The pathway to neutrinos

(an incomplete tale)

by

Michele Lucente

June 11th, 2014

Ecole Bilingue Internationale Clermont Ferrand

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some chemical compounds may attract your attention

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Daylight

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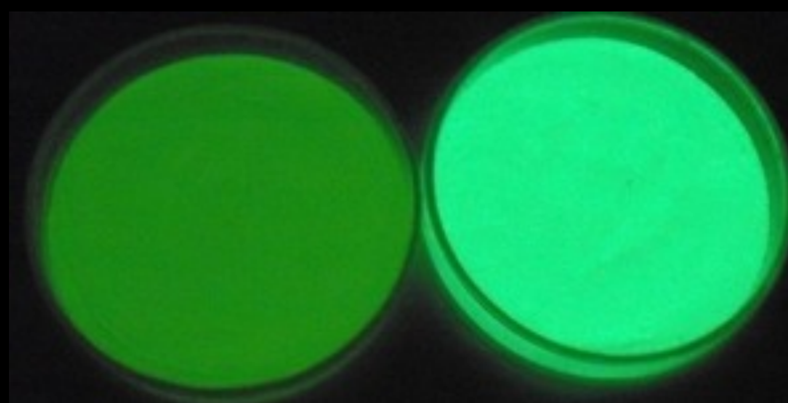

soon in the dark

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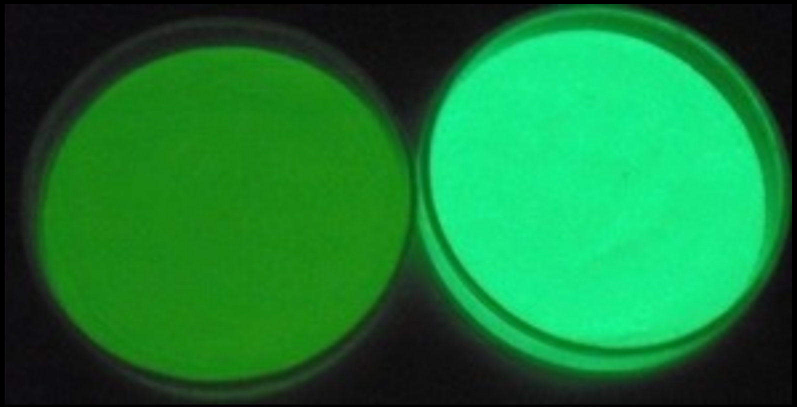


soon in the dark

after 4 minutes in the dark

Many physicists were interested in understanding **phosphorescence**

Among them

Antoine Henri Becquerel
(15 December 1852 – 25 August 1908)

Is phosphorescence different than light?

Becquerel used potassium **uranyl** disulfate

$K_2\mathbf{U}O_2(SO_4)_2 2H_2O$

PHYSIQUE. — *Sur les radiations émises par phosphorescence.* Note de M. HENRI BECQUEREL.

» On enveloppe une plaque photographique Lumière, au gélatino-bromure, avec deux feuilles de papier noir très épais, tel que la plaque ne se voile pas par une exposition au Soleil, durant une journée.

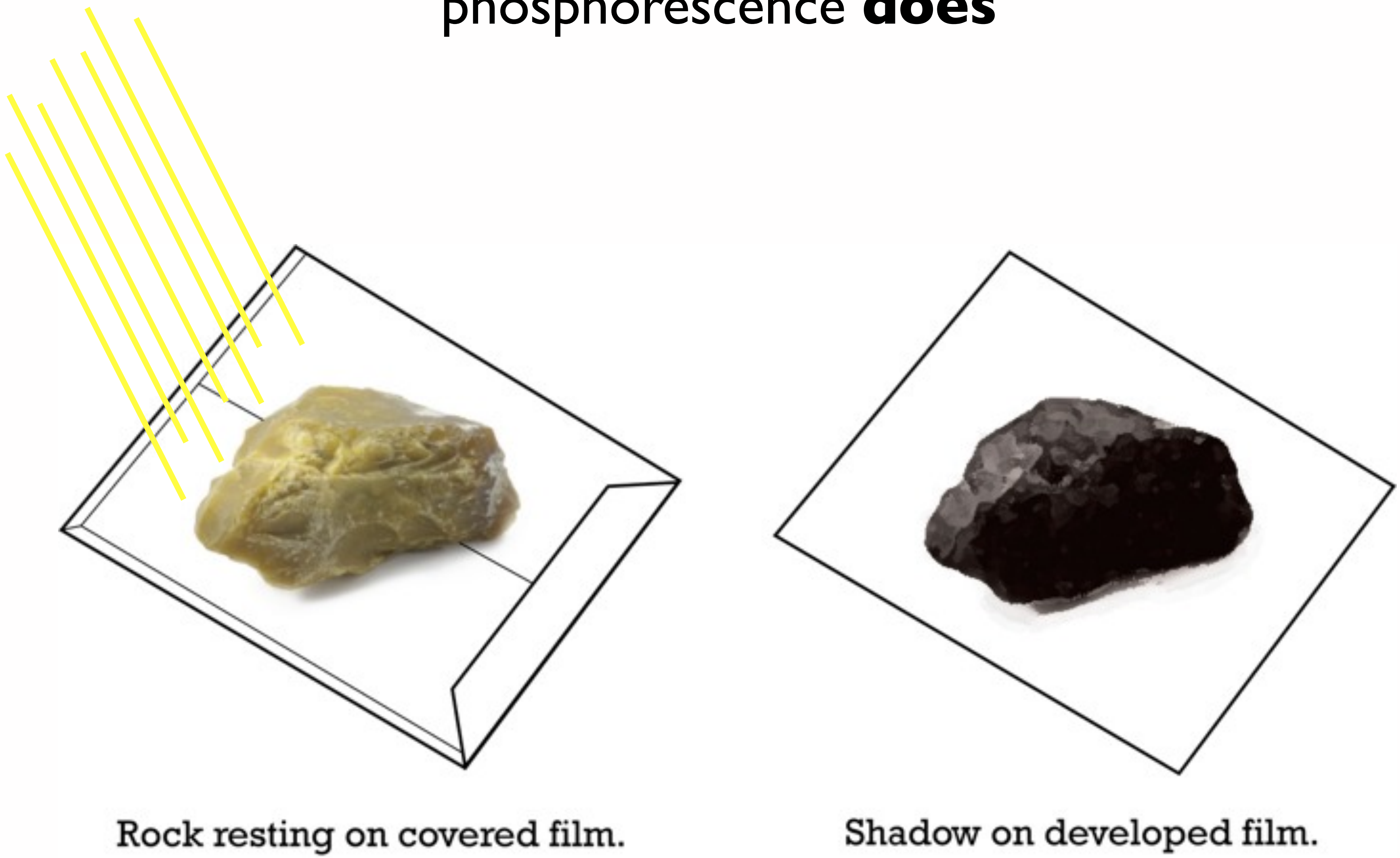
» On pose sur la feuille de papier, à l'extérieur, une plaque de la substance phosphorescente, et l'on expose le tout au Soleil, pendant plusieurs heures. Lorsqu'on développe ensuite la plaque photographique, on reconnaît que la silhouette de la substance phosphorescente apparaît en noir sur le cliché. Si l'on interpose entre la substance phosphorescente et le papier une pièce de monnaie, ou un écran métallique percé d'un dessin à jour, on voit l'image de ces objets apparaître sur le cliché.

» On peut répéter les mêmes expériences en interposant entre la substance phosphorescente et le papier une mince lame de verre, ce qui exclut la possibilité d'une action chimique due à des vapeurs qui pourraient émaner de la substance échauffée par les rayons solaires.

» On doit donc conclure de ces expériences que la substance phosphorescente en question émet des radiations qui traversent le papier opaque à la lumière et réduisent les sels d'argent. »

(*Comptes Rendus* **122**, 420, 1896)

Solar light do not impress the photographic plate, phosphorescence **does**



picture courtesy of

But the experiments were performed in Paris...

"He had devised another experiment in which [...] he interposed [...] a small cross of thin copper. On bringing the apparatus into daylight **the sun had gone in**, so it was put back into the **dark cupboard** and there left for another opportunity of insolation. But the sun persistently kept behind clouds for several days, and, tired of waiting (or with the unconscious pre- vision of genius), Becquerel developed the plate."

William Crookes

*(Proc. Roy. Soc. A **83**, xx, 1910)*

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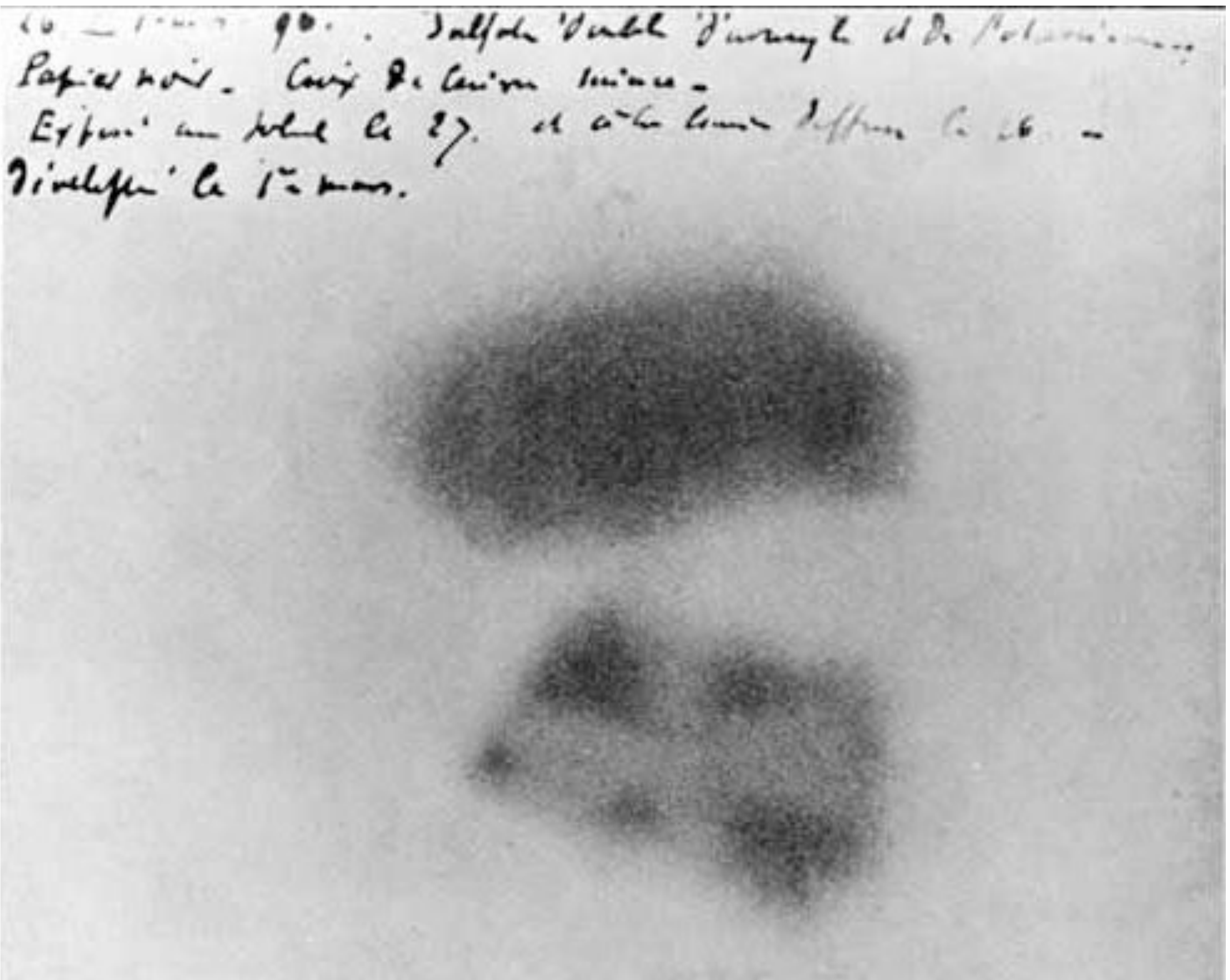
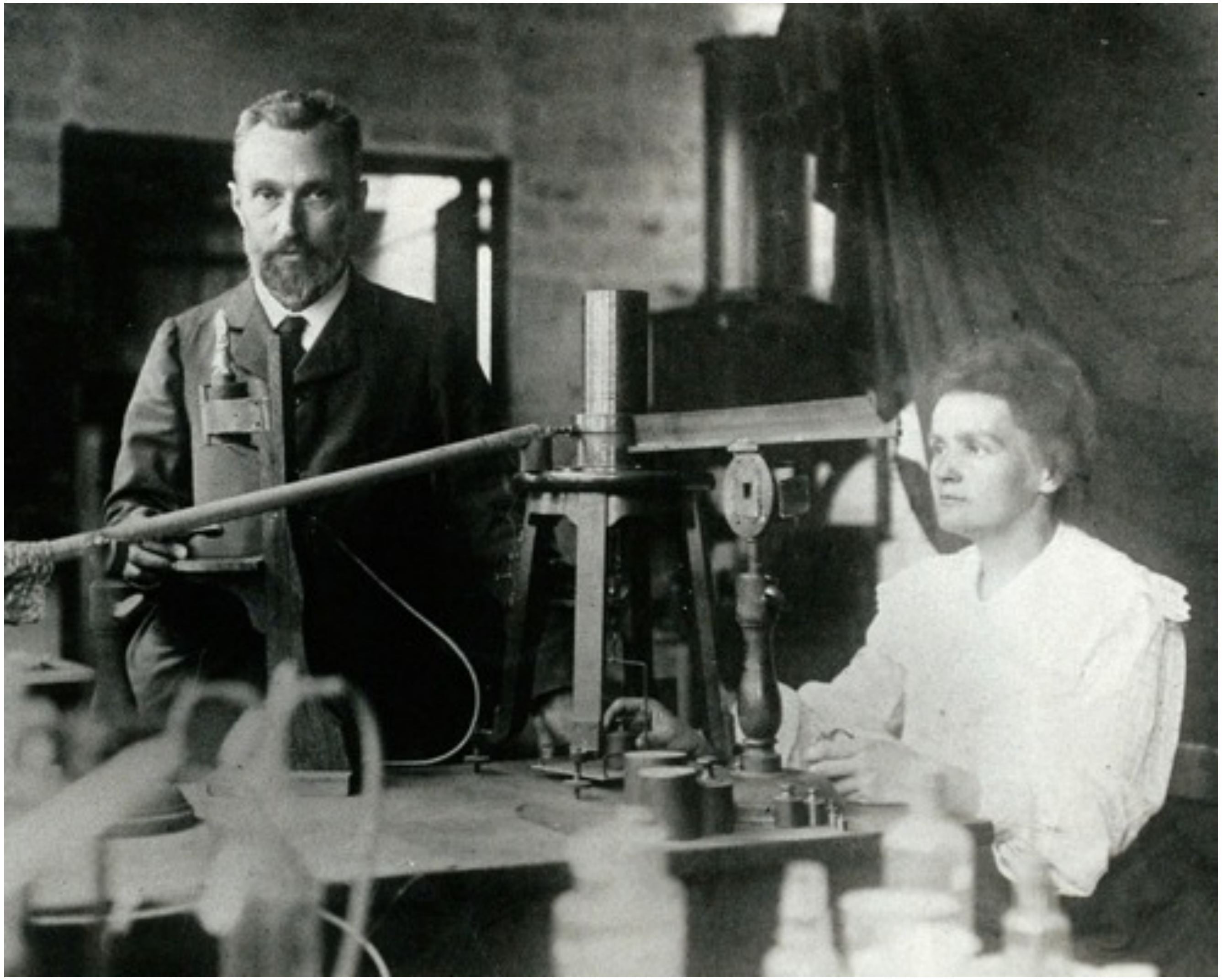


"To his astonishment [...] the image of the copper cross shining out white against the black background."

This is something different than phosphorescence,
It deserves further quantitative studies.



Marie Skłodowska-Curie (7 November 1867 – 4 July 1934)
Pierre Curie (15 May 1859 – 19 April 1906)

Pierre and Marie Curie investigated the “Becquerel rays” by chemical methods.

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Radium is 2.7 million times more active than uranium!

Radioactivity
became a popular word

Ok, but...what is radioactivity?

Ernest Rutherford

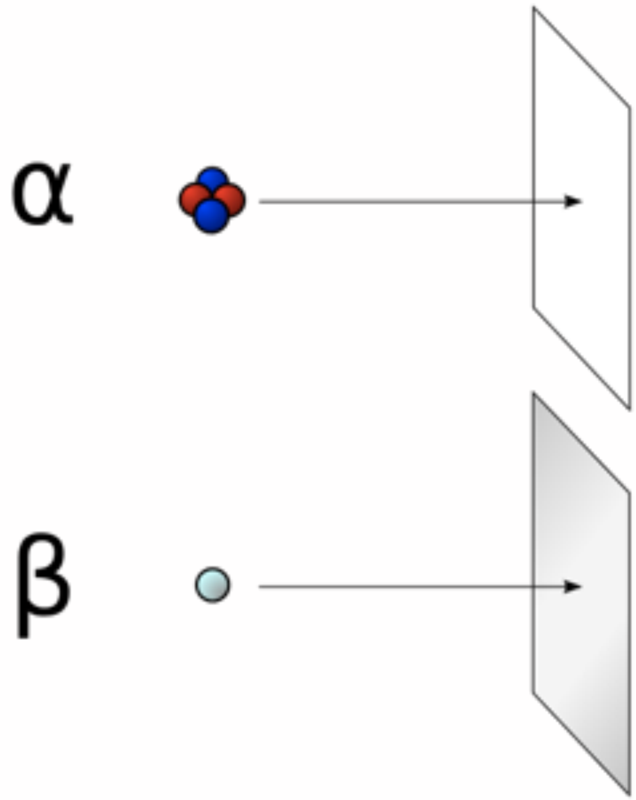
(30 August 1871 – 19 October 1937)

Rutherford studied the radioactivity absorption

Remarkable result:

"**The uranium radiation is complex**, and there are present at least two distinct types of radiation one that is very readily absorbed, which will be termed for convenience the **α-radiation**, and the other of a more penetrative character, which will be termed the **β-radiation**"

(*Phil. Mag*. **47**, 109, 1899)



Stopped by a sheet of paper

Stopped by an aluminium plate

After nearly 10 years of investigation...

Nature of the α-Particle.

The value of E/M—the ratio of the charge on the α-particle to its mass—has been measured by observing the deflection of the α-particle in a magnetic and in an electric field, and is equal to $5{\cdot}07 \times 10^3$ on the electromagnetic system.* The corresponding value of e/m for the hydrogen atom set free in the electrolysis of water is $9{\cdot}63 \times 10^3$. We have already seen that the evidence is strongly in favour of the view that $E = 2e$. Consequently $M = 3{\cdot}84m$, *i.e.*, the atomic weight of an α-particle is 3·84. The atomic weight of the helium atom is 3·96. Taking into account probable experimental errors in the estimates of the value of E/M for the α-particle, we may conclude that *an α-particle is a helium atom*, or, to be more precise, *the α-particle, after it has lost its positive charge, is a helium atom.*

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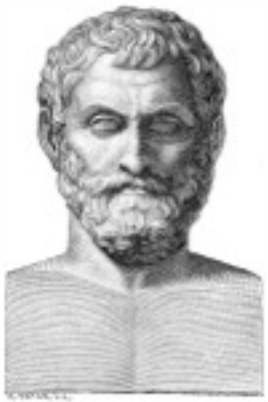
But what about β-rays?

One step backward

Human's dealing with electricity dates back to 18th century (*Gilbert, Franklin, Galvani, Volta, etc.*)



Well, we may actually go back up to Thales...
(624 BC - 546 BC)

At the end of the 19th century we had a very good knowledge of how electricity behaves.

But it took some other time to understand **what electricity is**

"Although we know nothing of what an atom is, yet we cannot resist forming some idea of a small particle, which represents it to the mind [...] there is an immensity of facts which justify us in believing that the atoms of matter are in some way endowed or associated with electrical powers, to which they owe their most striking qualities, and amongst them their chemical affinity."

M. Faraday

Experimental researches in electricity, 1839

"Of all electrical phenomena electrolysis appears the most likely to furnish us with a real insight into the true nature of the electric current, because we find currents of ordinary matter and currents of electricity forming essential parts of the same phenomenon."

J. C. Maxwell

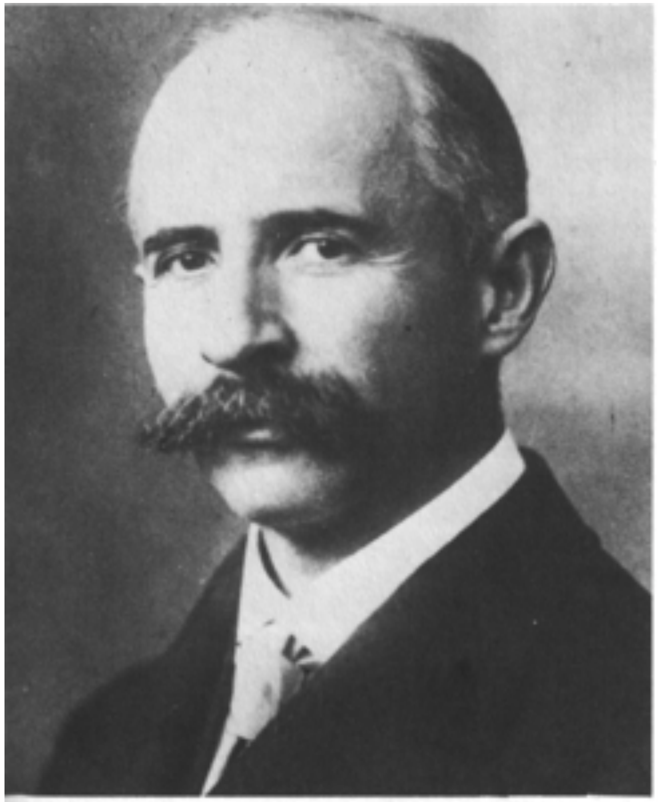
A Treatise on Electricity and Magnetism, 1873

Electricity linked with **matter**, and both show some **fundamental constituent**

Eventually in 1899
J. J. Thomson
(18 December 1856 – 30 August 1940)
discovered the **electron**,
measuring both its charge and mass.

In 1902 **Walter Kaufmann**
(June 5, 1871 – January 1, 1947)
measured the ratio m/e of the
"Becquerel's rays"

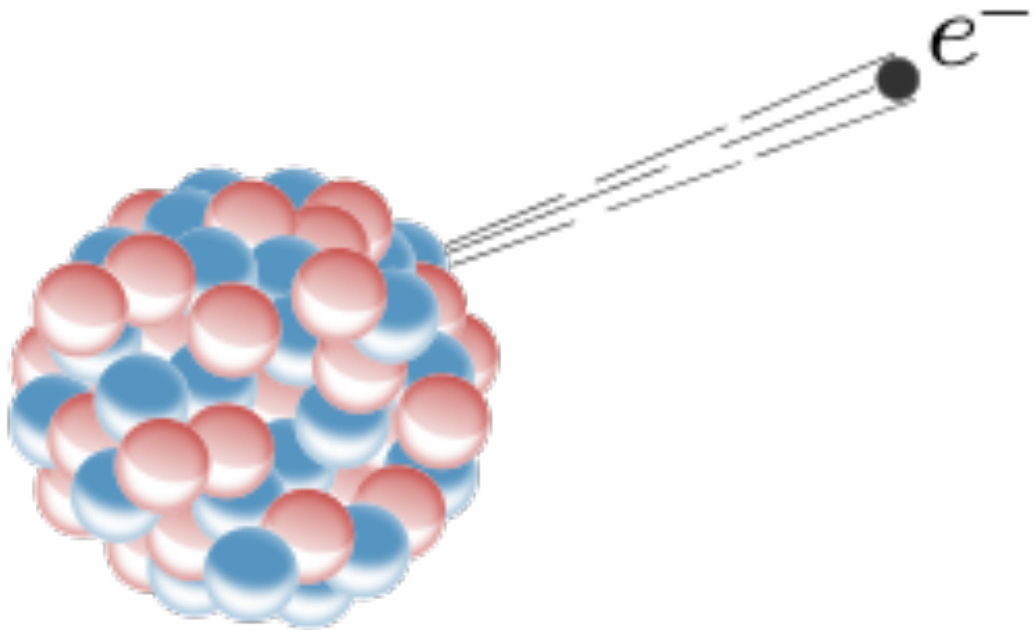
(Phys. Zeitschr. **4**, 54, 1902*)*



The result is in agreement with the electron's values

β-rays are composed by electrons!

To recap: β-rays are electrons sorting from atoms



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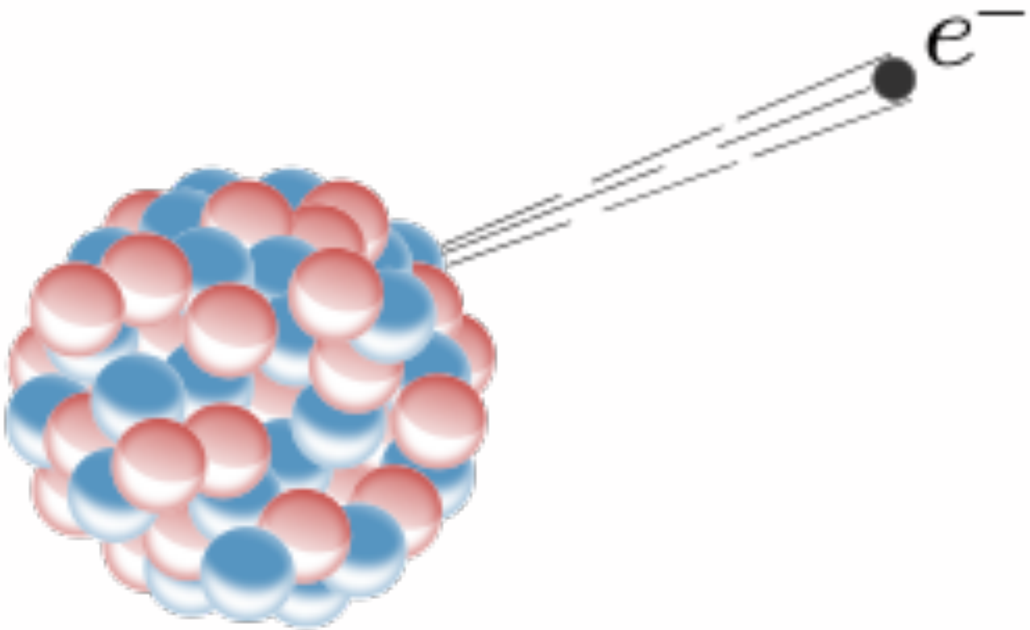


End of the story?

James Chadwick

(20 October 1891 – 24 July 1974)

let's study the energy of β-rays

(Verh. d. Deutsch. Phys. Ges. **16,** 383,1914*)*

The electron energy is not fixed in the decay, but can take any value between E_{min} and E_{max}

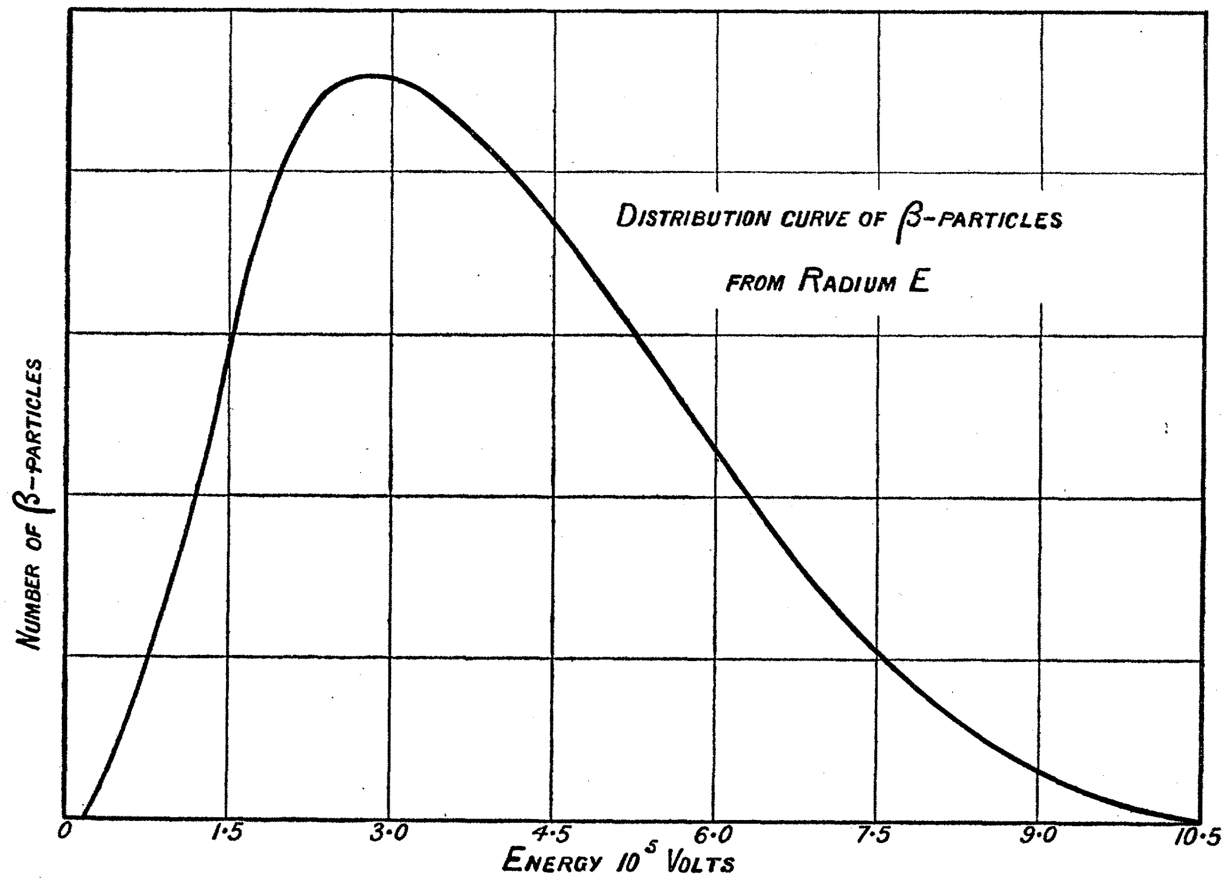
It's ok, at this time you don't know the internal structure of atoms.

1927: measurement of **total** energy in the decay using a calorimeter

(*Proc. Roy. Soc. A* **117**, 109, 1927)

The Average Energy of Disintegration of Radium E.

By C. D. Ellis, Ph.D., Lecturer in the University of Cambridge, and W. A. Wooster, B.A., Charles Abercrombie Smith Student of Peterhouse, Cambridge.



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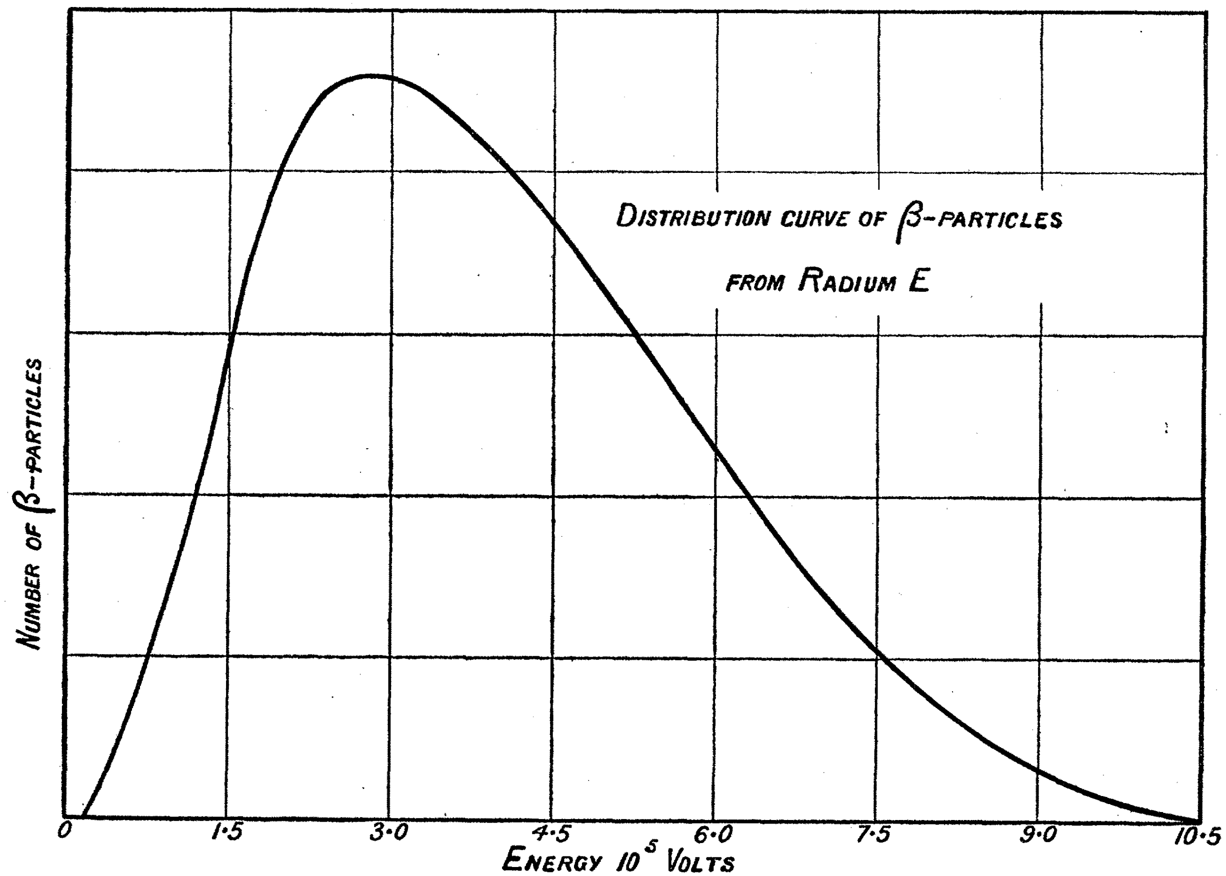

...the total energy is not constant!

Conservation of energy is a pillar in physics

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Niels Henrik David Bohr

(7 October 1885 – 18 November 1962)

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(*J. Chem. Soc.* **135**, 349, 1932)

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Wolfgang Ernst Pauli

(25 April 1900 – 15 December 1958)

"With his considerations about a violation of the energy law Bohr is on a completely wrong track".

(letter to O. Klein, February 18, 1929)

Actually several open problems challenged physicists at that time (conservation of energy, structure of nuclei, radiation of stars, etc.)

Bohr and **Pauli** discussed a lot the subject

"The quantum laws in free space offer no basis for a violation of the conservation principle"

(letter to W. Pauli, July 1, 1929)

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(letter to W. Pauli, July 1, 1929)

*"I must say that your paper has given me little satisfaction [...]
There is this disagreeable introduction of the electron's diameter [...] I do not exactly mean that this is unpermissible but it is a risky business [...]
Let the stars radiate in peace!"*

(letter to N. Bohr, July 17, 1929)

Anyway

Pauli's proposal

Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

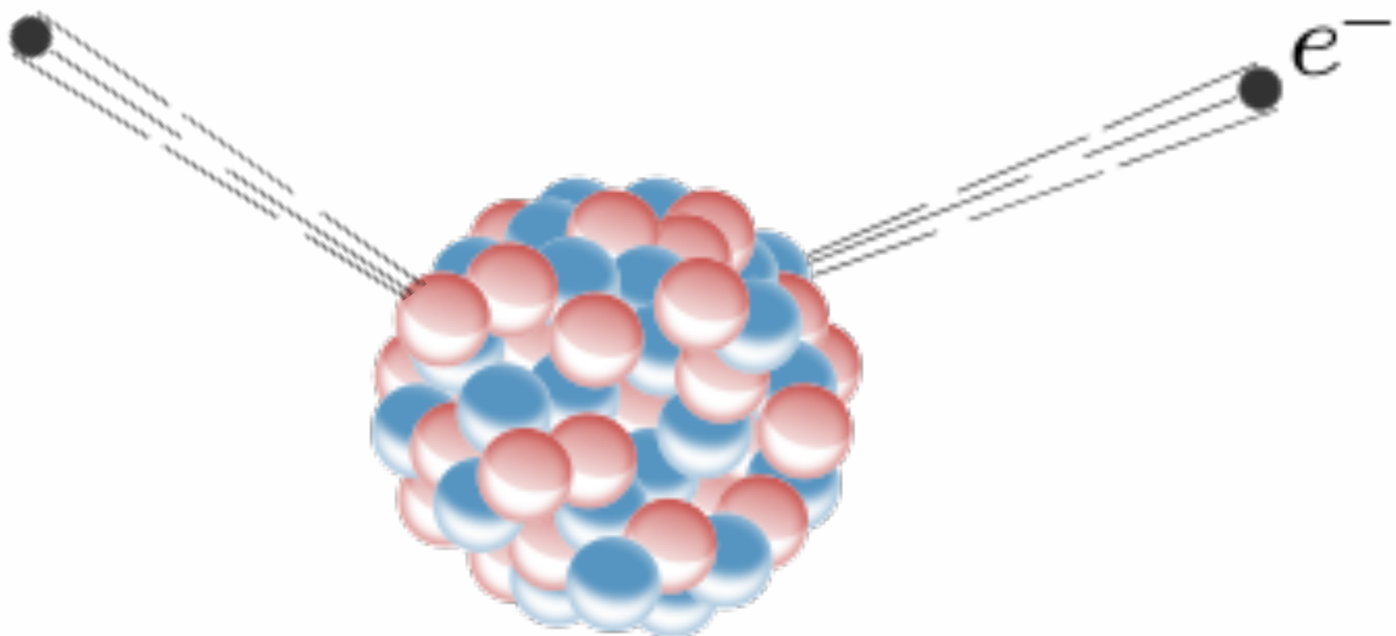
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik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

For those who do not speak German...

Open letter to the group of radioactive people at the
Gauverein meeting in Tübingen.
Zürich, Dec. 4, 1930

"Dear Radioactive Ladies and Gentlemen,
[...] I have hit upon a ***desperate remedy*** *to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that* ***in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light****.* ***The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass.*** *-The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant. [...]*
But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray. [...] I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes" [...]"

Pauli's vision



$E_{tot}=E_e+E_n$ is conserved

1932: Chadwick again

(*Nature* **129**, 312, 1932)

Possible Existence of a Neutron

[...]

theses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

A neutral particle was indeed found!

Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

The Oldoway Human Skeleton

A LETTER appeared in NATURE of Oct. 24, 1931, signed by Messrs. Leakey, Hopwood, and Reck, in which, among other conclusions, it is stated that "there is no possible doubt that the human skeleton came from Bed No. 2 and not from Bed No. 4". This must be taken to mean that the skeleton is to be considered as a natural deposit in Bed No. 2, which is overlaid by the later beds Nos. 3 and 4, and that all consideration of human interment is ruled out.

If this be true, it is a most unusual occurrence. The skeleton, which is of modern type, with filed teeth, was found completely articulated down even to the phalanges, and in a position of extraordinary contraction. Complete mammalian skeletons of any age are, as field palæontologists know, of great rarity. When they occur, their perfection can usually be explained as the result of sudden death and immediate covering by volcanic dust. Many of the more or less perfect skeletons which may be seen in museums have been rearticulated from bones found somewhat scattered as the result of death from floods, or in the neighbourhood of drying water-holes. We know of no case of a perfect articulated skeleton being found in company with such broken and scattered remains as appear to be abundant at Oldoway. Either the skeletons are all complete, as in the *Stenomylus* quarry at Sioux City, Nebraska, or are all scattered and broken in various degrees, as in ordinary bone beds. The probability, therefore, that the Oldoway skeleton represents an artificial burial is thus one that will occur to palæontologists.

The skeleton was exhumed in 1913, and published photographs show that the excavation made for its disinterment was extensive. It is, therefore, very difficult to believe that in 1931 there can be reliable evidence left at the site as to the conditions under which it was deposited. If naturally deposited in Bed No. 2, the skeleton is of the highest possible importance, because it would be of pre-Mousterian age, and would be in the company of *Pithecanthropus* and the Piltdown, Heidelberg, and Peking men, all of whose remains are fragmentary to the last degree. Of the few other human remains for which such antiquity is claimed, the Galley Hill skeleton and the Ipswich skeleton are, or apparently were, complete. The first of these was never seen *in situ* by any trained observer, and the latter has, we believe, been withdrawn by its discoverer. The other fragments, found long ago, are entirely without satisfactory evidence as to their mode of occurrence.

Is Chadwick's neutron the Pauli's neutron?

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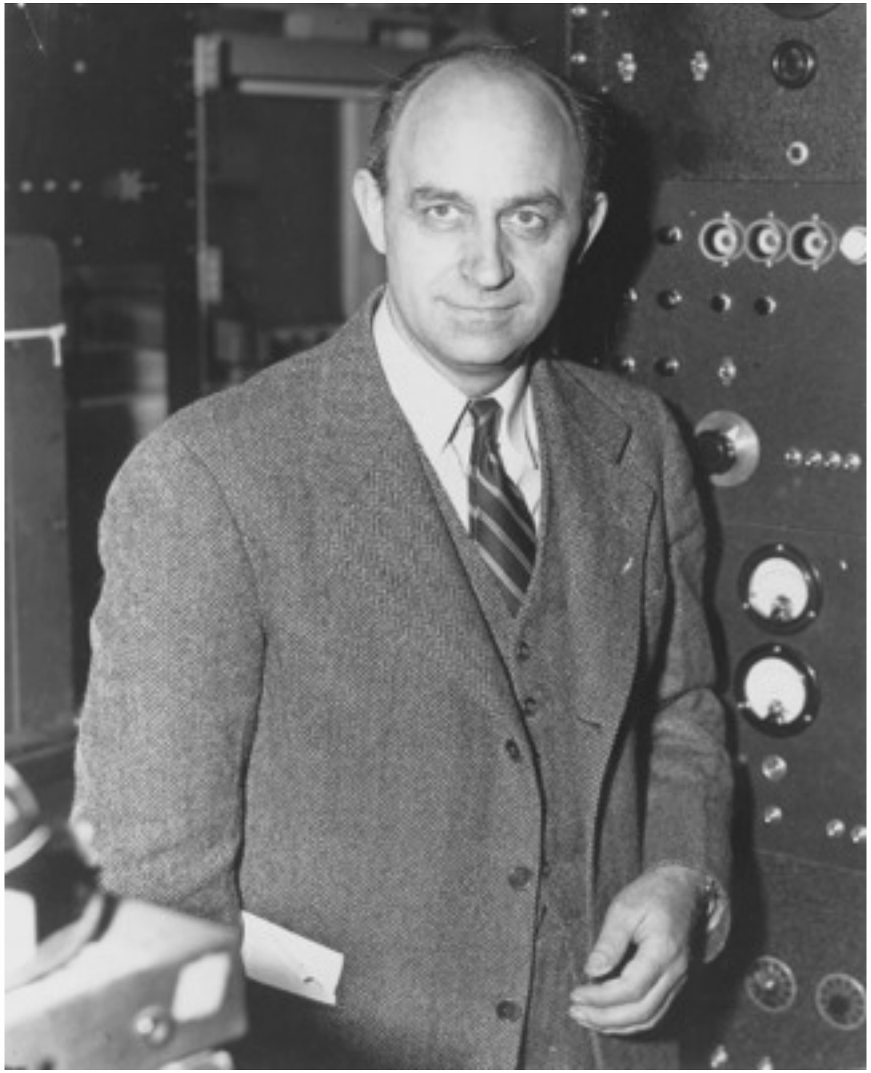
Chadwick's neutron at least 100 times heavier than Pauli's one

Fermi's attempt

Enrico Fermi
(29 September 1901 – 28 November 1954)



(*Nuov. Cim.* **11**, 1, 1934)

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di ENRICO FERMI

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 dell'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.*

It is proposed a quantitative theory of β-rays emission in which it is assumed the existence of the "neutrino"

Interlude: Italian in a nutshell

Alterazione (alteration): -**ino**, -**one**, -**etto**, or -**accio**

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Gatto

Gattino

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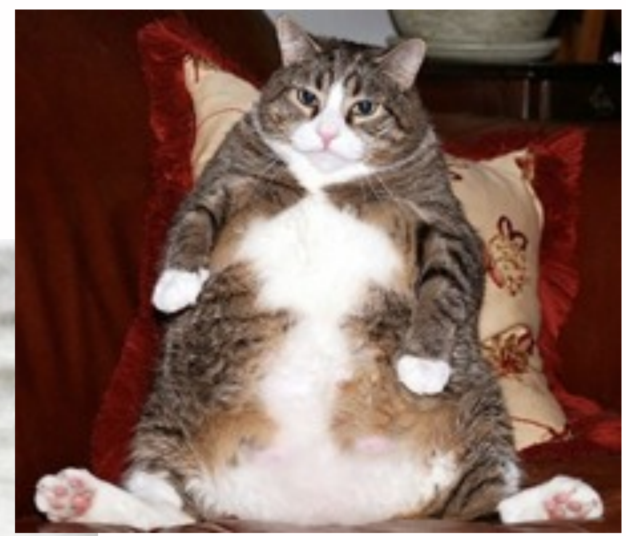
Gattino



Gattone

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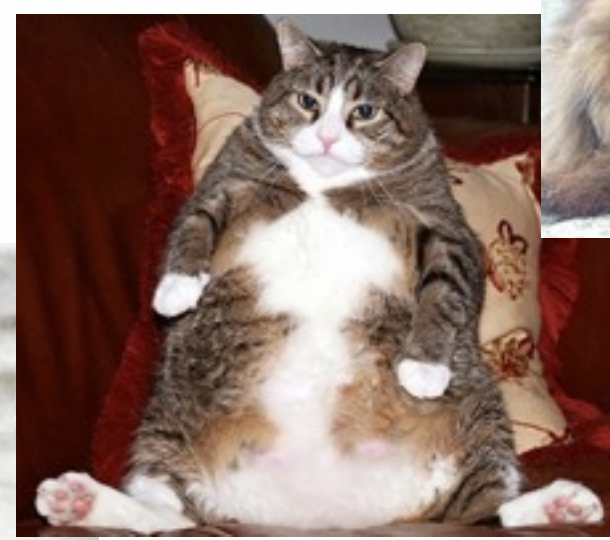
Gatto

Gattaccio



Gattone

Gattino

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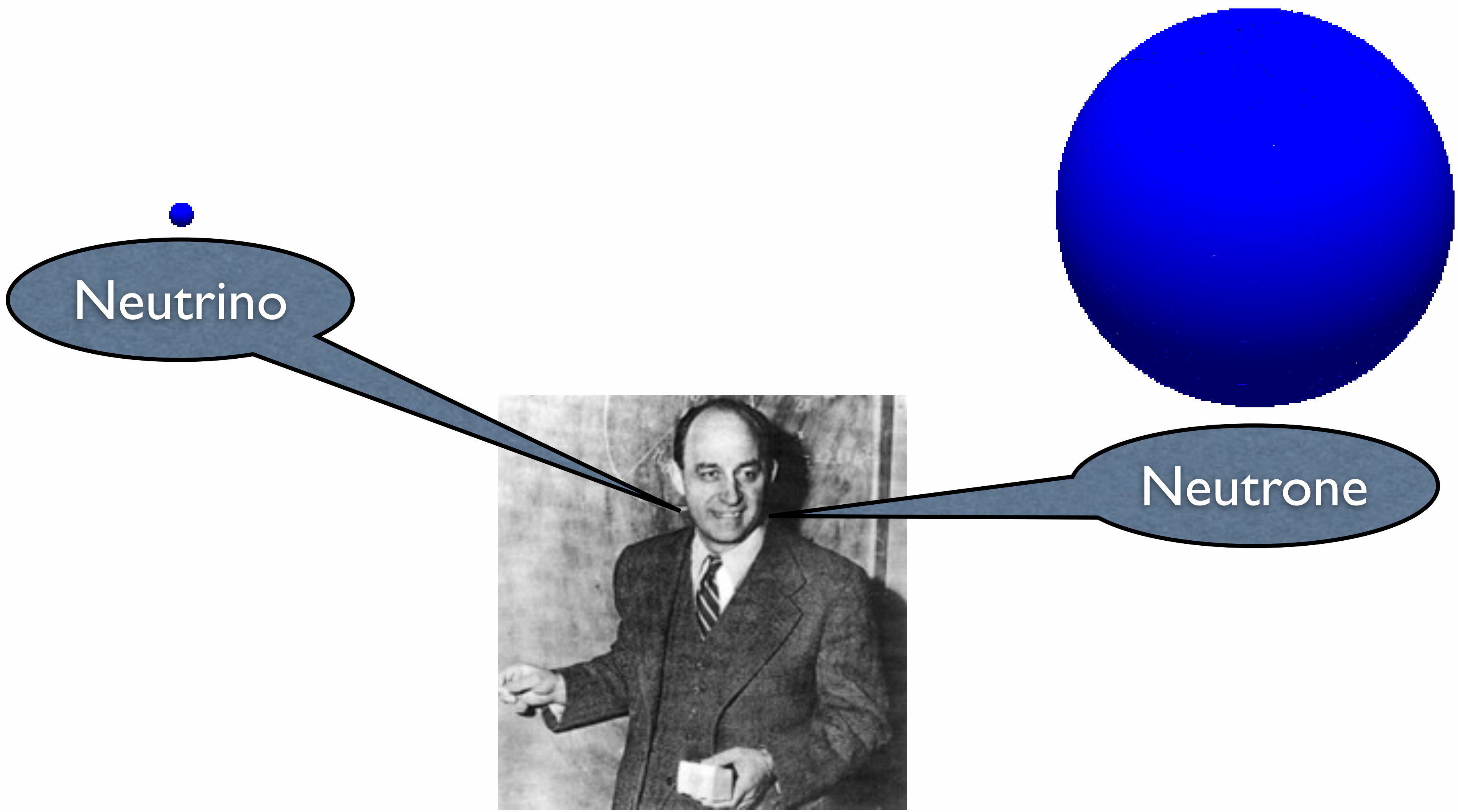
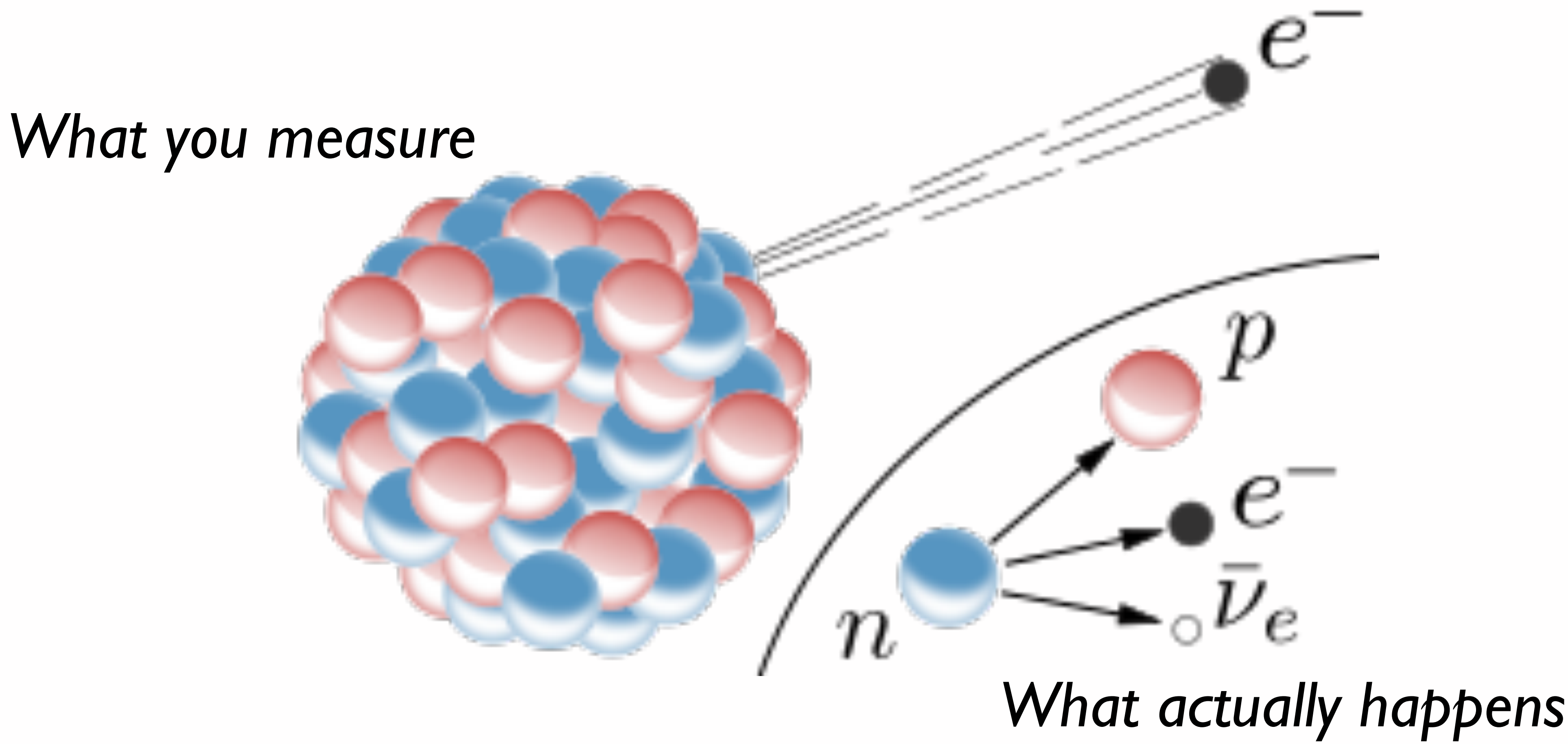
Italian in a nutshell

Pauli's neutron is like a tiny version of Chadwick's one



Fermi's *tentativo*



The neutrino interacts so feebly that it escapes the detection

Maybe too feebly...

"I have done a terrible thing, I have postulated a particle that cannot be detected."

(*Spaceship Neutrino* by C. Sutton, p. xi)

Not anyone was so pessimistic

Wang Ganchang
(May 28, 1907 – December 10, 1998)

A Suggestion on the Detection of the Neutrino
Phys. Rev. 61, 97, 1942

If there is β-decay, maybe **β-capture** will be there

$$n \rightarrow p + e^- + \overline{\nu}_e \quad \Rightarrow \quad \overline{\nu}_e + p \rightarrow n + e^+$$

Where to look for neutrinos?

Where to look for neutrinos?

Where a lot of β-decays happen

In 1956, 26 years after Pauli's proposal

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison,
H. W. Kruse, A. D. McGuire

(*Science* **124**, 103, 1956)

Introducing leptons

There exist two particles that are exactly as the electron, except that they are "**fatter**"

e

m_e

Introducing leptons

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m_e

$m_\mu \simeq 200\ m_e$

Introducing leptons

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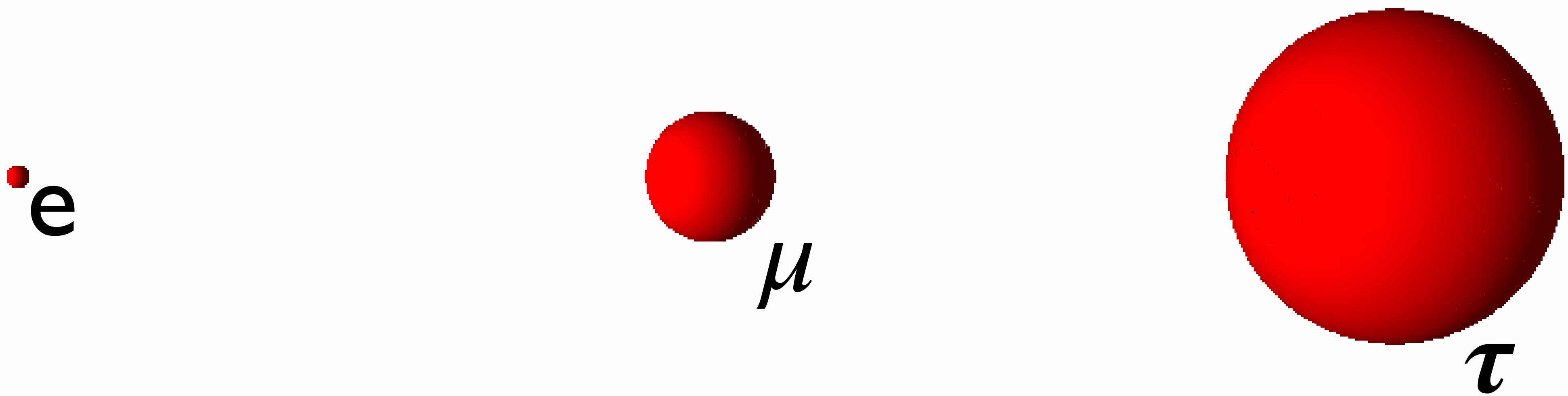

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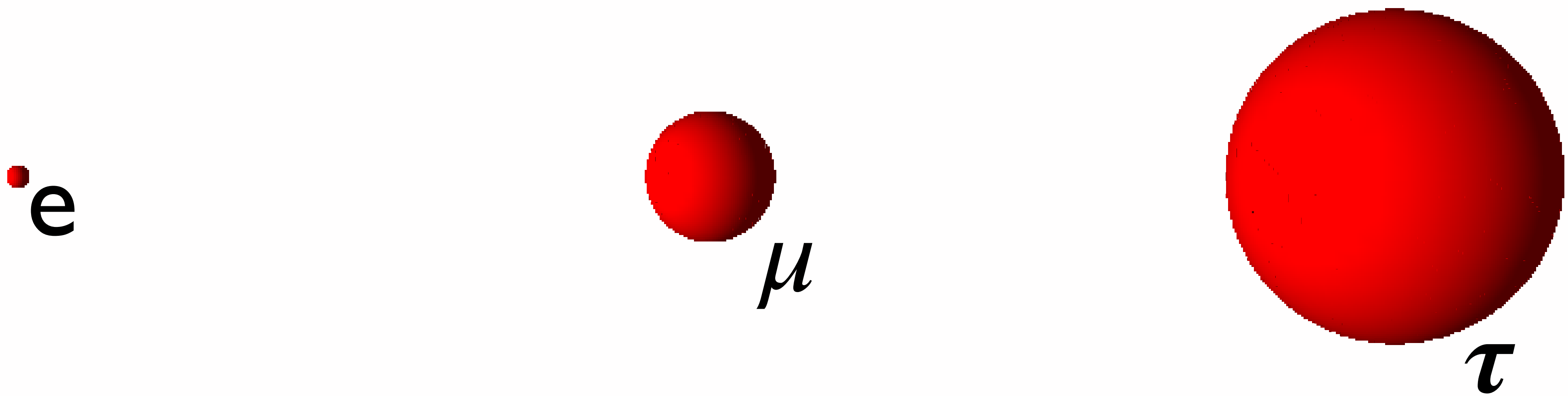


m_e

$m_\mu \simeq 200\ m_e$

$m_\tau \simeq 3500\ m_e$

We say that each lepton has a different **flavour**

How many types of neutrinos are there?

(*Phys.Rev.Lett.* **9**, 36, 1962)

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

$$\pi^{\pm} \to \mu^{\pm} + (\nu/\bar{\nu}).$$

~~$\nu + n \to p + e^-,$~~

~~$\bar{\nu} + p \to n + e^+,$~~

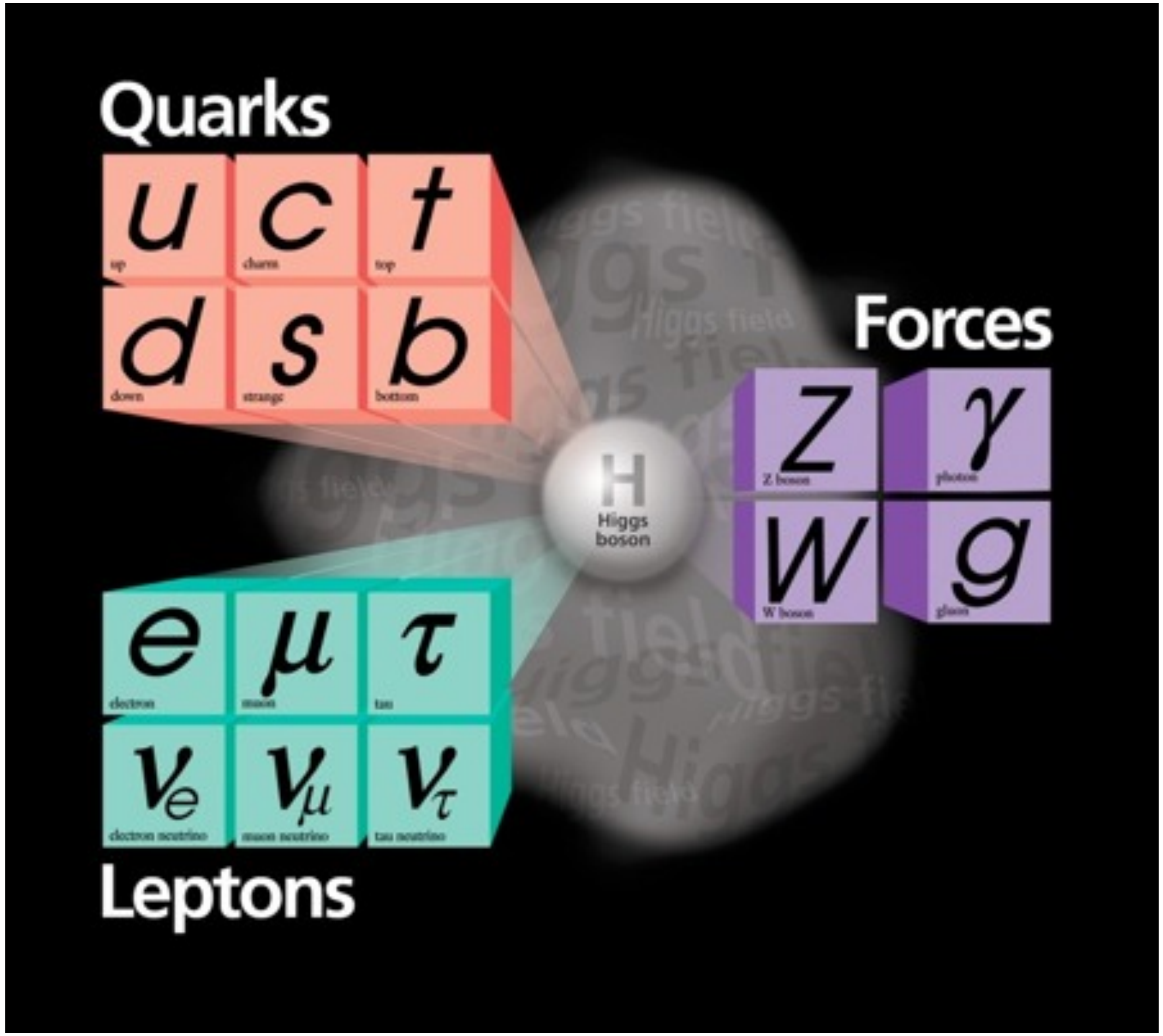
Not observed

$$\nu + n \to p + \mu^-,$$

$$\bar{\nu} + p \to n + \mu^+,$$

Neutrinos coming from muons are different from the ones coming from electrons!

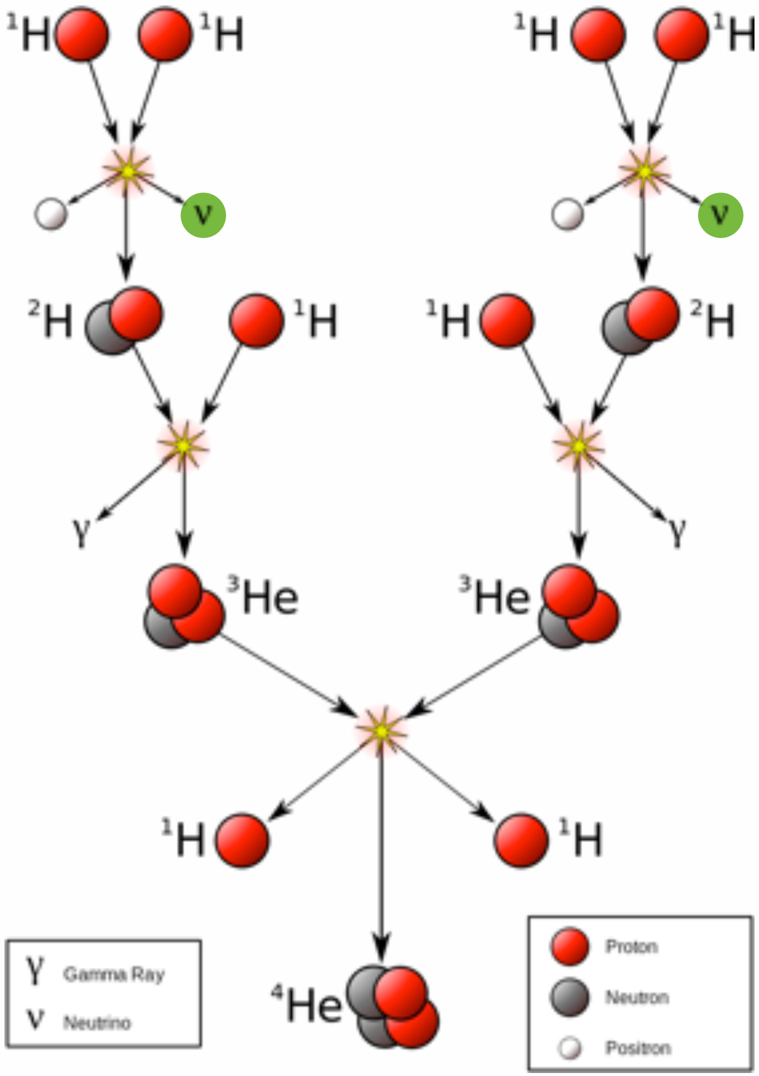
The Standard Model of particle physics



Correct, but still incomplete

A new puzzle!

Neutrinos are copiously produced in the Sun



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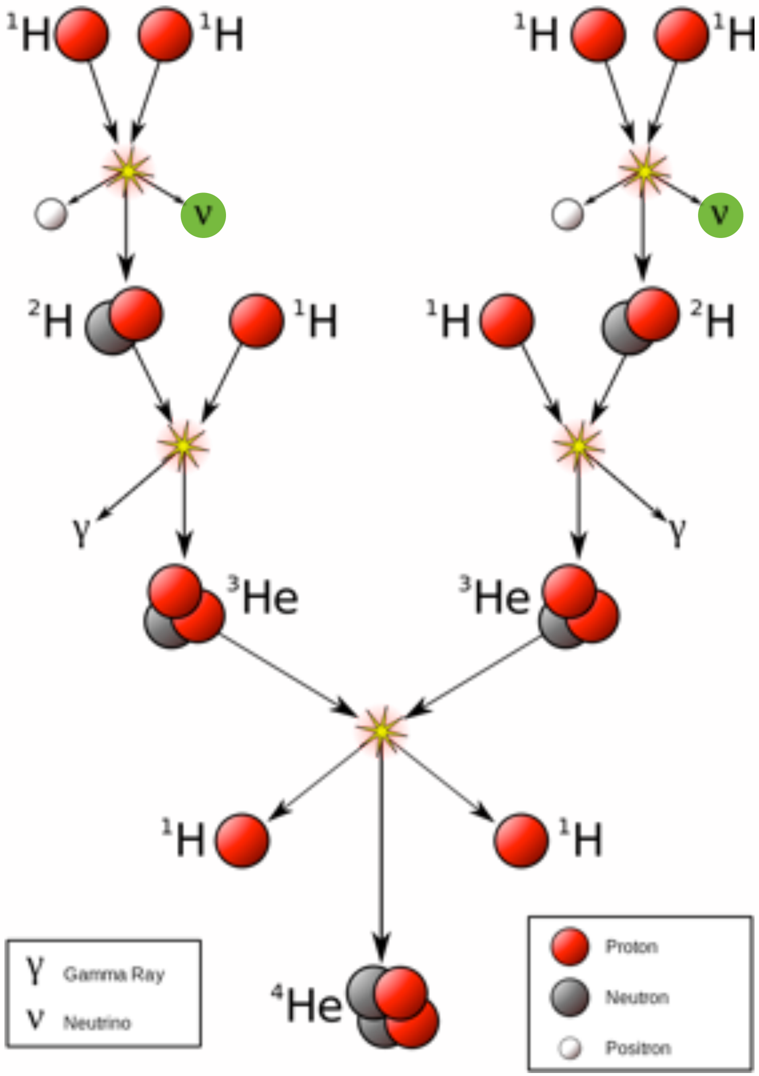

Knowing the energy produced in the Sun you expect

650 billions of solar neutrinos hitting each cm^2 each second on the Earth

Solar Neutrinos: A Scientific Puzzle

John N. Bahcall and Raymond Davis, Jr.

(*Science* **191**, 264, 1976)

Experiments observe only 30% of the total amount of expected neutrinos

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Theoreticians do not correctly understand how the Sun works

Solar Neutrinos: A Scientific Puzzle

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Experiments observe only 30% of the total amount of expected neutrinos

Solutions:

Theoreticians do not correctly understand how the Sun works

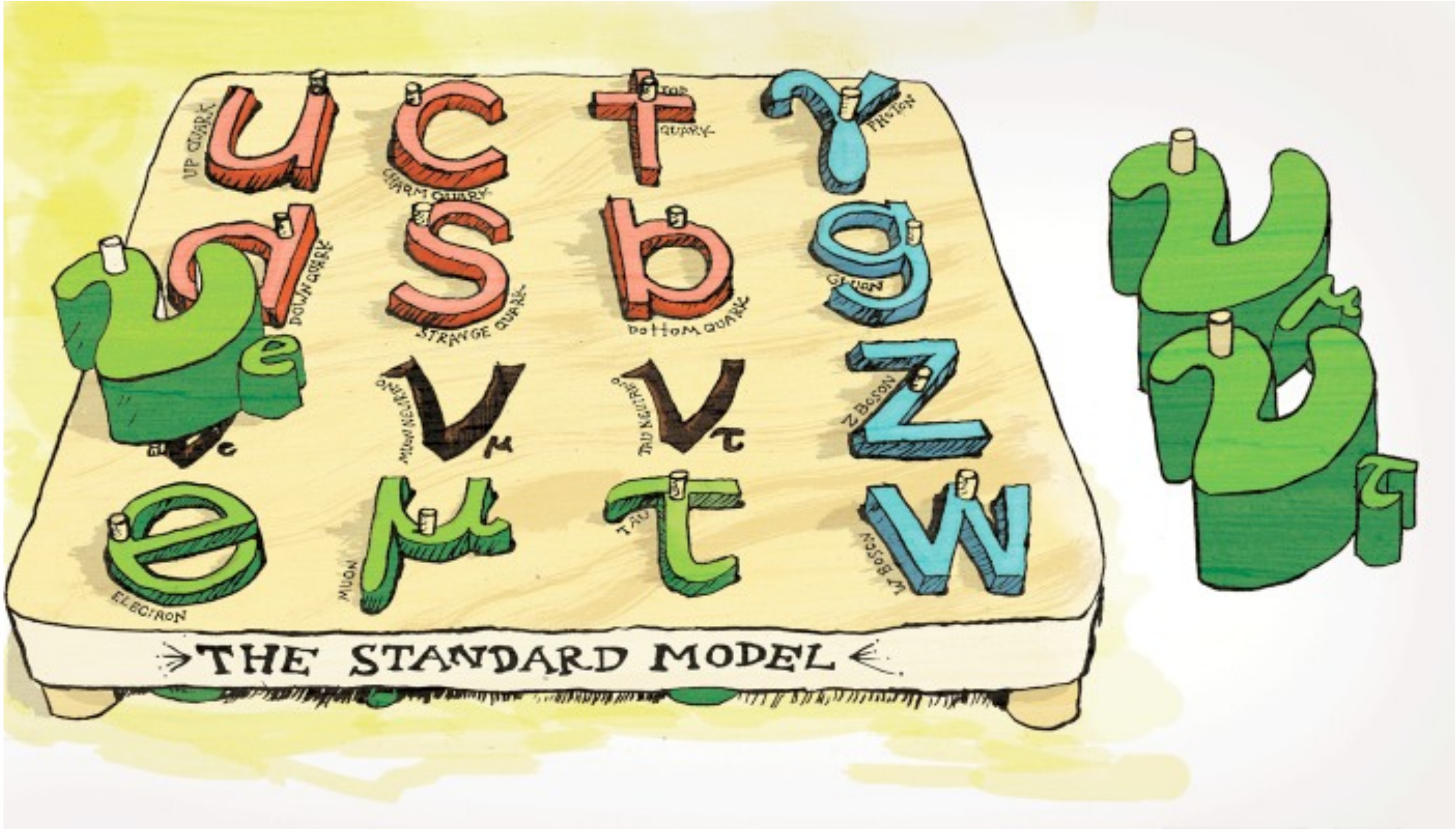
Or

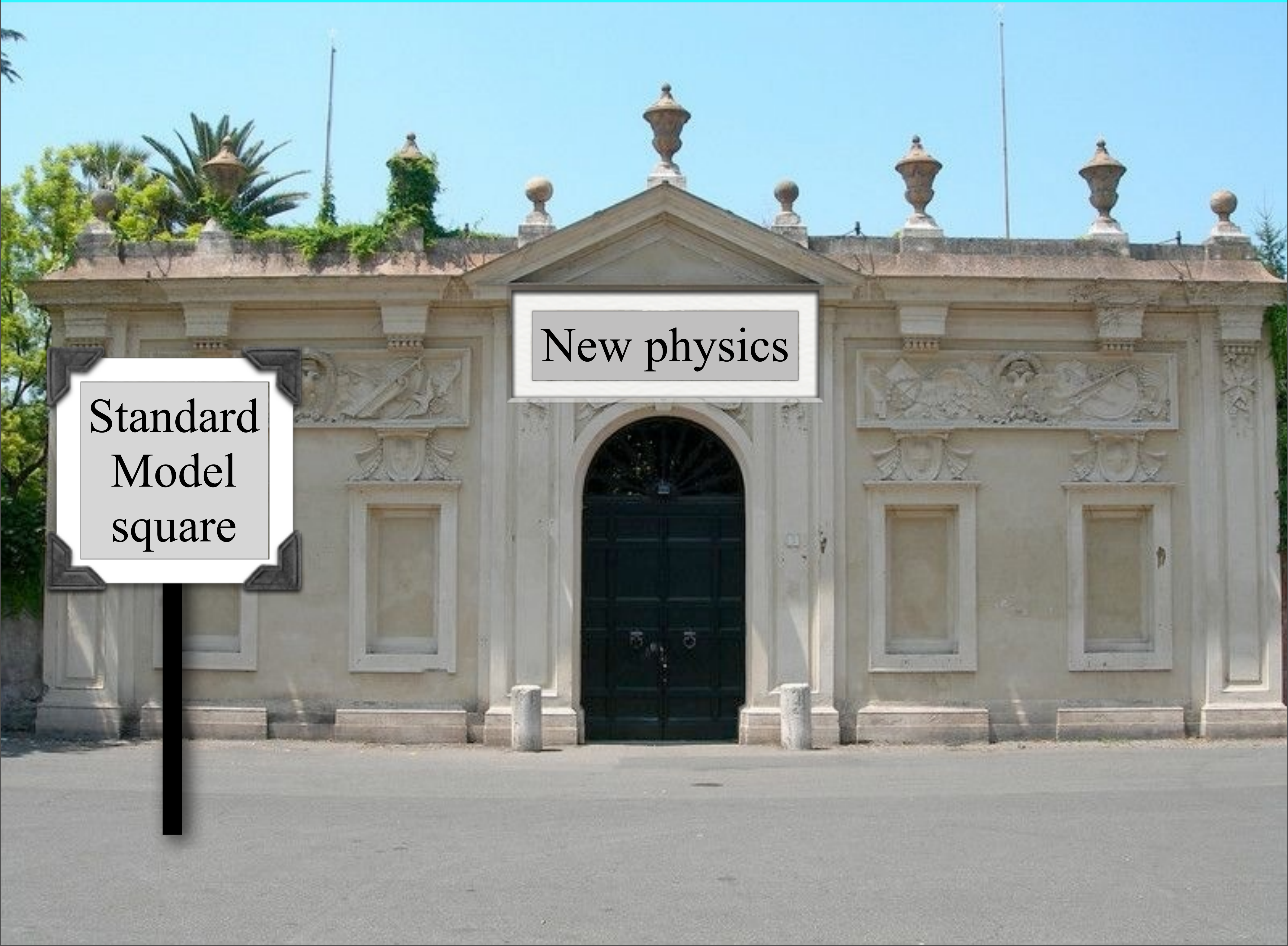
Experimentalists made some mistake

Actually...

From *BBC Horizon: Project Poltergeist* (Season 40, Episode 15)

Neutrinos do not completely fit into




Standard Model square
New physics

How to open the new physics door?

How to open the new physics door?

Our most powerful accelerator: **LHC**

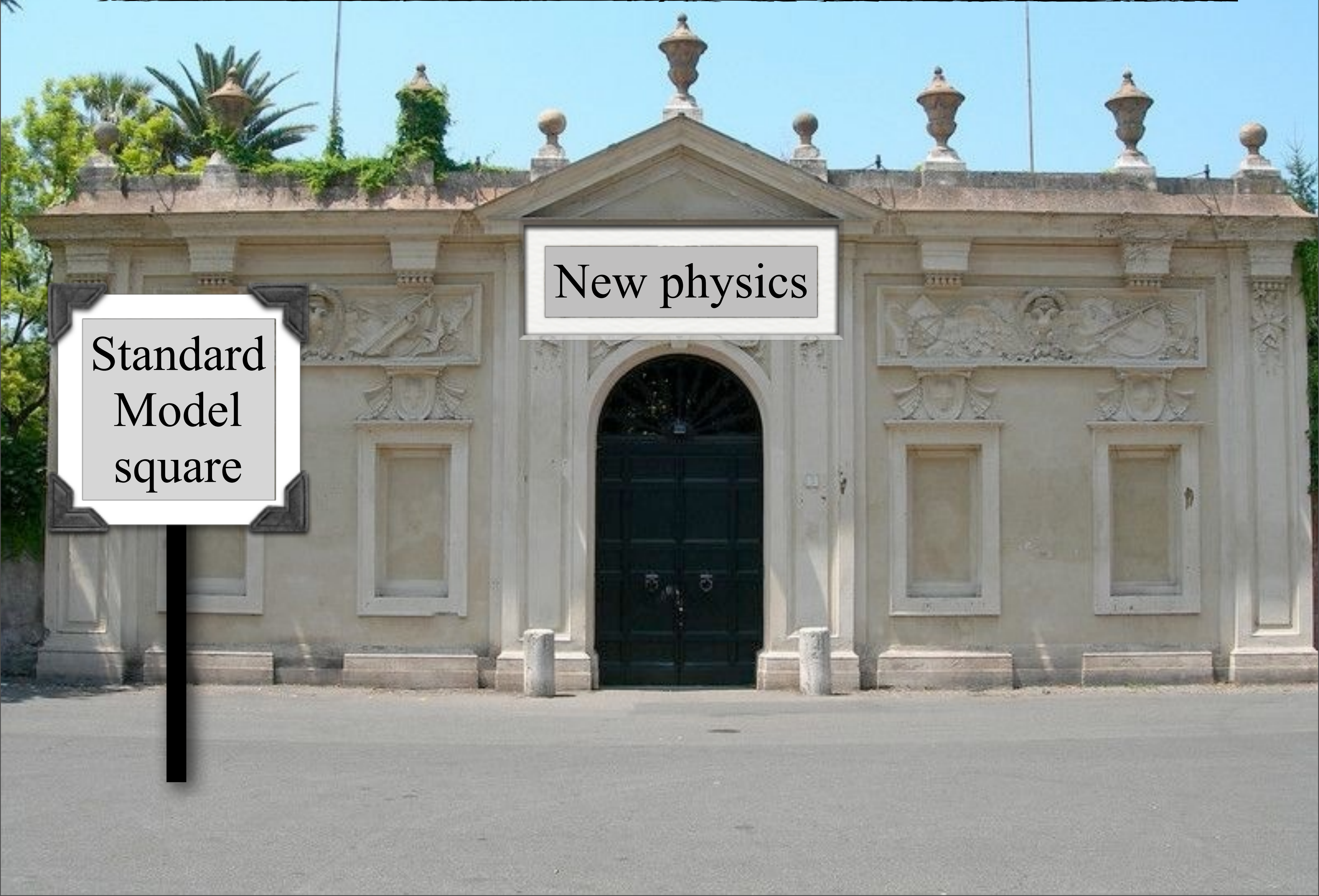
How to open the new physics door?

Our most powerful accelerator: **LHC**

But how to study physics at energies beyond the LHC ones?

We don't have the key to open this kind of door

Study neutrinos is like looking from the keyhole



New physics