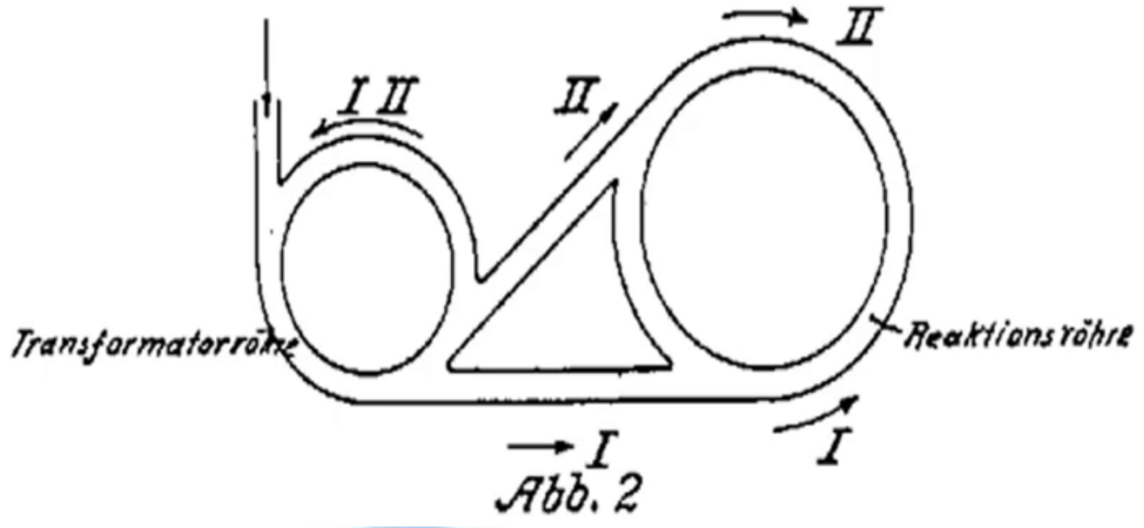
High-Energy Collisions through the Ages

Chris Quigg

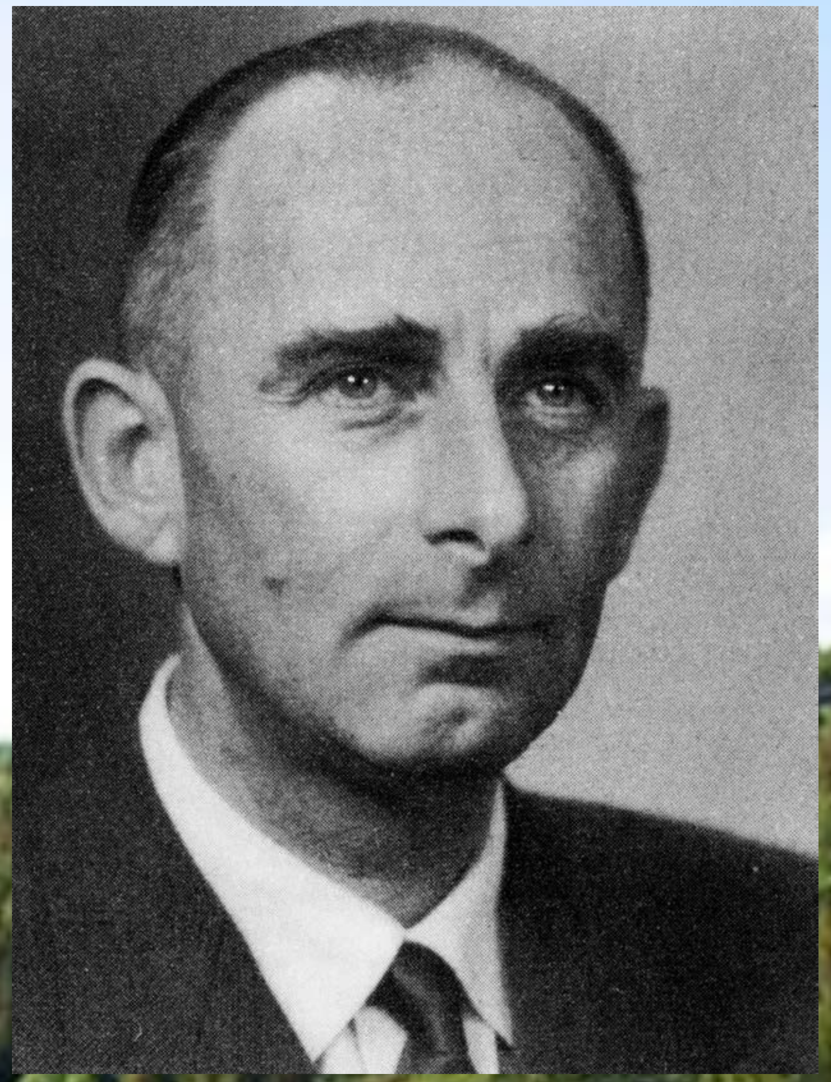
USCMS Summer Interns · June 5, 2024

"Dream Machines"

Shoe-Fitting Fluoroscope (50-kV)



Rolf Widerøe (1943), Tuddal (Telemark) NO:
colliding clouds inspire colliding beams
Kernmühle German patent issued 1953



XVIII. *THE DEPARTMENT OF PHYSICS.*

OFFICERS OF INSTRUCTION.

ALBERT A. MICHELSON, PH.D., *Head Professor of Physics.*
SAMUEL W. STRATTON, S.B., *Assistant Professor of Physics.*
GLEN M. HOBBS, S.B., *Assistant in Laboratory.*

INTRODUCTION.

Within the last twenty years the teaching and practice of Physics, have undergone a revolution more complete than in any of its sister sciences. This result may be attributed, to a very great extent, to the enormous development of its applications to electrical industries. No other industrial application since the invention of the steam-engine has so enhanced the appreciation of the importance of exact knowledge, or given a greater impetus to the search for new truths in the unexplored regions on the borderland of science.

So closely interwoven are the advances in pure science and its applications that it is difficult to say which has been of greater service to the other, but it is evident that it is as ill-advised to ignore the powerful stimulus furnished by the practical development of scientific ideas, as it is to belittle the influence which theoretical and experimental science have had on the world's material prosperity.

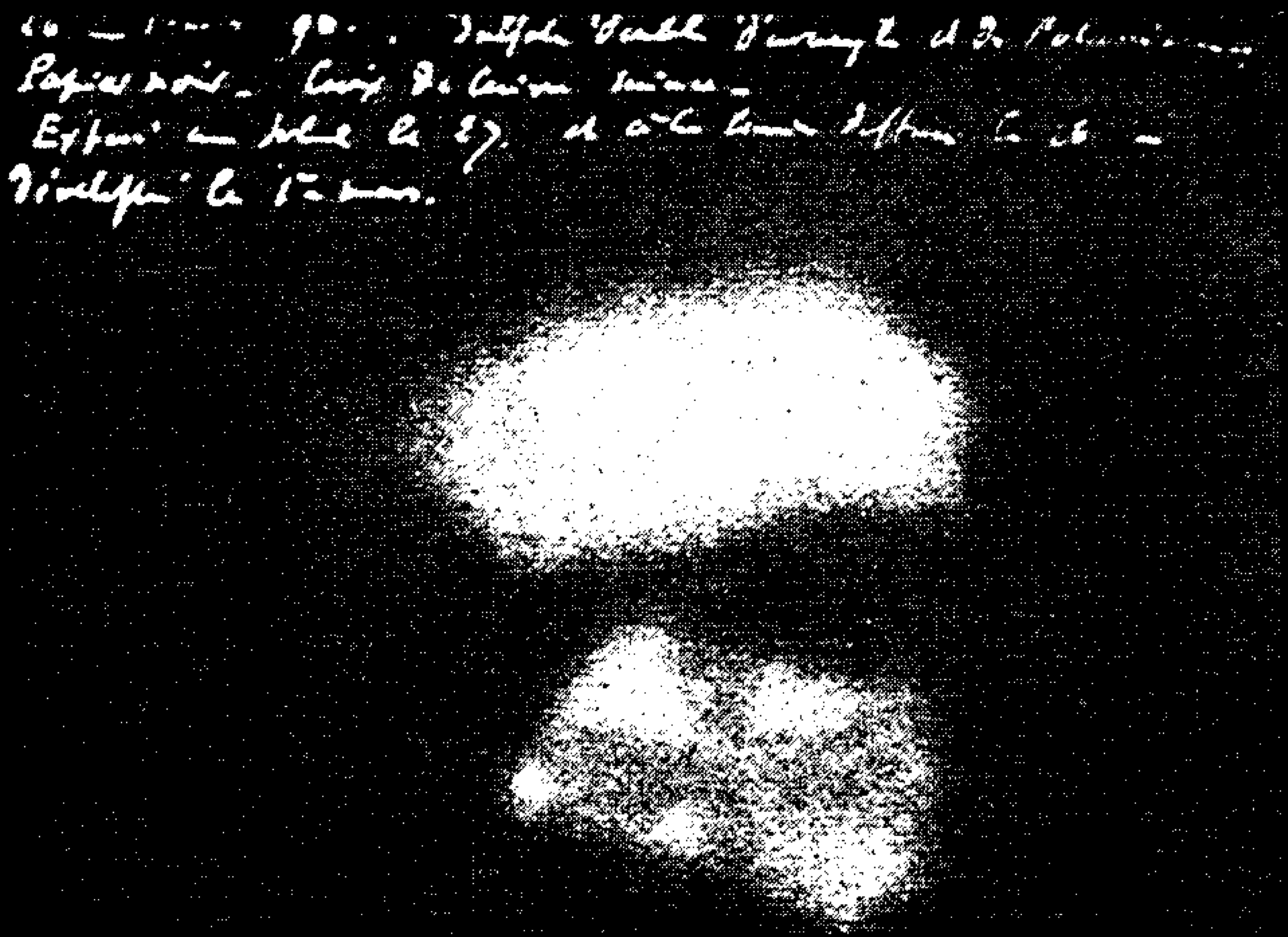
While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice.

It is here that the science of measurement shows its importance—where quantitative results are more to be desired than qualitative work. An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals.

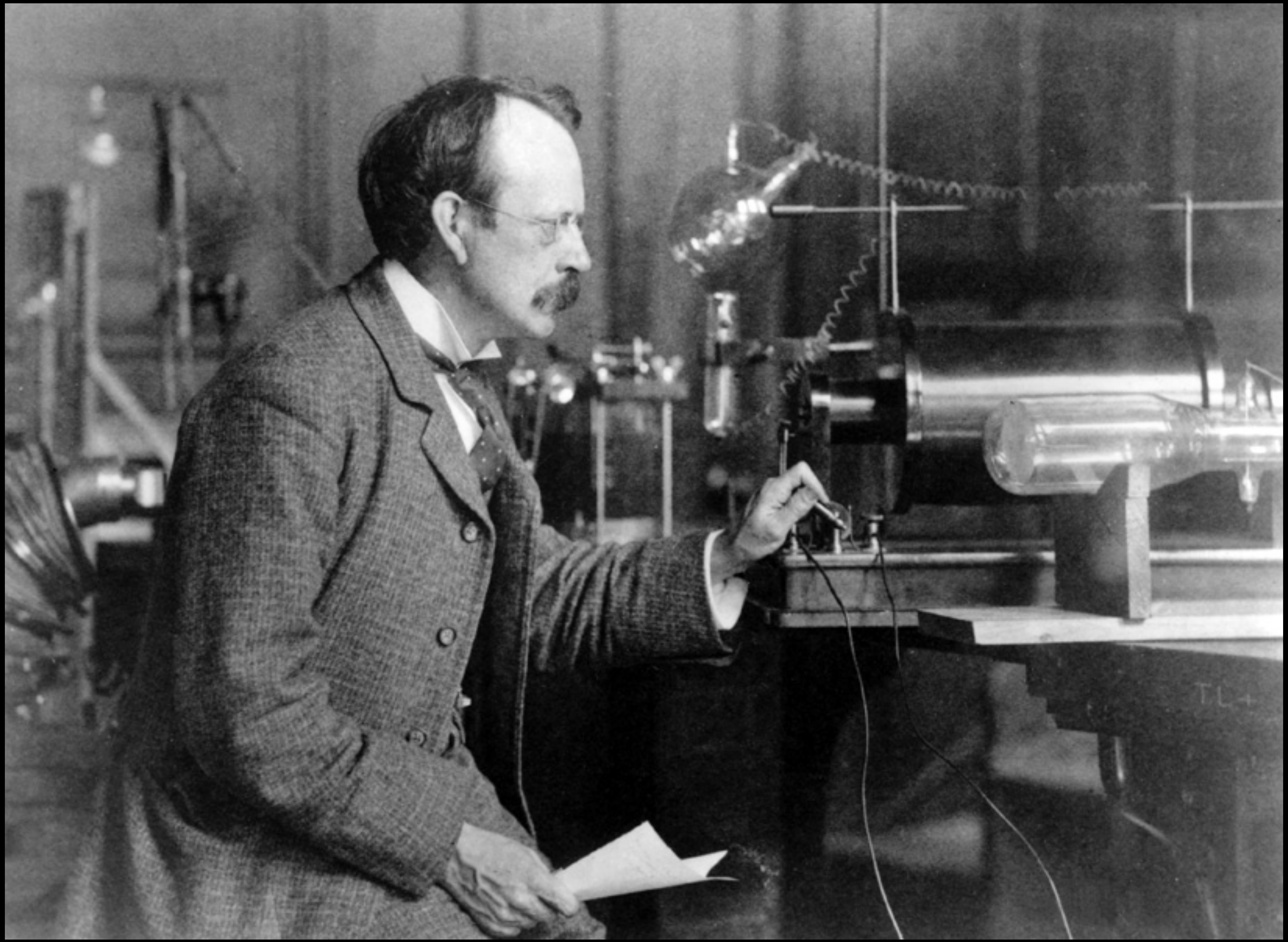
University of Chicago *Annual Register*, 1892–1893


Wilhelm Conrad Röntgen (Würzburg, 1895–1896)

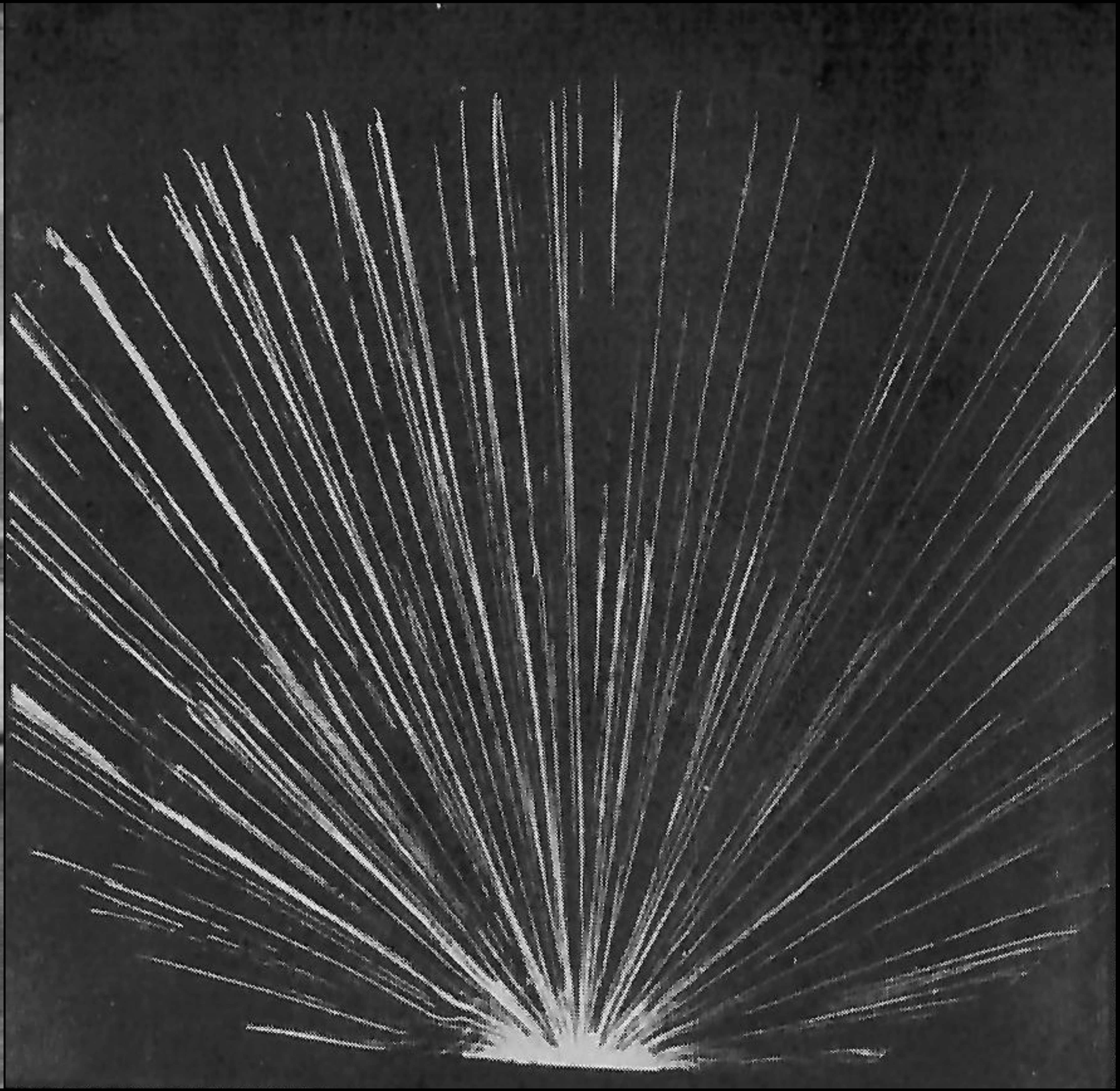
RADIOACTIVITY, NEW PROPERTY OF MATTER



Henri Becquerel (Paris, 1896)

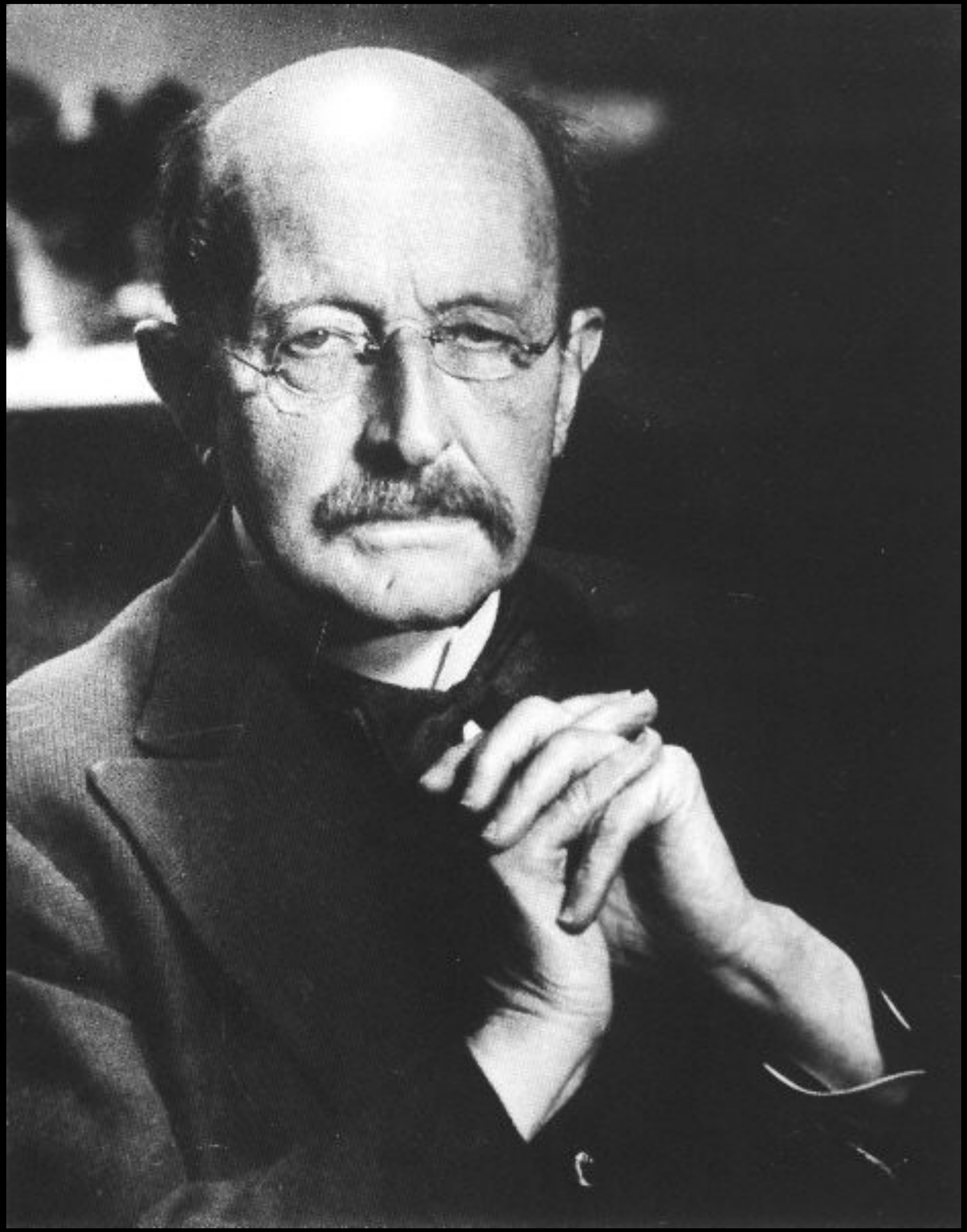


J. J. Thomson (Cambridge, 1897)



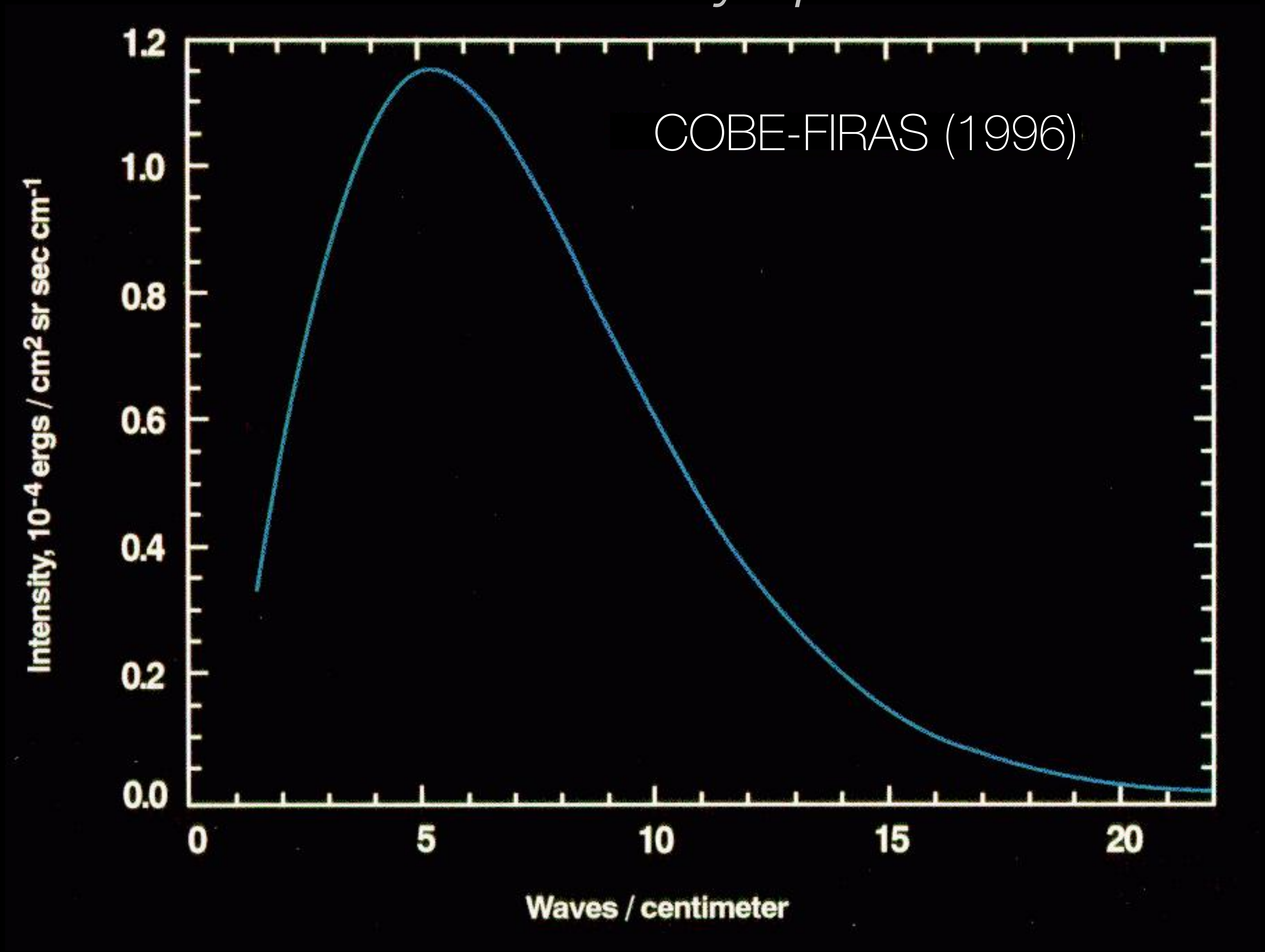
Thorium C = ^{212}Bi: 6.208 MeV; C' = ^{212}Po: 8.784 MeV

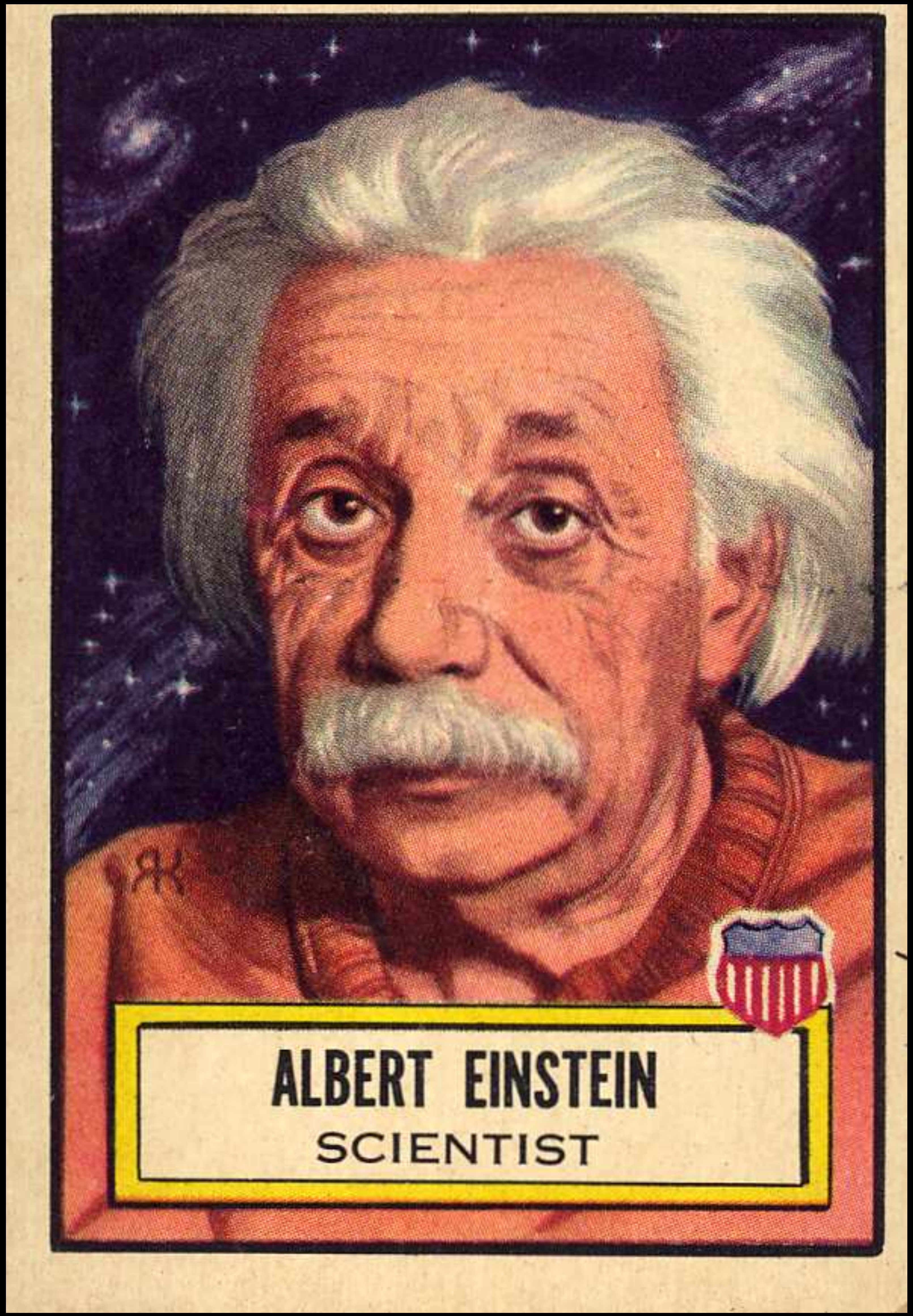
Maria Skłodowska-Curie & Pierre Curie (Paris, 1898–1902)



Max Planck (Berlin, 1900); Quanta

h… blackbody spectrum





Einstein (Bern, 1905) photoelectric effect / Brownian motion

20 ALBERT EINSTEIN

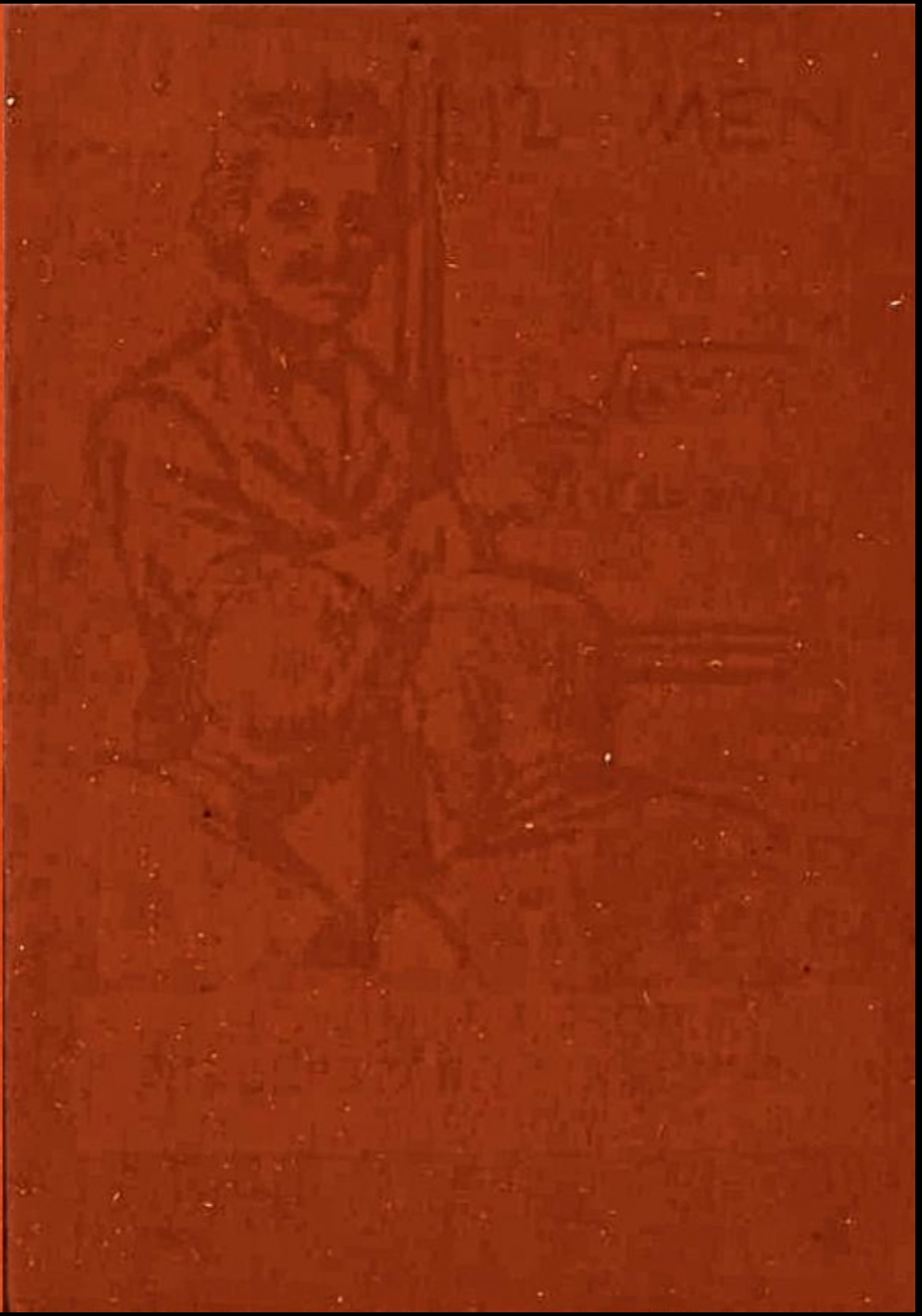
No. 18 of 22 Famous Americans

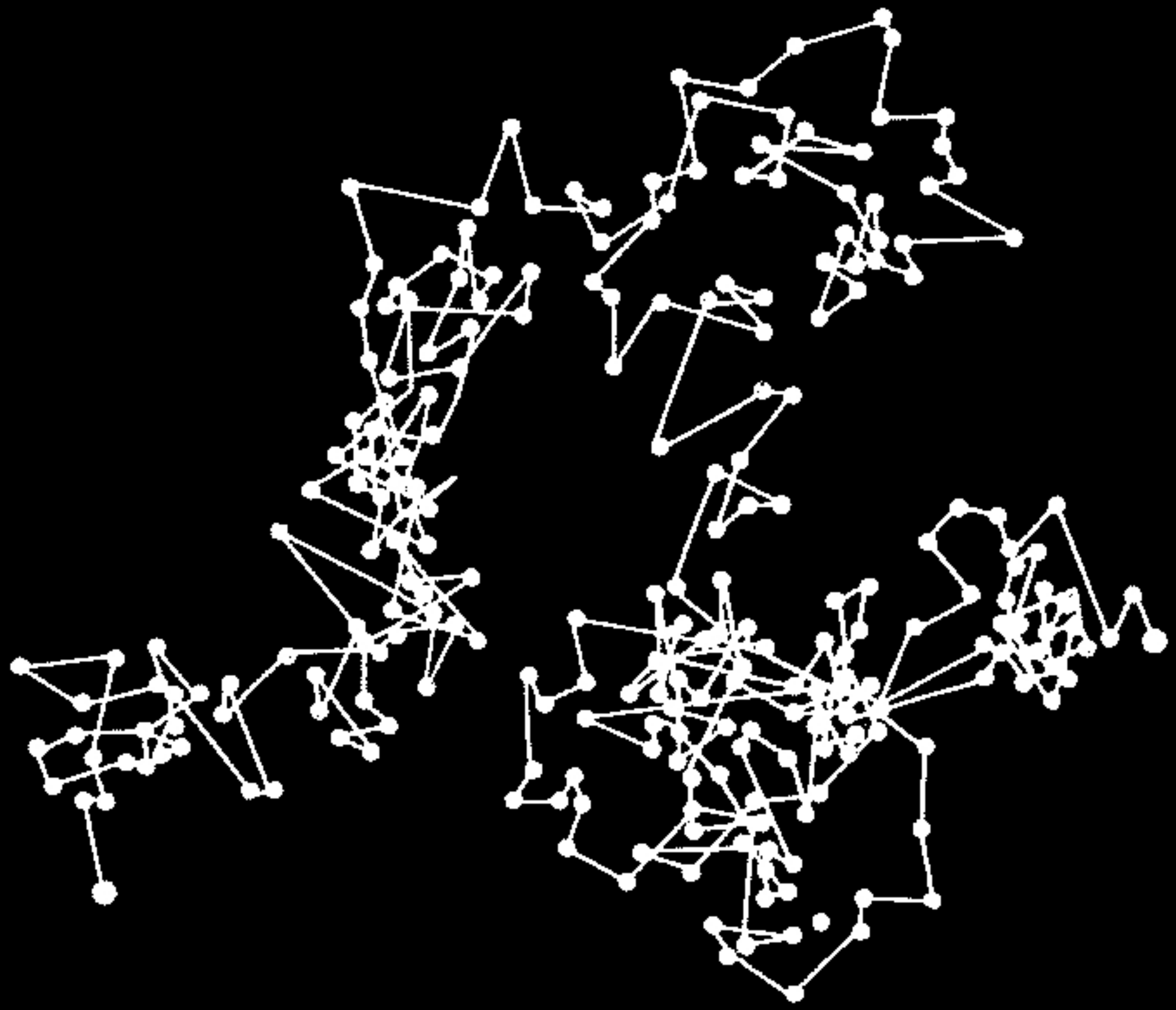
One of the great men of modern science, Albert Einstein was driven out of Germany by Adolf Hitler and came to the United States in 1933. He is a man of very simple tastes . . . even refusing to wear socks except in winter. His study is furnished with only an unpainted desk, a few unpainted shelves, a pencil and paper! He likes to wear old clothes . . . refusing to change from his baggy pants even when distinguished visitors are coming!

LOOK 'n SEE

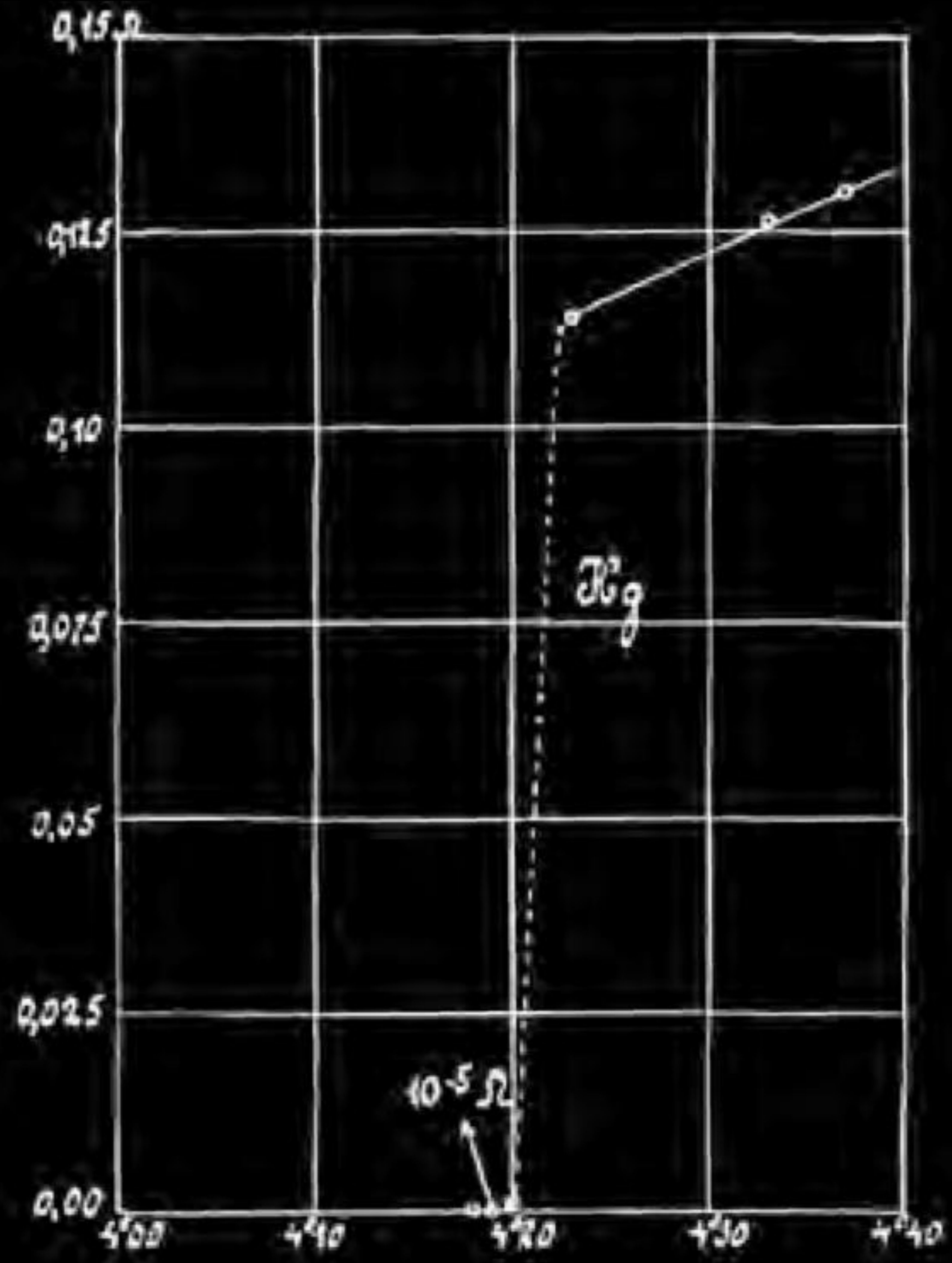
HOW MANY PEOPLE UNDERSTAND EINSTEIN'S THEORY?

PLACE THE RED PAPER OVER THIS CARD AND SEE THE ANSWER.



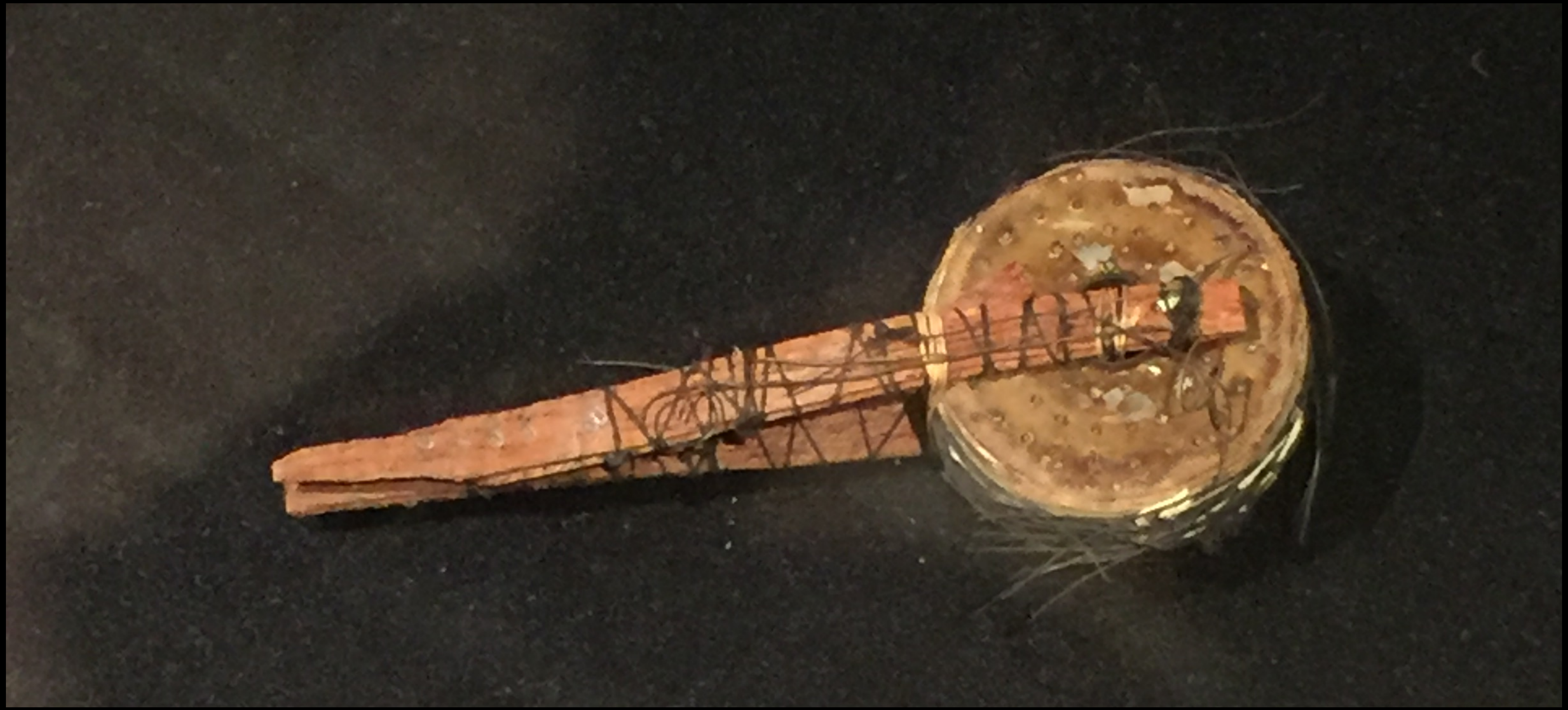



Jean Perrin (Paris, 1908)

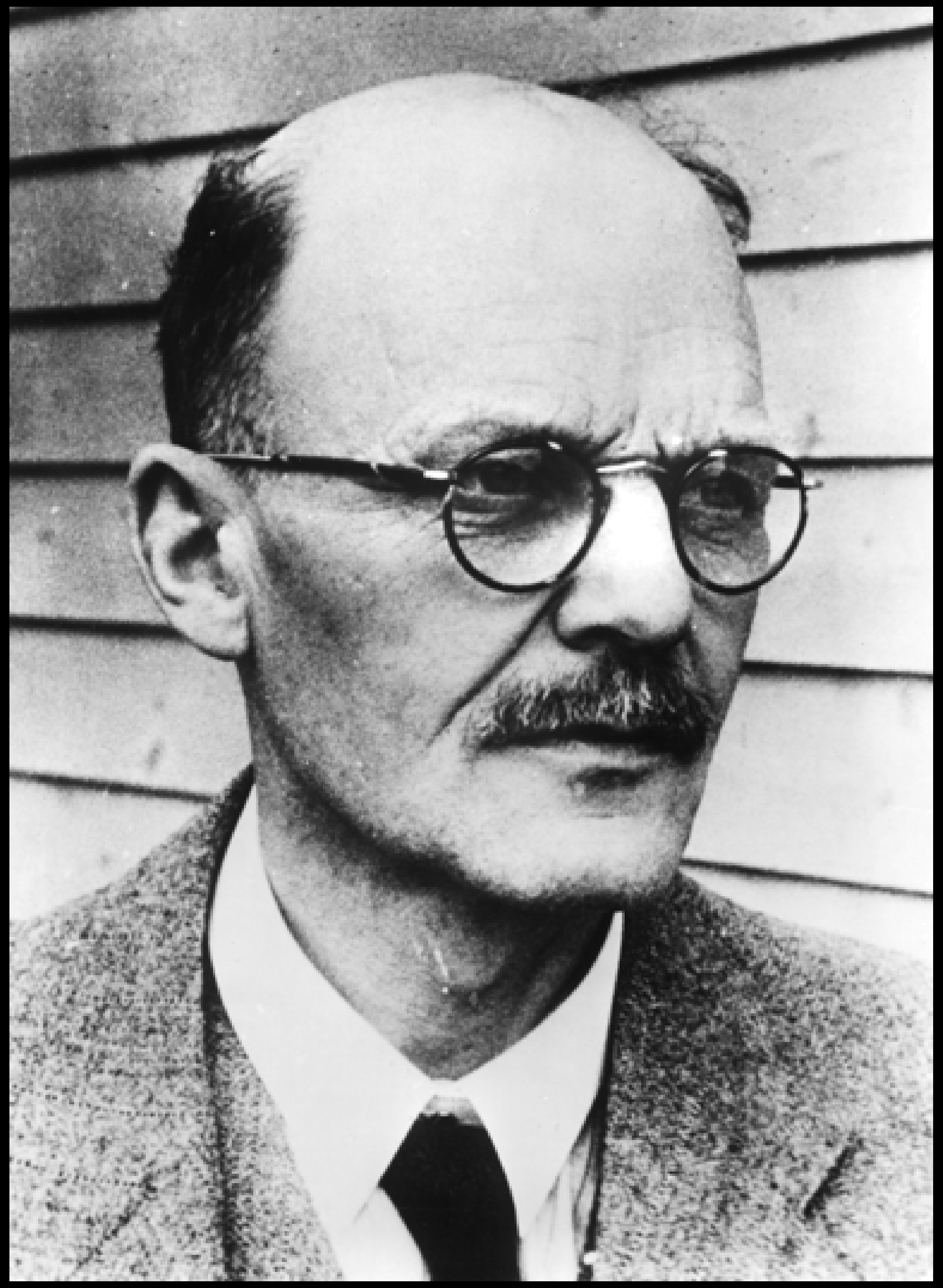


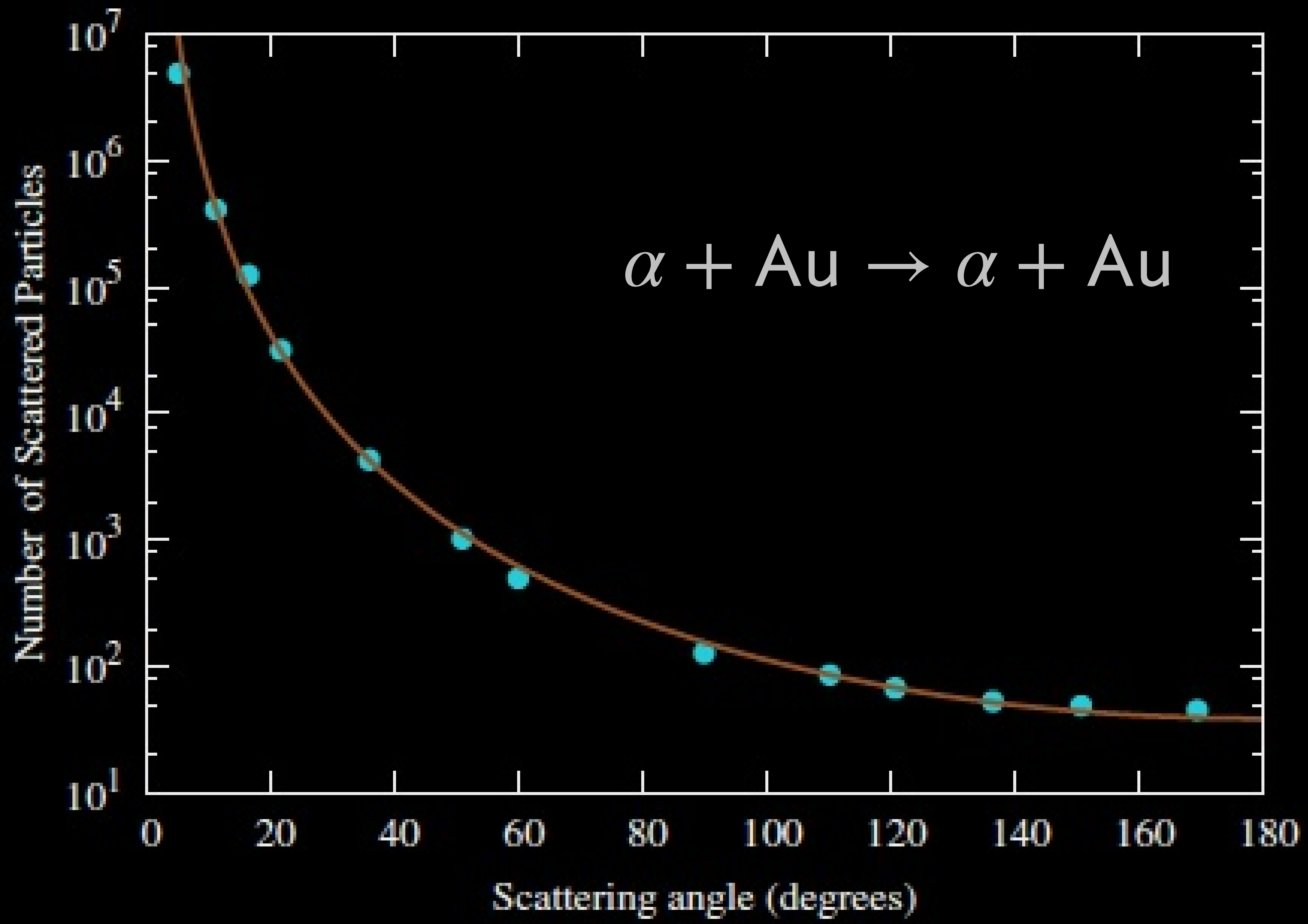
Heike Kamerlingh Onnes (Leiden, 1908)

Door meten tot weten



First superconducting magnet: Pb wire, 600 gauss (< 7.2 K)
Museum Boerhaave, Leiden





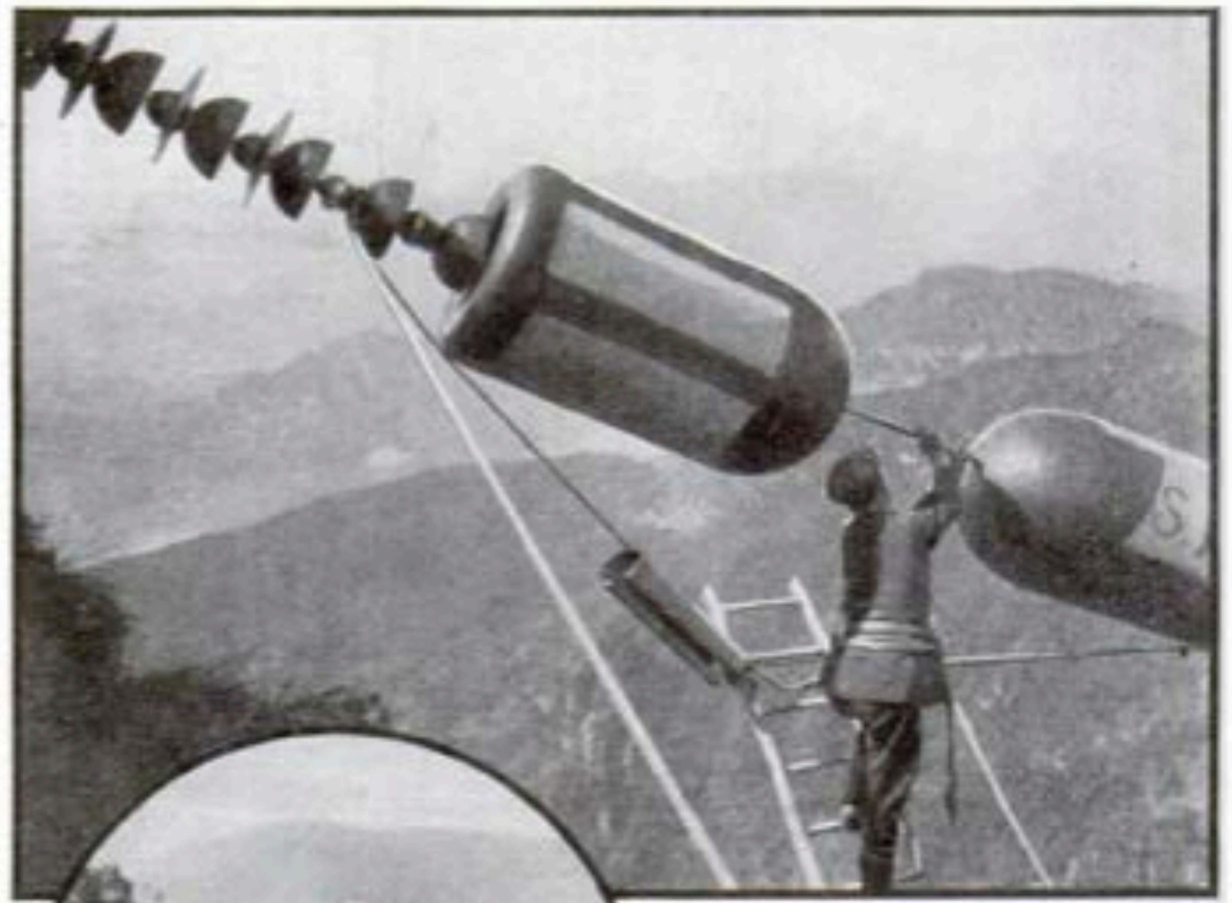
Hans Geiger, Ernest Marsden, *Ernest Rutherford* (Manchester, 1908–1913)

Arno Brasch, Fritz Lange, Kurt Urban: Monte Generoso (1927–1928)

18,000,000 Volts Captured *from the* Sky

Cable, Strung between Mountains, Acts as Antenna to Gather up Lightning

Dr. Kurt Urban, most shocked man in the world, on roof of Mt. Generoso lightningproof cabin.



Workmen installs metal "corona cylinders" in the Mt. Generoso cable to keep the high-voltage current from leaking into the air.

This apparently small spark is really one of several million volts, drawn from the sky, and leaping across a fifteen-foot gap in a preliminary test by experimenters at the Mt. Generoso station in Switzerland.

High-voltage currents, knowing no bonds, do strange things. Here is an arc that is leaping between two high-tension wires.

AT THE peril of their lives, three young Germans have just succeeded in drawing electric currents of 18,000,000 volts from the skies during a violent display of lightning. On the slopes of Mt. Generoso in Switzerland they duplicated Benjamin Franklin's famous experiment of catching atmospheric electricity with a kite and key, on a scale which that pioneer never dreamed of.

From the side of Generoso's bony-ridged slope, they stretched, as an aerial, a metallic cable across a chasm to a neighboring peak. Threaded through cylinders of galvanized metal, this antenna resembled a string of beads for a giantess. Its knobs were designed to keep the currents from leaping from the ends. Instead, an escape was provided in an adjustable spark gap, from which the electricity could be carried to a lightning-proof cabin sheathed with metal beneath the brow of the mountain. Here were meters and other instruments to gage the force of the electricity.

ONE day not long ago the daring three, Drs. A. Brasch, F. Lange, and Kurt Urban, of the University of Berlin, saw a storm of unusual intensity brewing. The sky became pitch dark. Peals of thunder hurried the scientists as they threw switches and tested instruments. Then with a rush of wind up the valley that almost swept away the aerial, the fury of the storm broke.

Tongues of electric flame played about the rocks of the mountain's face near the summit. Filled with metallic ore, it was a natural lightning rod. Great yellow sparks snapped every second across the spark gap. The pointers of the voltmeters within the cabin were doing a dance. There came a brief lull, ominous in its calm.

Suddenly a terrific thunderclap seemed to shake the whole mountain. The valley was lit up as by a million arc lights, and fantastic reflections danced over the white faces of the scientists. A bolt of flame crashed across the spark gap. For the first time, an eighteen-million-volt thunderbolt had been caught. The scientists had tapped the power of the lightning.

NOW that they know how to obtain voltages infinitely greater than any man-made machine has been able to produce, their dream is to apply the titanic forces to an apparatus like an X-ray tube and see what will happen. The ordinary glass X-ray tube would have to be half a mile long, an impossible constructional feat, to withstand such electrical pressure. But the experimenters have already built a strange tube, less than a dozen feet long, of alternate rings of aluminum, rubber, and paper, that will stand electric forces up to 2,600,000 volts—by a considerable margin the most powerful ever made.

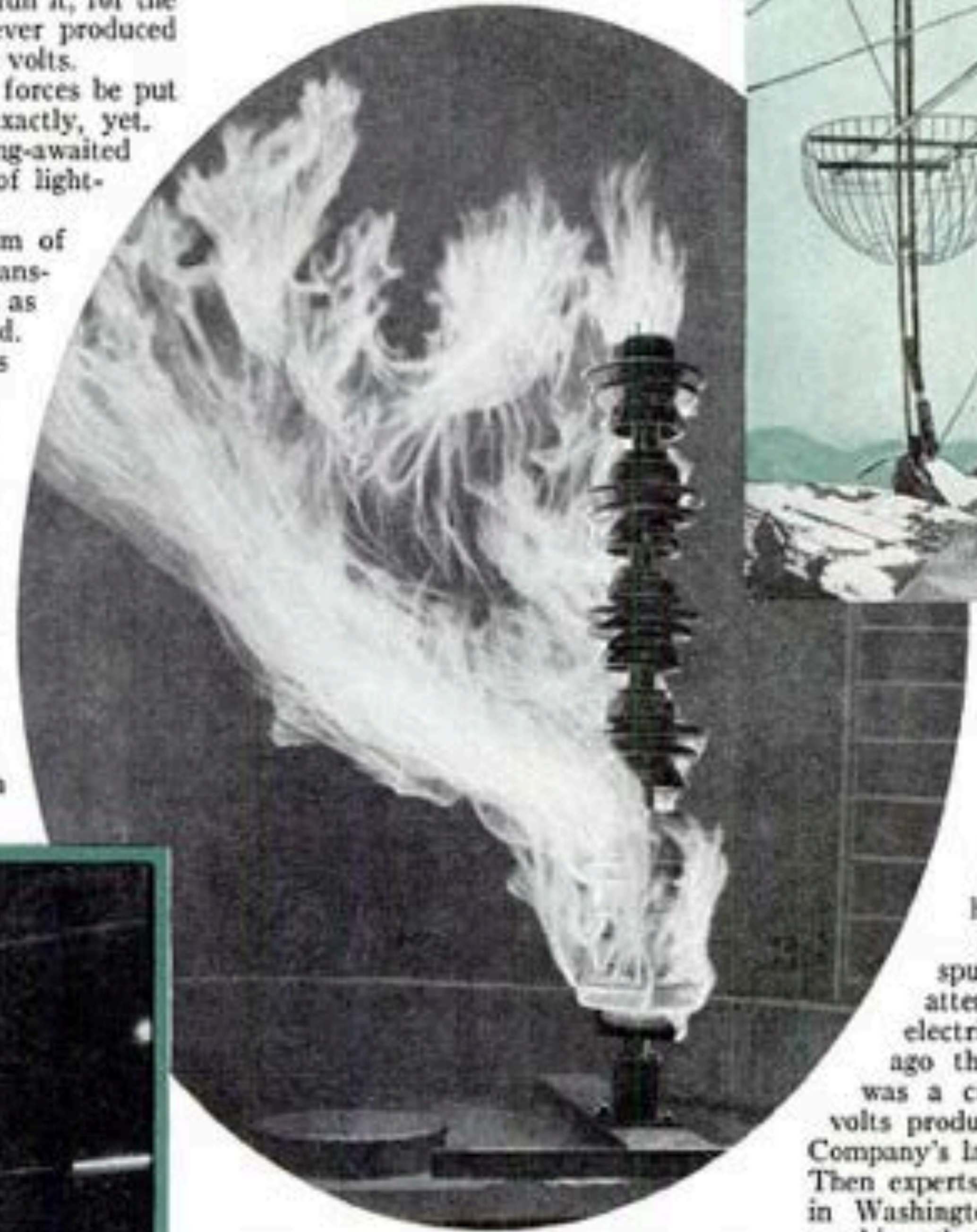
The rays from this tube far exceed in power those of all the radium in the world. They easily penetrate a wall of lead a yard thick, an impassable barrier to all ordinary X-rays. Next the experimenters plan to build a 7,000,000-volt tube of similar

design. Only lightning can run it, for the greatest electrical tension ever produced in a laboratory is 5,000,000 volts.

How can such staggering forces be put to use? No one knows exactly, yet. But there are several long-awaited tests for which the power of lightning may be tried.

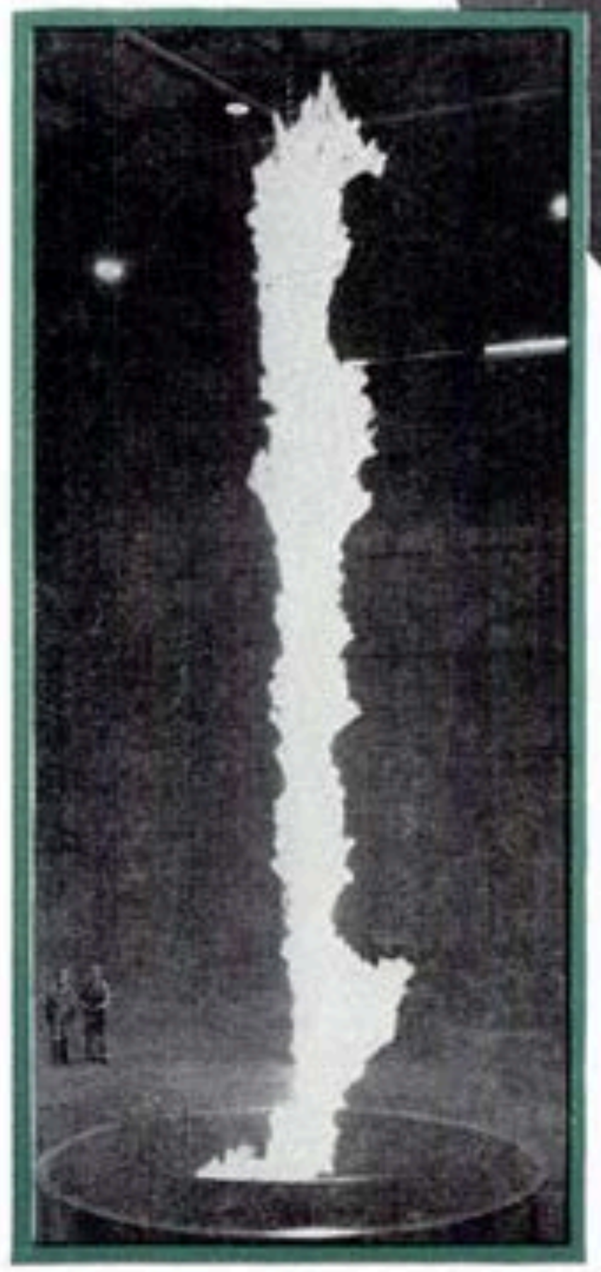
One of these is the dream of alchemists of old—the "transmutation of elements," such as turning base metals into gold. In recent years science has conceded that metals and other substances once held unchangeable can actually be transformed into entirely different ones under certain circumstances, requiring tremendous forces.

So far the only proved cases of transmutation have been done with the mysterious power of radium; thus, minute quantities of aluminum, phosphorus, and other things have been turned into hydrogen. Perhaps lightning's power may permit more useful transformations of other elements, when harnessed in a vacuum tube.



This is not lightning, but a discharge of laboratory electricity leaping from insulators. It shows why extraordinary apparatus is required in harnessing 18,000,000 volts.

Here is part of the apparatus that was used in the Mt. Generoso tests. This strange network was designed to carry the enormous voltage to the laboratory where the scientists waited in danger of instant death.



This 55-foot man-made arc was drawn out in Westinghouse laboratory in recent test.

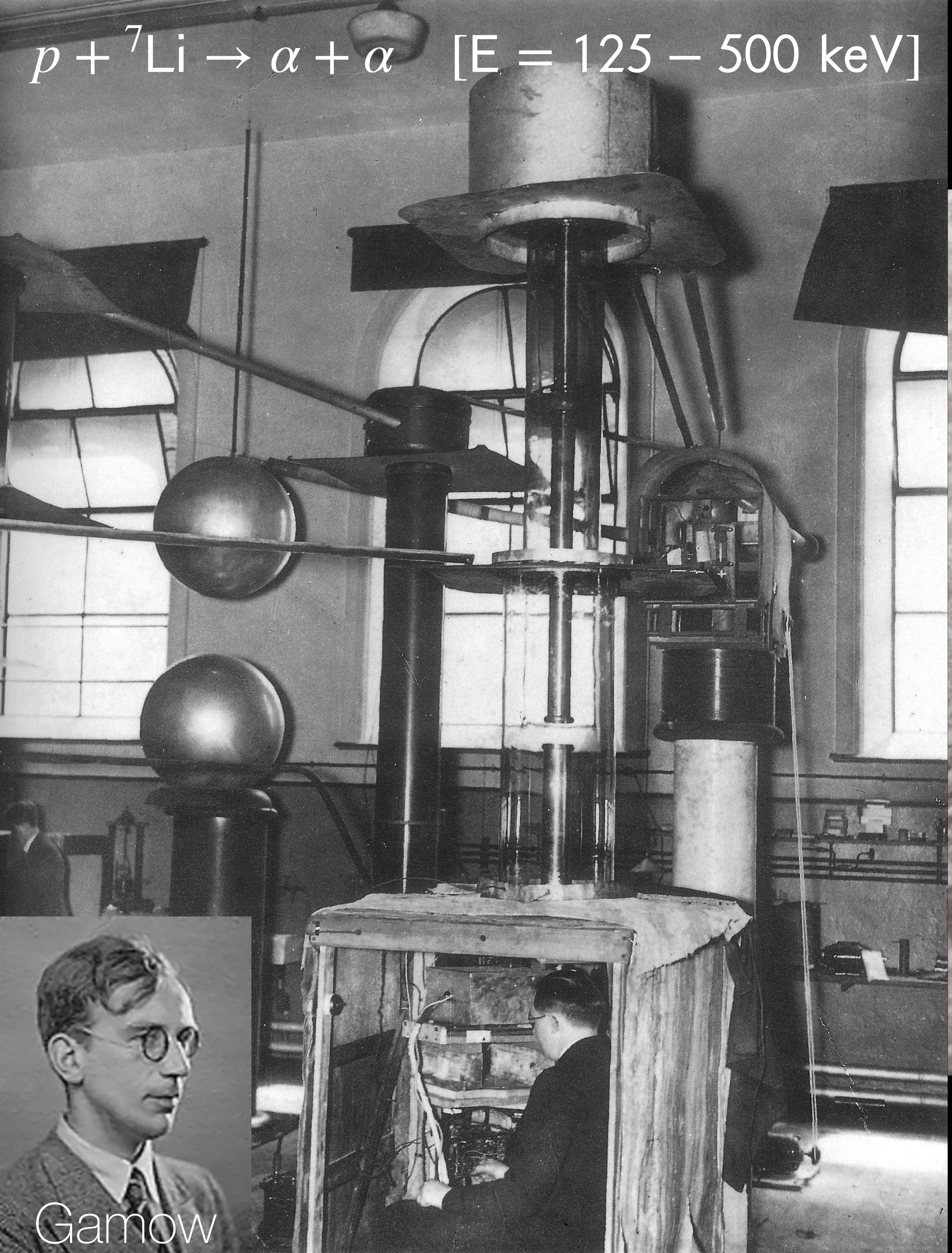
Then there is the question of unlocking the power of the atom. Some scientists hold that the energy contained in a single spoonful of water, for example, is sufficient to drive a modern steamship across the ocean. But this energy, if it does exist, is so securely locked up that no way has yet been found to release it. Should lightning's force break an entrance into this stronghold of power, the world might see a new era of industrial greatness based upon free atomic energy.

LASTLY, the rays from an electric tube operated by lightning's power may well have the most profound effect upon human beings. Whether beneficial or not, it is too early to say. Perhaps the audacious experimenters will find a curative ray more effective against cancer than any instrument hitherto known to science. On the other hand it may be a "death ray."

Such fascinating possibilities spur man's advance in his attempt to harness stupendous electric forces. Only a few years ago the pinnacle of these efforts was a crackling spark of 3,600,000 volts produced at the General Electric Company's laboratory in Pittsfield, Mass. Then experts at the Carnegie Institution in Washington, D. C., built a mighty machine that could command 5,000,000 volts. Meanwhile the German experimenters had already installed a preliminary apparatus on Mt. Generoso, a peak famed for the frequency and violence of its electric storms, and were drawing two-million-volt sparks (P. S. M., Jan. '29, p. 23). A higher, rebuilt antenna made their recent feat possible. One of the experimenters, Dr. Urban, has acquired the sobriquet of "most shocked man in the world" from being knocked unconscious by sky currents.

IT MUST be understood that their antenna is not directly struck by lightning, for if it were, despite an electrical "safety valve" they have provided, they would probably all be killed. The aerial takes current from the clouds in two ways. Electricity in the air itself leaks down the cables in steady sparks. But the greatest voltages are obtained when a lightning bolt passes close to the aerial and a sympathetic surge of electricity is induced in the wire. In this way they have now captured 18,000,000 volts, and even greater voltages, up to thirty million, are in sight!

$p + {}^{7}\mathrm{Li} \rightarrow \alpha + \alpha$ [E = 125 – 500 keV]



Gamow

Walton · Rutherford · Cockcroft (Cambridge, 1932)

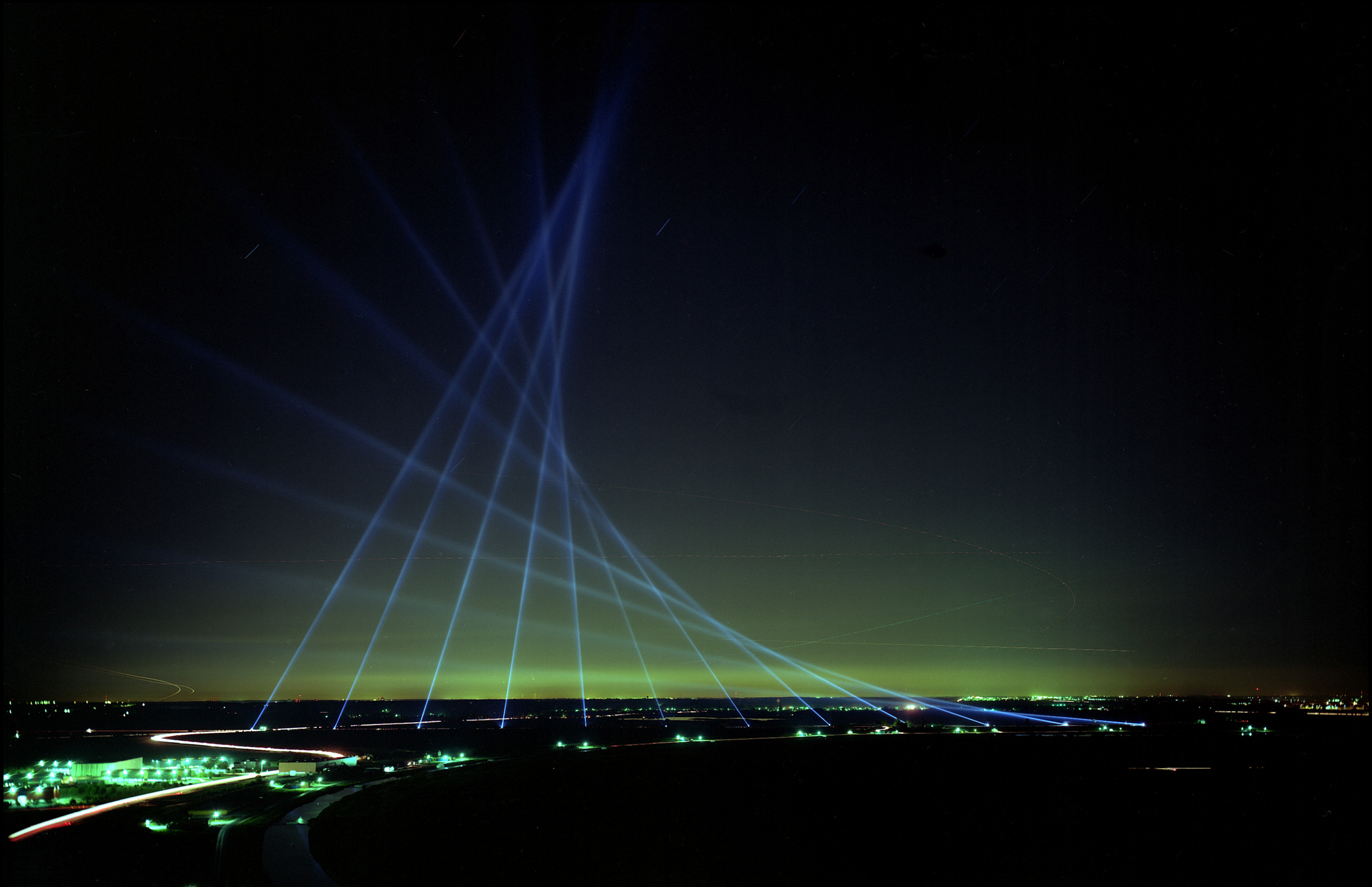
Fermilab's Cockcroft–Walton Machine: 750 keV, 1972–2012

Lawrence & Livingston Cyclotron (Berkeley, 1931–2)

60” cyclotron magnet frame (1938)

16-MeV deuterons from Lawrence’s 60” cyclotron

LIFE, February 5, 1940



Magnets for Giant Cyclotrons Made by Bethlehem

THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
THE CENTRAL ADMINISTRATION

ROBERT M. HUTCHINS · Chancellor
ERNEST CADMAN COLWELL · President
R. W. HARRISON · Vice-President and Dean of Faculties
J. A. CUNNINGHAM · Vice-President
LYNN A. WILLIAMS, JR. · Vice-President

November 5, 1948

Dear Mr. Grace:

The fabrication and erection by your company of the magnet frame for the University's 170" synchrocyclotron has now been completed. Although the synchrocyclotron will not be in operation until early in 1950, the erection of the magnet frame represents a major step toward completion.

The 2070 ton magnet frame was fabricated from low-carbon steel forgings in accordance with our specifications. The magnet is an assembly of some twenty-eight units, weighing up to 81 tons each. Dr. Samuel K. Allison, Director of our Institute for Nuclear Studies, has just advised me that in all of the vital dimensions, the deviations are smaller than 10/1000 of an inch. In view of the fact that such accuracy has been obtained in a length of 250 inches, we are impressed by the mechanical precision achieved.

The representatives of your company have, without exception, been most cooperative and helpful in all phases of the work. We are extremely grateful to you and your associates for the splendid results which have been achieved.

Sincerely yours,

Ernest Cadman Colwell

Ernest Cadman Colwell

E. G. Grace, chairman of Bethlehem Steel, reads letter (reproduced above) acknowledging Bethlehem's part in building the cyclotron for the University of Chicago. Left to right, A. B. Homer, president of Bethlehem Steel; E. C. Colwell, president of the University; Mr. Grace; and Dr. S. K. Allison, Director of Nuclear Studies at Chicago.

BIG ATOM-SMASHERS TO DELVE INTO SECRETS OF NUCLEAR STRUCTURE

Two of the nation's chief scientific and educational institutions, Columbia University and the University of Chicago, both actively engaged in nuclear research, are now constructing laboratories to be used exclusively for such studies. They will have the most powerful cyclotrons, popularly known as atom-smashers, which the world has ever seen. The steel for the 2500-ton magnets for both of these cyclotrons was produced at the Bethlehem plant.

Recent studies of the structure of matter have revealed that enormous forces are locked up in the atoms, or rather the nuclei—the small units from which matter is supposedly built up. These forces, so dramatically demonstrated to a startled world at Hiroshima and Nagasaki, will, when directed into peacetime channels, become a real boon to mankind.

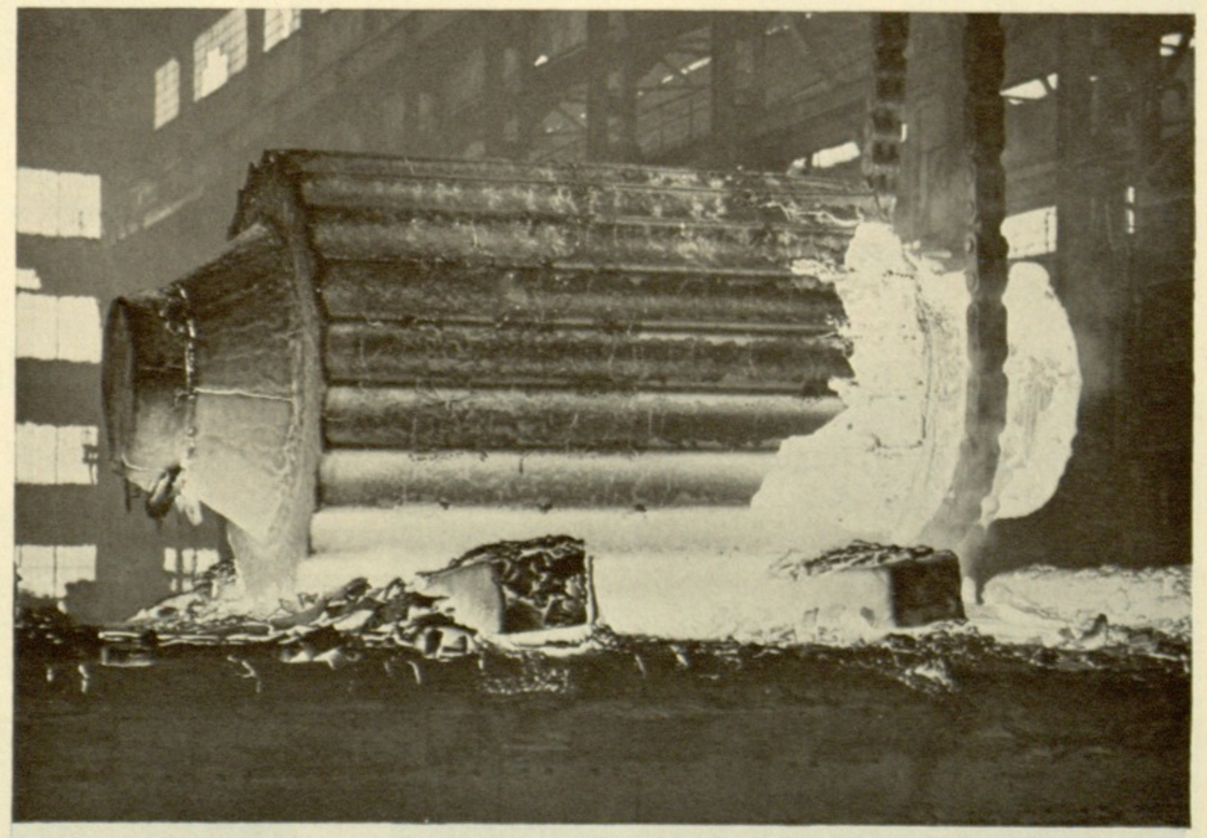
Due to the magnitude of the forces involved, the equipment used in their release must of necessity be massive.

The cyclotrons at the Columbia University and the University of Chicago laboratories are designed to fire protons, which are the bullets used in breaking up the nuclei, at the unprecedented energy of 400,000,000 electron volts, to give the protons a speed of over 150,000 miles per second, very close to that of light.

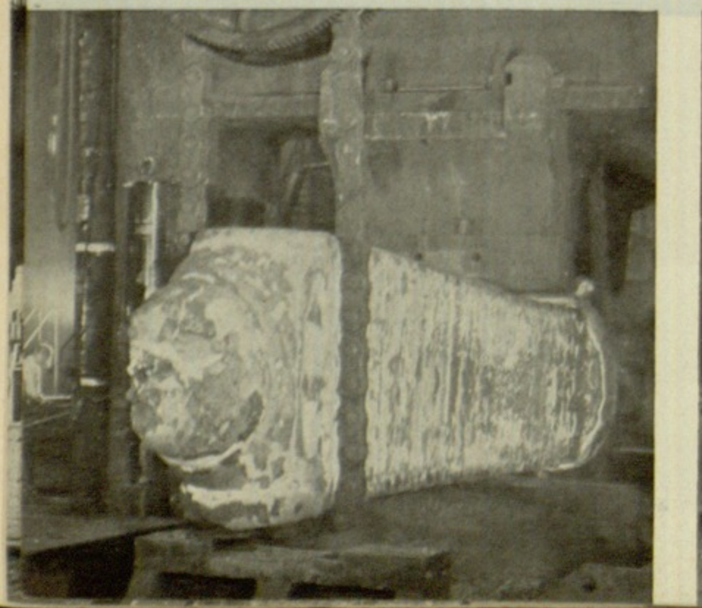
The central part of each of these giant cyclotrons, or synchro-cyclotrons as they are also called, is a huge electro-magnet which weighs about 2500 tons. In fact, each magnet is so big that it was necessary to erect it on the site and then build the laboratory around it. The Columbia magnet, for instance, consists of a rectangular yoke assembly, 33 ft. long, 21 ft. high, and 14 ft. wide, shaped as a window with an opening 22½ ft. x 10½ ft. in which the magnet pole pieces are placed. The University of Chicago magnet is a similar structure.

Bethlehem's contribution to this branch of science in the production of the steel for these magnets was made possible because of the exceptional facilities available at the Bethlehem, Pa., plant and the accumulated experience and skill dating back to the very beginning of the company. These huge magnets cannot be made in one piece, but must be assembled from a number of large sections bolted together to form the yoke and the poles. In the Columbia magnet this assembly is made up of 38 pieces, the largest of which weighs 60 tons. The Chicago unit consists of 28 pieces, the largest of which weighs over 80 tons. Both have a diameter of 170 inches.

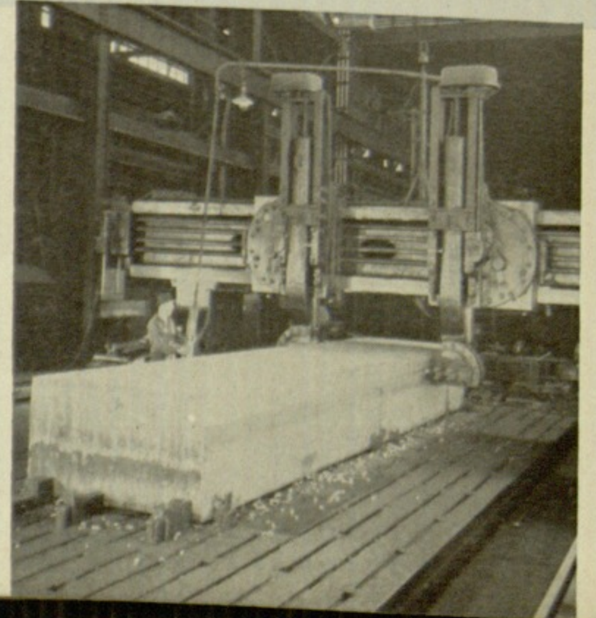
The magnet members were shaped from ingots weighing as much as 465,000 pounds, among the largest ever made.



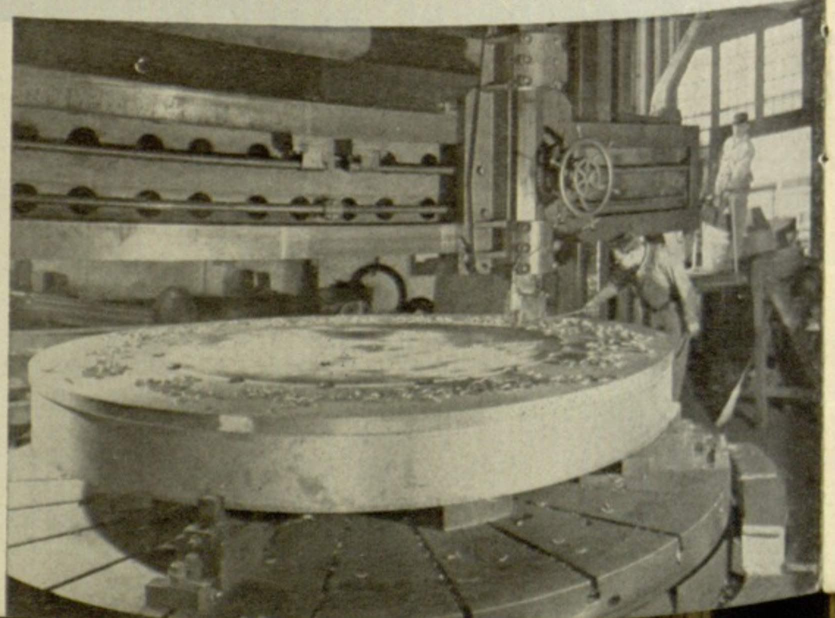
465,000-lb. ingot for the University of Chicago cyclotron.



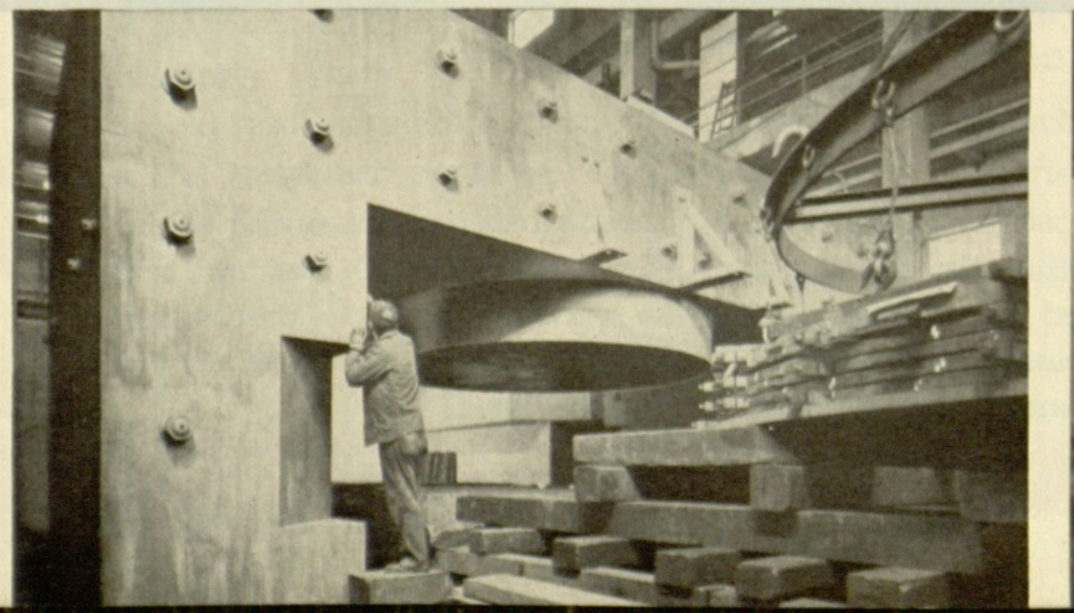
Shaping the ingot on 7500-ton press forge.



Machining a member of the magnet yoke.



Pole pieces are also intricately shaped.



The Chicago cyclotron during erection.

170-inch diameter pole pieces in place.


TRIUMF Cyclotron: 18-m diameter, 520 MeV, 10^{15} *p*/sec
vacuum chamber 46 cm high

Eur. Phys. J. H **36**, 183–201 (2011)
DOI: 10.1140/epjh/e2011-20014-4

THE EUROPEAN PHYSICAL JOURNAL H

The 1953 Cosmic Ray Conference at Bagnères de Bigorre: the Birth of Sub Atomic Physics

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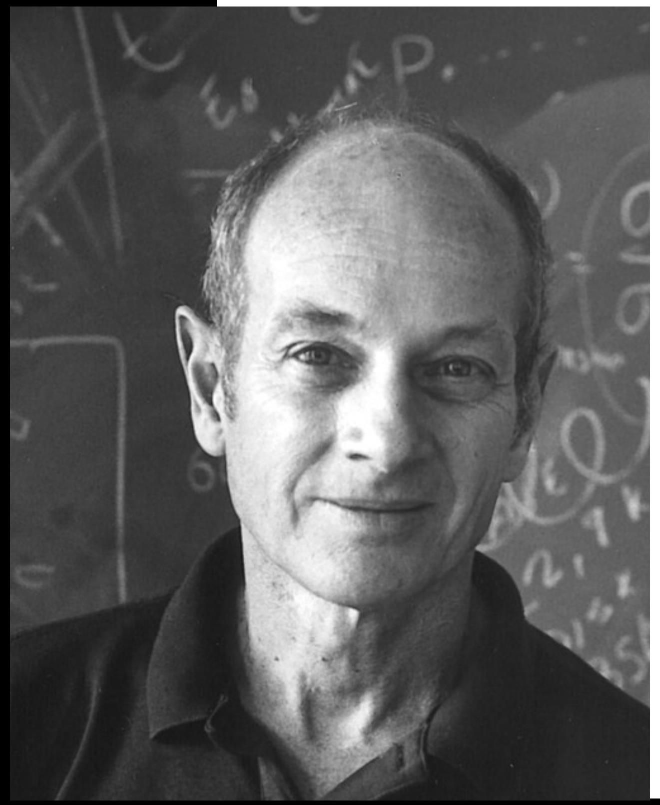
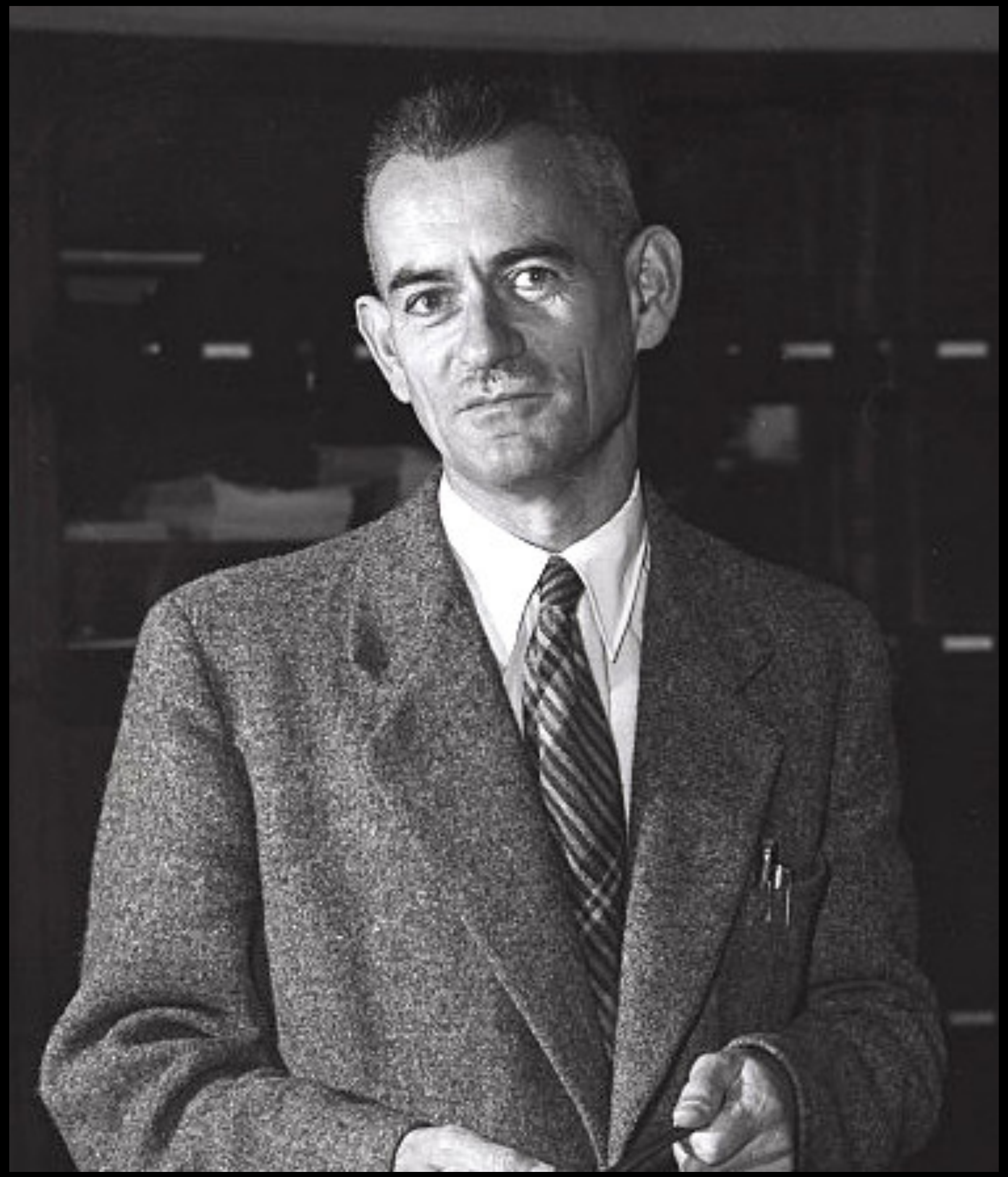
Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, 5640 South Ellis Ave., Chicago, IL 60637, USA



Received 2 March 2011
Published online 29 August 2011

Abstract. The cosmic ray conference at Bagnères de Bigorre in July, 1953 organized by Patrick Blackett and Louis Leprince-Ringuet was a seminal one. It marked the beginning of sub atomic physics and its shift from cosmic ray research to research at the new high energy accelerators. The knowledge of the heavy unstable particles found in the cosmic rays was essentially correct in fact and interpretation and defined the experiments that needed to be carried out with the new accelerators. A large fraction of the physicists who had been using cosmic rays for their research moved to the accelerators. This conference can be placed in importance in the same category as two other famous conferences, the Solvay congress of 1927 and the Shelter Island Conference of 1948.



Louis Leprince-Ringuet
Bagnères-de-Bigorre (1953)
« Mais nous devons aller vite, nous devons courir sans ralentir notre cadence : nous sommes poursuivis … nous sommes poursuivis par les machines ! »

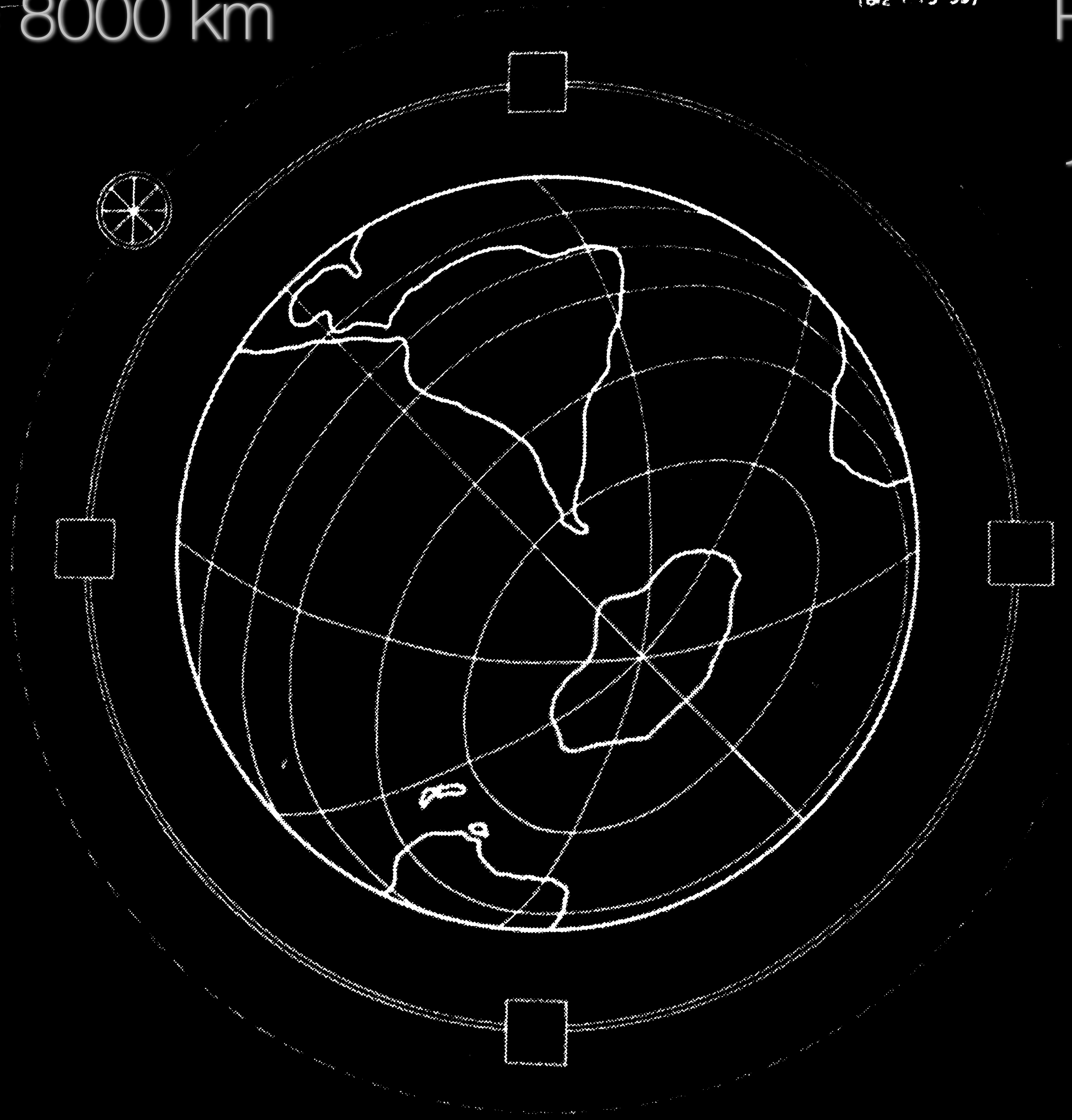
Phase stability (Veksler–McMillan) ↪ Synchrotrons

Brookhaven Cosmotron, 3+ GeV (1952–4)

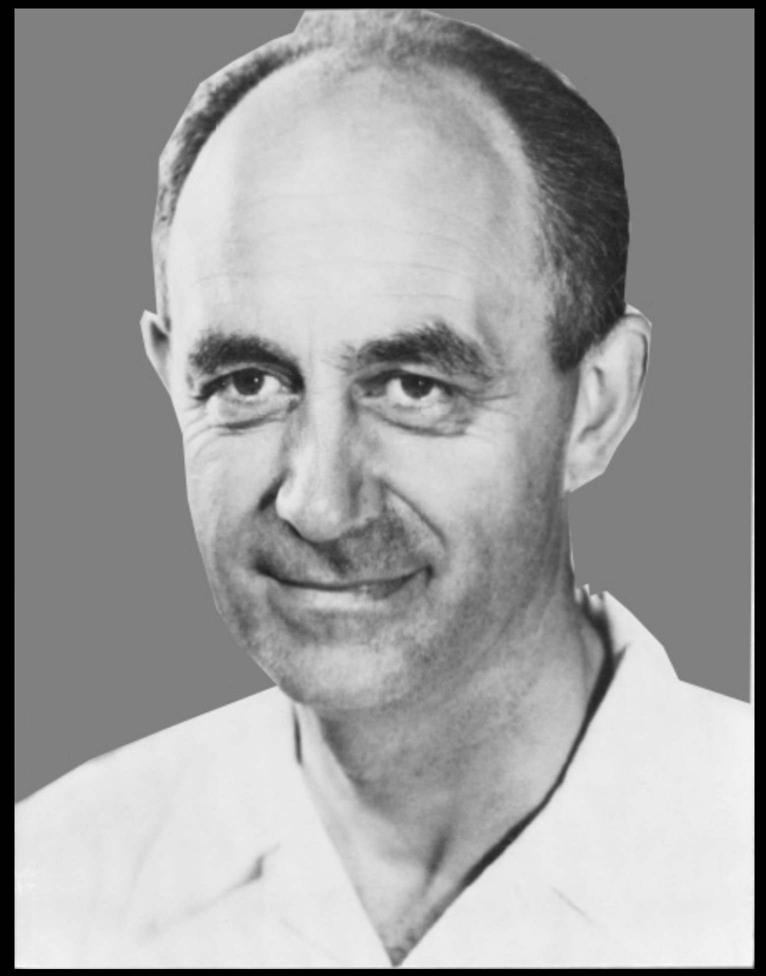
Berkeley Bevatron, 6.2 GeV (1954)

Fermi's Dream Machine (1954): 5000-TeV $p \sim E_{cm}$ = 3 TeV

2-tesla magnets at radius ≈ 8000 km



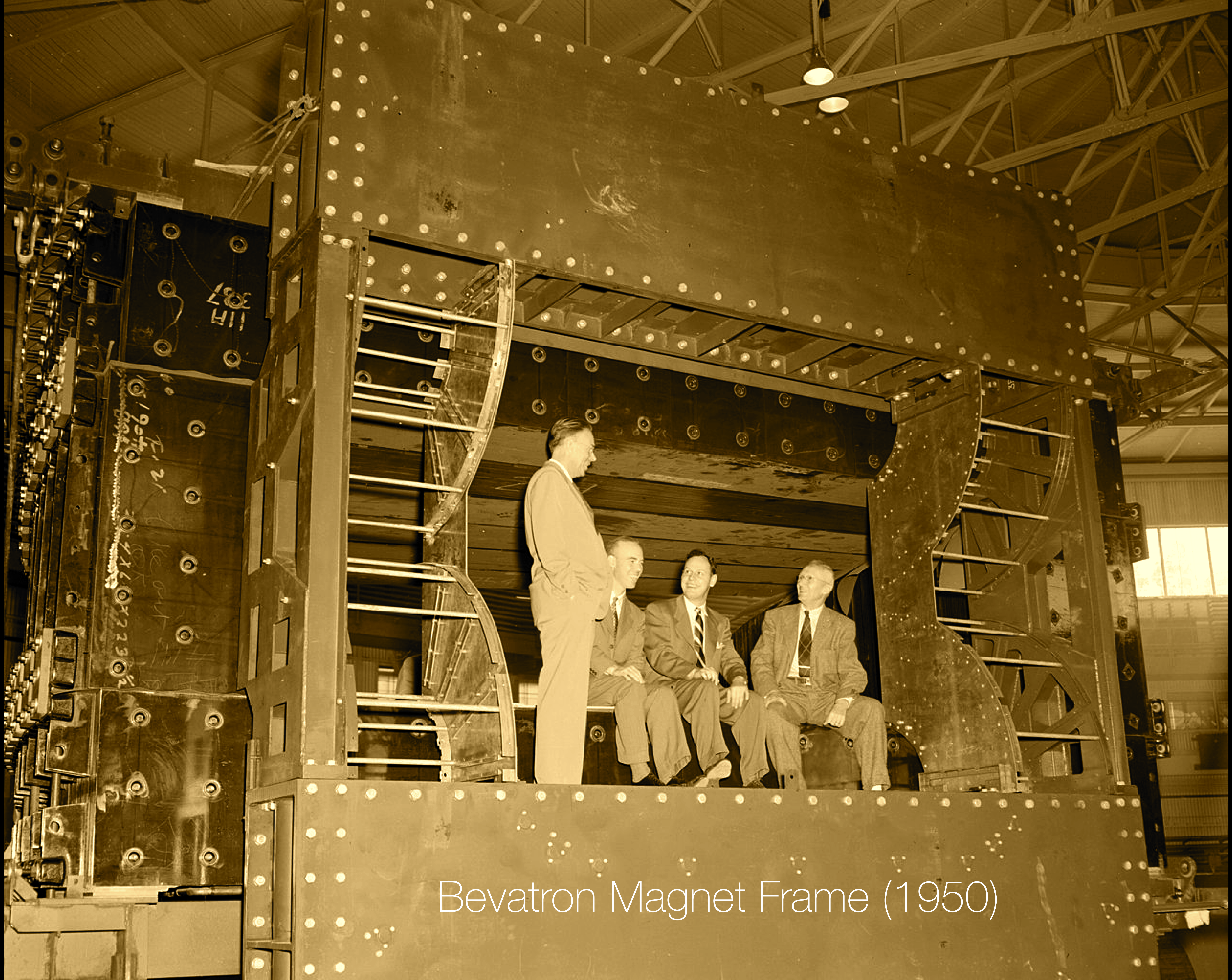
Projected operation 1994
cost $170 Billion
1954 inflation rate 0.75%



Why must accelerators be so large?

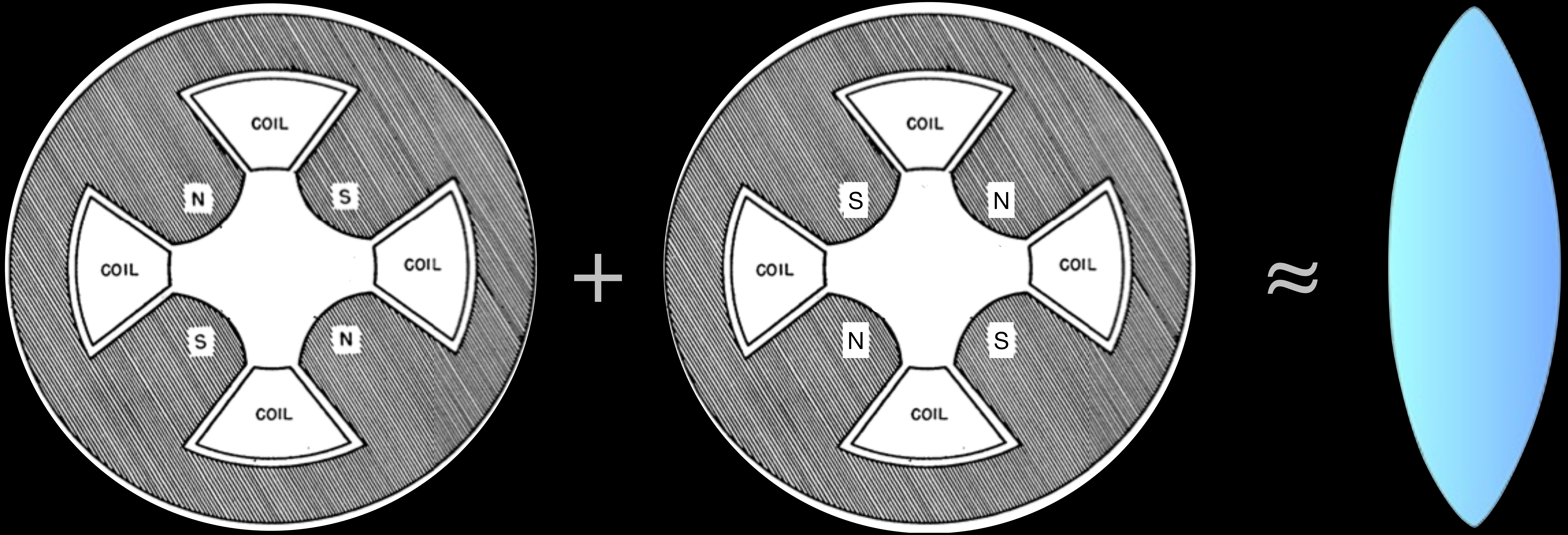
$$\text{radius} \approx \frac{10\ \text{km}}{3} \cdot \left(\frac{\text{Energy}}{1\ \text{TeV}}\right) \Big/ \left(\frac{\text{Magnetic Field}}{1\ \text{tesla}}\right)$$

+ aperture to contain unruly beam



Bevatron Magnet Frame (1950)

Alternating-gradient (strong) focusing



Christofilos (Athens, 1949)
Courant, Livingston, Snyder (Brookhaven, 1952)

Impact of alternating-gradient (strong) focusing

Synchrotron (circumference, *E*)	Beam Tube	Magnet Size
Cosmotron (230 ft, 3 GeV)	9 in x 3 ft	8 ft x 8 ft
Bevatron (400 ft, 6.2 GeV)	1 ft × 4 ft	9-1/2 ft × 20-1/2 ft
Brookhaven AGS (0.5 mi, 30 GeV)	2.7 in × 6 in	33 in × 39 in
Fermilab Main Ring (2π km, 400 GeV)	2 in × 4 in	14 in × 25 in
Fermilab Tevatron (≈ 1 TeV)	70 mm	4.3 T (SC, 4.2 K)
CERN LHC (27 km, → 7 TeV)	56 mm	8.3 T (SC, 1.3 K)

Main Ring volume under vacuum < Bevatron

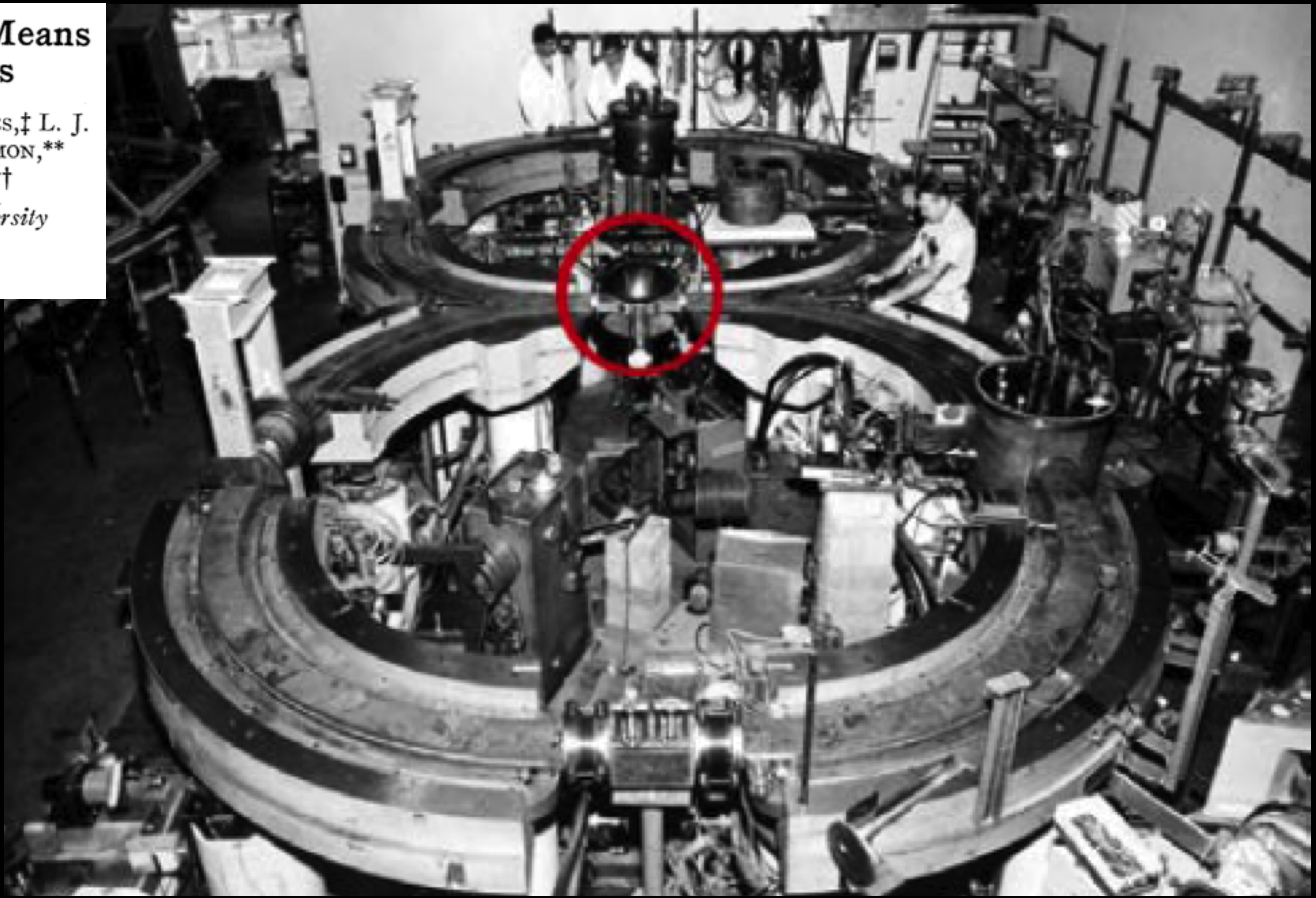
NYT, March 11, 1965: "Atom-Smasher Test Shows Way to Save on Energy"

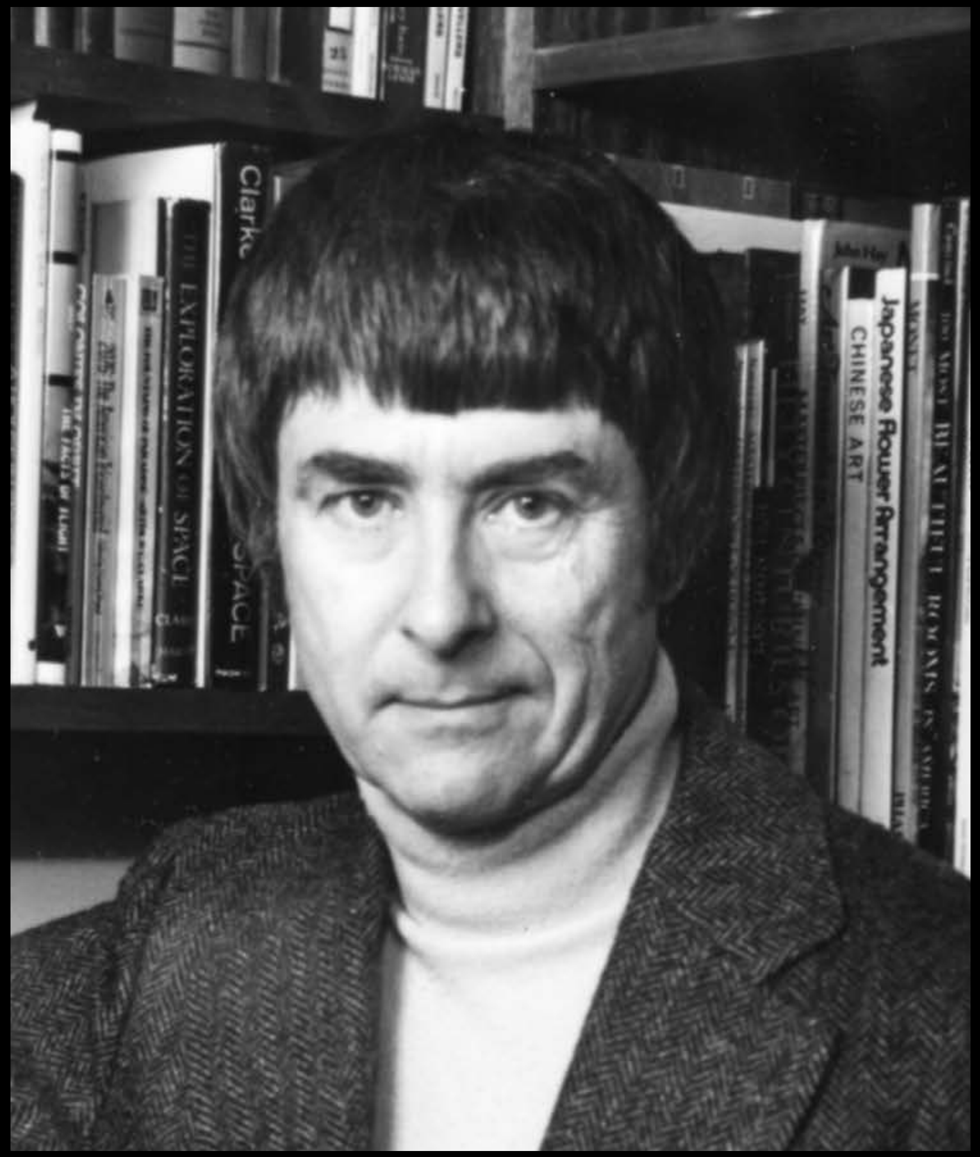
Attainment of Very High Energy by Means of Intersecting Beams of Particles

D. W. Kerst,* F. T. Cole,† H. R. Crane,‡ L. W. Jones,‡ L. J. Laslett,§ T. Ohkawa,‖ A. M. Sessler,¶ K. R. Symon,** K. M. Terwilliger,‡ and Nils Vogt Nilsen††

Midwestern Universities Research Association,‡‡ University of Illinois, Champaign, Illinois

(Received January 23, 1956)





O'Neill (1956)
25⊗25-GeV *pp*
~1.3 TeV fixed target

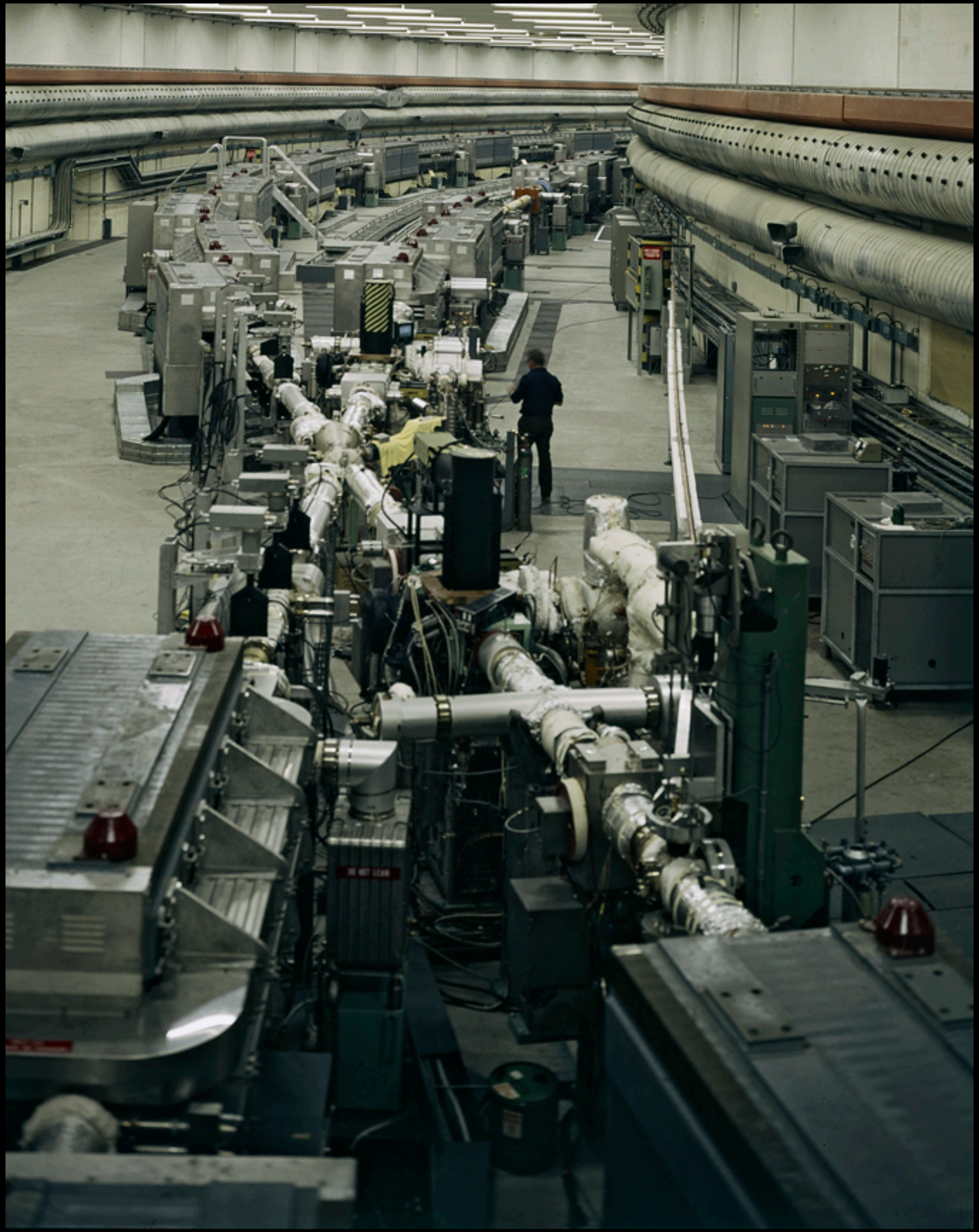
Carl Barber, Bernard Gittelman, G. K. O'Neill, Burton Richter: CBX

300-MeV electrons in collision ⇒ 350 GeV fixed-target

CERN Intersecting Storage Rings (1971)—Kjell Johnsen:
"the finest instrument one can imagine for research in accelerator physics"

0.3π km circumference
two independent rings
1.33-T dipoles
pp @ E_{cm} → 62 GeV
~ 2 TeV fixed-target
millions events/sec

also stored d, α, $\bar{p}$

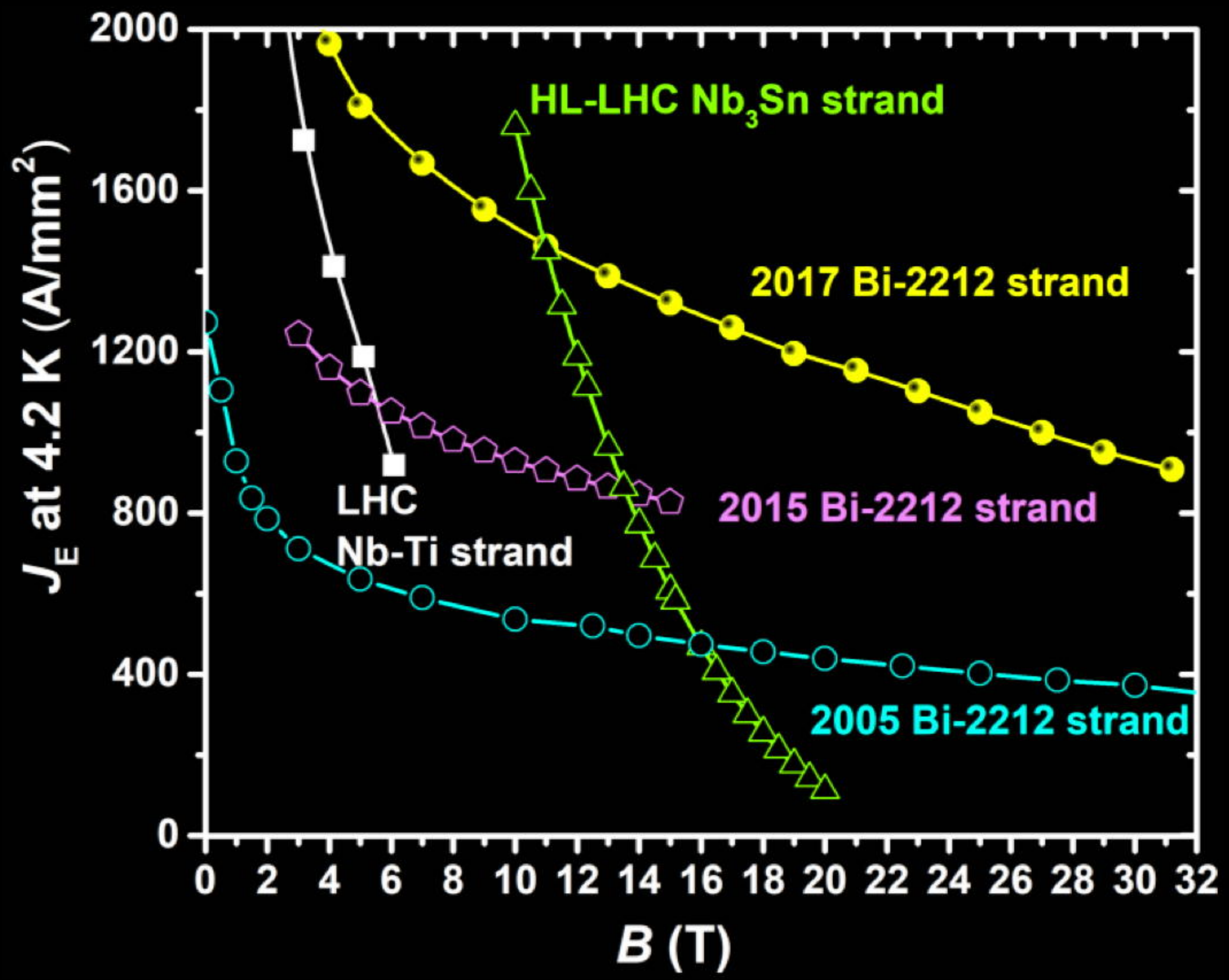


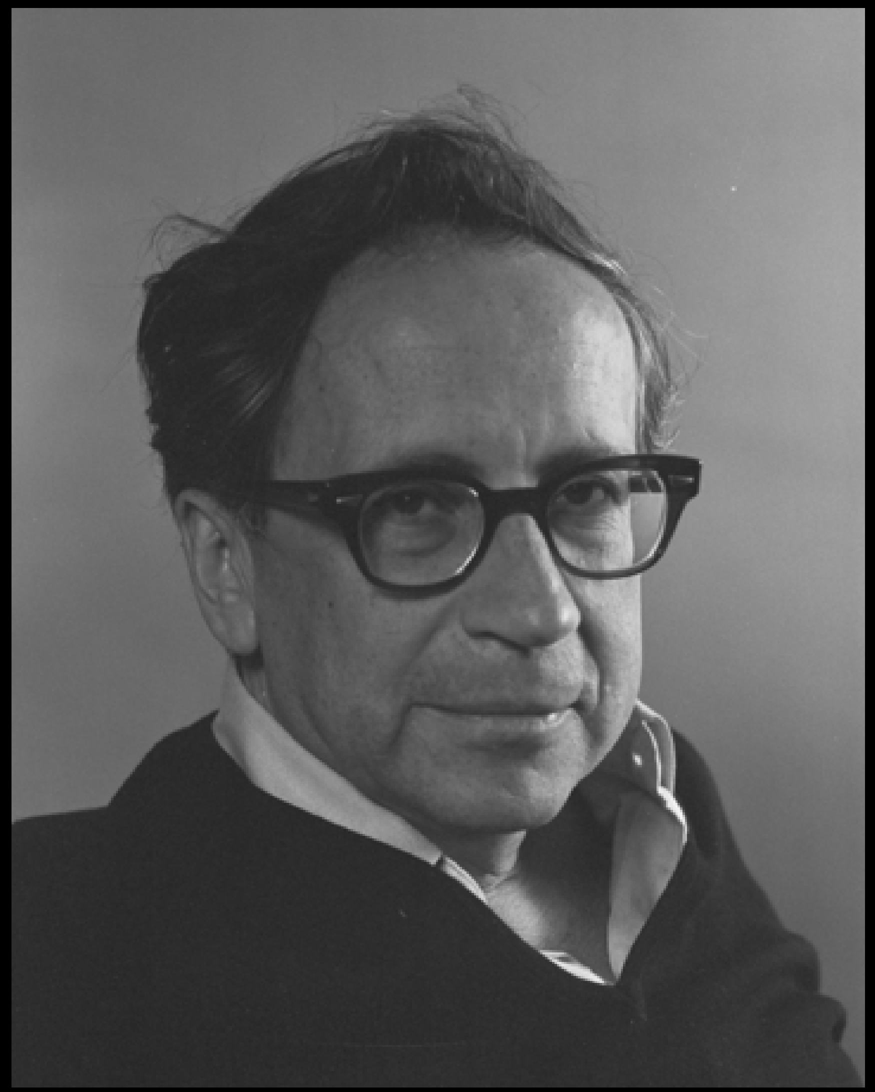
Underinstrumented!
discovered rising σ_t
CERN–Rome,
Pisa–Stony Brook

hints of *qq* scattering
Missed J/ψ, Υ
A learning experience

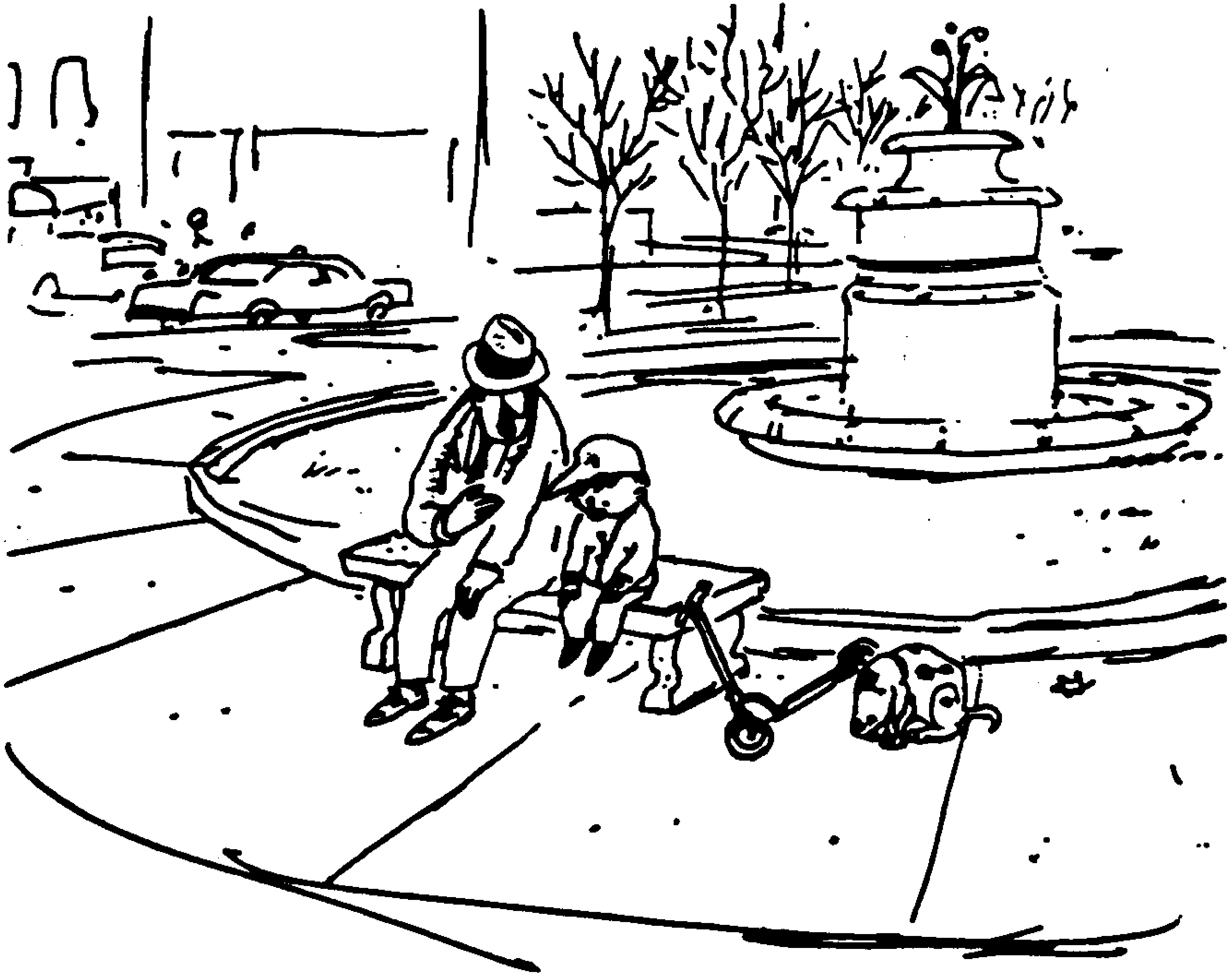
Superconducting accelerator magnets based on Type-II superconductors

John Hulm





Bernd Matthias



"Yep, with them new superconductors, they built that little SSC ring right there beneath your feet"

How can accelerators be so small?

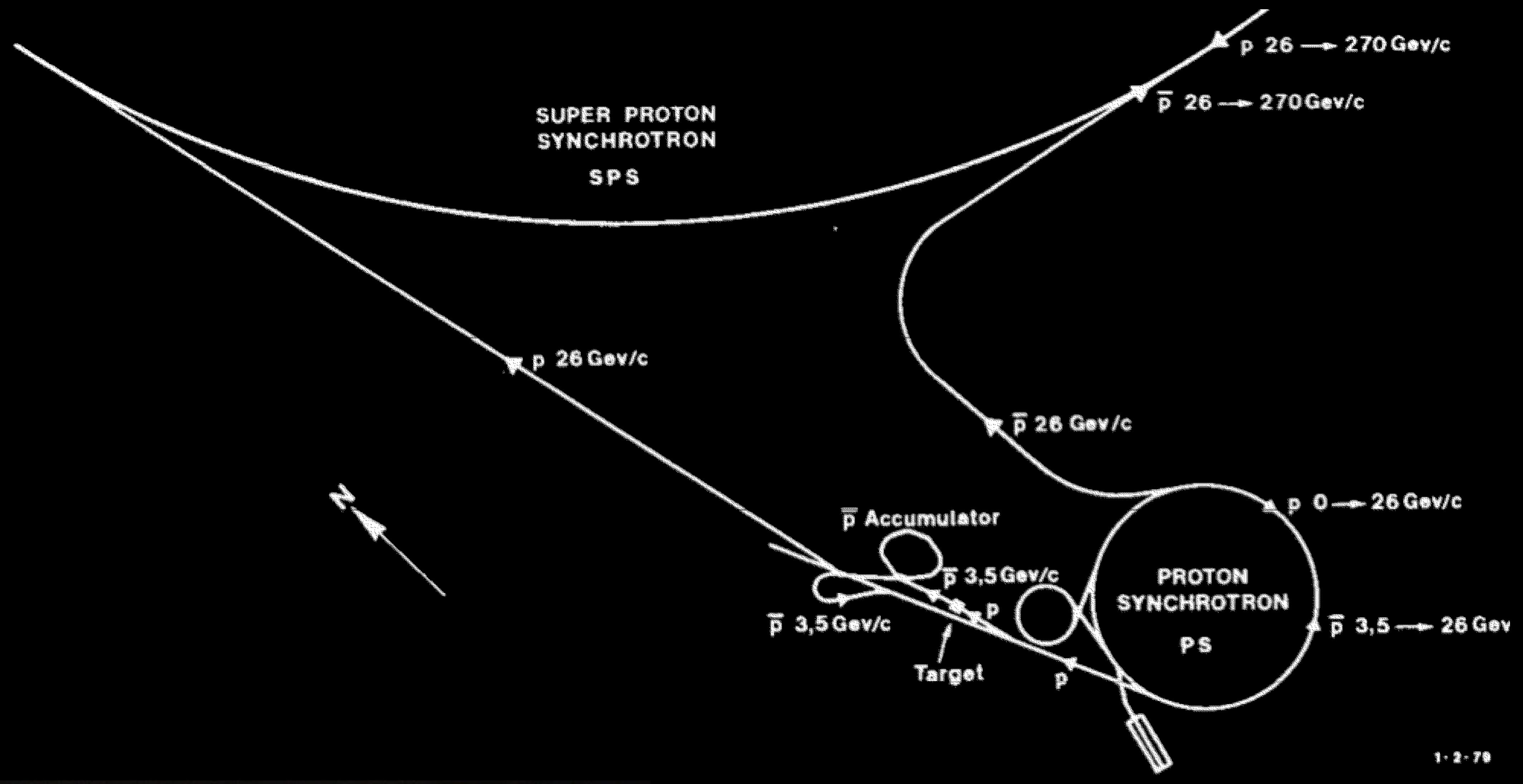
Development of large-scale cryogenic technology,
to maintain many km of magnets at a few kelvins.

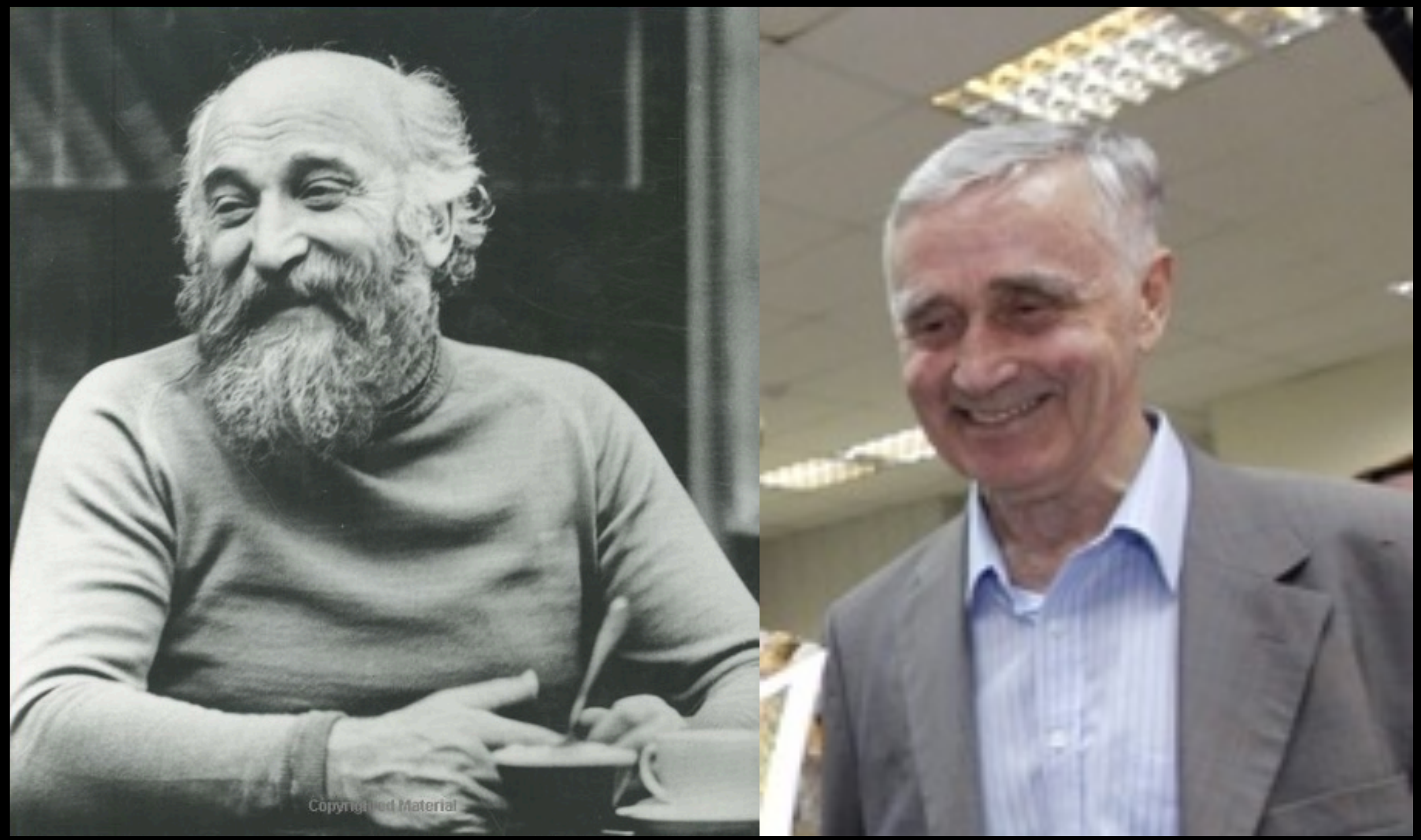
Active optics to achieve real-time corrections of orbits
enables reliable, highly tuned accelerators with small-aperture magnets.
Also “cooling,” or phase-space compaction, of stored (anti)protons.

Evolution of vacuum technology.
Beams stored for approximately 20 hours travel
~ 2×10^{10} km, about 150 times the Earth–Sun distance,
without encountering a stray air molecule. LHC: 10^{-13} atm.

Improvements in accelerating gradient
through efficient (superconducting) RF cavities

Simon van der Meer, Carlo Rubbia: *Sp$\bar{p}$S* Collider (1981)





G. I. Budker, A. N. Skrinsky (Novosibirsk, 1970s)

UA1: $Z^0 \rightarrow e^+e^-$


Tevatron proton-antiproton collider
CDF
D0


0745

WH15E

Tevatron Collider Pioneers

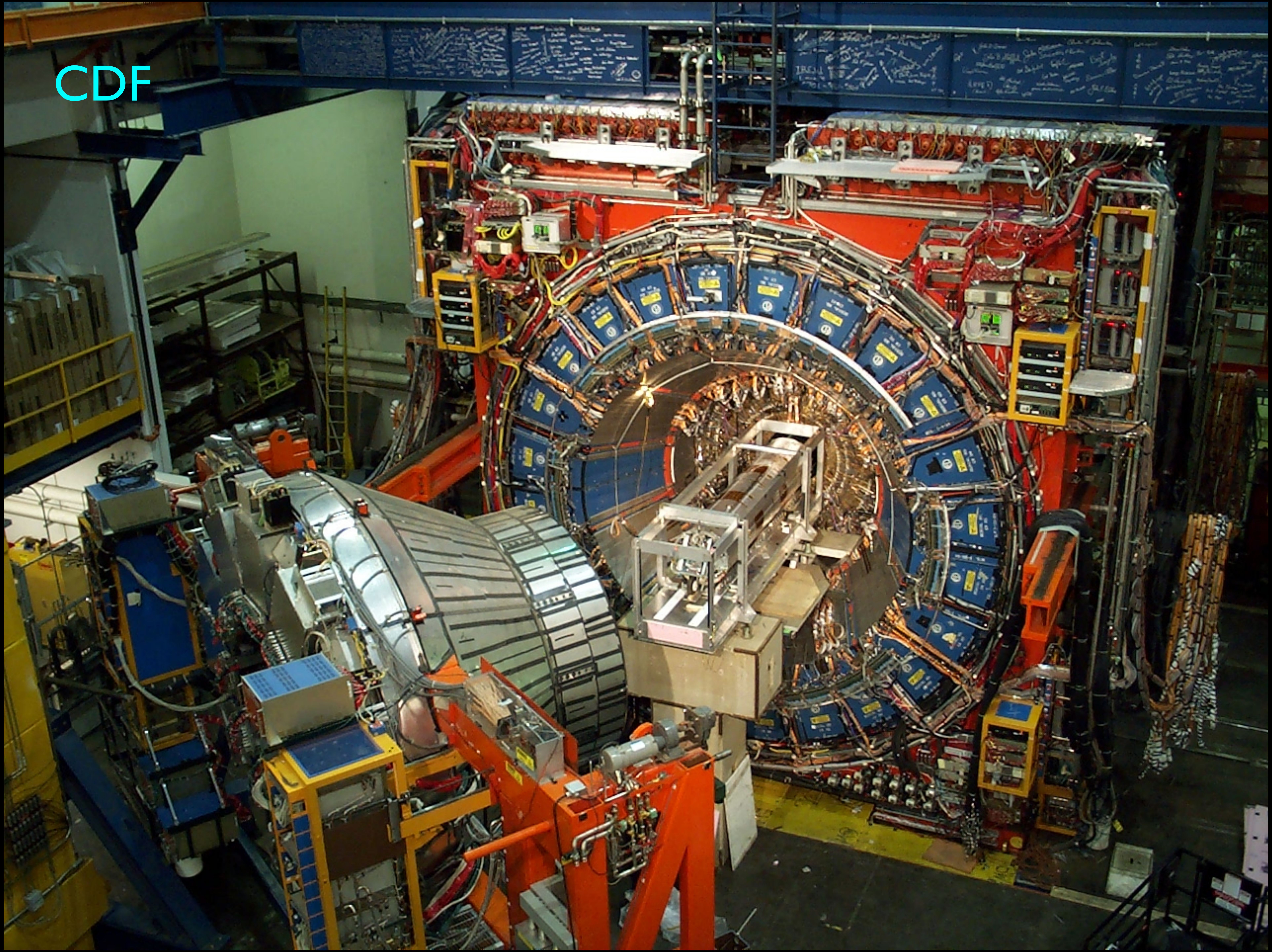
Alvin Tollestrup (Magnets)

Helen Edwards (Machine)

John Peoples (Antiprotons)


DIPOLE
QUADRUPOLE


P
$\bar{P}$
NO
FISHING IN
MAIN RING
PARKING


CDF

315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

By MALCOLM W. BROWNE

THREE HUNDRED AND FIFTEEN physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

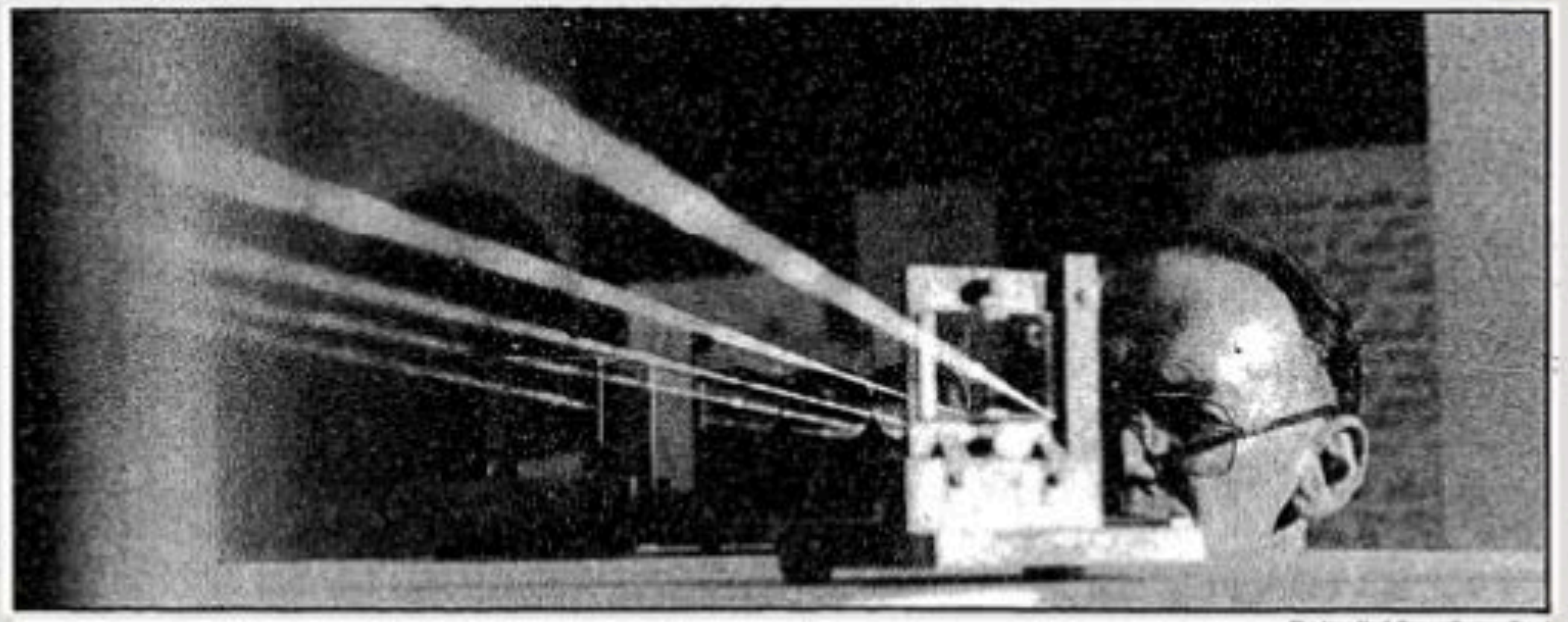
But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

NYT, January 5, 1993

In Centennial of One of Its Biggest Failures, Science Rejoices

Clark University Archives / Case Western Reserve University Archives

Albert A. Michelson (left) and Edward W. Morley.



The New York Times/Barney Taxel

Prof. Donald E. Schuele with a replica of the 1887 interferometer at Case Western Reserve University. It uses a laser beam.

By MALCOLM W. BROWNE

ONE hundred years ago this month, two experimenters in an Ohio basement gently rotated a carousel of mirrors floating in a tub of mercury and inadvertently smashed the reassuring vision of a clockwork cosmos that had prevailed since the time of Sir Isaac Newton.

Physicists and philosophers have anguished over the experiment ever since, but one by one, nearly all have been compelled to abandon cherished theory in the face of its evidence.

The experimenters, Albert Abraham Michelson and Edward William Morley, set out to prove the existence of "ether" — an intangible and invisible fluid thought by most 19th-century scientists to permeate the entire universe. Michelson and Morley expected to demonstrate that ether speeded or slowed light waves; if this were the case, the ether would represent a universal standard against which the positions and motions of everything in the universe could be measured.

Much to their consternation, they failed. But their failure was pivotal. A new generation of scientists, struggling to explain the shocking experiment, eventually demonstrated that nothing in the universe has absolute reality, and that causality itself ceases to operate at the microscopic level of existence.

The experiment was critical to Einstein's revolutionary contention that there is no such thing as a universal yardstick for space and time. So last week, scientists, educators and artists gathered in Cleveland to begin a six-month observance of what many scientists regard as science's most crucial failure.

"I think it was the most important experiment ever performed," said Dr. Philip L. Taylor, an organizer of the centennial. "If Michelson and Morley had obtained a different result, our whole view of space and time today would have been different."

"It came at a time of transition from a period when science was dominated by wealthy amateurs to the era of true scientific professionals," added Dr. Taylor, a professor of physics at Case Western Reserve University in Cleveland. "Michelson, one of the first of these professionals, was also the first American to win a Nobel prize, in 1907, for scientific achievement." (Only one other American, Theodore Roosevelt, had won a Nobel prize in any category. President Roosevelt received the peace prize in 1906.)

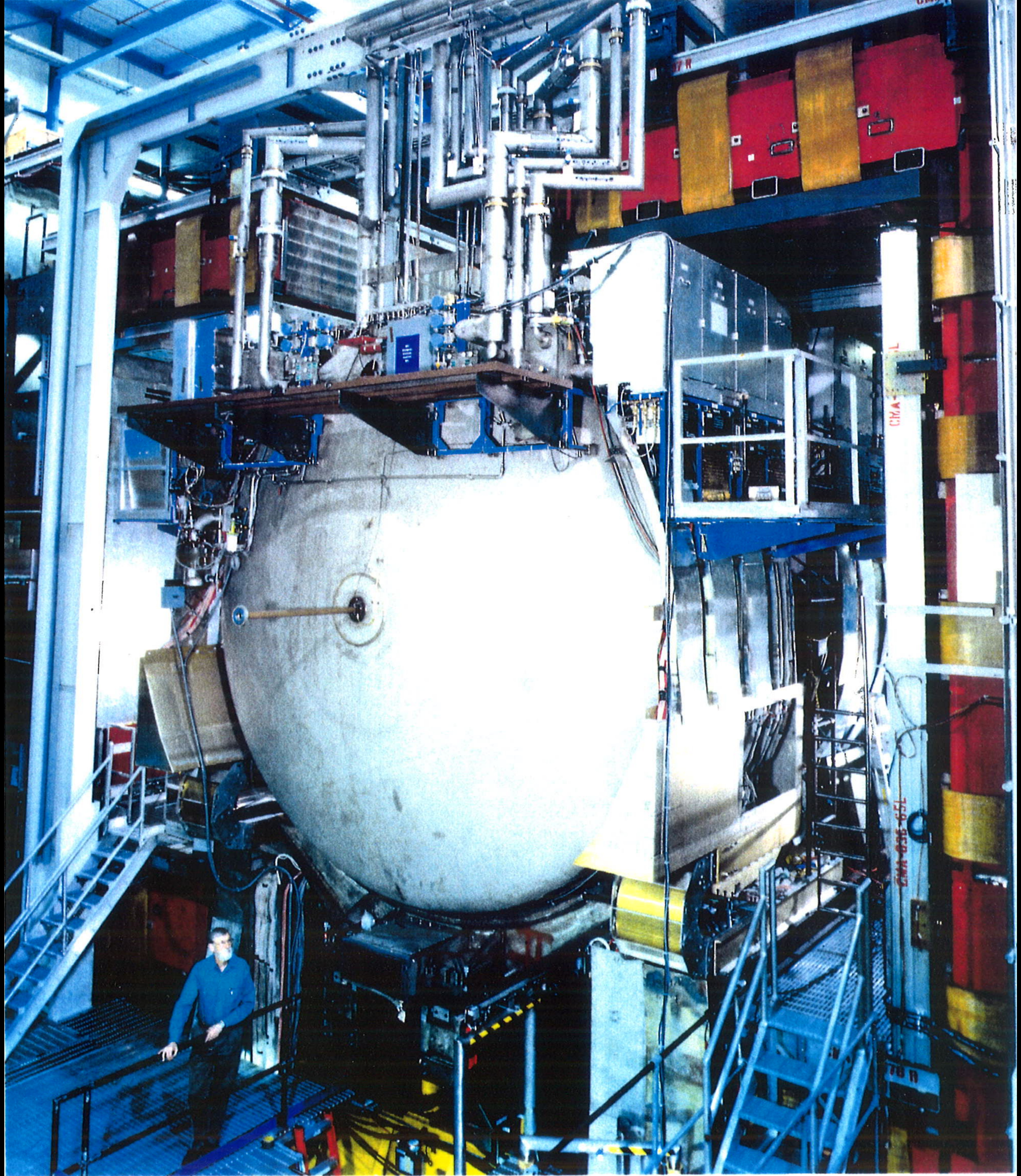
Dr. Taylor said the experiment marked "the birth of modern physics in America." But Michelson and Morley themselves were deeply troubled by its implications, and never fully accepted the radical interpretation developed for it by Einstein and other leading theorists.

Many experimenters before Michelson and Morley had demonstrated that light behaves in some ways like the waves that traverse bodies of water or the sound waves that travel through air. Reasoning by analogy,

Continued on Page C3

NYT, April 28, 1987

D0



Diverse searches for new phenomena

Limits on

supersymmetric particles

extra spatial dimensions

signs of new strong dynamics

leptoquarks

new gauge bosons

magnetic monopoles

. . .

Tevatron experiments did not find

what is not there!

CDF/D0 (1995)
top quark:
mass ≈ 173 GeV ≈ 186 u
lifetime ≈ 0.4 ys

The Tevatron Collider Physics Legacy

Paul D. Grannis[1] and Melvyn J. Shochet[2]

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Keywords

Tevatron, CDF, D0

Abstract

The proton–antiproton Tevatron Collider at Fermilab began physics operation in 1988, and by its shutdown in 2011 it had delivered more than 10 fb^{-1} of data to the two general-purpose detectors CDF and D0. Thus far, these experiments have published more than 800 papers studying the character of the strong nuclear force, measuring the properties of hadrons containing heavy quarks, elucidating the nature of the electroweak force, discovering and measuring the properties of the top quark, seeking evidence for the Higgs boson, and searching for new phenomena beyond the standard paradigm of particle physics. We summarize the results that define the physics legacy of the Tevatron program.

Contents

1. INTRODUCTION

The Tevatron was conceived in the early 1970s to double the beam energy of the original Fermilab Main Ring accelerator to approximately 1 TeV through the first use of superconducting magnets in an accelerator (1). Beams were commissioned in 1983. The proposal for a $p\bar{p}$ collider in 1976 (2) provided antiprotons from interactions between Main Ring protons in a heavy-metal target and antiproton accumulation rings employing stochastic cooling that could supply nearly 10^{11} antiprotons per hour. The antiprotons would be accelerated and stored in the same Tevatron magnet ring as the protons and brought into collision at up to six interaction regions. The first

Tevatron Collider Highlights beyond the Top Quark

CP violation in *B* mesons
Mesons with beauty and charm
Heavy-baryon spectroscopy
Higgs-boson searches

Hadron collider makes precision measurements!
Jets; *W*, *Z*, properties; B_s–$\bar{B}_s$ oscillation frequency

Global experimental collaborations

The Tevatron (1983–) gave us courage to think bigger

Thought experiment (1977) considering *WW* scattering had revealed

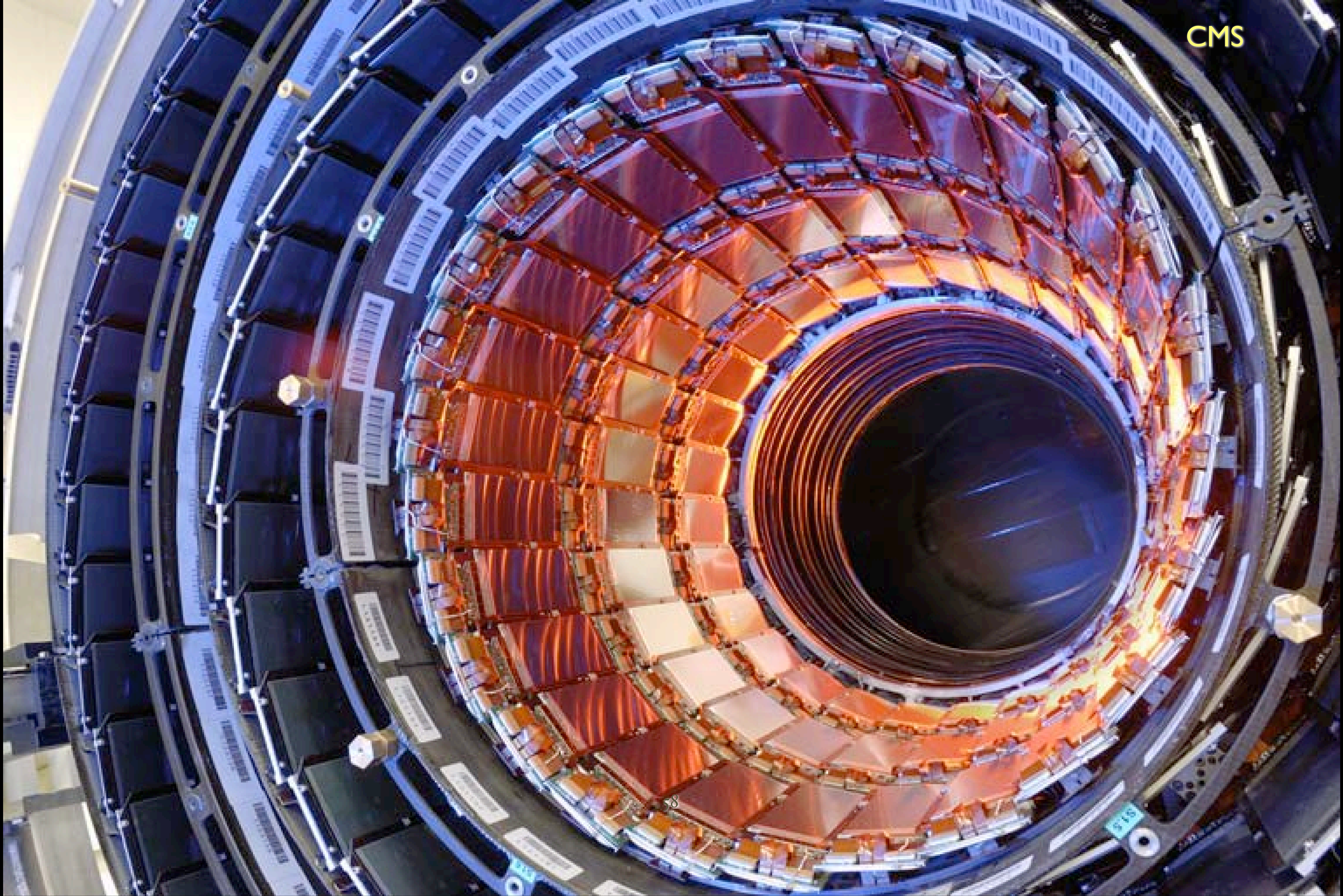
$$\left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} \approx 1\ \text{TeV}$$

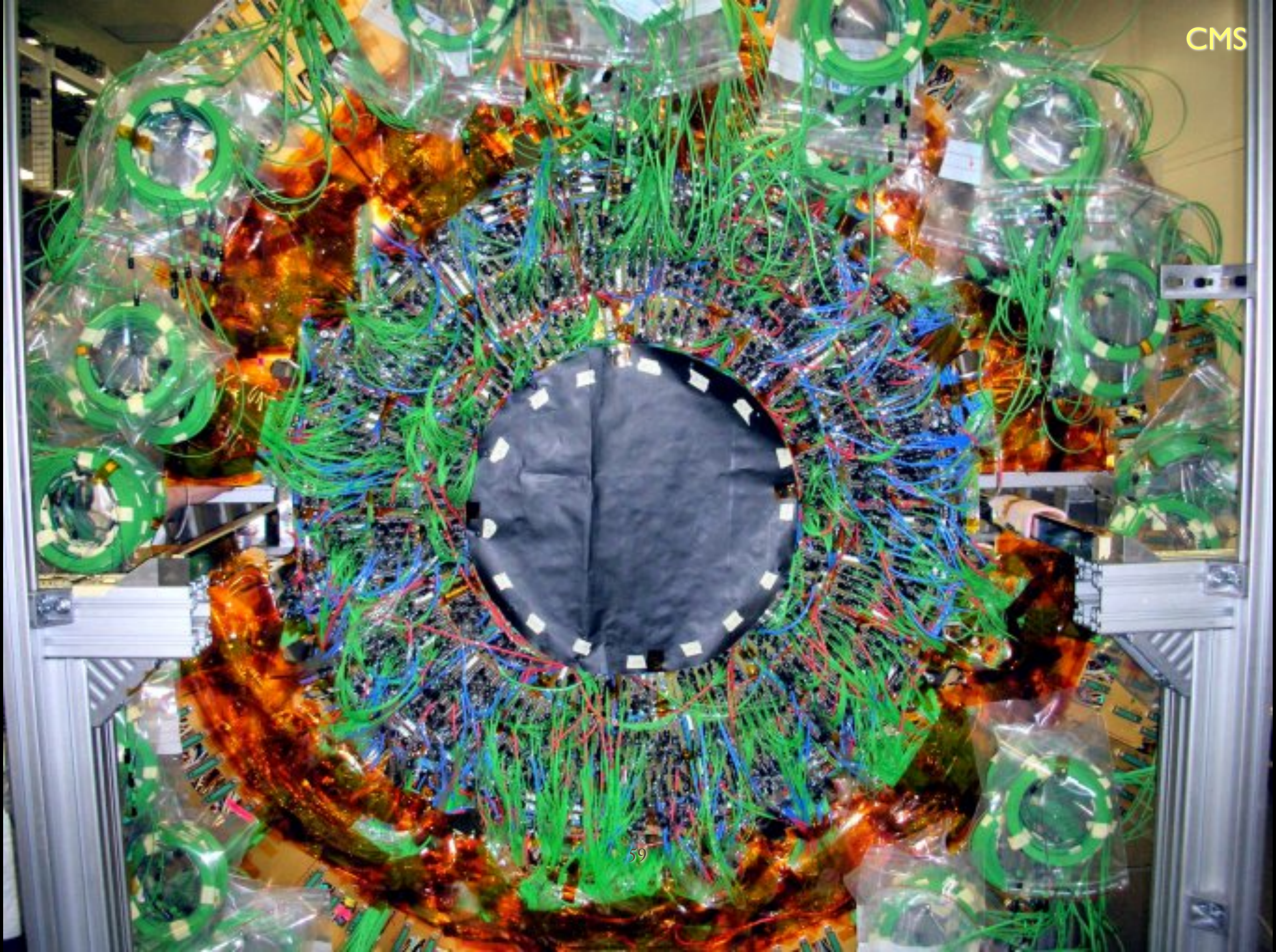
energy scale to discover the mechanism
of electroweak symmetry breaking

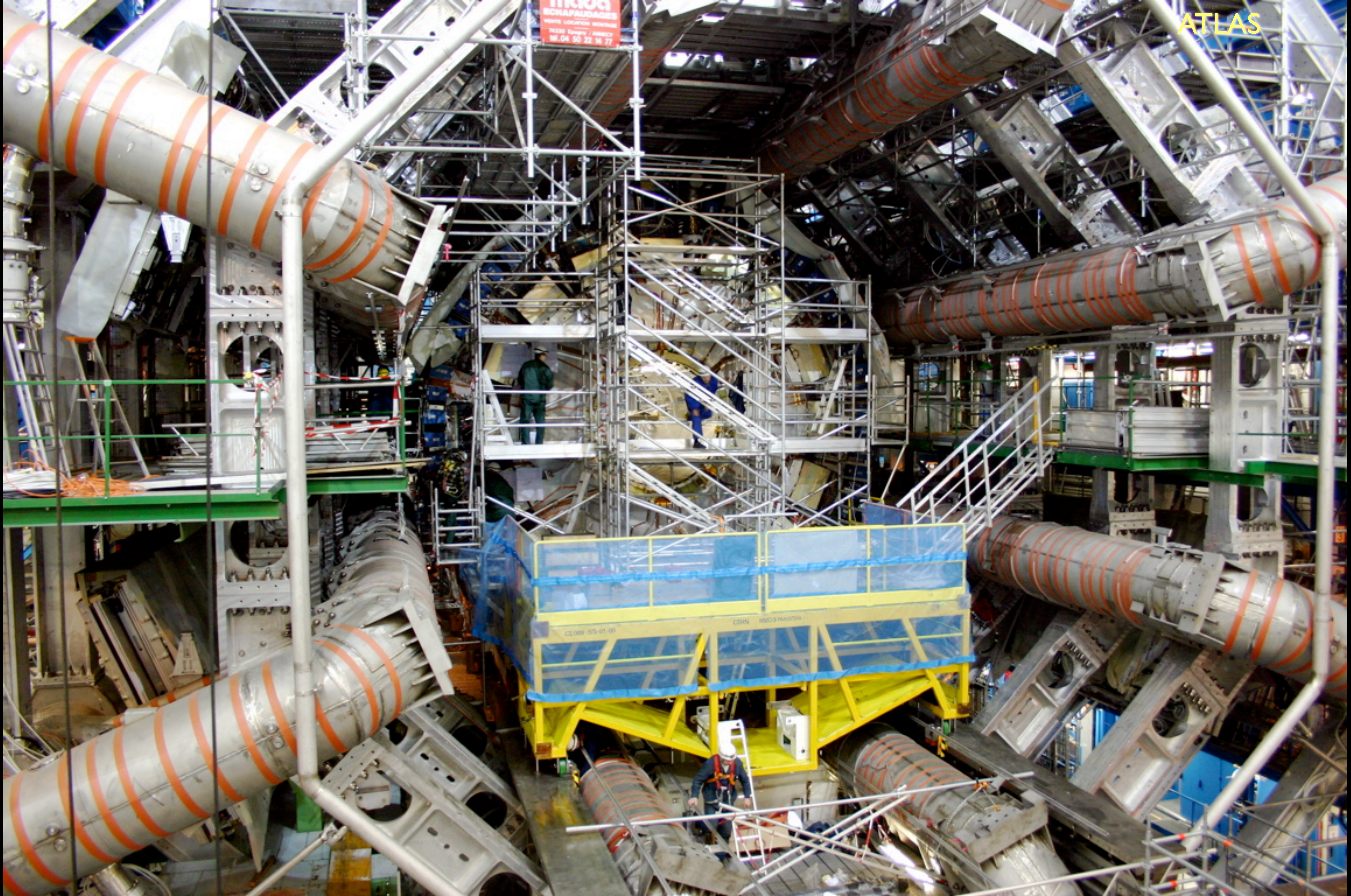

Large Hadron Collider
pp, E_{cm} = 1 TRy = 13.6 TeV
CMS
LHC*b*
ALICE
ATLAS
CERN

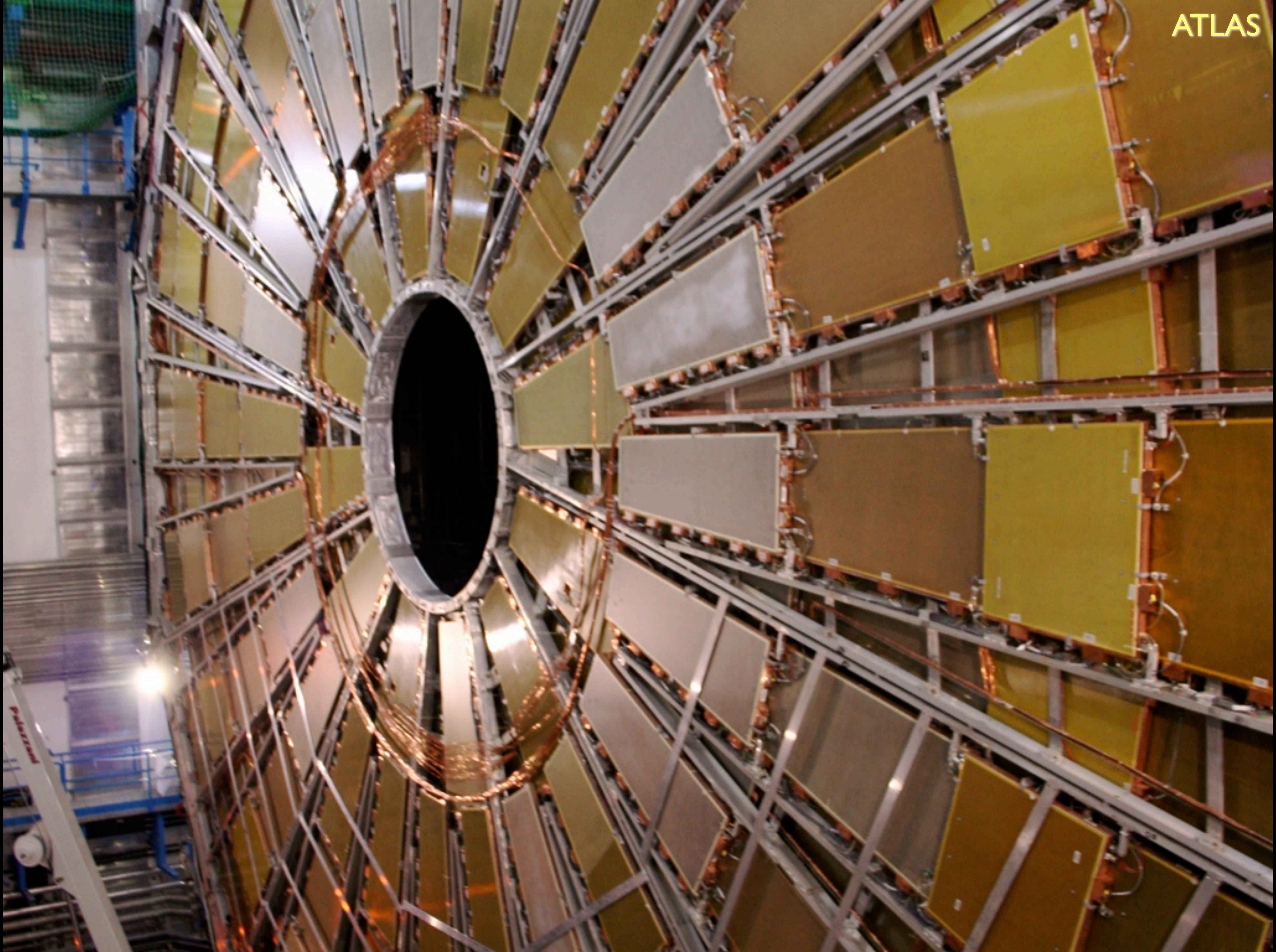

GENERAL
EMERGENCY


CMS


CMS

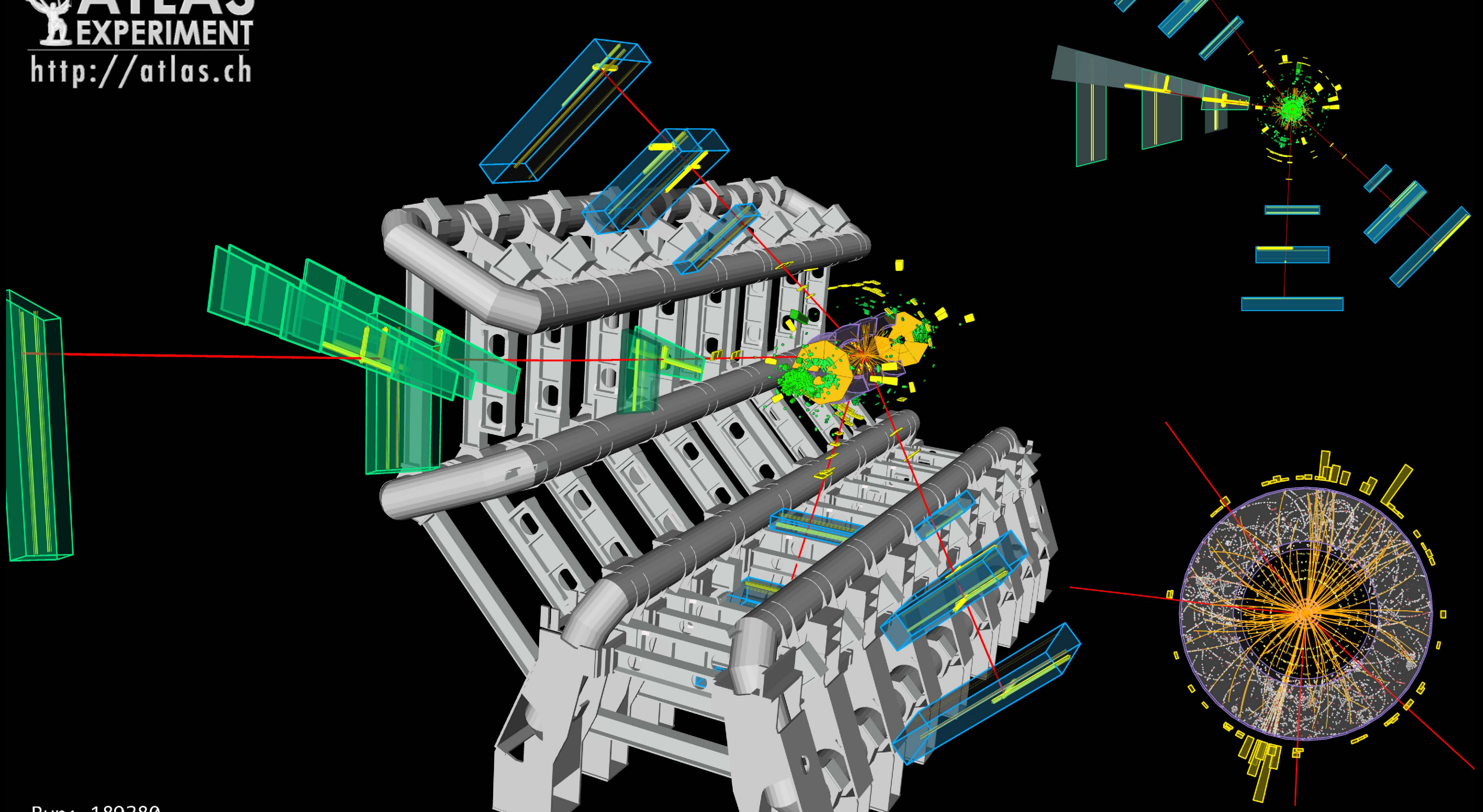

CMS
59


ATLAS


ATLAS

ATLAS EXPERIMENT
http://atlas.ch

$H(125\ \text{GeV}) \rightarrow ZZ^* \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ candidate



Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


July 4, 2012

Higgs discovery follow-ups

Refine Higgs-boson properties: (HL)-LHC, “Higgs Factory”

$e^+e^- \rightarrow H + Z$

Does *H* have partners?

How does *H* interact with itself?

Does *H* regulate *WW* scattering?

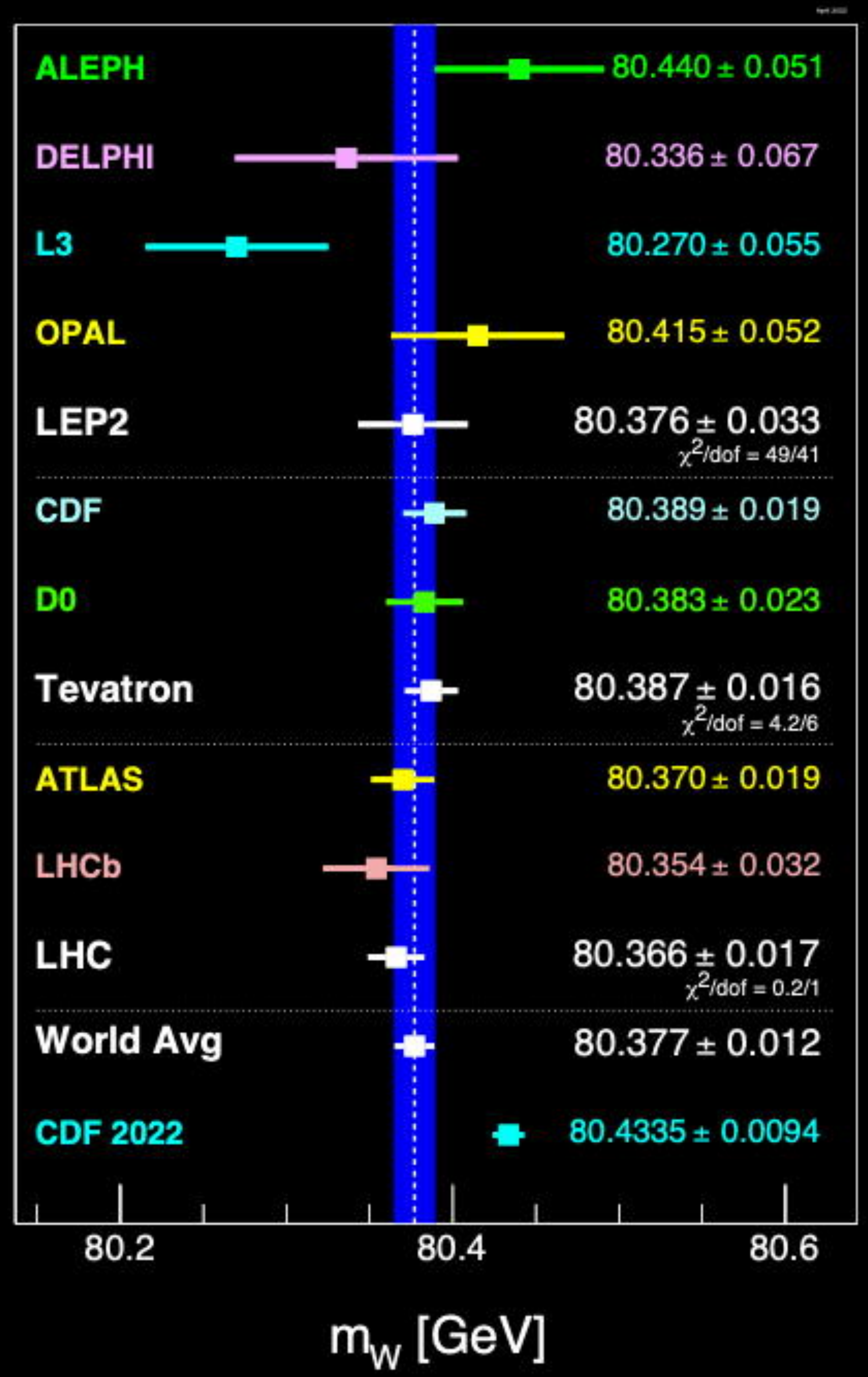
Vacuum-energy problem

→ Perspectives & (120+) Questions

→ Gedanken Worlds without Higgs


72 new hadrons at the LHC
Mass [GeV/c^2]
Date of arXiv submission
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
10.5
11.0
$b\bar{b}$
$b\bar{q}$
$c\bar{c}(q\bar{q})$
$cc\bar{q}\bar{q}$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$B_c(2S)^+$
$T_{\psi\psi}(6900)$
$T_{\psi\psi}(6600)$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Xi_b(6227)^-$
$\Xi_b(6227)^0$
$\Xi_b(6327)^0$
$\Xi_b(6333)^0$
$\Xi_b(6095)^0$
$\Xi_b(6087)^0$
$\Xi_b(5945)^0$
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Xi_b(5955)^-$
$\Xi_b'(5935)^-$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6070)^0$
$B_s^*(6114)^0$
$B_s^*(6063)^0$
$\Xi_b(6100)^-$
$X(4700)$
$X(4500)$
$X(4274)$
$X(4140)$
$P_\psi^N(4450)^+$
$P_\psi^N(4380)^+$
$P_\psi^N(4457)^+$
$P_\psi^N(4440)^+$
$P_\psi^N(4312)^+$
$\psi_3(3842)$
$X(4685)$
$X(4630)$
$T_{\psi s1}(4220)^+$
$T_{\psi s1}^\theta(4000)^+$
$T_{cc}(3875)^+$
$P_{\psi s}^\Lambda(4338)^0$
$T_{\psi s1}^\theta(4000)^0$
$X(3960)$
Ξ_{cc}^{++}
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$D_{s1}^*(2860)^+$
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$T_{cs0}(2900)^0$
$T_{cs1}(2900)^0$
$D_{s0}(2590)^+$
$\Omega_c(3327)^0$
$\Omega_c(3185)^0$
$T_{c\bar{s}0}^a(2900)^{++}$
$T_{c\bar{s}0}^a(2900)^0$

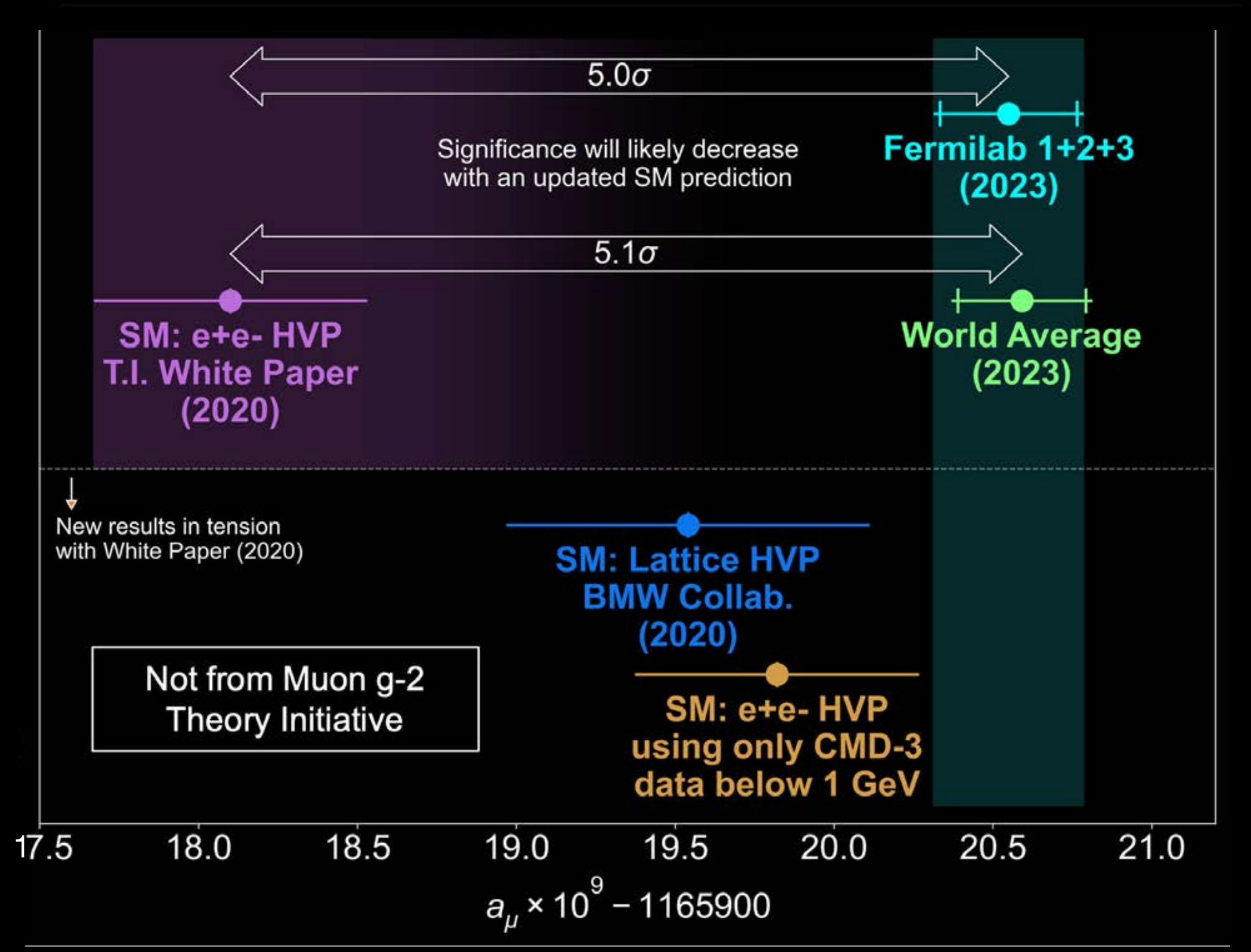
“sixth place of the decimal” and beyond …



ATLAS M_W (2024): 80.3665 ± 0.0159 GeV

CMS (2024): $a_\tau = 0.0009^{+0.0032}_{-0.0031}$

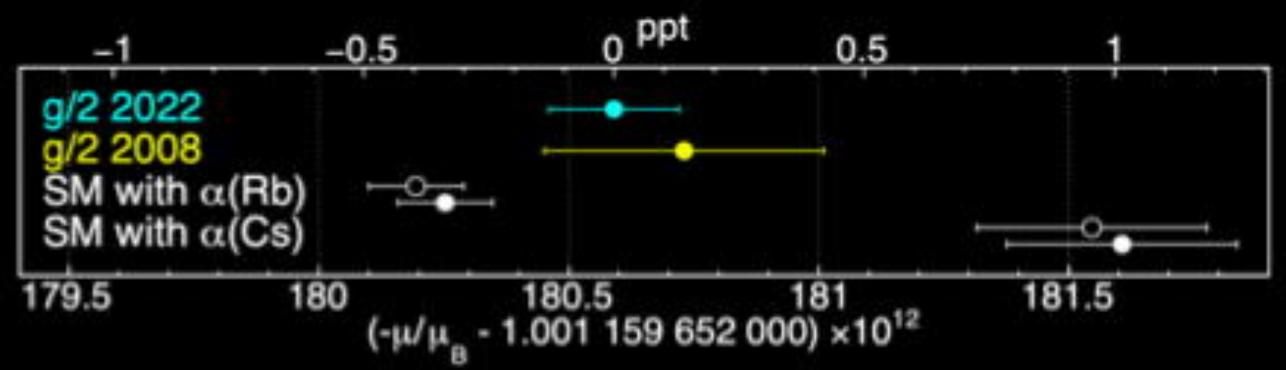
$(g-2)_\mu$



e magnetic dipole moment

measured to 0.13 ppt

$-\mu_e/\mu_B =$
$1.00115965218059(13)$



Harvard–NU

fine structure constant

Berkeley: $\alpha^{-1}(\mathrm{Cs}) =$
$137.035\,999\,046(27)$

Paris: $\alpha^{-1}(\mathrm{Rb}) =$
$137.035\,999\,206(11)$

(differ by 5.4 s.d.)

(Anti)proton magnetic moments: CPT test

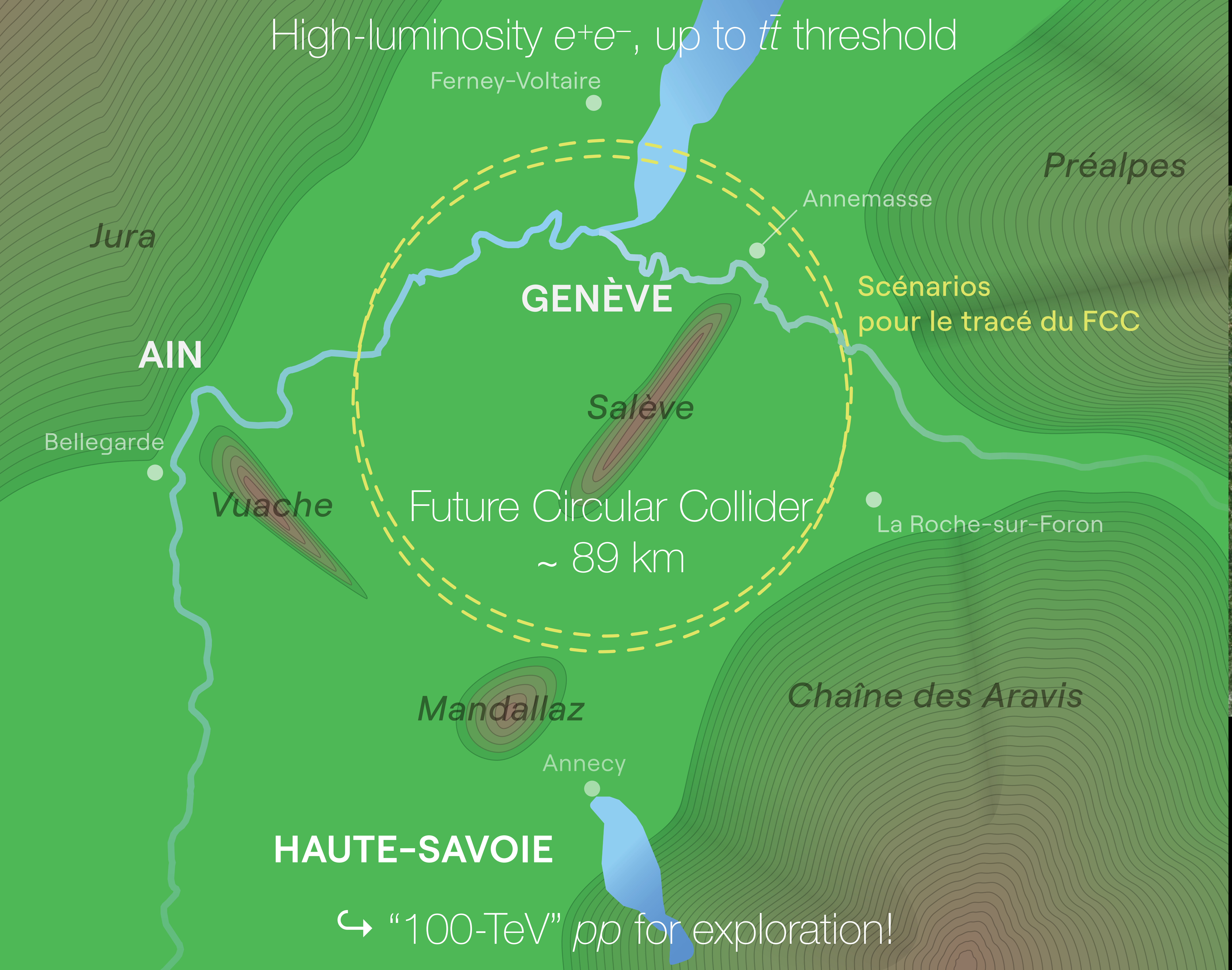
$$\mu_{\bar{p}} = -2.792\,847\,344\,1(42)\;\mu_N$$

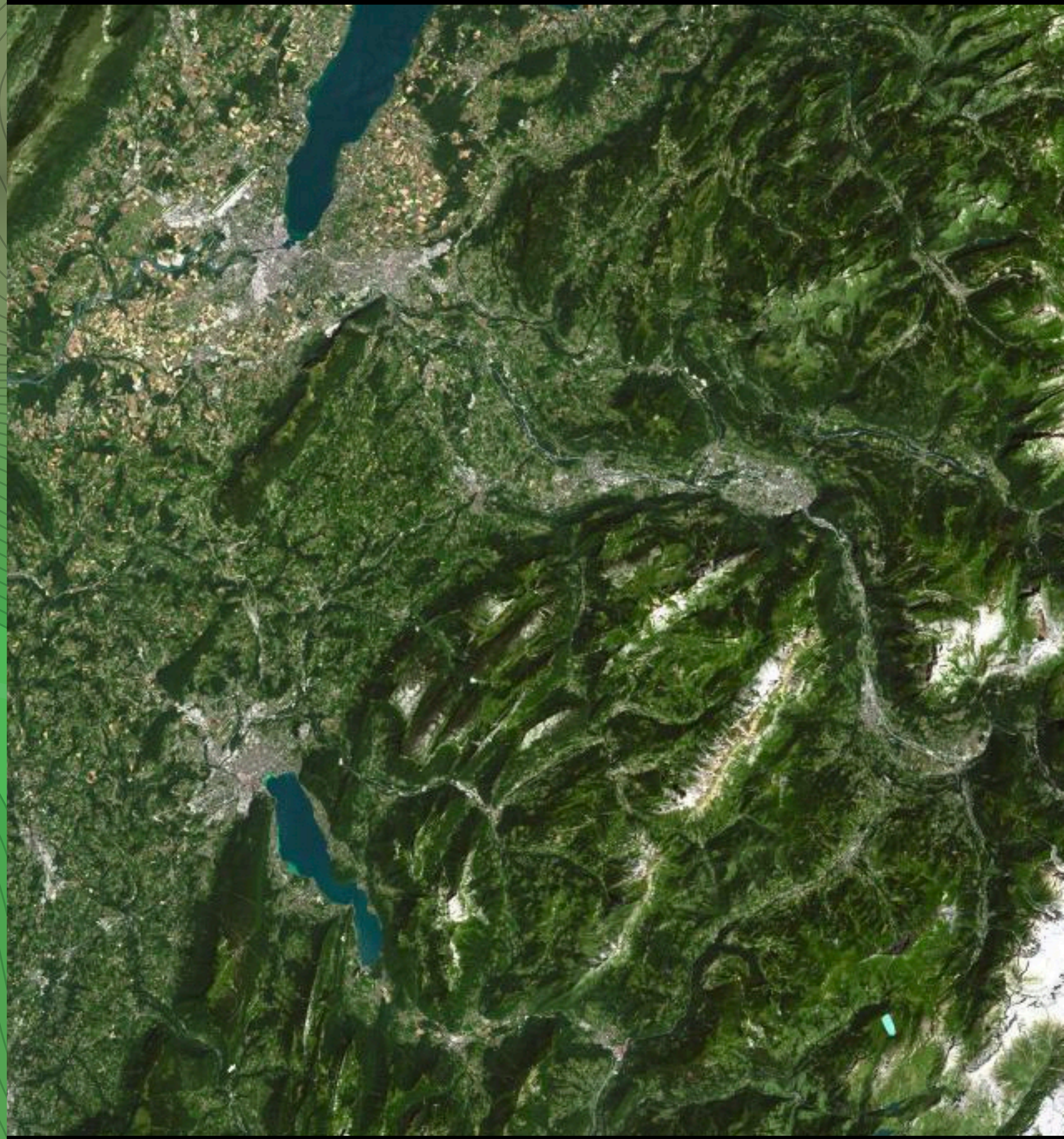
vs.

$$\mu_p = +2.792\,847\,344\,62(82)\;\mu_N$$

BASE Collaboration @CERN Antiproton Decelerator

High-luminosity e^+e^-, up to $t\bar{t}$ threshold



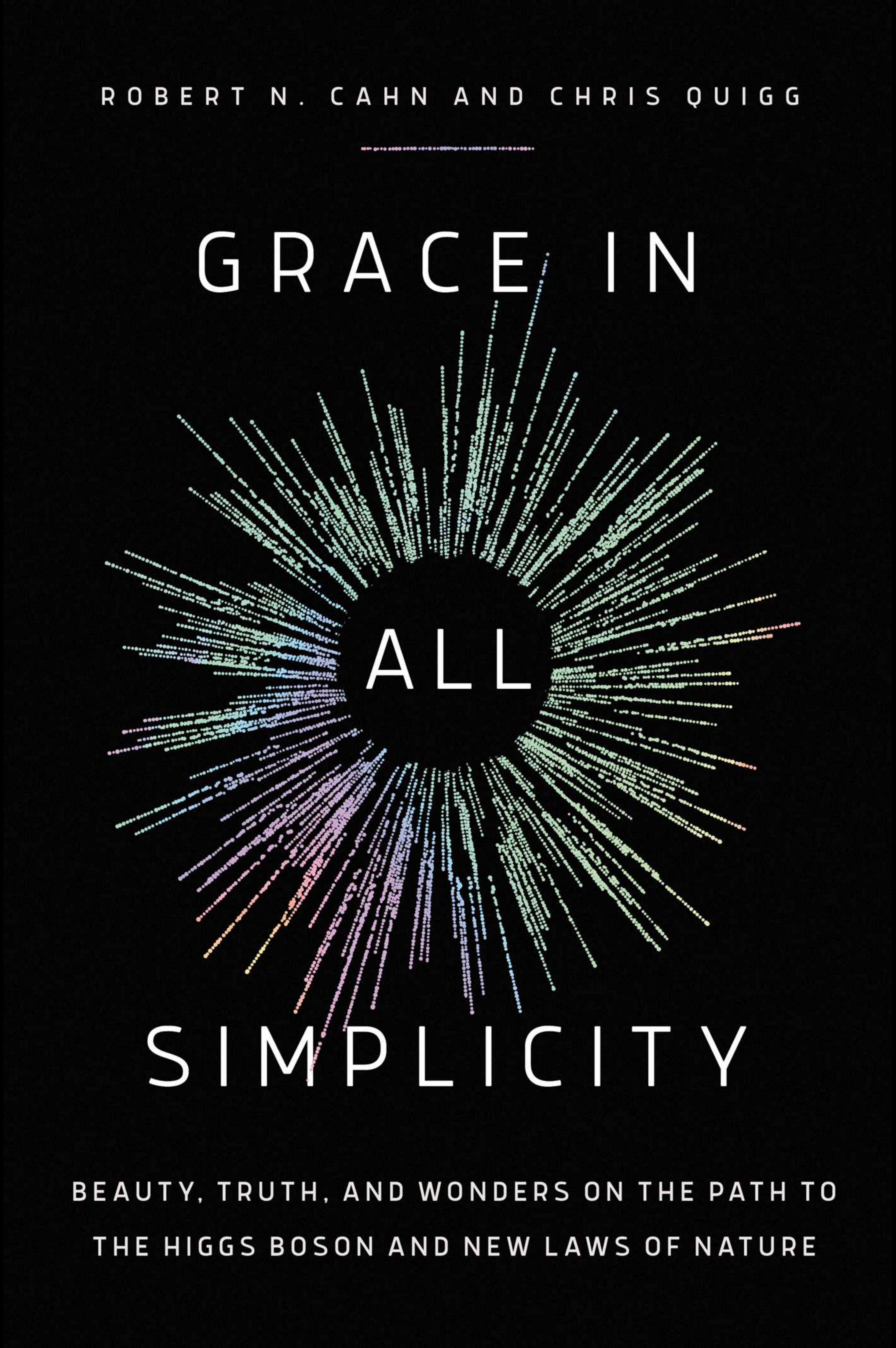


↪ "100-TeV" *pp* for exploration!

A 10-TeV μ+μ− Collider for the Nuclear Mill Centennial?

16.5 km

10 km


ROBERT N. CAHN AND CHRIS QUIGG
GRACE IN
ALL
SIMPLICITY
BEAUTY, TRUTH, AND WONDERS ON THE PATH TO
THE HIGGS BOSON AND NEW LAWS OF NATURE

From the Fermilab Design Report

Which, if any, of the particles that have so far been discovered, is, in fact, elementary, and is there any validity in the concept of "elementary" particles?

What new particles can be made at energies that have not yet been reached? Is there some set of building blocks that is still more fundamental than the neutron and the proton?

Is there a law that correctly predicts the existence and nature of all the particles, and if so, what is that law?

Will the characteristics of some of the very short-lived particles appear to be different when they are produced at such higher velocities that they no longer spend their entire lives within the strong influence of the particle from which they are produced?

Do new symmetries appear or old ones disappear for high momentum-transfer events?

What is the connection, if any, of electromagnetism and strong interactions?

Do the laws of electromagnetic radiation, which are now known to hold over an enormous range of lengths and frequencies, continue to hold in the wavelength domain characteristic of the subnuclear particles?

What is the connection between the weak interaction that is associated with the massless neutrino and the strong one that acts between neutron and proton?

Is there some new particle underlying the action of the "weak" forces, just as, in the case of the nuclear force, there are mesons, and, in the case of the electromagnetic force, there are photons? If there is not, why not?

In more technical terms: Is local field theory valid? A failure in locality may imply a failure in our concept of space. What are the fields relevant to a correct local field theory? What are the form factors of the particles? What exactly is the explanation of the electromagnetic mass difference? Do "weak" interactions become strong at sufficiently small distances? Is the Pomeranchuk theorem true? Do the total cross sections become constant at high energy? Will new symmetries appear, or old ones disappear, at higher energy?