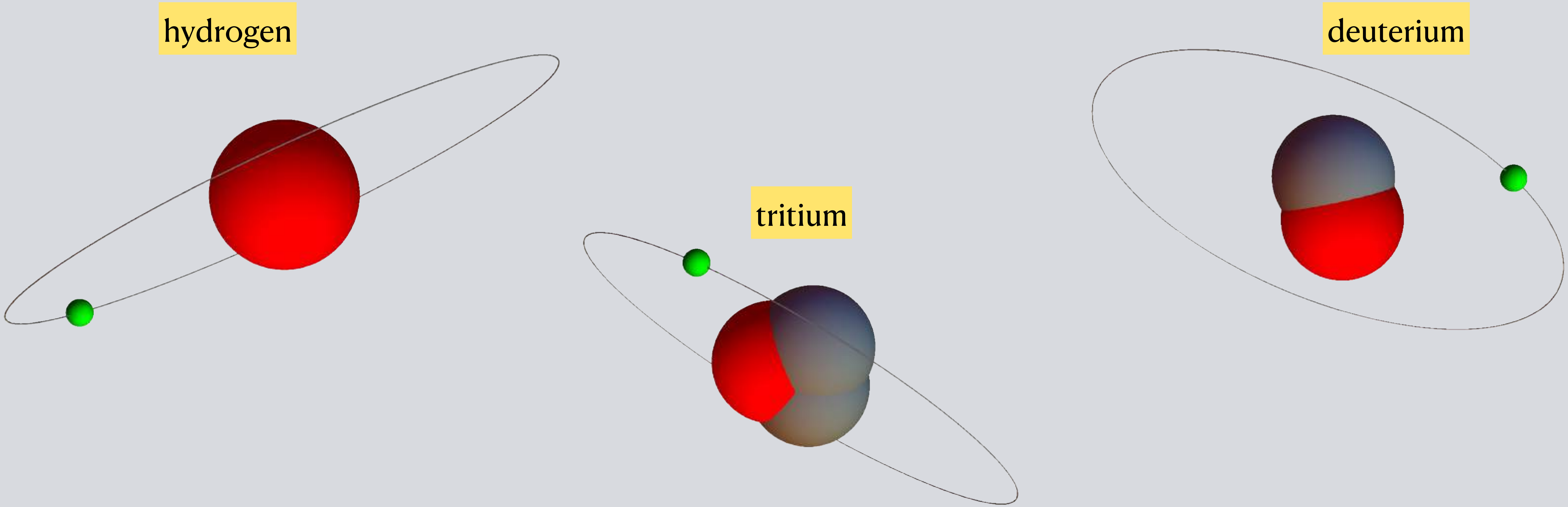


thence the new (and current) model, with protons and neutrons



(Iwanenko, Heisenberg, Majorana 1932-1933)

summary: the situation in mid-1933

in 30s, physicists focussed on understanding the nucleus.

- The limitations of ***electron-proton model*** began to emerge.
- Pauli 1930 model was ***just a variant*** of this type of model.
- In all these models, Pauli's included, matter particles were ***eternal*** - a typical non-relativistic feat.

The new p-n model explains a lot, but the β decay spectrum question is unsolved:
maybe neutrinos are needed anyway?

CHAPTER 2

Fermi 1933-1934: The first theory of β-rays and neutrinos. Conceptual and formal bases, implications. Electron capture

early 1900: the era of light-matter assimilation

L *ight quanta are created or destroyed (Einstein '05; Compton '23)*

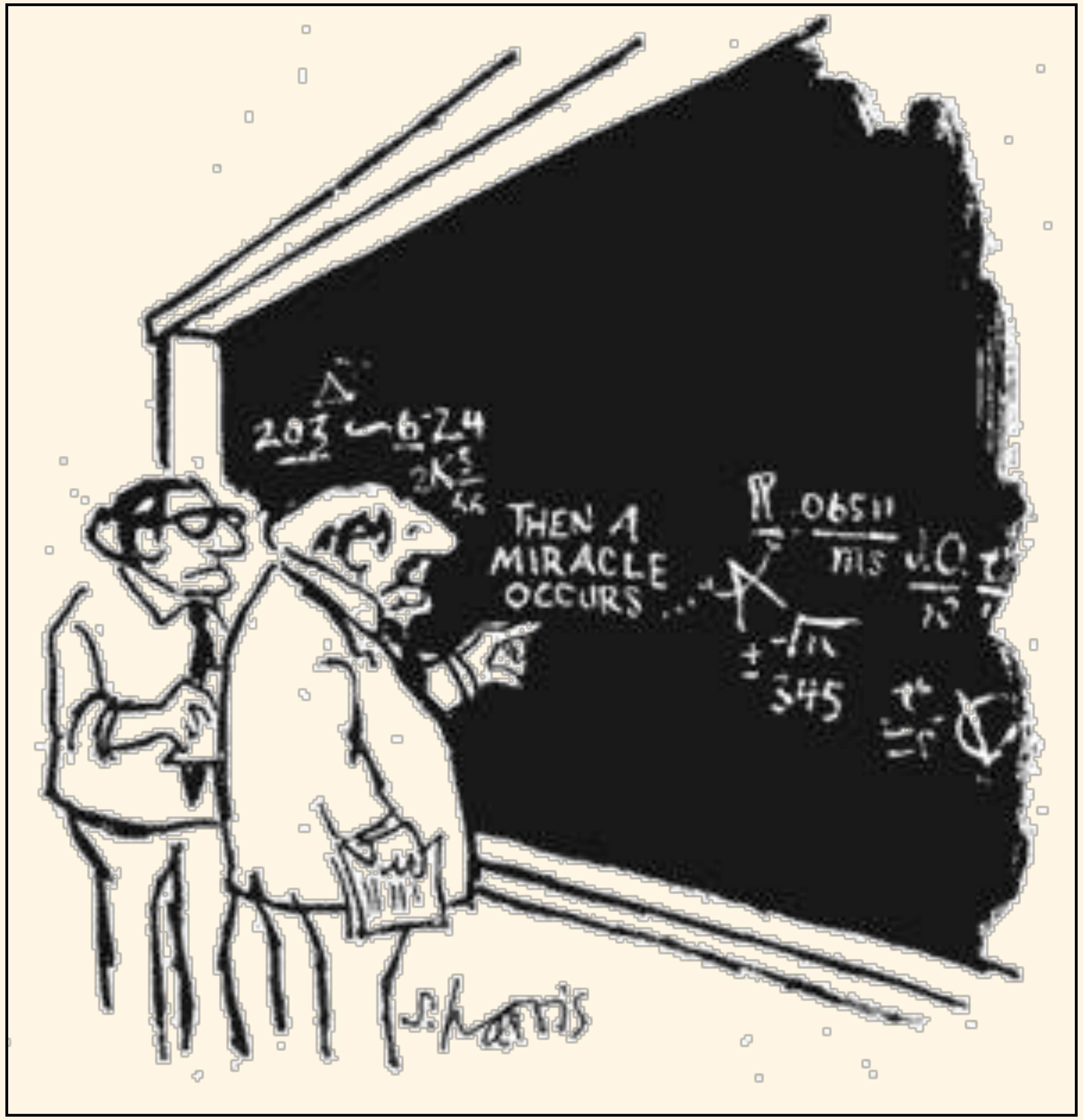
E *lectrons can be described as waves (Louis de Broglie '24)*

A *ttempt to model electron creation in β decay (Ambarzumian&Iwanenko '30)*

P *ondering over neutrino creation & its small mass (Perrin '33)*

Enter FERMI

At this point, it is the turn of Fermi, whose contribution (at its 90th anniversary) is usually acknowledged but only *rarely* discussed



First need:
understanding Dirac!

A message in a bottle
from Gamow helps those
who really want
to understand.

from "Thirty years that shook Physics" (1966)

Dirac 1930: recipe to deal with negative energy states

$$-mc^2 < E < mc^2$$

Dirac 1930: recipe to deal with negative energy states

also Fermi relied on the Dirac sea (1934)

In ciò sono da considerarsi solo gli stati di energia positiva; gli stati di energia negativa debbono eliminarsi con un artificio simile alla teoria dei buchi di Dirac

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*Dirac sea is **hypothesised** to guarantee the stability of matter*

the other key tool (Fermi 1934)

Il formalismo matematico più semplice per costruire una teoria in cui il numero delle particelle leggere (elettroni e neutrini) non sia necessariamente costante, si ha nel metodo di Dirac–Jordan–Klein delle « ampiezze di probabilità quantizzate ».

Nella teoria presente invece la possibilità della variazione del numero degli elettroni si ottiene introducendo i due operatori opposti ψ e ψ^* in termini separati della energia di interazione.

$$\psi = \sum_s \psi_s a_s \quad ; \quad \psi^* = \sum_s \psi_s^* a_s^* .$$

(it differs from a *quantised fermionic field;* today this is usually called *second quantization*)

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The new trick: modelling matter particles creation

$$-mc^2 < E < mc^2$$

The new trick: modelling matter particles creation

$-mc^2 < E < mc^2$

observation:

in this theory,

matter$\neq$antimatter

we are used to talk of "Dirac neutrino",
it would be fair to talk of "Fermi neutrino"

CHAPTER 3

Majorana 1937: Modern understanding of fermions.
New concept of neutrino

Dirac sea emptied!

Pauli & Weisskopf 1934 quantise a hypothetical zero-spin particles w/o Dirac sea ("anti-Dirac theory")

Majorana 1937 shows how to avoid Dirac sea for fermions

subsequent discussion confirms the value of Majorana's proposal

beginning of modern quantization for fermions

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di «antiparticelle» corrispondenti ai «vuoti» di energia negativa.*

L'interpretazione dei cosidetti «stati di energia negativa» proposta da Dirac (1) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria girando le difficoltà di convergenza, essa fornisce realmente risultati del tutto simmetrici. Tuttavia gli artifici suggeriti per dare alla teoria una forma simmetrica che si accordi con il suo contenuto, non sono del tutto soddisfacenti; sia perchè si parte sempre da una impostazione asimmetrica, sia perchè la simmetrizzazione viene in seguito ottenuta mediante tali procedimenti (come la cancellazione di costanti infinite) che possibilmente dovrebbero evitarsi. Perciò abbiamo tentato una nuova via che conduce più direttamente alla meta.

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Dirac-Jordan-Klein (Wigner, Fock, Fermi...)

$$\mathbf{\Psi}(x) = \sum_{s} \psi_s(x)\, \boldsymbol{a}_s$$

Majorana (and everybody after him)

$$\mathbf{\Psi}_C^{\mathrm{cplx}}(x) = \sum_{s=s_+} \left(\psi_s(x)\, \boldsymbol{c}_s + \psi_s^*(x)\, \bar{\boldsymbol{c}}_s^\dagger \right)$$

Dira[redacted]m...)

[redacted]

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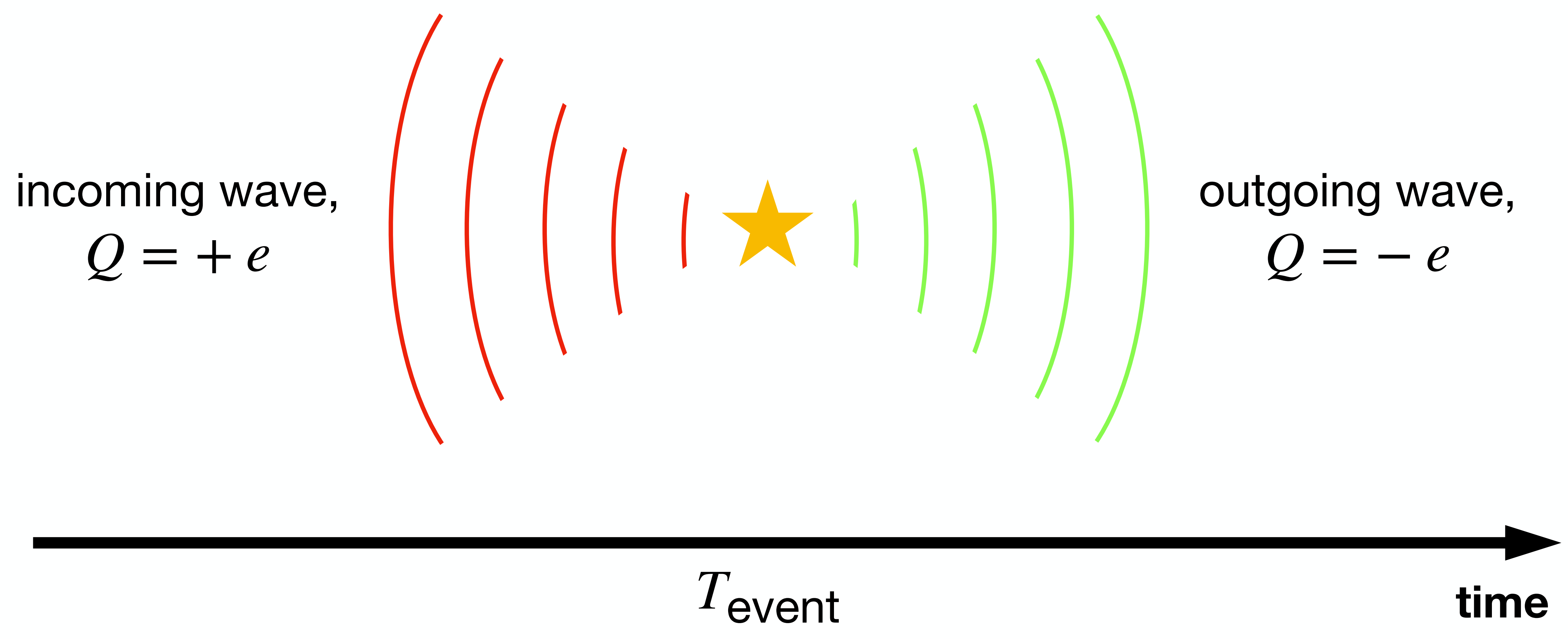
extended discussion of Majorana's electron/positron

Consider a nucleus - the star - that can emit an electron **increasing its charge** $\Delta Q = +e$

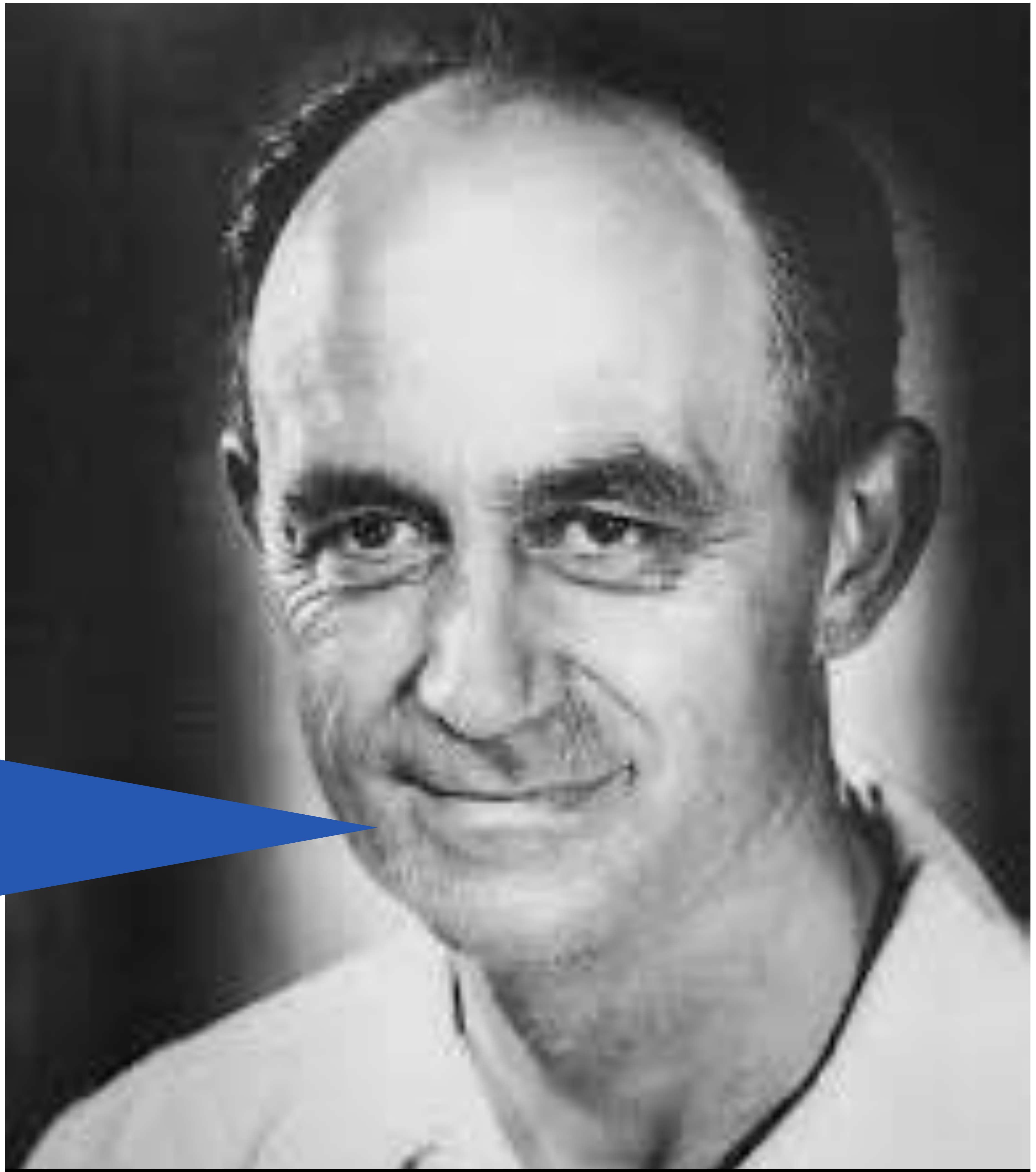
The same happens when a **negative energy electron** is emitted; but this time also the **energy of the nucleus increases**

Conclusion: a negative energy electron that is emitted can be thought of as a positive energy positron that was **previously absorbedy**.



… [Majorana] in a recent work finally devised a brilliant method that allows the positive and negative electron to be treated symmetrically, finally eliminating the need to resort to the extremely artificial and unsatisfactory hypothesis of an infinitely large electric charge spread throughout space, an issue that had been addressed in vain by many other scholars.

From the judgement on Majorana for the professorship competition in Palermo (1937)



Fermi 1937

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old treatment implies: particle≠antiparticle

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why not to use this for neutrinos?

$$\mathbf{\Psi}_a^{\text{real}}(x) = \sum_{s=s_+} \left(\psi_s(x)\ \boldsymbol{a}_s + \psi_s^*(x)\ \boldsymbol{a}_s^\dagger \right)$$

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CHAPTER 4

Completing the theory of weak interactions (mid 1930-mid 1950)
Identification of its weak point with the help of neutrinos

towards the theory of weak interactions

1) From muons to families (lineage of theorists: *Fermi→Yukawa→Sakata & Inoue, Pontecorvo, Puppi)*

2) Lepton numbers (lineage of theorists: *Weyl, Stueckelberg, Wigner→Marx; Zel'dovich; Konopinsky & Mahmoud)*

3) Nature of weak interactions (lineage of theorists: *Yang&Lee →Sudarshan&Marshak, Feynman&Gell-Mann)*

4) The idea of massless neutrinos (lineage of theorists: *Weyl→Salam, Landau, Lee&Yang)*

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❋ ❋ ❋

then: the weak point of of weak interaction theory

1. muon neutrino and universality of weak interactions

(Muon discovered shortly after Yukawa's hypothesis - 1935)

Sakata & Inoue 1942 postulate
$Y \rightarrow m + n,\ m \rightarrow e + \nu + n$
n=2^{nd} ***neutrino***, Y=Yukawa' field
(i.e.: $\pi \rightarrow \mu + \nu_{\mu}\ ,\ \ \mu \rightarrow e + \nu_{e} + \nu_{\mu}$)

Muon isn't Yukawa' particle 1945

寄 書

中間子と湯川粒子の關係に就て*

中間子の湯川理論はその發展過程の現段階に於て幾多の重大なる困難を呈示してゐる．此の困難の一部は恐らく Heisenberg(1) が強調してゐる如く相對論的量子力學の適用性に限界を與へる "普遍的長さ" の存在と密接に關聯してゐるものと考へられる．併しこれ等の困難の中には必ずしも斯樣な原理的な問題とは直接關係のない樣な種類のものも存在してゐるらしく思はれる．實際最近その中のあるものは Bhabha(2) が以前から主張してゐる如く攝動理論の不當なる適用に由來する純粹に數學的な性格をもつもので，場の反作用を正しく考慮するならば除き得るものであることが明かにされた(3)(4)．この論文に於ては素粒子の基本的性質に就ての新しい考察によつて更に一列の困難が解決されることを示さうと思ふ．

湯川理論は元來原子核力とベーター崩壞現象を統一的に說明せんとする要求に應じて成立したものであつて，原子核の領域に於ては著しい成功を收めることが出來た．宇宙線中に於ける新粒子——中間子——の發見はこの粒子を直ちに湯川粒子と同一視する見解に導き湯川理論を益々有力なものとしたのであつたが，宇宙線に關して行はれた諸實驗との比較が量的になるに從つてこの理論は幾多の難關に遭遇するに至つた．湯川理論によつて豫言された中間子の自然崩壞の現象は

間子は湯川粒子と互に密接な關係には在るが一應異つた種類の素粒子であると謂ふ見地に立脚した新しい中間子理論を提出する．斯樣な立場の理論に於ては中間子は Bose 粒子であることも Fermi 粒子であることも許されるが，吾々は後の可能性を採用する(9)．

湯川理論に從ふと重粒子（核子）及び輕粒子は夫々湯川粒子と次の圖式に示す如き相互作用を行ふ．

$$\left.\begin{array}{l} P \leftrightarrows N + Y^{+}, \\ N \leftrightarrows P + Y^{-}, \end{array}\right\} \quad (\mathrm{I})$$

$$\left.\begin{array}{l} e^{-} \rightleftarrows \nu + Y^{-}, \\ \nu \leftrightarrows e^{-} + Y^{+}. \end{array}\right\} \quad (\mathrm{II})$$

但し P は陽子，N は中性子，e^{-} は電子，ν は中性微子．$Y^{\pm}$ は正或は負に帶電せる湯川粒子を表はす．扨て吾々は中間子も亦 $\hbar/2$ の大いさのスピンを有する Fermi 粒子であると假定し，且つ（I）（II）と對應して

$$\left.\begin{array}{l} m^{+} \rightleftarrows n + Y^{+}, \\ n \rightleftarrows m^{+} + Y^{-}, \end{array}\right\} \quad (\mathrm{III})$$

で示される樣な相互作用を導入する．但し $m^{\pm}$ は正或は負に帶電した中間子．n は中間子に對應した中性粒子でその質量は非常に小さいと假定して置く（以下の計算に於てはこの質量は零に採つてある．從つて中性微子と同一物と見做しても差支ない）．

（III）なる假定を新しく導入することにより得られた結論を示すと次の通りである：

1. from muon to muon neutrino

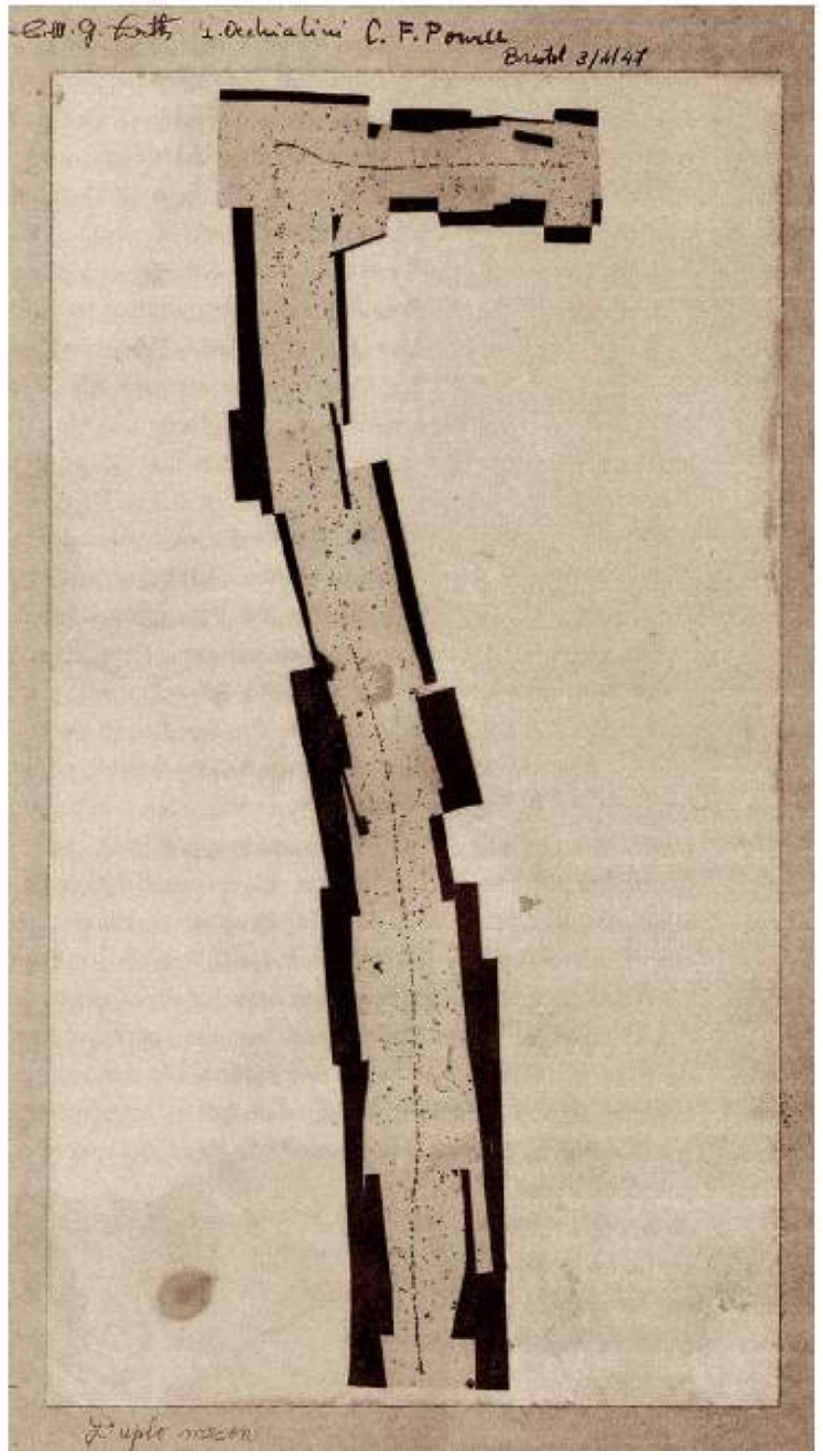
1. muon neutrino and universality of weak interactions

1947:

2 meson theory is proved

(today we prefer to say: pion has been discovered.)

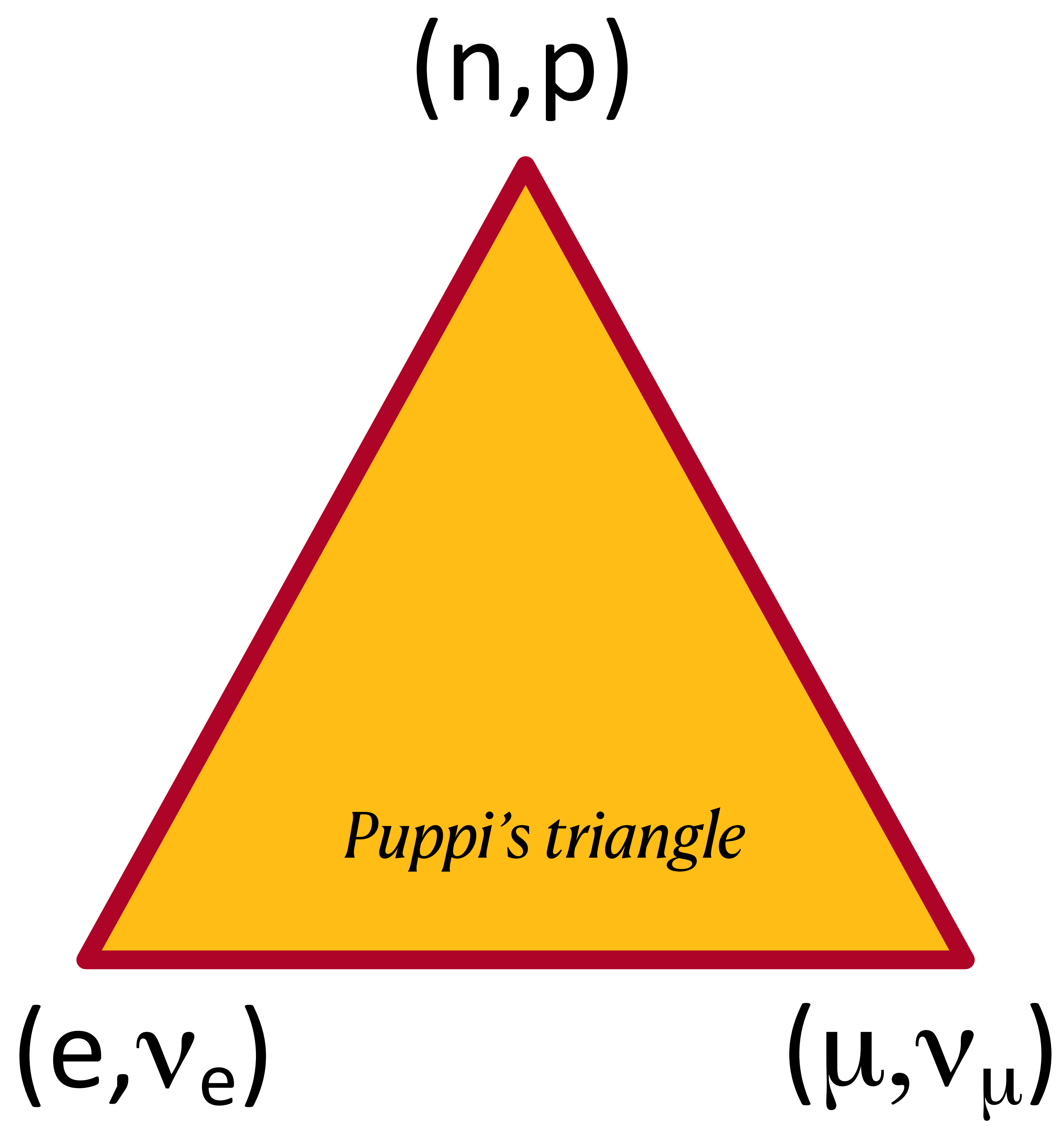
In 1949 Yukawa receives the Nobel prize



1. from muon to muon neutrino

1. muon neutrino and universality of weak interactions

- Pontecorvo: e-capture and μ-decay has same coupling (1947)
- Puppi: muon is associated to a **new type of neutrino** (1948)
- Weak interactions treat in the same way the pairs of particles.
  For the pair **(n,p)**, this is **almost** true.
- **Muon neutrino observed** (1962)



1. from muon to muon neutrino

2. a dilemma with leptons and its solution

why disintegrations such as $\mu \to e + \gamma$ do not occur?

— the lepton number Marx; Zel'dovich; Konopinsky Mahmoud 52-53 —

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

3. parity violation is hypothesised and then established!

J. C. Ward

from 'Memoirs of a Theoretical Physicist'

"Quite soon after this triumph, the experiment of Mrs. C. S. Wu *et al.* at Columbia, acting upon the suggestion of Yang and Lee, definitely established the non-conservation of parity in weak interactions, surprising everyone.

I wrote a note to Abdus, telling him of the result, adding that *Einstein must be spinning in his grave*, clockwise presumably."

3. universal V-A weak forces

🧐 **Ruderman+Finkelstein 1949**

Predictions of $R(\pi \to e+\nu)/R(\pi \to \mu+\nu)$ in various hypotheses

🤨 **Durbin+Loar+Steinberger 1951**

Pion parity determined from deuterium photodissociation

🙁 **Lokanathan+Steinberger 1955 & Anderson+Lattes 1957**

Apparently $R(\pi \to e+\nu)$ is just absent, ruling out V-A

🤩 **Sudarshan+Marshak 1957 & Feynman+Gell-Mann 1958**

Theory first! V-A implies that previous result is inaccurate

😘 **Fazzini *et al.*1958**

Measured $R(\pi \to e+\nu)/R(\pi \to \mu+\nu)$ confirms V-A structure

4. the neutrino connection

IL NUOVO CIMENTO Vol. V, N. 1 1° Gennaio 1957

On Parity Conservation and Neutrino Mass.

Abdus Salam
St. John's College - Cambridge

(ricevuto il 15 Novembre 1956)

Nuclear Physics 3 (1957) 127—131; *North-Holland Publishing Co., Amsterdam*

ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

L. LANDAU
Institute for Physical Problems, USSR Academy of Sciences, Moscow

Received 9 January 1957

Abstract: A variant of the theory is proposed in which non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.
Various possible consequences of non-conservation of parity are considered which pertain to the properties of the neutrino and in this connection some processes involving neutrinos are examined on the assumption that the neutrino mass is exactly zero.

PHYSICAL REVIEW VOLUME 105, NUMBER 5 MARCH 1, 1957

Parity Nonconservation and a Two-Component Theory of the Neutrino

T. D. Lee, *Columbia University, New York, New York*
AND
C. N. Yang, *Institute for Advanced Study, Princeton, New Jersey*
(Received January 10, 1957; revised manuscript received January 17, 1957)

A two-component theory of the neutrino is discussed. The theory is possible only if parity is not conserved in interactions involving the neutrino. Various experimental implications are analyzed. Some general remarks concerning nonconservation are made.

IL NUOVO CIMENTO Vol. VI, N. 1 1° Luglio 1957

Fermi Interaction with Non-Conservation of «Lepton Charge» and of Parity.

C. P. Enz
Swiss Federal Institute of Technology - Zürich

(ricevuto il 14 Maggio 1957)

IL NUOVO CIMENTO Vol. VI, N. 1 1° Luglio 1957

On the Conservation of the Lepton Charge.

W. Pauli
Swiss Federal Institute of Technology - Zürich

(ricevuto il 14 Maggio 1957)

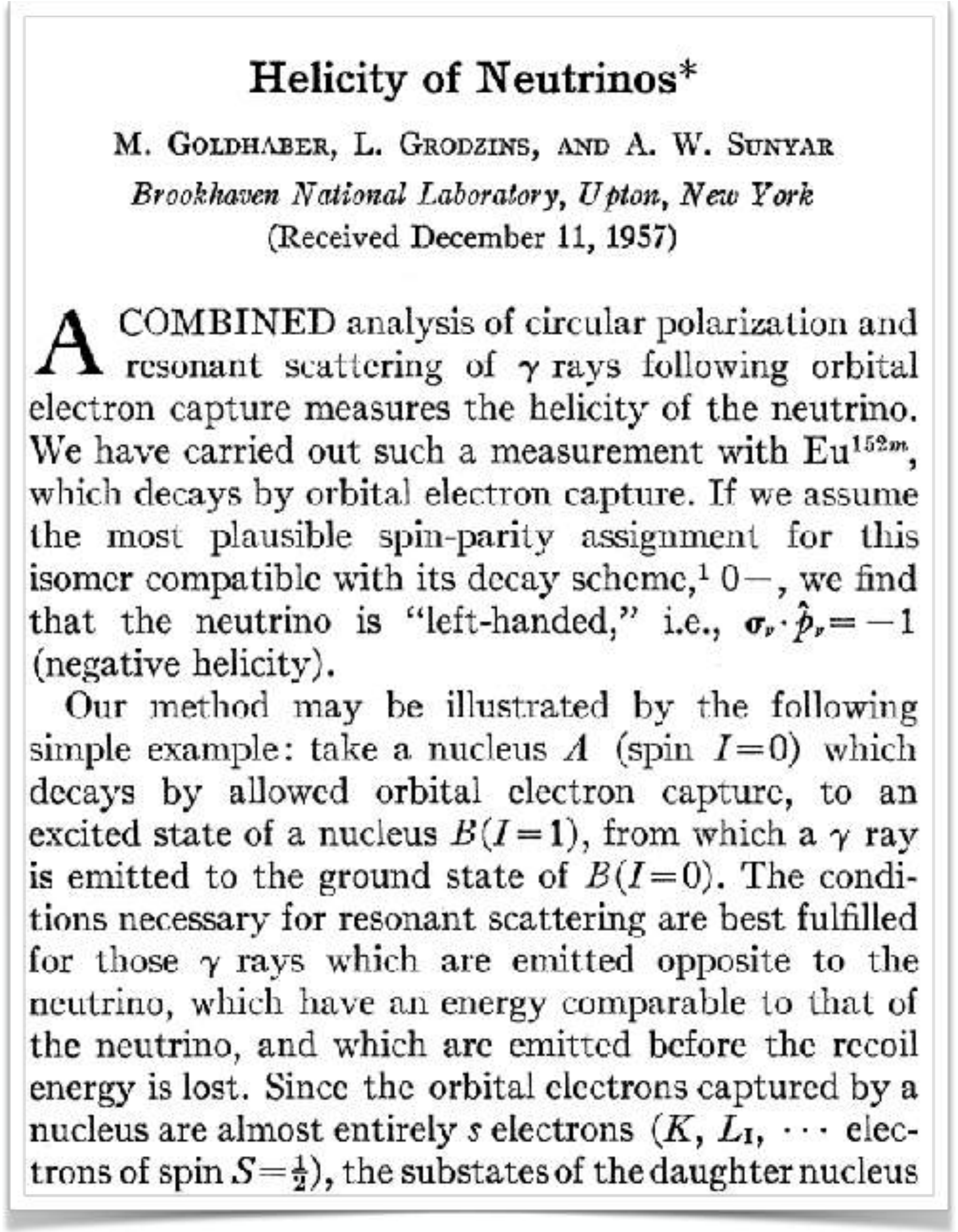
IL NUOVO CIMENTO Vol. VI, N. 2 1° Agosto 1957

Invariance Properties of Fermi Interactions.

D. L. Pursey
Tait Institute of Mathematical Physics,
University of Edinburgh, Scotland

(ricevuto il 1° Aprile 1957)

4. the neutrino connection



Helicity of Neutrinos*

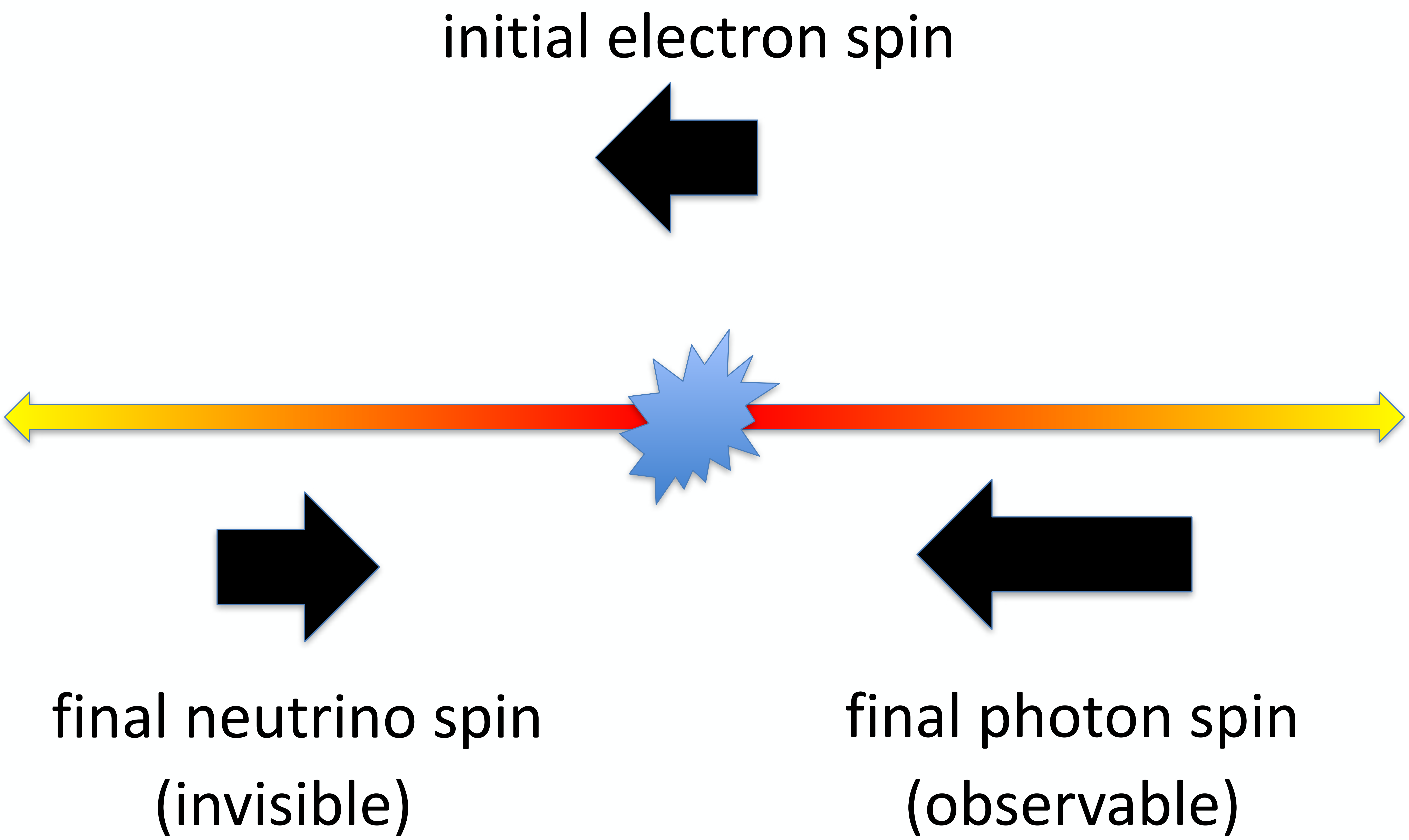
M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

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., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_I, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus



4. the neutrino connection

(a historical remark)

Weyl had found a simpler equation for 2-dim fermions for massless electrons already in 1929 (!!!)

we can omit $m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$ *if* ψ_R *is absent*

He suggested not to bother of mass, that is a gravitational effect - interesting view, isnt't?

GRAVITATION AND THE ELECTRON[1]

By Hermann Weyl

Palmer Physical Laboratory, Princeton University

Communicated March 7, 1929

The Problem.—The translation of Dirac's theory of the electron into general relativity is not only of formal significance, for, as we know, the Dirac equations applied to an electron in a spherically symmetric electrostatic field yield in addition to the correct energy levels those—or rather the negative of those—of an "electron" with opposite charge but the same mass. In order to do away with these superfluous terms the wave function ψ must be robbed of one of its pairs $\psi_1^+, \psi_2^+; \psi_1^-, \psi_2^-$ of components.[2] These two pairs occur unmixed in the action principle except for the term

$$m(\psi_1^+ \bar{\psi}_1^- + \psi_2^+ \bar{\psi}_2^- + \psi_1^- \bar{\psi}_2^+ + \psi_2^- \bar{\psi}_2^+) \quad (1)$$

which contains the mass m of the electron as a factor. But mass is a gravitational effect: it is the flux of the gravitational field through a surface enclosing the particle in the same sense that charge is the flux of the electric field.[3] In a satisfactory theory it must therefore be as impossible to introduce a non-vanishing mass without the gravitational field as it is to introduce charge without electromagnetic field. It is therefore certain that the term (1) can at most be right in the large scale, but must really be replaced by one which includes gravitation; this may at the same time remove the defects of the present theory.

- from a famous interview to Dirac -

***Wisconsin State Journal*, April 1929**

"Do you ever run across a fellow that even you can't understand?"

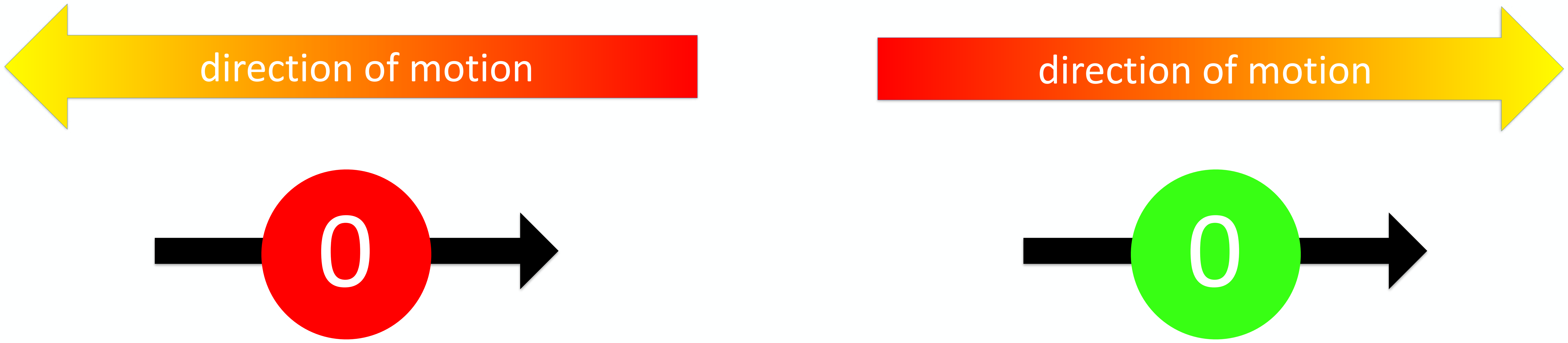
"Yes," says he.

"This well make a great reading for the boys down at the office," says I. "Do you mind releasing to me who he is?"

"Weyl," says he.

"standard" summary of these facts

- **V-A** (chiral) structure and assumption of neutrino **masslessness** leads to: *Helicity distinguishes neutrinos from antineutrinos*



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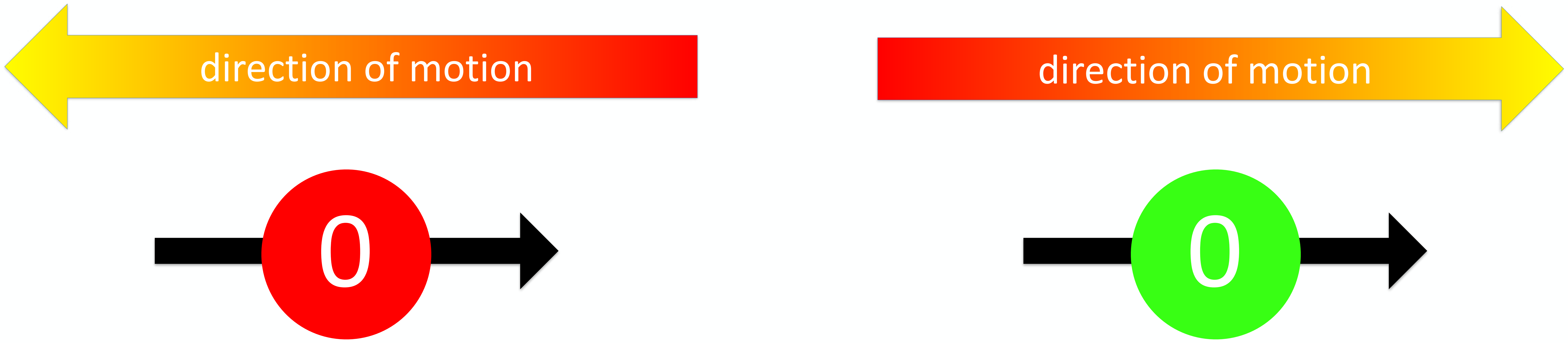
- **V-A** (chiral) structure and assumption of neutrino **masslessness** leads to: *Helicity distinguishes neutrinos from antineutrinos*



- A theorem from "standard model": **the 3 lepton numbers L_i are conserved**

However, the numbers $L_i - L_j$,

are not respected according to

neutrino appearance experiments

such as OPERA, T2K, NOνA.

However, the numbers $L_i - L_j$,

are not respected according to

neutrino appearance experiments

such as **OPERA, T2K, NOνA.**

In logic, this is called a **contradiction**

this is *the* weak point of weak interactions theory

(note, m_ν has not yet been mentioned)

CHAPTER 5

Pontecorvo & Sakata's successful approach to neutrino mass
(late 1950s to the new millennium)

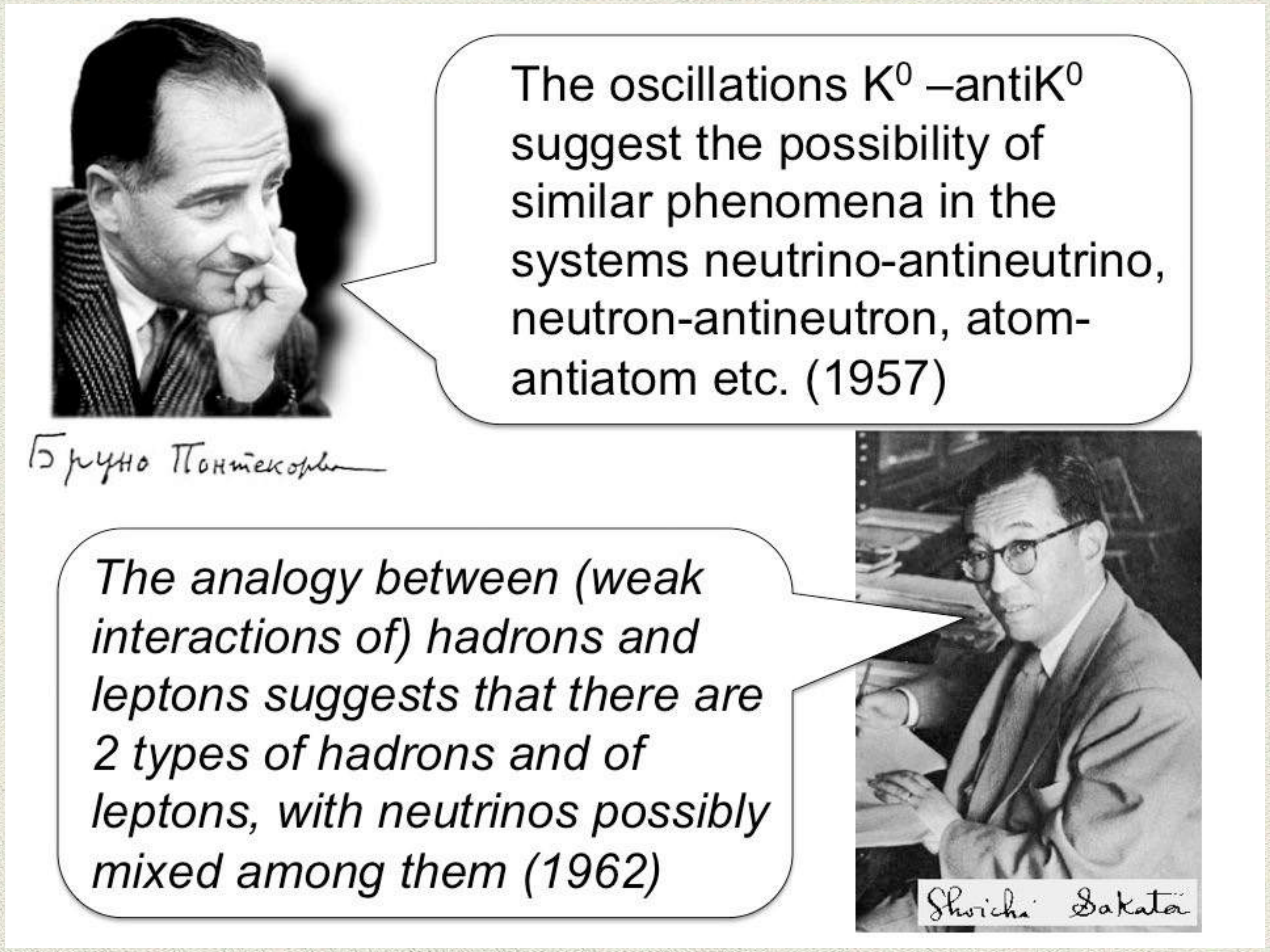
the method that has worked: **prehistory**

All began with $K^0 - \overline{K^0}$ *transitions* - Gell-Mann, Pais, Piccioni (55)

Pontecorvo suggests that a similar *transformation* could happen to neutrinos (57-58)

Two groups in Tokyo and Kyoto suppose that $\nu_e - \nu_\mu$ are mixed states (62)

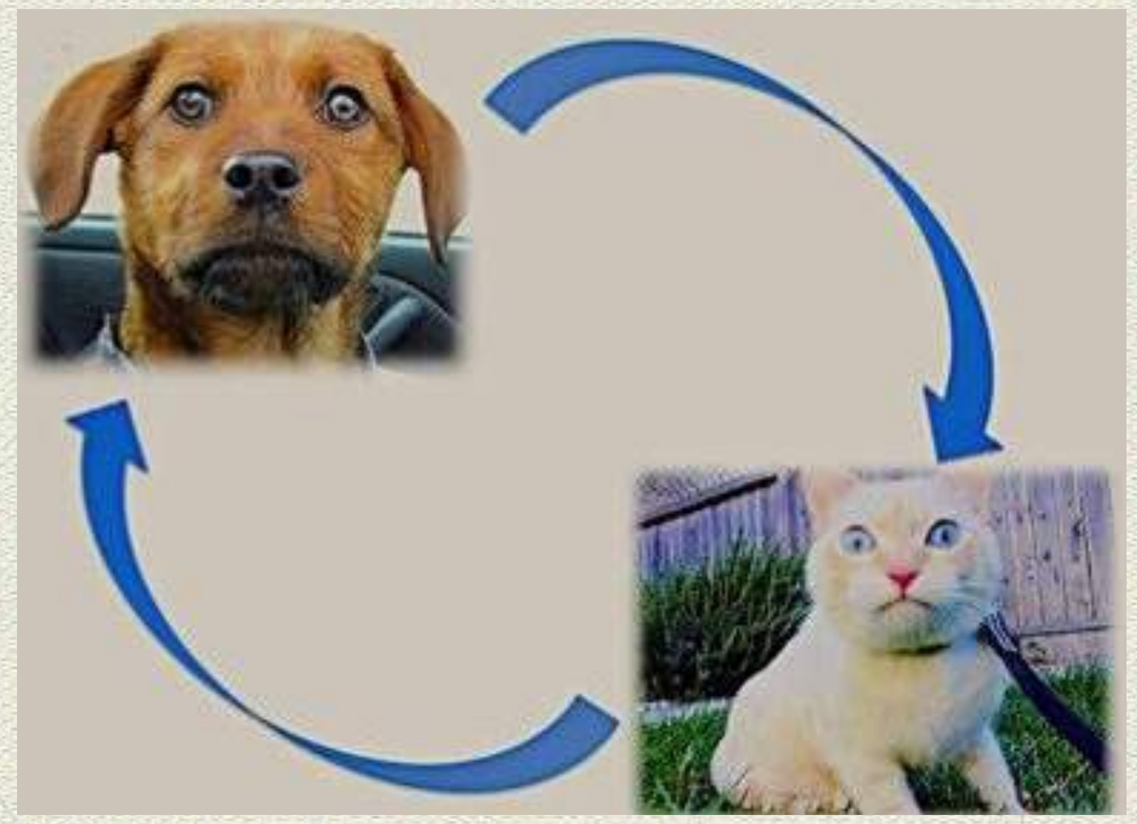
The second group, Sakata's, connect the point to neutrino masses and mention *transmutations*



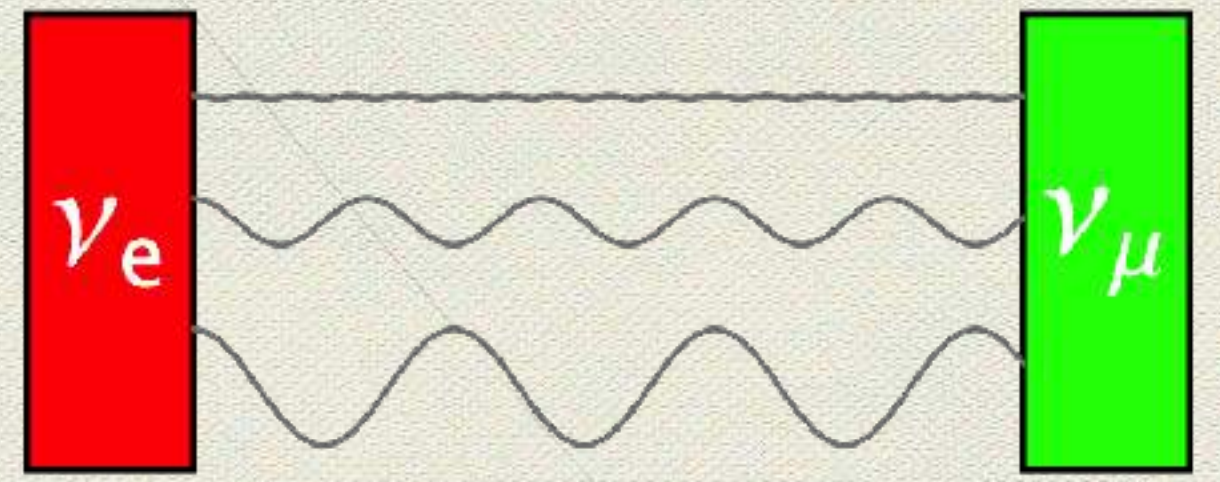
the method that has worked: **history**

Math description, almost right, by Pontecorvo + Gribov (1967,69)

- ***Solar neutrino****: Homestake experiment (since 1968); Kamiokande (1989); SAGE and Gallex (since nineties)…*
- ***Atmospheric neutrino****: Kamiokande (1988); then Super-Kamiokande (1998) but also Macro (1998); Soudan-II (1998)…*
- ***Then artificial beams:** reactors, accelerators….*



based on Reines 1995



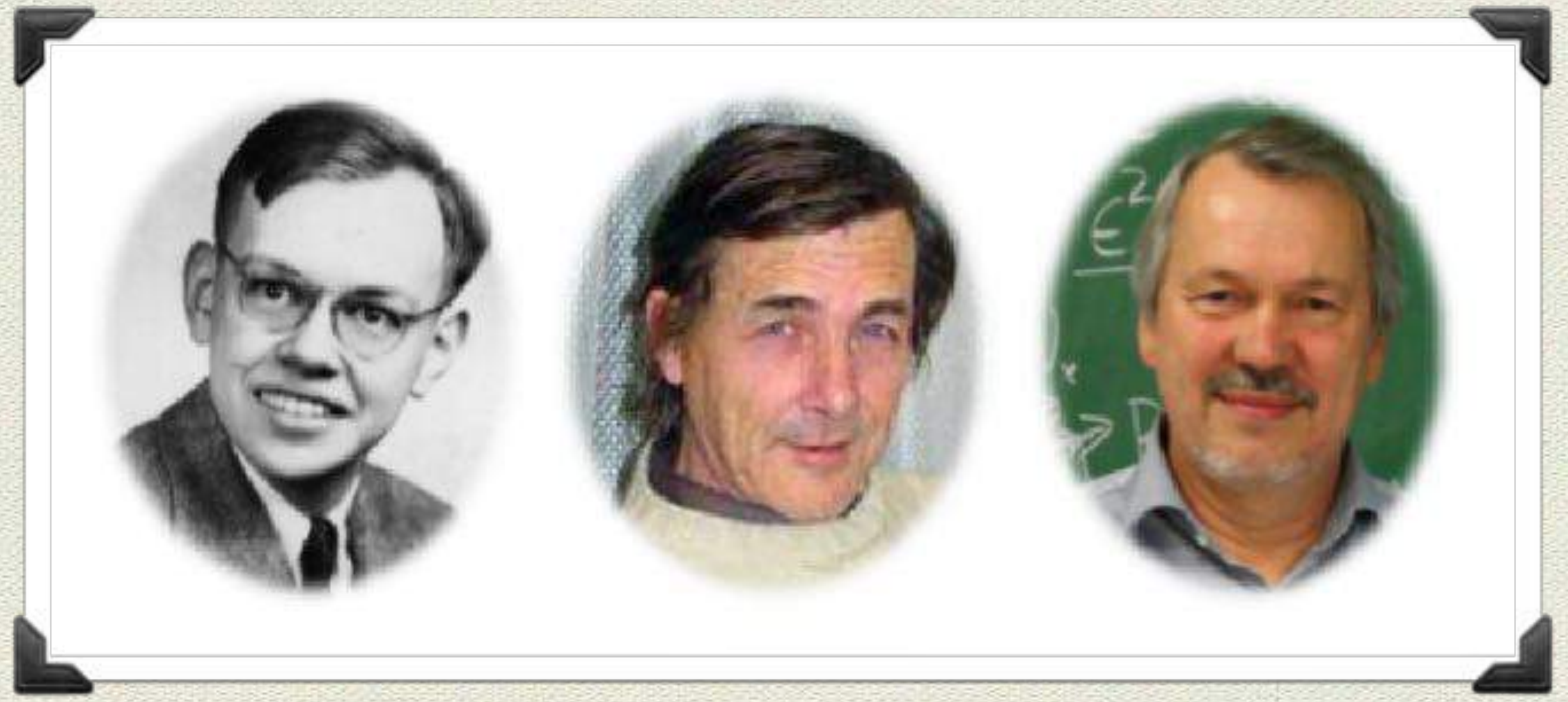
the method that has worked: present

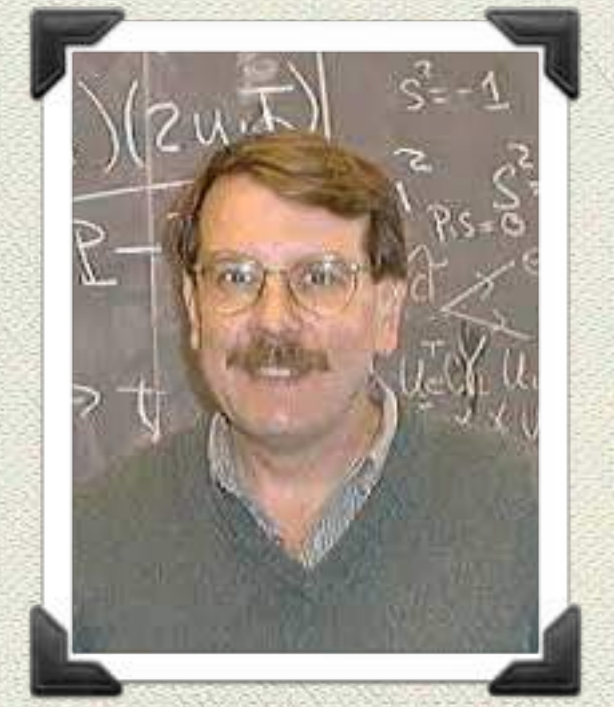
Wolfenstein (1978) on a suggestion of E.Zavattini gets a new effect clarified by Mikheyev + Smirnov (1985)

Next opportunities will come from

- ***Reactor neutrinos***: *JUNO*
- ***Accelerator neutrinos***: *HK, DUNE*

Lincoln Wolfenstein **Stas Mikheyev** **Alexei Smirnov**





Stephen Parke

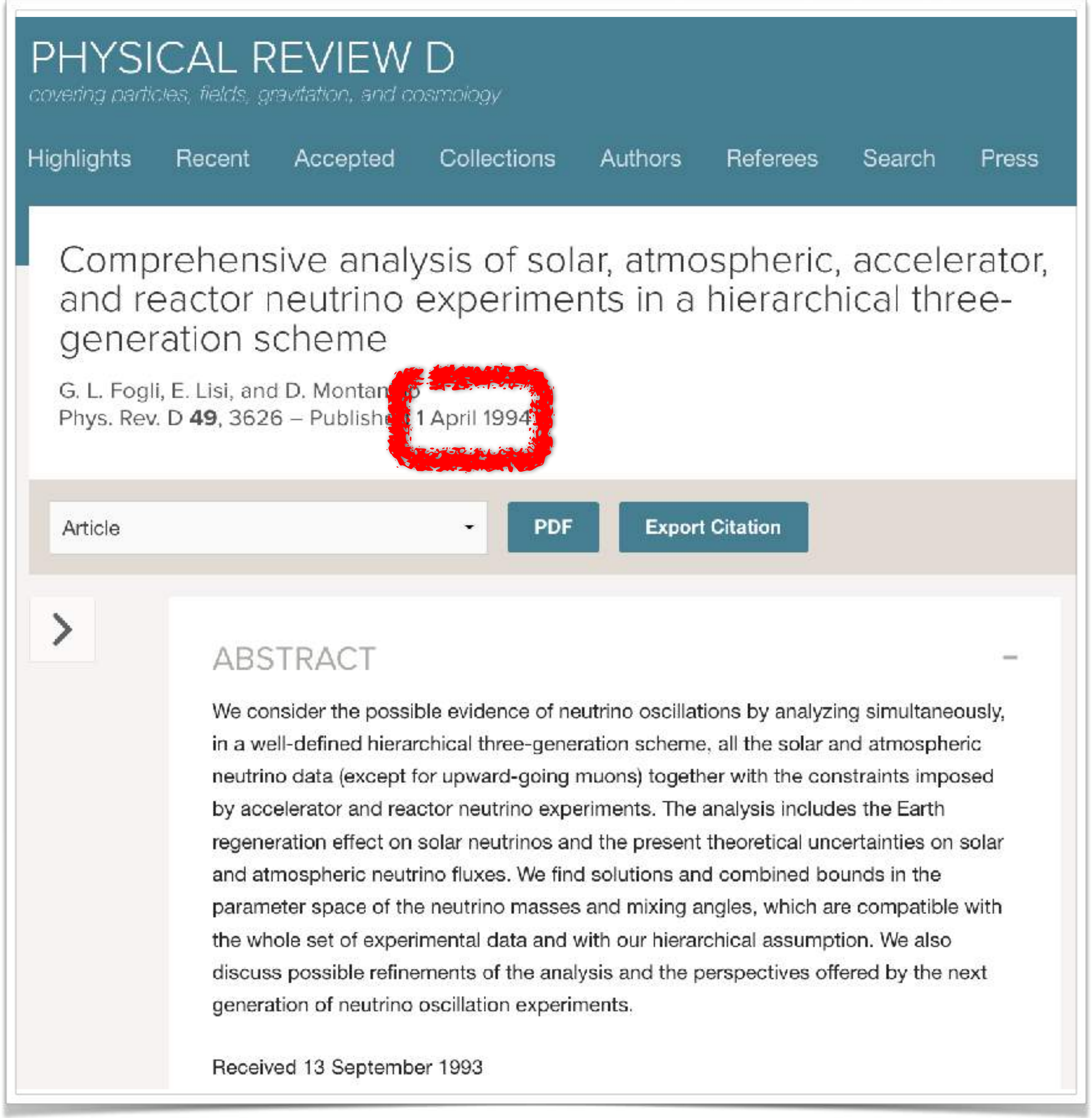
Emilio Zavattini

Serguey Petcov

1994 is another anniversary:
30 years of global analyses

….

- *Nobel 1995 to Cowan for neutrino observation*
- *Nobel 2002 to Davis and Koshiba for neutrino astronomy*
- *Nobel 2015 to Kajita and McDonald for neutrino oscillations*



PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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Comprehensive analysis of solar, atmospheric, accelerator, and reactor neutrino experiments in a hierarchical three-generation scheme

G. L. Fogli, E. Lisi, and D. Montan
Phys. Rev. D **49**, 3626 – Publishe 1 April 1994

Article PDF Export Citation

ABSTRACT

We consider the possible evidence of neutrino oscillations by analyzing simultaneously, in a well-defined hierarchical three-generation scheme, all the solar and atmospheric neutrino data (except for upward-going muons) together with the constraints imposed by accelerator and reactor neutrino experiments. The analysis includes the Earth regeneration effect on solar neutrinos and the present theoretical uncertainties on solar and atmospheric neutrino fluxes. We find solutions and combined bounds in the parameter space of the neutrino masses and mixing angles, which are compatible with the whole set of experimental data and with our hierarchical assumption. We also discuss possible refinements of the analysis and the perspectives offered by the next generation of neutrino oscillation experiments.

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Valencia

NuFit

Bari

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Revised: November 27, 2020
Accepted: December 29, 2020
Published: February 9, 2021

2020 global reassessment of the neutrino oscillation picture

P.F. de Salas,[a] D.V. Forero,[b] S. Gariazzo,[c,d] P. Martínez-Miravé,[c,e] O. Mena,[c] C.A. Ternes,[c,d] M. Tórtola[c,e] and J.W.F. Valle[c]

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Abstract: We present an updated global fit of neutrino oscillation data in the simplest three-neutrino framework. In the present study we include up-to-date analyses from a number of experiments. Concerning the atmospheric and solar sectors, besides the data considered previously, we give updated analyses of IceCube DeepCore and Sudbury Neutrino Observatory data, respectively. We have also included the latest electron antineutrino data collected by the Daya Bay and RENO reactor experiments, and the long-baseline T2K and NOνA measurements, as reported in the Neutrino 2020 conference. All in all, these new analyses result in more accurate measurements of θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{31}|$. The best fit value for the atmospheric angle θ_{23} lies in the second octant, but first octant solutions remain allowed at $\sim 2.4\sigma$. Regarding CP violation measurements, the preferred value of δ we obtain is 1.08π (1.58π) for normal (inverted) neutrino mass ordering. The global analysis still prefers normal neutrino mass ordering with 2.5σ statistical significance. This preference is milder than the one found in previous global analyses. These new results should be regarded as robust due to the agreement found between our Bayesian and frequentist approaches. Taking into account only oscillation data, there is a weak/moderate

https://doi.org/10.1007/JHEP02(2021)071

universe

MDPI

Review

NuFIT: Three-Flavour Global Analyses of Neutrino Oscillation Experiments

Maria Concepcion Gonzalez-Garcia [1,2,3,*], Michele Maltoni [4,*] and Thomas Schwetz [5,*]

1 Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, E-08010 Barcelona, Spain
2 Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, 647 Diagonal, E-08028 Barcelona, Spain
3 C.N. Yang Institute for Theoretical Physics, SUNY at Stony Brook, Stony Brook, NY 11794-3840, USA
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5 Institut für Astroteilchenphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany
* Correspondence: concha@insti.physics.sunysb.edu (M.C.G.-G.); michele.maltoni@csic.es (M.M.); schwetz@kit.edu (T.S.)

Abstract: In this contribution, we summarise the determination of neutrino masses and mixing arising from global analysis of data from atmospheric, solar, reactor, and accelerator neutrino experiments performed in the framework of three-neutrino mixing and obtained in the context of the NuFIT collaboration. Apart from presenting the latest status as of autumn 2021, we discuss the evolution of global-fit results over the last 10 years, and mention various pending issues (and their resolution) that occurred during that period in the global analyses.

PHYSICAL REVIEW D **104,** 083031 (2021)

Unfinished fabric of the three neutrino paradigm

Francesco Capozzi,[1] Eleonora Di Valentino,[2] Eligio Lisi,[3] Antonio Marrone,[4,3] Alessandro Melchiorri,[5,6] and Antonio Palazzo[4,3]

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[2] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*
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[5] *Dipartimento di Fisica, Università di Roma "La Sapienza," P.le Aldo Moro 2, 00185 Rome, Italy*
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(Received 5 July 2021; accepted 24 September 2021; published 26 October 2021)

In the current 3ν paradigm, neutrino flavor oscillations probe three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$, one CP-violating phase δ, and two independent differences between the squared masses m_i^2, that can be chosen as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$, where $\mathrm{sign}(\Delta m^2) = +(-)$ for normal (inverted) mass ordering. Absolute ν masses can be probed by the effective mass m_β in beta decay, by the total mass Σ in cosmology and—if neutrinos are Majorana—by another effective mass $m_{\beta\beta}$ in neutrinoless double beta decay. Within an updated global analysis of oscillation and nonoscillation data, we constrain these 3ν parameters, both separately and in selected pairs, and highlight the concordance or discordance among different constraints. Five oscillation parameters $(\delta m^2, |\Delta m^2|, \theta_{12}, \theta_{23}, \theta_{13})$ are consistently measured, with an overall accuracy ranging from $\sim 1\%$ for $|\Delta m^2|$ to $\sim 6\%$ for $\sin^2\theta_{23}$ (due to its persisting octant ambiguity). We find overall hints for normal ordering (at $\sim 2.5\sigma$), as well as for $\theta_{23} < \pi/4$ and for $\sin\delta < 0$ (both at 90% C.L.), and discuss some tensions among different datasets. Concerning nonoscillation data, we include the recent KATRIN constraints on m_β, and we combine the latest ^{76}Ge, ^{130}Te and ^{136}Xe bounds on $m_{\beta\beta}$, accounting for nuclear matrix element covariances. We also discuss some variants related to cosmic microwave background (CMB) anisotropy and lensing data, which may affect cosmological constraints on Σ and hints on $\mathrm{sign}(\Delta m^2)$. The default option, including all Planck results, irrespective of the so-called lensing anomaly, sets upper bounds on Σ at the level of $\sim 10^{-1}$ eV, and further favors normal ordering up to $\sim 3\sigma$. An alternative option, that includes recent ACT results plus other independent results (from WMAP and selected Planck data) globally consistent with standard lensing, is insensitive to the ordering but prefers $\Sigma \sim \text{few} \times 10^{-1}$ eV, with different implications for m_β and $m_{\beta\beta}$ searches. In general, the unfinished fabric of the 3ν paradigm appears to be at the junction of diverse searches in particle and nuclear physics, astrophysics and cosmology, whose convergence will be crucial to achieve a convincing completion.

CHAPTER 6

How to observe the mass scale? What is the nature of mass?
(again from 1930 but this time to the future)

Dear Radioactive Ladies and Gentlemen, … [neutrinos] differ from light quanta in that they do not travel with the velocity of light (1930)

The few ms neutrino burst from a core collapse supernova allows us to put an upper bound on neutrino mass (1968)

Thus, the **first method** proposed is the kinematical one:

a neutrino time-of-flight measurement

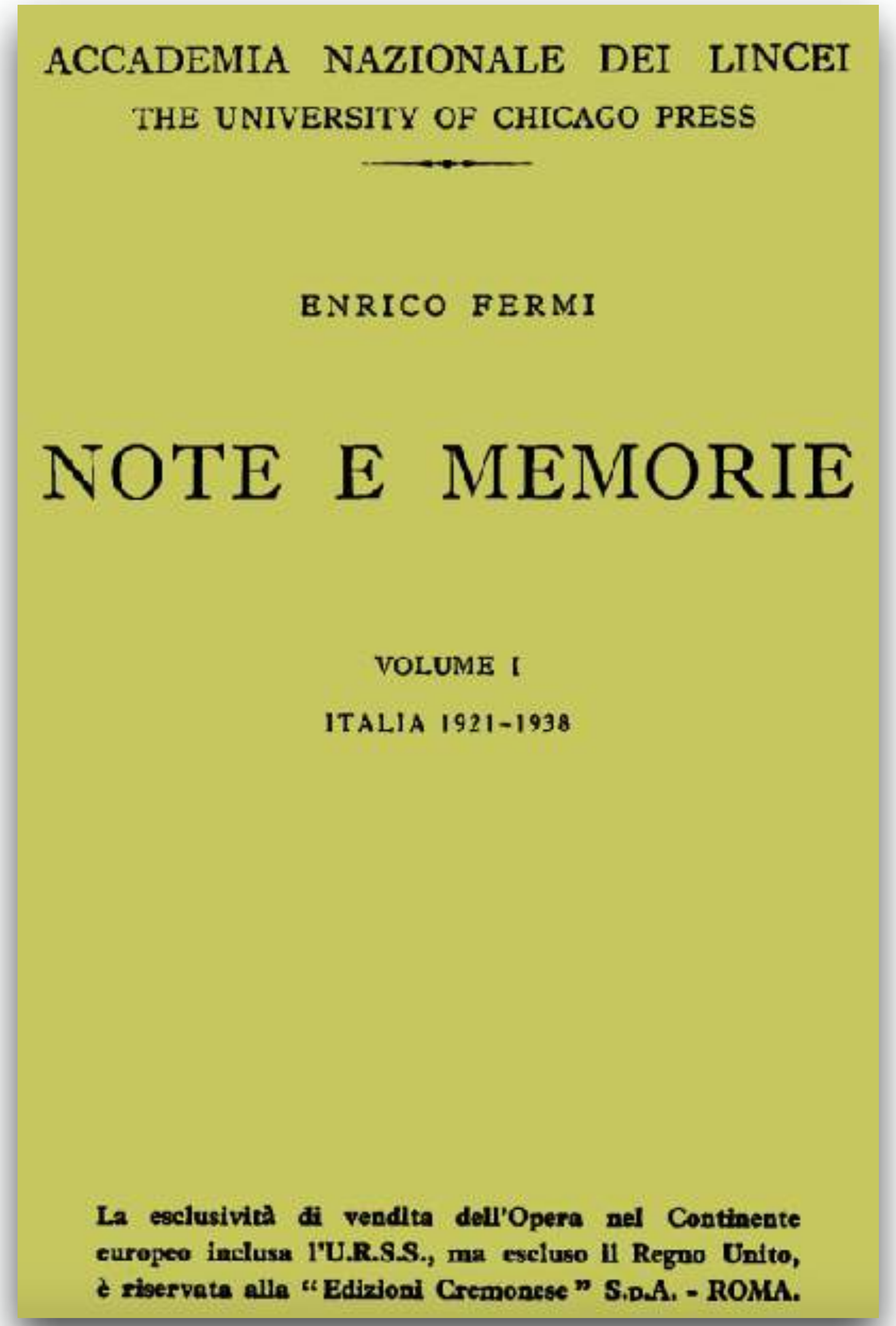
The most elaborate version yields

m_ν(kin) < 5.8 eV at 95% CL

exploiting SN1987A neutrino signal and a model

(see *arXiv* *1002.3349* and *Numass 2013* proceedings)

the shape of β ray spectrum at the endpoint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NOTE E MEMORIE

VOLUME I

ITALIA 1921-1938

La esclusività di vendita dell'Opera nel Continente europeo inclusa l'U.R.S.S., ma escluso il Regno Unito, è riservata alla "Edizioni Cremonese" S.p.A. - ROMA.

1934

TENTATIVO DI UNA TEORIA DEI RAGGI β (*)

« Nuovo Cimento », *11*, 1-19 (1934).

SUNTO. — Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria della irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.

Ist E_0 die Grenzenergie der β-Strahlen, so sieht man ohne Schwierigkeit dass die Verteilungskurve der β-Strahl Energie für Energien E in der Nähe von E_0 proportional ist ~~gegeben ist durch~~ zu

(36) $$\frac{P_\sigma^2}{v_\sigma} = \frac{1}{c^3}\left(\mu c^2 + E_0 - E\right)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per $\mu = 0$, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

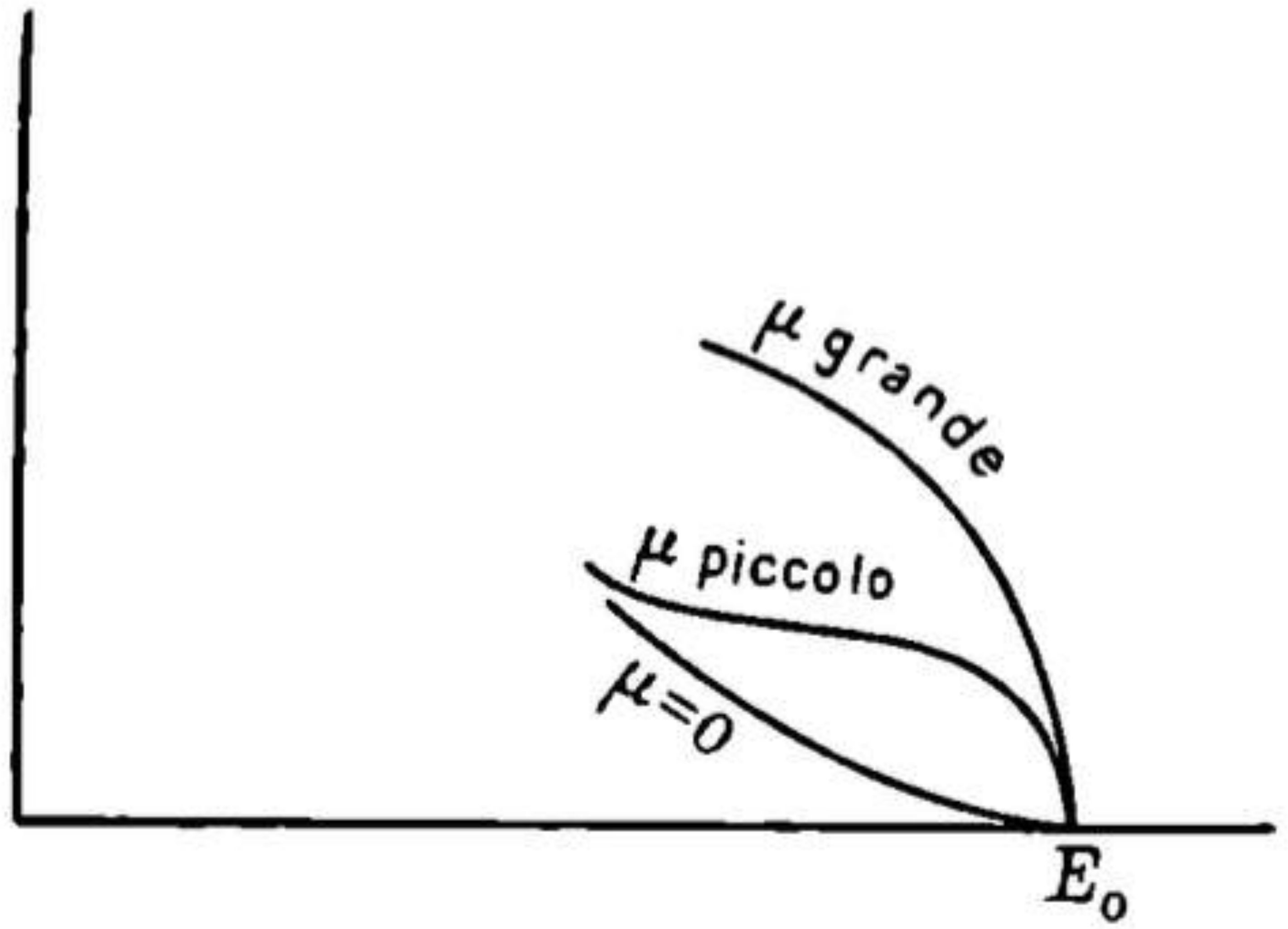


Fig. 1.

curve sperimentali si ha per la curva teorica corrispondente a $\mu = 0$. Arriviamo così a concludere che la massa del neutrino è uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone (5). Nei calcoli che seguono porremo per semplicità $\mu \doteq 0$.

(5) In una recente notizia F. PERRIN, « C. R. », *197*, 1625 (1933), giunge con argomenti qualitativi a una simile conclusione.

oscillation help just a little bit

McKellar, 1980

$$m_{\bar{\nu}_e}^2 = \sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}^2 \geq \sum_{i=1}^{3} U_{ei}^2\, (m_{\nu_i}^2 - m_{\nu_{min}}^2) \equiv m_{\text{osc}}^2$$

FV, 2000

where

$$m_{\text{osc}} = \begin{cases} 8.8 \text{ meV} & (\text{normal}, \ \pm 1.3\%) \\ 48.8 \text{ meV} & (\text{inverse}, \ \pm 0.6\%) \end{cases}$$

current best limit: $m_{\bar{\nu}_e} < 450$ meV - **Katrin collaboration**

cosmology probes the number of neutrinos

recall that *Big bang theory* is Gamow's stuff, not only Sheldon Cooper's 😉

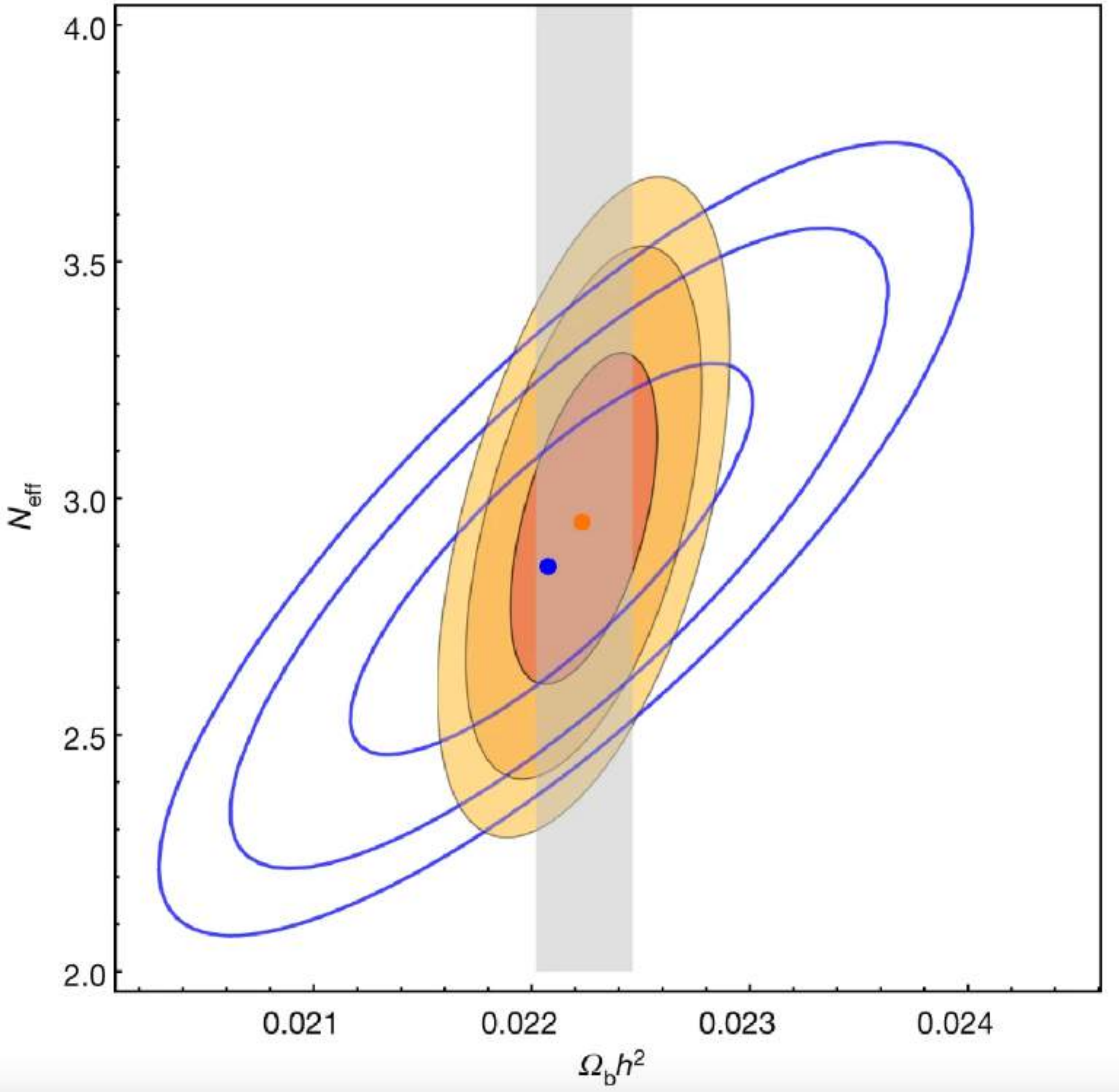
Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino ✉, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli ✉

— Show fewer authors

Nature **587**, 210–213 (2020) Cite this article



cosmology also probes sum of neutrino masses

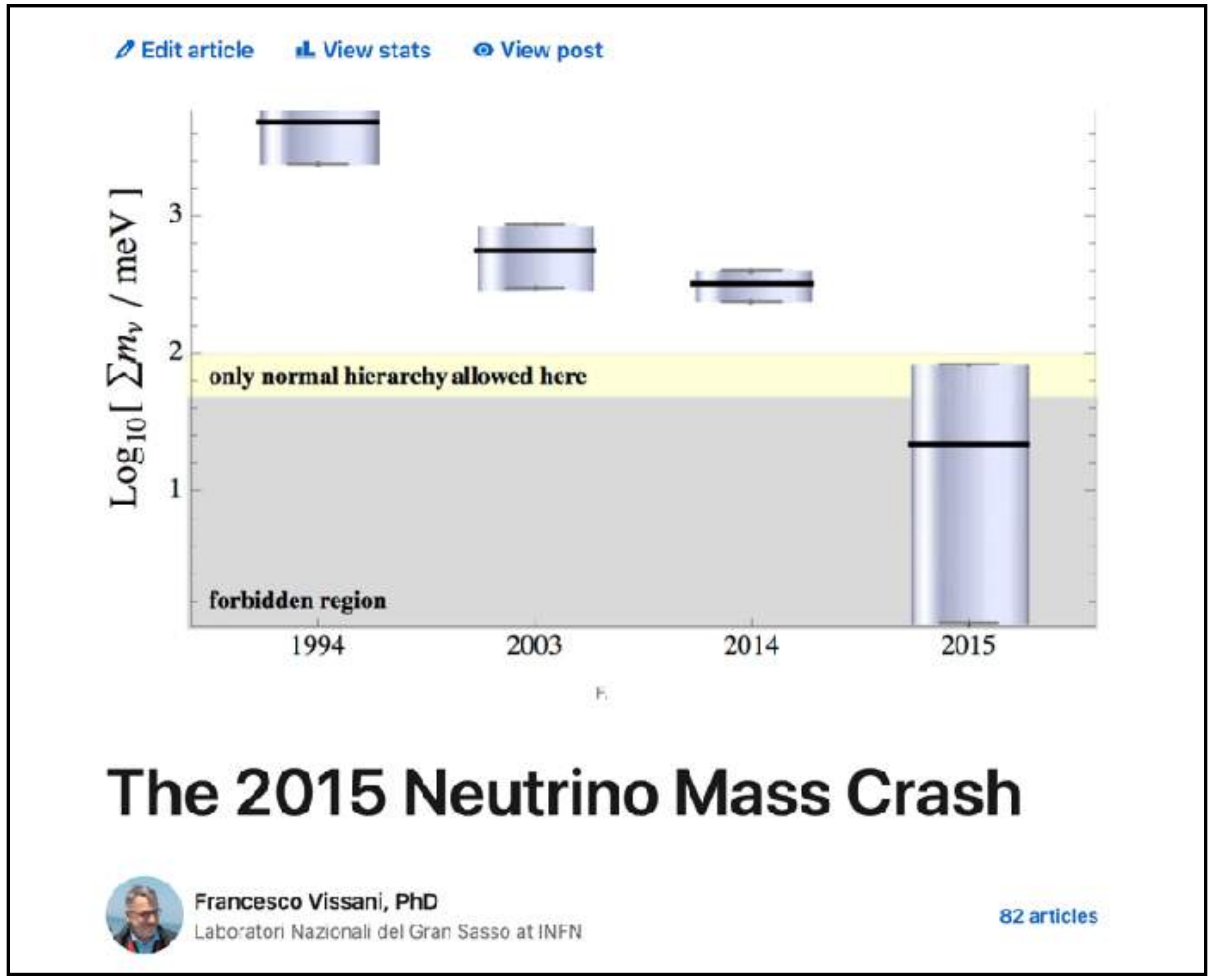
since 10 years at least

Neutrino masses tilts the distribution on small scales compared to large scales from cosmological ***models***

Large scale from the CMB and small scales from BAO (or the Lyman-α forest) provide ***observations***

Thence, the bound. A early result by Seljak *et al* (0604335) was criticised, but Planck confirmed it

$$\sum_i m_i < 110 \text{ meV at } 95\% \text{ CL}$$



significance of Majorana's proposal

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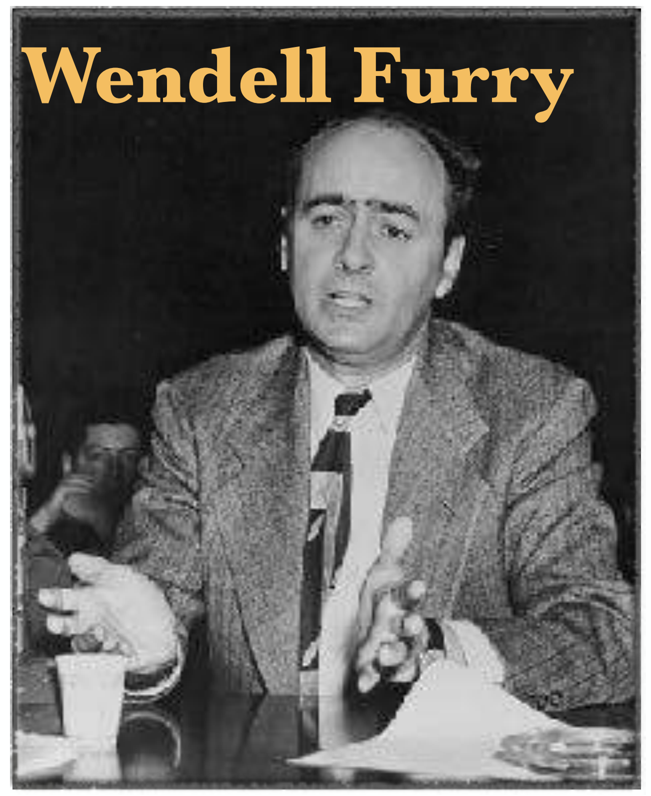

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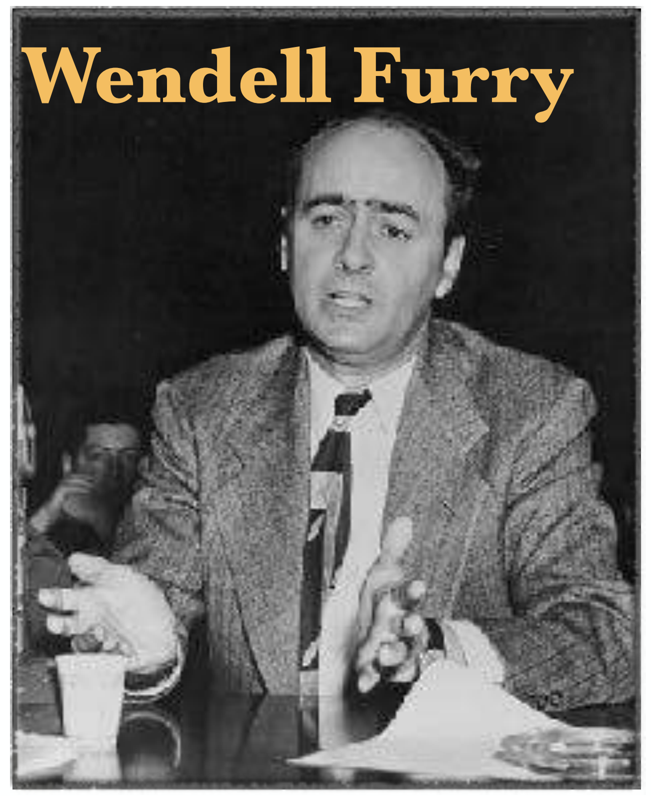

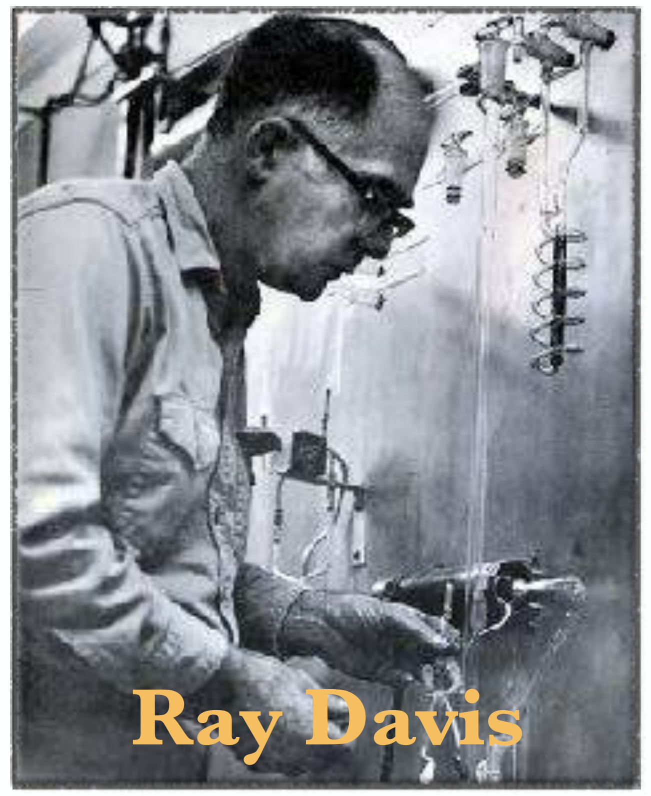

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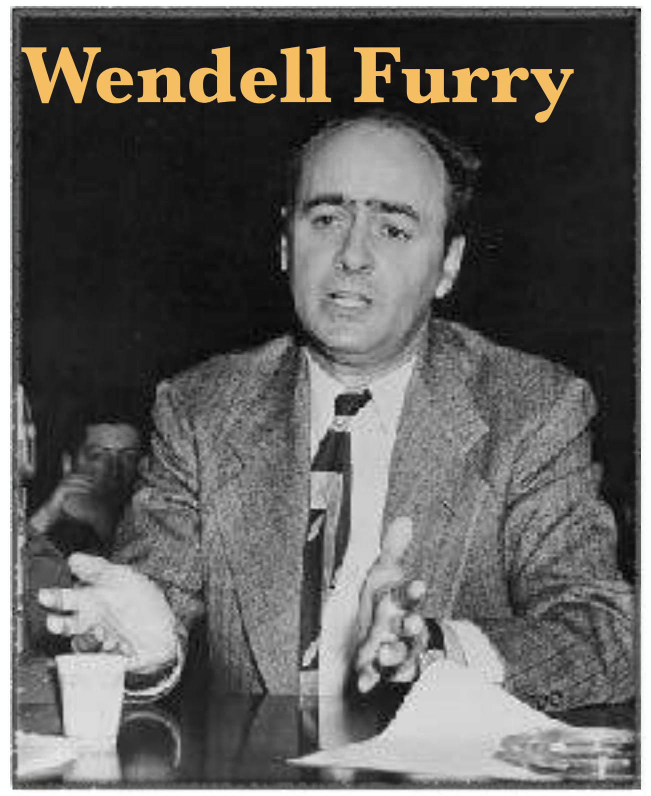
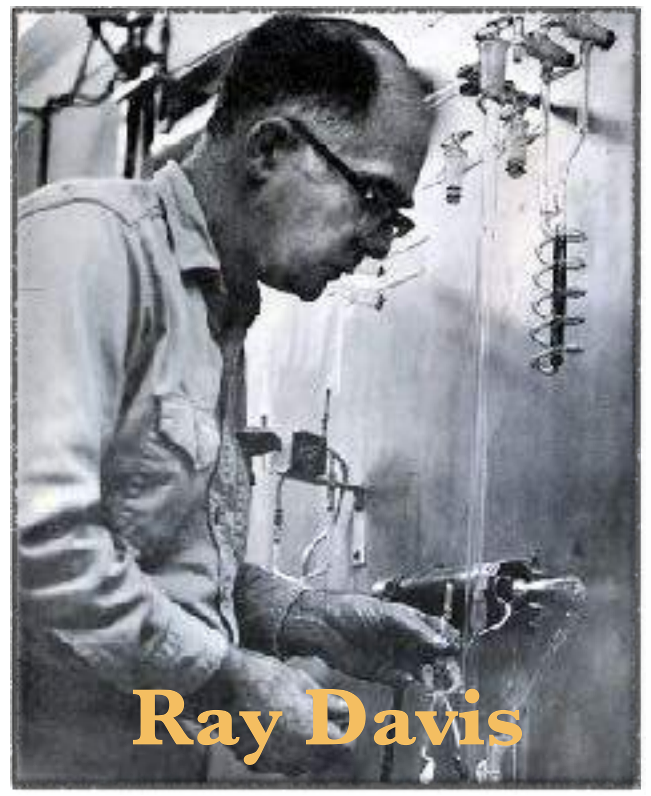
Is Majorana's theory ruled out?





no

in the V-A context, the $\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ *transition is almost entirely forbidden for relativistic neutrinos, being proportional to the small*

Majorana neutrino mass

— *only at order* $\dfrac{m_\nu c^2}{E_\nu}$, *neutrinos mix with antineutrinos* —

and, as first pointed out in 1960, also

$(Z, A) \rightarrow (Z, A+2) + 2e^{-}$

transition amplitude is proportional to Majorana' mass

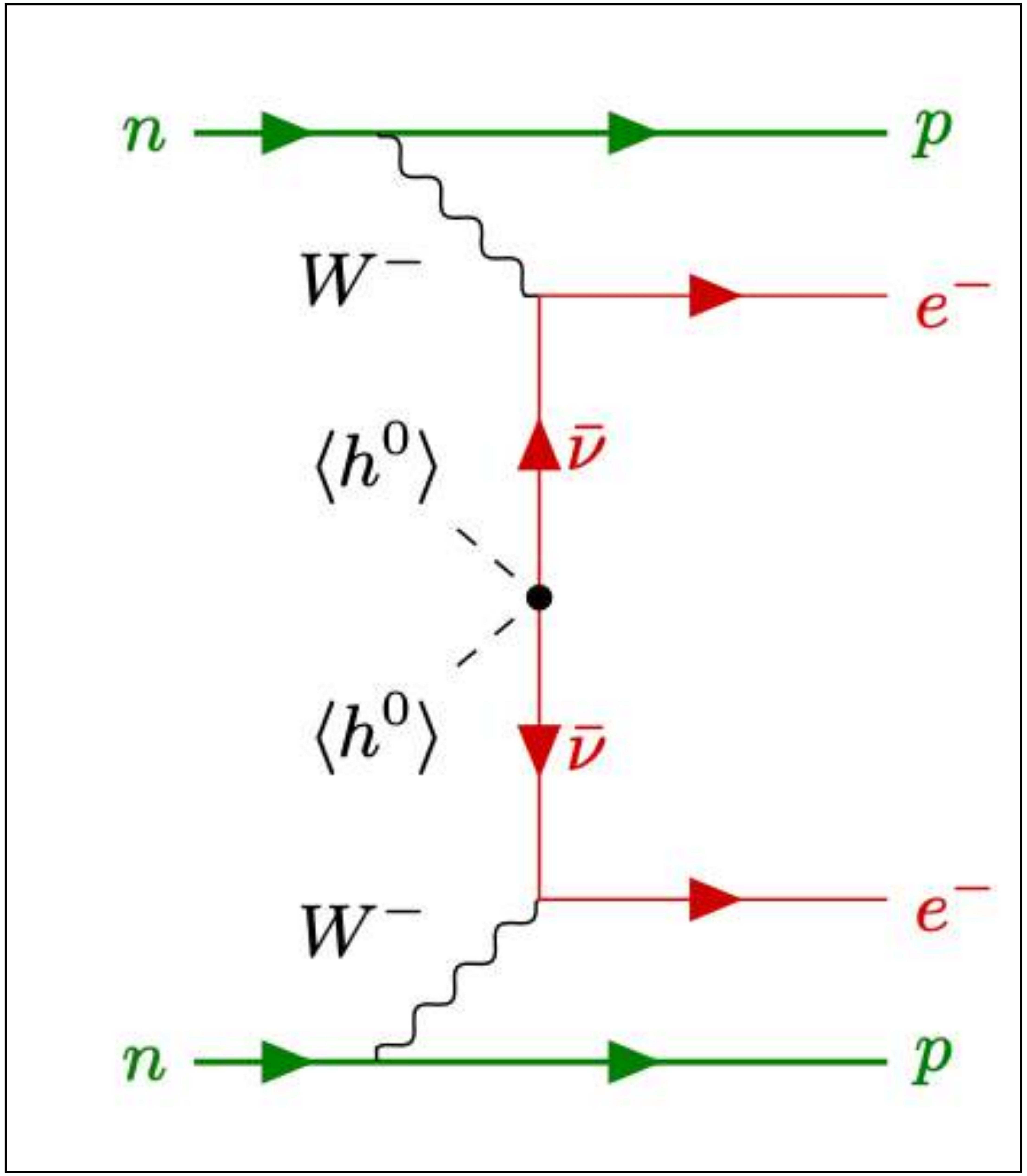
ANNALS OF PHYSICS: **11**, 510–533 (1960)

Lepton Conservation and Double Beta-Decay*†

EUGENE GREULING AND R. C. WHITTEN‡

Department of Physics, Duke University, Durham, North Carolina

Double beta-decay is investigated without assuming lepton conservation. If the lepton part of the universal *V–A* current operator is linear in the massless Majorana neutrino field, leptons are conserved. The intermediate state neutrino is completely polarized and may not be reabsorbed to produce a neutrinoless double beta-decay final state. Two slight modifications of the interaction, (1) finite neutrino mass, and/or (2) a deviation from exact equality of the effective *V* and *A* lepton currents, result in the creation of an incompletely polarized intermediate state neutrino which may then be reabsorbed. Neutrinoless double beta-decay, in violation of lepton conservation, is then possible. These neutrinoless modes of double beta-decay are computed for several nuclei and are compared with the usual lepton conserving two-neutrino mode. Measureable competition between these decay modes may exist. The abandonment of lepton conservation does not alter significantly any of the predictions of the universal *V–A* Fermi interaction for all first order beta-processes.



Agostini et al, RMP 2023

neutrinos can mix with antineutrinos: but only due to Majorana mass **in V-A model**

NEUTRINO 2024

XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

Topics

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- Neutrino mass
- Neutrinoless Double Beta Decay
- Neutrino interactions
- Accelerator neutrinos
- Reactor neutrinos
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
- Astrophysical neutrinos
- Geoneutrinos
- Neutrino role in cosmology
- Sterile neutrinos
- Theory of neutrino masses and mixing, Leptogenesis
- Beyond Standard Model searches in the neutrino sector
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https://agenda.infn.it/event/37667

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Thanks!

with partial support of INFN Gran Sasso, INAF Osservatorio di Brera, research grant number 2022E2J4RK ``PANTHEON: Perspectives in Astroparticle and Neutrino THEory with Old and New messengers" under the program PRIN 2022 funded by the Italian Ministero dell'Universita' e della Ricerca (MUR) & European Union – Next Generation EU

where I wrote about that

- *what is matter according to particle physics, and why try to observe its creation in a lab?, 2103.02642 (universe, 2021)*
- *first steps towards understanding neutrinos, 2310.07834 (quaderni di storia della fisica, 2024)*
- *a discussion of the cross section* $\bar{\nu}_e + p \to e^+ + n$*, 2311.16730 (mayorana conference proceedings, 2023)*
- *toward the discovery of matter creation with* $0\nu 2\beta$ *decay, 2202.01787 (rmp, 2023)*

a few references I found particularly useful

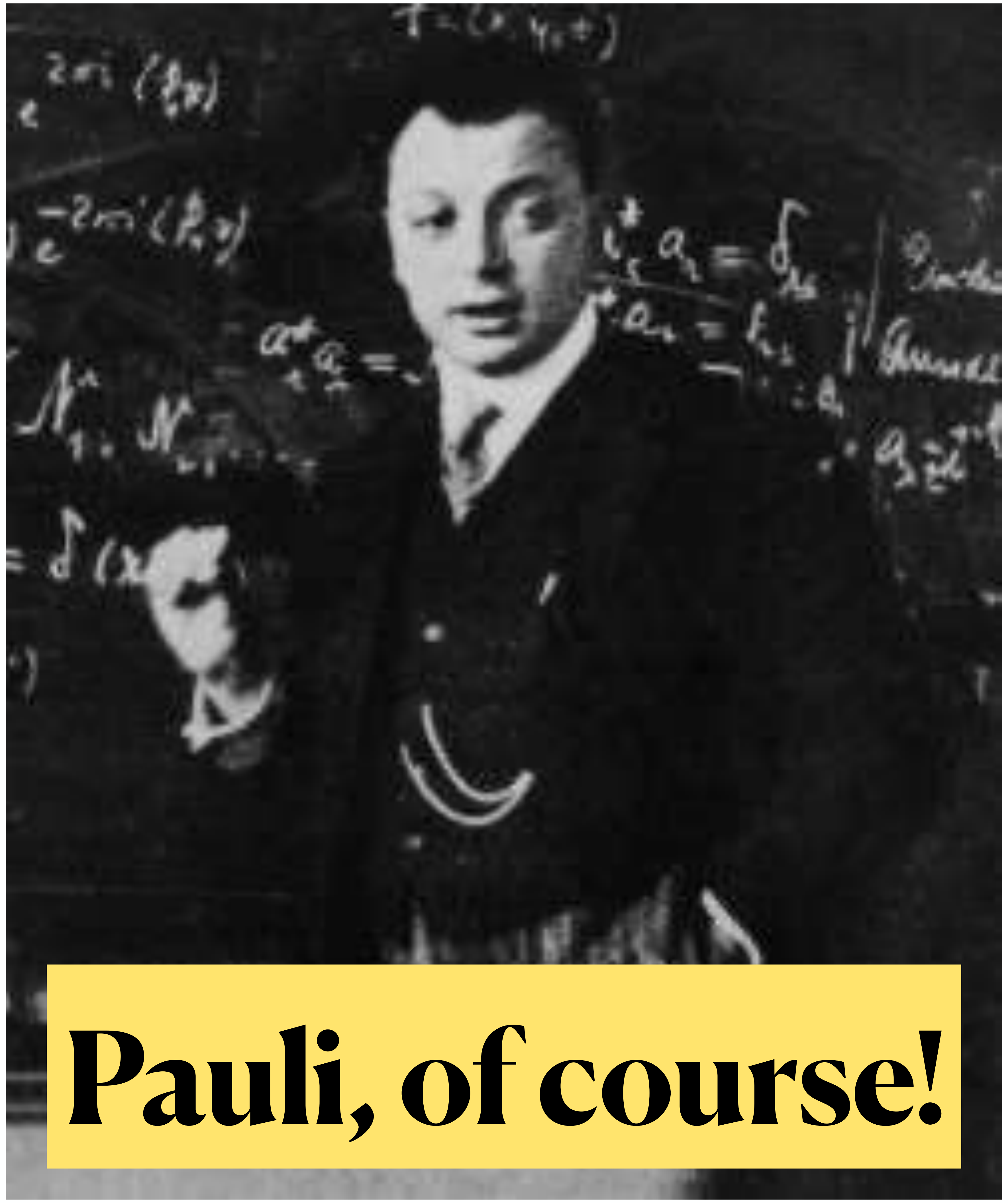
- *pages in the development of neutrino physics, Bruno Pontecorvo, 1983*
- *neutrino unbound, Carlo Giunti et al, https://www.nu.to.infn.it/*
- *neutrino. the mutant particle, 2016 - Italian version is free*
- *history of the neutrinos, https://neutrino-history.in2p3.fr/books/*

APPENDICES

ideas, formalism and a bit more of history

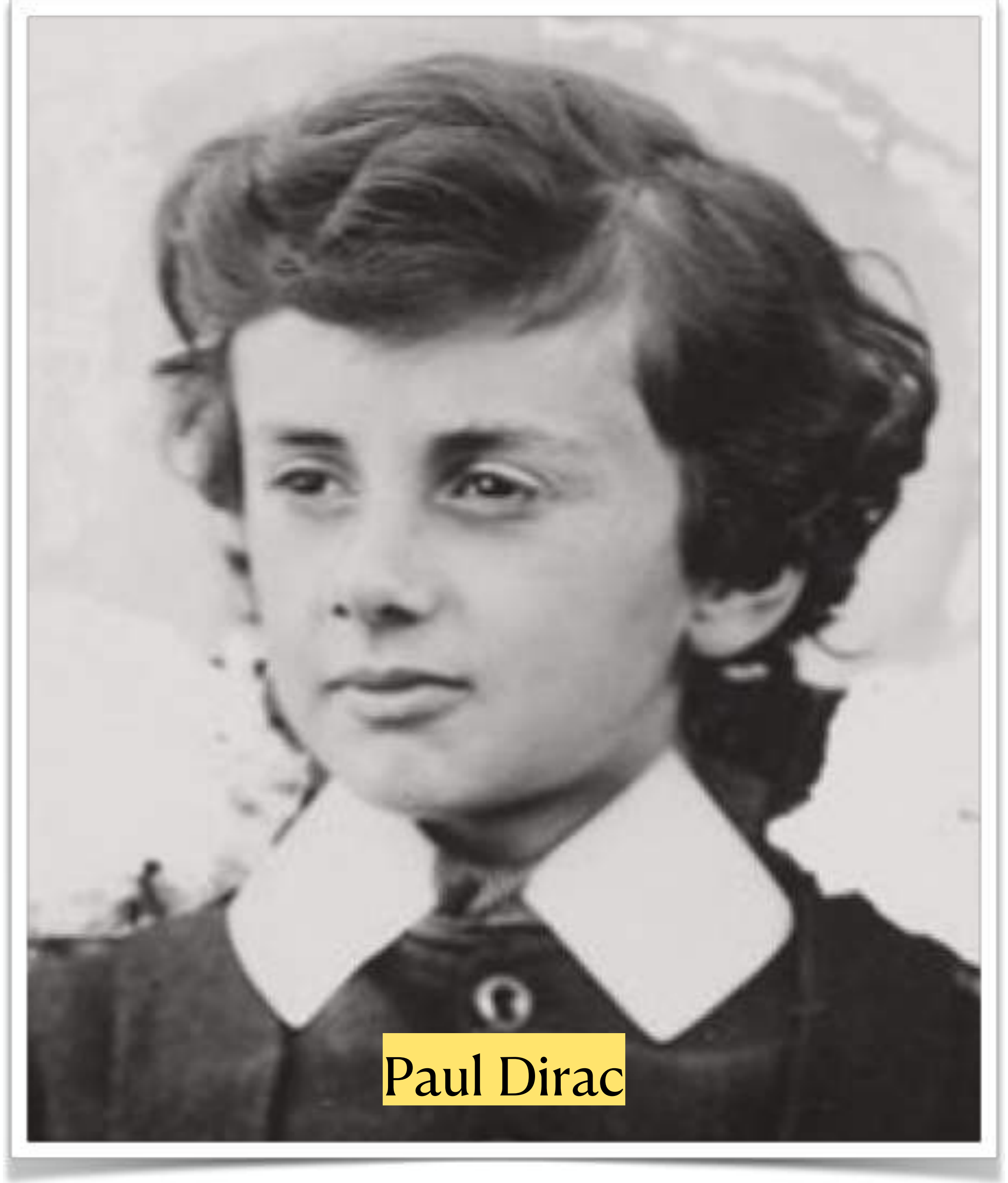
who is the star?

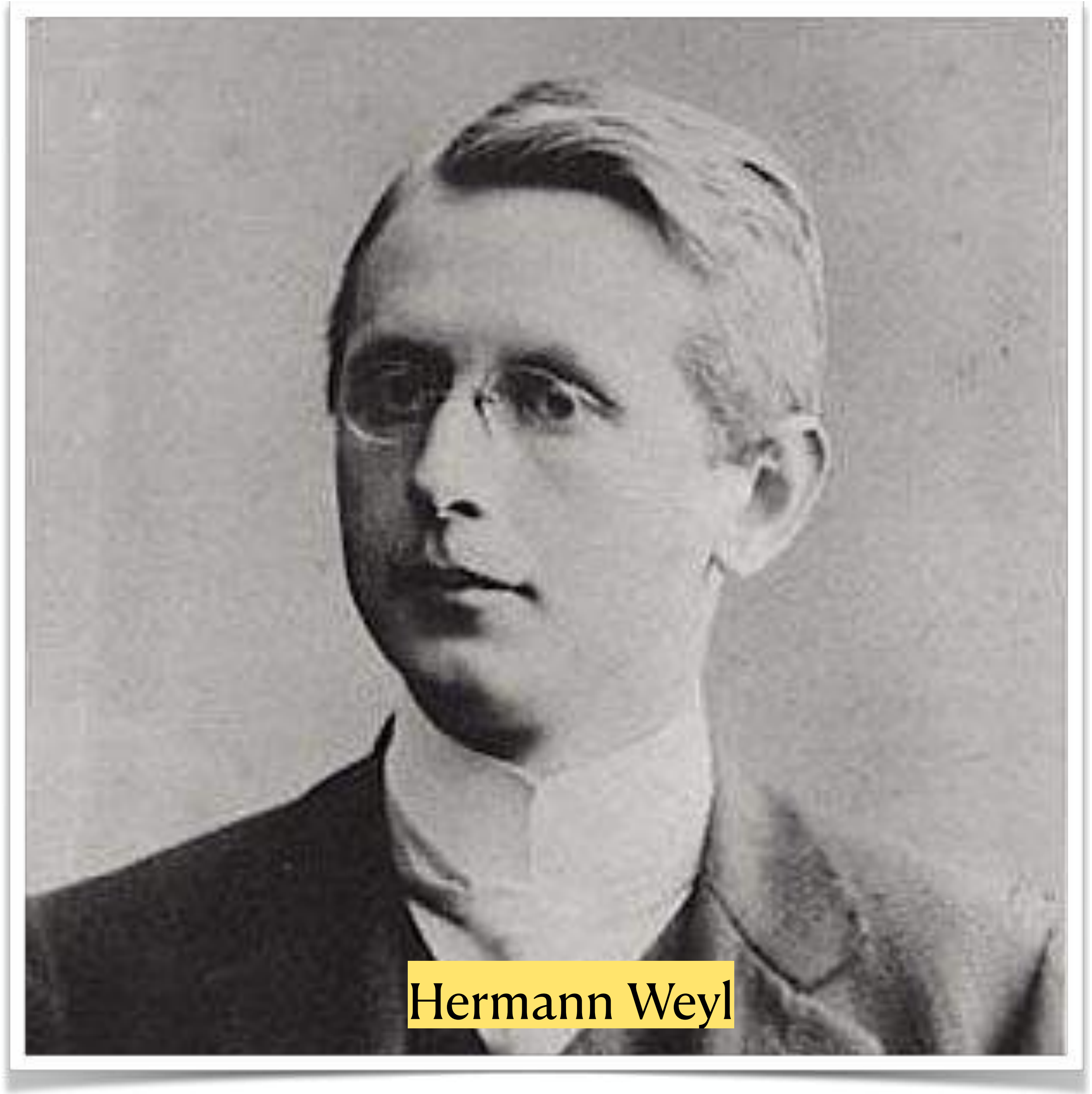
who was the star of the neutrino story?



but neutrino memory book is much richer, even if we limit ourselves only to 1st ten years - and thus to theorists

1928-30





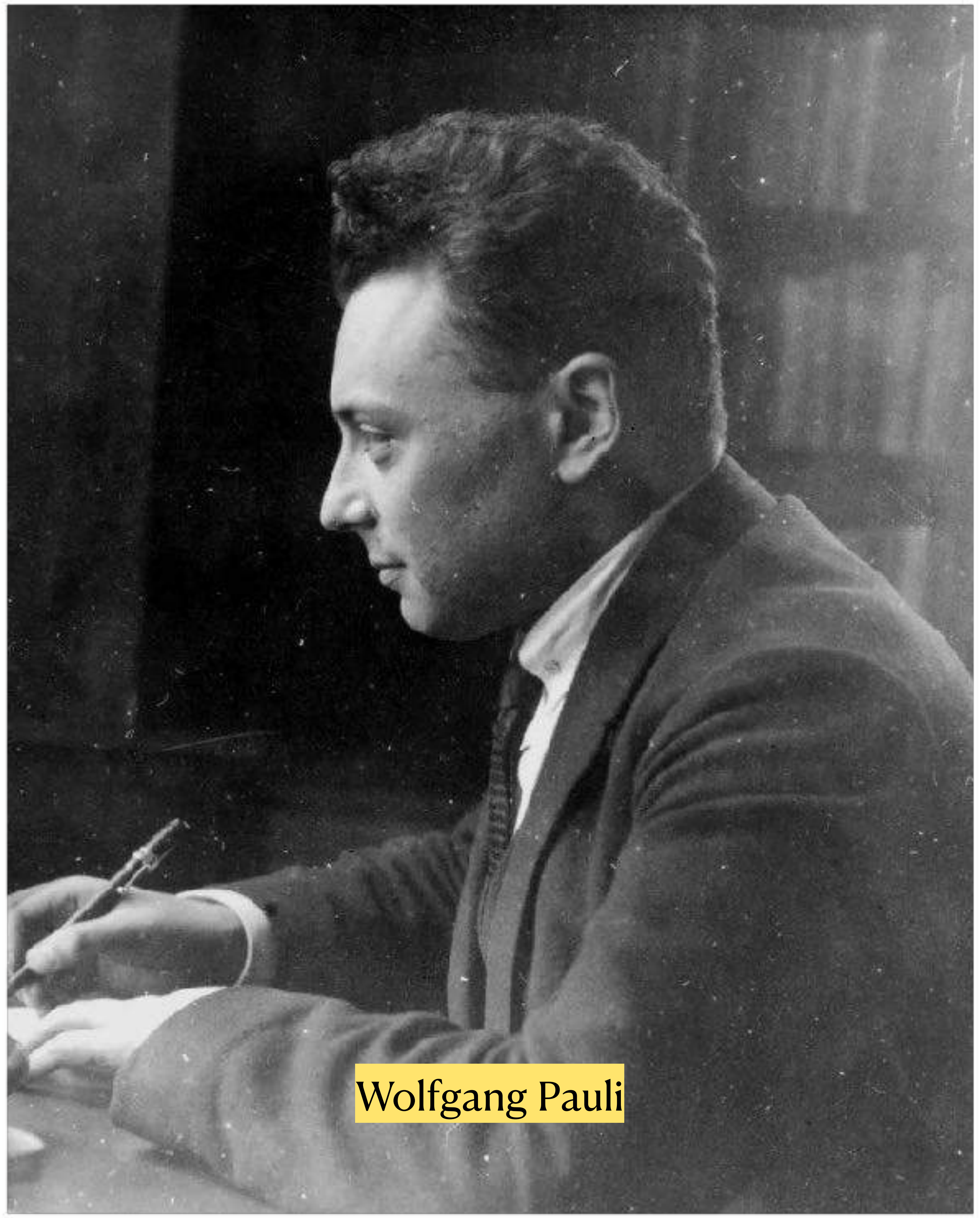
1929

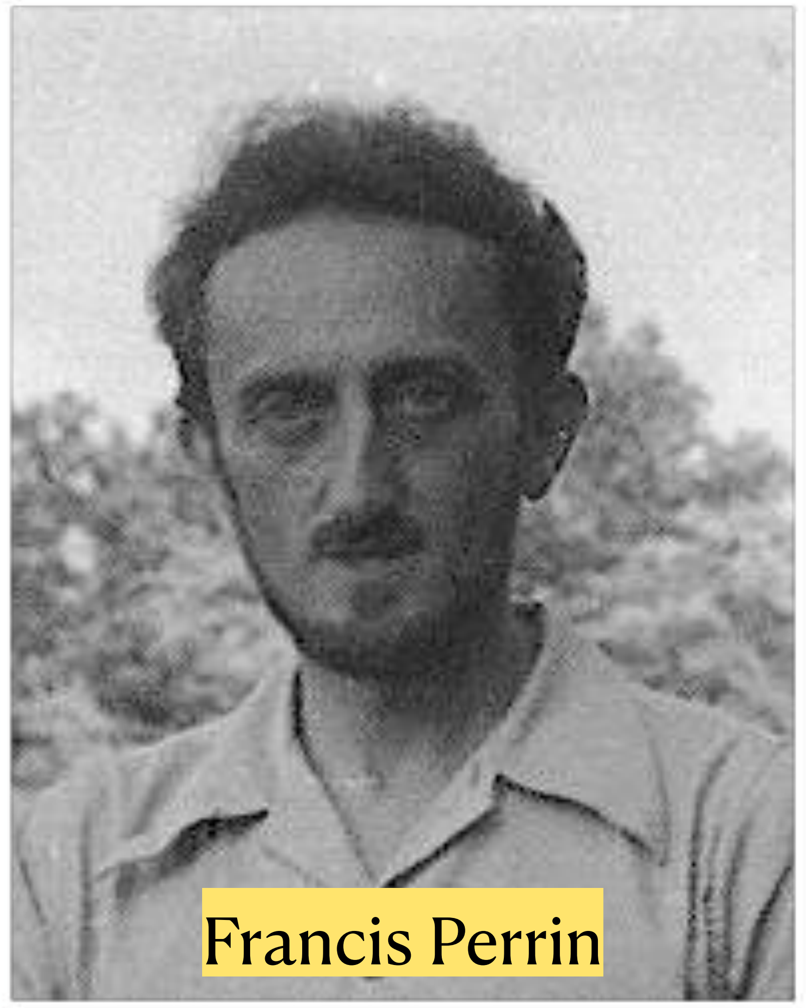
1930


Dmitri Iwanenko


Victor Ambarzumjan

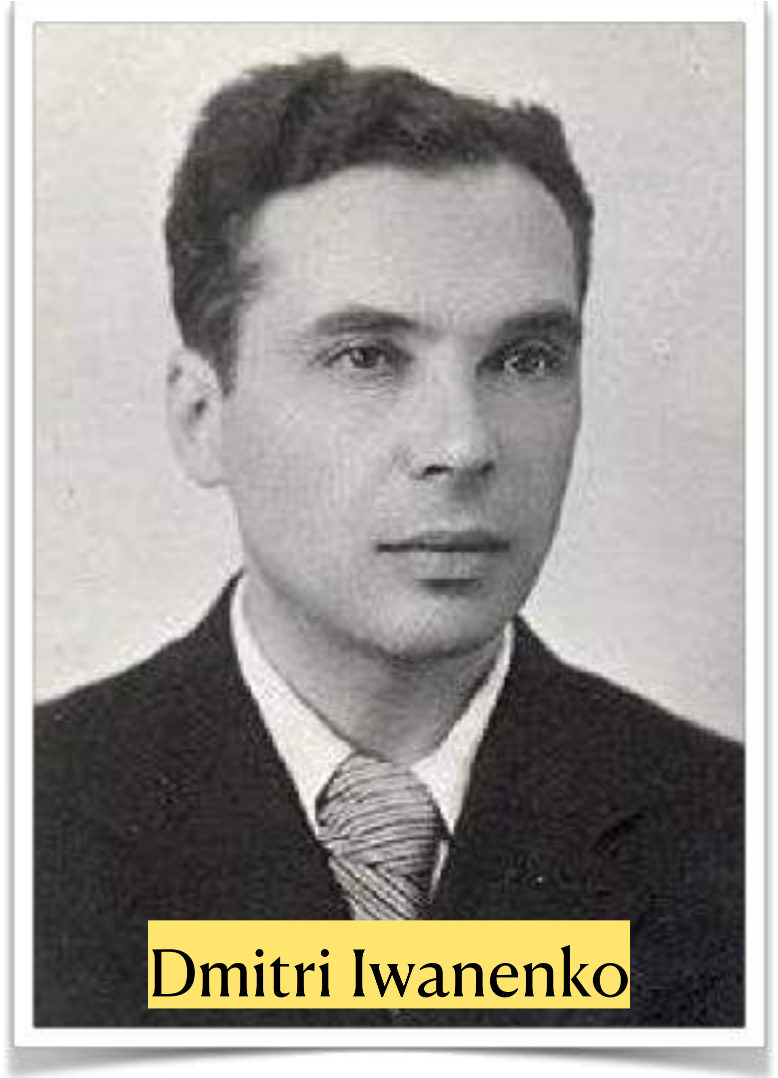
1930-56

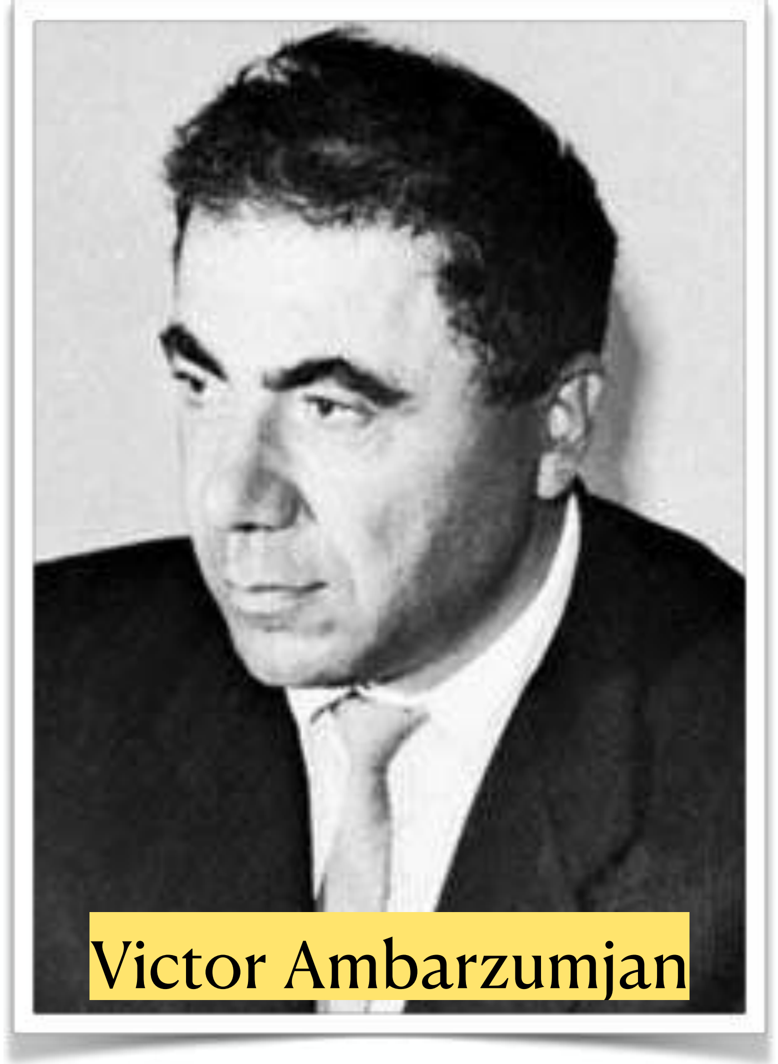

Wolfgang Pauli


Francis Perrin

1933

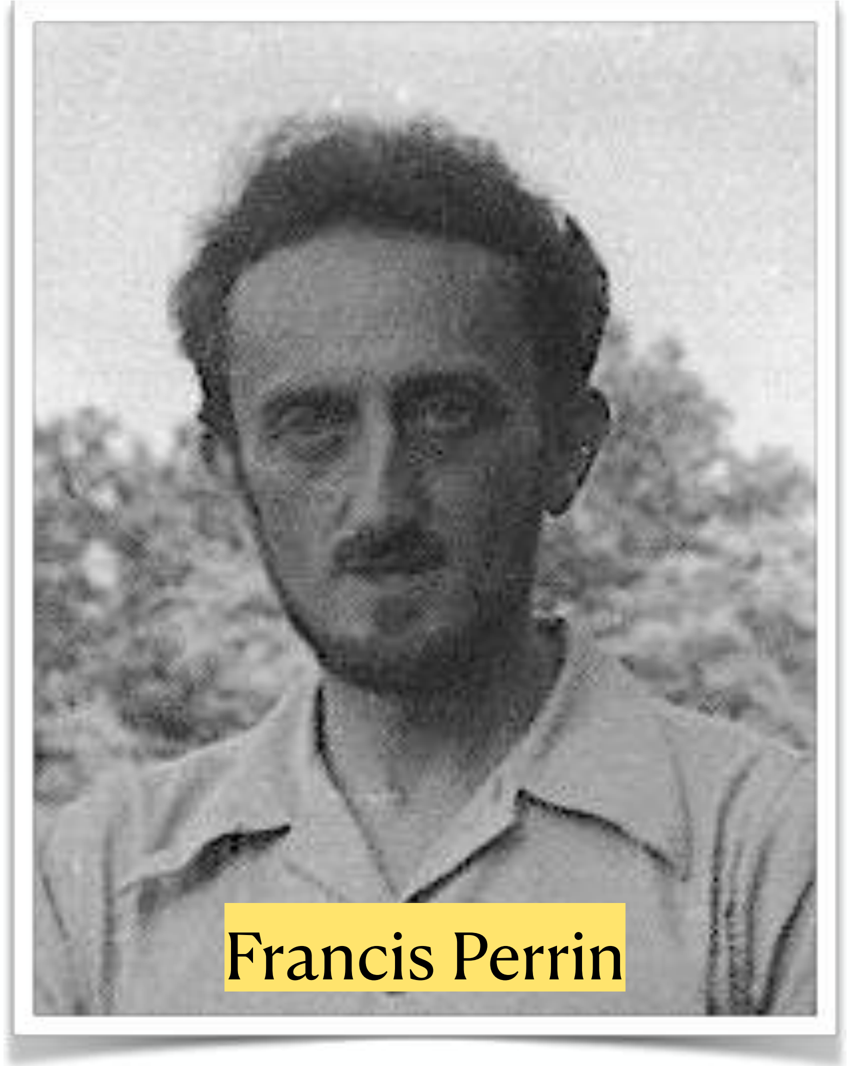
1930


Dmitri Iwanenko


Victor Ambarzumjan

1933-34


Enrico Fermi

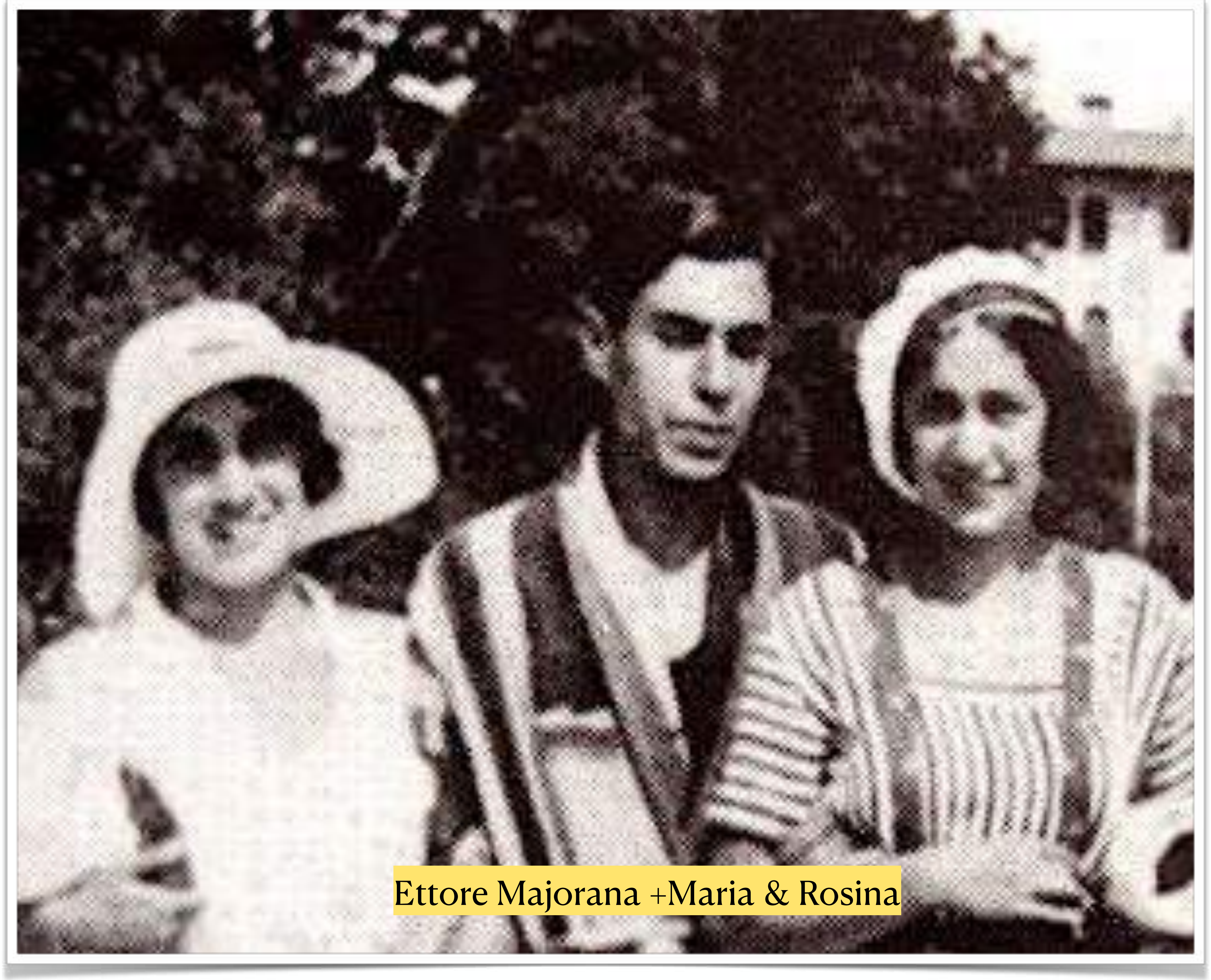

Francis Perrin

1933

1934


Gian Carlo Wick

1937


Ettore Majorana +Maria & Rosina

1937


Giulio Racah

even a minimal version has many stars

[***Dirac 1928:*** antimatter - nothing on neutrinos]

[***Weyl 1929:*** the right math in a wrong moment]

Pauli 1930: the new particle but in a completely outdated context

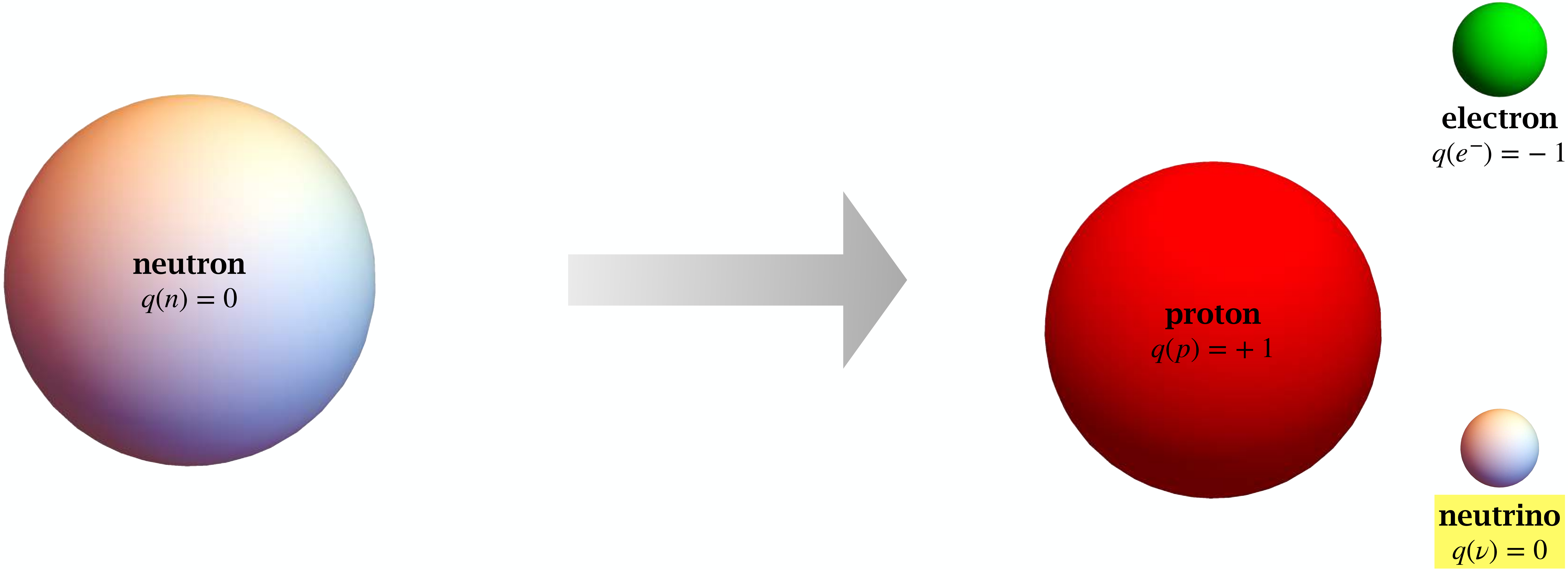
Fermi 1933: a calculable theory built over old Dirac's theory

Majorana 1937: modern quantum field theory & new idea of neutrino

(later: $0\nu 2\beta$, lepton number, parity violation, V-A, Cabibbo angle...)

how *not to* present Fermi

when Fermi's theory is presented with a diagram as follows



it conceals (does not reveal) the reasoning. Let's get back to history

importance of electron capture

entry into weak interactions world

- $n \to p + e + \nu$ *implies the existence of* $p + e + \nu \to n$
- *Consider the presence of a* ***neutrino hole:*** $p + e + \nu + \nu \to n + \nu$
- *Let's cancel the pair* $\nu + \nu$ *and we are left with* $p + e \to n + \nu$

first prediction of ***electron capture*** *(Wick 1934)*

electron capture and Dirac neutrino sea

electron capture and Dirac neutrino sea

the role of Wick's reaction:

JUNE 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 61

Experimental Evidence for the Existence of a Neutrino

JAMES S. ALLEN
Kansas State College, Manhattan, Kansas

(Received March 16, 1942)

Radioactive Be^7 was deposited on a platinum foil by means of a new evaporation technique. An electron multiplier tube was employed to count the recoil nuclei produced in the reaction, $Be^7+e_K\rightarrow Li^7+\eta+Q$. The maximum energy of the recoils was about 40 to 45 electron volts compared with the value of 58 electron volts to be expected for a neutrino of zero rest mass. An attempt was made to detect coincidences caused by the emission in opposite directions of a gamma-ray and a recoil nucleus. The observed coincidences were less than two percent of those expected for gamma-ray recoils. Apparently the recoils were caused by the emission of a neutrino and not by the emission of a gamma-ray.

on wide acceptance of Dirac sea

Heisenberg 1934 uses Dirac sea

"Bemerkungen zur Diracschen Theorie des Positrons," Zeit. Phys. **90** (1934), 209-231.

Remarks on the Dirac theory of positron

By **W. Heisenberg** in Leipzig

(Received on 21 June 1934)

Translated by D. H. Delphenich

I. Intuitive theory of matter waves.
   1. The inhomogeneous differential equation of the density matrix.
   2. The conservation laws.
   3. Applications (polarization of the vacuum).

II. Quantum theory of the wave field.
   1. Presentation of the field equations.
   2. Applications (the self-energy of light quanta).

If, as the Dirac theory of holes requires, all states of negative energy are occupied, except for finitely many of them, and also only finitely many positive energy states are occupied

If one represents the wave function in the form:

$$\psi(x,k) = \sum_n a_n u_n(x,k)\,,$$

where the equations:

$$a_n a_m^* + a_m^* a_n = \delta_{nm}$$

SM and neutrinos

neutrino masses in modern language

(extending the lagrangian density of the standard model)

$$\mathscr{L} = i\,\bar{\nu}_L\,\partial_a \gamma^a\,\nu_L$$

Lepton # conserving

Lepton # breaking

neutrino masses in modern language

(extending the lagrangian density of the standard model)

$$\mathscr{L} = i\,\bar{\nu}_L\,\partial_a \gamma^a\,\nu_L \quad -(m_{LL}\,\bar{\nu}_L C \bar{\nu}^t_L + \text{h.c.})$$

Lepton # conserving	*Lepton # breaking*

neutrino masses in modern language

(extending the lagrangian density of the standard model)

$$\mathscr{L} = i\,\bar{\nu}_L\,\partial_a\gamma^a\,\nu_L - (m_{LL}\,\bar{\nu}_L C \bar{\nu}_L^t + \text{h.c.})$$

$$-(m_{LR}\,\bar{\nu}_R \nu_L + \text{h.c.})$$

$$+ i\,\bar{\nu}_R\,\partial_a\gamma^a\,\nu_R - (m_{RR}\,\bar{\nu}_R C \bar{\nu}_R^t + \text{h.c.})$$

Lepton # conserving | *Lepton # breaking*

helicity and chirality

more on helicity-chirality connection

consider the wavefunction in Dirac representation:

$$\psi_\lambda(\overrightarrow{x}) = \frac{e^{i(\overrightarrow{x},\overrightarrow{p})}}{\sqrt{2V}}\, u_\lambda$$

with

$$\lambda = \pm 1 \;\; ; \;\; u_\lambda = \begin{pmatrix} \sqrt{1+\varepsilon}\;\varphi_\lambda \\ \lambda\sqrt{1-\varepsilon}\;\varphi_\lambda \end{pmatrix} \; ; \; \varepsilon = \frac{mc^2}{E}$$

more on helicity-chirality connection

evaluate the amount of "wrong" chirality

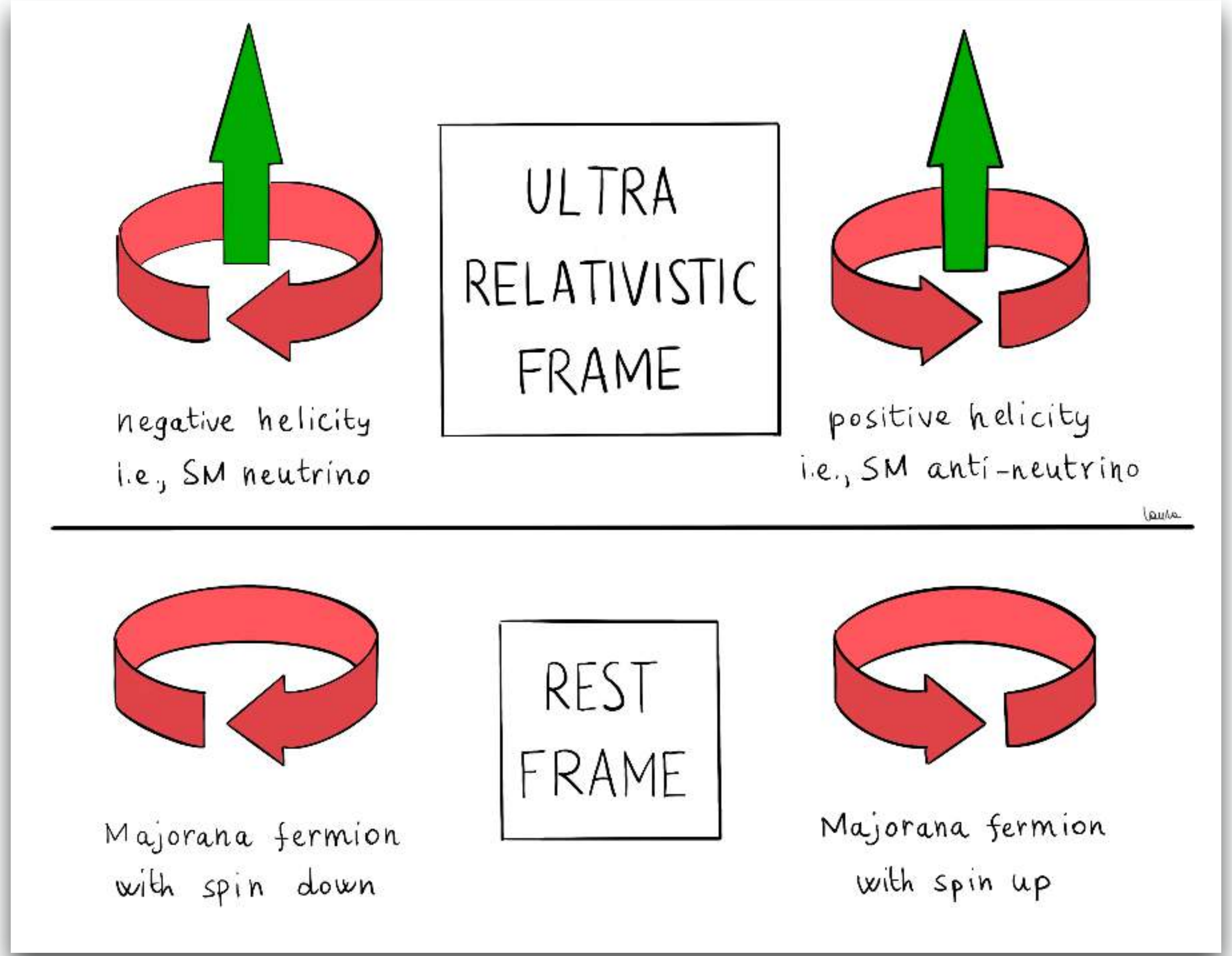
$$P_L\, u_+ \qquad \text{where} \quad P_L = \frac{1}{2}\begin{pmatrix} +1 & -1 \\ -1 & +1 \end{pmatrix}$$

we find easily

$$P_L\, u_+ = \frac{\varepsilon}{\sqrt{1+\varepsilon}+\sqrt{1-\varepsilon}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \varphi_+$$

which is small when $p \gg mc$, being $\propto \varepsilon = (mc^2)/E$

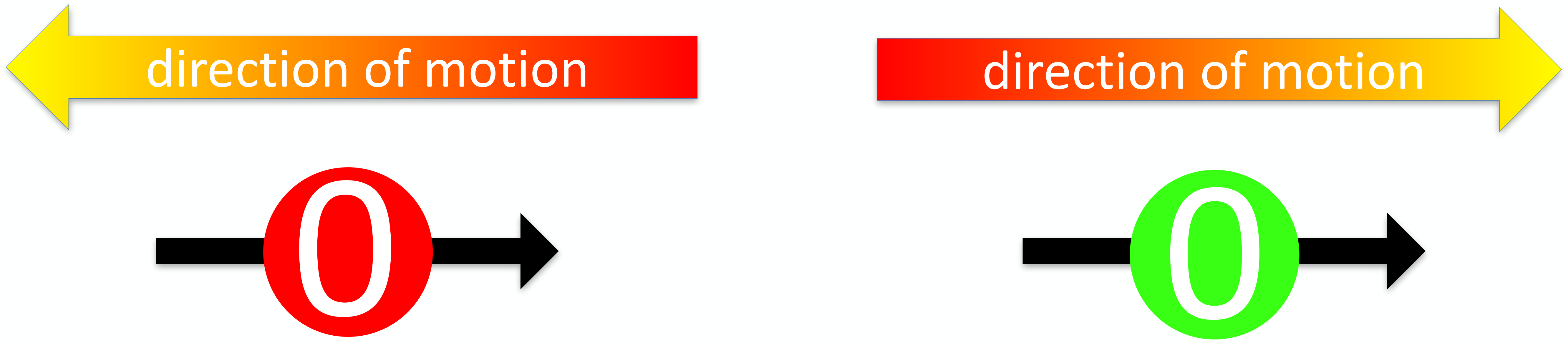
V-A and Majorana



FV, 2023

in the fast-moving system $\nu \neq \bar{\nu}$ **and** in the rest system $\nu = \bar{\nu}$ in V-A model

Majorana neutrinos in V-A context



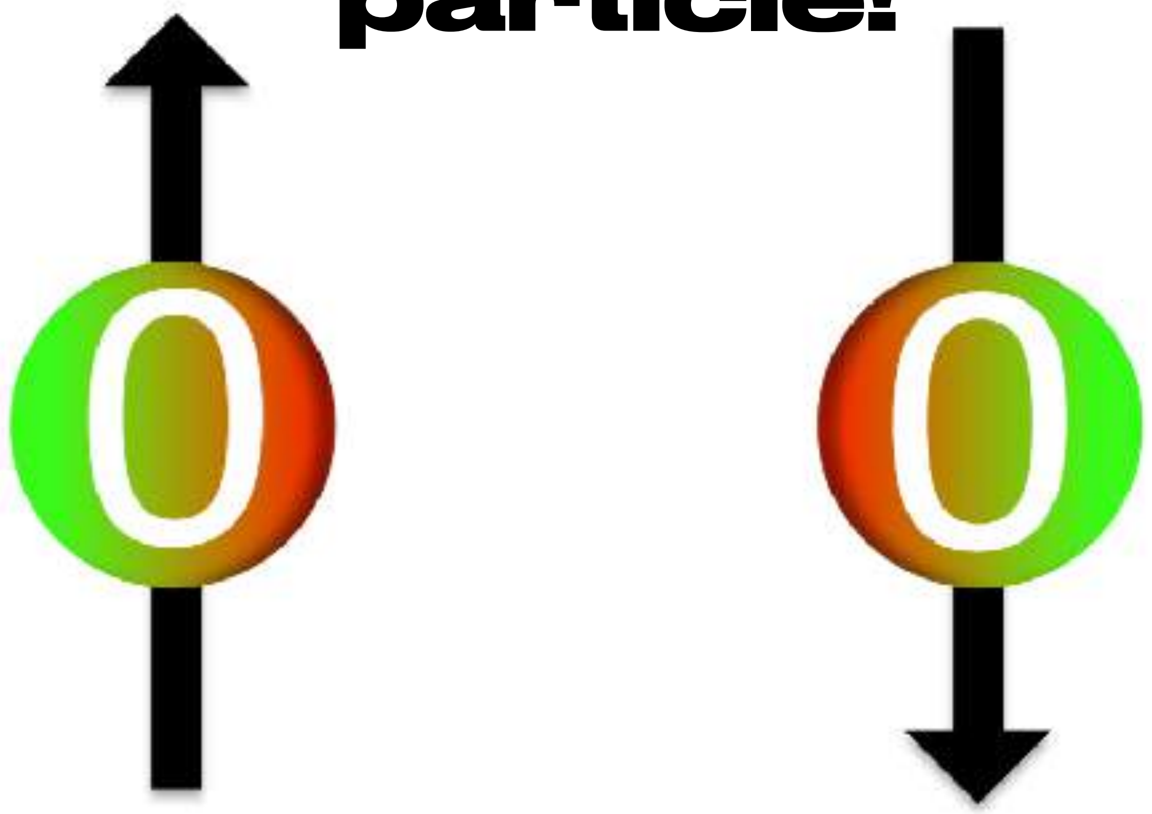
parallel/antiparallel means neutrino/antineutrino

Majorana neutrinos in V-A context

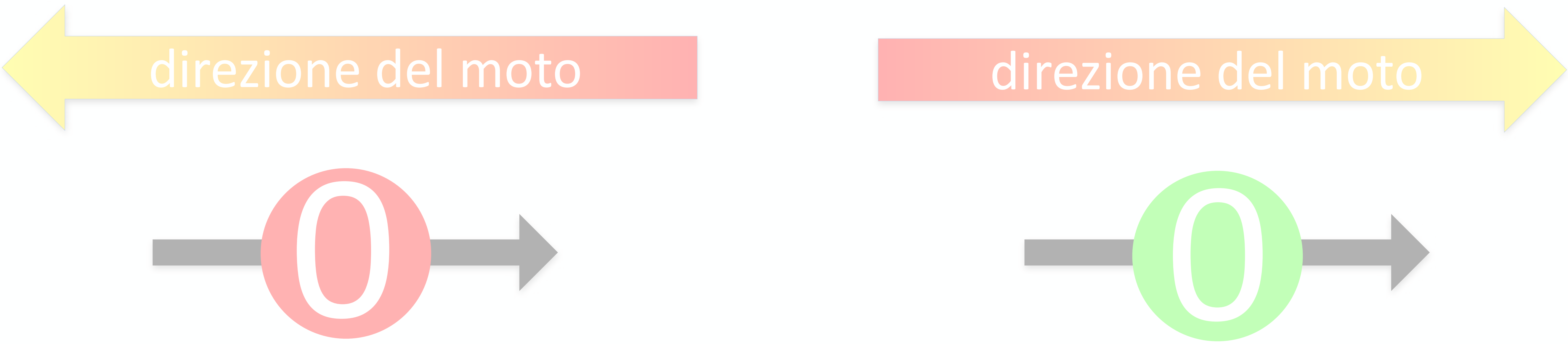
parallel/antiparallel means neutrino/antineutrino

Majorana neutrinos in V-A context

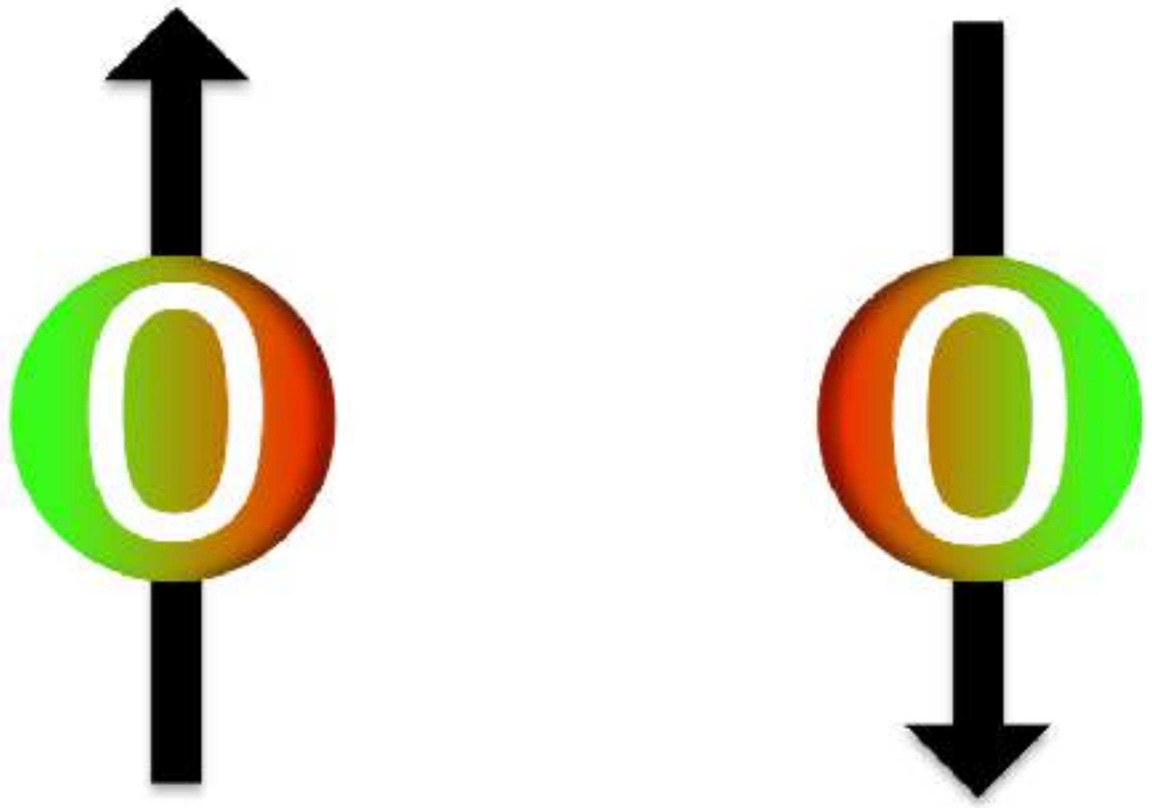
but in the rest system they seem to be the same particle!



Majorana neutrinos in V-A context

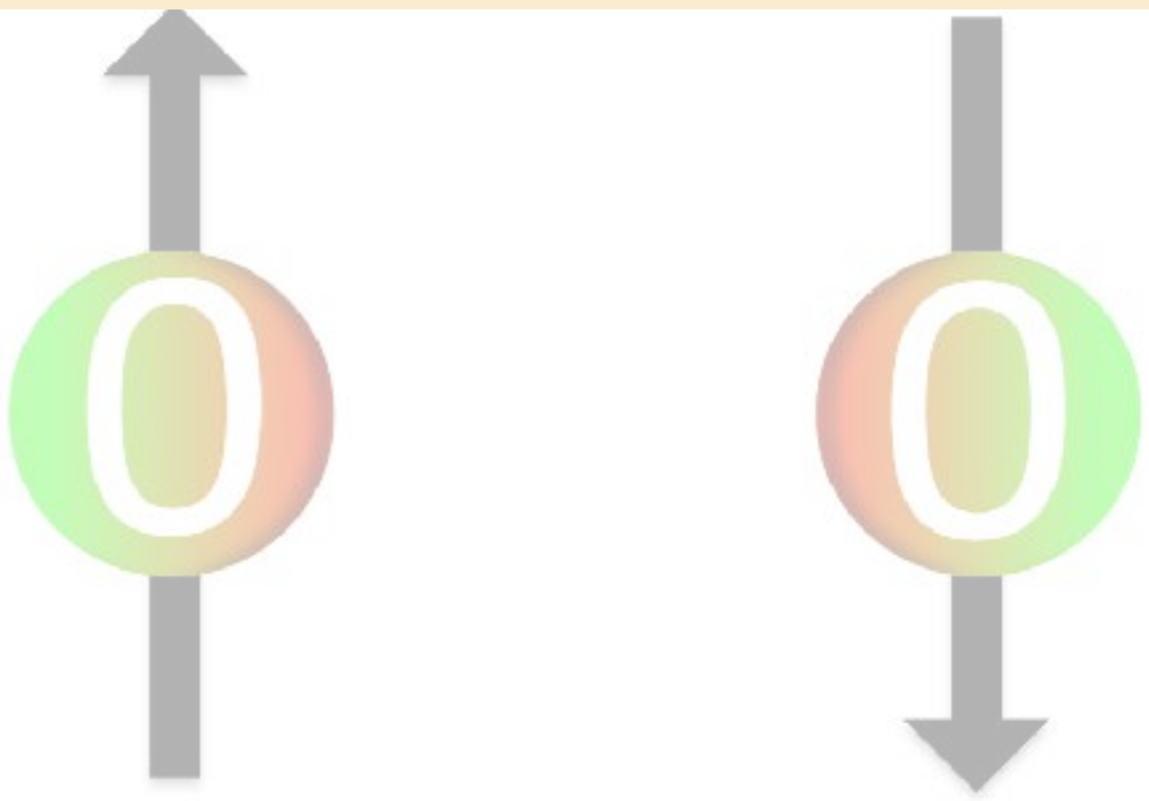


Majorana hypothesis: neutrino is matter and antimatter



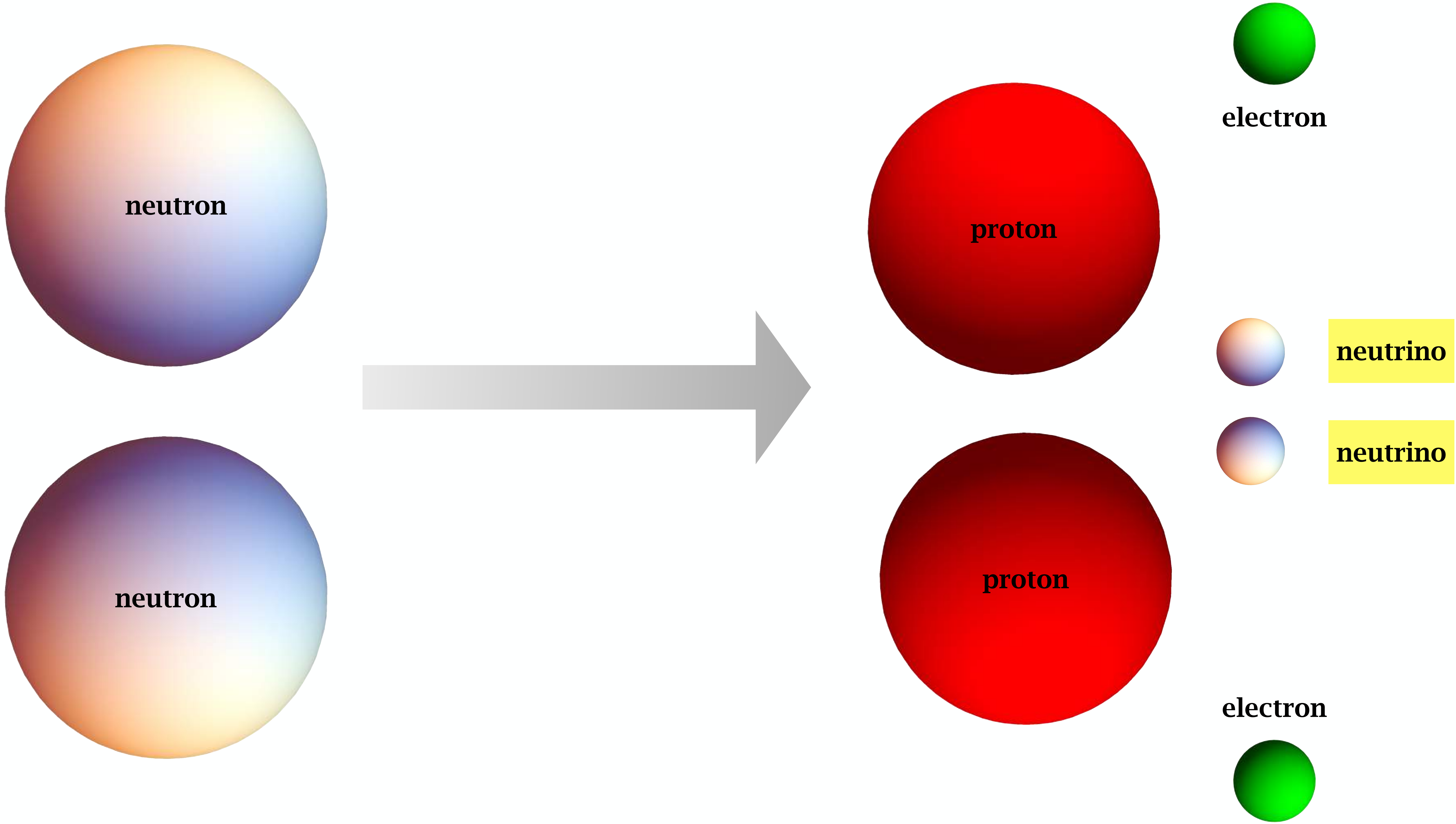
Majorana neutrinos in V-A context

all lepton number violating effects have to be $\propto m_\nu$

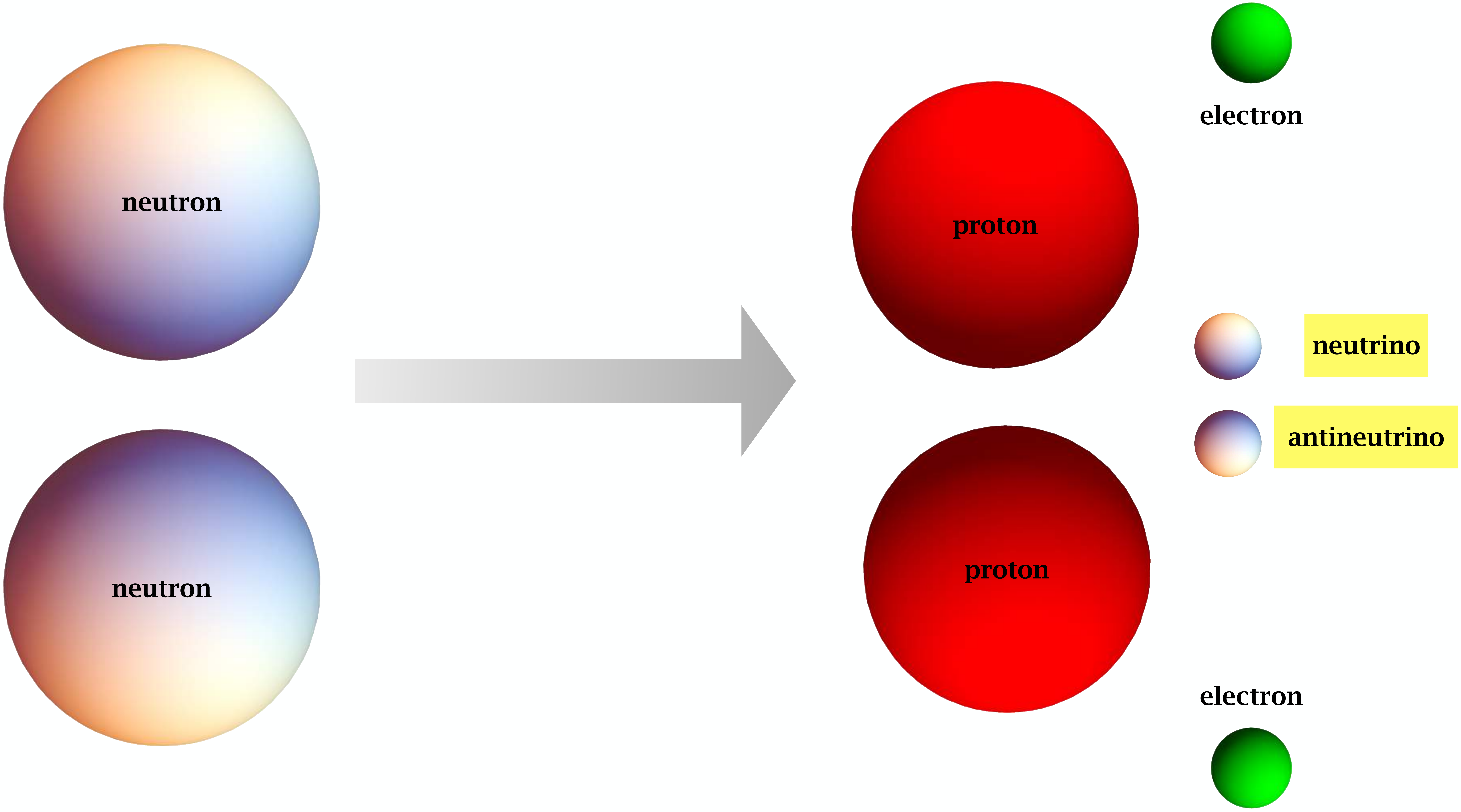


Majorana and electron creation

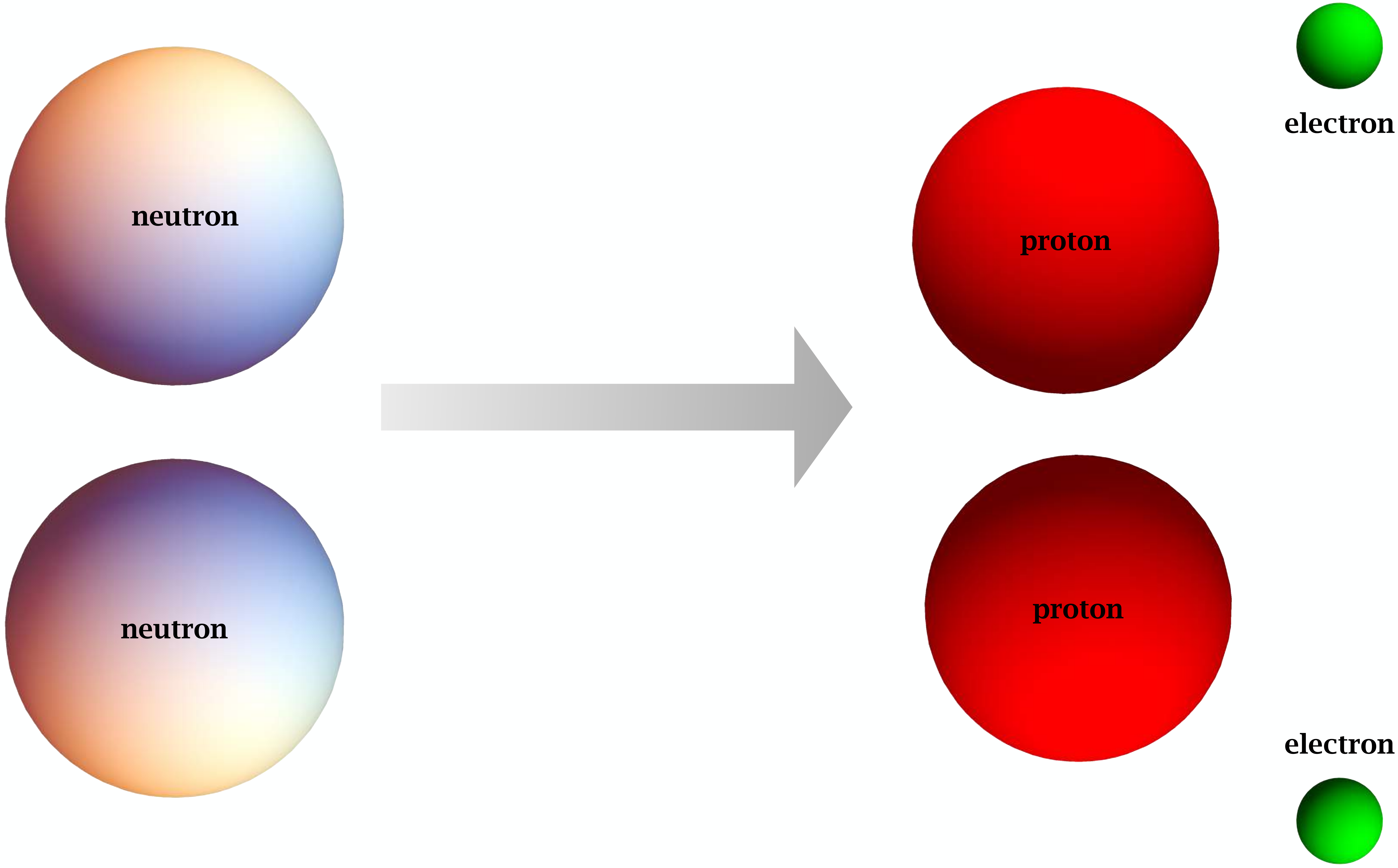
IMPLICATIONS



IMPLICATIONS



IMPLICATIONS



Electron creation and the parameter m_{ee}

FV, 2021

Consider the semi-leptonic Hamiltonian density leading to the emission of an electron $\mathscr{H} = \sqrt{2} G_F \boldsymbol{J}^+_\mu \boldsymbol{j}^{-\mu}$, where the leptonic current is

$$\boldsymbol{j}^-_\mu = \bar{e}\gamma_\mu \boldsymbol{\nu}_{Le} = \sum_{j=1}^{3} U_{ej}\, \bar{e}\gamma_\mu P_L \boldsymbol{\chi}_j \text{ with } \boldsymbol{\chi}_j = \boldsymbol{\chi}_j^* \tag{33}$$

where we have postulated that the neutrino mass eingestates are Majorana fields. The leptonic part of the amplitude, that describes the creation of a couple of electrons, is $\langle ee|T[\boldsymbol{j}^-_\nu(x)\boldsymbol{j}^-_\mu(y)]|0\rangle$ and it requires to evaluate the contraction

$$\langle 0|T[\boldsymbol{\nu}_{Le}(x)\,\boldsymbol{\nu}^t_{Le}(y)]|0\rangle$$

namely, an unusual type of propagator, that however is non-zero in Majorana's theory. In fact, from $\boldsymbol{\nu}_{Le} = U_{ej} P_L \boldsymbol{\chi}_j$, used above, and its transpose, written as $\boldsymbol{\nu}^t_{Le} = U_{ej}\, \bar{\boldsymbol{\chi}}_j P_L \gamma^0$, the core of the problem reduces to the calculation of an ordinary propagator, namely $\langle 0|T[\boldsymbol{\chi}_j(x)\,\overline{\boldsymbol{\chi}}_j(y)]|0\rangle$. The result is

$$\langle 0|T[\boldsymbol{\nu}_{Le}(x)\,\boldsymbol{\nu}^t_{Le}(y)]|0\rangle = P_L\gamma^0 \int \frac{d^4p}{(2\pi)^4}\, \frac{iU^2_{ej} m_j\, e^{-ip(x-y)}}{p^2 - m_j^2 + i0^+} \tag{34}$$

The virtual momentum in the denominator has a small time component due to kinematical constraints, whereas the spatial component is of the order of the radius $|\vec{p}| \sim 1/R_0$; therefore, the masses of the light neutrinos $m_j \ll 100$ MeV are absolutely negligible in the denominator, and the lifetime will depend upon neutrino masses and mixing only through

$$m_{ee} = \left| \sum_{j=1}^{3} U^2_{ej} m_j \right| = m_{\beta\beta} \tag{35}$$

Dirac, Sakata, Pontecorvo

- from a famous interview to Dirac -

***Wisconsin State Journal*, April 1929**

"Do you ever run across a fellow that even you can't understand?"

"Yes," says he.

"This well make a great reading for the boys down at the office," says I. "Do you mind releasing to me who he is?"

"Weyl," says he.

ROUNDY INTERVIEWS PROFESSOR DIRAC
An Enjoyable Time Is Had By All

I been hearing about a fellow they have up at the U. this spring --- a mathematical physicist, or something, they call him --- who is pushing Sir Isaac Newton, Einstein and all the others off the front page. So I thought I better go up and interview him for the benefit of State Journal readers, same as I do all other top notchers.

His name is Dirac and he is an Englishman. He has been giving lectures for the intelligentsia of math and physics departments --- and a few other guys who got in by mistake.

So the other afternoon I knocks at the door of Dr. Dirac's office in Sterling Hall and a pleasant voice says "Come in." And I want to say here and now that this sentence "come in" was about the longest one emitted by the doctor during our interview. He sure is all for efficiency in conversation. It suits me. I hate a talkative guy. I found the doctor a tall youngish-looking man, and the minute I seen the twinkle in his eye I knew I was going to like him. His friends at the U. say he is a real fellow too and a good company on a hike --- if you can keep him in sight, that is.

The thing that hit me in the eye about him was that he did not seem to be at all busy. Why if I went to interview an American scientist of his class --- supposing I could find one --- I would have to stick around an hour first. Then he would blow in carrying a big briefcase, and while he talked he would be pulling lecture notes, proof, reprints, books, manuscript, or what have you out of his bag. But Dirac is different.

He seems to have all the time there is in the world and his heaviest work is looking out the window. If he is a typical Englishman it's me for England on my next vacation!

Then we sat down and the interview began."Professor," says I, "I notice you have quite a few letters in front of your last name. Do they stand for anything in particular?"

"No," says he.

"You mean I can write my own ticket?"

"Yes," says he.

"Will it be all right if I say that P.A.M. stands for Poincare' Aloysius Mussolini?"

"Yes," says he.

"Fine," says I, "We are getting along great! Now doctor will you give me in a few words the low-down on all your investigations?"

"No," says he.

"Good," says I. "Will it be all right if I put it this way --- `Professor Dirac solves all the problems of mathematical physics, but is unable to find a better way of figuring out Babe Ruth's batting average'?"

"Yes," says he.

"What do you like best in America?", says I.

"Potatoes," says he.

"Same here," says I. "What is your favorite sport?"

"Chinese chess," says he.

That knocked me cold! It was sure a new one on me! Then I went on: "Do you go to the movies?"
"Yes," says he.

"When?", says I.

"In 1920 --- perhaps also in 1930," says he.

"Do you like to read the Sunday comics?"

"Yes," says he, warming up a bit more than usual.

"This is the most important thing yet, doctor," says I.

"It shows that me and you are more alike than I thought. And now I want to ask you something more: They tell me that you and Einstein are the only two real sure-enough high-brows and the only ones who can really understand each other. I wont ask you if this is straight stuff for I know you are too modest to admit it.

But I want to know this --- Do you ever run across a fellow that even you can't understand?"

"Yes," says he.

"This well make a great reading for the boys down at the office," says I. "Do you mind releasing to me who he is?"

"Weyl," says he.

The interview came to a sudden end just then, for the doctor pulled out his watch and I dodged and jumped for the door. But he let loose a smile as we parted and I knew that all the time he had been talking to me he was solving some problem that no one else could touch.

But if that fellow Professor Weyl ever lectures in this town again I sure am going to take a try at understanding him! A fellow ought to test his intelligence once in a while.

Shoichi Sakata

Japanese version 1942

Progress of Theoretical Physics, Vol. 1, No. 4, Nov.~Dec., 1946.

On the Correlations between Mesons and Yukawa Particles*.

By Shoichi SAKATA and Takesi INOUE.

(Received Sept. 18, 1946.)

Mass and Lifetime of Yukawa Particle.

3. For phenomena in atomic nuclei (nuclear forces, beta-decay etc.), Yukawa theory is conserved in its original form. But it is to be noted that the particle with mass determined from the range of nuclear forces, is the Yukawa particle and not the meson found in cosmic rays. This point is advantageous to explain the experimental results(6) about nuclear force range ($\hbar/m_u c$) which gives half the value ($\hbar/\mu c$) obtained from the meson mass data (m_u: mass of Yukawa particle, μ: mass of meson). In order to account for these results, $m_u = 2\mu$ is a reasonable assumption. More generally speaking, it is allowable to assume $m_u > \mu$.

Decay and Scattering of Meson.

6. According to our theory, the decay of mesons occurs by following process:

$$m^\pm \left\langle \begin{matrix} Y^\pm + n \\ m^\pm + e^\pm + \nu + Y^\mp \end{matrix} \right\rangle e^\pm + \nu + n. \qquad \text{(V)}$$

1960

Progress of Theoretical Physics, Vol. 23, No. 6, June 1960

A Unified Model for Elementary Particles

Ziro MAKI, Masami NAKAGAWA, Yoshio OHNUKI and Shoichi SAKATA

Institute for Theoretical Physics, Nagoya University, Nagoya

(Received March 2, 1960)

By extending the Sakata model, a unified model for elementary particles is proposed, the basic particles in the Sakata model are assumed to be constructed of the lepton and B^+, which is regarded as a new kind of matter. The full symmetry among three basic particles and the symmetrical property of the weak interactions which was recently pointed out by Gamba, Marshak and Okubo come automatically of this model. The nature of B^+ and the new mechanics which accounts for the binding of B^+ to the lepton will be the central problem to be studied in the future.

1962

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

A particle mixture theory of neutrino is proposed assuming the existence of two kinds of neutrinos. Based on the neutrino-mixture theory, a possible unified model of elementary particles is constructed by generalizing the Sakata-Nagoya model.*) Our scheme gives a natural explanation of smallness of leptonic decay rate of hyperons as well as the subtle difference of G_v's between μ-e and β-decay.

Starting with this scheme, the possibility of K_{e3} mode with $\Delta S/\Delta Q = -1$ is also examined, and some bearings on the dynamical role of the B-matter, a fundamental constituent of baryons in the Nagoya model, are clarified.

Bruno Pontecorvo

FROM THE HISTORY OF PHYSICS

Pages in the development of neutrino physics

B. M. Pontecorvo

Joint Institute for Nuclear Research, Dubna (Moscow region)

Usp. Fiz. Nauk **141**, 675–709 (December 1983)

This review is quite subjective in nature, is incomplete, and can certainly not be regarded as a chapter in the history of particle physics. It consists of a collection of several short sketches associated with neutrino physics. Two of them, concerning Pauli and Fermi, are among those which in recent years have been published fairly frequently by a number of physicists, including the present author, in connection with the recent fiftieth anniversary of the "invention" of the neutrino. The story concerning the work of Majorana on the Majorana fermions which follows has not been discussed in such detail previously, at any rate not in the pages of Soviet journals. Then follow some reminiscences of quite personal nature associated with the experimental and theoretical work of the author on the proposal and development of radiochemical methods for neutrino detection, among which is the chlorine-argon method, on the suggestion of the existence of neutrino oscillations and their use in neutrino astronomy of the sun, on the establishment of the concept of weak processes and important properties of muons, on the proposal of new type of investigations of the weak interaction, on experiments with high energy neutrinos . . . . In order to reduce to some extent the extremely subjective nature of the review, the author summarizes in Tables I–IV important events in the history of neutrino physics up to 1980, and also provides a list of the large installations for the study of neutrinos.

TABLE I. From the discovery of radioactivity to the neutrino hypothesis, the theory of β-decay and to the discovery of free neutrinos (1896–1956).

Year	Event	Authors
1896	Discovery of radioactivity	Becquerel
1899	Discovery of β-rays	Rutherford
1908–1928	Counters (proportional and Geiger) capable of detecting individual charged particles	Geiger Rutherford Müller
1912	Wilson chamber	Wilson
1914	Continuous β-ray spectrum	Chadwick
1925	Method of thick photographic plates	Mysovskiĭ
1927	Measurement of heat liberated upon absorption of β-rays	Ellis, Wooster
1927	Quantum theory of radiation	Dirac
1928	Relativistic equation for particles with spin 1/2	Dirac
1929	Two-component theory for fermions with zero mass	Weyl
1930	"Invention" of the neutrino	Pauli
1932	Discovery of the position	Anderson
1932	Discovery of the neutron	Chadwick
1932-1933	A nucleus consists of nucleons	Ivanenko; Heisenberg; Majorana
1933	Theory of β-decay	Fermi
1934	Artificial radioactivity	Curie, Joliot
1934	β-radioactivity with emission of positrons	Curie, Joliot
1934	First discussion of inverse β-decay	Bethe, Peierls
1934	Vavilov-Cherenkov effect	Vavilov, Cherenkov
1935	Meson theory of nuclear forces	Yukawa
1935	First experiment on observing recoil nucleus in β-decay	Leipunsky
1935	First investigation of double β-decay	Goeppert-Mayer
1936	Far-reaching consequences of the fact that the Fermi constant is not dimensionless	Heisenberg

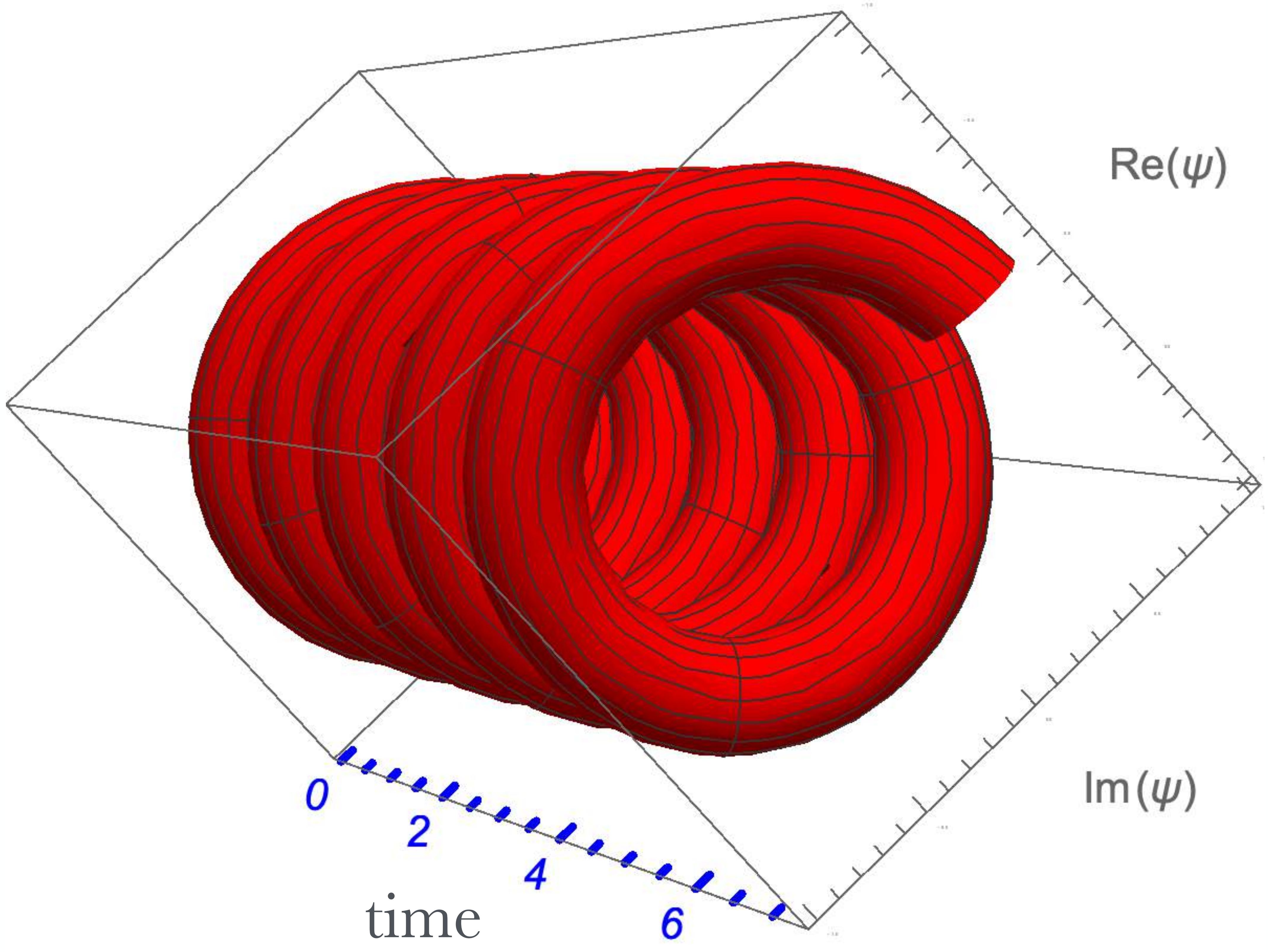
more plots

extended discussion of Majorana's electron/positron

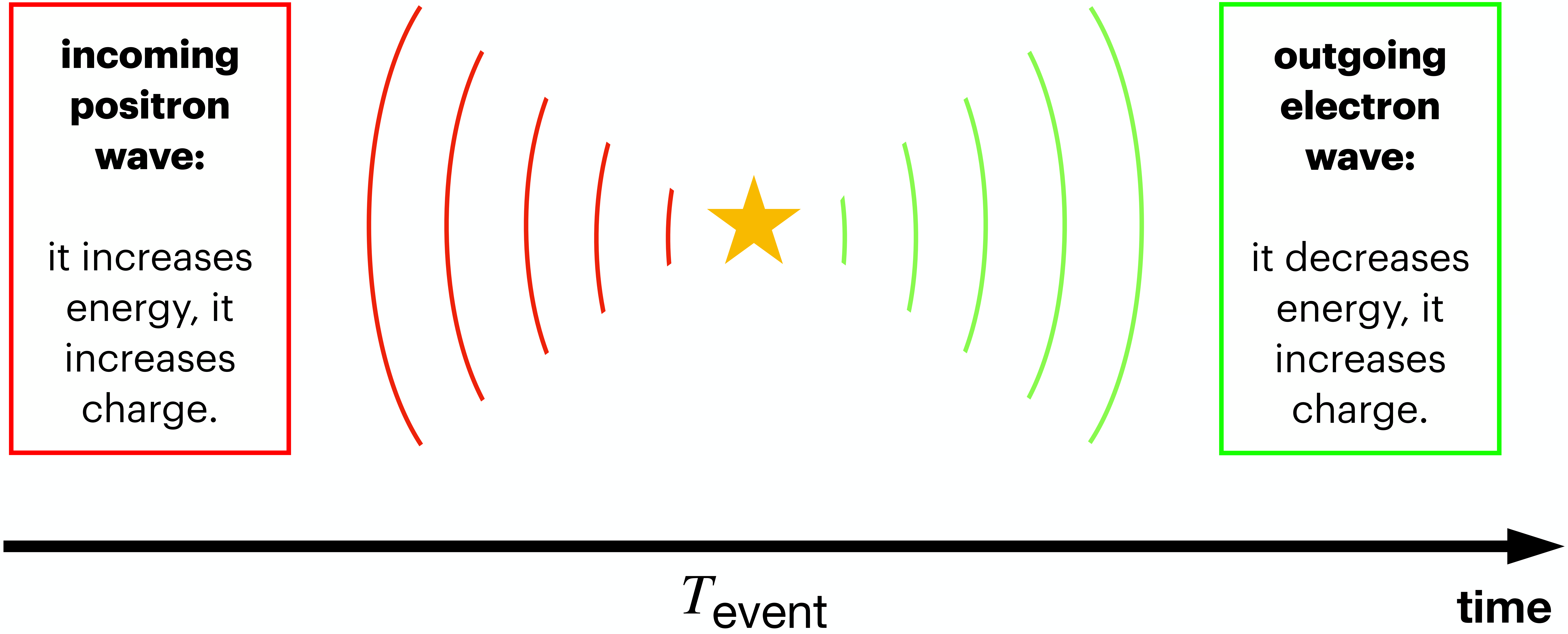
background

Einstein 1905: light waves with frequency f correspond to particles with energy $E = hf$

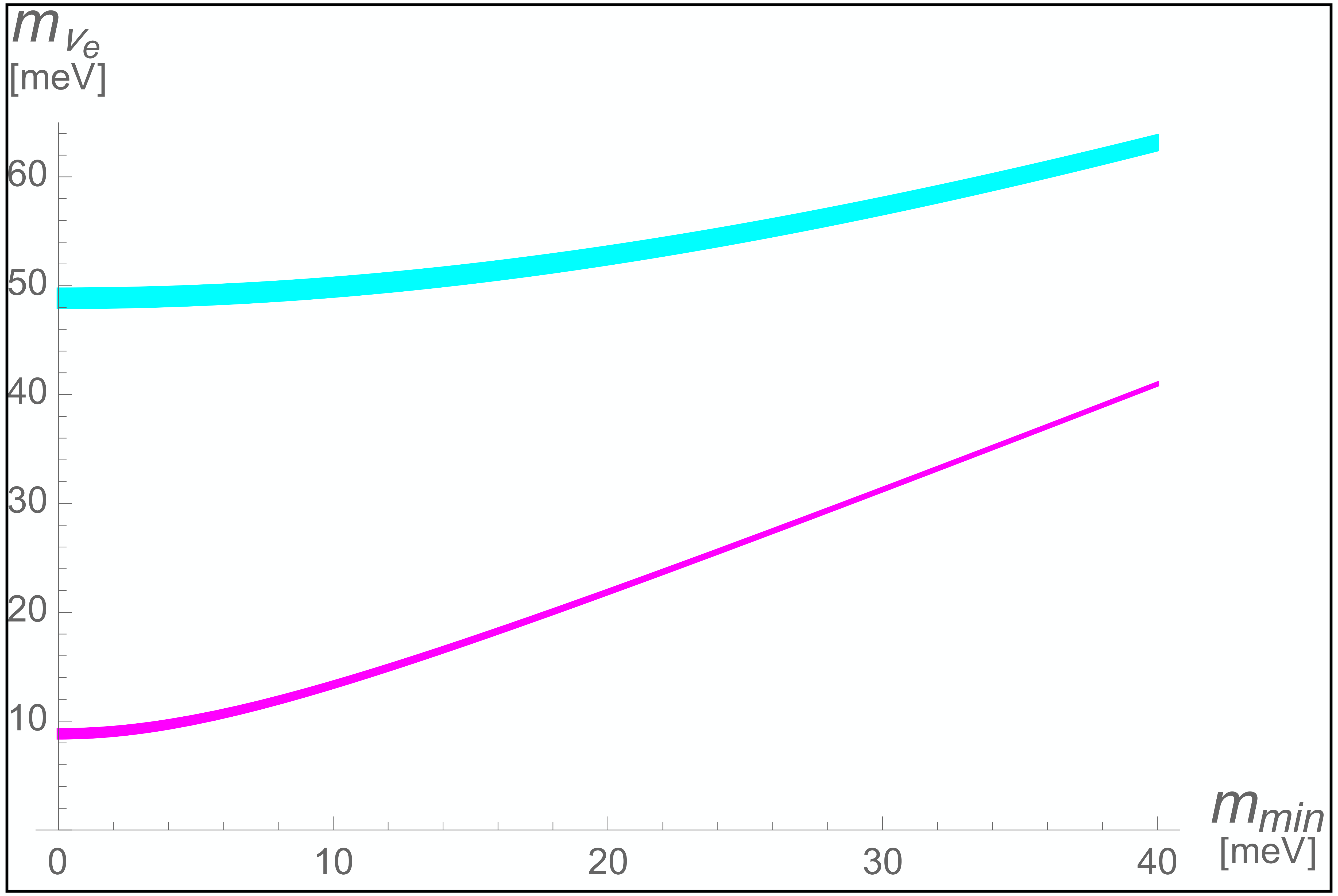
de Broglie 1924: every particle is associated with a **wave**, e.g. those oscillating with a period T i.e. with frequency $f = 1/T$



definition of quantum field according to Majorana



expectations for m_{ν_e} from oscillations



I emphasise that these are 3σ errors

a side note

“Natural science is born from an abstraction which apprehends only certain aspects of reality.

What is missing is added by the mind of the scientist, consciously or unconsciously.

If unconsciously, we get a philosophical *background*; if consciously, the result will be a philosophical *theory*.”

–*A G van Melsen,* From Atomos to Atom

a funny story

* 7-8 years ago, there was a **movement of opinion** to change the naming of the neutrino spectra compatible with the data: no longer 'normal hierarchy' and 'inverse hierarchy', but rather 'normal ordering' and 'inverse ordering'.

* For this reason, many colleagues decided to abandon the previously adopted acronyms NH and IH in favour of the new ones, NO and IO.

* When I was invited to present the summary talk at **Neutrino 2018**, I decided to voice my disappointment: I do not find it reasonable to call NO a case which can be easily argued to be the most likely one!!!

* So I prepared a few transparencies where a **new fun acronym** is proposed.

NH → NO

Normal hierarchy → Normal ordering

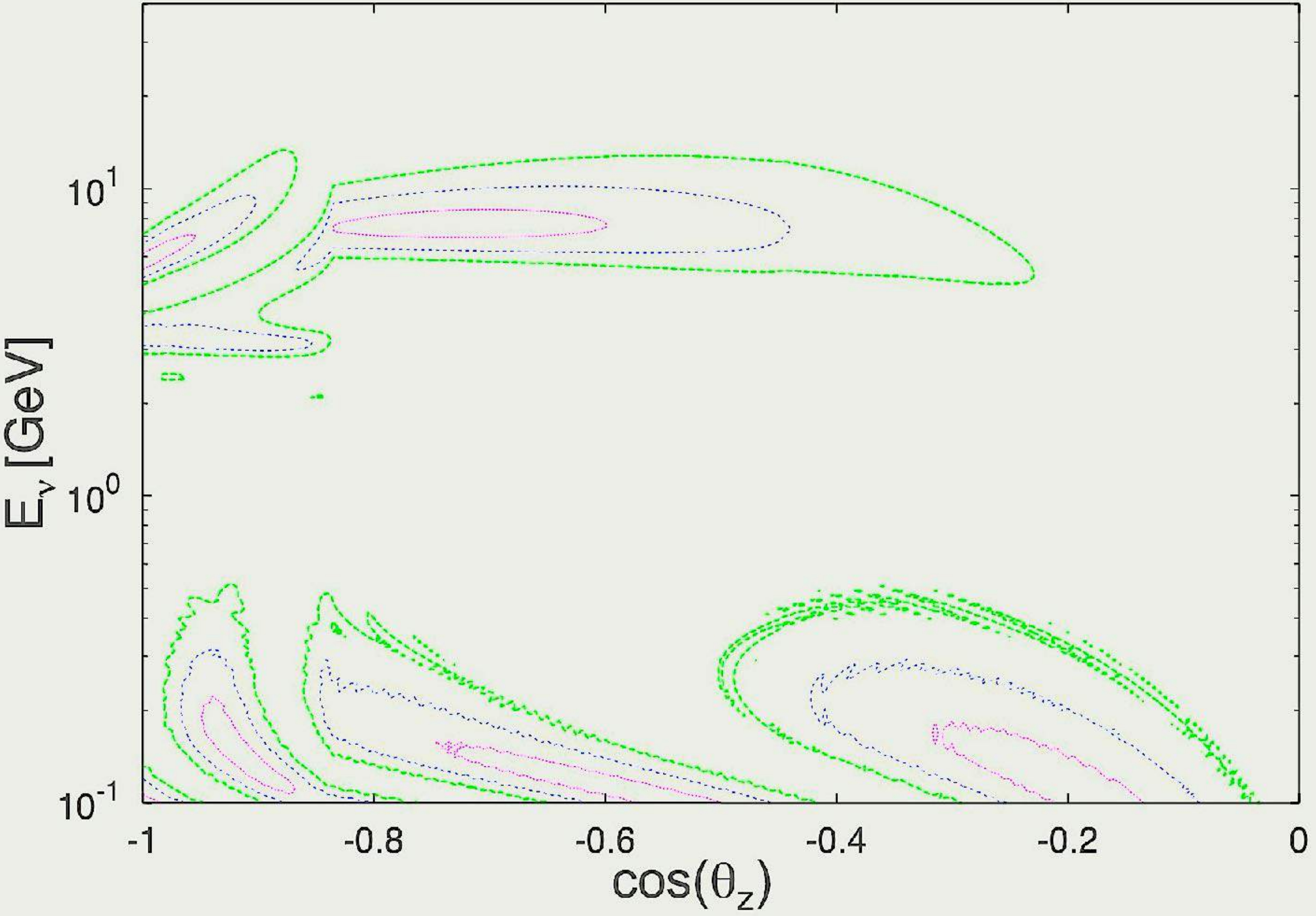
how could you call NO the

case that we know to be right?

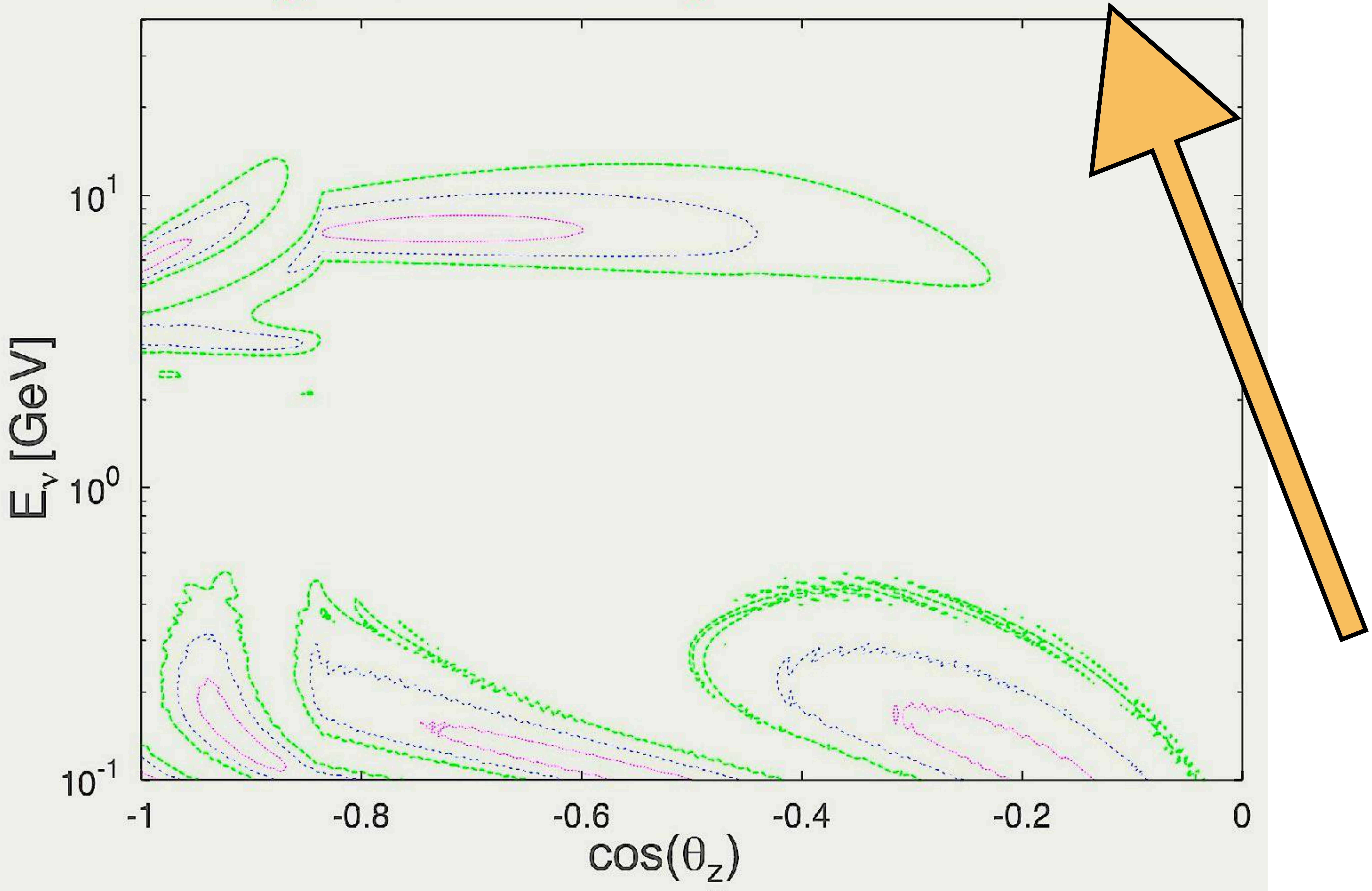
normal mass hierarchy is the most reasonable assumption since ever!

if you do not believe that, see the next slides for a proof

P_{ee}=0.7, 0.5, 0.3 through the Earth (La Thuile 2003)



P_{ee}=0.7, 0.5, 0.3 through the Earth (La Thuile 2003)



thereby, here is my proposal:

NO → YES

Normal ordering → Yearningly Expected Spectrum

summary

a summary of main neutrino concepts

- **Pauli**'s neutrino *is not exactly* our neutrino
- **Fermi**'s 1933 theory: *important, deep, outdated*
- **Dirac** setup suggest that (Fermi's) neutrino ≠ anti-neutrino
- **Majorana** 1937 has made *two big points* related between them
- In 50's people begun to think that Majorana was wrong; in a sense **Weyl** 1929 (sic!) came to his rescue
- **Pontecorvo & Sakata** have been most relevant - and are still relevant
- Neutrino mass scale still to be measured
- Today: serious clues in favor of *Majorana hypothesis*