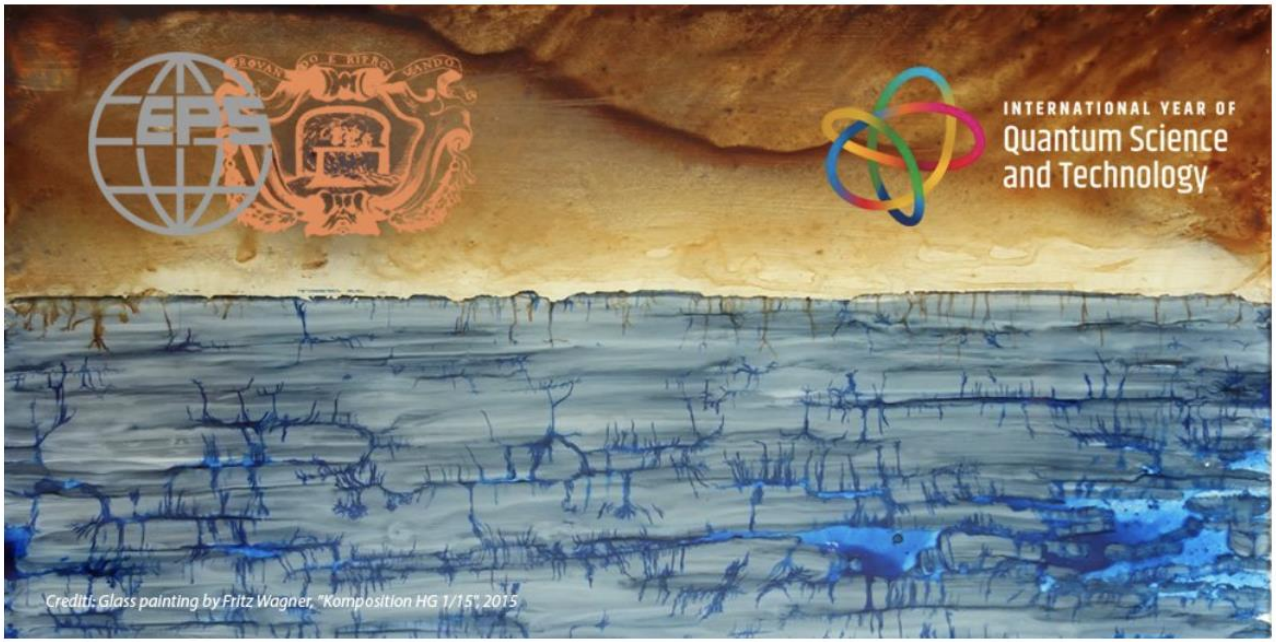
Joint EPS-SIF International School on Energy 2025

Course 8 – Nuclear Energy and its Challenging New Technologies

Varenna, 23-28 June 2025



Where it all began

Luisa Cifarelli
Università & INFN, Bologna – Centro Fermi, Roma
Società Italiana di Fisica – European Physical Society

How and where it all began …
at the Physics Institute of Via Panisperna in Rome

In 1870, after the proclamation of Rome as capital of the Kingdom of Italy the University of Rome aimed to equip itself with modern institutes and laboratories of physics and chemistry thanks to the vision of Finance Minister **Quintino Sella** (famous mineralogist and crystallographer)

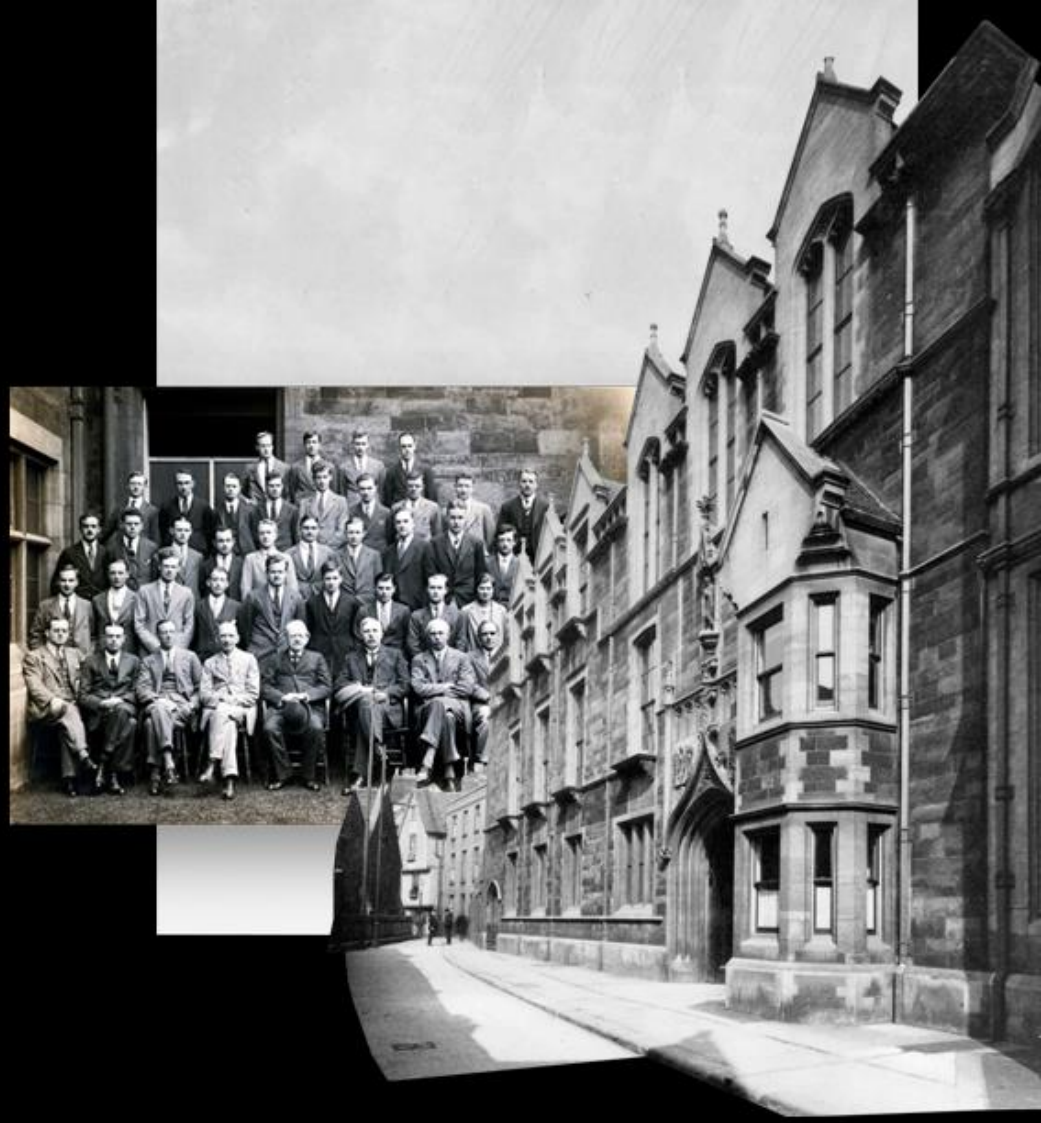
To this purpose Rome welcomed two important figures from the scientific world both professors and colleagues at the University of Palermo:

– the chemist **Stanislao Cannizzaro**
– the physicist **Pietro Blaserna**

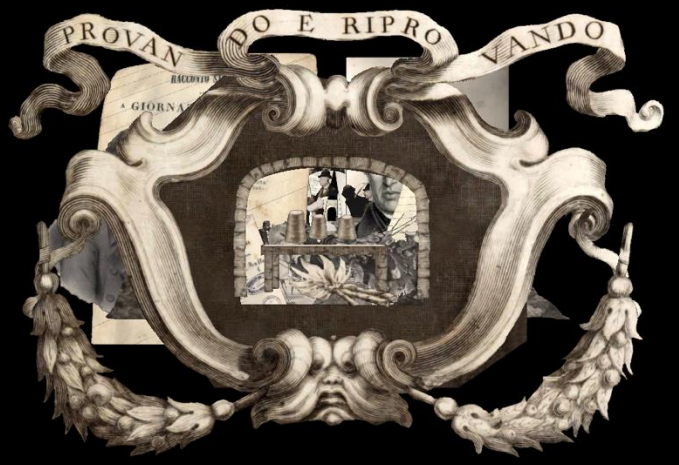
The area of Panisperna on the Viminale hill
was identified as a possible site for the future institutes
to be located outside the Sapienza University palace

The Institute of Chemistry directed by Cannizzaro
was housed in the existing ancient convent of
San Lorenzo in Panisperna and inaugurated in 1873

Instead, it was not until 1877 that construction work
began on the new building for the Institute of
Physics, designed by Blaserna on the model
of other European institutes



The Physics Institute
of Via Panisperna
in Rome
was built in 1877-1880
by Pietro Blaserna
inspired by foreign scientific institutes
such as the Cavendish Laboratory in Cambridge
(opened in 1874 under the direction of James Clerk Maxwell)

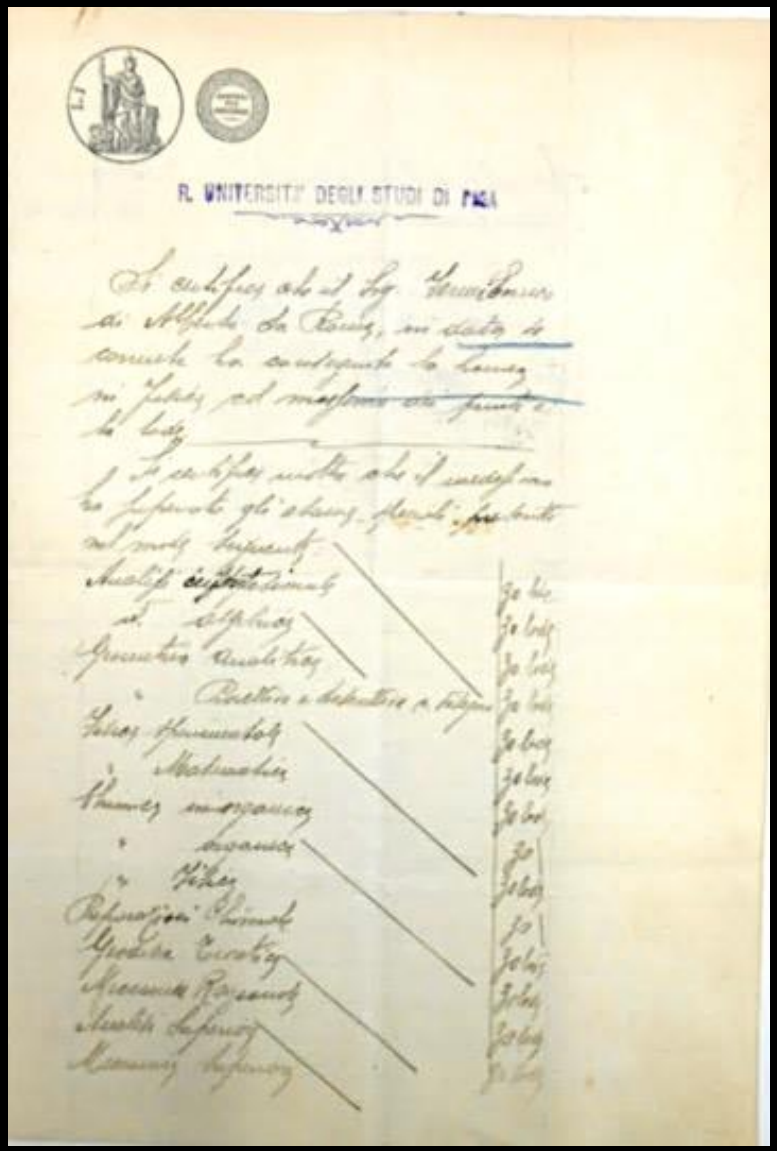


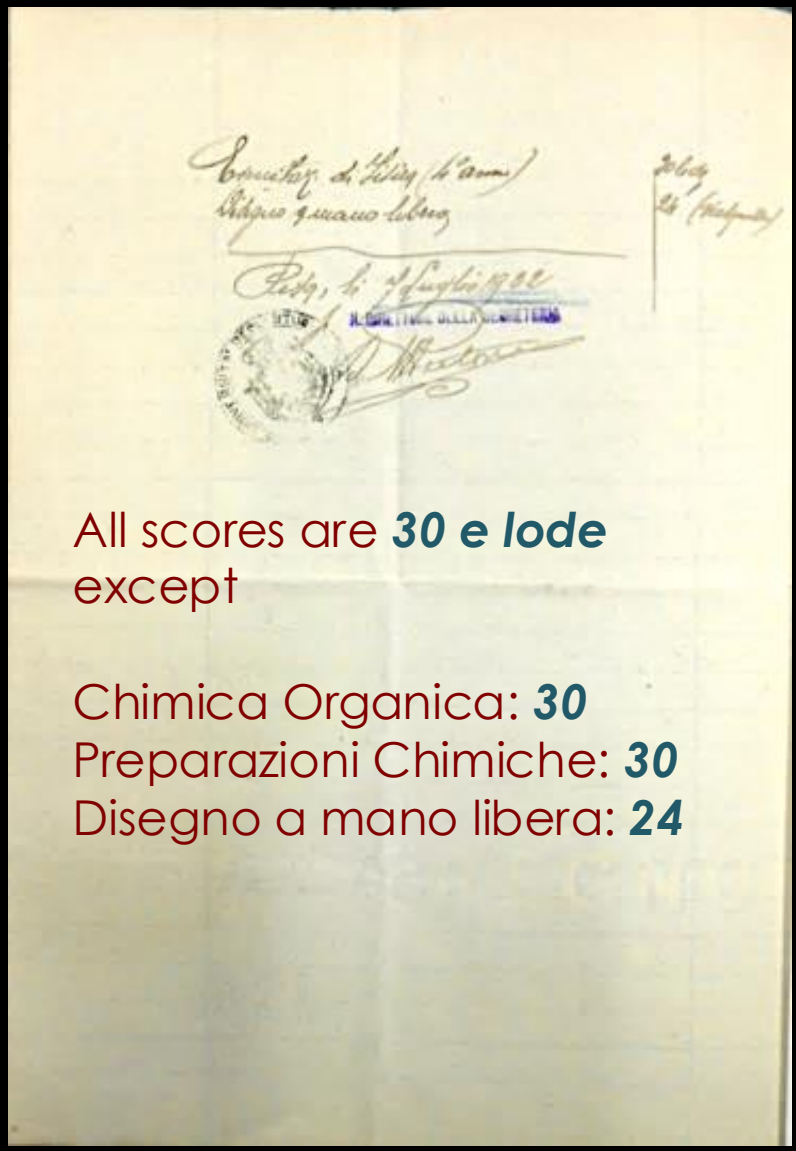
Pietro Blaserna

Varied scientific interests: from the properties of real gases to the study of air ionisation, from geophysics to electrical engineering, from acoustics to "musical physics" (violin player)

Rector of Rome University 1874-1876
Academician of the Lincei, President 1904-1916
Senator 1890, Vice President Senate 1906-1918 (death)
First President of Italian Physical Society 1897

- Enrico Fermi was born in Rome in 1901
- He obtained in 1922 his diploma from the *Scuola Normale Superiore* of Pisa





All scores are ***30 e lode*** except

Chimica Organica: ***30***
Preparazioni Chimiche: ***30***
Disegno a mano libera: ***24***

- Enrico Fermi was born in Rome in 1901
- He obtained in 1922 his diploma from the *Scuola Normale Superiore* of Pisa
- He was immediately attracted to quantum physics which at the time was not well known in Italy: he spent periods abroad in Göttingen (Max Born) and Leiden (Paul Ehrenfest) in 1923-1924
- In 1924-1926 Fermi was visiting professor of Mathematical Physics at the University of Florence

- In 1926 he obtained the first chair of Theoretical Physics in Italy, specially created for him at the University of Rome by Orso Mario Corbino

- In 1926 while still very young Fermi formulated a new statistical theory to describe the collective behaviour of particles on the quantum scale
  known today as Fermi-Dirac statistics

  → The exclusion principle introduced by Pauli in 1925 to explain the electronic structure of atoms was transformed into a universal principle

  → It is the first great theoretical success of Fermi

ISTITUTO FISICO
DELLA
R. UNIVERSITÀ DI ROMA
VIA PANISPERNA, 89-A

Roma, 25/IO/1926

Mr. P.A.M. Dirac
St.John's College
Cambridge

Dear Sir!

In your intersting paper"On the theory of Quantum Mechanics" (Proc.Roy.Soc.112,661,1926)you have put forward a theory of the Ideal Gas based on Pauli's exclusion Principle.

Now a theory of the ideal gas that is practically identical to yours was published by me at the beginning of 1926 (Zs.f.Phys,36,p. 902 ;Lincei Rend. February 1926)

Since I suppose that you have not seen my paper, I beg to attract your attention on it.

I am,Sir,

Yours Truly

Enrico Fermi

- In 1926 while still very young Fermi formulated a new statistical theory to describe the collective behaviour of particles on the quantum scale
  known today as Fermi-Dirac statistics

  → The exclusion principle introduced by Pauli in 1925 to explain the electronic structure of atoms was transformed into a universal principle

  → It is the first great theoretical success of Fermi

- In 1927 formulation of the Thomas-Fermi statistical atomic model

- In 1928-1932 several contributions of Fermi in Quantum Electrodynamics

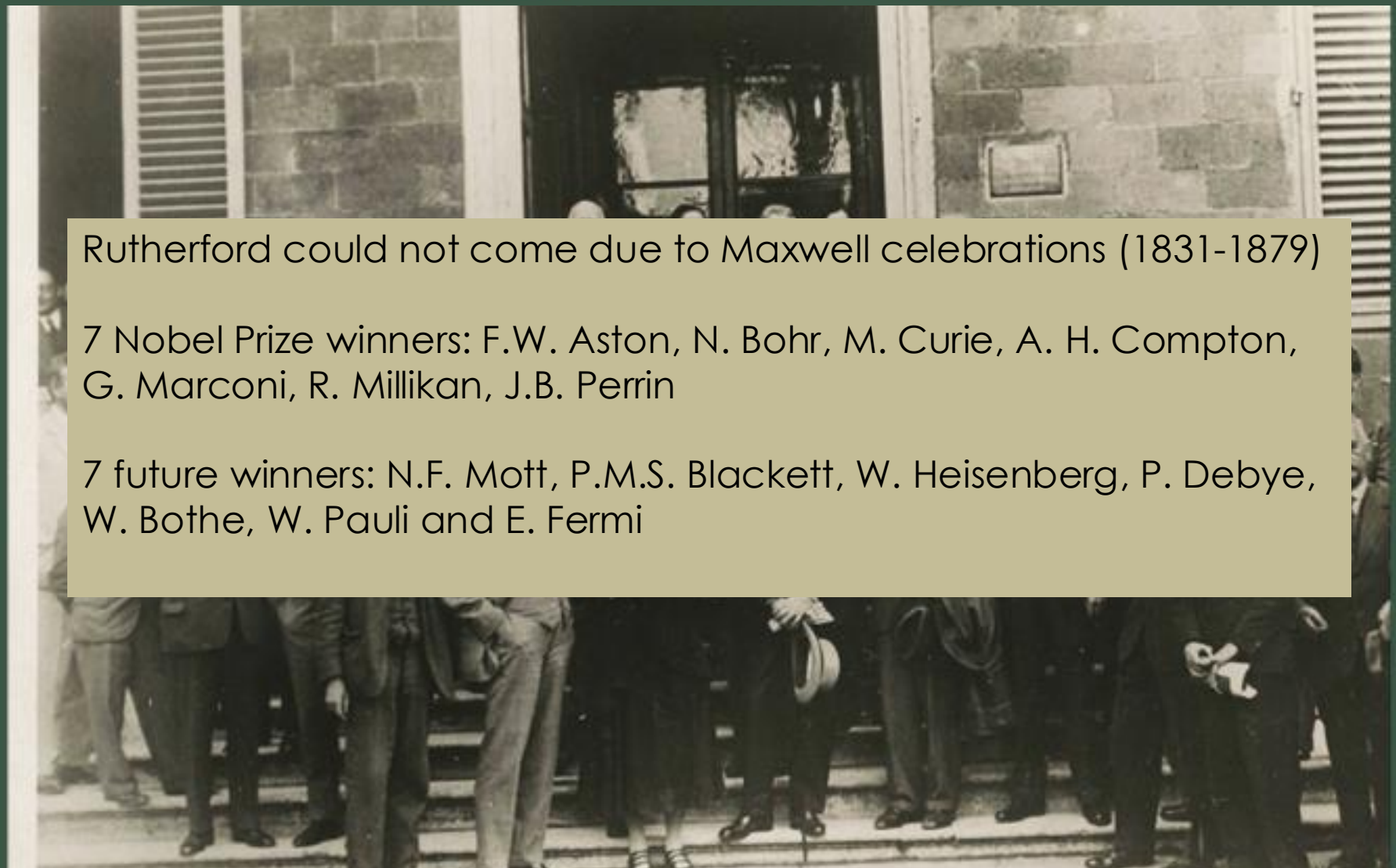
- In 1929 first interest of Fermi in nuclear physics as supervisor of Ettore Majorana's thesis on "The Mechanics of Radioactive Nuclei" (alpha decays)

- In 1931 the first International Congress of Nuclear Physics took place in Rome, in the Via Panisperna building

  - About 50 eminent Italian and foreign scientists were invited
  - Enrico Fermi was Secretary General of the Congress, Bruno Rossi, Gleb Watagin and Antonio Carrelli were Secretaries
  - Guglielmo Marconi (Nobel Prize, Senator and CNR President) was Honorary President
  - Orso Mario Corbino (Director of the Physics Institute and Senator; former Minister for Education and Economy) was President

PHOTOGRAPH OF THE FIRST INTERNATIONAL CONGRESS OF NUCLEAR PHYSICS PHYSICS INSTITUTE, ROME, 1931

PHOTOGRAPH OF THE FIRST INTERNATIONAL CONGRESS OF NUCLEAR PHYSICS PHYSICS INSTITUTE, ROME, 1931



Rutherford could not come due to Maxwell celebrations (1831-1879)

7 Nobel Prize winners: F.W. Aston, N. Bohr, M. Curie, A. H. Compton, G. Marconi, R. Millikan, J.B. Perrin

7 future winners: N.F. Mott, P.M.S. Blackett, W. Heisenberg, P. Debye, W. Bothe, W. Pauli and E. Fermi

PHOTOGRAPH OF THE FIRST INTERNATIONAL CONGRESS OF NUCLEAR PHYSICS PHYSICS INSTITUTE, ROME, 1931

In 1932:

- α (^{4}He), β (e^-), γ (photon) natural radioactivity known
- Neutron (Chadwick, 1932) discovered
- Positron (Anderson, 1932) discovered
- Nuclear model with protons & neutrons attempted (Heisenberg and Majorana)

… but mystery of beta decay

- Electrons confined in the nucleus then emitted?
- Energy non conservation?

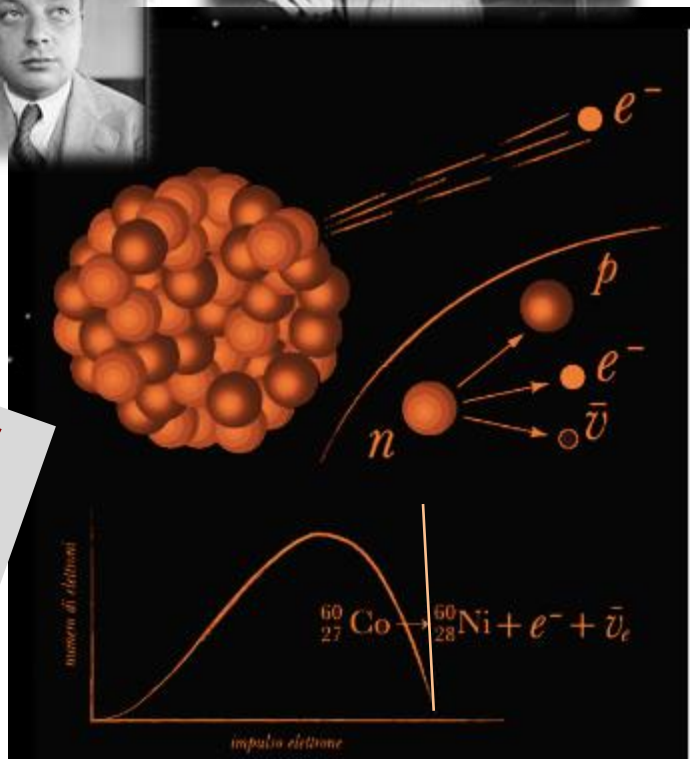
Hypothesis of Pauli (1930) of an "invisible" & light neutral particle that would explain the energy & momentum conservation violation

In 1933 *coup de génie* of Fermi

→ beta radiation theory
with electron and (anti)neutrino
non existing in the nucleus
but **created** in the decay

→ New type of interaction:
the nuclear weak interaction

"neutrino" baptized by Fermi



La Ricerca Scientifica 4 (2), 491, 1933 – Il Nuovo Cimento 11, 1, 1934

- In the 30s Fermi "*superstar*" in theoretical physics
  → but strongly and more&more attracted by nuclear physics

- In 1934 Joliot-Curie discovered artificial radioactivity
  induced by alpha particles

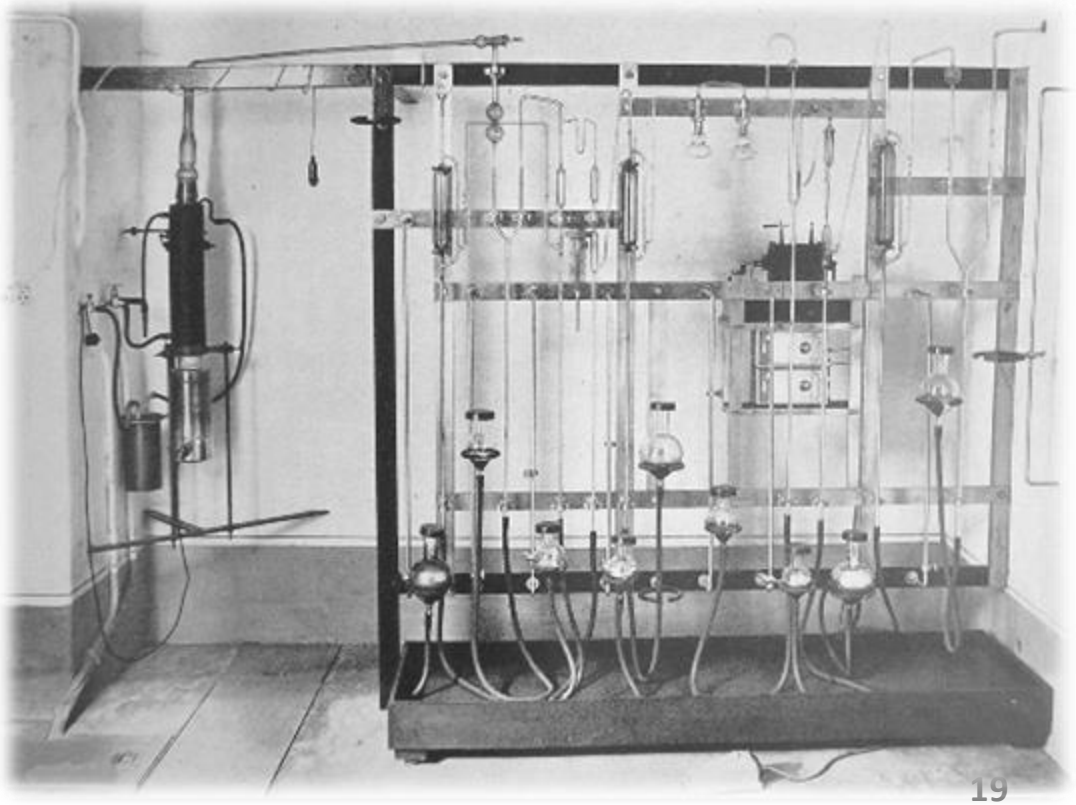
  → The dual genius of Fermi showed up:
  after theories … experiments
  and Fermi's *début*
  in experimental research

- Fermi's idea: use neutrons instead, smaller and more penetrating than alpha particles

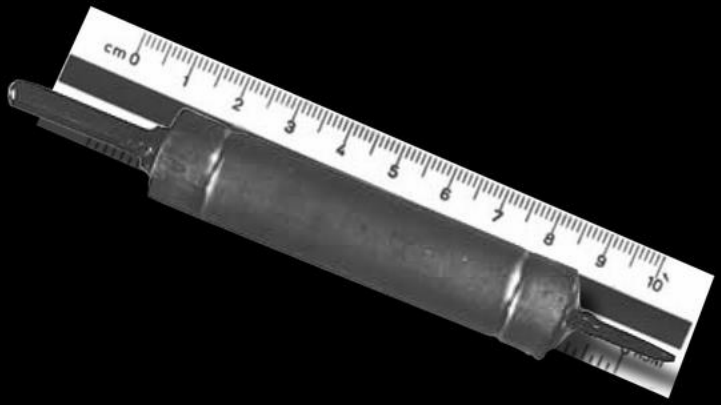
- How to get neutron sources?

- Neutron sources made of radon gas-beryllium powder sealed in thin glass tubes (^{222}Rn produces α which are absorbed by ^{9}Be producing n)
- Radon produced using radium from the Institute of Public Health ISP in Rome (G.C. Trabacchi)
- Low intensity (≈ 800 mCi → ≈ 2 x 10^7 n/s) & short lifetime (≈ 1week) of neutron sources

→ Simple but ingenious experimental procedures & equipment



Original neutron sources made of radon gas-beryllium powder sealed in thin glass tubes used in the 1934-1935 experiments in Rome (from Domus Galilaeana, Pisa)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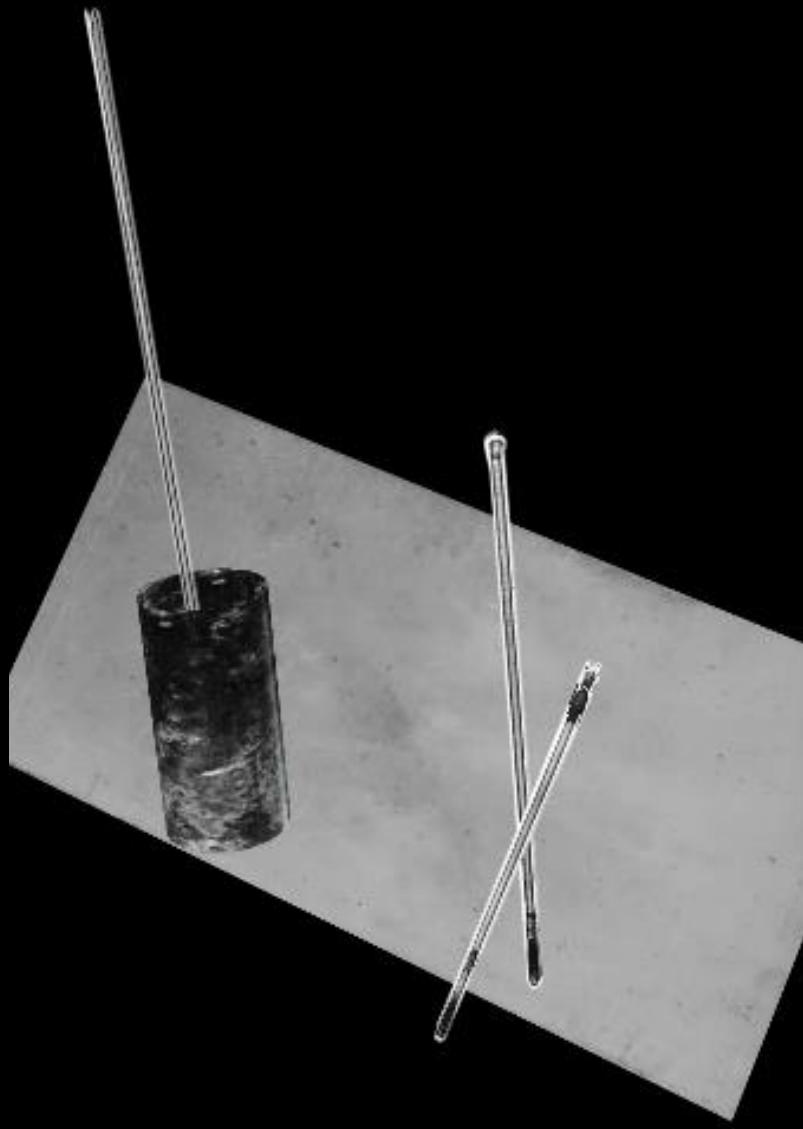


O. D'Agostino, E. Segrè, E. Amaldi, F. Rasetti, E. Fermi
plus B. Pontecorvo (the photographer)
and E. Majorana

"*I ragazzi di Via Panisperna*"
according to O.M. Corbino

Oscar D'Agostino
(1901-1975)

Franco Rasetti
(1901-2001)

Emilio Segrè
(1905-1989)

Ettore Majorana
(1906-1938 (?))

Edoardo Amaldi
(1908-1989)

Enrico Fermi
(1901-1954)

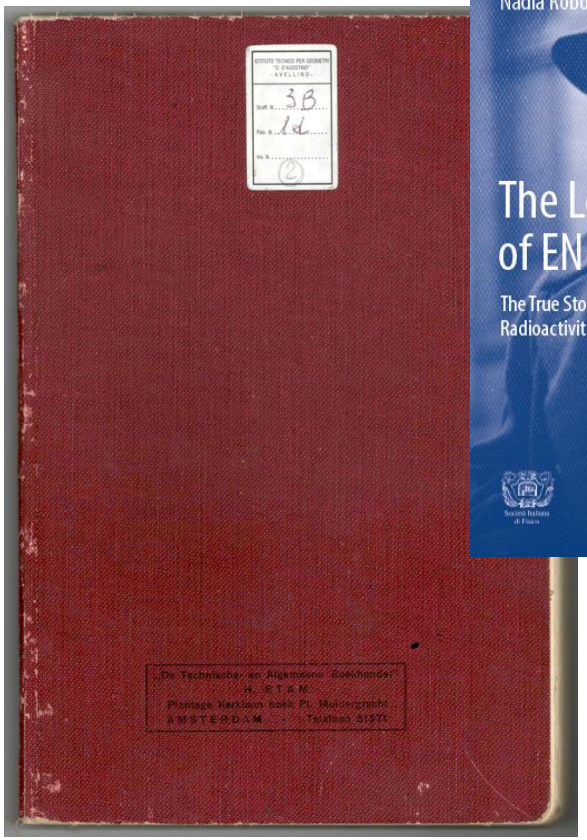
Bruno Pontecorvo
(1913-1993)

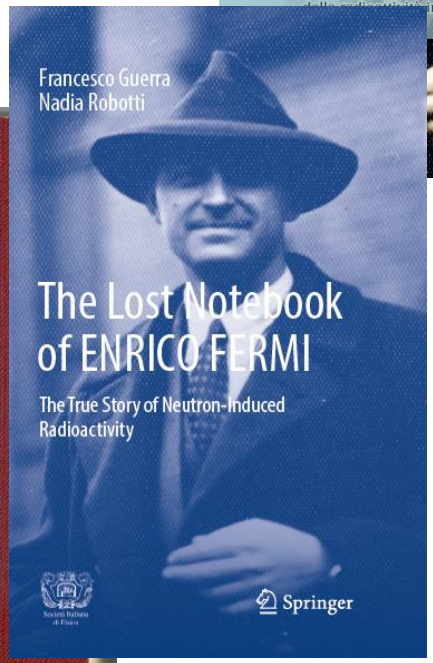
- March 1934

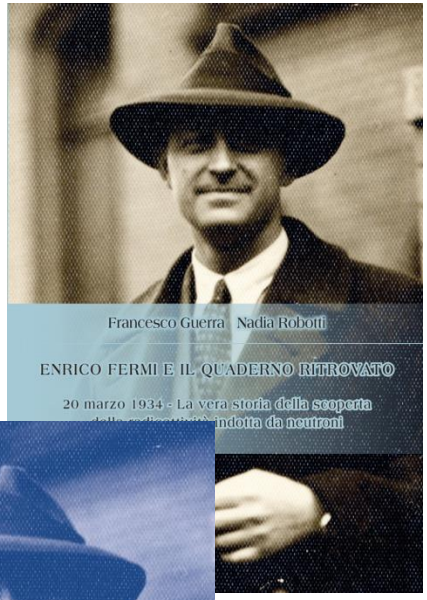
Discovery of the neutron-induced beta radioactivity of aluminium, then of fluorine (calcium fluoride CaF_2)

Documented in a **lost and regained notebook of Enrico Fermi** covering the March-April period

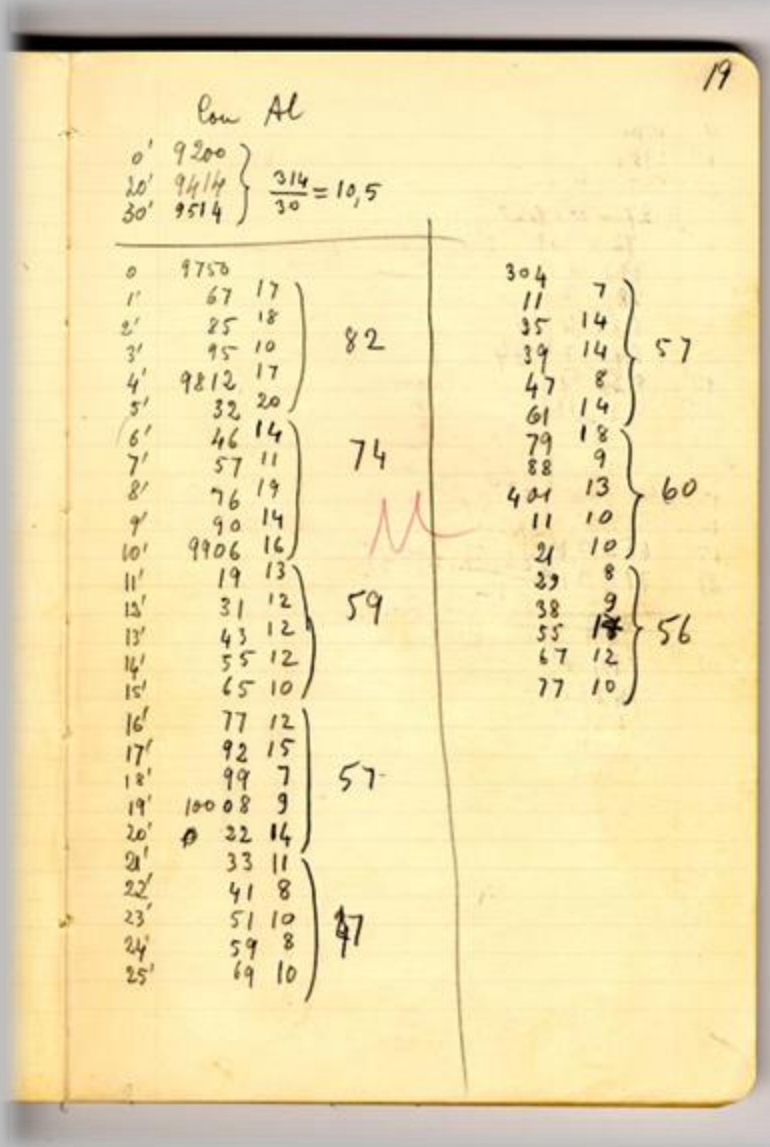
Discovered in 2002 in Avellino, birth city of O. D'Agostino, in the library of the Institute for Surveyors named after him among various other documents of his







The discovery of neutron-induced radioactivity

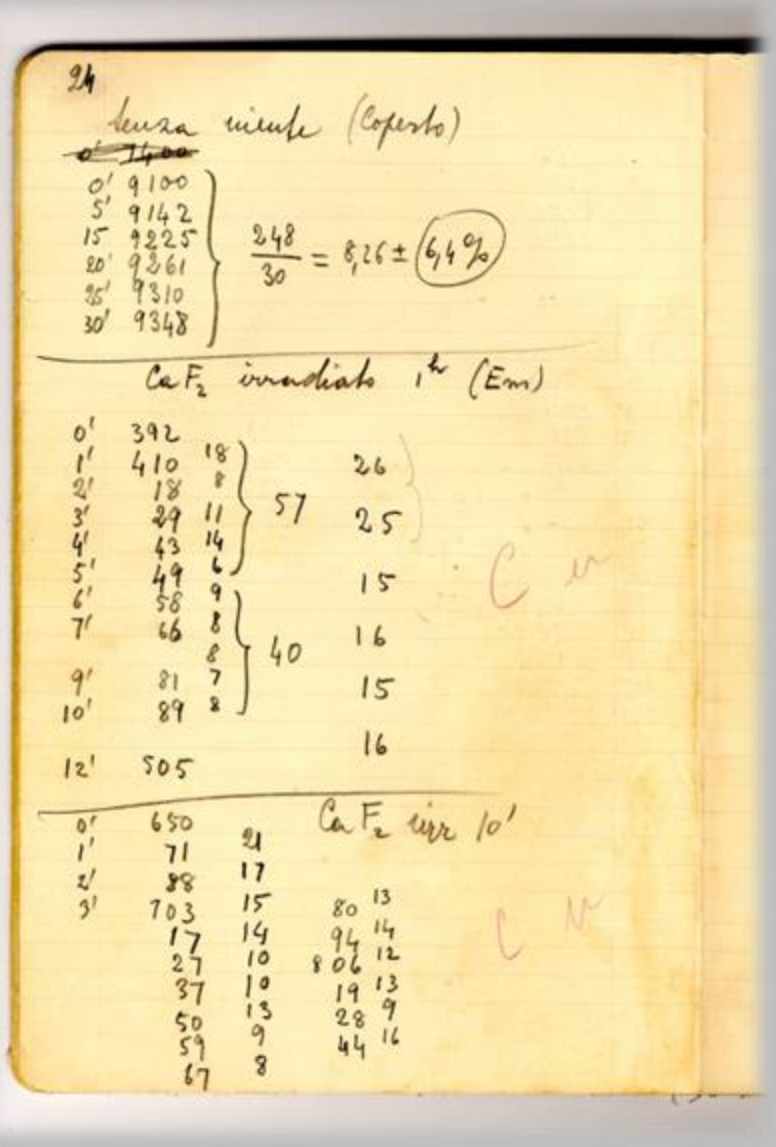


Con Al

0' 9200
20' 9414
30' 9514

$\frac{314}{30} = 10,5$

0	9750			304			
1'	67	17		11		7	
2'	85	18		35		14	
3'	95	10	82	39		14	57
4'	9812	17		47		8	
5'	32	20		61		14	
6'	46	14		79		18	
7'	57	11	74	88		9	
8'	76	19		401		13	60
9'	90	14		11		10	
10'	9906	16		21		10	
11'	19	13		29		8	
12'	31	12	59	38		9	
13'	43	12		55		17	56
14'	55	12		67		12	
15'	65	10		77		10	
16'	77	12					
17'	92	15					
18'	99	7	57				
19'	10008	9					
20'	0 22	14					
21'	33	11					
22'	41	8					
23'	51	10	47				
24'	59	8					
25'	69	10					



Senza rivele (Coperto)

0' 9100
5' 9142
15' 9225
20' 9261
25' 9310
30' 9348

$\frac{248}{30} = 8,26 \pm 6,4\%$

CaF_2 irradiato 1h (Em)

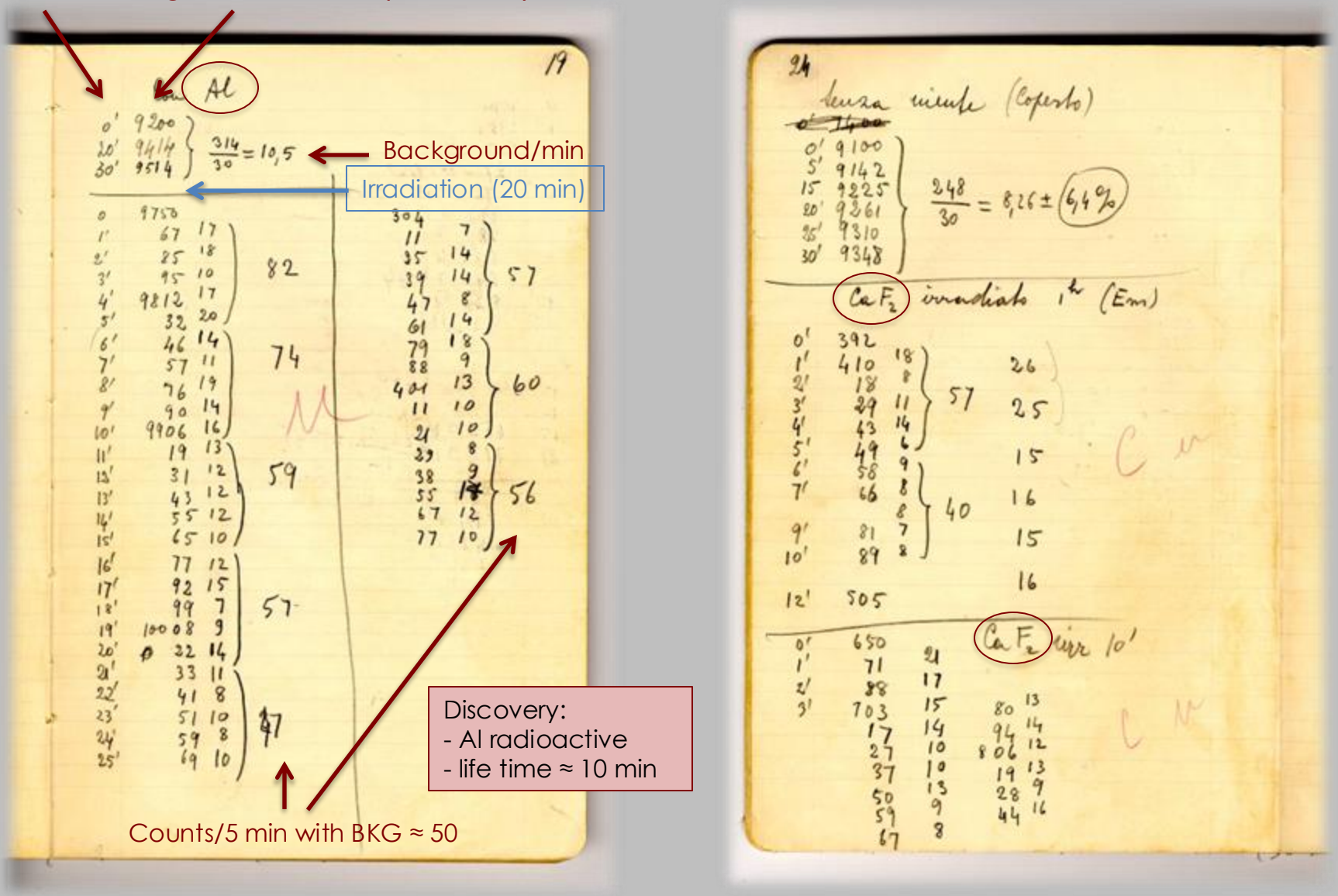
0'	392				
1'	410	18			26
2'	18	8			
3'	29	11	57		25
4'	43	14			
5'	49	6			15
6'	58	9			
7'	66	8			16
		8	40		
9'	81	7			15
10'	89	8			
					16
12'	505				

CaF_2 irr 10'

0'	650	21			
1'	71	17			
2'	88	15		80	13
3'	703	14		94	14
	17	10		806	12
	27	10		19	13
	37	13		28	9
	50	9		44	16
	59	8			
	67				

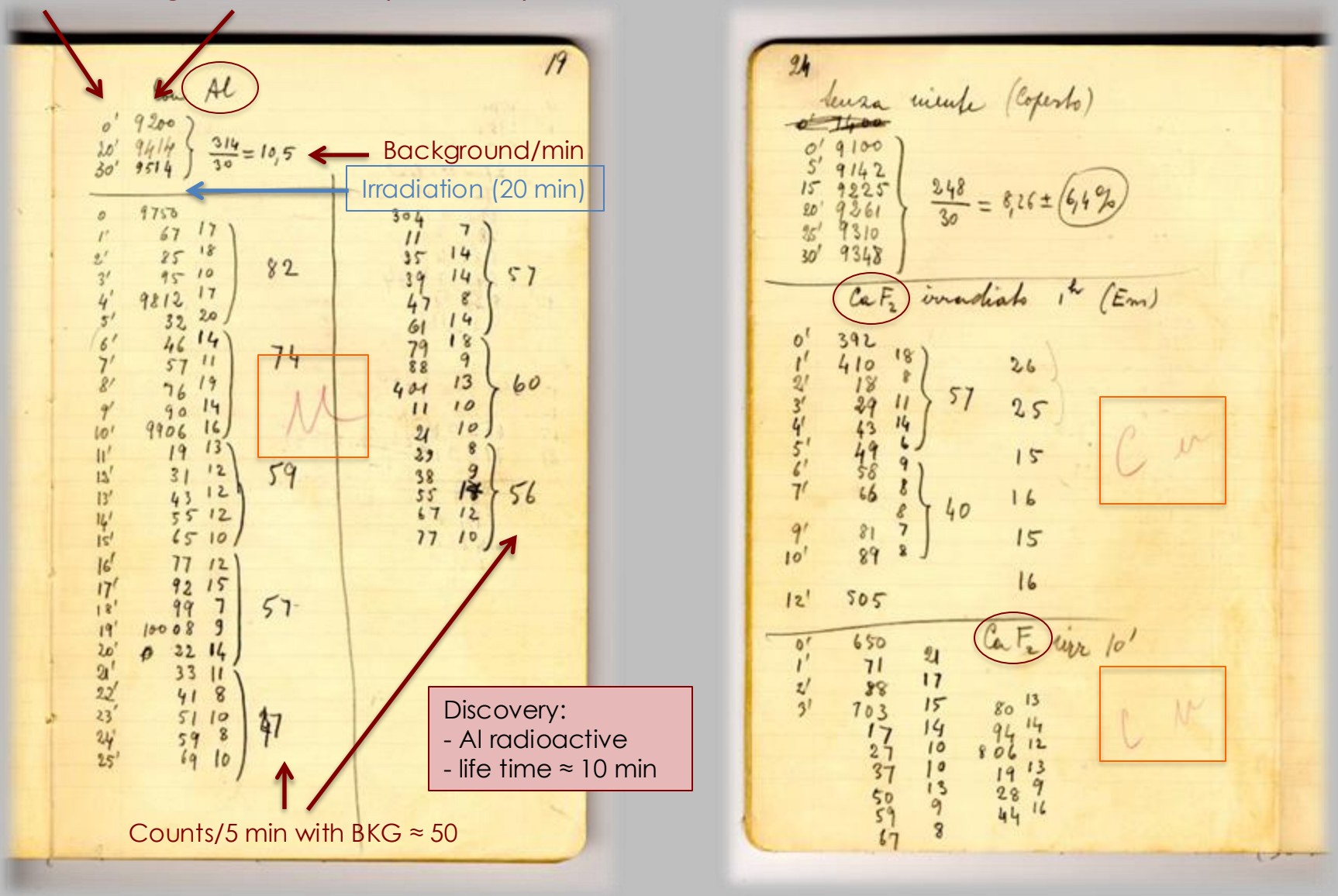
La Ricerca Scientifica 5 (1), 283, 25 March 1934

The discovery of neutron-induced radioactivity

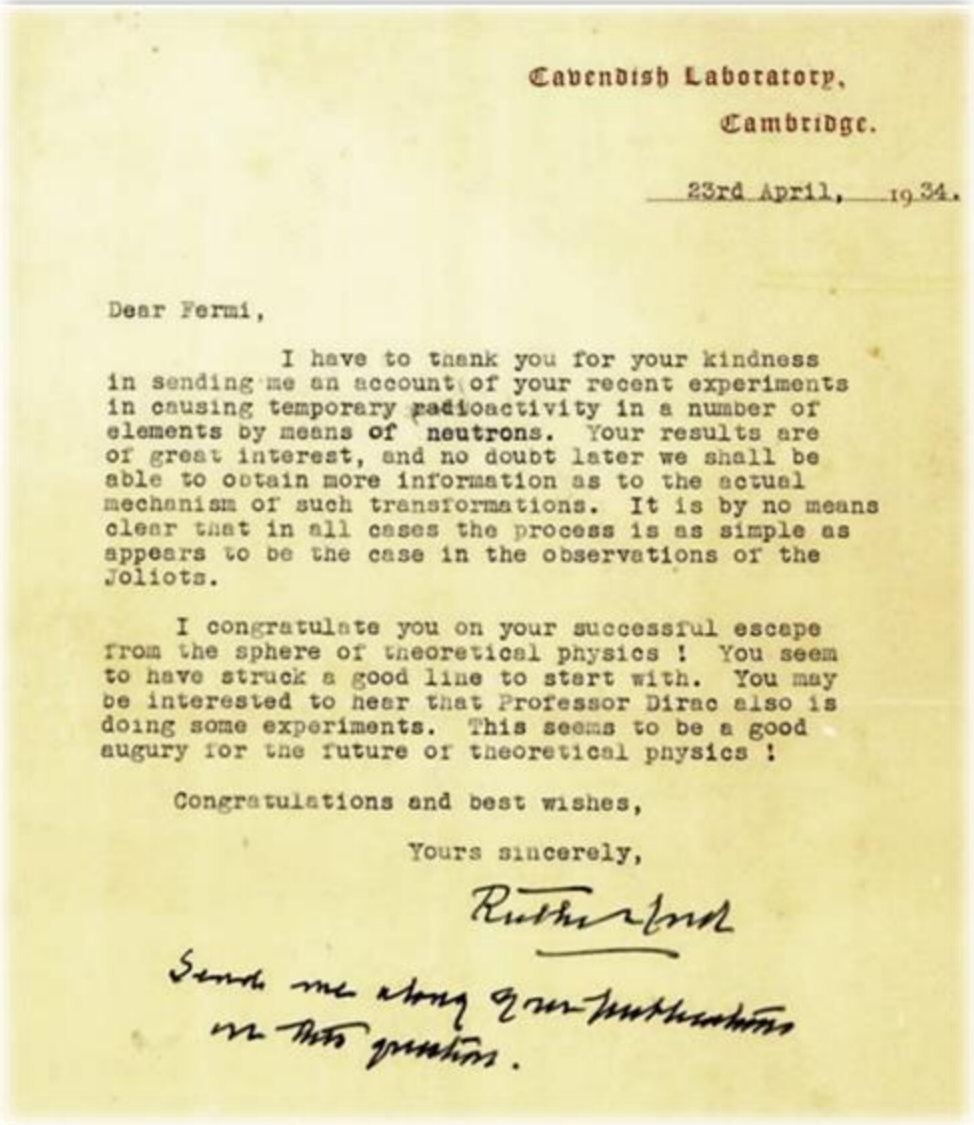


La Ricerca Scientifica 5 (1), 283, 25 March 1934

The discovery of neutron-induced radioactivity



La Ricerca Scientifica 5 (1), 283, 25 March 1934



Cavendish Laboratory,
Cambridge.

23rd April, 1934.

Dear Fermi,

I have to thank you for your kindness in sending me an account of your recent experiments in causing temporary radioactivity in a number of elements by means of neutrons. Your results are of great interest, and no doubt later we shall be able to obtain more information as to the actual mechanism of such transformations. It is by no means clear that in all cases the process is as simple as appears to be the case in the observations of the Joliots.

I congratulate you on your successful escape from the sphere of theoretical physics ! You seem to have struck a good line to start with. You may be interested to hear that Professor Dirac also is doing some experiments. This seems to be a good augury for the future of theoretical physics !

Congratulations and best wishes,

Yours sincerely,

Rutherford

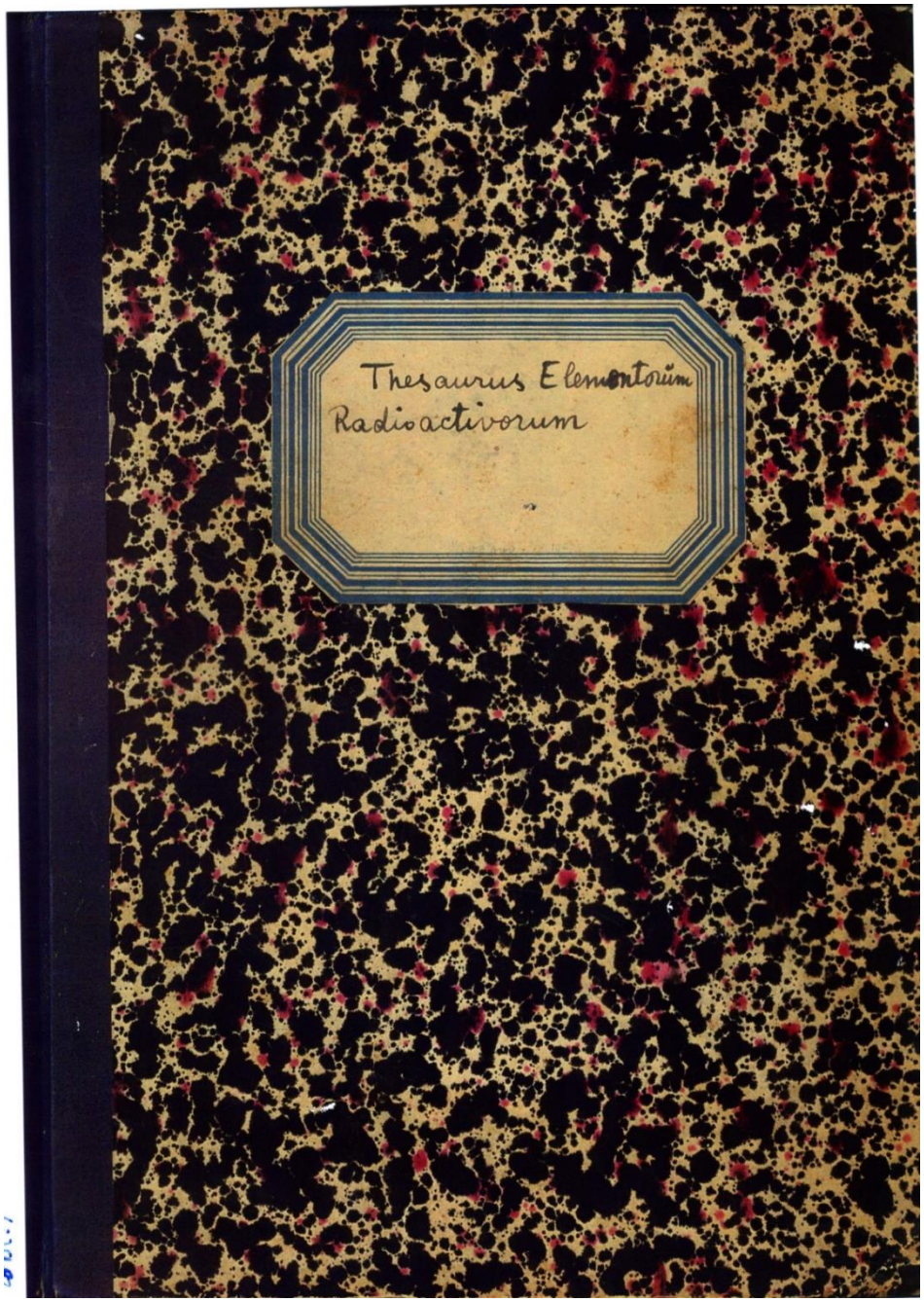
Send me along your publications on this question.

"I congratulate you on your successful escape from theoretical physics !

…

Dirac also is doing some experiments. This seems to be a good augury for theoretical physics !"

Ernest Rutherford



- Then Fermi carried out a systematic study of the activation of all the elements up to uranium

  1st half of Fermi's Nobel Prize in 1938

- "Discovery" of transuranic elements (ausonium & esperium)
  → These were in reality the first fission reactions ever observed that however could not yet be identified as such in 1934

It was two women, Ida Noddak (as early as 1934) and then Lise Meitner, in 1939, who had the intuition of nuclear fission

The **correct interpretation of nuclear fission** came in 1939 by Lise Meitner and Otto Fritsch (her nephew), relative to the experimental results in Berlin in 1939 by Otto Hahn and Fritz Strassman when bombarding uranium with slow neutrons

The 2nd half of Fermi's Nobel Prize in 1938 consisted in the slowing down of neutrons

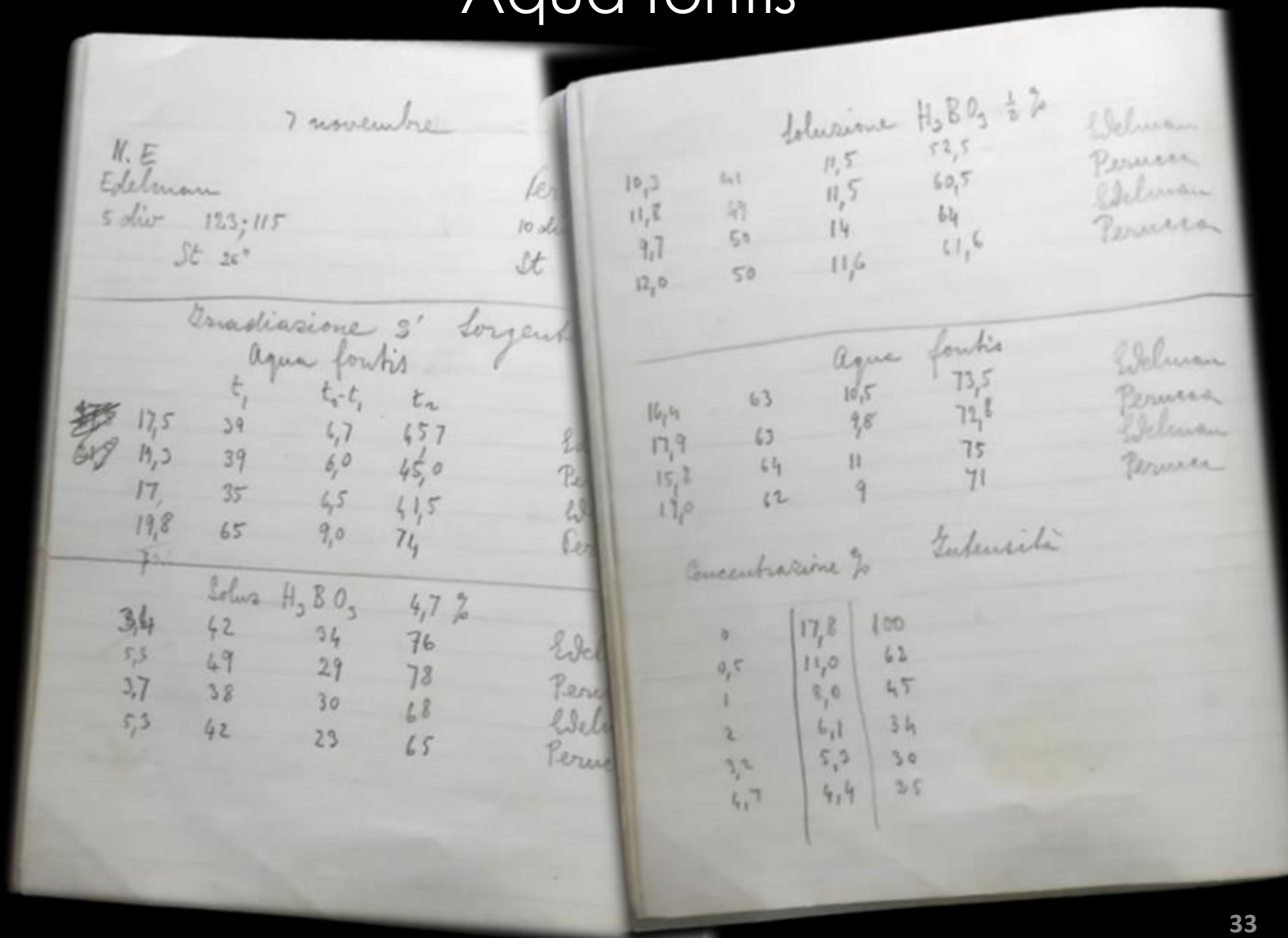
- Strange results and discrepancies in the results obtained during the summer of 1934
  → Fermi had the idea to insert different layers of different substances between the source and the sample to irradiate
- October 1934
  Discovery that neutrons that have been slowed down when passing through paraffin wax or water, substances rich in hydrogen, are much more efficient in producing induced radioactivity in samples of silver and of other heavy elements

In particular water from the goldfish fountain
in the garden of Via Panisperna

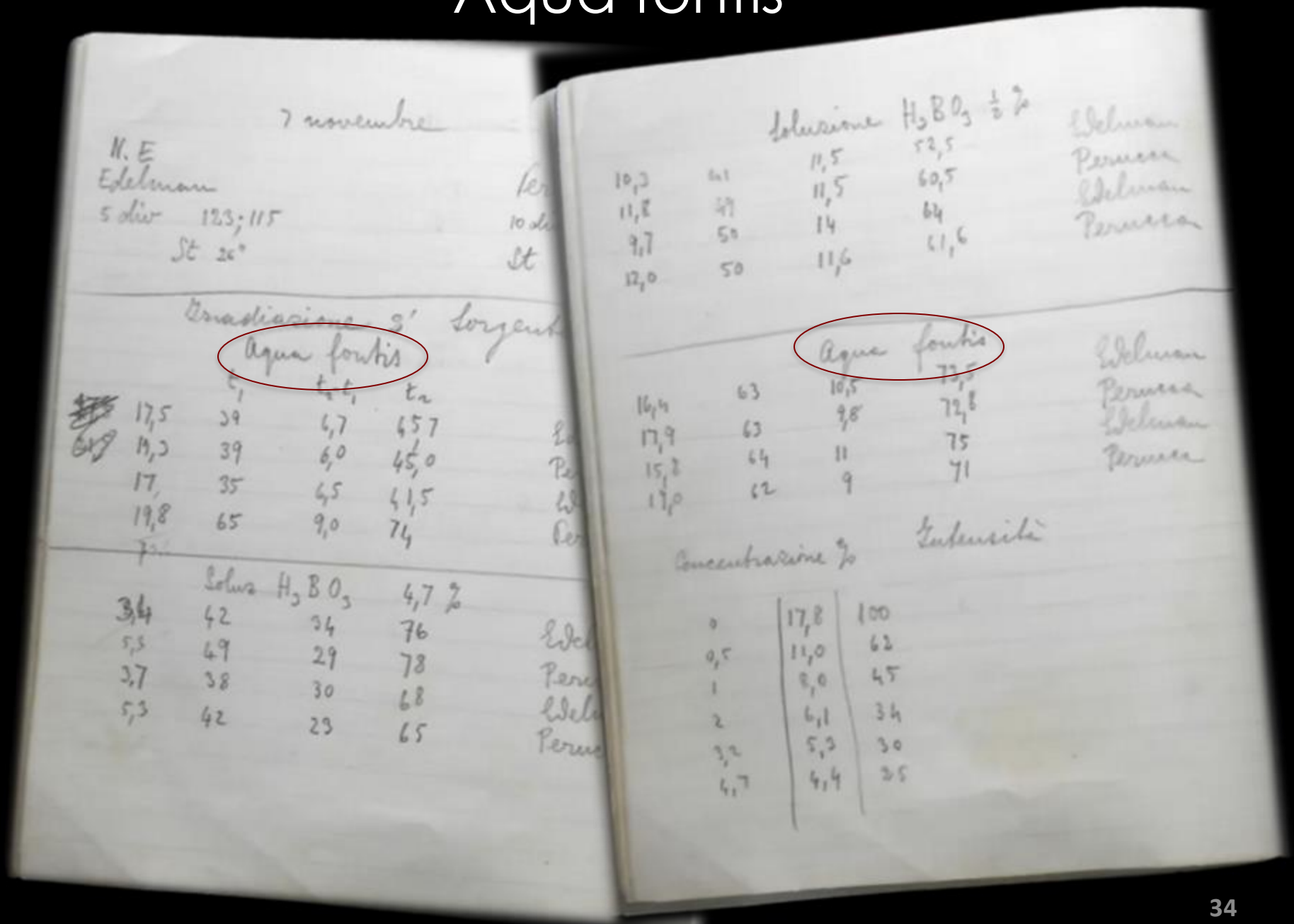
"AQUA FONTIS" (as found several times in one of Fermi's logbooks)

was used to demonstrate the efficiency of slow neutrons

Aqua fontis


7 novembre
N. E
Edelman
5 div 123; 115
St 26°
Irradiazione 3' Sorgente
Aqua fontis
t_1 t_2-t_1 t_2
17,5 39 6,7 45,7
19,3 39 6,0 45,0
17, 35 6,5 41,5
19,8 65 9,0 74
Soluz H_3BO_3 4,7 %
3,4 42 34 76
5,5 49 29 78
3,7 38 30 68
5,3 42 23 65
Soluzione H_3BO_3 ½ %
10,3 61 11,5 52,5
11,8 47 11,5 60,5
9,7 50 14 64
12,0 50 11,6 61,6
Aqua fontis
16,4 63 10,5 73,5
17,9 63 9,8 72,8
15,2 64 11 75
17,0 62 9 71
Concentrazione %
Intensità
0 17,8 100
0,5 11,0 62
1 8,0 45
2 6,1 34
3,2 5,3 30
4,7 4,4 25

Aqua fontis


7 novembre
N. E
Edelmann
5 div 123; 115
St 26°
Irradiazione 3' Sorgente
Aqua fontis
Soluz H_3BO_3 4,7 %
Soluzione H_3BO_3 ½ %
Aqua fontis
Concentrazione %
Intensità

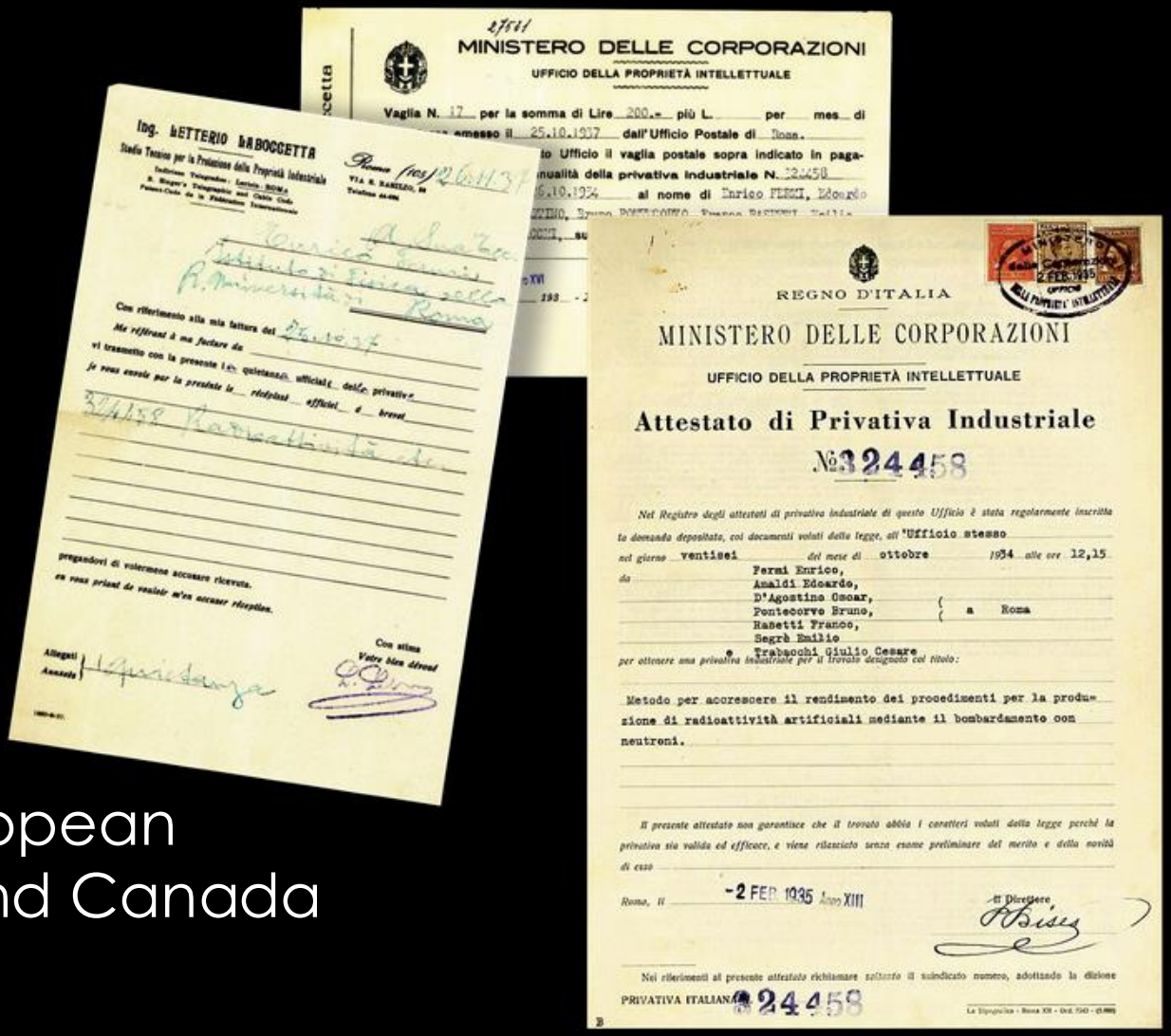
The 2nd half of Fermi's Nobel Prize in 1938 consisted in the slowing down of neutrons

- Strange results and discrepancies in the results obtained during the summer of 1934
  → Fermi had the idea to insert different layers of different substances between the source and the sample to irradiate
- October 1934
  Discovery that neutrons that have been slowed down when passing through paraffin wax or water, substances rich in hydrogen, are much more efficient in producing induced radioactivity in samples of silver and of other heavy elements

→ This discovery would have an exceptional scientific and technological impact

PATENT
for
the discovery
of the
slow neutrons
method
to enhance
artificial
radioactivity

First in Italy
then in other European
countries, USA and Canada



MINISTERO DELLE CORPORAZIONI

UFFICIO DELLA PROPRIETÀ INTELLETTUALE

Vaglia N. 17 per la somma di Lire 200.= più L. per mes di

Ing. ORESTE RABOCCETTA

REGNO D'ITALIA

MINISTERO DELLE CORPORAZIONI

UFFICIO DELLA PROPRIETÀ INTELLETTUALE

Attestato di Privativa Industriale

№ 324458

Nel Registro degli attestati di privativa industriale di questo Ufficio è stata regolarmente inscritta la domanda depositata, coi documenti voluti dalla legge, all'Ufficio stesso nel giorno ventisei del mese di ottobre 1934 alle ore 12,15 da Fermi Enrico, Amaldi Edoardo, D'Agostino Oscar, Pontecorvo Bruno, Rasetti Franco, Segrè Emilio e Trabacchi Giulio Cesare a Roma per ottenere una privativa industriale per il trovato designato col titolo:

Metodo per accrescere il rendimento dei procedimenti per la produzione di radioattività artificiali mediante il bombardamento con neutroni.

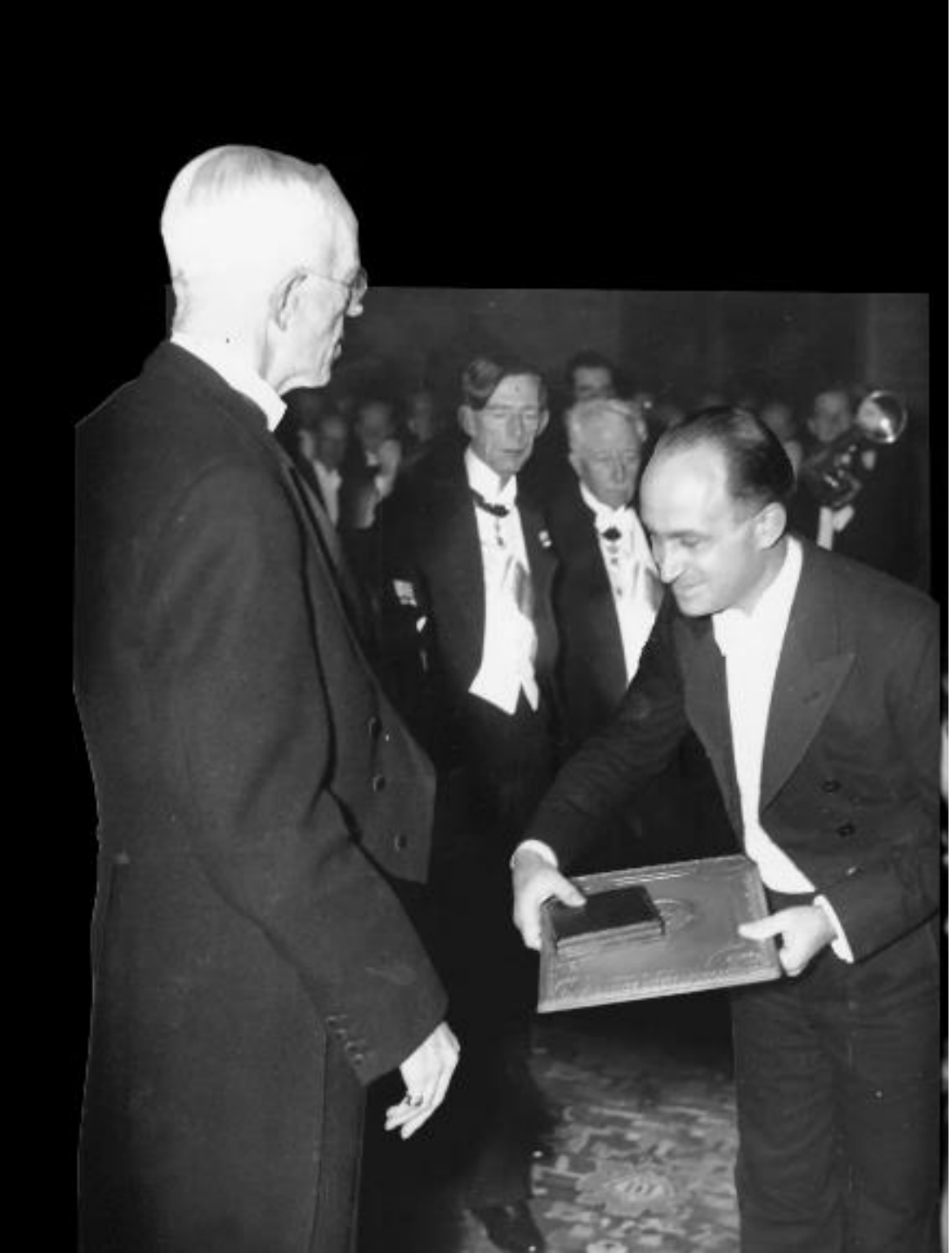
Il presente attestato non garentisce che il trovato abbia i caratteri voluti dalla legge perchè la privativa sia valida ed efficace, e viene rilasciato senza esame preliminare del merito e della novità di esso

Roma, li -2 FEB 1935 Anno XIII

Il Direttore

Nei riferimenti al presente attestato richiamare sempre il suindicato numero, adottando la dizione PRIVATIVA ITALIANA 324458

→ nuclear chain reactions



The significance of Fermi's discoveries, also at an applied level, earned him the Nobel Prize for Physics in1938

Guglielmo
Marconi
(1874 – 1937)

Orso Mario
Corbino
(1876 – 1937)

Meanwhile
Fermi's "patron saints"
have passed away …

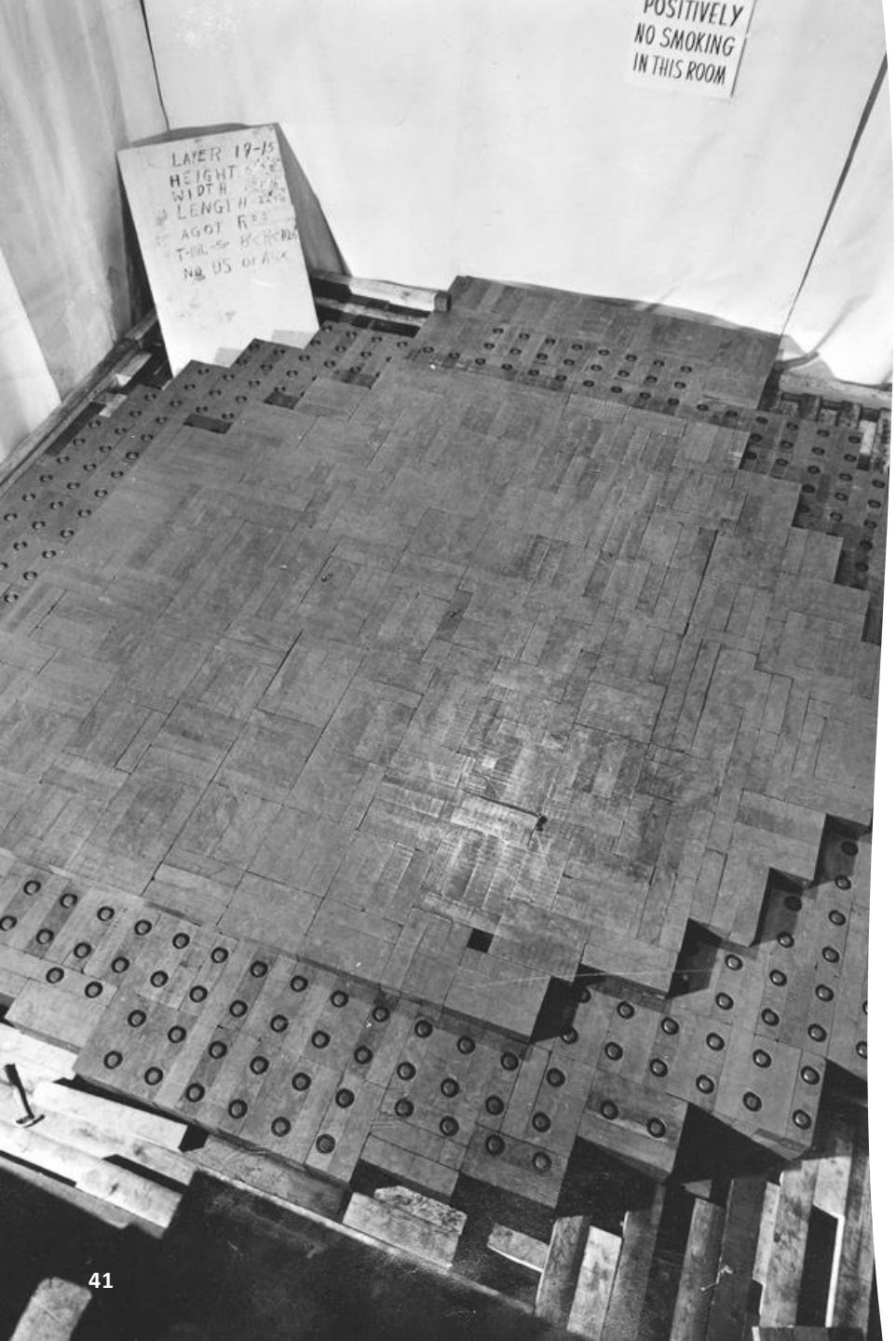
After the ceremony in Stockholm on 10 December 1938, Fermi carried out his decision to move with his family to the United States, where his research could develop much further, also because of the progressive involution of the Italian regime, going so far as the passing of the racial laws

In the USA

On arriving in New York in early January 1939 Fermi learned that in Berlin Otto Hahn had discovered nuclear fission and he immediately threw himself into the challenge of finding a way to exploit the enormous energy produced in this kind of process

On 2 December 1942, in Chicago, Fermi created the first nuclear pile (CP-I): with this device he succeeded in producing a controlled nuclear fission chain reaction using natural uranium as the fuel and extremely pure graphite as the moderator to slow down the neutrons

It was a decisive step towards the exploitation of nuclear energy



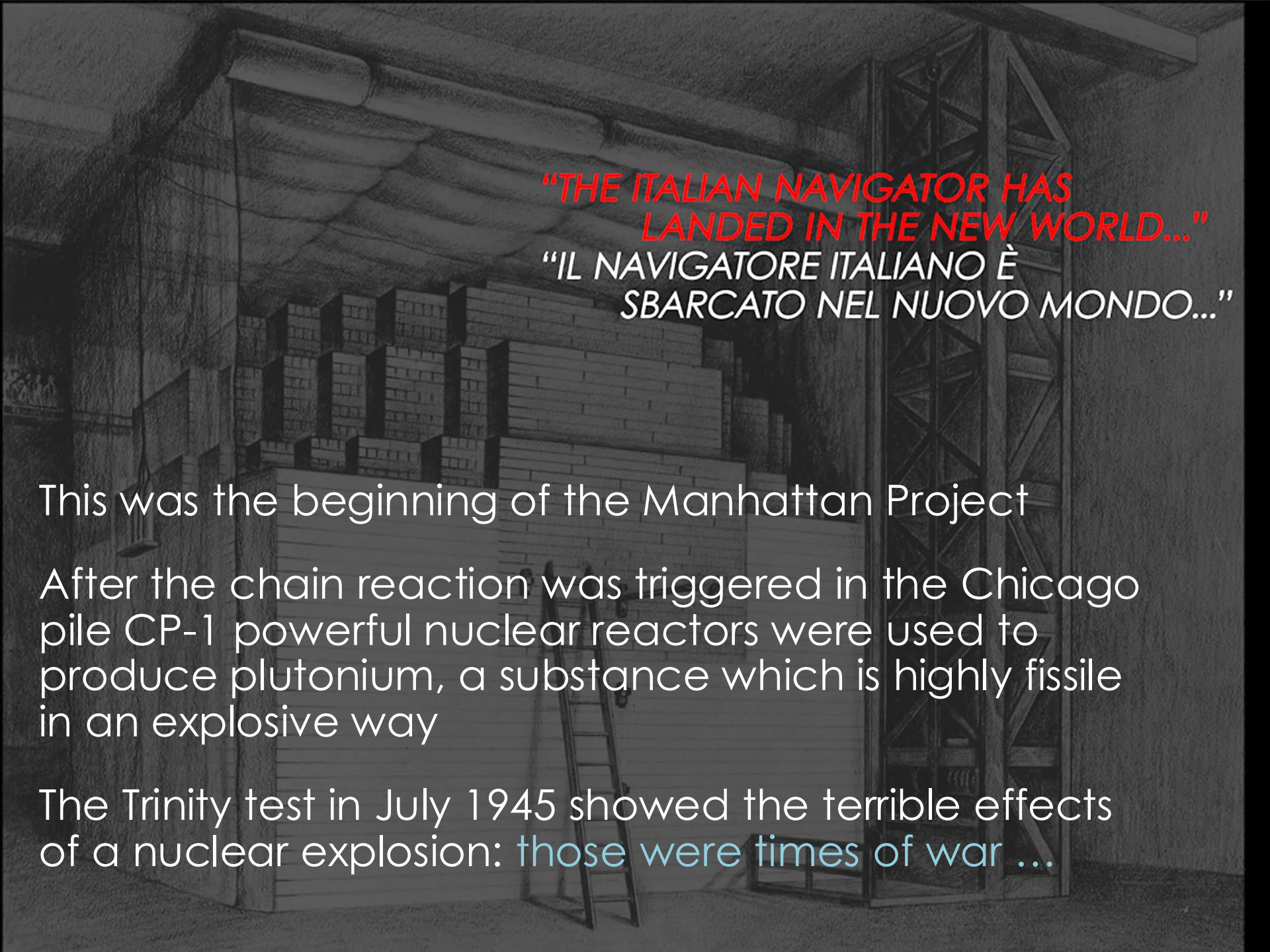
CP-1 was a pile of blocks of graphite and uranium (oxide) spheres

Graphite had been identified as a better substance to slow down neutrons (water would have absorbed too many of them)

Cadmium rods to absorb neutrons, Geiger counters to monitor the radiation level

Fermi, aware of how dangerous it could be, had planned to do the experiment in stages, stopping each time to check that the measurements made matched his calculations.

And everyone trusted Fermi to the point of having him perform the experiment on a university campus!



This was the beginning of the Manhattan Project

After the chain reaction was triggered in the Chicago pile CP-1 powerful nuclear reactors were used to produce plutonium, a substance which is highly fissile in an explosive way

The Trinity test in July 1945 showed the terrible effects of a nuclear explosion: those were times of war …

After the War

Fermi campaigned for new peaceful applications of nuclear technology

(motors, energy, medecine etc.)

USS Nautilus

Underneath the North Pole in 1958

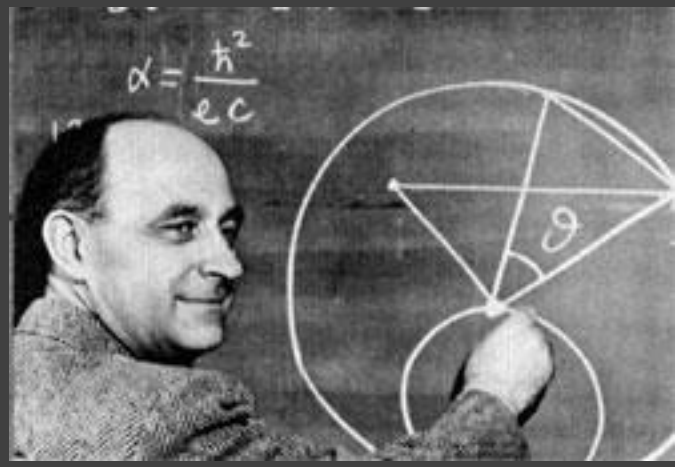
Fermi worked intensely on the new cyclotron accelerator in Chicago and discovered in 1952 the first example of a new class of particles, extremely short lived, called "resonances":

the Δ^{++} particle that would take on a crucial role in the understanding of the quark structure of the particles and of the strong interaction between quarks

→ Fermi produced a far-sighted vision for the development of accelerators

In the 1950s Fermi was universally considered one of the giants of physics of all times

He was 50 years old and, as well as his genius, he still had the enthusiasm and vivacity of a boy

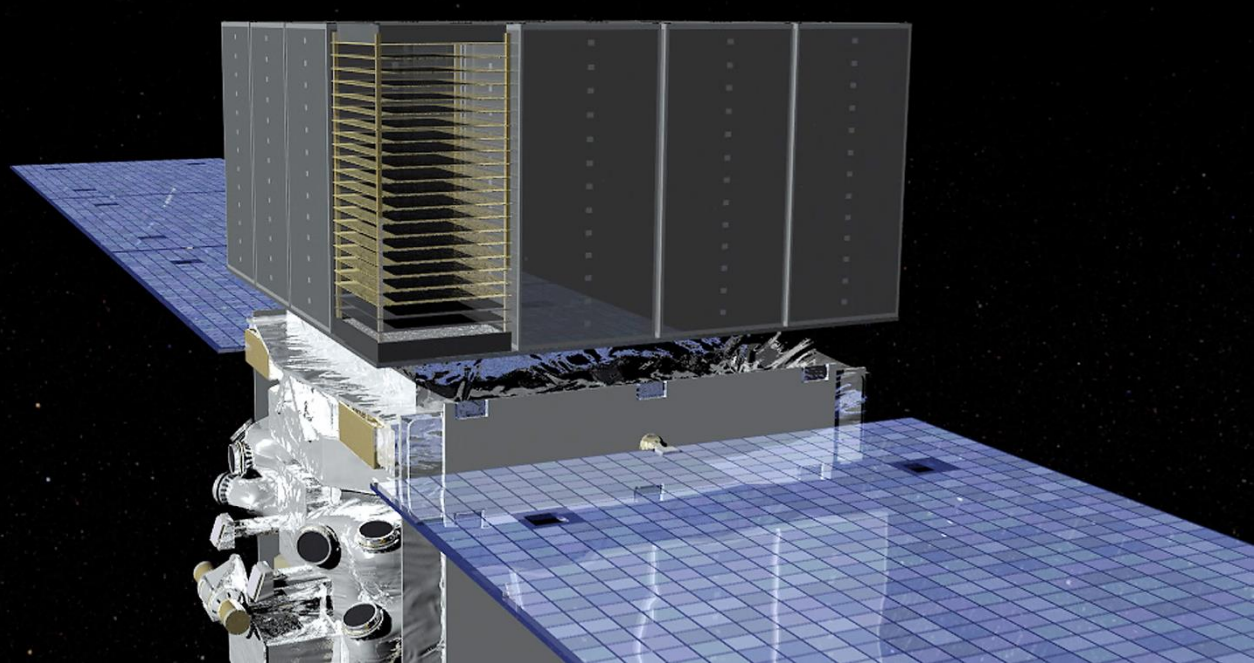


Fermi formulated a qualitatively correct theory on the acceleration of cosmic rays, particles that come from the Cosmos and that constantly bombard the Earth with energies that can be largely greater than those of the LHC at CERN

What accelerators are this powerful?

Fermi answered in 1949: the cosmic accelerators use gravitational energy

→ His theory has been scrutinized today by FERMI LAT satellite (NASA mission)



The Physics Institute in Rome at the end of the 19th century


ENRICO FERMI Historical Museum of Physics
and Study & Research Centre
Museo Storico della Fisica e
Centro Studi e Ricerche
ENRICO FERMI
NOW

ENRICO FERMI Historical Museum of Physics and Study & Research Centre

CENTRO RICERCHE ENRICOFERMI

MUSEO ENRICOFERMI

A LITTLE MORE RECENT HISTORY

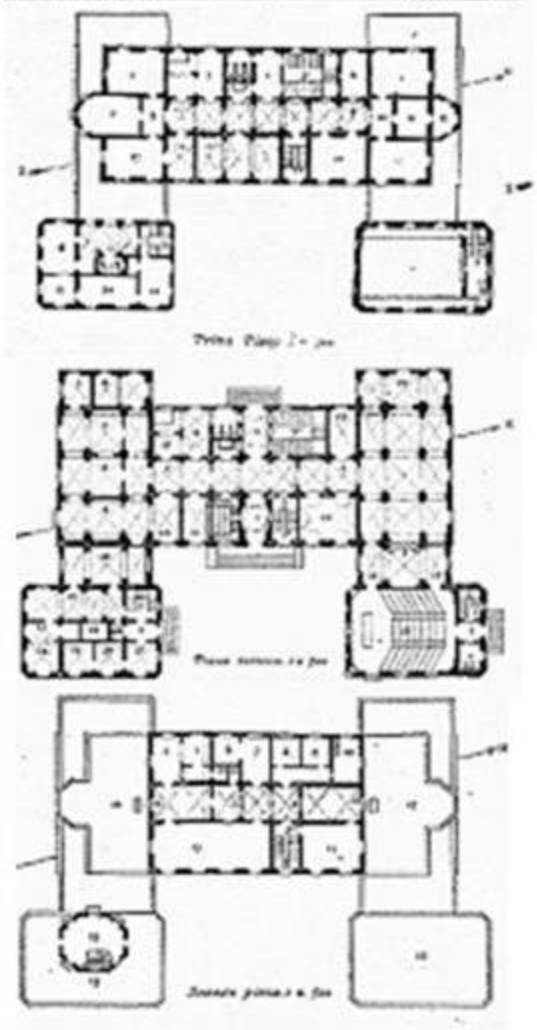
The *Fermi Centre / Centro Fermi*, established by Law no. 62 of 15 March 1999 as a "research centre", and not just a "museum", owes its existence to a group of scientists, politicians and citizens, whose precise desire was to enhance the brilliant figure of Fermi, not sufficiently known and recognised in Italy, through the creation of this institution.

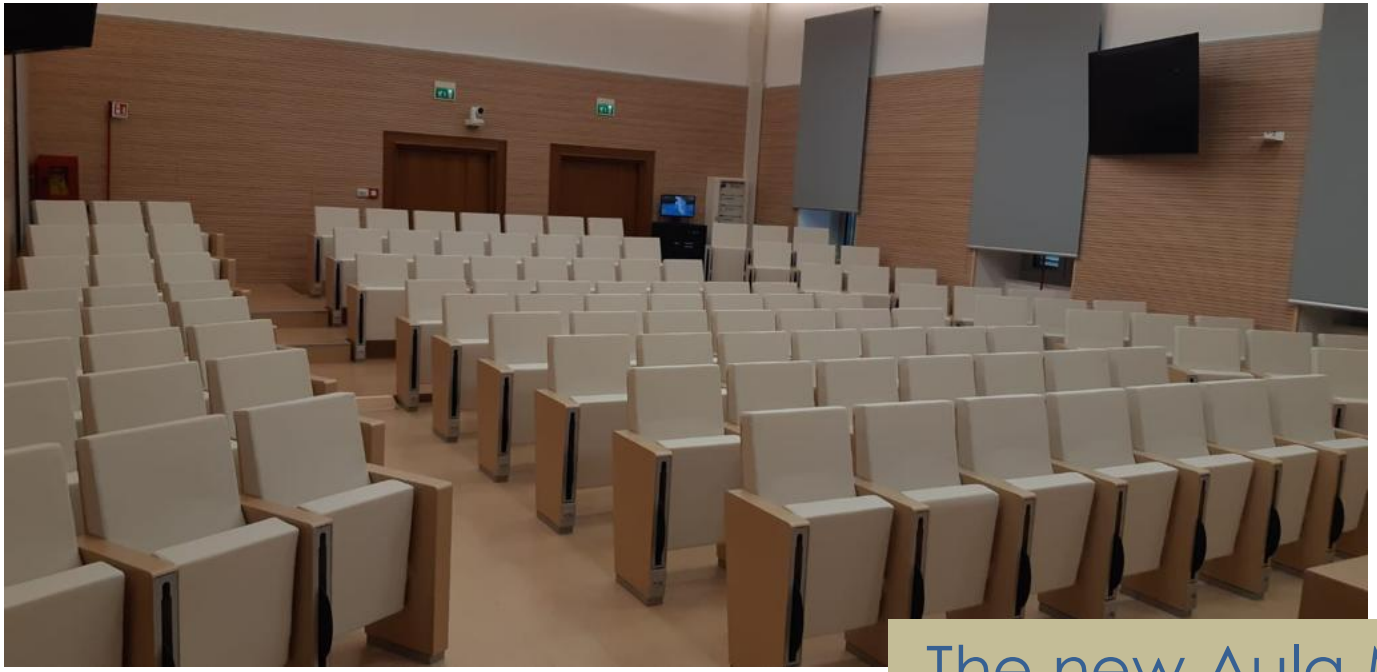
Among these convinced promoters was the physicist Antonino Zichichi, who was the initiator and founding president of *Centro Fermi,* in office from 2000 to 2011.

He was succeeded by: L. Cifarelli (2011-2019), L. Pietronero (2019-2024) and A. Bracco (2024-today)

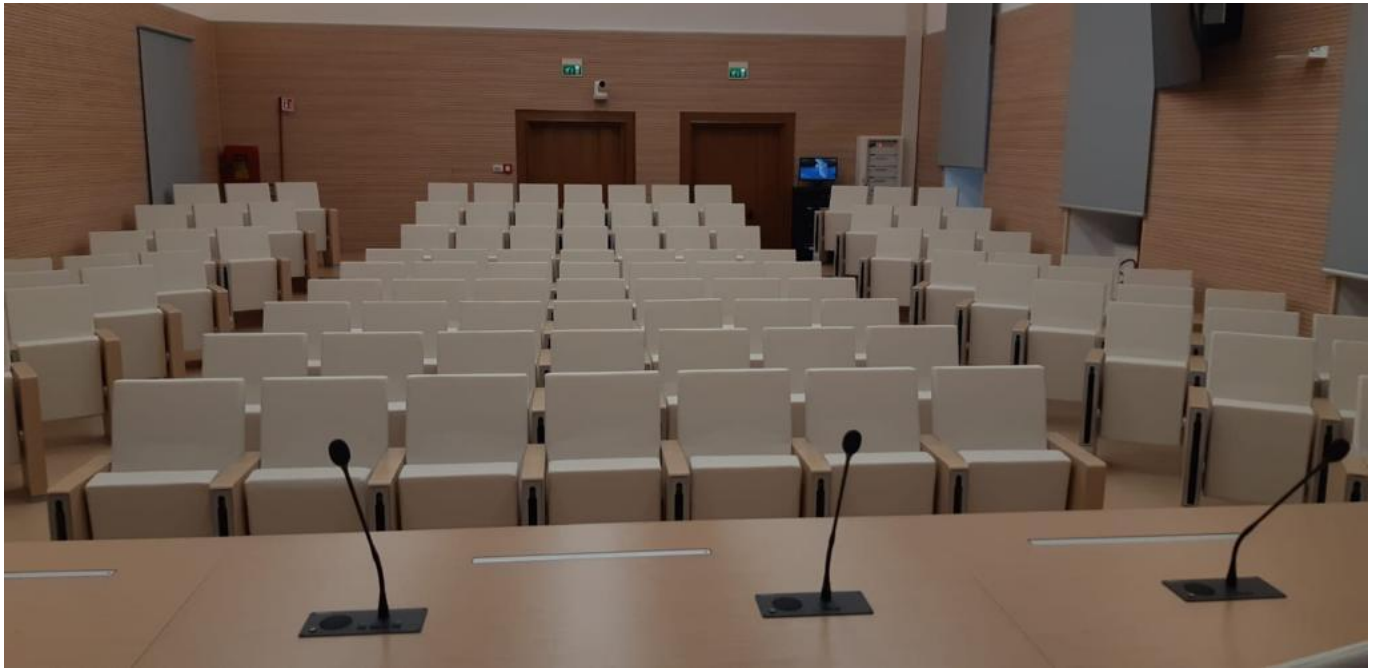
The old Aula Magna

L'ISTITUTO FISICO DI ROMA E LE ONORANZE A PIETRO BLASERNA.

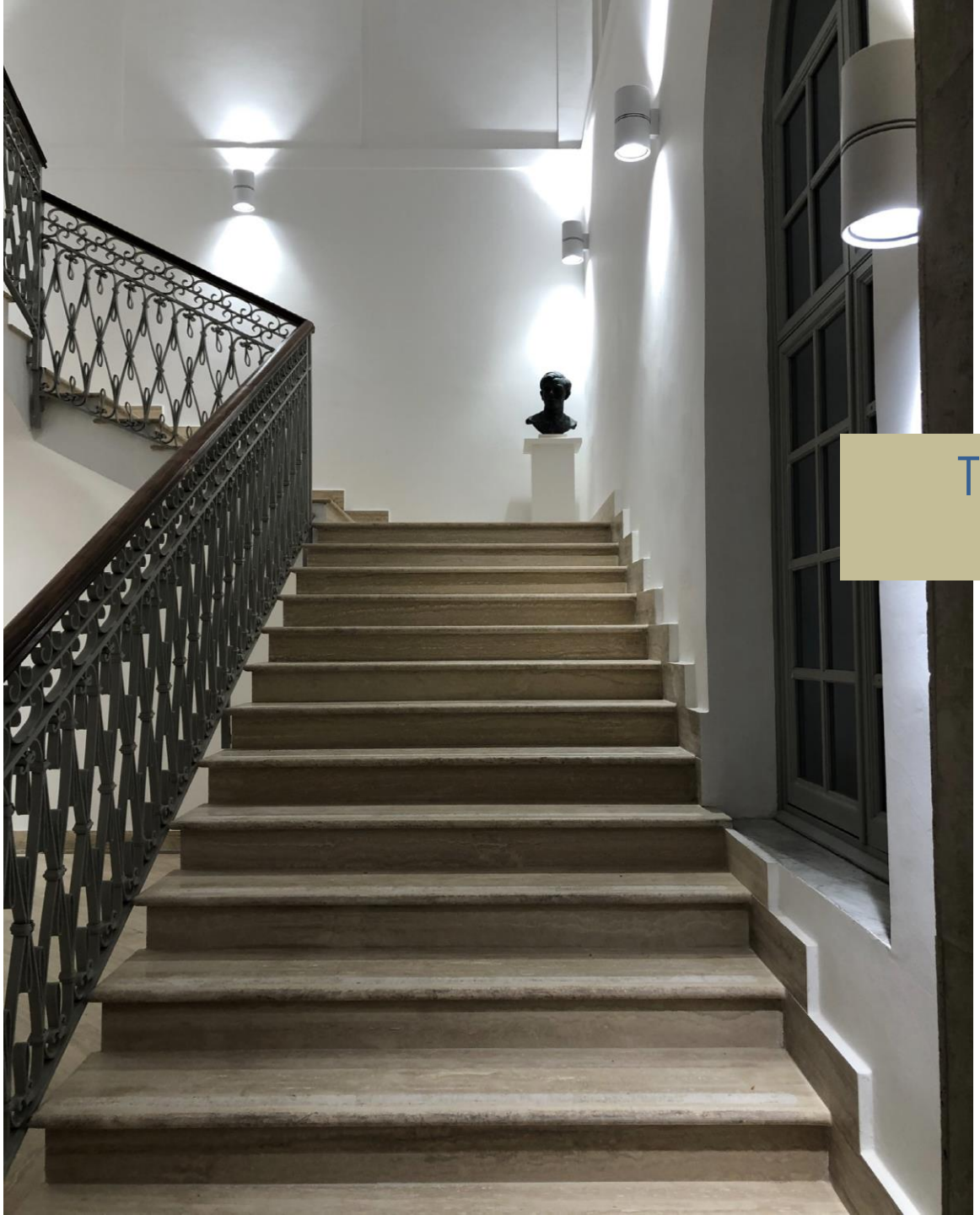




The new Aula Magna



The new Aula Magna
28 October 2019



The entrance of Centro Fermi

Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"

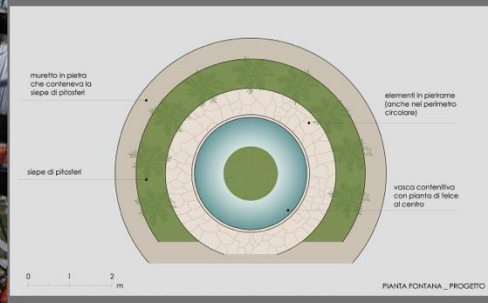
FOTO DI CANTIERE (2001)

FOTO DI CANTIERE (2002)

FOTO DI CANTIERE (2005)

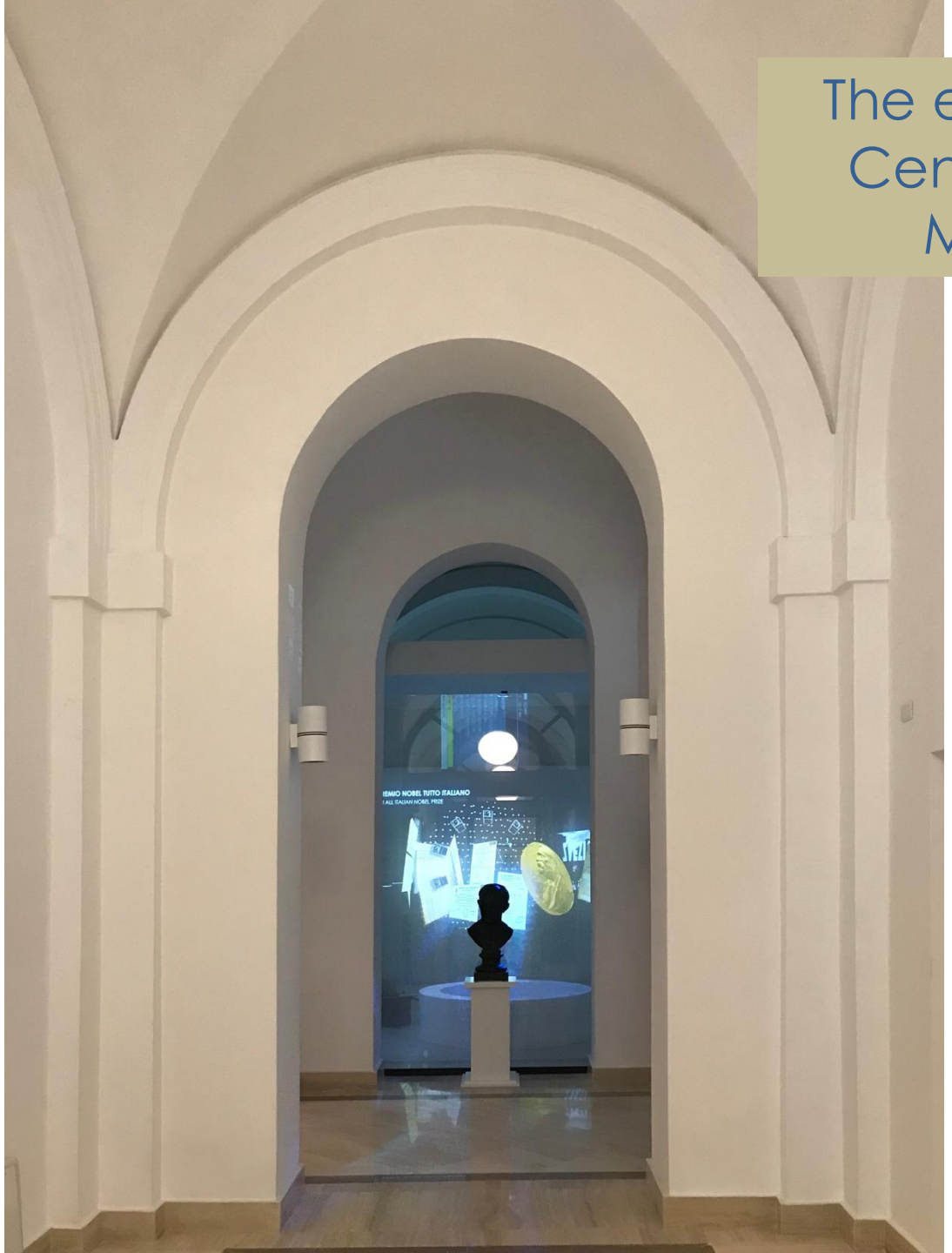
ANALISI CONOSCITIVA E ACQUISIZIONE DI TUTTE LE INFORMAZIONI

La fontana storica oltre ad un naturale deterioramento dovuto al tempo ha subito una serie di interventi che hanno stravolto la sua configurazione originaria.
Tali interventi vennero eseguiti tra il 2001 e il 2005, dettati da soluzioni progettuali che prevedevano lo smantellamento temporaneo della stessa. Smantellamento scongiurato a seguito di un intervento tempestivo da parte del Centro Fermi.
Allo stato attuale la fontana storica necessita di un restauro conservativo e di una ricostruzione delle parti asportate (muretto con siepe di pitosferi) nel corso delle precedenti lavorazioni.



Fermi Fountain
1st Historic Site of the European Physical Society
April 2012


ENRICO FERMI
Historical Museum of Physics
and Study & Research Centre



The entrance of Centro Fermi's Museum

MAPPA DEL MUSEO
MAP OF THE MUSEUM

life
UNA VITA SCINTILLANTE
A BRILLIANT LIFE

in
INVITO AL MUSEO
INVITATION TO THE MUSEUM

1.
IL NOSTRO UNIVERSO DI FERMIONI E BOSONI
OUR UNIVERSE OF FERMIONS AND BOSONS

2.
LA FORMIDABILE TEORIA DEI RAGGI BETA
THE FORMIDABLE THEORY OF BETA RADIATION

3.
UN PREMIO NOBEL TUTTO ITALIANO
AN ALL ITALIAN NOBEL PRIZE

4.
" IL NAVIGATORE ITALIANO
E' SBARCATO NEL NUOVO MONDO..."
" THE ITALIAN NAVIGATOR
HAS LANDED IN THE NEW WORLD ..."

5.
IL MISTERO DEI RAGGI COSMICI
THE MYSTERY OF COSMIC RAYS

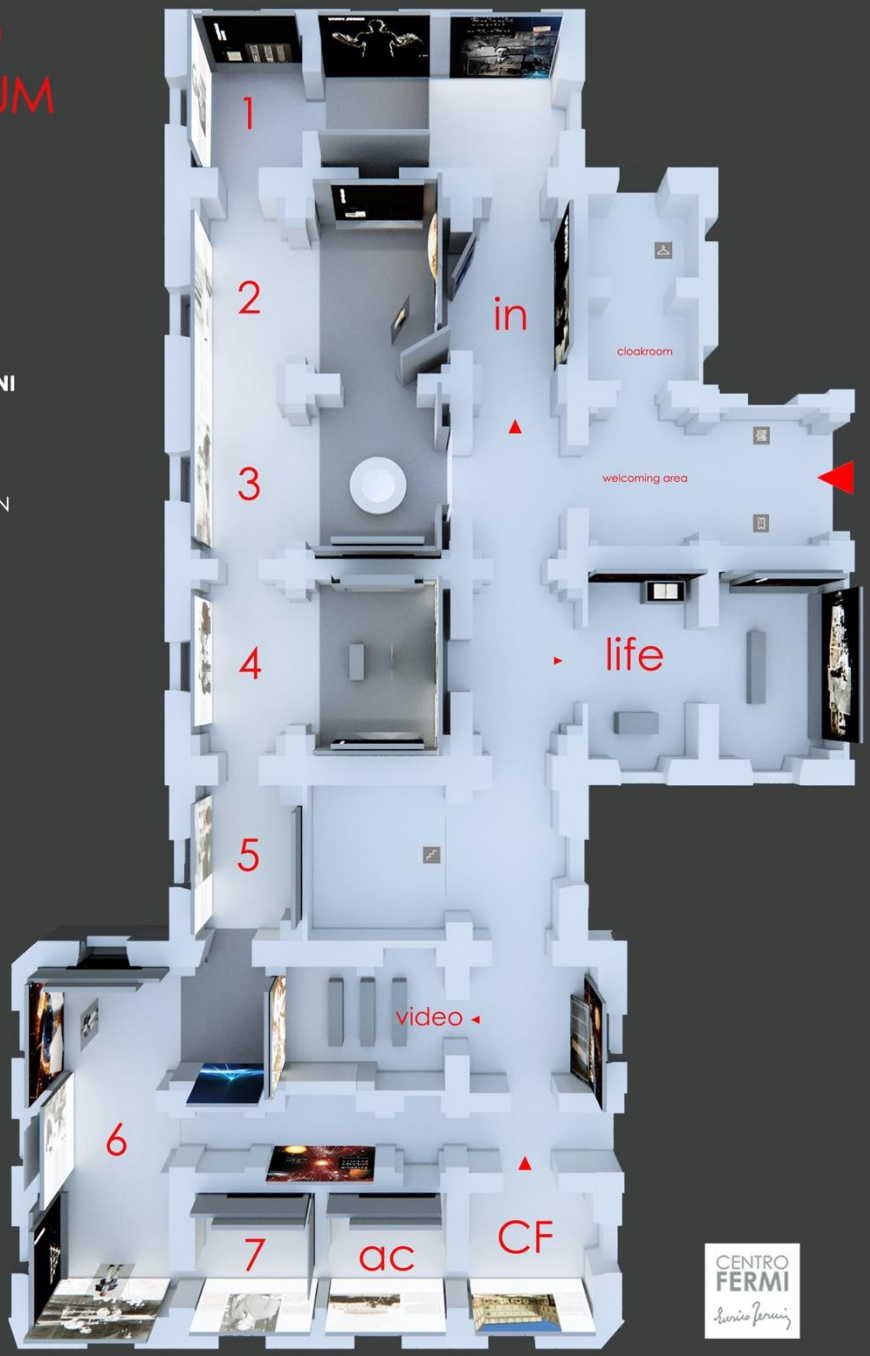
6.
E ADESSO GLI ACCELERATORI
AND NOW ACCELERATORS

7.
L'ULTIMO DONO DI FERMI ALL'ITALIA
FERMI'S LAST GIFT TO ITALY

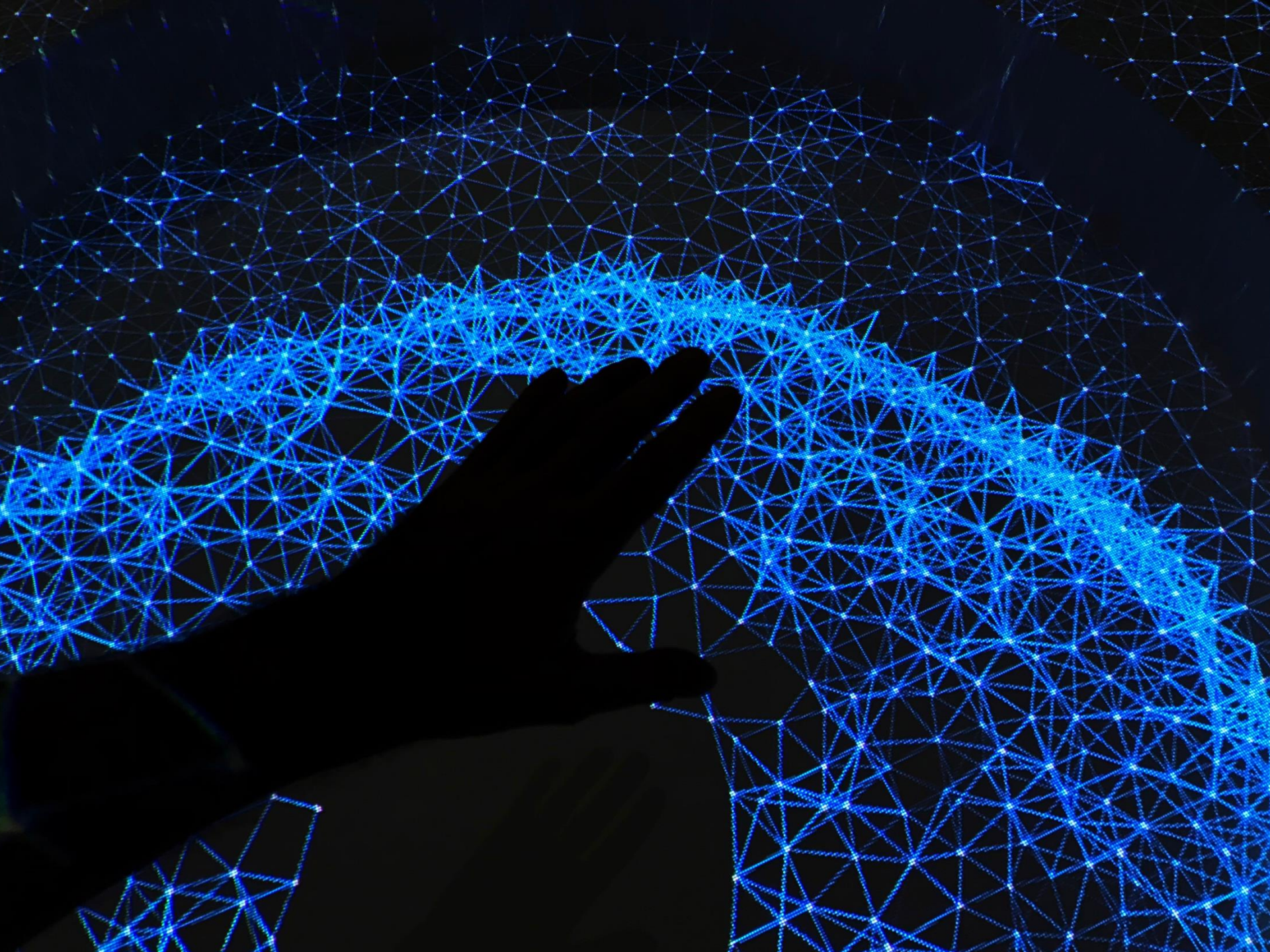
ac
UN AMBIENTE CREATIVO
A CREATIVE ENVIRONMENT

CF
I PROGETTI DEL CENTRO FERMI
CENTRO FERMI'S PROJECTS

video
VIDEOPROIEZIONI
VIDEO-PROJECTIONS



CENTRO FERMI



… All his life a dual genius between theories and experiments

Premature death in 1954 after memorable lessons on the interactions of pions and nucleons at the International School of Physics of the Italian Physical Society in Varenna, Lake Como

"Today, one would need another Fermi"

Luciano Maiani