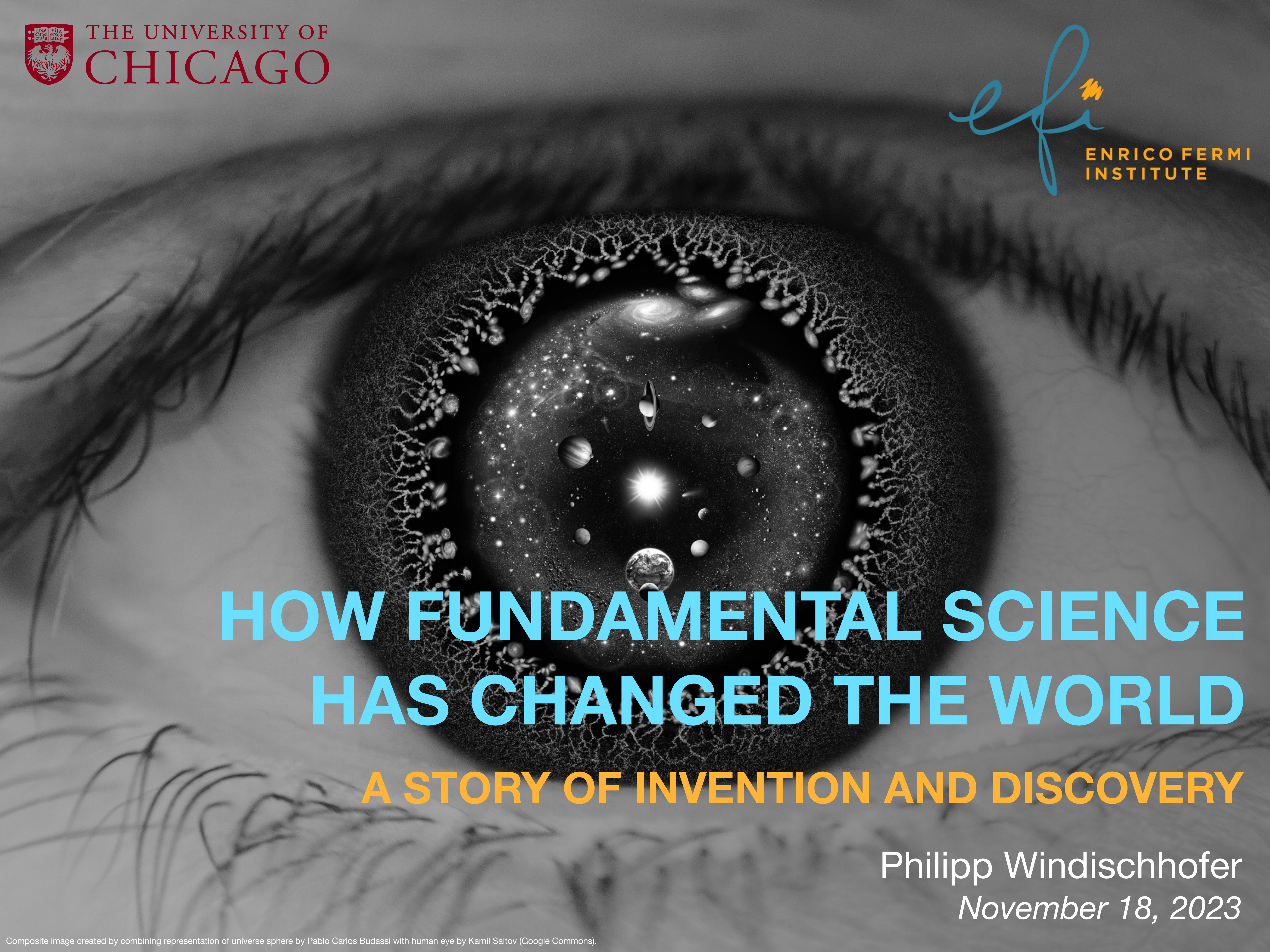
THE UNIVERSITY OF CHICAGO

ENRICO FERMI INSTITUTE



HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

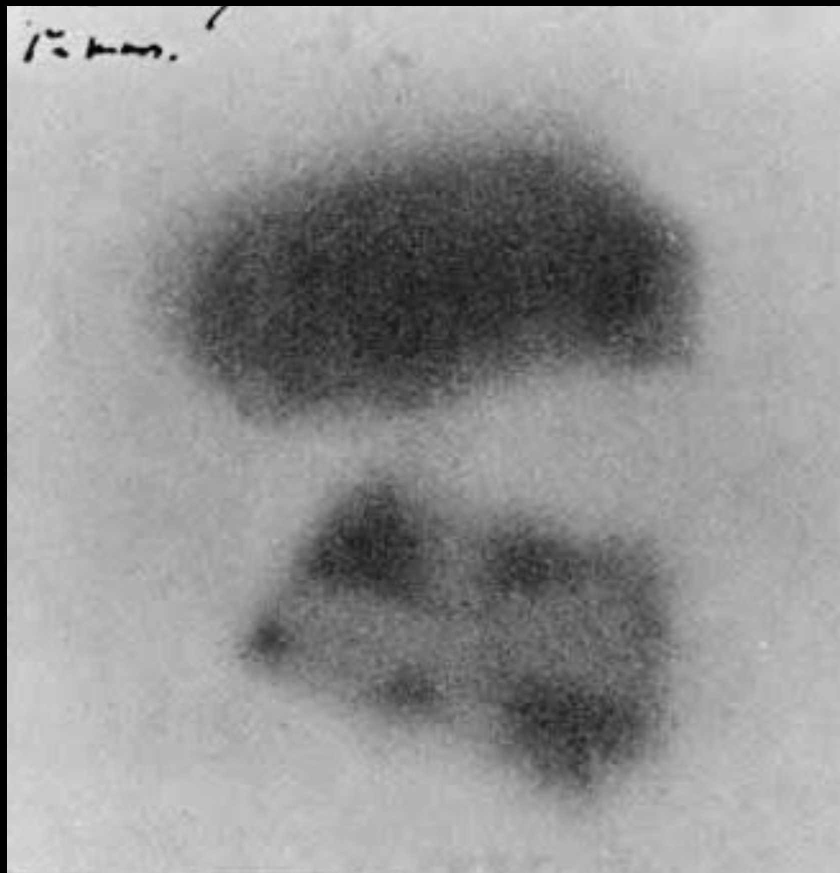
Philipp Windischhofer

November 18, 2023

Composite image created by combining representation of universe sphere by Pablo Carlos Budassi with human eye by Kamil Saitov (Google Commons).

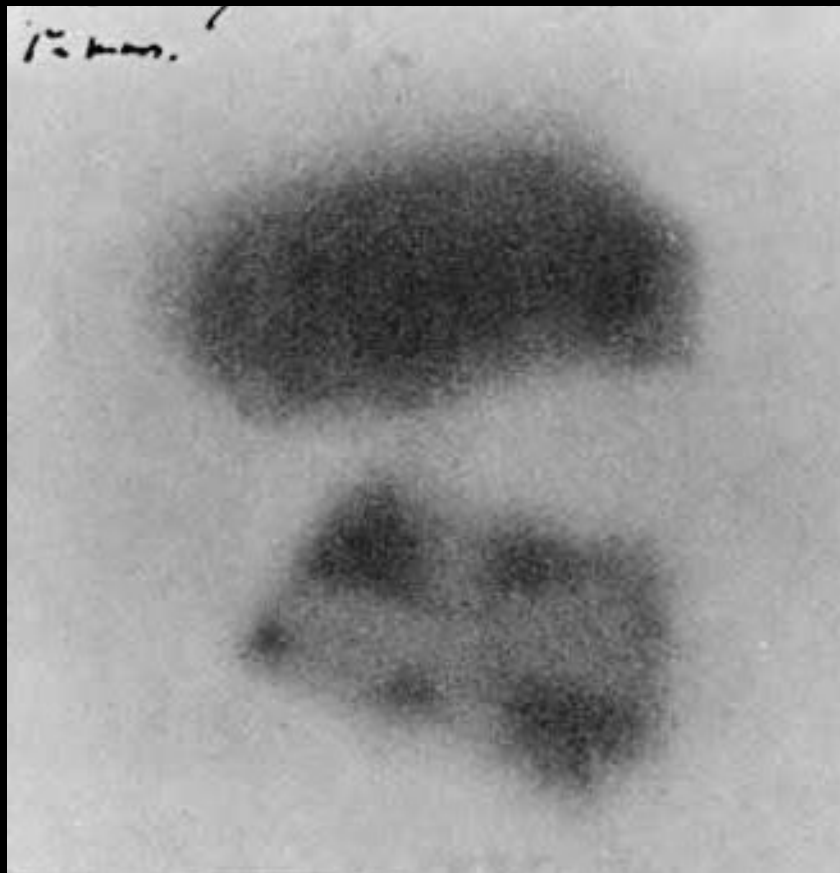
The discovery of radioactivity

The discovery of radioactivity



Henri Becquerel *(1896)*

The discovery of radioactivity



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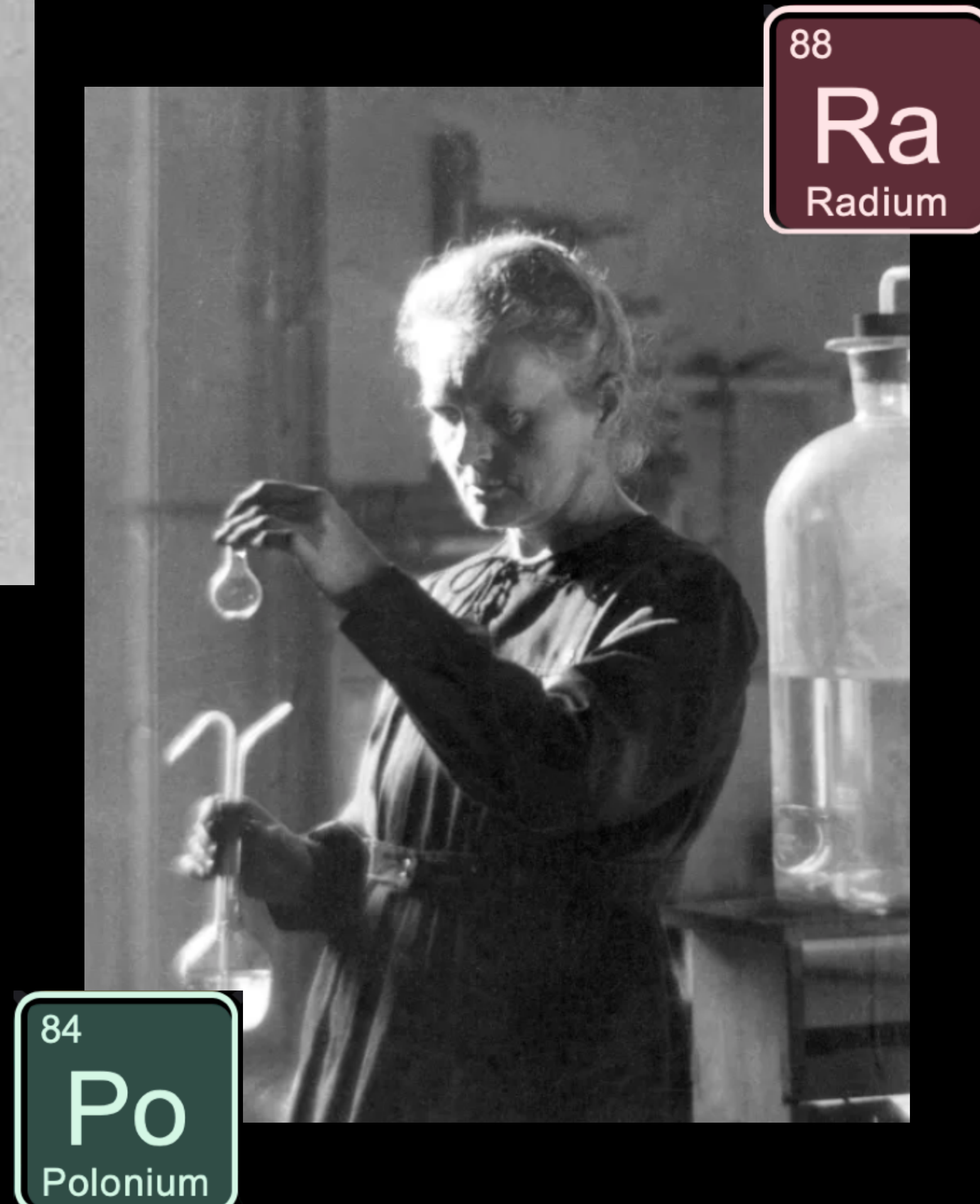
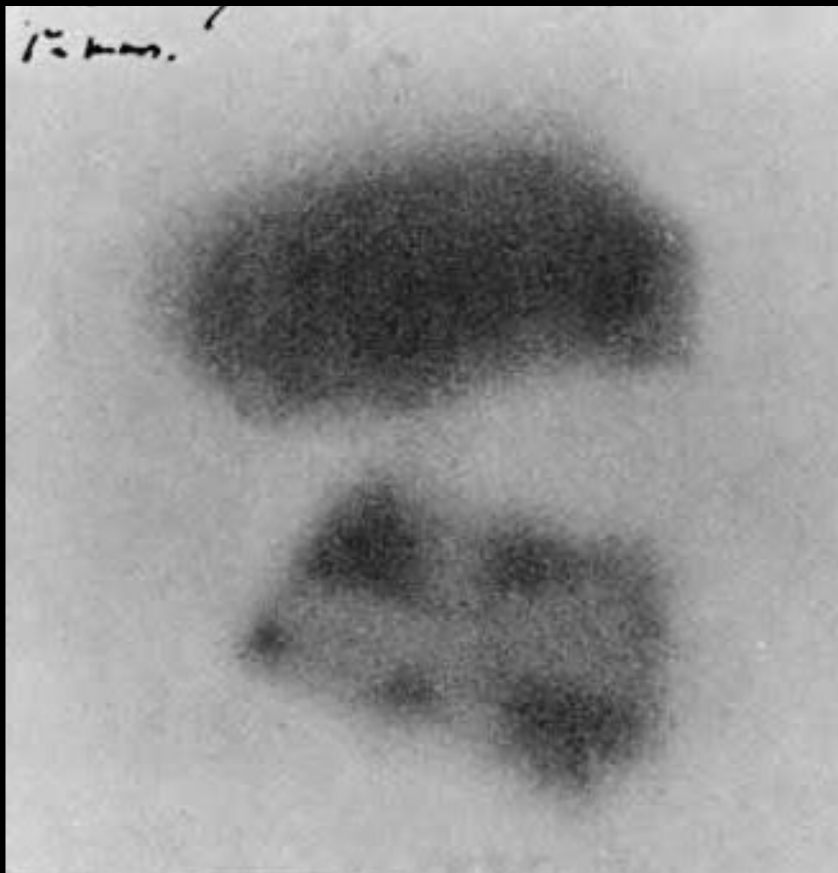


Marie Skłodowska-Curie
Pierre Curie
(1898)

The discovery of radioactivity



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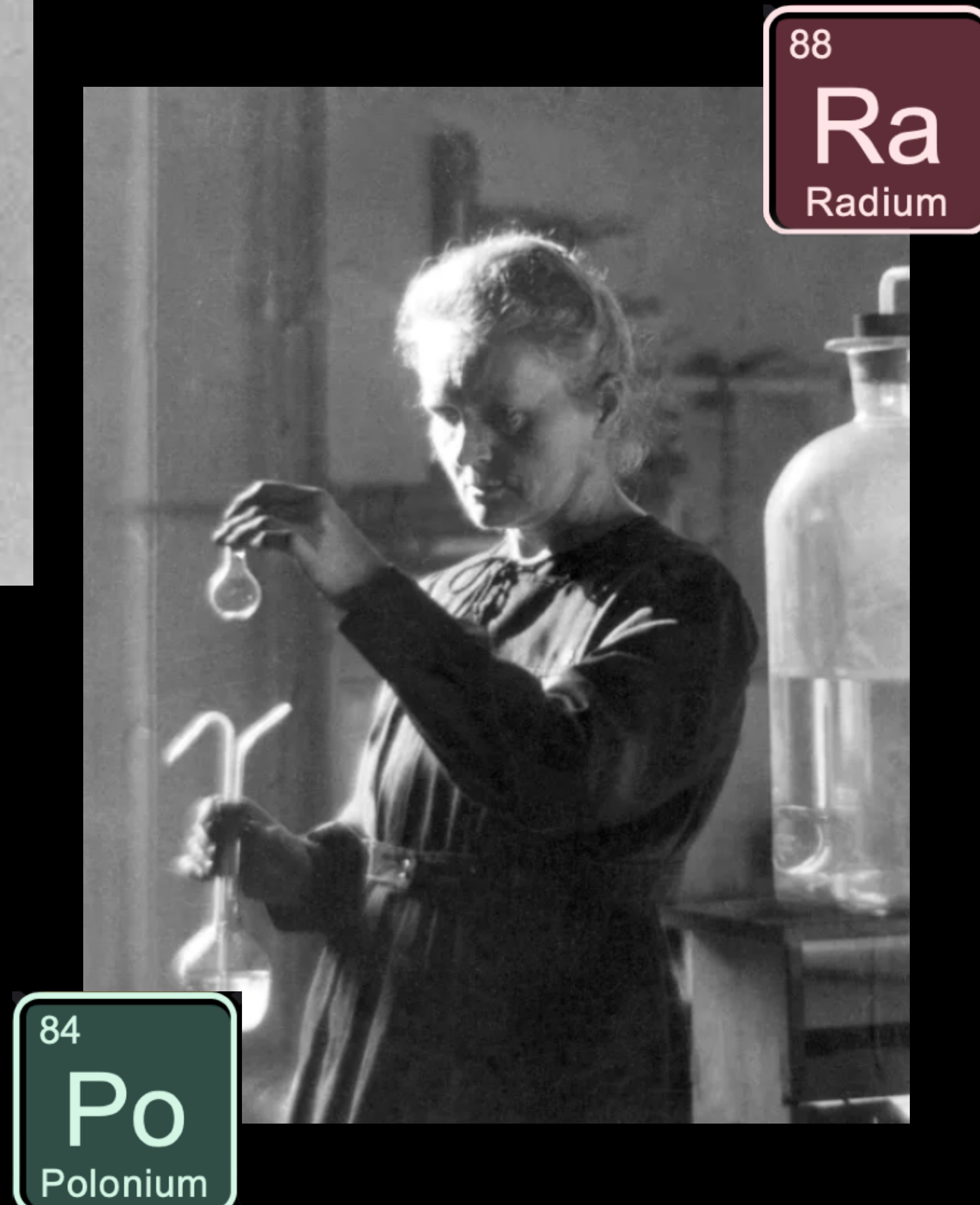
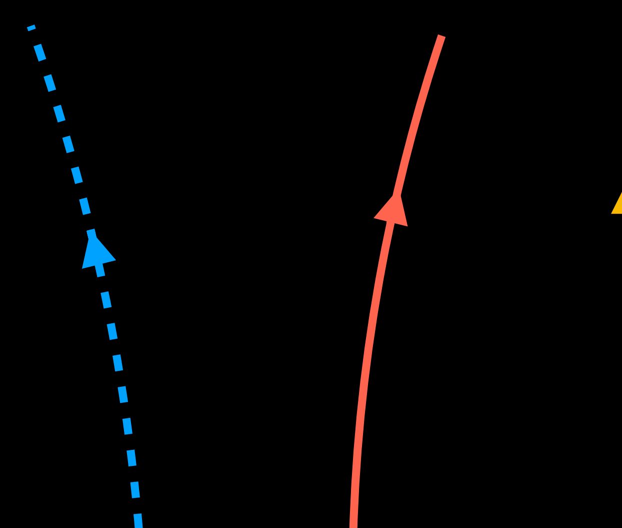


Marie Skłodowska-Curie
Pierre Curie
(1898)

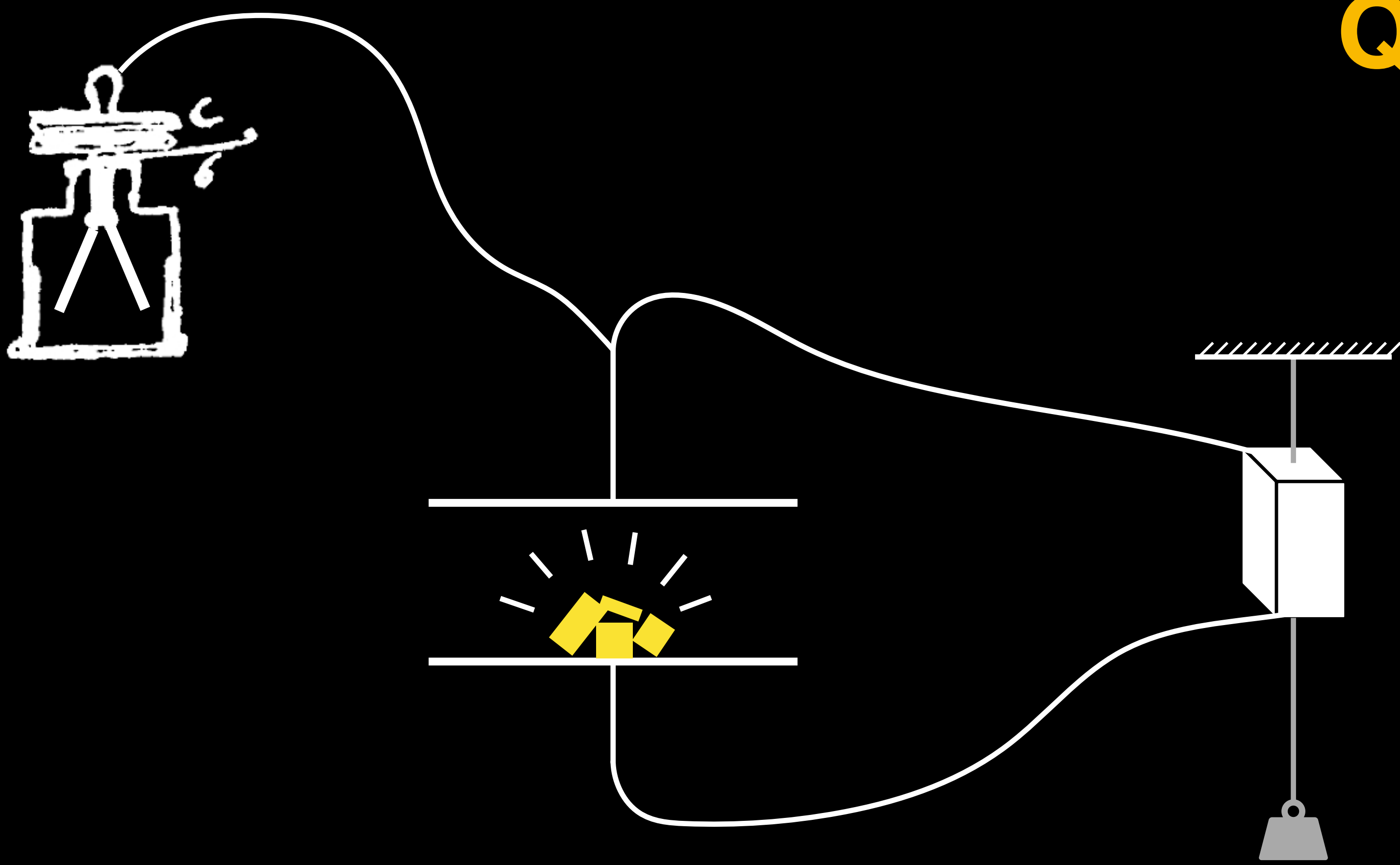
Ernest Rutherford
Paul Villard
(1903)

α β γ



Quantifying radioactivity

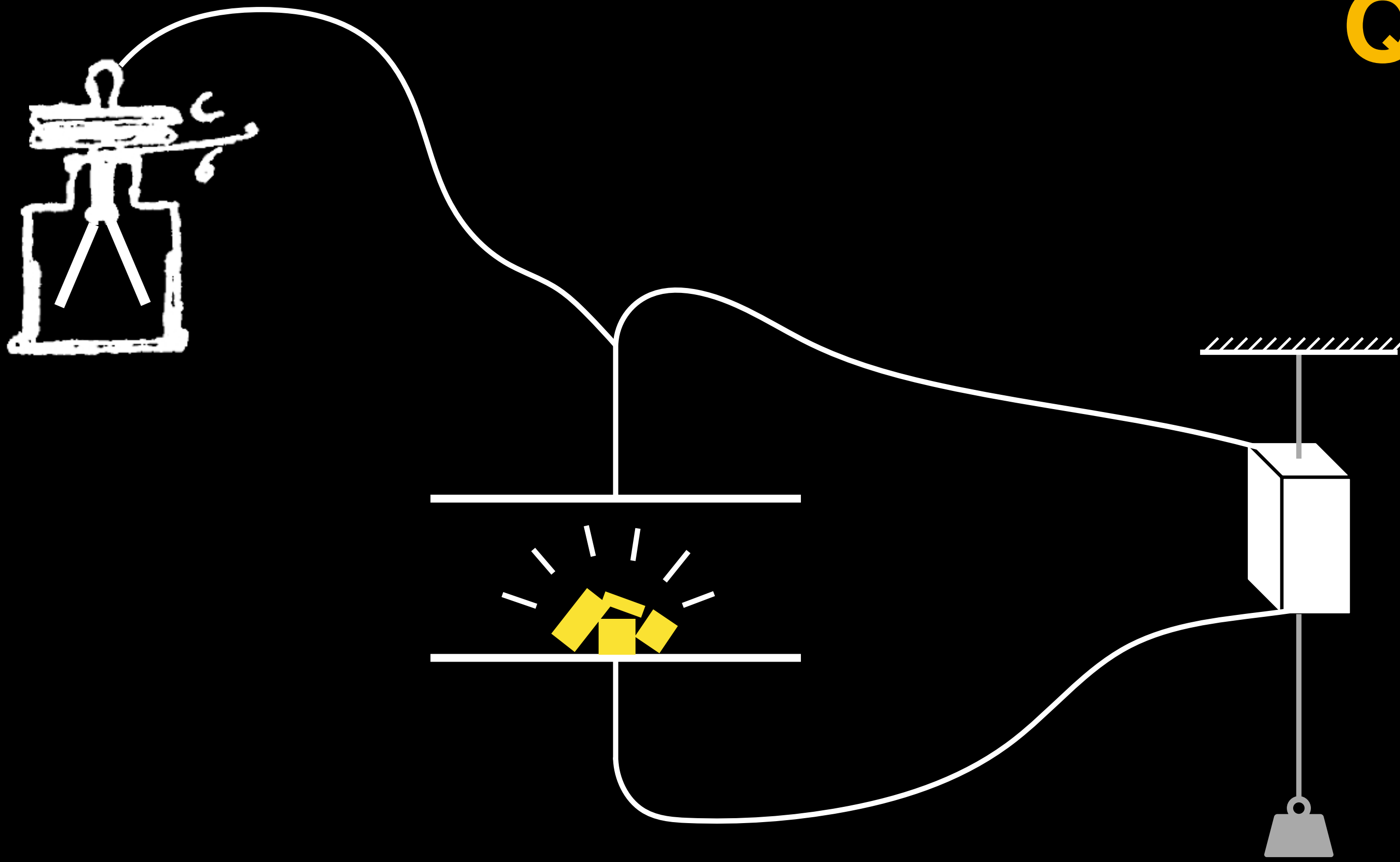
Quantifying radioactivity



Precision ionisation chamber

“Curie method”

Quantifying radioactivity

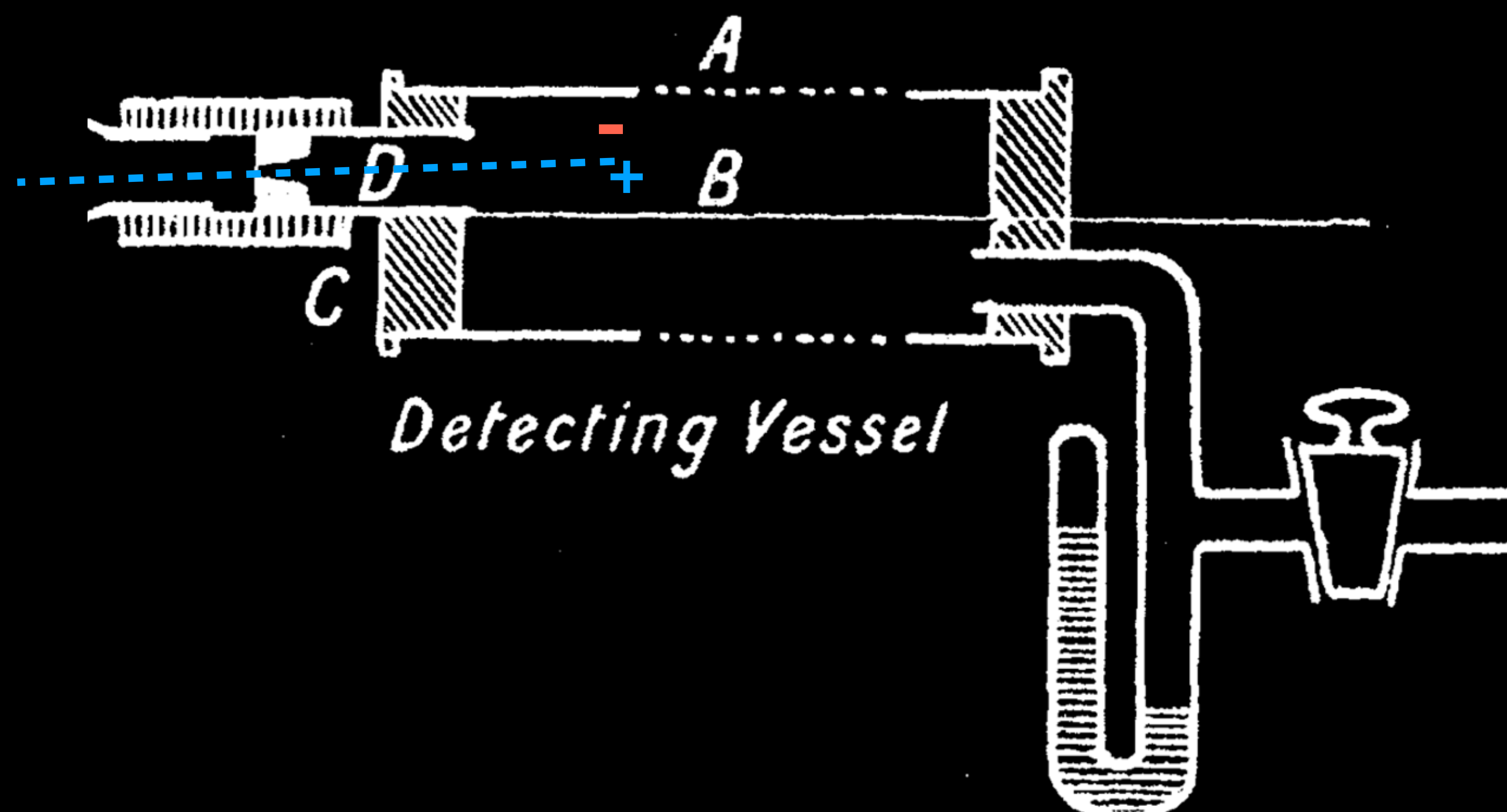


Precision ionisation chamber

“Curie method”

α-particle counter

Geiger and Rutherford



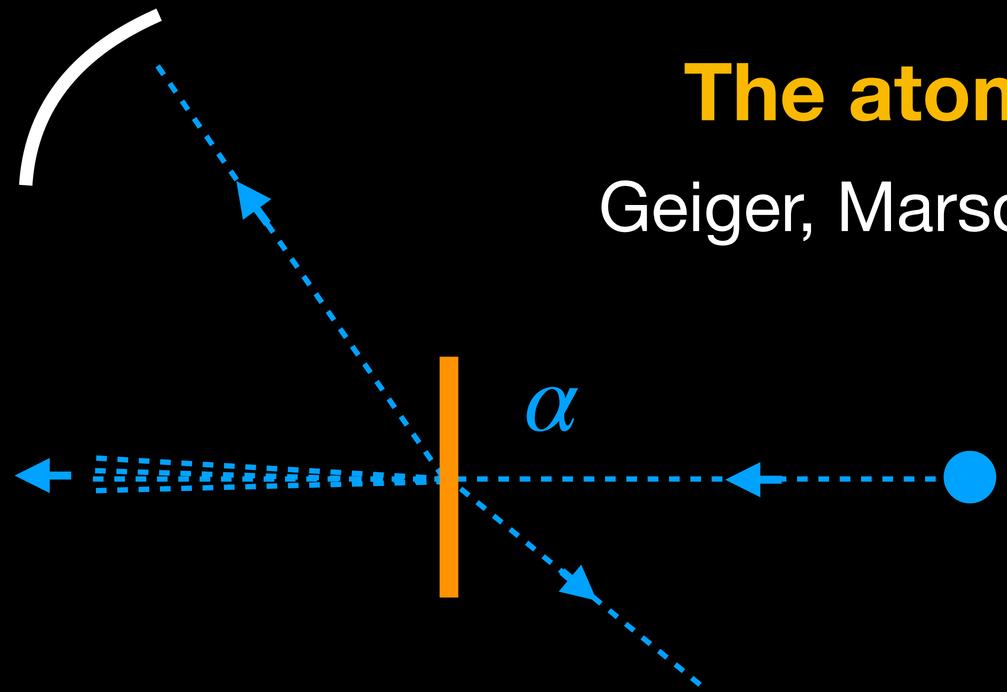
A tool for discovery

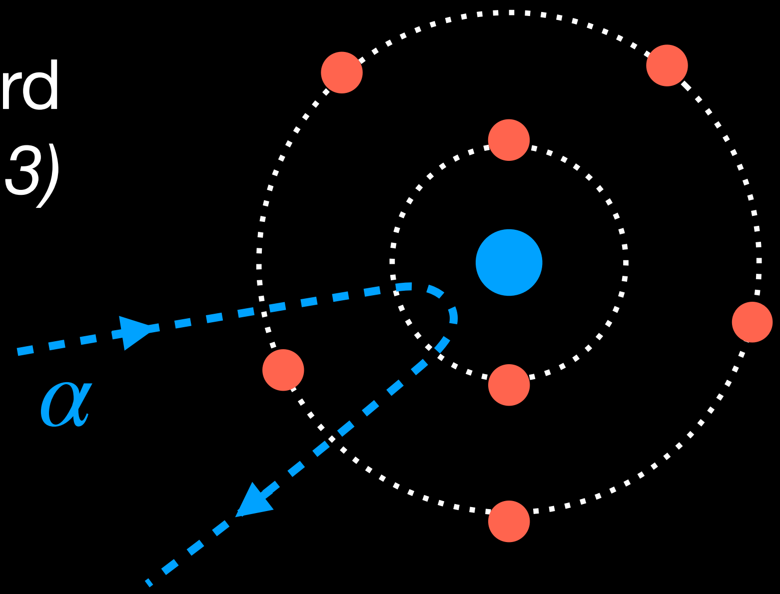
A tool for discovery

The atom has a nucleus!

Geiger, Marsden, and Rutherford

(1913)





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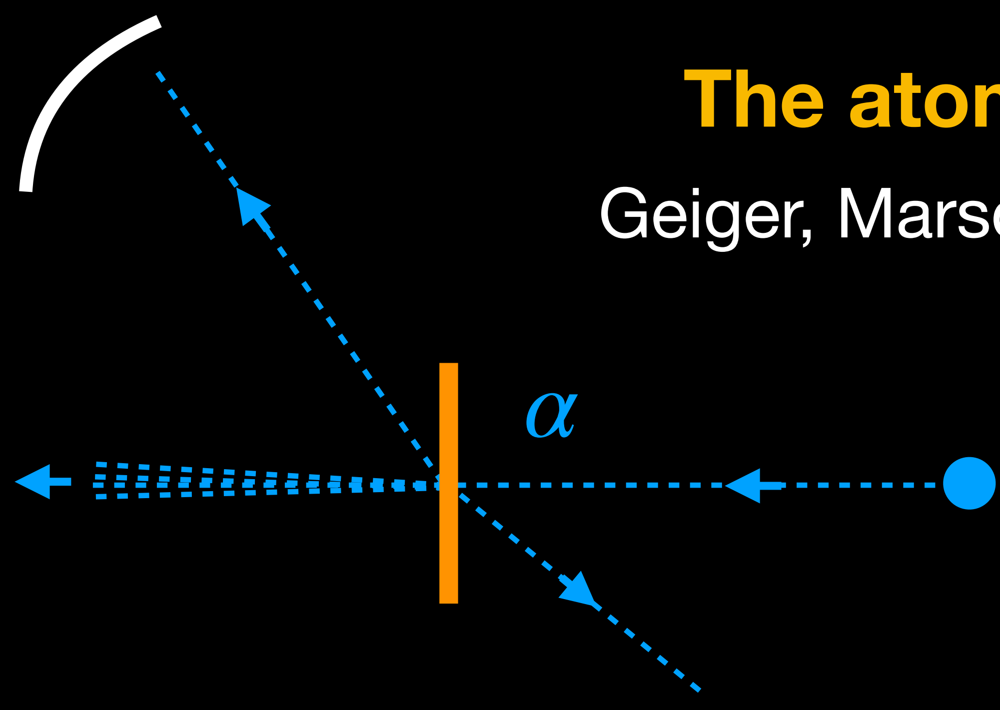
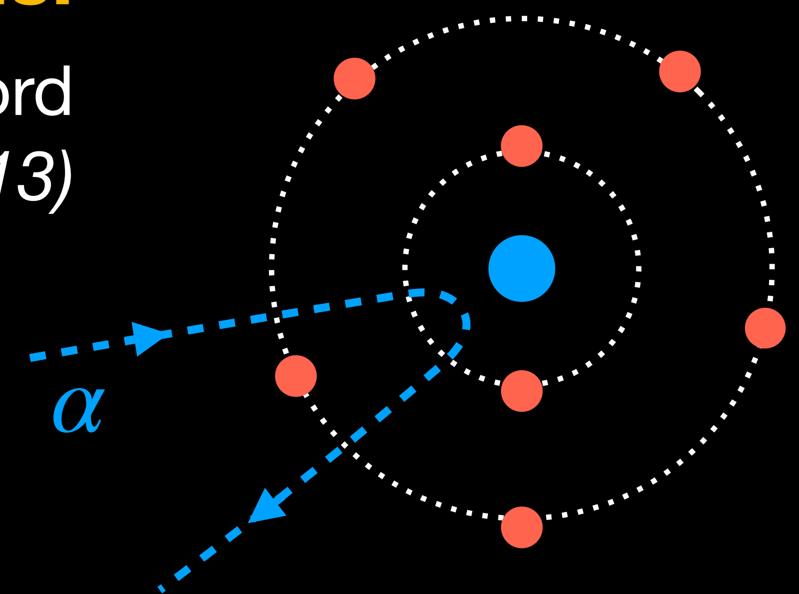
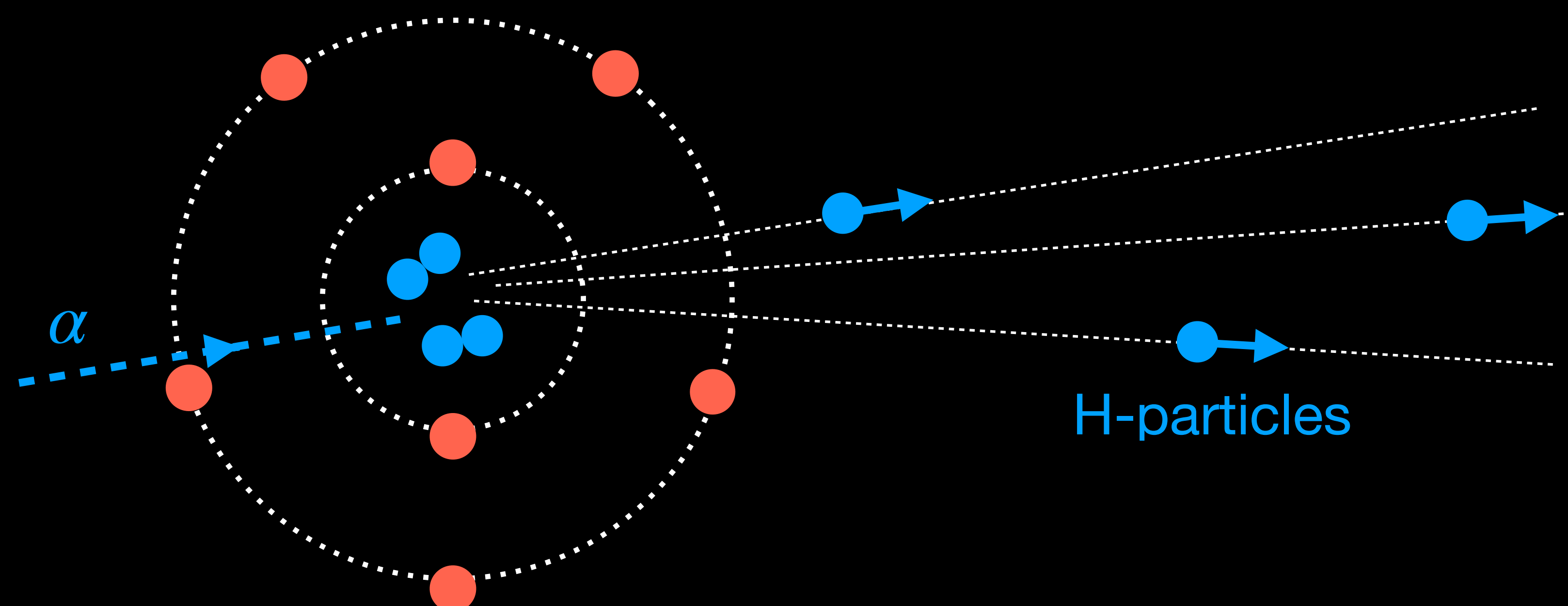
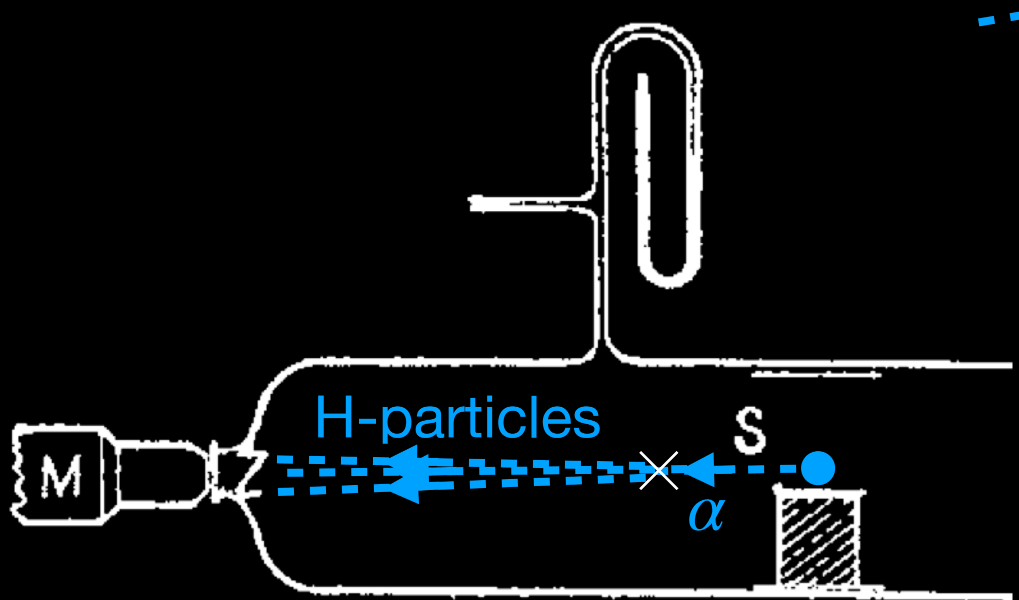


The atom has a nucleus!

Geiger, Marsden, and Rutherford *(1913)*





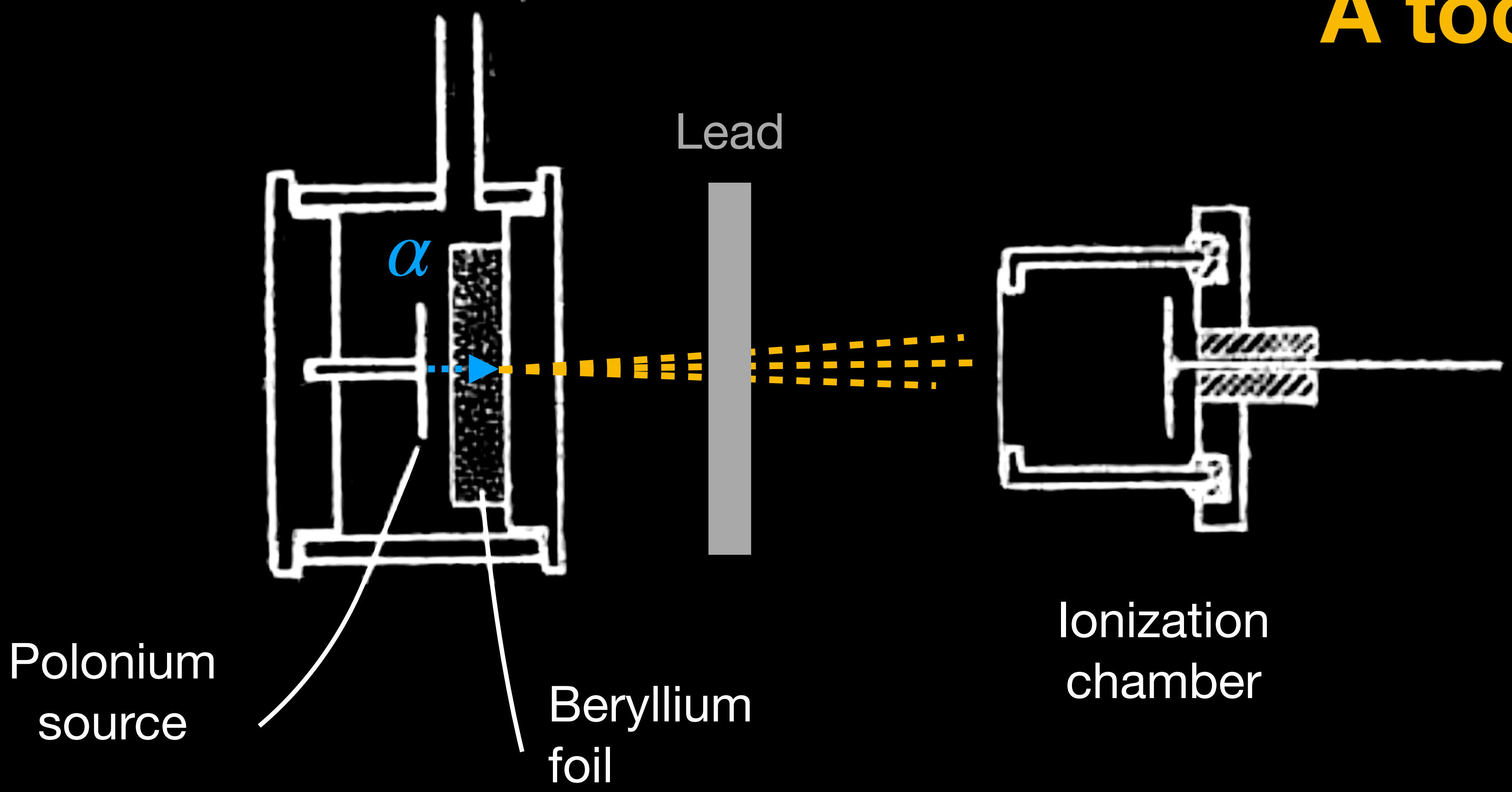


The nucleus consists of protons!

Marsden and Rutherford *(1919)*

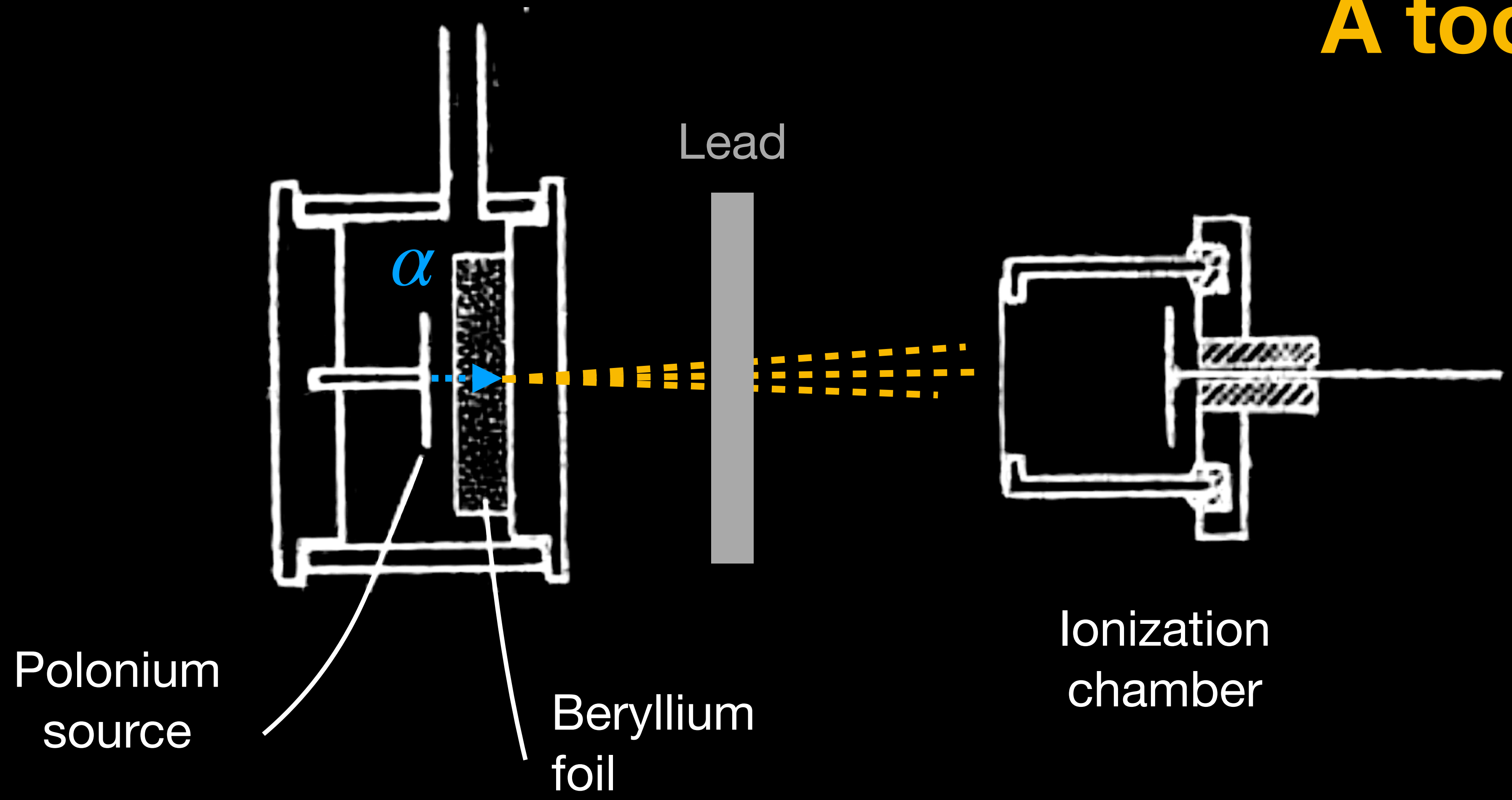
A tool for discovery

A tool for discovery



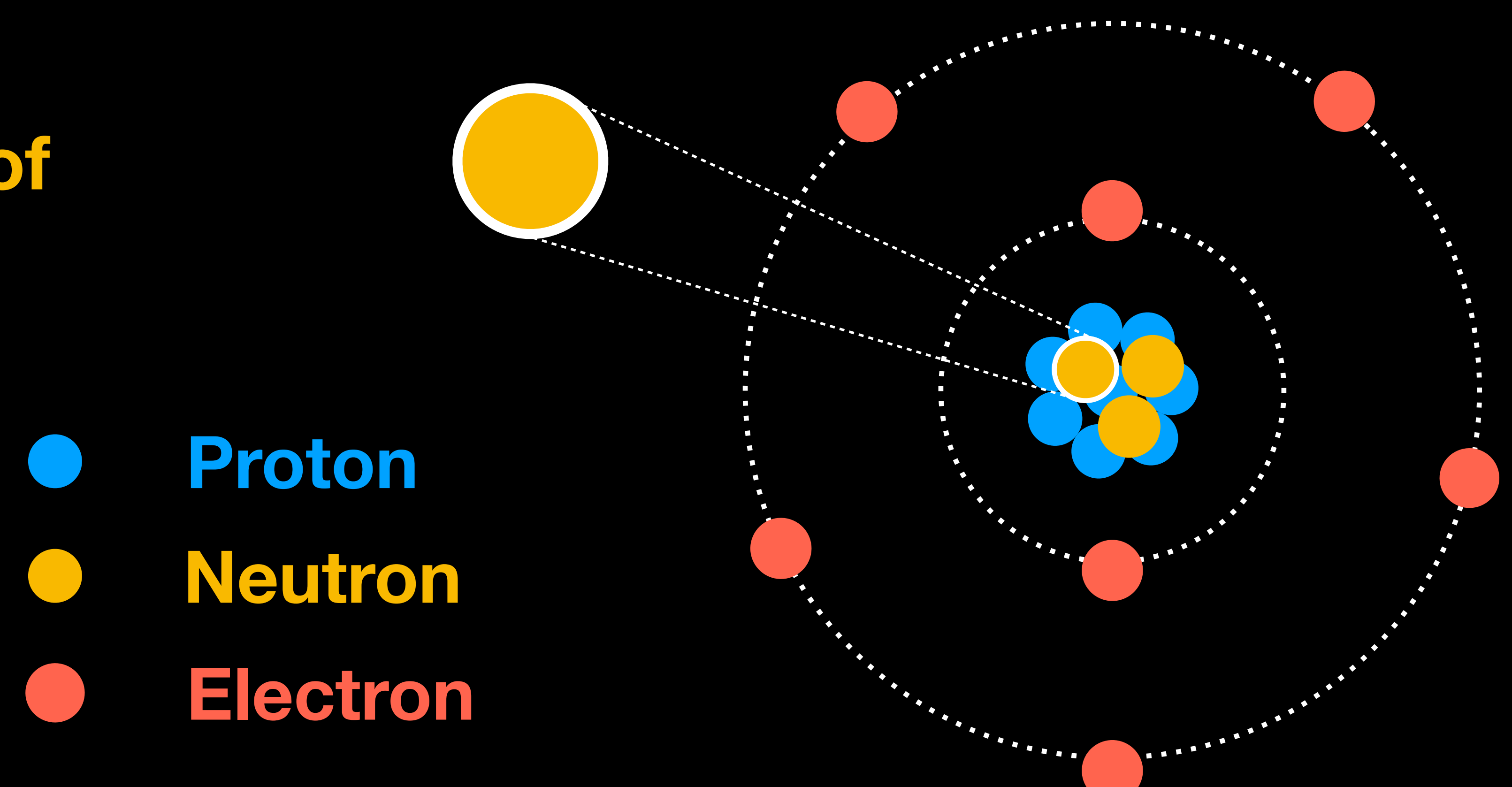
James Chadwick
(1932)

A tool for discovery

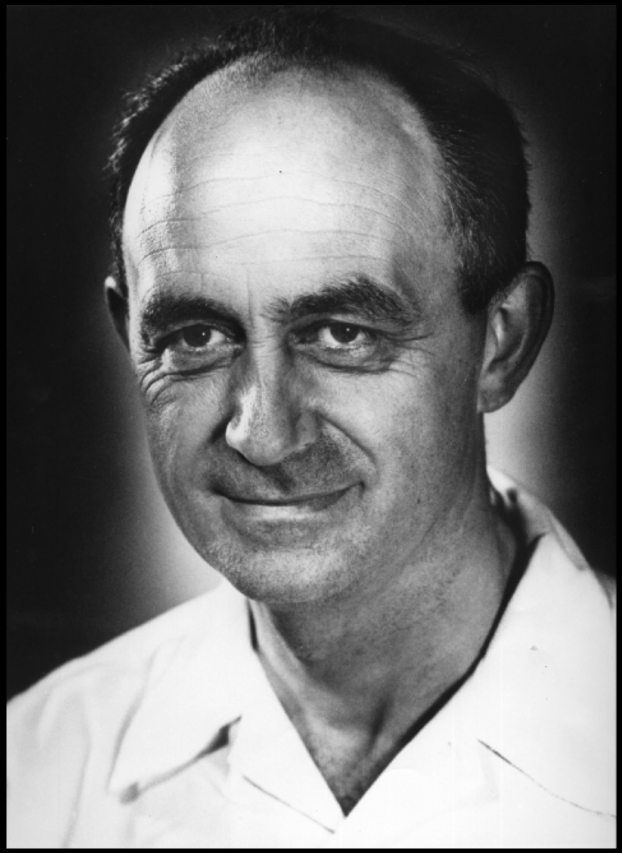


James Chadwick
(1932)

The nucleus consists of protons and neutrons!



Enrico Fermi



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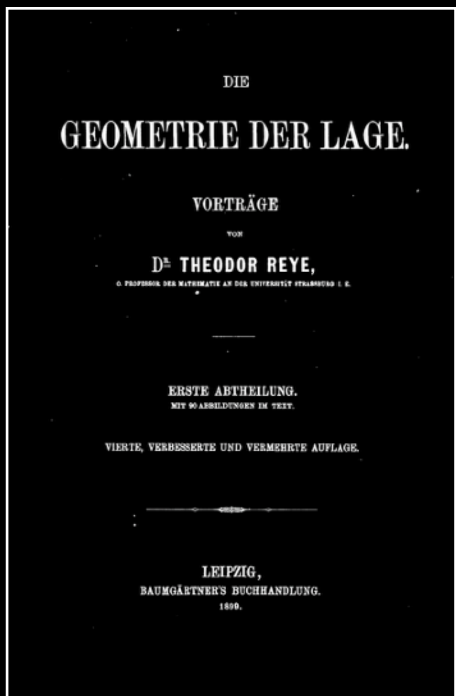
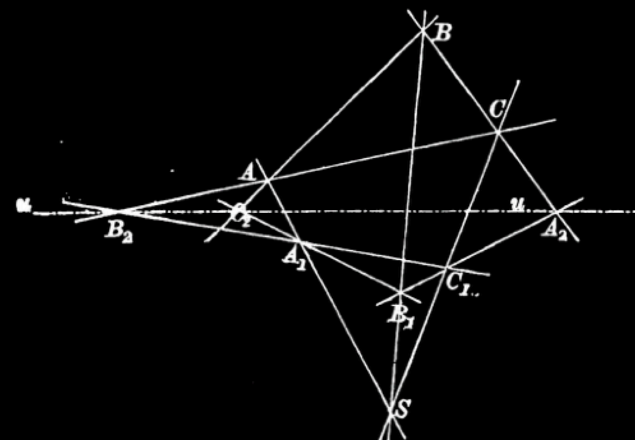
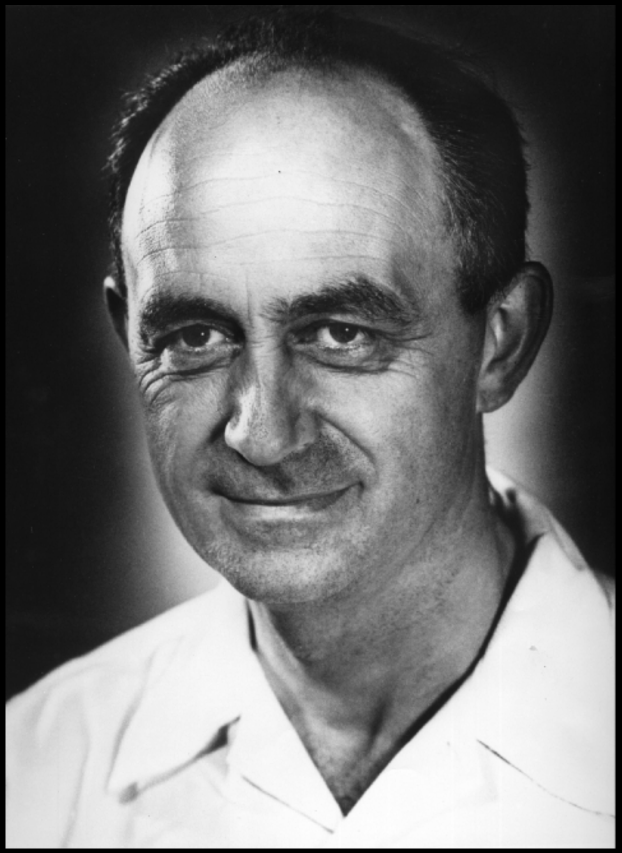

DIE
GEOMETRIE DER LAGE.
VORTRÄGE
VON
DR. THEODOR REYE,
O. PROFESSOR DER MATHEMATIK AN DER UNIVERSITÄT STRASSBURG I. E.
ERSTE ABTHEILUNG.
MIT 90 ABBILDUNGEN IM TEXT.
VIERTE, VERBESSERTE UND VERMEHRTE AUFLAGE.
LEIPZIG,
BAUMGÄRTNER'S BUCHHANDLUNG.
1899.

Geometry: his gateway into science





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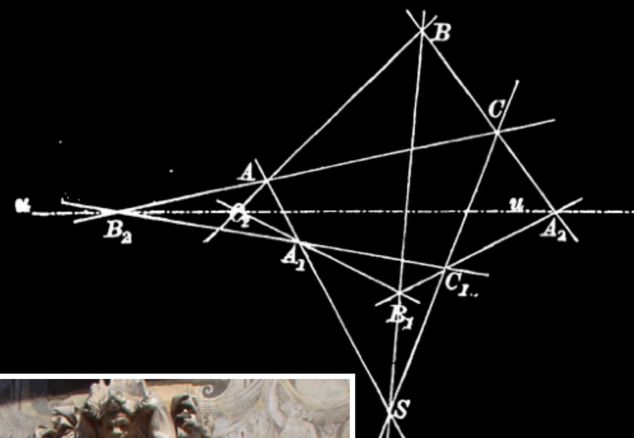
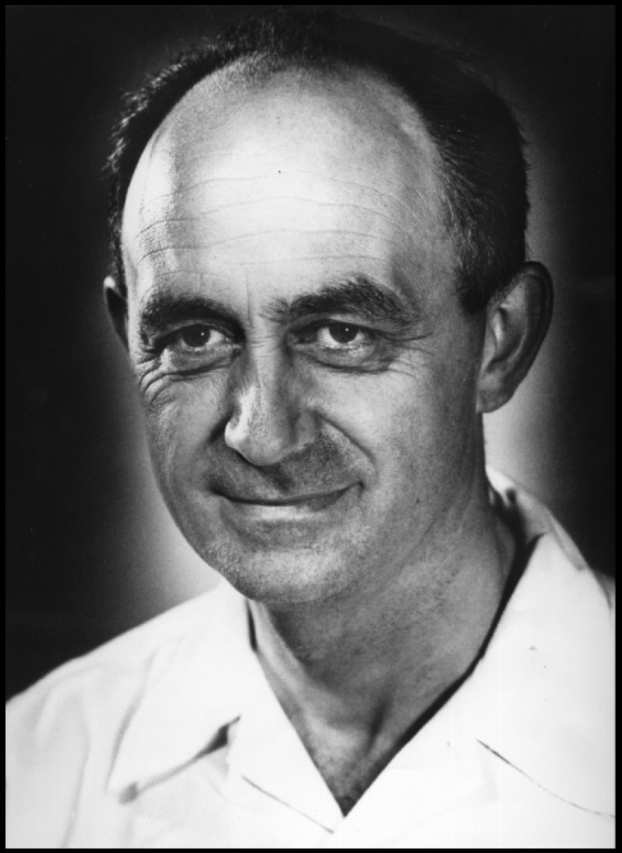


Pisa



Enrico Fermi

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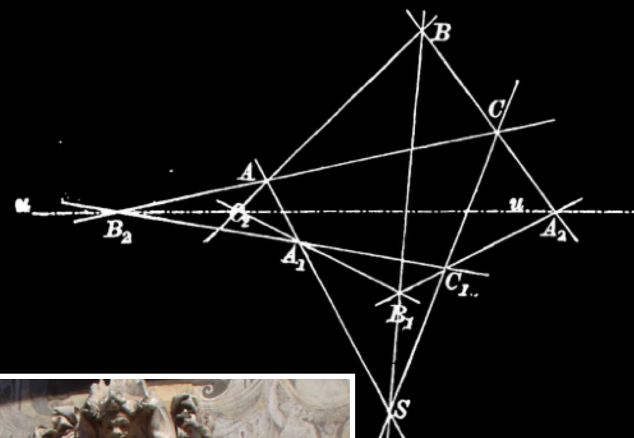

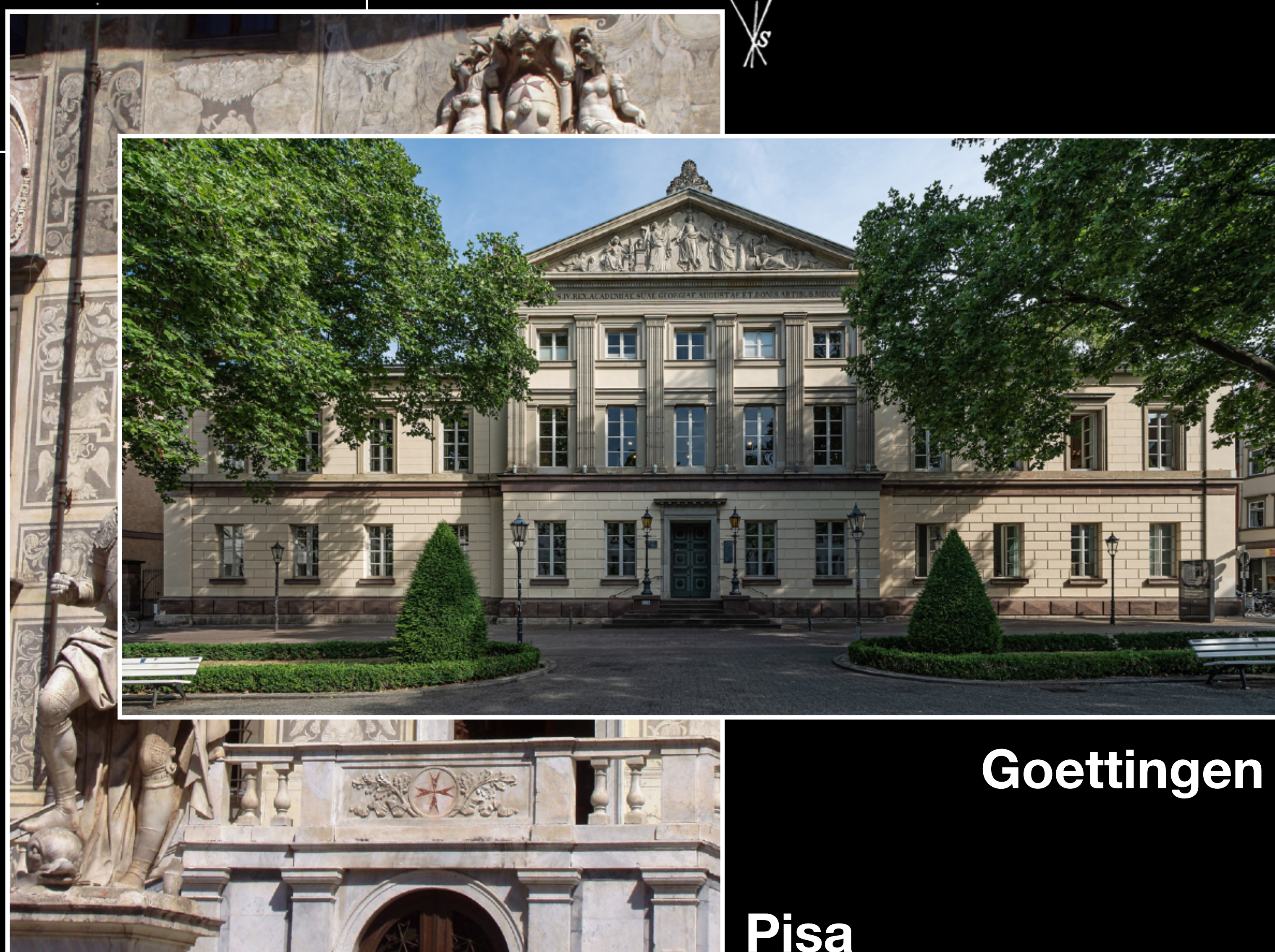

Goettingen

Pisa

Enrico Fermi

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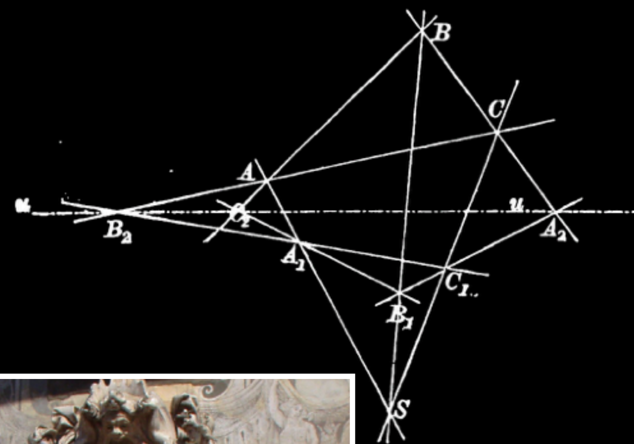
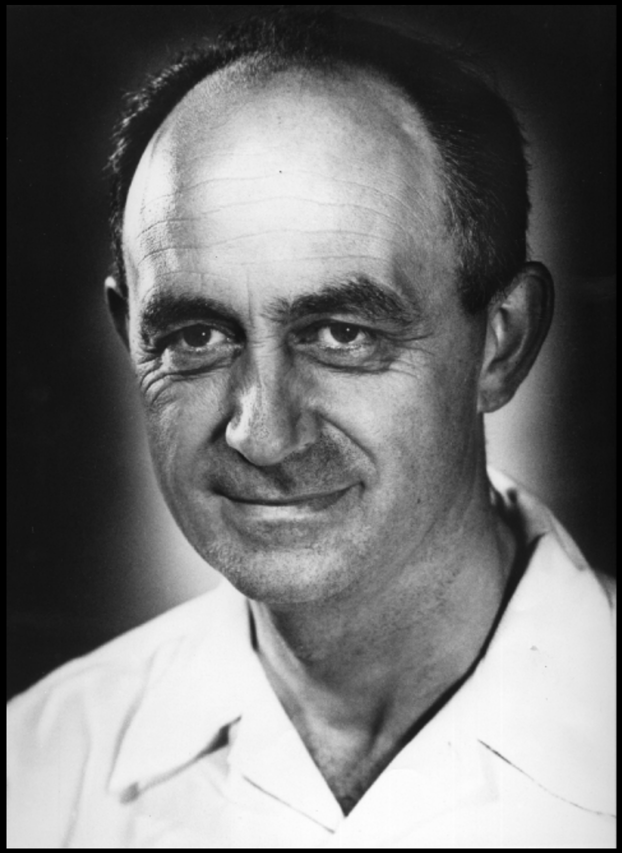
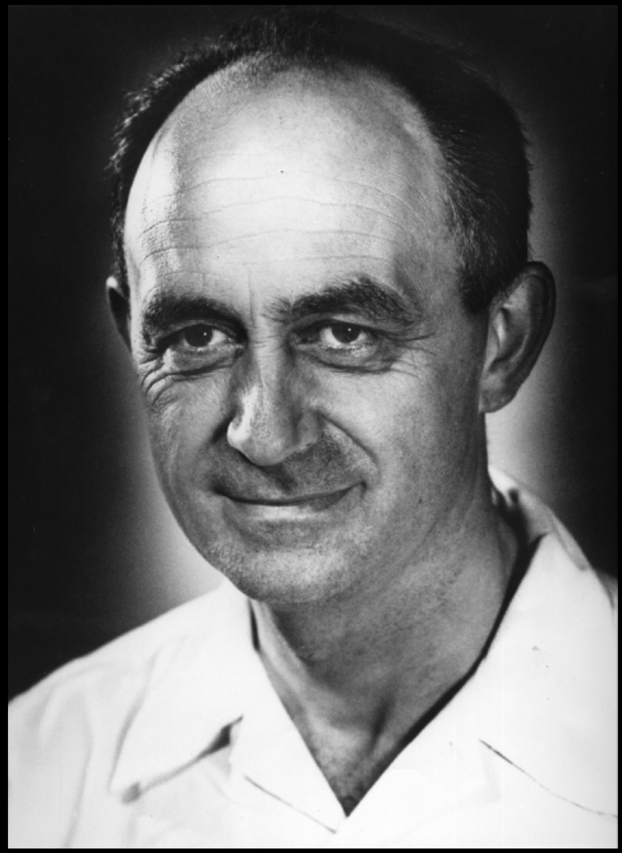


ttingen

Pisa



Enrico Fermi

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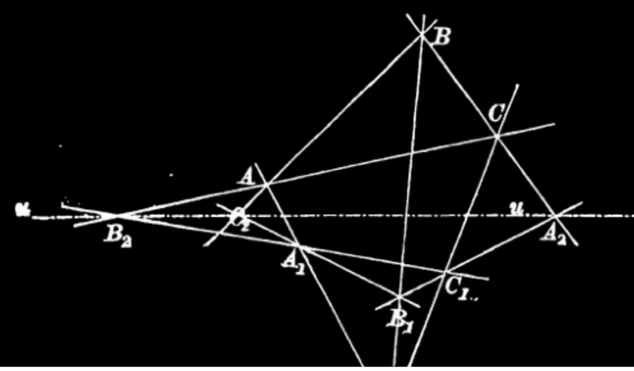

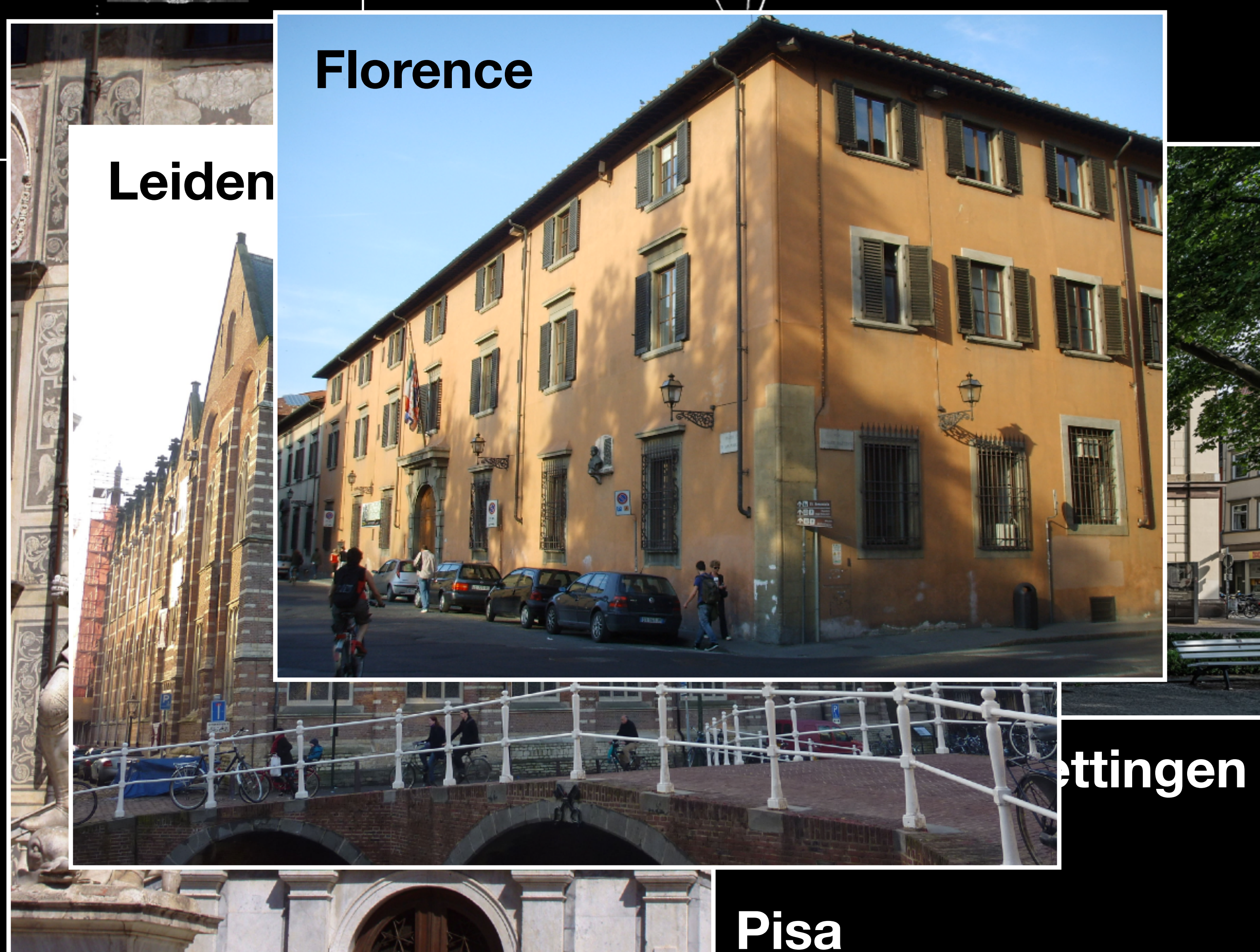

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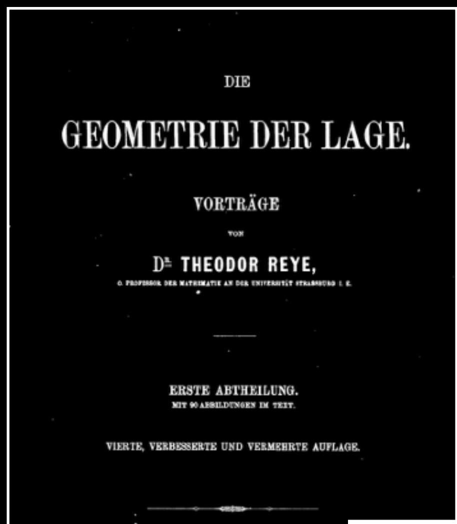

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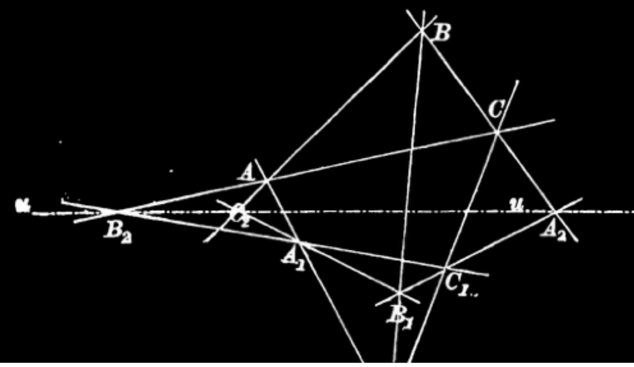
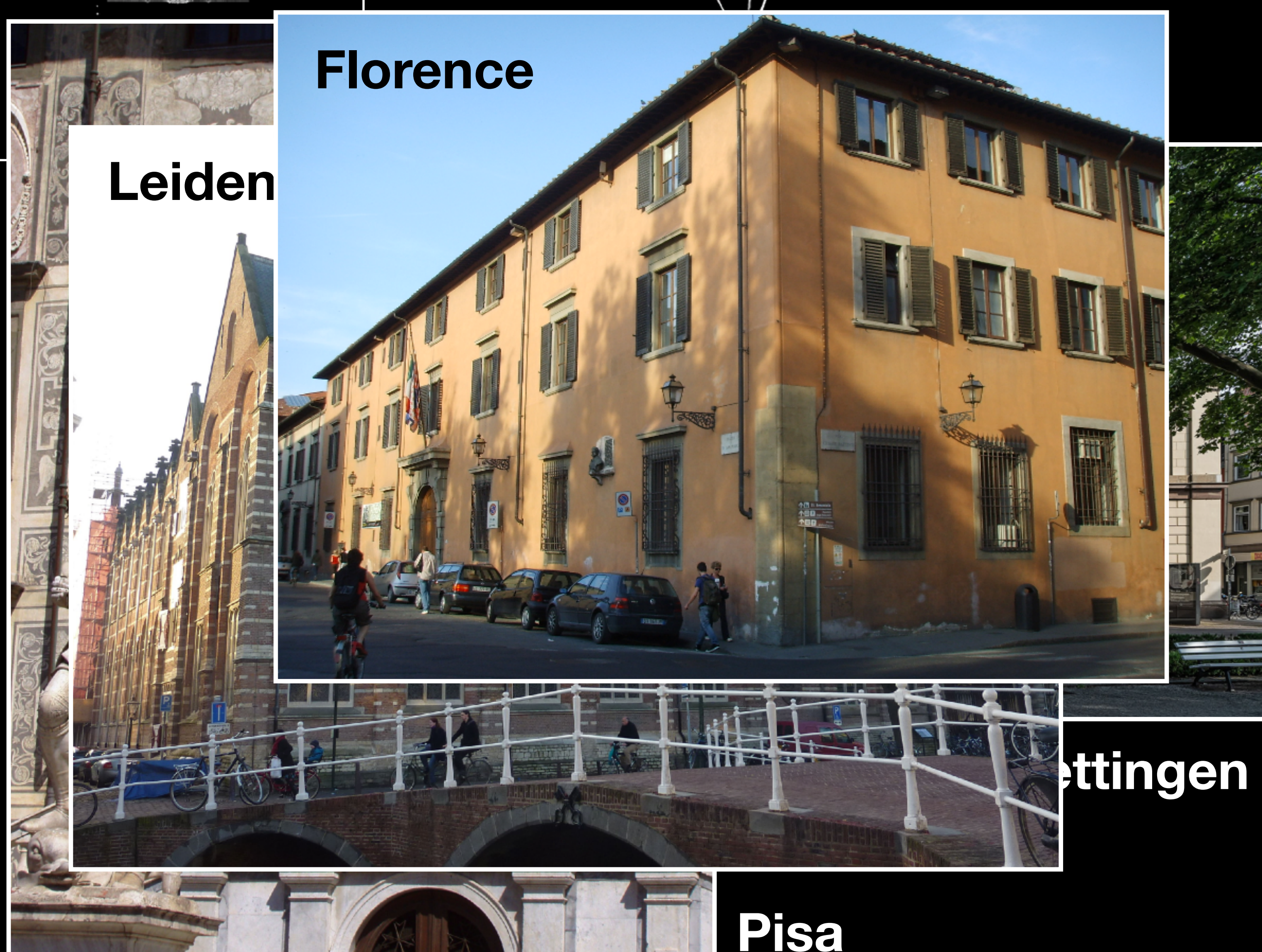
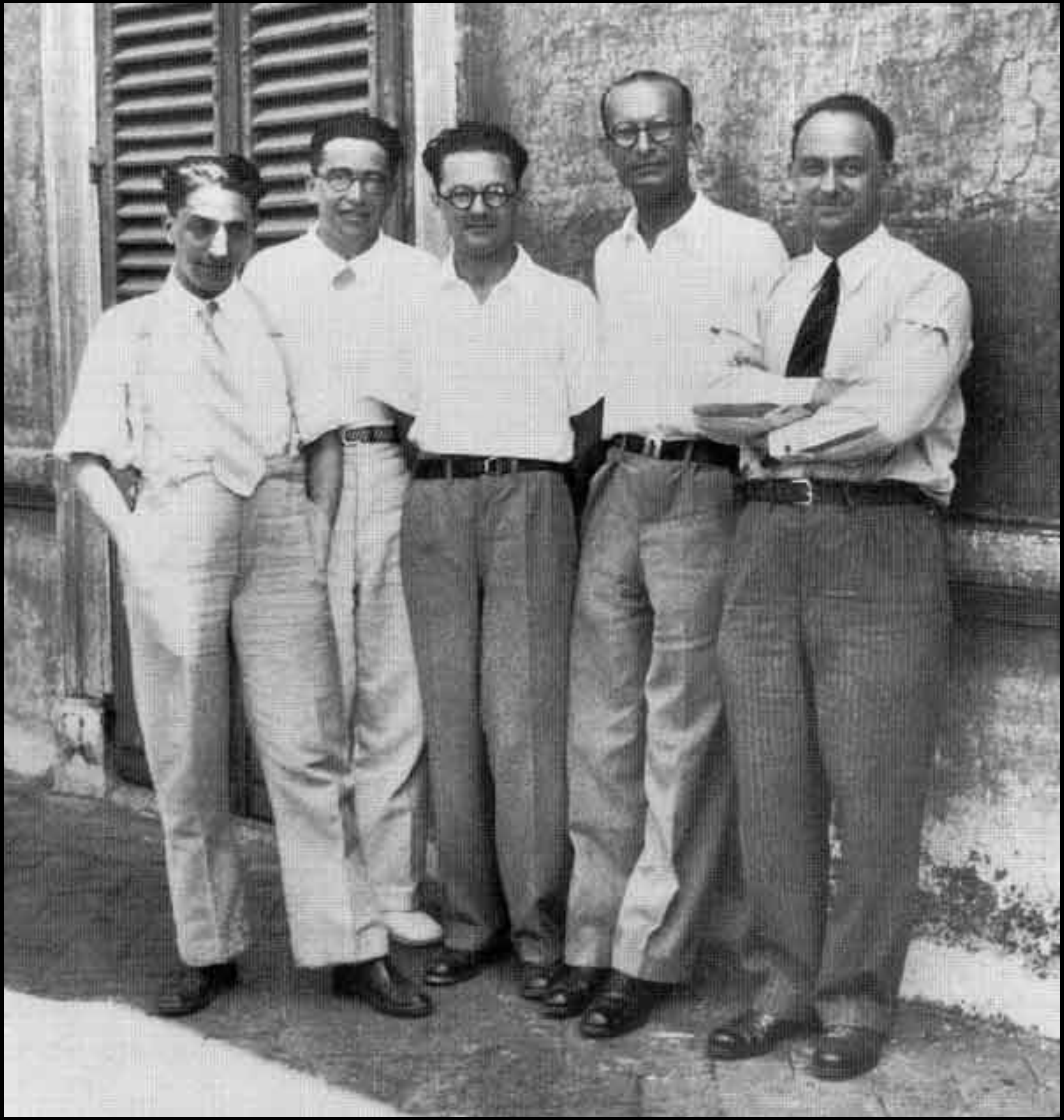




"I can calculate anything in physics within a factor 2 on a few sheets; to get it fully right may well take a physicist a year, but I am not interested in that."

Back in Rome: the Via Panisperna boys



Back in Rome: the Via Panisperna boys

“The pope”

Back in Rome: the Via Panisperna boys

Franco Rasetti
“The Cardinal Vicar”

“The pope”

Back in Rome: the Via Panisperna boys

Edoardo Amaldi
“The Young Boy”

Franco Rasetti
“The Cardinal Vicar”

“The pope”

Back in Rome: the Via Panisperna boys

Orso Corbino
"God almighty"

Edoardo Amaldi
"The Young Boy"

Franco Rasetti
"The Cardinal Vicar"

"The pope"

News from Paris: artificial radioactivity

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"Our latest experiments have shown a very striking fact."

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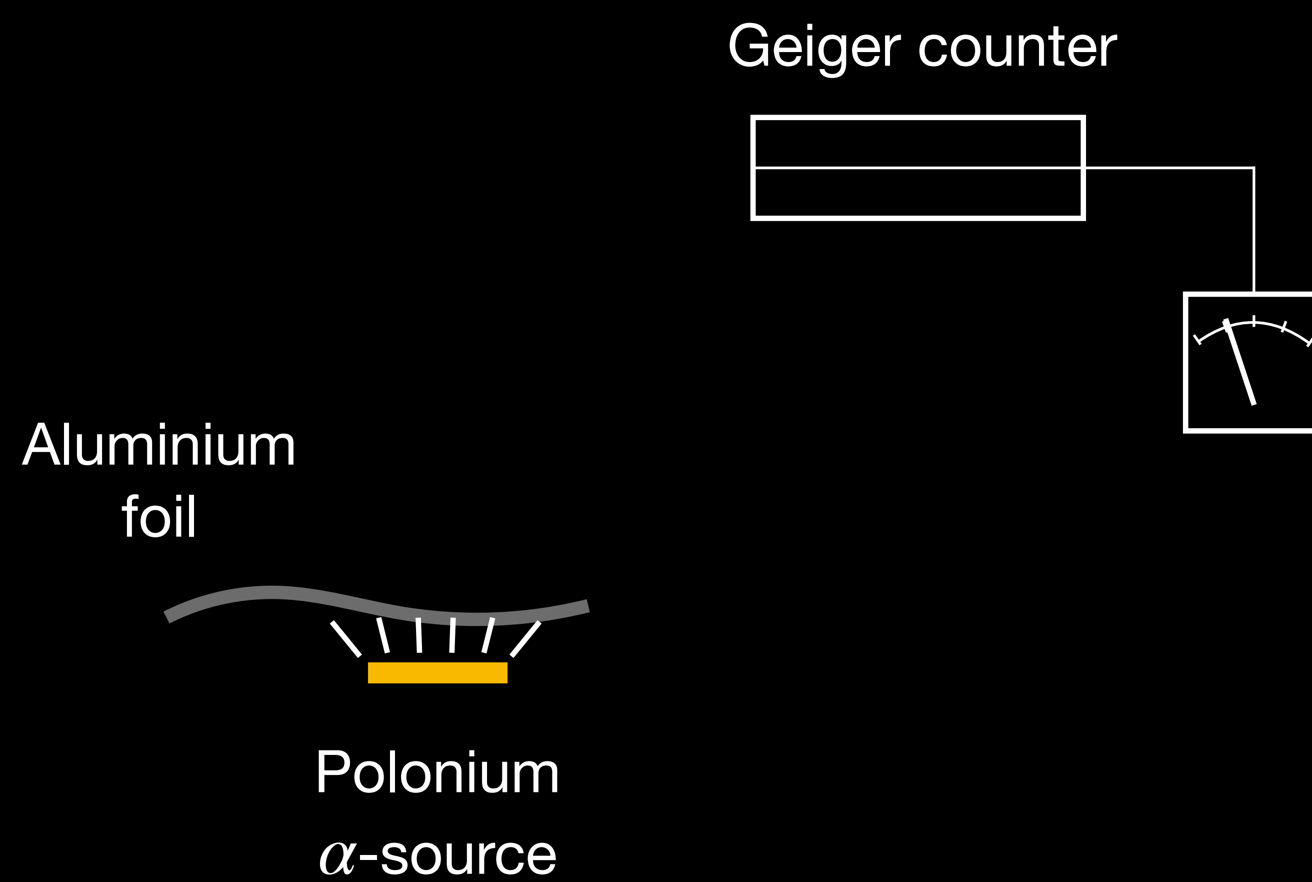
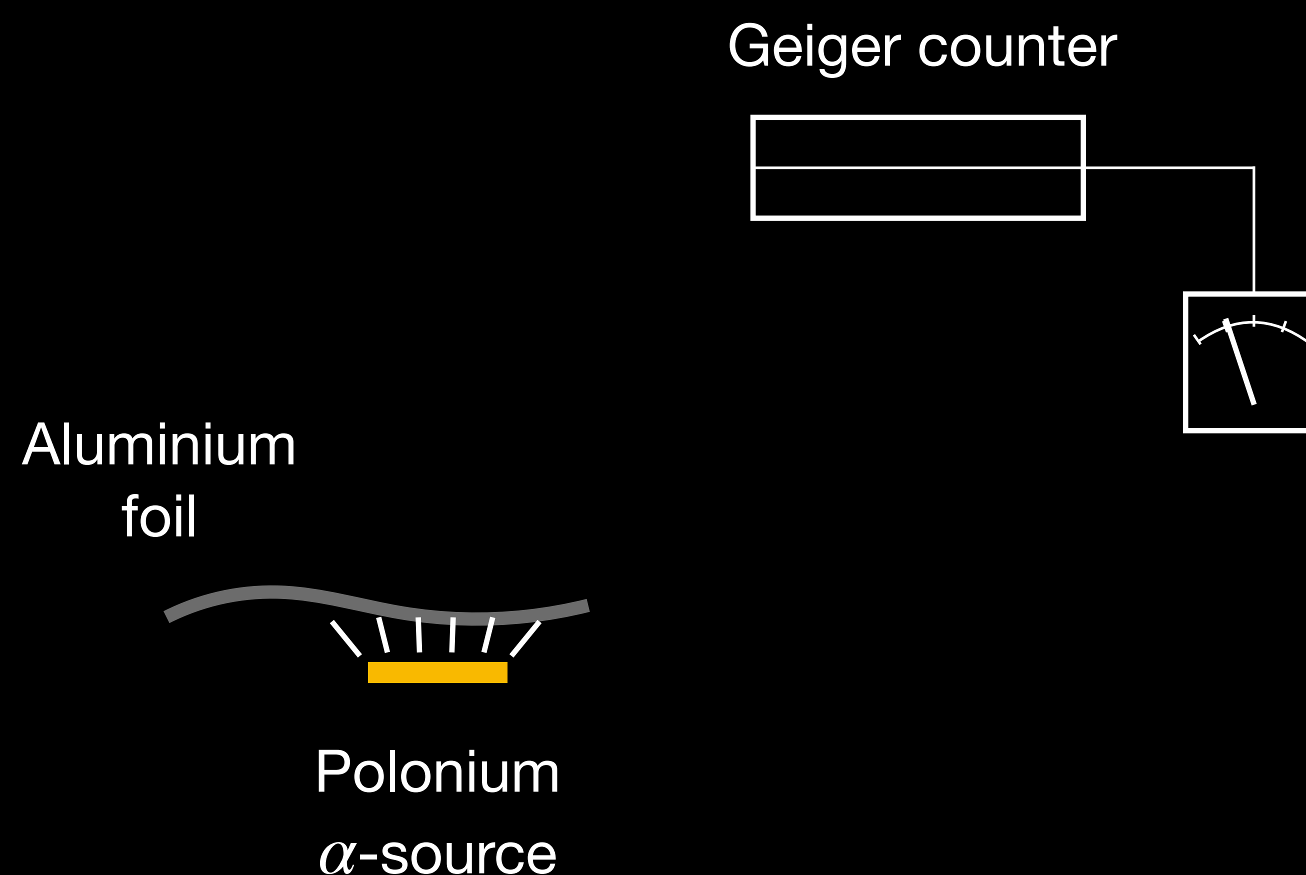


News from Paris: artificial radioactivity

Frédéric and
Irène Joliot-Curie

1934

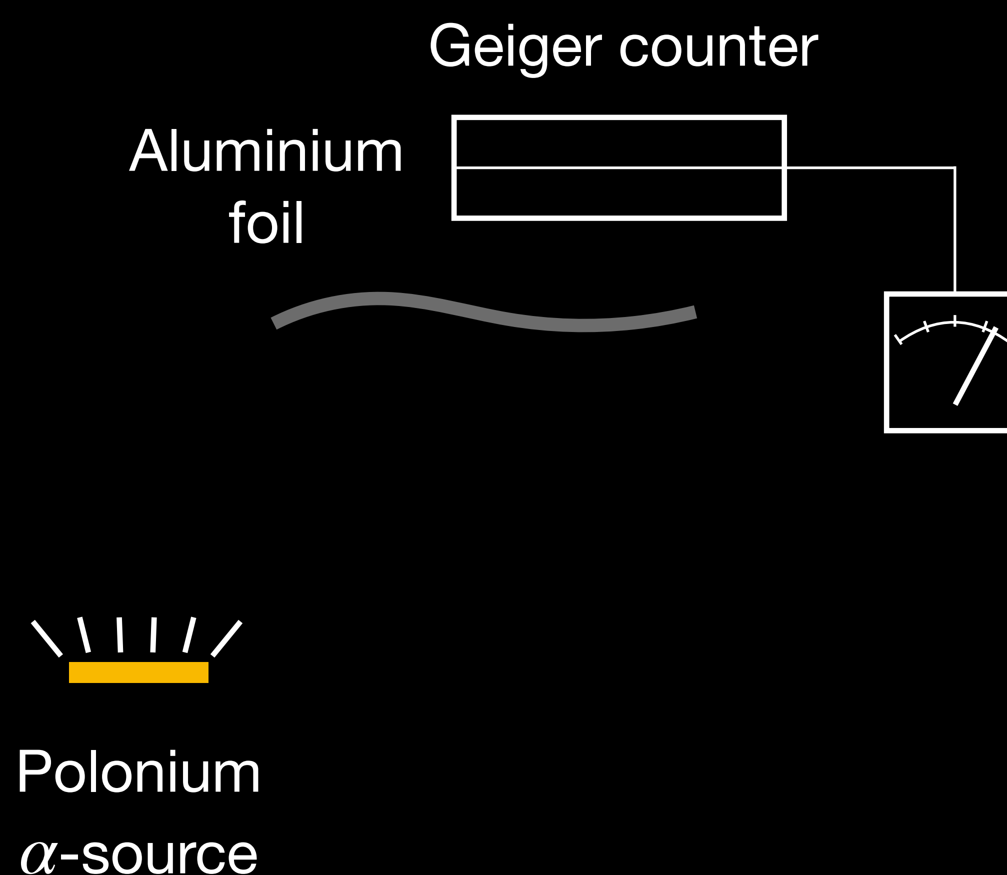
"Our latest experiments have shown a very striking fact."



"When an aluminium foil is irradiated on a polonium preparation …"

News from Paris: artificial radioactivity

"Our latest experiments have shown a very striking fact."

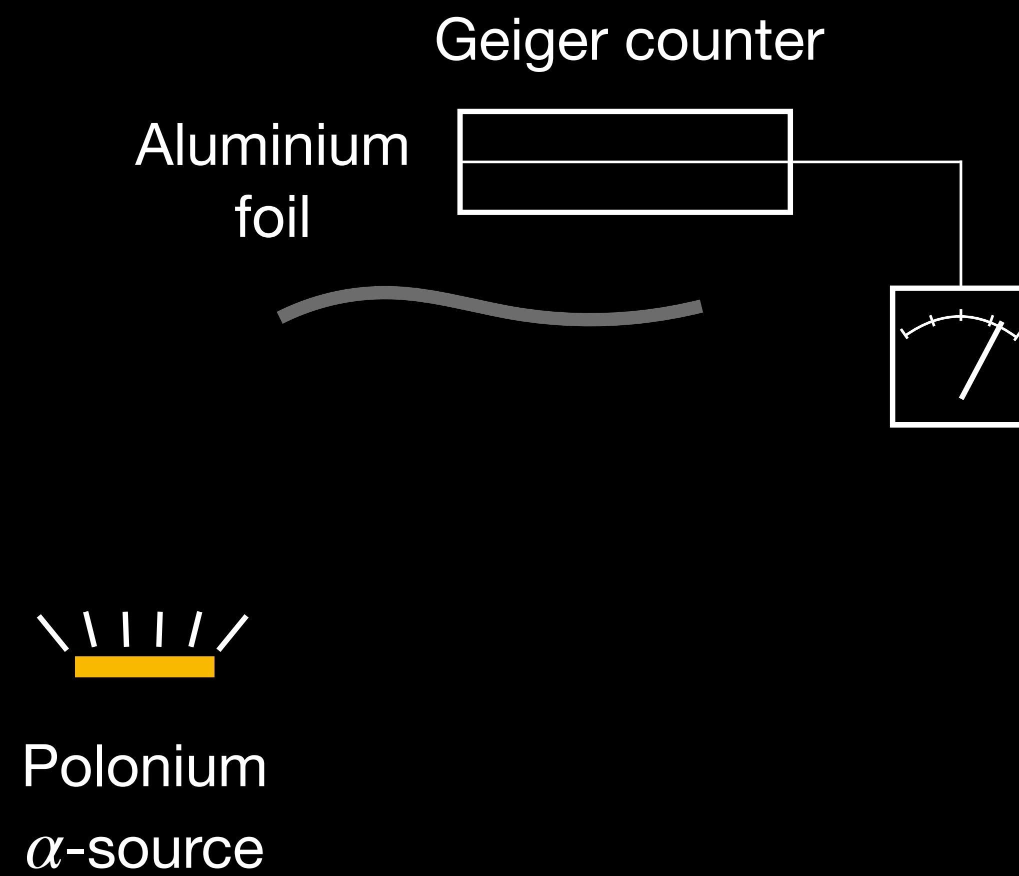


"… the emission of radiation does not cease immediately when the active preparation is removed."

News from Paris: artificial radioactivity

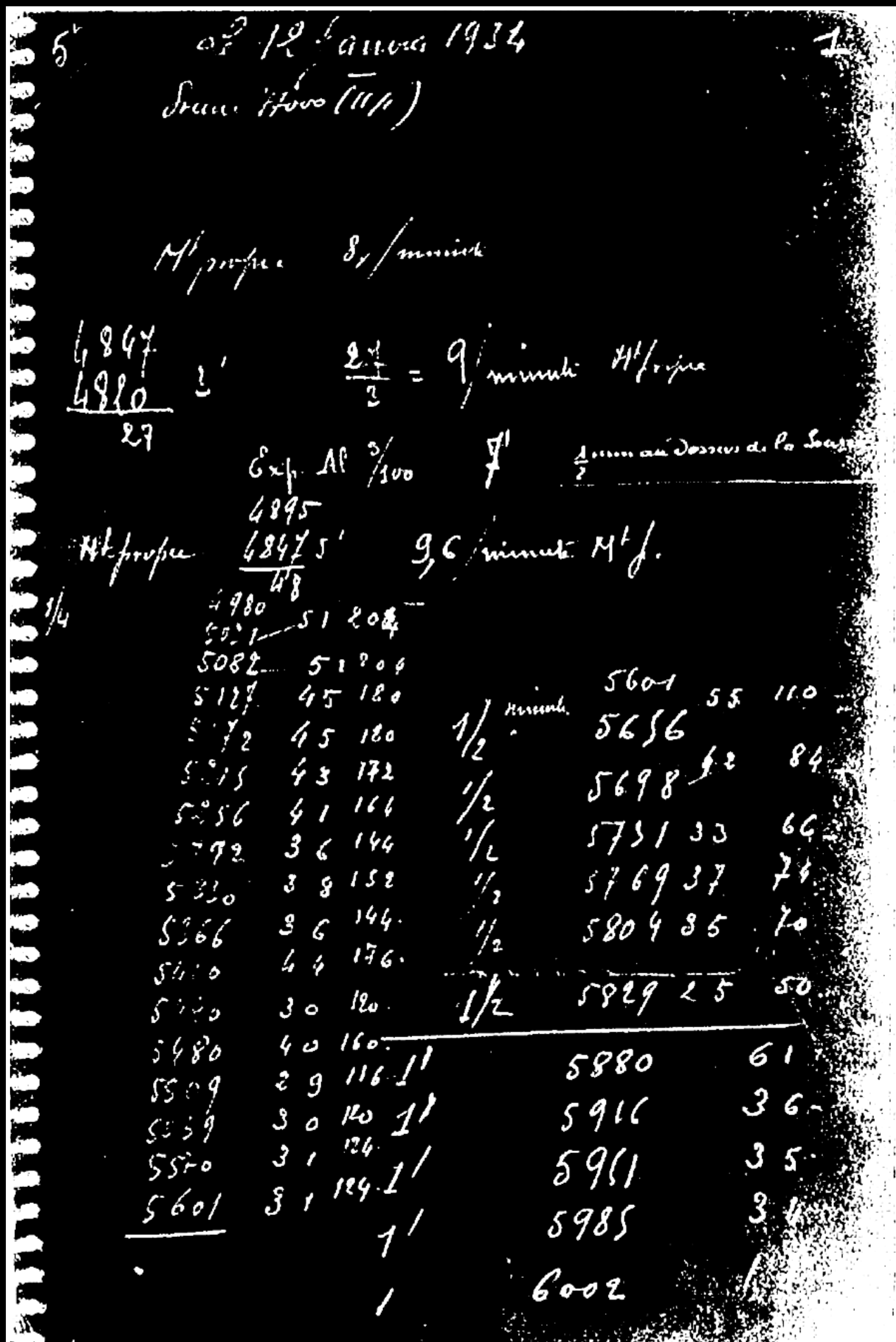
Frédéric and
Irène Joliot-Curie

"Our latest experiments have shown a very striking fact."



"The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radio-element."

News from Paris: artificial radioactivity



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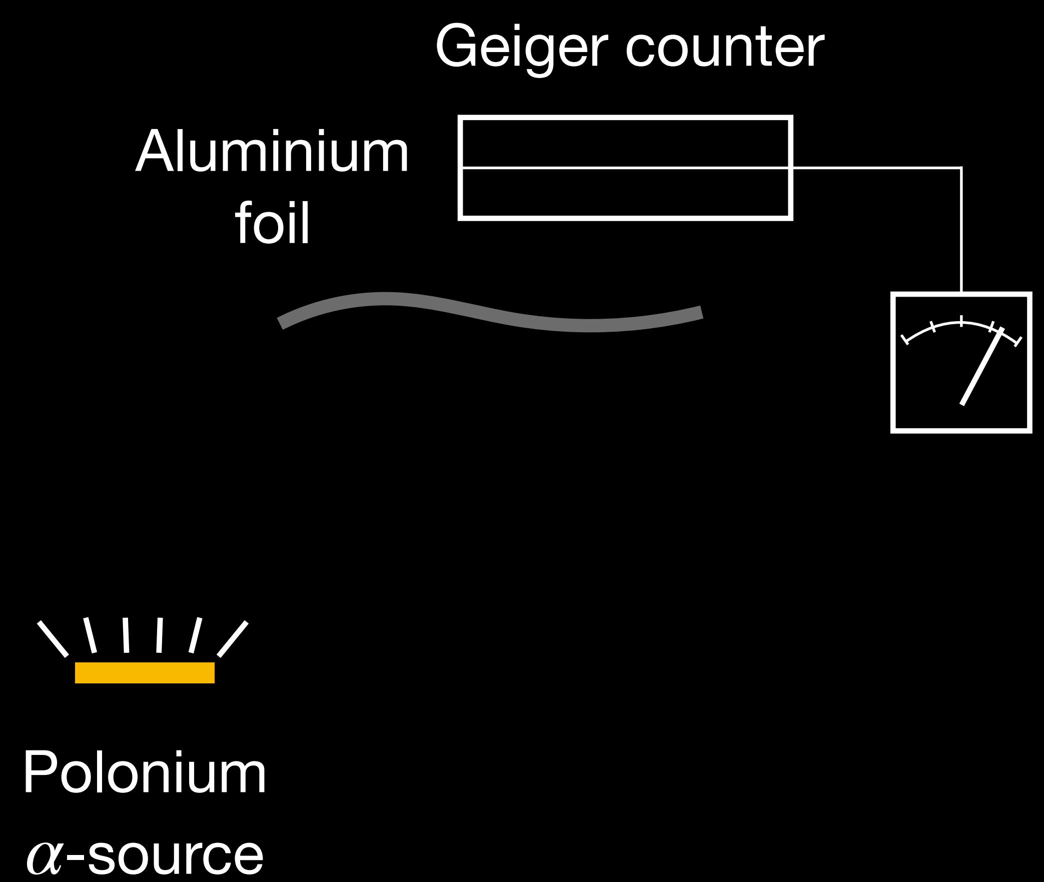

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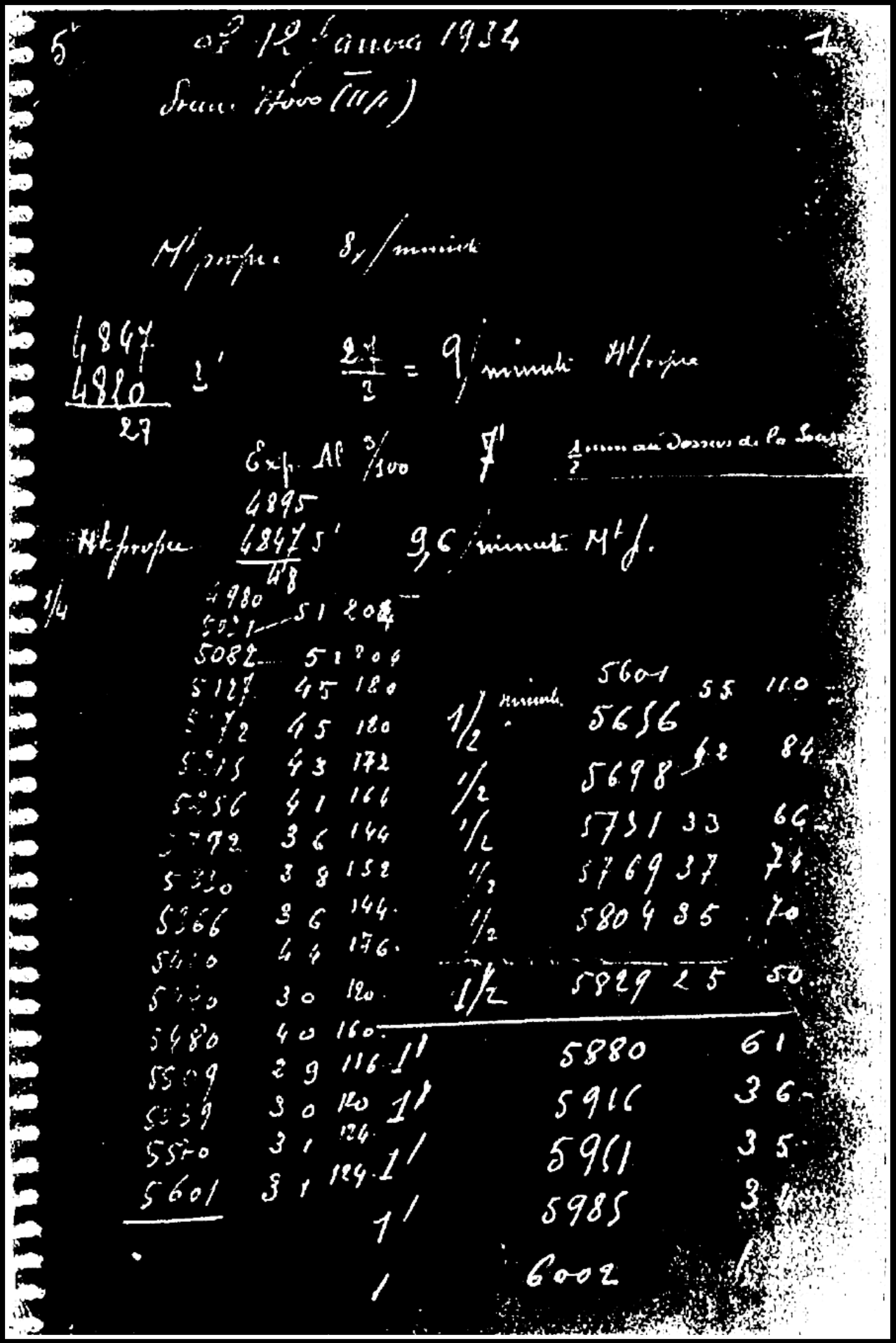

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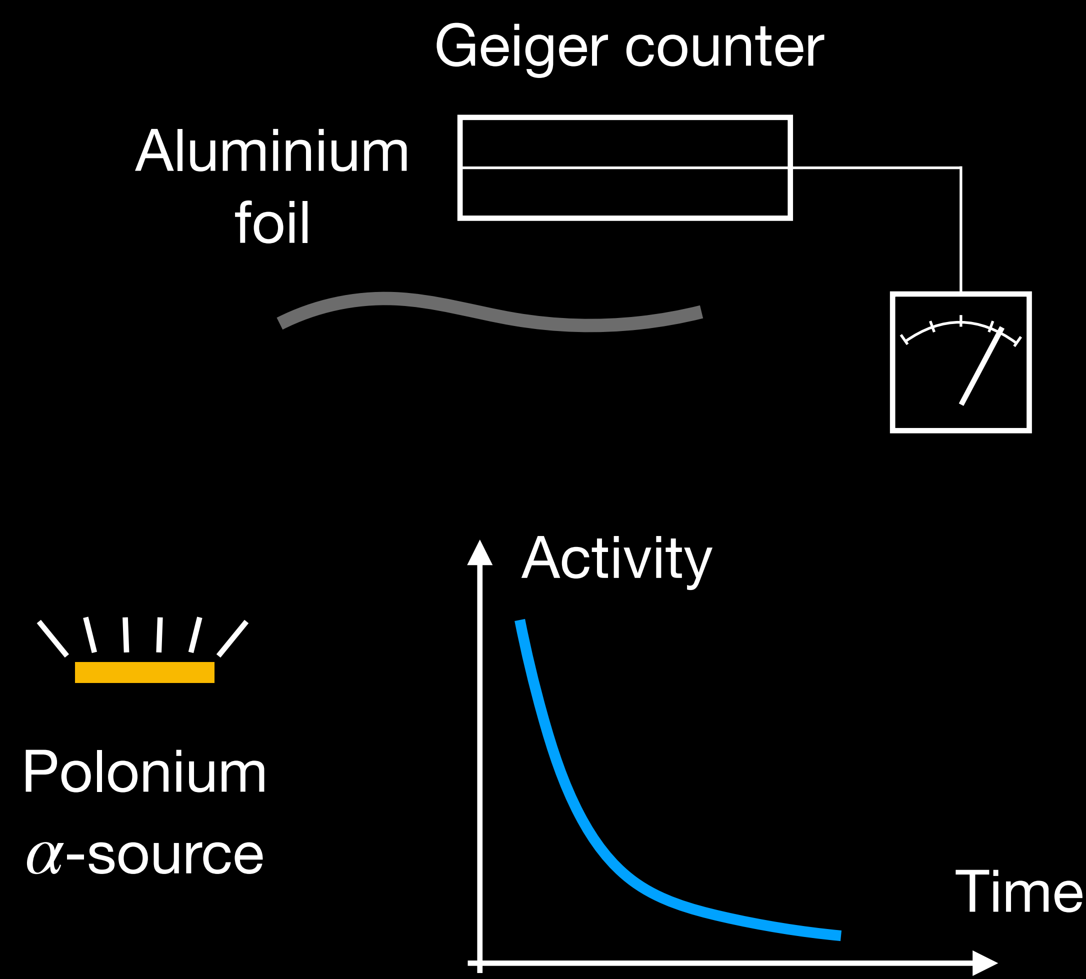

"The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radio-element."

Back to Rome

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Artificial Production of a New Kind of Radio-Element

By F. Joliot and I. Curie, Institut du Radium, Paris

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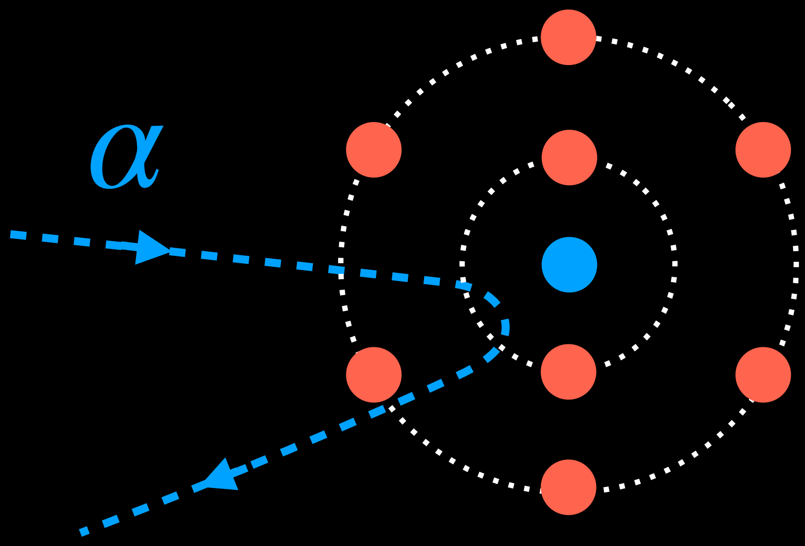

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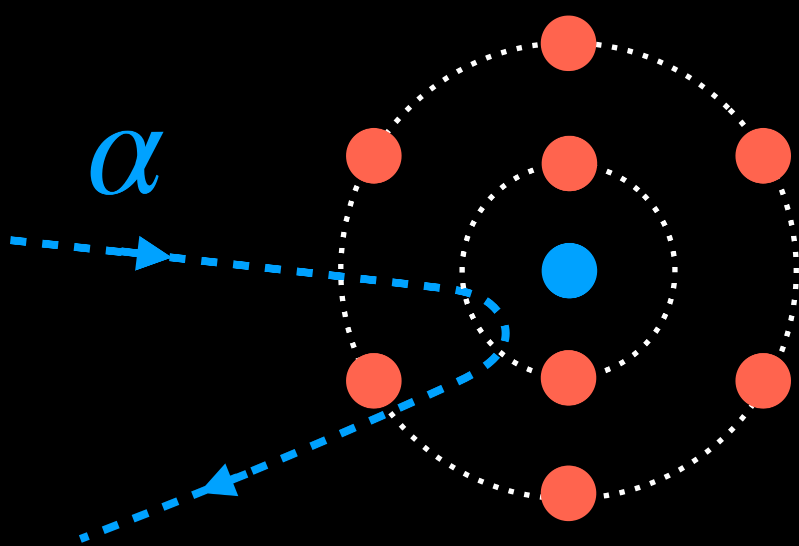
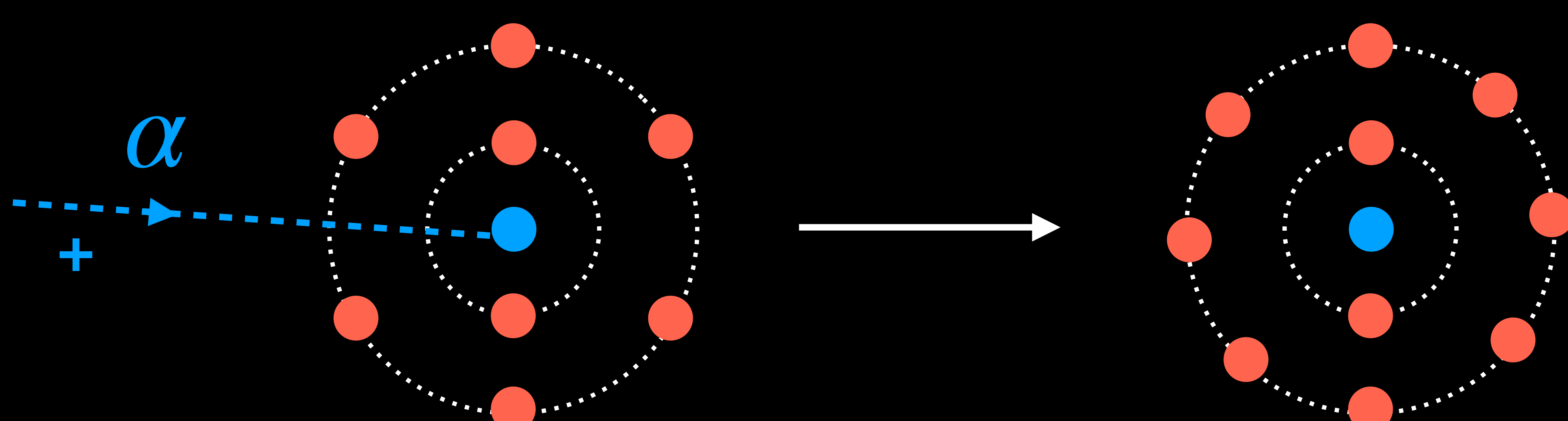


Aluminium atom

Phosphorus atom



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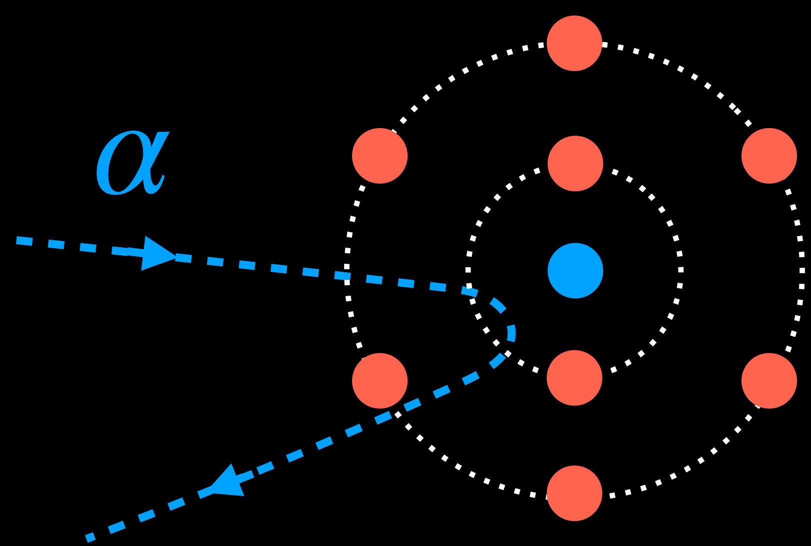
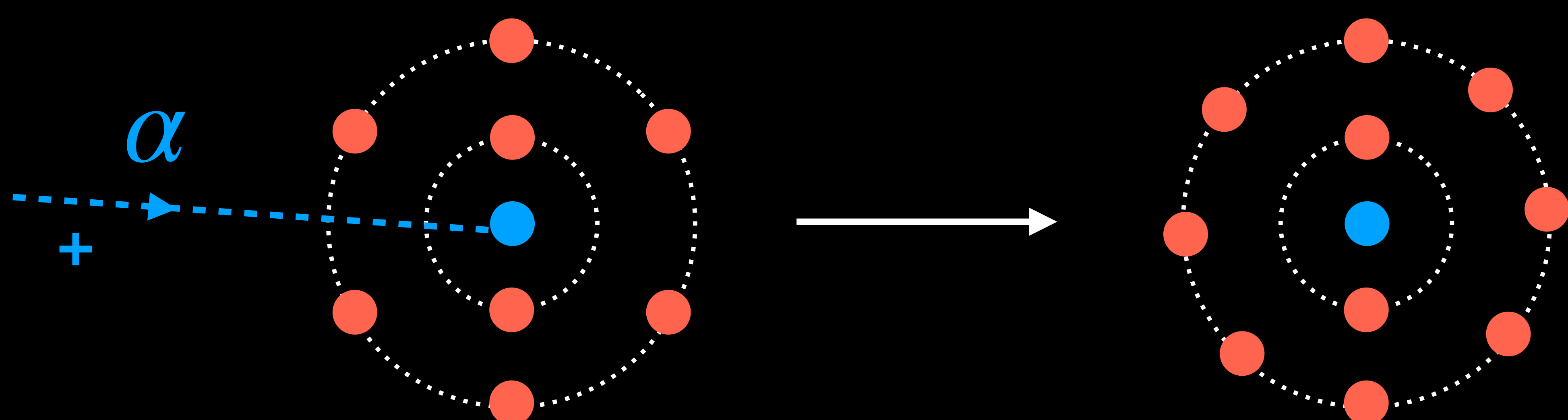


Fermi: High-intensity α-source,
but most α-particles do not reach the nucleus!

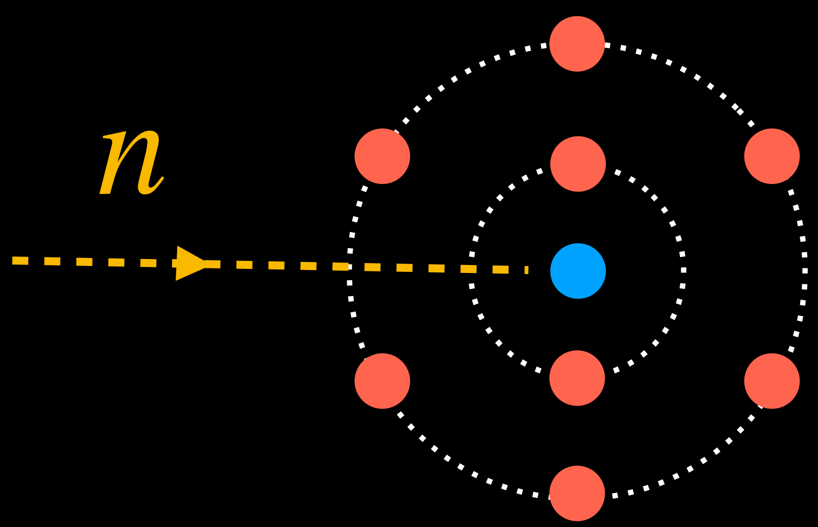
Aluminium atom

Phosphorus atom



What about neutrons?

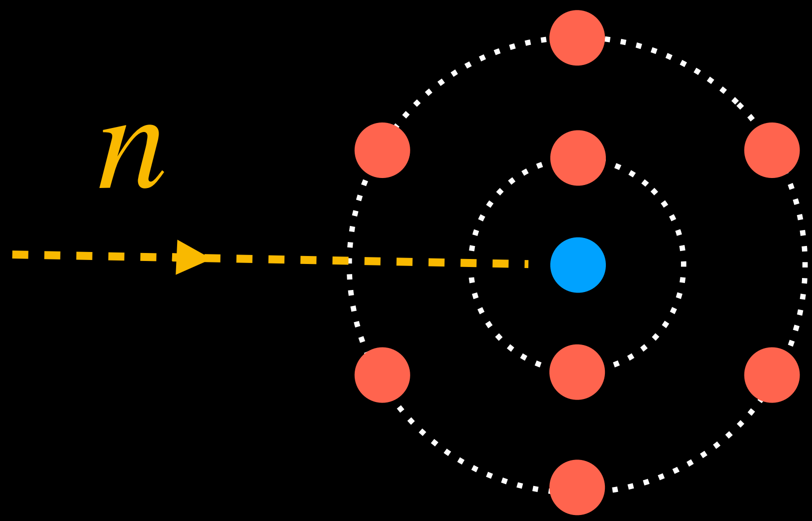
What about neutrons?



Fermi: Uncharged neutrons would not get deflected!

But: available neutron sources much weaker *(Chadwick and Rutherford also in the game!)*

What about neutrons?



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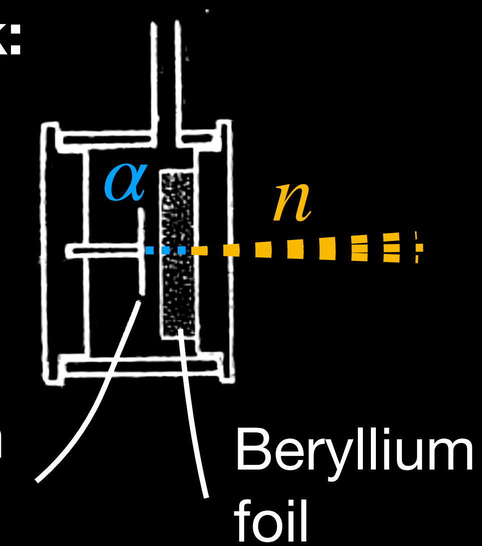
Chadwick:



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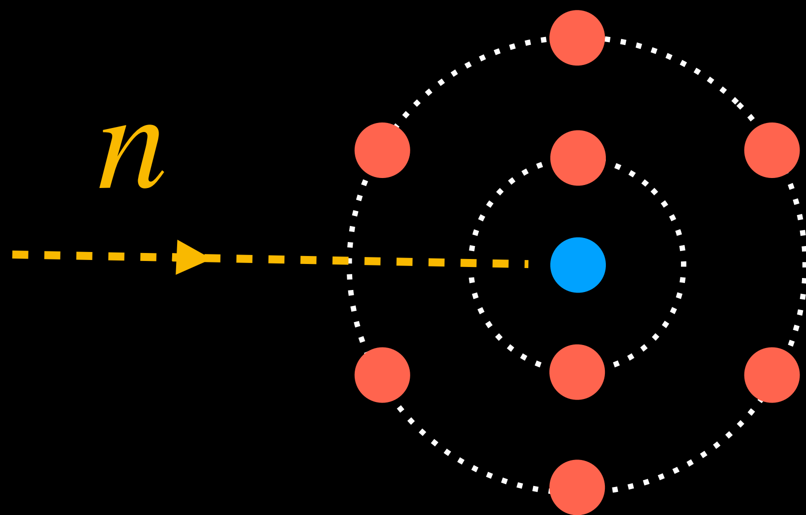


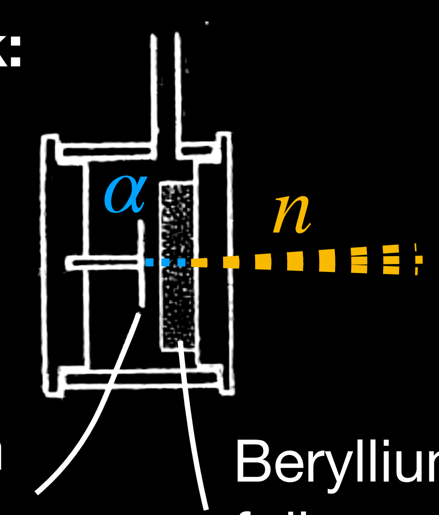
Fermi: Uncharged neutrons would not get deflected!

But: available neutron sources much weaker *(Chadwick and Rutherford also in the game!)*

Radium
(α-source)

(Institute of Public Health, Via Panisperna basement)

Chadwick:



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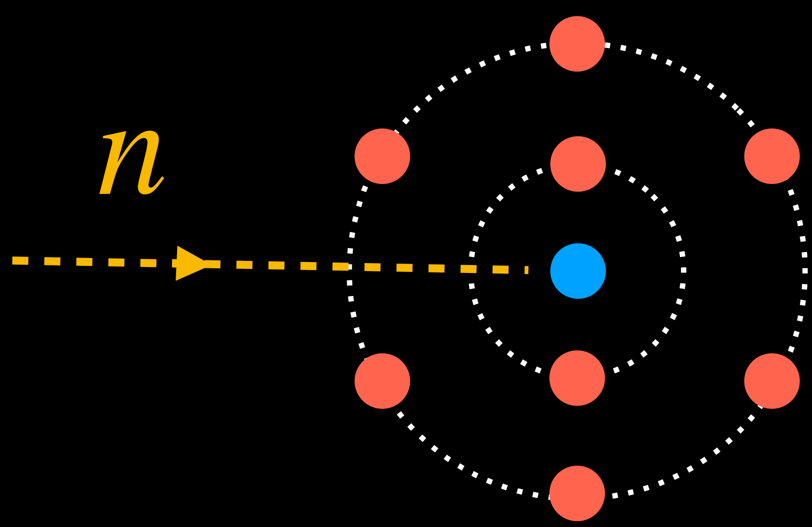

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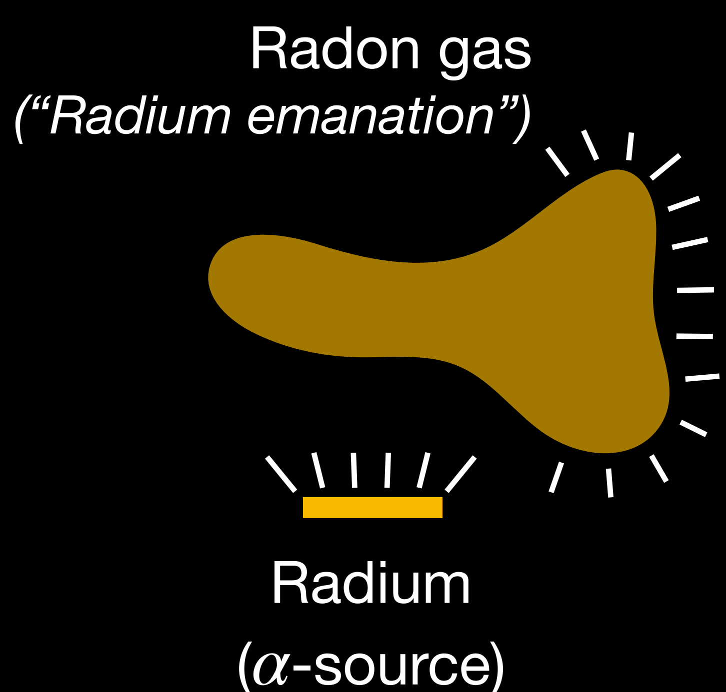
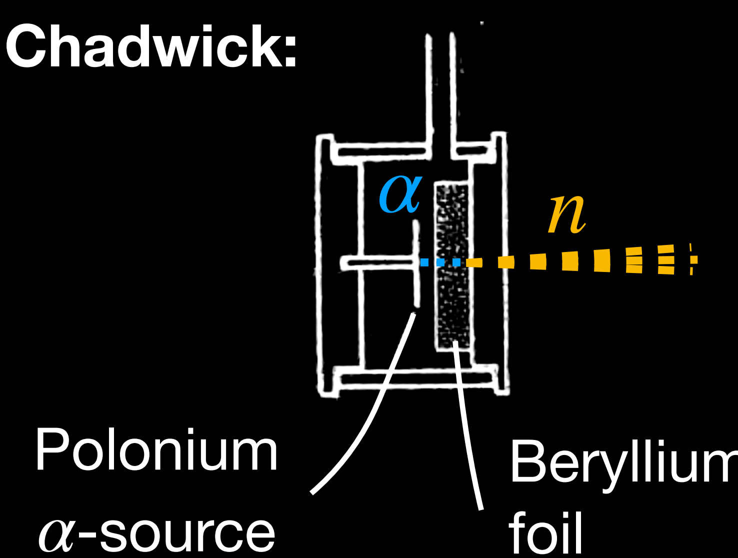


(Institute of Public Health, Via Panisperna basement)

Chadwick:



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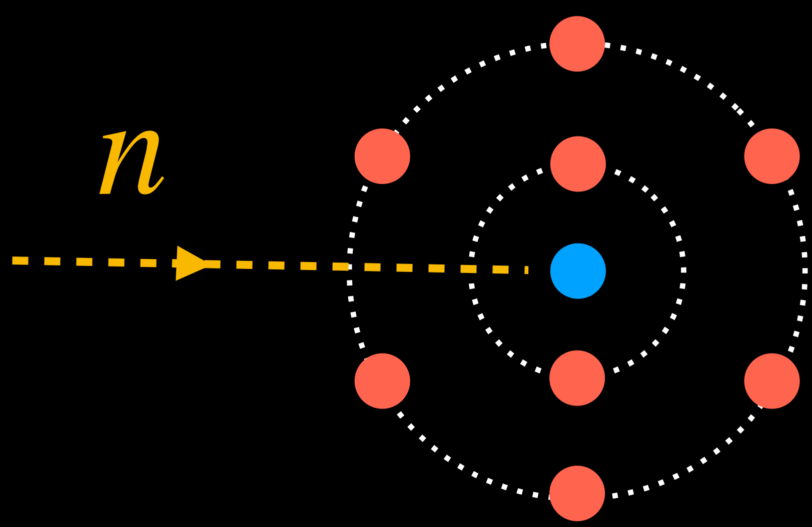

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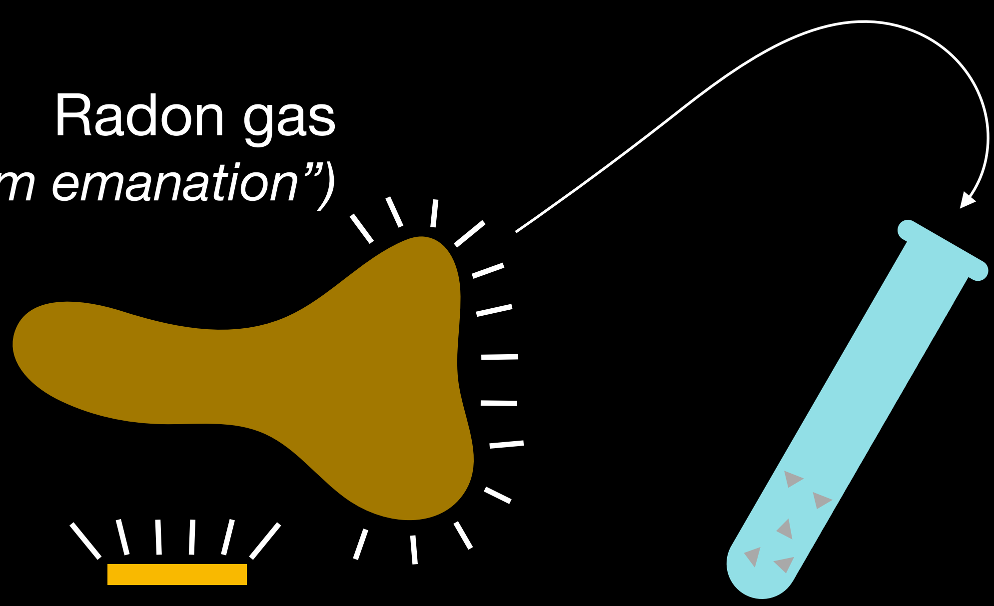
Radon gas
("Radium emanation")

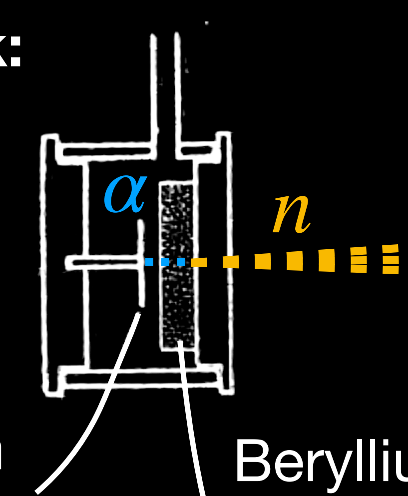


Radium
(α-source)

Beryllium powder

(Institute of Public Health, Via Panisperna basement)

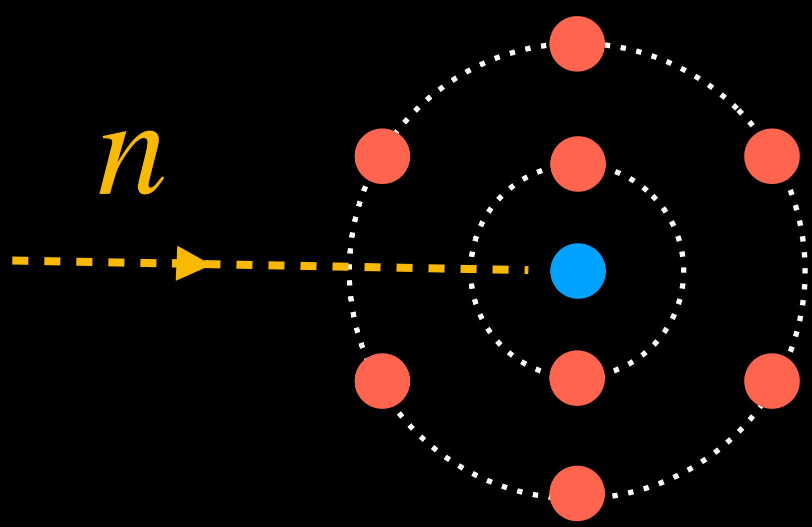
Chadwick:



Polonium
α-source

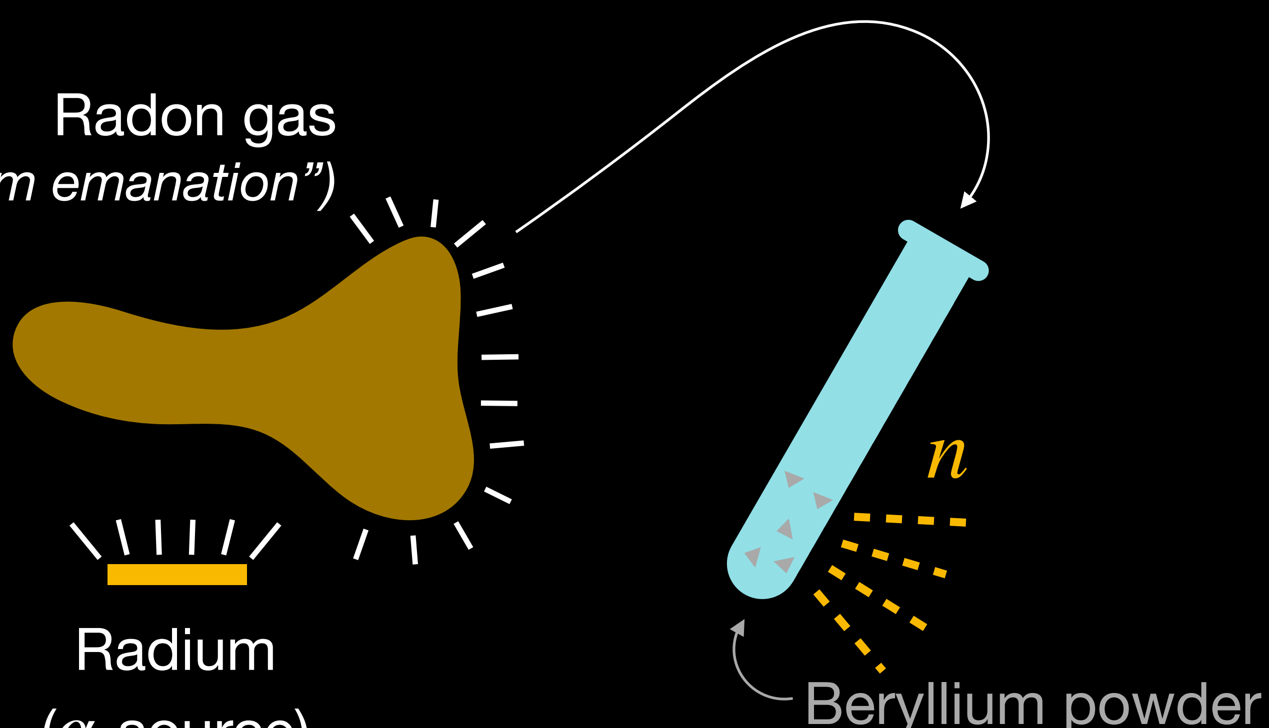
Beryllium
foil

What about neutrons?



Fermi: Uncharged neutrons would not get deflected!

But: available neutron sources much weaker *(Chadwick and Rutherford also in the game!)*



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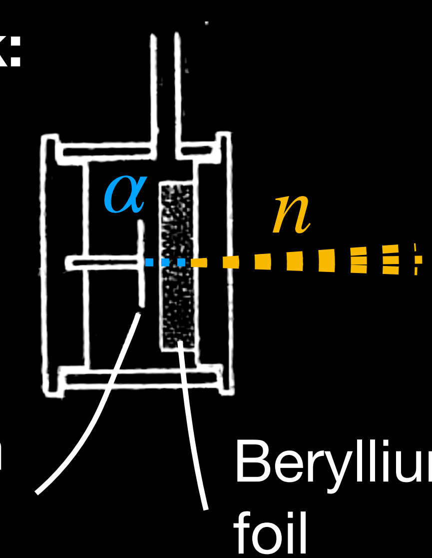

Neutron-induced radioactivity

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So far, we have obtained an effect with the following elements :

Phosphorus—Strong effect. Half-period about 3 hours. The disintegration electrons could be photographed in the Wilson chamber. Chemical separation of the active product showed that the unstable element formed under the bombardment is probably silicon.

Iron—Period about 2 hours. As the result of chemical separation of the active product, this is probably manganese.

Silicon—Very strong effect. Period about 3 minutes. Electrons photographed in the Wilson chamber.

Aluminium—Strong effect. Period about 12 minutes. Electrons photographed in the Wilson chamber.

Chlorine—Gives an effect with a period much longer than that of any element investigated at present.

Vanadium—Period about 5 minutes.

Copper—Effect rather small. Period about 6 minutes.

Arsenic—Period about two days.

Silver—Strong effect. Period about 2 minutes.

Tellurium. Period about 1 hour.

Iodine—Intense effect. Period about 30 minutes.

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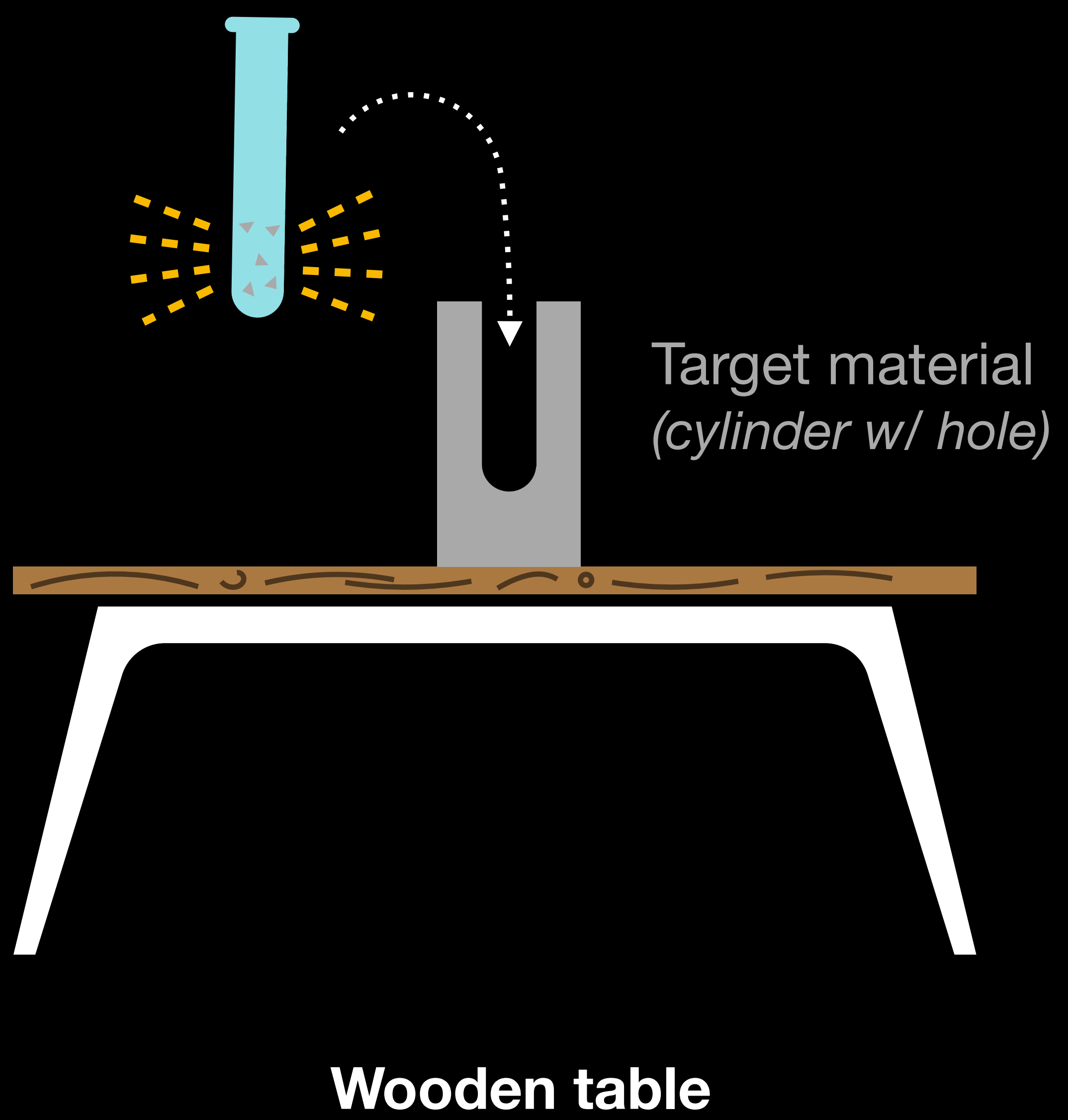

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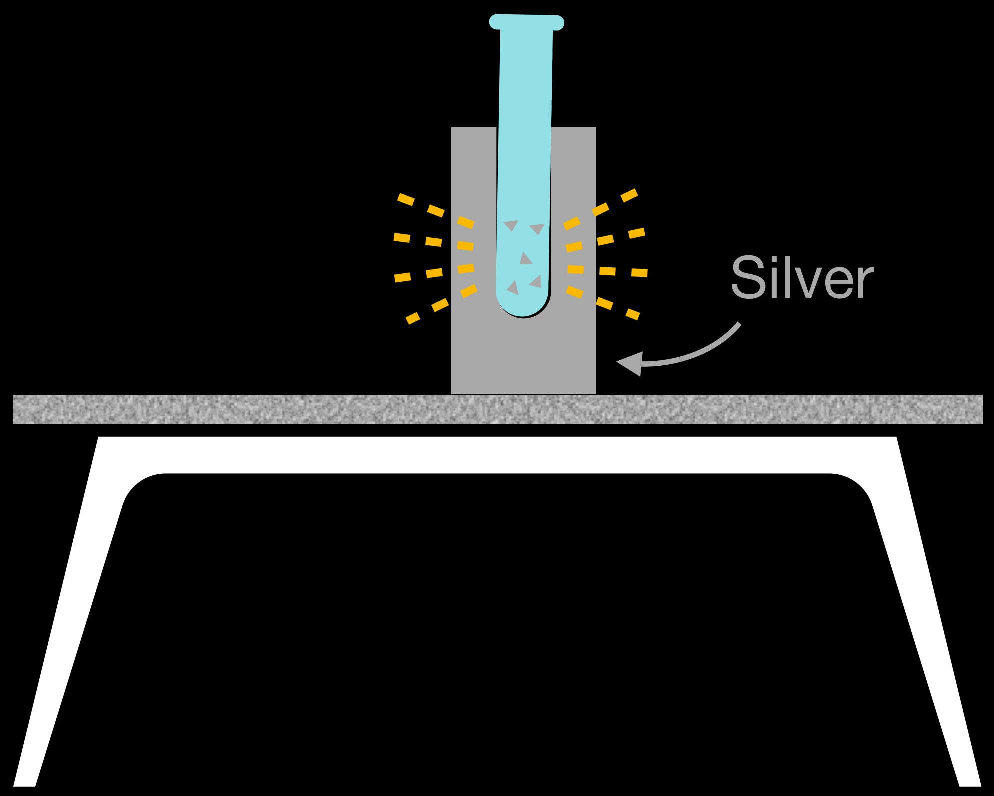
Much stronger effect for wood!

Fermi’s discovery

“We were working very hard in the neutron-induced radioactivity and the results we were obtaining made no sense.”



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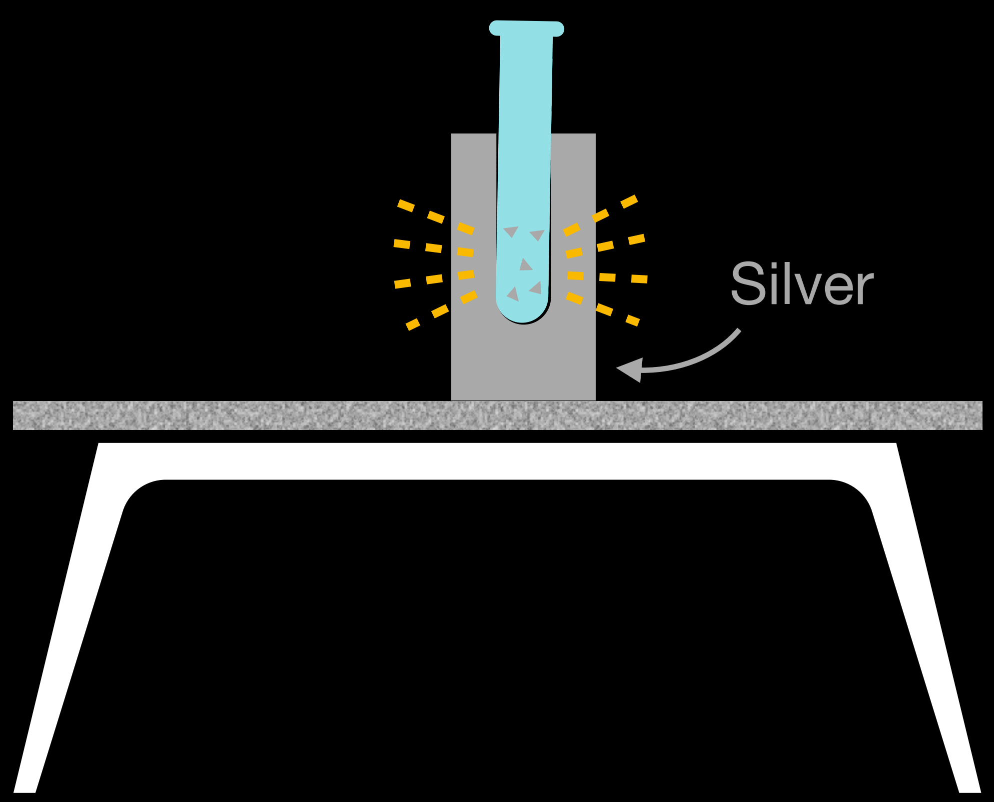
"We were working very hard in the neutron-induced radioactivity and the results we were obtaining made no sense."

"One day, as I came to the laboratory, it occurred to me that I should examine the effect of placing a piece of lead before the incident neutrons."



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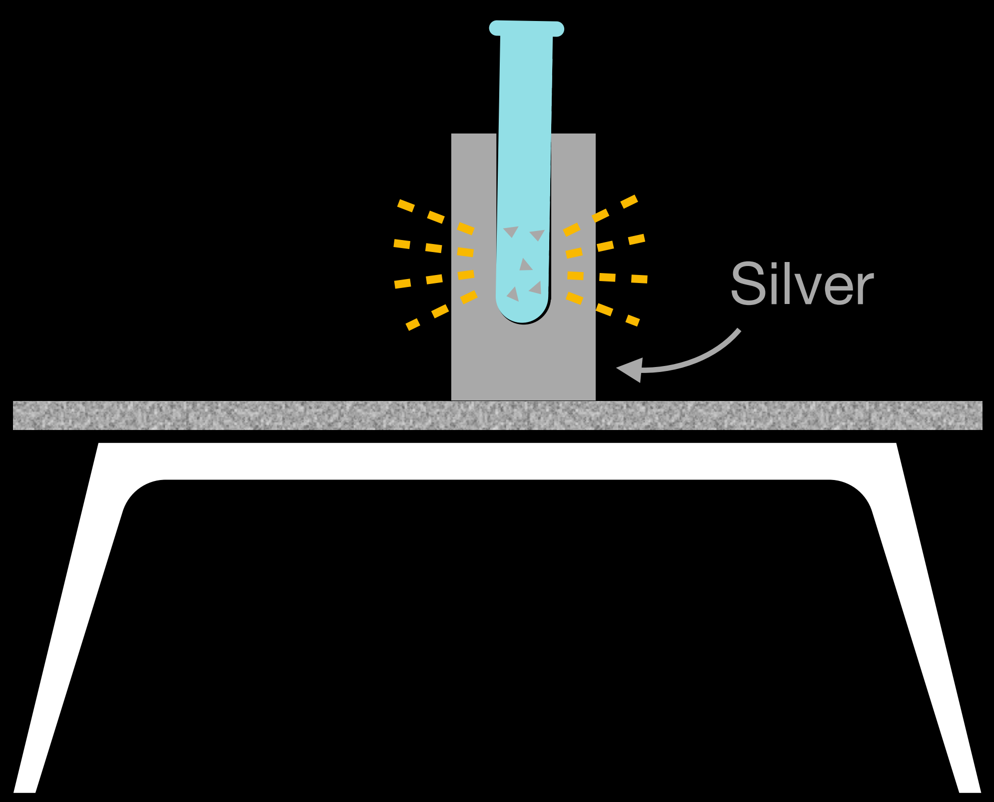

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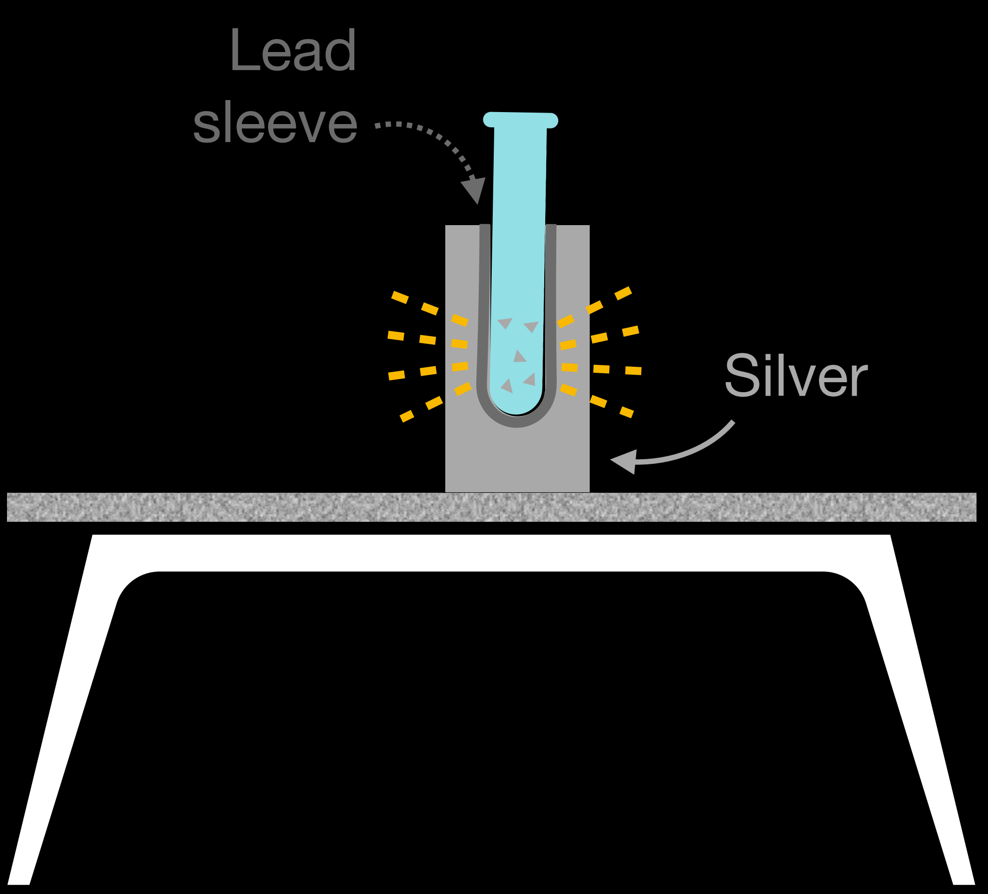

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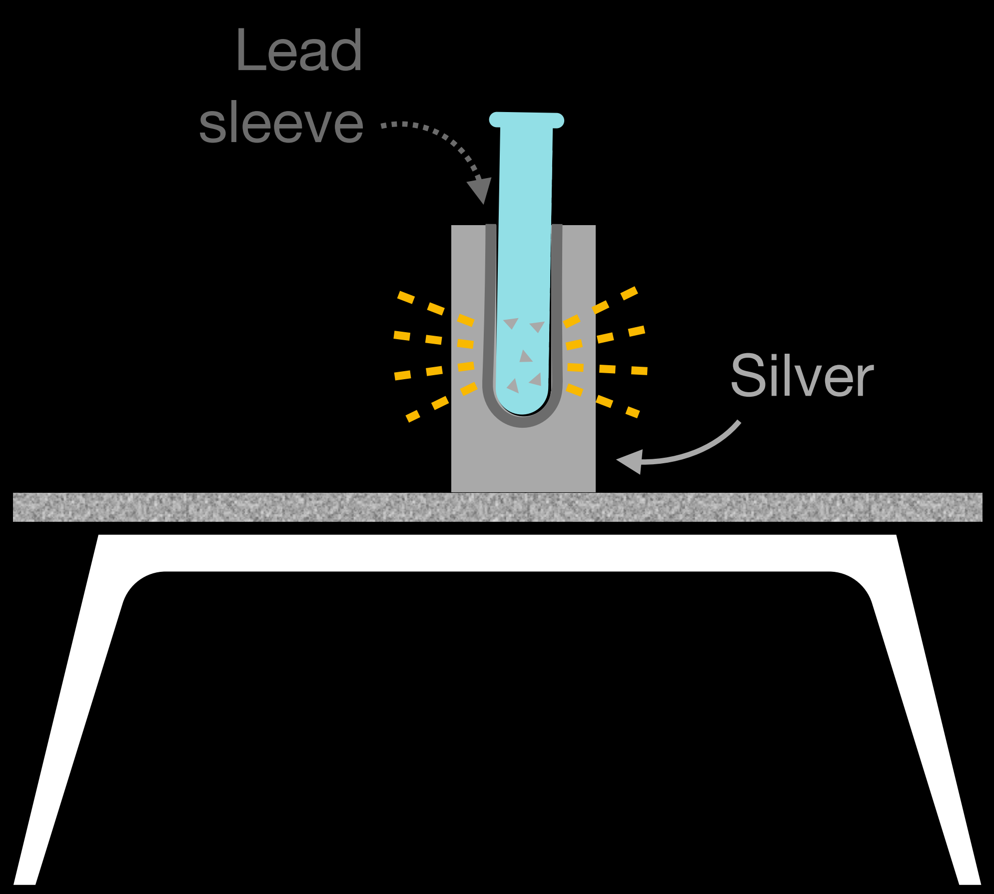

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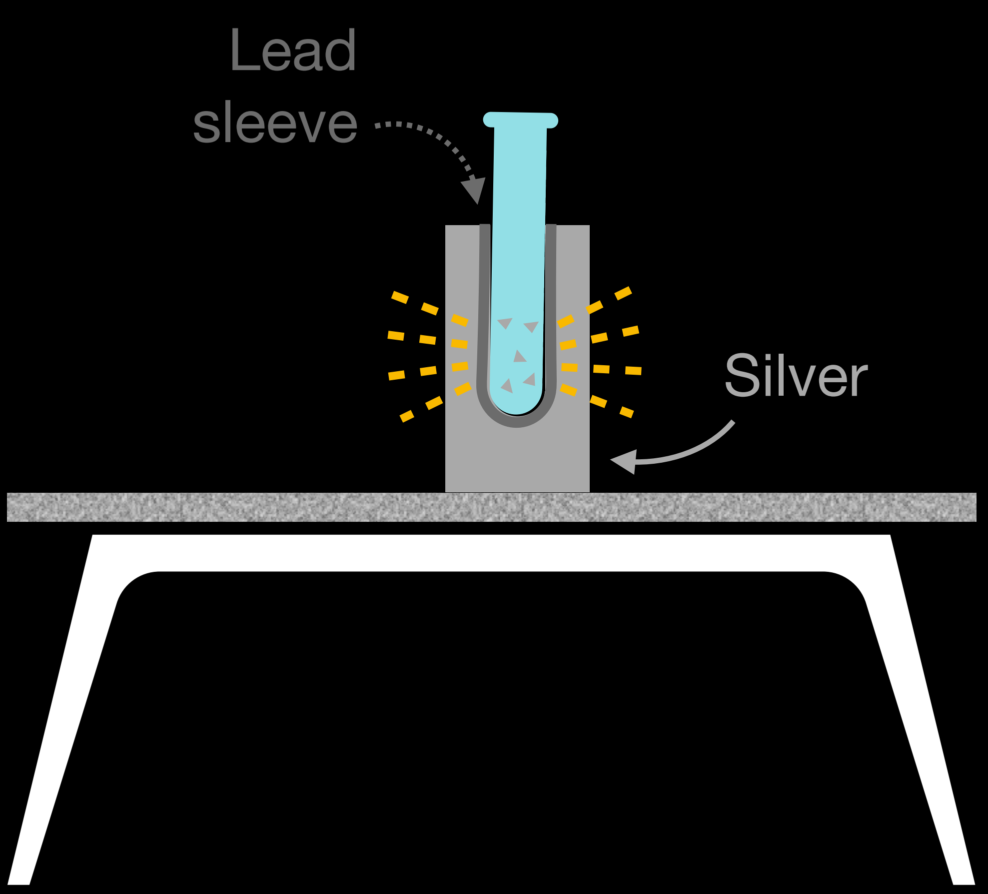

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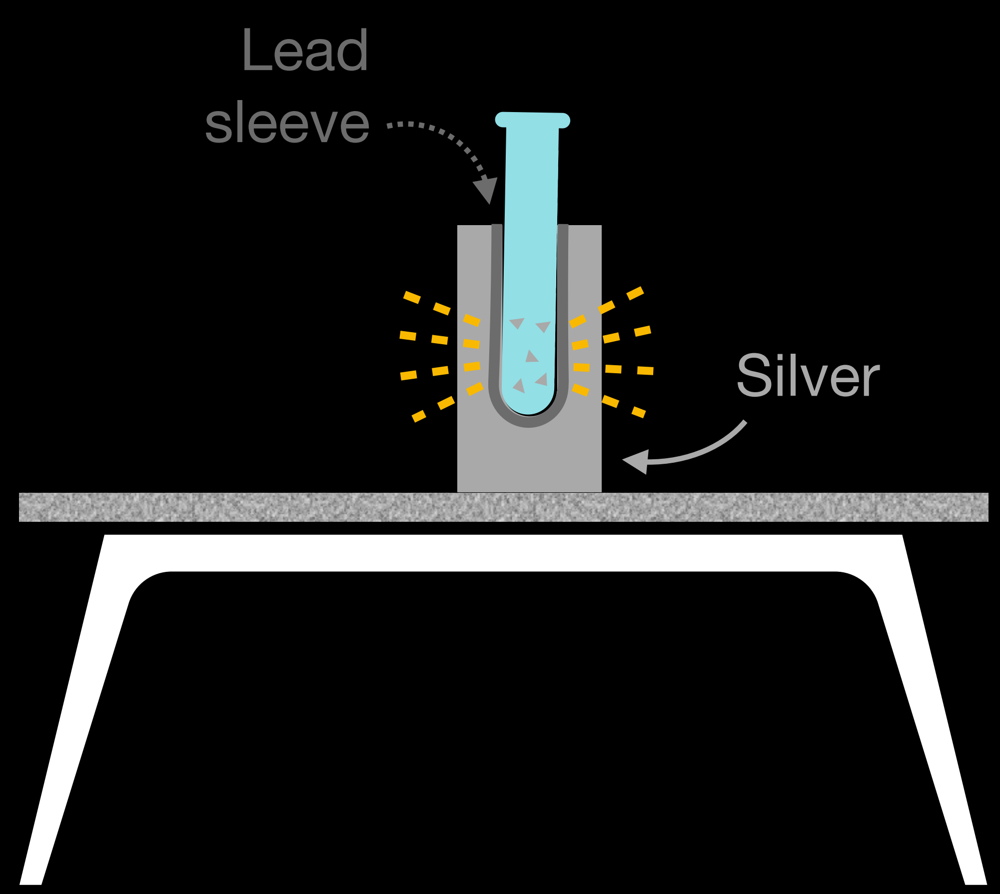

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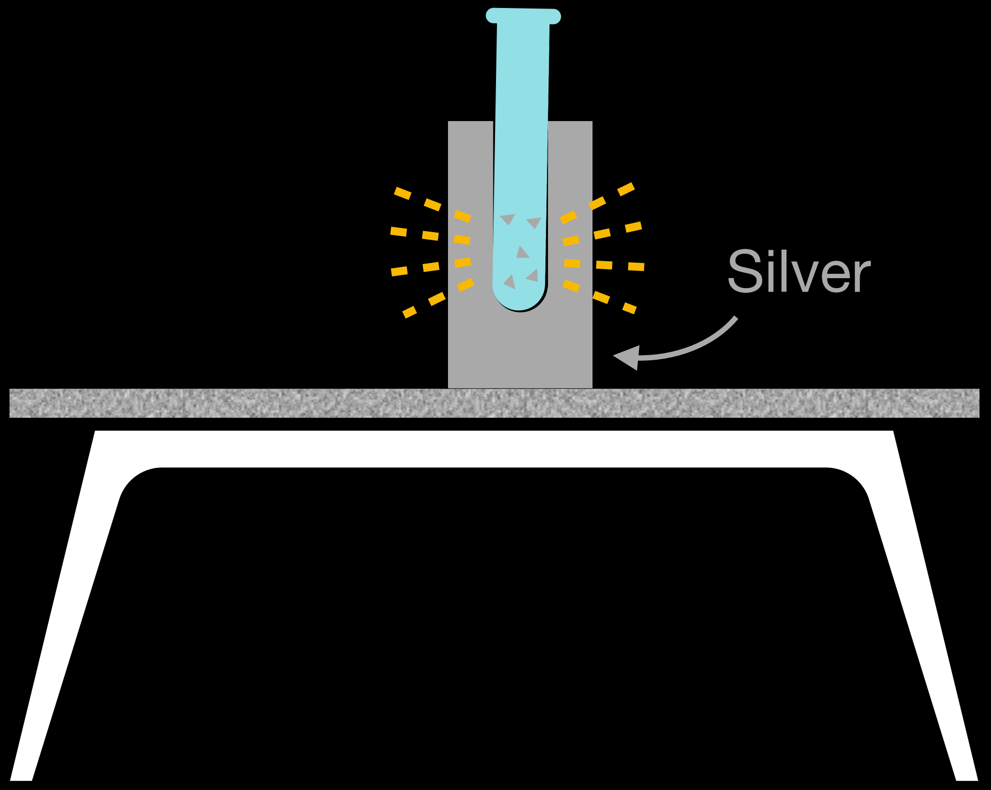

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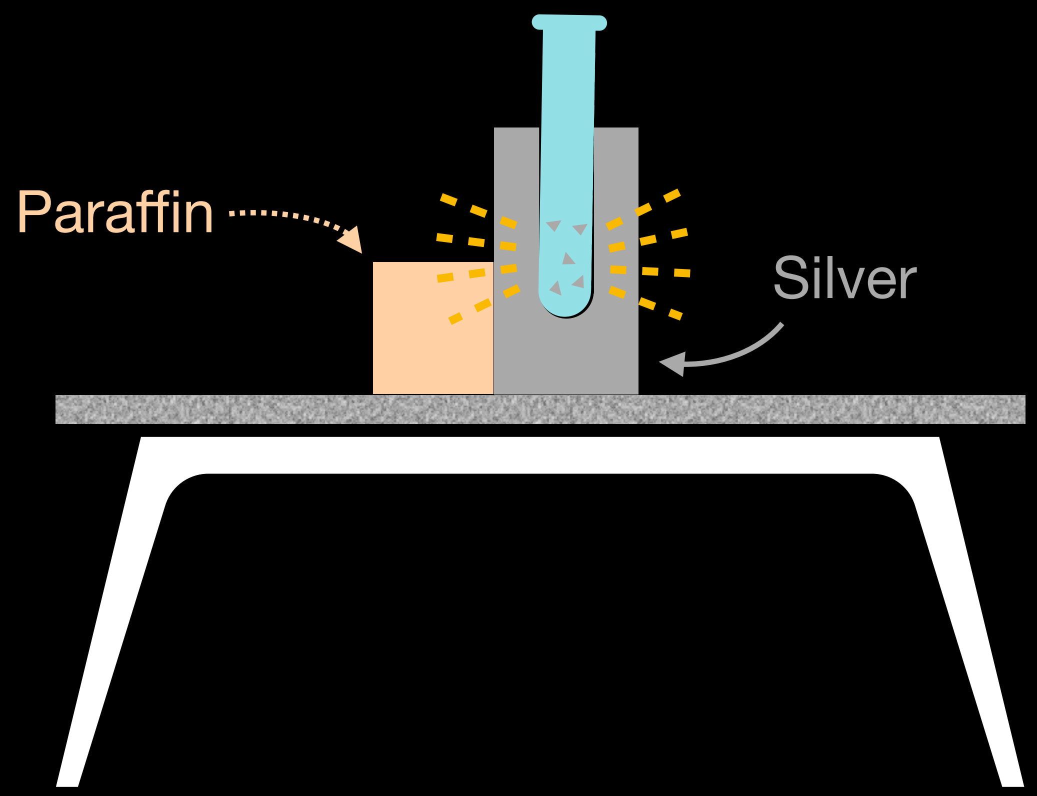

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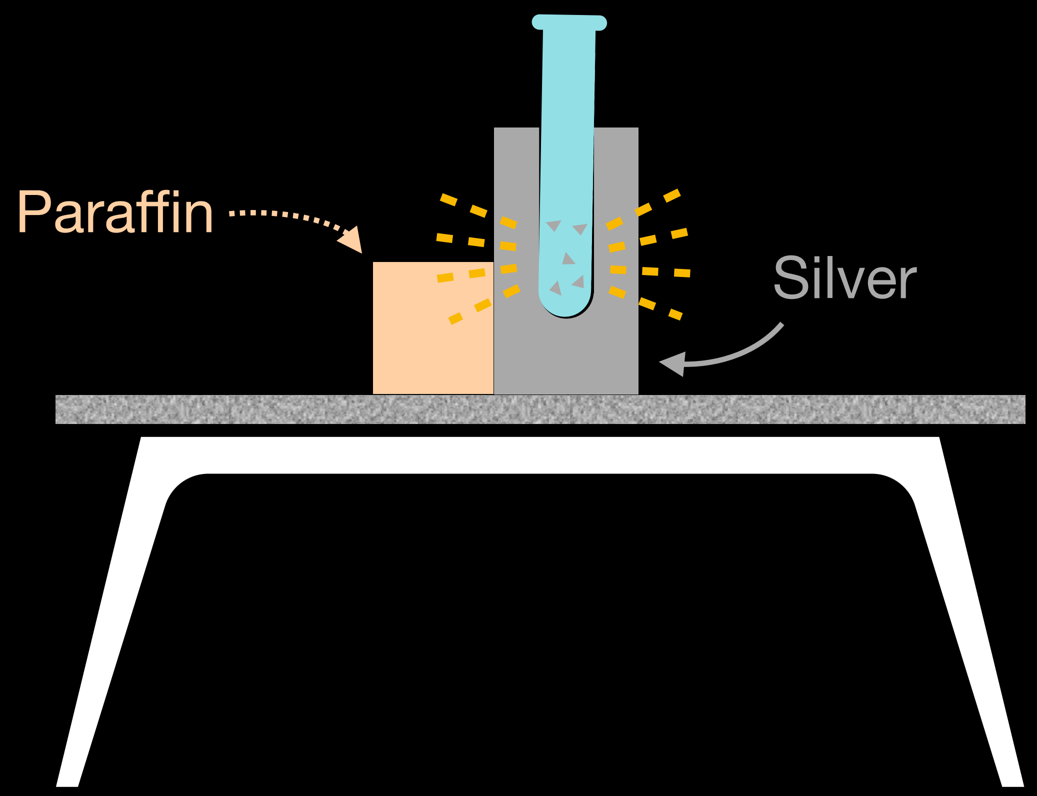
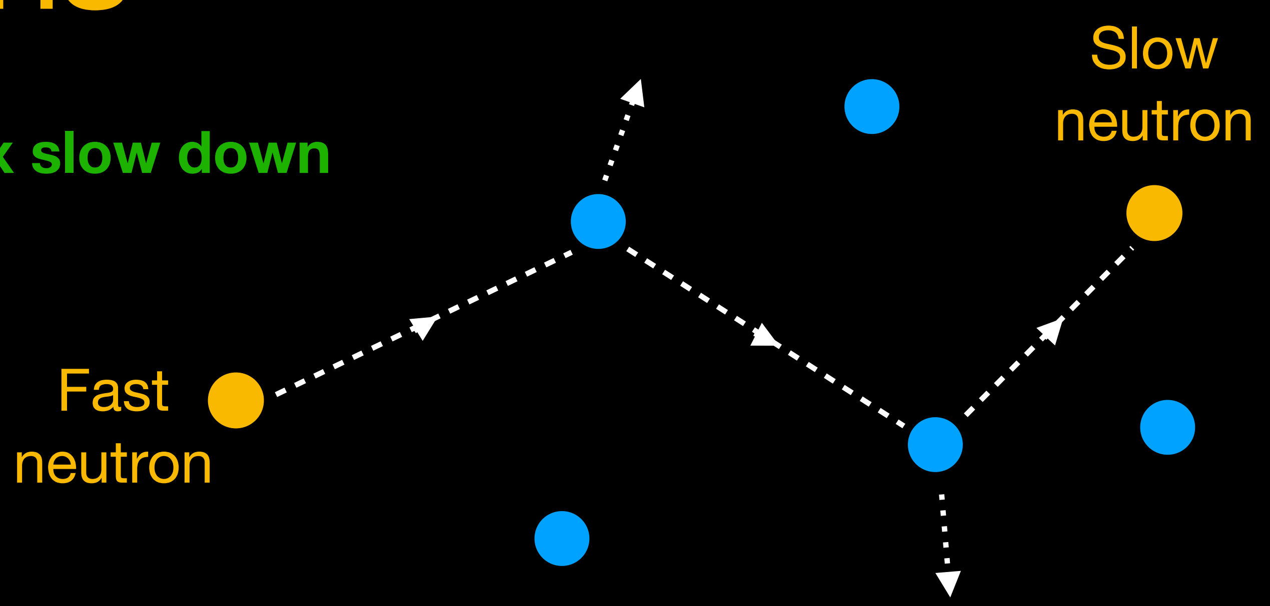
The activation became a lot stronger!



Slowing down neutrons

Collisions with hydrogen atoms in paraffin wax slow down (initially fast) neutrons



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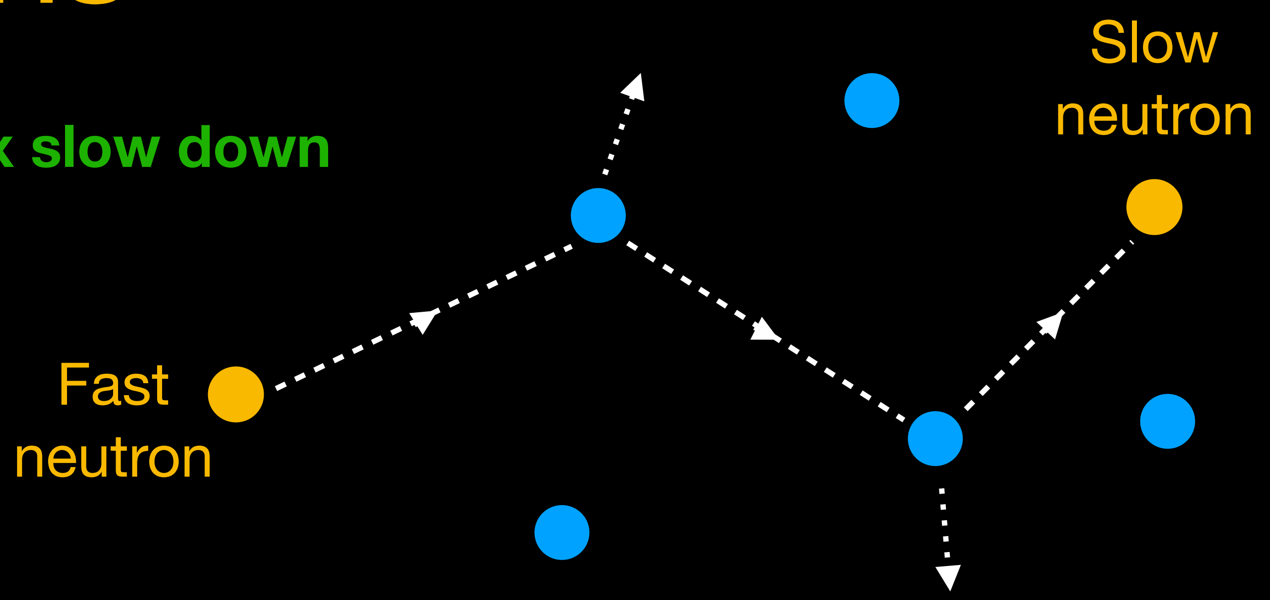

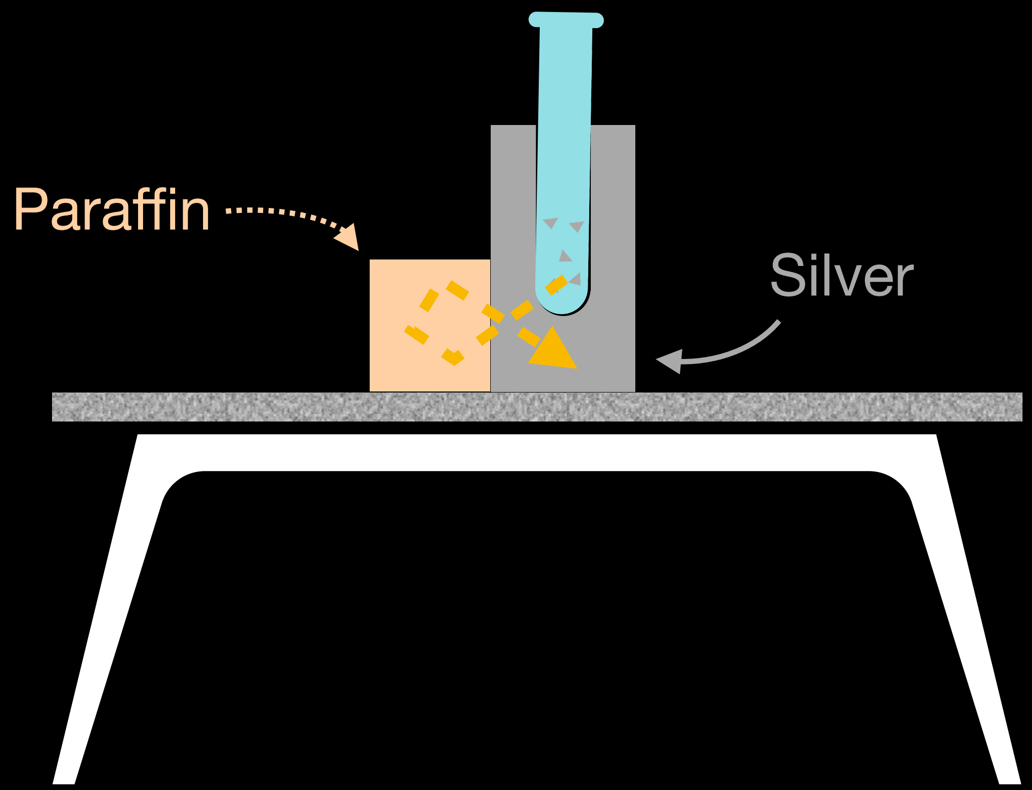

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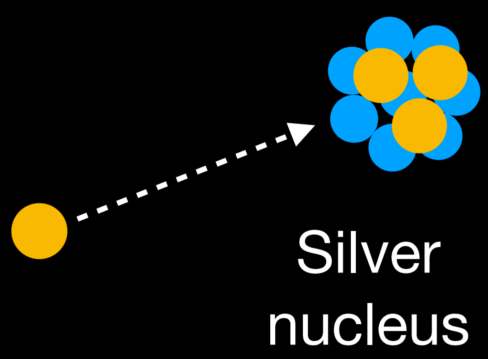
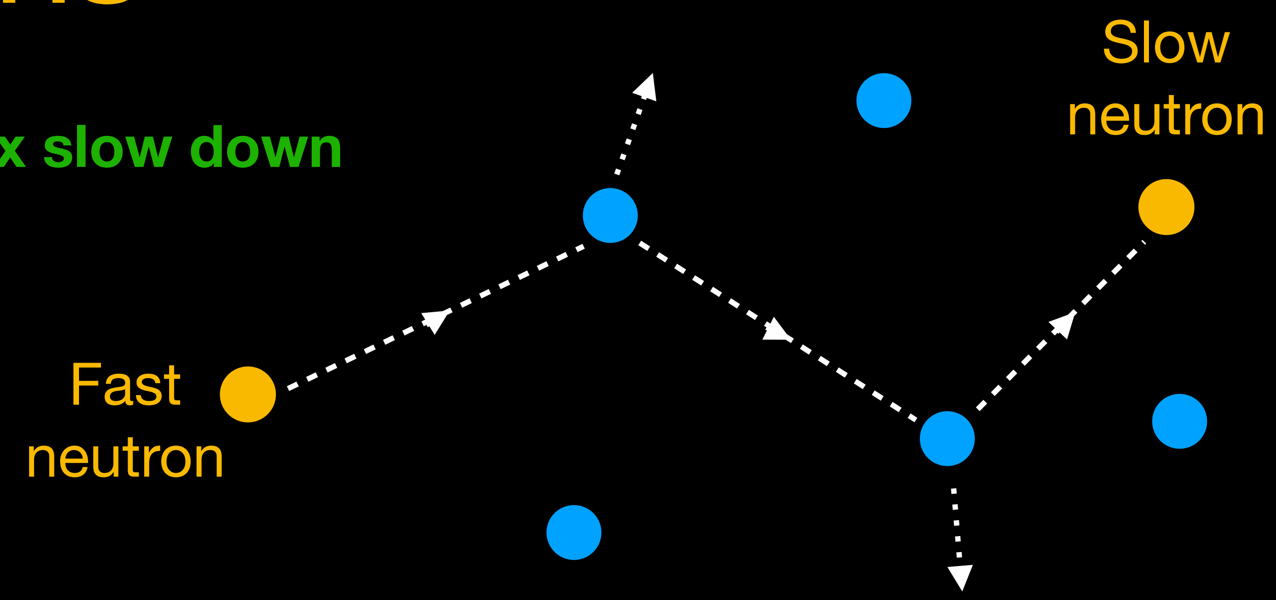
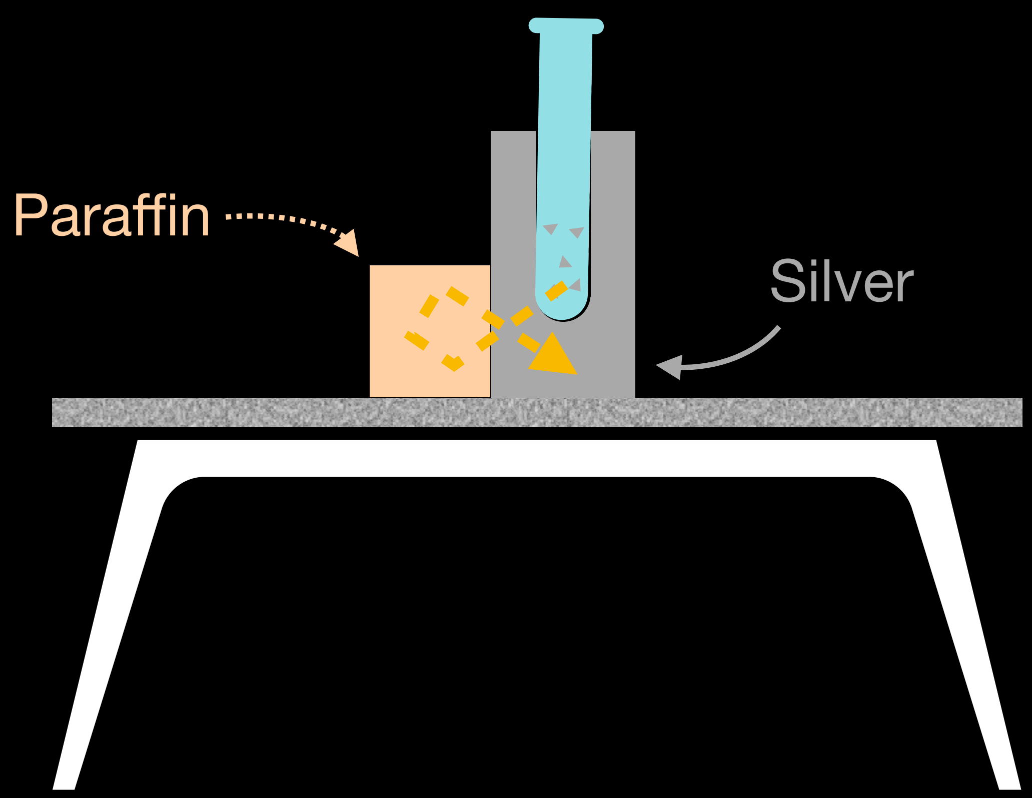




Slow neutrons more easily enter the target nucleus



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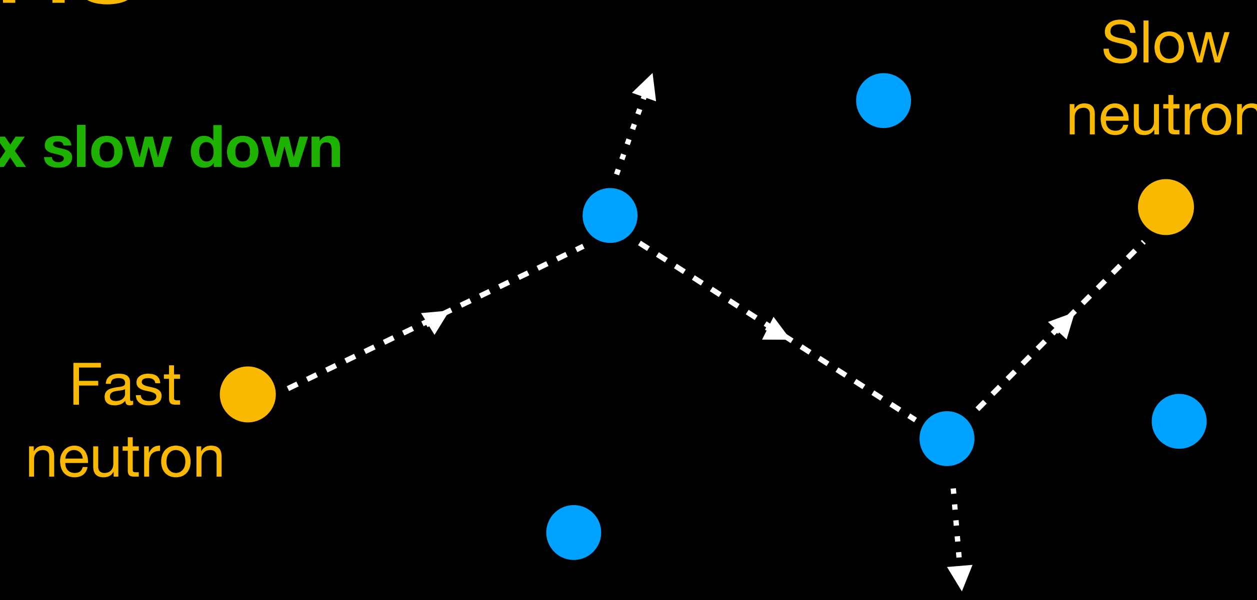

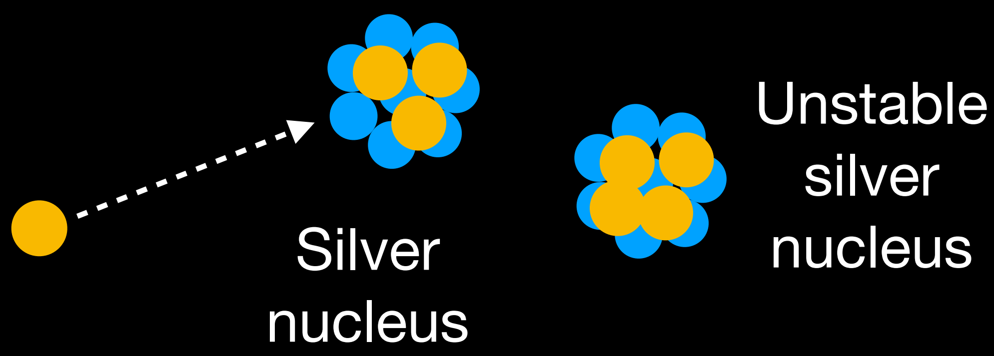

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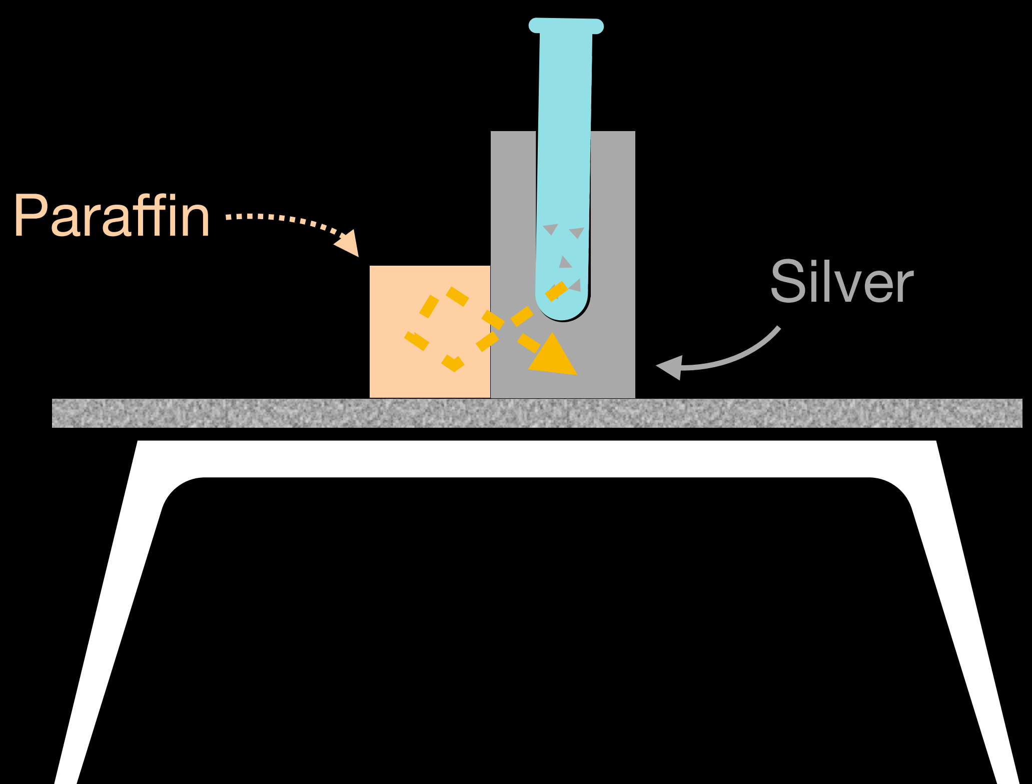

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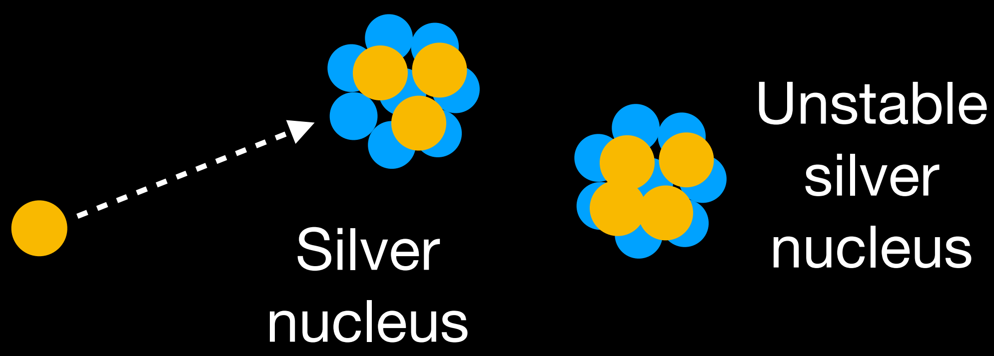

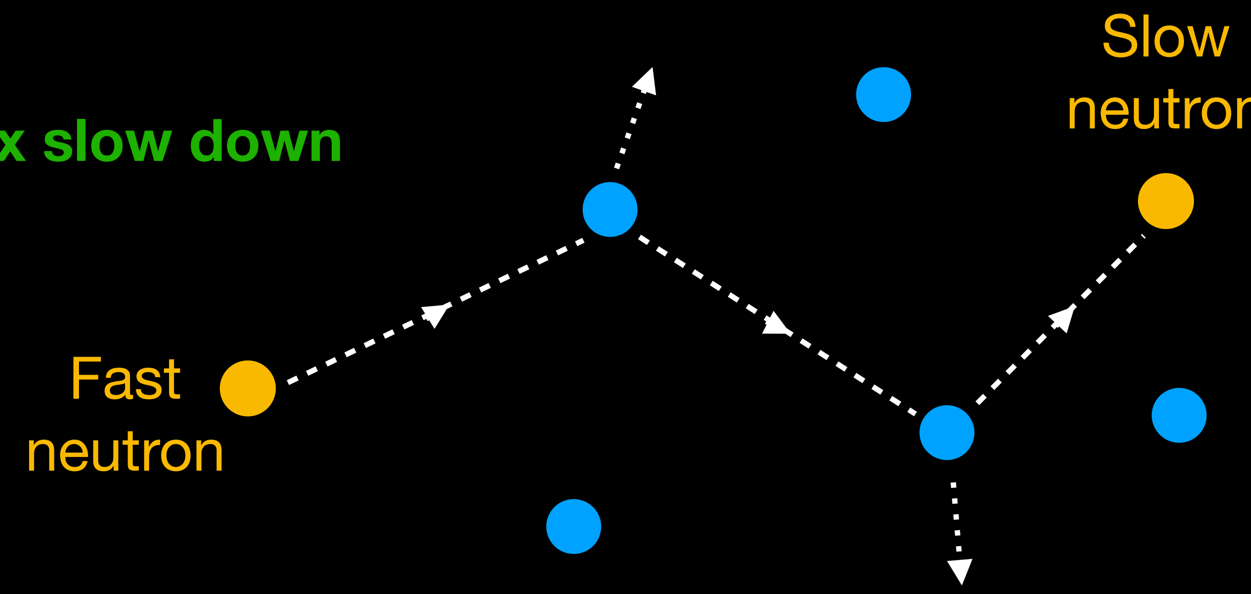

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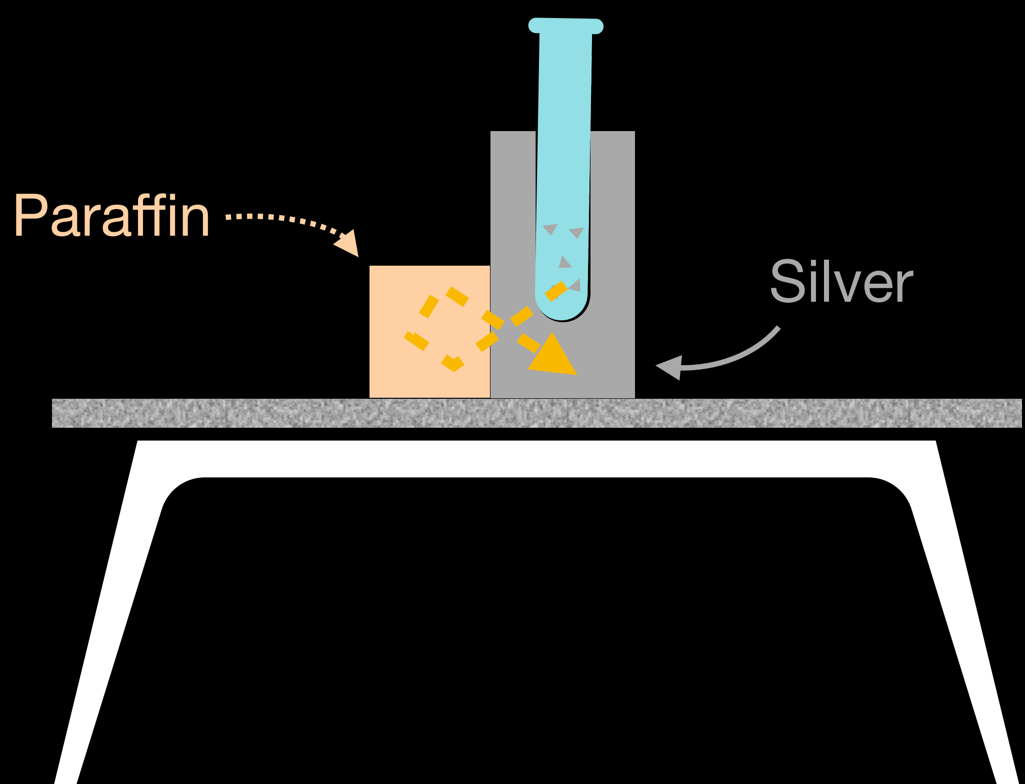
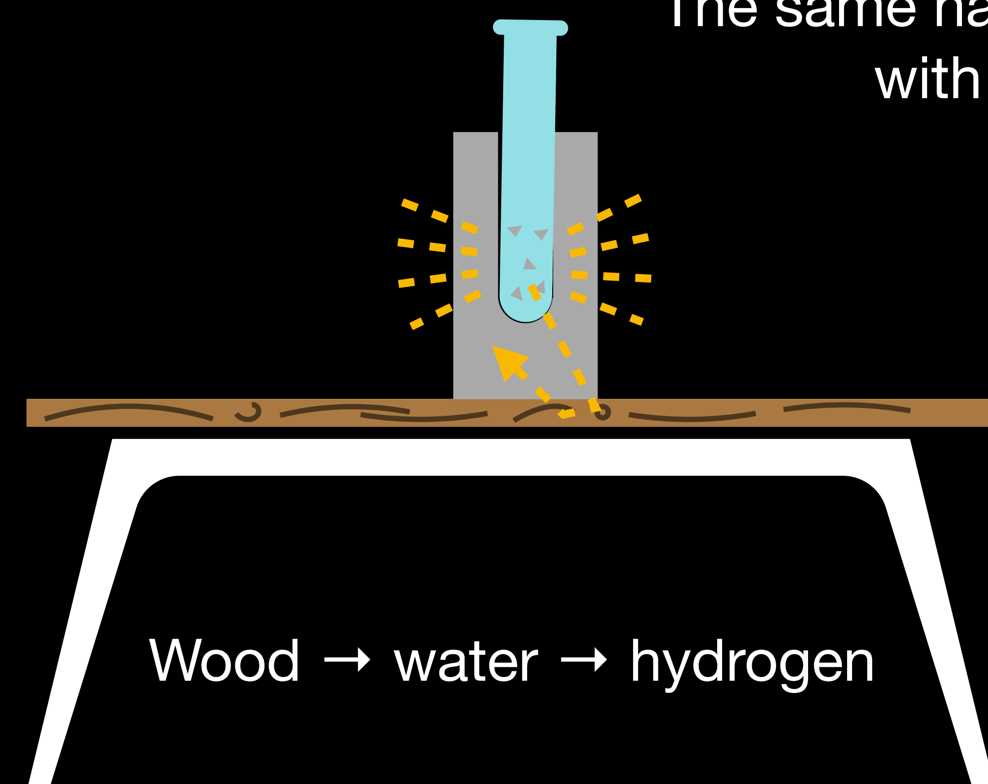


The same happens with wood!



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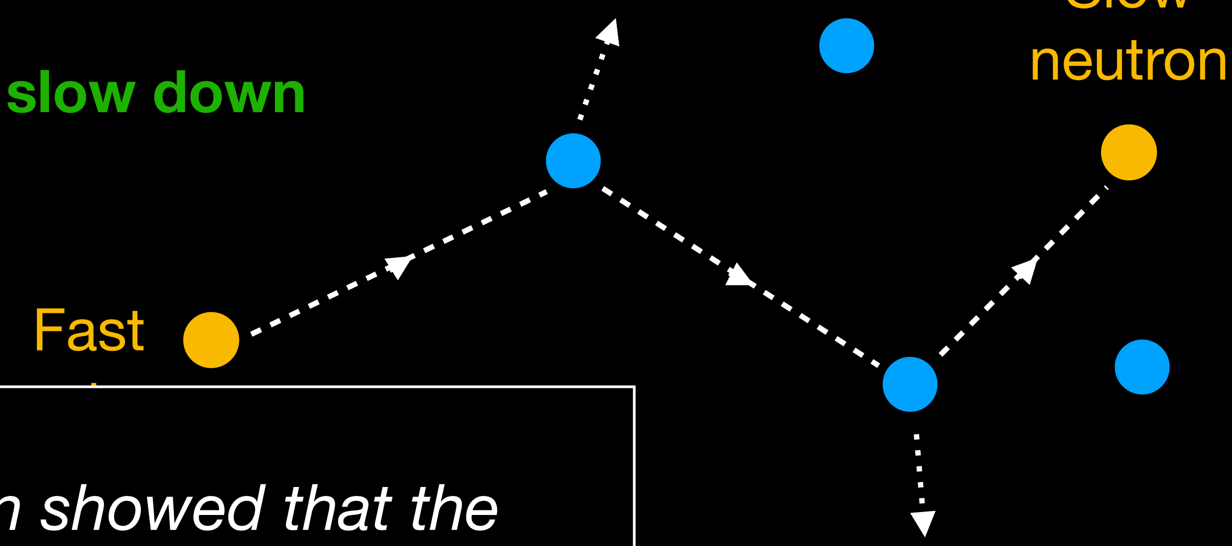
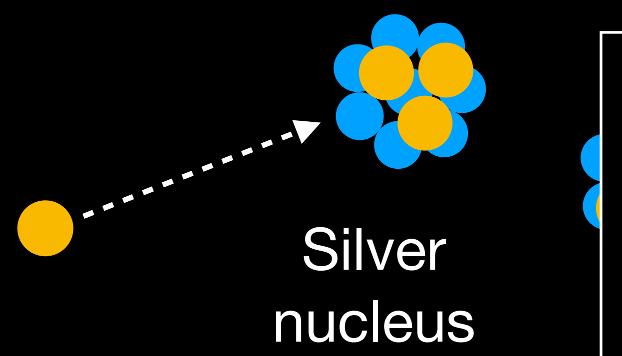
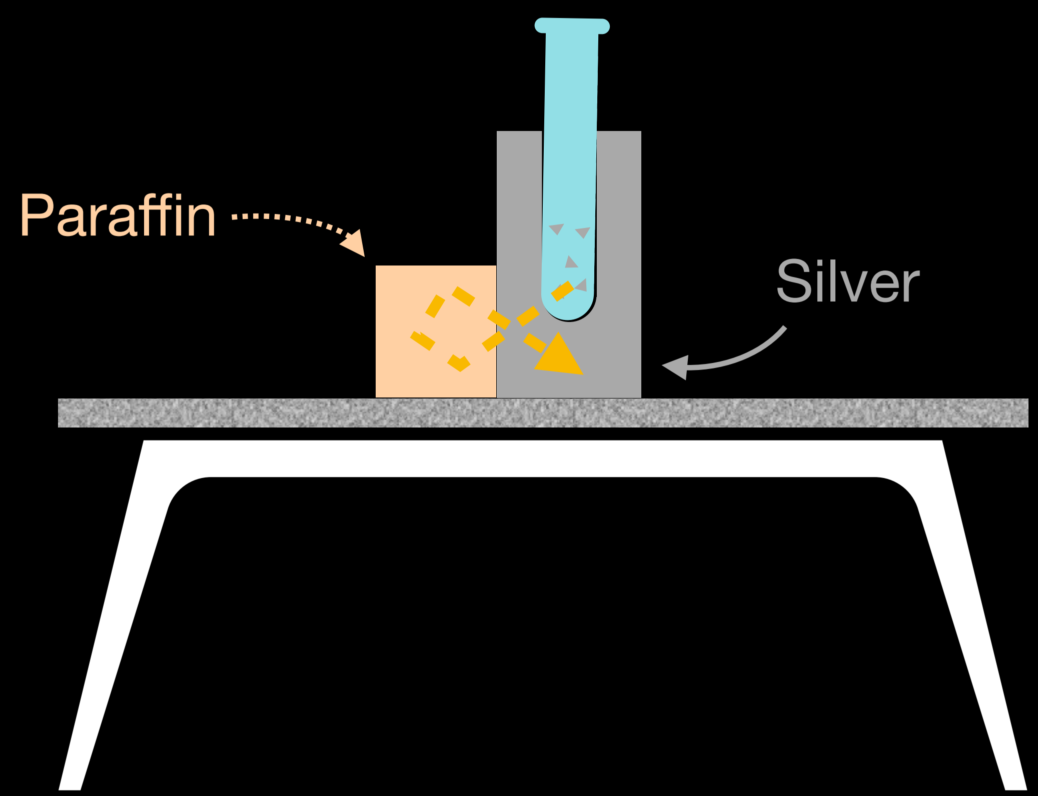




"Further investigation showed that the activation could be enormously increased by surrounding the source and the activated substance with a large amount of water or paraffin wax."

the target nucleus



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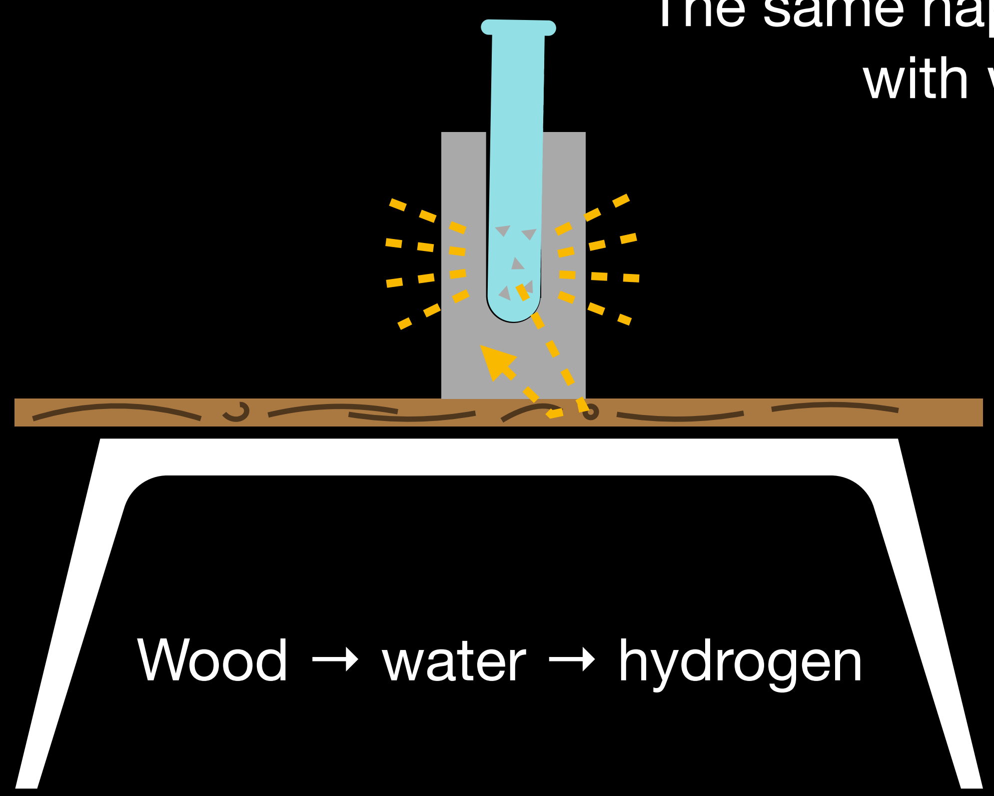

Patenting slow neutrons

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UNITED STATES PATENT OFFICE

2,206,634

PROCESS FOR THE PRODUCTION OF RADIOACTIVE SUBSTANCES

Enrico Fermi, Edoardo Amaldi, Bruno Pontecorvo, Franco Rasetti, and Emilio Segre, Rome, Italy, assignors to G. M. Giannini & Co., Inc., New York, N. Y., a corporation of New York

Application October 3, 1935, Serial No. 43,462
In Italy October 26, 1934

7 Claims. (Cl. 204—31)

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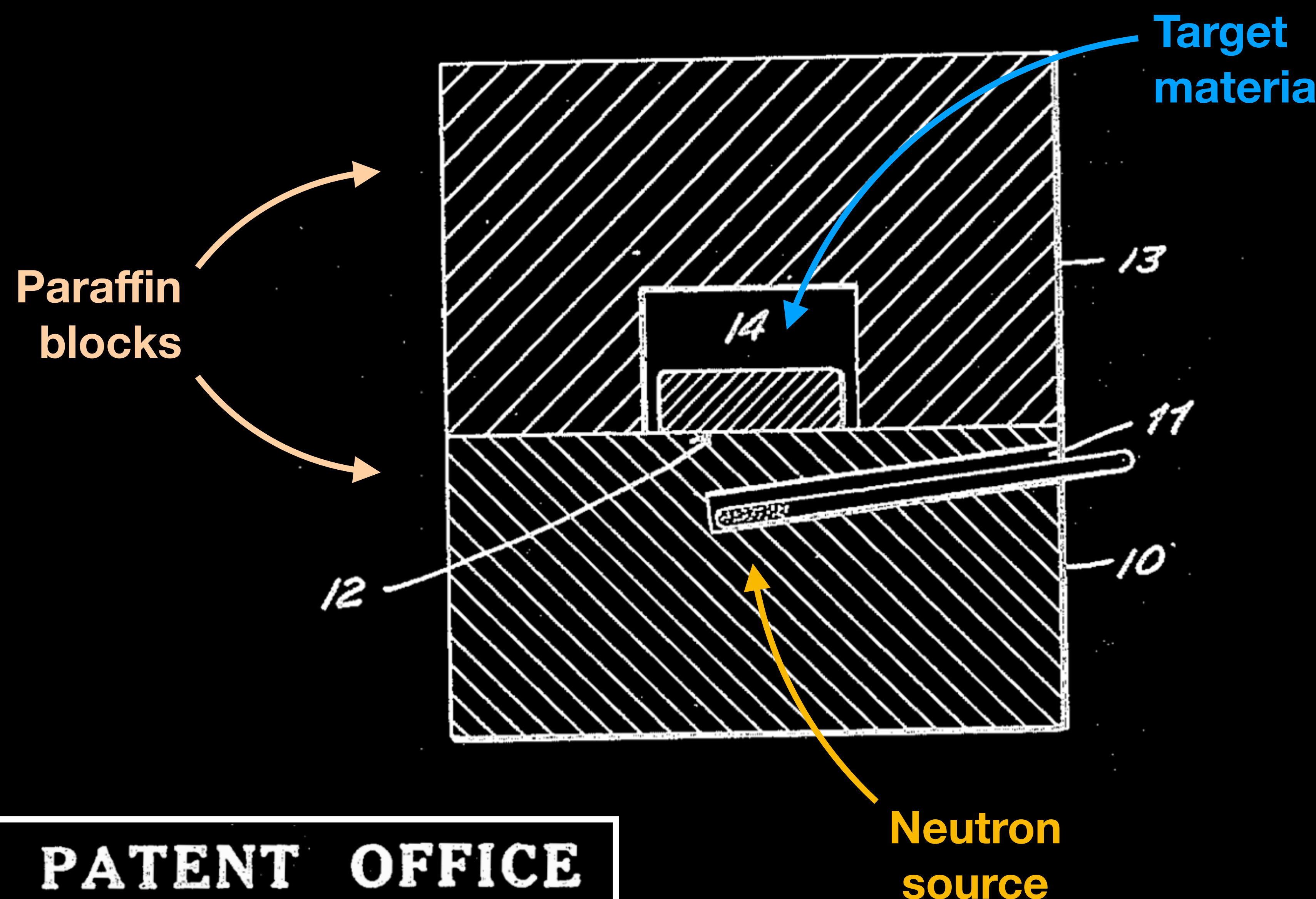

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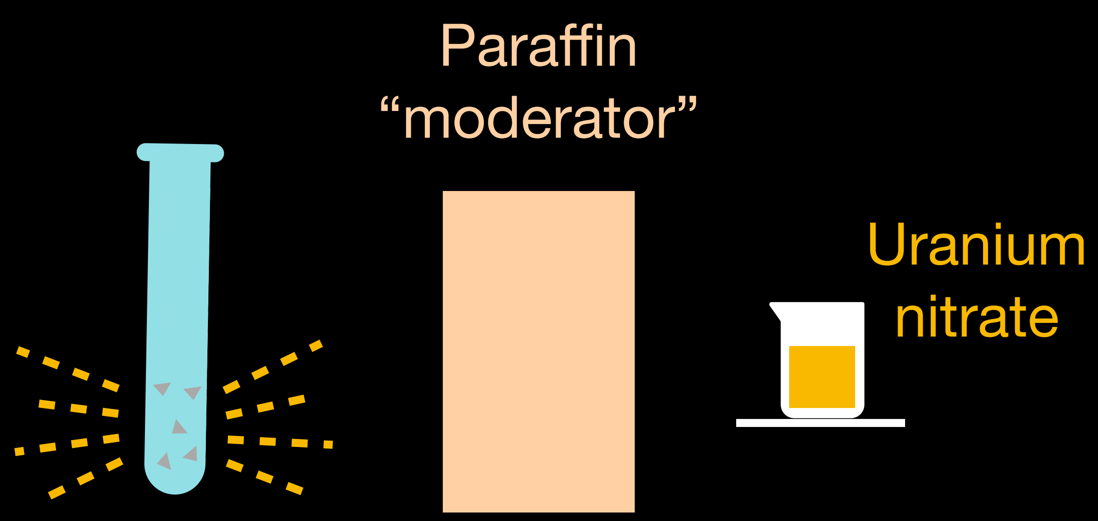
Fermi’s blunder

Exposing uranium to “thermal” neutrons



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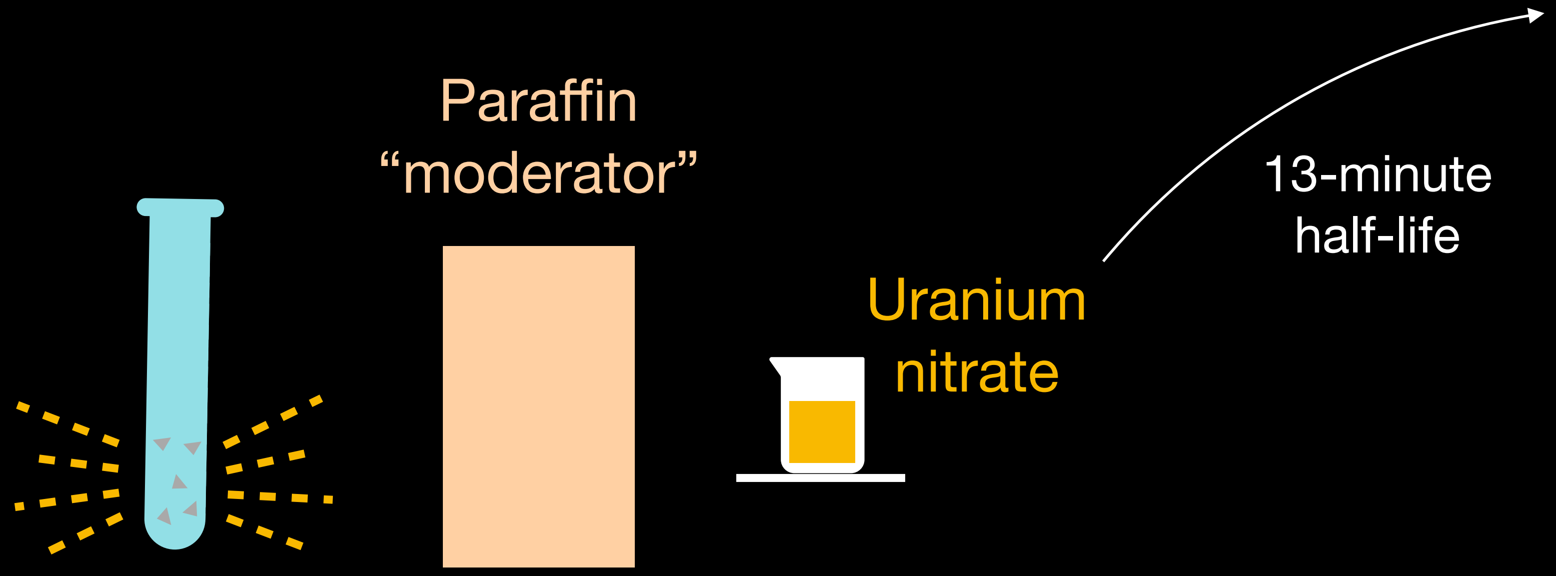

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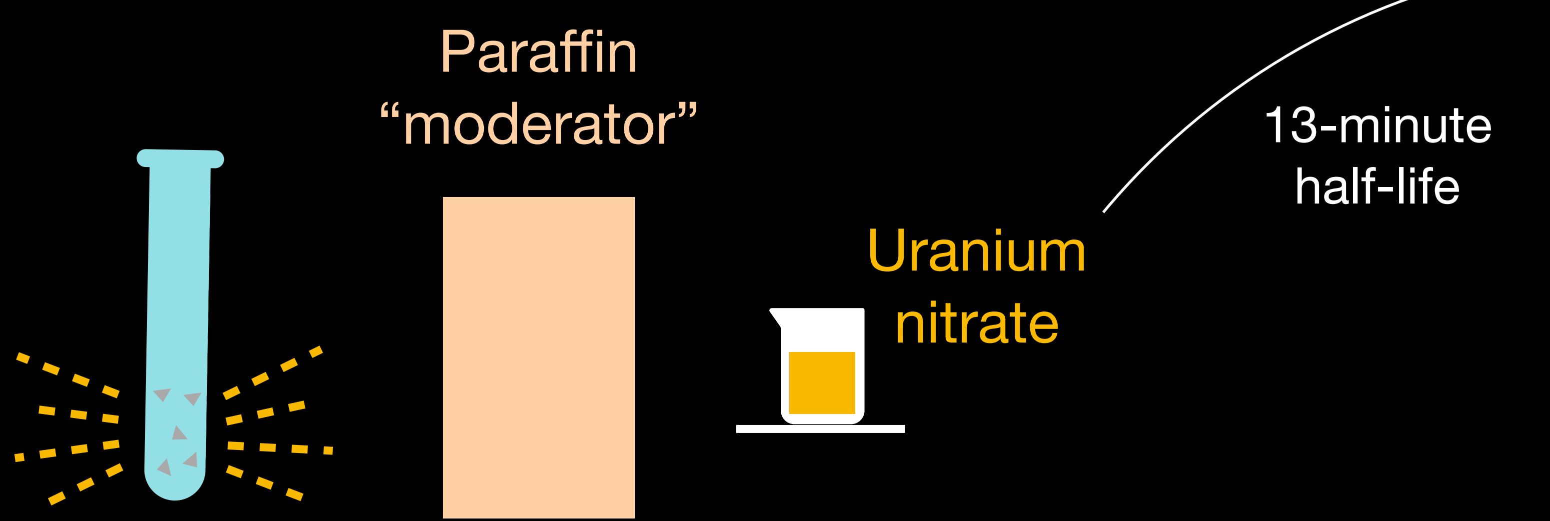

Chemical separation:

Uranium (92 protons)

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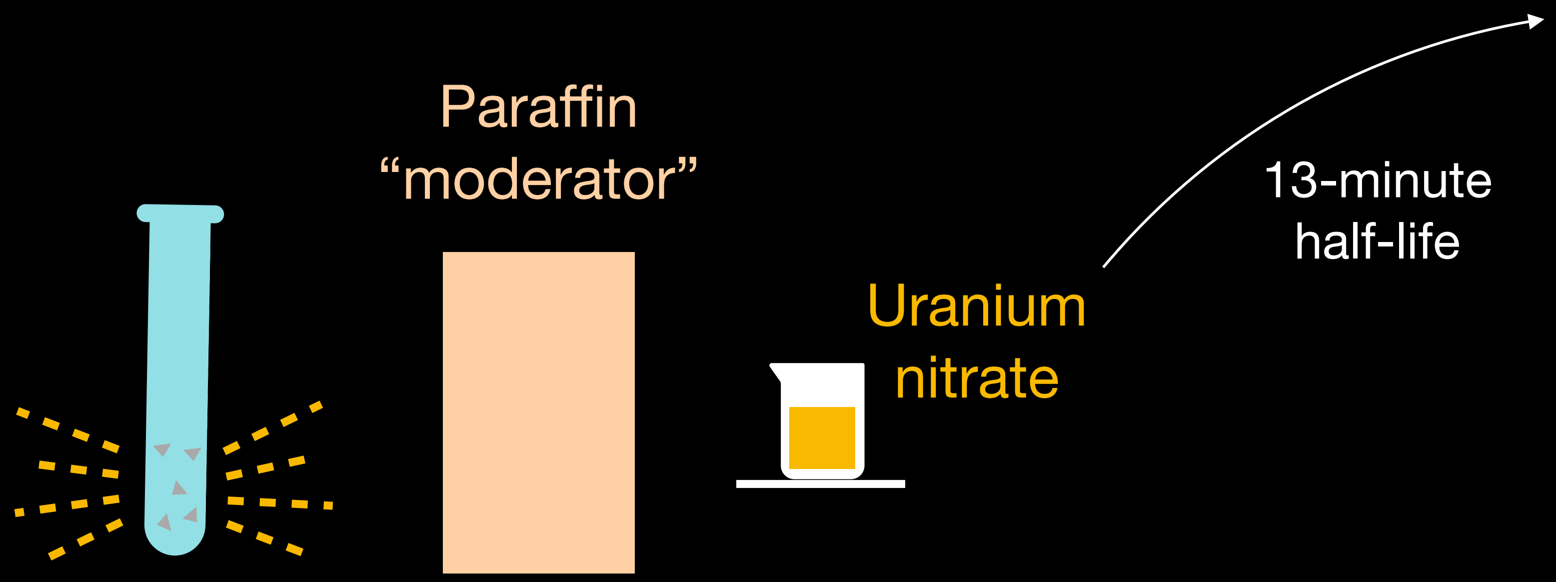

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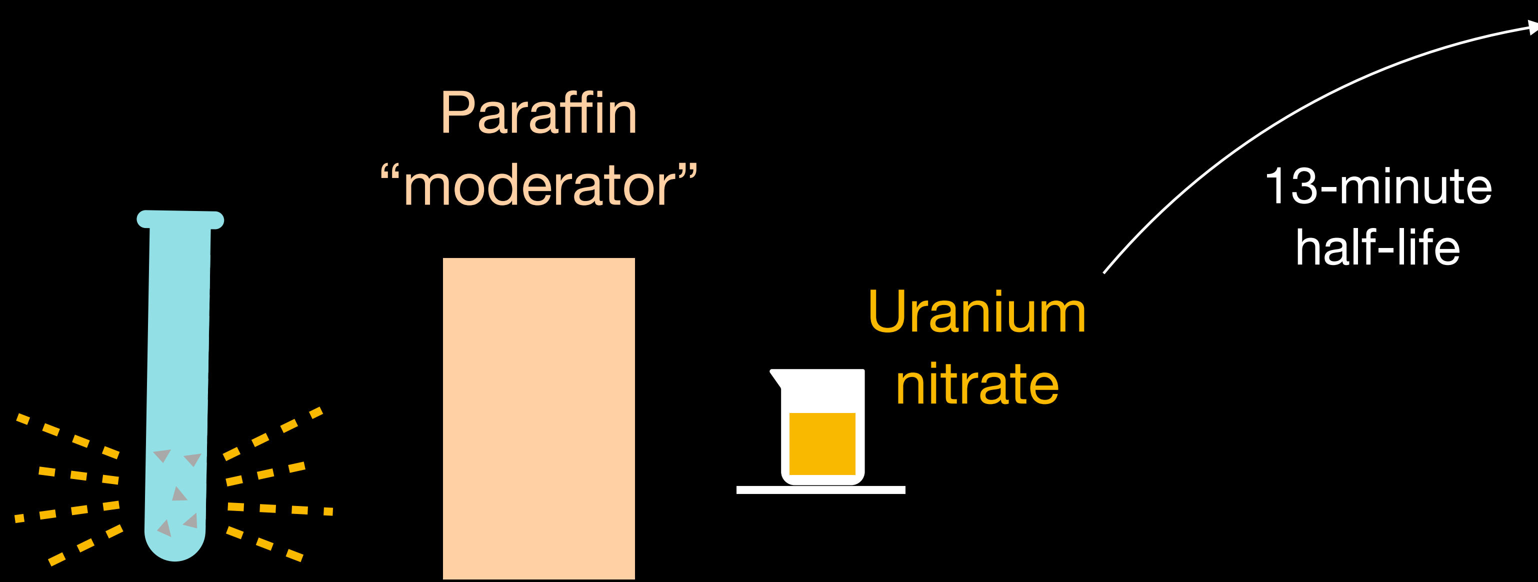

Chemical separation:

❌ Uranium (92 protons)

Palladium (91 protons)

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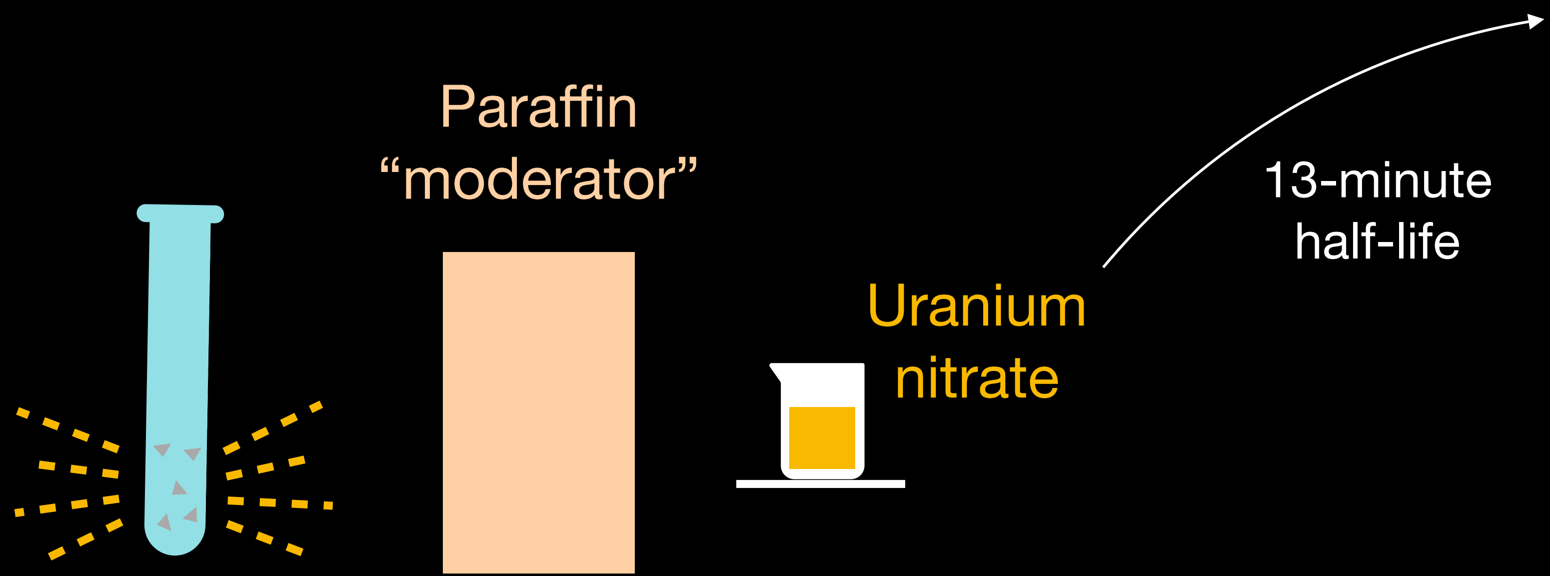

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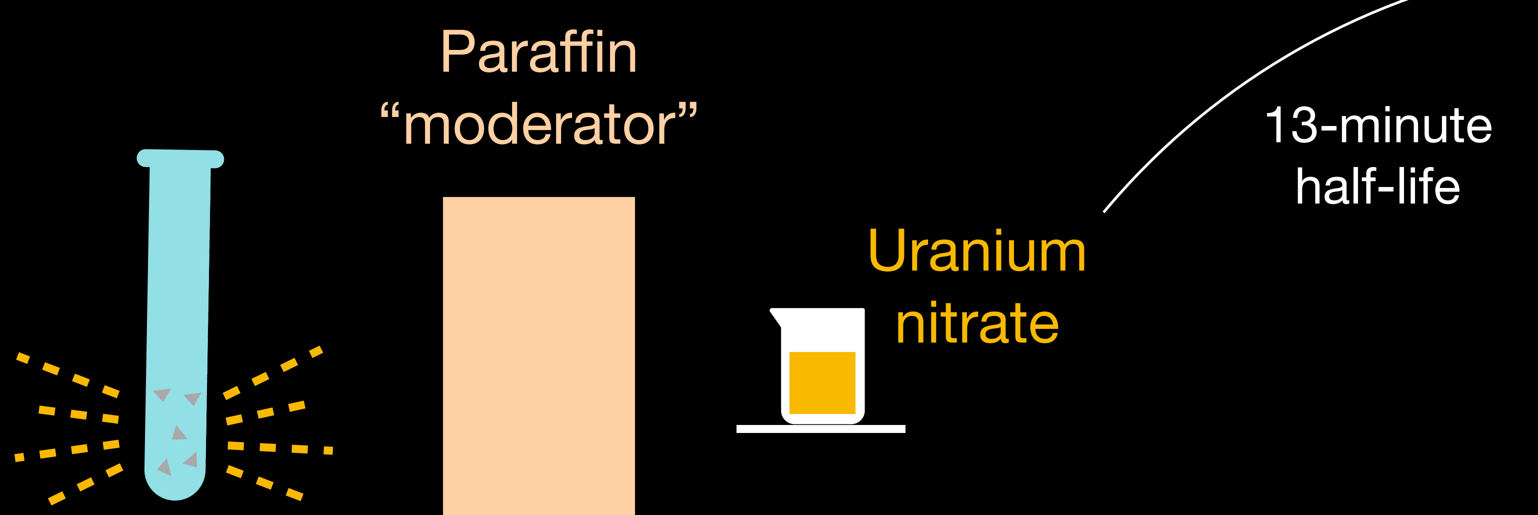

Chemical separation:

- ❌ Uranium (92 protons)
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- Thorium (90 protons)

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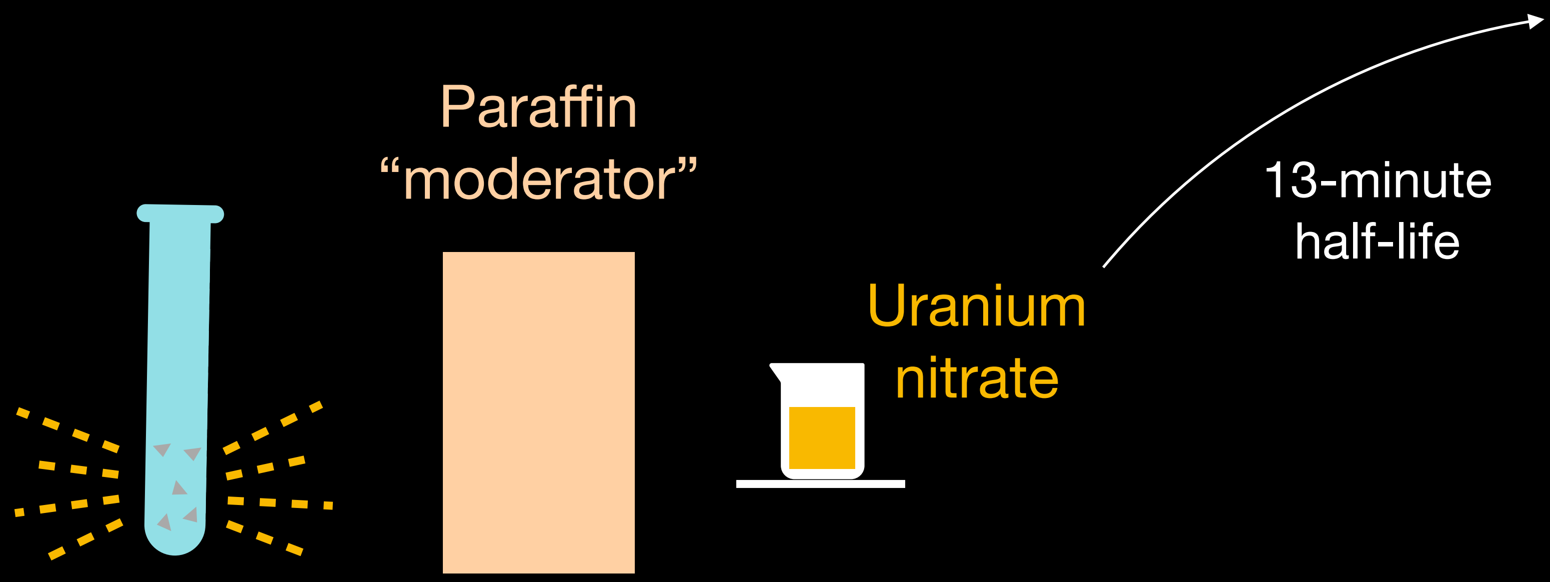

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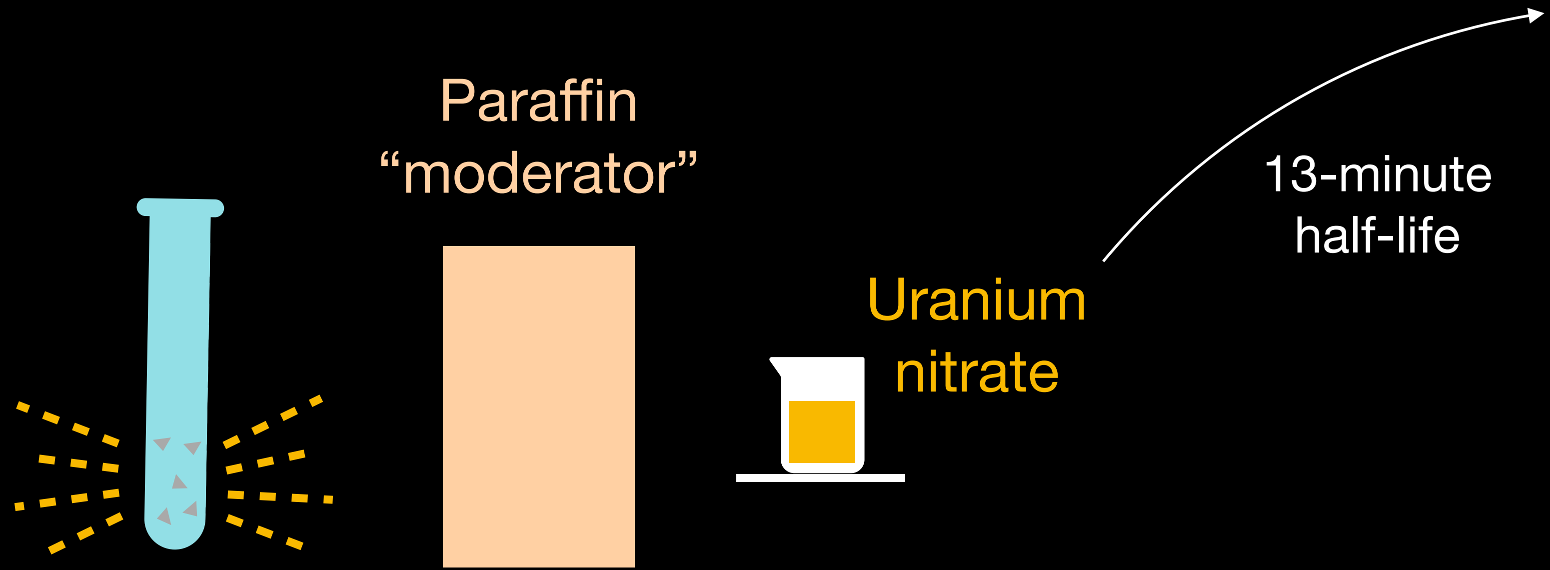

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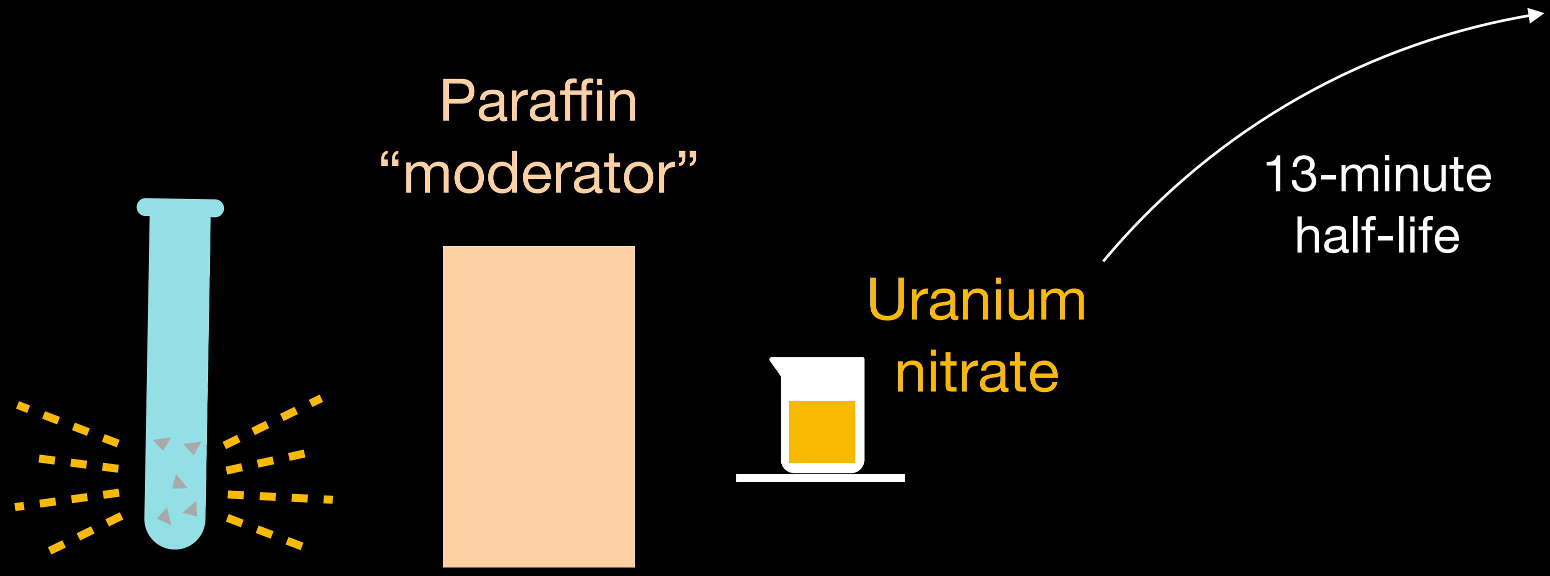

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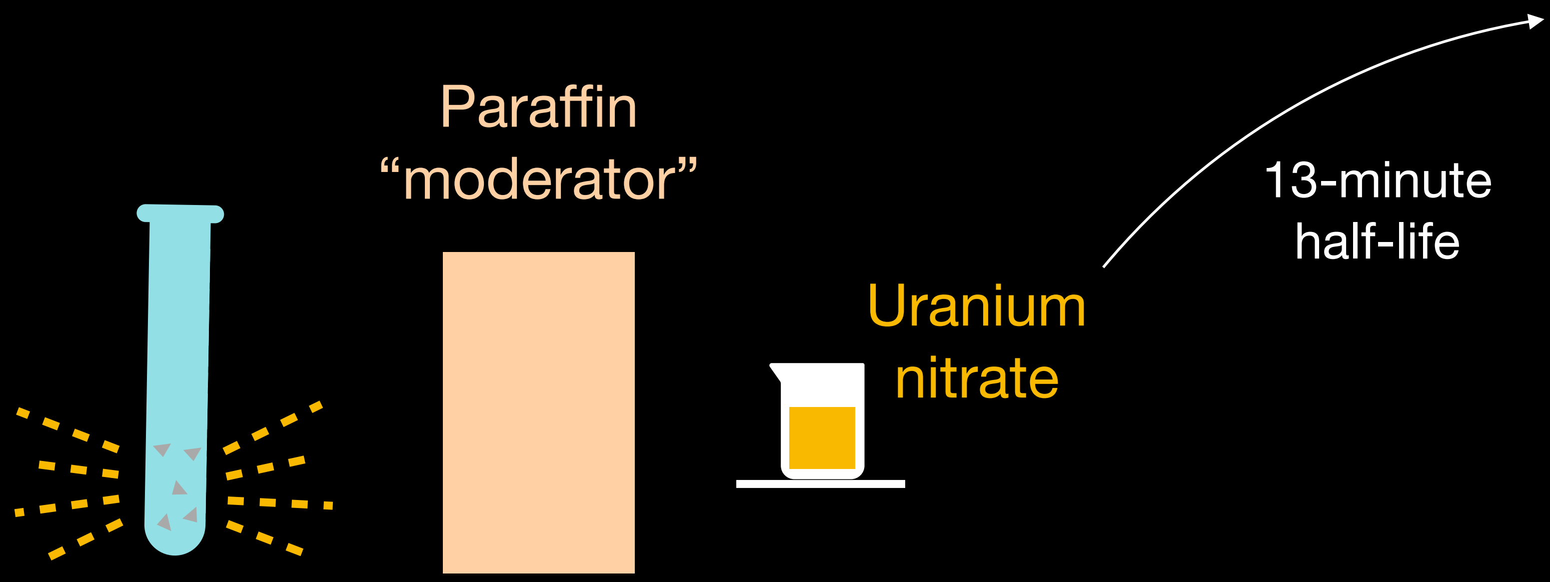

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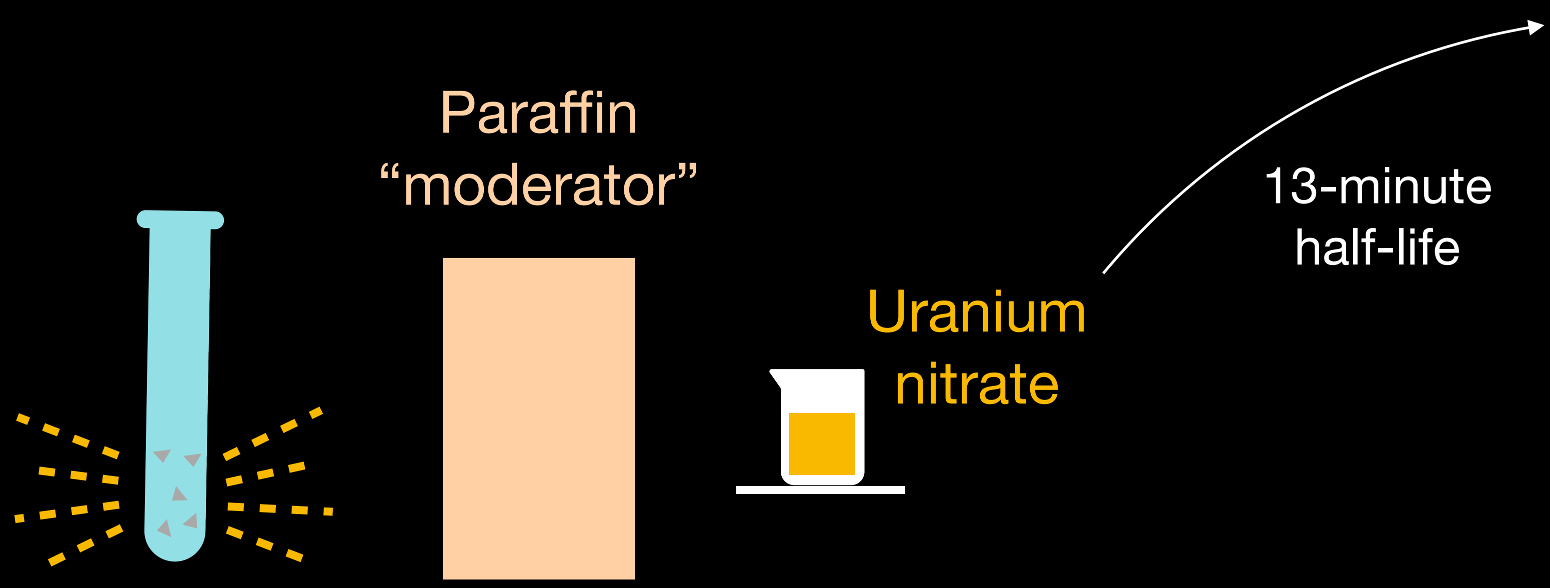
- ❌ Actinium (89 protons)
- Radium (88 protons)

Fermi’s blunder

Exposing uranium to “thermal” neutrons



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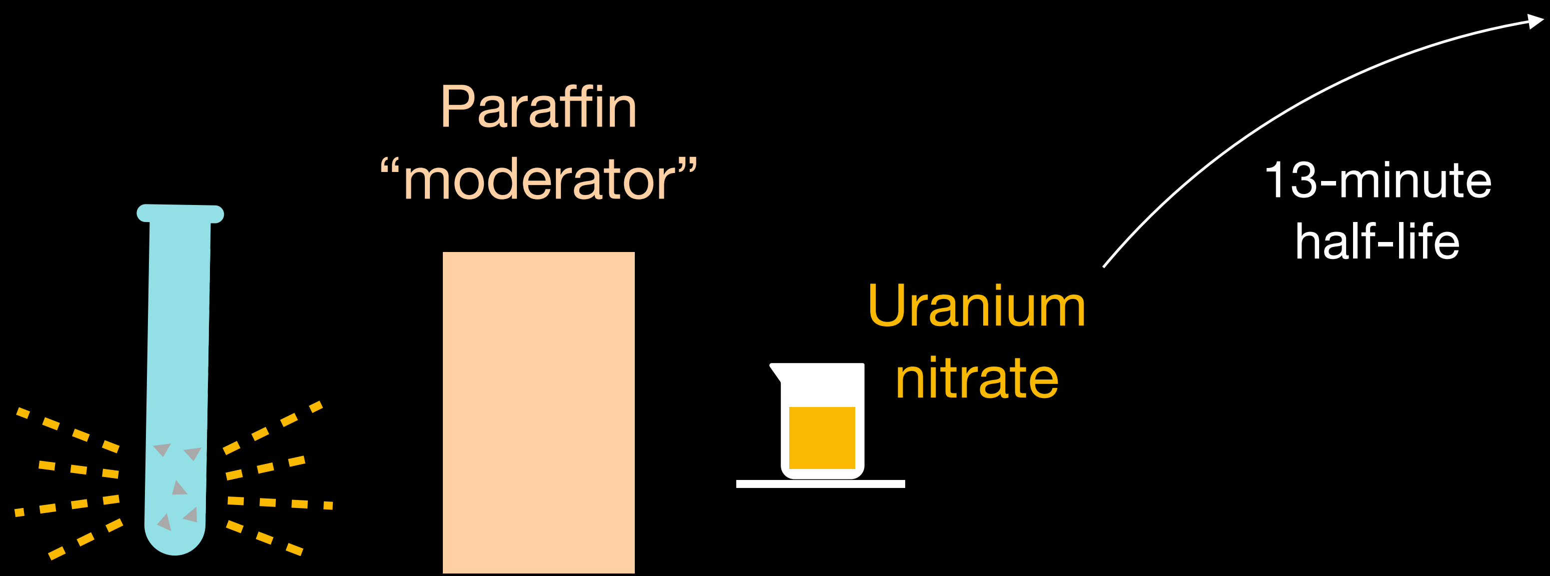

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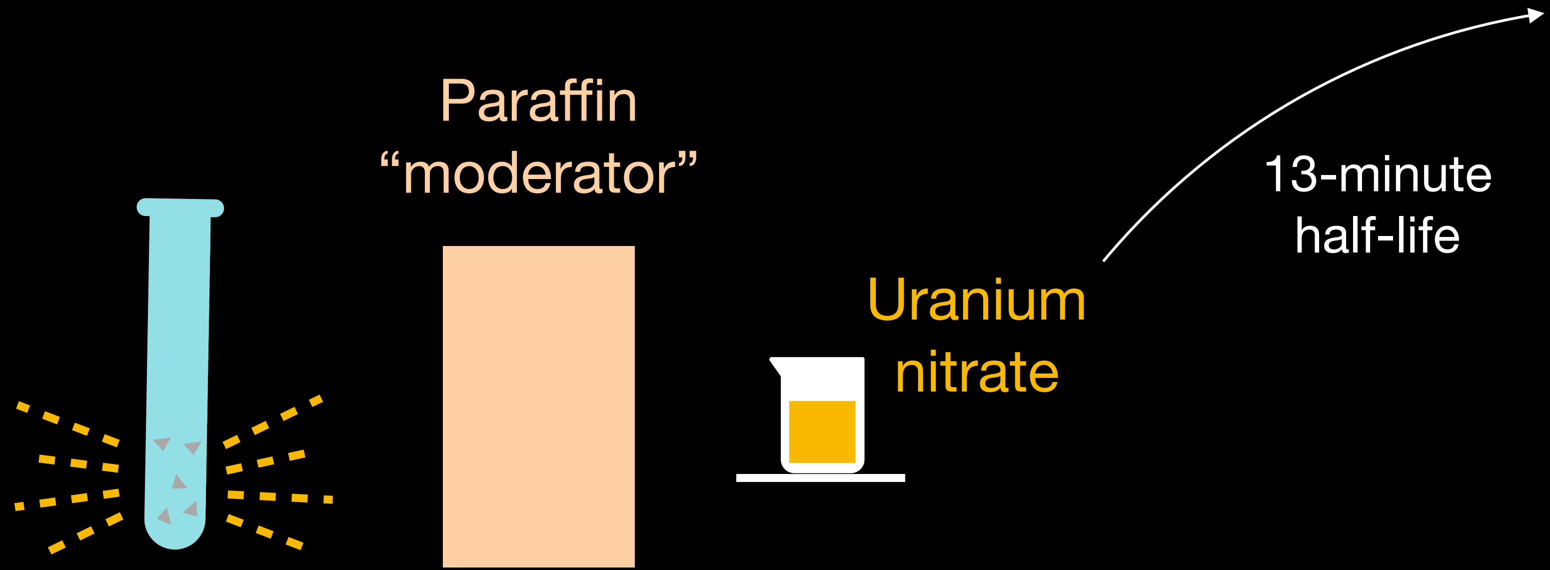

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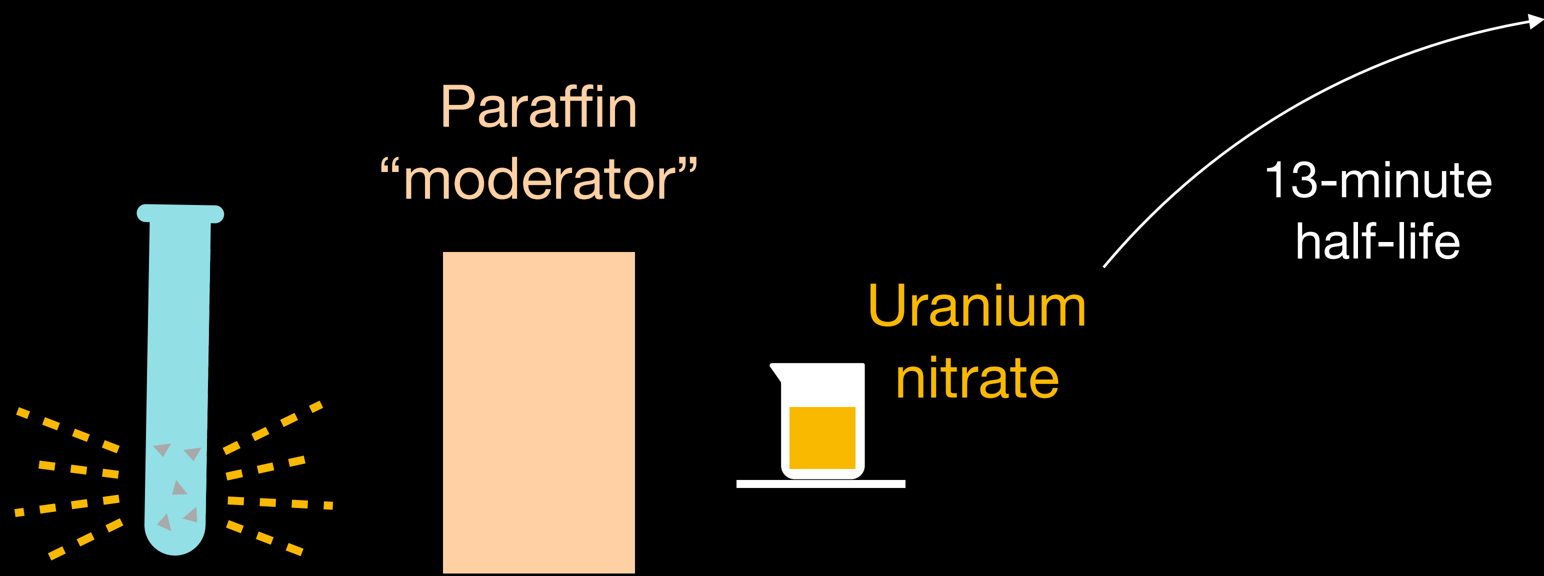

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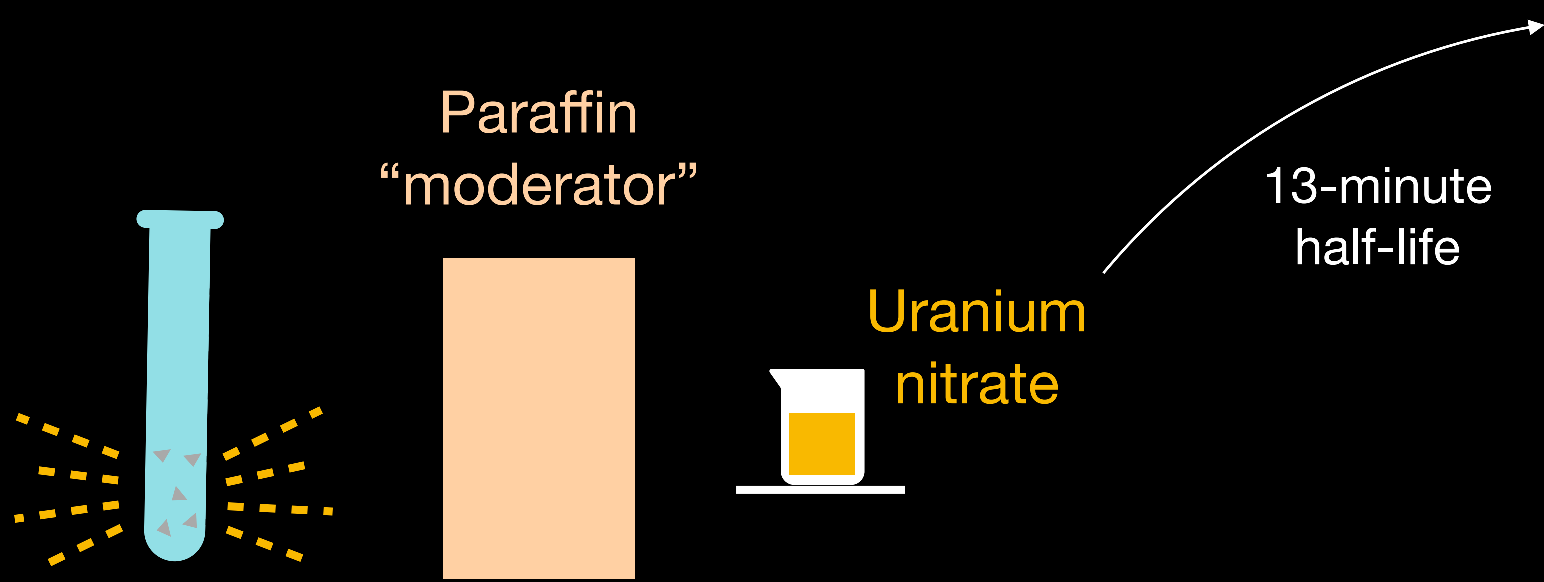

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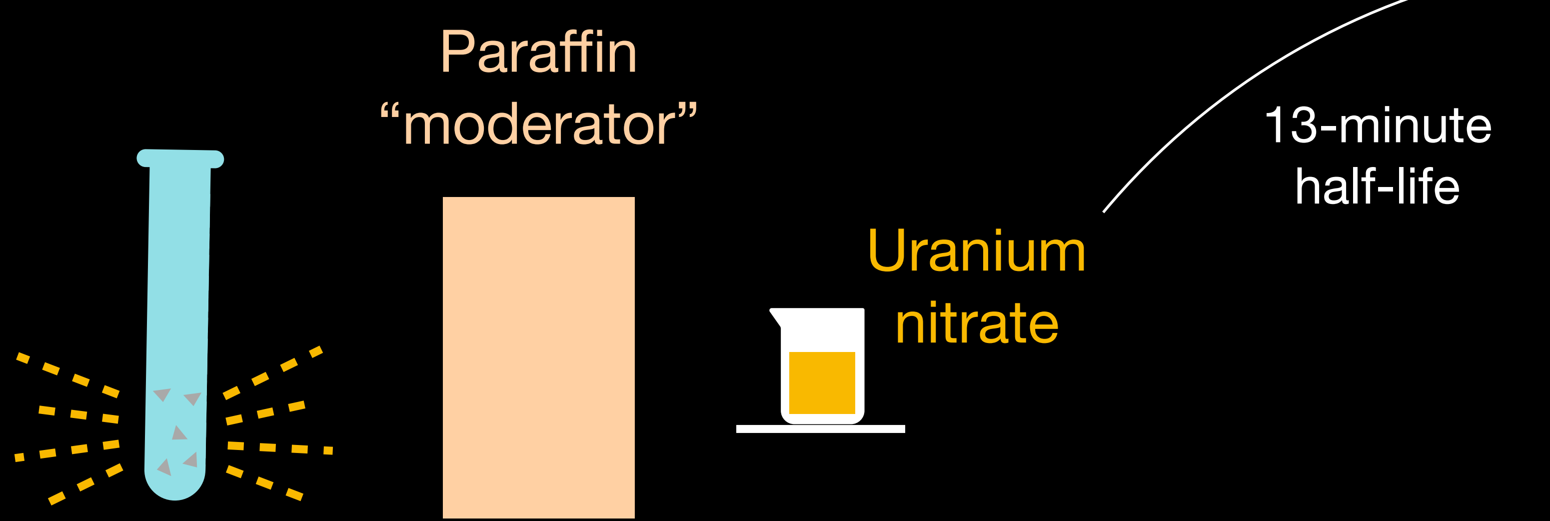

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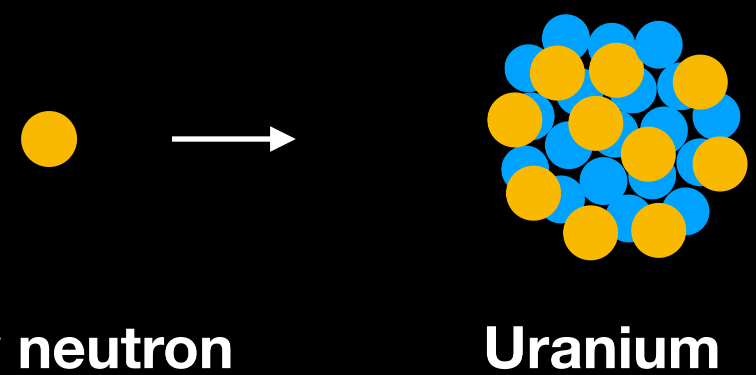

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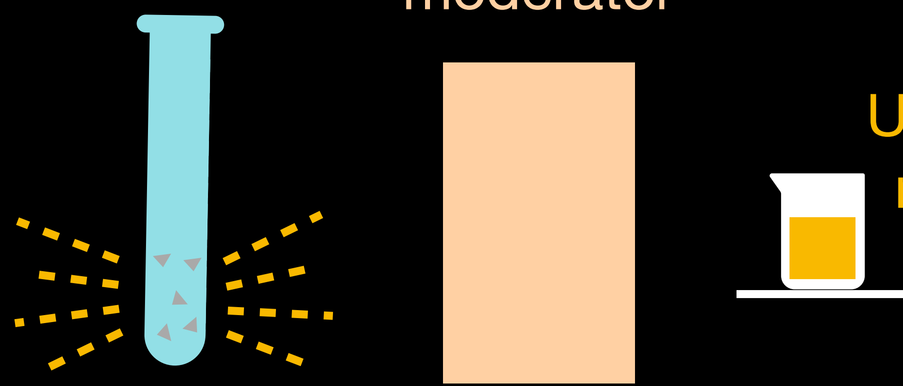

13-minute
half-life

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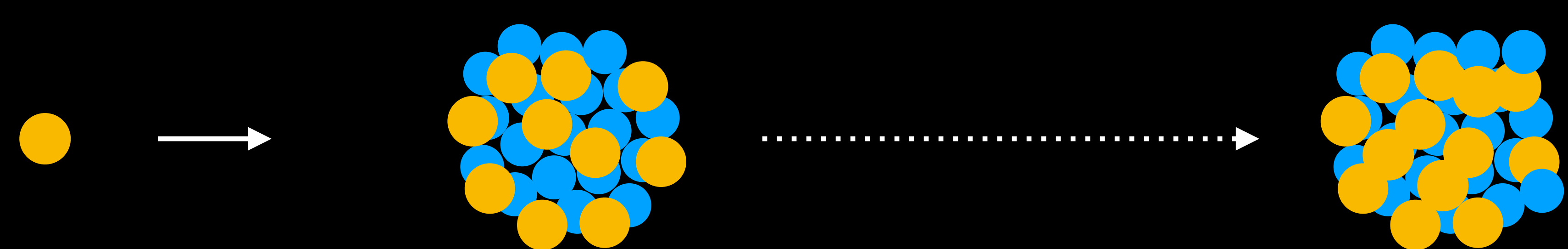

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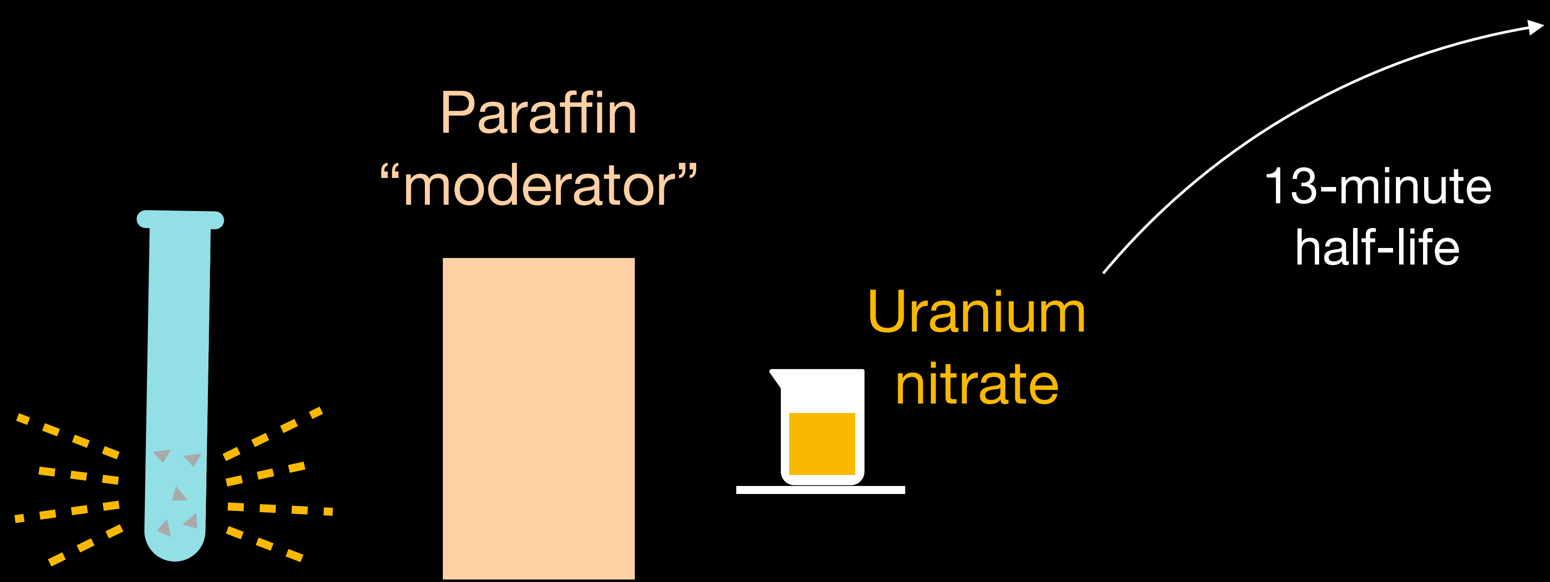

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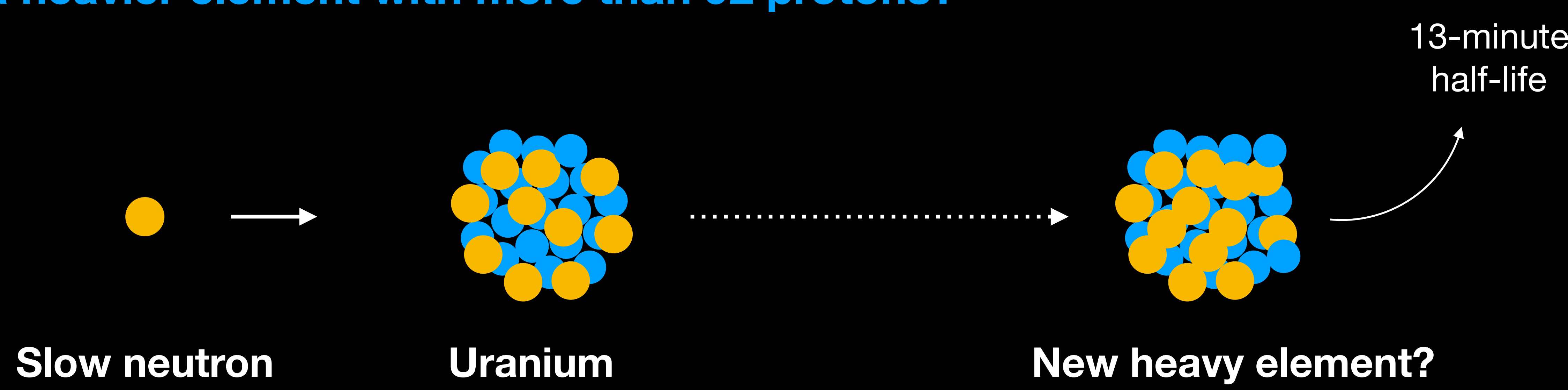

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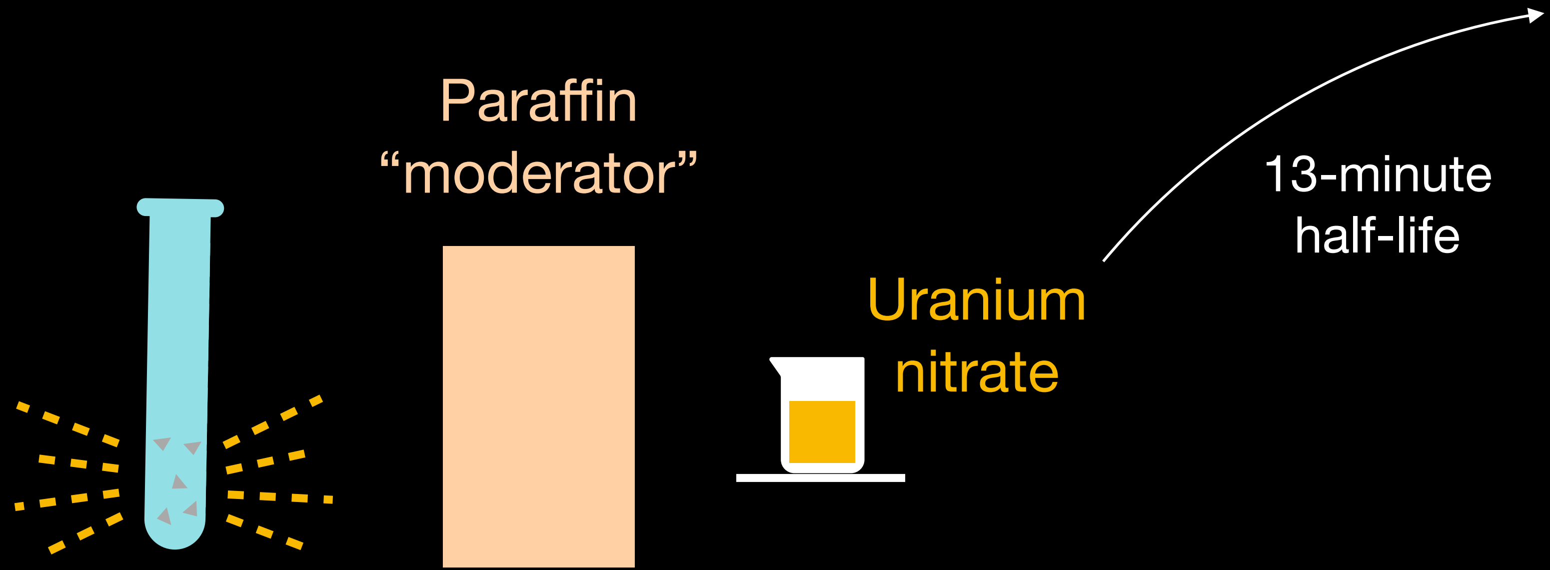

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13-minute

898 NATURE JUNE 16, 1934

Possible Production of Elements of Atomic Number Higher than 92

By PROF. E. FERMI, Royal University of Rome

Slow neutron Uranium New heavy element?

Fascists take over Italy

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At the Nobel Prize ceremony
in Sweden *(December 1938)*

Fascists take over Italy

At the Nobel Prize ceremony in Sweden *(December 1938)*

Safely arrived in New York *(January 2, 1939)*

Fermi at Columbia

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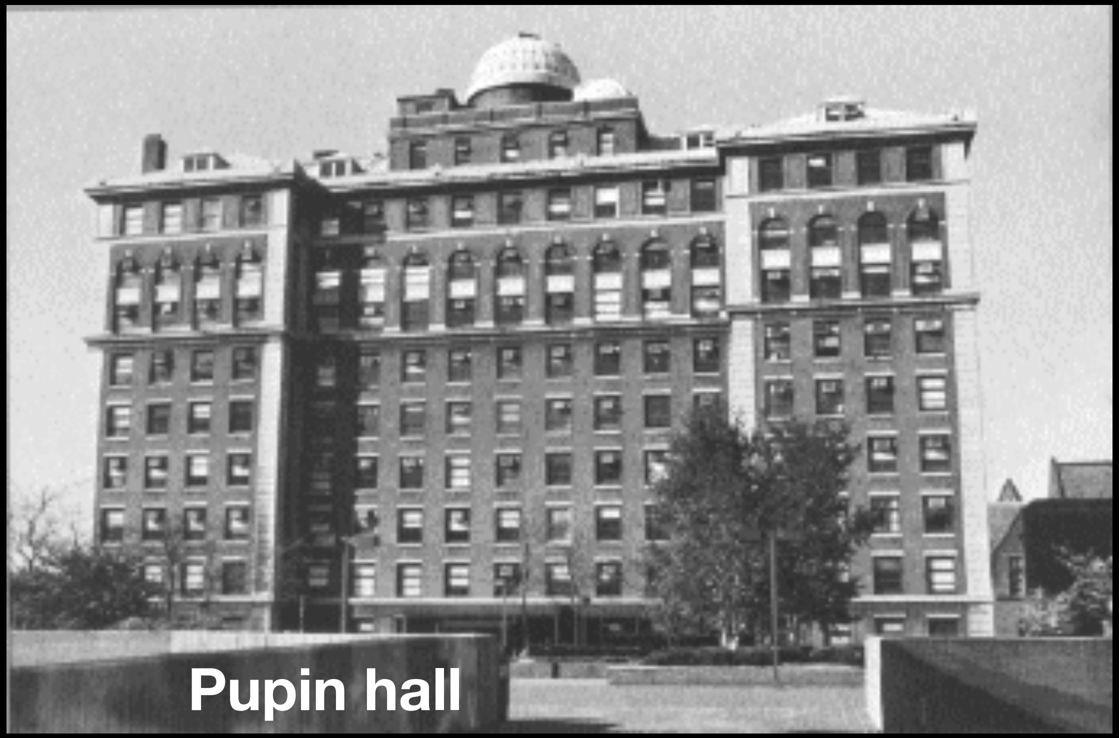
The uranium nucleus has been split in Berlin!

Results made public on January 6, 1939



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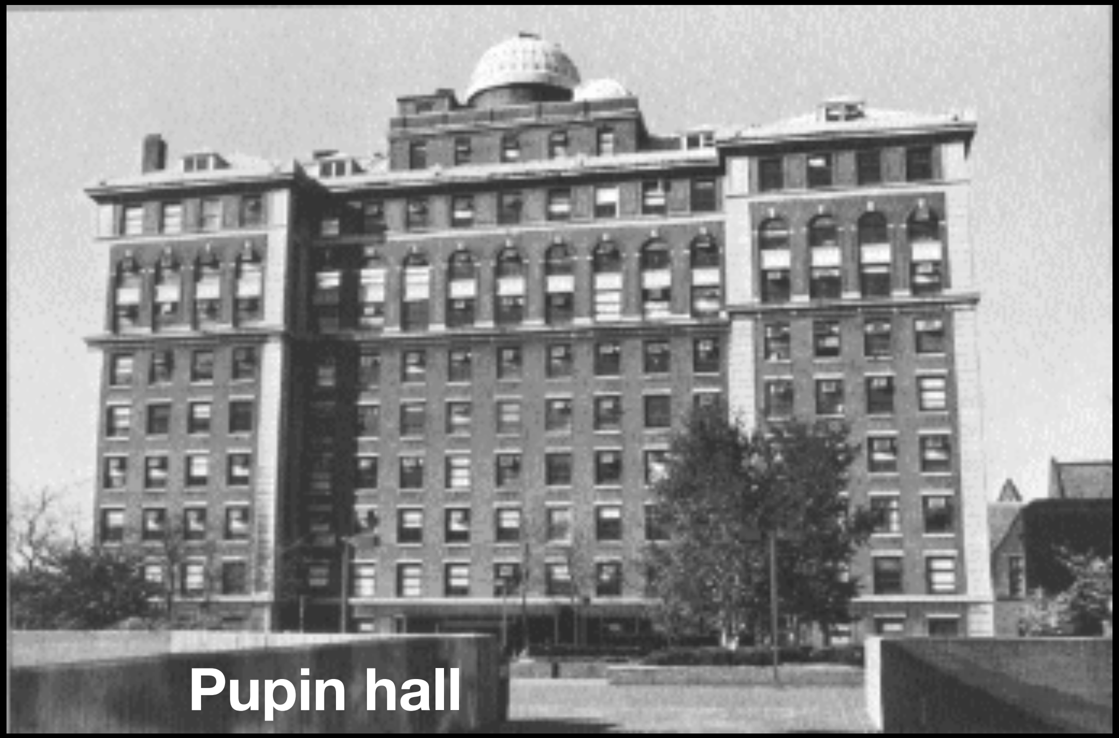

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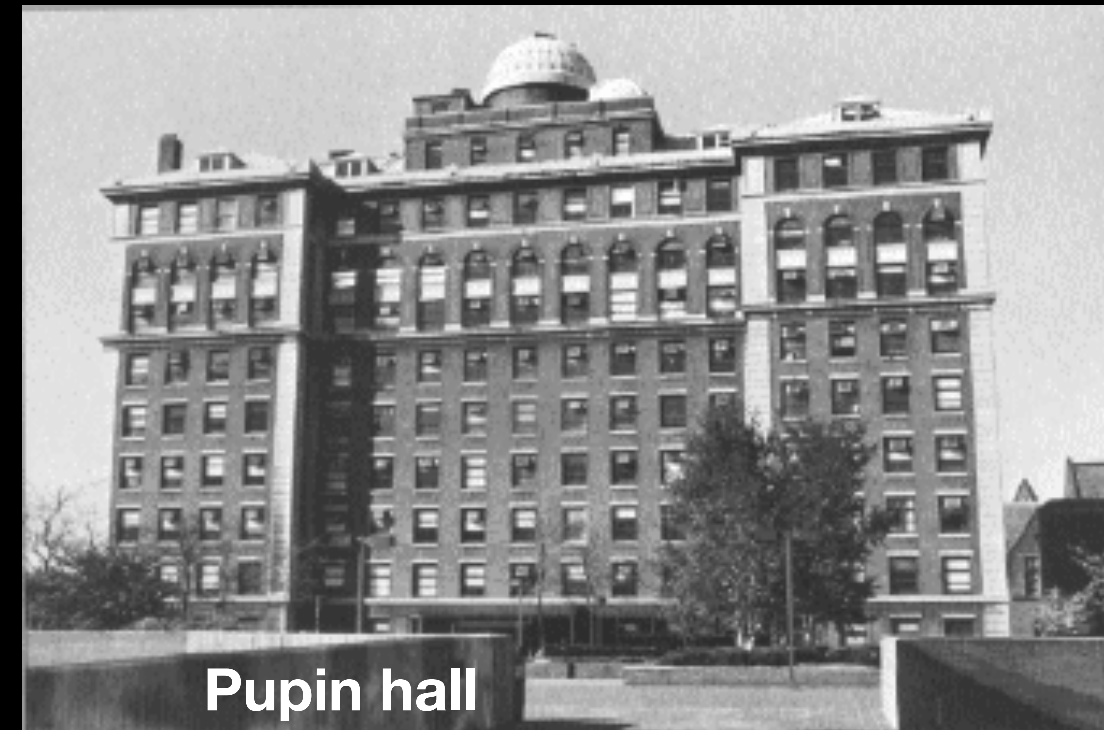

Heft 1.
6. 1. 1939

HAHN u. STRASSMANN: Über den Nachweis und das Verhalten der Erdalkalimetalle. 11

Über den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehenden Erdalkalimetalle[1].

Von O. HAHN und F. STRASSMANN, Berlin-Dahlem.

What happened in Berlin?

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Virtually the same experiment as in Fermi's Via Panisperna!

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$$\text{„Ra I“?} \xrightarrow[<1\text{ Min.}]{\beta} \text{Ac I} \xrightarrow[<30\text{ Min.}]{\beta} \text{Th?}$$

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“Radium” “Actinium” “Thorium”

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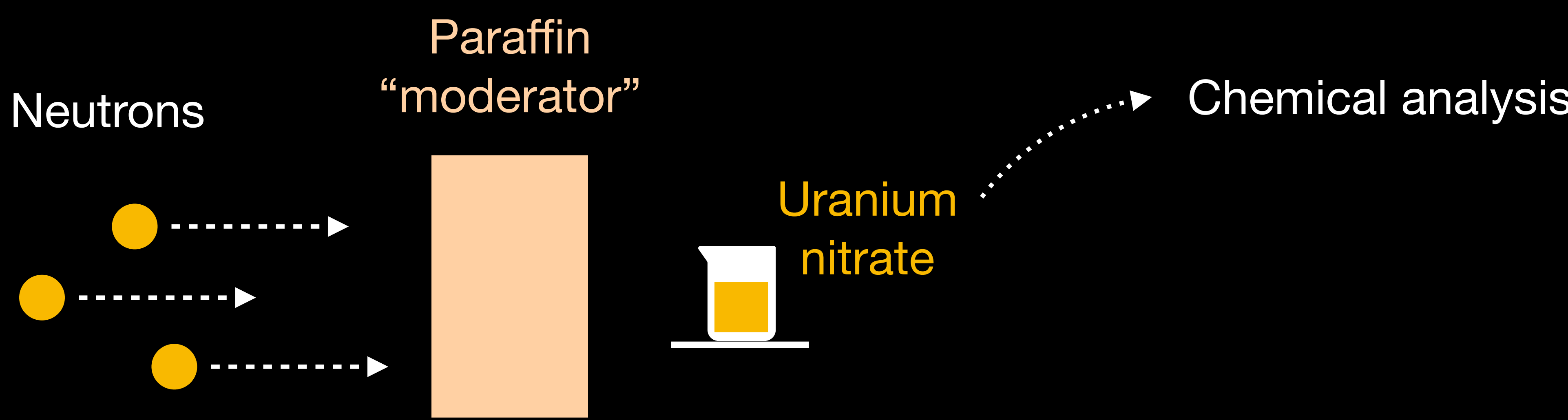

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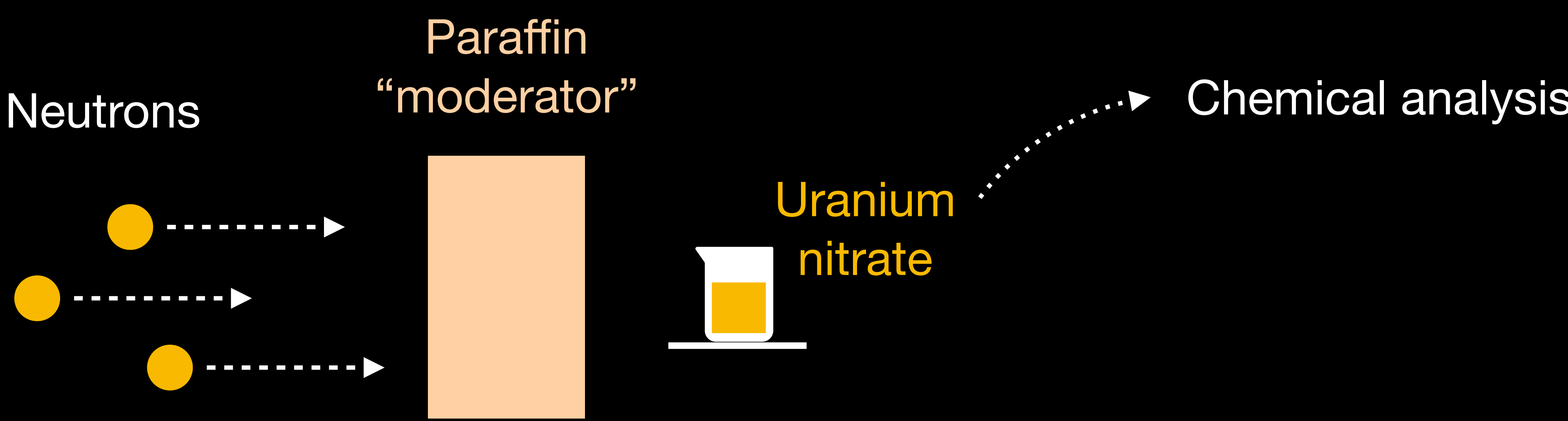

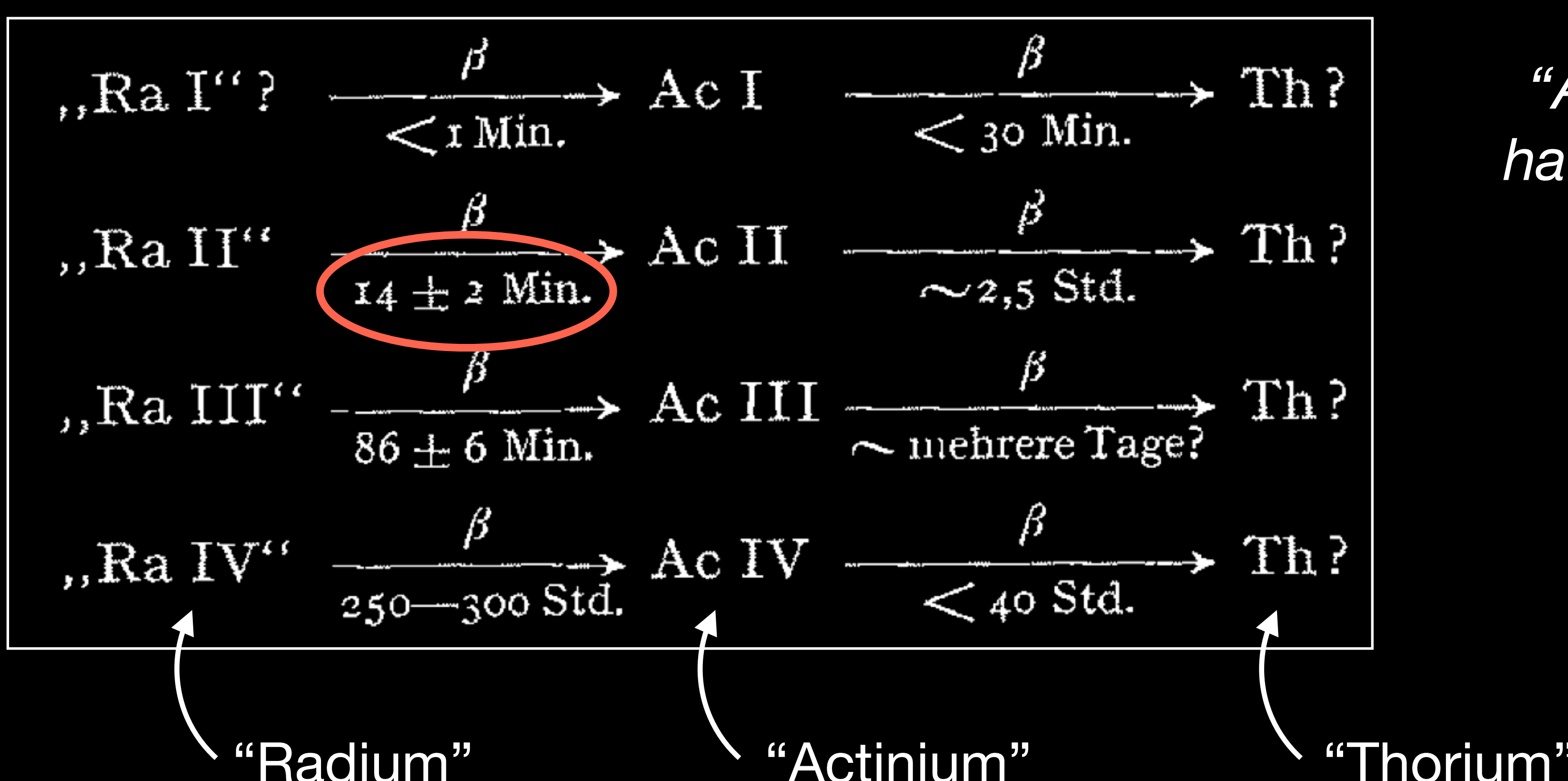

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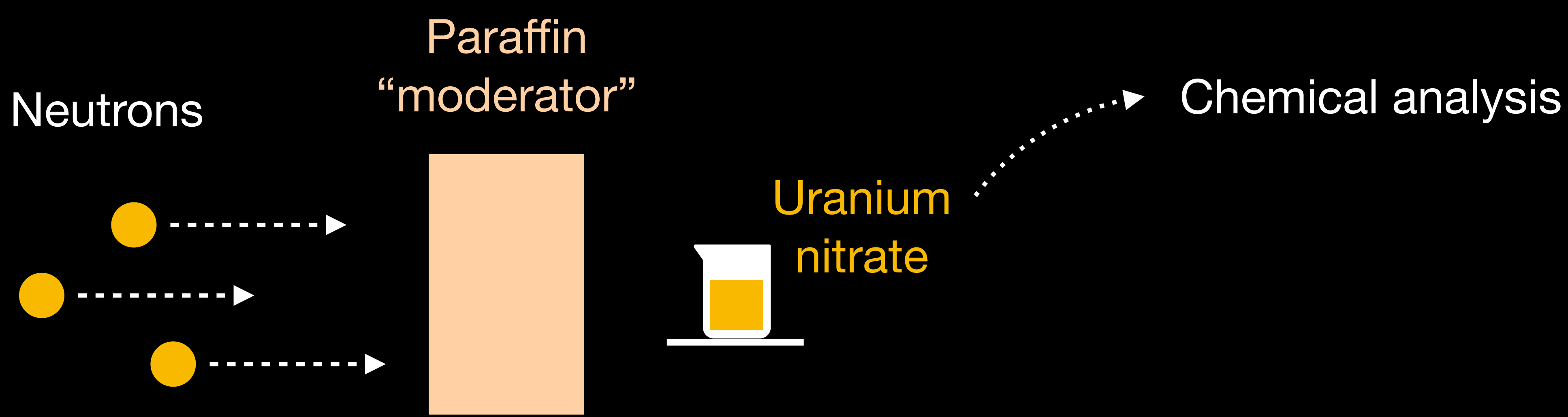

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"Radium" "Actinium" "Thorium"

"As chemists, we would actually have to say that the new elements are not radium, but barium."

"If our 'radium isotopes' are not radium, then our 'actinium isotopes' are not actinium, but lanthanum."

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The nucleus is highly dynamic!

A droplet of water instead of a bowling ball.

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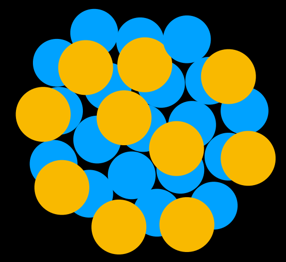

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(92 protons)

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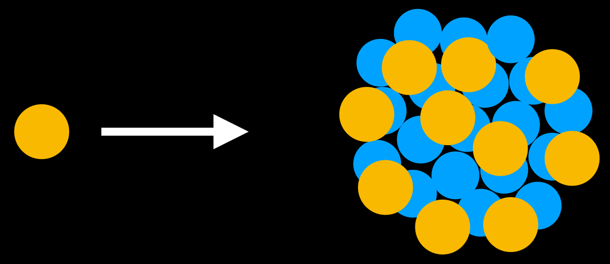

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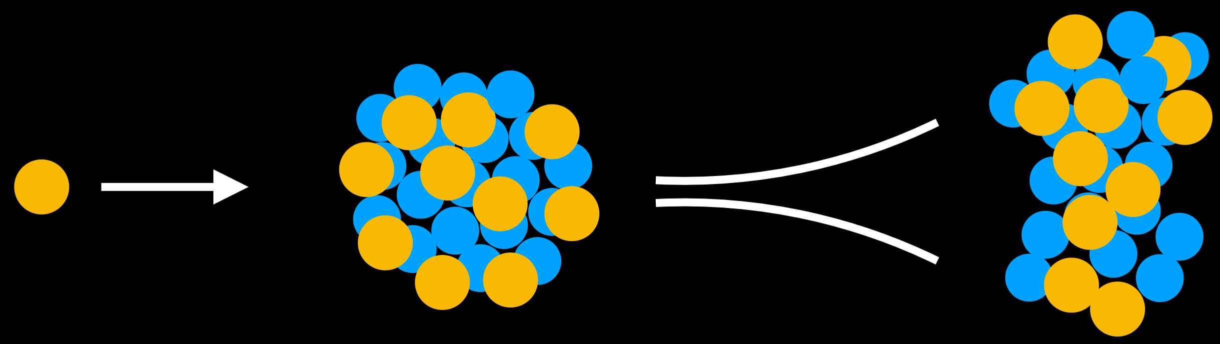

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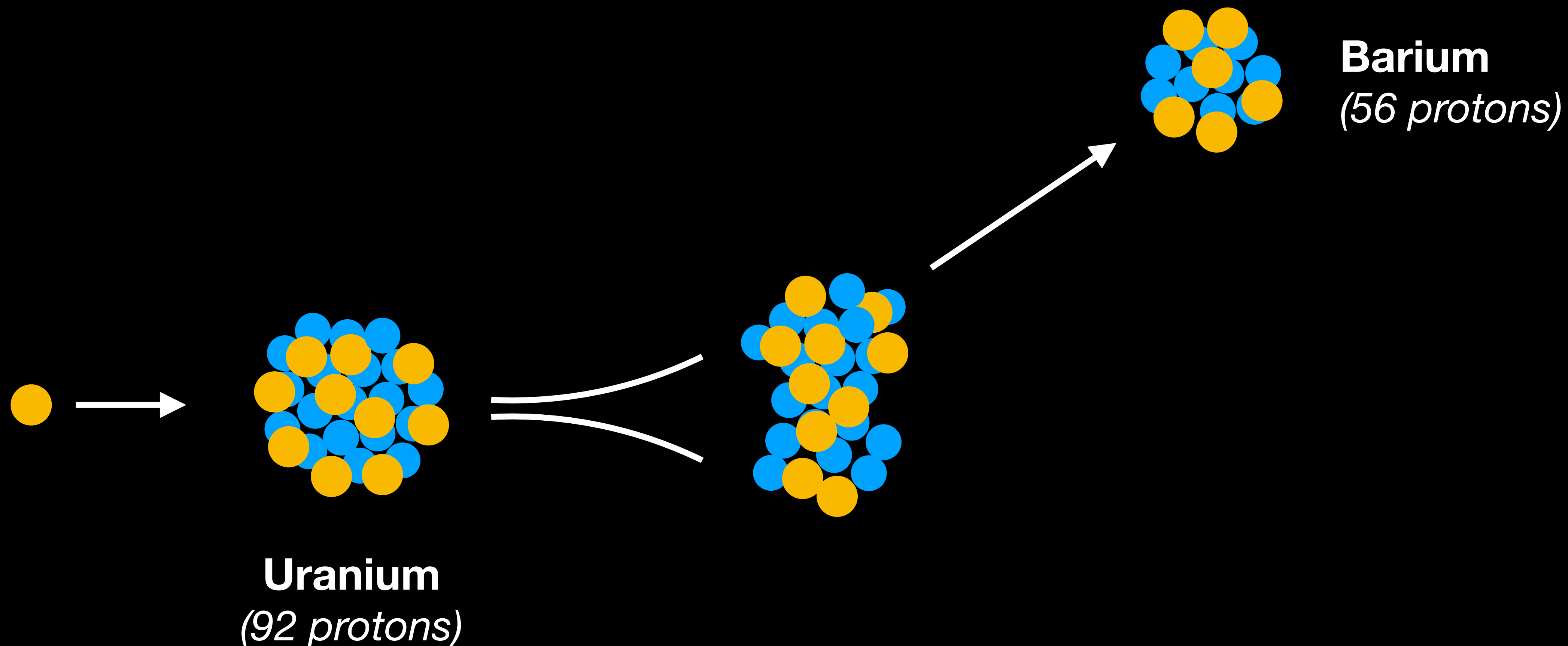

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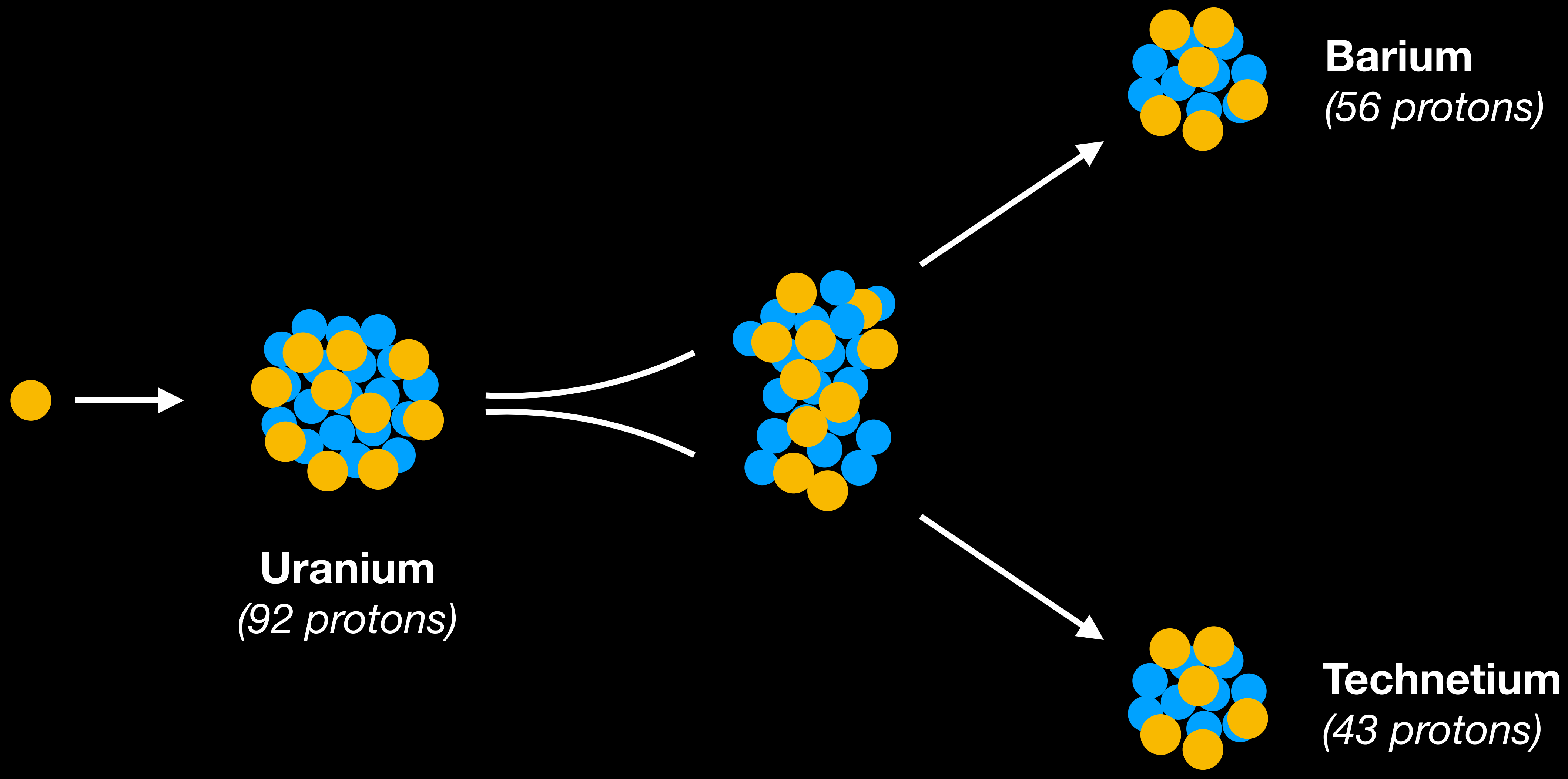

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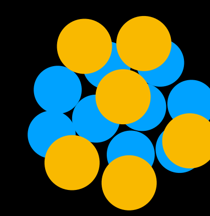
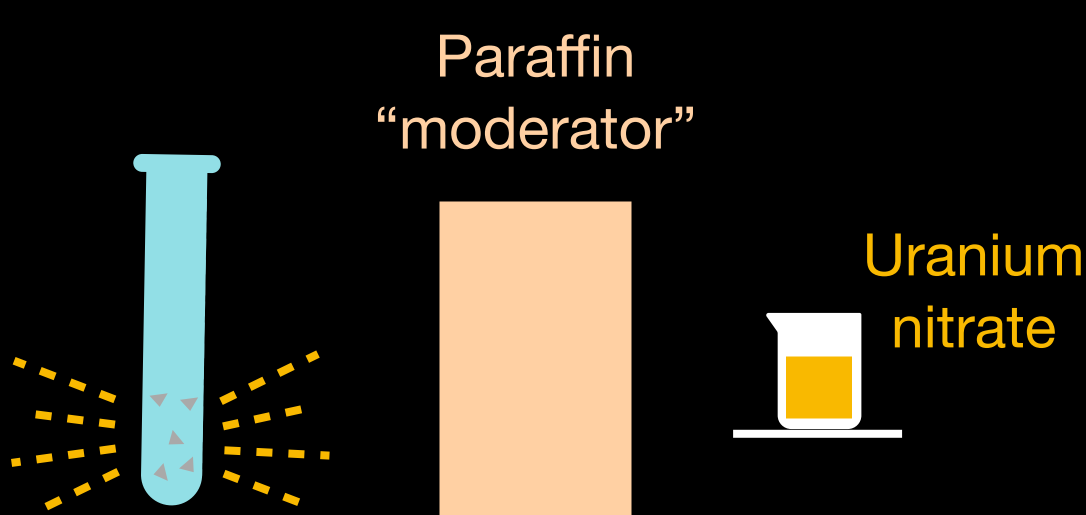


Barium
(56 protons)



13-minute
half-life

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Enrico Fermi, Via Panisperna *(1934)*

Fermi’s reaction

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"I want to see this for myself!"

Fermi's reaction

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Herbert Anderson

Fermi's reaction

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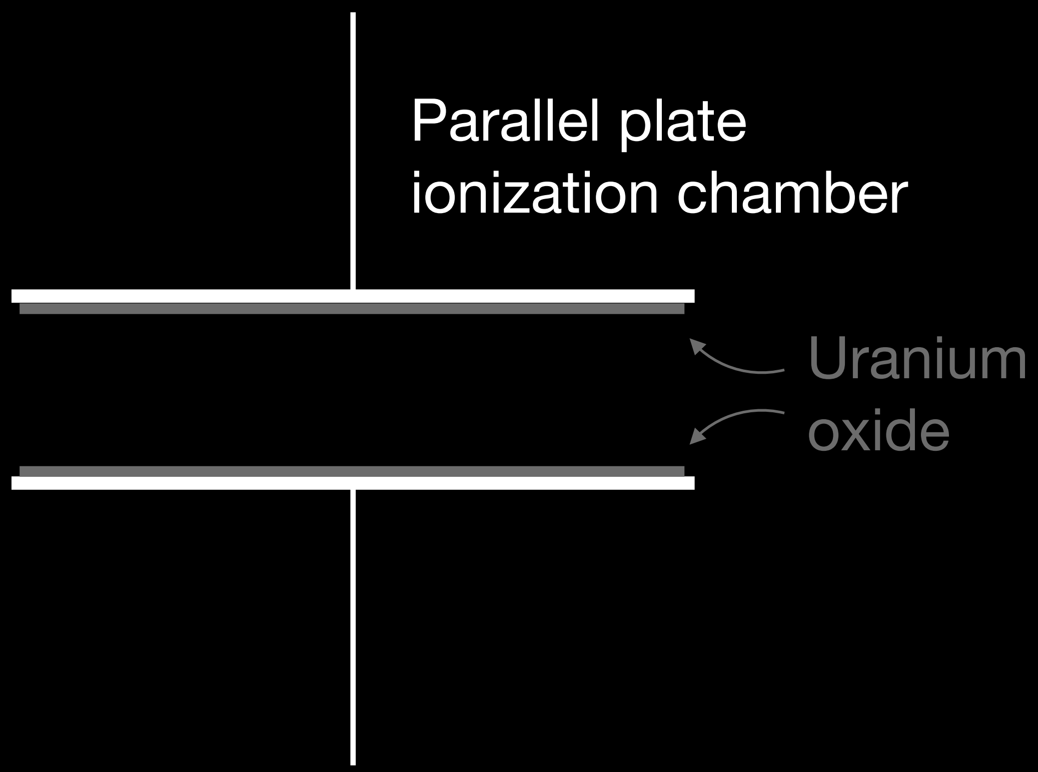

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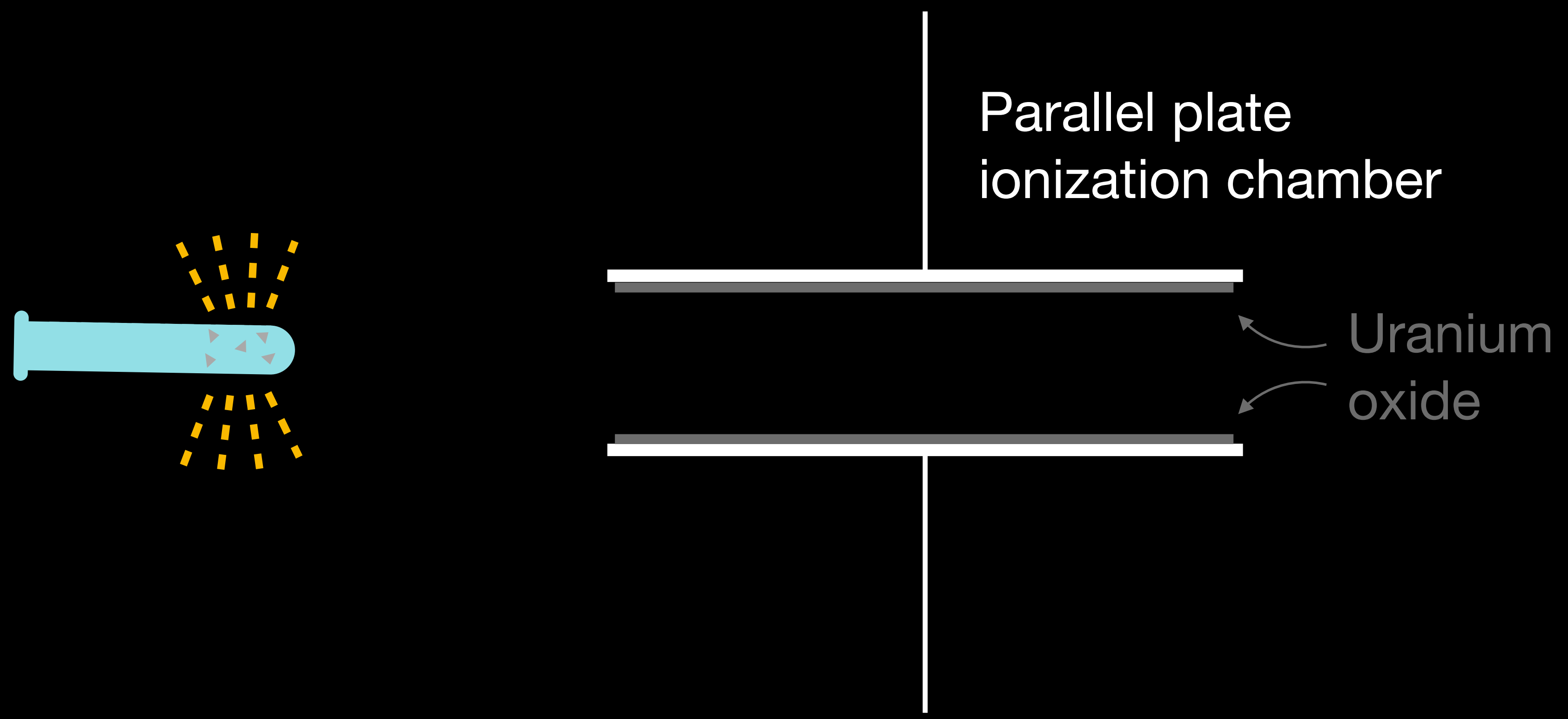

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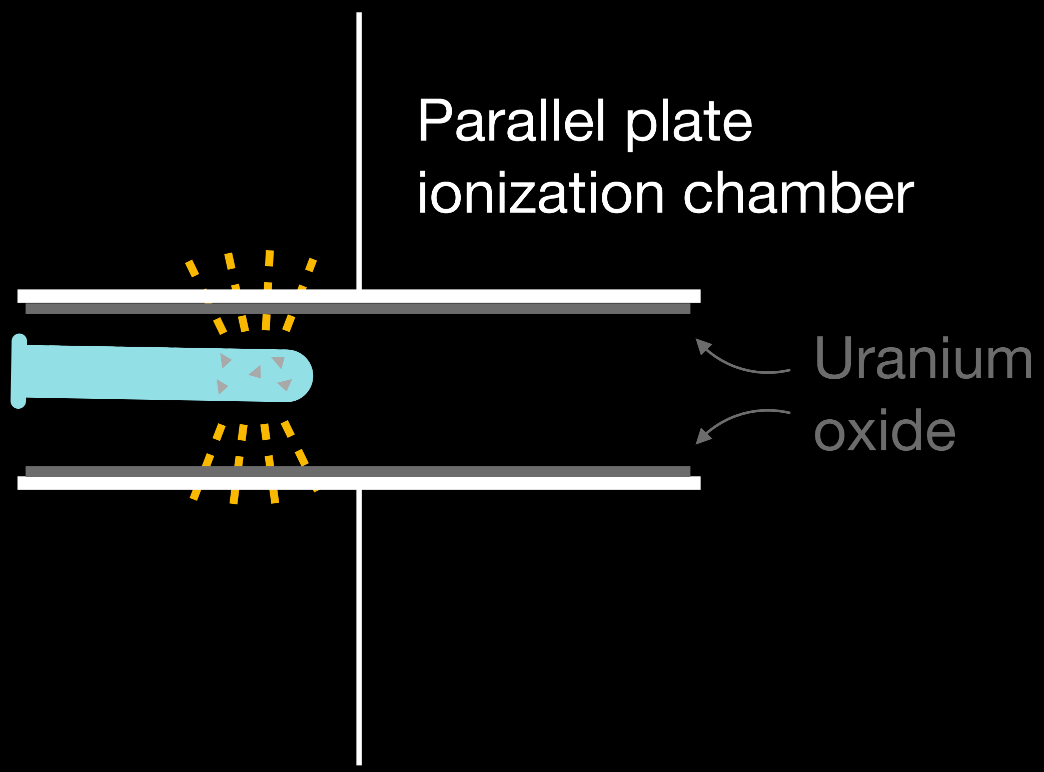

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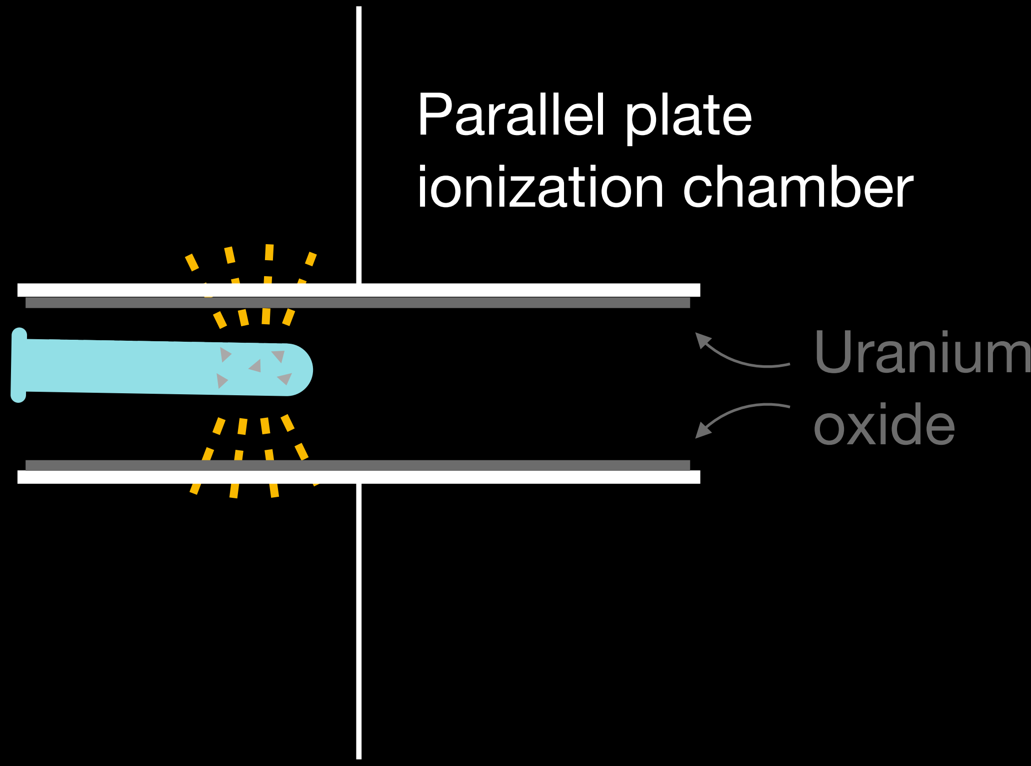

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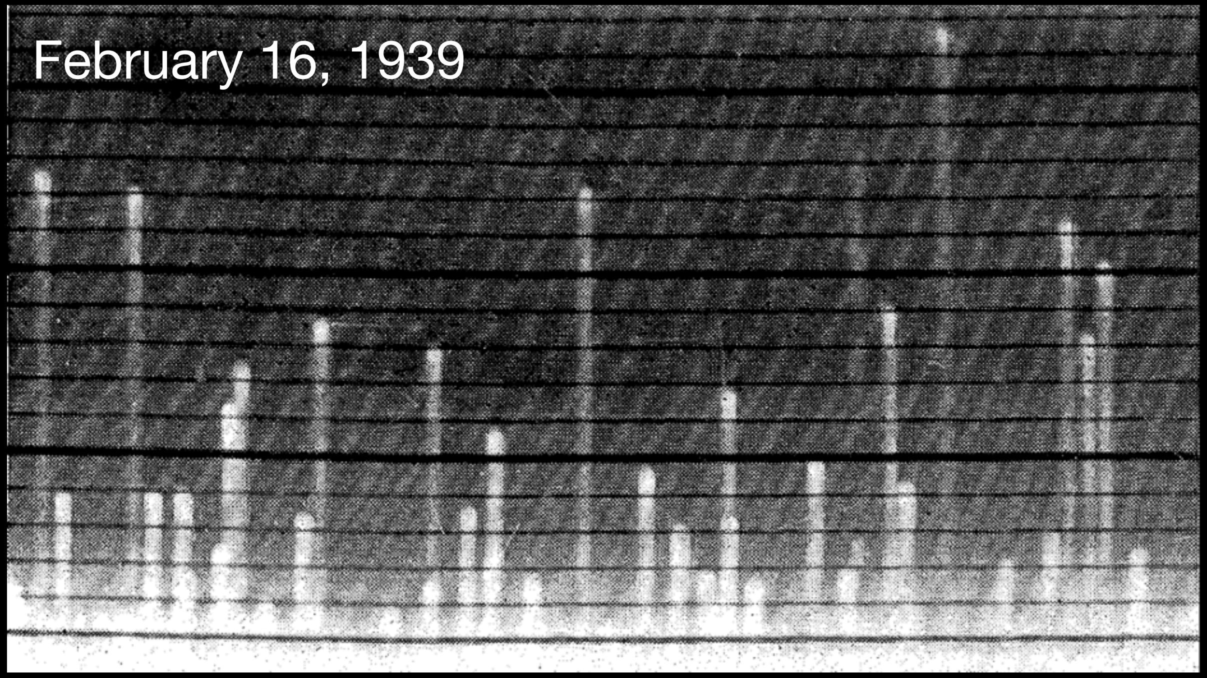

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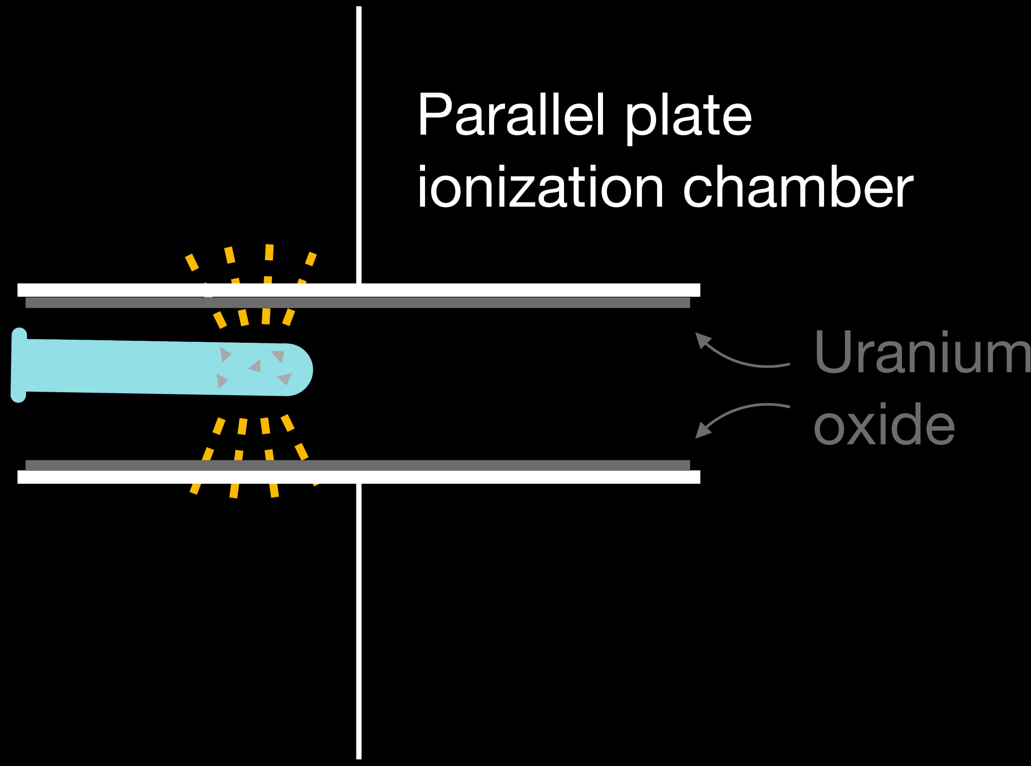

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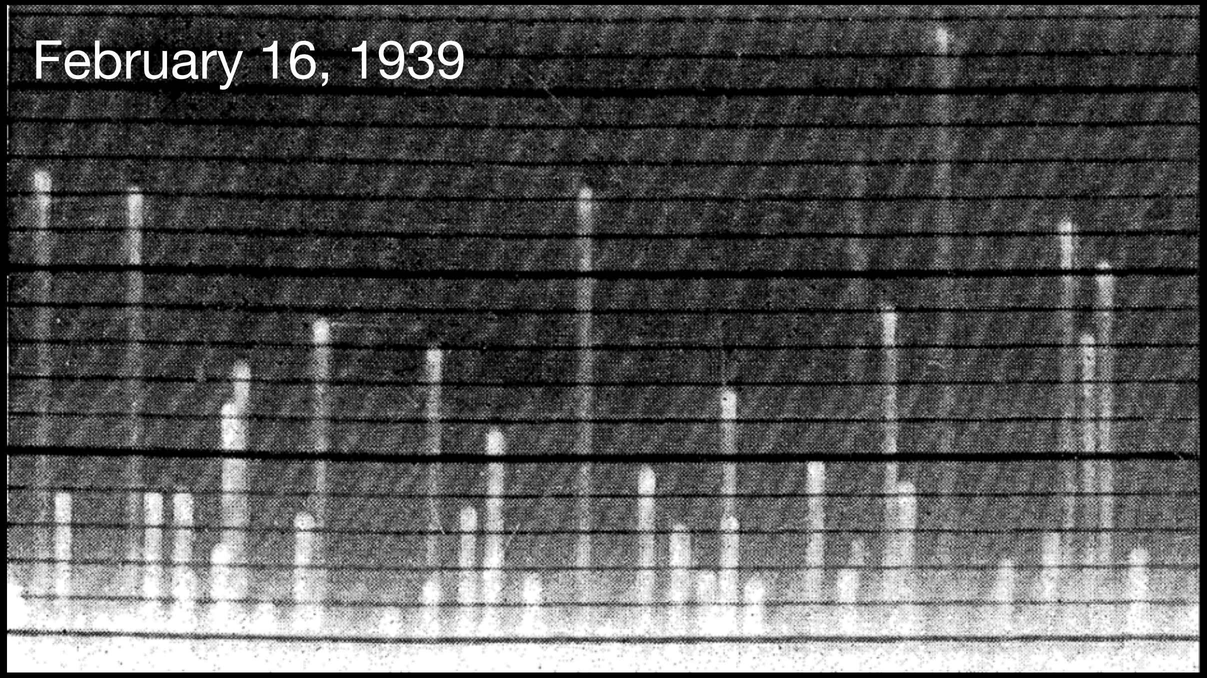

"A large number of small pulses from the α-particles of uranium were observed."

Fermi's reaction

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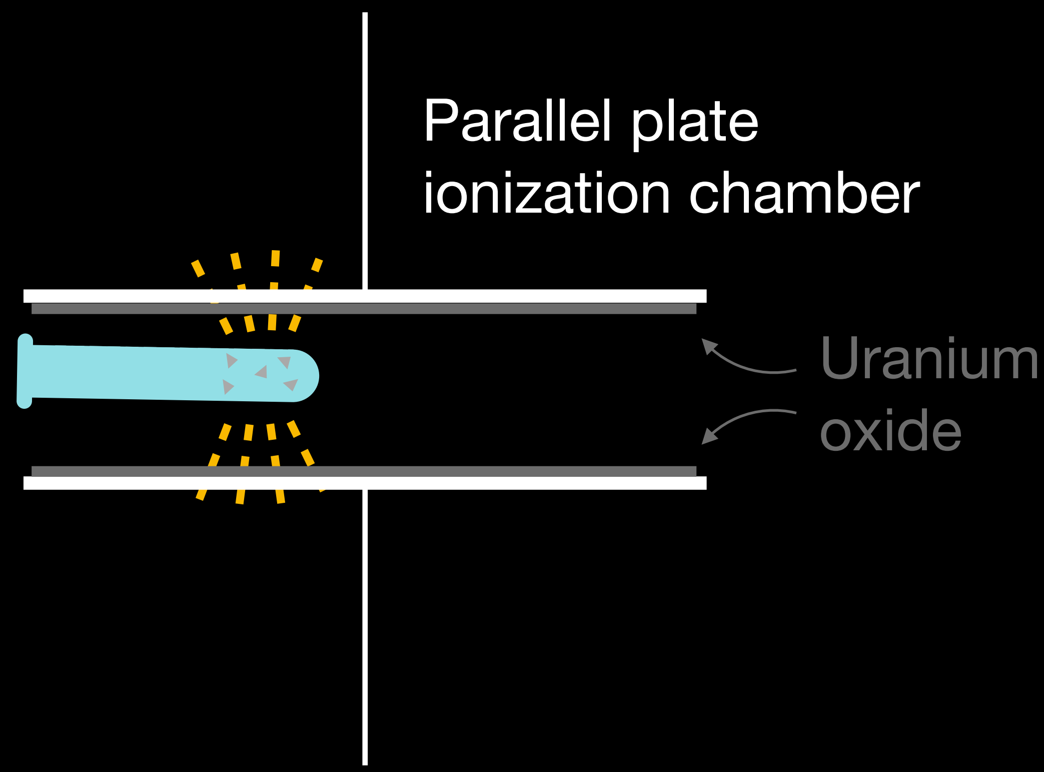

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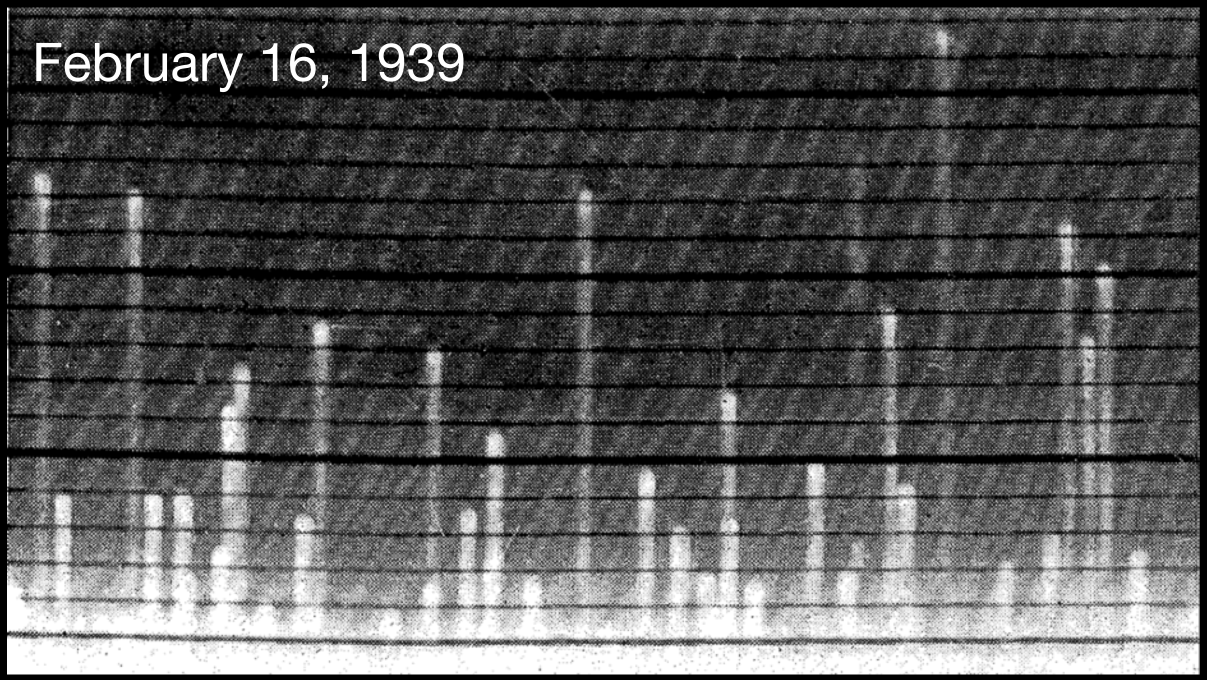
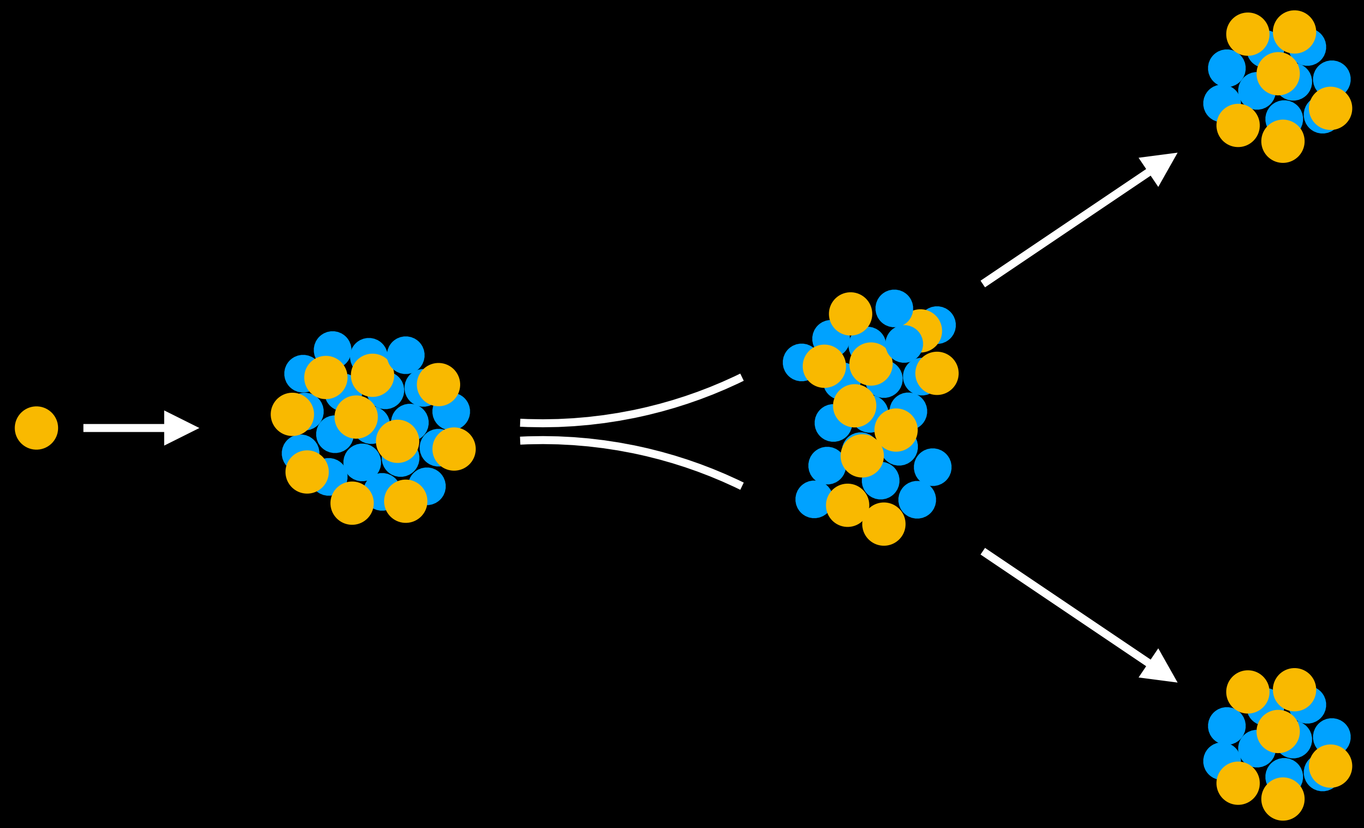


"A large number of small pulses from the α-particles of uranium were observed."

"When exposed to the bombardment of neutrons very large pulses occurred in addition."

A chain reaction?



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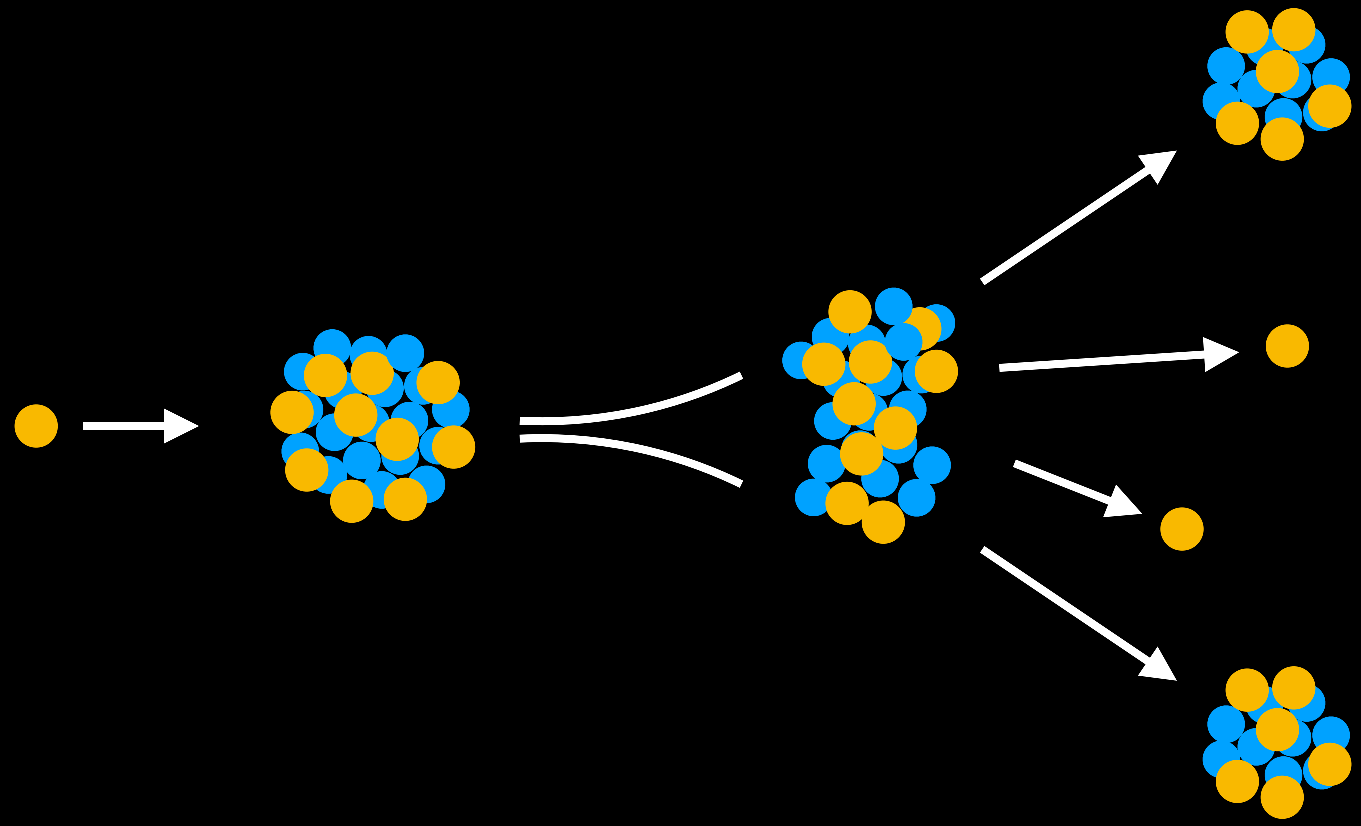

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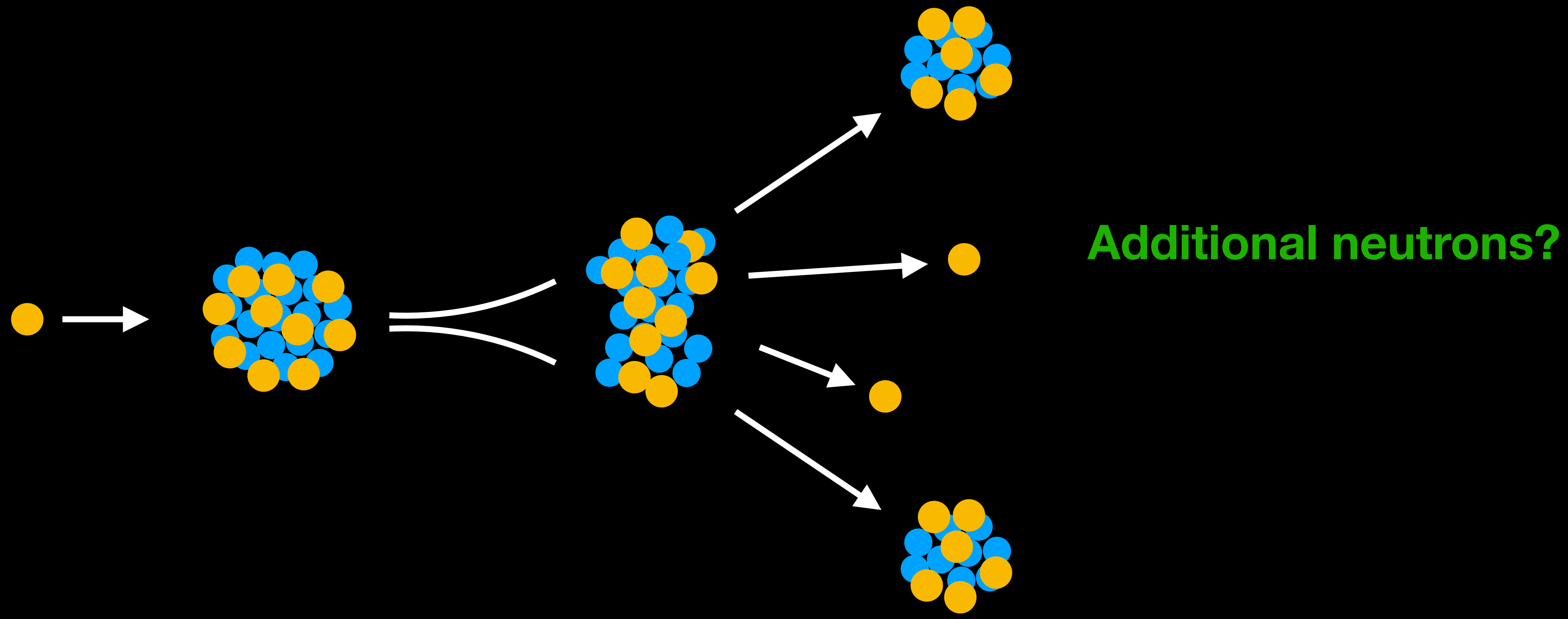

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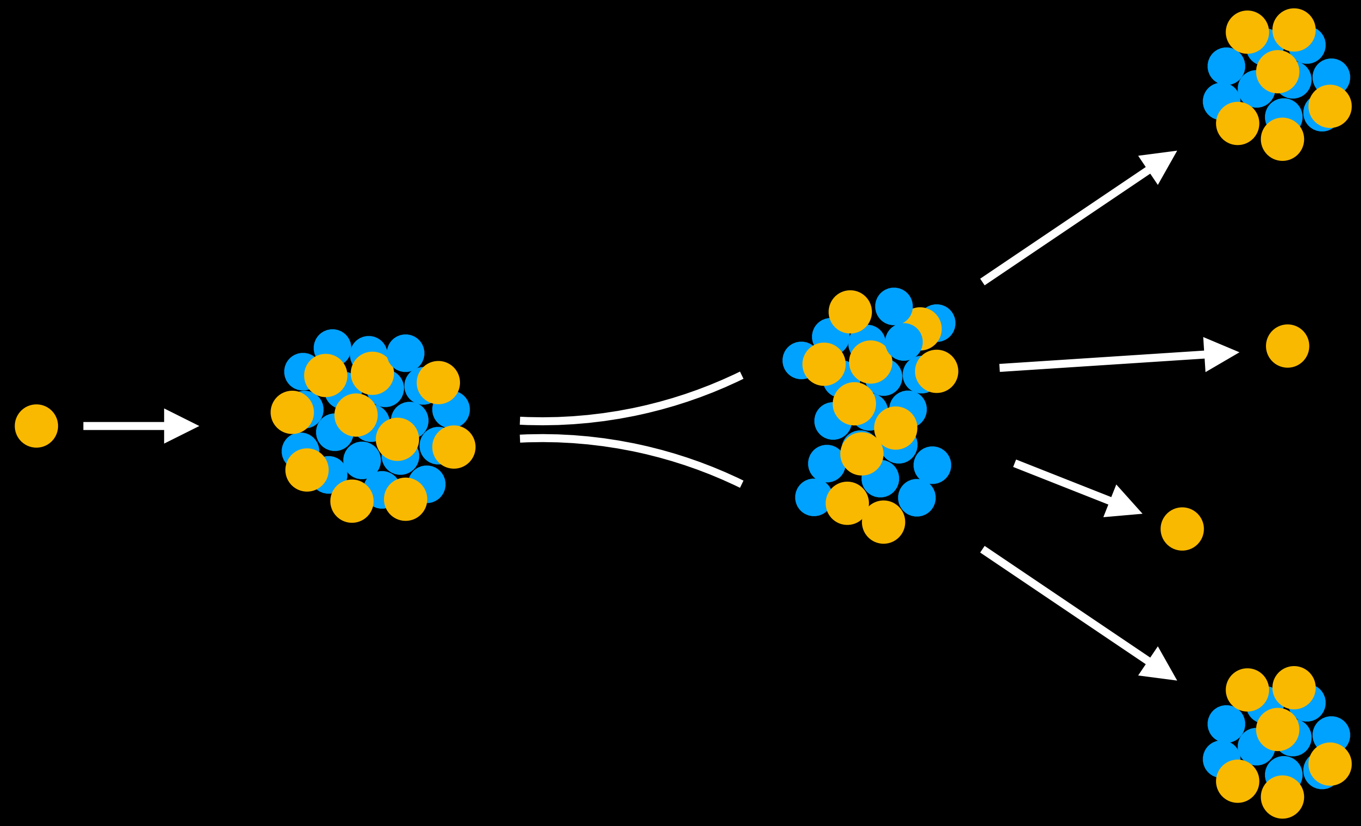

Additional neutrons?

If so, *how many*?

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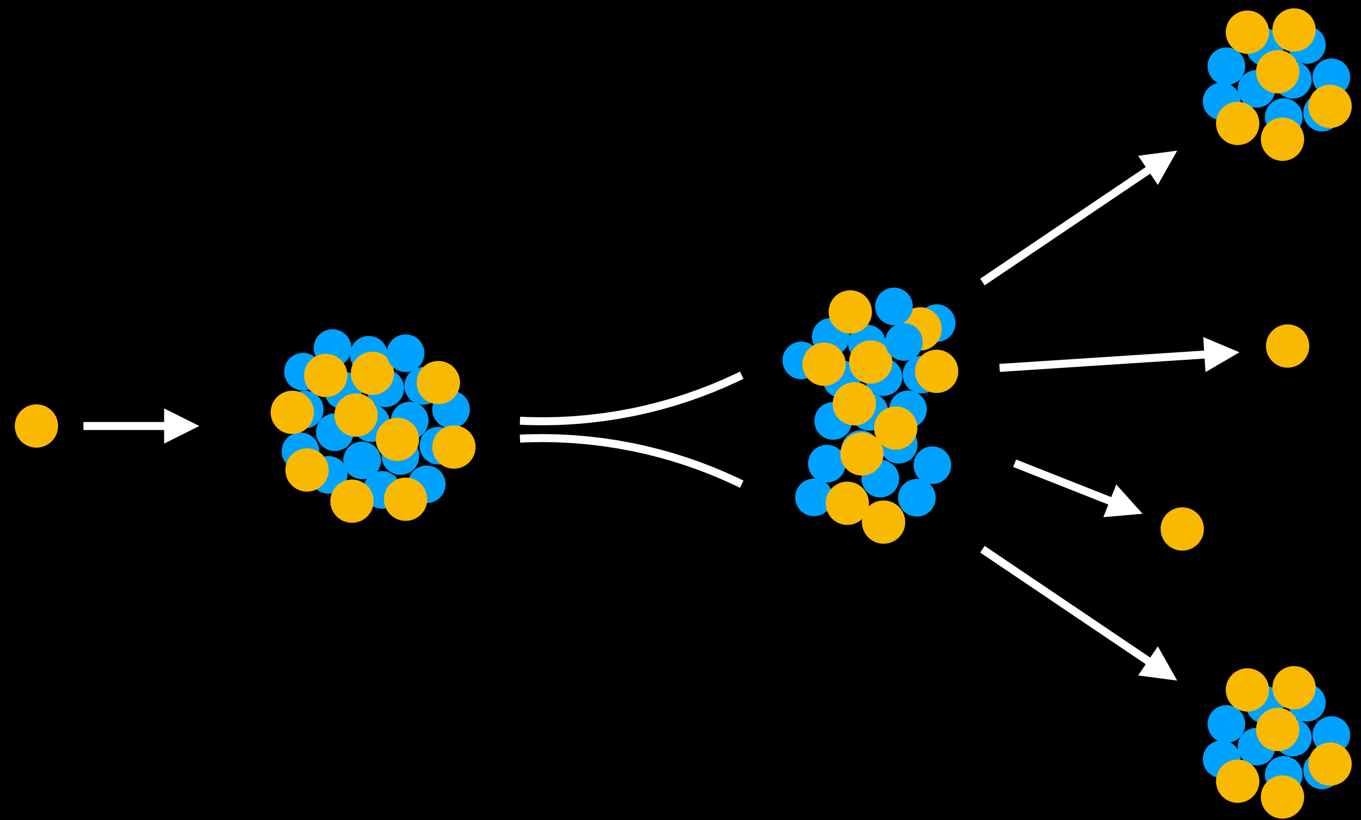


Additional neutrons?

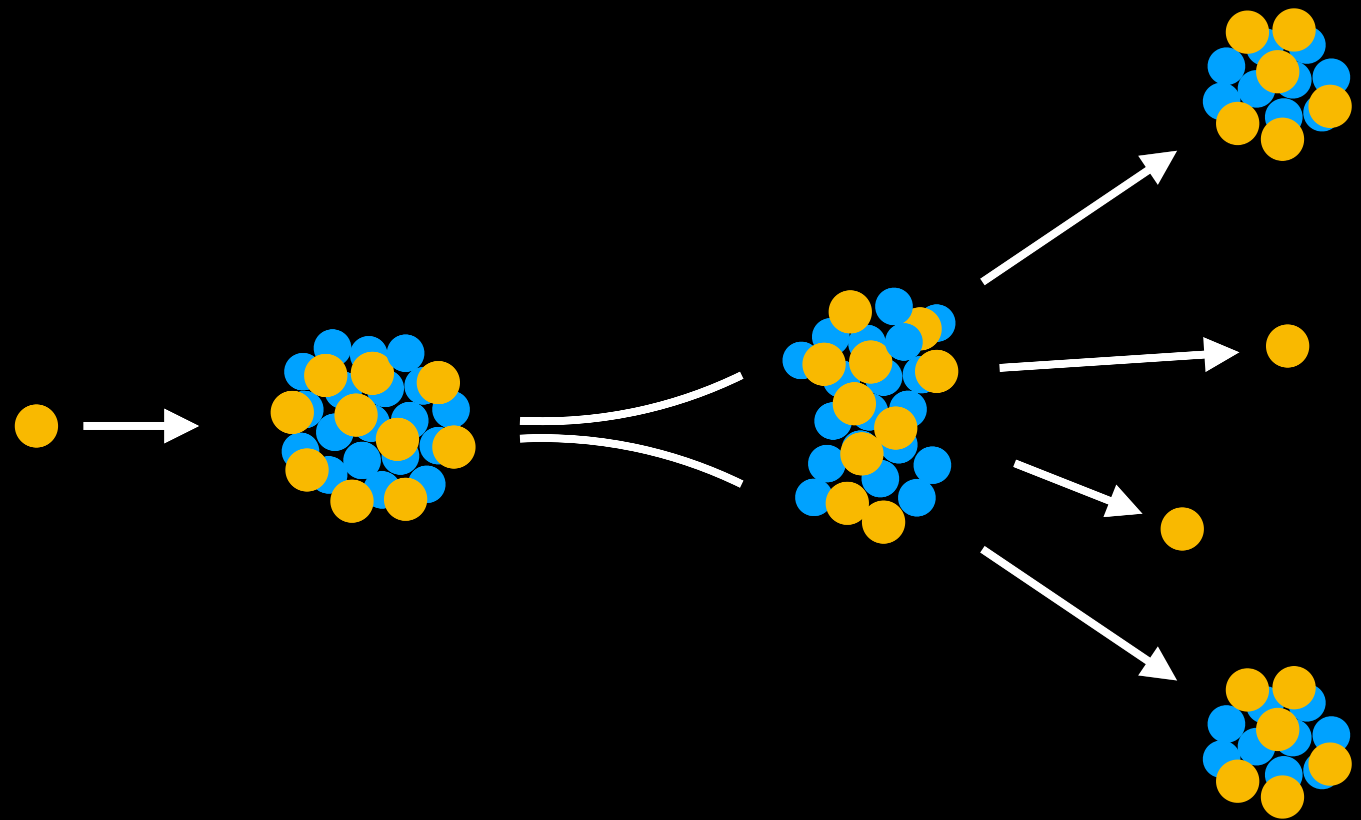
If so, *how many*?

Less than one

(on average)

Reaction will eventually stop

A chain reaction?



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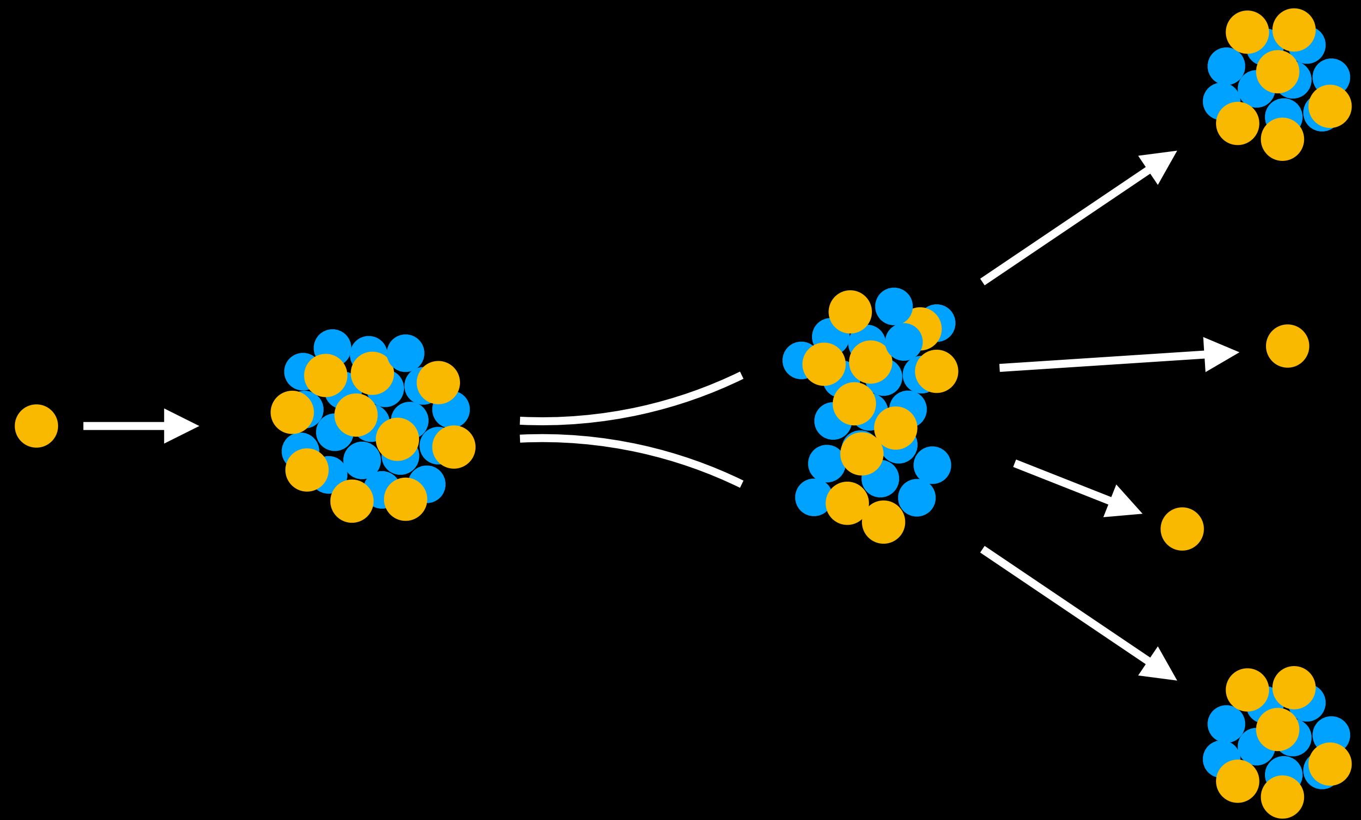

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Leo Szilard

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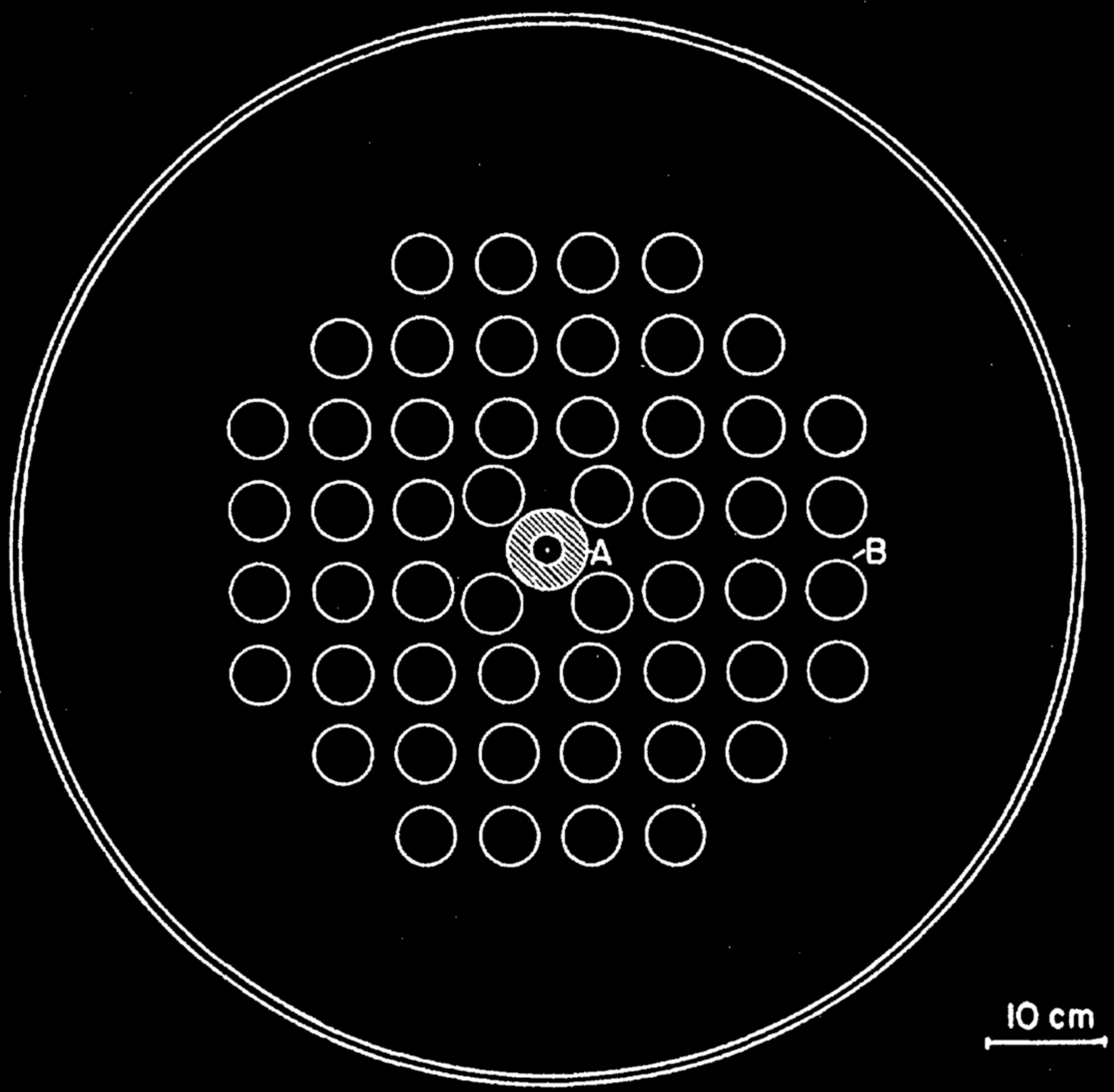

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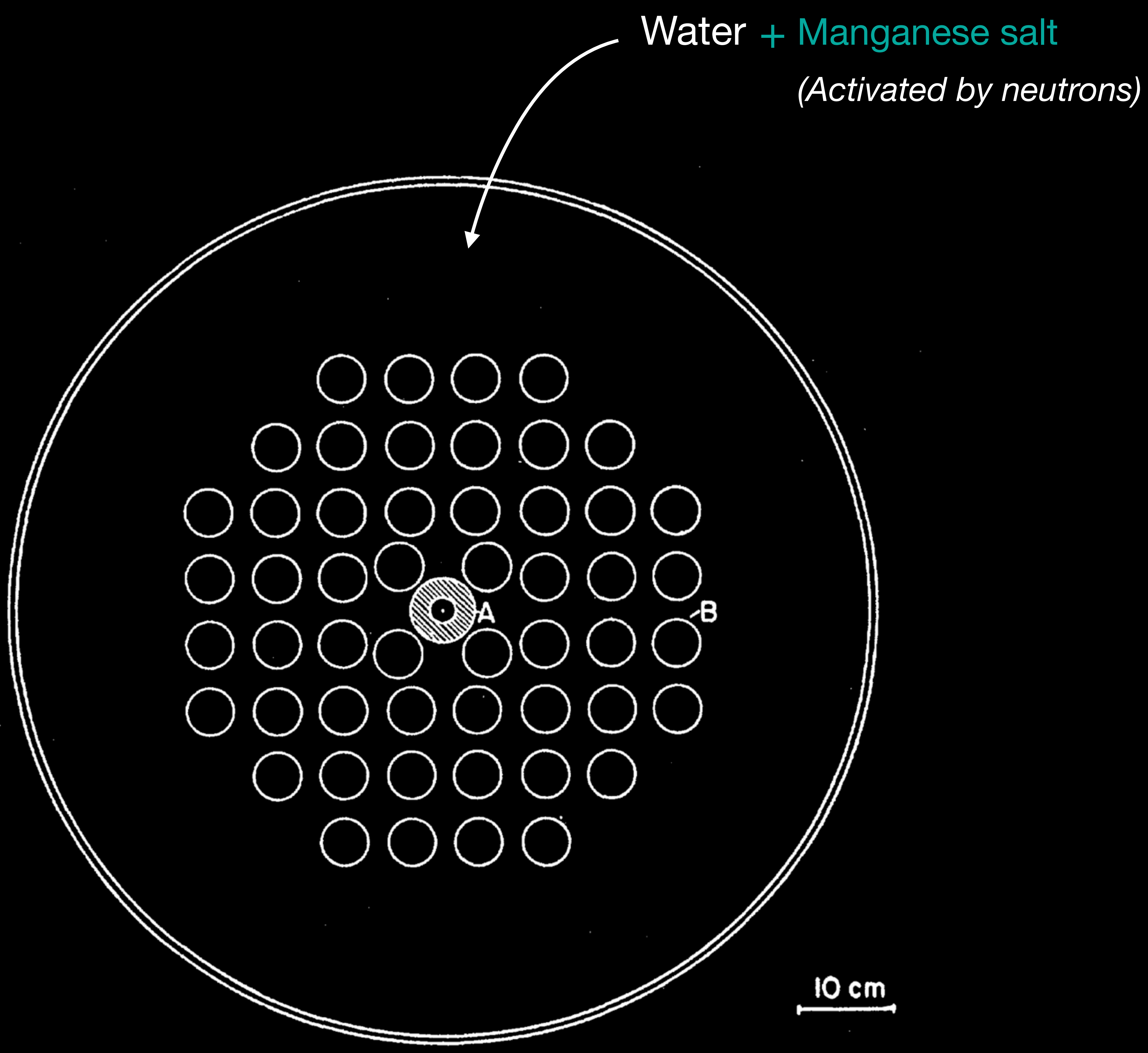

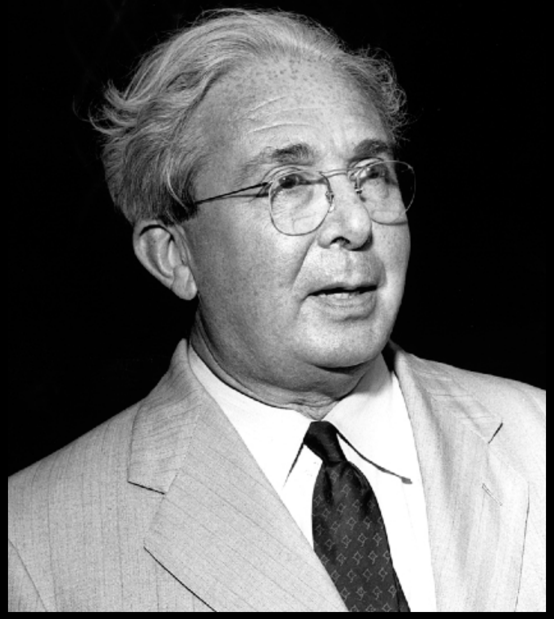

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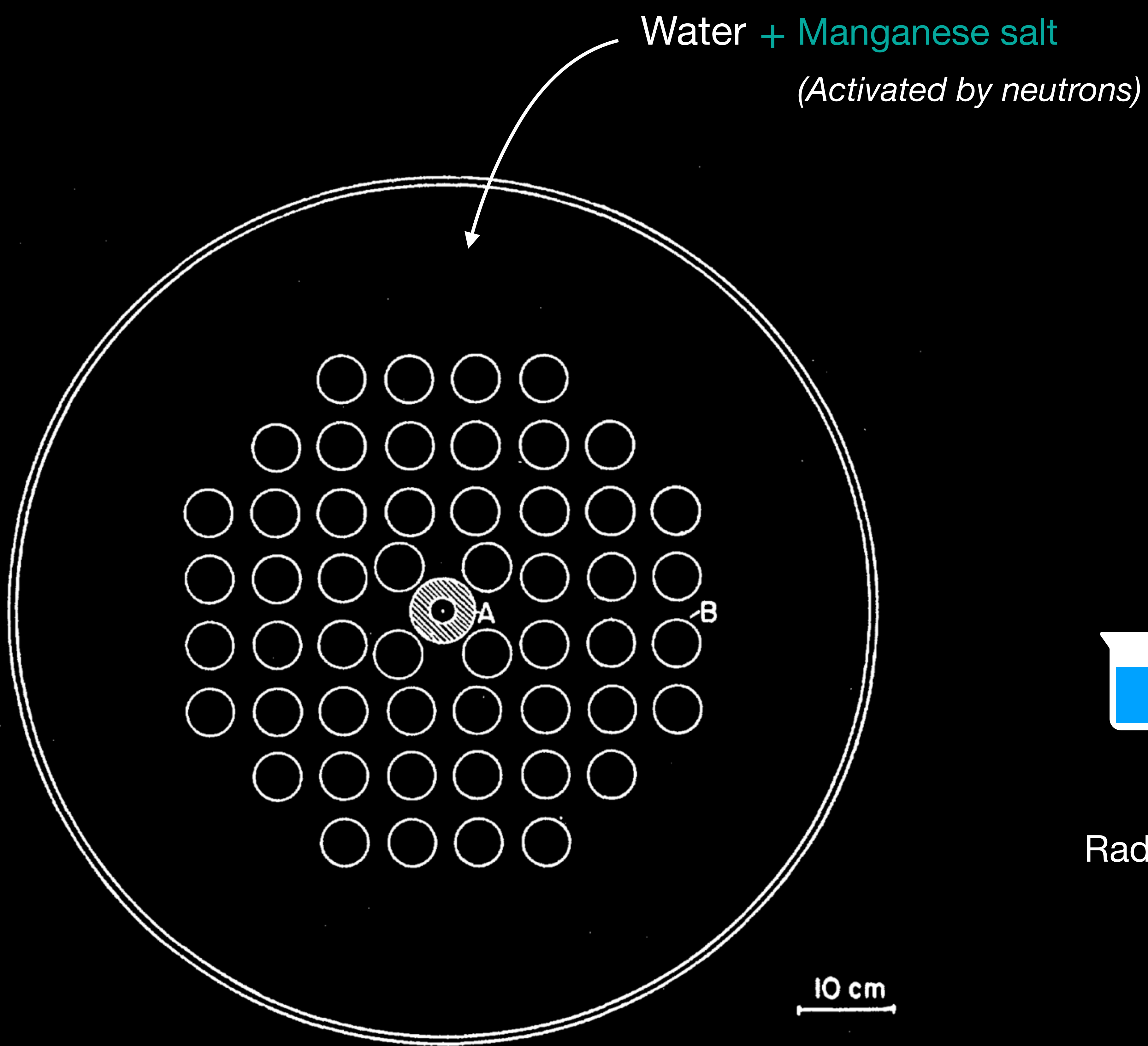
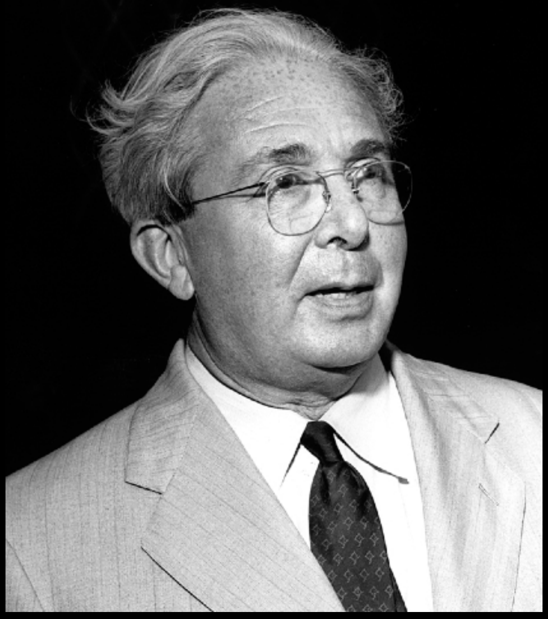
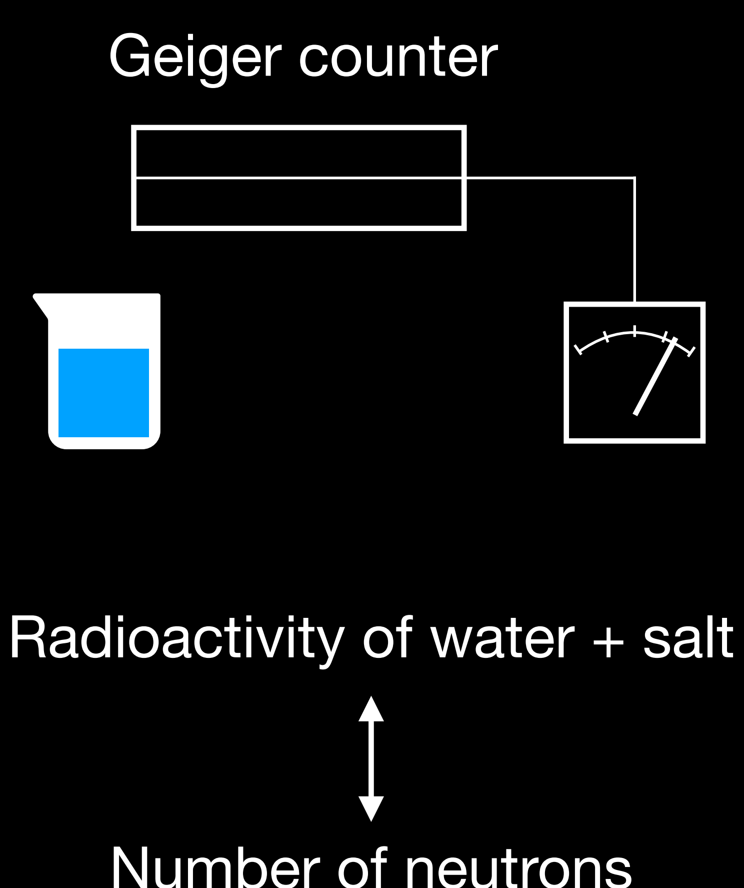




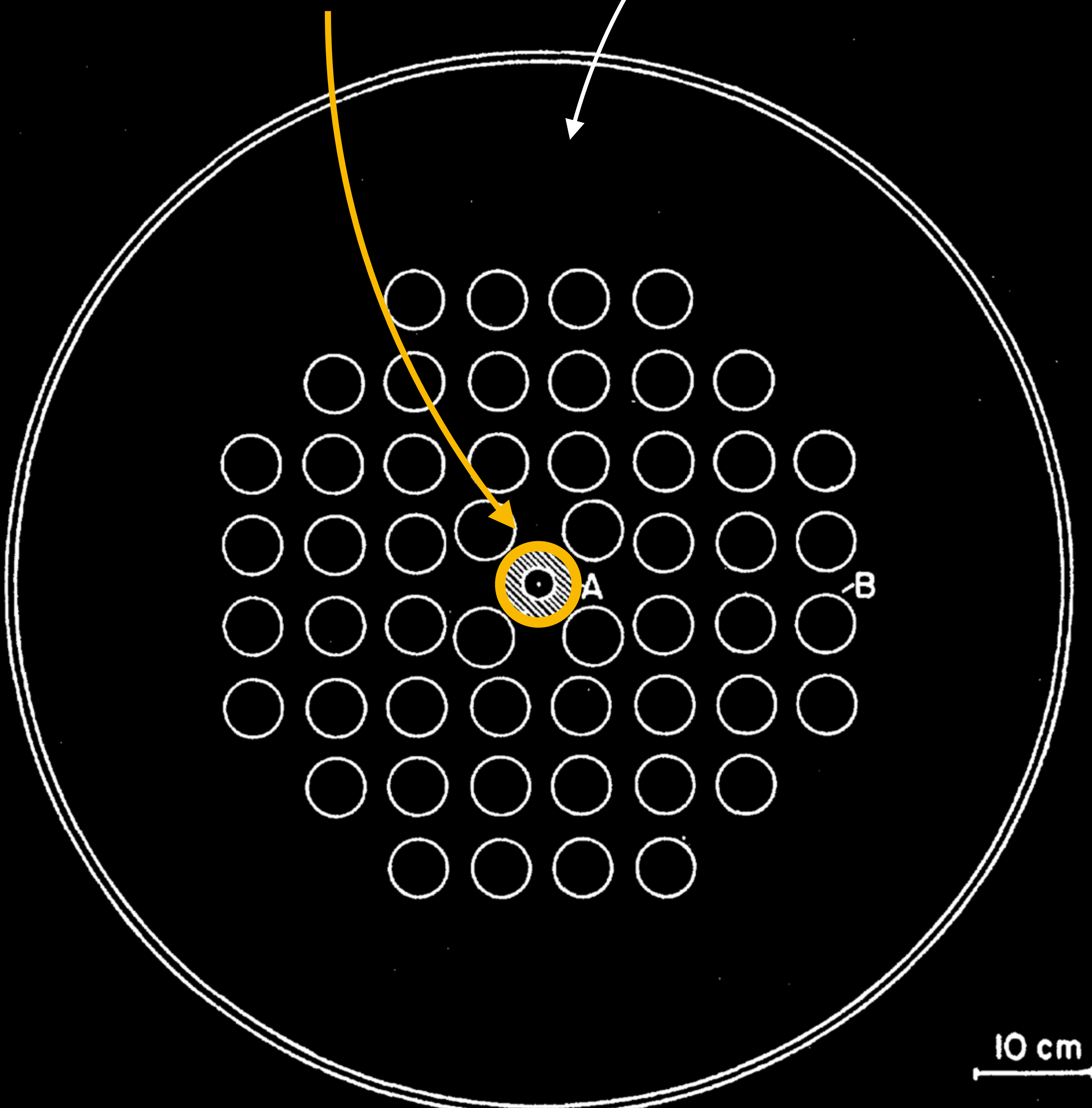
Leo Szilard



How many neutrons?

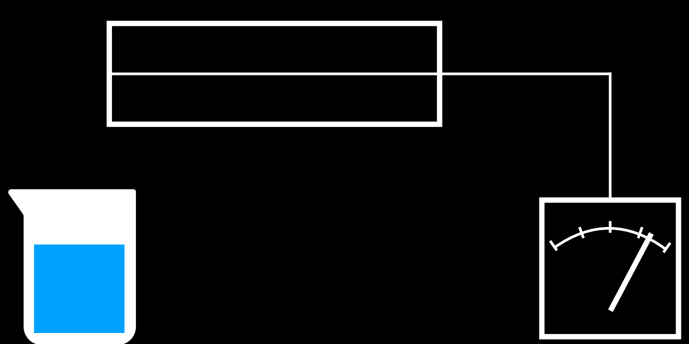
Radium-Beryllium
neutron source

Water + Manganese salt
(Activated by neutrons)



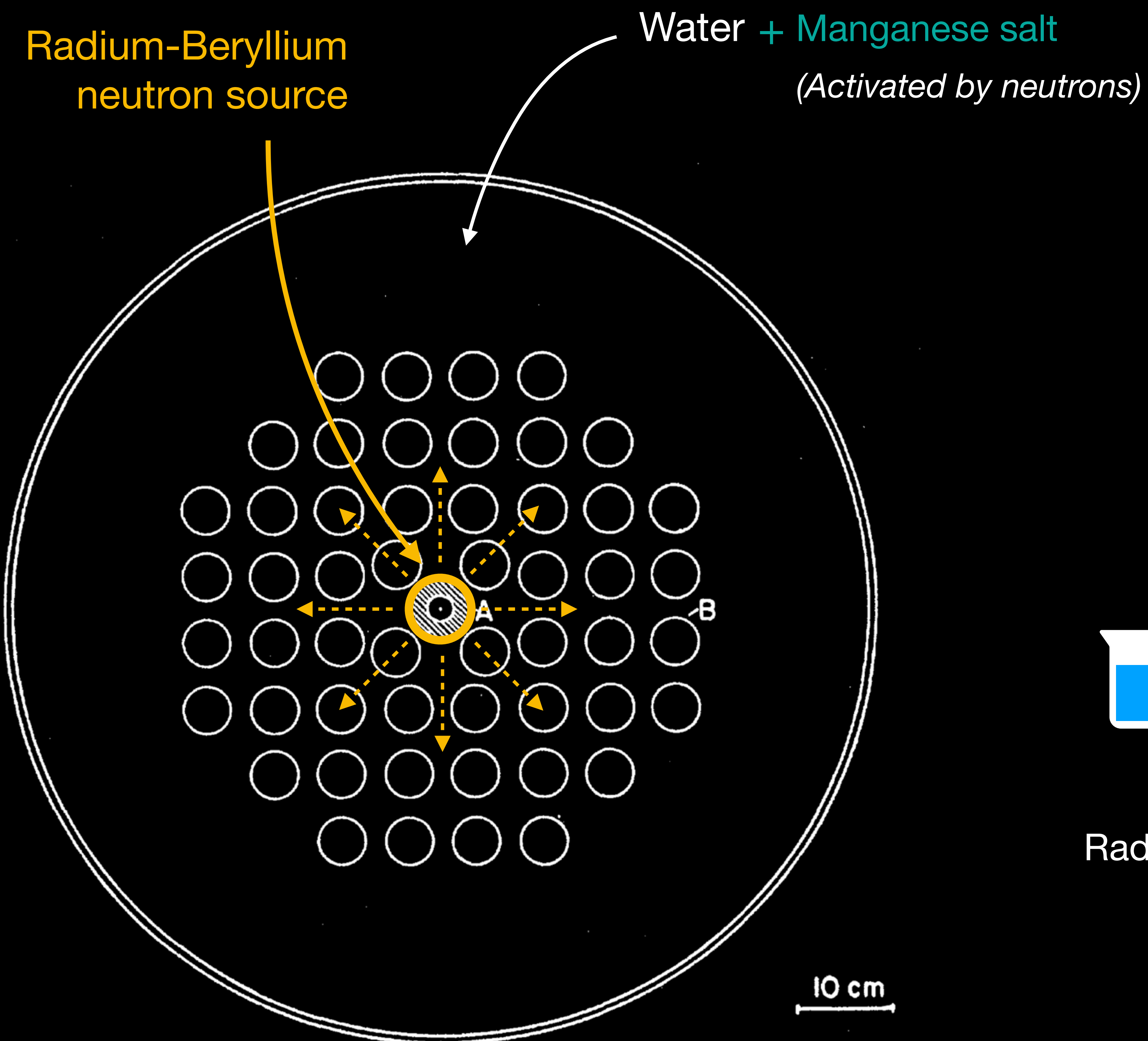
Leo Szilard

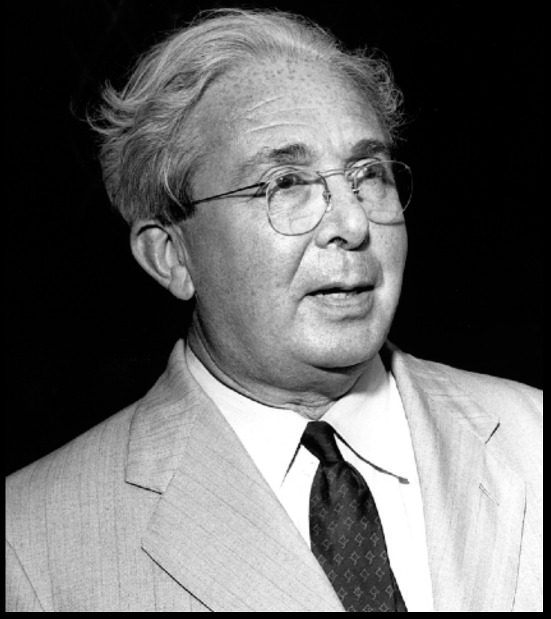
Geiger counter



Radioactivity of water + salt
↕
Number of neutrons

How many neutrons?





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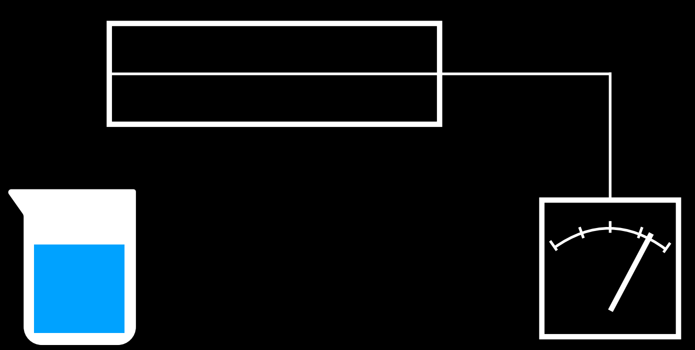

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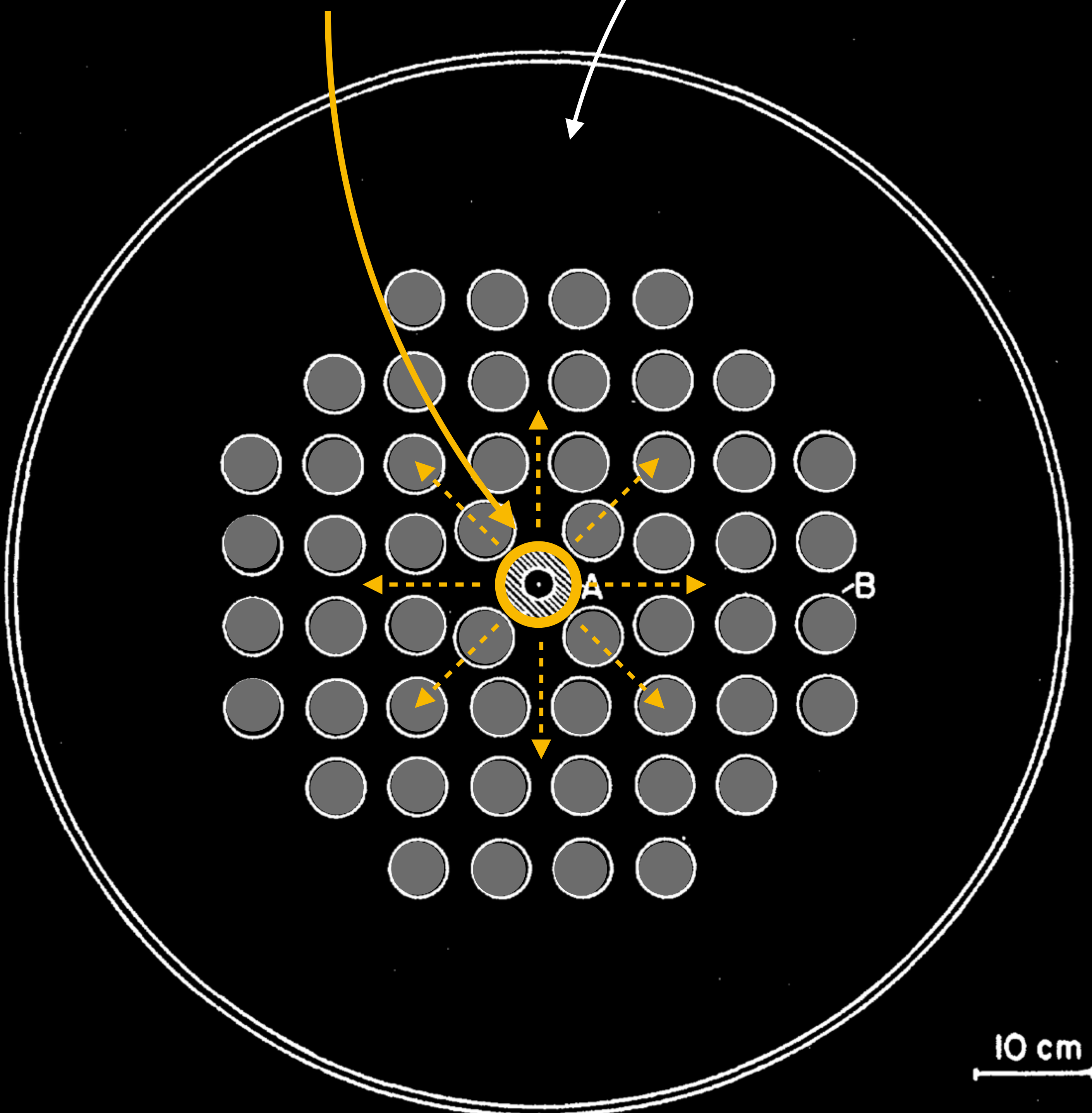

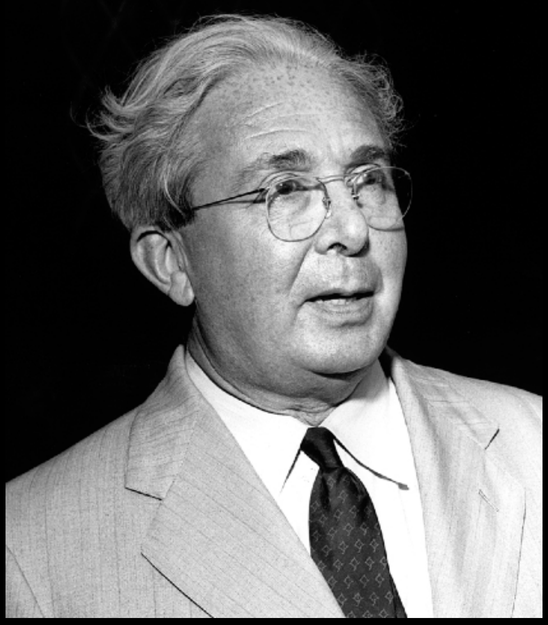

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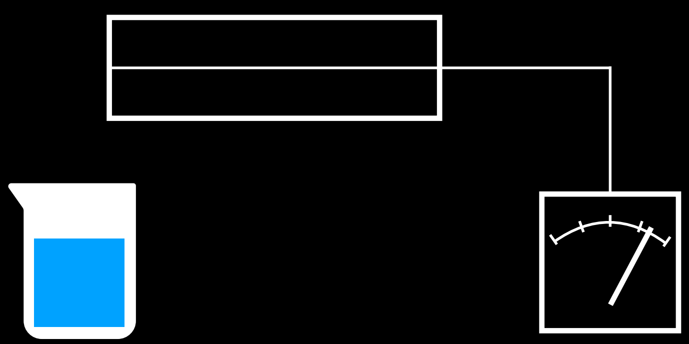

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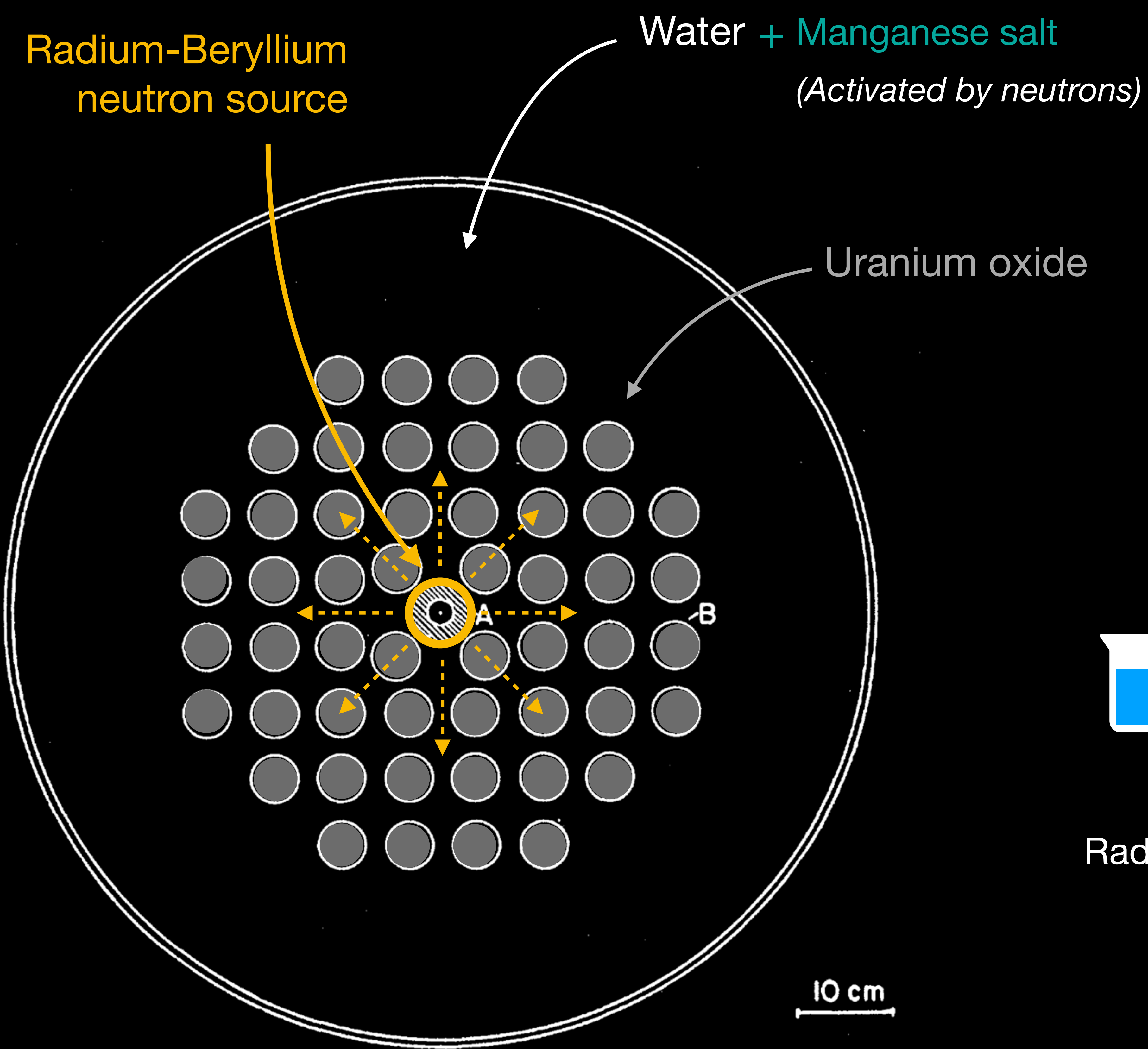

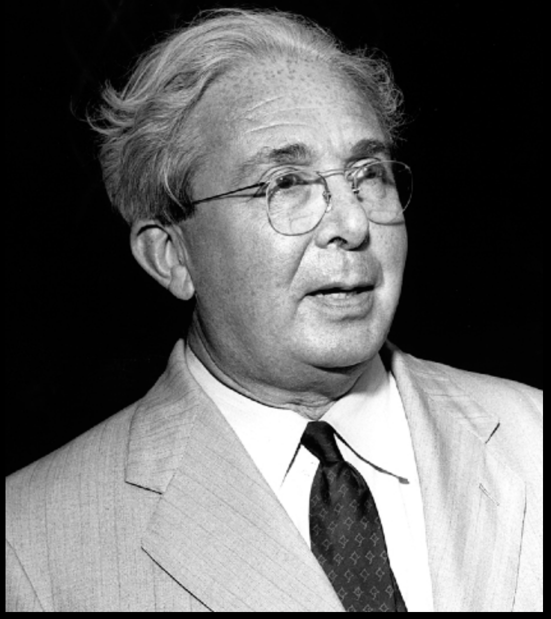

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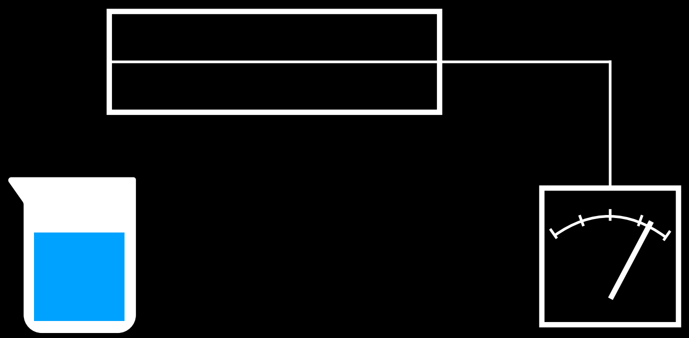

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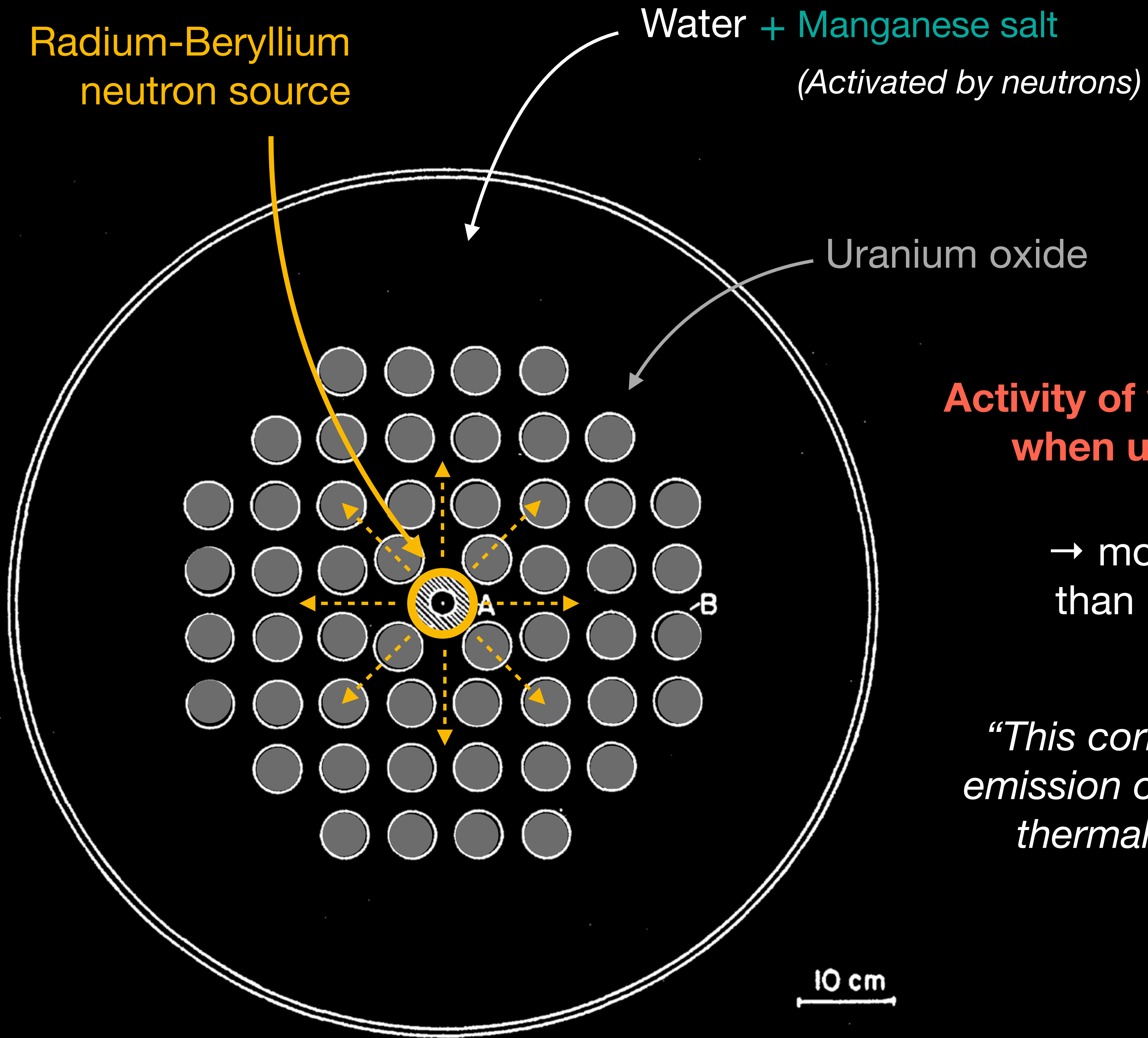
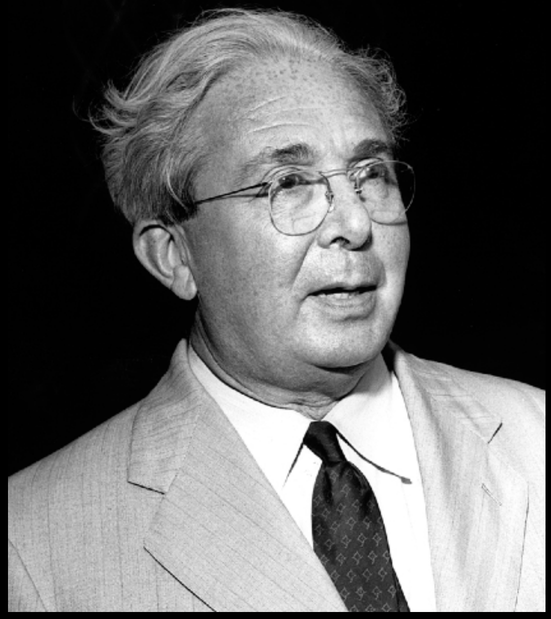




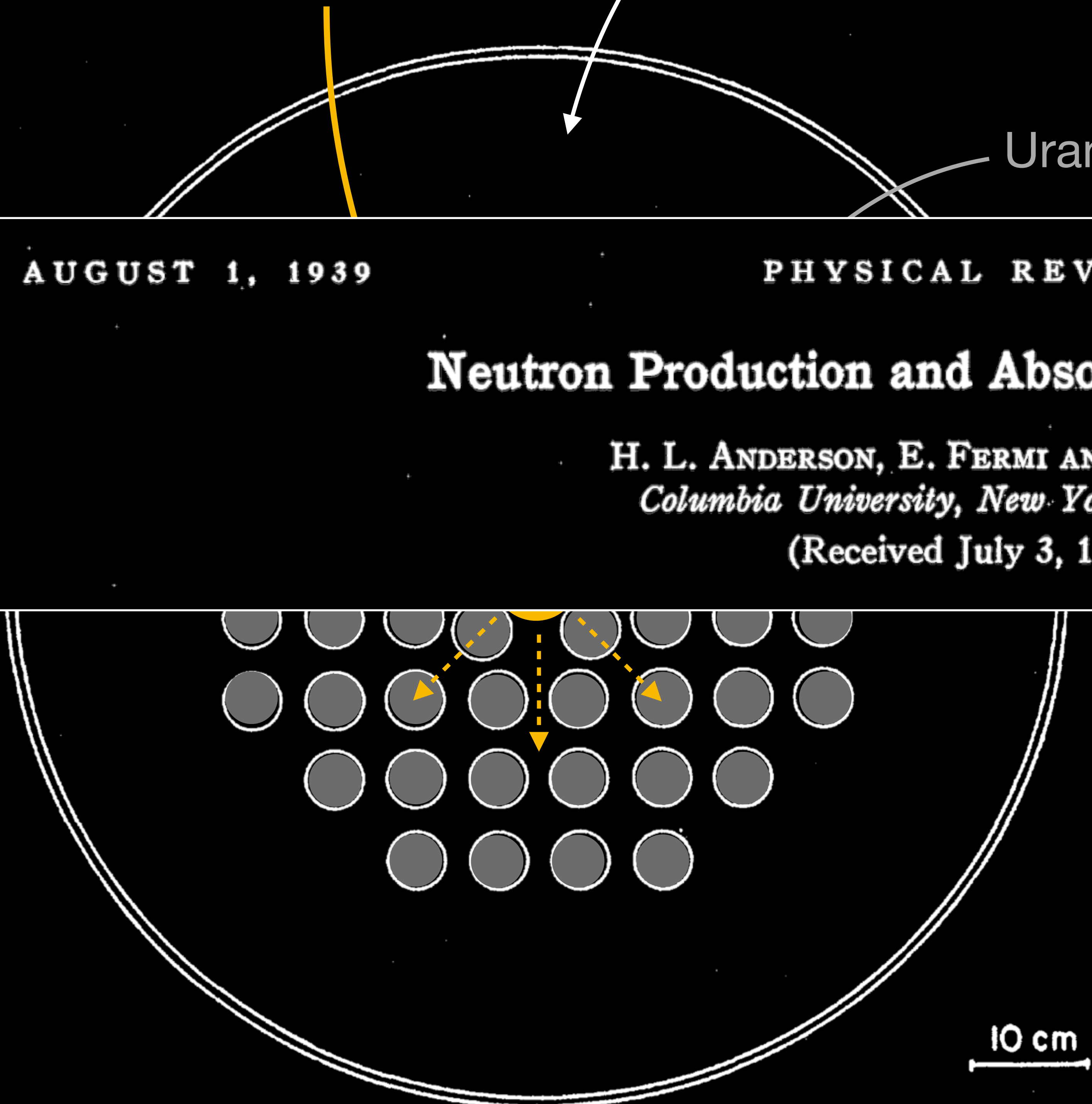
Leo Szilard

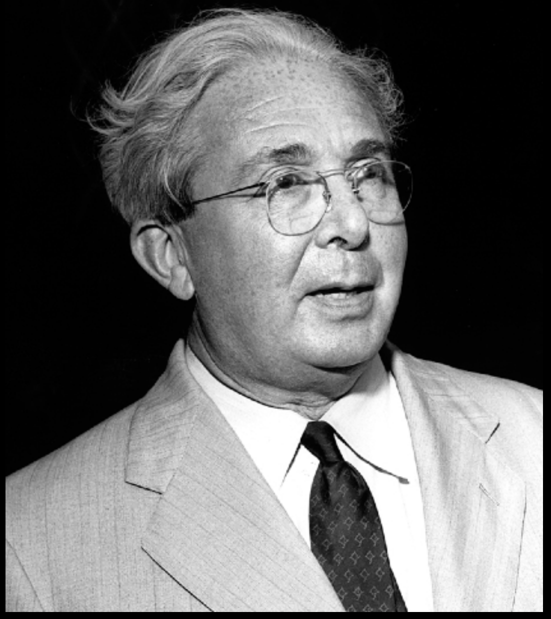
Activity of water increased by 10% when uranium was present!

→ more neutrons emitted than neutrons absorbed!

"This corresponds to an average emission of about 1.2 neutrons per thermal neutron absorbed by uranium."

How many neutrons?





AUGUST 1, 1939 PHYSICAL REVIEW VOLUME 56

Neutron Production and Absorption in Uranium*

H. L. Anderson, E. Fermi and Leo Szilard
Columbia University, New York, New York

(Received July 3, 1939)

"This corresponds to an average emission of about 1.2 neutrons per thermal neutron absorbed by uranium."

A practical chain reaction?

A self-sustaining chain reaction is possible in principle …

… how to make it work in practice?

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“1.5 neutrons per fission”

→ quite tight!

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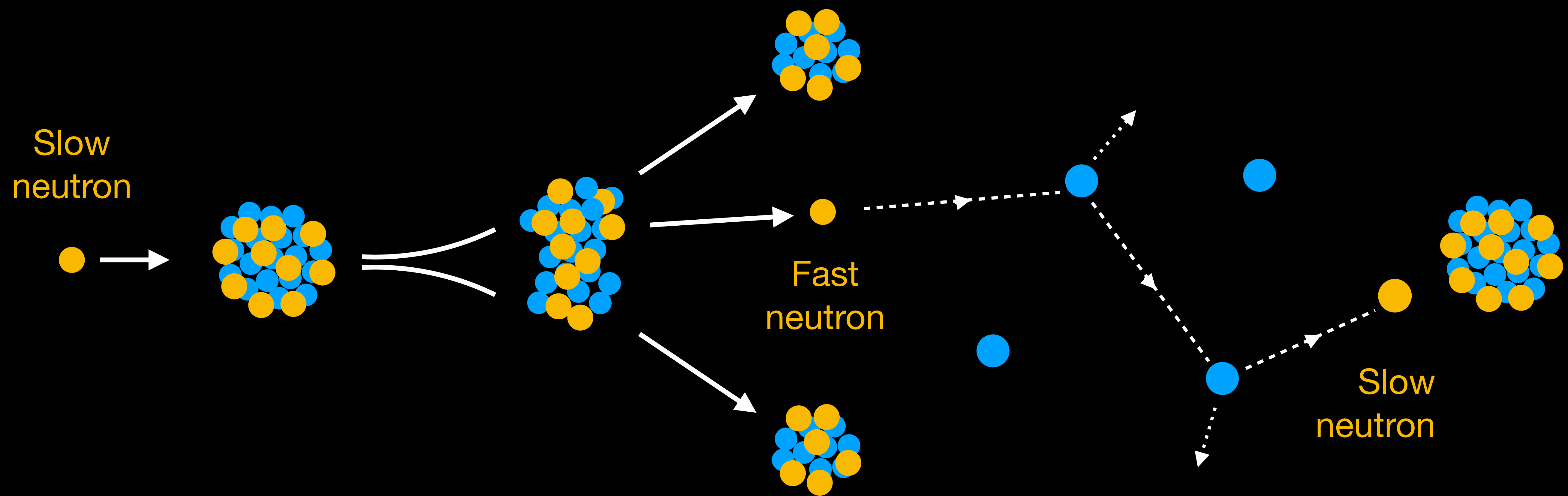

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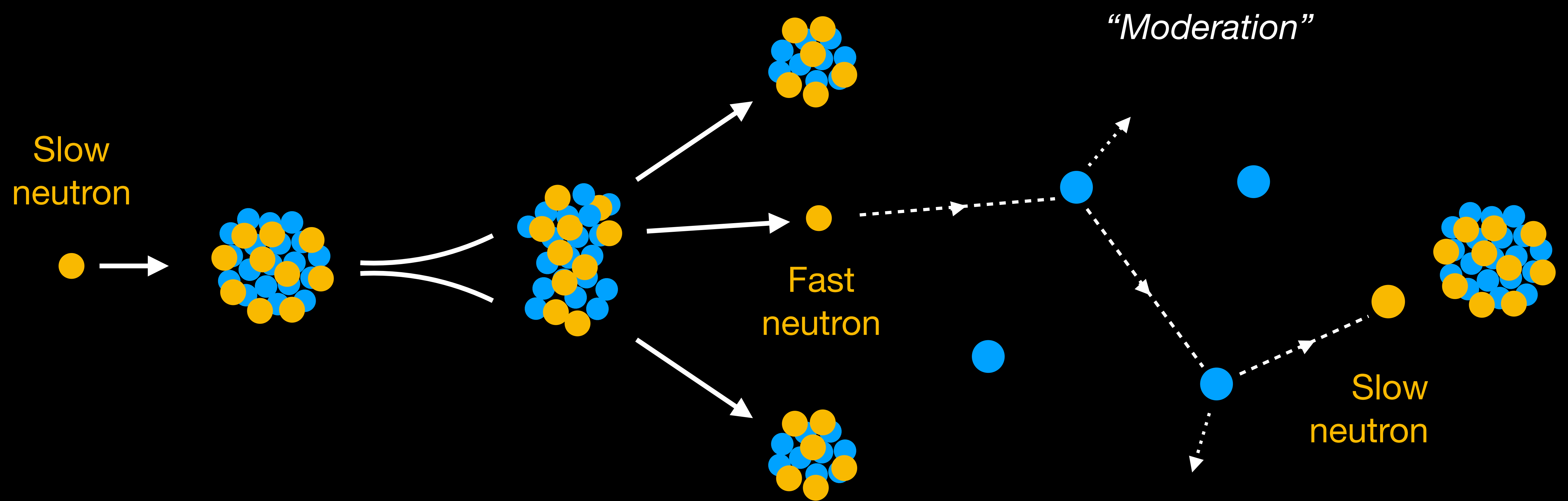

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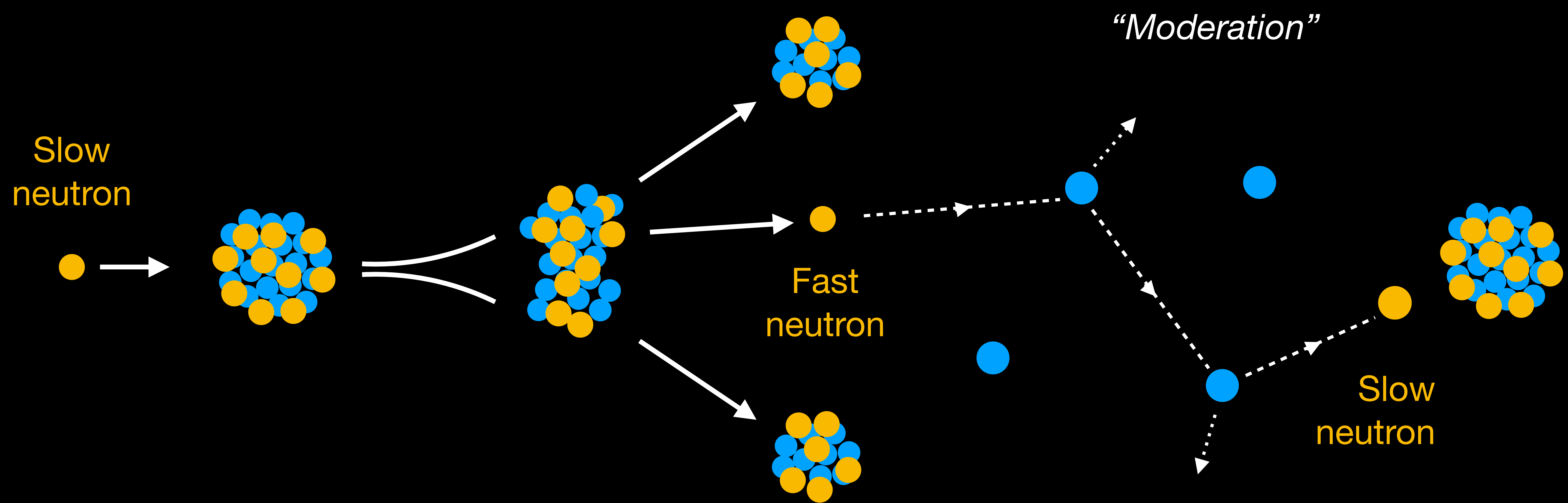

"1.5 neutrons per fission"

→ quite tight!

Need to slow down neutrons without losing them!

Which moderator to use?

Which moderator to use?

Light atoms

Densely packed

Minimum neutron absorption

Which moderator to use?

Light atoms

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Minimum neutron absorption

Light

Heavy

Which moderator to use?

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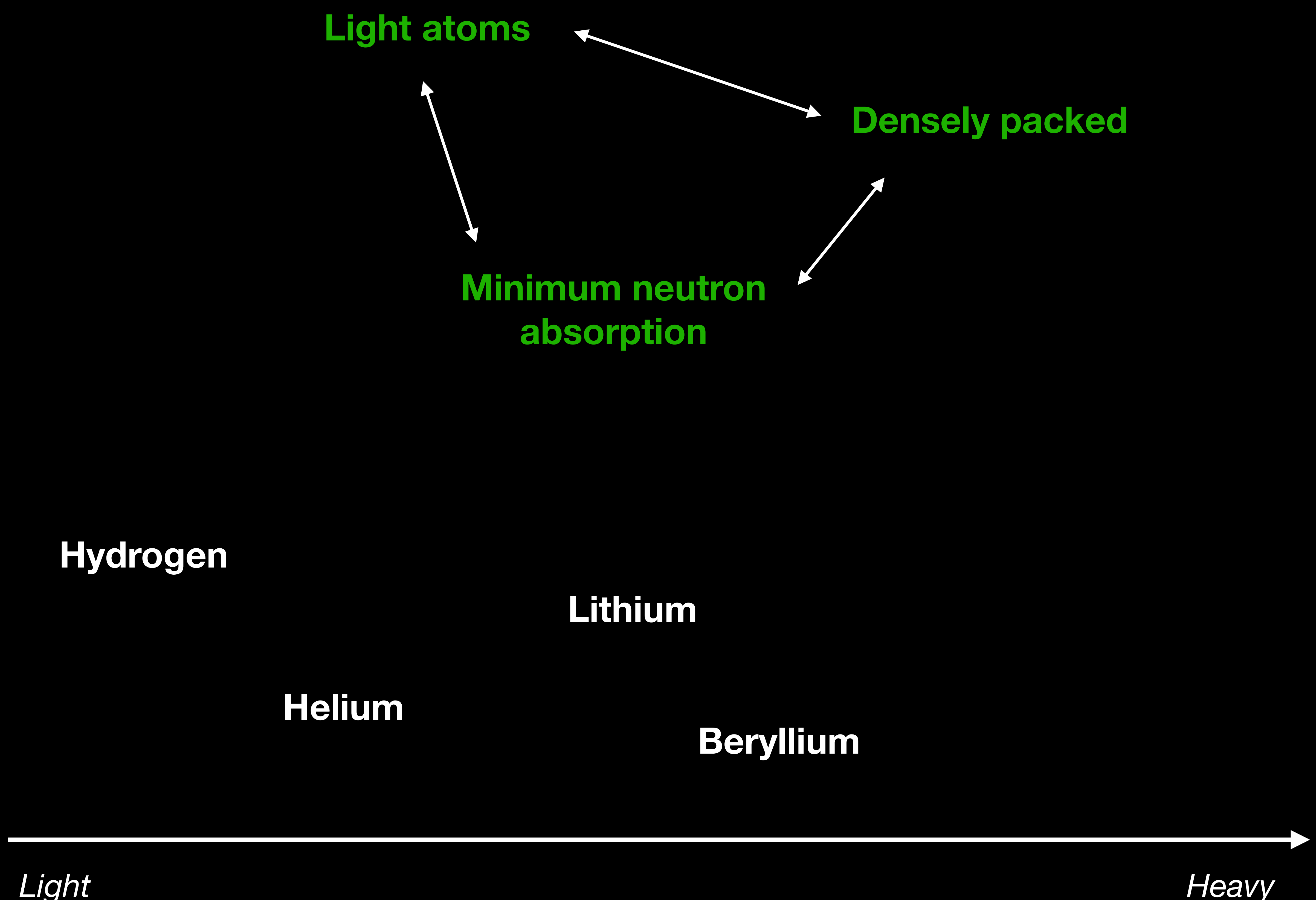
Minimum neutron absorption

Hydrogen

Helium

Light *Heavy*

Which moderator to use?



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Hydrogen

Helium

Lithium

Beryllium

Boron

Light

Heavy

Which moderator to use?

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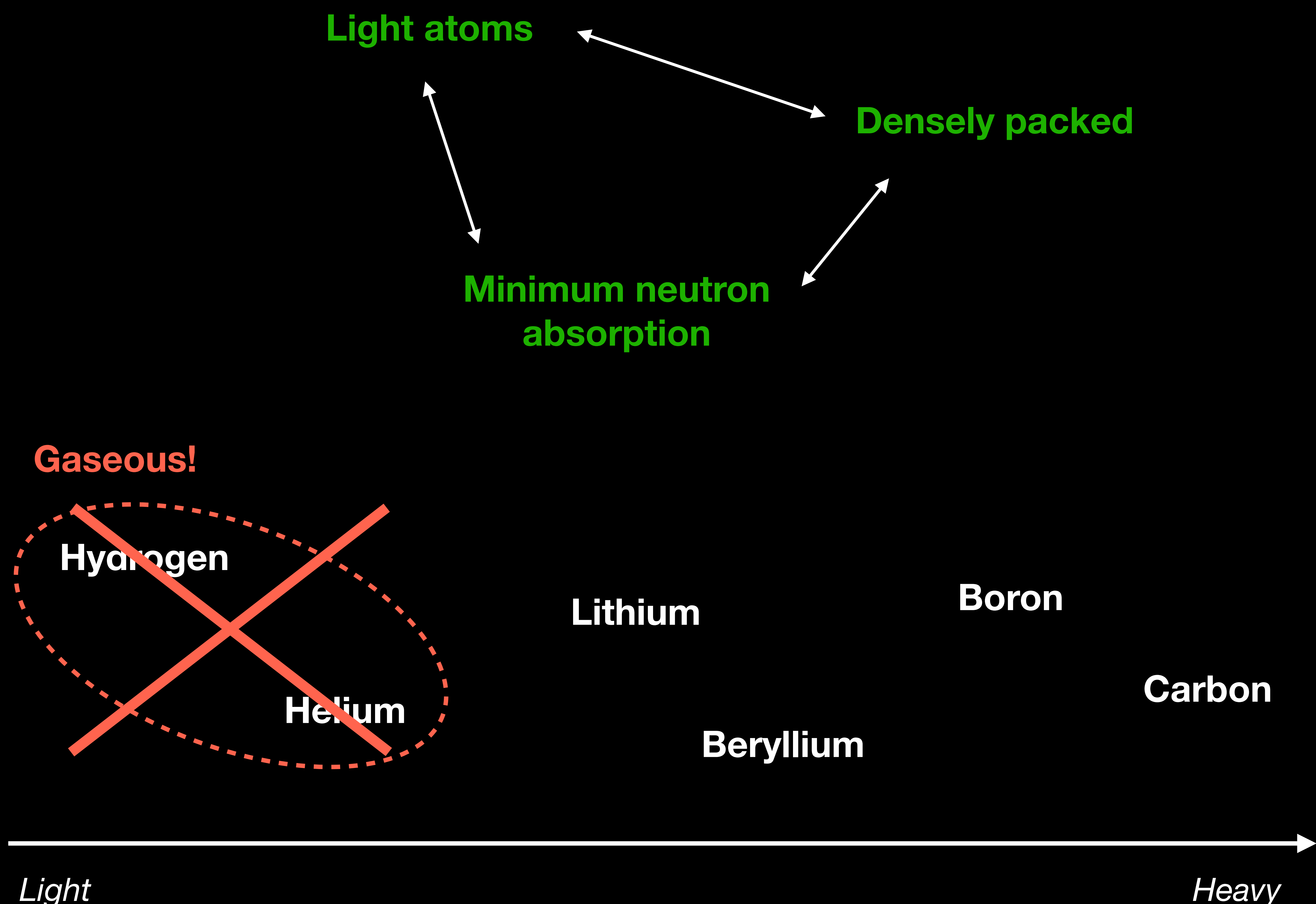

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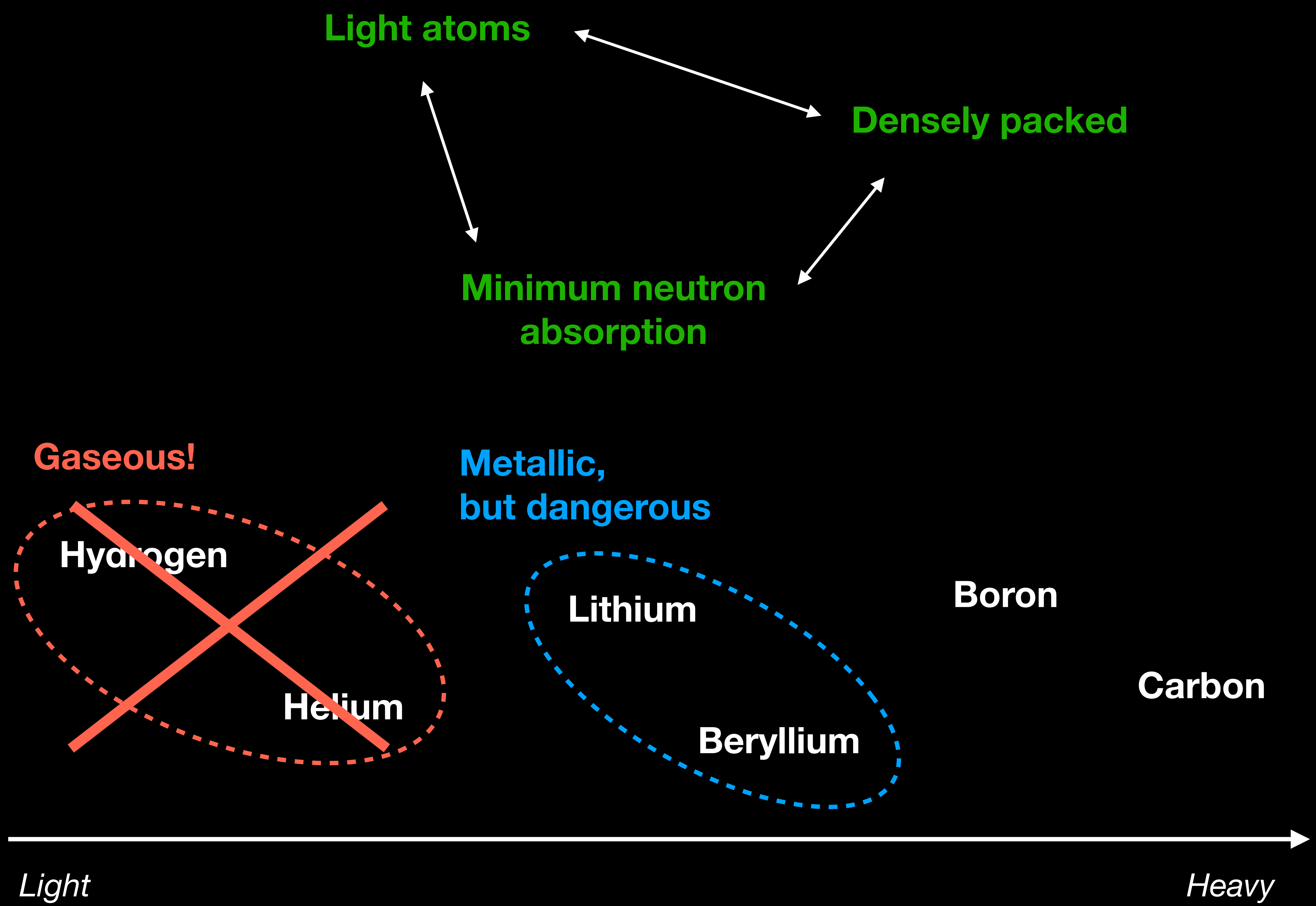

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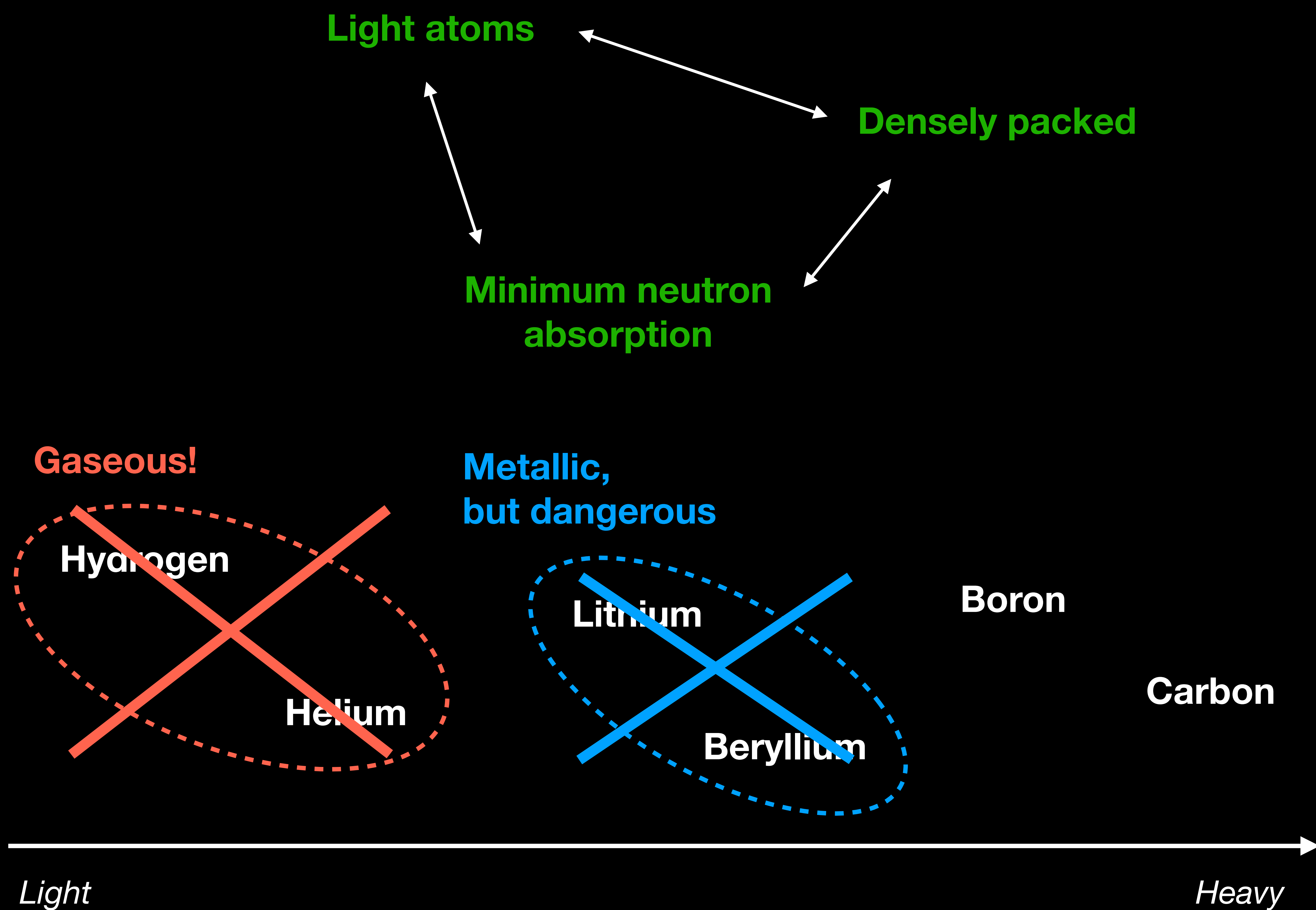

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Gaseous!

~~Hydrogen~~

~~Helium~~

Metallic, but dangerous

~~Lithium~~

~~Beryllium~~

Not easily available

Boron

Carbon

Light

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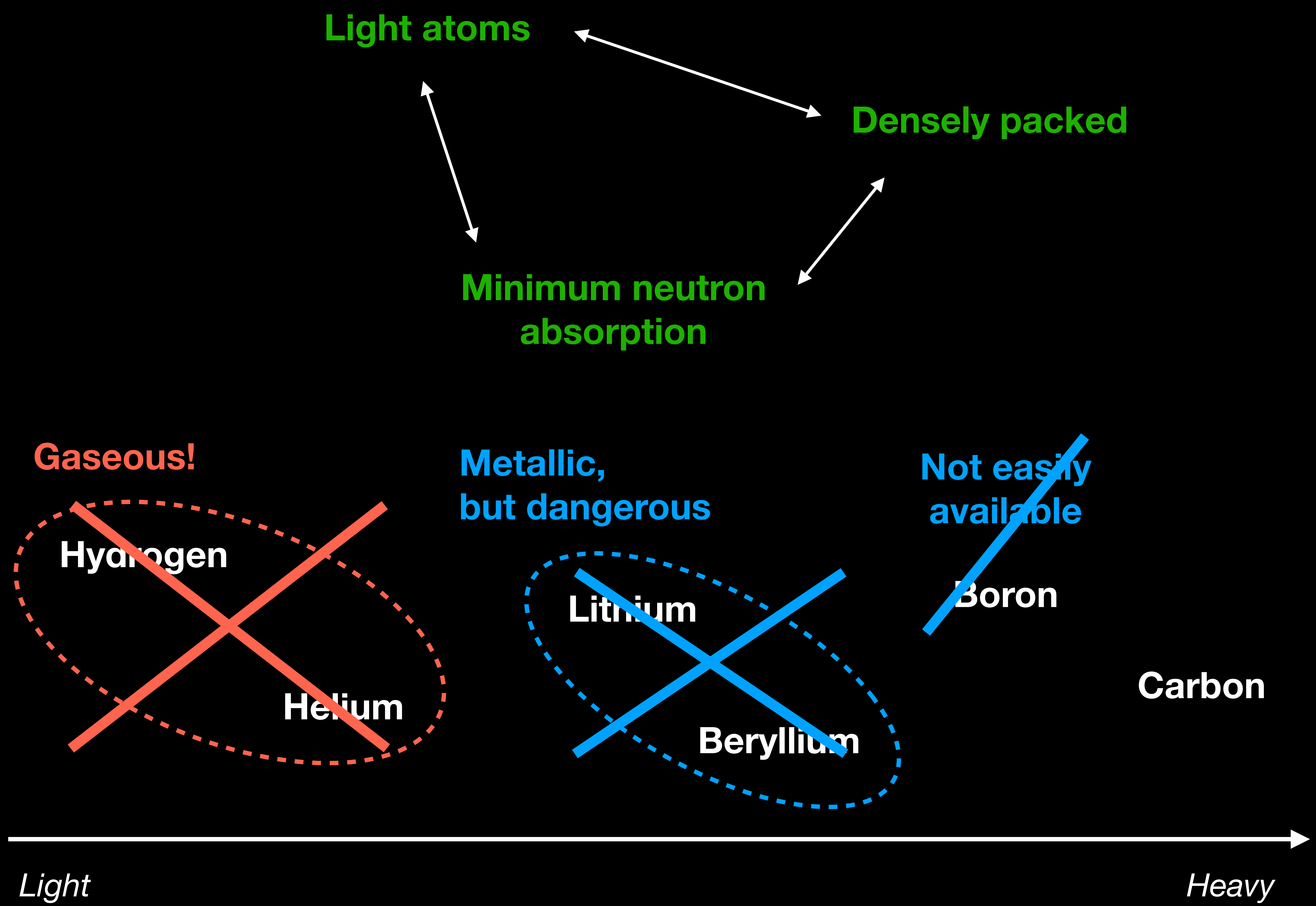

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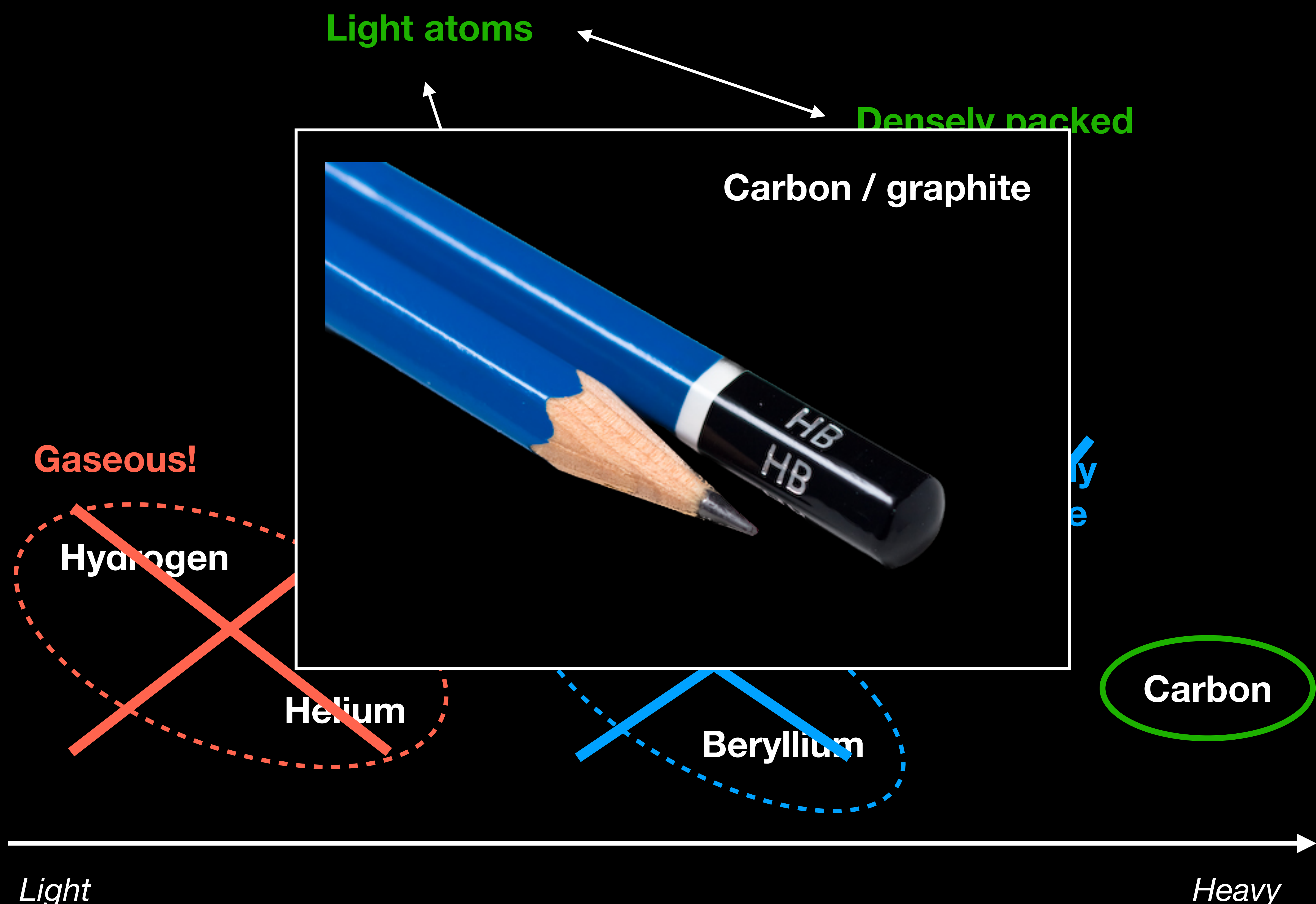
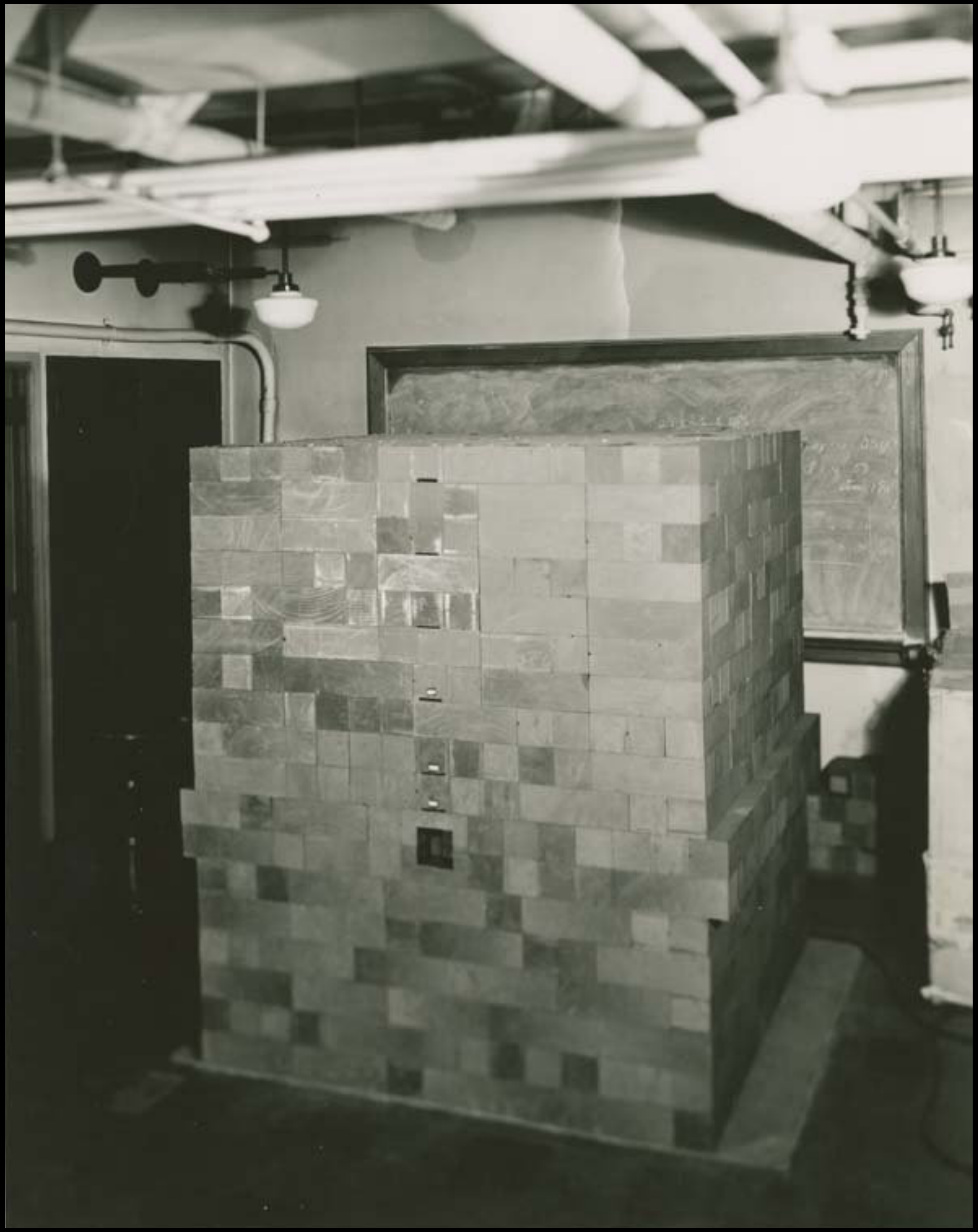
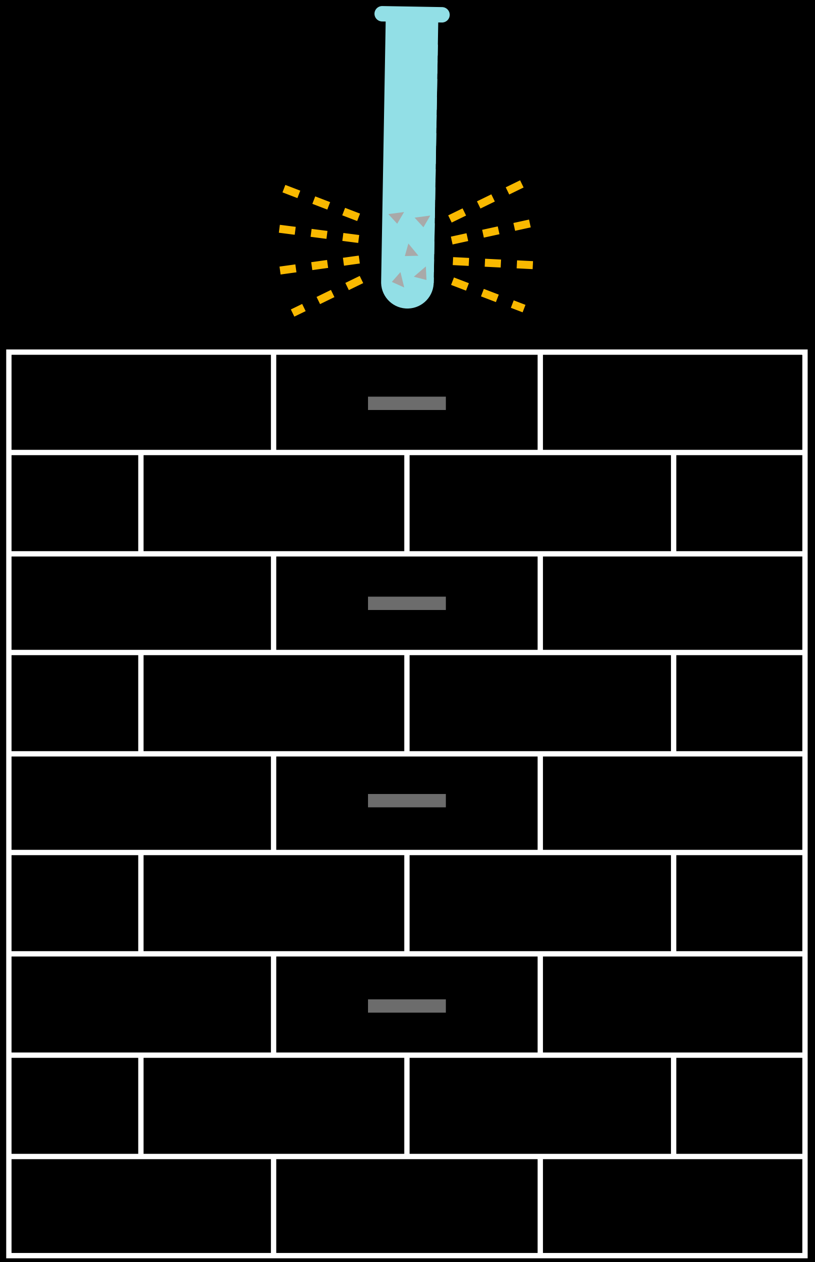


Measuring neutron diffusion

Spring 1940



Test pile at Columbia



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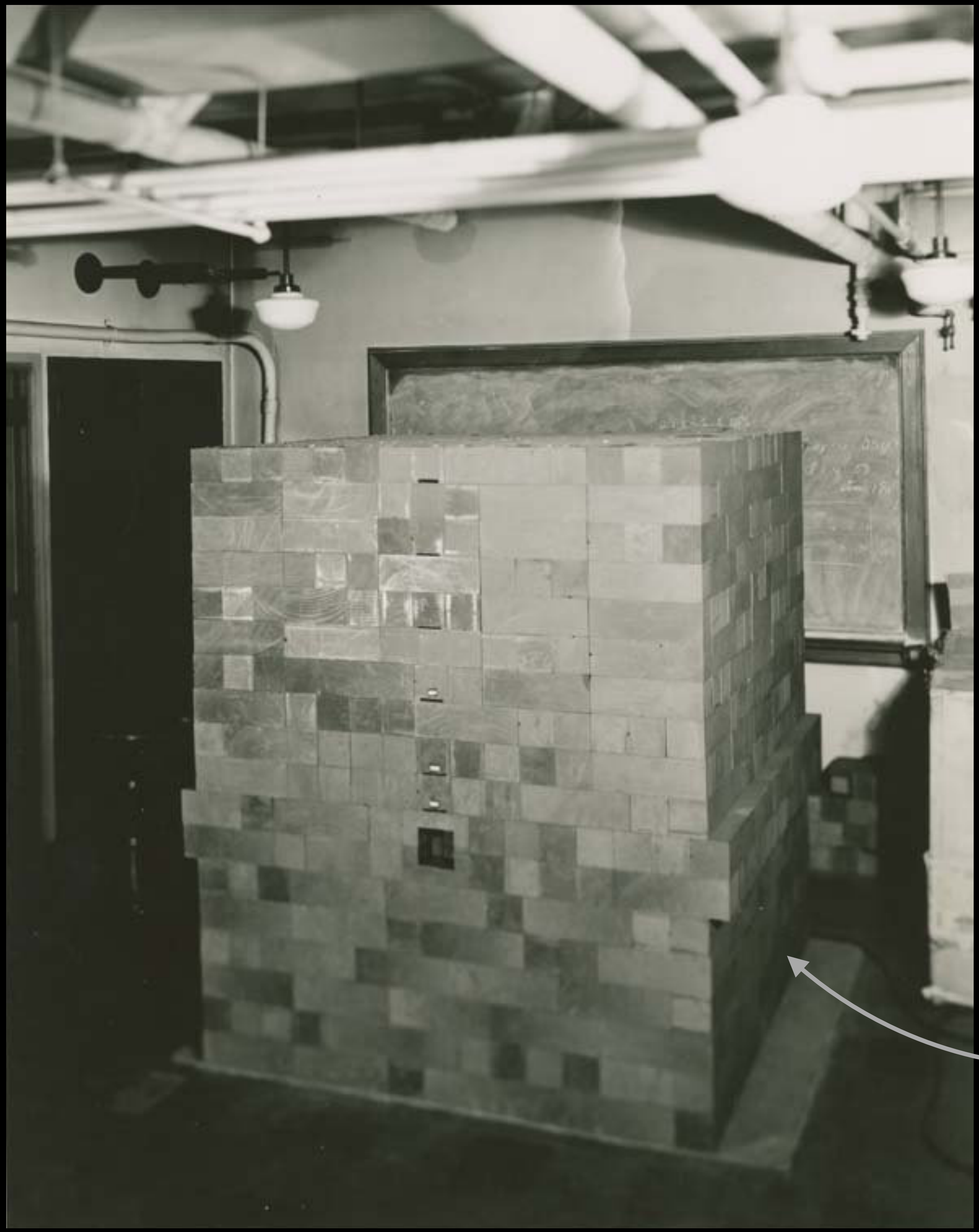
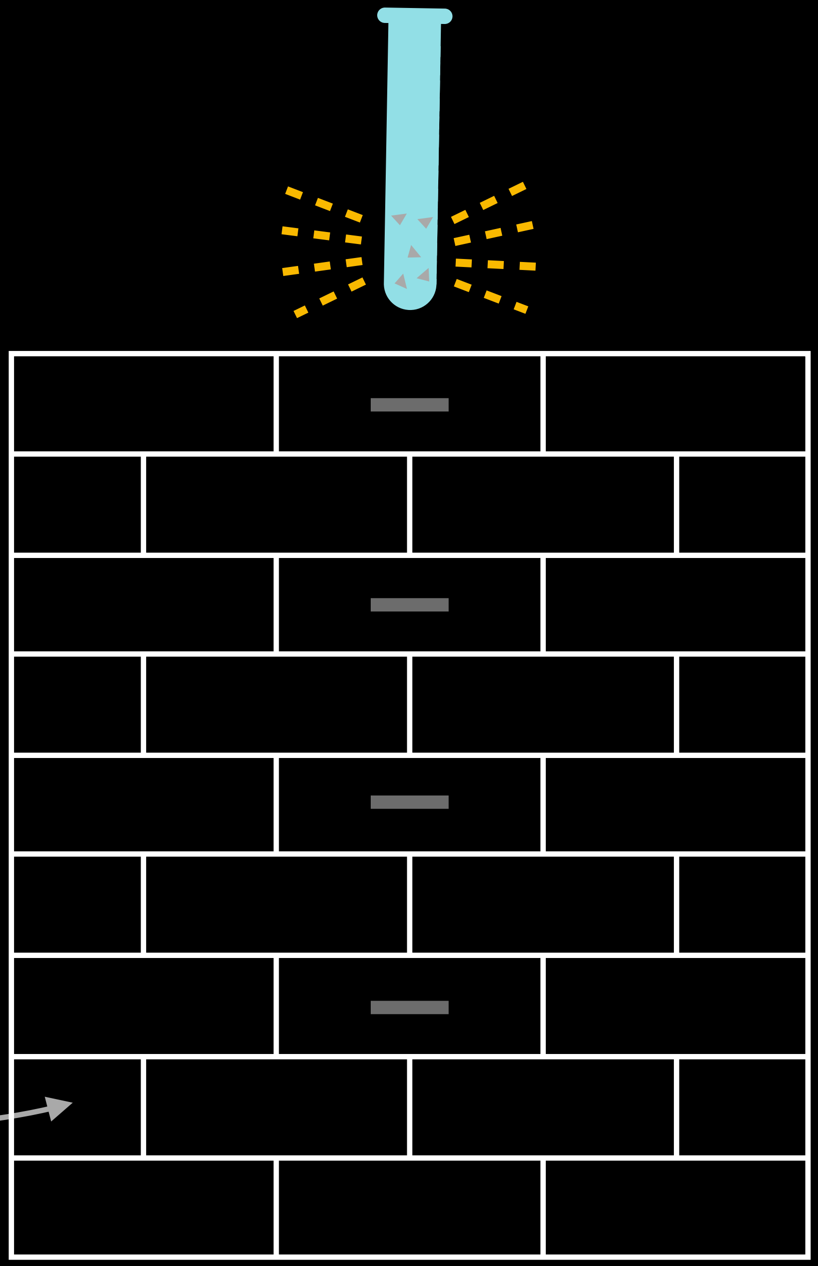


Test pile at Columbia

Graphite bricks



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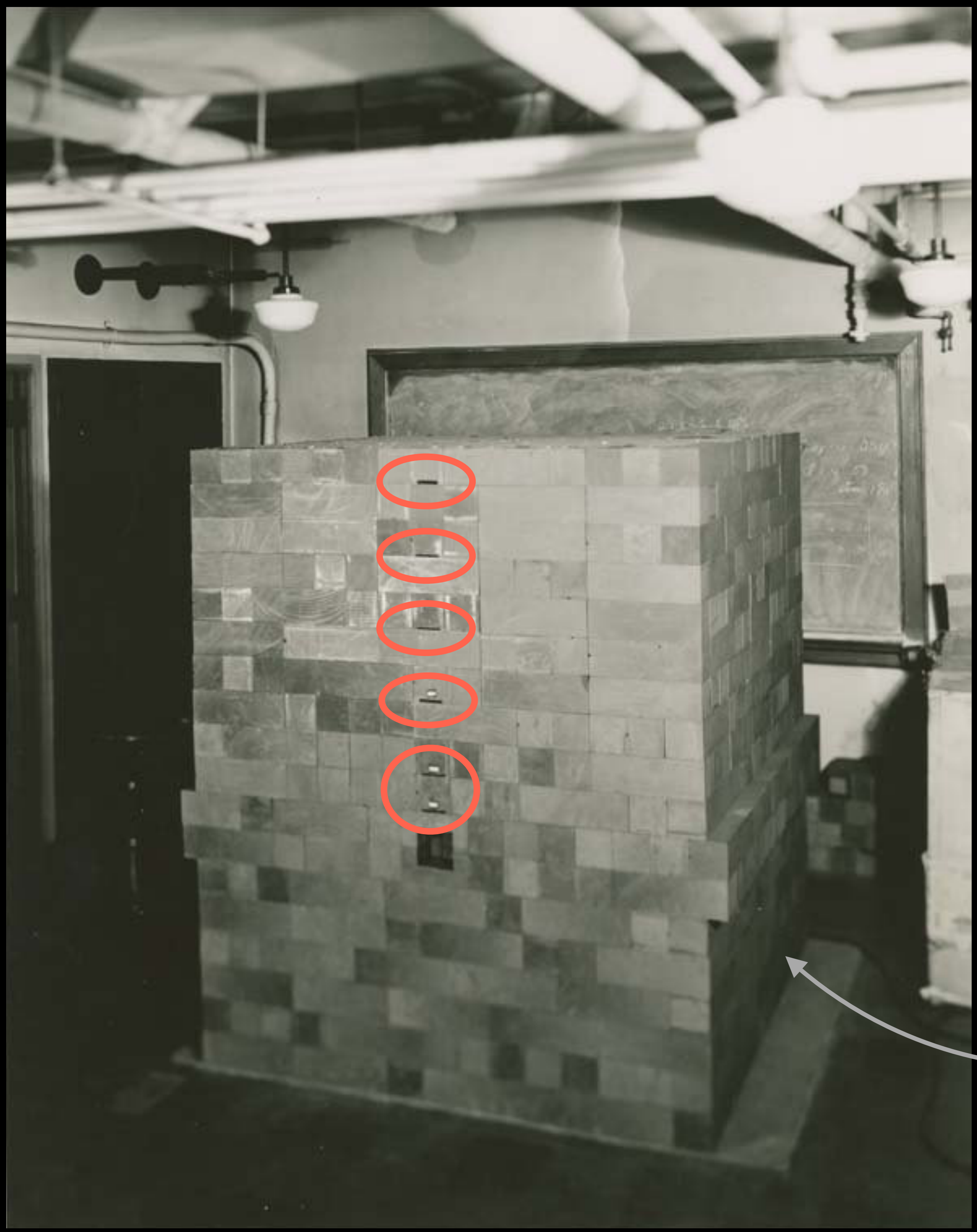
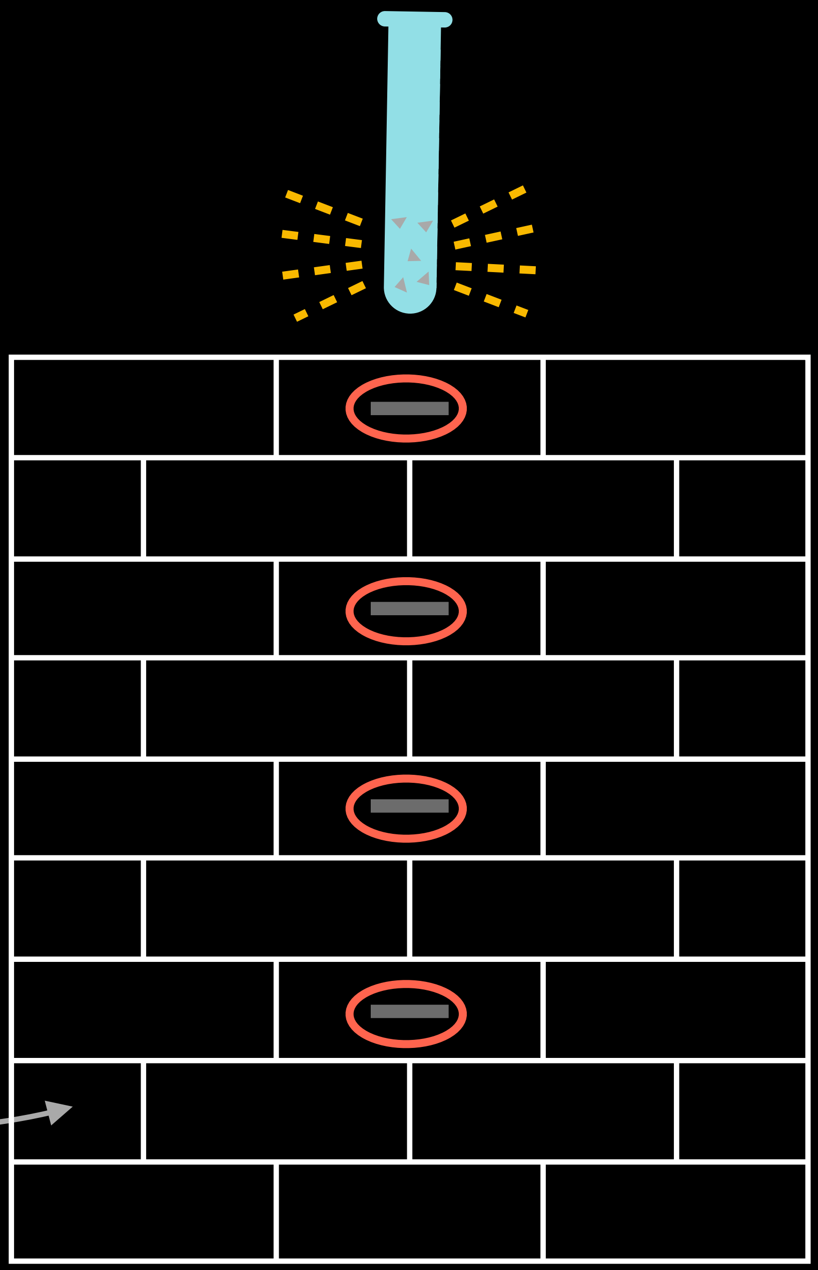


Test pile at Columbia

Graphite
bricks



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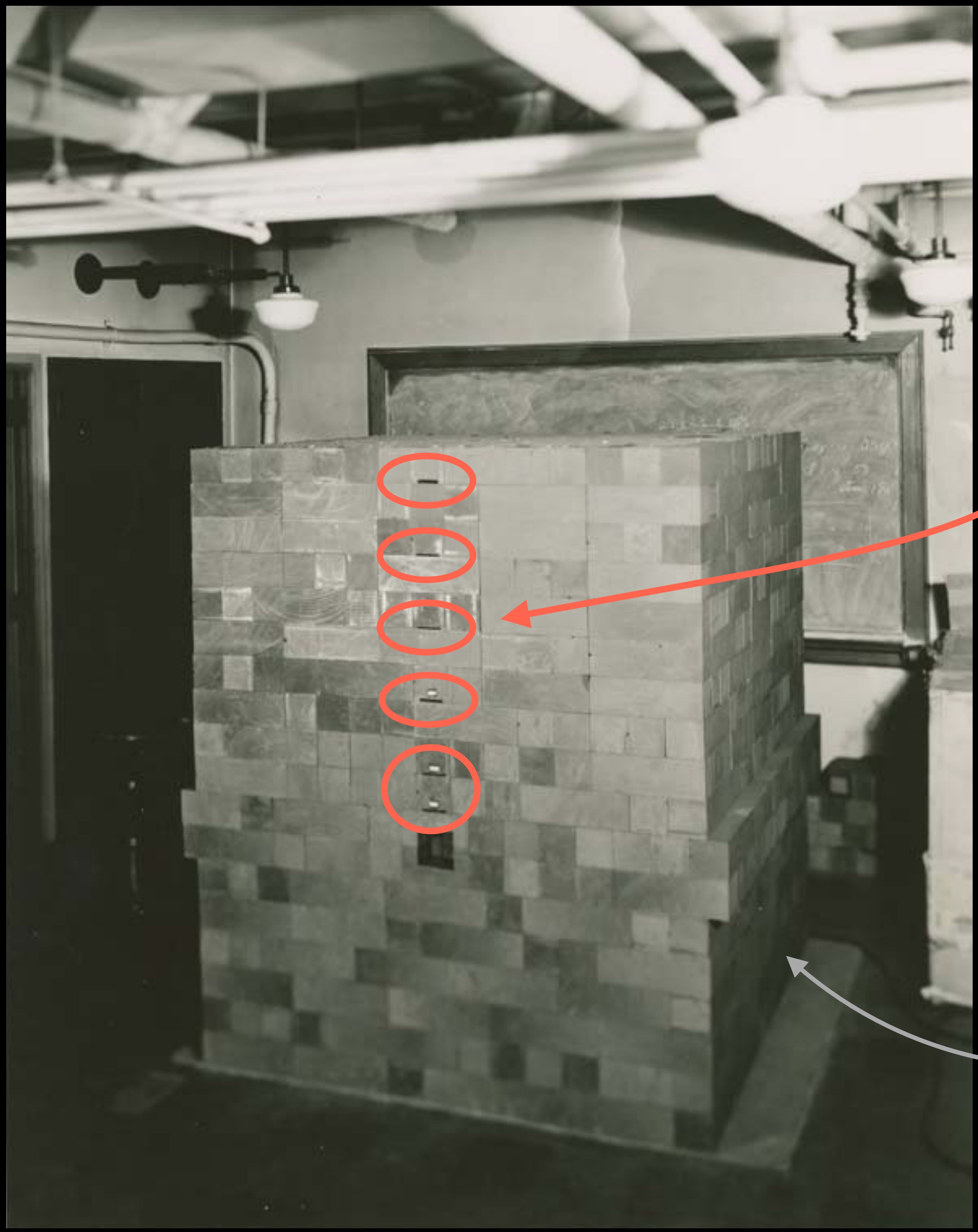
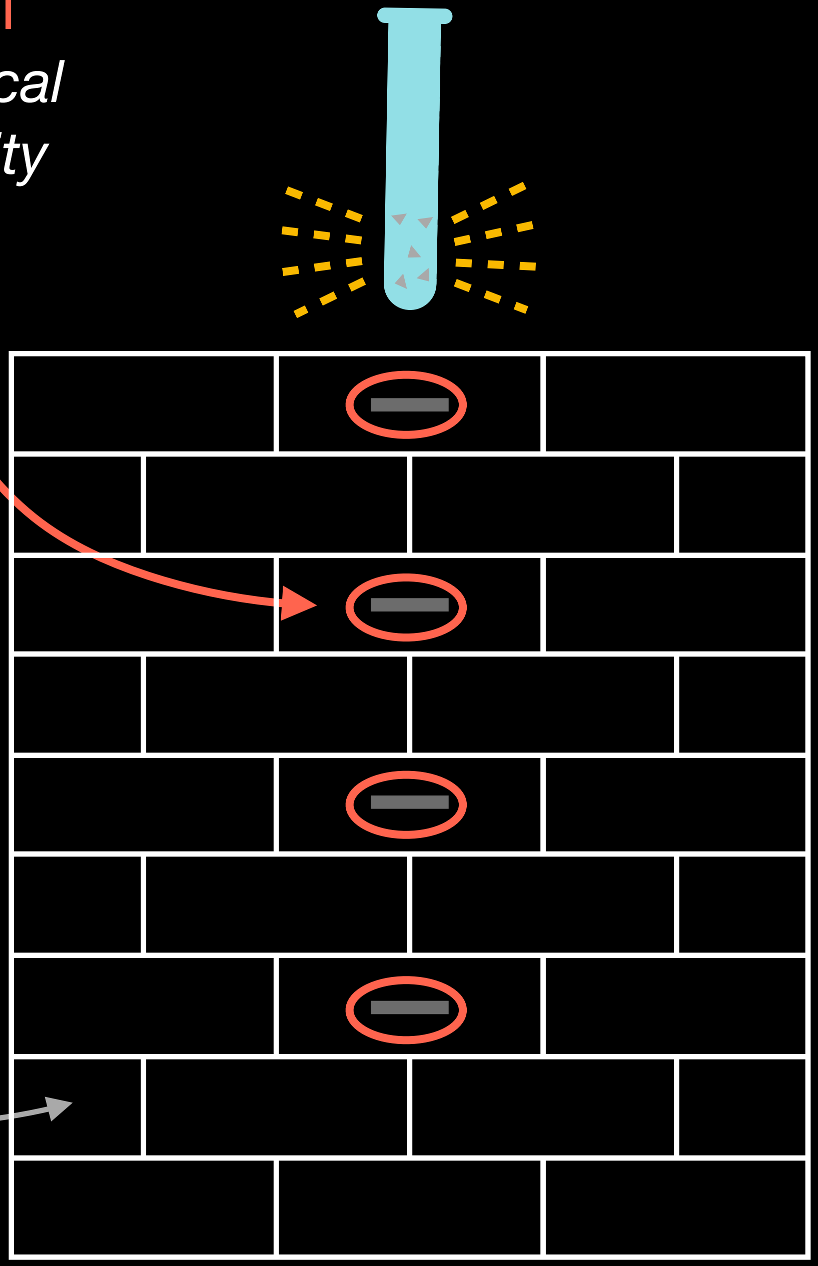
Spring 1940



Test pile at Columbia

Slots to insert rhodium foil
→ *measure local neutron density*



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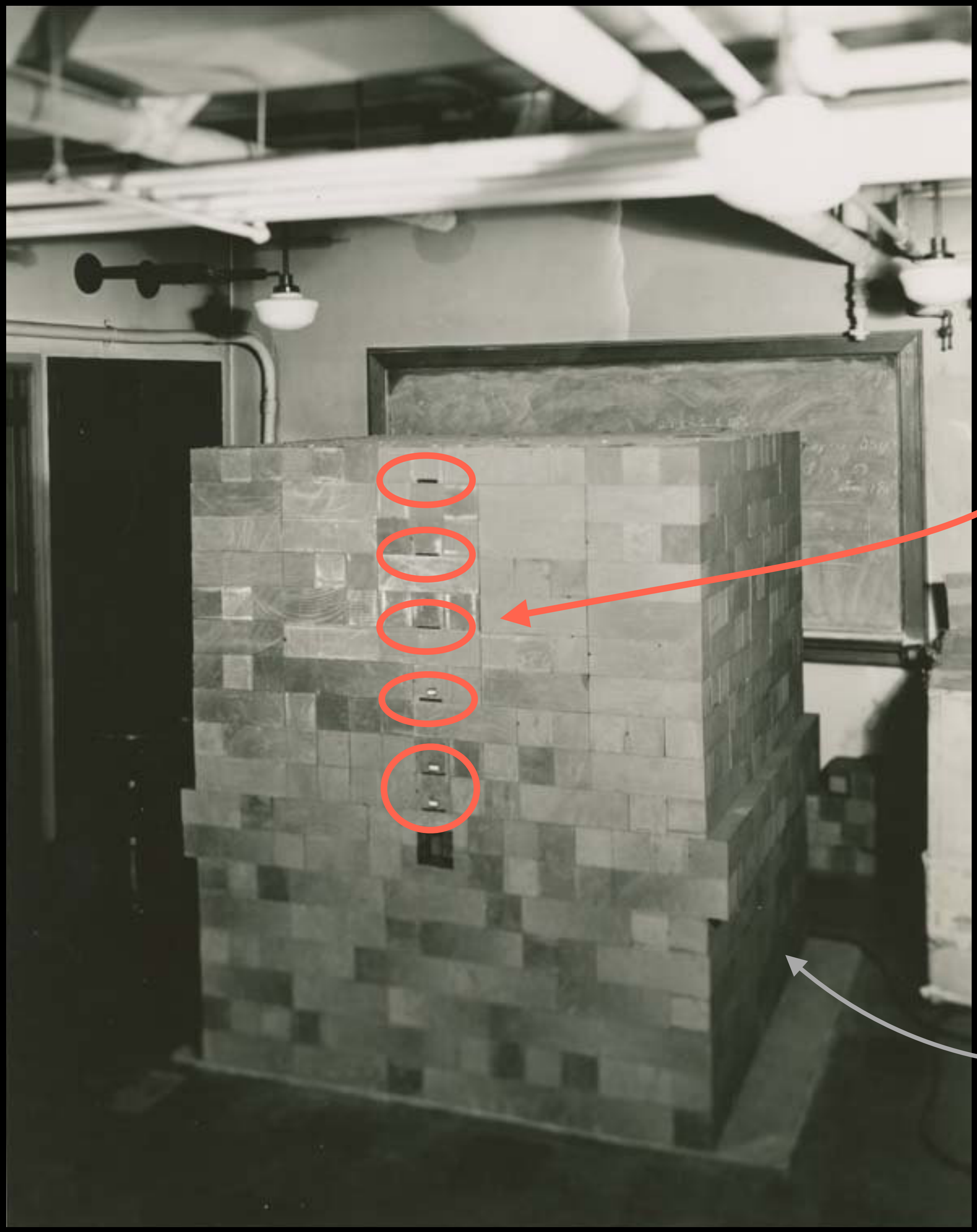
Spring 1940



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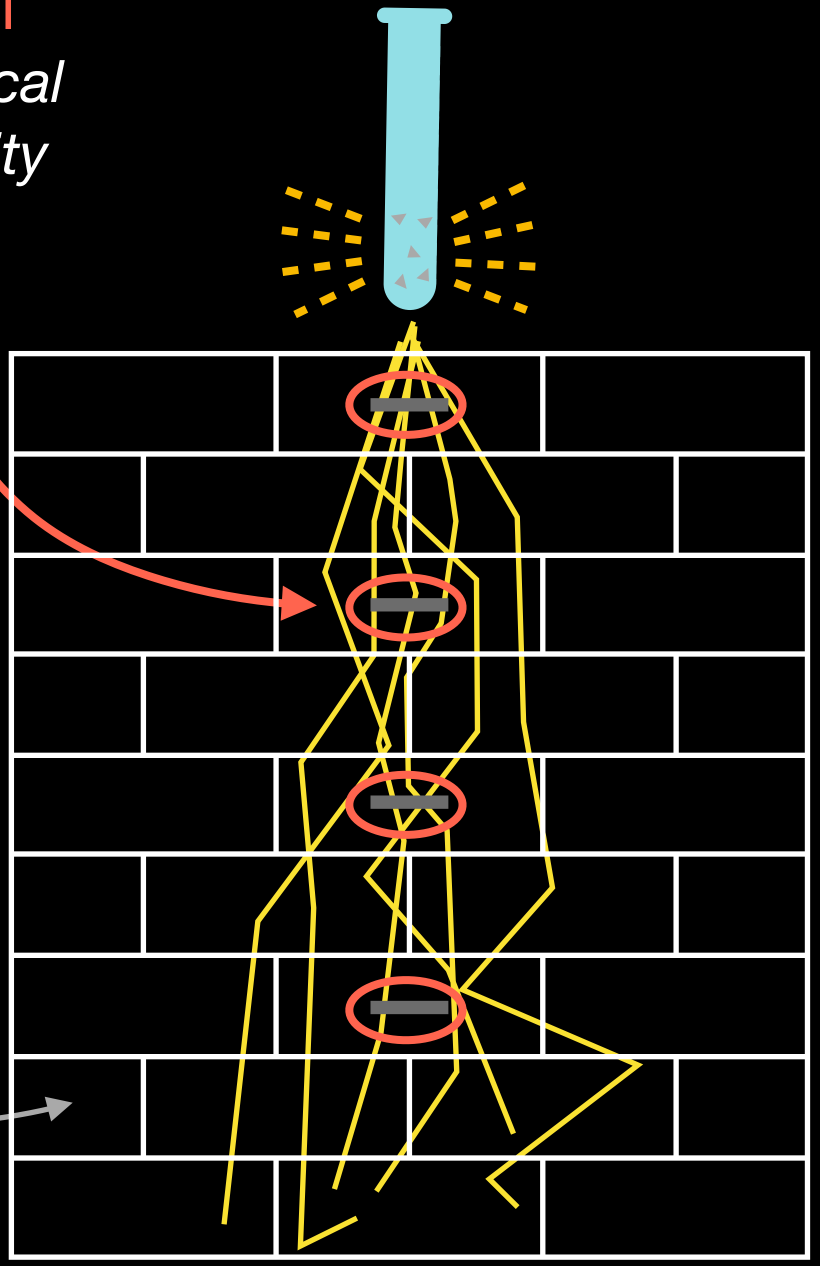

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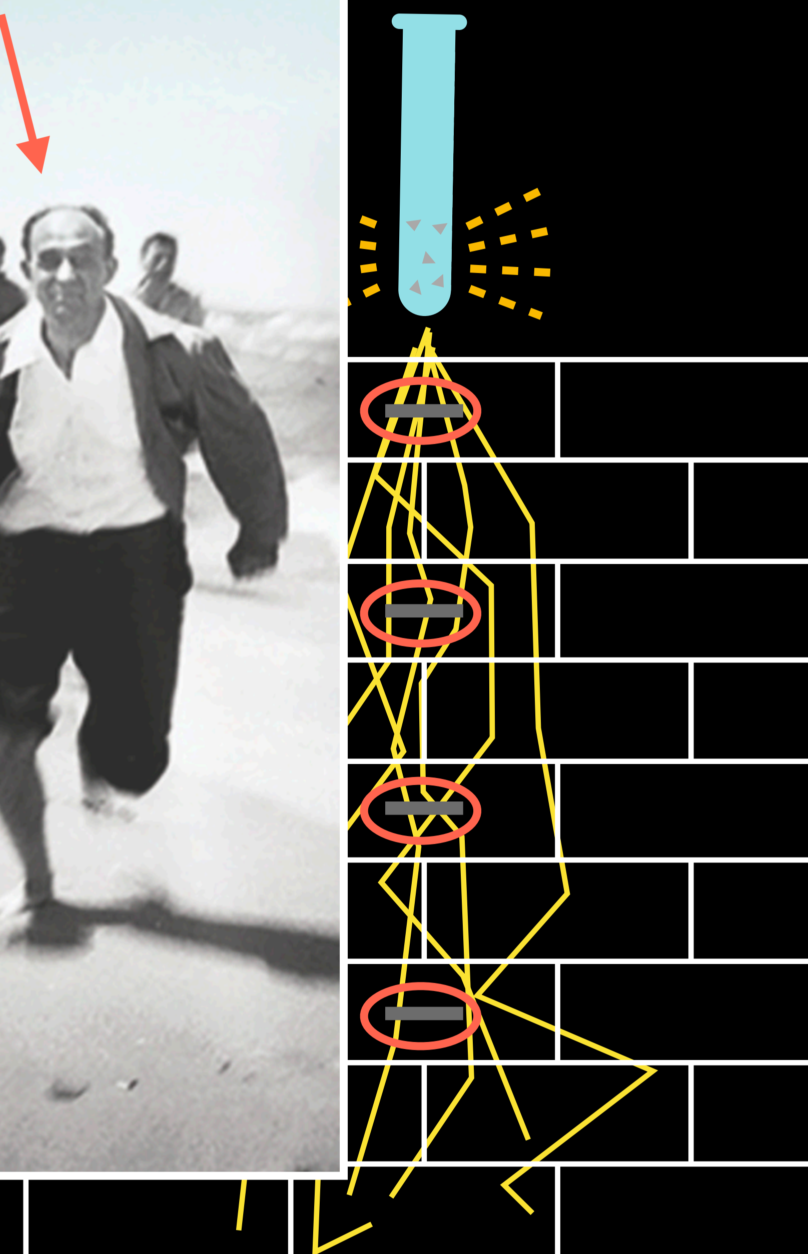

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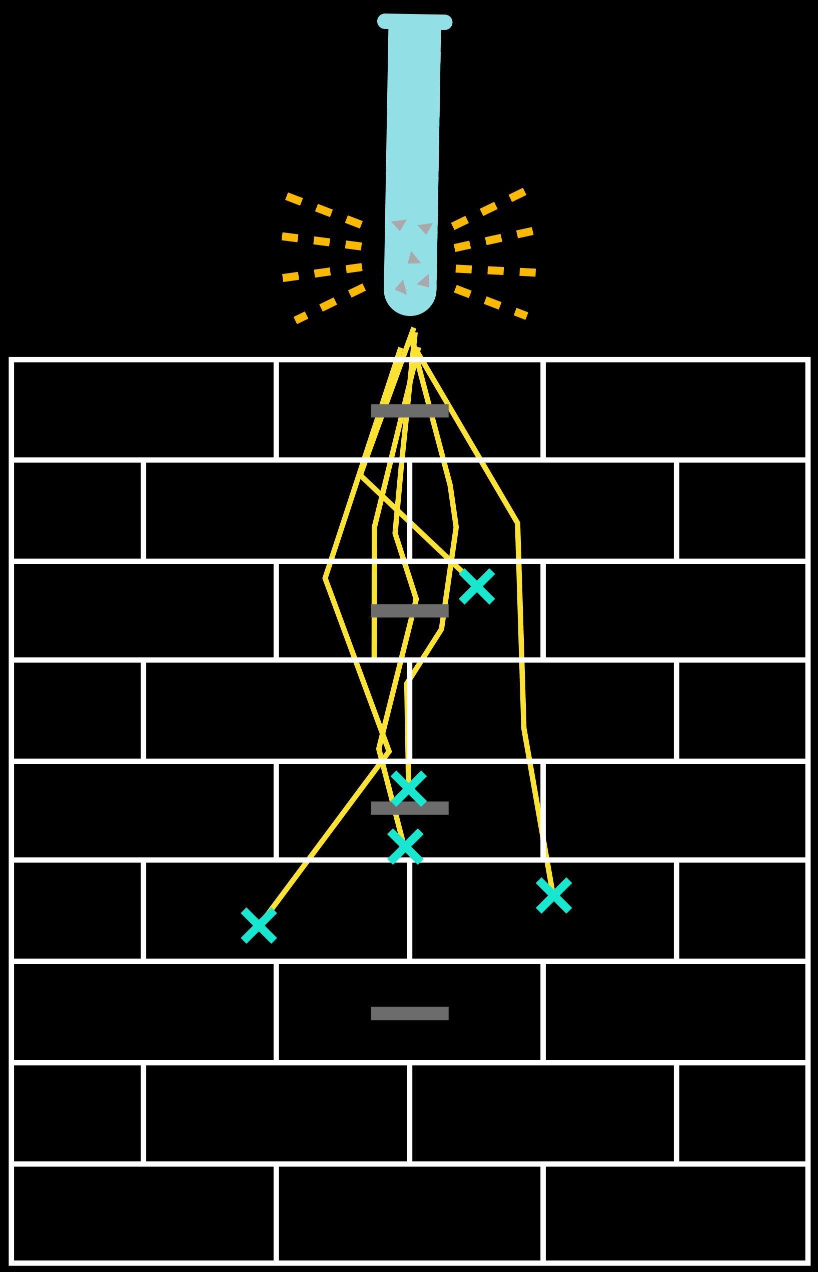
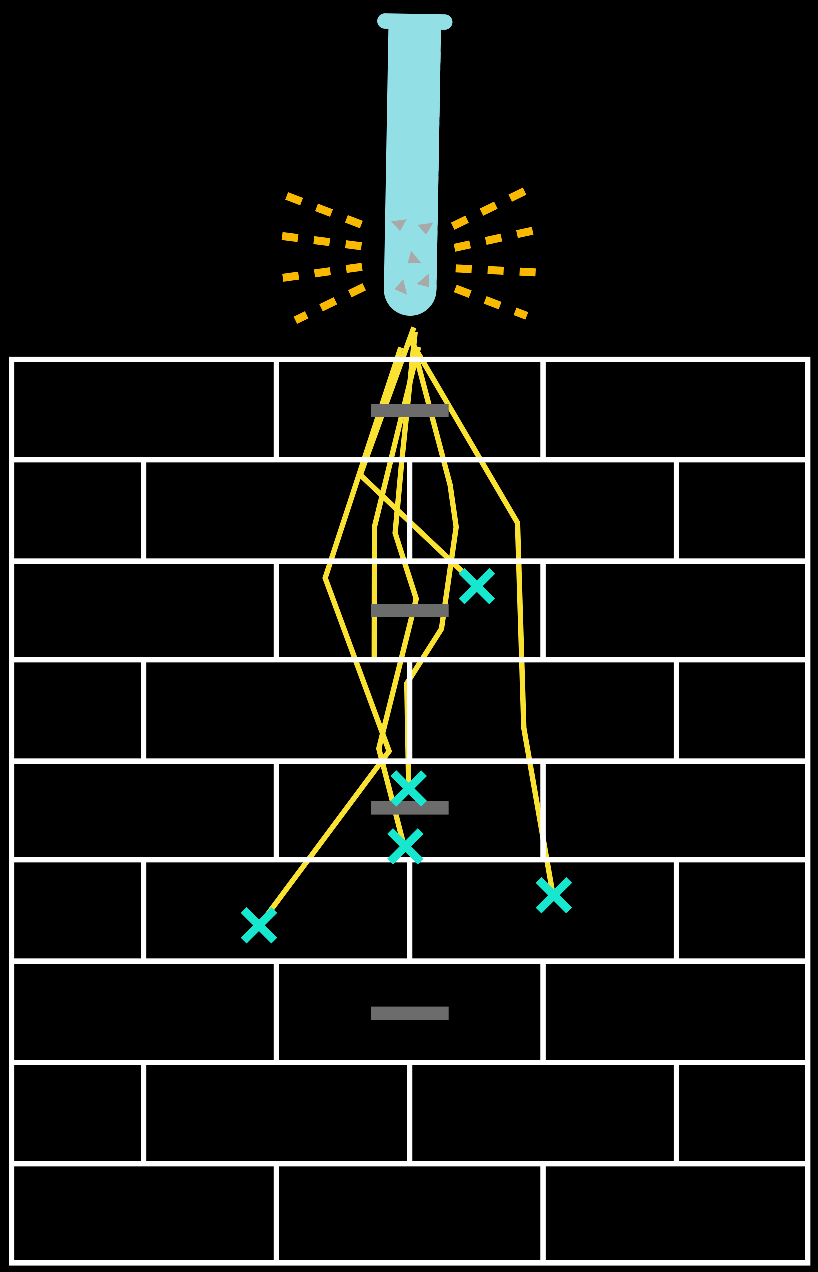


Measuring neutron diffusion

Spring 1940

Too many neurons are absorbed!



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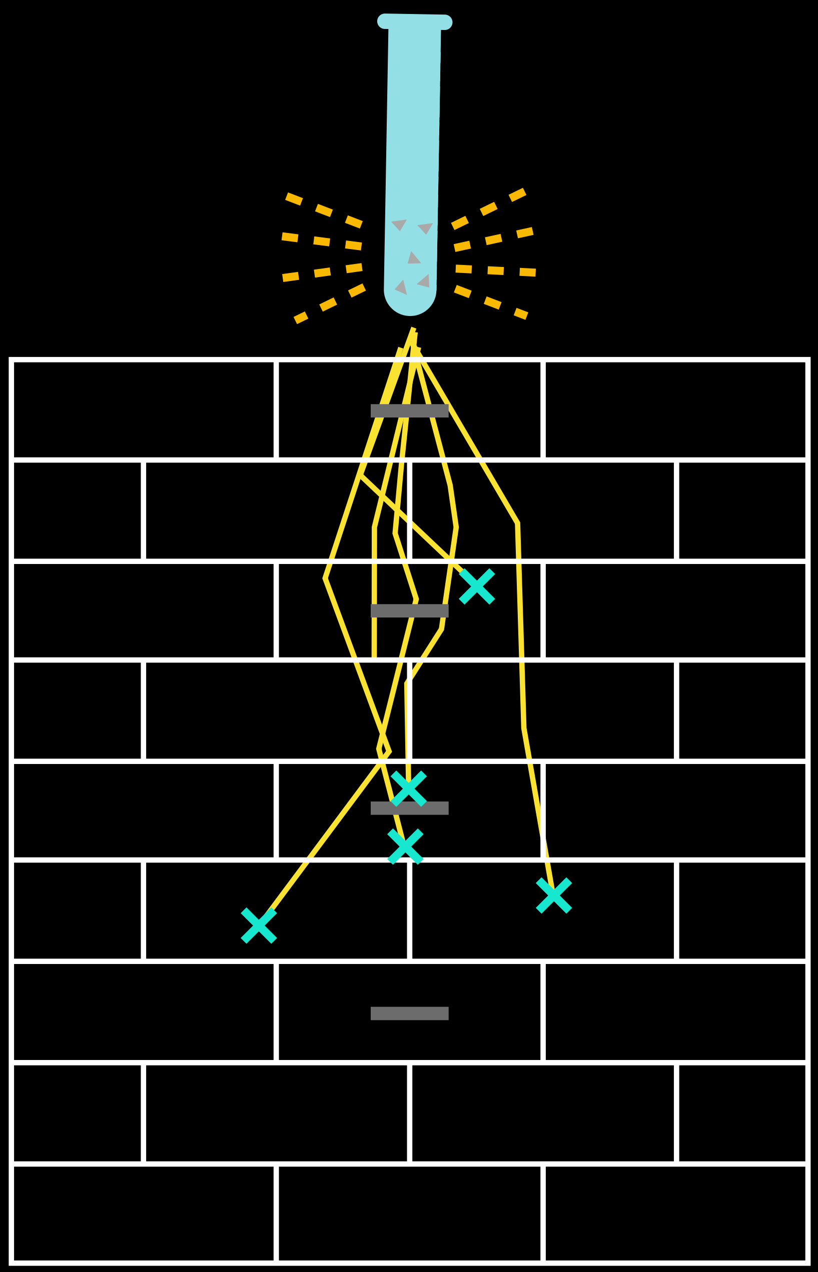

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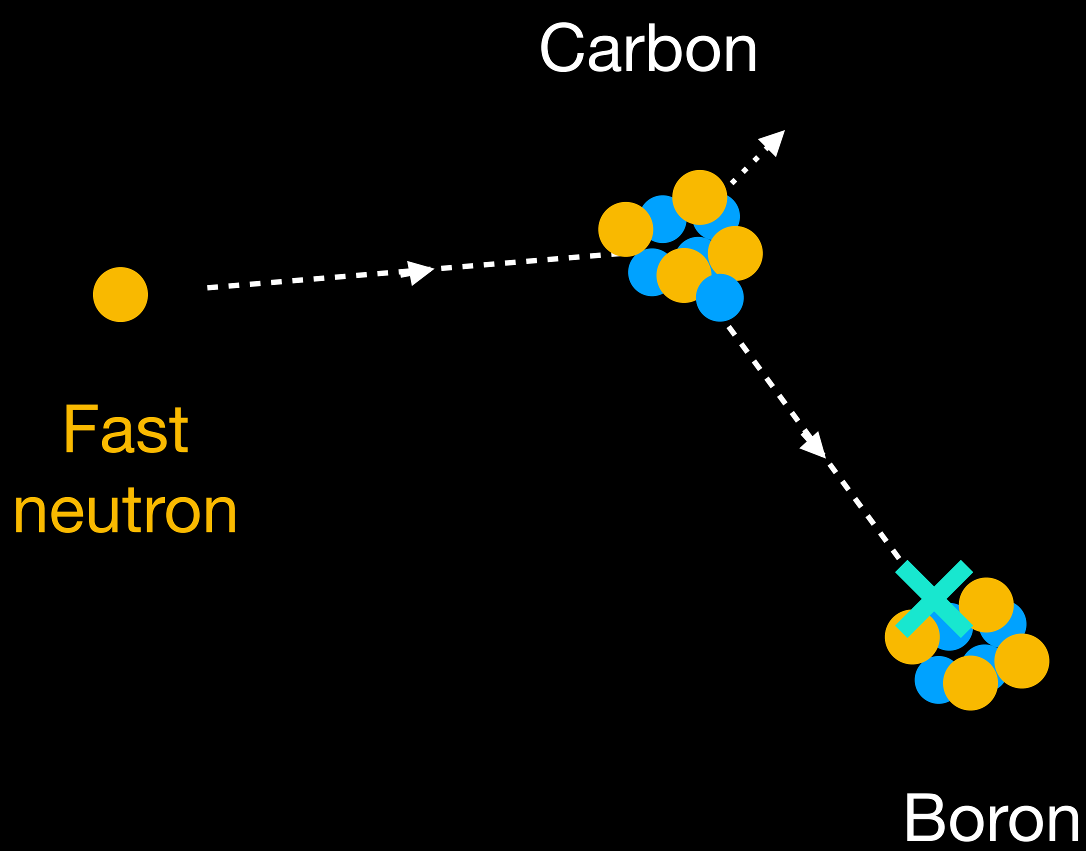

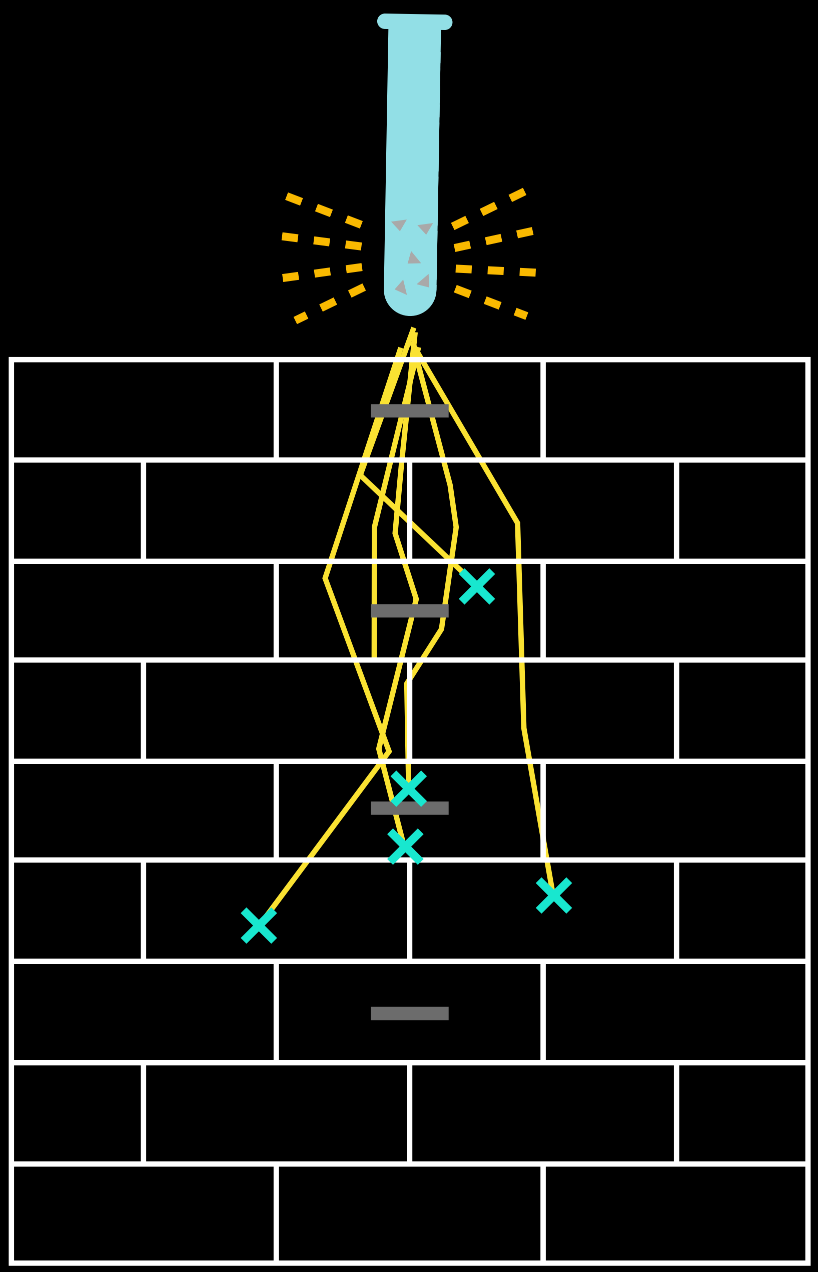

Szilard scrounges graphite

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February 7, 1941

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Edgewater Works
Cleveland, Ohio

Dear Mr. Batchelor:

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We should be very much interested to learn though the boron content of the best graphite which you are able to supply. For certain uses of graphite, we would be able to tolerate more boron than for other uses, although we are interested in every case in keeping the boron content as low as possible. Perhaps your graphite could be used at least for some of our work.

Very truly yours

L. Sz

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LS/eh

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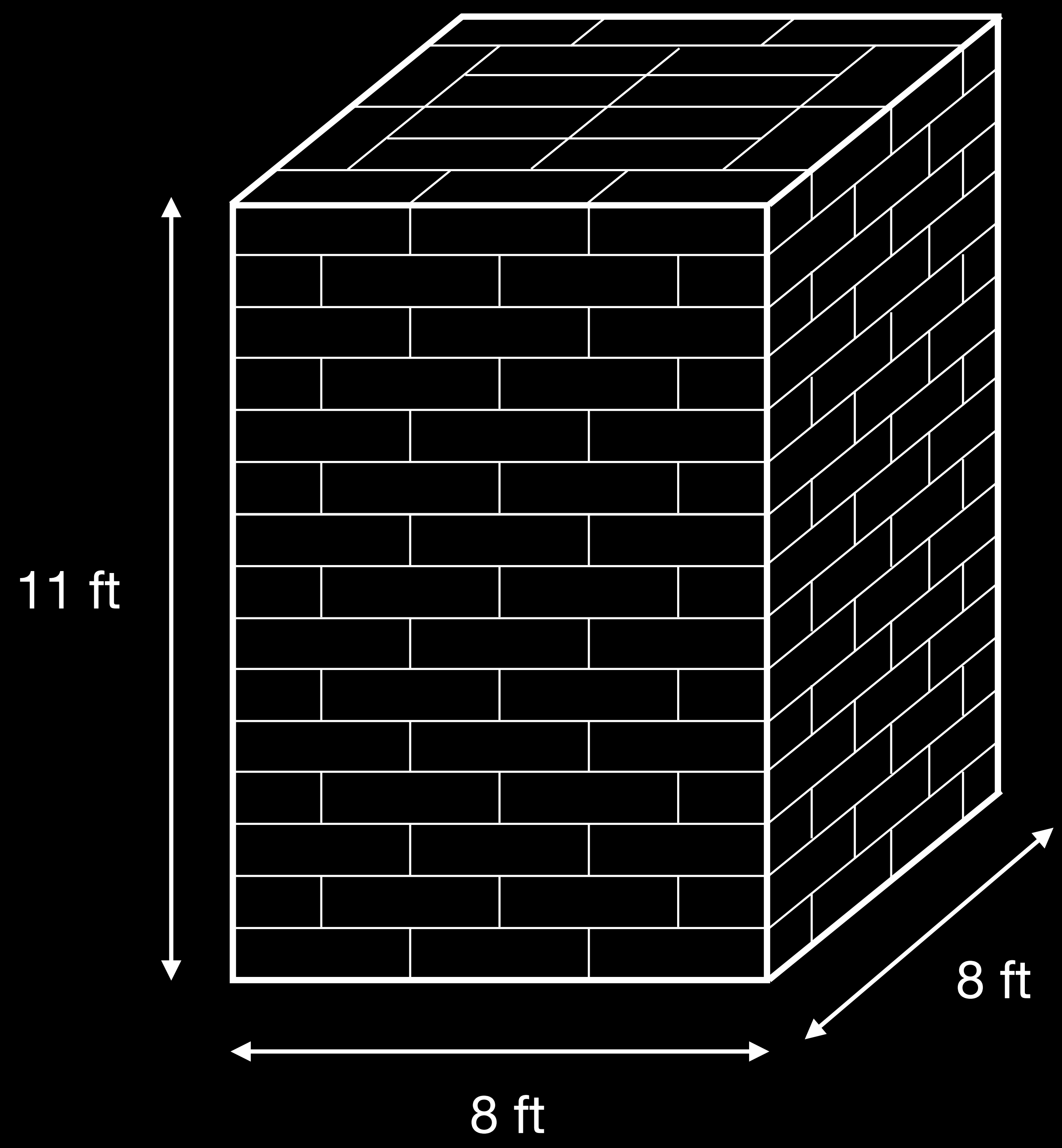
Test piles at Columbia

September 1941



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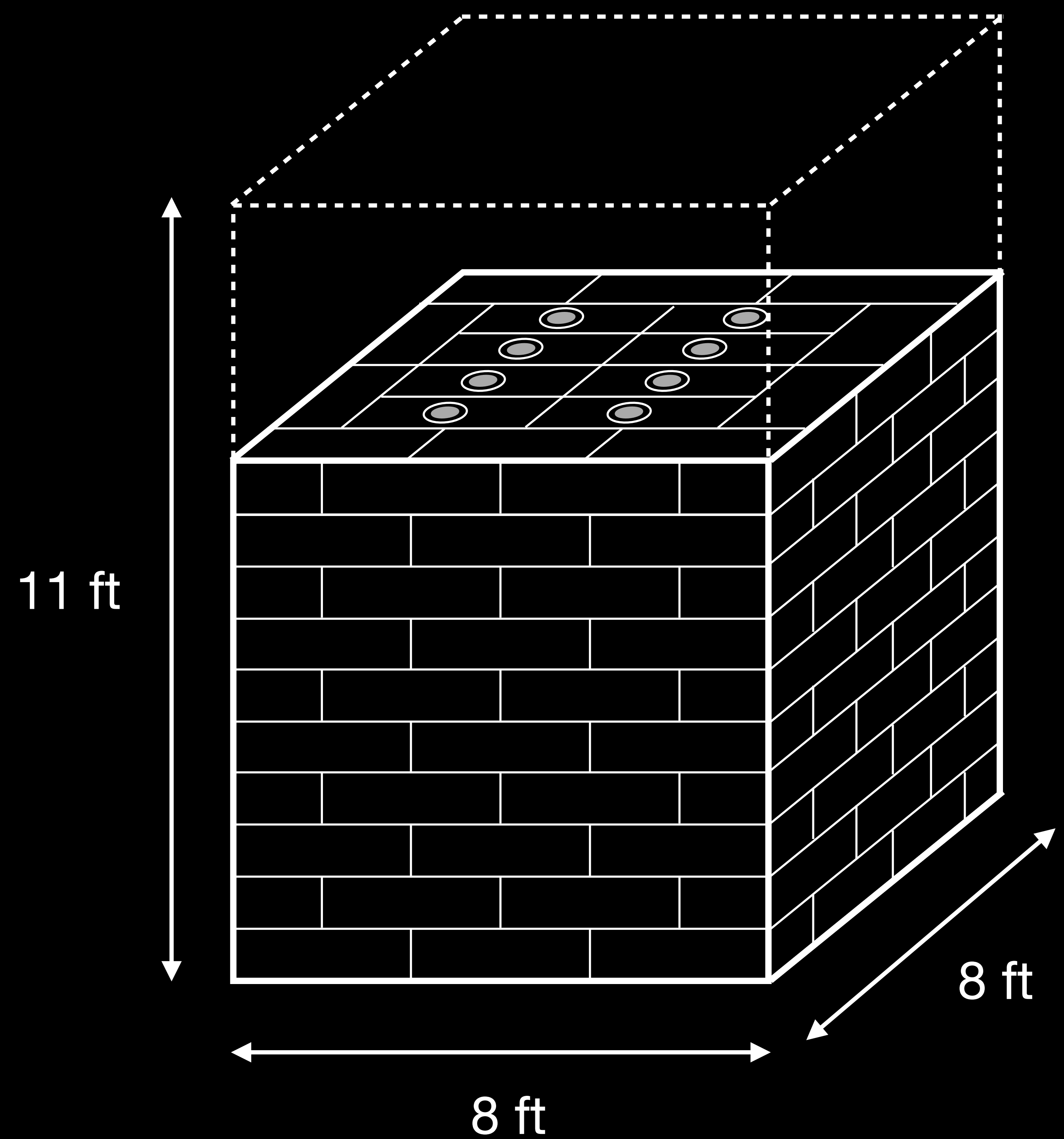

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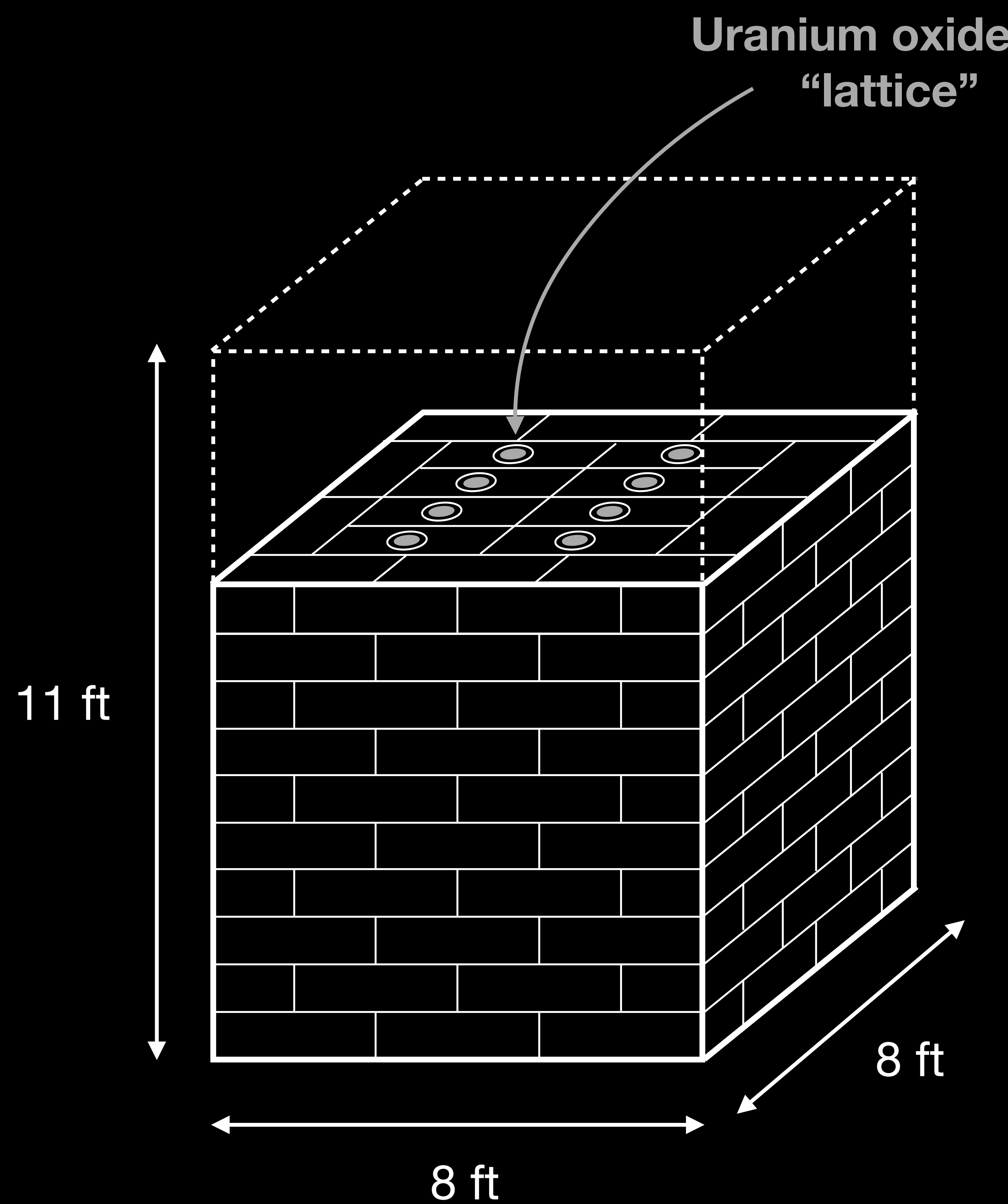

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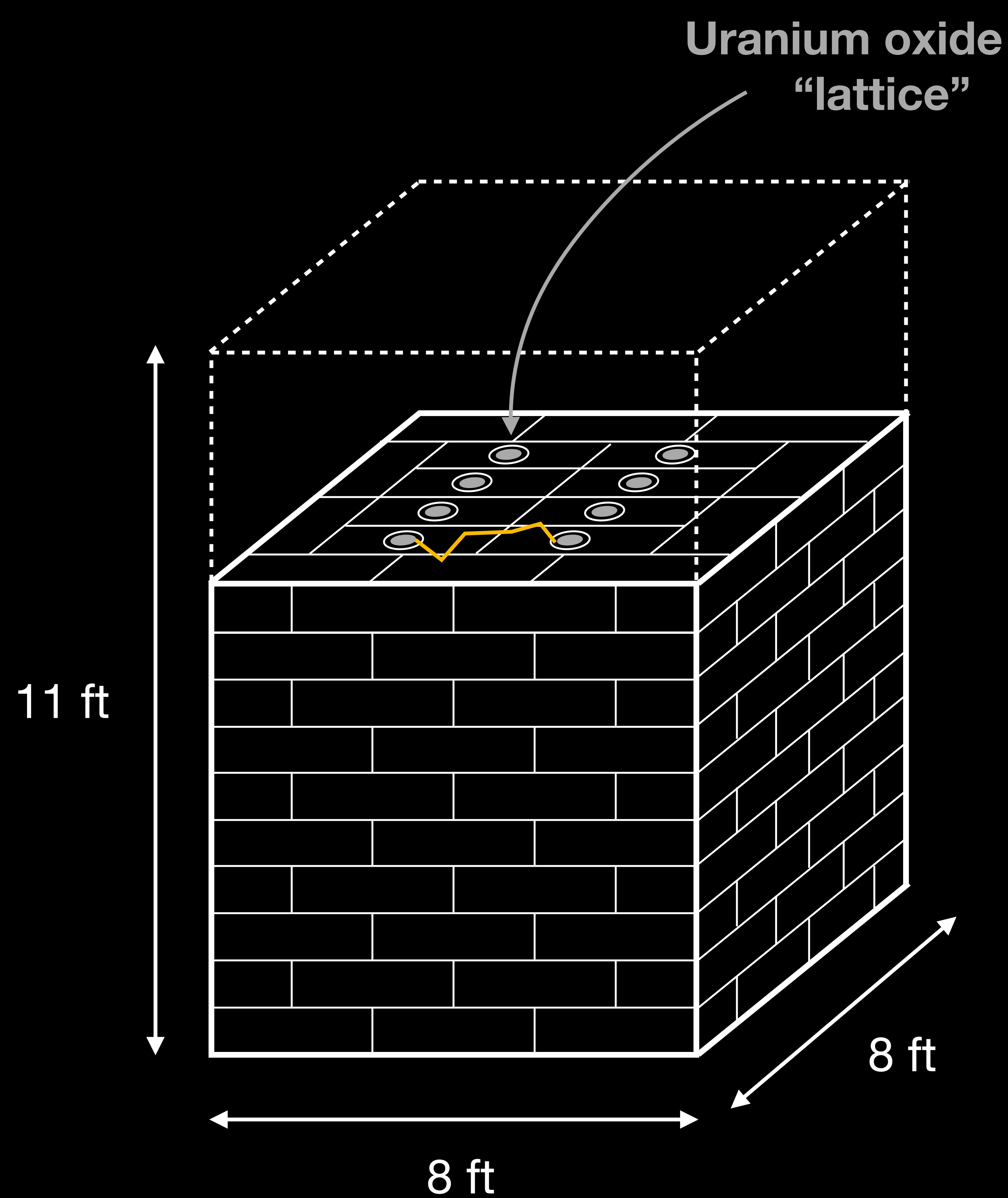

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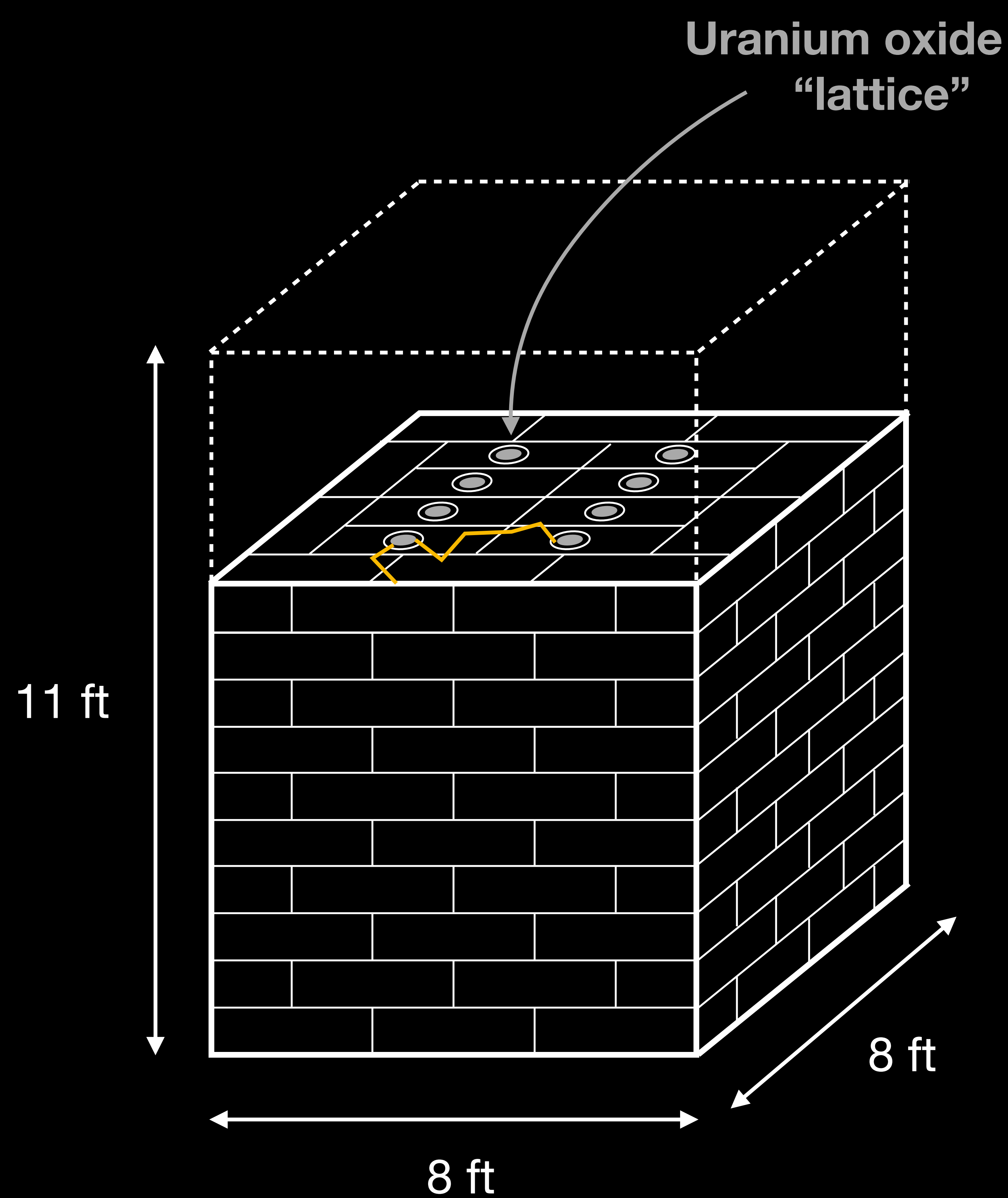

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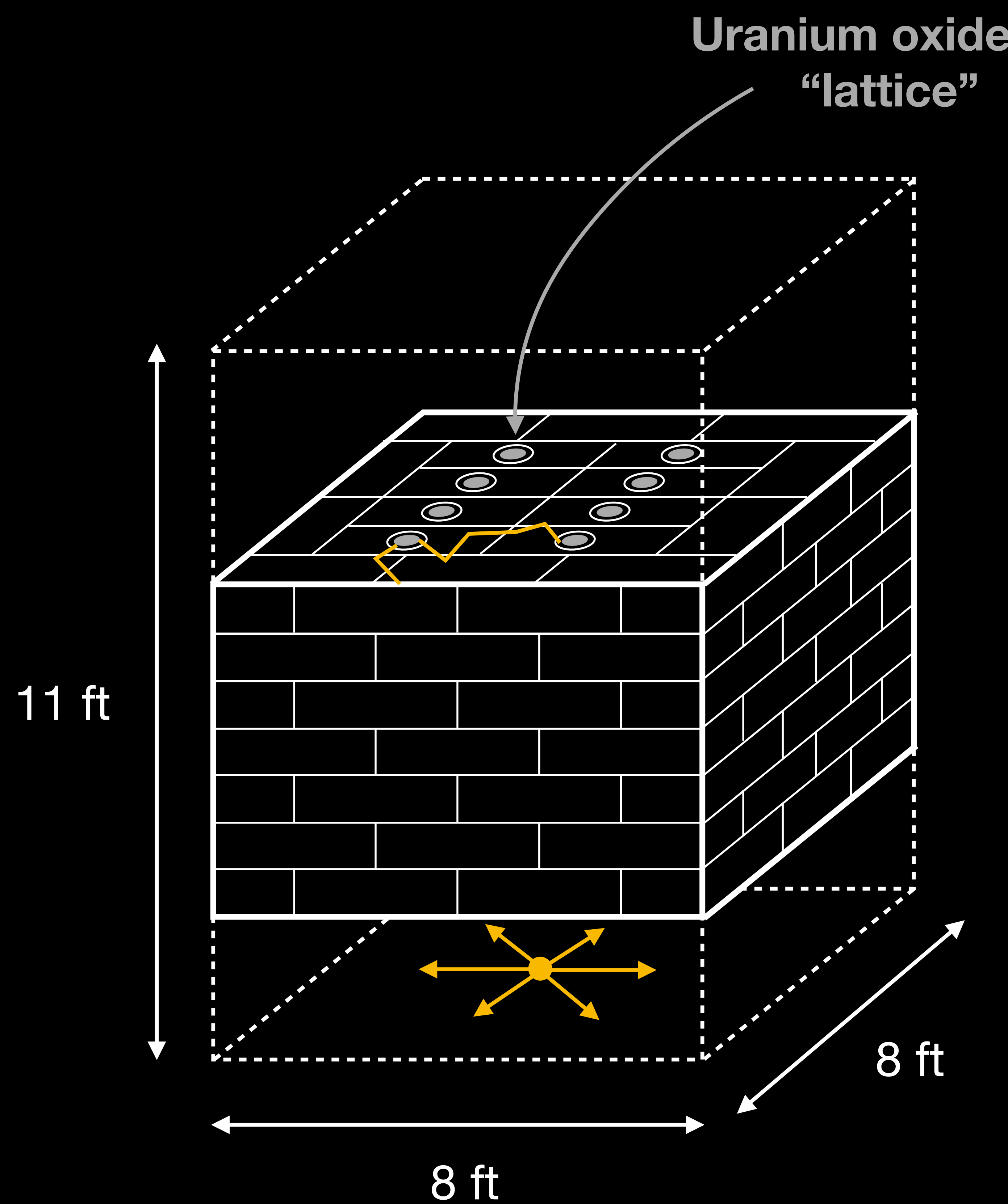

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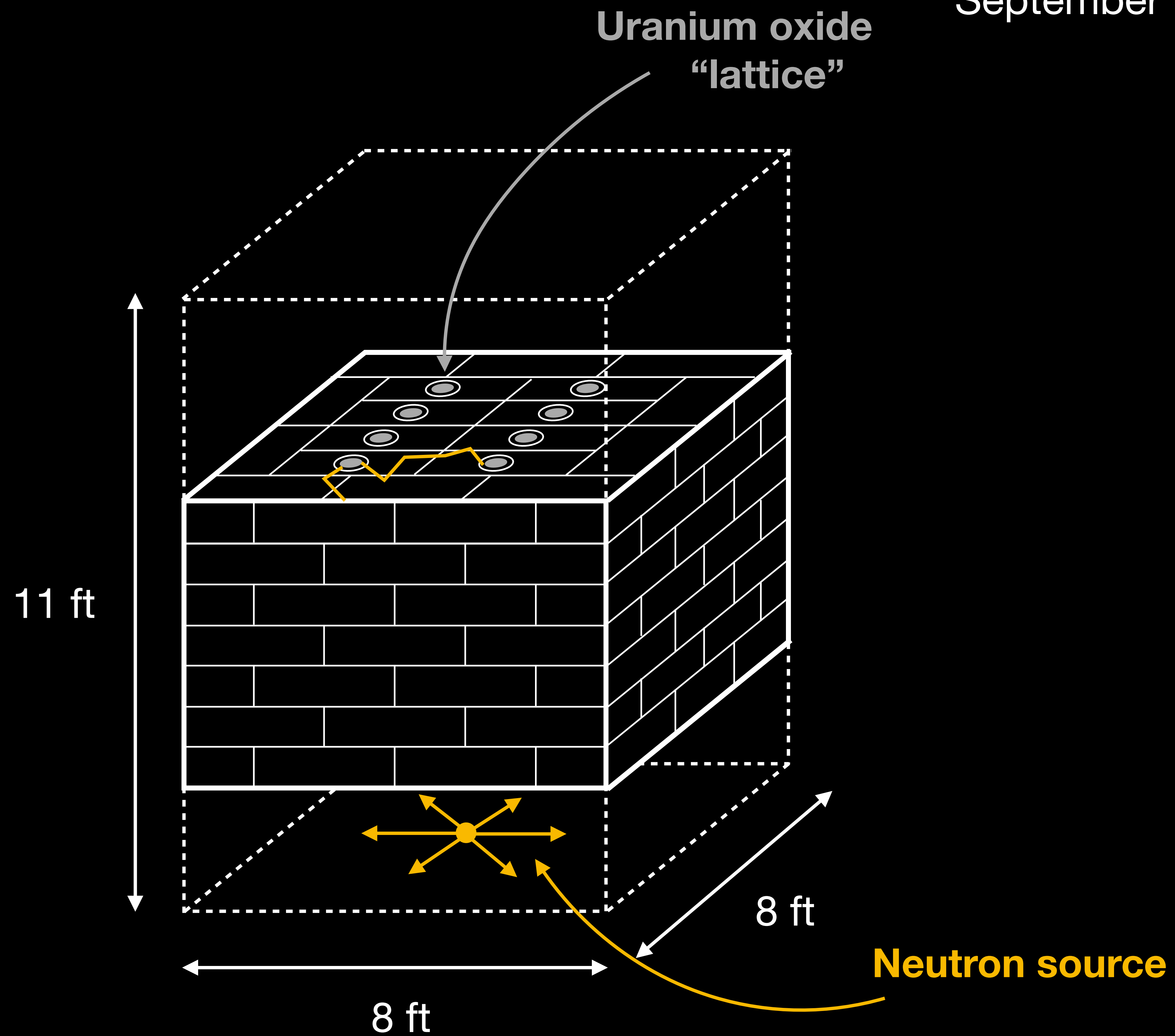

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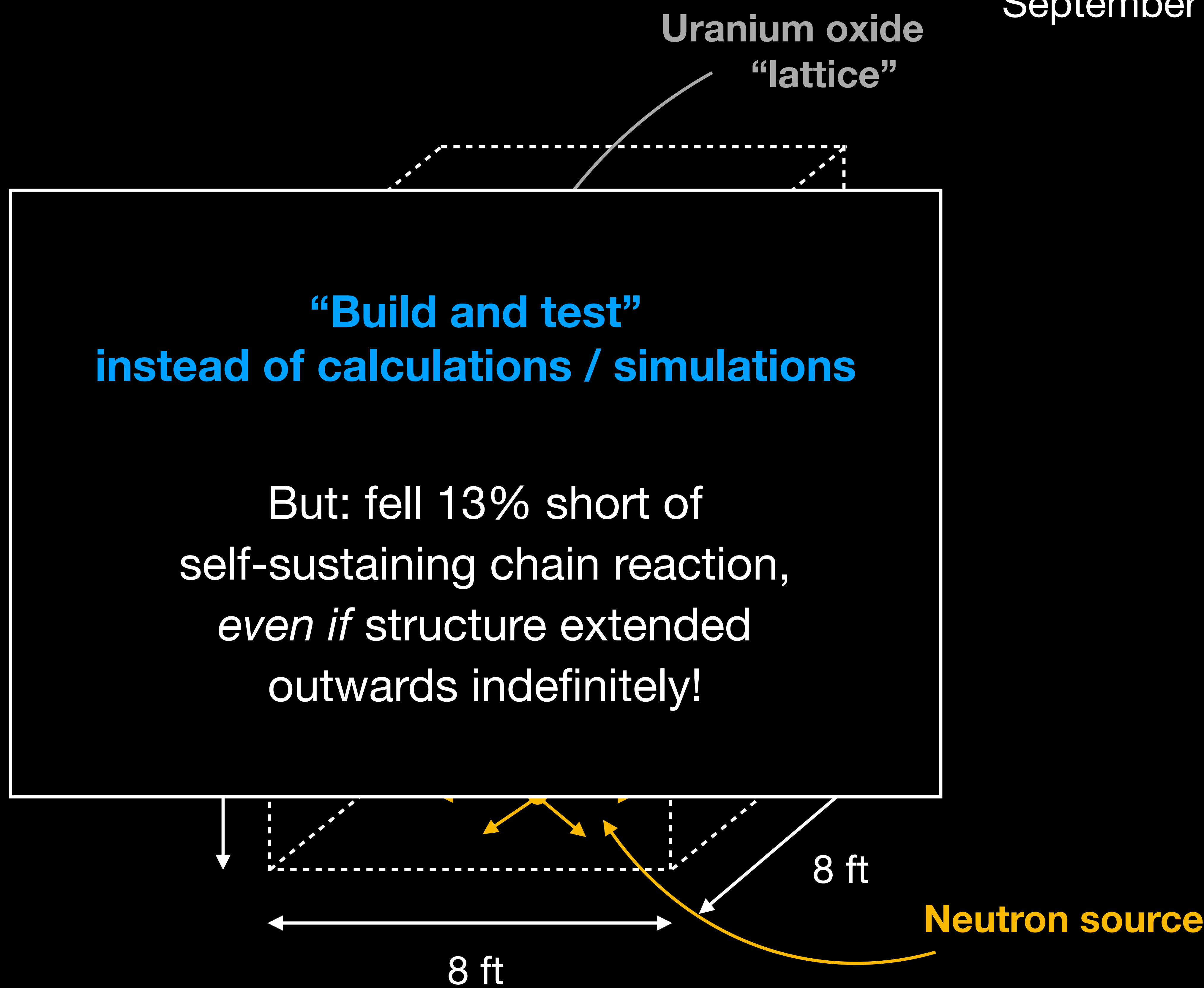


“Build and test”
instead of calculations / simulations

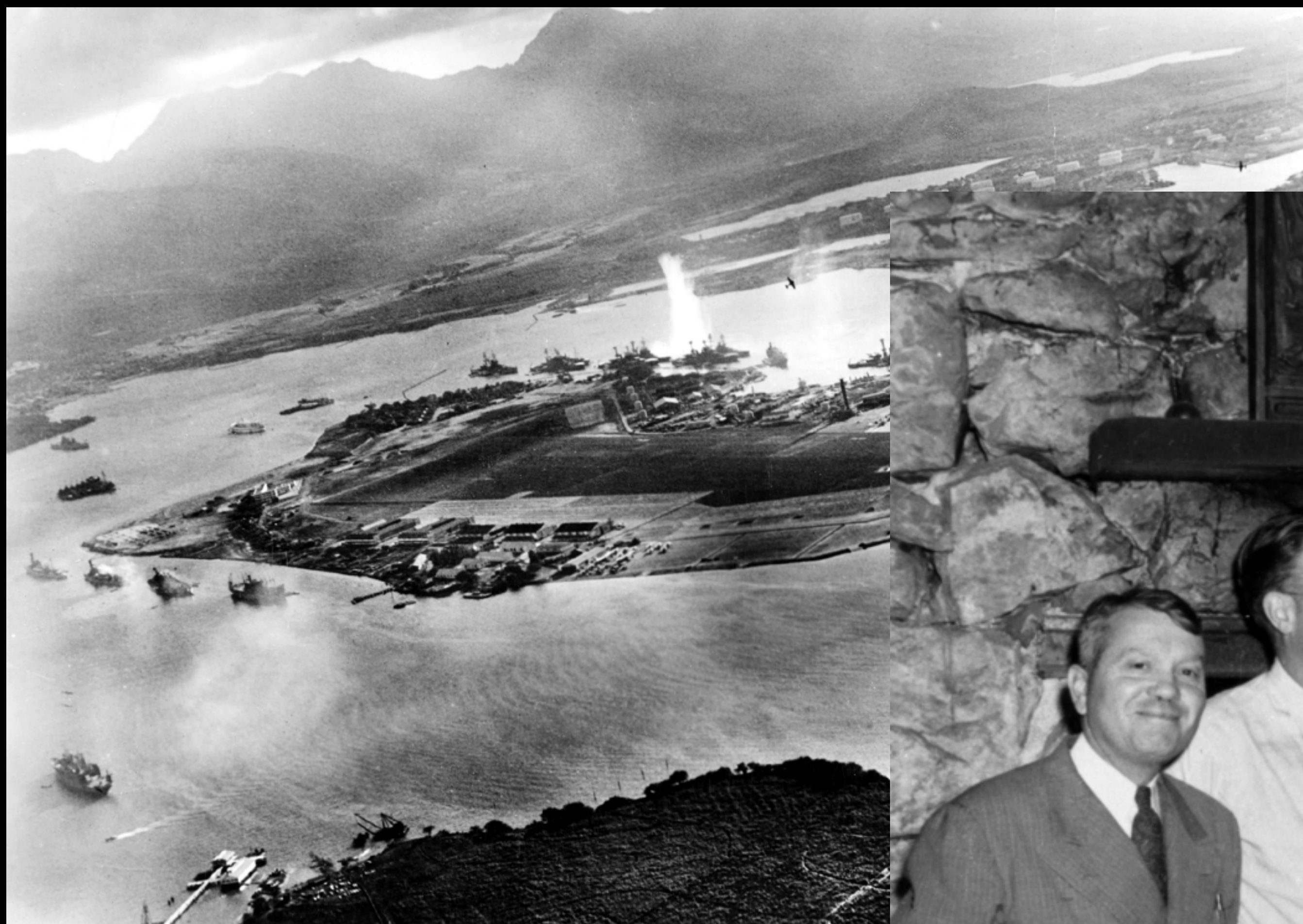
But: fell 13% short of
self-sustaining chain reaction,
even if structure extended
outwards indefinitely!

A sense of urgency …

A sense of urgency …

December 1941

A sense of urgency …



December 1941

A sense of urgency …

December 1941

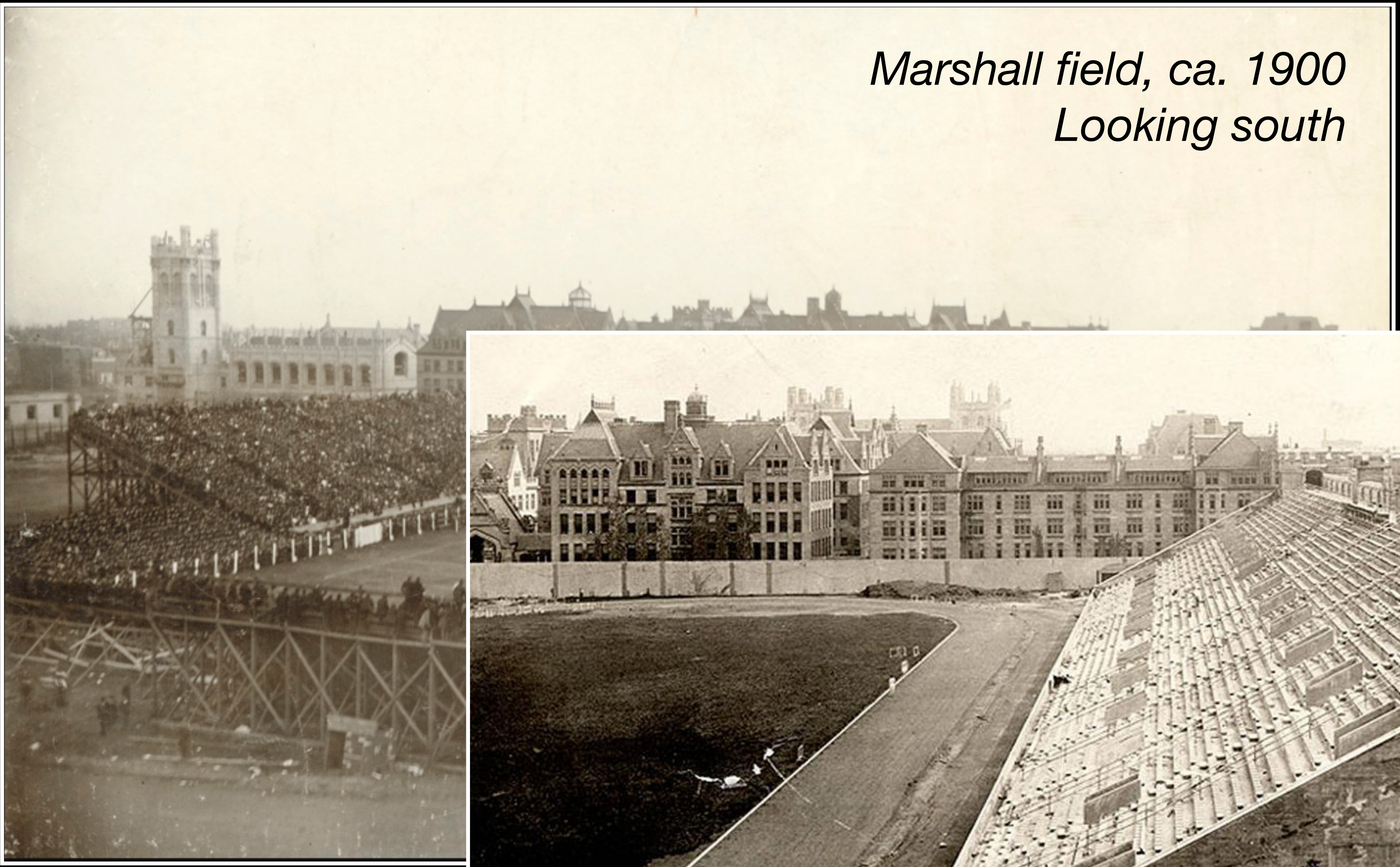
… and a move to Chicago

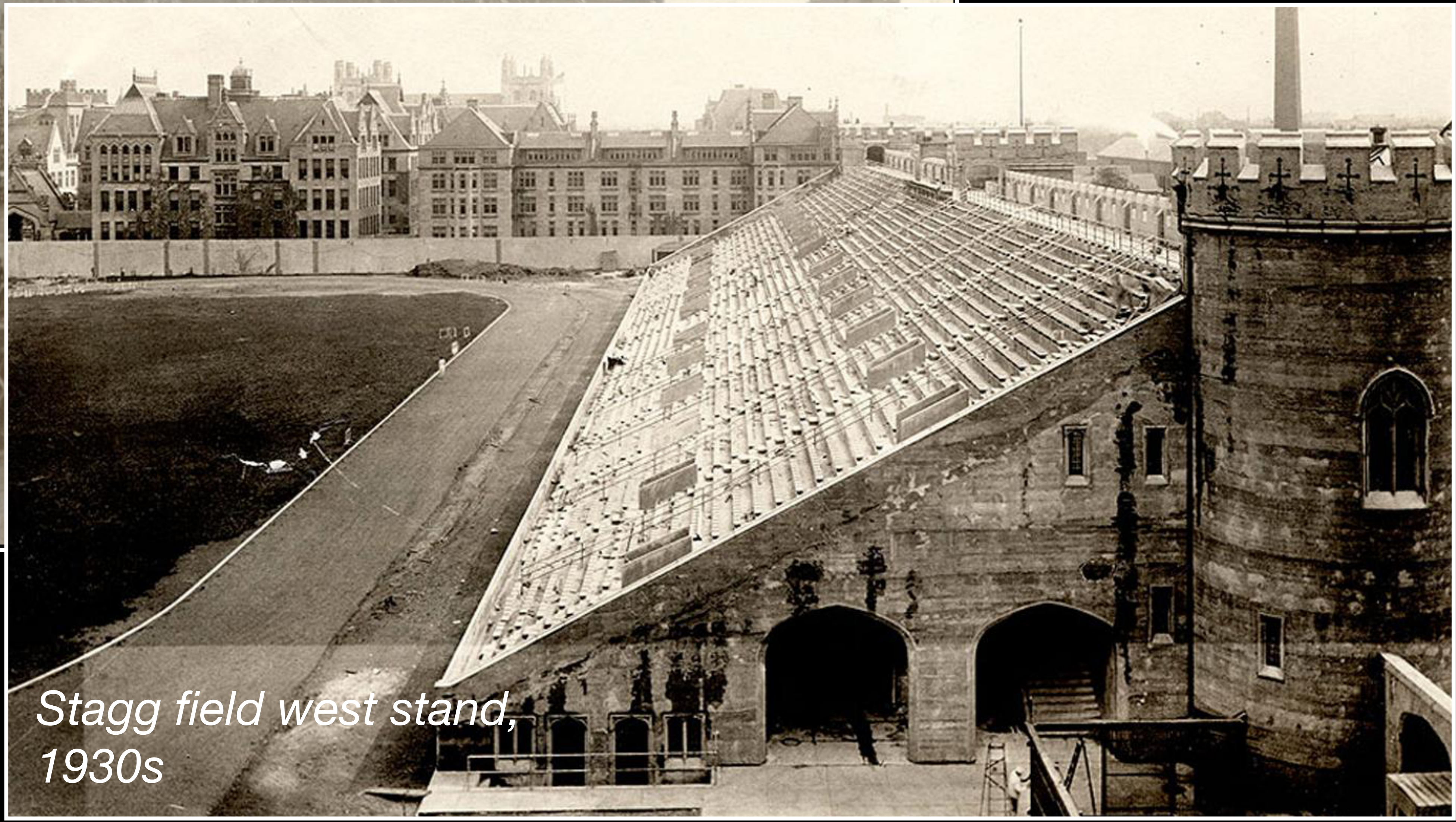
The metallurgical laboratory

Stagg Field

Stagg Field

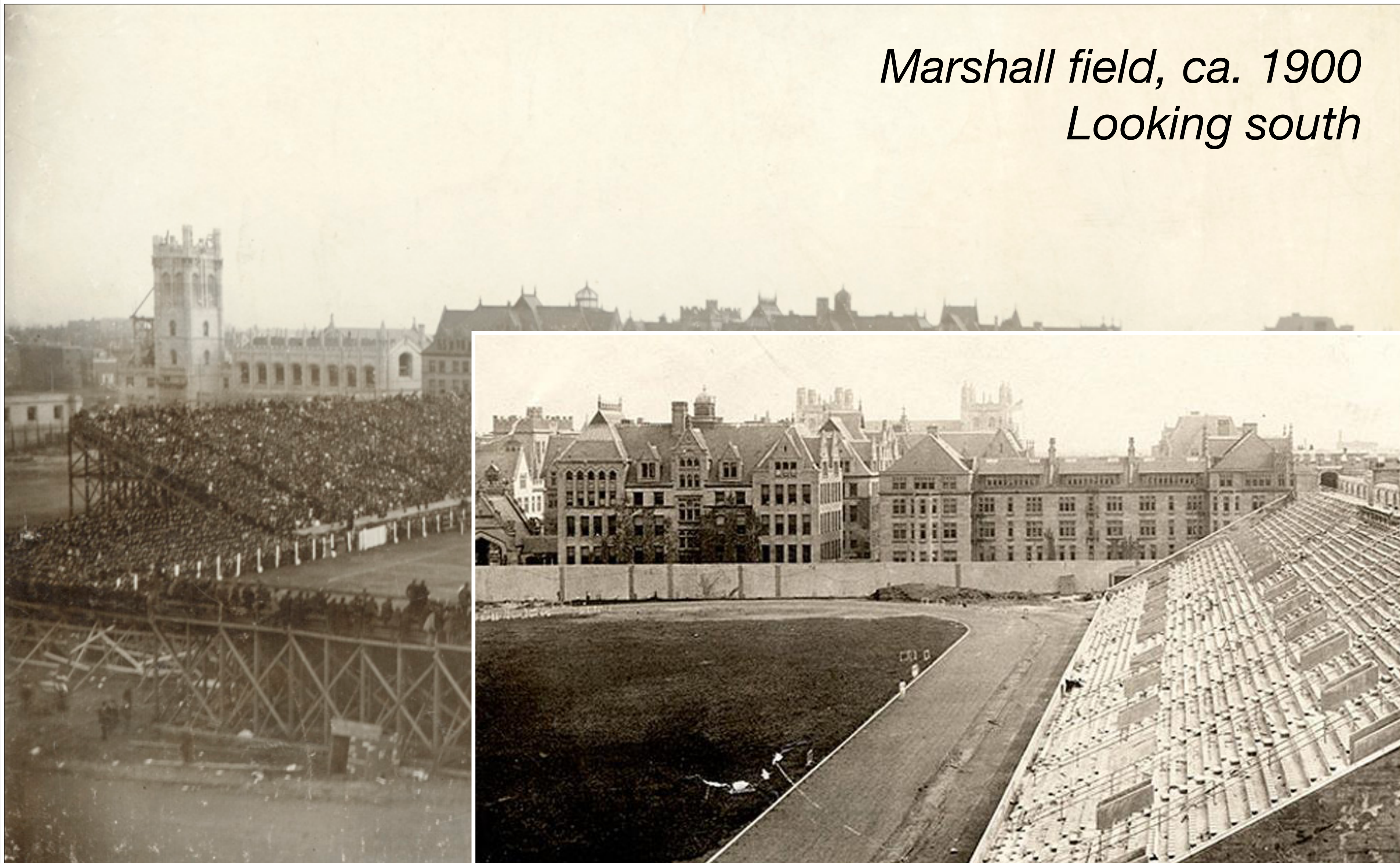
Stagg Field


Marshall field, ca. 1900
Looking south


Stagg field west stand,
1930s

Stagg Field

President Robert Hutchins on football (1939):
an "infernal nuisance" distracting from academics



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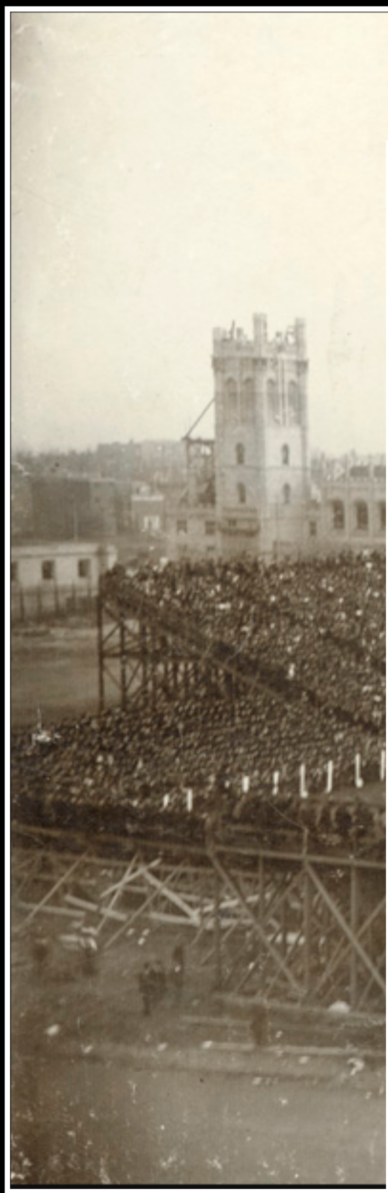
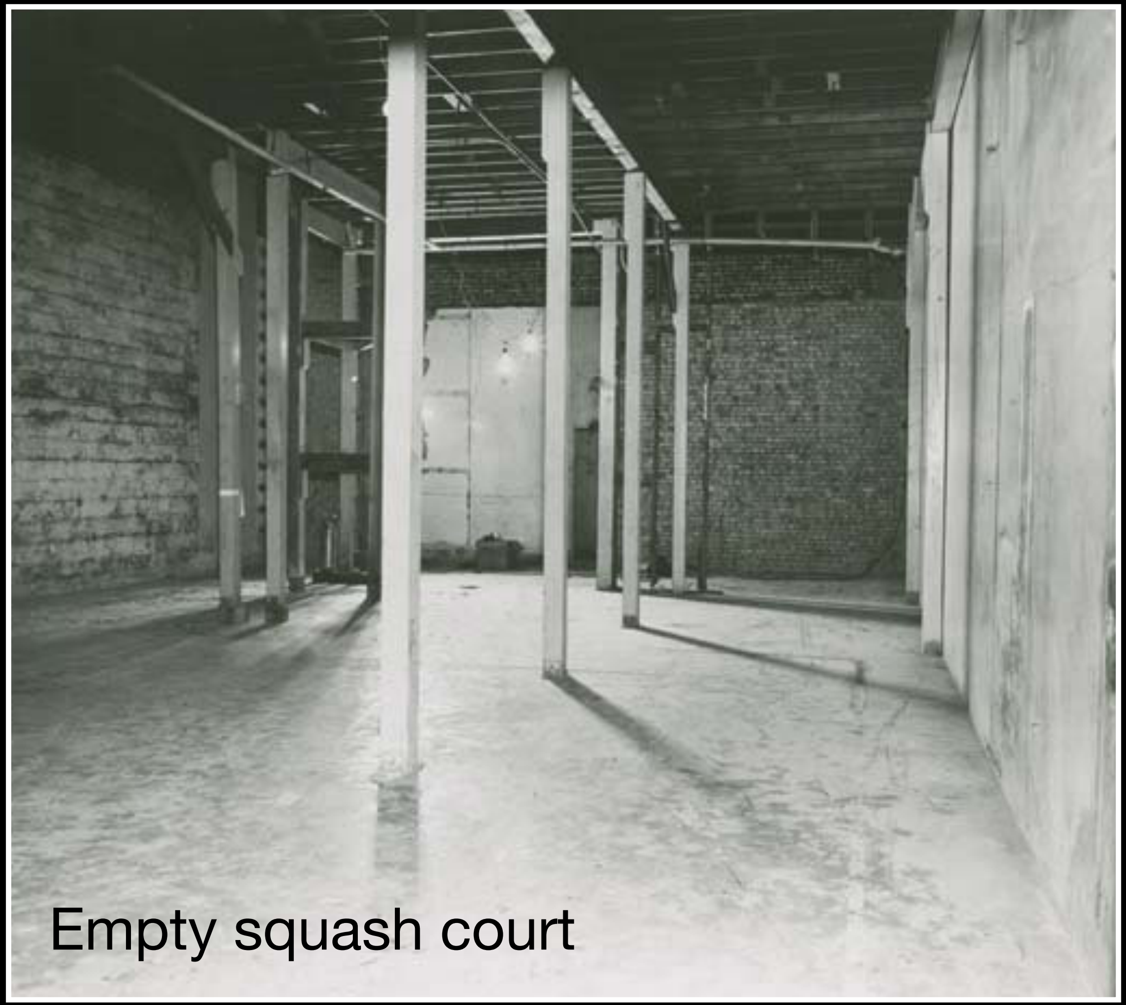


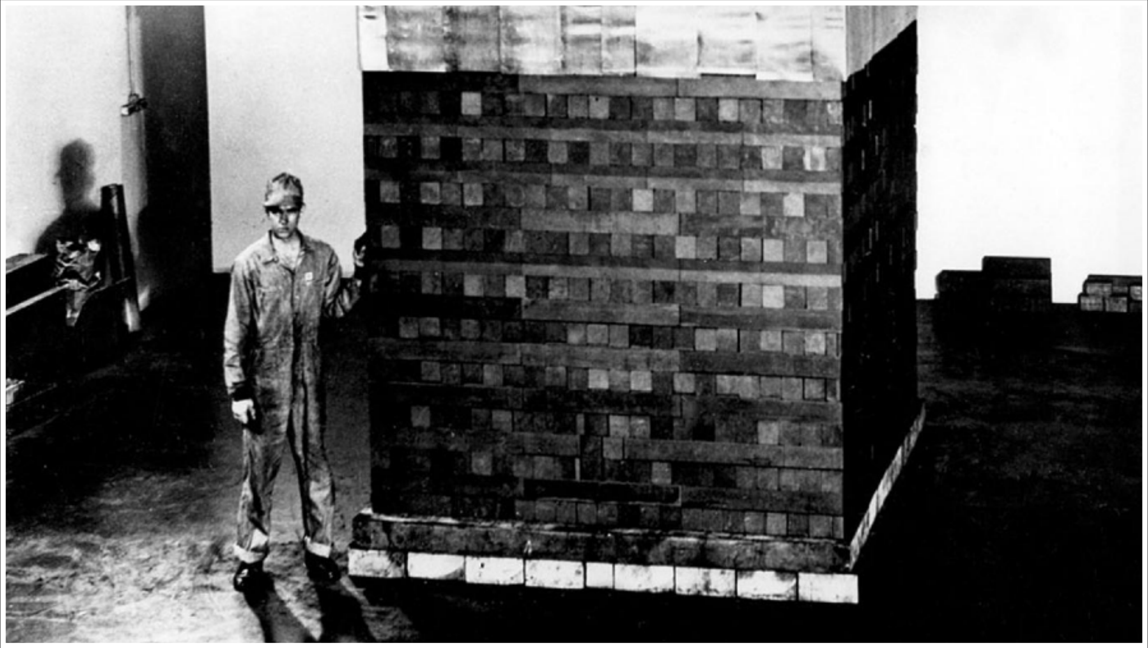
Marshall field, ca. 1900

Stagg field west stand, 1930s

First test piles at Stagg Field



Empty squash court



Improving the Pile

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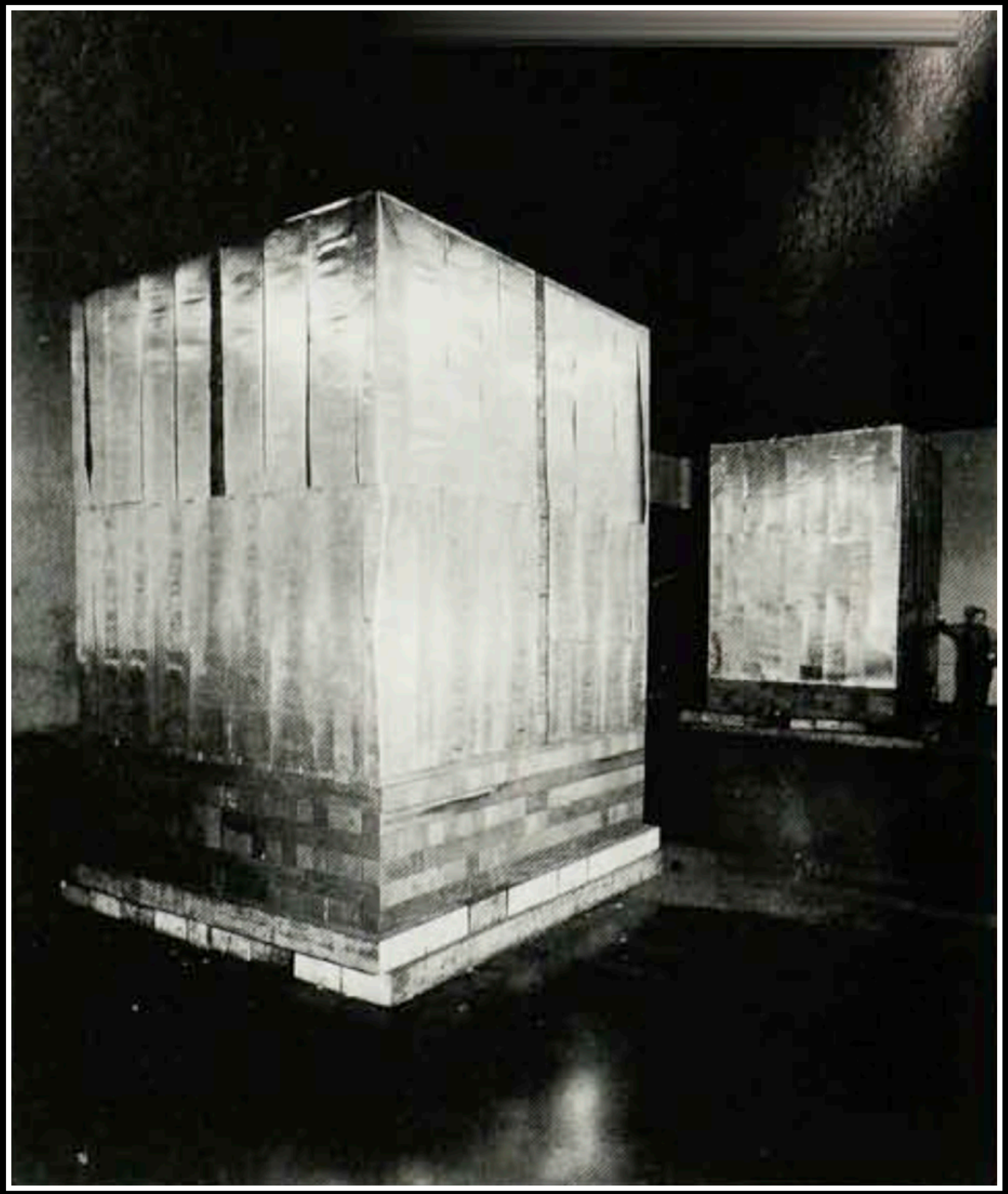
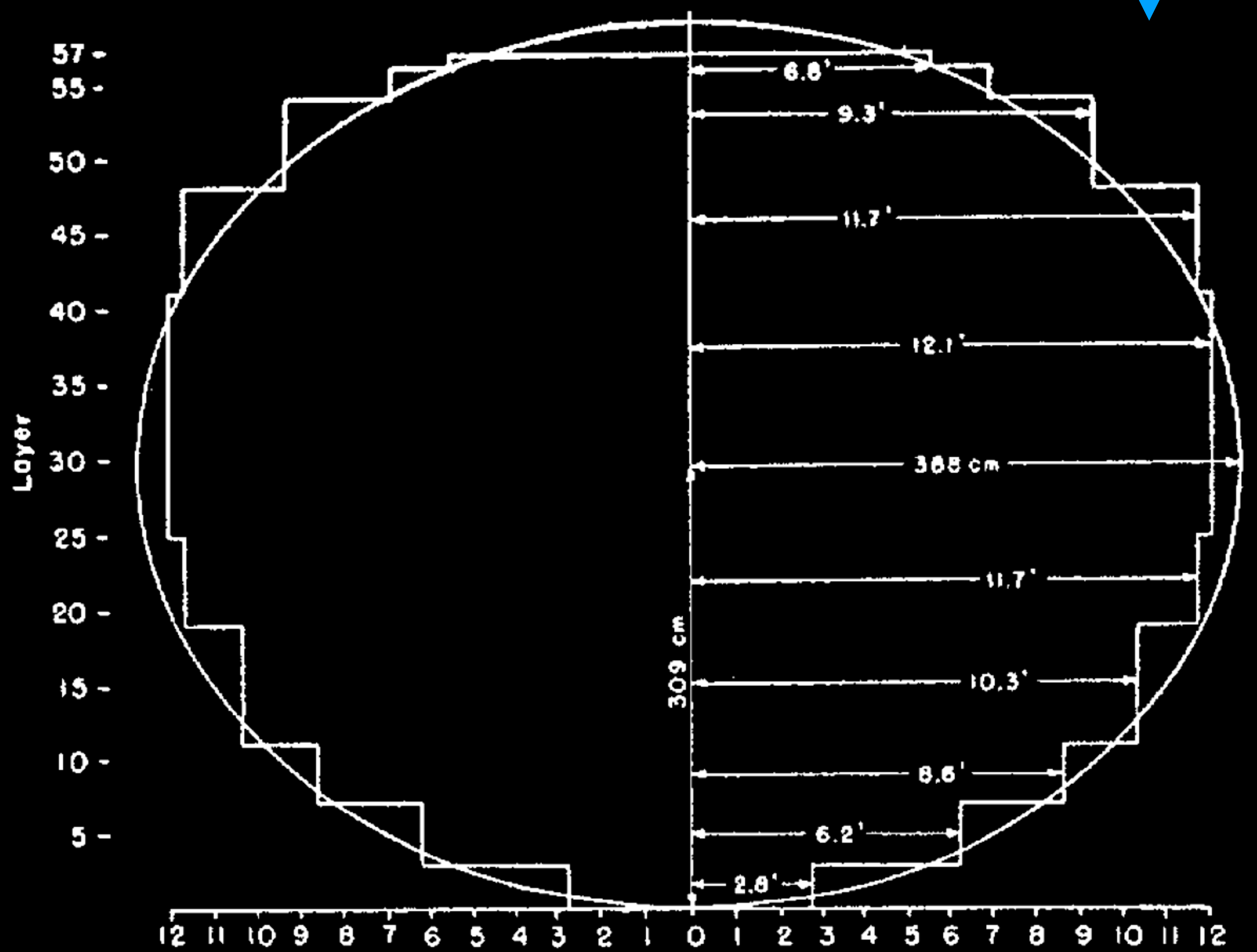


Columbia / early Chicago piles:
Rectangular → easy to build, but large neutron losses

Improving the Pile

Columbia / early Chicago piles:
Rectangular → easy to build, but large neutron losses

Loss-minimizing shape:
As close to a sphere as possible



Improving the pile

Improving the pile

Leona Woods

Improving the pile

Boron-trifluoride (BF_3) **counters …**

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Improving the pile

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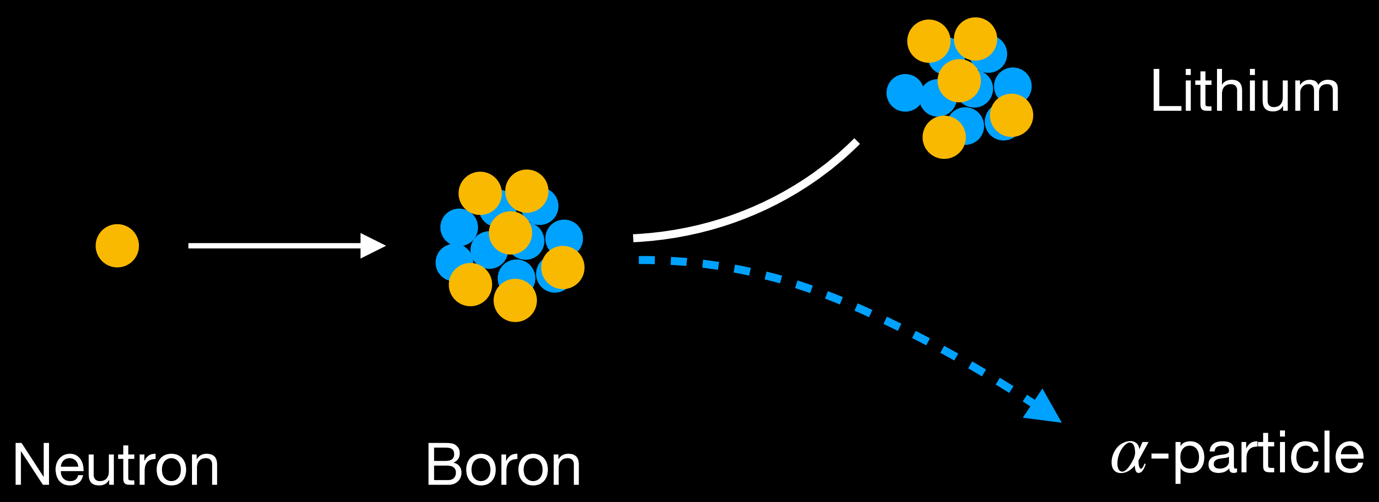

Leona Woods

Improving the pile

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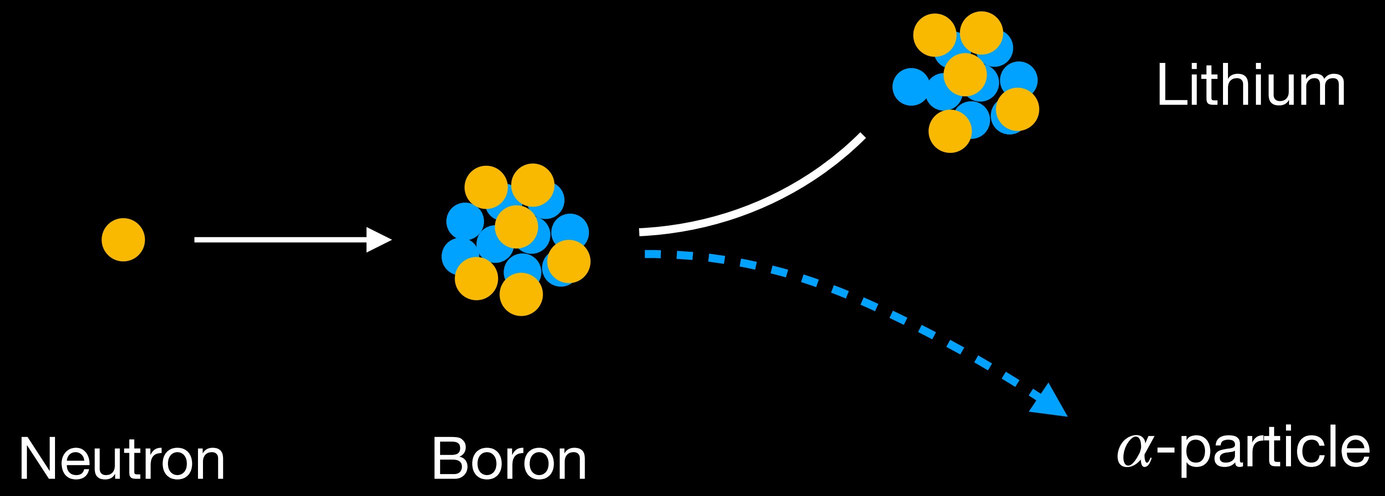

… turn a nuisance into a virtue

Leona Woods

Improving the pile

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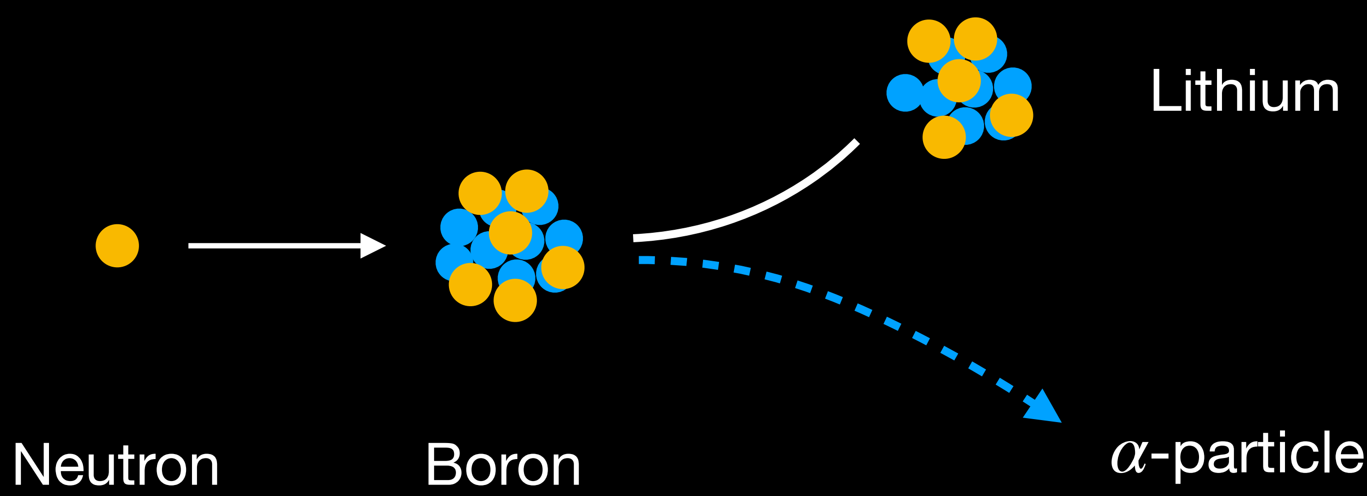
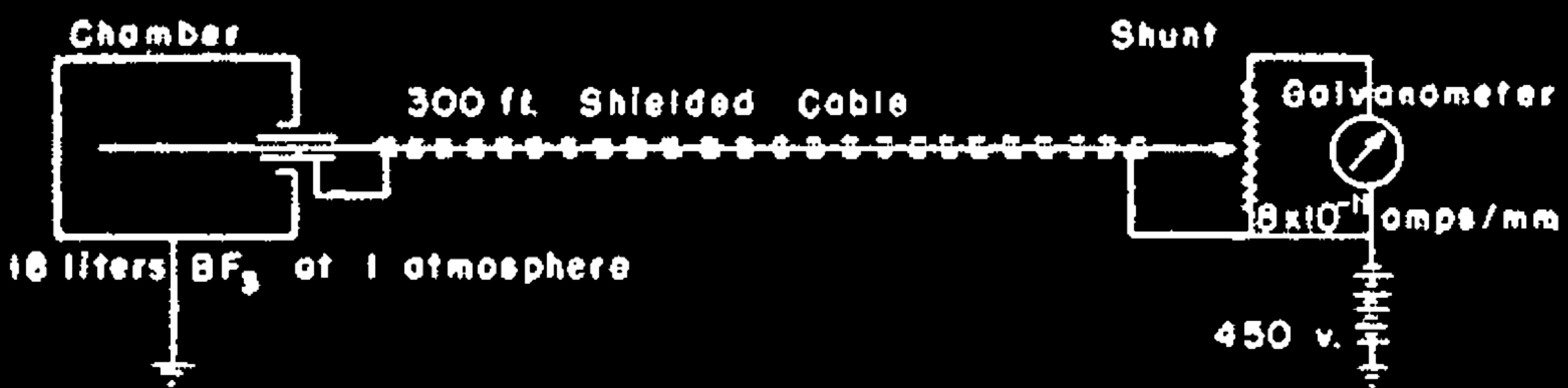


… turn a nuisance into a virtue

Leona Woods

Detection chamber inside the pile



Readout instrument

The site of the first pile

The site of the first pile

Argonne Forest Preserve

The site of the first pile

Argonne Forest Preserve

"Site A"
(Today: Close to Argonne National Lab)

The site of the first pile

The workers at Argonne were on strike!

The site of the first pile

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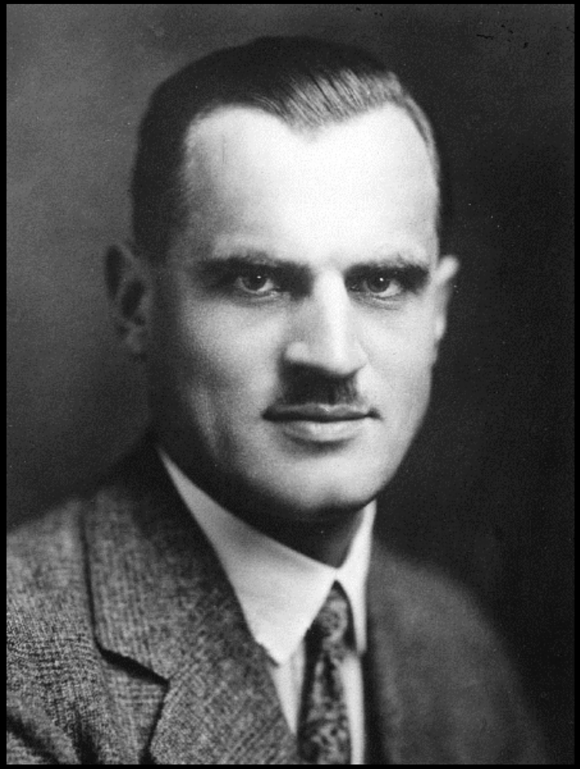
"Should we build the pile at Stagg Field?"

The site of the first pile



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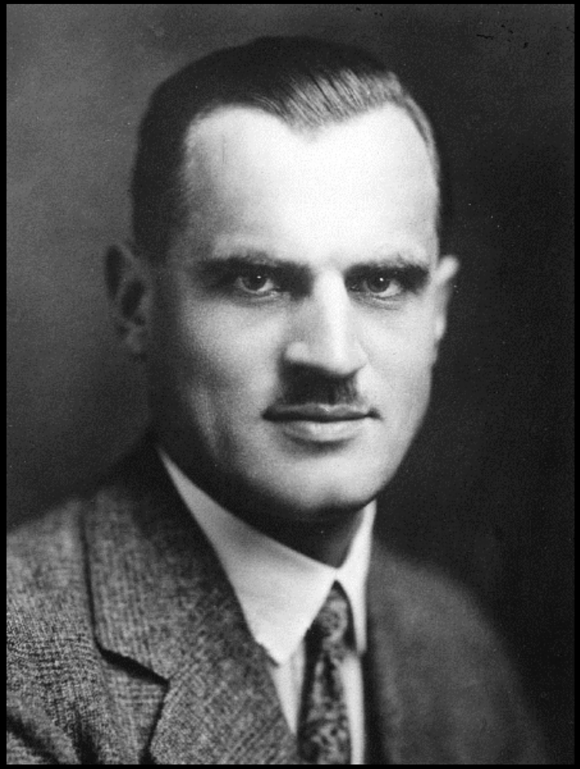
The site of the first pile



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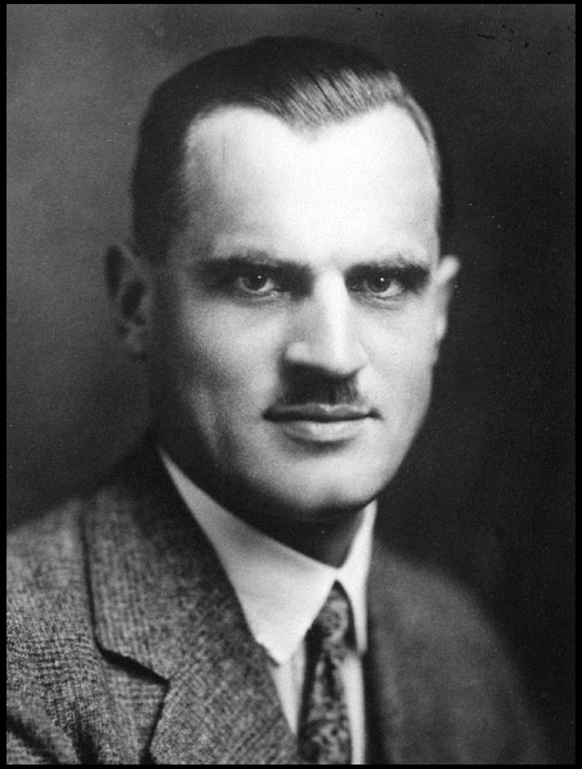

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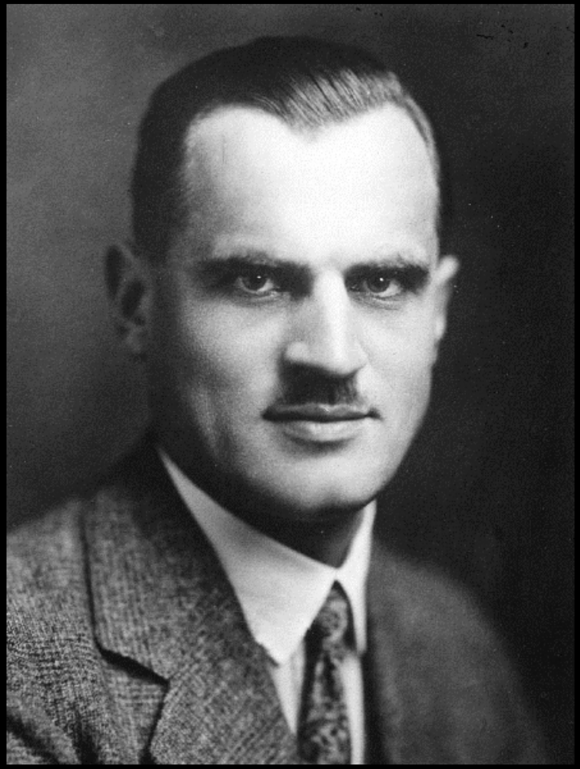

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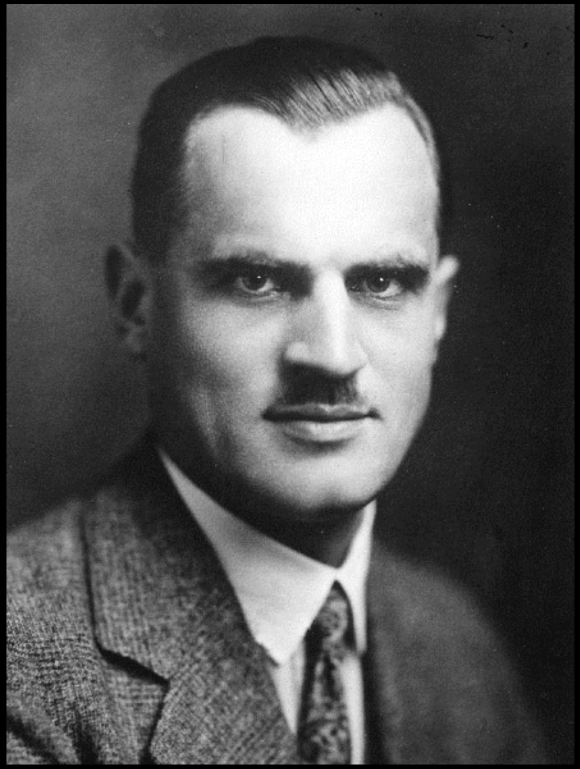

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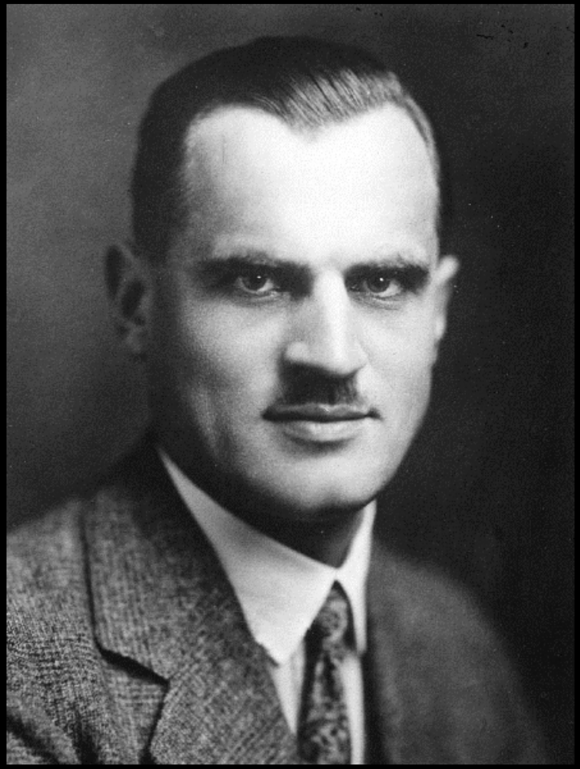

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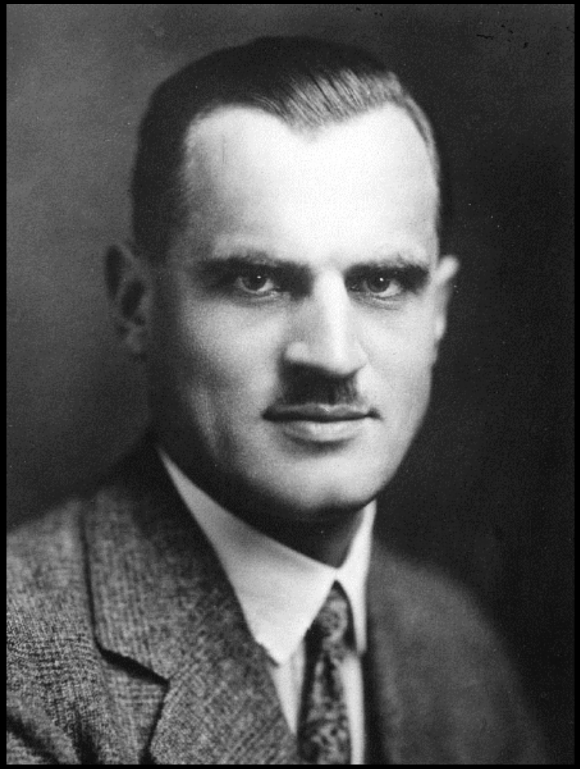

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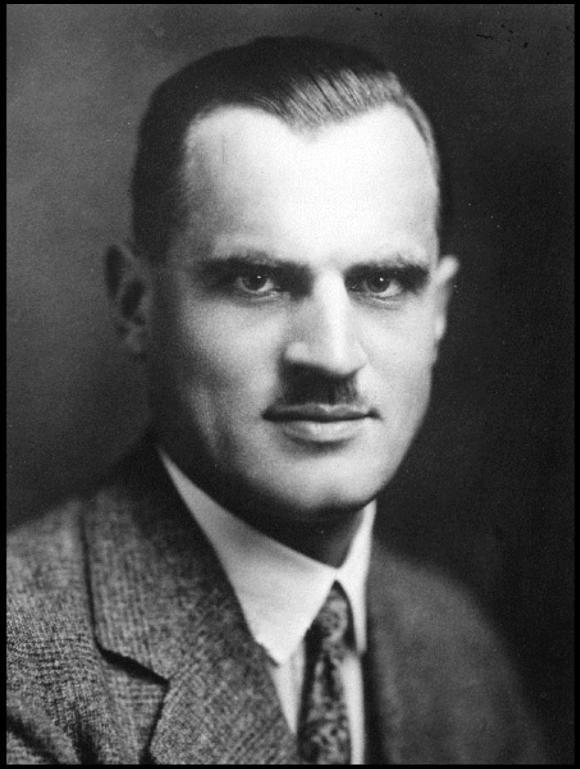

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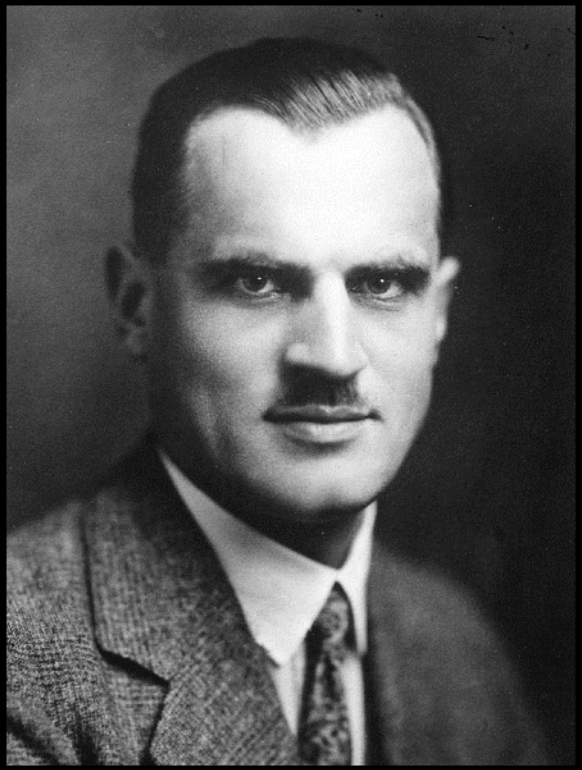
And this answer would have been wrong.

The site of the first pile



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And this answer would have been wrong.
So I assumed the responsibility myself."

Building CP-1

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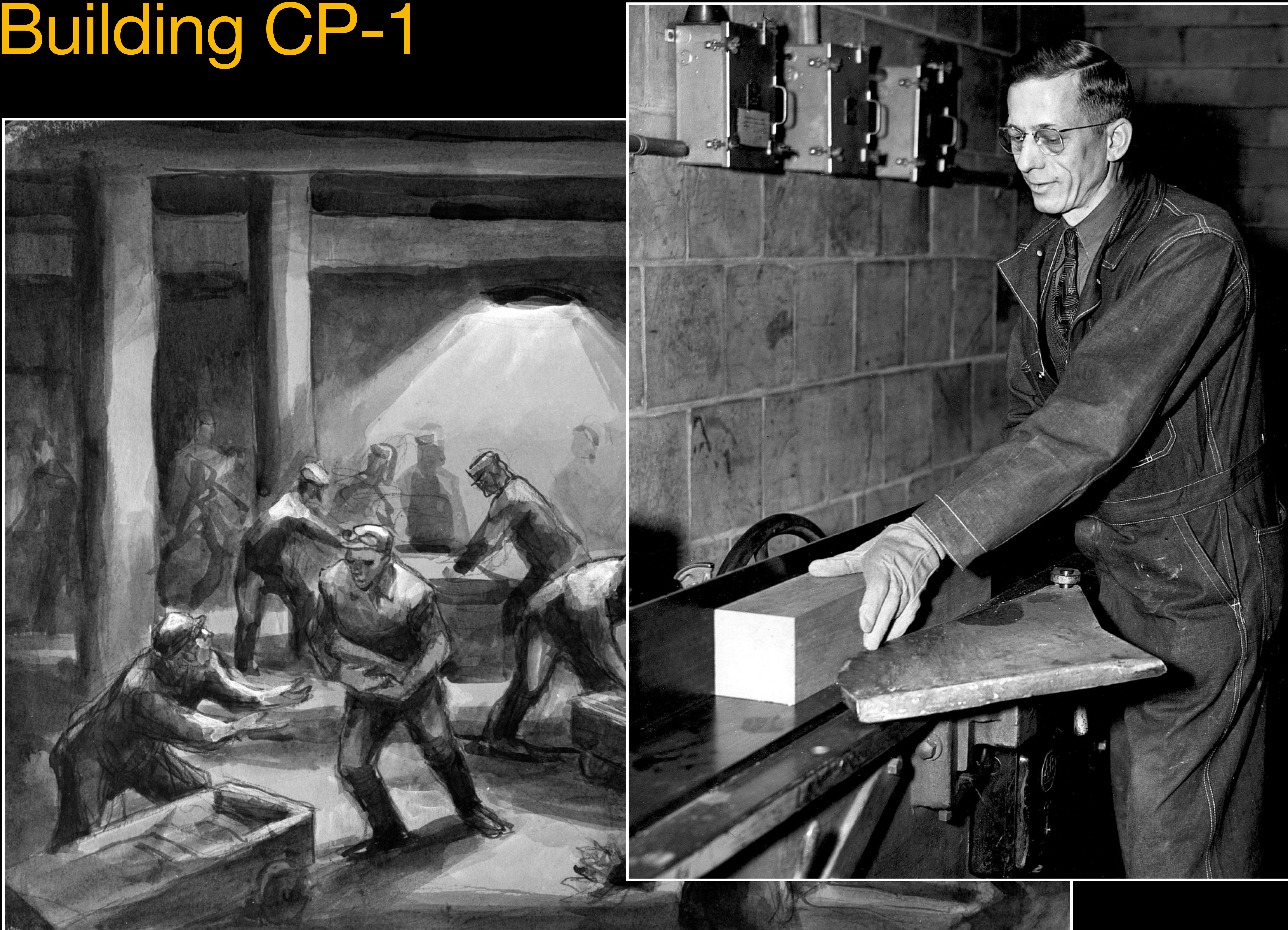

Building CP-1: layer by layer

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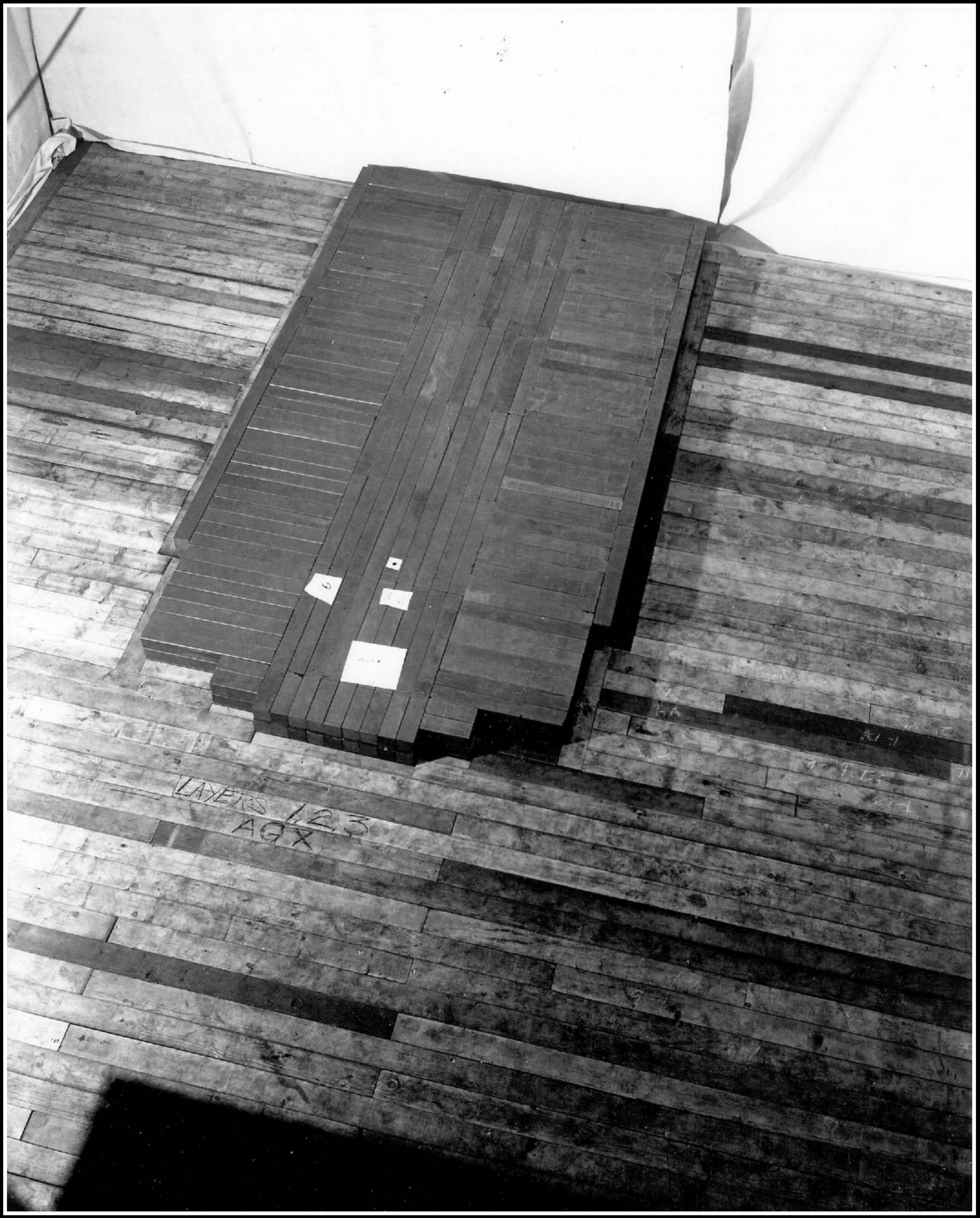

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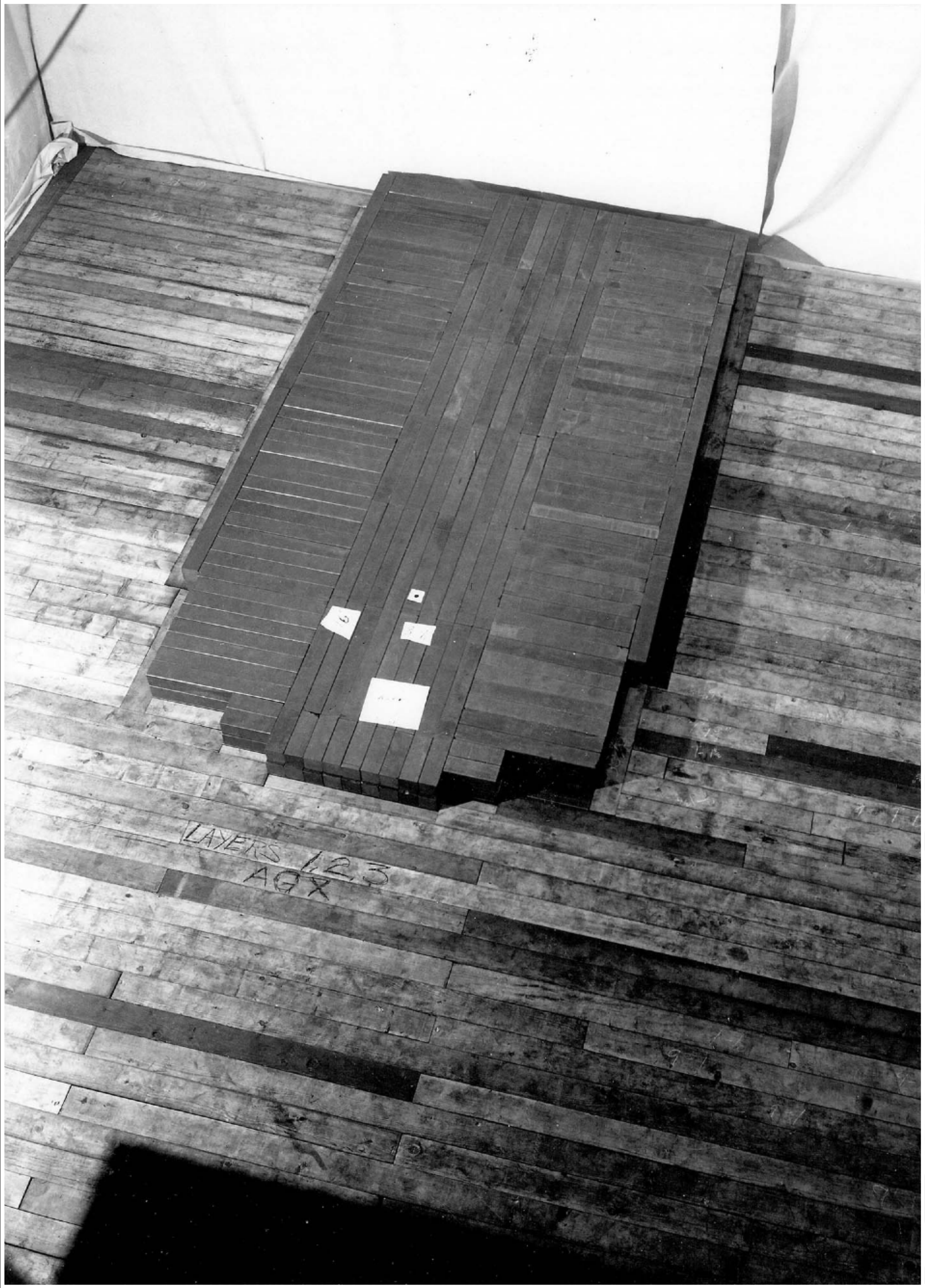

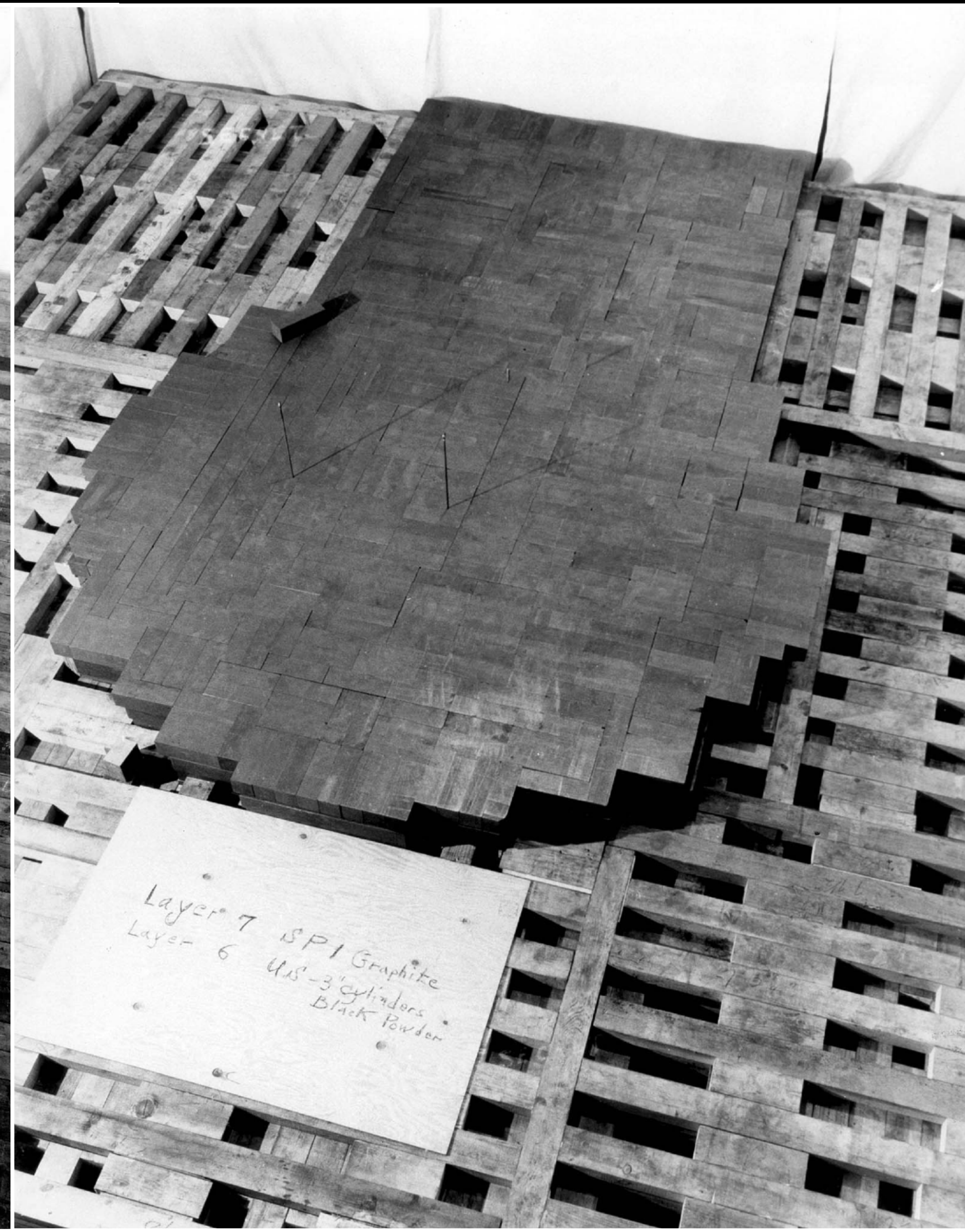

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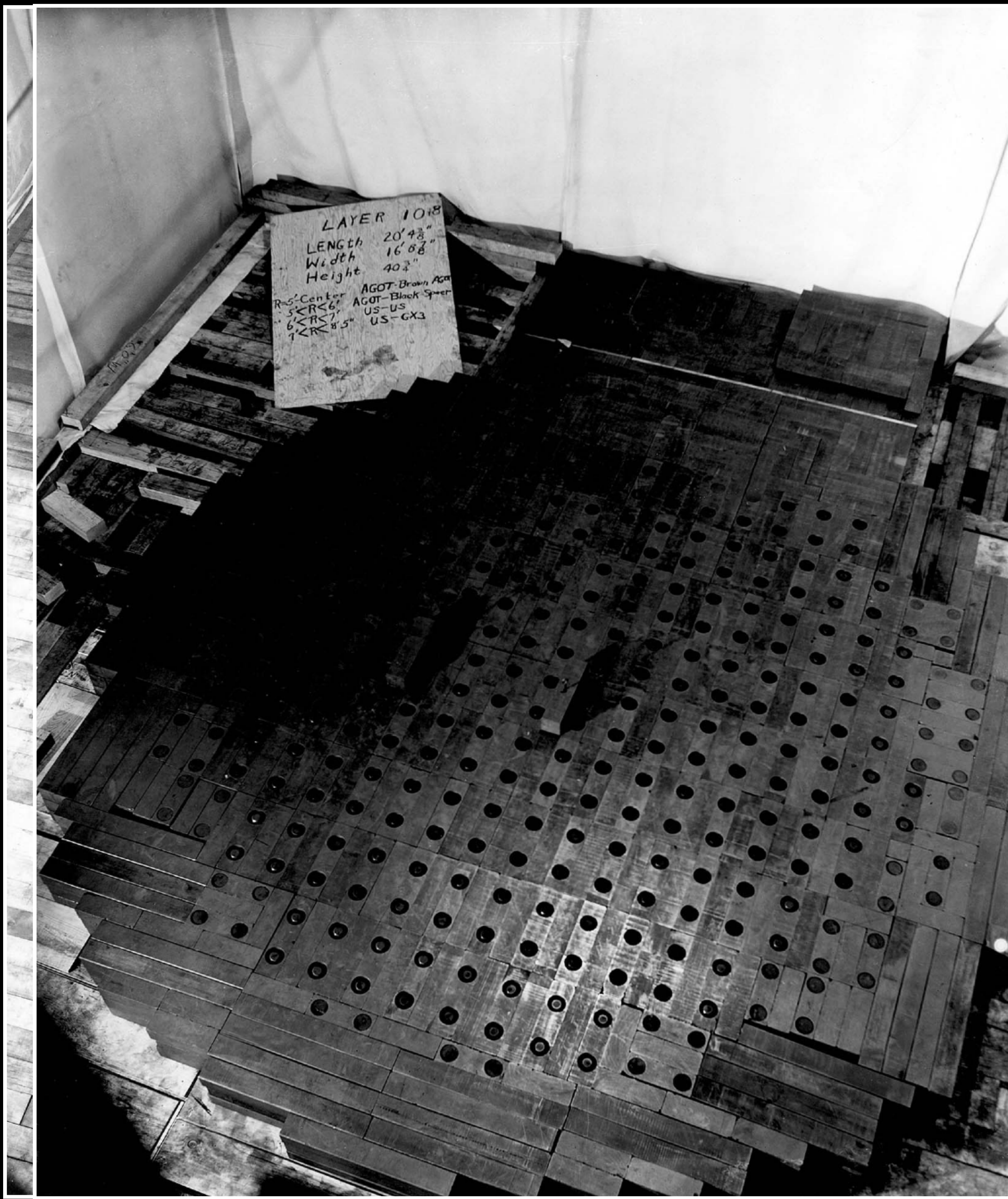

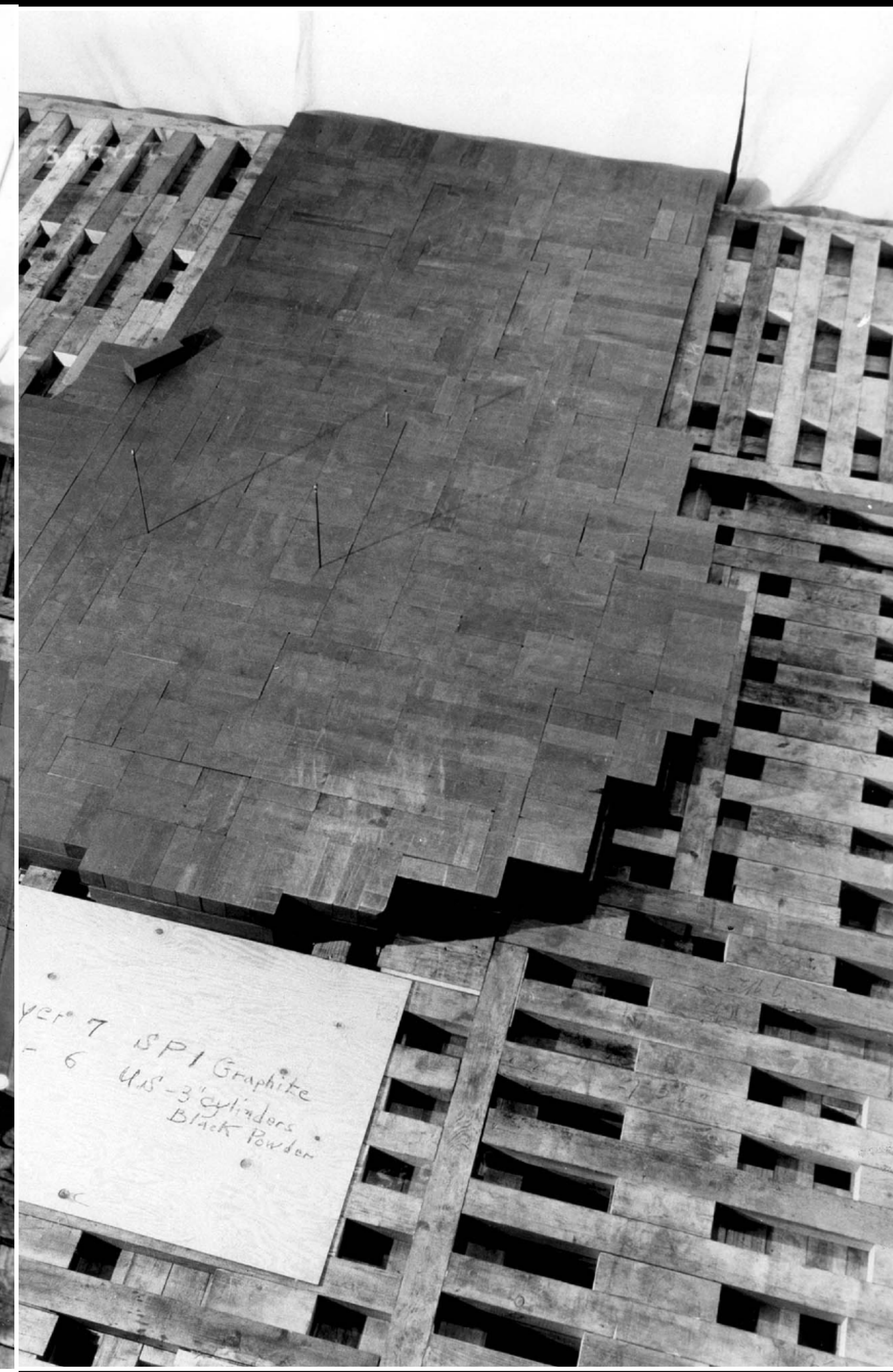

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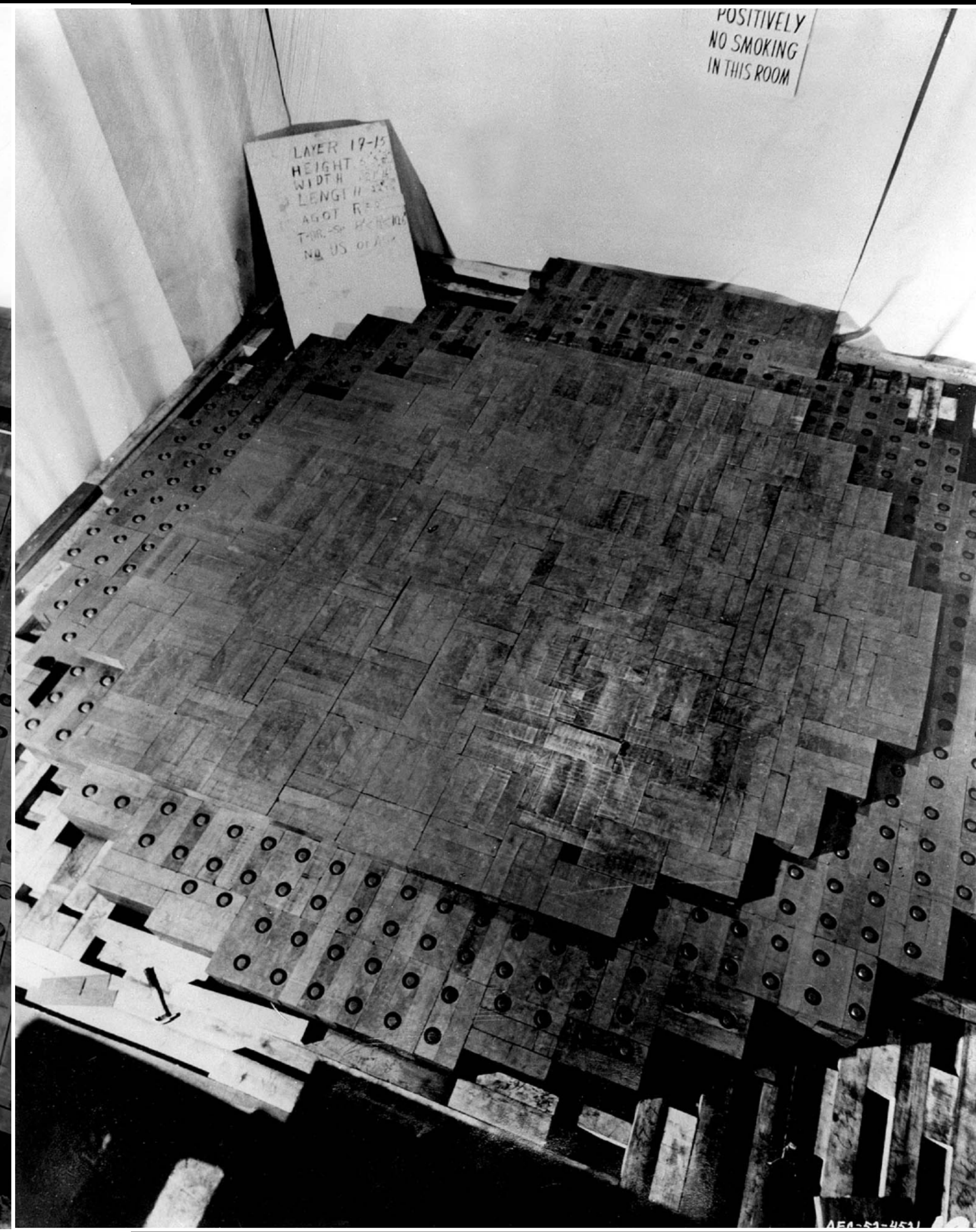

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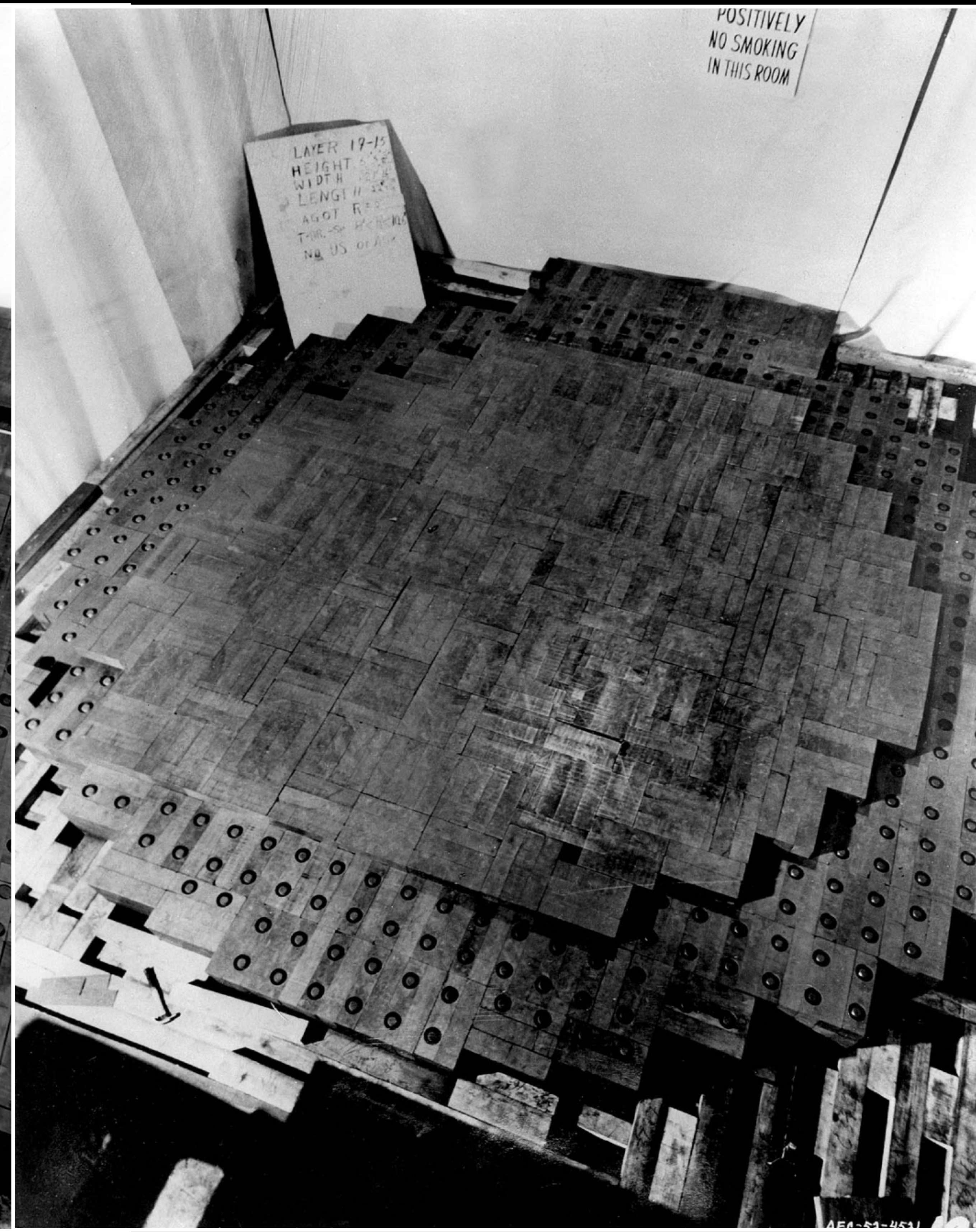

Approaching criticality … safely

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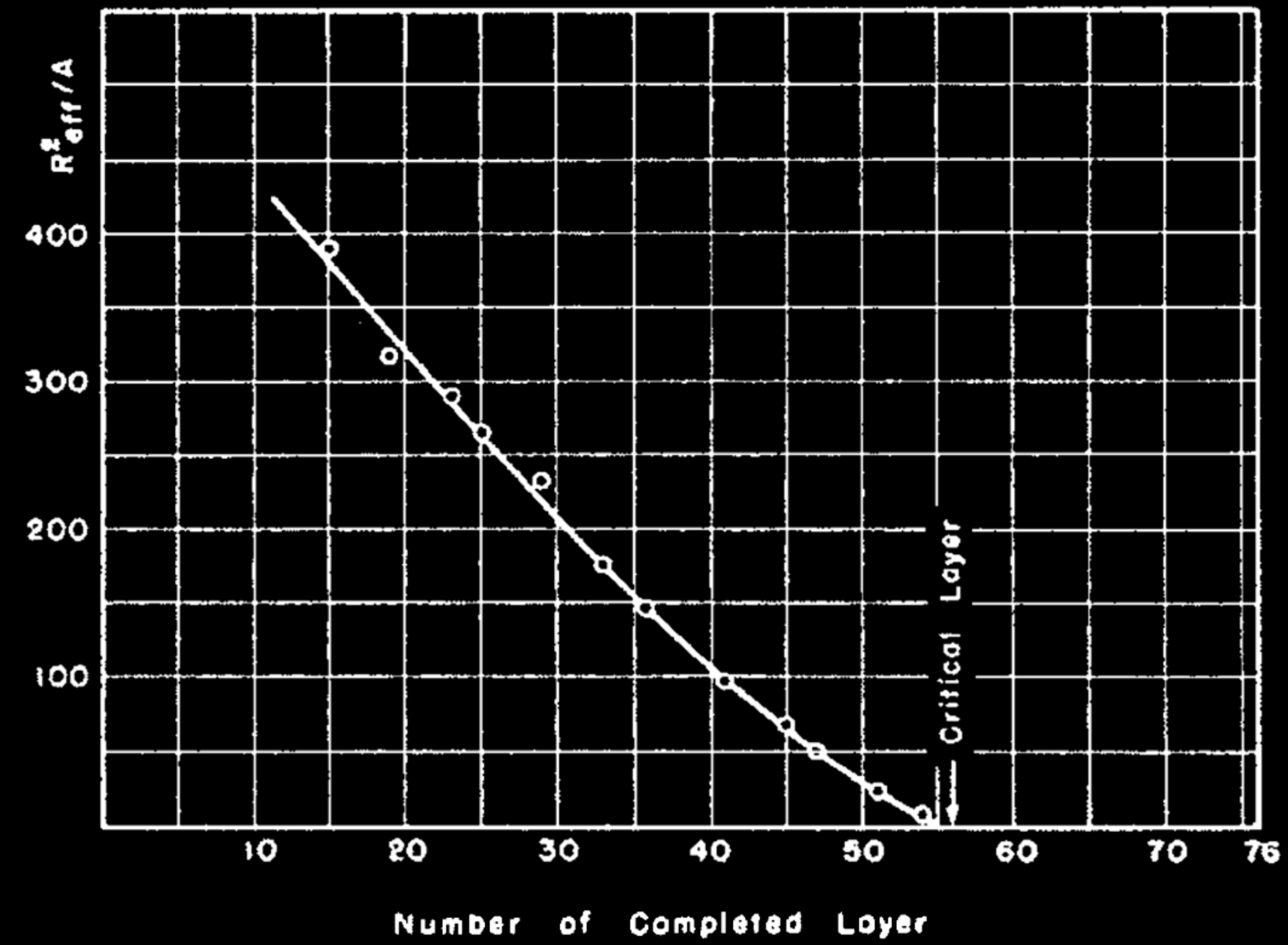
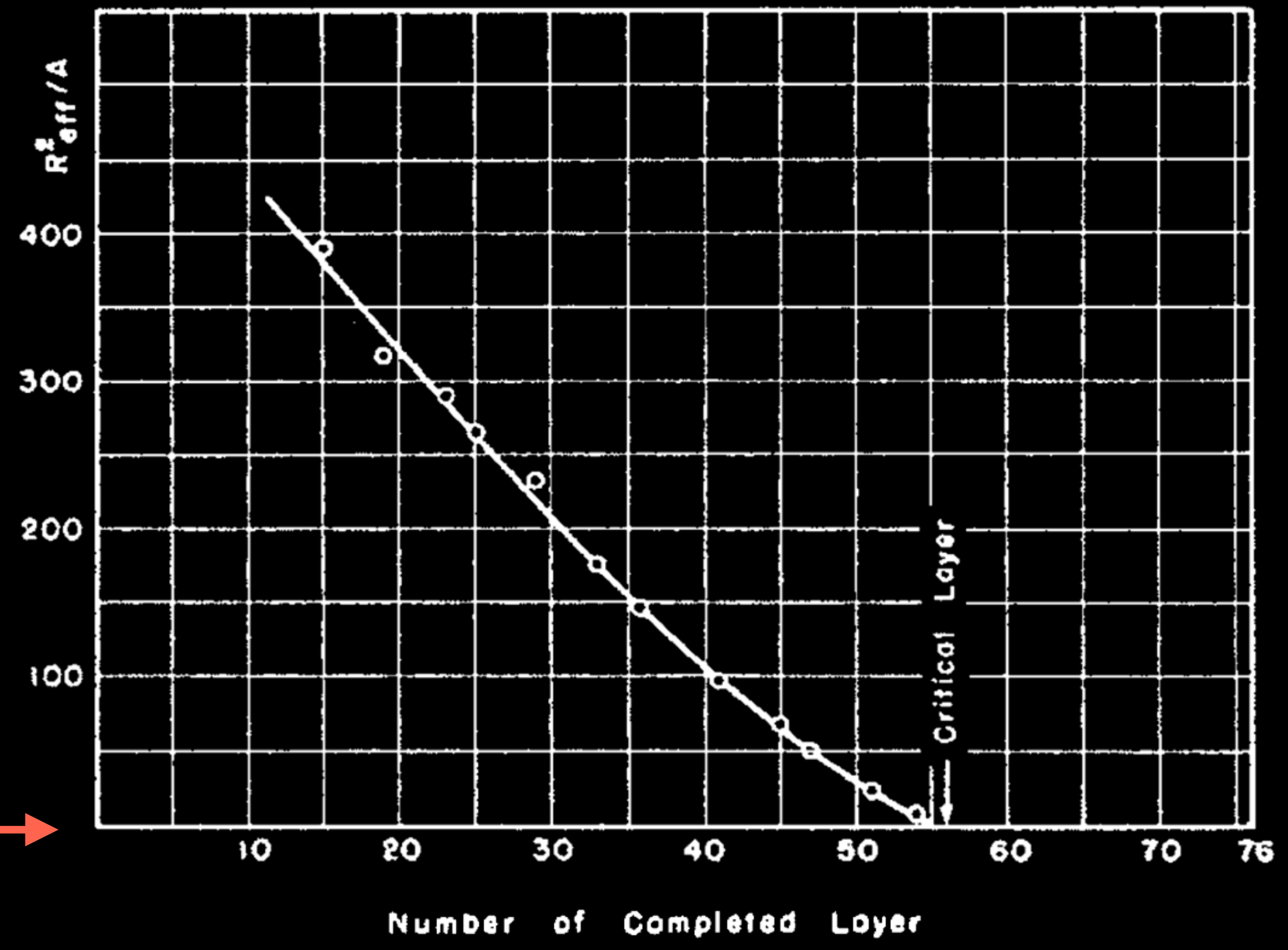


Approaching criticality … safely

Reaction becomes self-sustaining
("Pile becomes critical")



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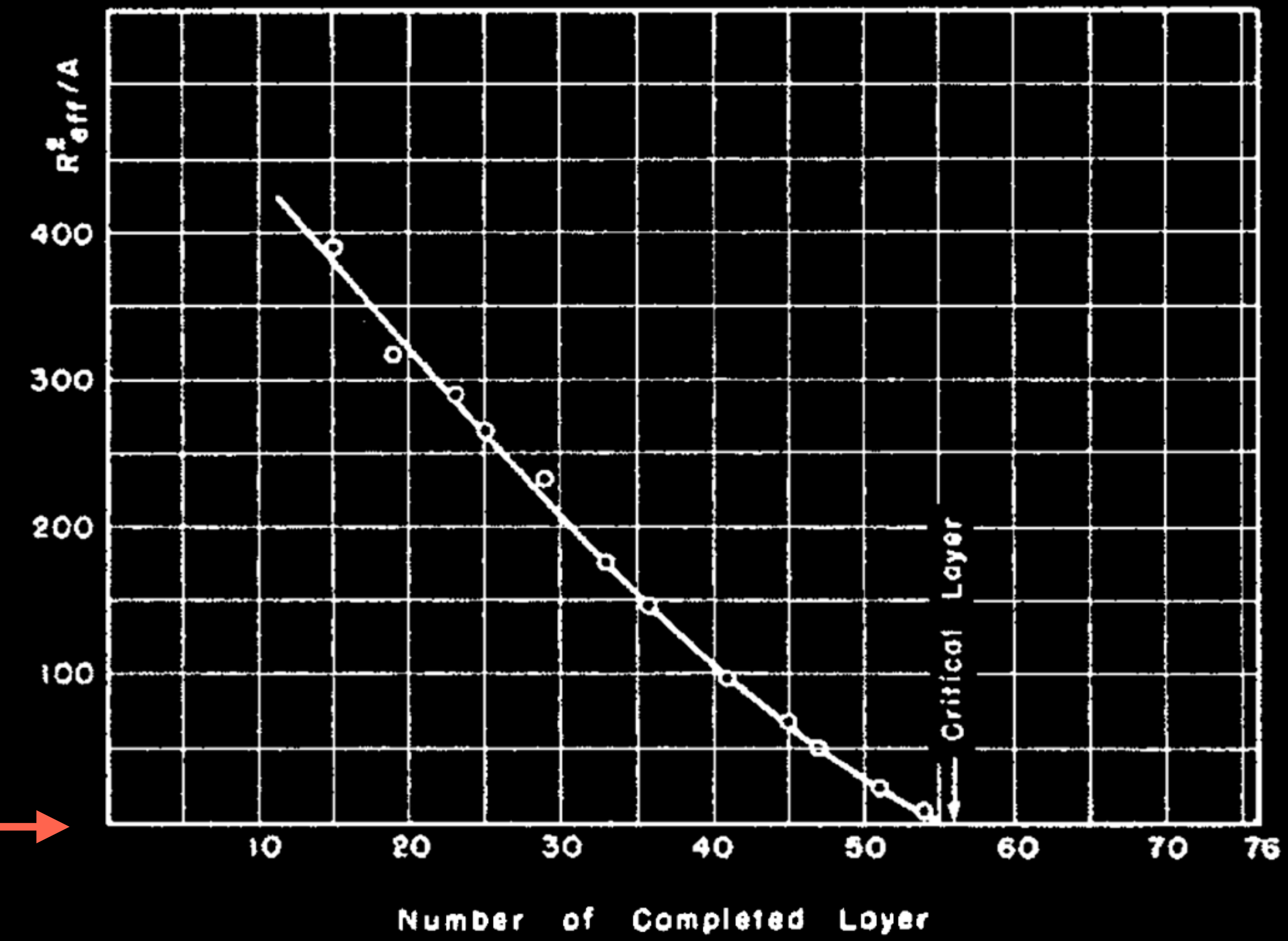

Reaction becomes self-sustaining

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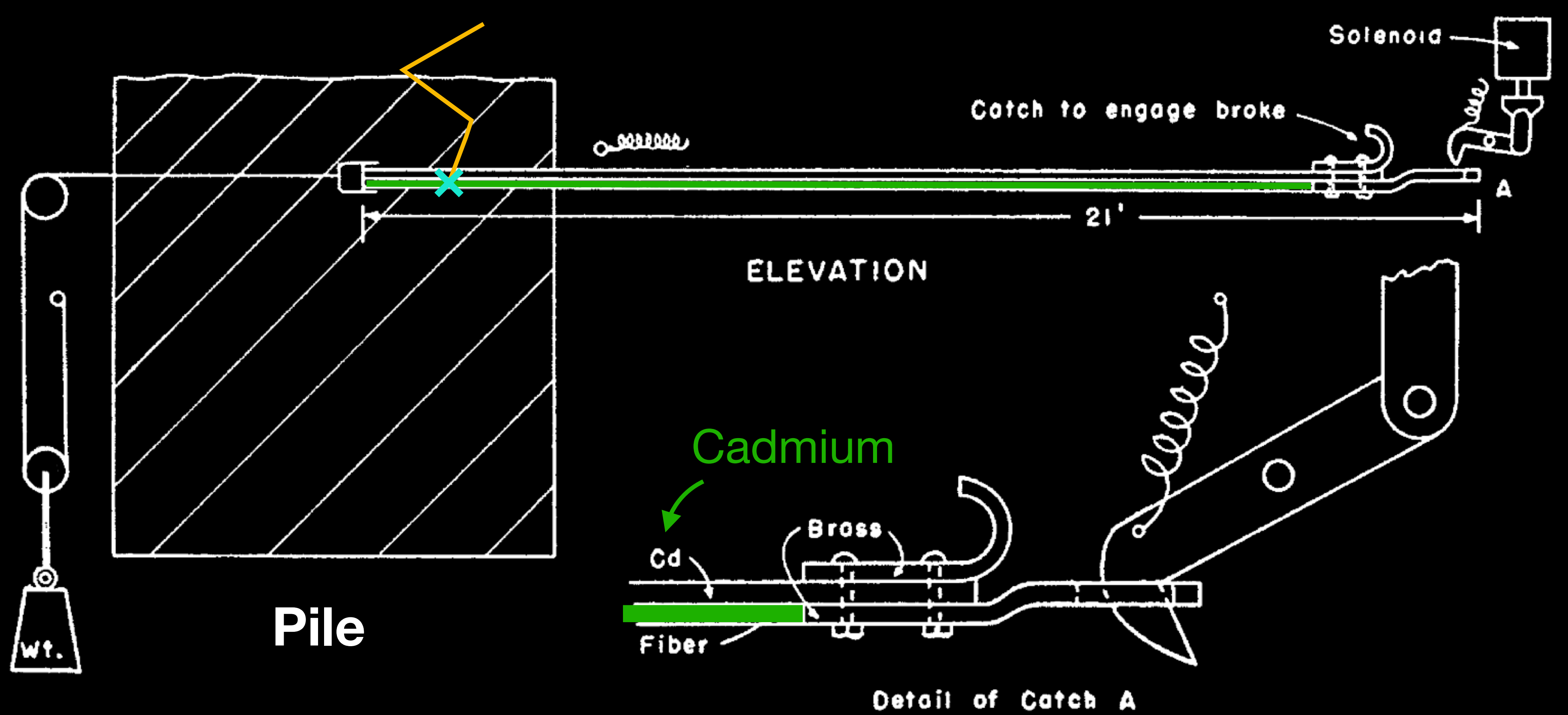
Neutron-absorbing "'Zip' rod":



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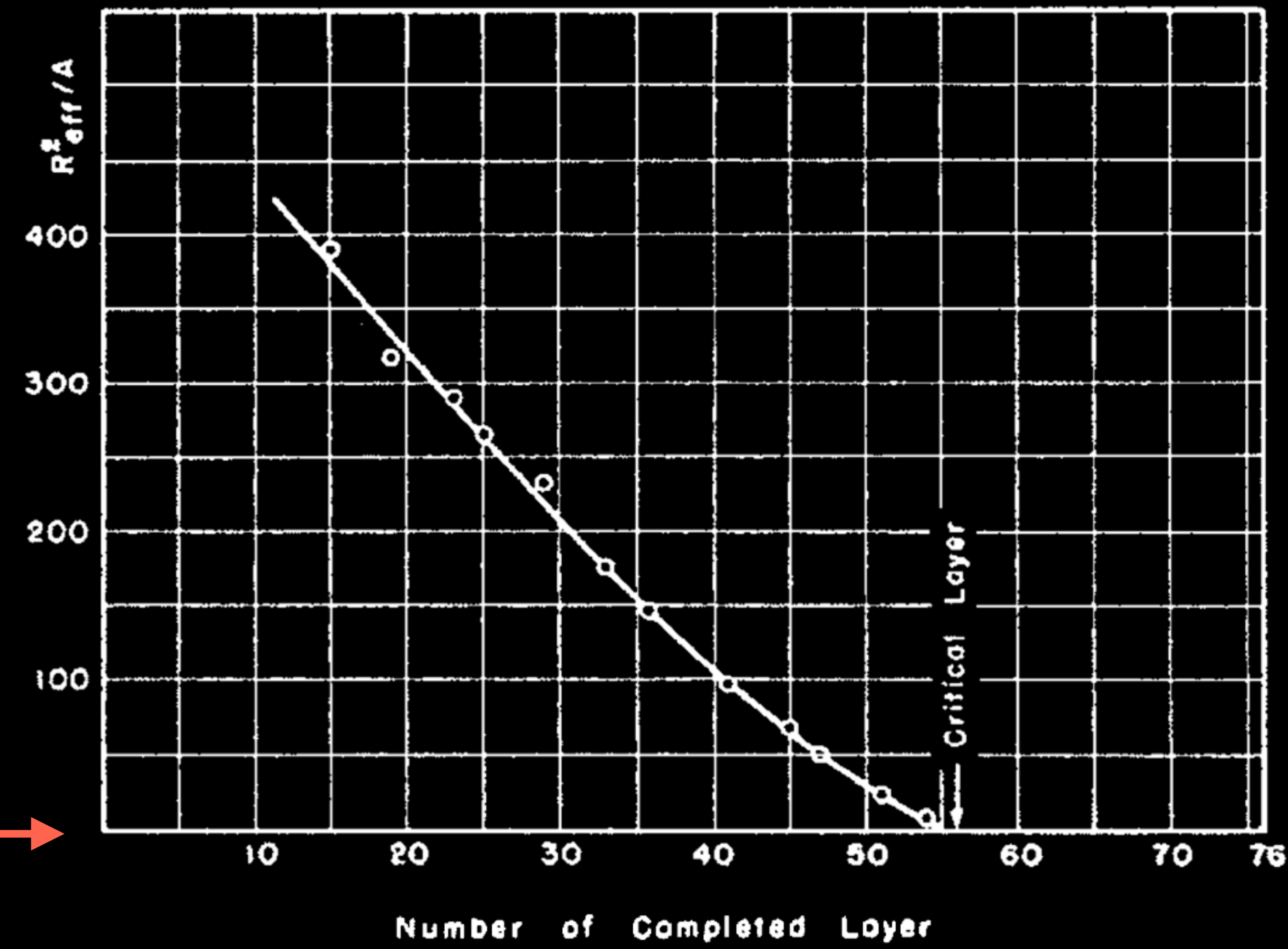

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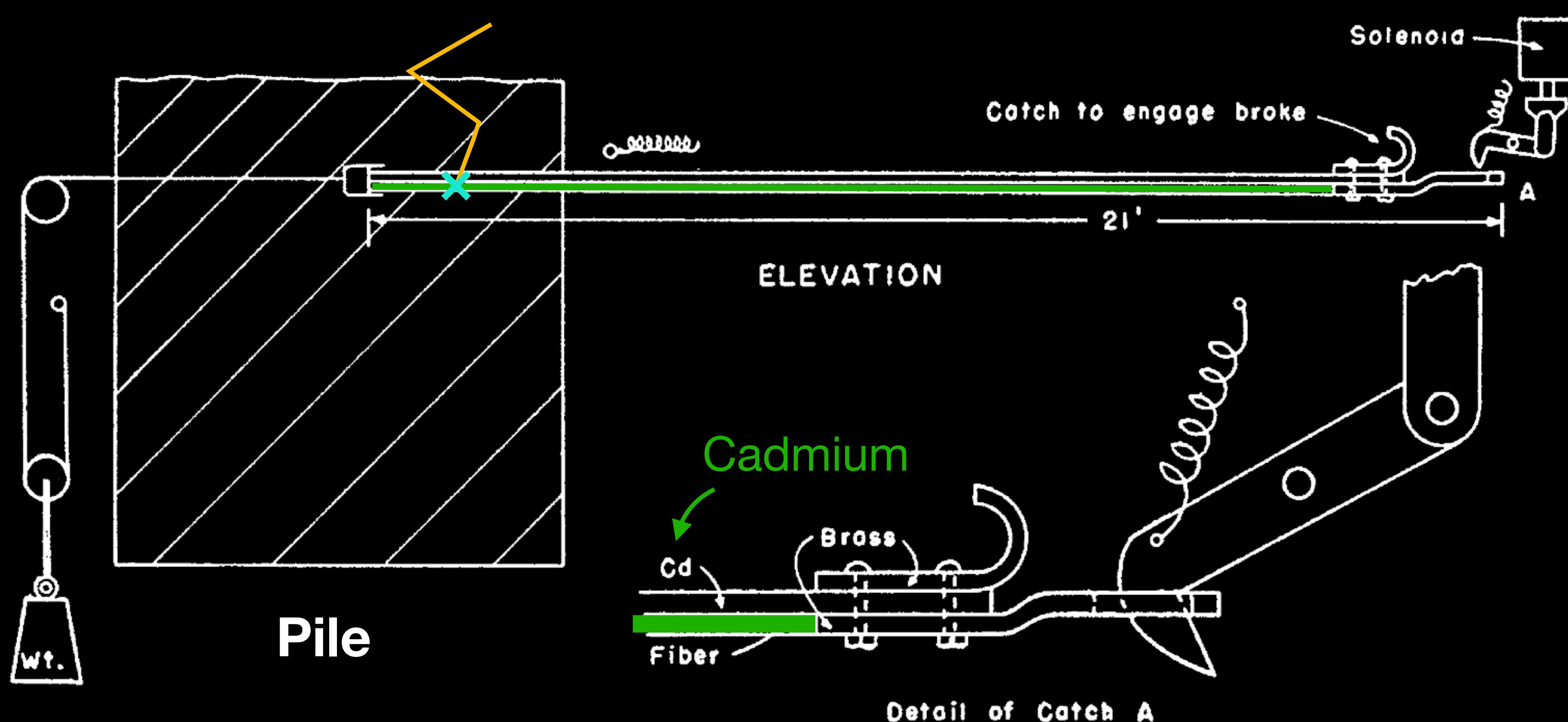
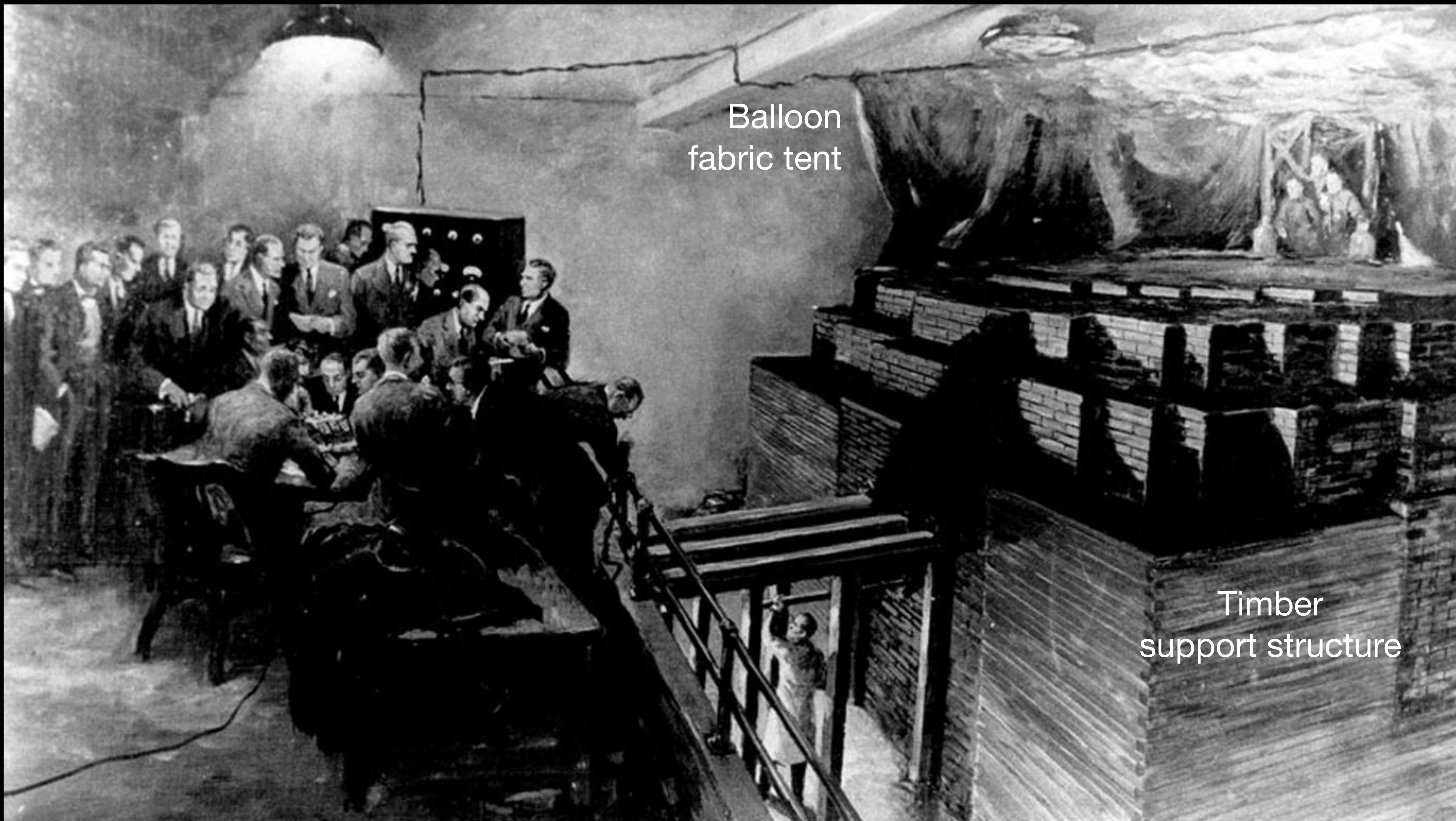


Magnetic hook, automatically released

December 2, 1942

December 2, 1942

December 2, 1942



December 2, 1942

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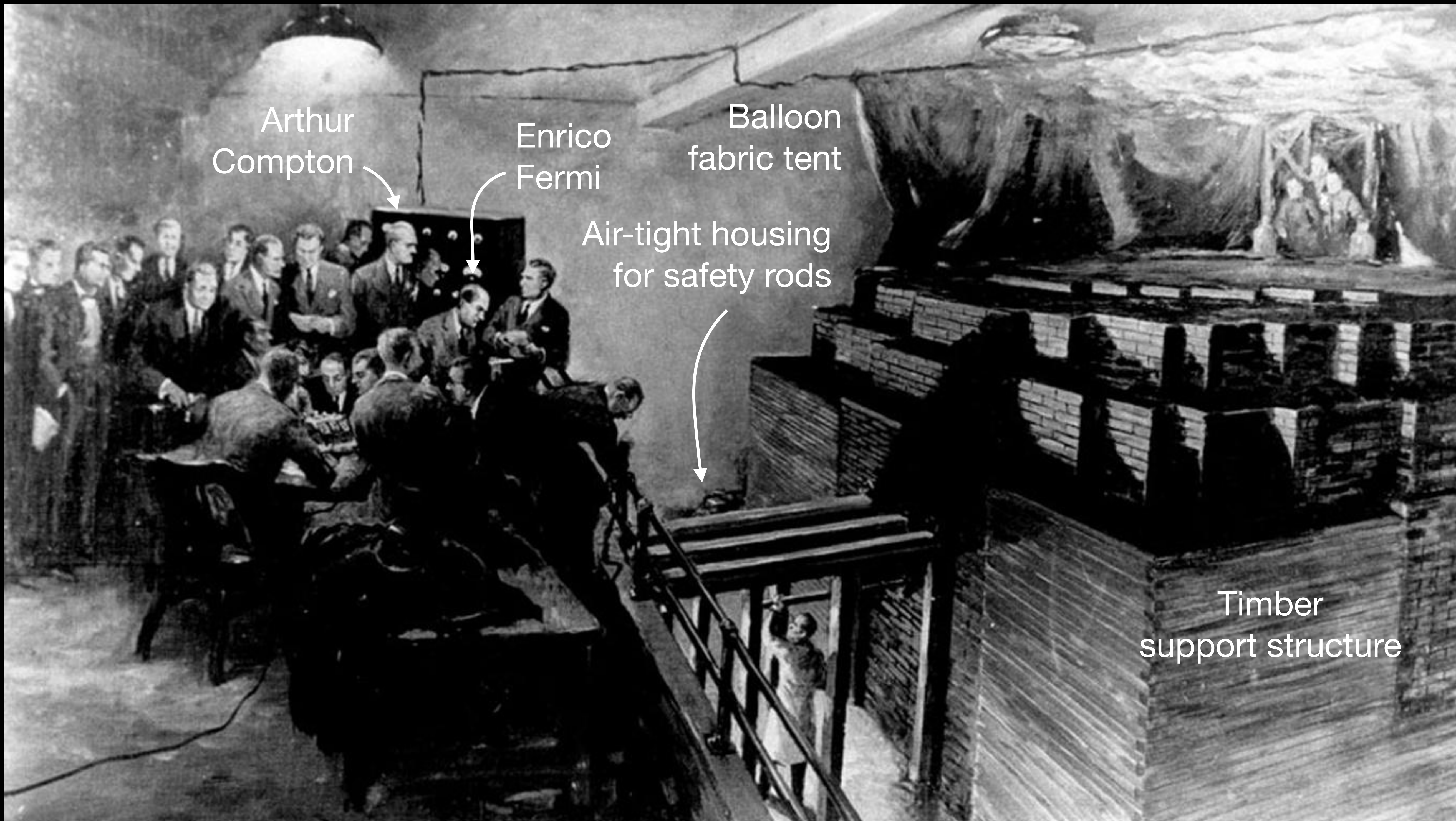

December 2, 1942

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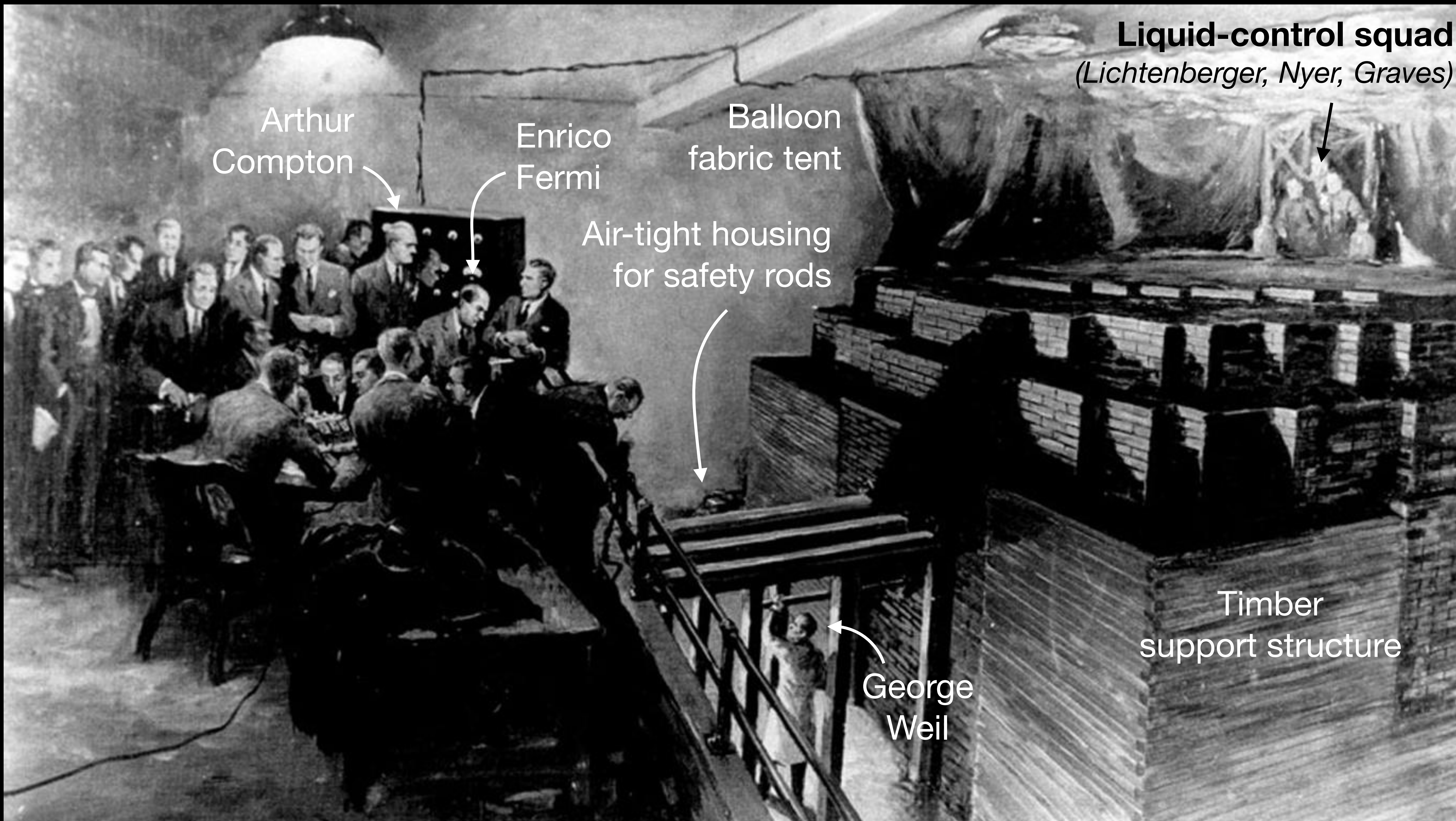

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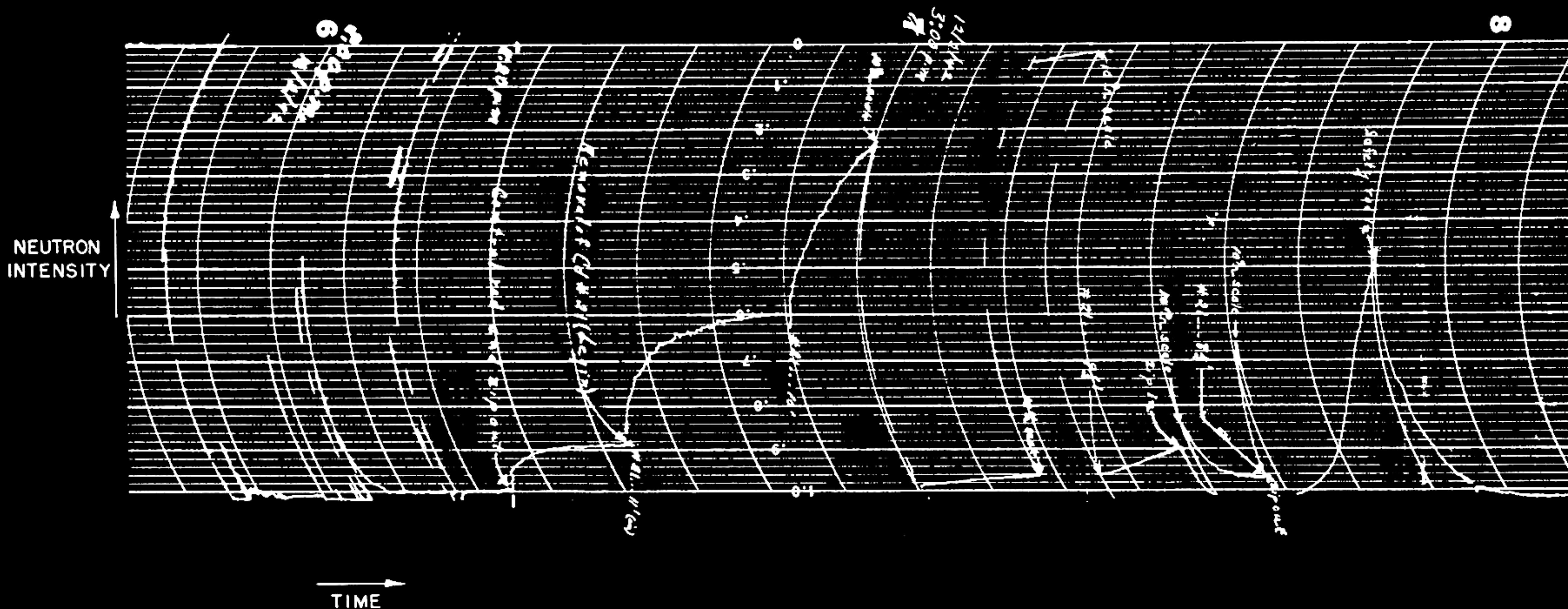
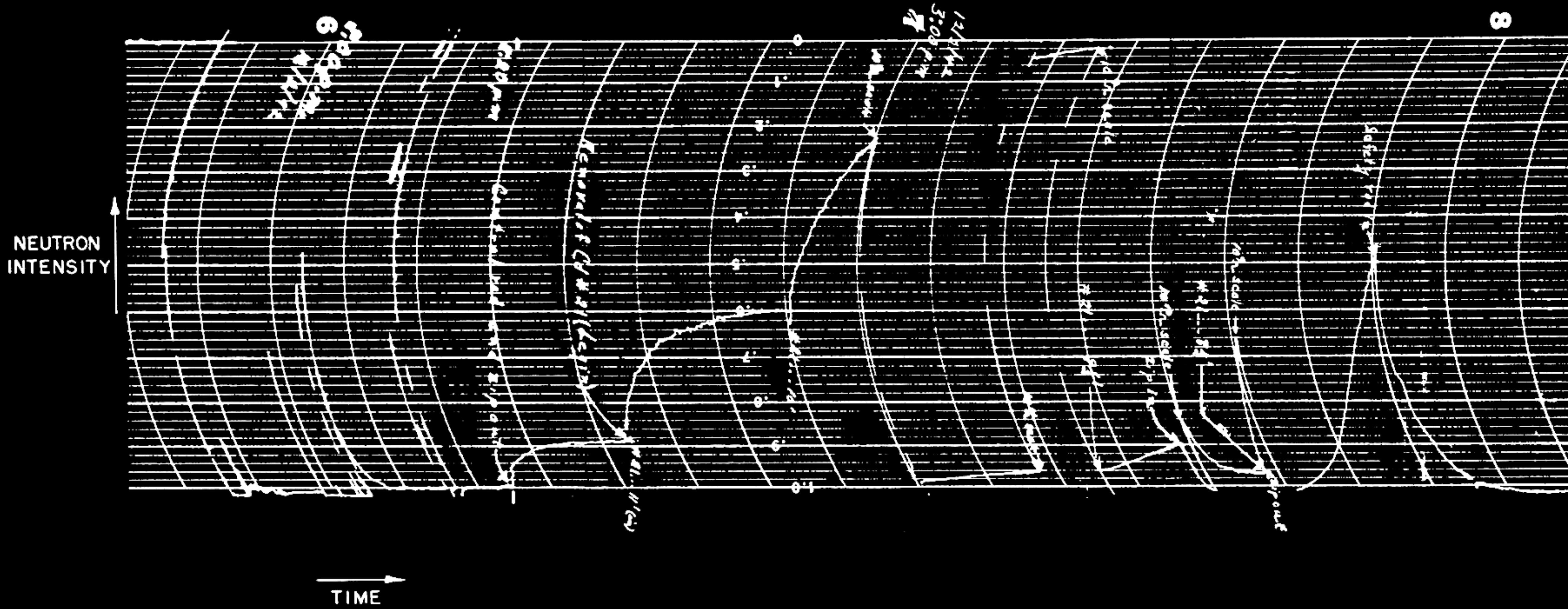


December 2, 1942

"'Zip' out"



December 2, 1942

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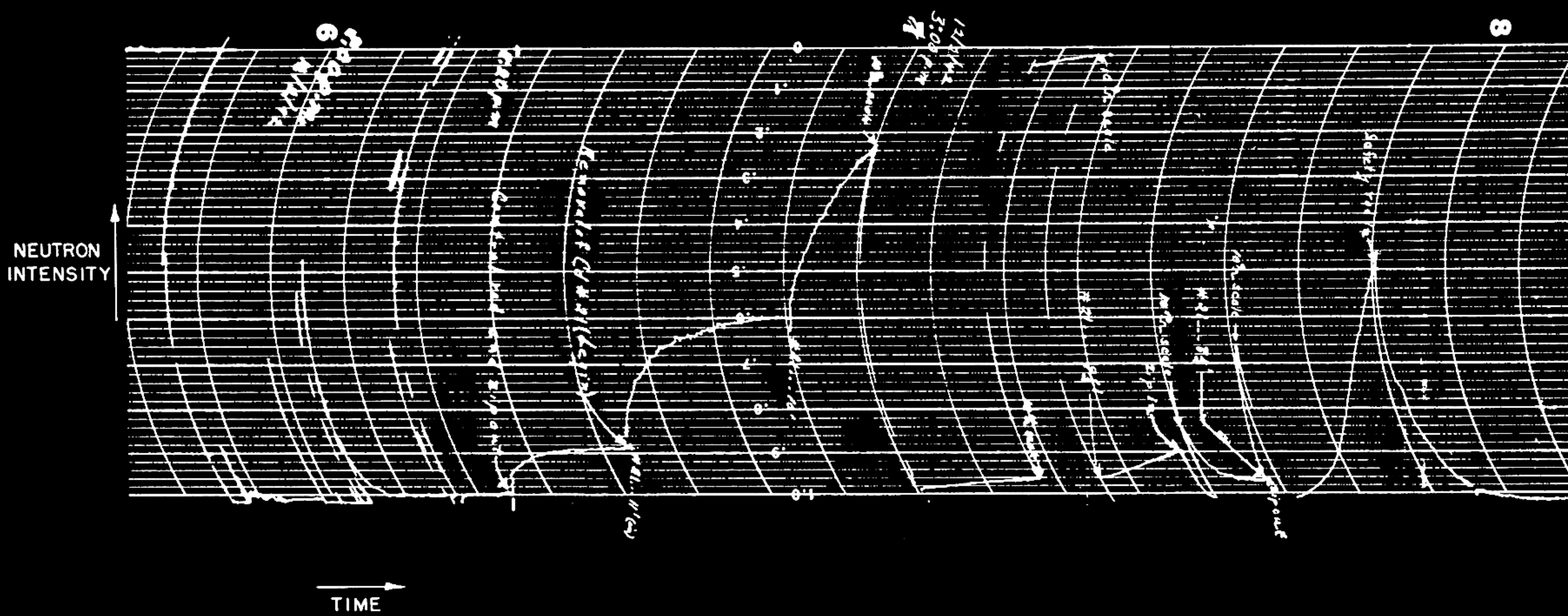
"Pull it to 13 feet, George."



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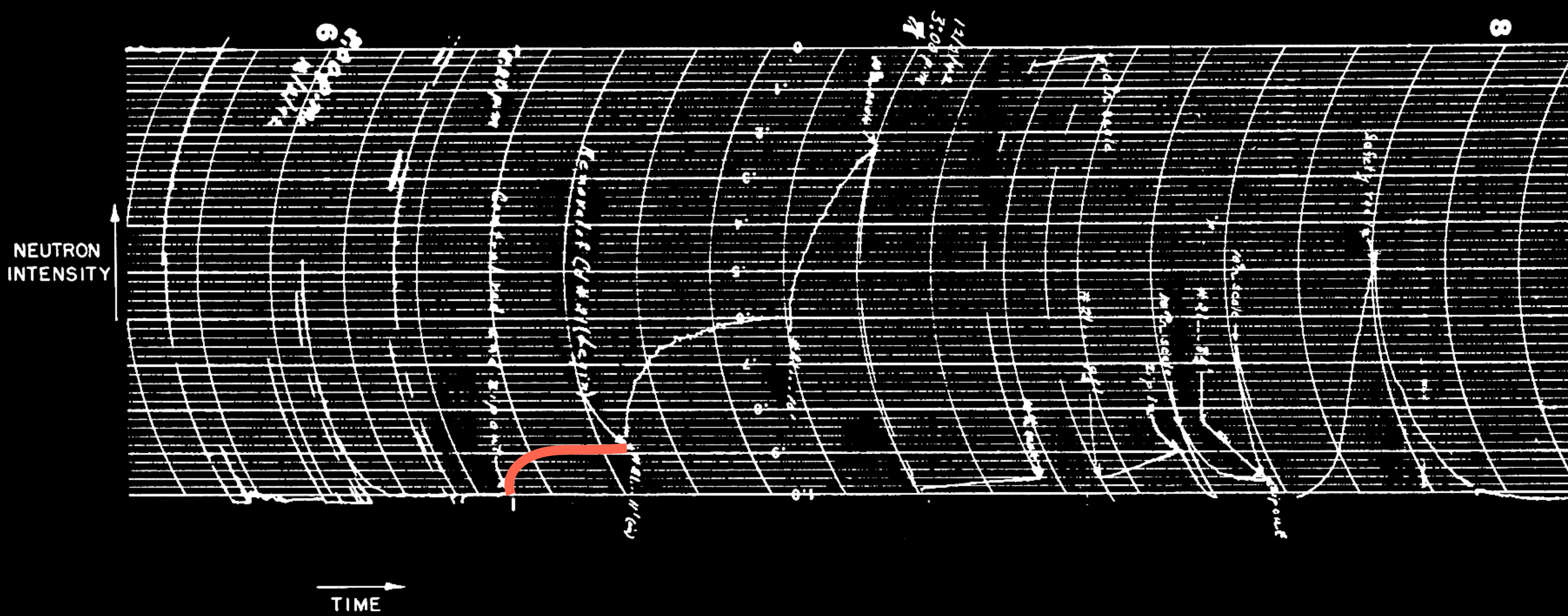

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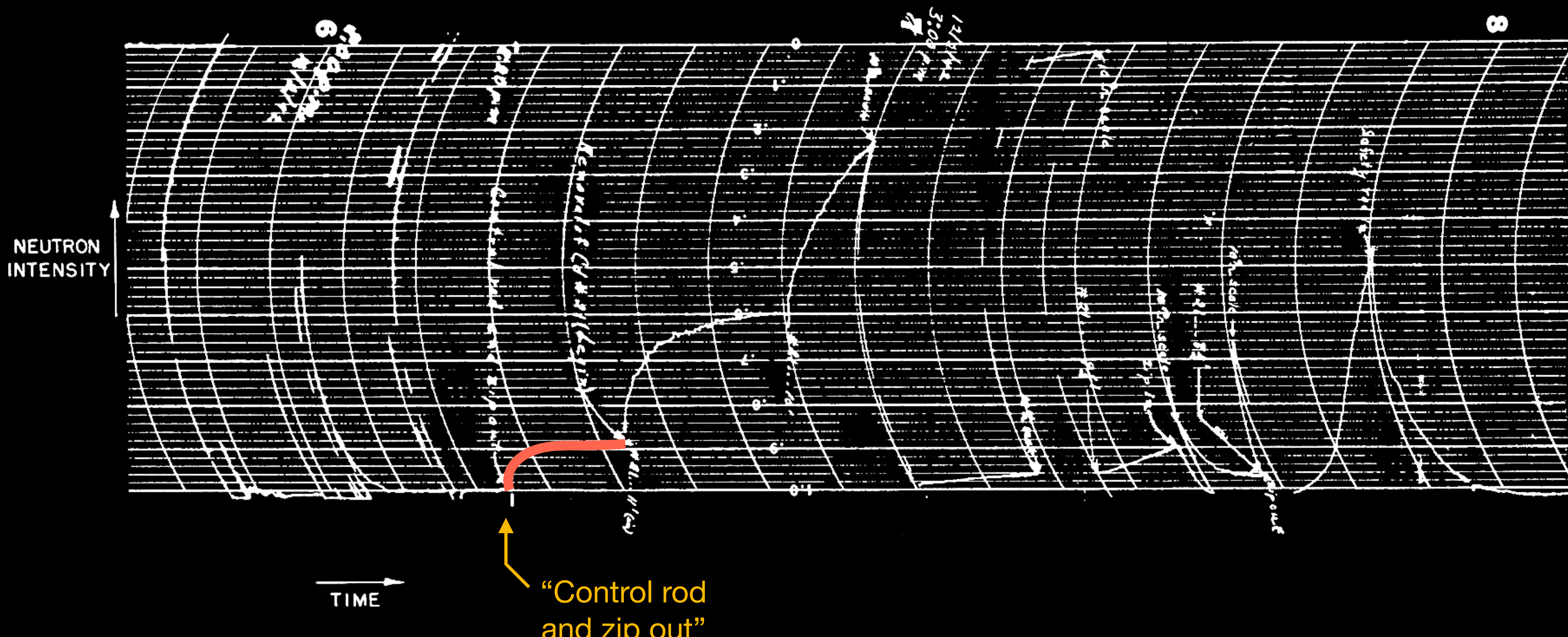

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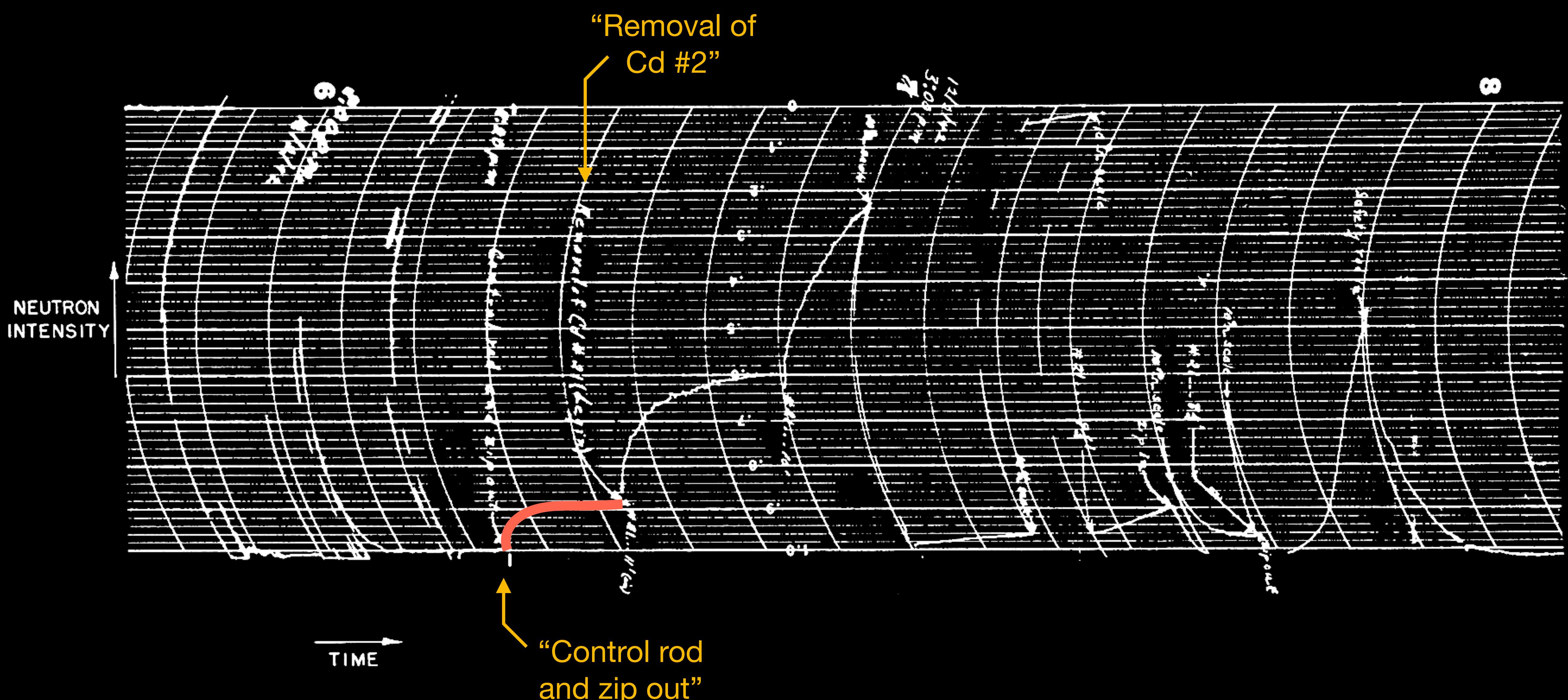

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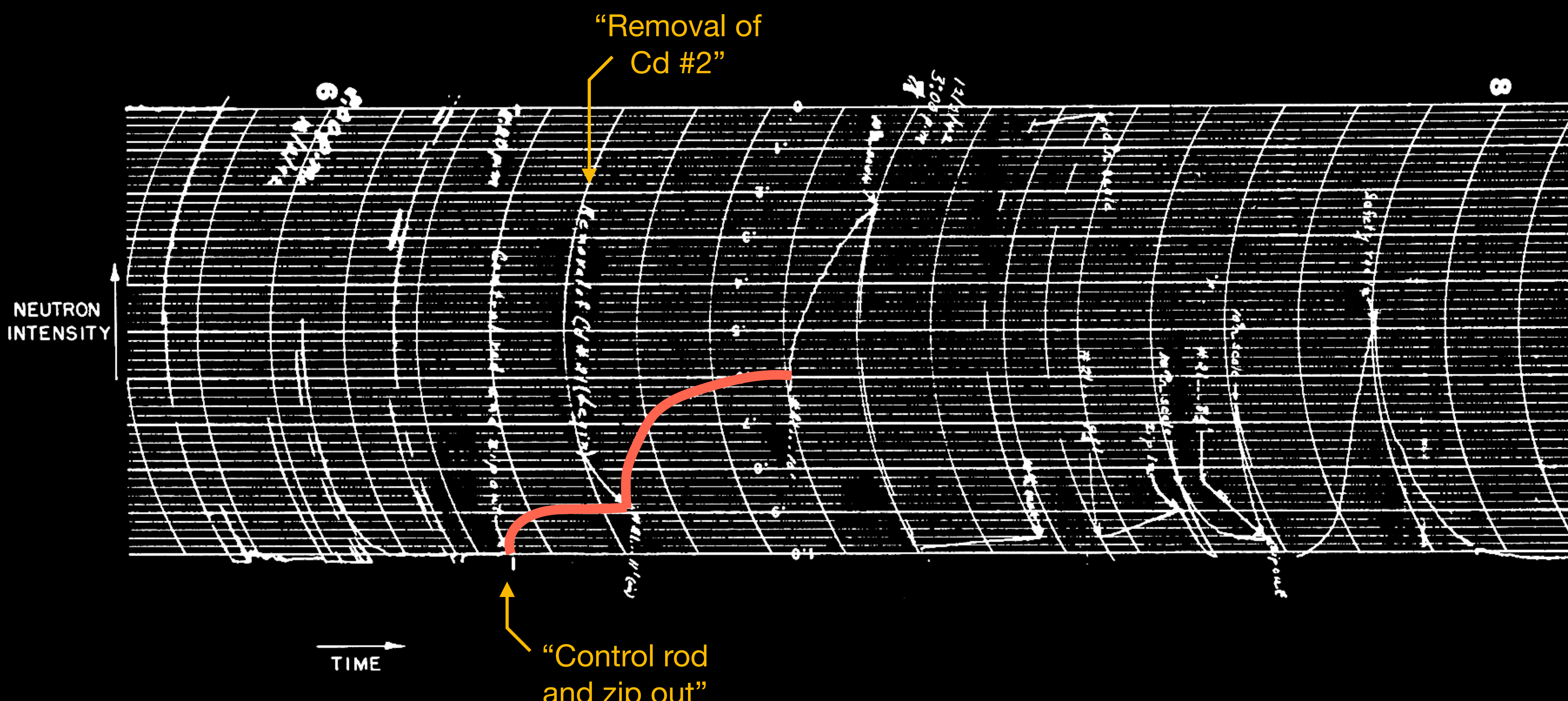

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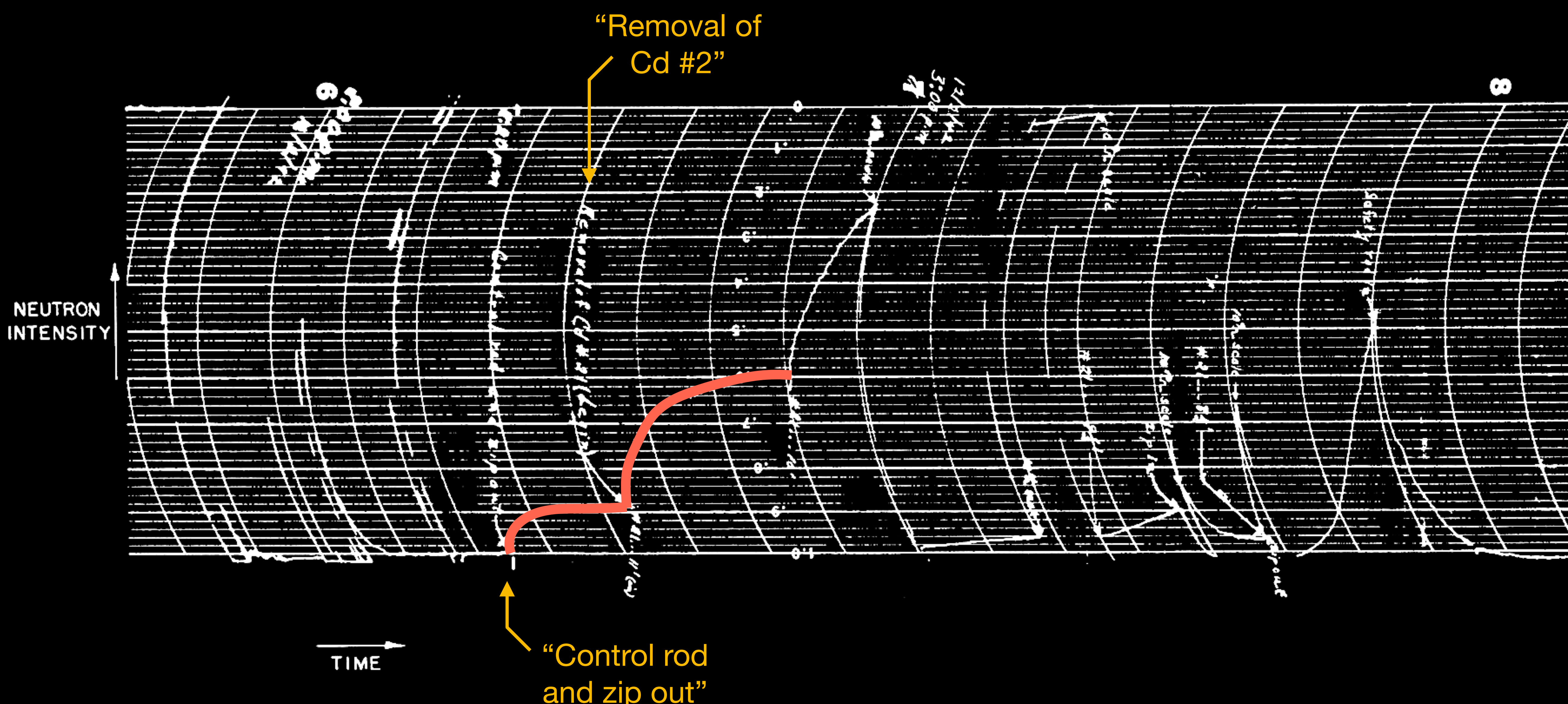

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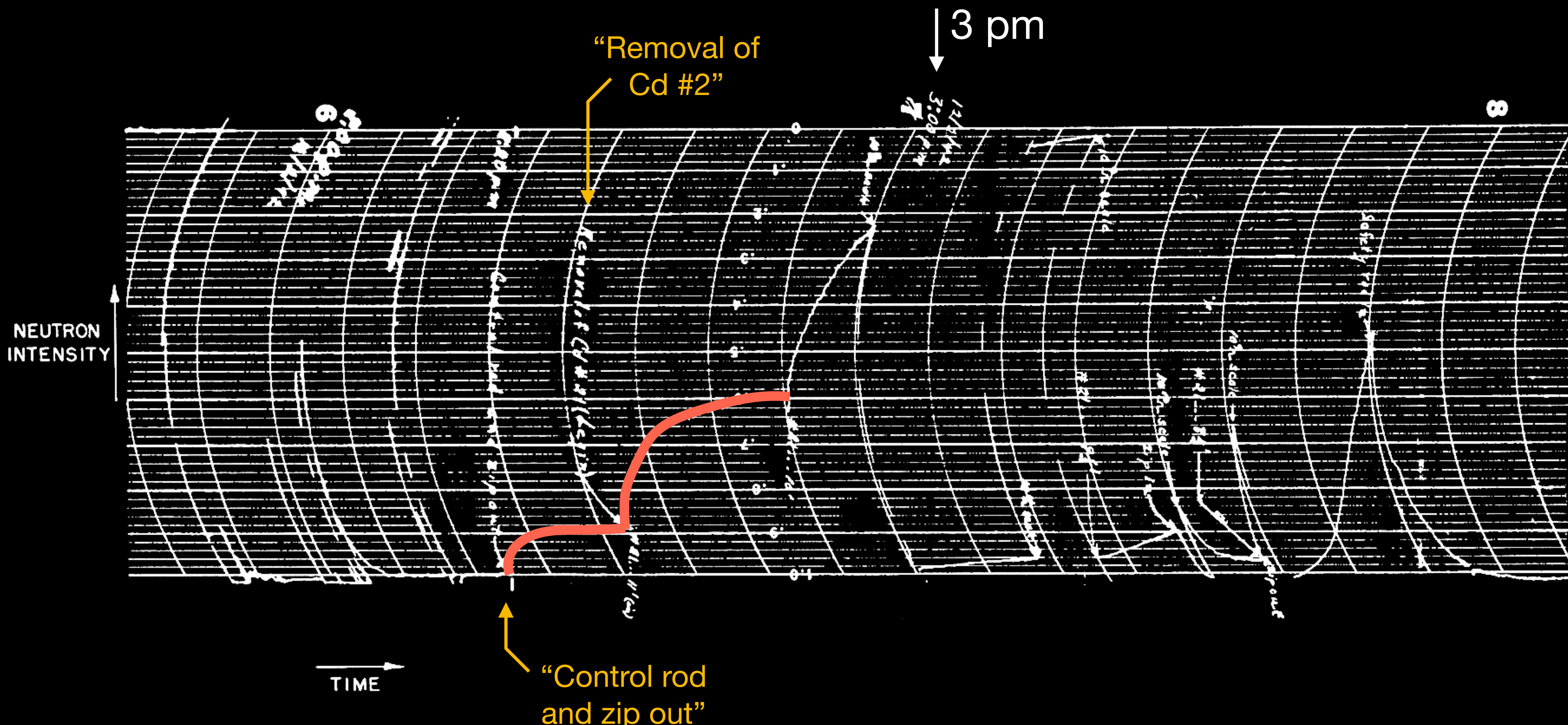

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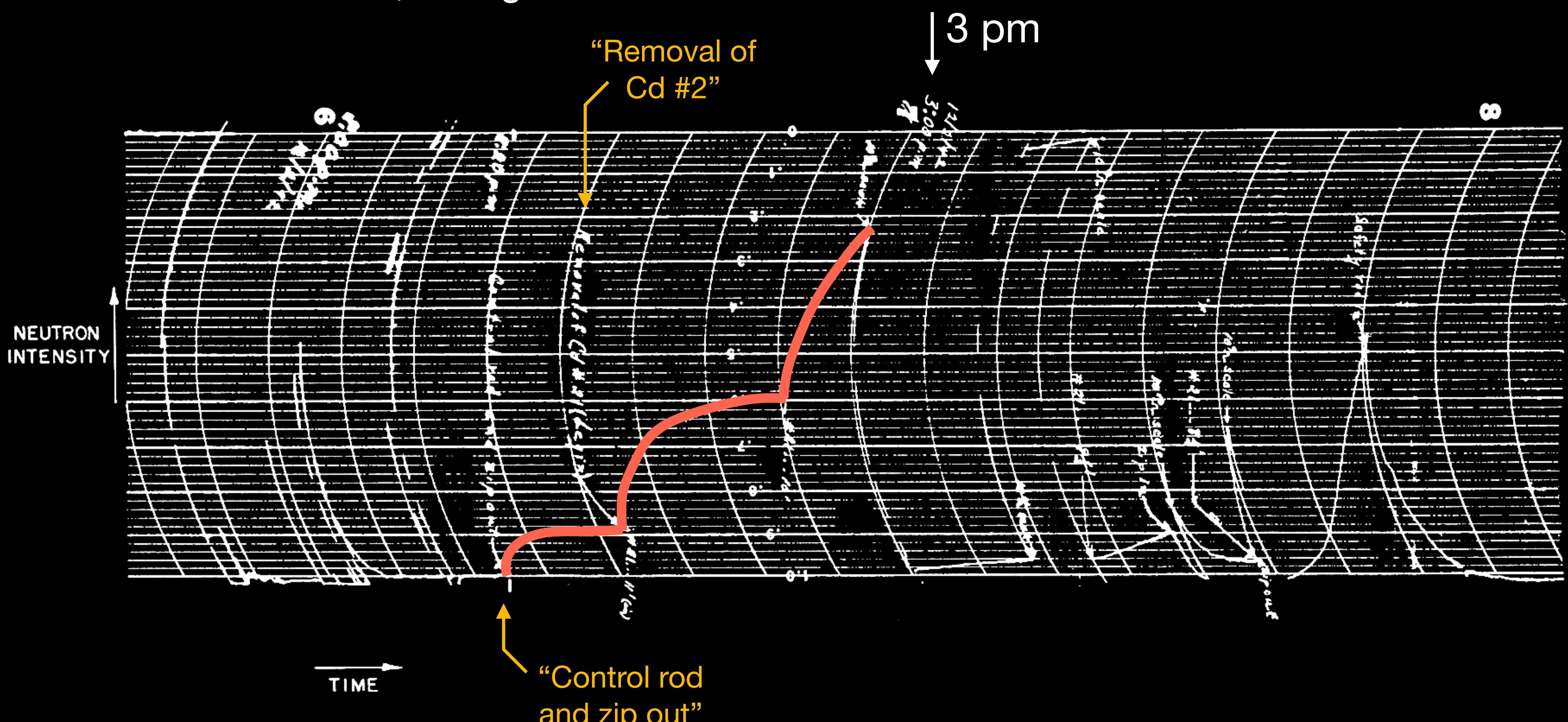

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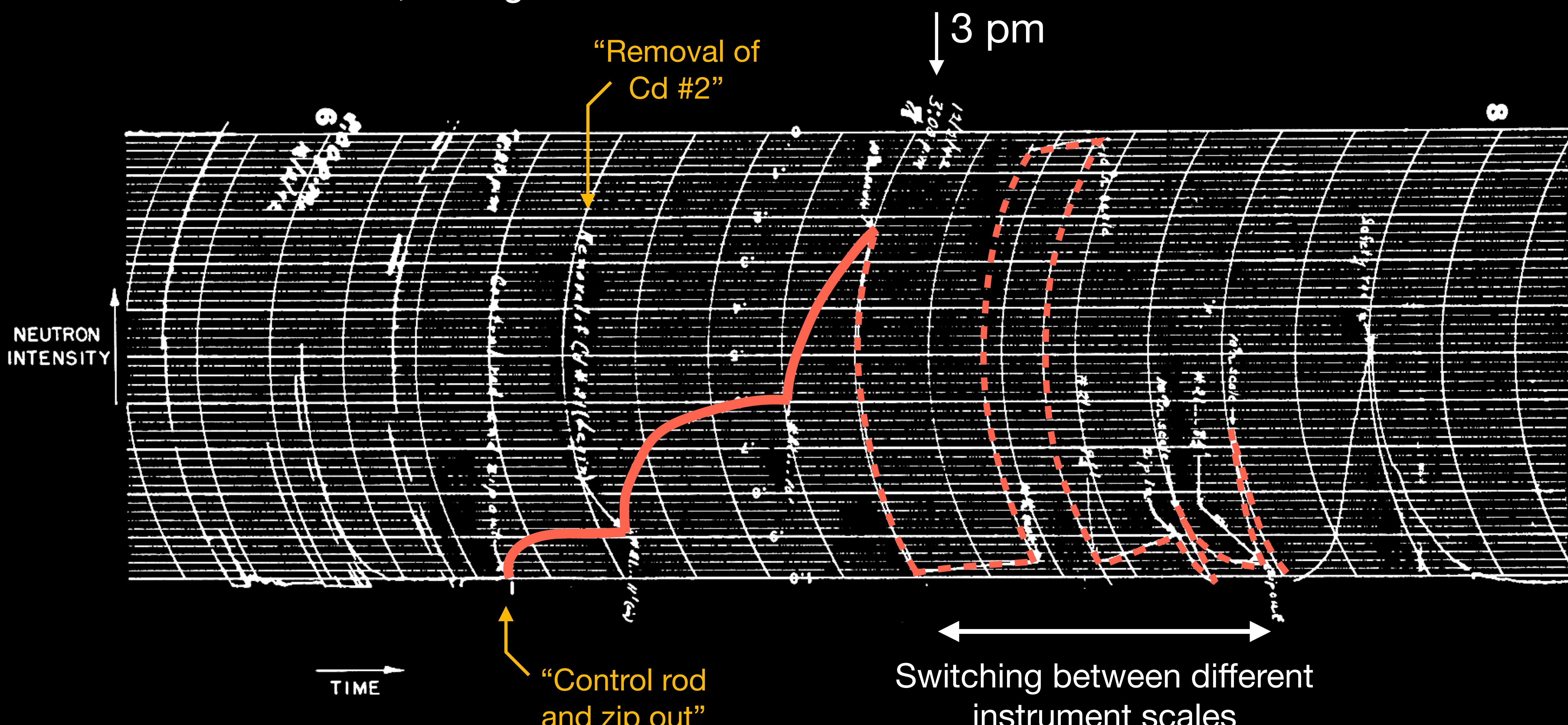

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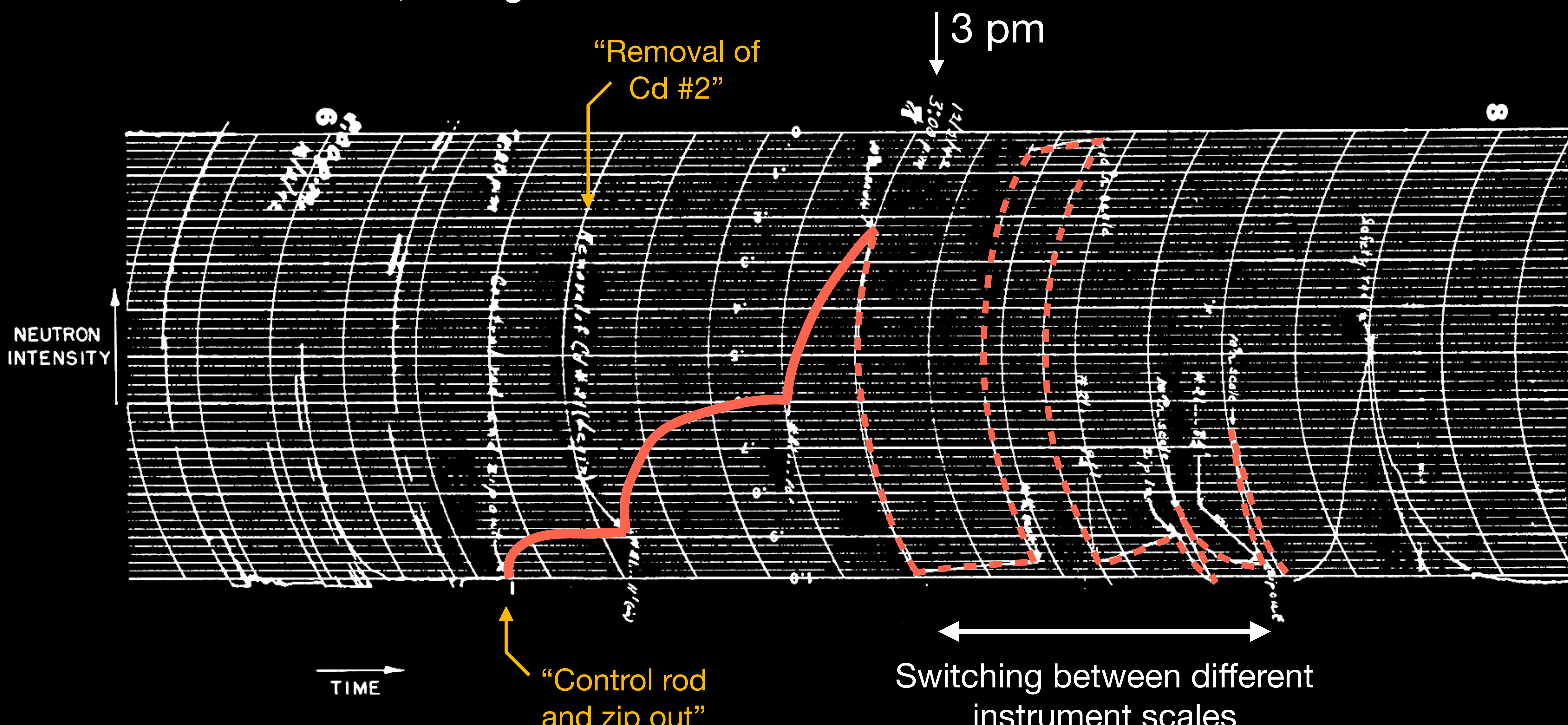

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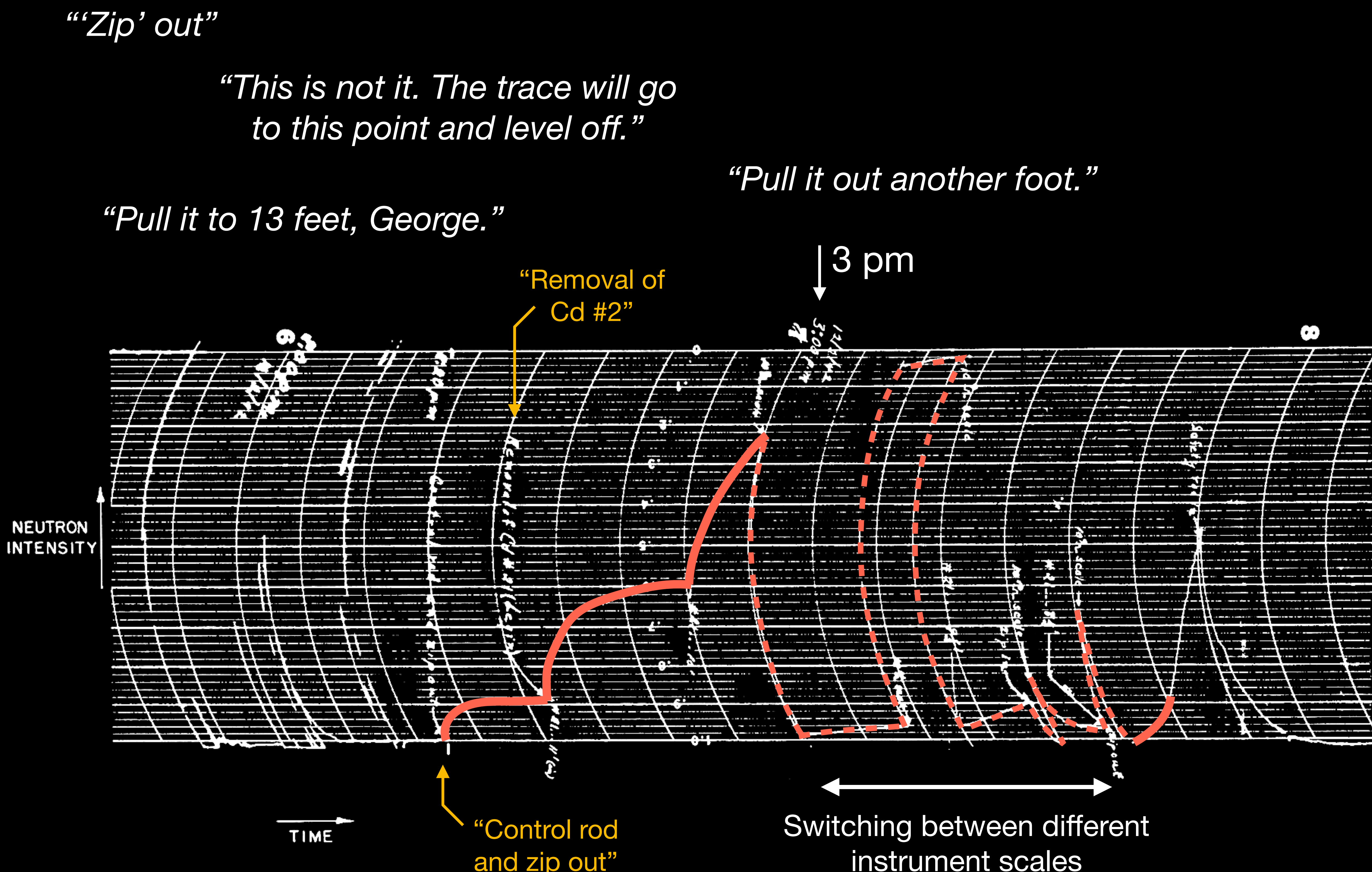

December 2, 1942

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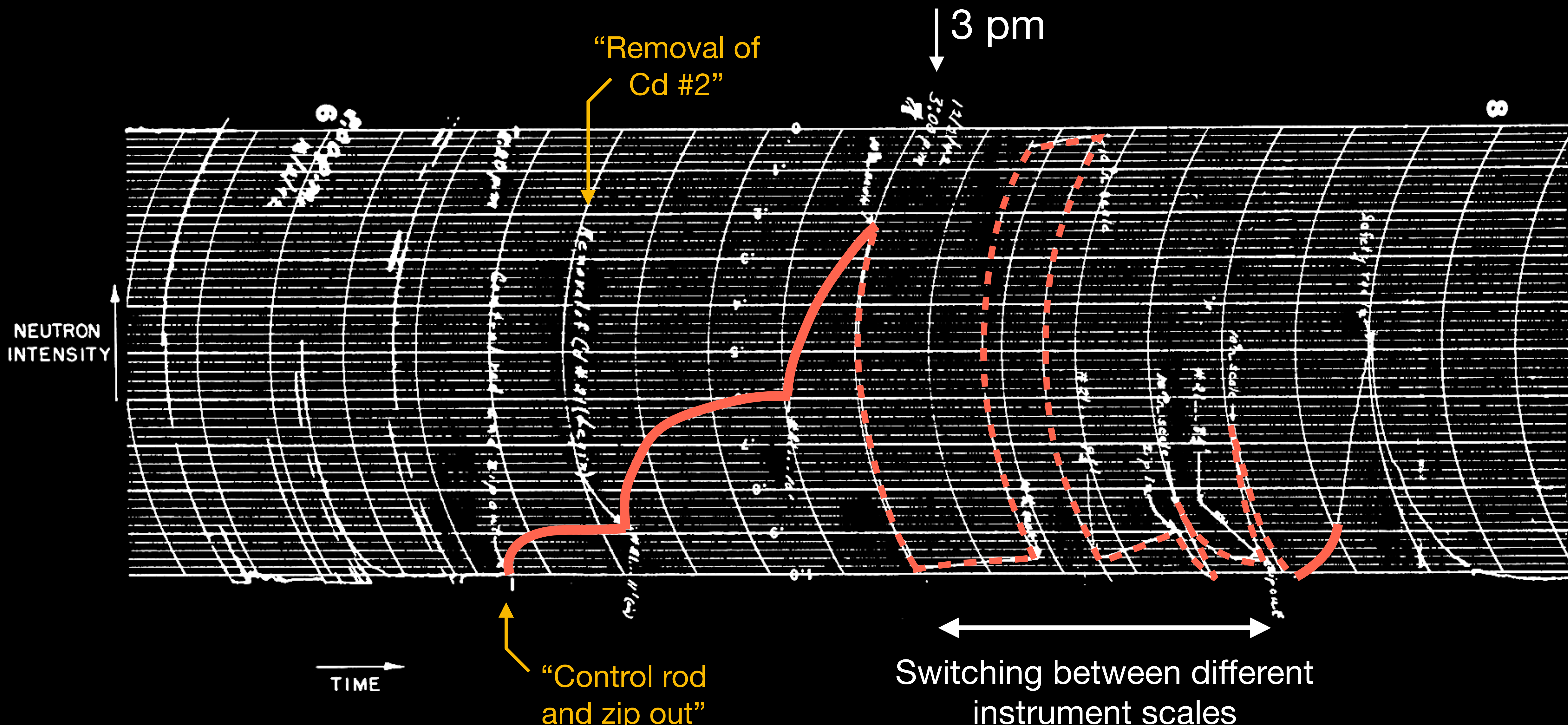

December 2, 1942

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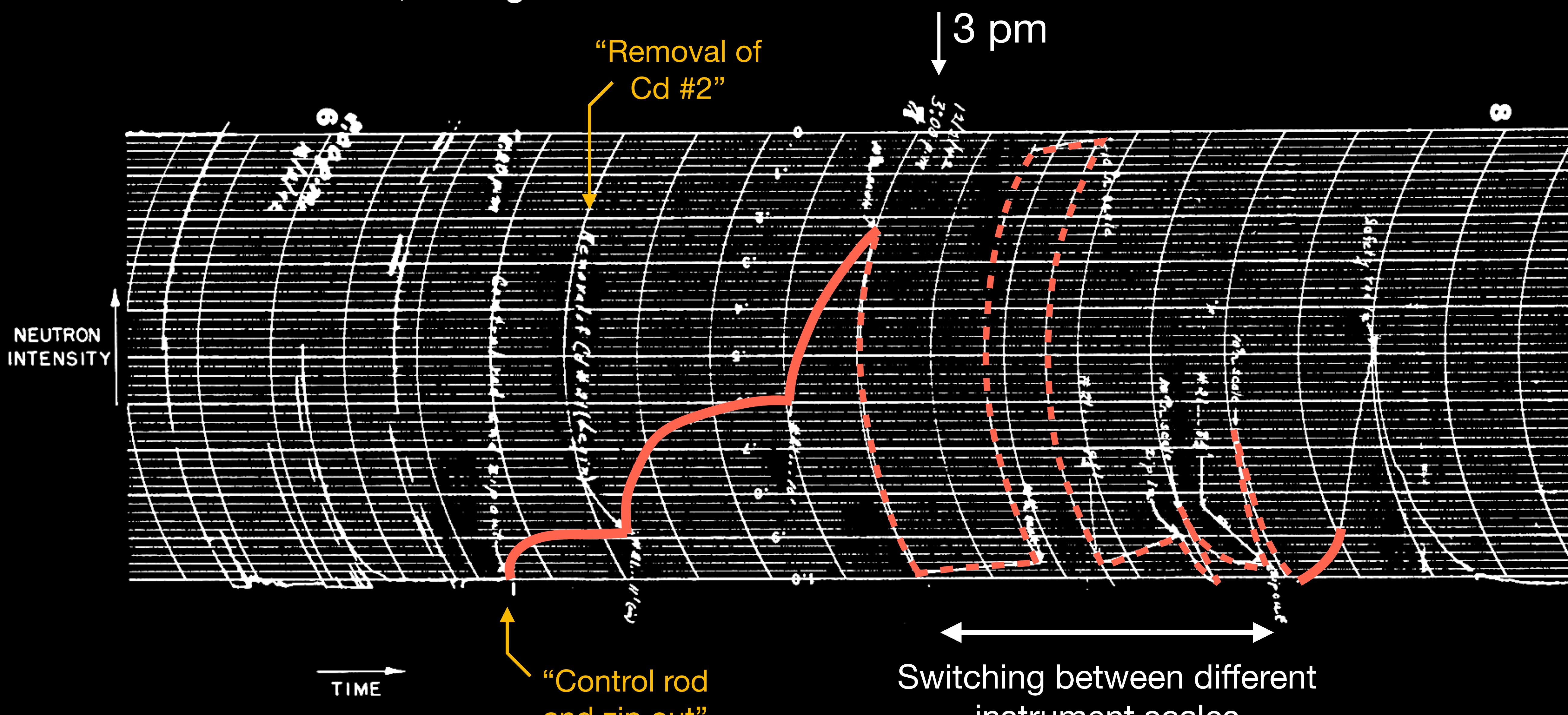

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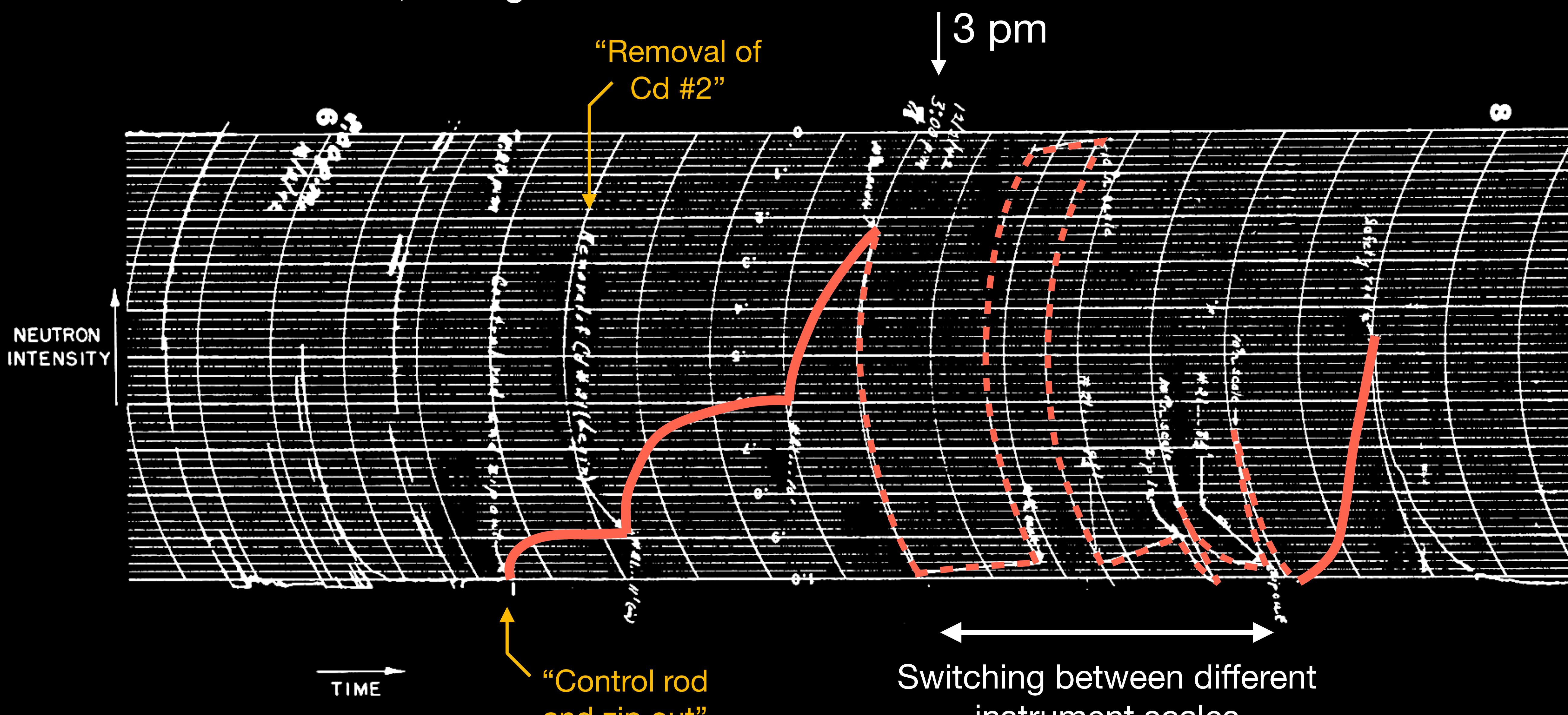


December 2, 1942

“This is going to do it.”

“‘Zip’ out”

*“Now it will become self-sustaining.
The trace will climb and continue to climb.
It will not level off.”*

*“This is not it. The trace will go
to this point and level off.”*

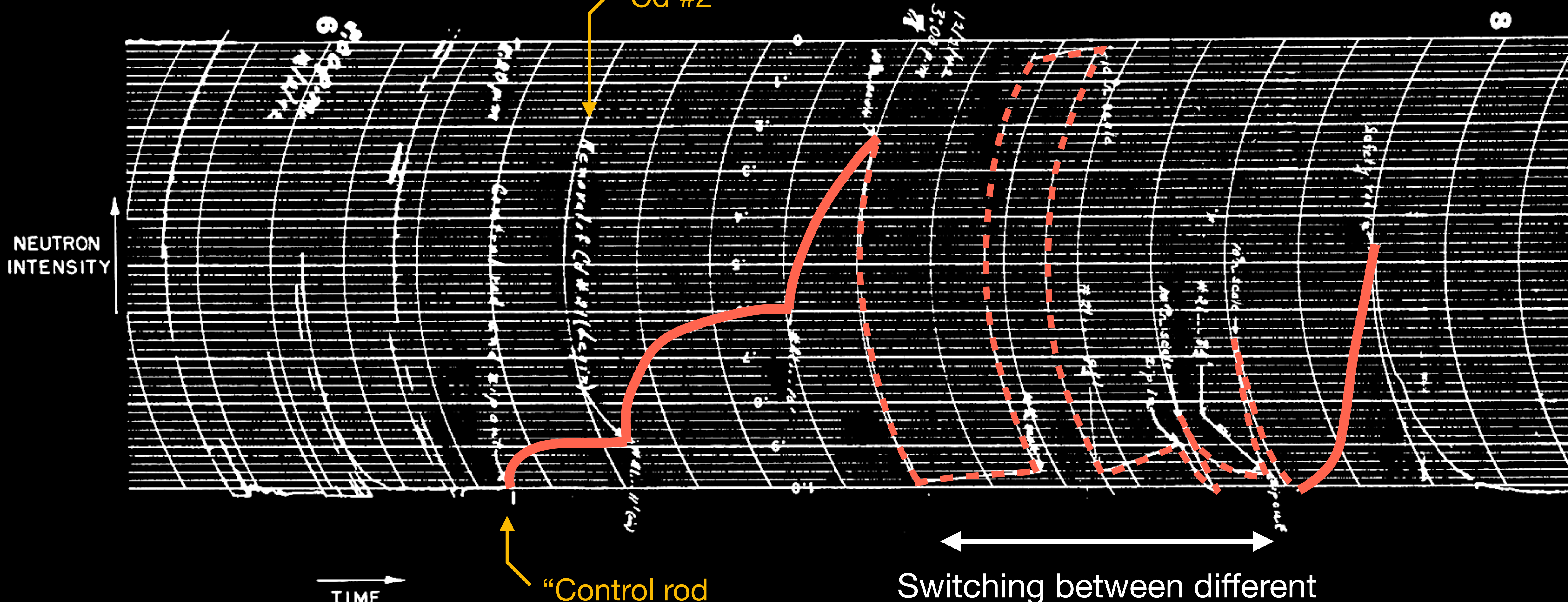
“Pull it out another foot.”

“O.K. ‘Zip’ in”

“Pull it to 13 feet, George.”

3 pm

“Removal of Cd #2”



“Control rod and zip out”

Switching between different instrument scales

December 2, 1942

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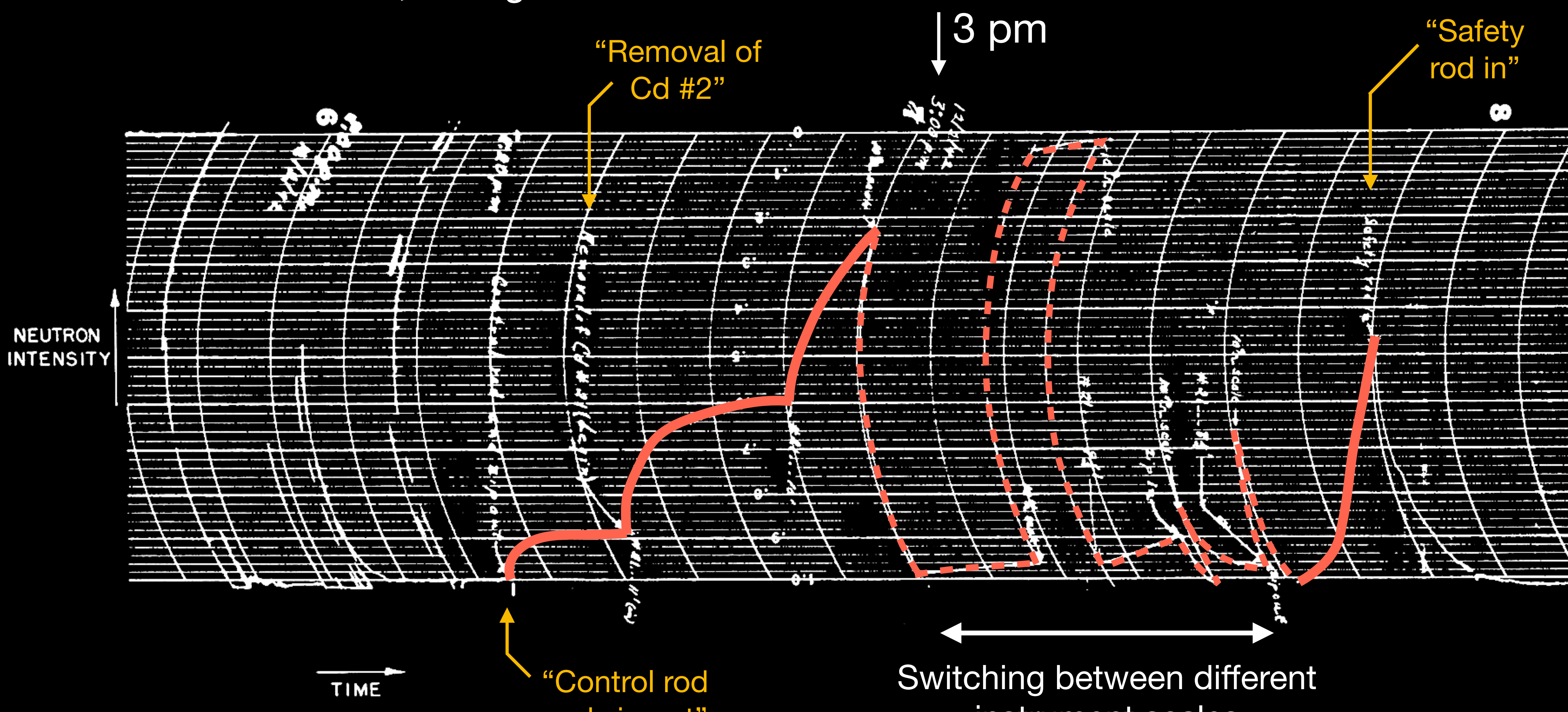

December 2, 1942

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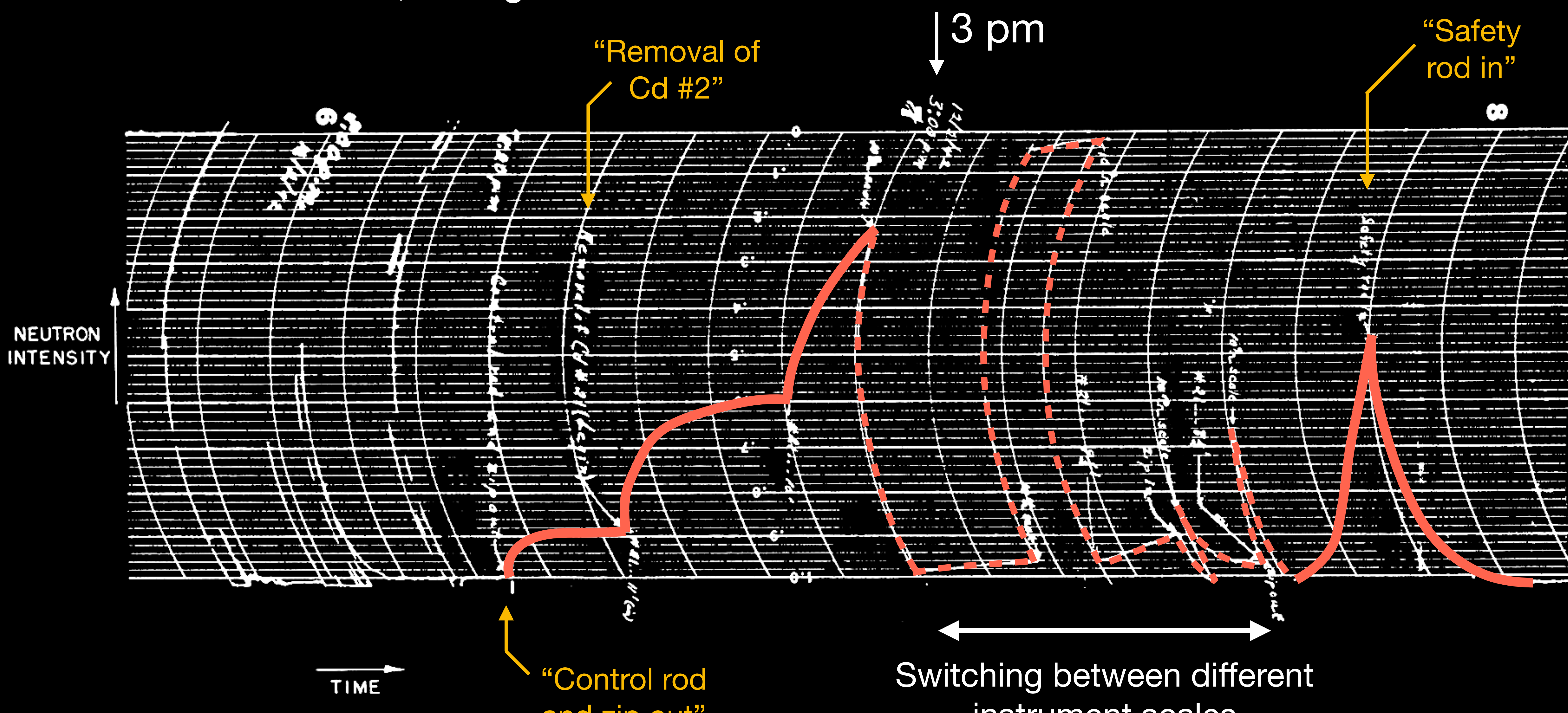


December 2, 1942

3.25 pm

December 2, 1942

3.25 pm

December 2, 1942

3.25 pm

December 2, 1942

3.25 pm

An impromptu celebration with Italian red wine and paper cups …


West Stand Stagg Field
THE University of Chicago.


1
2
3
4
5
6
7
8


“How did we get here?”
1
2
3
4
5
6
7
8


West Stand Stagg Field
THE University of Chicago.


We have arrived!

So, what did it take to get here?

So, what did it take to get here?

Curiosity

So, what did it take to get here?

Curiosity

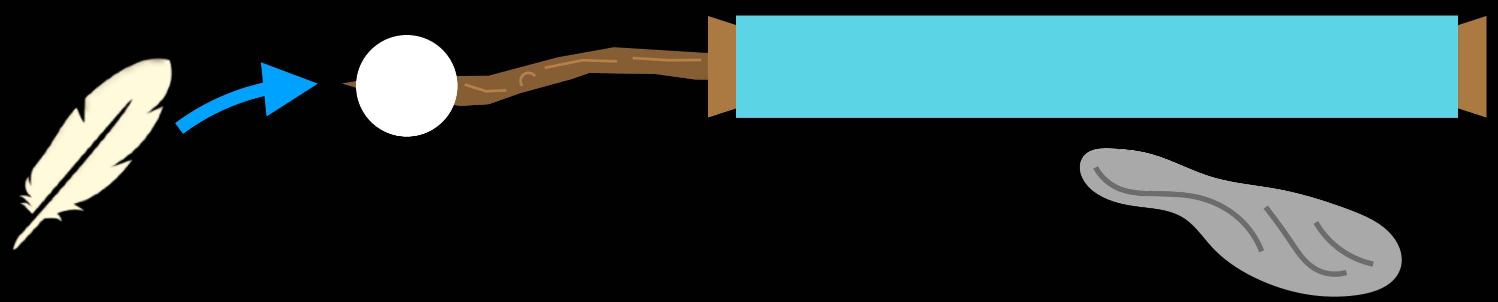
Giovanni Sagredo
“With these, I have found various marvelous things …”

So, what did it take to get here?

Curiosity

Stephen Gray

"I then resolved to procure me a large flint-glass tube, to see if I could make any further discovery with it."



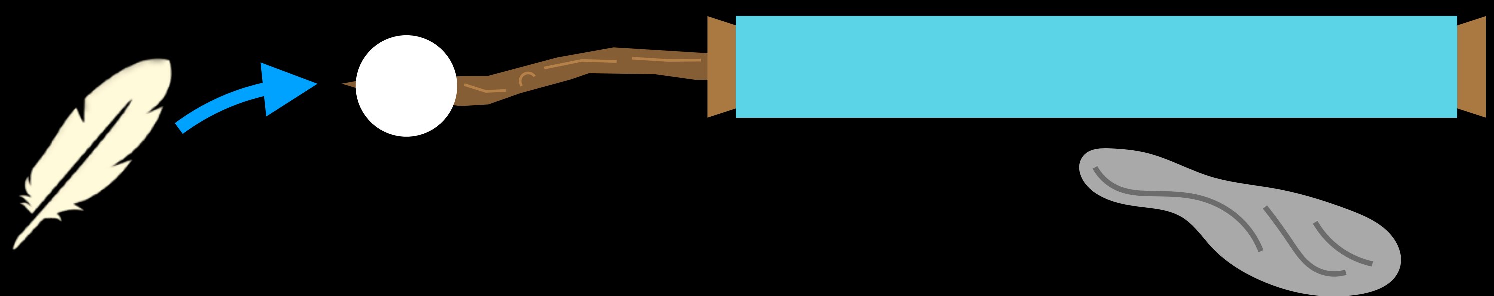
Giovanni Sagredo

"With these, I have found various marvelous things …"

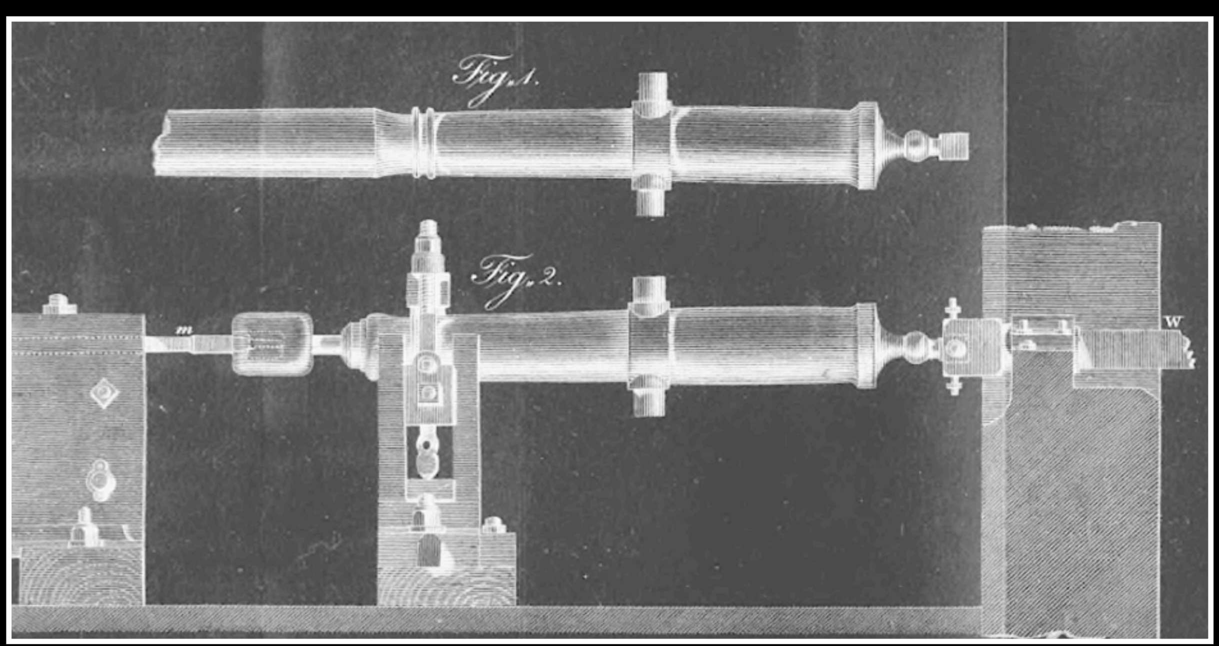
So, what did it take to get here?

Curiosity

Stephen Gray
"I then resolved to procure me a large flint-glass tube, to see if I could make any further discovery with it."



Count Rumford
"It was by accident that I was led to make the experiment …"



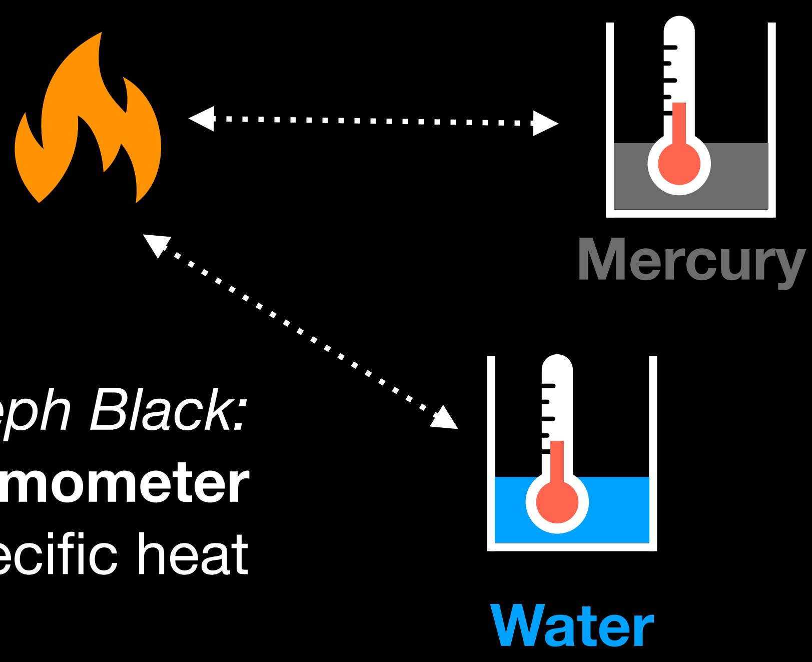
Giovanni Sagredo
"With these, I have found various marvelous things …"

So, what did it take to get here?

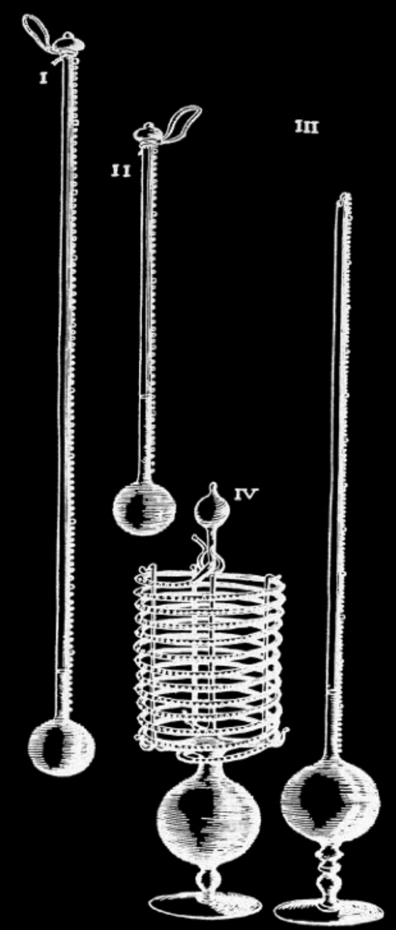
Precise instruments

So, what did it take to get here?

Precise instruments



Joseph Black:
Thermometer
→ Specific heat



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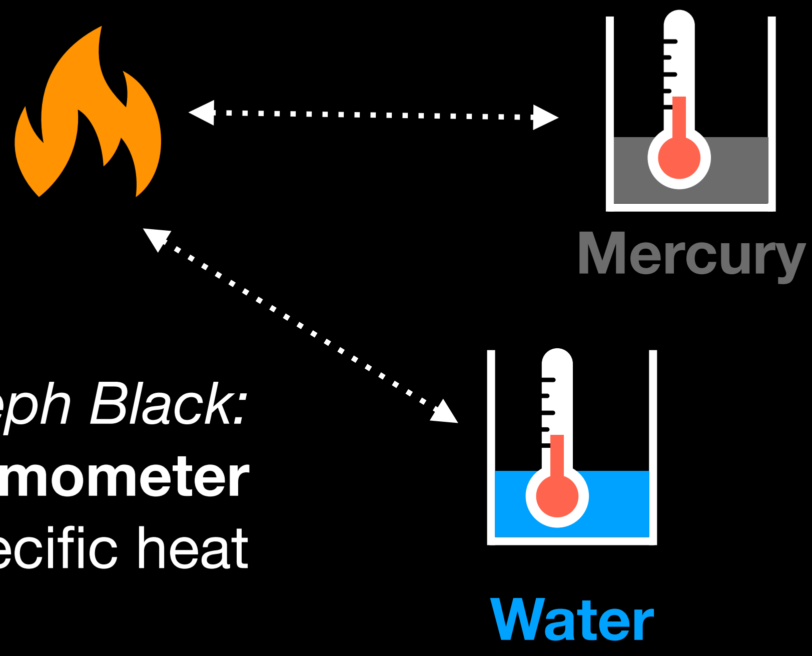
Precise instruments



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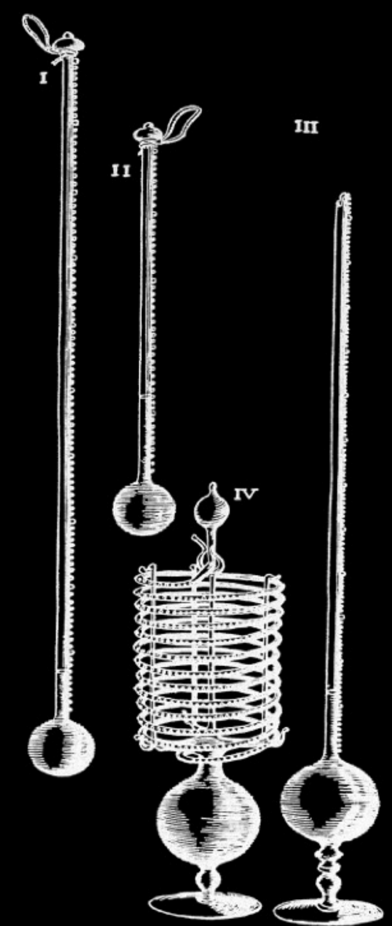
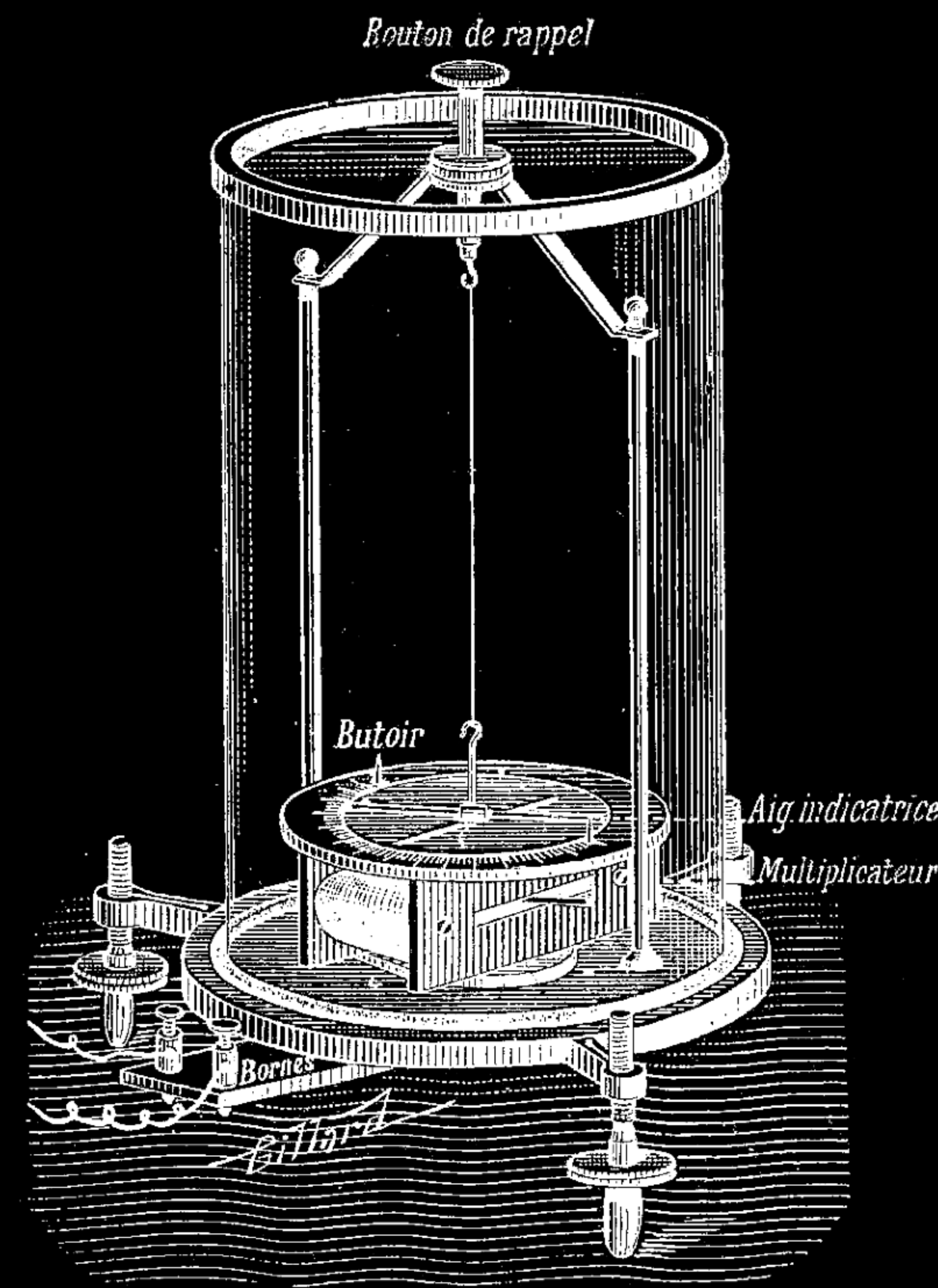


Michael Faraday:
Galvanometer → Induction



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Precise instruments

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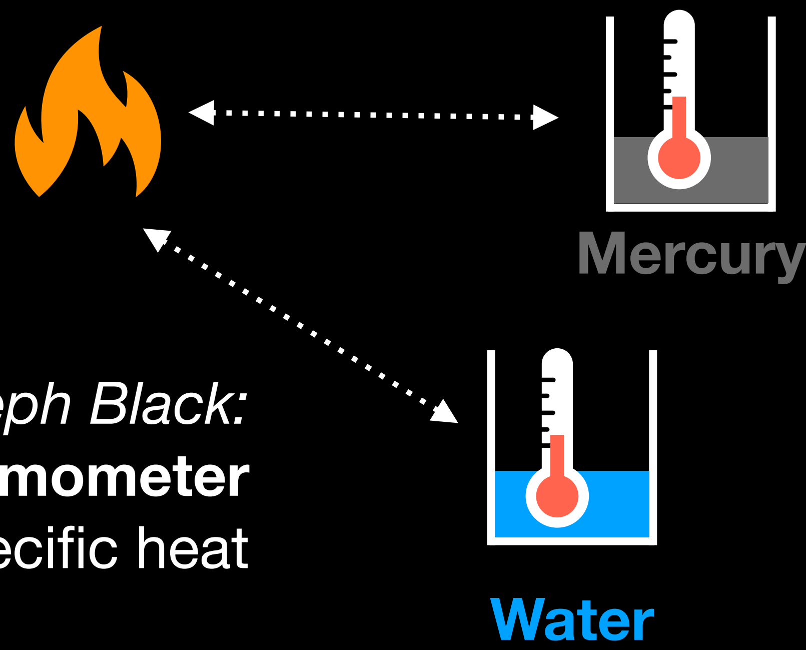

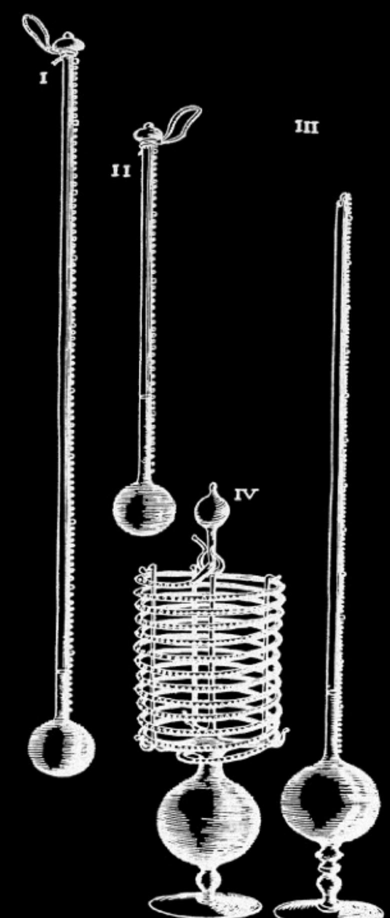

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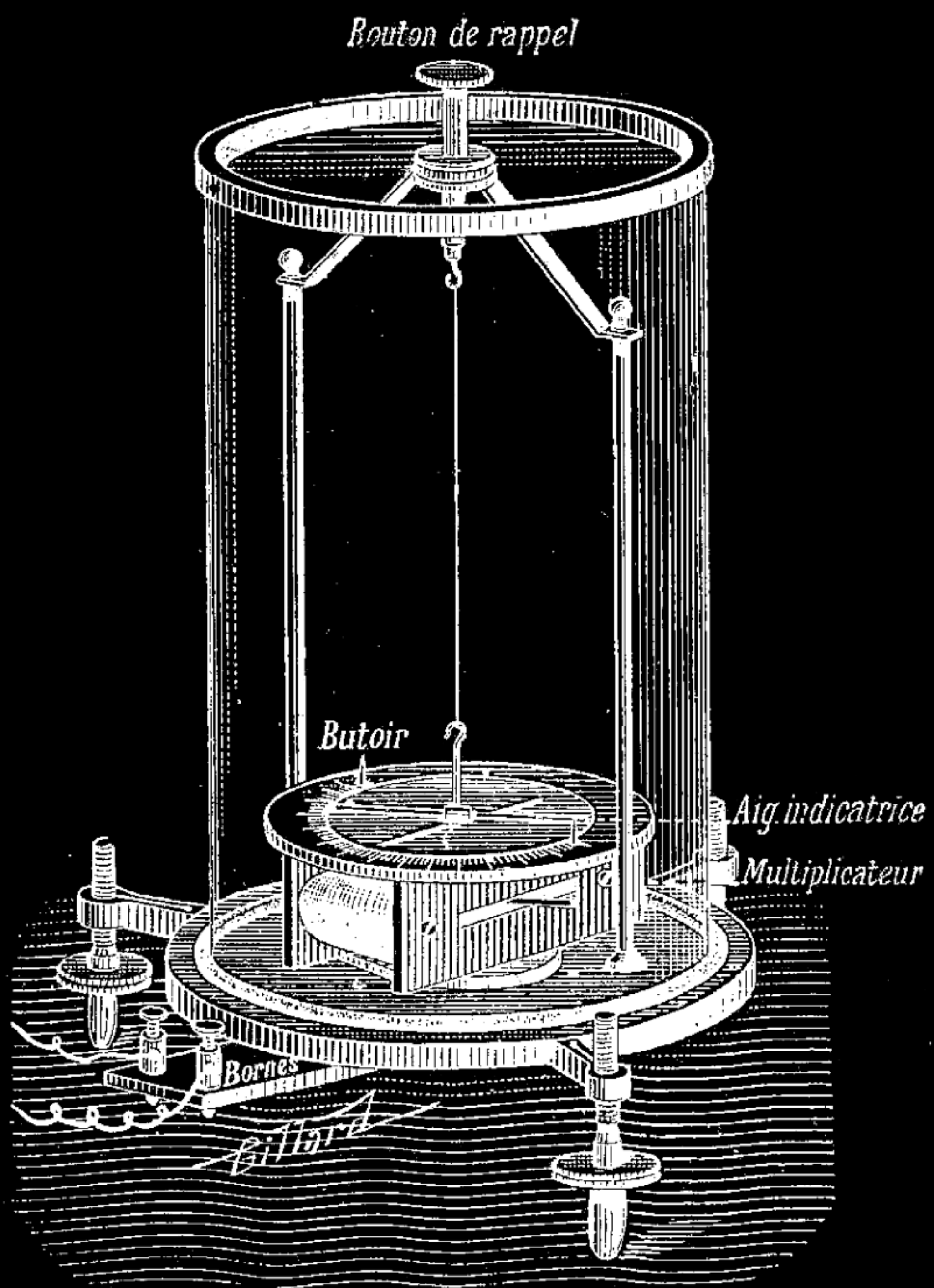

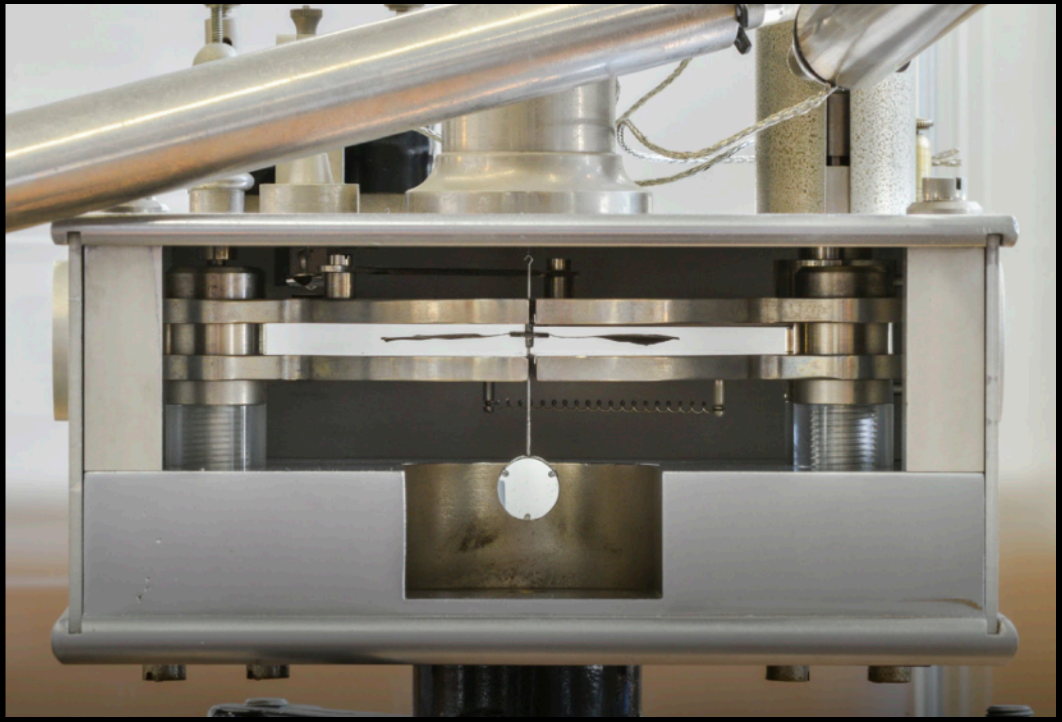

Marie & Pierre Curie
Electrometer
→ Polonium,
Radium

So, what did it take to get here?

Hard work

So, what did it take to get here?

Hard work

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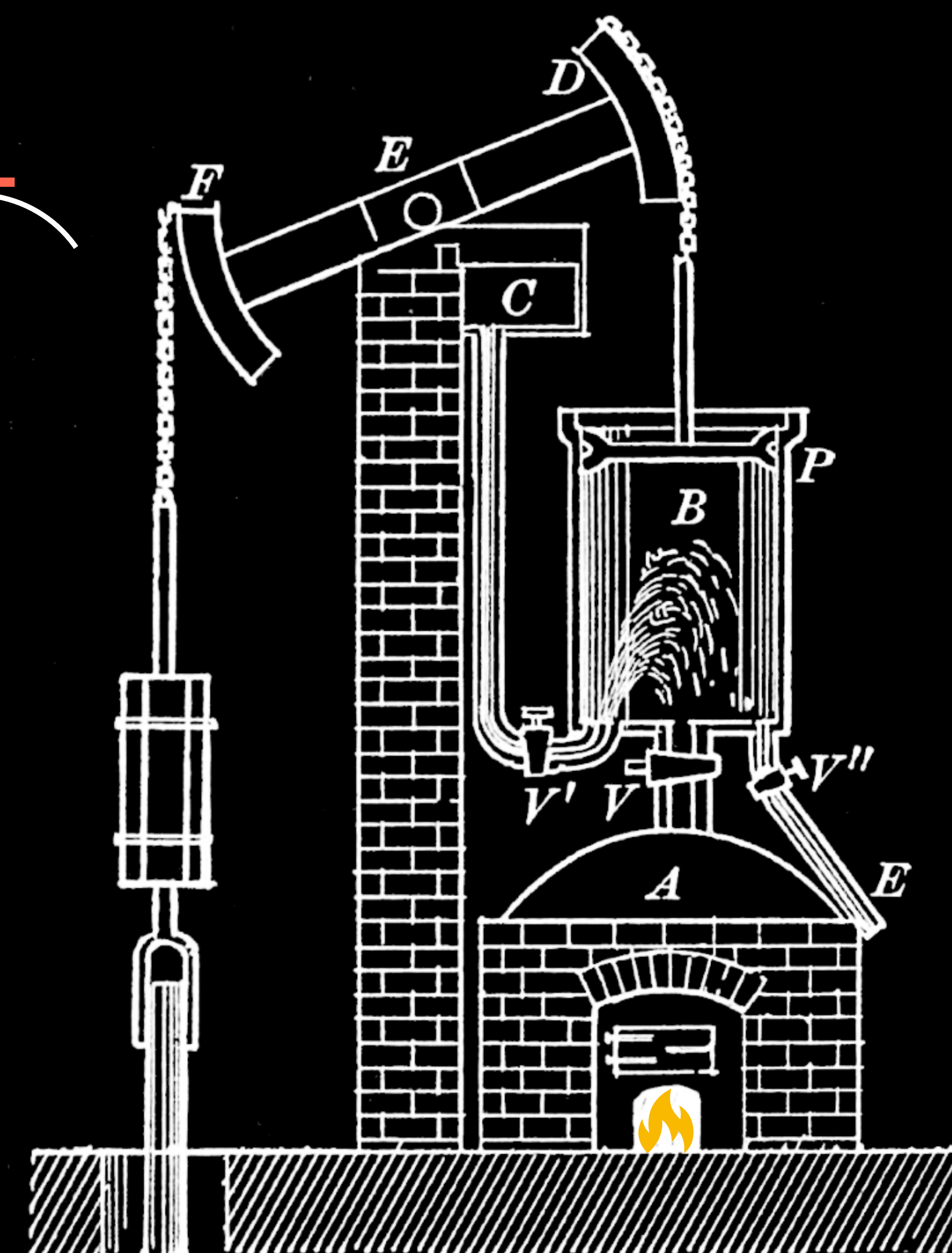
Hard work



“For ten consecutive years Mr. Newcomen worked at this fire-machine …”

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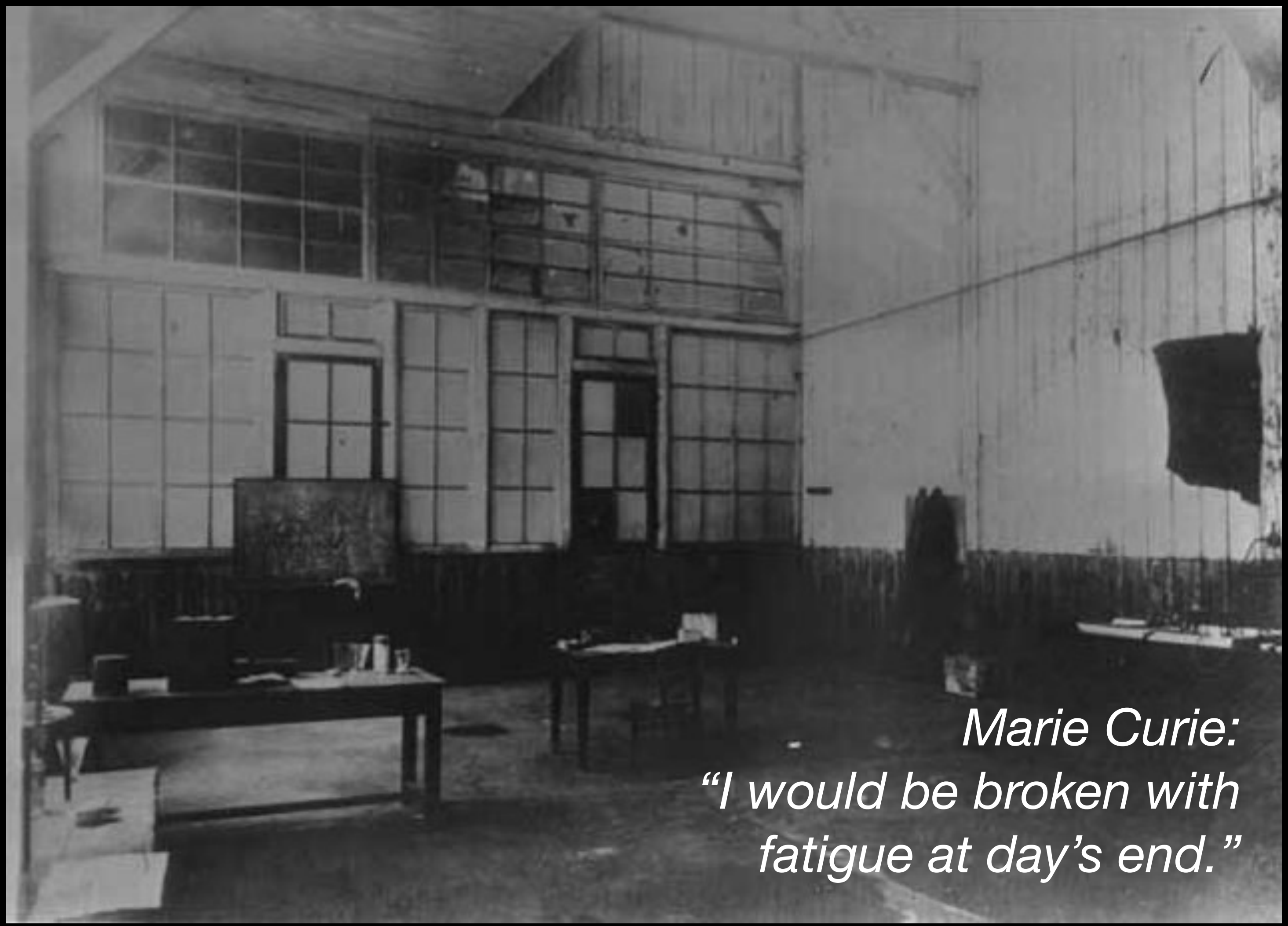
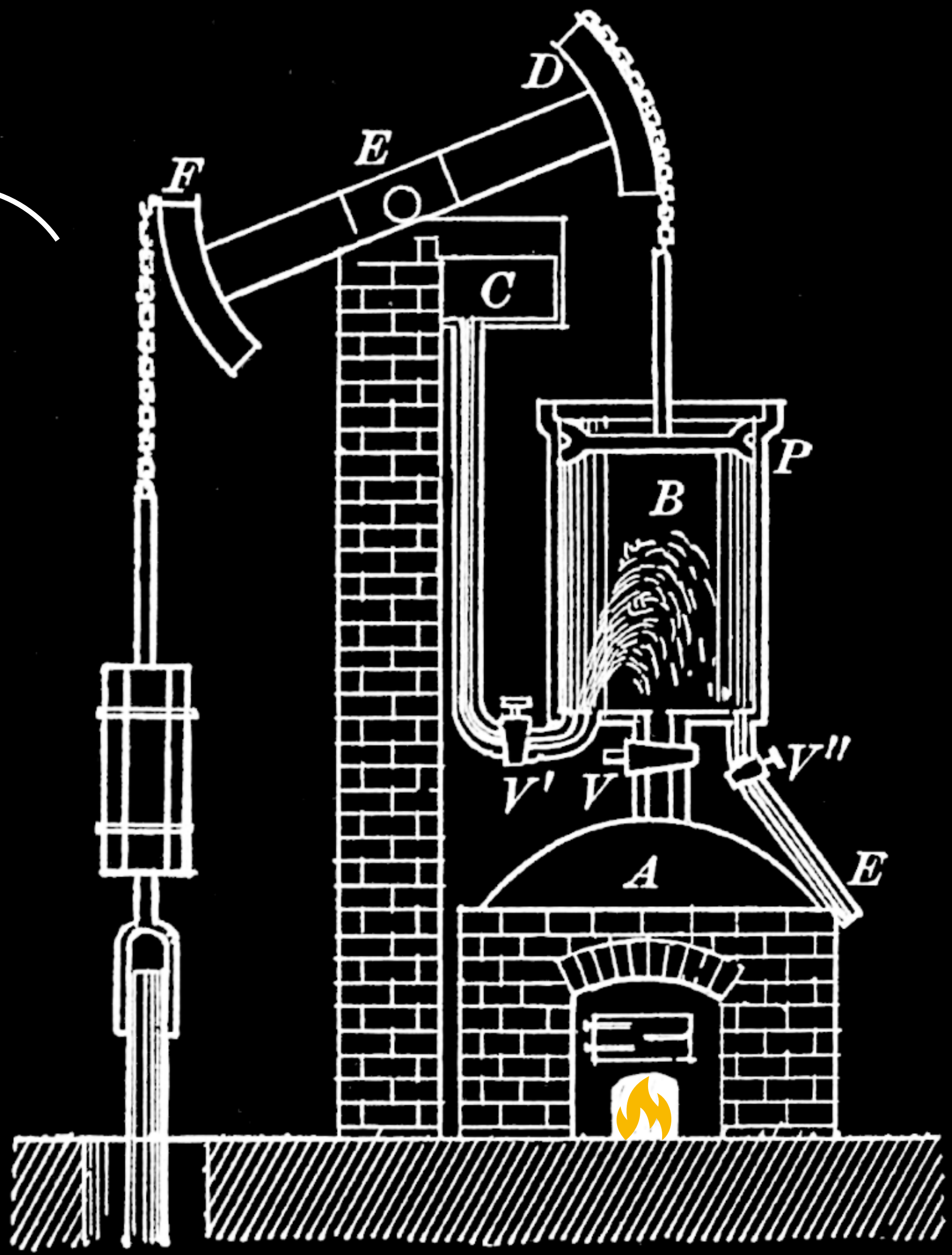
Hard work



Marie Curie:
“I would be broken with fatigue at day’s end.”



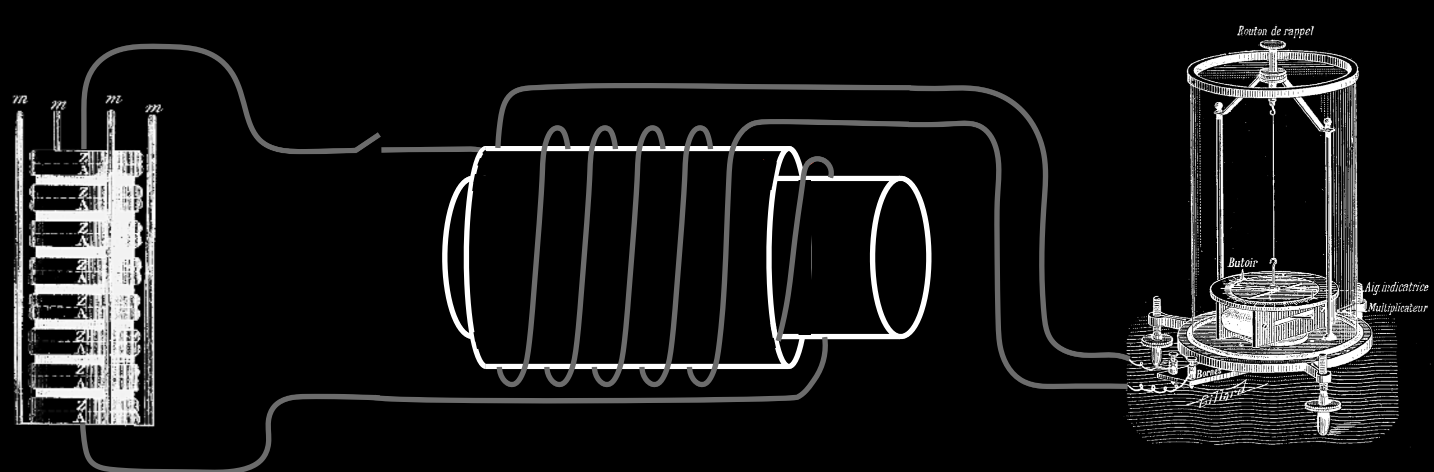
“For ten consecutive years Mr. Newcomen worked at this fire-machine …”

So, what did it take to get here?

The helping hand of the past

So, what did it take to get here?

The helping hand of the past



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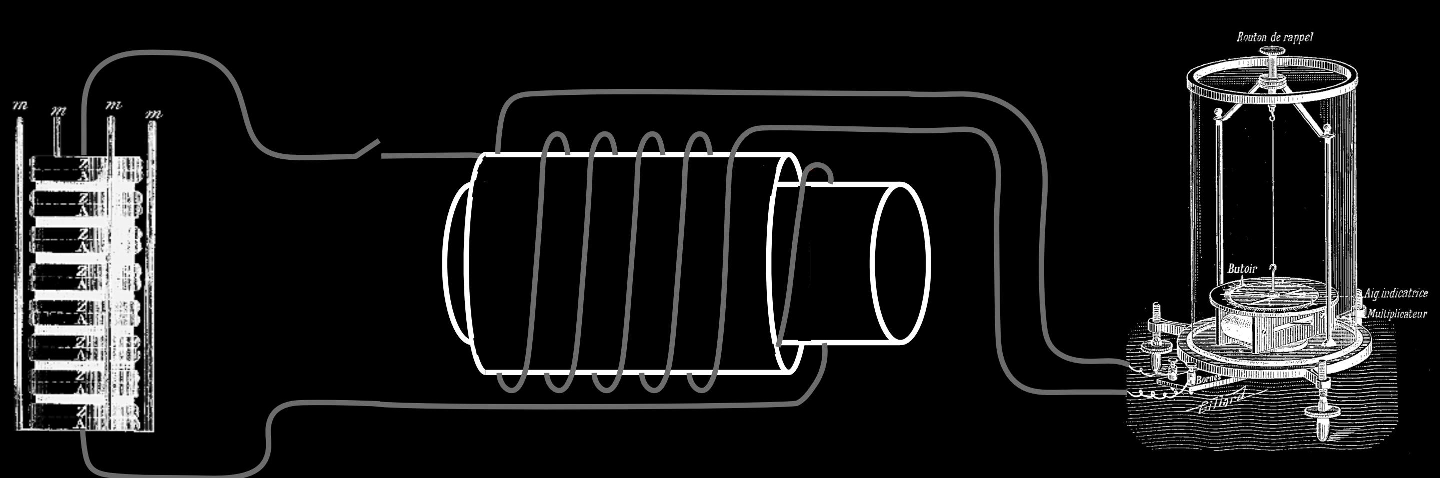

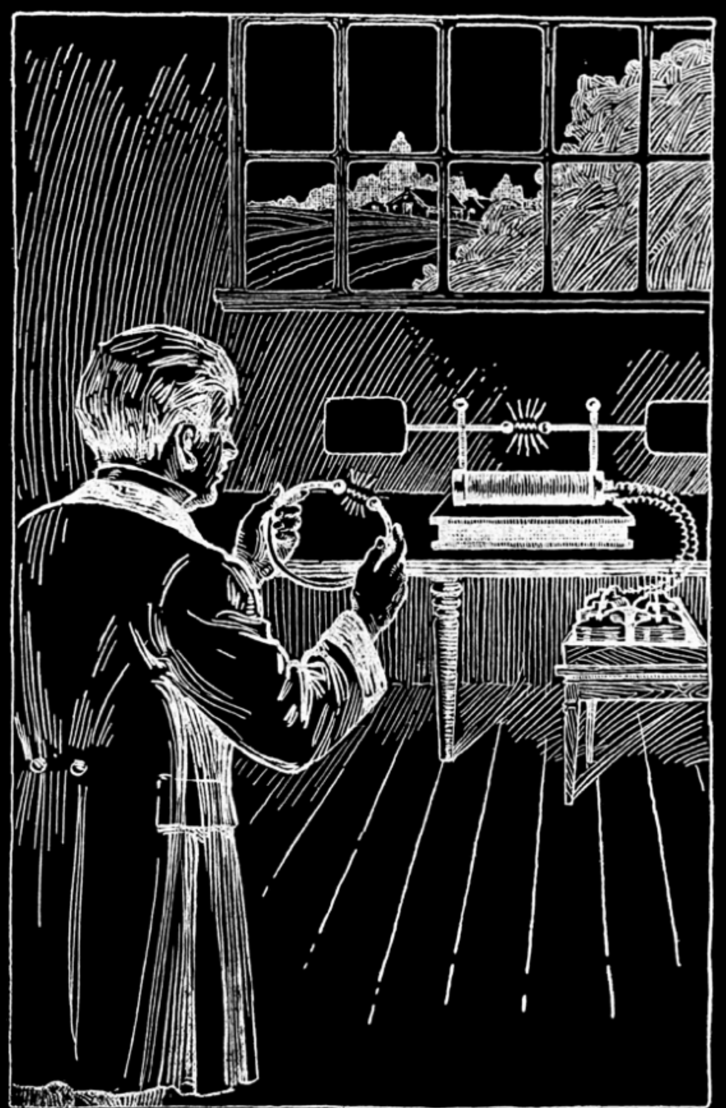

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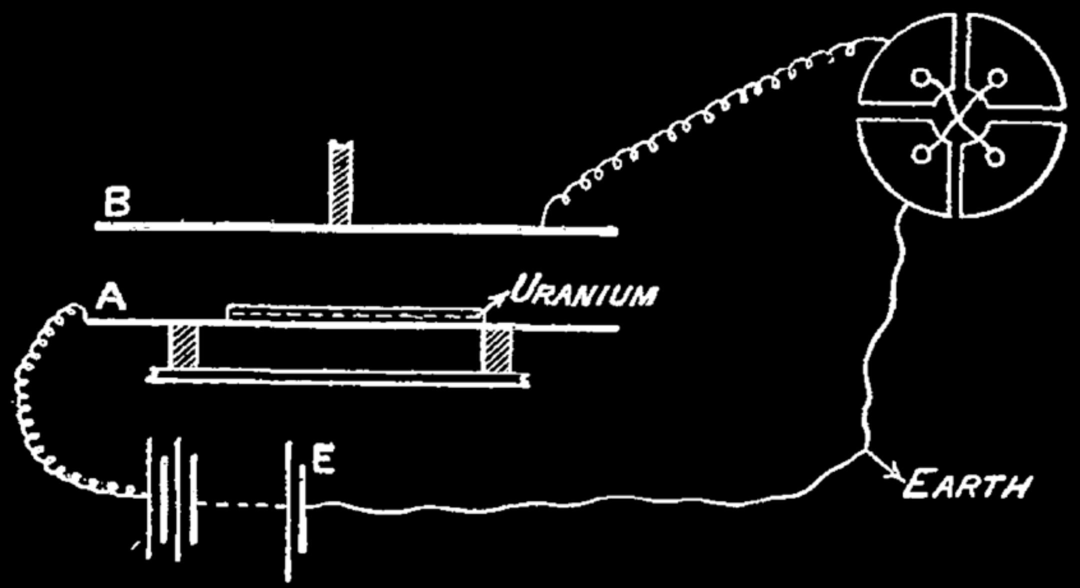

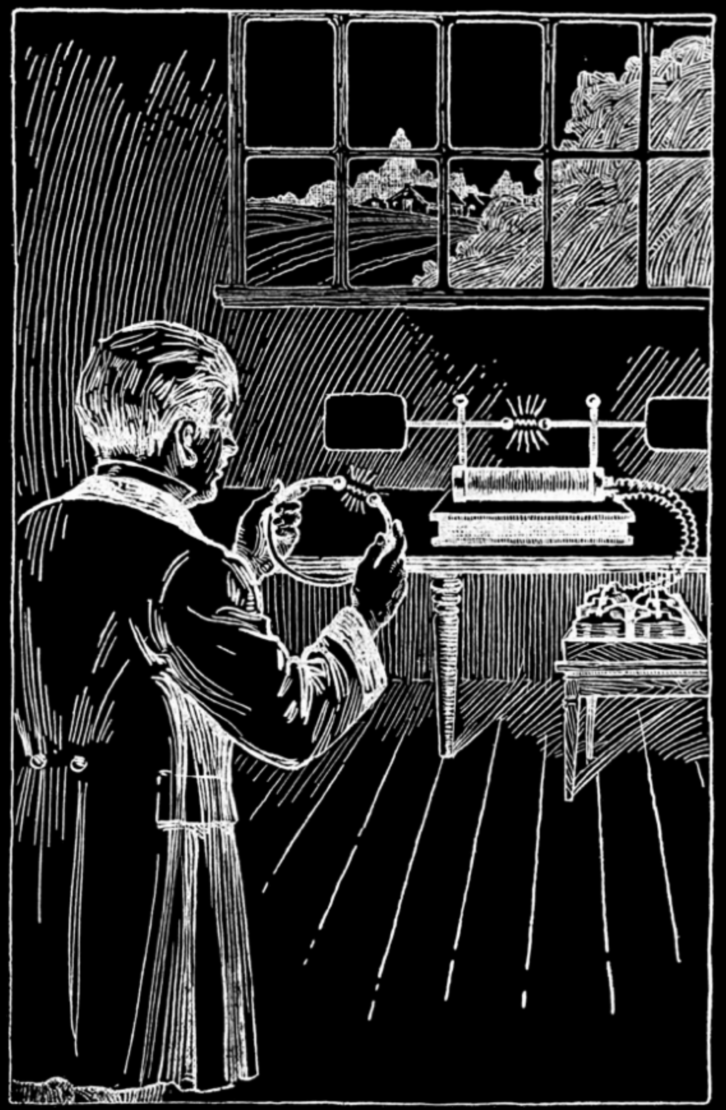

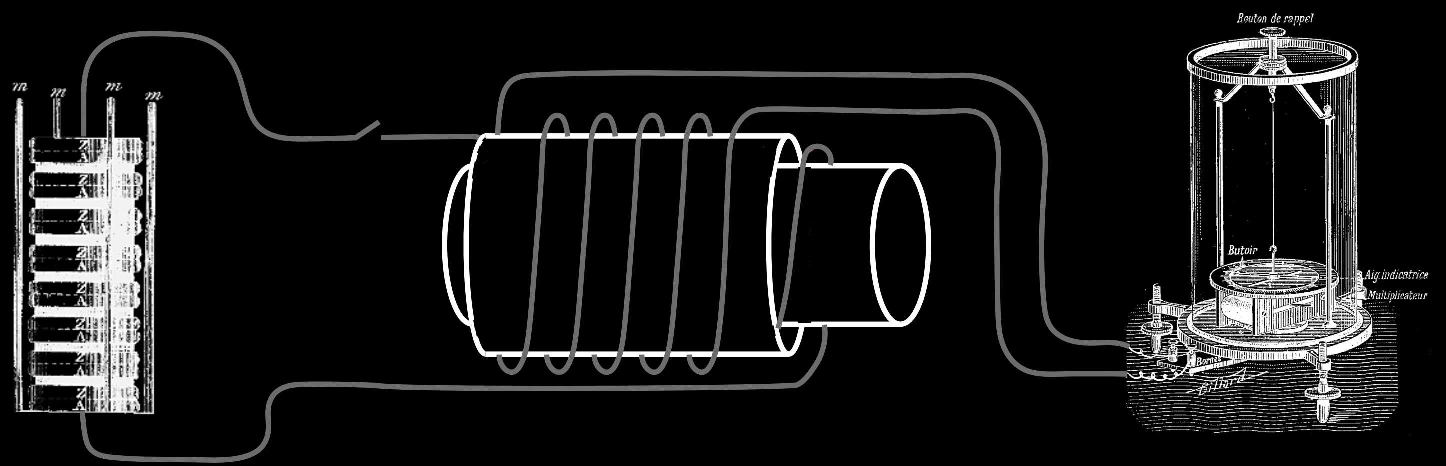

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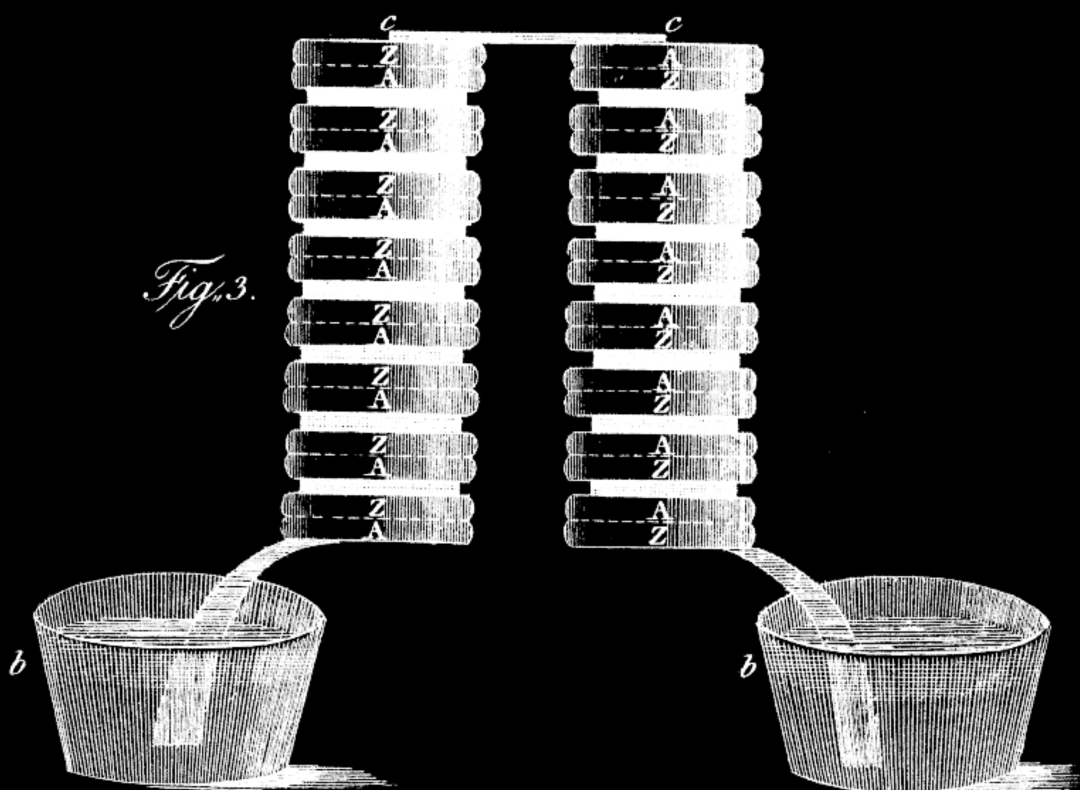

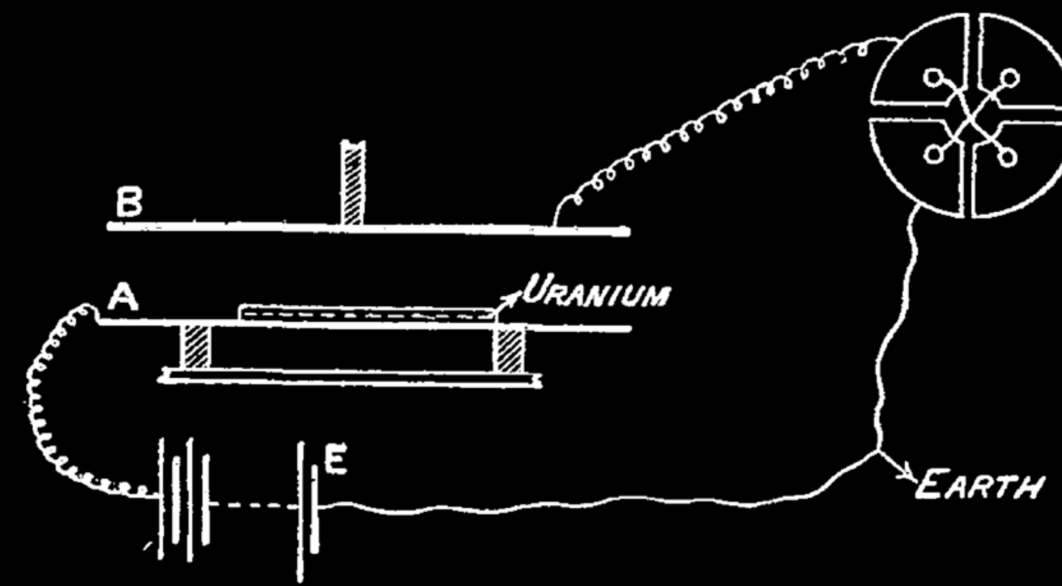

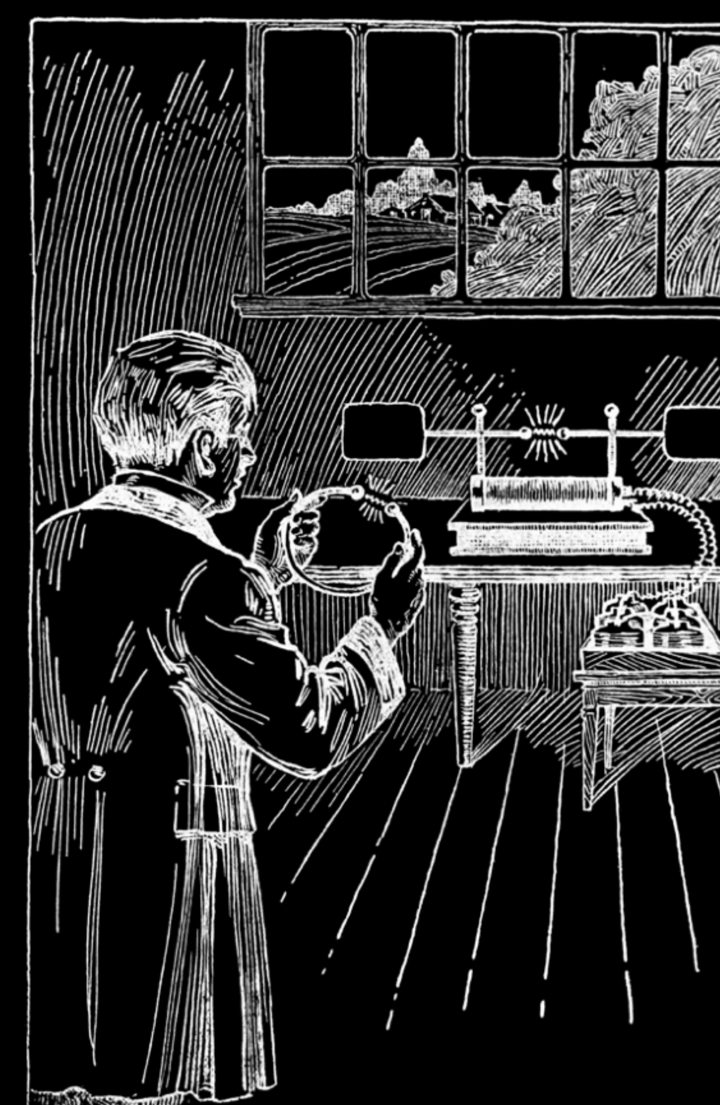

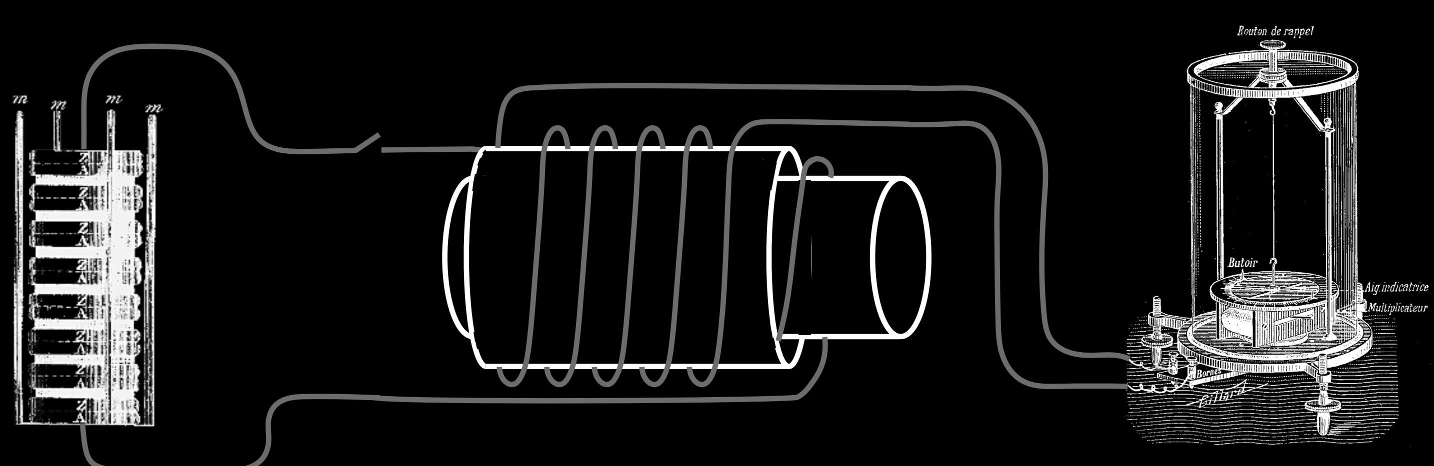

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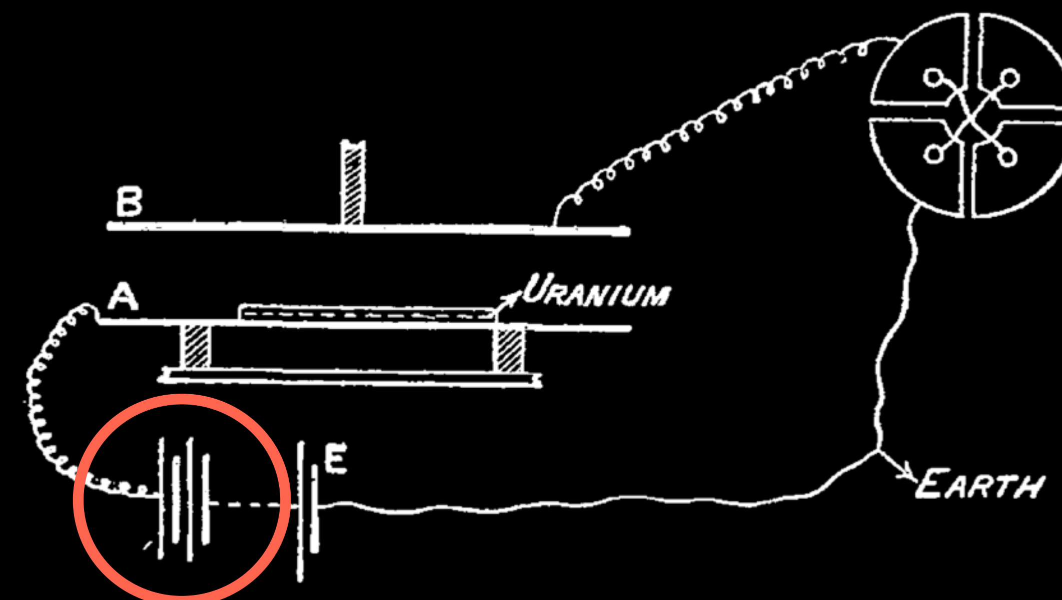

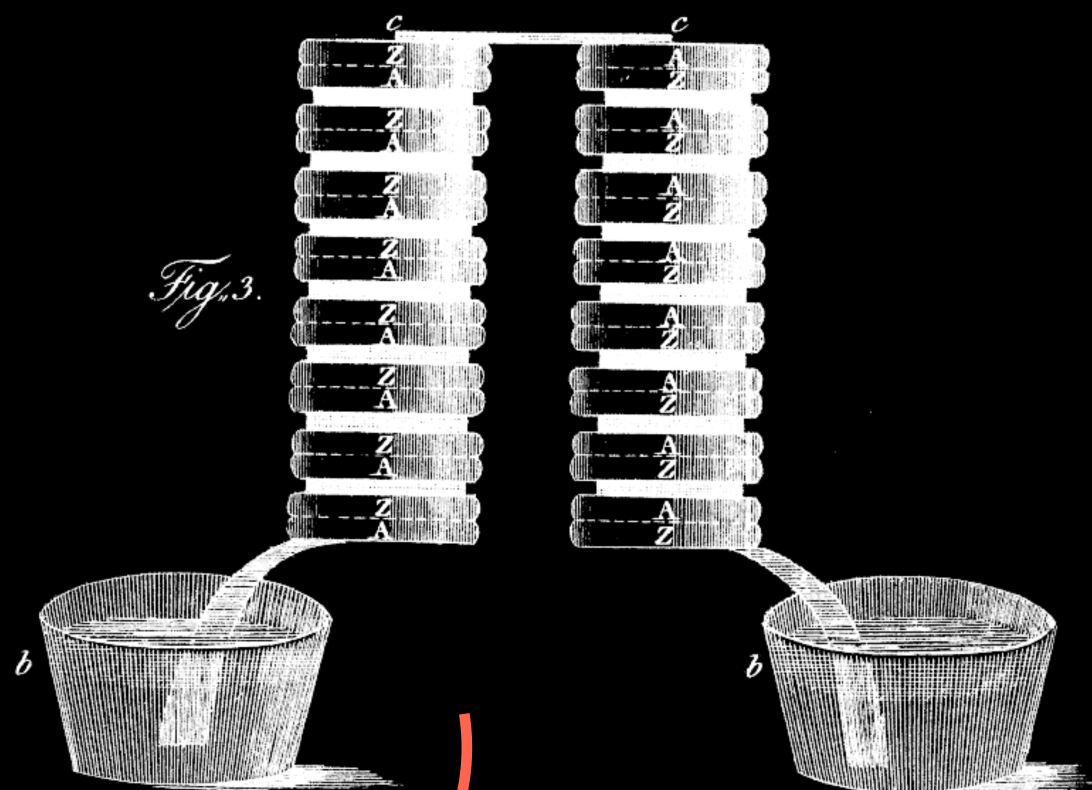

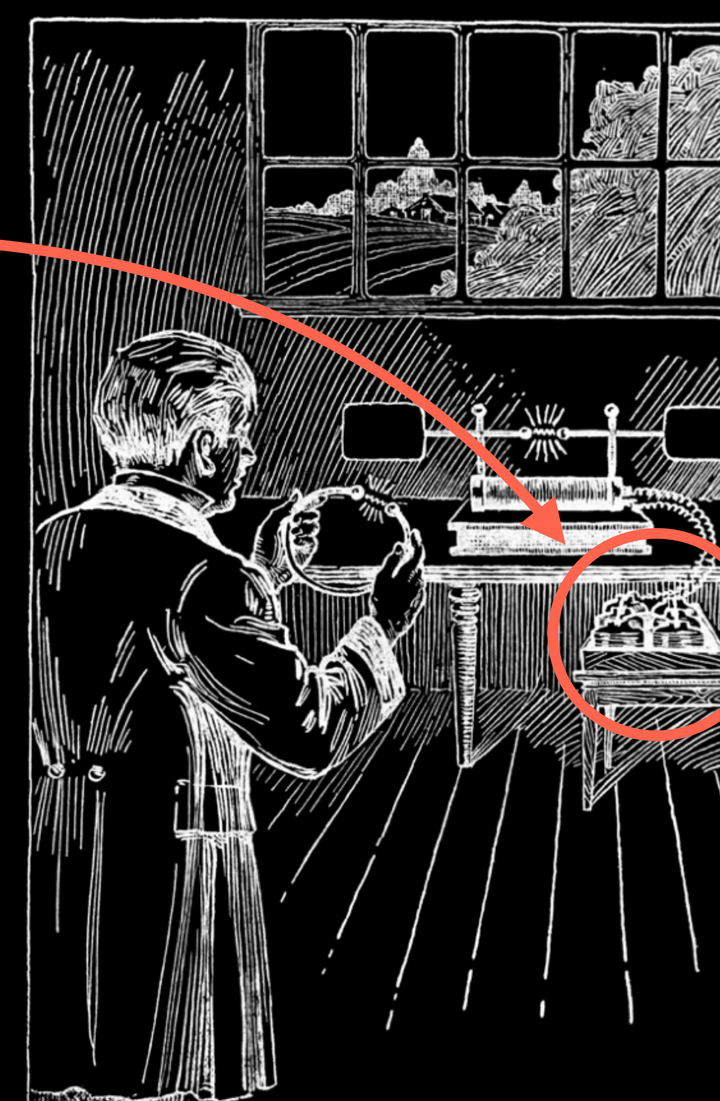

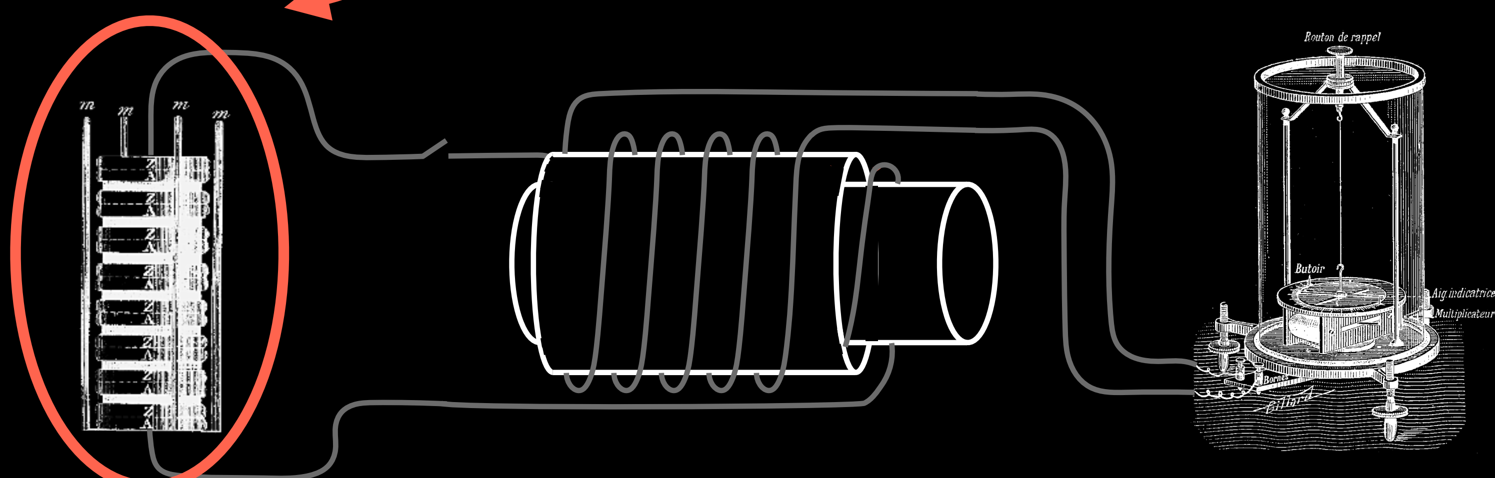

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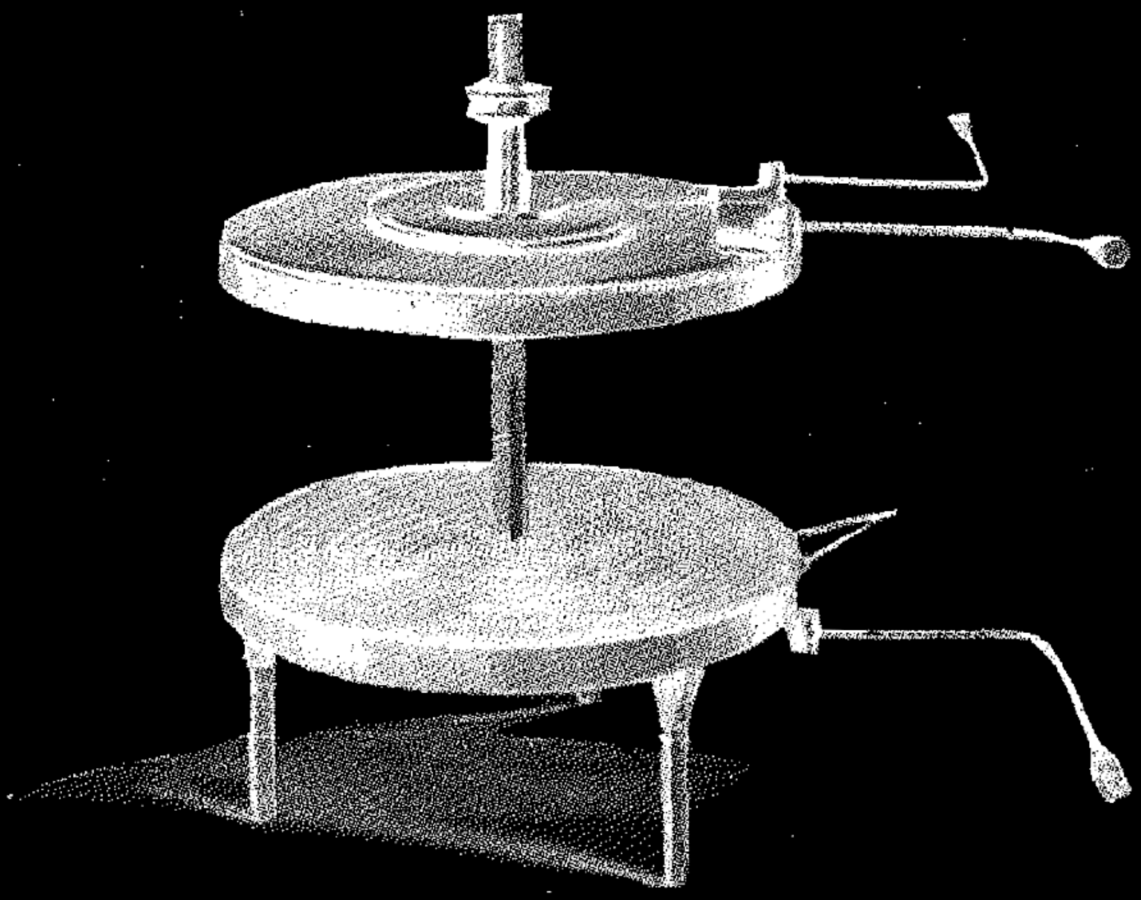

Heinrich Hertz

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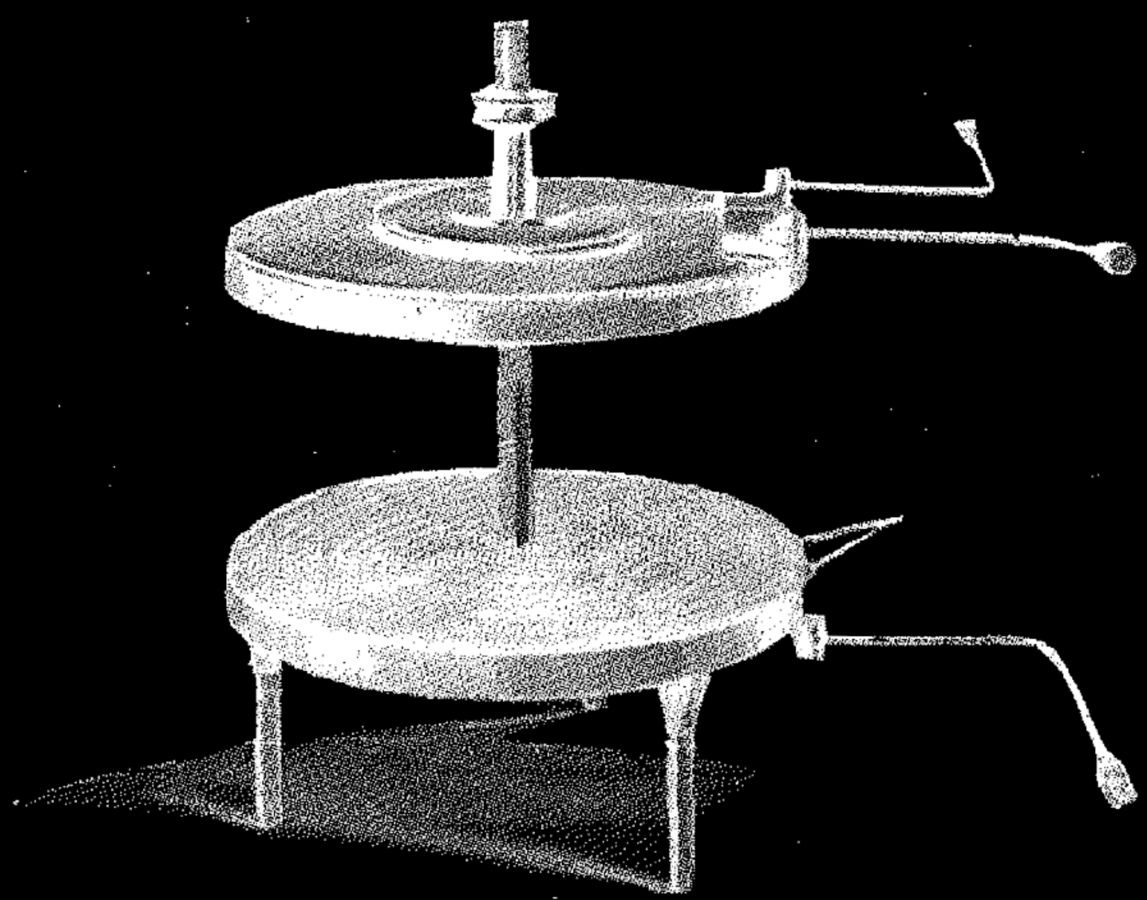
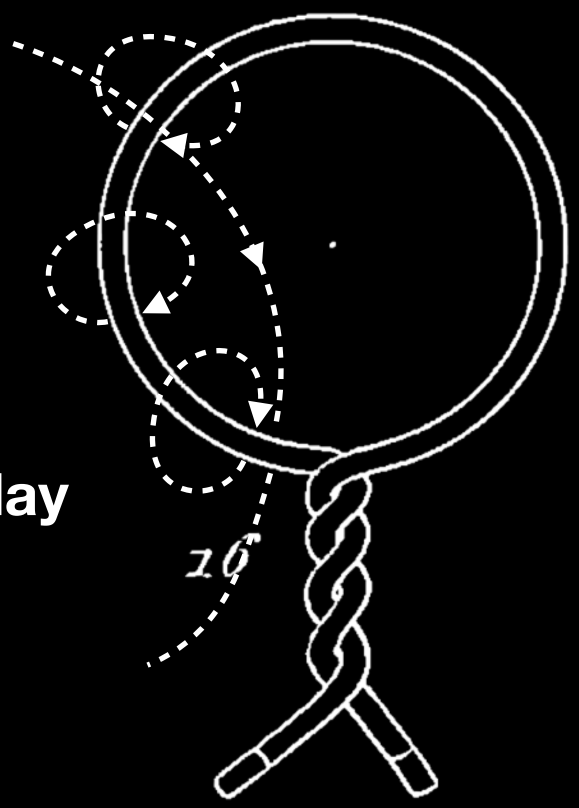


Michael Faraday



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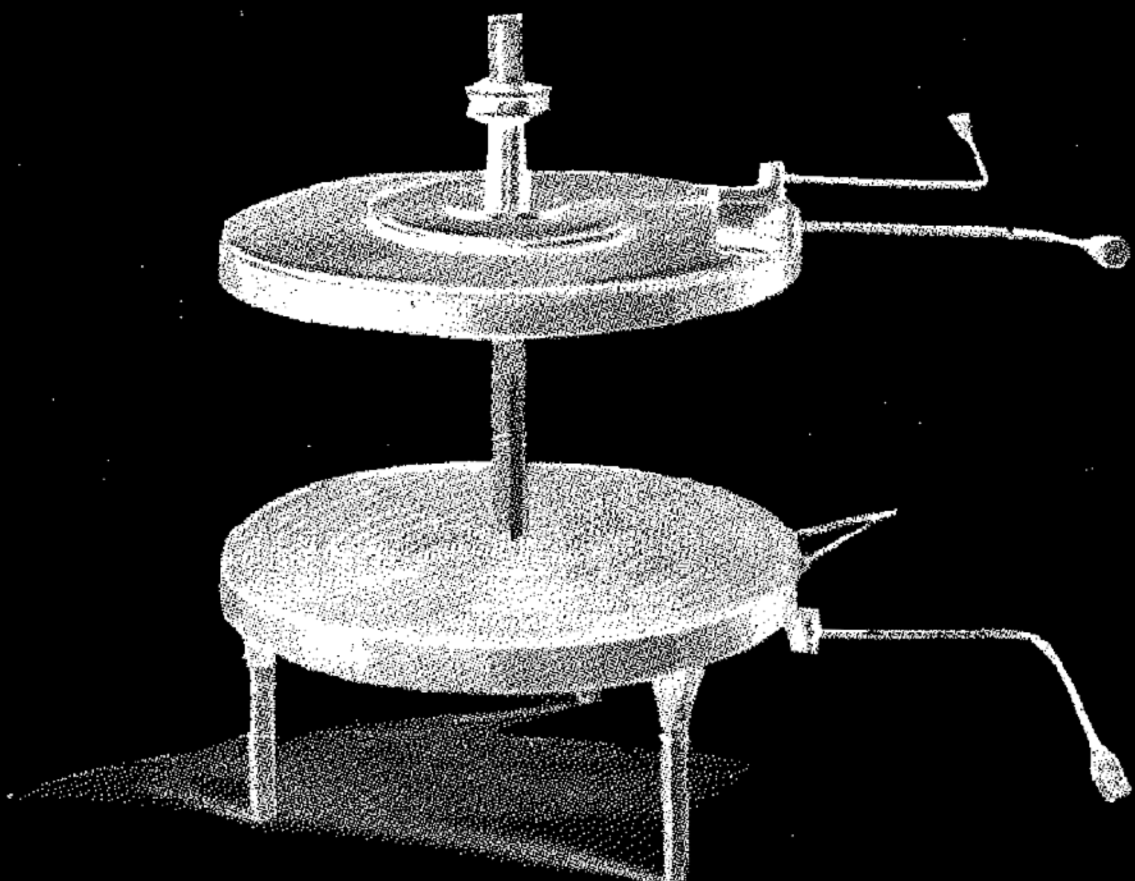

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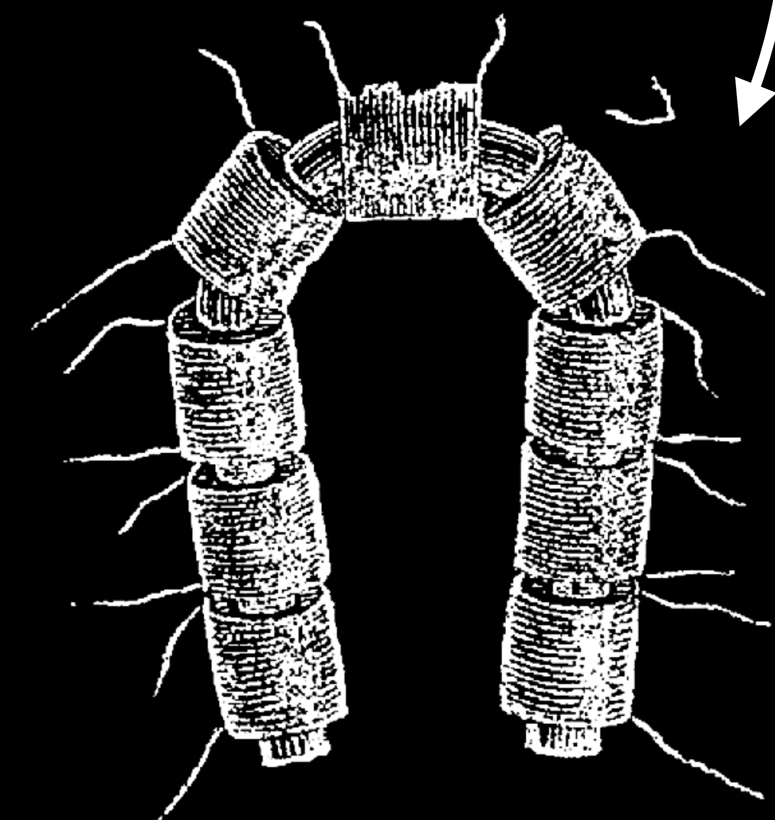

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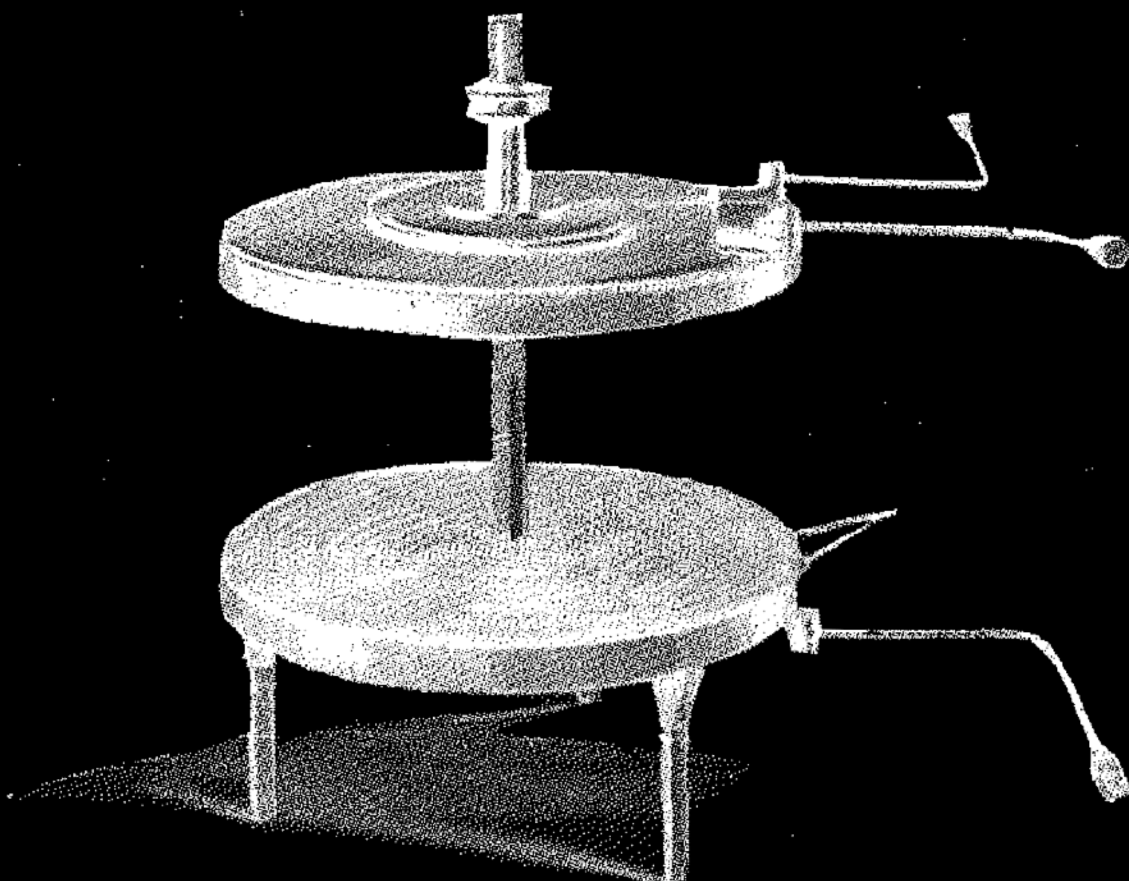

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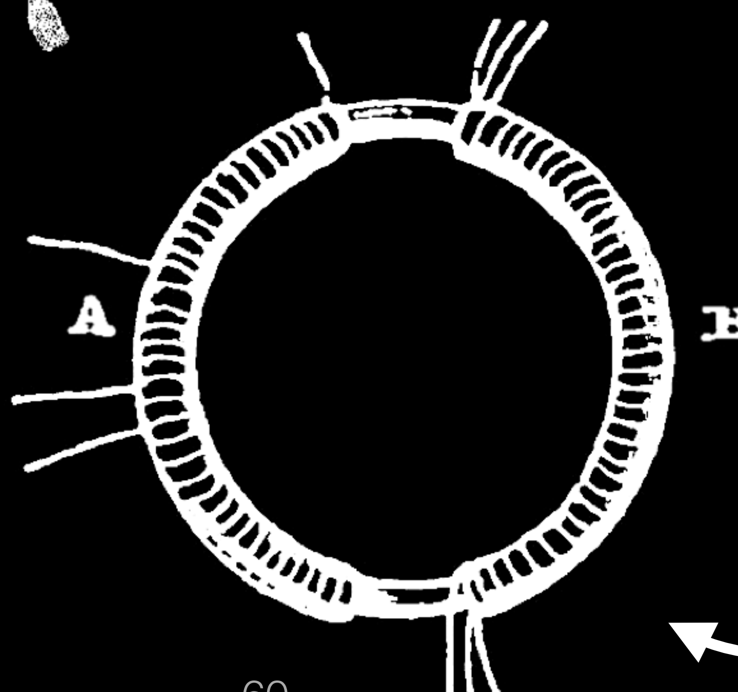

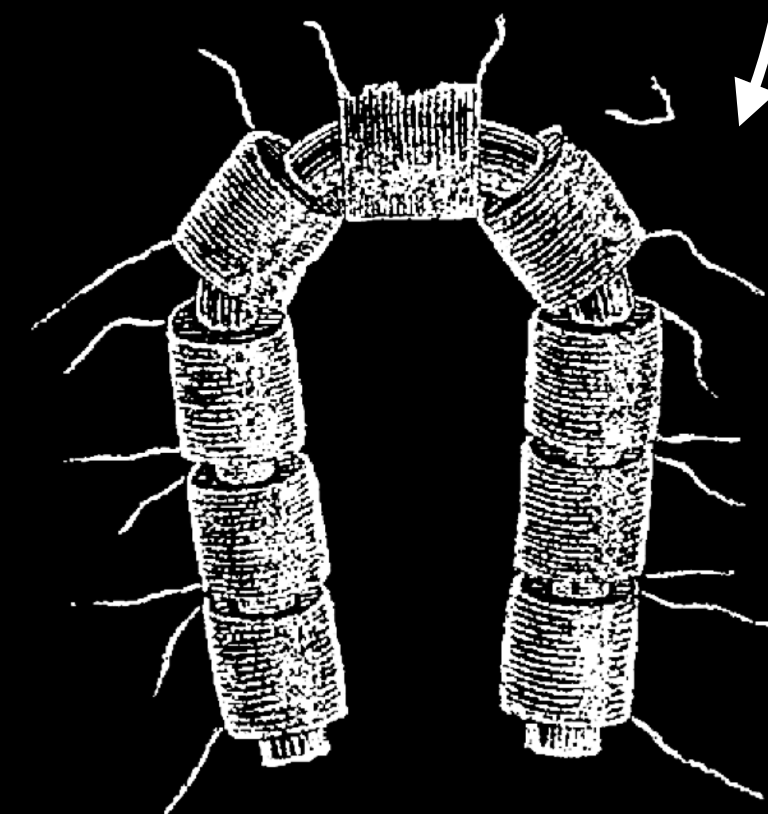

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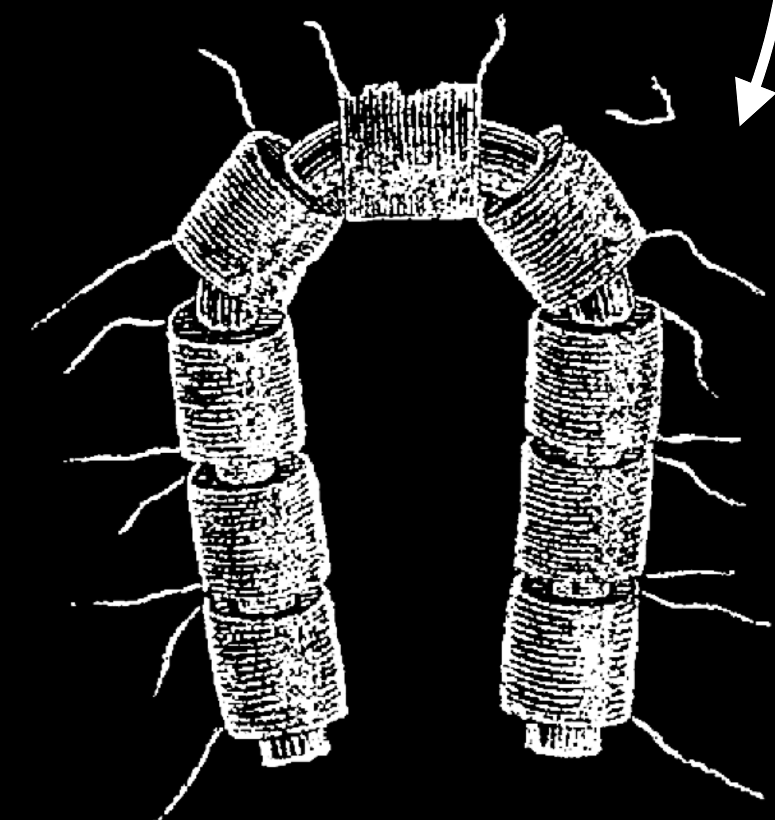

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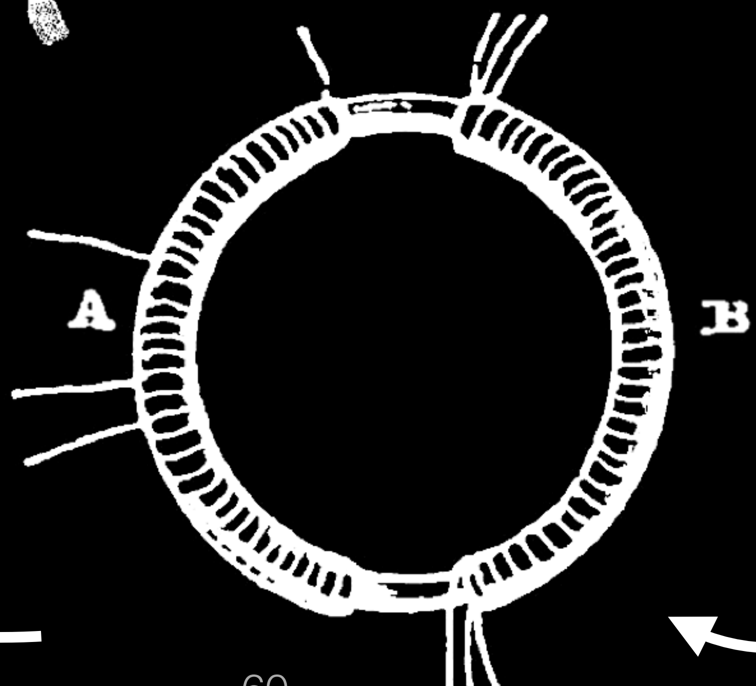

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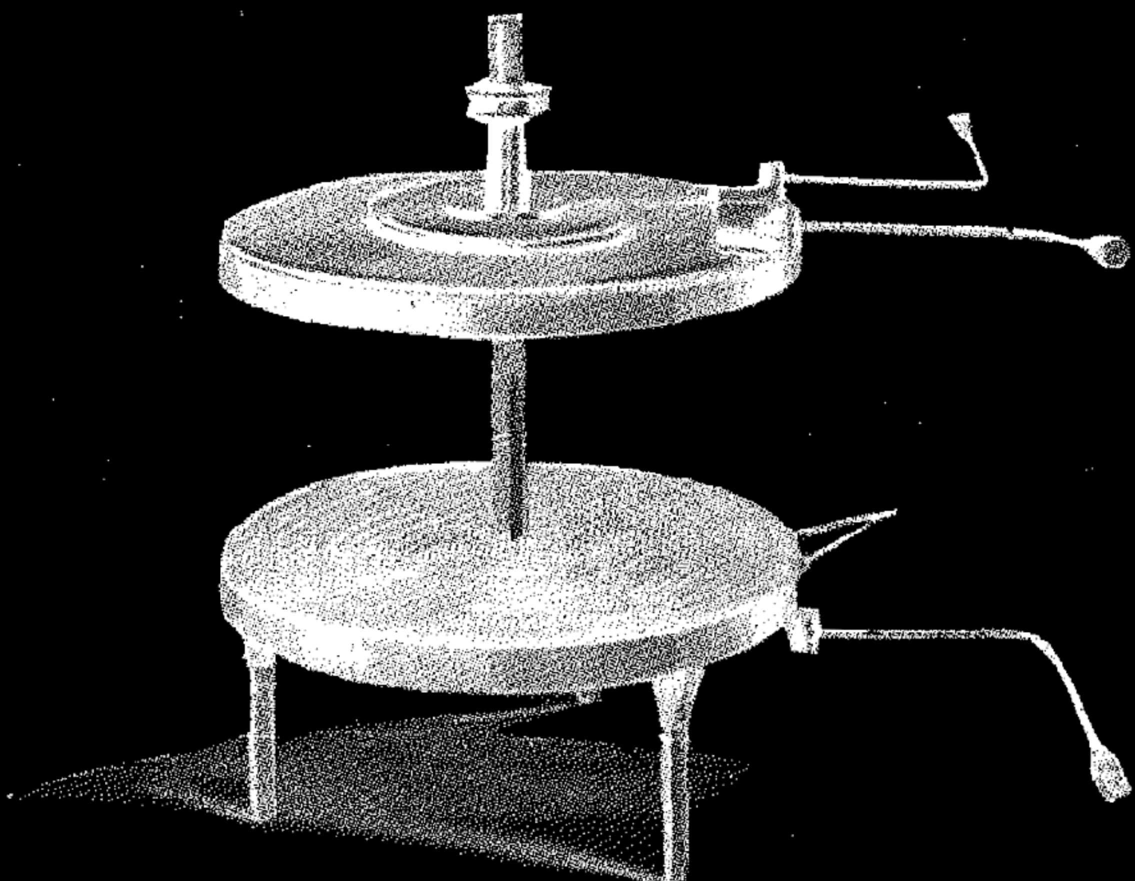

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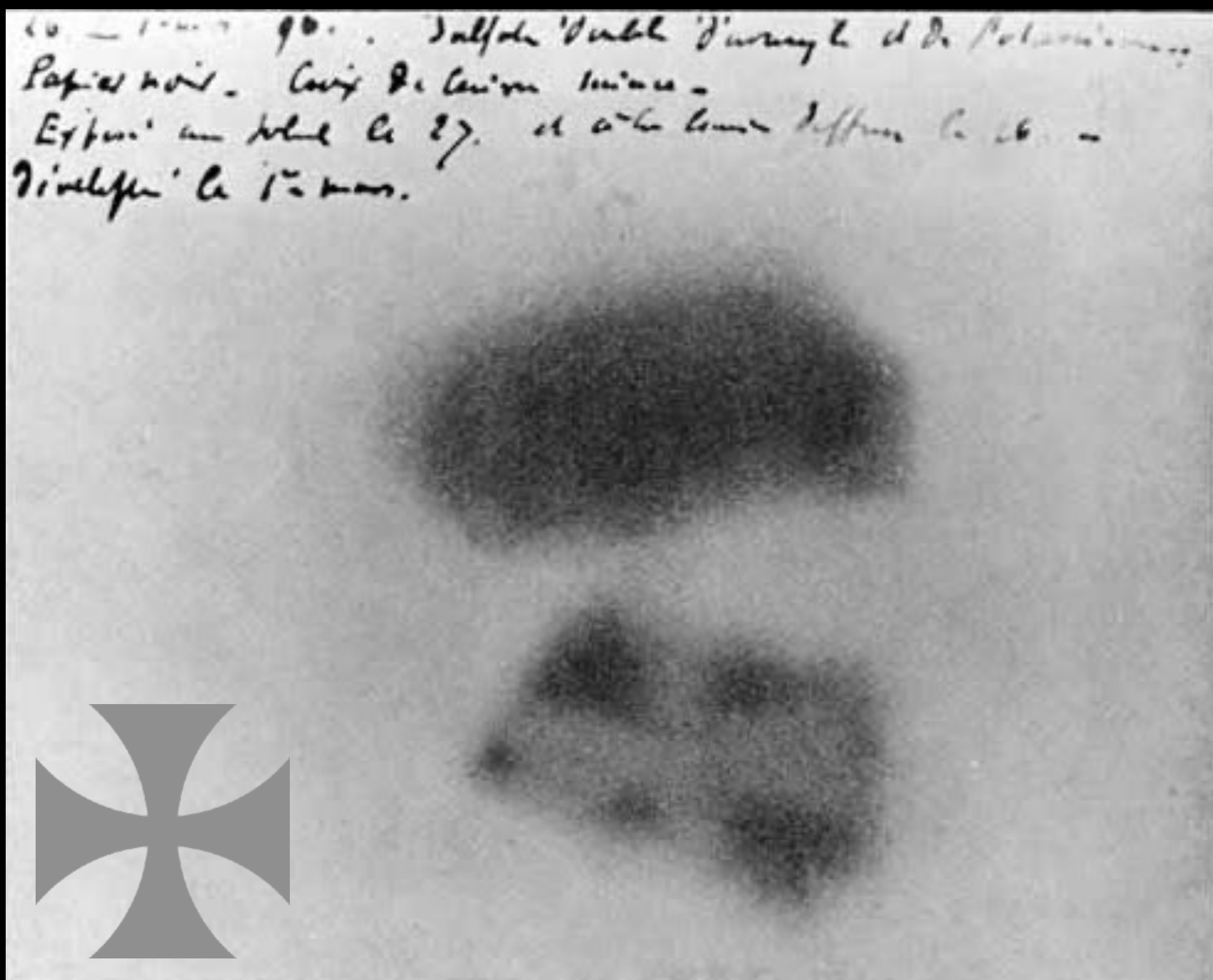

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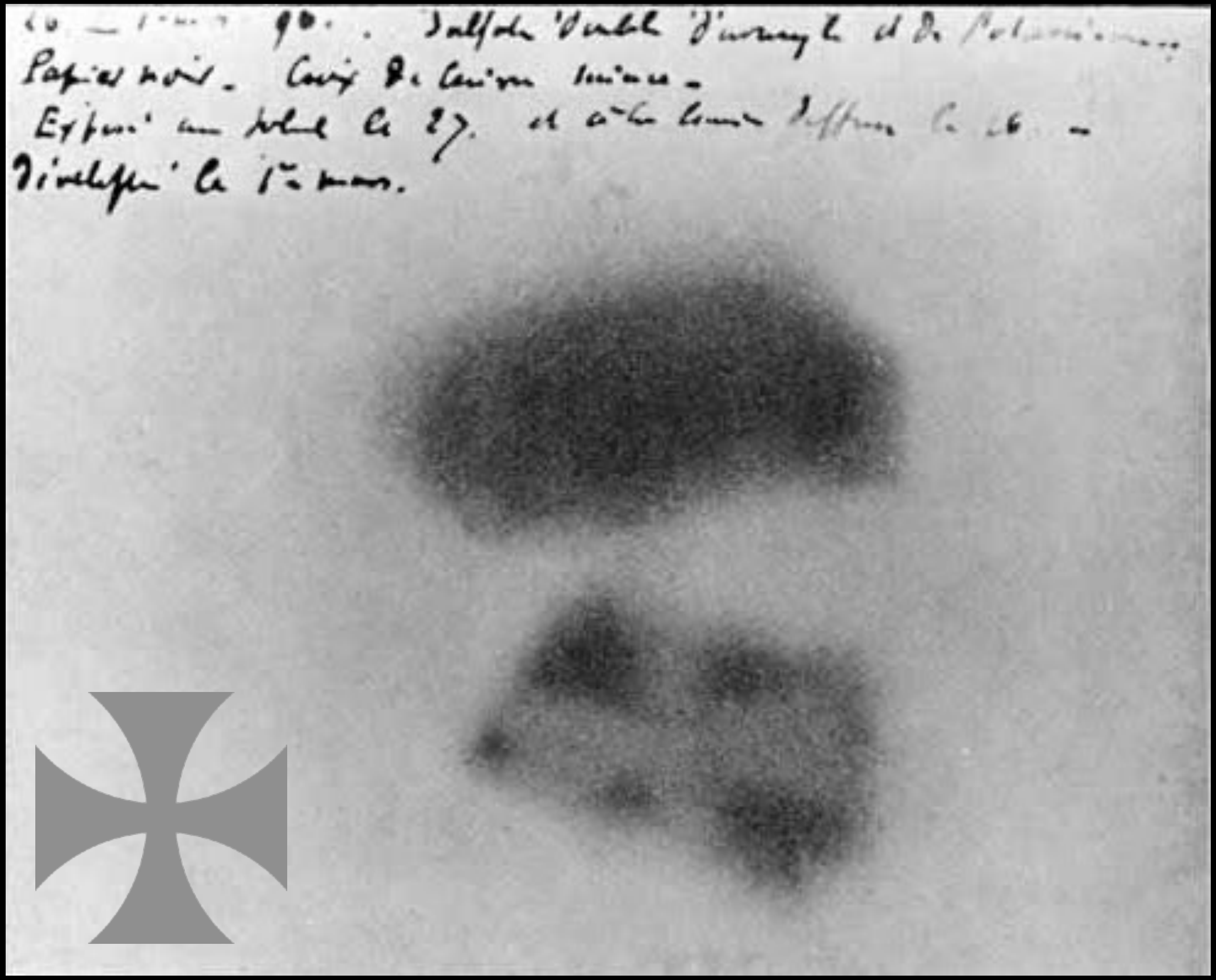

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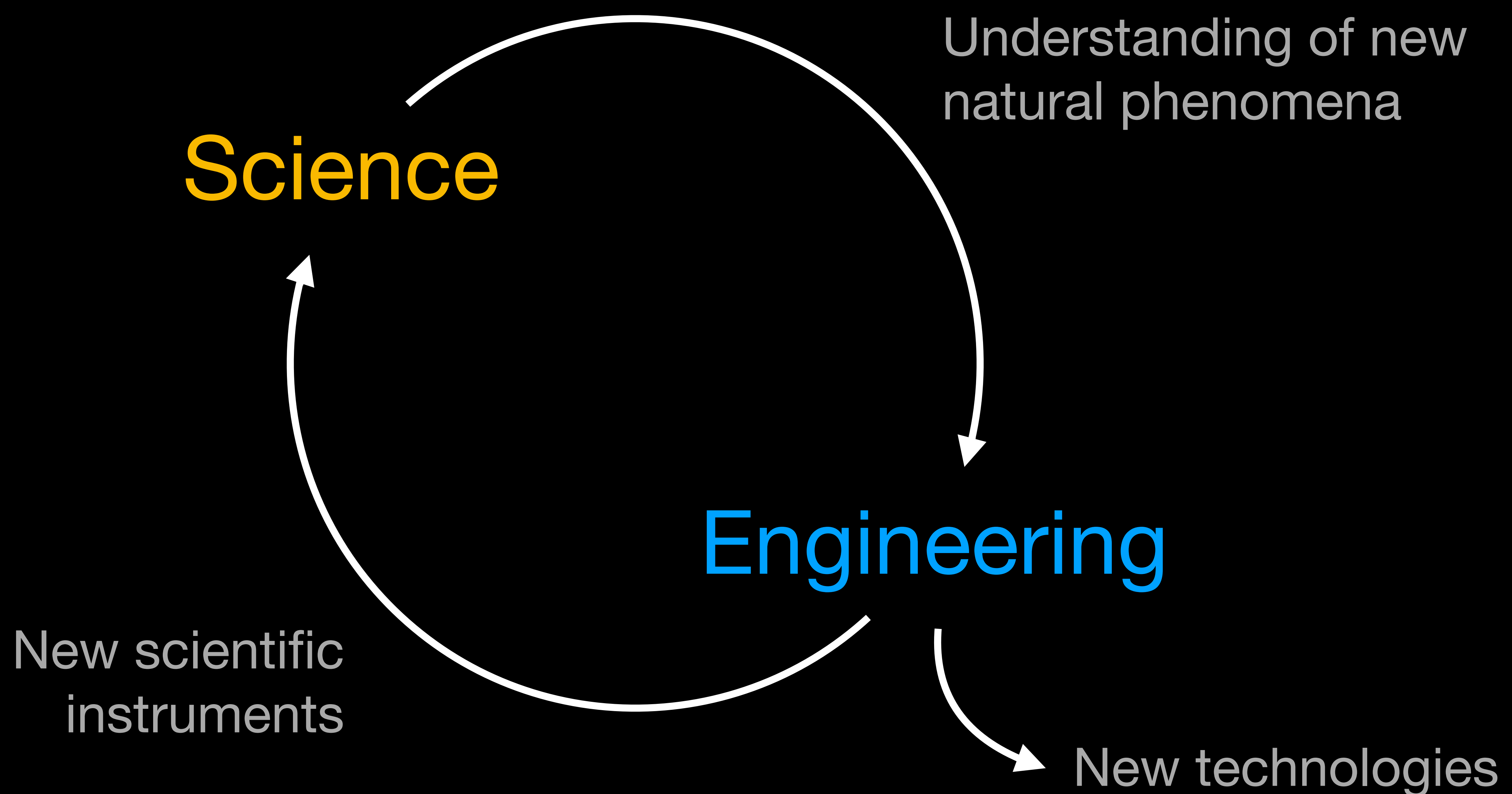

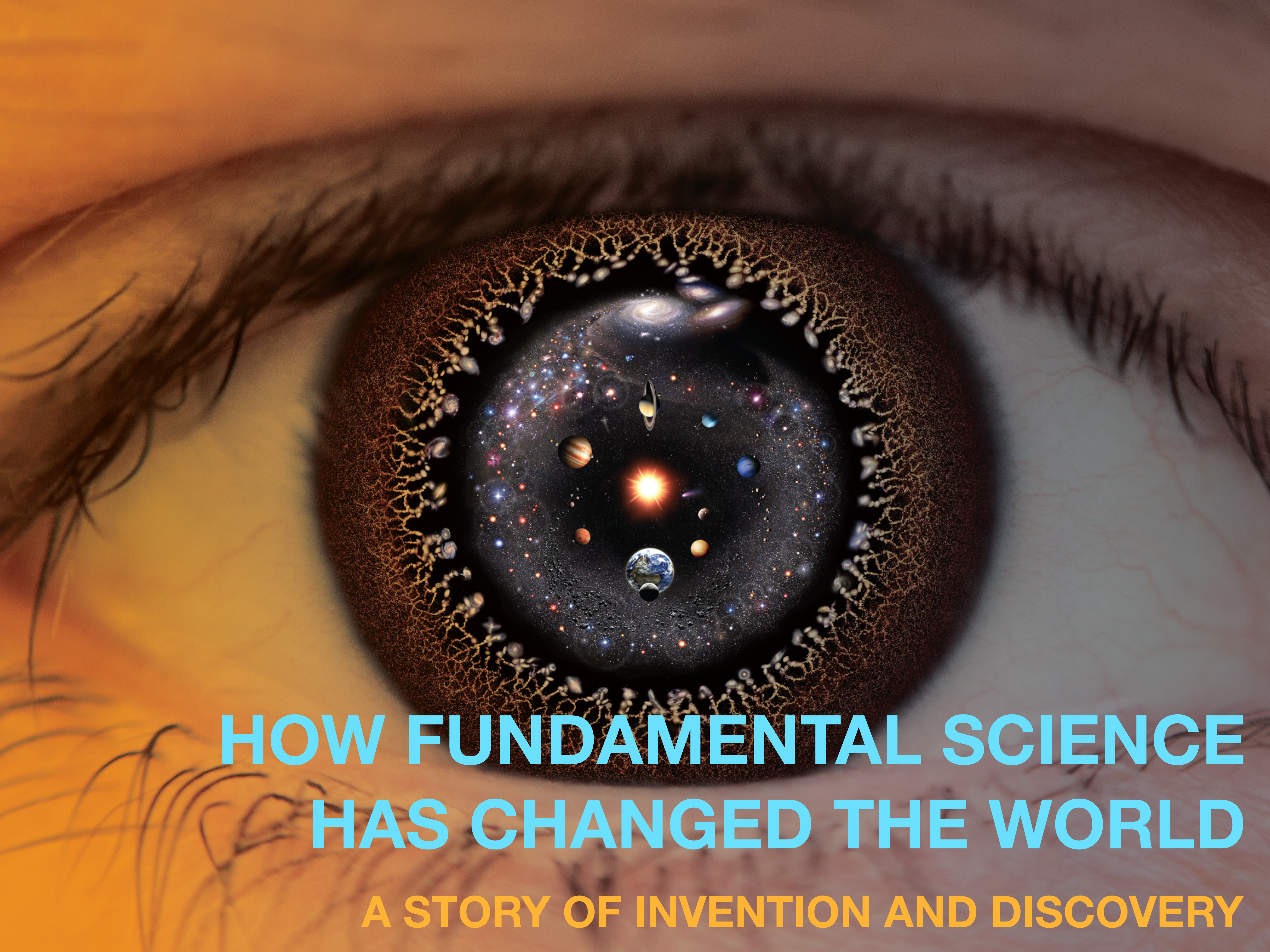

HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

Thank you!